Axion search prospects with the LZ experiment

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IoP 2014

Joint High Energy Particle Physics and Astro Particle Physics Groups

Annual Meeting

8 April 2014

Axions? (1)

- The Standard Model predicts a CP violating term in the QCD sector => $\theta_{QCD.}$
- But no CP violation observed in the Strong sector of the SM and neutron NOT having an electric dipole moment $\theta_{QCD} < 10^{-10}$
- Peccei-Quinn solution: an additional U(1) chiral symmetry, spontaneously broken, in the QCD Lagrangian an additional pseudo Goldston-Nambu boson

$$\mathcal{L}_{aG\tilde{G}} = -\frac{a(x)}{f_a}\frac{\alpha_s}{8\pi}G\tilde{G}$$

a(x) axion field

f_a scale of the U(1) symmetry breaking

R. D. Peccei and H. R. Quinn, Phys. Rev. D 16, 17911797 (1977)

Axions? (2)

- … the original PQ model has been ruled out. However

- "Invisible" axions (arising from an higher symmetry-breaking energy scale) still allowed (DFSZ and KSVZ models) => QCD axions.

- Extensions of the Standard Model of particle physics postulate other pseudo-Nambu-Goldstone bosons: axion-like-particles (ALPs)

S. Weinberg, Phys. Rev. Lett. 40, 223 (1978).F. Wilczeck, Phys. Rev. Lett. 40, 279 (1978).

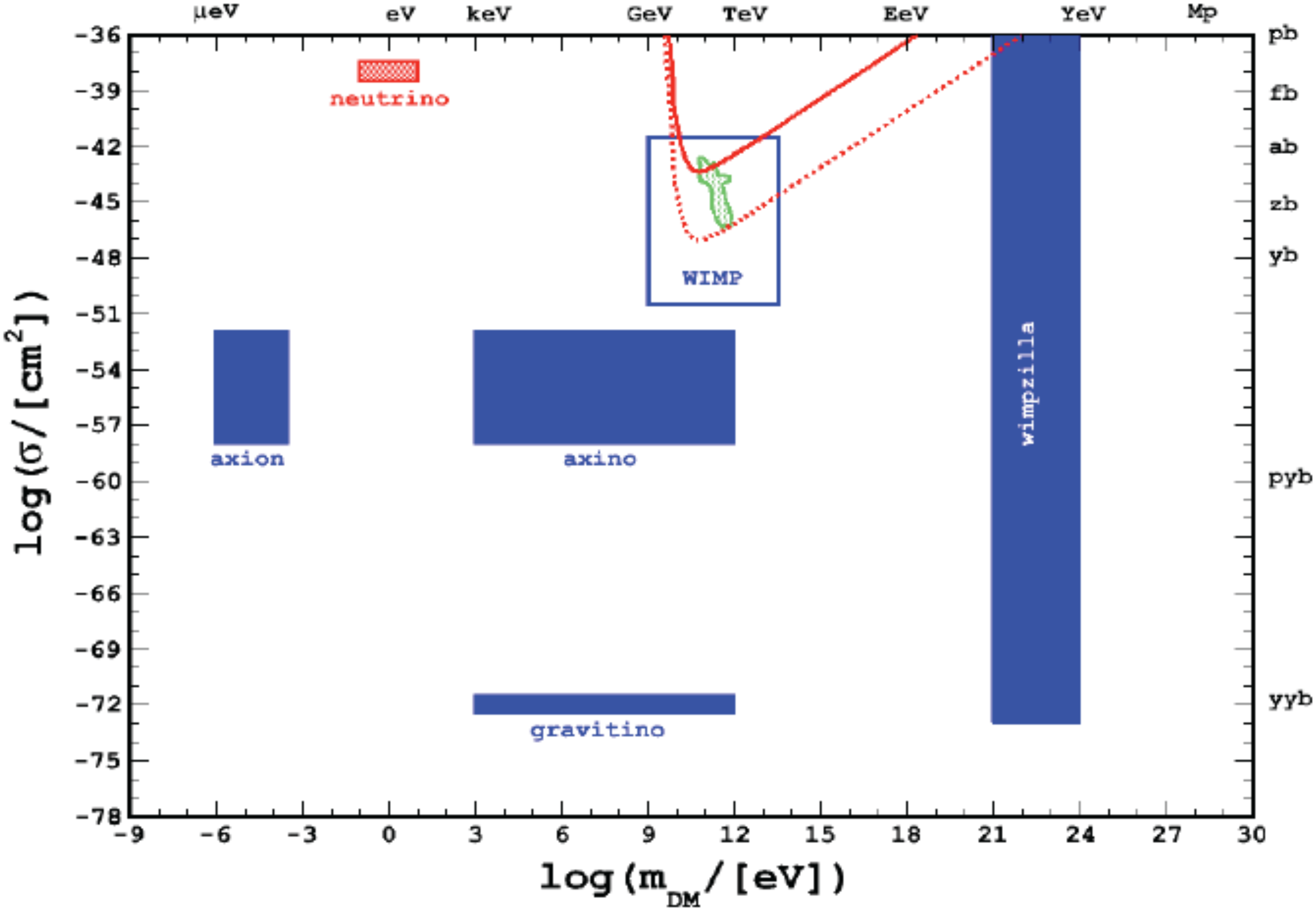
M. Dine, W. Fischler, and M. Srednicki, Phys. Lett B 104, 199 (1981), A. R. Zhitnitsky, Sov. J. Nucl. Phys. 31, 260 (1980).
J. E. Kim, Phys.Rev.Lett. 43, 103 (1979), M. A. Shifman, A. I. Vainshteinand, and V. I. Zakharov, Nucl. Phys. B 166, 493 (1980).

Axions? (3)

- Couplings to photons (g_{Ag}), electrons (g_{Ae}) and nuclei (g_{AN}).

- Astrophysical observations the most accessible way for direct detection.
  - Sun would constitute an intense source: production via Bremsstrahlung, Compton scattering, axio-recombination and axio-deexcitation.
  - Detection of ALPs slowly moving through our galaxy (referred to as galactic ALPs): generated via a non-thermal production mechanism in the early universe

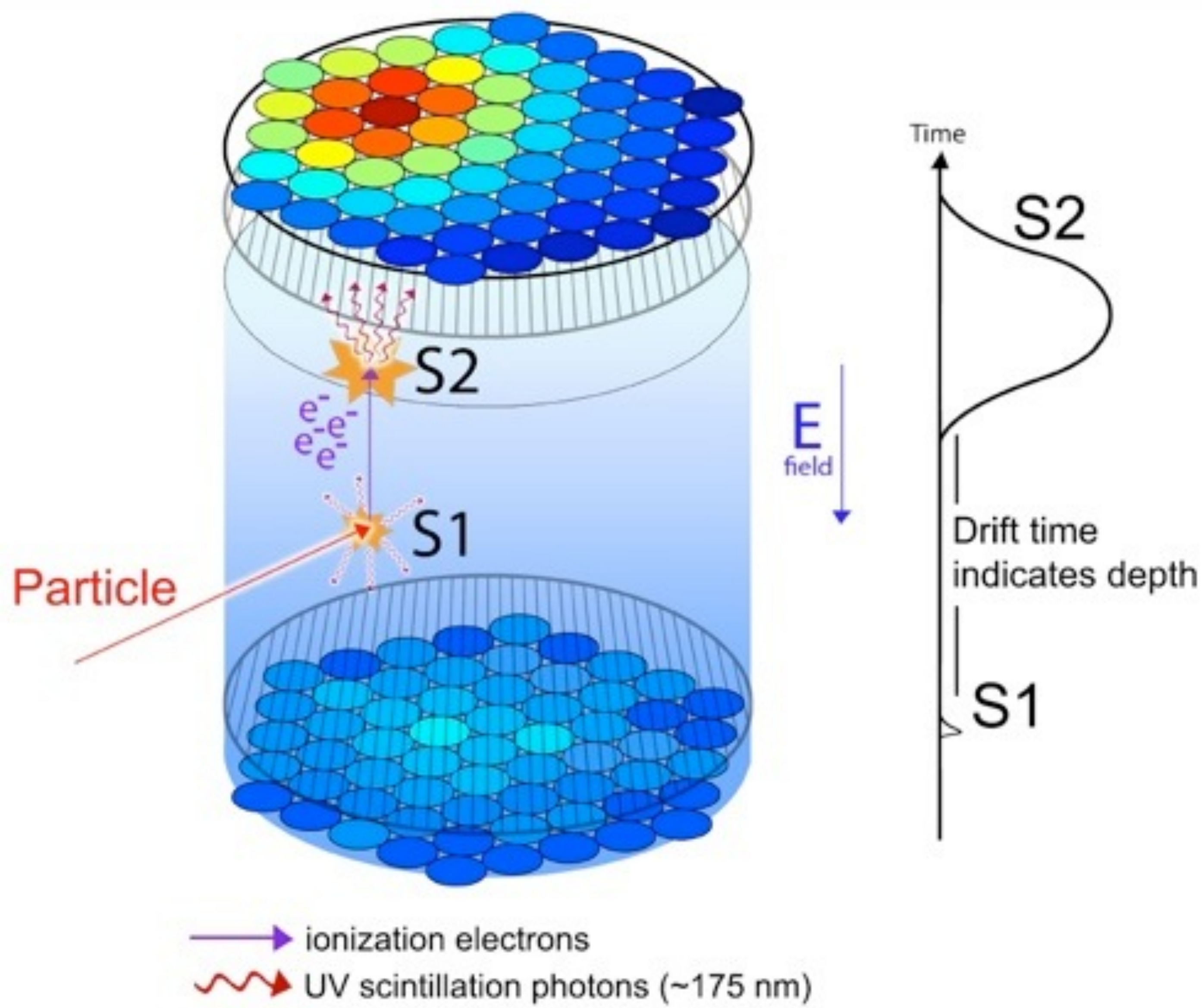
P. Sikivie, Phys. Rev. Lett. 51, 1415 (1983).


µeV
eV
keV
GeV
TeV
EeV
YeV
Mp
pb
fb
ab
zb
yb
pyb
yyb
neutrino
WIMP
axion
axino
wimpzilla
gravitino
log(σ/[cm²])
log(m_DM/[eV])
-36
-39
-42
-45
-48
-51
-54
-57
-60
-63
-66
-69
-72
-75
-78
-9
-6
-3
0
3
6
9
12
15
18
21
24
27
30

No new data will be shown…

if you want to look at some brand new experimental outcome you may like to have a look at arXiv:1404.1455

Axions in dual phase Xe dark matter TPC



Particle interaction with LXe producing

primary scintillation signal (S1)

secondary proportional signal (s2)

Standard WIMP search

- Background: Electronic recoils scattering (ER).
- Signal (WIMP): Nuclear recoils scattering (NR).

