Searching for Solar WISPs with Annual Modulation in ANAIS-112

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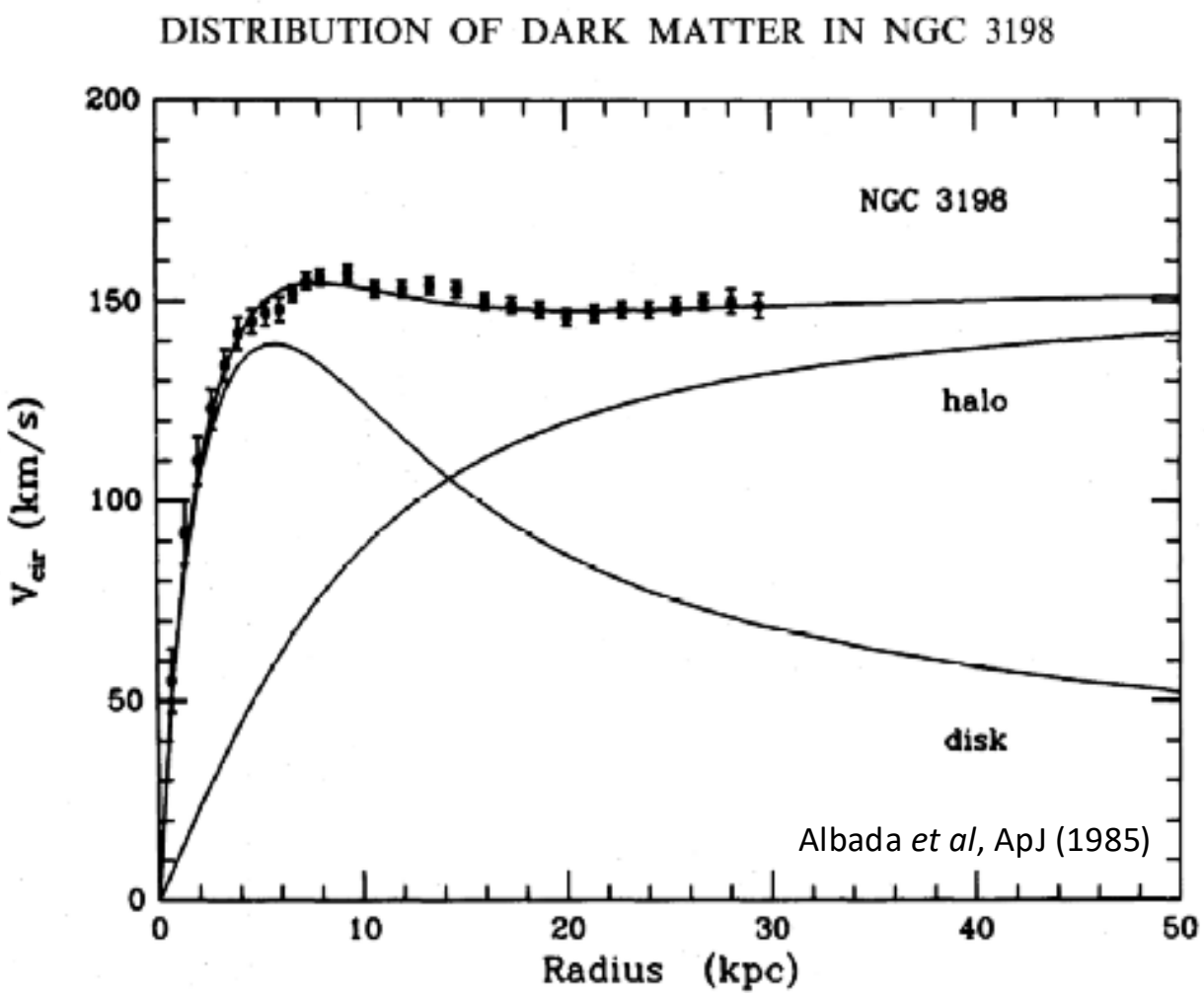
Universidad Zaragoza
1542
CAPA Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

Galactic Rotation Curves



- Stars at the galaxy's edge orbit faster than predicted by matter from the disk
- Dark matter needed to keep the stars from escaping

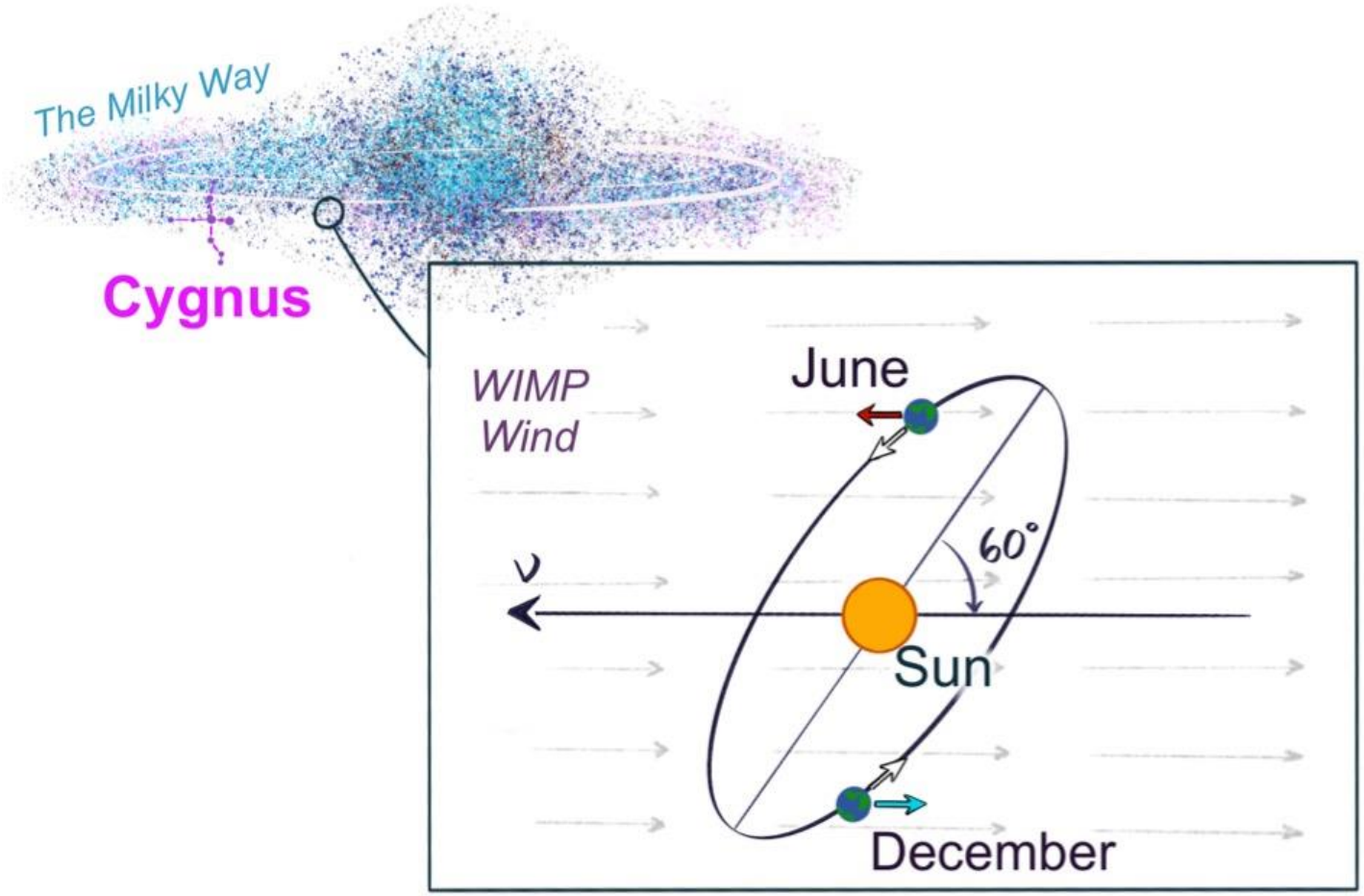
Annual Modulation Signature

Local dark matter distribution is assumed isotropic/uniform

Sun orbits galactic center, travelling through a dark matter wind

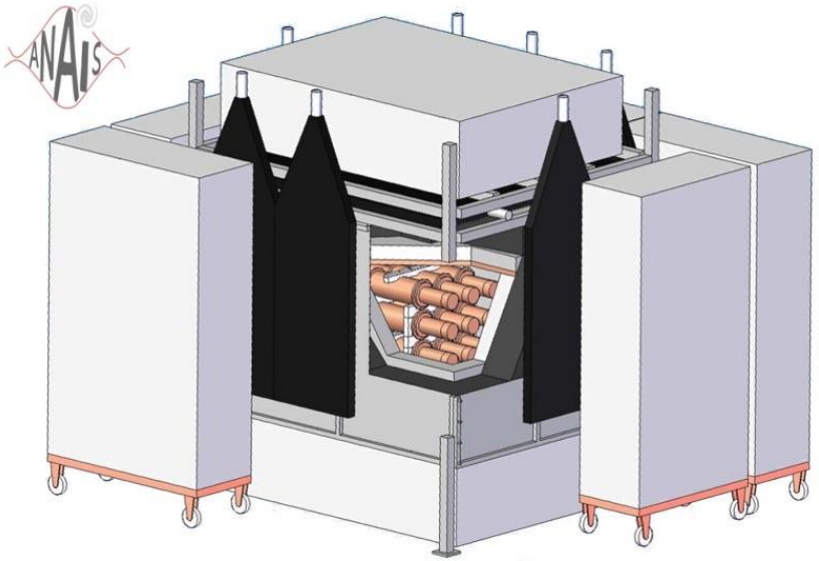
Earth orbits Sun, varying the

Fastest "wind" on **June 2 (Today!)**



K. Freese et.al.
PRD 33 (1986) 3495–3508.

The ANAIS-112 Experimental Program



Location: Laboratorio Subterraneo Canfranc (LSC)

