NAGOYA UNIVERSITY

ISEE

INSTITUTE FOR SPACE-EARTH ENVIRONMENTAL RESEARCH

Xe XENON Dark Matter Project

XENON1T Electronic Recoil Events excess: New Physics or Background?

XENON collaboration + X. Mougeot

arXiv:2006.09721

Masaki Yamashita for the XENON collaboration

2020/08/05 Kamioka Seminar

www.xenonexperiment.org

: https://twitter.com/XENONexperiment

: https://www.facebook.com/XENONexperiment

: https://www.instagram.com/xenon_experiment/

Outline

- XENON1T Detector
- What is Electronic Event?
- Background model
  - + Tritium
  - + Solar Axion
  - + neutrino magnetic moment
  - + Bosonic dark matter
- Future prospect

XENON1T Experiment

The XENON Collaboration: ~170 scientists

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

Chicago

UCSD

Rice

Purdue

Zurich

Tokyo

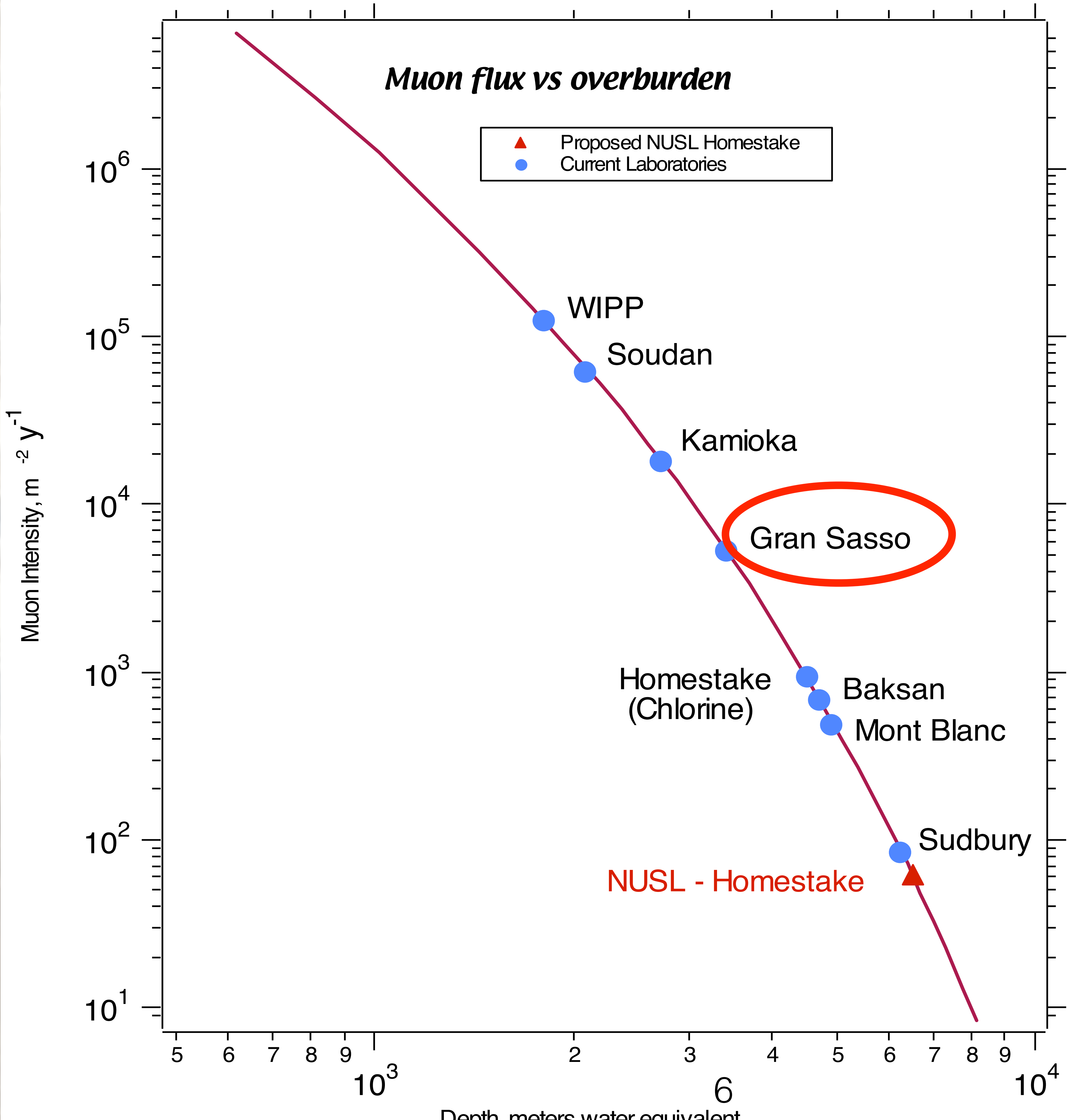
Nagoya

Coimbra | Subatech | LPNHE | LAL | Bologna | LNGS | Torino | Napoli | Weizmann | NYUAD | Kobe


Xe
XENON
Dark Matter Project
XENON Technical Meeting, May 12-14, 2020
Andrii Terliuk (MPIK/Uni He...
Alexey Elykov
Ethan Brown
Christopher Hils (JGU-Mai...
Michele Iacovacci
Manfred Lindner
arianna rocchetti
ChristianWittweg
Marc Schumann

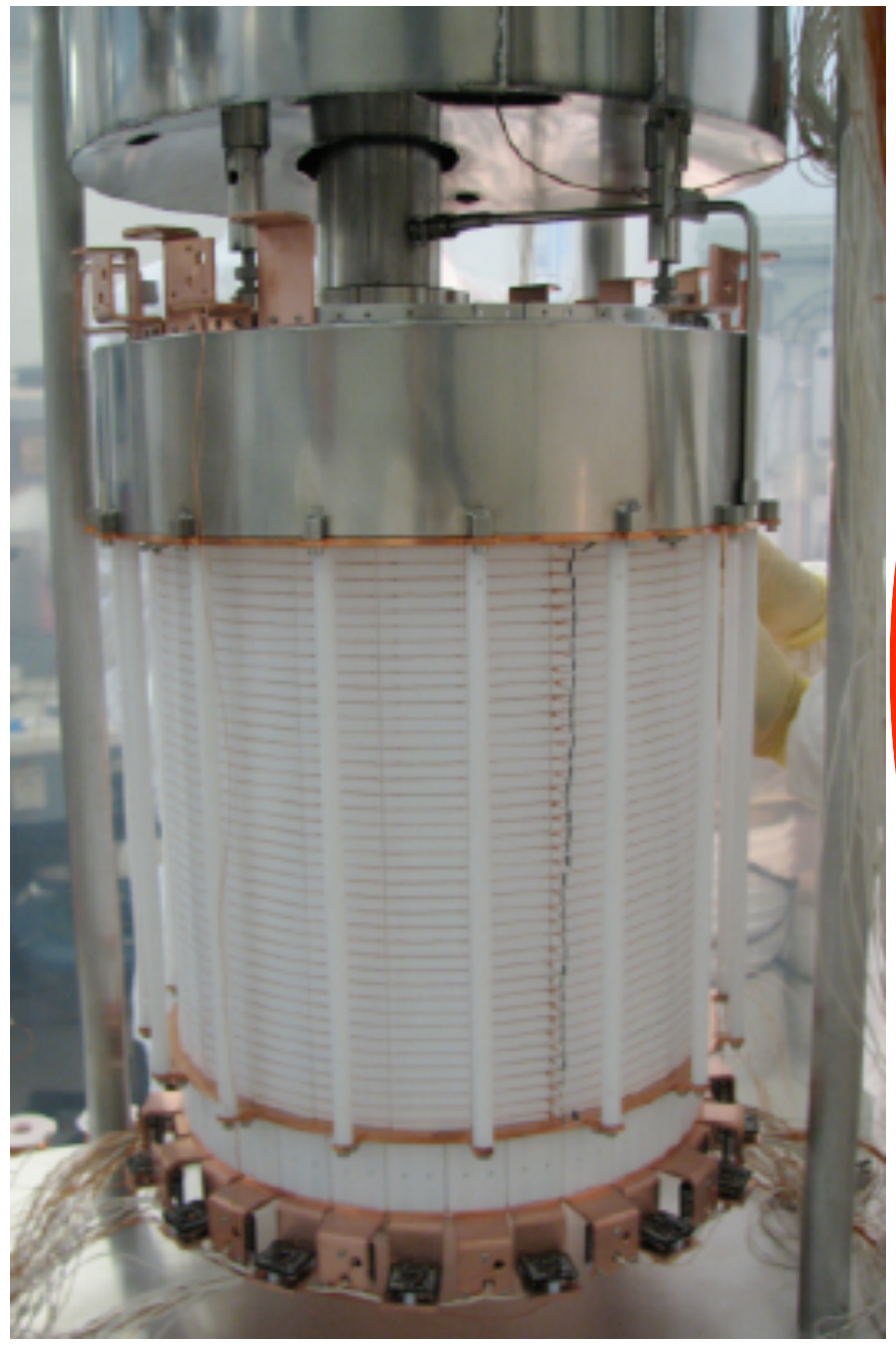
XENON1T at Gran Sasso, Italy

- Laboratori Nationali del Gran Sasso in Italy
- 1,400 m rock overburden (3,400 m.w.e)



History of XENON Experiment

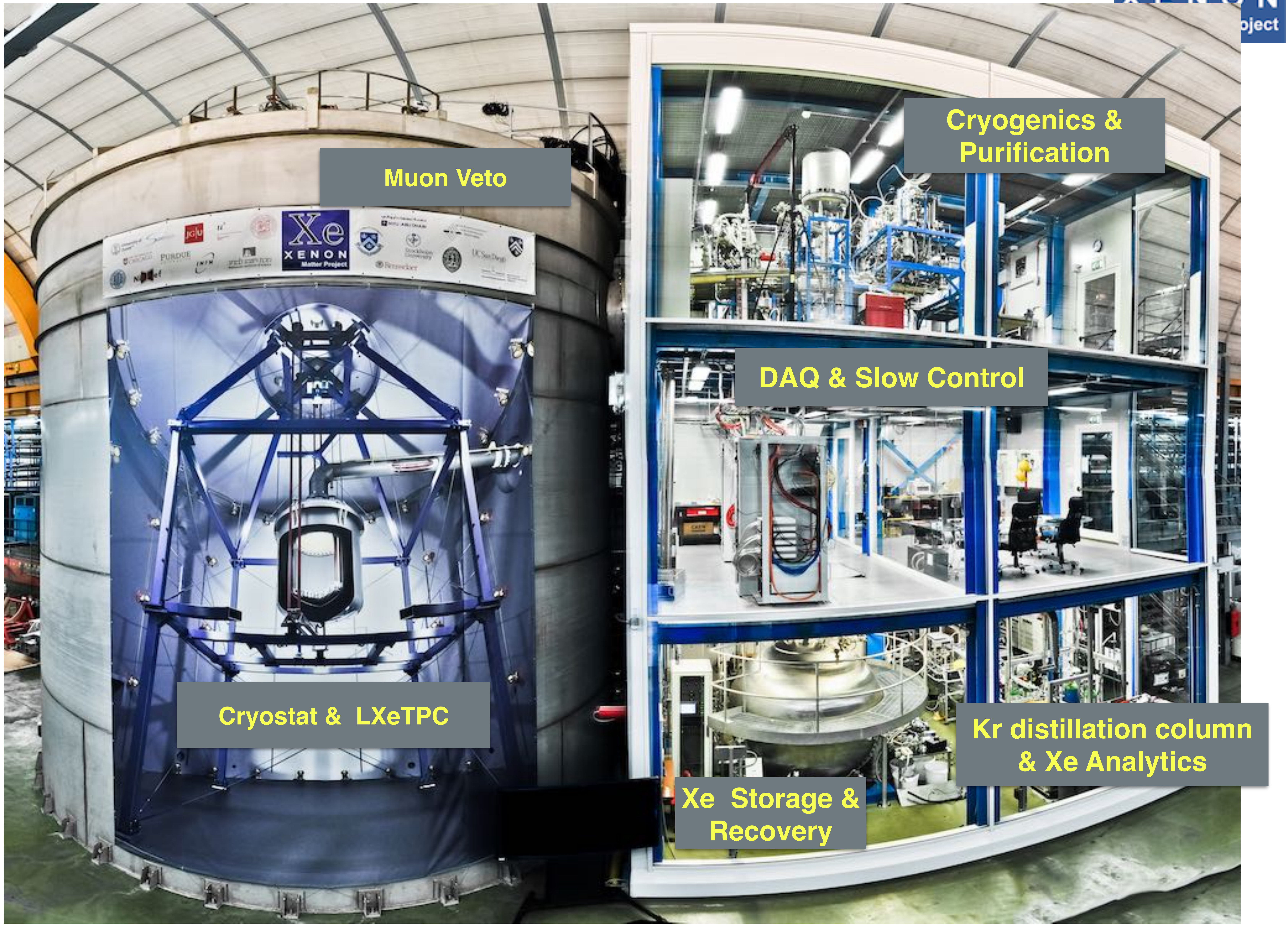
XENON10	XENON100	XENON1T	XENONnT



2005-2007	2008-2016	2012-2018	2019-202x
25 kg - 15cm drift	161 kg - 30 cm drift	3.2 ton - 1 m drift	8 ton - 1.5 m drift
$\sim 10^{-43}$ cm^2	$\sim 10^{-45}$ cm^2	$\sim 10^{-47}$ cm^2	$\sim 10^{-48}$ cm^2

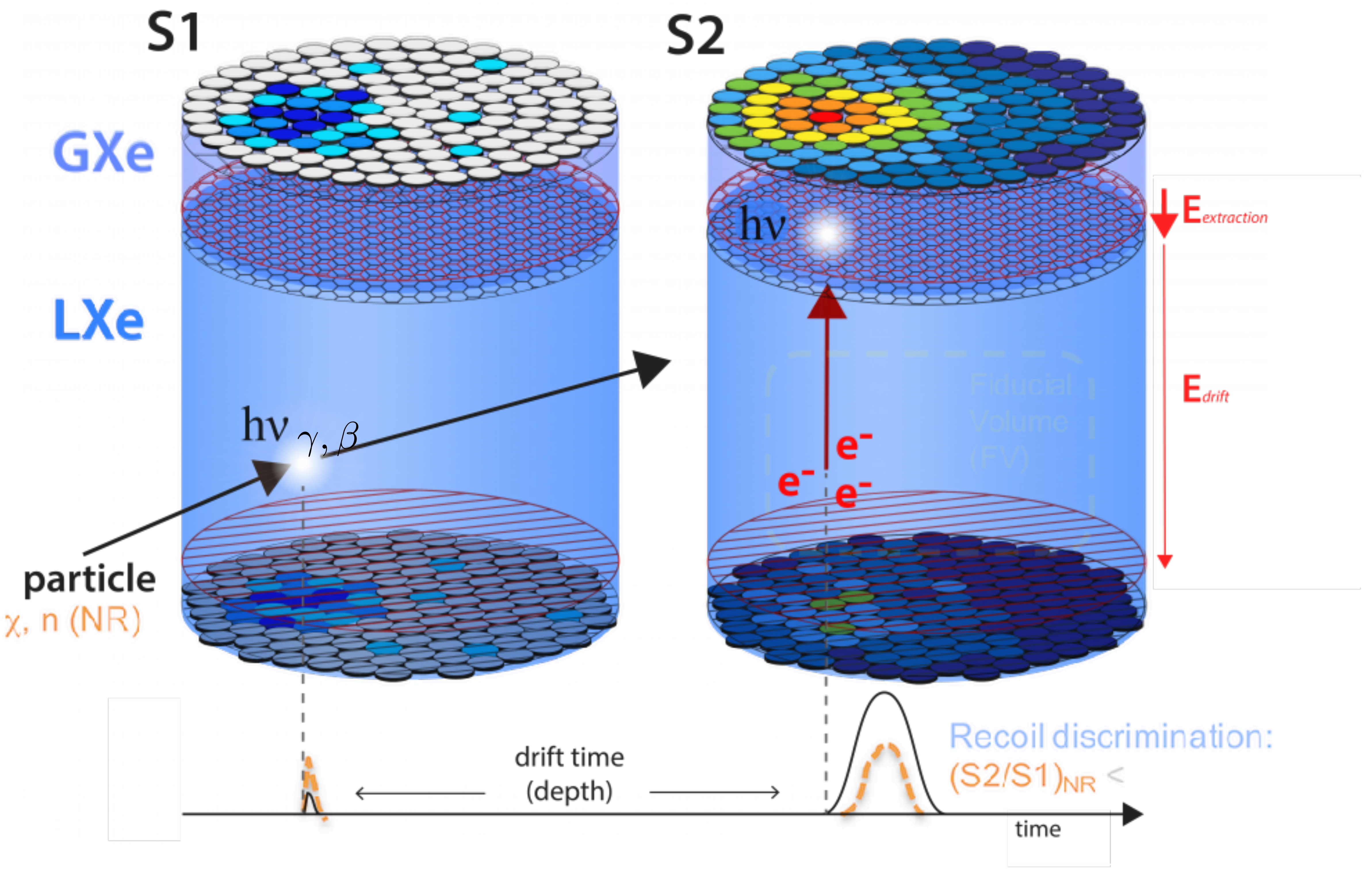
XENON1T Detector

- Direct Dark Matter (WIMP) search detector
- 3.2 tonne total/ 1 tonne fiducial LXe
- Two phase Xe TPC
- ~250 x 3 inch PMTs
- 2012-2018 (terminated)



Two-phase Xe Time Projection Chamber

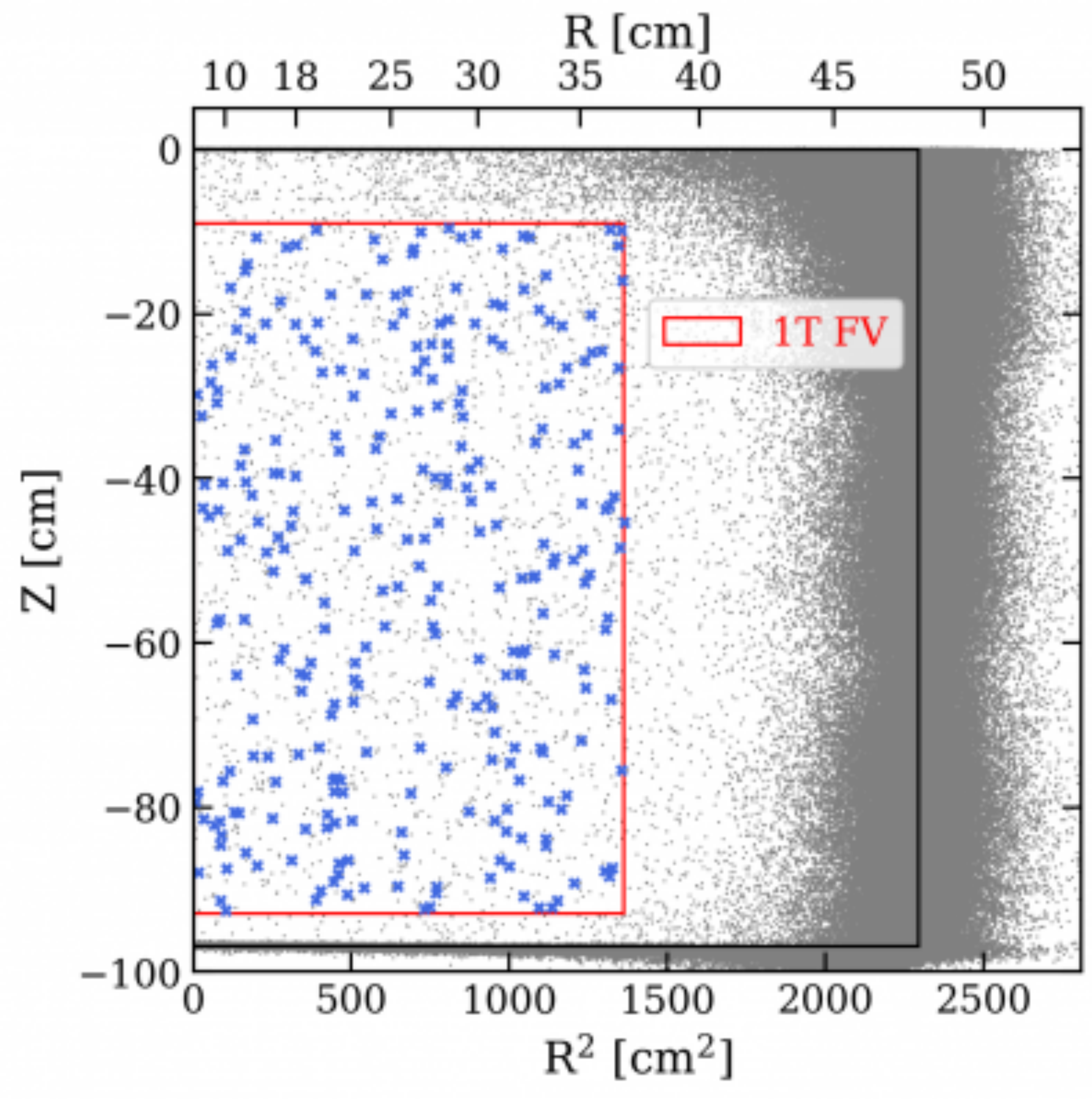
- **Scintillation light - S1**
- **Ionization electron -S2**



ER

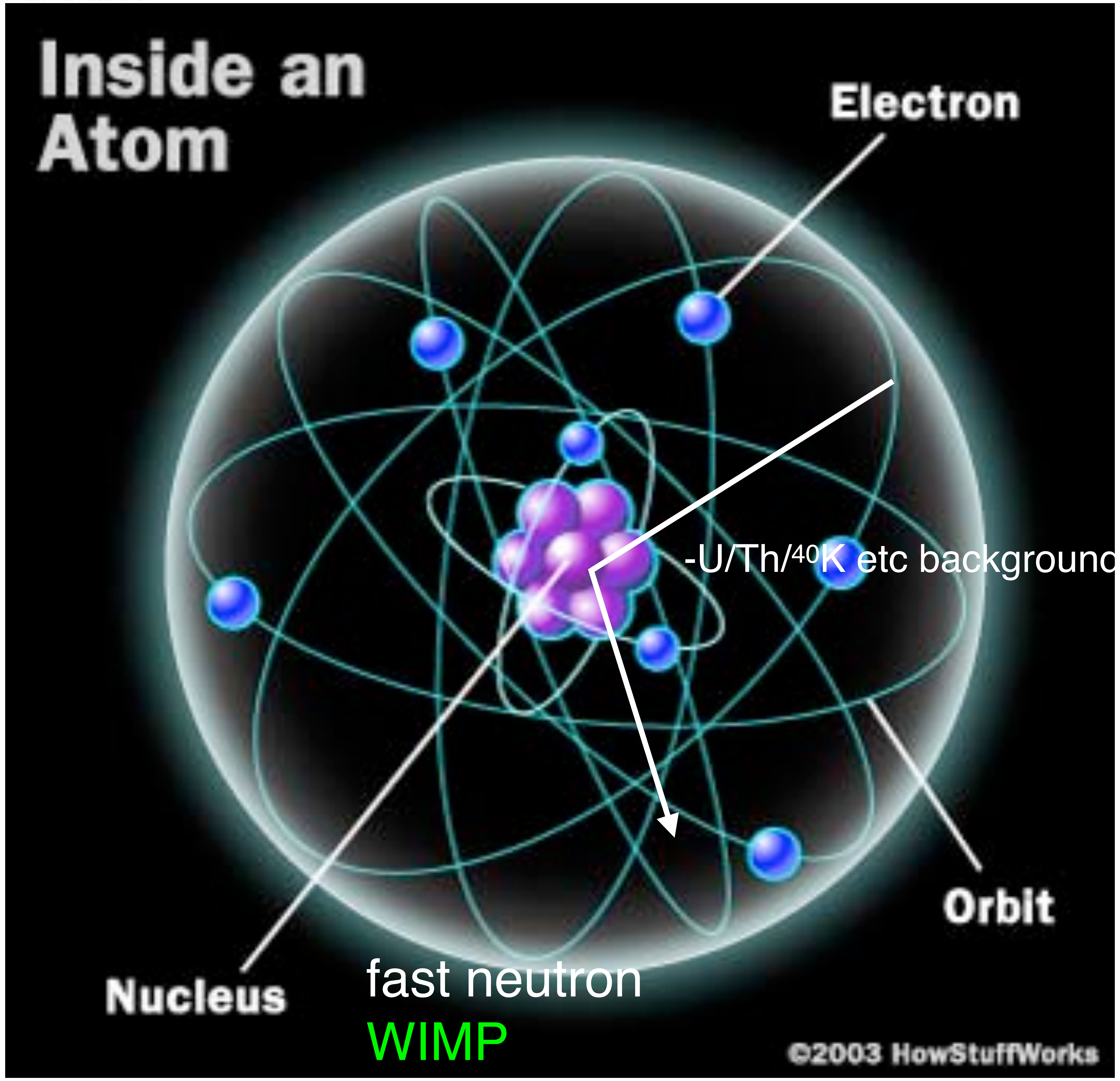
Two signals for each event:

- 3D event imaging: x-y (S2) and z (drift time)
- self-shielding, surface event rejection, single vs multiple scatter events
- Particle identification using S2/S1 ratio (nuclear recoil vs beta, gamma)

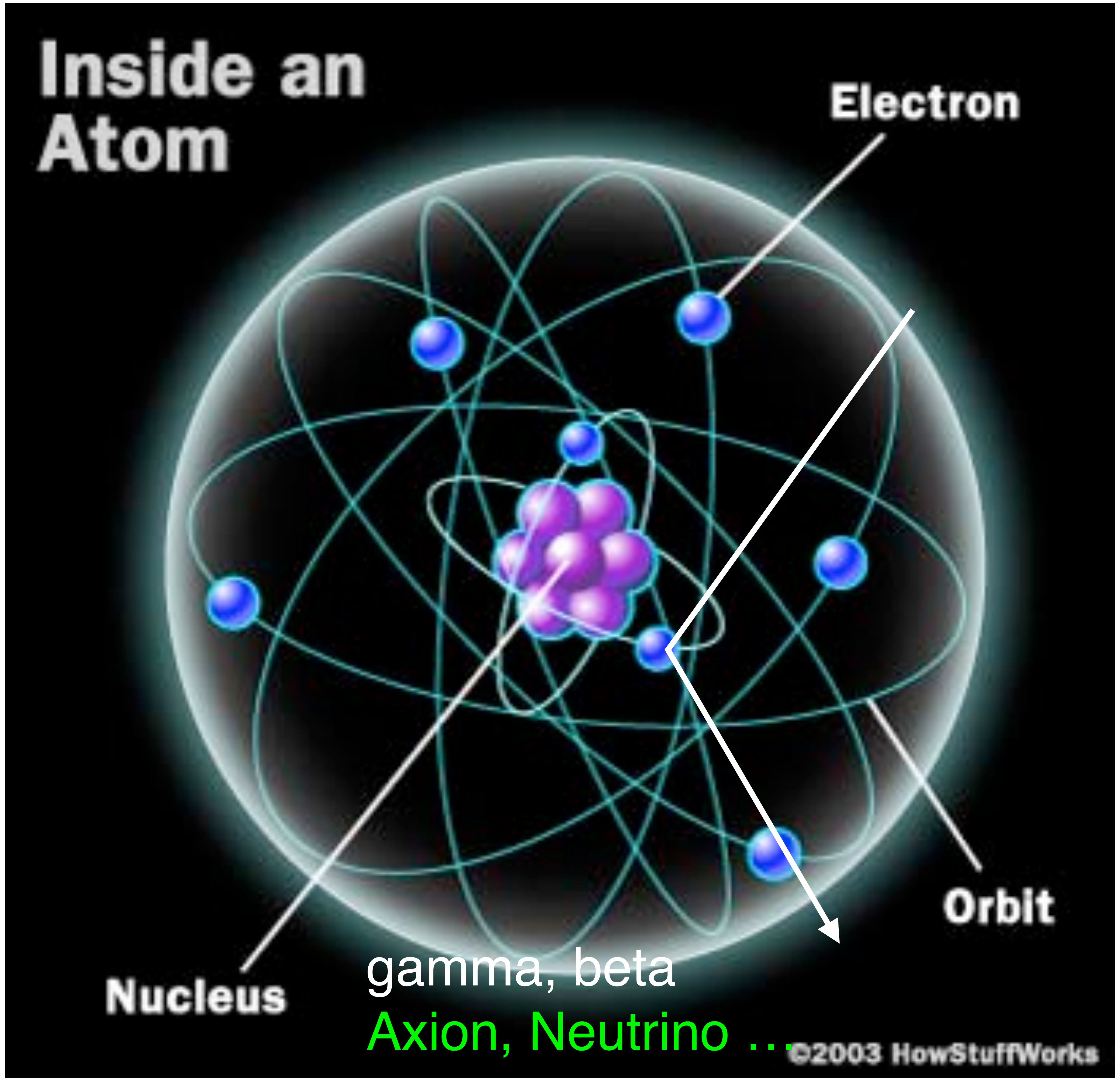


Interaction with dark matter

nuclear recoil

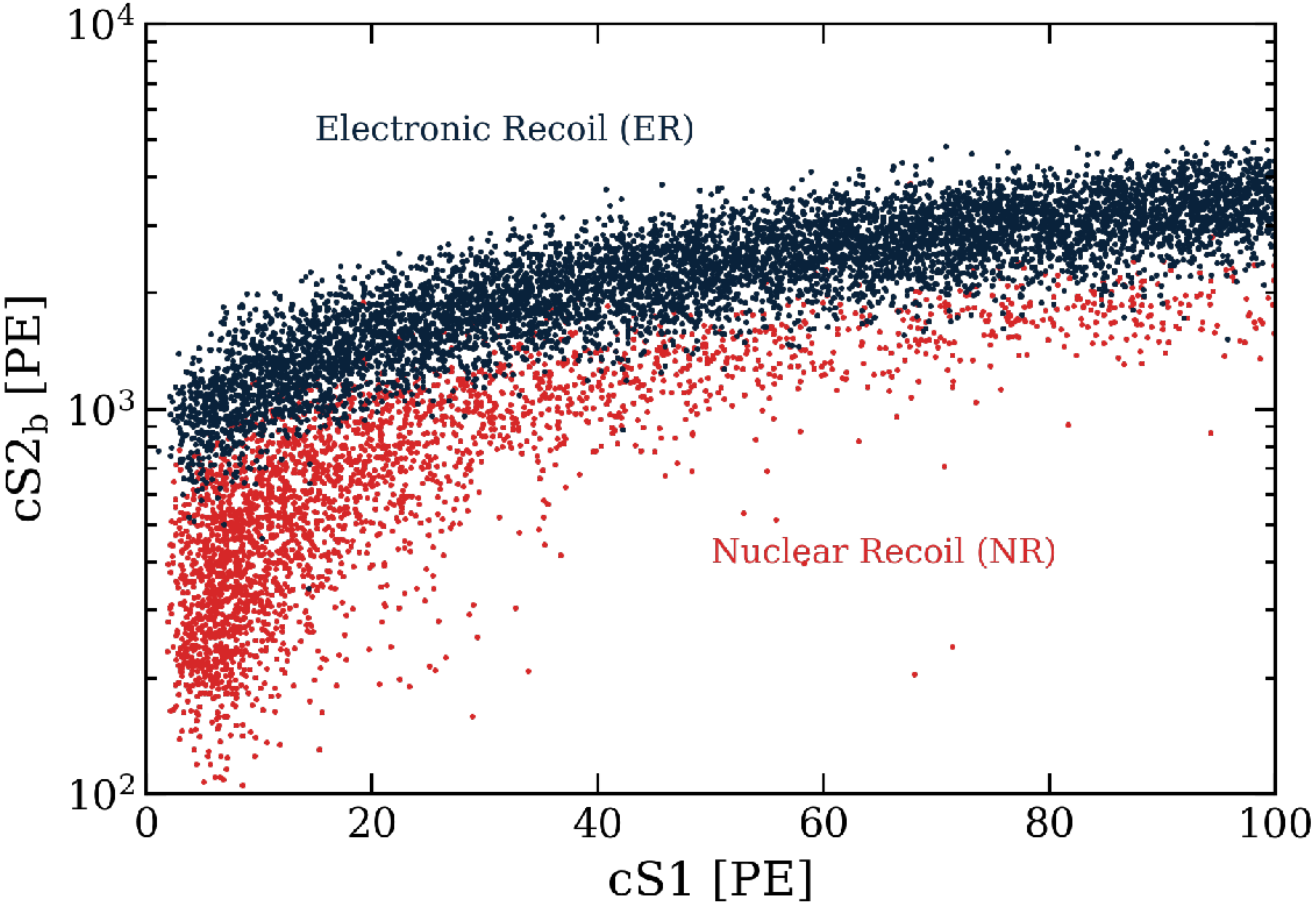


electronic recoil



Two-phase Xe Time Projection Chamber

- Recoil type discrimination from ratio of charge (S2) to light (S1)

