Search for New Physics in Electronic Recoil Data from XENONnT

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On behalf of the XENON Collaboration

CIPANP 2022, Lake Buena Vista, FL
Aug. 30, 2022

arXiv: 2207.11330

XENON Collaboration: ~170 Scientists

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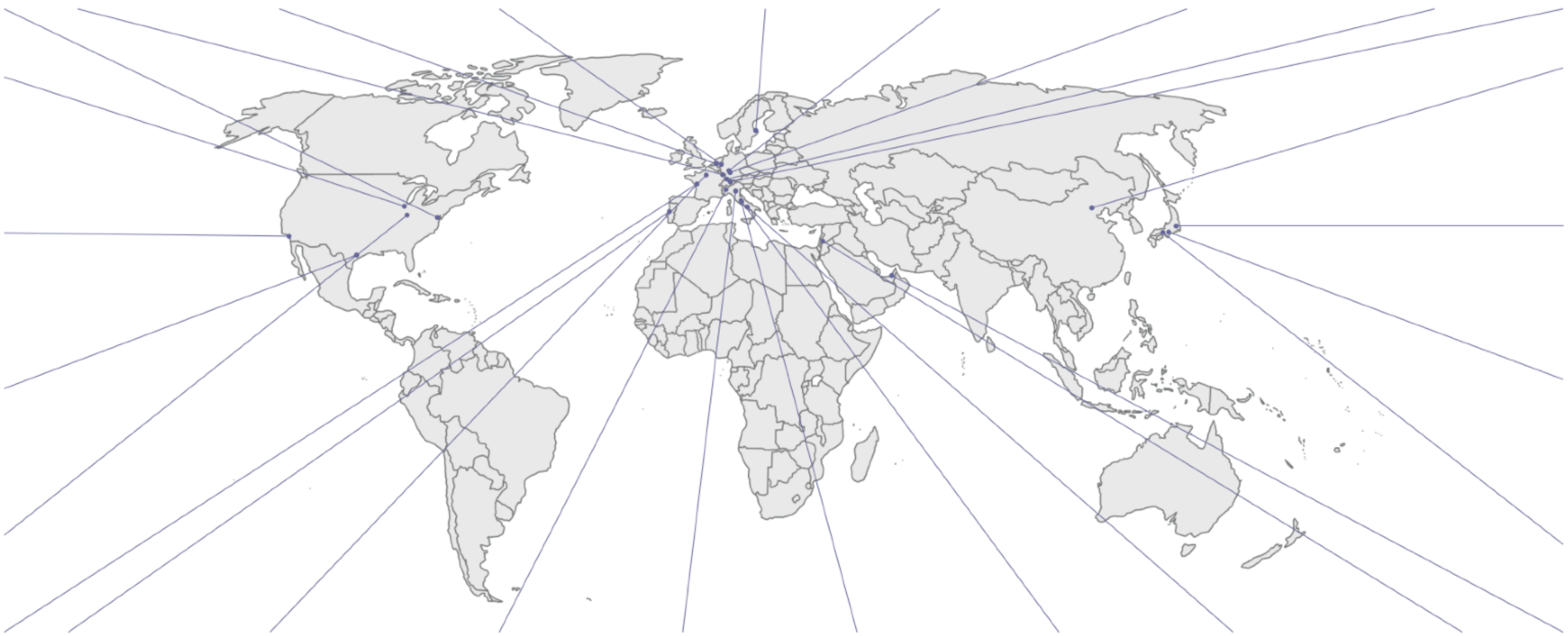

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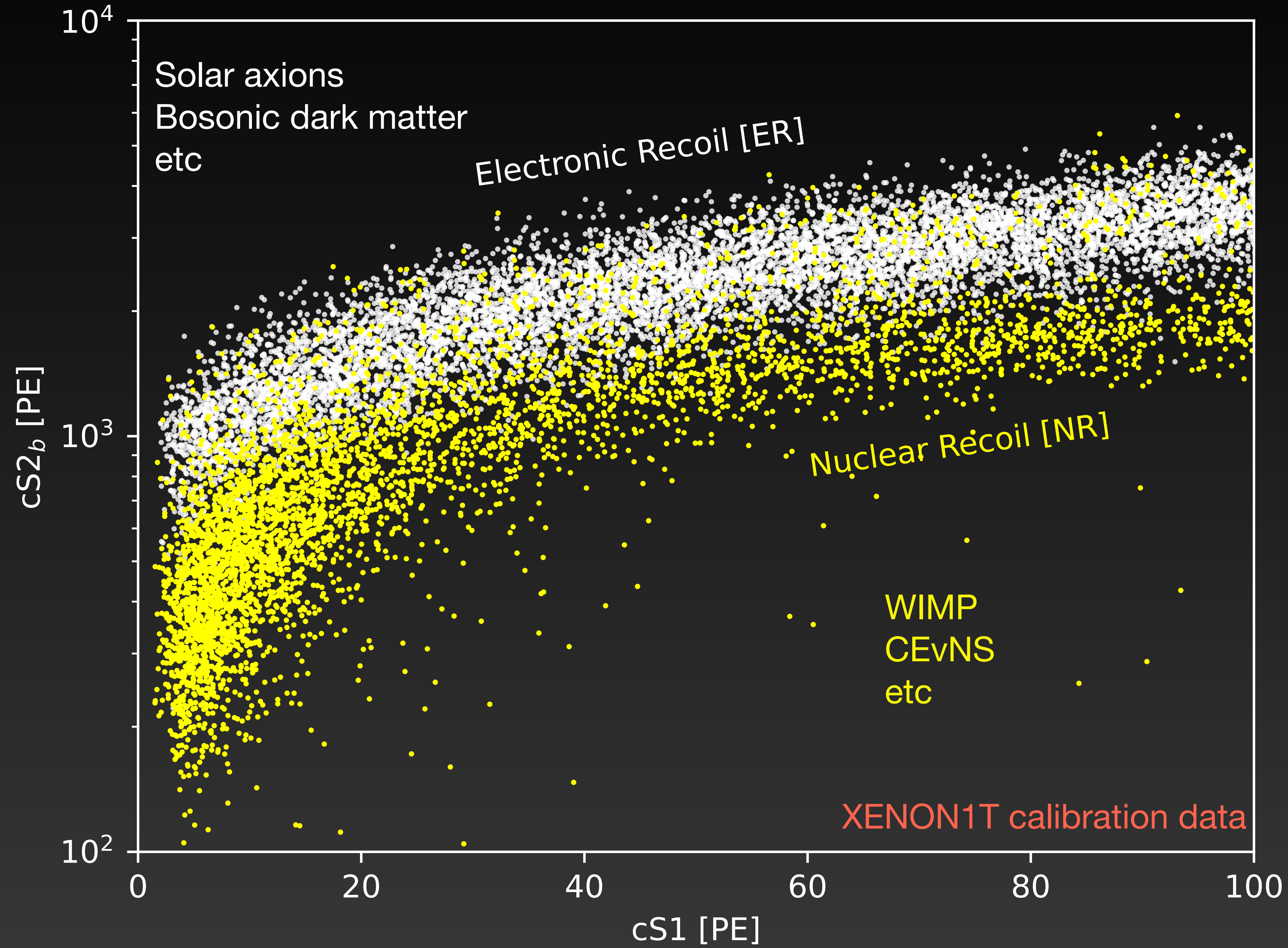
XENON Collaboration: ~170 Scientists

XENON Collaboration Meeting, July 2022, Torino

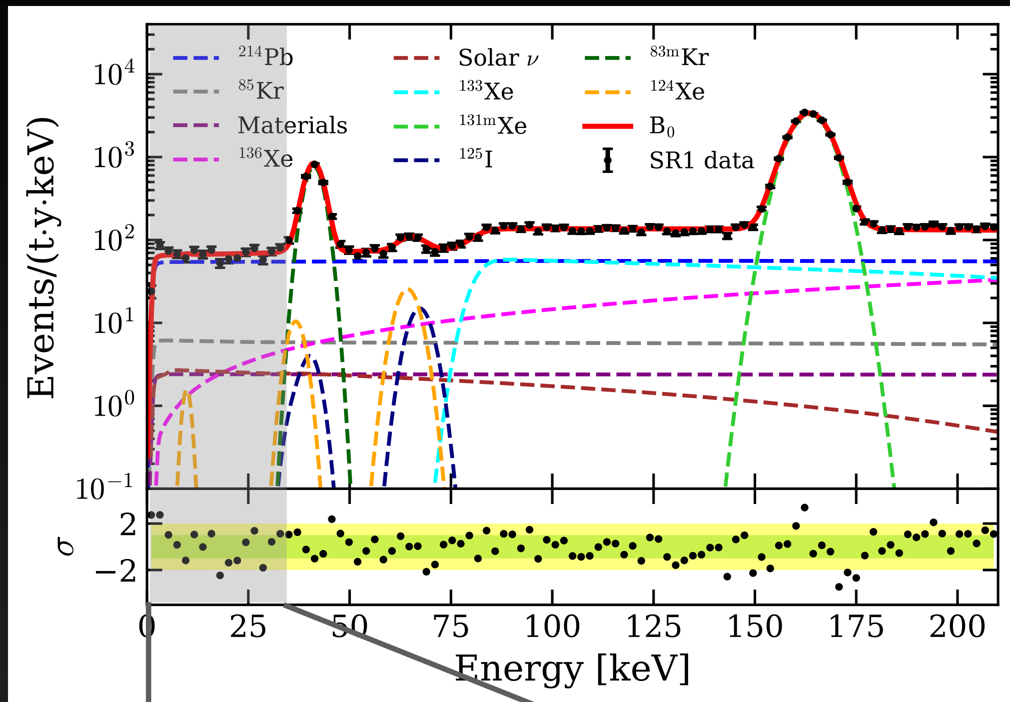
Search for ER Signals

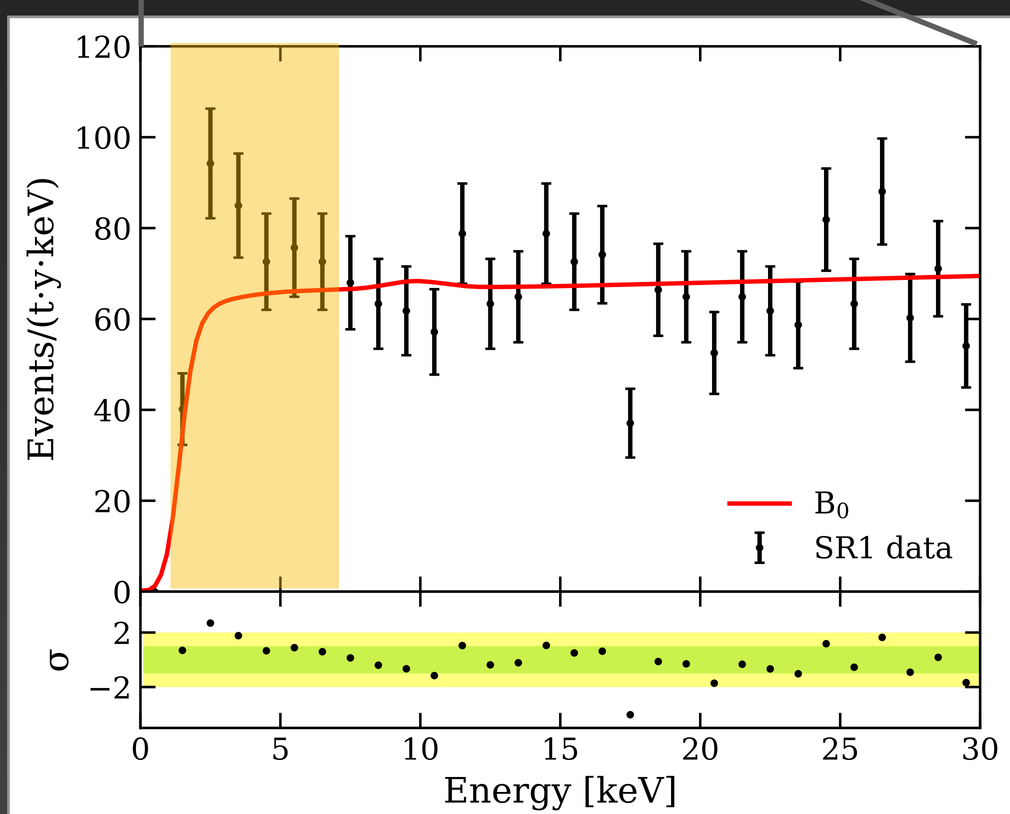


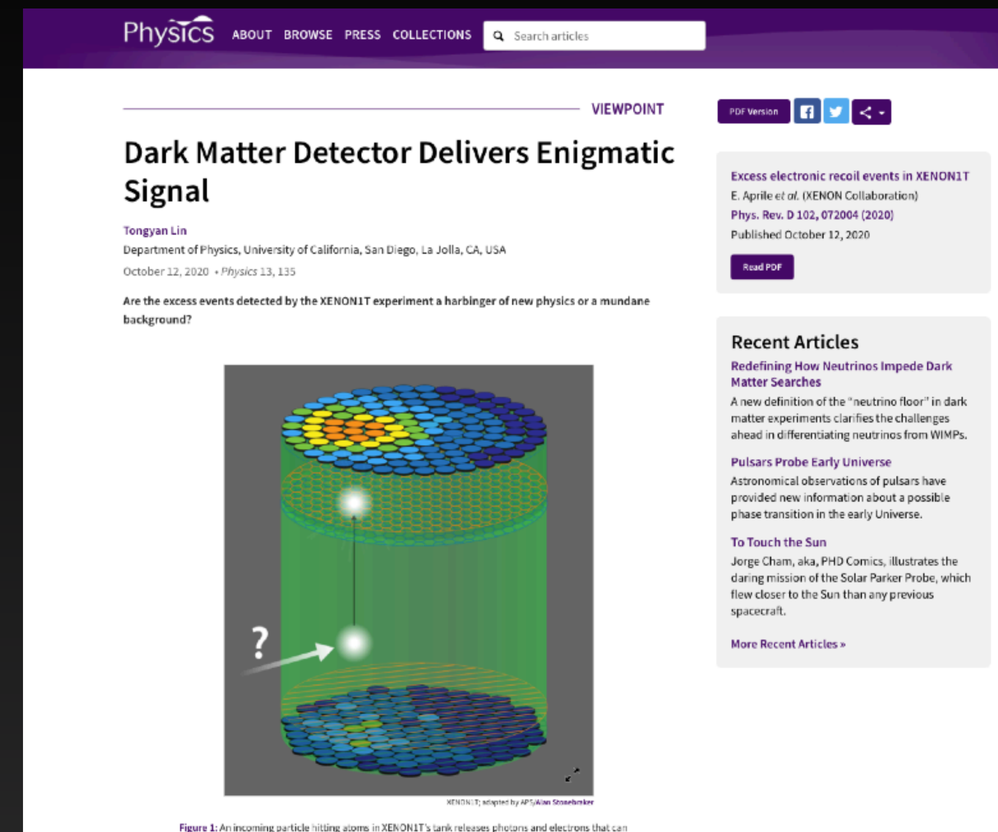
This talk focuses on ER searches

See Giovanni Volta's talk for WIMP search in XENONnT

XENON1T Excess



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VIEWPOINT

PDF Version

Dark Matter Detector Delivers Enigmatic Signal

Tongyan Lin
Department of Physics, University of California, San Diego, La Jolla, CA, USA
October 12, 2020 • *Physics* 13, 135

Are the excess events detected by the XENON1T experiment a harbinger of new physics or a mundane background?

XENON1T; adapted by APS/Alan Stonebraker

Figure 1: An incoming particle hitting atoms in XENON1T's tank releases photons and electrons that can

Excess electronic recoil events in XENON1T
E. Aprile *et al.* (XENON Collaboration)
Phys. Rev. D 102, 072004 (2020)
Published October 12, 2020
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1—7 keV
(reference region)

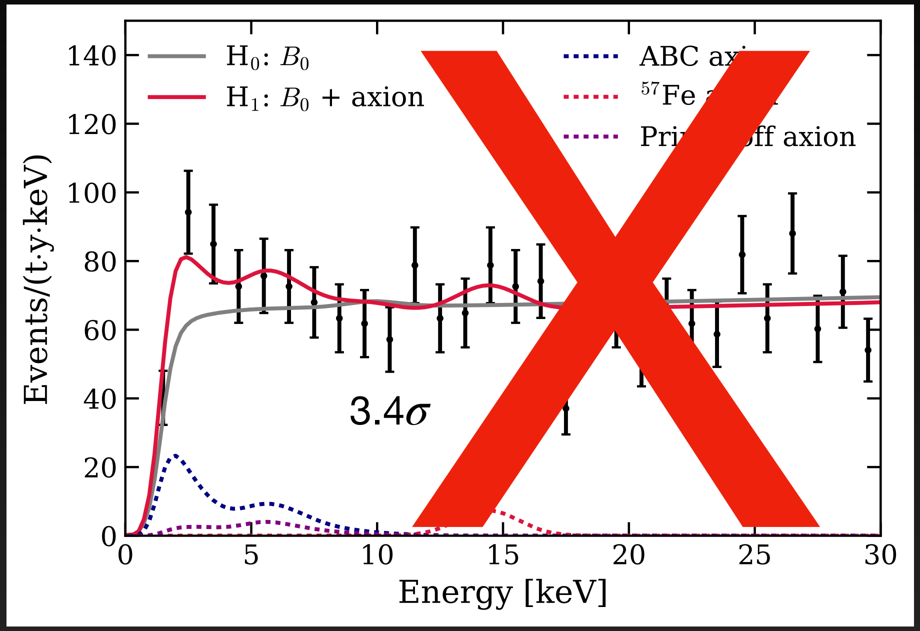
Expected: 232
Observed: 285

3.3 σ
Poissonian fluctuation
(naive estimate;
main analysis uses
profile likelihood ratio)

XENON Collaboration,
PRD 102, 072004 (2020)

What Caused the Excess?

Solar axions

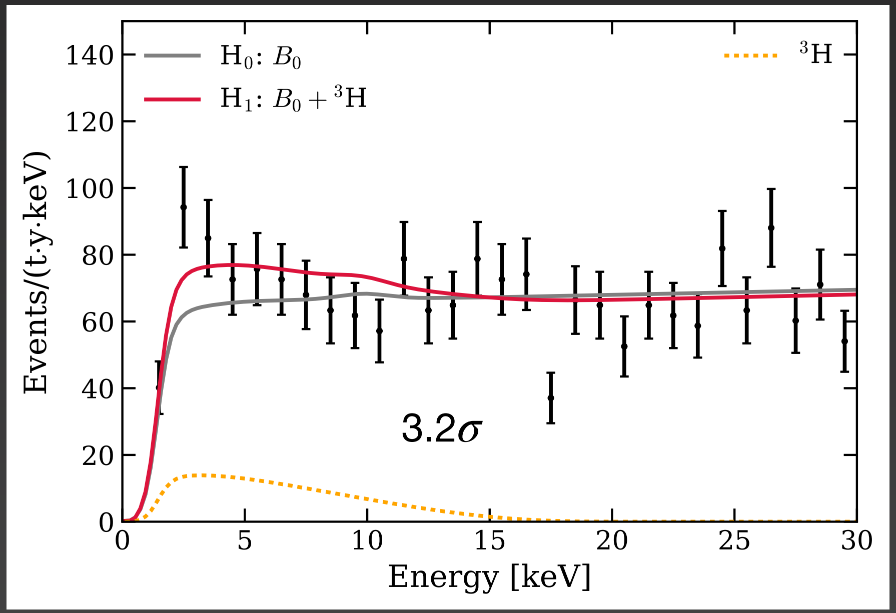


- Axions can be produced in the Sun via its couplings to electrons, photons, and nucleons
- Solar axions can be detected in LXe detectors via axio-electric effect and inverse Primakoff effect, which was not considered in XENON1T but is included in XENONnT
- Solar axion hypothesis is favored by XENON1T data at 3.4σ

New physics?
Or unexpected backgrounds?

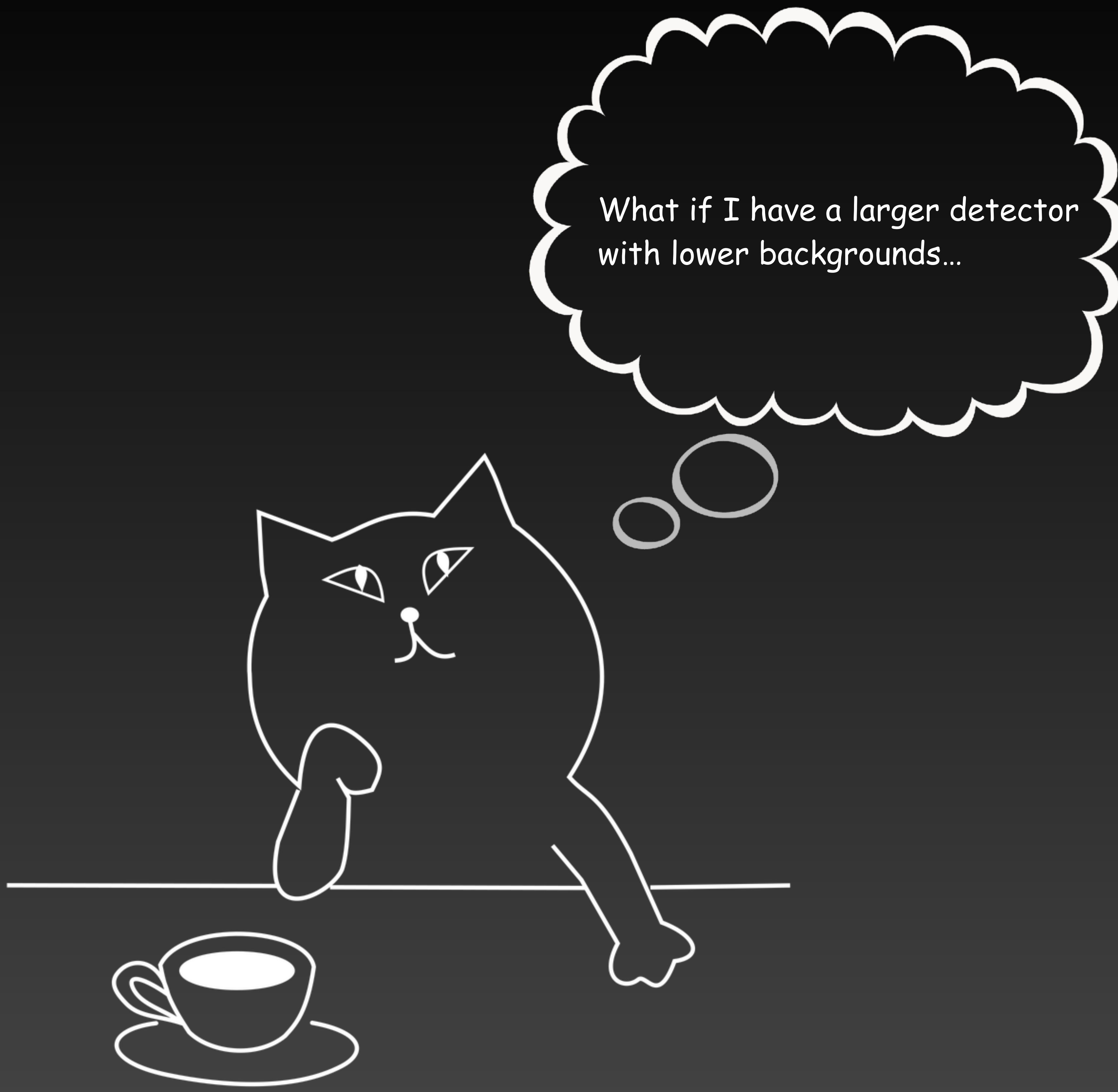
Tritium (^{3}H)

- Facts about tritium
  - Undergoes pure beta decay with a Q value of 18.6 keV
  - Long half-life (~12 years) compared to XENON1T operation time (~2 years)
  - Can be introduced to an underground detector in the forms of HT and/or HTO
- Facts about tritium hypothesis
  - Tritium hypothesis is favored by XENON1T data at 3.2 σ
  - No external constraint on the amount of tritium, in particular HT