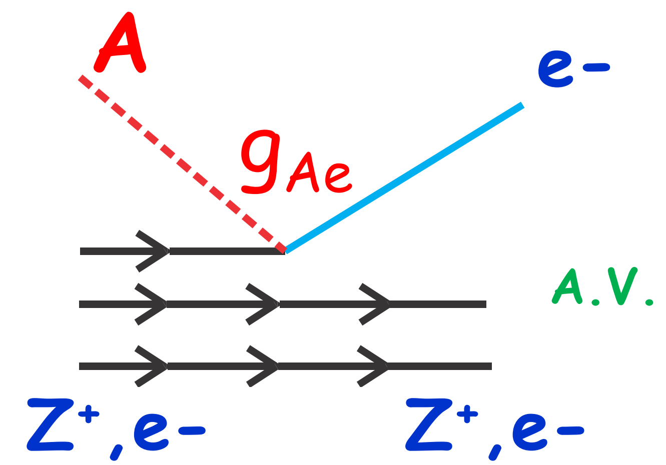
Axion signal: Electronic recoil scattering

- via axio-electric effect
- testing g_{Ae} (axion coupling with electrons)
- typical spectra above the ER background

Axio-electric effect and testable axions

Proportional to photo-electric cross section

$$\sigma_{Ae} = \sigma_{pe}(E_A)\frac{{g_{Ae}}^2}{\beta_A}\frac{3{E_A}^2}{16\pi\,\alpha_{em}\,{m_e}^2}\left(1-\frac{\beta_A^{2/3}}{3}\right)$$



F. T. Avignone and al., Phys. Rev. D 35, 2752 (1987),
M. Pospelov, A. Ritz, and M. Voloshin, Nucl. Rev. D 78, 115012 (2008), A. Derevianko and al., Phys. Rev. D 82, 065006 (2010).

Production and flux	Detection: Flux x σ_Ae	axions	Sensible to
Solar	continuum spectrum -> gAe^4	relativistic	QCD axions
Galaxy	monoenergetic peaks (m) -> gAe^2	non relativistic	ALPs (dark matter)

LUX -> LUX/ZEPLIN

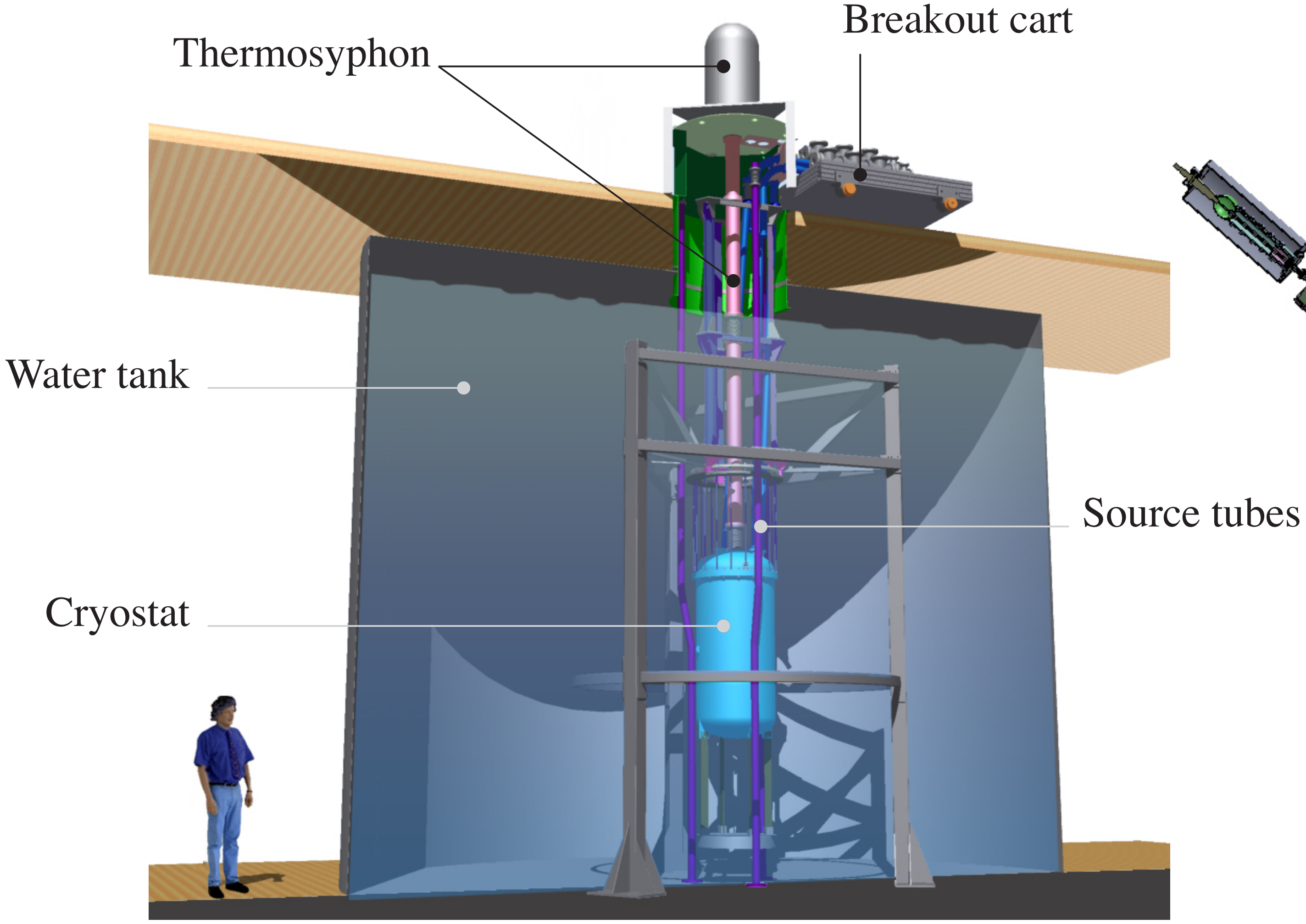
From 300 kg to 7 ton active LXe

Ultimate direct detection experiment - approaches coherent neutrino scattering backgrounds

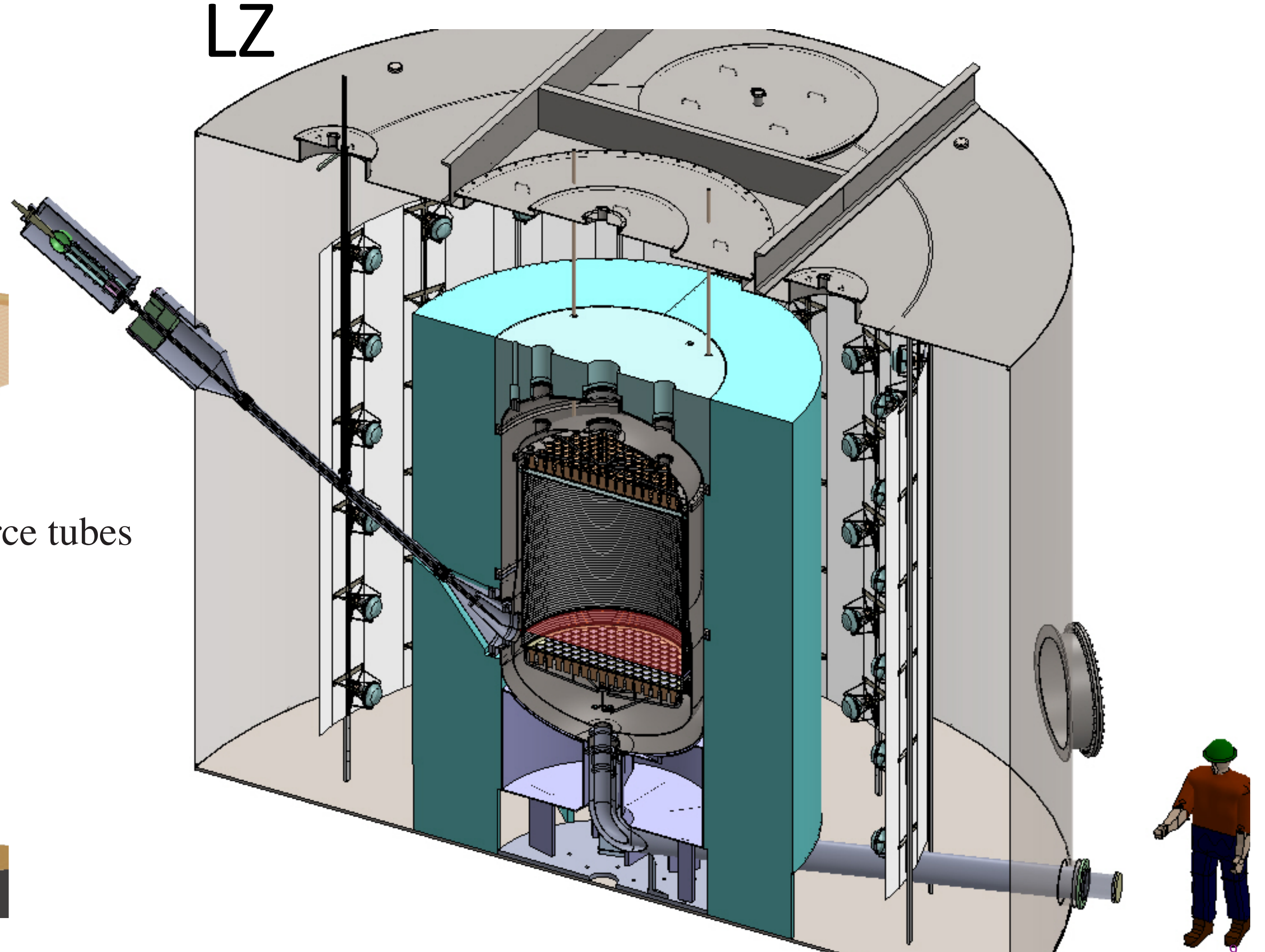
20 times LUX Xenon mass, active scintillator veto, Xe purity at sub ppt level

See talk by H. Araujo

LUX



LZ



LZ prospected analysis

- Exposure: 6000 kg x 1000 live days
- Efficiency: from electronic recoil events from LUX
- Energy scale: keV to phe (S1) conversion from LUX extended to 200 phe
- Background: 8.6 x 10^{-6} dru* (from expected *pp* Solar ν) folded with the ER efficiency
- A case study Profile Likelihood analysis

- Solar Axion search ROI: 2 - 30 phe (in S1)
- Galactic Axion search ROI: 2 - 100 phe (in S1)