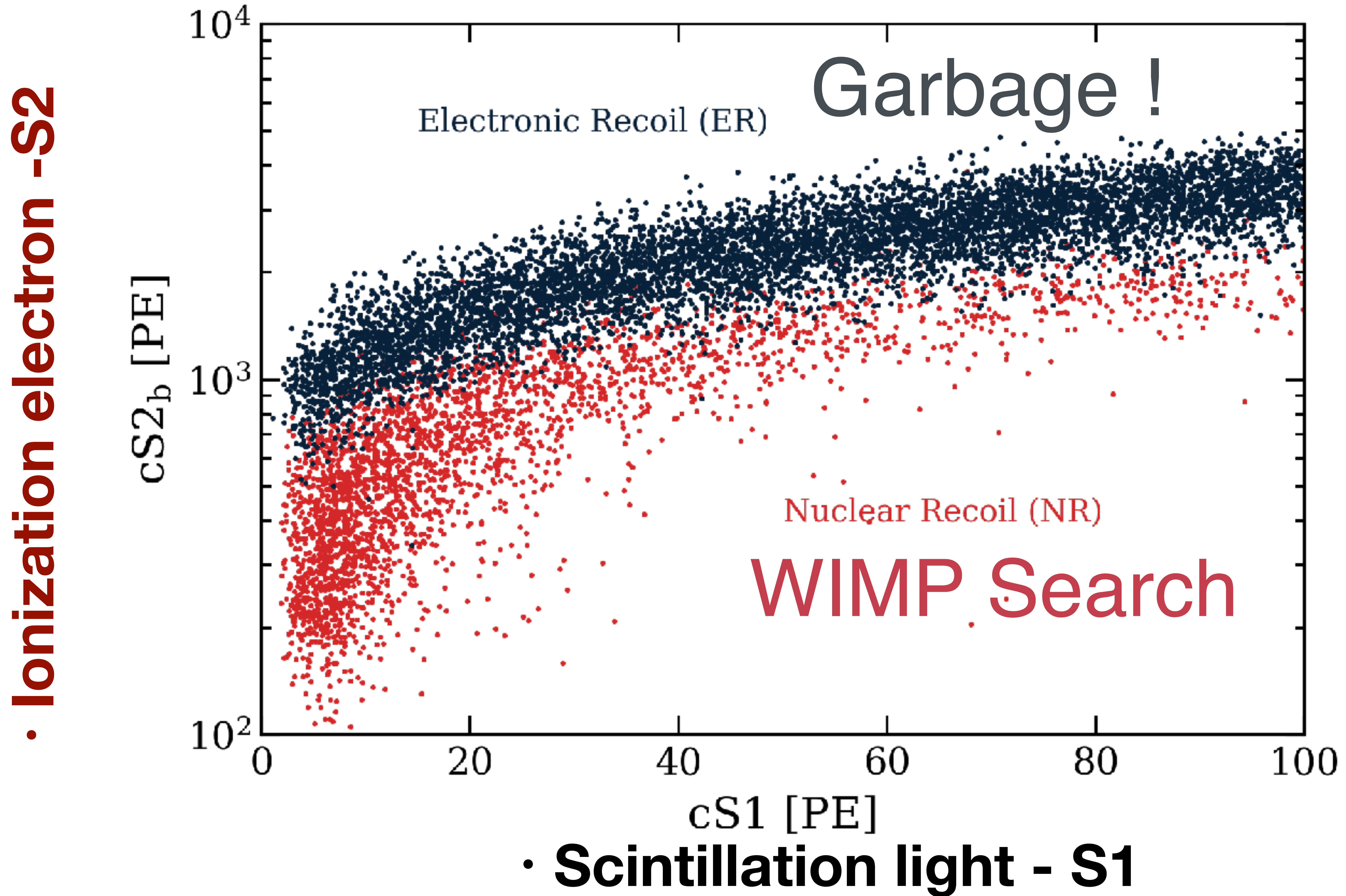


- Ionization electron -S2

- **Scintillation light - S1**

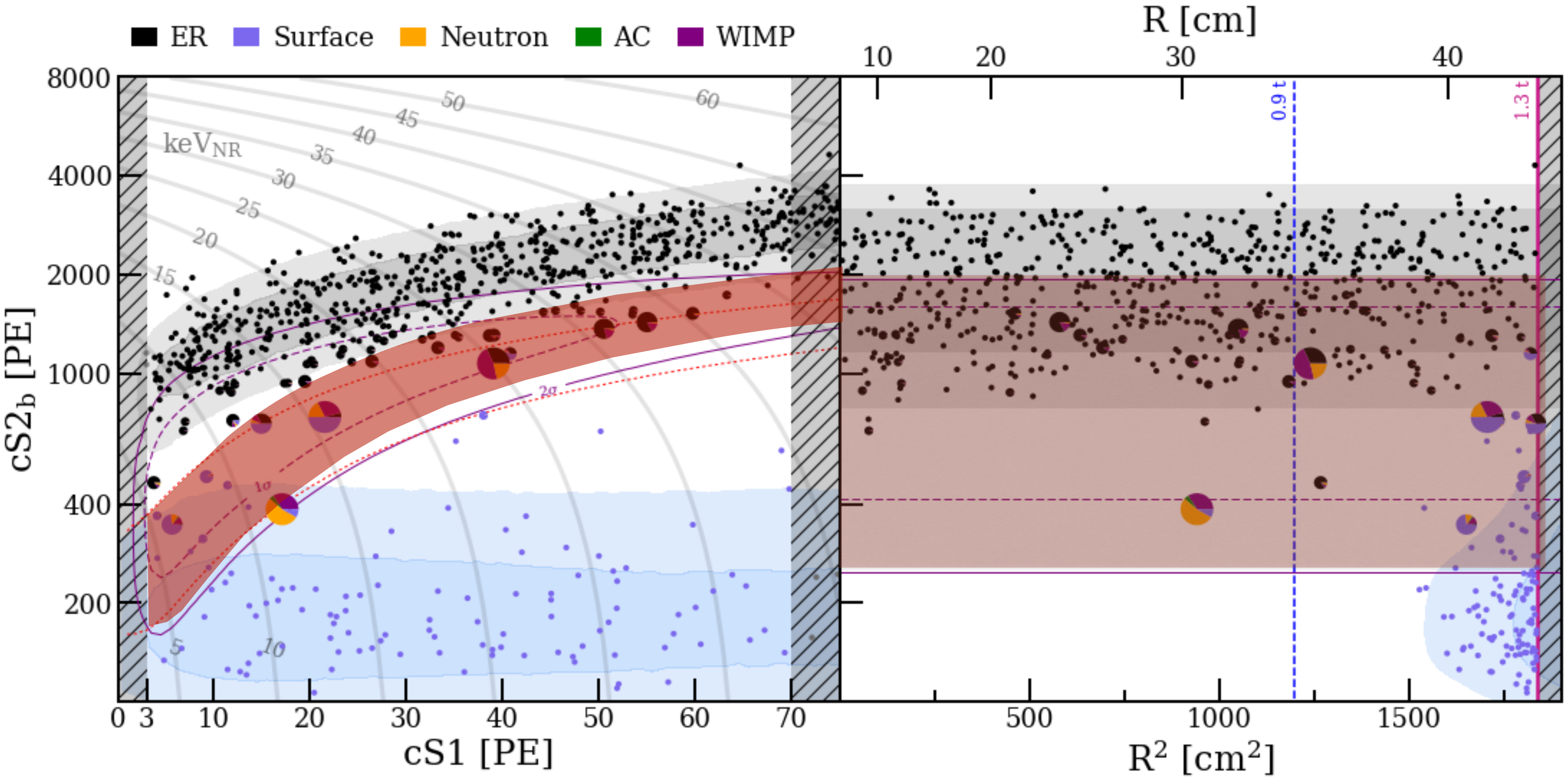
Two-phase Xe Time Projection Chamber

- Recoil type discrimination from ratio of charge (S2) to light (S1)



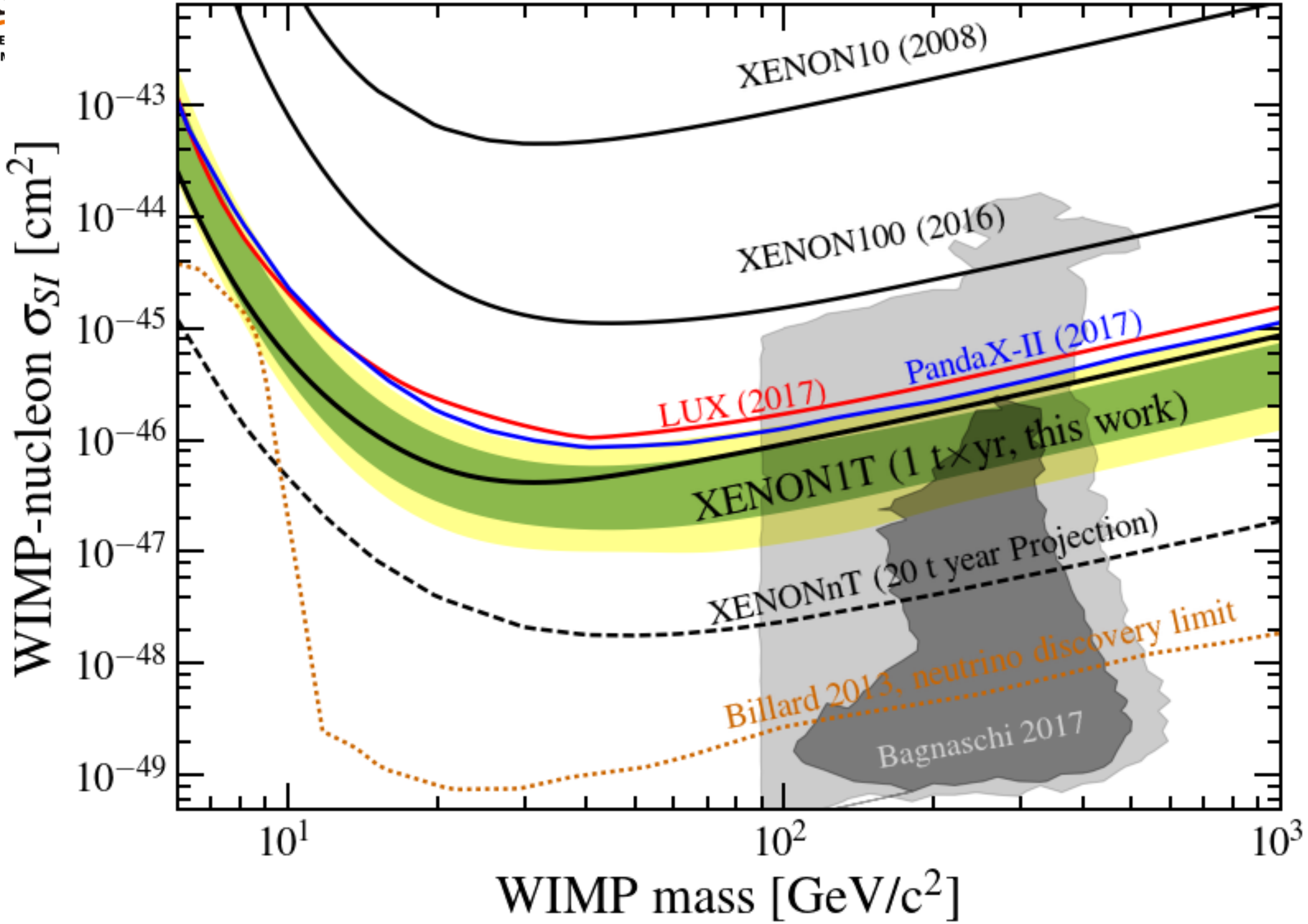
XENON1T WIMPs Search - 2018

One ton-year of search for WIMPs induced nuclear recoils

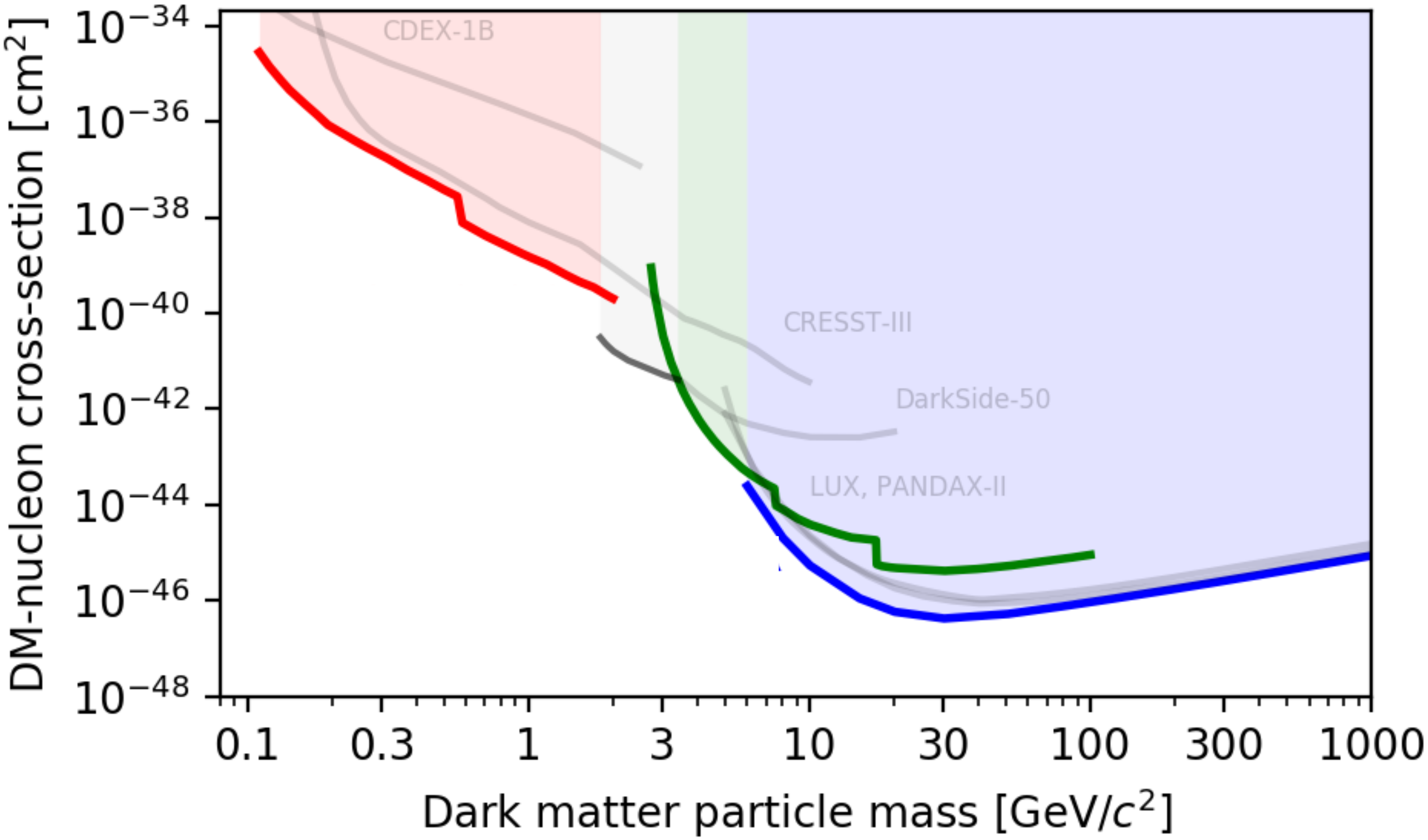


Most stringent result on WIMP Dark Matter down to 3 GeV/c² masses *[PRL 121, 111302 + PRL 123, 251801]*

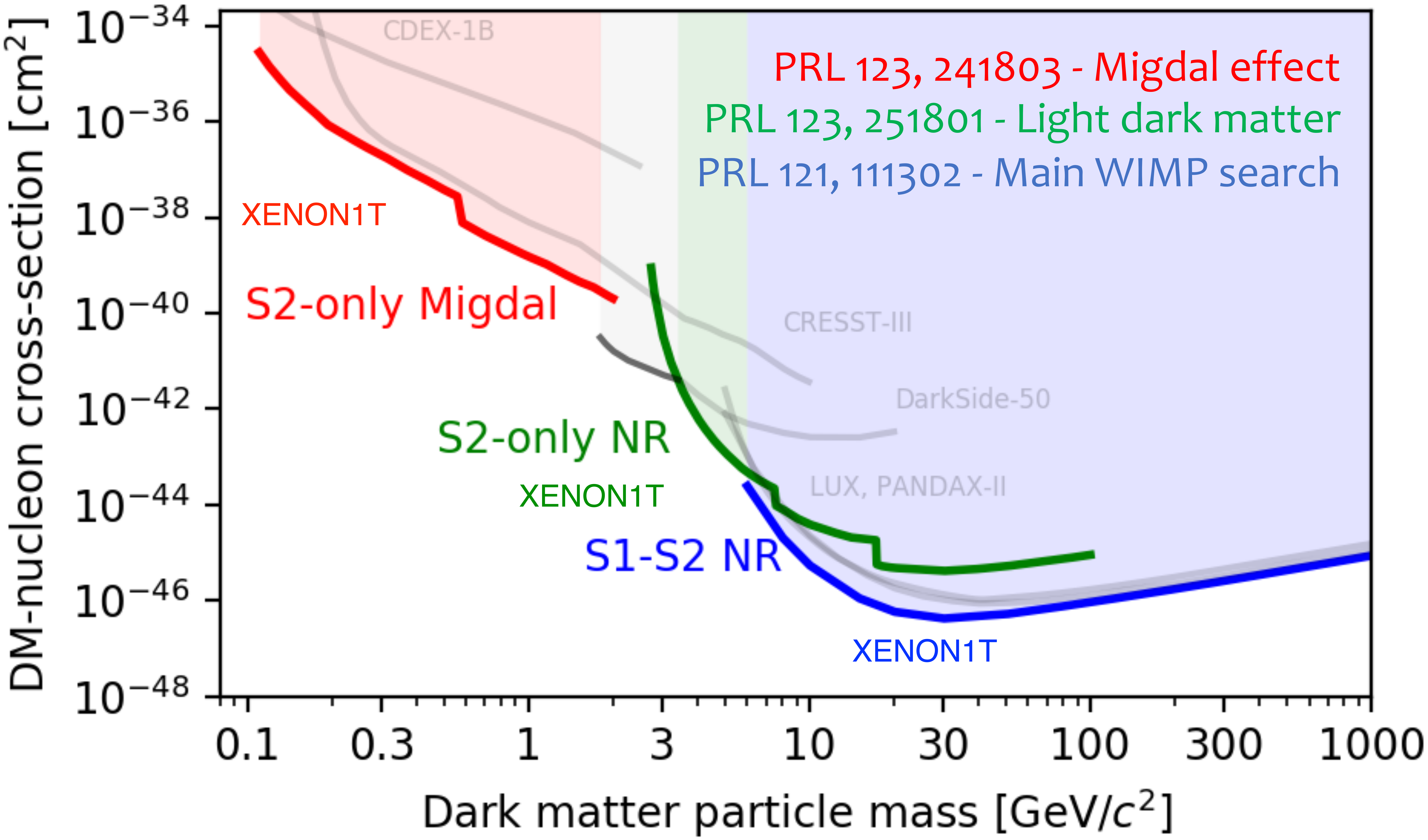
WIMP Search Result



Phys.Rev.Lett. 121 (2018) no.11, 111302



CDEX-1B
CRESST-III
DarkSide-50
LUX, PANDAX-II
DM-nucleon cross-section [cm^2]
10^{-34}
10^{-36}
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
0.1
0.3
1
3
10
30
100
300
1000
Dark matter particle mass [GeV/c^2]


PRL 123, 241803 - Migdal effect
PRL 123, 251801 - Light dark matter
PRL 121, 111302 - Main WIMP search
CDEX-1B
CRESST-III
DarkSide-50
LUX, PANDAX-II
XENON1T
S2-only Migdal
S2-only NR
XENON1T
S1-S2 NR
XENON1T
DM-nucleon cross-section [cm^2]
10^{-34}
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10^{-44}
10^{-46}
10^{-48}
0.1
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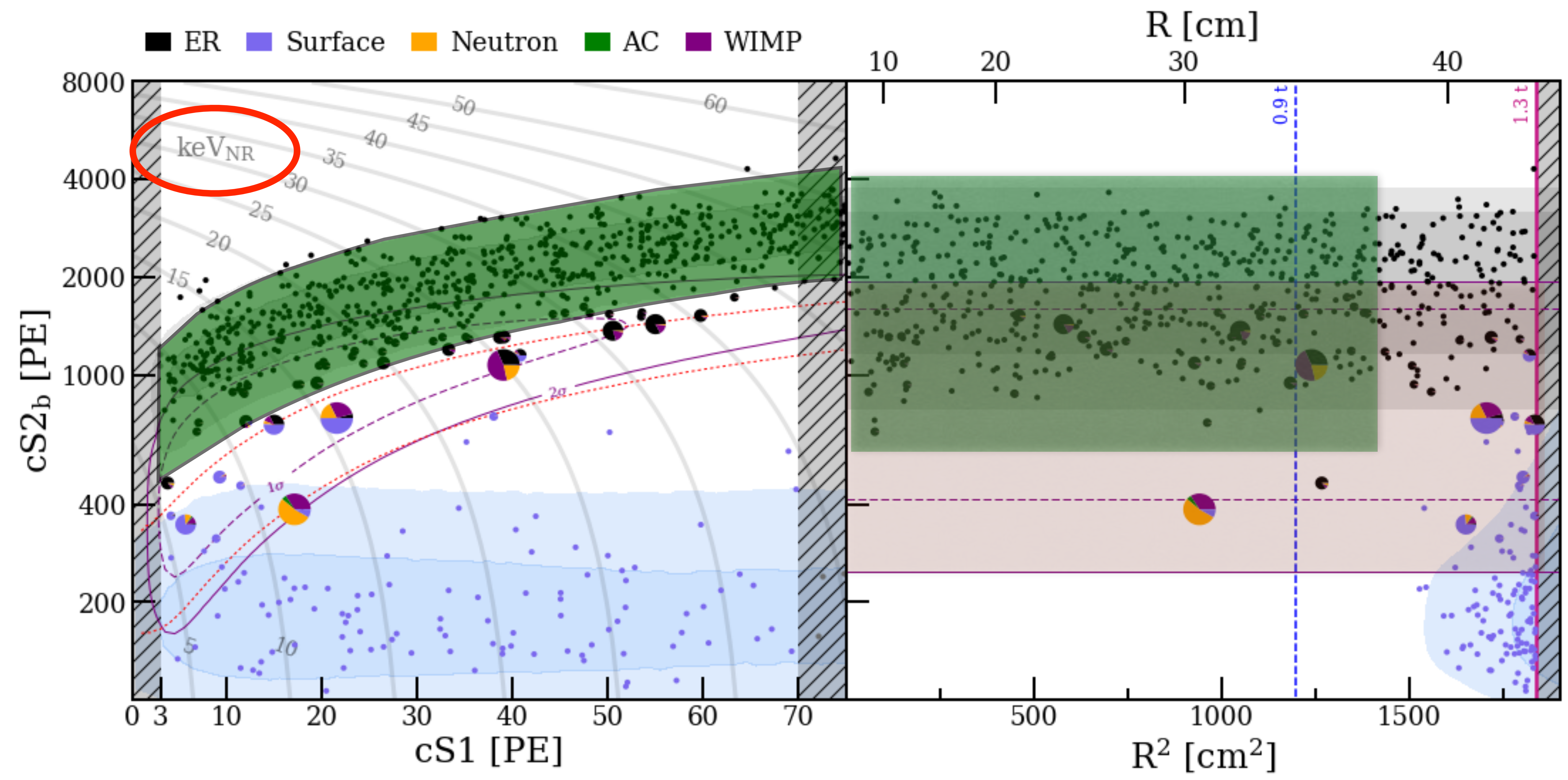
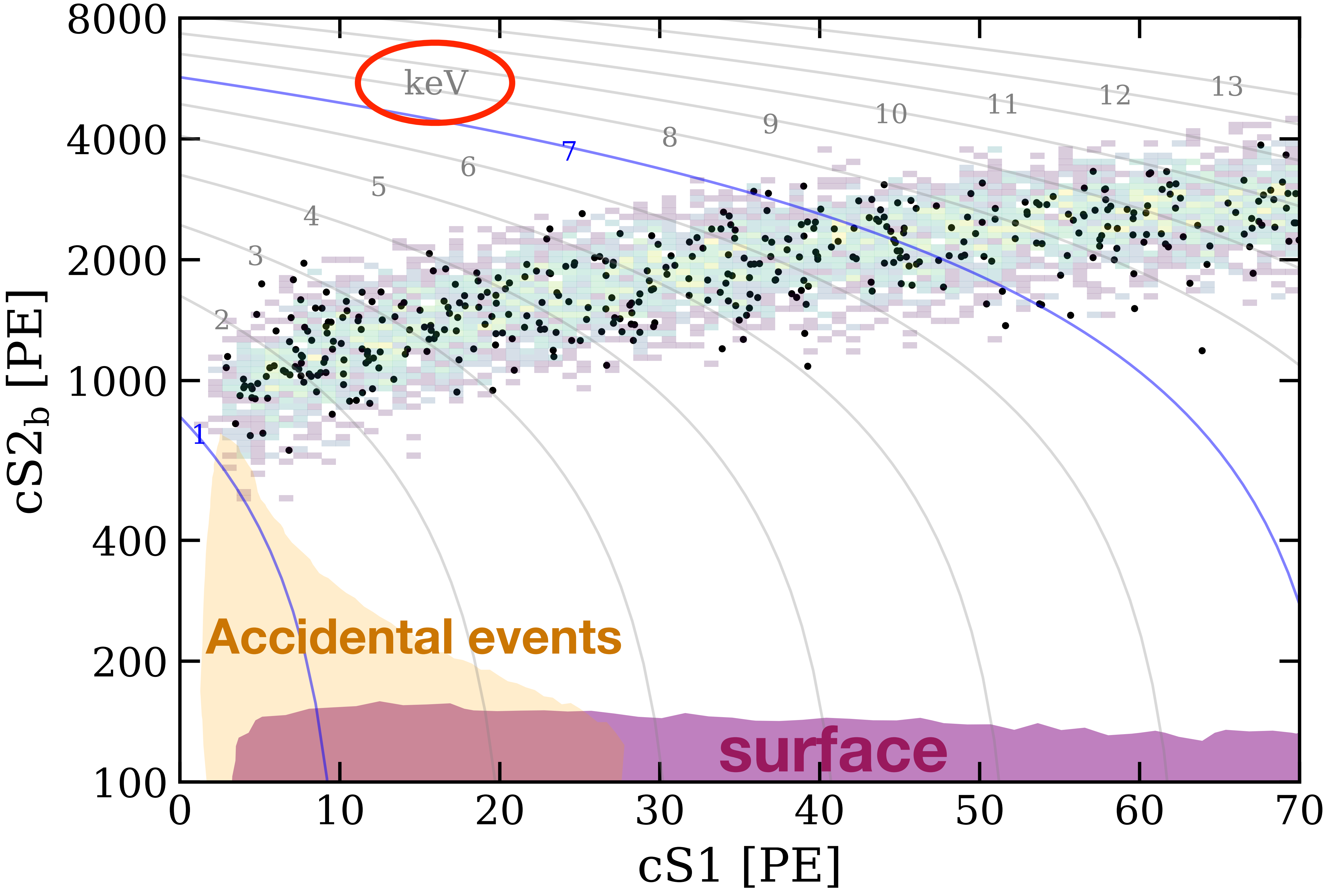
1
3
10
30
100
300
1000
Dark matter particle mass [GeV/c^2]