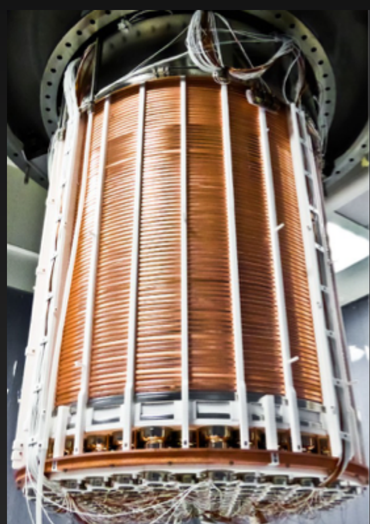


XENON Collaboration, PRD 102, 072004 (2020)

How to Decipher the Excess



XENONnT



XENON1T TPC

XENONnT TPC

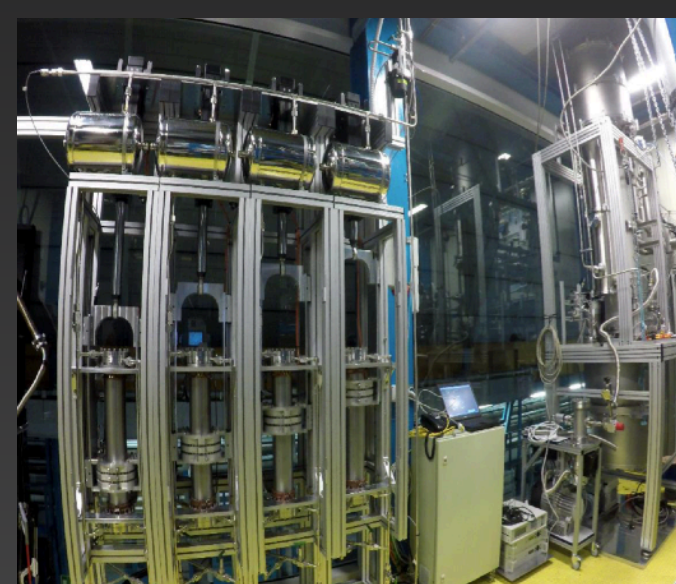
x3

Active volume

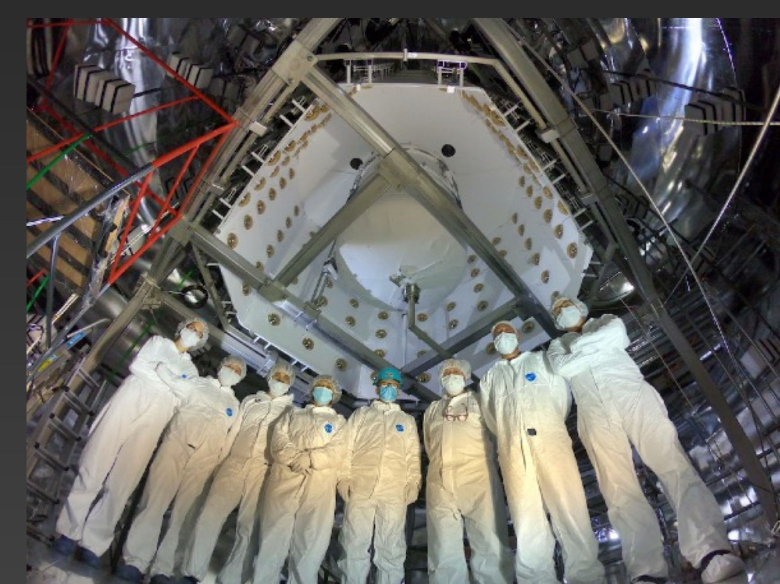
1/6

Background

Liquid purification system

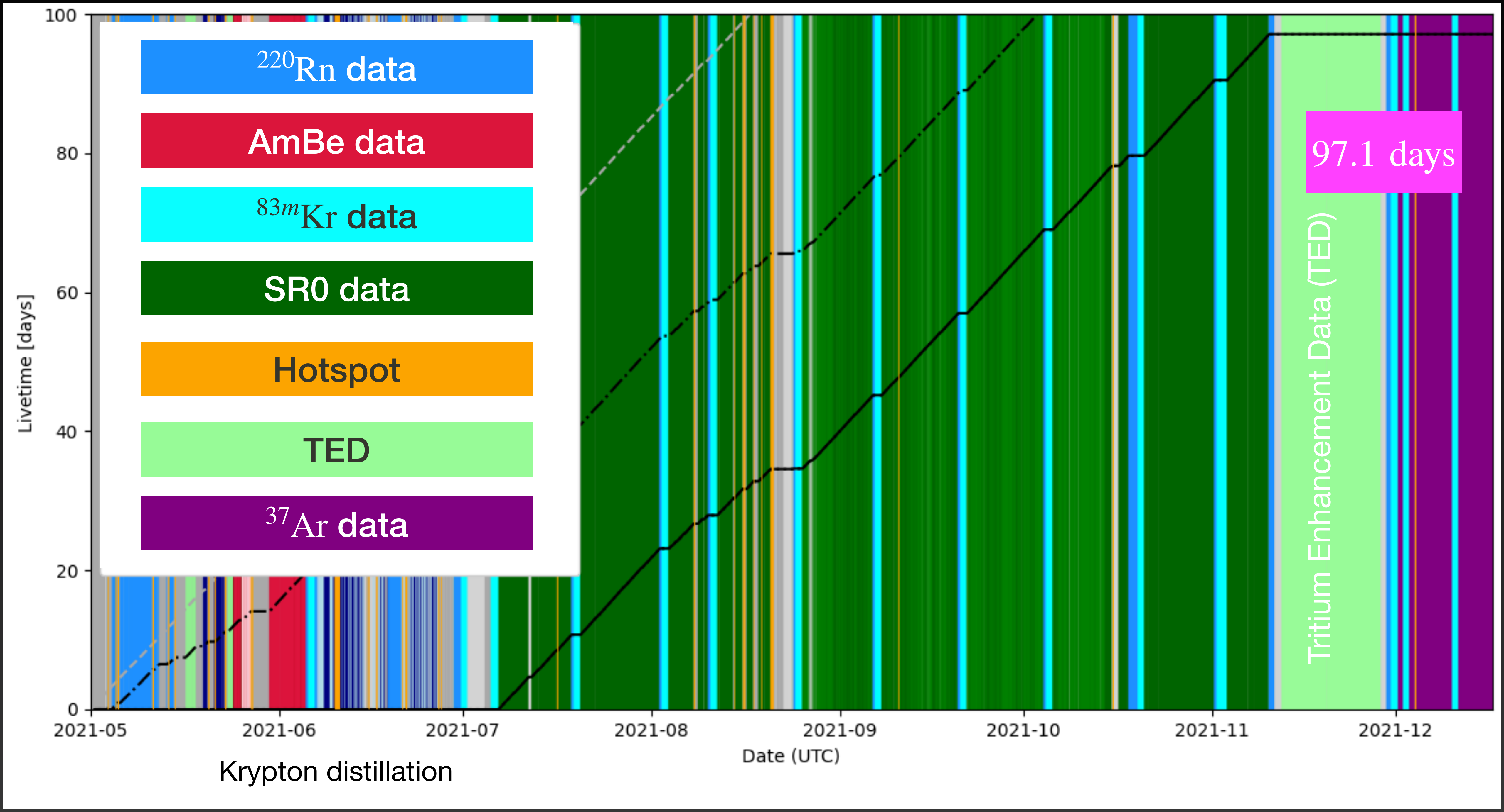


Radon distillation column



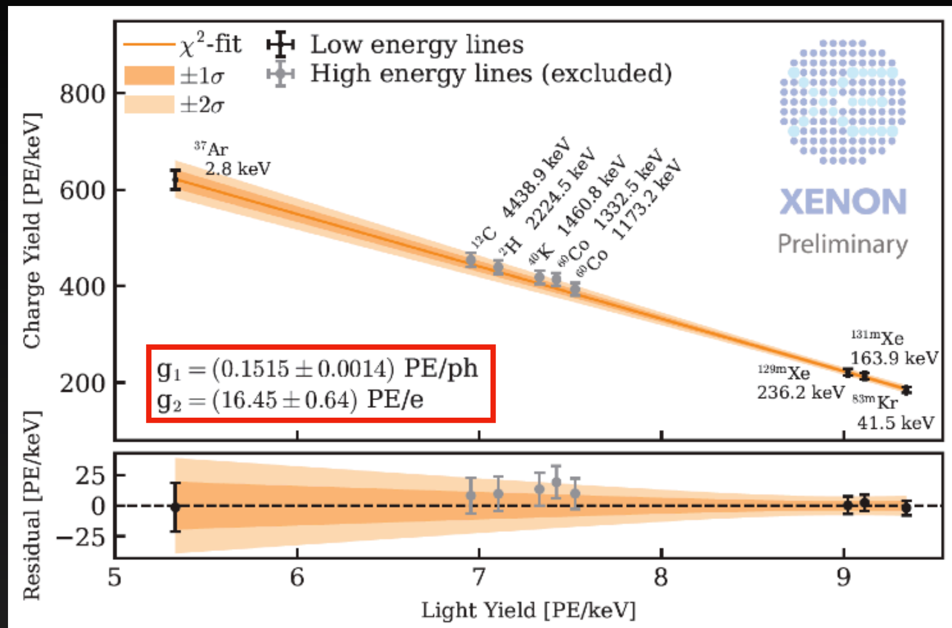
Neutron veto

XENONnT SR0

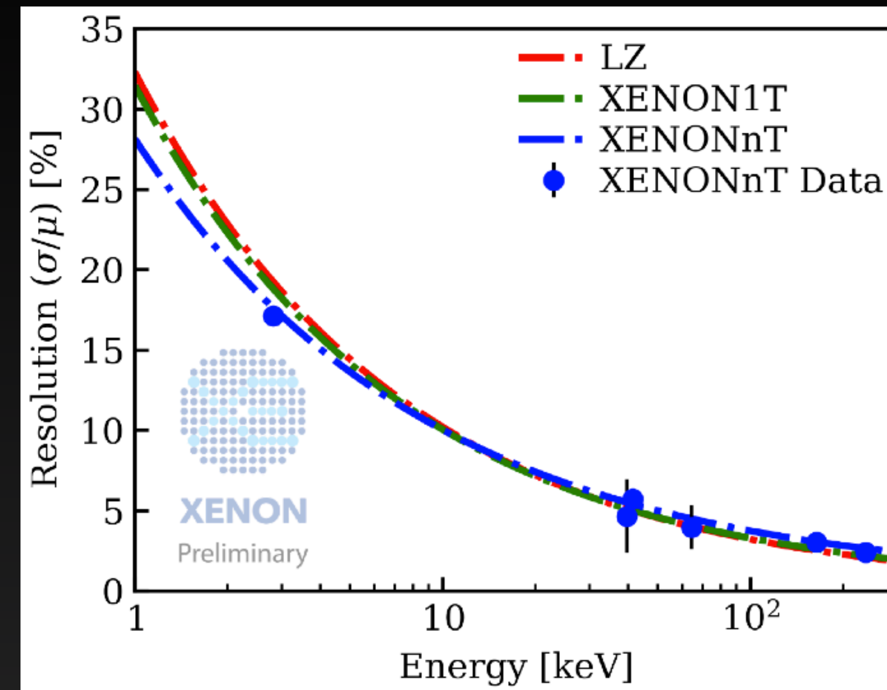


XENONnT SR0 recorded an exposure of 1.16 t y, ~x2 of XENON1T ER search

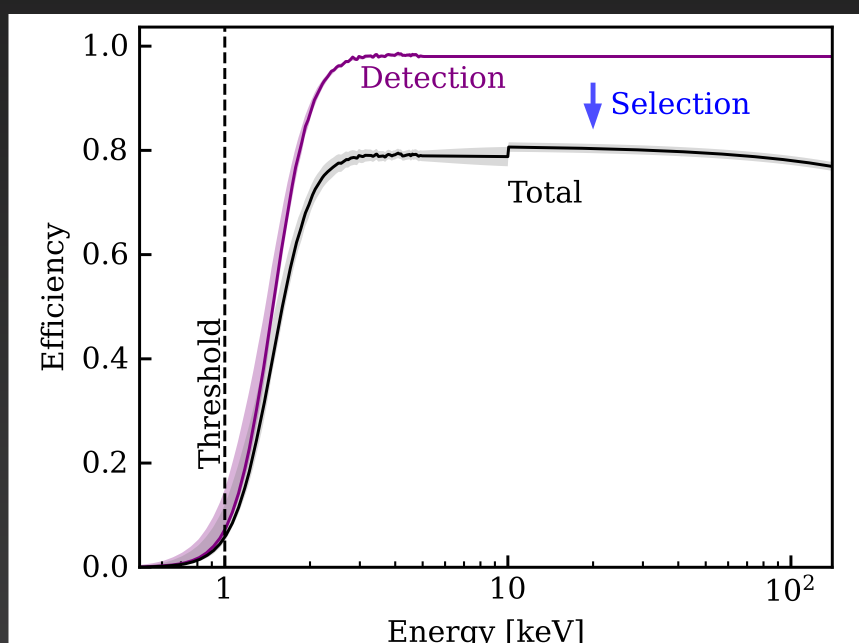
Energy Response Modeling and Validation



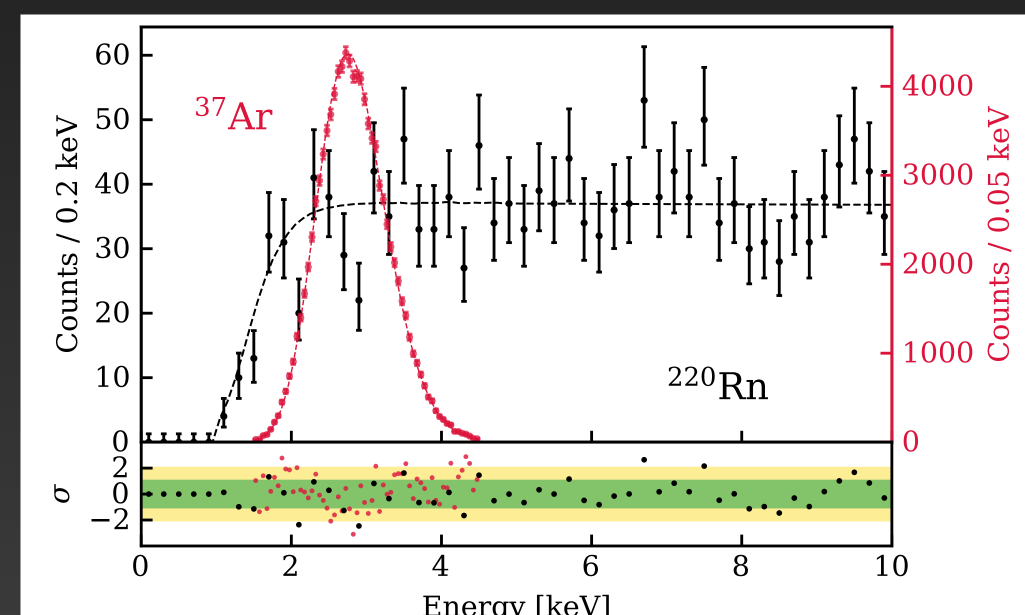
Energy reconstruction $E = (\frac{cS1}{g_1} + \frac{cS2}{g_2}) \cdot W$



Energy resolution



Efficiencies



Validation

- Skew-gaussian is used for energy smearing
- Efficiency/smearing is validated by $^{220}Rn/^{37}Ar$ calibration data

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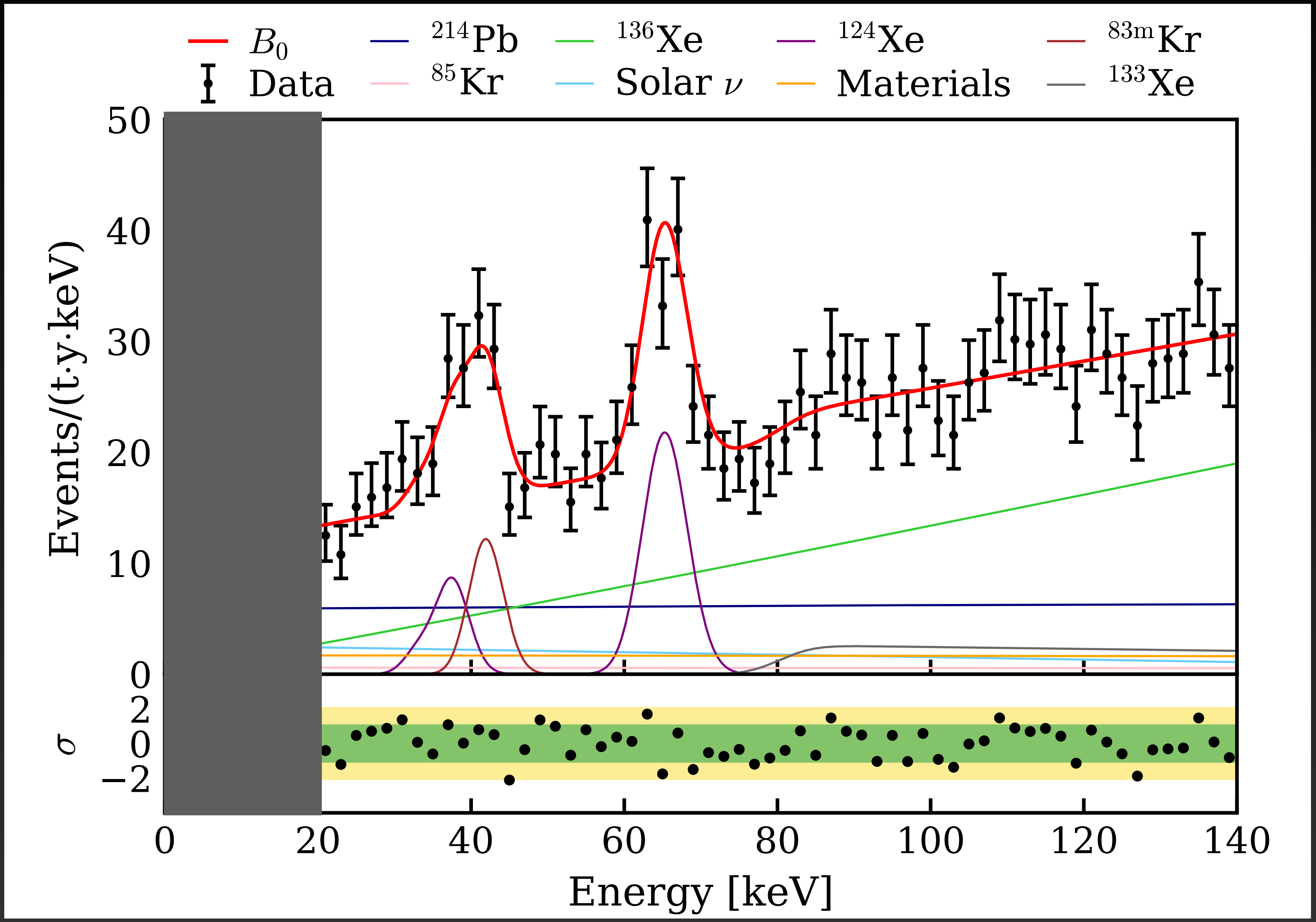
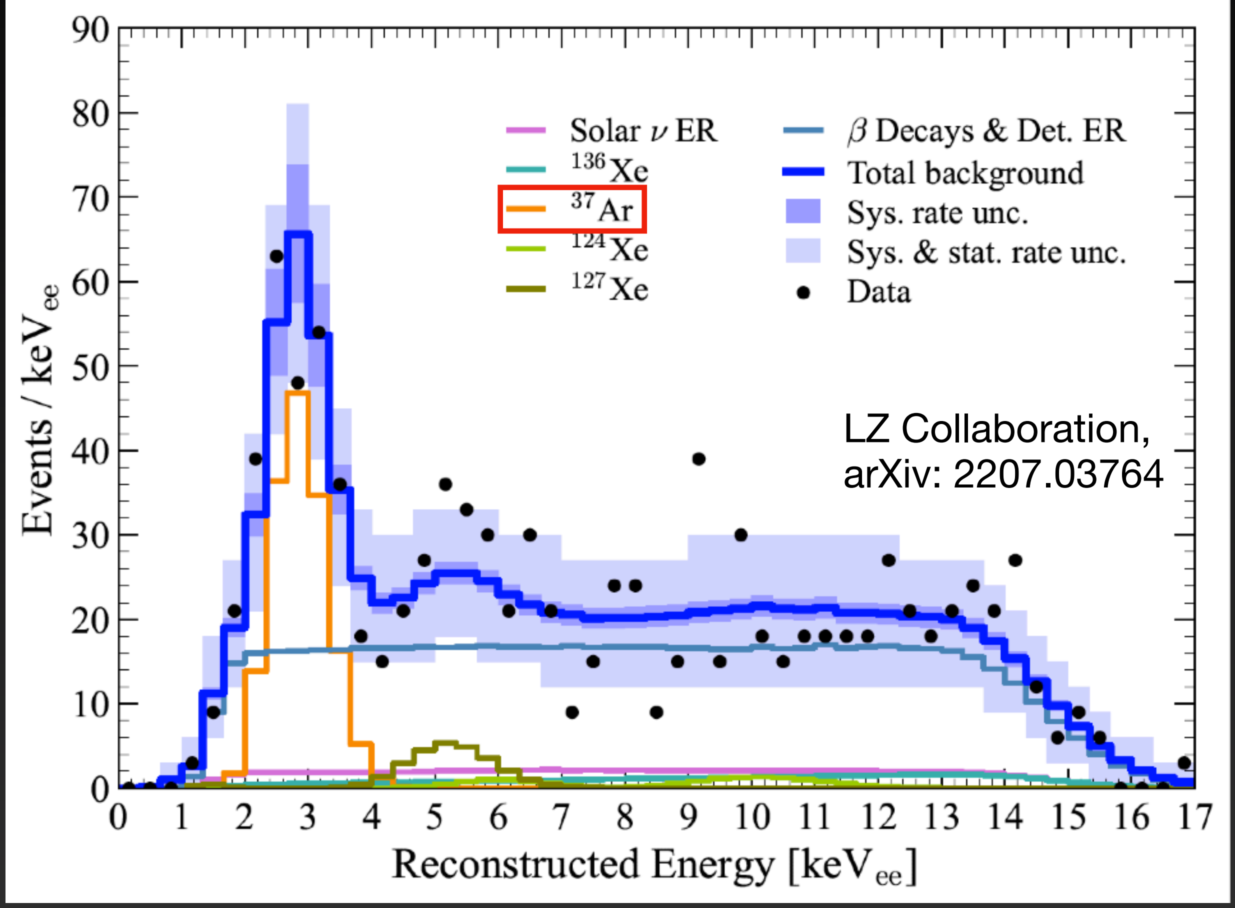
Backgrounds



- ^{222}Rn: $\sim 1.7\,\mu$Bq/kg (XENON1T SR1: $\sim 12\,\mu$Bq/kg)
- ^{nat}Kr: (56 ± 36) ppq (XENON1T SR1: (660 ± 110) ppq)
- ^{83m}Kr background is due to leftover of calibrations
- Spectral shape dominated by two double-weak decays:
  - ^{136}Xe $2\nu\beta\beta$
  - ^{124}Xe 2νECEC

Why Not Include ^{37}Ar Background?



