XENON

香港中文大學(深圳)
The Chinese University of Hong Kong, Shenzhen

Search for Dark Matter with XENONnT

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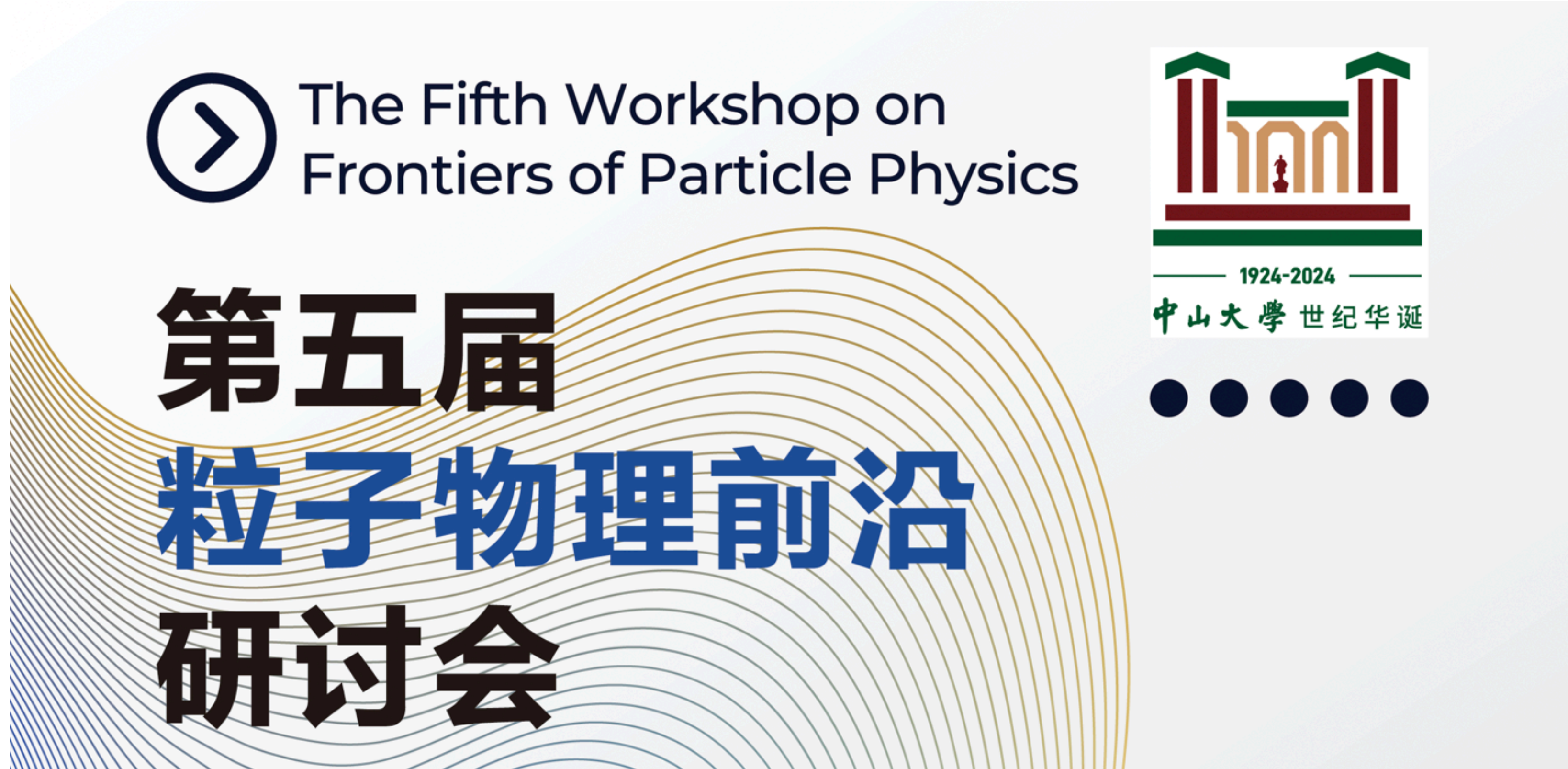