XENON1T Electronic Recoil band band





Nuclear recoil energy scale -> Electronic recoil energy scale

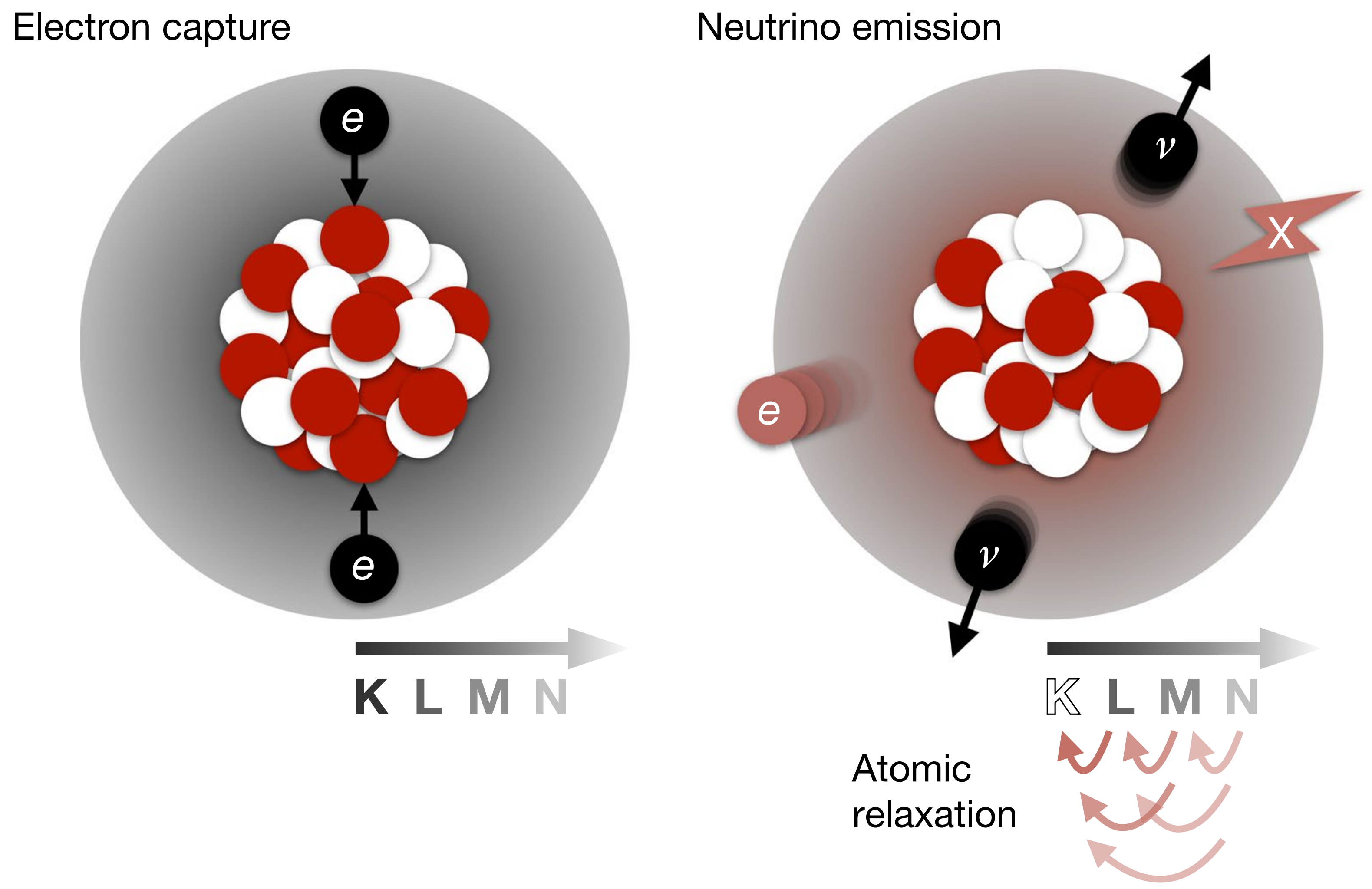
In the past …

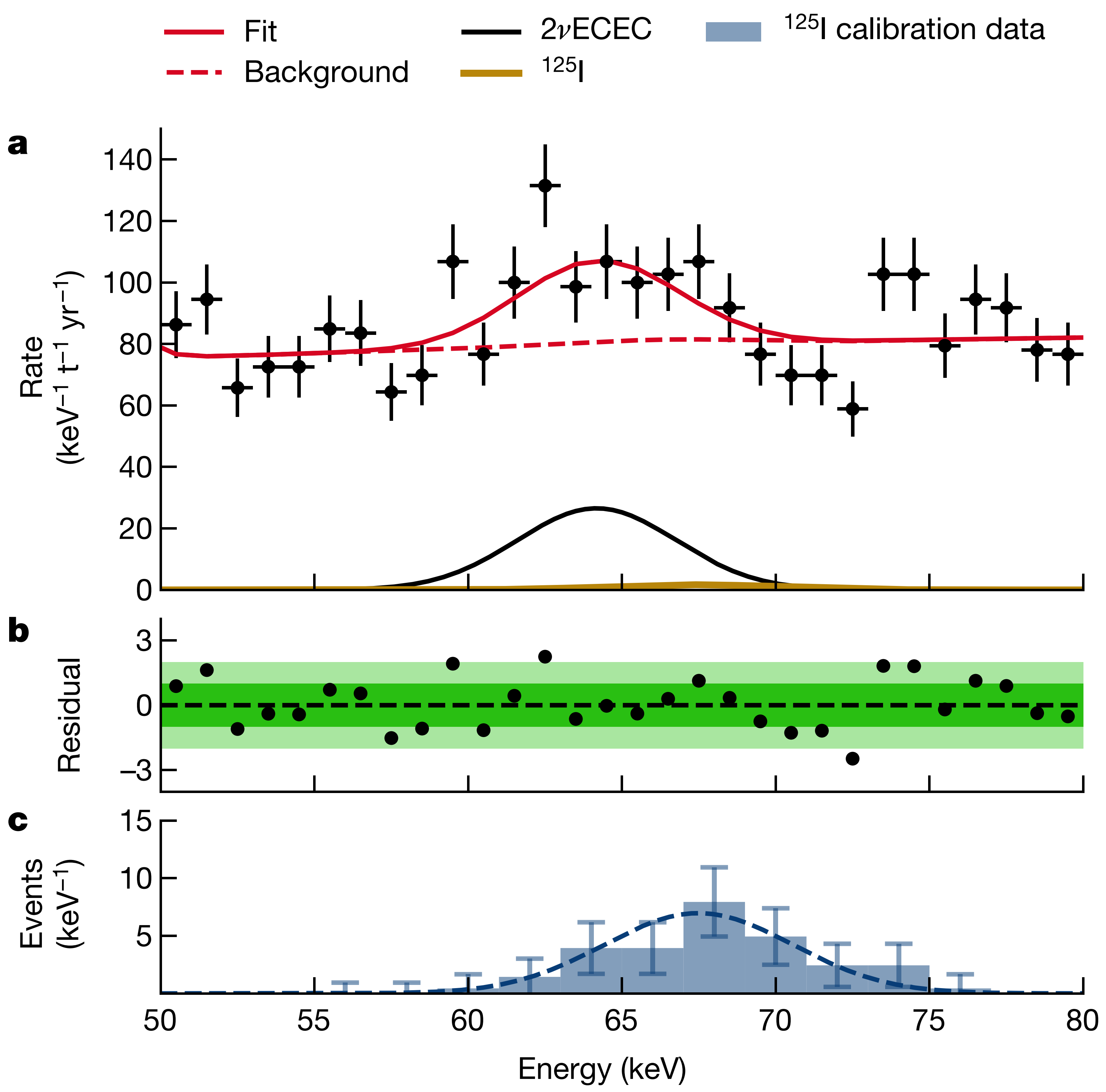
LETTER *Nature 568, 532–535*

https://doi.org/10.1038/s41586-019-1124-4

Observation of two-neutrino double electron capture in ^{124}Xe with XENON1T

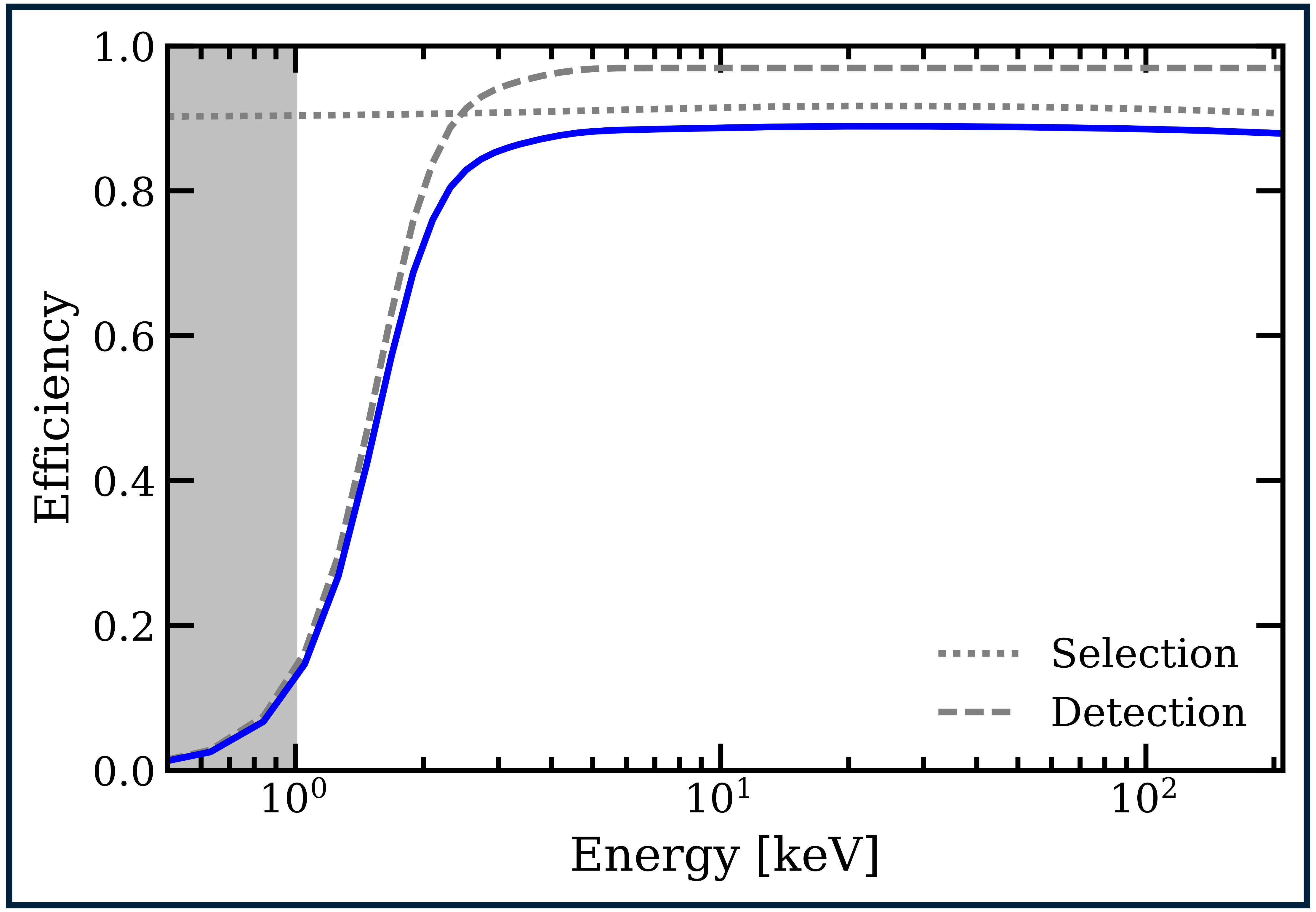
XENON Collaboration*





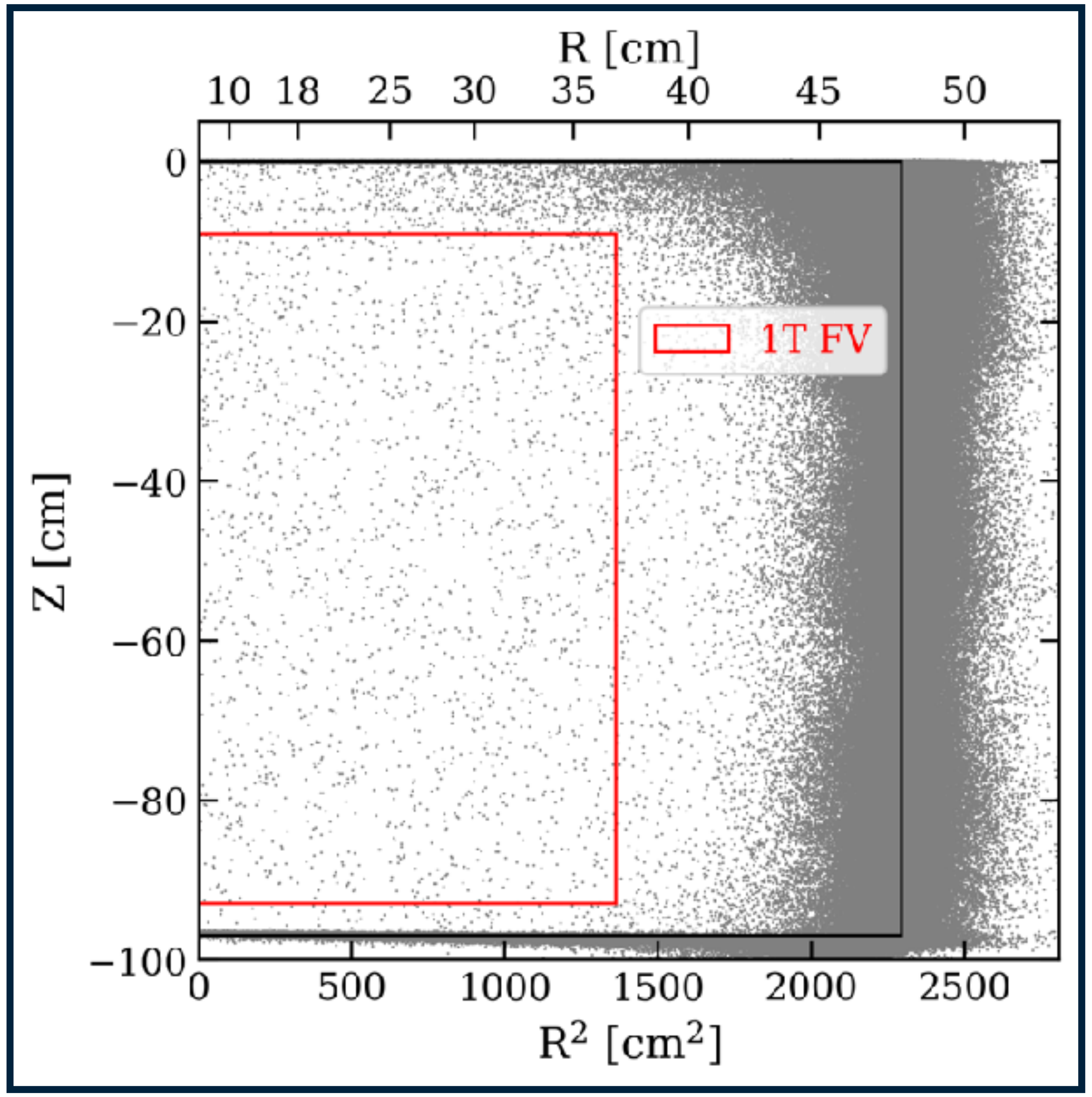
The direct observation of 2vECEC in ^{124}Xe with the XENON1T dark-matter detector.
The corresponding half-life of 1.8×10^{22} years is the longest measured directly so far.

Signal Efficiency and Fiducial volume



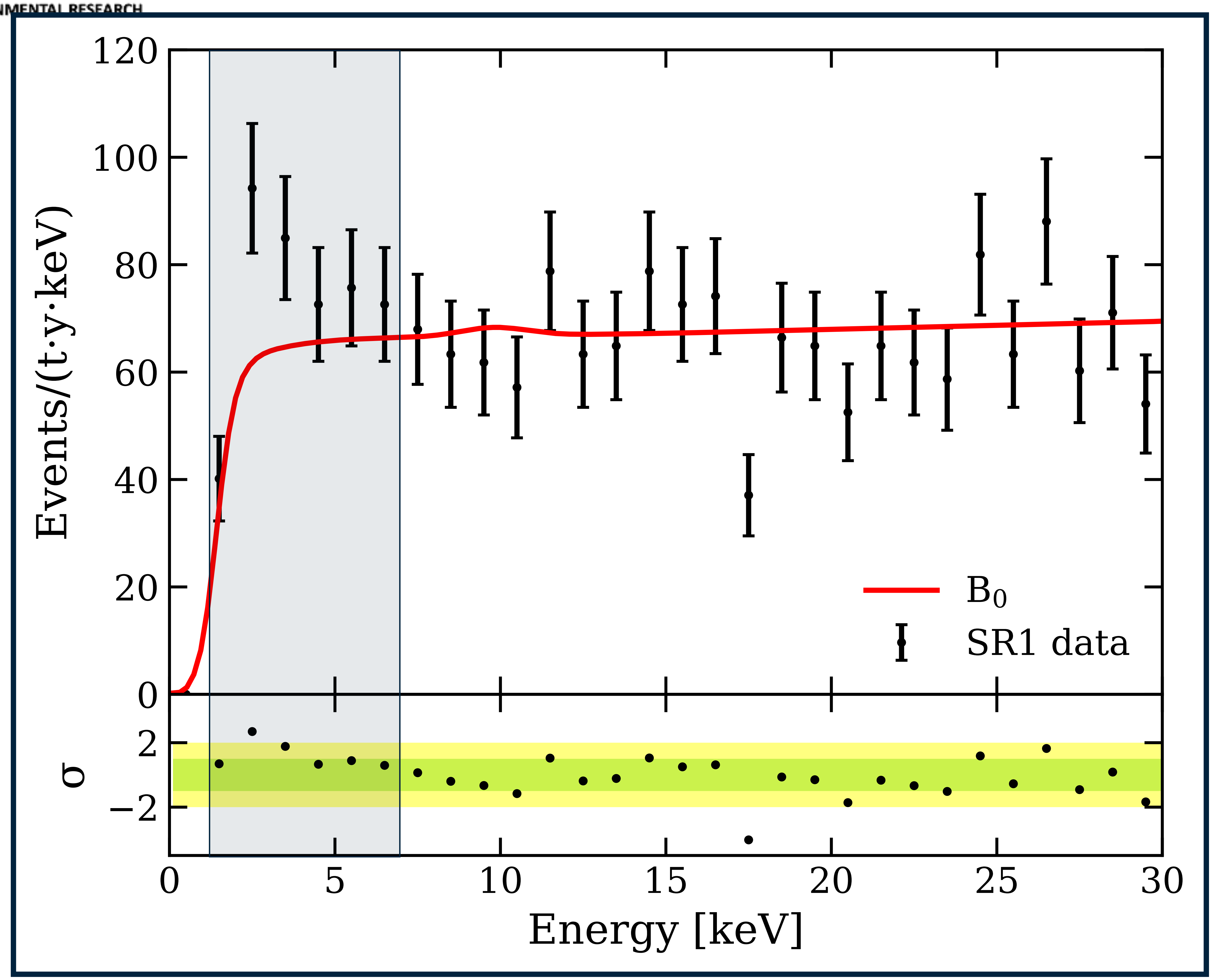
Similar selection criteria as WIMPs search in 2018

High acceptance for ER energy > 2 keV



Reduced fiducial volume for ER search

The Low Energy Excess (ER)



Excess between 1- 7 keV!

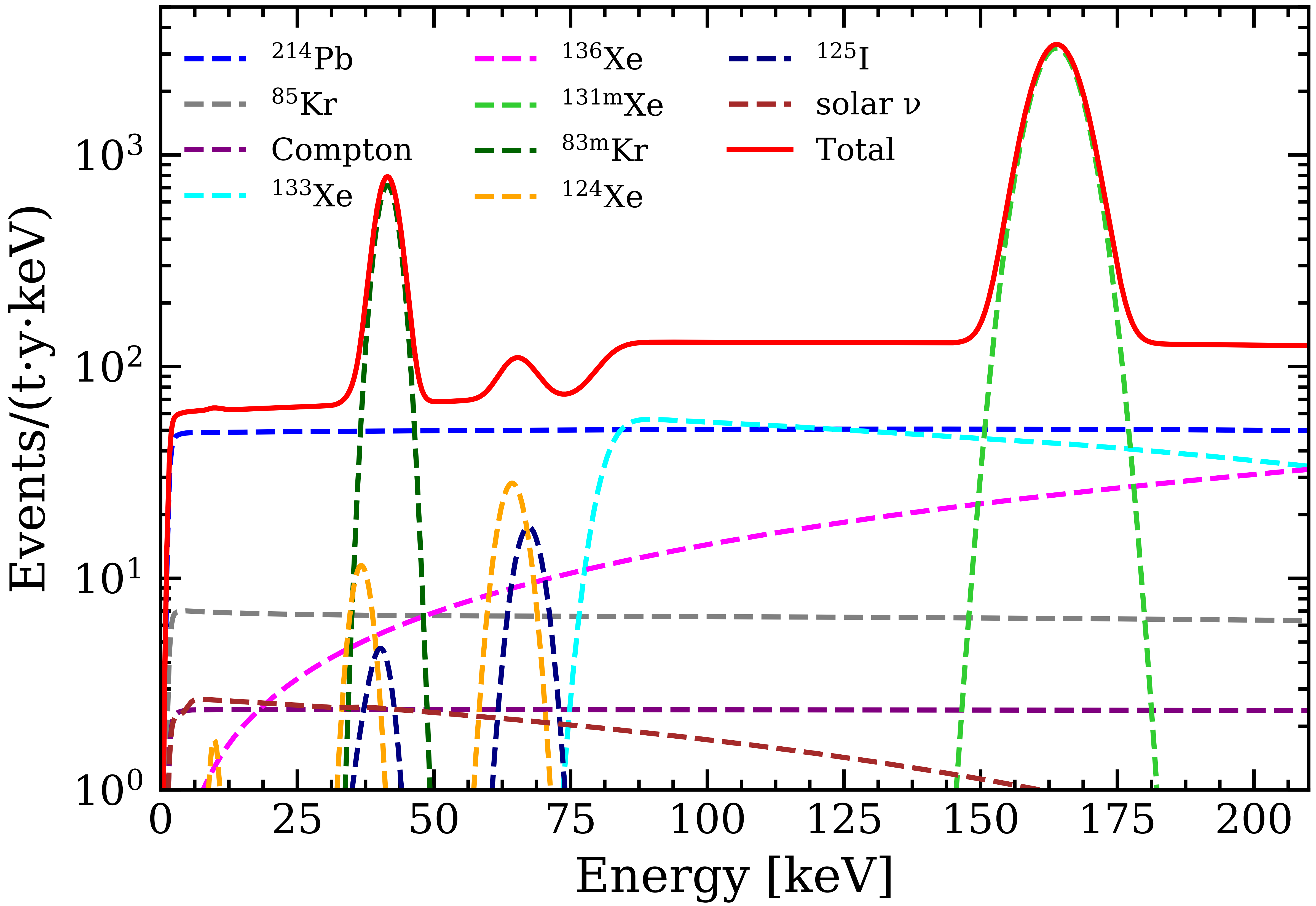
Expectation: 232±15

Observation: 285

Excess is most abundant between 2-3 keV

Background model

Search for an excess above background.



10 BG components

Intrinsic

^{214}Pb ^{136}Xe

^{85}Kr ^{124}Xe

Neutron activated

^{131m}Xe

^{133}Xe

^{125}I

Materials

Solar neutrinos

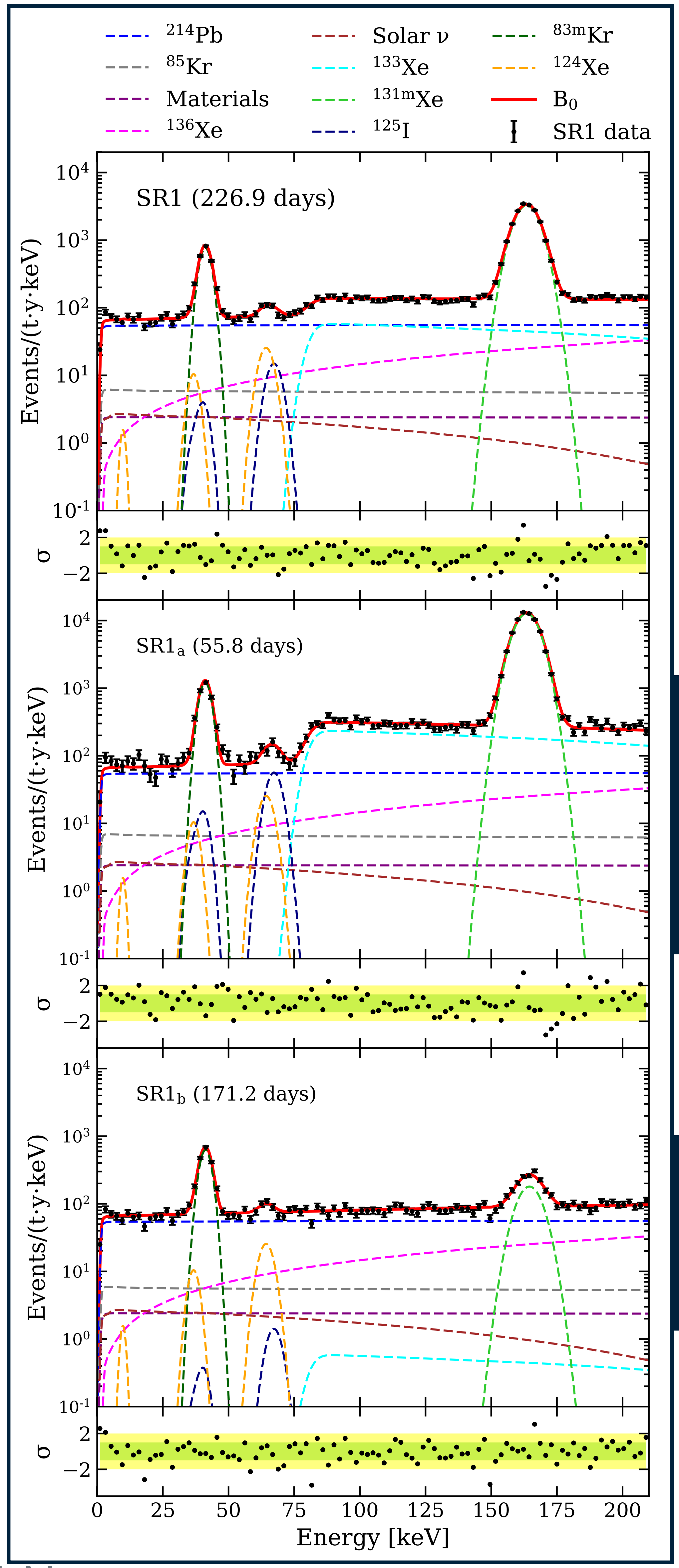
Predicted energy spectra based on detailed modeling of each background component
Rates constrained by measurements and/or time dependence

Background fit

SR1(all)

SR1a

SR1b



t-dependent Bg
< 50 days after
neutron calibration

> 50 days after
neutron calibration

Unbinned profile likelihood analysis

$$\mathcal{L}(\mu_s, \boldsymbol{\mu_b}, \boldsymbol{\theta}) = \mathrm{Poiss}(N|\mu_{tot}) \times \prod_i^N \left(\sum_j \frac{\mu_{b_j}}{\mu_{\mathrm{tot}}} f_{b_j}(E_i, \boldsymbol{\theta}) + \frac{\mu_s}{\mu_{\mathrm{tot}}} f_s(E_i, \boldsymbol{\theta}) \right) \times \prod_m C_{\mu_m}(\mu_{b_m}) \times \prod_n C_{\theta_n}(\theta_n), \quad (14)$$

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

Profile over the nuisance parameters

Combining the likelihoods of the 2 partitions

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

What is this?

Background?

Signal? (Beyond Standard Model)

What is this?

Background?

Signal? (Beyond Standard Model)

Solar Axions

- QCD axion
= Axions would also be produced in the Sun, with kinetic energies ~ keV

Neutrio Magnetic moment

In the (extended) SM:

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

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

Bosonic Dark matter

- candidate for Warm Dark Matter
- Axion-like particles like QCD axions.
- allows for ALPs to take on higher masses than QCD axions

What is this?

Background?

β-decay of tritium?

Low-energy (Q value 18.6 keV)
Long half life (12.3 years)
Atmospherically "abundant" and cosmogenically produced in xenon

Removed by purification system?