* dru = cts/kg/day/keV

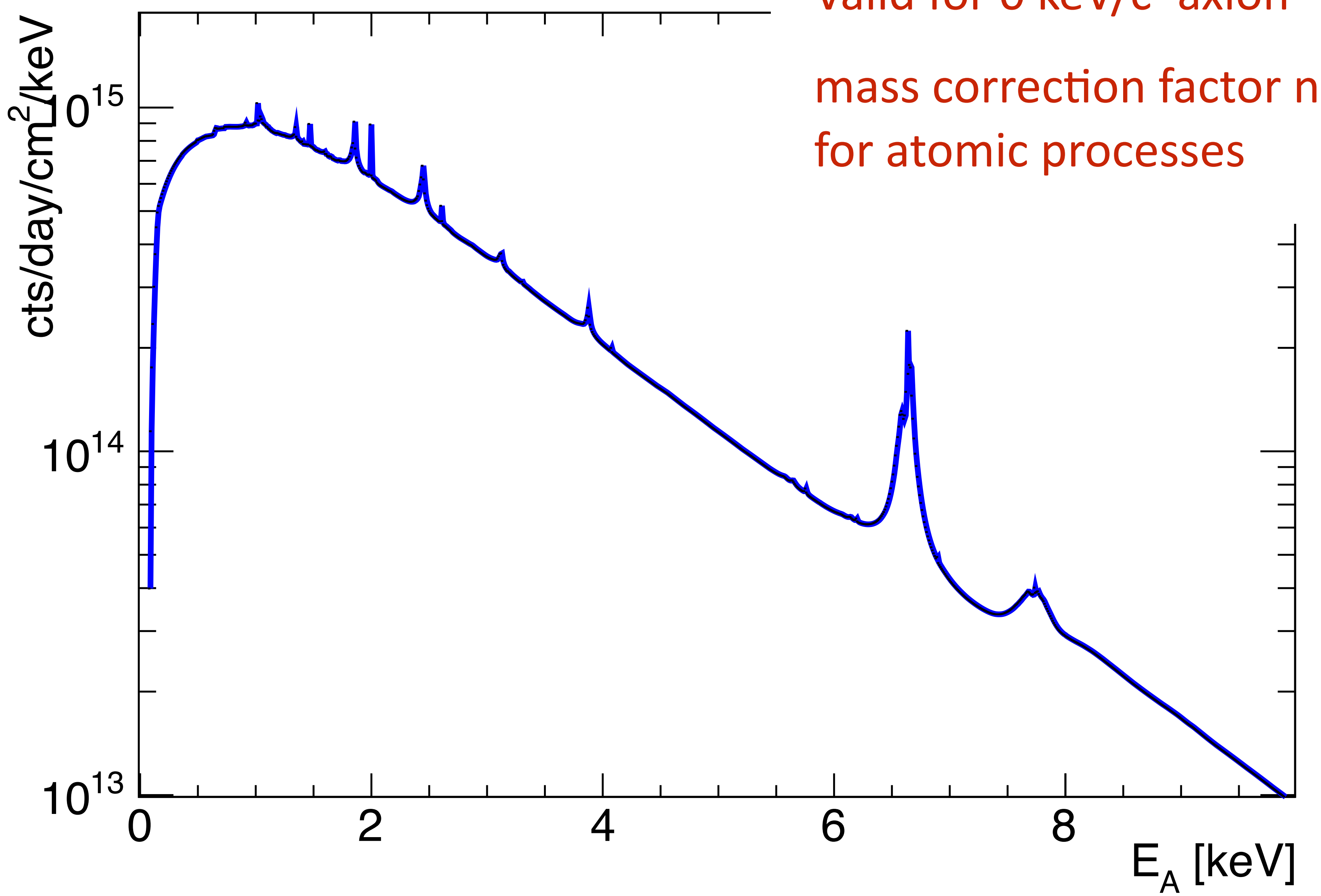
Axion from the Sun

Production in the Sun

M_A = 0 keV/c^2 and g_{Ae} = 1 × 10^{-10}

Bremsstrahlung + Compton + atomic axio-recombination and axio-deexcitation

J. Redondo (2013), arXiv:1310.0823



Valid for 0 keV/c^2 axion

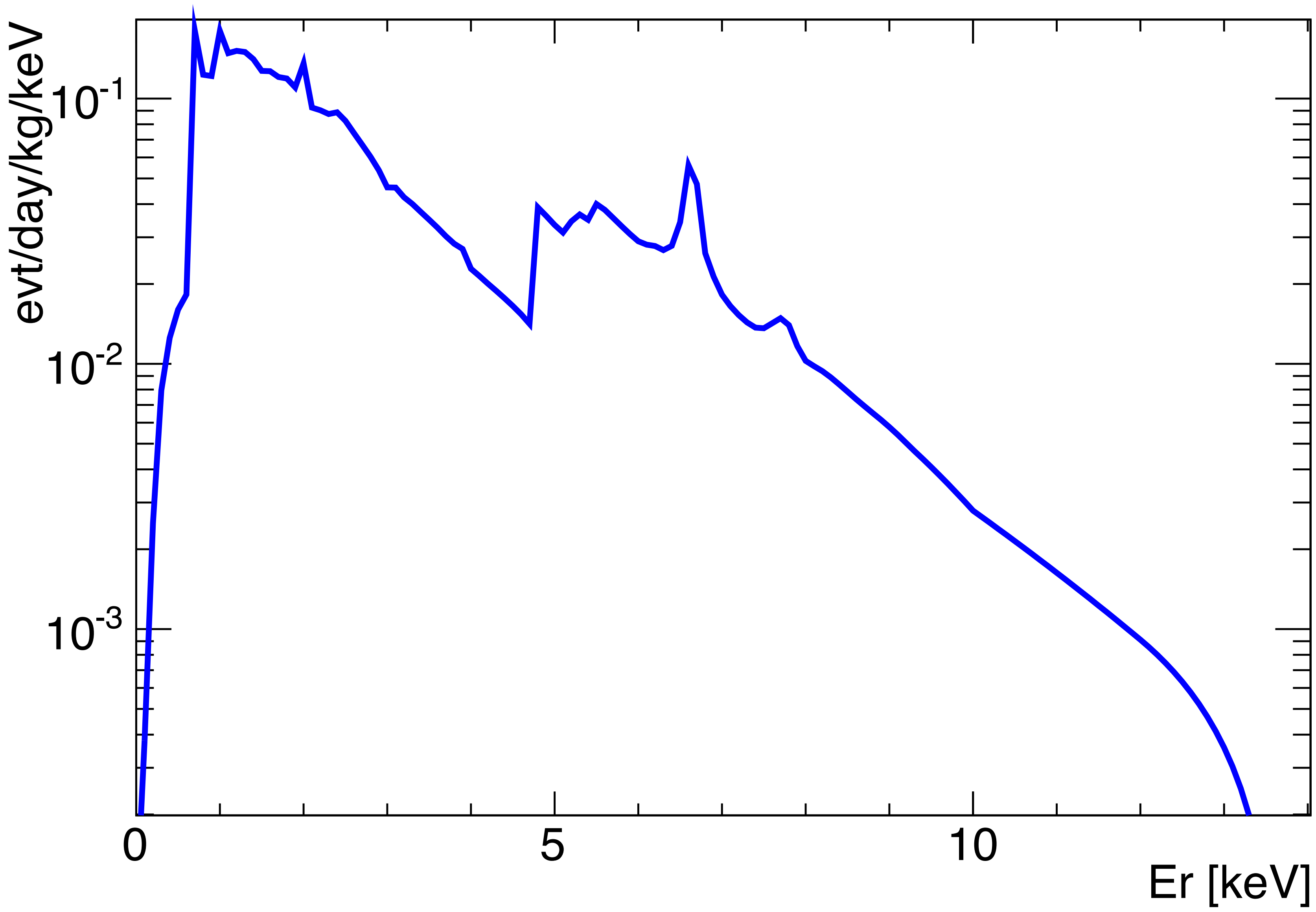
mass correction factor not available (yet) for atomic processes

Expected rate for Solar axions

M_A = 0 keV/c^2 and g_{Ae} = 1 × 10^{-10}

Flux from Bremsstrahlung + Compton + atomic axio-recombination and axio-deexcitation

