Istituto Nazionale di Fisica Nucleare

Observation of excess electronic recoil events in XENON1T

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On behalf of the XENON Collaboration and X. Mougeot

Online Seminar "@" LNF and Roma1

16th July 2020

Xe XENON Dark Matter Project

INFN Istituto Nazionale di Fisica Nucleare

~ 160 scientists

26 institutions

11 countries

XENON1T at LNGS

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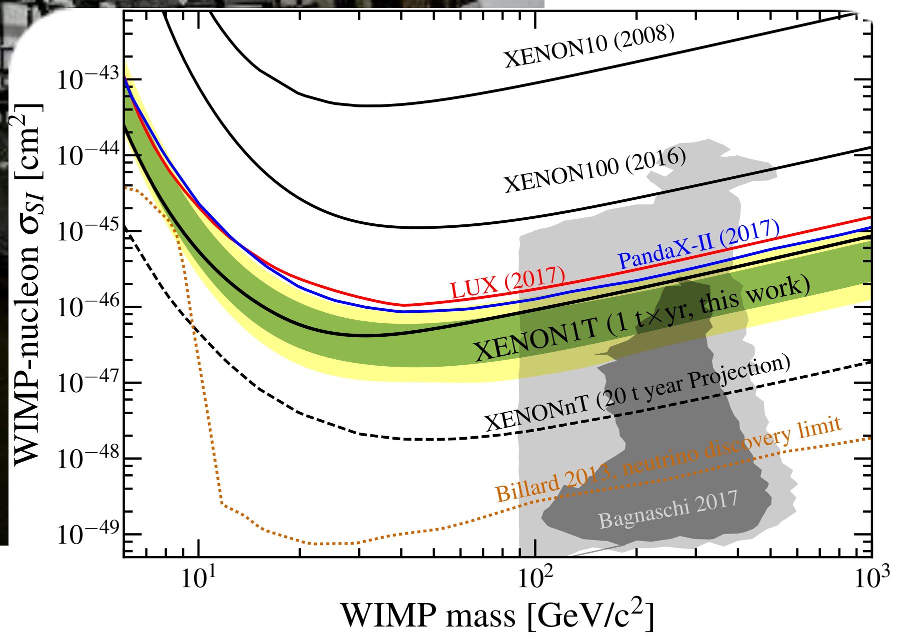
- Located at Laboratori Nazionali del Gran Sasso, IT
- 1500 m rock overburden (3600 m.w.e.)
- Operated 2016-2018

- Active water Cherenkov muon veto
- Removal of ^{85}Kr
- Continuous Xe purification

EPJC (2017) 77:881
EPJC (2017) 77:275
EPJC (2017) 77:890
JINST 9, P11006 (2014)

PRL 121, 111302 (2018)
PRL 122, 071301 (2019)
PRL 122, 141301 (2019)



- Dual-phase time projection chamber
- ~ 1 m diameter and drift
- 2 t LXe active (3.2 t total)
- 248 3'' PMTs
- Radiopure and screened materials

- Limits on numerous interactions and DM candidates
- Ongoing searches for 0νββ and more

Dual-phase time projection chamber

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Detector with:

- Low background
- Low threshold
- Large exposure (mass, livetime)

Combination of S1 and S2 signals allow:

- Position reconstruction
- Energy reconstruction
- ER/NR discrimination

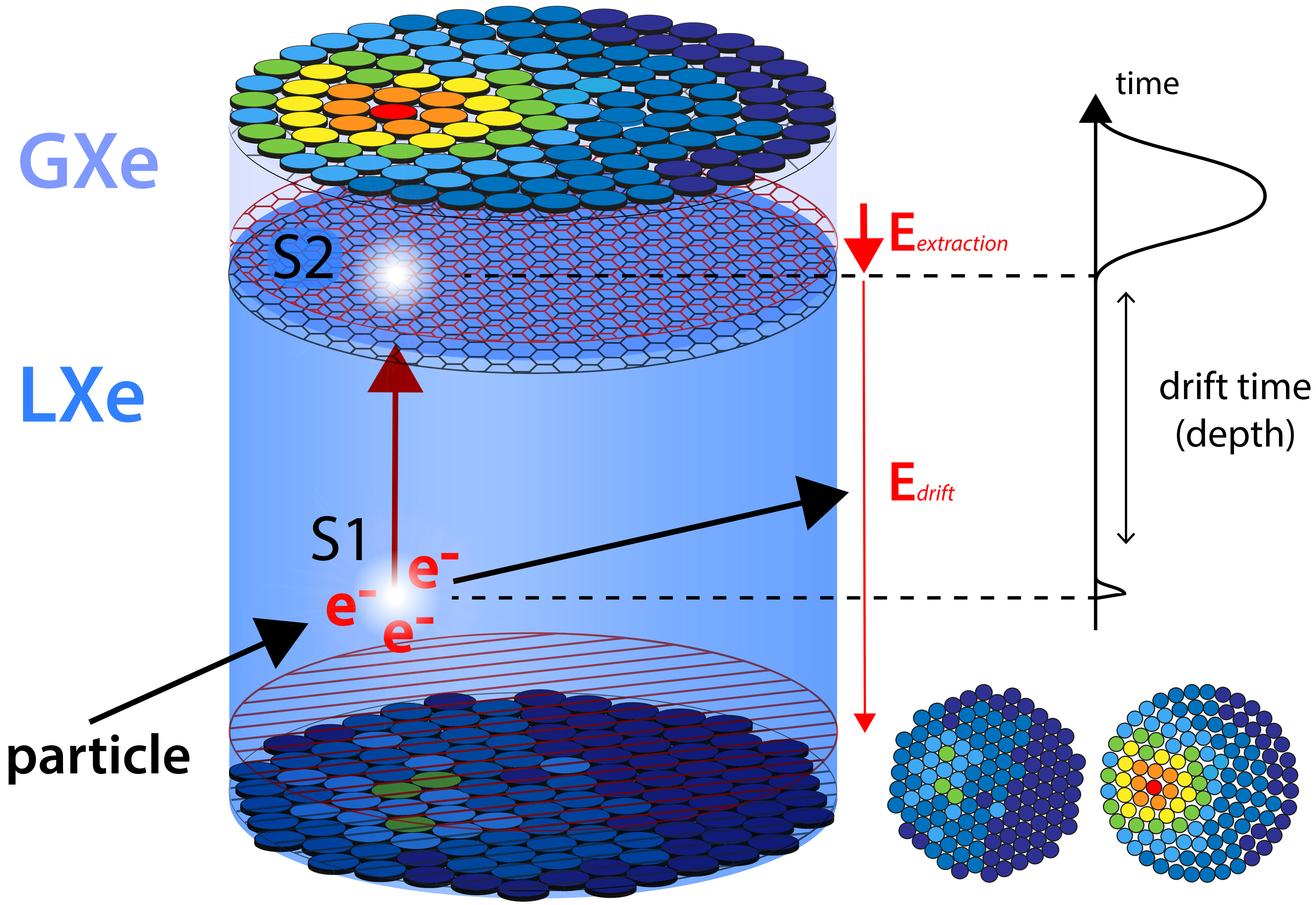

Image credit: Lutz Althüser

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Detector with:

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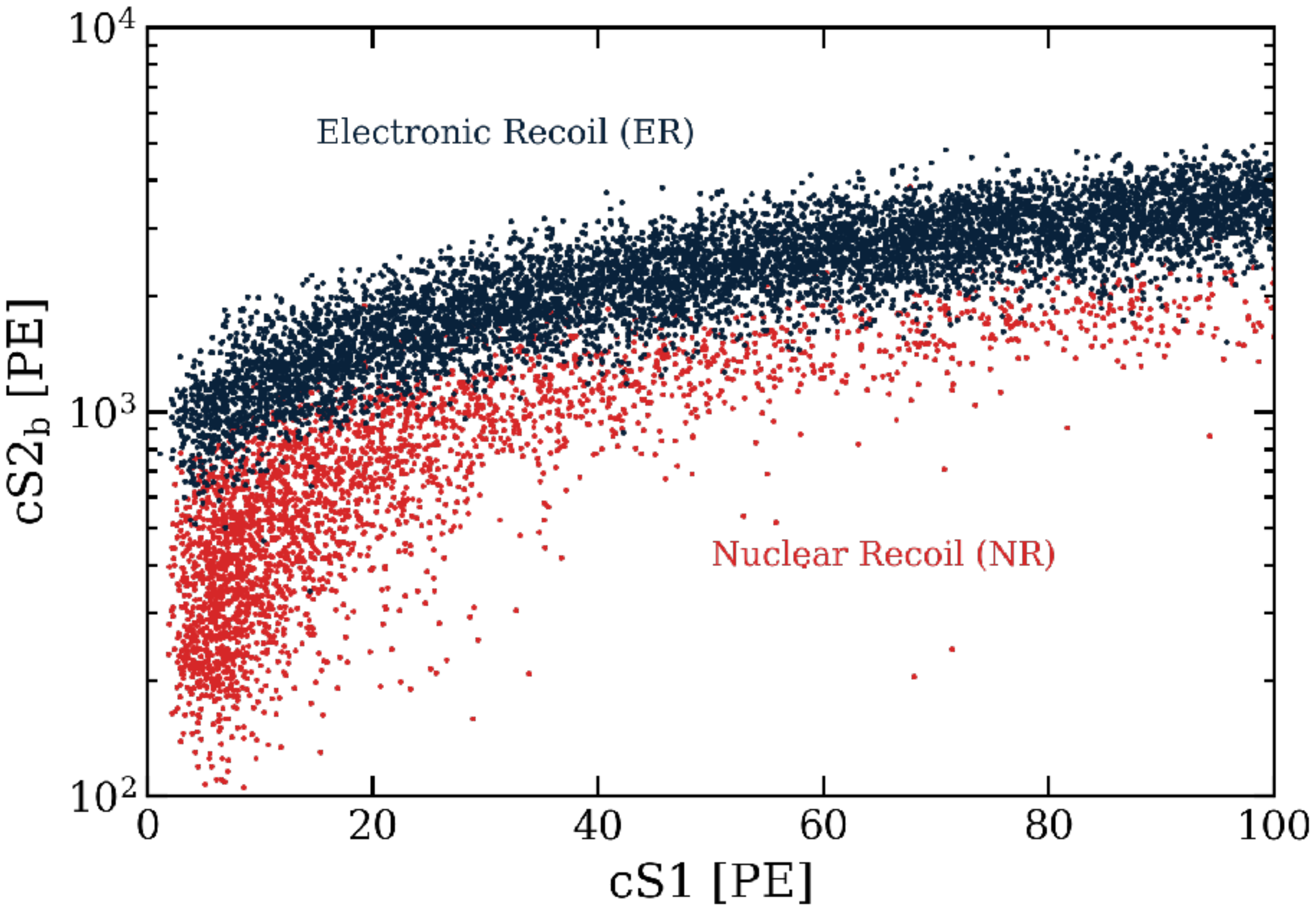

Signal and background discrimination

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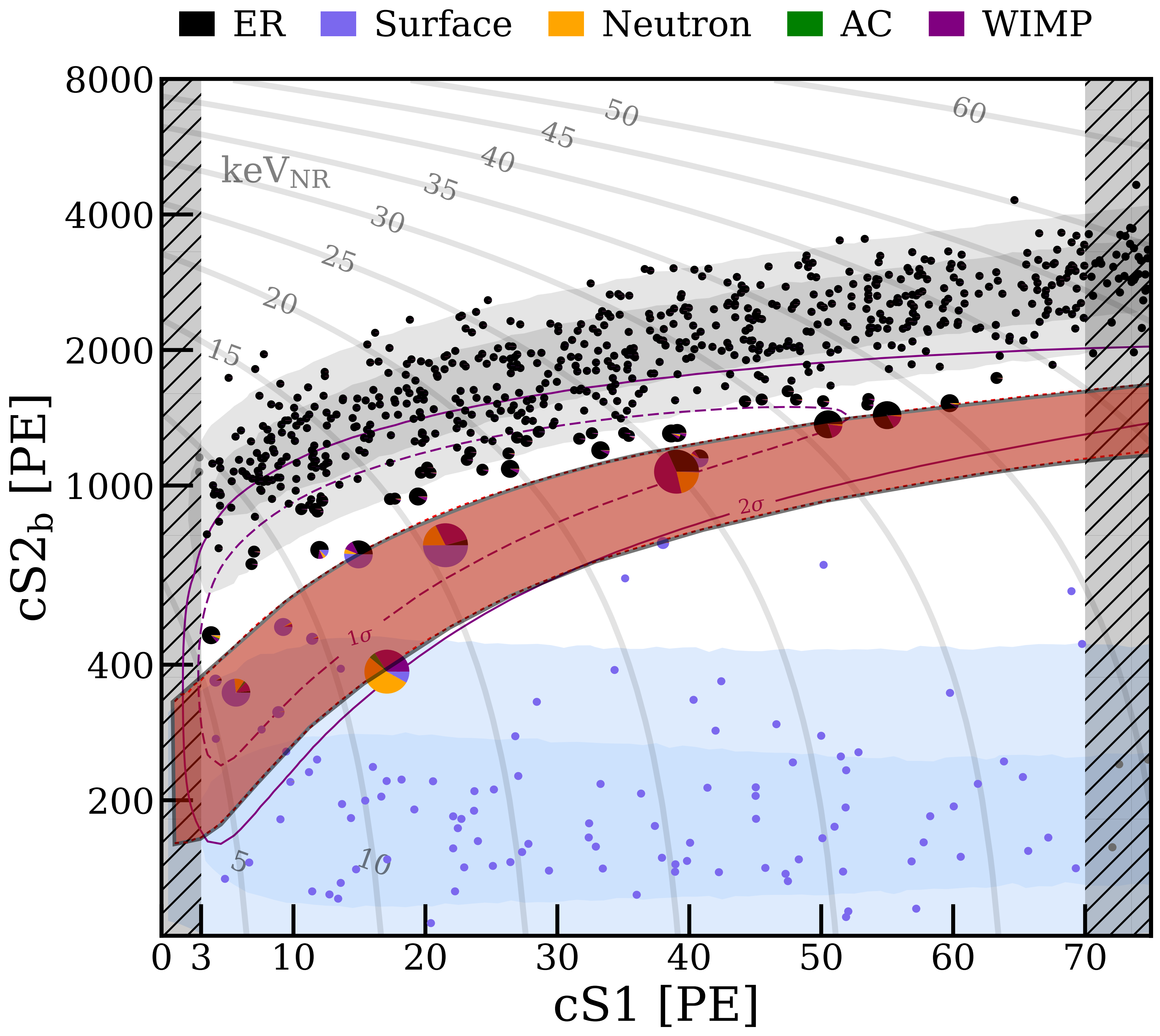
Detector with:

- Low background: 76 ± 2 events/t/yr/keV
- Low threshold: ~5 keV_{NR}
- Large exposure (mass, livetime): 1 tonne x year

Combination of S1 and S2 signals allow:

- Position reconstruction
- Energy reconstruction
- ER/NR discrimination



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

Signal and background discrimination

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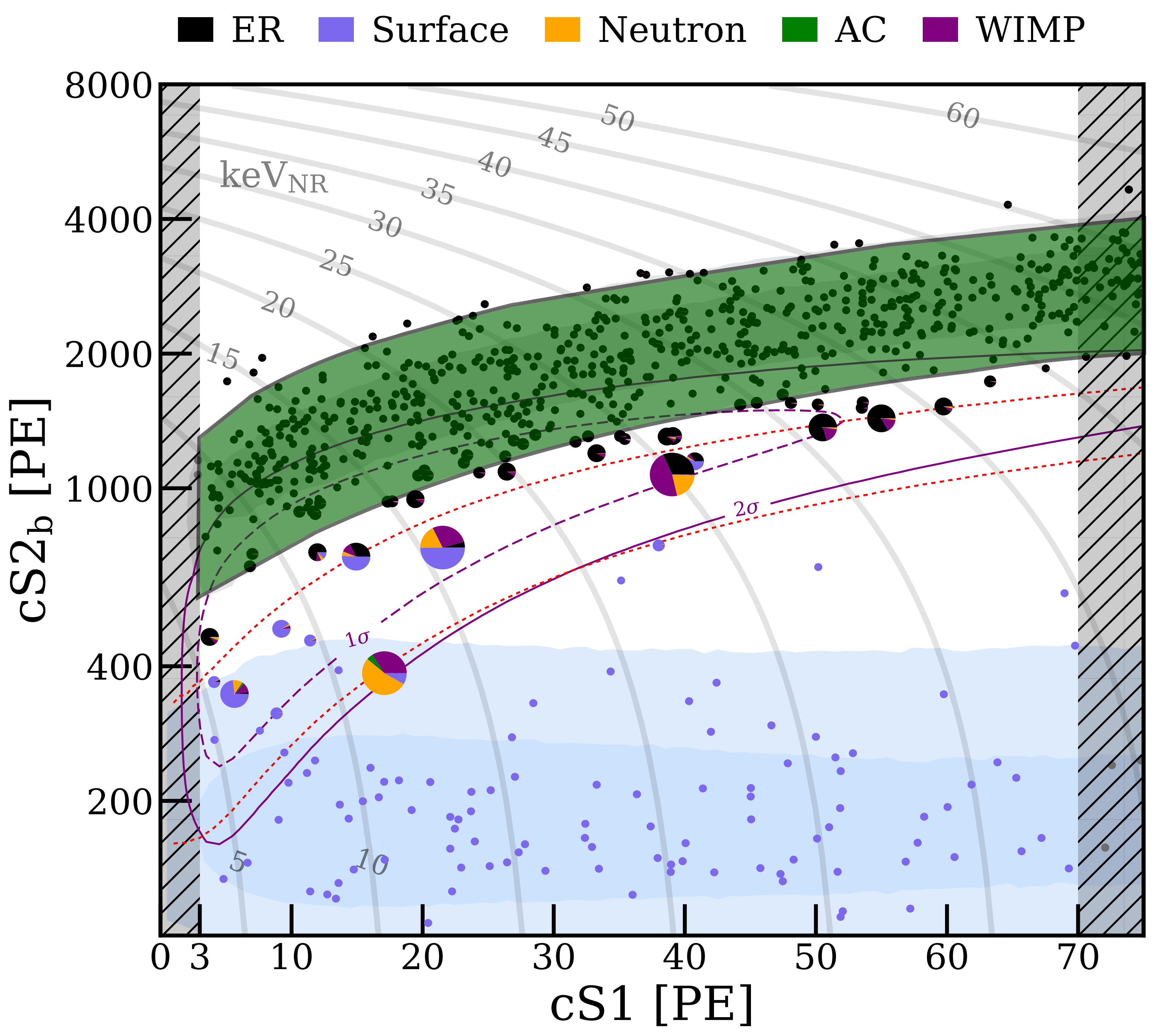
Detector with:

- Low background: 76 ± 2 events/t/yr/keV
- Low threshold: 1 keV_{ee}
- Large exposure (mass, livetime): 1 tonne x year

Combination of S1 and S2 signals allow:

- Position reconstruction
- Energy reconstruction
- ER/NR discrimination



Now use ultra-low ER background to search for excesses in ER band.

Energy reconstruction and resolution

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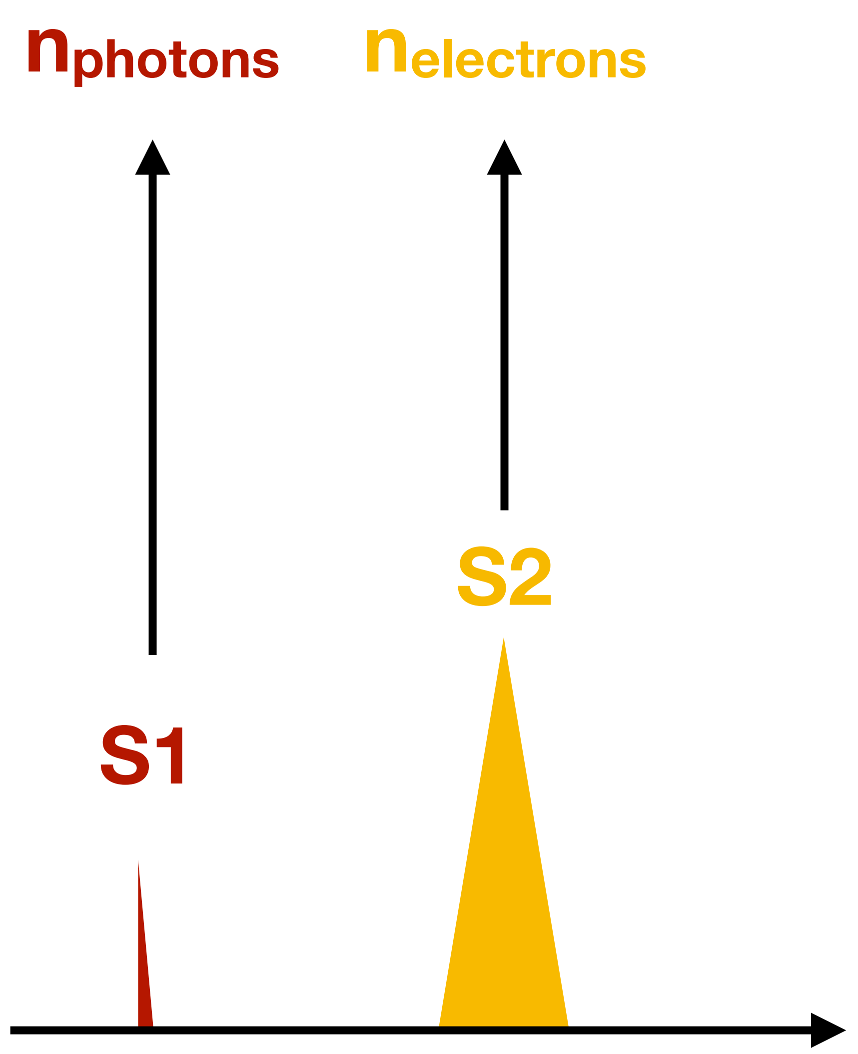
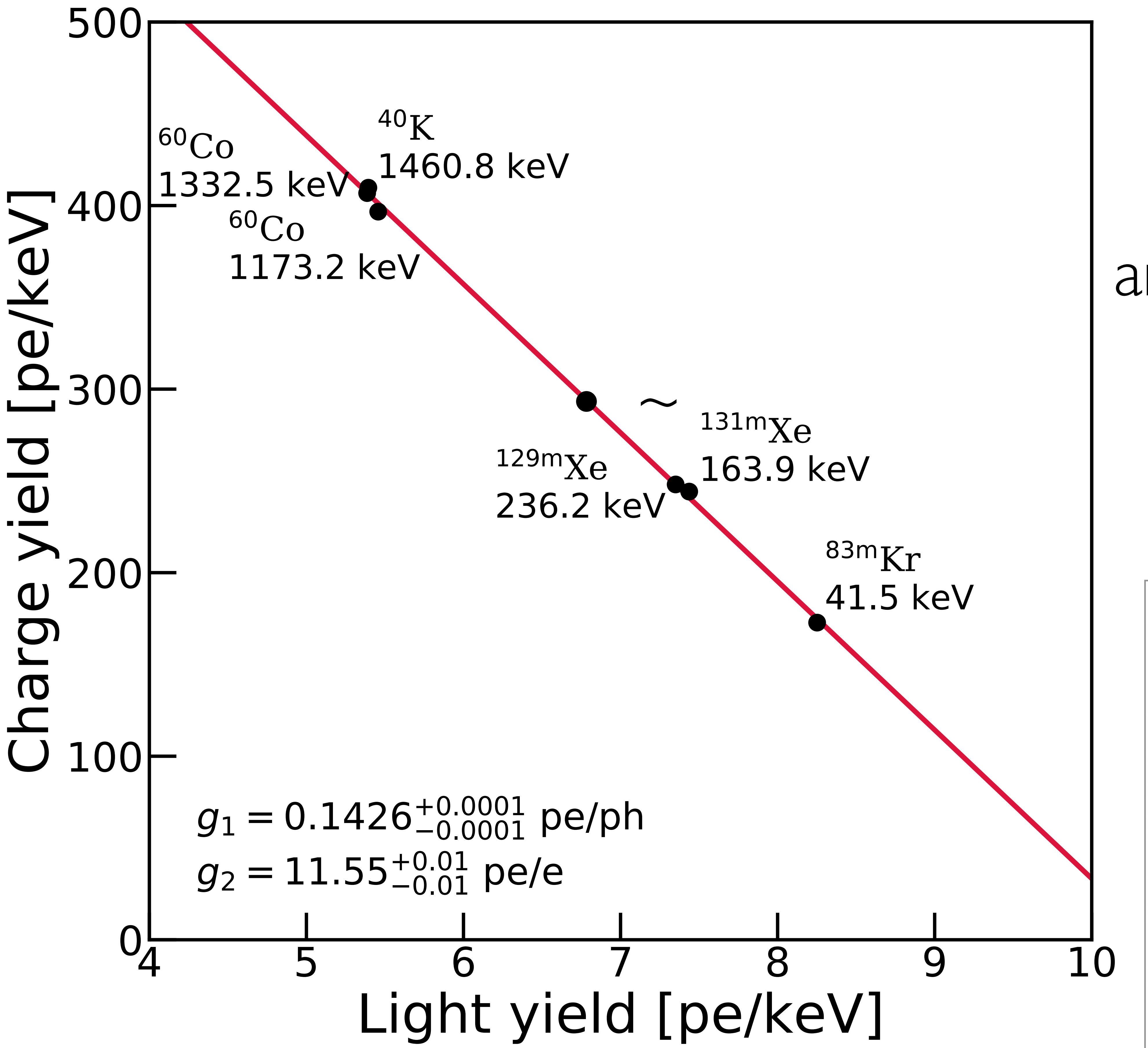
$$E = W \cdot \left(\frac{S1}{g_1} + \frac{S2}{g_2} \right)$$



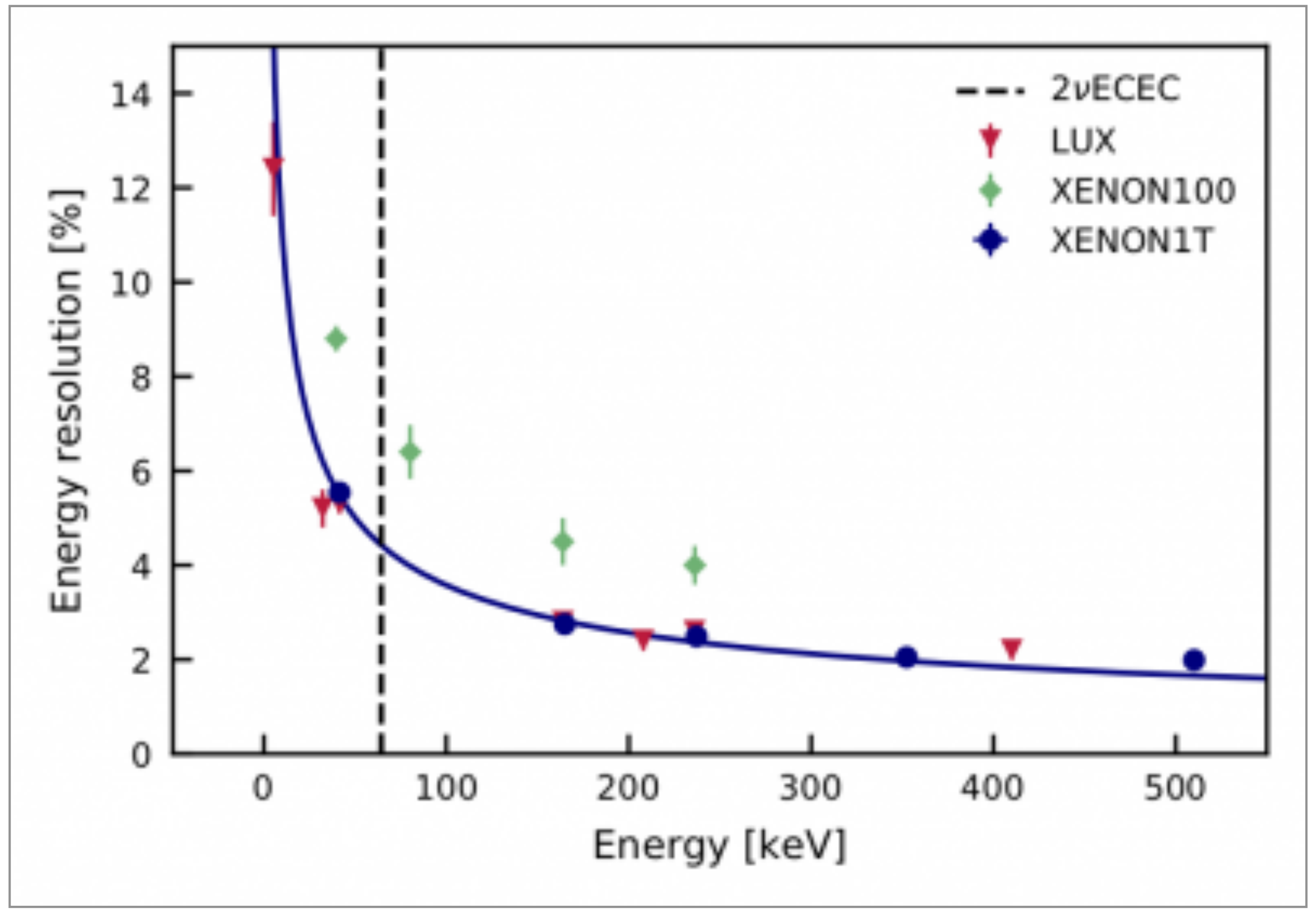
WIMPs, **X-rays**, ɣ (E<200 keV), β-electrons



