# Axions ($A^0$) and Other Very Light Bosons, Searches for

**See the related review(s):**

Axions and Other Similar Particles

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## $A^0$ (Axion) MASS LIMITS from Astrophysics and Cosmology

These bounds depend on model-dependent assumptions (i.e. — on a combination of axion parameters).

• • • We do not use the following data for averages, fits, limits, etc. • • •

| *VALUE* (MeV) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| $>0.2$ | BARROSO | 82 | ASTR | Standard Axion |
| $>0.25$ | [1] RAFFELT | 82 | ASTR | Standard Axion |
| $>0.2$ | [2] DICUS | 78C | ASTR | Standard Axion |
| | MIKAELIAN | 78 | ASTR | Stellar emission |
| $>0.3$ | [2] SATO | 78 | ASTR | Standard Axion |
| $>0.2$ | VYSOTSKII | 78 | ASTR | Standard Axion |

[1] Lower bound from 5.5 MeV $\gamma$-ray line from the sun.

[2] Lower bound from requiring the red giants' stellar evolution not be disrupted by axion emission.

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## $A^0$ (Axion) and Other Light Boson ($X^0$) Searches in Hadron Decays

Limits are for branching ratios.

• • • We do not use the following data for averages, fits, limits, etc. • • •

| *VALUE* | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| $<4 \times 10^{-8}$ | 95 | [1] ADACHI | 23K | BEL2 | $B^+ \to K^+ X^0$ |
| $<9 \times 10^{-8}$ | 95 | [2] ADACHI | 23K | BEL2 | $B^0 \to K^*(892)^0 X^0$ $(K^*(892)^0 \to K^+ \pi^-)$ |
| $<3.7 \times 10^{-10}$ | 95 | [3] CORTINA-GIL | 23B | NA62 | $K^+ \to \pi^+ A^0 A^0$, $A^0 \to e^+ e^-$ |
| $<4.2 \times 10^{-8}$ | 90 | [4] LEES | 22B | BABR | $B^\pm \to K^\pm A^0$ $(A^0 \to \gamma\gamma)$ |
| $<7 \times 10^{-13}$ | 95 | [5] ABRATENKO | 21 | MCBN | $K^+ \to \pi^+ X^0$ $(X^0 \to e^+ e^-)$ |
| $<1.5 \times 10^{-7}$ | 90 | [6] CORTINA-GIL | 21 | NA62 | $K^+ \to \mu^+ \nu X^0$ |
| $<5 \times 10^{-11}$ | 90 | [7] CORTINA-GIL | 21A | NA62 | $K^+ \to \pi^+ X^0$ |
| $<9 \times 10^{-10}$ | 90 | [8] CORTINA-GIL | 21C | NA62 | $K^+ \to \pi^+ X^0$ |
| $<1.5 \times 10^{-8}$ | 90 | [9] PARK | 21 | BELL | $B^0 \to X^0 X^0$ $(X^0 \to e^+ e^-$, $\mu^+ \mu^-$, $\pi^+ \pi^-)$ |
| $<2.4 \times 10^{-9}$ | 90 | [10] AHN | 19 | KOTO | $K^0_L \to \pi^0 X^0$, $m_{X^0} = 135$ MeV |
| $<2 \times 10^{-10}$ | 95 | [11] AAIJ | 17AQ | LHCB | $B^+ \to K^+ X^0$ $(X^0 \to \mu^+ \mu^-)$ |
| $<3.7 \times 10^{-8}$ | 90 | [12] AHN | 17 | KOTO | $K^0_L \to \pi^0 X^0$, $m_{X^0} = 135$ MeV |
| $<6 \times 10^{-11}$ | 90 | [13] BATLEY | 17 | NA48 | $K^\pm \to \pi^\pm X^0 (X^0 \to \mu^+ \mu^-)$ |
| | | [14] WON | 16 | BELL | $\eta \to \gamma X^0$ $(X^0 \to \pi^+ \pi^-)$ |
| $<1 \times 10^{-9}$ | 95 | [15] AAIJ | 15AZ | LHCB | $B^0 \to K^{*0} X^0$ $(X^0 \to \mu^+ \mu^-)$ |
| $<1.5 \times 10^{-6}$ | 90 | [16] ADLARSON | 13 | WASA | $\pi^0 \to \gamma X^0$ $(X^0 \to e^+ e^-)$, $m_{X^0} = 100$ MeV |
| $<2 \times 10^{-8}$ | 90 | [17] BABUSCI | 13B | KLOE | $\phi \to \eta X^0$ $(X^0 \to e^+ e^-)$ |

| | | | | | |
|---|---|---|---|---|---|
| | | [18] ARCHILLI | 12 | KLOE | $\phi \to \eta X^0$, $X^0 \to e^+ e^-$ |
| $<2 \times 10^{-15}$ | 90 | [19] GNINENKO | 12A | BDMP | $\pi^0 \to \gamma X^0$ ($X^0 \to e^+ e^-$) |
| $<3 \times 10^{-14}$ | 90 | [20] GNINENKO | 12B | BDMP | $\eta(\eta') \to \gamma X^0$ ($X^0 \to e^+ e^-$) |
| $<7 \times 10^{-10}$ | 90 | [21] ADLER | 04 | B787 | $K^+ \to \pi^+ X^0$ |
| $<7.3 \times 10^{-11}$ | 90 | [22] ANISIMOVSK... | 04 | B949 | $K^+ \to \pi^+ X^0$ |
| $<4.5 \times 10^{-11}$ | 90 | [23] ADLER | 02C | B787 | $K^+ \to \pi^+ X^0$ |
| $<4 \times 10^{-5}$ | 90 | [24] ADLER | 01 | B787 | $K^+ \to \pi^+ \pi^0 A^0$ |
| $<4.9 \times 10^{-5}$ | 90 | AMMAR | 01B | CLEO | $B^\pm \to \pi^\pm (K^\pm) X^0$ |
| $<5.3 \times 10^{-5}$ | 90 | AMMAR | 01B | CLEO | $B^0 \to K^0_S X^0$ |
| $<3.3 \times 10^{-5}$ | 90 | [25] ALTEGOER | 98 | NOMD | $\pi^0 \to \gamma X^0$, $m_{X^0} < 120$ MeV |
| $<5.0 \times 10^{-8}$ | 90 | [26] KITCHING | 97 | B787 | $K^+ \to \pi^+ X^0$ ($X^0 \to \gamma\gamma$) |
| $<5.2 \times 10^{-10}$ | 90 | [27] ADLER | 96 | B787 | $K^+ \to \pi^+ X^0$ |
| $<2.8 \times 10^{-4}$ | 90 | [28] AMSLER | 96B | CBAR | $\pi^0 \to \gamma X^0$, $m_{X^0} < 65$ MeV |
| $<3 \times 10^{-4}$ | 90 | [28] AMSLER | 96B | CBAR | $\eta \to \gamma X^0$, $m_{X^0}=$ 50–200 MeV |
| $<4 \times 10^{-5}$ | 90 | [28] AMSLER | 96B | CBAR | $\eta' \to \gamma X^0$, $m_{X^0}=$ 50–925 MeV |
| $<6 \times 10^{-5}$ | 90 | [28] AMSLER | 94B | CBAR | $\pi^0 \to \gamma X^0$, $m_{X^0}$=65–125 MeV |
| $<6 \times 10^{-5}$ | 90 | [28] AMSLER | 94B | CBAR | $\eta \to \gamma X^0$, $m_{X^0}$=200–525 MeV |
| $<7 \times 10^{-3}$ | 90 | [29] MEIJERDREES | 94 | CNTR | $\pi^0 \to \gamma X^0$, $m_{X^0}$=25 MeV |
| $<2 \times 10^{-3}$ | 90 | [29] MEIJERDREES | 94 | CNTR | $\pi^0 \to \gamma X^0$, $m_{X^0}$=100 MeV |
| $<2 \times 10^{-7}$ | 90 | [30] ATIYA | 93B | B787 | Sup. by ADLER 04 |
| $<3 \times 10^{-13}$ | | [31] NG | 93 | COSM | $\pi^0 \to \gamma X^0$ |
| $<1.1 \times 10^{-8}$ | 90 | [32] ALLIEGRO | 92 | SPEC | $K^+ \to \pi^+ X^0$ ($X^0 \to e^+ e^-$) |
| $<5 \times 10^{-4}$ | 90 | [33] ATIYA | 92 | B787 | $\pi^0 \to \gamma X^0$ |
| $<1 \times 10^{-12}$ | 95 | [34] BARABASH | 92 | BDMP | $\pi^\pm \to e^\pm \nu X^0$($X^0 \to e^+ e^-$, $\gamma\gamma$), $m_{X^0} = 8$ MeV |
| $<1 \times 10^{-12}$ | 95 | [35] BARABASH | 92 | BDMP | $K^\pm \to \pi^\pm X^0$($X^0 \to e^+ e^-$, $\gamma\gamma$), $m_{X^0} = 10$ MeV |
| $<1 \times 10^{-11}$ | 95 | [36] BARABASH | 92 | BDMP | $K^0_L \to \pi^0 X^0$($X^0 \to e^+ e^-$, $\gamma\gamma$), $m_{X^0} = 10$ MeV |
| $<1 \times 10^{-14}$ | 95 | [37] BARABASH | 92 | BDMP | $\eta' \to \eta X^0$($X^0 \to e^+ e^-$, $\gamma\gamma$), $m_{X^0} = 10$ MeV |
| $<4 \times 10^{-6}$ | 90 | [38] MEIJERDREES | 92 | SPEC | $\pi^0 \to \gamma X^0$ ($X^0 \to e^+ e^-$), $m_{X^0}=$ 100 MeV |
| $<1 \times 10^{-7}$ | 90 | [39] ATIYA | 90B | B787 | Sup. by KITCHING 97 |
| $<1.3 \times 10^{-8}$ | 90 | [40] KORENCHE... | 87 | SPEC | $\pi^+ \to e^+ \nu A^0$ ($A^0 \to e^+ e^-$) |
| $<1 \times 10^{-9}$ | 90 | [41] EICHLER | 86 | SPEC | Stopped $\pi^+ \to e^+ \nu A^0$ |
| $<2 \times 10^{-5}$ | 90 | [42] YAMAZAKI | 84 | SPEC | For 160<$m$<260 MeV |
| $<(1.5–4) \times 10^{-6}$ | 90 | [42] YAMAZAKI | 84 | SPEC | $K$ decay, $m_{X^0} \ll 100$ MeV |
| | | [43] ASANO | 82 | CNTR | Stopped $K^+ \to \pi^+ X^0$ |
| | | [44] ASANO | 81B | CNTR | Stopped $K^+ \to \pi^+ X^0$ |
| | | [45] ZHITNITSKII | 79 | | Heavy axion |

[1] ADACHI 23K quoted limit is for $m_{X^0} \simeq 3$ GeV, $c\tau_{X^0} = 1$ cm, and the decay channel $X^0 \to e^+ e^-$. See their Fig. 2 for limits with different lifetimes and decay channels, $X^0 \to \mu^+ \mu^-$, $\pi^+ \pi^-$, $K^+ K^-$.

[2] ADACHI 23K quoted limit is for $m_{X^0} \simeq 2$ GeV, $c\tau_{X^0} = 1$ cm, and the decay channel $X^0 \rightarrow e^+ e^-$. See their Fig. 2 for limits with different lifetimes and decay channels, $X^0 \rightarrow \mu^+ \mu^-$, $\pi^+ \pi^-$, $K^+ K^-$.

[3] CORTINA-GIL 23B limit extends over 10–170 MeV in mass. Quoted limit is at 155 MeV.

[4] LEES 22B quoted limit is for $m_{A^0} = 3.9$ GeV, assuming the promptly decaying axion. Limits of O($10^{-7}$) are obtained for $m_{A^0} = 0.175$–4.78 GeV. See their Figs.3 and 4 for mass and lifetime dependent limits.

[5] ABRATENKO 21 quoted limit is for $m_{X^0} = 150$ MeV and the lifetime $c\tau_{X^0} = 80$ m. See their Fig. 4 for the limits in the range of $m_{X^0} = 10$–210 MeV.

[6] CORTINA-GIL 21 quoted limit is for $m_{X^0} = 370$ MeV. Limits from O($10^{-5}$) and O($10^{-6}$) are obtained for $m_{X^0} = 10$–370 MeV (see their Fig. 7).

[7] CORTINA-GIL 21A quoted limit is for $m_{X^0} = 160$–250 MeV. Limits between $5 \times 10^{-11}$ and $2 \times 10^{-10}$ are obtained in the range of $m_{X^0} = 0$–110 and 154–260 MeV, assuming stable or invisibly decaying $X^0$. See their Fig. 4 for mass- and lifetime-dependent limits.

[8] CORTINA-GIL 21C quoted limit is for $m_{X^0} = 130$–140 MeV, and limits of $9 \times 10^{-10}$–$6 \times 10^{-7}$ are obtained in the mass range of $m_{X^0} = 110$–155 MeV, assuming $X^0$ escapes detection. See their Fig. 6 for mass- and lifetime-dependent limits.

[9] PARK 21 look for dark photons produced by decays of $B^0$ through off-shell Higgs-dark Higgs mixing. See their Fig. 5 for limits in the range of $m_{X^0} = 0.01$–2.62 GeV.

[10] AHN 19 is an update of AHN 17 from a new data set. See their Fig. 4 for the limits in the range of $m_{X^0} = 0$–250 MeV.

[11] AAIJ 17AQ limit is for $\tau_{X^0} = 10$ ps. See their Fig. 4 for limits in the range of $m_{X^0} = 250$–4700 MeV and $\tau_{X^0} = 0.1$–1000 ps.

[12] AHN 17 limit as a function of $m_{X^0}$ from 0 to 250 MeV is provided in their Fig. 5.

[13] BATLEY 17 limit is for $m_{X^0} = 216$ MeV and $\tau_{X^0} \leq 10$ ps. See their Fig. 4(c) for limits in the range of $m_{X^0} = 211$–354 MeV and longer lifetimes.

[14] WON 16 look for a vector boson coupled to baryon number. Derived limits on $\alpha' < 10^{-3}$–$10^{-2}$ for $m_{X^0} = 290$–520 MeV at 95% CL. See their Fig. 4 for mass-dependent limits.

[15] AAIJ 15AZ limit is for $\tau_{X^0} = 10$ ps and $m_{X^0} = 214$–4350 MeV. See their Fig. 4 for mass- and lifetime-dependent limits.

[16] ADLARSON 13 limits between $2.0 \times 10^{-5}$ and $1.5 \times 10^{-6}$ are obtained for $m_{X^0} = 20$–100 MeV (see their Fig. 8). Angular momentum conservation requires that $X^0$ has spin $\geq 1$.

[17] BABUSCI 13B limit is for B($\phi \rightarrow \eta X^0$)·B($X^0 \rightarrow e^+ e^-$) and applies to $m_{X^0} = 410$ MeV. It is derived by analyzing $\eta \rightarrow \pi^0 \pi^0 \pi^0$ and $\pi^- \pi^+ \pi^0$. Limits between $1 \times 10^{-6}$ and $2 \times 10^{-8}$ are obtained for $m_{X^0} \leq 450$ MeV (see their Fig. 6).

[18] ARCHILLI 12 analyzed $\eta \rightarrow \pi^+ \pi^- \pi^0$ decays. Derived limits on $\alpha'/\alpha < 2 \times 10^{-5}$ for $m_{X^0} = 50$–420 MeV at 90% CL. See their Fig. 8 for mass-dependent limits.

[19] GNINENKO 12A limit is for B($\pi^0 \rightarrow \gamma X^0$)·B($X^0 \rightarrow e^+ e^-$) and applies for $m_{X^0} = 90$ MeV and $\tau_{X^0} \simeq 1 \times 10^{-8}$ sec. Limits between $10^{-8}$ and $2 \times 10^{-15}$ are obtained for $m_{X^0} = 3$–120 MeV and $\tau_{X^0} = 1 \times 10^{-11}$–1 sec. See their Fig. 3 for limits at different masses and lifetimes.

[20] GNINENKO 12B limit is for B($\eta \rightarrow \gamma X^0$)·B($X^0 \rightarrow e^+ e^-$) and applies for $m_{X^0} = 100$ MeV and $\tau_{X^0} \simeq 6 \times 10^{-9}$ sec. Limits between $10^{-5}$ and $3 \times 10^{-14}$ are obtained

for $m_{X^0} \lesssim 550$ MeV and $\tau_{X^0} = 10^{-10}$–10 sec. See their Fig. 5 for limits at different mass and lifetime and for $\eta'$ decays.

[21] ADLER 04 limit applies for a mass near 180 MeV. For other masses in the range $m_{X^0} =$ 150–250 MeV the limit is less restrictive, but still improves ADLER 02C and ATIYA 93B.

[22] ANISIMOVSKY 04 bound is for $m_{X^0}$=0.

[23] ADLER 02C bound is for $m_{X^0} <$60 MeV. See Fig. 2 for limits at higher masses.

[24] The quoted limit is for $m_{X^0} =$ 0–80 MeV. See their Fig. 5 for the limit at higher mass. The branching fraction limit assumes pure phase space decay distributions.

[25] ALTEGOER 98 looked for $X^0$ from $\pi^0$ decay which penetrate the shielding and convert to $\pi^0$ in the external Coulomb field of a nucleus.

[26] KITCHING 97 limit is for B($K^+ \rightarrow \pi^+ X^0$)·B($X^0 \rightarrow \gamma\gamma$) and applies for $m_{X^0} \simeq 50$ MeV, $\tau_{X^0} < 10^{-10}$ s. Limits are provided for 0<$m_{X^0} <$ 100 MeV, $\tau_{X^0} < 10^{-8}$ s.

[27] ADLER 96 looked for a peak in missing-mass distribution. This work is an update of ATIYA 93. The limit is for massless stable $X^0$ particles and extends to $m_{X^0}$=80 MeV at the same level. See paper for dependence on finite lifetime.

[28] AMSLER 94B and AMSLER 96B looked for a peak in missing-mass distribution.

[29] MEIJERDREES 94 limit is based on inclusive photon spectrum and is independent of $X^0$ decay modes. It applies to $\tau(X^0) > 10^{-23}$ sec.

[30] ATIYA 93B looked for a peak in missing mass distribution. The bound applies for stable $X^0$ of $m_{X^0}$=150–250 MeV, and the limit becomes stronger ($10^{-8}$) for $m_{X^0}$=180–240 MeV.

[31] NG 93 studied the production of $X^0$ via $\gamma\gamma \rightarrow \pi^0 \rightarrow \gamma X^0$ in the early universe at $T \simeq 1$ MeV. The bound on extra neutrinos from nucleosynthesis $\Delta N_\nu < 0.3$ (WALKER 91) is employed. It applies to $m_{X^0} \ll 1$ MeV in order to be relativistic down to nucleosynthesis temperature. See paper for heavier $X^0$.

[32] ALLIEGRO 92 limit applies for $m_{X^0}$=150–340 MeV and is the branching ratio times the decay probability. Limit is $< 1.5 \times 10^{-8}$ at 99%CL.

[33] ATIYA 92 looked for a peak in missing mass distribution. The limit applies to $m_{X^0}$=0–130 MeV in the narrow resonance limit. See paper for the dependence on lifetime. Covariance requires $X^0$ to be a vector particle.

[34] BARABASH 92 is a beam dump experiment that searched for a light Higgs. Limits between $1 \times 10^{-12}$ and $1 \times 10^{-7}$ are obtained for $3 < m_{X^0} < 40$ MeV.

[35] Limits between $1 \times 10^{-12}$ and 1 are obtained for $4 < m_{X^0} < 69$ MeV.

[36] Limits between $1 \times 10^{-11}$ and $5 \times 10^{-3}$ are obtained for $4 < m_{X^0} < 63$ MeV.

[37] Limits between $1 \times 10^{-14}$ and 1 are obtained for $3 < m_{X^0} < 82$ MeV.

[38] MEIJERDREES 92 limit applies for $\tau_{X^0} = 10^{-23}$–$10^{-11}$ sec. Limits between $2 \times 10^{-4}$ and $4 \times 10^{-6}$ are obtained for $m_{X^0} =$ 25–120 MeV. Angular momentum conservation requires that $X^0$ has spin $\geq 1$.

[39] ATIYA 90B limit is for B($K^+ \rightarrow \pi^+ X^0$)·B($X^0 \rightarrow \gamma\gamma$) and applies for $m_{X^0} = 50$ MeV, $\tau_{X^0} < 10^{-10}$ s. Limits are also provided for $0 < m_{X^0} < 100$ MeV, $\tau_{X^0} < 10^{-8}$ s.

[40] KORENCHENKO 87 limit assumes $m_{A^0} = 1.7$ MeV, $\tau_{A^0} \lesssim 10^{-12}$ s, and B($A^0 \rightarrow e^+ e^-$) = 1.

[41] EICHLER 86 looked for $\pi^+ \rightarrow e^+ \nu A^0$ followed by $A^0 \rightarrow e^+ e^-$. Limits on the branching fraction depend on the mass and and lifetime of $A^0$. The quoted limits are valid when $\tau(A^0) \gtrsim 3. \times 10^{-10}$s if the decays are kinematically allowed.

[42] YAMAZAKI 84 looked for a discrete line in $K^+ \rightarrow \pi^+$X. Sensitive to wide mass range (5–300 MeV), independent of whether X decays promptly or not.

[43] ASANO 82 at KEK set limits for B($K^+ \rightarrow \pi^+ X^0$) for $m_{X^0}$ <100 MeV as BR $< 4. \times 10^{-8}$ for $\tau(X^0 \rightarrow n\gamma\text{'s}) > 1. \times 10^{-9}$ s, BR $< 1.4 \times 10^{-6}$ for $\tau < 1. \times 10^{-9}$s.

[44] ASANO 81B is KEK experiment. Set B($K^+ \rightarrow \pi^+ X^0$) $< 3.8 \times 10^{-8}$ at CL = 90%.

[45] ZHITNITSKII 79 argue that a heavy axion predicted by YANG 78 (3 $<m<$40 MeV) contradicts experimental muon anomalous magnetic moments.

## $A^0$ (Axion) Searches in Quarkonium Decays

Decay or transition of quarkonium. Limits are for branching ratio.

• • • We do not use the following data for averages, fits, limits, etc. • • •

| *VALUE* | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| $<8.3 \times 10^{-8}$ | 95 | [1] ABLIKIM | 23E | BES3 | $J/\psi \rightarrow A^0\gamma$ ($A^0 \rightarrow \gamma\gamma$) |
| $<3.1 \times 10^{-7}$ | 90 | [2] JIA | 22 | BELL | $\Upsilon(1S) \rightarrow A^0\gamma(A^0 \rightarrow \mu^+\mu^-)$ |
| $<2.8 \times 10^{-8}$ | 90 | [3] ABLIKIM | 16E | BES3 | $J/\psi \rightarrow A^0\gamma$ ($A^0 \rightarrow \mu^+\mu^-$) |
| $<4 \times 10^{-7}$ | 90 | [4] ABLIKIM | 12 | BES3 | $J/\psi \rightarrow A^0\gamma$ ($A^0 \rightarrow \mu^+\mu^-$) |
| $<4.0 \times 10^{-5}$ | 90 | [5] ANTREASYAN | 90C | CBAL | $\Upsilon(1S) \rightarrow A^0\gamma$ |
| $<5 \times 10^{-5}$ | 90 | [6] DRUZHININ | 87 | ND | $\phi \rightarrow A^0\gamma$ ($A^0 \rightarrow e^+e^-$) |
| $<2 \times 10^{-3}$ | 90 | [7] DRUZHININ | 87 | ND | $\phi \rightarrow A^0\gamma$ ($A^0 \rightarrow \gamma\gamma$) |
| $<7 \times 10^{-6}$ | 90 | [8] DRUZHININ | 87 | ND | $\phi \rightarrow A^0\gamma$ ($A^0 \rightarrow$ missing) |
| $<1.4 \times 10^{-5}$ | 90 | [9] EDWARDS | 82 | CBAL | $J/\psi \rightarrow A^0\gamma$ |

[1] ABLIKIM 23E obtained limits in the range of $8.3 \times 10^{-8}$–$1.8 \times 10^{-6}$ for 0.165 GeV $\leq m_{A^0} \leq$ 2.84 GeV. See their Fig. 5 for mass-dependent limits.

[2] JIA 22 limits between $3.1 \times 10^{-7}$–$1.6 \times 10^{-5}$ were obtained for 0.22 GeV $< m_{A^0} <$ 9.2 GeV. See their Fig. 4 for mass-dependent limits.

[3] ABLIKIM 16E limits between 2.8–495.3 $\times 10^{-8}$ were obtained for 0.212 GeV $< m_{A^0} <$ 3.0 GeV. See their Fig. 5 for mass-dependent limits.

[4] ABLIKIM 12 derived limits between $4 \times 10^{-7}$–$2.1 \times 10^{-5}$ for 0.212 GeV $< m_{A^0} <$ 3.0 GeV. See their Fig. 2(c) for mass-dependent limits.

[5] ANTREASYAN 90C assume that $A^0$ does not decay in the detector.

[6] The first DRUZHININ 87 limit is valid when $\tau_{A^0}/m_{A^0} < 3 \times 10^{-13}$ s/MeV and $m_{A^0} <$ 20 MeV.

[7] The second DRUZHININ 87 limit is valid when $\tau_{A^0}/m_{A^0} < 5 \times 10^{-13}$ s/MeV and $m_{A^0} <$ 20 MeV.

[8] The third DRUZHININ 87 limit is valid when $\tau_{A^0}/m_{A^0} > 7 \times 10^{-12}$ s/MeV and $m_{A^0} <$ 200 MeV.

[9] EDWARDS 82 looked for $J/\psi \rightarrow \gamma A^0$ decays by looking for events with a single $\gamma$ [of energy $\sim$ 1/2 the $J/\psi(1S)$ mass], plus nothing else in the detector. The limit is inconsistent with the axion interpretation of the FAISSNER 81B result.

## $A^0$ (Axion) Searches in Positronium Decays

Decay or transition of positronium. Limits are for branching ratio.

• • • We do not use the following data for averages, fits, limits, etc. • • •

| *VALUE* | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| $<4.4 \times 10^{-5}$ | 90 | [1] BADERT... | 02 | CNTR | o-Ps $\rightarrow \gamma X_1 X_2$, $m_{X_1}+m_{X_2} \leq$ 900 keV |
| $<2 \times 10^{-4}$ | 90 | MAENO | 95 | CNTR | o-Ps $\rightarrow A^0\gamma$ $m_{A^0}$=850–1013 keV |
| $<3.0 \times 10^{-4}$ | 90 | [2] ASAI | 94 | CNTR | o-Ps $\rightarrow A^0\gamma$ $m_{A^0}$=30–500 keV |

| | | | | | |
|---|---|---|---|---|---|
| $<2.8 \times 10^{-5}$ | 90 | [3] AKOPYAN | 91 | CNTR | o-Ps $\to$ $A^0\gamma$ ($A^0 \to \gamma\gamma$), $m_{A^0} < 30$ keV |
| $<1.1 \times 10^{-6}$ | 90 | [4] ASAI | 91 | CNTR | o-Ps $\to$ $A^0\gamma$, $m_{A^0} < 800$ keV |
| $<3.8 \times 10^{-4}$ | 90 | GNINENKO | 90 | CNTR | o-Ps $\to$ $A^0\gamma$, $m_{A^0} < 30$ keV |
| $<(1\text{–}5) \times 10^{-4}$ | 95 | [5] TSUCHIAKI | 90 | CNTR | o-Ps $\to$ $A^0\gamma$, $m_{A^0} = 300\text{–}900$ keV |
| $<6.4 \times 10^{-5}$ | 90 | [6] ORITO | 89 | CNTR | o-Ps $\to$ $A^0\gamma$, $m_{A^0} < 30$ keV |
| | | [7] AMALDI | 85 | CNTR | Ortho-positronium |
| | | [8] CARBONI | 83 | CNTR | Ortho-positronium |

[1] BADERTSCHER 02 looked for a three-body decay of ortho-positronium into a photon and two penetrating (neutral or milli-charged) particles.

[2] The ASAI 94 limit is based on inclusive photon spectrum and is independent of $A^0$ decay modes.

[3] The AKOPYAN 91 limit applies for a short-lived $A^0$ with $\tau_{A^0} < 10^{-13}\, m_{A^0}$ [keV] s.

[4] ASAI 91 limit translates to $g^2_{A^0 e^+ e^-}/4\pi < 1.1 \times 10^{-11}$ (90% CL) for $m_{A^0} < 800$ keV.

[5] The TSUCHIAKI 90 limit is based on inclusive photon spectrum and is independent of $A^0$ decay modes.

[6] ORITO 89 limit translates to $g^2_{A^0 e e}/4\pi < 6.2 \times 10^{-10}$. Somewhat more sensitive limits are obtained for larger $m_{A^0}$: $B < 7.6 \times 10^{-6}$ at 100 keV.

[7] AMALDI 85 set limits B($A^0\gamma$) / B($\gamma\gamma\gamma$) $< (1\text{–}5) \times 10^{-6}$ for $m_{A^0} = 900\text{–}100$ keV which are about 1/10 of the CARBONI 83 limits.

[8] CARBONI 83 looked for orthopositronium $\to$ $A^0\gamma$. Set limit for $A^0$ electron coupling squared, $g(eeA^0)^2/(4\pi) < 6. \times 10^{-10}\text{–}7. \times 10^{-9}$ for $m_{A^0}$ from 150–900 keV (CL = 99.7%). This is about 1/10 of the bound from $g-2$ experiments.

## $A^0$ (Axion) Search in Photoproduction

| *VALUE* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| | [1] ADHIKARI | 22C | GLUX | $m_{A^0} = 180\text{–}480$, $600\text{–}720$ MeV |
| | [2] BASSOMPIE... | 95 | | $m_{A^0} = 1.8 \pm 0.2$ MeV |

[1] ADHIKARI 22C search for $A^0 \to \gamma\gamma$ and $A^0 \to \pi^+\pi^-\pi^0$ decays, and set limits of $f_{A^0} \lesssim 0.5\text{–}14$ GeV at 90% CL. See their Fig. 4 for mass-dependent limits.

[2] BASSOMPIERRE 95 is an extension of BASSOMPIERRE 93. They looked for a peak in the invariant mass of $e^+e^-$ pairs in the region $m_{e^+e^-} = 1.8 \pm 0.2$ MeV. They obtained bounds on the production rate $A^0$ for $\tau(A^0) = 10^{-18}\text{–}10^{-9}$ sec. They also found an excess of events in the range $m_{e^+e^-} = 2.1\text{–}3.5$ MeV.

## $A^0$ (Axion) Production in Hadron Collisions

Limits are for $\sigma(A^0)$ / $\sigma(\pi^0)$.

| *VALUE* | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| | | [1] ACCIARRI | 23 | ARNT | $A^0 \to \mu^+\mu^-$ |
| | | [2] BERTUZZO | 23 | ARNT | $A^0 \to \mu^+\mu^-$ |
| | | [3] AAD | 22J | ATLS | $H \to A^0 A^0$, $Z A^0$ ($A^0 \to \mu^+\mu^-$) |

| | | | | |
|---|---|---|---|---|
| | | [4] TUMASYAN | 22AH | CMS | $H \to A^0 A^0$, $A^0 \to e^+ e^-$, $\mu^+ \mu^-$ |
| | | [5] TUMASYAN | 22R | CMS | $p p \to A^{*0} \to Z Z$, $Z H$ |
| | | [6] AAD | 21F | ATLS | Monojet + missing $p_T$ |
| | | [7] AAD | 21K | ATLS | Mono-$\gamma$ + missing $p_T$ |
| | | [8] AAD | 21N | ATLS | $\gamma\gamma$ scatt. in Pb+Pb |
| | | [9] CARRA | 21 | ATLS | $p p \to A^{*0} \to W W$, $Z \gamma$ |
| | | [10] AAIJ | 20AL | LHCB | $p p \to X^0 \to \mu^+ \mu^-$ |
| | | [11] GAVELA | 20 | CMS | $p p \to A^{*0} \to \gamma\gamma$, $Z Z$ |
| | | [12] SIRUNYAN | 19BQ | CMS | $X^0 \to \mu^+ \mu^-$ |
| | | [13] JAIN | 07 | CNTR | $A^0 \to e^+ e^-$ |
| | | [14] AHMAD | 97 | SPEC | $e^+$ production |
| | | [15] LEINBERGER | 97 | SPEC | $A^0 \to e^+ e^-$ |
| | | [16] GANZ | 96 | SPEC | $A^0 \to e^+ e^-$ |
| | | [17] KAMEL | 96 | EMUL | $^{32}$S emulsion, $A^0 \to e^+ e^-$ |
| | | [18] BLUEMLEIN | 92 | BDMP | $A^0 N_Z \to \ell^+ \ell^- N_Z$ |
| | | [19] MEIJERDREES | 92 | SPEC | $\pi^- p \to n A^0$, $A^0 \to e^+ e^-$ |
| | | [20] BLUEMLEIN | 91 | BDMP | $A^0 \to e^+ e^-$, $2\gamma$ |
| | | [21] FAISSNER | 89 | OSPK | Beam dump, $A^0 \to e^+ e^-$ |
| | | [22] DEBOER | 88 | RVUE | $A^0 \to e^+ e^-$ |
| | | [23] EL-NADI | 88 | EMUL | $A^0 \to e^+ e^-$ |
| | | [24] FAISSNER | 88 | OSPK | Beam dump, $A^0 \to 2\gamma$ |
| | | [25] BADIER | 86 | BDMP | $A^0 \to e^+ e^-$ |
| $<2. \times 10^{-11}$ | 90 | [26] BERGSMA | 85 | CHRM | CERN beam dump |
| $<1. \times 10^{-13}$ | 90 | [26] BERGSMA | 85 | CHRM | CERN beam dump |
| | | [27] FAISSNER | 83 | OSPK | Beam dump, $A^0 \to 2\gamma$ |
| | | [28] FAISSNER | 83B | RVUE | LAMPF beam dump |
| | | [29] FRANK | 83B | RVUE | LAMPF beam dump |
| | | [30] HOFFMAN | 83 | CNTR | $\pi p \to n A^0$ ($A^0 \to e^+ e^-$) |
| | | [31] FETSCHER | 82 | RVUE | See FAISSNER 81B |
| | | [32] FAISSNER | 81 | OSPK | CERN PS $\nu$ wideband |
| | | [33] FAISSNER | 81B | OSPK | Beam dump, $A^0 \to 2\gamma$ |
| | | [34] KIM | 81 | OSPK | 26 GeV $p N \to A^0$X |
| | | [35] FAISSNER | 80 | OSPK | Beam dump, $A^0 \to e^+ e^-$ |
| $<1. \times 10^{-8}$ | 90 | [36] JACQUES | 80 | HLBC | 28 GeV protons |
| $<1. \times 10^{-14}$ | 90 | [36] JACQUES | 80 | HLBC | Beam dump |
| | | [37] SOUKAS | 80 | CALO | 28 GeV $p$ beam dump |
| | | [38] BECHIS | 79 | CNTR | |
| $<1. \times 10^{-8}$ | 90 | [39] COTEUS | 79 | OSPK | Beam dump |
| $<1. \times 10^{-3}$ | 95 | [40] DISHAW | 79 | CALO | 400 GeV $p p$ |
| $<1. \times 10^{-8}$ | 90 | ALIBRAN | 78 | HYBR | Beam dump |
| $<6. \times 10^{-9}$ | 95 | ASRATYAN | 78B | CALO | Beam dump |
| $<1.5 \times 10^{-8}$ | 90 | [41] BELLOTTI | 78 | HLBC | Beam dump |
| $<5.4 \times 10^{-14}$ | 90 | [41] BELLOTTI | 78 | HLBC | $m_{A^0}$=1.5 MeV |

| | | | | | |
|---|---|---|---|---|---|
| $<4.1 \times 10^{-9}$ | 90 | [41] BELLOTTI | 78 | HLBC | $m_{A^0}$=1 MeV |
| $<1. \times 10^{-8}$ | 90 | [42] BOSETTI | 78B | HYBR | Beam dump |
| | | [43] DONNELLY | 78 | | |
| $<0.5 \times 10^{-8}$ | 90 | HANSL | 78D | WIRE | Beam dump |
| | | [44] MICELMAC... | 78 | | |
| | | [45] VYSOTSKII | 78 | | |

[1] ACCIARRI 23 search for axions in the NuMI neutrino beam target, which are produced through mixings with mesons due to the coupling with gluons, and exclude $f_{A^0}$ around tens of TeV for $m_{A^0}$ = 0.2–0.9 GeV. They assume a slightly suppressed axion coupling to muons. See their Fig. 4 for the limits.

[2] BERTUZZO 23 employs an analysis analogous to ACCIARRI 23. They search for leptophilic axions primarily produced via $\tau \rightarrow \mu A^0$ and $\tau \rightarrow e A^0$, and exclude $f_{A^0}$ around $1 \times 10^6$–$6 \times 10^7$ GeV for $m_{A^0}$ = 0.2–1.7 GeV. See their Fig. 2 for the limits.

[3] AAD 22J set upper limits for the cross sections of $H \rightarrow A^0 A^0 \rightarrow 4\mu$ and $H \rightarrow Z A^0 \rightarrow 2\ell 2\mu$. See their Figs. 14 and 17 for the respective mass-dependent limits.

[4] TUMASYAN 22AH set the limits of $O(10^{-6})$ with respect to the product of the branching fractions of $H \rightarrow A^0 A^0$ and $A^0 \rightarrow e^+ e^-$, $\mu^+ \mu^-$. They also derive limits on the effective axion couplings contributing to $H \rightarrow A^0 A^0$ and $H \rightarrow Z A^0$. See their Figs. 5 and 7 for the limits.

[5] TUMASYAN 22R is analogous to GAVELA 20, and set a limit on the products of the axion couplings to gluons and $Z$ bosons as $G_{AZZ}\ G_{Agg} <\ 6.64 \times 10^{-7}$ GeV$^{-2}$ at 95% CL for $f_{A^0}$ = 3 TeV and $m_{A^0} <$ 100 GeV. Here we use $c_{\widetilde{G}} = G_{Agg}\ f_{A^0}/4$ and $c_{\widetilde{Z}} = G_{AZZ}\ f_{A^0}/4$ to translate their limits. They also set a limit on the product of the axion couplings to gluons and $ZH$. See their Fig. 9 for the $f_{A^0}$-dependent limits.

[6] AAD 21F look for axion production with an energetic jet and large missing $p_T$, and set a limit on the axion coupling to gluons, $c_{\widetilde{G}}/f_{A^0} < 8 \times 10^{-6}$ GeV$^{-1}$ at 95 % CL for $m_{A^0}$ = 1 MeV. Using $c_{\widetilde{G}} = \alpha_s/8\pi$, we interpret the limit as $f_{A^0} >$ 0.4 TeV for $\alpha_s \simeq$ 0.08.

[7] AAD 21K look for axion production with an energetic photon and large missing $p_T$, and set a limit on the axion coupling to a $Z$ boson and photon, $G_{AZ\gamma} < 5.1 \times 10^{-4}$ GeV$^{-1}$ at 95 % CL for $m_{A^0}$ = 1 MeV and assuming $G_{A\gamma\gamma} = 0$.

[8] AAD 21N look for axion production using the measurement of light-by-light scattering based on Pb+Pb collision data. They set the limit on the axion-photon coupling, $G_{A\gamma\gamma} < 5.3 \times 10^{-5}$–$3.4 \times 10^{-4}$ GeV$^{-1}$ at 95 % CL for $m_{A^0}$ = 6–100 GeV. Here we use $\Lambda_a = G_{A\gamma\gamma}{}^{-1}$ to translate their limits. See their Fig. 9 for mass-dependent limits.

[9] CARRA 21 is analogous to GAVELA 20, and they use the differential cross sections for $WW$ and $Z\gamma$ production measured with the ATLAS detector to set limits on the product of the axion couplings to gauge bosons as $G_{AWW}\ G_{Agg} < 6.2 \times 10^{-7}$ GeV$^{-2}$ and $G_{AZ\gamma}\ G_{Agg} < 3.7 \times 10^{-7}$ GeV$^{-2}$ at 95 % CL for $m_{A^0} \lesssim$ 100 GeV.

[10] AAIJ 20AL look for a light new boson decaying into a pair of muons using the LHCb data with an integrated luminosity of 5.1 fb$^{-1}$, and set limits on the cross section over a range of $m_{X^0}$ = 0.22–3 and 20–60 GeV. See Figs. 8 and 9 for mass-dependent limits.

[11] GAVELA 20 focus on the axion production as an s-channel off shell mediator, and use the Run 2 CMS public data to set limits on the product of the axion couplings to gluons and photons as well as $Z$ bosons as $G_{A\gamma\gamma}\ G_{Agg} < 2.8 \times 10^{-7}$ GeV$^{-2}$ and $G_{AZZ}\ G_{Agg} < 9.8 \times 10^{-7}$ GeV$^{-2}$ for $m_{A^0} \lesssim$ 200 GeV. See their Fig.3 for the limits.

[12] SIRUNYAN 19BQ look for the pair production of a new light boson decaying into a pair of muons, and set limits on the product of the production cross section times branching

fraction to dimuons squared times acceptance over a range of $m_{X^0}$ = 0.25–8.5 GeV. See the right panel of their Fig. 1 for mass-dependent limits.

[13] JAIN 07 claims evidence for $A^0 \rightarrow e^+ e^-$ produced in $^{207}$Pb collision on nuclear emulsion (Ag/Br) for $m(A^0) = 7 \pm 1$ or $19 \pm 1$ MeV and $\tau(A^0) \leq 10^{-13}$ s.

[14] AHMAD 97 reports a result of APEX Collaboration which studied positron production in $^{238}$U+$^{232}$Ta and $^{238}$U+$^{181}$Ta collisions, without requiring a coincident electron. No narrow lines were found for 250 $< E_{e^+} <$ 750 keV.

[15] LEINBERGER 97 (ORANGE Collaboration) at GSI looked for a narrow sum-energy $e^+ e^-$-line at ∼ 635 keV in $^{238}$U+$^{181}$Ta collision. Limits on the production probability for a narrow sum-energy $e^+ e^-$ line are set. See their Table 2.

[16] GANZ 96 (EPos II Collaboration) has placed upper bounds on the production cross section of $e^+ e^-$ pairs from $^{238}$U+$^{181}$Ta and $^{238}$U+$^{232}$Th collisions at GSI. See Table 2 for limits both for back-to-back and isotropic configurations of $e^+ e^-$ pairs. These limits rule out the existence of peaks in the $e^+ e^-$ sum-energy distribution, reported by an earlier version of this experiment.

[17] KAMEL 96 looked for $e^+ e^-$ pairs from the collision of $^{32}$S (200 GeV/nucleon) and emulsion. No evidence of mass peaks is found in the region of sensitivity $m_{ee} >$2 MeV.

[18] BLUEMLEIN 92 is a proton beam dump experiment at Serpukhov with a secondary target to induce Bethe-Heitler production of $e^+ e^-$ or $\mu^+ \mu^-$ from the produce $A^0$. See Fig. 5 for the excluded region in $m_{A^0}$-$x$ plane. For the standard axion, 0.3 $<x<$25 is excluded at 95% CL. If combined with BLUEMLEIN 91, 0.008 $<x<$32 is excluded.

[19] MEIJERDREES 92 give $\Gamma(\pi^- p \rightarrow n A^0) \cdot B(A^0 \rightarrow e^+ e^-) / \Gamma(\pi^- p \rightarrow \text{all}) < 10^{-5}$ (90% CL) for $m_{A^0}$ = 100 MeV, $\tau_{A^0} = 10^{-11}$–$10^{-23}$ sec. Limits ranging from 2.5 × $10^{-3}$ to $10^{-7}$ are given for $m_{A^0}$ = 25–136 MeV.

[20] BLUEMLEIN 91 is a proton beam dump experiment at Serpukhov. No candidate event for $A^0 \rightarrow e^+ e^-$, $2\gamma$ are found. Fig. 6 gives the excluded region in $m_{A^0}$-$x$ plane ($x = \tan\beta = v_2/v_1$). Standard axion is excluded for 0.2 $< m_{A^0} <$ 3.2 MeV for most $x > 1$, 0.2–11 MeV for most $x < 1$.

[21] FAISSNER 89 searched for $A^0 \rightarrow e^+ e^-$ in a proton beam dump experiment at SIN. No excess of events was observed over the background. A standard axion with mass $2m_e$–20 MeV is excluded. Lower limit on $f_{A^0}$ of $\simeq 10^4$ GeV is given for $m_{A^0} = 2m_e$–20 MeV.

[22] DEBOER 88 reanalyze EL-NADI 88 data and claim evidence for three distinct states with mass ∼ 1.1, ∼ 2.1, and ∼ 9 MeV, lifetimes $10^{-16}$–$10^{-15}$ s decaying to $e^+ e^-$ and note the similarity of the data with those of a cosmic-ray experiment by Bristol group (B.M. Anand, Proc. of the Royal Society of London, Section A **A22** 183 (1953)). For a criticism see PERKINS 89, who suggests that the events are compatible with $\pi^0$ Dalitz decay. DEBOER 89B is a reply which contests the criticism.

[23] EL-NADI 88 claim the existence of a neutral particle decaying into $e^+ e^-$ with mass 1.60 ± 0.59 MeV, lifetime (0.15 ± 0.01) × $10^{-14}$ s, which is produced in heavy ion interactions with emulsion nuclei at ∼ 4 GeV/$c$/nucleon.

[24] FAISSNER 88 is a proton beam dump experiment at SIN. They found no candidate event for $A^0 \rightarrow \gamma\gamma$. A standard axion decaying to $2\gamma$ is excluded except for a region $x \simeq 1$. Lower limit on $f_{A^0}$ of $10^2$–$10^3$ GeV is given for $m_{A^0}$ = 0.1–1 MeV.

[25] BADIER 86 did not find long-lived $A^0$ in 300 GeV $\pi^-$ Beam Dump Experiment that decays into $e^+ e^-$ in the mass range $m_{A^0}$ = (20–200) MeV, which excludes the $A^0$ decay constant $f(A^0)$ in the interval (60–600) GeV. See their figure 6 for excluded region on $f(A^0)$-$m_{A^0}$ plane.

[26] BERGSMA 85 look for $A^0 \rightarrow 2\gamma$, $e^+ e^-$, $\mu^+ \mu^-$. First limit above is for $m_{A^0}$ = 1 MeV; second is for 200 MeV. See their figure 4 for excluded region on $f_{A^0} - m_{A^0}$ plane,

where $f_{A^0}$ is $A^0$ decay constant. For Peccei-Quinn PECCEI 77 $A^0$, $m_{A^0}$ <180 keV and $\tau$ >0.037 s. (CL = 90%). For the axion of FAISSNER 81B at 250 keV, BERGSMA 85 expect 15 events but observe zero.

[27] FAISSNER 83 observed 19 1-$\gamma$ and 12 2-$\gamma$ events where a background of 4.8 and 2.3 respectively is expected. A small-angle peak is observed even if iron wall is set in front of the decay region.

