



Observation of Excess Electronic Recoil Events in XENON1T

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On behalf of the XENON Collaboration + X. Mougeot

HEP seminar, Argonne National Laboratory

July 1, 2020

XENON Collaboration: ~170 scientists



Columbia



Rensselaer



Nikhef



Münster



KIT



Stockholm
University



Mainz



Max-Planck-Institut
für Kernphysik
Heidelberg



Freiburg



Chicago

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Purdue



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Subatech



LPNHE



IJCLab



L'Aquila



Bologna



INFN



Weizmann



NYUAD



Kobe



Tokyo



NAGOYA UNIVERSITY

Nagoya



XENON Technical Meeting, May 12-14, 2020

Andrij Terlik (MPIK/Uni Heidelberg)

Alexey Elykov

Ethan Brown

Christopher Hills (JGU-Mail)

Michele Iacovacci

ONE
Xenon1T Detector

TWO
Data Analysis

THREE
Excess

FOUR
Interpretations

XENON1T: All Systems



The XENON1T Time Projection Chamber (TPC)



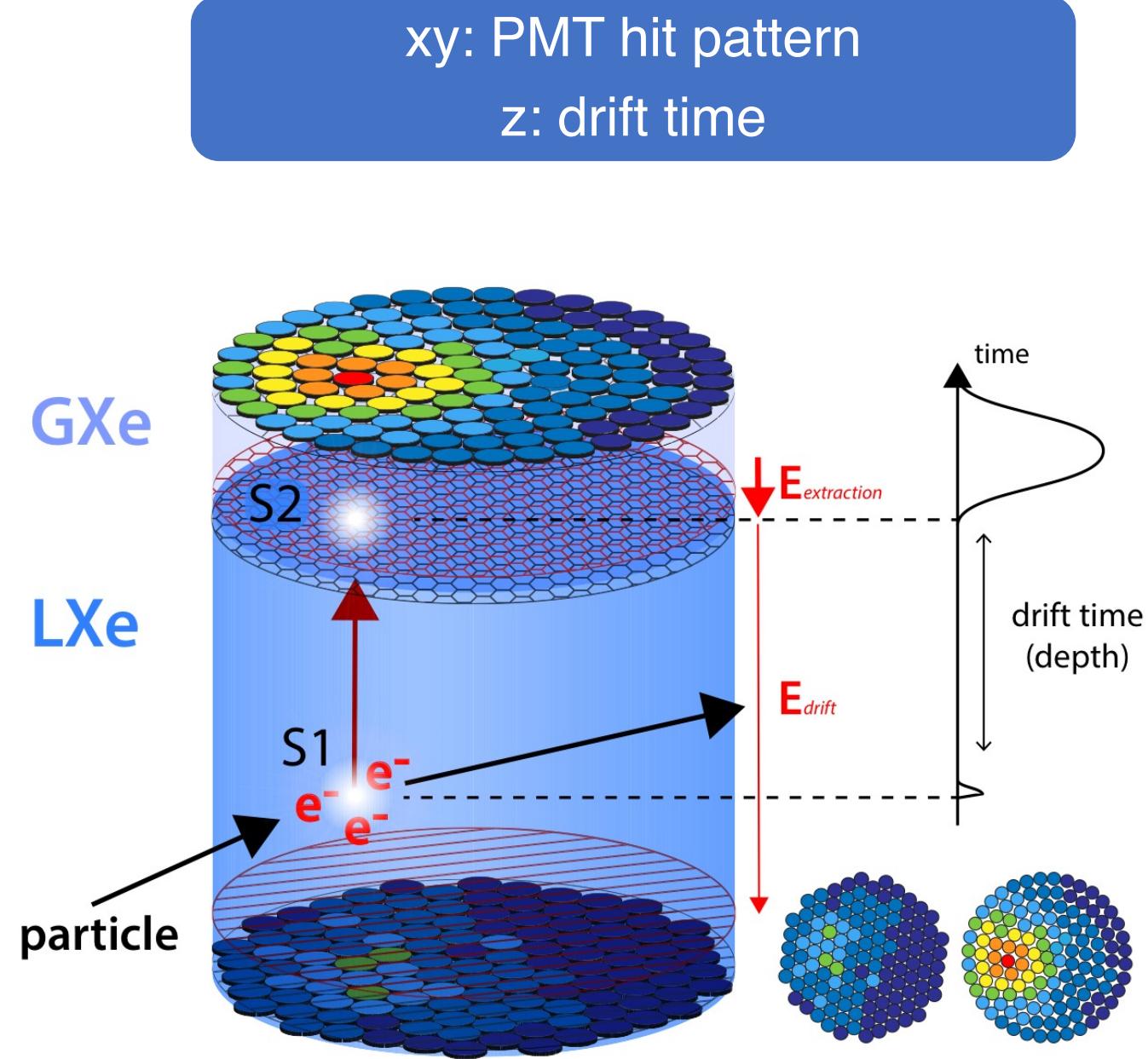
127 3" PMTs in the top array



121 3" PMTs in the bottom array

Two-phase Xenon TPC

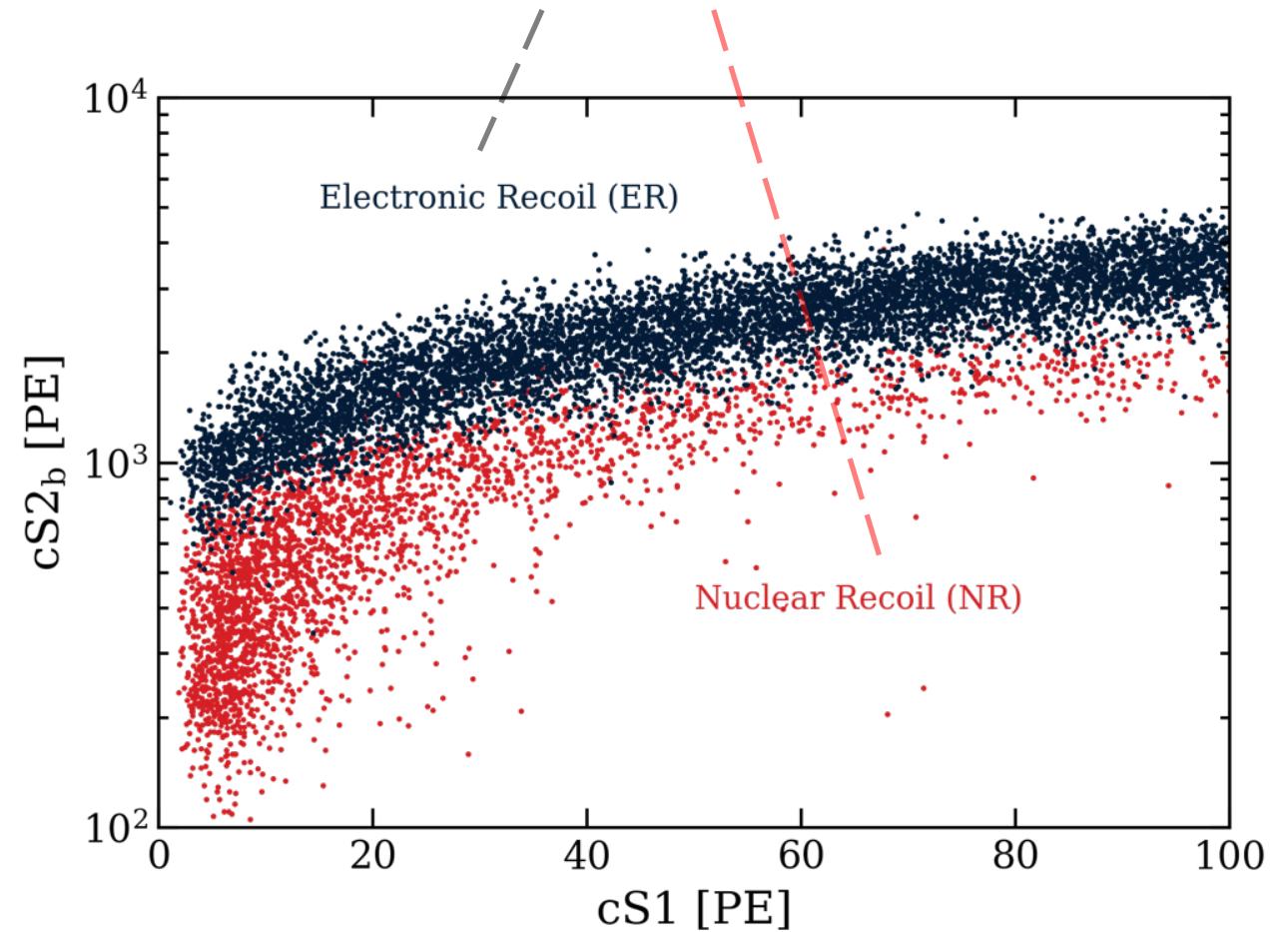
- 3D position imaging + self-shielding
- Recoil types:
Nuclear Recoil (NR)
Electronic Recoil (ER)
- Particle detector with *large exposure, low background, low threshold.*



Two-phase Xenon TPC

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Recoil types



Two-phase Xenon TPC

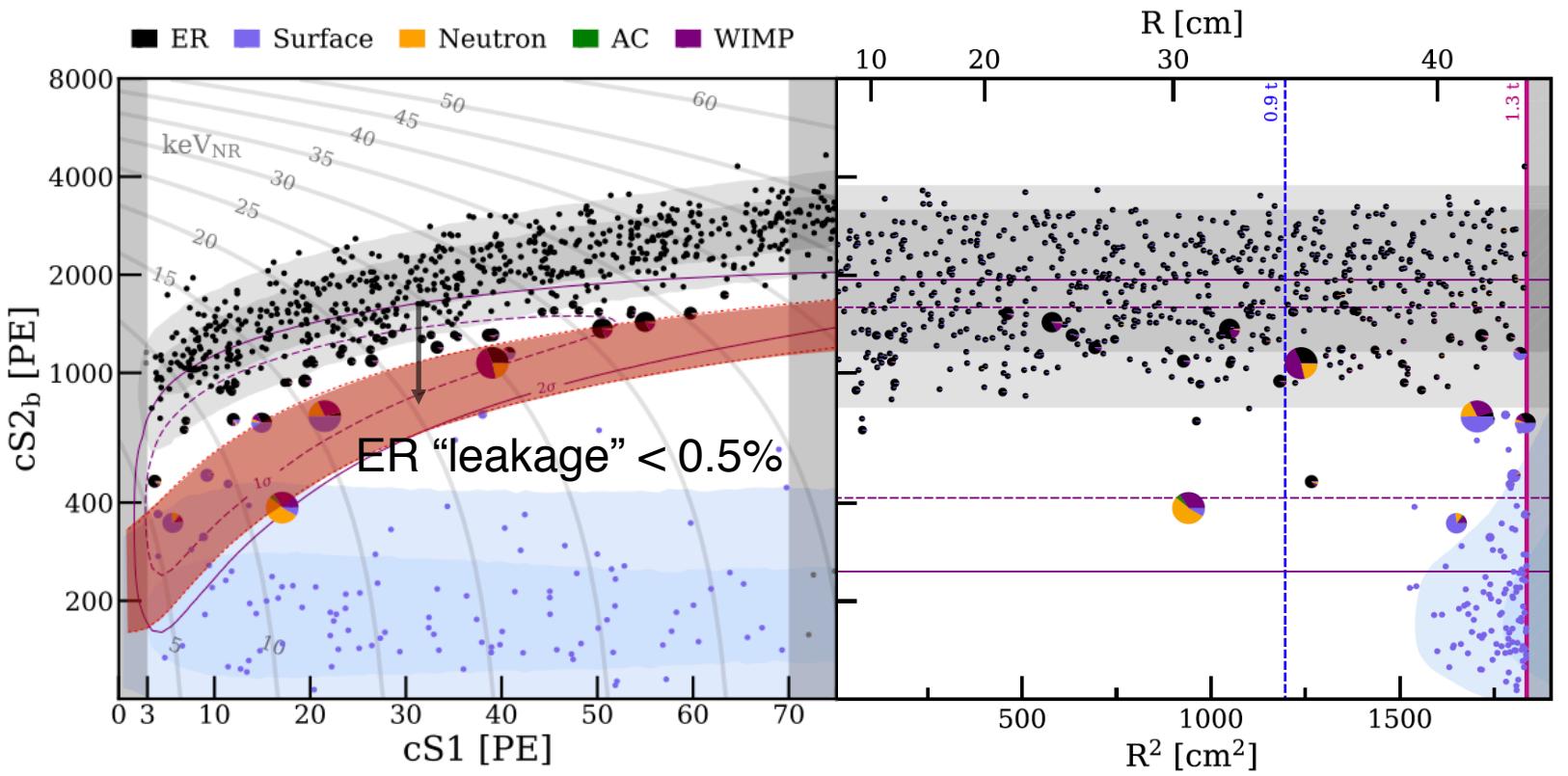
- 3D position imaging + self-shielding
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- Particle detector with *large exposure*,
low background,
low threshold.

$\sim 1 \text{ t} \cdot \text{y}$

$< 100 \text{ events}/(\text{t} \cdot \text{y} \cdot \text{keV}_{\text{ee}})$

$\sim 1 \text{ keV}_{\text{ee}} (5 \text{ keV}_{\text{nr}})$

NR Search



Best constraints on WIMP dark matter with masses $> 3 \text{ GeV}/c^2$

PRL 121, 111302

PRL 122, 141301

PRL 123, 251801

Two-phase Xenon TPC

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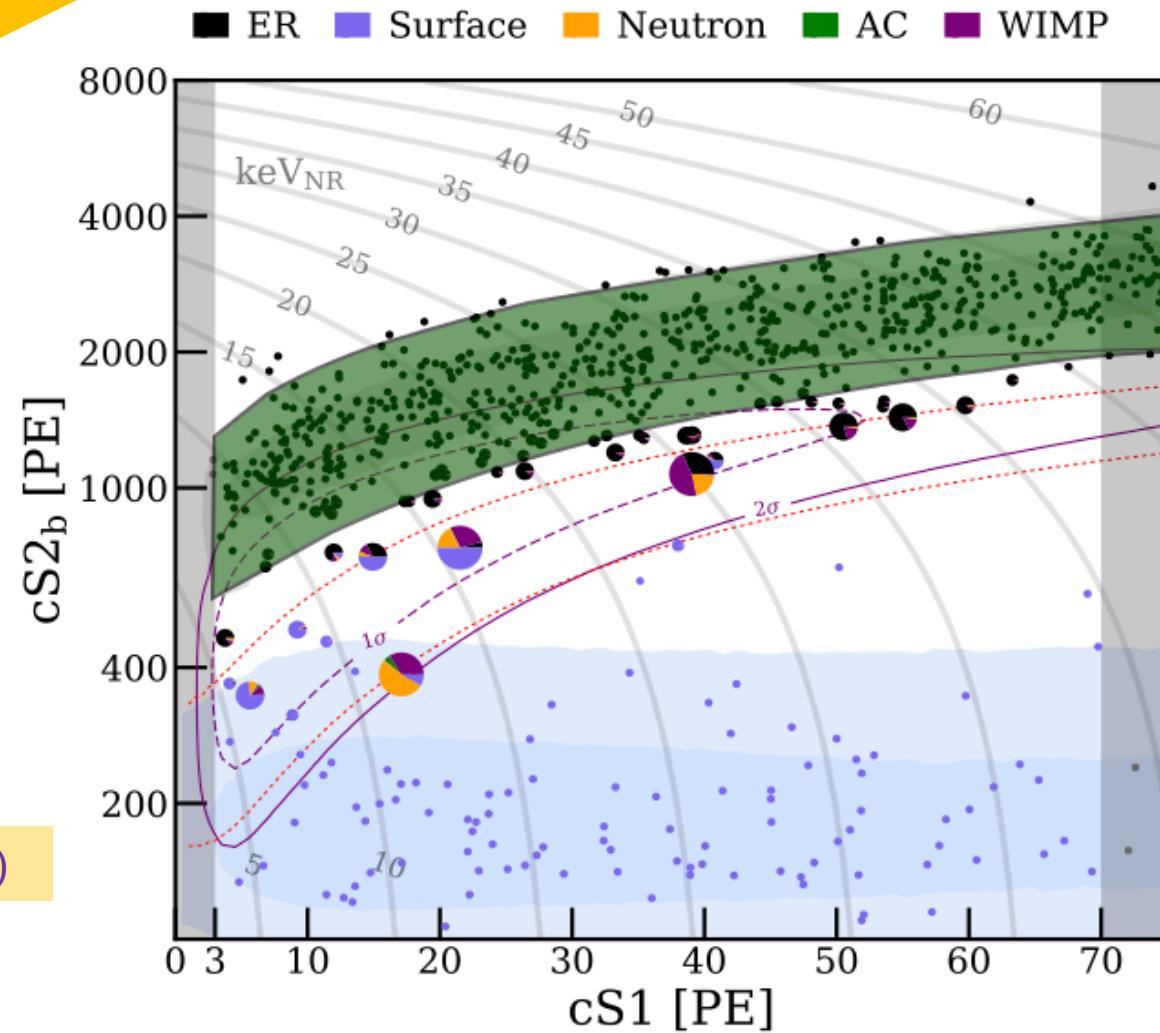
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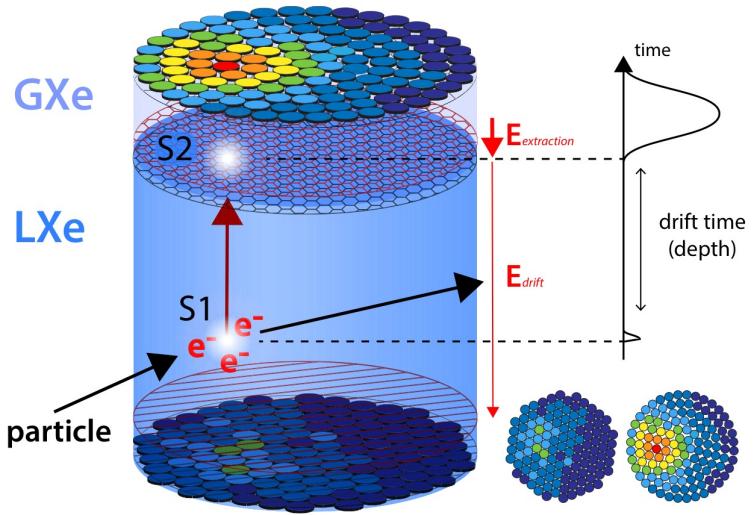
This talk

ER Search



Two-phase Xenon TPC

- 3D position imaging + self-shielding
- Recoil types:
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Electronic Recoil (ER)
- Particle detector with
large exposure,
low background,
low threshold.

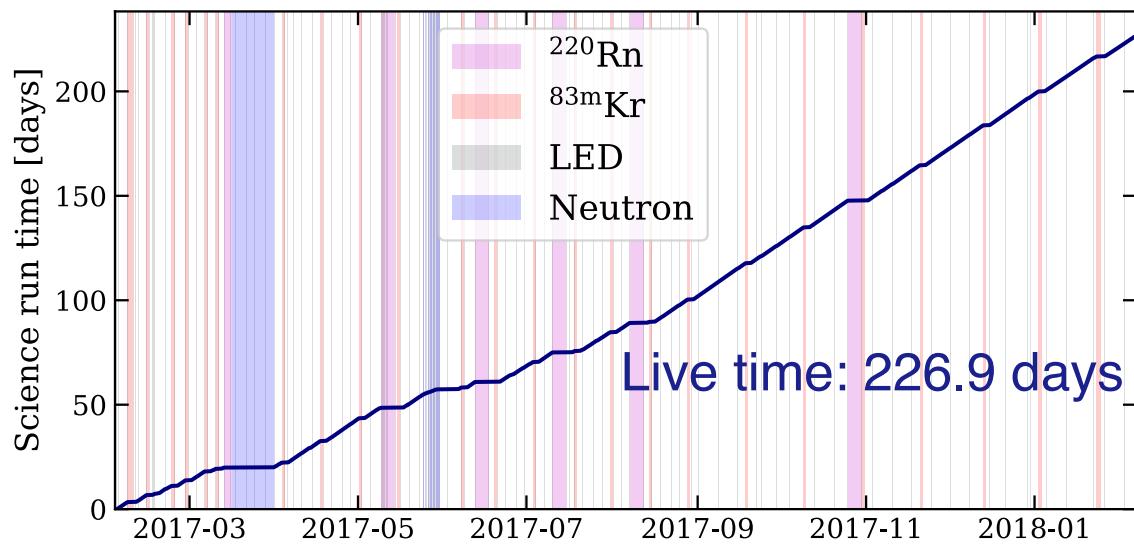


TWO Data Analysis

THREE Excess

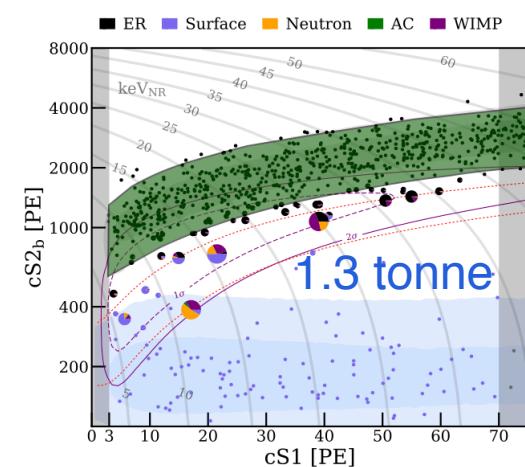
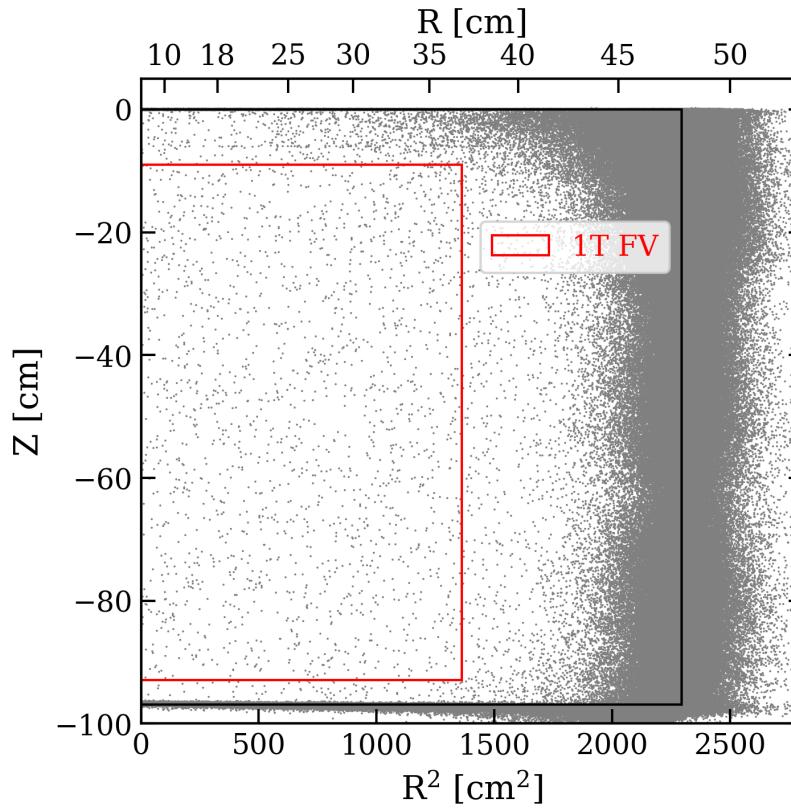
FOUR Interpretations

Exposure: $0.65 \text{ t} \cdot \text{y}$



Data taking: Feb. 2017 – Feb. 2018
Science Run 1 (SR1)

Single scatter events within (1, 210) keV

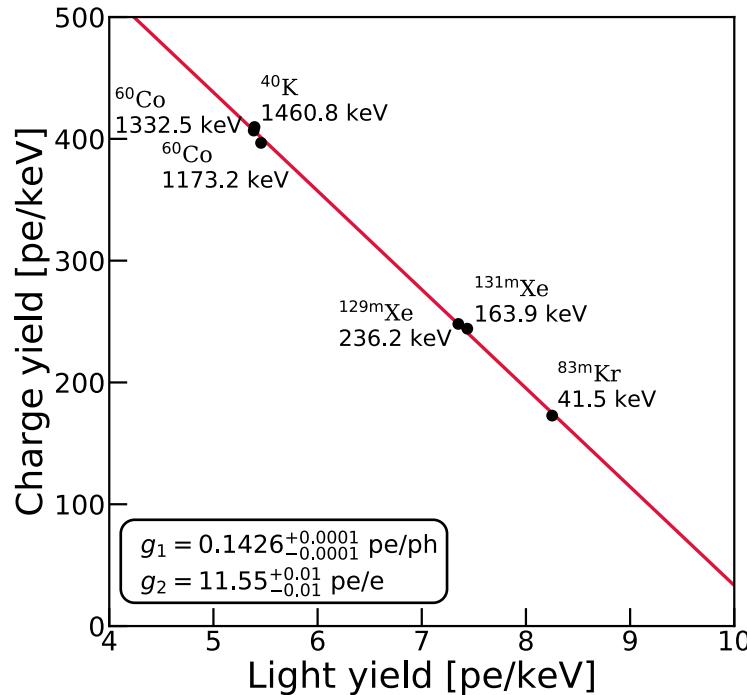
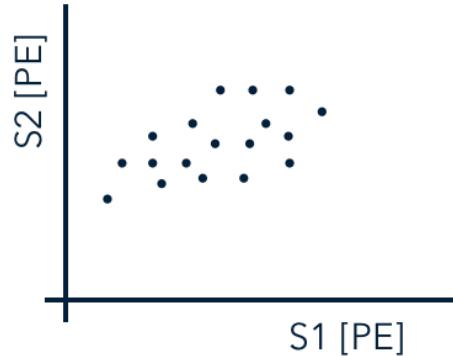