convolution to axio-electric effect, no detector effects considered

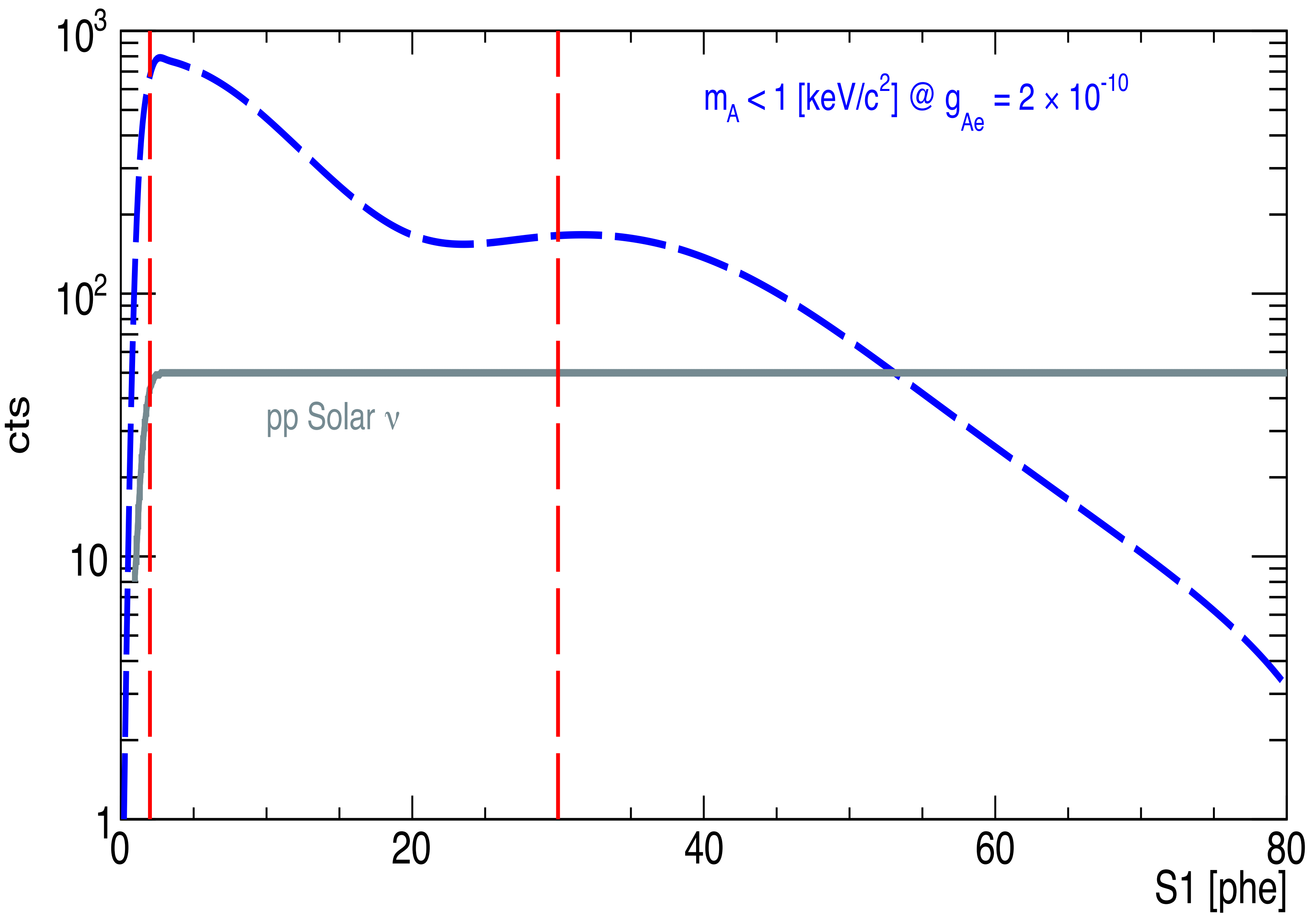


Expected rate for Solar axions

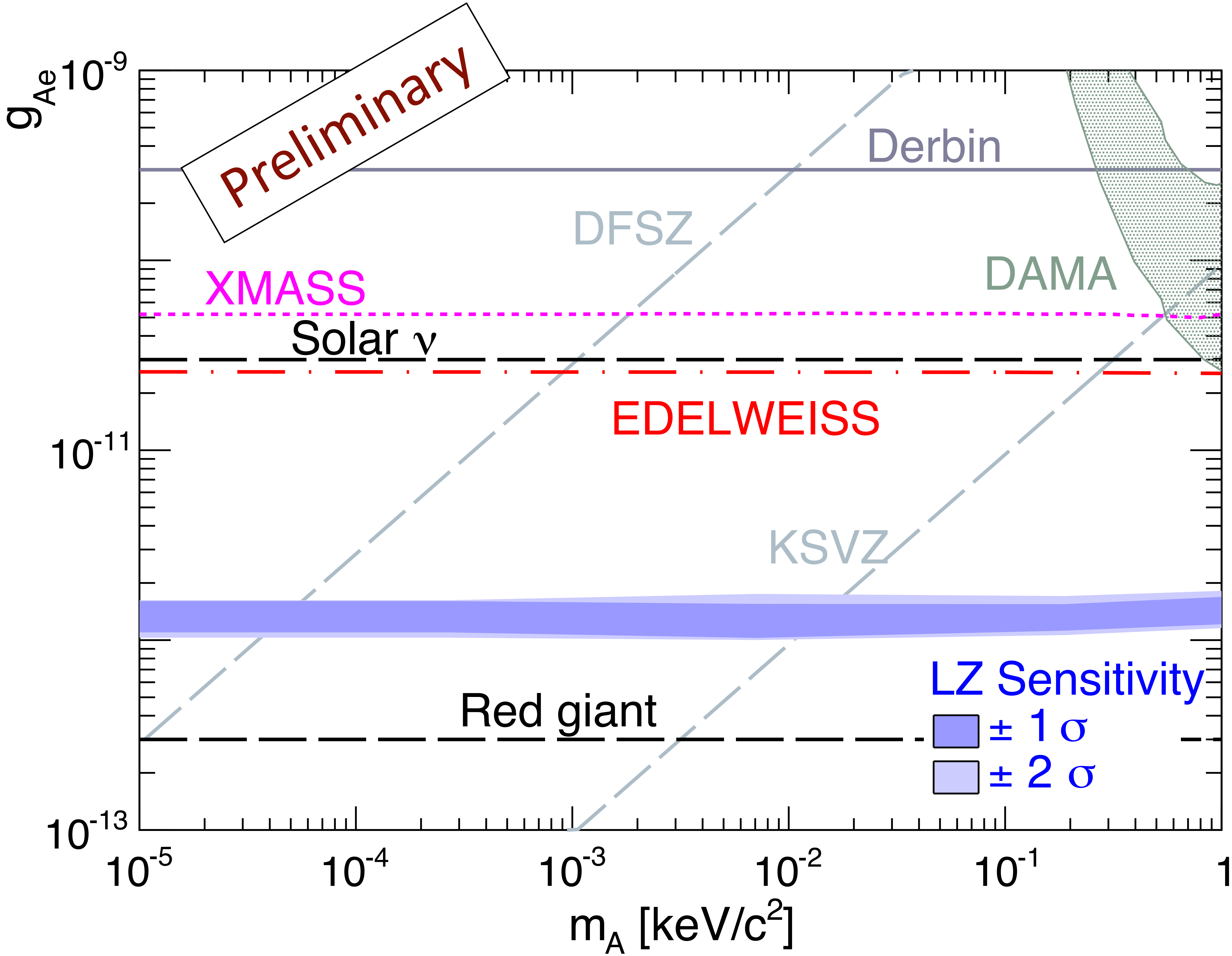
M_A = 0 keV/c^2 and g_{Ae} = 1 × 10^{-10}

Flux from Bremsstrahlung + Compton + atomic axio-recombination and axio-deexcitation

convolution to axio-electric effect, LZ expected performances assumed



Solar axion predicted sensitivity



Axion from the galaxy

Galactic flux

Assumption they constitute the whole of the galactic dark matter density, i.e. ρ_{DM} ~0.3 GeV/cm^3

total flux (as $\Phi = \rho_{DM}\, v_A/m_A$)

$$\Phi^{DM} = 9.0 \times 10^{15} \frac{\mathrm{keV}}{m_A} \beta_m$$

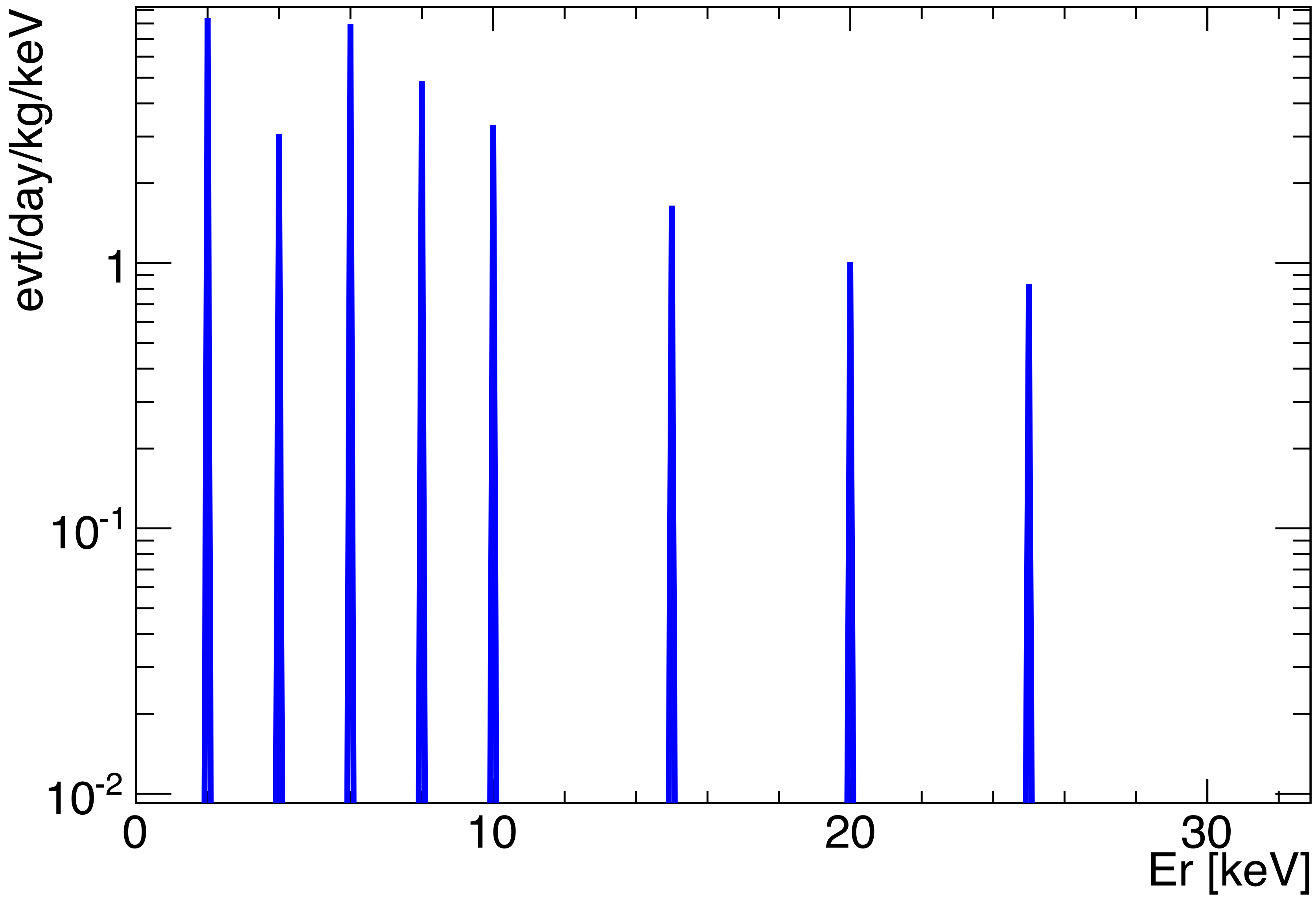
β_m is the mean velocity of the axion distribution relative to the Earth ~10^{-3}