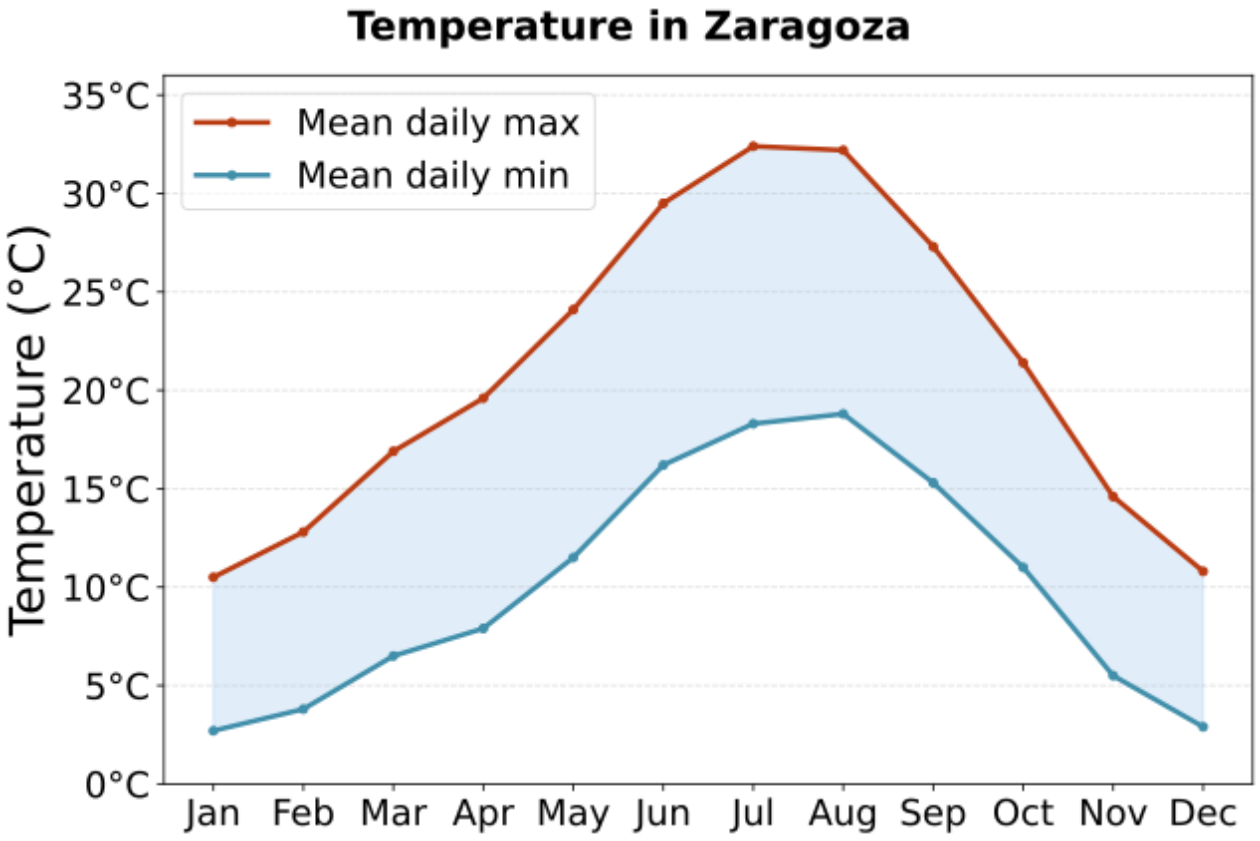
Science Program:
Annual modulation search for SHM dark matter with NaI

Detectors: 9 cylindrical NaI(Tl) scintillating crystals

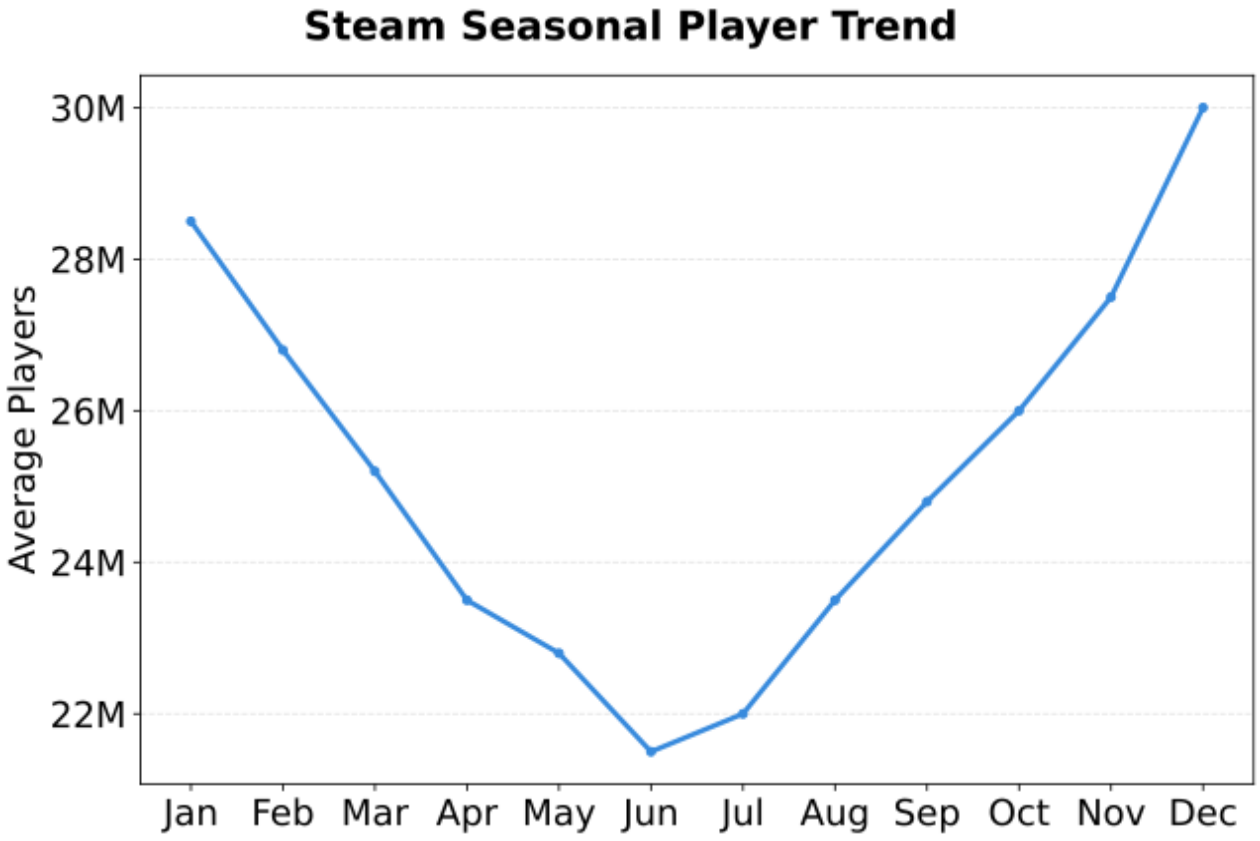
Data Taking:
August 2017 – January 2026

Boulby:
• NAIAD
Canfranc:
• ANAIS-112
• ANAIS+
Gran Sasso:
• DAMA/LIBRA
• COSINUS
• SABRE-North
Yangyang:
• KIMS
• COSINE-100
Yemilab:
• COSINE-100U
• COSINE-200
Kamioka:
• PICOLON
Stawell:
• SABRE-South
South Pole:
• DM-Ice17
Operating/Finished Experiments
Proposed Experiments

Annually Modulating Things



Data: AEMET 1991–2020 normals, climate Ebro valley.