1 tonne fiducial mass

- Reduce material and surface backgrounds
- Simplify analysis

Analysis space: energy

2D analysis



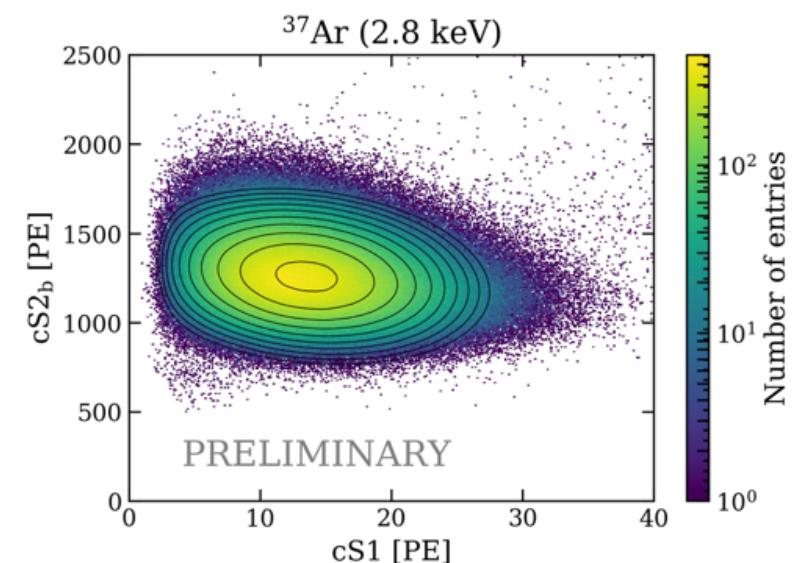
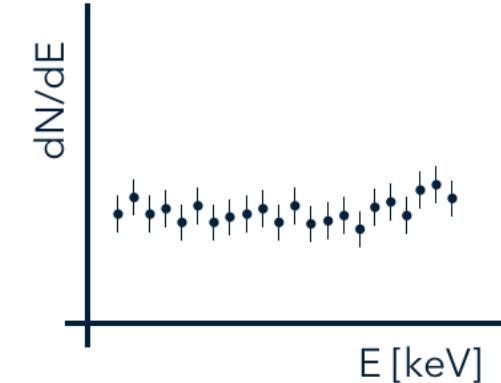
$$E = (n_{ph} + n_e) \cdot W = \left(\frac{S1}{g1} + \frac{S2}{g2} \right) \cdot W$$

$W = 13.7 \text{ eV/quanta}$
 $g1: S1$ signal gain [PE/ph]
 $g2: S2$ signal gain [PE/ e^-]

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

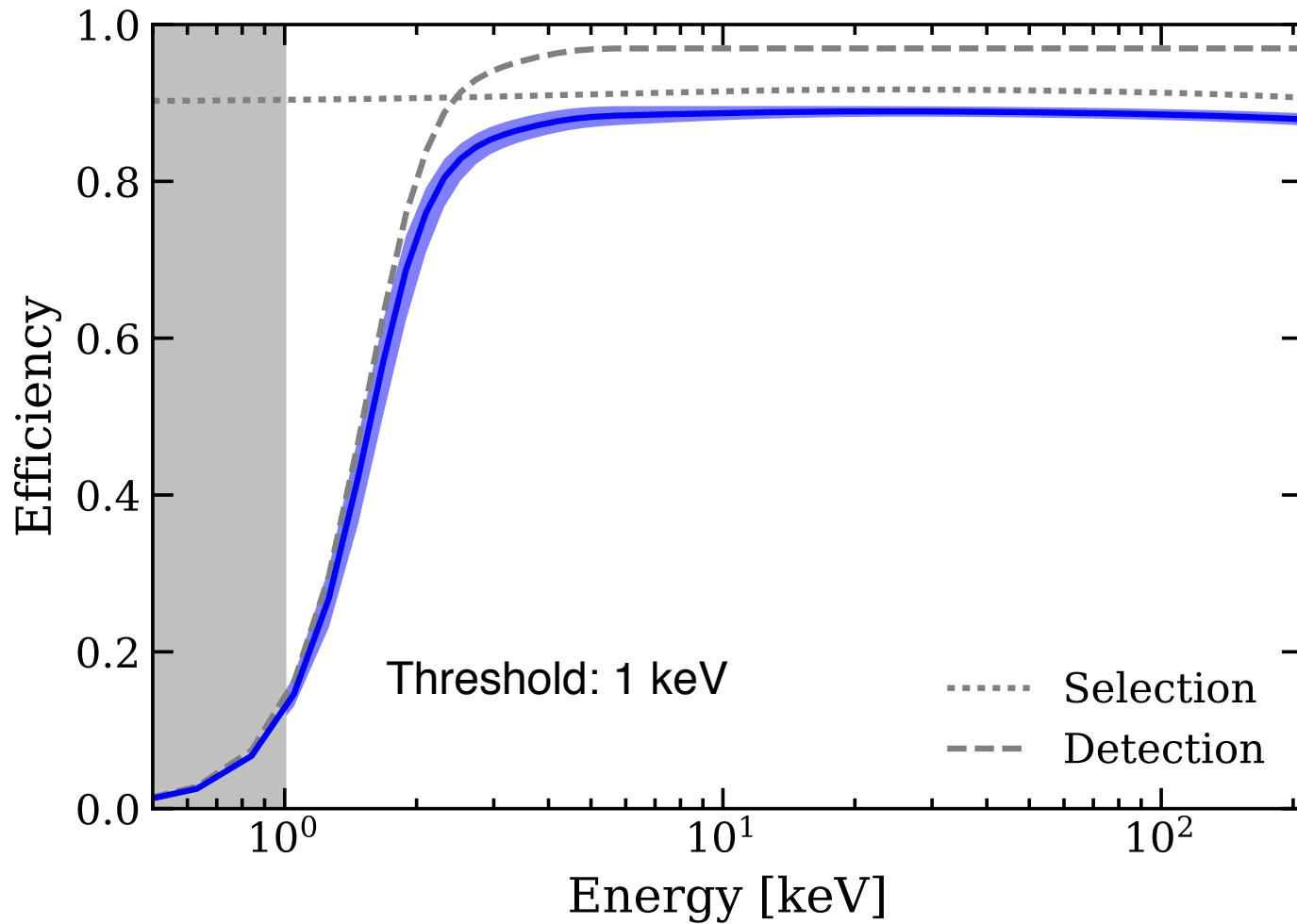
$$y = m \cdot x + b$$

1D analysis



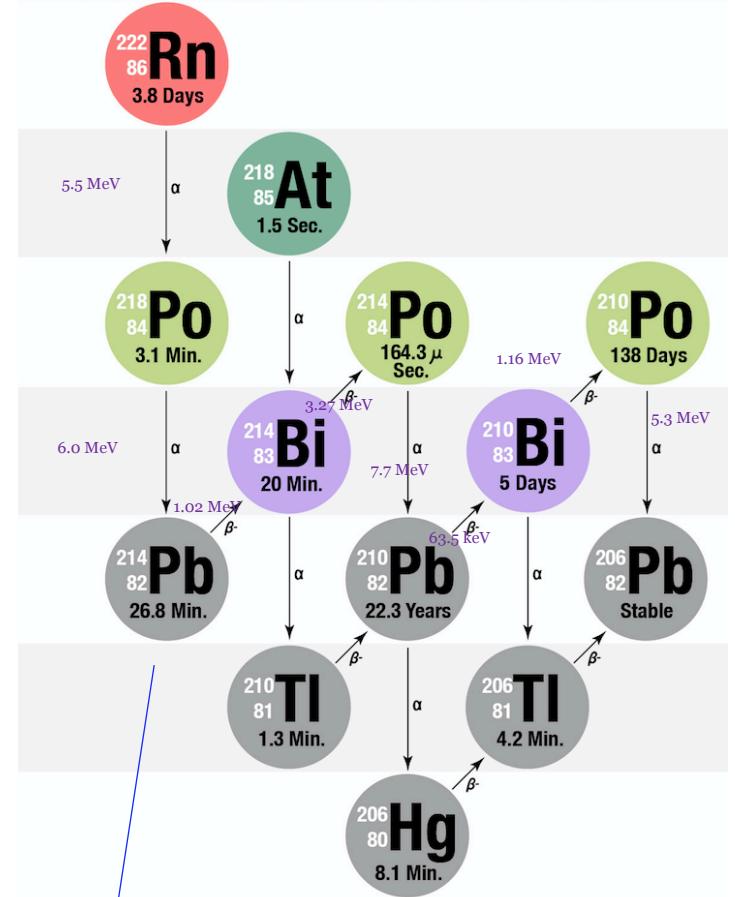
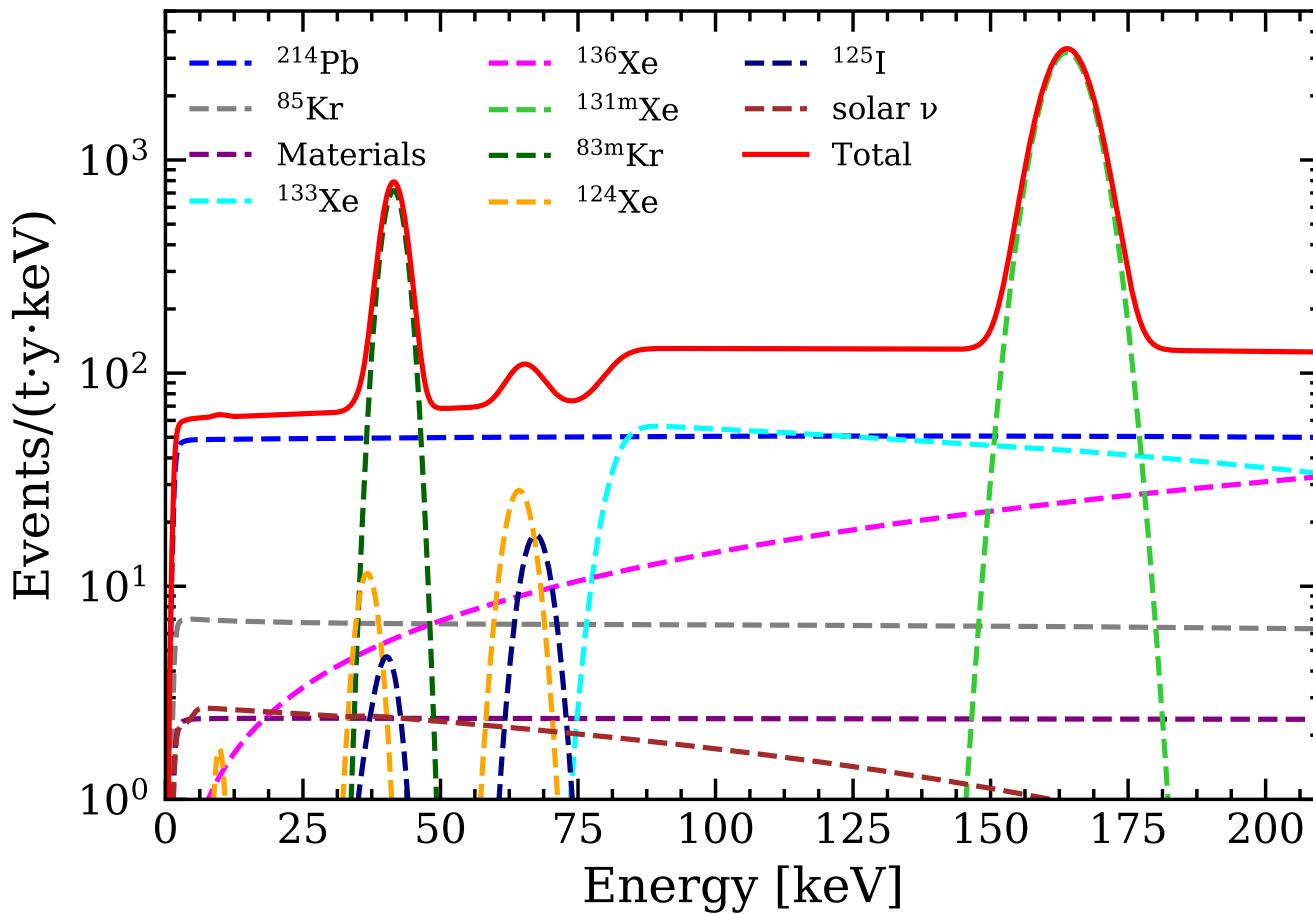
Efficiency

- Detection:
3-fold requirement
on S1
- Selection:
 - Single scatter
 - Standard data quality cuts



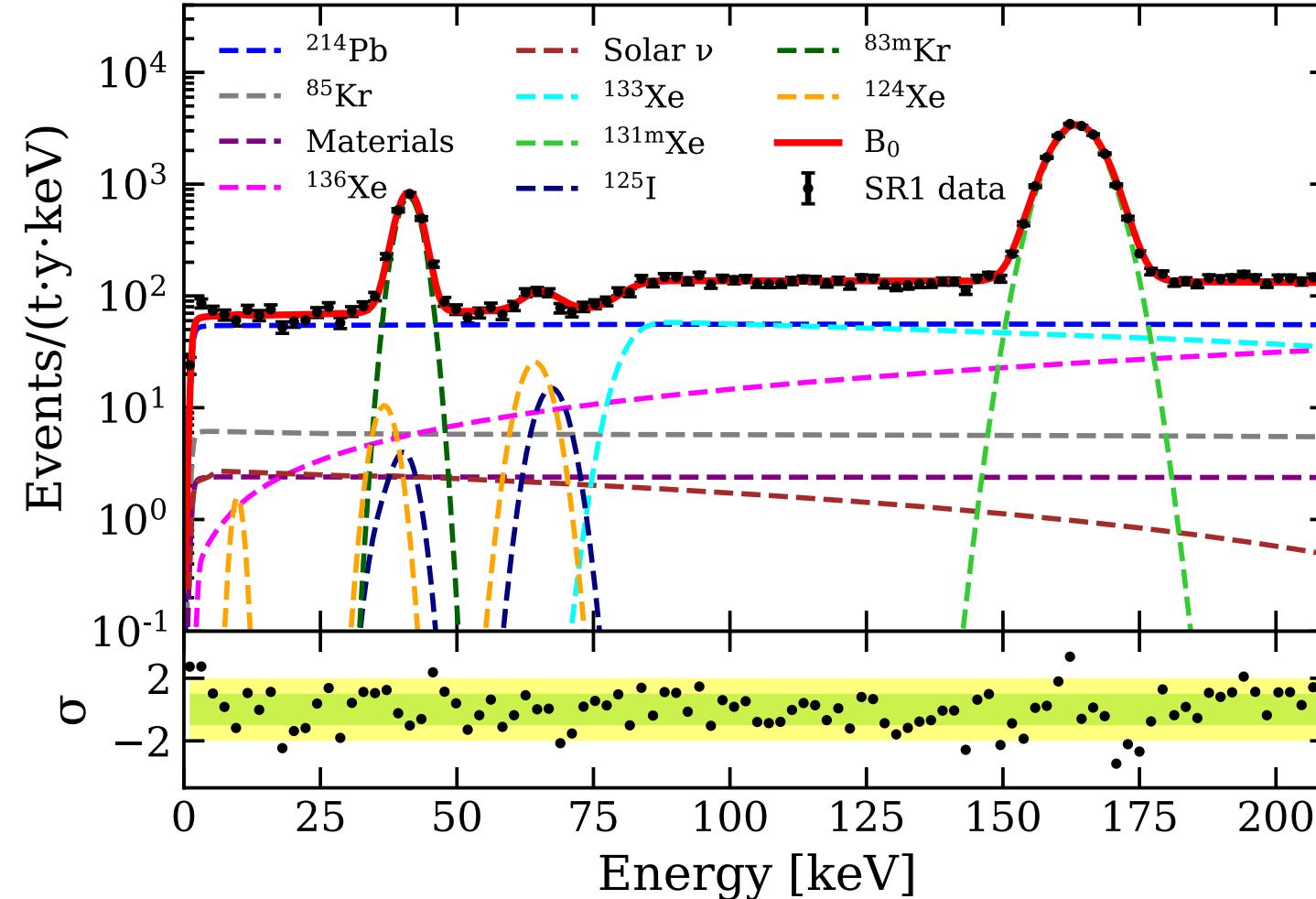
Background model

- 10 background components
- Background model denoted as B_0



^{214}Pb beta decay:
dominant background

Background-only fit



Unbinned, maximum likelihood

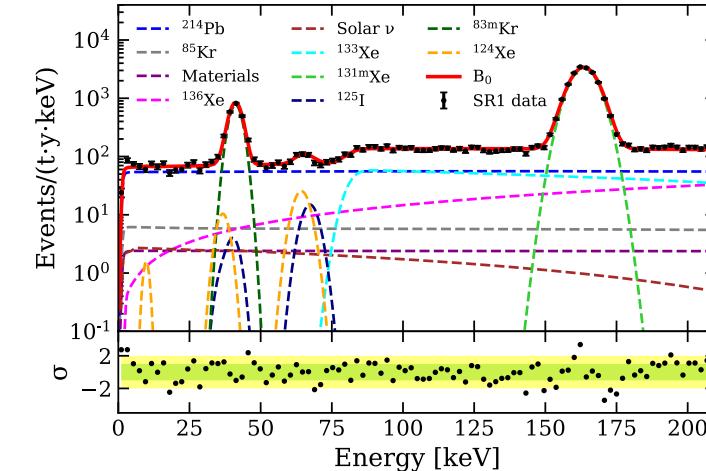
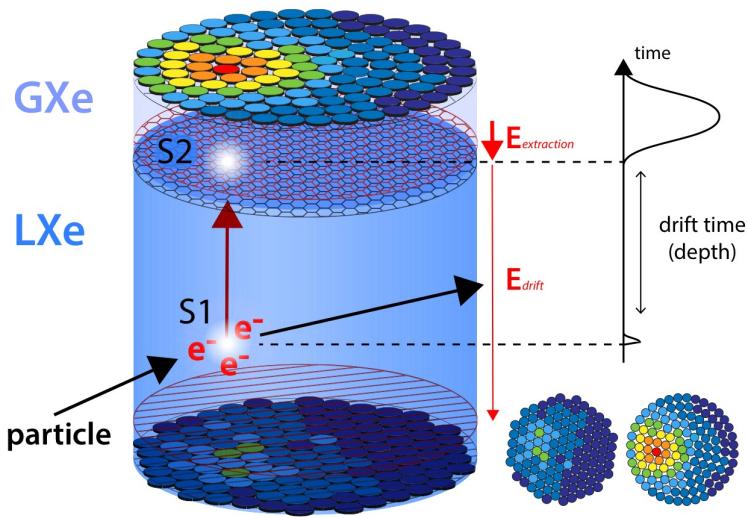
Good fit observed for most of the energy range

76 ± 2 events/($t \cdot y \cdot \text{keV}$) in $(1, 30)$ keV

Lowest ER background rate in this energy region!

Two-phase Xenon TPC

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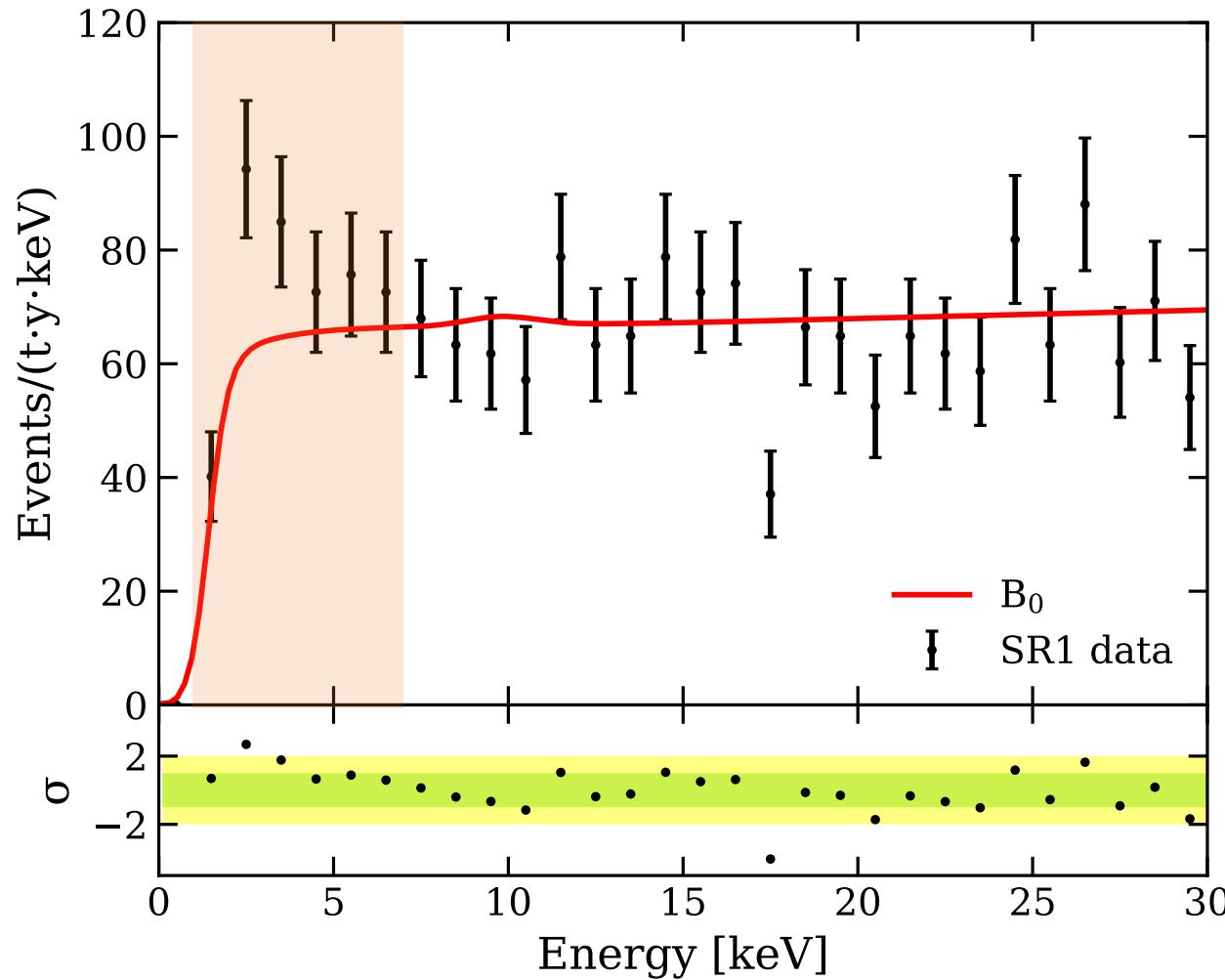


Lowest ER rate:
 76 ± 2 events/ $(t \cdot y \cdot \text{keV})$
within $(1, 30)$ keV