Reconstruct energy from combined S1 and S2 signals

Anti-correlation between light and charge for optimal resolution

Energy resolution < 5 % at 50 keV



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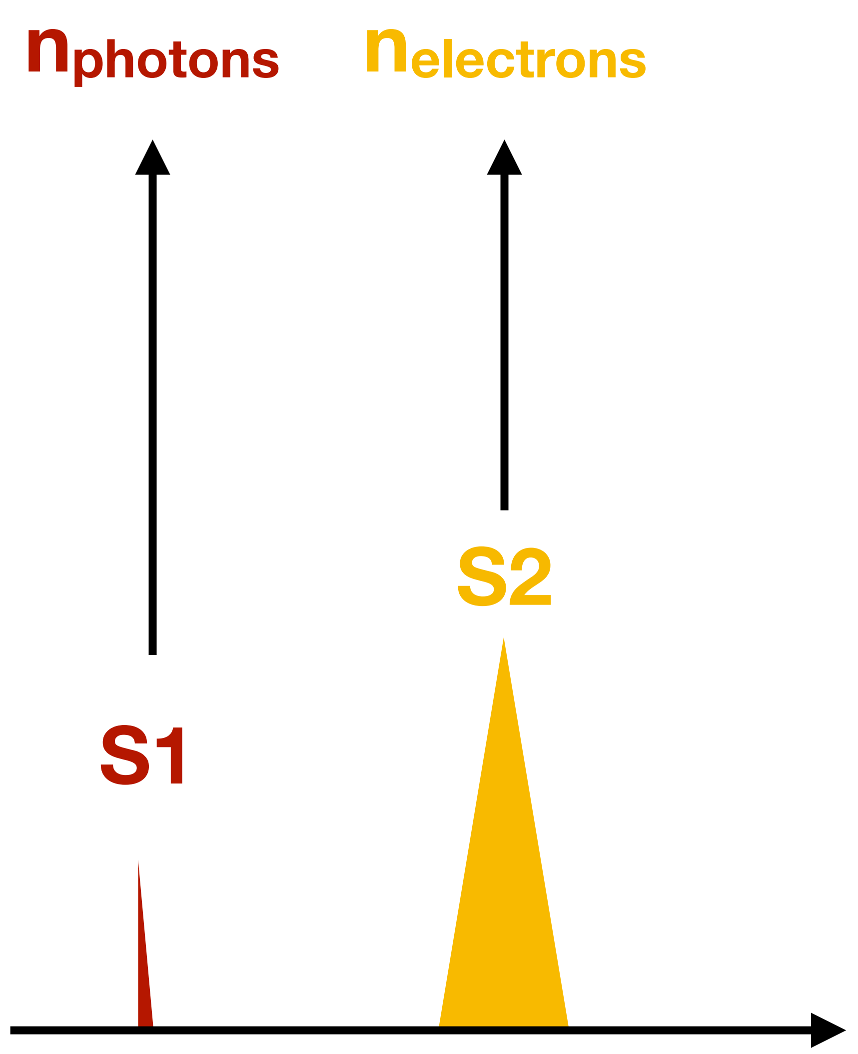
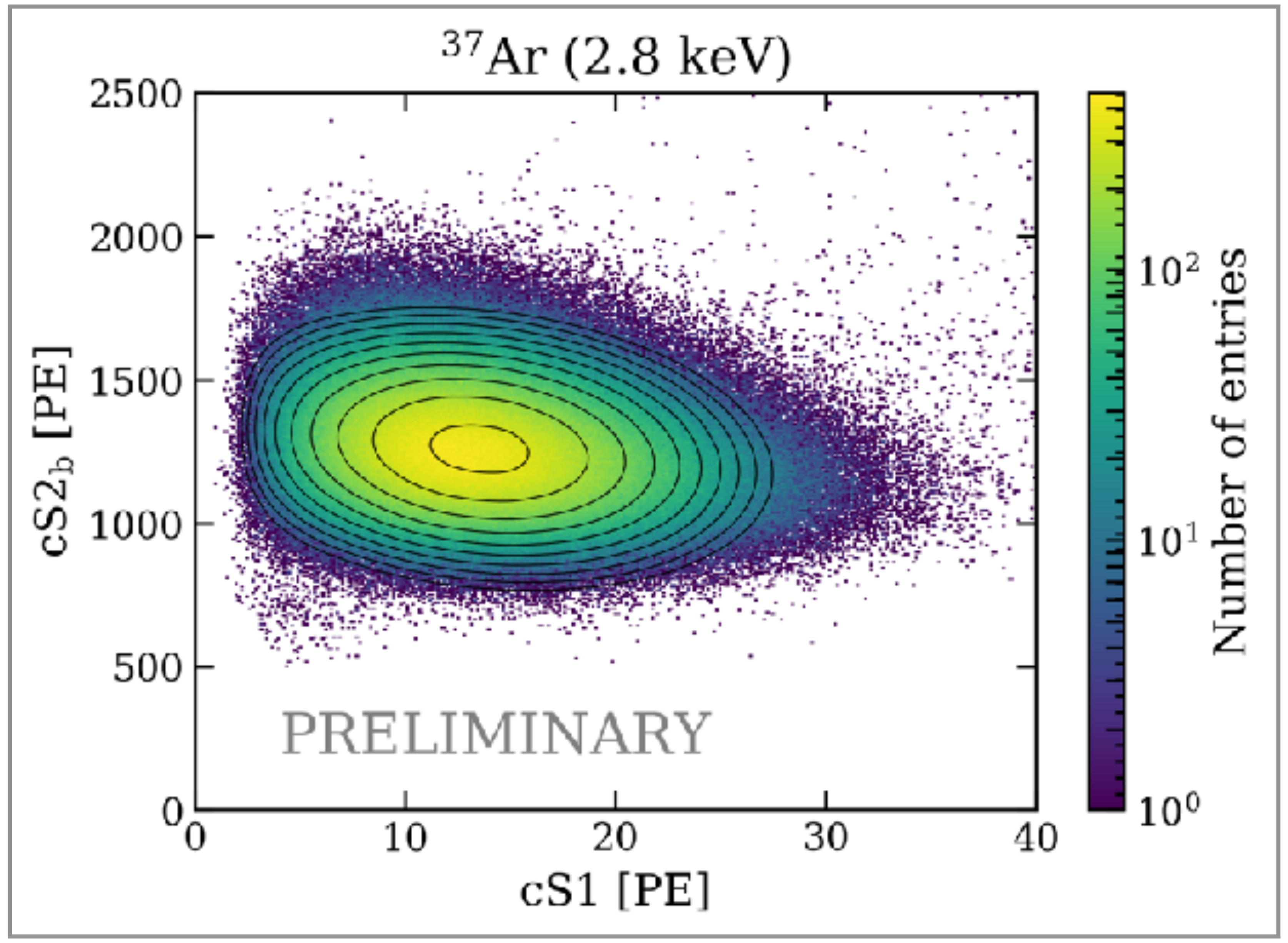
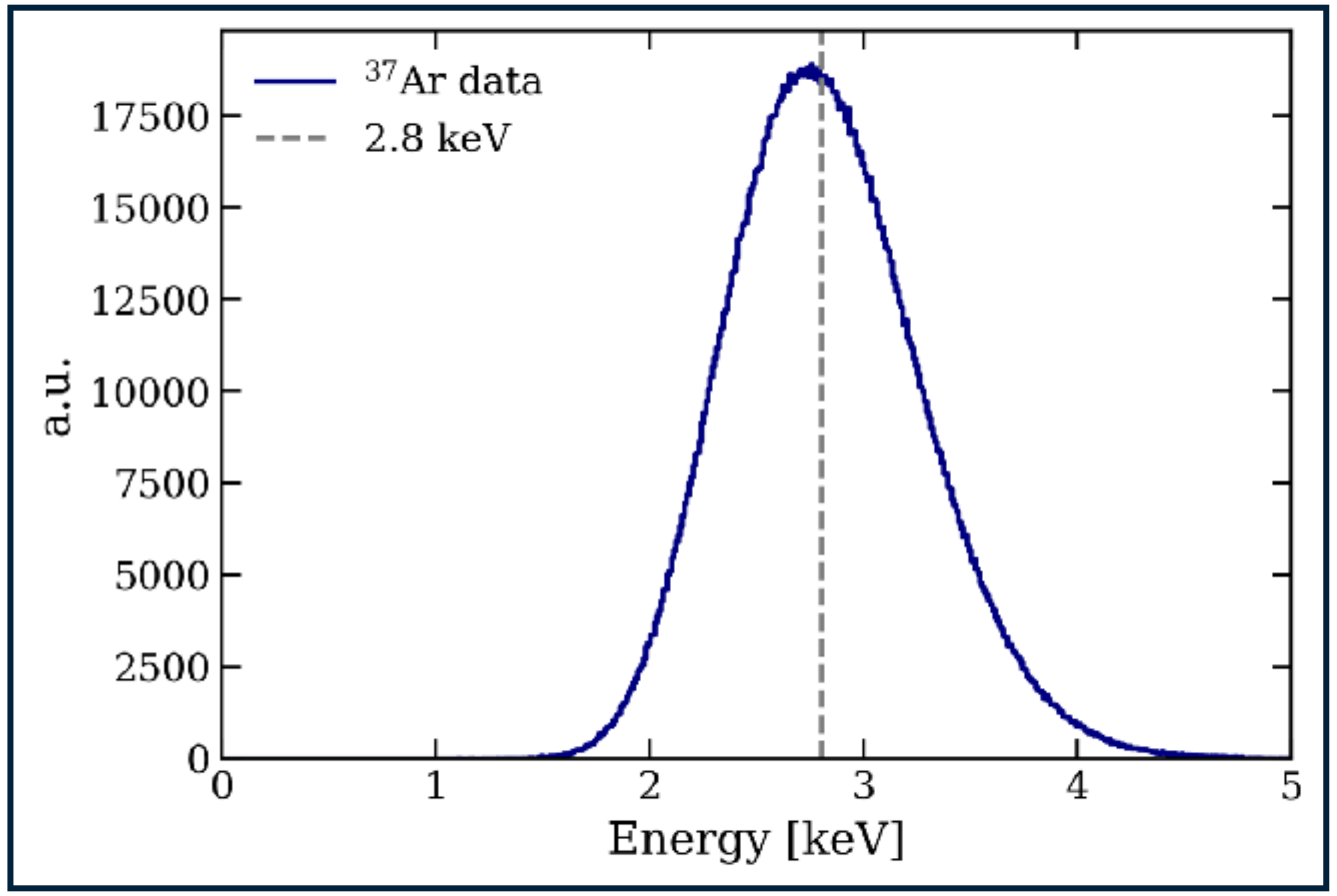
$$E = W \cdot \left(\frac{S1}{g_1} + \frac{S2}{g_2} \right)$$



WIMPs, **X-rays**, ɣ (E<200 keV), β-electrons

^{37}Ar calibration: 2.8 keV x-ray peak





Mean energy

Observed: 2.827 keV

Model: 2.834 keV

Resolution

Observed: 18.12%

Model: 18.88%

Data selection and detection efficiency

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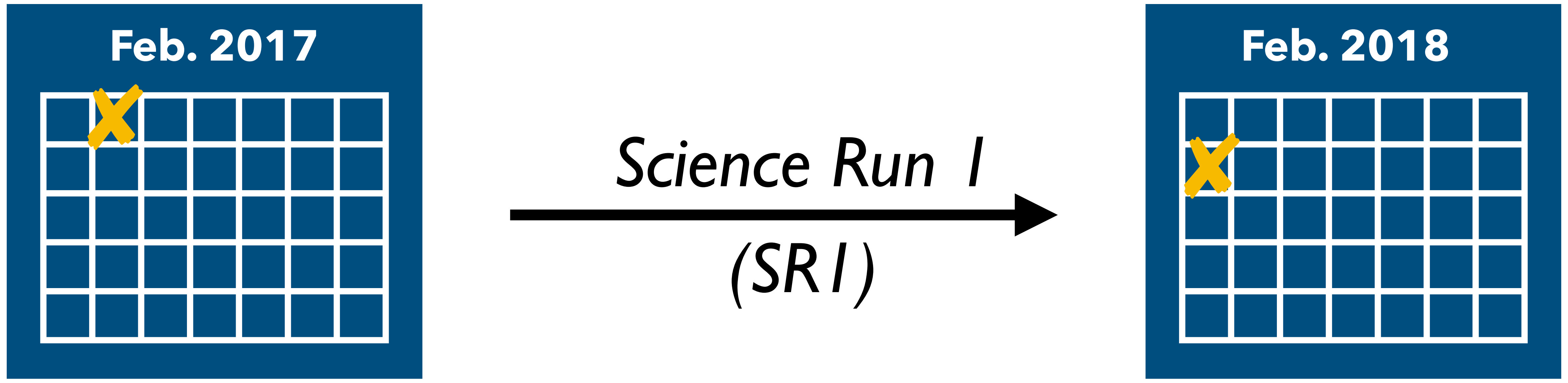


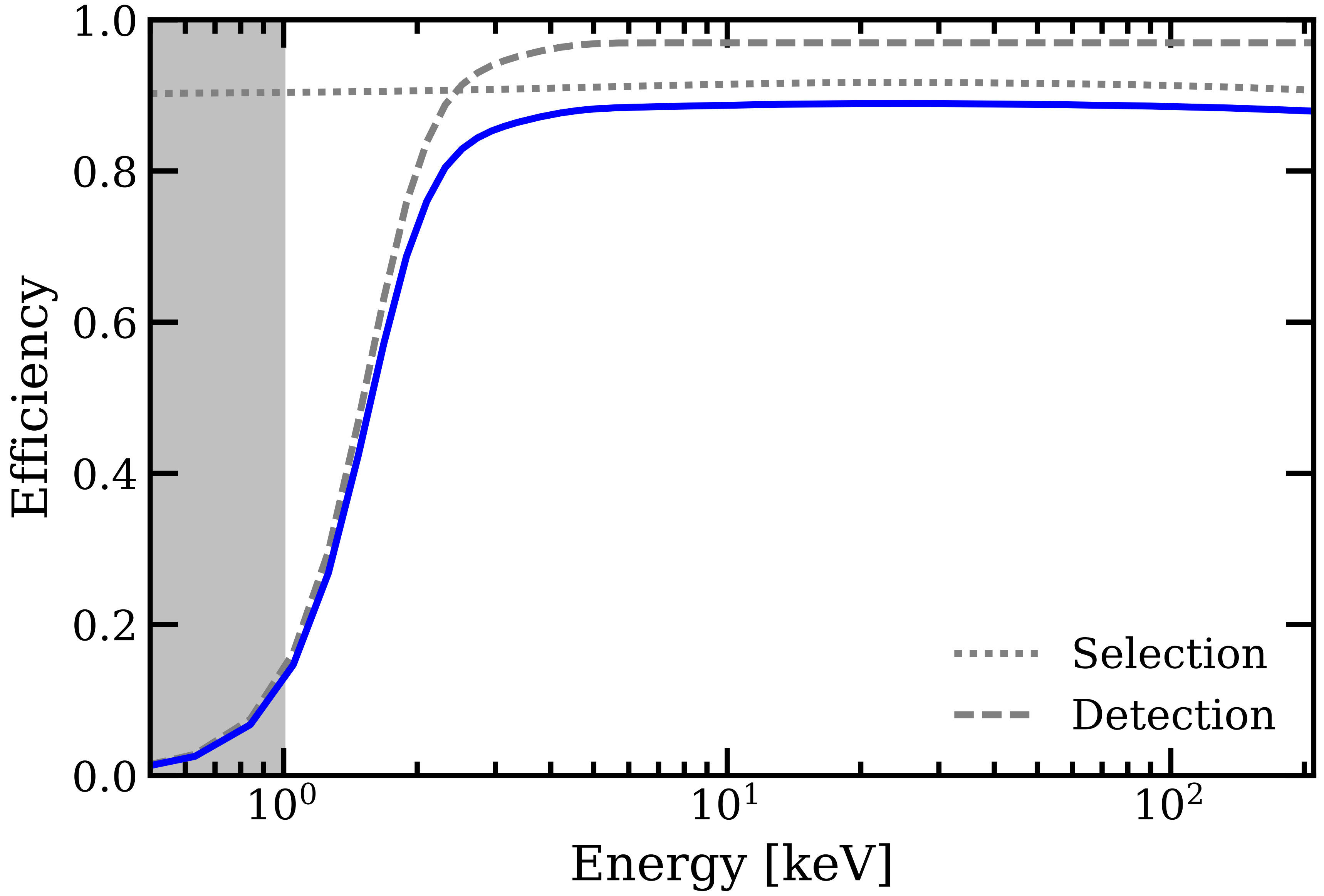
226.9 live days

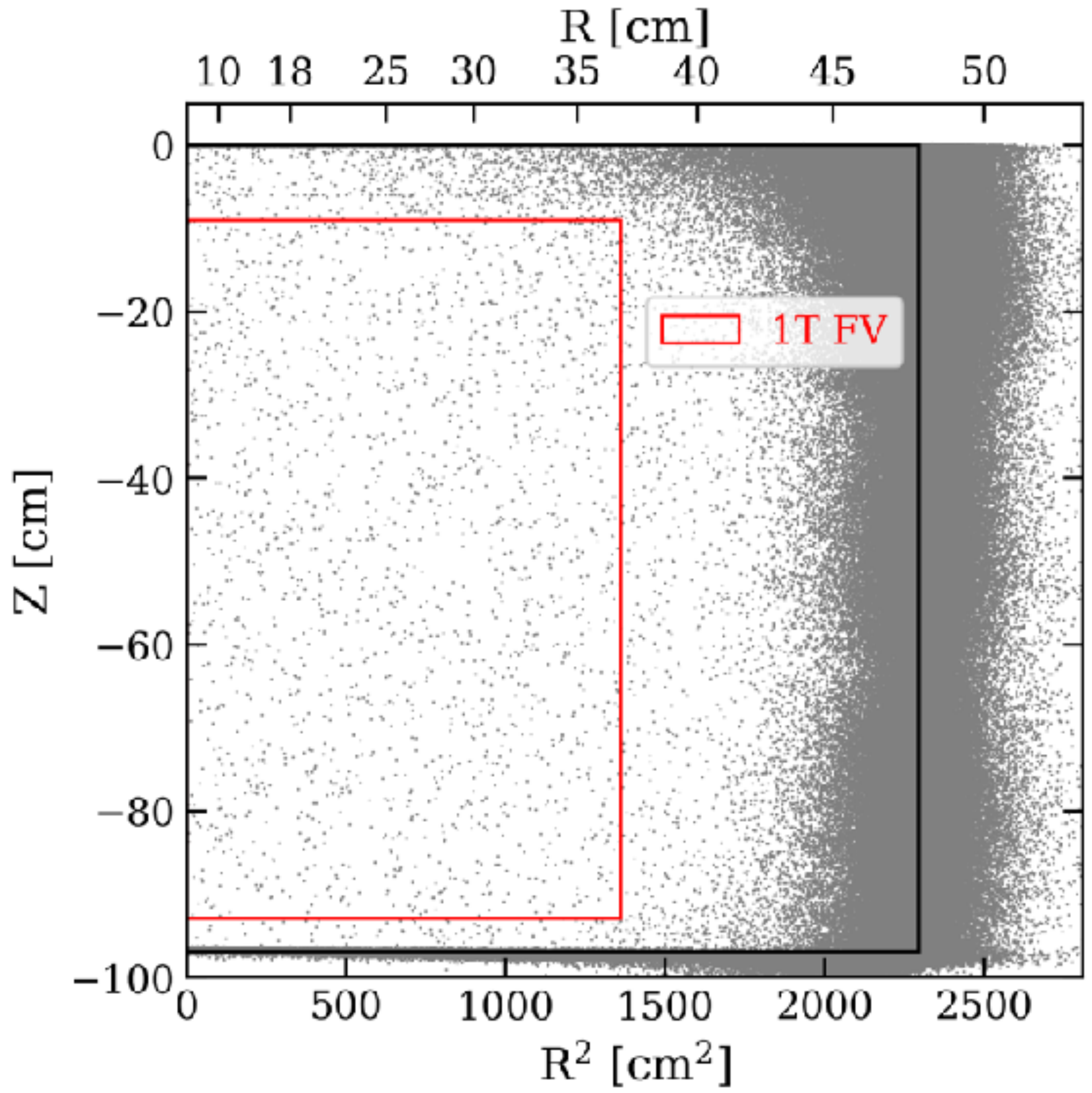
1 tonne fiducial volume

[1, 210] keV_{ee} energy range

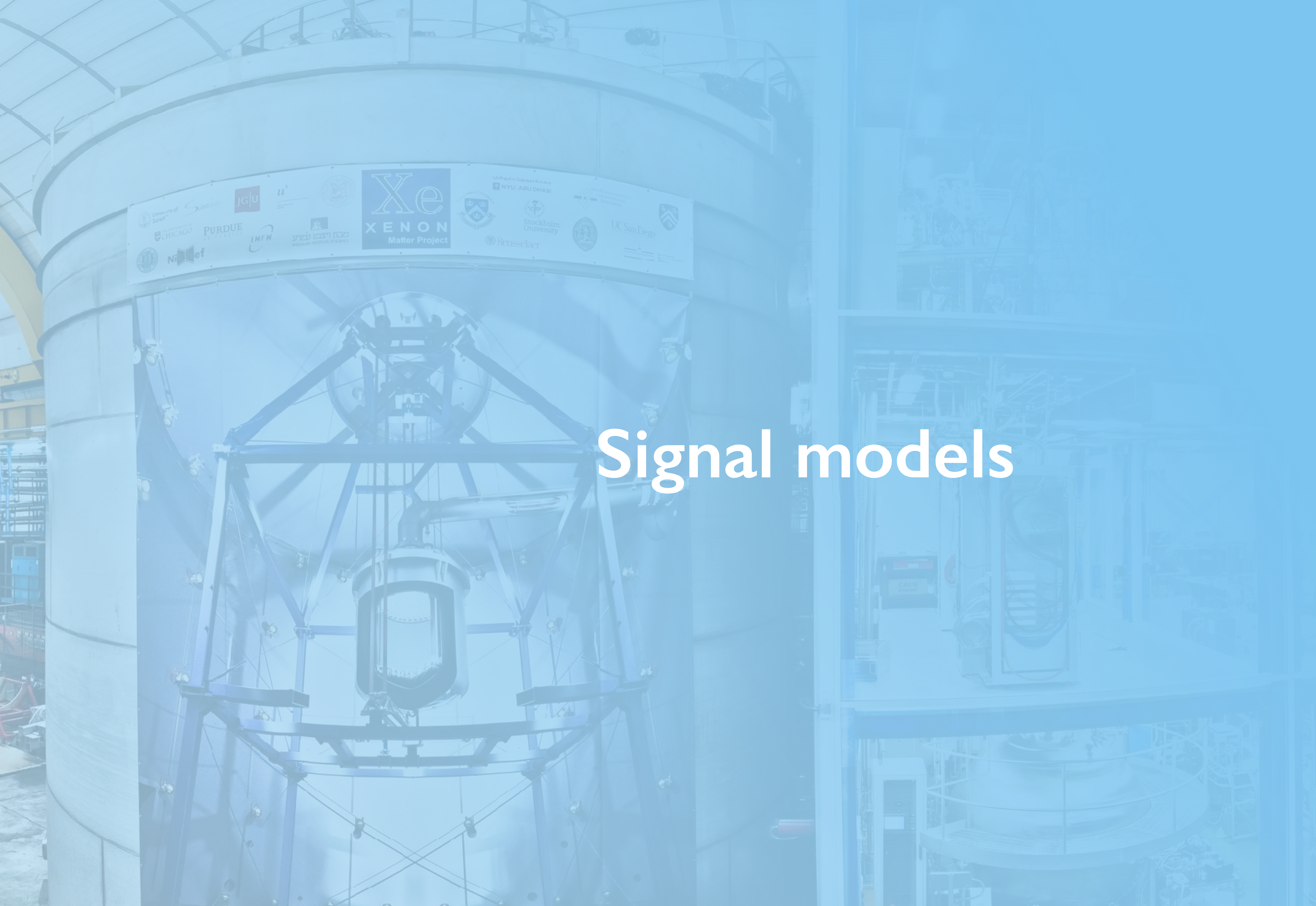
Consider efficiencies of reconstruction and data quality cuts

Threshold at 10 % detection efficiency





Signal models



QCD axions

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Could explain lack of CP violation in the strong interaction (*strong CP problem*)

Could make up the Dark Matter in the Universe

Mass anti-proportional to decay constant

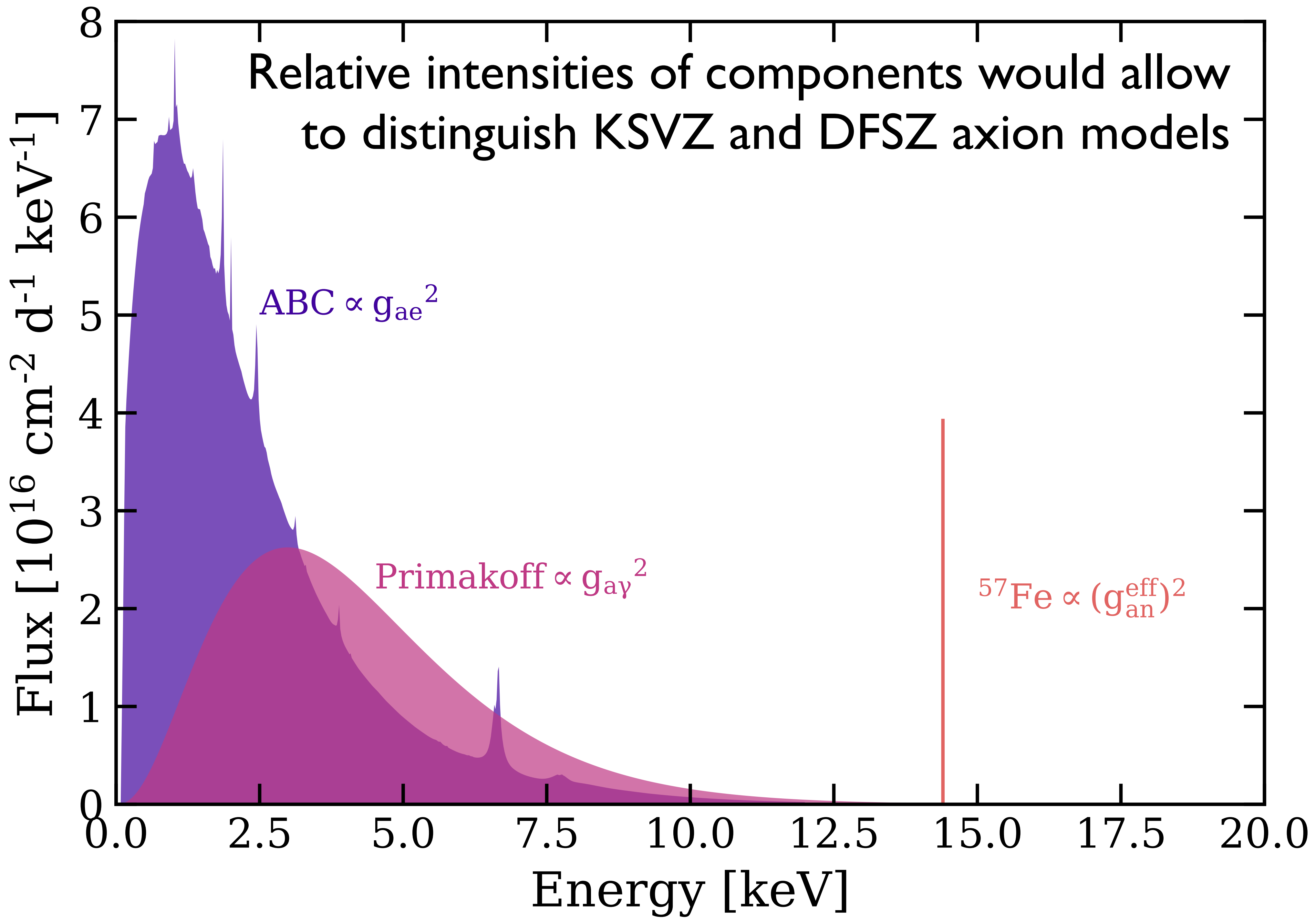
$$g_{ax} \propto m_a \propto \frac{1}{f_a}$$

Model-dependent couplings to matter

g_{ae}	$g_{a\gamma}$	g_{an}
axion-electron	**axion-photon**	**axion-nucleon**

To be Dark Matter axion masses of μeV – meV would be required

Axions would be produced in the sun with ~ keV kinetic energies



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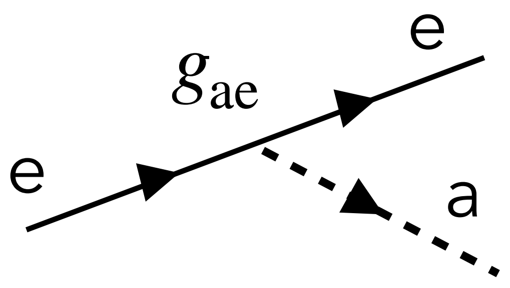
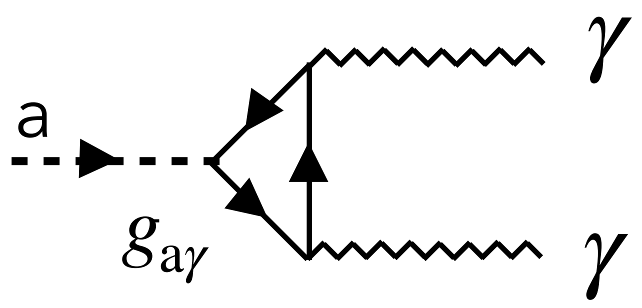
Production

Solar physics

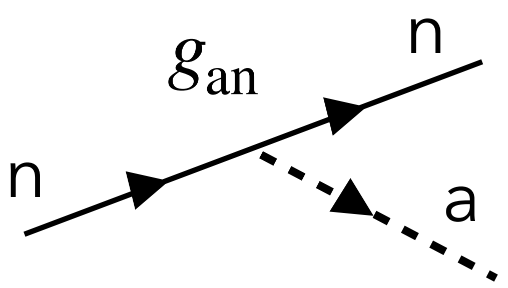
1. ABC



2. Primakoff

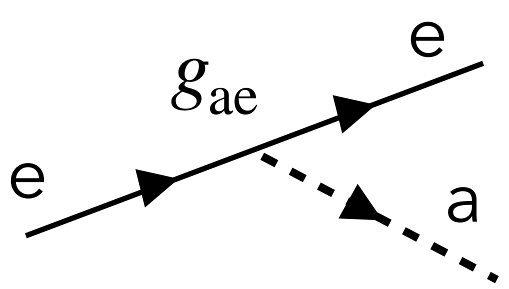


3. ^{57}Fe



Detection

Axioelectric effect

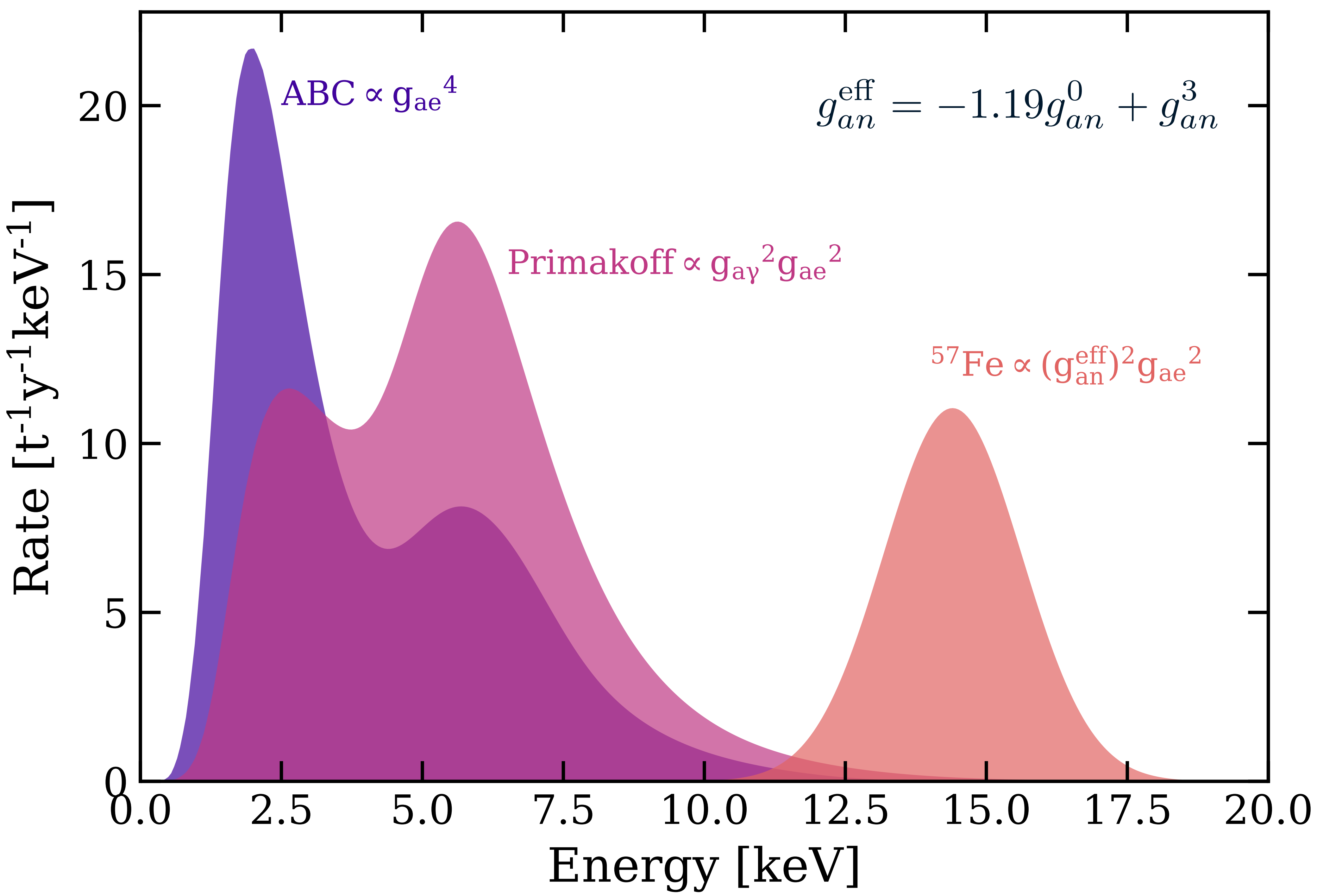


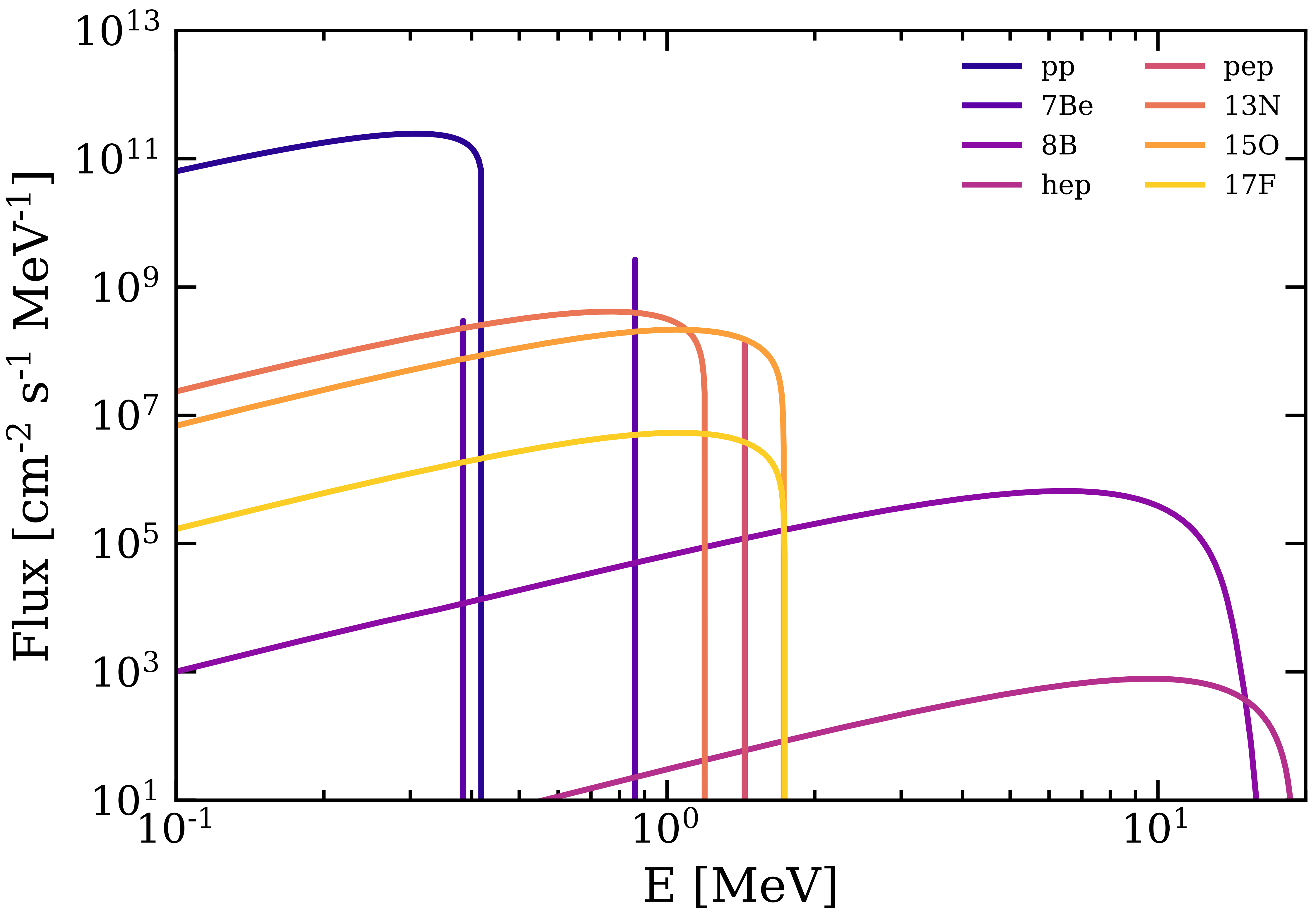
$$\sigma_{ae} = \sigma_{pe} \frac{g_{ae}^2}{\beta} \frac{3E_a^2}{16\pi\alpha m_e^2} \left(1 - \frac{\beta^{2/3}}{3}\right)$$

c.f. photoelectric effect

Reconstruction

XENON1T resolution, efficiency





Neutrinos acquire magnetic moment in extensions of the Standard Model

$$\mu_\nu \approx 3 \cdot 10^{-19} \left(\frac{m_\nu}{\mathrm{eV}}\right) \mu_\mathrm{B}$$

A larger value would imply new physics and Majorana nature of the neutrino

$$\mu_\nu \gtrsim 10^{-15} \mu_\mathrm{B}$$

Mainly solar pp and pep neutrinos elastically scatter off electrons in XENON1T.
Still subdominant to other backgrounds such as ^{214}Pb or ^{85}Kr.