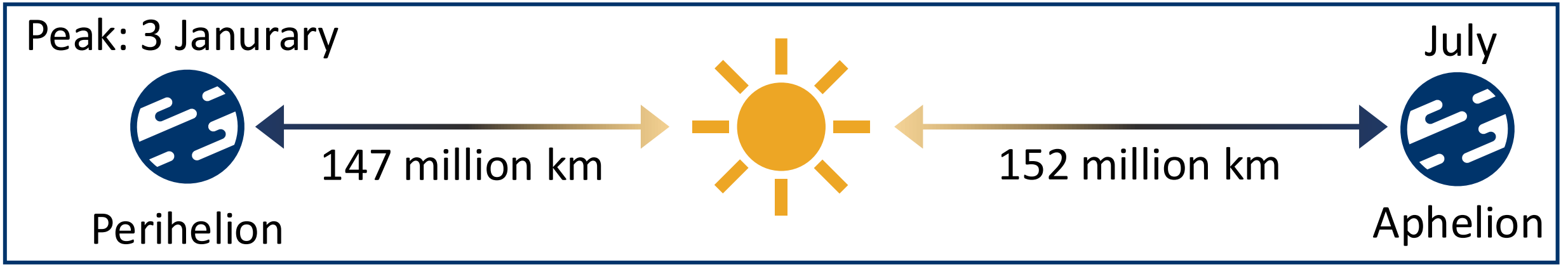


Data: steamdb

Many things modulate, but at different phases

Let's take advantage of this

Annual Modulation to Search for Solar Particles



$$S(t_i) = A\left(\cos(\omega(t_i - t_0)) + \frac{3}{2}\epsilon\cos^2(\omega(t_i - t_0))\right)$$

$$A = \frac{1}{2}\left(\frac{R_a}{(1-\epsilon)^2} - \frac{R_a}{(1+\epsilon)^2}\right)$$

$$\epsilon = 0.0167$$

When distance is 149.5 million km

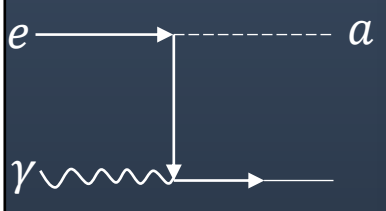
Rate of Axions:

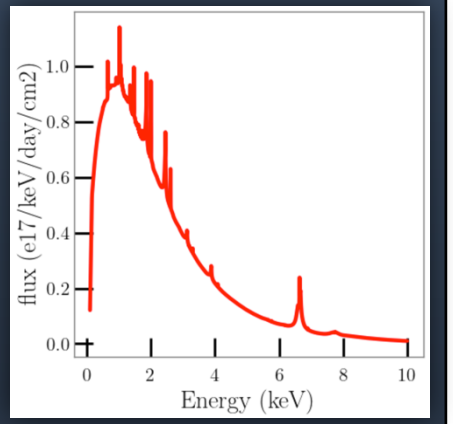
R_a depends on the production and detection mechanisms assumed

Solar Axion Production Mechanisms

ABC Processes

Atomic de-excitation, Bremmstralung, and Compton-like processes of electron with axions





g_{ae}^2

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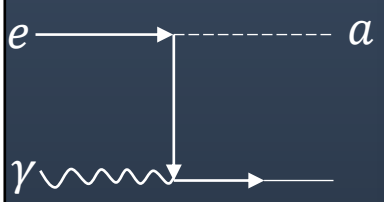
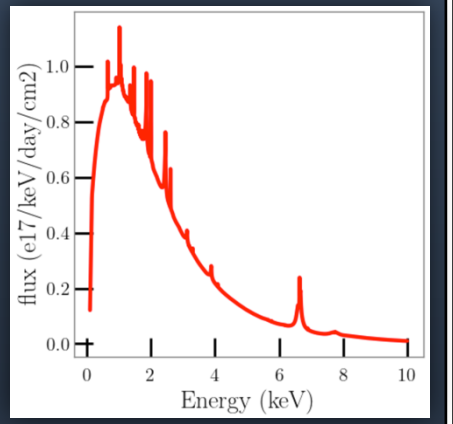
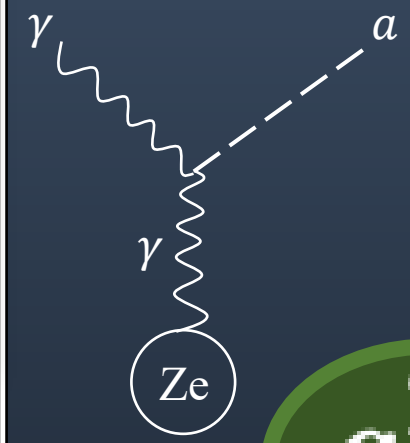


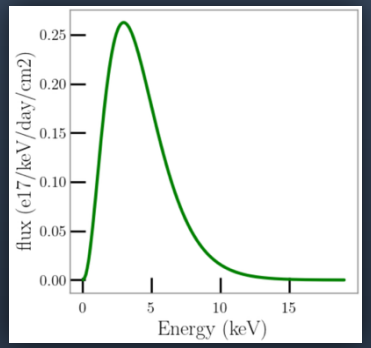


g_{ae}^2

Primakoff Effect

Photons convert into axions in the presence of solar magnetic field, peaks at 3 keV





$g_{a\gamma}^2$

Solar Axion Production Mechanisms

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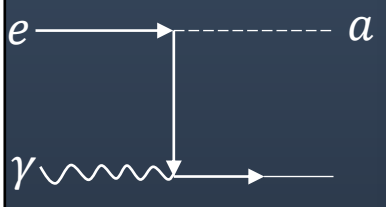

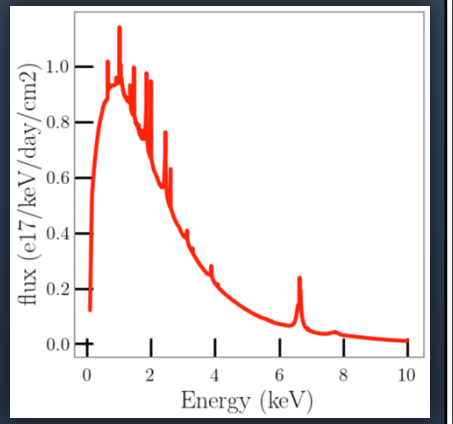

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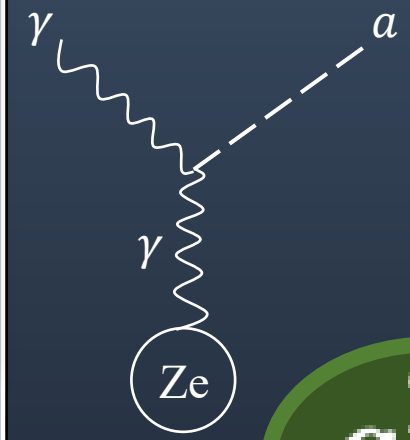
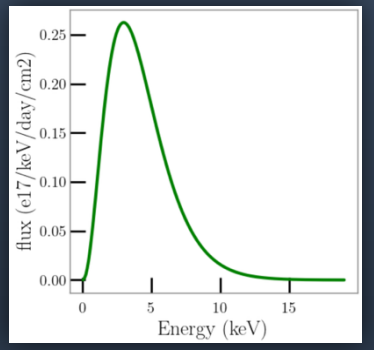
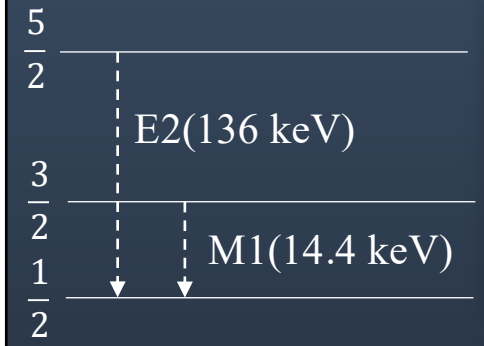


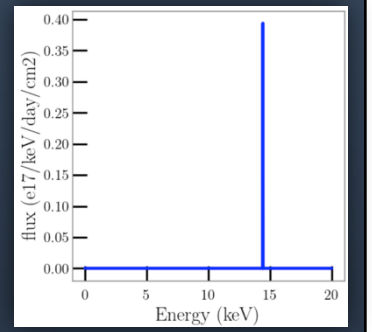


$g_{a\gamma}^2$

Fe-57 De-excitation

An axion is emitted from the M1 nuclear transition of ^{57}Fe in the Sun with energy 14.4 keV





g_{aN}^2

Detection Mechanisms

Axio-electric Effect

Similar to photoelectric effect: Axion takes the place of the photon in the interaction

$$\sigma_{ae} = \sigma_{pe} \frac{g_{ae}^2}{\beta_a} \frac{3E_a^2}{16\pi\alpha m_e^2} \left(1 - \frac{\beta_a^{2/3}}{3}\right)$$

Produced by:

ABC Processes	Primakoff	14.4 keV Fe-57
g_{ae}^2	g_{ae}^2	$g_{a\gamma}^2$	$g_{aN}^{\text{eff}\ 2}$

Detection Mechanisms

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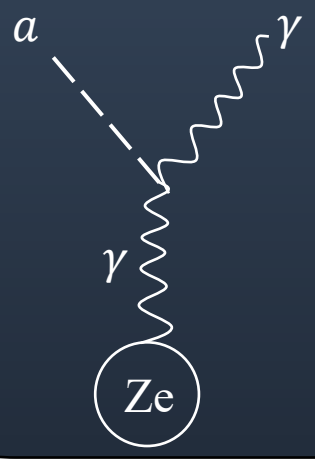
Produced by:

ABC Processes	Primakoff	14.4 keV Fe-57
g_{ae}^2	g_{ae}^2	$g_{a\gamma}^2$	$g_{aN}^{\text{eff}\ 2}$

Inverse Primakoff Effect

Axion interacts with electric field of ion in target material to convert to a photon

$$\frac{d\sigma}{d\Omega} = \frac{\alpha g_{a\gamma}^2}{16\pi} \frac{\sin^2\theta}{(1-\cos\theta)^2} |Z - F(q)|^2$$



Produced by:

Primakoff Effect

$g_{a\gamma}^2$ $g_{a\gamma}^2$

Expected Counting Rate in ANAIS-112

$$R = \frac{d\Phi_a}{dE_a} \times (\sigma_{ae}^{Na} N_{Na} + \sigma_{ae}^{I} N_I) \times MT \times F_{det}(E)$$

Production: g_{ae}^2, $g_{a\gamma}^2$, $g_{aN}^{eff\ 2}$

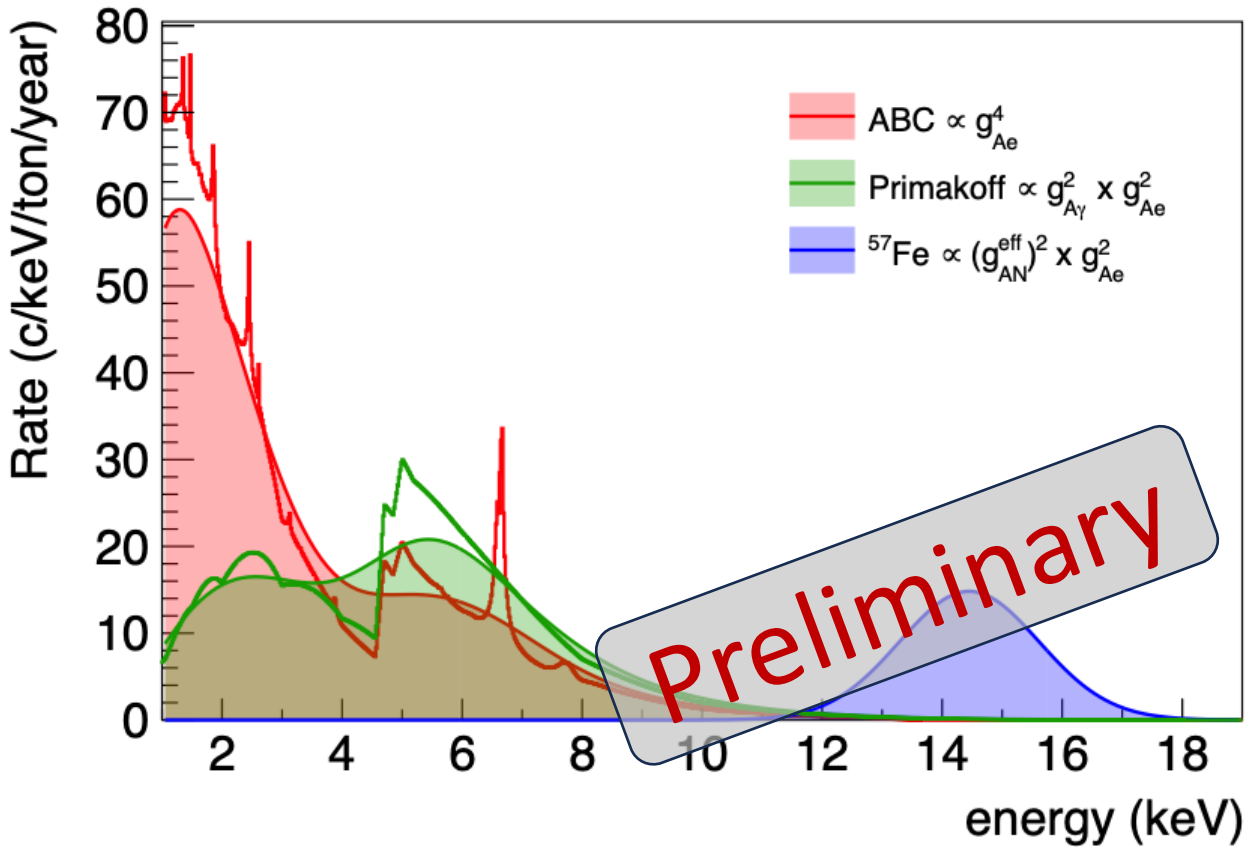
Detection: $g_{a\gamma}^2$, g_{ae}^2

Exposure

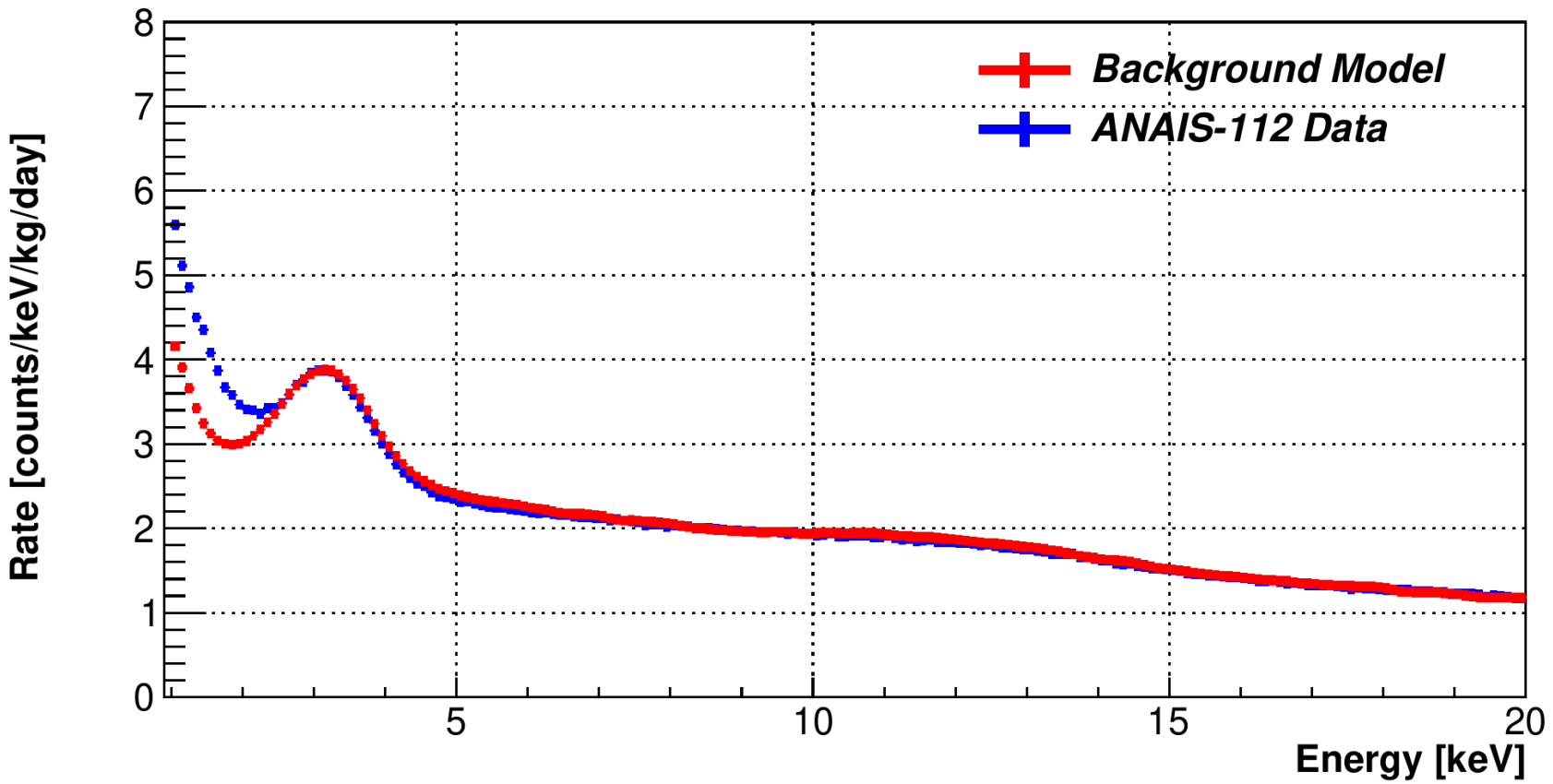
Detector Response (Resolution and Efficiency)