[28] FAISSNER 83B extrapolate SIN $\gamma$ signal to LAMPF $\nu$ experimental condition. Resulting 370 $\gamma$'s are not at variance with LAMPF upper limit of 450 $\gamma$'s. Derived from LAMPF limit that $\left[d\sigma(A^0)/d\omega \text{ at } 90^\circ\right] m_{A^0}/\tau_{A^0} < 14 \times 10^{-35}$ cm$^2$ sr$^{-1}$ MeV ms$^{-1}$. See comment on FRANK 83B.

[29] FRANK 83B stress the importance of LAMPF data bins with negative net signal. By statistical analysis say that LAMPF and SIN-A0 are at variance when extrapolation by phase-space model is done. They find LAMPF upper limit is 248 not 450 $\gamma$'s. See comment on FAISSNER 83B.

[30] HOFFMAN 83 set CL = 90% limit $d\sigma/dt$ B($e^+e^-$) $< 3.5 \times 10^{-32}$ cm$^2$/GeV$^2$ for 140 $< m_{A^0}$ <160 MeV. Limit assumes $\tau(A^0) < 10^{-9}$ s.

[31] FETSCHER 82 reanalyzes SIN beam-dump data of FAISSNER 81. Claims no evidence for axion since 2-$\gamma$ peak rate remarkably decreases if iron wall is set in front of the decay region.

[32] FAISSNER 81 see excess $\mu e$ events. Suggest axion interactions.

[33] FAISSNER 81B is SIN 590 MeV proton beam dump. Observed 14.5 ± 5.0 events of $2\gamma$ decay of long-lived neutral penetrating particle with $m_{2\gamma} \lesssim 1$ MeV. Axion interpretation with $\eta$-$A^0$ mixing gives $m_{A^0} = 250 \pm 25$ keV, $\tau_{(2\gamma)} = (7.3 \pm 3.7) \times 10^{-3}$ s from above rate. See critical remarks below in comments of FETSCHER 82, FAISSNER 83, FAISSNER 83B, FRANK 83B, and BERGSMA 85. Also see in the next subsection ALEKSEEV 82B, CAVAIGNAC 83, and ANANEV 85.

[34] KIM 81 analyzed 8 candidates for $A^0 \rightarrow 2\gamma$ obtained by Aachen-Padova experiment at CERN with 26 GeV protons on Be. Estimated axion mass is about 300 keV and lifetime is $(0.86\sim 5.6) \times 10^{-3}$ s depending on models. Faissner (private communication), says axion production underestimated and mass overestimated. Correct value around 200 keV.

[35] FAISSNER 80 is SIN beam dump experiment with 590 MeV protons looking for $A^0 \rightarrow e^+e^-$ decay. Assuming $A^0/\pi^0 = 5.5 \times 10^{-7}$, obtained decay rate limit 20/($A^0$ mass) MeV/s (CL = 90%), which is about $10^{-7}$ below theory and interpreted as upper limit to $m_{A^0} < 2m_{e^-}$.

[36] JACQUES 80 is a BNL beam dump experiment. First limit above comes from nonobservation of excess neutral-current-type events $\left[\sigma(\text{production})\sigma(\text{interaction}) < 7. \times 10^{-68}\right.$ cm$^4$, CL = 90%$\left.\right]$. Second limit is from nonobservation of axion decays into $2\gamma$'s or $e^+e^-$, and for axion mass a few MeV.

[37] SOUKAS 80 at BNL observed no excess of neutral-current-type events in beam dump.

[38] BECHIS 79 looked for the axion production in low energy electron Bremsstrahlung and the subsequent decay into either $2\gamma$ or $e^+e^-$. No signal found. CL = 90% limits for model parameter(s) are given.

[39] COTEUS 79 is a beam dump experiment at BNL.

[40] DISHAW 79 is a calorimetric experiment and looks for low energy tail of energy distributions due to energy lost to weakly interacting particles.

[41] BELLOTTI 78 first value comes from search for $A^0 \rightarrow e^+e^-$. Second value comes from search for $A^0 \rightarrow 2\gamma$, assuming mass $< 2m_{e^-}$. For any mass satisfying this, limit is above value×(mass$^{-4}$). Third value uses data of PL 60B 401 and quotes $\sigma$(production)$\sigma$(interaction) $< 10^{-67}$ cm$^4$.

[42] BOSETTI 78B quotes $\sigma$(production)$\sigma$(interaction) $< 2. \times 10^{-67}$ cm$^4$.

[43] DONNELLY 78 examines data from reactor neutrino experiments of REINES 76 and GURR 74 as well as SLAC beam dump experiment. Evidence is negative.

[44] MICELMACHER 78 finds no evidence of axion existence in reactor experiments of REINES 76 and GURR 74. (See reference under DONNELLY 78 below).

[45] VYSOTSKII 78 derived lower limit for the axion mass 25 keV from luminosity of the sun and 200 keV from red supergiants.

## $A^0$ (Axion) Searches in Reactor Experiments

• • • We do not use the following data for averages, fits, limits, etc. • • •

| *VALUE* | *DOCUMENT ID* | *TECN* | *COMMENT* |
|---|---|---|---|
| | [1] CHANG 07 | | Primakoff or Compton |
| | [2] ALTMANN 95 | CNTR | Reactor; $A^0 \to e^+e^-$ |
| | [3] KETOV 86 | SPEC | Reactor, $A^0 \to \gamma\gamma$ |
| | [4] KOCH 86 | SPEC | Reactor; $A^0 \to \gamma\gamma$ |
| | [5] DATAR 82 | CNTR | Light water reactor |
| | [6] VUILLEUMIER 81 | CNTR | Reactor, $A^0 \to 2\gamma$ |

[1] CHANG 07 looked for monochromatic photons from Primakoff or Compton conversion of axions from the Kuo-Sheng reactor due to axion coupling to photon or electron, respectively. The search places model-independent limits on the products $G_{A\gamma\gamma}G_{ANN}$ and $G_{Aee}G_{ANN}$ for $m(A^0)$ less than the MeV range.

[2] ALTMANN 95 looked for $A^0$ decaying into $e^+e^-$ from the Bugey 5 nuclear reactor. They obtain an upper limit on the $A^0$ production rate of $\omega(A^0)/\omega(\gamma) \times \mathrm{B}(A^0 \to e^+e^-) < 10^{-16}$ for $m_{A^0} = 1.5$ MeV at 90% CL. The limit is weaker for heavier $A^0$. In the case of a standard axion, this limit excludes a mass in the range $2m_e < m_{A^0} < 4.8$ MeV at 90% CL. See Fig. 5 of their paper for exclusion limits of axion-like resonances $Z^0$ in the $(m_{X^0}, f_{X^0})$ plane.

[3] KETOV 86 searched for $A^0$ at the Rovno nuclear power plant. They found an upper limit on the $A^0$ production probability of $0.8\ [100\ \mathrm{keV}/m_{A^0}]^6 \times 10^{-6}$ per fission. In the standard axion model, this corresponds to $m_{A^0} > 150$ keV. Not valid for $m_{A^0} \gtrsim 1$ MeV.

[4] KOCH 86 searched for $A^0 \to \gamma\gamma$ at nuclear power reactor Biblis A. They found an upper limit on the $A^0$ production rate of $\omega(A^0)/\omega(\gamma(M1)) < 1.5 \times 10^{-10}$ (CL=95%). Standard axion with $m_{A^0} = 250$ keV gives $10^{-5}$ for the ratio. Not valid for $m_{A^0} > 1022$ keV.

[5] DATAR 82 looked for $A^0 \to 2\gamma$ in neutron capture ($np \to dA^0$) at Tarapur 500 MW reactor. Sensitive to sum of $I = 0$ and $I = 1$ amplitudes. With ZEHNDER 81 $[(I = 0) - (I = 1)]$ result, assert nonexistence of standard $A^0$.

[6] VUILLEUMIER 81 is at Grenoble reactor. Set limit $m_{A^0} < 280$ keV.

## $A^0$ (Axion) and Other Light Boson ($X^0$) Searches in Nuclear Transitions

Limits are for branching ratio.

• • • We do not use the following data for averages, fits, limits, etc. • • •

| *VALUE* | *CL%* | *DOCUMENT ID* | *TECN* | *COMMENT* |
|---|---|---|---|---|
| $< 8.89 \times 10^{-6}$ | 90 | [1] DERBIN 23 | CNTR | M1 transition of $^{169}$Tm |
| $< 8.5 \times 10^{-6}$ | 90 | [2] DERBIN 02 | CNTR | $^{125m}$Te decay |

| | | | | | |
|---|---|---|---|---|---|
| | | [3] DEBOER | 97C | RVUE | M1 transitions |
| $< 5.5 \times 10^{-10}$ | 95 | [4] TSUNODA | 95 | CNTR | $^{252}$Cf fission, $A^0 \to ee$ |
| $< 1.2 \times 10^{-6}$ | 95 | [5] MINOWA | 93 | CNTR | $^{139}\text{La}^* \to {}^{139}\text{La}\,A^0$ |
| $< 2 \times 10^{-4}$ | 90 | [6] HICKS | 92 | CNTR | $^{35}$S decay, $A^0 \to \gamma\gamma$ |
| $< 1.5 \times 10^{-9}$ | 95 | [7] ASANUMA | 90 | CNTR | $^{241}$Am decay |
| $<(0.4\text{–}10) \times 10^{-3}$ | 95 | [8] DEBOER | 90 | CNTR | $^{8}\text{Be}^* \to {}^{8}\text{Be}\,A^0$, $A^0 \to e^+e^-$ |
| $<(0.2\text{–}1) \times 10^{-3}$ | 90 | [9] BINI | 89 | CNTR | $^{16}\text{O}^* \to {}^{16}\text{O}\,X^0$, $X^0 \to e^+e^-$ |
| | | [10] AVIGNONE | 88 | CNTR | $\text{Cu}^* \to \text{Cu}\,A^0$ ($A^0 \to 2\gamma$, $A^0 e \to \gamma e$, $A^0 Z \to \gamma Z$) |
| $< 1.5 \times 10^{-4}$ | 90 | [11] DATAR | 88 | CNTR | $^{12}\text{C}^* \to {}^{12}\text{C}\,A^0$, $A^0 \to e^+e^-$ |
| $< 5 \times 10^{-3}$ | 90 | [12] DEBOER | 88C | CNTR | $^{16}\text{O}^* \to {}^{16}\text{O}\,X^0$, $X^0 \to e^+e^-$ |
| $< 3.4 \times 10^{-5}$ | 95 | [13] DOEHNER | 88 | SPEC | $^{2}\text{H}^*$, $A^0 \to e^+e^-$ |
| $< 4 \times 10^{-4}$ | 95 | [14] SAVAGE | 88 | CNTR | Nuclear decay (isovector) |
| $< 3 \times 10^{-3}$ | 95 | [14] SAVAGE | 88 | CNTR | Nuclear decay (isoscalar) |
| $<10.6 \times 10^{-2}$ | 90 | [15] HALLIN | 86 | SPEC | $^{6}$Li isovector decay |
| $<10.8$ | 90 | [15] HALLIN | 86 | SPEC | $^{10}$B isoscalar decays |
| $< 2.2$ | 90 | [15] HALLIN | 86 | SPEC | $^{14}$N isoscalar decays |
| $< 4 \times 10^{-4}$ | 90 | [16] SAVAGE | 86B | CNTR | $^{14}\text{N}^*$ |
| | | [17] ANANEV | 85 | CNTR | $\text{Li}^*$, deut$^*$ $A^0 \to 2\gamma$ |
| | | [18] CAVAIGNAC | 83 | CNTR | $^{97}\text{Nb}^*$, deut$^*$ transition $A^0 \to 2\gamma$ |
| | | [19] ALEKSEEV | 82B | CNTR | $\text{Li}^*$, deut$^*$ transition $A^0 \to 2\gamma$ |
| | | [20] LEHMANN | 82 | CNTR | $\text{Cu}^* \to \text{Cu}\,A^0$ ($A^0 \to 2\gamma$) |
| | | [21] ZEHNDER | 82 | CNTR | $\text{Li}^*$, $\text{Nb}^*$ decay, *n*-capt. |
| | | [22] ZEHNDER | 81 | CNTR | $\text{Ba}^* \to \text{Ba}\,A^0$ ($A^0 \to 2\gamma$) |
| | | [23] CALAPRICE | 79 | | Carbon |

[1] DERBIN 23 use a thallium garnet bolometric detector to search for the 8.4 keV solar axion line emitted from the M1 nuclear transition of $^{169}$Tm. Their limits are equivalent to an upper bound on the KSVZ and DFSZ axion masses of 141 eV and 244 eV, respectively.

[2] DERBIN 02 looked for the axion emission in an M1 transition in $^{125m}$Te decay. They looked for a possible presence of a shifted energy spectrum in gamma rays due to the undetected axion.

[3] DEBOER 97C reanalyzed the existent data on Nuclear M1 transitions and find that a 9 MeV boson decaying into $e^+e^-$ would explain the excess of events with large opening angles. See also DEBOER 01 for follow-up experiments.

[4] TSUNODA 95 looked for axion emission when $^{252}$Cf undergoes a spontaneous fission, with the axion decaying into $e^+e^-$. The bound is for $m_{A^0}$=40 MeV. It improves to $2.5 \times 10^{-5}$ for $m_{A^0}$=200 MeV.

[5] MINOWA 93 studied chain process, $^{139}\text{Ce} \to {}^{139}\text{La}^*$ by electron capture and M1 transition of $^{139}\text{La}^*$ to the ground state. It does not assume decay modes of $A^0$. The bound applies for $m_{A^0} < 166$ keV.

[6] HICKS 92 bound is applicable for $\tau_{X^0} < 4 \times 10^{-11}$ sec.

[7] The ASANUMA 90 limit is for the branching fraction of $X^0$ emission per $^{241}\text{Am}\,\alpha$ decay and valid for $\tau_{X^0} < 3 \times 10^{-11}$ s.

[8] The DEBOER 90 limit is for the branching ratio $^8$Be$^*$ (18.15 MeV, $1^+$) $\rightarrow$ $^8$Be$A^0$, $A^0 \rightarrow e^+e^-$ for the mass range $m_{A^0}$ = 4–15 MeV.

[9] The BINI 89 limit is for the branching fraction of $^{16}$O$^*$(6.05 MeV, $0^+$) $\rightarrow$ $^{16}$O$X^0$, $X^0 \rightarrow e^+e^-$ for $m_X$ = 1.5–3.1 MeV. $\tau_{X^0} \lesssim 10^{-11}$ s is assumed. The spin-parity of $X$ is restricted to $0^+$ or $1^-$.

[10] AVIGNONE 88 looked for the 1115 keV transition C$^*$ $\rightarrow$ Cu$A^0$, either from $A^0 \rightarrow 2\gamma$ in-flight decay or from the secondary $A^0$ interactions by Compton and by Primakoff processes. Limits for axion parameters are obtained for $m_{A^0} < 1.1$ MeV.

[11] DATAR 88 rule out light pseudoscalar particle emission through its decay $A^0 \rightarrow e^+e^-$ in the mass range 1.02–2.5 MeV and lifetime range $10^{-13}$–$10^{-8}$ s. The above limit is for $\tau = 5 \times 10^{-13}$ s and $m$ = 1.7 MeV; see the paper for the $\tau$-$m$ dependence of the limit.

[12] The limit is for the branching fraction of $^{16}$O$^*$(6.05 MeV, $0^+$) $\rightarrow$ $^{16}$O$X^0$, $X^0 \rightarrow e^+e^-$ against internal pair conversion for $m_{X^0}$ = 1.7 MeV and $\tau_{X^0} < 10^{-11}$ s. Similar limits are obtained for $m_{X^0}$ = 1.3–3.2 MeV. The spin parity of $X^0$ must be either $0^+$ or $1^-$. The limit at 1.7 MeV is translated into a limit for the $X^0$-nucleon coupling constant: $g^2_{X^0 NN}/4\pi < 2.3 \times 10^{-9}$.

[13] The DOEHNER 88 limit is for $m_{A^0}$ = 1.7 MeV, $\tau(A^0) < 10^{-10}$ s. Limits less than $10^{-4}$ are obtained for $m_{A^0}$ = 1.2–2.2 MeV.

[14] SAVAGE 88 looked for $A^0$ that decays into $e^+e^-$ in the decay of the 9.17 MeV $J^P = 2^+$ state in $^{14}$N, 17.64 MeV state $J^P = 1^+$ in $^8$Be, and the 18.15 MeV state $J^P = 1^+$ in $^8$Be. This experiment constrains the isovector coupling of $A^0$ to hadrons, if $m_{A^0}$ = (1.1 $\rightarrow$ 2.2) MeV and the isoscalar coupling of $A^0$ to hadrons, if $m_{A^0}$ = (1.1 $\rightarrow$ 2.6) MeV. Both limits are valid only if $\tau(A^0) \lesssim 1 \times 10^{-11}$ s.

[15] Limits are for $\Gamma(A^0(1.8\text{ MeV}))/\Gamma(\pi\text{M1})$; i.e., for 1.8 MeV axion emission normalized to the rate for internal emission of $e^+e^-$ pairs. Valid for $\tau_{A^0} < 2 \times 10^{-11}$s. $^6$Li isovector decay data strongly disfavor PECCEI 86 model I, whereas the $^{10}$B and $^{14}$N isoscalar decay data strongly reject PECCEI 86 model II and III.

[16] SAVAGE 86B looked for $A^0$ that decays into $e^+e^-$ in the decay of the 9.17 MeV $J^P = 2^+$ state in $^{14}$N. Limit on the branching fraction is valid if $\tau_{A^0} \lesssim 1. \times 10^{-11}$s for $m_{A^0}$ = (1.1–1.7) MeV. This experiment constrains the iso-vector coupling of $A^0$ to hadrons.

[17] ANANEV 85 with IBR-2 pulsed reactor exclude standard $A^0$ at CL = 95% masses below 470 keV (Li* decay) and below $2m_e$ for deuteron* decay.

[18] CAVAIGNAC 83 at Bugey reactor exclude axion at any $m_{^{97}\text{Nb}^*\text{decay}}$ and axion with $m_{A^0}$ between 275 and 288 keV (deuteron* decay).

[19] ALEKSEEV 82 with IBR-2 pulsed reactor exclude standard $A^0$ at CL = 95% mass-ranges $m_{A^0}$ <400 keV (Li* decay) and 330 keV $< m_{A^0} <$2.2 MeV. (deuteron* decay).

[20] LEHMANN 82 obtained $A^0 \rightarrow 2\gamma$ rate $< 6.2 \times 10^{-5}$/s (CL = 95%) excluding $m_{A^0}$ between 100 and 1000 keV.

[21] ZEHNDER 82 used Gosgen 2.8GW light-water reactor to check $A^0$ production. No $2\gamma$ peak in Li$^*$, Nb$^*$ decay (both single $p$ transition) nor in $n$ capture (combined with previous Ba$^*$ negative result) rules out standard $A^0$. Set limit $m_{A^0}$ <60 keV for any $A^0$.

[22] ZEHNDER 81 looked for Ba$^*$ $\rightarrow$ $A^0$Ba transition with $A^0 \rightarrow 2\gamma$. Obtained $2\gamma$ coincidence rate $< 2.2 \times 10^{-5}$/s (CL = 95%) excluding $m_{A^0}$ >160 keV (or 200 keV depending on Higgs mixing). However, see BARROSO 81.

[23] CALAPRICE 79 saw no axion emission from excited states of carbon. Sensitive to axion mass between 1 and 15 MeV.

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## $A^0$ (Axion) Limits from Its Electron Coupling

Limits are for $\tau(A^0 \rightarrow e^+ e^-)$.

• • • We do not use the following data for averages, fits, limits, etc. • • •

| *VALUE* (s) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| | | [1] ANDREEV | 21 | NA64 | $e N \rightarrow e A^0 N$ ($A^0 \rightarrow$ invisibles) |
| | | [2] ANDREEV | 21B | NA64 | $e N \rightarrow e A^0 N$ ($A^0 \rightarrow e e$) |
| none $4 \times 10^{-16}$–$4.5 \times 10^{-12}$ | 90 | [3] BROSS | 91 | BDMP | $e N \rightarrow e A^0 N$ ($A^0 \rightarrow e e$) |
| | | [4] GUO | 90 | BDMP | $e N \rightarrow e A^0 N$ ($A^0 \rightarrow e e$) |
| | | [5] BJORKEN | 88 | CALO | $A \rightarrow e^+ e^-$ or $2\gamma$ |
| | | [6] BLINOV | 88 | MD1 | $e e \rightarrow e e A^0$ ($A^0 \rightarrow e e$) |
| none $1 \times 10^{-14}$–$1 \times 10^{-10}$ | 90 | [7] RIORDAN | 87 | BDMP | $e N \rightarrow e A^0 N$ ($A^0 \rightarrow e e$) |
| none $1 \times 10^{-14}$–$1 \times 10^{-11}$ | 90 | [8] BROWN | 86 | BDMP | $e N \rightarrow e A^0 N$ ($A^0 \rightarrow e e$) |
| none $6 \times 10^{-14}$–$9 \times 10^{-11}$ | 95 | [9] DAVIER | 86 | BDMP | $e N \rightarrow e A^0 N$ ($A^0 \rightarrow e e$) |
| none $3 \times 10^{-13}$–$1 \times 10^{-7}$ | 90 | [10] KONAKA | 86 | BDMP | $e N \rightarrow e A^0 N$ ($A^0 \rightarrow e e$) |

[1] ANDREEV 21 look for invisible decays of axions coupled to electrons, and set limits on $g_{Aee} < 4.6 \times 10^{-6}$–$3.1 \times 10^{-3}$ for $m_{A^0} = 10^{-3}$–1 GeV. This limits the axion contribution to the electron $g-2$ to an order of magnitude less than the current experimental uncertainty. See their Figs. 3 and 4 for mass-dependent limits.

[2] ANDREEV 21B set limits on $g_{Aee}$ in the range of $6.3 \times 10^{-6}$–$1.6 \times 10^{-3}$ for $m_{A^0} =$ 2–17 MeV at 90% CL. This excludes $6.6 \times 10^{-5} < g_{Aee} < 1 \times 10^{-4}$ at $m_{A^0} =$ 16.7 MeV corresponding to the ATOMKI anomaly. See their Fig. 2 for mass-dependent limits.

[3] The listed BROSS 91 limit is for $m_{A^0} = 1.14$ MeV. $B(A^0 \rightarrow e^+ e^-) = 1$ assumed. Excluded domain in the $\tau_{A^0}$–$m_{A^0}$ plane extends up to $m_{A^0} \approx 7$ MeV (see Fig. 5). Combining with electron $g-2$ constraint, axions coupling only to $e^+ e^-$ ruled out for $m_{A^0} < 4.8$ MeV (90% CL).

[4] GUO 90 use the same apparatus as BROWN 86 and improve the previous limit in the shorter lifetime region. Combined with $g-2$ constraint, axions coupling only to $e^+ e^-$ are ruled out for $m_{A^0} < 2.7$ MeV (90% CL).

[5] BJORKEN 88 reports limits on axion parameters ($f_A$, $m_A$, $\tau_A$) for $m_{A^0} < 200$ MeV from electron beam-dump experiment with production via Primakoff photoproduction, bremsstrahlung from electrons, and resonant annihilation of positrons on atomic electrons.

[6] BLINOV 88 assume zero spin, $m = 1.8$ MeV and lifetime $< 5 \times 10^{-12}$ s and find $\Gamma(A^0 \rightarrow \gamma\gamma) B(A^0 \rightarrow e^+ e^-) < 2$ eV (CL=90%).

[7] Assumes $A^0 \gamma\gamma$ coupling is small and hence Primakoff production is small. Their figure 2 shows limits on axions for $m_{A^0} < 15$ MeV.

[8] Uses electrons in hadronic showers from an incident 800 GeV proton beam. Limits for $m_{A^0} < 15$ MeV are shown in their figure 3.

[9] $m_{A^0} = 1.8$ MeV assumed. The excluded domain in the $\tau_{A^0}$–$m_{A^0}$ plane extends up to $m_{A^0} \approx 14$ MeV, see their figure 4.

[10] The limits are obtained from their figure 3. Also given is the limit on the $A^0\gamma\gamma$–$A^0e^+e^-$ coupling plane by assuming Primakoff production.

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## Search for $A^0$ (Axion) Resonance in Bhabha Scattering

The limit is for $\Gamma(A^0)[B(A^0 \to e^+e^-)]^2$.

| *VALUE* ($10^{-3}$ eV) | *CL%* | *DOCUMENT ID* | *TECN* | *COMMENT* |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $<$ 1.3 | 97 | [1] HALLIN 92 | CNTR | $m_{A^0}$ = 1.75–1.88 MeV |
| none 0.0016–0.47 | 90 | [2] HENDERSON 92C | CNTR | $m_{A^0}$= 1.5–1.86 MeV |
| $<$ 2.0 | 90 | [3] WU 92 | CNTR | $m_{A^0}$= 1.56–1.86 MeV |
| $<$ 0.013 | 95 | TSERTOS 91 | CNTR | $m_{A^0}$ = 1.832 MeV |
| none 0.19–3.3 | 95 | [4] WIDMANN 91 | CNTR | $m_{A^0}$= 1.78–1.92 MeV |
| $<$ 5 | 97 | BAUER 90 | CNTR | $m_{A^0}$ = 1.832 MeV |
| none 0.09–1.5 | 95 | [5] JUDGE 90 | CNTR | $m_{A^0}$ = 1.832 MeV, elastic |
| $<$ 1.9 | 97 | [6] TSERTOS 89 | CNTR | $m_{A^0}$ = 1.82 MeV |
| $<$(10–40) | 97 | [6] TSERTOS 89 | CNTR | $m_{A^0}$ = 1.51–1.65 MeV |
| $<$(1–2.5) | 97 | [6] TSERTOS 89 | CNTR | $m_{A^0}$ = 1.80–1.86 MeV |
| $<$ 31 | 95 | LORENZ 88 | CNTR | $m_{A^0}$ = 1.646 MeV |
| $<$ 94 | 95 | LORENZ 88 | CNTR | $m_{A^0}$ = 1.726 MeV |
| $<$ 23 | 95 | LORENZ 88 | CNTR | $m_{A^0}$ = 1.782 MeV |
| $<$ 19 | 95 | LORENZ 88 | CNTR | $m_{A^0}$ = 1.837 MeV |
| $<$ 3.8 | 97 | [7] TSERTOS 88 | CNTR | $m_{A^0}$ = 1.832 MeV |
| | | [8] VANKLINKEN 88 | CNTR | |
| | | [9] MAIER 87 | CNTR | |
| $<$2500 | 90 | MILLS 87 | CNTR | $m_{A^0}$ = 1.8 MeV |
| | | [10] VONWIMMER. 87 | CNTR | |

[1] HALLIN 92 quote limits on lifetime, $8 \times 10^{-14}$ – $5 \times 10^{-13}$ sec depending on mass, assuming $B(A^0 \to e^+e^-) = 100\%$. They say that TSERTOS 91 overstated their sensitivity by a factor of 3.

[2] HENDERSON 92C exclude axion with lifetime $\tau_{A^0}$=$1.4 \times 10^{-12}$ – $4.0 \times 10^{-10}$ s, assuming $B(A^0 \to e^+e^-)$=100%. HENDERSON 92C also exclude a vector boson with $\tau$=$1.4 \times 10^{-12}$ – $6.0 \times 10^{-10}$ s.

[3] WU 92 quote limits on lifetime $> 3.3 \times 10^{-13}$ s assuming $B(A^0 \to e^+e^-)$=100%. They say that TSERTOS 89 overestimate the limit by a factor of $\pi/2$. WU 92 also quote a bound for vector boson, $\tau > 8.2 \times 10^{-13}$ s.

[4] WIDMANN 91 bound applies exclusively to the case $B(A^0 \to e^+e^-)$=1, since the detection efficiency varies substantially as $\Gamma(A^0)_{\text{total}}$ changes. See their Fig. 6.

[5] JUDGE 90 excludes an elastic pseudoscalar $e^+e^-$ resonance for $4.5 \times 10^{-13}$ s $< \tau(A^0) < 7.5 \times 10^{-12}$ s (95% CL) at $m_{A^0}$ = 1.832 MeV. Comparable limits can be set for $m_{A^0}$ = 1.776–1.856 MeV.

[6] See also TSERTOS 88B in references.

[7] The upper limit listed in TSERTOS 88 is too large by a factor of 4. See TSERTOS 88B, footnote 3.

[8] VANKLINKEN 88 looked for relatively long-lived resonance ($\tau = 10^{-10}$–$10^{-12}$ s). The sensitivity is not sufficient to exclude such a narrow resonance.

[9] MAIER 87 obtained limits $R\Gamma \lesssim$ 60 eV (100 eV) at $m_{A^0} \simeq$ 1.64 MeV (1.83 MeV) for energy resolution $\Delta E_{\text{cm}} \simeq$ 3 keV, where $R$ is the resonance cross section normalized to that of Bhabha scattering, and $\Gamma = \Gamma^2_{ee}/\Gamma_{\text{total}}$. For a discussion implying that $\Delta E_{\text{cm}} \simeq$ 10 keV, see TSERTOS 89.

[10] VONWIMMERSPERG 87 measured Bhabha scattering for $E_{\text{cm}}$ = 1.37–1.86 MeV and found a possible peak at 1.73 with $\int \sigma dE_{\text{cm}} = 14.5 \pm 6.8$ keV·b. For a comment and a reply, see VANKLINKEN 88B and VONWIMMERSPERG 88. Also see CONNELL 88.

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## Search for $A^0$ (Axion) Resonance in $e^+e^- \rightarrow \gamma\gamma$

The limit is for $\Gamma(A^0 \rightarrow e^+e^-)\cdot\Gamma(A^0 \rightarrow \gamma\gamma)/\Gamma_{\text{total}}$

| *VALUE* ($10^{-3}$ eV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $<$ 0.18 | 95 | VO | 94 | CNTR | $m_{A^0}$=1.1 MeV |
| $<$ 1.5 | 95 | VO | 94 | CNTR | $m_{A^0}$=1.4 MeV |
| $<$12 | 95 | VO | 94 | CNTR | $m_{A^0}$=1.7 MeV |
| $<$ 6.6 | 95 | [1] TRZASKA | 91 | CNTR | $m_{A^0}$ = 1.8 MeV |
| $<$ 4.4 | 95 | WIDMANN | 91 | CNTR | $m_{A^0}$= 1.78–1.92 MeV |
| | | [2] FOX | 89 | CNTR | |
| $<$ 0.11 | 95 | [3] MINOWA | 89 | CNTR | $m_{A^0}$ = 1.062 MeV |
| $<$33 | 97 | CONNELL | 88 | CNTR | $m_{A^0}$ = 1.580 MeV |
| $<$42 | 97 | CONNELL | 88 | CNTR | $m_{A^0}$ = 1.642 MeV |
| $<$73 | 97 | CONNELL | 88 | CNTR | $m_{A^0}$ = 1.782 MeV |
| $<$79 | 97 | CONNELL | 88 | CNTR | $m_{A^0}$ = 1.832 MeV |

[1] TRZASKA 91 also give limits in the range (6.6–30) × $10^{-3}$ eV (95%CL) for $m_{A^0}$ = 1.6–2.0 MeV.

[2] FOX 89 measured positron annihilation with an electron in the source material into two photons and found no signal at 1.062 MeV ($<$ 9 × $10^{-5}$ of two-photon annihilation at rest).

[3] Similar limits are obtained for $m_{A^0}$ = 1.045–1.085 MeV.

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## Search for $X^0$ (Light Boson) Resonance in $e^+e^- \rightarrow \gamma\gamma\gamma$

The limit is for $\Gamma(X^0 \rightarrow e^+e^-)\cdot\Gamma(X^0 \rightarrow \gamma\gamma\gamma)/\Gamma_{\text{total}}$. $C$ invariance forbids spin-0 $X^0$ coupling to both $e^+e^-$ and $\gamma\gamma\gamma$.

| *VALUE* ($10^{-3}$ eV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $<$ 0.2 | 95 | [1] VO | 94 | CNTR | $m_{X^0}$=1.1–1.9 MeV |
| $<$ 1.0 | 95 | [2] VO | 94 | CNTR | $m_{X^0}$=1.1 MeV |
| $<$ 2.5 | 95 | [2] VO | 94 | CNTR | $m_{X^0}$=1.4 MeV |
| $<$120 | 95 | [2] VO | 94 | CNTR | $m_{X^0}$=1.7 MeV |
| $<$ 3.8 | 95 | [3] SKALSEY | 92 | CNTR | $m_{X^0}$= 1.5 MeV |

[1] VO 94 looked for $X^0 \rightarrow \gamma\gamma\gamma$ decaying at rest. The precise limits depend on $m_{X^0}$. See Fig. 2(b) in paper.

[2] VO 94 looked for $X^0 \to \gamma\gamma\gamma$ decaying in flight.

[3] SKALSEY 92 also give limits 4.3 for $m_{X^0} = 1.54$ and 7.5 for 1.64 MeV. The spin of $X^0$ is assumed to be one.

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## Light Boson ($X^0$) Search in Nonresonant $e^+e^-$ Annihilation at Rest

Limits are for the ratio of $n\gamma +\ X^0$ production relative to $\gamma\gamma$.

• • • We do not use the following data for averages, fits, limits, etc. • • •

| *VALUE* (units $10^{-6}$) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| $< 4.2$ | 90 | [1] MITSUI | 96 | CNTR | $\gamma X^0$ |
| $< 4$ | 68 | [2] SKALSEY | 95 | CNTR | $\gamma X^0$ |
| $<40$ | 68 | [3] SKALSEY | 95 | RVUE | $\gamma X^0$ |
| $< 0.18$ | 90 | [4] ADACHI | 94 | CNTR | $\gamma\gamma X^0$, $X^0 \to \gamma\gamma$ |
| $< 0.26$ | 90 | [5] ADACHI | 94 | CNTR | $\gamma\gamma X^0$, $X^0 \to \gamma\gamma$ |
| $< 0.33$ | 90 | [6] ADACHI | 94 | CNTR | $\gamma X^0$, $X^0 \to \gamma\gamma\gamma$ |

[1] MITSUI 96 looked for a monochromatic $\gamma$. The bound applies for a vector $X^0$ with $C=-1$ and $m_{X^0}$ <200 keV. They derive an upper bound on $eeX^0$ coupling and hence on the branching ratio B($o$-Ps $\to \gamma\gamma X^0$)$< 6.2 \times 10^{-6}$. The bounds weaken for heavier $X^0$.

[2] SKALSEY 95 looked for a monochromatic $\gamma$ without an accompanying $\gamma$ in $e^+e^-$ annihilation. The bound applies for scalar and vector $X^0$ with $C = -1$ and $m_{X^0}$ = 100–1000 keV.

[3] SKALSEY 95 reinterpreted the bound on $\gamma A^0$ decay of $o$-Ps by ASAI 91 where 3% of delayed annihilations are not from $^3S_1$ states. The bound applies for scalar and vector $X^0$ with $C = -1$ and $m_{X^0}$ = 0–800 keV.

[4] ADACHI 94 looked for a peak in the $\gamma\gamma$ invariant mass distribution in $\gamma\gamma\gamma\gamma$ production from $e^+e^-$ annihilation. The bound applies for $m_{X^0}$ = 70–800 keV.

[5] ADACHI 94 looked for a peak in the missing-mass mass distribution in $\gamma\gamma$ channel, using $\gamma\gamma\gamma\gamma$ production from $e^+e^-$ annihilation. The bound applies for $m_{X^0}$ <800 keV.

[6] ADACHI 94 looked for a peak in the missing mass distribution in $\gamma\gamma\gamma$ channel, using $\gamma\gamma\gamma\gamma$ production from $e^+e^-$ annihilation. The bound applies for $m_{X^0}$ = 200–900 keV.

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## Searches for Goldstone Bosons ($X^0$)

(Including Horizontal Bosons and Majorons.) Limits are for branching ratios.

• • • We do not use the following data for averages, fits, limits, etc. • • •

| *VALUE* | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| | | [1] ADACHI | 23A | BEL2 | $\tau^- \to e^- X^0$, Familon |
| | | [2] ADACHI | 23A | BEL2 | $\tau^- \to \mu^- X^0$, Familon |
| | | [3] FIORILLO | 23 | ASTR | Majoron, SN 1987A |
| | | [4] SANDNER | 23 | COSM | Majoron, CMB |
| | | [5] COLOMA | 22A | BORX | $\nu e$ non-standard interactions |
| $<4.3 \times 10^{-6}$ | 90 | [6] AGUILAR-AR... | 21A | PIEN | $\pi \to \mu\nu X^0$, Majoron |
| $<5.2 \times 10^{-8}$ | 90 | [7] AGUILAR-AR... | 21A | PIEN | $\pi \to e\nu X^0$, Majoron |
| $<9 \times 10^{-6}$ | 90 | [8] AGUILAR-AR... | 20 | PIEN | $\mu^+ \to e^+ X^0$, Familon |
| $<7 \times 10^{-12}$ | 90 | [9] BALDINI | 20 | MEG | $\mu^+ \to e^+ X^0$ ($X^0 \to \gamma\gamma$), Familon |
| $<9 \times 10^{-6}$ | 90 | [10] BAYES | 15 | TWST | $\mu^+ \to e^+ X^0$, Familon |

| | | | | | |
|---|---|---|---|---|---|
| | | [11] LATTANZI | 13 | COSM | Majoron dark matter decay |
| | | [12] LESSA | 07 | RVUE | Meson, $\ell$ decays to Majoron |
| | | [13] FARZAN | 03 | ASTR | Majoron, SN cooling |
| | | [14] DIAZ | 98 | THEO | $H^0 \rightarrow X^0 X^0$, $A^0 \rightarrow X^0 X^0 X^0$, Majoron |
| | | [15] BOBRAKOV | 91 | | Electron quasi-magnetic interaction |
| $<3.3 \times 10^{-2}$ | 95 | [16] ALBRECHT | 90E | ARG | $\tau \rightarrow \mu X^0$. Familon |
| $<1.8 \times 10^{-2}$ | 95 | [16] ALBRECHT | 90E | ARG | $\tau \rightarrow e X^0$. Familon |
| $<6.4 \times 10^{-9}$ | 90 | [17] ATIYA | 90 | B787 | $K^+ \rightarrow \pi^+ X^0$. Familon |
| $<1.4 \times 10^{-5}$ | 90 | [18] BALKE | 88 | CNTR | $\mu^+ \rightarrow e^+ X^0$. Familon |
| $<1.1 \times 10^{-9}$ | 90 | [19] BOLTON | 88 | CBOX | $\mu^+ \rightarrow e^+ \gamma X^0$. Familon |
| | | [20] CHANDA | 88 | ASTR | Sun, Majoron |
| | | [21] CHOI | 88 | ASTR | Majoron, SN 1987A |
| $<5 \times 10^{-6}$ | 90 | [22] PICCIOTTO | 88 | CNTR | $\pi \rightarrow e \nu X^0$, Majoron |
| $<1.3 \times 10^{-9}$ | 90 | [23] GOLDMAN | 87 | CNTR | $\mu \rightarrow e \gamma X^0$. Familon |
| $<3 \times 10^{-4}$ | 90 | [24] BRYMAN | 86B | RVUE | $\mu \rightarrow e X^0$. Familon |
| $<1 \times 10^{-10}$ | 90 | [25] EICHLER | 86 | SPEC | $\mu^+ \rightarrow e^+ X^0$. Familon |
| $<2.6 \times 10^{-6}$ | 90 | [26] JODIDIO | 86 | SPEC | $\mu^+ \rightarrow e^+ X^0$. Familon |
| | | [27] BALTRUSAIT... | 85 | MRK3 | $\tau \rightarrow \ell X^0$. Familon |
| | | [28] DICUS | 83 | COSM | $\nu(\text{hvy}) \rightarrow \nu(\text{light}) X^0$ |

[1] ADACHI 23A set limits in the range of $1.1 \times 10^{-3}$–$9.7 \times 10^{-3}$ for $0 < m_{X^0} < 1.6$ GeV on $\mathrm{B}(\tau^- \rightarrow e^- X^0)/\mathrm{B}(\tau^- \rightarrow e^- \overline{\nu}_e \nu_\tau)$. See their Fig. 2 for mass-dependent limits.

[2] ADACHI 23A set limits in the range of $7 \times 10^{-4}$–$1.22 \times 10^{-2}$ for $0 < m_{X^0} < 1.6$ GeV on $\mathrm{B}(\tau^- \rightarrow \mu^- X^0)/\mathrm{B}(\tau^- \rightarrow \mu^- \overline{\nu}_\mu \nu_\tau)$. See their Fig. 2 for mass-dependent limits.

[3] FIORILLO 23 used data from Kamiokande-II and IMB on the neutrino flux from SN1987A to constrain the universal neutrino Majoron Yukawa coupling, $g$. They set an upper limit of $g\, m_{X^0} \lesssim 10^{-9}$ MeV for Majoron masses 100 eV $\lesssim m_{X^0} \lesssim$ 100 MeV, using neutrino coalescence as production of Majorons which then decay back to neutrinos. See their Fig. 1 for the mass-dependent limits.

[4] SANDNER 23 study Majoron production via neutrino inverse decay and use Planck data to constrain the neutrino Majoron Yukawa coupling to $g \lesssim 2 \times 10^{-13}$–$1 \times 10^{-12}$ for Majoron masses $m_{X^0} =$ 1–10 eV. See their Fig. 1 for mass-dependent limits.

[5] COLOMA 22A used the spectral data of Borexino Phase II to constrain the neutrino non-standard interaction with electrons mediated by a scalar or a pseudoscalar. Limits on the universal coupling to neutrinos and electrons between $2 \times 10^{-6}$ and $10^{-4}$ are obtained for $m_{X^0} \lesssim$ 30–40 MeV. See their Fig. 6 for mass-dependent limits.

[6] AGUILAR-AREVALO 21A quoted limit applies to $m_{X^0} = 33.9$ MeV. Limits between $4.3 \times 10^{-6}$ and $7.5 \times 10^{-5}$ are obtained for $0 < m_{X^0} < 33.9$ MeV. The lifetime of $X^0$ is assumed to be long enough. See their Fig. 6 for mass-dependent limits.

[7] AGUILAR-AREVALO 21A quoted limit applies to $m_{X^0} = 85$ MeV. Limits between $5.2 \times 10^{-8}$ and $1.4 \times 10^{-6}$ are obtained for $0 < m_{X^0} < 120$ MeV, which improve the limits of PICCIOTTO 88 by an order of magnitude. The lifetime of $X^0$ is assumed to be long enough. See their Fig. 4 for mass-dependent limits.

[8] AGUILAR-AREVALO 20 obtained limits of order $10^{-5}$ for $m_{X^0} =$ 47.8–95.1 MeV. The quoted limit applies to $m_{X^0} = 75$ MeV. See their Fig. 1 for mass-dependent limits.

[9] BALDINI 20 obtained limits for $m_{X^0} =$ 20–45 MeV and $\tau_{X^0} < 40$ ps, and supersedes BOLTON 88 for $m_{X^0} =$ 20–40 MeV. See their Fig. 17 for mass-dependent limits.

[10] BAYES 15 limits are the average over $m_{X^0}$ = 13–80 MeV for the isotropic decay distribution of positrons. See their Fig. 4 and Table II for the mass-dependent limits as well as the dependence on the decay anisotropy. In particular, they find a limit $< 58 \times 10^{-6}$ at 90% CL for massless familons and for the same asymmetry as normal muon decay, a case not covered by JODIDIO 86.

[11] LATTANZI 13 use WMAP 9 year data as well as X-ray and $\gamma$-ray observations to derive limits on decaying majoron dark matter. A limit on the decay width $\Gamma(X^0 \rightarrow \nu\overline{\nu}) < 6.4 \times 10^{-19}$ s$^{-1}$ at 95% CL is found if majorons make up all of the dark matter.

[12] LESSA 07 consider decays of the form Meson $\rightarrow \ell\nu$Majoron and $\ell \rightarrow \ell'\nu\overline{\nu}$Majoron and use existing data to derive limits on the neutrino-Majoron Yukawa couplings $g_{\alpha\beta}$ ($\alpha$,$\beta$=$e,\mu,\tau$). Their best limits are $|g_{e\alpha}|^2 < 5.5 \times 10^{-6}$, $|g_{\mu\alpha}|^2 < 4.5 \times 10^{-5}$, $|g_{\tau\alpha}|^2 < 5.5 \times 10^{-2}$ at CL = 90%.

[13] FARZAN 03 set limits on the neutrino Majoron Yukawa coupling, $|g_{ee}| < 4 \times 10^{-7}$, by considering the SN cooling due to the massless Majoron emission via neutrino coalescence. They also exclude values around $10^{-5}$ for both $g_{e\mu}$ and $g_{\mu\mu}$ using the process $\nu\nu \rightarrow X^0 X^0$. See also their Figs. 3 and 4 for mass-dependent limits.

[14] DIAZ 98 studied models of spontaneously broken lepton number with both singlet and triplet Higgses. They obtain limits on the parameter space from invisible decay $Z \rightarrow H^0 A^0 \rightarrow X^0 X^0 X^0 X^0 X^0$ and $e^+ e^- \rightarrow Z H^0$ with $H^0 \rightarrow X^0 X^0$.

[15] BOBRAKOV 91 searched for anomalous magnetic interactions between polarized electrons expected from the exchange of a massless pseudoscalar boson (arion). A limit $x_e^2 < 2 \times 10^{-4}$ (95%CL) is found for the effective anomalous magneton parametrized as $x_e (G_F/8\pi\sqrt{2})^{1/2}$.

[16] ALBRECHT 90E limits are for B($\tau \rightarrow \ell X^0$)/B($\tau \rightarrow \ell\nu\overline{\nu}$). Valid for $m_{X^0} < 100$ MeV. The limits rise to 7.1% (for $\mu$), 5.0% (for $e$) for $m_{X^0}$ = 500 MeV.

[17] ATIYA 90 limit is for $m_{X^0} = 0$. The limit B $< 1 \times 10^{-8}$ holds for $m_{X^0} < 95$ MeV. For the reduction of the limit due to finite lifetime of $X^0$, see their Fig. 3.

[18] BALKE 88 limits are for B($\mu^+ \rightarrow e^+ X^0$). Valid for $m_{X^0} < 80$ MeV and $\tau_{X^0} > 10^{-8}$ sec.

[19] BOLTON 88 limit corresponds to $F > 3.1 \times 10^9$ GeV, which does not depend on the chirality property of the coupling.

[20] CHANDA 88 find $v_T < 10$ MeV for the weak-triplet Higgs vacuum expectation value in Gelmini-Roncadelli model, and $v_S > 5.8 \times 10^6$ GeV in the singlet Majoron model.

[21] CHOI 88 used the observed neutrino flux from the supernova SN 1987A to exclude the neutrino Majoron Yukawa coupling $h$ in the range $2 \times 10^{-5} < h < 3 \times 10^{-4}$ for the interaction $L_{\text{int}} = \frac{1}{2} ih\overline{\psi}^c_\nu \gamma_5 \psi_\nu \phi_X$. For several families of neutrinos, the limit applies for $(\Sigma h_i^4)^{1/4}$.

[22] PICCIOTTO 88 limit applies when $m_{X^0} < 55$ MeV and $\tau_{X^0} >$ 2ns, and it decreases to $4 \times 10^{-7}$ at $m_{X^0}$ = 125 MeV, beyond which no limit is obtained.

