Recent results and status of the XENON dark matter experiment

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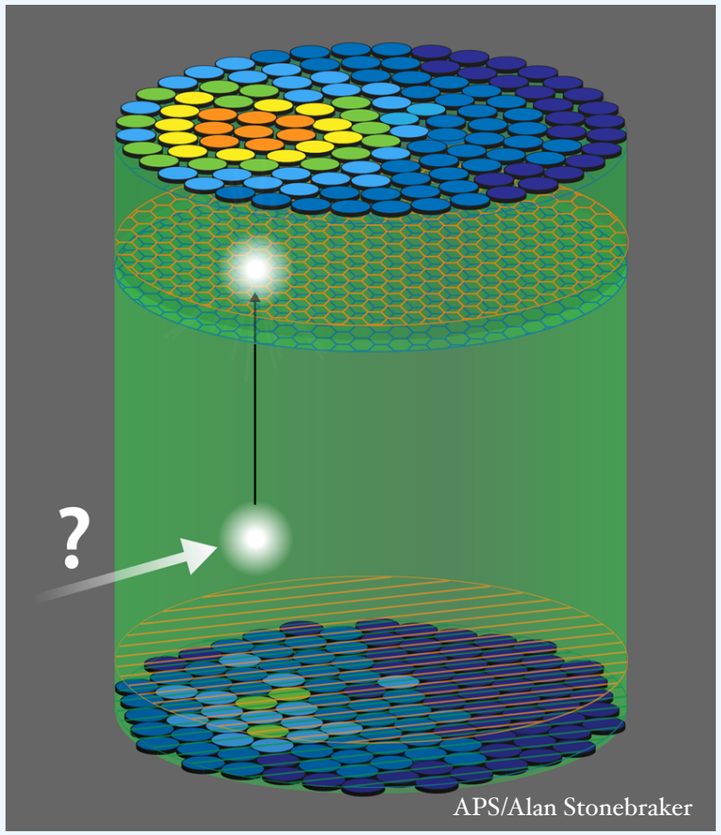
Krakow Jagiellonian University
Particle Physics Phenomenology and Experiments Seminar
20 December 2021

XENON

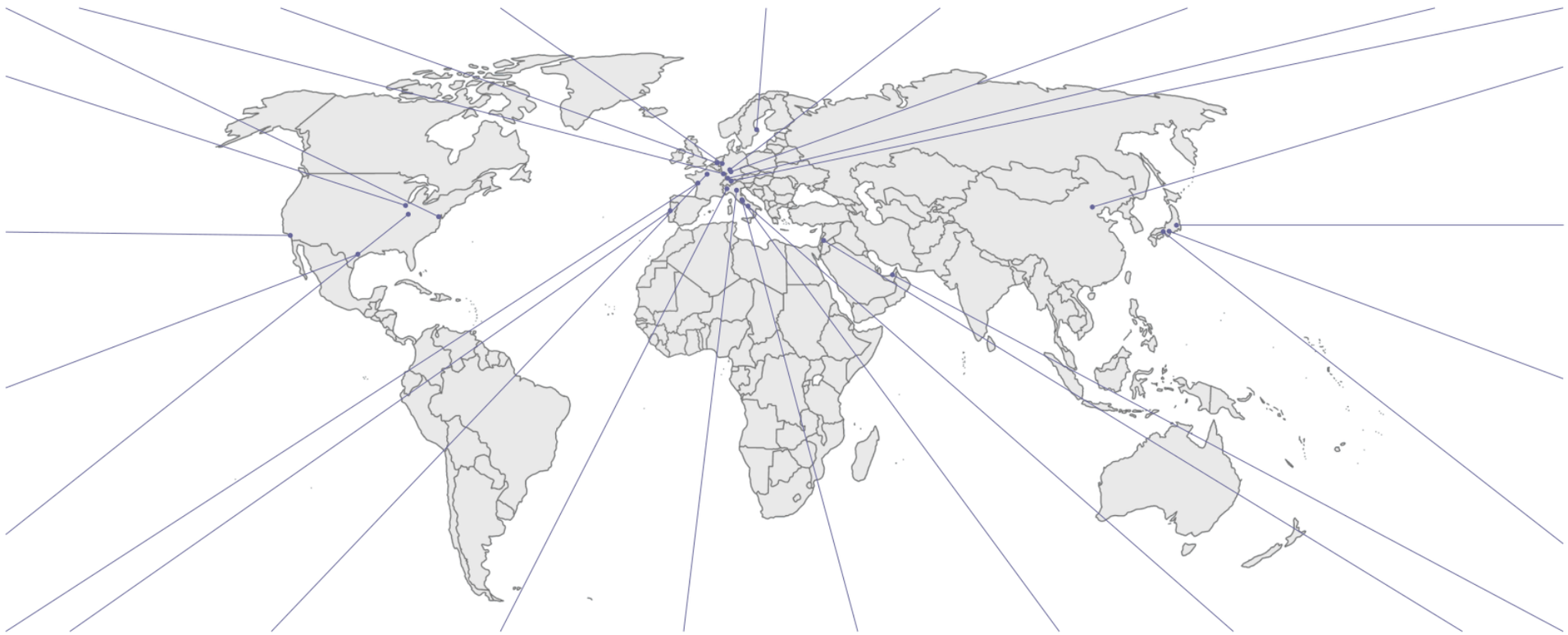
Universität Zürich[UZH]

Outline

- Overview of the XENON experiment
- Detection channels and recent results
- The low-energy excess
- The next stage - XENONnT



The XENON Collaboration



Columbia | KIT | Nikhef | Muenster | Stockholm | Mainz | MPIK, Heidelberg | Freiburg | Zurich

Chicago | Tsinghua | UCSD | Tokyo | Rice | Nagoya | Purdue | Kobe

Subatech | Coimbra | LPNHE | Torino | Bologna | L'Aquila | LNGS | Napoli | Weizmann | NYUAD

Founded in 2002

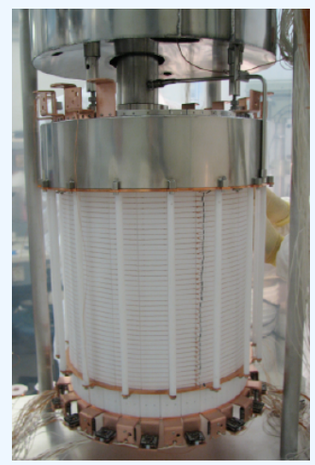
> 170 scientists

27 institutions from 11 countries

The XENON Project

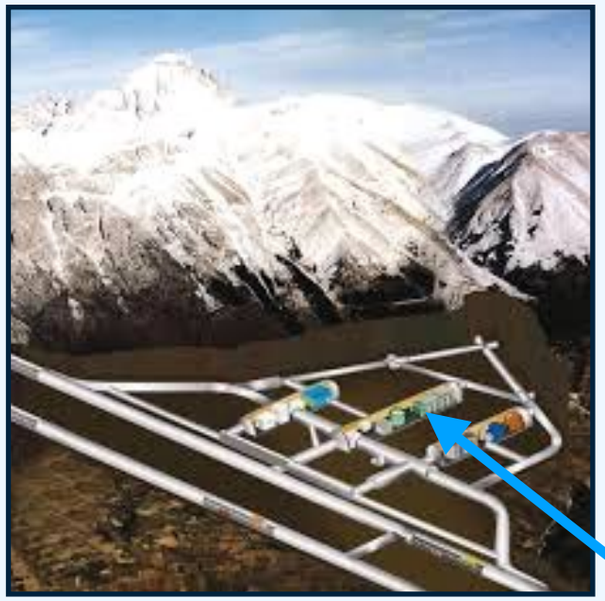
	XENON10	XENON100	XENON1T	XENONnT	DARWIN
	15 kg	161 kg	3.2 t	8.6 t	50 t
	2005 – 2007	2009	2016 – 2018	Now	
Exposure	0.87 kg • yr	48 kg • yr	1 t • yr	20 t • yr	200 t • yr
BG index	~ 1	~ $5 \cdot 10^{-3}$	~ $2 \cdot 10^{-4}$	~ $3 \cdot 10^{-5}$	

cnts/(keV • kg • yr)

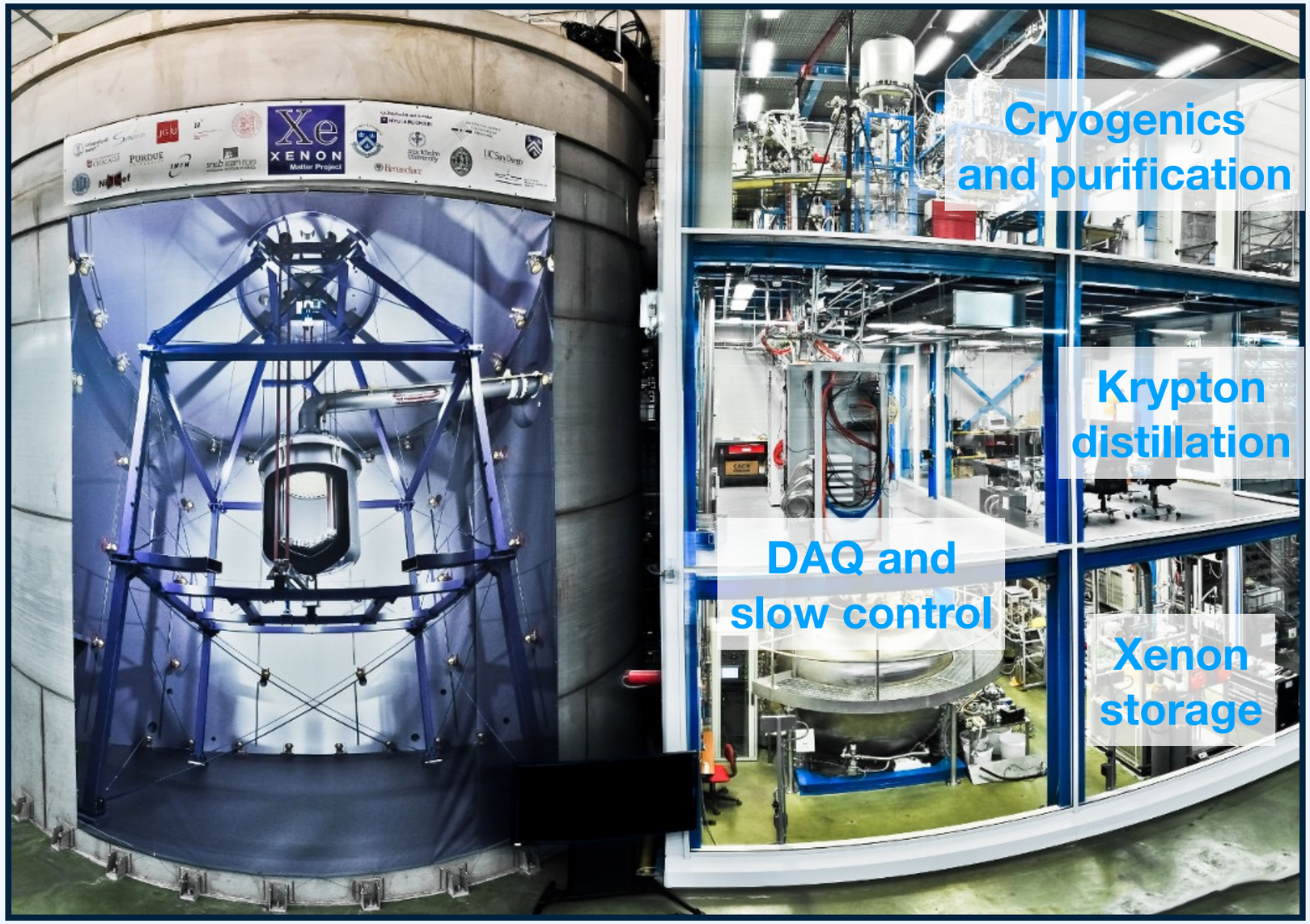


2 pixels

The XENON Experiment

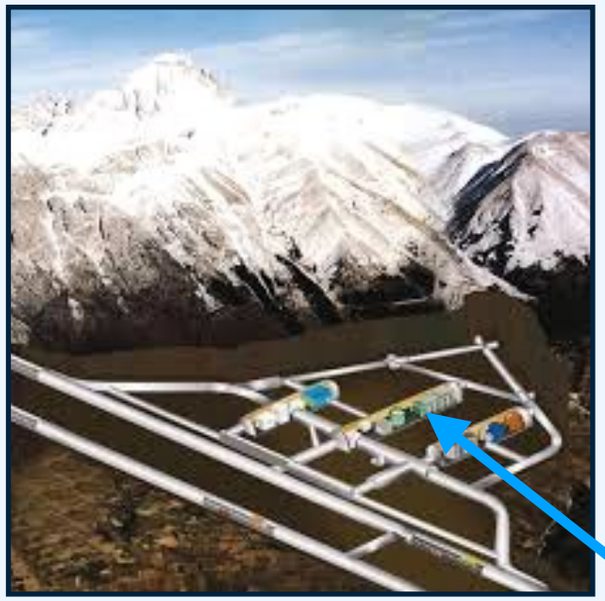


Laboratori Nazionali del Gran Sasso
1500 m overburden
(3600 m.w.e.)



LNGS hall B

The XENON Experiment



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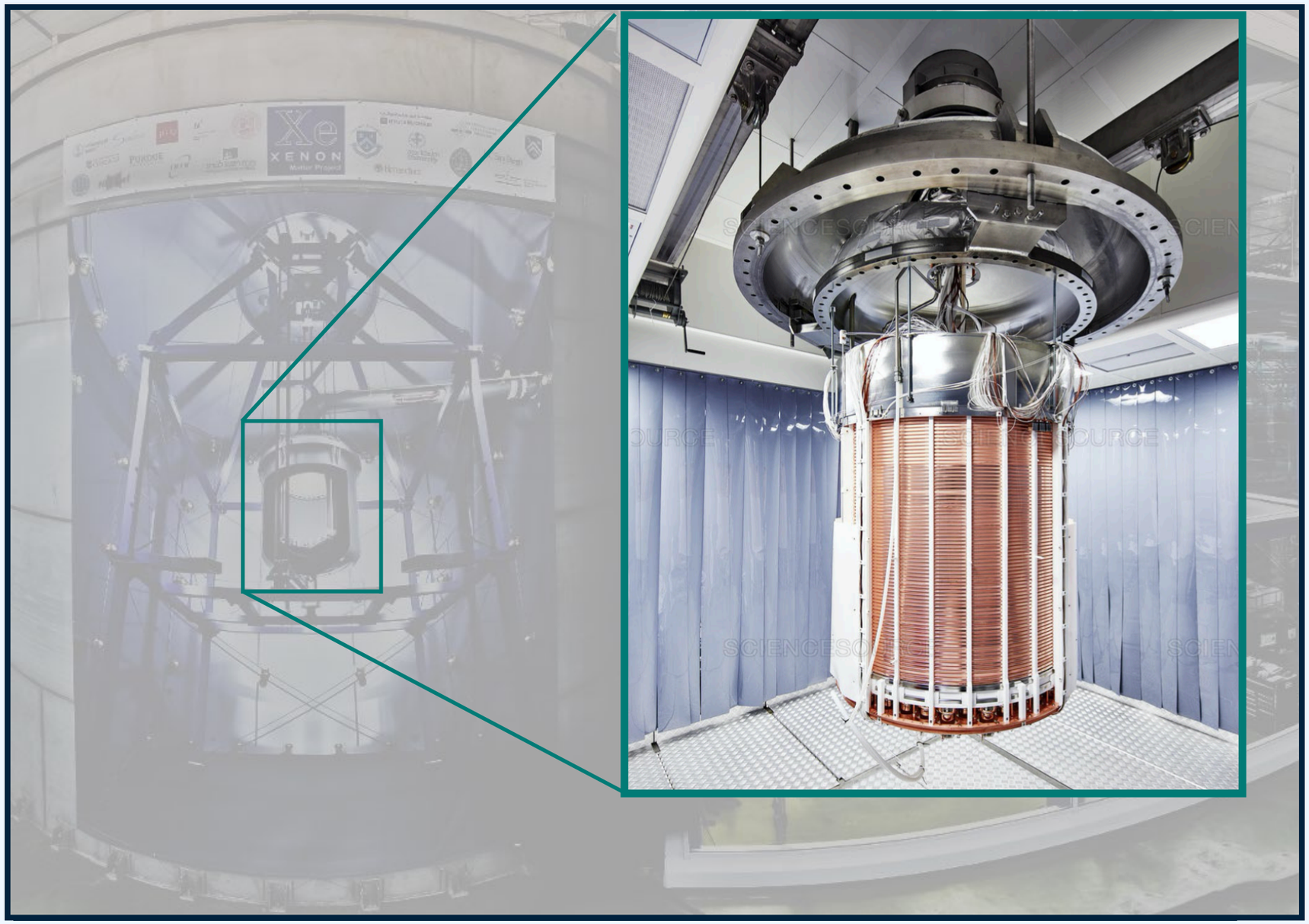
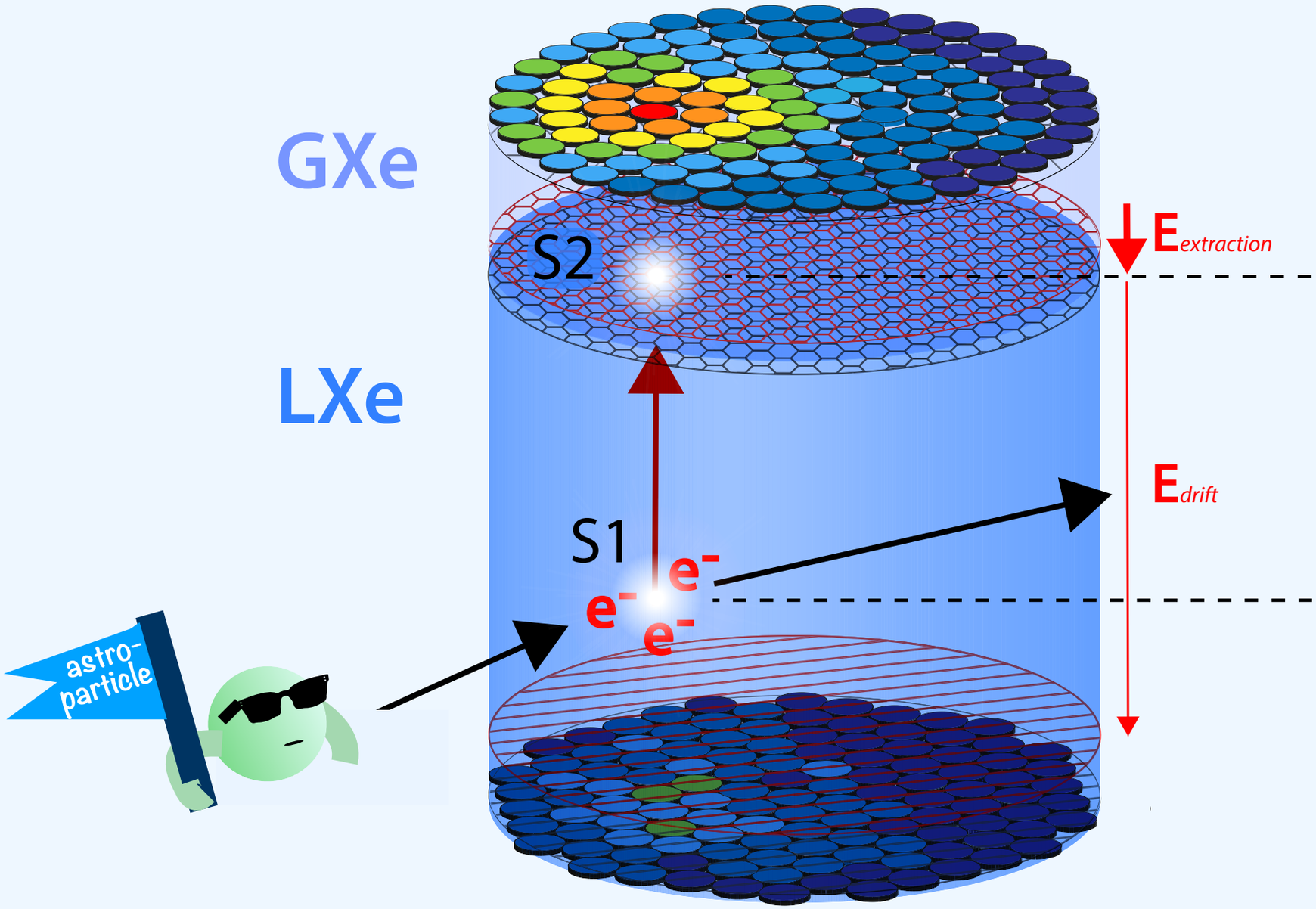


LNGS hall B

XENON1T

Dual-phase Time Projection Chamber



(liquid/gas xenon TPC)

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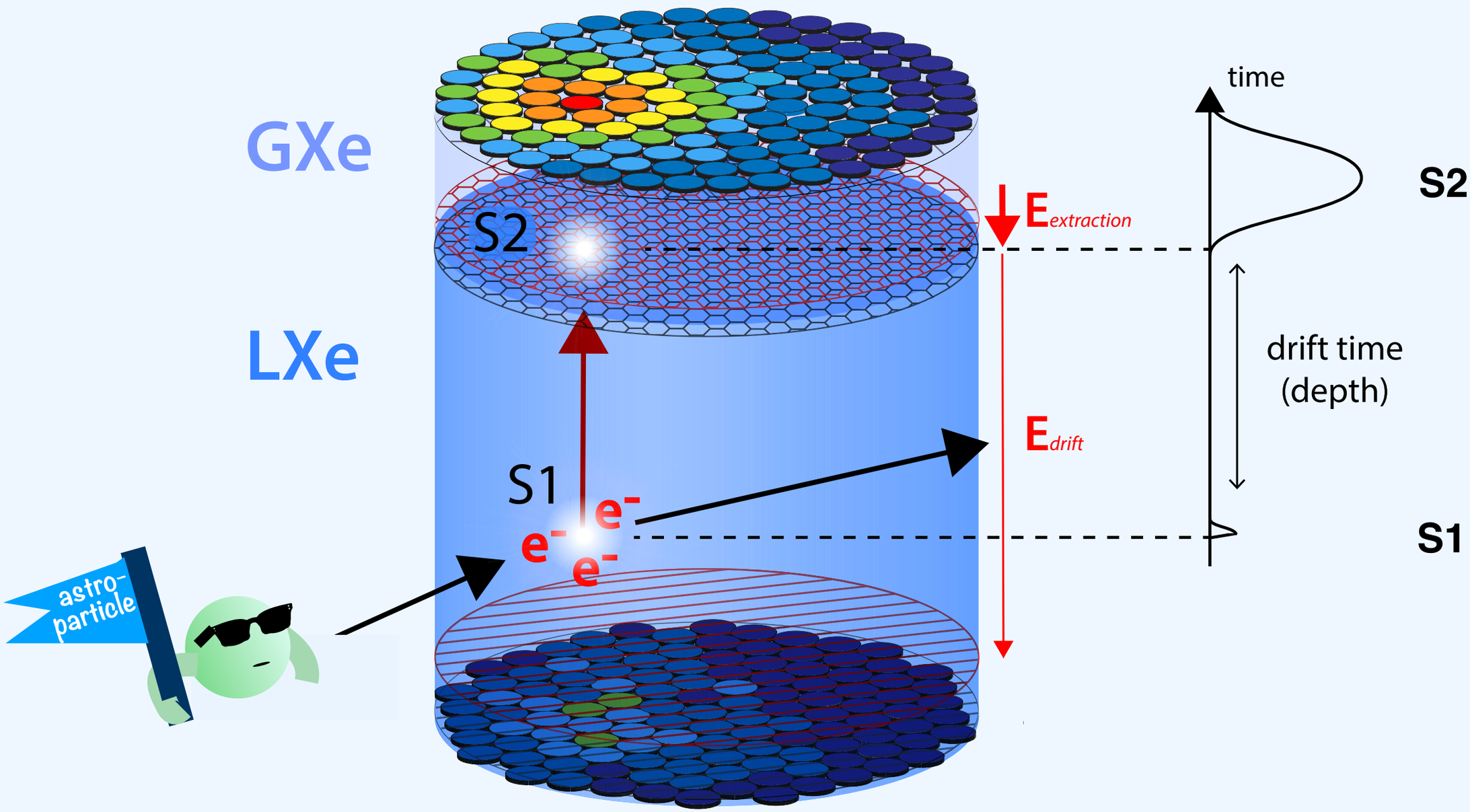

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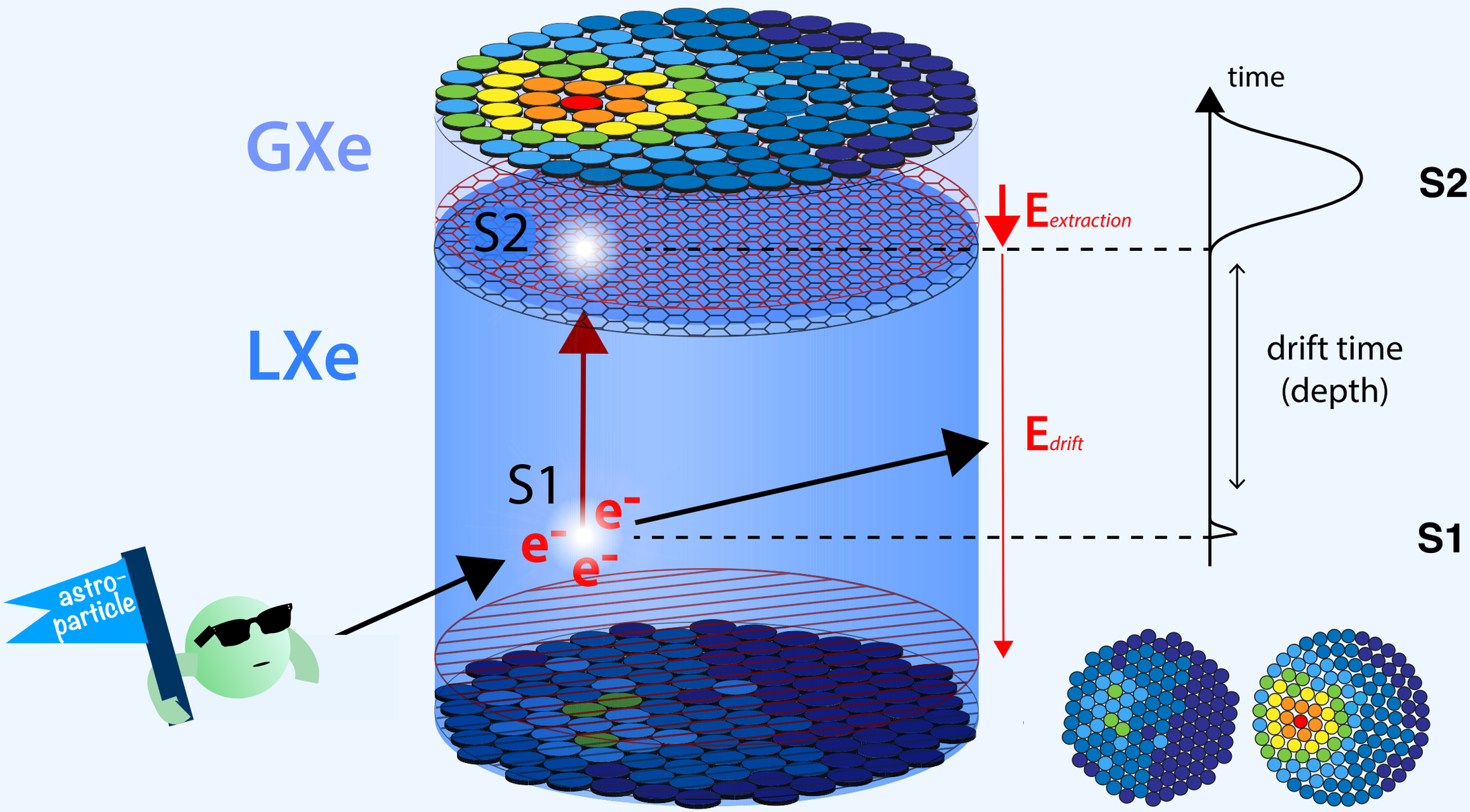

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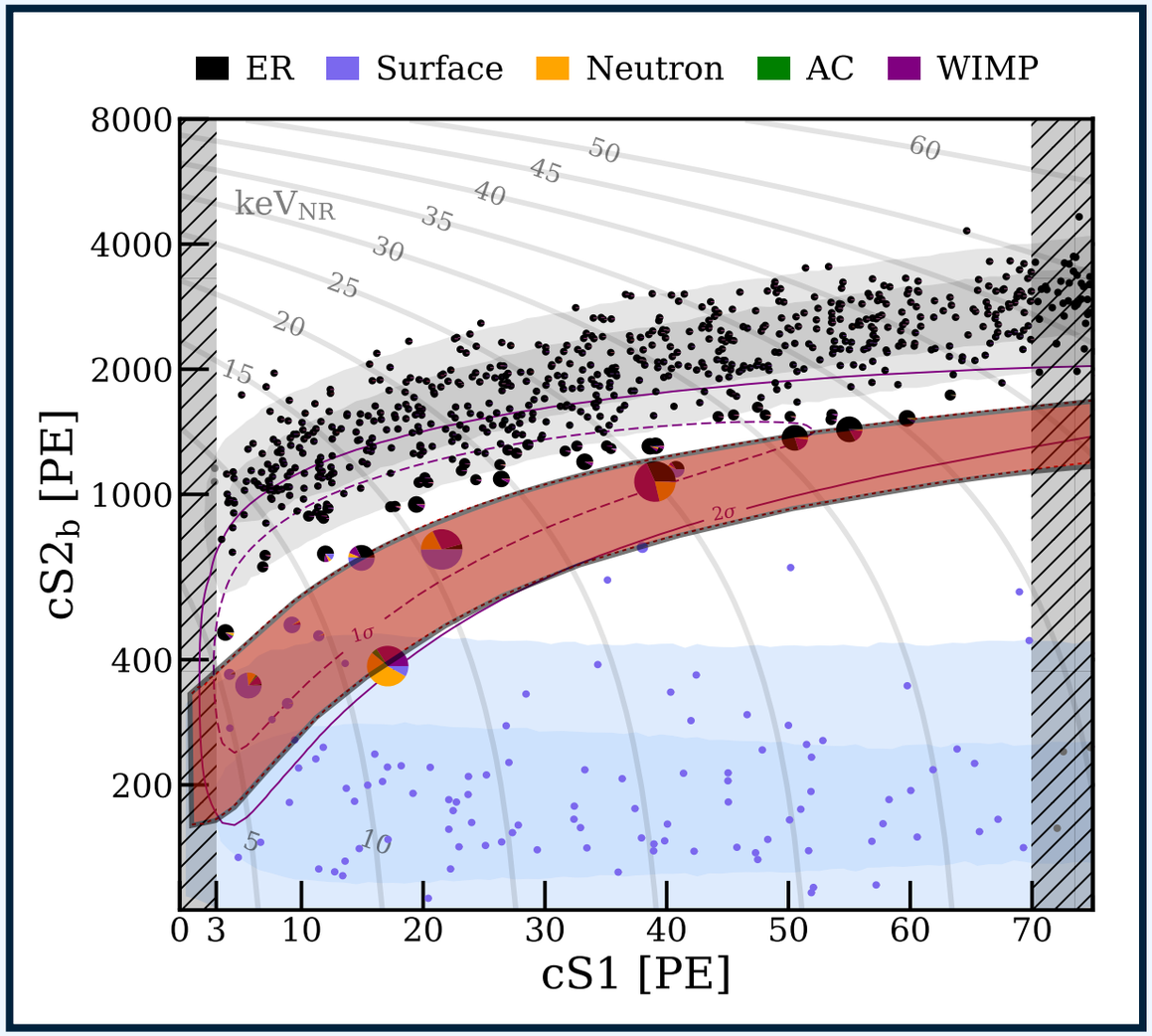
Interaction Types



Nuclear Recoils (NR)
neutron background;
WIMPs, coherent neutrino scattering

Interaction Types

Electronic Recoils (ER)
gamma, beta backgrounds;
neutrino physics, solar axions, boson dark matter

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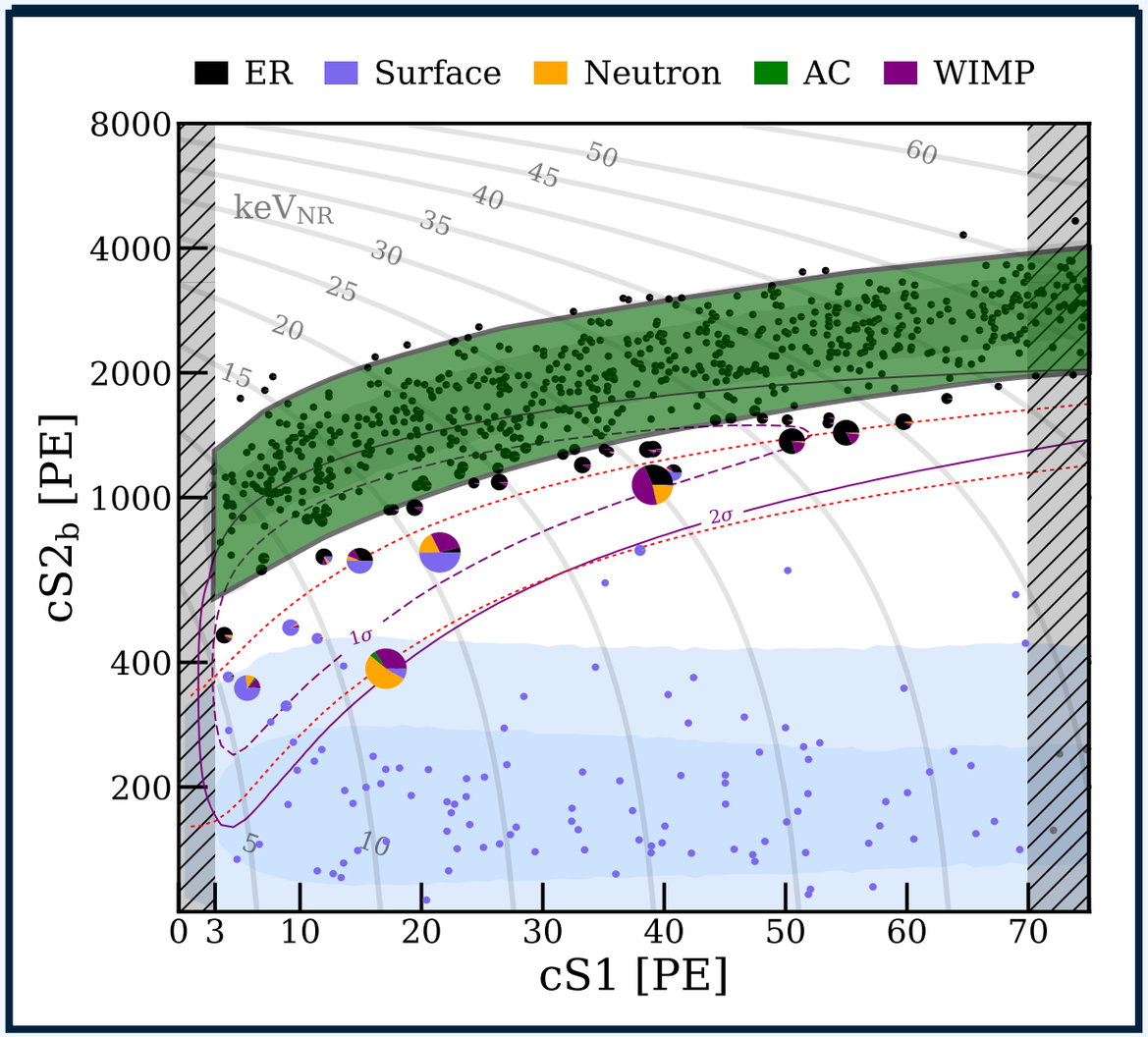

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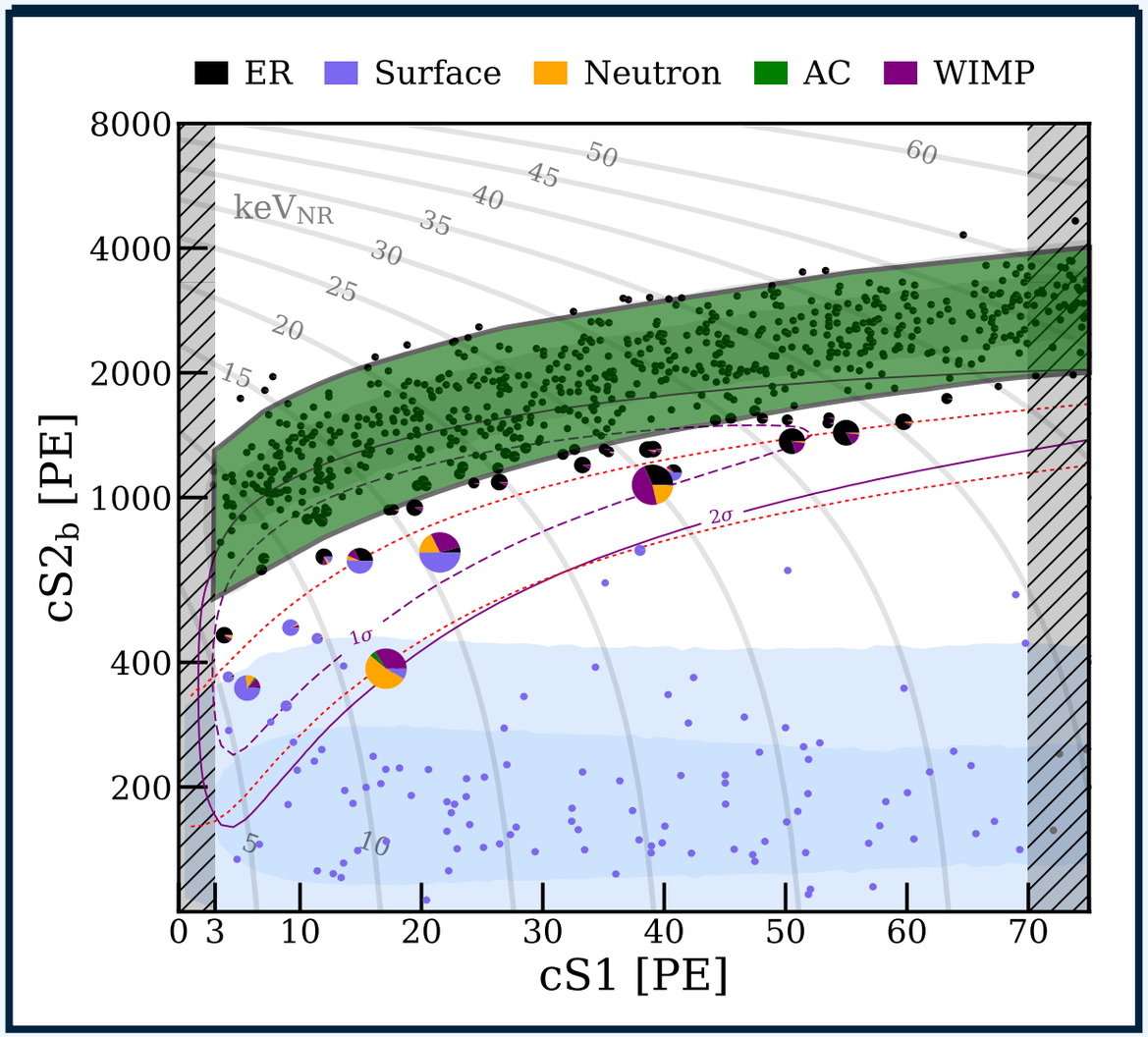

Discriminate NR from ER events; candidates above small neutron and instrumental backgrounds.

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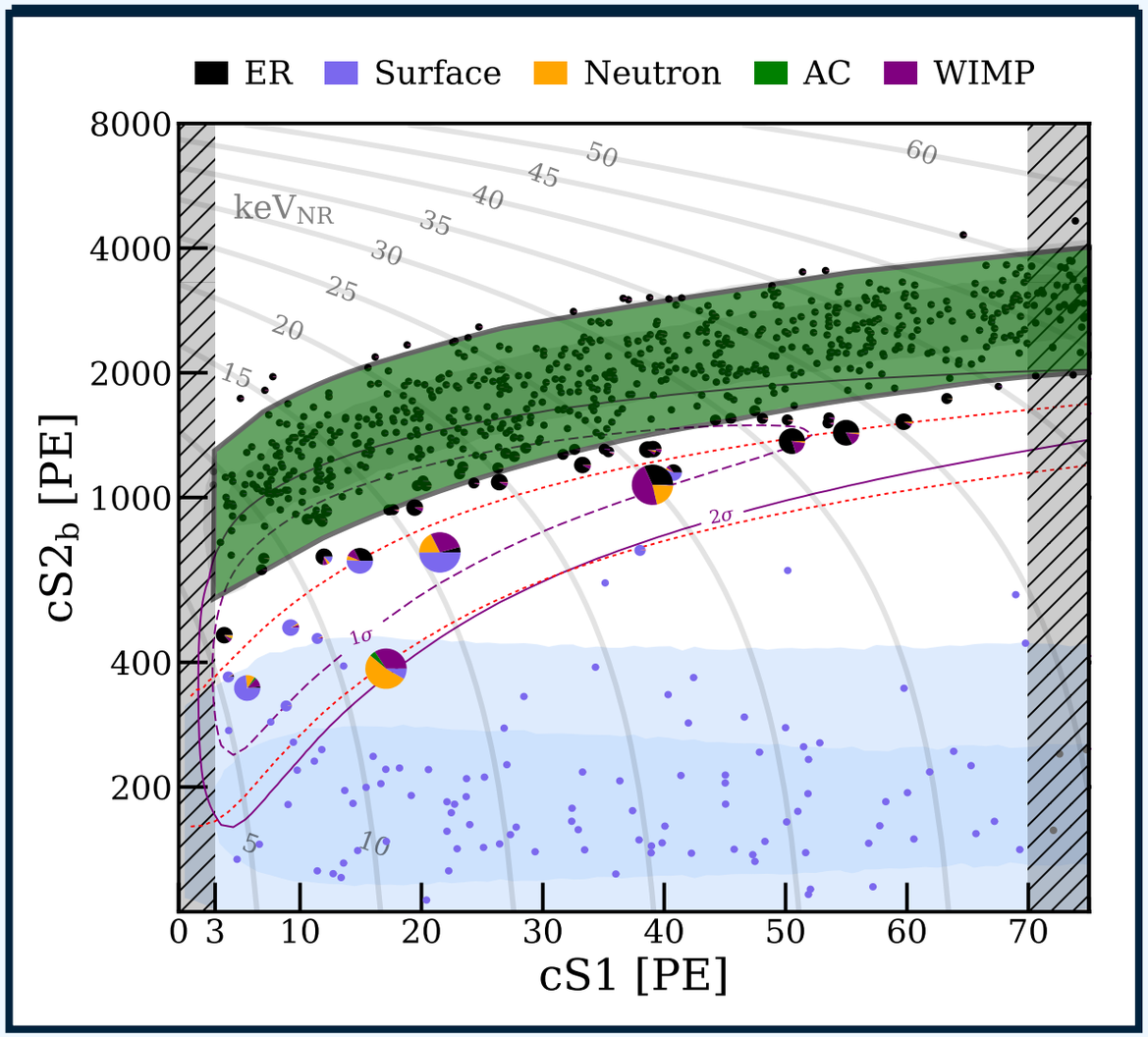


< 100 events/(t/yr/keV$_{ee}$)

Discriminate NR from ER events; candidates above small neutron and instrumental backgrounds.

Search for excess above known, well-modelled ER backgrounds.

The XENON Physics Program

WIMP DARK MATTER

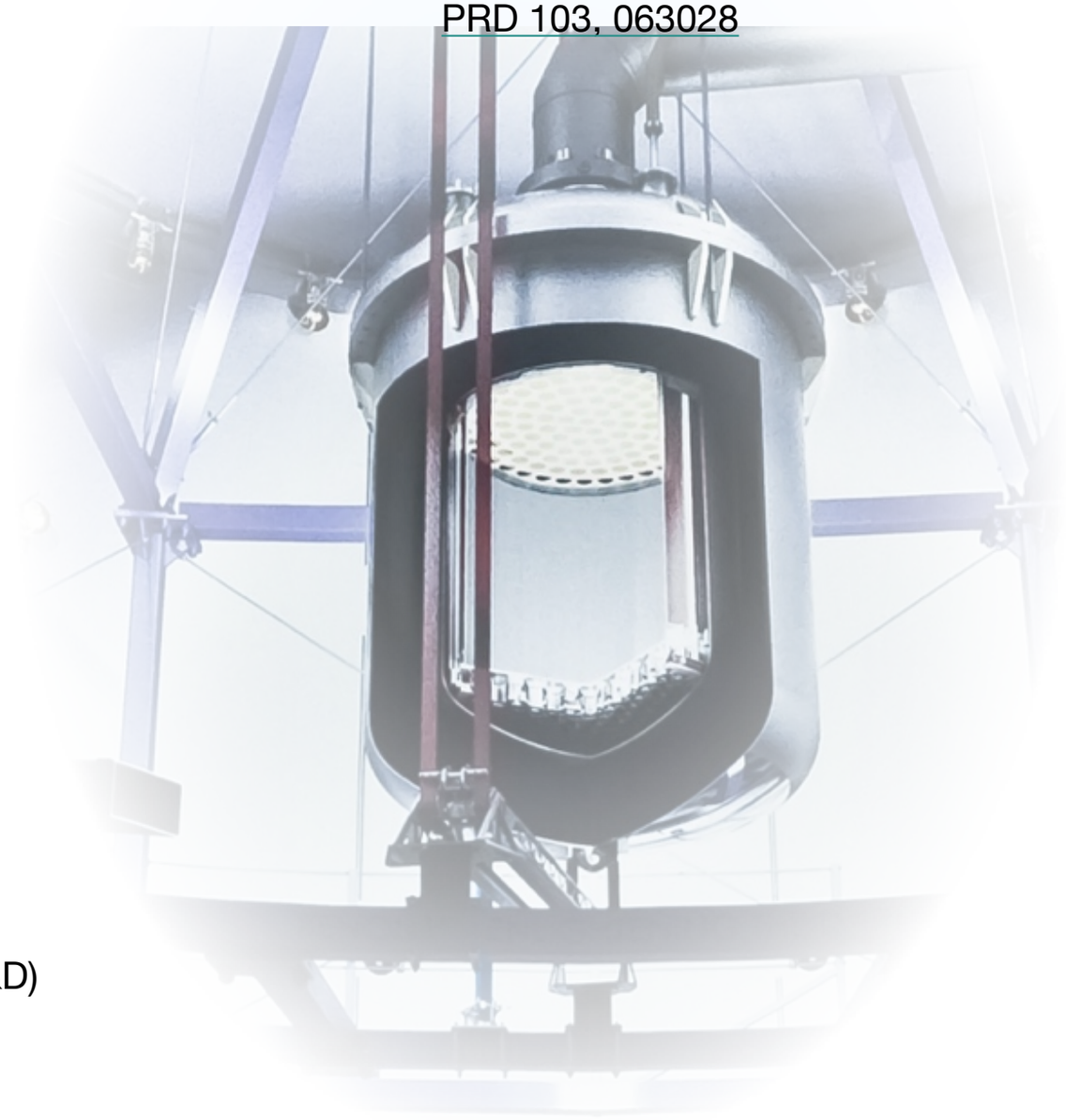
PRL 119, 181301
PRL 121, 111302
PRL 122, 071301
PRL 122, 141301
PRL 126, 091301
PRD 103, 063028

LIGHT DARK MATTER

PRL 123, 241803
PRL 123, 251801

BOSONIC DARK MATTER

PRD 102, 072004



SOLAR ^{8}B CEvNS

PRL 126, 091301

SOLAR AXIONS

PRD 102, 072004

DOUBLE ELECTRON CAPTURE

Nature 568, 532

NEUTRINO MAGNETIC MOMENT

PRD 102, 072004

NEUTRINOLESS DOUBLE-β DECAY

EPJ C (2020) 80:785 (analysis R&D)

TECHNICAL ANALYSIS PAPERS

PRD 99, 112009
PRD 100, 052014

Nuclear recoil searches

WIMP dark matter

Multiple observations via gravitational interactions indicate 85% of the matter in the Universe is dark.

WIMPs: Weakly Interacting Massive Particles favoured by supersymmetry (Beyond Standard Model) new physics expected at GeV masses with **weak-scale cross section** (thermal relic - "**WIMP miracle**")

Search for a scattering interaction in terrestrial detectors with target nuclei.

