Search for monoenergetic solar axions with the CAST experiment

Krešimir Jakovčić

(Rudjer Bošković Institute, Zagreb)

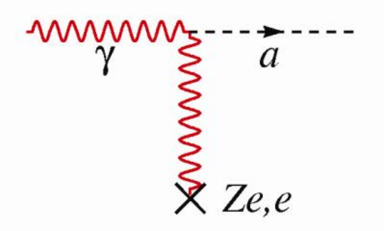
for the

CAST Collaboration

5th Patras Workshop on Axions, WIMPs and WISPs, 13-17 July 2009,
Durham, UK

"Primakoff" solar axions

- produced by the Primakoff conversion of thermal photons in the solar plasma :

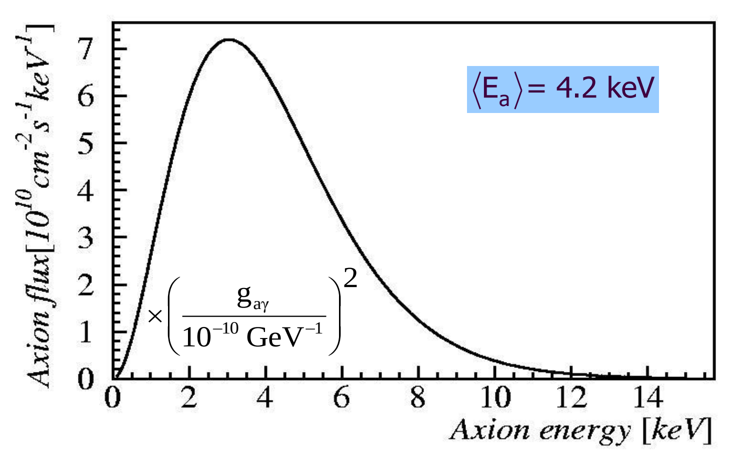


- based on the axion-photon coupling :

$$L_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma}\, \vec{E} \cdot \vec{B}\, a$$

- expected spectrum :

$$\frac{d\Phi_a}{dE_a} = 6.02 \times 10^{10}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{keV}^{-1} \left(\frac{g_{a\gamma}}{10^{-10}\ \mathrm{GeV}^{-1}}\right)^2 \left(\frac{E_a}{\mathrm{keV}}\right)^{2.481} e^{-E_a/1.205\,\mathrm{keV}}$$



Axion emission from the nuclear deexcitation

- additional production channel for solar axions
- based on axion-nucleon coupling

$$L_{\mathrm{aN}} = i\, a\, \bar{\psi}_{\mathrm{N}} \gamma_5 \left(g^0_{\mathrm{aN}} + g^3_{\mathrm{aN}} \tau_3\right) \psi_{\mathrm{N}}$$

$$g^0_{\mathrm{aN}} = -\frac{m_{\mathrm{N}}}{f_{\mathrm{a}}} \frac{1}{6} \left[2S + (3F - D) \frac{1 + z - 2w}{1 + z + w} \right]$$

$$g^3_{\mathrm{aN}} = -\frac{m_{\mathrm{N}}}{f_{\mathrm{a}}} \frac{1}{2} (D + F) \frac{1 - z}{1 + z + w}$$

$$\left.\begin{array}{l} F = 0.462 \\ D = 0.808 \end{array}\right\}$$ matrix elements of the SU(3) octet axial vector currents

$S = (-0.09 - 0.68)$ - flavor singlet axial vector matrix element

$z = m_u / m_d = (0.3 – 0.6)$

$w = m_u / m_s \approx 0.028$

- an excited nucleus could deexcite via emission of an axion $(J^{\pi}{}_{\text{axion}} = 0^-, 1^+, 2^-, \ldots)$

  → axions could be emitted in magnetic nuclear transitions

  → monoenergetic axions $(E_{\text{a}} = E_{\text{transition}})$

- excitation of nuclei in the Sun (kT ~ 1.3 keV) :
  - thermal excitation : ^{57}Fe (14.4 keV) , ^{83}Kr (9.4 keV)
  - nuclear reaction : $^{7}\text{Be} + e^- \rightarrow {}^{7}\text{Li}^*$ (478 keV) $+ \nu_e$

