$<(1.4–10) \times 10^{-3}$	[132] ERICSON	89	ASTR	D,K, SN 1987A
$< 3.6 \times 10^{-4}$	[133] MAYLE	89	ASTR	D,K, SN 1987A
<12	CHANDA	88	ASTR	D, Sun
$< 1 \times 10^{-3}$	RAFFELT	88	ASTR	D,K, SN 1987A
	[134] RAFFELT	88B	ASTR	red giant
< 0.07	FRIEMAN	87	ASTR	D, red giant
< 0.7	[135] RAFFELT	87	ASTR	K, red giant
$< 2–5$	TURNER	87	COSM	K, thermal production
< 0.01	[136] DEARBORN	86	ASTR	D, red giant
< 0.06	RAFFELT	86	ASTR	D, red giant
< 0.7	[137] RAFFELT	86	ASTR	K, red giant
< 0.03	RAFFELT	86B	ASTR	D, white dwarf
< 1	[138] 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	[139] FUKUGITA	82	ASTR	D, stellar cooling
< 0.07	FUKUGITA	82B	ASTR	D, red giant

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

[126] 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.

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

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

[129] 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 2.5×10^{-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 $g_{AN} \sim 10^{-6}$.

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

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

[132] 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.

[133] 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.

[134] 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.

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

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

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

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

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

Search for Relic Invisible Axions

Limits are for $[G_{A\gamma\gamma}/m_{A^0}]^2 \rho_A$ where $G_{A\gamma\gamma}$ denotes the axion two-photon coupling, $L_{\rm int} = \frac{G_{A\gamma\gamma}}{4} \phi_A F_{\mu\nu} \widetilde{F}^{\mu\nu} = G_{A\gamma\gamma} \phi_A \mathbf{E} \cdot \mathbf{B}$, and ρ_A is the axion energy density near the earth.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<2 \times 10^{-41}$		[140] HAGMANN	90	CNTR	$m_{A^0} = (5.4–5.9)10^{-6}$ eV
$<1.3 \times 10^{-42}$	95	[141] WUENSCH	89	CNTR	$m_{A^0} = (4.5–10.2)10^{-6}$ eV
$<2 \times 10^{-41}$	95	[141] WUENSCH	89	CNTR	$m_{A^0} = (11.3–16.3)10^{-6}$ eV

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

[141] WUENSCH 89 looks for condensed axions near the earth that could be converted to photons in the presence of an intense electromagetic 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 axion-two-photon coupling $G_{A\gamma\gamma}$ defined by $L = G_{A\gamma\gamma} \phi_A \mathbf{E} \cdot \mathbf{B}$.
Related limits from astrophysics can be found in the "Invisible A^0 (Axion) Mass Limits from Astrophysics and Cosmology" section.

VALUE (GeV^{-1})	CL%	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3.6 \times 10^{-7}$	95	[142] CAMERON	93	$m_{A^0} < 10^{-3}$ eV, optical rotation
$<6.7 \times 10^{-7}$	95	[143] CAMERON	93	$m_{A^0} < 10^{-3}$ eV, photon regeneration
$<3.6 \times 10^{-9}$	99.7	[144] LAZARUS	92	$m_{A^0} < 0.03$ eV
$<7.7 \times 10^{-9}$	99.7	[144] LAZARUS	92	$m_{A^0} = 0.03–0.11$ eV
$<7.7 \times 10^{-7}$	99	[145] RUOSO	92	$m_{A^0} < 10^{-3}$ eV
$<2.5 \times 10^{-6}$		[146] SEMERTZIDIS	90	$m_{A^0} < 7 \times 10^{-4}$ eV

[142] Experiment based on proposal by MAIANI 86.

[143] Experiment based on proposal by VANBIBBER 87.

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

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

[146] 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 $G_{Aee} \partial_\mu \phi_A \overline{e} \gamma^\mu \gamma_5 e$ in GeV^{-1}, or equivalenty, the dipole-dipole potential $\frac{G^2_{Aee}}{4\pi}\ ((\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) - 3(\boldsymbol{\sigma}_1 \cdot \boldsymbol{n})\ (\boldsymbol{\sigma}_2 \cdot \boldsymbol{n}))/r^3$ where $\boldsymbol{n} = \boldsymbol{r}/r$.

The limits below apply to invisible axion of $m_A \leq 10^{-6}$ eV.

VALUE (GeV^{-1})	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<2.9 \times 10^{-5}$	95	[147] BOBRAKOV	91		Induced magnetism
$<1.9 \times 10^{-3}$	66	[148] WINELAND	91	NMR	
$<8.9 \times 10^{-4}$	66	[149] RITTER	90		Torsion pendulum
$<6.4 \times 10^{-5}$	95	[147] VOROBYOV	88		Induced magnetism

[147] 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.

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

[149] RITTER 90 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.