Expected differential event rate

Nuclear and particle physics

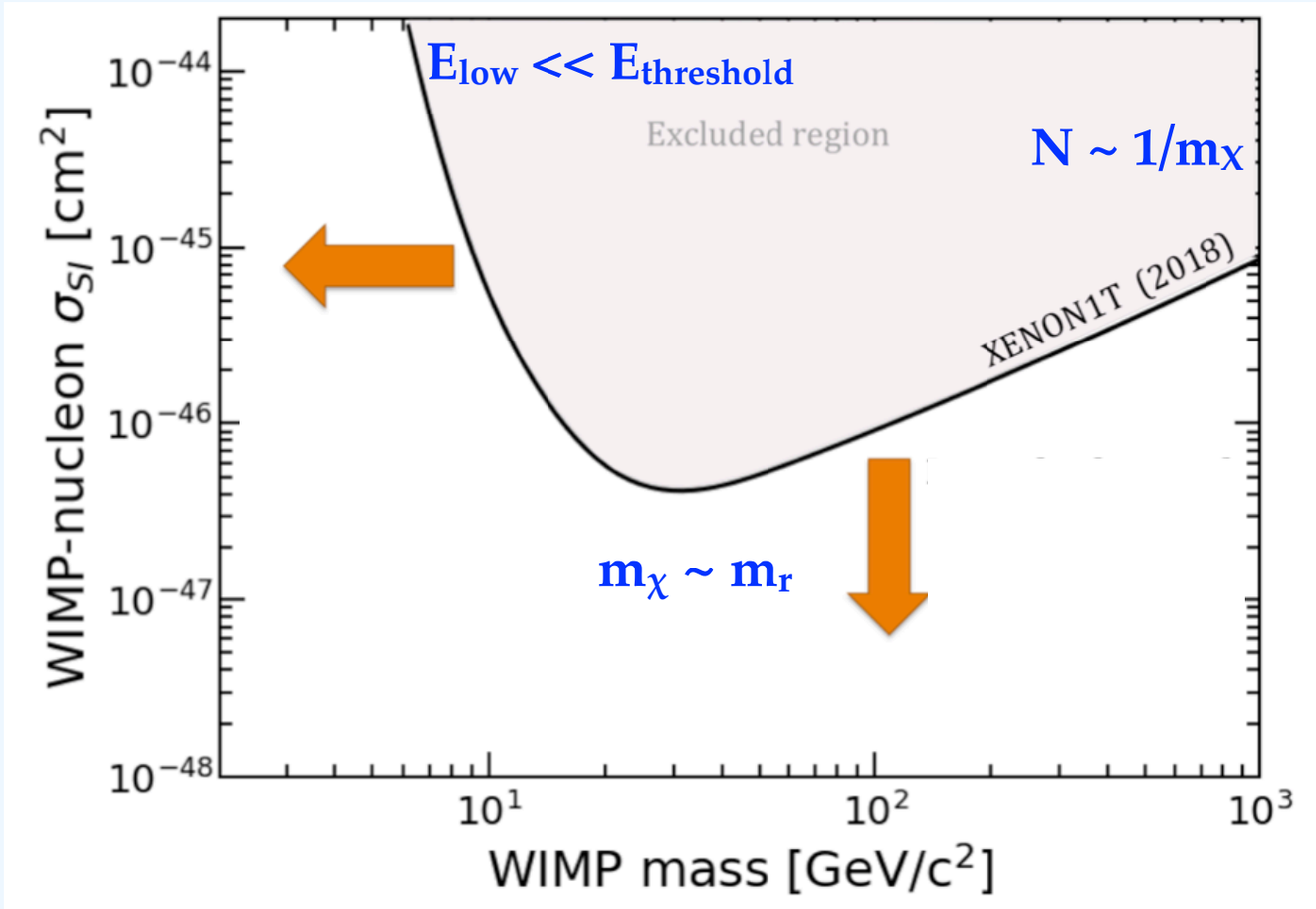
$$\frac{dR}{dE_r} = MT \times \frac{\rho_0 \sigma_0}{2 m_\chi m_r^2} F^2(E_r) \int_{v_{\min}} \frac{f(\vec{v})}{v} d^3 v$$

Detector

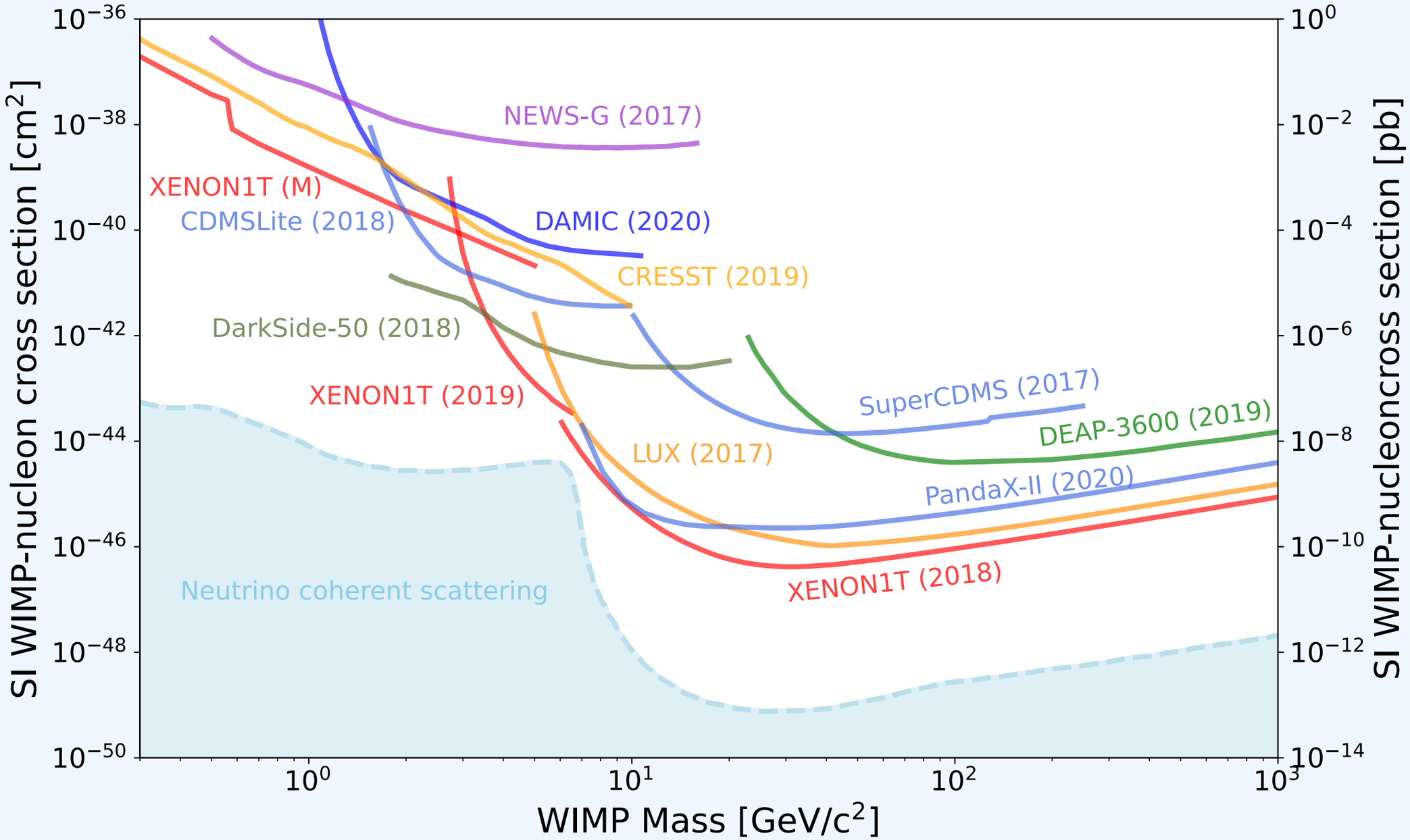
Astrophysics

WIMP masses in the range of 10 - 1000 GeV c^{-2} typically yield recoil energies of 1 - 100 keV.

NR-WIMP cross section vs mass parameter space

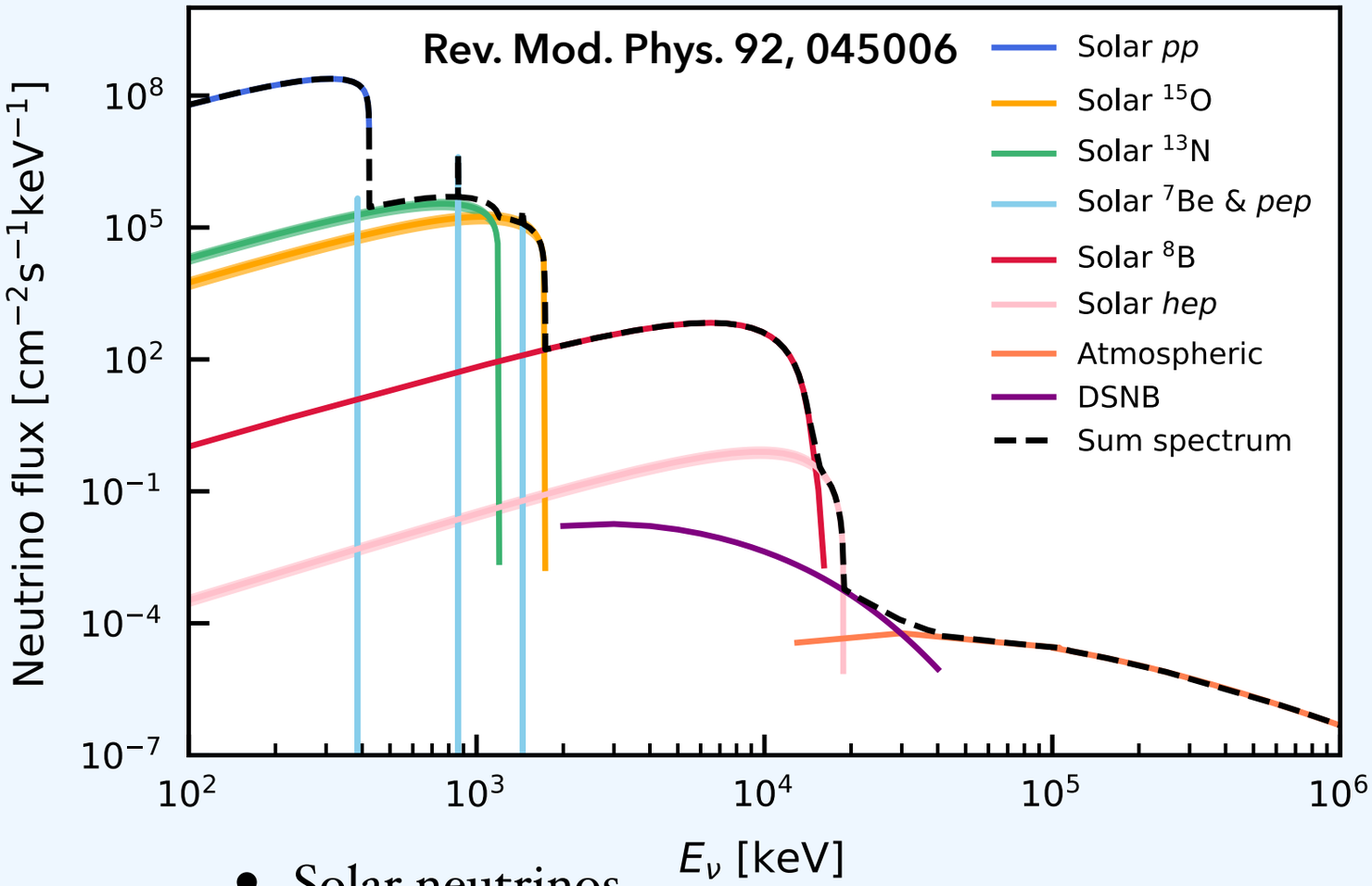


Spin-independent WIMP limits

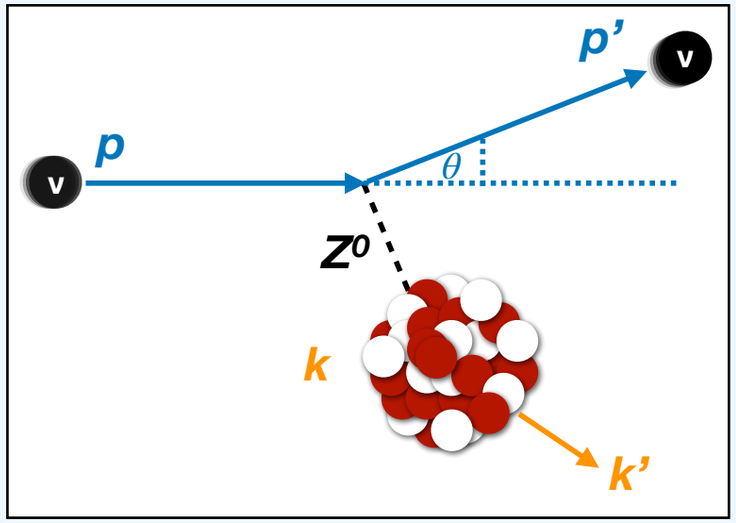


Currently most stringent result on WIMP Dark Matter down to 3 GeV/c² masses [PRL 121, 111302 + PRL 123, 251801]

Coherent neutrino-nucleus scattering



- Solar neutrinos
- Diffuse supernova neutrino background
- Atmospheric neutrinos



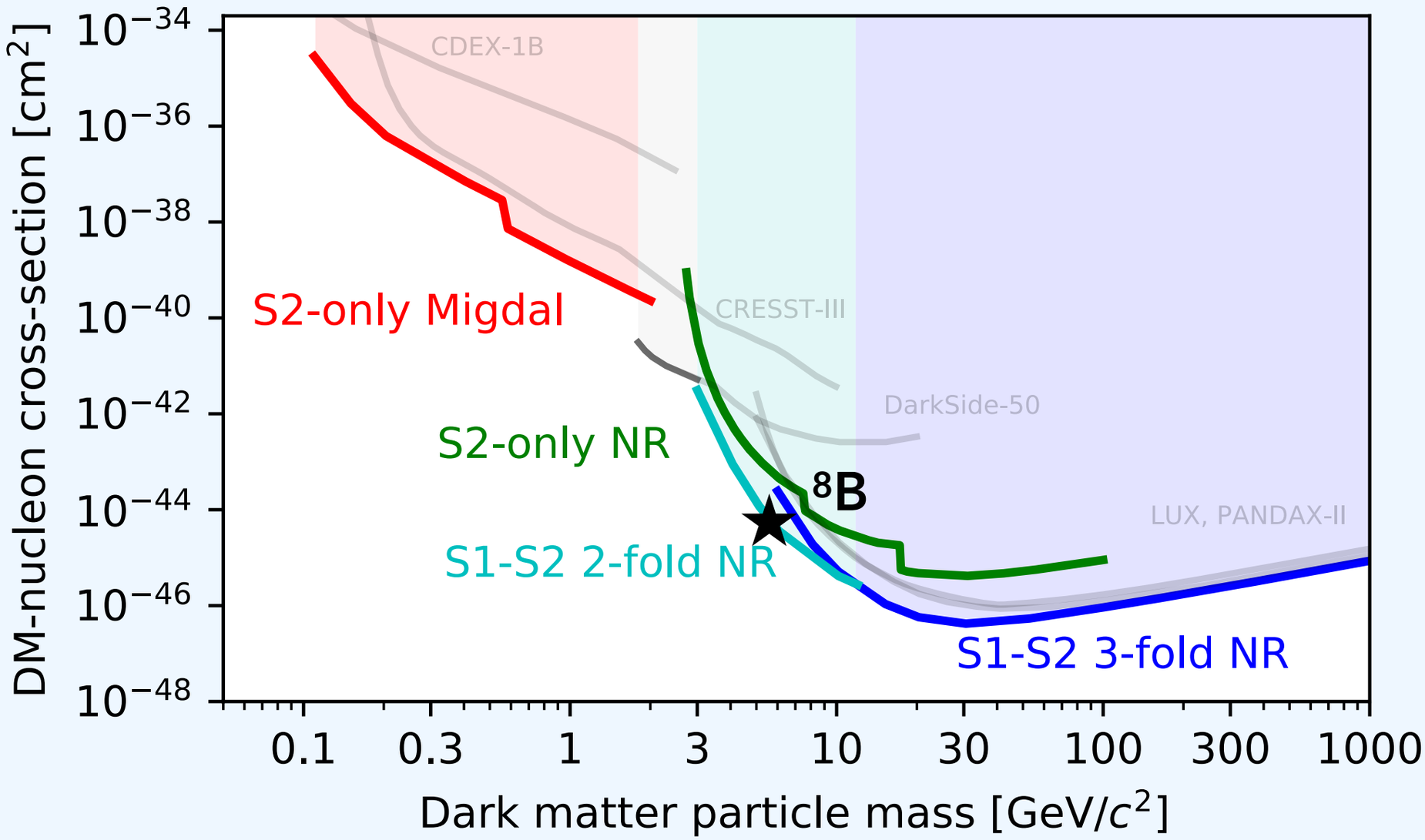
- Search for ^{8}B neutrinos
- Use measured flux (Borexino, SNO) to constrain xenon low-energy detector response
- constrain non-standard neutrino interactions
- set limit on DM-nucleus

expectation: 2.1 ^{8}B events (6 found, consistent with background)

The primary scintillation signal S1 limits the threshold.
Lower the threshold (from 3 to 2 PMT hits)
5% efficiency at 0.5 keV cutoff

Probing lower WIMP masses

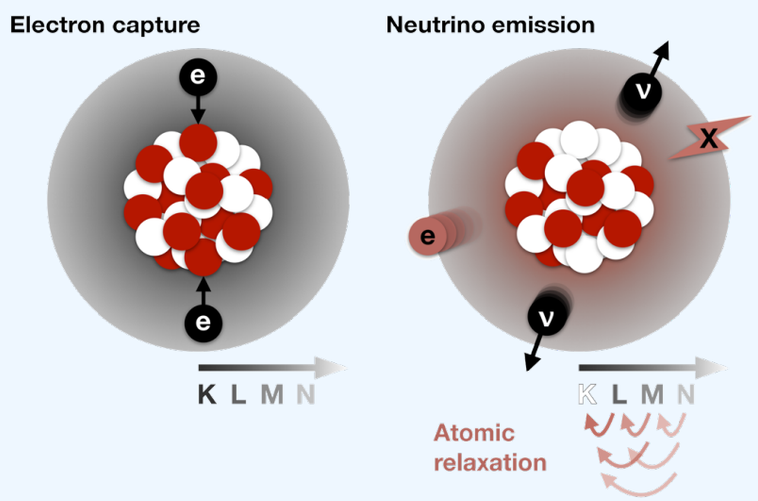
Phys. Rev. Lett. 126 (2021) 091301



Drop the discrimination requirement (S2/S1) and set limits with the S2 signal.
Can also look for secondary emission (Migdal effect) in S2-only data.

Electronic recoil searches

Two-neutrino double electron capture



$$T^{2\nu ECEC} = (1.8 \pm 0.5 stat \pm 0.1 sys) \times 10^{22}\ y$$

highlights sensitivity to rare processes

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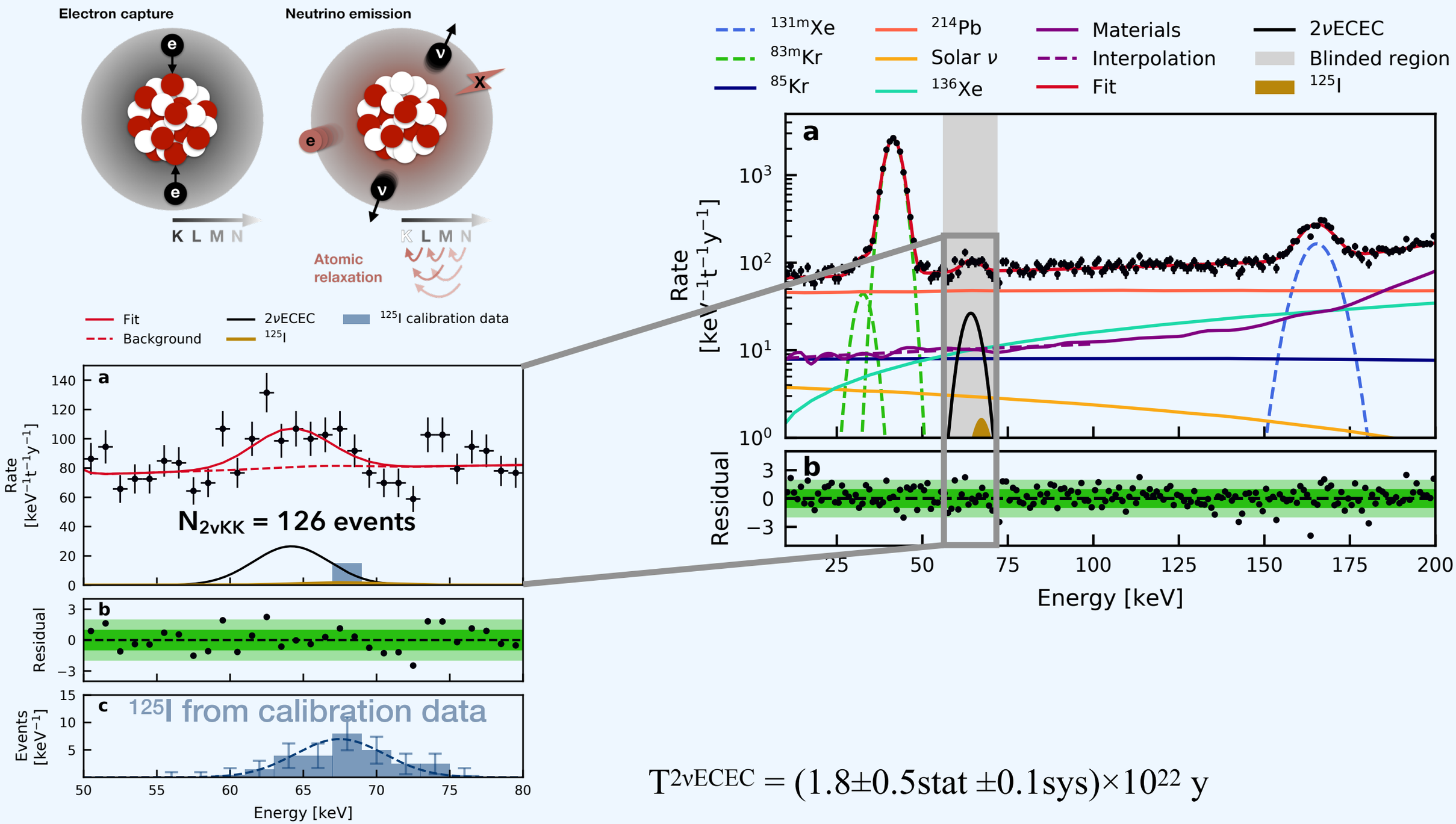

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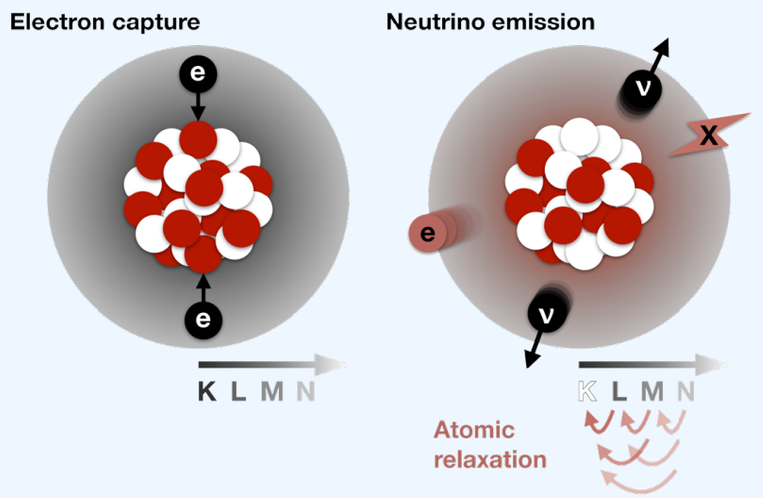

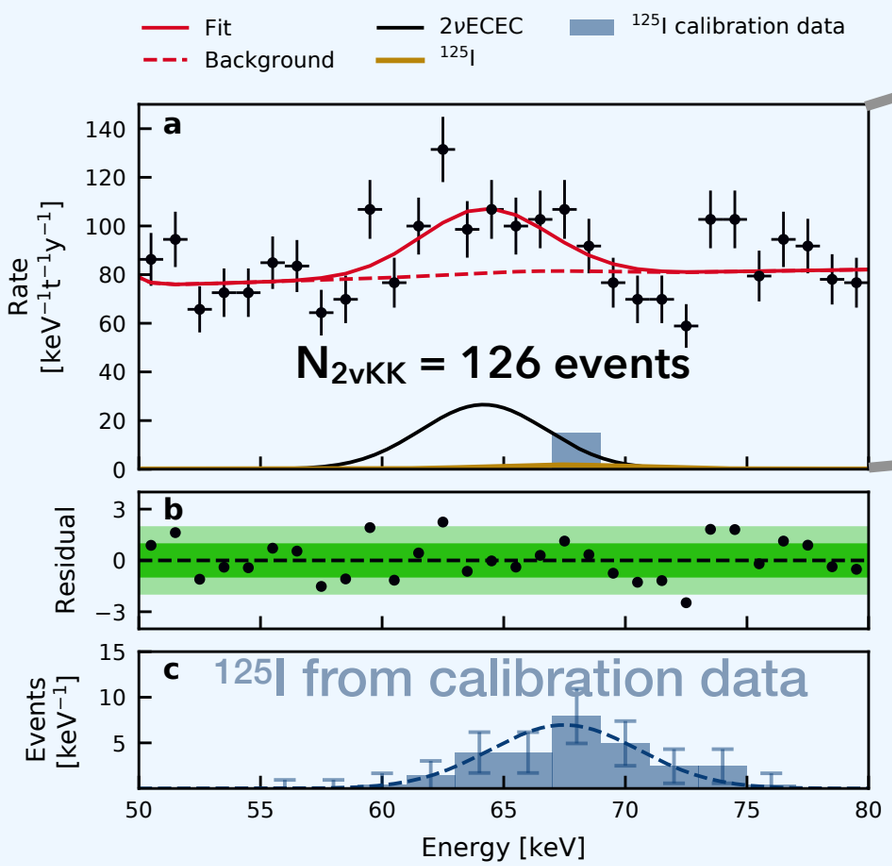

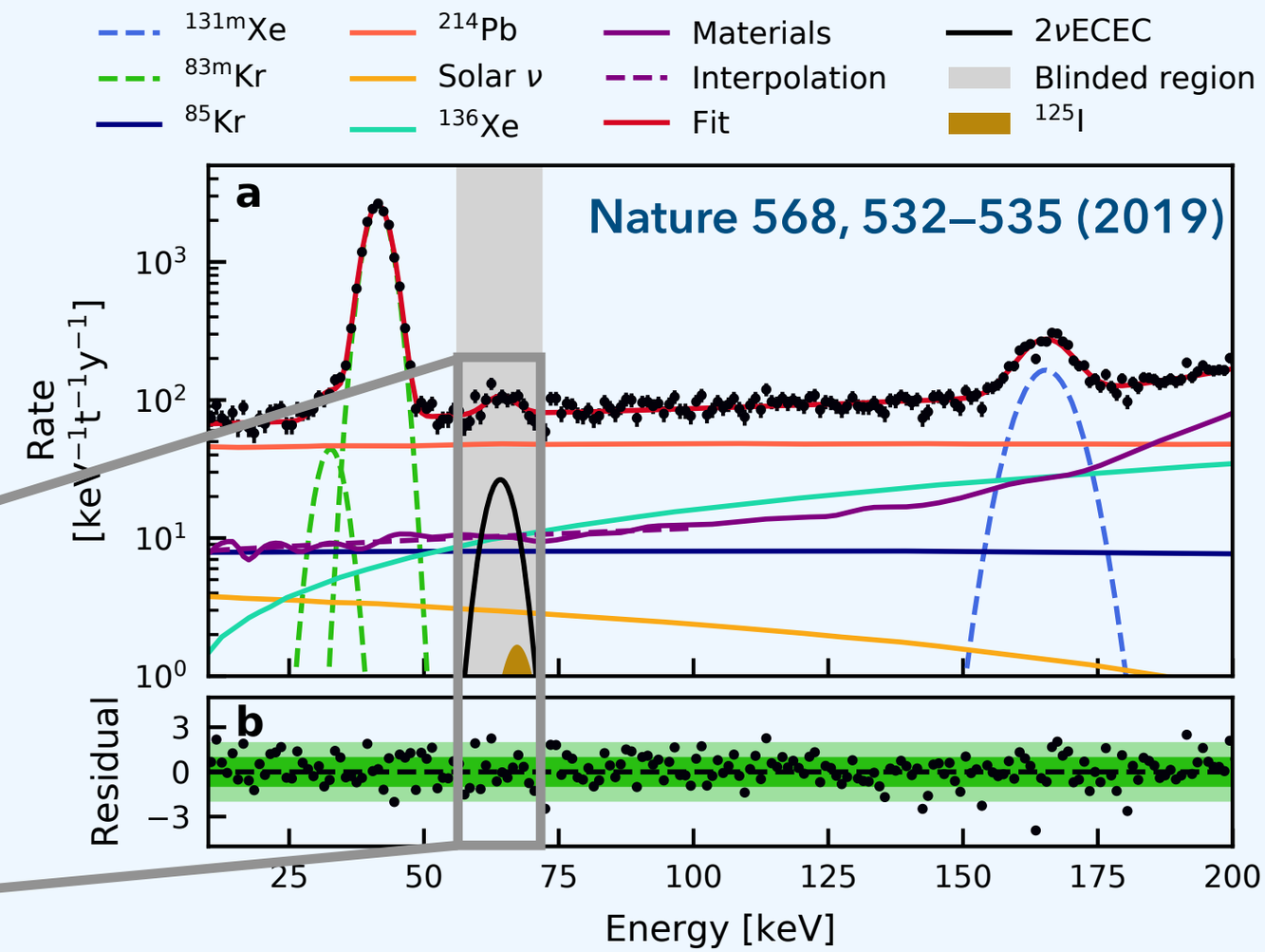

First observation of this process in ^{124}Xe
4.4σ above background
longest half-life directly measured

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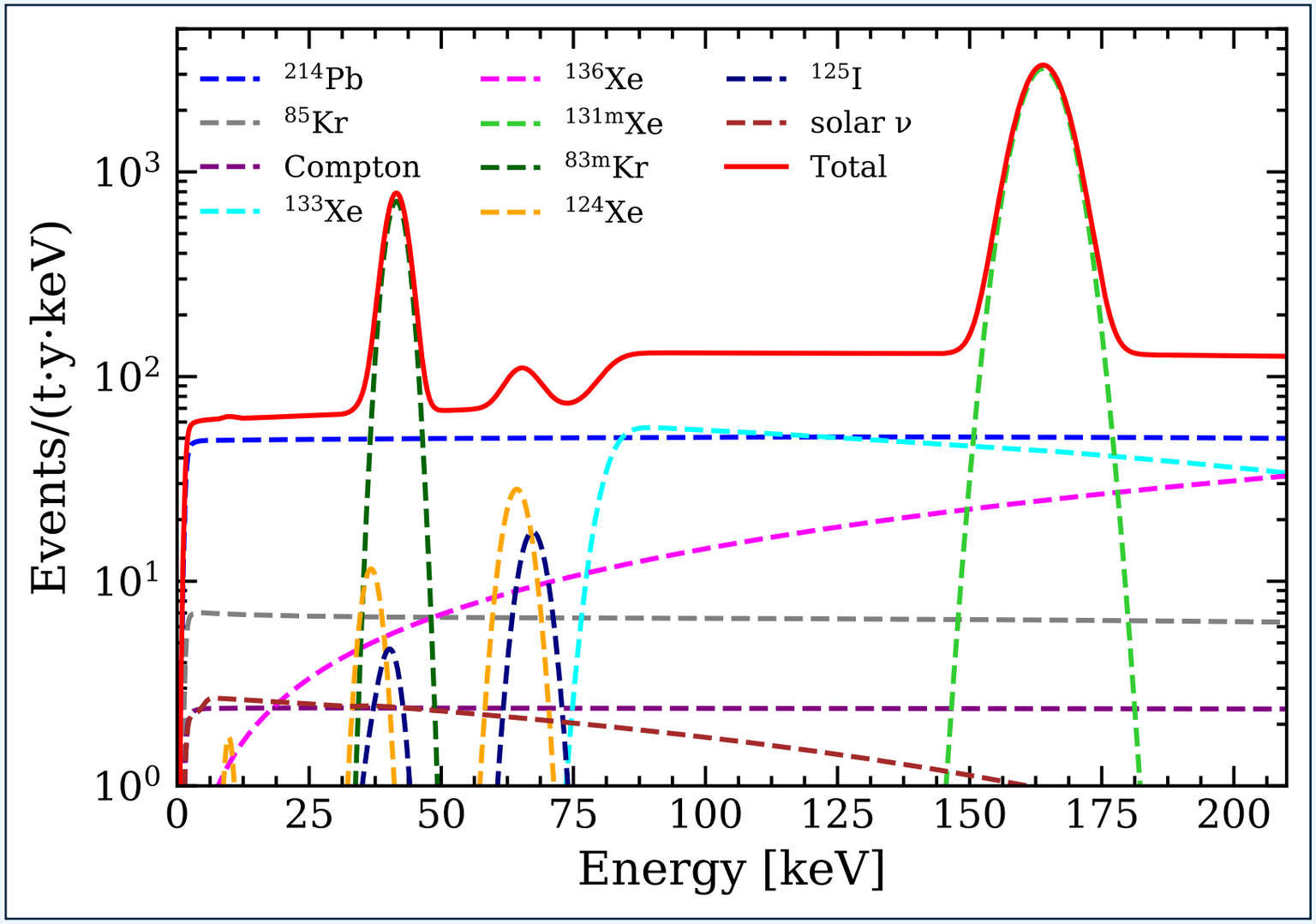
Background model for ER searches

Search for an excess above known backgrounds.

10 components



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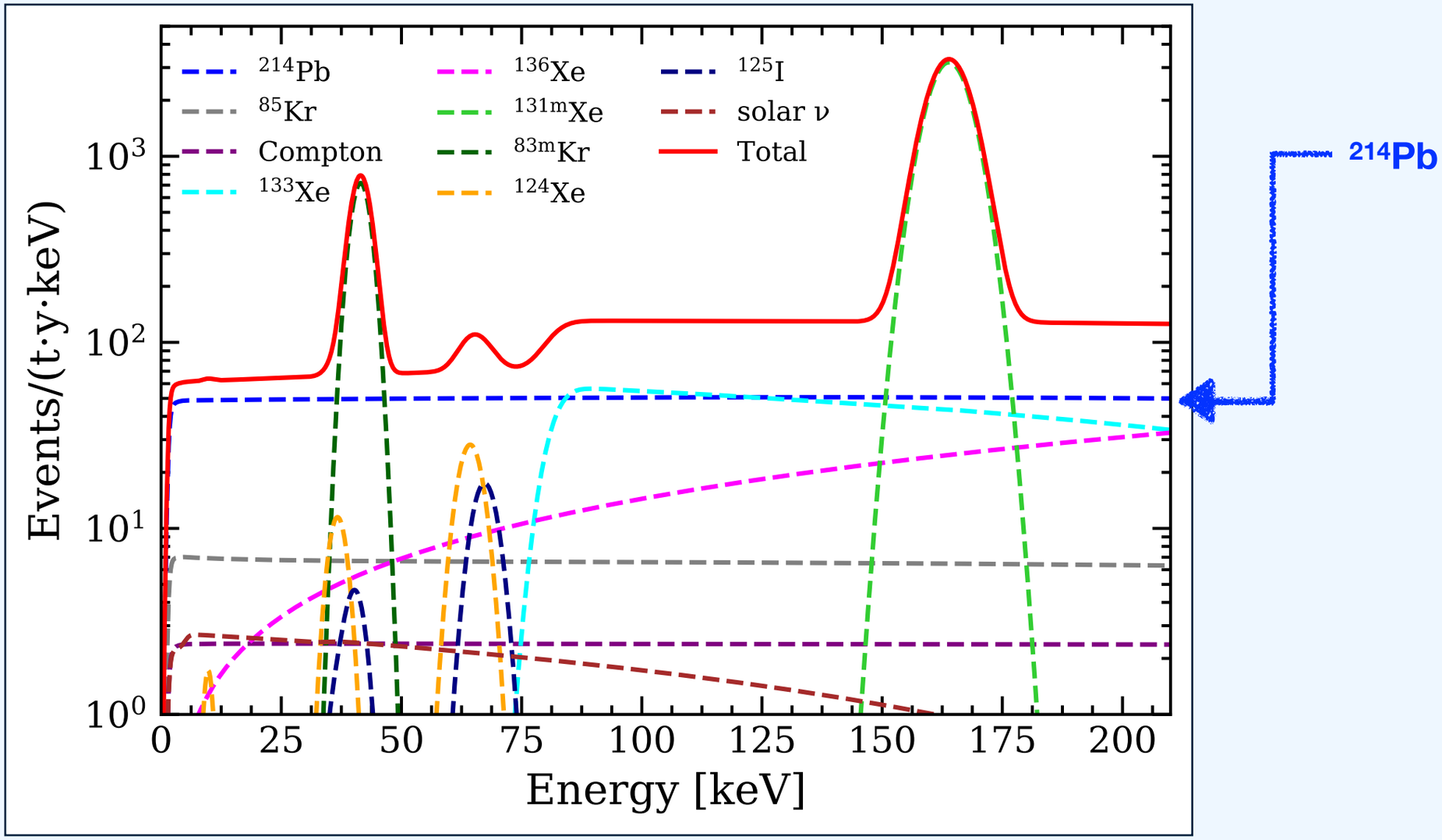

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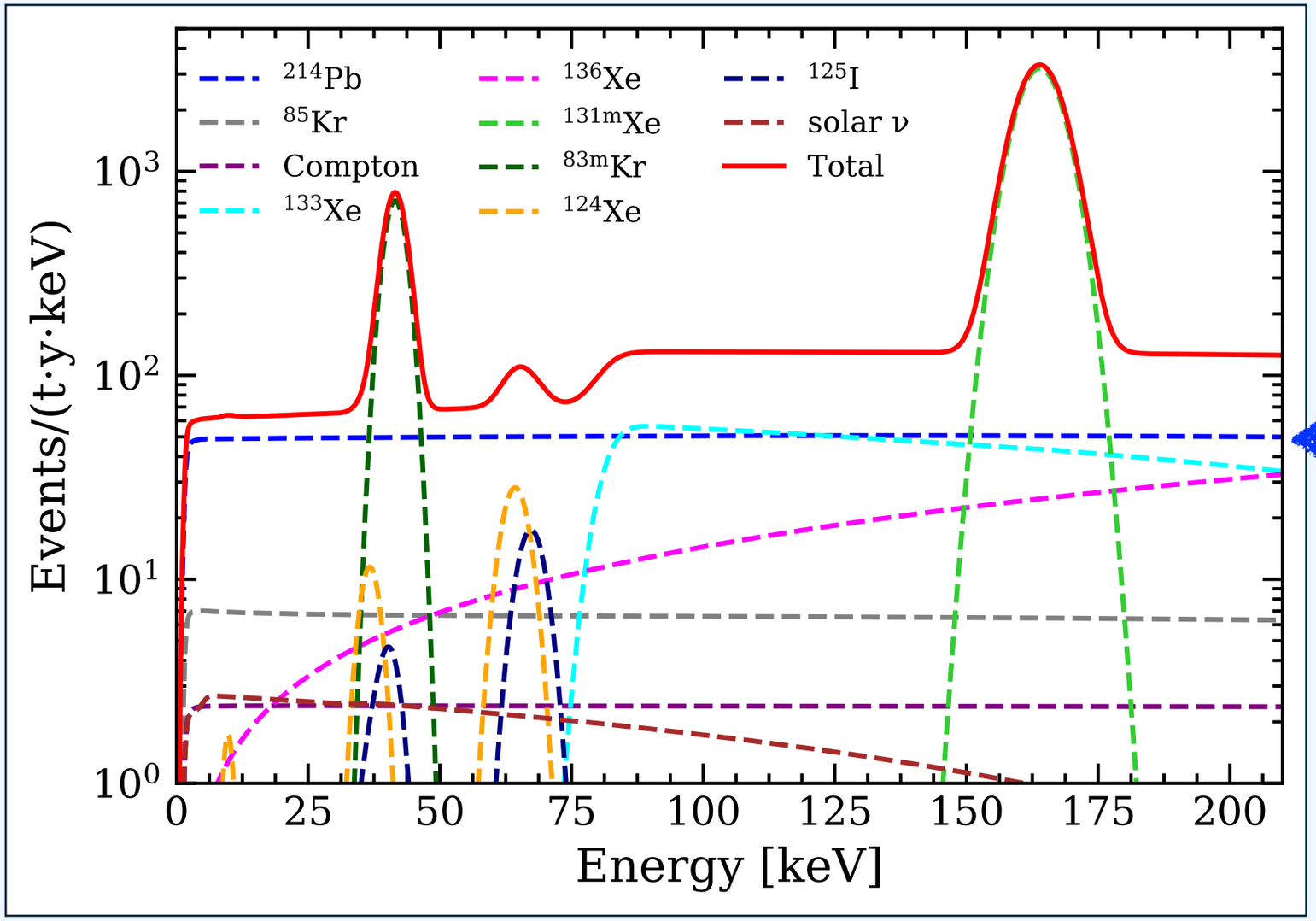

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^{214}Pb ^{136}Xe

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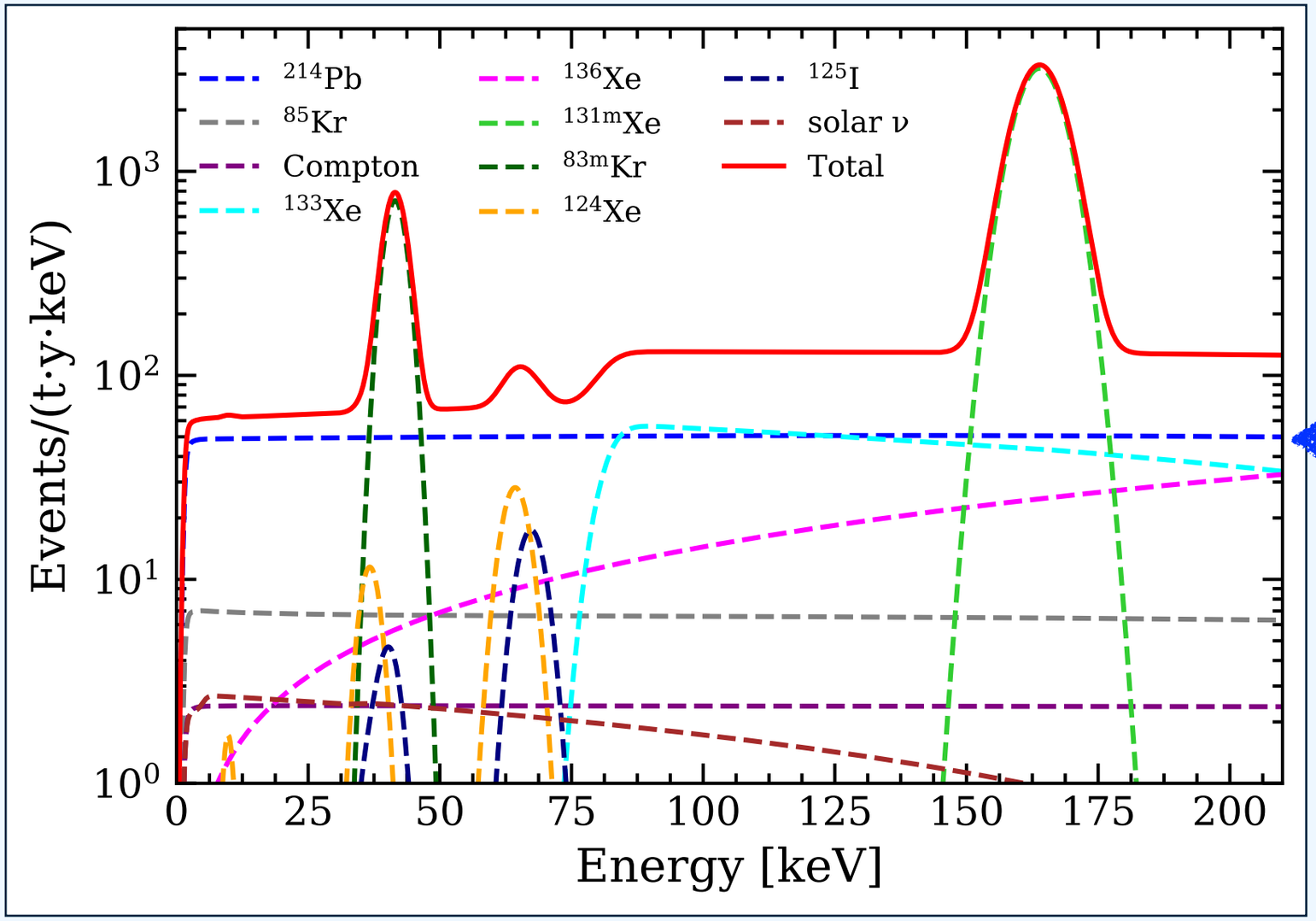

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Neutron activated

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

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

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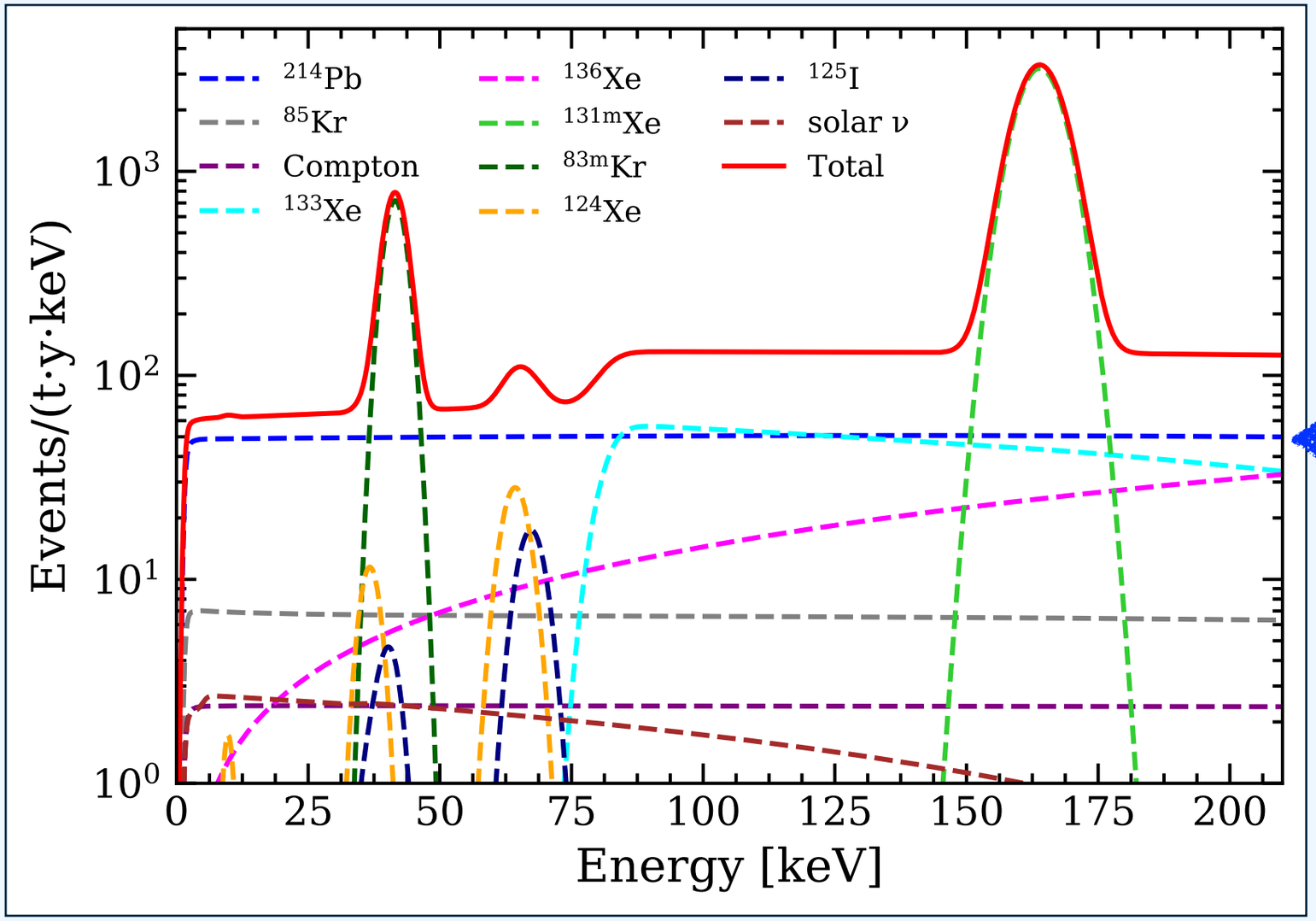

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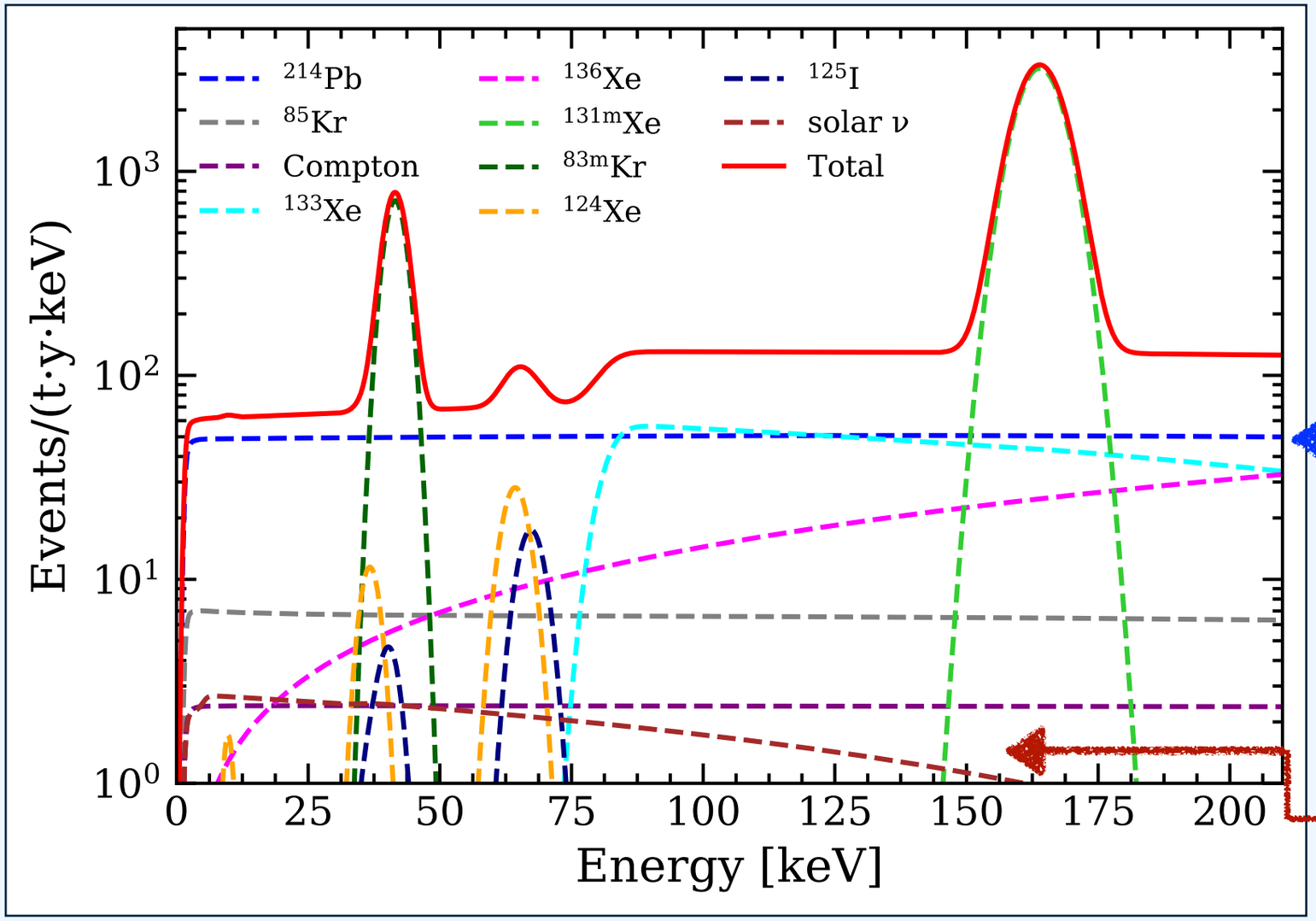