THREE
Excess

FOUR
Interpretations

Low-energy excess



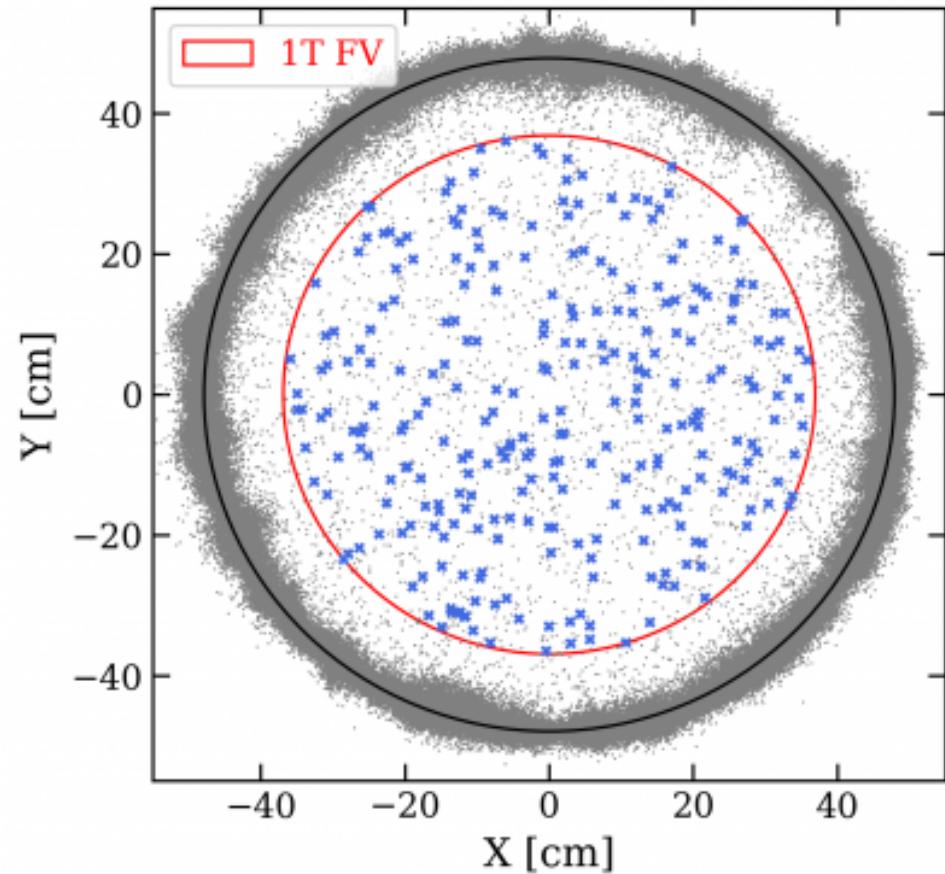
Between 1 and 7 keV

Expected: 232 events

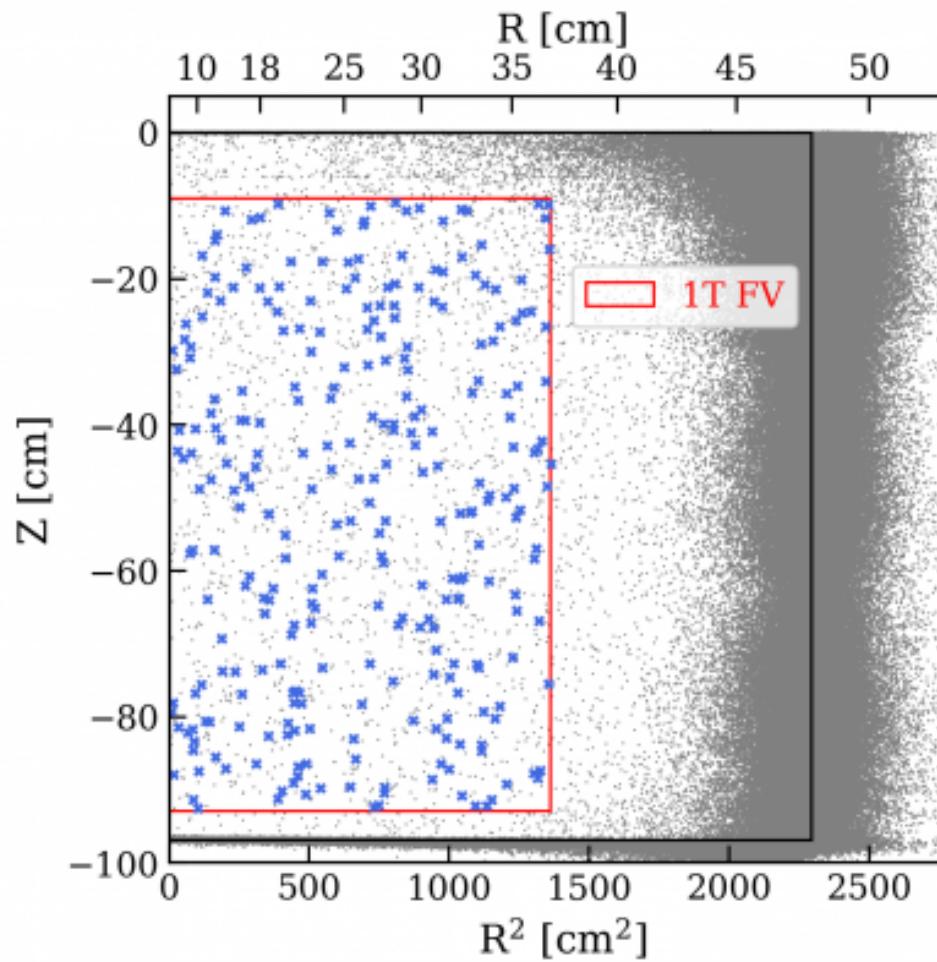
Observed: 285 events

3.3σ
(naive estimate; we use log likelihood ratio for main analysis)

Spatial distribution

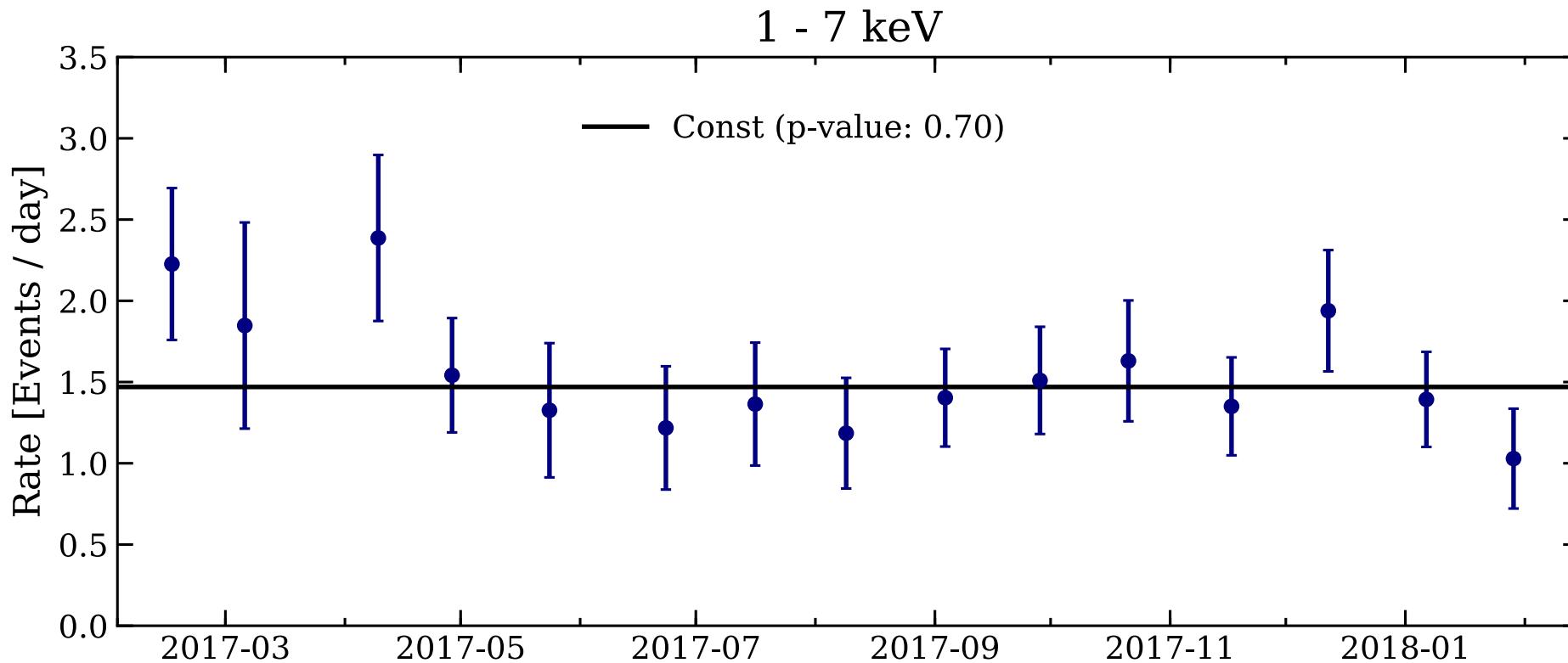


Single scatter events within
(1, 7) keV
(1, 210) keV



No strong spatial
dependence

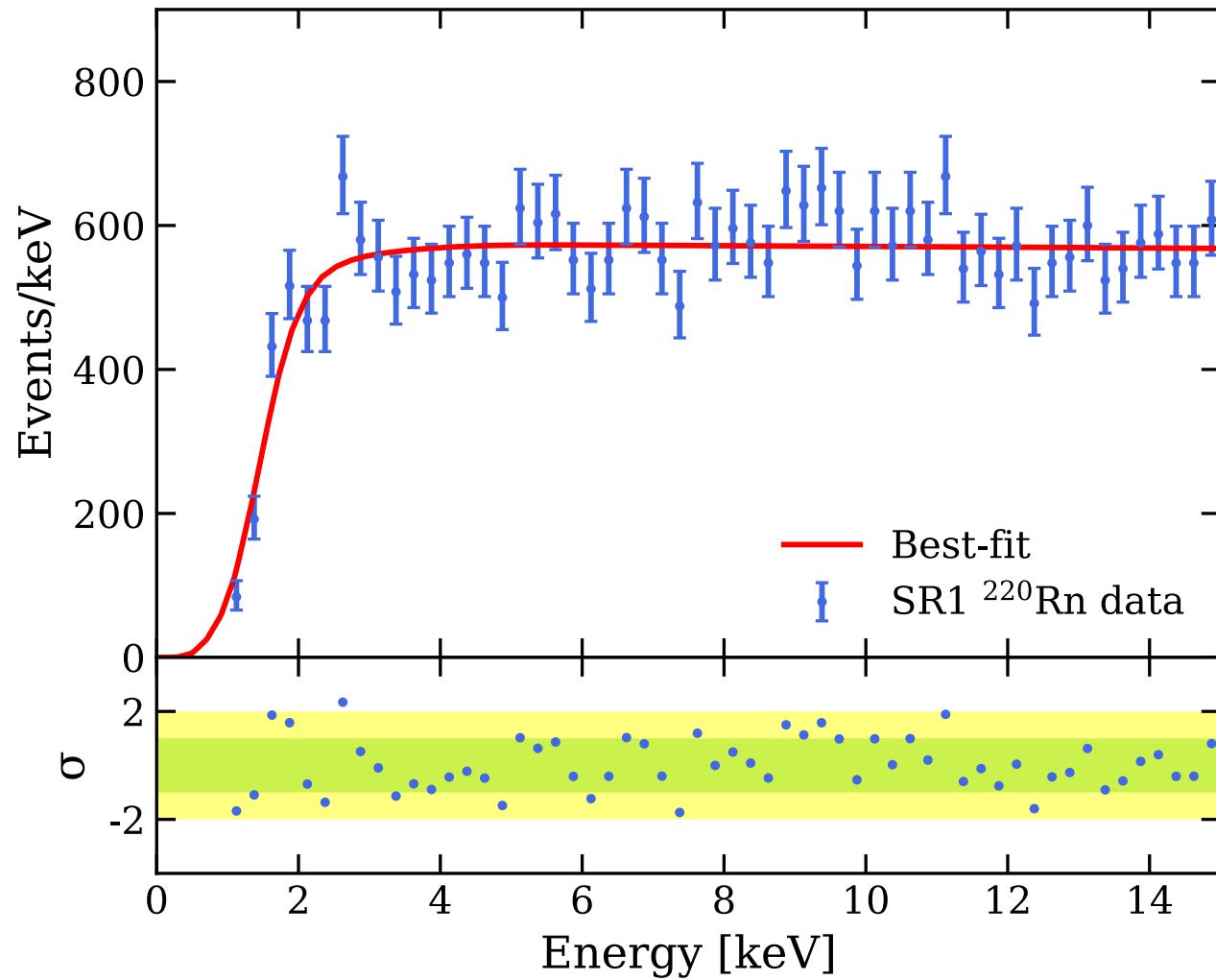
Time distribution



No strong time dependence

What can be the excess?

Efficiency and energy reconstruction

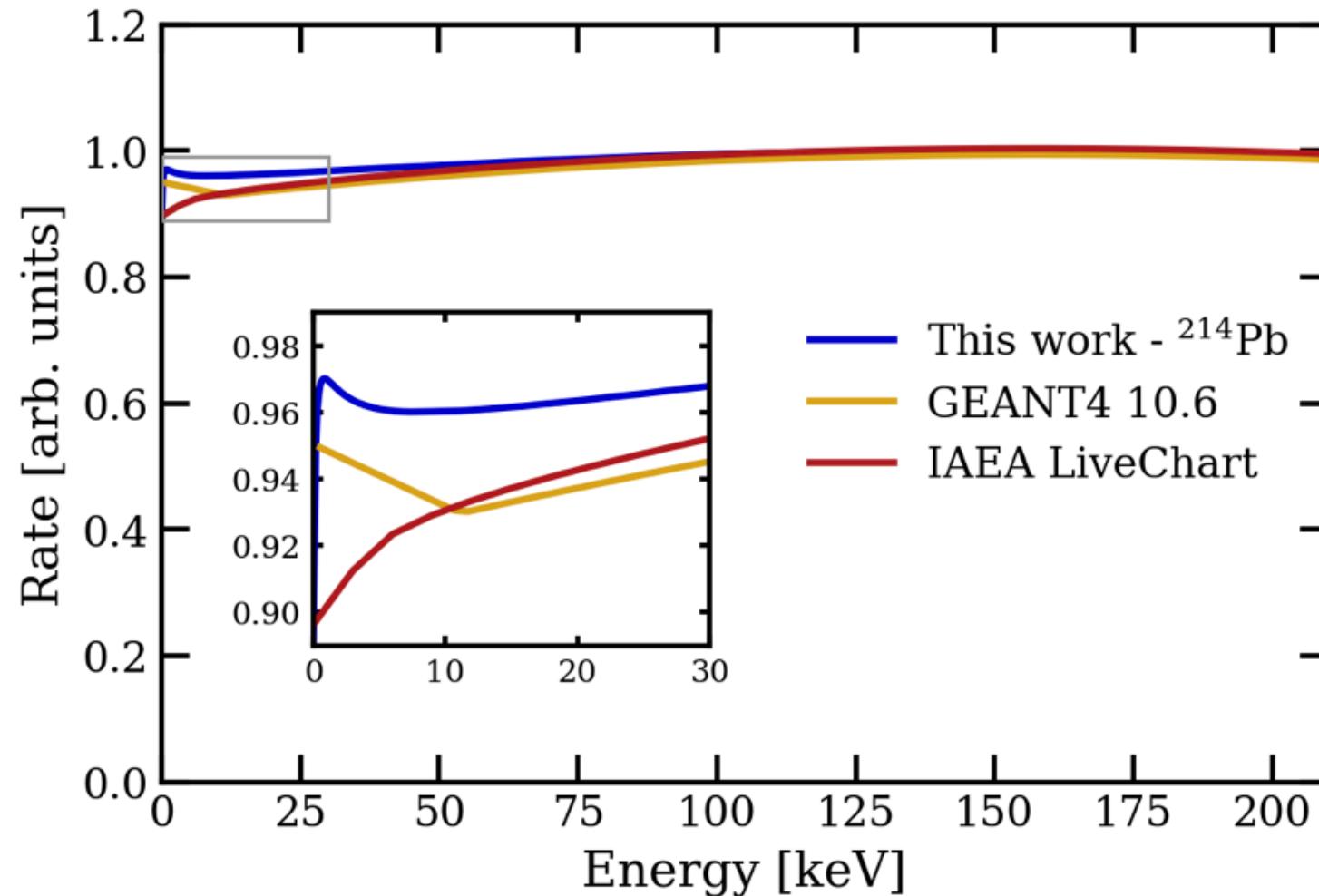


Misconstructed energy
and/or efficiency?

^{220}Rn (^{212}Pb) calibration
data is fit with similar
statistics framework

Good agreement between our
model and calibration data
(p-value: 0.50)

Beta decay spectrum shape

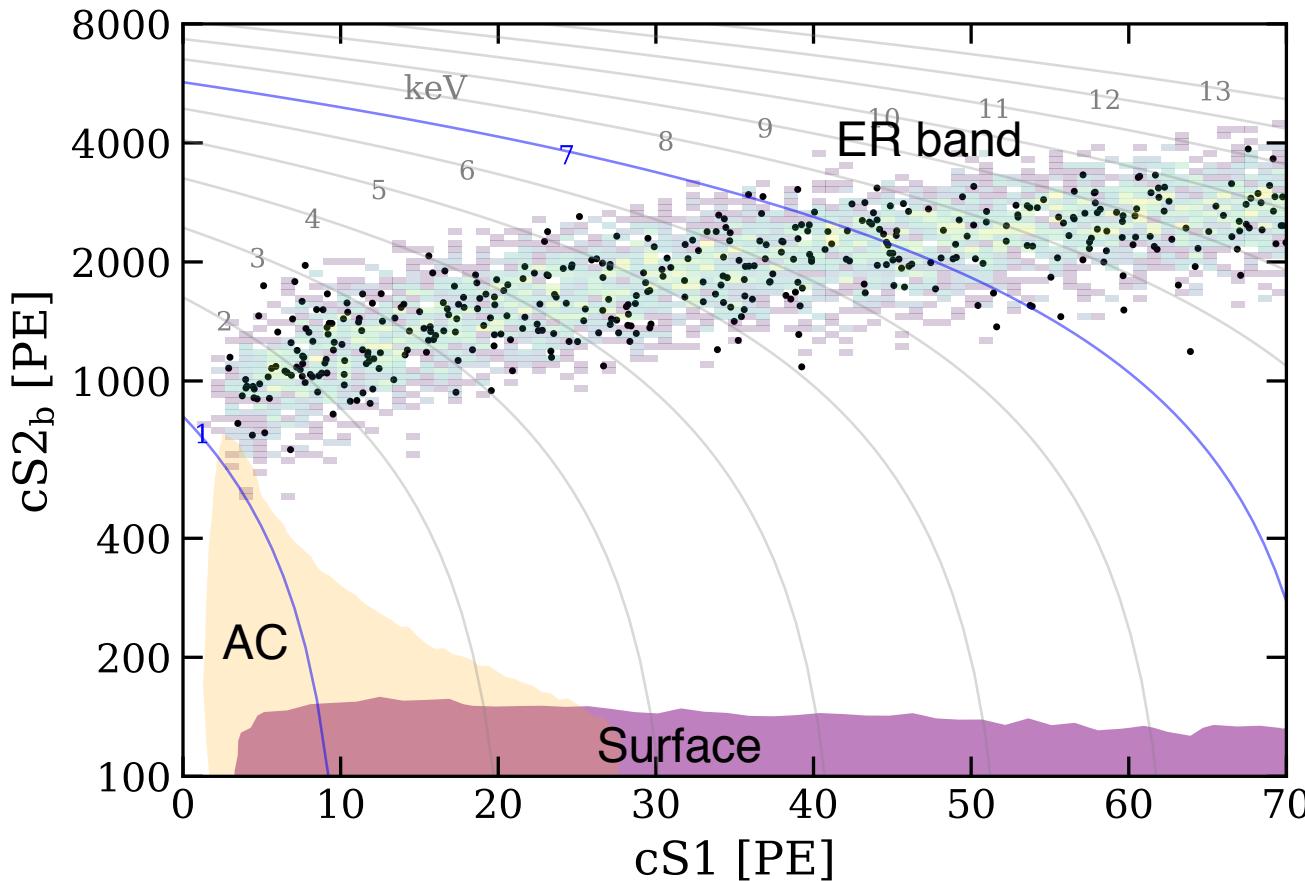


Low energy spectrum
could be affected by
atomic effects

Theoretical calculation on ^{214}Pb
beta decay shape uncertainty:
 $< 6\%$

Required shape uncertainty
to explain excess:
 $> 50\%$

Instrumental backgrounds

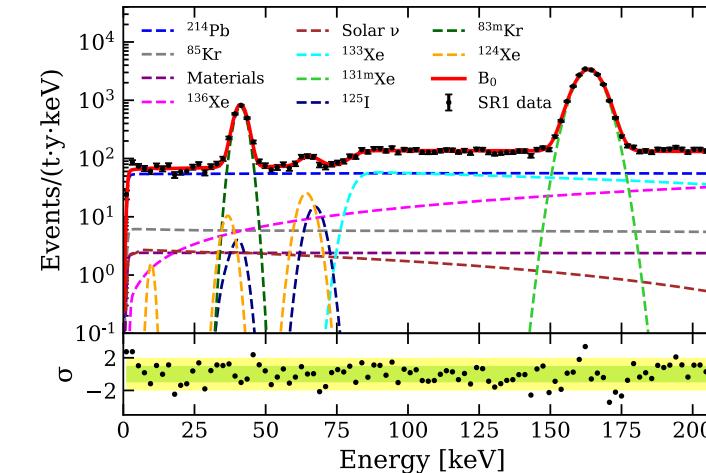
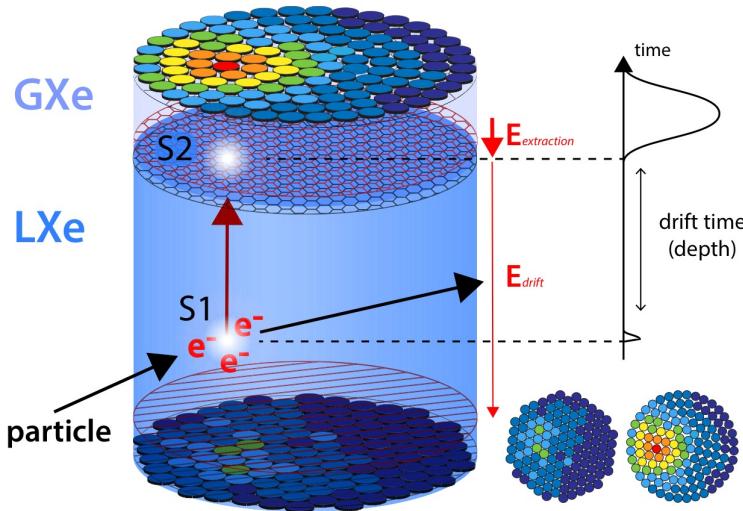


Instrumental backgrounds
(accidental coincidence,
surface) can be reconstructed
in low energy region

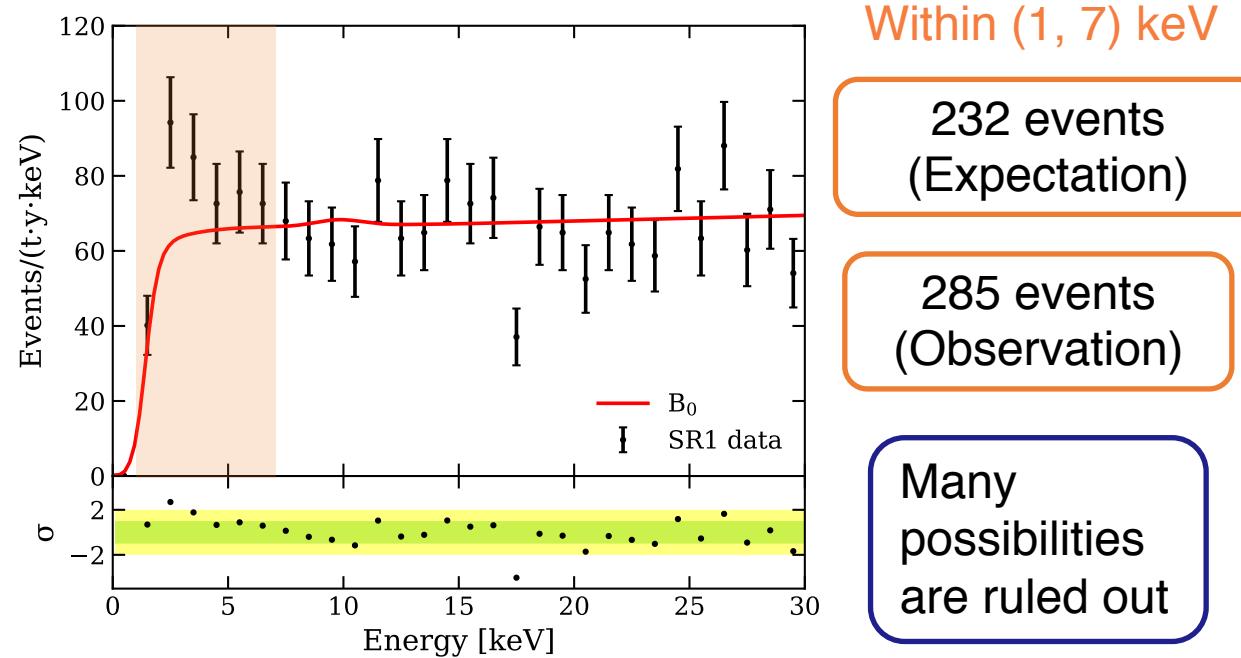
ER events all fall in
ER band as expected

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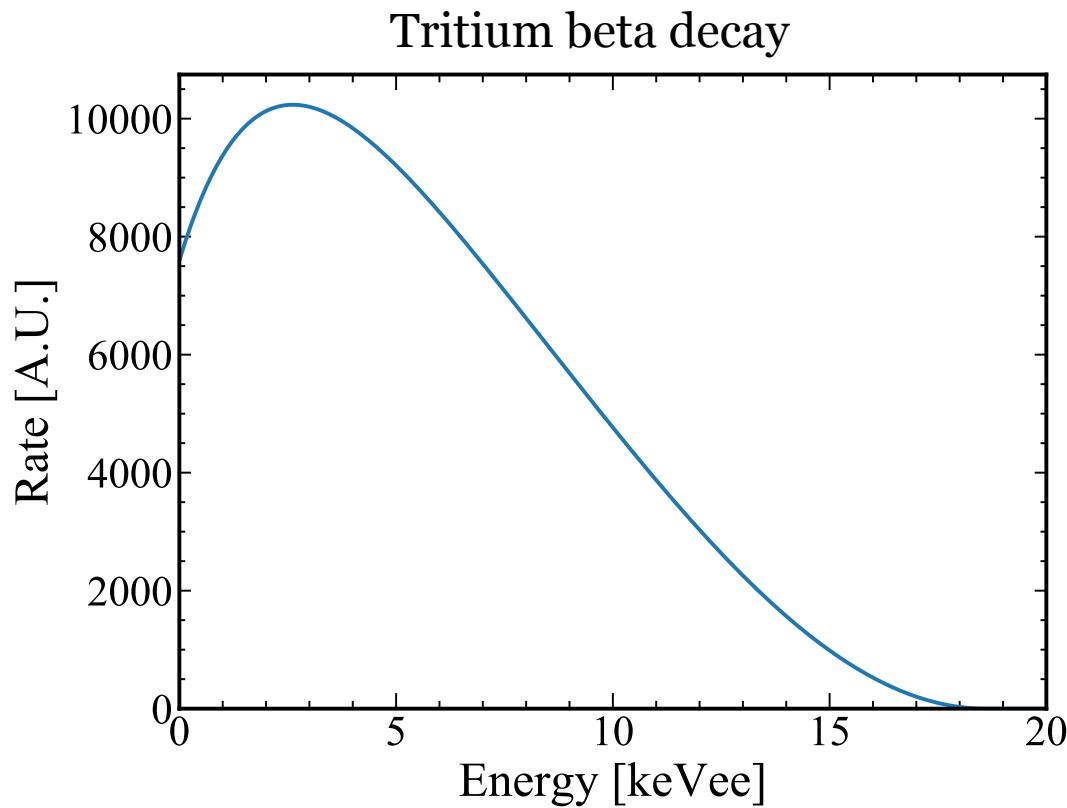