^{37}Ar is observed in the LZ experiment due to cosmogenic activation during transportation above ground

Facts about ^{37}Ar

- produces a 2.8 keV peak via electron capture
- short half-life: 35 days

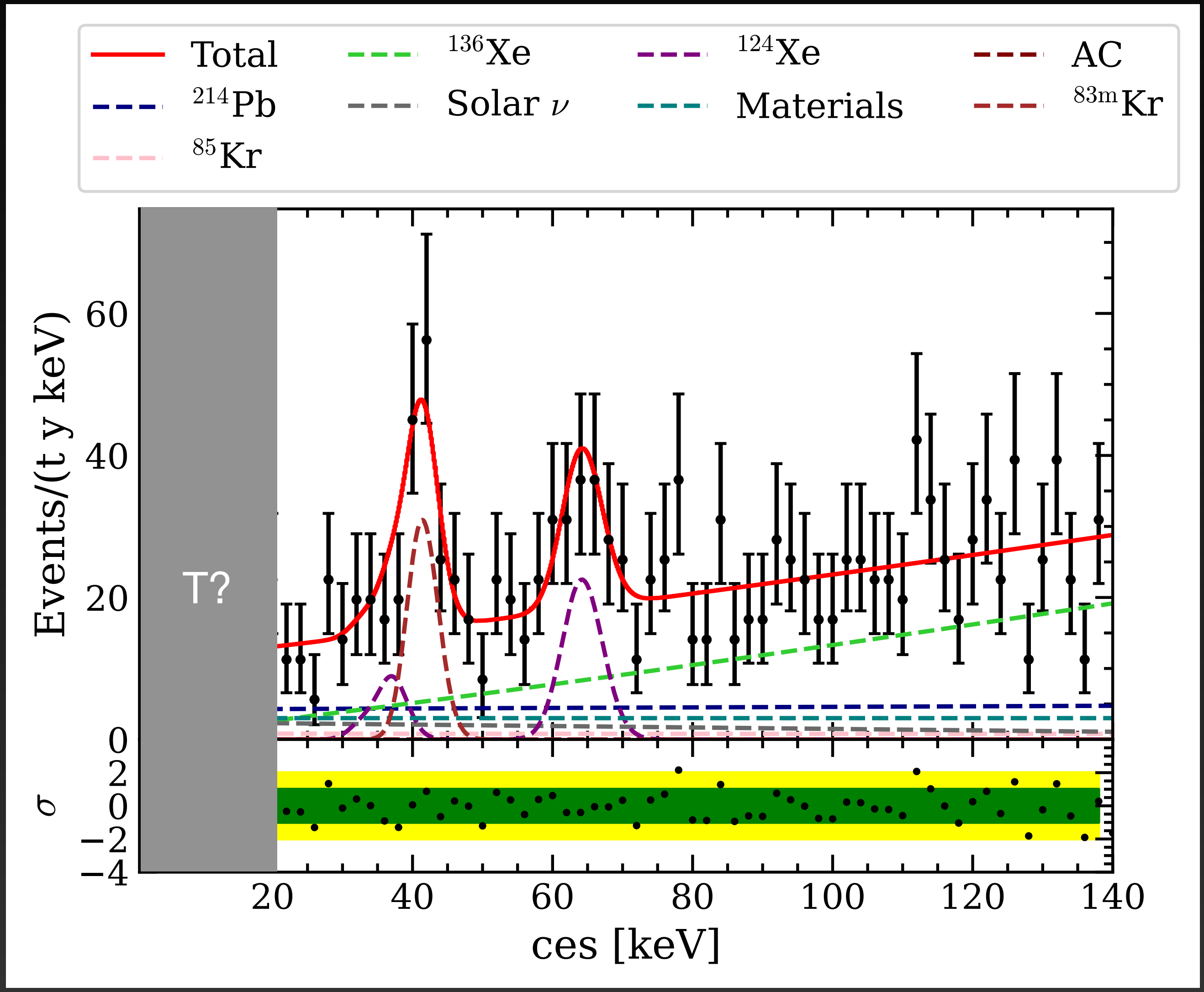
Why is ^{37}Ar not possible in XENONnT?

- Cosmogenic activation
  - Xenon in the XENONnT detector has been underground for years
  - Before taking SR0 data, the entire xenon inventory was cryogenically distilled by the Kr-removal system underground, which is also effective in ^{37}Ar removal. XENON Collaboration, PTEP 2022, 053H01.
  - ➡ Cosmogenic activation (or any initial presence of ^{37}Ar after distillation) is not possible
- Leak
  - 'leak' size is small using the conservative estimation of nat-Kr variation
  - combined with the measured ^{37}Ar activity in the lab air, the ^{37}Ar amount 'leaked' into the detector is negligible
  - ➡ ^{37}Ar leak during the SR0 operation is not possible

Special Treatment for Tritium

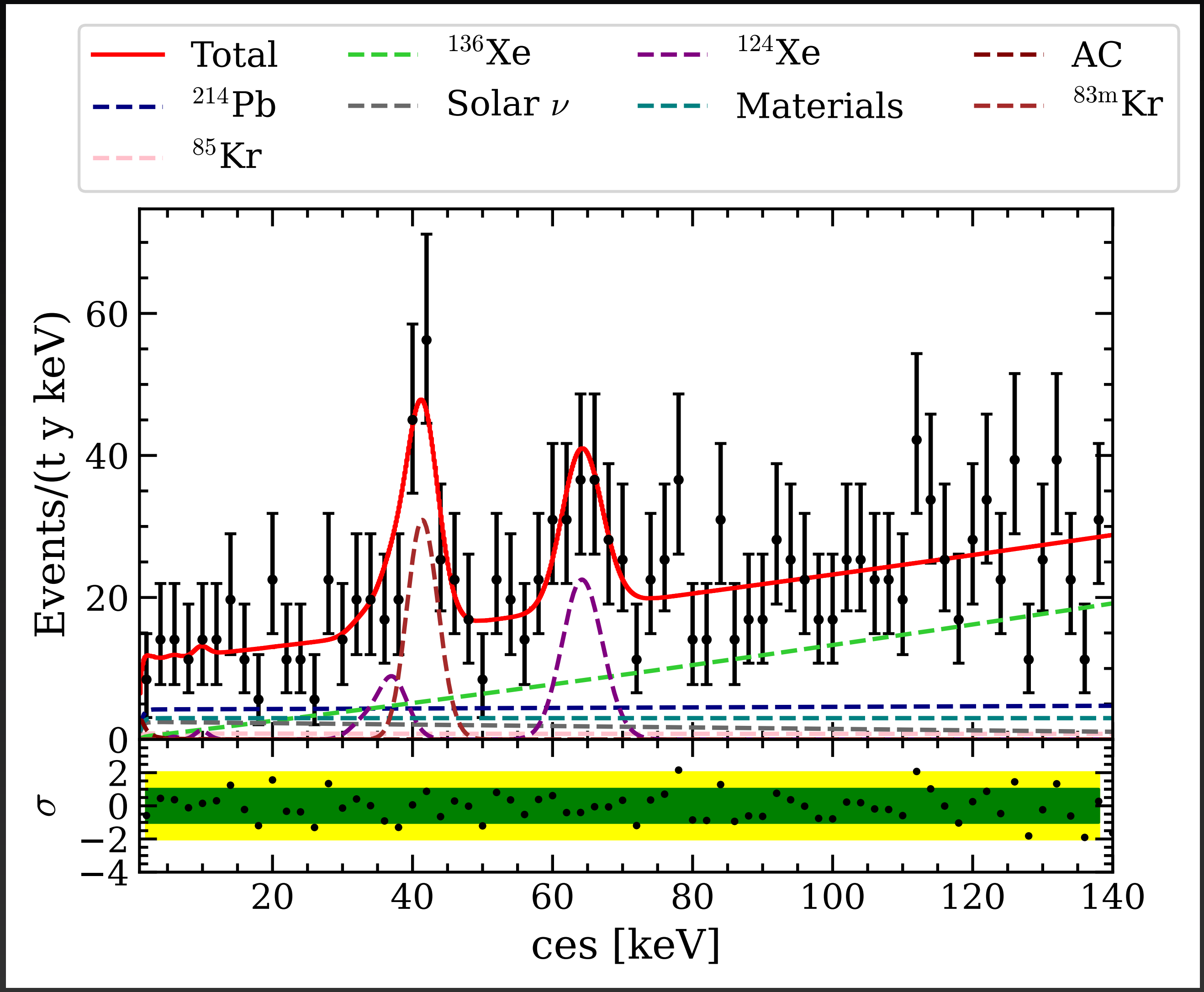
- TPC outgassed for ~3 months before filling GXe to reduce HTO/HT
- Initial HT was considerably reduced when the entire xenon inventory was processed through the Kr-removal system
- Xenon was transferred to the liquid storage system via high temperature getters with hydrogen removal unit (HRU) before filling
- Prior to cool down and filling, the cryostat and TPC were treated by continuously circulating GXe for ~3 weeks
- GXe or LXe was always purified via the getters when filled into the cryostat
- HRUs were regenerated before SR0

Tritium Enhanced Data (TED)



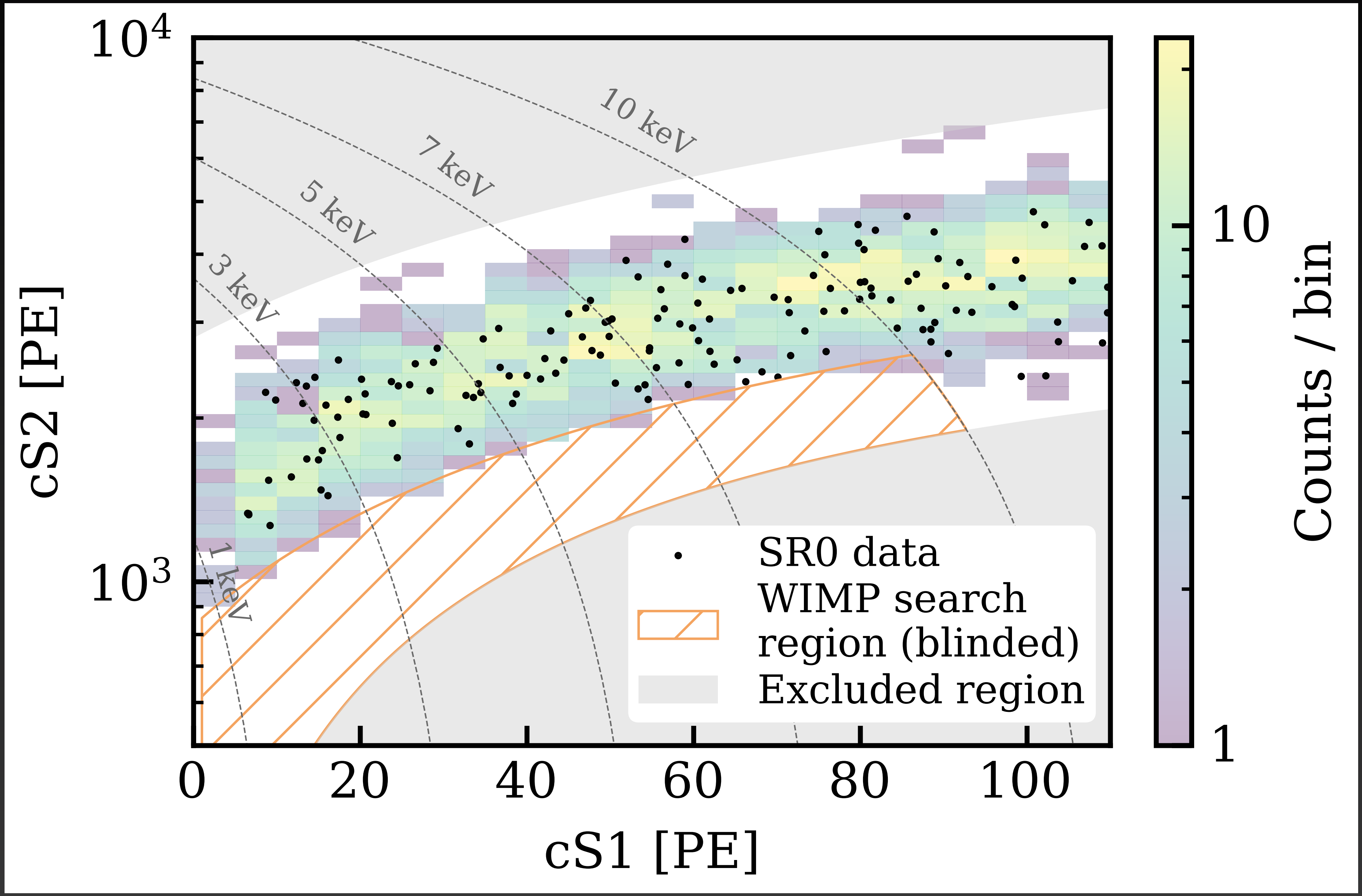
- Bypass the getter purifying the GXe volume to enhance H2/HT
- The enhancement factor is conservatively estimated to be 10, but can be much larger

Tritium Enhanced Data (TED)



- Bypass the getter purifying the GXe volume to enhance H2/HT
- The enhancement factor is conservatively estimated to be 10, but can be much larger
- No excess is found in TED data after unblinding

Unblind (Main) SR0 Data



- Unblinded ER region only
- NR region (for WIMP search) is still blinded

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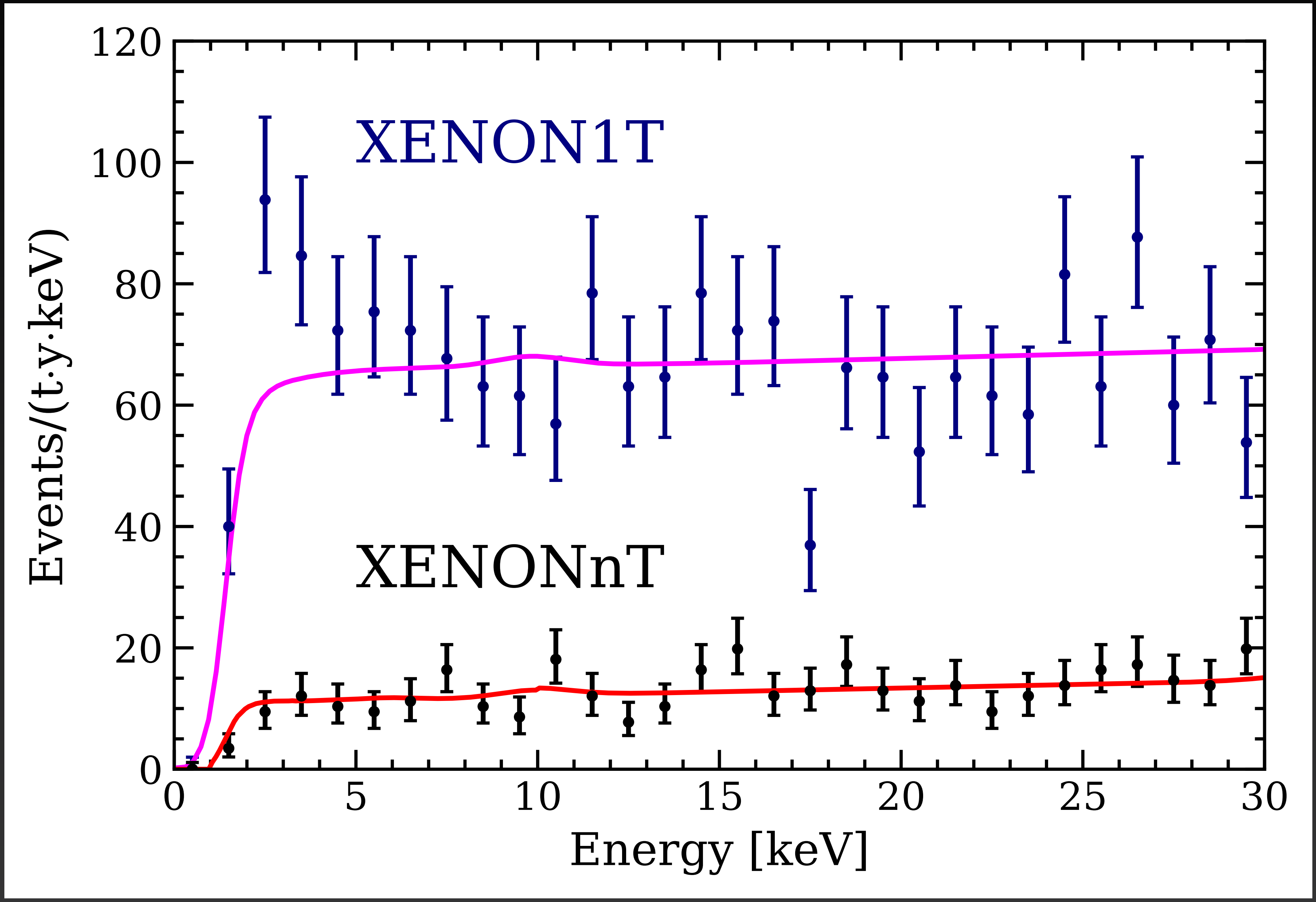
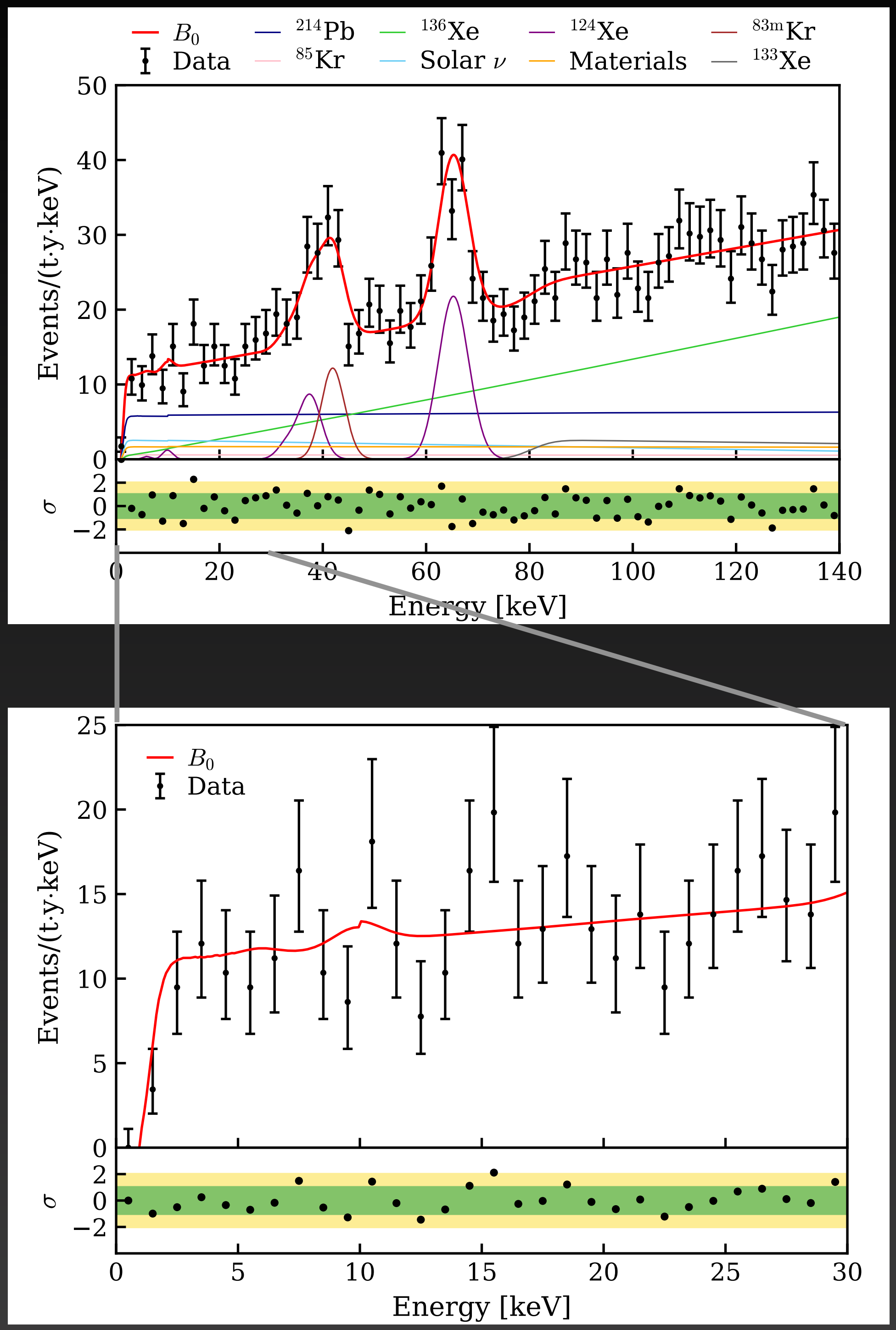
XENONnT Results



No excess is found in XENONnT!

Background-only Fit Results



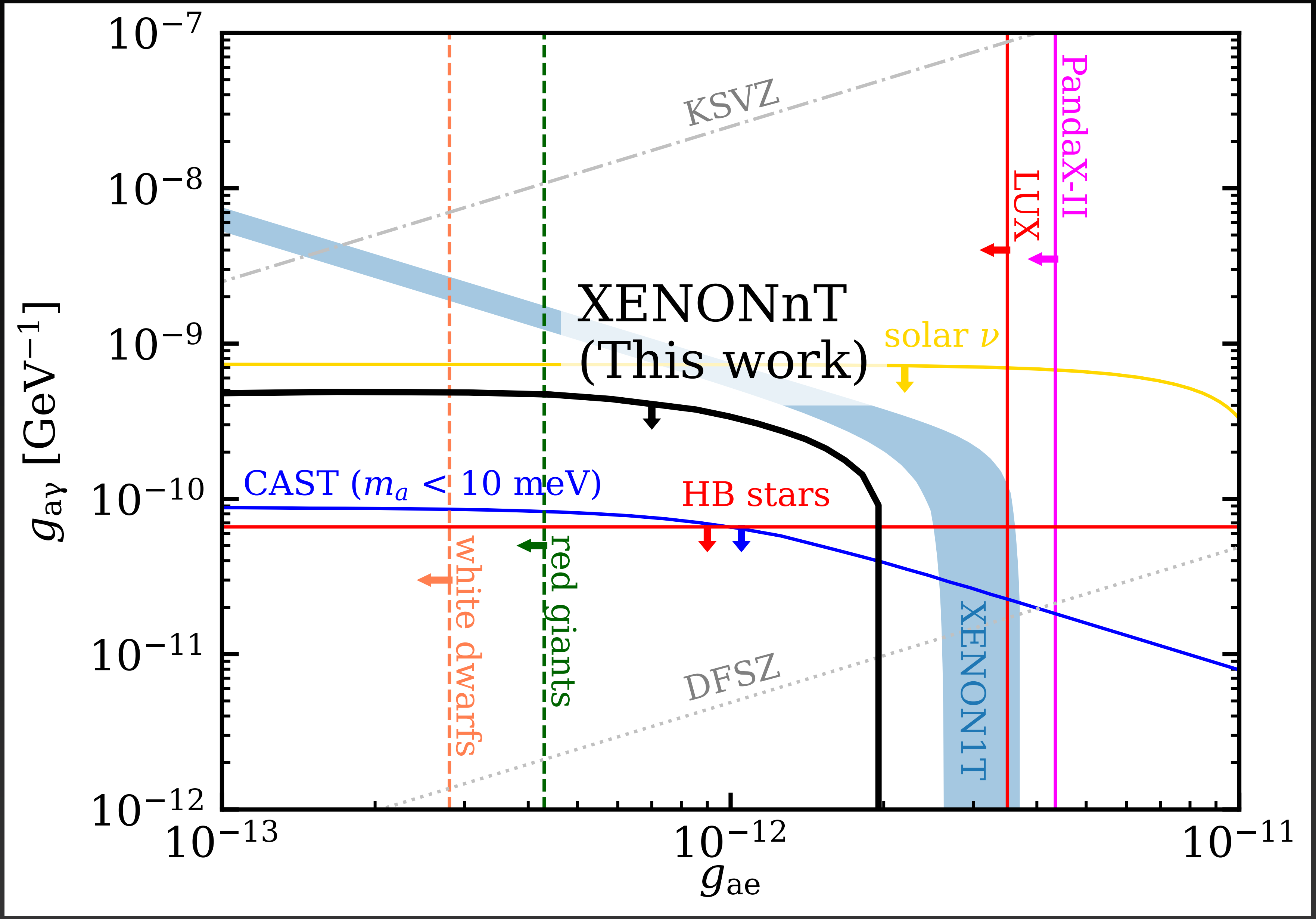
Best-fit values

	(1, 10) keV	(1, 140) keV
^{214}Pb	56 ± 7	980 ± 120
^{85}Kr	6 ± 4	90 ± 60
Materials	16 ± 3	270 ± 50
^{136}Xe	8.7 ± 0.3	1520 ± 50
Solar neutrino	25 ± 2	300 ± 30
^{124}Xe	2.6 ± 0.3	260 ± 30
AC	0.70 ± 0.03	0.71 ± 0.03
^{133}Xe	-	160 ± 60
^{83m}Kr	-	80 ± 16