^{57}Fe as a solar axion emitter

^{57}Fe could be a suitable emitter of 14.4 keV solar axions:

- exceptionally abundant among heavy elements in the Sun
  (solar abundance by mass fraction 2.8×10^{-5})
- the first excitation energy is 14.4 keV – not too high to be thermally excited in the Sun ($T_{\mathrm{Sun}} \sim 1.3$ keV)
- M1 transition between the first excited state and the ground state

→ strong emission of 14.4 keV axions is expected from this nucleus

- total ^{57}Fe solar axion flux expected at the Earth :

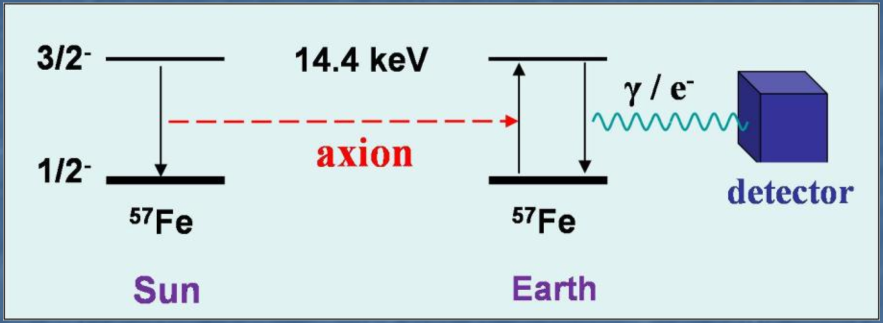
$$\boxed{\Phi_{\mathrm{a}} = 4.56\times10^{23}(g_{\mathrm{aN}}^{\mathrm{eff}})^2 \ \ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}}$$

where

$$\boxed{g_{\mathrm{aN}}^{\mathrm{eff}} \equiv (-1.19 g_{\mathrm{aN}}^{0} + g_{\mathrm{aN}}^{3})}$$