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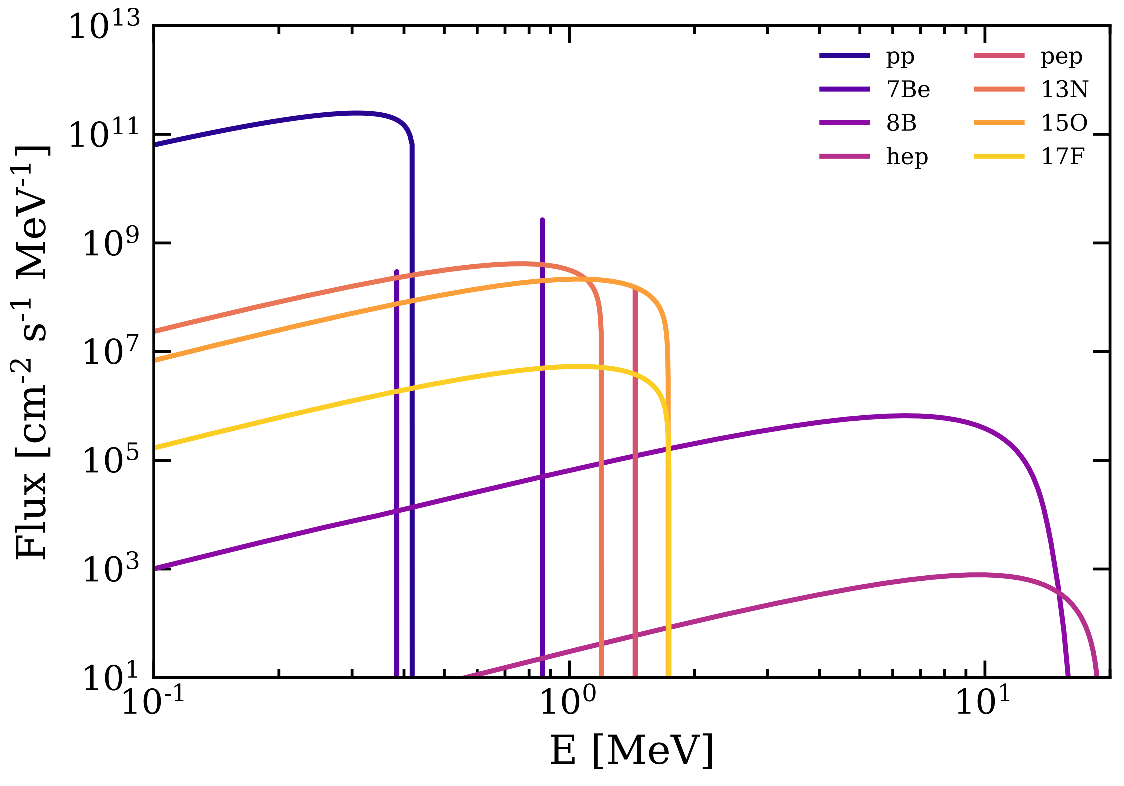
Production

Solar neutrinos



Detection

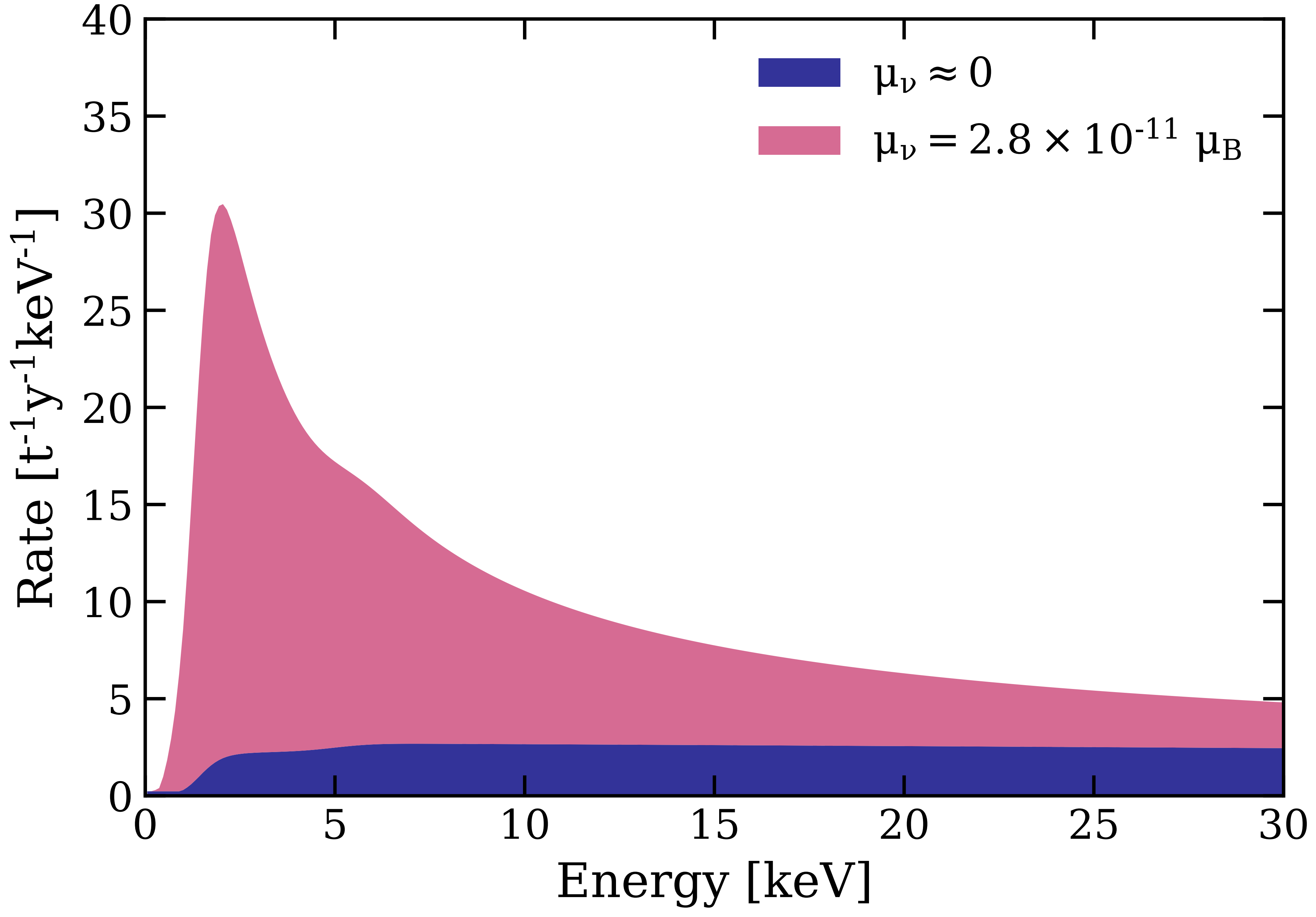
Elastic scattering off electrons

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

Enhancement of elastic electron scattering cross-section

Reconstruction

XENON1T resolution, efficiency



Bosonic Dark Matter

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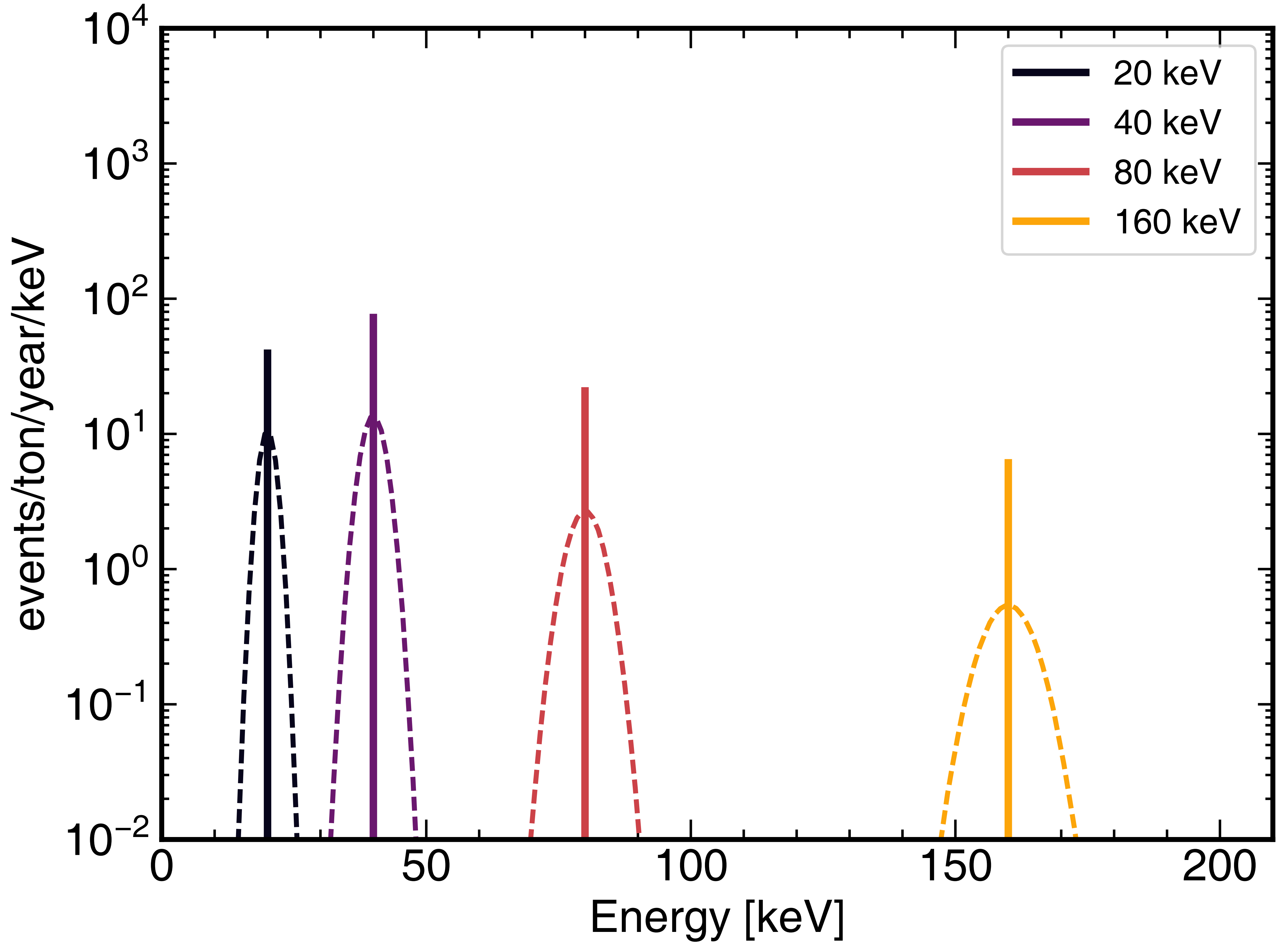
e.g. axion-like particles (ALPs)

Do not solve strong CP problem, but are viable Dark Matter candidates

No strict relationship between mass and coupling

Produce monoenergetic peak centered around the rest mass

Peak search with unknown position requires global rather than local significance



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

Backgrounds

Background model

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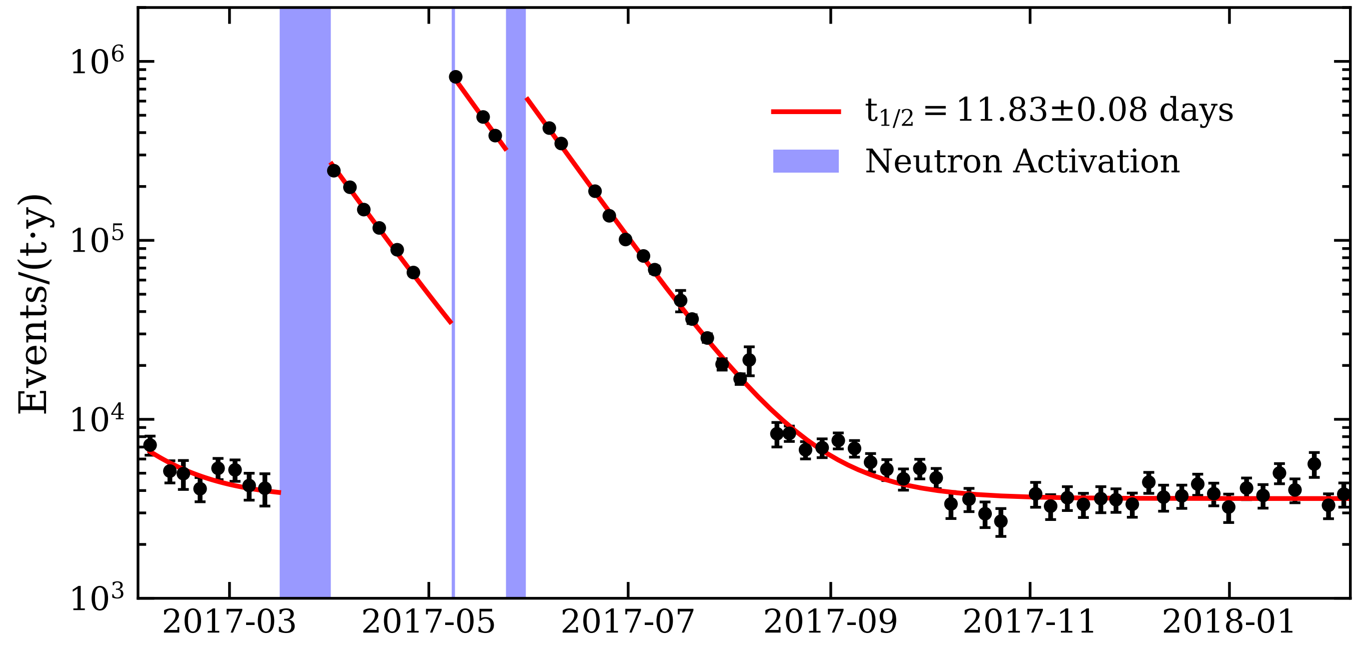
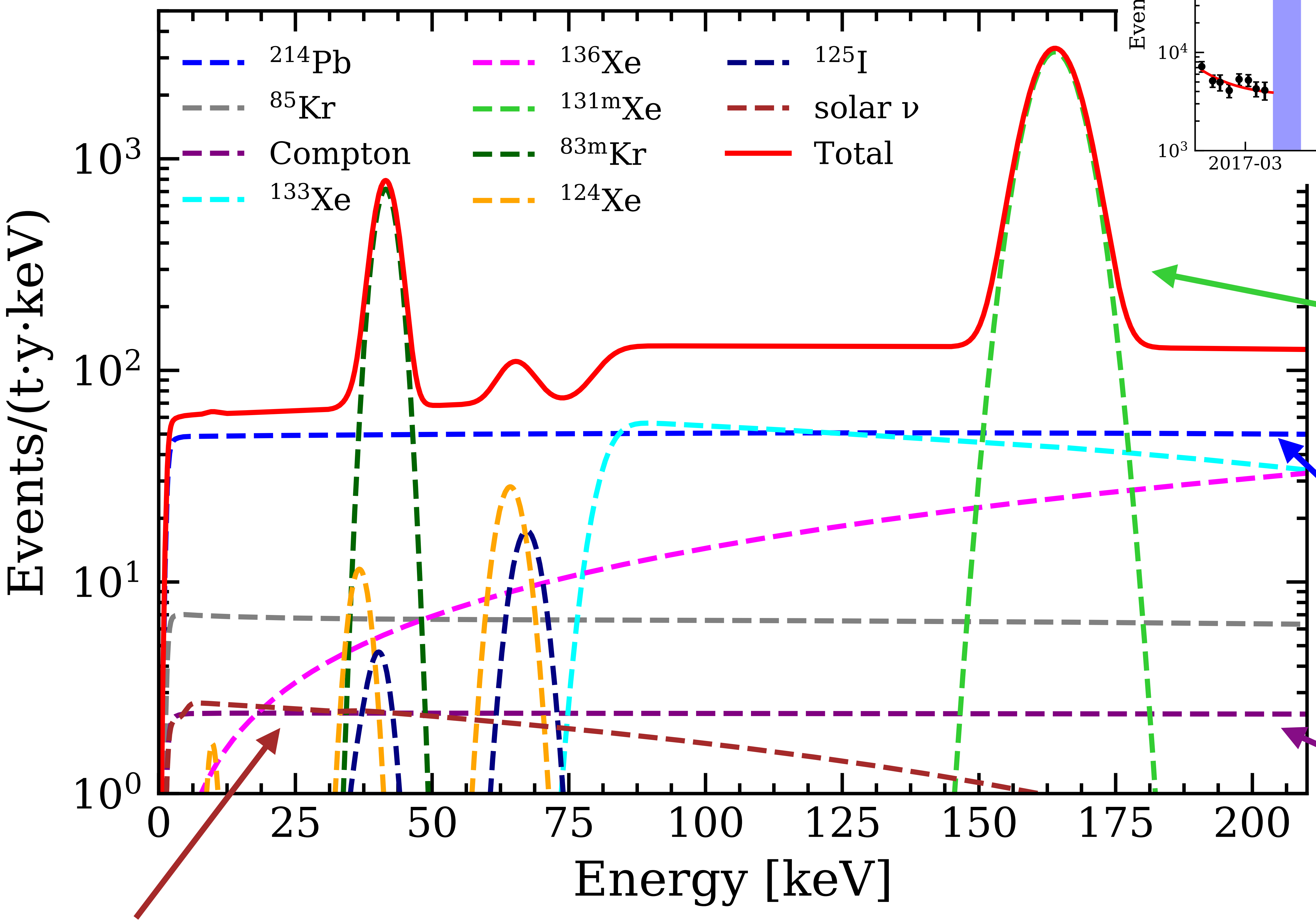
Look for an excess over background in [1, 210] keV interval

Predicted background spectra based on Geant4 simulations smeared with detector effects

Most rates constrained by independent measurements or time-dependence





Neutron-activations
^{131m}Xe, ^{133}Xe, ^{125}I

Intrinsic backgrounds
^{214}Pb, ^{136}Xe, ^{124}Xe, ^{85}Kr, ^{83m}Kr

Detector material γ

Solar neutrinos

Fitting the background model to measured data

Background fit and low-energy excess

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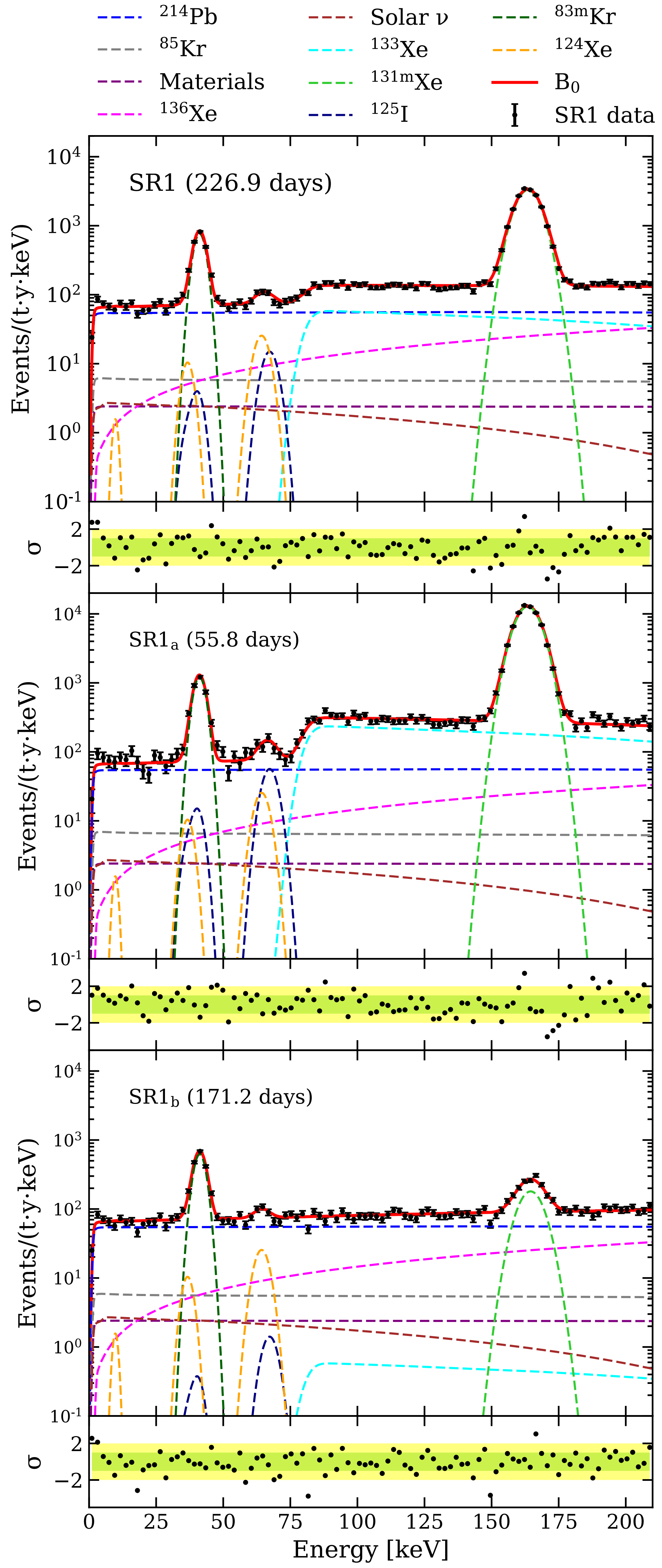
Unbinned maximum likelihood fit profiling over nuisance parameters

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

Partitioned full exposure into *clean* and *dirty* dataset with regard to neutron activations

$$\mathcal{L} = \mathcal{L}_{\mathrm{a}} \times \mathcal{L}_{\mathrm{b}}$$

76 ± 2 events/keV/t/yr in [1, 30] keV interval lowest ever achieved in this energy range and consistent with expectations



Background fit and low-energy excess

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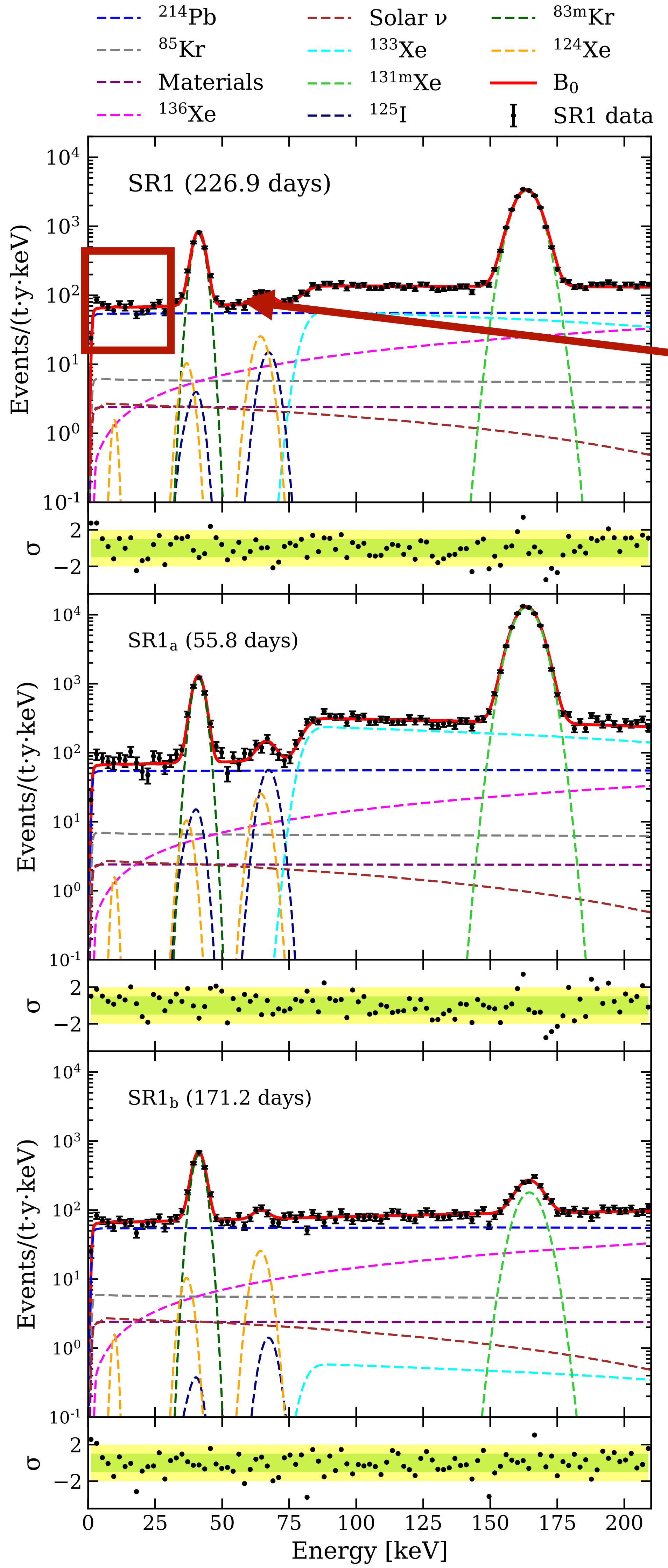
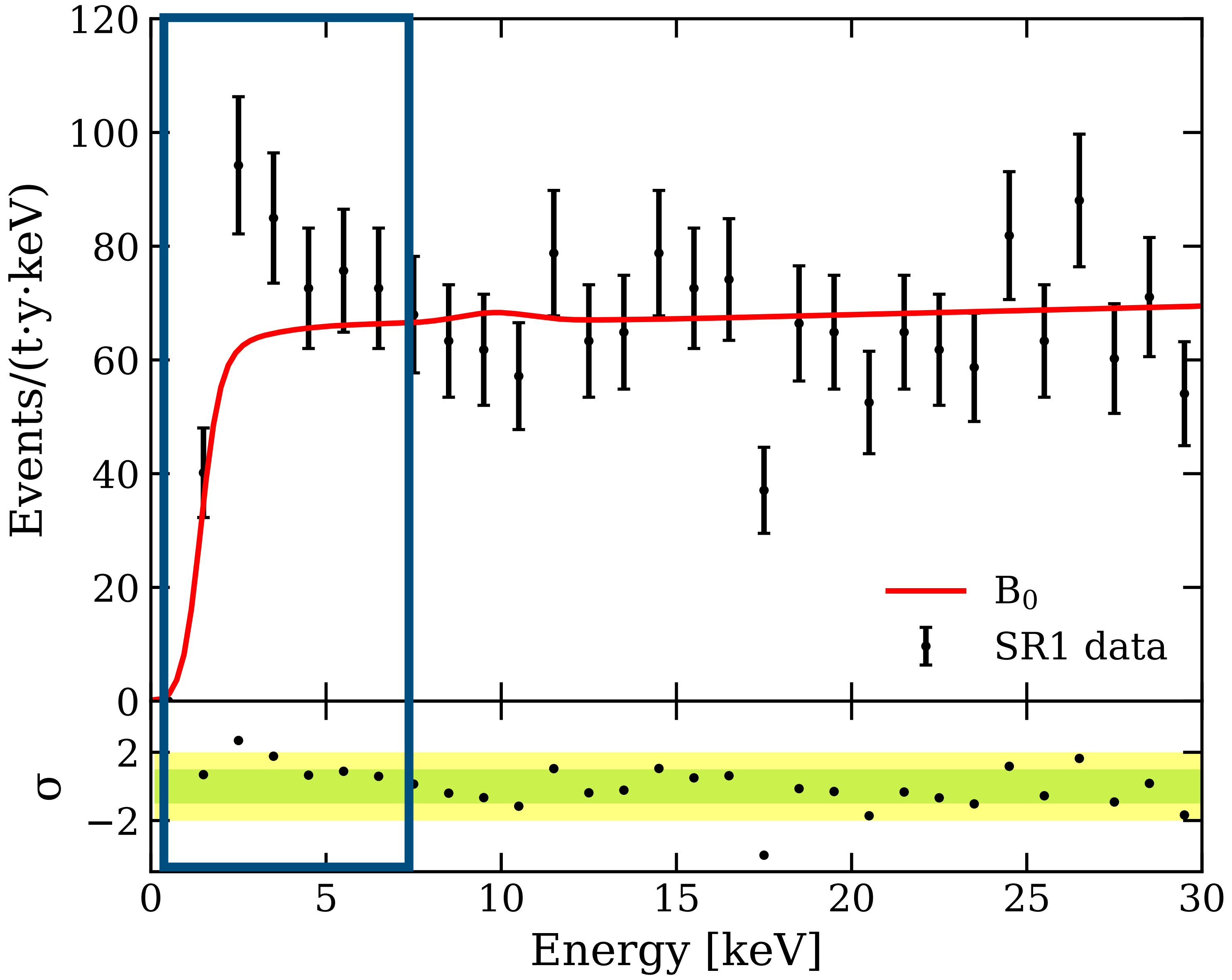




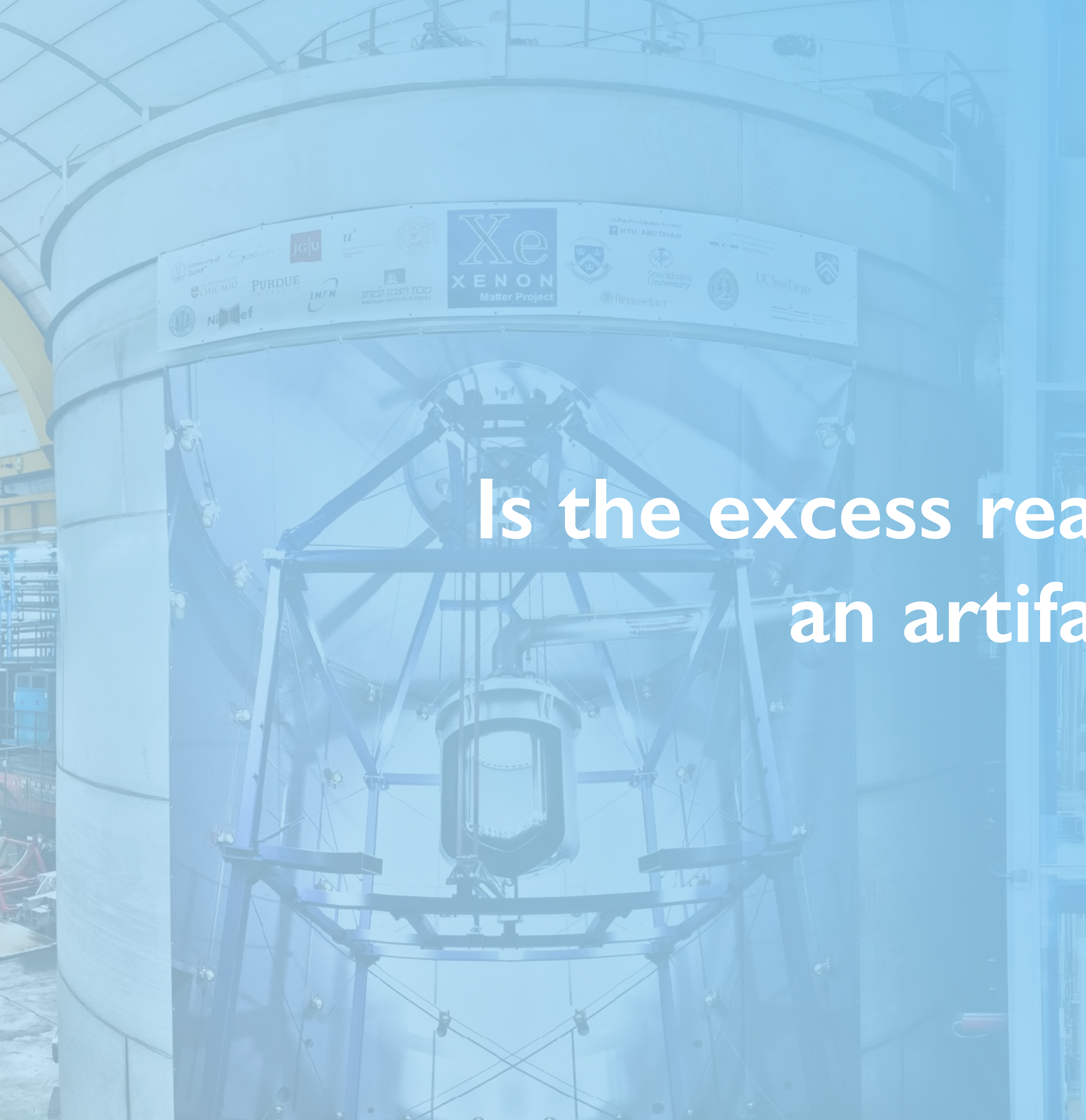
Excess between 1-7 keV

285 *events observed*

vs.