- ^{214}Pb best-fit rate: $(1.36 \pm 0.17_{\rm stat})\ \mu$Bq/kg
- Solar neutrino: the 2nd largest ER background below 10 keV
- The total ER background below 30 keV is $(16.1 \pm 1.3_{\rm stat})$ events/(t · y · keV), the lowest background ever achieved in a dark matter detector, ~x0.2 of XENON1T ER search

arXiv: 2207.11330

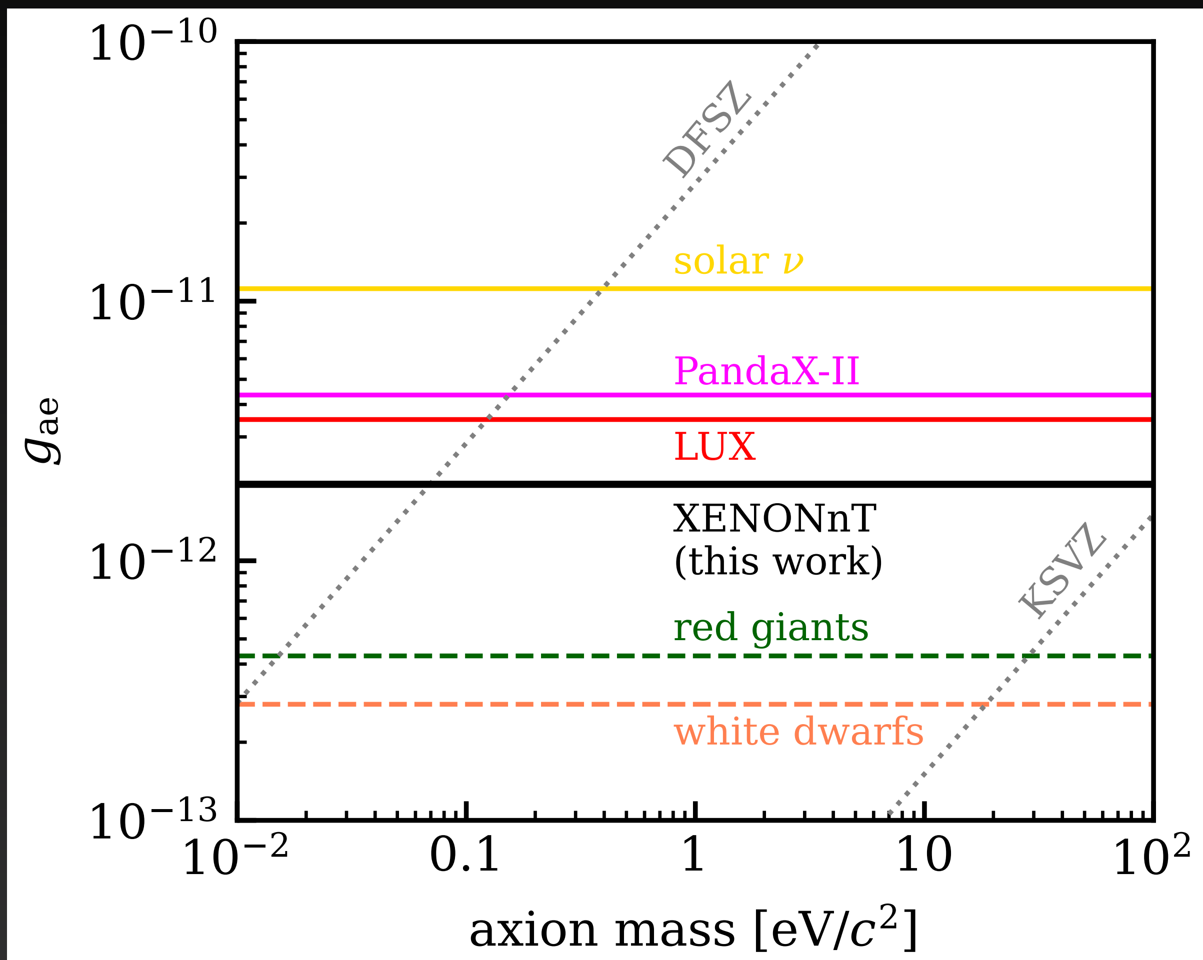
Solar Axion Limit

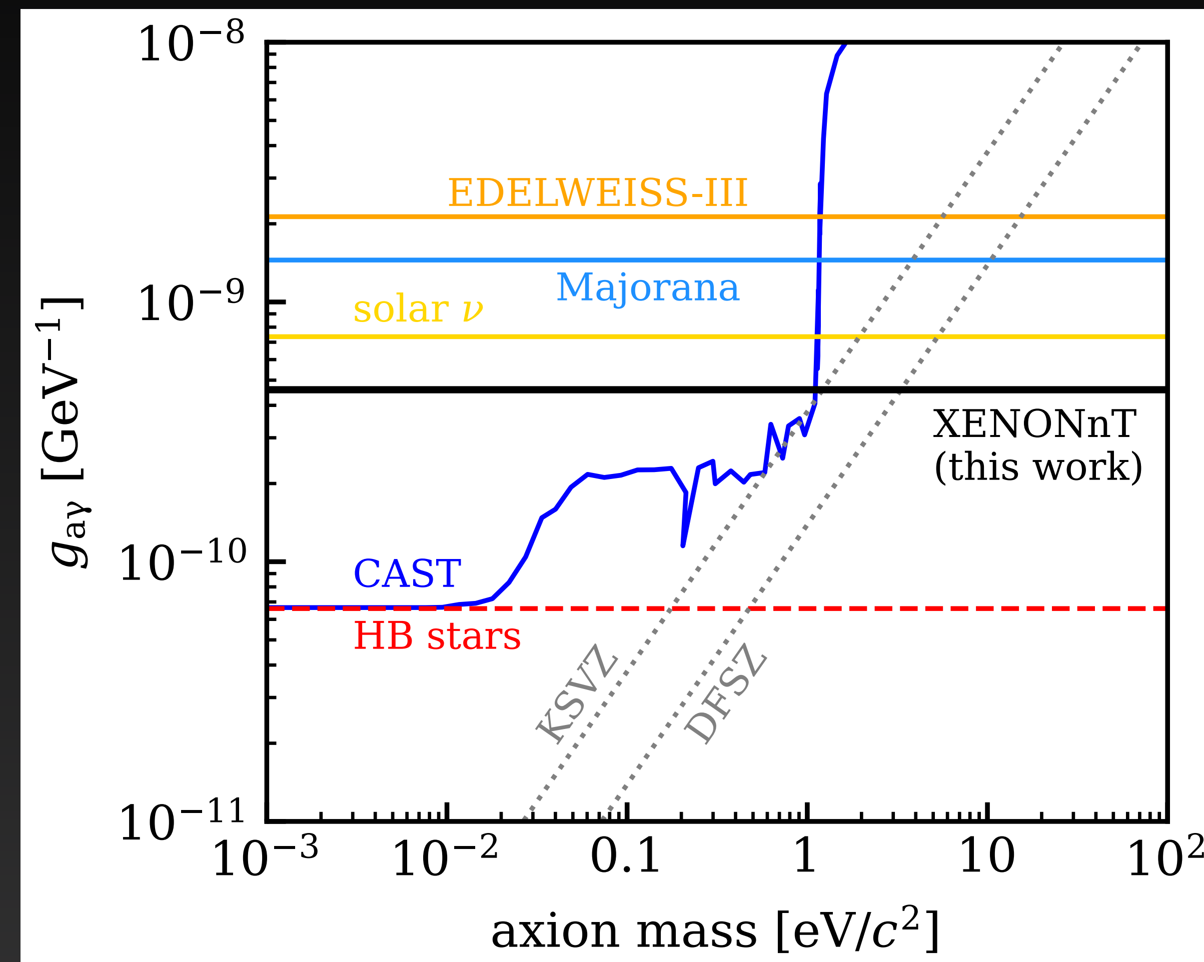


- Statistical inference is done in 3D space (g_{ae}, $g_{a\gamma}$, g_{an}^{eff})
- Projection to 2D space of g_{ae} and $g_{a\gamma}$ as they matter most for the low-energy region

arXiv: 2207.11330

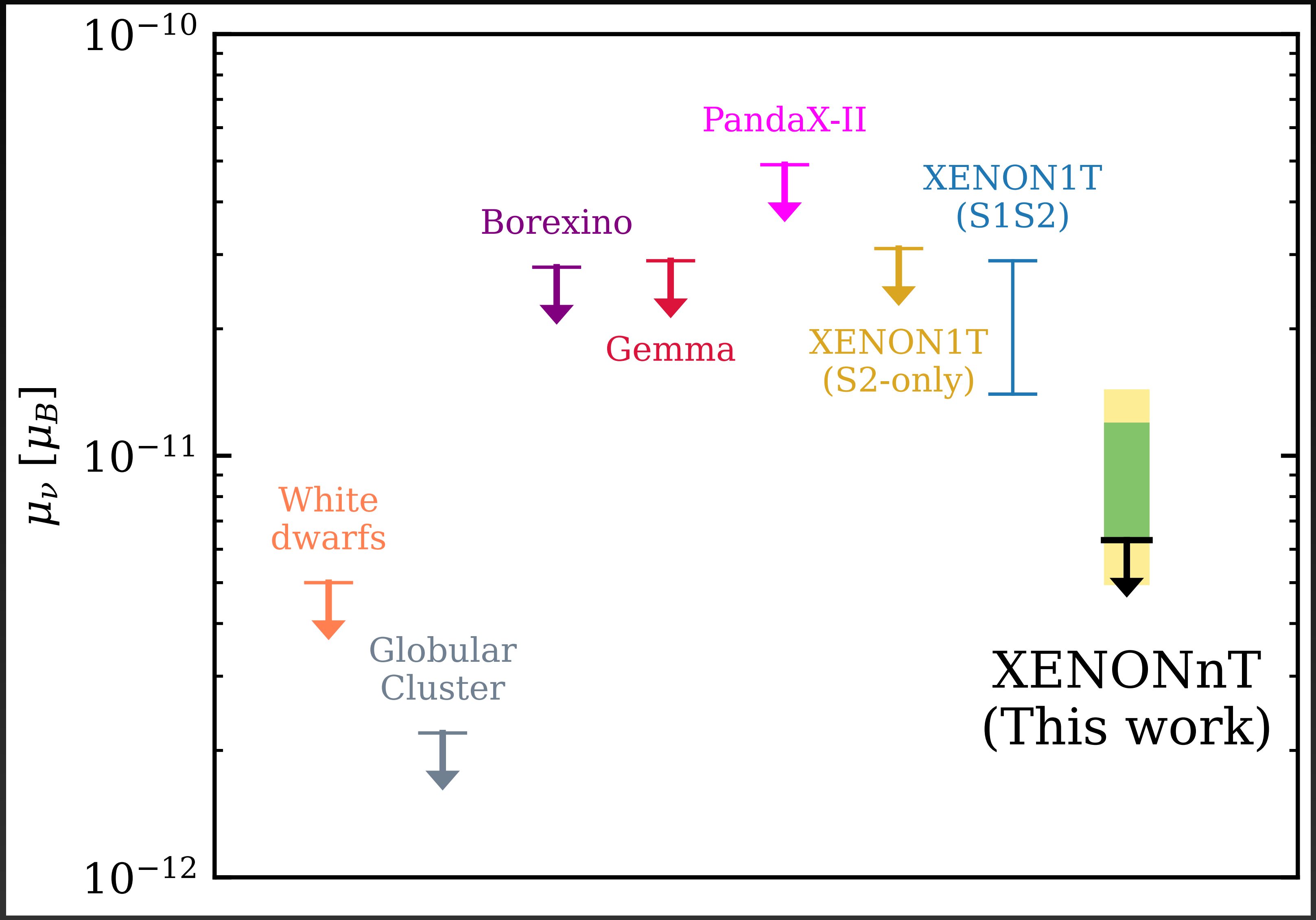
Solar Axion Limit





- Valid for axions with mass below 100 eV/c^2
- Best direct detection limit of g_{ae} for axion mass below 100 eV/c^2
- Best direct detection limit of $g_{a\gamma}$ for axion mass between 1 and 100 eV/c^2

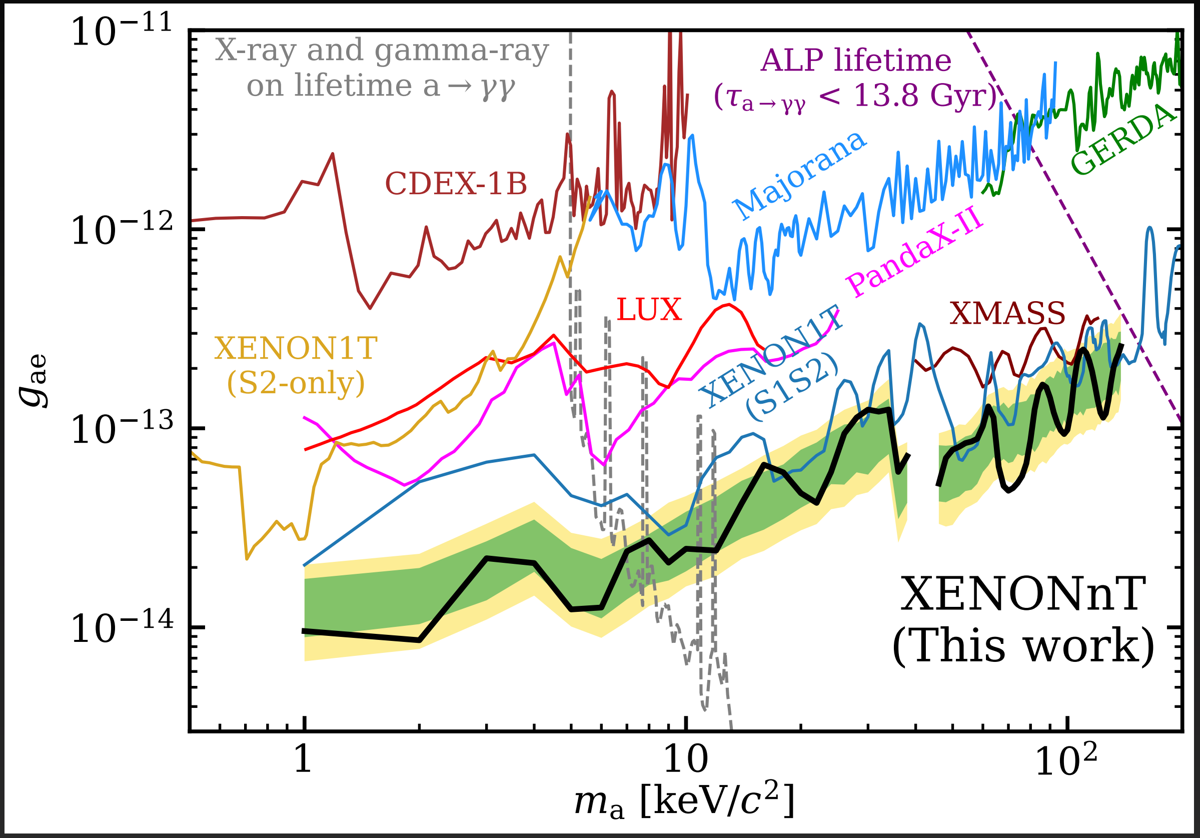
Neutrino Magnetic Moment Limit



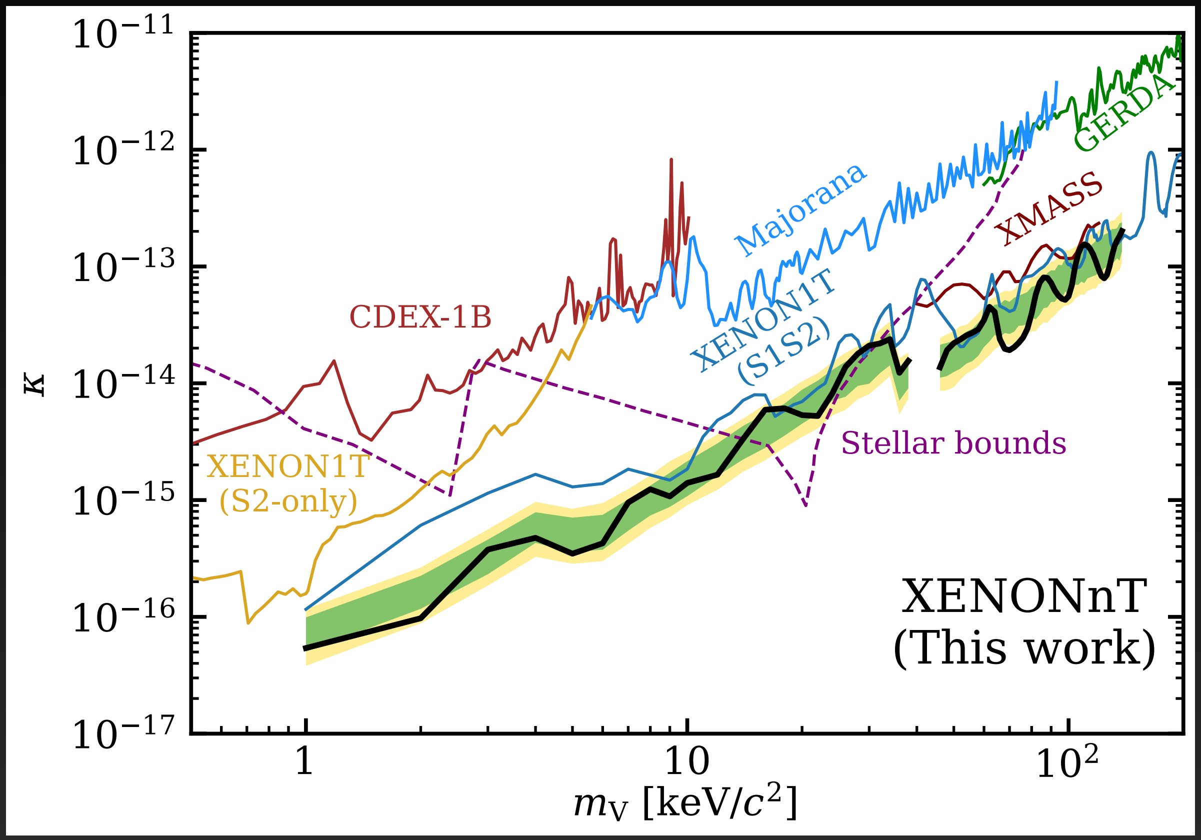
- Constrain the effective neutrino magnetic moment $\mu_\nu^{\rm eff}$ using solar neutrinos as LXe detectors are not sensitive to neutrino flavors
- XENONnT result: $\mu_\nu^{\rm eff} < 6.3 \times 10^{-12}\,\mu_{\rm B}$ (90% C.L.)

arXiv: 2207.11330

Bosonic Dark Matter



ALPs



Dark photon

- Bosonic DM:
  - ALPs
  - Dark photons
- Competitive limits for mass in (1, 39) and (33, 140) keV/c^2
  - No limit/sensitivity between (39, 44) keV/c^2 because $^{83m}\mathrm{Kr}$ background rate is not constrained
  - The maximum local significance ~1.8 σ at ~109 keV

arXiv: 2207.11330

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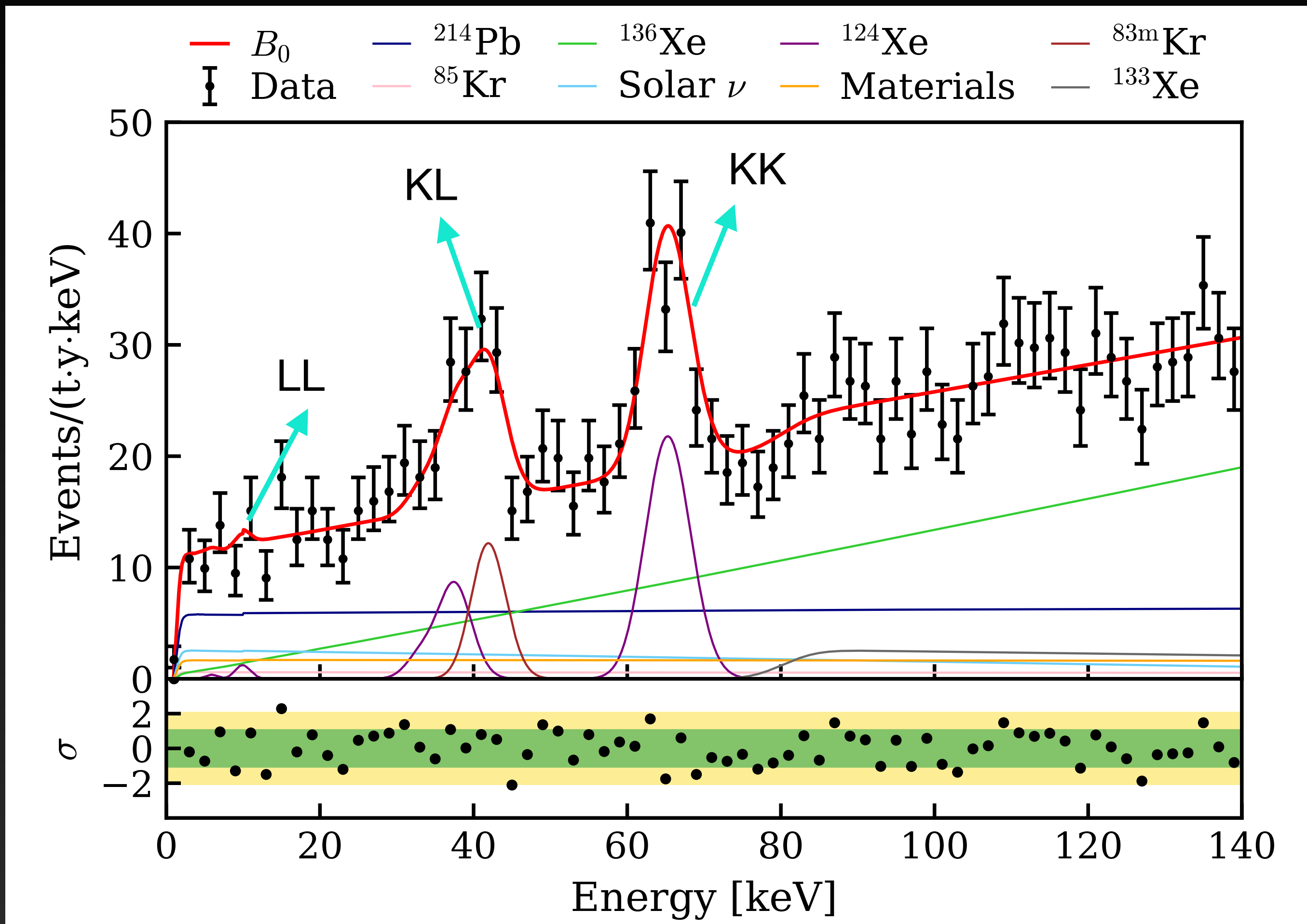
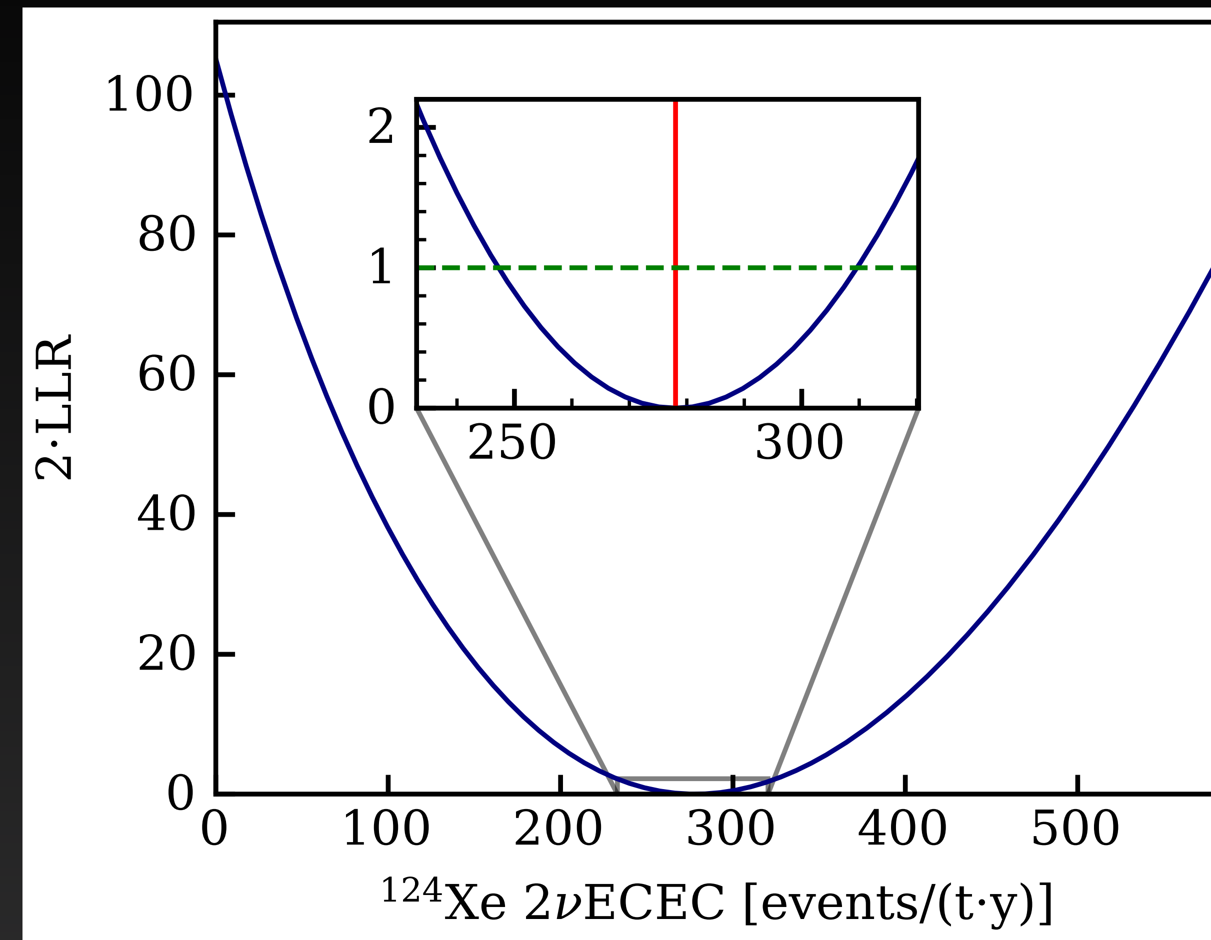
^{124}Xe 2νECEC