Detection of monoenergetic solar axions

- Resonant absorption

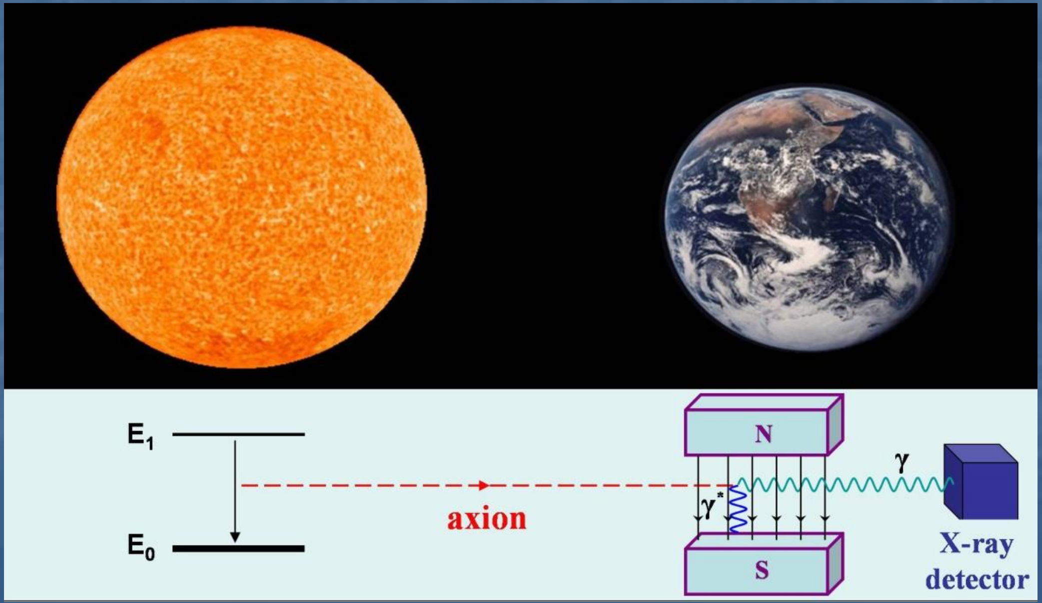


Axions	Document ID	Target mass	Detector	Upper limit
^{57}Fe	Krčmar et al., Phys. Lett. B 442 (1998) 38	31.5 mg	Si (Li)	$m_a < 745$ eV
	Derbin et al., JETP Lett. 85 (2007) 12	13.3 mg	Si (Li)	$m_a < 360$ eV
	Namba T., Phys. Lett. B 645 (2007) 398	197 mg	Si PIN	$m_a < 216$ eV
	Derbin et al., arXiv:0906.0256 (2009)	263 mg	Si (Li)	$m_a < 151$ eV
^{83}Kr	Krečak et al., Rad. Phys. Chem. 71 (2004) 793	193 mg	Prop.count.	$m_a < 5.5$ keV
^{7}Li	Krčmar et al., Phys. Rev. D 64 (2001) 115016	56.7 g	HPGe	$m_a < 32$ keV
	Derbin et al., JETP Lett. 81 (2005) 365	1.1 kg	HPGe	$m_a < 16$ keV
	Belli et al., Nucl. Phys. A 806 (2008) 388	243 g	HPGe	$m_a < 13.9$ keV

- axion-electron interaction
  - axioelectric process : $a + e^- + Z \rightarrow e^- + Z$
  - Compton conversion : $a + e^- \rightarrow e^- + \gamma$

^{57}Fe axions	Kekez et al., Phys. Lett. B 599 (2004) 143	$m_a < 400$ eV
^{7}Li axions	G. Bellini et al. (Borexino Coll.), Eur. Phys. J. C 54 (2008) 61	$g_{ae}(g^0_{aN} + g^3_{aN}) < 1.0\times10^{-10}$ for $m_a < 100$ keV