Signal? (Beyond Standard Model)

Solar Axions

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

Bosonic Dark matter

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- Axion-like particles like QCD axions.
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Statistical Inference

Unbinned likelihood ratio tests

Profiled over nuisance parameters

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

statistical significance:
→ q(0)

Solar Axions

3 independent* parameters

ABC rate
Primakoff rate
^{57}Fe rate

*No assumptions about specific QCD axion models

→

3-dimensional confidence volume

g_{ae}
$g_{a\gamma}$
g_{an}^{eff}

Toy-MC methods for significance

Neutrino Magnetic Moment

1 parameter

solar ν rate enhancement

→

1-dimensional confidence interval

μ_ν

smoothly transitions from upper- to two-sided limit at 3σ. (K.D. Morå, arXiv:1809.02024)

Tritium

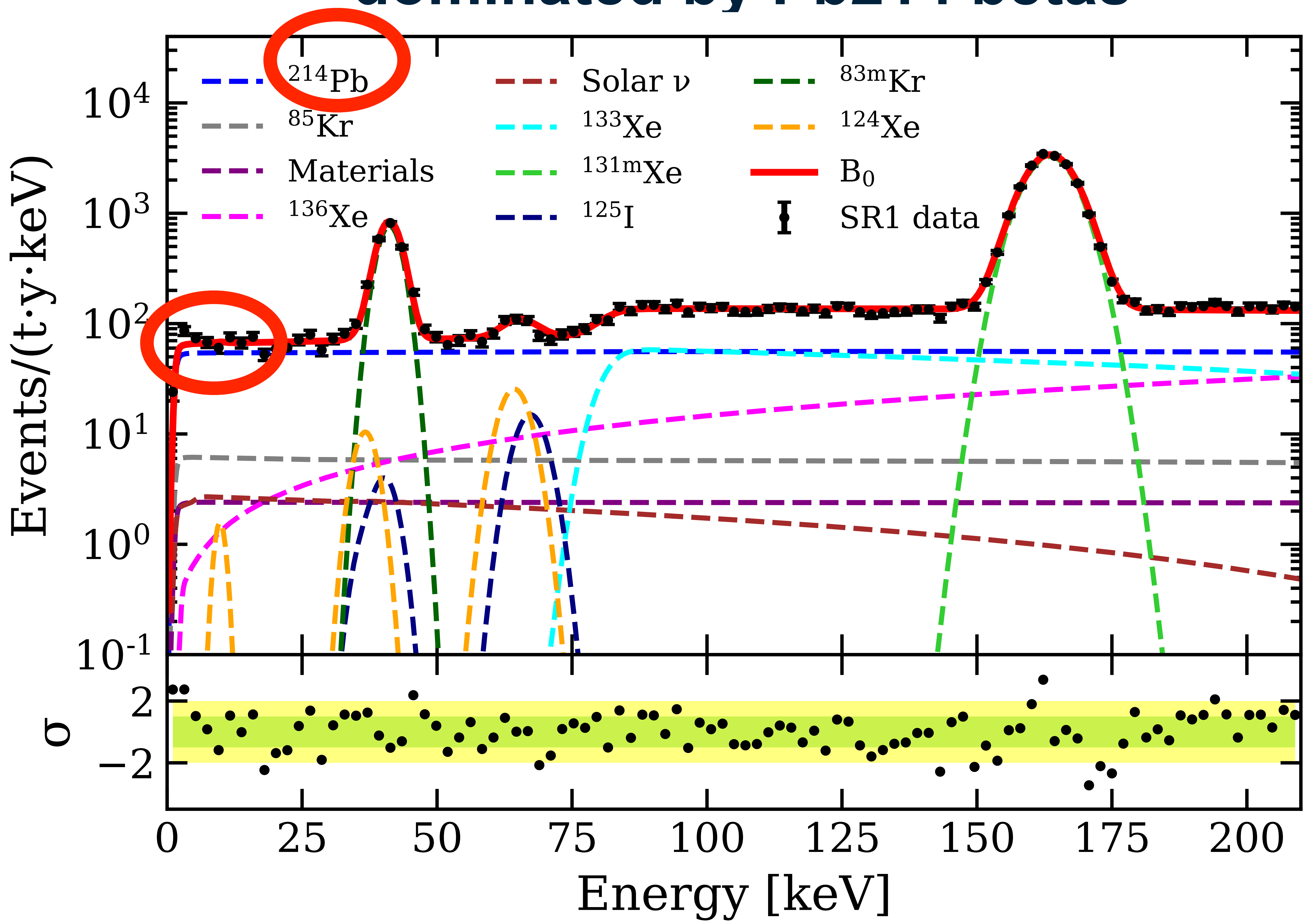
Solar Axion

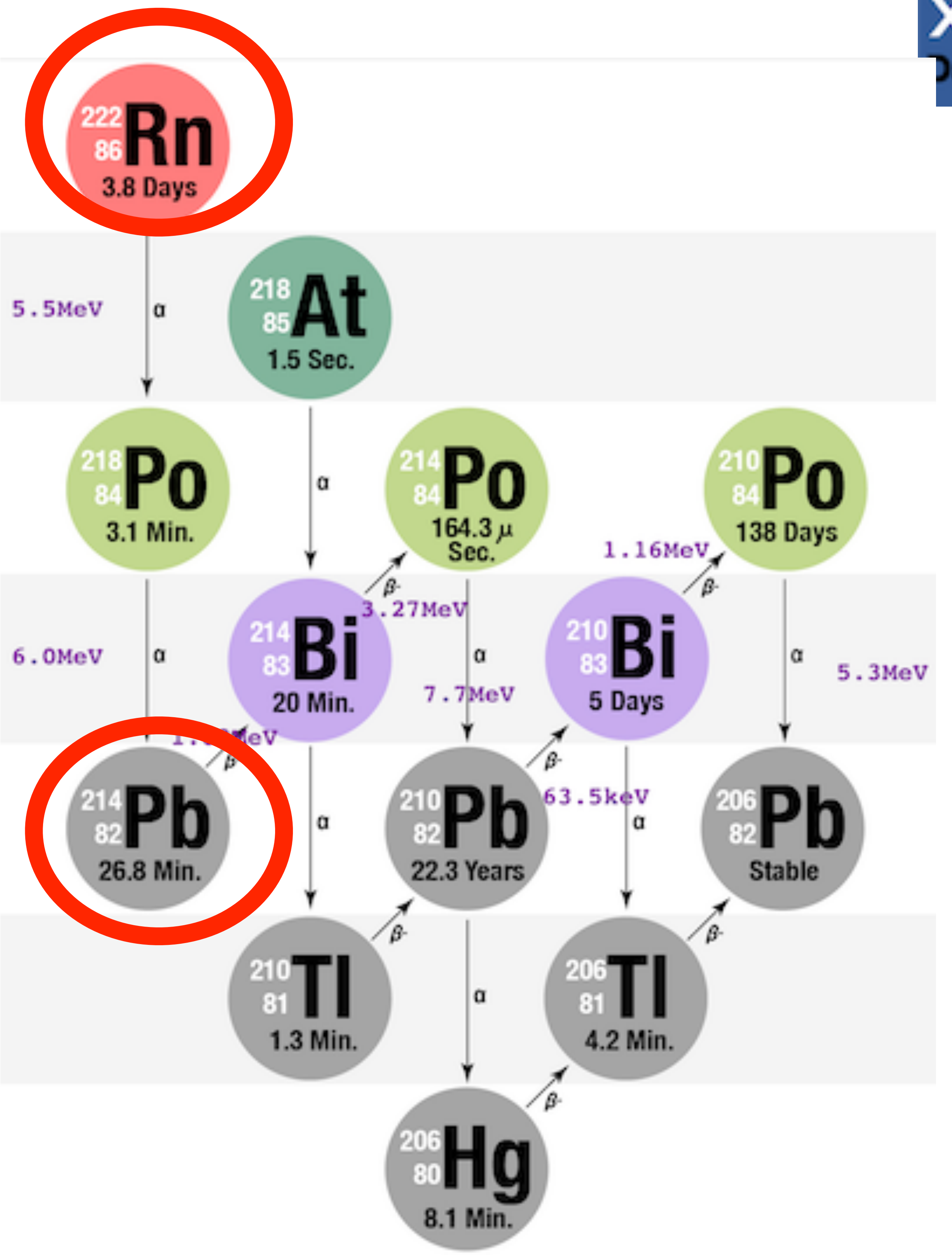
Neutrino magnetic moment + others

The XENON1T ER Background

- ER is the dominant background
- Surface background & neutron distribution are not uniform. Spatial likelihood is taken into consideration.

dominated by Pb214 betas



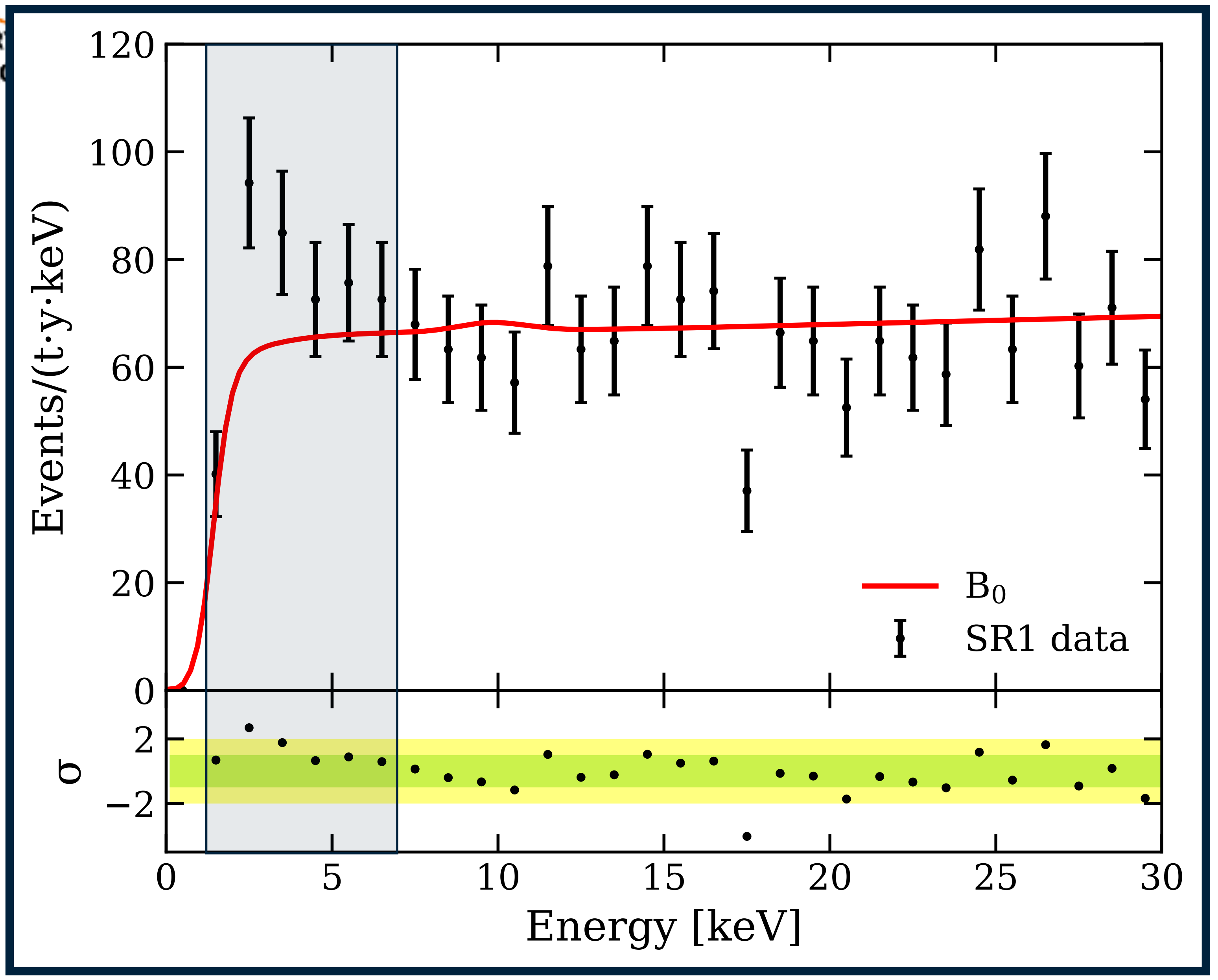


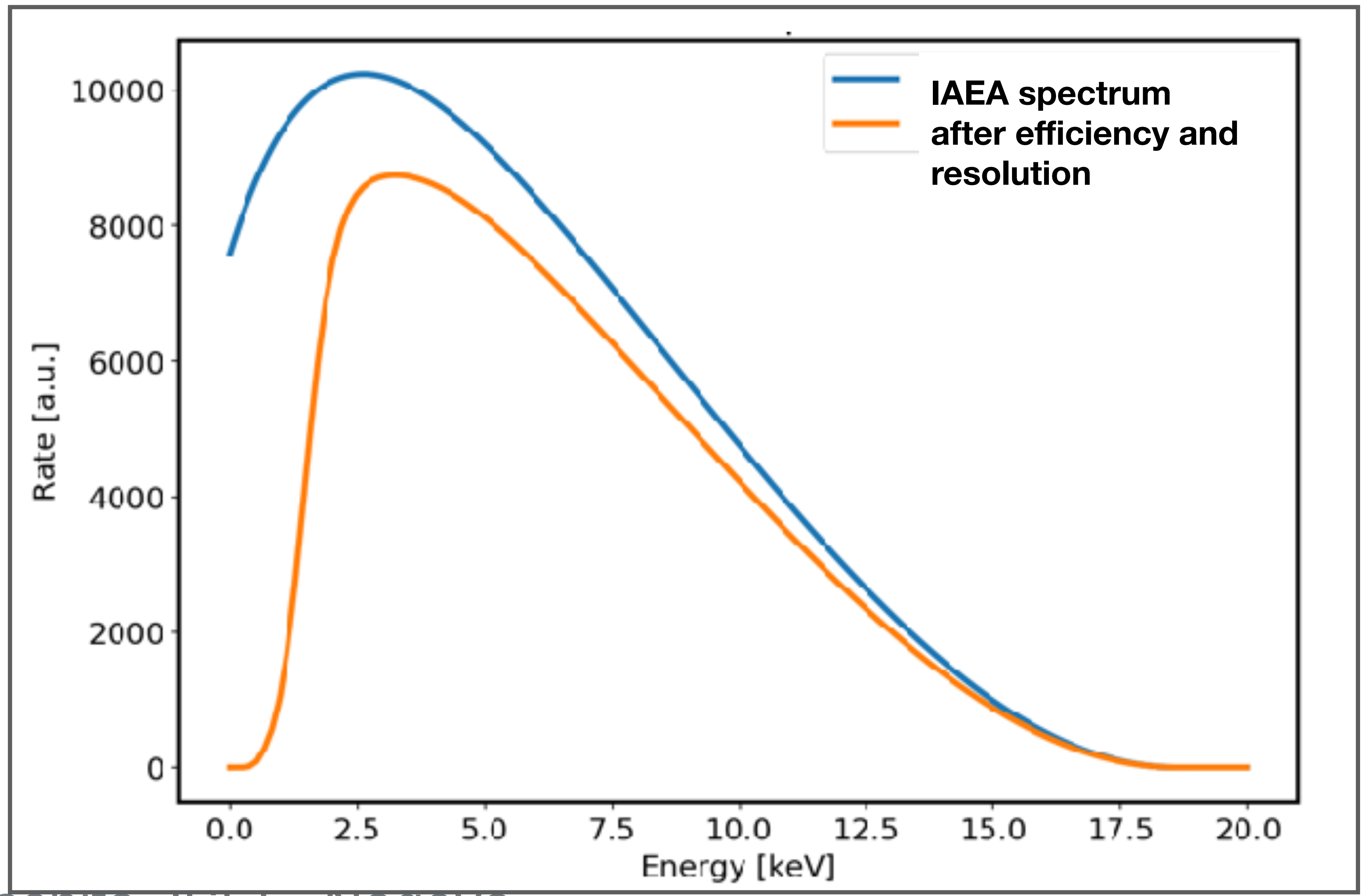
Decent matching across the whole energy range 1-210 keV

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

Lowest background rate ever achieved in this energy range!

Tritium (^3H) ?





Low energy (Q-value 18.6keV)

Long half life (12.3 years)

Two possible ways to introduce tritium:

Cosmogenic production

Atmospherically abundant

Tritium Fit

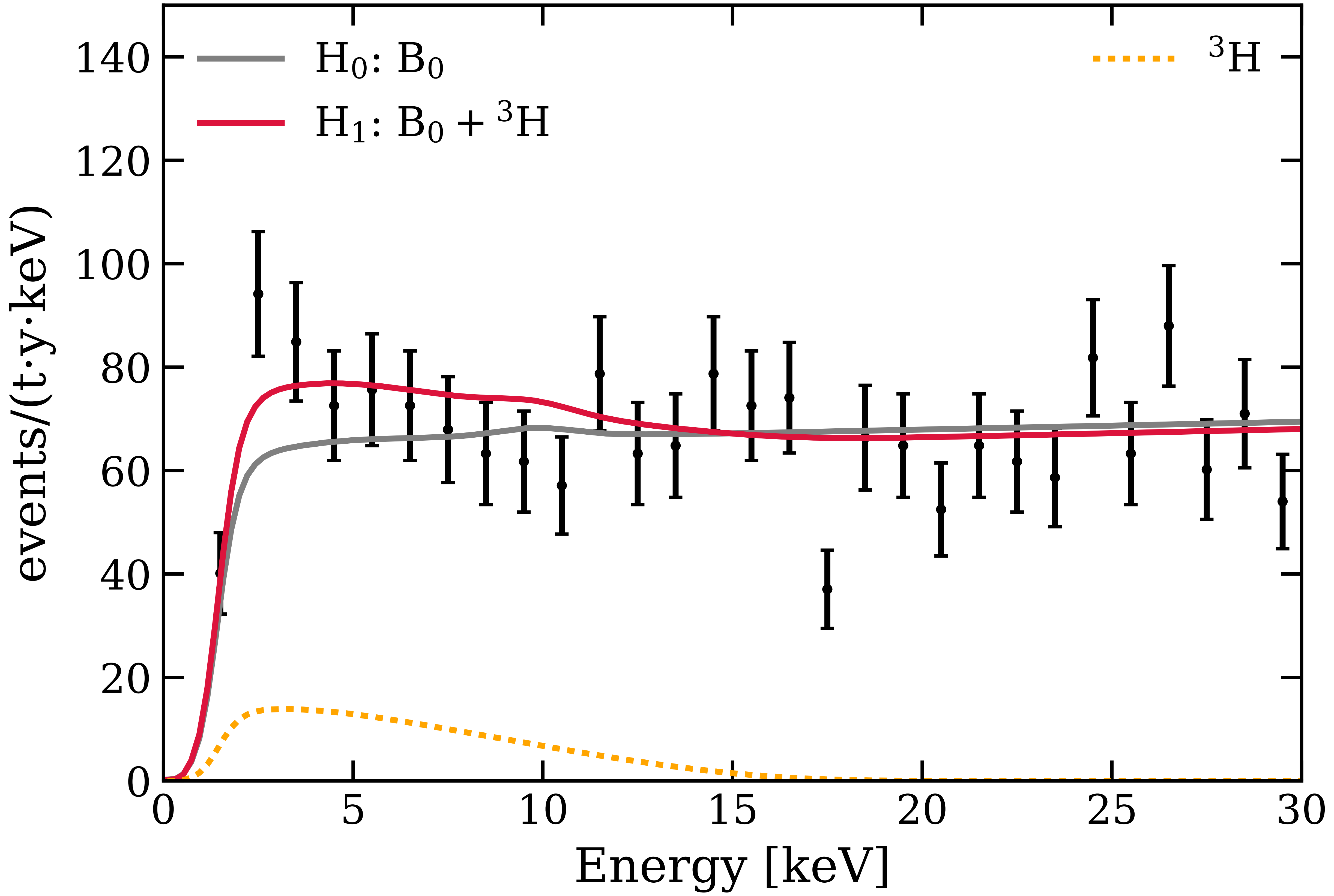
Tritium favored over background-only at 3.2σ

Tritium Rate

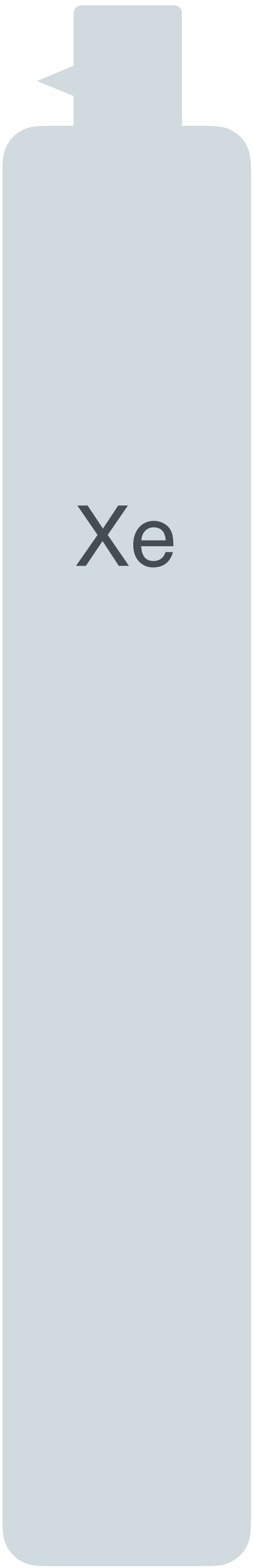
$$159 \pm 51\,\mathrm{events}/(\mathrm{t}\cdot\mathrm{y})$$

^{3}H:Xe concentration

$$6.2 \pm 2.0 \times 10^{-25}\ \mathrm{mol/mol}$$



Tritium hypothesis

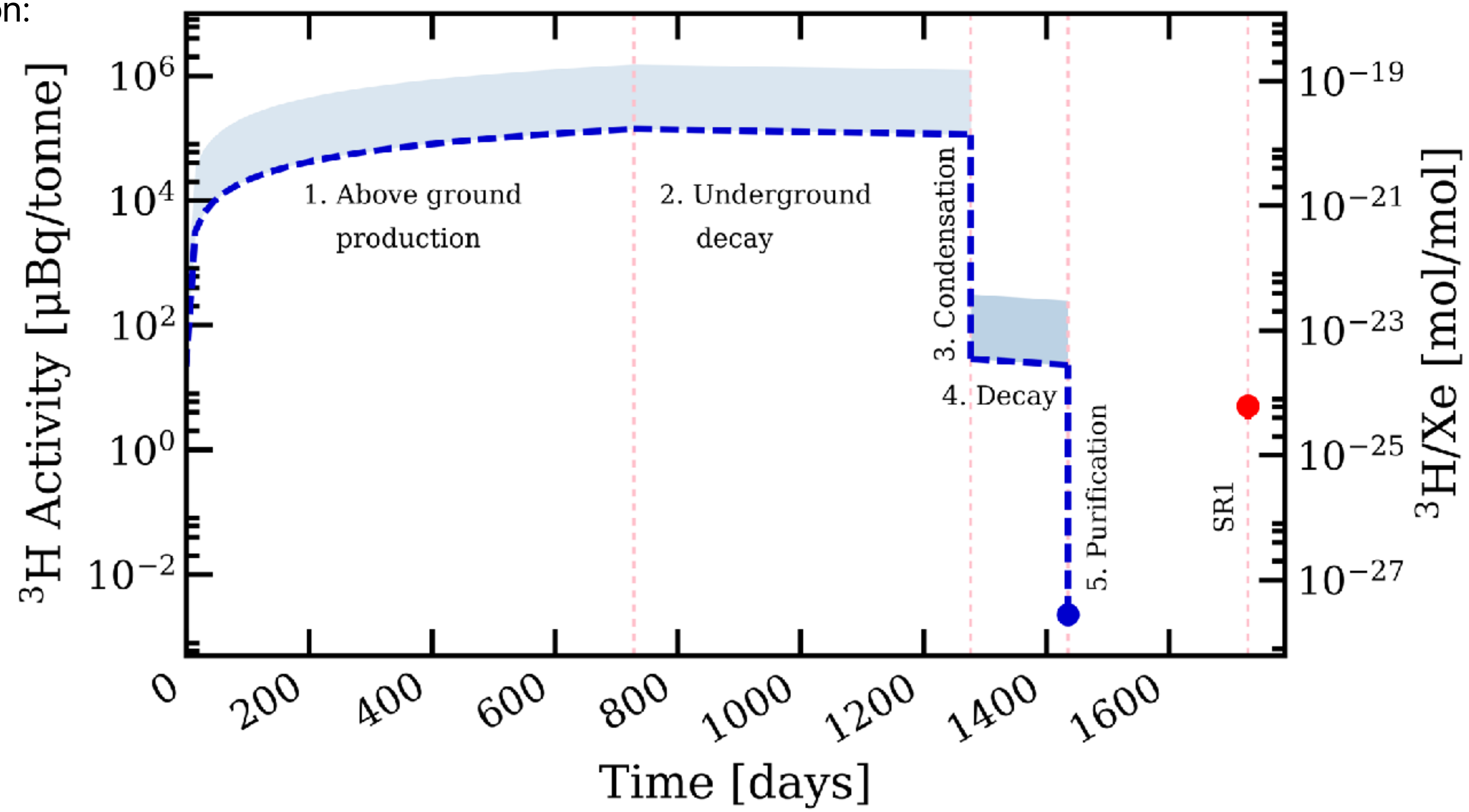


Cosmogenic activation of xenon: ~32 tritium atoms/kg/day (Zhang, 2016)

1 ppm water in bottles implies tritium forms predominately HTO.

Efficient removal (99.99%) in purification system (SAES getter with hydrogen removal unit)

From purification and handling, this component seems unlikely.



(note: tritium from activation While underground is negligible.)

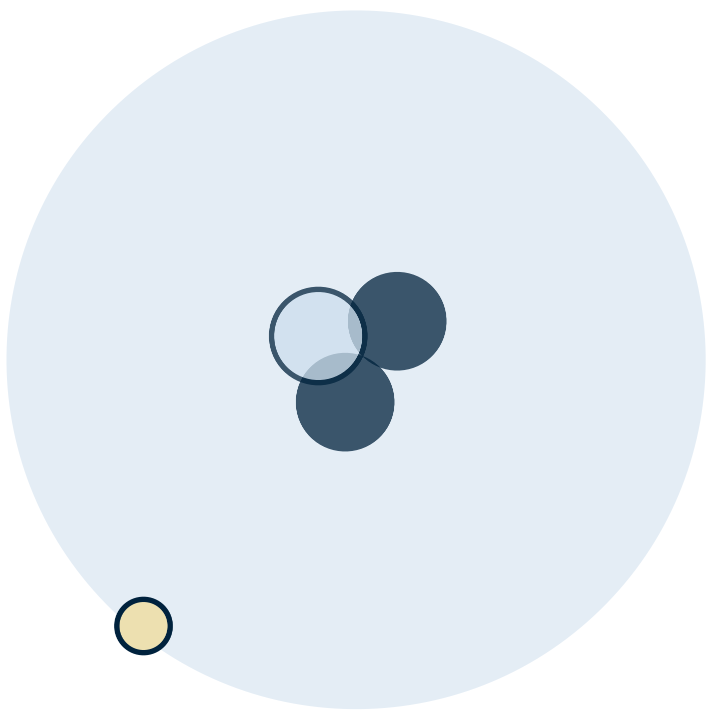
Tritium Hypothesis

Atmospheric abundance in materials

HTO:H_2O concentration* *(assume same for HT)*	$5\text{–}10 \times 10^{-18}$ mol/mol
Required (H_2O + H_2):Xe concentration to explain excess	**60–120 ppb**

Any T in xenon gas *prior to* filling would be removed.

What about T emanating from materials in equilibrium with removal?



H_2O

H_2O:Xe concentration constrained from light yield measurement

O(1) ppb

H_2

H_2:Xe concentration not constrained by any measurement.

O2-equivalent concentration is **<ppb** from xenon purity measurement (e-lifetime)

H_2 would require equilibrium emanation rate ~100x higher than electronegative impurities.

*IAEA/WMO, "Global Network of Isotopes in Precipitation. The GNIP Database." https://nucleus.iaea.1723org/wiser(2015).

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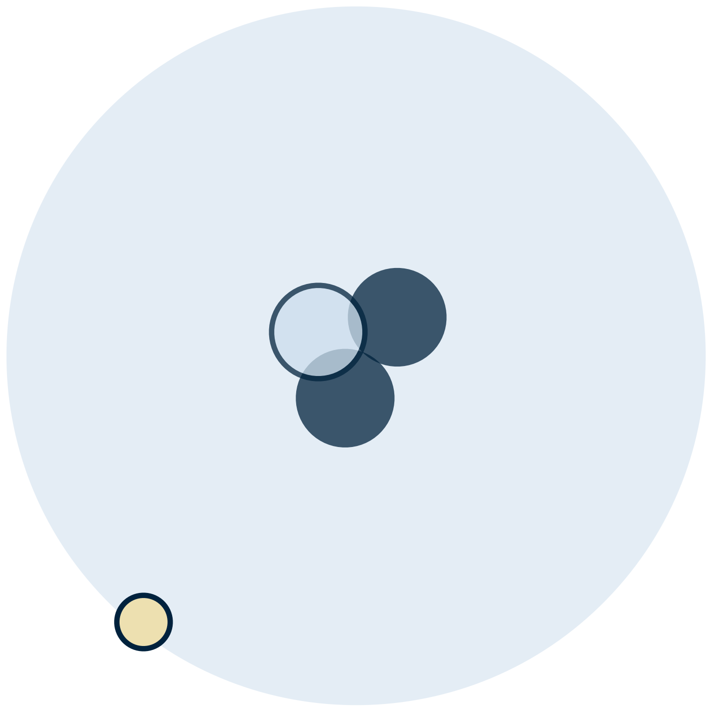

HTO:H_2O concentration* *(assume same for HT)*	$5–10 \times 10^{-18}$ mol/mol
Required (H_2O + H_2):Xe concentration to explain excess	**60–120 ppb**

H_2O

Unlikely

H_2O:Xe concentration constrained from light yield measurement

O(1) ppb

H_2

Maybe?