- ^{124}Xe 2νECEC rate is unconstrained in the entire analysis; BRs are fixed
- Stand out in the energy spectrum due to the ultra-low background
  - LL peak is visible even with only ~1% BR
  - KL & KK peaks are used for calibration purpose (energy resolution)
- The measured half-life $T_{1/2}^{2\nu ECEC} = (1.15 \pm 0.13_{stat} \pm 0.14_{sys}) \times 10^{22}$ yr with a significance of 10 σ
  - Statistical uncertainty decreases to the same level of the systematic uncertainty
  - Consistent with the latest XENON1T result, $T_{1/2}^{2\nu ECEC} = (1.1 \pm 0.2_{stat} \pm 0.1_{sys}) \times 10^{22}$ yr. XENON Collaboration, Phys. Rev. C 106, 024328

Summary

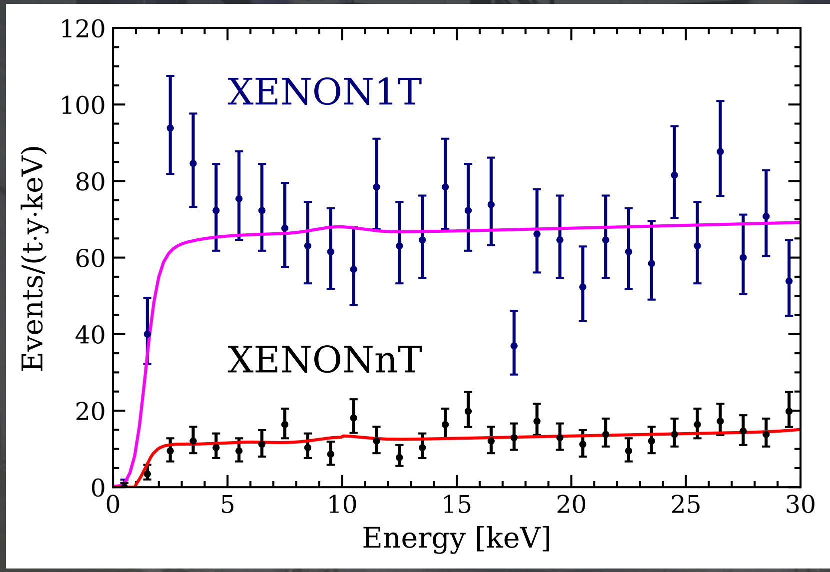
- This talk presents the XENONnT ER search with 1.16 tonne-year exposure

- XENONnT has achieved the lowest ER background rate ever in a dark matter detector, $(16.1 \pm 1.3_{\mathrm{stat}})\ \mathrm{events}/(\mathrm{t} \cdot \mathrm{y} \cdot \mathrm{keV})$ below 30 keV

- The XENON1T excess is NOT observed in XENONnT

- XENONnT places the competitive limits on several new physics models, including solar axions, neutrino magnetic moment, ALPs, and dark photons

- Improved measurement of $^{124}\mathrm{Xe}\ 2\nu\mathrm{ECEC}$ half life, $T_{1/2}^{2\nu\mathrm{ECEC}} = (1.15 \pm 0.13_{\mathrm{stat}} \pm 0.14_{\mathrm{sys}}) \times 10^{22}\ \mathrm{yr}$



arXiv: 2207.11330

www.xenonexperiment.org
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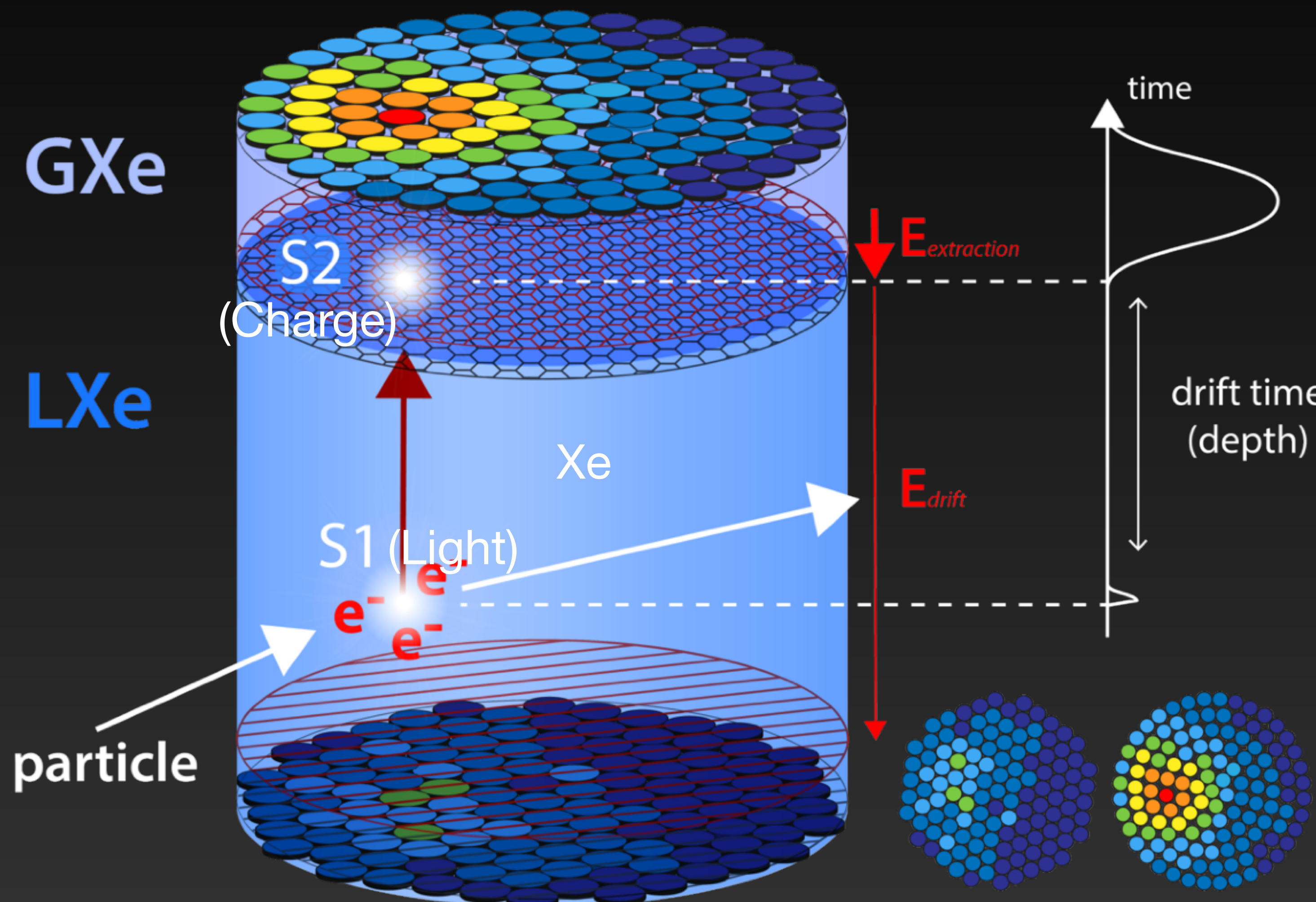
Back up

Two-phase Time Projection Chamber (TPC)



- Signal detection:
  - Light signal (S1)
  - Charge signal (S2)
- 3D position reconstruction
- Energy reconstruction

Energy reconstruction

ER events deposit all the energies into S1 and S2

$$E = (n_{\mathrm{ph}} + n_{\mathrm{e}}) \cdot W$$
$$= (\frac{cS1}{g1} + \frac{cS2_{\mathrm{b}}}{g2_{\mathrm{b}}}) \cdot W$$

Charge yield | Light yield

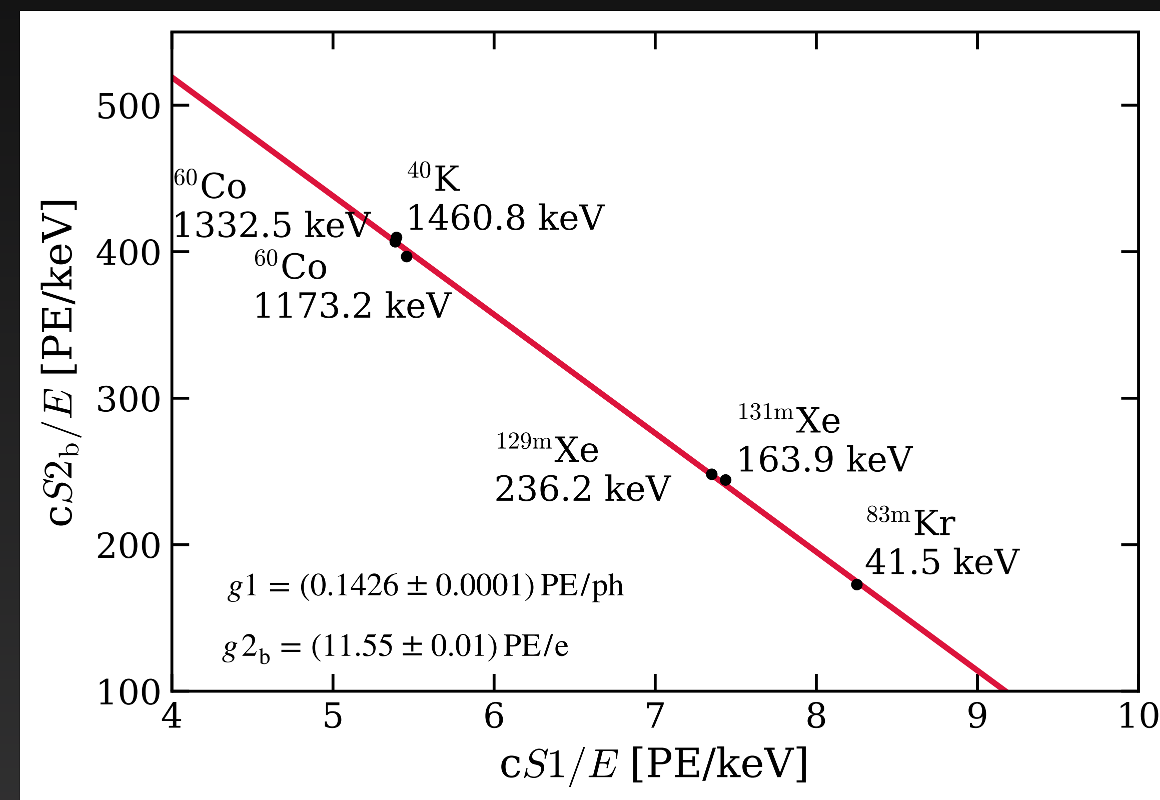
$$\frac{cS2_{\mathrm{b}}}{E} = -\frac{g2_{\mathrm{b}}}{g1}\frac{cS1}{E} + \frac{g2_{\mathrm{b}}}{W}$$

y = k x + b

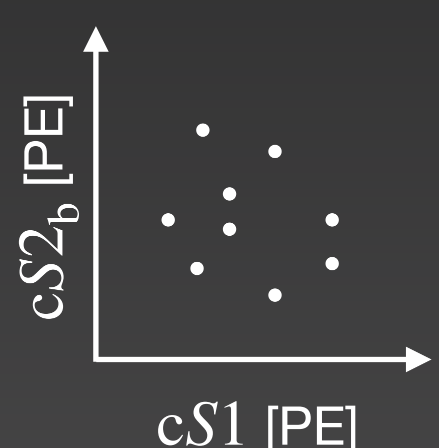
W : 13.7 eV/quanta

$$g1 = \frac{cS1}{n_{\mathrm{ph}}} \qquad g2_{\mathrm{b}} = \frac{cS2_{\mathrm{b}}}{n_{\mathrm{e}}}$$

$g1$, $g2_{\mathrm{b}}$: detector specific signal gains

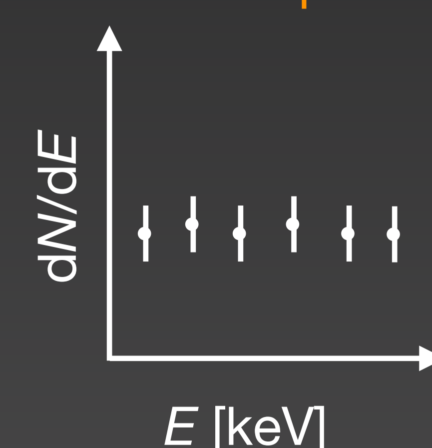


2D space

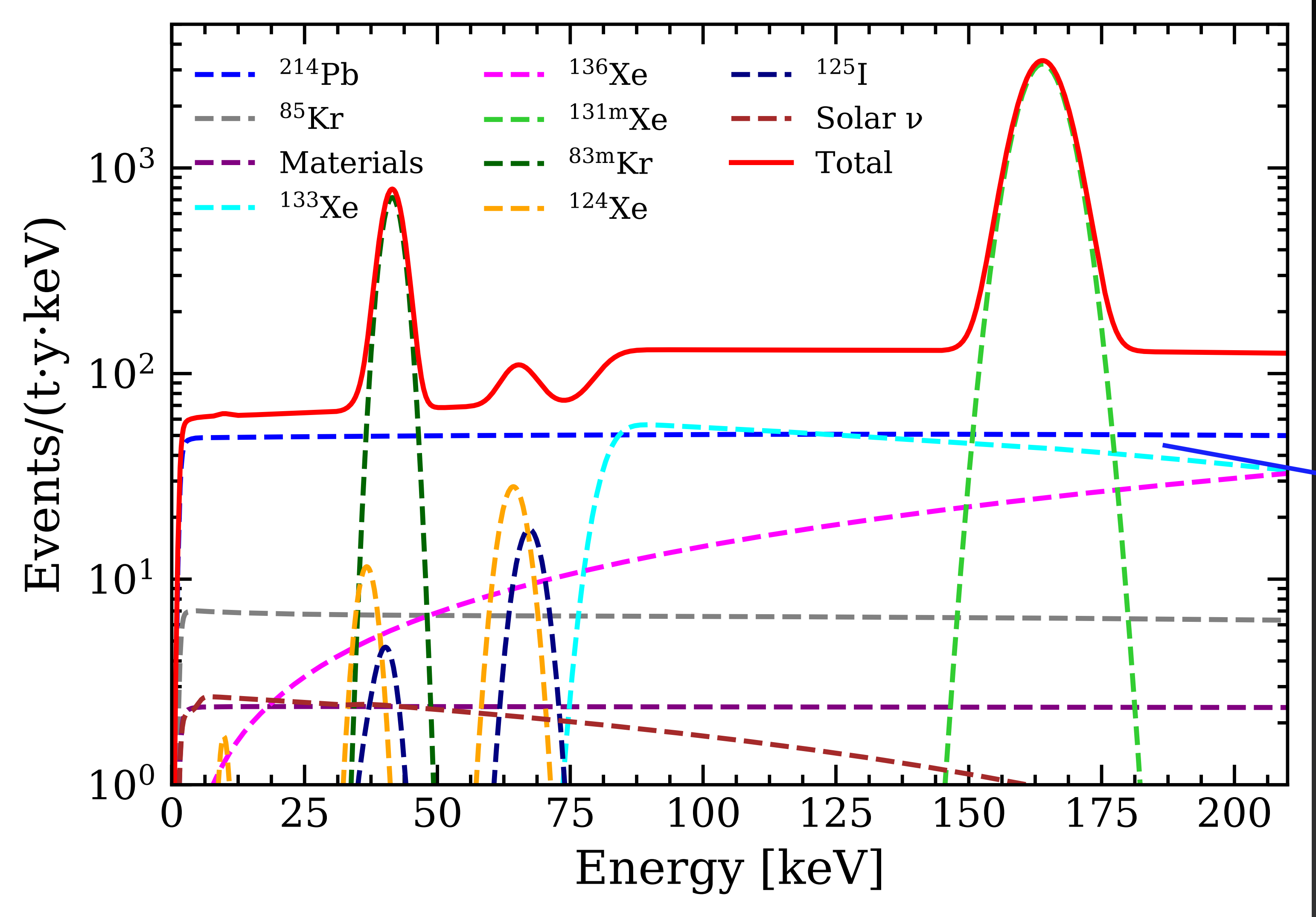


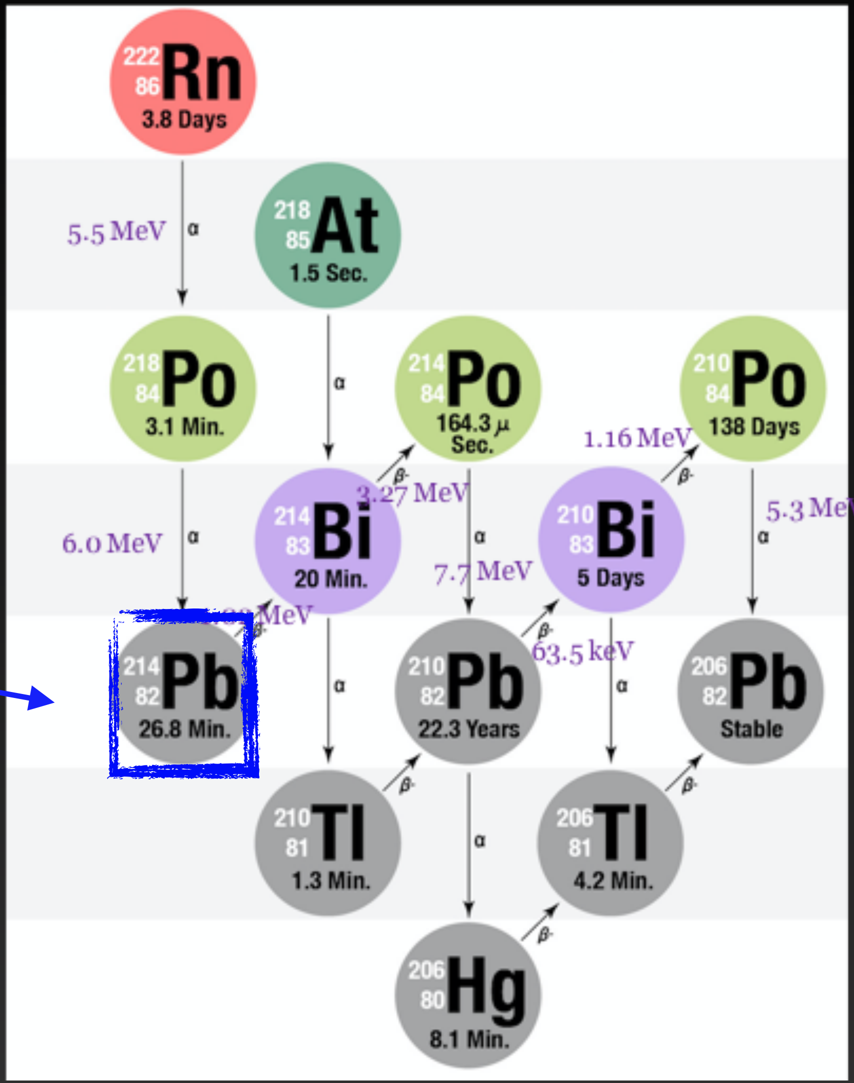
$$E = (\frac{cS1}{g1} + \frac{cS2_{\mathrm{b}}}{g2_{\mathrm{b}}}) \cdot W$$

1D space



ER Backgrounds in XENON1T



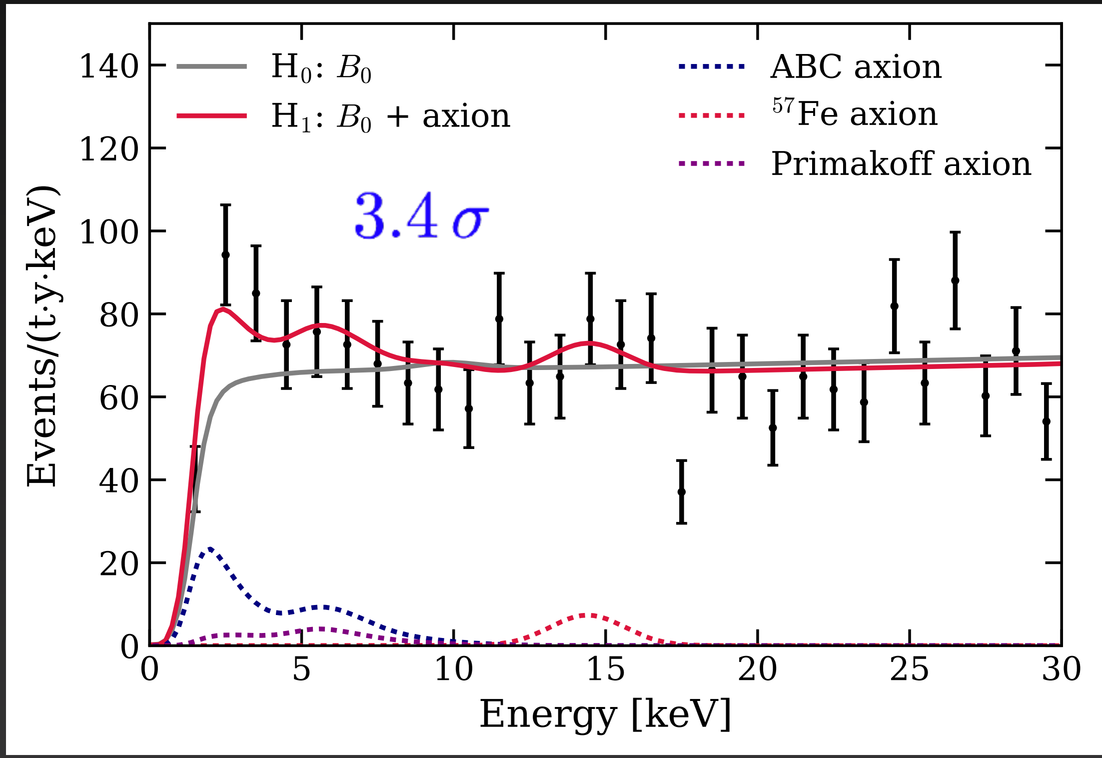


- Dominant background from beta decay of ^{214}Pb, a daughter of ^{222}Rn
- ~13 μBq/kg ^{222}Rn
- Lowest ER background level among all dark matter direct detection experiments (before XENONnT is online)