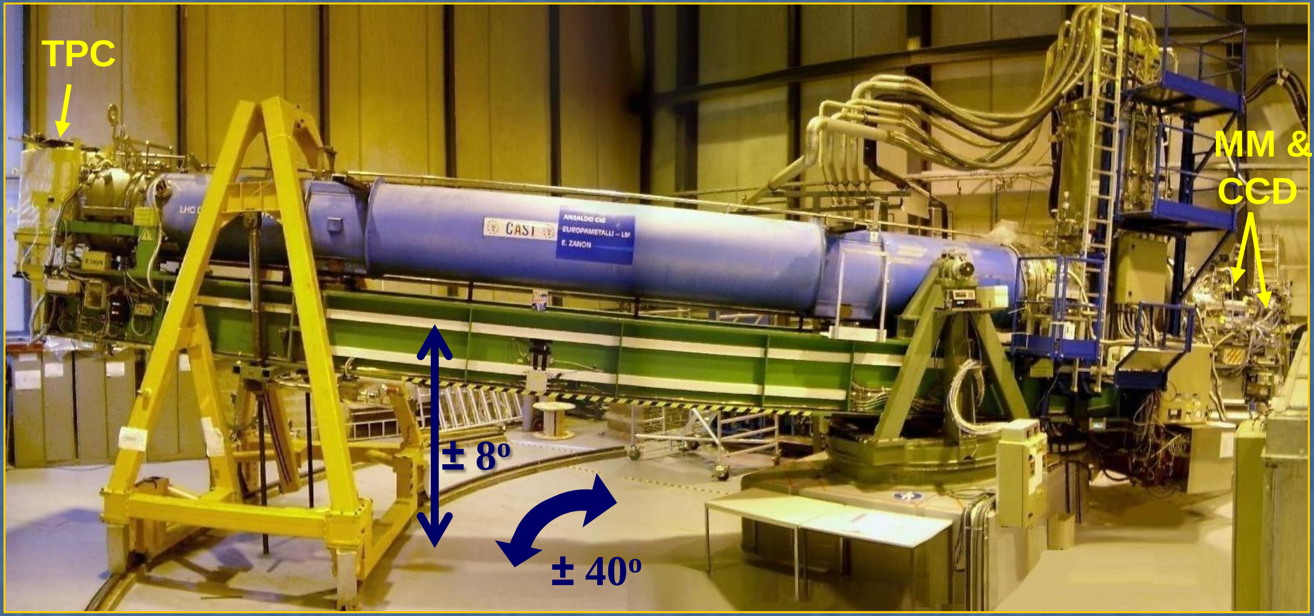
- axion helioscope method



Search for ^{57}Fe solar axions with CAST

[arXiv:0906.4488]

- Phase I setup (vacuum inside magnet bores)



LHC test magnet
(B=9 T, L=9.26 m)

Sun tracking time:
2×1.5h per day

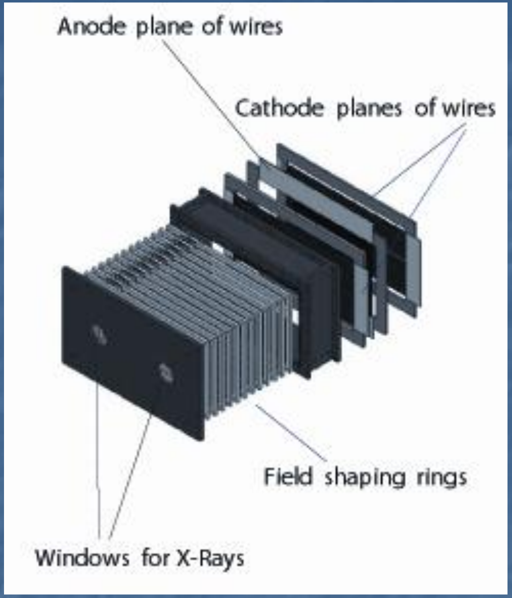
- conversion probability :

$$P_{a\to\gamma} = \left(\frac{g_{a\gamma} BL}{2}\right)^2 \frac{4}{q^2 L^2} \sin^2\left(\frac{qL}{2}\right)$$

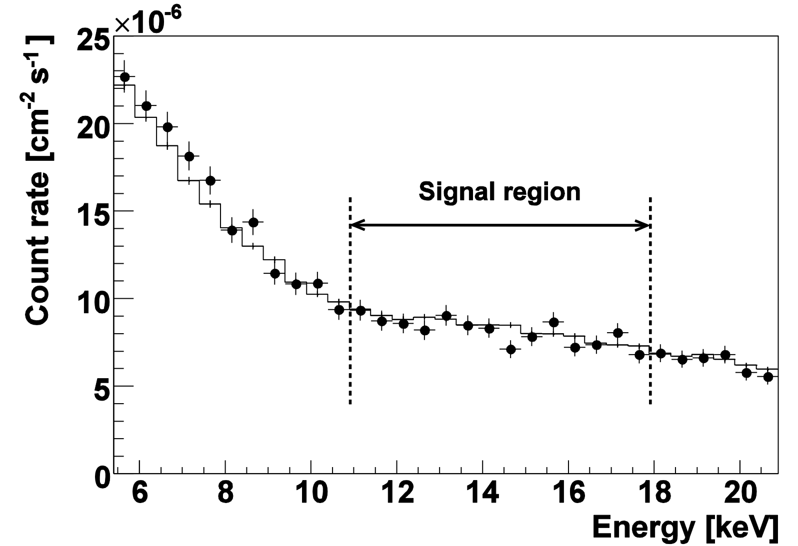
$$q = \frac{m_a^2}{2E_a}$$

axion-photon
momentum transfer

- CAST TPC detector
  - Covering both magnet bores
  - Geometry: 30cm ×15cm ×10cm
  - Gas: Ar 95% + CH_4 5%
  - Resolution @14.4 keV: 1.77 keV
  - Efficiency @14.4 keV : 13%

