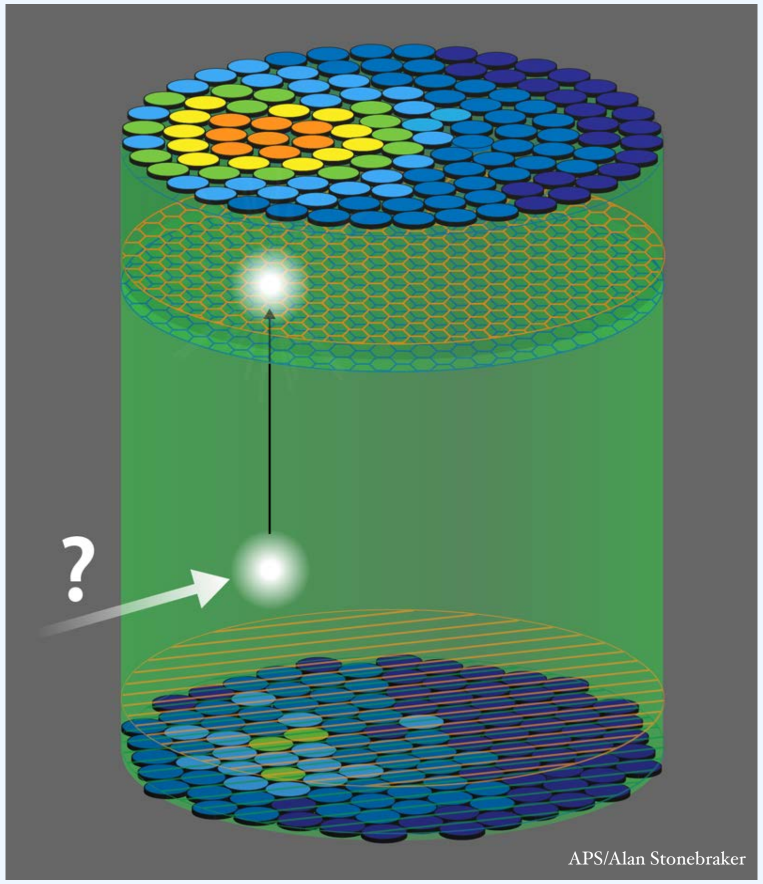
Excess electronic recoil events in XENON1T



Michelle Galloway (Universität Zürich)

for the XENON Collaboration

with X. Mougeot (CEA Saclay)

Universität Freiburg Seminar | 4 November 2020

XENON Dark Matter Project

Universität Zürich UZH

The XENON Collaboration

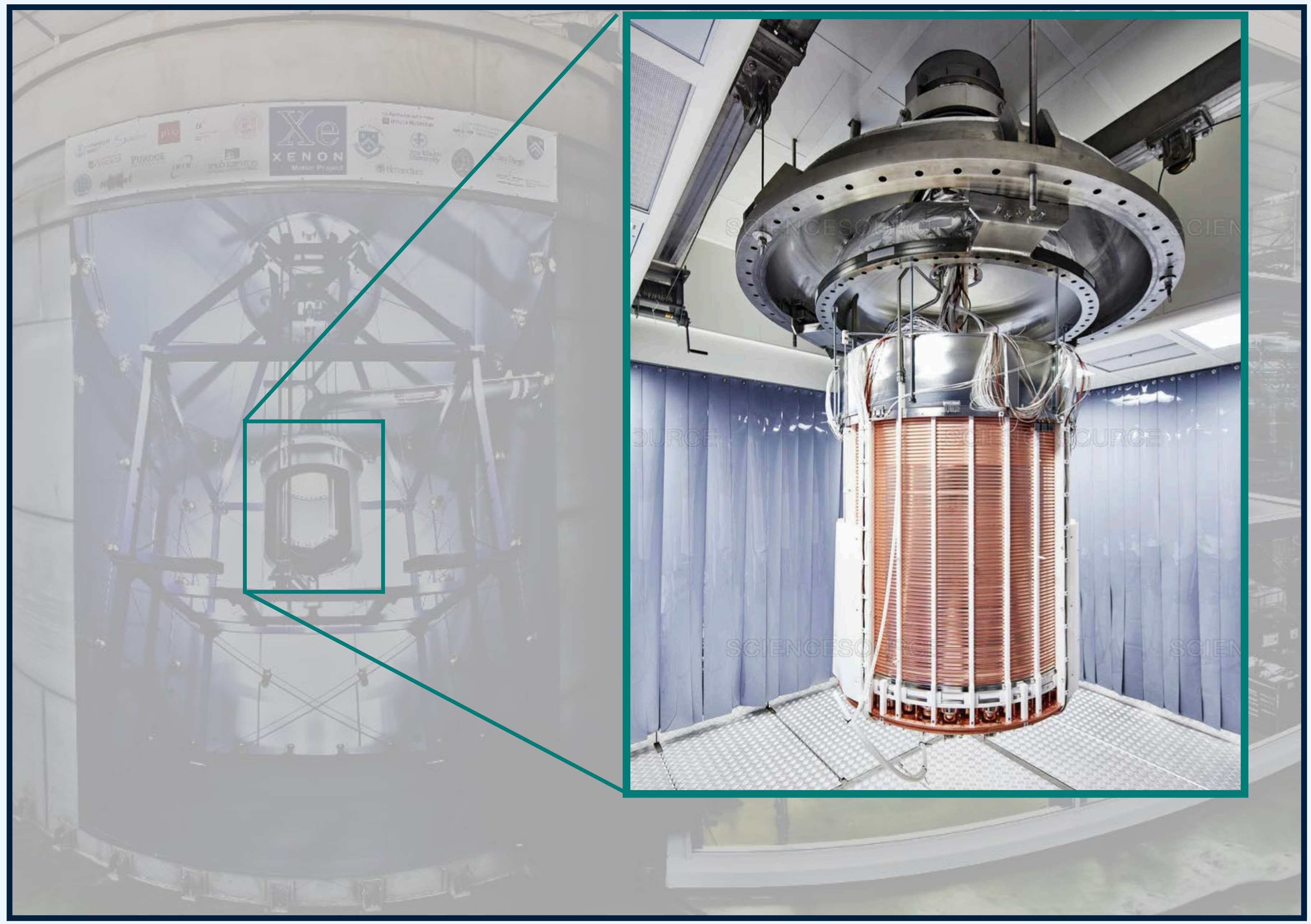
> 170 scientists

26 institutions

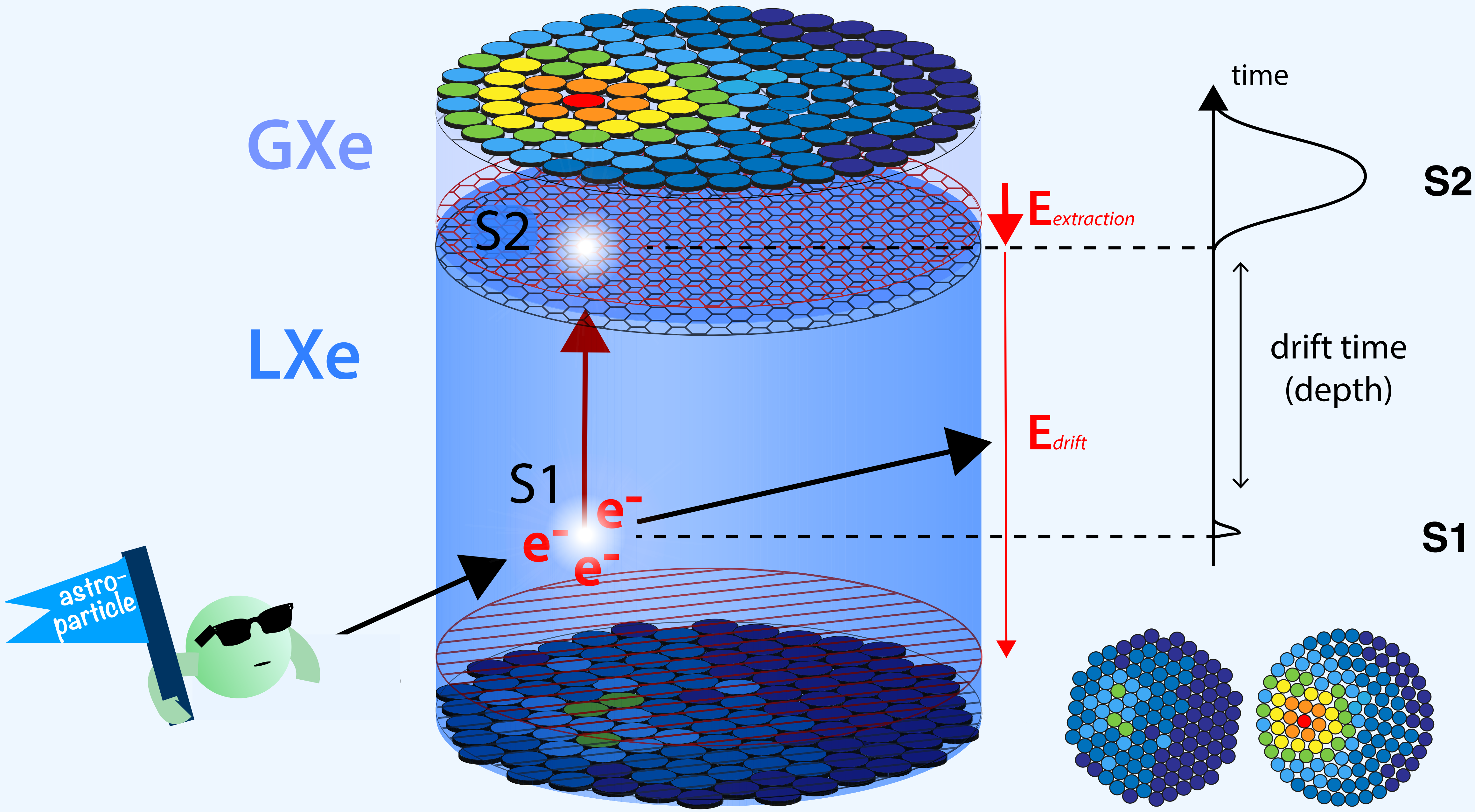
11 countries

The XENON Experiment

Laboratori Nazionali del Gran Sasso



Dual-phase Time Projection Chamber

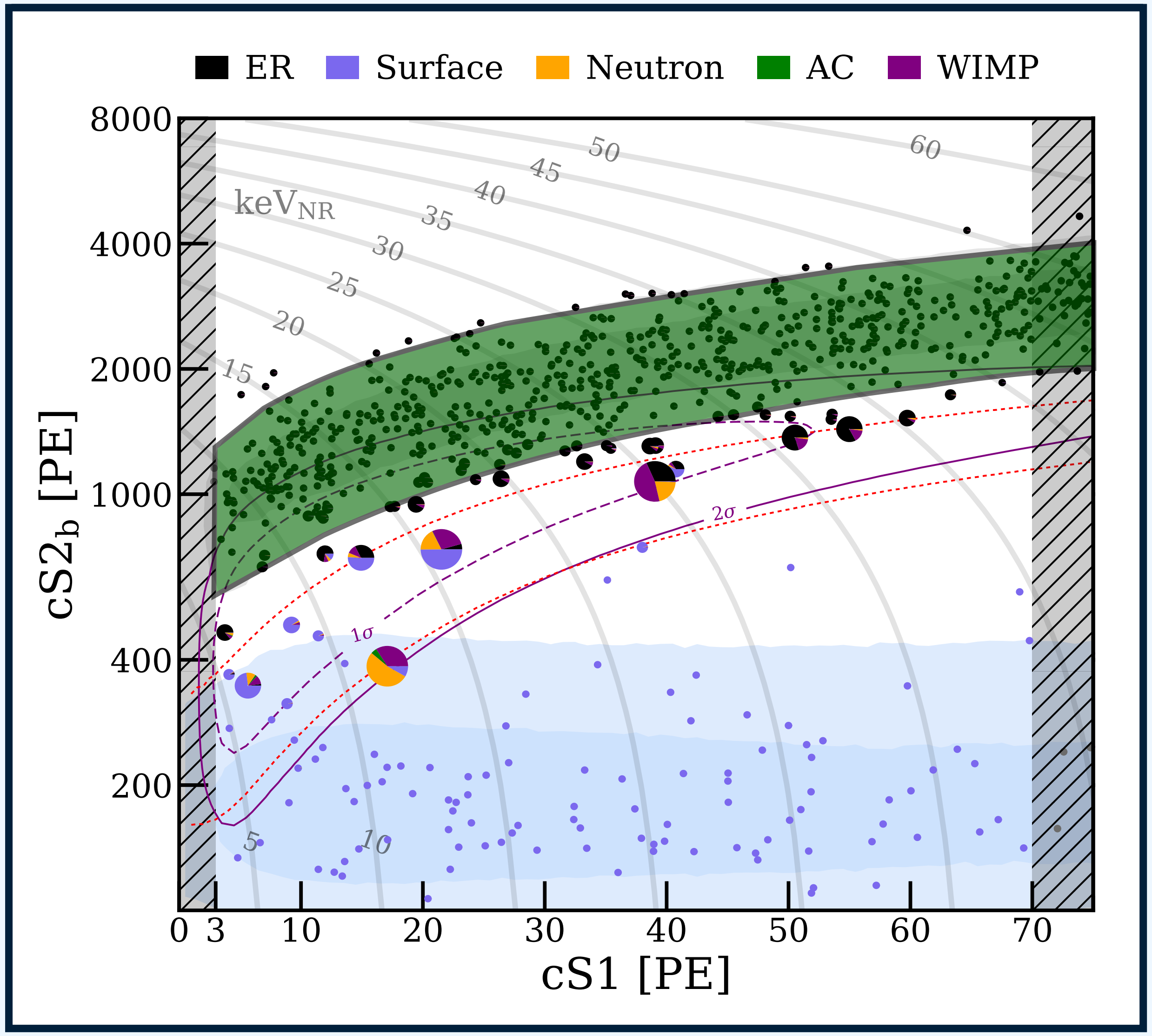


(liquid/gas xenon TPC)

Interaction types

Electronic Recoils (ER)
(gammas, betas, new physics)

Nuclear Recoils (NR)
(WIMPs, neutrons)

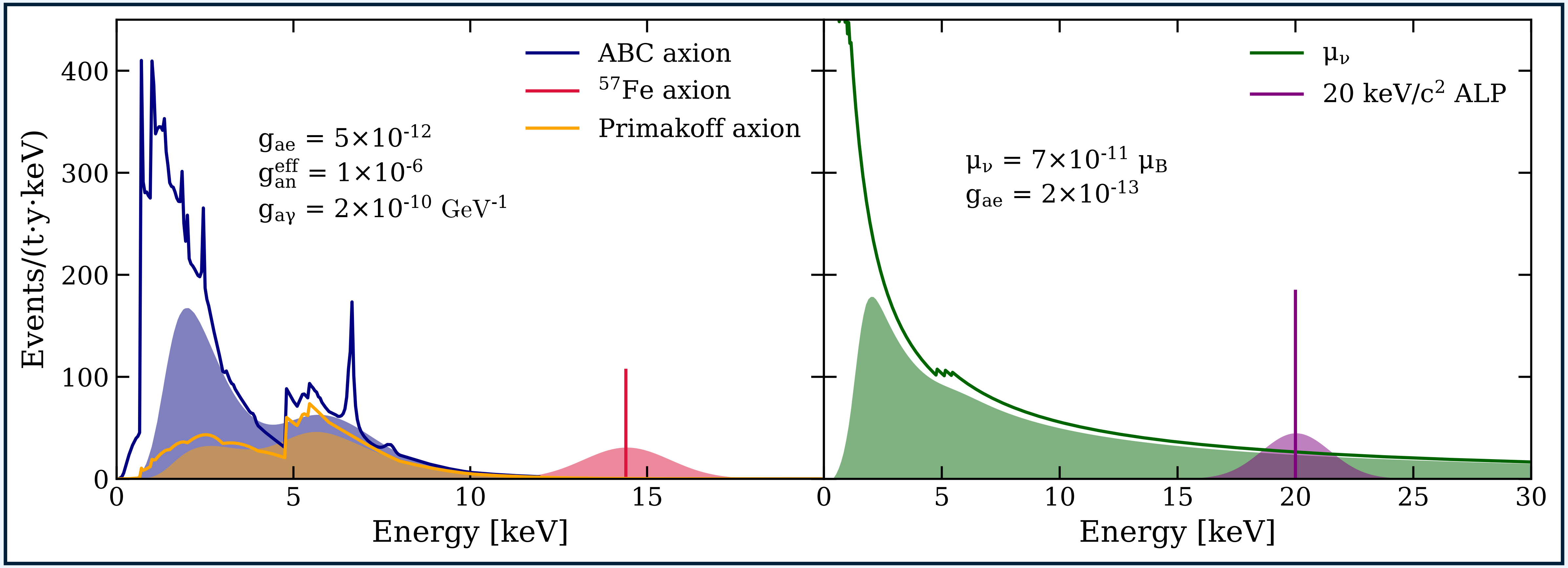


< 100 events/(t/yr/keV$_{ee}$)

Currently most stringent result on WIMP Dark Matter down to 3 GeV/c² masses [PRL 121, 111302 + PRL 123, 251801]

Search for excess above known ER backgrounds.

Search for new physics

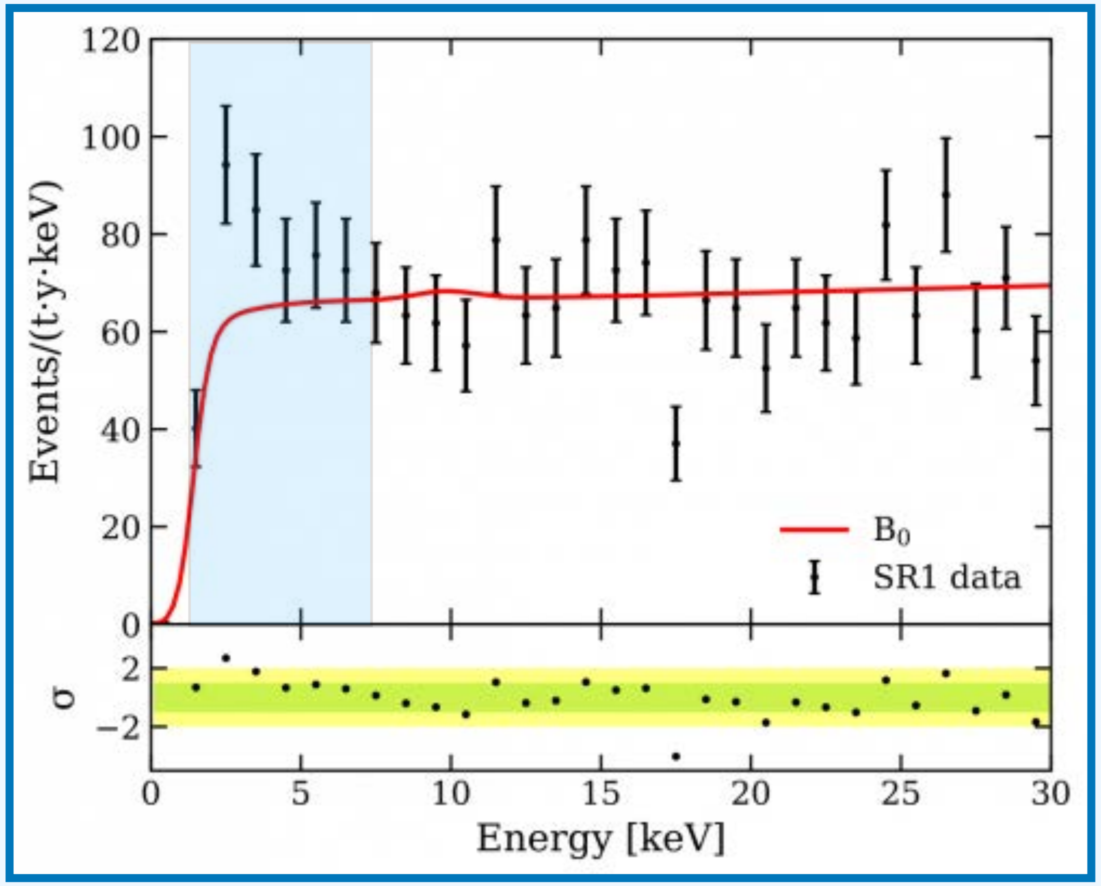


Solar axions:
Arise from Peccei-Quinn solution to strong-CP problem in QCD: pseudo-NG boson

Enhancement of the neutrino magnetic moment:
Majorana or Dirac nature

Bosonic dark matter (axion-like particles, dark photons):
keV-scale dark matter, mediator of dark sector (dark photon)

Excess found!



reference region 1-7 keV

3.3σ Poissonian fluctuation over null

Today's talk:

- Analysis methods

  validation

- Backgrounds
- Signal hypotheses
- Next steps: XENONnT

First hint of excess Sept. 2018

Excess electronic recoil events in XENON1T

XENON Collaboration • E. Aprile (Columbia U.) Show All(139)

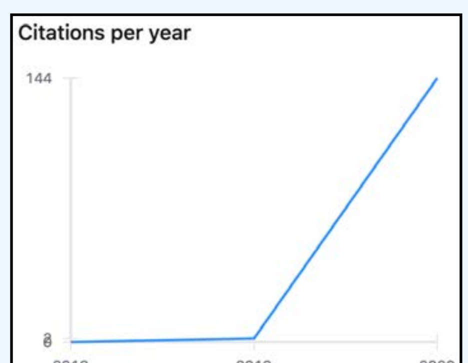
Jun 17, 2020

26 pages

Published in: *Phys.Rev.D* 102 (2020) 7, 072004

e-Print: 2006.09721 [hep-ex]

DOI: 10.1103/PhysRevD.102.072004



Theorists React to Potential Signal in Dark Matter Detector

Featured in Physics | Open Access

Excess electronic recoil events in XENON1T

E. Aprile *et al.* (XENON Collaboration)

Phys. Rev. D **102**, 072004 – Published 12 October 2020

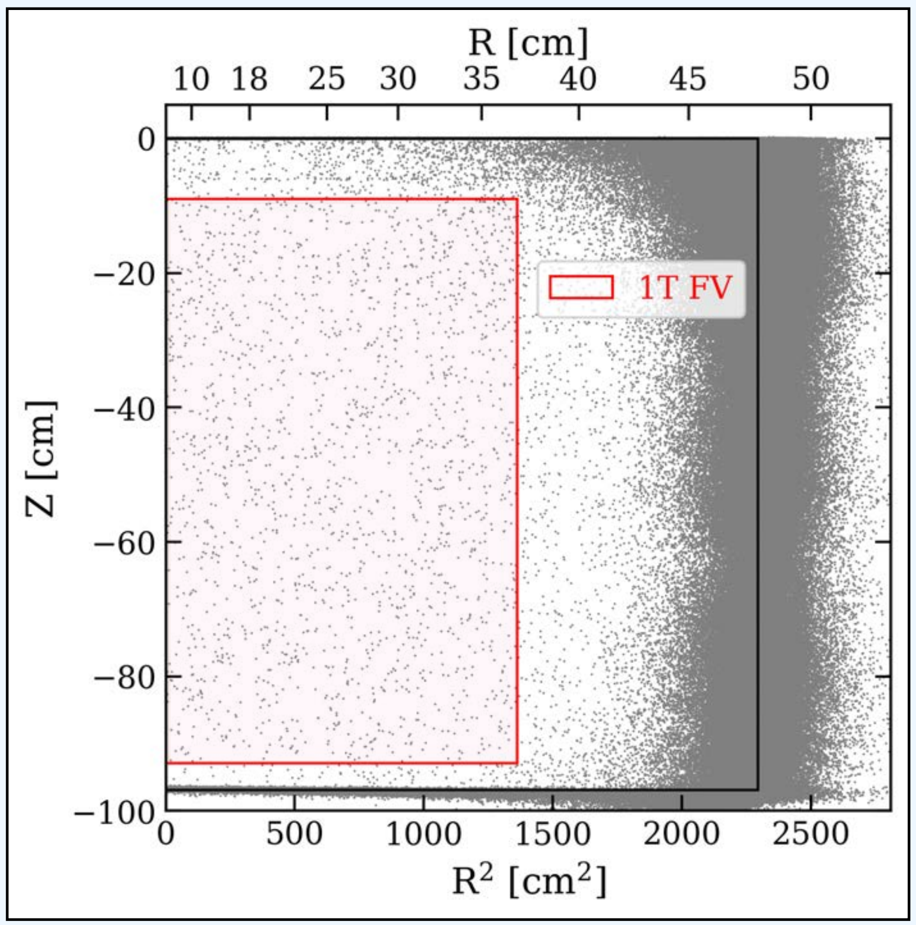
Physics See Viewpoint: Dark Matter Detector Delivers Enigmatic Signal

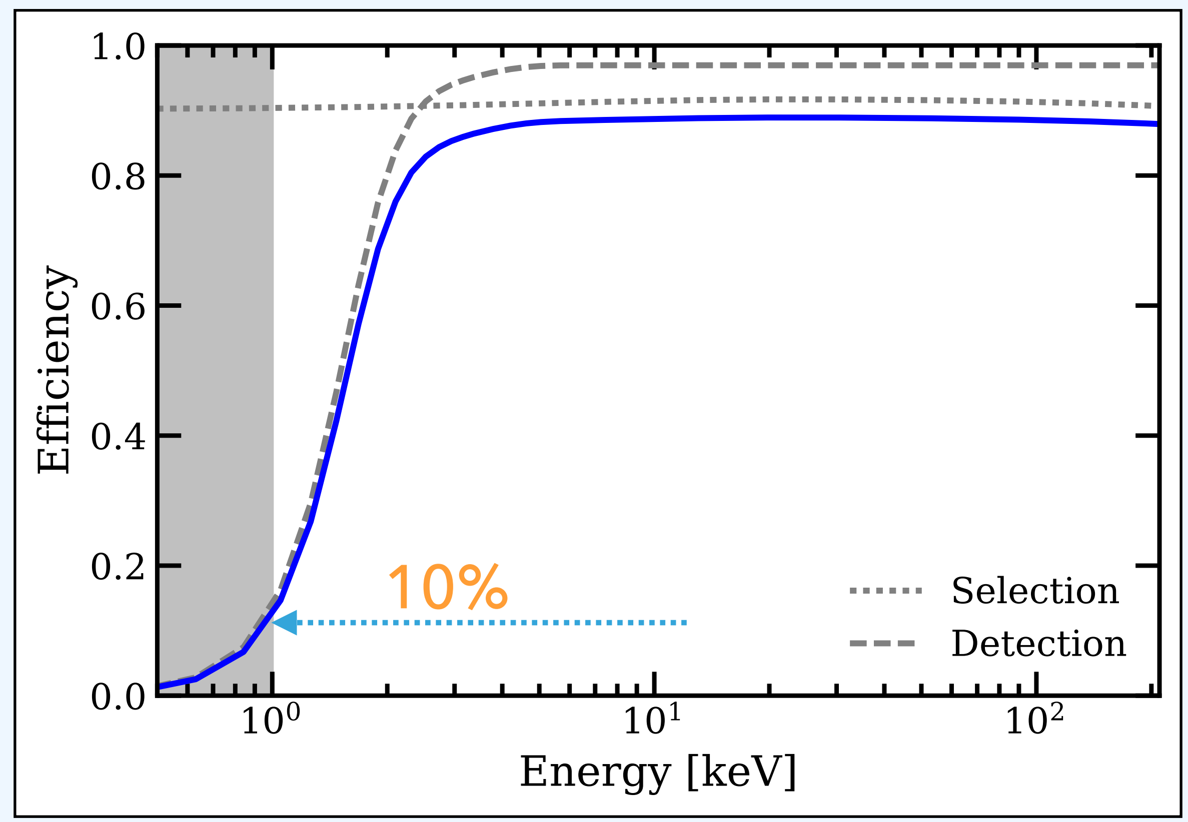
Data Analysis

Data selection

Science Run 1 (SR1)
226.9 days
0.65 tonne-yr exposure

- S1: 3-fold PMT coincidence; S2 500 pe threshold
- single-scatter events
- standard data quality cuts
- 1 keV threshold at 10% efficiency
- uncertainty on efficiency added as nuisance parameter

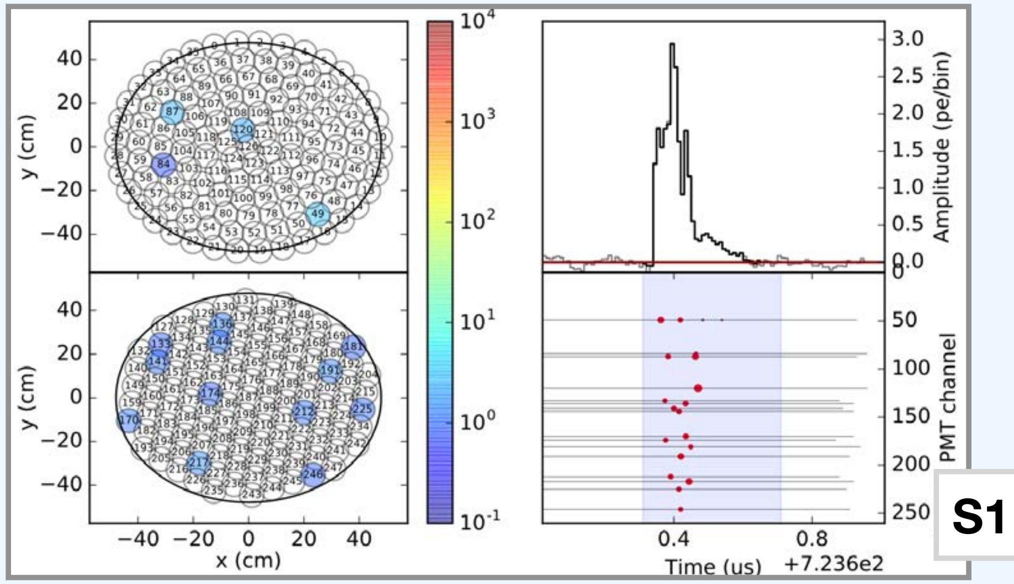


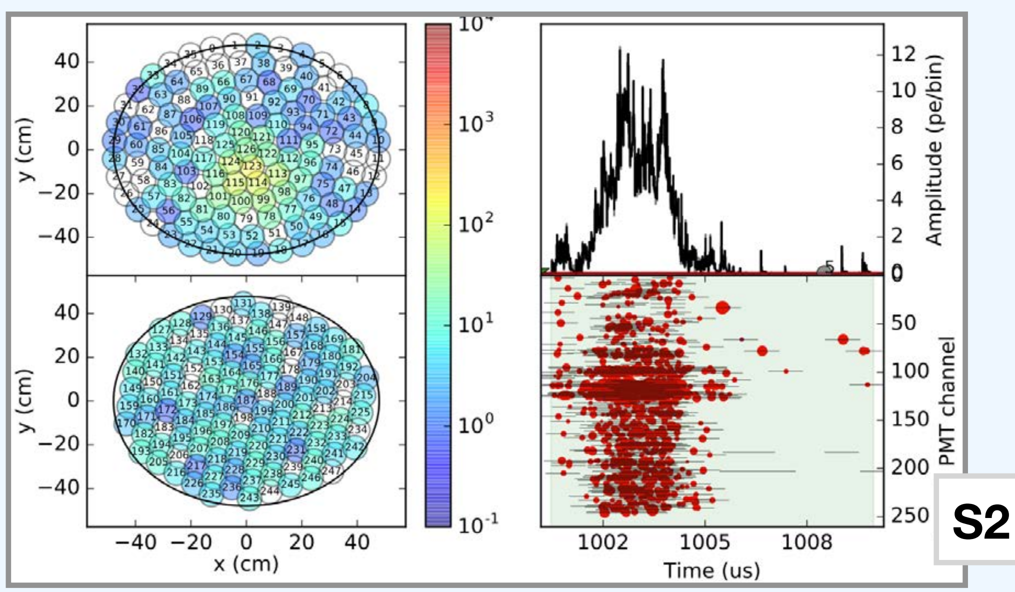


Fiducial volume 1042 kg

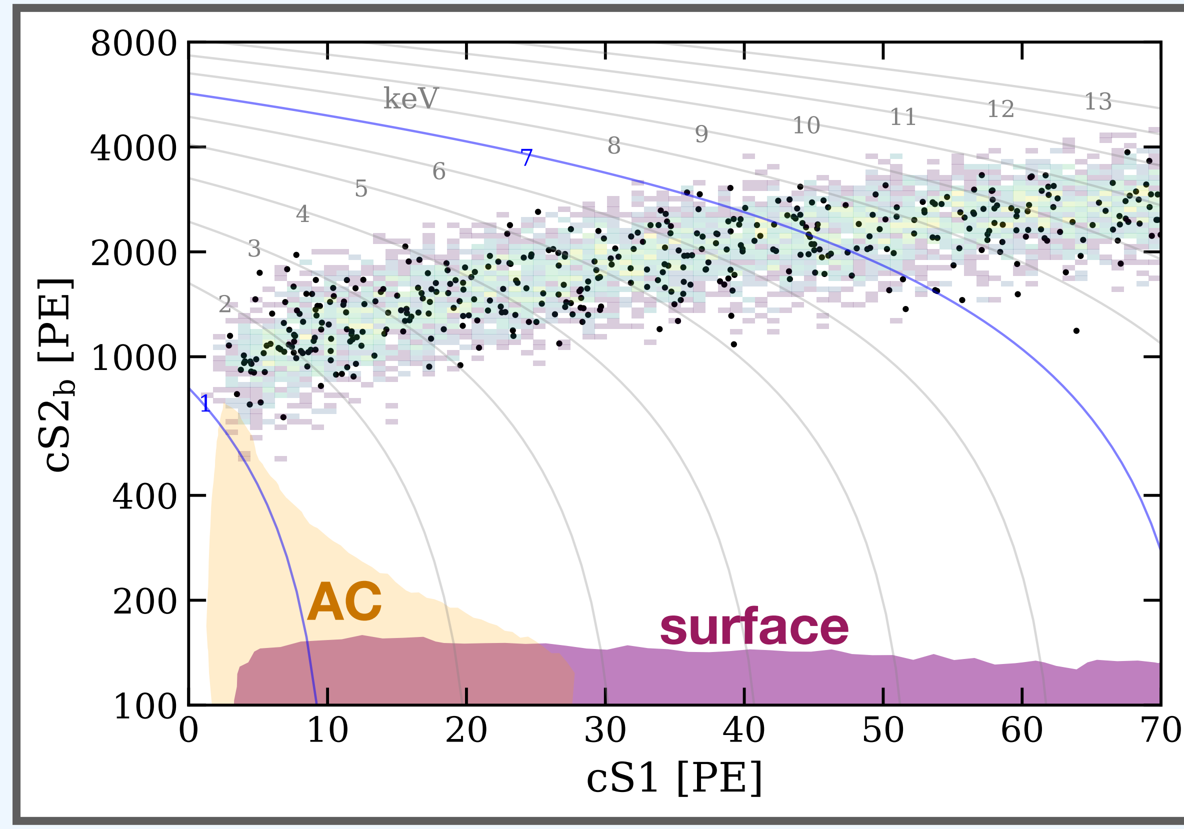
Analysis energy range: 1 - 210 keV_{ee}

Event quality and backgrounds





Event classification and
waveform inspection: all ok.

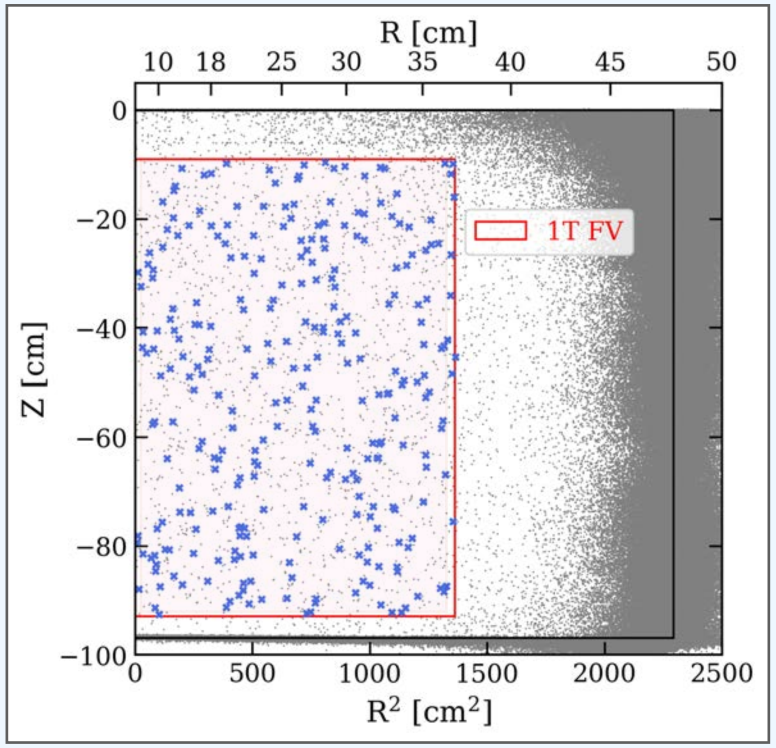


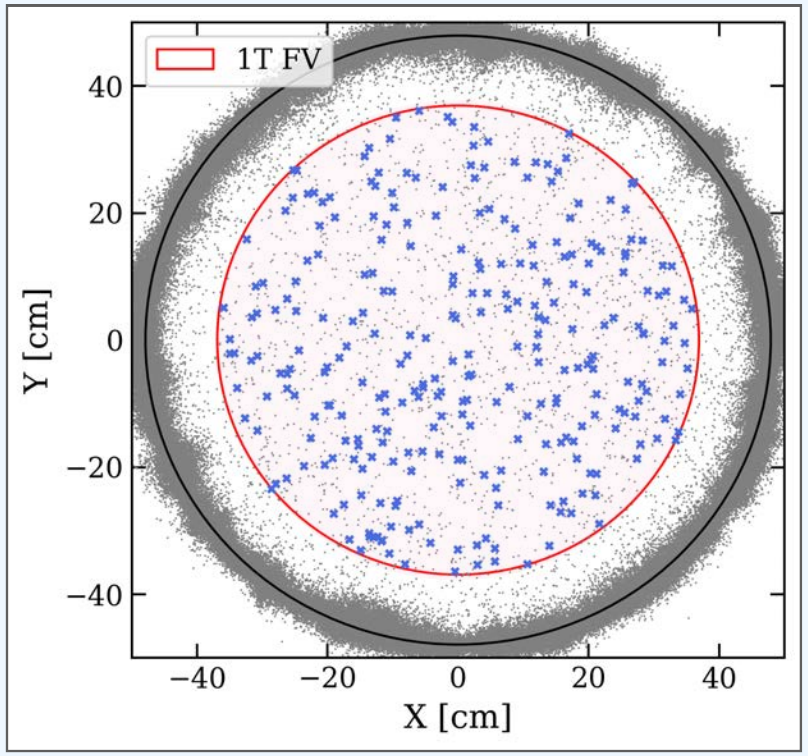
Instrumental backgrounds

No accidental coincidences (AC) or surface
backgrounds reconstructed in ROI
falls within ER band (physical events)

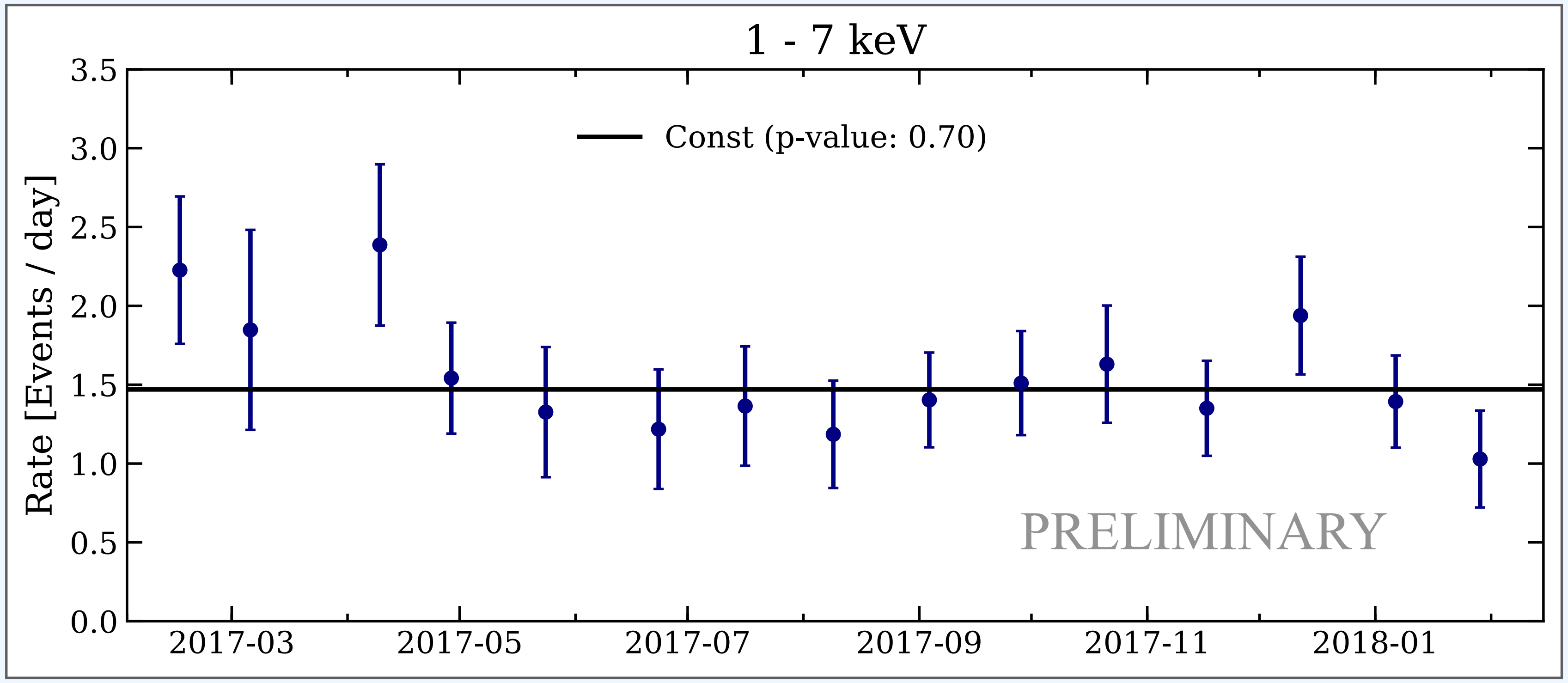
Valid events

Event location and classification





Events are uniformly distributed within fiducial volume

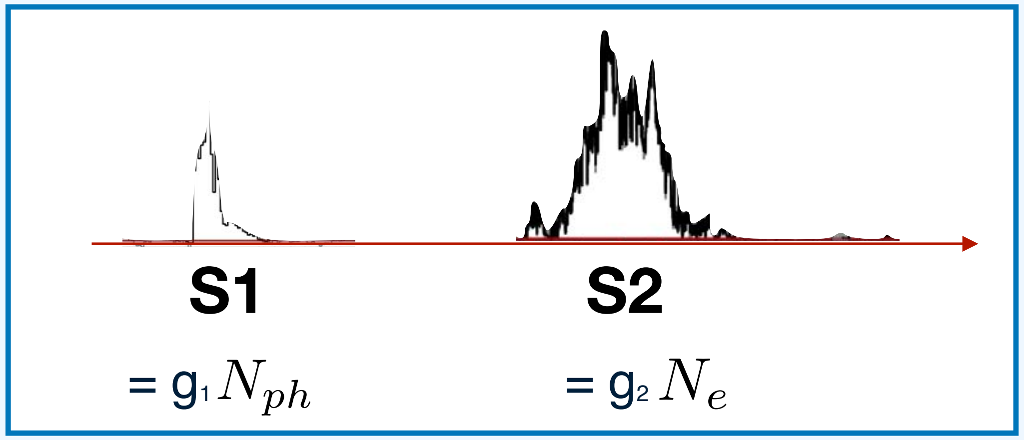


Consistent with constant time, but with very low statistics!