H_2:Xe concentration not constrained by any measurement.

O2-equivalent concentration is **<ppb** from xenon purity measurement (e-lifetime)

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*IAEA/WMO, "Global Network of Isotopes in Precipitation. The GNIP Database." https://nucleus.iaea.1723org/wiser(2015).

Atmospheric abundance in materials

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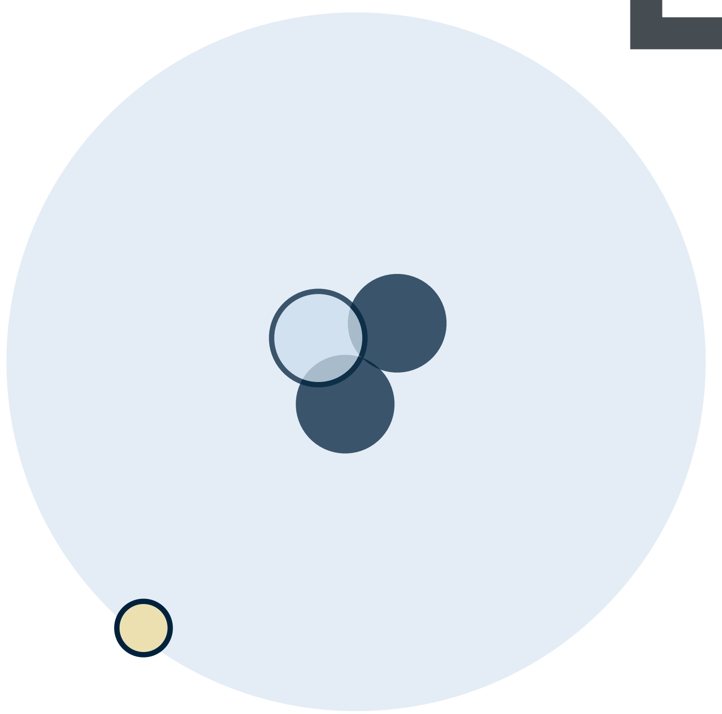

HTO:H_2O concentration*
(assume same for HT)

$$5\text{--}10 \times 10^{-18}\ \mathrm{mol/mol}$$

ppb

And there are additional uncertainties...

- Unknown radiochemistry in liquid xenon environment (isotopic exchange, diffusion, solubility, etc.)
- Presence of other tritiated molecules?

H_2O:Xe concentration constrained from
light yield measurement

O(1) ppb

constrained by any
measurement.

Maybe?

O2-equivalent concentration is **<ppb** from xenon purity measurement (e-lifetime)

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Tritium

Solar Axion

Neutrino magnetic moment + others

Solar Axion

Axion

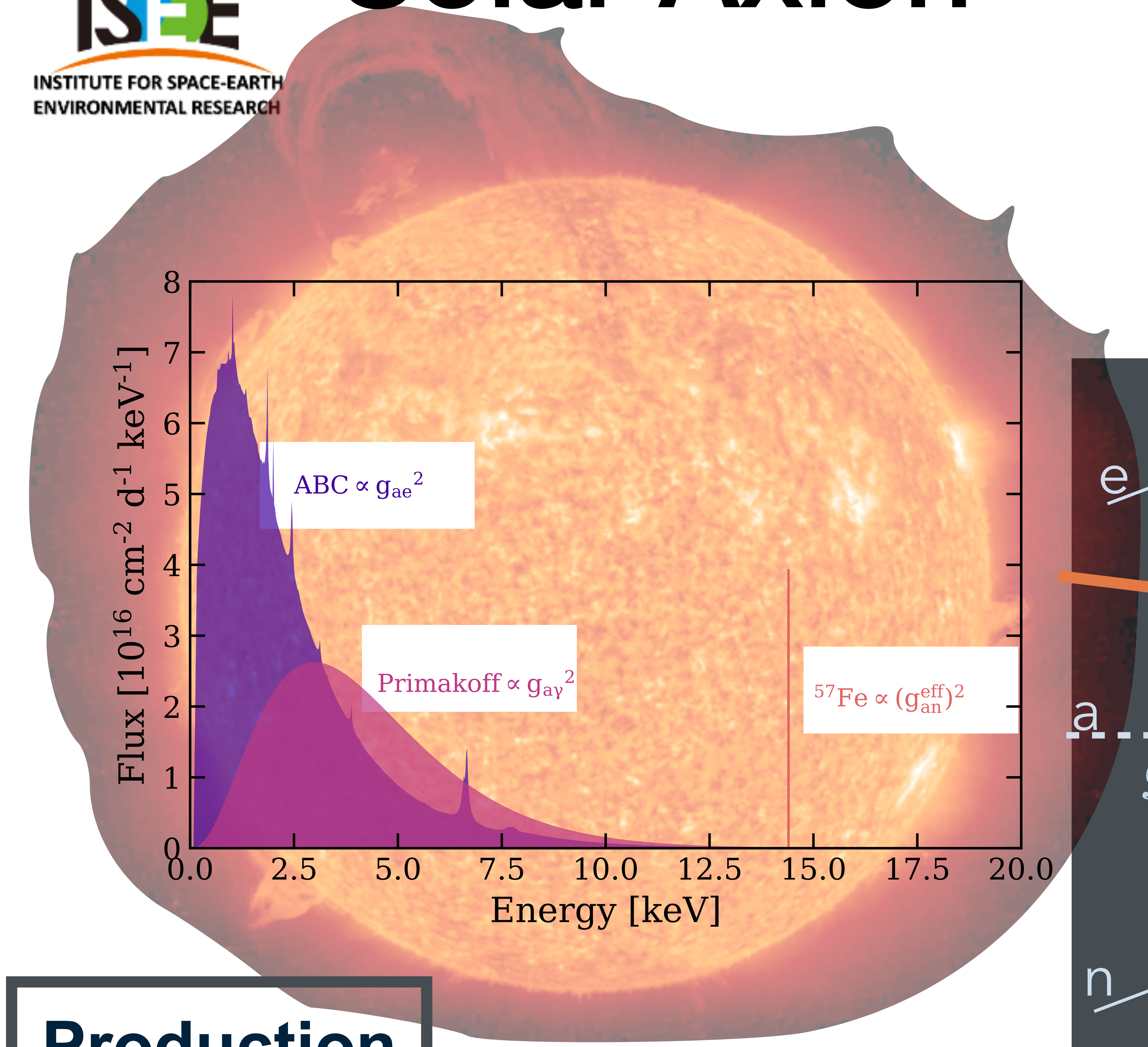
Solution to the "strong CP problem"

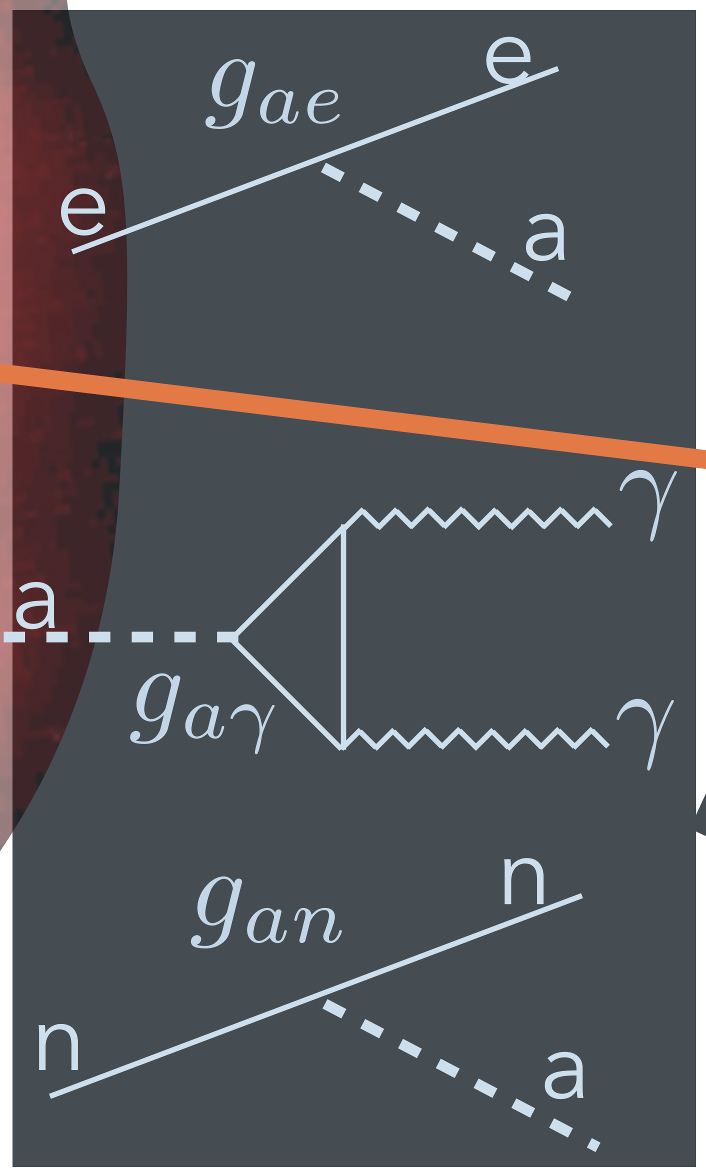
Natural candidates of the dark matter

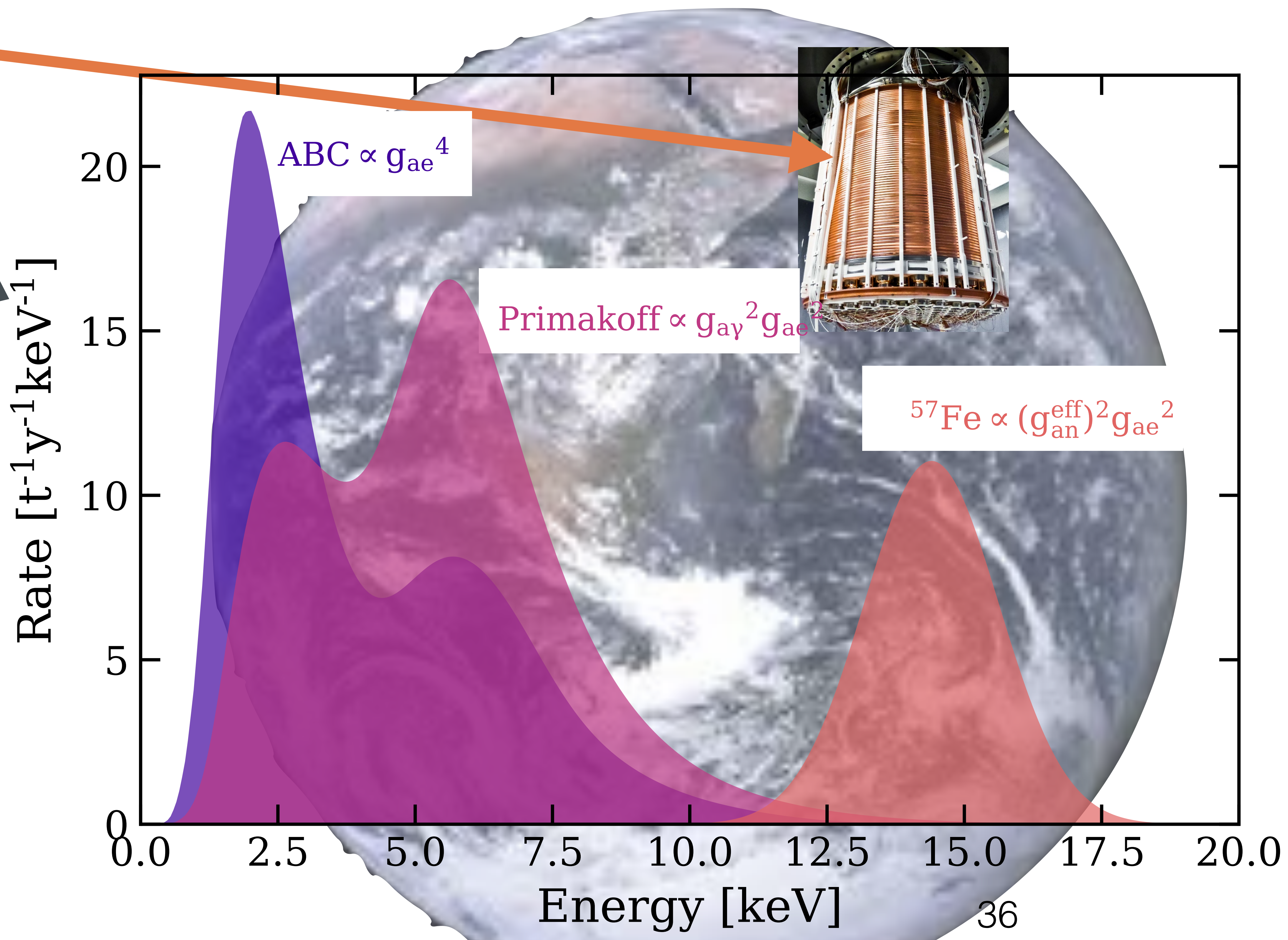
Detection

Axions would also be produced in the Sun, with kinetic energies ~ keV

However, solar axion is not a dark matter.



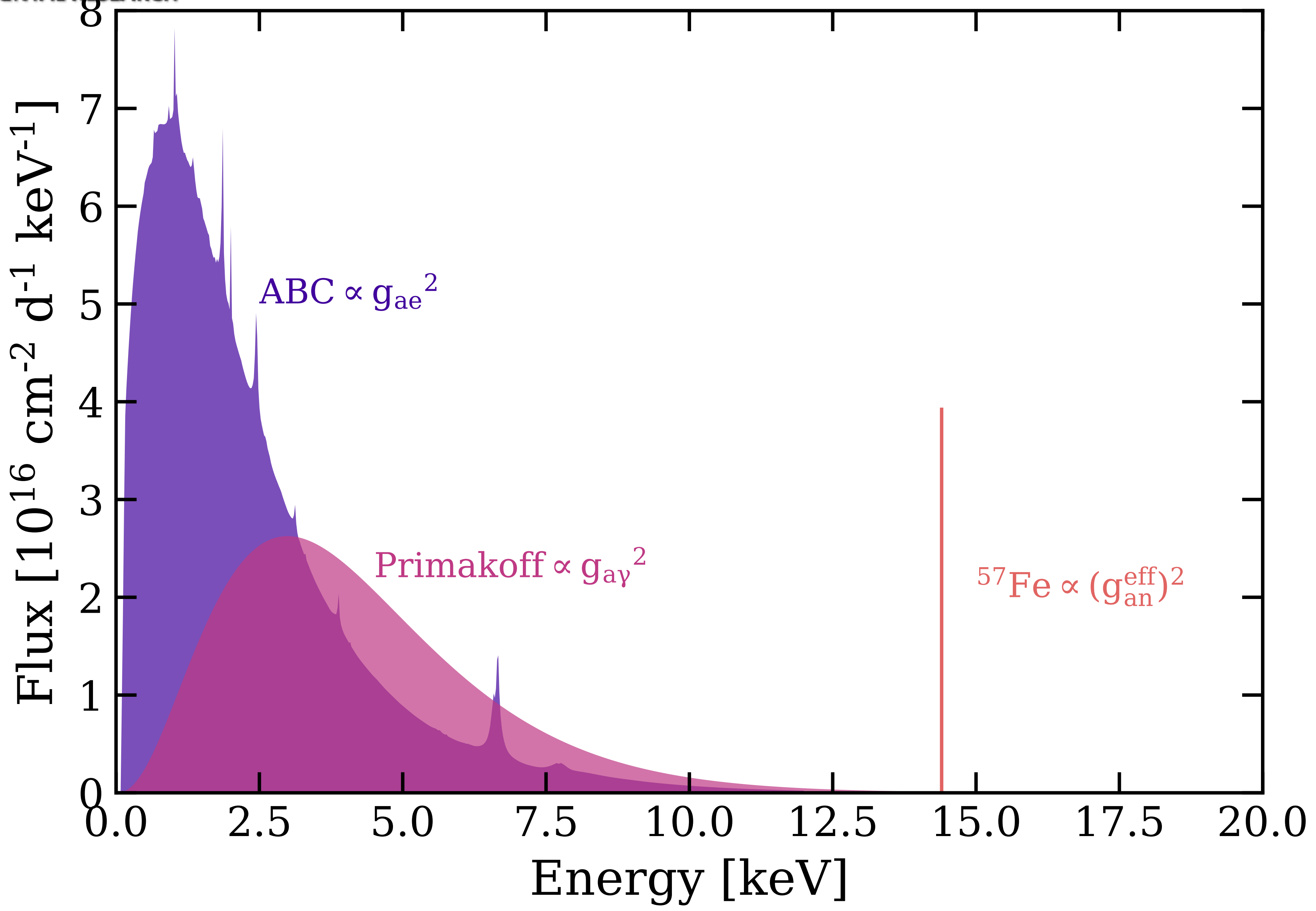




Production

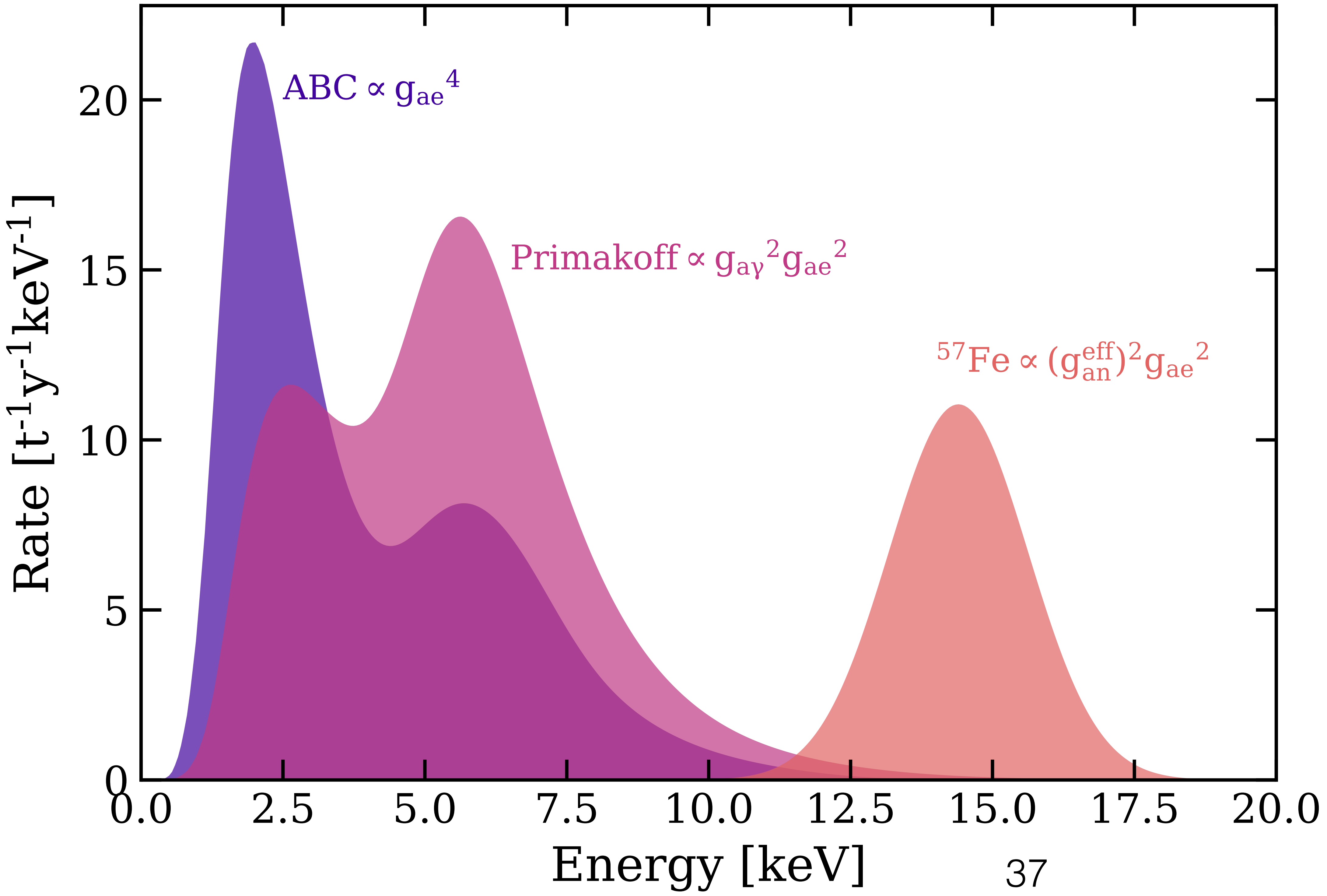
- **ABC axion (Redondo 2013, Dimopoulos 1986) (atomic recombination, Bremsstrahlung, Compton)**
- **Primakoff (Primakoff 1951, Dicus 1978)**
- **M1 transition of 57Fe (Moriyama 1995)**

Solar Axion



Axioelectric effect

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

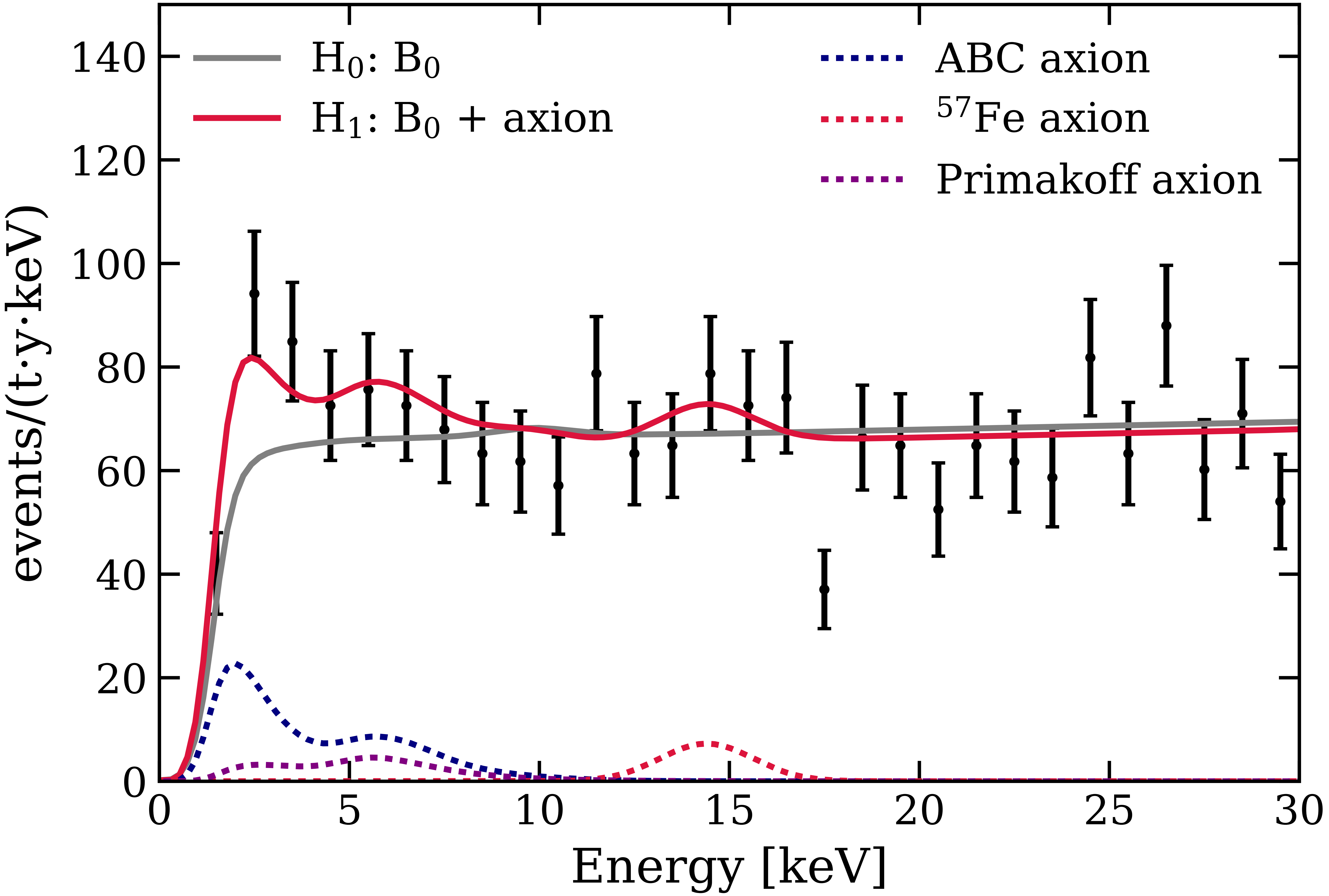


Fitting Axions to the Excess

- Unbinned profile likelihood analysis

- XENON1T BG + Axion (ABC, Primakov, 57Fe)

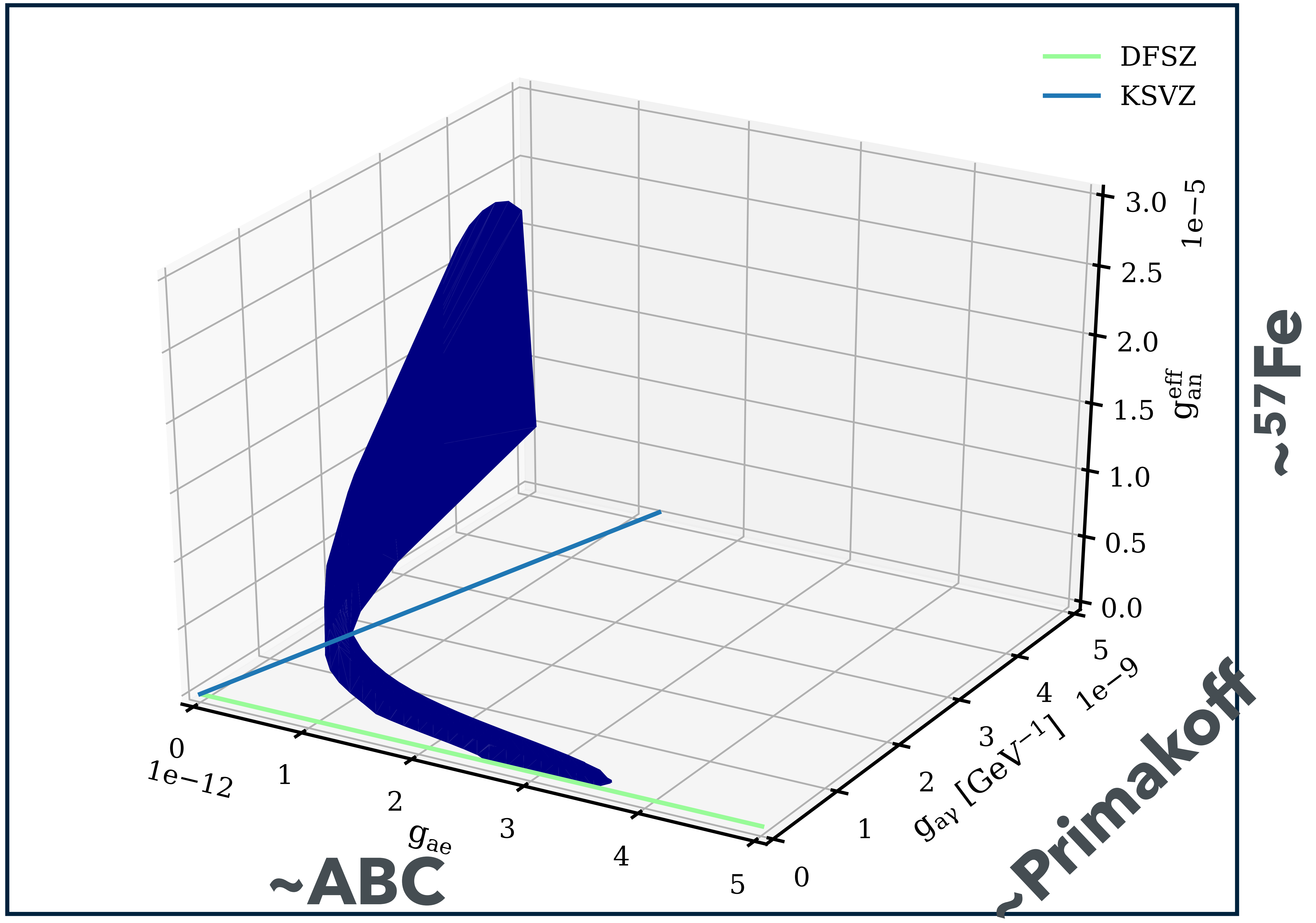
- + Tritium background will com later.