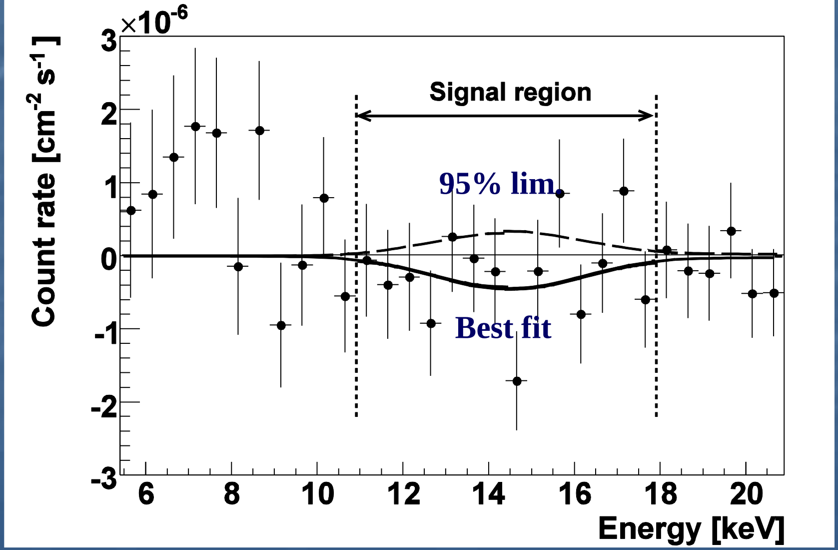


- 2819 effective hours of data-taking
  - tracking data : 203 hours
  - background data : 2616 hours



- expected number of detected 14.4 keV photons :

$$\boxed{N_s = \Phi_a P_{a\rightarrow\gamma} S\, t\, \varepsilon_{14.4}}$$

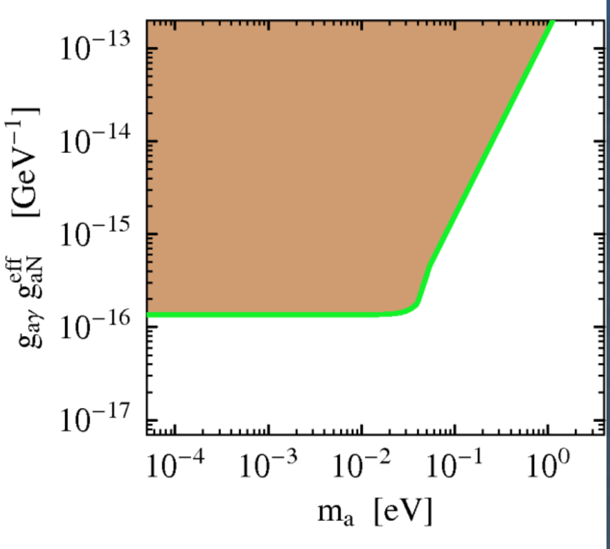


- Best fit value : $N_s = -42 \pm 27$ counts

→ No signal for ^{57}Fe solar axions

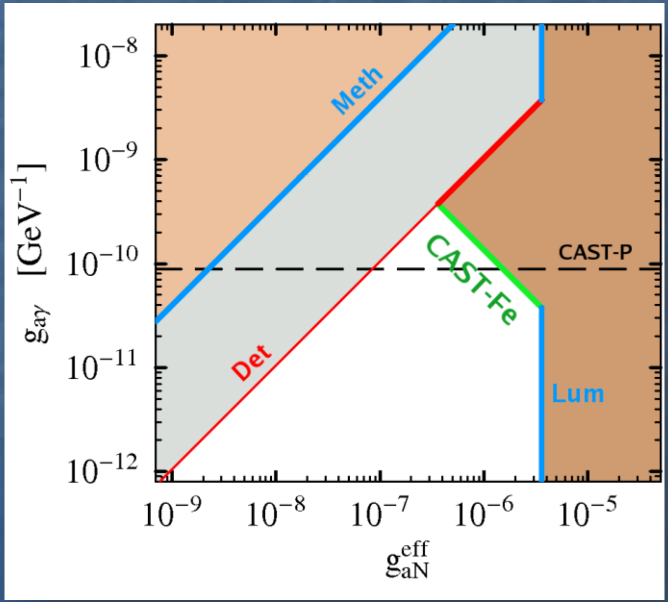
→ 95% CL upper limit : $N_s < 32$ counts