Lowest ER rate:
 76 ± 2 events/ $(t \cdot y \cdot \text{keV})$
within $(1, 30)$ keV



FOUR
Interpretations

Tritium background

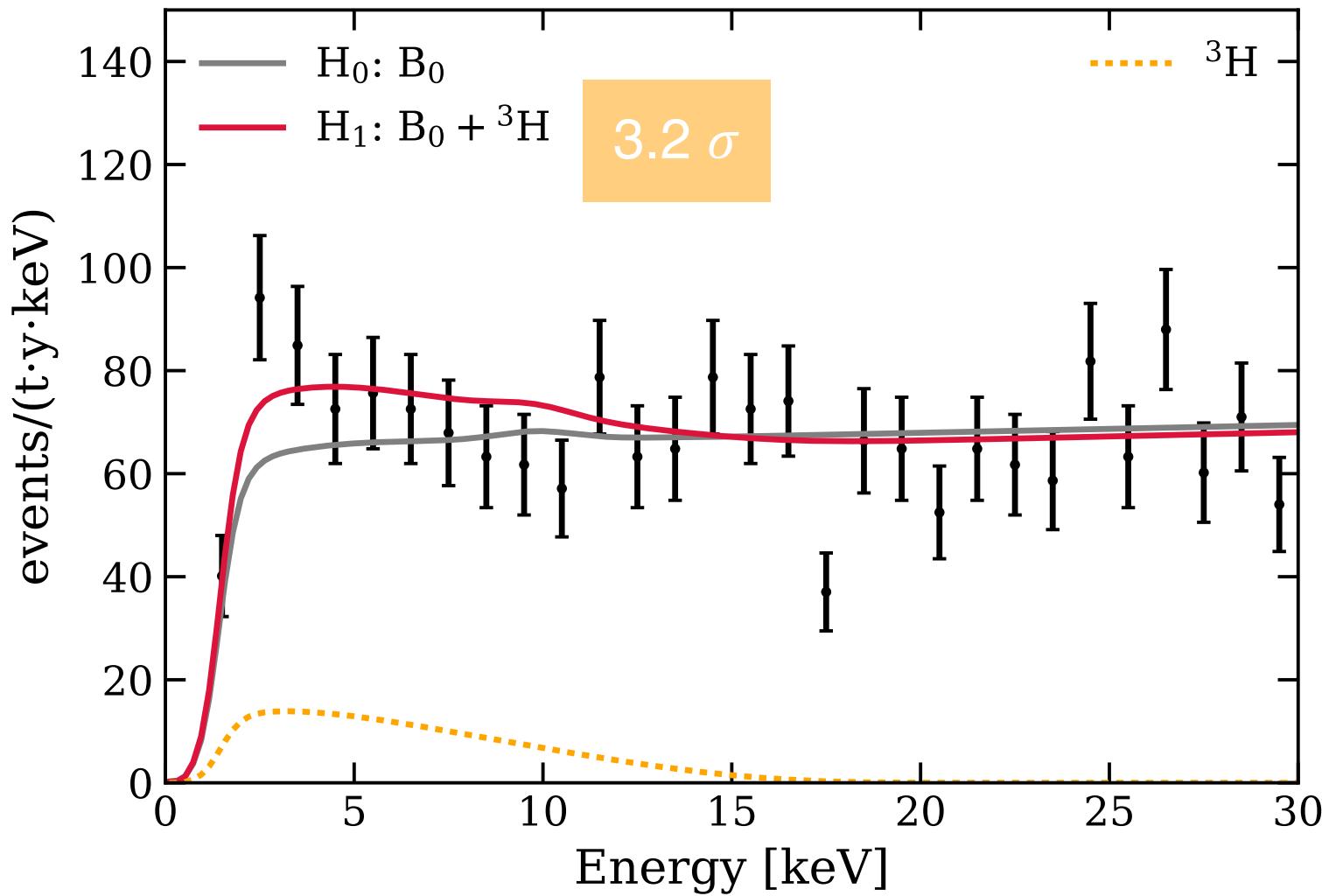


Low-energy (Q value 18.6 keV)

Long half life (12.3 years)

- Two possible ways to enter detector
- Cosmogenic activation in xenon
 - Atmospheric abundance

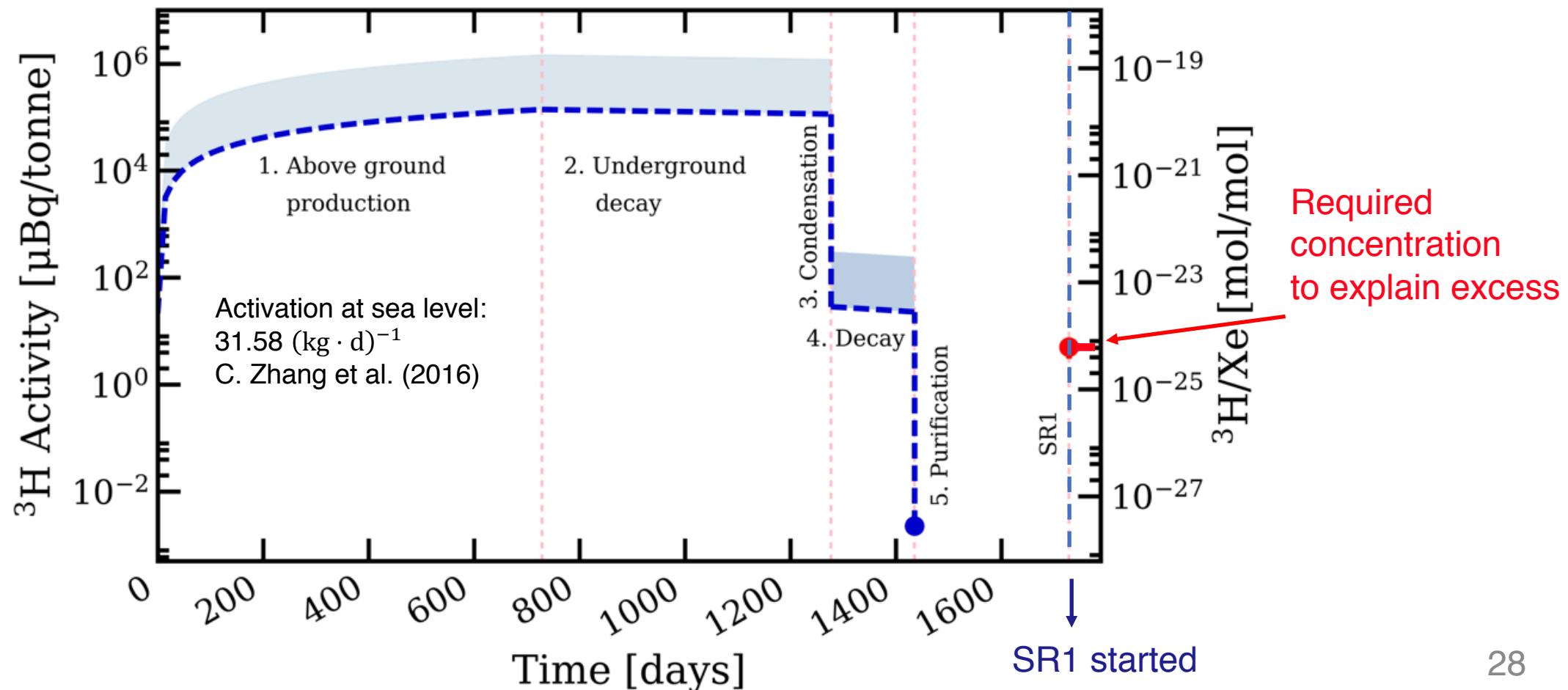
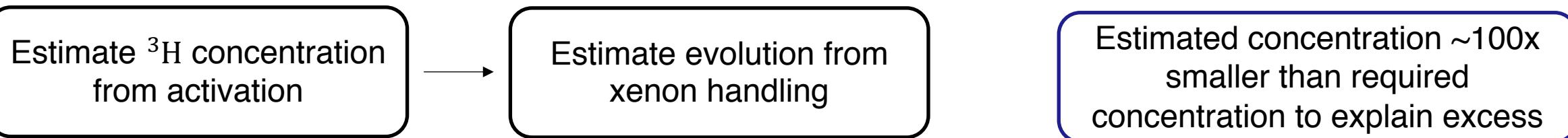
Tritium hypothesis



Fitted rate: 159 ± 51 events/($t \cdot y$) →

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

Cosmogenic activation in xenon



Atmospheric abundance in materials

Required ${}^3\text{H}$: Xe to explain excess
 $\sim 10^{-24}$ mol/mol

HTO: H_2O
 $\sim 10^{-17}$ mol/mol

HT: H_2 (assuming same as HTO: H_2O)
 $\sim 10^{-17}$ mol/mol

Required H_2O : Xe to explain excess
 ~ 100 ppb

Required H_2 : Xe to explain excess
 ~ 100 ppb

H_2O : Xe concentration constrained
from light yield measurement
 $\text{O}(1)$ ppb

H_2 : Xe concentration NOT constrained
by any measurement
?

Solar axions

Production

ABC Primakoff ^{57}Fe
 g_{ae} $g_{a\gamma}$ g_{an}^{eff}
 Axion-electron Axion-photon Axion-nucleon

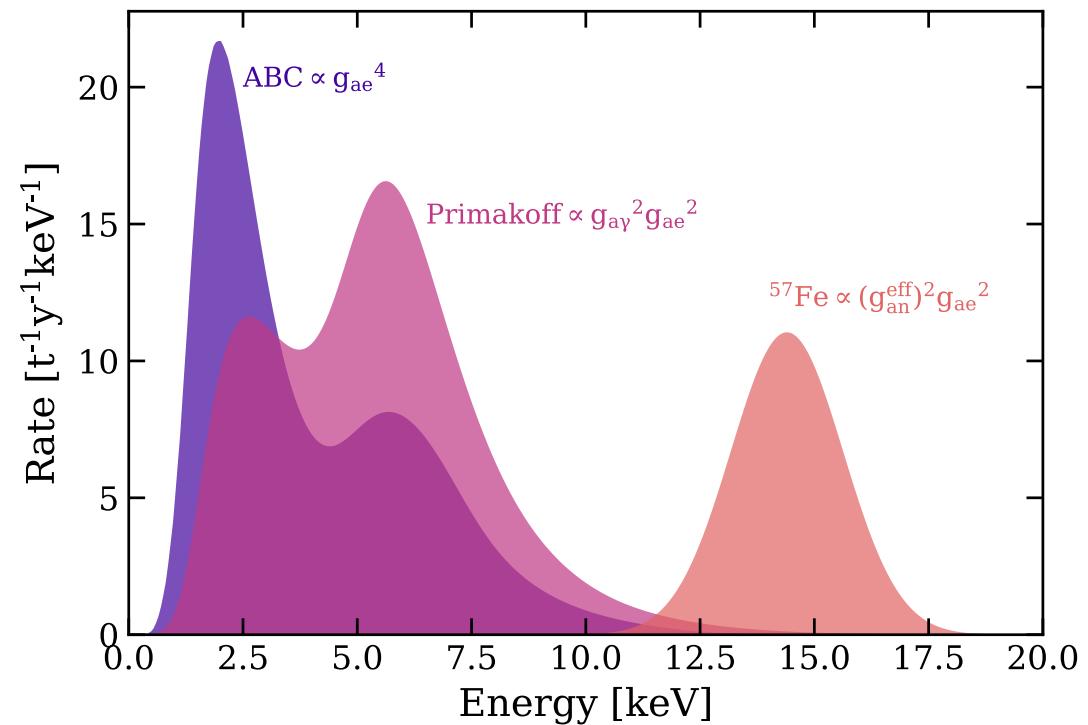
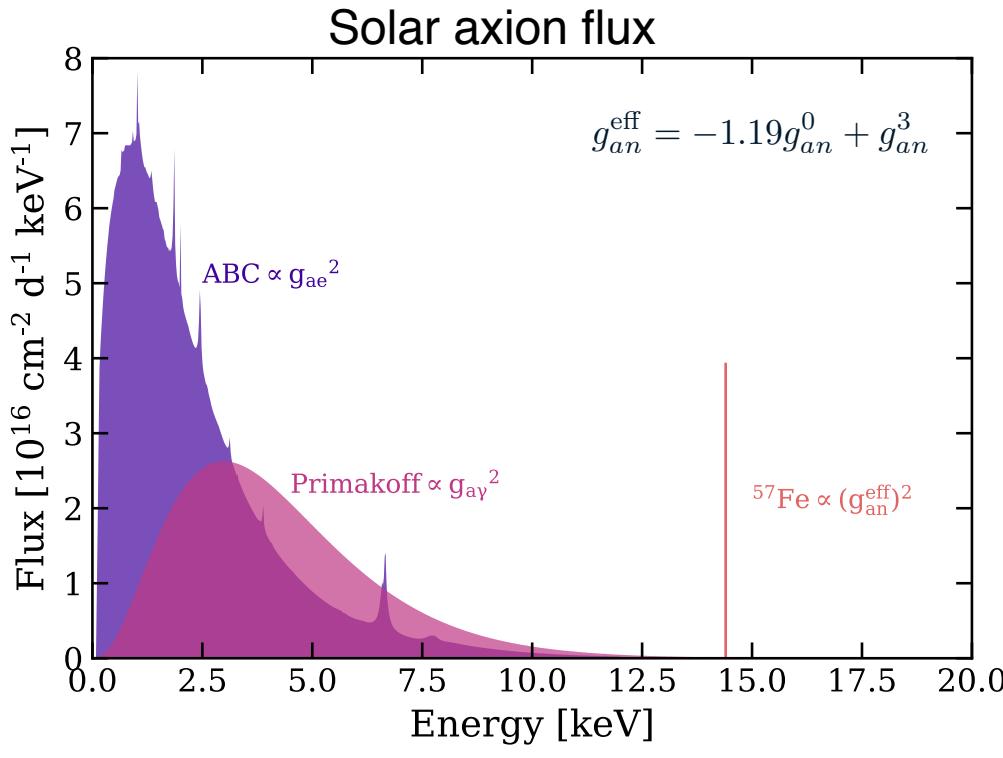
Detection

Axio-electric effect

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

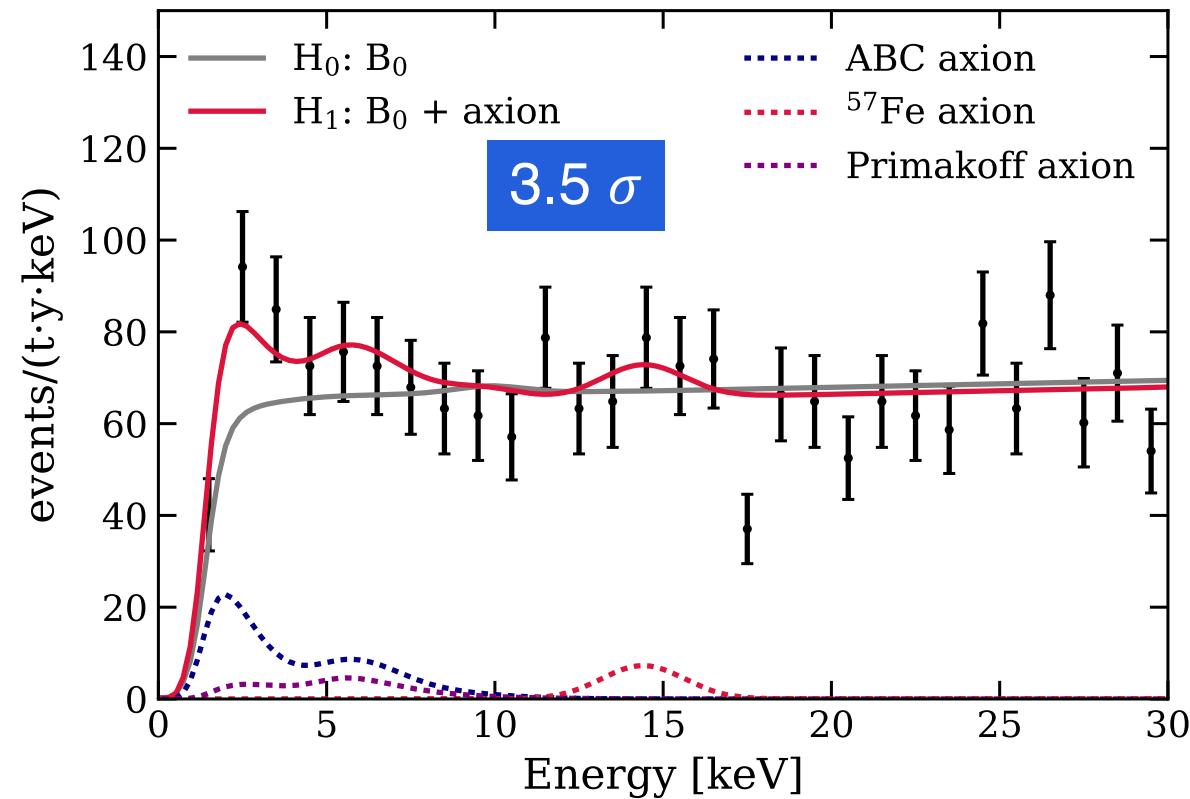
Reconstruction

XENON1T resolution,
efficiency

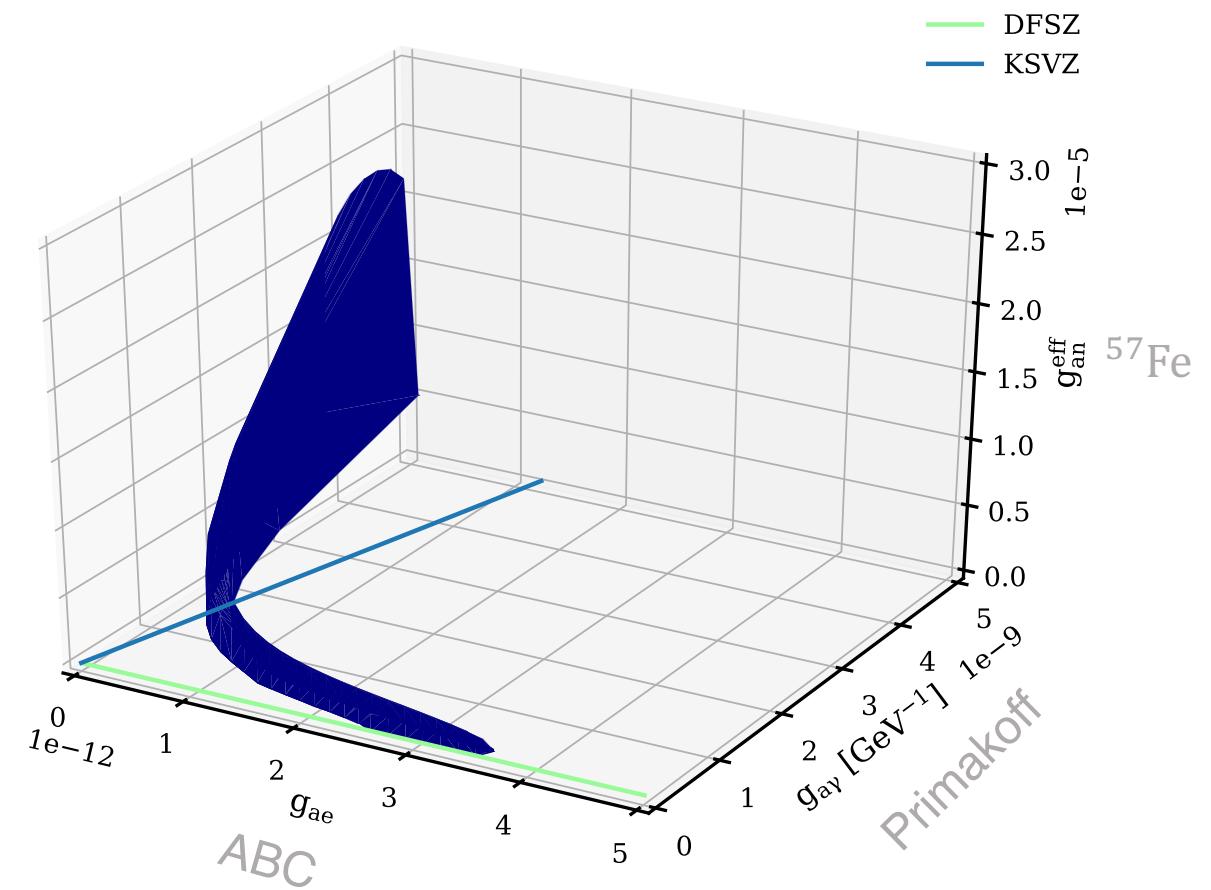


Solar axion result

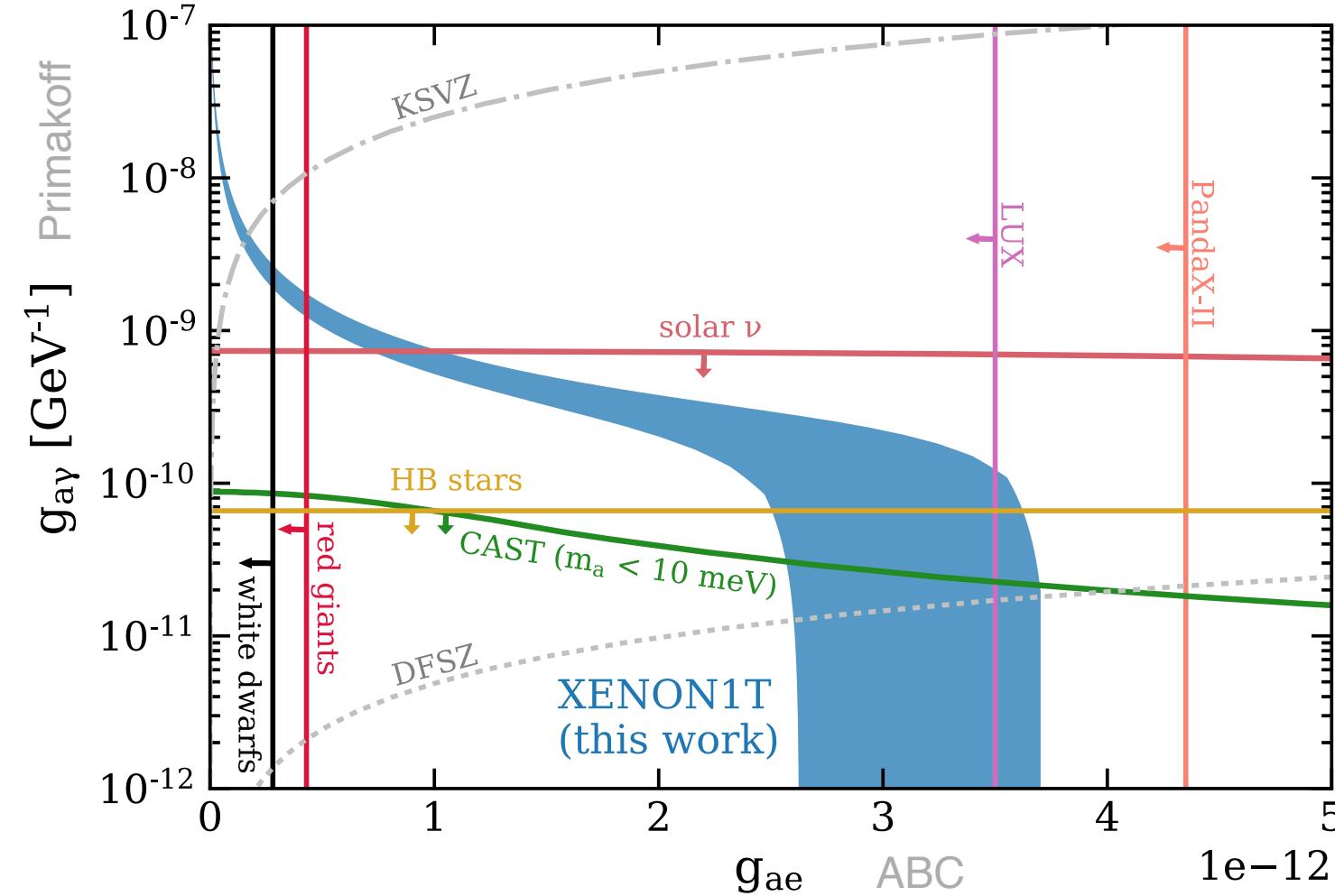
Three couplings are independent in the fit
(no model dependence)