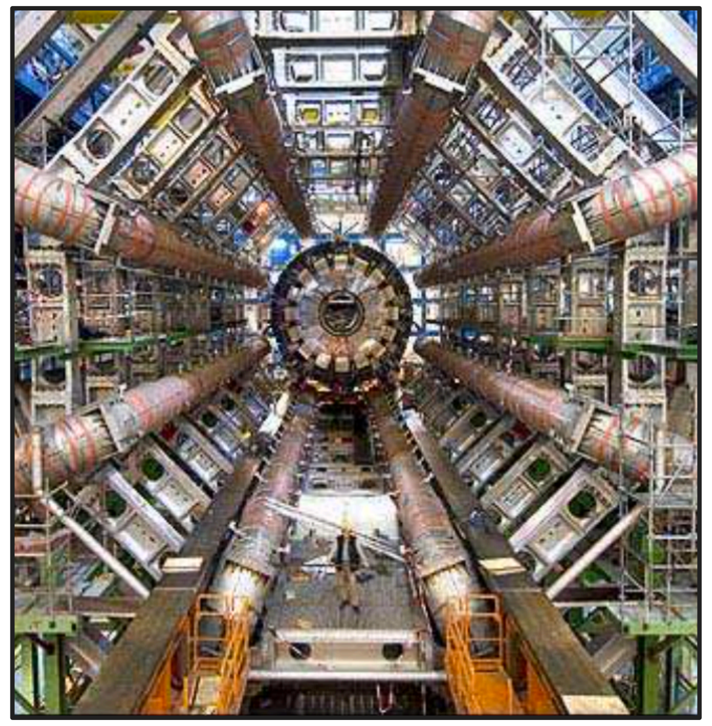
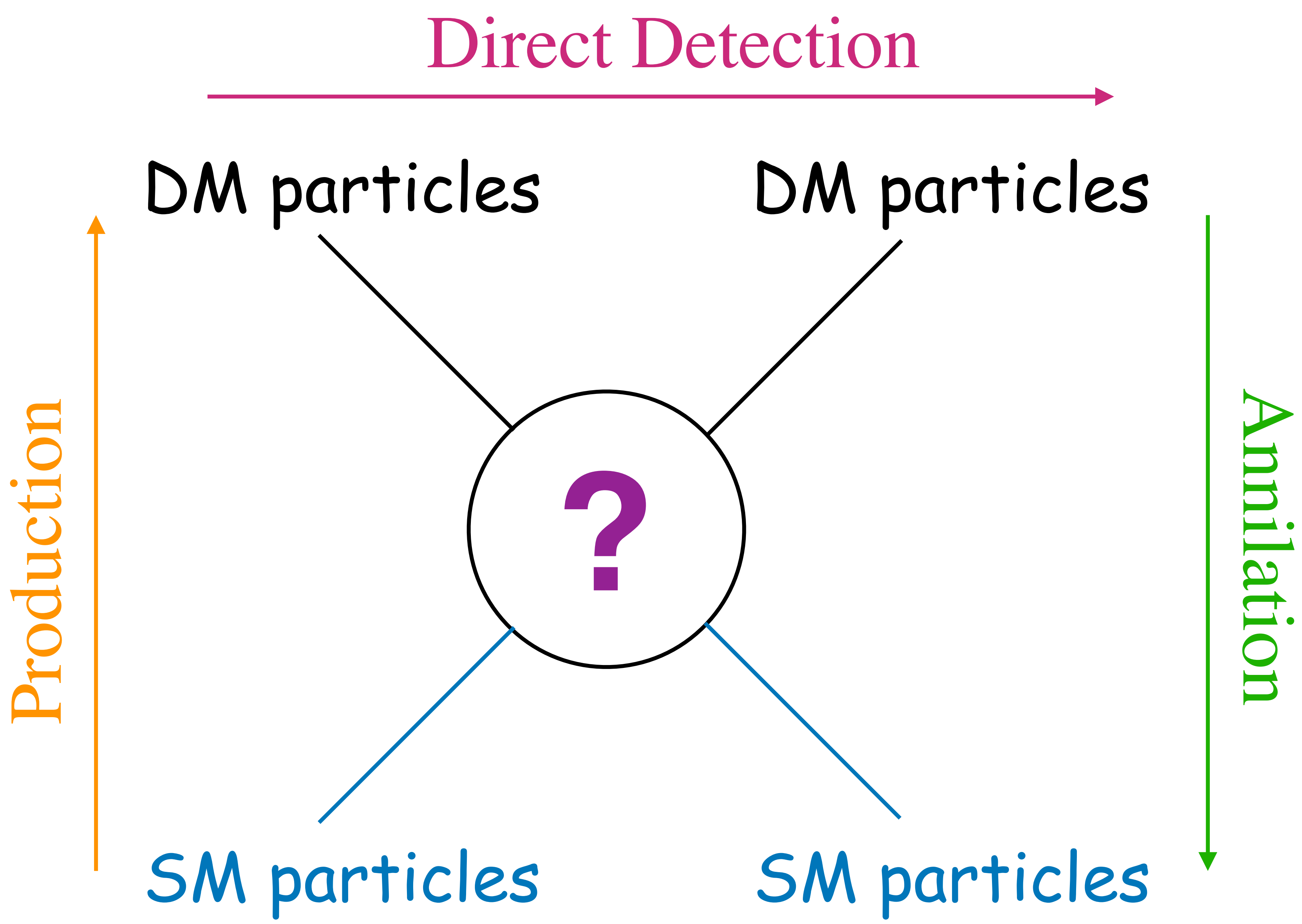
The Chinese University of Hong Kong, Shenzhen
On behalf of the XENON Collaboration