Axion favored over background-only at 3.5σ

Solar Axion Results

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



Excludes one of:

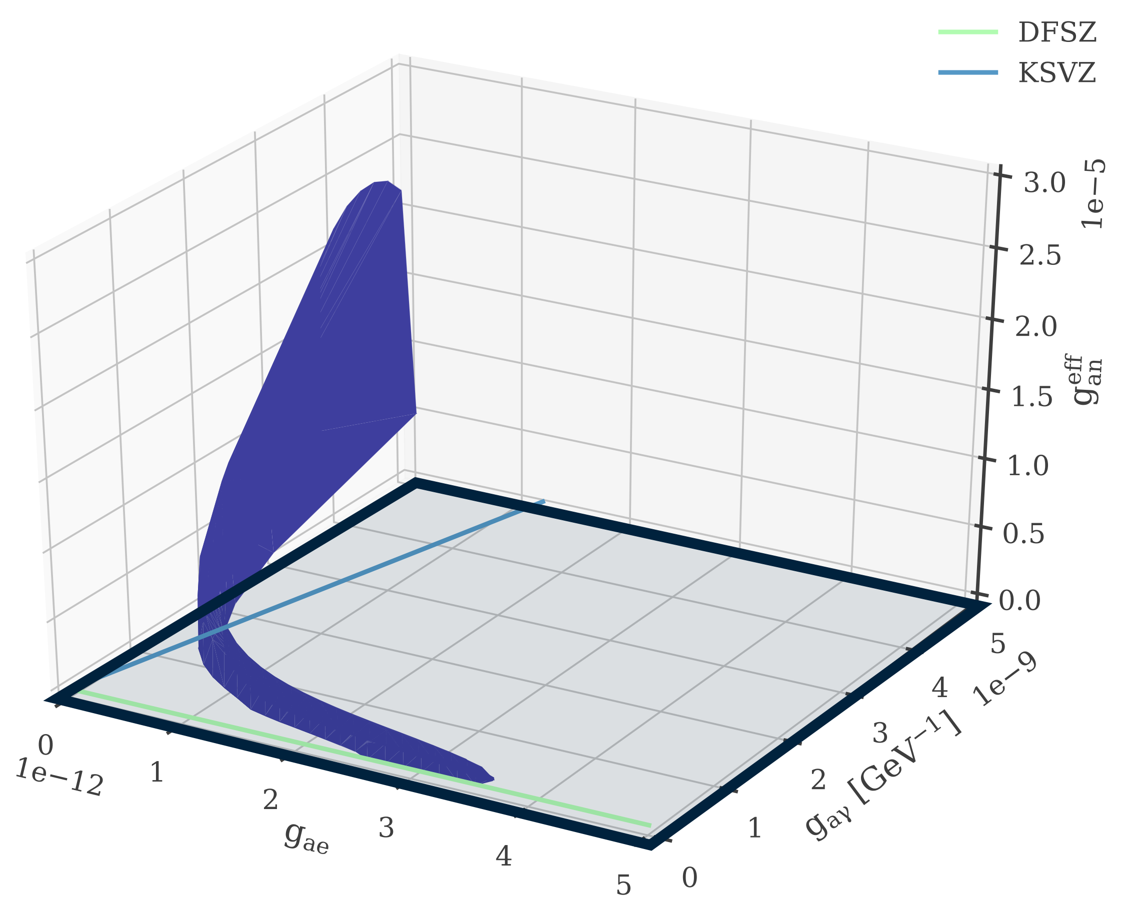
- $g_{ae} = 0$
- $g_{a\gamma} = g_{an}^{eff} = 0$

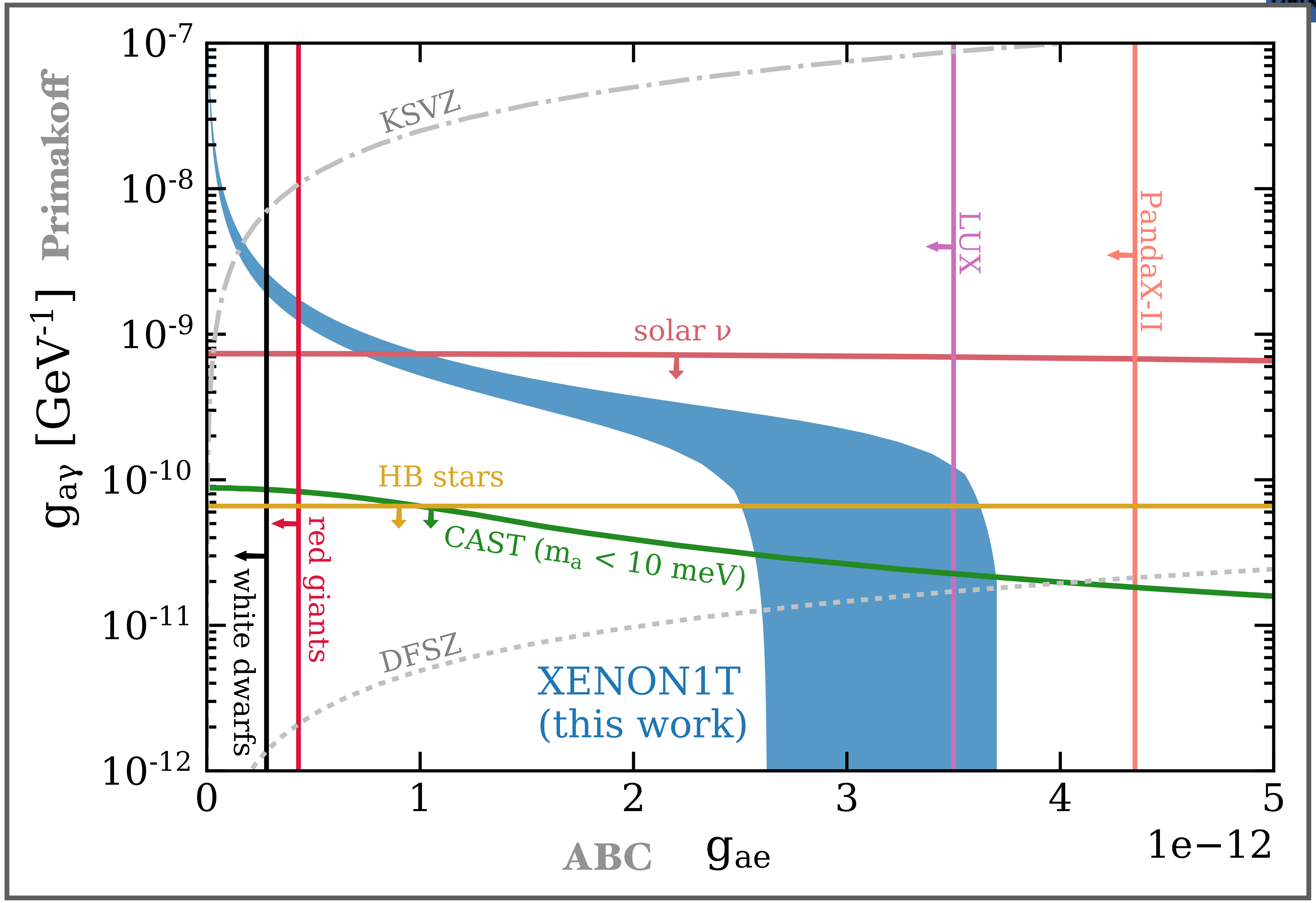
$$g_{ae} < 3.7 \times 10^{-12}$$
$$g_{ae} g_{an}^{eff} < 4.6 \times 10^{-18}$$
$$g_{ae} g_{a\gamma} < 7.6 \times 10^{-22}\ \text{GeV}^{-1}$$

Allowed Parameter Space

Tension:
Red giants
White dwarfs
HB stars

- extra cooling
- if axions take away energy from starts too much..



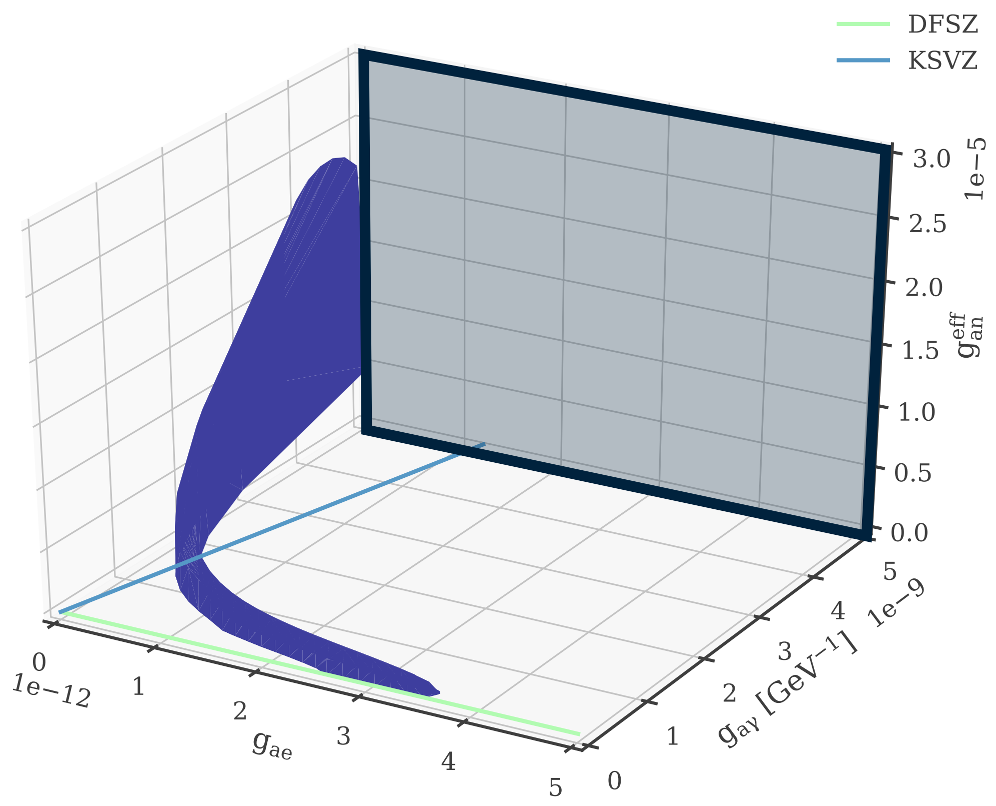


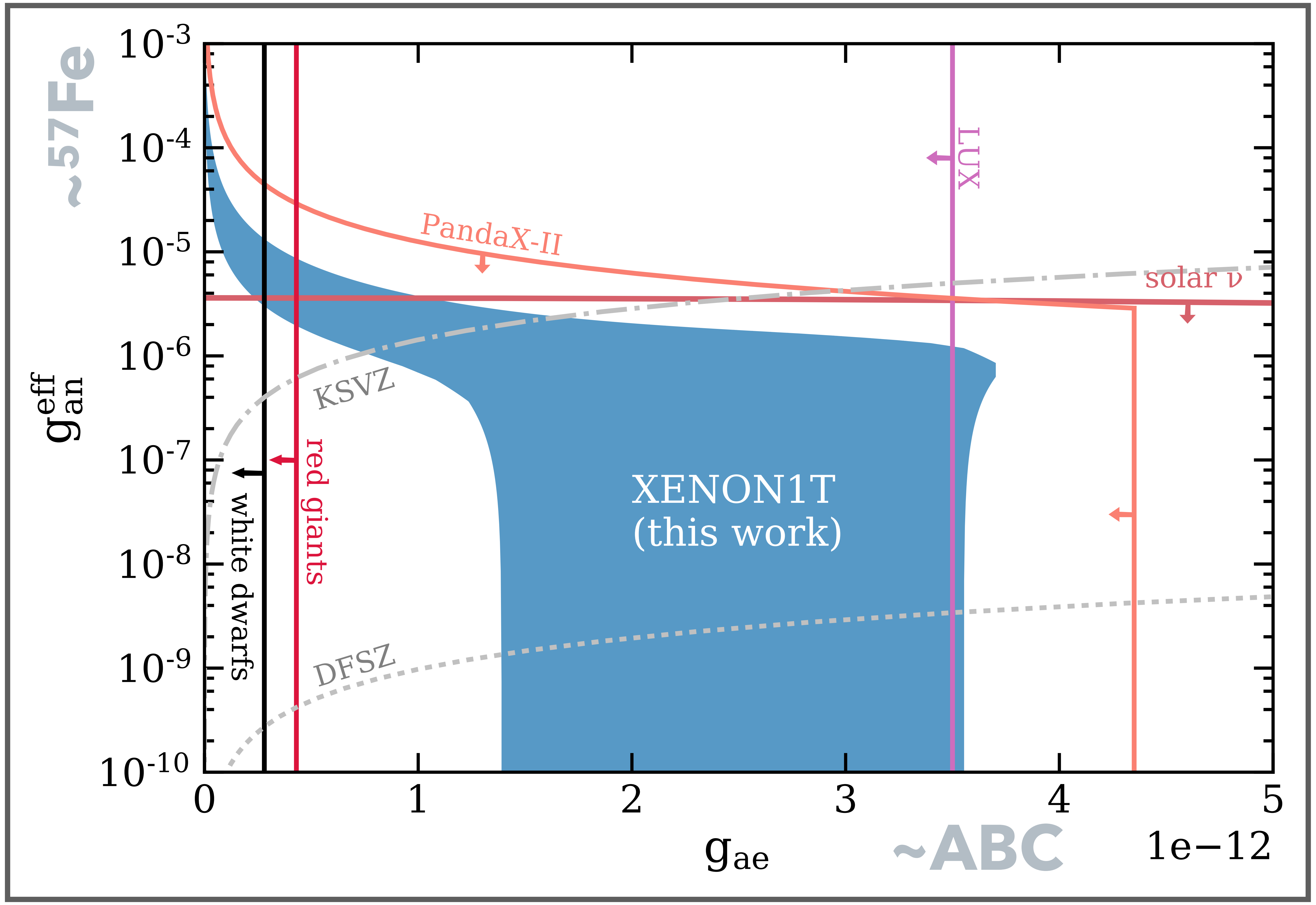
In tension with astrophysical constraints from stellar cooling
(arXiv 2003.01100)

Allowed Parameter Space

Profile over Primakoff

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





Poor fit for small ABC rate → Only accept ^{57}Fe value near best-fit

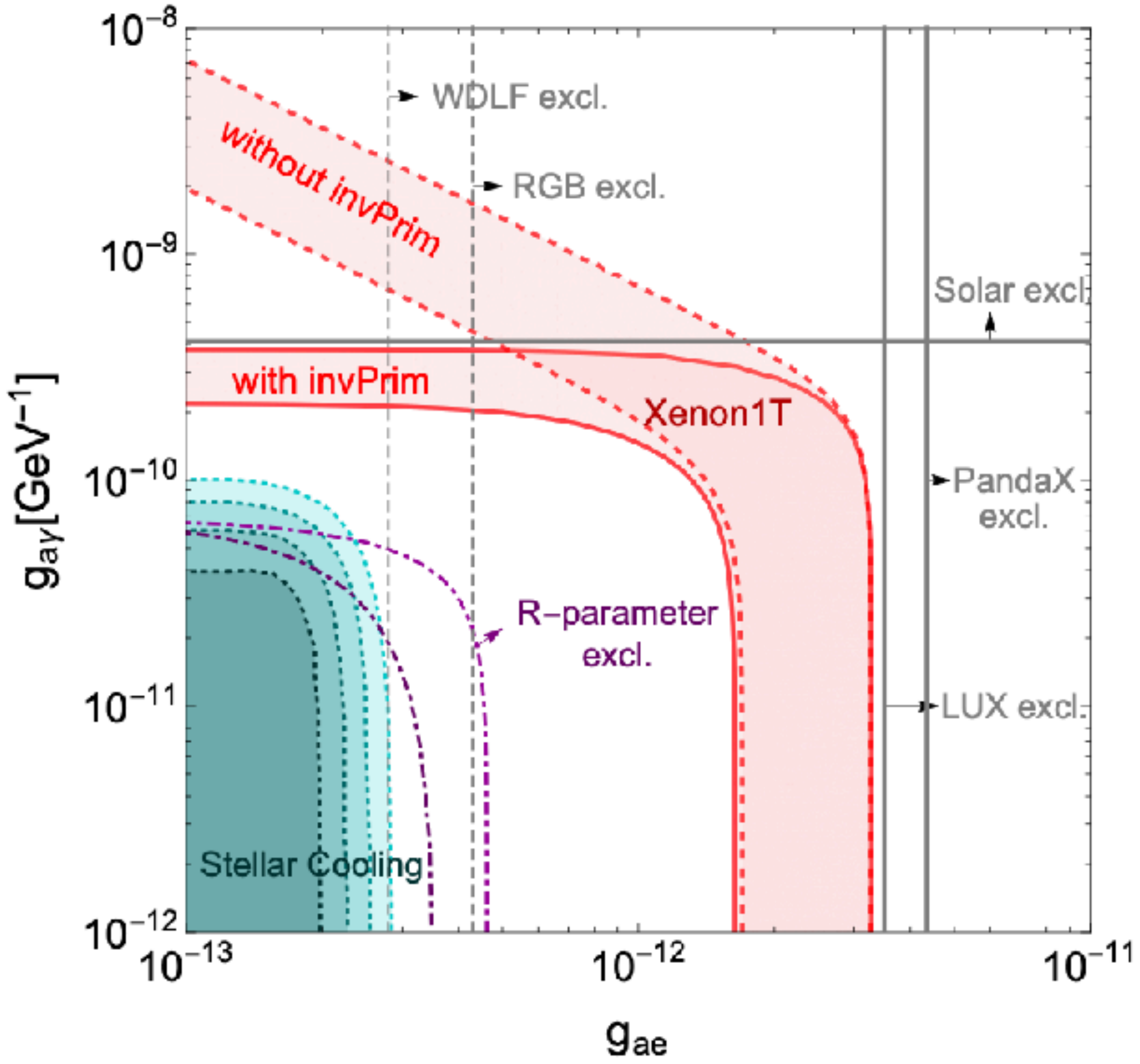
Considering the Inverse Primakoff Process

(arXiv 2006.14598v1)

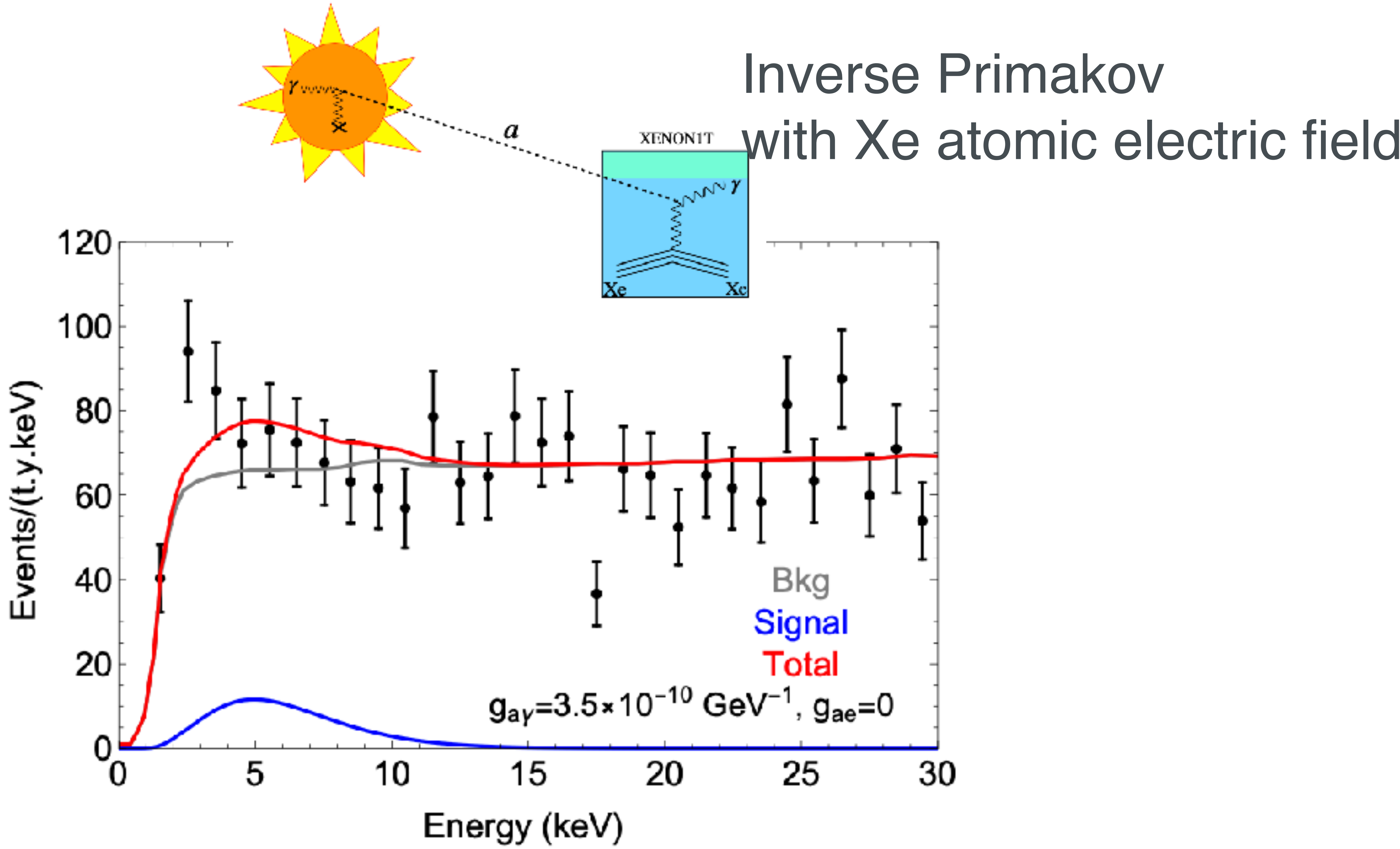
Interesting additions from theorists to our data analysis

Re-examining the Solar Axion Explanation for the XENON1T Excess

Christina Gao,[1] Jia Liu,[2] Lian-Tao Wang,[2,3] Xiao-Ping Wang,[4] Wei Xue,[5] and Yi-Ming Zhong[6]



Considering inverse Primakoff process can weaken the tension with stellar cooling constraint

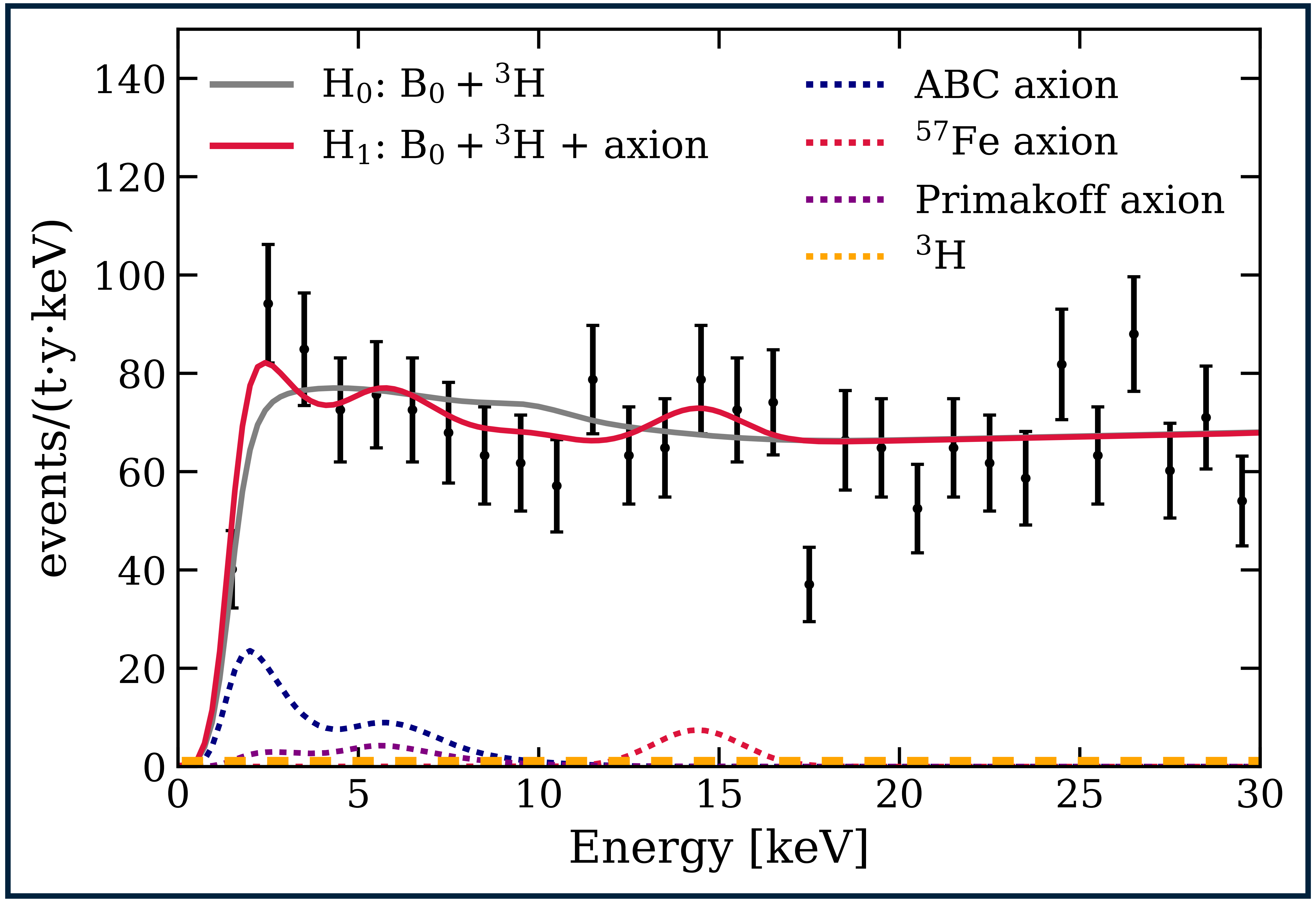


If inverse Primakoff process dominates, it will not fit the excess as good

Tritium + solar axion

Axion + ^3H favored over ^3H hypothesis at 2.1σ

Tritium (3H) is almost zero, but likelihood ratio L_{signal} vs L_{bg} is small so the significance is reduced.



Can we distinguish the two hypothesis by additional checks?

Tritium

Solara Axion

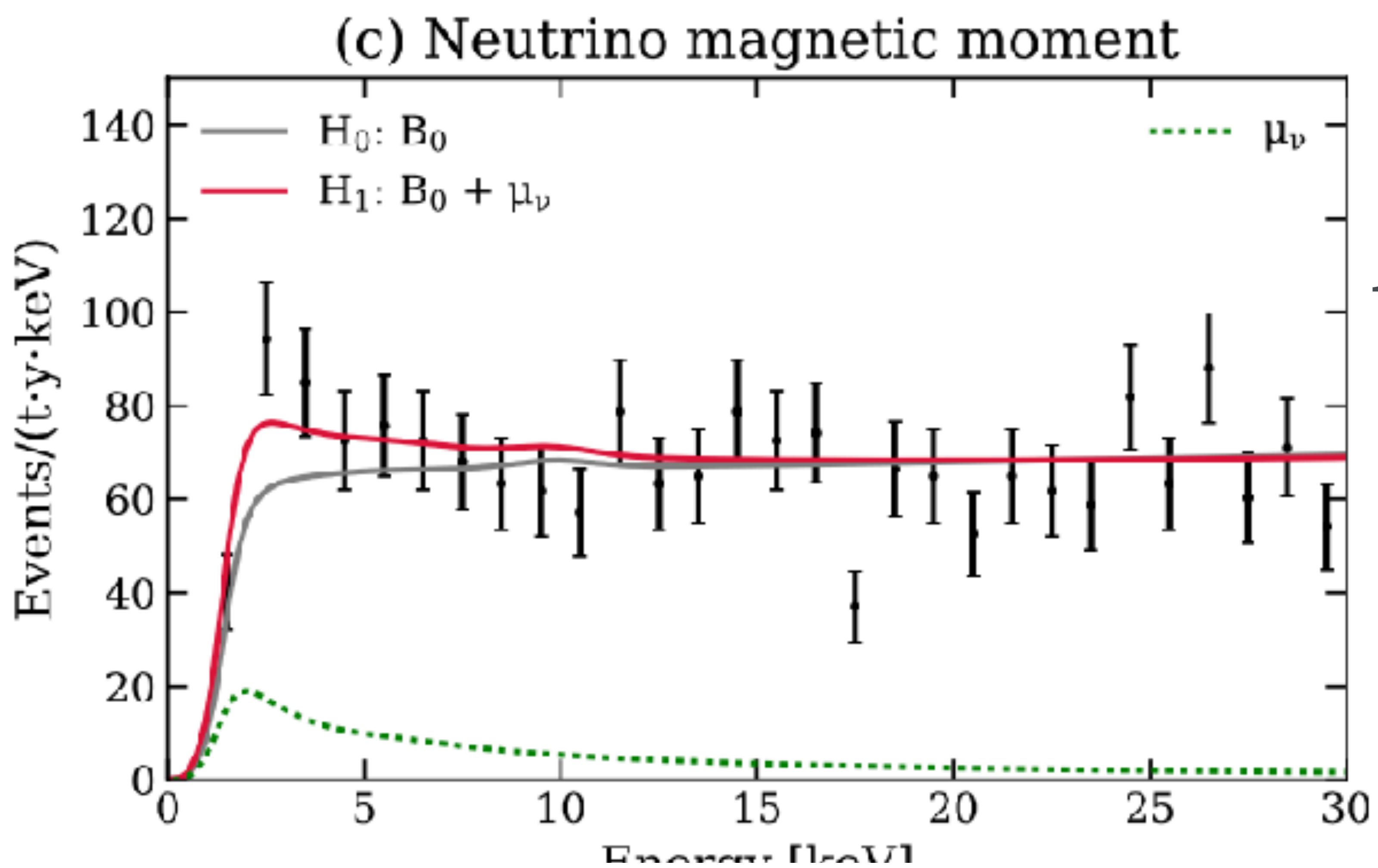
Neutrino magnetic moment + others

Summary and Interpretations of the Excess

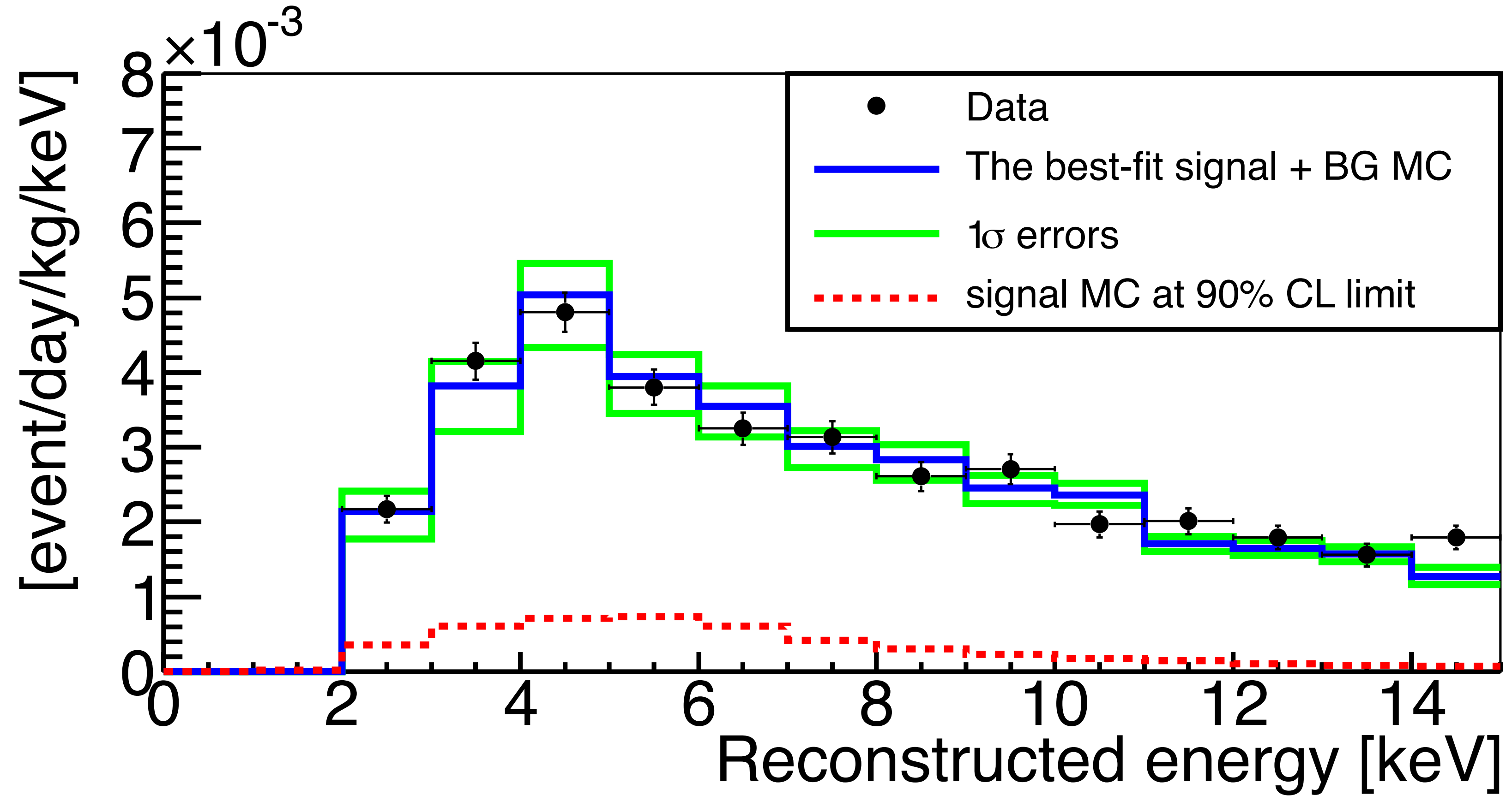
XENON1T observes ER excess events in 1-7 keV region