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



Solar axion result in $(g_{ae}, g_{a\gamma})$ space



In strong tension with
astrophysical constraints

Neutrino magnetic moment

Production

*

Detection

*

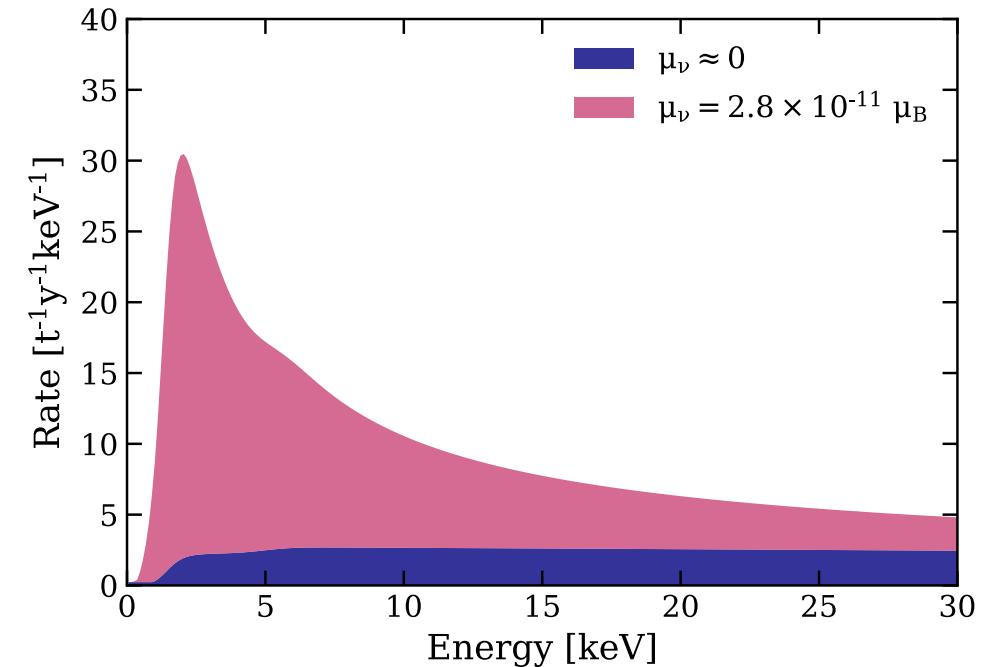
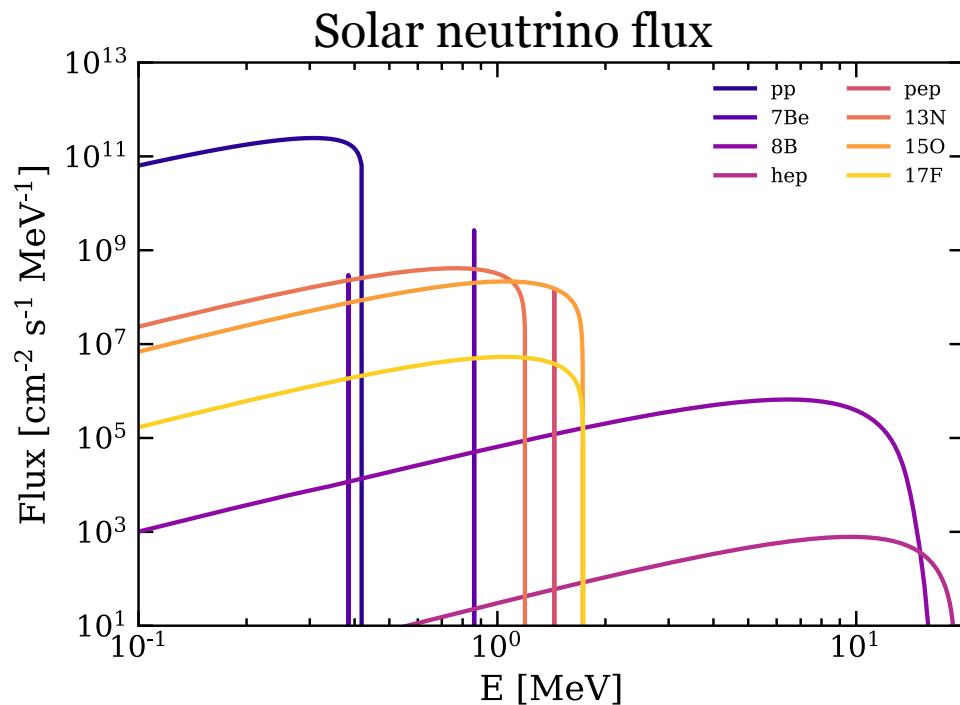
Reconstruction

Solar neutrinos

σ enhancement

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

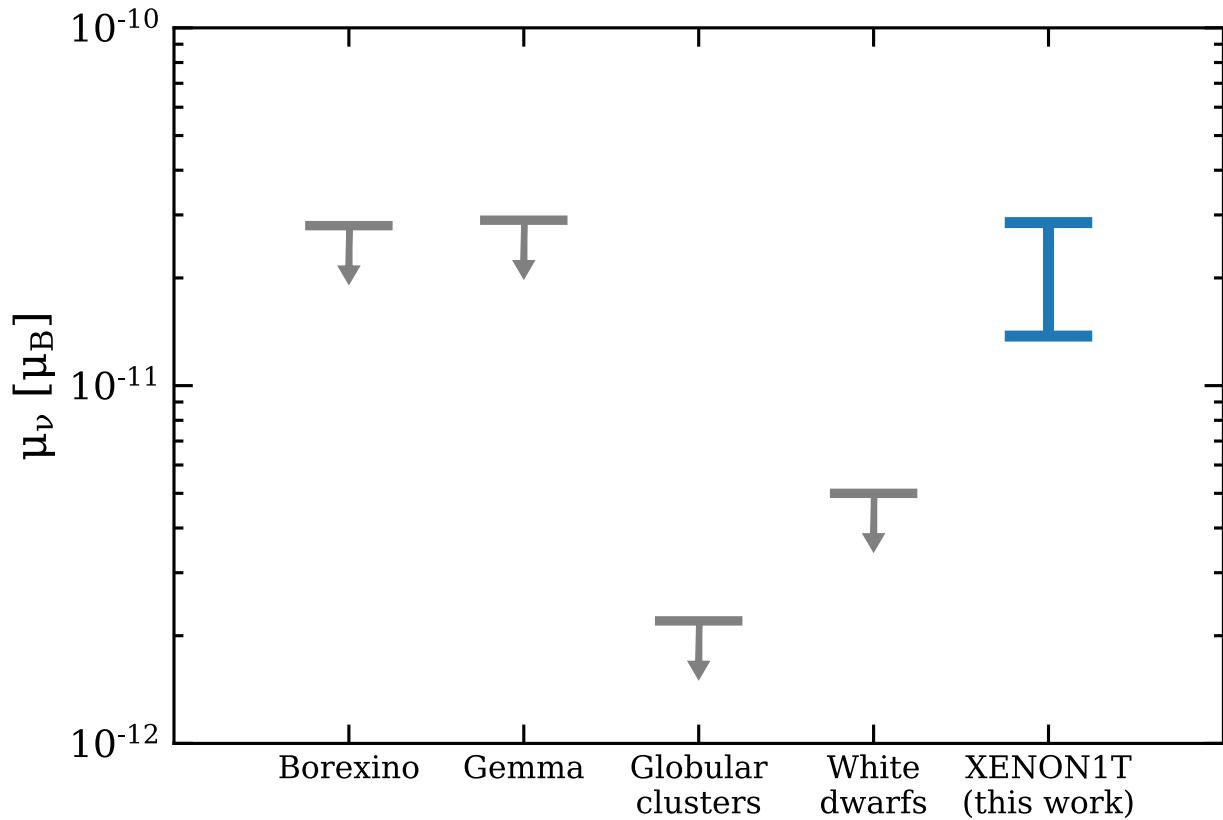
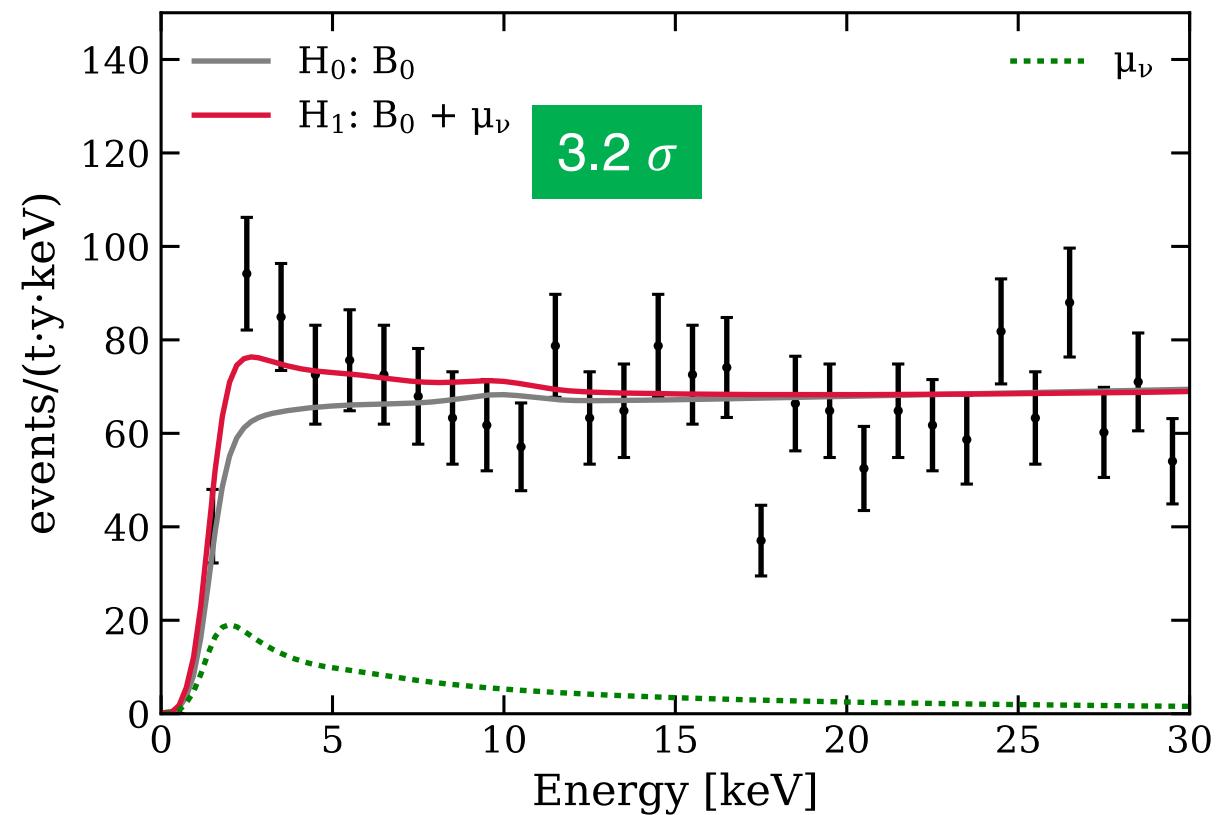
XENON1T resolution,
efficiency



Neutrino magnetic moment result

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

**In strong tension with
astrophysical constraints**



Additional checks on the three hypotheses

SR2

Threshold impact

S2-only

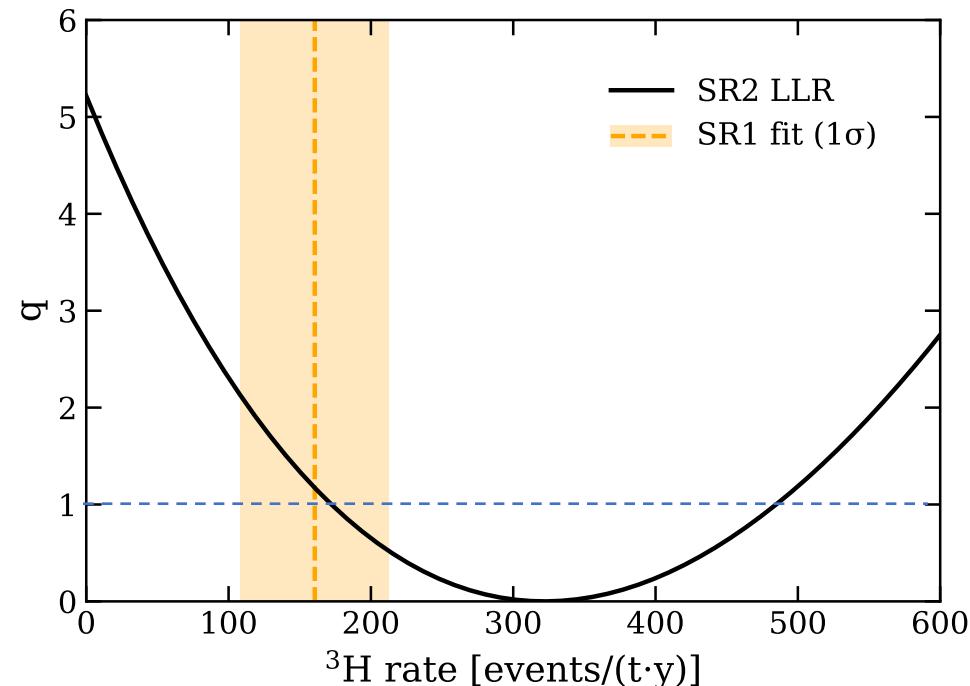
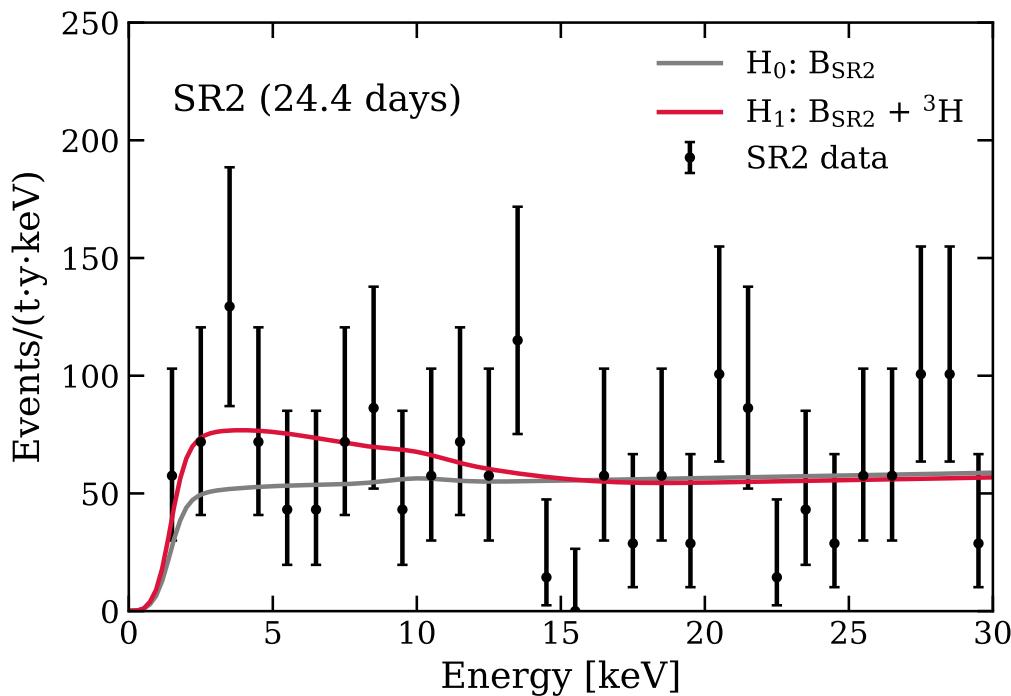
Additional data: Science Run 2 (SR2)

20% lower background

Improved purification

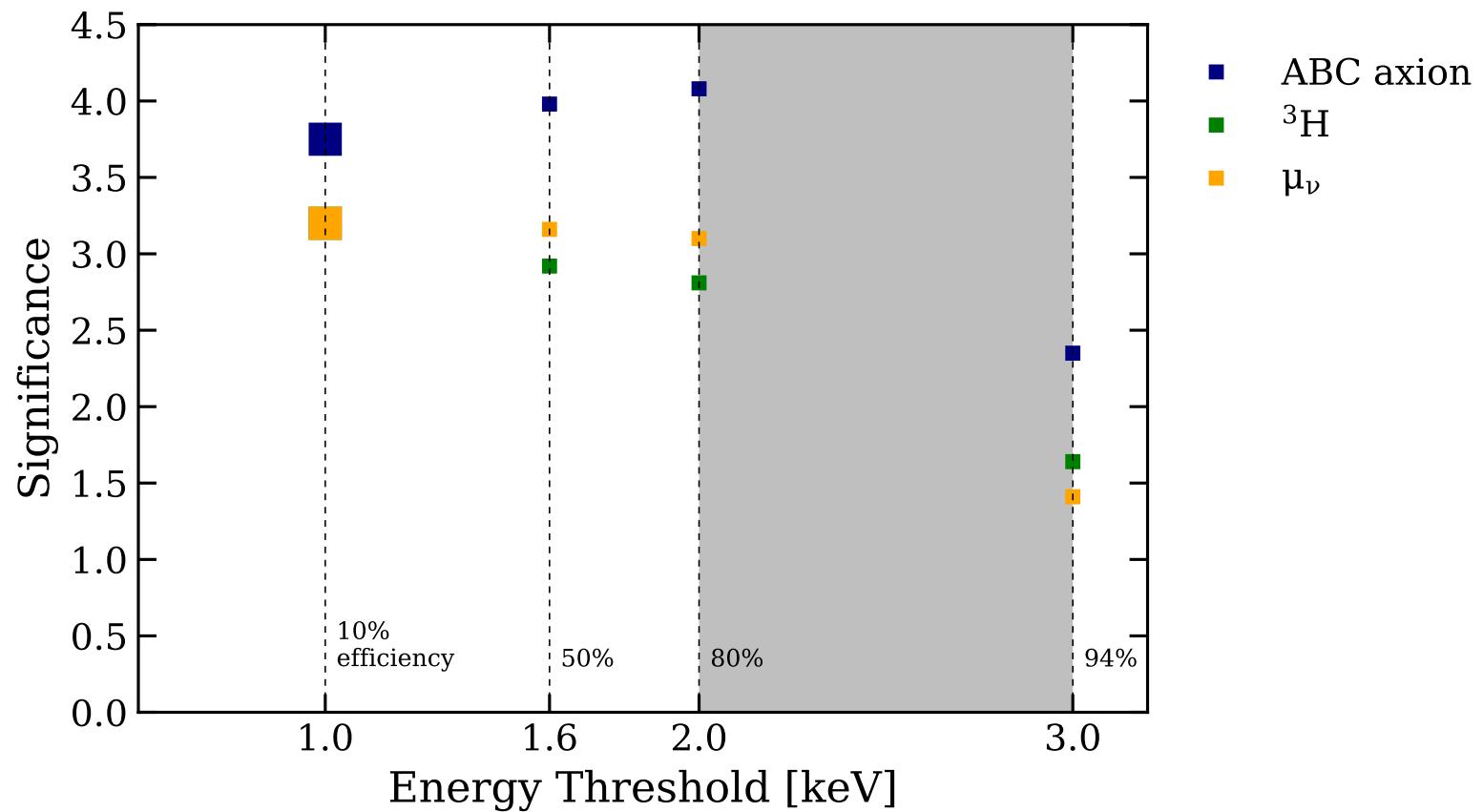
SR1: 159 ± 51 events/(t·y)
SR2: 320 ± 160 events/(t·y)

Fitted rate for tritium is
consistent with SR1



Threshold systematics

Increasing the energy threshold
does not change the result

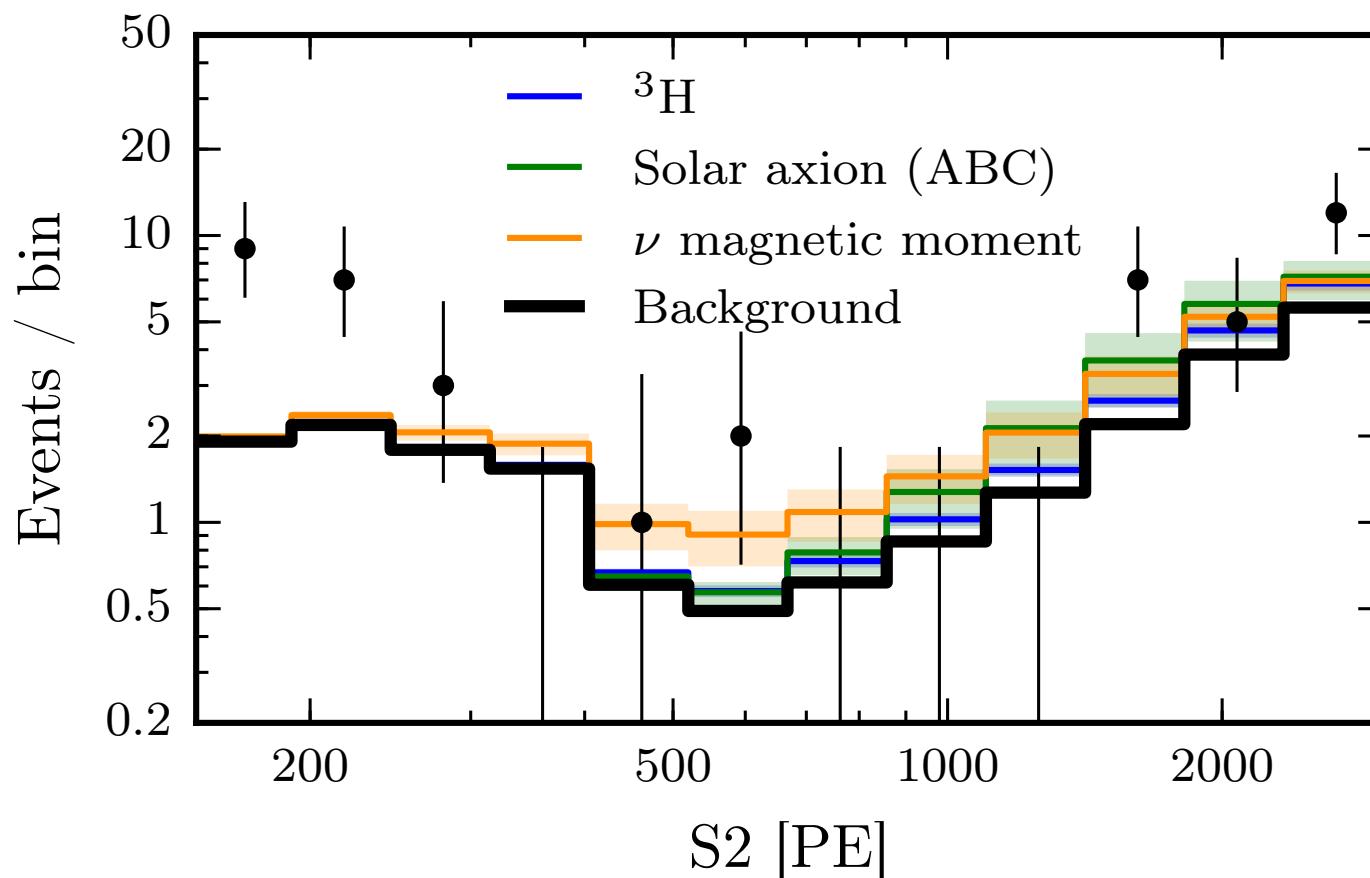


S2-only analysis

S2-only allows for a lower energy threshold

$\mu_\nu < 3.1 \times 10^{-11} \mu_B$
 $g_{ae} < 4.8 \times 10^{-12}$
 $R_{H_3} < 2256 \text{ events}/(t \cdot y)$

Consistent with all three hypotheses



Summary of three hypotheses

- Data is consistent with all three hypotheses
- We can neither exclude nor confirm tritium background
- Solar axion hypothesis is most favored by data
- Solar axion and neutrino magnetic moment results are in strong tension with astrophysical constraints
- Additional checks show similar results

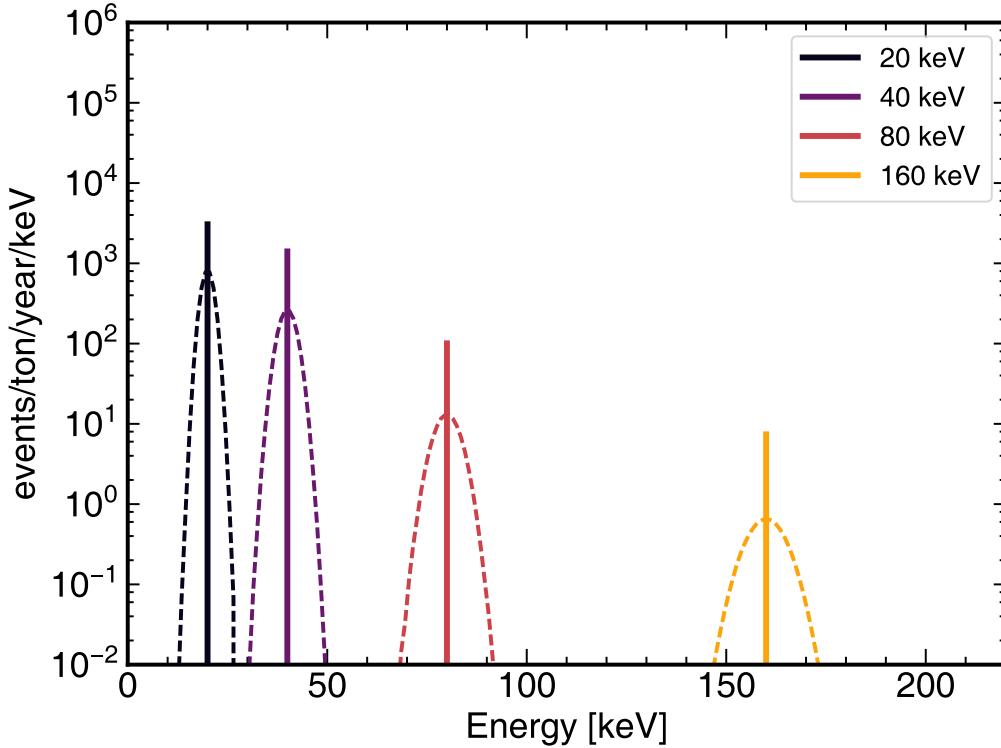
Solar axion
3.5 σ

${}^3\text{H}$
3.2 σ

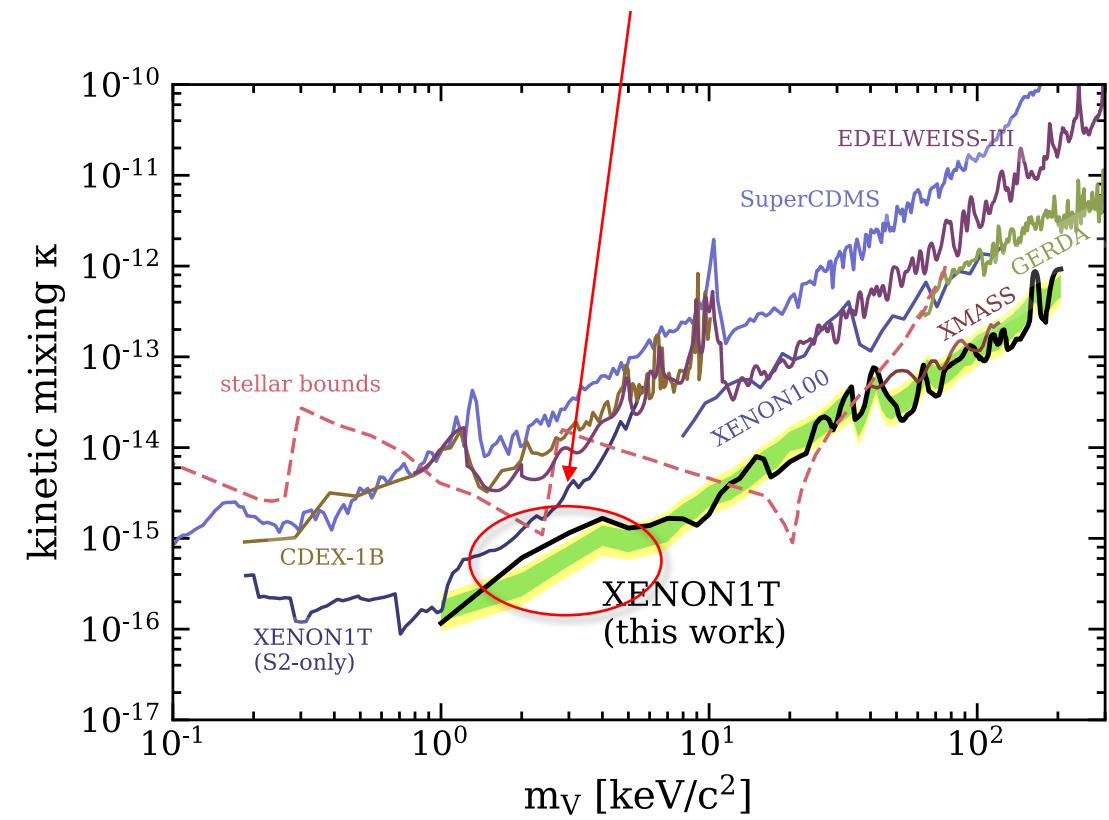
ν magnetic moment
3.2 σ

What else can be the excess?