(*dedicated annual modulation analysis in progress*)

Spatio-temporal uniformity expected from a signal

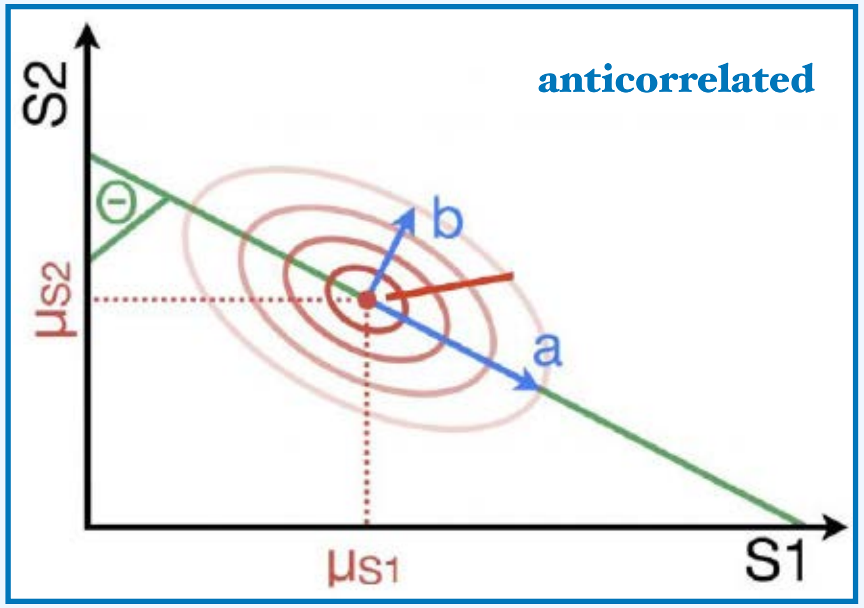
Energy Reconstruction

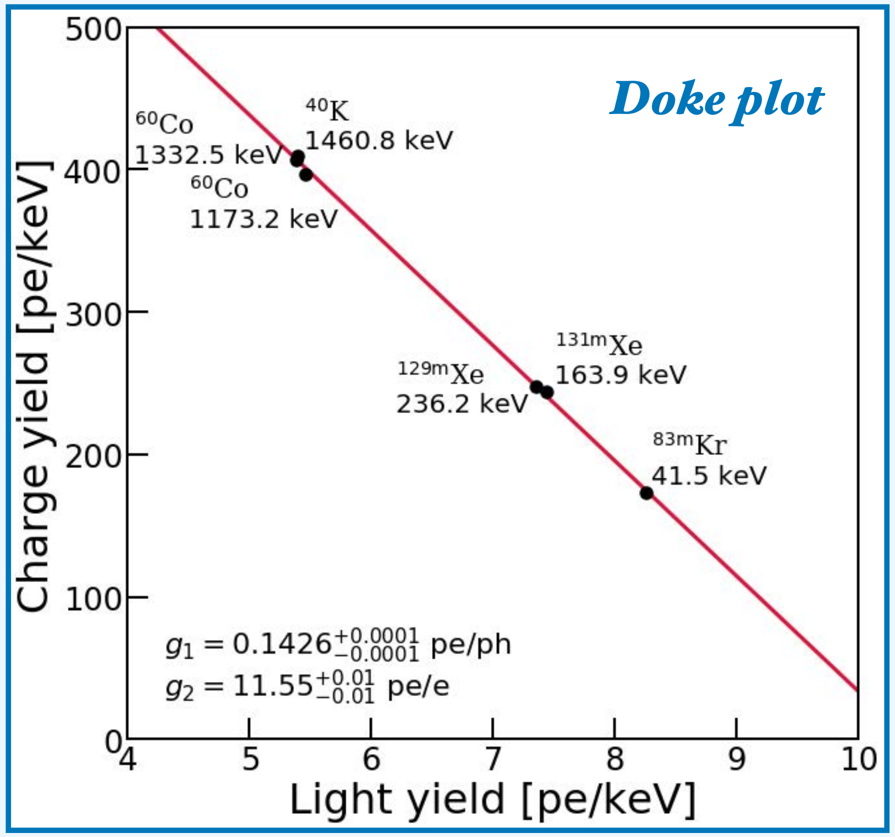


$$E = (N_{ph} + N_e) \cdot W$$

with W = 13.7 eV/quanta for xenon

g_1 and **g_2**:
detector-specific gain constants;
extract g_1/g_2 from calibration data





$$\frac{S2}{E} = -\frac{g_2}{g_1}\frac{S1}{E} + \frac{g_2}{W}$$

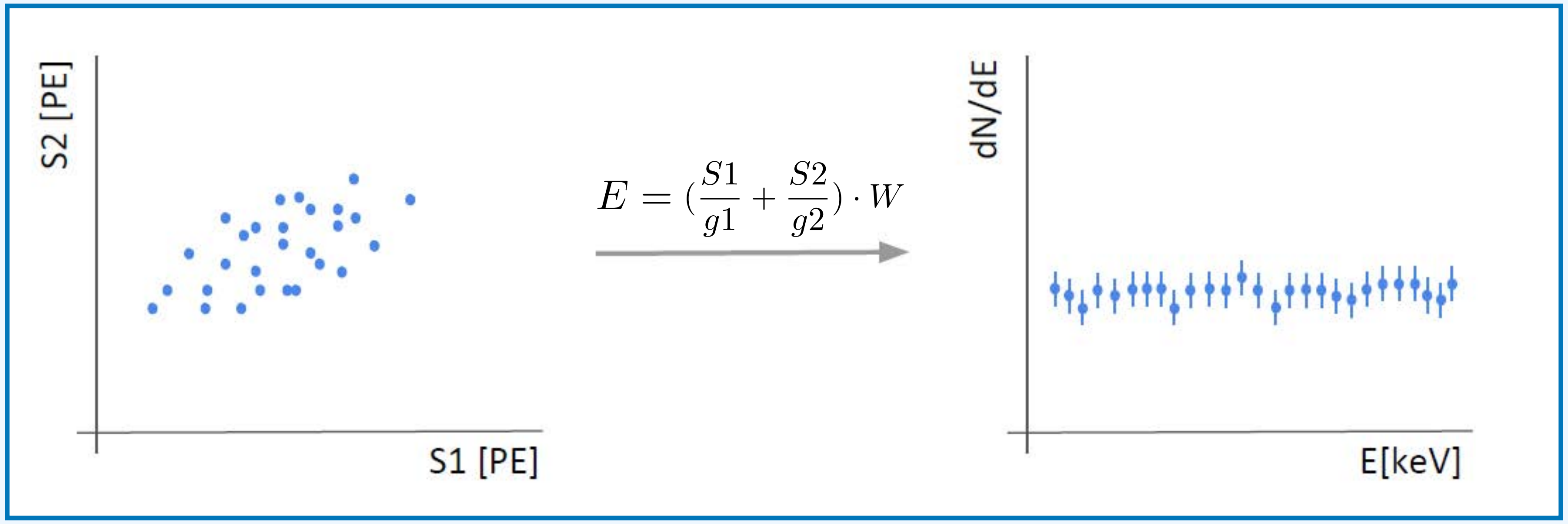
g_1 and g_2 are used to reconstruct energy of each event