Neutrino Magnetic Moment (3.2σ)

ν magnetic moment enhance the cross section. (Solar ν in this case)

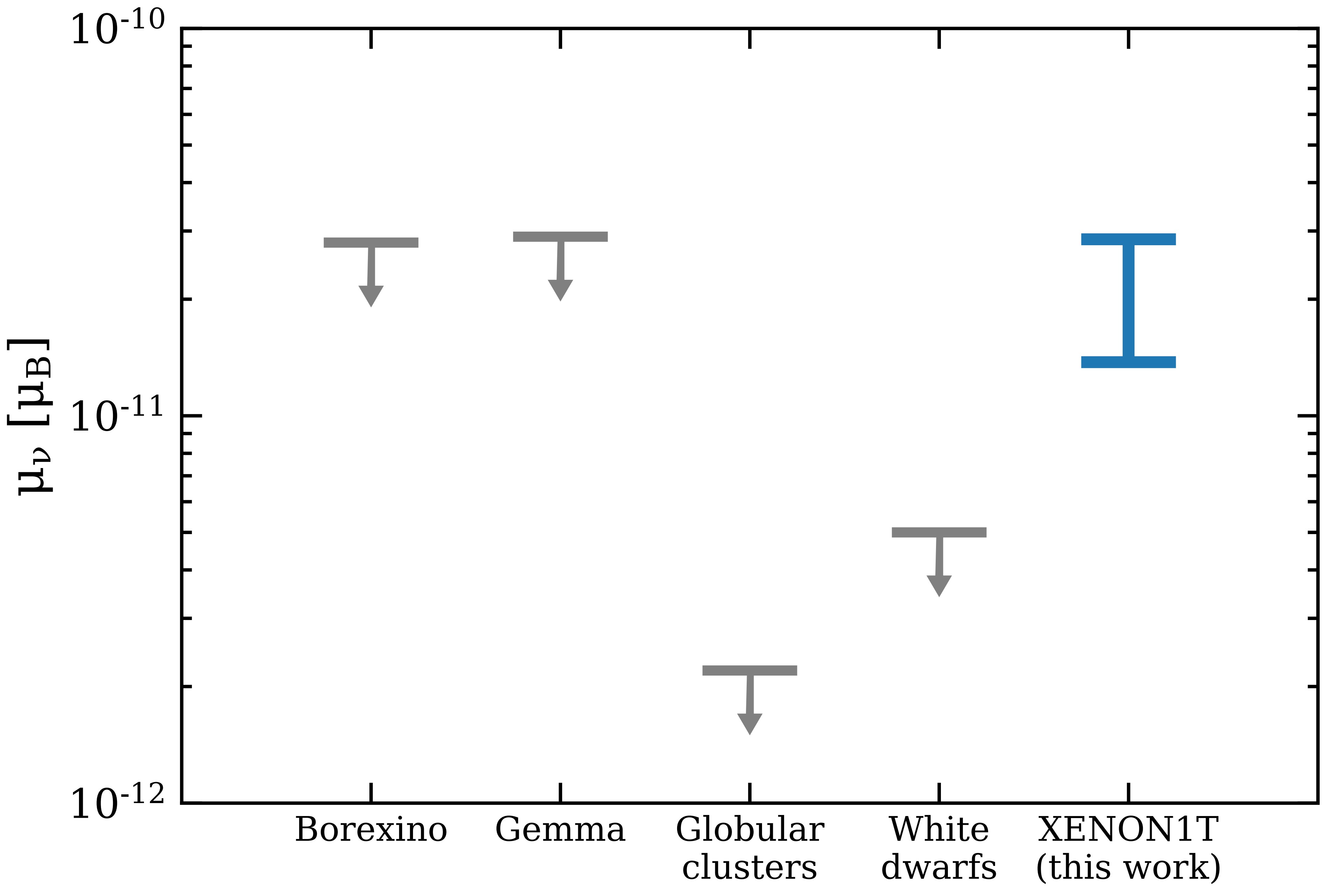


10^{-4} cpd/keV



XMASS
arXiv:2005.11891

$< 1.8\times10^{-10}\ \mu_B$



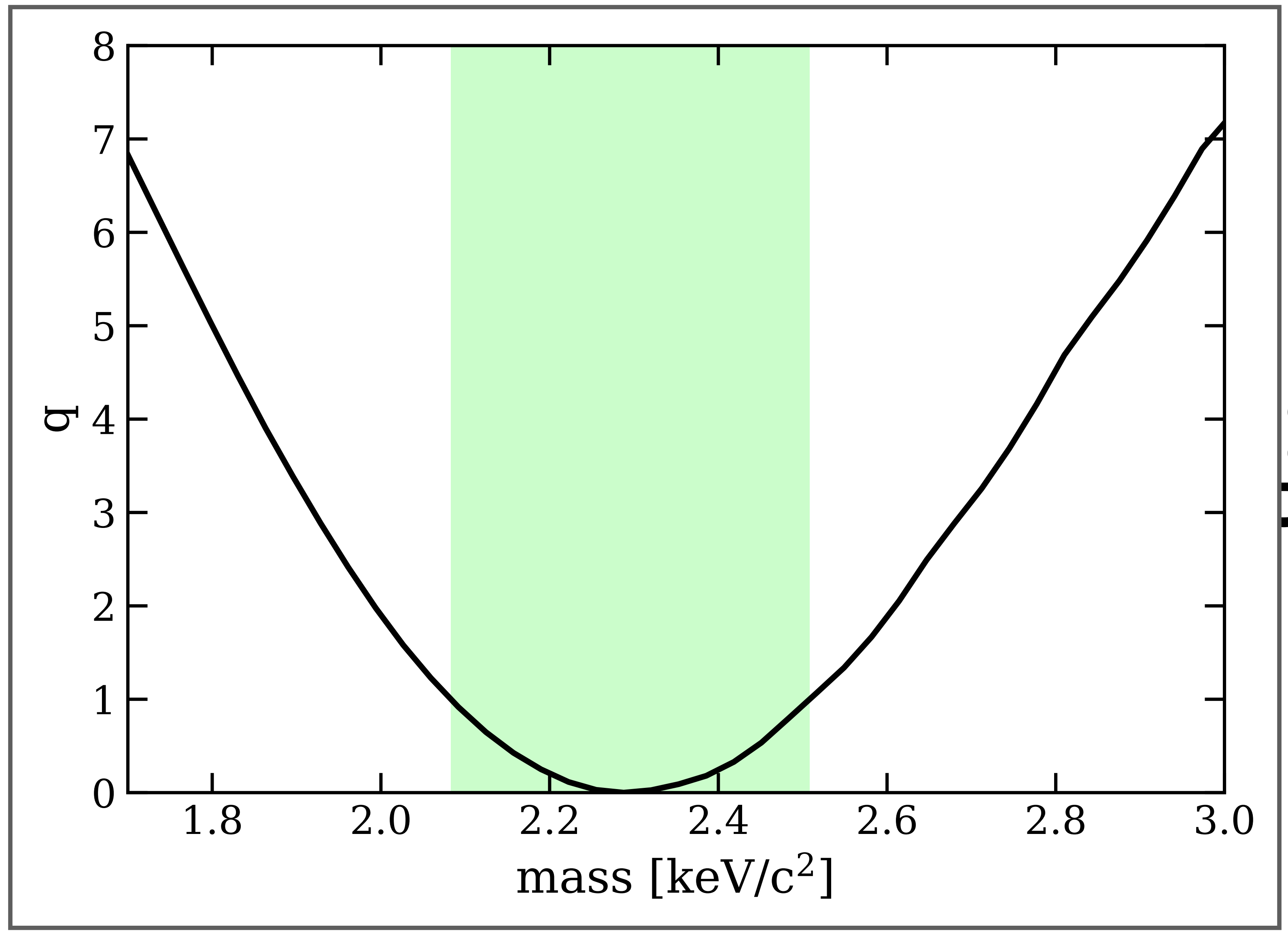
$$\mu_\nu \in (1.4,\ 2.9) \times 10^{-11}\ \mu_B$$

90% confidence interval

Summary and Interpretations of the Excess

XENON1T observes ER excess events in 1-7 keV region

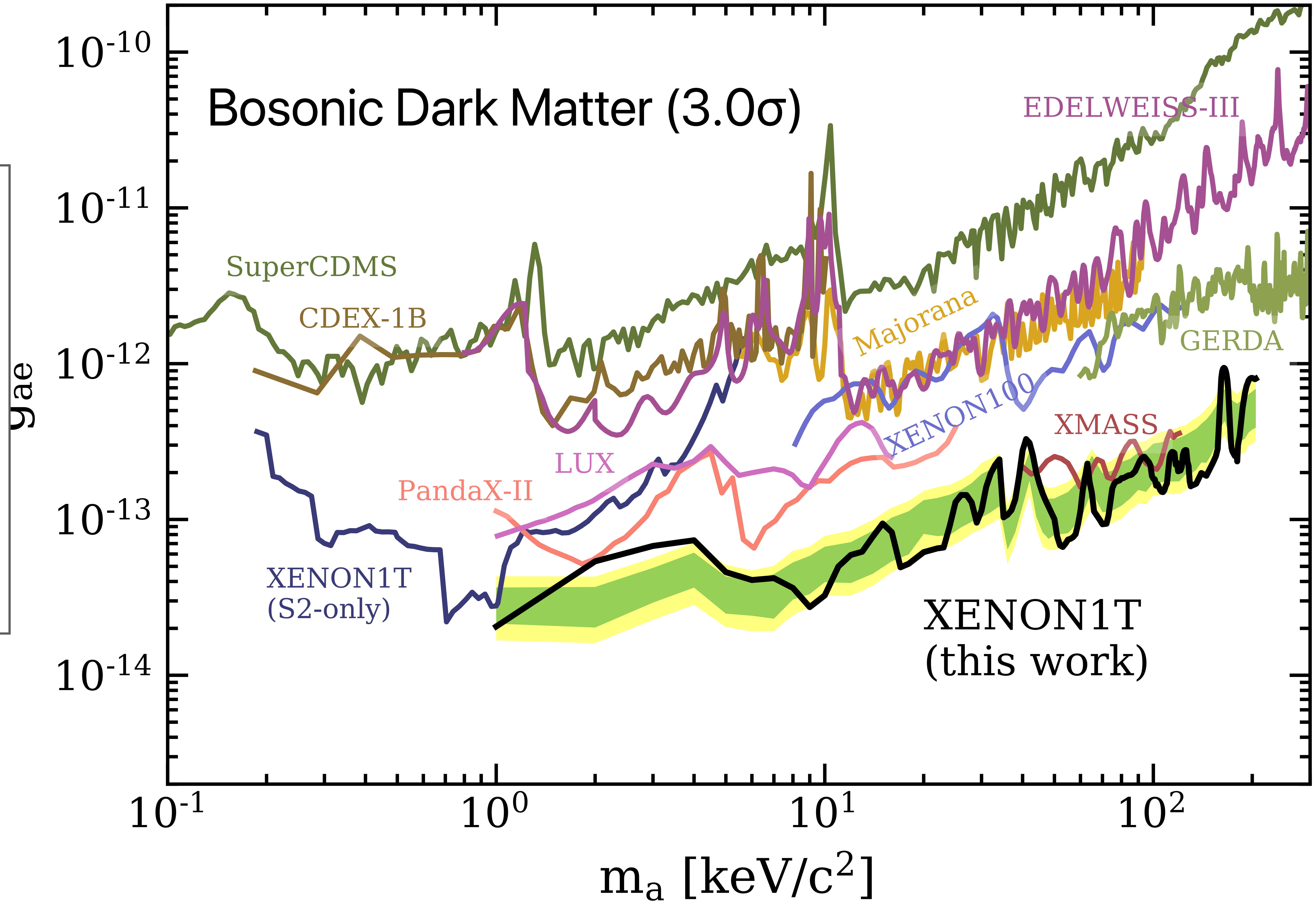
Fitting a mono-energetic peak to the excess:
2.3 +/- 0.2 keV



Best fit: ~60 events/tonne/year

4.0 σ local significance

3.0 σ (global).



Summary

Background?

β-decay of tritium?

3.2σ

Low-energy (Q value 18.6 keV)
Long half life (12.3 years)
Atmospherically “abundant” and cosmogenically produced in xenon

Removed by purification system?

Signal? (Beyond Standard Model)

Solar Axions **3.5σ**

- QCD axion
= Axions would also be produced in the Sun, with kinetic energies ~ keV

Neutrio Magnetic moment **3.2σ**

In the (extended) SM:

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

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

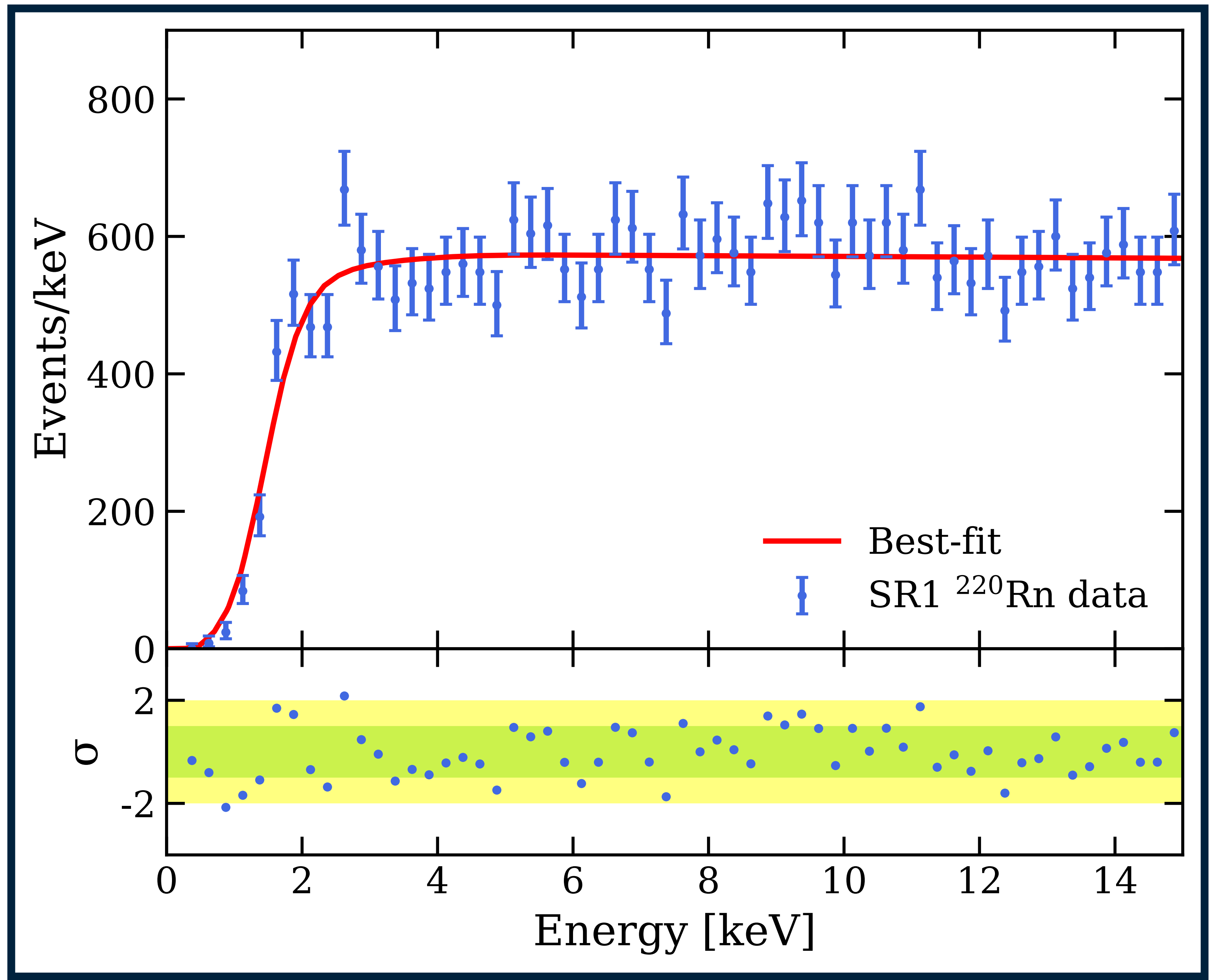
Bosonic Dark matter **3.0σ**

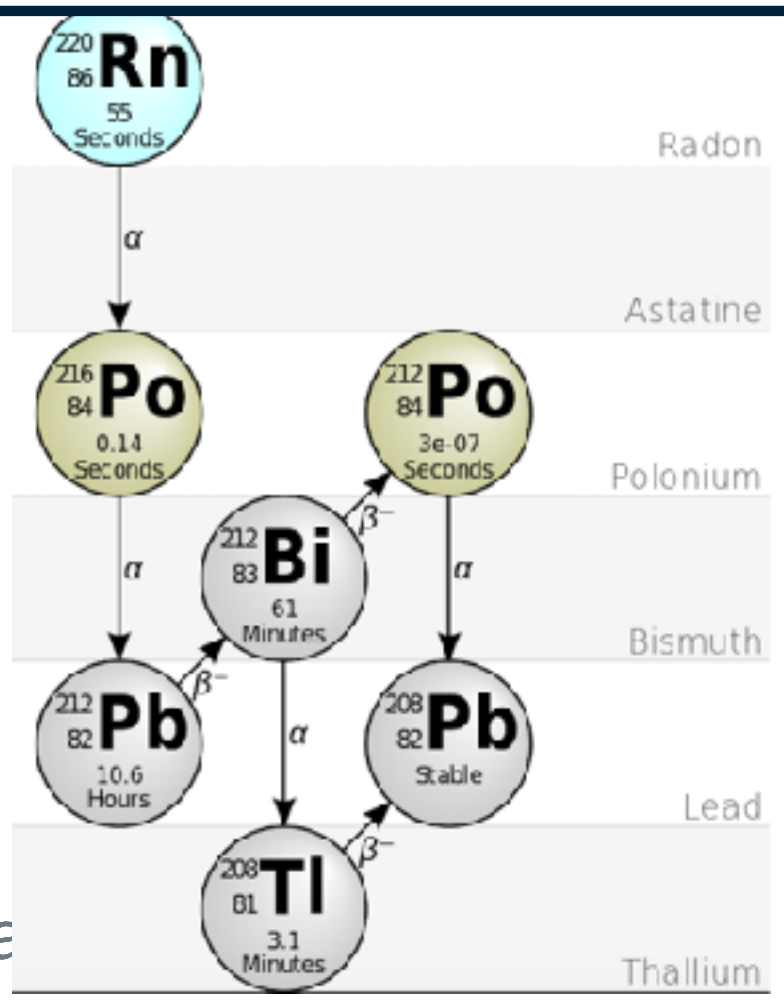
- candidate for Warm Dark Matter
- Axion-like particles like QCD axions.
- allows for ALPs to take on higher masses than QCD axions

More detail on analysis (FAQ)

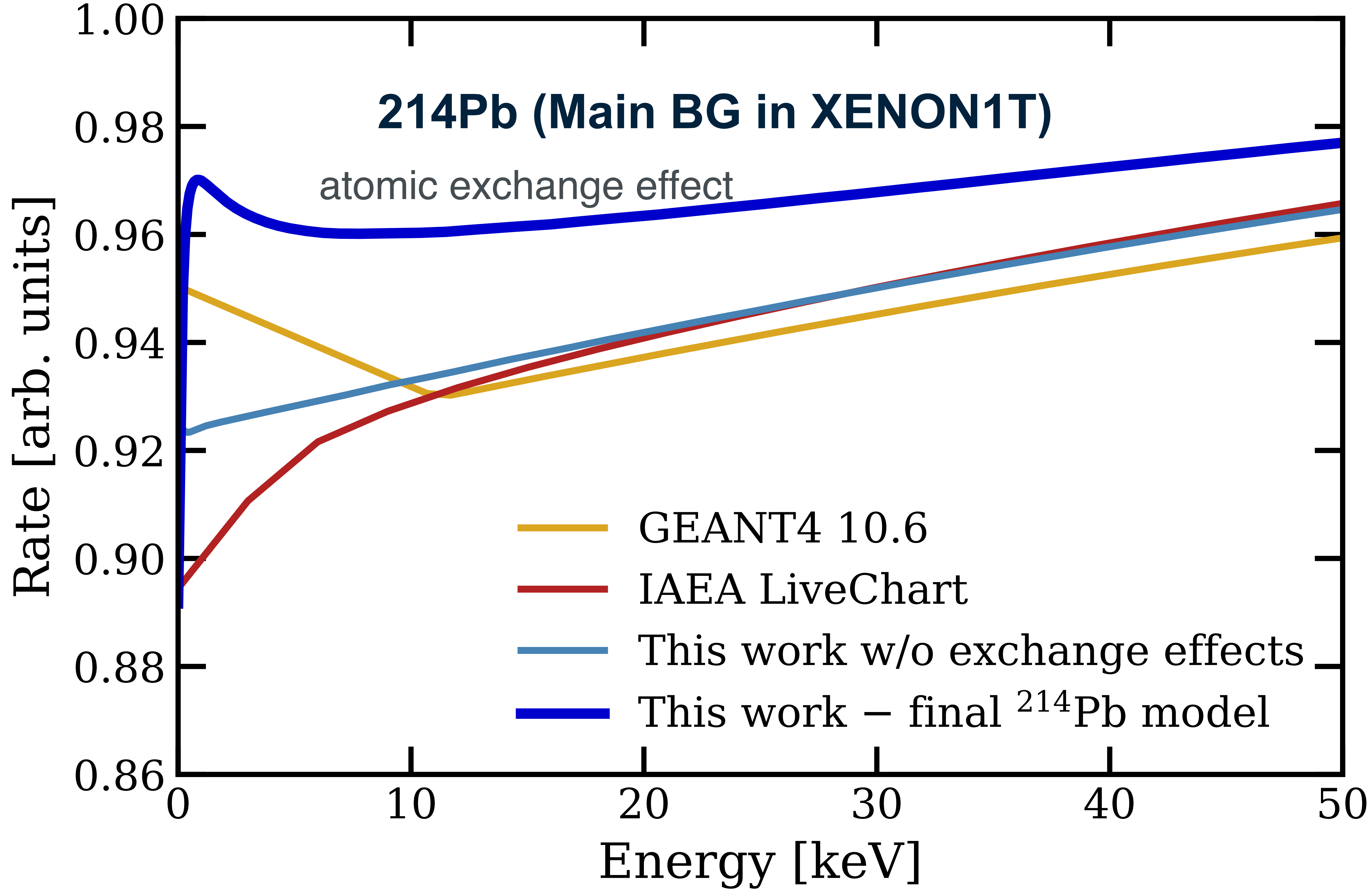
XENON1T's Response to Betas

Decent matching between data and MC down to the energy threshold <~2keV !





beta decay of Pb212 is used to calibrate detector's response to ER background



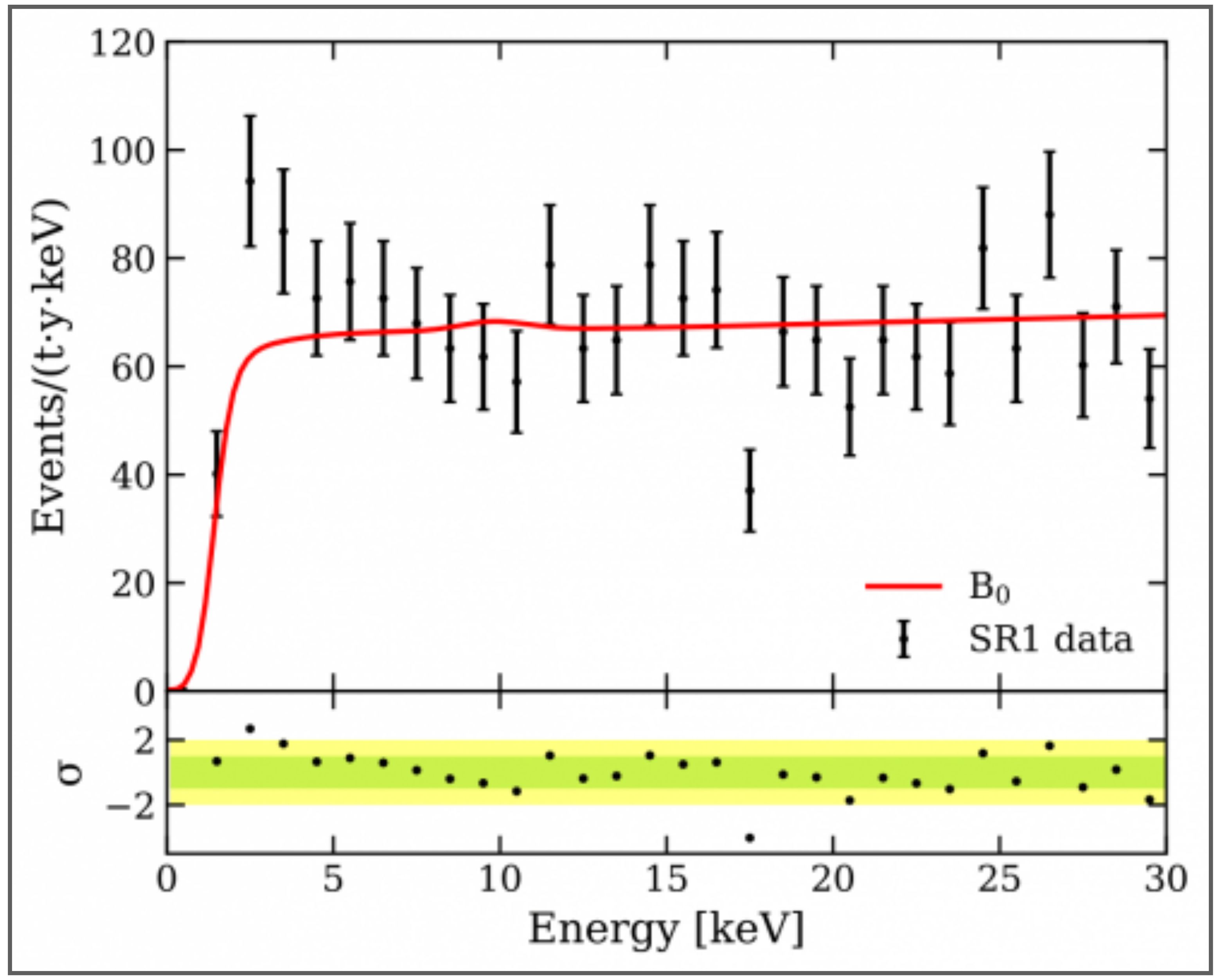
Atomic effects can increase rate at low energies, *but have a small impact.*