*(**232 ± 15**) events expected (from best-fit)*

*Would be a **3.3σ** fluctuation*
(naive estimate – we use likelihood ratio tests for main analysis)



Is the excess real or merely an artifact?

Mismodeling of efficiency or energy reconstruction?

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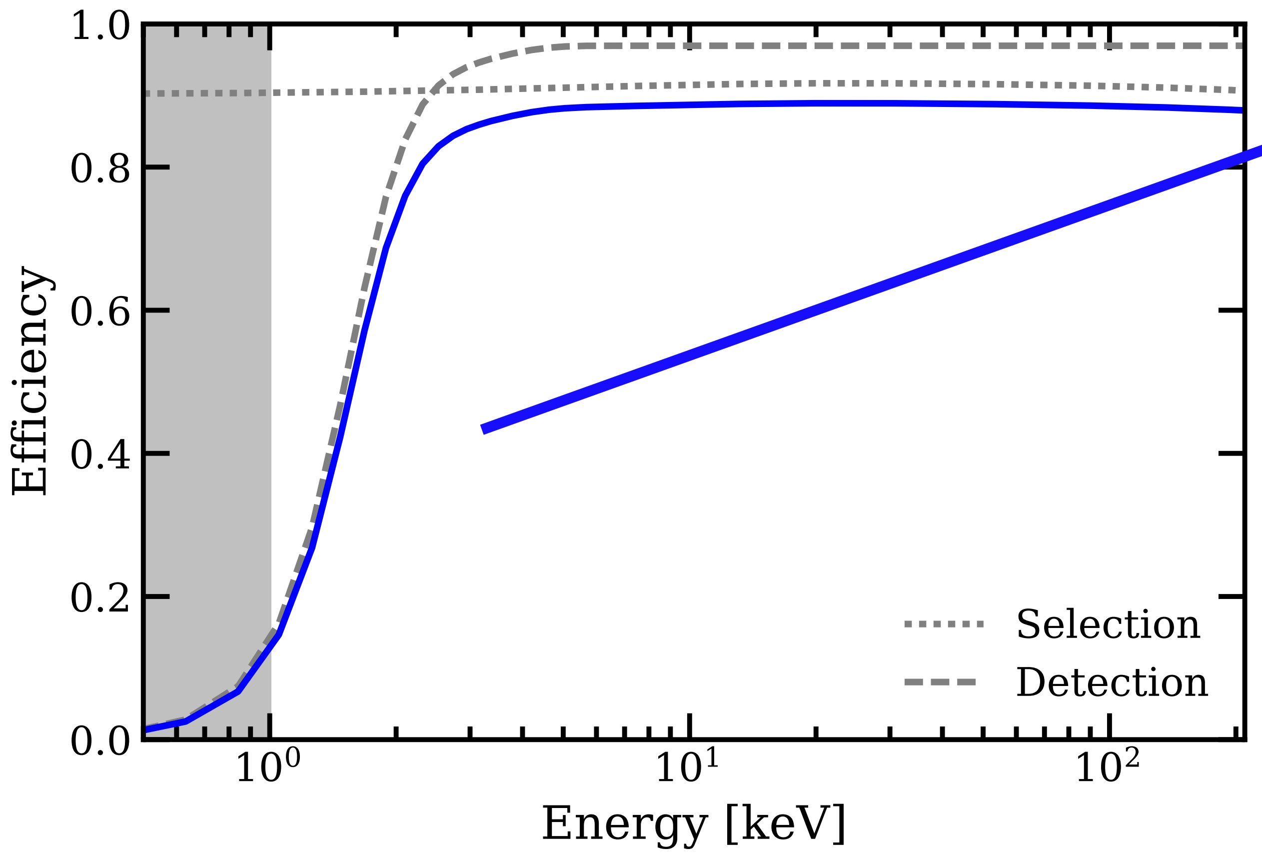
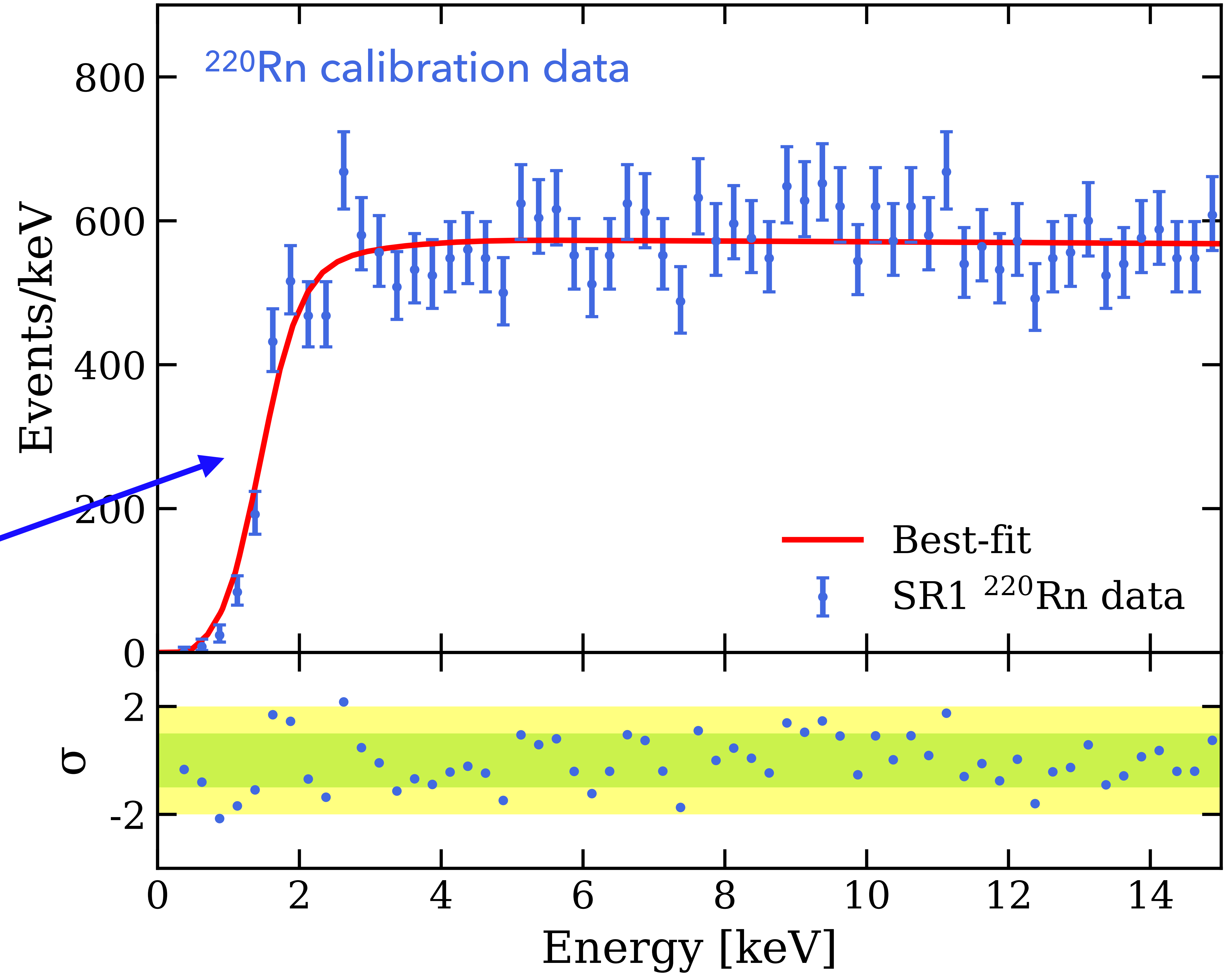
Fit simulated ^{220}Rn events to calibration data:
^{212}Pb β-decay as analog to main background
^{214}Pb from β-decay

Validates efficiency and energy reconstruction

g.o.f. p-value 0.58

Unlikely the cause of the excess





Shape of the ^{214}Pb background spectrum

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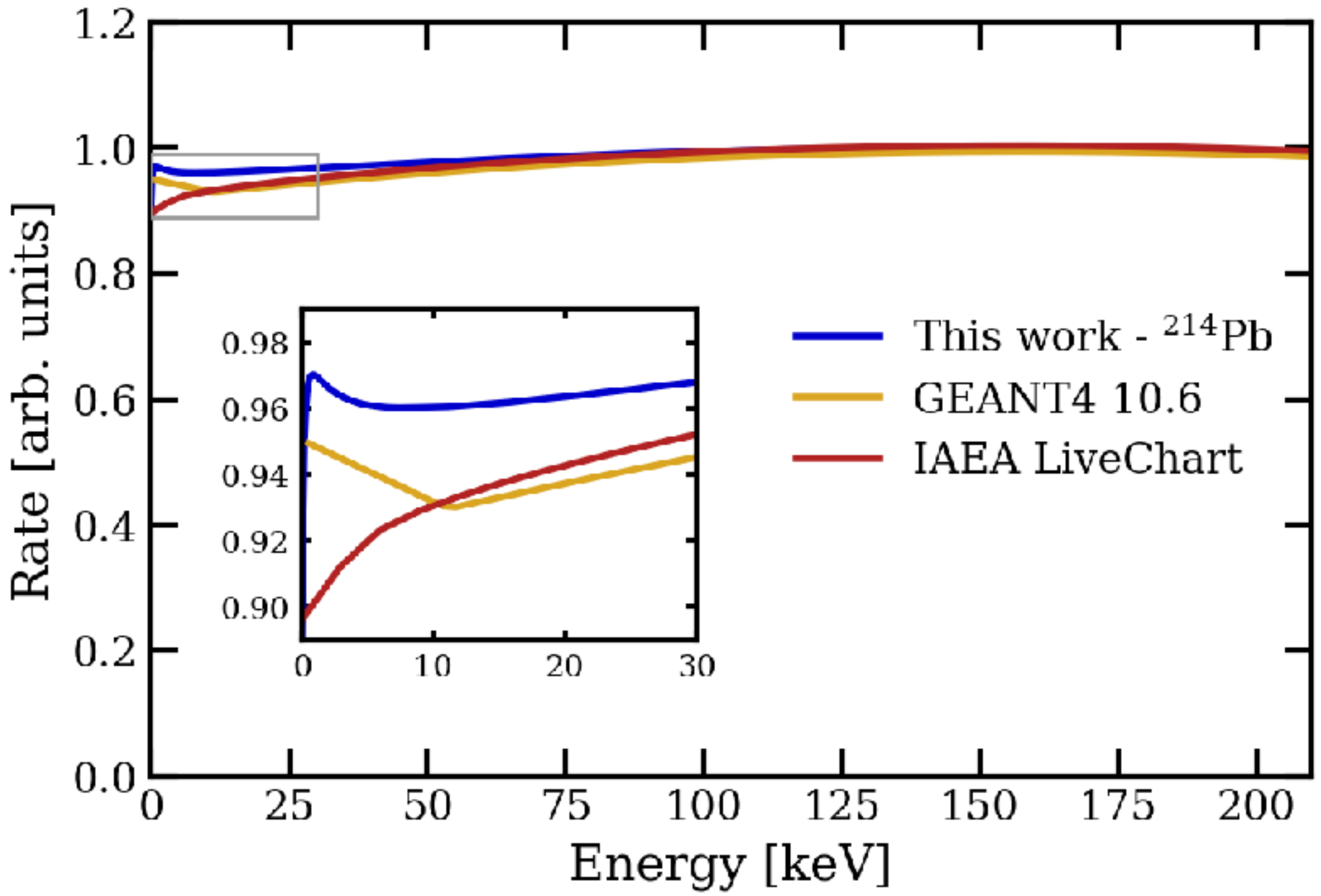
Atomic effects (e.g. static Coulomb effect of nucleus on β-particle) can enhance the rate at low energies

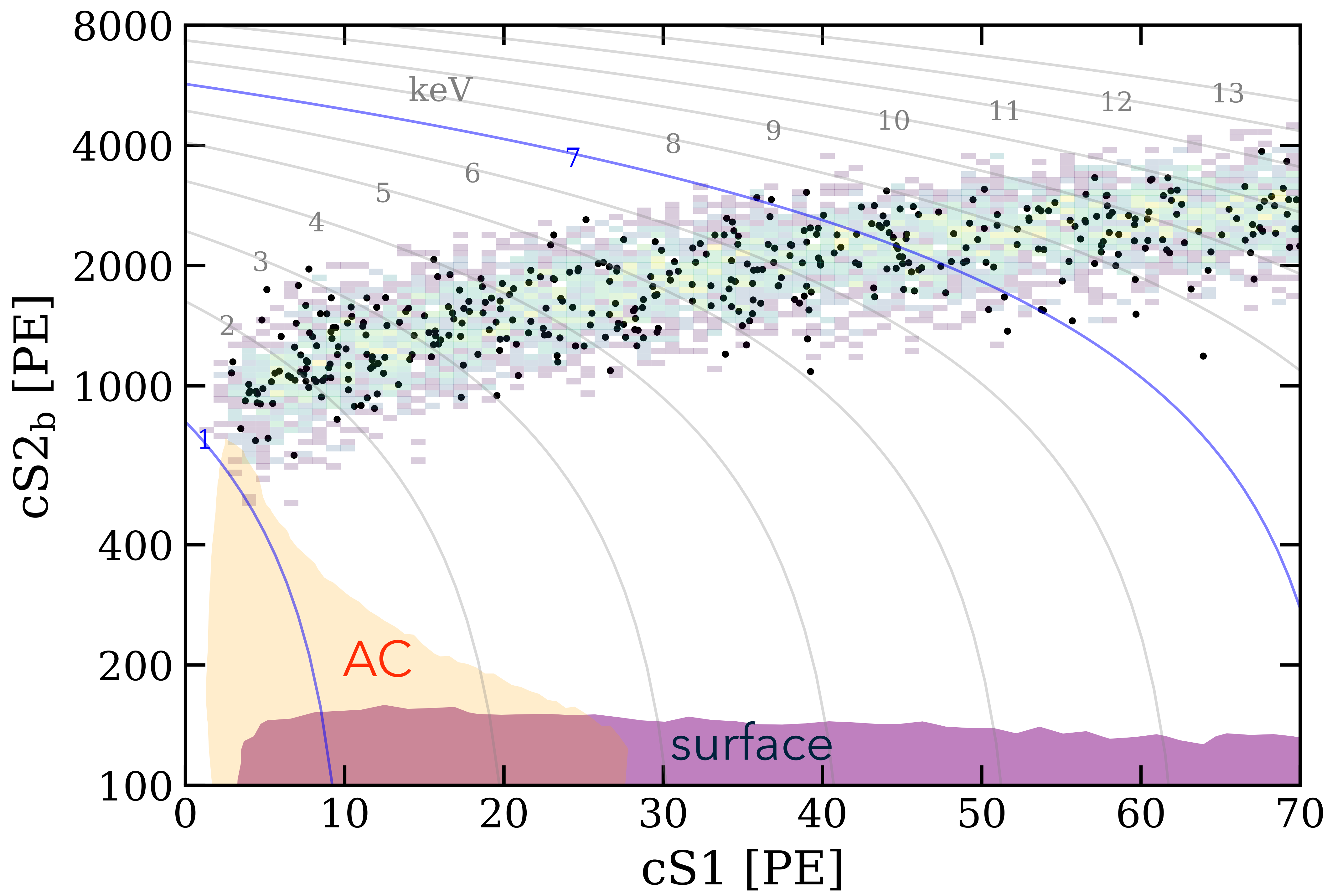
These are not properly considered in the default Geant4 nuclear decay module or spectra from nuclear databases

Teamed up with X. Mougeot (CEA) in order to calculate the correct shape of the spectrum at low energy



Rate uncertainty of 6 % cannot account for the excess (would require a 50 % enhancement)

Instrumental background?



Unlikely the cause of the excess

Accidental coincidence background events and misreconstructed events from detector surfaces are not observed

These appear at a different S2/S1 ratio compared to true ER events

All observed events fall in the ER band

Statistical fluctuations and binning artefacts

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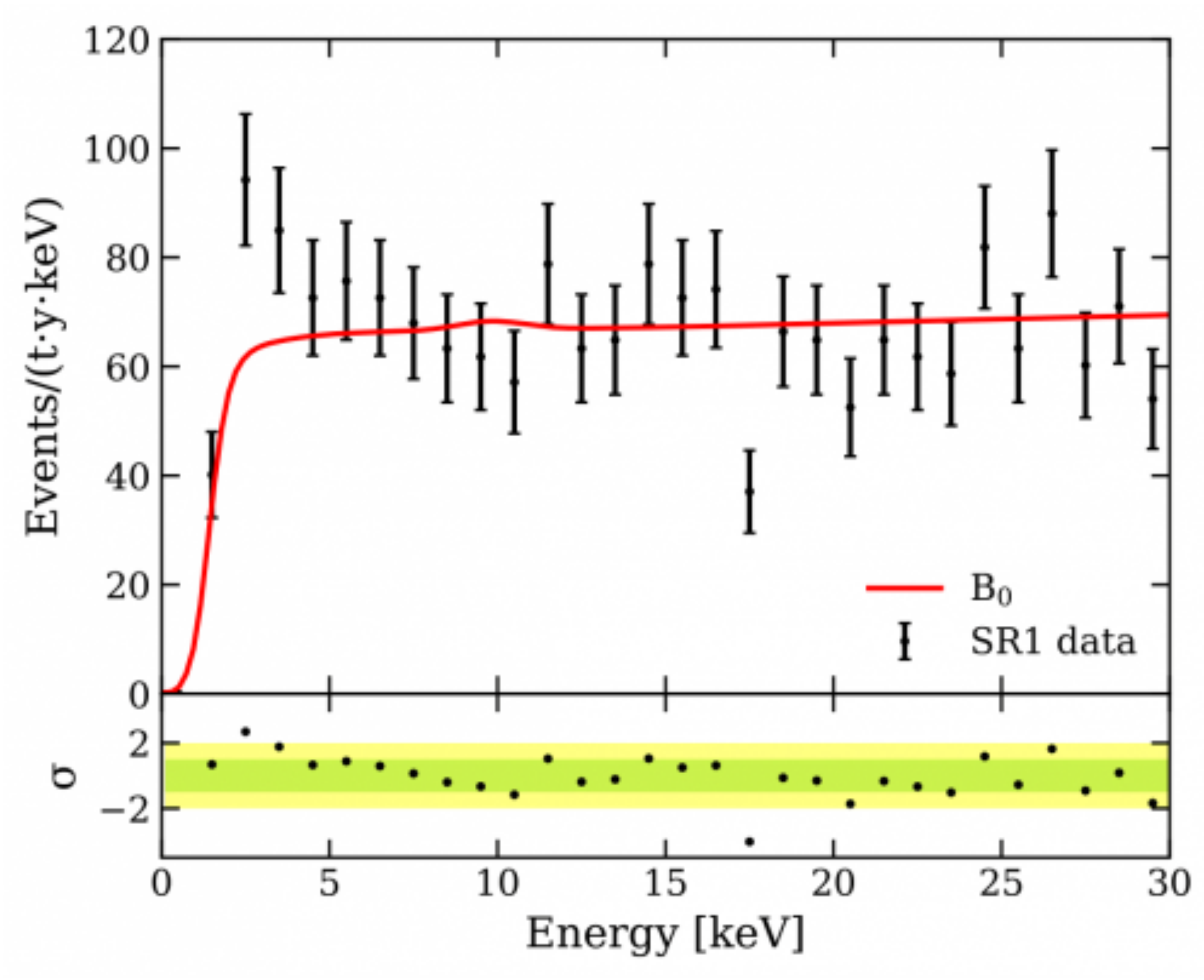
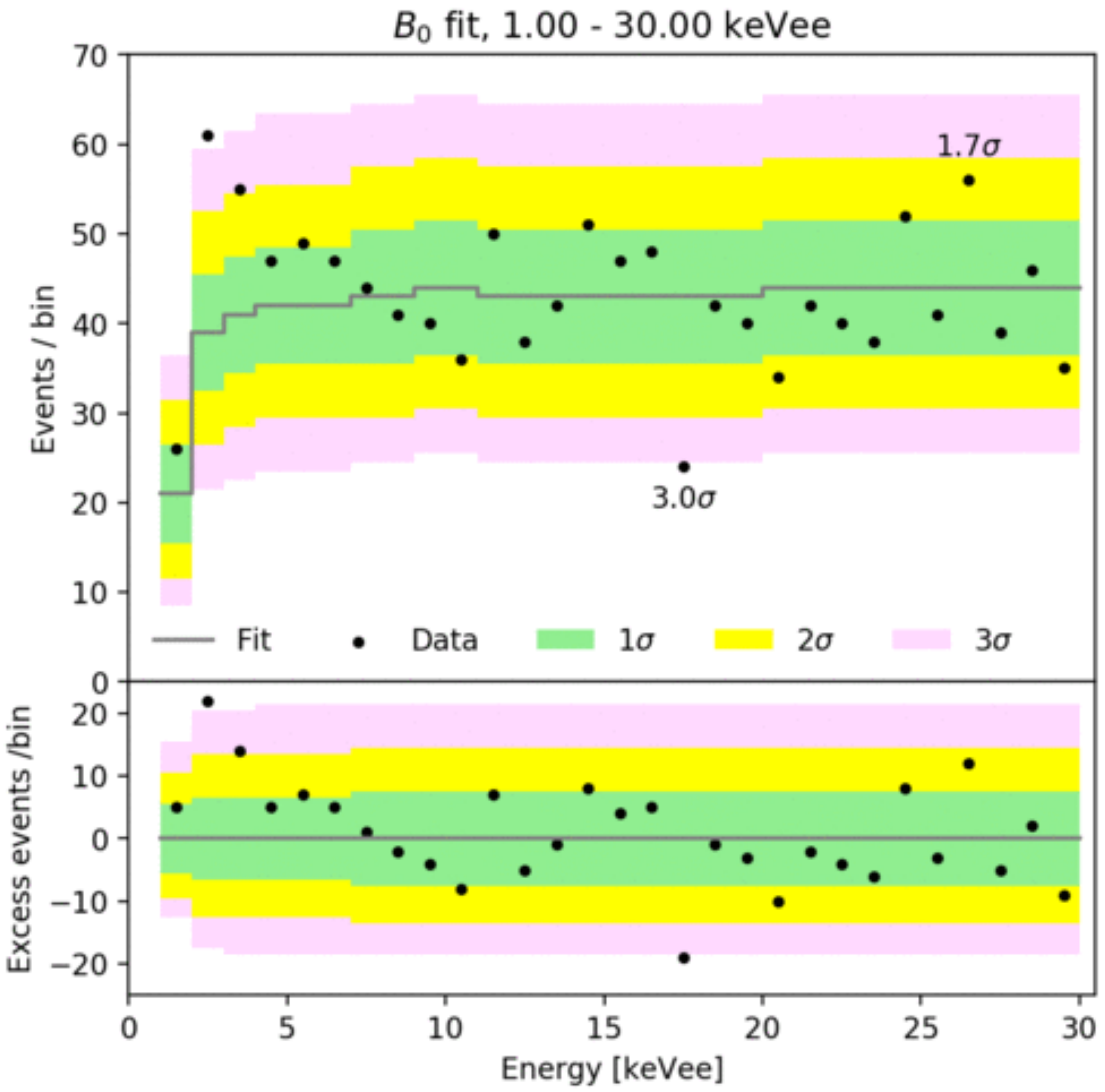


Isn't the dip around 17 keV odd?

Data between 2 keV and 10 keV falling steadily?

Single-bin outliers boosted in local p-value, but need to compare to global p-value of excess



We use an unbinned profile-likelihood analysis

Statistical fluctuations and binning artefacts

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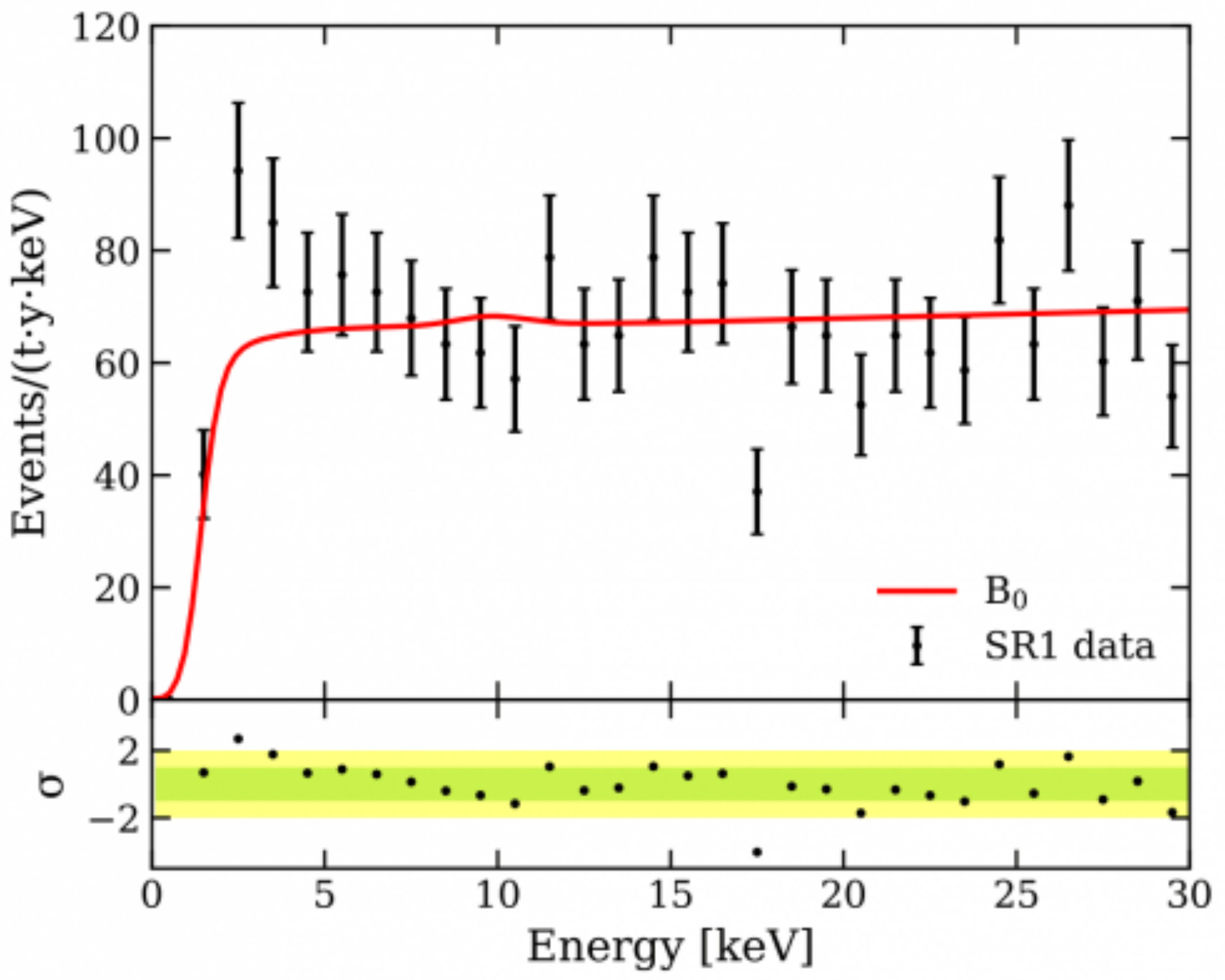

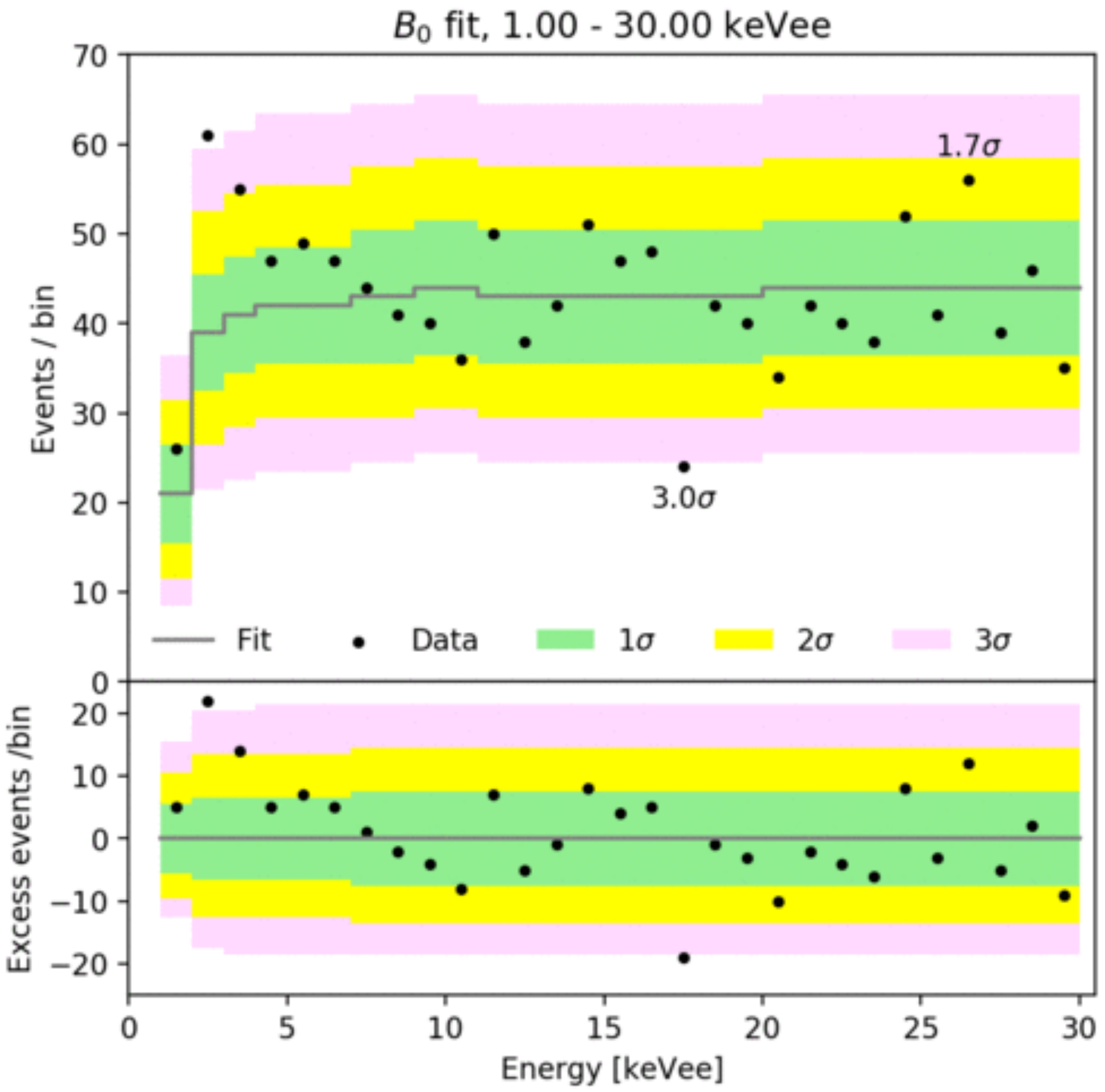

Isn't the dip around 17 keV odd?