Expected rate for Galactic ALPs

M_A = n keV/c^2 and $g_{Ae} = 1 \times 10^{-10}$

axion flux $\Phi = \rho_{DM}\, v_A/m_A$

convolution to axio-electric effect, no detector effects considered

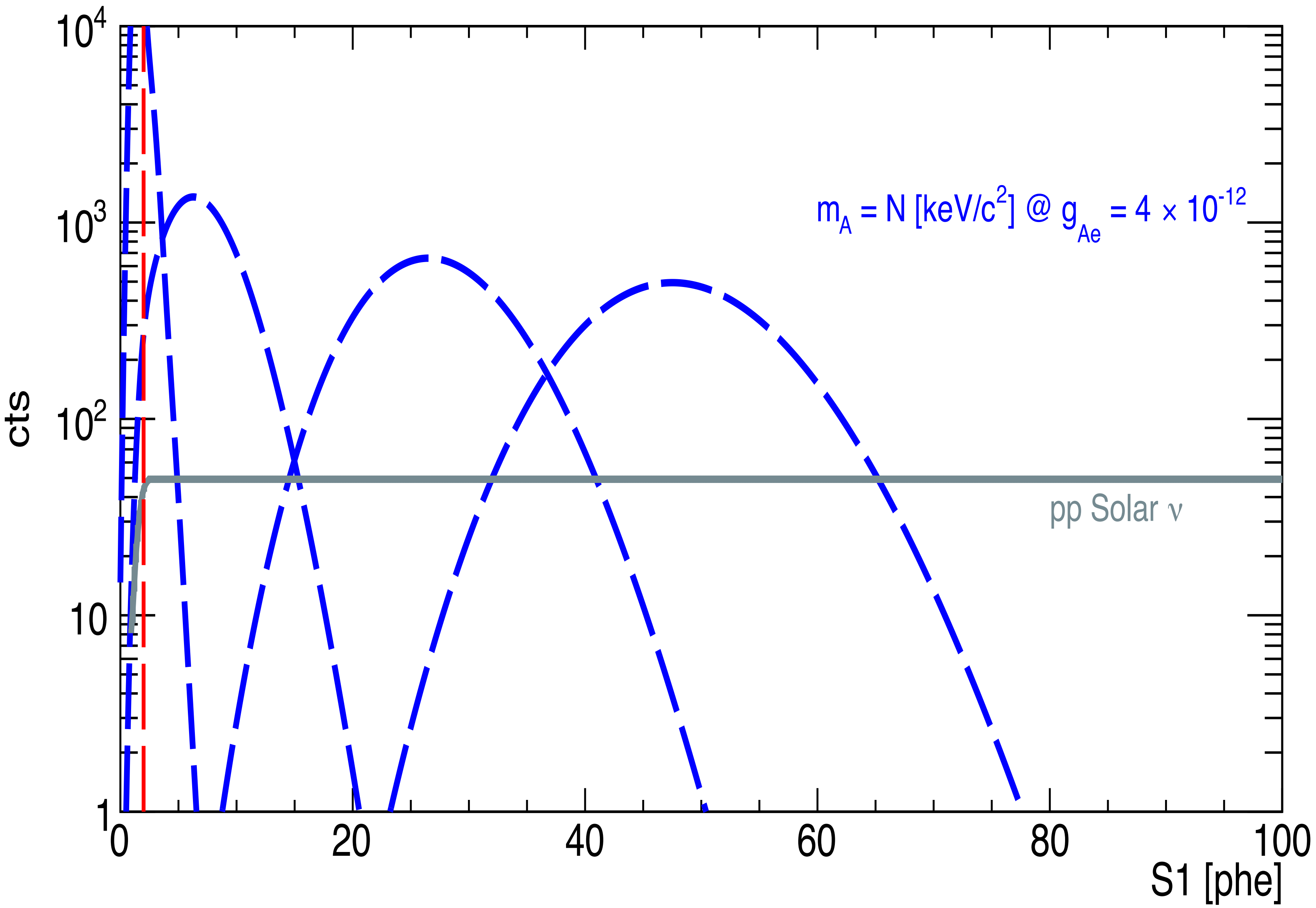


Expected rate for Galactic ALPs

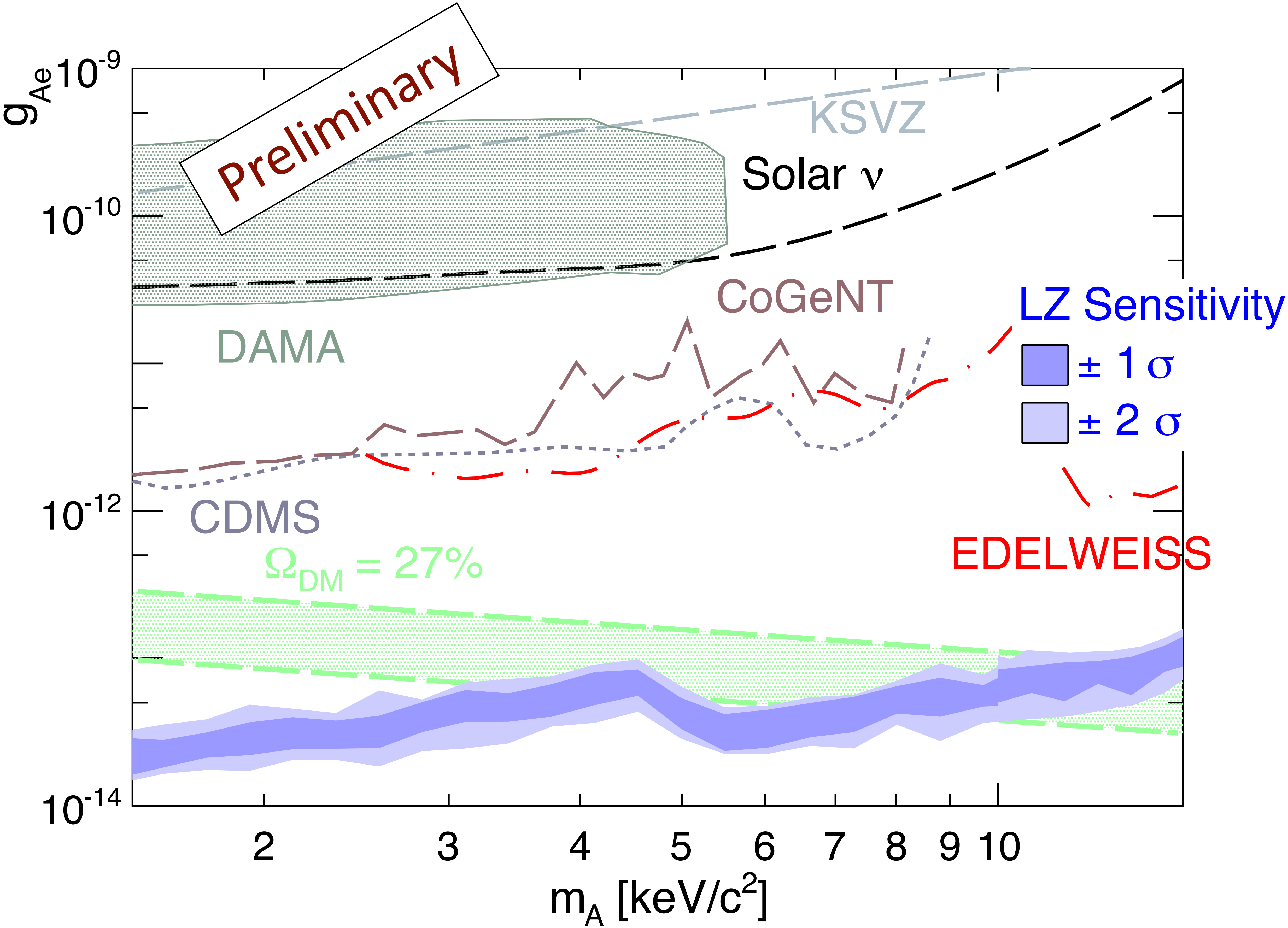
M_A = n keV/c^2 and $g_{Ae} = 1 \times 10^{-10}$

axion flux $\Phi = \rho_{DM}\, v_A/m_A$

convolution to axio-electric effect, LZ expected performances assumed



Galactic axion predicted sensitivity



Summary

Dual phase Xe TPC particularly suitable in testing invisible axions (coupling with the electrons, g_{Ae})

Inputs:

axio-electric effect

Solar axion flux

axion abundance in the galaxy

LZ case study

-> testing g_{Ae} for axion from the Sun down to 1×10^{-12}

=> QCD axions mass excluded above ~ 0.03 eV/c^2 (DFSZ) and ~ 10 eV/c^2 (KSVZ)

-> testing g_{Ae} for axion in the galaxy below to 1×10^{-13} in the mass range $2 < m_A < 10$ keV/c^2

=> probing the axion dark matter scenario.

“I can now rejoice even in the falsification of a cherished theory, because even this is a scientific success.”

– Sir John Carew Eccles

In K. R. Popper, *Conjectures and Refutations*.

… However we do prefer discovery

Backup slides

Axion models

1. QCD axions:
   - KSVZ: coupled to new, heavy quarks and do not interact with ordinary quarks and leptons at the tree level leading to a strong suppression of g_{Ae}.
   - DFSZ: Standard Model quarks and leptons carry a Peccei-Quinn charge.

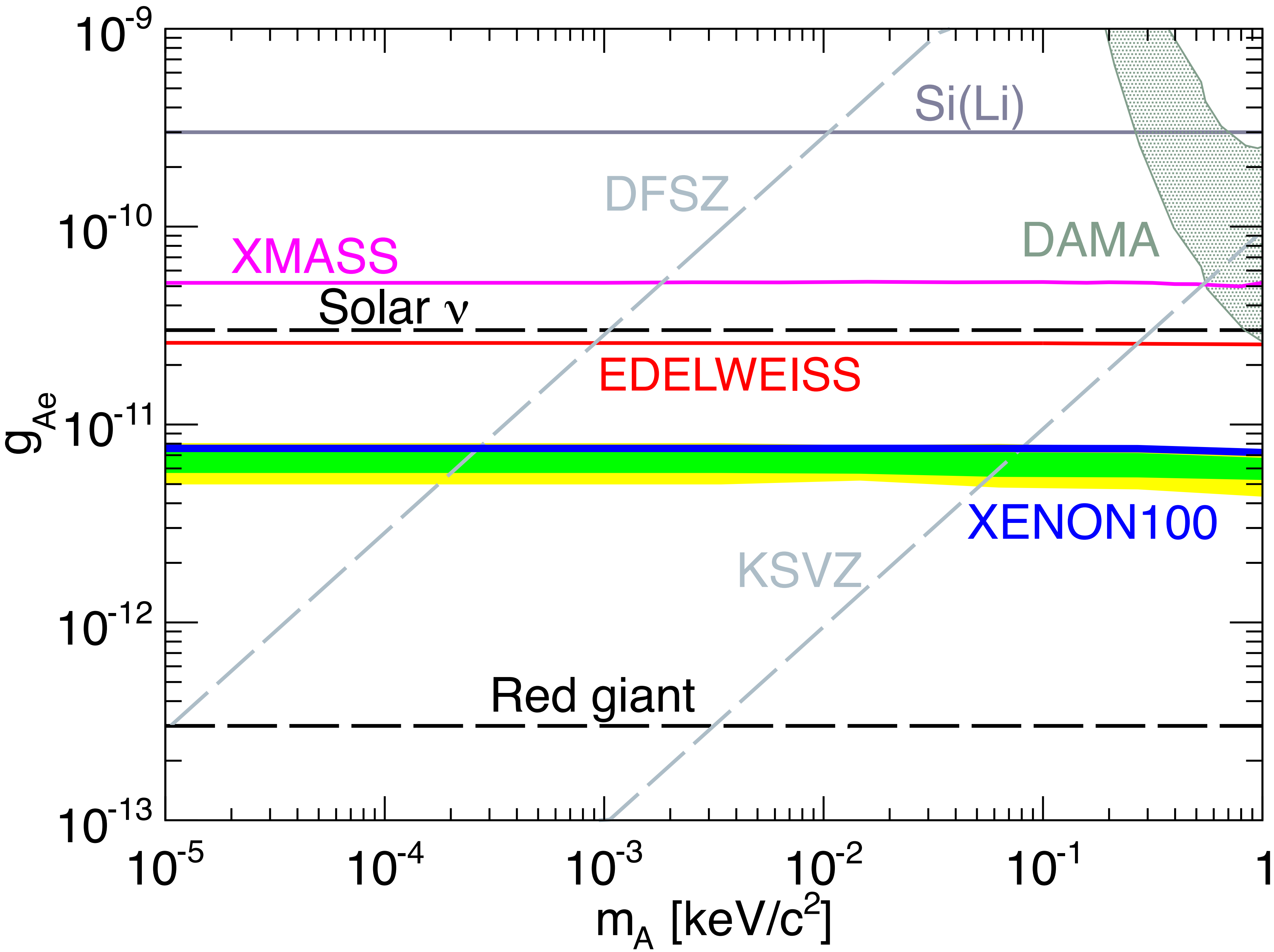
   Experimental searches and astrophysical constraints can be translated to limits on f_A, or equivalently on the axion mass, within a given axion model.