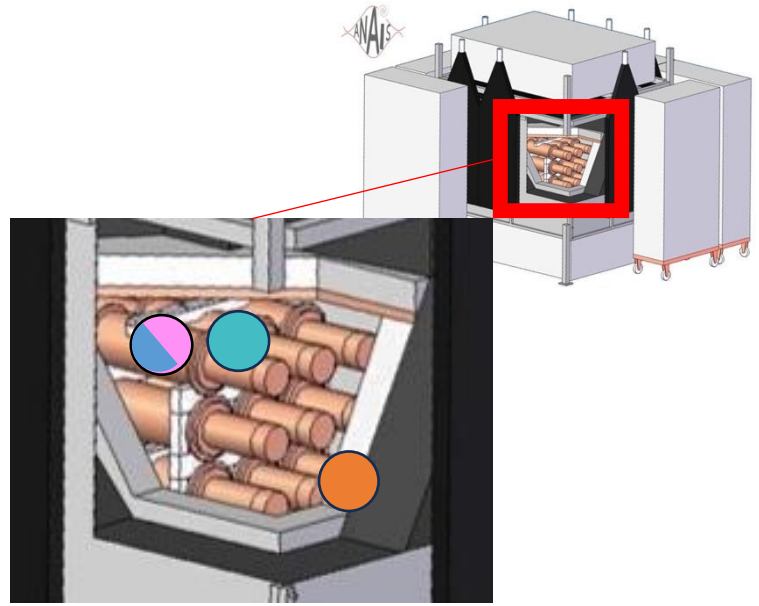
$$R \propto g^4$$

- Optimize sensitivity by:
  - Increasing exposure (on orders 10^4)
  - Selecting target material with best axioelectric cross-sections



Backgrounds in ANAIS-112





- ^{238}U, ^{232}Th, ^{40}K, and ^{210}Pb in **external** "dead" material also contaminate

- ^{40}K and ^{210}Pb **internal** isotopes dominate the background

- ^{3}H, ^{22}Na, and others are **cosmogenic** radioisotopes activated by cosmic-rays

- **Surface** ^{210}Pb from radon exposure

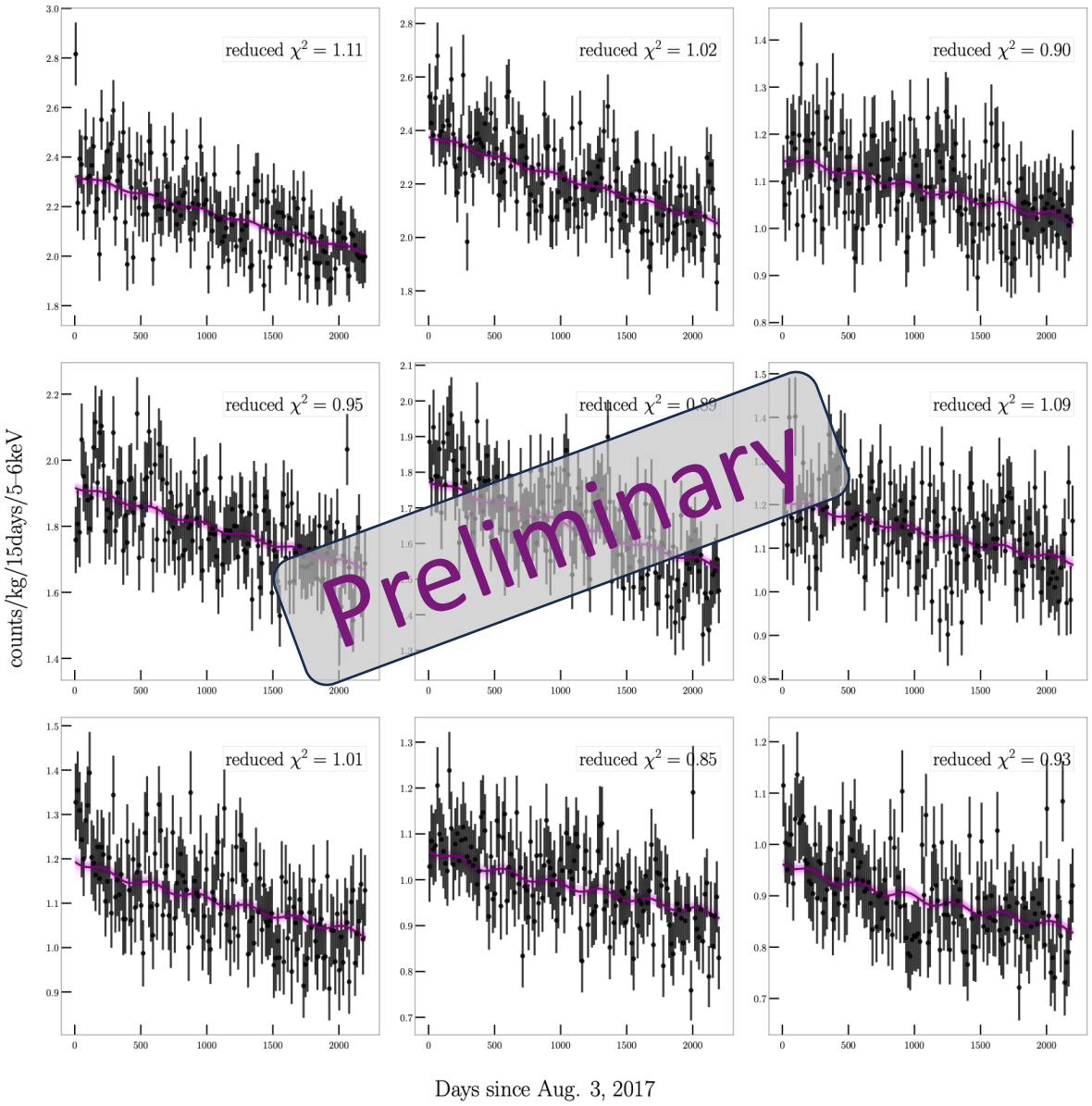
Solar Annual Modulation Search

Fit signal + background:

$$S(t_i) = A\left(\cos(\omega(t_i - t_0)) + \frac{3}{2}\epsilon\cos^2(\omega(t_i - t_0))\right)$$
$$+$$
$$B_d(t_i) = R_{0,d}\left(f_d\ \phi^{MC}_{bkg,d}(t_i) + (1 - f_d)\ \phi_{flat}(t_i)\right)$$