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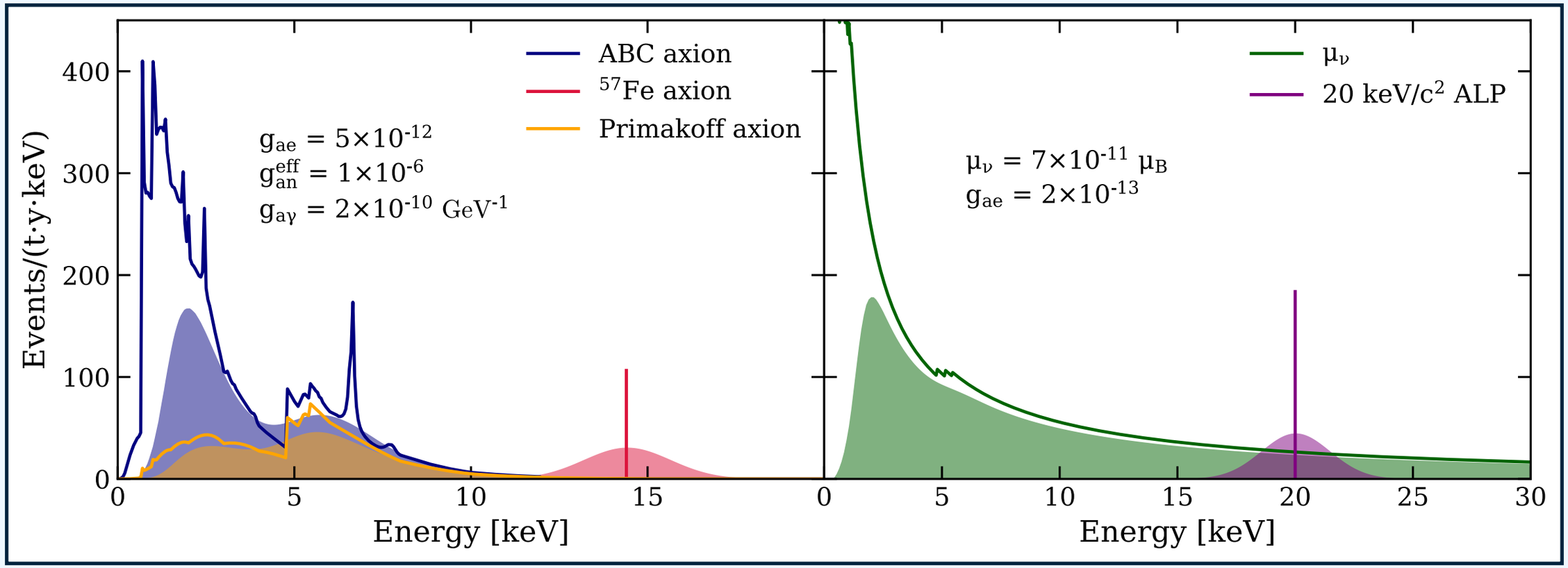
Materials

Solar neutrinos

Search for new physics



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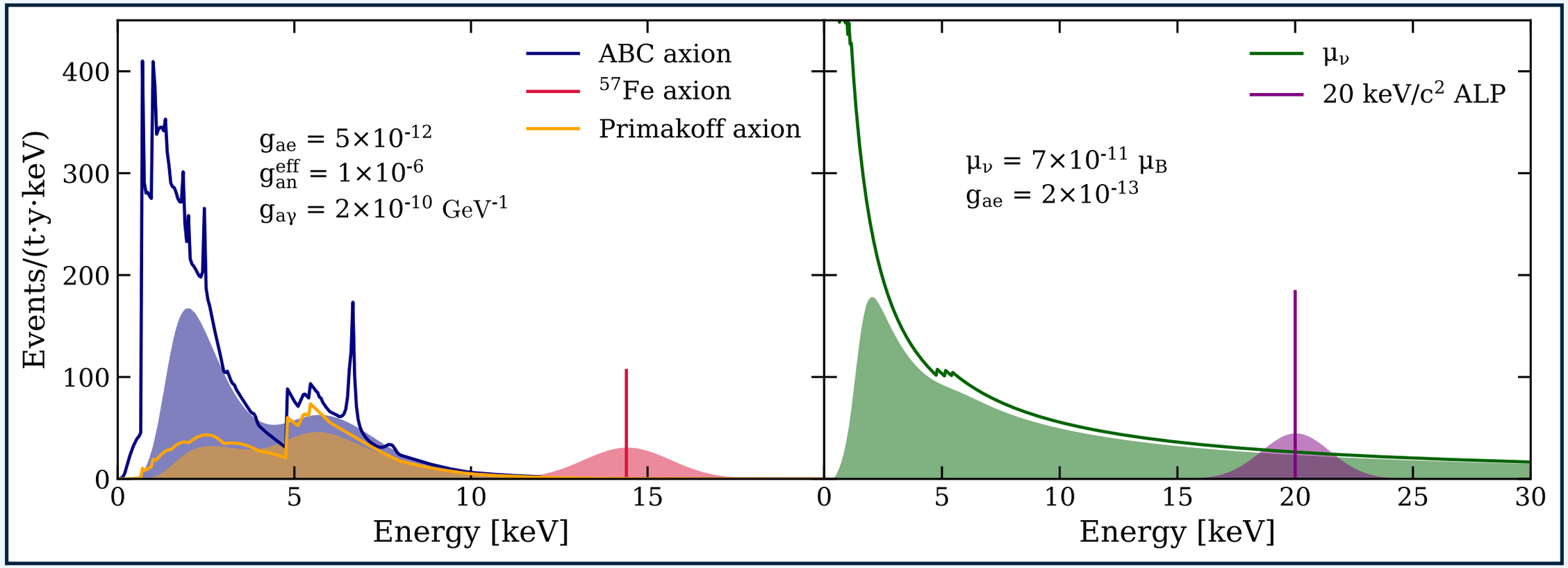

Solar axions:

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

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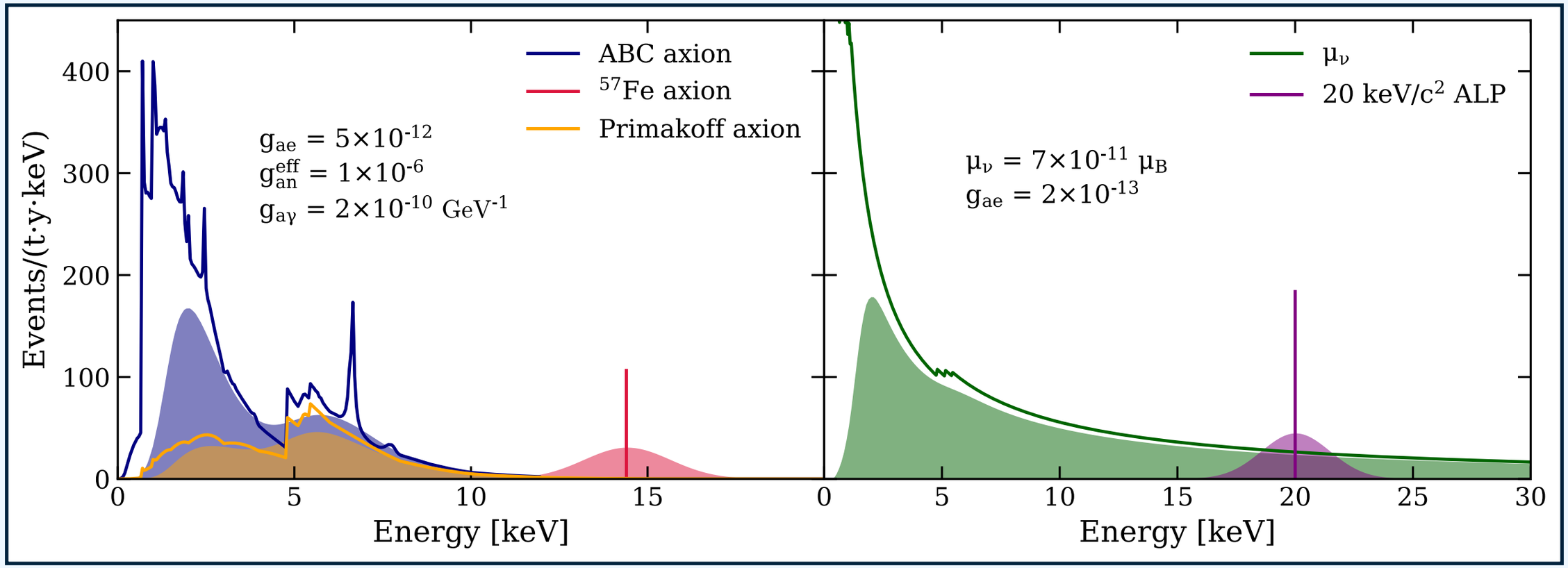

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Enhancement of the neutrino magnetic moment:
Majorana or Dirac nature

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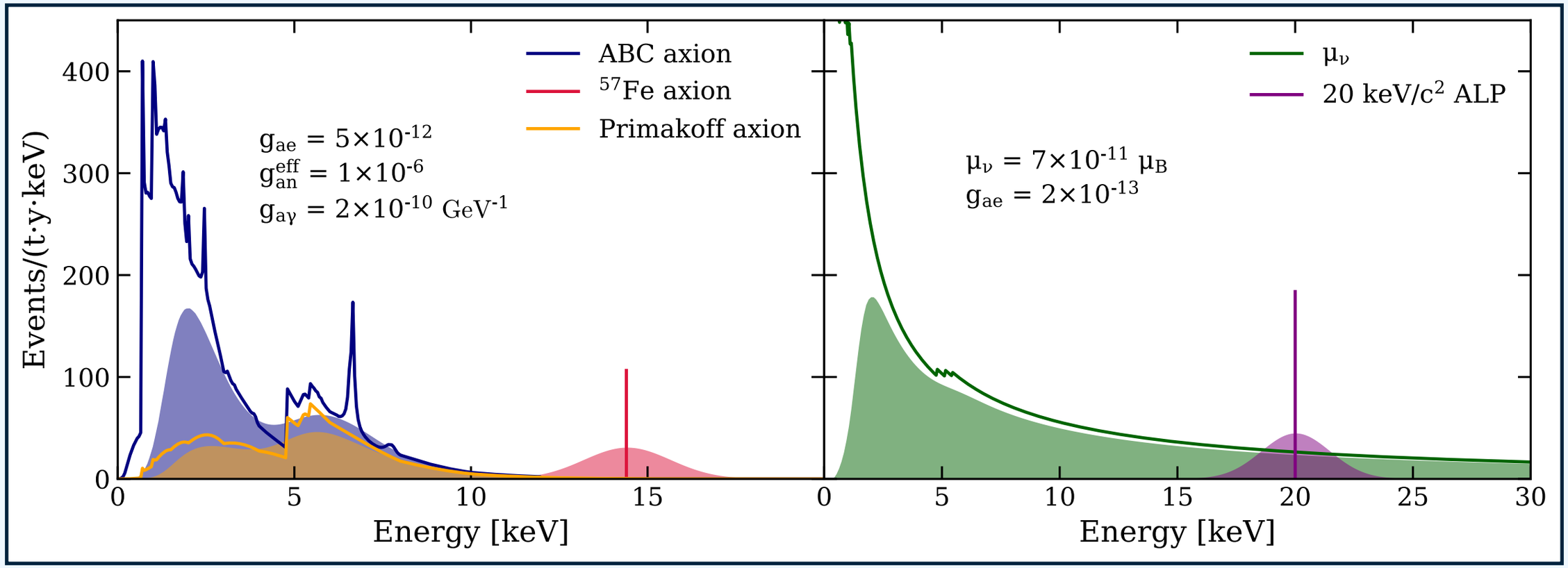

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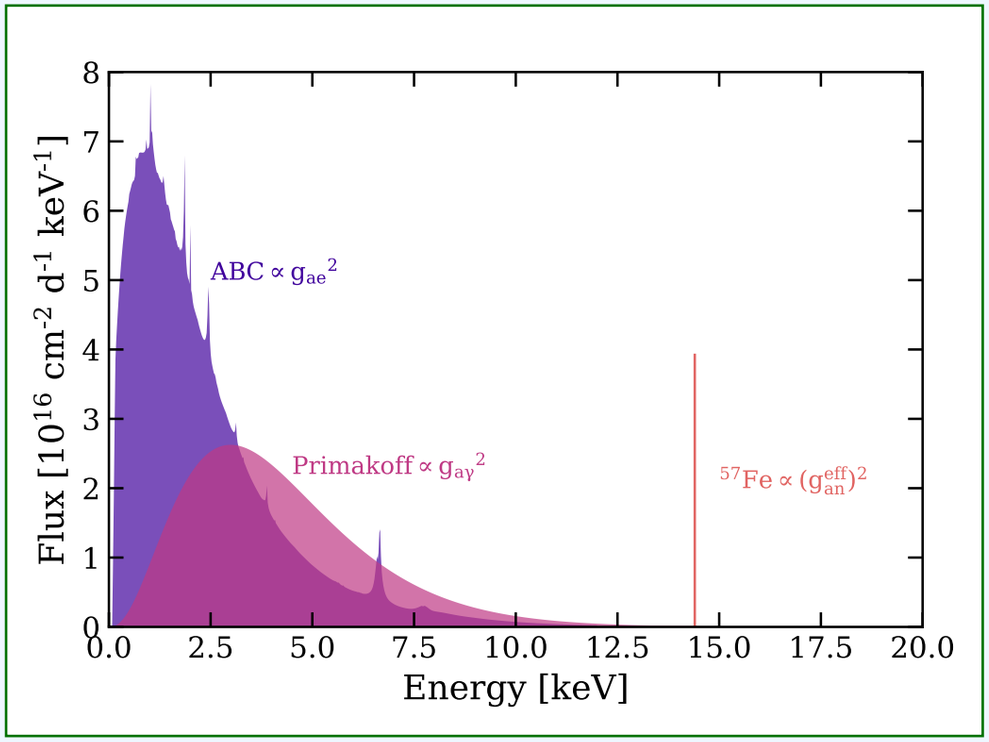
Bosonic dark matter (axion-like particles, dark photons):
keV-scale dark matter, mediator of dark sector (dark photon)

Solar axions

Production



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

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

Solar axions

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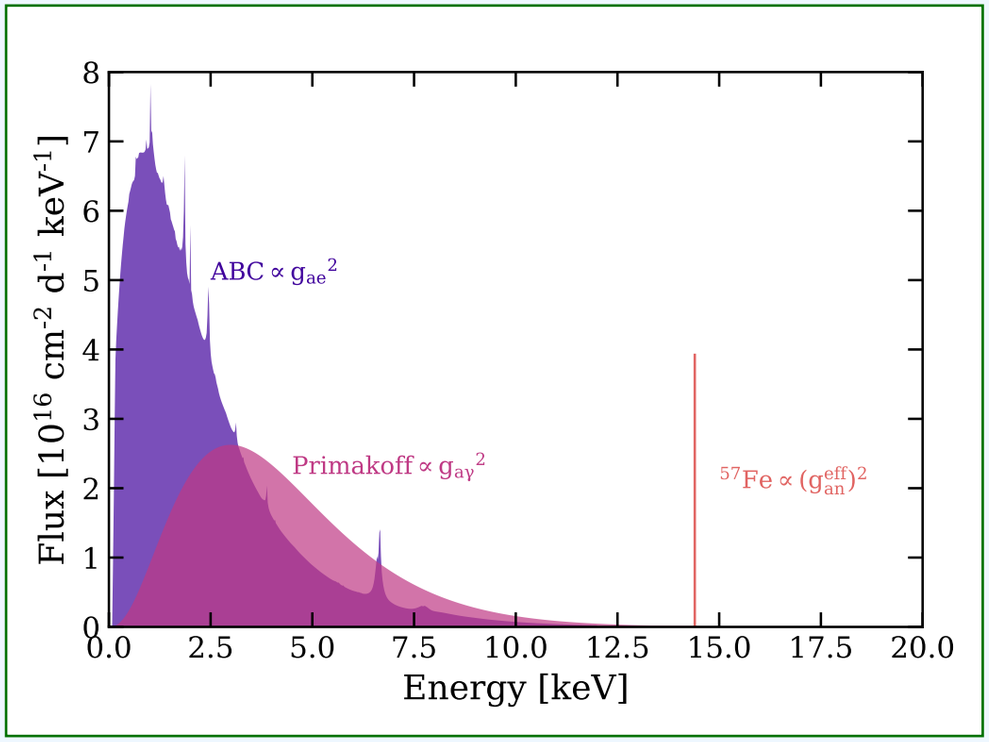

ABC: atomic recombination & de-excitation, bremsstrahlung, and Compton interactions

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axion-electron

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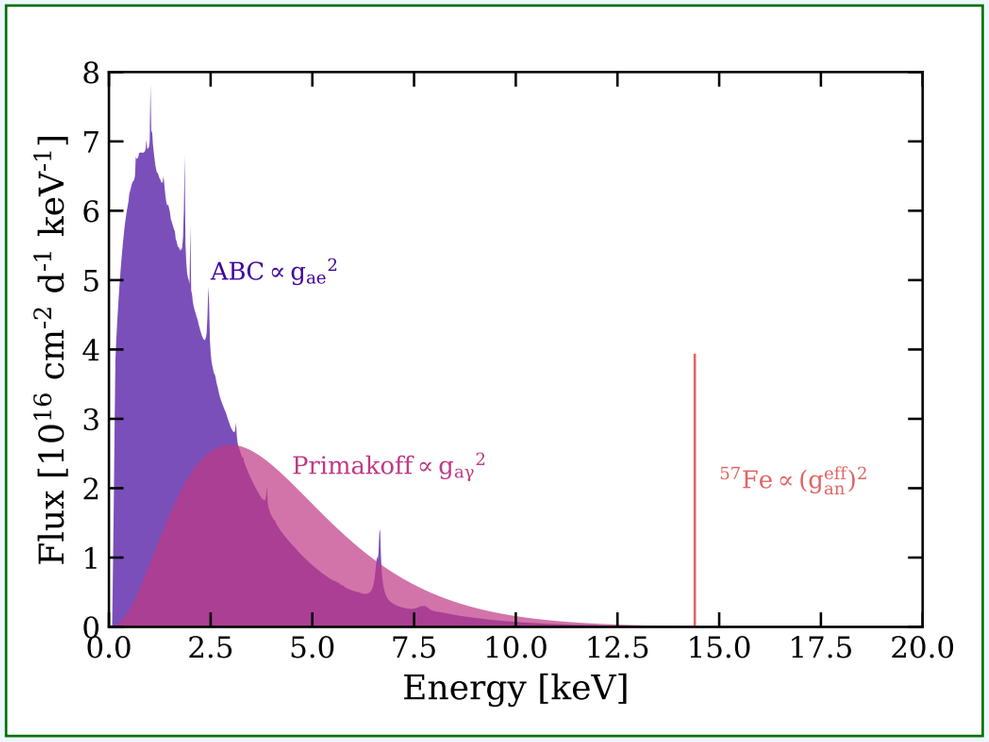

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$g_{a\gamma}$

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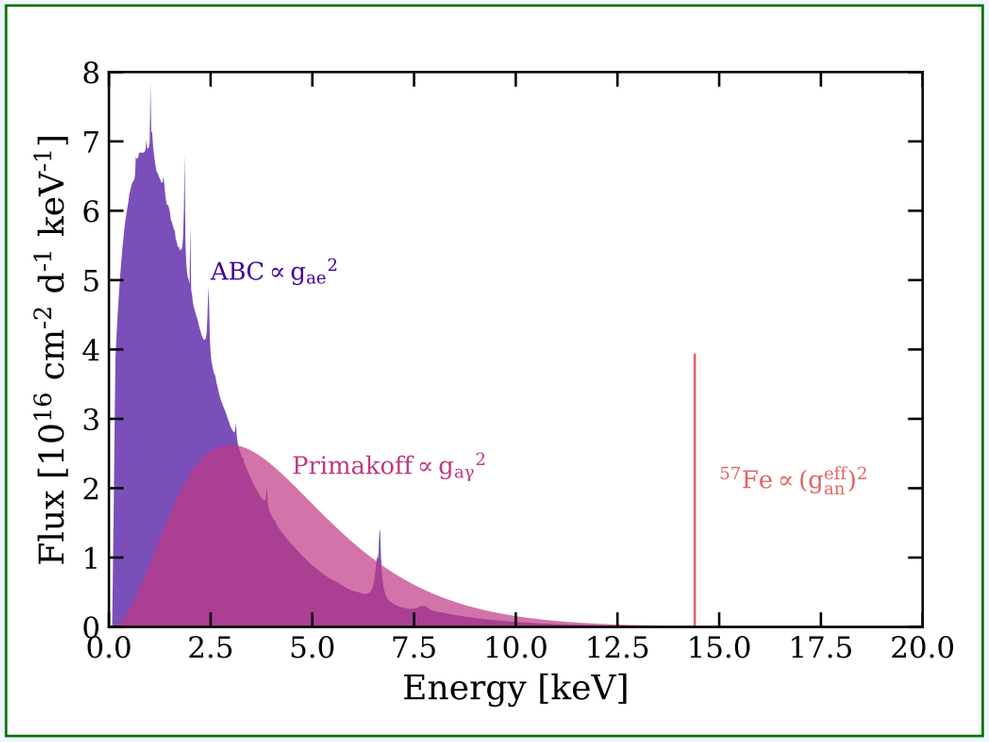

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Nuclear de-excitation — g_{an} axion-nucleon

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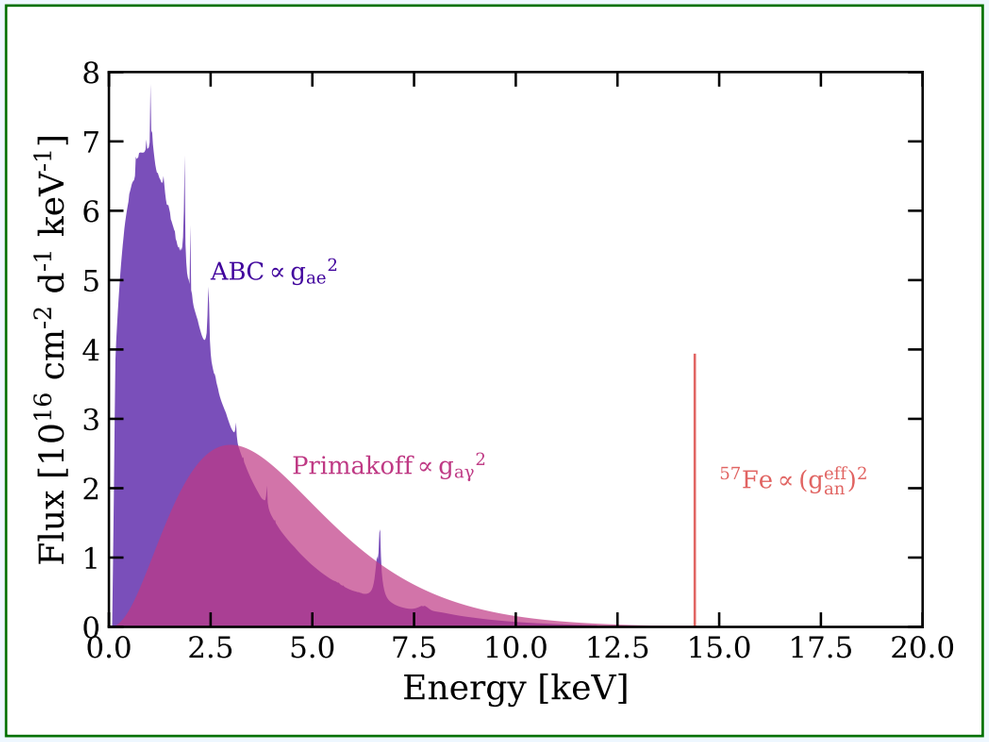
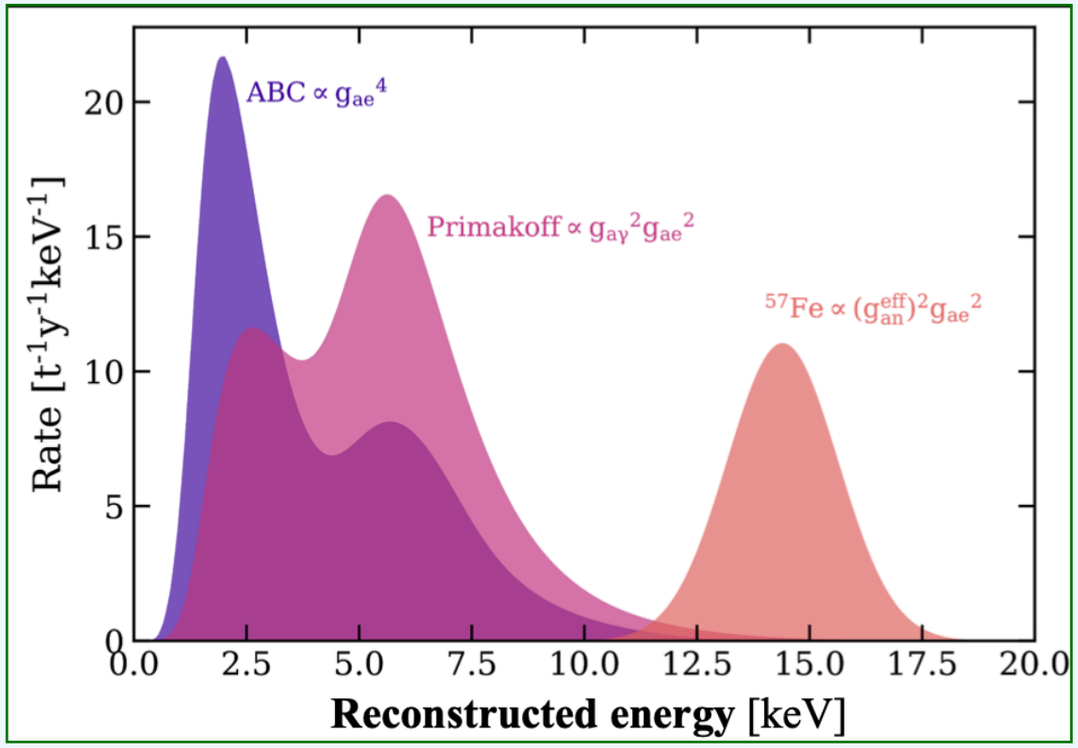


Detector effects

Detection



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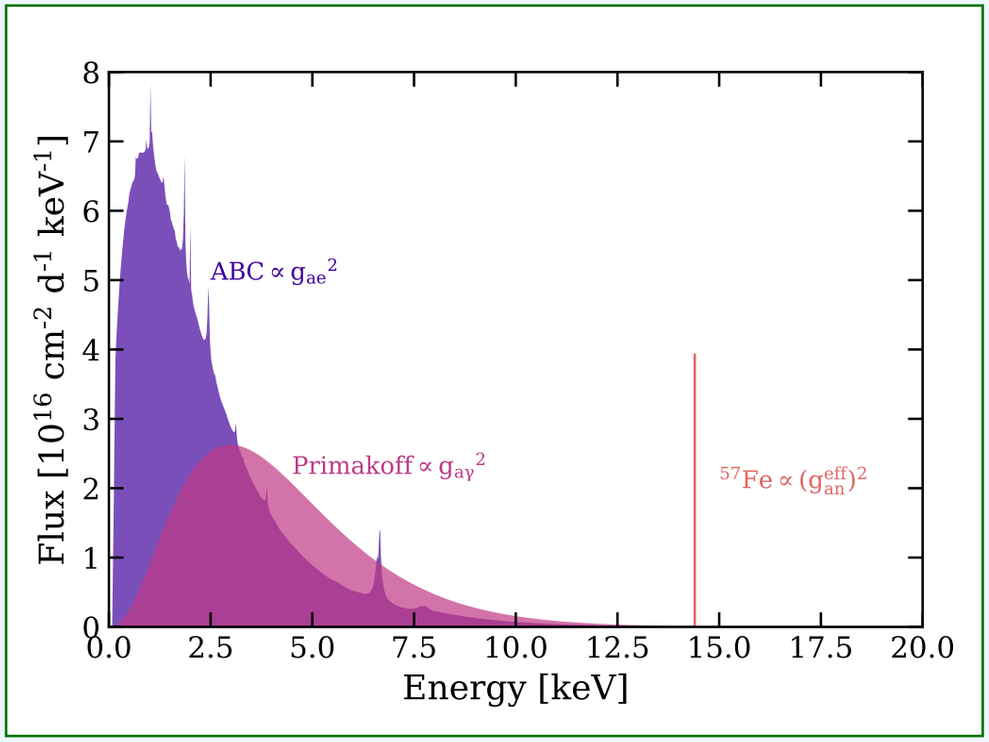
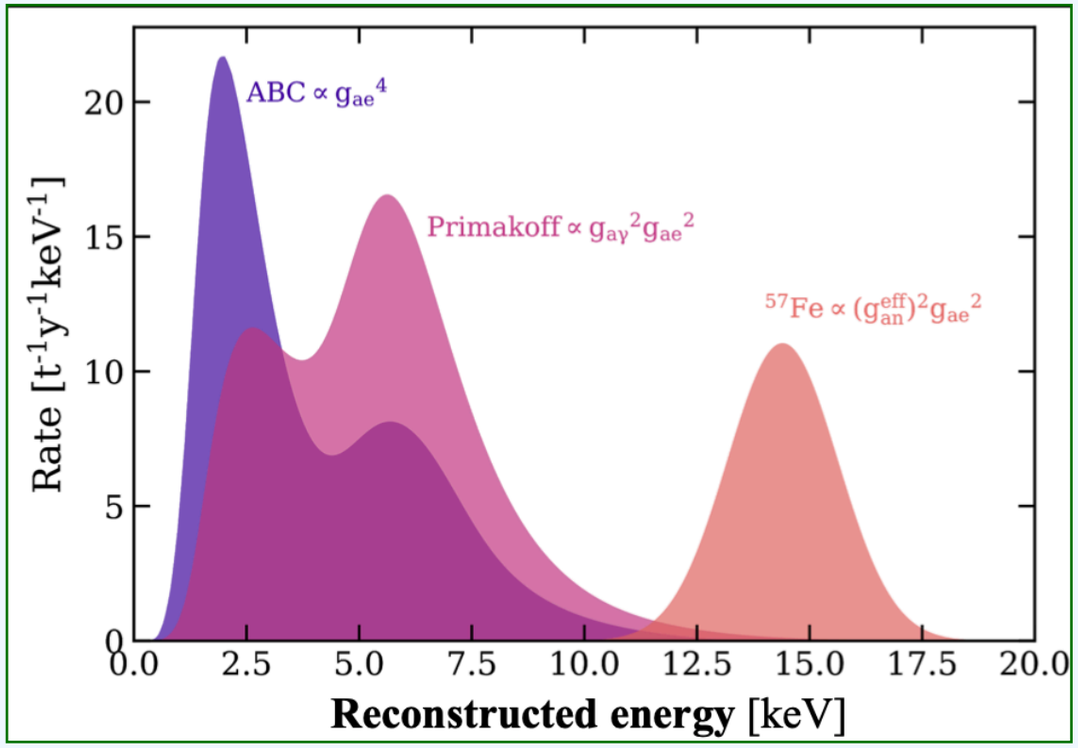
Solar axions

Production



Detector effects

Detection



Three production mechanisms in the Sun

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

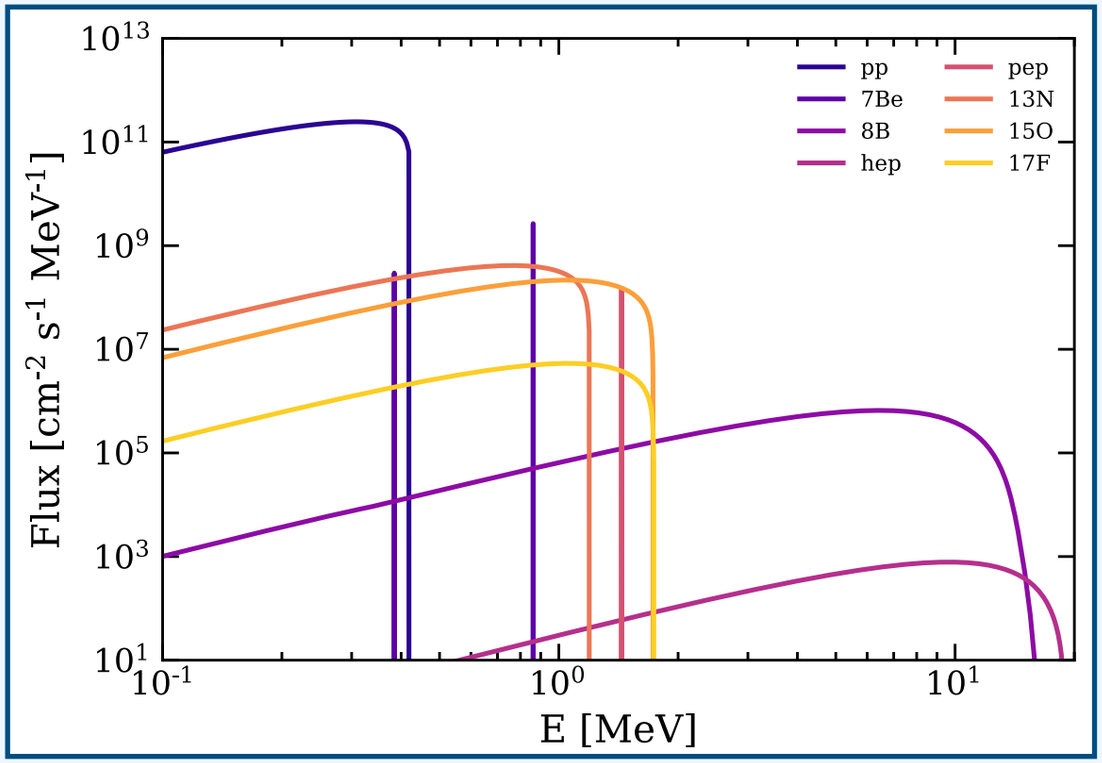
Xenon detection via axioelectric effect

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

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

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

Enhanced neutrino magnetic moment

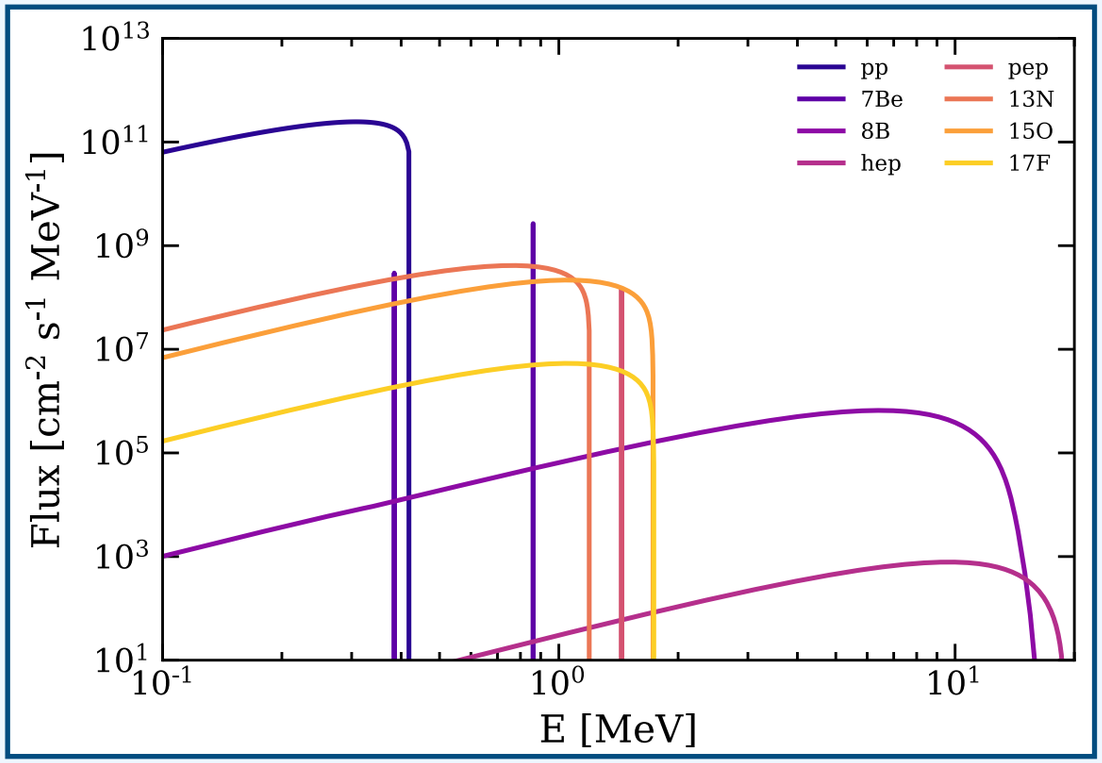


Neutrinos are massless in the SM, but oscillations indicate mass, thus a magnetic moment.

solar neutrino (pp) - electron scattering

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

Enhanced neutrino magnetic moment



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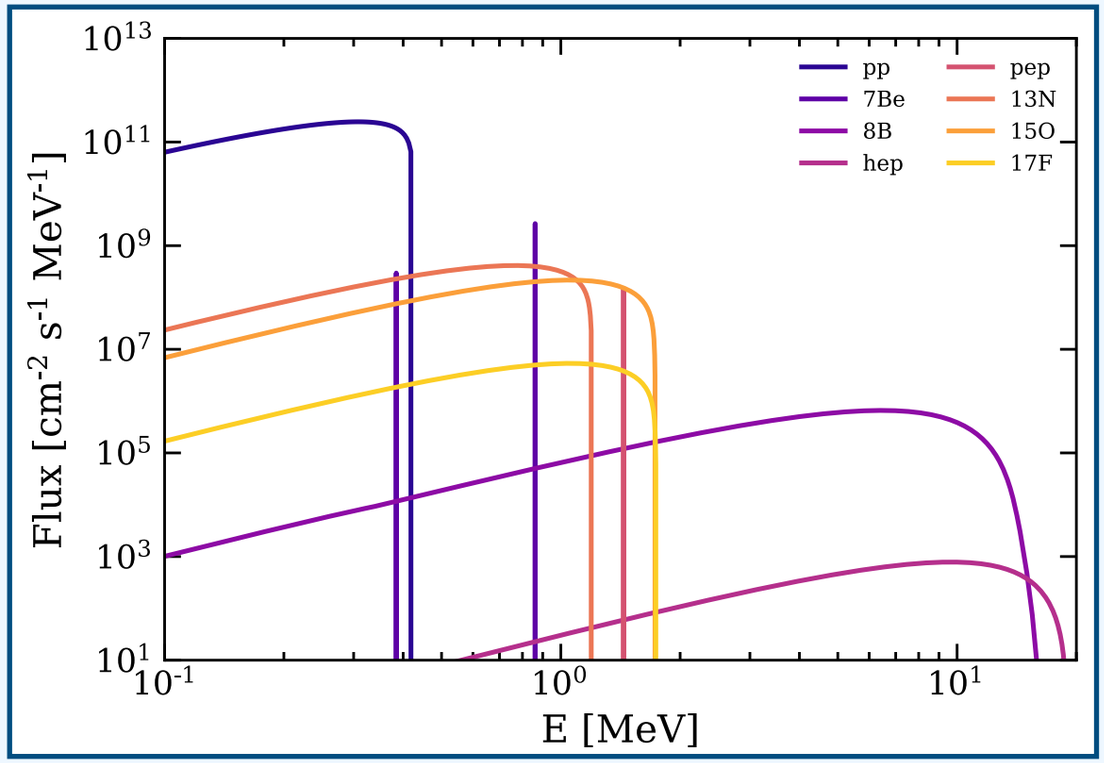
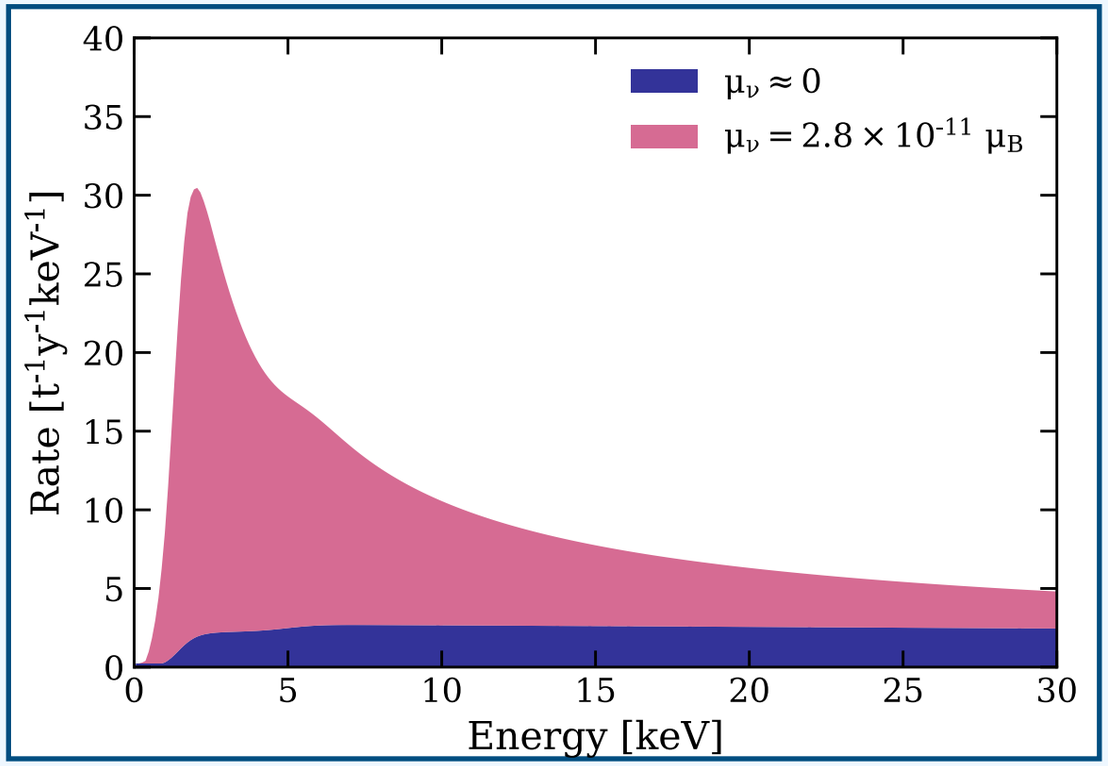
Minimally-extended Standard Model:

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

Enhanced neutrino magnetic moment





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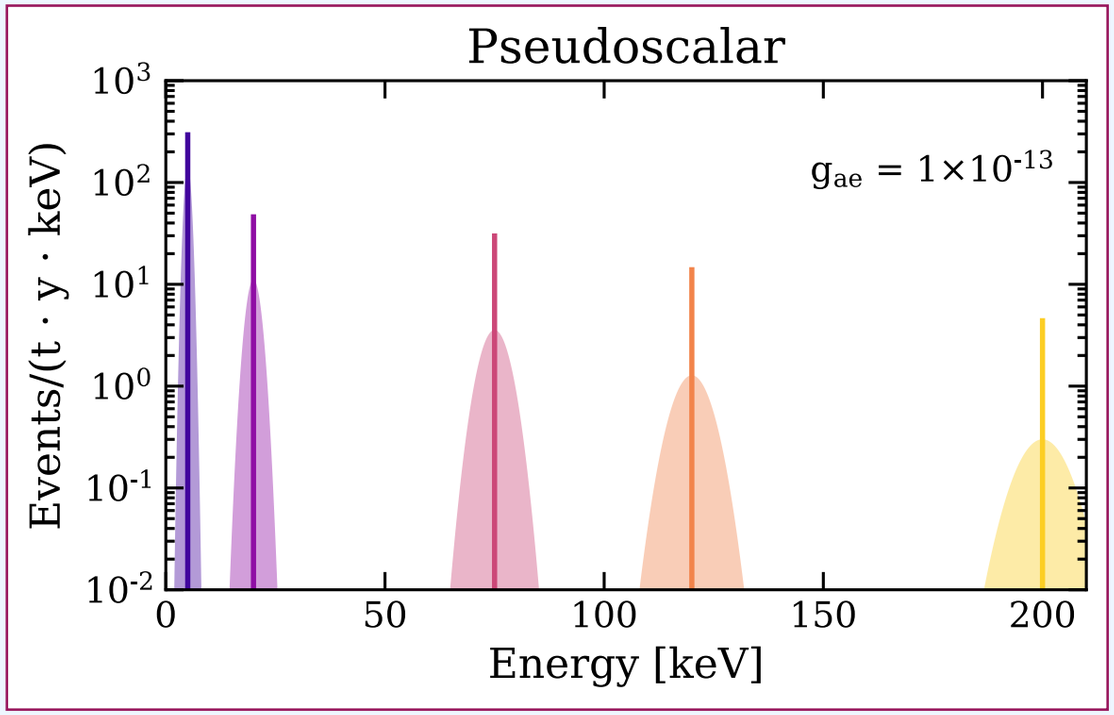
A larger magnetic moment would imply new physics, and possibly solve Dirac vs Majorana.