Data between 2 keV and 10 keV falling steadily?

Single-bin outliers boosted in local p-value, but need to compare to global p-value of excess

We use an unbinned profile-likelihood analysis

Is it a *new* background?

Tritium background hypothesis

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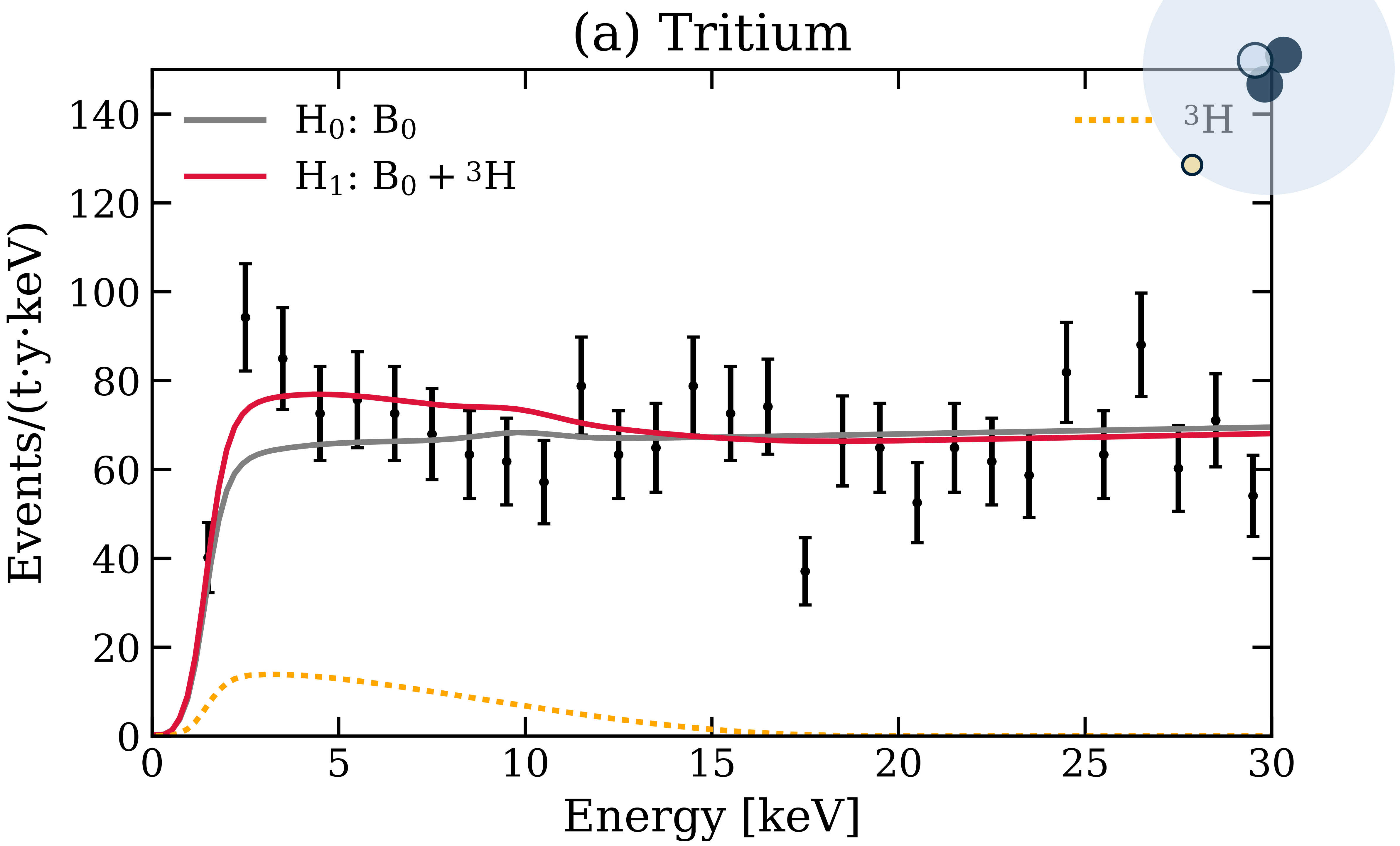
Low energy β-decay with Q-value of 18.6 keV

Long half-life of 12.3 years

Atmospherically abundant and cosmogenically produced in xenon

Removed by the continuous gas purification

Best fit: (159 ± 51) events/keV/t/yr



$$(6.2 \pm 2.0) \cdot 10^{-25} \frac{\text{mol}}{\text{mol}}$$

Less than three ^{3}H atoms per kg Xe

Tritium favored over background at 3.2σ

Tritium from cosmogenic activation

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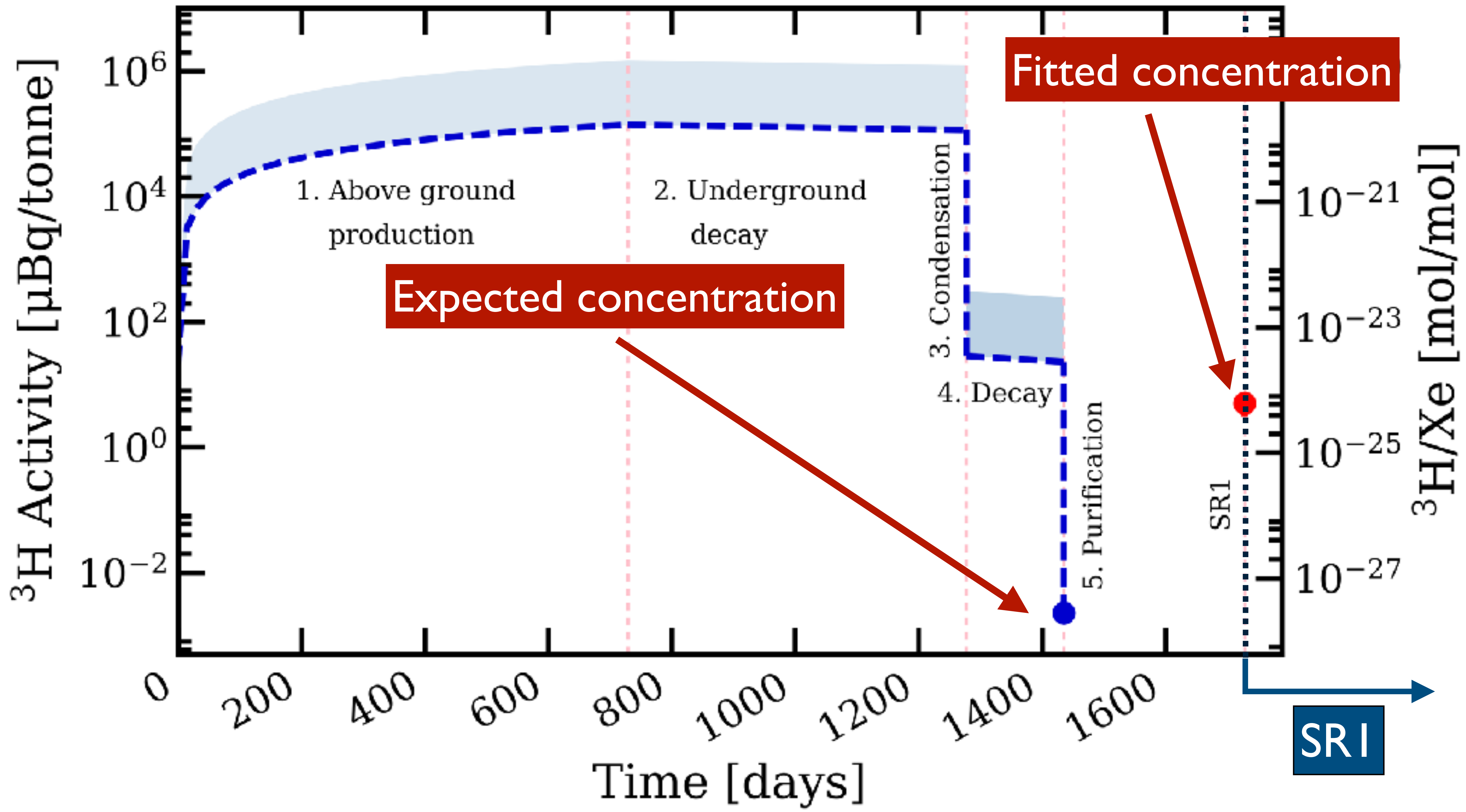
Xe spallation produces ^3H: 31.58/kg/d (C. Zhang et al. 2016)

Measured H_2O abundance in Xe bottles suggests HTO as dominant species

Estimate concentration from activation and its evolution through Xe handling



Estimated tritium activity. Not measurements.

Tritium from natural abundance in materials

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Any ^3H in Xe would be removed prior to filling

^3H could be contained within detector materials as HT (H_2) and HTO (H_2O)

Could be emanated from materials in equilibrium with online removal?

Would require **60 - 120 ppb** as the combined **H_2O + H_2** concentration in Xe

H_2O/Xe

O(1) ppb from light yield measurement

H_2

Not constrained by measurement, but O_2 equivalent concentration **< ppb** from Xe purity

100 x higher emanation rate needed than for electronegative impurities

Additional tritium uncertainties

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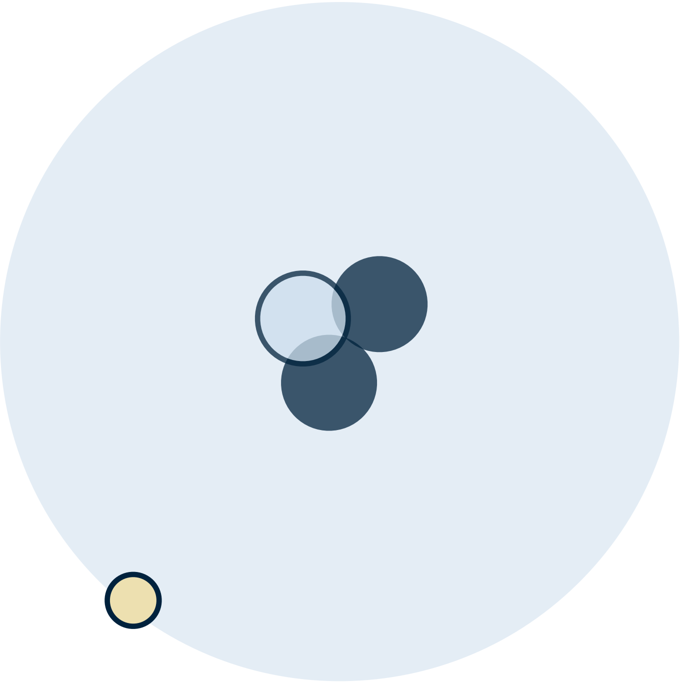
Unknown radiochemistry of ^{3}H in liquid xenon environment

Presence of tritiated molecules?

Underground activation inside the detector from fast neutrons?



Cosmogenic activation
Unlikely

Atmospheric abundance in materials
Maybe

Can neither confirm nor rule out tritium hypothesis

Report significances of other signals with and without tritium included in the background model

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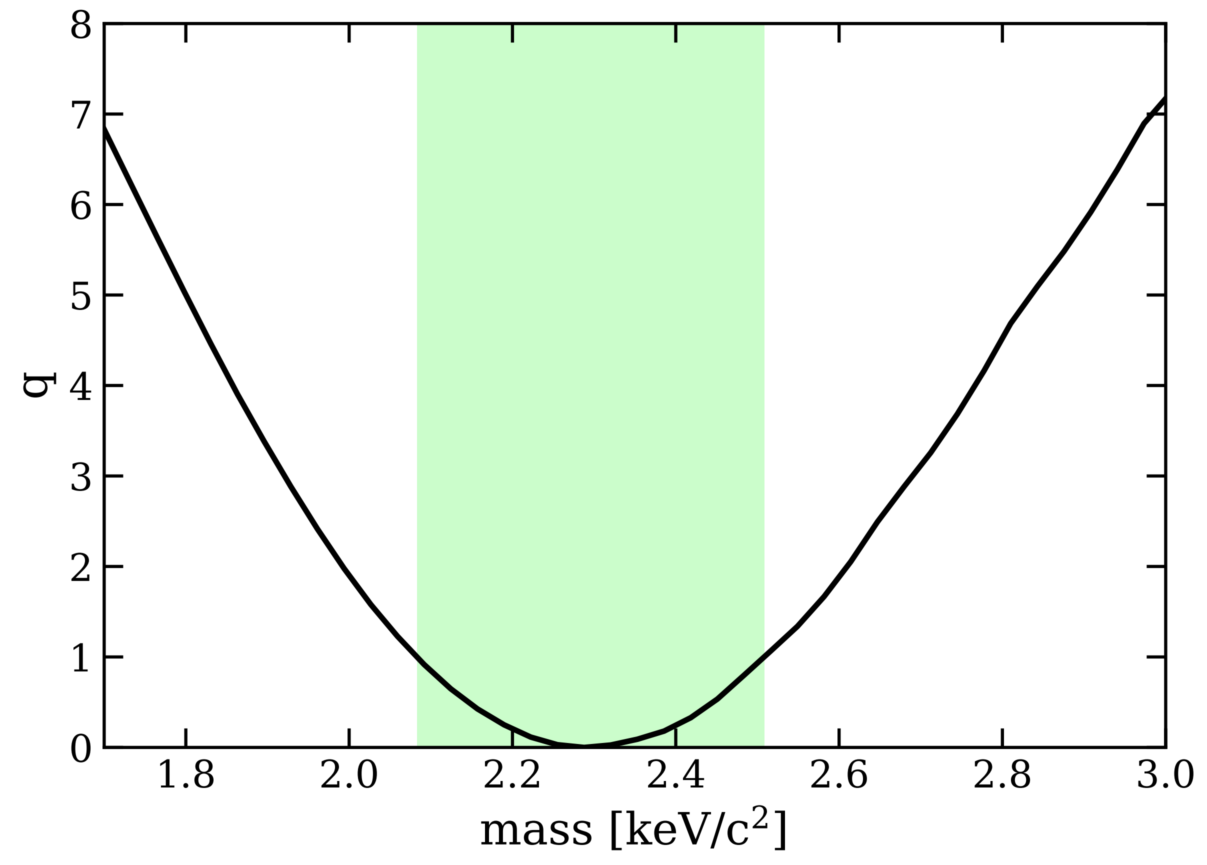
^{37}Ar K-electron capture with 2.8 keV energy released as X-rays and Auger electrons

C.f. best fit for bosonic Dark Matter (monoenergetic peak) at 2.3 keV



Air leak	**Kr distillation and activity**
Thermal neutron activation	**Under investigation, but no apparent correlation with neutron calibrations**
Cosmic activation of ^{40}Ca in PTFE	**Under investigation**

Additional checks

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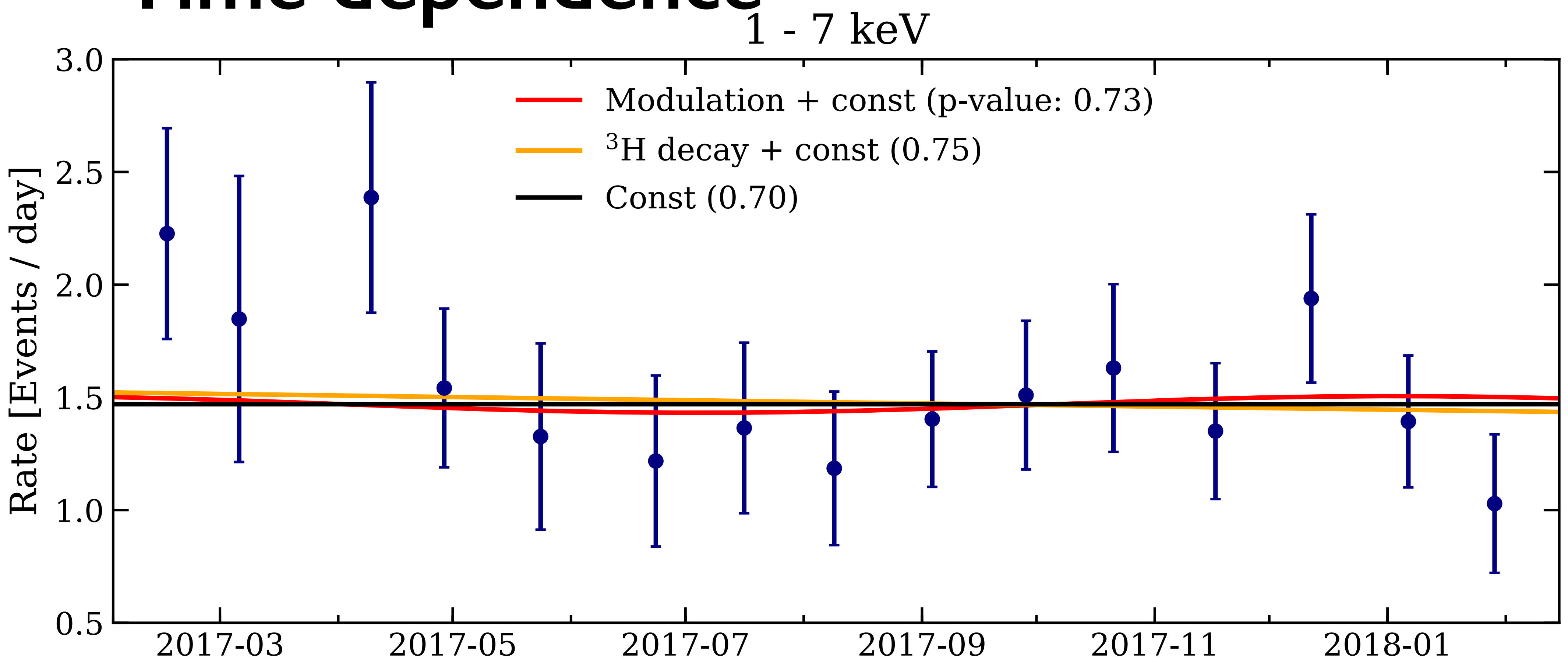
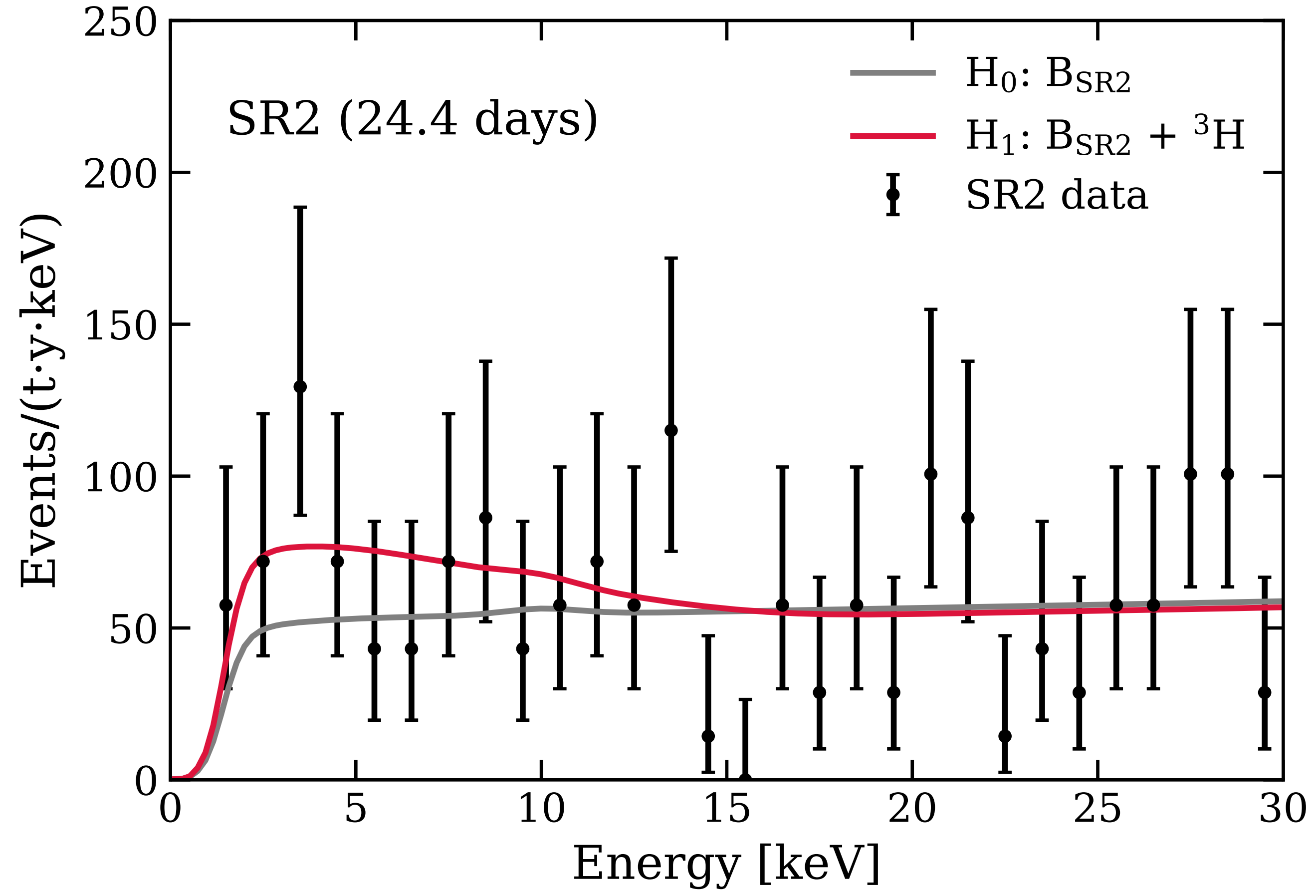
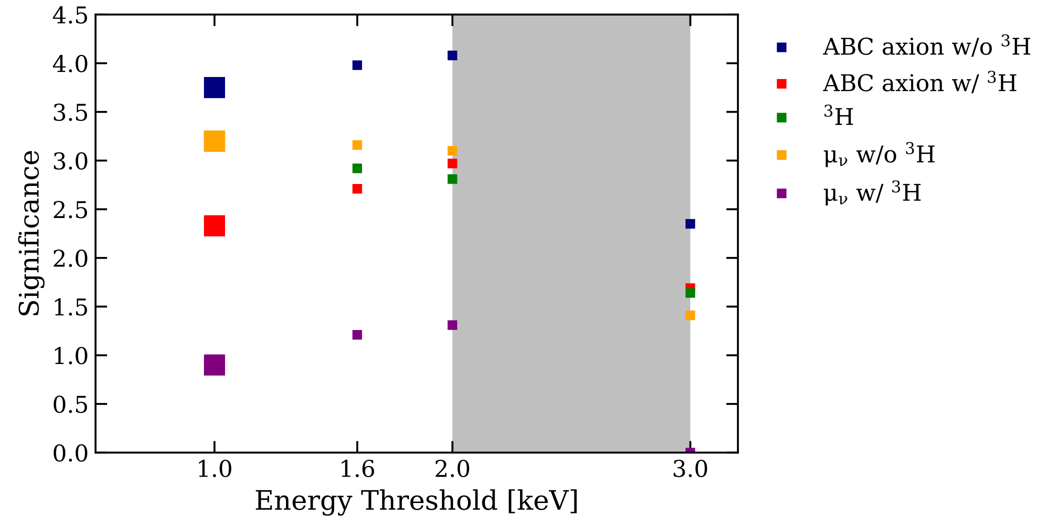
Time dependence