The Fifth Workshop on Frontiers of Particle Physics
April 15, 2024



Three ways to detect dark matter



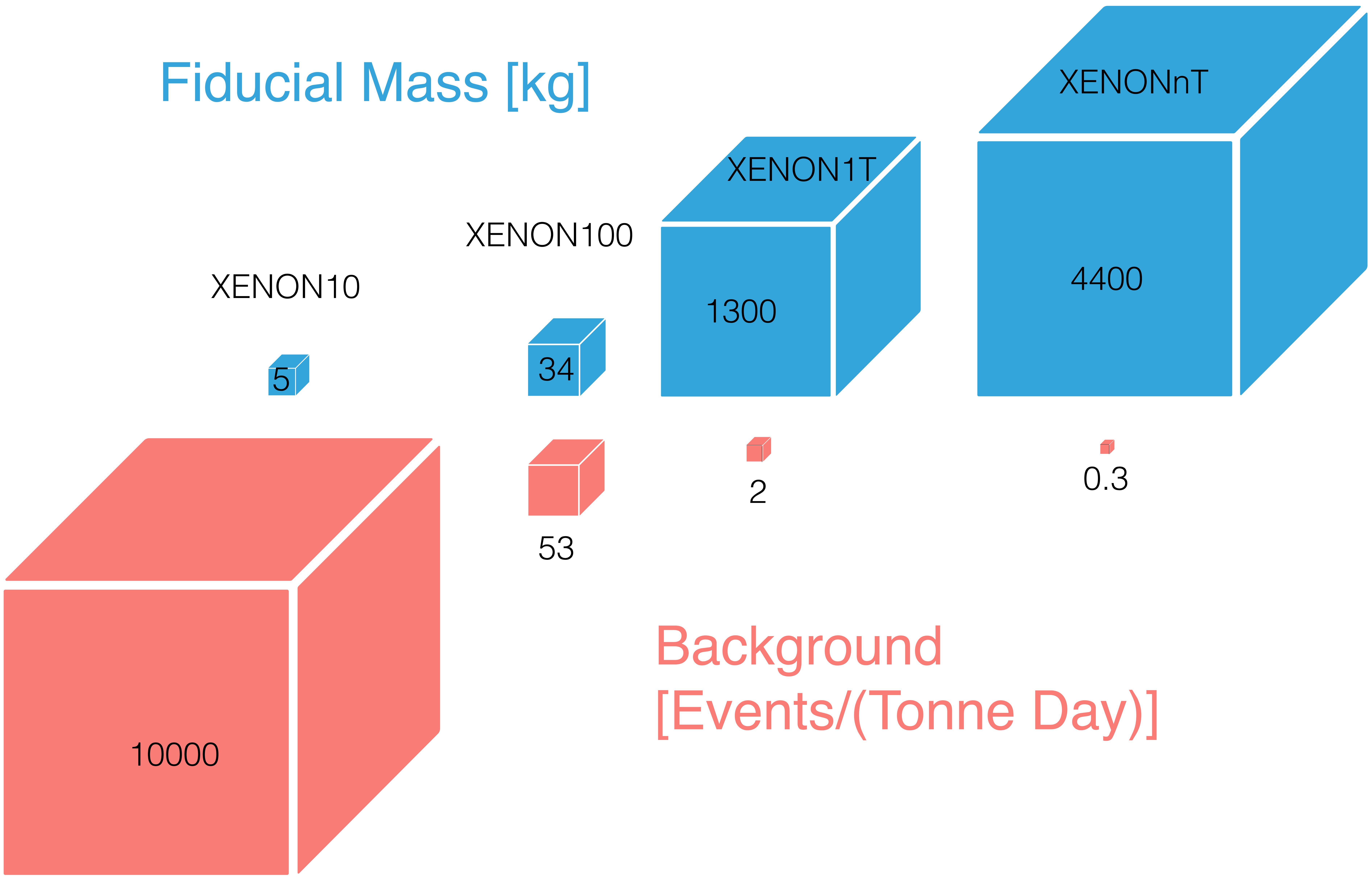


The evolution of XENON experiments




	XENON10	XENON100	XENON1T	XENONnT
Science data taking	2005-2007	2008-2016	2012-2018	2021-2025
Xe Target	14 kg	62 kg	2 t	5.9 t
Background	~2000000 ER events/(keV t y)	1800 ER events/(keV t y)	82 ER events/(keV t y)	15.8 ER events/(keV t y)
WIMP sensitivity	$\sim 10^{-43}$ cm^2	$\sim 10^{-45}$ cm^2	4×10^{-47} cm^2	$\sim 10^{-48}$ cm^2 (projected)