[23] GOLDMAN 87 limit corresponds to $F > 2.9 \times 10^9$ GeV for the family symmetry breaking scale from the Lagrangian $L_{\text{int}} = (1/F)\overline{\psi}_\mu \gamma^\mu\ (a+b\gamma_5)\ \psi_e \partial_\mu \phi_{X^0}$ with $a^2+b^2 = 1$. This is not as sensitive as the limit $F > 9.9 \times 10^9$ GeV derived from the search for $\mu^+ \rightarrow e^+ X^0$ by JODIDIO 86, but does not depend on the chirality property of the coupling.

[24] Limits are for $\Gamma(\mu \rightarrow eX^0)/\Gamma(\mu \rightarrow e\nu\overline{\nu})$. Valid when $m_{X^0}$ = 0–93.4, 98.1–103.5 MeV.

[25] EICHLER 86 looked for $\mu^+ \rightarrow e^+ X^0$ followed by $X^0 \rightarrow e^+ e^-$. Limits on the branching fraction depend on the mass and and lifetime of $X^0$. The quoted limits are valid when $\tau_{X^0} \lesssim 3. \times 10^{-10}$ s if the decays are kinematically allowed.

[26] JODIDIO 86 corresponds to $F > 9.9 \times 10^9$ GeV for the family symmetry breaking scale with the parity-conserving effective Lagrangian $L_{\text{int}} = (1/F)\ \overline{\psi}_\mu \gamma^\mu \psi_e \partial^\mu \phi_{X^0}$.

[27] BALTRUSAITIS 85 search for light Goldstone boson($X^0$) of broken U(1). CL = 95% limits are $\text{B}(\tau \rightarrow \mu^+ X^0)/\text{B}(\tau \rightarrow \mu^+ \nu\nu) < 0.125$ and $\text{B}(\tau \rightarrow e^+ X^0)/\text{B}(\tau \rightarrow e^+ \nu\nu) < 0.04$. Inferred limit for the symmetry breaking scale is $m > 3000$ TeV.

[28] The primordial heavy neutrino must decay into $\nu$ and familon, $f_A$, early so that the red-shifted decay products are below critical density, see their table. In addition, $K \rightarrow \pi f_A$ and $\mu \rightarrow e f_A$ are unseen. Combining these excludes $m_{\text{heavy}\nu}$ between $5 \times 10^{-5}$ and $5 \times 10^{-4}$ MeV ($\mu$ decay) and $m_{\text{heavy}\nu}$ between $5 \times 10^{-5}$ and 0.1 MeV ($K$-decay).

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## Majoron Searches in Neutrinoless Double $\beta$ Decay

Limits are for the half-life of neutrinoless $\beta\beta$ decay with a Majoron emission. No experiment currently claims any such evidence. Only the best or comparable limits for each isotope are reported.

| $t_{1/2}(10^{21}$ yr) | *CL%* | *ISOTOPE* | *TRANSITION* | *METHOD* | *DOCUMENT ID* |
|---|---|---|---|---|---|
| **$>7200$** | **90** | **$^{128}$Te** | | **CNTR** | [1] BERNATOW... 92 |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $> 120$ | 90 | $^{82}$Se | $0\nu 1\chi$ | CUPID-0 | [2] AZZOLINI 23 |
| $> 640$ | 90 | $^{76}$Ge | $0\nu 1\chi$ | GERDA | [3] AGOSTINI 22 |
| $>4300$ | 90 | $^{136}$Xe | $0\nu 1\chi$ | EXO-200 | [4] AL-KHARUSI 21 |
| $> 4.4$ | 90 | $^{100}$Mo | $0\nu 1\chi$ | NEMO-3 | [5] ARNOLD 19 |
| $> 37$ | 90 | $^{82}$Se | $0\nu 1\chi$ | NEMO-3 | [6] ARNOLD 18 |
| $> 420$ | 90 | $^{76}$Ge | $0\nu 1\chi$ | GERDA | [7] AGOSTINI 15A |
| $> 400$ | 90 | $^{100}$Mo | $0\nu 1\chi$ | NEMO-3 | [8] ARNOLD 15 |
| $>1200$ | 90 | $^{136}$Xe | $0\nu 1\chi$ | EXO-200 | [9] ALBERT 14A |
| $>2600$ | 90 | $^{136}$Xe | $0\nu 1\chi$ | KamLAND-Zen | [10] GANDO 12 |
| $> 16$ | 90 | $^{130}$Te | $0\nu 1\chi$ | NEMO-3 | [11] ARNOLD 11 |
| $> 1.9$ | 90 | $^{96}$Zr | $2\nu 1\chi$ | NEMO-3 | [12] ARGYRIADES 10 |
| $> 1.52$ | 90 | $^{150}$Nd | $0\nu 1\chi$ | NEMO-3 | [13] ARGYRIADES 09 |
| $> 27$ | 90 | $^{100}$Mo | $0\nu 1\chi$ | NEMO-3 | [14] ARNOLD 06 |
| $> 15$ | 90 | $^{82}$Se | $0\nu 1\chi$ | NEMO-3 | [15] ARNOLD 06 |
| $> 14$ | 90 | $^{100}$Mo | $0\nu 1\chi$ | NEMO-3 | [16] ARNOLD 04 |
| $> 12$ | 90 | $^{82}$Se | $0\nu 1\chi$ | NEMO-3 | [17] ARNOLD 04 |
| $> 2.2$ | 90 | $^{130}$Te | $0\nu 1\chi$ | Cryog. det. | [18] ARNABOLDI 03 |
| $> 0.9$ | 90 | $^{130}$Te | $0\nu 2\chi$ | Cryog. det. | [19] ARNABOLDI 03 |
| $> 8$ | 90 | $^{116}$Cd | $0\nu 1\chi$ | $CdWO_4$ scint. | [20] DANEVICH 03 |
| $> 0.8$ | 90 | $^{116}$Cd | $0\nu 2\chi$ | $CdWO_4$ scint. | [21] DANEVICH 03 |
| $> 500$ | 90 | $^{136}$Xe | $0\nu 1\chi$ | Liquid Xe Scint. | [22] BERNABEI 02D |
| $> 5.8$ | 90 | $^{100}$Mo | $0\nu 1\chi$ | ELEGANT V | [23] FUSHIMI 02 |
| $> 0.32$ | 90 | $^{100}$Mo | $0\nu 1\chi$ | Liq. Ar ioniz. | [24] ASHITKOV 01 |
| $> 0.0035$ | 90 | $^{160}$Gd | $0\nu 1\chi$ | $^{160}Gd_2SiO_5$:Ce | [25] DANEVICH 01 |
| $> 0.013$ | 90 | $^{160}$Gd | $0\nu 2\chi$ | $^{160}Gd_2SiO_5$:Ce | [26] DANEVICH 01 |
| $> 2.3$ | 90 | $^{82}$Se | $0\nu 1\chi$ | NEMO 2 | [27] ARNOLD 00 |
| $> 0.31$ | 90 | $^{96}$Zr | $0\nu 1\chi$ | NEMO 2 | [28] ARNOLD 00 |
| $> 0.63$ | 90 | $^{82}$Se | $0\nu 2\chi$ | NEMO 2 | [29] ARNOLD 00 |
| $> 0.063$ | 90 | $^{96}$Zr | $0\nu 2\chi$ | NEMO 2 | [29] ARNOLD 00 |
| $> 0.16$ | 90 | $^{100}$Mo | $0\nu 2\chi$ | NEMO 2 | [29] ARNOLD 00 |
| $> 2.4$ | 90 | $^{82}$Se | $0\nu 1\chi$ | NEMO 2 | [30] ARNOLD 98 |

| | | | | | |
|---|---|---|---|---|---|
| $>$ 7.2 | 90 | $^{136}$Xe | $0\nu 2\chi$ | TPC | [31] LUESCHER 98 |
| $>$ 7.91 | 90 | $^{76}$Ge | | SPEC | [32] GUENTHER 96 |
| $>$ 17 | 90 | $^{76}$Ge | | CNTR | BECK 93 |

[1] BERNATOWICZ 92 studied double-$\beta$ decays of $^{128}$Te and $^{130}$Te, and found the ratio $\tau(^{130}\text{Te})/\tau(^{128}\text{Te}) = (3.52 \pm 0.11) \times 10^{-4}$ in agreement with relatively stable theoretical predictions. The bound is based on the requirement that Majoron-emitting decay cannot be larger than the observed double-beta rate of $^{128}$Te of $(7.7 \pm 0.4) \times 10^{24}$ year. We calculated 90% CL limit as $(7.7\text{–}1.28 \times 0.4{=}7.2) \times 10^{24}$.

[2] AZZOLINI 23 use 9.95 kg·yr of data, collected by the CUPID-0 experiment, to place a limit on the single Majoron mode of the $0\nu\beta\beta$ decay of $^{82}$Se. Various limits on modes involving the emission of multiple Majorons are given too. The resulting constraint on the Majoron-neutrino coupling constant is $g_{\nu\chi} < 1.8\text{–}4.4 \times 10^{-5}$. The range is due to the variability of the used nuclear matrix elements.

[3] AGOSTINI 22 use 32.8 kg·yr of GERDA phase 2 data to derive a limit of $g_{\nu\chi} < 1.8\text{–}4.4 \times 10^{-5}$ on the neutrino-Majoron coupling. The range reflects the author's evaluation of the spread of nuclear matrix elements.

[4] AL-KHARUSI 21 utilize the complete dataset of the EXO-200 experiment, corresponding to an exposure of 234 kg yr, to place a limit on the one Majoron mode of the neutrinoless double beta decay of $^{136}$Xe. Several limits are reported, the one given here corresponds to a spectral index of 1, resulting in a limit of $g_{\nu\chi} <$ 0.4–0.9 $\times 10^{-5}$ on the Majoron-neutrino coupling constant. The range reflects the spread of the nuclear matrix elements.

[5] ARNOLD 19 uses the NEMO-3 tracking calorimeter to determine limits for the Majoron emitting double beta decay, with spectral index n = 3. The limit corresponds to the range of the $g_{ee}$ coupling of 0.013–0.035; dependimg on the nuclear matrix elements used.

[6] ARNOLD 18 use the NEMO-3 tracking detector. The limit corresponds to $\langle g_{ee}\rangle <$ 3.2–8.0 $\times 10^{-5}$; the range corresponds to different nuclear matrix element calculations.

[7] AGOSTINI 15A analyze a 20.3 kg yr of data set of the GERDA calorimeter to determine $g_{\nu\chi} <$ 3.4–8.7 $\times 10^{-5}$ on the Majoron-neutrino coupling constant. The range reflects the spread of the nuclear matrix elements.

[8] ARNOLD 15 use the NEMO-3 tracking calorimeter with 3.43 kg yr exposure to determine the limit on Majoron emission. The limit corresponds to $g_{\nu\chi} <$ 1.6–3.0 $\times 10^{-4}$. The spread reflects different nuclear matrix elements. Supersedes ARNOLD 06.

[9] ALBERT 14A utilize 100 kg yr of exposure of the EXO-200 tracking calorimeter to place a limit on the $g_{\nu\chi} <$ 0.8–1.7 $\times 10^{-5}$ on the Majoron-neutrino coupling constant. The range reflects the spread of the nuclear matrix elements.

[10] GANDO 12 use the KamLAND-Zen detector to obtain the limit on the $0\nu\chi$ decay with Majoron emission. It implies that the coupling constant $g_{\nu\chi} <$ 0.8–1.6 $\times 10^{-5}$ depending on the nuclear matrix elements used.

[11] ARNOLD 11 use the NEMO-3 detector to obtain the reported limit on Majoron emission. It implies that the coupling constant $g_{\nu\chi} <$ 0.6–1.6 $\times 10^{-4}$ depending on the nuclear matrix element used. Supercedes ARNABOLDI 03.

[12] ARGYRIADES 10 use the NEMO-3 tracking detector and $^{96}$Zr to derive the reported limit. No limit for the Majoron electron coupling is given.

[13] ARGYRIADES 09 use $^{150}$Nd data taken with the NEMO-3 tracking detector. The reported limit corresponds to $\langle g_{\nu\chi}\rangle <$ 1.7–3.0 $\times 10^{-4}$ using a range of nuclear matrix elements that include the effect of nuclear deformation.

[14] ARNOLD 06 use $^{100}$Mo data taken with the NEMO-3 tracking detector. The reported limit corresponds to $\langle g_{\nu\chi}\rangle <$ (0.4–1.8) $\times 10^{-4}$ using a range of matrix element calculations. Superseded by ARNOLD 15.

[15] NEMO-3 tracking calorimeter is used in ARNOLD 06 . Reported half-life limit for $^{82}$Se corresponds to $\langle g_{\nu\chi} \rangle < (0.66\text{–}1.9) \times 10^{-4}$ using a range of matrix element calculations. Supersedes ARNOLD 04.

[16] ARNOLD 04 use the NEMO-3 tracking detector. The limit corresponds to $\langle g_{\nu\chi} \rangle <$ (0.5–0.9)$10^{-4}$ using the matrix elements of SIMKOVIC 99, STOICA 01 and CIVITARESE 03. Superseded by ARNOLD 06.

[17] ARNOLD 04 use the NEMO-3 tracking detector. The limit corresponds to $\langle g_{\nu\chi} \rangle <$ (0.7–1.6)$10^{-4}$ using the matrix elements of SIMKOVIC 99, STOICA 01 and CIVITARESE 03.

[18] Supersedes ALESSANDRELLO 00. Array of $TeO_2$ crystals in high resolution cryogenic calorimeter. Some enriched in $^{130}$Te. Derive $\langle g_{\nu\chi} \rangle <$ 17–33 × $10^{-5}$ depending on matrix element.

[19] Supersedes ALESSANDRELLO 00. Cryogenic calorimeter search.

[20] Limit for the $0\nu\chi$ decay with Majoron emission of $^{116}$Cd using enriched $CdWO_4$ scintillators. $\langle g_{\nu\chi} \rangle <$ 4.6–8.1 × $10^{-5}$ depending on the matrix element. Supersedes DANEVICH 00.

[21] Limit for the $0\nu2\chi$ decay of $^{116}$Cd. Supersedes DANEVICH 00.

[22] BERNABEI 02D obtain limit for $0\nu\chi$ decay with Majoron emission of $^{136}$Xe using liquid Xe scintillation detector. They derive $\langle g_{\nu\chi} \rangle <$ 2.0–3.0 × $10^{-5}$ with several nuclear matrix elements.

[23] Replaces TANAKA 93. FUSHIMI 02 derive half-life limit for the $0\nu\chi$ decay by means of tracking calorimeter ELEGANT V. Considering various matrix element calculations, a range of limits for the Majoron-neutrino coupling is given: $\langle g_{\nu\chi} \rangle <$(6.3–360) × $10^{-5}$.

[24] ASHITKOV 01 result for $0\nu\chi$ of $^{100}$Mo is less stringent than ARNOLD 00.

[25] DANEVICH 01 obtain limit for the $0\nu\chi$ decay with Majoron emission of $^{160}$Gd using $Gd_2SiO_5$:Ce crystal scintillators.

[26] DANEVICH 01 obtain limit for the $0\nu2\chi$ decay with 2 Majoron emission of $^{160}$Gd.

[27] ARNOLD 00 reports limit for the $0\nu\chi$ decay with Majoron emission derived from tracking calorimeter NEMO 2. Using $^{82}$Se source: $\langle g_{\nu\chi} \rangle < 1.6 \times 10^{-4}$. Matrix element from GUENTHER 96.

[28] Using $^{96}$Zr source: $\langle g_{\nu\chi} \rangle < 2.6 \times 10^{-4}$. Matrix element from ARNOLD 99.

[29] ARNOLD 00 reports limit for the $0\nu2\chi$ decay with two Majoron emission derived from tracking calorimeter NEMO 2.

[30] ARNOLD 98 determine the limit for $0\nu_\chi$ decay with Majoron emission of $^{82}$Se using the NEMO-2 tracking detector. They derive $\langle g_{\nu_\chi} \rangle <$ 2.3–4.3 × $10^{-4}$ with several nuclear matrix elements.

[31] LUESCHER 98 report a limit for the $0\nu$ decay with Majoron emission of $^{136}$Xe using Xe TPC. This result is more stringent than BARABASH 89. Using the matrix elements of ENGEL 88, they obtain a limit on $\langle g_{\nu\chi} \rangle$ of 2.0 × $10^{-4}$.

[32] See Table 1 in GUENTHER 96 for limits on the Majoron coupling in different models.

## Invisible $A^0$ (Axion) MASS LIMITS from Astrophysics and Cosmology

$v_1 = v_2$ is usually assumed ($v_i$ = vacuum expectation values). For a review of these limits, see RAFFELT 91 and TURNER 90. In the comment lines below, D and K refer to DFSZ and KSVZ axion types, discussed in the above minireview.

| *VALUE* (eV) | *CL%* | *DOCUMENT ID* | *TECN* | *COMMENT* |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| | | [1] CHENG 23 | ASTR | BH superradiance |
| $> 3.2 \times 10^{-19}$ | 95 | [2] DELLA-MON...23 | ASTR | Ultralight DM soliton halo core |

| | | | | | |
|---|---|---|---|---|---|
| $<141$ | 90 | [3] DERBIN | 23 | CNTR | K, solar axions |
| $< 0.24$ | 95 | [4] NOTARI | 23 | COSM | K, Hot dark matter |
| | | [5] ROGERS | 23 | COSM | Ultra-light axion DM |
| none $10^{-24}$–$5 \times 10^{-23}$ | 95 | [6] SMARRA | 23 | EPTA | Ultralight DM mass limit |
| | | [7] XIA | 23 | ASTR | Fuzzy DM |
| | | [8] LAGUE | 22 | COSM | Ultralight axion DM |
| none 0.15–$1.5 \times 10^{-12}$ | 95 | [9] YUAN | 22A | ASTR | BH superradiance |
| $> 1.4 \times 10^{-21}$ | 95 | [10] BANIK | 21 | ASTR | Fuzzy DM |
| $< 1.9 \times 10^{4}$ | | [11] BAUMHOLZ... | 21 | COSM | warm dark matter |
| | | [12] CROON | 21 | ASTR | SN 1987A, axion-muon coupling |
| | | [13] FUJIKURA | 21 | ASTR | Microlensing |
| | | [14] MARTINCAM.. | 21 | ASTR | SN 1987A, $\Lambda$ decay |
| none 1.3–$2.7 \times 10^{-13}$ | | [15] NG | 21 | ASTR | BH superradiance |
| $> 2 \times 10^{-20}$ | 95 | [16] ROGERS | 21 | COSM | Lyman-$\alpha$ |
| none 0.8–$6.5 \times 10^{-13}$ | 95 | [17] TSUKADA | 21 | ASTR | BH superradiance |
| $> 2 \times 10^{-17}$ | | [18] IRSIC | 20 | COSM | Isocurvature fluctuations |
| | | [19] PODDAR | 20 | ASTR | Compact binary systems |
| $> 2.1 \times 10^{-21}$ | | [20] SCHUTZ | 20 | COSM | Fuzzy DM |
| none 6.4–$8.0 \times 10^{-13}$ | 95 | [21] SUN | 20 | ASTR | BH superradiance |
| none 2.9–$4.6 \times 10^{-21}$ | | [22] DAVOUDIASL | 19 | ASTR | BH superradiance |
| none $10^{-21}$–$6 \times 10^{-20}$ | | [23] MARSH | 19 | ASTR | Fuzzy DM |
| none 1.1–$4 \times 10^{-13}$ | 95 | [24] PALOMBA | 19 | ASTR | BH superradiance |
| $< 0.06$ | | [25] CHANG | 18 | ASTR | K, SN 1987A |
| | | [26] PORAYKO | 18 | PPTA | Fuzzy DM |
| $< 0.67$ | 95 | [27] ARCHIDIACO... | 13A | COSM | K, hot dark matter |
| none 0.7–$3 \times 10^{5}$ | | [28] CADAMURO | 11 | COSM | D abundance |
| $<105$ | 90 | [29] DERBIN | 11A | CNTR | D, solar axion |
| | | [30] ANDRIAMON... | 10 | CAST | K, solar axions |
| $< 0.72$ | 95 | [31] HANNESTAD | 10 | COSM | K, hot dark matter |
| | | [32] ANDRIAMON... | 09 | CAST | K, solar axions |
| $<191$ | 90 | [33] DERBIN | 09A | CNTR | K, solar axions |
| $<334$ | 95 | [34] KEKEZ | 09 | HPGE | K, solar axions |
| $< 1.02$ | 95 | [35] HANNESTAD | 08 | COSM | K, hot dark matter |
| $< 1.2$ | 95 | [36] HANNESTAD | 07 | COSM | K, hot dark matter |
| $< 0.42$ | 95 | [37] MELCHIORRI | 07A | COSM | K, hot dark matter |
| $< 1.05$ | 95 | [38] HANNESTAD | 05A | COSM | K, hot dark matter |
| 3 to 20 | | [39] MOROI | 98 | COSM | K, hot dark matter |
| $< 0.007$ | | [40] BORISOV | 97 | ASTR | D, neutron star |
| $< 4$ | | [41] KACHELRIESS | 97 | ASTR | D, neutron star cooling |
| $<(0.5–6) \times 10^{-3}$ | | [42] KEIL | 97 | ASTR | SN 1987A |
| $< 0.018$ | | [43] RAFFELT | 95 | ASTR | D, red giant |
| $< 0.010$ | | [44] ALTHERR | 94 | ASTR | D, red giants, white dwarfs |
| | | [45] CHANG | 93 | ASTR | K, SN 1987A |
| $< 0.01$ | | WANG | 92 | ASTR | D, white dwarf |
| $< 0.03$ | | WANG | 92C | ASTR | D, C-O burning |
| none 3–8 | | [46] BERSHADY | 91 | ASTR | D, K, intergalactic light |

| | | | | |
|---|---|---|---|---|
| $<10$ | [47] KIM | 91C | COSM | D, K, mass density of the universe, supersymmetry |
| | [48] RAFFELT | 91B | ASTR | D,K, SN 1987A |
| $<1\ \times 10^{-3}$ | [49] RESSELL | 91 | ASTR | K, intergalactic light |
| none $10^{-3}$–3 | BURROWS | 90 | ASTR | D,K, SN 1987A |
| | [50] ENGEL | 90 | ASTR | D,K, SN 1987A |
| $<0.02$ | [51] RAFFELT | 90D | ASTR | D, red giant |
| $<1\ \times 10^{-3}$ | [52] BURROWS | 89 | ASTR | D,K, SN 1987A |
| $<(1.4–10) \times 10^{-3}$ | [53] ERICSON | 89 | ASTR | D,K, SN 1987A |
| $<3.6\ \times 10^{-4}$ | [54] MAYLE | 89 | ASTR | D,K, SN 1987A |
| $<12$ | CHANDA | 88 | ASTR | D, Sun |
| $<1\ \times 10^{-3}$ | RAFFELT | 88 | ASTR | D,K, SN 1987A |
| | [55] RAFFELT | 88B | ASTR | red giant |
| $<0.07$ | FRIEMAN | 87 | ASTR | D, red giant |
| $<0.7$ | [56] RAFFELT | 87 | ASTR | K, red giant |
| $<2–5$ | TURNER | 87 | COSM | K, thermal production |
| $<0.01$ | [57] DEARBORN | 86 | ASTR | D, red giant |
| $<0.06$ | RAFFELT | 86 | ASTR | D, red giant |
| $<0.7$ | [58] RAFFELT | 86 | ASTR | K, red giant |
| $<0.03$ | RAFFELT | 86B | ASTR | D, white dwarf |
| $<1$ | [59] KAPLAN | 85 | ASTR | K, red giant |
| $<0.003–0.02$ | IWAMOTO | 84 | ASTR | D, K, neutron star |
| $>1\ \times 10^{-5}$ | ABBOTT | 83 | COSM | D,K, mass density of the universe |
| $>1\ \times 10^{-5}$ | DINE | 83 | COSM | D,K, mass density of the universe |
| $<0.04$ | ELLIS | 83B | ASTR | D, red giant |
| $>1\ \times 10^{-5}$ | PRESKILL | 83 | COSM | D,K, mass density of the universe |
| $<0.1$ | BARROSO | 82 | ASTR | D, red giant |
| $<1$ | [60] FUKUGITA | 82 | ASTR | D, stellar cooling |
| $<0.07$ | FUKUGITA | 82B | ASTR | D, red giant |

[1] CHENG 23 employ an improved approximation of the boson cloud eigenfrequency to calculate the superradiance rate. They find that sensitivity depends on initial spin distribution and the merger timescale, and identify two preferred ranges for boson mass centered at $1.78 \times 10^{-12}$ and $7.94 \times 10^{-13}$ eV.

[2] DELLA-MONICA 23 consider the solitonic core implied by ultralight scalar dark matter in the centre of the Milky Way and the effect its presence would have on the precisely tracked orbits of the stars orbiting our galaxy's central supermassive black hole, Sagittarius A$^*$.

[3] DERBIN 23 employ a thulium garnet crystal bolometer to search for the 8.4 keV solar axion line emitted from the M1 nuclear transition of thulium-169, $^{169}$Tm. Mass bound applies to KSVZ axions, value for DFSZ is 244 eV.

[4] NOTARI 23 improved the evaluation of axion production from pion scatterings by using pion-pion scattering data and incorporating the momentum dependence of the Boltzmann equation. The limit is based on the Planck 2018, BAO, and Pantheon SN Ia data.

[5] ROGERS 23 use the CMB and BOSS galaxy-clustering data to set limits on the abundance of ultralight axion DM. They obtained $\Omega_{A^0} < 0.002$ for $m_{A^0} = 10^{-30}$–$10^{-28}$ eV and set upper limits ranging from 0.002 to 0.07 for $m_{A^0} = 10^{-32}$–$10^{-25}$ eV. See their Fig. 22 for mass-dependent limits.

[6] SMARRA 23 is the European Pulsar Timing Array's constraint on the contribution of ultralight DM to the DM density in our local galactic neighbourhood. Ultralight DM cannot saturate the known DM density of 0.3 GeV/cc for masses inside this mass interval of $10^{-24}$–$5 \times 10^{-23}$ eV.

[7] XIA 23 is analogous to PORAYKO 18 and use the Fermi-LAT pulsar timing array. They set a bound on the local density as $\rho_{A^0} \lesssim 8$ GeV/cm$^3$ for $m_{A^0} \lesssim 10^{-23}$ eV at 95% CL, with weaker constraints up to $10^{-22}$ eV. See their Fig. 1 for the mass-dependent limits.

[8] LAGUE 22 used the BOSS galaxy-clustering data to set limits on the abundance of ultralight axion dark matter. When combined with the CMB data, they obtained $\Omega_{A^0} h^2 < 0.004$ for $m_{A^0} = 10^{-31}$–$10^{-26}$ eV. See their Figs. 1 and 15 for mass-dependent limits.

[9] YUAN 22A use the data of Advanced LIGO and Advanced Virgo's first three observing runs to search for stochastic GW background produced by scalar bosonic clouds formed by the BH superradiant instability. They set the limit, taking into account all the unstable modes.

[10] BANIK 21 use the subhalo mass function inferred from the analyses of the GD-1 and Pal 5 stellar streams. The limit is strengthened to $2.2 \times 10^{-21}$ eV when adding dwarf satellite counts.

[11] BAUMHOLZER 21 study the freeze-in production of axion dark matter through couplings to photons, and set the limit using Lyman-$\alpha$ forest data and the observed number of Milky Way subhalos.

[12] CROON 21 study the supernova cooling effect of the axion-muon coupling, taking account of semi-Compton scattering and muon-proton bremsstrahlung, as well as the loop-induced axion-photon coupling, and exclude the range of $g_{A\mu\mu} \simeq 7 \times 10^{-3}$–$2 \times 10^{-10}$ for $m_{A^0} < 0.5$ GeV. See their Fig. 8 for mass-dependent limits.

[13] FUJIKURA 21 use the EROS-2 survey and the Subaru HSC observation to set limits on spherically symmetric axion clumps, taking account of the finite lens and source size effects. $f_{A^0} \gtrsim 10^{12}$ GeV can be constrained depending on the fraction of the axion dark matter collapsed into clumps, and the clump densities. See their Figs. 7–10 for the limits.

[14] MARTINCAMALICH 21 considered axion emission from a supernova core through the $\Lambda$ hyperon decay, and set the limit on $\mathrm{B}(\Lambda \to \; n A^0) \lesssim 8 \times 10^{-9}$, or equivalently, $f_{A^0}/\mathrm{C}_{sd} \gtrsim 2.6 \times 10^9$ GeV in terms of the flavor-violating axion coupling to the down and strange quarks.

[15] NG 21 use the binary black holes reported by LIGO and Virgo to determine the black hole spin distribution at formation and the scalar boson mass simultaneously, neglecting the boson self-interaction.

[16] ROGERS 21 set the limit by using a framework involving Bayesian emulator optimization to accurately forward-model the Lyman-$\alpha$ flux power spectrum, and comparing this with small-scale data to constrain the predicted suppression of cosmic structure growth.

[17] TSUKADA 21 look for a stochastic GW background produced by extragalactic BH-hidden photon cloud systems through the superradiant instability. They assume a uniform spin distribution at birth of isolated BHs from 0 to 1.

[18] IRSIC 20 used the Lyman-$\alpha$ forest constraint on small-scale isocurvature perturbation to derive limits on the axion mass and decay constant, assuming that the axion makes up all dark matter in the post-inflationary scenario. See their Fig. 1 for other astrophysical limits as well as the limits on the case of the temperature-dependent axion mass.

[19] PODDAR 20 used the observed decay in orbital period of four compact binary systems to derive a limit on the emission of axions with $m_{A^0} < 1 \times 10^{-19}$ eV, assuming they couple to nucleons and the strong *CP* phase vanishes at the potential minimum. They exclude $f_{A^0} \lesssim 10^{11}$ GeV for such axions.

[20] SCHUTZ 20 set a limit on fuzzy dark matter based on the existing limits for warm dark matter derived from the inferred subhalo mass function.

[21] SUN 20 look for quasimonochromatic gravitational waves emitted from boson clouds around the Cygnus X-1 black hole. The quoted limit assume the black hole age of $5 \times 10^6$ years. A mass range of 9.6–15.5 $\times 10^{-13}$ eV is disfavored when repeated induction of bosenova for string axions with decay constant $f_{A^0} \simeq 10^{15}$ GeV prevents the superradiance from being saturated.

[22] DAVOUDIASL 19 used the observed data of M87* by the Event Horizon Telescope to set the limit. A mass range of 0.85–4.6 $\times 10^{-21}$ eV is disfavored for a spin-1 boson.

[23] MARSH 19 considered heating of star clusters due to the stochastic oscillations of the core and granular quasiparticles in the outer halo. The limit was derived by requiring the survival of the old star cluster in Eridanus II, where the lower end is set by the validity of diffusion approximation. The effect of tidal stripping is also discussed for lower masses.

[24] PALOMBA 19 used the LIGO O2 dataset to derive limits on nearly monochromatic gravitational waves emitted by boson clouds formed around a stellar-mass black hole. They exclude boson masses in a range of $1.1 \times 10^{-13}$ and $4 \times 10^{-13}$ eV for high initial black hole spin, and $1.2 \times 10^{-13}$ and $1.8 \times 10^{-13}$ eV for moderate spin. See their Figs. 2 and 3 for limits based on various values of black hole initial spin, boson cloud age, and distance.

[25] CHANG 18 update axion bremsstrahlung emission rates in nucleon-nucleon collisions, shifting the excluded mass range to higher values. They rule out the hadronic axion with mass up to a few hundred eV, closing the hadronic axion window. See their Fig. 11 for results based on several different choices of the temperature and density profile of the proto-neutron star.

[26] PORAYKO 18 look for time-dependent oscillations in the gravitational potential generated by ultralight scalar dark matter, and set a bound on its local density as $\rho_{A^0} \lesssim 6$ GeV/cm$^3$ for $m_{A^0} \lesssim 10^{-23}$ eV at 95% CL. See their Fig. 4 for the limits.

[27] ARCHIDIACONO 13A is analogous to HANNESTAD 05A. The limit is based on the CMB temperature power spectrum of the Planck data, the CMB polarization from the WMAP 9-yr data, the matter power spectrum from SDSS-DR7, and the local Hubble parameter measurement by the Carnegie Hubble program.

[28] CADAMURO 11 use the deuterium abundance to show that the $m_{A^0}$ range 0.7 eV – 300 keV is excluded for axions, complementing HANNESTAD 10.

[29] DERBIN 11A look for solar axions produced by Compton and bremsstrahlung processes, in the resonant excitation of $^{169}$Tm, constraining the axion-electron × axion nucleon couplings.

[30] ANDRIAMONJE 10 search for solar axions produced from $^7$Li (478 keV) and D($p$,$\gamma$)$^3$He (5.5 MeV) nuclear transitions. They show limits on the axion-photon coupling for two reference values of the axion-nucleon coupling for $m_A < 100$ eV.

[31] This is an update of HANNESTAD 08 including 7 years of WMAP data.

[32] ANDRIAMONJE 09 look for solar axions produced from the thermally excited 14.4 keV level of $^{57}$Fe. They show limits on the axion-nucleon × axion-photon coupling assuming $m_A < 0.03$ eV.

[33] DERBIN 09A look for Primakoff-produced solar axions in the resonant excitation of $^{169}$Tm, constraining the axion-photon × axion-nucleon couplings.

[34] KEKEZ 09 look at axio-electric effect of solar axions in HPGe detectors. The one-loop axion-electron coupling for hadronic axions is used.

[35] This is an update of HANNESTAD 07 including 5 years of WMAP data.

[36] This is an update of HANNESTAD 05A with new cosmological data, notably WMAP (3 years) and baryon acoustic oscillations (BAO). Lyman-$\alpha$ data are left out, in contrast to HANNESTAD 05A and MELCHIORRI 07A, because it is argued that systematic errors are large. It uses Bayesian statistics and marginalizes over a possible neutrino hot dark matter component.

[37] MELCHIORRI 07A is analogous to HANNESTAD 05A, with updated cosmological data, notably WMAP (3 years). Uses Bayesian statistics and marginalizes over a possible

neutrino hot dark matter component. Leaving out Lyman-$\alpha$ data, a conservative limit is 1.4 eV.

[38] HANNESTAD 05A puts an upper limit on the mass of hadronic axion because in this mass range it would have been thermalized and contribute to the hot dark matter component of the universe. The limit is based on the CMB anisotropy from WMAP, SDSS large scale structure, Lyman $\alpha$, and the prior Hubble parameter from HST Key Project. A $\chi^2$ statistic is used. Neutrinos are assumed not to contribute to hot dark matter.

[39] MOROI 98 points out that a KSVZ axion of this mass range (see CHANG 93) can be a viable hot dark matter of Universe, as long as the model-dependent $g_{A\gamma}$ is accidentally small enough as originally emphasized by KAPLAN 85; see Fig. 1.

[40] BORISOV 97 bound is on the axion-electron coupling $g_{ae} < 1 \times 10^{-13}$ from the photo-production of axions off of magnetic fields in the outer layers of neutron stars.

[41] KACHELRIESS 97 bound is on the axion-electron coupling $g_{ae} < 1 \times 10^{-10}$ from the production of axions in strongly magnetized neutron stars. The authors also quote a stronger limit, $g_{ae} < 9 \times 10^{-13}$ which is strongly dependent on the strength of the magnetic field in white dwarfs.

[42] KEIL 97 uses new measurements of the axial-vector coupling strength of nucleons, as well as a reanalysis of many-body effects and pion-emission processes in the core of the neutron star, to update limits on the invisible-axion mass.

[43] RAFFELT 95 reexamined the constraints on axion emission from red giants due to the axion-electron coupling. They improve on DEARBORN 86 by taking into proper account degeneracy effects in the bremsstrahlung rate. The limit comes from requiring the red giant core mass at helium ignition not to exceed its standard value by more than 5% (0.025 solar masses).

[44] ALTHERR 94 bound is on the axion-electron coupling $g_{ae} < 1.5 \times 10^{-13}$, from energy loss via axion emission.

[45] CHANG 93 updates ENGEL 90 bound with the Kaplan-Manohar ambiguity in $z=m_u/m_d$ (see the Note on the Quark Masses in the Quark Particle Listings). It leaves the window $f_A=3\times10^5$–$3\times10^6$ GeV open. The constraint from Big-Bang Nucleosynthesis is satisfied in this window as well.

[46] BERSHADY 91 searched for a line at wave length from 3100–8300 Å expected from $2\gamma$ decays of relic thermal axions in intergalactic light of three rich clusters of galaxies.

[47] KIM 91C argues that the bound from the mass density of the universe will change drastically for the supersymmetric models due to the entropy production of saxion (scalar component in the axionic chiral multiplet) decay. Note that it is an *upperbound* rather than a lowerbound.

[48] RAFFELT 91B argue that previous SN 1987A bounds must be relaxed due to corrections to nucleon bremsstrahlung processes.

[49] RESSELL 91 uses absence of any intracluster line emission to set limit.

[50] ENGEL 90 rule out $10^{-10} \lesssim g_{AN} \lesssim 10^{-3}$, which for a hadronic axion with EMC motivated axion-nucleon couplings corresponds to $2.5 \times 10^{-3}$ eV $\lesssim m_{A^0} \lesssim 2.5 \times 10^4$ eV. The constraint is loose in the middle of the range, i.e. for $g_{AN} \sim 10^{-6}$.

[51] RAFFELT 90D is a re-analysis of DEARBORN 86.

[52] The region $m_{A^0} \gtrsim 2$ eV is also allowed.

[53] ERICSON 89 considered various nuclear corrections to axion emission in a supernova core, and found a reduction of the previous limit (MAYLE 88) by a large factor.

[54] MAYLE 89 limit based on naive quark model couplings of axion to nucleons. Limit based on couplings motivated by EMC measurements is 2–4 times weaker. The limit from axion-electron coupling is weak: see HATSUDA 88B.

[55] RAFFELT 88B derives a limit for the energy generation rate by exotic processes in helium-burning stars $\epsilon < 100$ erg g$^{-1}$ s$^{-1}$, which gives a firmer basis for the axion limits based on red giant cooling.

[56] RAFFELT 87 also gives a limit $g_{A\gamma} < 1 \times 10^{-10}$ GeV$^{-1}$.

[57] DEARBORN 86 also gives a limit $g_{A\gamma} < 1.4 \times 10^{-11}$ GeV$^{-1}$.

[58] RAFFELT 86 gives a limit $g_{A\gamma} < 1.1\times10^{-10}$ GeV$^{-1}$ from red giants and $< 2.4\times10^{-9}$ GeV$^{-1}$ from the sun.

[59] KAPLAN 85 says $m_{A^0} < 23$ eV is allowed for a special choice of model parameters.

[60] FUKUGITA 82 gives a limit $g_{A\gamma} < 2.3 \times 10^{-10}$ GeV$^{-1}$.

## Search for Relic Invisible Axions

Limits are for the dimensionless quantity $[G_{A\gamma\gamma}/m_{A^0}]^2\rho_A$ where $G_{A\gamma\gamma}$ denotes the axion two-photon coupling, $L_{\text{int}} = -\frac{G_{A\gamma\gamma}}{4}\phi_A F_{\mu\nu}\widetilde{F}^{\mu\nu} = G_{A\gamma\gamma}\phi_A\mathbf{E}\cdot\mathbf{B}$, and $\rho_A$ is the axion energy density near the earth, unless otherwise stated. Notice that for QCD axions $G_{A\gamma\gamma}/m_{A^0}$ does not depend on $m_{A^0}$. For the reference values $m_{A^0} = 1$ $\mu$eV, $G_{A\gamma\gamma} = 3.9 \times 10^{-16}$ GeV$^{-1}$ (that would apply to KSVZ axions at that mass), and $\rho_A = 300$ MeV/cm$^3$ one finds $[G_{A\gamma\gamma}/m_{A^0}]^2\rho_A = 3.5 \times 10^{-43}$.

| *VALUE* | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $<1.3 \times 10^{-3}$ | 95 | [1] ADACHI | 23D | CMB | $m_{A^0} = 0.096$–$2.2 \times 10^{-20}$ eV |
| $<7.5 \times 10^{-43}$ | 90 | [2] DI-VORA | 23 | QUAX | $m_{A^0} = 42.8178$–$42.8190$ $\mu$eV |
| $<2.3 \times 10^{-42}$ | 90 | [3] JEWELL | 23 | HYST | $m_{A^0} =18.44$–$18.71$ $\mu$eV |
| $<2.0 \times 10^{-42}$ | 90 | [4] JEWELL | 23 | HYST | $m_{A^0} = 16.96$–$17.12$, $17.14$–$17.28$ $\mu$eV |
| $<2.5 \times 10^{-42}$ | 90 | [5] KIM | 23 | CASK | $m_{A^0} = 9.39$–$9.51$ $\mu$eV |
| $<3.0 \times 10^{-4}$ | 95 | [6] OSHIMA | 23 | DANC | $m_{A^0} = 4.1 \times 10^{-16}$–$2.0 \times 10^{-12}$ eV |
| $<2.56 \times 10^{-24}$ | 95 | [7] THOMSON | 23 | UPLD | $m_{A^0} = 1.12$–$1.20$ $\mu$eV |
| $<6.09 \times 10^{-43}$ | 90 | [8] YANG | 23 | CAPP | $m_{A^0} = 19.883$–$19.926$ $\mu$eV |
| $<6.6 \times 10^{-44}$ | 90 | [9] YI | 23 | CASK | $m_{A^0} = 4.51$–$4.59$ $\mu$eV |
| $<2.6 \times 10^{-44}$ | 90 | [10] YI | 23A | CASK | $m_{A^0} = 4.51$–$4.59$ $\mu$eV |
| $<4.7 \times 10^{-5}$ | 95 | [11] ADE | 22 | CMB | $m_{A^0} = 0.16$–$4.8 \times 10^{-20}$ eV |
| $<1.0 \times 10^{-41}$ | 90 | [12] ALESINI | 22 | QUAX | $m_{A^0} = 42.8210$–$42.8223$ $\mu$eV |
| $<7 \times 10^{-33}$ | 95 | [13] BATTYE | 22 | ASTR | $m_{A^0} = 4.2$–$60$ $\mu$eV |
| $<5.8 \times 10^{-41}$ | 95 | [14] CHANG | 22 | TASE | $m_{A^0} = 19.4687$–$19.8436$ $\mu$eV |
| $<3.2 \times 10^{-6}$ | 95 | [15] FERGUSON | 22 | CMB | $m_{A^0} = 0.047$–$4.7 \times 10^{-20}$ eV |
| $<8.4 \times 10^{-43}$ | 90 | [16] LEE | 22 | CASK | $m_{A^0} = 19.764$–$19.890$ $\mu$eV |
| $<4.9 \times 10^{-39}$ | 95 | [17] QUISKAMP | 22 | ORGN | $m_{A^0} = 63.2$–$67.1$ $\mu$eV |
| $<3.6 \times 10^{-43}$ | 90 | [18] YOON | 22 | CASK | $m_{A^0} = 19.764$–$19.890$ $\mu$eV |
| $<1.03 \times 10^{-35}$ | 95 | [19] ZHOU | 22 | ASTR | $m_{A^0} = 3.18$–$4.35$ $\mu$eV |
| $<2.8 \times 10^{-4}$ | 95 | [20] ADE | 21 | CMB | $m_{A^0} = 0.16$–$4.8 \times 10^{-20}$ eV |
| $<1.1 \times 10^{-41}$ | 90 | [21] ALESINI | 21 | QUAX | $m_{A^0} = 43$ $\mu$eV |
| $<1 \times 10^{-44}$ | 90 | [22] BARTRAM | 21A | ADMX | $m_{A^0} = 3.3$–$4.2$ $\mu$eV |
| $<1.6 \times 10^{-29}$ | 95 | [23] DEVLIN | 21 | TRAP | $m_{A^0} = 2.7906$–$2.7914$ neV |
| $<1.4 \times 10^{-23}$ | 95 | [24] GRAMOLIN | 21 | SHFT | $m_{A^0} = 0.012$–$12$ neV |
| $<7 \times 10^{-43}$ | 90 | [25] KWON | 21 | CASK | $m_{A^0} = 10.7126$–$10.7186$ $\mu$eV |
| $<4.6 \times 10^{-40}$ | 95 | [26] MELCON | 21 | RADE | $m_{A^0} = 34.6738$–$34.6771$ $\mu$eV |
| $<3.5 \times 10^{-28}$ | 95 | [27] SALEMI | 21 | ABRA | $m_{A^0} = 0.41$–$8.27$ neV |
| $<3 \times 10^{-3}$ | 95 | [28] THOMSON | 21 | | $m_{A^0} = 7.44$–$19.38$ neV |

| | | | | | |
|---|---|---|---|---|---|
| $<1 \times 10^{-2}$ | 95 | [28] THOMSON | 21 | | $m_{A^0} = 74.4\text{–}74.5\ \mu\text{eV}$ |
| | | [29] YUAN | 21 | ASTR | $m_{A^0} = 10^{-20}\text{–}10^{-17}$ eV |
| $<1.9 \times 10^{-44}$ | 90 | [30] BRAINE | 20 | ADMX | $m_{A^0} = 2.81\text{–}3.31\ \mu\text{eV}$ |
| $<2 \times 10^{-35}$ | 90 | [31] CRISOSTO | 20 | SLIC | $m_{A^0} = 180.07\text{–}180.15$ neV |
| $<4 \times 10^{-37}$ | 95 | [32] DARLING | 20A | ASTR | $m_{A^0} = 4.2\text{–}165.6\ \mu\text{eV}$ |
| $<3.2 \times 10^{-36}$ | 95 | [33] FOSTER | 20 | ASTR | $m_{A^0} = 5\text{–}7,\ 10\text{–}11\mu\text{eV}$ |
| $<5.7 \times 10^{-41}$ | 90 | [34] JEONG | 20 | CASK | $m_{A^0} = 13.0\text{–}13.9\ \mu\text{eV}$ |
| | | [35] KENNEDY | 20 | | $m_{S^0} = 10^{-19}\text{–}10^{-17}$ eV |
| $<4.8 \times 10^{-42}$ | 90 | [36] LEE | 20A | CASK | $m_{A^0} = 6.62\text{–}6.82\ \mu\text{eV}$ |
| $<2.6 \times 10^{-39}$ | 95 | [37] ALESINI | 19 | QUAX | $m_{A^0} = 37.5\ \mu\text{eV}$ |
| $<6 \times 10^{-5}$ | | [38] FUJITA | 19 | ASTR | $m_{A^0} < 10^{-21}$ eV |
| $<2 \times 10^{-27}$ | 95 | [39] OUELLET | 19A | ABRA | $m_{A^0} = 0.31\text{–}8.3$ neV |
| $<7.3 \times 10^{-40}$ | 90 | [40] BOUTAN | 18 | ADMX | $m_{A^0} = 17.38\text{–}17.57\ \mu\text{eV}$ |
| $<1.8 \times 10^{-39}$ | 90 | [40] BOUTAN | 18 | ADMX | $m_{A^0} = 21.03\text{–}23.98\ \mu\text{eV}$ |
| $<3.4 \times 10^{-39}$ | 90 | [40] BOUTAN | 18 | ADMX | $m_{A^0} = 29.67\text{–}29.79\ \mu\text{eV}$ |
| $<1.4 \times 10^{-44}$ | 90 | [41] DU | 18 | ADMX | $m_{A^0} = 2.66\text{–}2.81\ \mu\text{eV}$ |
| $<2.87 \times 10^{-42}$ | 90 | [42] ZHONG | 18 | HYST | $m_{A^0} = 23.15\text{–}24\ \mu\text{eV}$ |
| | | [43] BRANCA | 17 | AURG | $m_{S^0} = 3.5\text{–}3.9$ peV |
| $<3 \times 10^{-42}$ | 90 | [44] BRUBAKER | 17 | HYST | $m_{A^0} = 23.55\text{–}24.0\ \mu\text{eV}$ |
| $<1.0 \times 10^{-29}$ | 95 | [45] CHOI | 17 | CASK | $m_{A^0} = 24.7\text{–}29.1\ \mu\text{eV}$ |
| $<5.9 \times 10^{-36}$ | 90 | [46] MCALLISTER | 17 | ORGN | at $m_{A^0} = 110\ \mu\text{eV}$ |
| $<8.6 \times 10^{-42}$ | 90 | [47] HOSKINS | 16 | ADMX | $m_{A^0} = 3.36\text{–}3.52$ or $3.55\text{–}3.69\ \mu\text{eV}$ |
| | | [48] BECK | 13 | | $m_{A^0} = 0.11$ meV |
| $<3.5 \times 10^{-43}$ | | [49] HOSKINS | 11 | ADMX | $m_{A^0} = 3.3\text{–}3.69 \times 10^{-6}$ eV |
| $<2.9 \times 10^{-43}$ | 90 | [50] ASZTALOS | 10 | ADMX | $m_{A^0} = 3.34\text{–}3.53 \times 10^{-6}$ eV |
| $<1.9 \times 10^{-43}$ | 97.7 | [51] DUFFY | 06 | ADMX | $m_{A^0} = 1.98\text{–}2.17 \times 10^{-6}$ eV |
| $<5.5 \times 10^{-43}$ | 90 | [52] ASZTALOS | 04 | ADMX | $m_{A^0} = 1.9\text{–}3.3 \times 10^{-6}$ eV |
| | | [53] KIM | 98 | THEO | |
| $<2 \times 10^{-41}$ | | [54] HAGMANN | 90 | CNTR | $m_{A^0} = (5.4\text{–}5.9)10^{-6}$ eV |
| $<6.3 \times 10^{-42}$ | 95 | [55] WUENSCH | 89 | CNTR | $m_{A^0} = (4.5\text{–}10.2)10^{-6}$ eV |
| $<5.4 \times 10^{-41}$ | 95 | [55] WUENSCH | 89 | CNTR | $m_{A^0} = (11.3\text{–}16.3)10^{-6}$ eV |

[1] ADACHI 23D is analogous to ADE 21. They used POLARBEAR data, and take account of a stochastic local axion field amplitude with the time-averaged local axion density $\rho_A = 0.3$ GeV/cm$^3$. Limits are set at $G_{A\gamma\gamma} < 2.4 \times 10^{-11}$ GeV$^{-1}$ ($m_{A^0}/10^{-21}$ eV), which is 2.2 times larger than the deterministic case. See Fig. 5 for mass-dependent limits.