Enhancement:

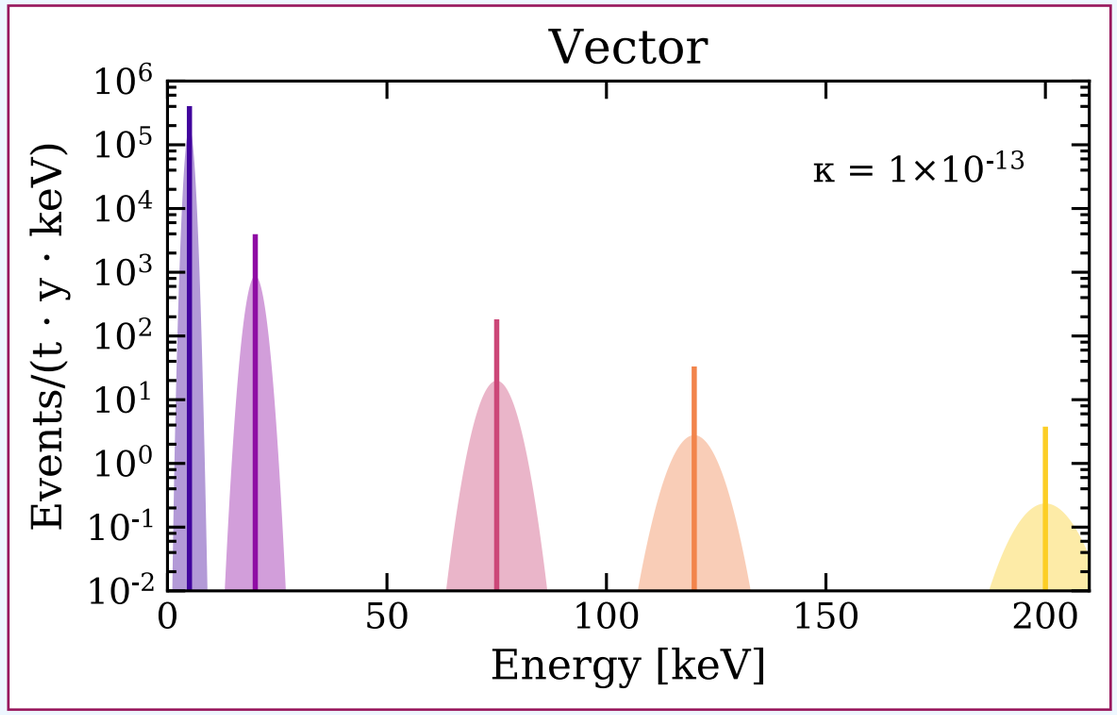
$\mu_\nu \gtrsim 10^{-15} \mu_B$ ⟶ *Majorana fermion*

Bosonic dark matter

axion-like particles



dark photons



Thermal DM, non-relativistic: deposited energy is rest mass of particle.

$$R \simeq \frac{1.5\times10^{19}}{A} g_{ae}^2 \left(\frac{m_a}{\mathrm{keV}/c^2}\right)\left(\frac{\sigma_{pe}}{\mathrm{b}}\right)\mathrm{kg}^{-1}\mathrm{d}^{-1}$$

$$R \simeq \frac{4.7\times10^{23}}{A} \kappa^2 \left(\frac{\mathrm{keV}/c^2}{m_V}\right)\left(\frac{\sigma_{pe}}{\mathrm{b}}\right)\mathrm{kg}^{-1}\mathrm{d}^{-1}$$

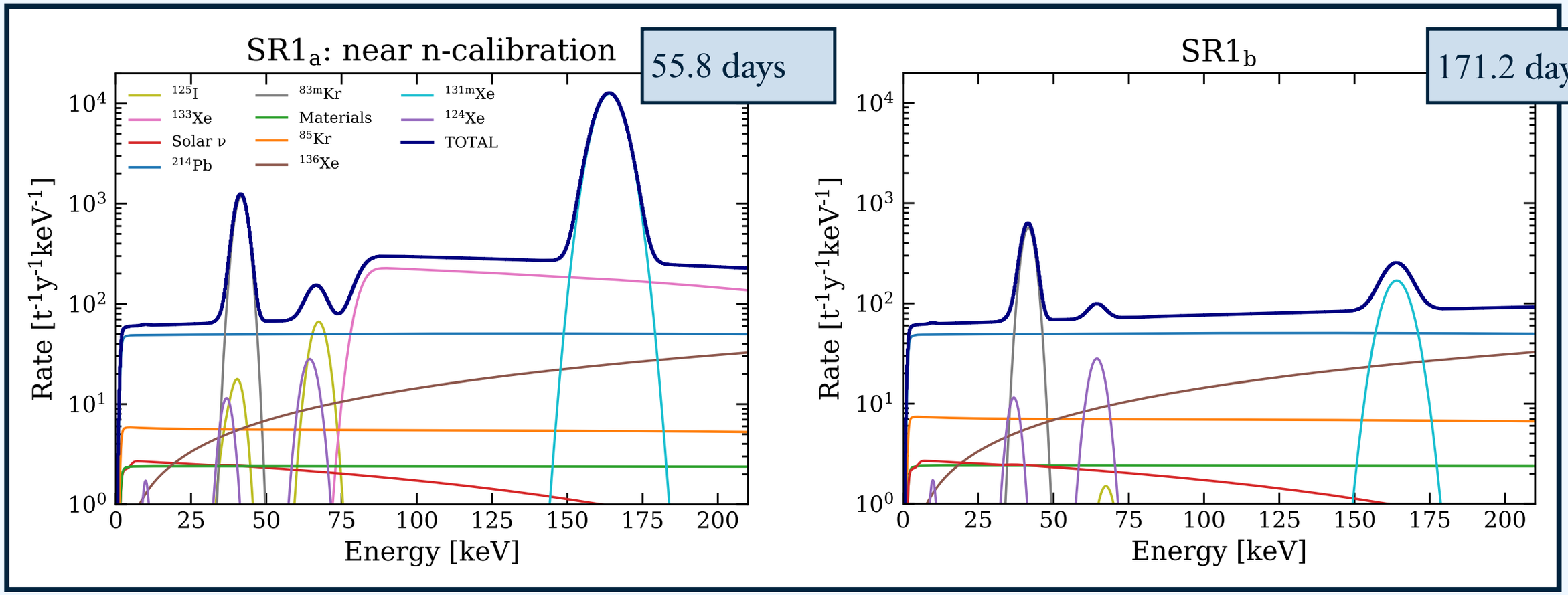
Detection via axioelectric effect

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

Kinetic mixing with SM photons

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

Background model and inference



Background model B_0
Partitioned into two datasets and fit simultaneously

$SR1_a$: activated backgrounds, peaks
$SR1_b$: allows to constrain the dominant ^{214}Pb background at low energies

- Unbinned profile likelihood
- Likelihood of 2 partitions combined

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

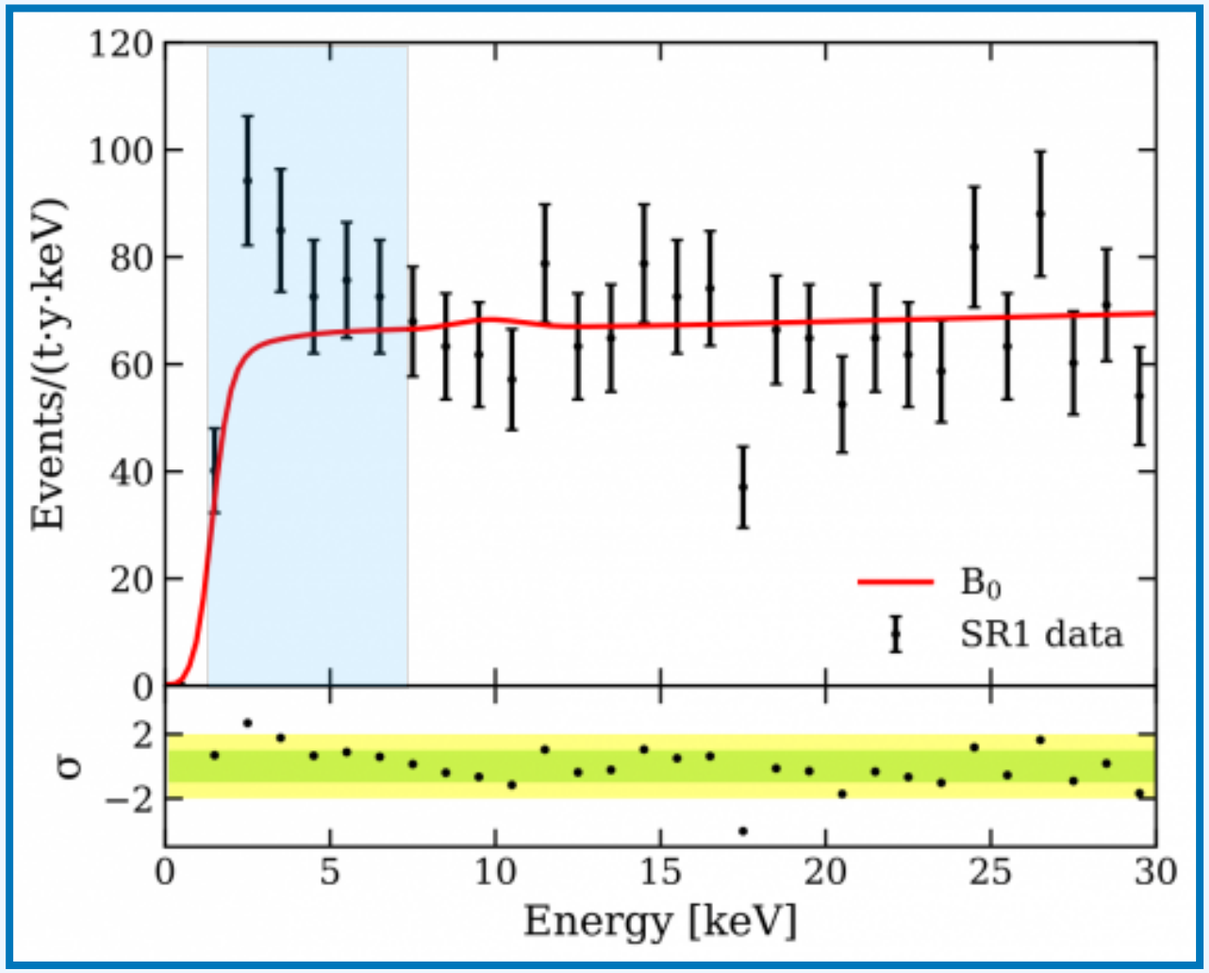
- Test statistic q for inference

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

max. L with specified signal parameter μ_s

nuisance parameters that maximise L

Excess found



reference region 1-7 keV

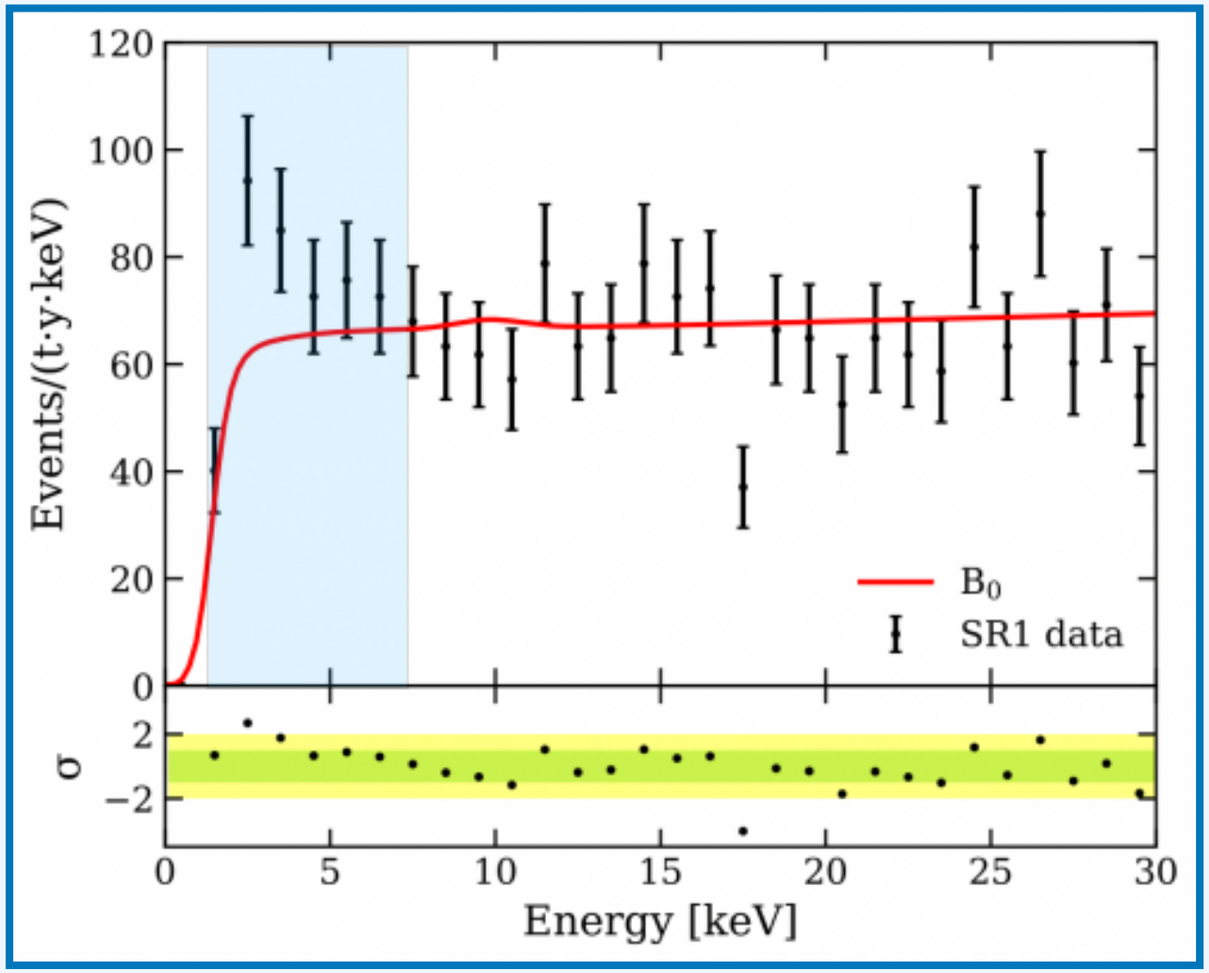
285 events observed

vs.

232 events expected (from best-fit)

3.3σ Poissonian fluctuation over null

Excess found



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

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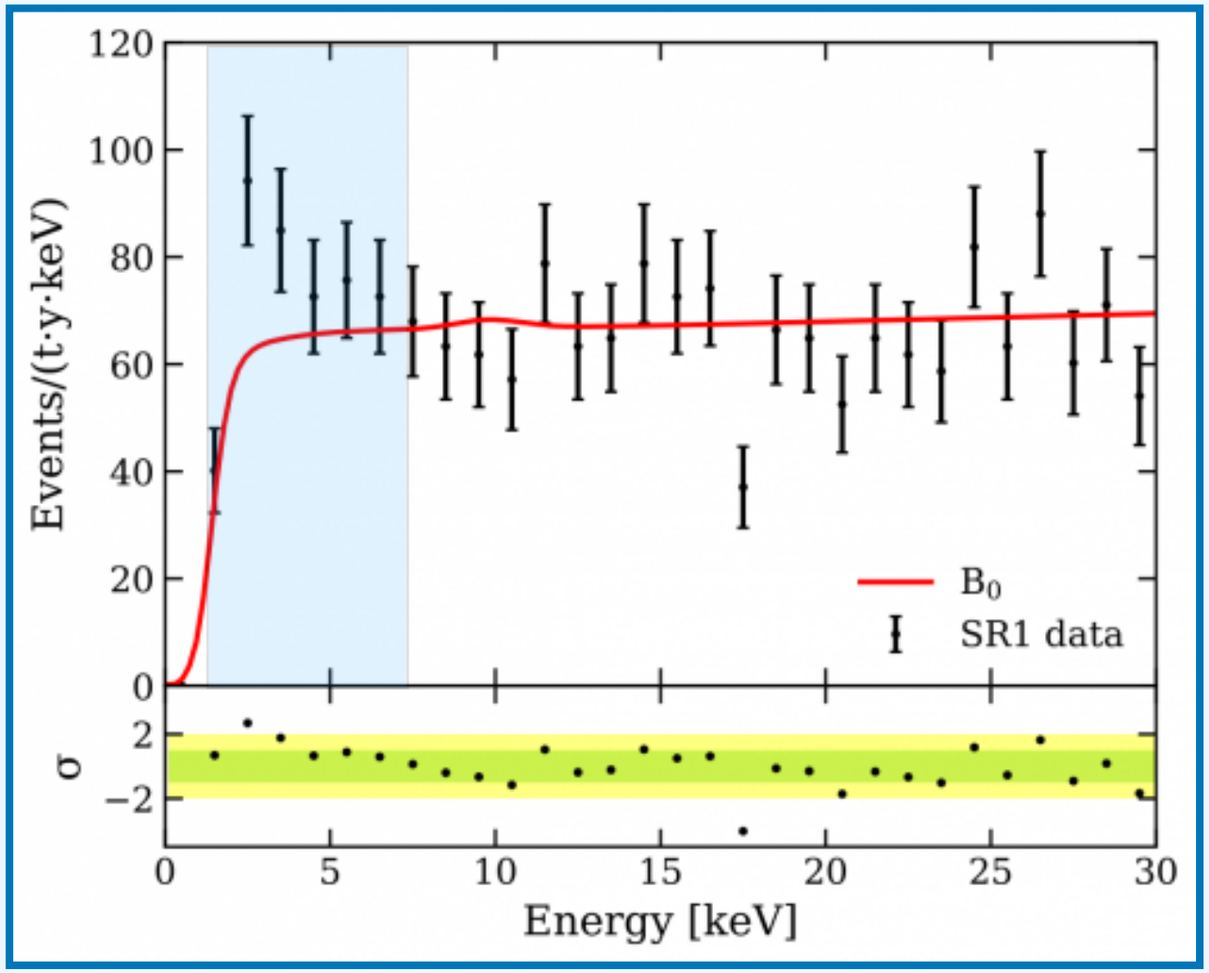

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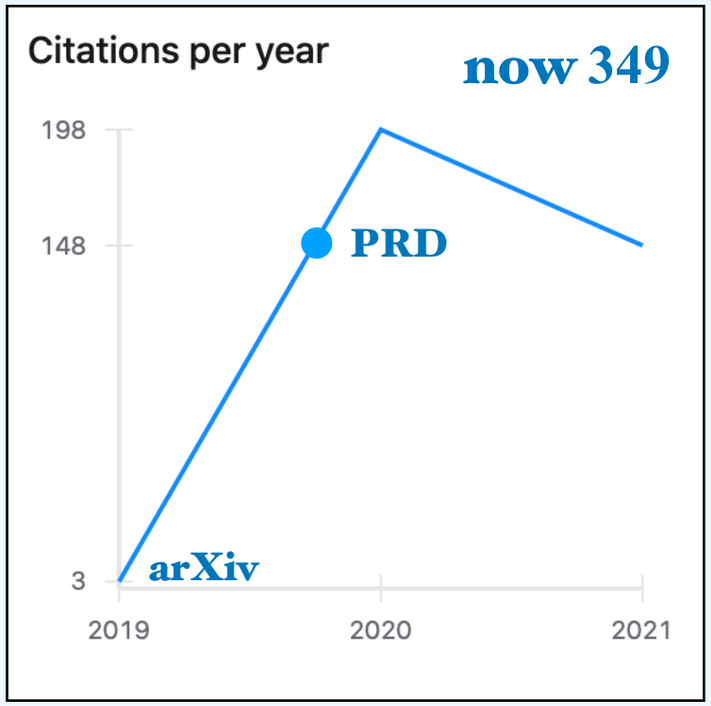
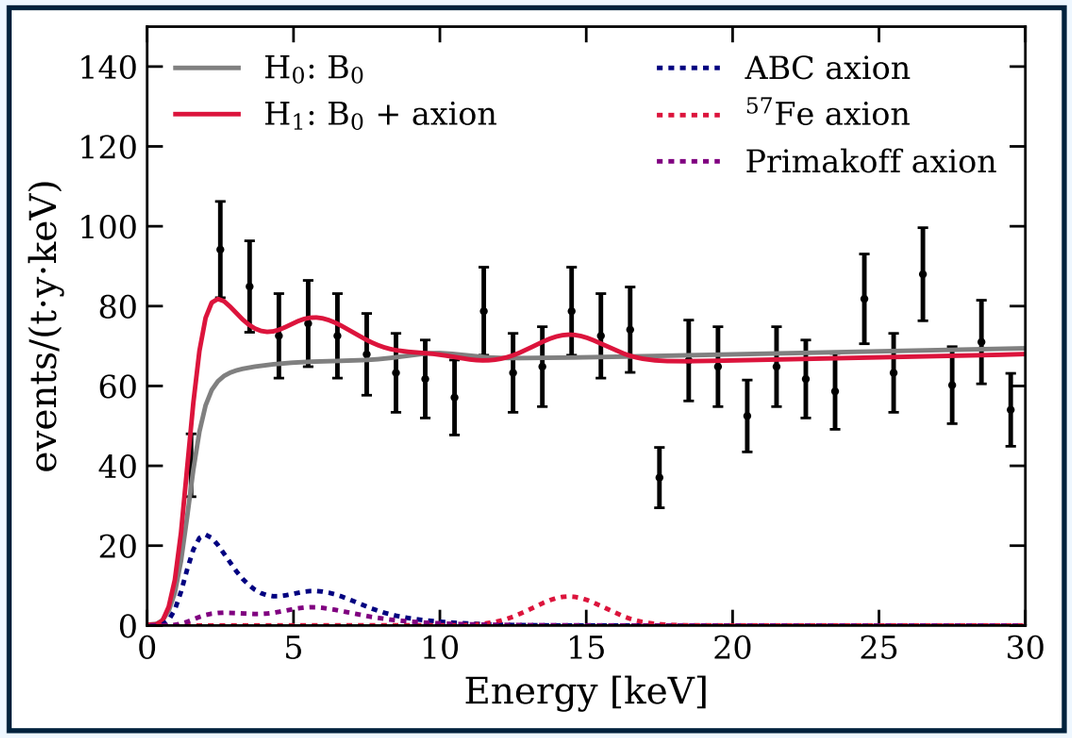


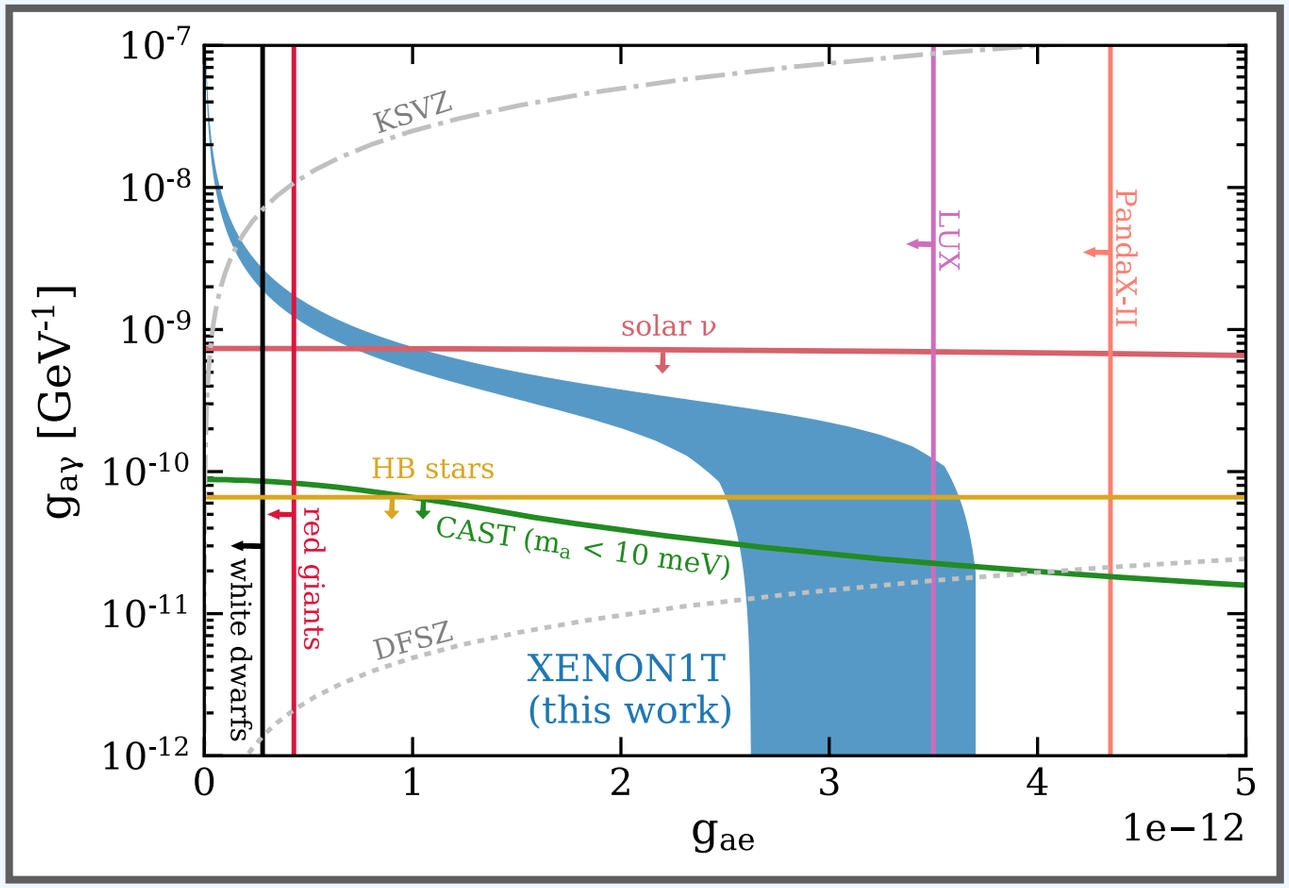
Solar axion results



Axion favored over background-only at 3.4σ

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

Primakoff

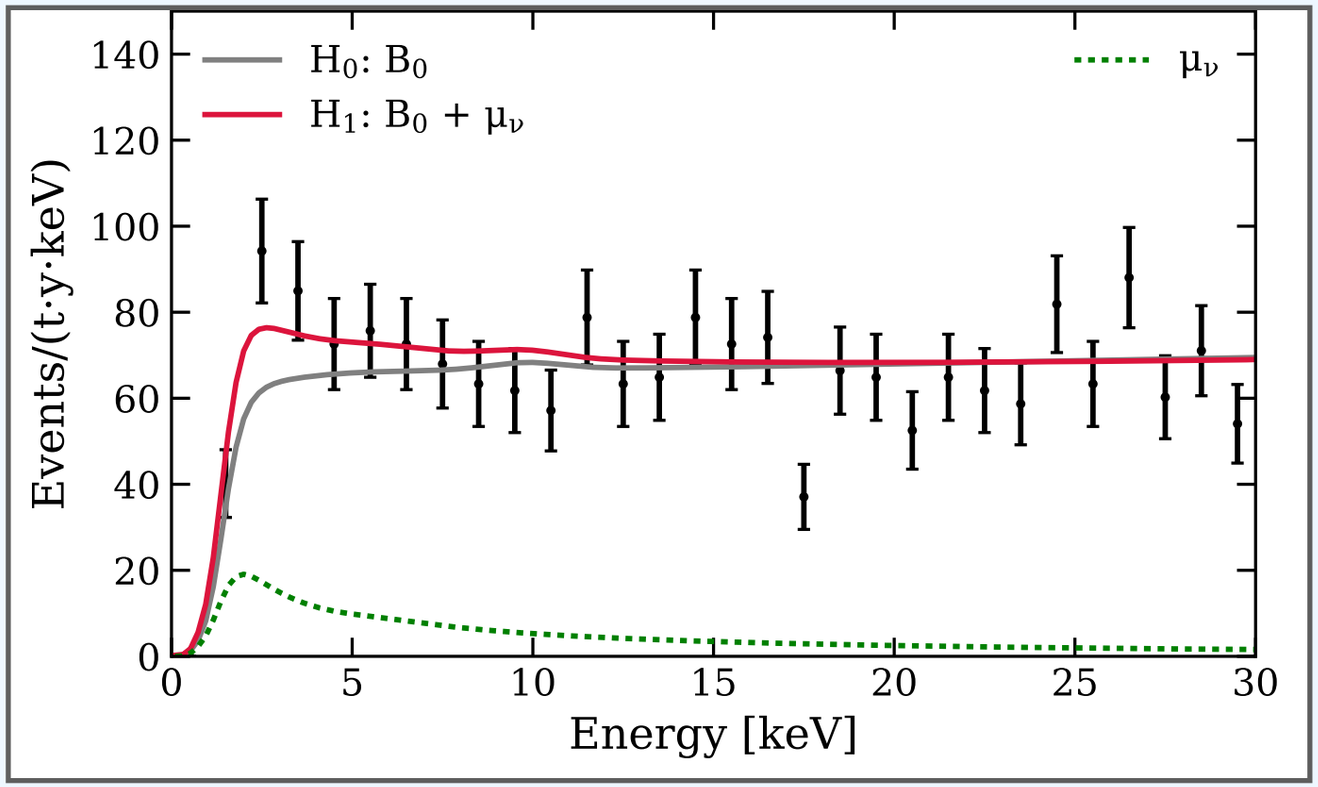


ABC

Couplings not independent from g_{ae} ; can be factored out.
Relative rates unconstrained (model-independent)

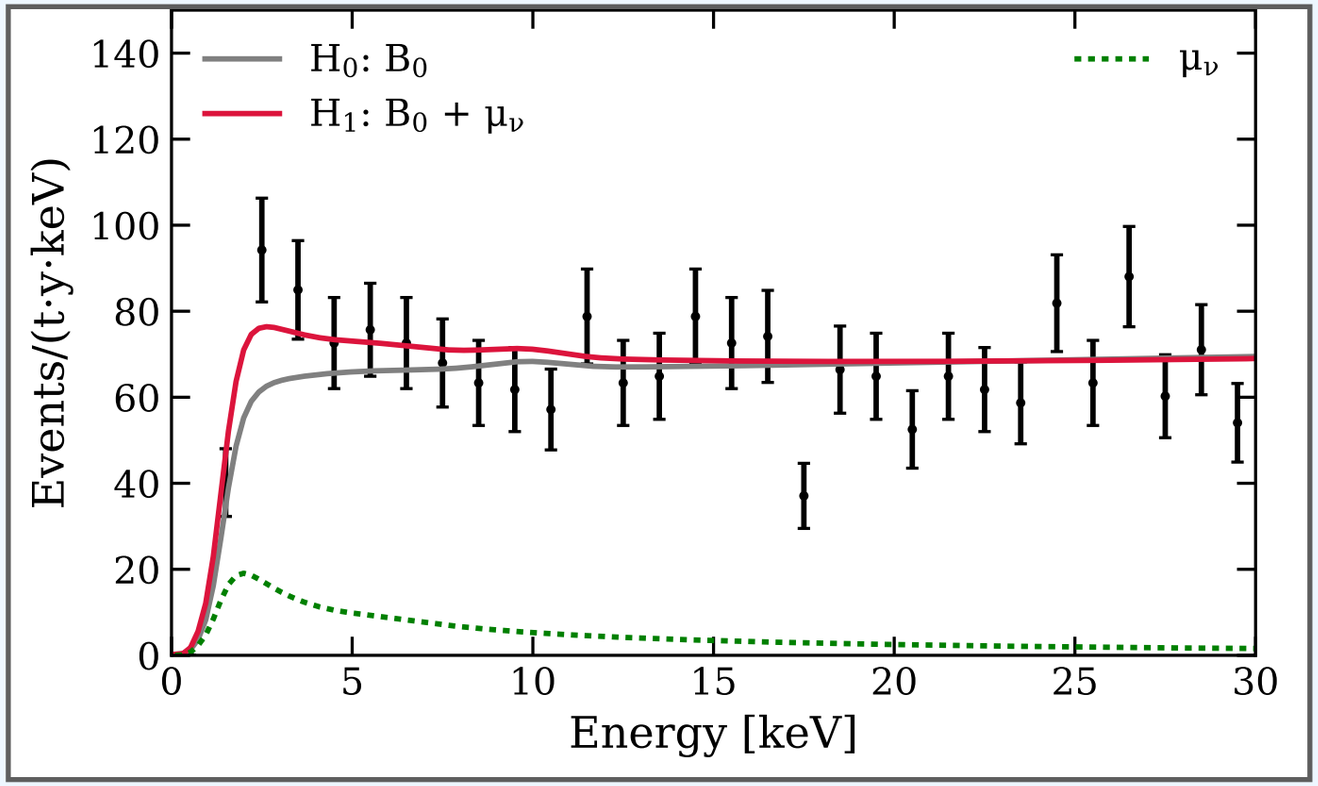
Strong tension with astrophysical constraints from stellar cooling (arXiv:2003.01100)

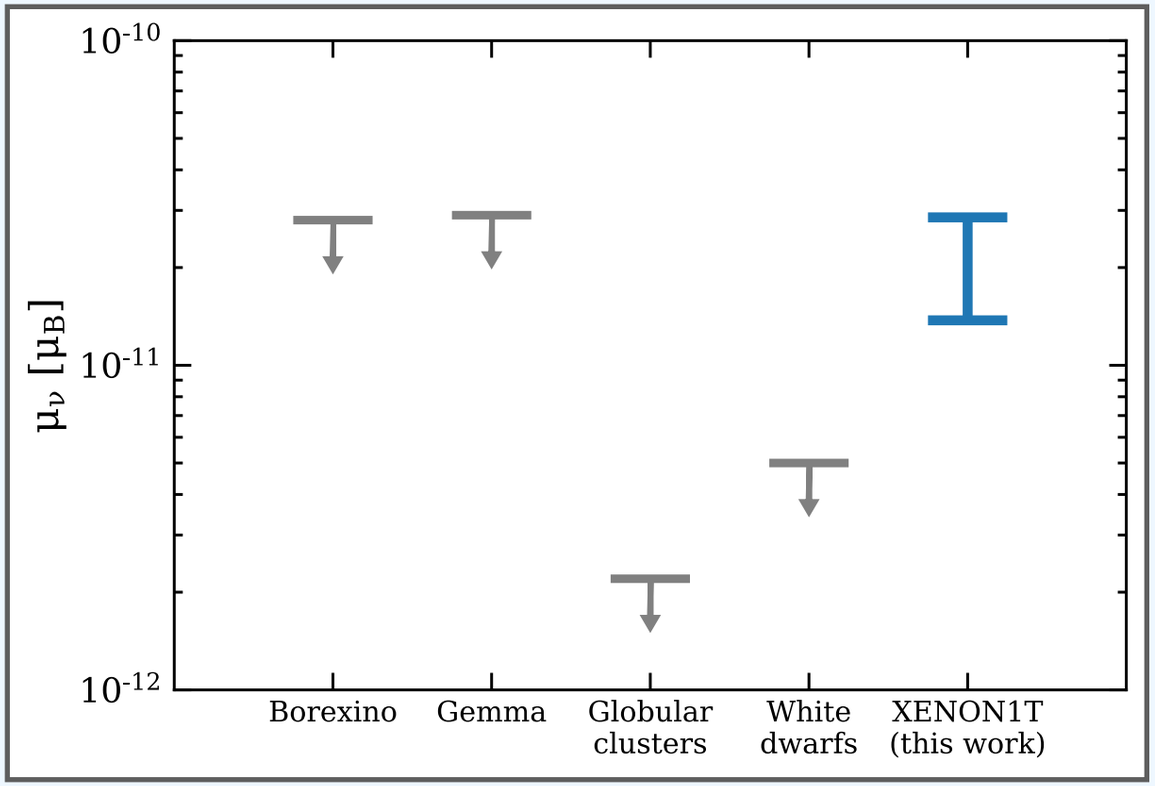
Neutrino magnetic moment



Neutrino magnetic moment favored over background-only at 3.2σ

Neutrino magnetic moment



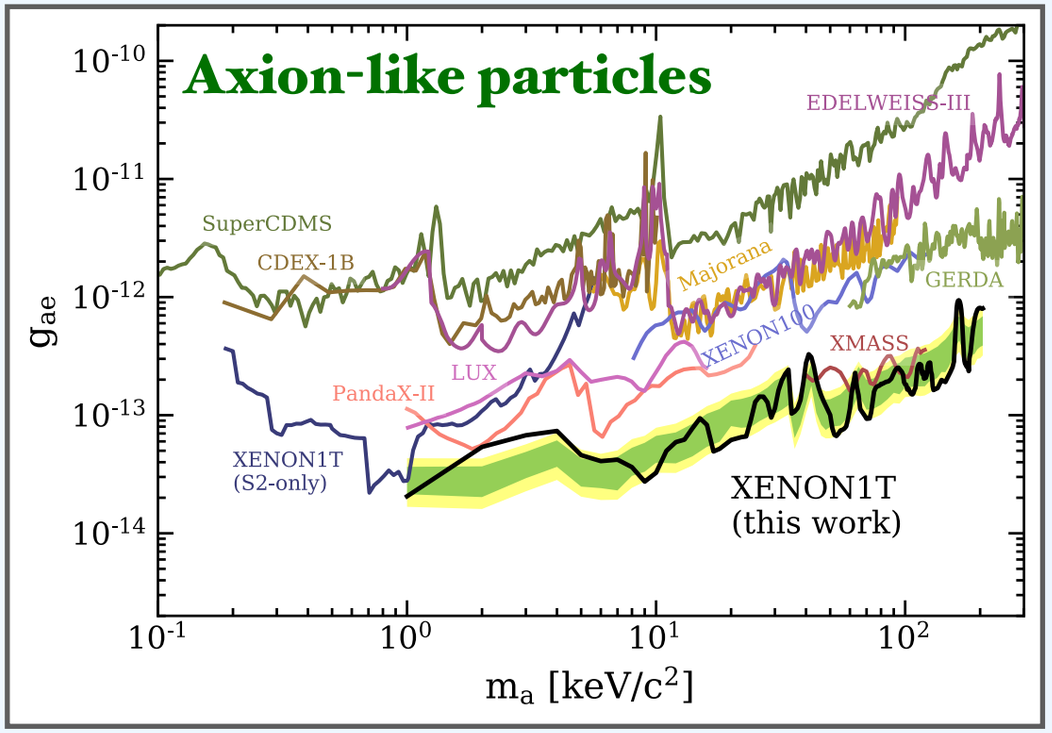


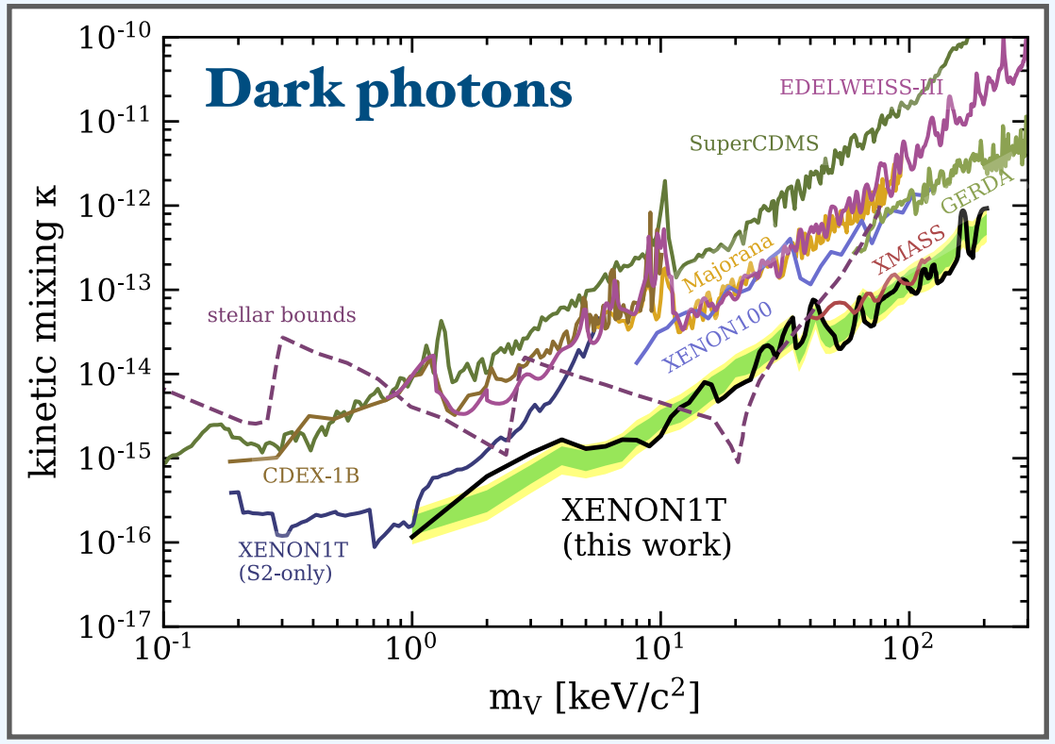
Neutrino magnetic moment favored over background-only at 3.2σ

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

Compatible with other experiments.
In tension with astrophysical constraints.

Bosonic dark matter

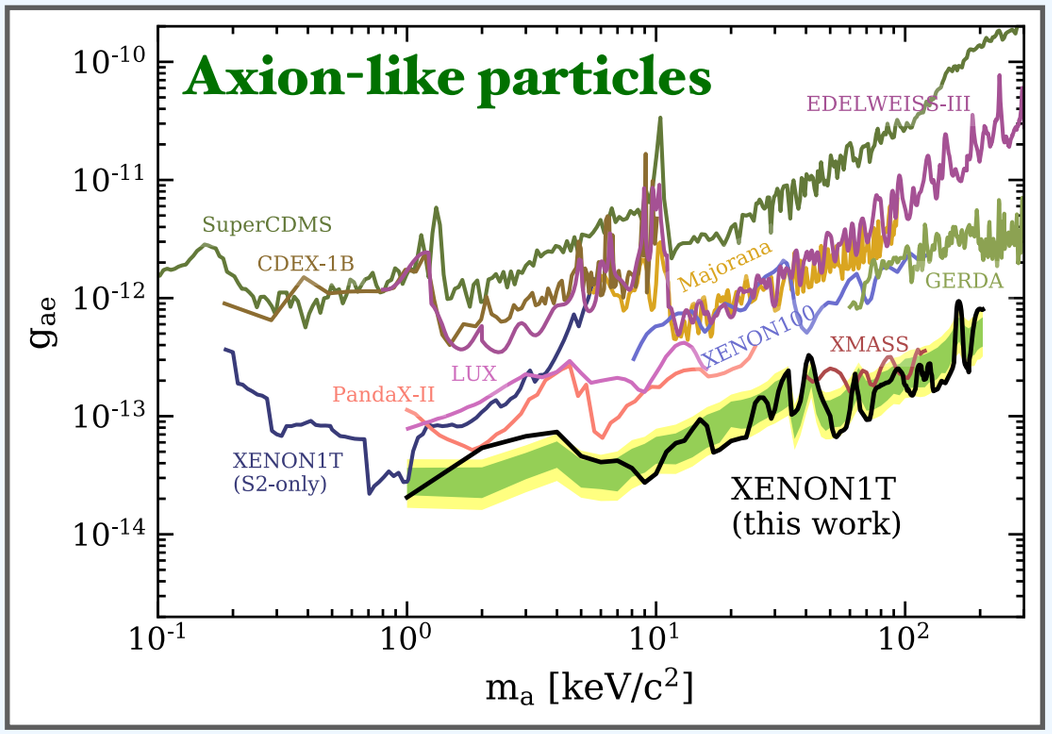


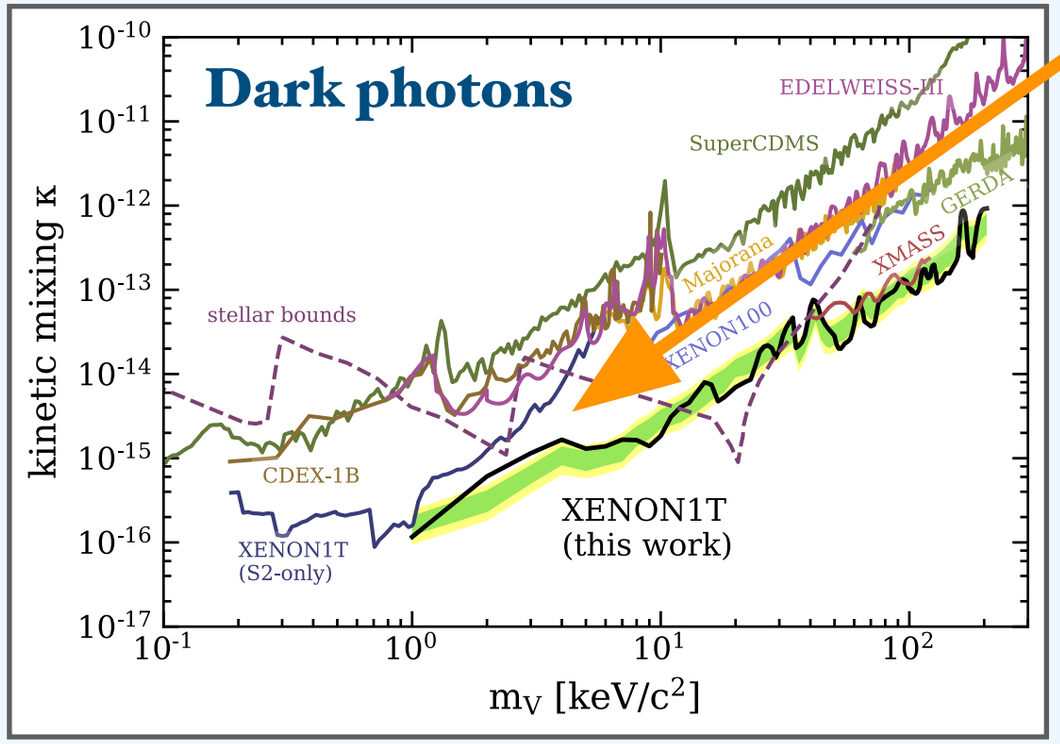


68% CL coverage interval

90% CL upper limits and sensitivities

Bosonic dark matter





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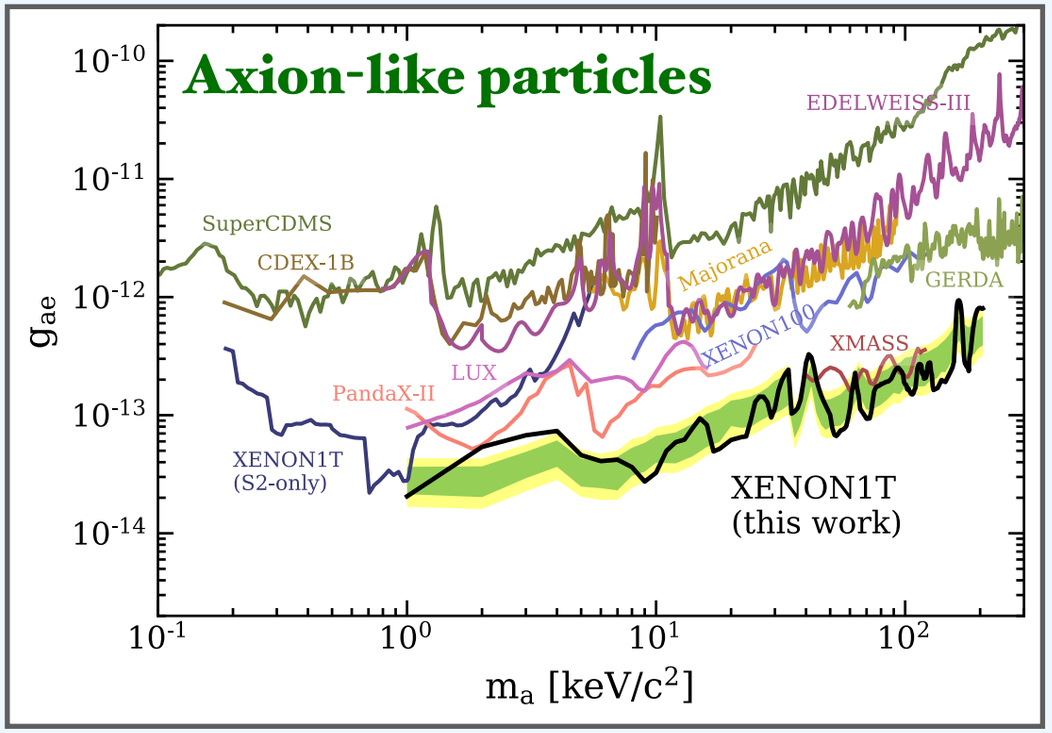
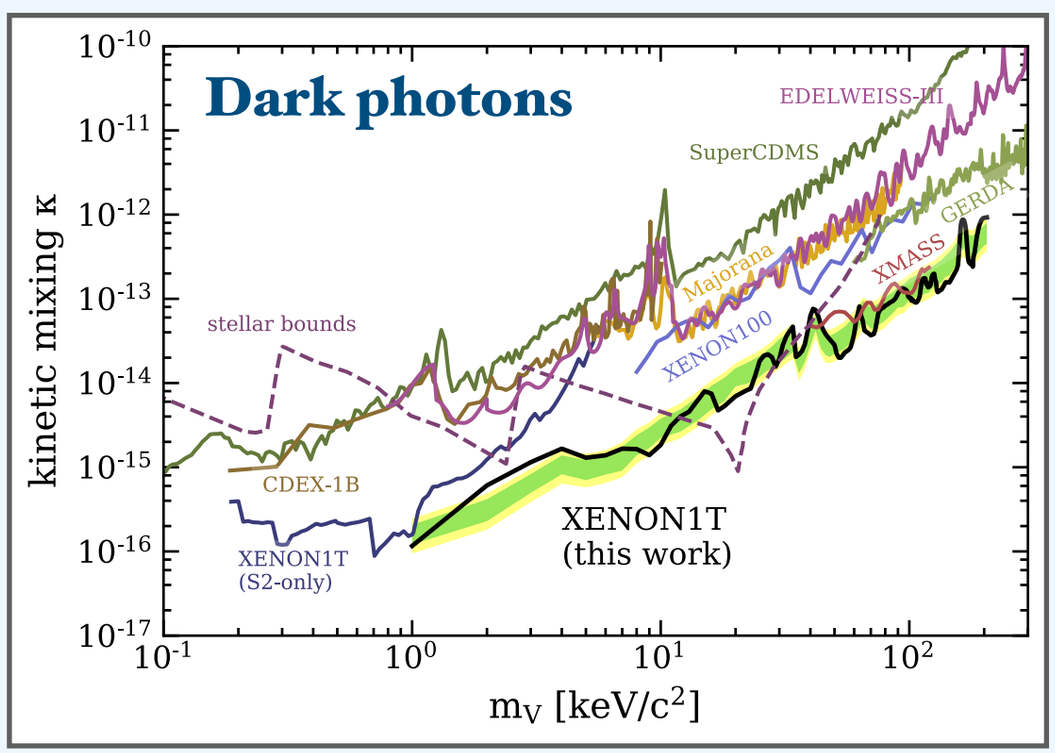
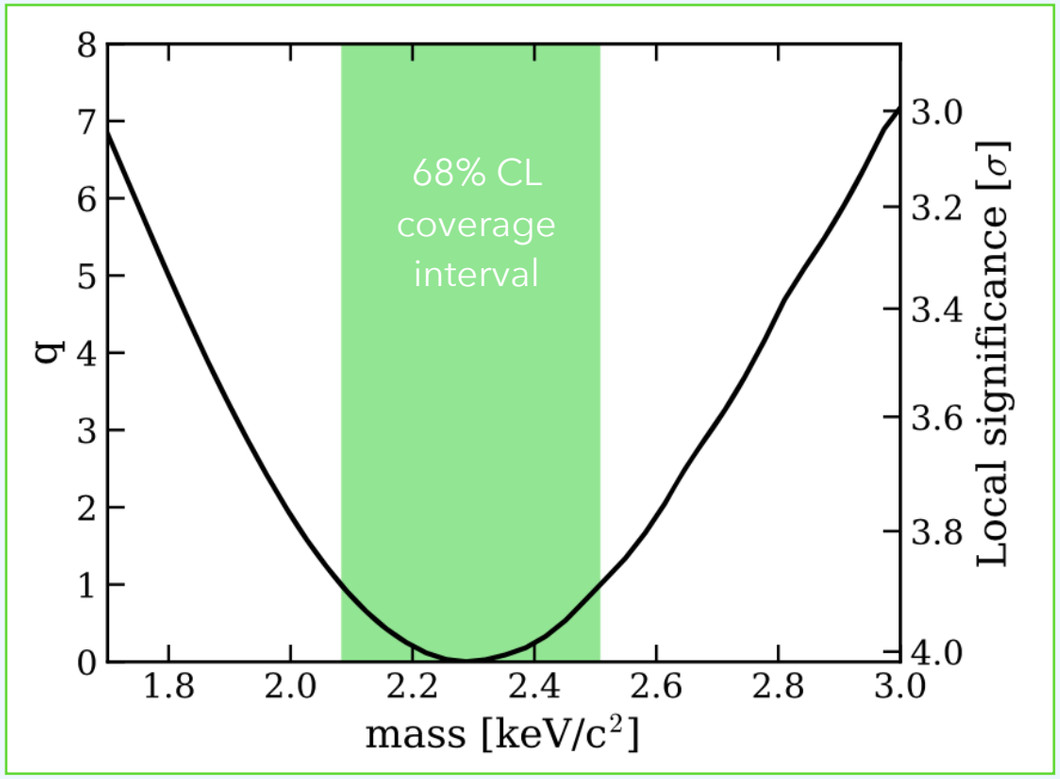




90% CL upper limits and sensitivities

Fitting a mono-energetic peak to the excess:

2.3 +/- 0.2 keV



Best fit: ~60 events/tonne/year

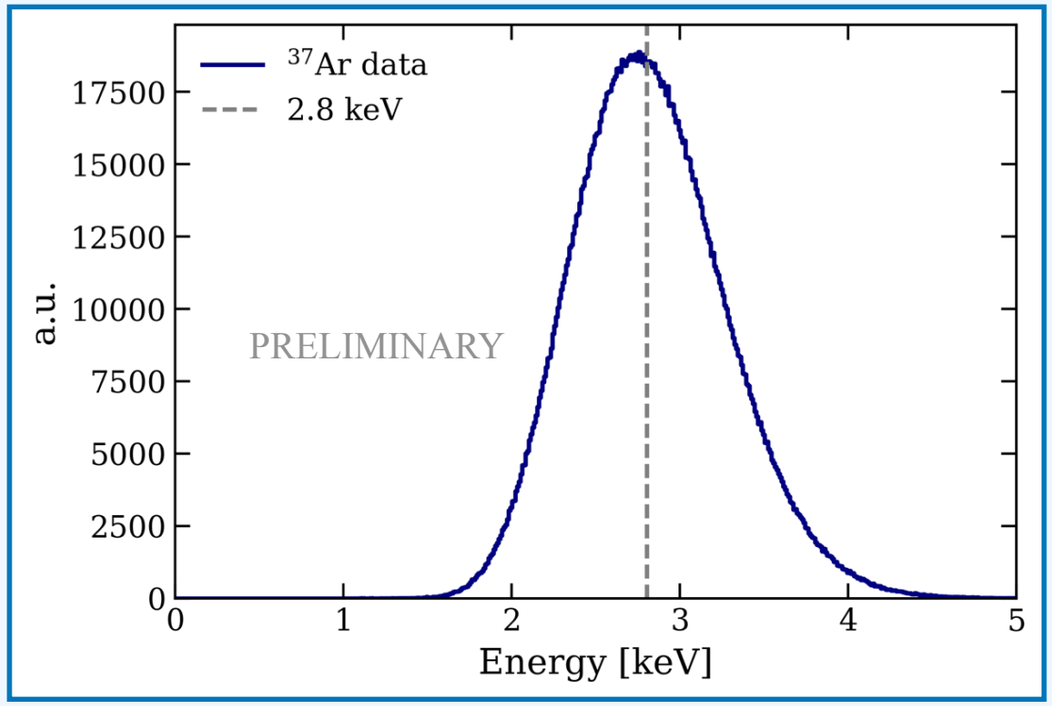
4.0 σ local significance

3.0 σ (global)

Investigation of the Excess

Energy reconstruction and resolution

Calibration with ^{37}Ar after the science run: decays via electron capture with 2.8 keV deposition.