$$E = (\frac{S1}{g1} + \frac{S2}{g2}) \cdot W$$

Energy Reconstruction

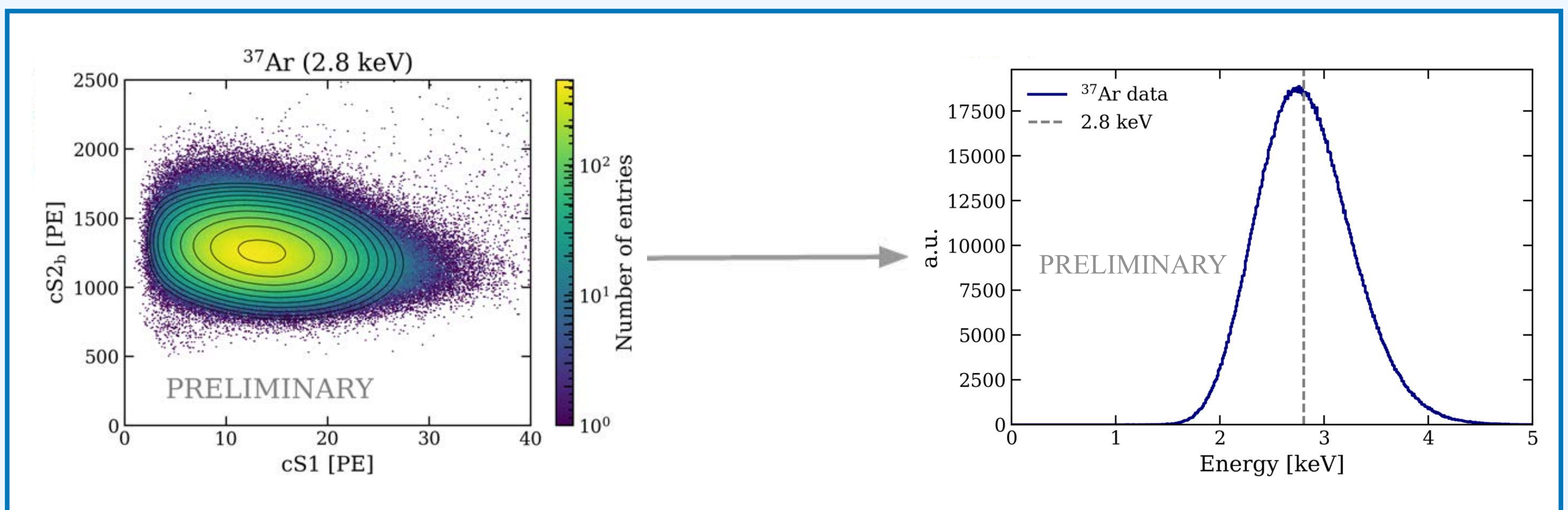
2D analysis

1D analysis

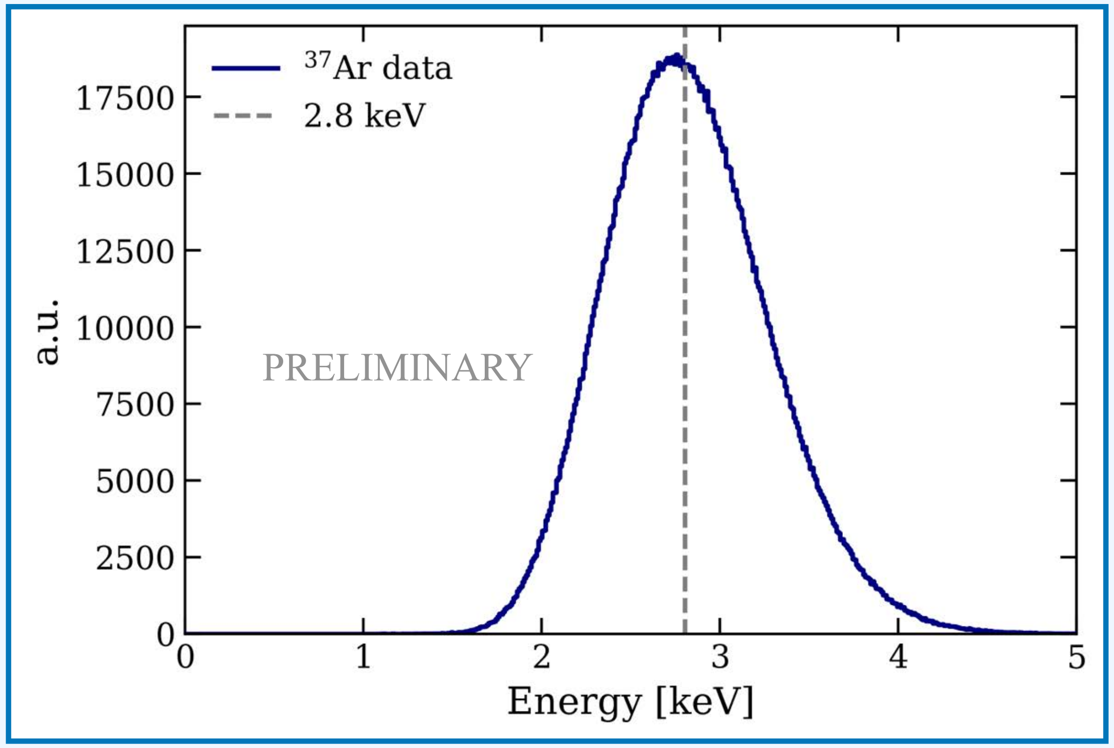


S2/S1 space

Combined Energy Scale



Energy reconstruction and resolution

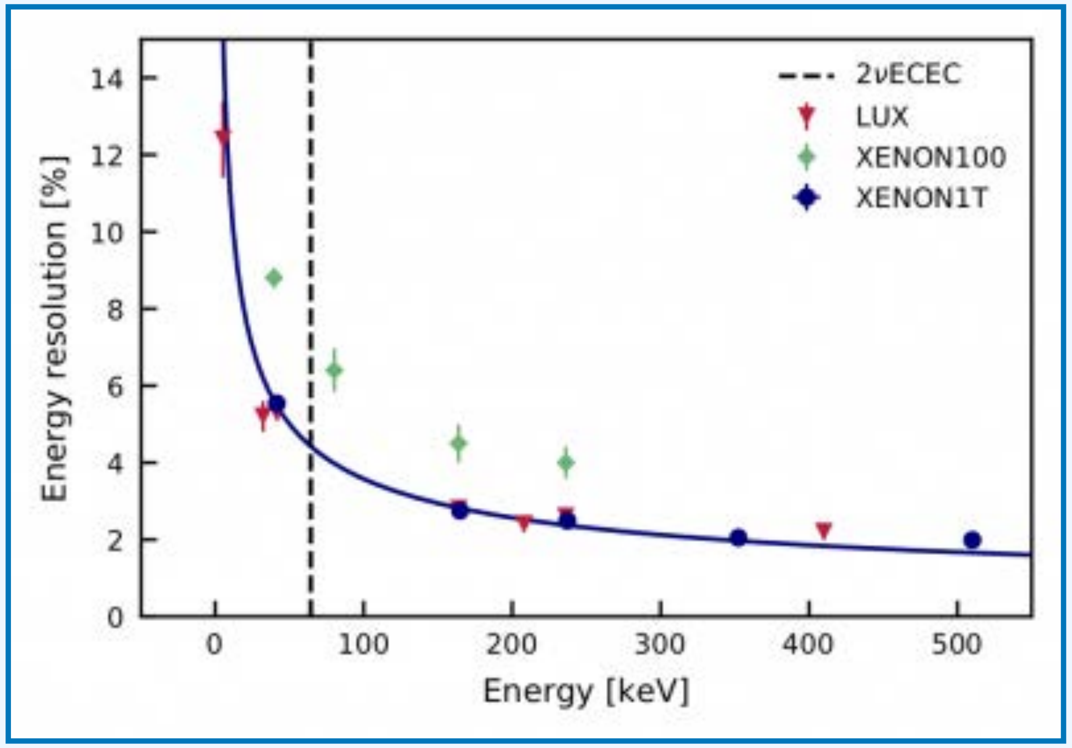


^{37}Ar 2.8 keV reconstructed peak

Mean energy

Observed: 2.827 keV

Model: 2.834 keV



Energy Resolution

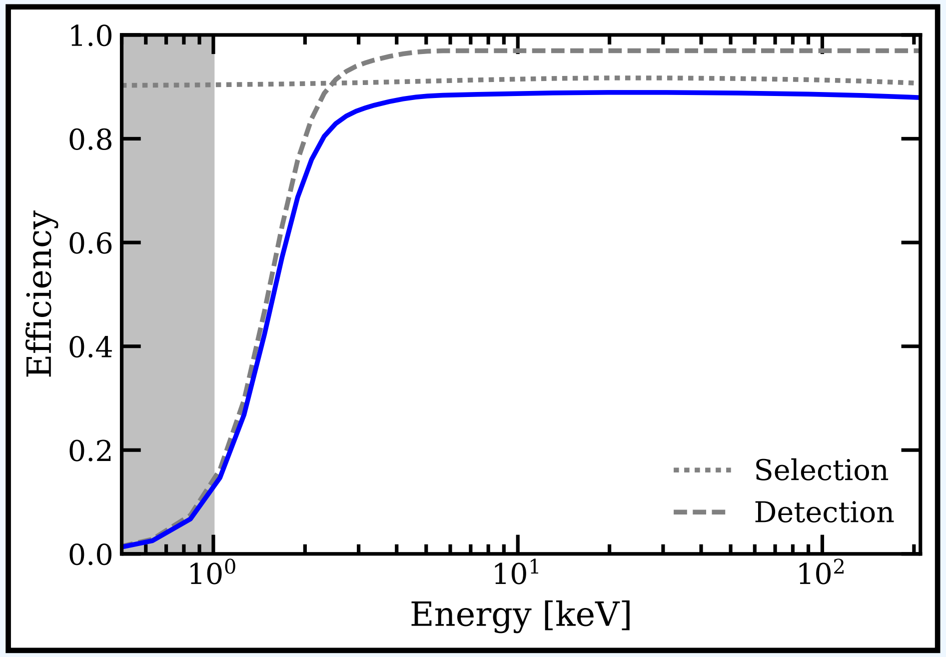
^{37}Ar Resolution

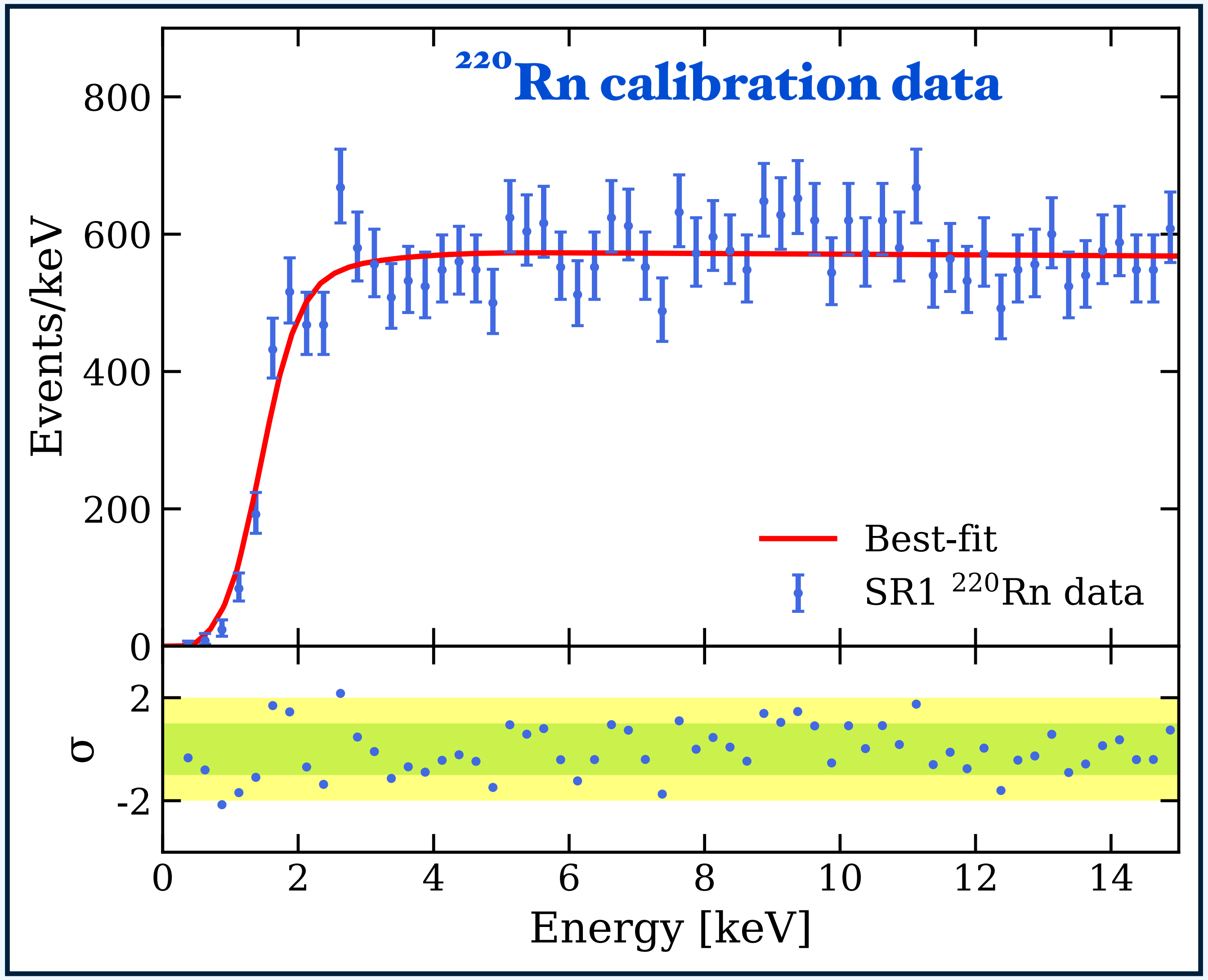
Observed: 18.12%

Model: 18.88%

Validates energy reconstruction and resolution down to 2.8 keV

Efficiency and Reconstruction





All signal and background models are convolved with efficiency and resolution

Fit to ^{220}Rn (^{212}Pb) calibration data using same analysis framework

p-value of 0.50

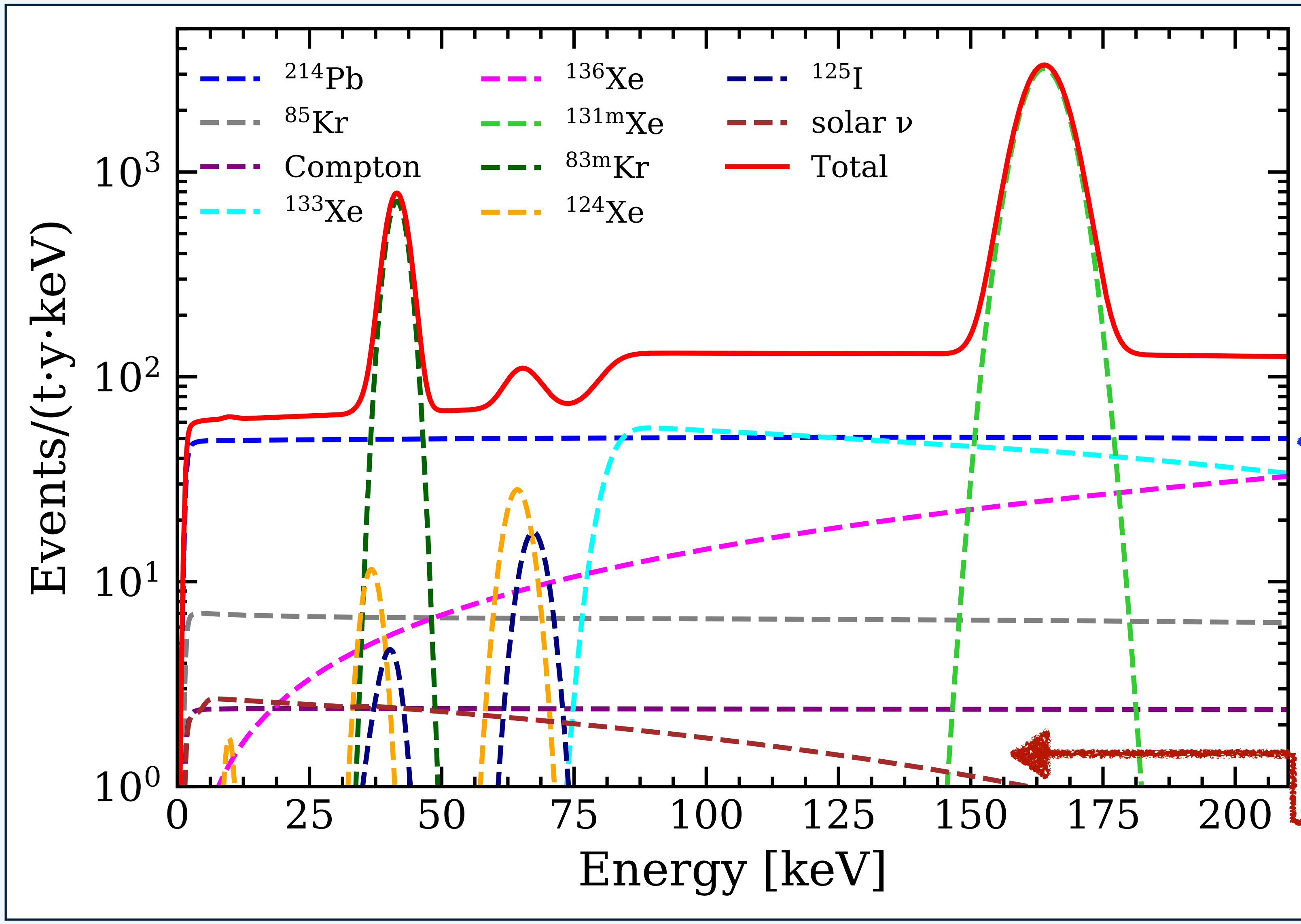
^{220}Rn calibration reconstructs as expected

Validates efficiency and energy reconstruction down to threshold

Background model and likelihood fit

Background model (B_o)

Search for an excess above known backgrounds.



10 components

Intrinsic

^{214}Pb ^{136}Xe

^{85}Kr ^{124}Xe

Neutron activated

^{131m}Xe ($T_{1/2}$ = 11.9 d)

^{133}Xe ($T_{1/2}$ = 5.3 d)

^{125}I ($T_{1/2}$ = 60 d)

Materials

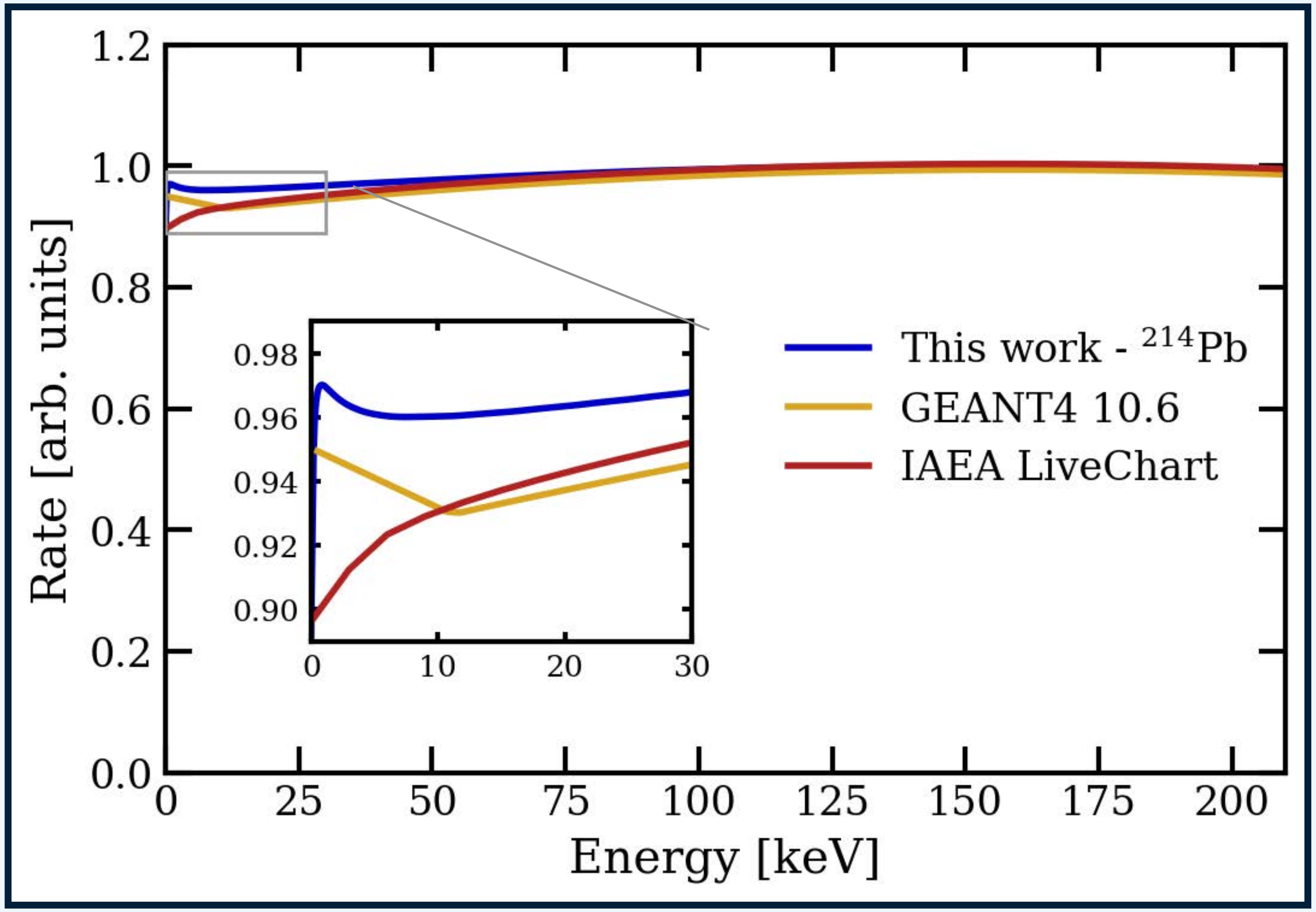
Solar neutrinos

Predicted energy spectra based on detailed modeling of each background component.

Rates constrained by measurements and/or time dependence, except ^{214}Pb and ^{124}Xe.

^{214}Pb β-decay spectral model

^{214}Pb dominant background component



Atomic screening and exchange effects can increase rate at low energies.

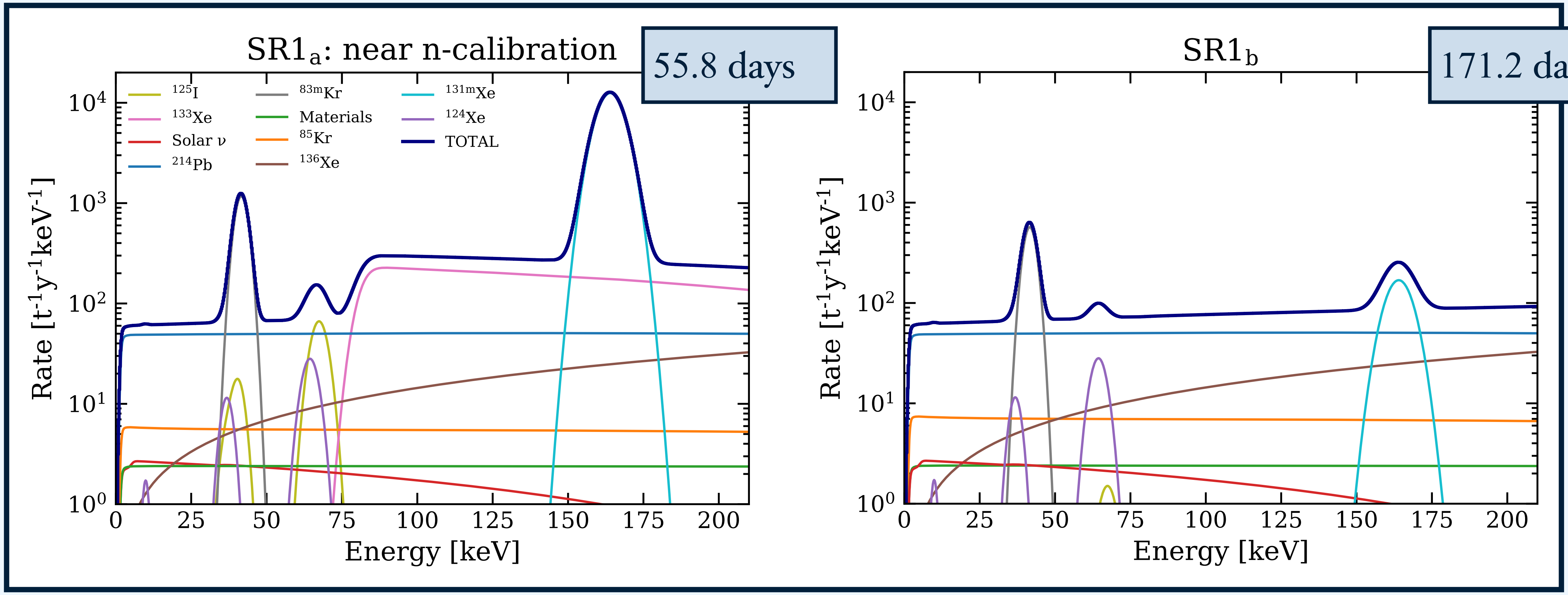
~6% uncertainty on the shape

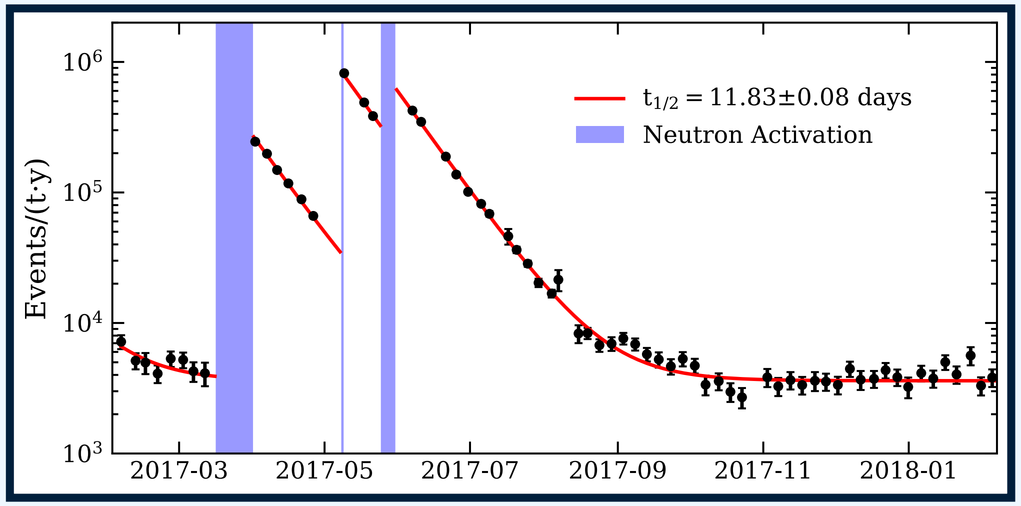
~50% needed to account for excess

^{212}Pb, ^{85}Kr also calculated.

Calculated spectra by X. Mougeot

Background model





Time-evolution and model of ^{131m}Xe

Background model B₀

Partitioned into two datasets and fit simultaneously

SR1$_a$: activated backgrounds, peaks

SR1$_b$: allows to constrain ^{214}Pb background

Statistical Method

Unbinned profile likelihood analysis

- Profile over the nuisance parameters (background components, efficiency)

expected total signal events

expected total background events

i - over all observed events, N = 42251

background PDF

signal PDF

$$\mathcal{L}(\mu_s, \boldsymbol{\mu_b}, \boldsymbol{\theta}) = \mathrm{Poiss}(N|\mu_{tot}) \times \prod_i^N \left(\sum_j \frac{\mu_{b_j}}{\mu_{\mathrm{tot}}} f_{b_j}(E_i, \boldsymbol{\theta}) + \frac{\mu_s}{\mu_{\mathrm{tot}}} f_s(E_i, \boldsymbol{\theta}) \right) \times \prod_m C_{\mu_m}(\mu_{b_m}) \times \prod_n C_{\theta_n}(\theta_n),$$

$$\mu_{\mathrm{tot}} \equiv \sum_j \mu_{b_j} + \mu_s$$

μ_b, θ : nuisance parameters

θ = includes shape parameters for the eff. spectral uncertainty & peak location uncertainty

constraints on the expected nr of background (m) events and shape parameters (n=6)