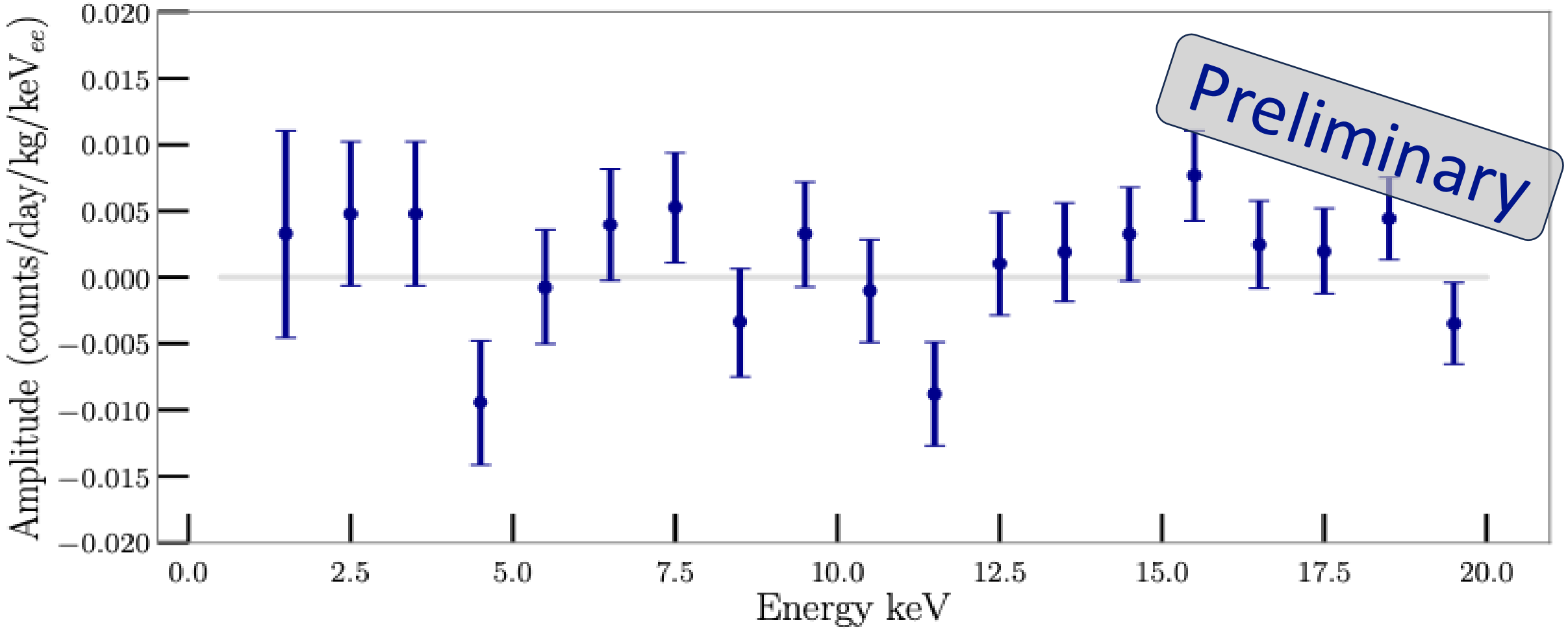
simultaneously across all 9 detectors

- Energy bins of 1 keV
- 1 – 20 keV
- Time bins 15 days
- 358 kg×yr exposure



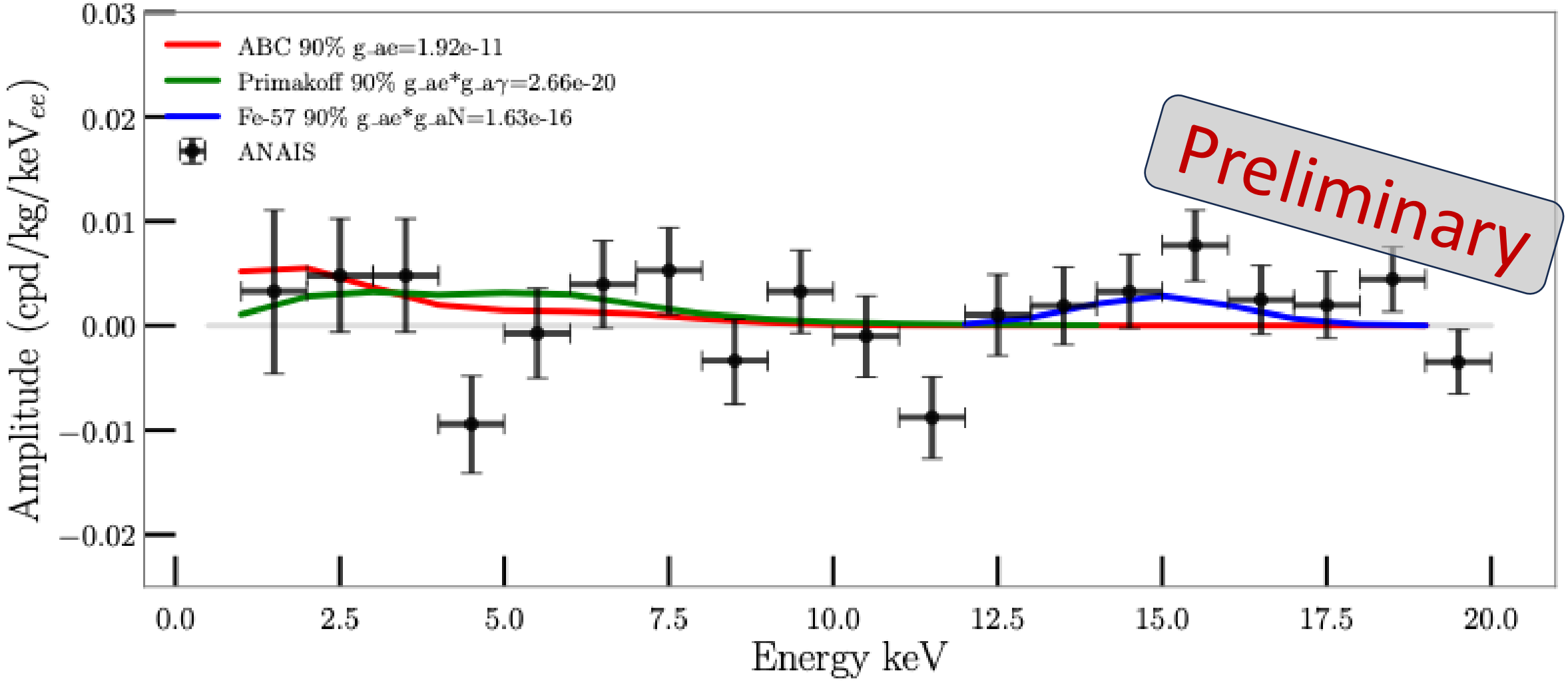
Solar Annual Modulation Search

- Agreement with no modulation hypothesis to 2σ



Solar Annual Modulation Search

- Sensitivity to axion couplings



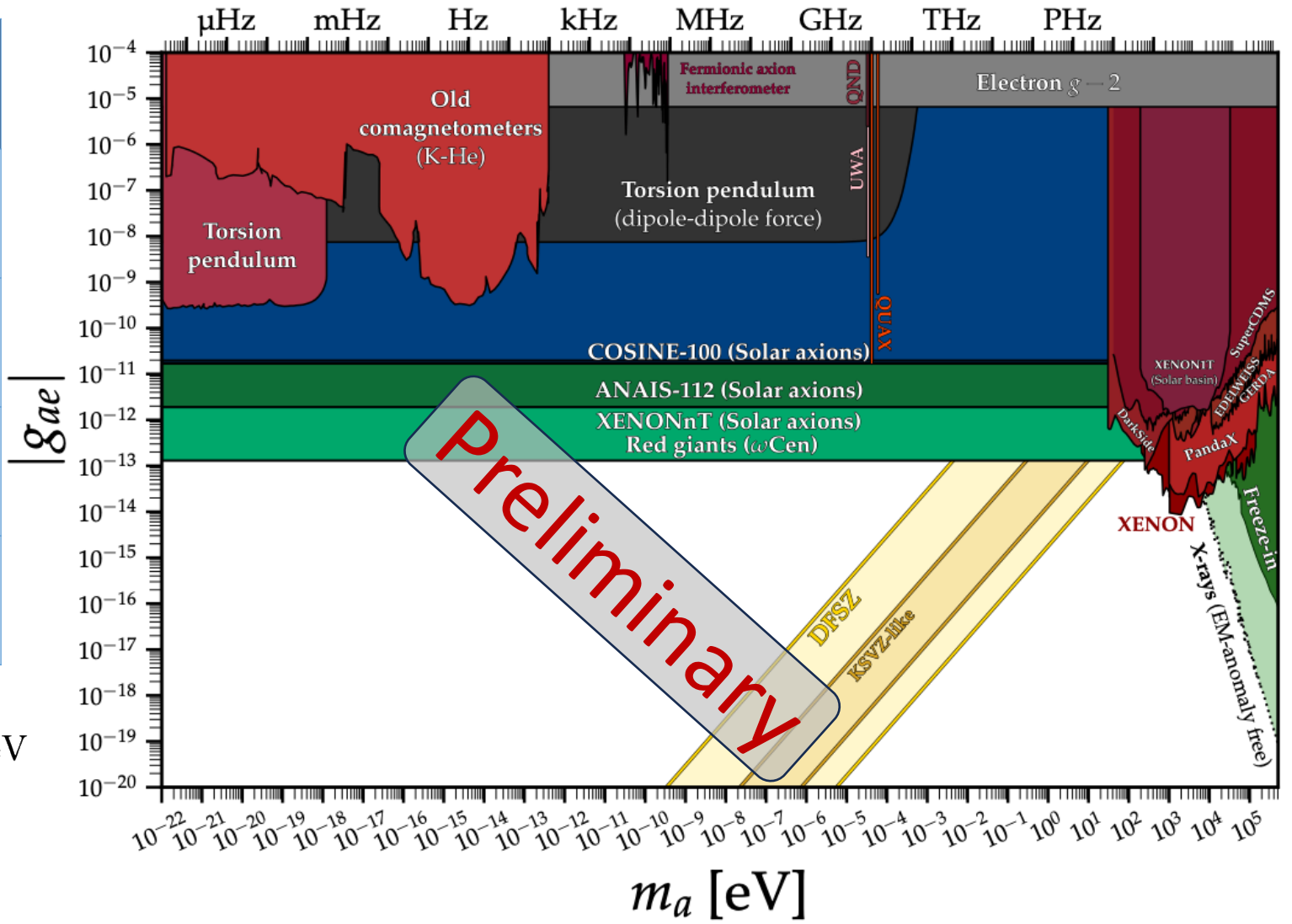
Solar Particle Search with ANAIS-112

Preliminary

	This work	Literature Best
* $g_{ae}^2 \times g_{aN}^{eff\,2}$	1.63×10^{-16}	PandaX-4T 2.1×10^{-18} arxiv.org/pdf/2408.07641
* $g_{ae}^2 \times g_{ae}^2$	2.01×10^{-11}	XENONnT 1.9×10^{-12} arxiv.org/2207.11330
** $g_{ae}^2 \times g_{a\gamma}^2$	2.97×10^{-20}	CAST 8.1×10^{-23} arxiv.org/pdf/1302.6283
* $g_{a\gamma}^2 \times g_{a\gamma}^2$	3.17×10^{-9}	XENON1T $\sim 10^{-10}$ DOI: 10.1103/PhysRevLett.125.131805

* for axion masses $m_a < 1$ keV

** $< 10^{-2}$ eV



Thank you!