PRD 102, 072004 (2020)

Solar Axion Hypothesis

Model independence: three components scale independently



Most favored hypothesis by the XENON1T low-energy excess data

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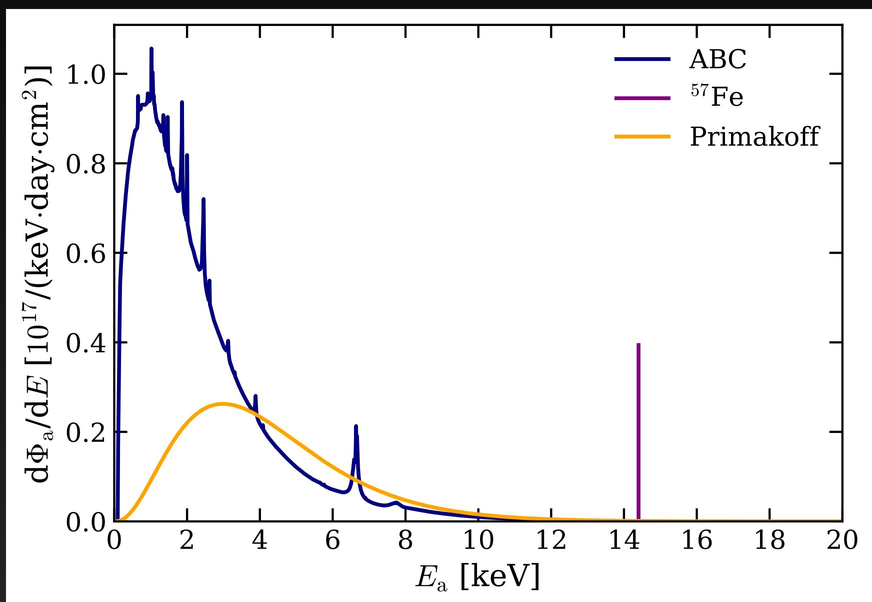
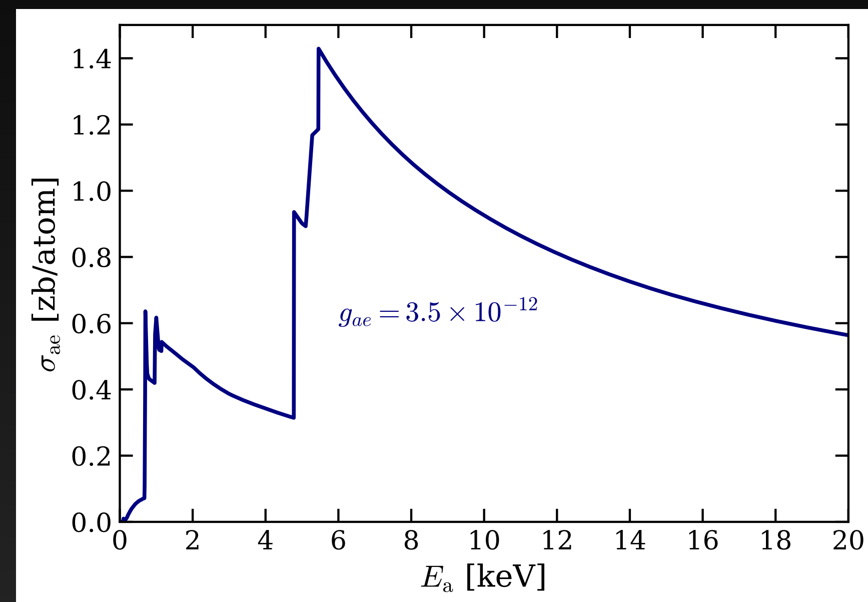
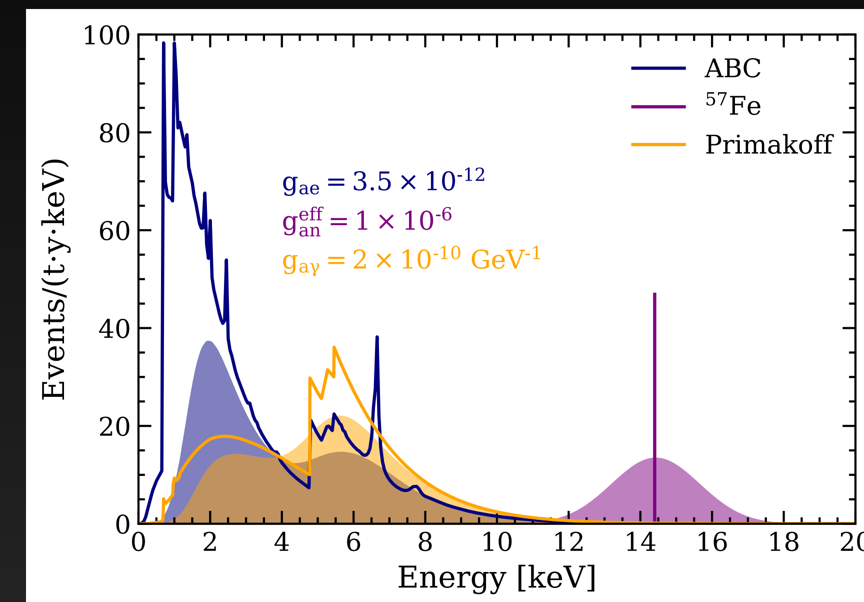
Solar Axion Hypothesis







Production * Detection

Reconstruction
(Efficiency, energy resolution)
= Final spectra

Axion

Electron	Photon	Nucleon
g_{ae}	$g_{\mathrm{a}\gamma}$	g_{an}

Axio-electric effect

$$\sigma_{\mathrm{ae}} = \sigma_{\mathrm{pe}} \frac{g_{\mathrm{ae}}^2 E_{\mathrm{a}}^2}{8\pi\alpha m_{\mathrm{e}}^2}$$

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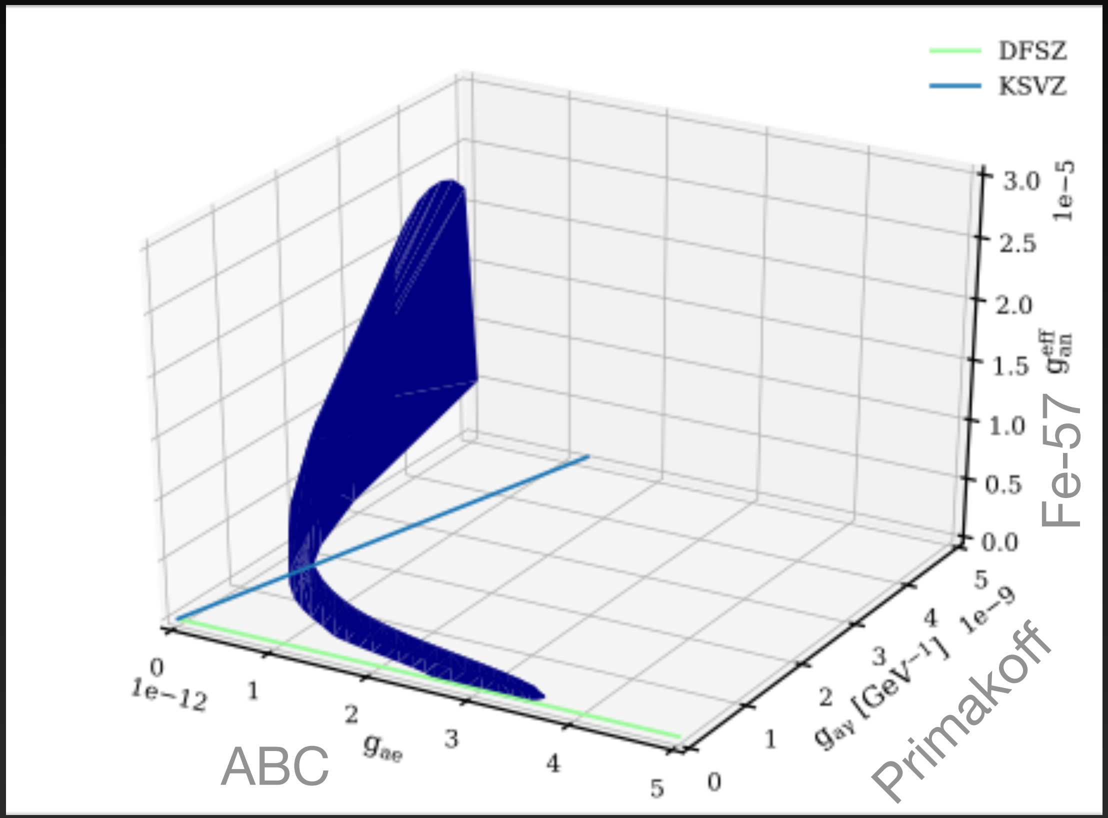
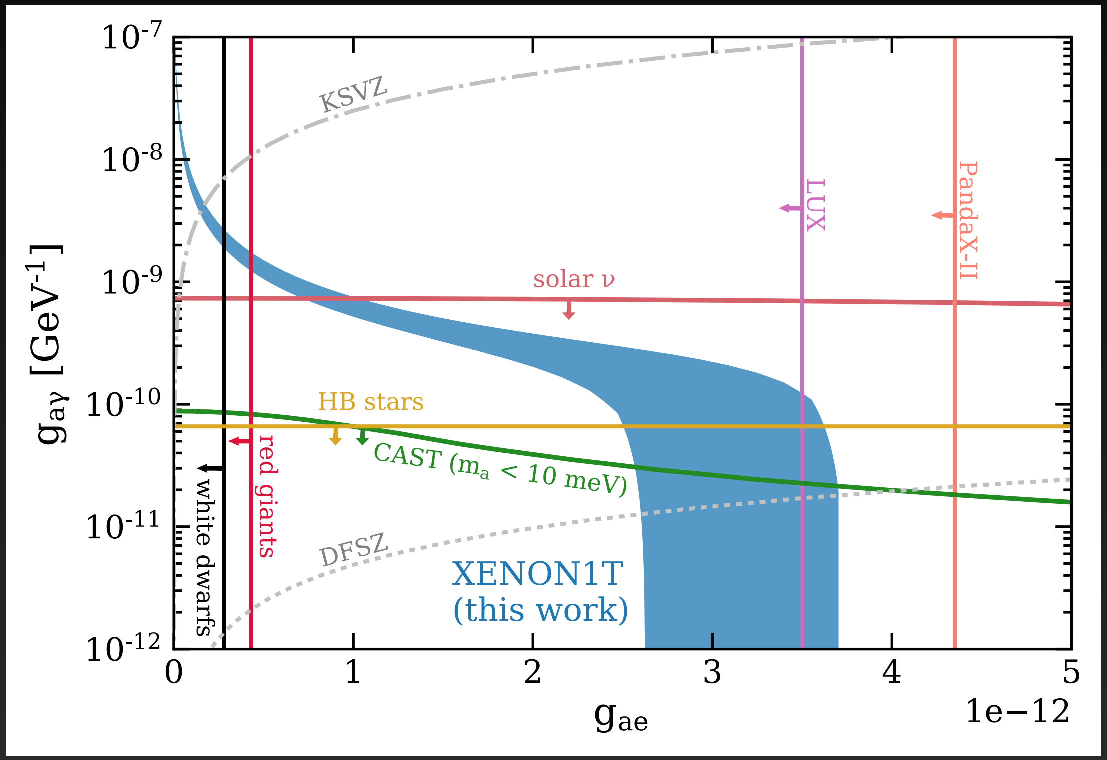
Solar Axion Results

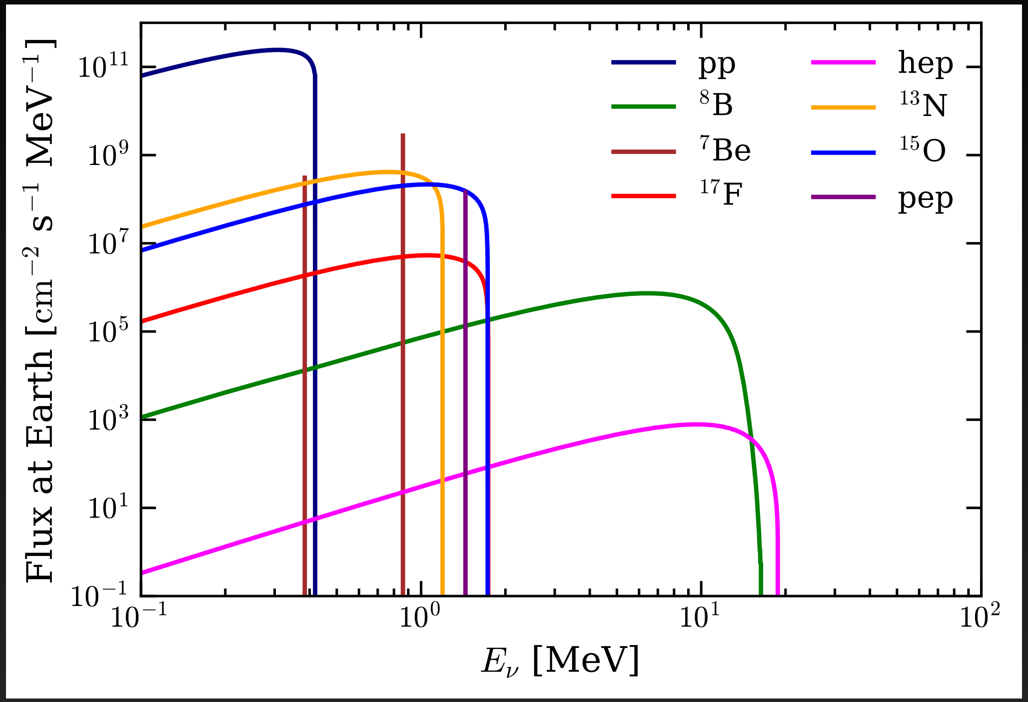




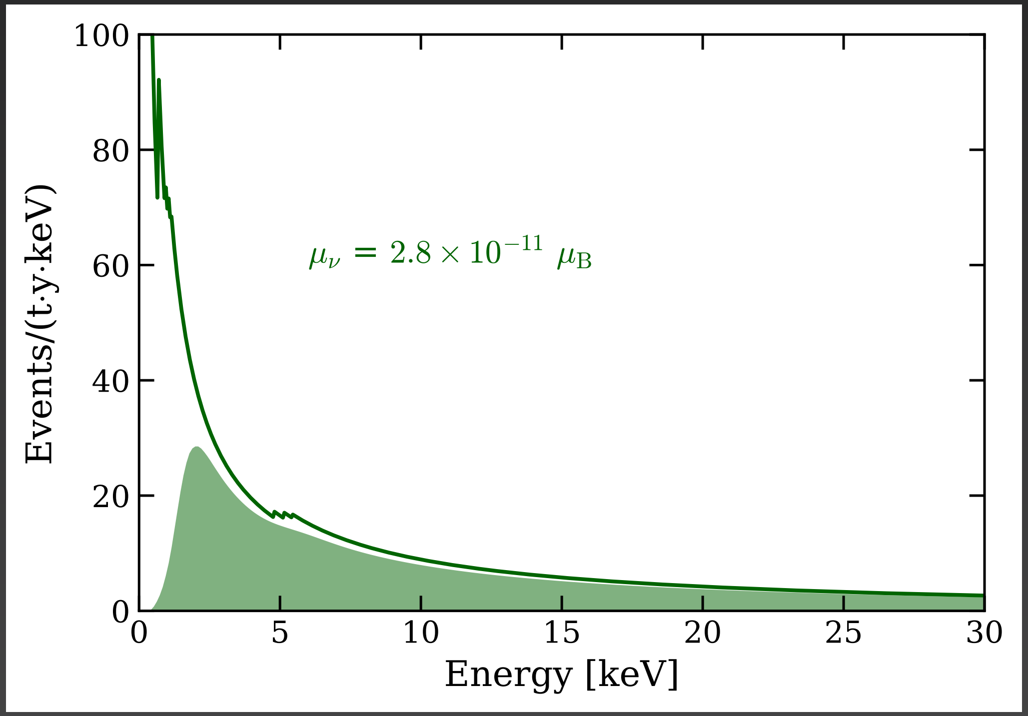
90% confidence level volume in three axion coupling space

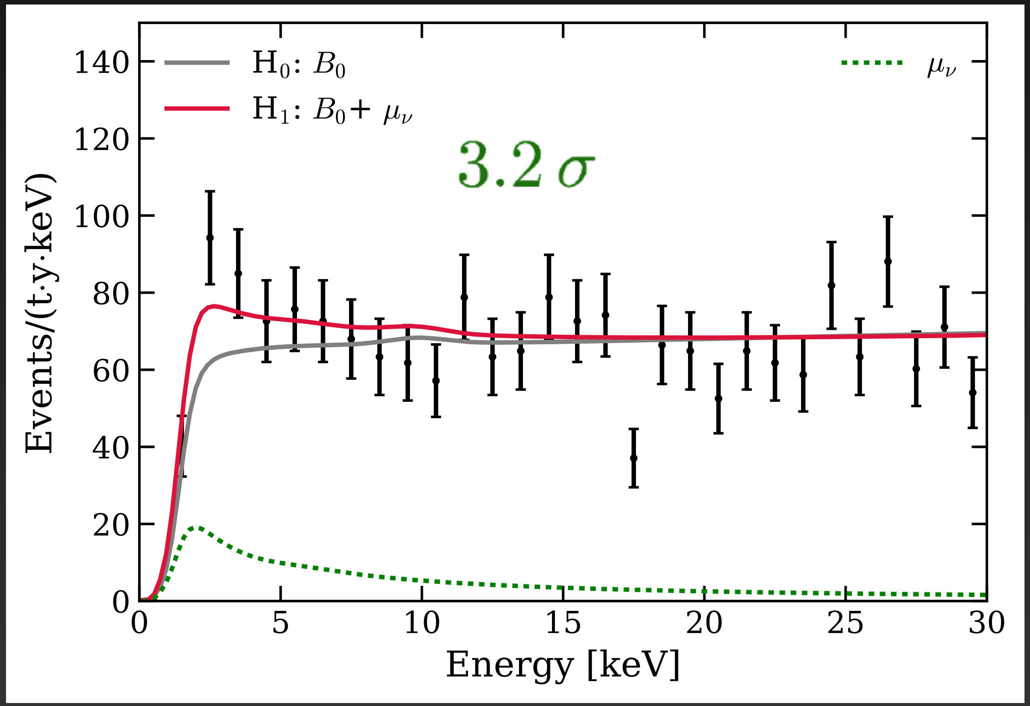
Project to 2D for easy visualization

Neutrino Magnetic Moment Hypothesis



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





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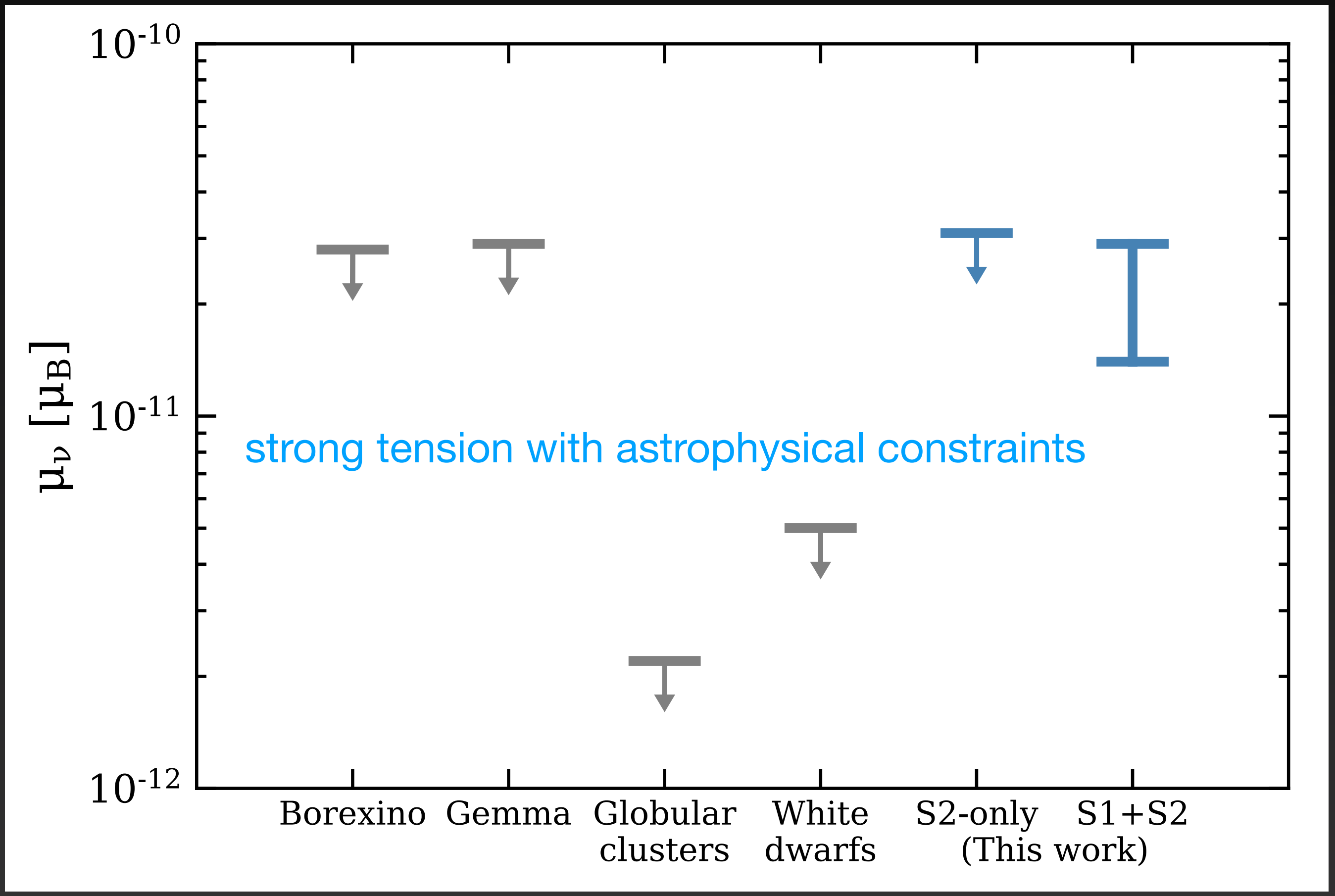
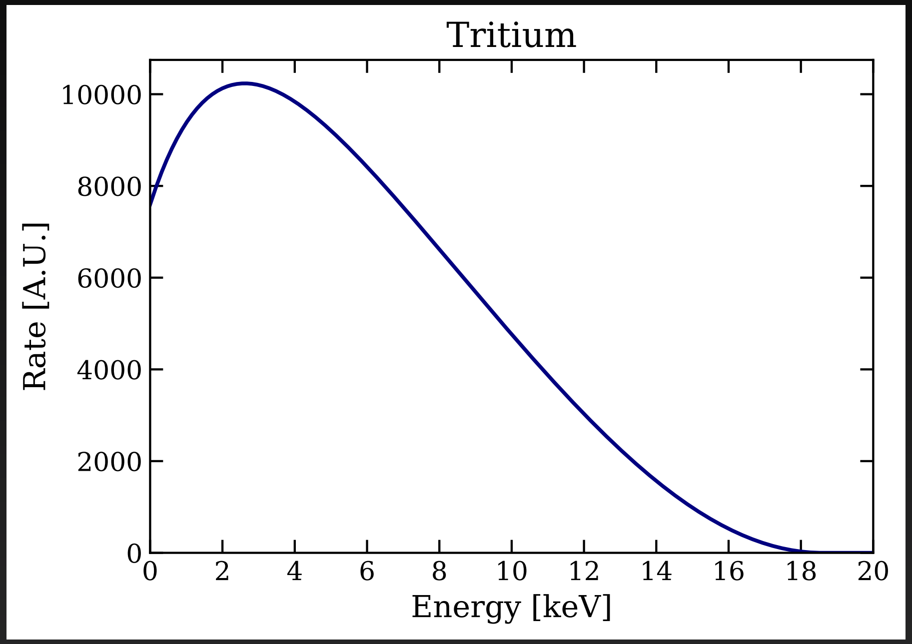
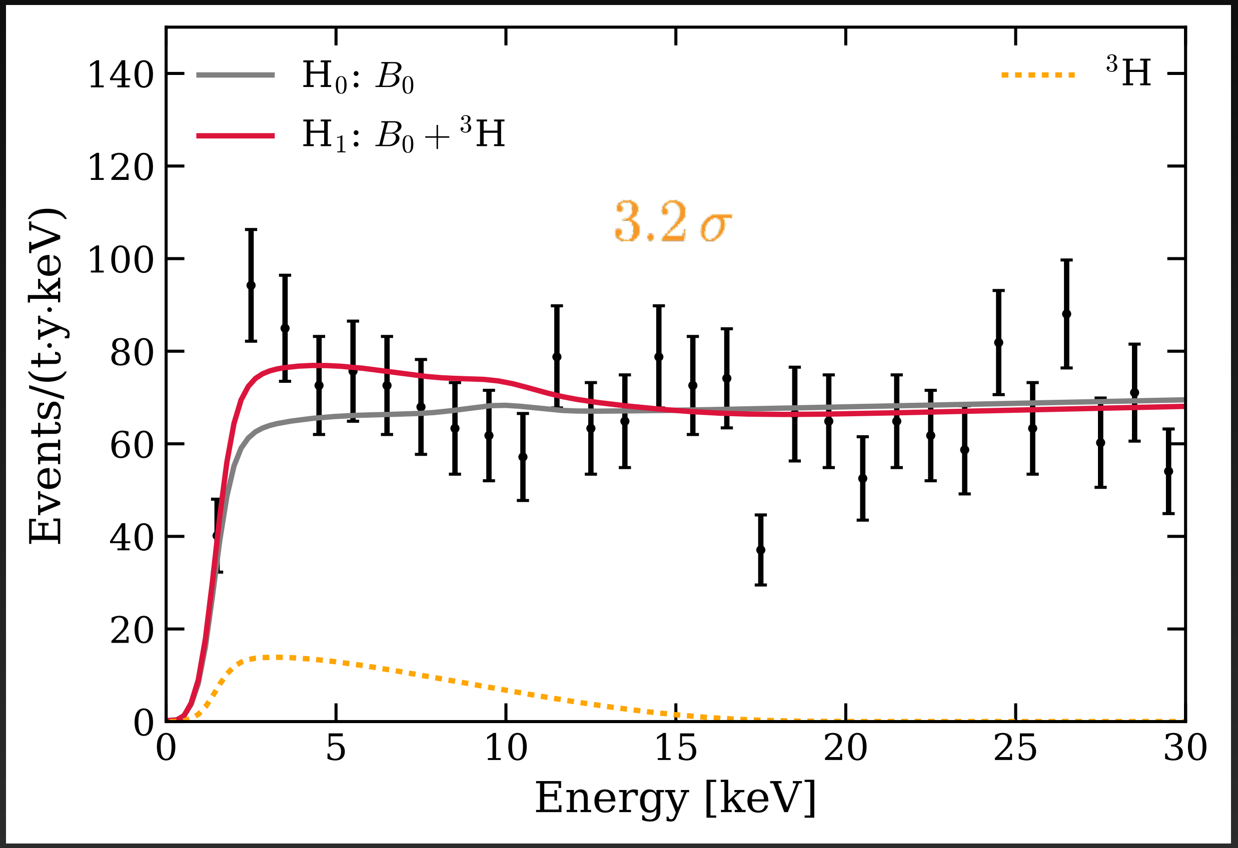
Neutrino Magnetic Moment