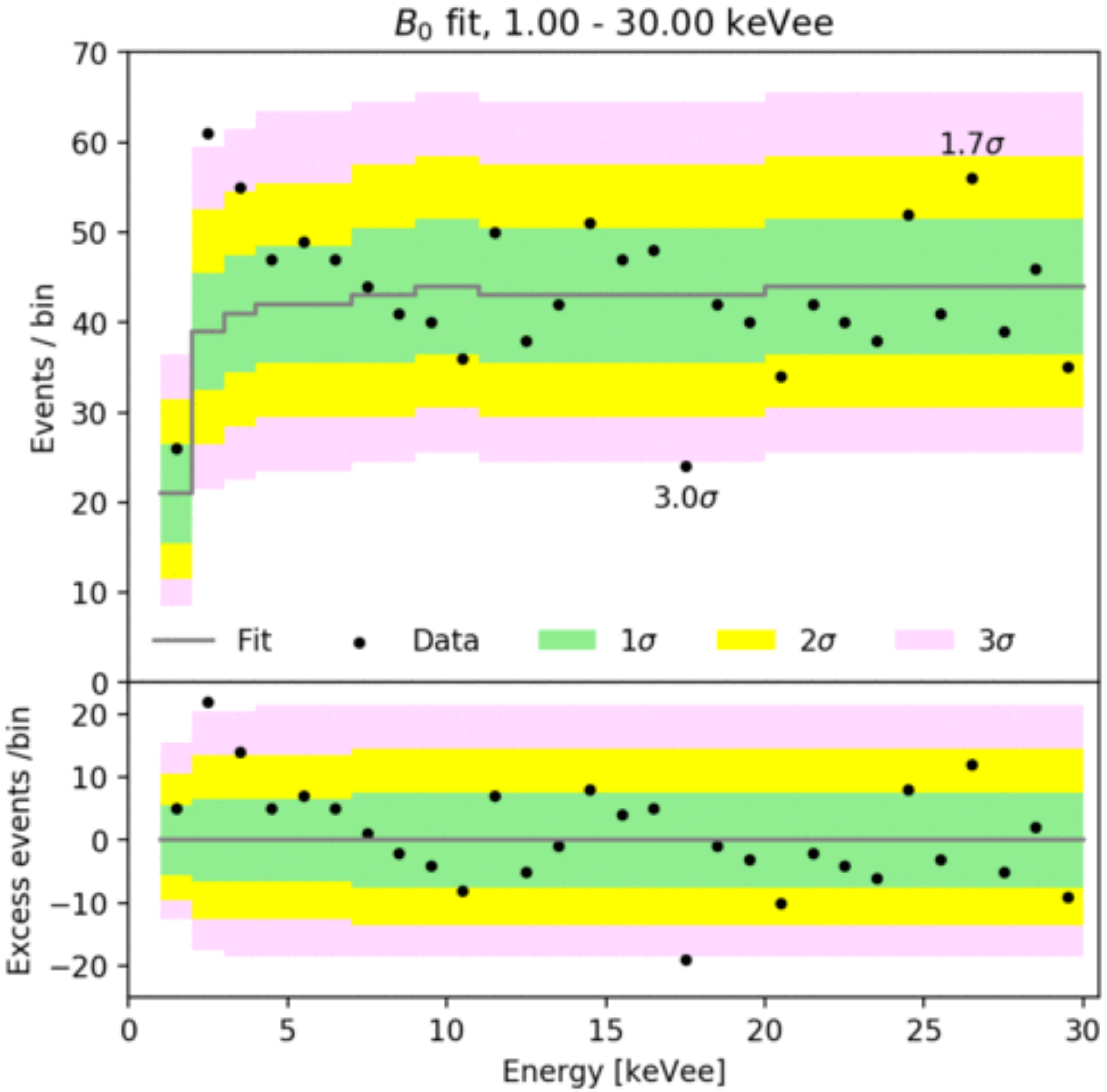
~6% uncertainty on the shape

~50% needed to account for excess

Teamed up with expert on β-decay spectra (X. Mougeot)

Fluctuations and correlations



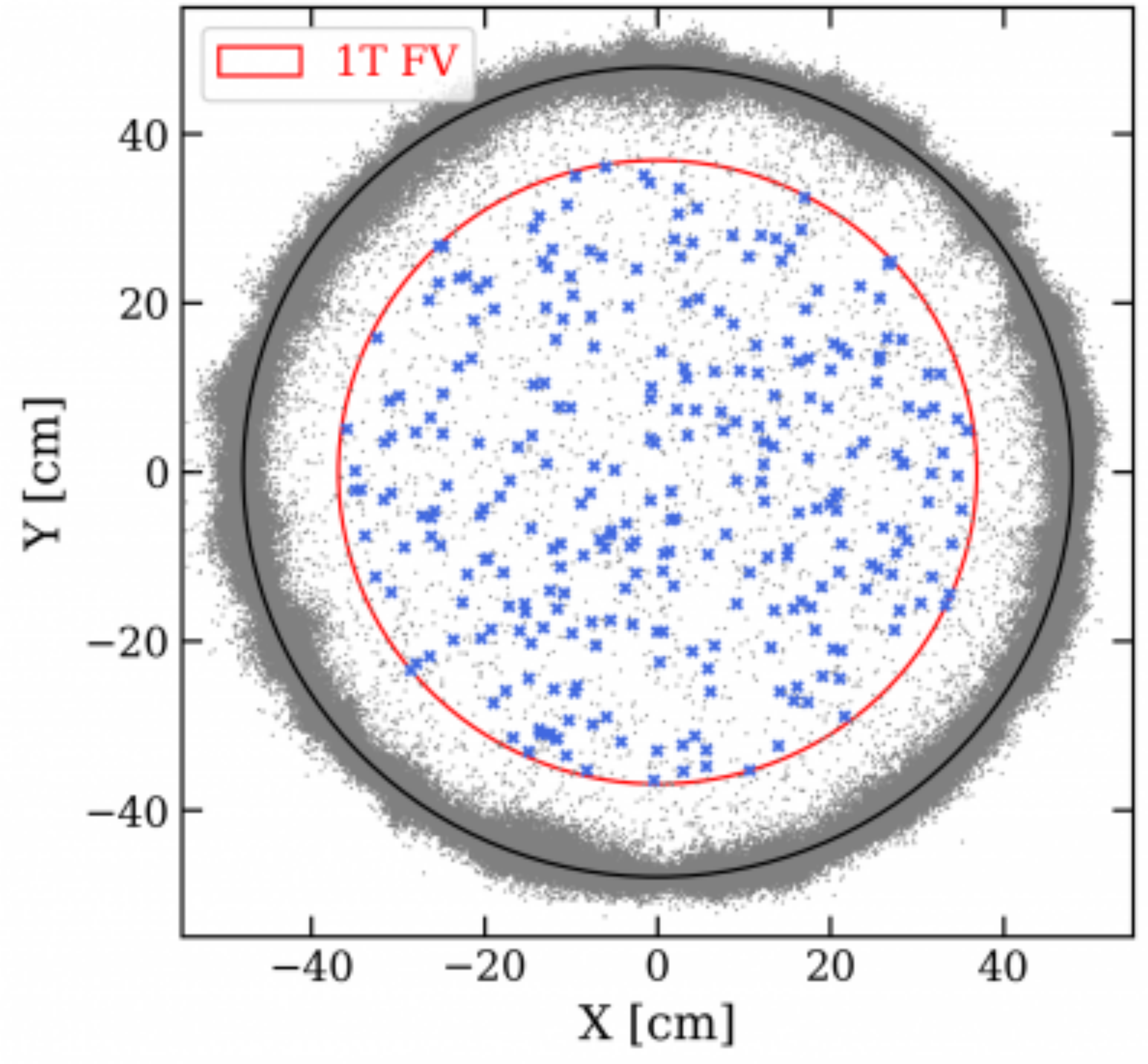


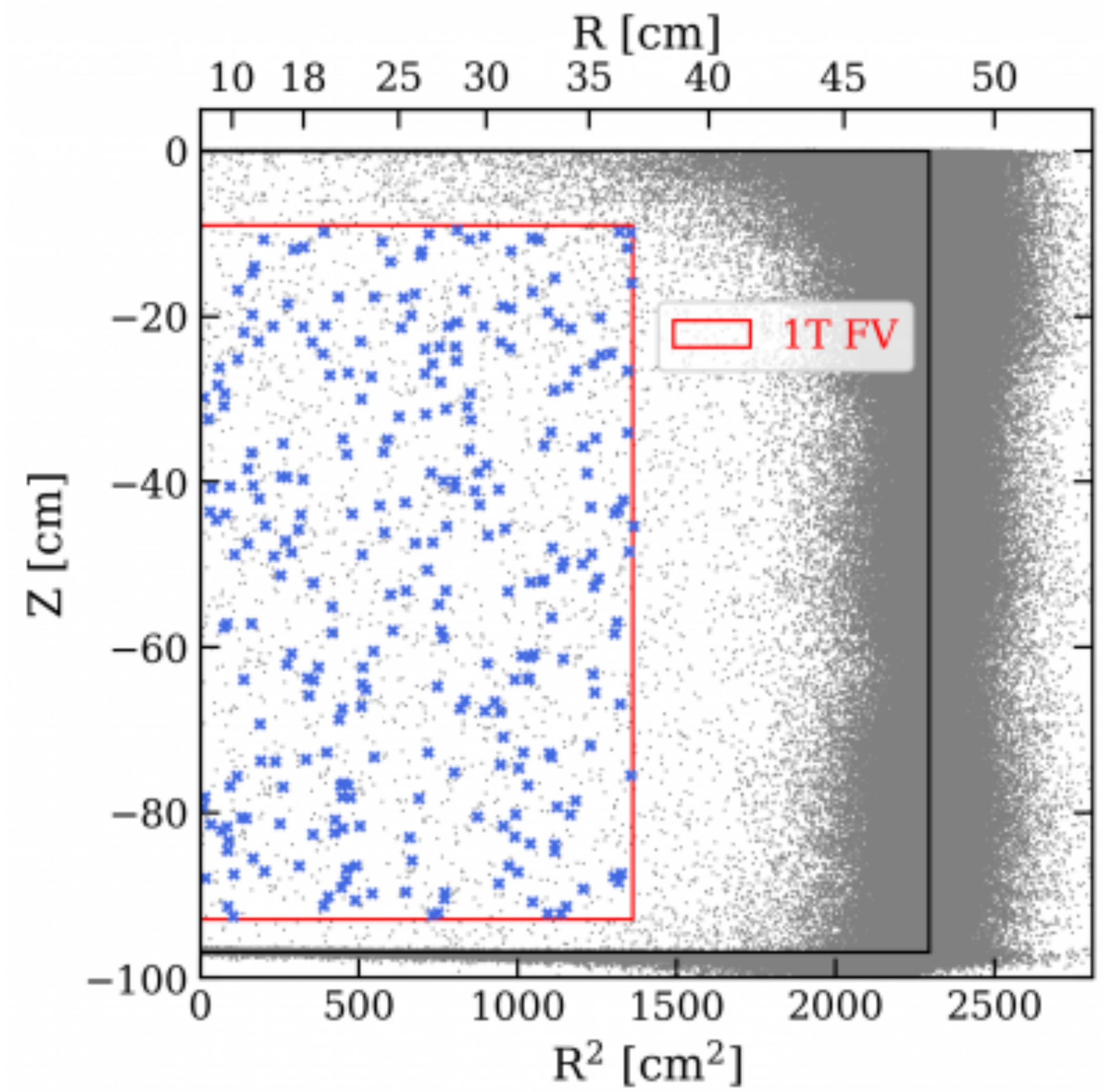
statistical fluke? (see 17 keV dip)

funny correlation? (1-10 keV rising steadily)

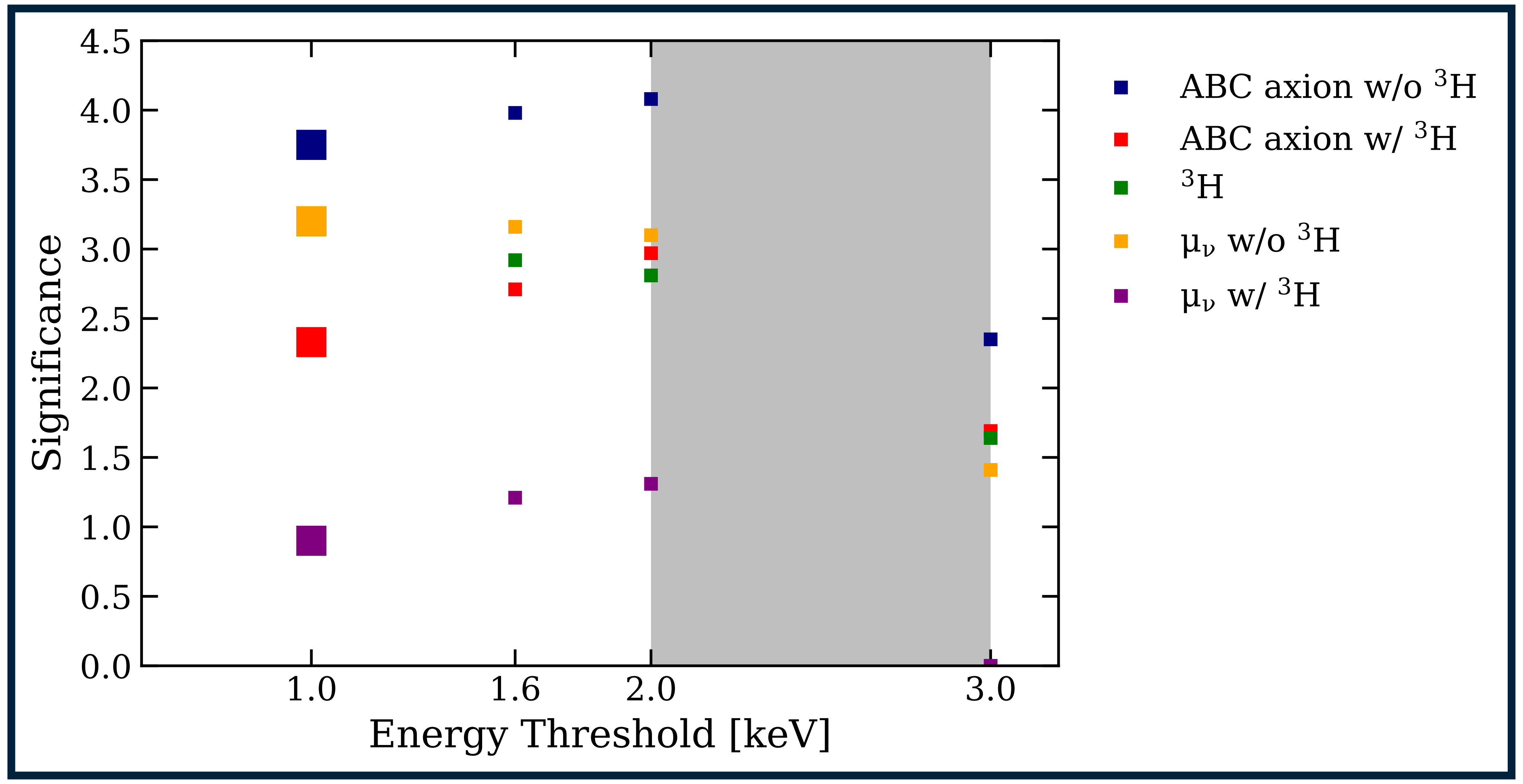
Note: we use an unbinned profile likelihood analysis

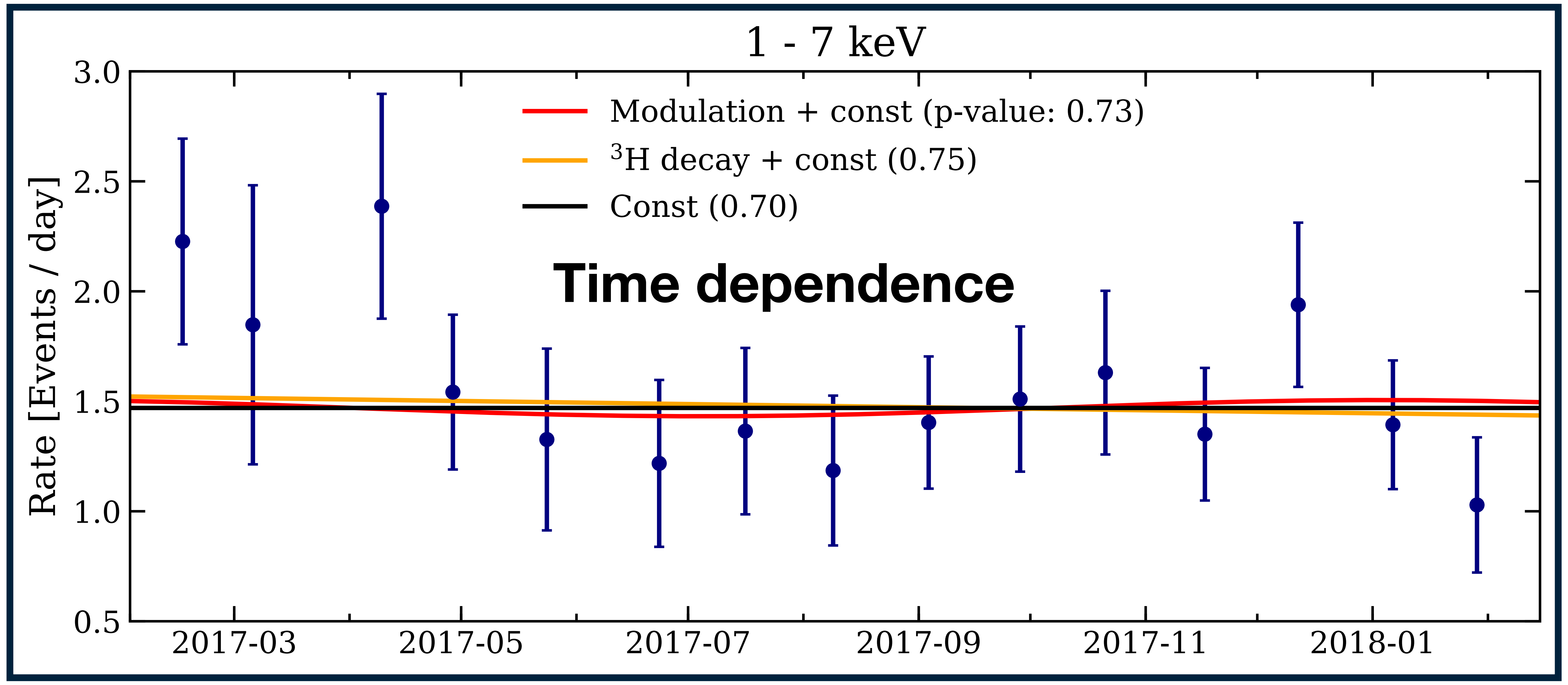
Uniformity, Energy threshold, time dependency…





Threshold effects



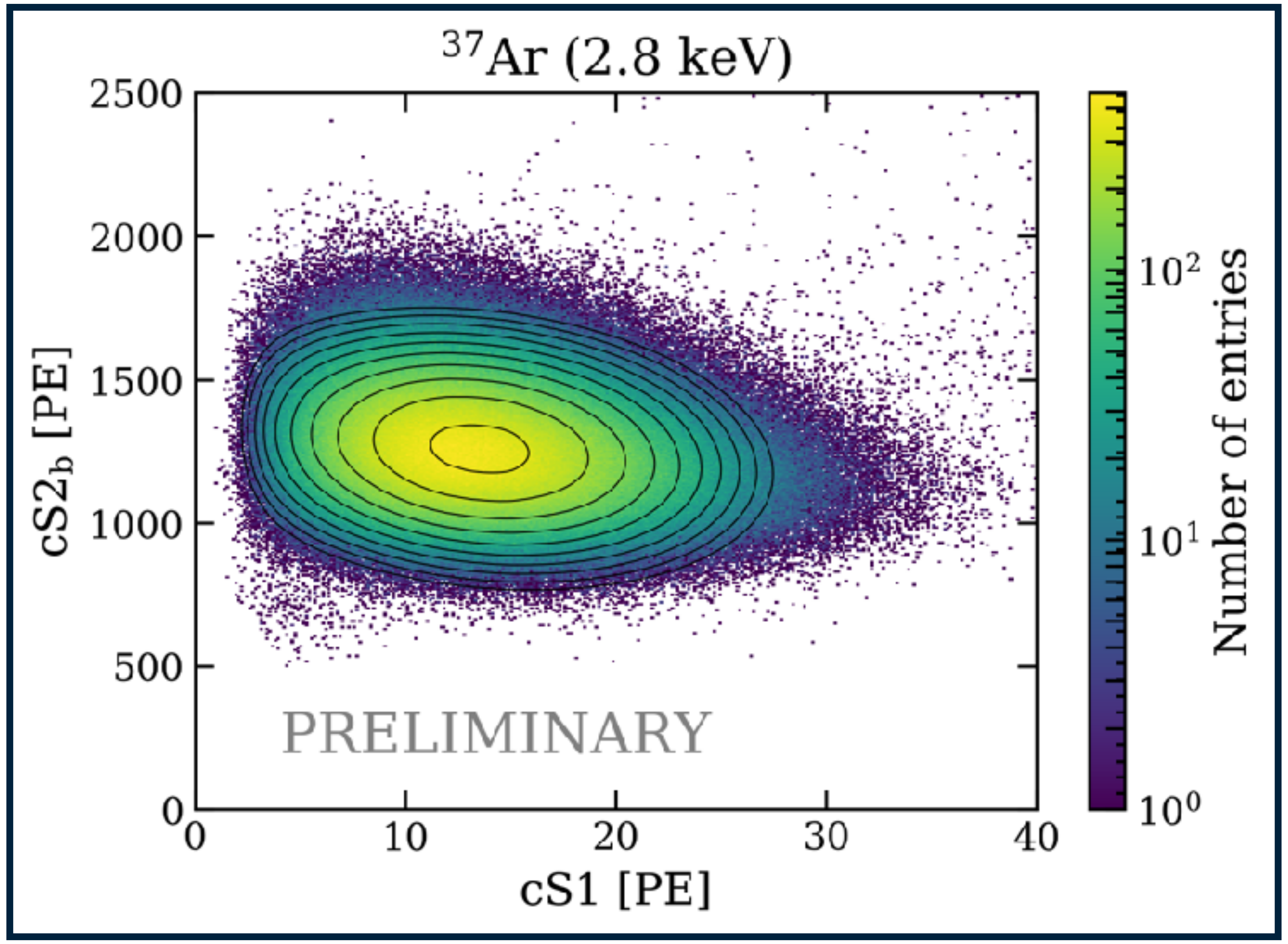


Energy Calibration at Low Energy

$$E = W(n_{ph} + n_e)$$

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

g1 and g2: detector-specific gain **constants**



Calibration of XENON1T down to **2.8 keV**

XENON1T results are …
inconclusive.
Then?

Others arXiv 88 posts

Next Step: XENONnT

Sensitivity Paper :arXiv:2007.08796

3x

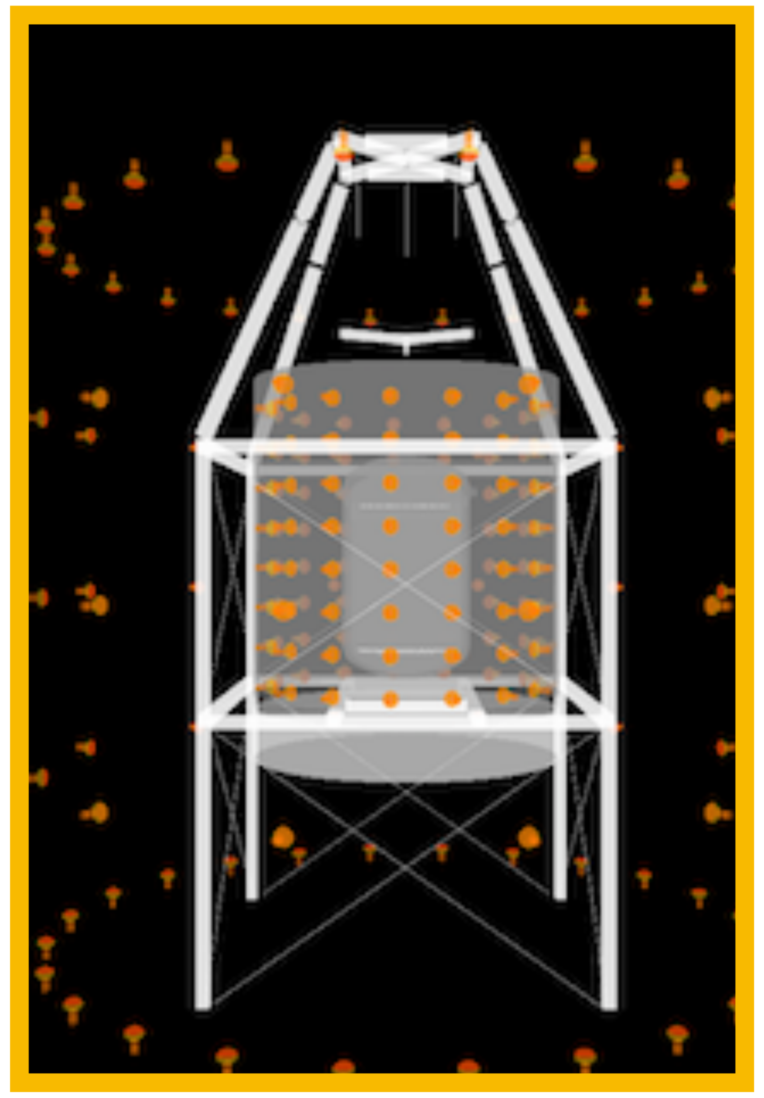
Larger active volume

~1/6

Reduced background level

Commissioning ongoing

New Apparatus in XENONnT



Neutron veto

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

LXe purification

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

^{222}Rn distillation

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

NAGOYA UNIVERSITY

ISEE INSTITUTE FOR SPACE-EARTH ENVIRONMENTAL RESEARCH

The New York Times

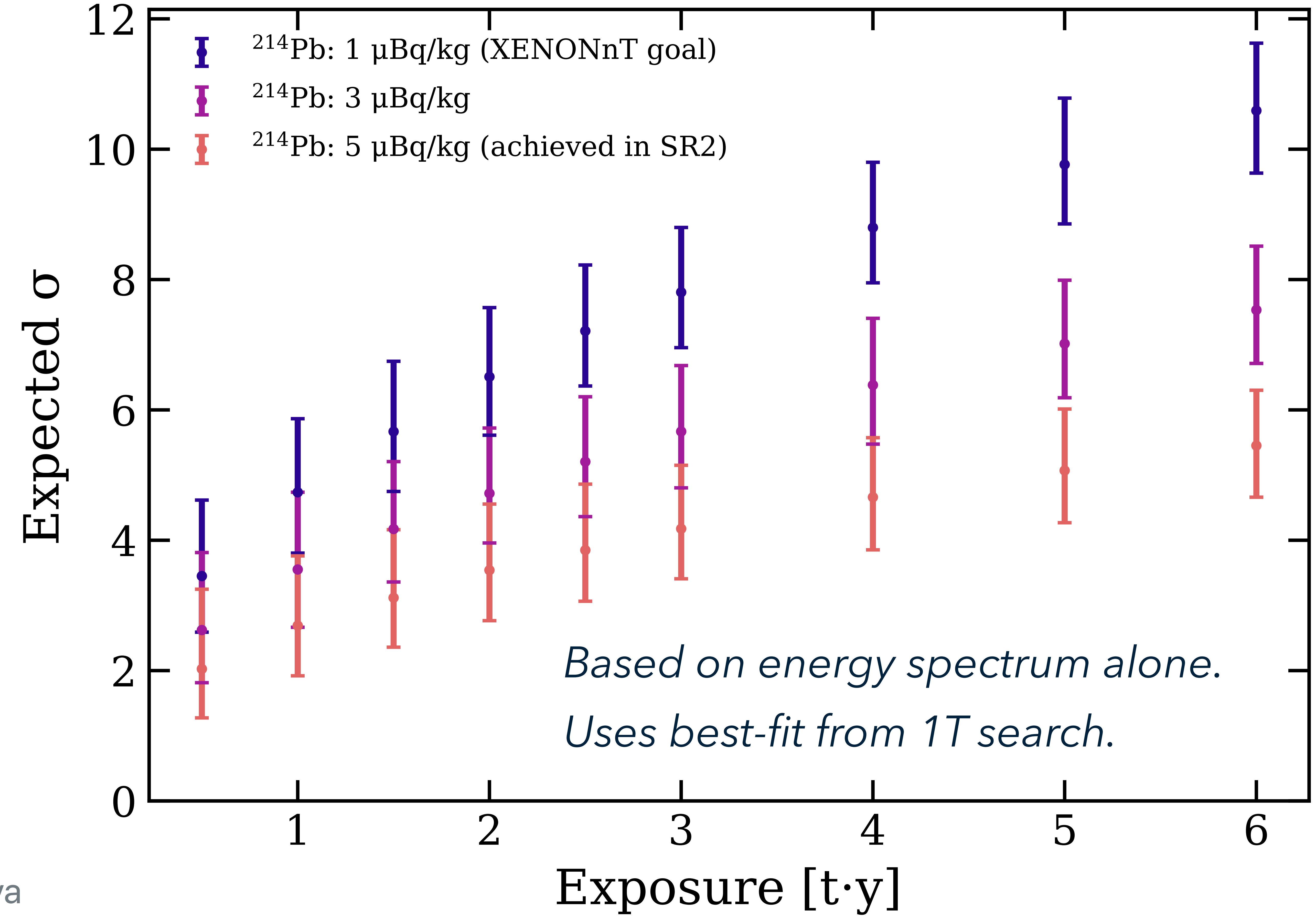
Will Coronavirus Freeze the Search for Dark Matter?

An experiment under 4,600 feet of Italian rock wasn’t immune from the pandemic’s interruption.

Masatoshi Kobayashi and Danilo Tatananni with the closed-up detector. “We did it,” they wrote Dr. Aprile.
Masatoshi Kobayashi

Next Steps: XENONnT

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



Summary

- ER Excess Events in XENON1T
  - Solar Axion 3.5σ
  - Neutrino Magnetic Moment (3.2σ)
  - Bosonic Dark Matter (3.0σ)
  - Tritium Background (3.0σ)
  - Solar Axion + Tritium + Background (2.1σ)
- XENONnT will tell us next year (commissioning phase now)
- Stay tune!