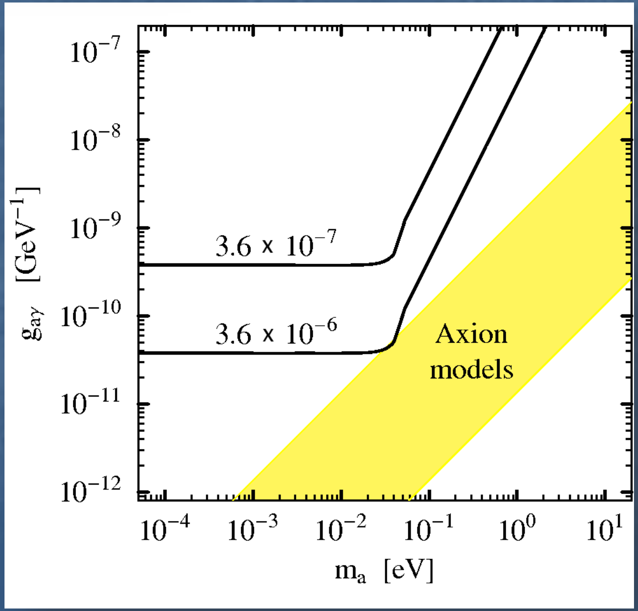
Results :



$$g_{a\gamma} g_{aN}^{eff} < 1.36\times10^{-16}\ \mathrm{GeV}^{-1}$$

for $m_a < 0.03$ eV





Search for high-energy axions with CAST

[arXiv:0904.2103]

1) $^{7}\mathrm{Li}^{*} \rightarrow {}^{7}\mathrm{Li} + a$ (478 keV)

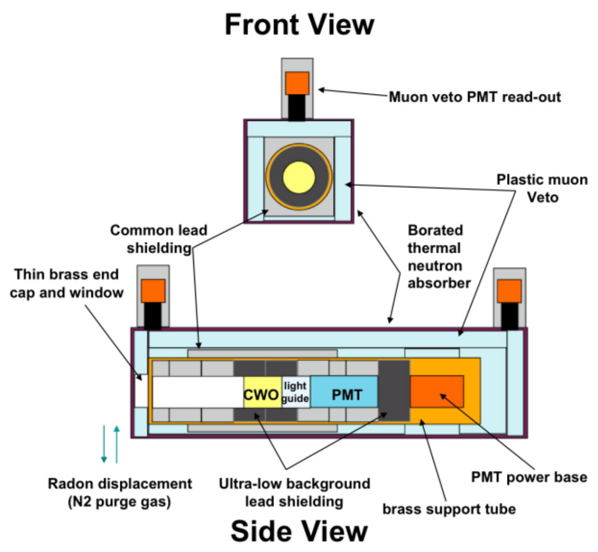
$^{7}\mathrm{Be} + e^{-} \rightarrow {}^{7}\mathrm{Li}^{*} + \nu_e$