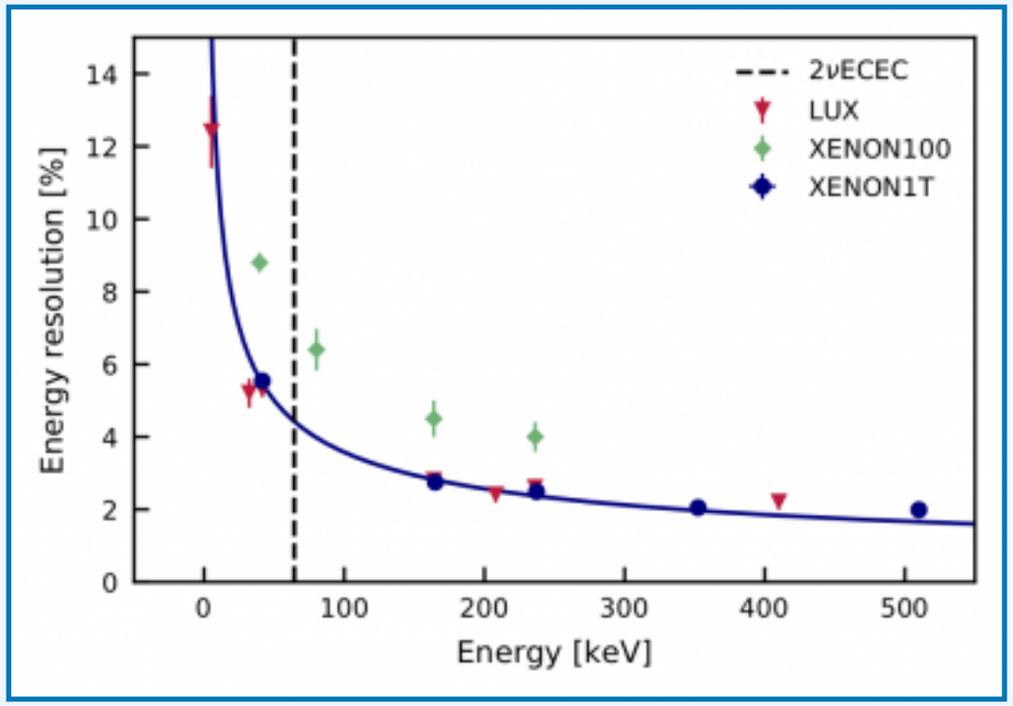


^{37}Ar 2.8 keV reconstructed peak

Mean energy

Observed: 2.827 keV

Model: 2.834 keV



Energy Resolution

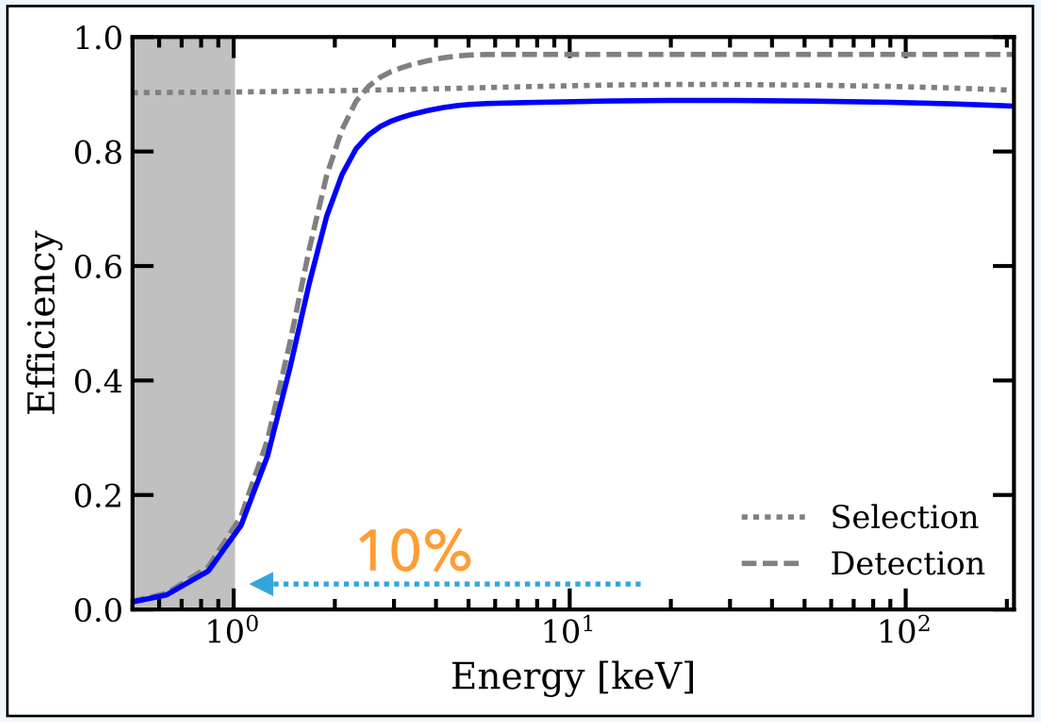
^{37}Ar Resolution

Observed: 18.12%

Model: 18.88%

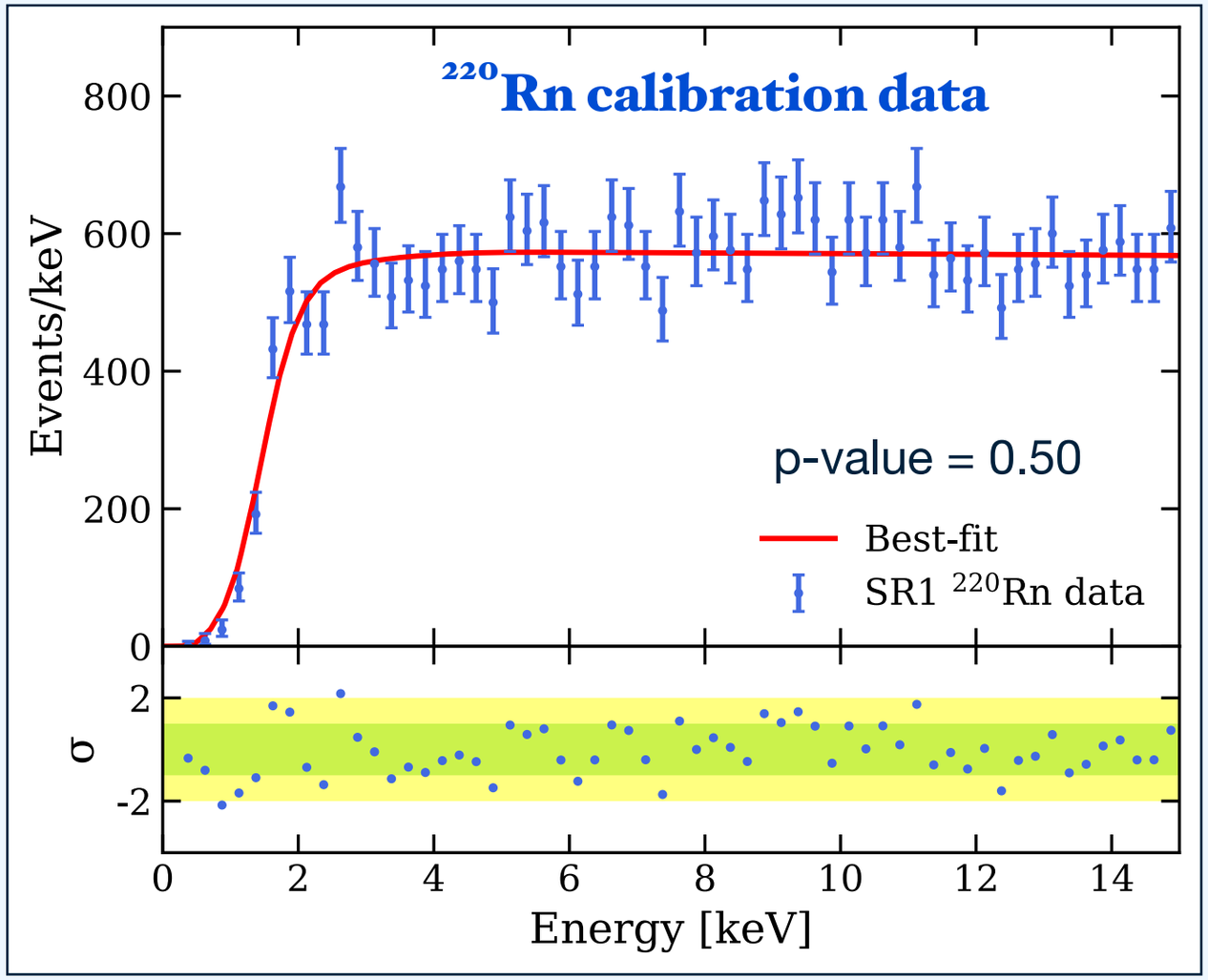
Validates energy reconstruction and resolution down to 2.8 keV.

Threshold



All signal and background models are first convolved with efficiency and resolution.

- 1 keV threshold at 10% efficiency
- excess peaks in the 2 - 3 keV region (80% efficiency)

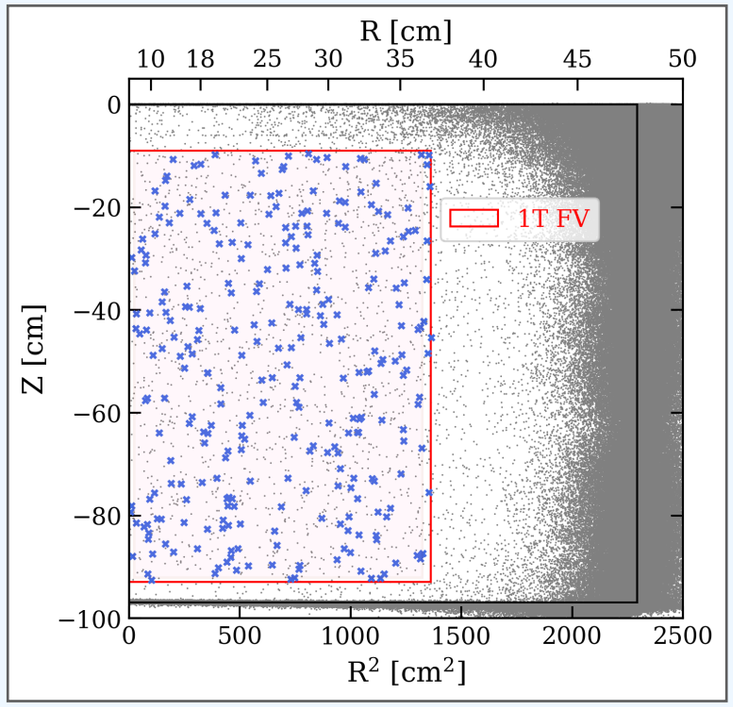


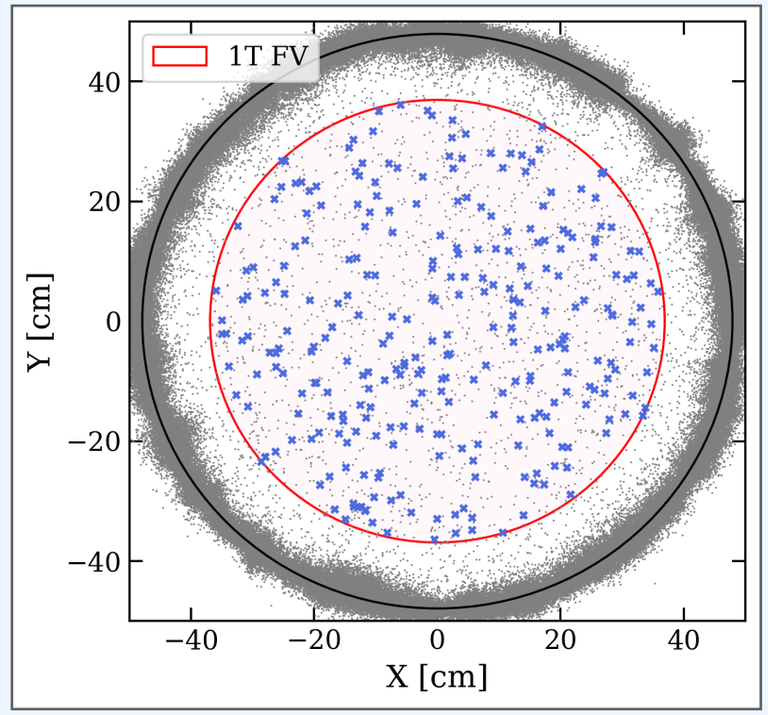
Fit to ^{220}Rn (^{212}Pb) calibration data using same analysis framework

^{220}Rn calibration reconstructs as expected:

Validates efficiency and energy reconstruction down to threshold.

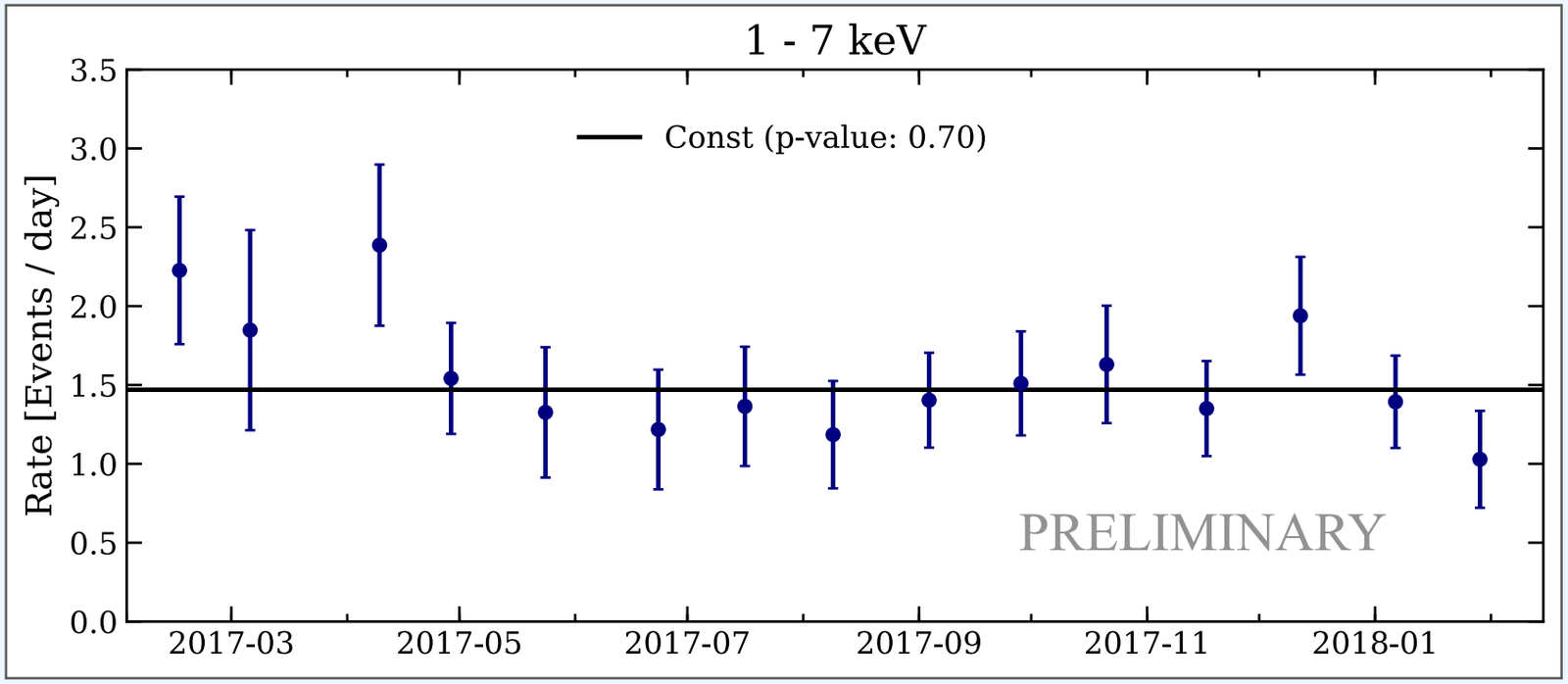
Event spatio-temporal uniformity





Expectation: a signal would be distributed uniformly in space and time.

Events are uniformly distributed within fiducial volume (1042 kg in center of TPC).



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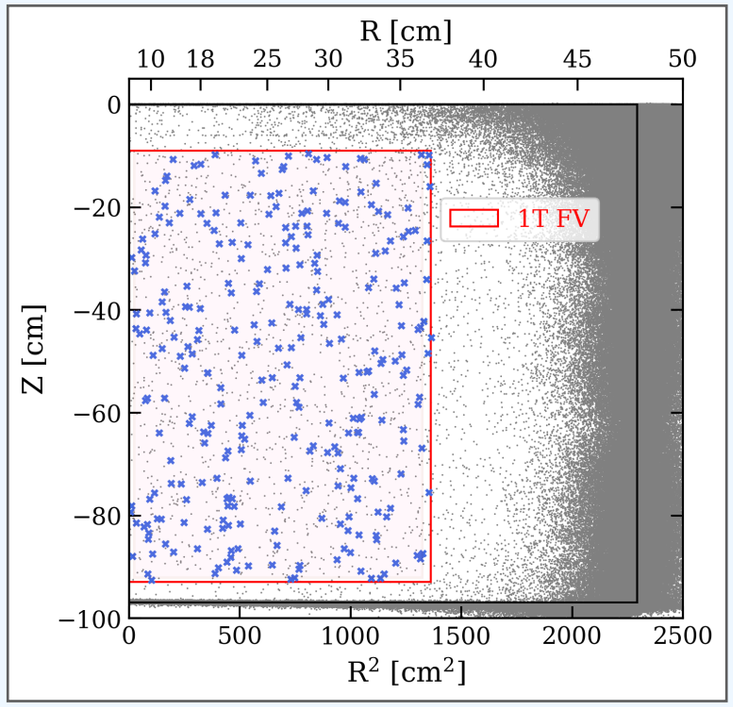

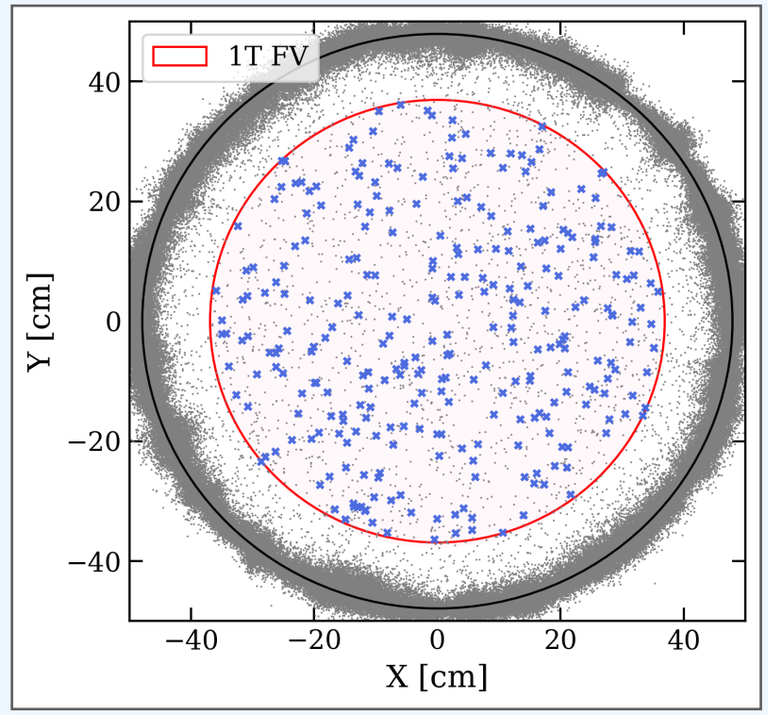

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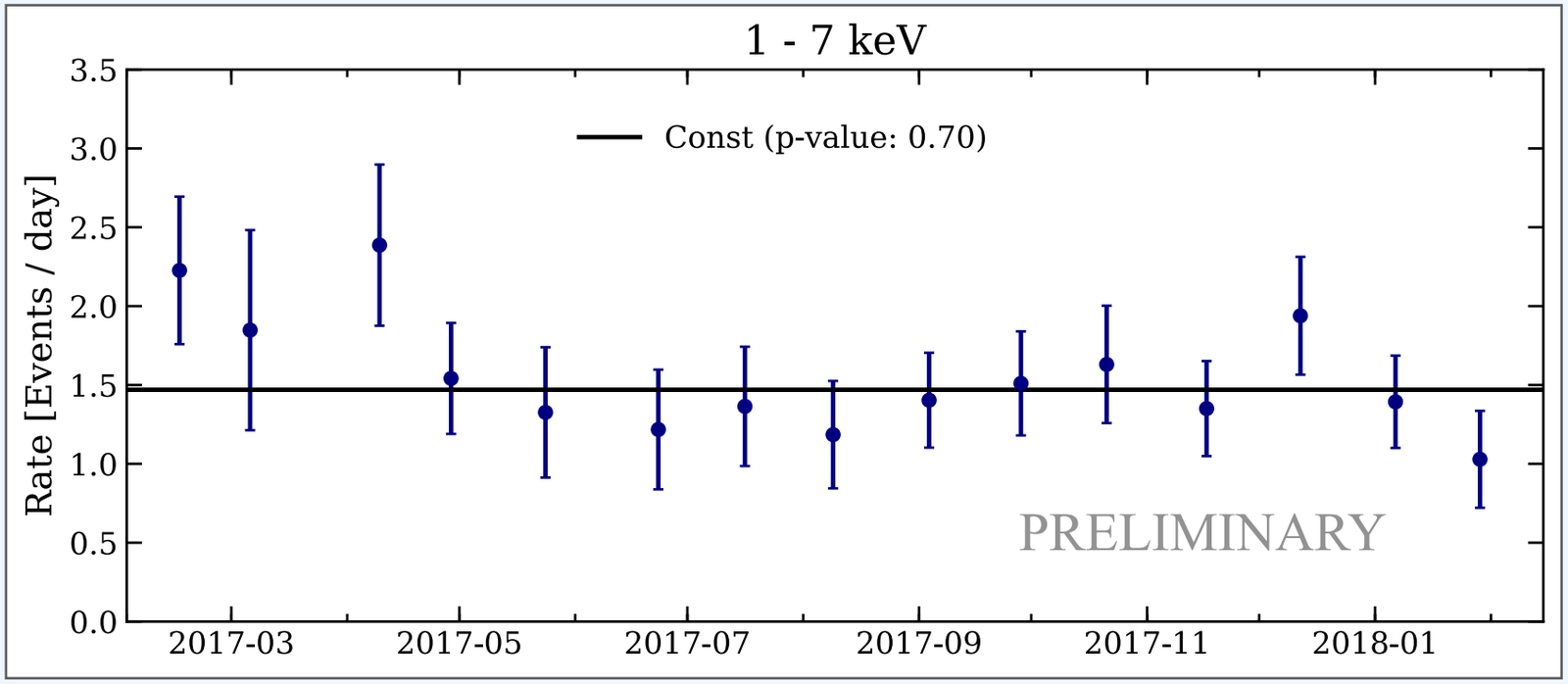
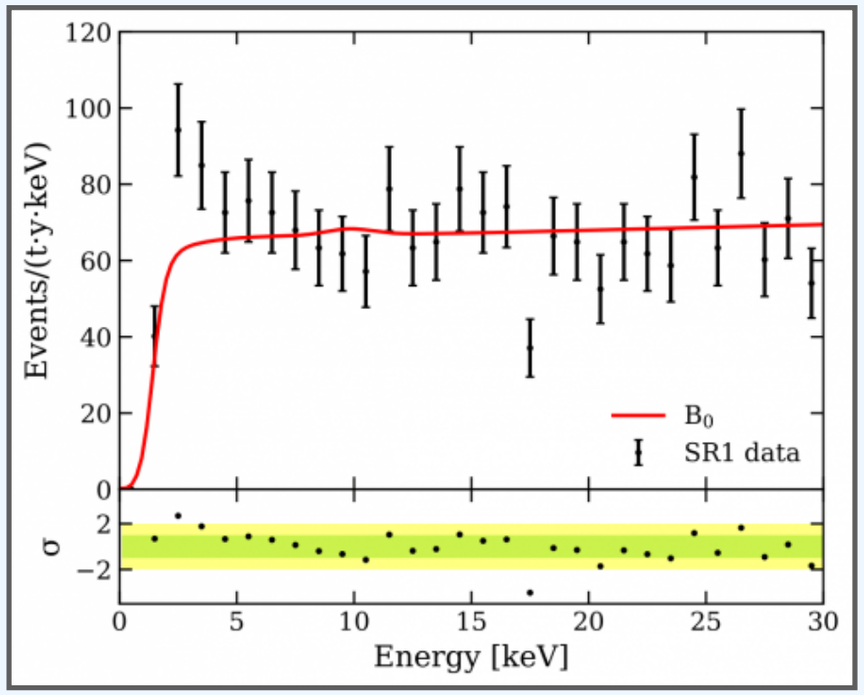


Consistent with constant time, but with very low statistics!

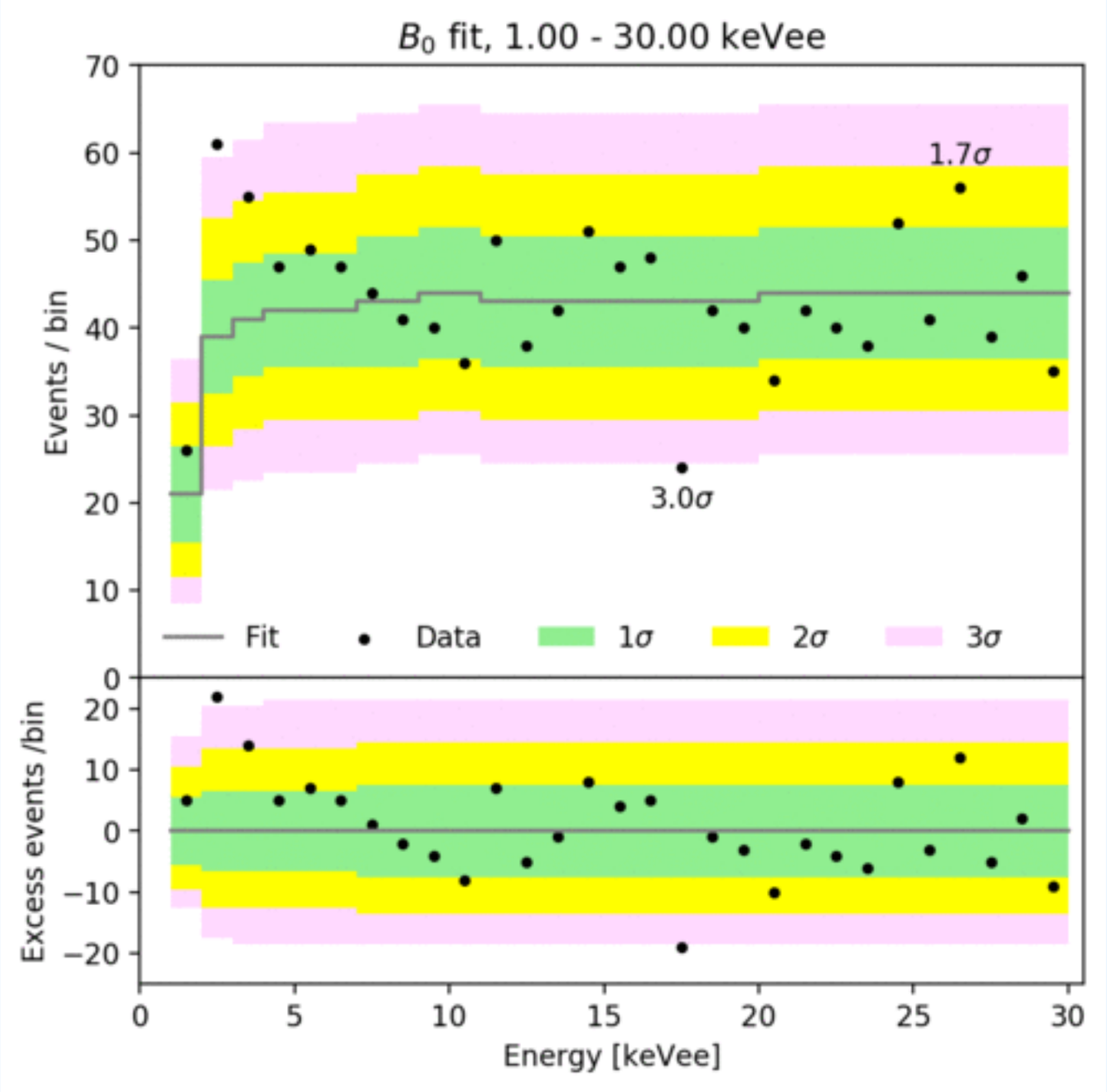
(*dedicated annual modulation analysis in progress*)

Fluctuations and correlations



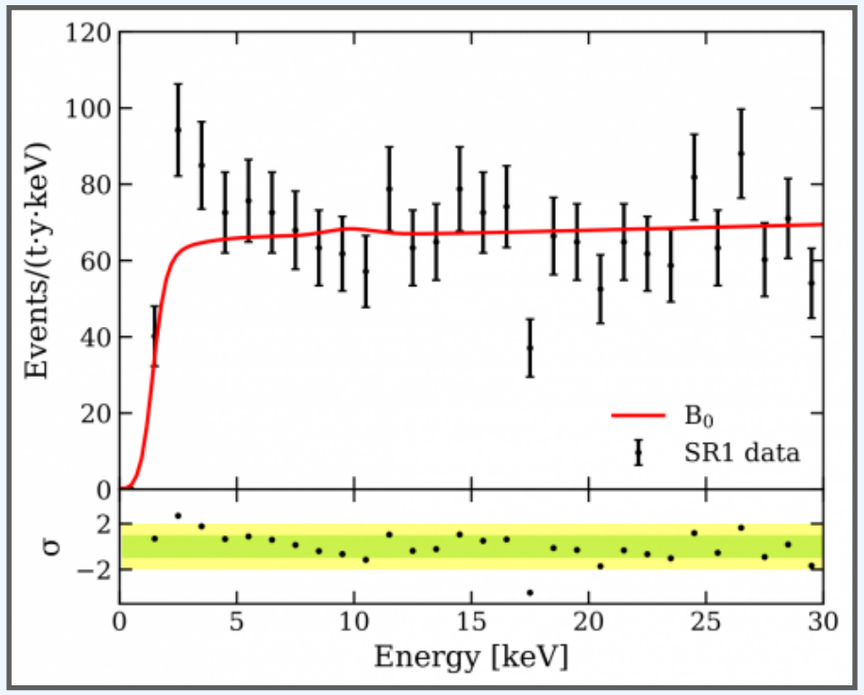
statistical fluke? (see 17 keV dip)

funny correlation? (1-10 keV rising steadily)



An unbinned profile likelihood analysis was used for this analysis.

Fluctuations and correlations



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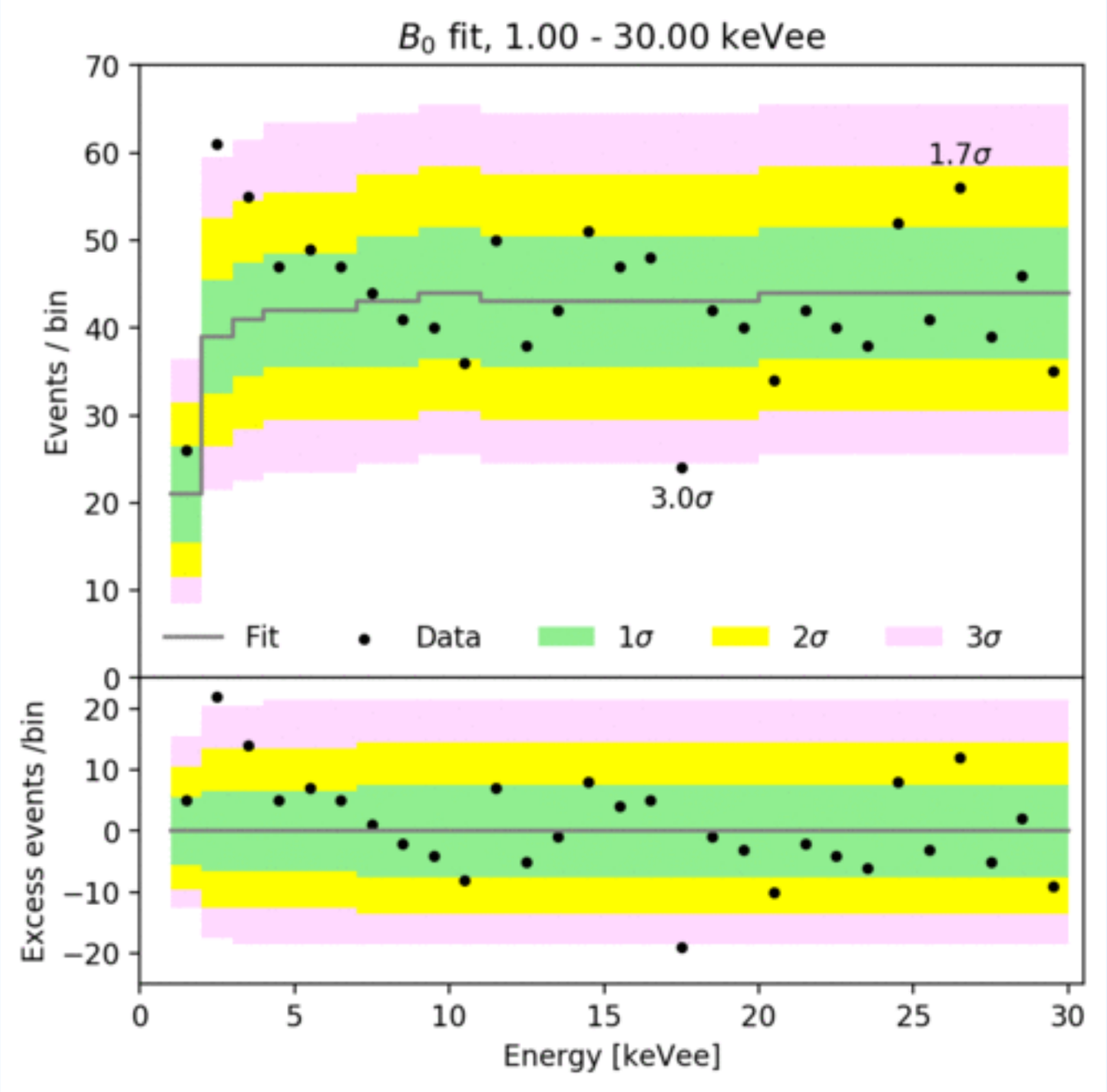

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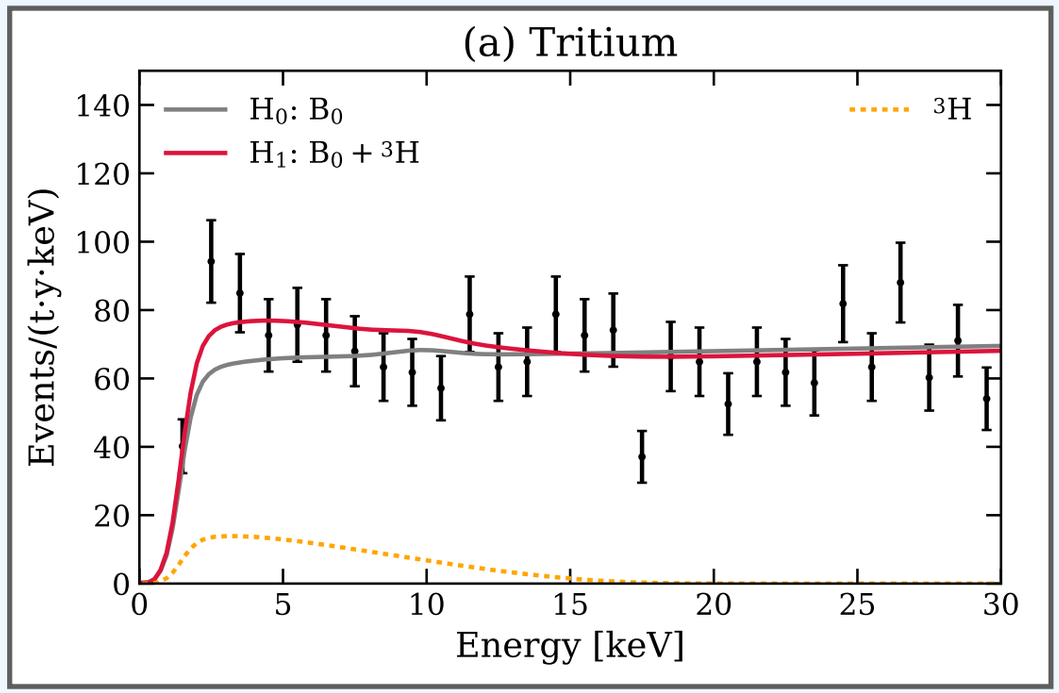
New background: tritium



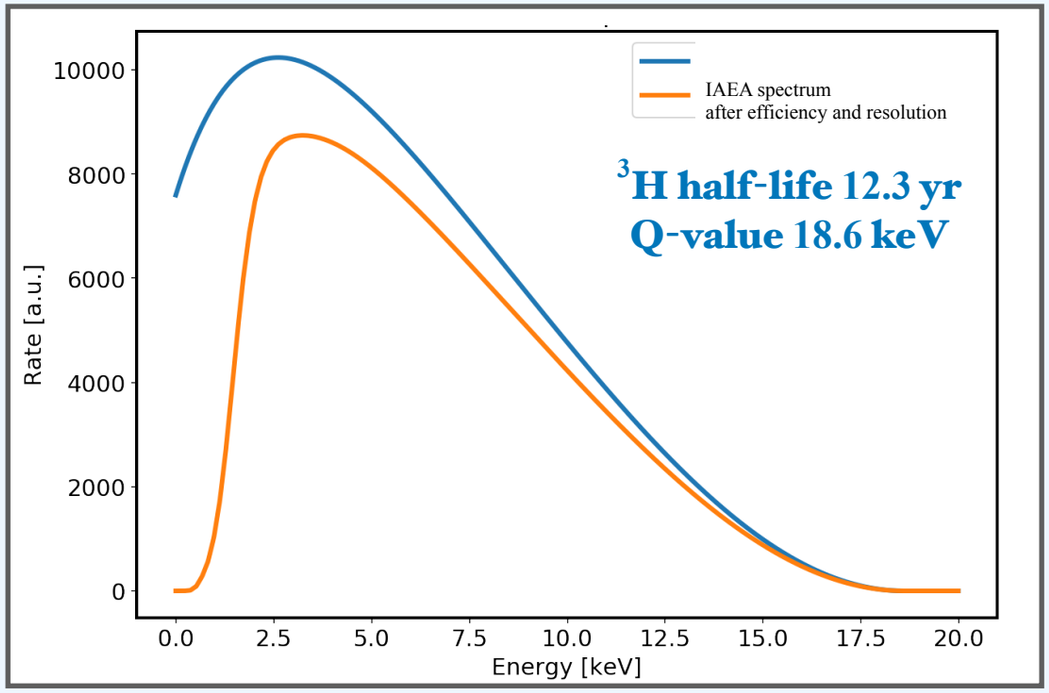
Tritium favored over background-only at 3.2σ

Best-fit tritium rate: 159 ± 51 events/(t · y)

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

possible in molecular form as tritiated hydrogen or water

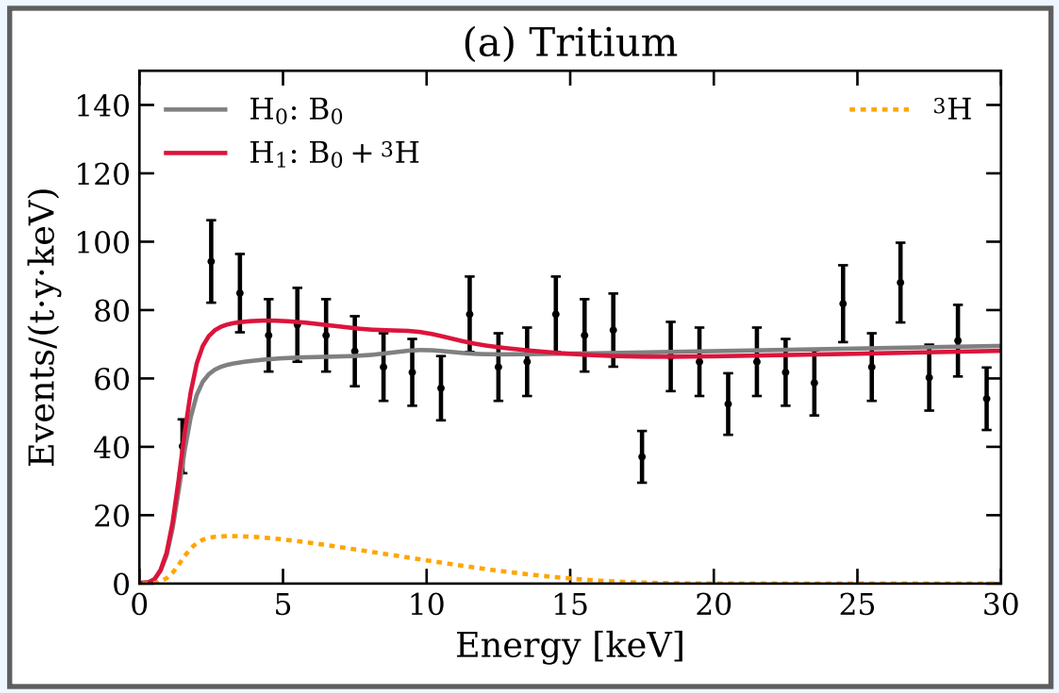
^{3}H:H in H_2O is 5 - 10 x 10^{-18} mol/mol



- Cosmogenic production ruled out (Xe purification)
- Possible emanation from materials (PTFE, SS) from natural abundance
- Tritiated water ruled out (would inhibit light collection).
- Tritiated hydrogen unlikely but difficult to quantify.

We can neither confirm nor exclude its presence.

New background: tritium



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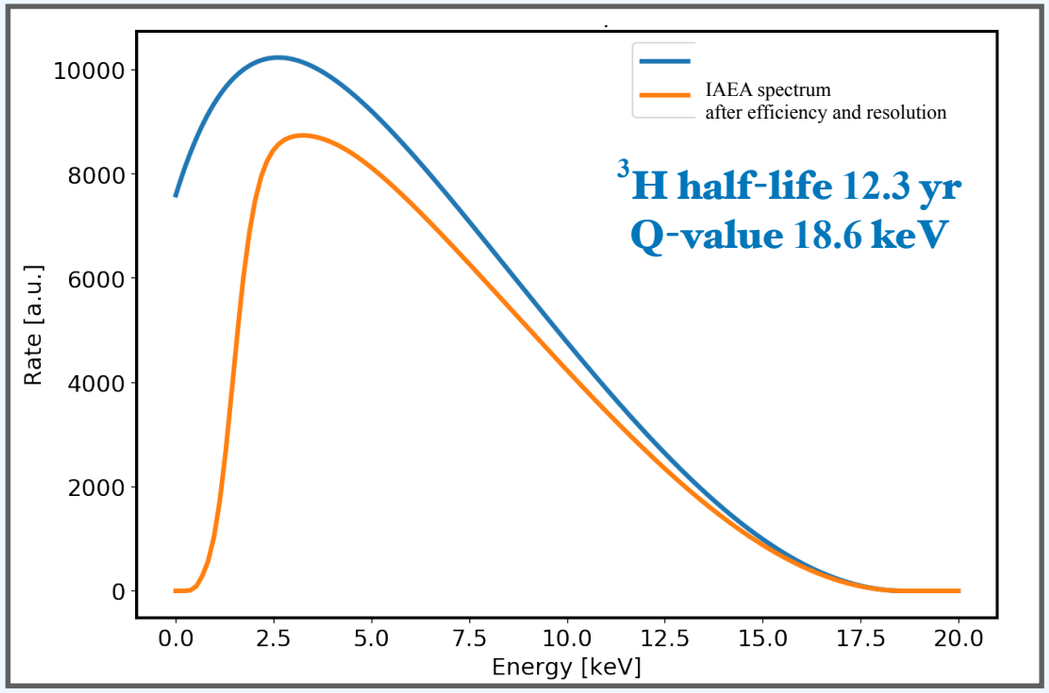
< 3 tritium atoms per kg of xenon!

possible in molecular form as tritiated hydrogen or water

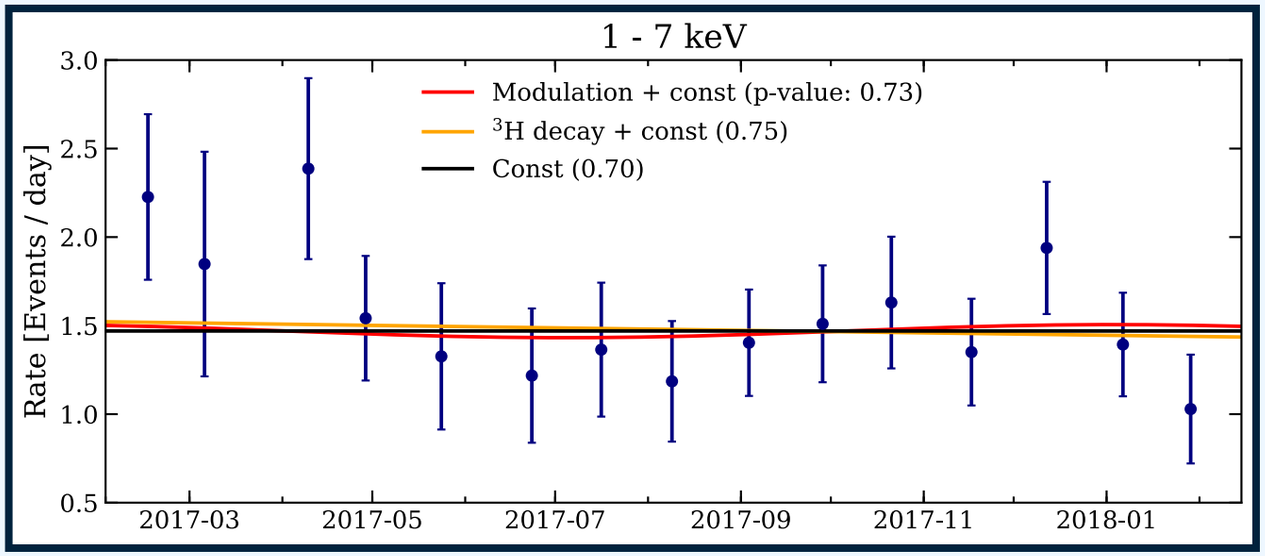
^{3}H:H in H_2O is 5 - 10 x 10^{-18} mol/mol



- Cosmogenic production ruled out (Xe purification)
- Possible emanation from materials (PTFE, SS) from natural abundance
- Tritiated water ruled out (would inhibit light collection).
- Tritiated hydrogen unlikely but difficult to quantify.

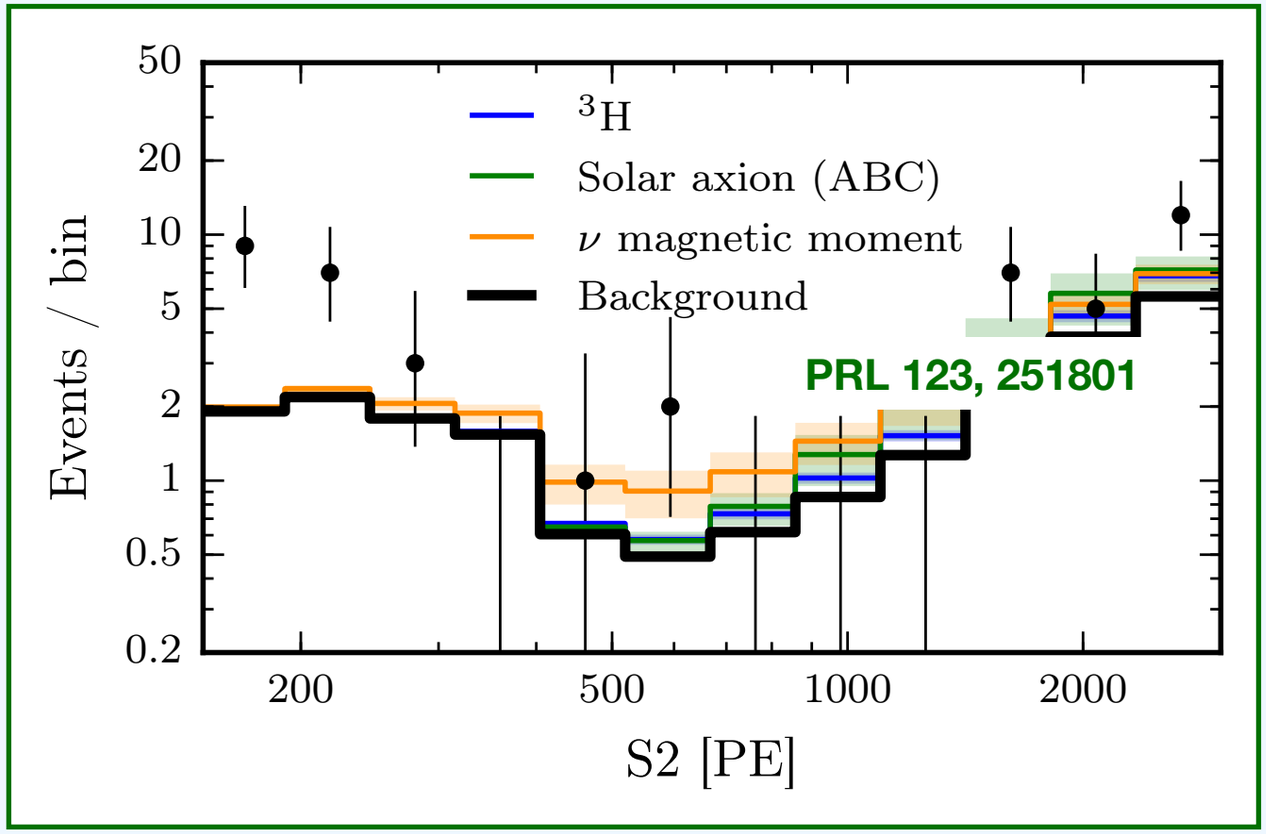
We can neither confirm nor exclude its presence.

Further checks



Time dependence revisited for signals (constant in time), tritium decay, and annual modulation.

All p-values are similar.



S2-only allows for a lower energy threshold
O(100 eV)

$$\mu_\nu < 3.1 \times 10^{-11}\ \mu_B$$

$$g_{ae} < 4.8 \times 10^{-12}$$

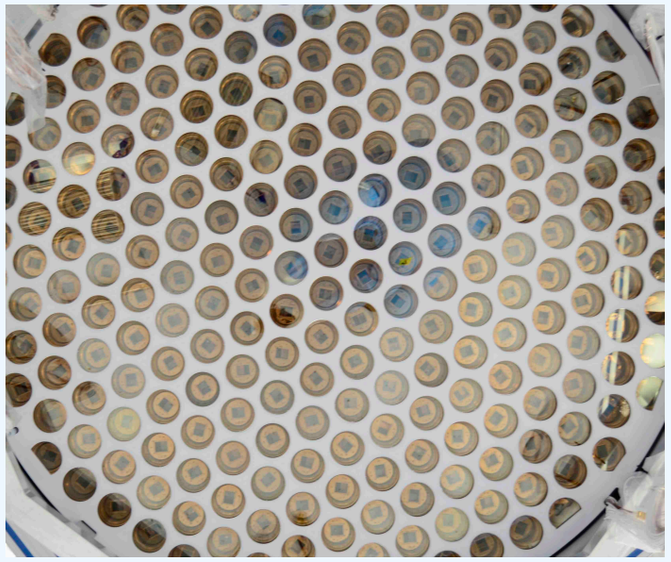
$$R_{\mathrm{H3}} < 2256\ \mathrm{events/t/y}$$

Both checks consistent with all hypotheses.

Our results are... inconclusive.

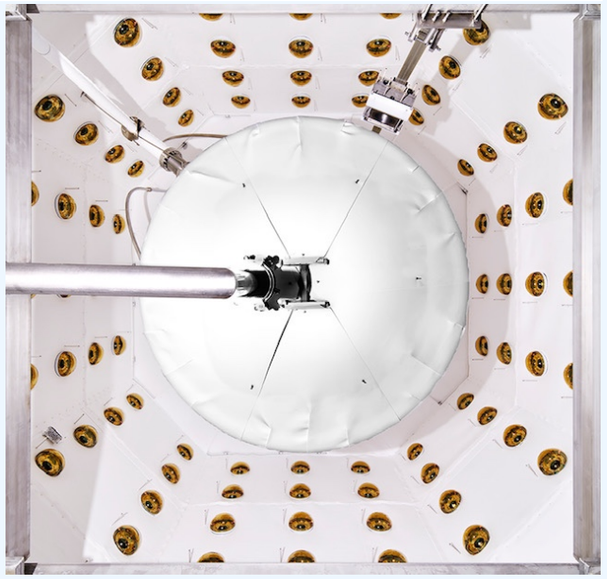
(what’s next?)