[2] DI-VORA 23 searches for axions in a narrow mass window using an 8T haloscope and a travelling wave parametric amplifier to achieve noise close to the quantum limit. This is an improvement on their previous scan at the same mass, ALESINI 21. See Fig. 7 for mass-dependent limits and a comparison.

[3] JEWELL 23 is an update of BRUBAKER 17. See their Fig. 11 for the mass-dependent limits.

[4] JEWELL 23 correct an underestimation of intermediate frequency noise in BACKES 21. See their Fig. 11 for the mass-dependent limits.

[5] KIM 23 is an update of KWON 21 on the CAPP-PACE experiment. See their Fig. 4 for mass-dependent limits.

[6] OSHIMA 23 report first limits from the DANCE experiment. This experiment is based on a novel bow-tie cavity design that searches for the oscillating rotation of polarised laser light driven by the DM axion-photon mixing at low frequencies. See their Fig. 6 for mass-dependent limits.

[7] THOMSON 23 used an AC microwave cavity to search for dark matter axions. The axion signal is resonantly enhanced when the axion mass matches the difference between a cavity which is pumped with power and another resonant mode close in frequency that is used to read out the signal. See their Fig. 7 for the mass-dependent limits.

[8] YANG 23 extends the first phase of CAPP 18T to KSVZ axions between 4.8077 and 4.8181 GHz. They used an 18T high-temperature superconducting magnet haloscope. See their Fig. 5 for mass-dependent limits. Quoted value is for their limit derived with a Bayesian method.

[9] YI 23 is analogous to LEE 20A, using the CAPP-12TB haloscope. See their Fig. 4 for mass-dependent limits.

[10] YI 23A used the same data as YI 23, but instead of the standard halo model, they searched for axion dark matter in the Sagittarius tidal stream with a velocity $v = 300$ km/sec and a velocity dispersion $\delta v = 20$ km/sec. See their Fig. 4 for mass-dependent limits.

[11] ADE 22 is an update of ADE 21 based on the expanded data of the 2012–2015 observing seasons. See their Fig. 3 for mass-dependent limits over the extended mass range $1 \times 10^{-23}$–$6 \times 10^{-19}$ eV.

[12] ALESINI 22 is an update of ALESINI 21, using the TM030 mode of the cylindrical dielectric cavity. See their Fig. 8 for mass-dependent limits.

[13] BATTYE 22 is analogous to DARLING 20A, and use plasma ray tracing technique to analyze the propagation of radio photons converted from axion dark matter in the magnetosphere of PSR J1745-2900. The quoted limit assumes $\rho_A = 6.5 \times 10^4$ GeV/cm$^3$ in the vicinity of the magnetar. See their Fig. 1 for mass-dependent limits.

[14] CHANG 22 used a microwave cavity detector to search for dark matter axions. See Fig. 3 for the mass-dependent limits.

[15] FERGUSON 22 is analogous to ADE 21. They use the data of the SPT-3G's 2019 observing season. See their Fig. 5 for mass-dependent limits over the extended mass range 0.047–$9.5 \times 10^{-20}$ eV.

[16] LEE 22 is analogous to LEE 20A. They used an 18T high-temperature superconducting magnet haloscope. See their Fig. 5 for mass-dependent limits.

[17] QUISKAMP 22 is a 15.28 to 16.23 GHz microwave cavity haloscope with 11.5 T B-field. See Fig. 4 for mass-dependent limits.

[18] YOON 22 analyzed the data from LEE 22 and changed from a frequentist to a Bayesian method to set limits. See their Fig. 27 for mass-dependent limits.

[19] ZHOU 22 is analogous to DARLING 20A, and they use the data from the MeerKAT radio telescope's observation of the neutron star J0806.4-4123, which is 250 pc from Earth. See their Fig.3 for mass-dependent limits.

[20] ADE 21 looks for a time-variable global rotation of the CMB polarization induced by the harmonic oscillations of local axion-like dark matter and uses data from the 2012 observing season of the Keck Array, part of the BICEP program. The limits get 25% weaker for $m_{A^0} = 4.8 \times 10^{-20}$–$5.7 \times 10^{-19}$ eV. See their Eq. (80) and Fig. 6 for mass-dependent limits.

[21] ALESINI 21 is an update of ALESINI 19. See their Figs. 5 and 6 for the mass-dependent limits.

[22] BARTRAM 21A is analogous to DU 18. See their Fig.4 for mass-dependent limits.

[23] DEVLIN 21 use the superconducting resonant detection circuit of a cryogenic Penning trap with a single antiproton. See their Fig. 3 for mass-dependent limits.

[24] GRAMOLIN 21 use two detection channels, each consisting of two stacked toroids to look for the axion-induced oscillating magnetic field. The quoted limit applies at $m_{A^0}$ = 0.02 neV. See their Fig. 4 for mass-dependent limits.

[25] KWON 21 is analogous to LEE 20A. They also obtain weaker limits in the range of $m_{A^0}$ = 10.16–11.37 $\mu$eV. See their Fig. 4 for mass-dependent limits.

[26] MELCON 21 use a radio frequency cavity consisting of 5 sub-cavities coupled by inductive irises installed inside the CAST dipole magnet to look for higher axion masses. See their Fig. 9 for mass-dependent limits.

[27] SALEMI 21 is an update of OUELLET 19A. See their Fig. 4 for mass-dependent limits.

[28] THOMSON 21 use a resonant cavity supporting two spatially overlapping microwave modes, which is sensitive to the axion mass corresponding to the sum or difference of the two resonant frequencies. The original limit was retracted due to a sign error. See their Fig. 2 in the erratum for the corrected limits.

[29] YUAN 21 use polarimetric observations of Sgr A$^*$ taken by the Event Horizon Telescope to search for periodic oscillation of the polarization induced by axion dark matter, assuming a solitonic core near the Galactic center. They obtained limits in the range of $G_{A\gamma\gamma} = 8 \times 10^{-13}$–$3 \times 10^{-11}$ GeV$^{-1}$.

[30] BRAINE 20 is analogous to DU 18. See Fig. 4 for their mass-dependent limits.

[31] CRISOSTO 20 used a resonant LC circuit to look for lighter axion dark matter. They obtained a similar, slightly weaker limit for $m_{A^0}$ = 174.98–175.19 and 177.34–177.38 neV. See their Fig. 4 for mass-dependent limits.

[32] DARLING 20A use VLA data to look for radio-frequency radiation converted from axion dark matter in the magnetosphere of the Galactic Center magnetar PSR J1745-2900. They extended the results of DARLING 20, which used only data with the highest angular resolution, by adding sub-optimal data. They use $\rho_A = 6.5 \times 10^4$ GeV/cm$^3$ in the vicinity of the magnetar. See their Fig. 2 for mass-dependent limits.

[33] FOSTER 20 look for radio-frequency radiation converted from axion dark matter in the magnetic field around neutron stars. They use the observed data of isolated local neutron stars and in the Galactic center. The quoted limit applies to $m_{A^0} \simeq 7$ $\mu$eV. See their Fig. 2 for mass-dependent limits.

[34] JEONG 20 is analogous to LEE 20A, and they use a double-cell cavity to look for axions with mass $> 10$ $\mu$eV. See their Fig. 5 for mass-dependent limits.

[35] KENNEDY 20 is analogous to BRANCA 17, and they compare the frequency ratios of the Si cavity measured by a Sr optical lattice clock and by a H maser. Assuming the local density of moduli dark matter, $\rho_S = 0.3$ GeV/cm$^3$, they obtain a limit $G_{S\gamma\gamma} < 5.8 \times 10^{-24}$ GeV$^{-1}$ at $m_{S^0} = 2 \times 10^{-19}$ eV. See their Fig. 2 for mass-dependent limits as well as limits on the modulus coupling to electrons.

[36] LEE 20A used a microwave cavity detector at the IBS/CAPP to search for dark matter axions. See Fig. 3 for the mass-dependent limits.

[37] ALESINI 19 used a superconducting resonant cavity made of NbTi to increase the quality factor. The limit applies to a mass range of 0.2 neV around $m_{A^0} = 37.5$ $\mu$eV.

[38] FUJITA 19 look for photon birefringence under the oscillating axion background using the polarimetric imaging observation of a protoplanetary disk, AB Aur. See their Fig. 2 for a more conservative limit taking account of possible systematic effects.

[39] OUELLET 19A look for the axion-induced oscillating magnetic field generated by a toroidal magnetic field. The quoted limit applies at $m_{A^0} = 8$ neV. See their Fig. 3 for the mass-dependent limits.

[40] BOUTAN 18 use a small high frequency cavity installed above the main ADMX cavity to look for heavier axion dark matter. See their Fig. 4 for mass-dependent limits.

[41] DU 18 is analogous to DUFFY 06. They upgraded a dilution refrigerator to reduce the system noise. The quoted limit is around $m_{A^0} = 2.69$ $\mu$eV for the boosted Maxwellian axion line shape. See Fig. 4 for their mass-dependent limits.

[42] ZHONG 18 is analogous to BRUBAKER 17. The quoted limit applies at $m_{A^0} = 23.76$ $\mu$eV. See Fig. 4 for their mass-dependent limits.

[43] BRANCA 17 look for modulations of the fine-structure constant and the electron mass due to moduli dark matter by using the cryogenic resonant-mass AURIGA detector. The

limit on the assumed dilatonic coupling implies $G_{S\gamma\gamma} < 1.5 \times 10^{-24}$ GeV$^{-1}$ for the scalar to two-photon coupling. See Fig. 5 for the mass-dependent limits.

[44] BRUBAKER 17 used a microwave cavity detector at the Yale Wright Laboratory to search for dark matter axions. See Fig. 3 for the mass-dependent limits.

[45] CHOI 17 used a microwave cavity detector with toroidal geometry. See Fig. 4 for their mass-dependent limits.

[46] MCALLISTER 17 used a high-frequency microwave cavity haloscope at 26.6 GHz in a 7 T magnetic field. See Fig. 4 for mass-dependent limits.

[47] HOSKINS 16 is analogous to DUFFY 06. See Fig. 12 for mass-dependent limits in terms of the local dark matter density.

[48] BECK 13 argues that dark-matter axions passing through Earth may generate a small observable signal in resonant S/N/S Josephson junctions. A measurement by HOFFMANN 04 [Physical Review **B70** 180503 (2004)] is interpreted in terms of subdominant dark matter axions with $m_{A^0} = 0.11$ meV.

[49] HOSKINS 11 is analogous to DUFFY 06. See Fig. 4 for the mass-dependent limit in terms of the local density.

[50] ASZTALOS 10 used the upgraded detector of ASZTALOS 04 to search for halo axions. See their Fig. 5 for the $m_{A^0}$ dependence of the limit.

[51] DUFFY 06 used the upgraded detector of ASZTALOS 04, while assuming a smaller velocity dispersion than the isothermal model as in Eq. (8) of their paper. See Fig. 10 of their paper on the axion mass dependence of the limit.

[52] ASZTALOS 04 looked for a conversion of halo axions to microwave photons in magnetic field. At 90% CL, the KSVZ axion cannot have a local halo density more than 0.45 GeV/cm$^3$ in the quoted mass range. See Fig. 7 of their paper on the axion mass dependence of the limit.

[53] KIM 98 calculated the axion-to-photon couplings for various axion models and compared them to the HAGMANN 90 bounds. This analysis demonstrates a strong model dependence of $G_{A\gamma\gamma}$ and hence the bound from relic axion search.

[54] HAGMANN 90 experiment is based on the proposal of SIKIVIE 83.

[55] WUENSCH 89 looks for condensed axions near the earth that could be converted to photons in the presence of an intense electromagnetic field via the Primakoff effect, following the proposal of SIKIVIE 83. The theoretical prediction with $[G_{A\gamma\gamma}/m_{A^0}]^2 = 2 \times 10^{-14}$ MeV$^{-4}$ (the three generation DFSZ model) and $\rho_A = 300$ MeV/cm$^3$ that makes up galactic halos gives $(G_{A\gamma\gamma}/m_{A^0})^2\ \rho_A = 4 \times 10^{-44}$. Note that our definition of $G_{A\gamma\gamma}$ is $(1/4\pi)$ smaller than that of WUENSCH 89.

## Invisible $A^0$ (Axion) Limits from Photon Coupling

Limits are for the modulus of the axion-two-photon coupling $G_{A\gamma\gamma}$ defined by $L = -G_{A\gamma\gamma}\phi_A \mathbf{E}\cdot\mathbf{B}$. For scalars $S^0$ the limit is on the coupling constant in $L = G_{S\gamma\gamma}\phi_S(\mathbf{E}^2 - \mathbf{B}^2)$. The relation between $G_{A\gamma\gamma}$ and $m_{A^0}$ is not used unless stated otherwise, i.e., many of these bounds apply to low-mass axion-like particles (ALPs), not to QCD axions.

| *VALUE* (GeV$^{-1}$) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $<3 \times 10^{-11}$ | 95 | [1] PANT | 24 | ASTR | $m_{A^0} = 0.3$–$1$ neV |
| $<5.5 \times 10^{-11}$ | 95 | [2] BATTYE | 23 | DM | $m_{A^0} = 3.9$–$4.7$ $\mu$eV |
| $<2 \times 10^{-13}$ | 95 | [3] BEAUFORT | 23 | ASTR | $m_{A^0} = 3$–$38$ keV |
| $<2 \times 10^{-12}$ | 99 | [4] BERNAL | 23 | COSM | $m_{A^0} = 8$–$25$ eV |
| $<4 \times 10^{-14}$ | 99 | [5] CAPOZZI | 23 | COSM | $m_{A^0} = 30$–$800$ eV |

| | | | | |
|---|---|---|---|---|
| $<1.3 \times 10^{-7}$ | 95 | [6] CAPOZZI | 23A | DUMP | $m_{A^0} = 10^{3}$–$2 \times 10^{8}$ eV |
| $<5 \times 10^{-12}$ | 95 | [7] DAVIES | 23 | ASTR | $m_{A^0} = 5$–$200$ neV |
| $<1.7 \times 10^{-10}$ | | [8] DIAMOND | 23 | ASTR | $m_{A^0} = 2$–$56$ MeV |
| $<6 \times 10^{-29}$ | 95 | [9] FILZINGER | 23 | | Dilaton-like dark matter |
| $<4.5 \times 10^{-12}$ | 95 | [10] HOOF | 23 | ASTR | $m_{A^0} = 4 \times 10^{-10}$ eV |
| $<3 \times 10^{-12}$ | 95 | [11] HOOF | 23 | ASTR | $m_{A^0} = 60$ MeV |
| $<2.7 \times 10^{-11}$ | 99.7 | [12] JACOBSEN | 23 | ASTR | $m_{A^0} < 3 \times 10^{-7}$ eV |
| $<2 \times 10^{-11}$ | 99 | [13] LI | 23H | ASTR | $m_{A^0} = 1$–$100$ neV |
| $<3.0 \times 10^{-12}$ | 95 | [14] NOORDHUIS | 23 | ASTR | $m_{A^0} = 10^{-9}$–$10^{-5}$ eV |
| $<5 \times 10^{-11}$ | 95 | [15] PANT | 23 | ASTR | $m_{A^0} = 0.1$–$1000$ neV |
| $<5 \times 10^{-26}$ | 95 | [16] SHERRILL | 23 | DM | Dilaton-like dark matter |
| $<8 \times 10^{-9}$ | 95 | [17] SULAI | 23 | DM | $m_{A^0} = 0.25$–$2 \times 10^{-14}$ eV |
| $<7.9 \times 10^{-12}$ | | [18] YAO | 23 | ASTR | $m_{A^0} \lesssim 10^{-13}$ eV |
| $<3.8 \times 10^{-22}$ | 95 | [19] ZHANG | 23A | | Dilaton-like dark matter |
| $<5 \times 10^{-10}$ | 90 | [20] APRILE | 22B | XENT | Solar axions |
| $<1.45 \times 10^{-9}$ | 95 | [21] ARNQUIST | 22 | MAJD | $m_{A^0} < 100$ eV |
| $<7 \times 10^{-11}$ | 95 | [22] ARZA | 22 | DM | $m_{A^0}=0.2$–$7 \times 10^{-17}$eV |
| $3$–$6 \times 10^{-11}$ | 95 | [23] BERNAL | 22 | COSM | $m_{A^0} = 8$–$20$ eV |
| $<3.76 \times 10^{-11}$ | 95 | [24] CALORE | 22 | ASTR | $m_{A^0} < 10^{-11}$ eV |
| $<2 \times 10^{-10}$ | | [25] CAPUTO | 22 | ASTR | $m_{A^0} = 1$–$500$ MeV |
| $<3 \times 10^{-14}$ | 95 | [26] CASTILLO | 22 | ASTR | $m_{A^0} = 3 \times 10^{-23}$ eV |
| $<6 \times 10^{-12}$ | 90 | [27] DEROCCO | 22 | ASTR | $m_{A^0} = 5$–$30$ keV |
| $<5.4 \times 10^{-12}$ | 95 | [28] DESSERT | 22A | ASTR | $m_{A^0} \lesssim 3 \times 10^{-7}$ eV |
| $<2.1 \times 10^{-11}$ | 95 | [29] ECKNER | 22 | ASTR | $m_{A^0} < 2 \times 10^{-7}$ eV |
| $<1 \times 10^{-11}$ | 95 | [30] FOSTER | 22 | ASTR | $m_{A^0} = 16.5$–$32.5$ $\mu$eV |
| $<1.14 \times 10^{-5}$ | 95 | [31] KIRITA | 22 | SAPH | $m_{A^0} = 0.5$–$500$ meV |
| $<2 \times 10^{-16}$ | | [32] LANGHOFF | 22 | COSM | $m_{A^0} = 0.1$–$3 \times 10^{4}$ keV |
| $<6 \times 10^{-12}$ | 95 | [33] LI | 22 | ASTR | $m_{A^0} = 0.2$–$20$ neV |
| $<1.3 \times 10^{-11}$ | 95 | [34] LI | 22C | ASTR | $m_{A^0} = 8$–$200$ neV |
| $<1 \times 10^{-5}$ | | [35] LUCENTE | 22 | ASTR | $m_{A^0} \lesssim 0.4$ MeV |
| $<9.2 \times 10^{-11}$ | 95 | [36] BASU | 21 | ASTR | $m_{A^0} = 3.6 \times 10^{-21}$ eV |
| $<1.8 \times 10^{-10}$ | 95 | [37] BI | 21 | ASTR | $m_{A^0} = 2$–$6 \times 10^{-7}$ eV |
| $<1.6 \times 10^{-10}$ | 95 | [38] DOLAN | 21A | ASTR | $m_{A^0} = 1$–$570$ keV |
| $<5 \times 10^{-11}$ | 95 | [39] GUO | 21 | ASTR | $m_{A^0} = 8$–$23$ neV |
| $<1.2 \times 10^{-4}$ | 95 | [40] HOMMA | 21 | SAPH | $m_{A^0} = 0.4$–$600$ meV |
| $<1.2 \times 10^{-11}$ | 95 | [41] LI | 21B | ASTR | $m_{A^0} = 0.5$–$500$ neV |
| | | [42] LLOYD | 21 | ASTR | Magnetars |
| $<1 \times 10^{-13}$ | 95 | [43] REGIS | 21 | ASTR | $m_{A^0} = 2.7$–$5.3$ eV |
| $<1.8 \times 10^{-11}$ | 95 | [44] XIAO | 21 | ASTR | $m_{A^0} < 3.5 \times 10^{-11}$eV |
| $<7 \times 10^{-4}$ | 95 | [45] ABUDINEN | 20 | BEL2 | $m_{A^0} = 0.2$–$1$ GeV |
| $<2 \times 10^{-4}$ | 90 | [46] BANERJEE | 20A | NA64 | $m_{A^0} < 55$ MeV |
| $<1.0 \times 10^{-11}$ | 95 | [47] BUEHLER | 20 | ASTR | $m_{A^0} < 3$ neV |
| $<5 \times 10^{-10}$ | | [48] CALORE | 20 | ASTR | $m_{A^0} \lesssim 10^{-11}$ eV |

| | | | | |
|---|---|---|---|---|
| | | [49] CARENZA | 20 | ASTR | Globular clusters |
| $2–4 \times 10^{-10}$ | 95 | [50] DENT | 20A | ASTR | Solar axions |
| | | [51] DEPTA | 20 | COSM | Axion-like particles |
| $<3.6 \times 10^{-12}$ | 95 | [52] DESSERT | 20A | ASTR | $m_{A^0} < 5 \times 10^{-11}$ eV |
| | | [53] ESTEBAN | 20 | ANIT | Axion-like particles |
| $4–6 \times 10^{-10}$ | 90 | [54] GAO | 20 | ASTR | Solar axions |
| $<2.8 \times 10^{-11}$ | 95 | [55] KOROCHKIN | 20 | ASTR | $m_{A^0} = 25$ eV |
| none $6.0 \times 10^{-9}–1.3 \times 10^{-5}$ | | [56] LUCENTE | 20A | ASTR | $m_{A^0} < 270$ MeV |
| $<2.6 \times 10^{-11}$ | 95 | [57] MEYER | 20 | FLAT | $m_{A^0} < 3 \times 10^{-10}$ eV |
| $<8.4 \times 10^{-8}$ | 99 | [58] YAMAMOTO | 20 | COSM | $m_{A^0} < 4 \times 10^{-6}$ eV |
| $<1 \times 10^{-3}$ | 95 | [59] ALONI | 19 | PRMX | $m_{A^0} = 0.16$ GeV |
| $<1.4 \times 10^{-14}$ | 95 | [60] CAPUTO | 19 | ASTR | $m_{A^0} = 5 \times 10^{-24}$ eV |
| $<9.6 \times 10^{-14}$ | 95 | [61] FEDDERKE | 19 | CMB | $m_{A^0} = 10^{-22}$ eV |
| $<7 \times 10^{-13}$ | 95 | [62] IVANOV | 19 | ASTR | $m_{A^0} = 5 \times 10^{-23}$ eV |
| $<4 \times 10^{-11}$ | 95 | [63] LIANG | 19 | ASTR | $m_{A^0} = 1.2 \times 10^{-7}$ eV |
| | | [64] FORTIN | 18 | ASTR | Axion-like particles |
| $<3 \times 10^{-12}$ | | [65] JAECKEL | 18 | ASTR | $m_{A^0} = 30–100$ MeV |
| $<5.0 \times 10^{-3}$ | 90 | [66] YAMAJI | 18 | LSW | $m_{A^0} = 46–1020$ eV |
| $<1 \times 10^{-11}$ | 99.9 | [67] ZHANG | 18 | ASTR | $m_{A^0} = 0.6–4$ neV |
| | | [68] ADE | 17 | CMB | Axion-like particles |
| $<6.6 \times 10^{-11}$ | 95 | [69] ANASTASSO... | 17 | CAST | $m_{A^0} < 0.02$ eV |
| | | [70] DOLAN | 17 | RVUE | Axion-like particles |
| $<2.51 \times 10^{-4}$ | 95 | [71] INADA | 17 | LSW | $m_{A^0} < 0.1$ eV |
| $>1.5 \times 10^{-11}$ | 95 | [72] KOHRI | 17 | ASTR | $m_{A^0} = 0.7–50$ neV |
| $<2.6 \times 10^{-12}$ | 95 | [73] MARSH | 17 | ASTR | $m_{A^0} \leq 10^{-13}$ eV |
| $<6 \times 10^{-13}$ | | [74] TIWARI | 17 | COSM | $m_{A^0} \leq 10^{-15}$ eV |
| $<5 \times 10^{-12}$ | 95 | [75] AJELLO | 16 | ASTR | $m_{A^0} = 0.5–5$ neV |
| $<1.2 \times 10^{-7}$ | 95 | [76] DELLA-VALLE | 16 | LASR | $m_{A^0} = 1.3$ meV |
| $<7.2 \times 10^{-8}$ | 95 | [77] DELLA-VALLE | 16 | LASR | $m_{A^0} < 0.5$ meV |
| $<8 \times 10^{-4}$ | | [78] JAECKEL | 16 | ALPS | $m_{A^0} = 0.1–100$ GeV |
| $<6 \times 10^{-21}$ | | [79] LEEFER | 16 | | $m_{S^0} < 10^{-18}$ eV |
| | | [80] ANASTASSO... | 15 | CAST | Chameleons |
| $<1.47 \times 10^{-10}$ | 95 | [81] ARIK | 15 | CAST | $m_{A^0} = 0.39–0.42$ eV |
| $<3.5 \times 10^{-8}$ | 95 | [82] BALLOU | 15 | LSW | $m_{A^0} < 2 \times 10^{-4}$ eV |
| | | [83] BRAX | 15 | ASTR | $m_{S^0} < 4 \times 10^{-12}$ eV |
| $<5.42 \times 10^{-4}$ | 95 | [84] HASEBE | 15 | LASR | $m_{A^0} = 0.15$ eV |
| | | [85] MILLEA | 15 | COSM | Axion-like particles |
| | | [86] VANTILBURG | 15 | | Dilaton-like dark matter |
| $<4.1 \times 10^{-10}$ | 99.7 | [87] VINYOLES | 15 | ASTR | $m_{A^0} = 0.6–185$ eV |
| $<3.3 \times 10^{-10}$ | 95 | [88] ARIK | 14 | CAST | $m_{A^0} = 0.64–1.17$ eV |
| $<6.6 \times 10^{-11}$ | 95 | [89] AYALA | 14 | ASTR | Globular clusters |
| $<1.4 \times 10^{-7}$ | 95 | [90] DELLA-VALLE | 14 | LASR | $m_{A^0} = 1$ meV |
| | | [91] EJLLI | 14 | COSM | $m_{A^0} = 2.66–48.8$ $\mu$eV |
| $<8 \times 10^{-8}$ | 95 | [92] PUGNAT | 14 | LSW | $m_{A^0} < 0.3$ meV |

| | | | | | |
|---|---|---|---|---|---|
| $<1 \times 10^{-11}$ | | [93] REESMAN | 14 | ASTR | $m_{A^0} < 1 \times 10^{-10}$ eV |
| $<2.1 \times 10^{-11}$ | 95 | [94] ABRAMOWSKI | 13A | IACT | $m_{A^0} = 15$–$60$ neV |
| $<2.15 \times 10^{-9}$ | 95 | [95] ARMENGAUD | 13 | EDEL | $m_{A^0} < 200$ eV |
| $<4.5 \times 10^{-8}$ | 95 | [96] BETZ | 13 | LSW | $m_{A^0} = 7.2 \times 10^{-6}$ eV |
| $<8 \times 10^{-11}$ | | [97] FRIEDLAND | 13 | ASTR | Red giants |
| $>2 \times 10^{-11}$ | | [98] MEYER | 13 | ASTR | $m_{A^0} < 1 \times 10^{-7}$ eV |
| $<8.3 \times 10^{-12}$ | 95 | [99] WOUTERS | 13 | ASTR | $m_{A^0} < 7 \times 10^{-12}$ eV |
| | | [100] CADAMURO | 12 | COSM | Axion-like particles |
| $<2.5 \times 10^{-13}$ | 95 | [101] PAYEZ | 12 | ASTR | $m_{A^0} < 4.2 \times 10^{-14}$ eV |
| $<2.3 \times 10^{-10}$ | 95 | [102] ARIK | 11 | CAST | $m_{A^0} = 0.39$–$0.64$ eV |
| $<6.5 \times 10^{-8}$ | 95 | [103] EHRET | 10 | ALPS | $m_{A^0} < 0.7$ meV |
| $<2.4 \times 10^{-9}$ | 95 | [104] AHMED | 09A | CDMS | $m_{A^0} < 100$ eV |
| $< 1.2$–$2.8 \times 10^{-10}$ | 95 | [105] ARIK | 09 | CAST | $m_{A^0} = 0.02$–$0.39$ eV |
| | | [106] CHOU | 09 | | Chameleons |
| $<7 \times 10^{-10}$ | | [107] GONDOLO | 09 | ASTR | $m_{A^0} <$ few keV |
| $<1.3 \times 10^{-6}$ | 95 | [108] AFANASEV | 08 | | $m_{S^0} < 1$ meV |
| $<3.5 \times 10^{-7}$ | 99.7 | [109] CHOU | 08 | | $m_{A^0} < 0.5$ meV |
| $<1.1 \times 10^{-6}$ | 99.7 | [110] FOUCHE | 08 | | $m_{A^0} < 1$ meV |
| $< 5.6$–$13.4 \times 10^{-10}$ | 95 | [111] INOUE | 08 | | $m_{A^0} = 0.84$–$1.00$ eV |
| $<5 \times 10^{-7}$ | | [112] ZAVATTINI | 08 | | $m_{A^0} < 1$ meV |
| $<8.8 \times 10^{-11}$ | 95 | [113] ANDRIAMON... | 07 | CAST | $m_{A^0} < 0.02$ eV |
| $<1.25 \times 10^{-6}$ | 95 | [114] ROBILLIARD | 07 | | $m_{A^0} < 1$ meV |
| $2$–$5 \times 10^{-6}$ | | [115] ZAVATTINI | 06 | | $m_{A^0} = 1$–$1.5$ meV |
| $<1.1 \times 10^{-9}$ | 95 | [116] INOUE | 02 | | $m_{A^0} = 0.05$–$0.27$ eV |
| $<2.78 \times 10^{-9}$ | 95 | [117] MORALES | 02B | | $m_{A^0} < 1$ keV |
| $<1.7 \times 10^{-9}$ | 90 | [118] BERNABEI | 01B | | $m_{A^0} < 100$ eV |
| $<1.5 \times 10^{-4}$ | 90 | [119] ASTIER | 00B | NOMD | $m_{A^0} < 40$ eV |
| | | [120] MASSO | 00 | THEO | induced $\gamma$ coupling |
| $<2.7 \times 10^{-9}$ | 95 | [121] AVIGNONE | 98 | SLAX | $m_{A^0} < 1$ keV |
| $<6.0 \times 10^{-10}$ | 95 | [122] MORIYAMA | 98 | | $m_{A^0} < 0.03$ eV |
| $<3.6 \times 10^{-7}$ | 95 | [123] CAMERON | 93 | | $m_{A^0} < 10^{-3}$ eV, optical rotation |
| $<6.7 \times 10^{-7}$ | 95 | [124] CAMERON | 93 | | $m_{A^0} < 10^{-3}$ eV, photon regeneration |
| $<3.6 \times 10^{-9}$ | 99.7 | [125] LAZARUS | 92 | | $m_{A^0} < 0.03$ eV |
| $<7.7 \times 10^{-9}$ | 99.7 | [125] LAZARUS | 92 | | $m_{A^0} = 0.03$–$0.11$ eV |
| $<7.7 \times 10^{-7}$ | 99 | [126] RUOSO | 92 | | $m_{A^0} < 10^{-3}$ eV |
| $<2.5 \times 10^{-6}$ | | [127] SEMERTZIDIS | 90 | | $m_{A^0} < 7 \times 10^{-4}$ eV |

[1] PANT 24 searches for the imprint of axion-photon oscillations in the very-high-energy gamma-ray spectrum of the quasar QSO B1420+326 observed by the MAGIC telescope. Three small disconnected regions of mass-coupling parameter space below 1 neV are ruled out. See Fig. 4 for the limits.

[2] BATTYE 23 look for dark-matter axions falling into pulsar magnetospheres and converting into narrow radio lines. Unlike the earlier FOSTER 22 they search for evidence of conversion in the time-domain signal of a single pulsar, using 1 hour of MeerKAT data on the pulsar PSR J2144-3933. The quoted limit applies to an assumed magnetic field of $2 \times 10^{12}$ G and a dark matter density of 0.45 GeV/cm$^3$.

[3] BEAUFORT 23 extends DEROCCO 22 who searched for the X-ray decay of axions that build up in the gravitational well of the Sun over its lifetime, the 'solar basin'. They use data from NuSTAR and SphinX telescopes and extends the previous study by accounting for the axion production via photon coalescence.

[4] BERNAL 23 use gamma-ray data from 739 blazars observed by FermiLAT and 38 blazars by Cherenkov observatories. They estimate optical depth, subtract the astrophysical component, and attribute the residual to axion two-photon decay. The quoted limit is for $m_{A^0} \simeq$ 25 eV. See their Fig. 3 for the mass-dependent limits.

[5] CAPOZZI 23 use Planck CMB and Lyman-alpha observations to set limits on early energy injection by decaying dark matter axions that would affect CMB anisotropies and the reionisation history of the Universe. The quoted limit applies to $m_{A^0} = 100$ eV and the reionization model of Fauchere-Giguere. See Fig.4 for mass-dependent constraints from different reionization models.

[6] CAPOZZI 23A search for axions produced in electromagnetic showers in proton beam dumps and fixed target experiments. In this case, they reinterpret MiniBoone data. Quoted limit applies at 100 MeV but the limit does not extend to arbitrarily large couplings. See Fig. 7 for mass-dependent limits.

[7] DAVIES 23 is analogous to AJELLO 16, and use the Fermi-LAT data from three quasars (3C454.3, CTA 102, and 3C279), considering the blazer jets as the regions where the axion-photon oscillations occur. See Fig. 8 for the mass-dependent limits.

[8] DIAMOND 23 demonstrate that a window of decaying 10-MeV-mass ALP parameter space previously thought to be excluded by the lack of gamma-ray emission from the SN 1987A explosion is actually unconstrained because of the formation of a fireball that would prevent decay photons from escaping. They nevertheless re-exclude this window by considering the non-detection of the sub-MeV emission by the Pioneer Venus Orbiter. The quoted limit is at $m_{A^0} = 56$ MeV. See their Fig. 2 for mass-dependent limits.

[9] FILZINGER 23 searched for oscillations in the fine structure constant induced by dilaton-like dark matter by measuring the frequency ratio between the E3 and E2 transitions of $^{171}\mathrm{Yb}^+$. They assume the local dark matter density $\rho_S = 0.4$ GeV/cm$^3$. The quoted limit is set at $m_{S^0} \simeq 4 \times 10^{-23}$ eV. See their Fig. 4 for the limits over $m_{S^0} = 1 \times 10^{-24}$–$1 \times 10^{-17}$ eV.

[10] HOOF 23 consider axions emitted from SN1987A converting to gamma rays in Galactic magnetic fields, using temporal information of the Solar Maximum Mission data. They set a limit $G_{A\gamma\gamma} \lesssim 5 \times 10^{-12}$ for masses $m_{A^0} \lesssim 2 \times 10^{-10}$ eV. See left panel in Fig. 3 for mass-dependent limits.

[11] HOOF 23 look for gamma rays resulting from the decay of axions produced from SN1987A, using the Solar Maximum Mission data. See right panel in Fig. 3 for mass-dependent limits.

[12] JACOBSEN 23 search for the imprints of axion-photon mixing on the TeV spectra of several blazars using data from the HAWC air shower detector.

[13] LI 23H look for gamma-ray spectral irregularities induced by axion-photon oscillations from AGN VER J0521+211, using the Fermi-LAT and VERITAS data. See their Fig. 4 for mass-dependent limits.

[14] NOORDHUIS 23 places strong constraints on the axion-photon coupling over a broad mass window using the fact that the polar cap regions of pulsars can generate a population of axions, which would then convert into an observable outgoing radio flux in the presence of the neutron star's B-field. They search for this signal in 27 pulsars and set mass-dependent limits shown in their Fig. 2.

[15] PANT 23 study the effect of axion-photon oscillations on the gamma-ray spectrum from the extragalactic neutrino source, TXS 0506+056. The quoted limit is at $m_{A^0} \simeq 2.7 \times 10^{-7}$ eV. See their Fig. 2 for mass-dependent limits.

[16] SHERRILL 23 search for scalar dilaton-like dark matter via oscillations in the fundamental constants. Their most competitive constraint is on the scalar photon coupling (Fig. 6, upper panel) that affects the fine-structure constant, which they extract using an optical-to-optical clock comparison between $^{171}\text{Yb}^{+}$ and $^{87}\text{Sr}$. Quoted limit applies at the smallest mass in their search window for this case of $10^{-20}$ eV.

[17] SULAI 23 looked for ultralight axion dark matter using the "Earth as a transducer" concept over the 0.5 to 5 Hz frequency range. They situate several magnetometers at magnetically quiet places and search for spatially-correlated magnetic field patterns induced by axion dark matter interacting in the effective cavity formed between the Earth's surface and the ionosphere. See their Fig. 12 for mass-dependent limits in context. This limit extends to higher-frequencies than their previous limit using archival geomagnetic field data collected by the SuperMAG collaboration, see ARZA 22

[18] YAO 23 study an optical circular polarization in blazers induced by the axion-photon mixing. The quoted limit assumes the transverse magnetic field at the jet's emission site, with $B_T = 1$ G, and this limit inversely scales with $B_T$. See their Fig. 3 for the limits' dependence on $B_T$ and electron density.

[19] ZHANG 23A searched for oscillations in the fine structure constant induced by dilaton-like dark matter by measuring the frequencies of a hyperfine-structure transition in $^{87}\text{Rb}$ and an electronic transition in $^{164}\text{Dy}$, and by comparing them with that of a quartz oscillator. They assume the local dark matter density $\rho_S \simeq 0.4$ GeV/cm$^3$. The quoted limit is set at $m_{S^0} \simeq 1 \times 10^{-17}$ eV. See their Fig. 3 for the limits over $m_{S^0} = 1 \times 10^{-17}$–$8.3 \times 10^{-13}$ eV.

[20] APRILE 22B is an update of APRILE 20 based on a similar solar axion modeling to DENT 20A and GAO 20. They exclude the XENON1T excess found in APRILE 20. The quoted limit holds for small $g_{Aee}$. See Fig. 6 for correlation between $G_{A\gamma\gamma}$ and $g_{Aee}$.

[21] ARNQUIST 22 is analogous to AVIGNONE 98, and supersedes ANASTASSOPOULOS 17 for $m_{A^0} \gtrsim 1.2$ eV.

[22] ARZA 22 search for low-mass axions as dark matter using the Earth as a transducer for axion-photon conversion. The concept works because the region between the Earth and the ionosphere forms an insulating cavity that parametrically enhances the axion signal by the radius of the Earth. The result is an oscillating and spatially correlated magnetic field induced via the interaction between axion dark matter and the geomagnetic field, which they searched for using archival magnetometer field data over 20 years compiled by the SuperMAG collaboration. Quoted limit applies for masses 3–4 $\times 10^{-17}$ eV, see Fig. 1 for mass-dependent limits.

[23] BERNAL 22 explored the possibility that the excess in the cosmic optical background measured by New Horizonss Long Range Reconnaisance Imager was due to axion dark matter decaying into monoenergetic photons. See their Fig. 2 for the axion-photon coupling to explain the excess.

[24] CALORE 22 update CALORE 20 by evaluating axion fluxes from progenitors of various masses and performing a template-based analysis using 12 years of Fermi-LAT data in the energy range from 50 MeV to 500 GeV. See their Fig. 10 for mass-dependent limits.

[25] CAPUTO 22 study the effect of energy deposition by radiative decay of axions produced via the Primakoff process and photon coalescence in the supernova core, and set the limits by the radiative energy deposition $< 10^{50}$ erg and progenitor radius $= 5 \times 10^{13}$ cm. The quoted limit is at $m_{A^0} = 150$ MeV. See their Fig. 2 for mass-dependent limits.

[26] CASTILLO 22 update CAPUTO 19 using the polarization measurements of the Crab Pulsar by the QUIJOTE MFI instrument and 20 Galactic pulsars from the PPTA project. See their Table 1 for the assumed local axion energy density $\rho_A$ for each pulsar and their Fig. 7 for the mass-dependent limits in the range of $3 \times 10^{-23}$ eV $\leq m_{A^0} \leq 10^{-19}$ eV.

[27] DEROCCO 22 uses the NuSTAR data to search for monochromatic X-ray lines produced by the decay of solar axions trapped on bound orbits. The quoted limit applies to $m_{A^0} \simeq$ 9 keV. They also derive limits in the plane of $g_{Aee}$ and $G_{A\gamma\gamma}$. See their Figs. 2 and 4 for mass-dependent limits.

[28] DESSERT 22A look for an axion-induced linear polarization using data from multiple magnetic white dwarf stars. See their Figs. 1 and 8 for the mass-dependent limits.

[29] ECKNER 22 set limits by using sub-PeV diffuse gamma-ray data from HAWC and Tibet AS$\gamma$ by assuming that gamma rays produced simultaneously with high-energy neutrinos from extragalactic sources suggested by IceCube are converted to axions in the magnetic field at the source and reconverted to gamma rays in the Galactic magnetic field. See their Fig. 4 for mass-dependent limits.

[30] FOSTER 22 is an update of FOSTER 20 in the list of limits on relic invisible axions. They search for axion-photon transitions generated by neutron stars in the Galactic center region. They use improved population models of the Galactic center neutron stars and a Navarro-Frenk-White (NFW) model of the galactic dark matter distribution. The quoted limit applies to $m_{A^0} \simeq$ 17–25 $\mu$eV. See their Fig. 1 for mass-dependent limits.

[31] KIRITA 22 update HOMMA 21 by increasing the laser energy and developing a background discrimination method using the beam cross-section dependence of the background originated from optical elements. The quoted limits applies to $m_{A^0} = 0.18$ eV. See their Fig. 11 for mass-dependent limits.

[32] LANGHOFF 22 set limits by considering the freeze-in production of axions coupled only to photons. The quoted limit applies to $m_{A^0} = 2$ MeV for the reheating temperature equal to 5 MeV. See their Fig. 1 for mass-dependent limits.

[33] LI 22 is analogous to LI 21B, and use the spectra of the blazar FSRQ 4C+21.35 measured by MAGIC, VERITAS, and Fermi-LAT. The quoted limit applies to $m_{A^0} \simeq 8 \times 10^{-10}$ eV. See their Fig. 1 for mass-dependent limits.

[34] LI 22C is analogous to LI 21B, and use the spectra of the blazars Mrk 421 and PG 1553+113 measured by MAGIC and Fermi-LAT. The quoted limit applies to $m_{A^0} \simeq$ $1 \times 10^{-8}$ eV. See their Fig. 4 for mass-dependent limits.

[35] LUCENTE 22 developed a method to correctly incorporate the effects of axions decaying into photons inside the core of horizontal-branch stars. They update CARENZA 20 by evaluating axion energy transfer in the range of axion mean free path where the diffusive energy transport and free streaming approximations are not applicable. See their Fig. 1 for the limits.

[36] BASU 21 searched for birefringence induced by axion dark matter using multiple images of the polarized source in the strongly gravitationally lensed system CLASS B1152+199. They assume the axion makes up all dark matter, and used the axion density in the emitting region, $\rho_A = 20$ GeV/cm$^3$. Limits between $9.2 \times 10^{-11}$–$7.7 \times 10^{-8}$ GeV$^{-1}$ are obtained for $m_{A^0} = 3.6 \times 10^{-21}$–$4.6 \times 10^{-18}$eV. See their Fig. 2 for mass-dependent limits.

[37] BI 21 look for the gamma-ray spectral distortions induced by axion-photon oscillations in the presence of the Galactic magnetic field, using the measurements of sub-PeV gamma-rays from the Crab Nebula by the Tibet AS$\gamma$ and HAWC experiments, together with MAGIC and HEGRA gamma-ray data. See their Fig. 3 for mass-dependent limits.

[38] DOLAN 21A study the effect of axion production on the evolution of asymptotic giant branch stars, and use the white-dwarf initial-final mass relation to set the limits. See their Fig. 1 for mass-dependent limits.

[39] GUO 21 is analogous to AJELLO 16, and use the Fermi-LAT and H.E.S.S. II measurements of PG 1553+113 and PKS 2155-304. See their Fig. 6 for mass-dependent limits.

[40] HOMMA 21 look for the production of axion resonance states and their subsequent stimulated decays by combining linearly polarized creation laser pulses and circularly polarized inducing laser pulses. The quoted limit is at $m_{A^0} \simeq 0.178$ eV. See their Fig. 14 for mass-dependent limits.

[41] LI 21B is analogous to AJELLO 16, and use the spectra of the blazar Mrk 421 measured by ARGO-YBJ and Fermi-LAT. They consider ALP-photon mixing in the magnetic fields of both the blazar jet and the Galaxy. The quoted limit applies to $m_{A^0} \simeq 1 \times 10^{-9}$ eV. See their Fig. 5 for mass-dependent limits.