- Combine likelihoods of the 2 partitions

$$\mathcal{L} = \mathcal{L}_a \times \mathcal{L}_b$$

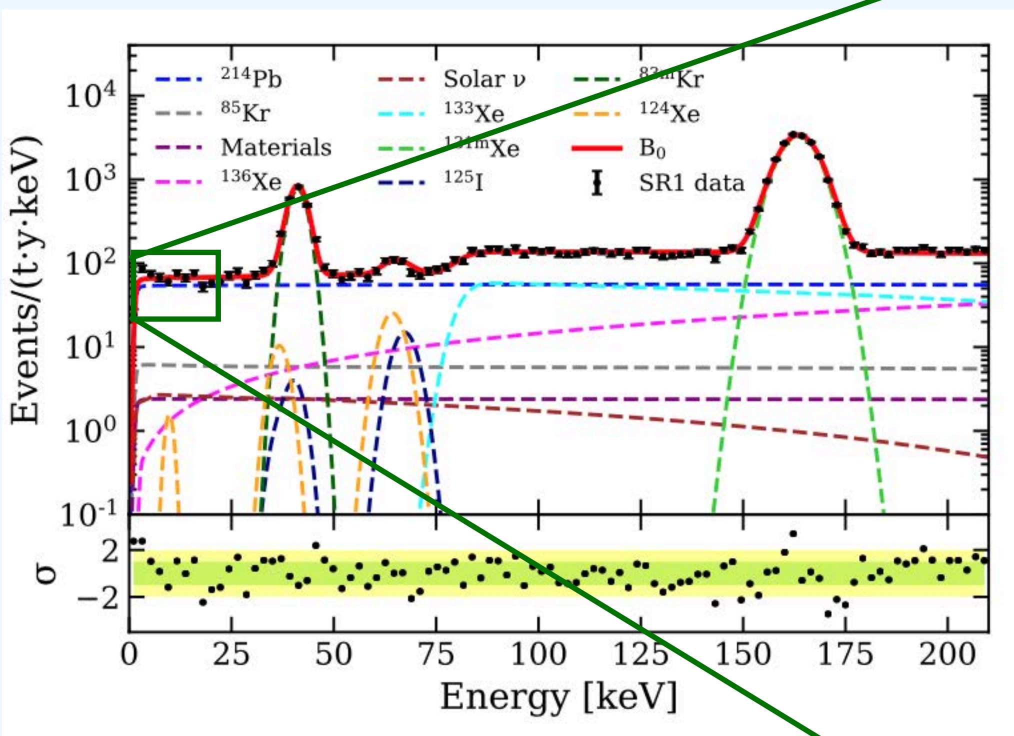
- Test statistic q for inference

$$q(\mu_s) = -2\ln \frac{\mathcal{L}(\mu_s, \hat{\hat{\boldsymbol{\mu}}}_b, \hat{\hat{\boldsymbol{\theta}}})}{\mathcal{L}(\hat{\mu}_s, \hat{\boldsymbol{\mu}}_b, \hat{\boldsymbol{\theta}})}$$

max. L with specified signal parameter μ_s

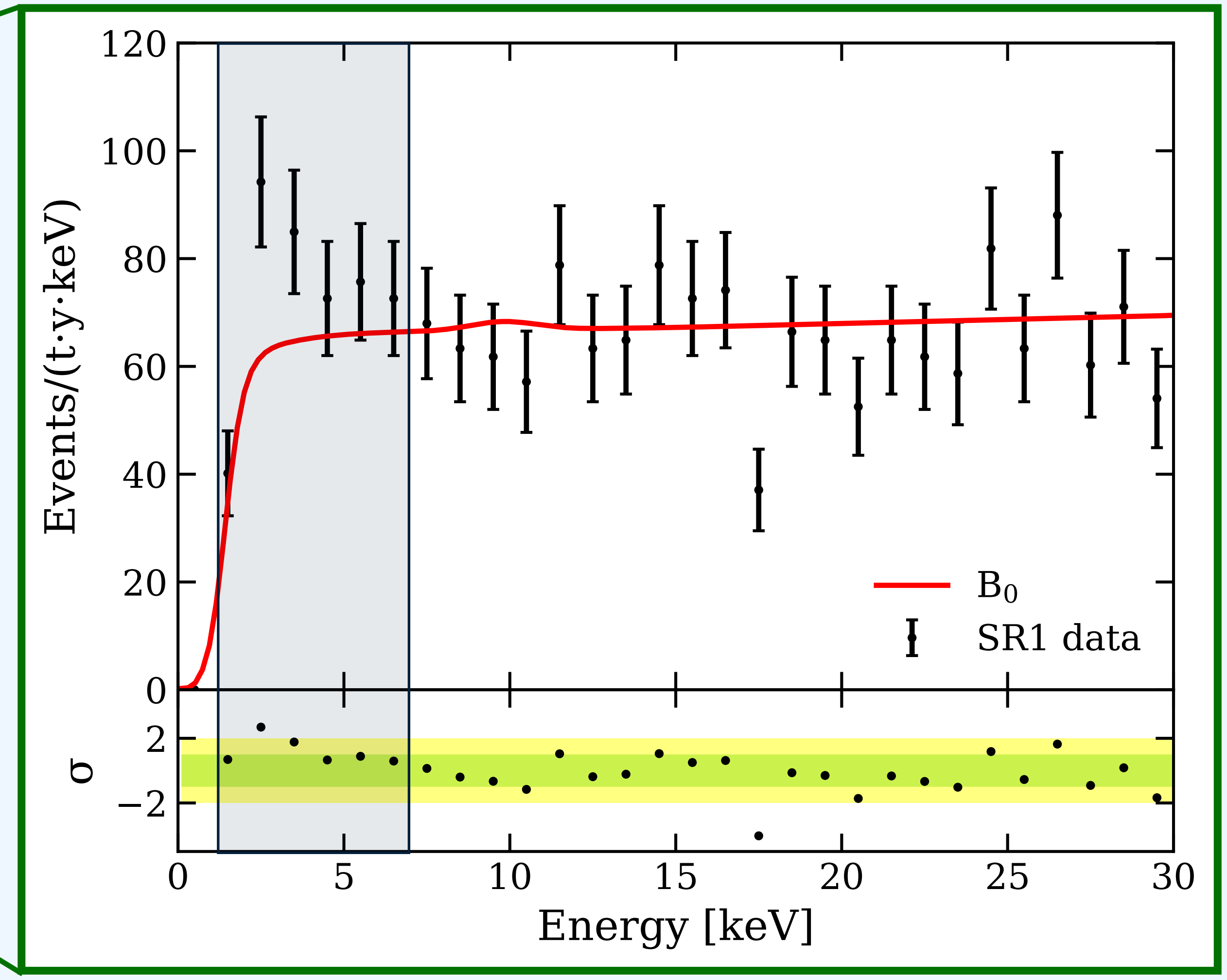
nuisance parameters that maximise L

Background fit



(76 +/- 2) events/(t · y · keV)
in [1, 30] keV

Lowest background rate ever achieved in this energy range!



Excess between 1-7 keV

285 events observed

vs.

232 events expected (from best-fit)

Would be a **3.3σ** fluctuation

(naive estimate — we use likelihood ratio tests for main analysis)

Is it a new background?

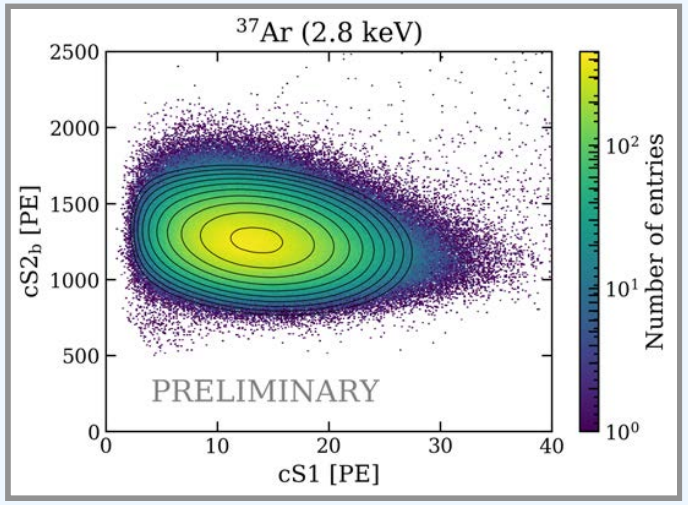
Argon-37 ?

Suppose it is in the xenon from the beginning:

- < 5 ppm Ar in xenon bottles (measured)
  ^{37}Ar : ^{nat}Ar ~ 10^{-20} mol/mol (nat. abundance)
- 35 day half-life plus removal through cryogenic distillation

Negligible by the start of XENON1T

^{37}Ar energy deposition (EC)



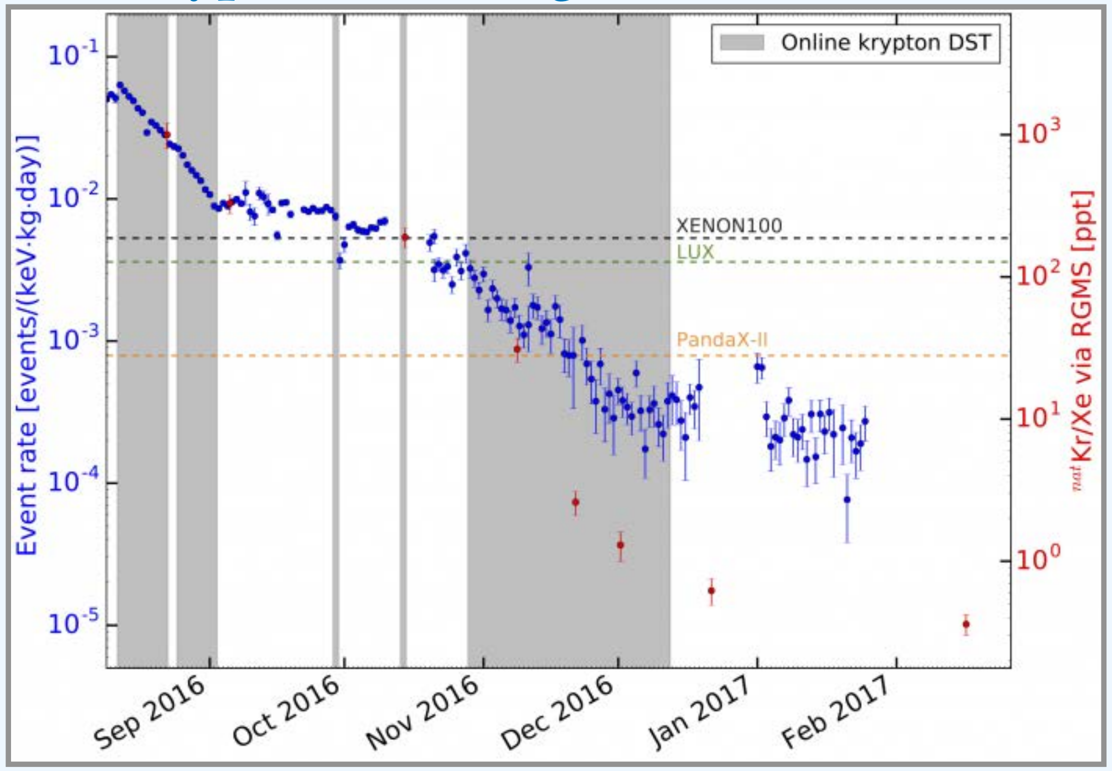
What if it leaks in?

- Air leak from < 0.9 liter/yr
  ^{85}Kr measurements in SR1
- ^{37}Ar abundance: < 3.2 mBq/m^3
  Measurements at LNGS (July 2020)

< 5.2 events/tonne/yr

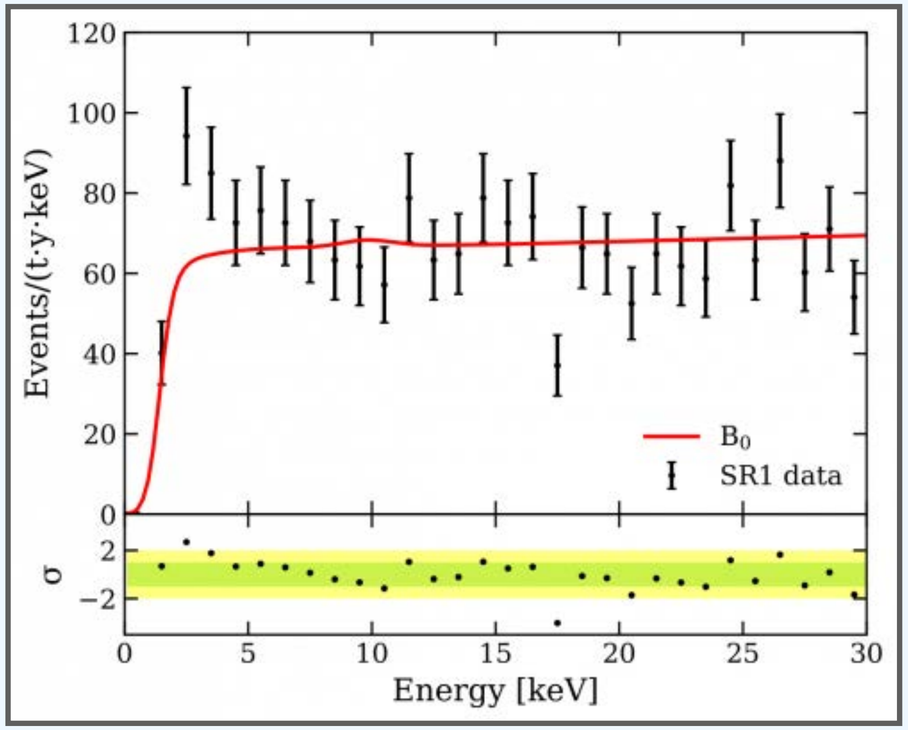
(~65 events/tonne/y needed for excess at 2.8 keV)

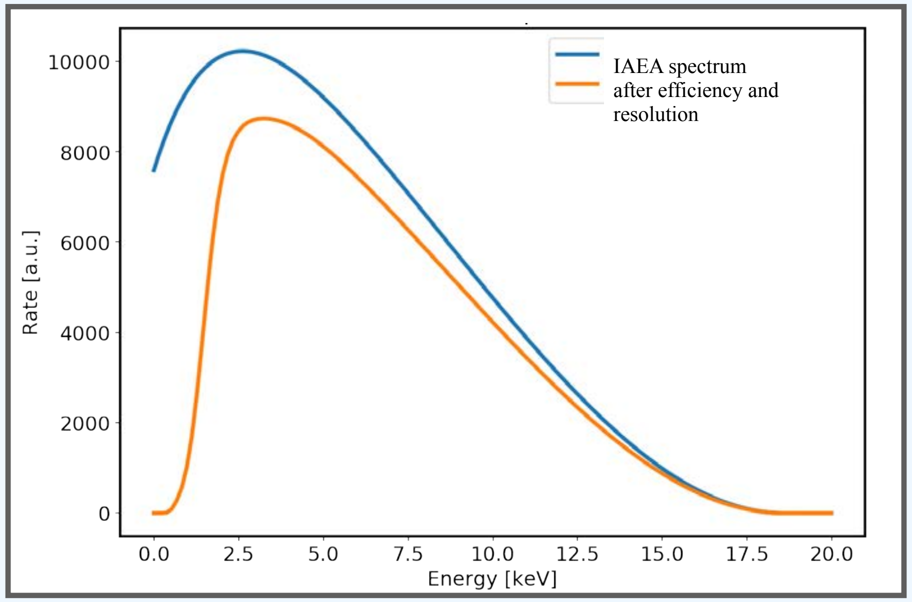
Krypton residual gas measurements



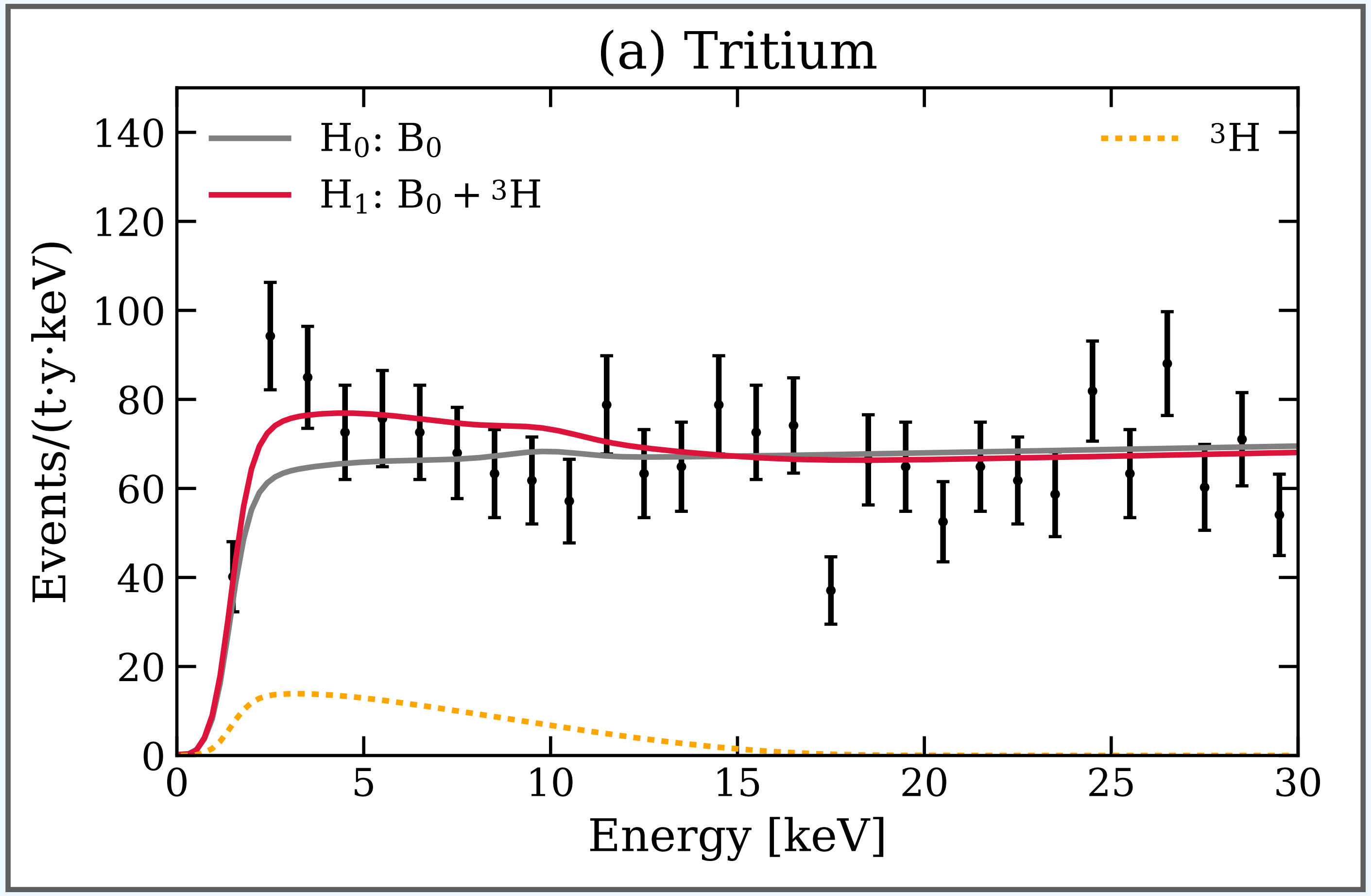
We conclude that ^{37}Ar cannot explain the excess.

Tritium hypothesis





^{3}H half-life 12.3 years
Q-value 18.6 keV



Tritium favored over background-only at 3.2σ

Best-fit tritium rate: 159 ± 51 events/$(\mathrm{t} \cdot \mathrm{y} \cdot \mathrm{keV})$

^{3}H:Xe concentration: $(6.2 \pm 2.0) \times 10^{-25}$ mol/mol

< 3 tritium atoms per kg of xenon!

Tritium: activation

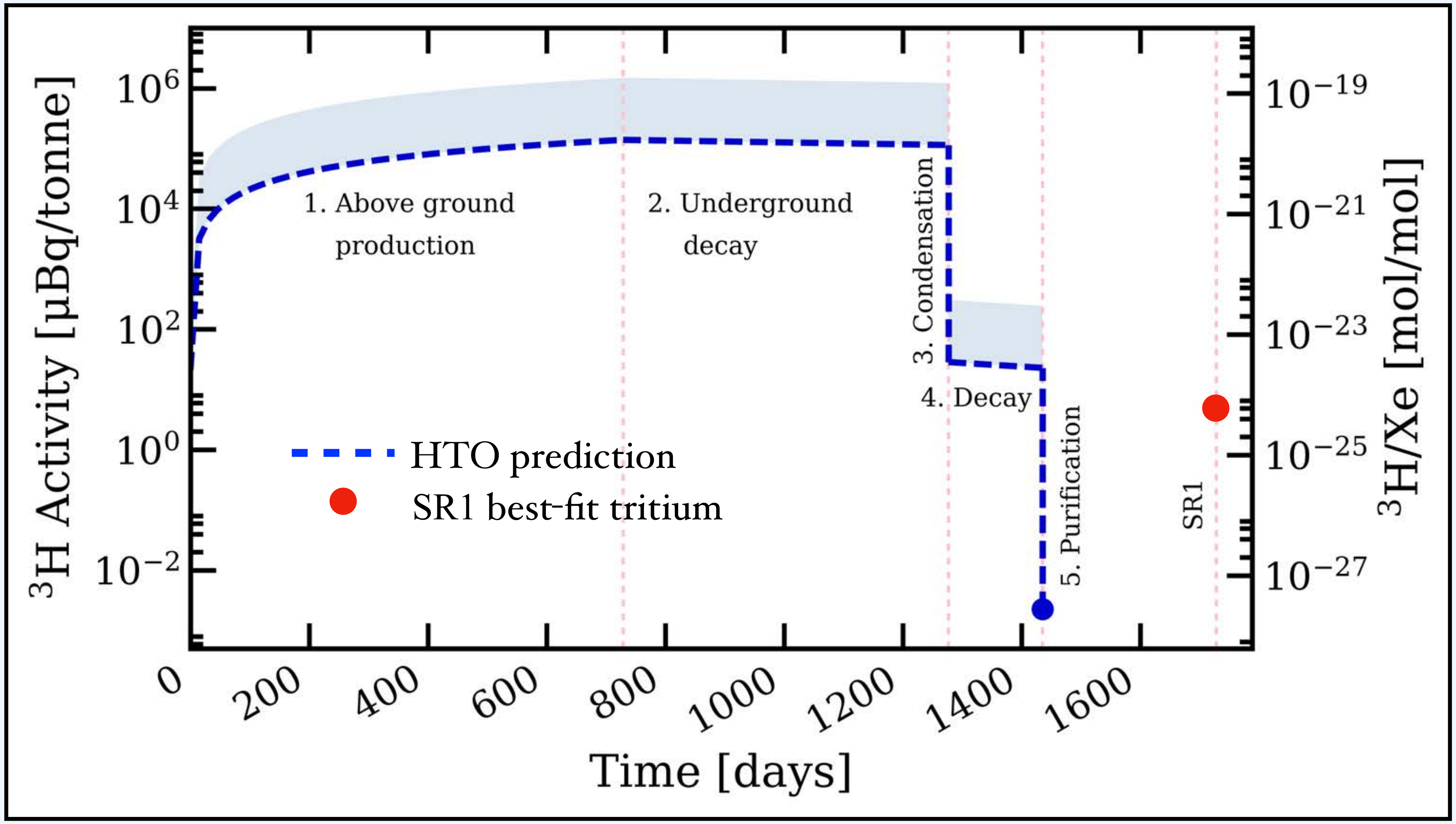
Above ground cosmogenic activation (sea level) of xenon: ~32 tritium atoms/kg/d (Zhang et al, 2016)

1 ppm water in bottles → HTO.