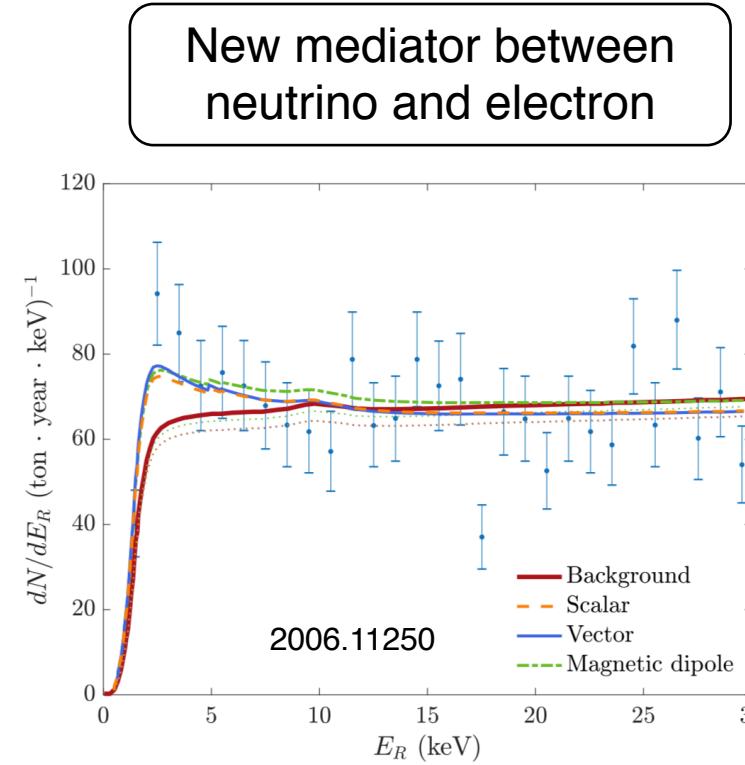
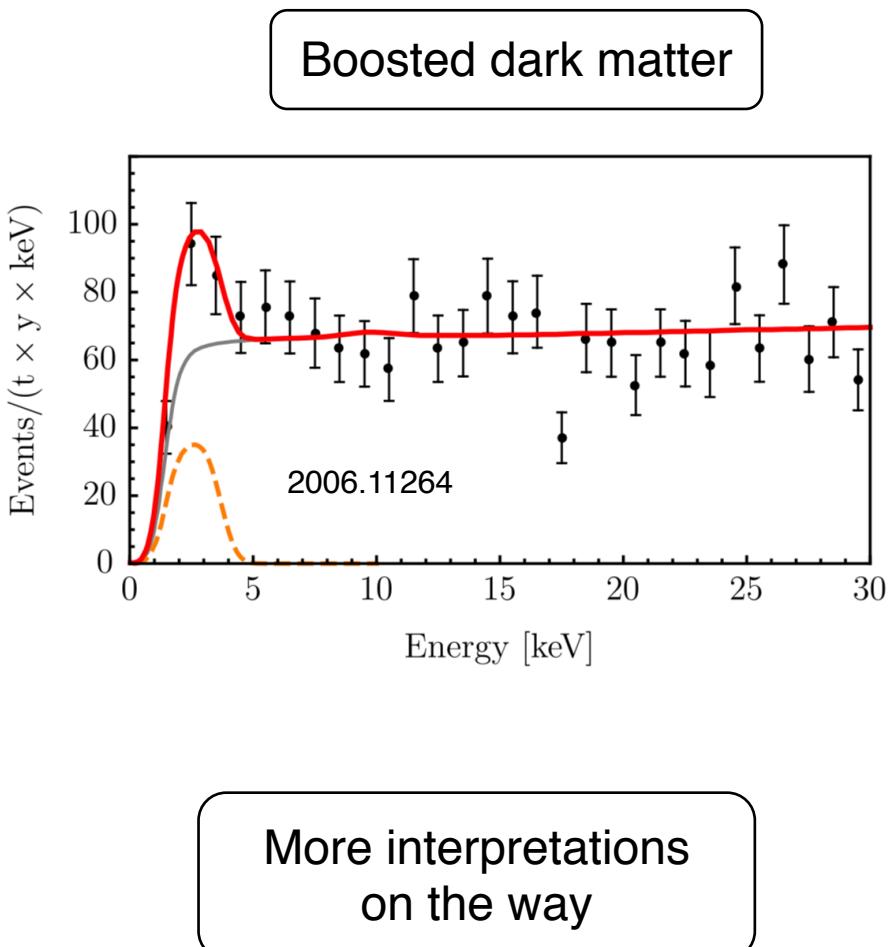
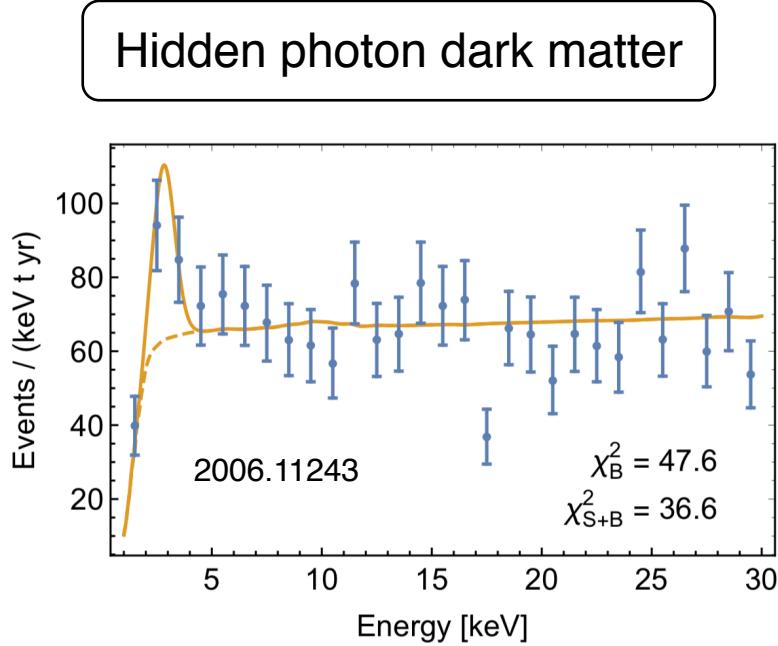
Bosonic dark matter like dark photon would generate mono-energetic peaks



low-mass
bosonic dark matter?

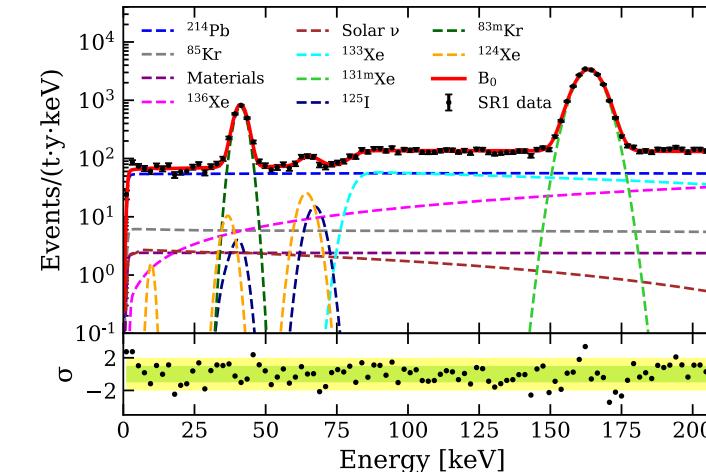
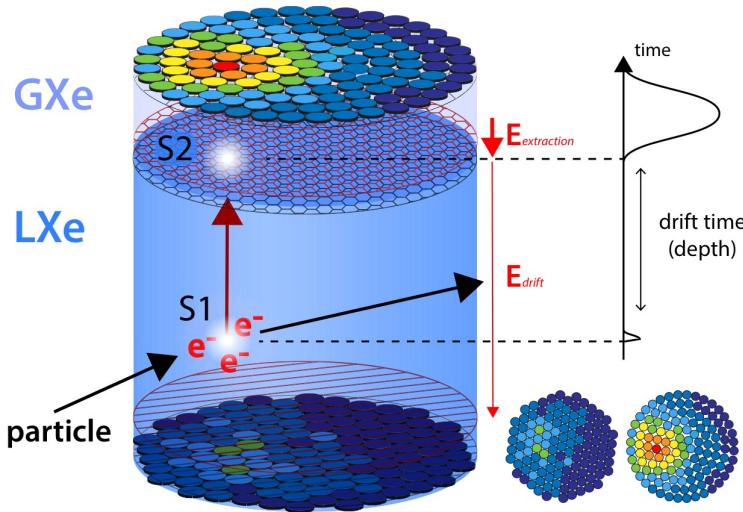


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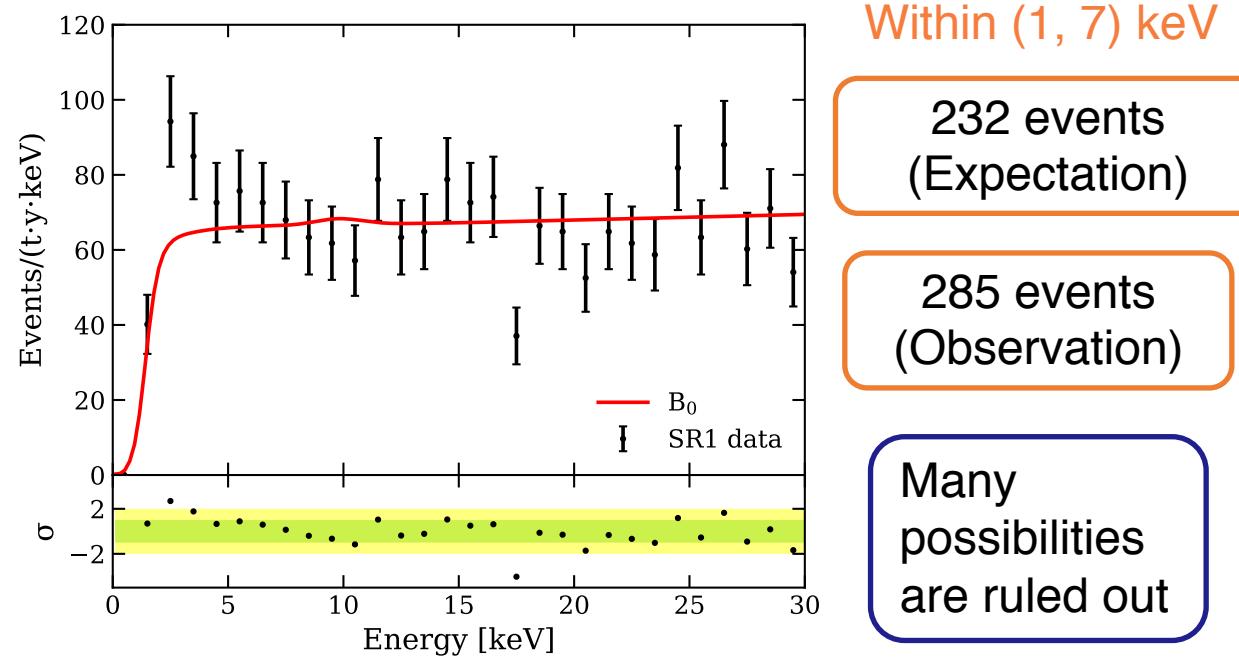


Two-phase Xenon TPC

- 3D position imaging + self-shielding
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 within $(1, 30)$ keV



Interpretations

- Solar axion**
 3.5σ
- ν magnetic moment**
 3.2σ
- ^3H**
 3.2σ
- Many others**

Outlook: XENONnT



x3

Active volume

1/6

Background



commissioning
ongoing

It will be interesting to see what
XENONnT and others find!

Freeman Dyson
(1923 - 2020)



Thank you.

“New directions in science are launched by new tools much more often than by new concepts. The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained.”

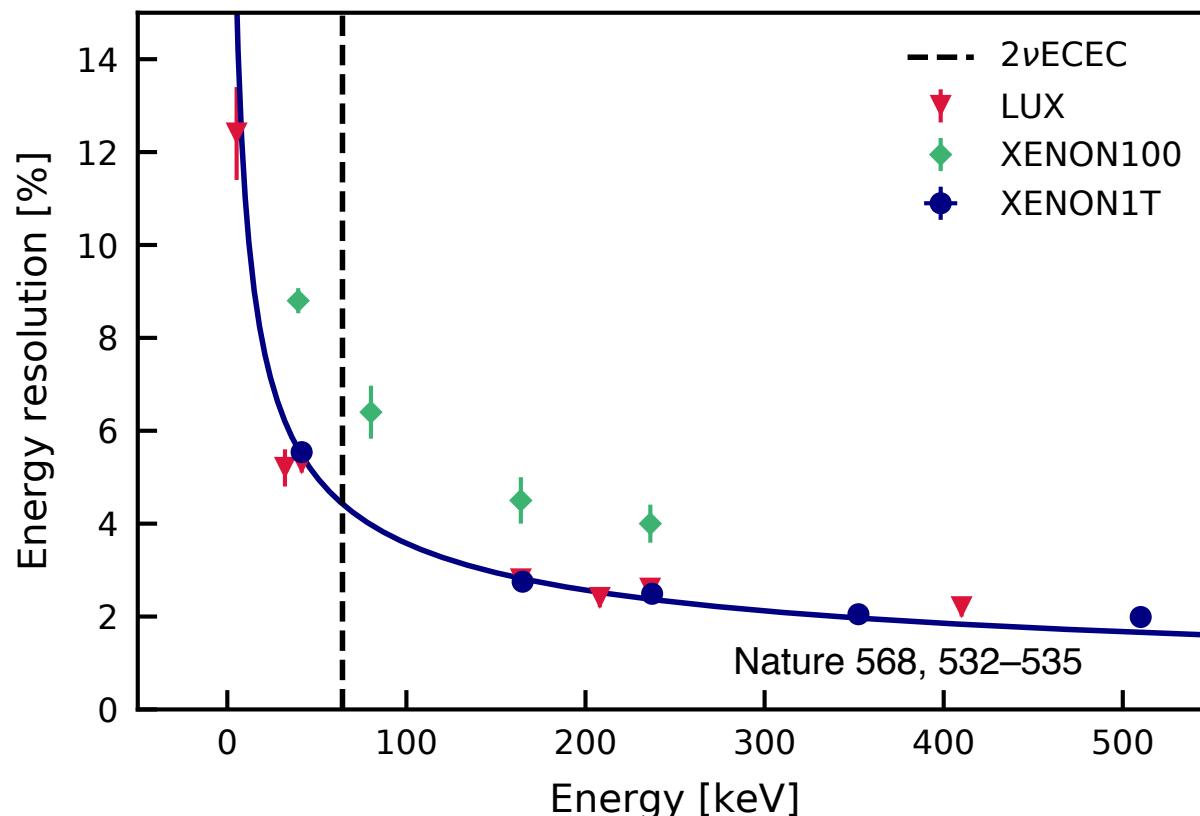
— Freeman Dyson

Back up

Energy resolution

Resolution fit with empirical function

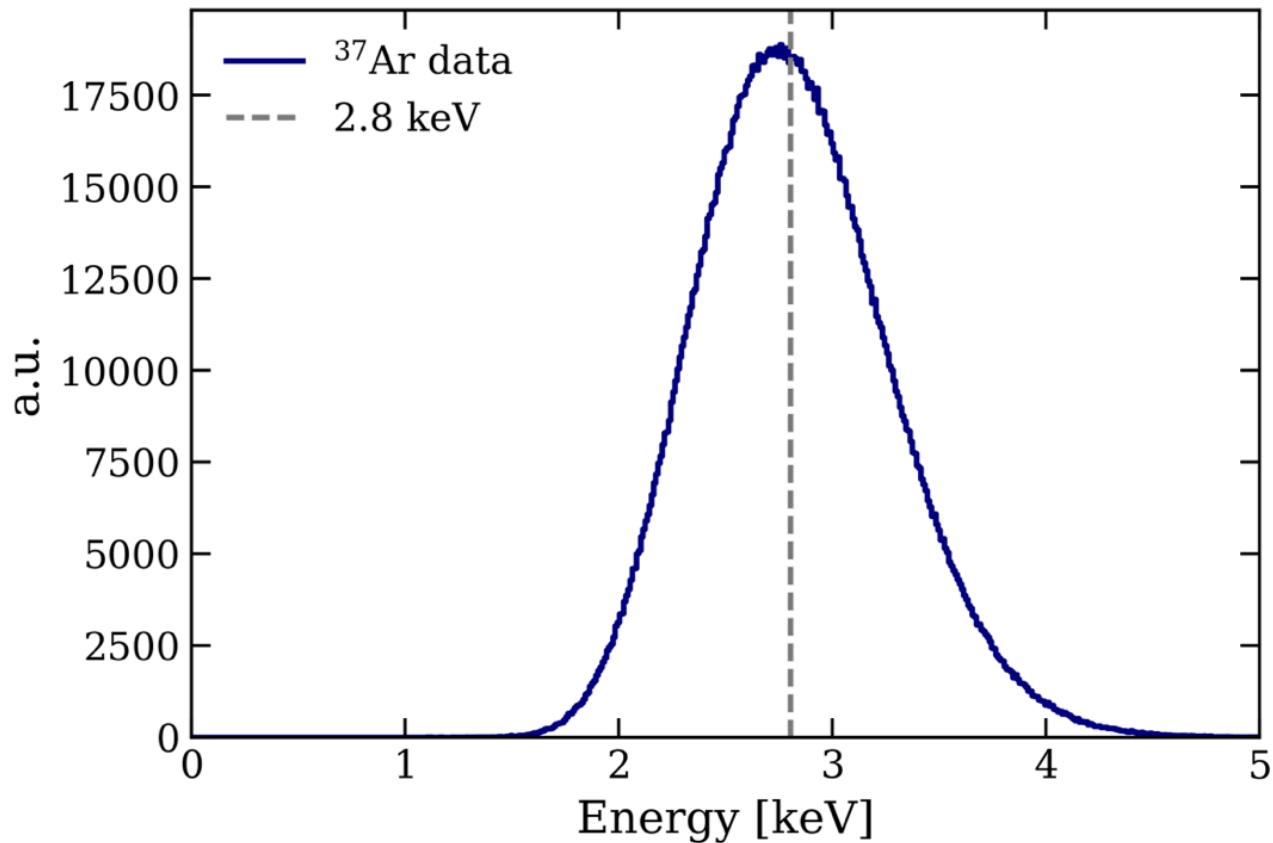
Verified to low energies with XENON1T's microphysics model



Energy reconstruction at low energy

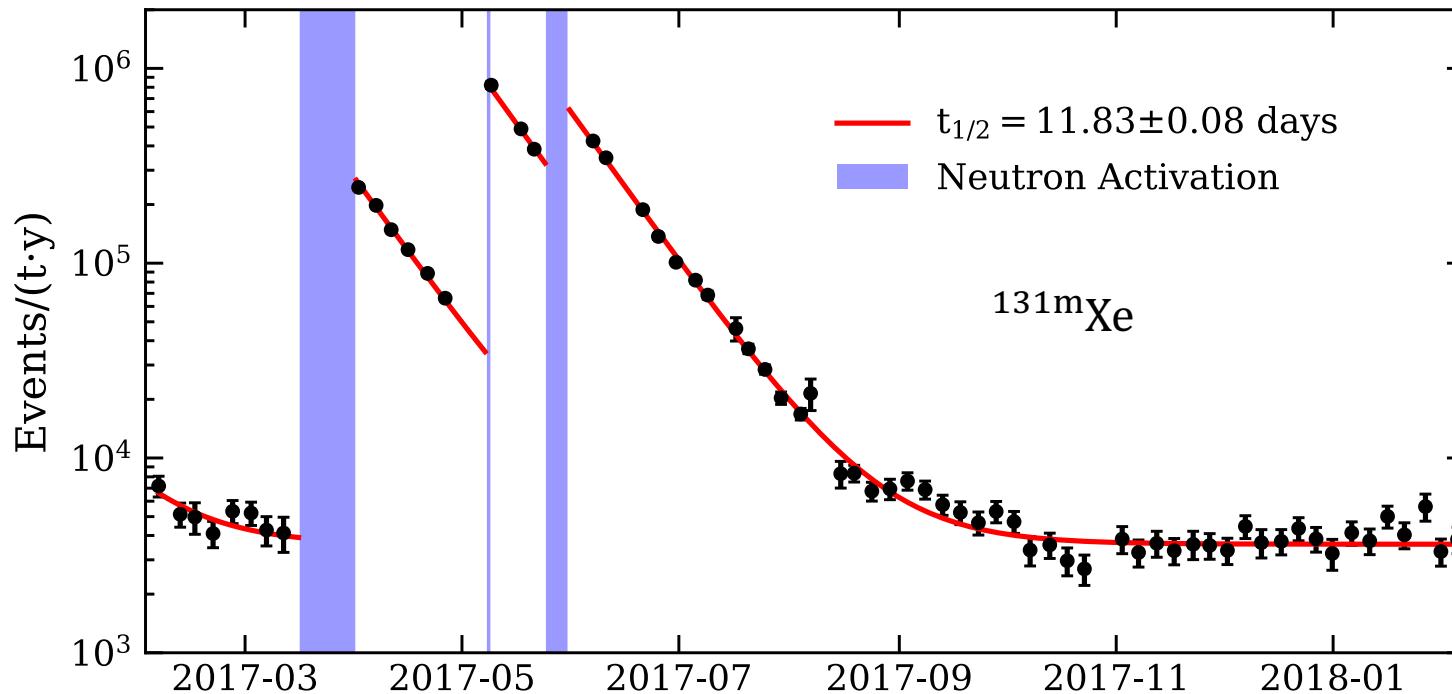
Validates energy reconstruction
down to 2.8 keV!