Tritium Background Hypothesis





Peaked at low energies

Long half-life (12.3 years)

Fitted rate: (159 ± 51) events/(t·y)

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

~3 tritium atoms per kg xenon

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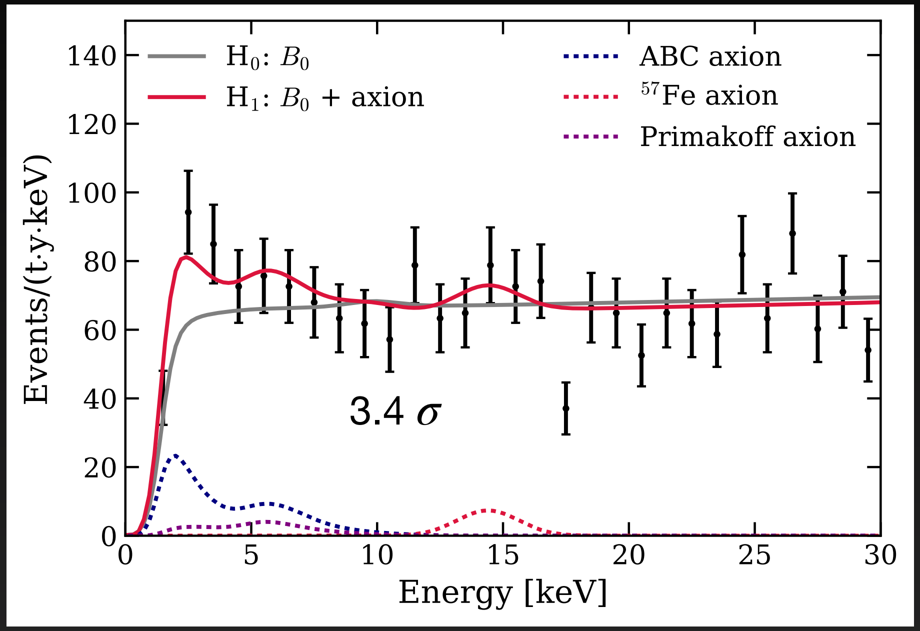
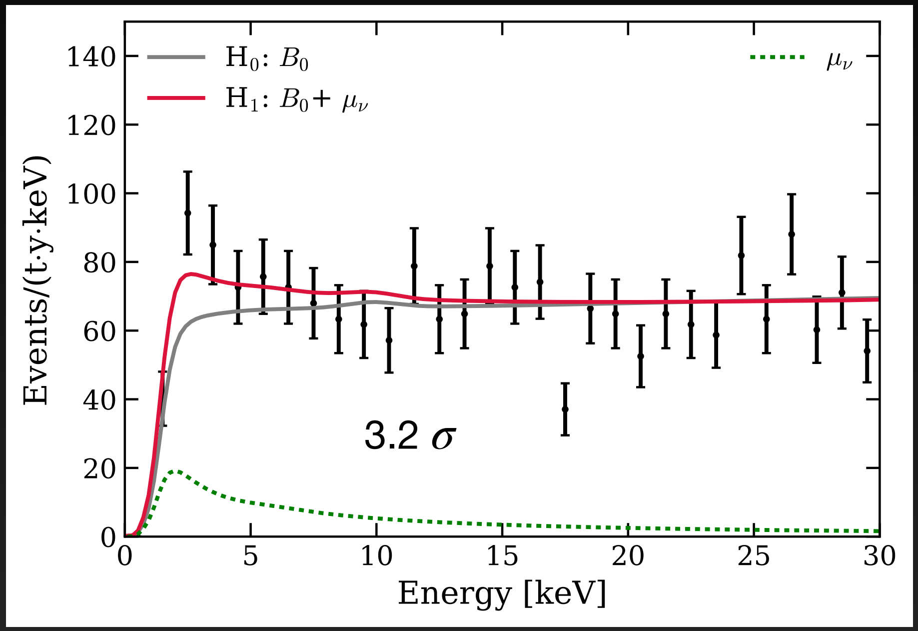
Possible Explanations

Solar axion

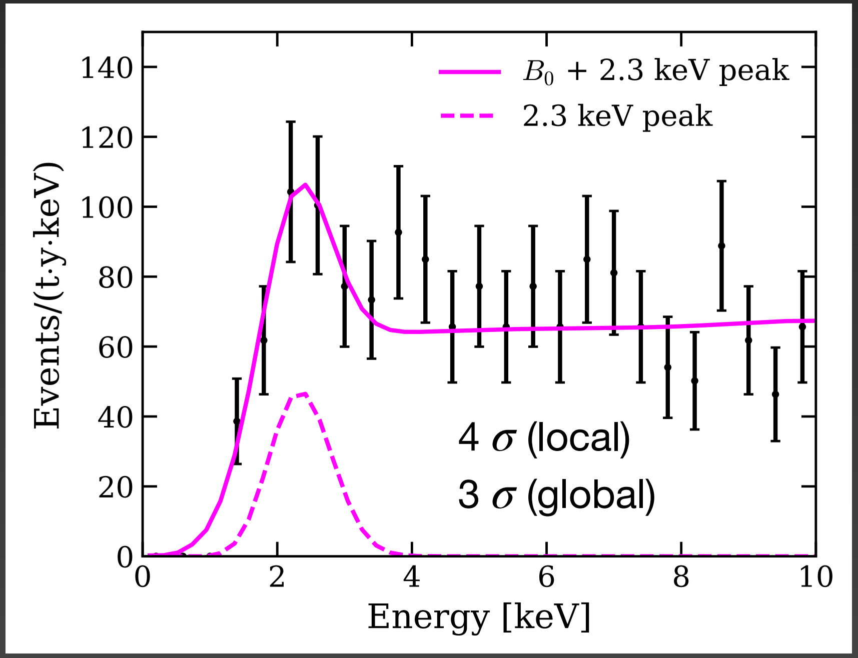


Solar neutrino with an enhanced magnetic moment

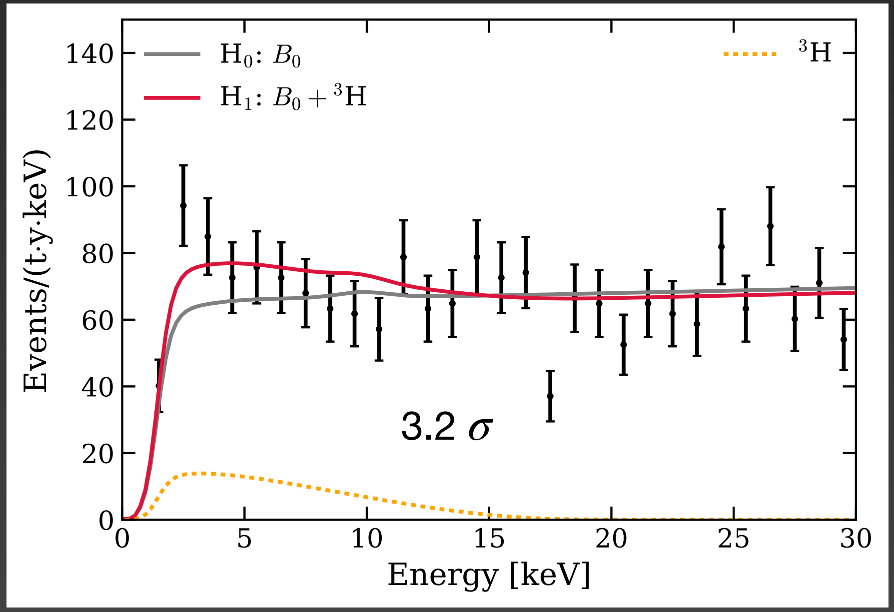


New physics?
Or unexpected backgrounds?

A generic mono-energetic peak
Best-fit @2.3 keV



Tritium



XENON Collaboration,
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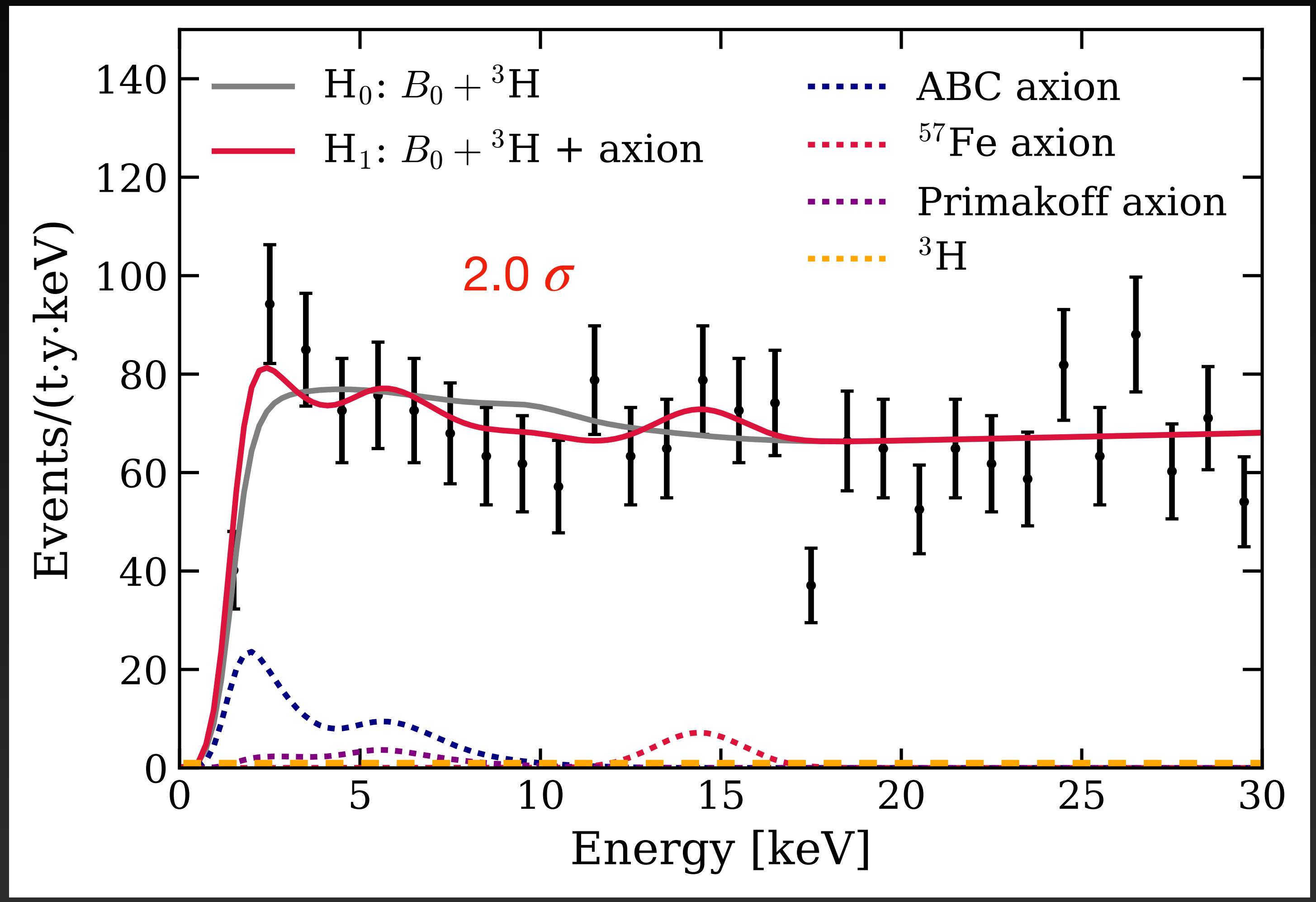
Solar Axion vs. Tritium



An unconstrained tritium component is added to both alternate and null hypothesis

Tritium is outperformed by solar axions

The significance of solar axion hypothesis is reduced to 2.0 σ

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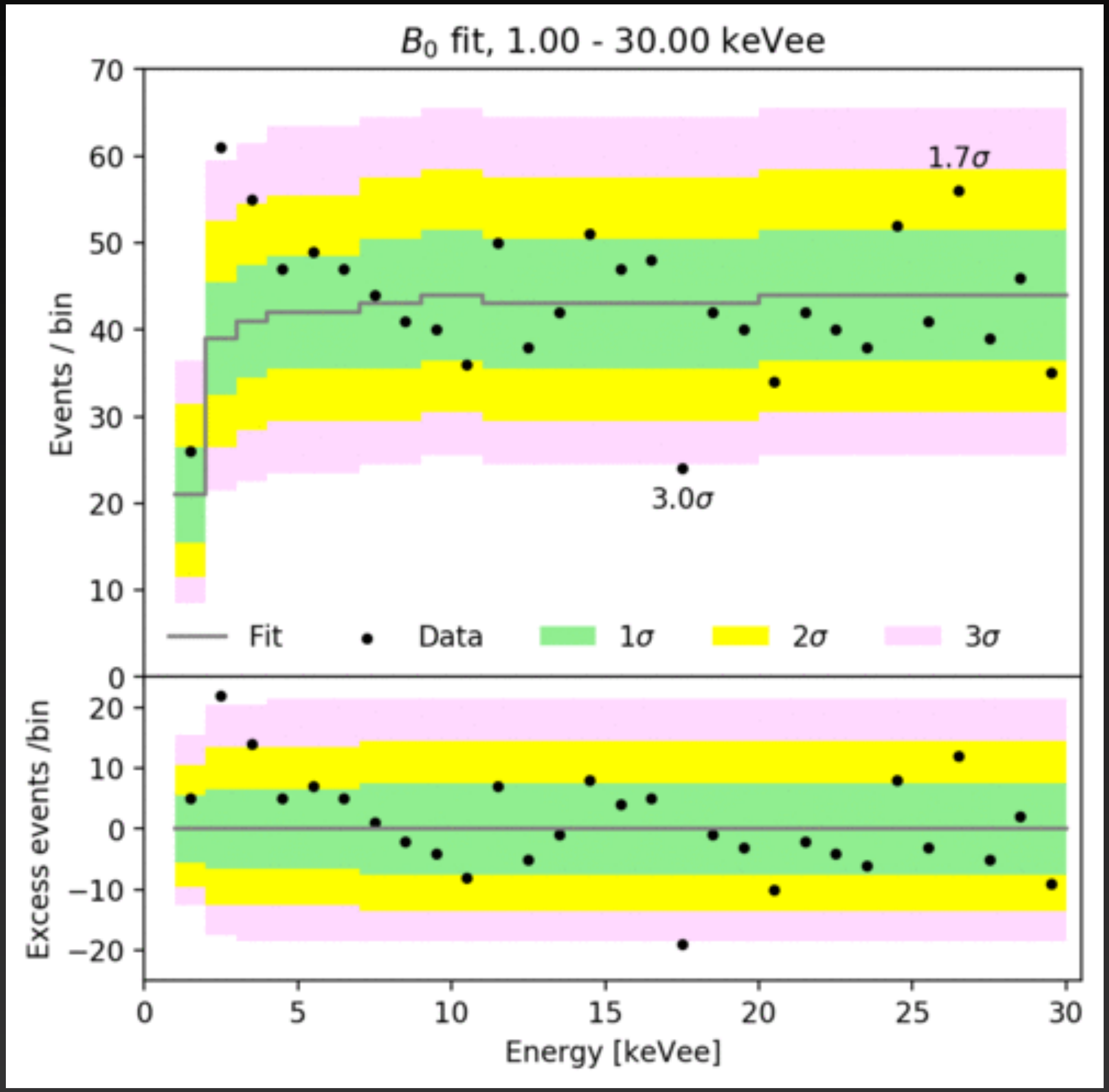
Deficit around 17 keV?