Coldtrap

Efficient removal (99.99%) in purification system

Evolution of tritiated water (HTO)



From purification and handling, this component seems unlikely.

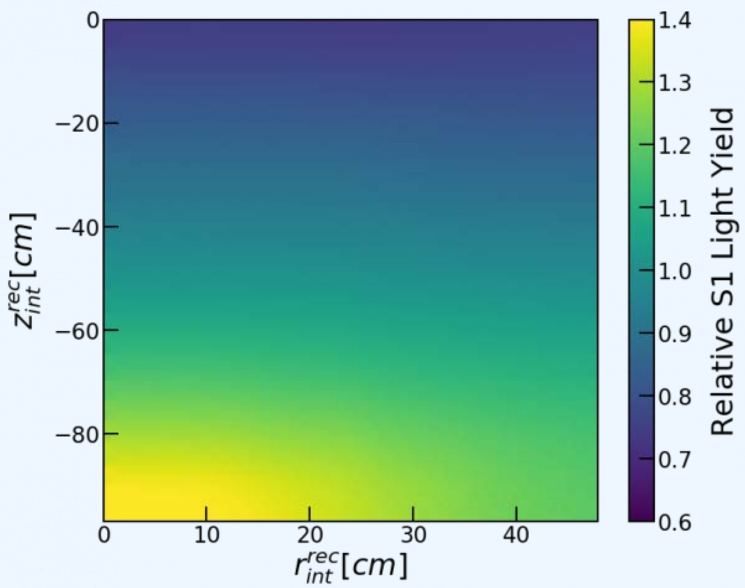
Tritium: emanation

Tritium is naturally abundant in water (HTO) and hydrogen (HT) - emanation from materials

$^3H:H$ in H_2O is **5 - 10 x 10^{-18} mol/mol** *

Best-fit tritium (~ 6 x 10^{-25} mol/mol) requires **> 30 ppb of (H_2O + H_2)** impurities

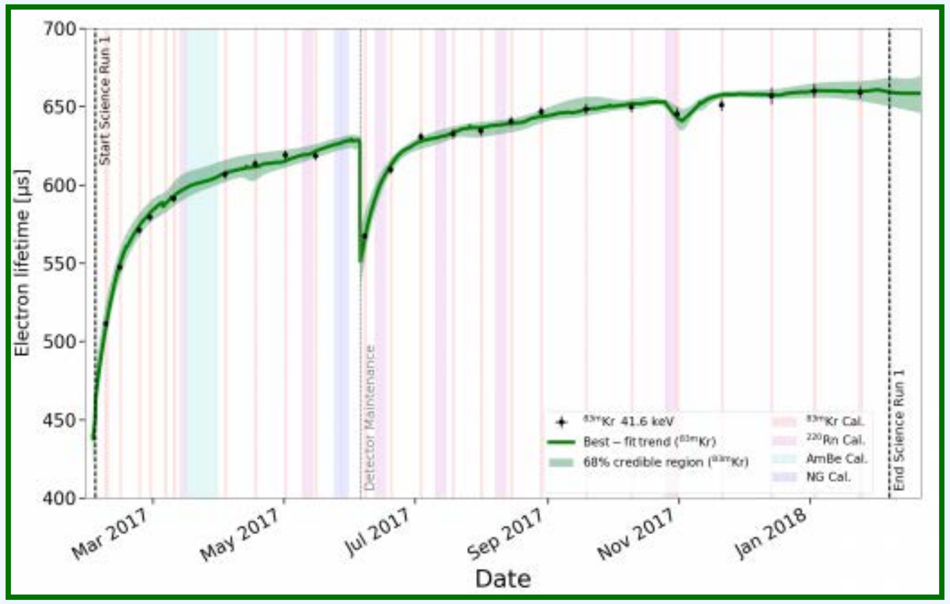
HTO



Our light yield implies
O(1) ppb H_2O

HT

- **No direct measure** of H_2 abundance or impurity concentration
- For **O_2-equivalent** impurities, electron lifetime indicates **O(0.1) ppb**
- **x 100 higher H_2** concentration than O_2-eq. molecules - possible?



HTO, HT emanation unlikely based on LXe purity.

*Hydrology measurements from IAEA nuclear database

Tritium hypothesis

caveats:

Many unknowns about tritium in a cryogenic LXe environment

- Radiochemistry, particularly isotopic exchange (formation of other molecules?)
- Diffusion properties of tritiated molecules
- Desorption and emanation from materials
- For HT - uncertainties in concentration.

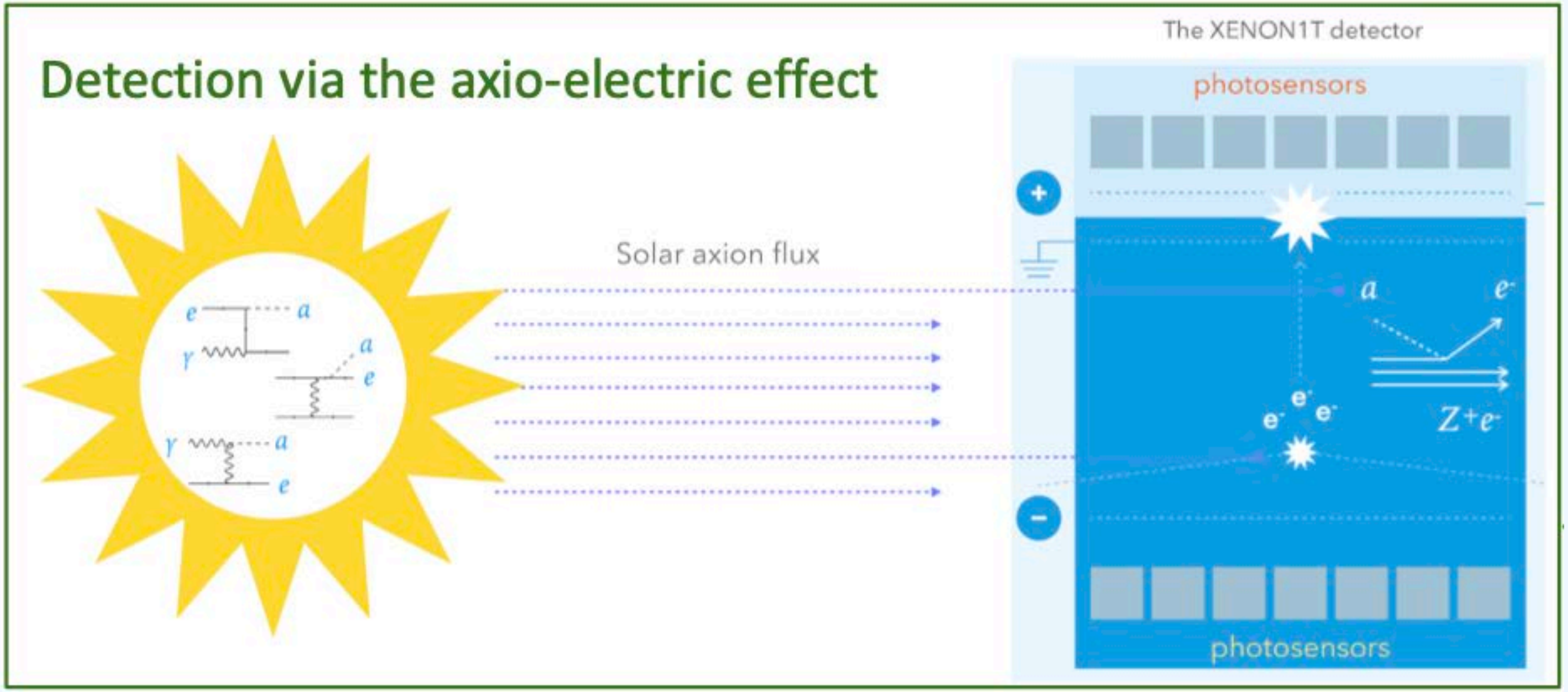
We can neither confirm nor exclude the presence of tritium.

- We don't include it in the background model.
- Report additional σ results (but not constraints on signal parameters) with tritium included as a background component.

*with input from KIT Tritium Laboratory and IAEA experts

Searches for new physics

Solar axions



Solar axions - emerge with keV-scale energies (not dark matter)

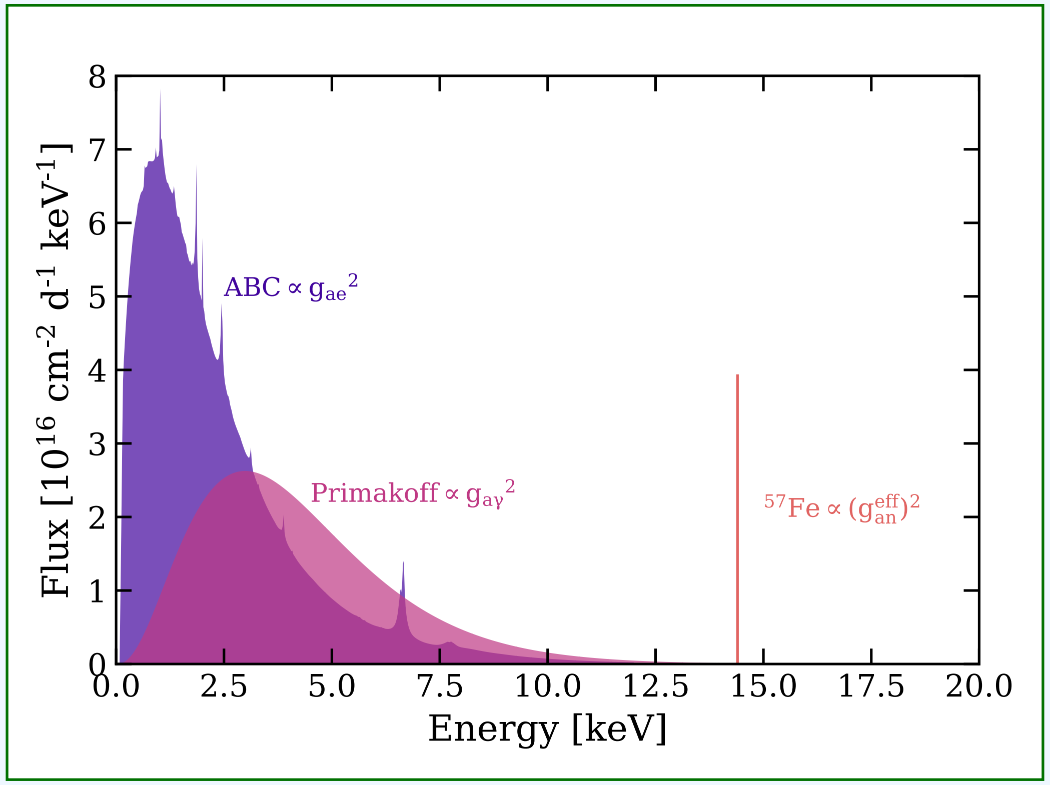
Three production mechanisms in the Sun

QCD axion specifically:

$$m_a \simeq \frac{6 \times 10^6 \text{ GeV}}{f_a} \text{ eV/c}^2$$

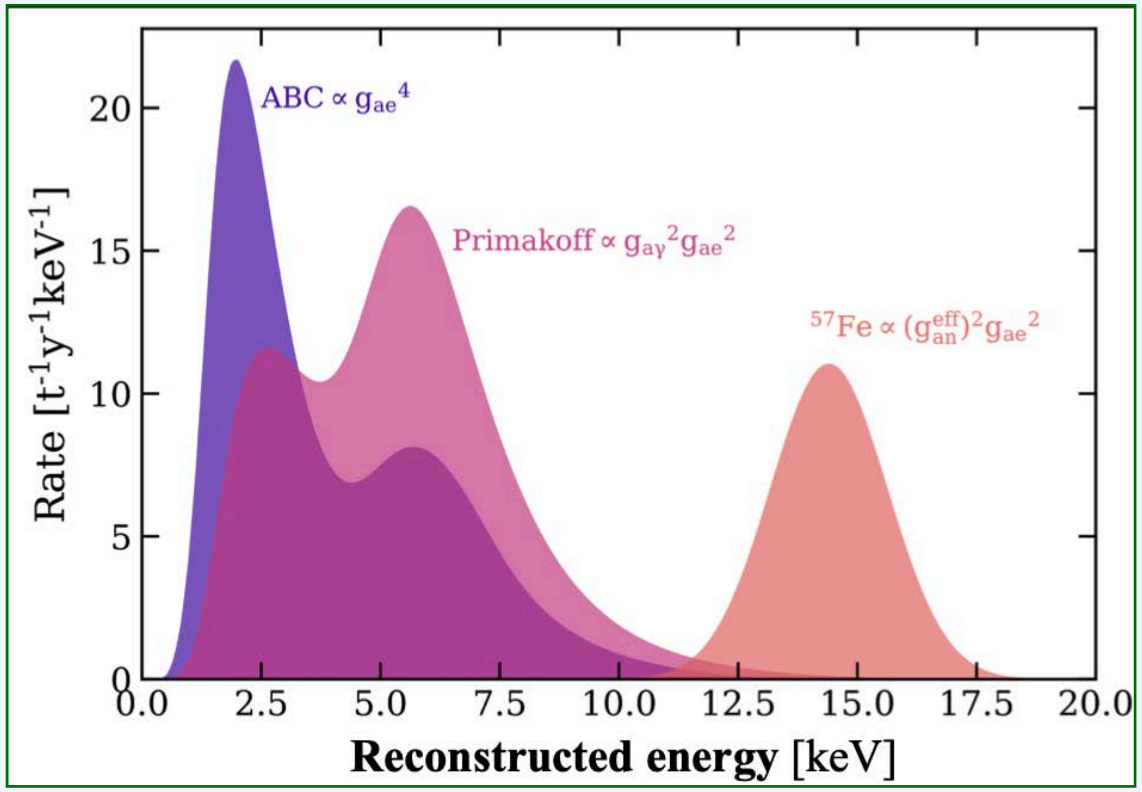
Solar axion

Production



Detector effects

Detection



ABC: atomic recombination & de-excitation, bremsstrahlung, and Compton interactions

g_{ae} axion-electron

Primakoff effect

$g_{a\gamma}$ axion-photon

Nuclear de-excitation

g_{an} axion-nucleon

Detection via Axioelectric effect

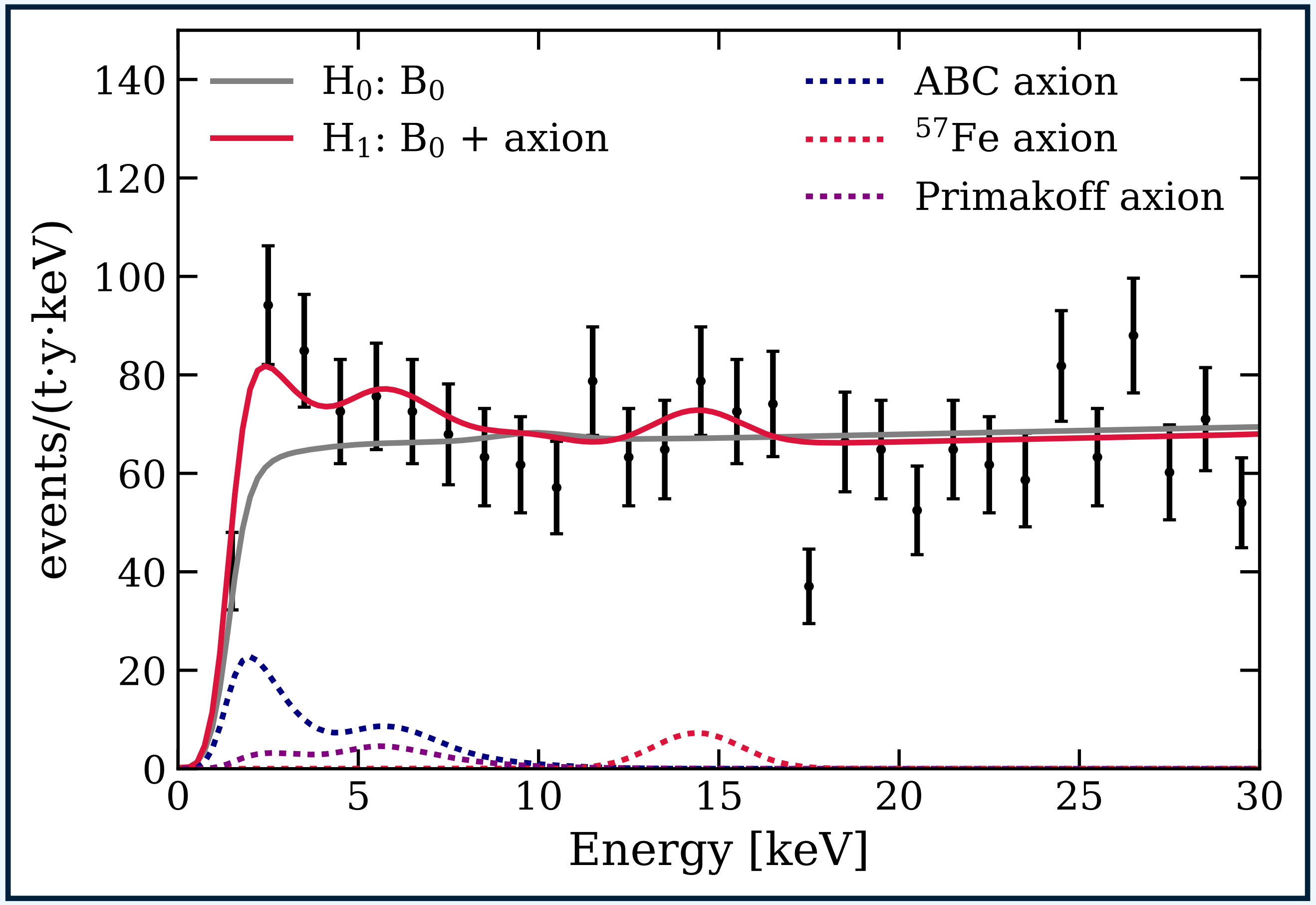
$$\sigma_{ae} = \sigma_{pe} \frac{g_{ae}^2}{\beta} \frac{3E_a^2}{16\pi\alpha m_e^2} \left(1 - \frac{\beta^{2/3}}{3}\right)$$

For Primakoff and ^{57}Fe - can only deduce product of 2 couplings.

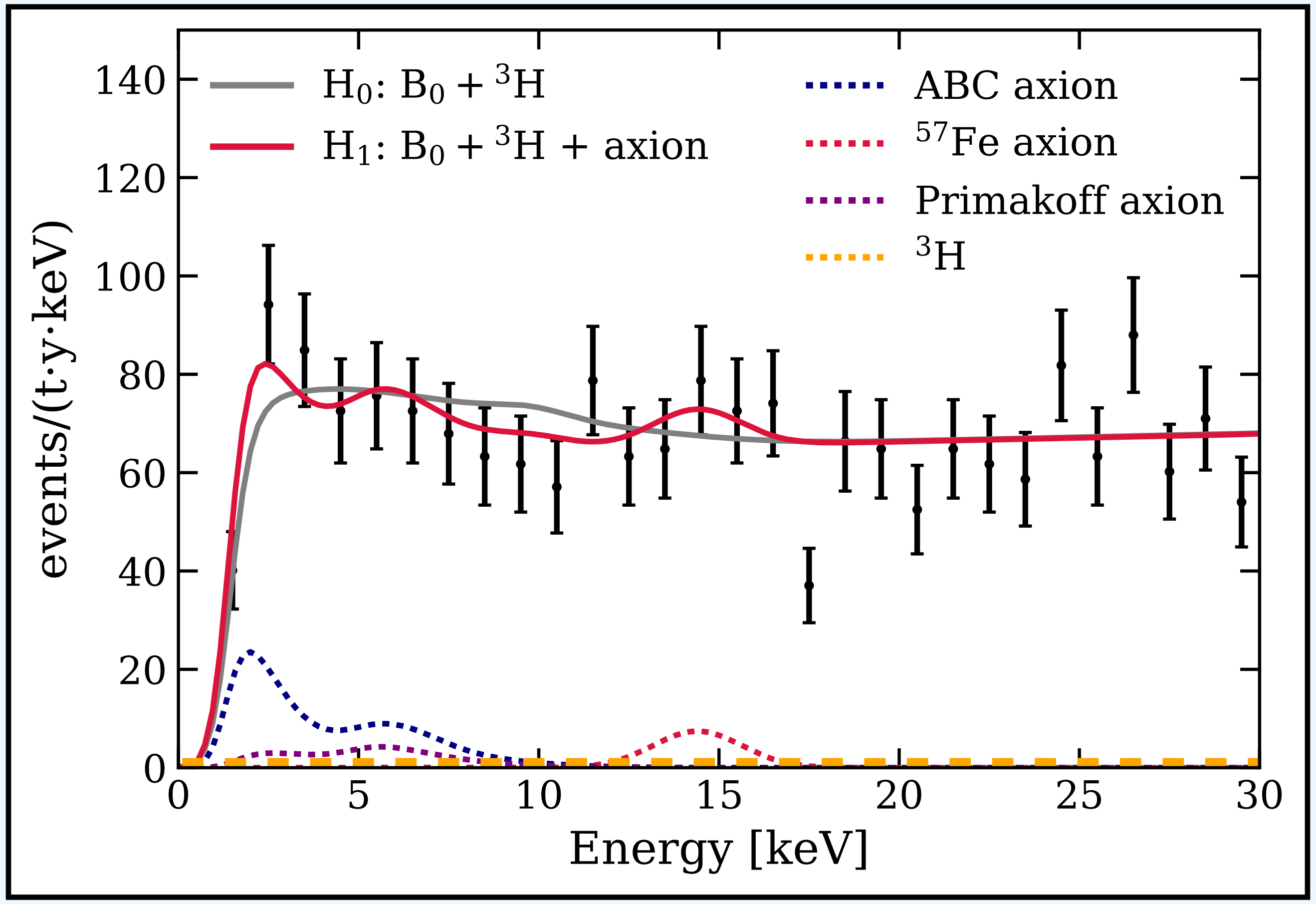
All three components left unconstrained in the fit.