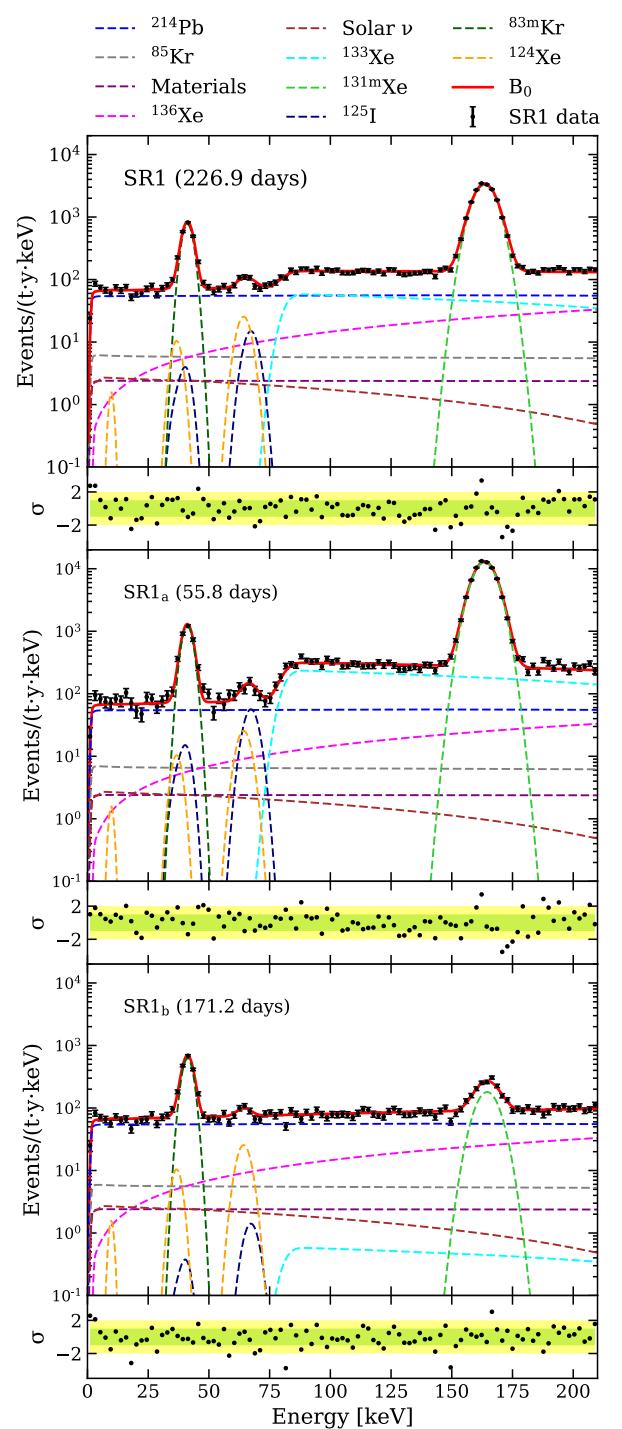
	Model	Observation
Mean [keV]	2.834	2.827
Resolution	18.88%	18.12%



Time-dependent backgrounds

Time-dependent backgrounds:
infer rate from time information





Partition result

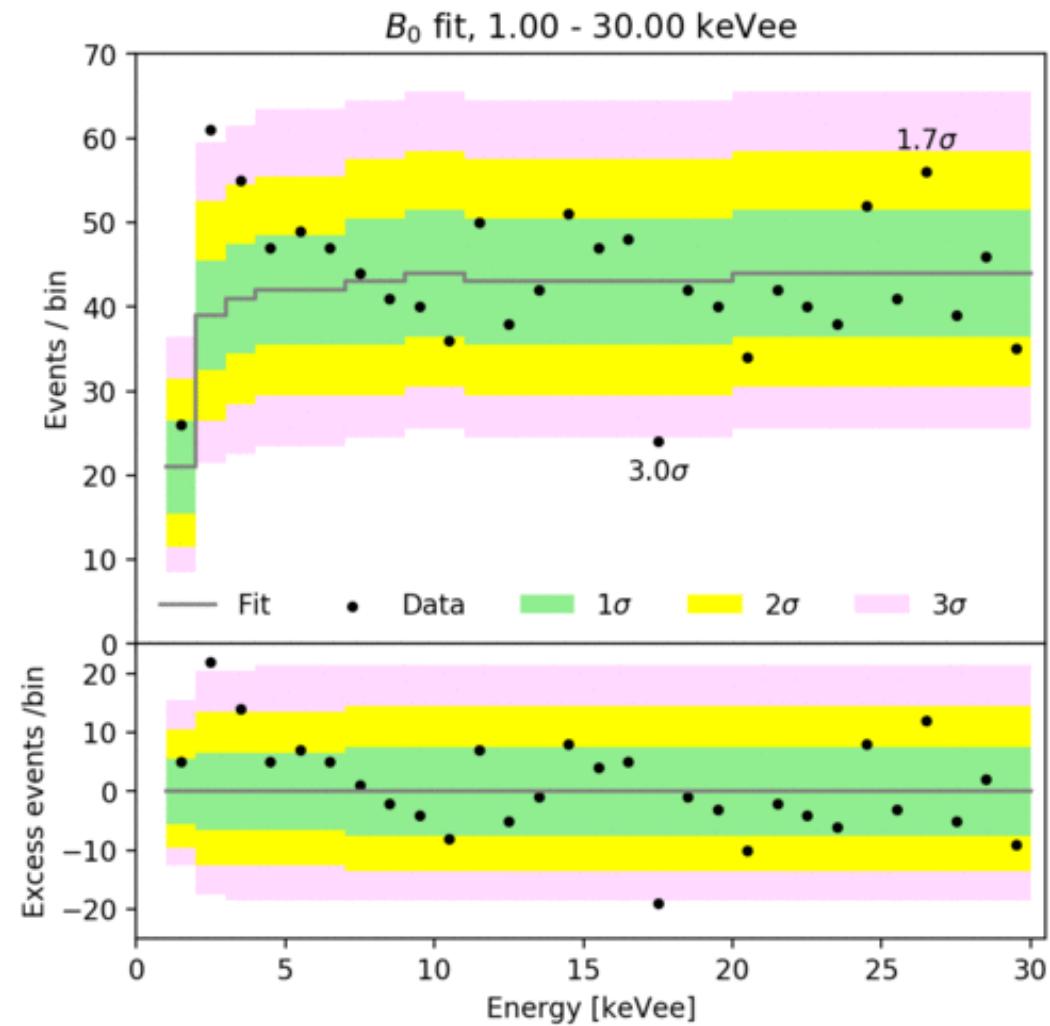
Component	Expected Events	Fitted Events	Constant in time? (shared across partitions)
^{214}Pb	(3450, 8530)	7480 +/- 160	YES
^{85}Kr	890 +/- 50	773 +/- 80	NO
^{136}Xe	2120 +/- 210	2150 +/- 120	YES
^{133}Xe	3900 +/- 410	4009 +/- 85	NO
^{131}Xe	23760 +/- 640	24270 +/- 150	NO
$^{83\text{m}}\text{Kr}$	2500 +/- 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	YES
	KL	38 +/- 15	YES
	LL	2.8 +/- 1.1	YES
^{125}I	K	79 +/- 33	NO
	L	15.3 +/- 6.5	NO
	M	3.4 +/- 1.5	NO

unconstrained in the fit

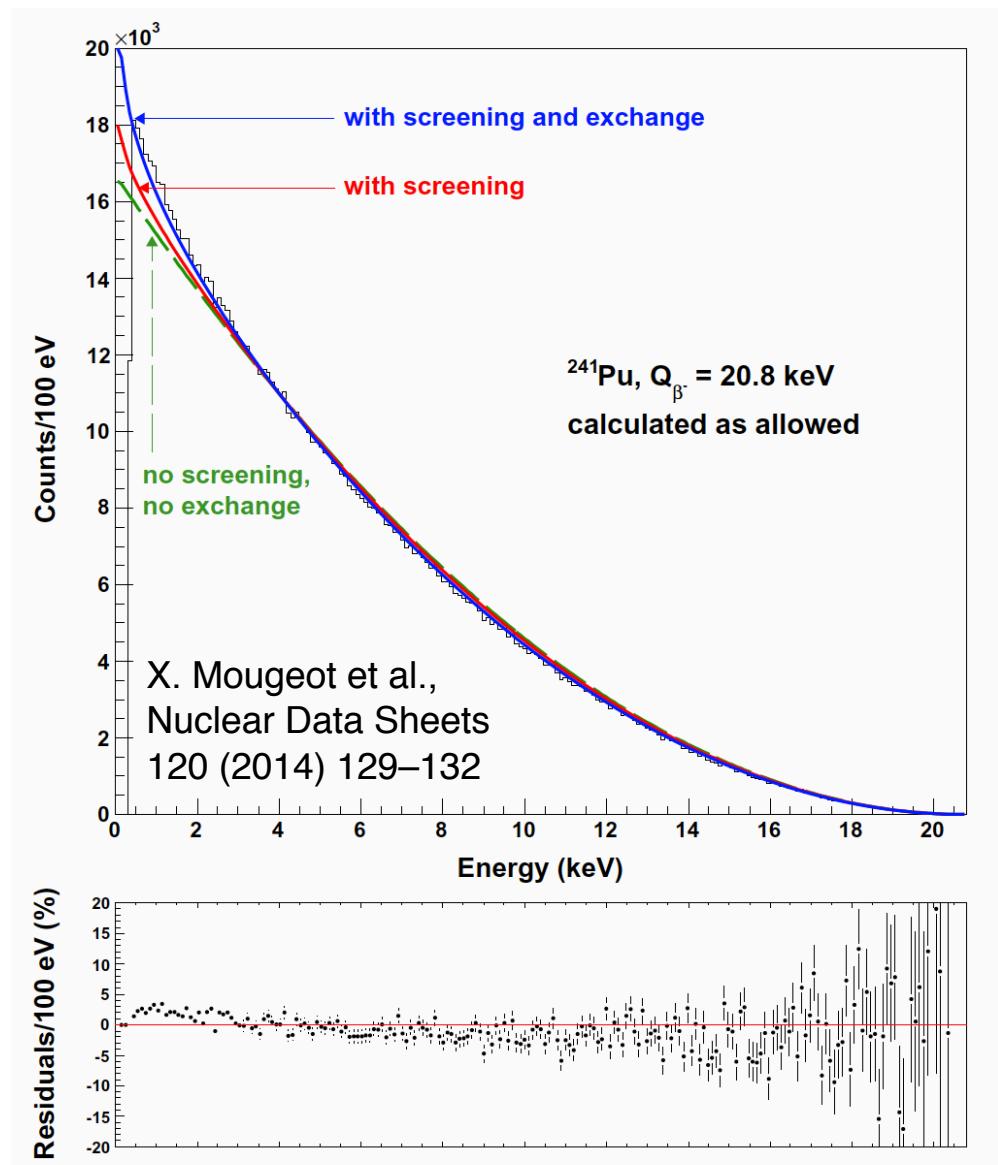
Dip at \sim 18 keV: binning effect

Change binning: fluctuates between 1.5σ and 3.4σ

Global significance: 2.3σ



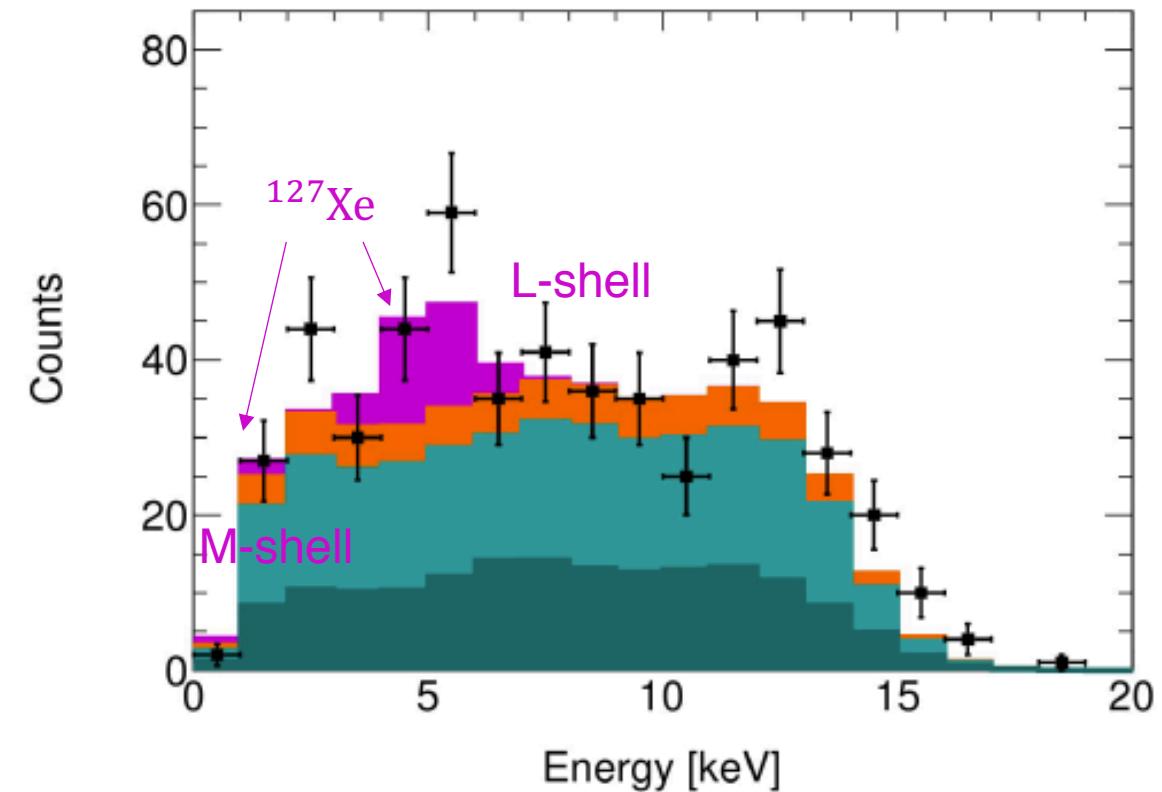
Beta spectrum shape calculation



Pu241: first-forbidden
non-unique transition

^{127}Xe background

- ^{127}Xe is produced from cosmogenic activation and has a short half-life of 36.4 days
- Xenon gas used in XENON1T was underground for 0(years)



Ar37 background

Initially in the xenon gas?

- Effective removal constant of 1.8 days during cryogenic distillation
- 90-day distillation during commissioning before taking science data

Constant leak from air?

- Requires a leak of ~ 6 L/ day and increase ^{nat}Kr by ~20 ppt
- ^{nat}Kr concentration in SR1 is 0.3 – 0.6 ppt from measurement

Solar axions

QCD axion: naturally raised in Peccei-Quinn theory to solve the strong CP problem

Axions would be produced in the Sun with energies \sim keV

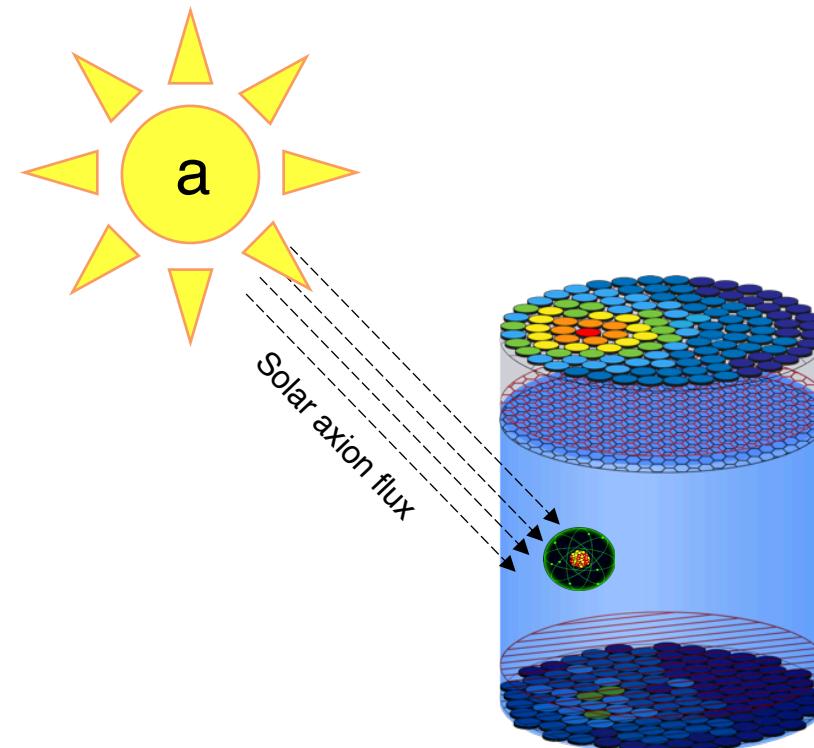
Axions would be absorbed by xenon atoms and deposit the same amount of energy

*CP Conservation in the Presence of Pseudoparticles**

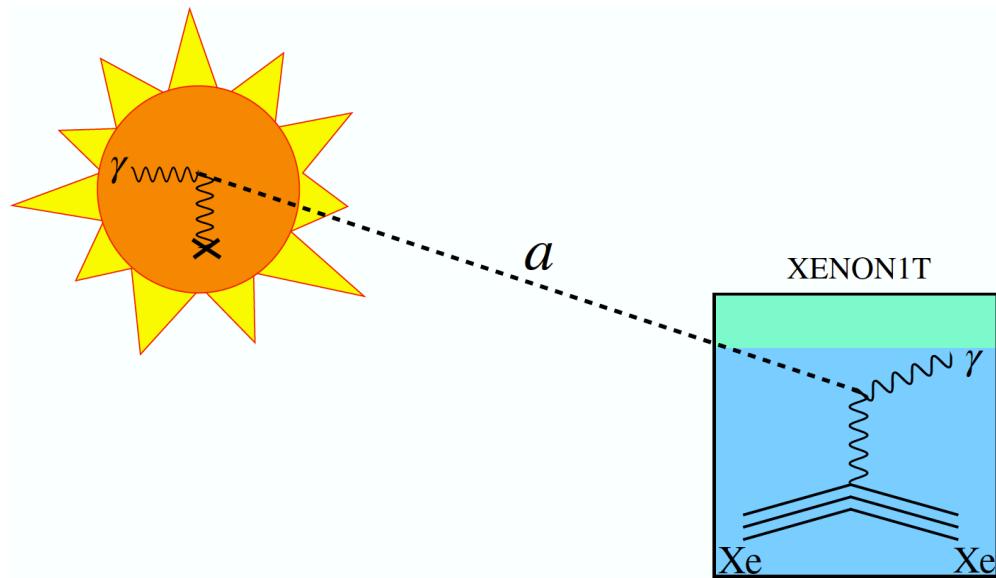
R. D. Peccei and Helen R. Quinn†

Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305
(Received 31 March 1977)

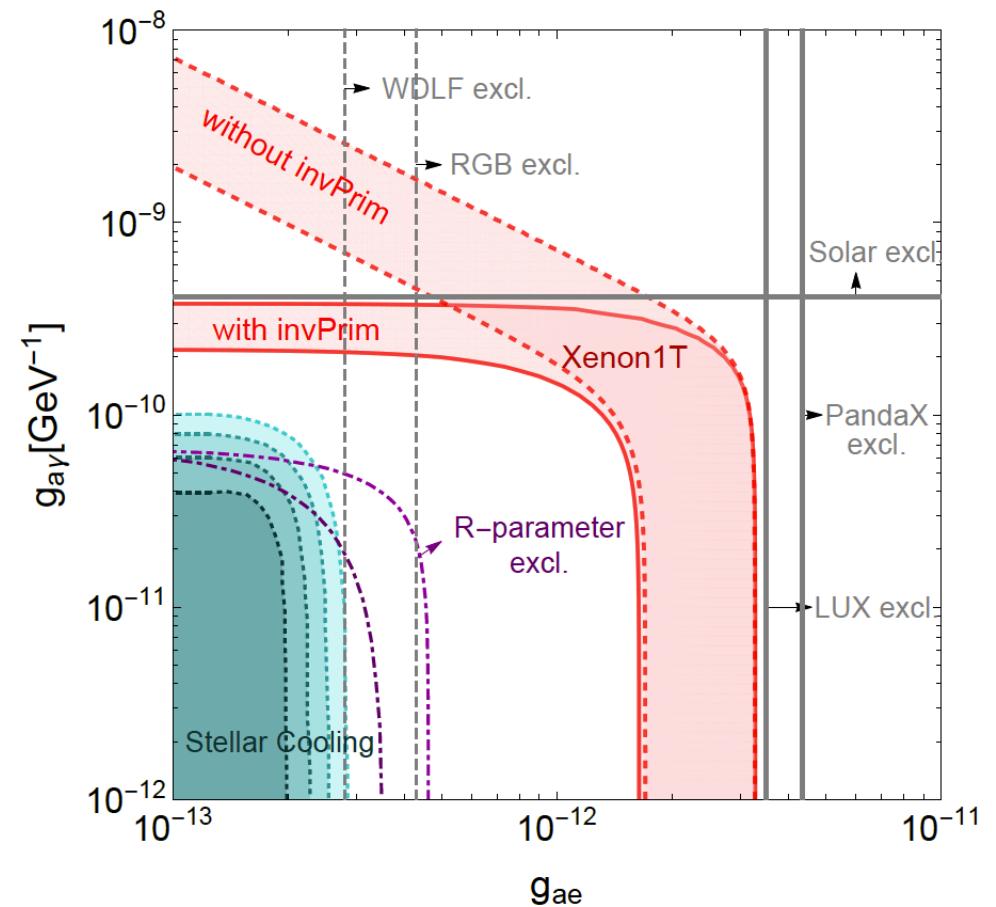
We give an explanation of the *CP* conservation of strong interactions which includes the effects of pseudoparticles. We find it is a natural result for any theory where at least one flavor of fermion acquires its mass through a Yukawa coupling to a scalar field which has nonvanishing vacuum expectation value.