XENONnT



PMT array (494 PMTs in total, in 2 arrays)

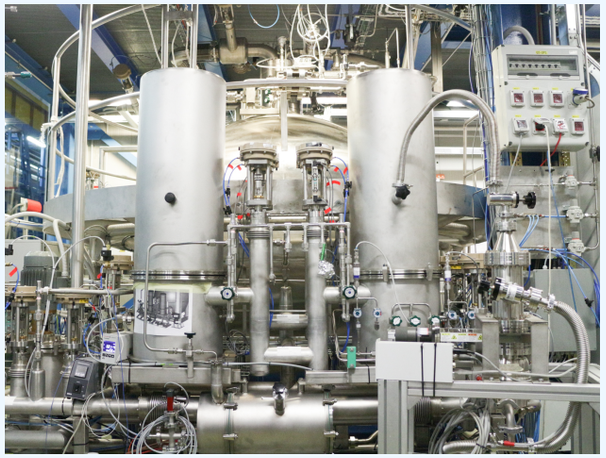
TPC (5.9 t LXe, 4 t fiducial)



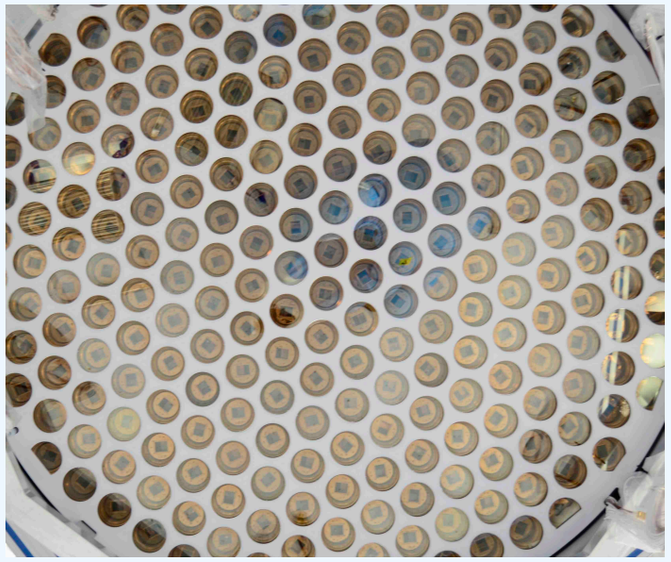
Neutron veto (120 PMTs, Gd-doped water)

XENONnT is currently taking science data!

XENONnT



Liquid xenon purification system



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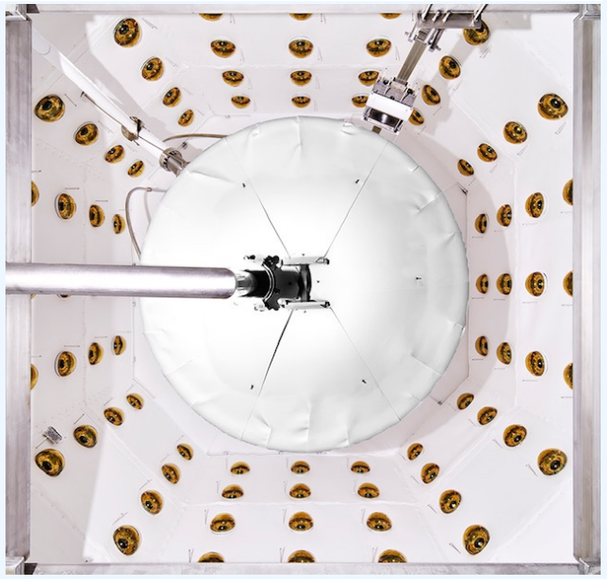

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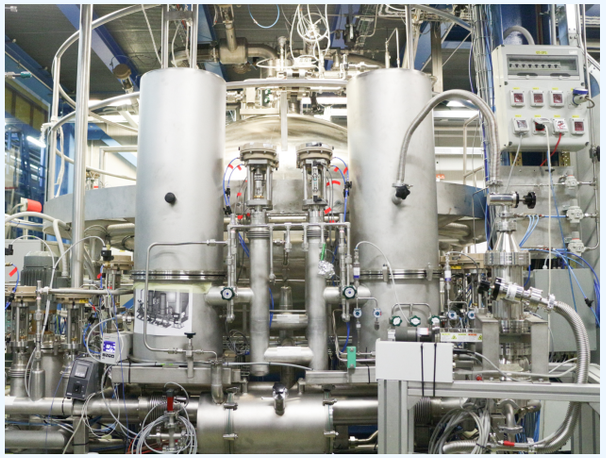

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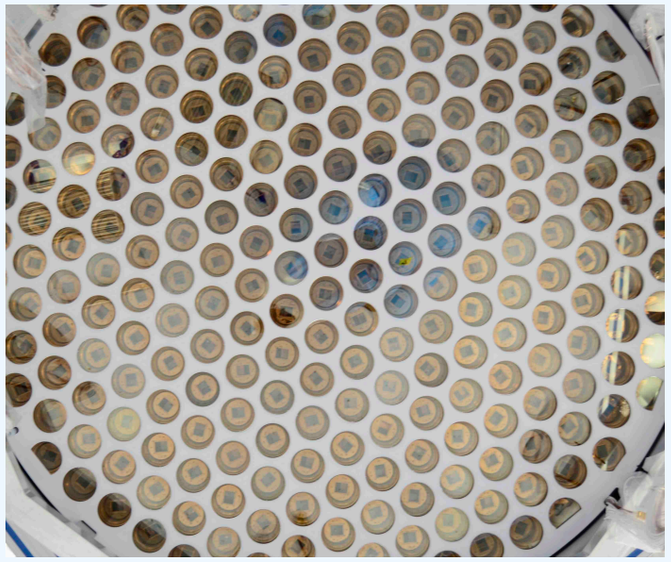

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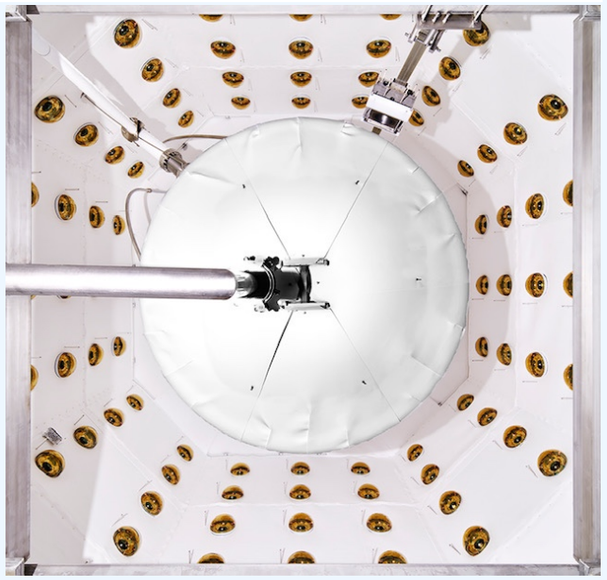


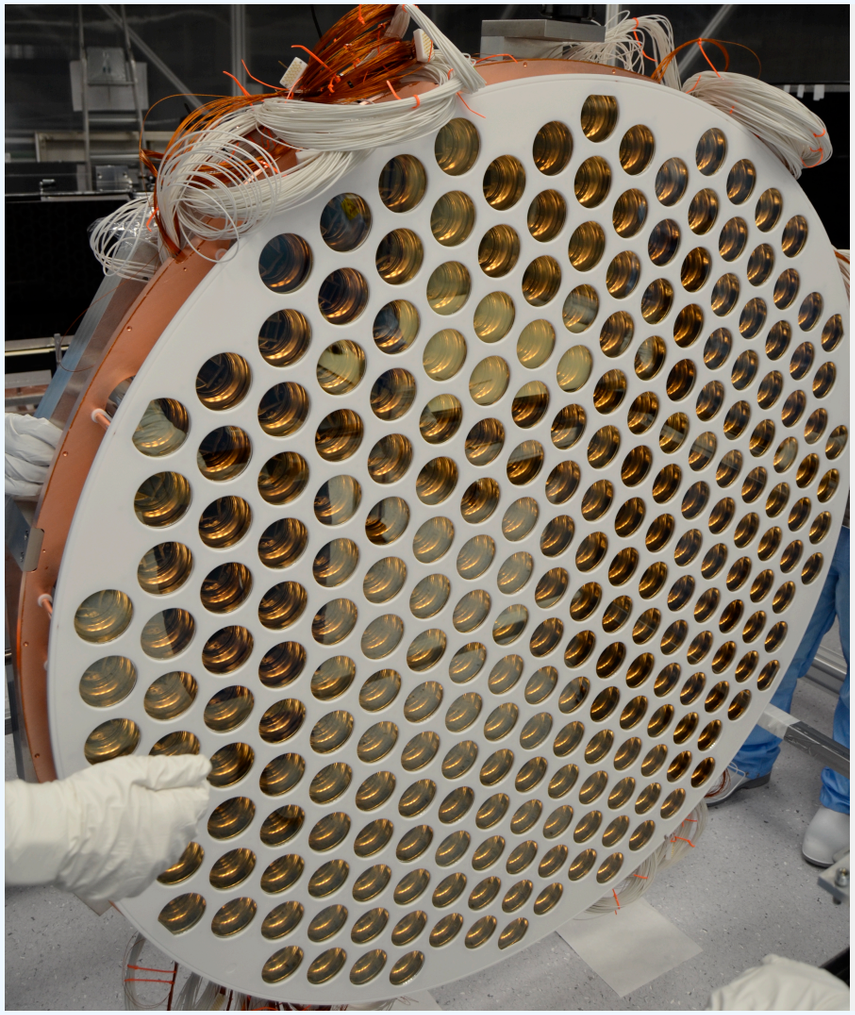
Neutron veto (120 PMTs, Gd-doped water)

Rn distillation column

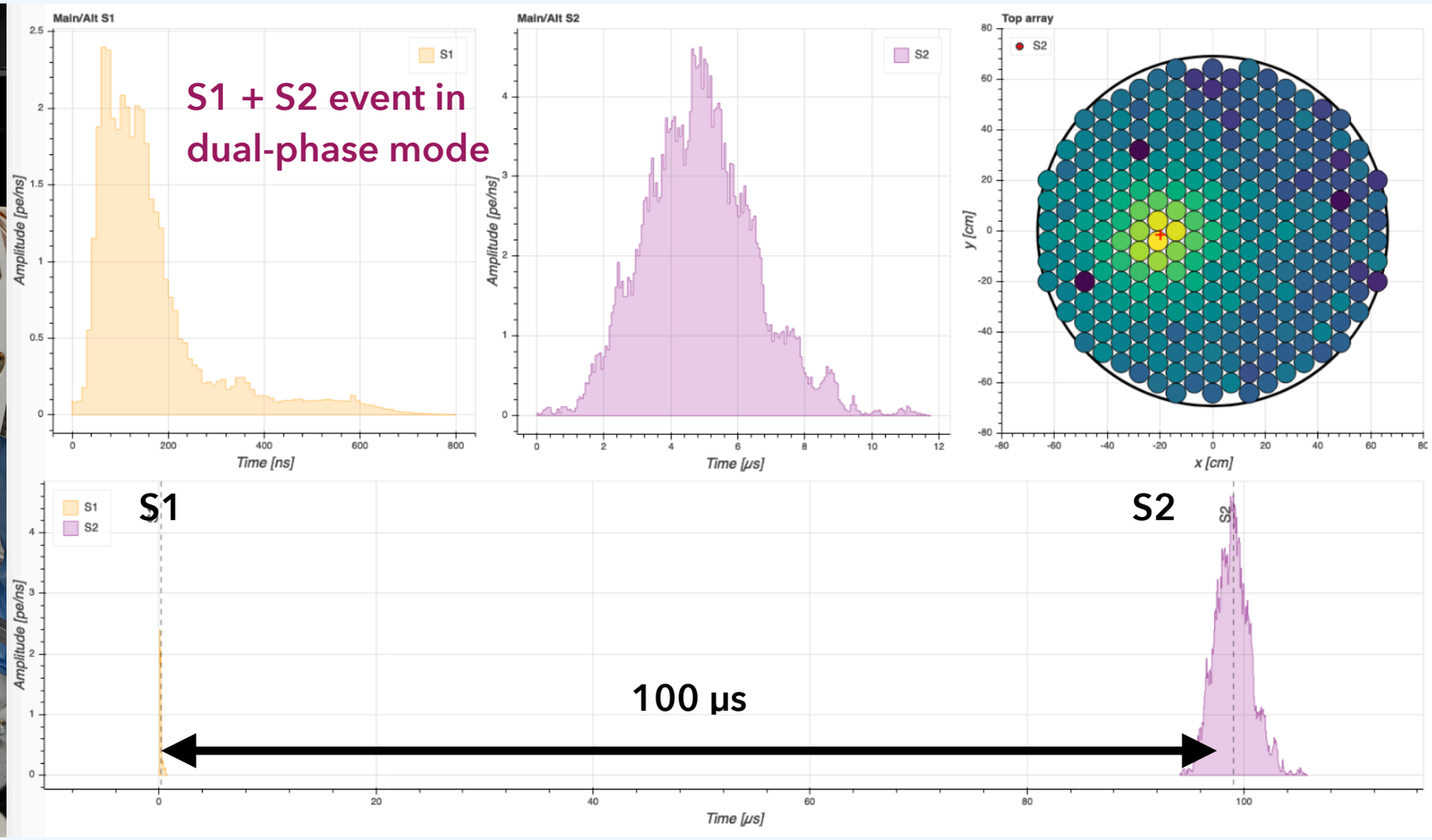
reduce ^{222}Rn (^{214}Pb)

XENONnT is currently taking science data!

XENONnT

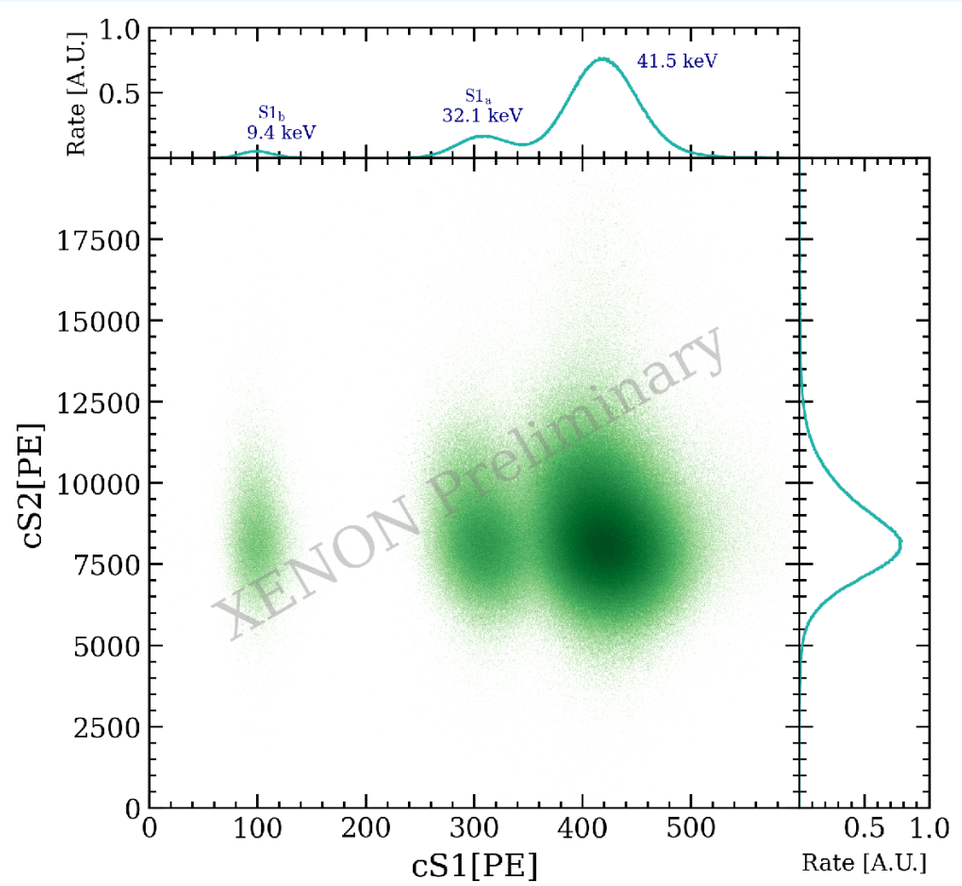


PMT array during assembly



Waveform during current operation

XENONnT: Detector performance

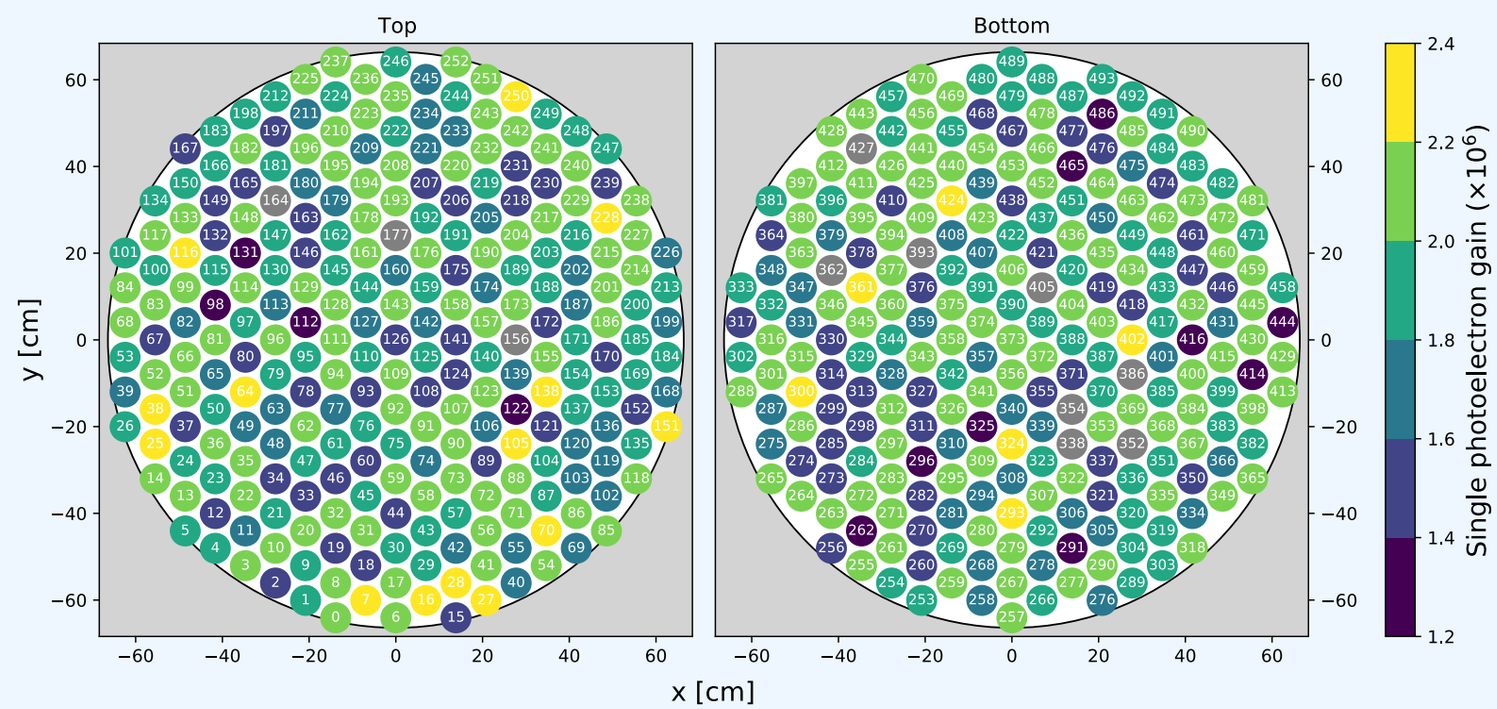


^{83m}Kr calibration

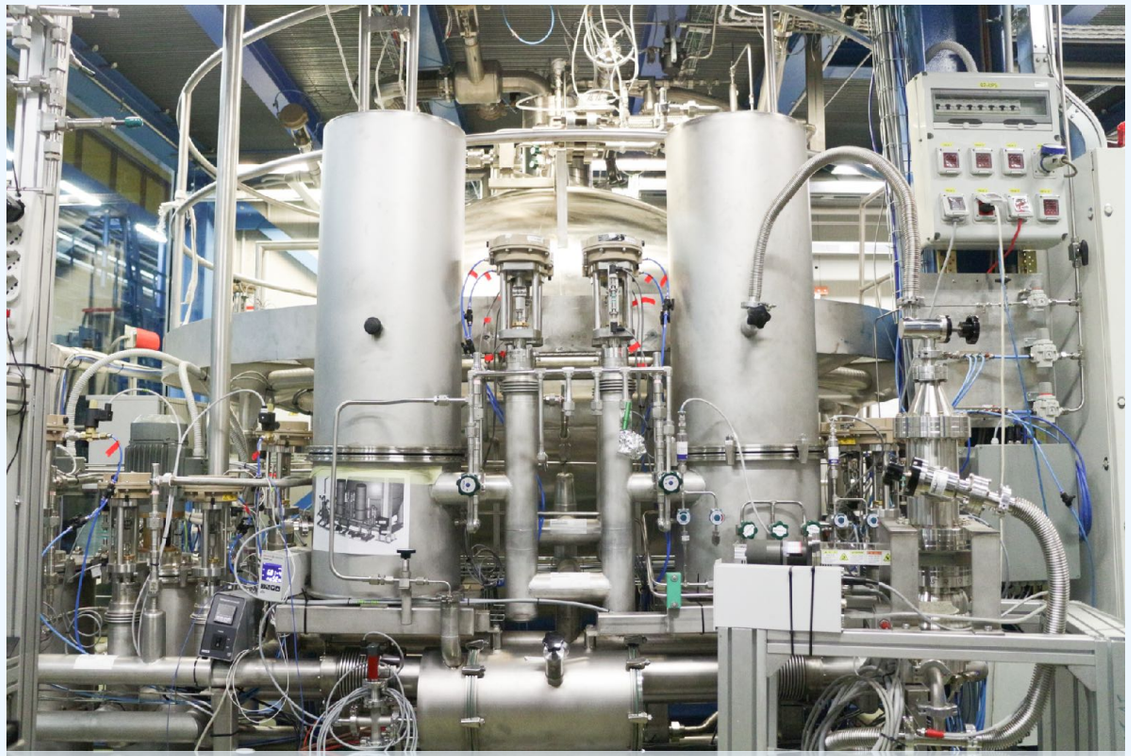
- Resolved peaks in S1-S2 space resolved
- Photon detection efficiency ~ 0.17 PE/photon (XENON1T 0.14 PE/photon)
- Energy resolution at 41.5 keV ~ 7.6 % (XENON1T 8 %)
- S2 resolution of 15.1 % (XENON1T 13.7 %)

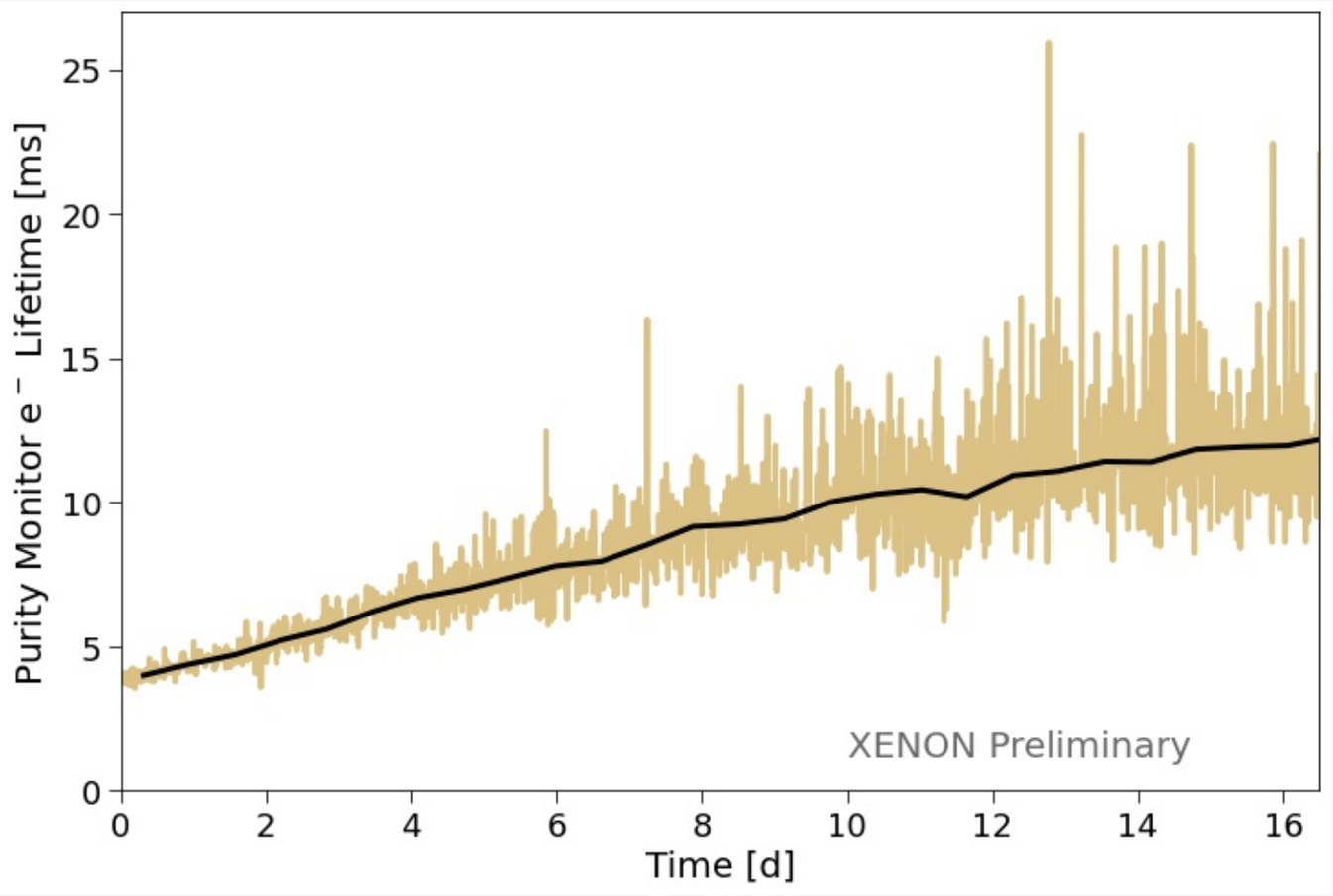
PMTs

- 485 PMTs used in data analysis
- Average quantum efficiency 34 %



XENONnT: purification





Ionization electrons - survival probability

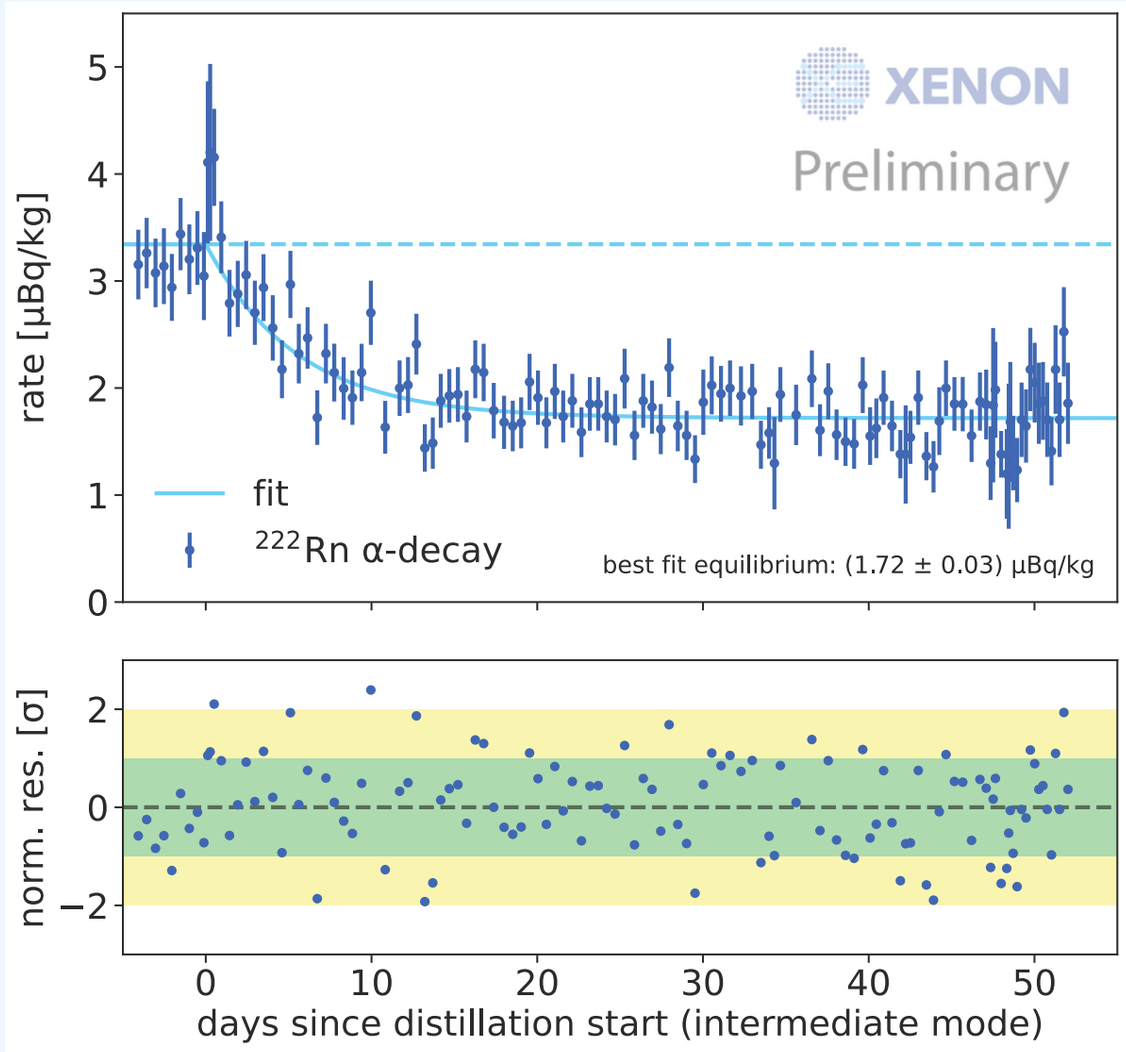
- High purification flux for removing electronegative impurities: 2 l /min LXe ≈ 350 kg/h
- Low-Rn filters for science data taking
- Achieved electron-lifetime of > 20 ms

XENON1T: 0.65 ms ≈ 0.9 x maximum drift-time (30 % cathode survival)

XENONnT: 2.2 ms maximum drift (> 90 % cathode survival)

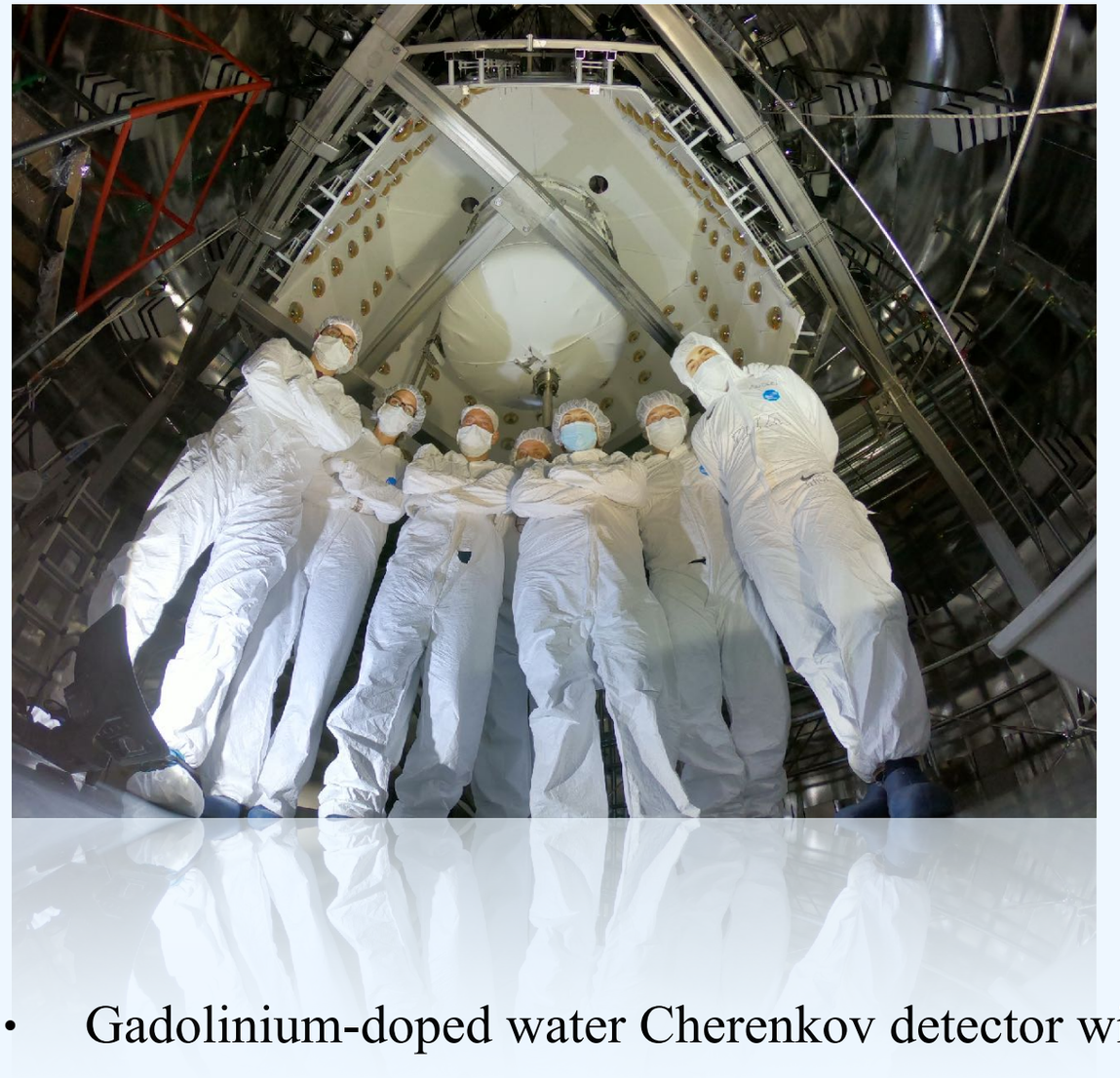
XENONnT: Radon distillation

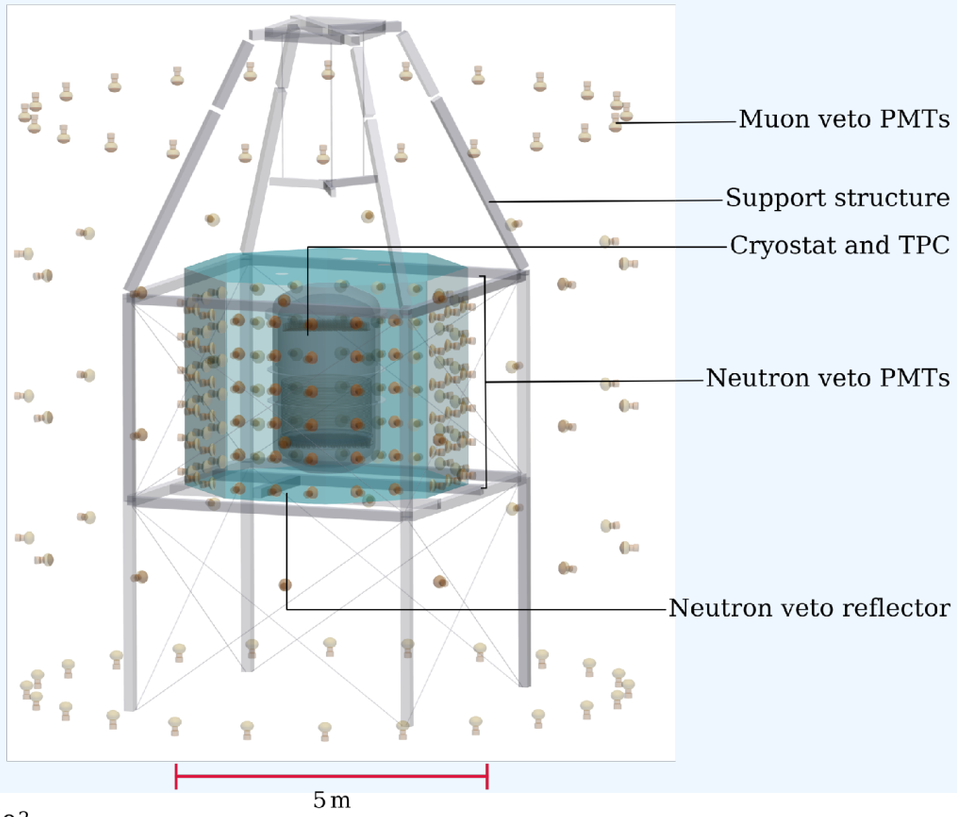
Constant removal of emanating radon from xenon using difference in vapor pressure

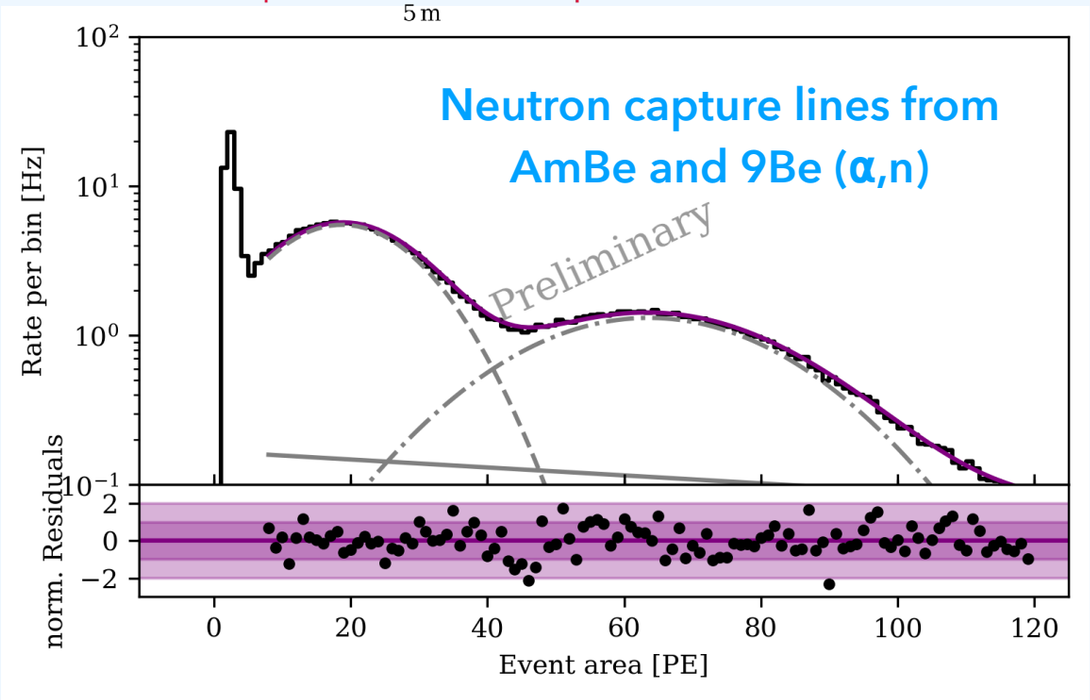


- Reached equilibrium concentration of 1.72 μBq/kg by gas extraction only
- Background goal 1 μBq/kg
- Additional factor 2 in Rn removal possible via liquid extraction

XENONnT: neutron veto



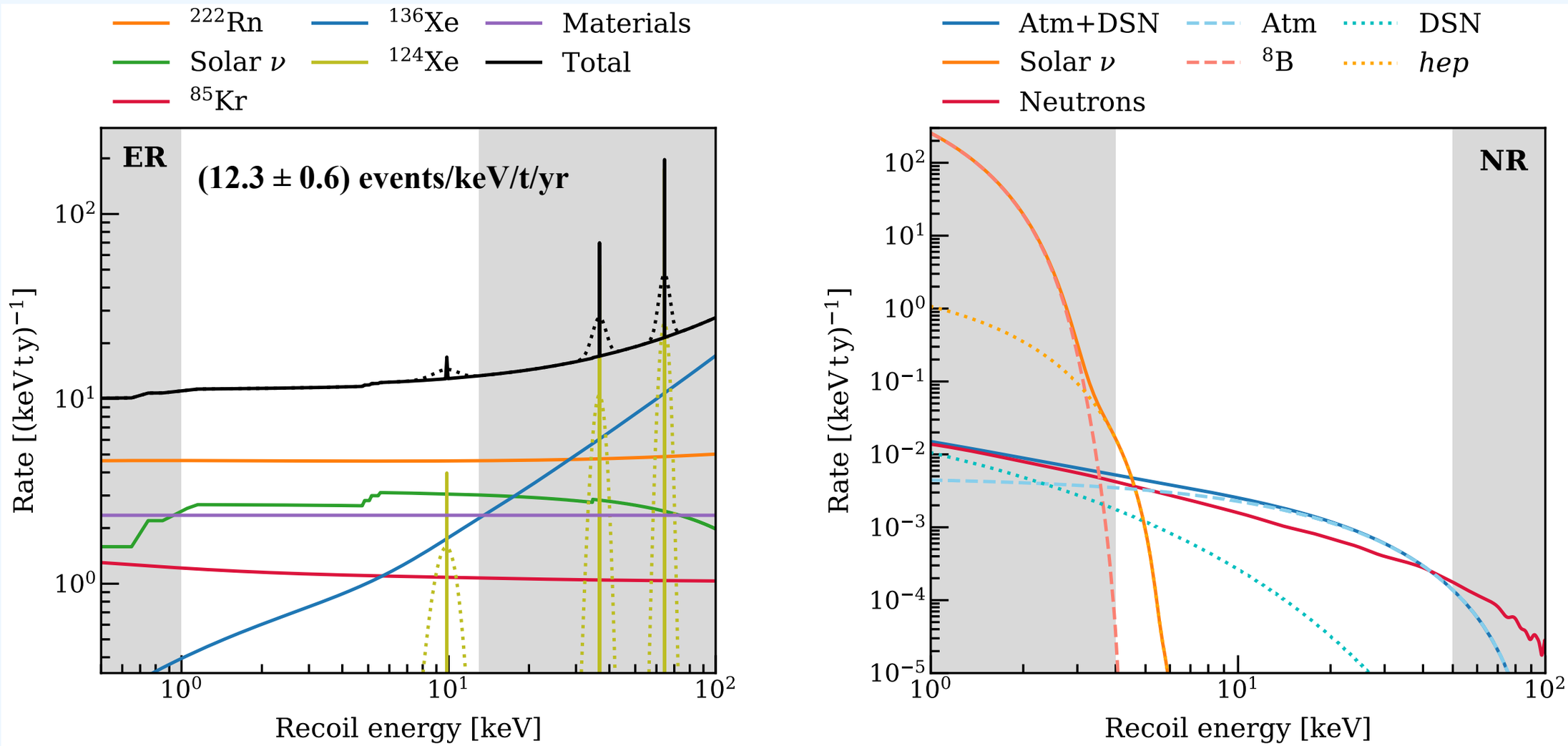




- Gadolinium-doped water Cherenkov detector with 0.5 % $Gd_2(SO_4)_3$
- Optically separate inner region of existing muon veto
- 120 PMTs
- Projected 87 % neutron tagging efficiency

XENONnT: background projections

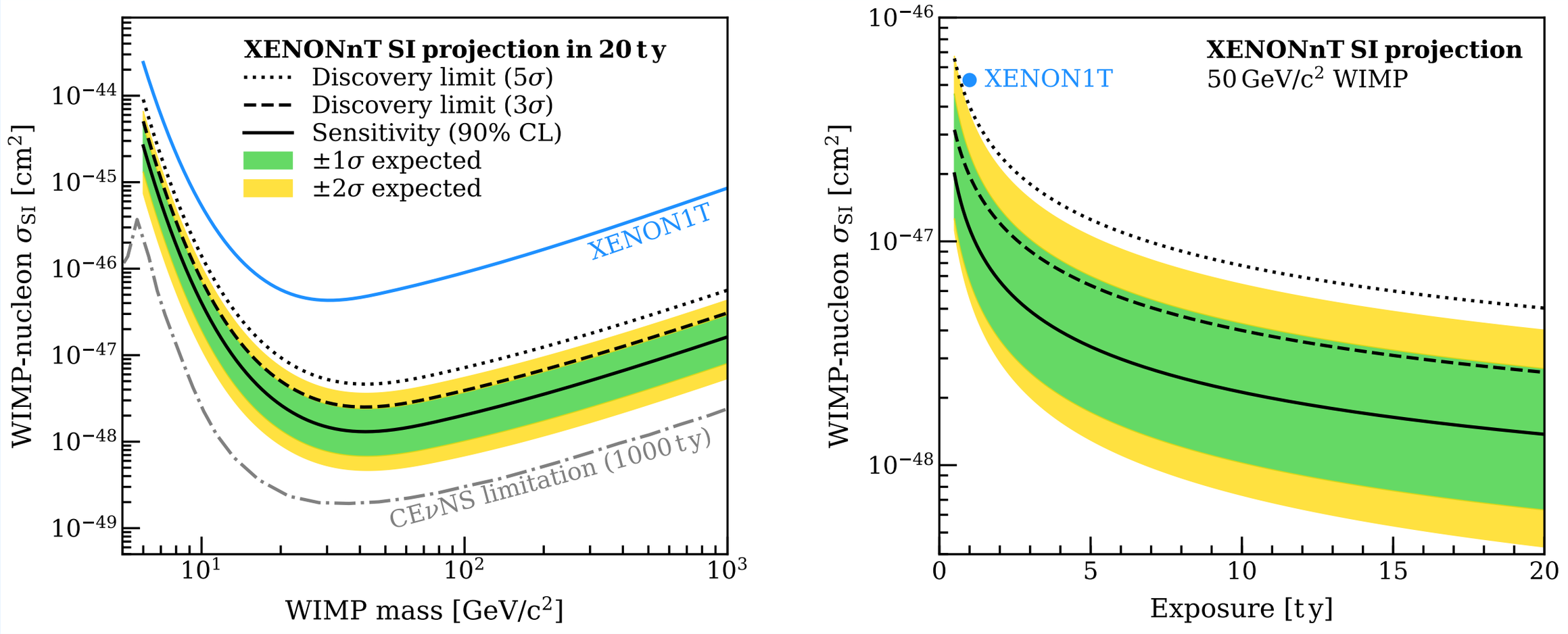
JCAP 11 (2020) 031



- Total ER rate reduced by factor six
- ER background for WIMP and axion search dominated by **^{222}Rn** (2νββ of ^{136}Xe above 30 keV)
- **Neutrino-dominated NR**: target < 1 neutron NR event per 20 t-yr target exposure

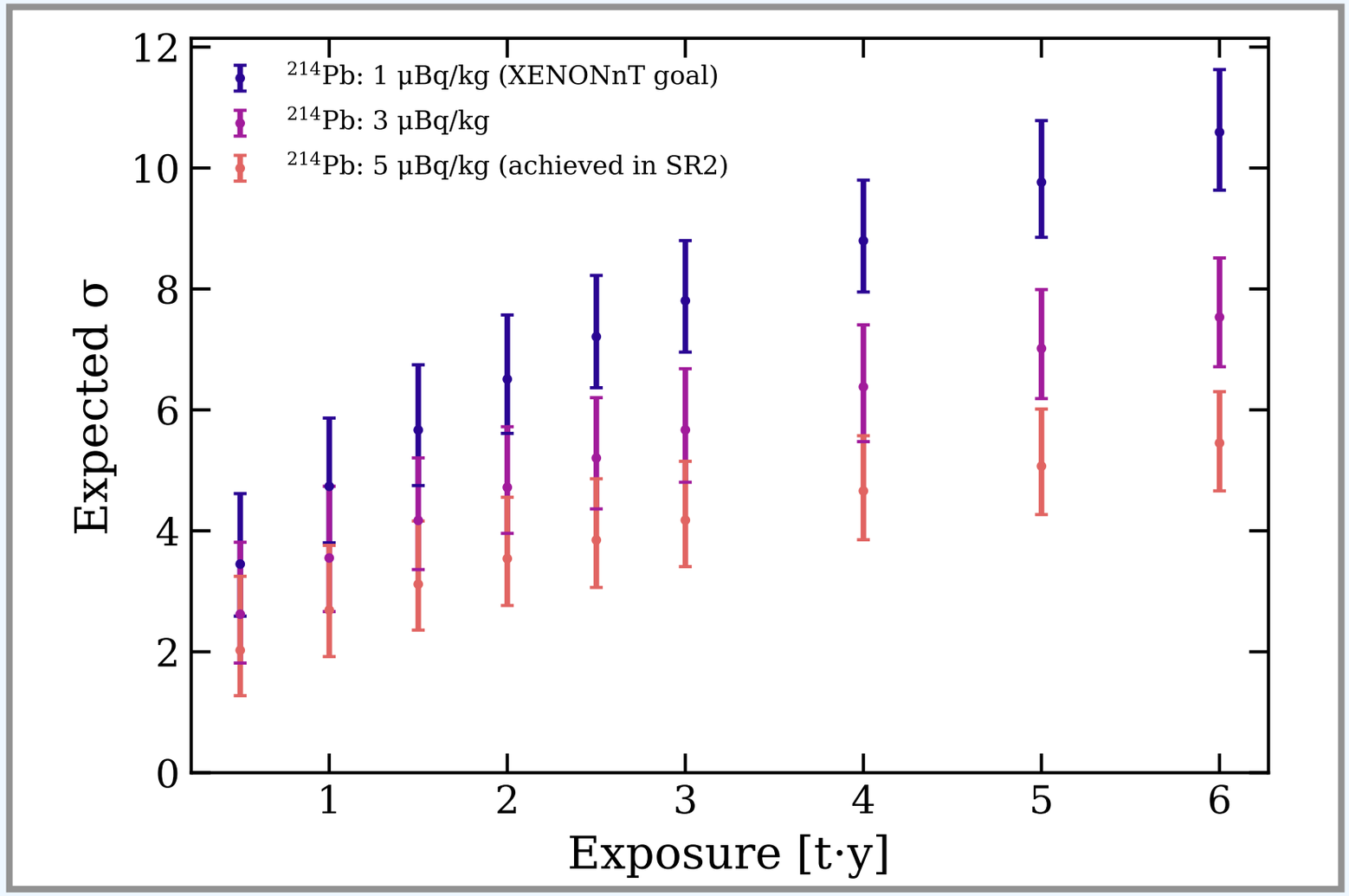
XENONnT: background projections

JCAP 11 (2020) 031



- Improve existing WIMP limits by more than one order of magnitude with 20 tonne-year exposure
- Reach neutrino fog (and detect ^{8}B neutrinos from the sun)
- Discovery potential beyond 10^{-47} cm^2 for 50 GeV/c^2 WIMP in ~ one year live time

XENONnT: excess



Vary the ^{214}Pb contribution

(now 1.72 μBq/kg)

Discriminate based on energy spectrum alone.