$$m_A = 6\,\mathrm{eV} \times \left(\frac{10^6 \mathrm{GeV}}{f_A} \right)$$

2. Axion-Like-Particles:
   - non-thermal relics
   - thermal relics

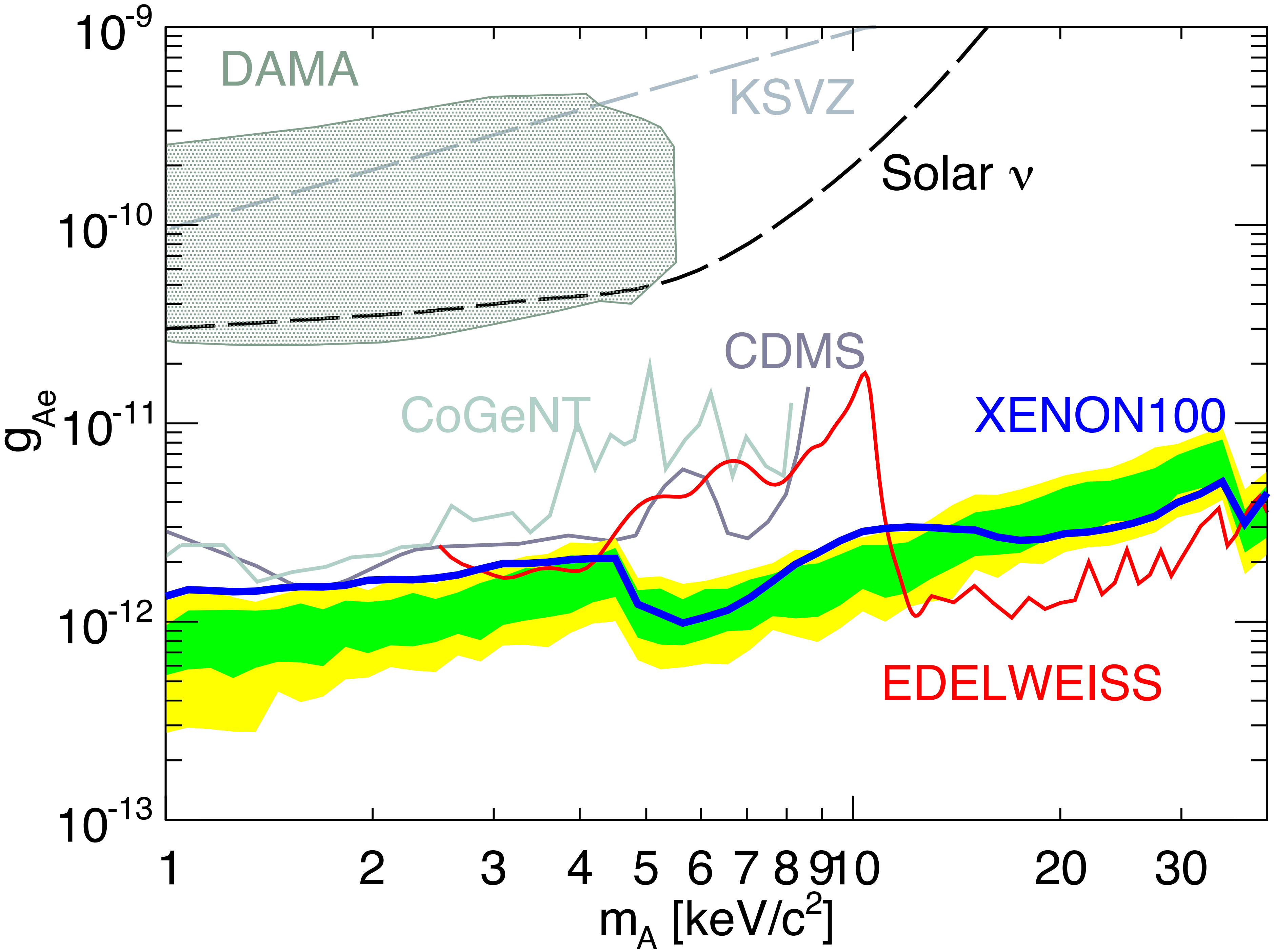
XENON100 Solar axion result

arXiv:1404.1455



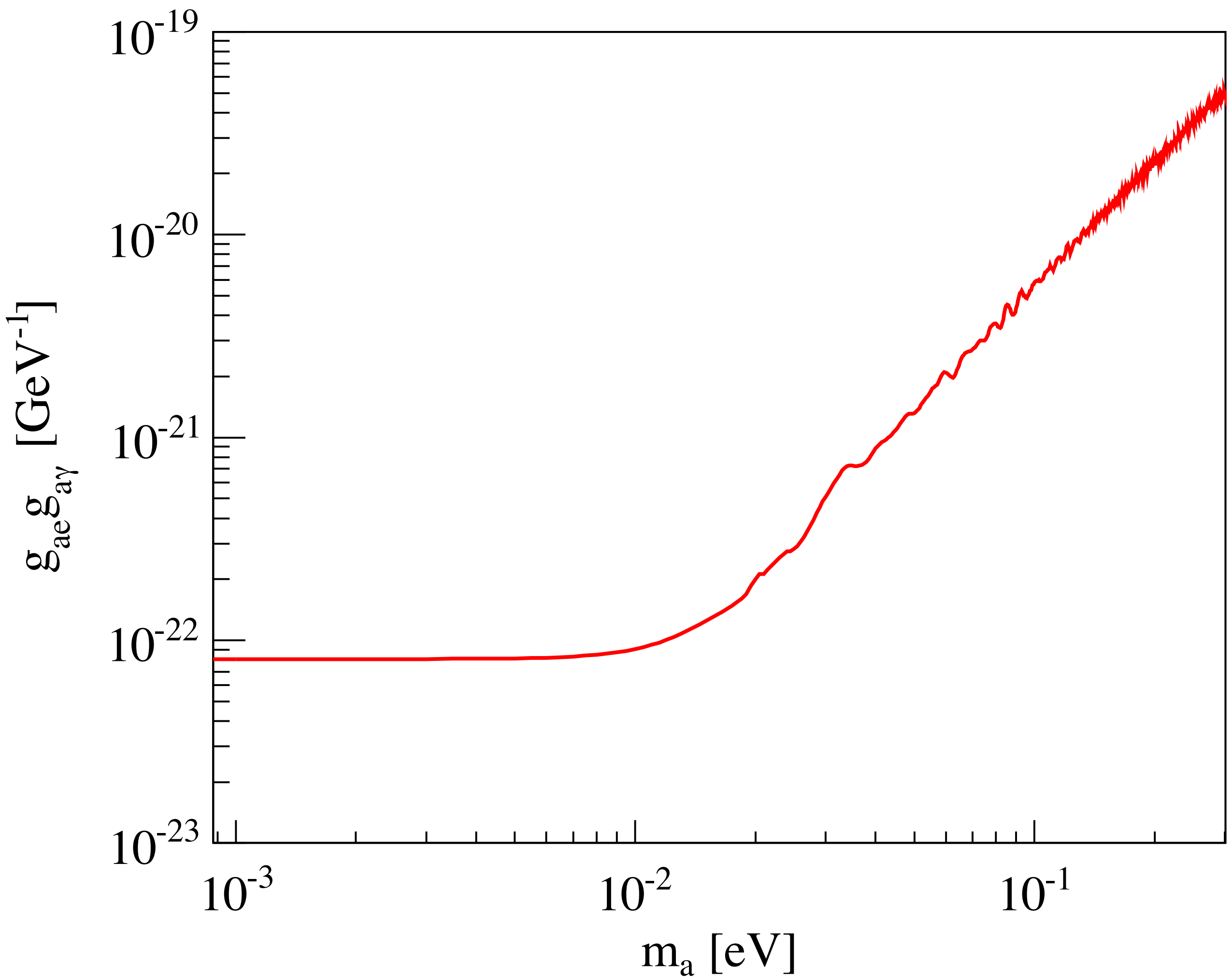
XENON100 Galactic axion result

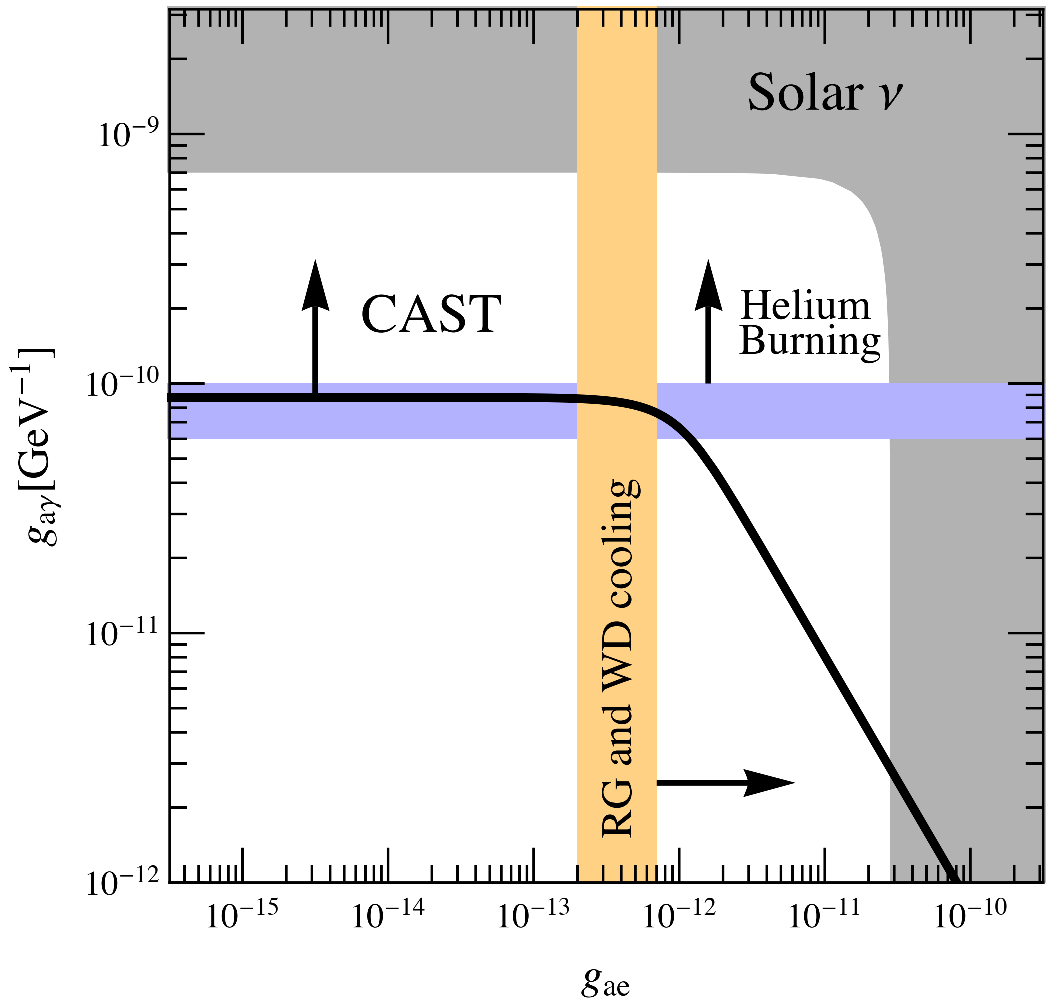
arXiv:1404.1455



CAST

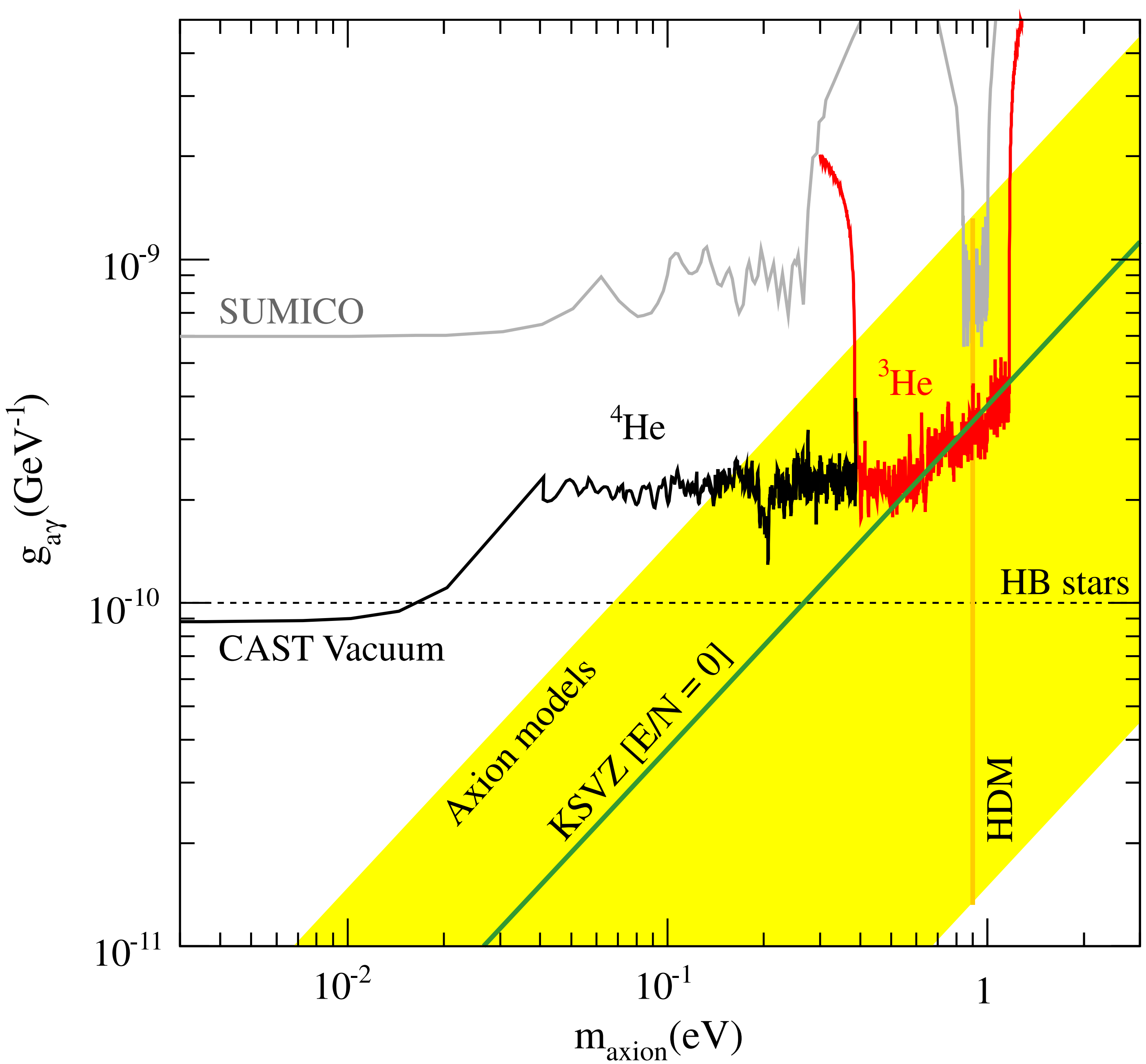
JCAP05(2013) 010





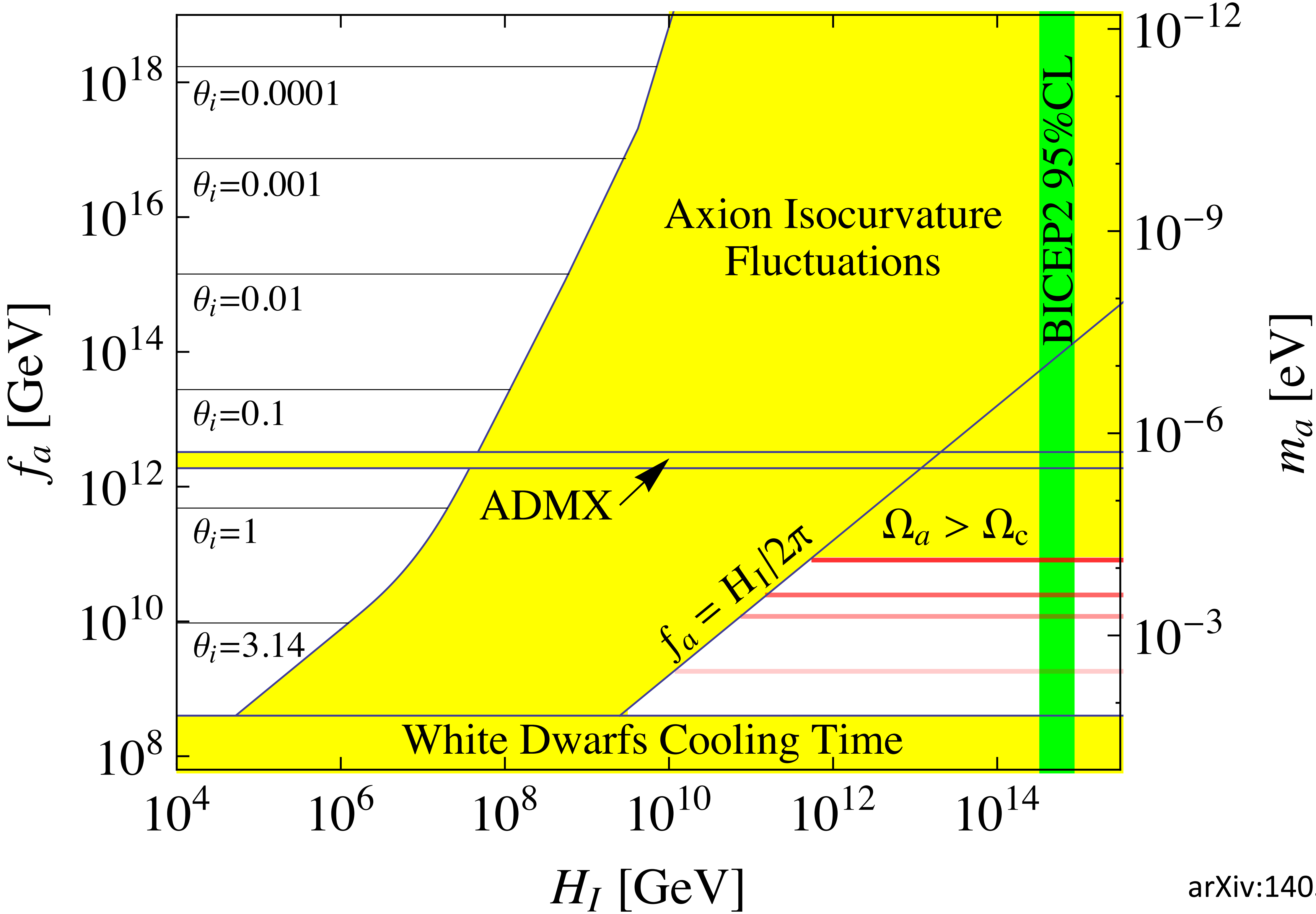
CAST (2)