Inverse Primakoff effect



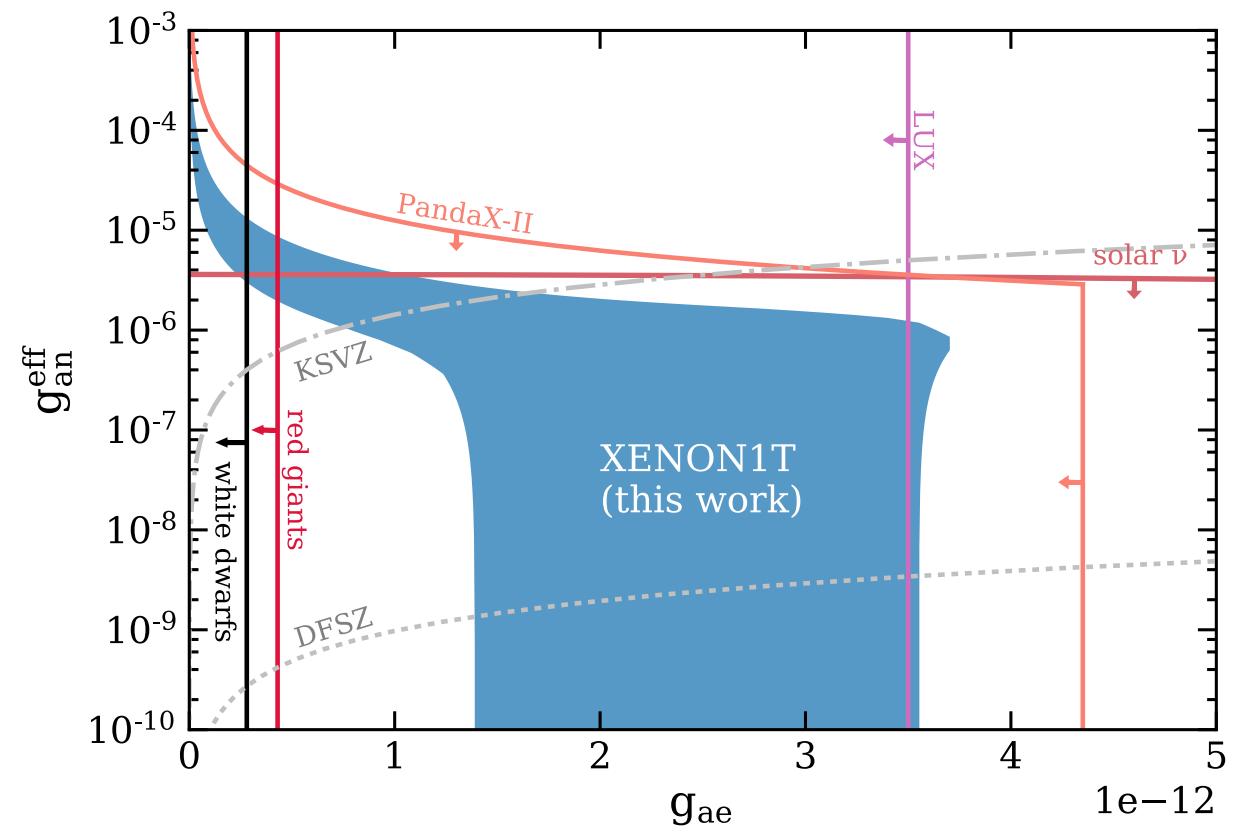
Additional detection channel:
inverse Primakoff effect



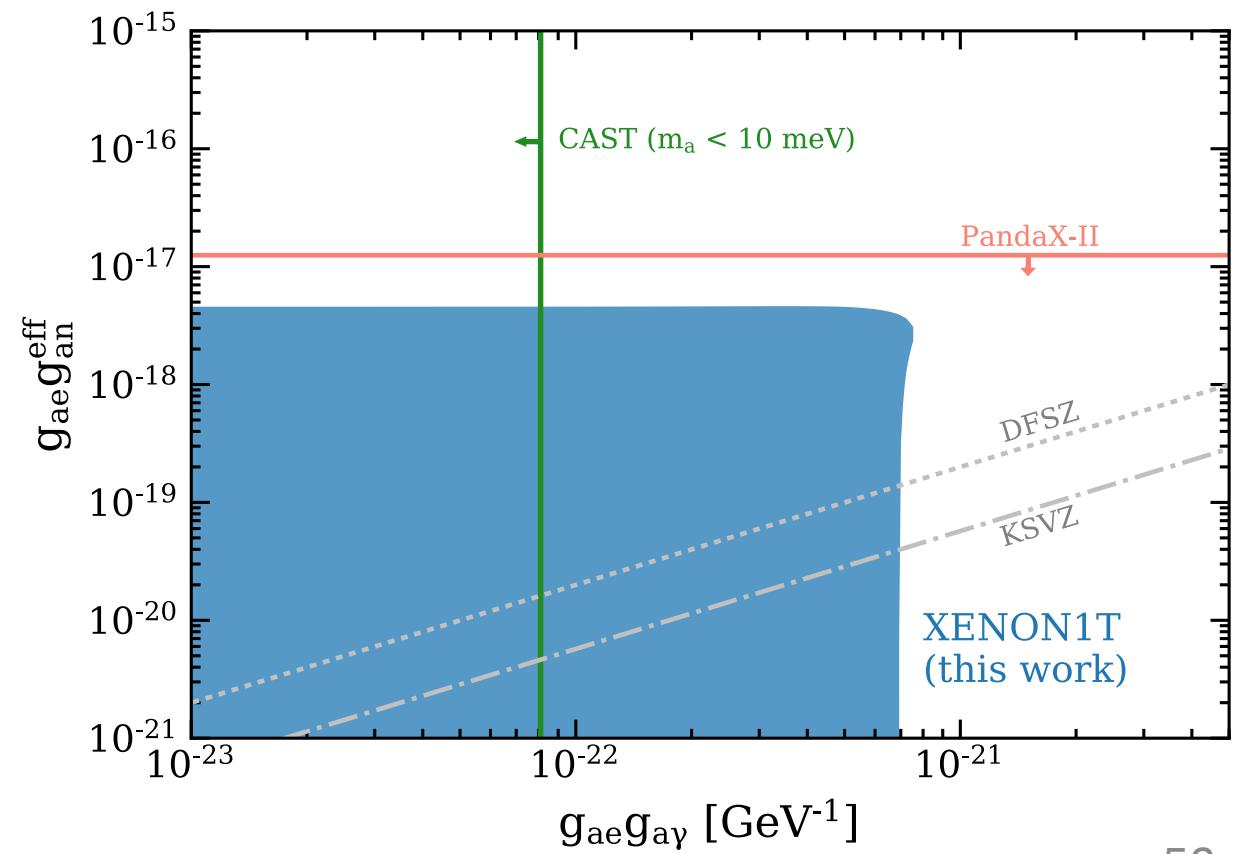
Tension with astrophysical
constraints is alleviated

Axion couplings

g_{an}^{eff} vs. g_{ae}



g_{an}^{eff} vs. $g_{a\gamma}$



Axion mass

DFSZ

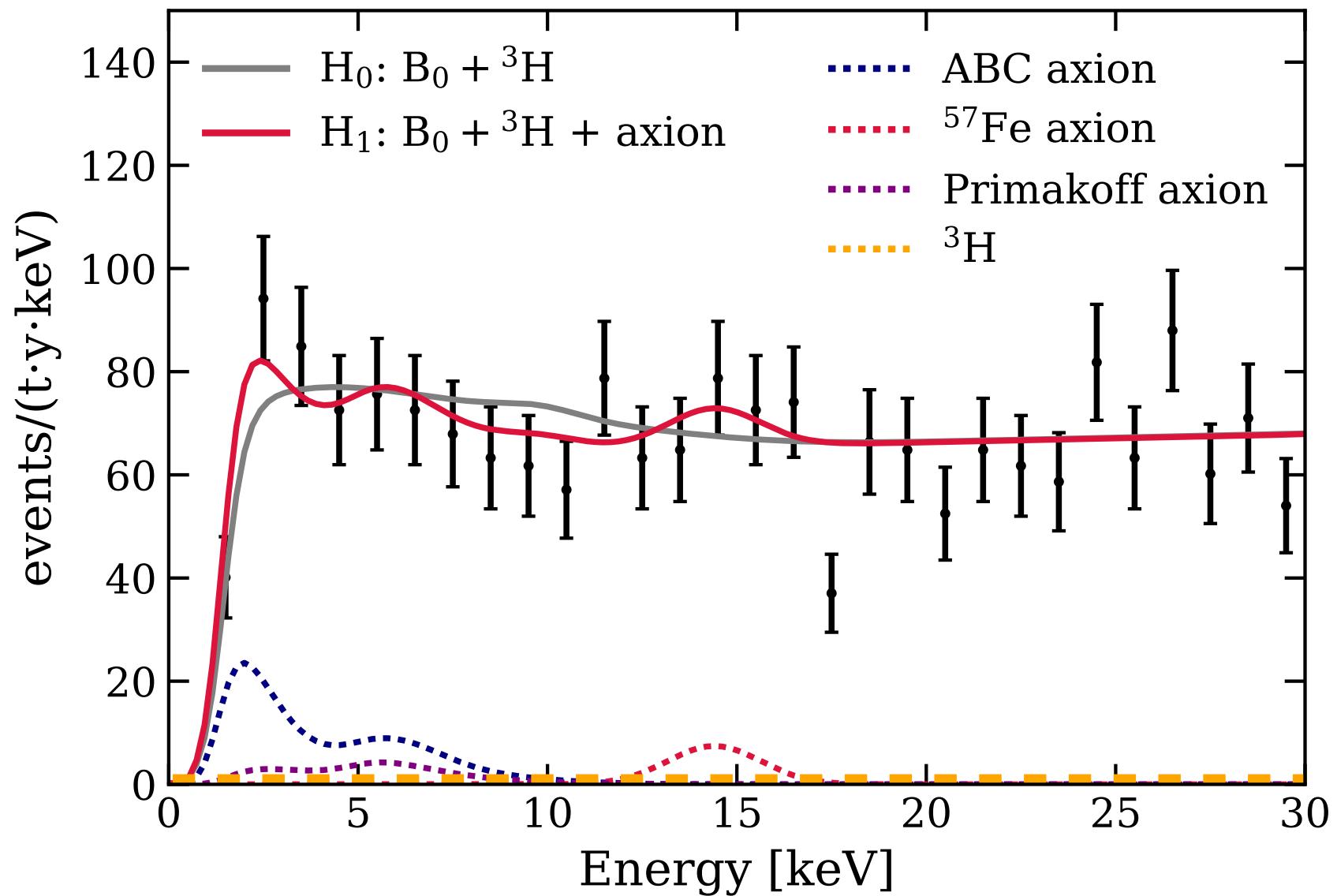
$$m_a \in (0.1, 4) \text{ eV/c}^2$$

KSVZ

$$m_a \in (46, 56) \text{ eV/c}^2$$

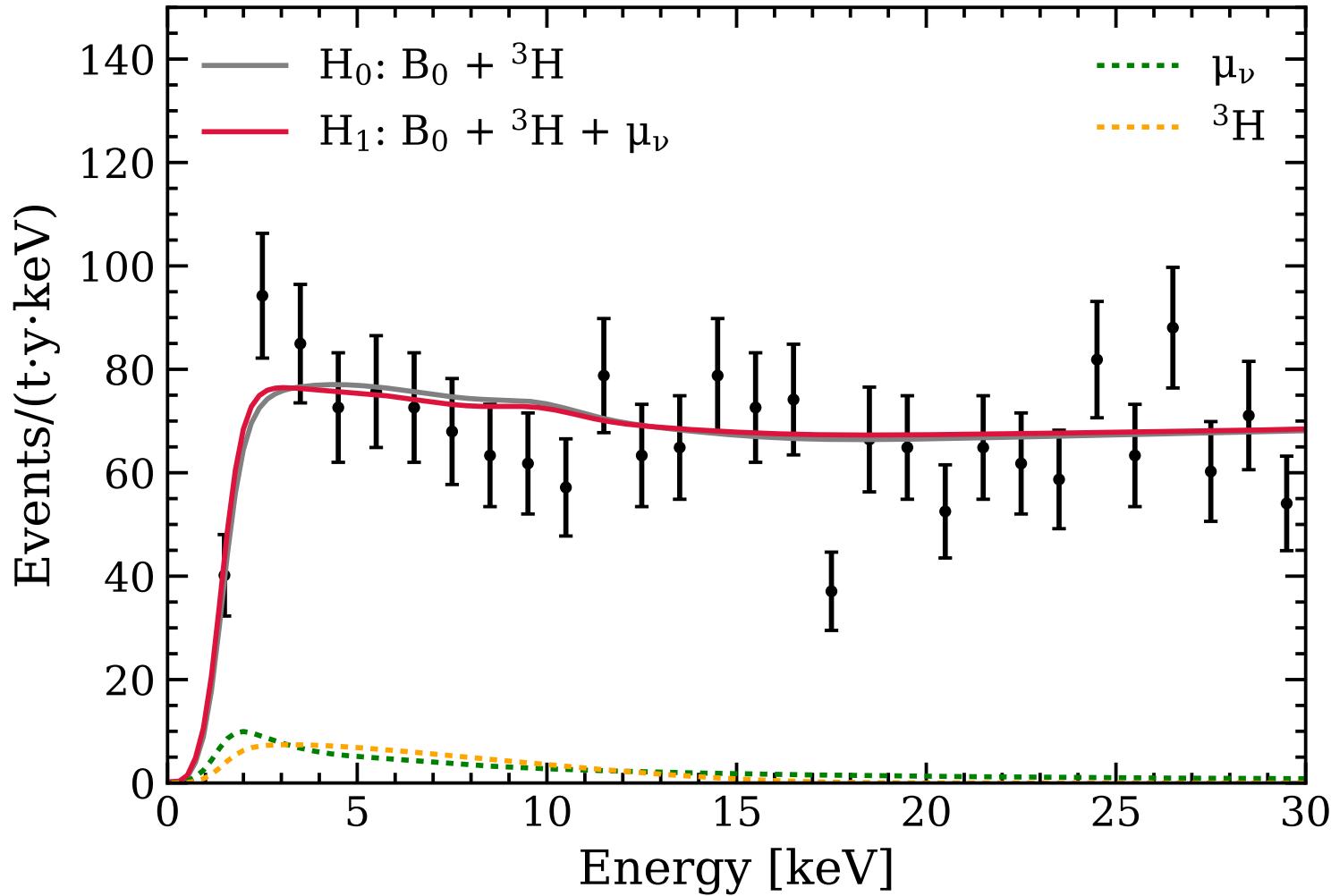
$$E = 6$$

Axion + ${}^3\text{H}$ favored over ${}^3\text{H}$: 2.1σ



NMM + ${}^3\text{H}$ favored over ${}^3\text{H}$: 0.9σ

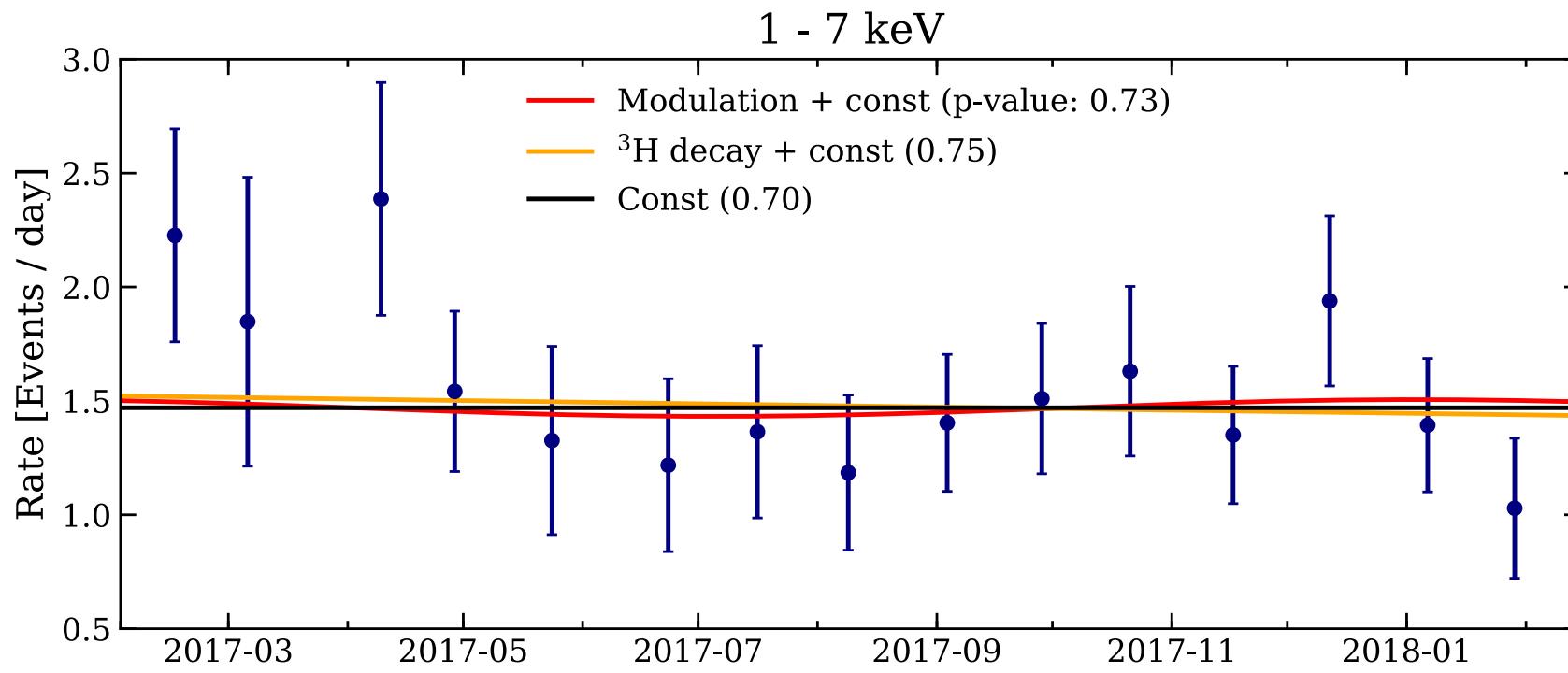
Neutrino magnetic moment vs tritium background



Time dependence w/ specific model

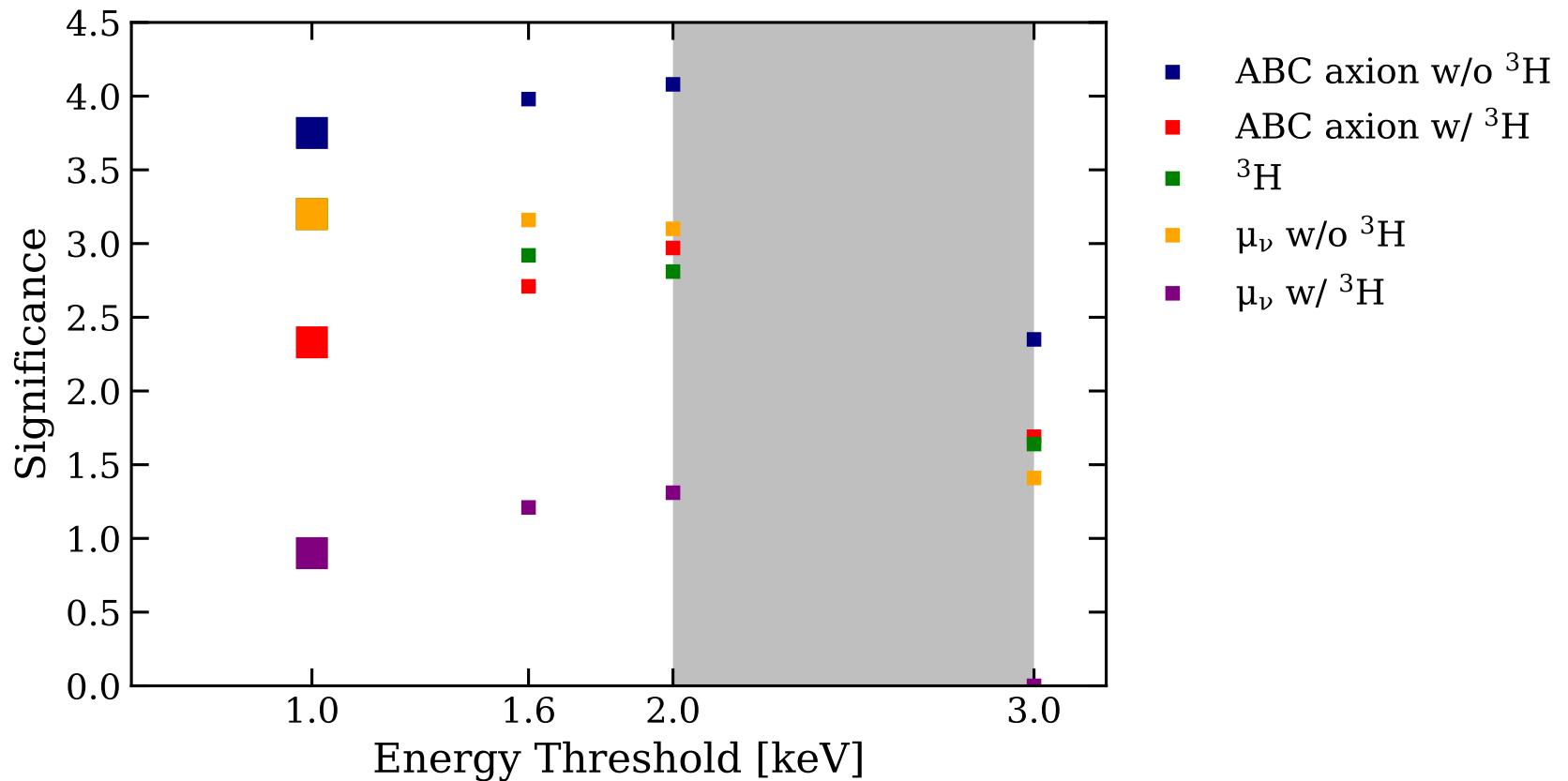
Time dependence consistent with all three:

- Constant in time
- “solar” modulation signal
- Tritium decay

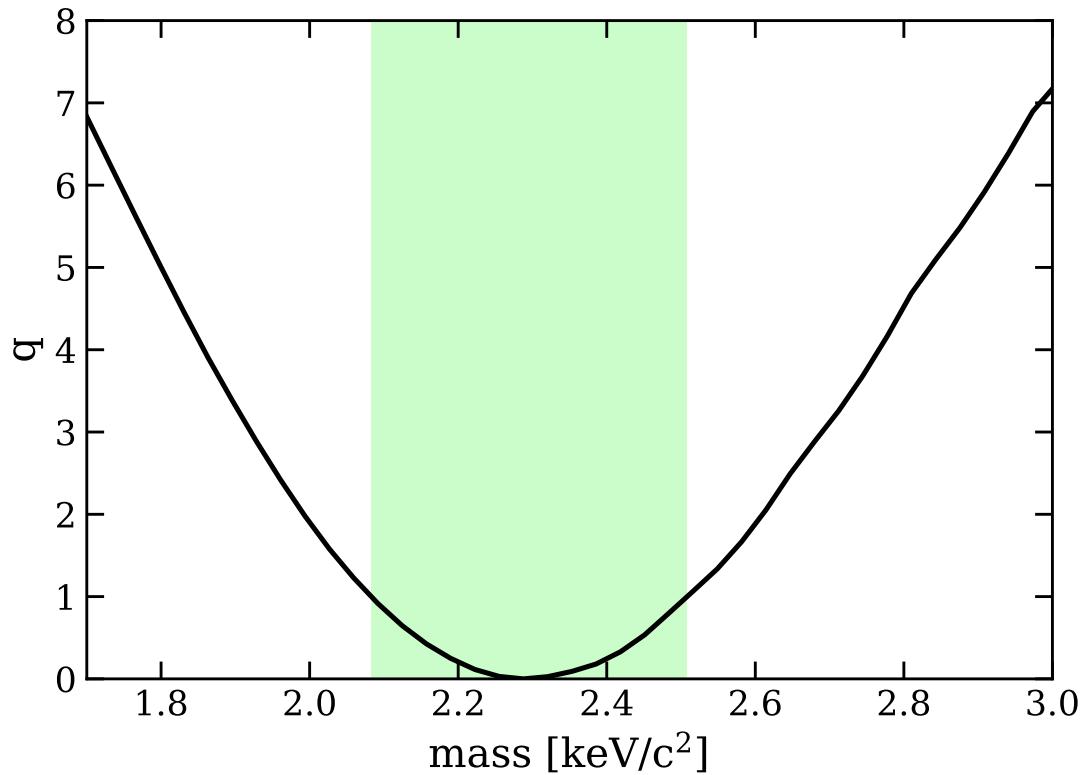


Threshold impact

Increasing the energy threshold
does not change the result

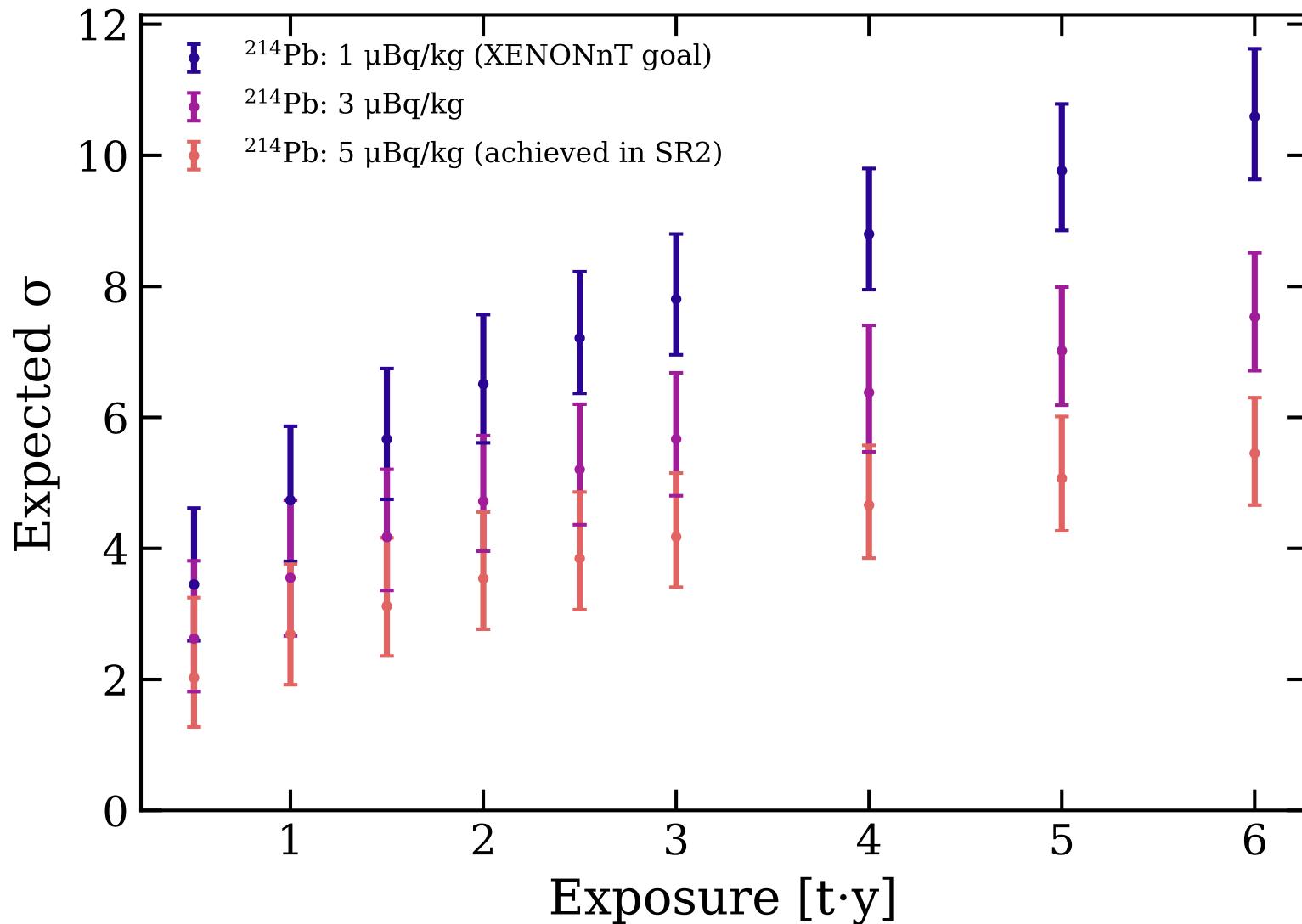


Bosonic Dark Matter (peak search)



Best-fit: $(2.3 \pm 0.2) \text{ keV}$

Discrimination in nT



Effect of tritium on WIMP search

If excess is from tritium, would expect a
~25% hit to WIMP sensitivity (depending
on concentration)