[42] LLOYD 21 is analogous to FORTIN 18, and set limits on the product of the axion couplings to photons and nucleons as $g_{ANN}\, G_{A\gamma\gamma} \lesssim 4.6{\times}10^{-19}$ GeV$^{-1}$ for $m_{A^0} \lesssim 10^{-5}$ eV by using the quiescent soft gamma-ray flux upper limits in five magnetars. We use $g_{ANN} = G_{AN}\, 2m_N$ to translate their limits. See their Table II and Fig. 3 for the limits.

[43] REGIS 21 look for monochromatic photons from axion decay, using the MUSE spectroscopic data on the Leo T dwarf spheroidal galaxy. They assume that axions make up all of dark matter and use the integrated dark matter density along the line of sight determined by observations.

[44] XIAO 21 use X-ray data from Betelgeuse to look for signals from axions produced in the stellar core that were converted to X-rays by the Galactic magnetic field. See their Fig. 1 for the mass-dependent limit.

[45] ABUDINEN 20 look for the process $e^+ e^- \rightarrow \gamma A^0$ ($A^0 \rightarrow \gamma\gamma$) and set upper limits of around $10^{-3}$ over the mass range. The quoted limit is at $m_{A^0} = 0.3$ GeV. See their Fig. 5 for mass dependent limits.

[46] BANERJEE 20A look for axions produced from high-energy bremsstrahlung photons through the Primakoff effect with the electric field of the target nuclei. They exclude $G_{A\gamma\gamma} = 2 \times 10^{-4}$–$5 \times 10^{-2}$ GeV$^{-1}$ for $m_{A^0} < 55$ MeV. See their Fig. 5 for mass-dependent limits.

[47] BUEHLER 20 look for the $\gamma$-ray transparency due to axion-photon oscillations using high-energy photon events from 79 sources in the Second Fermi-LAT Catalog of High-Energy Sources. The quoted limit is for the intergalactic magnetic field strength and coherence length of $B = 1$ nG and $s = 1$ Mpc. See their Figs. 4 and 5 for mass-dependent limits and for different magnetic-field parameters.

[48] CALORE 20 use the isotropic diffuse $\gamma$-ray background measured by the Fermi-LAT to constrain the $\gamma$-ray flux converted in the Galactic magnetic field from axions produced from past core-collapse supernovae. They also derive a limit on a heavier axion with $m_{A^0} \gtrsim$ keV decaying into two photons of $G_{A\gamma\gamma} \lesssim 5 \times 10^{-11}$ GeV$^{-1}$ for $m_{A^0} = 5$ keV. See their Figs. 5 and 7 for the limits as well as limits in the presence of axion-nucleon couplings.

[49] CARENZA 20 extend the globular cluster bound of AYALA 14 to heavier masses ($m_{A^0} \leq$ a few 100 keV) by taking account of the coalescence process $\gamma + \gamma \rightarrow A^0$ as well as the decay of the ALP inside the stellar core. See their Fig.4 for mass-dependent limits.

[50] DENT 20A is analogous to GAO 20. The quoted limit is from their arXiv:2006.15118v3 (v2 is their published version), using the relativistic Hartree-Fock form factor. The limit is up to two times weaker than the published one. See Fig. 4 in their arXiv version 3 for the correlation between $G_{A\gamma\gamma}$ and $g_{Aee}$ corresponding to the excess reported in APRILE 20.

[51] DEPTA 20 correct the underestimated D abundance in MILLEA 15, and derive robust cosmological bounds by allowing the reheating temperature, $N_{\text{eff}}$, and neutrino chemical potential to vary. See their Fig. 6 for mass-dependent limits.

[52] DESSERT 20A use the NuSTAR data of the Quintuplet and Westerlund 1 super star clusters to look for X-rays converted in the Galactic magnetic field from the axions produced in stellar cores. See their Fig. 3 for the mass-dependent limits.

[53] ESTEBAN 20 show that the two anomalous ANITA events can be explained by the reflected radio pulses that are resonantly produced in the ionosphere via axion-photon

conversion for $m_{A^0} \lesssim 1 \times 10^{-7}$ eV , if an axion clump passes the Earth about once a month. See their Fig.5 for the region consistent with this interpretation for different values of the axion density inside the clumps.

[54] GAO 20 correct the limit of APRILE 20 by including inverse Primakoff scattering in the XENON1T detector. The quoted limit is from their arXiv:2006.14598v4 (v3 is their published version), taking account of the atomic form factor of Xe as pointed out in ABE 20J. The limit is weaker by a factor of 1.5–2 than the published one. See Fig. 3 in their arXiv version 4 for correlation between $G_{A\gamma\gamma}$ and $g_{Aee}$ corresponding to the excess reported in APRILE 20.

[55] KOROCHKIN 20 assume the axion makes up all dark matter, and look for a dip in the observed gamma-ray spectrum of the blazer 1ES 1218+304 by Fermi/LAT and VERITAS due to the extragalactic background light produced by the axion decay. Their analysis favors nonzero axion-induced absorption with $G_{A\gamma\gamma} = 3 \times 10^{-11}$–$2 \times 10^{-10}$ GeV$^{-1}$ over a range of $m_{A^0} = 2$–$18$ eV. See their Fig. 1 for mass-dependent limits between $0.25 < m_{A^0} < 25$ eV.

[56] LUCENTE 20A study the SN 1987A energy-loss argument on the axion-like particle production. In addition to the Primakoff process, they take account of photon coalescence as well as gravitational trapping that become relevant at $m_{A^0} > 100$ MeV. See their Fig. 12 for the mass-dependent limit.

[57] MEYER 20 look for prompt $\gamma$-rays converted in the Galactic magnetic fields from axions produced via the Primakoff process in a sample of 20 extragalactic core-collapse supernovae. The limits assume a progenitor mass of 10 times the solar mass and certain models for the optical emission and the galactic magnetic field. See their Figs. 2 and 6 in the erratum for mass- and model-dependent limits.

[58] YAMAMOTO 20 look for X-ray photons converted by the Earth's magnetic field from the axions produced by the two-body decay of dark matter, and set the limits by using the Suzaku data. The quoted limit is for the monochromatic X-ray line from the galactic dark matter with lifetime $\tau = 4.32 \times 10^{17}$ sec. They also derive limits on the continuum spectrum from the extragalactic component. See their Fig. 7 for the limits.

[59] ALONI 19 used the data collected by the PRIMEX experiment to derive a limit based on a data-driven method. See their Fig. 2 for mass-dependent limits.

[60] CAPUTO 19 look for an oscillating variation of the polarization angle of the pulsar J0437-4715, where they assume the local axion energy density $\rho_A = 0.3$ GeV/cm$^3$. See their Fig. 2 for mass-dependent limits for $5 \times 10^{-24}$ eV $\leq m_{A^0} \leq 2 \times 10^{-19}$ eV.

[61] FEDDERKE 19 look for a uniform reduction of the CMB polarization at large scales, which is induced by the oscillating axion background during CMB decoupling. The quoted limit is based on the assumption that axions make up all of the dark matter. See their Fig. 3 for mass-dependent limits for $m_{A^0} = 10^{-22}$–$10^{-19}$ eV.

[62] IVANOV 19 look for the axion-induced periodic changes in the polarization angle of parsec-scale jets in active galactic nuclei observed by the MOJAVE program, where they use the axion energy density $\rho_A = 20$ GeV/cm$^3$. See their Fig. 6 for mass-dependent limits for $5 \times 10^{-23}$ eV $\leq m_{A^0} \leq 1.2 \times 10^{-21}$ eV.

[63] LIANG 19 look for spectral irregularities in the spectrum of 10 bright H.E.S.S. sources in the Galactic plane, assuming photon-ALP mixing in the Galactic magnetic fields. See their Fig. 2 for mass-dependent limits with different Galactic magnetic field models.

[64] FORTIN 18 studied the conversion of axion-like particles produced in the core of a magnetar to hard X-rays in the magnetosphere. See their Fig. 5 for mass-dependent limits with different values of the magnetar core temperature.

[65] JAECKEL 18 study axions produced through the Primakoff process from SN 1987A, which subsequently decay into photon pairs. See their Fig. 1 for the mass-dependent limits in the range of $m_{A^0} = 0.01$–$100$ MeV.

[66] YAMAJI 18 search for axions with an x-ray LSW at Spring-8, using the Laue-case conversion in a silicon crystal. They also obtain $G_{A\gamma\gamma} < 4.2 \times 10^{-3}$ GeV$^{-1}$ for $m_{A^0} <$ 10 eV. See their Fig. 5 for mass-dependent limits.

[67] ZHANG 18 look for spectral irregularities in the spectrum of PKS 2155-304 measured by Fermi LAT, assuming photon-ALP mixing in the intercluster and Galactic magnetic fields. See their Figs. 2 and 3 for mass-dependent limits with different values of the intercluster magnetic field parameters.

[68] ADE 17 look for cosmic birefringence from axion-like particles using CMB polarization data taken by the BICEP2 and Keck Array experiments. They set a limit $G_{A\gamma\gamma} H_I < 7.2 \times 10^{-2}$ at 95 %CL for $m_{A^0} < 10^{-28}$ eV, where $H_I$ is the Hubble parameter during inflation.

[69] ANASTASSOPOULOS 17 looked for solar axions by the CAST axion helioscope in the vacuum phase, and supersedes ANDRIAMONJE 07.

[70] DOLAN 17 update existing limits on $G_{A\gamma\gamma}$ for axion-like particles. The limits from the proton beam dump experiments in their Fig. 2 contained an error, and the corrected version is shown in Fig. 1 of DOLAN 21.

[71] INADA 17 search for axions with an x-ray LSW at Spring-8. See their Fig. 4 for mass-dependent limits.

[72] KOHRI 17 attributed to axion-photon oscillations the excess of cosmic infrared background observed by the CIBER experiment. See their Fig. 5 for the region preferred by their scenario.

[73] MARSH 17 is similar to WOUTERS 13, using Chandra observations of M87. See their Fig. 6 for mass-dependent limits.

[74] TIWARI 17 use observed limits of the cosmic distance-duality relation to constrain the photon-ALP mixing based on 3D simulations of the magnetic field configuration. The quoted value is for the averaged magnetic field of 1nG with a coherent length of 1 Mpc. See their Fig. 5 for mass-dependent limits.

[75] AJELLO 16 look for irregularities in the energy spectrum of the NGC1275 measured by Fermi LAT, assuming photon-ALP mixing in the intra-cluster and Galactic magnetic fields. See their Fig. 2 for mass-dependent limits.

[76] DELLA-VALLE 16 look for the birefringence induced by axion-like particles. See their Fig. 14 for mass-dependent limits.

[77] DELLA-VALLE 16 look for the dichroism induced by axion-like particles. See their Fig. 14 for mass-dependent limits.

[78] JAECKEL 16 use the LEP data of $Z \rightarrow 2\gamma$ and $Z \rightarrow 3\gamma$ to constrain the ALP production via $e^+ e^- \rightarrow Z \rightarrow A^0 \gamma \, (A^0 \rightarrow \gamma\gamma)$, assuming the ALP coupling with two hypercharge bosons. See their Fig. 4 for mass-dependent limits.

[79] LEEFER 16 derived limits by using radio-frequency spectroscopy of dysprosium and atomic clock measurements. See their Fig. 1 for mass-dependent limits as well as limits on Yukawa-type couplings of the scalar to the electron and nucleons.

[80] ANASTASSOPOULOS 15 search for solar chameleons with CAST and derived limits on the chameleon coupling to photons and matter. See their Fig. 12 for the exclusion region.

[81] ARIK 15 is analogous to ARIK 09, and search for solar axions for $m_{A^0}$ around 0.2 and 0.4 eV. See their Figs. 1 and 3 for the mass-dependent limits.

[82] Based on OSQAR photon regeneration experiment. See their Fig. 6 for mass-dependent limits on scalar and pseudoscalar bosons.

[83] BRAX 15 derived limits on conformal and disformal couplings of a scalar to photons by searching for a chaotic absorption pattern in the X-ray and UV bands of the Hydra A galaxy cluster and a BL lac object, respectively. See their Fig. 8.

[84] HASEBE 15 look for an axion via a four-wave mixing process at quasi-parallel colliding laser beams. They also derived limits on a scalar coupling to photons $G_{S\gamma\gamma} < 2.62 \times 10^{-4}$ GeV$^{-1}$ at $m_{S^0} = 0.15$ eV. See their Figs. 11 and 12 for mass-dependent limits.

[85] MILLEA 15 is similar to CADAMURO 12, including the Planck data and the latest inferences of primordial deuterium abundance. See their Fig. 3 for mass-dependent limits.

[86] VANTILBURG 15 look for harmonic variations in the dyprosium transition frequency data, induced by coherent oscillations of the fine-structure constant due to dilaton-like dark matter, and set the limits, $G_{S\gamma\gamma} < 6 \times 10^{-27}$ GeV$^{-1}$ at $m_{S^0} = 6 \times 10^{-23}$ eV. See their Fig. 4 for mass-dependent limits between $1 \times 10^{-24} < m_{S^0} < 1 \times 10^{-15}$ eV.

[87] VINYOLES 15 performed a global fit analysis based on helioseismology and solar neutrino observations. See their Fig. 9.

[88] ARIK 14 is similar to ARIK 11. See their Fig. 2 for mass-dependent limits.

[89] AYALA 14 derived the limit from the helium-burning lifetime of horizontal-branch stars based on number counts in globular clusters.

[90] DELLA-VALLE 14 use the new PVLAS apparatus to set a limit on vacuum magnetic birefringence induced by axion-like particles. See their Fig. 6 for the mass-dependent limits.

[91] EJLLI 14 set limits on a product of primordial magnetic field and the axion mass using CMB distortion induced by resonant axion production from CMB photons. See their Fig. 1 for limits applying specifically to the DFSZ and KSVZ axion models.

[92] PUGNAT 14 is analogous to EHRET 10. See their Fig. 5 for mass-dependent limits on scalar and pseudoscalar bosons.

[93] REESMAN 14 derive limits by requiring effects of axion-photon interconversion on gamma-ray spectra from distant blazars to be no larger than errors in the best-fit optical depth based on a certain extragalactic background light model. See their Fig. 5 for mass-dependent limits.

[94] ABRAMOWSKI 13A look for irregularities in the energy spectrum of the BL Lac object PKS 2155–304 measured by H.E.S.S. The limits depend on assumed magnetic field around the source. See their Fig. 7 for mass-dependent limits.

[95] ARMENGAUD 13 is analogous to AVIGNONE 98. See Fig. 6 for the limit.

[96] BETZ 13 performed a microwave-based light shining through the wall experiment. See their Fig. 13 for mass-dependent limits.

[97] FRIEDLAND 13 derived the limit by considering blue-loop suppression of the evolution of red giants with 7–12 solar masses.

[98] MEYER 13 attributed to axion-photon oscillations the observed excess of very high-energy $\gamma$-rays with respect to predictions based on extragalactic background light models. See their Fig.4 for mass-dependent lower limits for various magnetic field configurations.

[99] WOUTERS 13 look for irregularities in the X-ray spectrum of the Hydra cluster observed by Chandra. See their Fig. 4 for mass-dependent limits.

[100] CADAMURO 12 derived cosmological limits on $G_{A\gamma\gamma}$ for axion-like particles. See their Fig. 1 for mass-dependent limits.

[101] PAYEZ 12 derive limits from polarization measurements of quasar light (see their Fig. 3). The limits depend on assumed magnetic field strength in galaxy clusters. The limits depend on assumed magnetic field and electron density in the local galaxy supercluster.

[102] ARIK 11 search for solar axions using $^3$He buffer gas in CAST, continuing from the $^4$He version of ARIK 09. See Fig. 2 for the exact mass-dependent limits.

[103] ALPS is a photon regeneration experiment. See their Fig. 4 for mass-dependent limits on scalar and pseudoscalar bosons.

[104] AHMED 09A is analogous to AVIGNONE 98.

[105] ARIK 09 is the $^4$He filling version of the CAST axion helioscope in analogy to INOUE 02 and INOUE 08. See their Fig. 7 for mass-dependent limits.

[106] CHOU 09 use the GammeV apparatus in the afterglow mode to search for chameleons, (pseudo)scalar bosons with a mass depending on the environment. For pseudoscalars they exclude at $3\sigma$ the range $2.6 \times 10^{-7}$ GeV$^{-1}$ $<$ $G_{A\gamma\gamma}$ $<$ $4.2 \times 10^{-6}$ GeV$^{-1}$ for vacuum $m_{A^0}$ roughly below 6 meV for density scaling index exceeding 0.8.

[107] GONDOLO 09 use the all-flavor measured solar neutrino flux to constrain solar interior temperature and thus energy losses.

[108] LIPSS photon regeneration experiment, assuming scalar particle $S^0$. See Fig. 4 for mass-dependent limits.

[109] CHOU 08 perform a variable-baseline photon regeneration experiment. See their Fig. 3 for mass-dependent limits. Excludes the PVLAS result of ZAVATTINI 06.

[110] FOUCHE 08 is an update of ROBILLIARD 07. See their Fig. 12 for mass-dependent limits.

[111] INOUE 08 is an extension of INOUE 02 to larger axion masses, using the Tokyo axion helioscope. See their Fig. 4 for mass-dependent limits.

[112] ZAVATTINI 08 is an upgrade of ZAVATTINI 06, see their Fig. 8 for mass-dependent limits. They now exclude the parameter range where ZAVATTINI 06 had seen a positive signature.

[113] ANDRIAMONJE 07 looked for Primakoff conversion of solar axions in 9T superconducting magnet into X-rays. Supersedes ZIOUTAS 05.

[114] ROBILLIARD 07 perform a photon regeneration experiment with a pulsed laser and pulsed magnetic field. See their Fig. 4 for mass-dependent limits. Excludes the PVLAS result of ZAVATTINI 06 with a CL exceeding 99.9%.

[115] ZAVATTINI 06 propagate a laser beam in a magnetic field and observe dichroism and birefringence effects that could be attributed to an axion-like particle. This result is now excluded by ROBILLIARD 07, ZAVATTINI 08, and CHOU 08.

[116] INOUE 02 looked for Primakoff conversion of solar axions in 4T superconducting magnet into X ray.

[117] MORALES 02B looked for the coherent conversion of solar axions to photons via the Primakoff effect in Germanium detector.

[118] BERNABEI 01B looked for Primakoff coherent conversion of solar axions into photons via Bragg scattering in NaI crystal in DAMA dark matter detector.

[119] ASTIER 00B looked for production of axions from the interaction of high-energy photons with the horn magnetic field and their subsequent re-conversion to photons via the interaction with the NOMAD dipole magnetic field.

[120] MASSO 00 studied limits on axion-proton coupling using the induced axion-photon coupling through the proton loop and CAMERON 93 bound on the axion-photon coupling using optical rotation. They obtained the bound $g_p^2/4\pi < 1.7 \times 10^{-9}$ for the coupling $g_p \overline{p} \gamma_5 p \phi_A$.

[121] AVIGNONE 98 result is based on the coherent conversion of solar axions to photons via the Primakoff effect in a single crystal germanium detector.

[122] Based on the conversion of solar axions to *X*-rays in a strong laboratory magnetic field.

[123] Experiment based on proposal by MAIANI 86.

[124] Experiment based on proposal by VANBIBBER 87.

[125] LAZARUS 92 experiment is based on proposal found in VANBIBBER 89.

[126] RUOSO 92 experiment is based on the proposal by VANBIBBER 87.

[127] SEMERTZIDIS 90 experiment is based on the proposal of MAIANI 86. The limit is obtained by taking the noise amplitude as the upper limit. Limits extend to $m_{A^0} = 4 \times 10^{-3}$ where $G_{A\gamma\gamma}$ $<$ $1 \times 10^{-4}$ GeV$^{-1}$.

## Limit on Invisible $A^0$ (Axion) Electron Coupling

The limit is for $g_{Aee}\, \phi_A\, \overline{e}(i\,\gamma_5)e$, or equivalently, the dipole-dipole potential $-\frac{g^2_{Aee}}{16\pi m^2_e}\,((\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) - 3(\boldsymbol{\sigma}_1 \cdot \boldsymbol{n})\,(\boldsymbol{\sigma}_2 \cdot \boldsymbol{n}))/r^3$ where $\boldsymbol{n}=\boldsymbol{r}/r$ and the sign of the potential was corrected based on DAIDO 17.

| *VALUE* | *CL%* | *DOCUMENT ID* | *TECN* | *COMMENT* |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $<2.35 \times 10^{-12}$ | 90 | [1] AALBERS 23A | LZ | Solar axions |
| $<1.3 \times 10^{-14}$ | 90 | [2] AALBERS 23A | LZ | $m_{A^0} = 1\text{–}17$ keV |
| $<1.61 \times 10^{-11}$ | 90 | [3] ADHIKARI 23 | C100 | Solar axions |
| $<6 \times 10^{-13}$ | 90 | [4] ADHIKARI 23A | C100 | $m_{A^0} = 10\text{–}1000$ keV |
| $<8 \times 10^{-14}$ | 90 | [5] AGNES 23A | DS50 | $m_{A^0} = 0.03\text{–}20$ keV |
| | | [6] APRILE 23B | XE1T | Neutron star merger |
| $<3 \times 10^{-9}$ | 95 | [7] CAPOZZI 23A | DUMP | $m_{A^0} = 10^4\text{–}2 \times 10^7$ eV |
| $<6 \times 10^{-15}$ | | [8] WADEKAR 23 | ASTR | $m_{A^0} = 100$ keV |
| $<4 \times 10^{-12}$ | 90 | [9] APRILE 22 | XE1T | $m_{A^0} = 0.01\text{–}0.4$ keV |
| $<9 \times 10^{-15}$ | 90 | [10] APRILE 22B | XENT | $m_{A^0} = 1\text{–}39$, $44\text{–}140$ keV |
| $<2 \times 10^{-12}$ | 90 | [11] APRILE 22B | XENT | Solar axions |
| | | [12] DESSERT 22 | ASTR | Magnetic white dwarf |
| $<2.6 \times 10^{-6}$ | 95 | [13] IKEDA 22 | | $m_{A^0} = 33.117\text{–}33.130\ \mu$eV |
| $<2.5 \times 10^{-18}$ | | [14] LANGHOFF 22 | COSM | $m_{A^0} = 20\text{–}3 \times 10^4$ keV |
| | | [15] WANG 22C | | $m_{A^0} \leq 0.47$ meV |
| | | [16] XIAO 22 | ASTR | Betelgeuse |
| | | [17] CALORE 21 | ASTR | Core-collapse SNe |
| $<2.5 \times 10^{-10}$ | | [18] LUCENTE 21 | ASTR | SN 1987A |
| $<5.1 \times 10^{-12}$ | 90 | [19] AGOSTINI 20 | HPGE | $m_{A^0} = 0.06\text{–}1$ MeV |
| $<1 \times 10^{-9}$ | 90 | [20] AMARAL 20 | SCDM | $m_{A^0} = 1.2\text{–}50$ eV |
| $<2 \times 10^{-14}$ | 90 | [21] APRILE 20 | XE1T | $m_{A^0} = 1$ keV |
| $2.6\text{–}3.7 \times 10^{-12}$ | 90 | [22] APRILE 20 | XE1T | Solar axions |
| $<6 \times 10^{-13}$ | 90 | [23] ARALIS 20 | SCDM | $m_{A^0} = 0.04\text{–}500$ keV |
| $<1.3 \times 10^{-13}$ | 95 | [24] CAPOZZI 20 | ASTR | Tip of the Red Giant Branch |
| $<1.7 \times 10^{-11}$ | 95 | [25] CRESCINI 20 | QUAX | $m_{A^0} = 42.4\text{–}43.1\ \mu$eV |
| $<1.8 \times 10^{-9}$ | | [26] GHOSH 20A | COSM | $m_{A^0} \lesssim 0.5$ MeV |
| $<1.48 \times 10^{-13}$ | 95 | [27] STRANIERO 20 | ASTR | Tip of the Red Giant Branch |
| $<2.48 \times 10^{-11}$ | 90 | [28] WANG 20A | CDEX | Solar axions |
| $<4 \times 10^{-13}$ | 90 | [29] WANG 20A | CDEX | $m_{A^0} = 1.5$ keV |
| $<1.7 \times 10^{-11}$ | 90 | [30] ADHIKARI 19B | C100 | Solar axions |
| $<2.3 \times 10^{-14}$ | 90 | [31] APRILE 19D | XE1T | $m_{A^0} = 0.186\text{–}1$ keV |
| | | [32] DESSERT 19 | ASTR | Magnetic white dwarf |
| $<2.6 \times 10^{-10}$ | 95 | [33] TERRANO 19 | | Torsion pendulum |
| $<1.5 \times 10^{-13}$ | 90 | [34] ABE 18F | XMAS | $m_{A^0} = 40\text{–}120$ keV |
| $<1.1 \times 10^{-11}$ | 90 | [35] ARMENGAUD 18 | EDE3 | Solar axions |
| $<4 \times 10^{-13}$ | 90 | [36] ARMENGAUD 18 | EDE3 | $m_{A^0} = 0.8\text{–}500$ keV |
| $<4.9 \times 10^{-10}$ | 95 | [37] CRESCINI 18 | QUAX | $m_{A^0} = 58\ \mu$eV |
| | | [38] FICEK 18 | THEO | $m_{A^0} < 10$ keV |

| | | | | | |
|---|---|---|---|---|---|
| $<4.5 \times 10^{-13}$ | 90 | [39] ABGRALL | 17 | HPGE | $m_{A^0} = 11.8$ keV |
| $<3.5 \times 10^{-12}$ | 90 | [40] AKERIB | 17B | LUX | Solar axions |
| $<4.2 \times 10^{-13}$ | 90 | [41] AKERIB | 17B | LUX | $m_{A^0} =$ 1–16 keV |
| $<2.3 \times 10^{-13}$ | 90 | [42] APRILE | 17B | X100 | $m_{A^0} = 6$ keV |
| $<4 \times 10^{-4}$ | 90 | [43] FICEK | 17 | THEO | $m_{A^0} < 1$ keV |
| $<4.35 \times 10^{-12}$ | 90 | [44] FU | 17A | PNDX | Solar axions |
| $<4.3 \times 10^{-14}$ | 90 | [45] FU | 17A | PNDX | $m_{A^0} = 2$ keV |
| $<5 \times 10^{-13}$ | 90 | [46] LIU | 17A | CDEX | $m_{A^0} = 13$ keV |
| $<2.5 \times 10^{-11}$ | 90 | [47] LIU | 17A | CDEX | Solar axions |
| $<0.15$ | 95 | [48] LUO | 17 | | $m_{A^0} = 300$ eV |
| $<3.3 \times 10^{-13}$ | 68 | [49] BATTICH | 16 | ASTR | White dwarf cooling |
| $<7 \times 10^{-13}$ | | [50] CORSICO | 16 | ASTR | White dwarf cooling |
| $<1.39 \times 10^{-11}$ | 90 | [51] YOON | 16 | KIMS | Solar axions |
| $<7.4 \times 10^{-9}$ | 95 | [52] TERRANO | 15 | | $m_{A^0} < 30\ \mu$eV |
| $<8 \times 10^{-13}$ | 90 | [53] ABE | 14F | XMAS | $m_{A^0} = 60$ keV |
| $<7.7 \times 10^{-12}$ | 90 | [54] APRILE | 14B | X100 | Solar axions |
| | | [55] APRILE | 14B | X100 | $m_{A^0} =$ 5–7 keV |
| $<$ 0.96–8.2 $\times 10^{-8}$ | 90 | [56] DERBIN | 14 | CNTR | $m_{A^0} =$ 0.1–1 MeV |
| $<2.8 \times 10^{-13}$ | 99 | [57] MILLER-BER... | 14 | ASTR | White dwarf cooling |
| $<5.4 \times 10^{-11}$ | 90 | [58] ABE | 13D | XMAS | Solar axions |
| $<1.07 \times 10^{-12}$ | 90 | [59] ARMENGAUD | 13 | EDEL | $m_{A^0} = 12.5$ keV |
| $<2.59 \times 10^{-11}$ | 90 | [60] ARMENGAUD | 13 | EDEL | Solar axions |
| | | [61] BARTH | 13 | CAST | Solar axions |
| $<$ 1.4–9.7 $\times 10^{-7}$ | 90 | [62] DERBIN | 13 | CNTR | $m_{A^0} =$ 0.1–1 MeV |
| $<1.5 \times 10^{-8}$ | 68 | [63] HECKEL | 13 | | $m_{A^0} \leq 0.1\ \mu$eV |
| $<4.3 \times 10^{-13}$ | 95 | [64] VIAUX | 13A | ASTR | Low-mass red giants |
| $<7 \times 10^{-13}$ | 95 | [65] CORSICO | 12 | ASTR | White dwarf cooling |
| $<2.2 \times 10^{-10}$ | 90 | [66] DERBIN | 12 | CNTR | Solar axions |
| $<$ 0.02–1 $\times 10^{-10}$ | 90 | [67] AALSETH | 11 | CNTR | $m_{A^0} =$ 0.3–8 keV |
| $<1.4 \times 10^{-12}$ | 90 | [68] AHMED | 09A | CDMS | $m_{A^0} = 2.5$ keV |
| $<4 \times 10^{-9}$ | | [69] DAVOUDIASL | 09 | ASTR | Earth cooling |
| $<2.7 \times 10^{-8}$ | 66 | [70] NI | 94 | | Induced magnetism |
| | | [70] CHUI | 93 | | Induced magnetism |
| $<3.6 \times 10^{-7}$ | 66 | [71] PAN | 92 | | Torsion pendulum |
| $<2.9 \times 10^{-8}$ | 95 | [70] BOBRAKOV | 91 | | Induced magnetism |
| $<1.9 \times 10^{-6}$ | 66 | [72] WINELAND | 91 | NMR | |
| $<7 \times 10^{-7}$ | 66 | [71] RITTER | 90 | | Torsion pendulum |
| $<6.6 \times 10^{-8}$ | 95 | [70] VOROBYOV | 88 | | Induced magnetism |

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[1] AALBERS 23A look for solar axions from the ABC processes. See their Fig. 6 for the limits.

[2] AALBERS 23A look for absorption of axion dark matter. The quoted limit is for $m_{A^0} \simeq$ 1.4 keV. The local density $\rho_A = 0.3$ GeV/cm$^3$ is assumed. See their Fig. 7 for mass-dependent limits.

[3] ADHIKARI 23 is an update of ADHIKARI 19B.

[4] ADHIKARI 23A look for absorption and Compton-like processes of axion dark matter. The quoted limit is for $m_{A^0} \simeq$ 37 keV. See their Fig. 4 for mass-dependent limits.

[5] AGNES 23A look for absorption of axion dark matter. The quoted limit is for $m_{A^0} \simeq$ 0.25 keV. The local density $\rho_A = 0.3$ GeV/cm$^3$ is assumed. See their Fig. 2 for mass-dependent limits.

[6] APRILE 23B look for an absorption signal of axions within $\pm$500 seconds of the GW signals, including the neutron star merger GW170817. They set a 90% CL upper limit on the product of coincident fluence and cross section of axions to be less than $10^{-29}$ cm$^2$/cm$^2$ in the recoil energy range of 5.5–210 keV$_{ee}$.

[7] CAPOZZI 23A search for axions produced in electromagnetic showers in proton beam dumps and fixed target experiments. In this case, they reinterpret MiniBoone data. Quoted limit applies at 1 MeV. See Fig. 8 for mass-dependent limits.

[8] WADEKAR 23 use the Leo T dwarf galaxy's interstellar medium to derive limits, requiring the heating rate from axion dark matter absorption into hydrogen atoms and two-photon decay to be less than the astrophysical cooling rate. See Fig. 2 for limits over $m_{A^0} =$ 1–100 keV, which loosen for lighter masses.

[9] APRILE 22 extend APRILE 19D to lower masses by removing the background of ionization signals correlated with high-energy events. The quoted limit applies to $m_{A^0} = 0.1$ keV. See their Fig. 15 for mass-dependent limits.

[10] APRILE 22B is an update of APRILE 20, and set the limit, $g_{Aee} \lesssim 9 \times 10^{-15}$–$3 \times 10^{-13}$. The quoted limit applies to $m_{A^0} = 2$ keV. They exclude the XENON1T excess found in APRILE 20. See their Fig. 6 for mass-dependent limits.

[11] APRILE 22B is an update of APRILE 20. They exclude the XENON1T excess found in APRILE 20. The quoted limit holds for small $G_{A\gamma\gamma}$. See their Fig. 6 for correlation between $g_{Aee}$ and $G_{A\gamma\gamma}$ .

[12] DESSERT 22 is an update of DESSERT 19. They used the Chandra observation of the magnetic white dwarf RE J0317-853 to look for converted X-rays in the magnetosphere from axions produced in the core through electron bremsstrahlung. They obtained the limit, $g_{Aee} \cdot G_{A\gamma\gamma} < 1.3 \times 10^{-25}$ GeV$^{-1}$ at 95% CL for $m_{A^0} \lesssim 10^{-5}$ eV. See their Fig. 1 for mass-dependent limits.

[13] IKEDA 22 look for magnons excited by dark matter axions, using data taken with a hybrid quantum system consisting of a superconducting qubit and a spherical ferrimagnetic crystal. The quoted limit assumes the local dark matter density $\rho_A = 0.45$ GeV/cm$^3$ and the velocity $v = 220$ km/sec. See their Fig. 4 for the limits.

[14] LANGHOFF 22 set limits by considering the freeze-in production of axions coupled to electrons without anomalous coupling to photons. The quoted limit applies to $m_{A^0} = 15$ MeV for the reheating temperature equal to 5 MeV. See their Fig. 2 for mass-dependent limits.

[15] WANG 22C use the spin-amplifier based on hyperpolarized $^{129}$Xe to set limits on the product of the axion couplings to electrons and nucleons as $g_{Aee}\, g_{Ann} < 4 \times 10^2$ (95 % CL) at $m_{A^0} = 0.1$ meV. Here $g_{Ann}$ is the dimensionless axion-neutron coupling. See their Fig. 4 for the mass-dependent limits.

[16] XIAO 22 extend XIAO 21 in the list of photon coupling limits by including the production of axions from Compton and bremsstrahlung processes, and set limits on the product of the axion couplings to electrons and photons as $G_{A\gamma\gamma}\, g_{Aee} < 0.4$–$2.8 \times 10^{-24}$ GeV$^{-1}$ (95 % CL) for $m_{A^0} < 3.5 \times 10^{-11}$eV. See their Fig. 5 for the limits. They are comparable to those of DESSERT 19 and more restrictive than the CAST bounds of BARTH 13.

[17] CALORE 21 consider the production of axions from Galactic and extragalactic SNe via nucleon-nucleon bremsstrahlung and their subsequent decay into electron-positron pairs, and exclude the range of $g_{Aee} \simeq 10^{-19}$–$10^{-11}$ at $g_{App} = 10^{-9}$ for $m_{A^0} =$ 3–30 MeV. See their Fig. 7 for the limits.

[18] LUCENTE 21 study the axion production in a supernova via electron-proton bremsstrahlung and electron-positron fusion, and exclude the range of $g_{Aee} \simeq 10^{-10}$–$10^{-8}$ for

$m_{A^0}$ = 1–160 MeV. The quoted limit is at $m_{A^0}$ = 120 MeV. See their Fig. 12 for the mass-dependent limits.

[19] AGOSTINI 20 is analogous to AHMED 09A. The quoted limit applies to $m_{A^0}$ = 150 keV. Their limits in their Fig. 3 were later found to be incorrect due to an error of their Eqs. (1) and (2). See Fig. 3 in AGOSTINI 22A for the corrected limits.

[20] AMARAL 20 use a second-generation SuperCDMS high-voltage eV-resolution detector to set limits on dark-matter axion absorption. The quoted limit is for $m_{A^0} \simeq$ 17 eV. The local density $\rho_A = 0.3$ GeV/cm$^3$ is assumed. See their Fig. 3 for mass-dependent limits.

[21] APRILE 20 is an update of APRILE 17B where they look for an absorption signal of axion dark matter. They obtained the limit, $g_{Aee} \lesssim 2 \times 10^{-14}$–$1 \times 10^{-12}$ at 90%CL for $m_{A^0}$ = 1–200 keV. They also found an excess over known backgrounds, which favors the mass $m_{A^0} = 2.3 \pm 0.2$ keV with a 3 $\sigma$ significance. See their Fig. 10 for mass-dependent limits.

[22] APRILE 20 look for solar axions from the ABC interactions, the Primakoff conversion, and the 14.4 keV M1 transition of $^{57}$Fe, and set limits on $g_{Aee}$, $G_{A\gamma\gamma}$, $g_{ANN}$, and their products. An excess is observed at low energies between 2 and 3 keV. See their Fig.8 for correlation between the couplings. The quoted limit applies to the case of vanishing $G_{A\gamma\gamma}$ and $g_{ANN}$.

[23] ARALIS 20 is analogous to AHMED 09A. The quoted limit applies to $m_{A^0}$ = 0.3 keV. The limits at masses above 3 keV in their Fig. 9 was later found to be incorrect due to an error in their analysis. See Fig. 2 in ARALIS 21 for the corrected limits.

[24] CAPOZZI 20 obtains a limit on the axion-electron coupling from the brightness of the tip of the red-giant branch in $\omega$ Centauri. A similar limit of $< 1.6 \times 10^{-13}$ is obtained in NGC 4258.

[25] CRESCINI 20 is an update of CRESCINI 18. They assume a local axion dark matter density, $\rho_A = 0.3$ GeV/cm$^3$. See their Fig.4 for the limits.

[26] GHOSH 20A study thermal production of axion via coupling to leptons in the early universe and estimate its contribution to $\Delta N_{\rm eff}$. The quoted limit is for $\Delta N_{\rm eff} < 0.5$. See their Fig. 7 for their mass-dependent limits.

[27] STRANIERO 20 is analogous to CAPOZZI 20, with 22 galactic globular clusters used to derive the limit.

[28] WANG 20A is an update of LIU 17A. See their Fig. 9.

[29] WANG 20A is an update of LIU 17A. They assume a local axion dark matter density, $\rho_A$ = 0.3 GeV/cm$^3$. See their Fig. 10 for limits between $0.185 < m_{A^0} < 10$ keV.

[30] ADHIKARI 19B is analogous to LIU 17A.

[31] APRILE 19D is analogous to APRILE 17B, but they use only ionization signals. The quoted limit applies to $m_{A^0}$ = 0.7 keV. See their Fig. 5(e) for mass-dependent limits.

[32] DESSERT 19 used the Suzaku observations of a magnetic white dwarf (RE J0317-853) to look for X-ray signatures converted from axions in the surrounding magnetic fields. They obtained the limit, $g_{Aee} \cdot G_{A\gamma\gamma} < 1.6 \times 10^{-24}$ GeV$^{-1}$ at 95%CL for $m_{A^0} \lesssim 10^{-5}$ eV. See their Fig. 2 for mass-dependent limits.

[33] TERRANO 19 look for the axion-induced oscillating magnetic field acting on the electron spin, using data taken with a rotating torsion pendulum containing polarized electrons. The quoted limit applies to $m_{A^0} = 10^{-23}$–$10^{-18}$ eV and assumes a local axion dark matter density, $\rho_A = 0.45$ GeV/cm$^3$. See their Fig. 5 for mass-dependent limits.

[34] ABE 18F is an update of ABE 14F. The quoted limit applies to $m_{A^0}$ = 60 keV. See their Fig. 5 for mass-dependent limits.

[35] ARMENGAUD 18 is analogous to LIU 17A.

[36] ARMENGAUD 18 is analogous to AHMED 09A. See the left panel of Fig. 5 for mass-dependent limits.

[37] CRESCINI 18 look for collective excitations of the electron spins caused by dark matter axions. The quoted limit assumes the local dark matter density, $\rho_A$ = 0.45 GeV/cm$^3$.

[38] FICEK 18 use the measurements of the hyperfine structure of antiprotonic helium to constrain a dipole-dipole potential between electron and antiproton. See their Fig. 3 for limits on various spin- and velocity-dependent potentials.

[39] ABGRALL 17 is analogous to AHMED 09A using the MAJORANA DEMONSTRATOR. See their Fig. 2 for limits between 6 keV $< m_{A^0} <$ 97 keV.

[40] AKERIB 17B is analogous to LIU 17A.

[41] AKERIB 17B is analogous to AHMED 09A. See their Fig. 7 for mass-dependent limits.

[42] APRILE 17B is analogous to AHMED 09A. They found a bug in their code and needed to correct the limits in Fig. 7 of APRILE 14B. See their Fig. 1 for the corrected limits between 1 keV $< m_{A^0} <$ 40 keV.

[43] FICEK 17 look for spin-dependent interactions between electrons by comparing precision spectroscopic measurements in $^4$He with theoretical calculations. See their Fig. 1 for limits up to $m_{A^0}$ = 10 keV.

[44] FU 17A is analogous to LIU 17A. See their Fig. 3 for mass-dependent limits.

[45] FU 17A is analogous to AHMED 09A. See their Fig. 4 for mass-dependent limits.

[46] LIU 17A is analogous to AHMED 09A. See their Fig. 9 for limits between 0.25 keV $< m_{A^0} <$ 20 keV.

[47] LIU 17A look for solar axions produced from Compton, bremsstrahlung, atomic-recombination and deexcitation channels, and set a limit for $m_{A^0} <$ 1 keV.

[48] LUO 17 use a recent measurement of the dipole-dipole interaction between two iron atoms at the nanometer scale and set a limit for $m_{A^0} <$ 1 keV. See their Fig. 3 for mass-dependent limits.

[49] BATTICH 16 is analogous to CORSICO 16 and used the pulsating DB white dwarf PG 1351+489.

[50] CORSICO 16 studied the cooling rate of the pulsating DA white dwarf L19-2 based on an asteroseismic model.

[51] YOON 16 look for solar axions with the axio-electric effect in CsI(Tl) crystals and set a limit for $m_{A^0} <$ 1 keV.

[52] TERRANO 15 used a torsion pendulum and rotating attractor with 20-pole electron-spin distributions. See their Fig. 4 for a mass-dependent limit up to $m_{A^0}$ = 500 $\mu$eV.

[53] ABE 14F set limits on the axioelectric effect in the XMASS detector assuming the pseudoscalar constitutes all the local dark matter. See their Fig. 3 for limits between $m_{A^0}$ = 40–120 keV.

[54] APRILE 14B look for solar axions using the XENON100 detector.

[55] APRILE 14B is analogous to AHMED 09A. Their Fig. 7 was later found to be incorrect due to a bug in their code. See Fig. 1 in APRILE 17B for the corrected limits.

[56] DERBIN 14 is an update of DERBIN 13 with a BGO scintillating bolometer. See their Fig. 3 for mass-dependent limits.

[57] MILLER-BERTOLAMI 14 studied the impact of axion emission on white dwarf cooling in a self-consistent way.

[58] ABE 13D is analogous to DERBIN 12, using the XMASS detector.

[59] ARMENGAUD 13 is similar to AALSETH 11. See their Fig. 10 for limits between 3 keV $< m_{A^0} <$ 100 keV.

[60] ARMENGAUD 13 is similar to DERBIN 12, and take account of axio-recombination and axio-deexcitation effects. See their Fig. 12 for mass-dependent limits.

[61] BARTH 13 search for solar axions produced by axion-electron coupling, and obtained the limit, $g_{Aee} \cdot G_{A\gamma\gamma} <$ 8.1 $\times$ 10$^{-23}$ GeV$^{-1}$ at 95%CL.

[62] DERBIN 13 looked for 5.5 MeV solar axions produced in $pd \to {}^3\mathrm{He}\, A^0$ in a BGO detector through the axioelectric effect. See their Fig. 4 for mass-dependent limits.

[63] HECKEL 13 studied the influence of 2 or 4 stationary sources each containing $6.0 \times 10^{24}$ polarized electrons, on a rotating torsion pendulum containing $9.8 \times 10^{24}$ polarized electrons. See their Fig. 4 for mass-dependent limits.

[64] VIAUX 13A constrain axion emission using the observed brightness of the tip of the red-giant branch in the globular cluster M5.

[65] CORSICO 12 attributed the excessive cooling rate of the pulsating white dwarf R548 to emission of axions with $g_{Aee} \simeq 4.8 \times 10^{-13}$.

[66] DERBIN 12 look for solar axions with the axio-electric effect in a Si(Li) detector. The solar production is based on Compton and bremsstrahlung processes.

[67] AALSETH 11 is analogous to AHMED 09A. See their Fig. 4 for mass-dependent limits.

[68] AHMED 09A assume keV-mass pseudoscalars are the local dark matter and constrain the axio-electric effect in the CDMS detector. See their Fig. 5 for mass-dependent limits.

[69] DAVOUDIASL 09 use geophysical constraints on Earth cooling by axion emission.

[70] These experiments measured induced magnetization of a bulk material by the spin-dependent potential generated from other bulk material with aligned electron spins, where the magnetic field is shielded with superconductor. The sign of the limit set by CHUI 93 is opposite to that of the axion-mediated dipole-dipole potential.

[71] These experiments used a torsion pendulum to measure the potential between two bulk matter objects where the spins are polarized but without a net magnetic field in either of them. The limits reflect the corrected sign of the dipole-dipole potential.

[72] WINELAND 91 looked for an effect of bulk matter with aligned electron spins on atomic hyperfine splitting using nuclear magnetic resonance.