Uses best-fits from 1T search.

XENONnT will discriminate axions from tritium with ~ few months of data

Summary

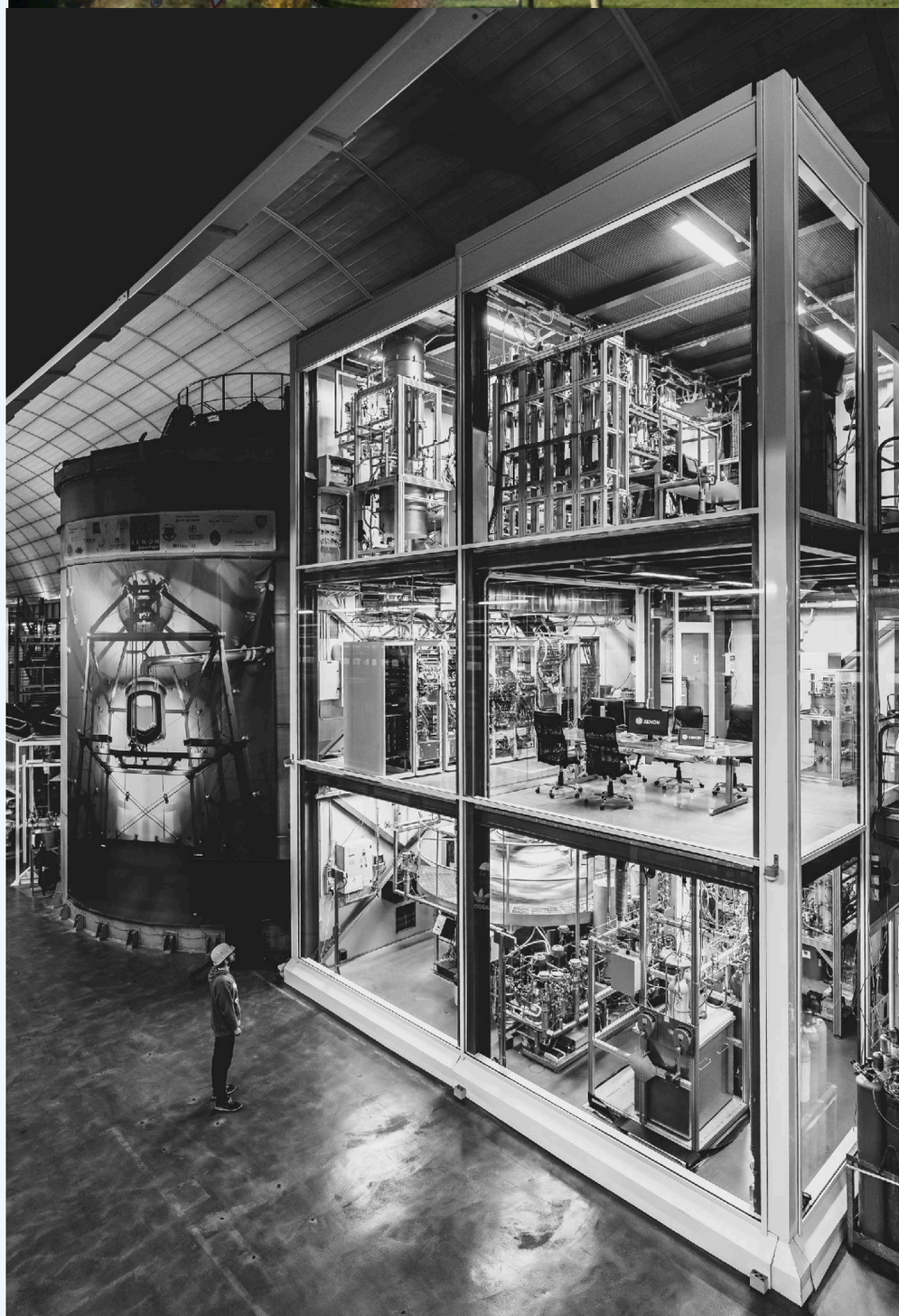
- XENON1T still holds the best limit for SI WIMPs (although may change soon)
- Lower dark matter masses and other physics can be probed with new analysis techniques to lower the threshold
- An excess at low energies is best fit with solar axions, but in tension with astrophysical constraints
- XENONnT is currently taking science data with 1/6 of the 1T background and 20 times more exposure.

www.xenonexperiment.org

instagram.com/xenon_experiment

twitter.com/xenonexperiment

XENON



Extra

Coherent neutrino-nucleus scattering

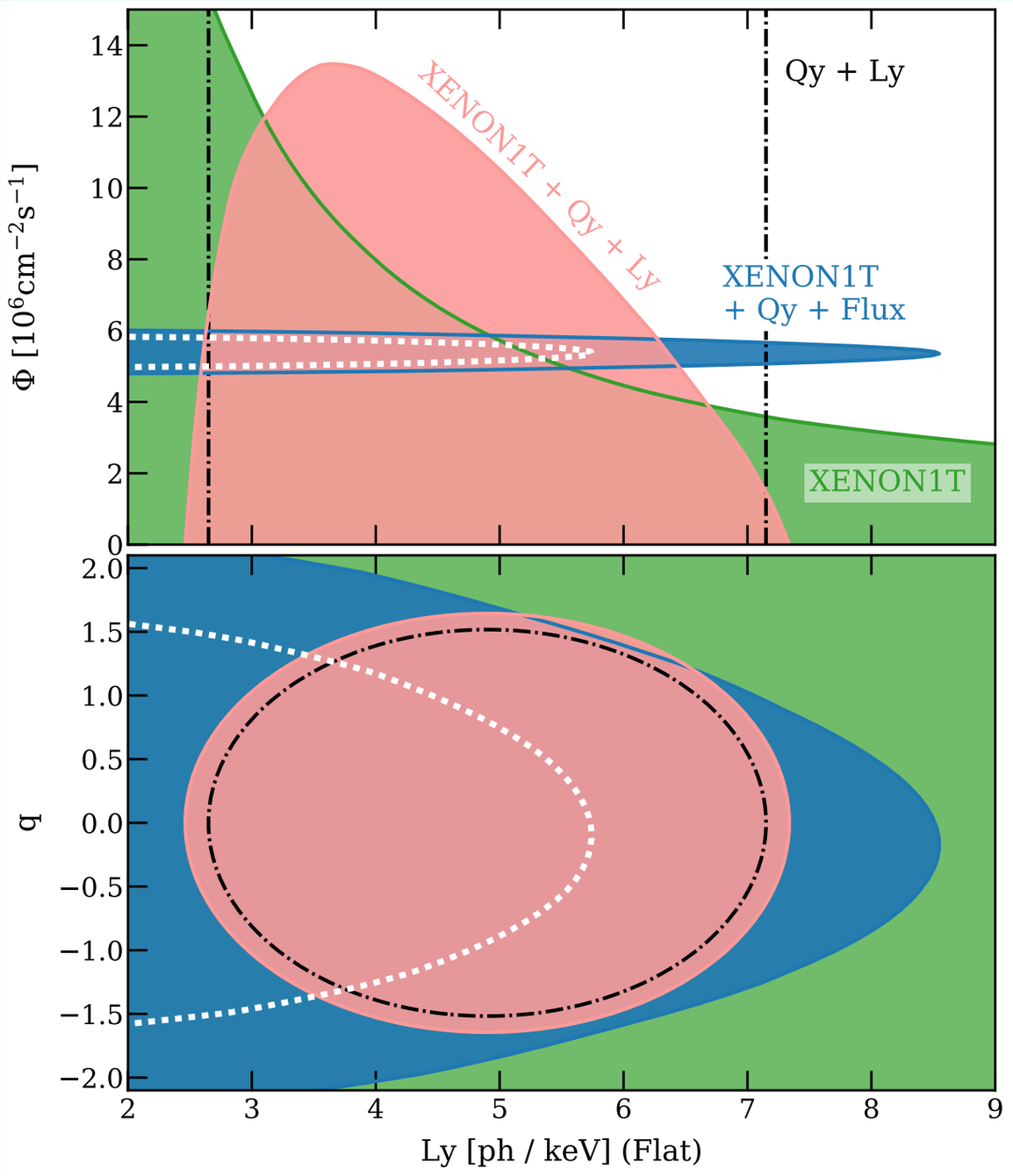
Neutrino flux: ϕ

Light yield: Ly

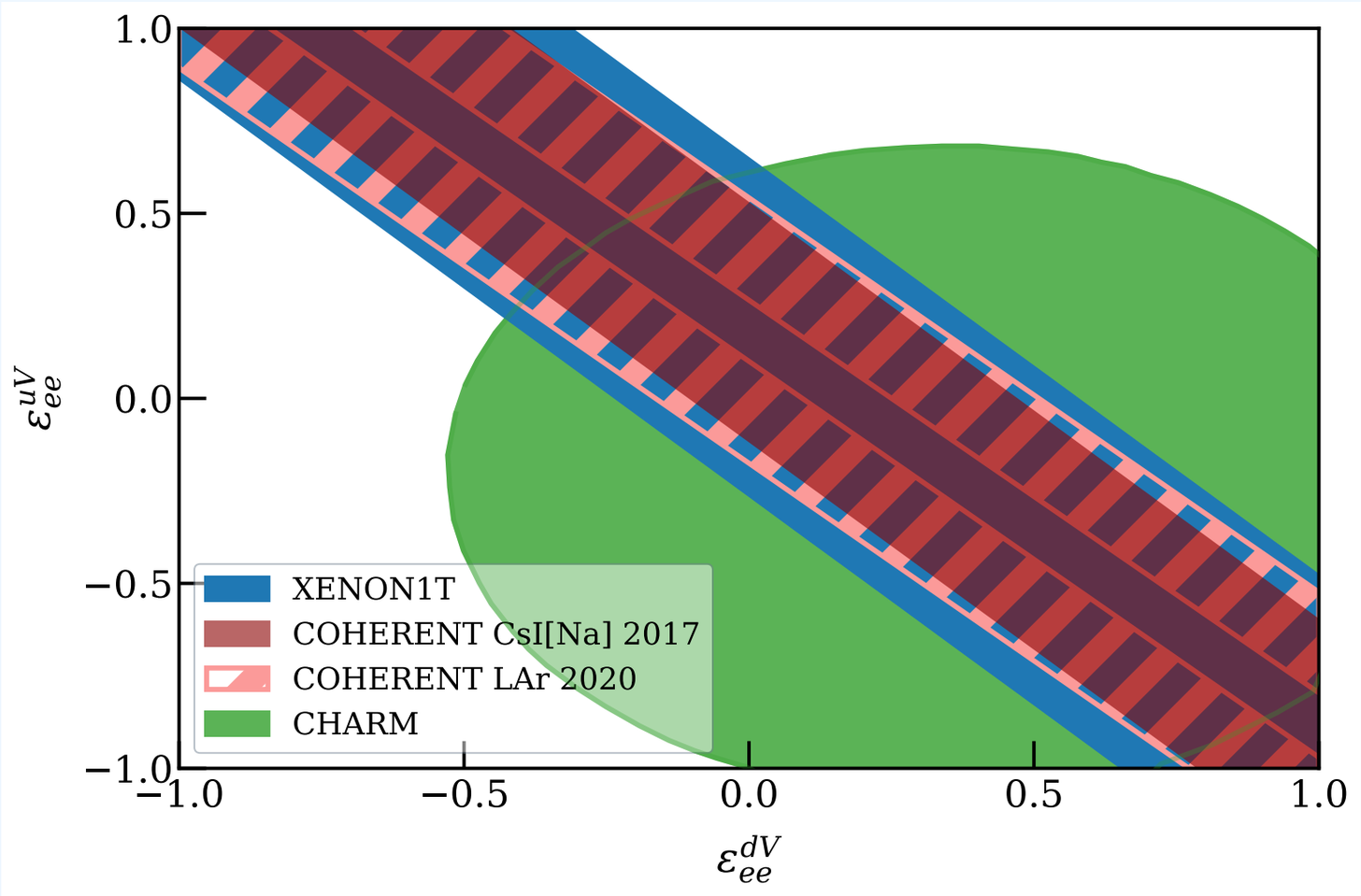
Charge yield: Ly

- Light yield and signal rate highly correlated, so **XENON1T-only result** becomes an upper limit on the combination of both
- Combination of XENON1T, LLNL charge yield and LUX light yield enables to set **upper limit on neutrino flux**

  $\Phi < 1.4 \cdot 10^7\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (90 % C.L.)
- Measured neutrino flux from SNO enables to set **upper limit on the light yield**



Coherent neutrino-nucleus scattering



- neutrino interactions with up, down quarks
- SM interaction is at 0.0, 0.00

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4.6 x 10^{27} nuclei/tonne Xe

ν_e survival probability

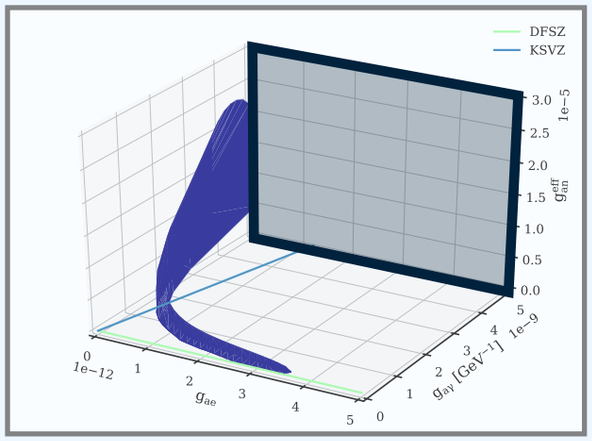
Neutrino flux

CEvNS cross-section

$$\frac{dR_e}{dT} = \mathcal{N} \cdot \int_{E_{\nu,\,\min}} P_e(E_\nu) \cdot \frac{dN}{dE_\nu} \cdot \frac{d\sigma(E_\nu, T)}{dT} dE_\nu$$

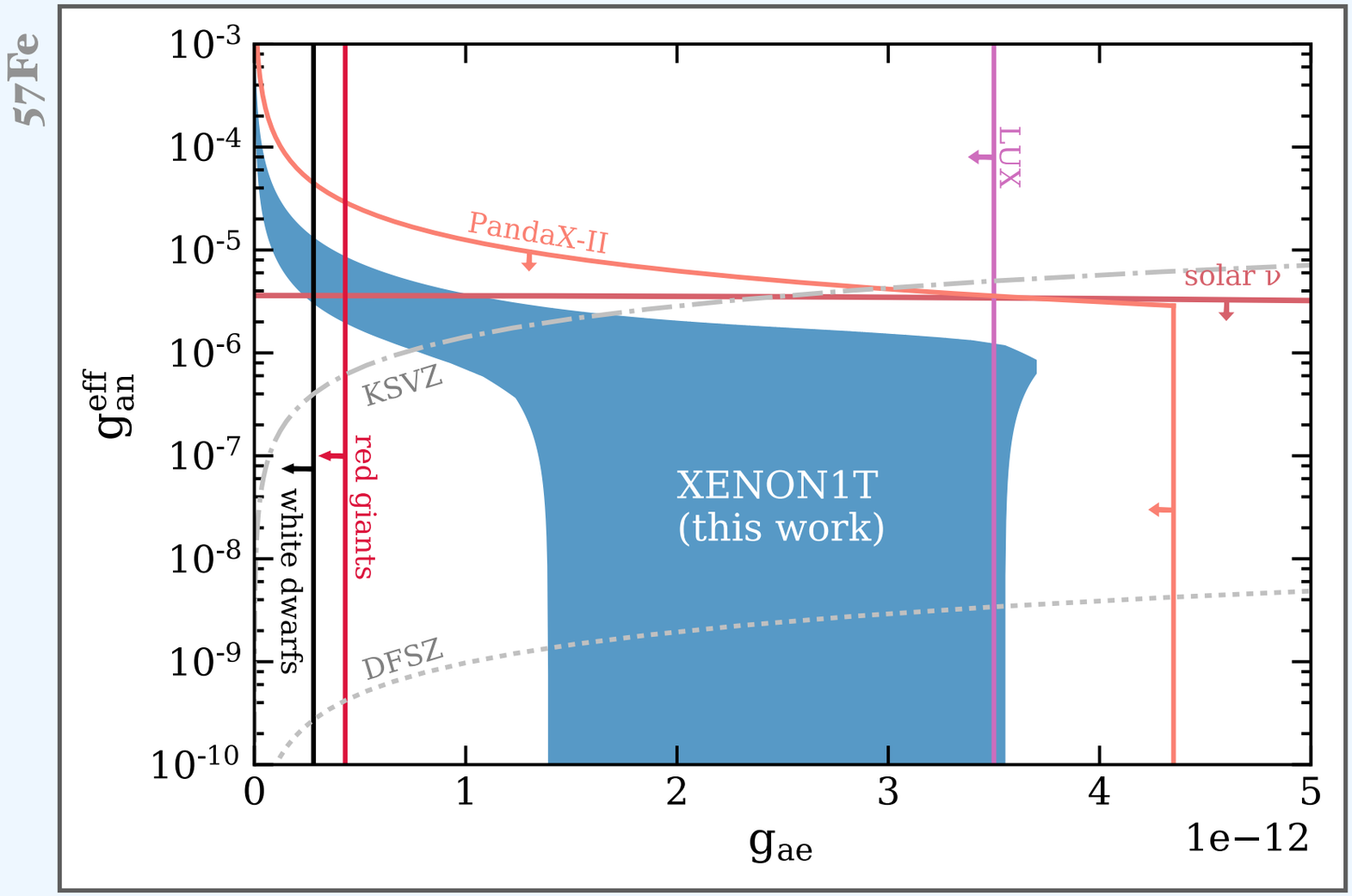
Axion statistical inference

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



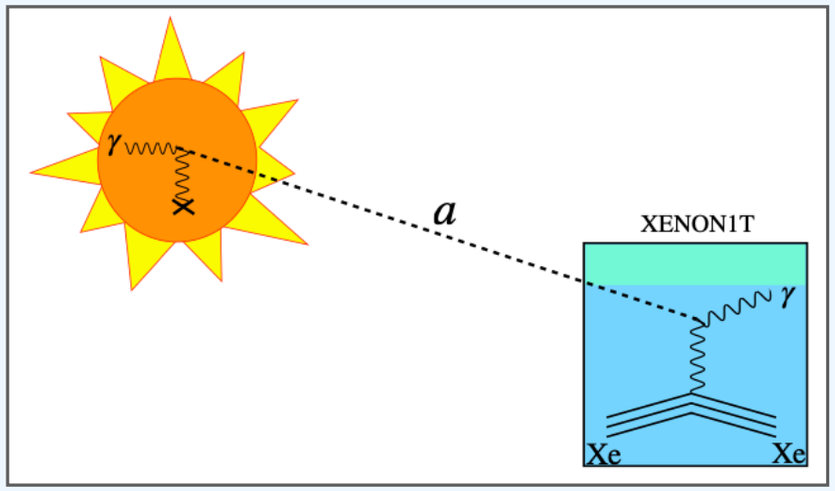
$$g_{ae} < 3.7 \times 10^{-12}$$
$$g_{ae} g_{an}^{eff} < 4.6 \times 10^{-18}$$
$$g_{ae} g_{a\gamma} < 7.6 \times 10^{-22} \text{ GeV}^{-1}$$

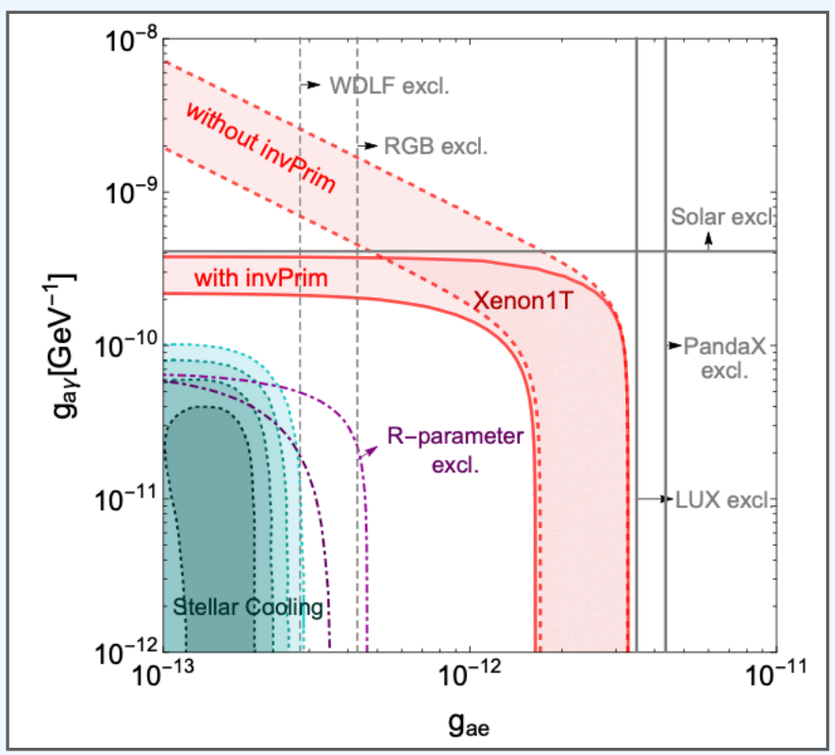
Poor fit for small ABC rate

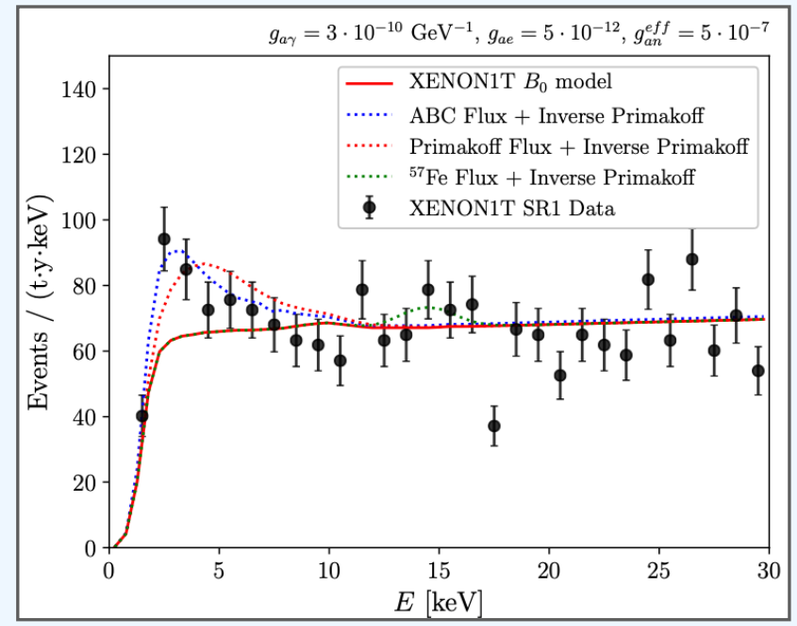


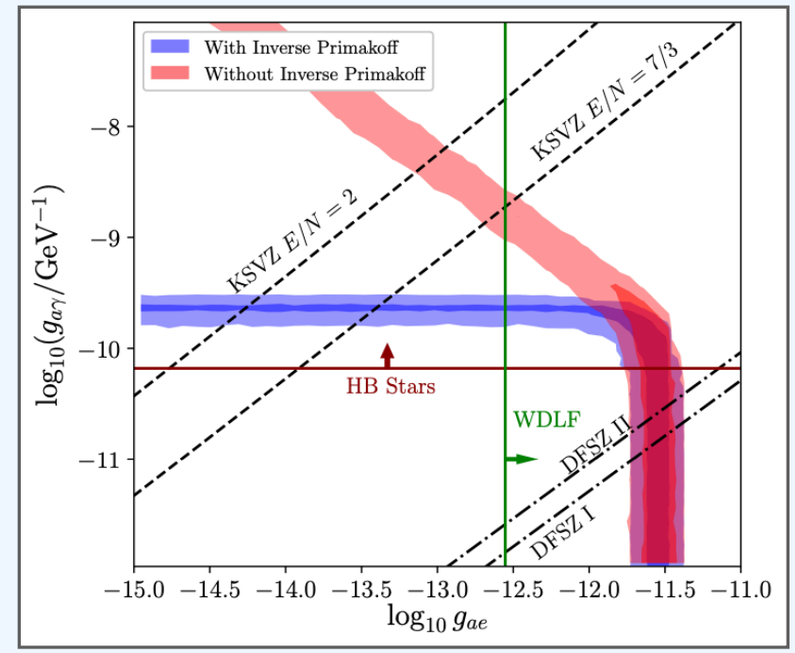
Strong tension with astrophysical constraints from stellar cooling
(arXiv:2003.01100)

Axions via Inverse Primakoff effect









C. Gao, et al.
arXiv:2006.14598

Coherent interaction of axion with field of atom via axion-photon coupling.
Minimising the tension with stellar constraints.

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)

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background PDF

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

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

- Combine likelihoods of the 2 partitions $\mathcal{L} = \mathcal{L}_a \times \mathcal{L}_b$

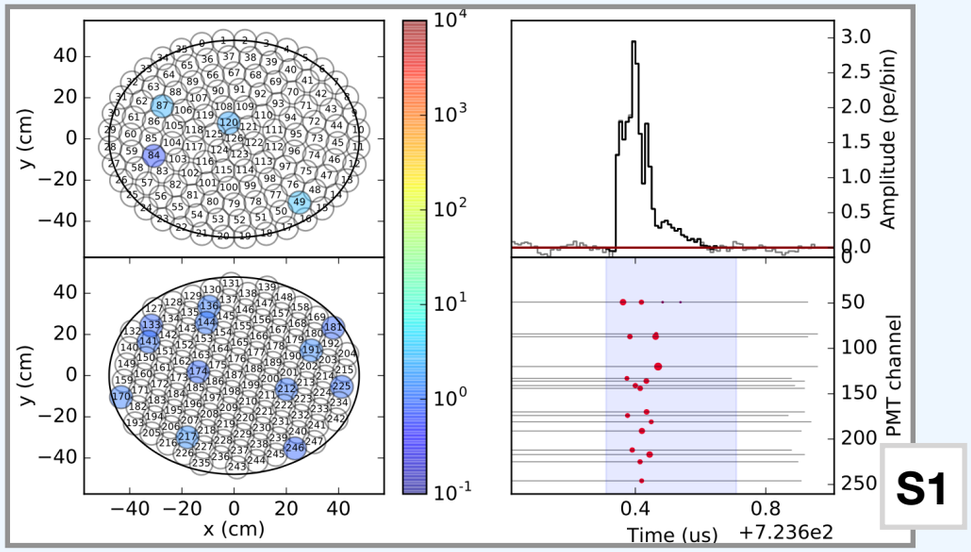
- Test statistic q for inference

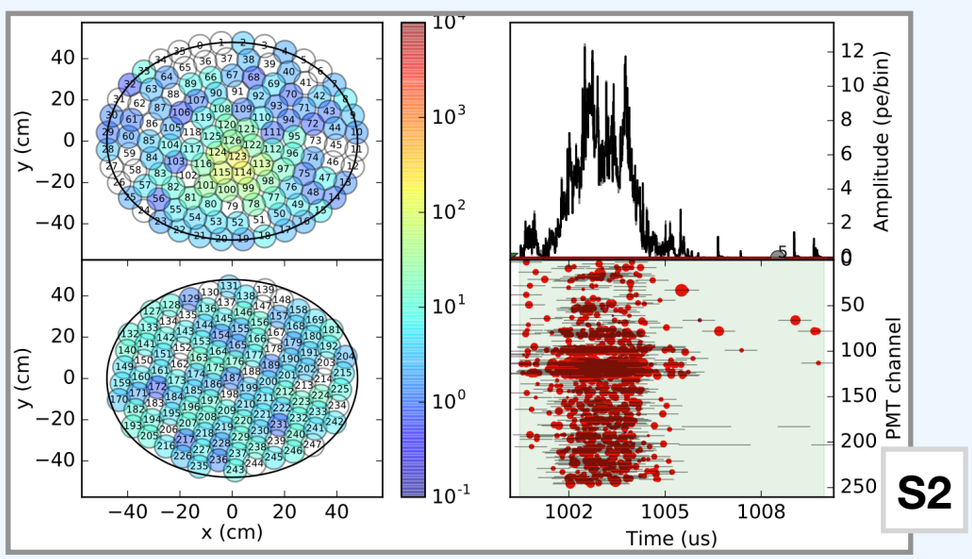
$$q(\mu_s) = -2\ln \frac{\mathcal{L}(\mu_s, \hat{\hat{\boldsymbol{\mu}}}_b, \hat{\hat{\boldsymbol{\theta}}})}{\mathcal{L}(\hat{\mu}_s, \hat{\boldsymbol{\mu}}_b, \hat{\boldsymbol{\theta}})}$$

max. L with specified signal parameter μ_s

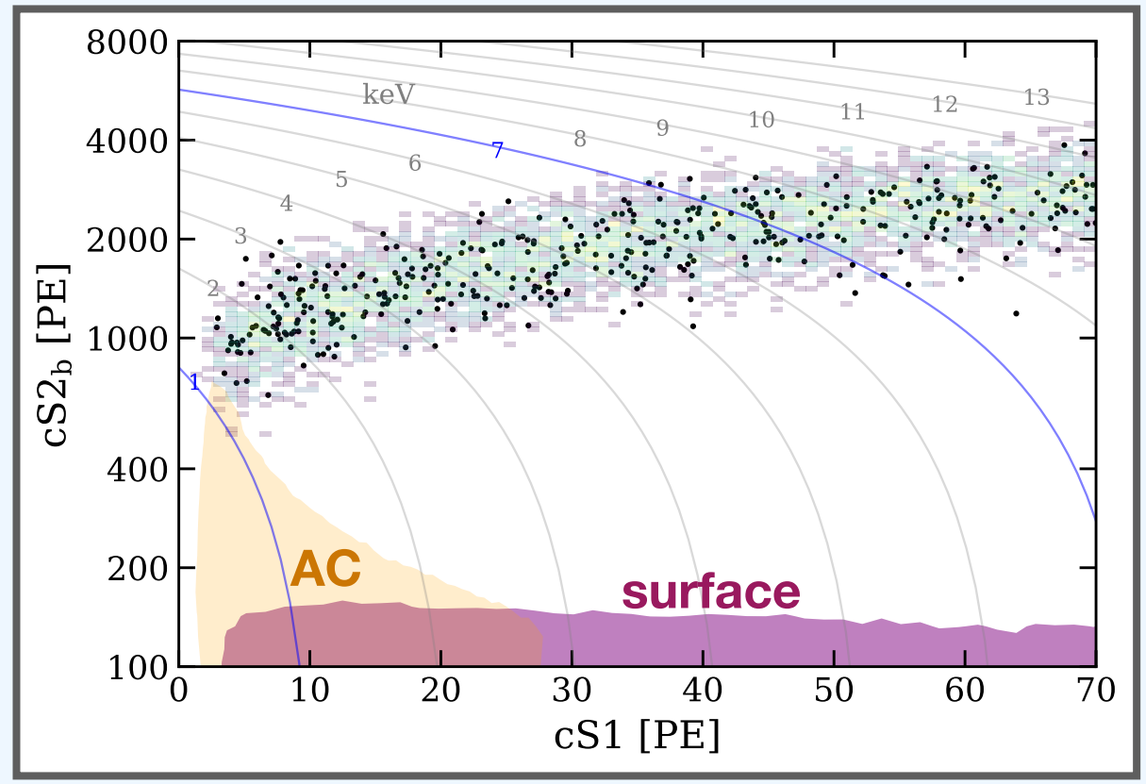
nuisance parameters that maximise L

Event quality and backgrounds





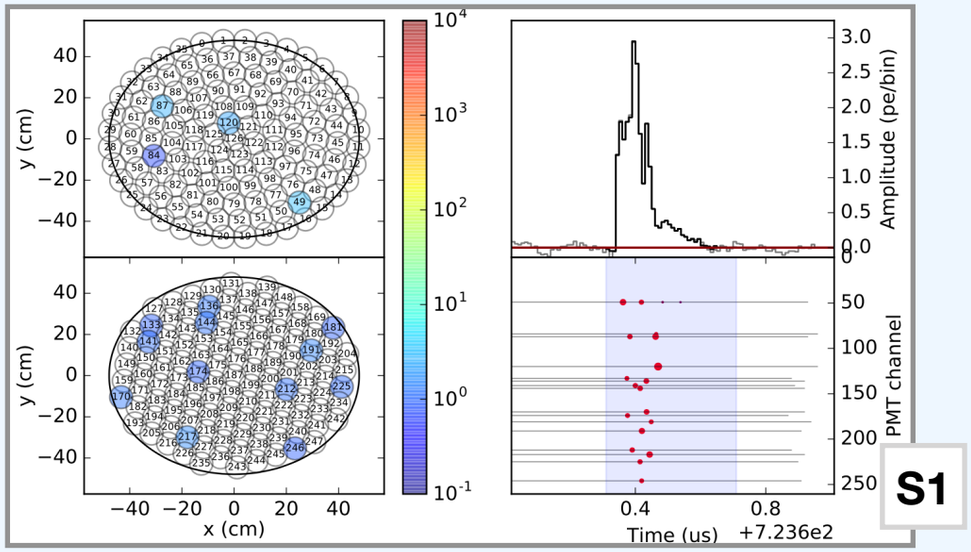
Event classification and waveform inspection: all ok.

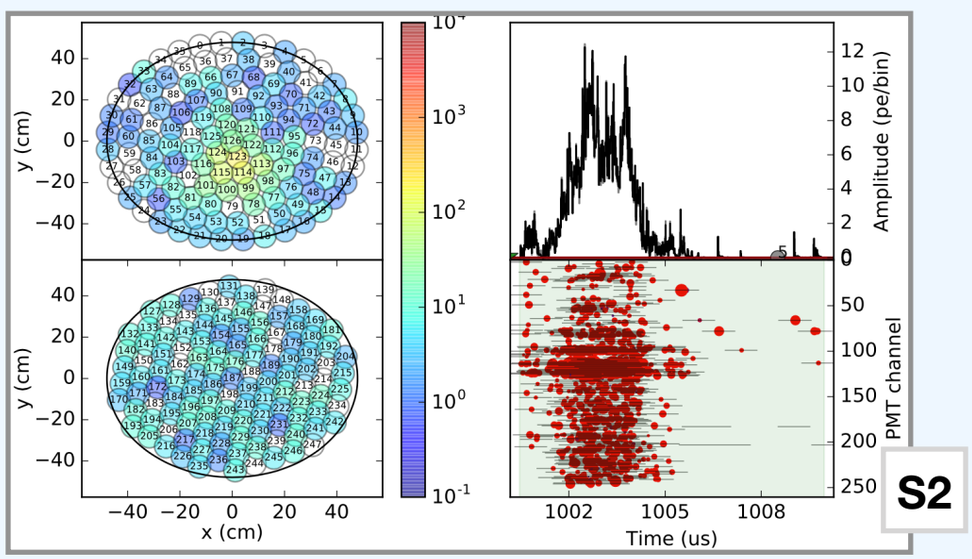


Instrumental backgrounds

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

Event quality and backgrounds





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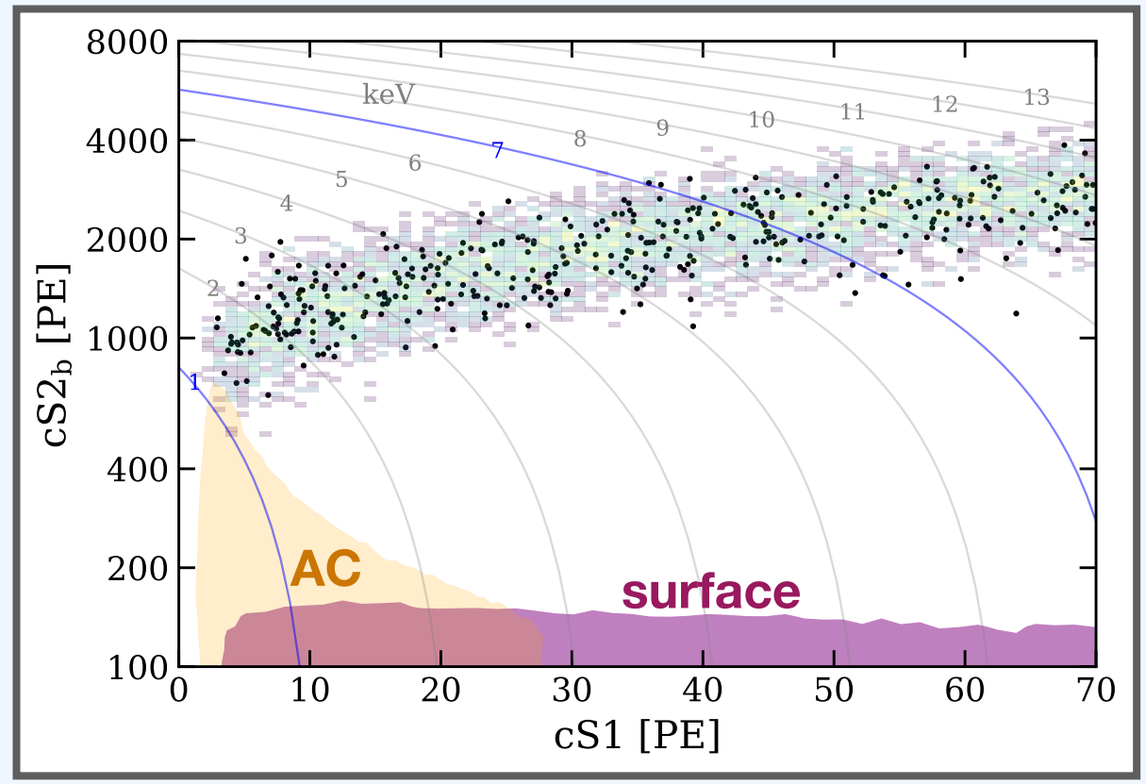

Instrumental backgrounds

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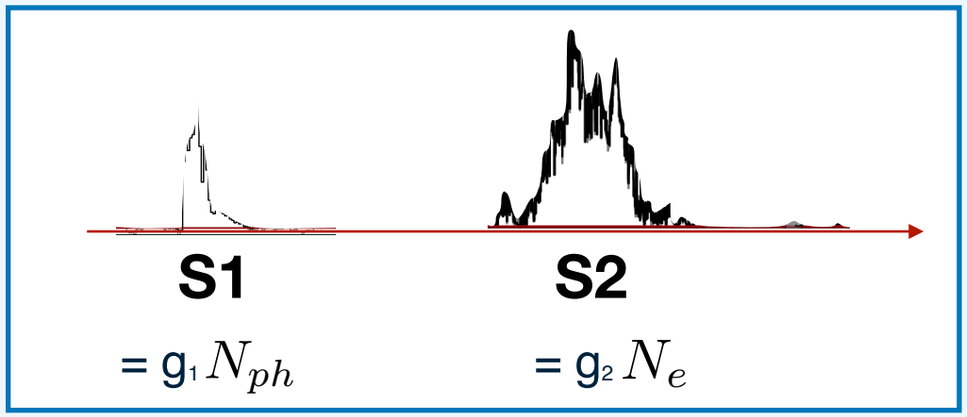
Valid events

Energy Reconstruction

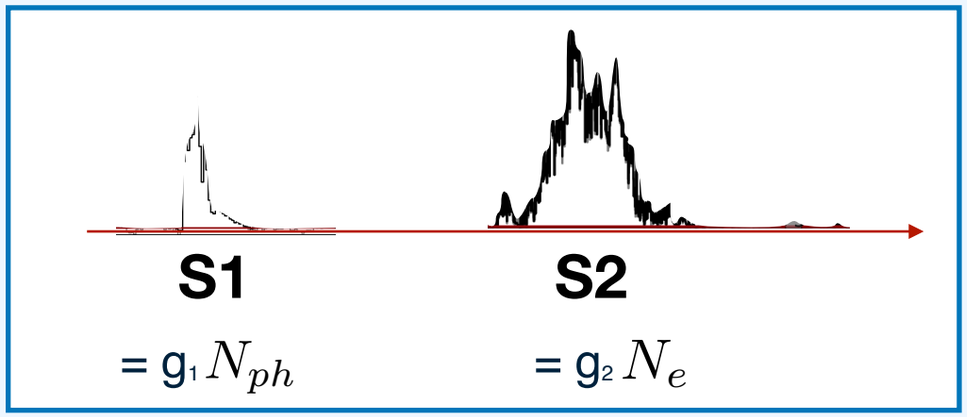


$$E = (N_{ph} + N_e) \cdot W$$

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

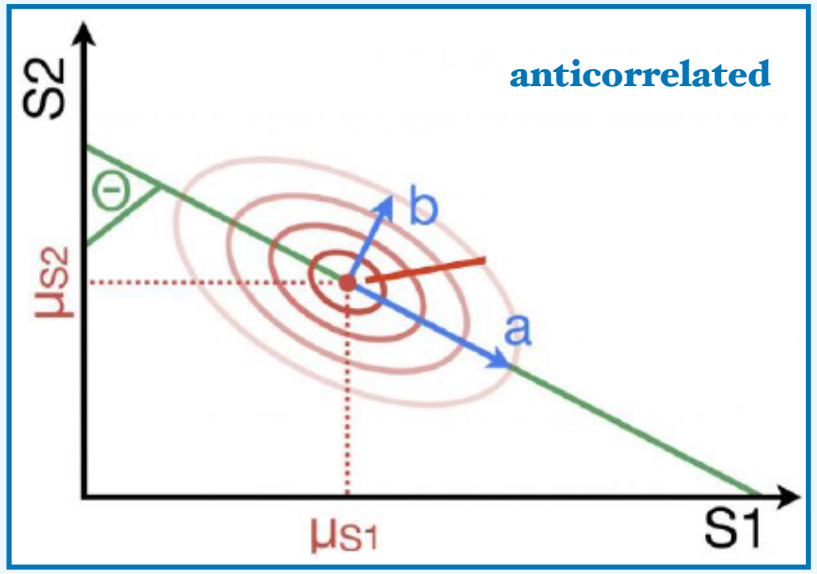
Energy Reconstruction



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

with W = 13.7 eV/quanta for xenon

g1 and **g2**:
detector-specific gain constants;
extract g1/g2 from calibration data



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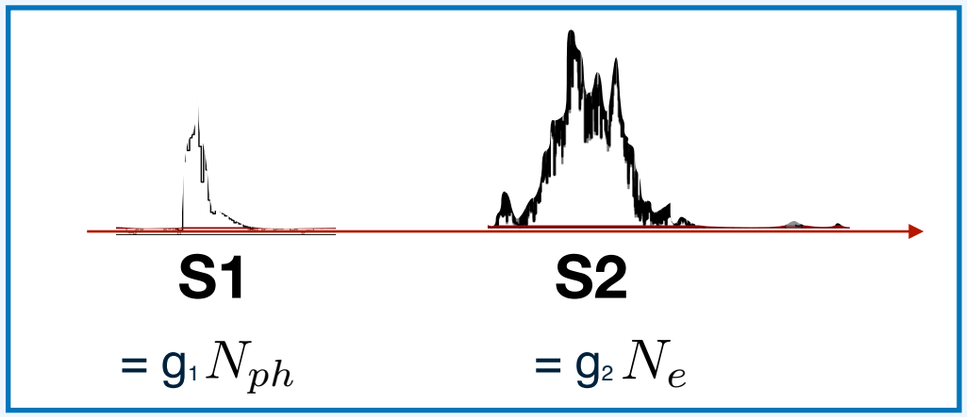

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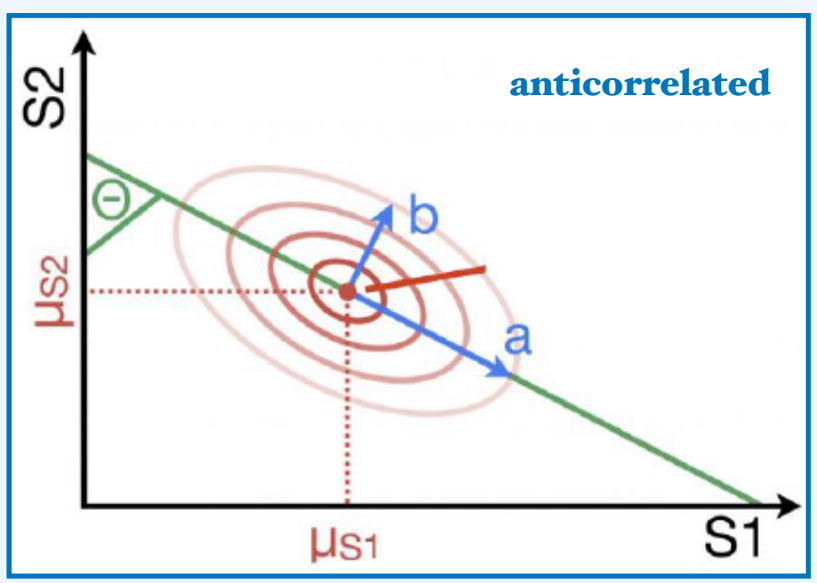

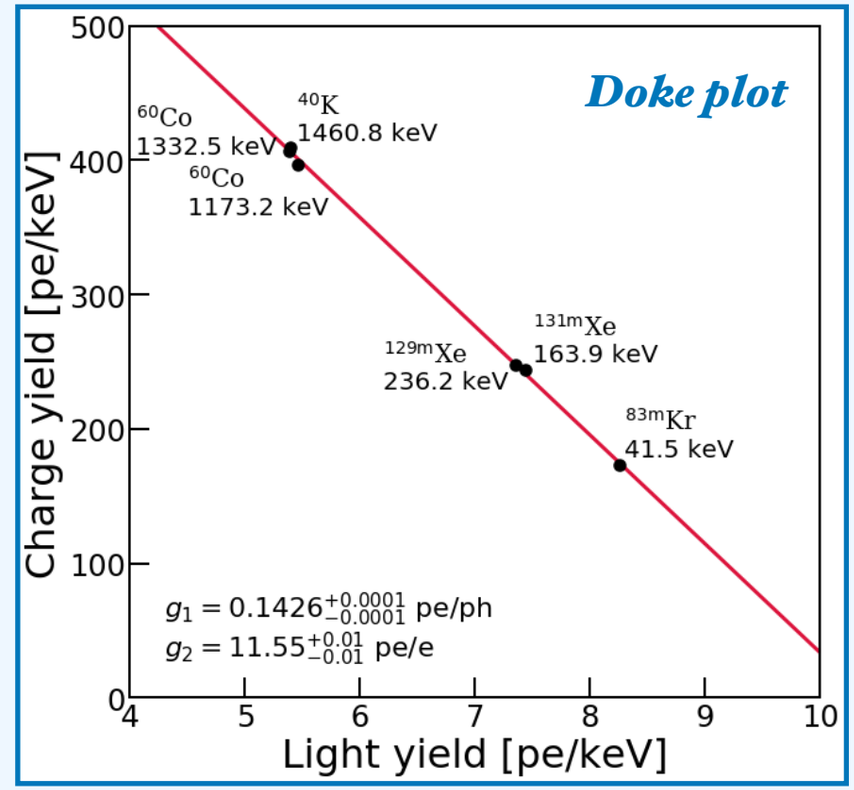

$$\frac{S2}{E} = -\frac{g_2}{g_1}\frac{S1}{E} + \frac{g_2}{W}$$

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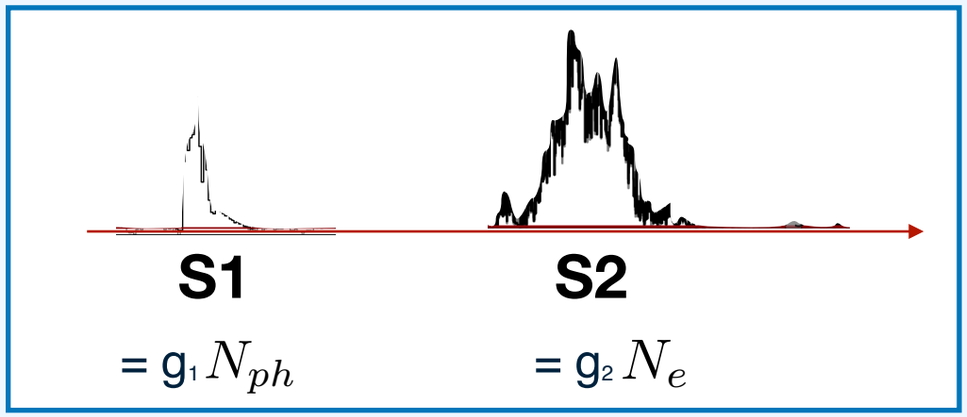