CAST tests the coupling to photons, $g_{A\gamma}$, has excluded axions within the KSVZ model in the mass range between 0.64 - 1.17 eV/c^2



PRL 112, 091302 (2014)

In view of BICEP2 results

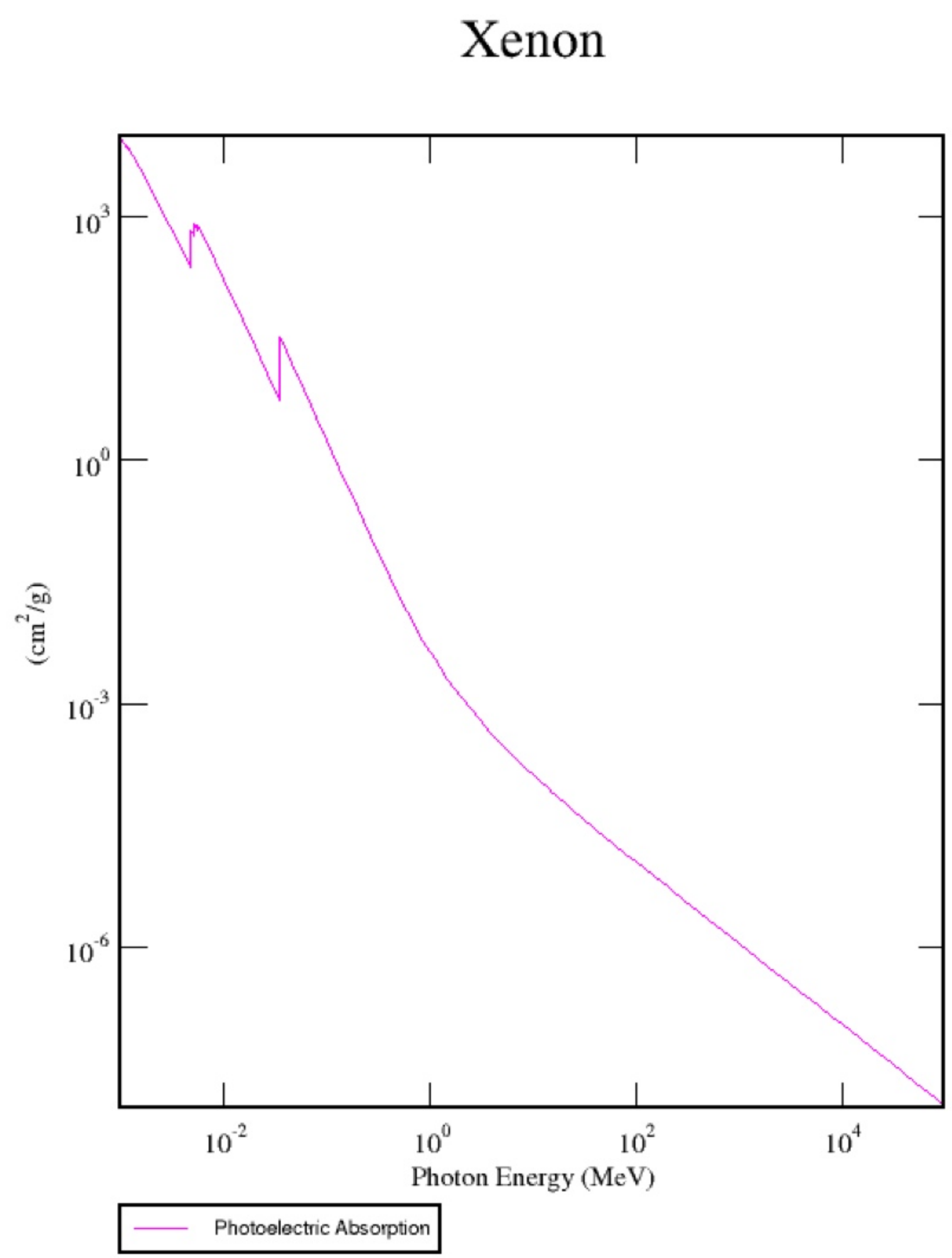


arXiv:1403.4594

Axio-electric effect and testable axions

Proportional to photo-electric cross section

$$\sigma_{Ae} = \sigma_{pe}(E_A)\frac{{g_{Ae}}^2}{\beta_A}\frac{3{E_A}^2}{16\pi\,\alpha_{em}\,{m_e}^2}\left(1-\frac{\beta_A^{2/3}}{3}\right)$$