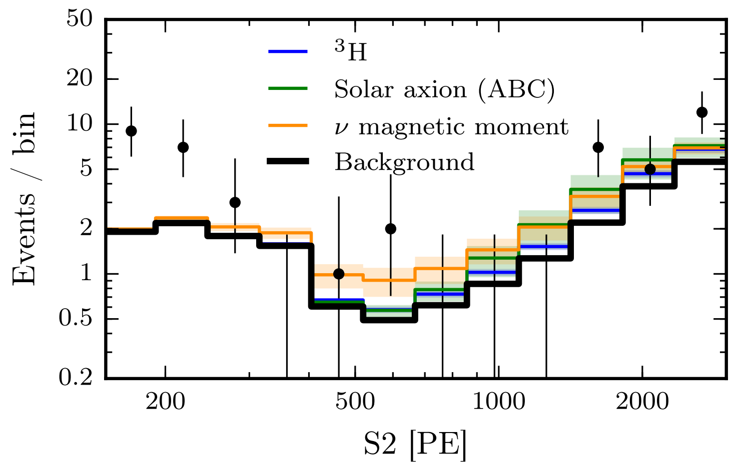
24.4 additional days of data



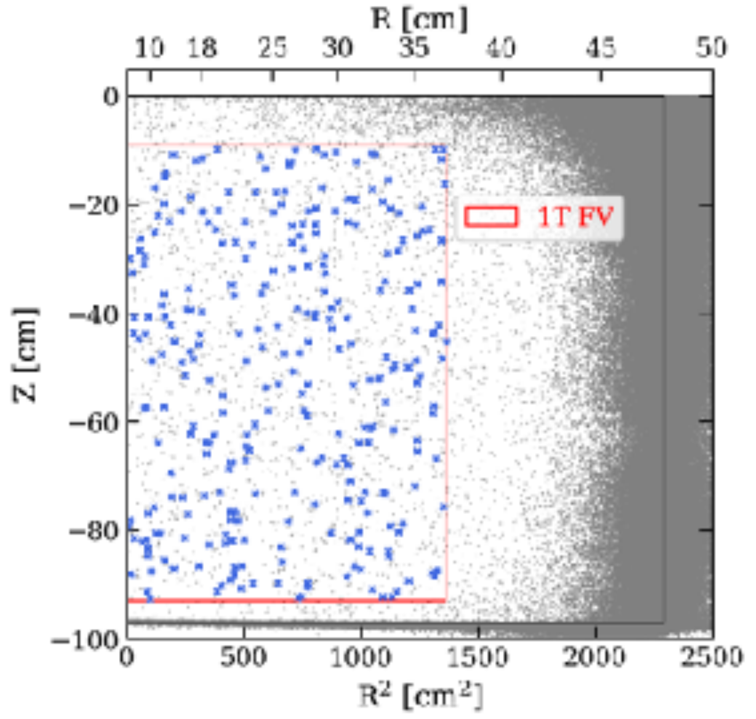
Threshold effects

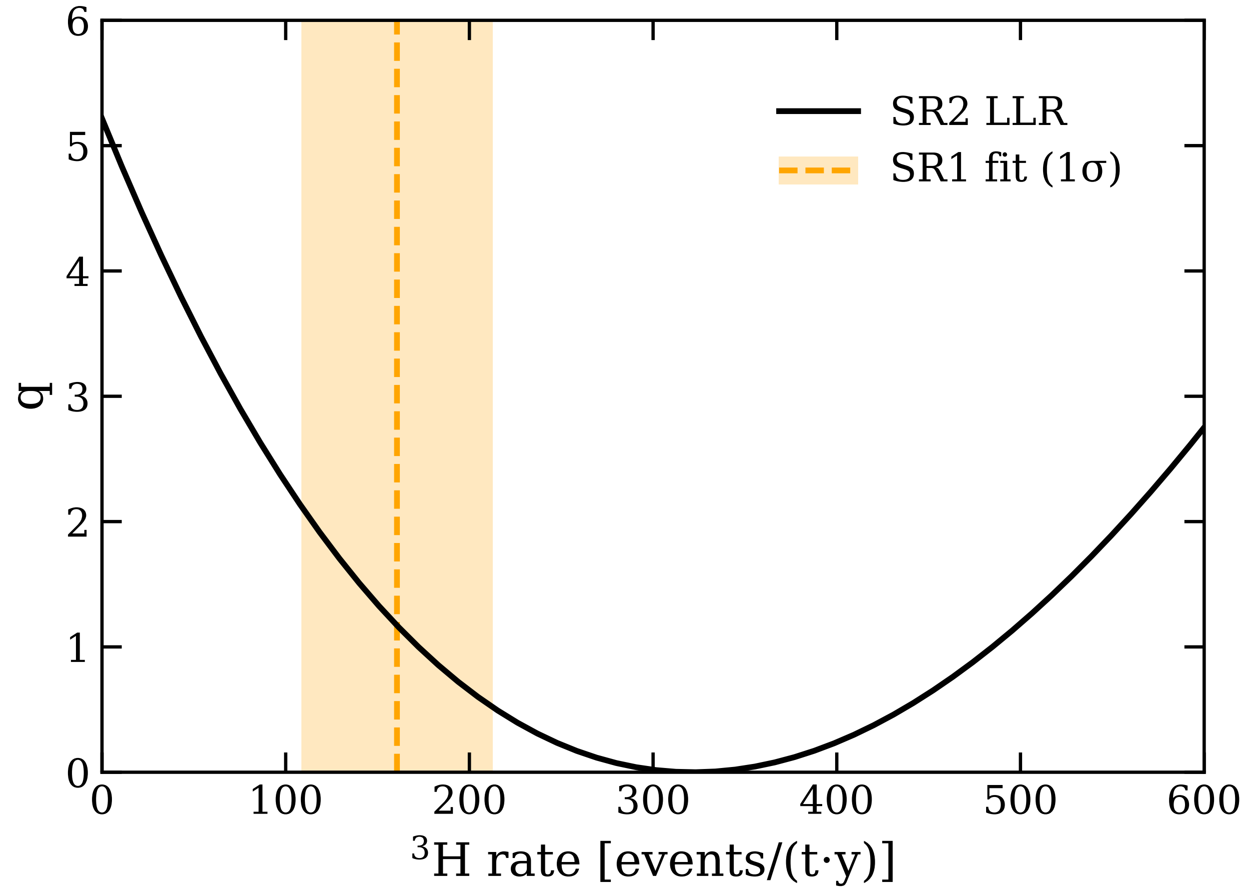


S2-only

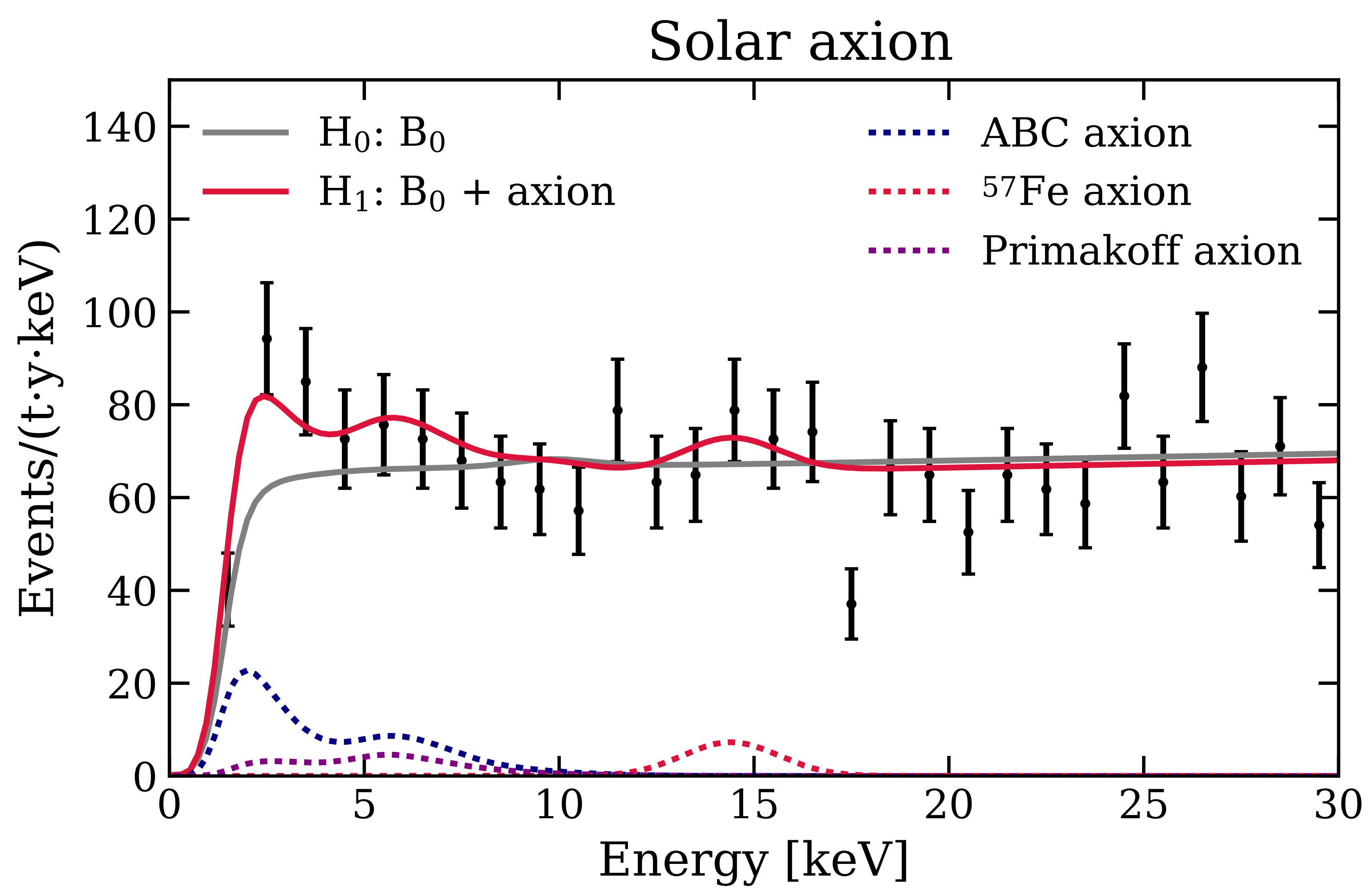


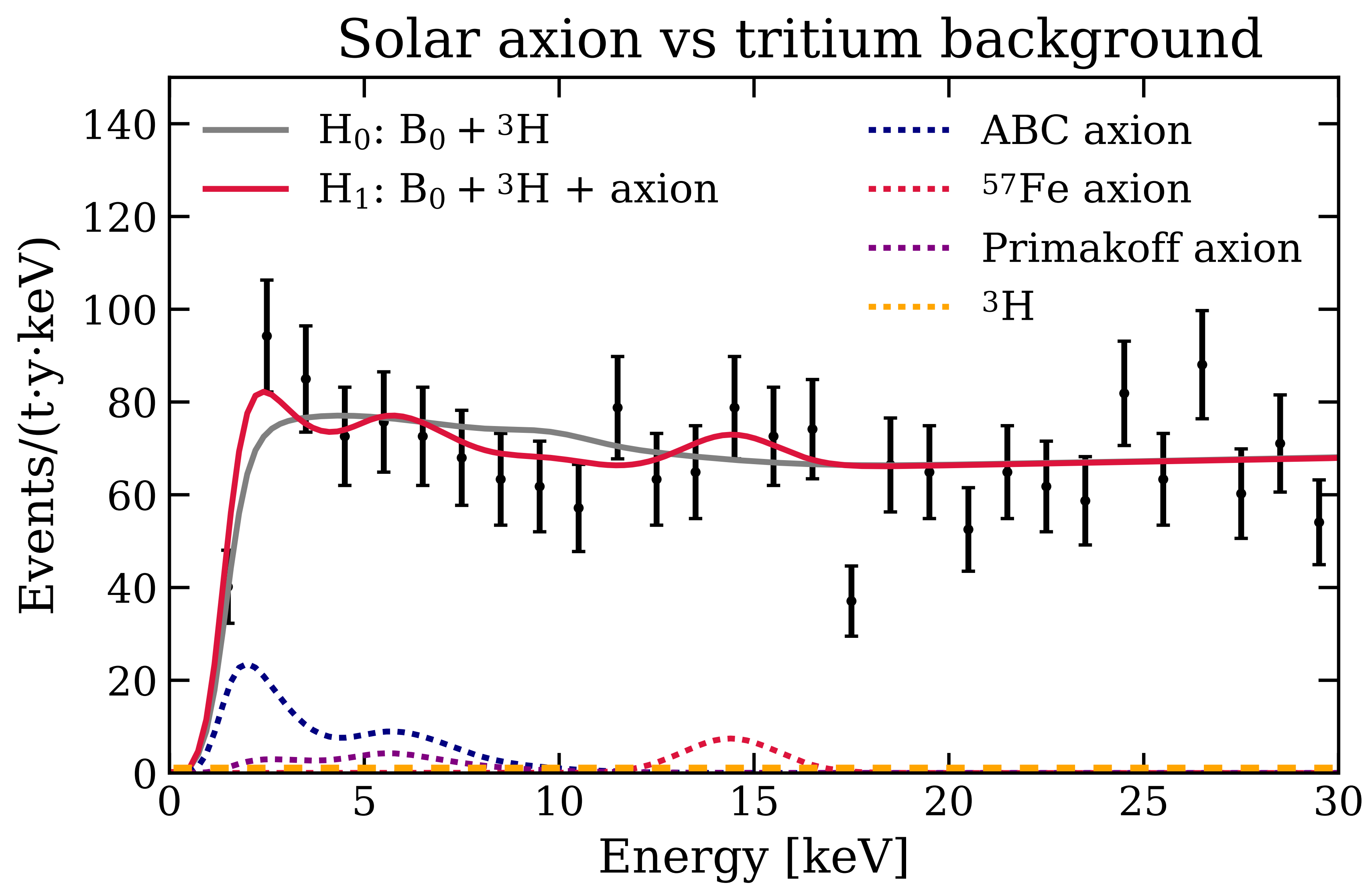
Spatial distribution





Check the signal models



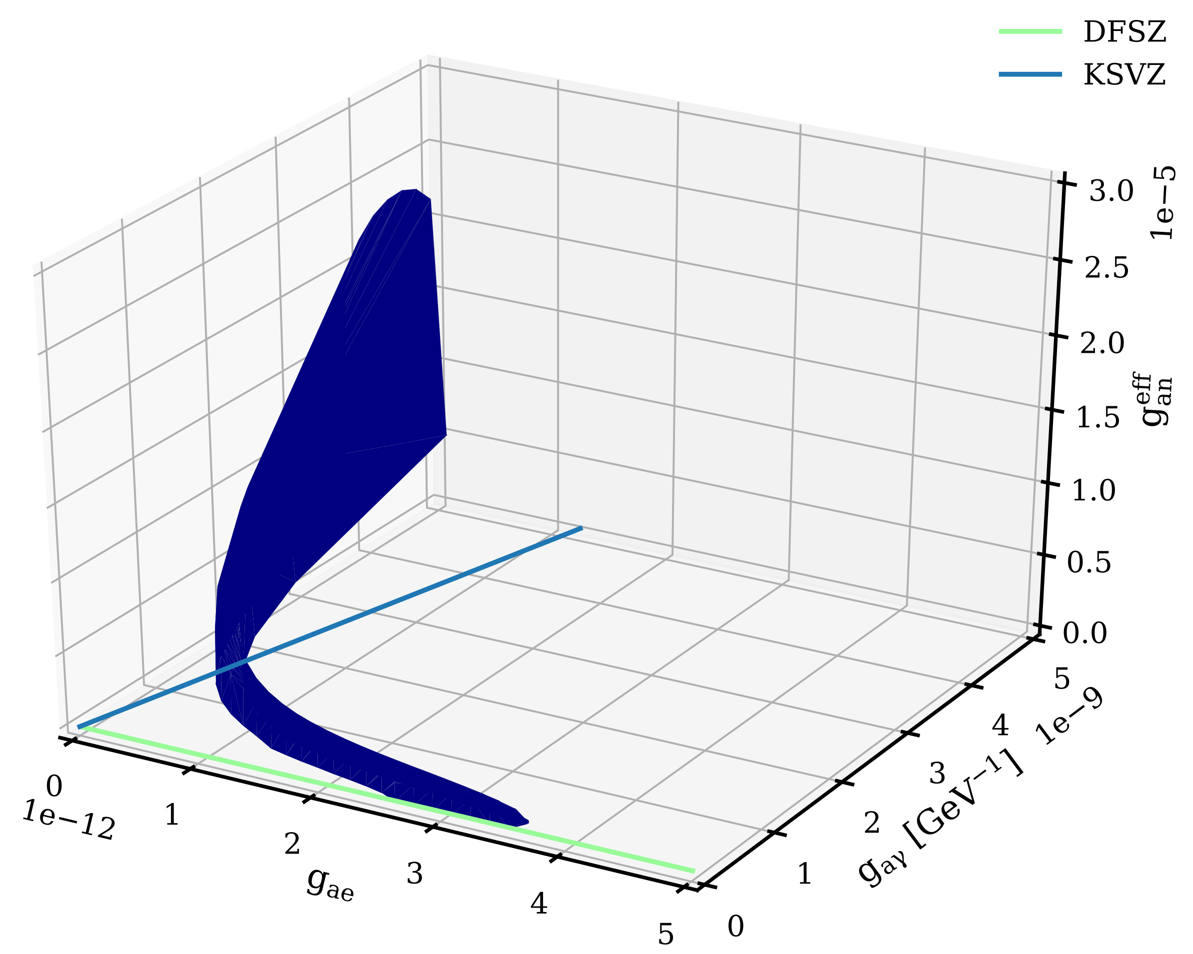


Solar axion favored over background-only at **3.5σ**

Axion + ^{3}H favored **over** **^{3}H** hypothesis **at 2.1σ**

Three fit parameters for ABC, Primakoff and ^{57}Fe couplings

90 % confidence volume



Interpreting the confidence volume

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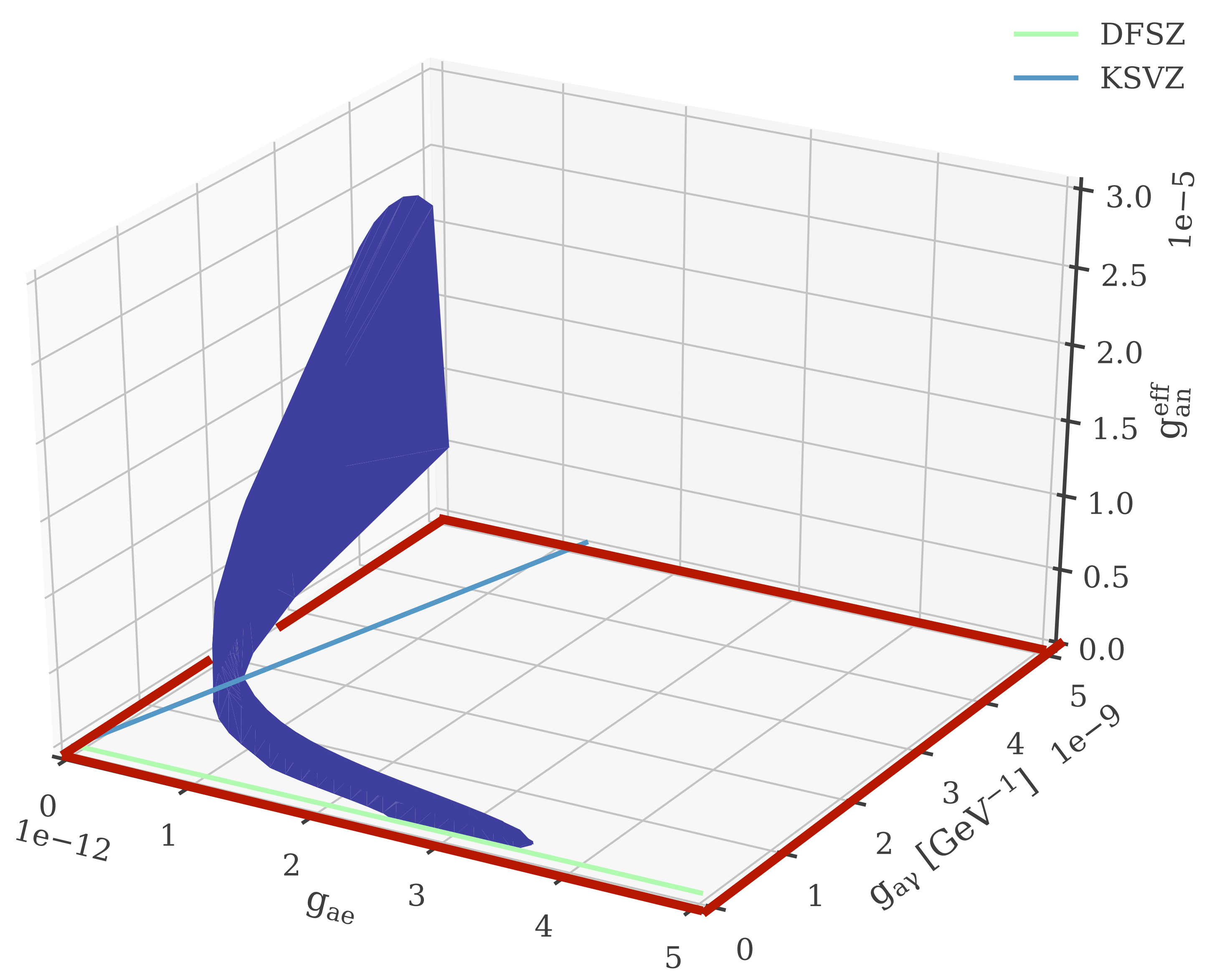
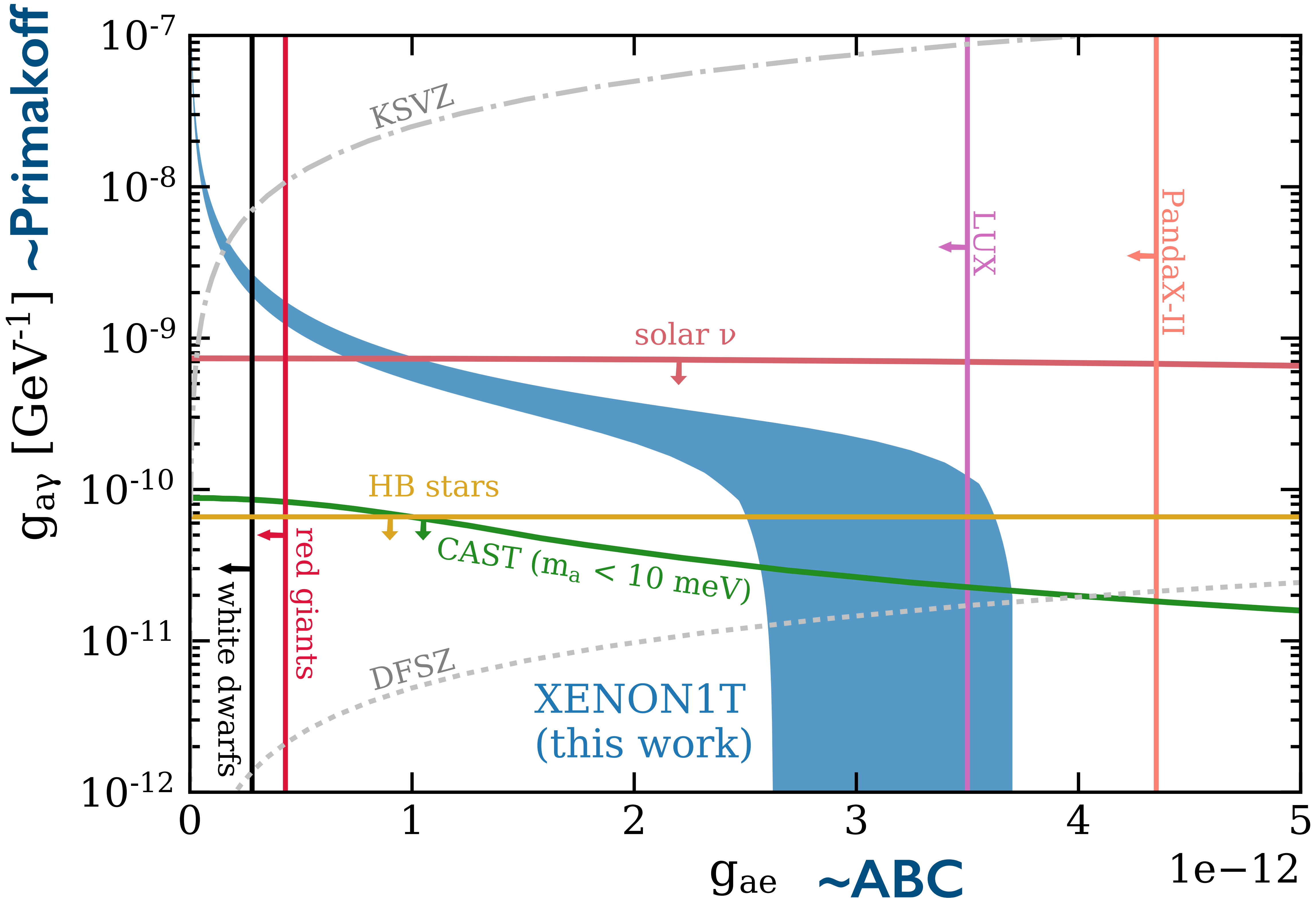
Project 90 % confidence volume onto 2D plane

Profile over ^{57}Fe as an example





Excludes either ABC=0 or Primakoff=0.

In tension with astrophysical constraints, e.g. from stellar cooling *(arXiv 1708.02111)*

Neutrino magnetic moment results

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Single fit parameter **μ_ν**

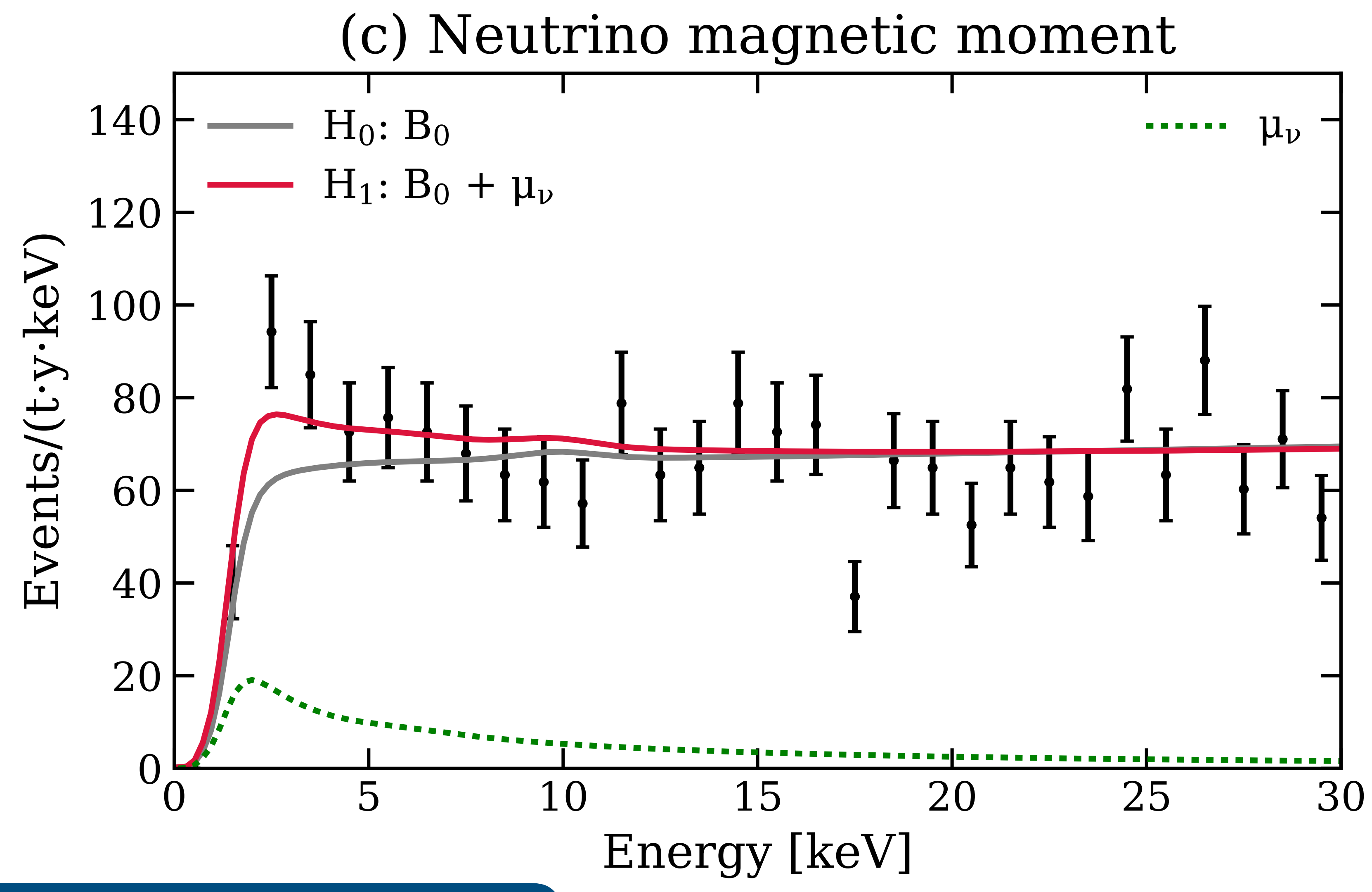
Neutrino magnetic moment favored over background only at **3.2σ**

Significance decreases to **0.9σ** when tritium is included in the background model

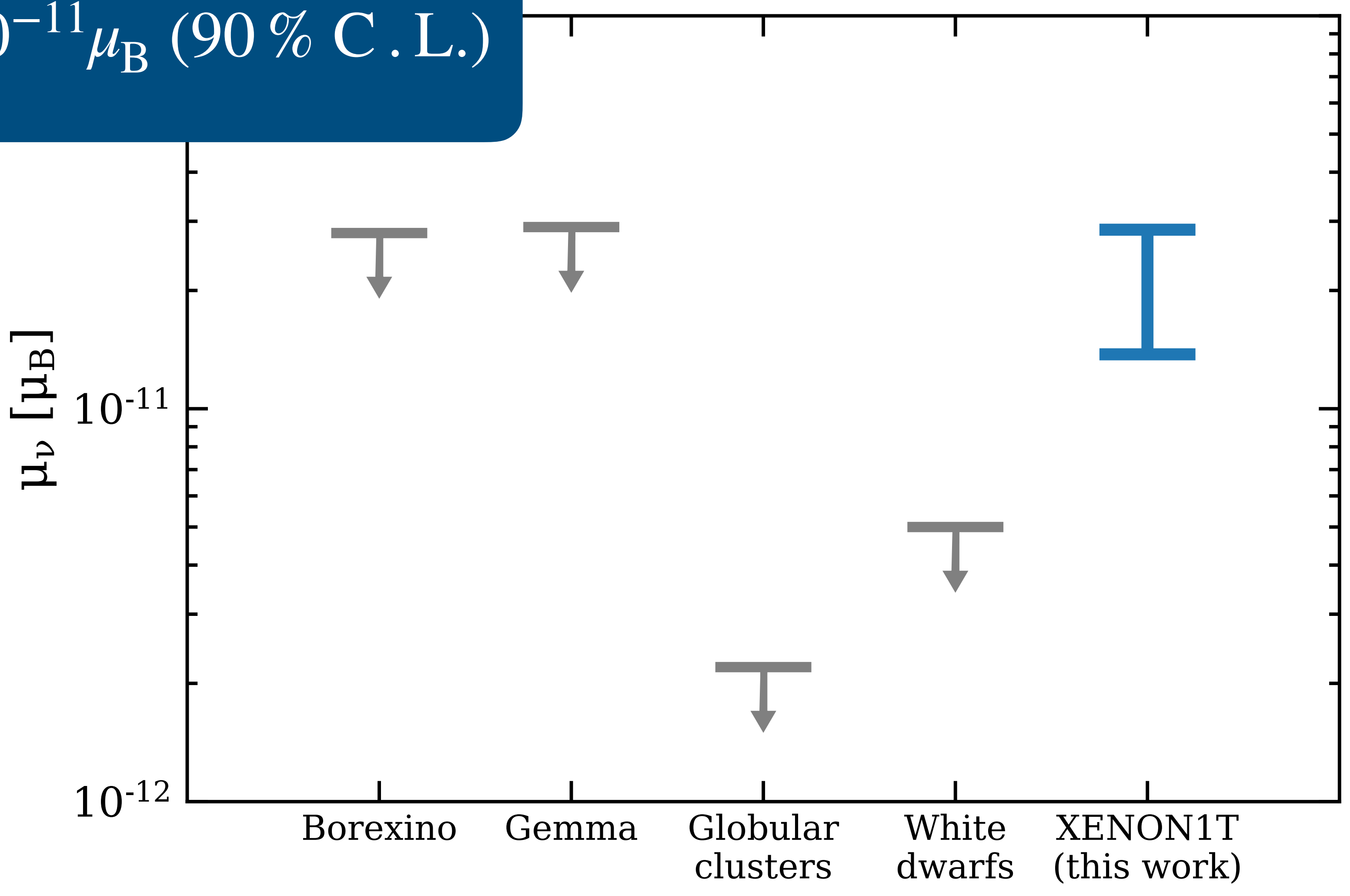
Compatible with other experiments, but in tension with astrophysical constraints

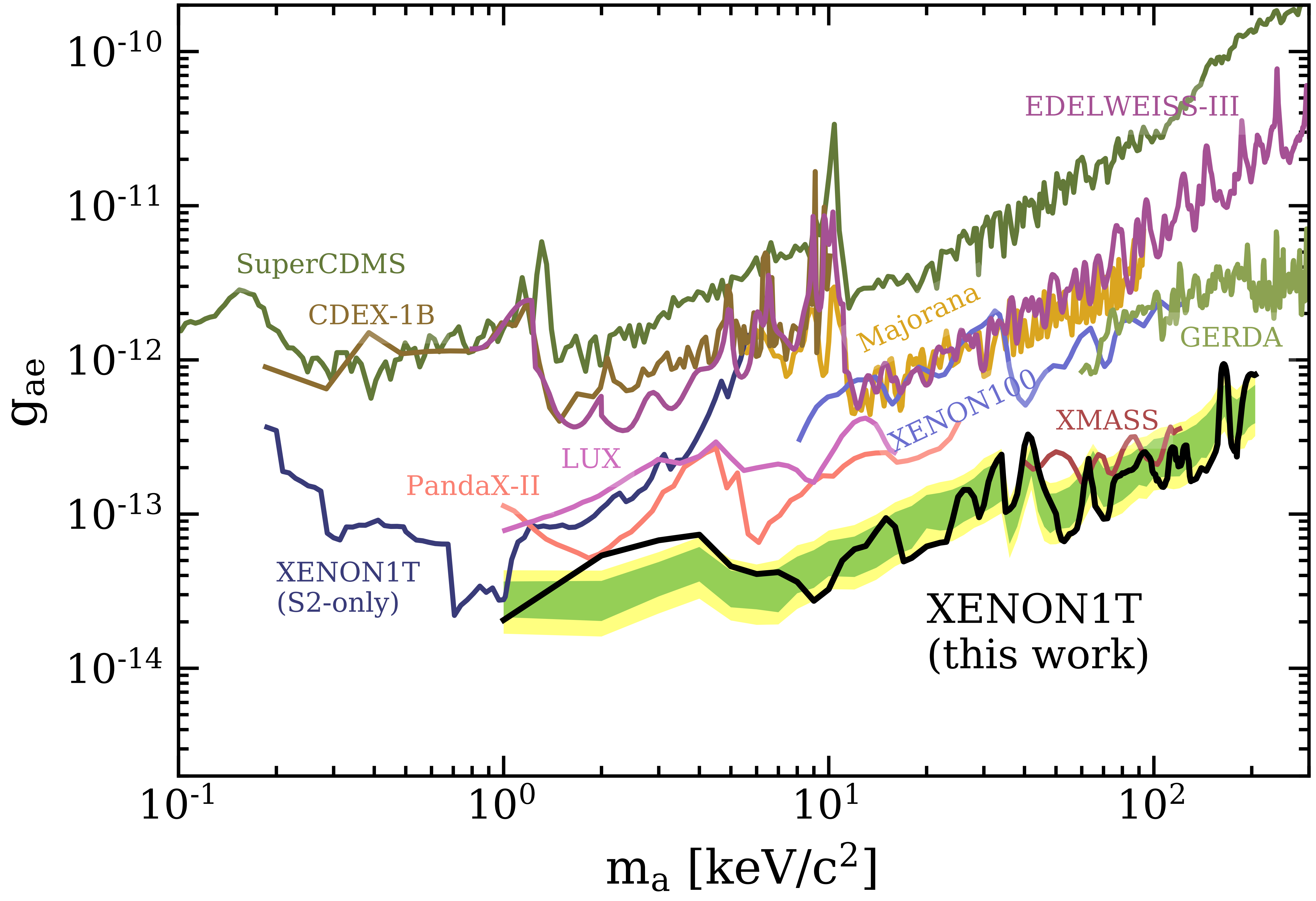
arXiv 1910.10568

arXiv 1907.00115

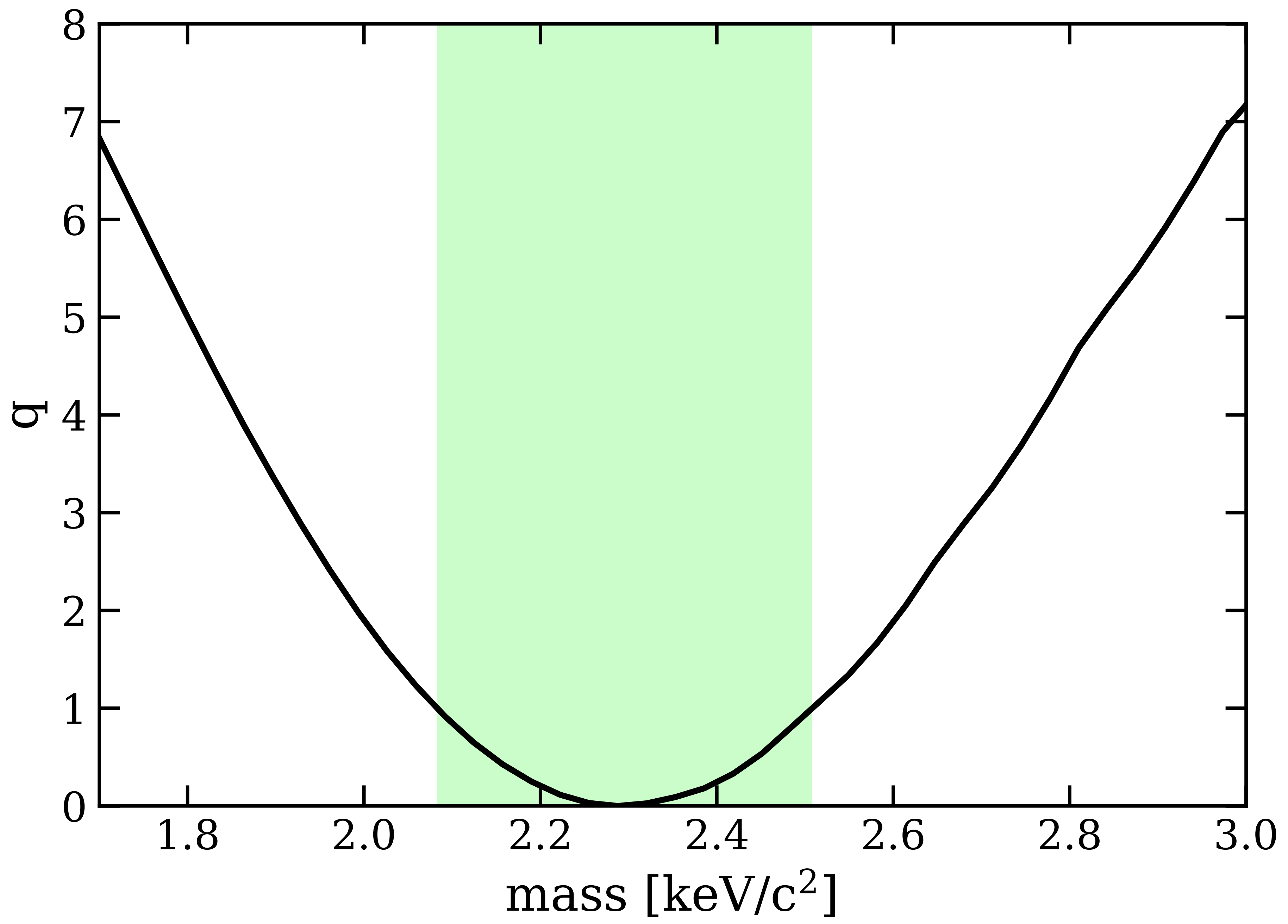


$\mu_\nu \in [1.4, 2.9] \cdot 10^{-11} \mu_B$ (90 % C.L.)