Fiducial mass and background



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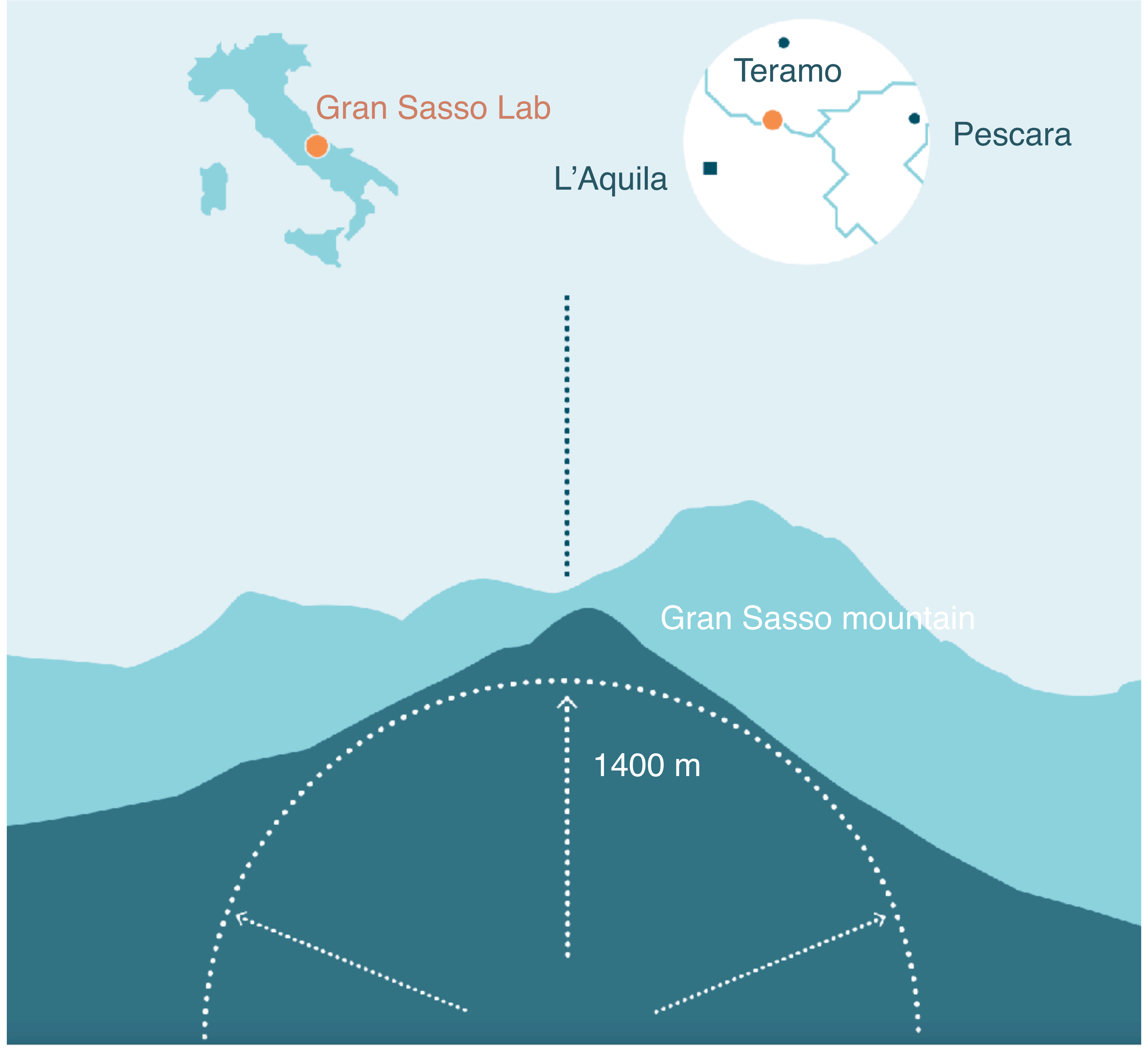
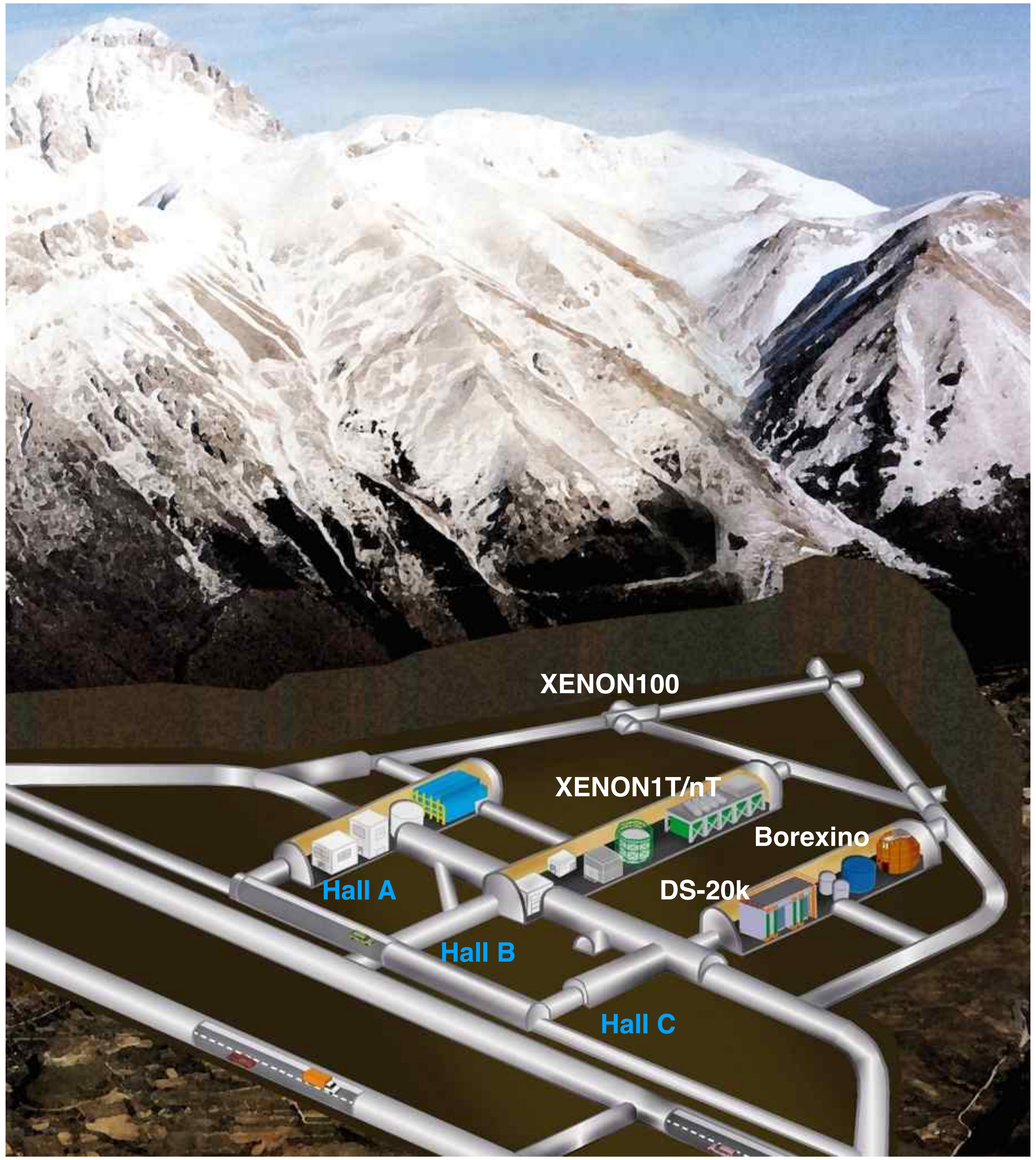
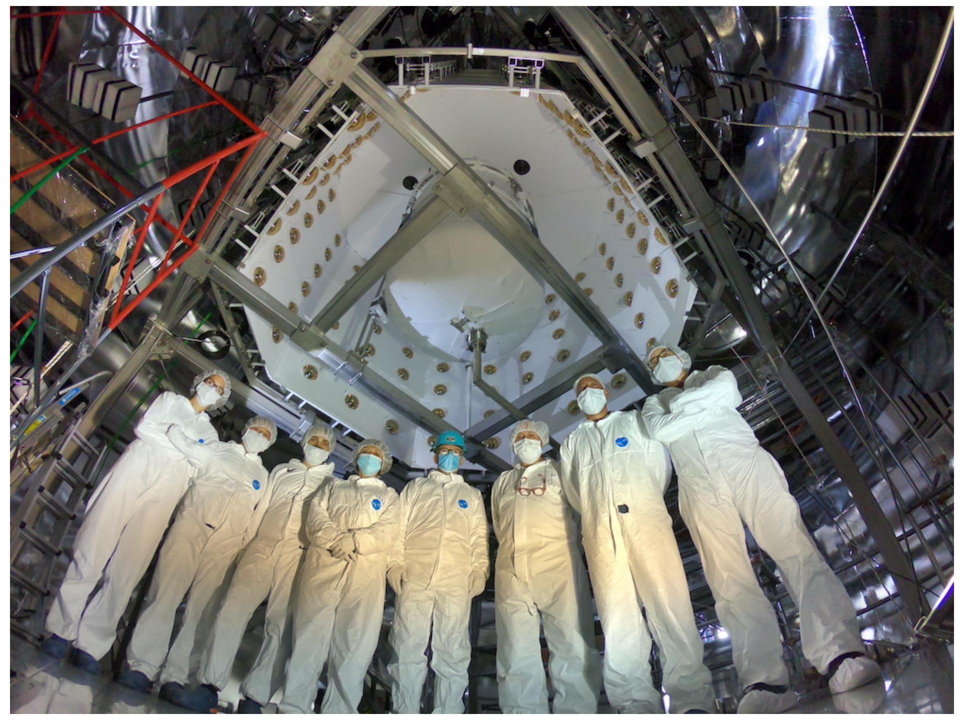