Acknowledgements

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Backup

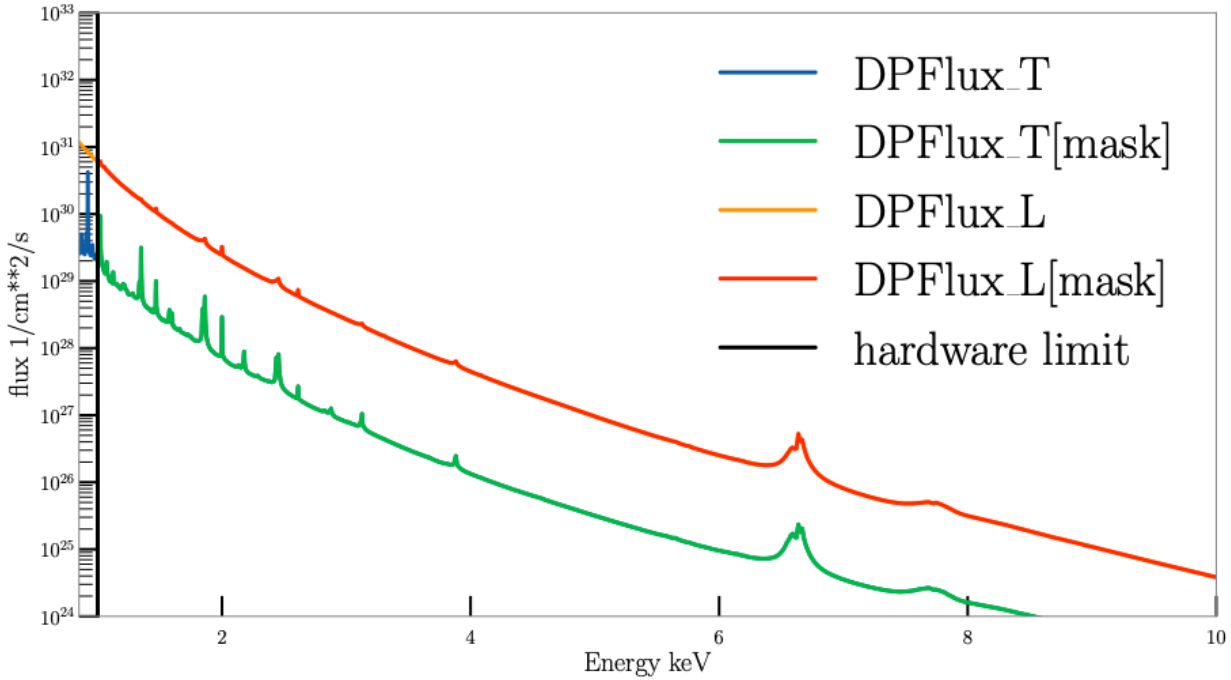
Dark Photons

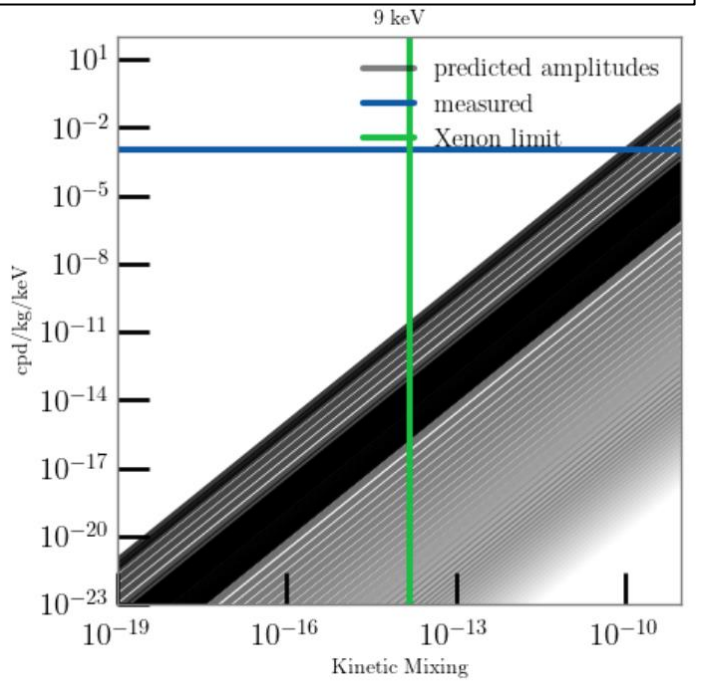
- These methods can also be applied to searching for solar dark photons
  - This is a work in progress
- Majority of events expected in first keV bin

$$\frac{dR}{d\omega} = \frac{1}{\rho}\frac{1}{v}\left[\frac{d\Phi_T}{d\omega}\Gamma_T(\omega) + \frac{d\Phi_L}{d\omega}\Gamma_L(\omega)\right]$$

$$\frac{d\Phi_t}{d\omega} = \chi^2 m^4 \int_0^{R_\odot} \frac{r^2 dr}{\pi^2 d_\odot^2} \frac{\omega\sqrt{\omega^2 - m^2}}{(m^2 - m_\gamma^2)^2 + (\omega\Gamma)^2} \frac{\Gamma}{e^{\omega/T} - 1},$$

$$\frac{d\Phi_l}{d\omega} = \chi^2 m^2 \omega^2 \int_0^{R_\odot} \frac{r^2 dr}{2\pi^2 d_\odot^2} \frac{\omega\sqrt{\omega^2 - m^2}}{(\omega^2 - m_\gamma^2)^2 + (\omega\Gamma)^2} \frac{\Gamma}{e^{\omega/T} - 1},$$





Computing Dark Photon Rates

detector mass density ρ

- Rates go as χ^4

$$\frac{dR}{d\omega} = \frac{1}{\rho}\frac{1}{v}\left[\frac{d\Phi_T}{d\omega}\Gamma_T(\omega) + \frac{d\Phi_L}{d\omega}\Gamma_L(\omega)\right] \qquad \left[\frac{dR}{d\omega}\right] = (\text{mass})^{-1}(\text{time})^{-1}(\text{energy})^{-1}$$

For keV solar DPs one typically has $v \simeq 1$

except very close to threshold $\omega \simeq m_V$ where $v = \sqrt{1 - m_V^2/\omega^2}$

$$\Gamma_T(\omega) = \frac{\chi^2 m_V^4 \,\mathrm{Im}\,\epsilon_r}{\omega^3 |\Delta\epsilon_r|^2}\left[1 + \frac{2m_V^2}{\omega^2}\frac{\mathrm{Re}\,\Delta\epsilon_r}{|\Delta\epsilon_r|^2} + \frac{m_V^4}{\omega^4 |\Delta\epsilon_r|^2}\right]^{-1}$$

$$\Gamma_L(\omega) = \frac{\chi^2 m_V^2 \,\mathrm{Im}\,\epsilon_r}{\omega\,|\epsilon_r|^2}$$

$$\epsilon_r = (n+ik)^2 = \left(n^2 - k^2\right) + i(2nk)$$

$$\mathrm{Re}\,\epsilon_r = n^2 - k^2$$

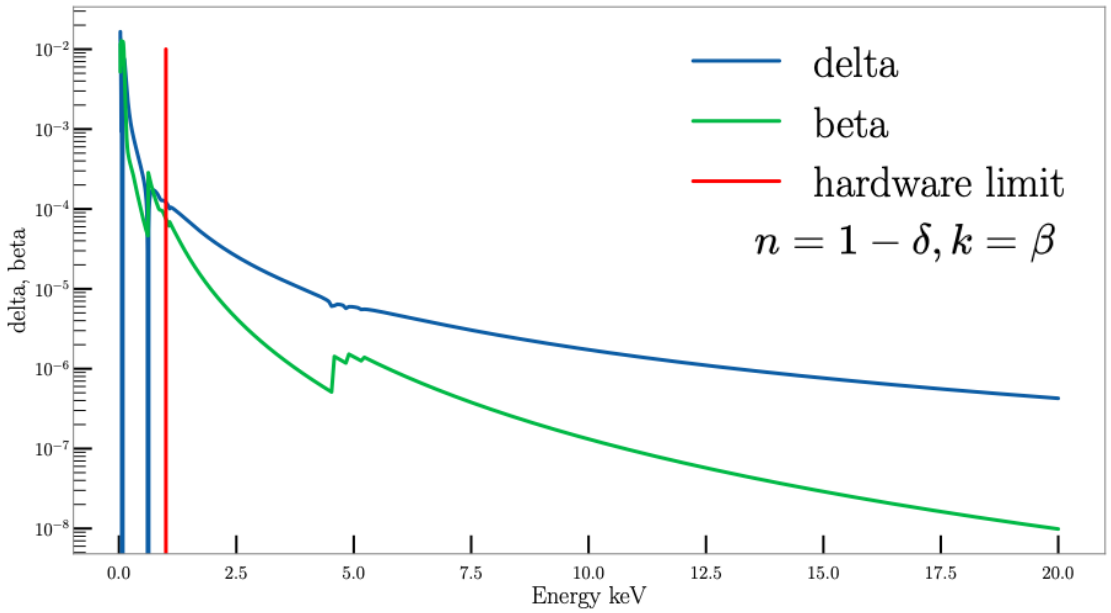
$$\mathrm{Im}\,\epsilon_r = 2nk$$

$$\Delta\epsilon_r = \epsilon_r - 1$$

$$|\Delta\epsilon_r|^2 = (\mathrm{Re}\,\Delta\epsilon_r)^2 + (\mathrm{Im}\,\Delta\epsilon_r)^2$$