2.3 +/- 0.2 keV
3.0σ (global)



Summary of hypotheses and significances

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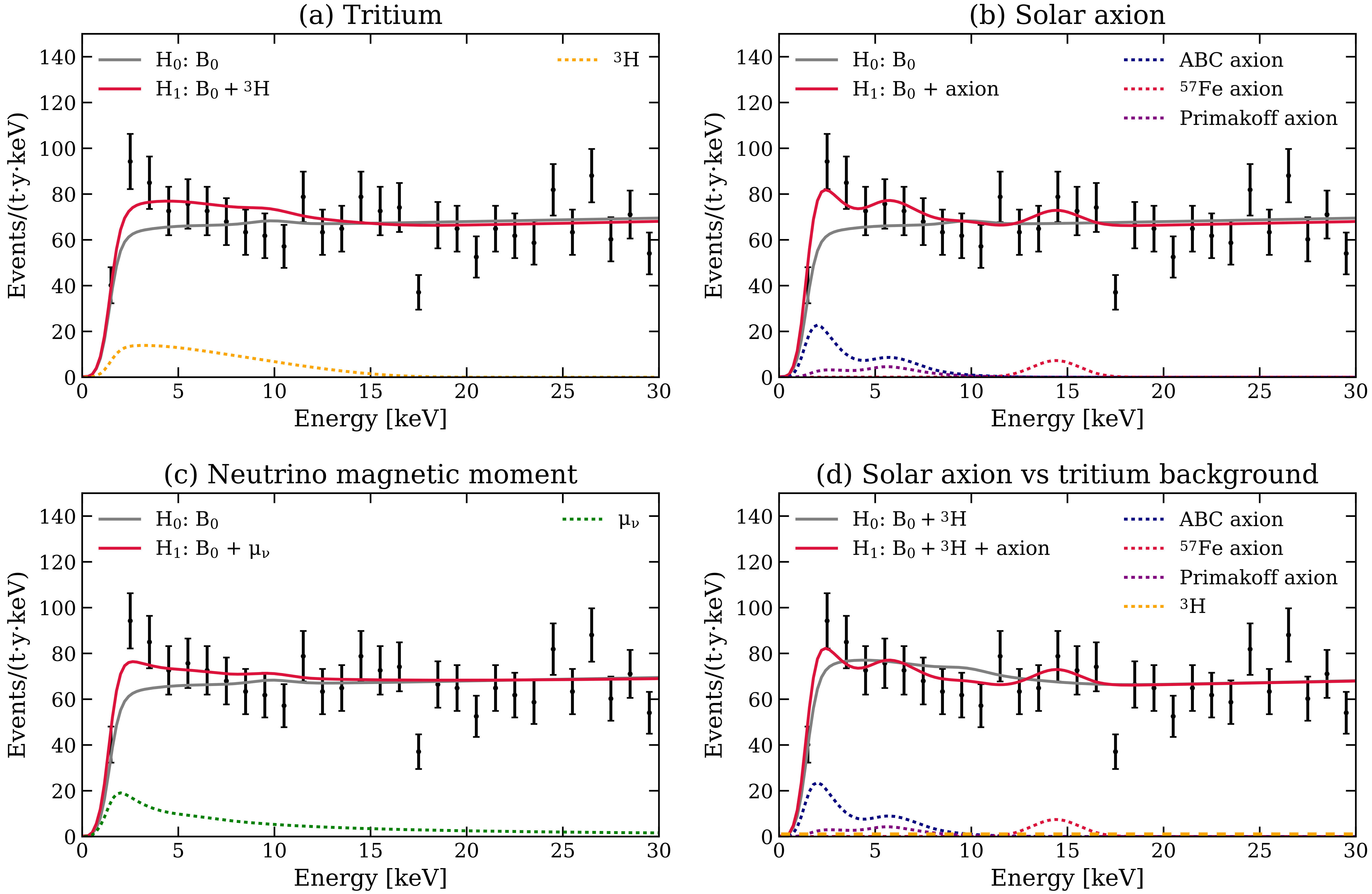
Tritium favored over background-only at **3.2σ**

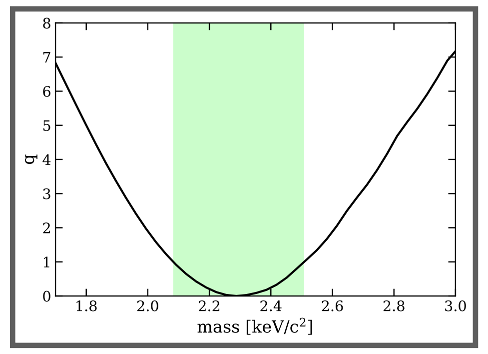


Solar axion favored over background-only at **3.5σ**

Neutrino magnetic moment favored over background-only at **3.2σ**

Axion + ^{3}H favored **over ^{3}H** hypothesis **at 2.1σ**

Monoenergetic peak at 2.3 ± 0.2 keV favored over background-only at **3.0σ (global)**



So, to conclude…

… our results can still be interpreted with various hypothesis.

But that might not be for long.

Outlook to XENONnT

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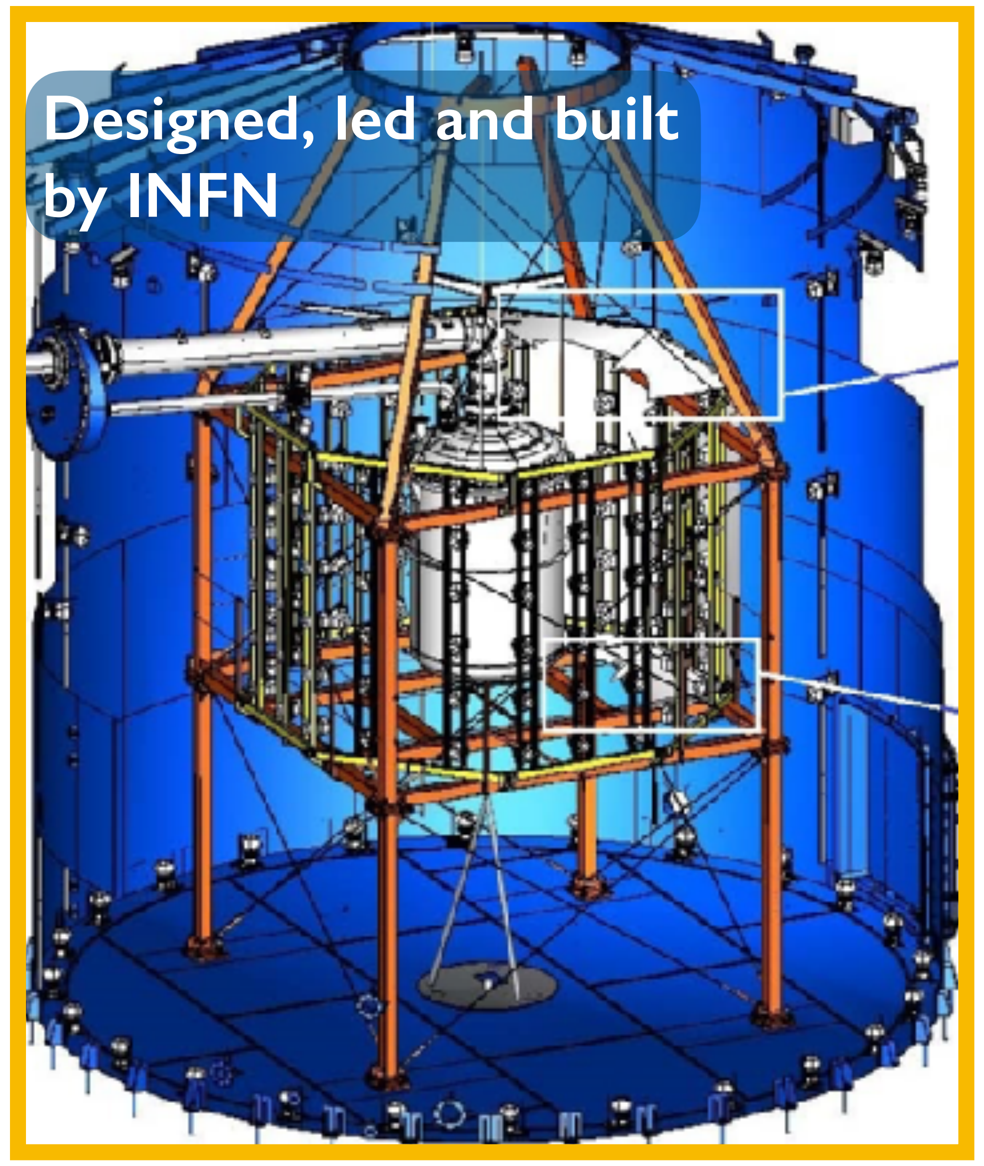


Neutron veto

- Inner region of existing muon veto
- optically separate
- 120 additional PMTs
- Gd in the water tank
- 0.5 % $Gd_2(SO_4)_3$

Larger TPC

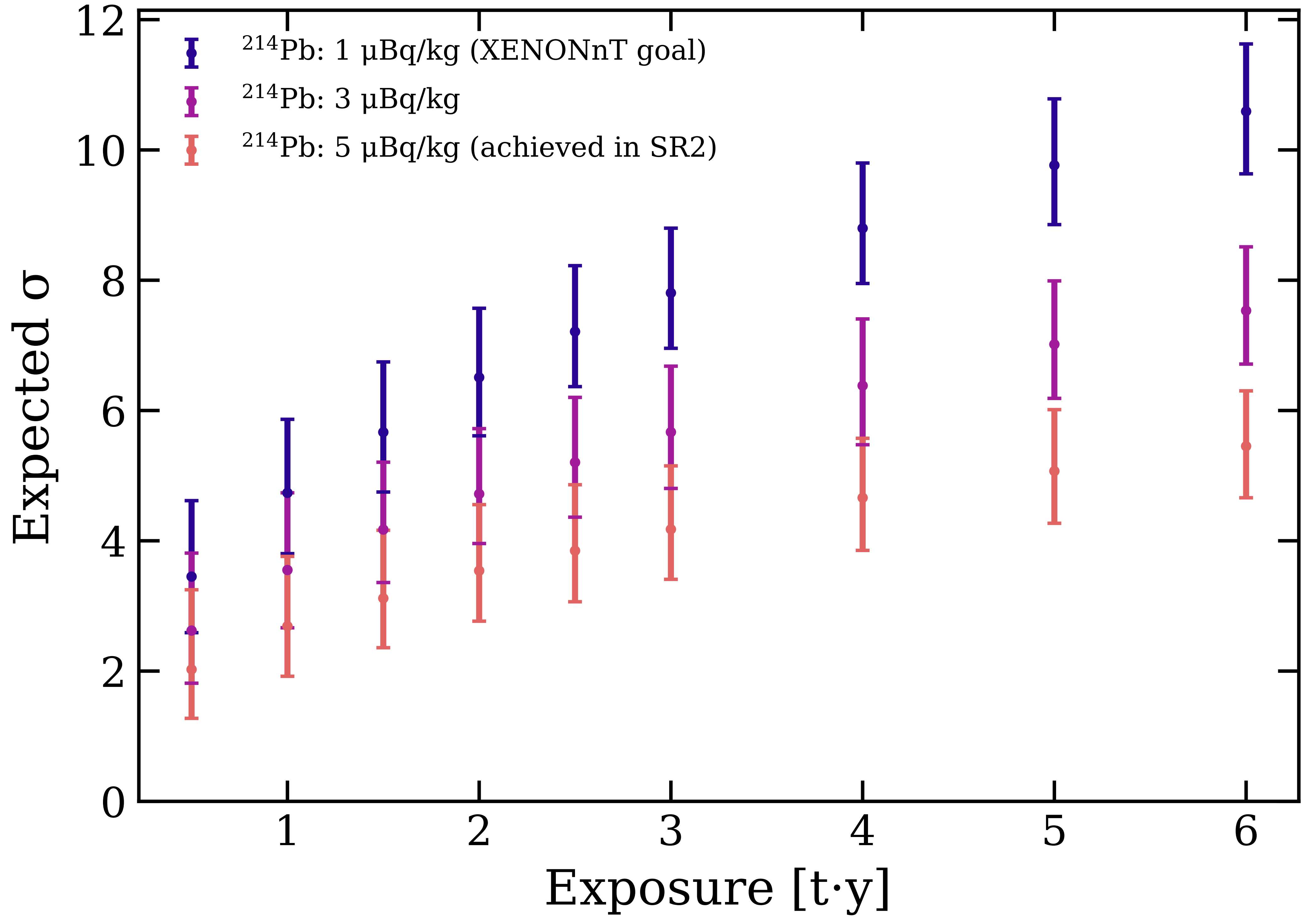
- Total 8.4 t LXe
- 5.9 t in TPC
- ~ 4 t fiducial
- 248 → 494 PMTs

^{222}Rn distillation

- Reduce Rn (^{214}Pb) from pipes, cables, cryogenic system
- New system, PoP in XENON1T

LXe purification

- Faster xenon cleaning
- 5 L/min LXe (2500 slpm)
- XENON1T ~ 100 slpm



Commissioning ongoing

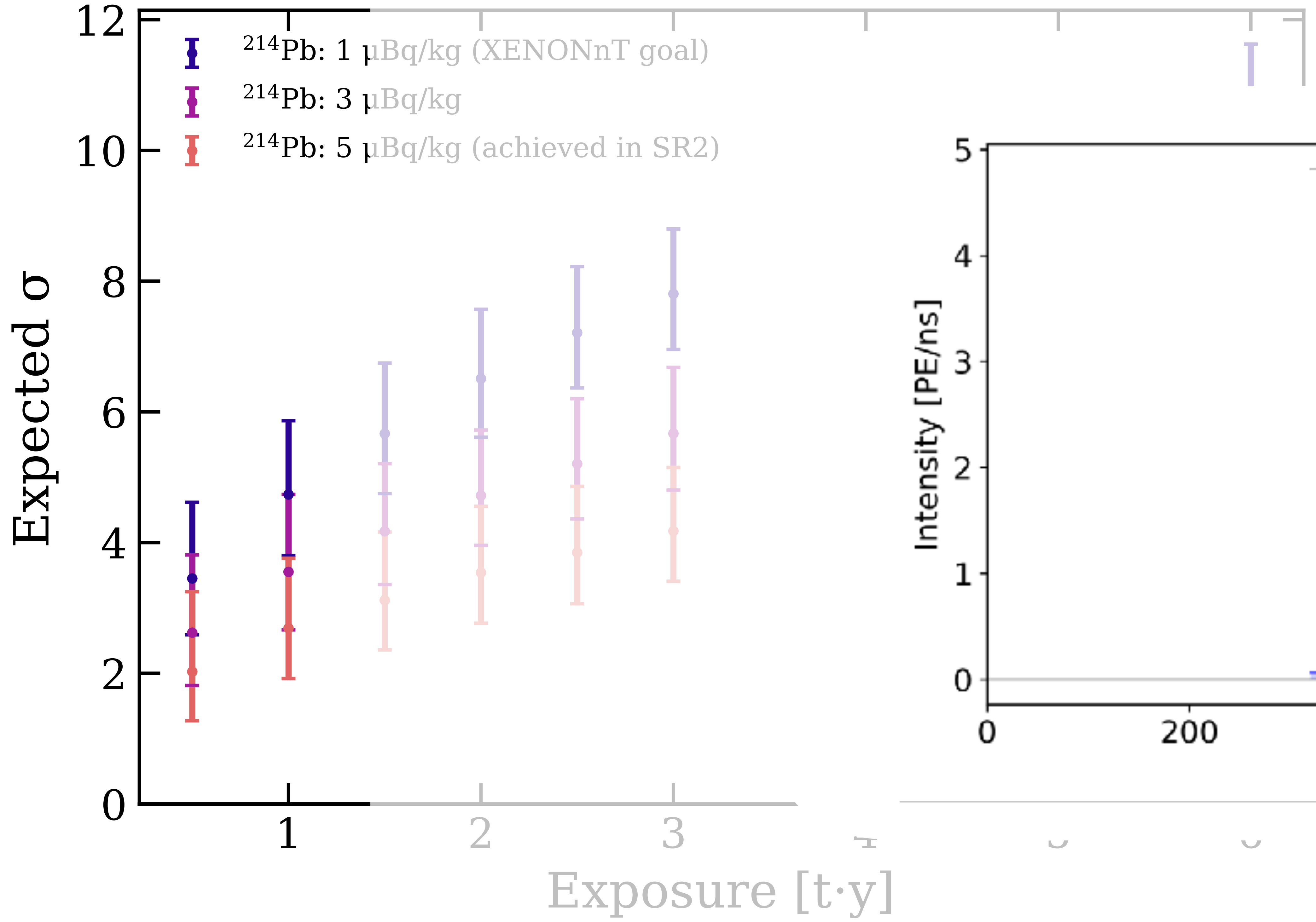
6 tonnes active mass (4 tonne fiducial)

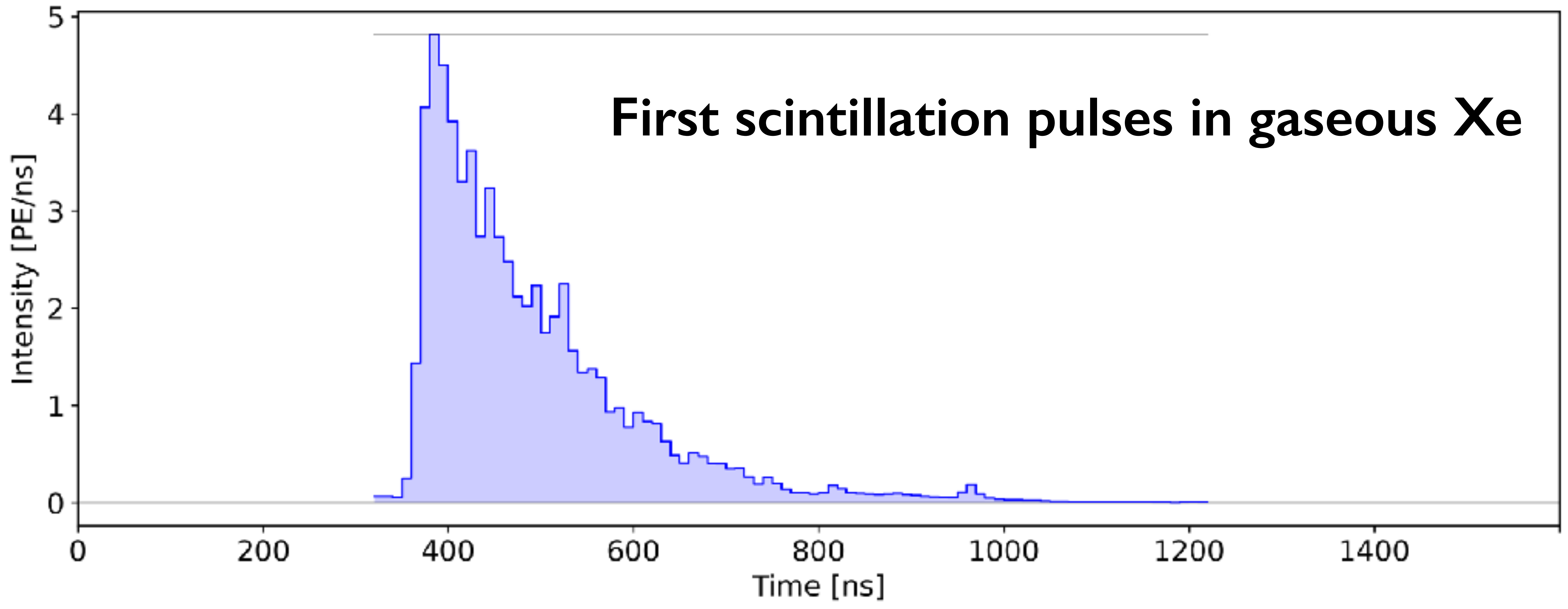
Background reduced to 1/6 of XENON1T with 1 μBq/kg concentration of ^{222}Rn

Baseline scenario: search based on energy only as presented here

Discriminate axion hypothesis from tritium with a few months of data

Commissioning ongoing





Discriminate axion hypothesis from tritium with a few months of data

Outlook to XENONnT

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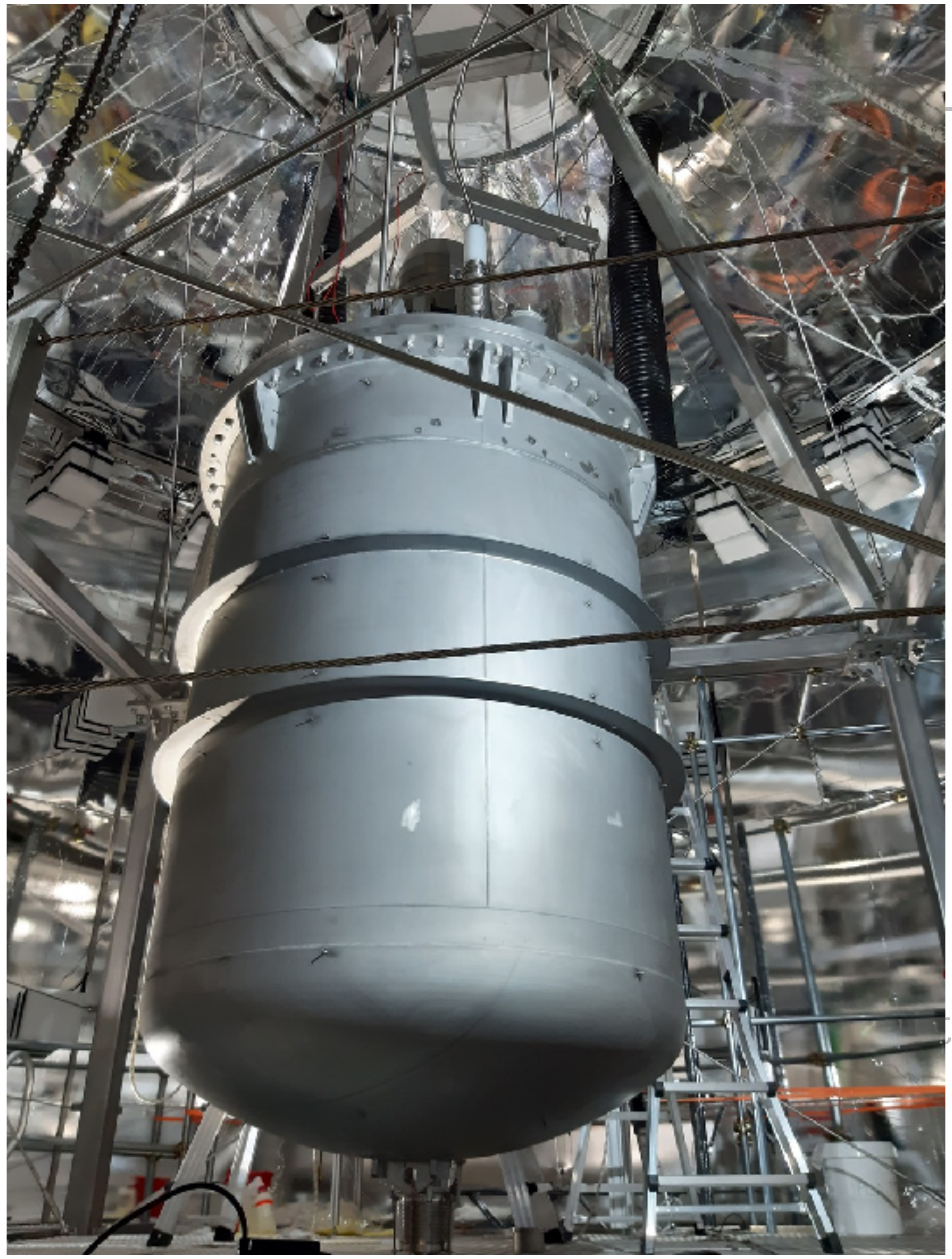
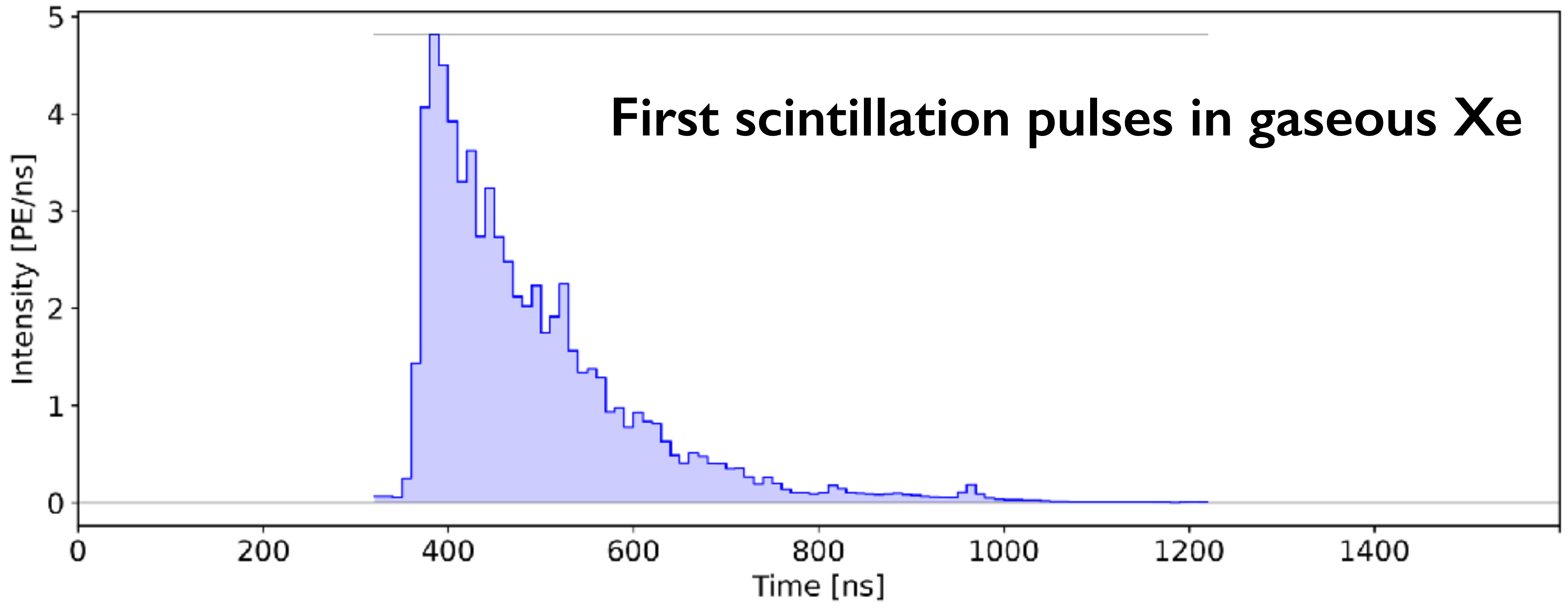


Commissioning ongoing



Discriminate axion hypothesis from tritium with a few months of data

Summary and conclusions

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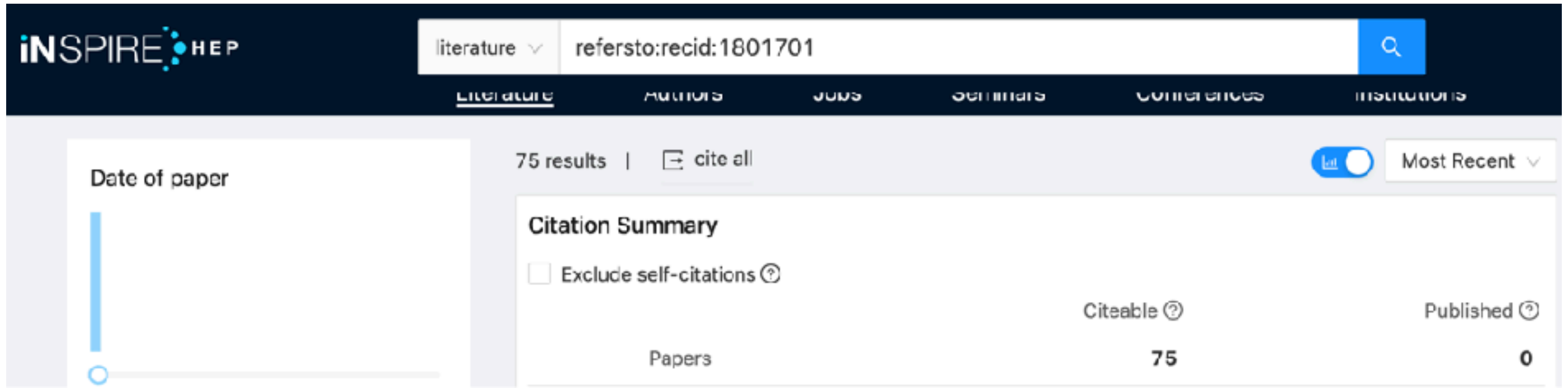
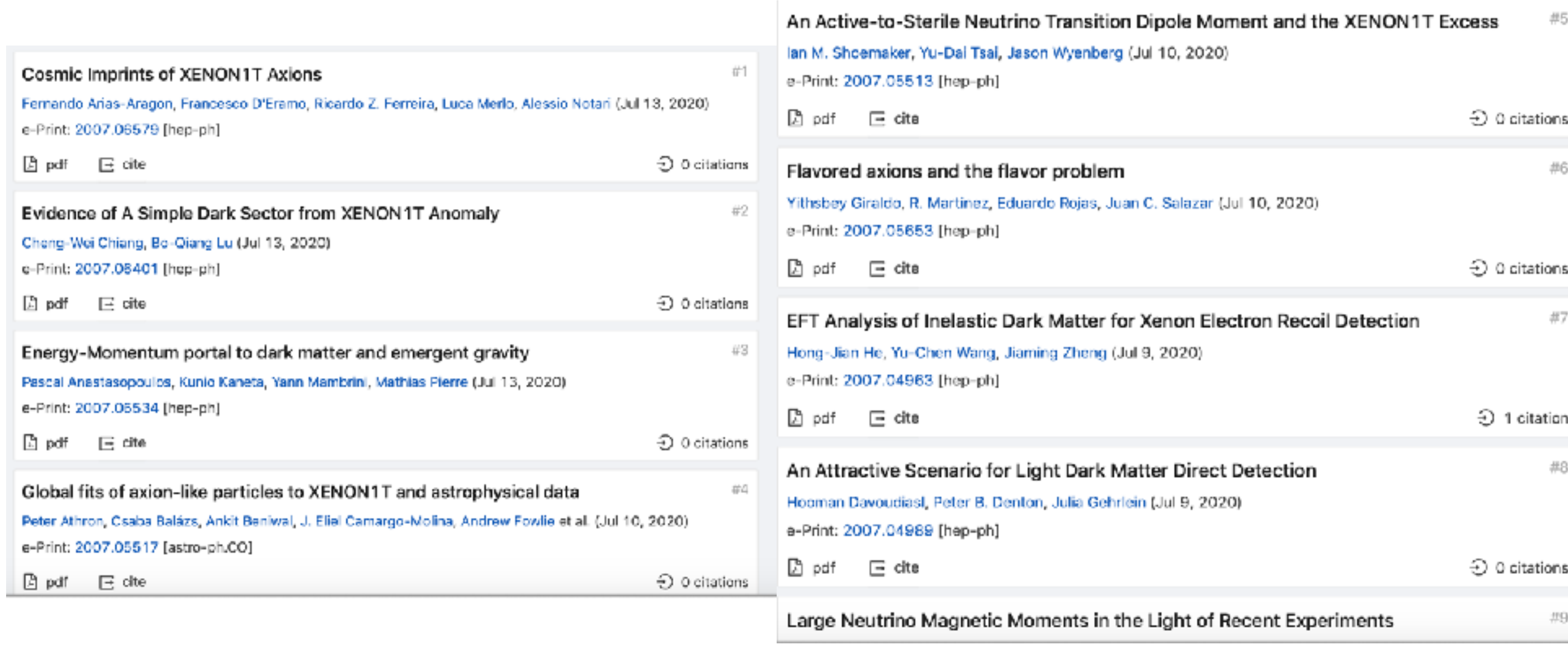
- Solar axions favoured over background at 3.5 sigma, *but*
- a tritium background at 3.2 sigma can neither be confirmed nor excluded, *and*
- there is a discrepancy with stellar constraints for axion-electron couplings.
- Above holds also for solar axion-like particles.
- ALP dark matter peak at 2.3 +/- 0.2 keV has 4.0 local significance, but note **3.0 sigma global!**

It is too soon to draw any conclusions; however

XENONnT is coming soon!!!