REFERENCES FOR Searches for Axions (A^0) and Other Very Light Bosons

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Also 93C PRL 71 305 (erratum) Atiya, Chiang, Frank, Haggerty, Igo+ (BNL 787 Collab.)
ATIYA 93B PR D48 R1 +Chiang, Frank, Haggerty, Ito+ (BNL 787 Collab.)
BASSOMPIE... 93 EPL 22 239 Bassompierre, Bologna+ (LAPP, TORI, LYON)
BECK 93 PRL 70 2853 +Bensch, Bockholt, Heusser, Hirsch+(MPIH, KIAE, SASSO)
CAMERON 93 PR D47 3707 +Cantatore, Melissinos+ (ROCH, BNL, FNAL, TRST)
MINOWA 93 PRL 71 4120 +Inoue, Asanuma, Imamura (TOKY)
NG 93 PR D48 2941 (AST)
TANAKA 93 PR D48 5412 +Ejiri (OSAK)
ALLIEGRO 92 PRL 68 278 +Campagnari+ (BNL, FNAL, PSI, WASH, YALE)
ATIYA 92 PRL 69 733 +Chiang, Frank, Haggerty, Ito+ (BNL, LANL, PRIN, TRIU)
BERNATOW... 92 PRL 69 2341 Bernatowicz, Brannon, Brazzle, Cowsik+ (WUSL, TATA)
BLUEMLEIN 92 IJMP A7 3835 +Brunner, Grabosch+ (BERL, BUDA, JINR, SERP)
HALLIN 92 PR D45 3955 +Calaprice, McPherson, Saettler (PRIN)
HENDERSON 92C PRL 69 1733 +Asoka-Kumar, Greenberg, Lynn+ (YALE, BNL)
HICKS 92 PL B276 423 +Alburger (OHIO, BNL)
LAZARUS 92 PRL 69 2333 +Smith, Cameron, Melissinos+ (BNL, ROCH, FNAL)
MEIJERDREES 92 PRL 68 3845 Meijer Drees, Waltham+ (SINDRIM I Collab.)
RUOSO 92 ZPHY C56 505 +Cameron, Cantatore+ (ROCH, BNL, FNAL, TRST)
SKALSEY 92 PRL 68 456 +Kolata (MICH, NDAM)
WANG 92 MPL A7 1497 (ILL)
WANG 92C PL B291 97 (ILL)
WU 92 PRL 69 1729 +Asoka-Kumar, Greenberg, Henderson+(BNL, YALE, CUNY)
AKOPYAN 91 PL B272 443 +Atoyan, Gninenko, Sukhov (INRM)
ASAI 91 PRL 66 2440 +Orito, Yoshimura, Haga (ICEPP)
BERSHADY 91 PRL 66 1398 +Ressell, Turner (CHIC, FNAL, EFI)
BLUEMLEIN 91 ZPHY C51 341 +Brunner, Grabosch+ (BERL, BUDA, JINR, SERP)
BOBRAKOV 91 JETPL 53 294 +Borisov, Lasakov, Serebrov, Tal'daev, Trofimova (PNPI)
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BROSS 91 PRL 67 2942 +Crisler, Pordes, Volk, Errede, Wrbanek (FNAL, ILL)
KIM 91C PRL 67 3465 (SEOUL)
RAFFELT 91B PRL 67 2605 +Seckel (MPIM, BART)
RESSELL 91 PR D44 3001 (CHIC, FNAL)
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WALKER 91 APJ 376 51 +Steigman, Schramm, Olive+ (HSCA, OSU, CHIC, MINN)
WIDMANN 91 ZPHY A340 209 +Bauer, Connell, Maier, Major+ (STUT, GSI, STUTM)
WINELAND 91 PRL 67 1735 +Bollinger, Heinzen, Itano, Raizen (NBSB)
ALBRECHT 90E PL B246 278 +Ehrlichmann, Harder, Krueger+ (ARGUS Collab.)
ANTREASYAN 90C PL B251 204 +Bartels, Besset, Bieler, Bienlein+ (Crystal Ball Collab.)
ASANUMA 90 PL B237 588 +Minowa, Tsukamoto, Orito, Tsunoda (TOKY)
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BURROWS 90 PR D42 3297 +Ressell, Turner (ARIZ, CHIC, FNAL)
DEBOER 90 JPG 16 L1 de Boer, Lehmann, Steyaert (LVLN)
ENGEL 90 PRL 65 960 +Seckel, Hayes (BART, LANL)
GNINENKO 90 PL B237 287 +Klubakov, Poblaguev, Postoev (INRM)
GUO 90 PR D41 2924 +Kaplan, Alde+ (NIU, LANL, FNAL, CASE, TEXA)
HAGMANN 90 PR D42 1297 +Sikivie, Sullivan, Tanner (FLOR)
JUDGE 90 PRL 65 972 +Krusche, Schreckenbach, Tsertos, Kienle (ILLG, GSI)
RAFFELT 90C PRPL 198 1 (MPIM)
RAFFELT 90D PR D41 1324 (MPIM)
RITTER 90 PR D42 977 +Goldblum, Ni, Gillies, Speake (VIRG)
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TSUCHIAKI 90 PL B236 81 +Orito, Yoshida, Minowa (ICEPP)
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FISHER 89 PL B218 257 +Boehm, Bovet, Egger+ (CIT, NEUC, PSI)
FOX 89 PR C39 288 +Kemper, Cottle, Zingarelli (FSU)
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