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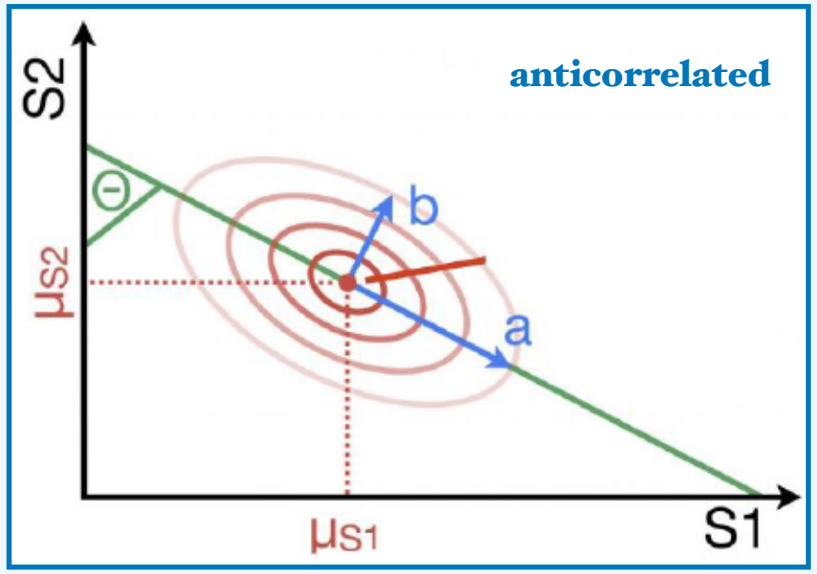
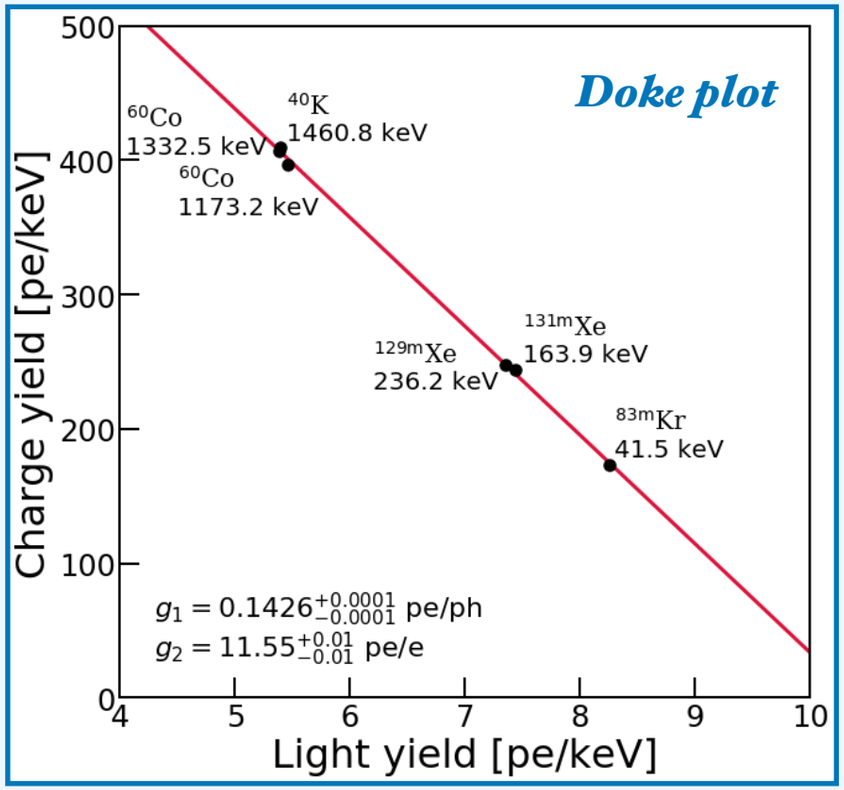




$$\frac{S2}{E} = -\frac{g_2}{g_1}\frac{S1}{E} + \frac{g_2}{W}$$

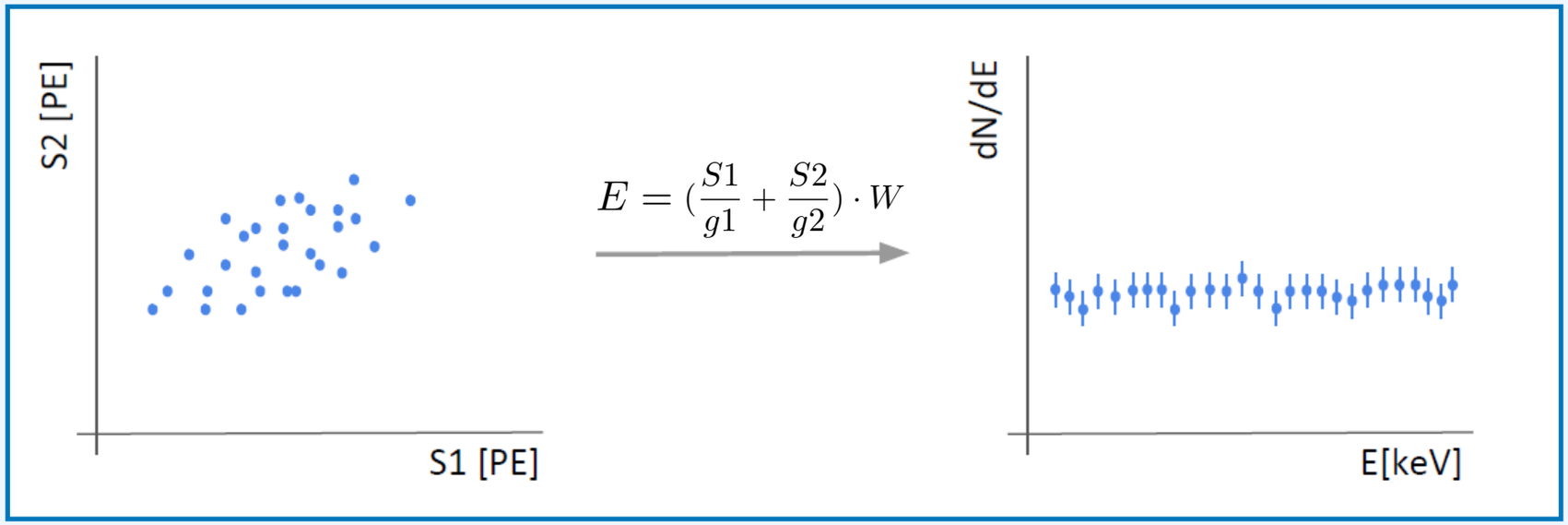
g1 and g2 are used to reconstruct energy of each event

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

Energy Reconstruction

2D analysis

1D analysis



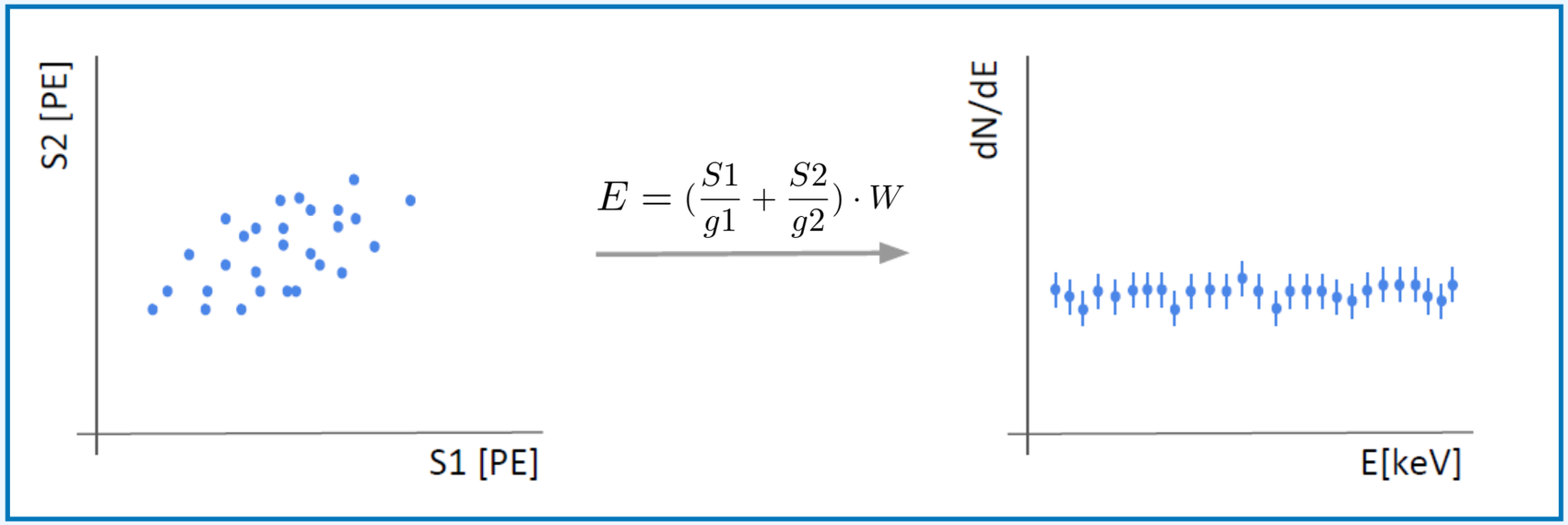
S2/S1 space

Combined Energy Scale

Energy Reconstruction

2D analysis

1D analysis



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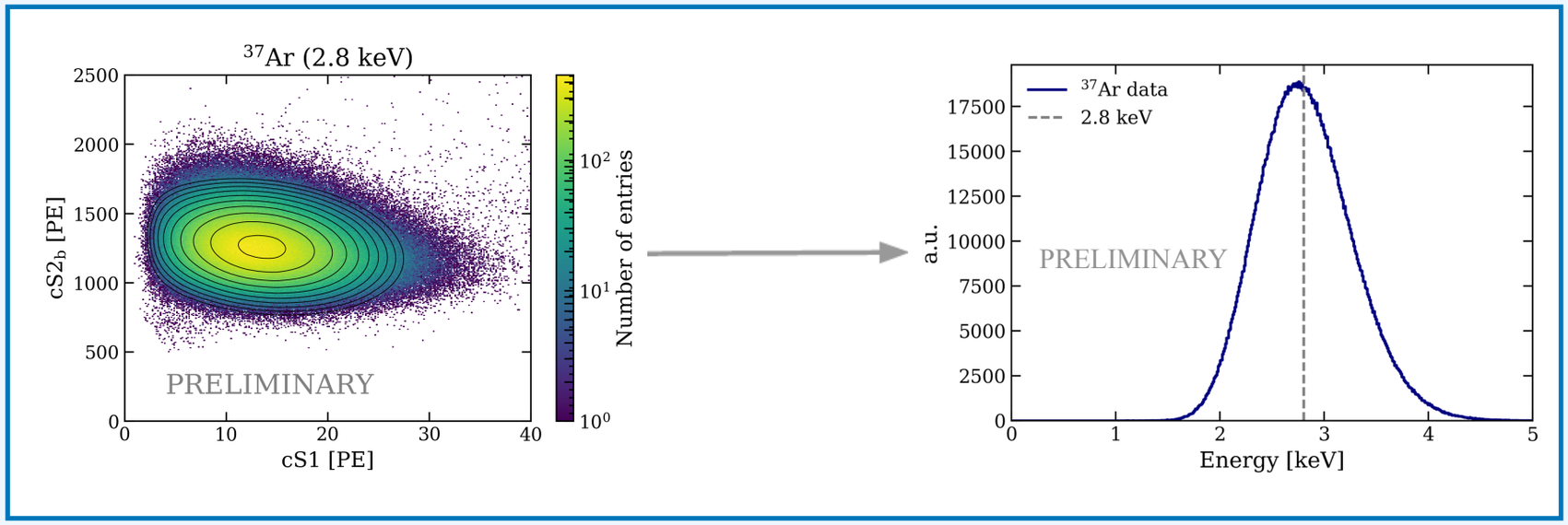
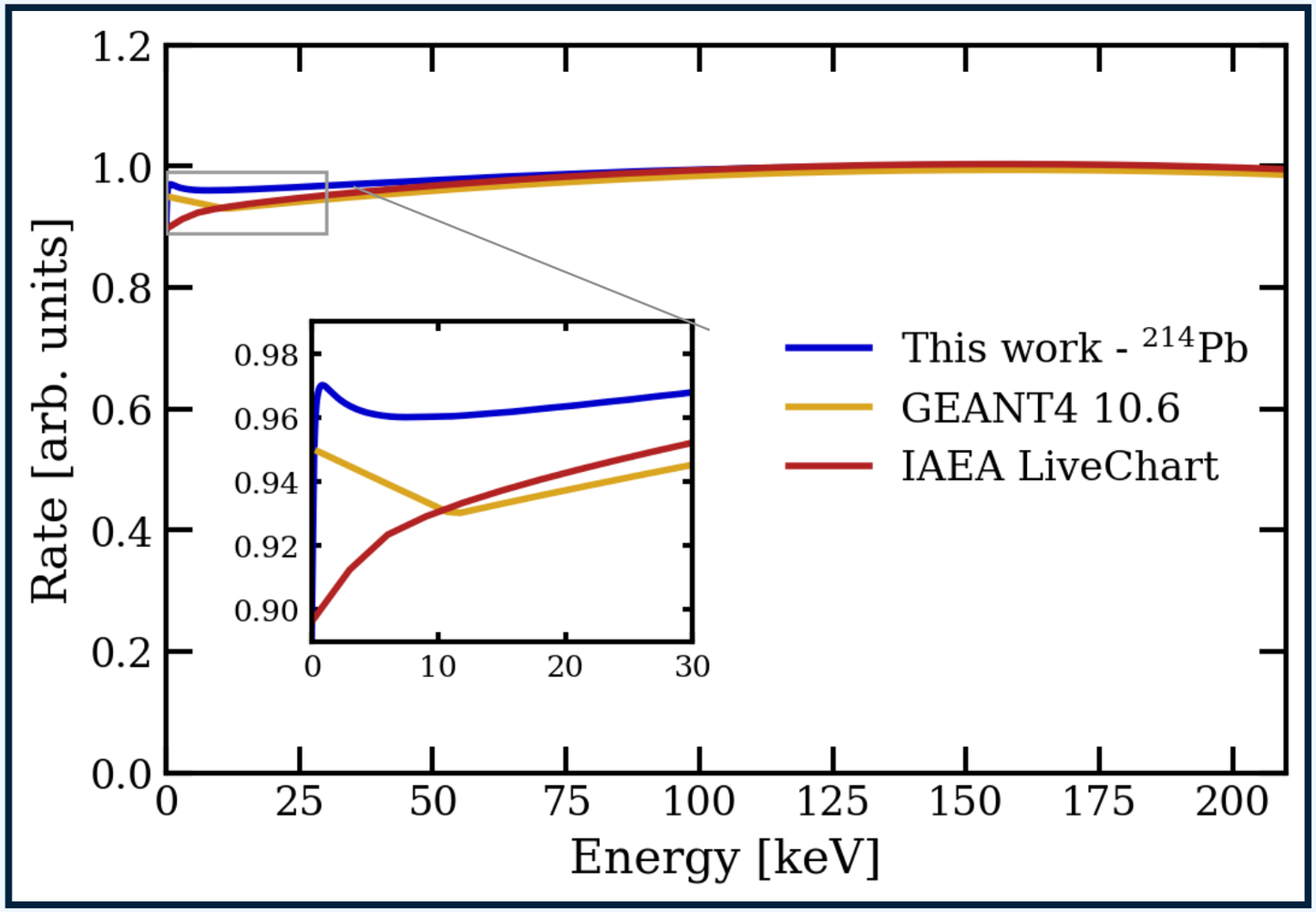


^{214}Pb β-decay spectral model

^{214}Pb dominant background component



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

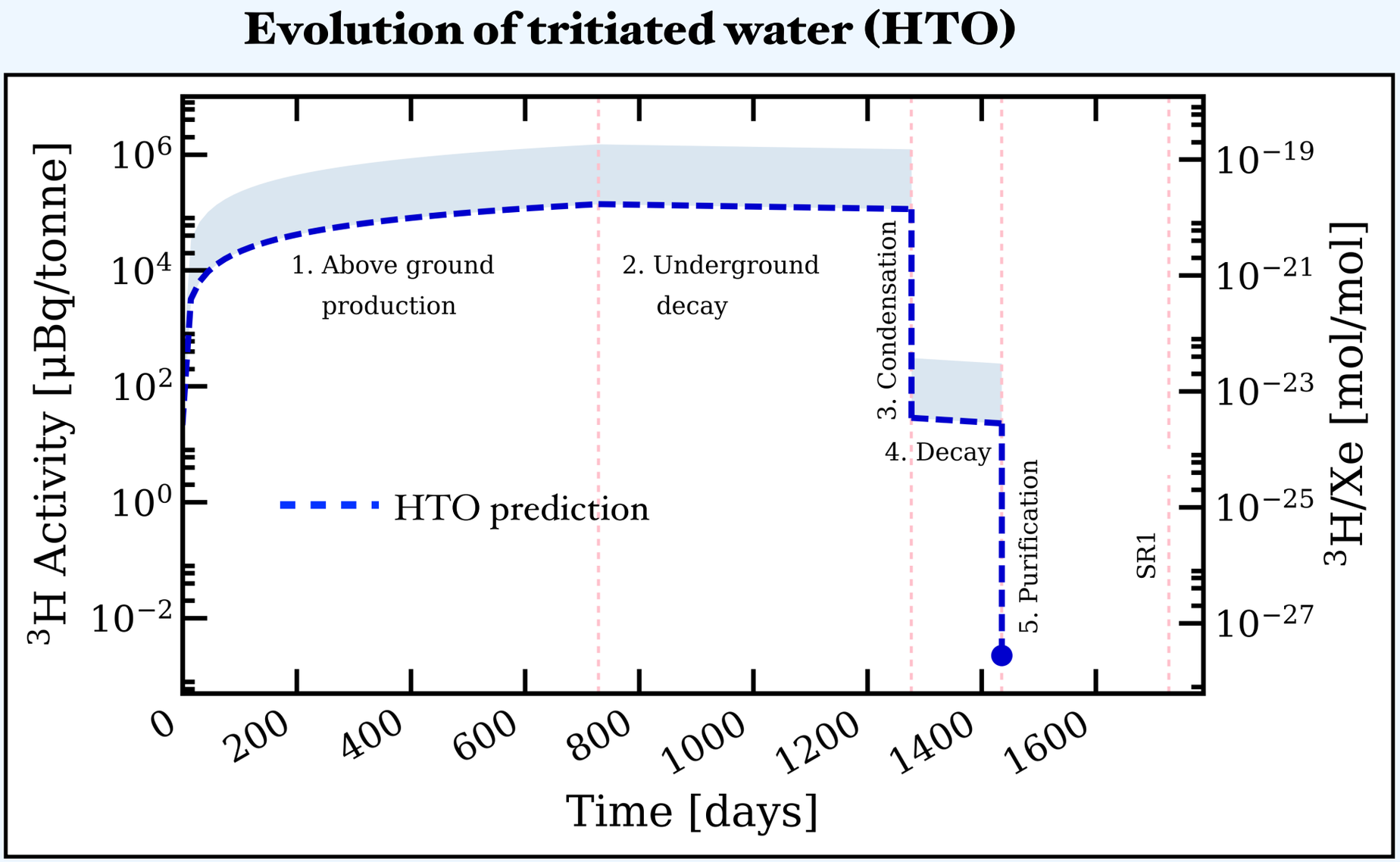
~6% uncertainty on the shape

~50% needed to account for excess

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

Calculated spectra by X. Mougeot

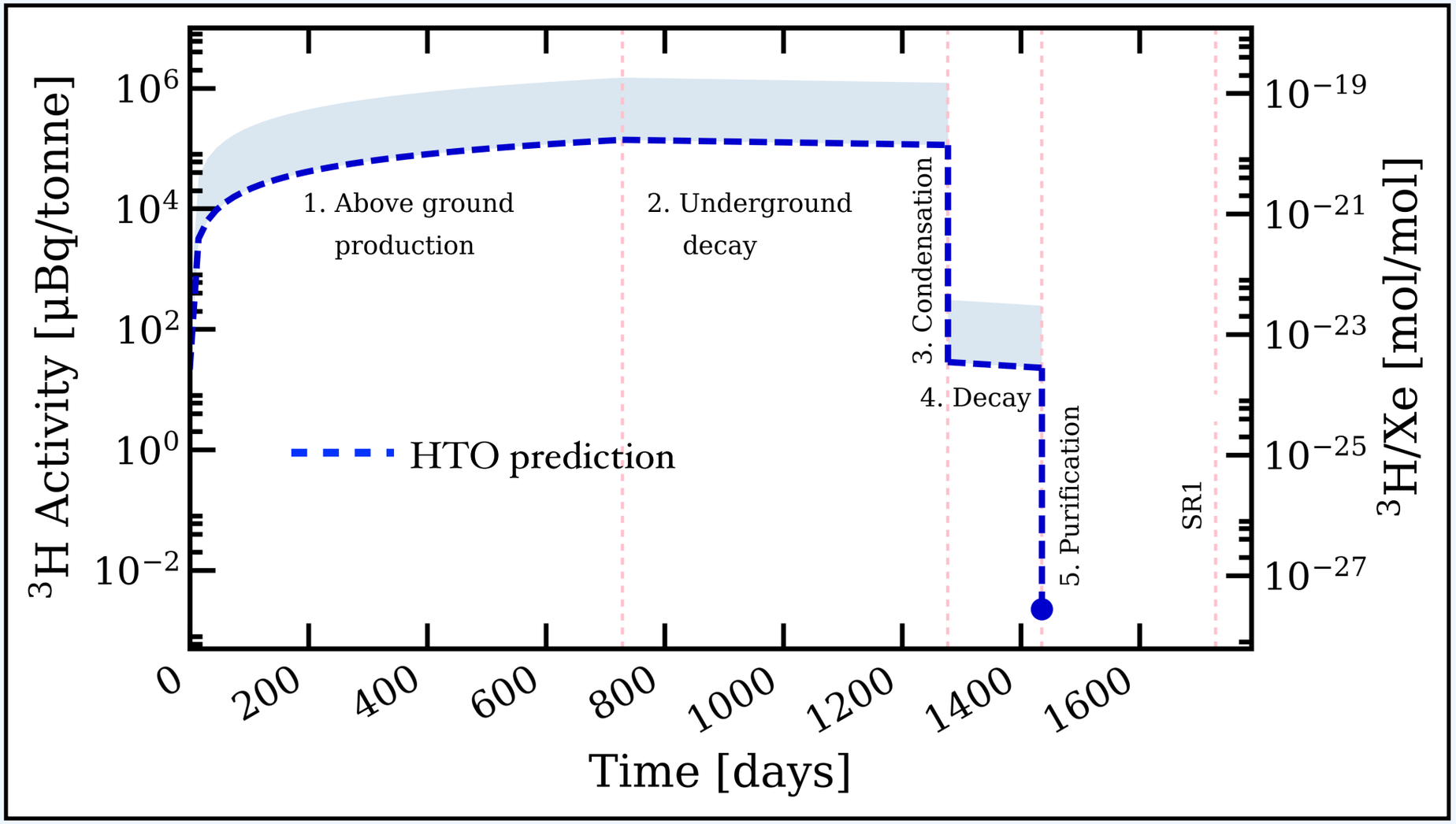
Tritium: activation



Tritium: activation

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

Evolution of tritiated water (HTO)



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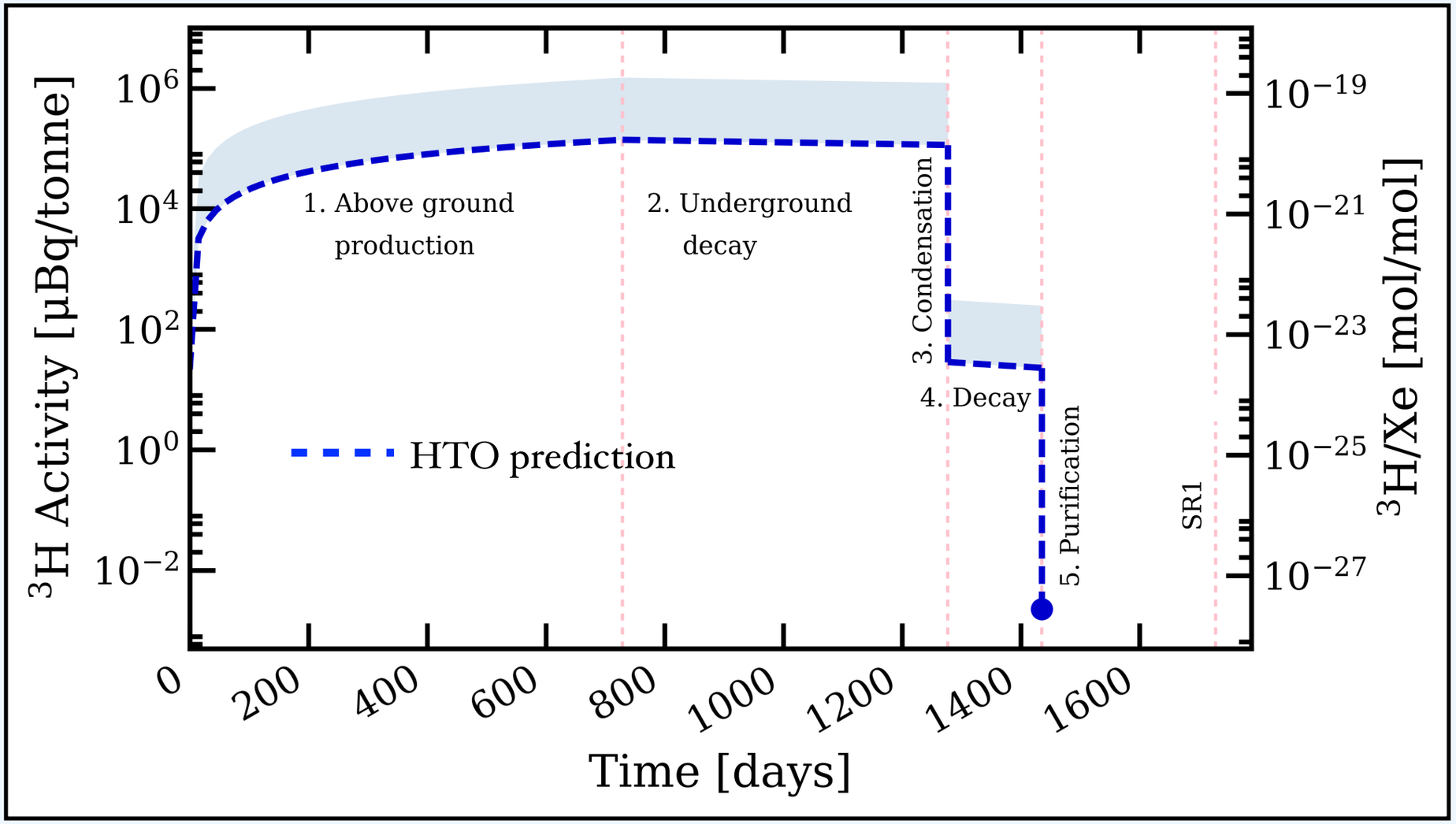

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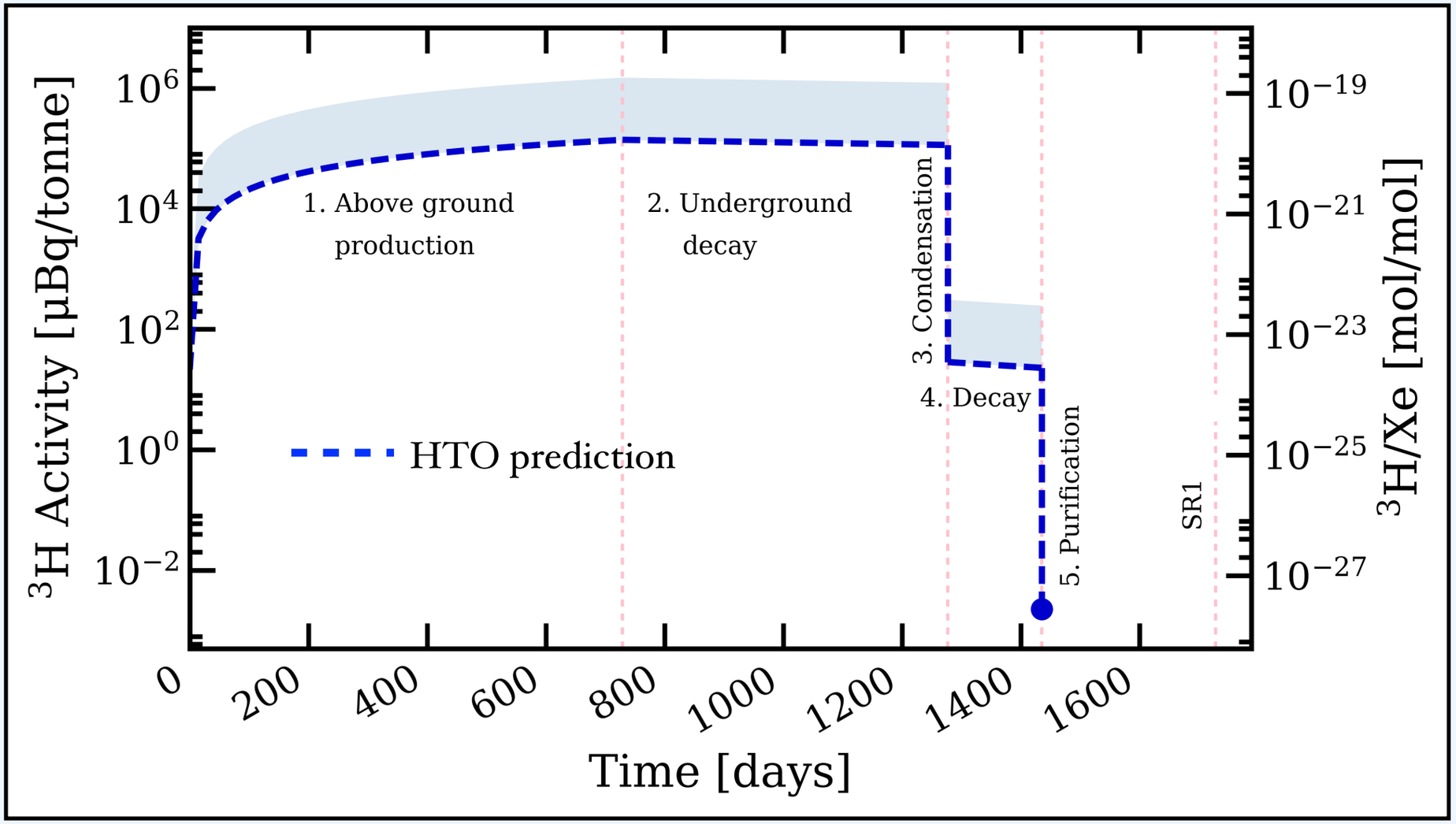

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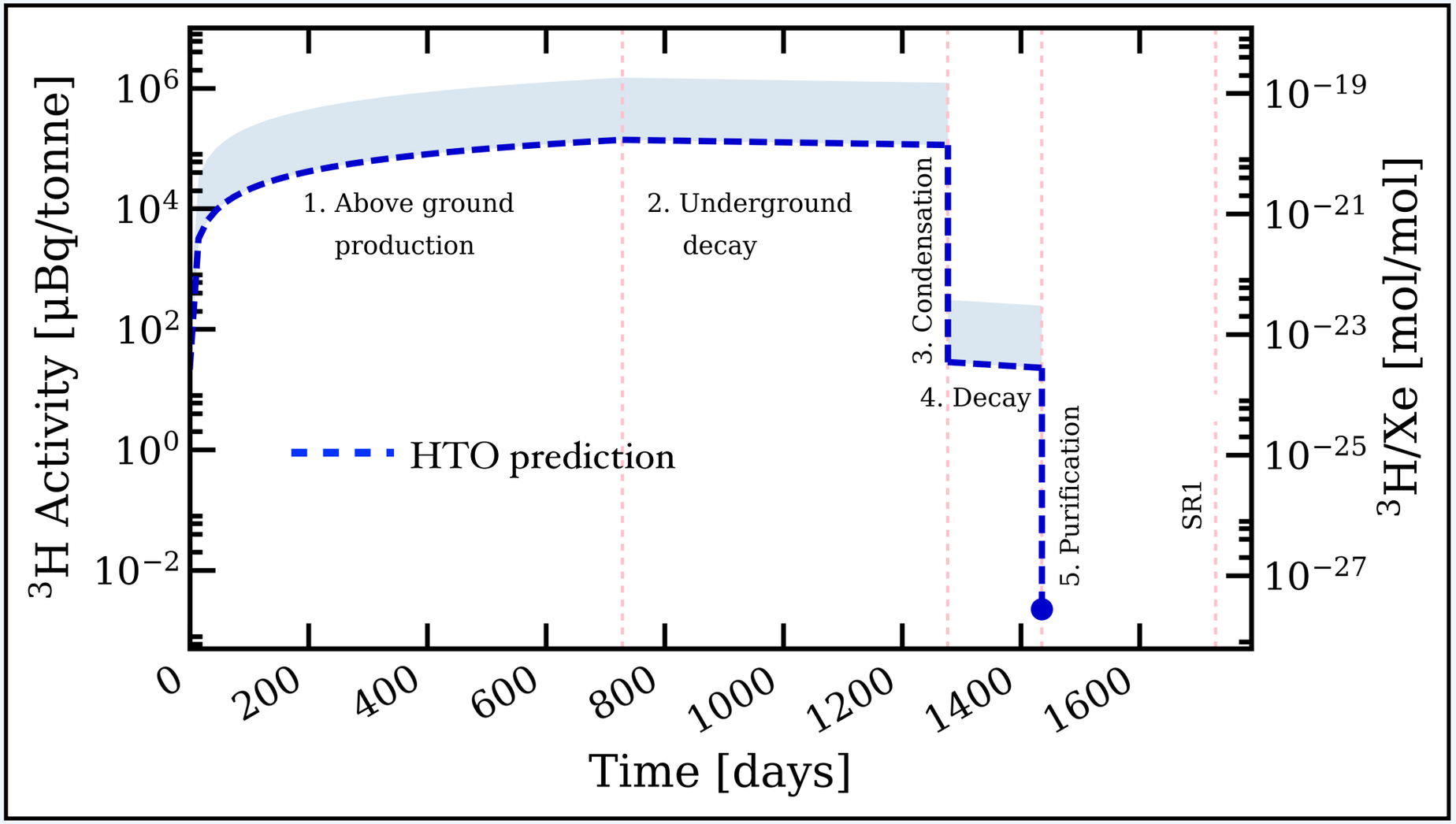

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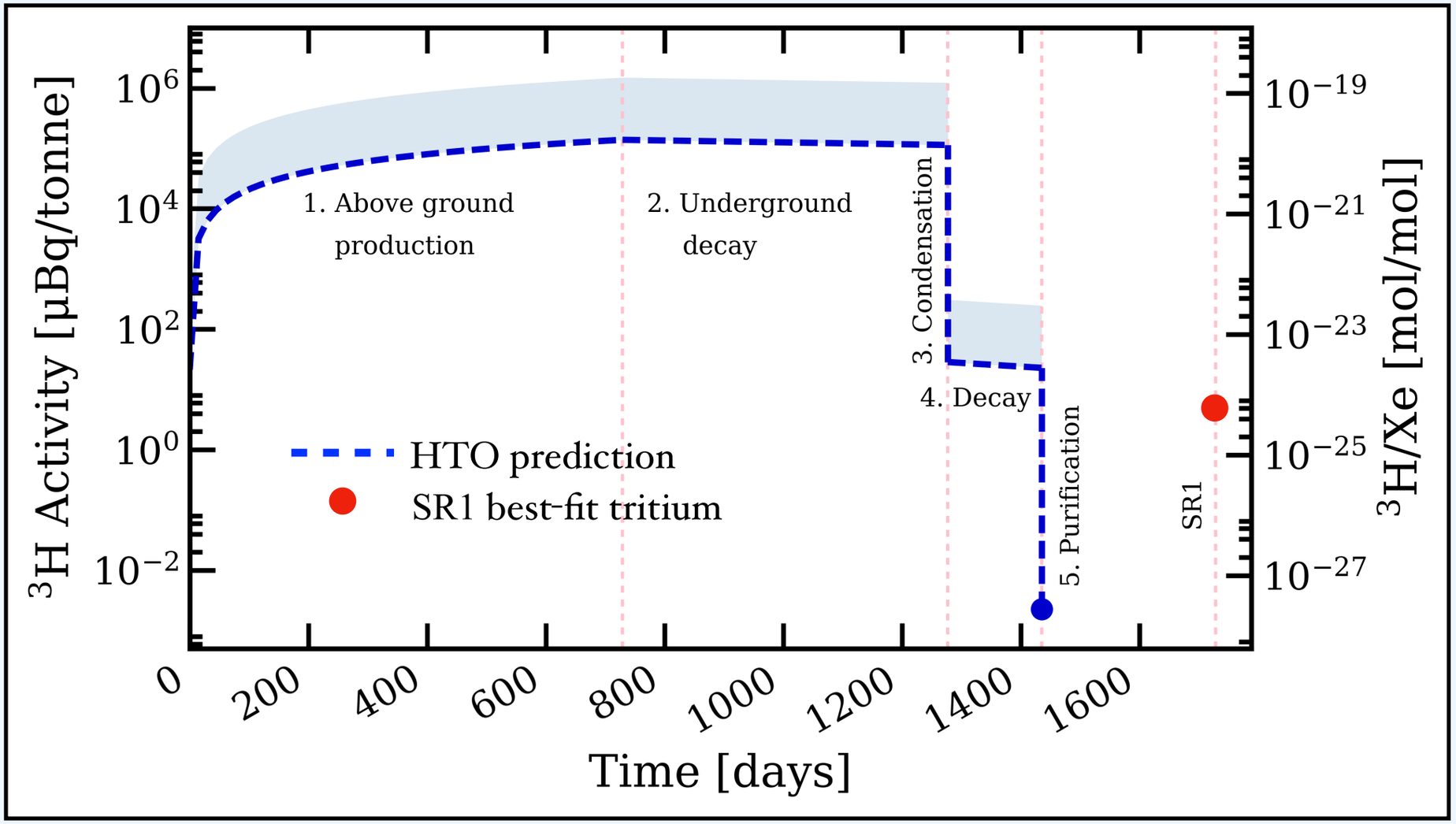

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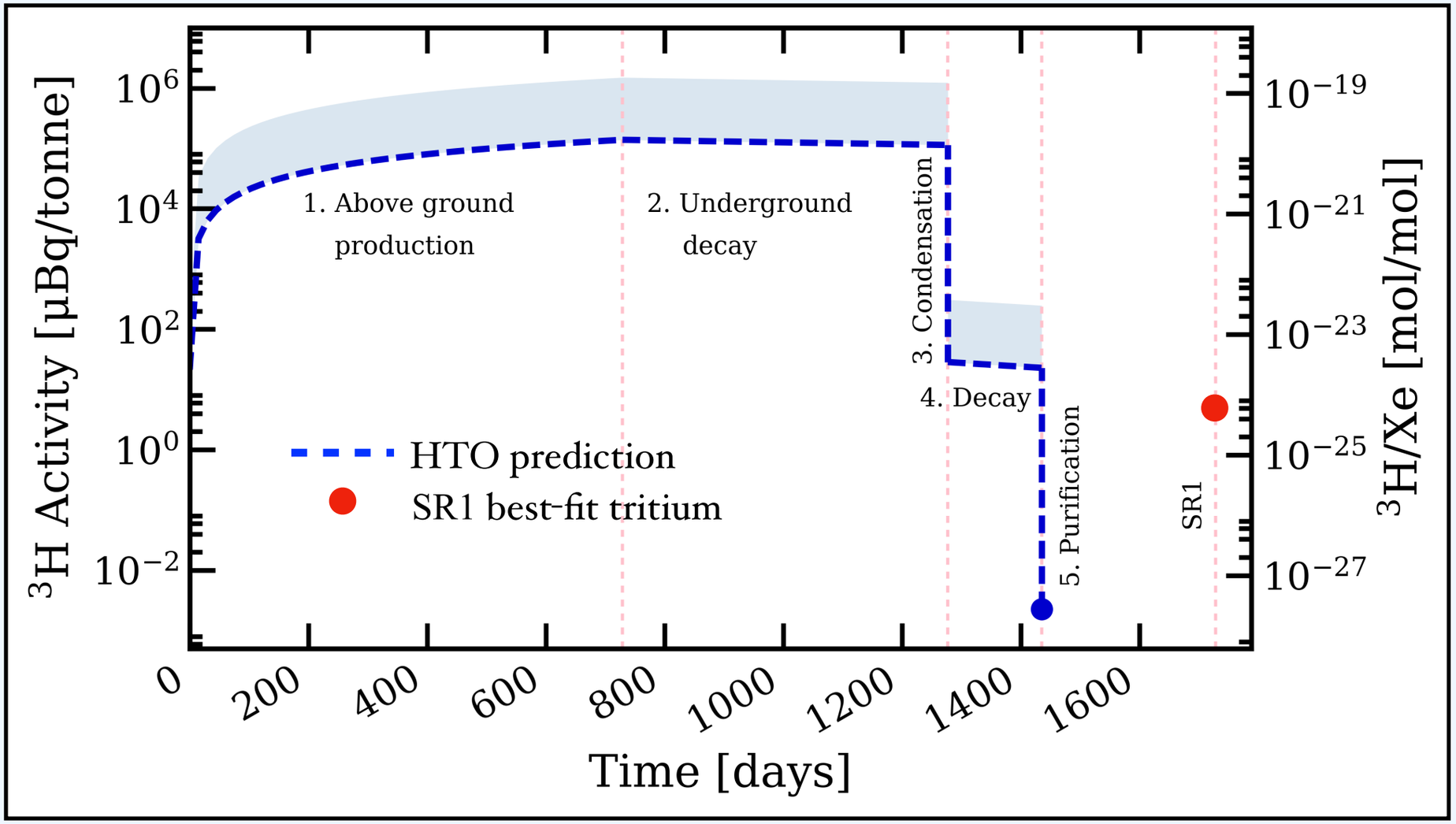

From purification and handling, this component seems unlikely.

Tritium: emanation

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

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

*Hydrology measurements from IAEA nuclear database

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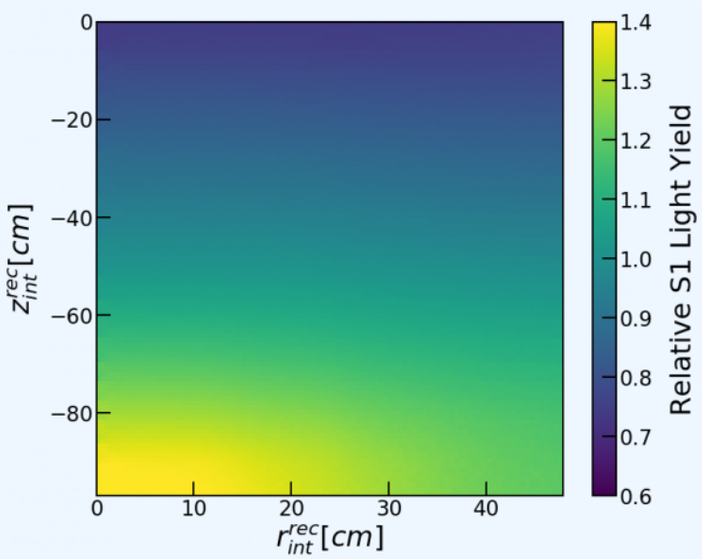

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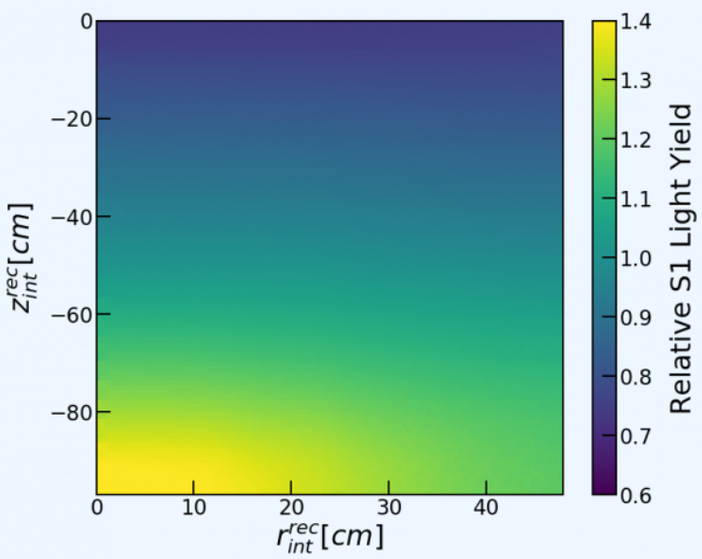

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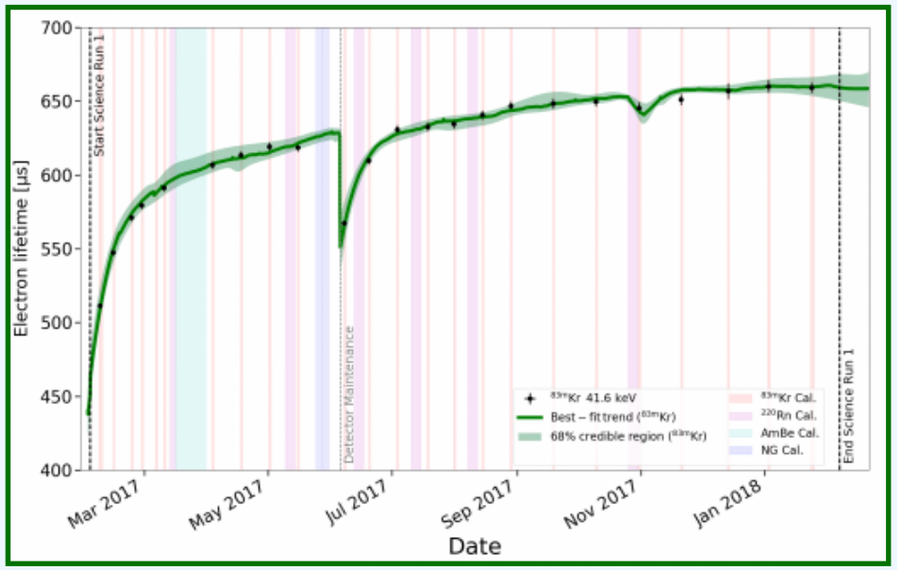

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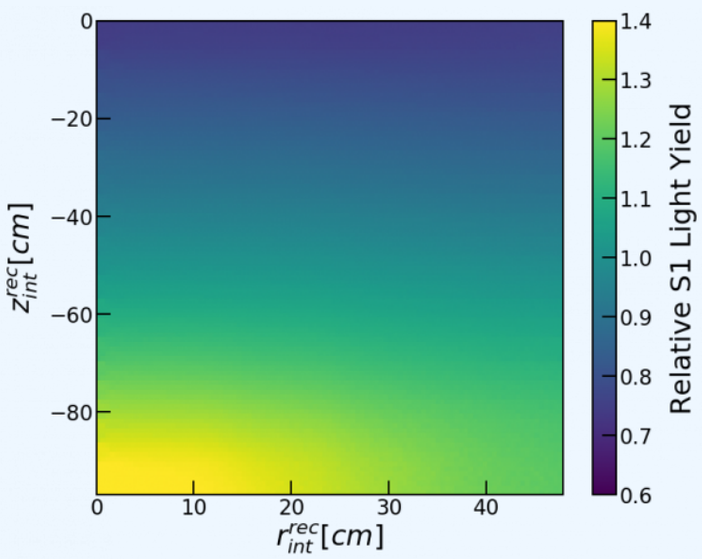

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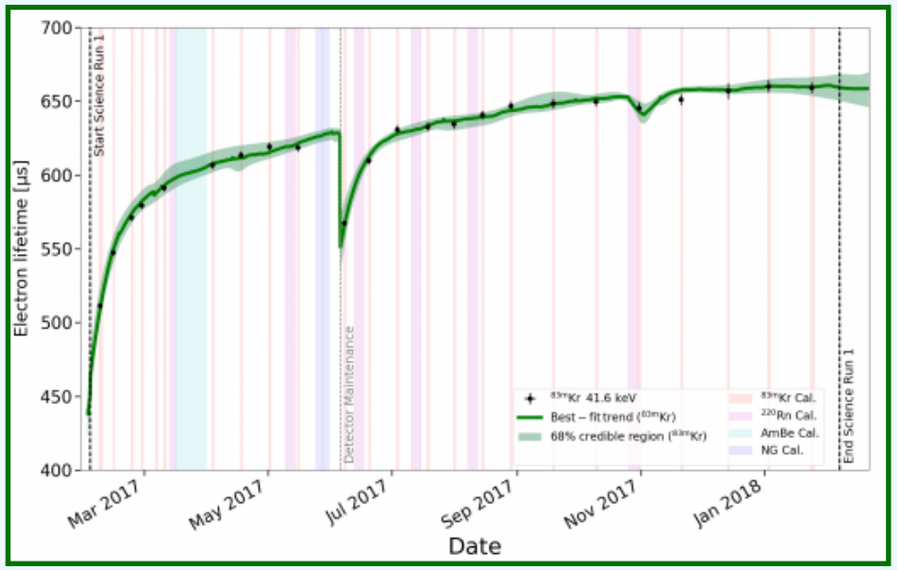

HTO, HT emanation unlikely based on **LXe purity.**

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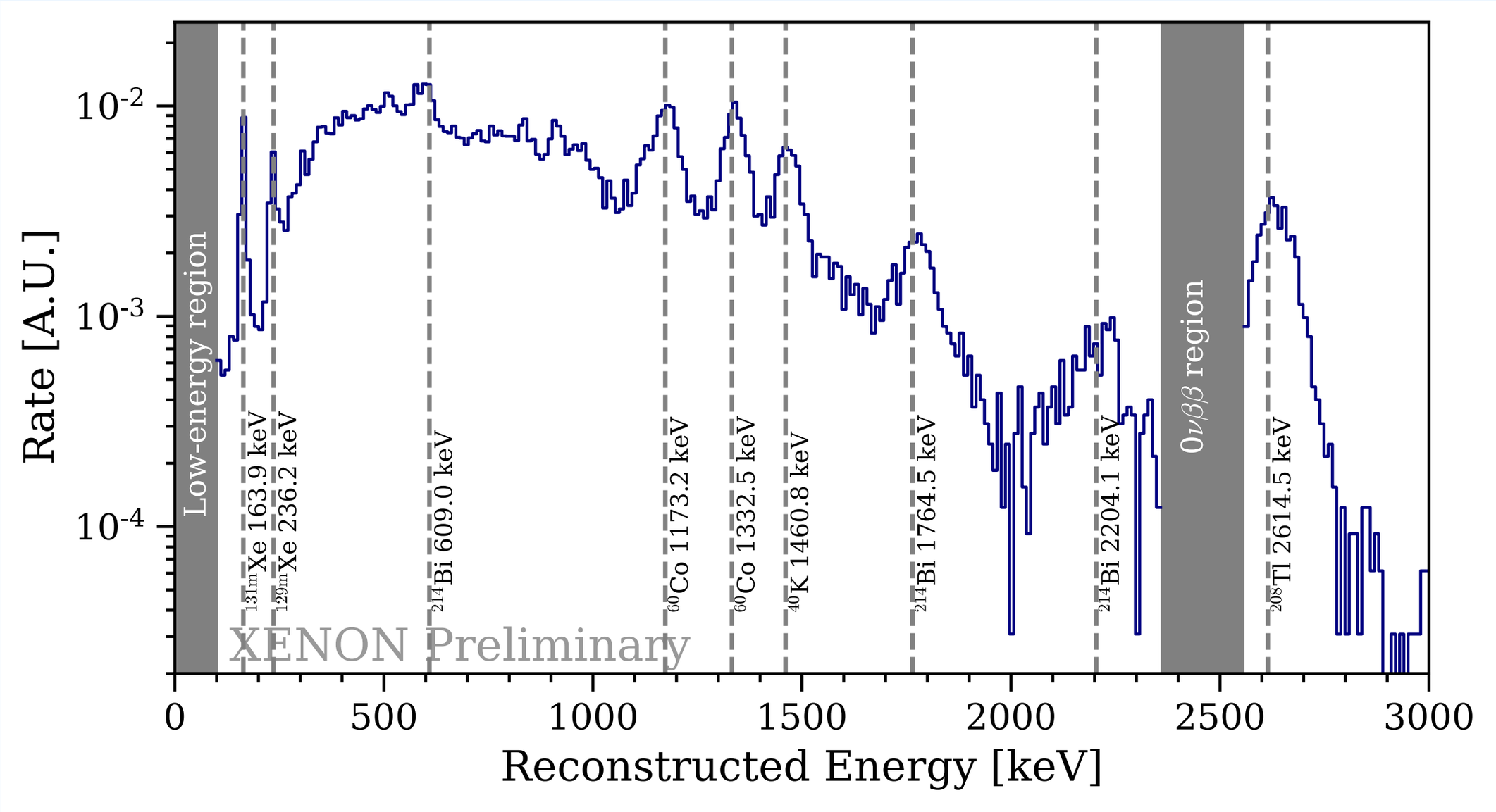
XENONnT



XENONnT measured ER spectrum