75 citations in one month





https://arxiv.org/abs/2006.09721
Please check our official website for updates.

Xe XENON Dark Matter Project

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www.xenonexperiment.org
Twitter: https://twitter.com/XENONexperiment
Facebook: https://www.facebook.com/XENONexperiment
Instagram: https://www.instagram.com/xenon_experiment/

Thank you for your attention.

QCD axion models

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Dine-Fischler-Srednicki-Zhitnitsky (DFSZ)

DFSZ: two Higgs doublets model couplings to leptons at tree level

$$g_{ae} = \frac{m_e}{3 f_a} \cos^2 \beta_{DFSZ}$$

quarks/electrons related by Beta

$$\tan(\beta_{DFSZ}) = \left(\frac{X_u}{X_d}\right)^{1/2}$$

axion mass proportional to decay constant

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

$$g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - \frac{2}{3}\frac{4+z}{1+z}\right)$$

axion-photon coupling same for both models

Kim-Shifman-Vainshtein-Zhakharov (KSVZ)

KSVZ: heavy quark model couplings to leptons only at loop level

$$g_{ae} = \frac{3\alpha^2 N m_e}{2\pi f_a}\left(\frac{E}{N}\ln\frac{f_a}{m_e} - \frac{2}{3}\frac{4+z+w}{1+z+w}\ln\frac{\Lambda}{m_e}\right)$$

photons/electrons related by E/N

$$z = m_u/m_d, \quad m_{u/d}$$

$$w = m_u/m_s$$

Relative contributions from each component can allow to distinguish between models (Primakoff dominates in KSVZ models); can also constrain β_{DFSZ}

Nuclear transition contribution always relatively small

Profiling over Primakoff axions

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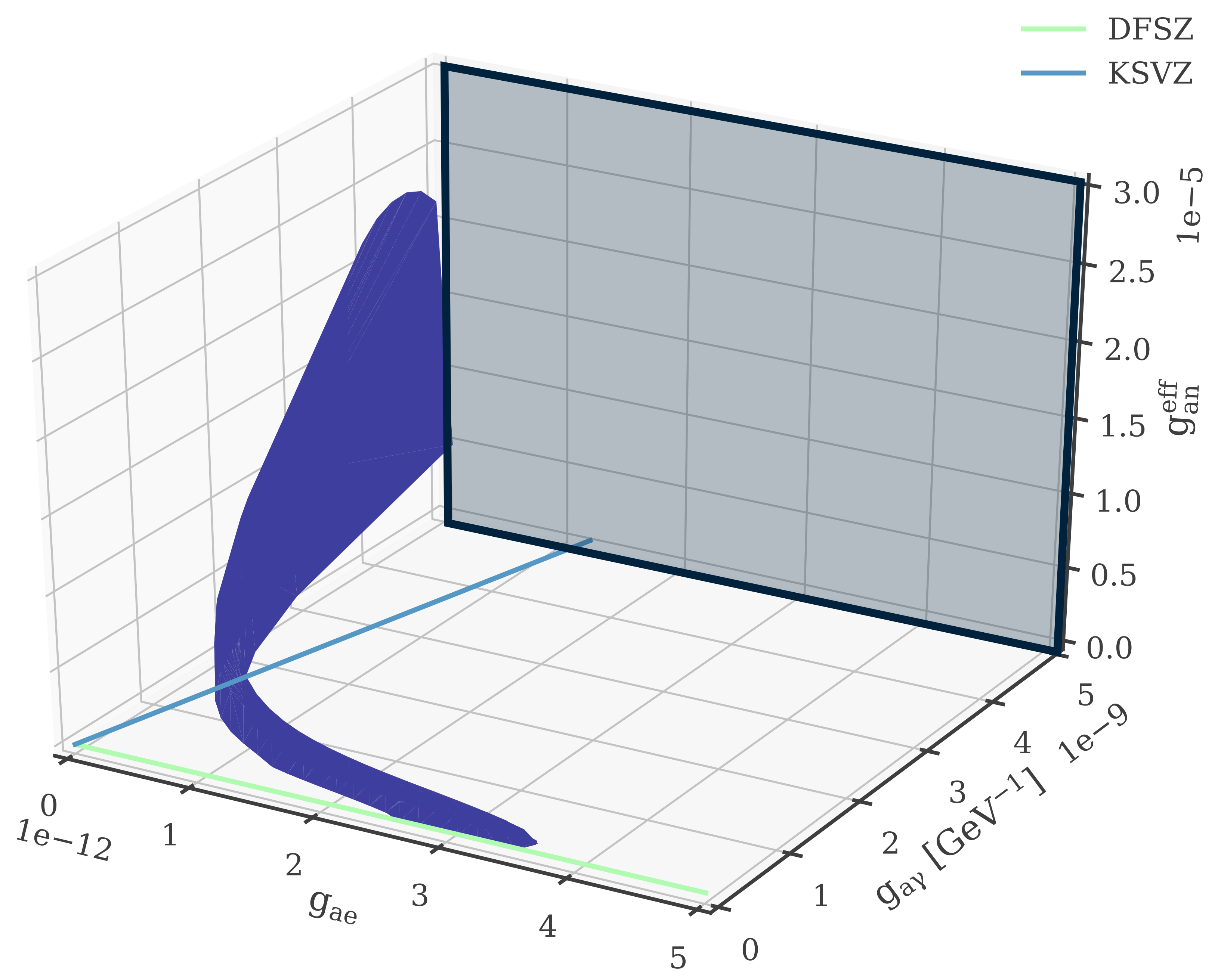
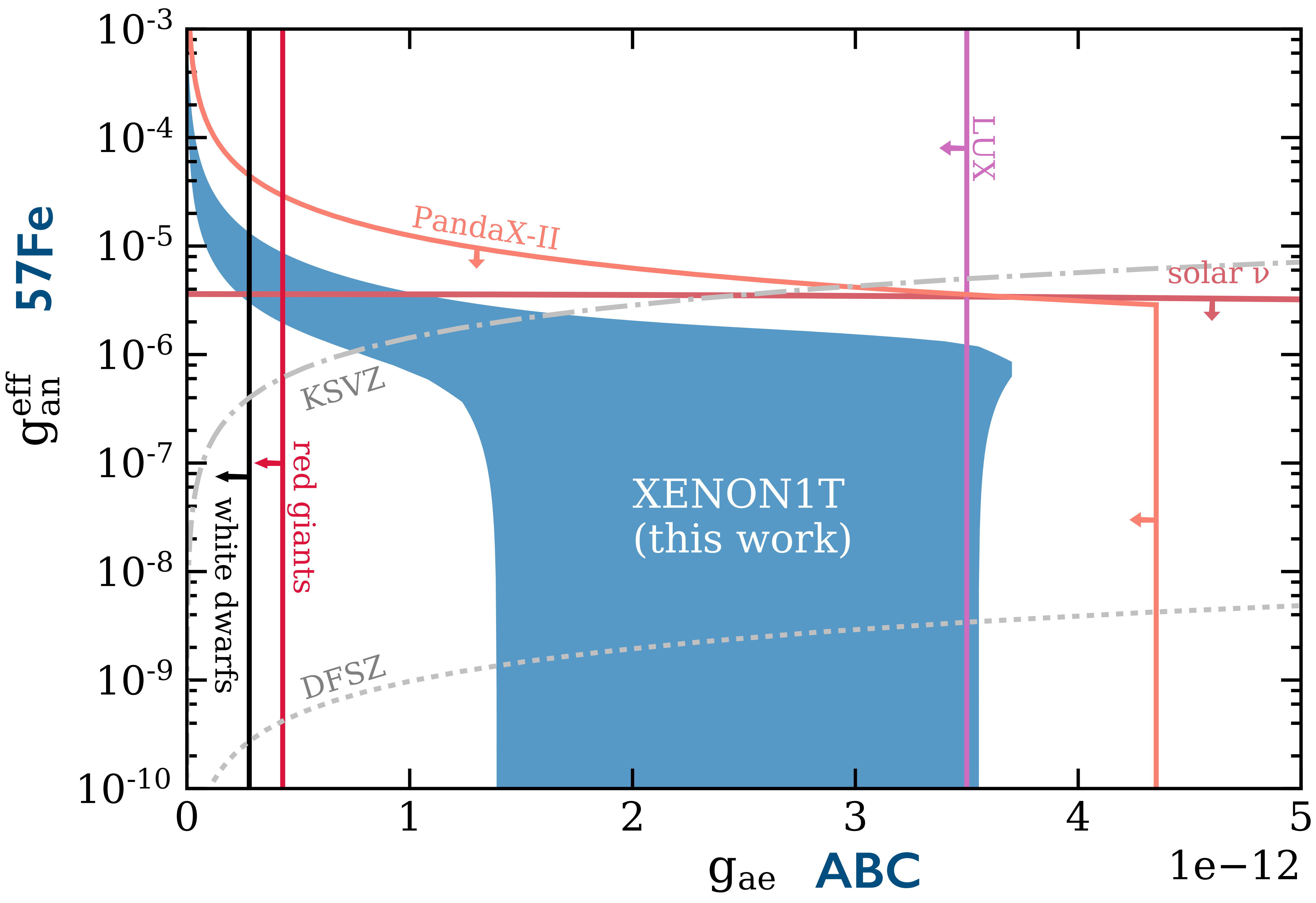
3D confidence volume (90% C.L.)





Poor fit for small ABC rate

Discrepancy with astrophysical constraints from stellar cooling *(arXiv:2003.01100)*

Profiling over ABC axions

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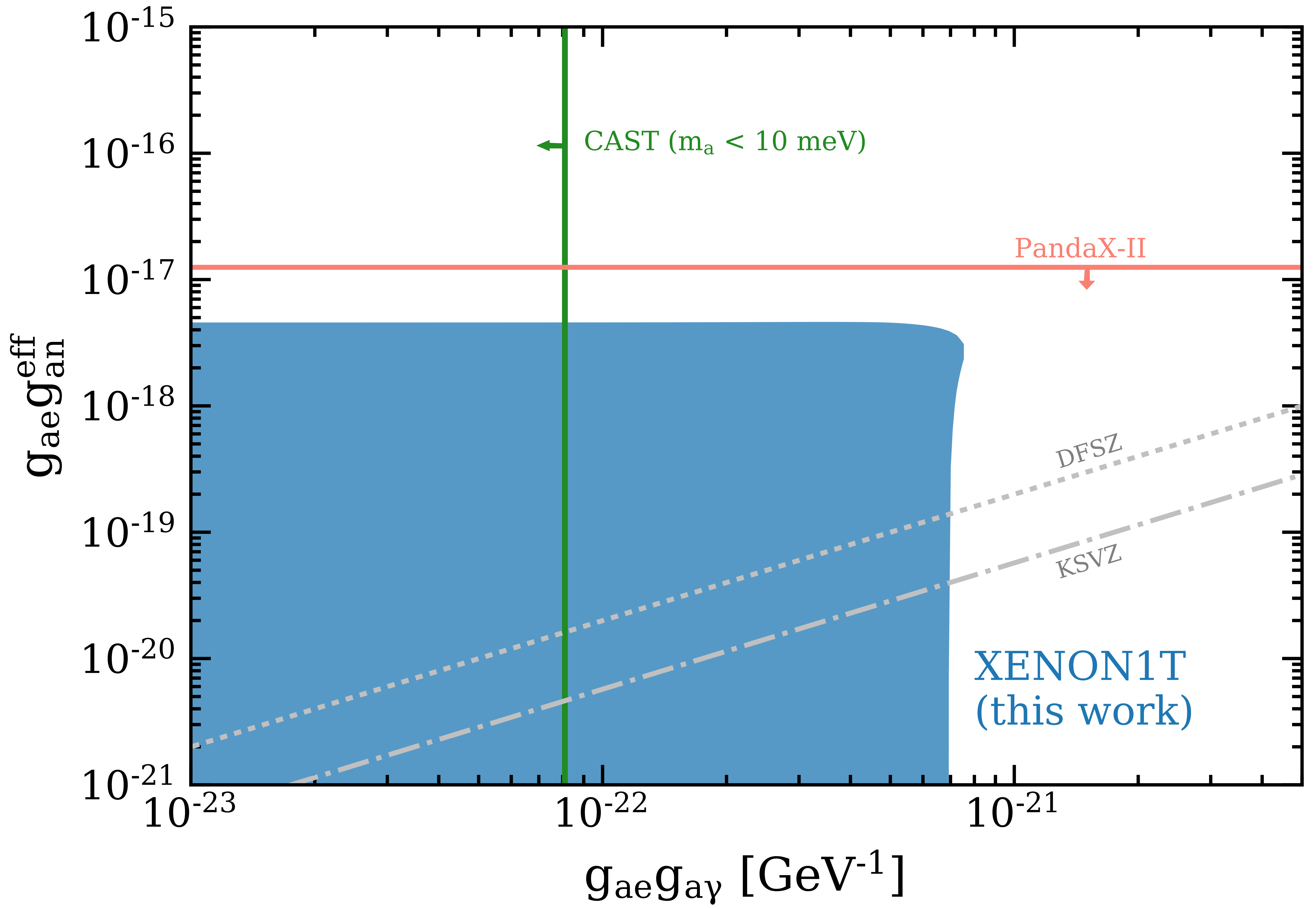

Primakoff and ^{57}Fe components can be absent if the ABC component is present

No statistical significance for Primakoff or ^{57}Fe on their own

QCD axion interpretation

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Please note, these are not confidence intervals!

Overlap of specific benchmark models with our model-independent confidence volume.

Should be interpreted as approximate, consistent mass ranges

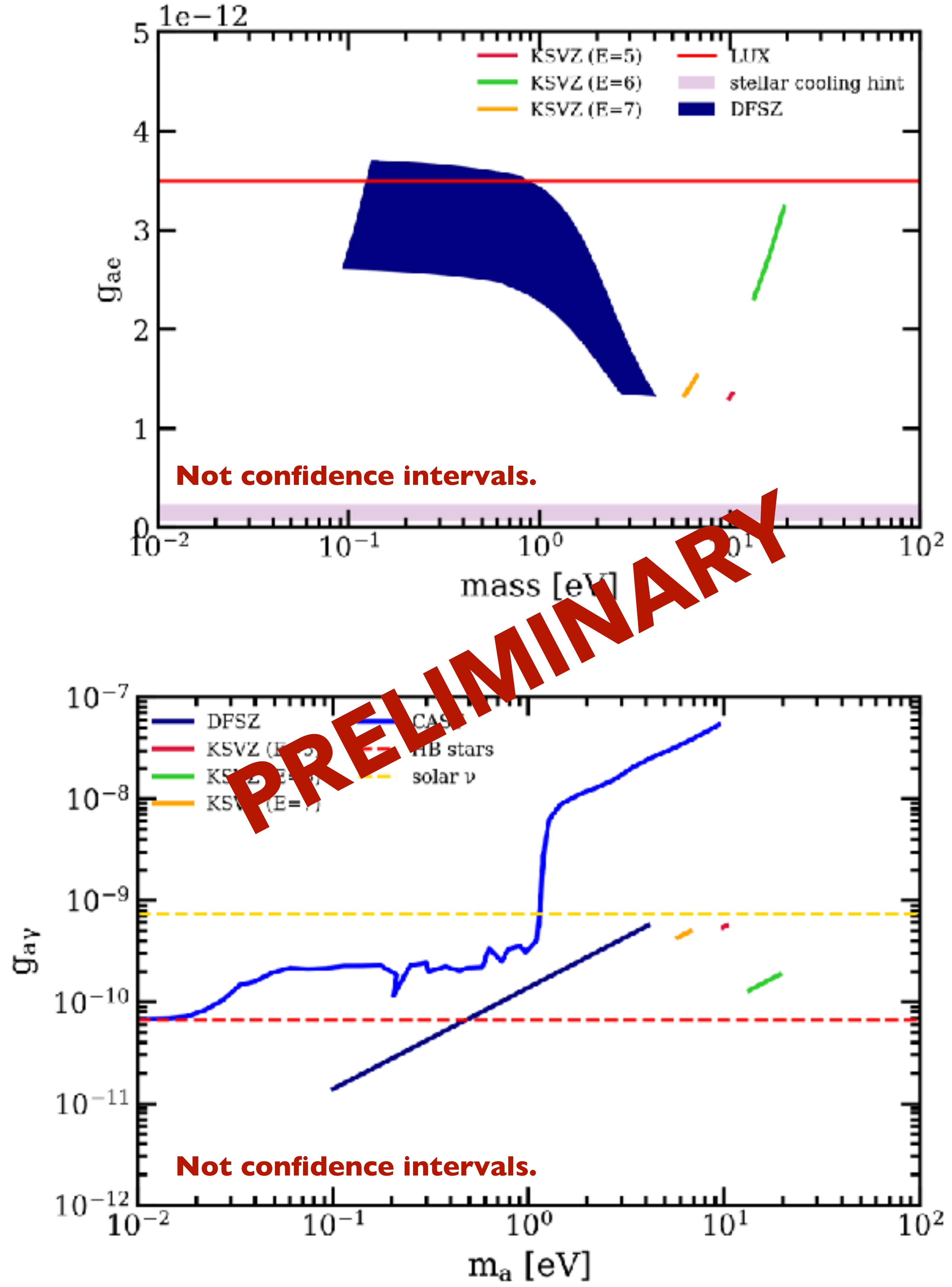
DFSZ (GUT)

m_a ~ 0.1–4 eV

KSVZ (hadronic)

m_a ~ 6–20 eV

E ~ 5-7



Background fit

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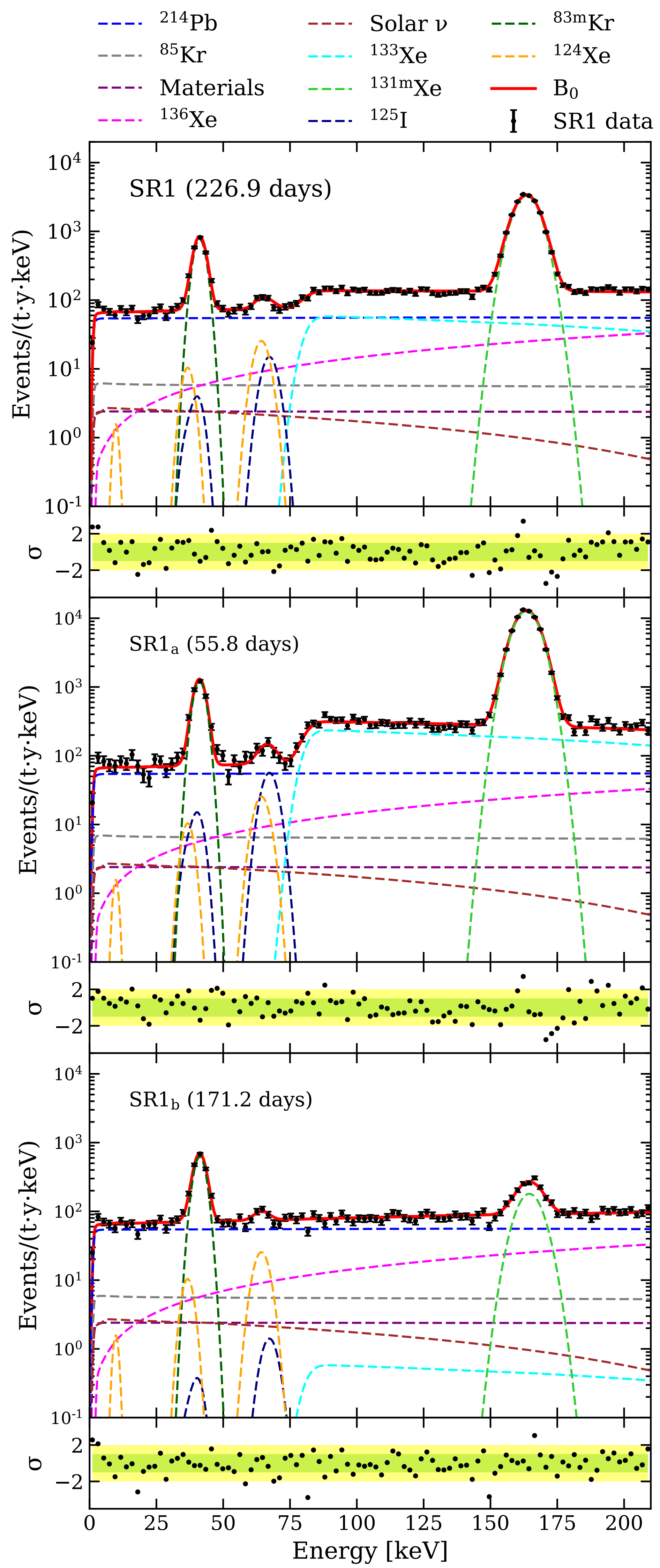
Component		Expected Events	Fitted Events	Constant in time? (shared across partitions)
^{214}Pb		(3450, 8530)	7480 +/- 160	YES
^{85}Kr		890 +/- 50	773 +/- 80	NO
^{136}Xe		2120 +/- 210	2150 +/- 120	YES
^{133}Xe		3900 +/- 410	4009 +/- 85	NO
^{131}Xe		23760 +/- 640	24270 +/- 150	NO
^{83m}Kr		2500 +/- 250	2671 +/- 53	NO
Materials		323 (fixed)	323 (fixed)	YES
Solar neutrino		220.7 +/- 6.6	220.8 +/- 4.7	YES
^{124}Xe	KK	125 +/- 50	113 +/- 24	YES
	KL	38 +/- 15	34.0 +/- 7.3	YES
	LL	2.8 +/- 1.1	2.56 +/- 0.55	YES
^{125}I	K	79 +/- 33	67 +/- 12	NO
	L	15.3 +/- 6.5	13.1 +/- 2.3	NO
	M	3.4 +/- 1.5	2.94 +/- 0.50	NO

unconstrained in the fit



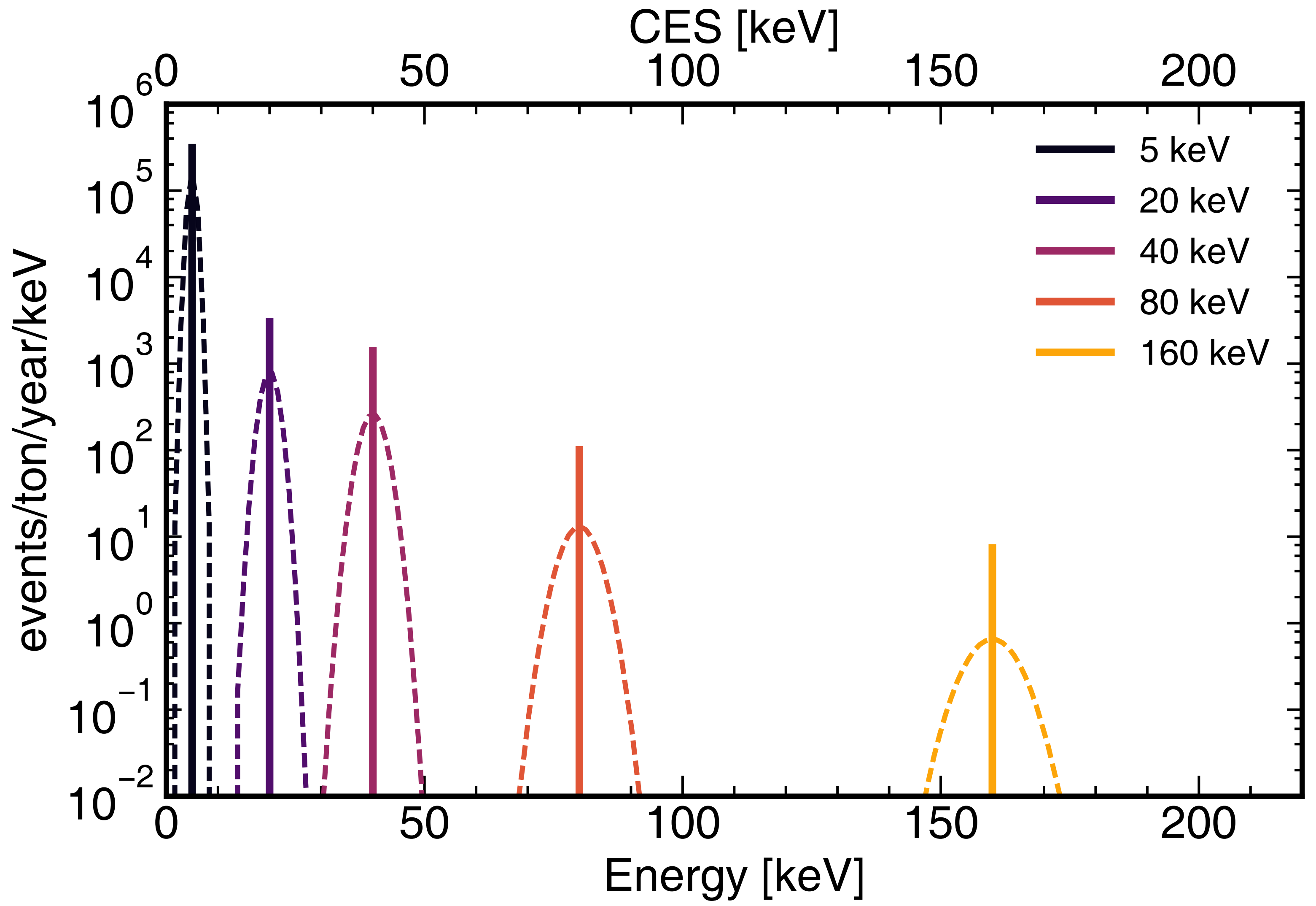
Axion-like particles

No strict relationship between mass and coupling

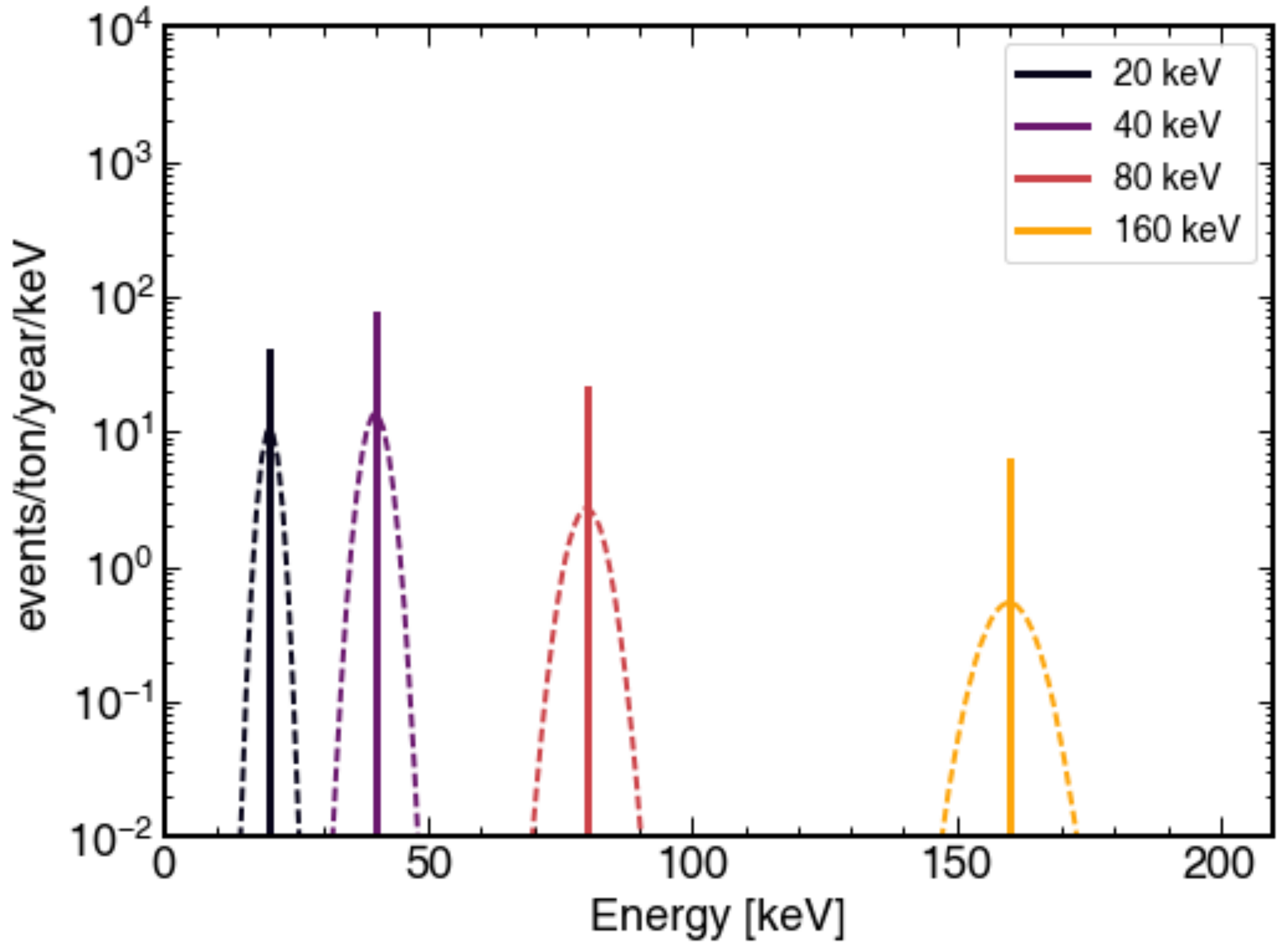
Non-specific mass requires global significance

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

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



Dark photons



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

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

If we confirm a peak, is it an ALP or a dark photon?