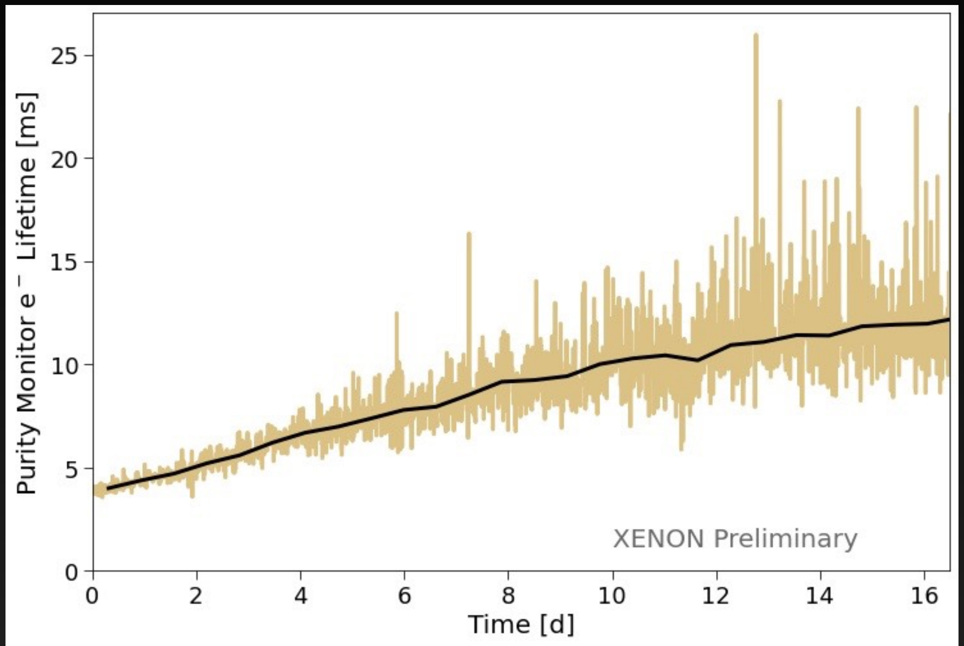


Unbinned likelihood used in analysis

Deficit gone with rebinning

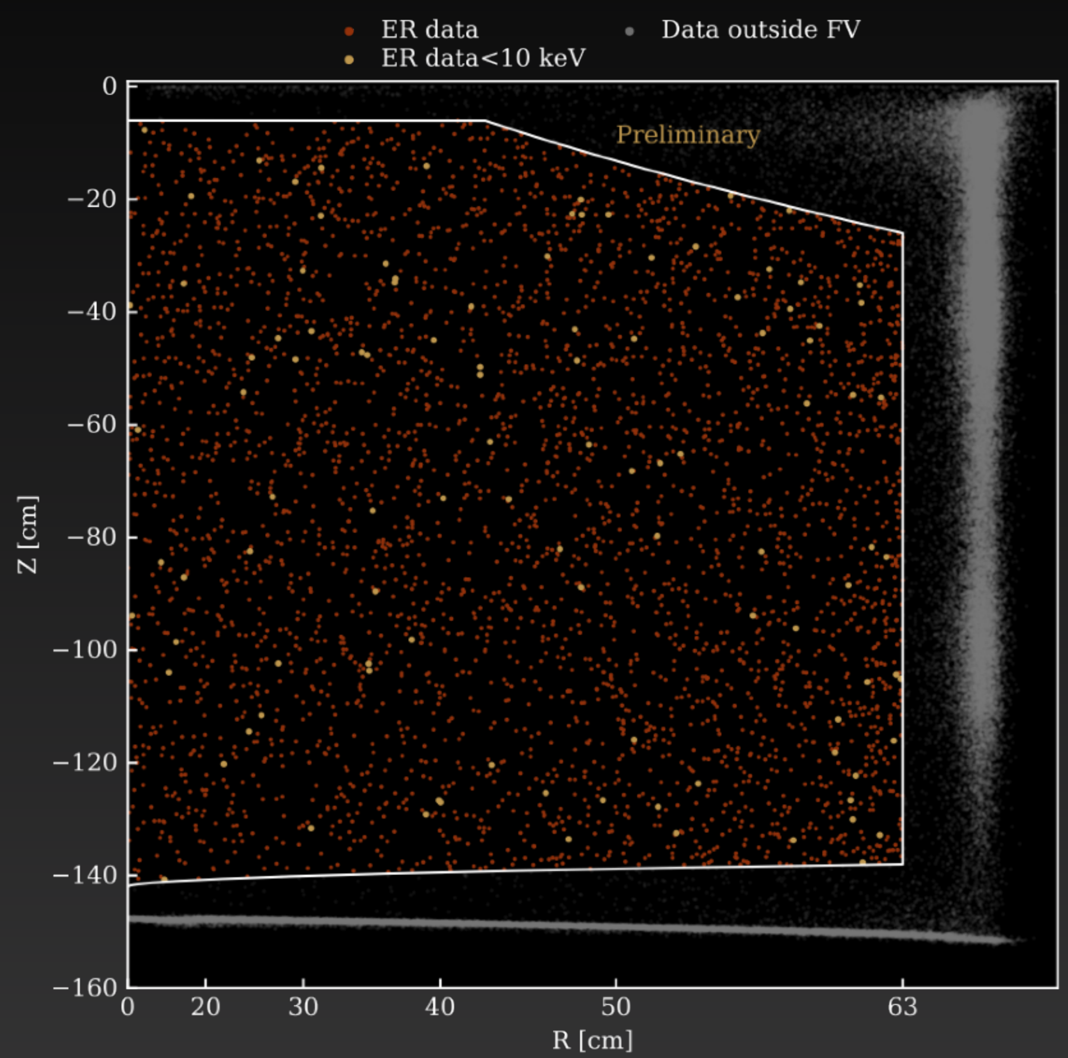
XENONnT Upgrades

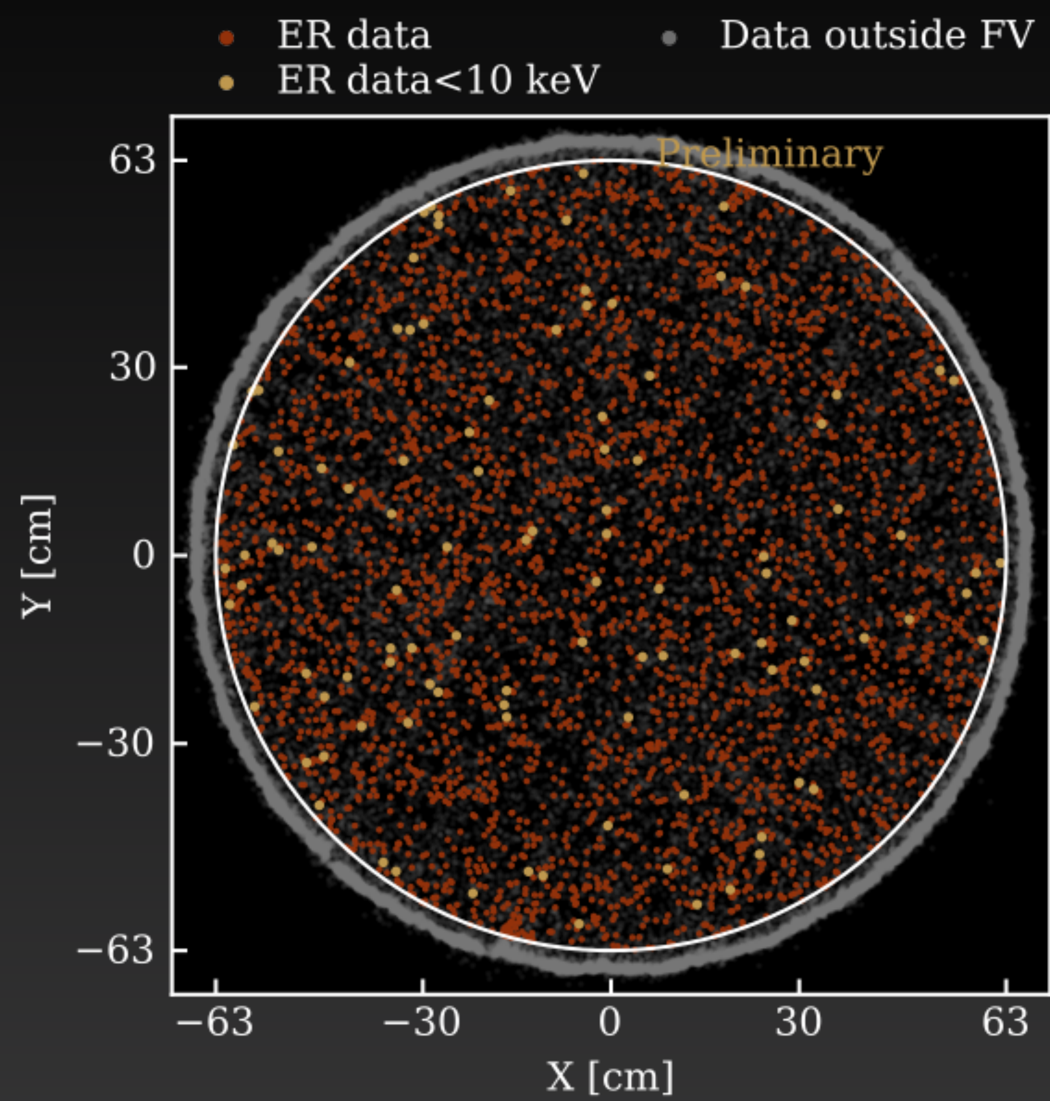
Liquid purification system



- Excellent purity achieved within the 8.5 tonne total mass
- Unprecedented long electron lifetime in a LXe TPC (currently 20 ms)
- System uses ultra-low radon emanation purifiers

Event distribution





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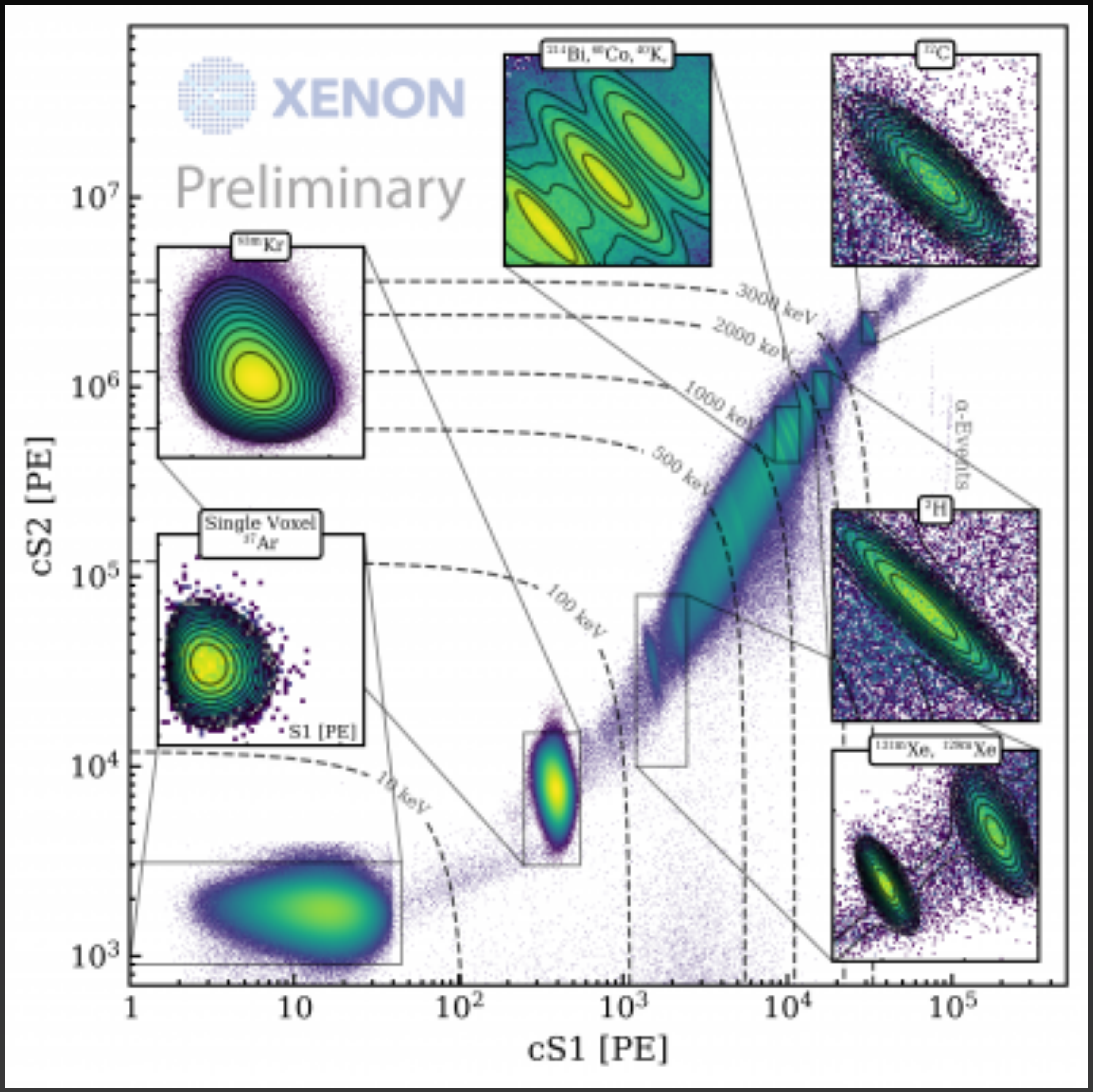
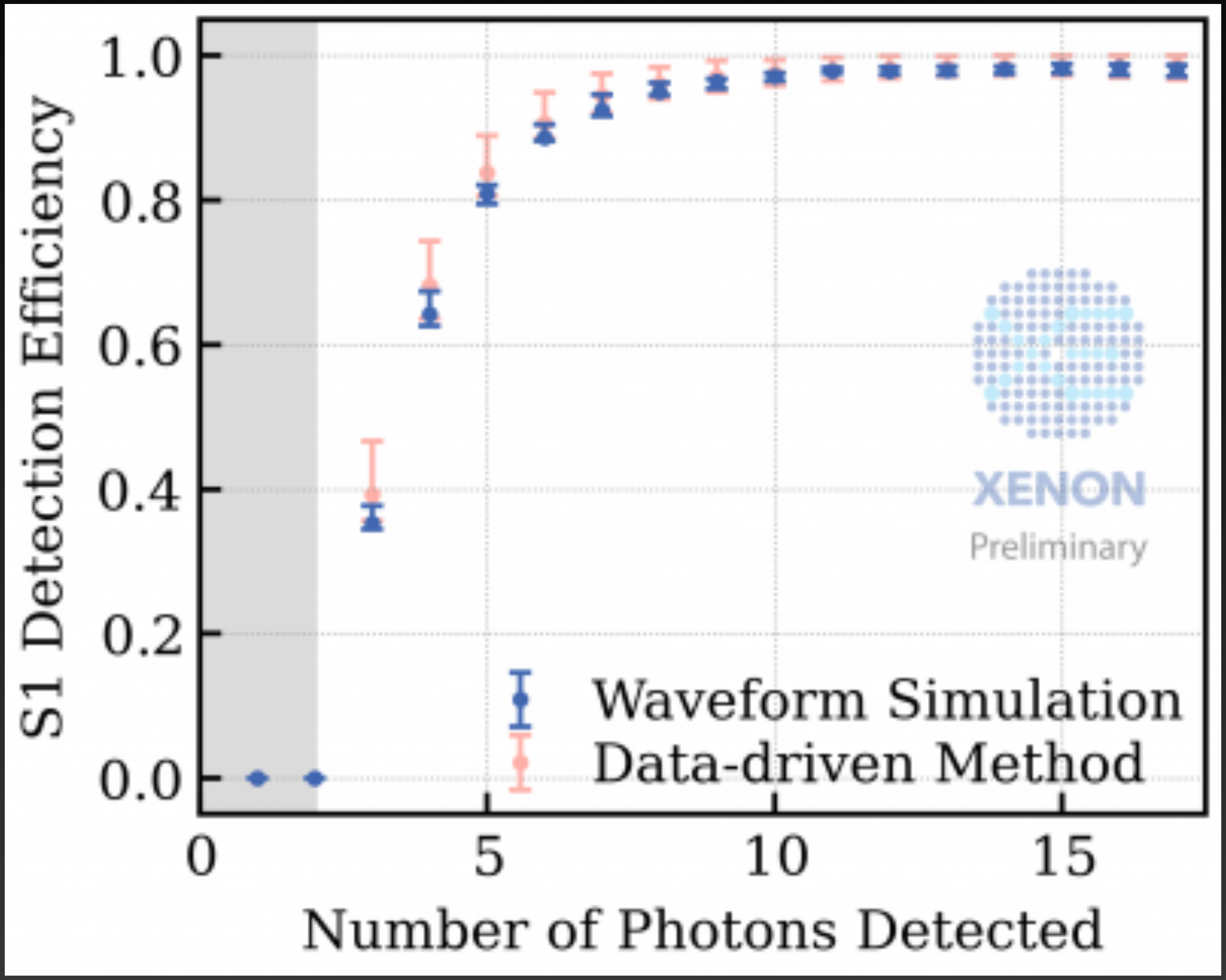
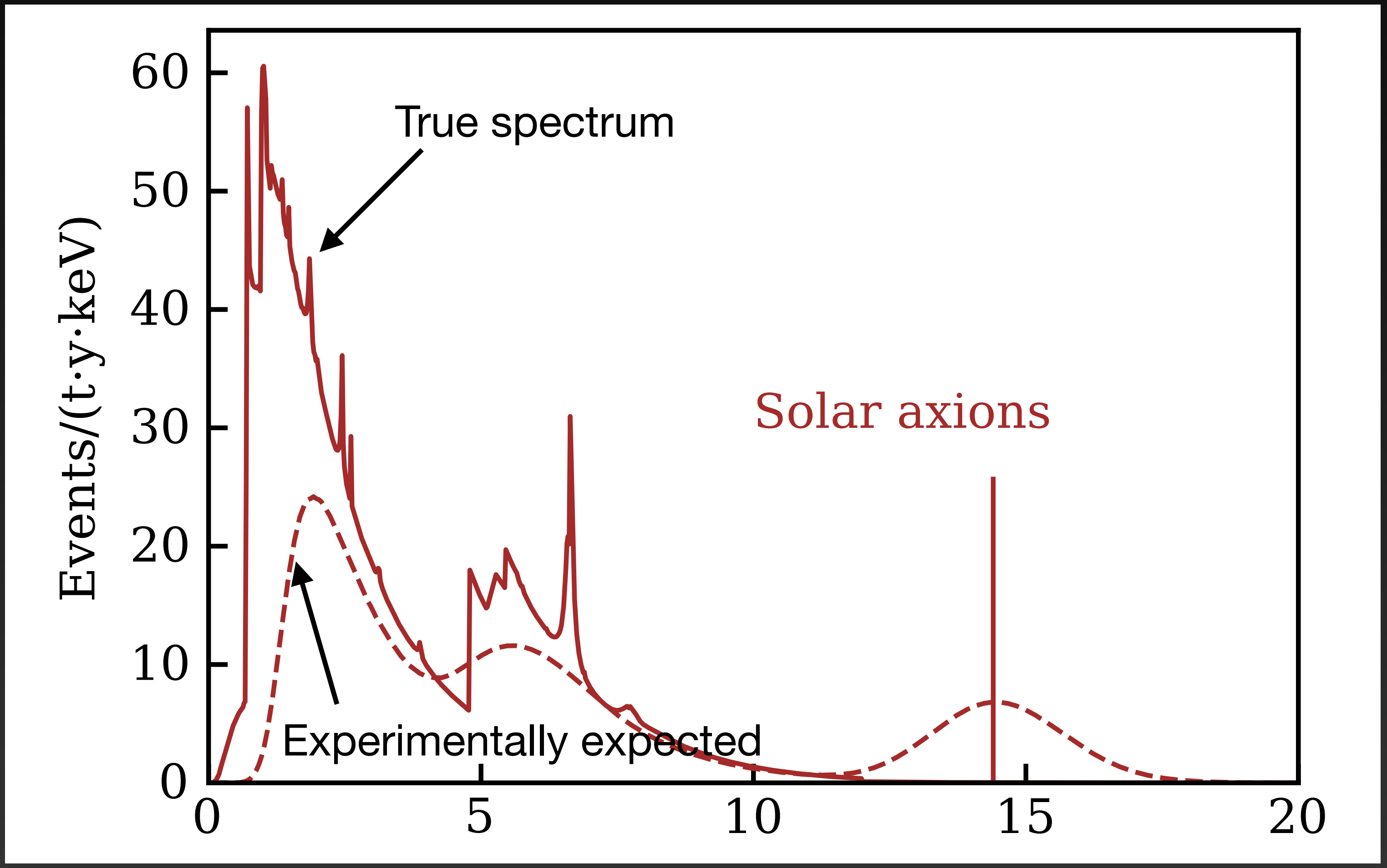
Energy Reconstruction

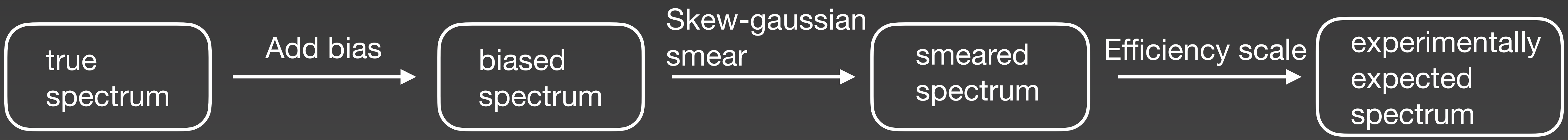


Detection Efficiency

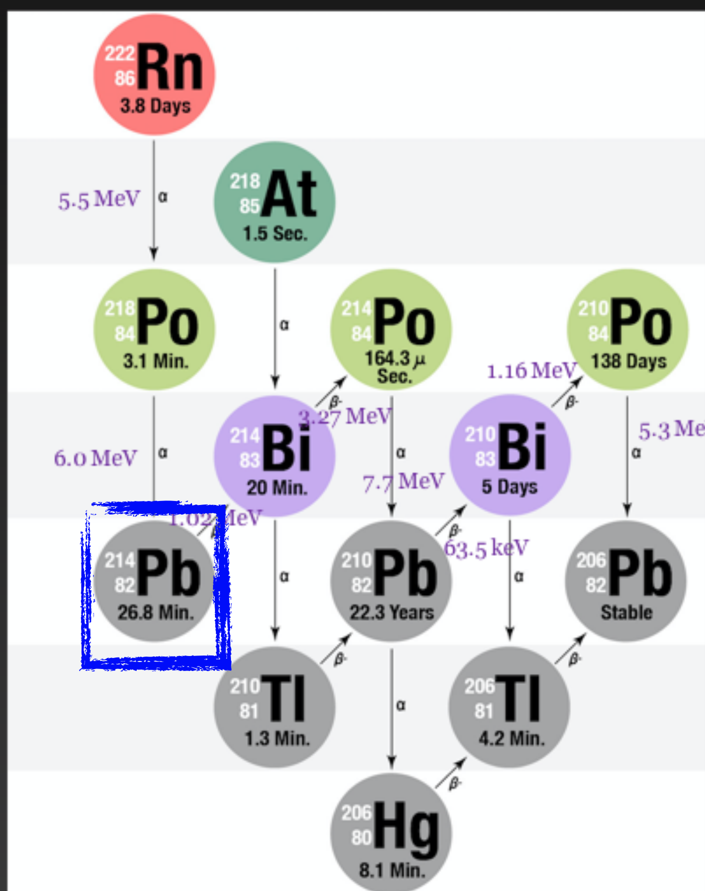


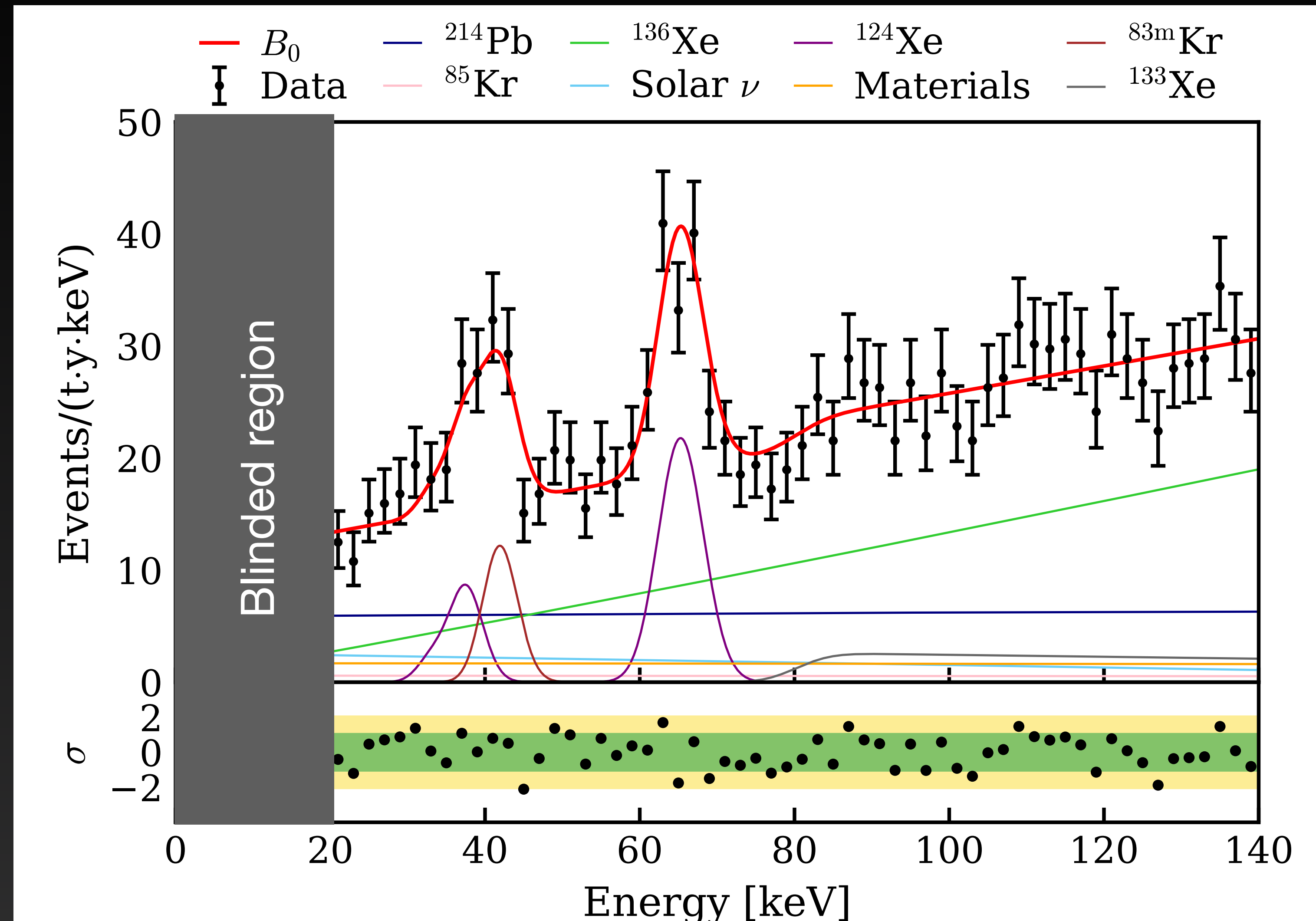
Energy Spectrum Modeling





Backgrounds





- ^{222}Rn: $\sim 1.7\,\mu$Bq/kg (XENON1T SR1: $\sim 12\,\mu$Bq/kg)
- (660 ± 110) ppq(56 ± 36) ppq
- ^{214}Pb rate is constrained by a uniform distribution between ^{214}Po and ^{218}Po in the fit
  - : $(0.777 \pm 0.006_{\text{stat}} \pm 0.032_{\text{sys}})\,\mu$Bq/kg
  - ^{218}Po: $(1.691 \pm 0.006_{\text{stat}} \pm 0.072_{\text{sys}})\,\mu$Bq/kg
- Spectral shape dominated by two double-weak decays:
  - ^{124}Xe 2νECEC
  - ^{136}Xe $2\nu\beta\beta$
- ^{83m}Kr background is due to leftover of calibrations; unconstrained in the fit