A case study Profile Likelihood test

Full likelihood function

$$\mathcal{L} = \mathcal{L}_1(g_{Ae}, N_b, L_Y) \times \mathcal{L}_2(L_Y)$$

$$\mathcal{L}_1 = \mathrm{Poiss}(N|N_s + N_b) \prod_{i=1}^{n} \frac{N_s f_s(S1_i) + N_b f_b(S1_i)}{N_s + N_b},$$

$$\mathcal{L}_2(L_Y(t)) = \exp(-\frac{(t - t_{obs})^2}{2}).$$

Test statistics

$$q(g_{Ae}) = -2 \log \lambda(g_{Ae}) = -2 \log \frac{\mathcal{L}(g_{Ae}, \hat{\hat{N}}_b, \hat{\hat{L}}_Y)}{\mathcal{L}(\hat{g}_{Ae}, \hat{N}_b, \hat{L}_Y)}$$

Signal spectrum

$$\mathcal{L}_1 = \mathrm{Poiss}(N|N_s + N_b) \prod_{i=1}^{n} \frac{N_s f_s(S1_i) + N_b f_b(S1_i)}{N_s + N_b},$$

Axion signal rate in terms of photoelectrons

$$\frac{dR}{dn} = \int_0^\infty \frac{dR}{dE_R} \times \mathrm{Poiss}\left(n|n^{exp}\right)$$

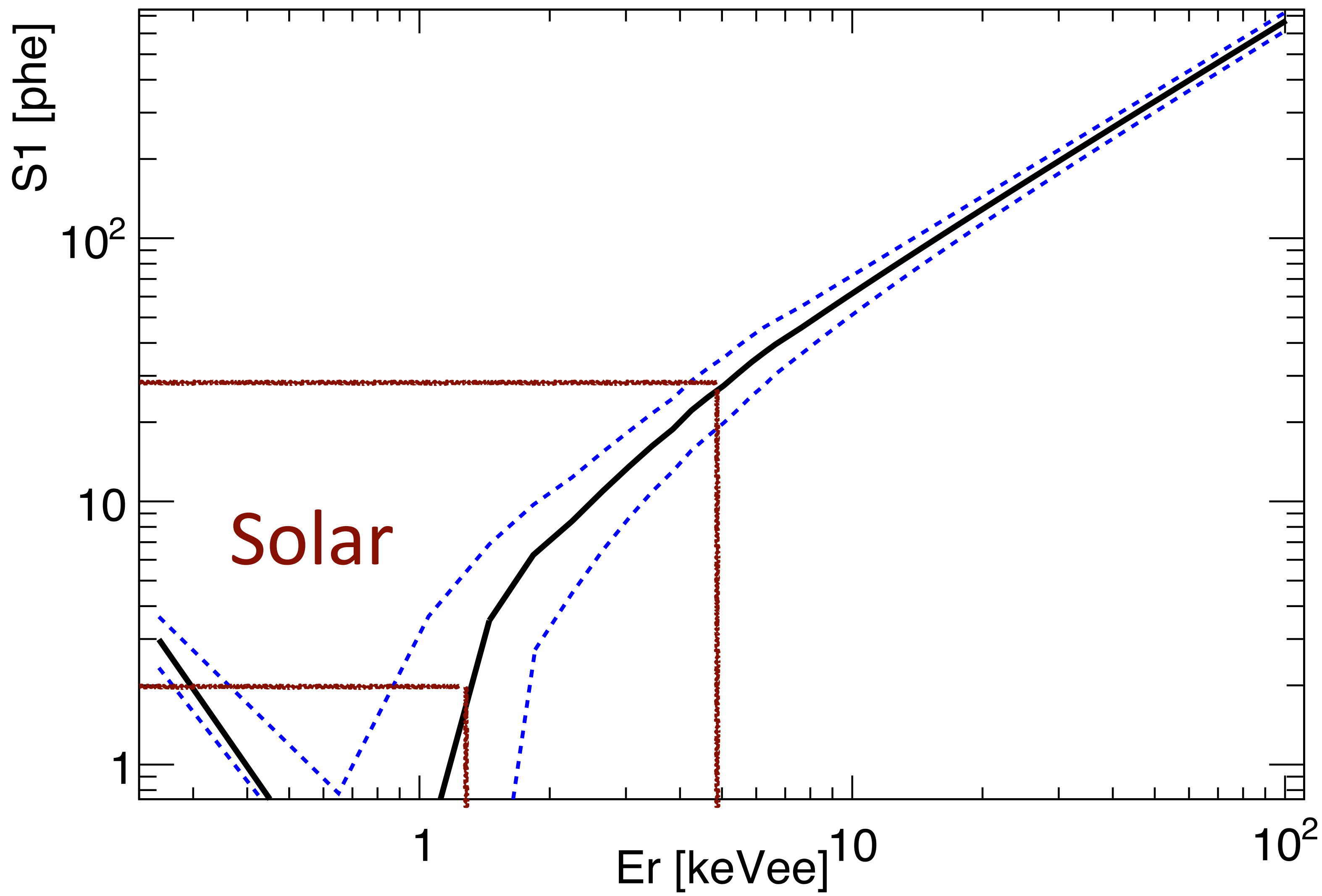
With the rate given by $\frac{dR^{Solar}}{dE_R}$ or $\frac{dR^{DM}}{dm_A}$

Considering the LUX energy scale conversion

$$\frac{dR}{dS1} = \sum_{n=1}^{\infty} \mathrm{Gauss}(S1|n, \sqrt{n}\sigma_{PMT}) \times \frac{dR}{dn} \times \epsilon(S1)$$

Energy to S1 signal conversion

Solar Axion ROI: 2 - 30 phe (in S1)

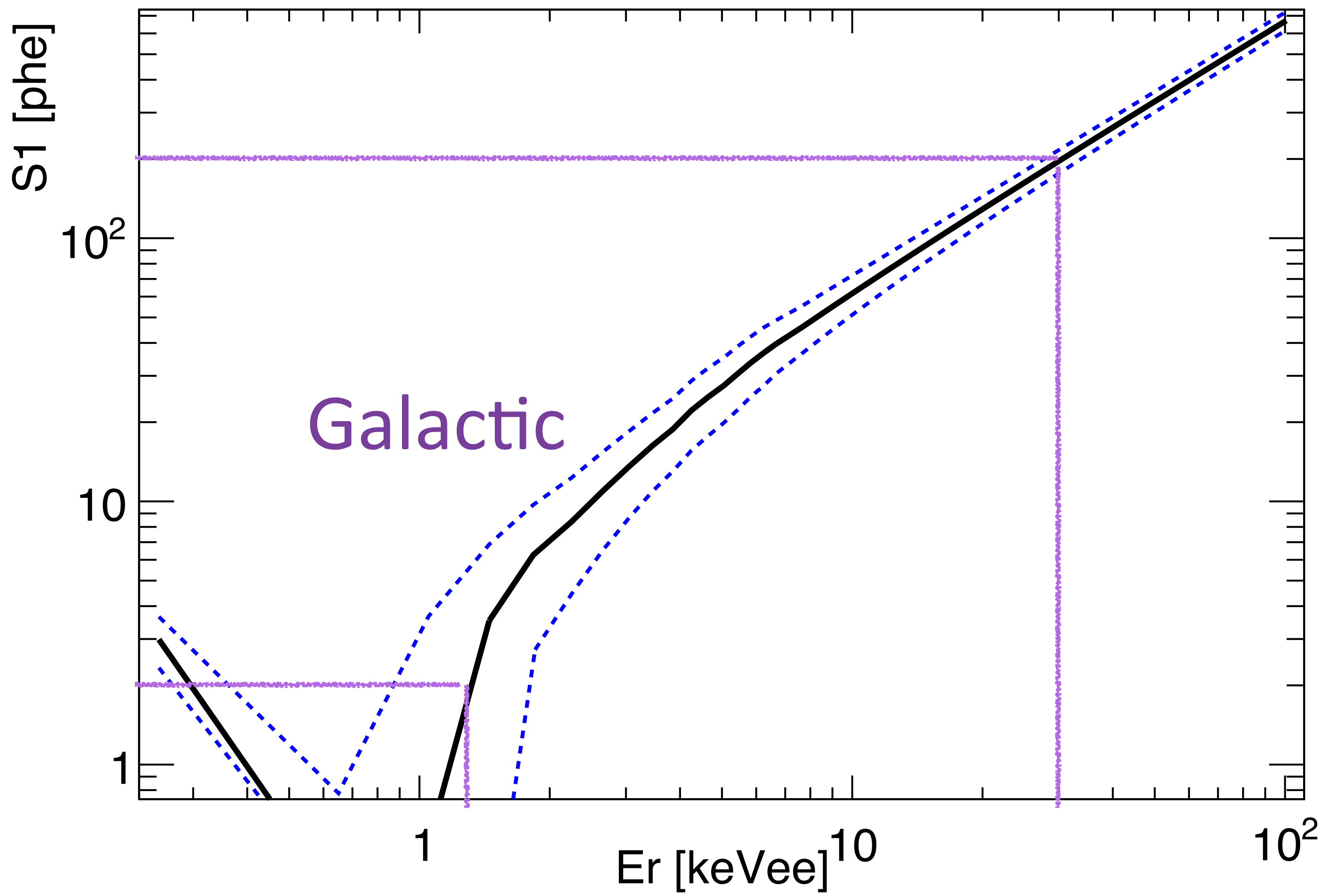


From LUX light yield, extended to higher value (the original is limited to 10 keVee)

If it drops below 0 phe the PLR takes it as 0 => no S1 produced

Energy to S1 signal conversion

Galactic Axion ROI: 2 - 200 phe (in S1)



From LUX light yield, extended to higher value (the original is limited to 10 keVee)

If it drops below 0 phe the PLR takes it as 0 => no S1 produced

Energy scale nuisance parameters

$$\mathcal{L}_2(L_Y(t)) = \exp(-\frac{(t - t_{obs})^2}{2})$$

The +/- σ considered as nuisance parameters gaussian distributer around the median