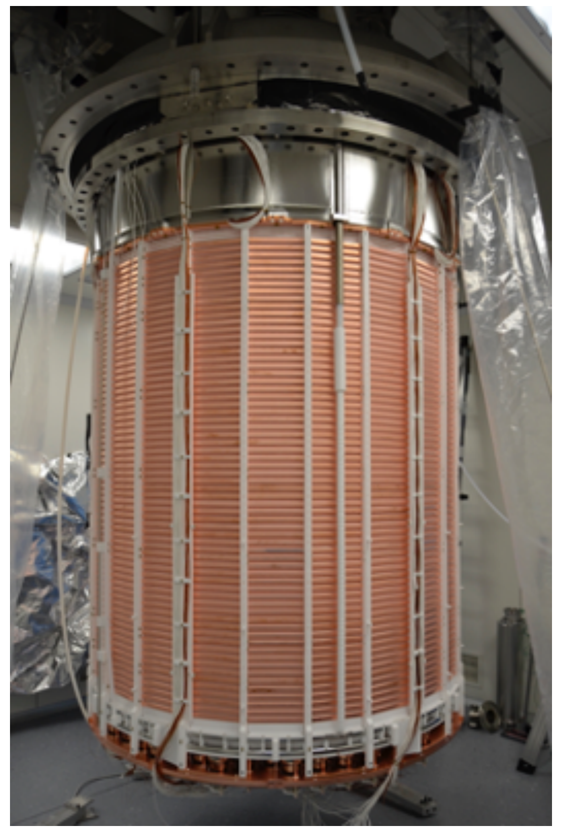


The XENONnT experiment

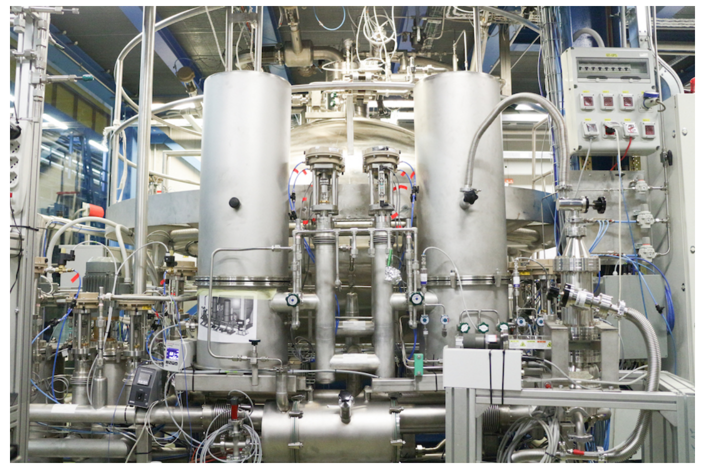


Neutron veto

Radon distillation column