## Invisible $A^0$ (Axion) Limits from Nucleon Coupling

Limits are for the axion mass in eV.

| *VALUE* (eV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $< 0.01$ | 95 | [1] LELLA | 24 | ASTR | SN1987A |
| | | [2] KARANTH | 23 | | Deuteron EDM |
| | | [3] LEE | 23 | | Axion dark matter |
| $< 0.016$ | 95 | [4] BUSCHMANN | 22 | ASTR | Neutron star cooling |
| $<320$ | 90 | [5] GAVRILYUK | 22 | CNTR | Solar axion |
| | | [6] SCHULTHESS | 22 | | Neutron EDM |
| | | [7] AYBAS | 21 | CASP | Nucleon EDM |
| | | [8] BHUSAL | 21 | | Solar axion |
| | | [9] JIANG | 21 | NMR | Axion dark matter |
| | | [10] ROUSSY | 21 | | Molecular EDM |
| | | [11] ZHANG | 21B | ASTR | Neutron star inspiral |
| $< 24$ | 90 | [12] ABDELHAME... | 20 | CNTR | Solar axion |
| | | [13] ABDELHAME... | 20 | CNTR | Solar axion |
| | | [14] APRILE | 20 | XE1T | Solar axion |
| | | [15] KLIMCHITSK... | 20 | | Casimir effect |
| $< 7.3$ | 90 | [16] WANG | 20A | CDEX | Solar axion |
| $< 0.03$ | | [17] LEINSON | 19 | ASTR | Neutron star cooling |
| $< 9.6 \times 10^{-3}$ | 95 | [18] LLOYD | 19 | ASTR | $\gamma$-rays from NS |
| | | [19] SMORRA | 19 | | $\overline{p}$ $g$-factor |
| | | [20] WU | 19 | NMR | Axion dark matter |
| $< 65$ | 95 | [21] AKHMATOV | 18 | CNTR | Solar axion |
| $< 6.6$ | 90 | [22] ARMENGAUD | 18 | EDE3 | Solar axion |
| $< 0.085$ | 90 | [23] BEZNOGOV | 18 | ASTR | Neutron star cooling |

| | | | | | |
|---|---|---|---|---|---|
| $<$ 12.7 | 95 | [24] GAVRILYUK | 18 | CNTR | Solar axion |
| $<$ 0.01 | | [25] HAMAGUCHI | 18 | ASTR | Neutron star cooling |
| | | [26] ABEL | 17 | | Neutron EDM |
| $<$ 93 | 90 | [27] ABGRALL | 17 | HPGE | Solar axion |
| $<$ 4 | 90 | [28] FU | 17A | PNDX | Solar axion |
| | | [29] KLIMCHITSK... | 17A | | Casimir effect |
| $<$177 | 90 | [30] LIU | 17A | CDEX | Solar axion |
| $<$ 0.079 | 95 | [31] BERENJI | 16 | ASTR | $\gamma$-rays from NS |
| $<$100 | 95 | [32] GAVRILYUK | 15 | CNTR | Solar axion |
| | | [33] KLIMCHITSK... | 15 | | Casimir-less |
| | | [34] BEZERRA | 14 | | Casimir effect |
| | | [35] BEZERRA | 14A | | Casimir effect |
| | | [36] BEZERRA | 14B | | Casimir effect |
| | | [37] BEZERRA | 14C | | Casimir effect |
| | | [38] BLUM | 14 | COSM | $^4$He abundance |
| | | [39] LEINSON | 14 | ASTR | Neutron star cooling |
| $<$250 | 95 | [40] ALESSANDRIA | 13 | CNTR | Solar axion |
| $<$155 | 90 | [41] ARMENGAUD | 13 | EDEL | Solar axion |
| $<$ 8.6 $\times 10^3$ | 90 | [42] BELLI | 12 | CNTR | Solar axion |
| $<$ 1.4 $\times 10^4$ | 90 | [43] BELLINI | 12B | BORX | Solar axion |
| $<$145 | 95 | [44] DERBIN | 11 | CNTR | Solar axion |
| | | [45] BELLINI | 08 | CNTR | Solar axion |
| | | [46] ADELBERGER | 07 | | Test of Newton's law |

[1] LELLA 24 update constraints on the axion-proton coupling from supernova 1987A based on the SN cooling argument (including a treatment of the trapping regime) as well as the non-observation of any coincident axion-induced events in the Kamiokande II neutrino detector. They exclude QCD axion models above 0.01 eV, and axion-like particles in a window that extends up to 300 MeV. See their Fig. 3 for mass-dependent limits.

[2] KARANTH 23 utilized an in-plane polarized deuteron beam in a storage ring to constrain the axion-induced oscillating EDM of the deuteron for $m_{A^0}$ = 0.496–0.502 neV. Assuming axions account for all dark matter with $\rho_A \simeq$ 0.55 GeV/cm$^3$, they derived constraints on axion couplings to the deuteron EDM operator, gluons, and the deuteron spin. For detailed limits, see their Figs. 19–21.

[3] LEE 23 analyzed data from a K$-^3$He comagnetometer, accounting for stochastic effects, to limit the axion-neutron coupling $g_{Ann} < 2.4 \times 10^{-10}$ GeV$^{-1}$ at 95% CL for $m_{A^0}$ = 0.4–4 feV. They assumed axions form all dark matter with a density of 0.3 GeV/cm$^3$. See their Fig. 5 for the limits.

[4] BUSCHMANN 22 studied the axion emission from five neutron stars with ages $\sim 10^5$–$10^6$ years, comparing the simulation with axions to age and luminosity measurements. The mass bound assumes the KSVZ axion model with $C_p = -0.47$ and $C_n = -0.02$. See their Fig. 3 for the limits on the DFSZ axion model.

[5] GAVRILYUK 22 look for solar axions from the ABC interactions with the experimental setup similar to GAVRILYUK 15. The mass bound assumes the KSVZ axion model, $S =$ 0.5, and $m_u/m_d$ = 0.56.

[6] SCHULTHESS 22 look for a time-oscillating neutron EDM caused by the coupling between axion dark matter and gluons, using a Ramsey-type apparatus for a cold neutron beam. See their Fig. 4 for limits in the range of $m_{A^0} = 10^{-19}$–$4 \times 10^{-12}$ eV.

[7] AYBAS 21 limits the axion couplings to the nucleon EDM and the nucleons as $g_{AN\gamma} < 9.5 \times 10^{-4}$ GeV$^{-2}$ and $g_{ANN}/2m_N < 0.28$ GeV$^{-1}$ (95 % CL) for $m_{A^0}$ = 162–166 neV, based on a measurement of $^{207}$Pb solid-state NMR in a polarized ferroelecrtric crystal. Here $m_N$ is the nucleon mass and $g_{ANN}$ is the dimensionless axion-nucleon

coupling. They assume that axions make up all the dark matter with $\rho_A \simeq 0.46$ GeV/cm$^3$. See their Fig. 3 for the limits.

[8] BHUSAL 21 looked for 5.5 MeV solar axions produced by $p d \to {}^3\text{He}\, A^0$ through the axion-induced dissociation of deuterons by using SNO data, and set a limit on the isovector axion-nucleon coupling, $|g^3_{aN}| < 2 \times 10^{-5}$ GeV$^{-1}$, which is equivalent to $|g_{Ann} - g_{App}| < 4 \times 10^{-5}$ in terms of the dimensionless axion-nucleon couplings.

[9] JIANG 21 use the spin-amplifier based on hyperpolarized $^{129}$Xe gas to set limits on the axion couplings to nucleons as $g_{ANN}/2m_N < 3.2 \times 10^{-9}$ GeV$^{-1}$ (95 % CL) at $m_{A^0} = 52.94$ feV, and comparable limits in the mass range of 8.3–744 feV. Here $m_N$ is the nucleon mass and $g_{ANN}$ is the dimensionless axion-nucleon coupling. They assume that axions make up all the dark matter with $\rho_A \simeq 0.4$ GeV/cm$^3$. See their Fig. 4b for the limits.

[10] ROUSSY 21 look for a time-oscillating EDM of molecular ions HfF$^+$ induced by axion dark matter couplings to gluons. See their Fig. 3 for limits in the range of $m_{A^0} = 10^{-22}$–$10^{-15}$ eV.

[11] ZHANG 21B use the gravitational waves from the binary neutron star inspiral GW170817 to look for a type of axion whose mass is suppressed due to cancellation with additional contributions. They exclude $1.6 \times 10^{16} < f_A < 10^{18}$ GeV at 3 $\sigma$ for $m_{A^0} \lesssim 10^{-13}$ eV. See their Fig. 1 for mass-dependent limits.

[12] ABDELHAMEED 20 look for the resonant excitation of $^{169}$Tm (8.41 keV) by solar axions produced via the Primakoff effect. The mass bound assumes the KSVZ axion model, $S = 0.5$, and $m_u/m_d = 0.56$. They set a limit on the product of axion couplings to photons and nucleons as $G_{A\gamma\gamma} \cdot g_{App} < 1.44 \times 10^{-14}$ GeV$^{-1}$ (90 % CL).

[13] ABDELHAMEED 20 look for the resonant excitation of $^{169}$Tm (8.41 keV) by solar axions produced via the axion-electron coupling. They set a limit on the product of axion couplings to electrons and nucleons as $g_{Aee} \cdot g_{App} < 2.81 \times 10^{-16}$ (90 % CL).

[14] APRILE 20 look for solar axions from the ABC interactions, the Primakoff conversion, and the 14.4 keV M1 transition of $^{57}$Fe. An excess is observed at low energies between 2 and 3 keV. See their Fig.8 for correlation between the couplings.

[15] KLIMCHITSKAYA 20 use the measurement of the Casimir force between a Au-coated microsphere and a SiC plate to constrain the force due to two-axion exchange for $17.8 < m_{A^0} < 100$ eV. See their Fig. 2 for mass-dependent limits.

[16] WANG 20A is an update of LIU 17A. The limit assumes the DFSZ axion. See their Fig. 7 for the limit on product of axion couplings to electrons and nucleons.

[17] LEINSON 19 is analogous to BEZNOGOV 18, but estimating the axion luminosity based on the Tolman's analytic solution to the Einstein equations of spherical fluids in hydrostatic equilibrium. The dimensionless axion-neutron coupling is constrained as $g_{Ann} < 1.0 \times 10^{-10}$.

[18] LLOYD 19 is analogous to BERENJI 16. They highlight that the limit obtained with this technique strongly depends on the assumed NS core temperature.

[19] SMORRA 19 look for spin-precession effects from ultra-light axion dark matter in the $\overline{p}$ spin-flip resonance data. Assuming $\rho_A = 0.4$ GeV/cm$^3$, they constrain the dimensionless axion-antiproton coupling as $g_{A\overline{p}\overline{p}} < 2$–9 at 95% CL for $m_{A^0} = 2 \times 10^{-23}$–$4 \times 10^{-17}$ eV. See the right panel of their Fig. 3.

[20] WU 19 look for axion-induced time-oscillating features of the NMR spectrum of acetonitrile-2-$^{13}$C. Assuming $C_p = C_n$ and $\rho_A = 0.4$ GeV/cm$^3$, they constrain the dimensionless axion-nucleon coupling as $g_{ANN} < 6 \times 10^{-5}$ for $m_{A^0} = 10^{-21}$–$1.3 \times 10^{-17}$ eV. Note that the limits for $m_{A^0} < 10^{-21}$ eV in their Fig. 3(a) should be weaker than those for heavier masses. See ADELBERGER 19 and WU 19C on this issue.

[21] AKHMATOV 18 is an update of GAVRILYUK 15.

[22] ARMENGAUD 18 is analogous to ALESSANDRIA 13. The quoted limit assumes the DFSZ axion model. See their Fig. 4 for the limit on product of axion couplings to electrons and nucleons.

[23] BEZNOGOV 18 constrain the axion-neutron coupling by assuming that thermal evolution of the hot neutron star HESS J1731-347 is dominated by the lowest possible neutrino emission. The quoted limit assumes the KSVZ axion with the effective Peccei-Quinn charge of the neutron $C_n = -0.02$. The dimensionless axion-neutron couling is constrained as $g_{Ann} < 2.8 \times 10^{-10}$.

[24] GAVRILYUK 18 look for the resonant excitation of $^{83}$Kr (9.4 keV) by solar axions produced via the Primakoff effect. The mass bound assumes $m_u/m_d = 0.56$ and $S = 0.5$.

[25] HAMAGUCHI 18 studied the axion emission from the neutron star in Cassiopeia A based on the minimal cooling scenario which explains the observed rapid cooling rate. The quoted limit corresponds to $f_A > 5 \times 10^8$ GeV obtained for the KSVZ axion with $C_p = -0.47$ and $C_n = -0.02$.

[26] ABEL 17 look for a time-oscillating neutron EDM and an axion-wind spin-precession effect respectively induced by axion dark matter couplings to gluons and nucleons. See their Fig. 4 for limits in the range of $m_{A^0} = 10^{-24}$–$10^{-17}$ eV.

[27] ABGRALL 17 limit assumes the hadronic axion model used in ALESSANDRIA 13. See their Fig. 4 for the limit on product of axion couplings to electrons and nucleons.

[28] FU 17A look for the 14.4 keV $^{57}$Fe solar axions. The limit assumes the DFSZ axion model. See their Fig. 3 for mass-dependent limits on the axion-electron coupling. Notice that in this figure the DFSZ and KSVZ lines should be interchanged.

[29] KLIMCHITSKAYA 17A use the differential measurement of the Casimir force between a Ni-coated sphere and Au and Ni sectors of the structured disc to constrain the axion coupling to nucleons for 2.61 meV $< m_{A^0} <$ 0.9 eV. See their Figs. 1 and 2 for mass dependent limits.

[30] LIU 17 is analogous to ALESSANDRIA 13. The limit assumes the hadronic axion model. See their Fig. 6(b) for the limit on product of axion couplings to electrons and nucleons.

[31] BERENJI 16 used the Fermi LAT observations of neutron stars to look for photons from axion decay. They assume the effective Peccei-Quinn charge of the neutron $C_n = 0.1$ and a neutron-star core temperature of 20 MeV.

[32] GAVRILYUK 15 look for solar axions emitted by the M1 transition of $^{83}$Kr (9.4 keV). The mass bound assumes $m_u/m_d = 0.56$ and $S = 0.5$.

[33] KLIMCHITSKAYA 15 use the measurement of differential forces between a test mass and rotating source masses of Au and Si to constrain the force due to two-axion exchange for $1.7 \times 10^{-3} < m_{A^0} < 0.9$ eV. See their Figs. 1 and 2 for mass dependent limits.

[34] BEZERRA 14 use the measurement of the thermal Casimir-Polder force between a Bose-Einstein condensate of $^{87}$Rb atoms and a $SiO_2$ plate to constrain the force mediated by exchange of two pseudoscalars for 0.1 meV $< m_{A^0} <$ 0.3 eV. See their Fig. 2 for the mass-dependent limit on pseudoscalar coupling to nucleons.

[35] BEZERRA 14A is analogous to BEZERRA 14. They use the measurement of the Casimir pressure between two Au-coated plates to constrain pseudoscalar coupling to nucleons for $1 \times 10^{-3}$ eV $< m_{A^0} <$ 15 eV. See their Figs. 1 and 2 for the mass-dependent limit.

[36] BEZERRA 14B is analogous to BEZERRA 14. BEZERRA 14B use the measurement of the normal and lateral Casimir forces between sinusoidally corrugated surfaces of a sphere and a plate to constrain pseudoscalar coupling to nucleons for 1 eV $< m_{A^0} <$ 20 eV. See their Figs. 1–3 for mass-dependent limits.

[37] BEZERRA 14C is analogous to BEZERRA 14. They use the measurement of the gradient of the Casimir force between Au- and Ni-coated surfaces of a sphere and a plate to constrain pseudoscalar coupling to nucleons for $3 \times 10^{-5}$ eV $< m_{A_0} <$ 1 eV. See their Figs. 1, 3, and 4 for the mass-dependent limits.

[38] BLUM 14 studied effects of an oscillating strong *CP* phase induced by axion dark matter on the primordial $^4$He abundance. See their Fig. 1 for mass-dependent limits.

[39] LEINSON 14 attributes the excessive cooling rate of the neutron star in Cassiopeia A to axion emission from the superfluid core, and found $C_n^2\ m_{A^0}^2 \simeq 5.7\times10^{-6}$ eV$^2$, where $C_n$ is the effective Peccei-Quinn charge of the neutron.

[40] ALESSANDRIA 13 used the CUORE experiment to look for 14.4 keV solar axions produced from the M1 transition of thermally excited $^{57}$Fe nuclei in the solar core, using the axio-electric effect. The limit assumes the hadronic axion model. See their Fig. 4 for the limit on product of axion couplings to electrons and nucleons.

[41] ARMENGAUD 13 is analogous to ALESSANDRIA 13. The limit assumes the hadronic axion model. See their Fig. 8 for the limit on product of axion couplings to electrons and nucleons.

[42] BELLI 12 looked for solar axions emitted by the M1 transition of $^7$Li$^*$ (478 keV) after the electron capture of $^7$Be, using the resonant excitation $^7$Li in the LiF crystal. The mass bound assumes $m_u/m_d = 0.55$, $m_u/m_s = 0.029$, and the flavor-singlet axial vector matrix element $S = 0.4$.

[43] BELLINI 12B looked for 5.5 MeV solar axions produced in the $p d \rightarrow {}^3\text{He}\ A^0$.The limit assumes the hadronic axion model. See their Figs. 6 and 7 for mass-dependent limits on productsof axion couplings to photons, electrons, and nucleons.

[44] DERBIN 11 looked for solar axions emitted by the M1 transition of thermally excited $^{57}$Fe nuclei in the Sun, using their possible resonant capture on $^{57}$Fe in the laboratory. The mass bound assumes $m_u/m_d = 0.56$ and the flavor-singlet axial vector matrix element $S = 3F - D \simeq 0.5$.

[45] BELLINI 08 consider solar axions emitted in the M1 transition of $^7$Li$^*$ (478 keV) and look for a peak at 478 keV in the energy spectra of the Counting Test Facility (CTF), a Borexino prototype. For $m_{A^0} < 450$ keV they find mass-dependent limits on products of axion couplings to photons, electrons, and nucleons.

[46] ADELBERGER 07 use precision tests of Newton's law to constrain a force contribution from the exchange of two pseudoscalars. See their Fig. 5 for limits on the pseudoscalar coupling to nucleons, relevant for $m_{A^0}$ below about 1 meV.

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## Axion Limits from *T*-violating Medium-Range Forces

The limit is for the coupling $g = g_{\rm p}\ g_{\rm s}$ in a *T*-violating potential between nucleons, nucleon and electron, or electrons of the form $V = \frac{g\hbar^2}{8\pi m_p}(\boldsymbol{\sigma}\cdot\hat{\boldsymbol{r}})\ (\frac{1}{r^2} + \frac{1}{\lambda r})\ e^{-r/\lambda}$, where $g_{\rm s}$ and $g_{\rm p}$ are dimensionless scalar and pseudoscalar coupling constants, $m_p$ is the fermion mass with the pseudoscalar coupling (whereas the mass $m_s$ of the fermion with the scalar coupling does not explicitly appear), and $\lambda = \hbar/(m_A c)$ is the range of the force.

| VALUE | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | |
| | [1] AYRES 23 | EDM | ultracold neutrons |
| | [2] PODDAR 23 | ASTR | solar system |
| | [3] ZHANG 23 | NMR | polarized $^{129}$Xe and $^{131}$Xe |
| | [4] CRESCINI 22 | SQID | paramagnetic GSO crystal |
| | [5] FENG 22 | NMR | polarized $^{129}$Xe and $^{131}$Xe |
| | [6] AFACH 21 | GNME | Optical magnetometers |
| | [7] DZUBA 18 | THEO | atomic EDM |
| | [8] STADNIK 18 | THEO | atomic and molecular EDMs |
| | [9] CRESCINI 17 | SQID | paramagnetic GSO crystal |
| | [10] AFACH 15 | | ultracold neutrons |
| | [11] STADNIK 15 | THEO | nucleon spin contributions for nuclei |

| | | | |
|---|---|---|---|
| [12] TERRANO | 15 | | torsion pendulum |
| [13] BULATOWICZ | 13 | NMR | polarized $^{129}$Xe and $^{131}$Xe |
| [14] CHU | 13 | | polarized $^{3}$He |
| [15] TULLNEY | 13 | SQID | polarized $^{3}$He and $^{129}$Xe |
| [16] RAFFELT | 12 | | stellar energy loss |
| [17] HOEDL | 11 | | torsion pendulum |
| [18] PETUKHOV | 10 | | polarized $^{3}$He |
| [19] SEREBROV | 10 | | ultracold neutrons |
| [20] IGNATOVICH | 09 | RVUE | ultracold neutrons |
| [21] SEREBROV | 09 | RVUE | ultracold neutrons |
| [22] BAESSLER | 07 | | ultracold neutrons |
| [23] HECKEL | 06 | | torsion pendulum |
| [24] NI | 99 | | paramagnetic Tb $F_3$ |
| [25] POSPELOV | 98 | THEO | neutron EDM |
| [26] YOUDIN | 96 | | |
| [27] RITTER | 93 | | torsion pendulum |
| [28] VENEMA | 92 | | nuclear spin-precession frequencies |
| [29] WINELAND | 91 | NMR | |

[1] AYRES 23 at PSI use their neutron EDM setup to look for a mm to micron-range spin-dependent force between ultracold spin-polarized neutrons stored in vacuum and the unpolarised nucleons in the surrounding apparatus. They constrain a nucleon-neutron monopole-dipole interaction parameterised by the coupling $g^N_s\, g^n_p$. They set a limit of $g^N_s g^n_p < 10^{-20}$ (95% CL) for a 1 meV mass axion, see Fig. 6.

[2] PODDAR 23 search for long-range monopole-dipole forces between the polarized population of electrons inside the Earth and the unpolarised nucleons in the Sun, which would affect the precession of orbital perihelion. However, the most competitive limit is obtained by combining the monopole-monopole force constraints on $g^N_s$ from planetary precession with the strongest stellar bound on the pseudoscalar electron coupling ($g^e_p$), shown in Fig. 5.

[3] ZHANG 23 look for changes of the ratio of precession frequencies between $^{129}$Xe and $^{131}$Xe as the bias field is flipped in Earth's gravitational field after Earth roation effect is subtracted. They find $g^n_p g^N_s < 1 \times 10^{-26}$–$3.7 \times 10^{-36}$ for $\lambda = 0.3$–$1 \times 10^{10}$ m. See their Fig. 4 for limits as a function of $\lambda$.

[4] CRESCINI 22 is an update of CRESCINI 17, and find $g^e_p g^N_s \leq 5.7 \times 10^{-32}$ and $g^e_p g^e_s \leq 1.6 \times 10^{-31}$ for $\lambda \gtrsim 10$ cm at 95% CL. See their Fig. 4 for limits as a function of $\lambda$.

[5] FENG 22 look for changes of the ratio of precession frequencies between $^{129}$Xe and $^{131}$Xe when a BGO crystal is positioned near the atomic cell. They find $g^n_p g^N_s < 2 \times 10^{-20}$–$3 \times 10^{-24}$ for $\lambda = 0.11$–$0.55$ mm. See their Fig. 4 for limits as a function of $\lambda$.

[6] AFACH 21 look for axion domain walls coupled to atomic spins by using the global network of optical magnetometers. Assuming that the axion domain walls make up all dark matter, they exclude the effective decay constant below $4 \times 10^5$ GeV for $m_{A^0}$ in the range of $10^{-15}$–$10^{-11}$ eV. See their Fig. 4 for the mass-dependent limits.

[7] DZUBA 18 used atomic EDM measurements to derive limits on the product of the pseudoscalar coupling to nucleon and the scalar coupling to electron, which improved on the laboratory bounds for $m_{A^0} > 0.01$ eV. See their Fig. 1 for mass-dependent limits.

[8] STADNIK 18 used atomic and molecular EDM experiments to derive limits on the product of the pseudoscalar couplings to electron and the scalar coupling to nucleon and electron.

See their Fig. 2 for mass-dependent limits, which improved on the laboratory bounds for $m_{A^0} > 0.01$ eV.

[9] CRESCINI 17 use the QUAX-$g_p g_s$ experiment to look for variation of a paramagnetic GSO crystal magnetization when rotating lead disks are positioned near the crystal, and find $g = g_p^e g_s^N < 4.3 \times 10^{-30}$ for $\lambda = 0.1$–$0.2$ m at 95% CL. See their Fig. 6 for limits as a function of $\lambda$.

[10] AFACH 15 look for a change of spin precession frequency of ultracold neutrons when a magnetic field with opposite directions is applied, and find $g < 2.2 \times 10^{-27}$ $(\mathrm{m}/\lambda)^2$ at 95% CL for 1 $\mu$m $< \lambda <$ 5 mm. See their Fig. 3 for their limits.

[11] STADNIK 15 studied proton and neutron spin contributions for nuclei and derive the limits $g < 10^{-28}$–$10^{-23}$ for $\lambda > 3 \times 10^{-4}$ m using the data of TULLNEY 13. See their Figs. 1 and 2 for $\lambda$-dependent limits.

[12] TERRANO 15 used a torsion pendulum and rotating attractor, and derived a restrictive limit on the product of the pseudoscalar coupling to electron and the scalar coupling to nucleons, $g < 9 \times 10^{-29}$–$5 \times 10^{-26}$ for $m_{A^0} < 1.5$–$400$ $\mu$eV. See their Fig. 5 for mass-dependent limits.

[13] BULATOWICZ 13 looked for NMR frequency shifts in polarized $^{129}$Xe and $^{131}$Xe when a zirconia rod is positioned near the NMR cell, and find $g < 1 \times 10^{-19}$–$1 \times 10^{-24}$ for $\lambda = 0.01$–$1$ cm. See their Fig. 4 for their limits.

[14] CHU 13 look for a shift of the spin precession frequency of polarized $^3$He in the presence of an unpolarized mass, in analogy to YOUDIN 96. See Fig. 3 for limits on $g$ in the approximate $m_{A^0}$ range 0.02–2 meV.

[15] TULLNEY 13 look for a shift of the precession frequency difference between the colocated $^3$He and $^{129}$Xe in the presence an unpolarized mass, and derive limits g $< 3 \times 10^{-29}$–$2 \times 10^{-22}$ for $\lambda > 3 \times 10^{-4}$ m. See their Fig. 3 for $\lambda$-dependent limits.

[16] RAFFELT 12 show that the pseudoscalar couplings to electron and nucleon and the scalar coupling to nucleon are individually constrained by stellar energy-loss arguments and searches for anomalous monopole-monopole forces, together providing restrictive constraints on $g$. See their Figs. 2 and 3 for results.

[17] HOEDL 11 use a novel torsion pendulum to study the force by the polarized electrons of an external magnet. In their Fig. 3 they show restrictive limits on $g$ in the approximate $m_{A^0}$ range 0.03–10 meV.

[18] PETUKHOV 10 use spin relaxation of polarized $^3$He and find $g < 3 \times 10^{-23}$ $(\mathrm{cm}/\lambda)^2$ at 95% CL for the force range $\lambda = 10^{-4}$–$1$ cm.

[19] SEREBROV 10 use spin precession of ultracold neutrons close to bulk matter and find $g < 2 \times 10^{-21}$ $(\mathrm{cm}/\lambda)^2$ at 95% CL for the force range $\lambda = 10^{-4}$–$1$ cm.

[20] IGNATOVICH 09 use data on depolarization of ultracold neutrons in material traps. They show $\lambda$-dependent limits in their Fig. 1.

[21] SEREBROV 09 uses data on depolarization of ultracold neutrons stored in material traps and finds $g < 2.96 \times 10^{-21}$ $(\mathrm{cm}/\lambda)^2$ for the force range $\lambda = 10^{-3}$–$1$ cm and $g < 3.9 \times 10^{-22}$ $(\mathrm{cm}/\lambda)^2$ for $\lambda = 10^{-4}$–$10^{-3}$ cm, each time at 95% CL, significantly improving on BAESSLER 07.

[22] BAESSLER 07 use the observation of quantum states of ultracold neutrons in the Earth's gravitational field to constrain $g$ for an interaction range 1 $\mu$m–a few mm. See their Fig. 3 for results.

[23] HECKEL 06 studied the influence of unpolarized bulk matter, including the laboratory's surroundings or the Sun, on a torsion pendulum containing about $9 \times 10^{22}$ polarized electrons. See their Fig. 4 for limits on $g$ as a function of interaction range.

[24] NI 99 searched for a $T$-violating medium-range force acting on paramagnetic Tb $F_3$ salt. See their Fig. 1 for the result.

[25] POSPELOV 98 studied the possible contribution of $T$-violating Medium-Range Force to the neutron electric dipole moment, which is possible when axion interactions violate

*CP*. The size of the force among nucleons must be smaller than gravity by a factor of $2 \times 10^{-10}$ $(1\,\text{cm}/\lambda_A)$, where $\lambda_A = \hbar/m_A c$.

[26] YOUDIN 96 compared the precession frequencies of atomic $^{199}$Hg and Cs when a large mass is positioned near the cells, relative to an applied magnetic field. See Fig. 3 for their limits.

[27] RITTER 93 studied the influence of bulk mass with polarized electrons on an unpolarized torsion pendulum, providing limits in the interaction range from 1 to 100 cm.

[28] VENEMA 92 looked for an effect of Earth's gravity on nuclear spin-precession frequencies of $^{199}$Hg and $^{201}$Hg atoms.

[29] WINELAND 91 looked for an effect of bulk matter with aligned electron spins on atomic hyperfine resonances in stored $^9\text{Be}^+$ ions using nuclear magnetic resonance.

## Hidden Photons: Kinetic Mixing Parameter Limits

Limits are on the kinetic mixing parameter $\chi$ which is defined by the Lagrangian

$$L = -\frac{1}{4} F_{\mu\nu}F^{\mu\nu} - \frac{1}{4} F'_{\mu\nu}F'^{\mu\nu} - \frac{\chi}{2} F_{\mu\nu}F'^{\mu\nu} + \frac{m^2_{\gamma'}}{2} A'_{\mu}A'^{\mu},$$

where $A_\mu$ and $A'_\mu$ are the photon and hidden-photon fields with field strengths $F_{\mu\nu}$ and $F'_{\mu\nu}$, respectively, and $m_{\gamma'}$ is the hidden-photon mass.

| *VALUE* | *CL%* | *DOCUMENT ID* | *TECN* | *COMMENT* |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $< 4 \times 10^{-6}$ | 90 | [1] ABREU 24 | FASR | $m_{\gamma'} \simeq 50$ MeV |
| $< 1 \times 10^{-3}$ | 90 | [2] AAD 23BO | ATLS | $m_{\gamma'} = 5$–$40$ GeV |
| $< 1.3 \times 10^{-8}$ | 90 | [3] AAD 23I | ATLS | $m_{\gamma'} = 0.017$–$15$ GeV |
| | | [4] AAD 23T | ATLS | $m_{\gamma'} \lesssim 40$ GeV |
| $< 1 \times 10^{-16}$ | 90 | [5] AALBERS 23A | LZ | $m_{\gamma'} = 1$–$17$ keV |
| $< 1.6 \times 10^{-3}$ | 90 | [6] ABLIKIM 23AF | BES3 | $m_{\gamma'} = 1.5$–$2.9$ GeV |
| | | [7] ABUDINEN 23B | BEL2 | $m_{\gamma'} = 4$–$9.7$ GeV |
| $< 1.61 \times 10^{-14}$ | 90 | [8] ADHIKARI 23 | C100 | $m_{\gamma'} = 215$ eV |
| $< 6 \times 10^{-14}$ | 90 | [9] ADHIKARI 23A | C100 | $m_{\gamma'} = 10$–$1000$ keV |
| $< 2.1 \times 10^{-3}$ | 95 | [10] ADRIAN 23 | HPS | $m_{\gamma'} = 19$–$81$ MeV |
| $< 1.1 \times 10^{-16}$ | 90 | [11] AGNES 23A | DS50 | $m_{\gamma'} = 0.03$–$20$ keV |
| $< 2 \times 10^{-12}$ | 95 | [12] AN 23A | | $m_{\gamma'} = 4.1$–$6.2$ $\mu$eV |
| $< 5 \times 10^{-6}$ | 90 | [13] ANDREEV 23 | NA64 | $m_{\gamma'} = 10^{-3}$–$1.5$ GeV |
| $< 5.0 \times 10^{-14}$ | 68 | [14] BAJJALI 23 | BRAS | $m_{\gamma'} = 49.63$–$74.44$ $\mu$eV |
| $< 2 \times 10^{-7}$ | 90 | [15] CORTINA-GIL 23C | NA62 | $m_{\gamma'} = 10$–$700$ MeV |
| $< 2.2 \times 10^{-3}$ | 90 | [16] HAYRAPETY... 23G | CMS | $m_{\gamma'} = 1.1$–$7.9$ GeV |
| $< 3 \times 10^{-11}$ | 95 | [17] KOTAKA 23 | DORR | $m_{\gamma'} = 74$–$110$ $\mu$eV |
| $< 2 \times 10^{-15}$ | | [18] LI 23I | ASTR | $m_{\gamma'} = 10^{-3}$–$10^{5}$ eV |
| $< 7.9 \times 10^{-13}$ | 95 | [19] RAMANATH... 23 | QULP | $m_{\gamma'} = 19.7$–$30.5$ $\mu$eV |
| $< 1.6 \times 10^{-9}$ | 95 | [20] ROMANENKO 23 | LSW | $m_{\gamma'} = 0.21$–$5.7$ $\mu$eV |
| | | [21] XIA 23 | ASTR | $m_{\gamma'} \lesssim 10^{-23}$eV |
| | | [22] AAD 22J | ATLS | $m_{\gamma'} = 1$–$60$ GeV |

| | | | | | |
|---|---|---|---|---|---|
| | | [23] AAD | 22S | ATLS | $m_{\gamma'} \lesssim 10$ GeV |
| $< 2 \times 10^{-15}$ | 90 | [24] APRILE | 22 | XE1T | $m_{\gamma'} = 0.9$ keV |
| $< 2 \times 10^{-15}$ | 90 | [25] APRILE | 22 | XE1T | $m_{\gamma'} = 0.01$–$0.4$ keV |
| $< 5 \times 10^{-17}$ | 90 | [26] APRILE | 22B | XENT | $m_{\gamma'} = 1$–$39, 44$–$140$ keV |
| $< 1 \times 10^{-2}$ | 90 | [27] BATTAGLIERI | 22 | BDMP | $m_{\gamma'} = 3$–$100$ MeV |
| $(4.6^{+0.5}_{-0.4}) \times 10^{-15}$ | 68 | [28] BOLTON | 22 | ASTR | $m_{\gamma'} = (8.4 \pm 0.6) \times 10^{-14}$ eV |
| $< 1 \times 10^{-13}$ | 90 | [29] CERVANTES | 22 | ORPH | $m_{\gamma'} = 65.5$–$69.3$ $\mu$eV |
| $< 1 \times 10^{-12}$ | 90 | [30] CHILES | 22 | | $m_{\gamma'} = 0.7$–$0.8$ eV |
| $< 8.7 \times 10^{-11}$ | 95 | [31] HOCHBERG | 22 | SNSP | $m_{\gamma'} = 0.73$–$30$ eV |
| | | [32] LEES | 22 | BABR | $m_{\gamma'} = 1 \times 10^{-3}$–$3.16$ GeV |
| $< 7.97 \times 10^{-9}$ | 95 | [33] LU | 22 | ASTR | $m_{\gamma'} \lesssim 3 \times 10^{-5}$ eV |
| $< 6.86 \times 10^{-11}$ | 90 | [34] MANENTI | 22 | MDHI | $m_{\gamma'} = 1.61$ eV |
| $< 3 \times 10^{-2}$ | 95 | [35] THOMAS | 22 | | $m_{\gamma'} = 1$–$80$ GeV |
| | | [36] TUMASYAN | 22AH | CMS | $m_{\gamma'} = 4$–$62.5$ GeV |
| | | [37] TUMASYAN | 22N | CMS | $m_{\gamma'} = 0.6$–$49$ GeV |
| | | [38] WU | 22A | PPTA | $m_{\gamma'} \lesssim 10^{-23}$eV |
| $< 8 \times 10^{-6}$ | 90 | [39] ANDREEV | 21 | NA64 | $m_{\gamma'} = 1 \times 10^{-3}$–$1$ GeV |
| $< 2.3 \times 10^{-4}$ | 90 | [40] ANDREEV | 21A | NA64 | $m_{\gamma'} = 0.1$–$0.35$ GeV |
| $< 1.6 \times 10^{-4}$ | 95 | [41] BI | 21 | ASTR | $m_{\gamma'} = 0.03$–$0.06$ eV |
| $< 3 \times 10^{-5}$ | 90 | [42] CAZZANIGA | 21 | NA64 | $m_{\gamma'} = 10$–$390$ MeV |
| $< 1.68 \times 10^{-15}$ | 90 | [43] DIXIT | 21 | CNTR | $m_{\gamma'} = 24.86$ $\mu$eV |
| $< 2 \times 10^{-16}$ | 90 | [44] GHOSH | 21 | RVUE | $m_{\gamma'} = 2$–$30$ $\mu$eV |
| $< 1.8 \times 10^{-13}$ | | [45] GODFREY | 21 | | $m_{\gamma'} = 0.2637$–$0.2648$ $\mu$eV |
| $< 3 \times 10^{-12}$ | 95 | [46] KOPYLOV | 21A | CNTR | $m_{\gamma'} = 9$–$40$ eV |
| $< 2 \times 10^{-2}$ | 95 | [47] KRIBS | 21 | | $m_{\gamma'} \lesssim 10$ GeV |
| | | [48] SCHMIDT | 21 | THEO | $m_{\gamma'} < 0.6$ GeV |
| $< 3 \times 10^{-8}$ | 90 | [49] TSAI | 21 | BDMP | $m_{\gamma'} = 0.78$ GeV |
| $< 1 \times 10^{-4}$ | 90 | [50] AAIJ | 20C | LHCB | $m_{\gamma'} = 214$ MeV |
| | | [51] AAIJ | 20C | LHCB | $m_{\gamma'} = 218$–$315$ MeV |
| | | [52] ABLIKIM | 20AB | BES3 | $m_{\gamma'} = 0.2$–$2.1$ GeV |
| $< 4.1 \times 10^{-12}$ | 90 | [53] AGOSTINI | 20 | HPGE | $m_{\gamma'} = 60$ keV – 1 MeV |
| $< 3.3 \times 10^{-14}$ | 90 | [54] AMARAL | 20 | SCDM | $m_{\gamma'} = 1.2$–$50$ eV |
| $< 1.2 \times 10^{-14}$ | 90 | [55] AN | 20 | XE1T | $m_{\gamma'} = 200$ eV |
| $< 6.72 \times 10^{-13}$ | 95 | [56] ANDRIANAV... | 20 | FUNK | $m_{\gamma'} = 1.95$–$8.55$ eV |
| $< 1 \times 10^{-16}$ | 90 | [57] APRILE | 20 | XE1T | $m_{\gamma'} = 1$–$200$ keV |
| $< 9 \times 10^{-16}$ | 90 | [58] ARALIS | 20 | SCDM | $m_{\gamma'} = 0.04$–$500$ keV |

| | | | | | | |
|---|---|---|---|---|---|---|
| $< 3$ | $\times 10^{-5}$ | 90 | [59] ARGUELLES | 20 | THEO | $m_{\gamma'} = 0.01$ GeV |
| $< 7$ | $\times 10^{-14}$ | 90 | [60] ARNAUD | 20 | EDEL | $m_{\gamma'} = 1$–$40$ eV |
| $< 8.2$ | $\times 10^{-5}$ | 90 | [61] BANERJEE | 20 | NA64 | $m_{\gamma'} = 1.5$–$24$ MeV |
| $< 7$ | $\times 10^{-15}$ | 90 | [62] BARAK | 20 | SENS | $m_{\gamma'} = 1.2$–$12.8$ eV |
| | | | [63] KRASNIKOV | 20 | RVUE | $m_{\gamma'} = 16.7$ MeV |
| $< 1.4$ | $\times 10^{-14}$ | 90 | [64] SHE | 20 | CDEX | $m_{\gamma'} = 10$–$300$ eV |
| $< 1.3$ | $\times 10^{-15}$ | 90 | [65] SHE | 20 | CDEX | $m_{\gamma'} = 0.1$–$4$ keV |
| $< 1$ | $\times 10^{-3}$ | 90 | [66] SIRUNYAN | 20AQ | CMS | $m_{\gamma'} = 11.5$–$75$ GeV, 110–200 GeV |
| $< 4.3$ | $\times 10^{-10}$ | 95 | [67] TOMITA | 20 | | $m_{\gamma'} = 115.79$–$115.85$ $\mu$eV |
| $< 9$ | $\times 10^{-16}$ | 90 | [68] WANG | 20A | CDEX | $m_{\gamma'} = 0.185$–$10$ keV |
| | | | [69] AABOUD | 19G | ATLS | $m_{\gamma'} = 20$–$60$ GeV |
| $< 6$ | $\times 10^{-3}$ | 90 | [70] ABLIKIM | 19A | BES3 | $m_{\gamma'} = 0.01$–$2.4$ GeV |
| $< 3.4$ | $\times 10^{-3}$ | 90 | [71] ABLIKIM | 19H | BES3 | $m_{\gamma'} = 0.1$–$2.1$ GeV |
| $< 8$ | $\times 10^{-15}$ | 90 | [72] AGUILAR-AR... | 19A | DAMC | $m_{\gamma'} = 1.2$–$30$ eV |
| $< 9$ | $\times 10^{-17}$ | 90 | [73] APRILE | 19D | XE1T | $m_{\gamma'} = 0.186$–$5$ keV |
| $< 7.5$ | $\times 10^{-6}$ | 90 | [74] BANERJEE | 19 | NA64 | $m_{\gamma'} = 1$–$200$ MeV |
| $< 2$ | $\times 10^{-11}$ | | [75] BHOONAH | 19 | ASTR | $m_{\gamma'} = 10^{-22}$–$10^{-10}$ eV |
| $< 5$ | $\times 10^{-12}$ | 95 | [76] BRUN | 19 | SHUK | $m_{\gamma'} = 20.8$–$28.3$ $\mu$eV |
| $< 4.4$ | $\times 10^{-4}$ | 90 | [77] CORTINA-GIL | 19 | NA62 | $m_{\gamma'} = 60$–$110$ MeV |
| $< 3$ | $\times 10^{-5}$ | 95 | [78] DANILOV | 19 | TEXO | $m_{\gamma'} = 20$ eV - 1 MeV |
| $< 6$ | $\times 10^{-9}$ | 95 | [79] HOCHBERG | 19 | | $m_{\gamma'} = 0.8$–$4$ eV |
| $< 1$ | $\times 10^{-11}$ | 95 | [80] KOPYLOV | 19 | CNTR | $m_{\gamma'} = 9$–$40$ eV |
| $< 1.5$ | $\times 10^{-9}$ | | [81] KOVETZ | 19 | COSM | $m_{\gamma'} = 10^{-23}$–$10^{-13}$ eV |
| $< 3$ | $\times 10^{-14}$ | 95 | [82] NGUYEN | 19 | WDMX | $m_{\gamma'} = 6$ neV – 2.07 $\mu$eV |
| $< 4.5$ | $\times 10^{-14}$ | 90 | [83] ABE | 18F | XMAS | $m_{\gamma'} = 40$–$120$ keV |
| $< 2.5$ | $\times 10^{-3}$ | 95 | [84] ADRIAN | 18 | HPS | $m_{\gamma'} = 19$–$81$ MeV |
| $< 4.4$ | $\times 10^{-4}$ | 90 | [85] ANASTASI | 18B | KLOE | $m_{\gamma'} = 519$–$987$ MeV |
| $< 4$ | $\times 10^{-15}$ | 90 | [86] ARMENGAUD | 18 | EDE3 | $m_{\gamma'} = 0.8$–$500$ keV |
| | | | [87] BANERJEE | 18 | NA64 | $m_{\gamma'} = 1$–$23$ MeV |
| $< 1.8$ | $\times 10^{-5}$ | 90 | [88] BANERJEE | 18A | NA64 | $m_{\gamma'} = 1$–$100$ MeV |
| $< 1$ | $\times 10^{-8}$ | 90 | [89] KNIRCK | 18 | | $m_{\gamma'} = 0.67$–$0.92$ meV |
| $< 3.1$ | $\times 10^{-14}$ | 90 | [90] ABGRALL | 17 | HPGE | $m_{\gamma'} = 11.8$ keV |
| $< 6$ | $\times 10^{-4}$ | 90 | [91] ABLIKIM | 17AA | BES3 | $m_{\gamma'} = 1.5$–$3.4$ GeV |
| $< 7$ | $\times 10^{-15}$ | 90 | [92] ANGLOHER | 17 | CRES | $m_{\gamma'} = 0.3$–$0.7$ keV |
| $< 1.2$ | $\times 10^{-4}$ | 90 | [93] BANERJEE | 17 | NA64 | $m_{\gamma'} = 0.002$–$0.4$ GeV |

| | | | | | |
|---|---|---|---|---|---|
| $< 2 \times 10^{-11}$ | | [94] CHANG | 17 | ASTR | $m_{\gamma'} = 15$ MeV |
| $< 4.5 \times 10^{-3}$ | 90 | [95] DUBININA | 17 | EMUL | $m_{\gamma'} = 1.1$–24 MeV |
| $< 4 \times 10^{-4}$ | 90 | [96] LEES | 17E | BABR | $m_{\gamma'} = 4.7$ GeV |
| | | [97] AAD | 16AG | ATLS | $m_{\gamma'} = 0.1$–2 GeV |
| $< 4.4 \times 10^{-4}$ | 90 | [98] ANASTASI | 16 | KLOE | $m_{\gamma'} = 527$–987 MeV |
| $< 1.7 \times 10^{-6}$ | 95 | [99] KHACHATRY... | 16 | CMS | $m_{\gamma'} = 2$ GeV |
| $< 4 \times 10^{-2}$ | 95 | [100] AAD | 15CD | ATLS | $m_{\gamma'} = 15$–55 GeV |
| $< 1.4 \times 10^{-3}$ | 90 | [101] ADARE | 15 | | $m_{\gamma'} = 30$–90 MeV |
| | | [102] AN | 15A | | $m_{\gamma'} = 12$ eV - 40 keV |
| | | [103] ANASTASI | 15 | KLOE | $m_{\gamma'} = 2m_{\mu}$ - 1 GeV |
| $< 1.7 \times 10^{-3}$ | 90 | [104] ANASTASI | 15A | KLOE | $m_{\gamma'} = 5$–320 MeV |
| $< 4.2 \times 10^{-4}$ | 90 | [105] BATLEY | 15A | NA48 | $m_{\gamma'} = 36$ MeV |
| | | [106] JAEGLE | 15 | BELL | $m_{\gamma'} = 0.1$–3.5 GeV |
| $< 3 \times 10^{-13}$ | | [107] KAZANAS | 15 | ASTR | $m_{\gamma'} = 2m_e - 100$ MeV |
| $< 6 \times 10^{-12}$ | | [108] SUZUKI | 15 | | $m_{\gamma'} = 1.9$–4.3 eV |
| $< 2.3 \times 10^{-13}$ | 99.7 | [109] VINYOLES | 15 | ASTR | $m_{\gamma'} = 8$ eV |
| $< 2 \times 10^{-13}$ | | [110] ABE | 14F | XMAS | $m_{\gamma'} = 40$–120 keV |
| $< 1.8 \times 10^{-3}$ | 90 | [111] AGAKISHIEV | 14 | HDES | $m_{\gamma'} = 63$ MeV |
| $< 9.0 \times 10^{-4}$ | 90 | [112] BABUSCI | 14 | KLOE | $m_{\gamma'} = 969$ MeV |
| | | [113] BATELL | 14 | BDMP | $m_{\gamma'} = 10^{-3}$–1 GeV |
| $< 1.3 \times 10^{-7}$ | 95 | [114] BLUEMLEIN | 14 | BDMP | $m_{\gamma'} = 0.6$ GeV |
| $< 3 \times 10^{-18}$ | | [115] FRADETTE | 14 | COSM | $m_{\gamma'} = 50$–300 MeV |
| $< 3.5 \times 10^{-4}$ | 90 | [116] LEES | 14J | BABR | $m_{\gamma'} = 0.2$ GeV |
| $< 9 \times 10^{-4}$ | 95 | [117] MERKEL | 14 | A1 | $m_{\gamma'} = 40$–300 MeV |
| $< 3 \times 10^{-15}$ | | [118] AN | 13B | ASTR | $m_{\gamma'} = 2$ keV |
| $< 7 \times 10^{-14}$ | | [119] AN | 13C | XE10 | $m_{\gamma'} = 100$ eV |
| $< 8 \times 10^{-4}$ | | [120] DIAMOND | 13 | BDMP | $m_{\gamma'} = 30$–250 MeV |
| $< 2 \times 10^{-3}$ | 90 | [121] GNINENKO | 13 | BDMP | $m_{\gamma'} = 25$–120 MeV |
| $< 2.2 \times 10^{-13}$ | | [122] HORVAT | 13 | HPGE | $m_{\gamma'} = 230$ eV |
| $< 8.06 \times 10^{-5}$ | 95 | [123] INADA | 13 | LSW | $m_{\gamma'} = 0.04$ eV$-$26 keV |
| $< 2 \times 10^{-10}$ | 95 | [124] MIZUMOTO | 13 | | $m_{\gamma'} = 1$ eV |
| $< 1.7 \times 10^{-7}$ | | [125] PARKER | 13 | LSW | $m_{\gamma'} = 53$ $\mu$eV |
| $< 5.32 \times 10^{-15}$ | | [126] PARKER | 13 | | $m_{\gamma'} = 53$ $\mu$eV |
| $< 1 \times 10^{-15}$ | | [127] REDONDO | 13 | ASTR | $m_{\gamma'} = 2$ keV |
| $< 8 \times 10^{-8}$ | 90 | [128] GNINENKO | 12A | BDMP | $m_{\gamma'} = 1$–135 MeV |
| $< 1 \times 10^{-7}$ | 90 | [129] GNINENKO | 12B | CHRM | $m_{\gamma'} = 1$–500 MeV |
| $< 1 \times 10^{-3}$ | 90 | [130] ABRAHAMY... | 11 | | $m_{\gamma'} = 175$–250 MeV |
| $< 9 \times 10^{-8}$ | 95 | [131] BLUEMLEIN | 11 | BDMP | $m_{\gamma'} = 70$ MeV |

| | | | |
|---|---|---|---|
| $< 1 \quad \times 10^{-7}$ | [132] BJORKEN | 09 | BDMP $m_{\gamma'} = 2$–$400$ MeV |
| $< 5 \quad \times 10^{-9}$ | [133] BJORKEN | 09 | ASTR $m_{\gamma'} = 2$–$50$ MeV |

[1] ABREU 24 look for hidden photons produced from the $pp$ collision in the decay channel $\gamma' \rightarrow e^+ e^-$, and exclude at 90% CL the region of $\chi = 4 \times 10^{-6}$–$2 \times 10^{-4}$ and $m_{\gamma'} = 10$–$80$ MeV, with the newly excluded region near the higher values of $\chi$. See their Fig. 7 for mass-dependent limits.