Model-dependent couplings to matter (DFSZ, KSVZ), but search is Model-independent!

Solar axion results



Axion favored over background-only at 3.4σ

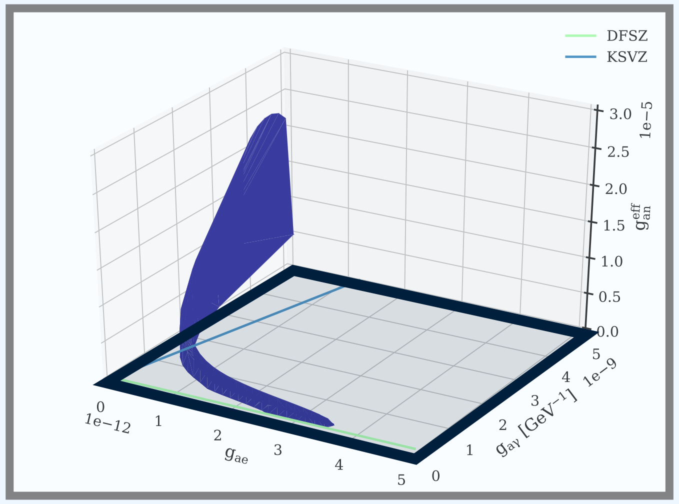


Axion + ^{3}H favored over ^{3}H hypothesis at 2.0σ

With both axion and tritium in the fit **best-fit tritium is zero in favor of axions.**

Statistical inference

3D confidence volume (90% C.L.)
Projected onto 2D regions

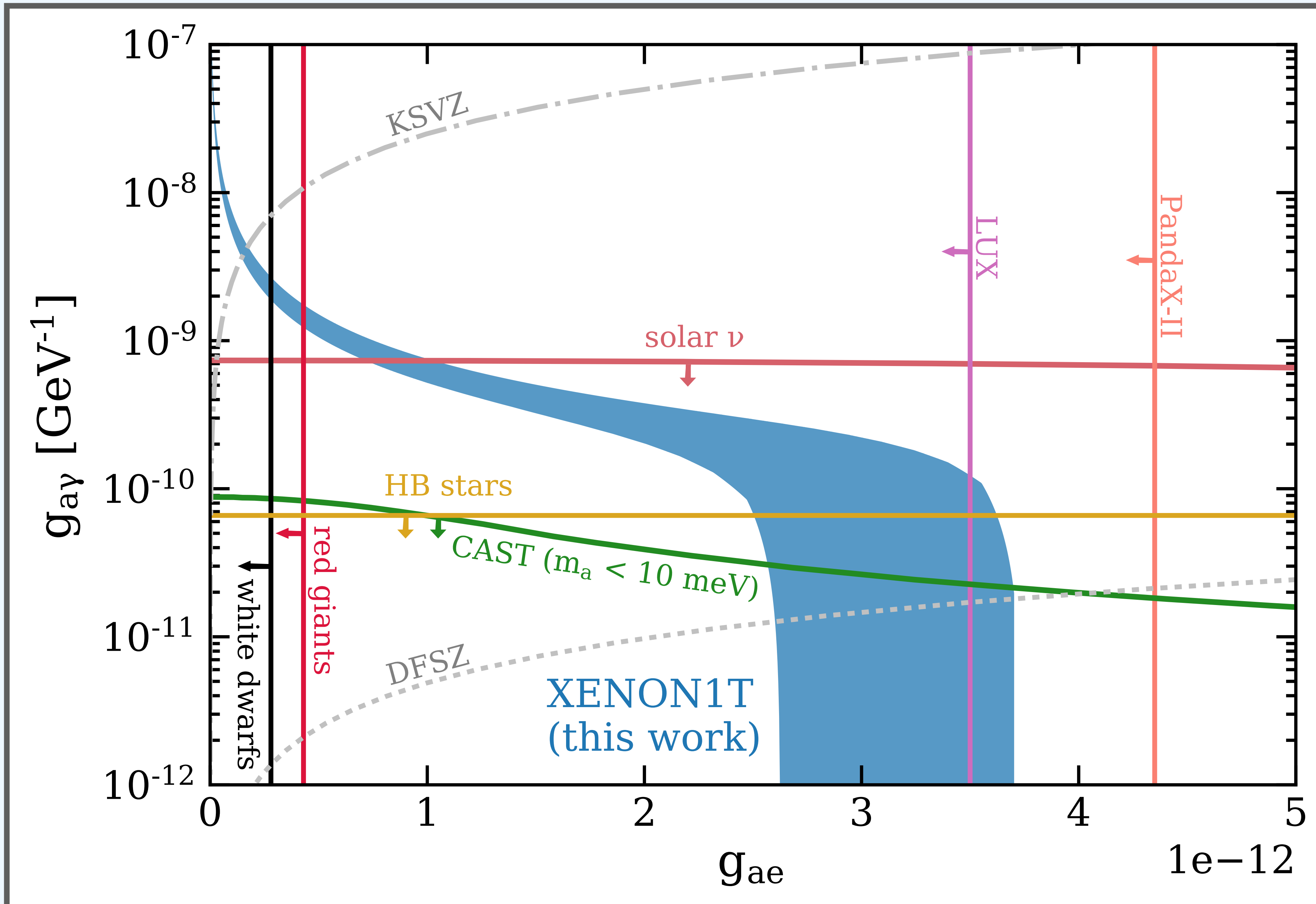


$$g_{ae} < 3.7 \times 10^{-12}$$
$$g_{ae} g_{an}^{eff} < 4.6 \times 10^{-18}$$
$$g_{ae} g_{a\gamma} < 7.6 \times 10^{-22}\ \text{GeV}^{-1}$$

Strong tension with astrophysical constraints from stellar cooling

(arXiv:2003.01100)

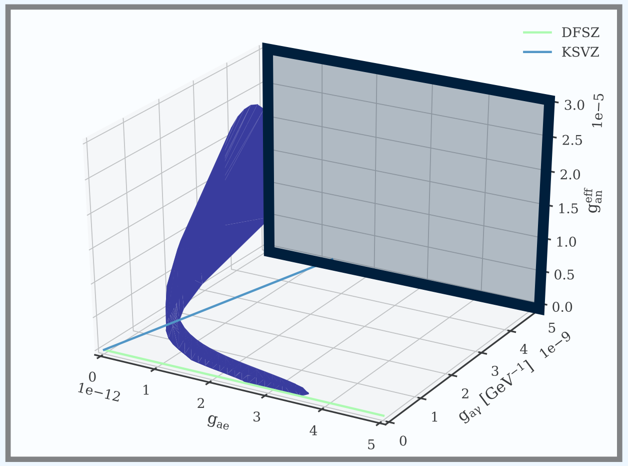
Primakoff



ABC

Statistical inference

3D confidence volume (90% C.L.)



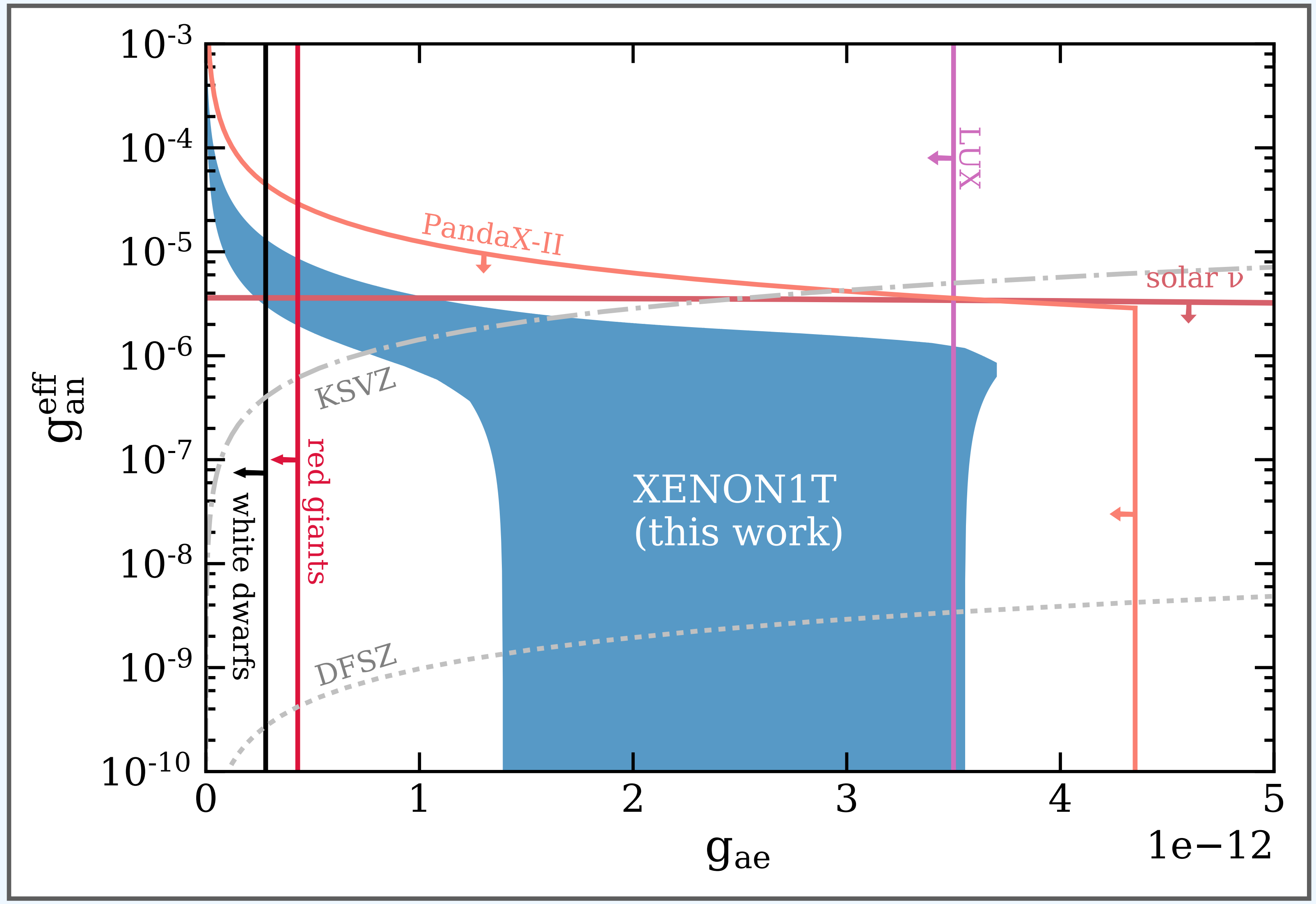
$g_{ae} < 3.7 \times 10^{-12}$

$g_{ae} g_{an}^{eff} < 4.6 \times 10^{-18}$

$g_{ae} g_{a\gamma} < 7.6 \times 10^{-22}$ GeV^{-1}

Poor fit for small ABC rate

57Fe

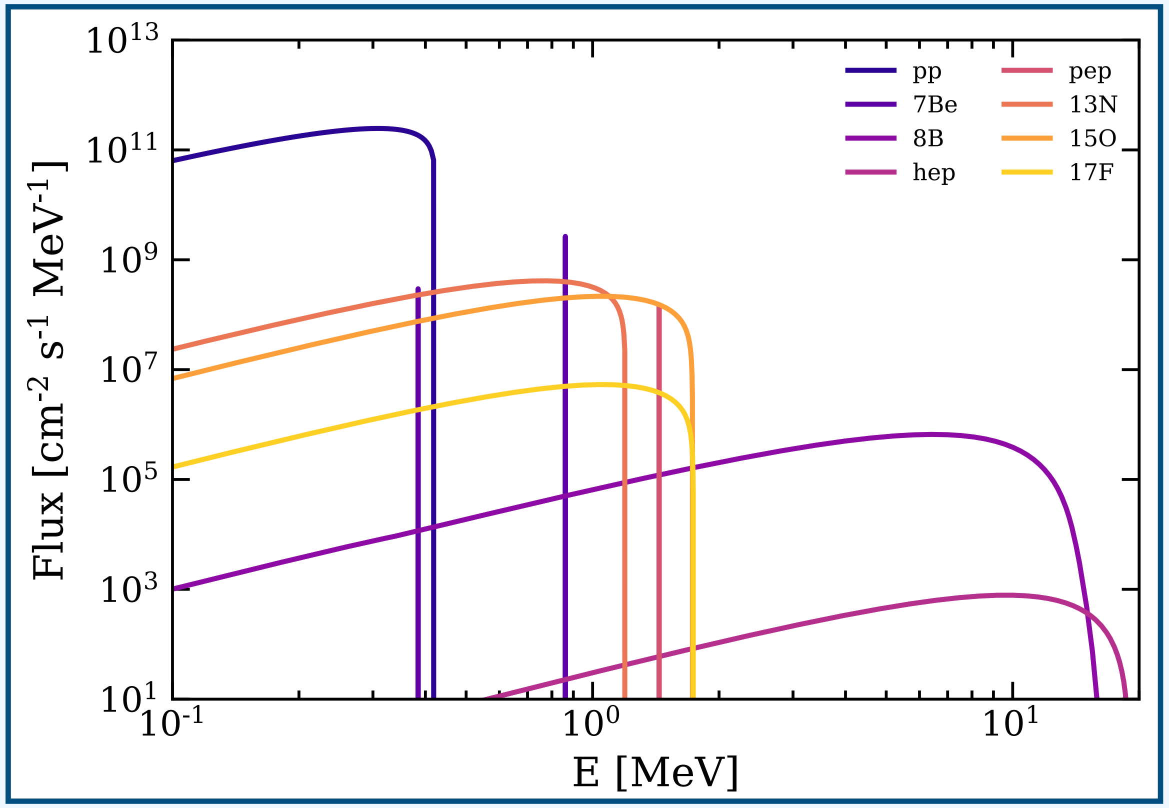


ABC

Strong tension with astrophysical constraints from stellar cooling

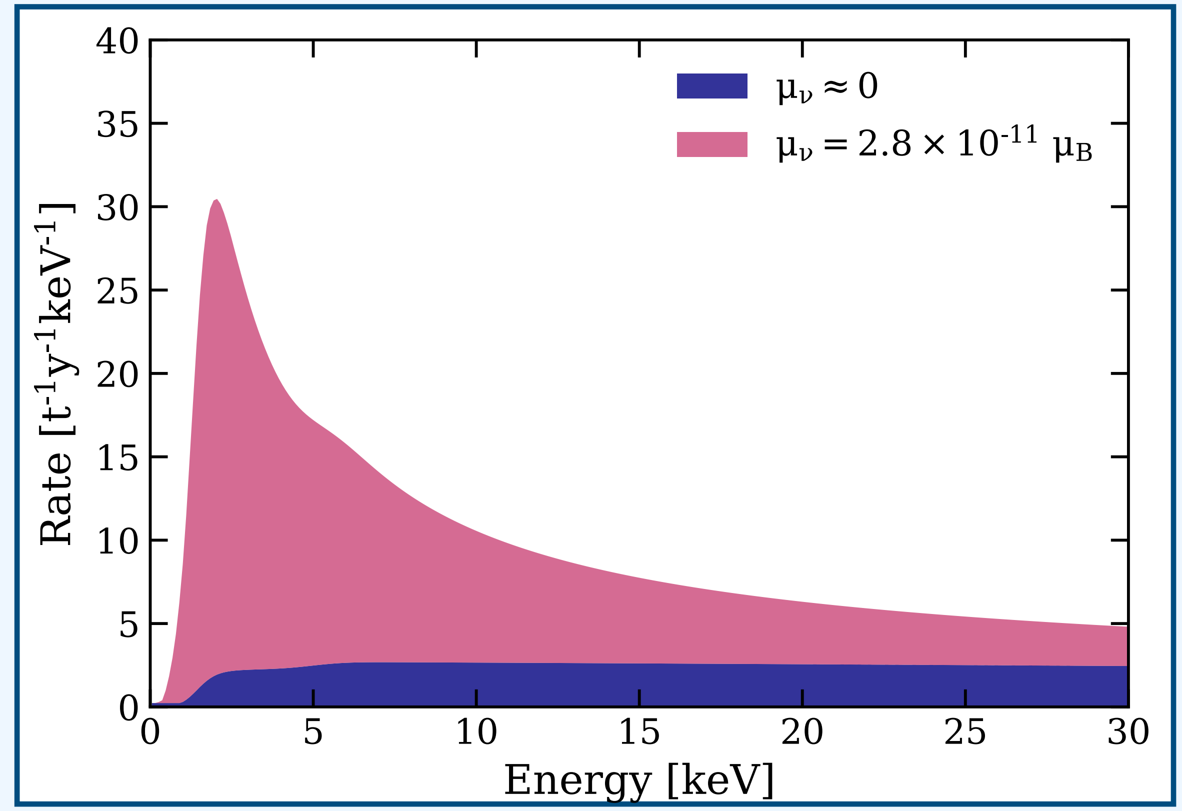
(arXiv:2003.01100)

Enhanced neutrino magnetic moment



solar neutrino (pp) - electron scattering

$$\frac{d\sigma_\mu}{dE_r} = \mu_\nu^2 \alpha \left(\frac{1}{E_r} - \frac{1}{E_\nu} \right)$$



A larger magnetic moment would imply new physics, and possibly solve Dirac vs Majorana.