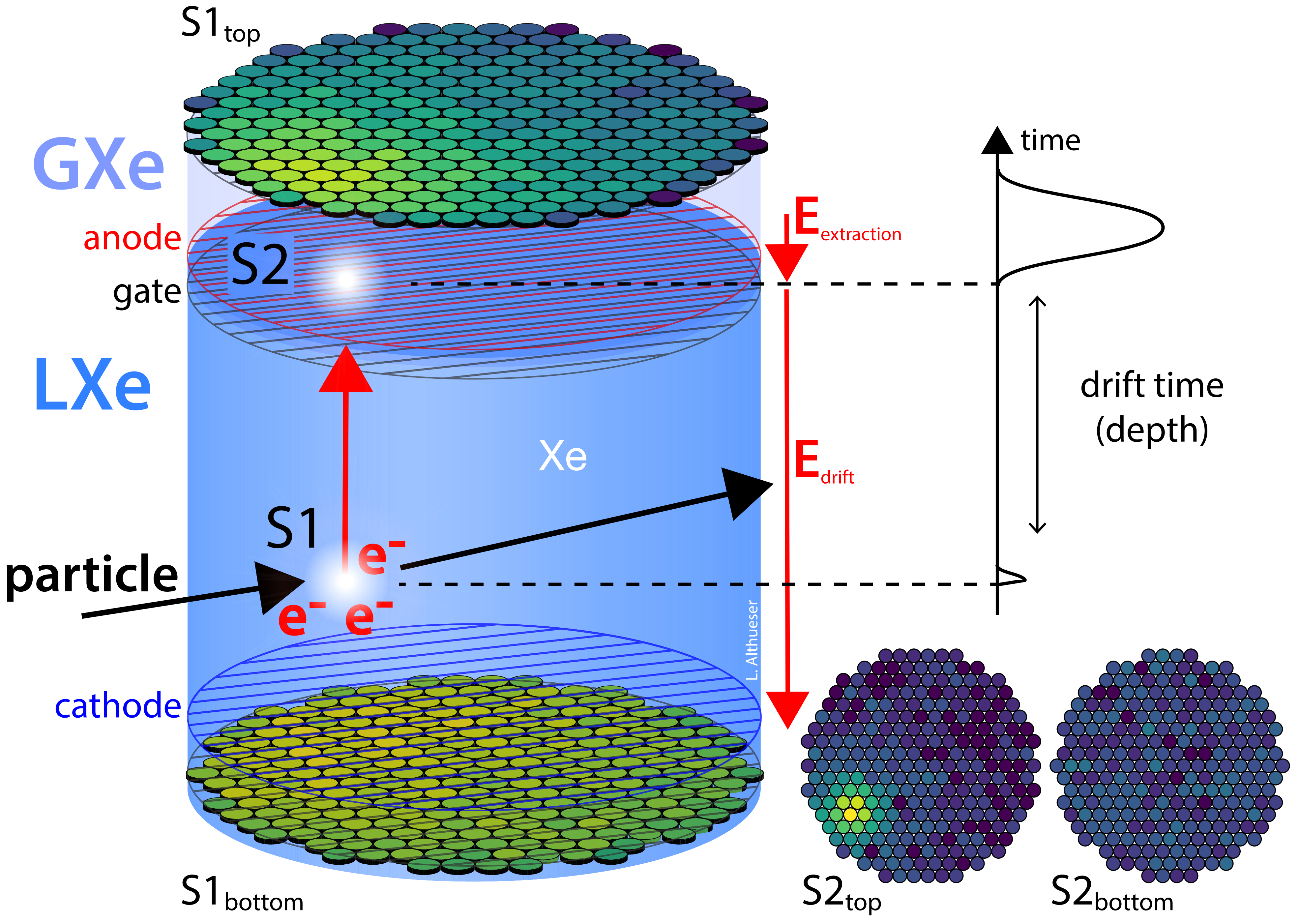
XENONnT TPC



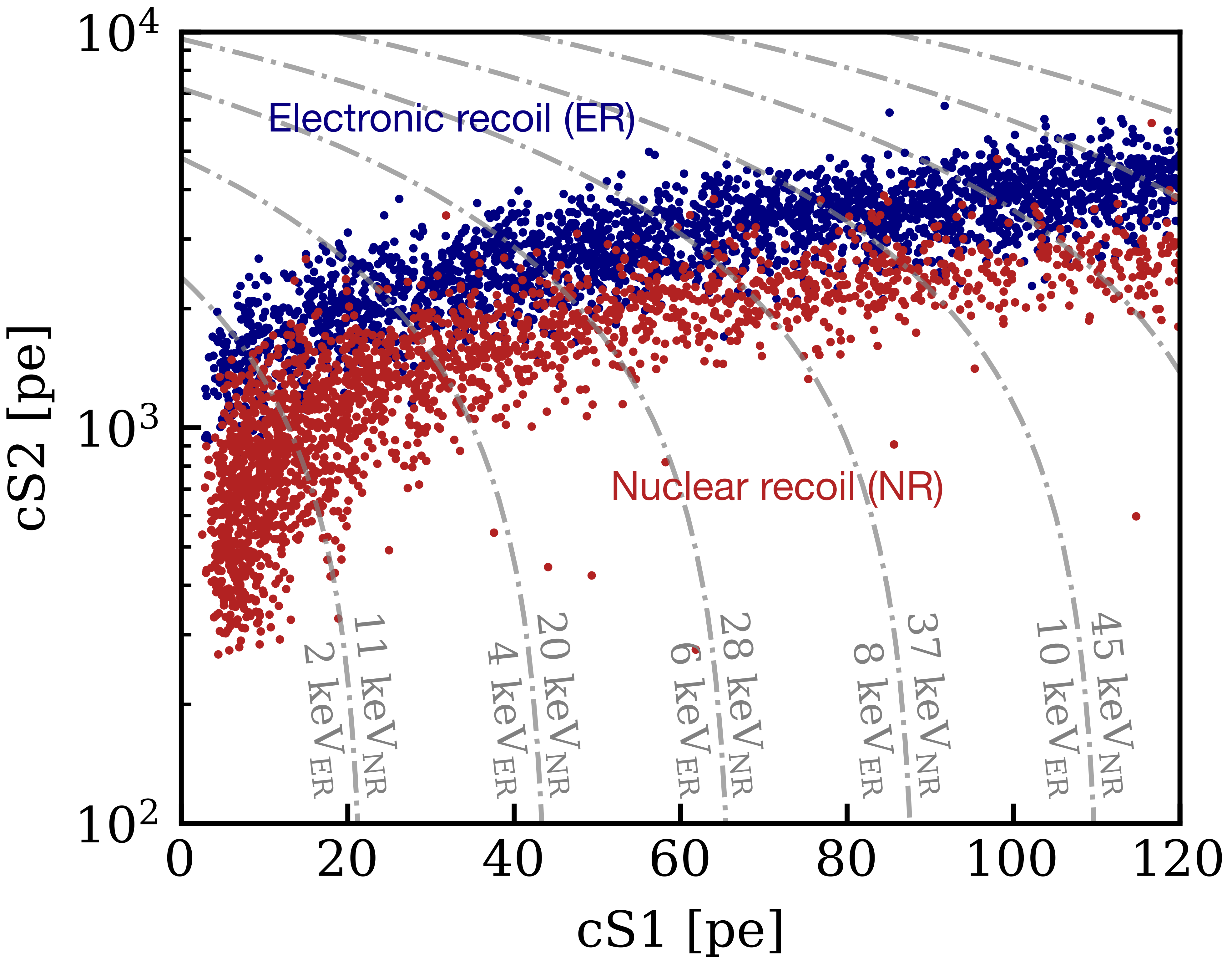
Liquid xenon purification system

Krypton distillation column

Why TPC?