$$\boxed{\Phi_a^{Li} \simeq 10^{-15}\ \Phi_a^{Fe}}$$

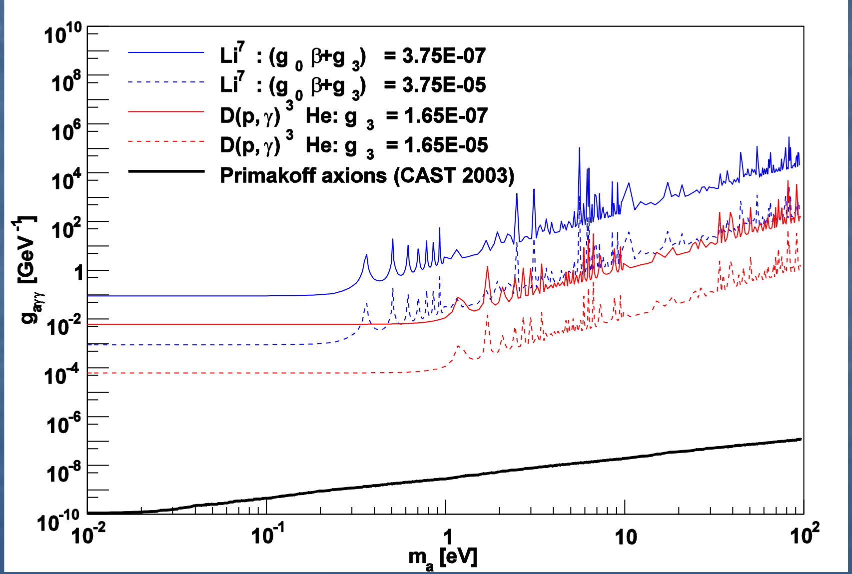
2) $p + d \rightarrow {}^{3}\mathrm{He} + a$ (5.5 MeV)

$$\boxed{\Phi_a^{pd} \simeq 10^{-13}\ \Phi_a^{Fe}}$$

Calorimeter :



Results :



Conclusions

- The first implementation of the axion helioscope method to search for monoenergetic solar axions :

  14.4 keV (^{57}Fe), 478 keV (^{7}Li), and 5.5 MeV (p+d)

- No axion signal was found

- Model-independent limits on $g_{a\gamma}$ and g_{aN} for $m_a < 0.03$ eV were set

- Backup slides

- differential ^{57}Fe solar axion flux expected at the Earth :

$$\frac{d\Phi_a(E_a)}{dE_a} = \frac{1}{4\pi d_E^2}\int_0^{R_S} N_a \underbrace{\frac{1}{\sqrt{2\pi}\,\sigma(T)}\, e^{-\frac{(E_a-E_1)^2}{2\sigma(T)^2}}}_{\text{Doppler broadening}} \rho(r)\; 4\pi r^2 dr$$

^{57}Fe axion emission rate per 1 g of solar matter

$$N_a = N_{^{57}\mathrm{Fe}}\,\frac{(2J_1+1)e^{-E_1/kT}}{(2J_0+1)+(2J_1+1)e^{-E_1/kT}}\,\frac{1}{\tau_\gamma}\,\frac{\Gamma_a}{\Gamma_\gamma}$$

$$\sigma(T) = E_1\sqrt{\frac{kT}{m_{\mathrm{Fe}}}} \longrightarrow \text{FWHM} \approx 5\ \text{eV}$$

for ^{57}Fe nucleus:

$N_{^{57}\mathrm{Fe}} = 3.0\times 10^{17}\,\mathrm{g}^{-1}$

$J_0 = 1/2 \qquad J_1 = 3/2$

$\tau_\gamma = 1.3\times 10^{-6}\,\mathrm{s}$

$\beta = -1.19 \qquad \eta = 0.8$

$$\frac{\Gamma_a}{\Gamma_\gamma} = \left(\frac{k_a}{k_\gamma}\right)^3 \frac{1}{2\pi\alpha}\left[\frac{g_{aN}^0\beta + g_{aN}^3}{(\mu_0 - 1/2)\beta + \mu_3 - \eta}\right]^2$$

$k_a = \sqrt{E_a^2 - m_a^2} \approx k_\gamma \qquad \mu_0 = 0.88 \qquad \mu_3 = 4.71$

$\Phi_a = 4.56\times 10^{23}\,(g_{aN}^{\mathrm{eff}})^2\ \ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ where $g_{aN}^{\mathrm{eff}} \equiv (-1.19\,g_{aN}^0 + g_{aN}^3)$