$$|\epsilon_r|^2 = (\mathrm{Re}\,\epsilon_r)^2 + (\mathrm{Im}\,\epsilon_r)^2$$

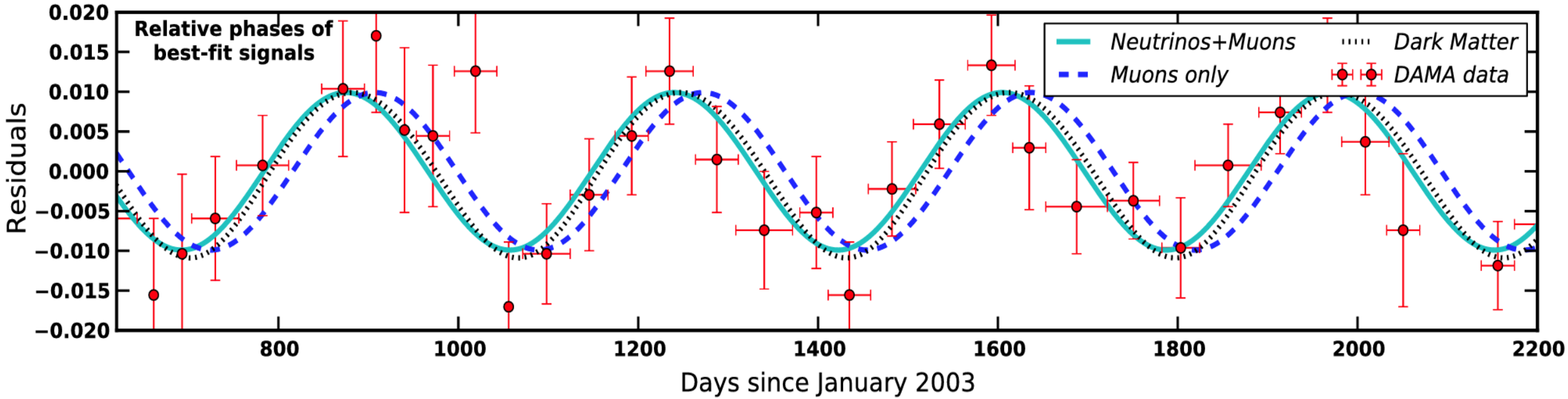
Index of Refraction of NaI from CXRO database



Cosmic rays and solar neutrinos

Neutrons produced by **solar neutrinos and cosmic-ray muons modulate** with fixed phases

- $(\phi_\nu \,\&\, \phi_\mu) = (3 \,\&\, 179$ days)
- Need ~ 1000 m^3 for this production



J. H. Davis. *PRL* **113**:081302, 2014.

Computing Rates for Inverse Primakoff

- Rates go as g_{ay}^4
  - Axions coupled with photons can be converted into photons in electric field of ions in NaI
  - Quantify their interaction with the differential cross-section:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha g_{a\gamma\gamma}^2 E_a^3 p_a \sin^2\theta}{4\pi\left(E_a^2 + p_a^2 - 2E_a p_a \cos\theta\right)^2}|Z - F(q)|^2$$

with $q = \sqrt{E_a^2 + p_a^2 - 2E_a p_a \cos\theta - m_a^2}$. For $m_a \ll E_a$,

$$\frac{d\sigma_{el}}{d\Omega} \simeq \frac{\alpha\, g_{a\gamma}^2}{16\pi} \frac{\sin^2\theta}{(1-\cos\theta)^2}|Z - F(q)|^2$$

$$q \simeq 2\,E_a\,\sin(\theta/2)$$

- Where form fact is

$$F(q) = \sum_{i=1}^{4} a_i \exp\left[-b_i\left(\frac{|q|}{4\pi}\right)^2\right] + c \qquad (5)$$

with $|q|$ in Å^{-1} (Conversion: 1 $\text{Å}^{-1} \approx 1.973$ keV) and all the fitting coefficients provided in their Table 1. They provide coefficients for Xe, Ge, Na^+, I^-, and Pb.

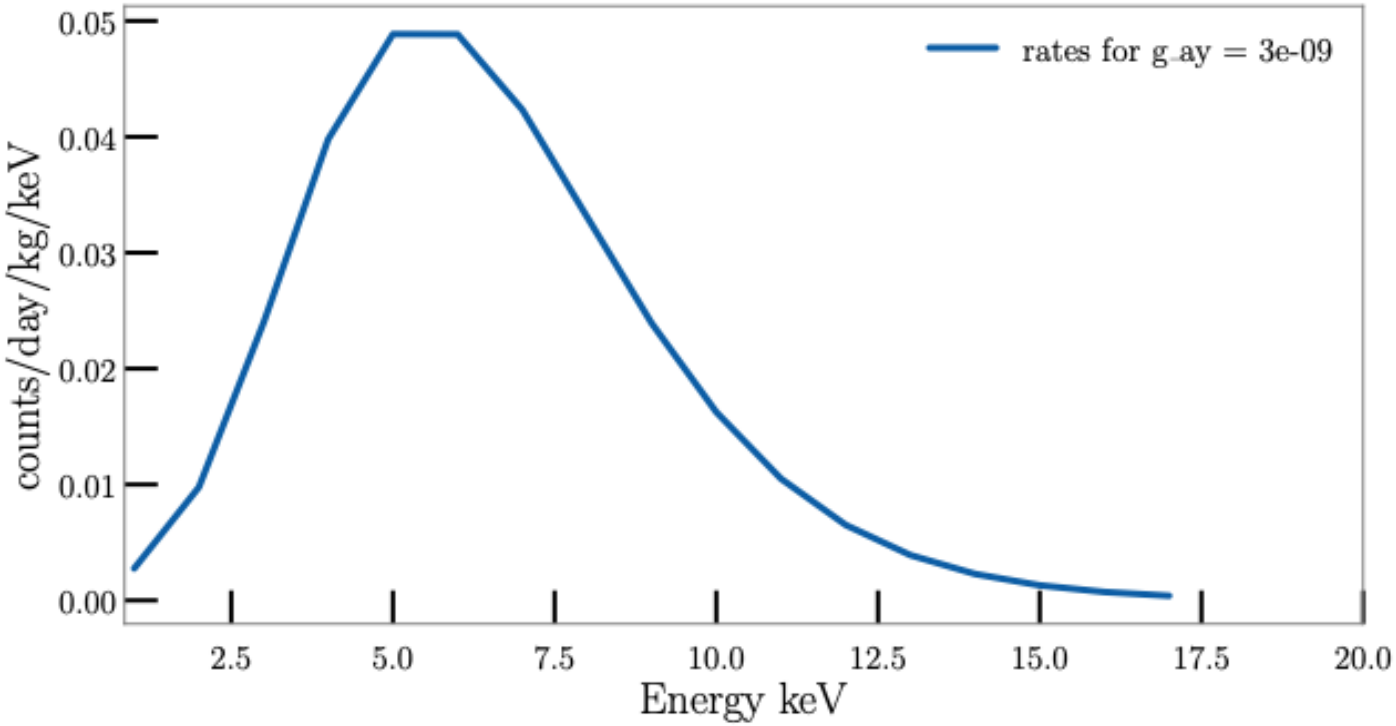
Form factor info in this paper

	Z	a_1	b_1	a_2	b_2	a_3	b_3	a_4	b_4	c
Xe	54	20.2933	3.92820	19.0298	0.34400	8.97670	26.4659	1.99000	64.2658	3.71180
Ge	32	16.0816	2.85090	6.37470	0.25160	3.70680	11.4468	3.68300	54.7625	2.13130
Na^+	11	3.25650	2.66710	3.93620	6.11530	1.39980	0.20010	1.00320	14.0390	0.40400
I^-	53	20.2332	4.35790	18.9970	0.38150	7.80690	29.5259	2.88680	84.9304	4.07140

Computing Rates for Inverse Primakoff cont.

- Differentional cross-section for NaI is additive of Na and I
- Compute the total cross-section by integrating over the solid angle
- Rates can then be computed the same method as in the other processes where:

$$R(E) = \Phi_A(E) \times \sigma_{Ae}(E) \times MT \times F_{det}(E)$$



Alpha Spectra Crystals

- ANAIS

Detector	Powder Name	Date of arrival at Canfranc
D0, D1	<90 ppb K	December 2012
D2	WIMPScint-II	March 2015
D3	WIMPScint-III	March 2016
D4, D5	WIMPScint-III	November 2016
D6, D7, D8	WIMPScint-III	March 2017

Component	Half life
^{210}Pb	22.20 years
^{60}Co	5.27 years
^{125}I	59.4 days
^{121}Te	19.3 days
^{121m}Te	154 days
^{123m}Te	119.2 days
^{125m}Te	57.40 days
^{127m}Te	106 days
^{3}H	12.32 years
^{109}Cd	461.3 days
^{22}Na	2.60 years
^{113}Sn	115.08 days