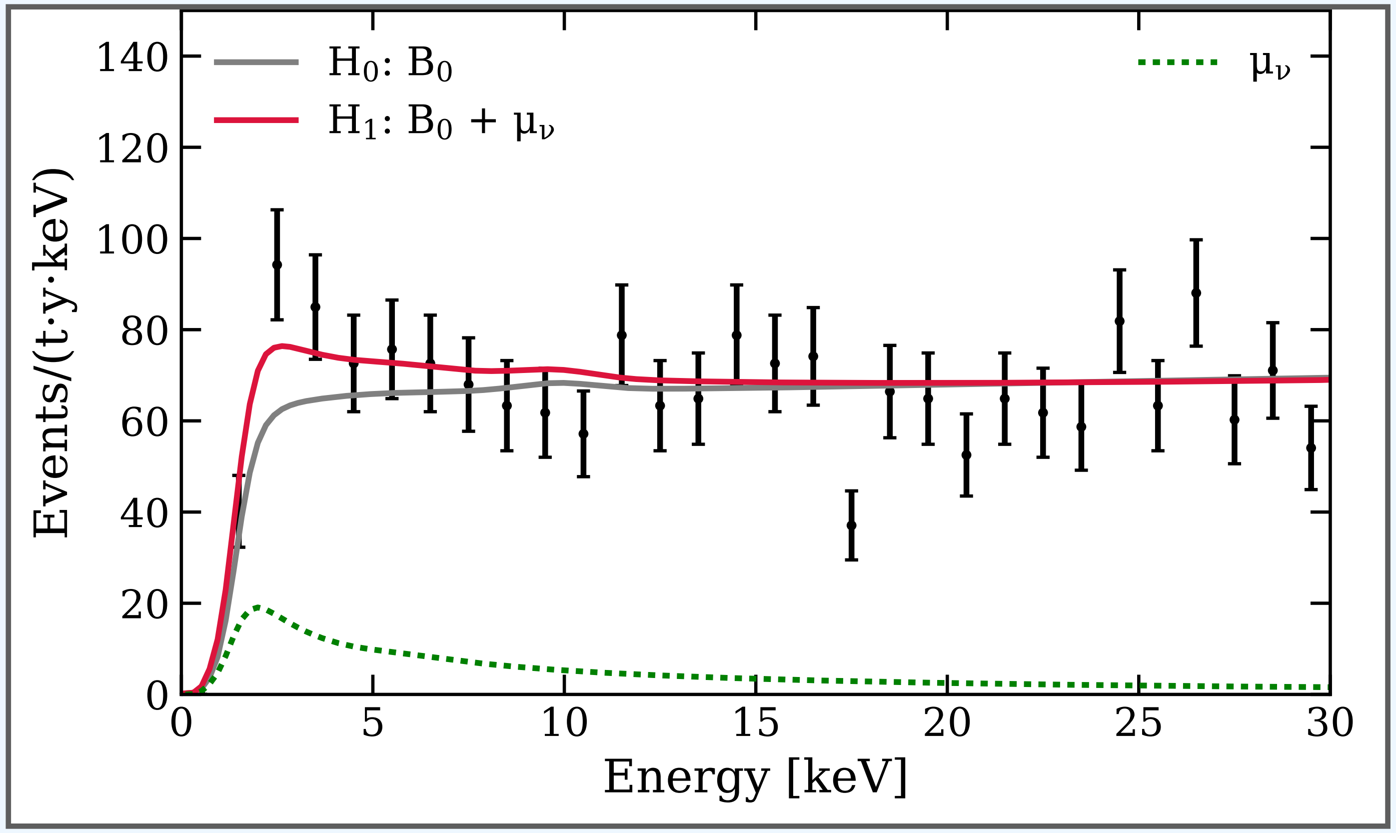
Minimally-extended Standard Model:

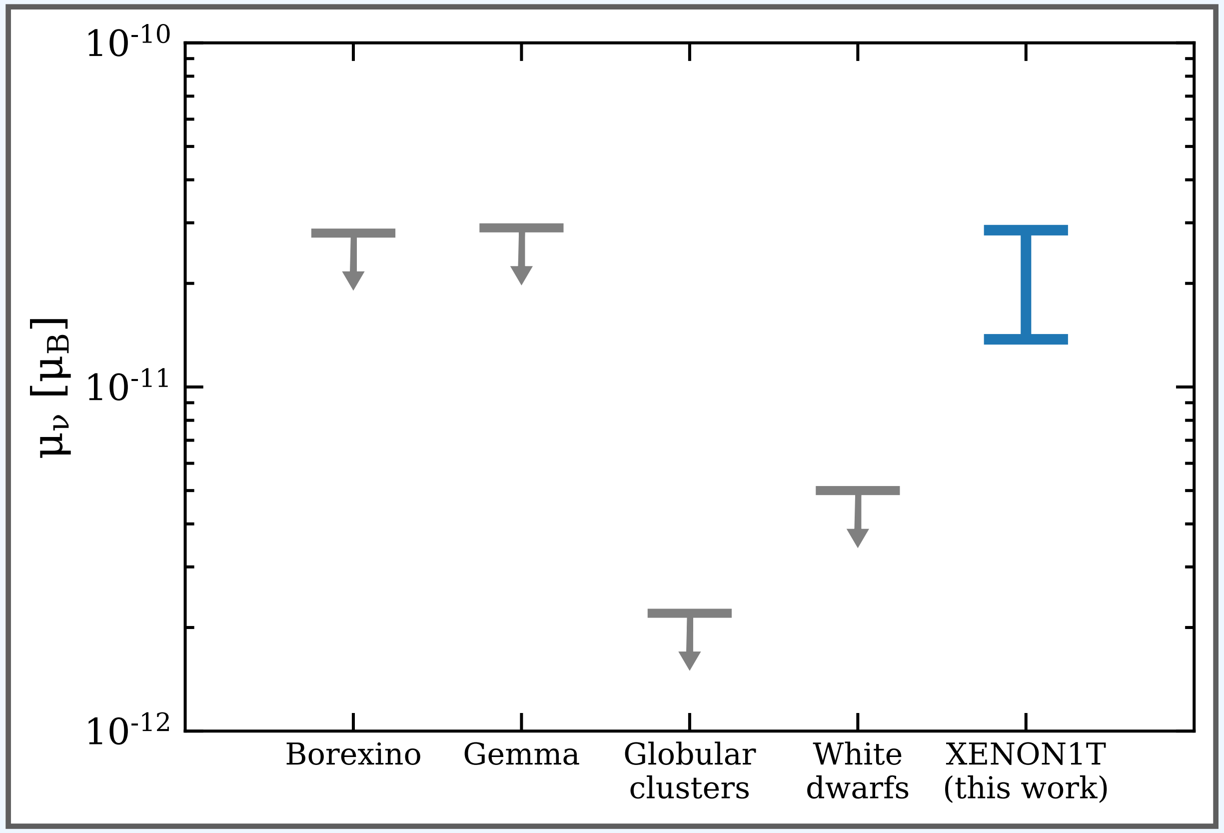
$$\mu_\nu = \frac{3eG_F m_\nu}{8\pi^2\sqrt{2}} = 3 \times 10^{-19} \mu_B \times \left(\frac{m_\nu}{1\,\mathrm{eV}} \right)$$

Enhancement:

$\left(\gtrsim 10^{-15} \mu_{\mathrm{B}} \right) \longrightarrow$ *Majorana fermion*

Neutrino magnetic moment





Neutrino magnetic moment favored over background-only at 3.2σ

$$\mu_\nu \in (1.4,\ 2.9) \times 10^{-11}\ \mu_B$$
(90% C.L.)

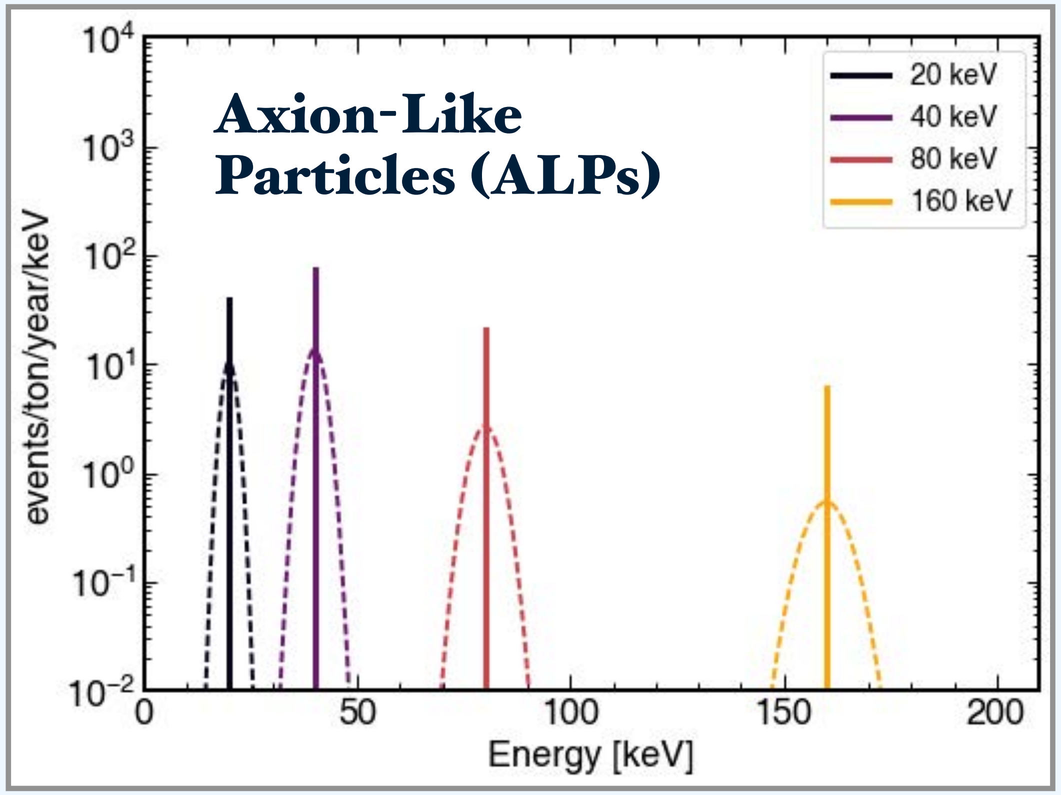
reduces to 0.9σ with a tritium component

Compatible with other experiments

In tension with astrophysical constraints

Bosonic dark matter

pseudoscalar

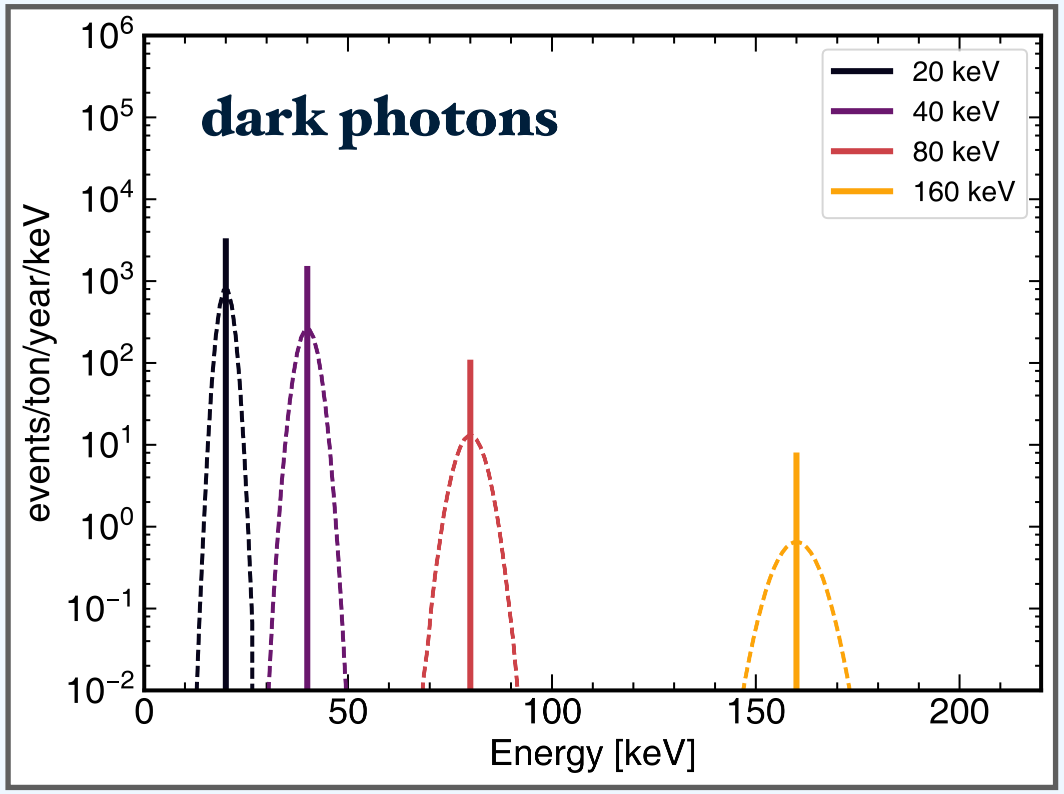


$$R \simeq \frac{1.5\times 10^{19}}{A} g_{\mathrm{ae}}^2 \left(\frac{m_{\mathrm{a}}}{\mathrm{keV}/c^2}\right)\left(\frac{\sigma_{\mathrm{pe}}}{\mathrm{b}}\right) \mathrm{kg}^{-1}\mathrm{d}^{-1}$$

Detection via axioelectric effect

$$\sigma_{\mathrm{ae}} = \sigma_{\mathrm{pe}} \frac{g_{\mathrm{ae}}^2}{\beta} \frac{3E_{\mathrm{a}}^2}{16\pi\alpha m_{\mathrm{e}}^2}\left(1 - \frac{\beta^{2/3}}{3}\right)$$

vector

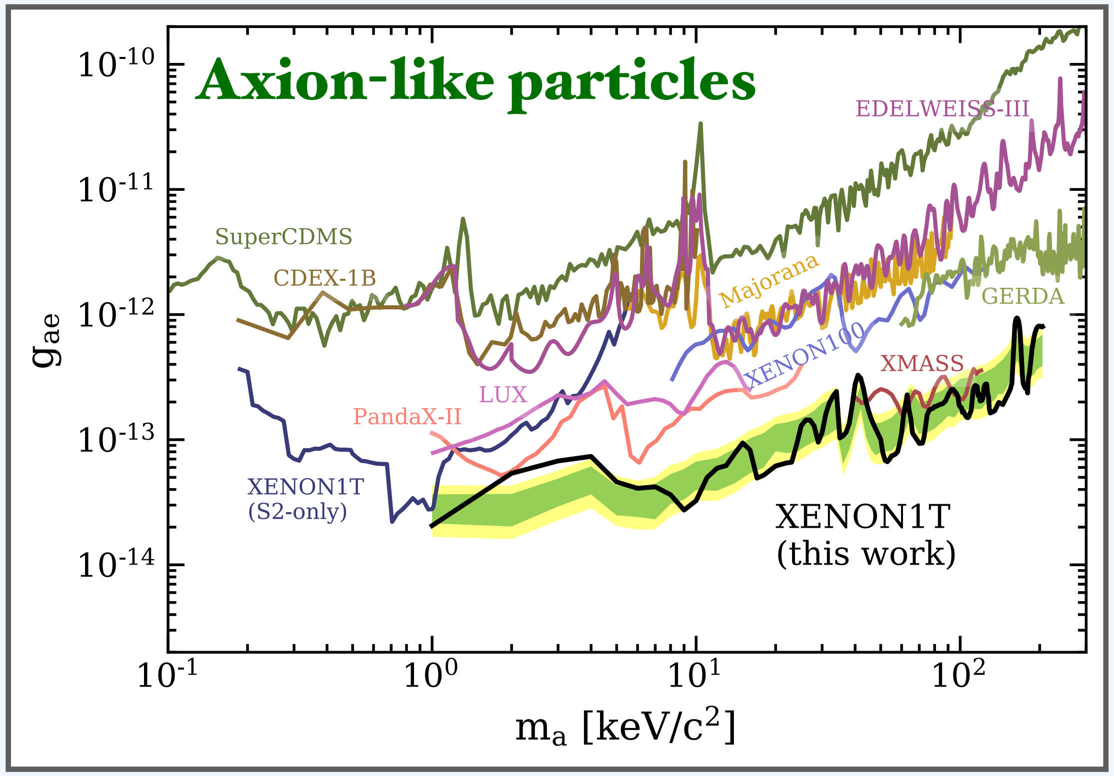


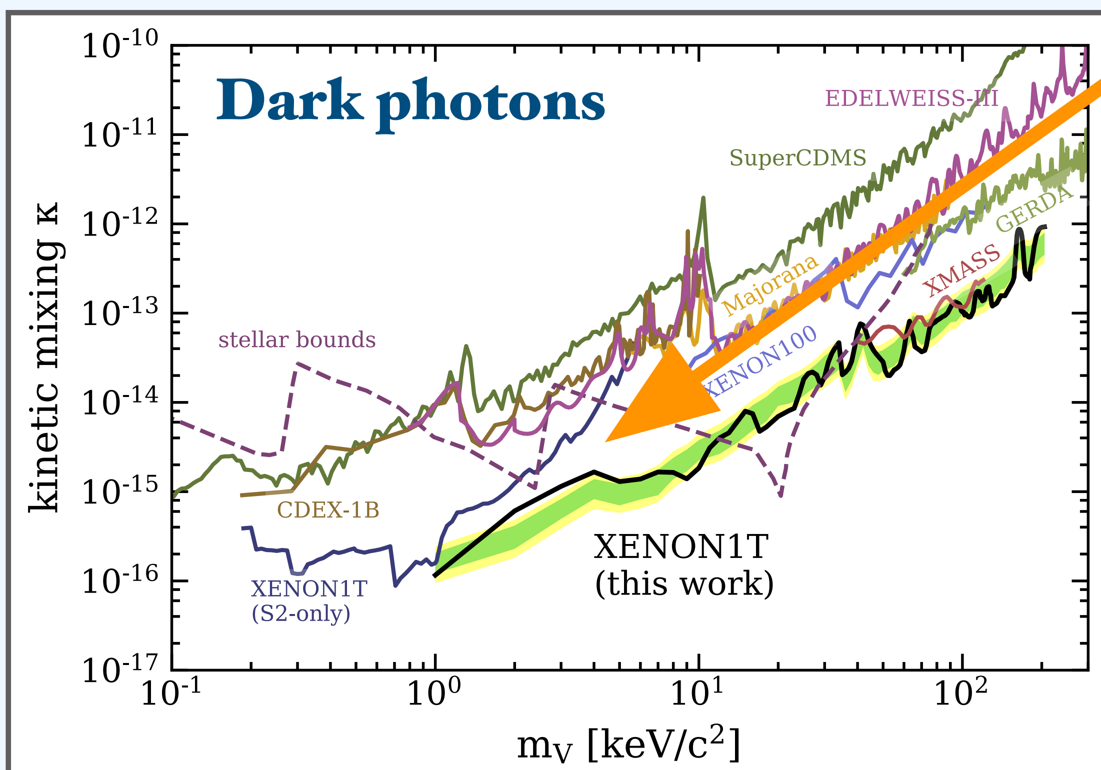
$$R \simeq \frac{4.7\times 10^{23}}{A} \kappa^2 \left(\frac{\mathrm{keV}/c^2}{m_{\mathrm{V}}}\right)\left(\frac{\sigma_{\mathrm{pe}}}{\mathrm{b}}\right) \mathrm{kg}^{-1}\mathrm{d}^{-1}$$

Kinetic mixing with SM photons

$$\sigma_{\mathrm{V}} \simeq \frac{\sigma_{\mathrm{pe}}}{\beta}\kappa^2$$

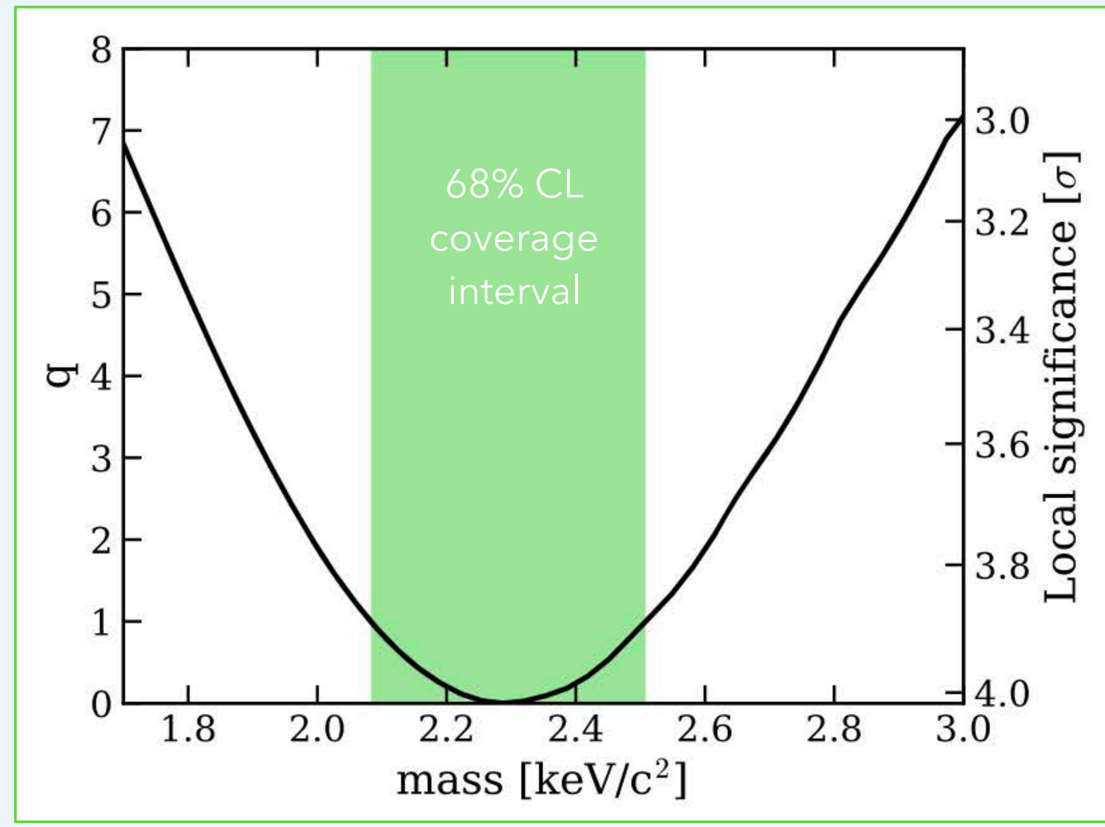
Bosonic dark matter





90% CL upper limits and sensitivities

Fitting a mono-energetic peak to the excess:
2.3 +/- 0.2 keV



Best fit: ~60 events/tonne/year
4.0 σ local significance
3.0 σ (global)

Further investigations