[2] AAD 23BO look for rare decays of the $Z$ boson, $Z \rightarrow \gamma' + H'$, with dark Higgs decaying into a pair of hidden photons, assuming that at least two of the hidden photons decay into $e^+ e^-$ or $\mu^+ \mu^-$. The quoted limit assumes the hidden fine structure constant $\alpha_D = 0.1$ and the dark Higgs mass ranging 20 to 70 GeV. See their Fig.5 for the mass-dependent limits.

[3] AAD 23I look for exotic decays of the SM-like Higgs boson, $H \rightarrow \gamma' \gamma'$ with hidden photons decaying into displaced lepton or light quark pairs, and set limits on the kinetic mixing within $1 \times 10^{-4}$–$1 \times 10^{-8}$ for the given mass range. The quoted limit is for $m_{A^0} \simeq 13$ GeV with a branching fraction of 0.1 for the Higgs decaying into hidden photon pairs. See their Fig. 13 for the mass-dependent limits.

[4] AAD 23T is analogous to AAD 22S, but using the $ZH$ production mode, and set the upper limit on the branching ratio $B(H \rightarrow \gamma\gamma')$ within 0.0219–0.0252 (95% CL).

[5] AALBERS 23A look for an absorption of hidden photon dark matter. The quoted limit is for $m_{\gamma'} = 1.4$ keV. The local density $\rho_{\gamma'} = 0.3$ GeV/cm$^3$ is assumed. See their Fig. 7 for mass-dependent limits.

[6] ABLIKIM 23AF look for invisible decays of hidden photons produced in the reaction $e^+ e^- \rightarrow \gamma\gamma'$. They set limits within the $1.6 \times 10^{-3}$–$5.7 \times 10^{-3}$. See their Fig. 3 for mass-dependent limits.

[7] ABUDINEN 23B look for hidden photons in the dark Higgsstrahlung process, $e^+ e^- \rightarrow \gamma' H'$ ($\gamma' \rightarrow \mu^+ \mu^-$) with $H'$ being invisible. They set upper limits on the product of the kinetic mixing and the hidden gauge coupling, $\chi^2 \cdot \alpha_D$, in the range of $1.7 \times 10^{-8}$–$2 \times 10^{-6}$ at 90% CL for a 1 GeV dark Higgs mass. See their Fig. 3 for the mass-dependent limits.

[8] ADHIKARI 23 look for the annual modulation signal induced by solar flux of hidden photons. See their Fig. 10 for mass-dependent limits.

[9] ADHIKARI 23A look for absorption and Compton-like processes of hidden photon dark matter. The quoted limit is for $m_{\gamma'} \simeq 12$ keV. Limits between $6 \times 10^{-14}$–$3 \times 10^{-11}$ are obtained. See their Fig. 4 for mass-dependent limits.

[10] ADRIAN 23 is an update of ADRIAN 18, and use the data from the 2016 engineering run at 2.3 GeV. The quoted limit is at $m_{\gamma'} \simeq 74$ MeV. See their Fig. 28 for the mass-dependent limits.

[11] AGNES 23A look for an absorption of hidden photon dark matter. The quoted limit is for $m_{\gamma'} = 0.03$ keV. The local density $\rho_{\gamma'} = 0.3$ GeV/cm$^3$ is assumed. See their Fig. 2 for mass-dependent limits.

[12] AN 23A look for absorption of hidden photon dark matter at radio telescopes, setting limits based on data from the FAST telescope. The local density $\rho_{\gamma'} = 0.3$ GeV/cm$^3$ is assumed. See their Fig. 1 for mass-dependent limits.

[13] ANDREEV 23 is an update of ANDREEV 21 and ANDREEV 21A. The quoted limit applies to $m_{\gamma'} = 1$ MeV. See their Fig. 3 for mass-dependent limits.

[14] BAJJALI 23 look for hidden photon dark matter by using a 12–18 GHz dish antenna at U. Hamburg that is sensitive to vertically aligned hidden photon polarizations. They assume a local density of $\rho_{\gamma'} = 0.3$ GeV/cm$^3$. See their Figure 12 for mass-dependent limits in the range of $m_{\gamma'} = 50$–$75\ \mu eV$ under the assumption of randomly aligned hidden photon polarizations, defined as "1 sigma sensitivity". The run is labelled BRASS-p.

[15] CORTINA-GIL 23C NA62 beam dump experiment searches for hidden photons decaying to $\mu^+\mu^-$, extending their previous search CORTINA-GIL 19. The quoted limit applies at 300 MeV but does not extend to arbitrarily large kinetic mixing parameters. See Fig. 4 for mass-dependent limits.

[16] HAYRAPETYAN 23G search for kinetically mixed hidden photons in proton-proton collisions at the LHC that would generate a narrow peak in the mass spectrum of dimuon events. The mass window between 2.6 and 4.2 GeV is left unconstrained to avoid $J/\psi$ and $\psi(2S)$ resonances. Mass dependent limits given in their Fig. 6.

[17] KOTAKA 23 is an update of TOMITA 20, and set limits $\chi < 0.3$–$2 \times 10^{-10}$ for the quoted mass range. The local density $\rho_{\gamma'} = 0.39$ GeV/cm$^3$ is assumed. See their Fig. 5 for mass-dependent limits.

[18] LI 23I set cooling bounds on the emission of hidden photons from the Sun, red giant, and horizontal branch stars, including emission of both the transverse and longitudinal modes. Cooling bounds are computed assuming a static model as opposed to considering the impact on stellar evolution. The result is comparable to earlier estimates of the same bound e.g. REDONDO 13. Limit applies at the most constraining mass around 200 eV for the solar bound.

[19] RAMANATHAN 23 look for hidden photon dark matter using a gold-plated copper dish antenna cooled to 20 mK. The local density $\rho_{\gamma'} = 0.45$ GeV/cm$^3$ is assumed. Limits between $7.9 \times 10^{-13}$ and $3.81 \times 10^{-12}$ are obtained. See their Fig. 5 for mass-dependent limits.

[20] ROMANENKO 23 employed two superconducting radio frequency cavities with a high quality factor, optimized for detecting the longitudinal polarization of the hidden photon. The quoted limit is set at $m_{\gamma'} \simeq 5\mu$eV. See their Fig. 4 for the mass-dependent limits.

[21] XIA 23 is analogous to WU 22A and use the Fermi-LAT pulsar timing array. They set a bound on the local density as $\rho_{\gamma'} \lesssim 7$ GeV/cm$^3$ for $m_{\gamma'} \lesssim 10^{-23}$ eV at 95% CL, with weaker constraints up to $10^{-22}$ eV. See their Fig. 1 for the mass-dependent limits.

[22] AAD 22J look for exotic decays of the SM-like Higgs boson, $H \to \gamma'\gamma' \to 4\ell$ and $H \to Z\gamma' \to 4\ell$, and set limits on the kinetic mixing and the Higgs portal coupling. See their Figs. 19 and 20 for the mass-dependent limits.

[23] AAD 22S look for decays of a Higgs boson into $\gamma$ and $\gamma'$ using the VBF production mode, and set the upper limit on the branching ratio at 0.018 (95% CL) for the 125 GeV Higgs boson. For the quoted mass range, the signal acceptance changes by less than 1%.

[24] APRILE 22 is analogous to AN 20, and set limits $\chi < 3 \times 10^{-13}$ (eV/$m_{\gamma'}$) for $m_{\gamma'} <$ 3 eV (90% C.L.). For $m_{\gamma'} > 3$ eV, see their Fig. 16 for mass-dependent limits.

[25] APRILE 22 extend APRILE 19 to lower masses by removing the background of ionization signals correlated with high-energy events. The quoted limit applies to $m_{\gamma'} = 0.09$ keV. See their Fig. 15 for mass-dependent limits.

[26] APRILE 22B is an update of APRILE 20, and set limits $\chi \lesssim 5 \times 10^{-17}$–$2 \times 10^{-13}$. The quoted limit applies to $m_{\gamma'} = 1$ keV. They exclude the XENON1T excess found in APRILE 20. See their Fig. 6 for mass-dependent limits.

[27] BATTAGLIERI 22 is analogous to BATELL 14, and derived limits from the electron beam dump experiment at Jefferson Lab (BDX-MINI). Limits at the level of $7 \times 10^{-5}$–$1 \times 10^{-2}$ are obtained for the dark matter mass $m_{\gamma'}/3$ and the hidden gauge coupling $\alpha_D = 0.1$. See their Fig. 11.

[28] BOLTON 22 use the Ly-$\alpha$ forest at z $\simeq$ 0.1 as a calorimeter for heating in the intergalactic medium by the resonant conversion of hidden photon dark matter to photons, which is assumed to be responsible for the tension between the predicted and observed Ly-$\alpha$ absorption linewidths.

[29] CERVANTES 22 use a dielectrically loaded Fabry-Perot open cavity to look for hidden photon dark matter. The local density $\rho_{\gamma'}$ = 0.45 GeV/cm$^3$ is assumed. See their Fig. 5 for mass-dependent limits.

[30] CHILES 22 look for hidden photon dark matter by using a layered dielectric target and a superconducting nanowire single-photon detector. The local density $\rho_{\gamma'}$ = 0.4 GeV/cm$^3$ is assumed. See their Fig. 4 for mass-dependent limits.

[31] HOCHBERG 22 update HOCHBERG 19. The quoted limit applies to $m_{A^0}$ $\simeq$ 11 eV. See their Fig. 5 for mass-dependent limits.

[32] LEES 22 look for a hidden fermion-fermion bound state decaying into three hidden photons, which subsequently decay into $e^+e^-$, $\mu^+\mu^-$, or $\pi^+\pi^-$. For the bound-state mass in the range of 0.05–9.5 GeV, limits at the level of $5\times10^{-5}$–$1\times10^{-3}$ are obtained. See their Fig. 6 for mass-dependent limits.

[33] LU 22 derive the limit by studying the effect of photons oscillating into hidden photons on the surface luminosity of the neutron star RX J1856.6-3754.

[34] MANENTI 22 look for hidden photon dark matter by using a multilayer dielectric haloscope. Limits between $6.86\times10^{-11}$ and $5\times10^{-8}$ are obtained for $m_{\gamma'}$ $\simeq$ 1.1–3.1 eV. See their Fig. 11 for mass-dependent limits.

[35] THOMAS 22 improved KRIBS 21 by taking account of the changes in the parton distribution functions due to the inclusion of hidden photons. The quoted limit is at $m_{\gamma'}$ $\simeq$ 4 GeV. Limits in the range of $3\times10^{-2}$–$9\times10^{-2}$ are obtained for $m_{\gamma'}$ = 1–80 GeV. See their Fig. 1 for the limits.

[36] TUMASYAN 22AH look for exotic decays of the SM-like Higgs boson, $H \rightarrow Z\gamma' \rightarrow 4\ell$, and set limits on the Higgs portal coupling. See their Fig. 6 for the limits.

[37] TUMASYAN 22N look for exotic decays of the SM-like Higgs boson, $H \rightarrow \gamma'\gamma'$ ($\gamma' \rightarrow \mu^+\mu^-$), and set limits on the branching fraction product. See their Fig. 7 for mass- and lifetime-dependent limits.

[38] WU 22A look for direction-dependent oscillations in the gravitational potential generated by ultralight hidden photon dark matter, and set a bound on its local density as $\rho_{\gamma'} \lesssim$ 5 GeV/cm$^3$ for $m_{\gamma'} \lesssim 10^{-23}$ eV at 95% CL.

[39] ANDREEV 21 is analogous to BANERJEE 18A. The quoted limit applies to $m_{\gamma'}$ = 1 MeV. See their Fig. 3 for mass-dependent limits.

[40] ANDREEV 21A extends the limits of BANERJEE 19 by taking account of production through the resonant annihilation of secondary positrons with atomic electrons. The quoted limit is at $m_{\gamma'}$ = 0.23 GeV, assuming the fermion dark matter of mass $m_{\gamma'}/3$ and the hidden gauge coupling $\alpha_D$ = 0.1. See their Fig.3 for mass-dependent limits.

[41] BI 21 look for the gamma-ray spectral attenuation due to scattering with hidden photons constituting all dark matter, using the measurements of sub-PeV gamma-rays from the Crab Nebula by the Tibet AS$\gamma$ and HAWC experiments, together with MAGIC and HEGRA gamma-ray data. See their Fig. 4 for mass-dependent limits.

[42] CAZZANIGA 21 look for semi-visible decays of hidden photons, $\gamma' \rightarrow \chi_1\chi_2$ ($\chi_2 \rightarrow \chi_1 e^+e^-$), where $\chi_1$ and $\chi_2$ are hidden fermions. They exclude $3\times10^{-5} \lesssim \chi \lesssim 2\times10^{-2}$ assuming the hidden gauge coupling $\alpha_D$ = 0.1, and the fermion masses $m_{\chi_1}$ = $m_{\gamma'}/3$, $(m_{\chi_2} - m_{\chi_1})/m_{\chi_1}$ = 0.4. See their Fig. 4 for mass-dependent limits.

[43] DIXIT 21 look for hidden photon dark matter by using a superconducting transmon qubit dispersively coupled to a high $Q$ storage cavity. The local density $\rho_{\gamma'} = 0.4$ GeV/cm$^3$ is assumed. See their Fig.4 for mass-dependent limits.

[44] GHOSH 21 use existing haloscope axion search limits to set limits on hidden photon dark matter, considering the polarization of hidden photons. The quoted limit is at $m_{\gamma'} \simeq 3$ $\mu$eV. See their Fig. 1 for mass-dependent limits.

[45] GODFREY 21 look for hidden photon dark matter by using a wideband antenna, and set $5\sigma$ limits on $\chi$. The local density $\rho_{\gamma'} = 0.38$ GeV/cm$^3$ is assumed. See their updated Fig. 12 in arXiv:2101.02805v4 for mass-dependent limits in the range of $m_{\gamma'} = 0.207$–$1.24$ $\mu$eV.

[46] KOPYLOV 21A is an update of KOPYLOV 19, but use Ne gas instead of Ar. The quoted limit applies to $m_{\gamma'} = 12$ eV. See their Fig. 4 for mass-dependent limits.

[47] KRIBS 21 used the HERA data on neutral current deep inelastic $ep$ scattering to derive the limits, which become weaker for heavier masses. See their Fig. 3 for mass-dependent limits.

[48] SCHMIDT 21 use the microscopic Parton-Hadron-String Dynamics approach to extract limits by comparing the theoretically calculated dilepton spectra with the HADES data on the search for $\gamma' \rightarrow e^+ e^-$. See their Fig. 5 for the mass-dependent limits for various allowed surplus of the hidden photon contribution over the standard model yield.

[49] TSAI 21 update the limits from the CHARM and NuCal experiments, taking account of additional production channels from proton bremsstrahlung and $\eta$ meson decays, respectively. Limits between $3 \times 10^{-8}$ and $1 \times 10^{-4}$ are obtained for $0.01 < m_{\gamma'} < 0.8$ GeV (see their Fig. 1).

[50] AAIJ 20C look for hidden photons produced from the $pp$ collision in the decay channel $\gamma' \rightarrow \mu^+ \mu^-$. For prompt decaying hidden photons, limits at the level of $10^{-4}$–$10^{-3}$ are obtained for $m_{\gamma'} = 0.214$–$30$ GeV. See their Fig. 2 for mass-dependent limits.

[51] AAIJ 20C look for hidden photons produced from the $pp$ collision in the decay channel $\gamma' \rightarrow \mu^+ \mu^-$. For hidden photons with lifetimes of order ps, limits at the level of $10^{-5}$ are obtained for $m_{\gamma'} = 218$–$315$ MeV. See their Fig. 4 for mass-dependent limits.

[52] ABLIKIM 20AB search for $J/\psi \rightarrow \eta' \gamma'$ ($\gamma' \rightarrow \gamma \pi^0$), and set the upper limit on the product branching fraction of order $10^{-7}$. See their Fig. 7 for mass-dependent limits.

[53] AGOSTINI 20 is analogous to ABE 14F. The quoted limit applies to $m_{\gamma'} = 150$ keV. The local density $\rho_{\gamma'} = 0.3$ GeV/cm$^3$ is assumed. Their limits in their Fig. 3 were later found to be incorrect due to an error of their Eqs. (1) and (2). See Fig. 3 in AGOSTINI 22A for the corrected limits.

[54] AMARAL 20 use a second-generation SuperCDMS high-voltage eV-resolution detector to set limits on dark-matter hidden photon absorption. The quoted limit is for $m_{\gamma'} \simeq$ 17 eV. The local density $\rho_{\gamma'} = 0.3$ GeV/cm$^3$ is assumed. See their Fig. 3 for mass-dependent limits.

[55] AN 20 updates the direct detection limit of AN 13C on solar flux of hidden photons; $\chi < 1.6 \times 10^{-12}$ (eV/$m_{\gamma'}$) for $m_{\gamma'} < 6$ eV (90% C.L.). For $m_{\gamma'} > 6$ eV, see their Fig. 1 for mass-dependent limits.

[56] ANDRIANAVALOMAHEFA 20 is analogous to SUZUKI 15, but uses a mirror that is about one order of magnitude larger than in similar studies in the past. Limits at the level of $10^{-12}$ are obtained for $m_{\gamma'} = 2.5$–$7$ eV. See their Fig.23 and Table III for mass-dependent limits.

[57] APRILE 20 is analogous to ABE 14F, and set limits $\chi \lesssim 10^{-16}$–$10^{-12}$. The quoted limit applies to $m_{\gamma'} = 1$ keV. They also found an excess over known backgrounds, which

favors the mass $m_{\gamma'} = 2.3 \pm 0.2$ keV with a 3 $\sigma$ significance. See their Fig. 10 for mass-dependent limits.

[58] ARALIS 20 is analogous to ABE 14F. The quoted limit applies to $m_{\gamma'} = 0.1$ keV. The local density $\rho_{\gamma'} = 0.3$ GeV/cm$^3$ is assumed. The limits at masses above 3 keV in their Fig. 10 was later found to be incorrect due to an error in their analysis. See Fig. 3 in ARALIS 21 for the corrected limits.

[59] ARGUELLES 20 examine hidden-photon production in atmospheric cosmic-ray showers and its decay in IceCube and Super-Kamiokande. The quoted limit assumes a lifetime of $c\tau = 0.1$ km. See their Fig. 16 for mass- and lifetime-dependent limits.

[60] ARNAUD 20 look for the absorption signal of hidden photon dark matter in a Ge detector. The quoted limit applies to $m_{\gamma'} \simeq 9$ eV. The local density $\rho_{\gamma'} = 0.3$ GeV/cm$^3$ is assumed. See their Fig. 3 for mass-dependent limits.

[61] BANERJEE 20 is an update of BANERJEE 18. They exclude $8.2 \times 10^{-5} \lesssim \chi \lesssim 1 \times 10^{-2}$ for $m_{\gamma'} = 1.5$–24 MeV. In particular, they exclude $\chi = 1.2 \times 10^{-4}$–$6.8 \times 10^{-4}$ for the 16.7 MeV gauge boson. See their Fig. 5 for mass-dependent limits.

[62] BARAK 20 is analogous to AGUILAR-AREVALO 19A, and look for hidden photon dark matter by using the Skipper CCD. The quoted limit applies to $m_{\gamma'} = 12.8$ eV. See their Fig. 4 for mass-dependent limits.

[63] KRASNIKOV 20 showed that the limit of BANERJEE 20 combined with the measured anomalous magnetic moment of the electron exclude the 16.7 MeV gauge boson suggested by the ATOMKI (KRASZNAHORKAY 16) experiment if it has pure vector or axial-vector interactions.

[64] SHE 20 look for solar hidden photons. The quoted limit applies to $m_{\gamma'} = 180$ eV. See their Fig. 4 for mass-dependent limits.

[65] SHE 20 look for hidden photon dark matter and set limits $\chi < 1.3 \times 10^{-15}$–$2.8 \times 10^{-14}$ for the quoted mass range. The local density $\rho_{\gamma'} = 0.3$ GeV/cm$^3$ is assumed. See their Fig. 6 for mass-dependent limits.

[66] SIRUNYAN 20AQ look for a narrow resonance decaying into a pair of muons. For $m_{\gamma'} < 45$ GeV, they use dedicated high-rate dimuon triggers to reduce the muon transverse momentum thresholds. The quoted limit applies to $m_{\gamma'} = 50$ GeV, and limits of order $10^{-3}$ are obtained for the quoted mass range. See their Fig. 3 for mass-dependent limits.

[67] TOMITA 20 look for hidden photon dark matter using a planar metal plate and cryogenic receiver and set limits $\chi < 1.8$–$4.3 \times 10^{-10}$ for the quoted mass range. The local density $\rho_{\gamma'} = 0.39$ GeV/cm$^3$ is assumed. See their Fig. 7 for mass-dependent limits.

[68] WANG 20A is analogous to ABE 14F. The quoted limit applies to $m_{\gamma'} = 185$ eV. The local density $\rho_{\gamma'} = 0.3$ GeV/cm$^3$ is assumed. See their Fig. 11 for mass-dependent limits.

[69] AABOUD 19G look for $h \to \gamma' \gamma'$ ($\gamma' \to \mu^+ \mu^-$) and exclude a kinetic mixing around $10^{-9}$–$10^{-8}$ for B($h \to \gamma' \gamma'$) = 0.01 and 0.1. See their Fig. 9 for mass-dependent limits.

[70] ABLIKIM 19A look for $J/\psi \to \gamma' \eta$ ($\gamma' \to e^+ e^-$). Limits between $6 \times 10^{-3}$ and $5 \times 10^{-2}$ are obtained (see their Fig. 8).

[71] ABLIKIM 19H look for $J/\psi \to \gamma' \eta'$ ($\gamma' \to e^+ e^-$). Limits between $3.4 \times 10^{-3}$ and $2.6 \times 10^{-2}$ are obtained. See their Fig. 5 for mass-dependent limits.

[72] AGUILAR-AREVALO 19A look for the absorption signal of hidden photon dark matter by using a CCD. The quoted limit applies to $m_{\gamma'} = 17$ eV. The local density $\rho_{\gamma'} = 0.3$ GeV/cm$^3$ is assumed. See their Fig. 4 for mass-dependent limits.

[73] APRILE 19D is analogous to ABE 14F. The quoted limit applies to $m_{\gamma'} = 0.7$ keV. See their Fig. 5(f) for mass-dependent limits.

[74] BANERJEE 19 is an update of BANERJEE 18A. The quoted limit is at $m_{\gamma'} = 1$ MeV. See their Fig. 3 for mass-dependent limits.

[75] BHOONAH 19 examine heating of Galactic Center gas clouds by hidden photon dark matter. The quoted limit applies to $m_{\gamma'} \simeq 10^{-12}$ eV. See their Fig. 2 for mass-dependent limits.

[76] BRUN 19 is analogous to SUZUKI 15. The limit is derived under an assumption that hidden photons constitute the local dark matter density $\rho_{\gamma'} = 0.3$ GeV/cm$^3$.

[77] CORTINA-GIL 19 look for an invisible hidden photon in the reaction $K^+ \rightarrow \pi^+ \pi^0$ ($\pi^0 \rightarrow \gamma\gamma'$). The quoted limit applies to $m_{\gamma'} = 62.5$–65 MeV. See their Figs. 6 and 7 for mass-dependent limits.

[78] DANILOV 19 examined the hidden photon production in nuclear reactors, correctly taking account of the effective photon mass in the reactor and detector. The limit gets weaker for $m_{\gamma'}$ less than the effective photon mass in proportion to $1/m^2_{\gamma'}$. See their Fig. 1 for mass-dependent limits.

[79] HOCHBERG 19 look for the absorption signal of hidden photon dark matter by using superconducting-nanowire single-photon detectors. The quoted limit applies to $m_{\gamma'} \simeq$ 1 eV. The local density $\rho_{\gamma'} = 0.3$ GeV/cm$^3$ is assumed. See their Fig. 4 for mass-dependent limits.

[80] KOPYLOV 19 look for hidden-photon dark matter using a counter with an aluminum cathode and derive limits assuming it constitute all the local dark matter. The quoted limit applies to $m_{\gamma'} = 12$ eV. See their Fig. 7 for mass-dependent limits.

[81] KOVETZ 19 examine heating of the early Universe plasma by hidden photon dark matter, and derive the limits by requiring that the cosmic mean 21 cm brightness temperature relative to the CMB temperature satisfy $T_{21} > -100$ mK. The quoted limit applies to $m_{\gamma'} \simeq 2 \times 10^{-14}$ eV. See their Fig. 3 for mass-dependent limits.

[82] NGUYEN 19 look for hidden photon dark matter with a resonant cavity, and set limits $\sim 10^{-12}$ for $m_{\gamma'} = 0.2$–$2.07\mu$eV. The quoted limit applies to $m_{\gamma'} = 1.3$ $\mu$eV. The local density $\rho_{\gamma'} = 0.3$ GeV/cm$^3$ is assumed. See their Fig. 19 for mass-dependent limits.

[83] ABE 18F is an update of ABE 14F. The quoted limit applies to $m_{\gamma'} \simeq 40$ keV. See their Fig. 5 for mass-dependent limits.

[84] ADRIAN 18 look for a hidden photon resonance in the reaction $e^- Z \rightarrow e^- Z \gamma'$ ($\gamma' \rightarrow e^+ e^-$). The quoted limit applies to $m_{\gamma'} = 40$ MeV. See their Fig. 4 for mass-dependent limits.

[85] ANASTASI 18B look for a hidden photon resonance in the reaction $e^+ e^- \rightarrow \gamma' \gamma$ ($\gamma' \rightarrow \mu^+ \mu^-$). The quoted limit is obtained by combining the result of ANASTASI 16 and it applies to $m_{\gamma'} \simeq 519$–987 MeV. See their Fig. 9 for mass-dependent limits.

[86] ARMENGAUD 18 is analogous to ABE 14F. The quoted limits applies to $m_{\gamma'} = 1.6$ keV. See the right panel of Fig. 5 for mass-dependent limits.

[87] BANERJEE 18 look for hidden photons produced in the reaction $e^- Z \rightarrow e^- Z \gamma'$ ($\gamma' \rightarrow e^+ e^-$), and exclude $9.2 \times 10^{-5} \lesssim \chi \lesssim 1 \times 10^{-2}$ for $m_{\gamma'} = 1$–23 MeV. They also set a limit on the electron coupling to a 16.7 MeV gauge boson suggested by the ATOMKI (KRASZNAHORKAY 16) experiment. See their Fig. 3 for mass-dependent limits.

[88] BANERJEE 18A look for invisible decays of hidden photons produced in the reaction $e^- Z \rightarrow e^- Z \gamma'$ . The quoted limit is at $m_{\gamma'} = 1$ MeV. See their Fig. 15 for mass-dependent limits.

[89] KNIRCK 18 is analogous to SUZUKI 15. See their Fig. 5 for mass-dependent limits.

[90] ABGRALL 17 is analogous to ABE 14F using the MAJORANA DEMONSTRATOR. See their Fig. 3 for limits between 6 keV $< m_{\gamma'} <$ 97 keV.

[91] ABLIKIM 17AA look for $e^+ e^- \to \gamma\gamma'$ ($\gamma' \to e^+ e^-$ or $\mu^+ \mu^-$) . Limits between $10^{-3}$ and $10^{-4}$ are obtained (see their Fig. 3).

[92] ANGLOHER 17 is analogous to ABE 14F. The quoted limit is at $m_{\gamma'} =$ 0.7 keV. See their Fig. 8 for mass-dependent limits.

[93] BANERJEE 17 look for invisible decays of hidden photons produced in the reaction $e^- Z \to e^- Z \gamma'$. The quoted limit applies to $m_{\gamma'} =$ 2 MeV. See their Fig. 3 for mass-dependent limits.

[94] CHANG 17 examine the hidden photon emission from SN1987A, including the effects of finite temperature and density on $\chi$ and obtain limits $\chi$ ($m_{\gamma'}$/MeV) $\lesssim 3 \times 10^{-9}$ for $m_{\gamma'} <$ 15 MeV and $\chi \lesssim 10^{-9}$ for $m_{\gamma'} =$ 15–120 MeV.

[95] DUBININA 17 look for $\mu^+ \to e^+ \overline{\nu}_\mu \nu_e \gamma'$ ($\gamma' \to e^+ e^-$) in a nuclear photoemulsion. The quoted limit applies to $m_{\gamma'} =$ 1.1 MeV. Limits between $4.5 \times 10^{-3}$ and $10^{-2}$ are obtained (see their Fig. 3).

[96] LEES 17E look for invisible decays of hidden photons produced in the reaction $e^+ e^- \to \gamma\gamma'$. See their Fig. 5 for limits in the mass range $m_{\gamma'} \leq$ 8 GeV.

[97] AAD 16AG look for hidden photons promptly decaying into collimated electrons and/or muons, assuming that they are produced in the cascade decays of squarks or the Higgs boson. See their Fig. 10 and Fig.13 for their limits on the cross section times branching fractions.

[98] ANASTASI 16 look for the decay $\gamma' \to \pi^+ \pi^-$ in the reaction $e^+ e^- \to \gamma\gamma'$. Limits between $4.3 \times 10^{-3}$ and $4.4 \times 10^{-4}$ are obtained for 527 $< m_{\gamma'} <$ 987 MeV (see their Fig. 9).

[99] KHACHATRYAN 16 look for $\gamma' \to \mu^+ \mu^-$ in a dark SUSY scenario where the SM-like Higgs boson decays into a pair of the visible lightest neutralinos with mass 10 GeV, both of which decay into $\gamma'$ and a hidden neutralino with mass 1 GeV. See the right panel in their Fig. 2.

[100] AAD 15CD look for $H \to Z\gamma' \to 4\ell$ with the ATLAS detector at LHC and find $\chi <$ 4–17 $\times 10^{-2}$ for $m_{\gamma'} =$ 15–55 GeV. See their Fig. 6.

[101] ADARE 15 look for a hidden photon in $\pi^0$, $\eta^0 \to \gamma e^+ e^-$ at the PHENIX experiment. See their Fig. 4 for mass-dependent limits.

[102] AN 15A derived limits from the absence of ionization signals in the XENON10 and XENON100 experiments, assuming hidden photons constitute all the local dark matter. Their best limit is $\chi < 1.3 \times 10^{-15}$ at $m_{\gamma'} =$ 18 eV. See their Fig. 1 for mass-dependent limits.

[103] ANASTASI 15 look for a production of a hidden photon and a hidden Higgs boson with the KLOE detector at DAΦNE, where the hidden photon decays into a pair of muons and the hidden Higgs boson lighter than $m_{\gamma'}$ escape detection. See their Figs. 6 and 7 for mass-dependent limits on a product of the hidden fine structure constant and the kinetic mixing.

[104] ANASTASI 15A look for the decay $\gamma' \to e^+ e^-$ in the reaction $e^+ e^- \to e^+ e^- \gamma$. Limits between $1.7 \times 10^{-3}$ and $1 \times 10^{-2}$ are obtained for $m_{\gamma'} =$ 5–320 MeV (see their Fig. 7).

[105] BATLEY 15A look for $\pi^0 \to \gamma\gamma'$ ($\gamma' \to e^+ e^-$) at the NA48/2 experiment. Limits between $4.2 \times 10^{-4}$ and $8.8 \times 10^{-3}$ are obtained for $m_{\gamma'} =$ 9–120 MeV (see their Fig. 4).

[106] JAEGLE 15 look for the decay $\gamma' \to e^+ e^-$, $\mu^+ \mu^-$, or $\pi^+ \pi^-$ in the dark Higgstrahlung channel, $e^+ e^- \to \gamma' H'$ ($H' \to \gamma' \gamma'$) at the BELLE experiment. They set limits on a product of the branching fraction and the Born cross section as well as a product of the hidden fine structure constant and the kinetic mixing. See their Figs. 3 and 4.

[107] KAZANAS 15 set limits by studying the decay of hidden photons $\gamma' \to e^+ e^-$ inside and near the progenitor star of SN1987A. See their Fig. 6 for mass-dependent limits.

[108] SUZUKI 15 looked for hidden-photon dark matter with a dish antenna and derived limits assuming they constitute all the local dark matter. Their limits are $\chi < 6 \times 10^{-12}$ for $m_{\gamma'} = 1.9$–$4.3$ eV. See their Fig. 7 for mass-dependent limits.

[109] VINYOLES 15 performed a global fit analysis based on helioseismology and solar neutrino observations, and set the limits $\chi m_{\gamma'} < 1.8 \times 10^{-12}$ eV for $m_{\gamma'} = 3 \times 10^{-5}$–8 eV. See their Fig. 11.

[110] ABE 14F look for the photoelectric-like interaction in the XMASS detector assuming the hidden photon constitutes all the local dark matter. Limits between $2 \times 10^{-13}$ and $1 \times 10^{-12}$ are obtained, where the relation $\chi^2 = \alpha'/\alpha$ is used to translate the original bound on the ratio of the hidden and EM fine-structure constants. See their Fig. 3 for mass-dependent limits.

[111] AGAKISHIEV 14 look for hidden photons $\gamma' \to e^+ e^-$ at the HADES experiment, and set limits on $\chi$ for $m_{\gamma'} = 0.02$–$0.6$ GeV. See their Fig. 5 for mass-dependent limits.

[112] BABUSCI 14 look for the decay $\gamma' \to \mu^+ \mu^-$ in the reaction $e^+ e^- \to \mu^+ \mu^- \gamma$. Limits between $4 \times 10^{-3}$ and $9.0 \times 10^{-4}$ are obtained for 520 MeV $< m_{\gamma'} <$ 980 MeV (see their Fig. 7).

[113] BATELL 14 derived limits from the electron beam dump experiment at SLAC (E-137) by searching for events with recoil electrons by sub-GeV dark matter produced from the decay of the hidden photon. Limits at the level of $10^{-4}$–$10^{-1}$ are obtained for $m_{\gamma'} = 10^{-3}$–1 GeV, depending on the dark matter mass and the hidden gauge coupling (see their Fig. 2).

[114] BLUEMLEIN 14 analyzed the beam dump data taken at the U-70 accelerator to look for $\gamma'$-bremsstrahlung and the subsequent decay into muon pairs and hadrons. See their Fig. 4 for mass-dependent excluded region.

[115] FRADETTE 14 studied effects of decay of relic hidden photons on BBN and CMB to set constraints on very small values of the kinetic mixing. See their Figs. 4 and 7 for mass-dependent excluded regions.

[116] LEES 14J look for hidden photons in the reaction $e^+ e^- \to \gamma \gamma'$ ($\gamma' \to e^+ e^-$, $\mu^+ \mu^-$). Limits at the level of $10^{-4}$–$10^{-3}$ are obtained for 0.02 GeV $< m_{\gamma'} <$ 10.2 GeV. See their Fig. 4 for mass-dependent limits.

[117] MERKEL 14 look for $\gamma' \to e^+ e^-$ at the A1 experiment at the Mainz Microtron (MAMI). See their Fig. 3 for mass-dependent limits.

[118] AN 13B examined the stellar production of hidden photons, correcting an important error of the production rate of the longitudinal mode which now dominates. See their Fig. 2 for mass-dependent limits based on solar energy loss.

[119] AN 13C use the solar flux of hidden photons to set a limit on the atomic ionization rate in the XENON10 experiment. They find $\chi\, m_{\gamma'} < 3 \times 10^{-12}$ eV for $m_{\gamma'} < 1$ eV. See their Fig. 2 for mass-dependent limits.

[120] DIAMOND 13 analyzed the beam dump data taken at the SLAC millicharge experiment to constrain a hidden photon invisibly decaying into lighter long-lived particles, which undergo elastic scattering off nuclei in the detector. Limits between $8 \times 10^{-4}$–$2 \times 10^{-2}$ are obtained. The quoted limit is applied when the dark gauge coupling is set equal to the electromagnetic coupling. See their Fig.4 for mass-dependent limits.

[121] GNINENKO 13 used the data taken at the SINDRUM experiment to constrain the decay, $\pi^0 \to \gamma \gamma'$ ($\gamma' \to e^+ e^-$) to derive limits. See their Fig. 2 for their mass-dependent excluded region.

[122] HORVAT 13 look for hidden-photo-electric effect in HPGe detectors induced by solar hidden photons. See their Fig. 3 for mass-dependent limits.

[123] INADA 13 search for hidden photons using an intense X-ray beamline at SPring-8. See their Fig. 4 for mass-dependent limits.

[124] MIZUMOTO 13 look for solar hidden photons. See their Fig. 5 for mass-dependent limits.

[125] PARKER 13 look for hidden photons using a cryogenic resonant microwave cavity. See their Fig.5 for mass-dependent limits.

[126] PARKER 13 derived a limit for the hidden photon CDM with a randomly oriented hidden photon field.

[127] REDONDO 13 examined the solar emission of hidden photons including the enhancement factor for the longitudinal mode pointed out by AN 13B, and also updated stellar-energy loss arguments. See their Fig.3 for mass-dependent limits, including a review of the currently best limits from other arguments.

[128] GNINENKO 12A obtained bounds on $\text{B}(\pi^0 \to \gamma\gamma') \cdot \text{B}(\gamma' \to e^+e^-)$ from the NOMAD and PS191 neutrino experiments, and derived limits between $8 \times 10^{-8}$–$2 \times 10^{-4}$. See their Fig.4 for mass-dependent excluded regions.

[129] GNINENKO 12B used the data taken at the CHARM experiment to constrain the decay, $\eta(\eta') \to \gamma\gamma'$ $(\gamma' \to e^+e^-)$, and derived limits between $1 \times 10^{-7}$–$1 \times 10^{-4}$. See their Fig.4 for mass-dependent excluded region.

[130] ABRAHAMYAN 11 look for $\gamma' \to e^+e^-$ in the electron-nucelon fixed-target experiment at the Jefferson Laboratory (APEX). See their Fig. 5 for mass-dependent limits.

[131] BLUEMLEIN 11 analyzed the beam dump data taken at the U-70 accelerator to look for $\pi^0 \to \gamma\gamma'$ $(\gamma' \to e^+e^-)$. See their Fig. 5 for mass-dependent limits.

[132] BJORKEN 09 analyzed the beam dump data taken at E137, E141, and E774 to constrain a hidden photon produced by bremsstrahlung, subsequently decaying into $e^+e^-$, and derived limits between $10^{-7}$ and $10^{-2}$. See their Fig. 1 for mass-dependent excluded region.

[133] BJORKEN 09 required the energy loss in the $\gamma'$ emission from the core of SN1987A not to exceed $10^{53}$ erg/s, and derived limits between $5 \times 10^{-9}$ and $2 \times 10^{-6}$. See their Fig. 1 for mass-dependent excluded region.

