constructed by identifying f_A with other large mass scales such as the Planck mass, the GUT scale, the SUSY-breaking scale, and so on. It has been found, however, that invisible axions are not completely elusive. Cosmological considerations on the matter density of our universe suggest [10] $f_A < \mathcal{O}(10^{12})$ GeV as a possible upper bound on the scale. Lower bounds of $f_A > \mathcal{O}(10^7)$ GeV are obtained from astrophysics [11], where axion emission from the center of stellar objects can speed up their evolutionary time scales. The recent observation of the supernova SN1987A improves the lower bound to $f_A > \mathcal{O}(10^{10})$ GeV. Various terrestrial experiments to detect invisible axions by making use of their coupling to photons have been proposed [12], and the first result of such experiments appeared recently.

Observation of a narrow-peak structure in positron spectra from heavy ion collisions [13] suggested a particle of mass 1.8 MeV that decays into e^+e^-. Variants of the original axion model, which keep $f_A = v$, but drop the constraints of tree-level flavor conservation, were proposed [14]. Extensive searches for this particle, A^0(1.8 MeV), ended up with another negative result [6].

There is also a Note on invisible axions later in this section.

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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).

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>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 γ-ray line from the sun.
[2] Lower bound from requiring the red giants' stellar evolution not be disrupted by axion emission.

A^0 (Axion) and Other Light Boson (X^0) Searches in Stable Particle Decays

Limits are for branching ratios.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<1.7 \times 10^{-9}$	90		[3] ATIYA	93	CNTR	$K^+ \to \pi^+ A^0$
$<2 \times 10^{-7}$	90		[4] ATIYA	93B	CNTR	$K^+ \to \pi^+ A^0$
$<3 \times 10^{-13}$			[5] NG	93	COSM	$\pi^0 \to \gamma X^0$
$<1.1 \times 10^{-8}$	90		[6] ALLIEGRO	92	CALO	$K^+ \to \pi^+ A^0$ $(A^0 \to e^+e^-)$
$<5 \times 10^{-4}$	90		[7] ATIYA	92	CNTR	$\pi^0 \to \gamma X^0$
$<4 \times 10^{-6}$	90		[8] MEIJERDREES	92	SPEC	$\pi^0 \to \gamma X^0$, $X^0 \to e^+e^-$, m_{X^0}= 100 MeV
$<1 \times 10^{-7}$	90		[9] ATIYA	90B	CNTR	$K^+ \to \pi^+ A^0$, $(A^0 \to \gamma\gamma)$
$<1.3 \times 10^{-8}$	90		[10] KORENCHE...	87	SPEC	$\pi^+ \to e^+ \nu A^0$ $(A^0 \to e^+e^-)$
$<1 \times 10^{-9}$	90	0	[11] EICHLER	86	SPEC	Stopped $\pi^+ \to e^+ \nu A^0$
$<2 \times 10^{-5}$	90		[12] YAMAZAKI	84	SPEC	For 160<m<260 MeV
$<(1.5–4) \times 10^{-6}$	90		[12] YAMAZAKI	84	SPEC	K decay, $m_{A^0} \ll$ 100 MeV
		0	[13] ASANO	82	CNTR	Stopped $K^+ \to \pi^+ A^0$
		0	[14] ASANO	81B	CNTR	Stopped $K^+ \to \pi^+ A^0$
			[15] ZHITNITSKII	79		Heavy axion

[3] ATIYA 93 looked for a peak in missing mass distribution. The limit is for massless stable A^0 particles and extends to m_{A^0}=80 MeV at the same level. See paper for dependence on finite lifetime.
[4] ATIYA 93B looked for a peak in missing mass distribution. The bound applies for stable A^0 of m_{A^0}=150–250 MeV, and the limit becomes stronger (10^{-8}) for m_{A^0}=180–240 MeV.
[5] NG 93 studied the production of X^0 via $\gamma\gamma \to \pi^0 \to \gamma X^0$ in the early universe at $T \simeq 1$ MeV. The bound on extra neutrinos from nucleosyntheis $\Delta N_\nu < 0.3$ (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.
[6] ALLIEGRO 92 limit applies for m_{A^0}=150–340 MeV, and B($A^0 \to e^+e^-$)=100% assumed. Limit is $< 1.5 \times 10^{-8}$ at 99%CL.
[7] 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.
[8] MEIJERDREES 92 limit applies for $\tau_{X^0} = 10^{-23}$–10^{-11} sec. Limits between 2×10^{-4} and 4×10^{-6} are obtained form m_{X^0} = 25–120 MeV. Angular momentum conservation requires that X^0 has spin ≥ 1.
[9] ATIYA 90B limit is for B($K^+ \to \pi^+ A^0$)·B($A^0 \to \gamma\gamma$) and applies for $m_{A^0} = 50$ MeV, $\tau_{A^0} < 10^{-10}$ s. Limits are also provided for $0 < m_{A^0} < 100$ MeV, $\tau_{A^0} < 10^{-8}$ s.
[10] KORENCHENKO 87 limit assumes $m_{A^0} = 1.7$ MeV, $\tau_{A^0} \lesssim 10^{-12}$ s, and B($A^0 \to e^+e^-$) = 1.
[11] EICHLER 86 looked for $\pi^+ \to e^+ \nu A^0$ followed by $A^0 \to e^+e^-$. 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.
[12] YAMAZAKI 84 looked for a discrete line in $K^+ \to \pi^+$X. Sensitive to wide mass range (5–300 MeV), independent of whether X decays promptly or not.