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| LUCENTE | 20A | JCAP 2012 008 | G. Lucente *et al.* | |
| MEYER | 20 | PRL 124 231101 | M. Meyer, T. Petrushevska | (Fermi-LAT Collab.) |
| Also | | PRL 125 119901 (errat.) | M. Meyer, T. Petrushevska | (Fermi-LAT Collab.) |
| PODDAR | 20 | PR D101 083007 | T.K. Poddar, S. Mohanty, S. Jana | |

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| SCHUTZ | 20 | PR D101 123026 | K. Schutz | (MIT) |
| SHE | 20 | PRL 124 111301 | Z. She *et al.* | (CDEX Collab.) |
| SIRUNYAN | 20AQ | PRL 124 131802 | A.M. Sirunyan *et al.* | (CMS Collab.) |
| STRANIERO | 20 | AA 644 A166 | O. Straniero *et al.* | (SASSO, BGNA, GRAN) |
| SUN | 20 | PR D101 063020 | L. Sun, R. Brito, M. Isi | (CIT, ROMAI, MIT) |
| TOMITA | 20 | JCAP 2009 012 | N. Tomita *et al.* | |
| WANG | 20A | PR D101 052003 | Y. Wang *et al.* | (CDEX Collab.) |
| YAMAMOTO | 20 | JCAP 2002 011 | R. Yamamoto *et al.* | |
| AABOUD | 19G | PR D99 012001 | M. Aaboud *et al.* | (ATLAS Collab.) |
| ABLIKIM | 19A | PR D99 012006 | M. Ablikim *et al.* | (BESIII Collab.) |
| Also | | PR D104 099901 (errat.) | M. Ablikim *et al.* | (BESIII Collab.) |
| ABLIKIM | 19H | PR D99 012013 | M. Ablikim *et al.* | (BESIII Collab.) |
| ADELBERGER | 19 | PRL 123 169001 | E.G. Adelberger, W.A. Terrano | (WASH, PRIN) |
| ADHIKARI | 19B | ASP 114 101 | P. Adhikari *et al.* | (COSINE-100 Collab.) |
| AGUILAR-AR... | 19A | PRL 123 181802 | A. Aguilar-Arevalo *et al.* | (DAMIC Collab.) |
| AHN | 19 | PRL 122 021802 | J.K. Ahn *et al.* | (KOTO Collab.) |
| ALESINI | 19 | PR D99 101101 | D. Alesini *et al.* | (QUAX Collab.) |
| ALONI | 19 | PRL 123 071801 | D. Aloni *et al.* | (REHO, MIT, CERN, HAIF) |
| APRILE | 19 | PRL 122 071301 | E. Aprile *et al.* | (XENON1T Collab.) |
| APRILE | 19D | PRL 123 251801 | E. Aprile *et al.* | (XENON1T Collab.) |
| ARNOLD | 19 | EPJ C79 440 | R. Arnold *et al.* | (NEMO-3 Collab.) |
| BANERJEE | 19 | PRL 123 121801 | D. Banerjee *et al.* | (NA64 Collab.) |
| BHOONAH | 19 | PR D100 023001 | A. Bhoonah *et al.* | |
| BRUN | 19 | PRL 122 201801 | P. Brun, L. Chevalier, C. Flouzat | (SACL) |
| CAPUTO | 19 | PR D100 063515 | A. Caputo *et al.* | |
| CORTINA-GIL | 19 | JHEP 1905 182 | E. Cortina Gil *et al.* | (NA62 Collab.) |
| DANILOV | 19 | PRL 122 041801 | M. Danilov, S. Demidov, D. Gorbunov | (LEBD, INRM+) |
| DAVOUDIASL | 19 | PRL 123 021102 | H. Davoudiasl, P.B. Denton | (BNL) |
| DESSERT | 19 | PRL 123 061104 | C. Dessert, A.J. Long, B.R. Safdi | (MICH) |
| FEDDERKE | 19 | PR D100 015040 | M.A. Fedderke, P.W. Graham, S. Rajendran | (STAN+) |
| FUJITA | 19 | PRL 122 191101 | T. Fujita, R. Tazaki, K. Toma | (KYOT, GEVA, TOHO) |
| HOCHBERG | 19 | PRL 123 151802 | Y. Hochberg *et al.* | (HEBR, MIT, NIST) |
| IVANOV | 19 | JCAP 1902 059 | M.M. Ivanov *et al.* | |
| KOPYLOV | 19 | JCAP 1907 008 | A. Kopylov, I. Orekhov, V. Petukhov | (INRM) |
| KOVETZ | 19 | PR D99 123511 | E.D. Kovetz, I. Cholis, D.E. Kaplan | (JHU) |
| LEINSON | 19 | JCAP 1911 031 | L.B. Leinson | |
| LIANG | 19 | JCAP 1906 042 | Y-F. Liang *et al.* | |
| LLOYD | 19 | PR D100 063005 | S.J. Lloyd *et al.* | |
| MARSH | 19 | PRL 123 051103 | D.J.E. Marsh, J.C. Niemeyer | (GOET) |
| NGUYEN | 19 | JCAP 1910 014 | L.H. Nguyen, A. Lobanov, D. Horns | (WISPDMX Collab.) |
| OUELLET | 19A | PRL 122 121802 | J.L. Ouellet *et al.* | (ABRACADABRA Collab.) |
| PALOMBA | 19 | PRL 123 171101 | C. Palomba *et al.* | |
| SIRUNYAN | 19BQ | PL B796 131 | A.M. Sirunyan *et al.* | (CMS Collab.) |
| SMORRA | 19 | NAT 575 310 | C. Smorra *et al.* | |
| TERRANO | 19 | PRL 122 231301 | W. Terrano *et al.* | (WASH) |
| WU | 19 | PRL 122 191302 | T. Wu *et al.* | (CASPEr-ZULF Collab.) |
| WU | 19C | PRL 123 169002 | T. Wu *et al.* | (CASPEr-ZULF Collab.) |
| ABE | 18F | PL B787 153 | K. Abe *et al.* | (XMASS Collab.) |
| ADRIAN | 18 | PR D98 091101 | P.H. Adrian *et al.* | (HPS Collab.) |
| AKHMATOV | 18 | PPN 49 599 | Z.A. Akhmatov *et al.* | |
| ANASTASI | 18B | PL B784 336 | A. Anastasi *et al.* | (KLOE-2 Collab.) |
| ARMENGAUD | 18 | PR D98 082004 | E. Armengaud *et al.* | (EDELWEISS-III Collab.) |
| ARNOLD | 18 | EPJ C78 821 | R. Arnold *et al.* | (NEMO-3 Collab.) |
| BANERJEE | 18 | PRL 120 231802 | D. Banerjee *et al.* | (NA64 Collab.) |
| BANERJEE | 18A | PR D97 072002 | D. Banerjee *et al.* | (NA64 Collab.) |
| BEZNOGOV | 18 | PR C98 035802 | M.V. Beznogov *et al.* | |
| BOUTAN | 18 | PRL 121 261302 | C. Boutan *et al.* | (ADMX Collab.) |
| CHANG | 18 | JHEP 1809 051 | J.C. Chang, R. Essig, S.D. McDermott | |
| CRESCINI | 18 | EPJ C78 703 | N. Crescini *et al.* | (QUAX Collab.) |
| DU | 18 | PRL 120 151301 | N. Du *et al.* | (ADMX Collab.) |
| DZUBA | 18 | PR D98 035048 | V.A. Dzuba *et al.* | |
| FICEK | 18 | PRL 120 183002 | F. Ficek *et al.* | |
| FORTIN | 18 | JHEP 1806 048 | J.-F. Fortin, K. Sinha | (LAVL, OKLA) |
| GAVRILYUK | 18 | JETPL 107 589 | Yu.M. Gavrilyuk *et al.* | |
| HAMAGUCHI | 18 | PR D98 103015 | K. Hamaguchi *et al.* | |
| JAECKEL | 18 | PR D98 055032 | J. Jaeckel, P. C. Malta, J. Redondo | |
| KNIRCK | 18 | JCAP 1811 031 | S. Knirck *et al.* | |
| PORAYKO | 18 | PR D98 102002 | N.K. Porayako *et al.* | (PPTA Collab.) |
| STADNIK | 18 | PRL 120 013202 | Y.V. Stadnik, V.A. Dzuba, V.V. Flambaum | |
| YAMAJI | 18 | PL B782 523 | T. Yamaji *et al.* | (TOKY, RIKEN, KEK) |
| ZHANG | 18 | PR D97 063009 | C. Zhang *et al.* | |

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| ZHONG | 18 | PR D97 092001 | L. Zhong *et al.* | (HAYSTAC Collab.) |
| AAIJ | 17AQ | PR D95 071101 | R. Aaij *et al.* | (LHCb Collab.) |
| ABEL | 17 | PR X7 041034 | C. Abel *et al.* | (nEDM Collab.) |
| ABGRALL | 17 | PRL 118 161801 | N. Abgrall *et al.* | (MAJORANA Collab.) |
| ABLIKIM | 17AA | PL B774 252 | M. Ablikim *et al.* | (BESIII Collab.) |
| ADE | 17 | PR D96 102003 | P.A.R. Ade *et al.* | (BICEP2/Keck Array Collab.) |
| AHN | 17 | PTEP 2017 021C01 | J.K. Ahn *et al.* | (KOTO Collab.) |
| AKERIB | 17B | PRL 118 261301 | D.S. Akerib *et al.* | (LUX Collab.) |
| ANASTASSO... | 17 | NATP 13 584 | V. Anastassopoulos *et al.* | (CAST Collab.) |
| ANGLOHER | 17 | EPJ C77 299 | G. Angloher *et al.* | (CRESST-II Collab.) |
| APRILE | 17B | PR D95 029904 | E. Aprile *et al.* | (XENON100 Collab.) |
| BANERJEE | 17 | PRL 118 011802 | D. Banerjee *et al.* | (NA64 Collab.) |
| BATLEY | 17 | PL B769 67 | J.R. Batley *et al.* | (NA48/2 Collab.) |
| BRANCA | 17 | PRL 118 021302 | A. Branca *et al.* | (AURIGA Collab.) |
| BRUBAKER | 17 | PRL 118 061302 | B.M. Brubaker *et al.* | (YALE, UCB, NIST+) |
| CHANG | 17 | JHEP 1701 107 | J.H. Chang, R. Essig, S.D. McDermott | (STON) |
| CHOI | 17 | PR D96 061102 | J. Choi *et al.* | (CAPP-ACTION Collab.) |
| CRESCINI | 17 | PL B773 677 | N. Crescini *et al.* | (QUAX-gpgs Collab.) |
| DAIDO | 17 | PL B772 127 | R. Daido, F. Takahashi | |
| DOLAN | 17 | JHEP 1712 094 | M.J. Dolan *et al.* | |
| Also | | JHEP 2103 190 (errat.) | M.J. Dolan *et al.* | (MELB, BRCO, DESY) |
| DUBININA | 17 | PAN 80 461 | V.V. Dubinina *et al.* | |
| FICEK | 17 | PR A95 032505 | F. Ficek *et al.* | |
| FU | 17A | PRL 119 181806 | C. Fu *et al.* | (PandaX-II Collab.) |
| INADA | 17 | PRL 118 071803 | T. Inada *et al.* | |
| KLIMCHITSK... | 17A | PR D95 123013 | G.L. Klimchitskaya, V.M. Mostepanenko | |
| KOHRI | 17 | PR D96 051701 | K. Kohri, H. Kodama | (KEK, KYOT) |
| LEES | 17E | PRL 119 131804 | J.P. Lees *et al.* | (BABAR Collab.) |
| LIU | 17 | PL B766 117 | X.-H. Liu | (TINT) |
| LIU | 17A | PR D95 052006 | S.K. Liu *et al.* | (CDEX Collab.) |
| LUO | 17 | PR D96 055028 | P. Luo *et al.* | |
| MARSH | 17 | JCAP 1712 036 | M.C.D. Marsh *et al.* | |
| MCALLISTER | 17 | PDU 18 67 | B.T. McAllister *et al.* | (WAUS) |
| TIWARI | 17 | PR D95 023005 | P. Tiwari | (Technion) |
| AAD | 16AG | JHEP 1602 062 | G. Aad *et al.* | (ATLAS Collab.) |
| ABLIKIM | 16E | PR D93 052005 | M. Ablikim *et al.* | (BESIII Collab.) |
| AJELLO | 16 | PRL 116 161101 | M. Ajello *et al.* | (Fermi-LAT Collab.) |
| ANASTASI | 16 | PL B757 356 | A. Anastasi *et al.* | (KLOE-2 Collab.) |
| BATTICH | 16 | JCAP 1608 062 | T. Battich *et al.* | |
| BERENJI | 16 | PR D93 045019 | B. Berenji *et al.* | |
| CORSICO | 16 | JCAP 1607 036 | A.H. Corsico *et al.* | |
| DELLA-VALLE | 16 | EPJ C76 24 | F. Della Valle *et al.* | (PVLAS Collab.) |
| HOSKINS | 16 | PR D94 082001 | J. Hoskins *et al.* | (ADMX Collab.) |
| JAECKEL | 16 | PL B753 482 | J. Jaeckel, M. Spannowsky | (HEID, DURH) |
| KHACHATRY... | 16 | PL B752 146 | V. Khachatryan *et al.* | (CMS Collab.) |
| KRASZNAHO... | 16 | PRL 116 042501 | A.J. Krasznahorkay *et al.* | (HINR, ANIK+) |
| LEEFER | 16 | PRL 117 271601 | N. Leefer *et al.* | (MAINZ, BONN, LBL, UCB+) |
| WON | 16 | PR D94 092006 | E. Won *et al.* | (BELLE Collab.) |
| YOON | 16 | JHEP 1606 011 | Y.S. Yoon *et al.* | (KIMS Collab.) |
| AAD | 15CD | PR D92 092001 | G. Aad *et al.* | (ATLAS Collab.) |
| AAIJ | 15AZ | PRL 115 161802 | R. Aaij *et al.* | (LHCb Collab.) |
| ADARE | 15 | PR C91 031901 | A. Adare *et al.* | (PHENIX Collab.) |
| AFACH | 15 | PL B745 58 | S. Afach *et al.* | (ETH, PSI, CAEN, +) |
| AGOSTINI | 15A | EPJ C75 416 | M. Agostini *et al.* | (GERDA Collab.) |
| AN | 15A | PL B747 331 | H. An *et al.* | (CIT, VICT, VIEN) |
| ANASTASI | 15 | PL B747 365 | A. Anastasi *et al.* | (KLOE-2 Collab.) |
| ANASTASI | 15A | PL B750 633 | A. Anastasi *et al.* | (KLOE-2 Collab.) |
| ANASTASSO... | 15 | PL B749 172 | V. Anastassopoulos *et al.* | (CAST Collab.) |
| ARIK | 15 | PR D92 021101 | M. Arik *et al.* | (CAST Collab.) |
| ARNOLD | 15 | PR D92 072011 | R. Arnold *et al.* | (NEMO-3 Collab.) |
| BALLOU | 15 | PR D92 092002 | R. Ballou *et al.* | (OSQAR Collab.) |
| BATLEY | 15A | PL B746 178 | J.R. Batley *et al.* | (NA48/2 Collab.) |
| BAYES | 15 | PR D91 052020 | R. Bayes *et al.* | (TWIST Collab.) |
| BRAX | 15 | PR D92 083501 | P. Brax, P. Brun, D. Wouters | (SACL, SACL5) |
| GAVRILYUK | 15 | JETPL 101 664<br>Translated from ZETFP 101 739. | Yu.M. Gavrilyuk *et al.* | |
| HASEBE | 15 | PTEP 2015 073C01 | T. Hasebe *et al.* | |
| JAEGLE | 15 | PRL 114 211801 | I. Jaegle *et al.* | (BELLE Collab.) |
| KAZANAS | 15 | NP B890 17 | D. Kazanas *et al.* | |
| KLIMCHITSK... | 15 | EPJ C75 164 | G.L. Klimchitskaya, V.M. Mostepanenko | |
| MILLEA | 15 | PR D92 023010 | M. Millea, L. Knox, B. Fields | (UCD, ILL) |

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| STADNIK | 15 | EPJ C75 110 | Y.V. Stadnik, V.V. Flambaum | (SYDN) |
| SUZUKI | 15 | JCAP 1509 042 | J. Suzuki *et al.* | |
| TERRANO | 15 | PRL 115 201801 | W.A. Terrano *et al.* | (WASH) |
| VANTILBURG | 15 | PRL 115 011802 | K. Van Tilburg *et al.* | |
| VINYOLES | 15 | JCAP 1510 015 | N. Vinyoles *et al.* | |
| ABE | 14F | PRL 113 121301 | K. Abe *et al.* | (XMASS Collab.) |
| AGAKISHIEV | 14 | PL B731 265 | G. Agakishiev *et al.* | (HADES Collab.) |
| ALBERT | 14A | PR D90 092004 | J.B. Albert *et al.* | (EXO-200 Collab.) |
| APRILE | 14B | PR D90 062009 | E. Aprile *et al.* | (XENON100 Collab.) |
| ARIK | 14 | PRL 112 091302 | M. Arik *et al.* | (CAST Collab.) |
| AYALA | 14 | PRL 113 191302 | A. Ayala *et al.* | |
| BABUSCI | 14 | PL B736 459 | D. Babusci *et al.* | (KLOE-2 Collab.) |
| BATELL | 14 | PRL 113 171802 | B. Batell, R. Essig, Z. Surujon | (EFI, STON) |
| BEZERRA | 14 | PR D89 035010 | V.B. Bezerra *et al.* | |
| BEZERRA | 14A | EPJ C74 2859 | V.B. Bezerra *et al.* | |
| BEZERRA | 14B | PR D90 055013 | V.B. Bezerra *et al.* | |
| BEZERRA | 14C | PR D89 075002 | V.B. Bezerra *et al.* | |
| BLUEMLEIN | 14 | PL B731 320 | J. Bluemlein, J. Brunner | (CPPM, DESY) |
| BLUM | 14 | PL B737 30 | K. Blum *et al.* | (IAS, PRIN) |
| DELLA-VALLE | 14 | PR D90 092003 | F. Della Valle *et al.* | (PVLAS Collab.) |
| DERBIN | 14 | EPJ C74 3035 | A.V. Derbin *et al.* | |
| EJLLI | 14 | PR D90 123527 | D. Ejlli | |
| FRADETTE | 14 | PR D90 035022 | A. Fradette *et al.* | |
| LEES | 14J | PRL 113 201801 | J.P. Lees *et al.* | (BABAR Collab.) |
| LEINSON | 14 | JCAP 1408 031 | L. Leinson | |
| MERKEL | 14 | PRL 112 221802 | H. Merkel *et al.* | (A1 at MAMI) |
| MILLER-BER... | 14 | JCAP 1410 069 | M.M. Miller Bertolami *et al.* | |
| PUGNAT | 14 | EPJ C74 3027 | P. Pugnat *et al.* | (OSQAR Collab.) |
| REESMAN | 14 | JCAP 1408 021 | R. Reesman *et al.* | (OSU) |
| ABE | 13D | PL B724 46 | K. Abe *et al.* | (XMASS Collab.) |
| ABRAMOWSKI | 13A | PR D88 102003 | A. Abramowski *et al.* | (H.E.S.S. Collab.) |
| ADLARSON | 13 | PL B726 187 | P. Adlarson *et al.* | (WASA-at-COSY Collab.) |
| ALESSANDRIA | 13 | JCAP 1305 007 | F. Alessandria *et al.* | (CUORE Collab.) |
| AN | 13B | PL B725 190 | H. An, M. Pospelov, J. Pradler | |
| AN | 13C | PRL 111 041302 | H. An, M. Pospelov, J. Pradler | |
| ARCHIDIACO... | 13A | JCAP 1310 020 | M. Archidiacono *et al.* | |
| ARMENGAUD | 13 | JCAP 1311 067 | E. Armengaud *et al.* | (EDELWEISS-II Collab.) |
| BABUSCI | 13B | PL B720 111 | D. Babusci *et al.* | (KLOE-2 Collab.) |
| BARTH | 13 | JCAP 1305 010 | K. Barth *et al.* | (CAST Collab.) |
| BECK | 13 | PRL 111 231801 | C. Beck | |
| BETZ | 13 | PR D88 075014 | M. Betz *et al.* | (CROWS Collab.) |
| BULATOWICZ | 13 | PRL 111 102001 | M. Bulatowicz *et al.* | |
| CHU | 13 | PR D87 011105 | P.-H. Chu *et al.* | (DUKE, IND, SJTU) |
| DERBIN | 13 | EPJ C73 2490 | A. V. Derbin *et al.* | |
| DIAMOND | 13 | PRL 111 221803 | M.D. Diamond, P. Schuster | |
| FRIEDLAND | 13 | PRL 110 061101 | A. Friedland, M. Giannotti, M. Wise | |
| GNINENKO | 13 | PR D87 035030 | S.N. Gninenko | (INRM) |
| HECKEL | 13 | PRL 111 151802 | B. R. Heckel *et al.* | |
| HORVAT | 13 | PL B721 220 | R. Horvat *et al.* | |
| INADA | 13 | PL B722 301 | T. Inada *et al.* | |
| LATTANZI | 13 | PR D88 063528 | M. Lattanzi *et al.* | |
| MEYER | 13 | PR D87 035027 | M. Meyer, D. Horns, M. Raue | |
| MIZUMOTO | 13 | JCAP 1307 013 | T. Mizumoto *et al.* | |
| PARKER | 13 | PR D88 112004 | S. Parker *et al.* | |
| REDONDO | 13 | JCAP 1308 034 | J. Redondo, G. Raffelt | |
| TULLNEY | 13 | PRL 111 100801 | K. Tullney *et al.* | |
| VIAUX | 13A | PRL 111 231301 | N. Viaux *et al.* | |
| WOUTERS | 13 | APJ 772 44 | D. Wouters, P. Brun | (SACL) |
| ABLIKIM | 12 | PR D85 092012 | M. Ablikim *et al.* | (BESIII Collab.) |
| ARCHILLI | 12 | PL B706 251 | F. Archilli *et al.* | (KLOE-2 Collab.) |
| BELLI | 12 | PL B711 41 | P. Belli *et al.* | (DAMA-KIEV) |
| BELLINI | 12B | PR D85 092003 | G. Bellini *et al.* | (Borexino Collab.) |
| CADAMURO | 12 | JCAP 1202 032 | D. Cadamuro *et al.* | (MPIM) |
| CORSICO | 12 | JCAP 1212 010 | A.H. Corsico *et al.* | (LAPL, RGSUL, WASH+) |
| DERBIN | 12 | JETPL 95 339 | A.V. Derbin *et al.* | (PNPI) |
| | | Translated from ZETFP 95 379. | | |
| GANDO | 12 | PR C86 021601 | A. Gando *et al.* | (KamLAND-Zen Collab.) |
| GNINENKO | 12A | PR D85 055027 | S.N. Gninenko | (INRM) |
| GNINENKO | 12B | PL B713 244 | S.N. Gninenko | (INRM) |
| PAYEZ | 12 | JCAP 1207 041 | A. Payez *et al.* | (LIEG) |
| RAFFELT | 12 | PR D86 015001 | G. Raffelt | (MPIM) |

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| AALSETH | 11 | PRL 106 131301 | C.E. Aalseth *et al.* | (CoGeNT Collab.) |
| ABRAHAMY... | 11 | PRL 107 191804 | S. Abrahamyan *et al.* | |
| ARIK | 11 | PRL 107 261302 | M. Arik *et al.* | (CAST Collab.) |
| ARNOLD | 11 | PRL 107 062504 | R. Arnold *et al.* | (NEMO-3 Collab.) |
| BLUEMLEIN | 11 | PL B701 155 | J. Bluemlein, J. Brunner | (DESY) |
| CADAMURO | 11 | JCAP 1102 003 | D. Cadamuro *et al.* | (MPIM, AARHUS) |
| DERBIN | 11 | PAN 74 596 | A.V. Derbin *et al.* | (PNPI) |
| | | Translated from YAF 74 620. | | |
| DERBIN | 11A | PR D83 023505 | A.V. Derbin *et al.* | (PNPI) |
| HOEDL | 11 | PRL 106 041801 | S.A. Hoedl *et al.* | (WASH) |
| HOSKINS | 11 | PR D84 121302 | J. Hoskins *et al.* | (ADMX Collab.) |
| ANDRIAMON... | 10 | JCAP 1003 032 | S. Andriamonje *et al.* | (CAST Collab.) |
| ARGYRIADES | 10 | NP A847 168 | J. Argyriades *et al.* | (NEMO-3 Collab.) |
| ASZTALOS | 10 | PRL 104 041301 | S.J. Asztalos *et al.* | (ADMX Collab.) |
| EHRET | 10 | PL B689 149 | K. Ehret *et al.* | (ALPS Collab.) |
| HANNESTAD | 10 | JCAP 1008 001 | S. Hannestad *et al.* | |
| PETUKHOV | 10 | PRL 105 170401 | A.K. Petukhov *et al.* | |
| SEREBROV | 10 | JETPL 91 6 | A.P. Serebrov *et al.* | |
| | | Translated from ZETFP 91 8. | | |
| AHMED | 09A | PRL 103 141802 | Z. Ahmed *et al.* | (CDMS Collab.) |
| ANDRIAMON... | 09 | JCAP 0912 002 | S. Andriamonje *et al.* | |
| ARGYRIADES | 09 | PR C80 032501 | J. Argyriades *et al.* | (NEMO-3 Collab.) |
| ARIK | 09 | JCAP 0902 008 | E. Arik *et al.* | (CAST Collab.) |
| BJORKEN | 09 | PR D80 075018 | J. Bjorken *et al.* | |
| CHOU | 09 | PRL 102 030402 | A.S. Chou *et al.* | (GammeV Collab.) |
| DAVOUDIASL | 09 | PR D79 095024 | H. Davoudiasl, P. Huber | |
| DERBIN | 09A | PL B678 181 | A.V. Derbin *et al.* | |
| GONDOLO | 09 | PR D79 107301 | P. Gondolo, G. Raffelt | (UTAH, MPIM) |
| IGNATOVICH | 09 | EPJ C64 19 | V.K. Ignatovich, Y.N. Pokotilovski | (JINR) |
| KEKEZ | 09 | PL B671 345 | D. Kekez *et al.* | |
| SEREBROV | 09 | PL B680 423 | A.P. Serebrov | (PNPI) |
| AFANASEV | 08 | PRL 101 120401 | A. Afanasev *et al.* | |
| BELLINI | 08 | EPJ C54 61 | G. Bellini *et al.* | (Borexino Collab.) |
| CHOU | 08 | PRL 100 080402 | A.S. Chou *et al.* | (GammeV Collab.) |
| FOUCHE | 08 | PR D78 032013 | M. Fouche *et al.* | |
| HANNESTAD | 08 | JCAP 0804 019 | S. Hannestad *et al.* | |
| INOUE | 08 | PL B668 93 | Y. Inoue *et al.* | |
| ZAVATTINI | 08 | PR D77 032006 | E. Zavattini *et al.* | (PVLAS Collab.) |
| ADELBERGER | 07 | PRL 98 131104 | E.G. Adelberger *et al.* | |
| ANDRIAMON... | 07 | JCAP 0704 010 | S. Andriamonje *et al.* | (CAST Collab.) |
| BAESSLER | 07 | PR D75 075006 | S. Baessler *et al.* | |
| CHANG | 07 | PR D75 052004 | H.M. Chang *et al.* | (TEXONO Collab.) |
| HANNESTAD | 07 | JCAP 0708 015 | S. Hannestad *et al.* | |
| JAIN | 07 | JP G34 129 | P.L. Jain, G. Singh | |
| LESSA | 07 | PR D75 094001 | A.P. Lessa, O.L.G. Peres | |
| MELCHIORRI | 07A | PR D76 041303 | A. Melchiorri, O. Mena, A. Slosar | |
| ROBILLIARD | 07 | PRL 99 190403 | C. Robilliard *et al.* | |
| ARNOLD | 06 | NP A765 483 | R. Arnold *et al.* | (NEMO-3 Collab.) |
| DUFFY | 06 | PR D74 012006 | L.D. Duffy *et al.* | |
| HECKEL | 06 | PRL 97 021603 | B.R. Heckel *et al.* | |
| ZAVATTINI | 06 | PRL 96 110406 | E. Zavattini *et al.* | (PVLAS Collab.) |
| HANNESTAD | 05A | JCAP 0507 002 | S. Hannestad, A. Mirizzi, G. Raffelt | |
| ZIOUTAS | 05 | PRL 94 121301 | K. Zioutas *et al.* | (CAST Collab.) |
| ADLER | 04 | PR D70 037102 | S. Adler *et al.* | (BNL E787 Collab.) |
| ANISIMOVSK... | 04 | PRL 93 031801 | V.V. Anisimovsky *et al.* | (BNL E949 Collab.) |
| ARNOLD | 04 | JETPL 80 377 | R. Arnold *et al.* | (NEMO-3 Collab.) |
| | | Translated from ZETFP 80 429. | | |
| ASZTALOS | 04 | PR D69 011101 | S.J. Asztalos *et al.* | |
| HOFFMANN | 04 | PR B70 180503 | C. Hoffmann *et al.* | |
| ARNABOLDI | 03 | PL B557 167 | C. Arnaboldi *et al.* | |
| CIVITARESE | 03 | NP A729 867 | O. Civitarese, J. Suhonen | |
| DANEVICH | 03 | PR C68 035501 | F.A. Danevich *et al.* | |
| FARZAN | 03 | PR D67 073015 | Y. Farzan | (SLAC, SISSA) |
| ADLER | 02C | PL B537 211 | S. Adler *et al.* | (BNL E787 Collab.) |
| BADERT... | 02 | PL B542 29 | A. Badertscher *et al.* | |
| BERNABEI | 02D | PL B546 23 | R. Bernabei *et al.* | (DAMA Collab.) |
| DERBIN | 02 | PAN 65 1302 | A.V. Derbin *et al.* | |
| | | Translated from YAF 65 1335. | | |

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| FUSHIMI | 02 | PL B531 190 | K. Fushimi *et al.* | (ELEGANT V Collab.) |
| INOUE | 02 | PL B536 18 | Y. Inoue *et al.* | |
| MORALES | 02B | ASP 16 325 | A. Morales *et al.* | (COSME Collab.) |
| ADLER | 01 | PR D63 032004 | S. Adler *et al.* | (BNL E787 Collab.) |
| AMMAR | 01B | PRL 87 271801 | R. Ammar *et al.* | (CLEO Collab.) |
| ASHITKOV | 01 | JETPL 74 529 | V.D. Ashitkov *et al.* | |
| | | Translated from ZETFP 74 601. | | |
| BERNABEI | 01B | PL B515 6 | R. Bernabei *et al.* | (DAMA Collab.) |
| DANEVICH | 01 | NP A694 375 | F.A. Danevich *et al.* | |
| DEBOER | 01 | JP G27 L29 | F.W.N. de Boer *et al.* | |
| STOICA | 01 | NP A694 269 | S. Stoica, H.V. Klapdor-Kleingrothous | |
| ALESSAND... | 00 | PL B486 13 | A. Alessandrello *et al.* | |
| ARNOLD | 00 | NP A678 341 | R. Arnold *et al.* | |
| ASTIER | 00B | PL B479 371 | P. Astier *et al.* | (NOMAD Collab.) |
| DANEVICH | 00 | PR C62 045501 | F.A. Danevich *et al.* | |
| MASSO | 00 | PR D61 011701 | E. Masso | |
| ARNOLD | 99 | NP A658 299 | R. Arnold *et al.* | (NEMO Collab.) |
| NI | 99 | PRL 82 2439 | W.-T. Ni *et al.* | |
| SIMKOVIC | 99 | PR C60 055502 | F. Simkovic *et al.* | |
| ALTEGOER | 98 | PL B428 197 | J. Altegoer *et al.* | |
| ARNOLD | 98 | NP A636 209 | R. Arnold *et al.* | (NEMO-2 Collab.) |
| AVIGNONE | 98 | PRL 81 5068 | F.T. Avignone *et al.* | (Solar Axion Experiment) |
| DIAZ | 98 | NP B527 44 | M.A. Diaz *et al.* | |
| KIM | 98 | PR D58 055006 | J.E. Kim | |
| LUESCHER | 98 | PL B434 407 | R. Luescher *et al.* | |
| MORIYAMA | 98 | PL B434 147 | S. Moriyama *et al.* | |
| MOROI | 98 | PL B440 69 | T. Moroi, H. Murayama | |
| POSPELOV | 98 | PR D58 097703 | M. Pospelov | |
| AHMAD | 97 | PRL 78 618 | I. Ahmad *et al.* | (APEX Collab.) |
| BORISOV | 97 | JETP 83 868 | A.V. Borisov, V.Y. Grishinia | (MOSU) |
| DEBOER | 97C | JP G23 L85 | F.W.N. de Boer *et al.* | |
| KACHELRIESS | 97 | PR D56 1313 | M. Kachelriess, C. Wilke, G. Wunner | (BOCH) |
| KEIL | 97 | PR D56 2419 | W. Keil *et al.* | |
| KITCHING | 97 | PRL 79 4079 | P. Kitching *et al.* | (BNL E787 Collab.) |
| LEINBERGER | 97 | PL B394 16 | U. Leinberger *et al.* | (ORANGE Collab.) |
| ADLER | 96 | PRL 76 1421 | S. Adler *et al.* | (BNL E787 Collab.) |
| AMSLER | 96B | ZPHY C70 219 | C. Amsler *et al.* | (Crystal Barrel Collab.) |
| GANZ | 96 | PL B389 4 | R. Ganz *et al.* | (GSI, HEID, FRAN, JAGL+) |
| GUENTHER | 96 | PR D54 3641 | M. Gunther *et al.* | (MPIK, SASSO) |
| KAMEL | 96 | PL B368 291 | S. Kamel | (SHAMS) |
| MITSUI | 96 | EPL 33 111 | T. Mitsui *et al.* | (TOKY) |
| YOUDIN | 96 | PRL 77 2170 | A.N. Youdin *et al.* | (AMHT, WASH) |
| ALTMANN | 95 | ZPHY C68 221 | M. Altmann *et al.* | (TUM, LAPP, CPPM) |
| BASSOMPIE... | 95 | PL B355 584 | G. Bassompierre *et al.* | (LAPP, LCGT, LYON) |
| MAENO | 95 | PL B351 574 | T. Maeno *et al.* | (TOKY) |
| RAFFELT | 95 | PR D51 1495 | G. Raffelt, A. Weiss | (MPIM, MPIG) |
| SKALSEY | 95 | PR D51 6292 | M. Skalsey, R.S. Conti | (MICH) |
| TSUNODA | 95 | EPL 30 273 | T. Tsunoda *et al.* | (TOKY) |
| ADACHI | 94 | PR A49 3201 | S. Adachi *et al.* | (TMU) |
| ALTHERR | 94 | ASP 2 175 | T. Altherr, E. Petitgirard, T. del Rio Gaztelurrutia | |
| AMSLER | 94B | PL B333 271 | C. Amsler *et al.* | (Crystal Barrel Collab.) |
| ASAI | 94 | PL B323 90 | S. Asai *et al.* | (TOKY) |
| MEIJERDREES | 94 | PR D49 4937 | M.R. Drees *et al.* | (BRCO, OREG, TRIU) |
| NI | 94 | Physica B194 153 | W.T. Ni *et al.* | (NTHU) |
| VO | 94 | PR C49 1551 | D.T. Vo *et al.* | (ISU, LBL, LLNL, UCD) |
| ATIYA | 93 | PRL 70 2521 | M.S. Atiya *et al.* | (BNL E787 Collab.) |
| Also | | PRL 71 305 (errat.) | M.S. Atiya *et al.* | (BNL E787 Collab.) |
| ATIYA | 93B | PR D48 1 | M.S. Atiya *et al.* | (BNL E787 Collab.) |
| BASSOMPIE... | 93 | EPL 22 239 | G. Bassompierre *et al.* | (LAPP, TORI, LYON) |
| BECK | 93 | PRL 70 2853 | M. Beck *et al.* | (MPIK, KIAE, SASSO) |
| CAMERON | 93 | PR D47 3707 | R.E. Cameron *et al.* | (ROCH, BNL, FNAL+) |
| CHANG | 93 | PL B316 51 | S. Chang, K. Choi | |
| CHUI | 93 | PRL 71 3247 | T.C.P. Chui, W.T. Ni | (NTHU) |
| MINOWA | 93 | PRL 71 4120 | M. Minowa *et al.* | (TOKY) |
| NG | 93 | PR D48 2941 | K.W. Ng | (AST) |
| RITTER | 93 | PRL 70 701 | R.C. Ritter *et al.* | |
| TANAKA | 93 | PR D48 5412 | J. Tanaka, H. Ejiri | (OSAK) |
| ALLIEGRO | 92 | PRL 68 278 | C. Alliegro *et al.* | (BNL, FNAL, PSI+) |
| ATIYA | 92 | PRL 69 733 | M.S. Atiya *et al.* | (BNL, LANL, PRIN+) |
| BARABASH | 92 | PL B295 154 | L.S. Barabash *et al.* | (JINR, CERN, SERP+) |
| BERNATOW... | 92 | PRL 69 2341 | T. Bernatowicz *et al.* | (WUSL, TATA) |

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| BLUEMLEIN | 92 | IJMP A7 3835 | J. Bluemlein *et al.* | (BERL, BUDA, JINR+) |
| HALLIN | 92 | PR D45 3955 | A.L. Hallin *et al.* | (PRIN) |
| HENDERSON | 92C | PRL 69 1733 | S.D. Henderson *et al.* | (YALE, BNL) |
| HICKS | 92 | PL B276 423 | K.H. Hicks, D.E. Alburger | (OHIO, BNL) |
| LAZARUS | 92 | PRL 69 2333 | D.M. Lazarus *et al.* | (BNL, ROCH, FNAL) |
| MEIJERDREES | 92 | PRL 68 3845 | R. Meijer Drees *et al.* | (SINDRUM I Collab.) |
| PAN | 92 | MPL A7 1287 | S.S. Pan, W.T. Ni, S.C. Chen | (NTHU) |
| RUOSO | 92 | ZPHY C56 505 | G. Ruoso *et al.* | (ROCH, BNL, FNAL, TRST) |
| SKALSEY | 92 | PRL 68 456 | M. Skalsey, J.J. Kolata | (MICH, NDAM) |
| VENEMA | 92 | PRL 68 135 | B.J. Venema *et al.* | |
| WANG | 92 | MPL A7 1497 | J. Wang | (ILL) |
| WANG | 92C | PL B291 97 | J. Wang | (ILL) |
| WU | 92 | PRL 69 1729 | X.Y. Wu *et al.* | (BNL, YALE, CUNY) |
| AKOPYAN | 91 | PL B272 443 | M.V. Akopyan *et al.* | (INRM) |
| ASAI | 91 | PRL 66 2440 | S. Asai *et al.* | (ICEPP) |
| BERSHADY | 91 | PRL 66 1398 | M.A. Bershady, M.T. Ressell, M.S. Turner | (CHIC+) |
| BLUEMLEIN | 91 | ZPHY C51 341 | J. Bluemlein *et al.* | (BERL, BUDA, JINR+) |
| BOBRAKOV | 91 | JETPL 53 294 | V.F. Bobrakov *et al.* | (PNPI) |
| | | Translated from ZETFP 53 283. | | |
| BROSS | 91 | PRL 67 2942 | A.D. Bross *et al.* | (FNAL, ILL) |
| KIM | 91C | PRL 67 3465 | J.E. Kim | (SEOUL) |
| RAFFELT | 91 | PRPL 198 1 | G.G. Raffelt | (MPIM) |
| RAFFELT | 91B | PRL 67 2605 | G. Raffelt, D. Seckel | (MPIM, BART) |
| RESSELL | 91 | PR D44 3001 | M.T. Ressell | (CHIC, FNAL) |
| TRZASKA | 91 | PL B269 54 | W.H. Trzaska *et al.* | (TAMU) |
| TSERTOS | 91 | PL B266 259 | H. Tsertos *et al.* | (ILLG, GSI) |
| WALKER | 91 | APJ 376 51 | T.P. Walker *et al.* | (HSCA, OSU, CHIC+) |
| WIDMANN | 91 | ZPHY A340 209 | E. Widmann *et al.* | (STUT, GSI, STUTM) |
| WINELAND | 91 | PRL 67 1735 | D.J. Wineland *et al.* | (NBSB) |
| ALBRECHT | 90E | PL B246 278 | H. Albrecht *et al.* | (ARGUS Collab.) |
| ANTREASYAN | 90C | PL B251 204 | D. Antreasyan *et al.* | (Crystal Ball Collab.) |
| ASANUMA | 90 | PL B237 588 | T. Asanuma *et al.* | (TOKY) |
| ATIYA | 90 | PRL 64 21 | M.S. Atiya *et al.* | (BNL E787 Collab.) |
| ATIYA | 90B | PRL 65 1188 | M.S. Atiya *et al.* | (BNL E787 Collab.) |
| BAUER | 90 | NIM B50 300 | W. Bauer *et al.* | (STUT, VILL, GSI) |
| BURROWS | 90 | PR D42 3297 | A. Burrows, M.T. Ressell, M.S. Turner | (ARIZ+) |
| DEBOER | 90 | JP G16 L1 | F.W.N. de Boer, J. Lehmann, J. Steyaert | (LOUV) |
| ENGEL | 90 | PRL 65 960 | J. Engel, D. Seckel, A.C. Hayes | (BART, LANL) |
| GNINENKO | 90 | PL B237 287 | S.N. Gninenko *et al.* | (INRM) |
| GUO | 90 | PR D41 2924 | R. Guo *et al.* | (NIU, LANL, FNAL, CASE+) |
| HAGMANN | 90 | PR D42 1297 | C. Hagmann *et al.* | (FLOR) |
| JUDGE | 90 | PRL 65 972 | S.M. Judge *et al.* | (ILLG, GSI) |
| RAFFELT | 90D | PR D41 1324 | G.G. Raffelt | (MPIM) |
| RITTER | 90 | PR D42 977 | R.C. Ritter *et al.* | (UVA) |
| SEMERTZIDIS | 90 | PRL 64 2988 | Y.K. Semertzidis *et al.* | (ROCH, BNL, FNAL+) |
| TSUCHIAKI | 90 | PL B236 81 | M. Tsuchiaki *et al.* | (ICEPP) |
| TURNER | 90 | PRPL 197 67 | M.S. Turner | (FNAL) |
| BARABASH | 89 | PL B223 273 | A.S. Barabash *et al.* | (ITEP, INRM) |
| BINI | 89 | PL B221 99 | M. Bini *et al.* | (FIRZ, CERN, AARH) |
| BURROWS | 89 | PR D39 1020 | A. Burrows, M.S. Turner, R.P. Brinkmann | (ARIZ+) |
| Also | | PRL 60 1797 | M.S. Turner | (FNAL, EFI) |
| DEBOER | 89B | PRL 62 2639 | F.W.N. de Boer, R. van Dantzig | (ANIK) |
| ERICSON | 89 | PL B219 507 | T.E.O. Ericson, J.F. Mathiot | (CERN, IPN) |
| FAISSNER | 89 | ZPHY C44 557 | H. Faissner *et al.* | (AACH3, BERL, PSI) |
| FOX | 89 | PR C39 288 | J.D. Fox *et al.* | (FSU) |
| MAYLE | 89 | PL B219 515 | R. Mayle *et al.* | (LLL, CERN, MINN, FNAL+) |
| Also | | PL B203 188 | R. Mayle *et al.* | (LLL, CERN, MINN, FNAL+) |
| MINOWA | 89 | PRL 62 1091 | H. Minowa *et al.* | (ICEPP) |
| ORITO | 89 | PRL 63 597 | S. Orito *et al.* | (ICEPP) |
| PERKINS | 89 | PRL 62 2638 | D.H. Perkins | (OXF) |
| TSERTOS | 89 | PR D40 1397 | H. Tsertos *et al.* | (GSI, ILLG) |
| VANBIBBER | 89 | PR D39 2089 | K. van Bibber *et al.* | (LLL, TAMU, LBL) |
| WUENSCH | 89 | PR D40 3153 | W.U. Wuensch *et al.* | (ROCH, BNL, FNAL) |
| Also | | PRL 59 839 | S. de Panfilis *et al.* | (ROCH, BNL, FNAL) |
| AVIGNONE | 88 | PR D37 618 | F.T. Avignone *et al.* | (PRIN, SCUC, ORNL+) |
| BALKE | 88 | PR D37 587 | B. Balke *et al.* | (LBL, UCB, COLO, NWES+) |
| BJORKEN | 88 | PR D38 3375 | J.D. Bjorken *et al.* | (FNAL, SLAC, VPI) |
| BLINOV | 88 | SJNP 47 563 | A.E. Blinov *et al.* | (NOVO) |
| | | Translated from YAF 47 889. | | |

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| BOLTON | 88 | PR D38 2077 | R.D. Bolton *et al.* | (LANL, STAN, CHIC+) |
| Also | | PRL 56 2461 | R.D. Bolton *et al.* | (LANL, STAN, CHIC+) |
| Also | | PRL 57 3241 | D. Grosnick *et al.* | (CHIC, LANL, STAN+) |
| CHANDA | 88 | PR D37 2714 | R. Chanda, J.F. Nieves, P.B. Pal | (UMD, UPR+) |
| CHOI | 88 | PR D37 3225 | K. Choi *et al.* | (JHU) |
| CONNELL | 88 | PRL 60 2242 | S.H. Connell *et al.* | (WITW) |
| DATAR | 88 | PR C37 250 | V.M. Datar *et al.* | (IPN) |
| DEBOER | 88 | PRL 61 1274 | F.W.N. de Boer, R. van Dantzig | (ANIK) |
| Also | | PRL 62 2644 (errat.) | F.W.N. de Boer, R. van Dantzig | (ANIK) |
| Also | | PRL 62 2638 | D.H. Perkins | (OXF) |
| Also | | PRL 62 2639 | F.W.N. de Boer, R. van Dantzig | (ANIK) |
| DEBOER | 88C | JP G14 L131 | F.W.N. de Boer *et al.* | (LOUV) |
| DOEHNER | 88 | PR D38 2722 | J. Dohner *et al.* | (HEIDP, ANL, ILLG) |
| EL-NADI | 88 | PRL 61 1271 | M. el Nadi, O.E. Badawy | (CAIR) |
| ENGEL | 88 | PR C37 731 | J. Engel, P. Vogel, M.R. Zirnbauer | |
| FAISSNER | 88 | ZPHY C37 231 | H. Faissner *et al.* | (AACH3, BERL, SIN) |
| HATSUDA | 88B | PL B203 469 | T. Hatsuda, M. Yoshimura | (KEK) |
| LORENZ | 88 | PL B214 10 | E. Lorenz *et al.* | (MPIM, PSI) |
| MAYLE | 88 | PL B203 188 | R. Mayle *et al.* | (LLL, CERN, MINN, FNAL+) |
| PICCIOTTO | 88 | PR D37 1131 | C.E. Picciotto *et al.* | (TRIU, CNRC) |
| RAFFELT | 88 | PRL 60 1793 | G. Raffelt, D. Seckel | (UCB, LLL, UCSC) |
| RAFFELT | 88B | PR D37 549 | G.G. Raffelt, D.S.P. Dearborn | (UCB, LLL) |
| SAVAGE | 88 | PR D37 1134 | M.J. Savage, B.W. Filippone, L.W. Mitchell | (CIT) |
| TSERTOS | 88 | PL B207 273 | A. Tsertos *et al.* | (GSI, ILLG) |
| TSERTOS | 88B | ZPHY A331 103 | A. Tsertos *et al.* | (GSI, ILLG) |
| VANKLINKEN | 88 | PL B205 223 | J. van Klinken *et al.* | (GRON, GSI) |
| VANKLINKEN | 88B | PRL 60 2442 | J. van Klinken | (GRON) |
| VONWIMMER... | 88 | PRL 60 2443 | U. von Wimmersperg | (BNL) |
| VOROBYOV | 88 | PL B208 146 | P.V. Vorobiev, Y.I. Gitarts | (NOVO) |
| DRUZHININ | 87 | ZPHY C37 1 | V.P. Druzhinin *et al.* | (NOVO) |
| FRIEMAN | 87 | PR D36 2201 | J.A. Frieman, S. Dimopoulos, M.S. Turner | (SLAC+) |
| GOLDMAN | 87 | PR D36 1543 | T. Goldman *et al.* | (LANL, CHIC, STAN+) |
| KORENCHE... | 87 | SJNP 46 192<br>Translated from YAF 46 313. | S.M. Korenchenko *et al.* | (JINR) |
| MAIER | 87 | ZPHY A326 527 | K. Maier *et al.* | (STUT, GSI) |
| MILLS | 87 | PR D36 707 | A.P. Mills, J. Levy | (BELL) |
| RAFFELT | 87 | PR D36 2211 | G.G. Raffelt, D.S.P. Dearborn | (LLL, UCB) |
| RIORDAN | 87 | PRL 59 755 | E.M. Riordan *et al.* | (ROCH, CIT+) |
| TURNER | 87 | PRL 59 2489 | M.S. Turner | (FNAL, EFI) |
| VANBIBBER | 87 | PRL 59 759 | K. van Bibber *et al.* | (LLL, CIT, MIT+) |
| VONWIMMER... | 87 | PRL 59 266 | U. von Wimmersperg *et al.* | (WITW) |
| BADIER | 86 | ZPHY C31 21 | J. Badier *et al.* | (NA3 Collab.) |
| BROWN | 86 | PRL 57 2101 | C.N. Brown *et al.* | (FNAL, WASH, KYOT+) |
| BRYMAN | 86B | PRL 57 2787 | D.A. Bryman, E.T.H. Clifford | (TRIU) |
| DAVIER | 86 | PL B180 295 | M. Davier, J. Jeanjean, H. Nguyen Ngoc | (LALO) |
| DEARBORN | 86 | PRL 56 26 | D.S.P. Dearborn, D.N. Schramm, G. Steigman | (LLL+) |
| EICHLER | 86 | PL B175 101 | R.A. Eichler *et al.* | (SINDRUM Collab.) |
| HALLIN | 86 | PRL 57 2105 | A.L. Hallin *et al.* | (PRIN) |
| JODIDIO | 86 | PR D34 1967 | A. Jodidio *et al.* | (LBL, NWES, TRIU) |
| Also | | PR D37 237 (errat.) | A. Jodidio *et al.* | (LBL, NWES, TRIU) |
| KETOV | 86 | JETPL 44 146<br>Translated from ZETFP 44 114. | S.N. Ketov *et al.* | (KIAE) |
| KOCH | 86 | NC 96A 182 | H.R. Koch, O.W.B. Schult | (JULI) |
| KONAKA | 86 | PRL 57 659 | A. Konaka *et al.* | (KYOT, KEK) |
| MAIANI | 86 | PL B175 359 | L. Maiani, R. Petronzio, E. Zavattini | (CERN) |
| PECCEI | 86 | PL B172 435 | R.D. Peccei, T.T. Wu, T. Yanagida | (DESY) |
| RAFFELT | 86 | PR D33 897 | G.G. Raffelt | (MPIM) |
| RAFFELT | 86B | PL 166B 402 | G.G. Raffelt | (MPIM) |
| SAVAGE | 86B | PRL 57 178 | M.J. Savage *et al.* | (CIT) |
| AMALDI | 85 | PL 153B 444 | U. Amaldi *et al.* | (CERN) |
| ANANEV | 85 | SJNP 41 585<br>Translated from YAF 41 912. | V.D. Ananev *et al.* | (JINR) |
| BALTRUSAIT... | 85 | PRL 55 1842 | R.M. Baltrusaitis *et al.* | (Mark III Collab.) |
| BERGSMA | 85 | PL 157B 458 | F. Bergsma *et al.* | (CHARM Collab.) |
| KAPLAN | 85 | NP B260 215 | D.B. Kaplan | (HARV) |
| IWAMOTO | 84 | PRL 53 1198 | N. Iwamoto | (UCSB, WUSL) |
| YAMAZAKI | 84 | PRL 52 1089 | T. Yamazaki *et al.* | (INUS, KEK) |
| ABBOTT | 83 | PL 120B 133 | L.F. Abbott, P. Sikivie | (BRAN, FLOR) |
| CARBONI | 83 | PL 123B 349 | G. Carboni, W. Dahme | (CERN, MUNI) |
| CAVAIGNAC | 83 | PL 121B 193 | J.F. Cavaignac *et al.* | (ISNG, LAPP) |
| DICUS | 83 | PR D28 1778 | D.A. Dicus, V.L. Teplitz | (TEXA, UMD) |
| DINE | 83 | PL 120B 137 | M. Dine, W. Fischler | (IAS, PENN) |

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| ELLIS | 83B | NP B223 252 | J. Ellis, K.A. Olive | (CERN) |
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| FRANK | 83B | PR D28 1790 | J.S. Frank *et al.* | (LANL, YALE, LBL+) |
| HOFFMAN | 83 | PR D28 660 | C.M. Hoffman *et al.* | (LANL, ARZS) |
| PRESKILL | 83 | PL 120B 127 | J. Preskill, M.B. Wise, F. Wilczek | (HARV, UCSBT) |
| SIKIVIE | 83 | PRL 51 1415 | P. Sikivie | (FLOR) |
| Also | | PRL 52 695 (errat.) | P. Sikivie | (FLOR) |
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| FETSCHER | 82 | JP G8 L147 | W. Fetscher | (ETH) |
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| BARROSO | 81 | PL 106B 91 | A. Barroso, N.C. Mukhopadhyay | (SIN) |
| FAISSNER | 81 | ZPHY C10 95 | H. Faissner *et al.* | (AACH3) |
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