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

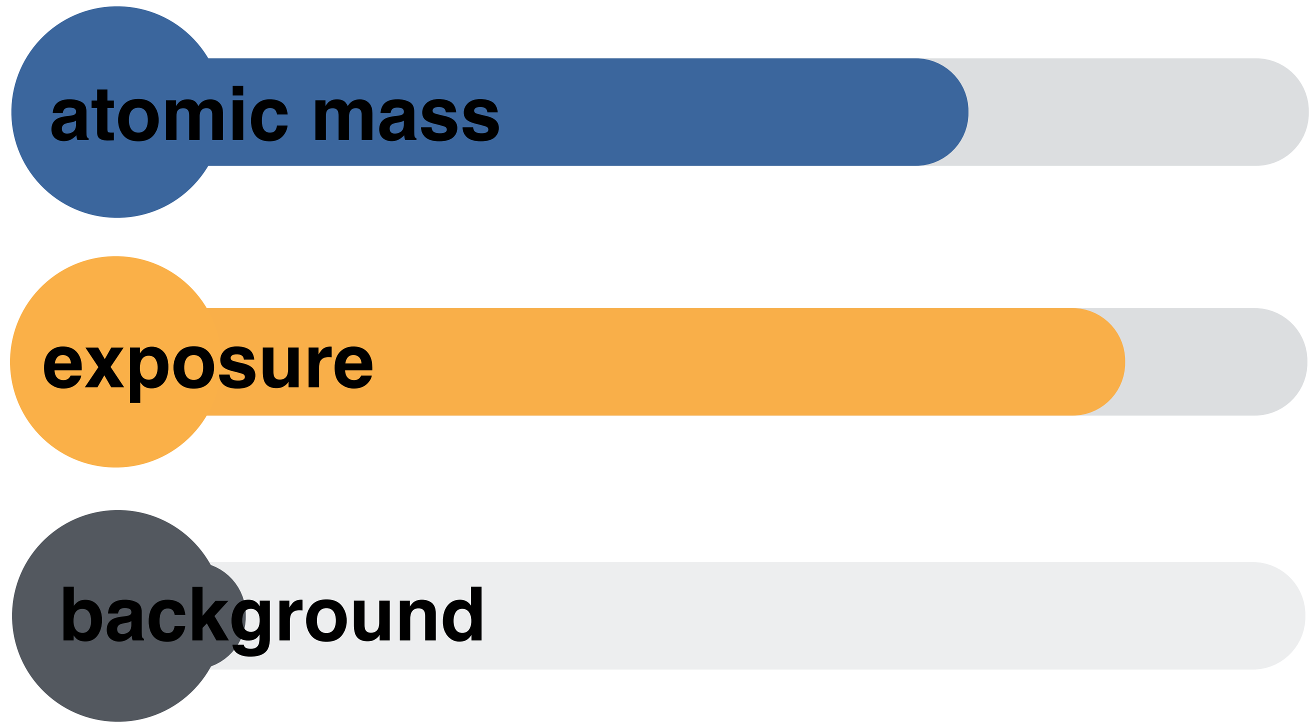


Particle interaction identification
- S2/S1 ratio: ER/NR discrimination

Why xenon?

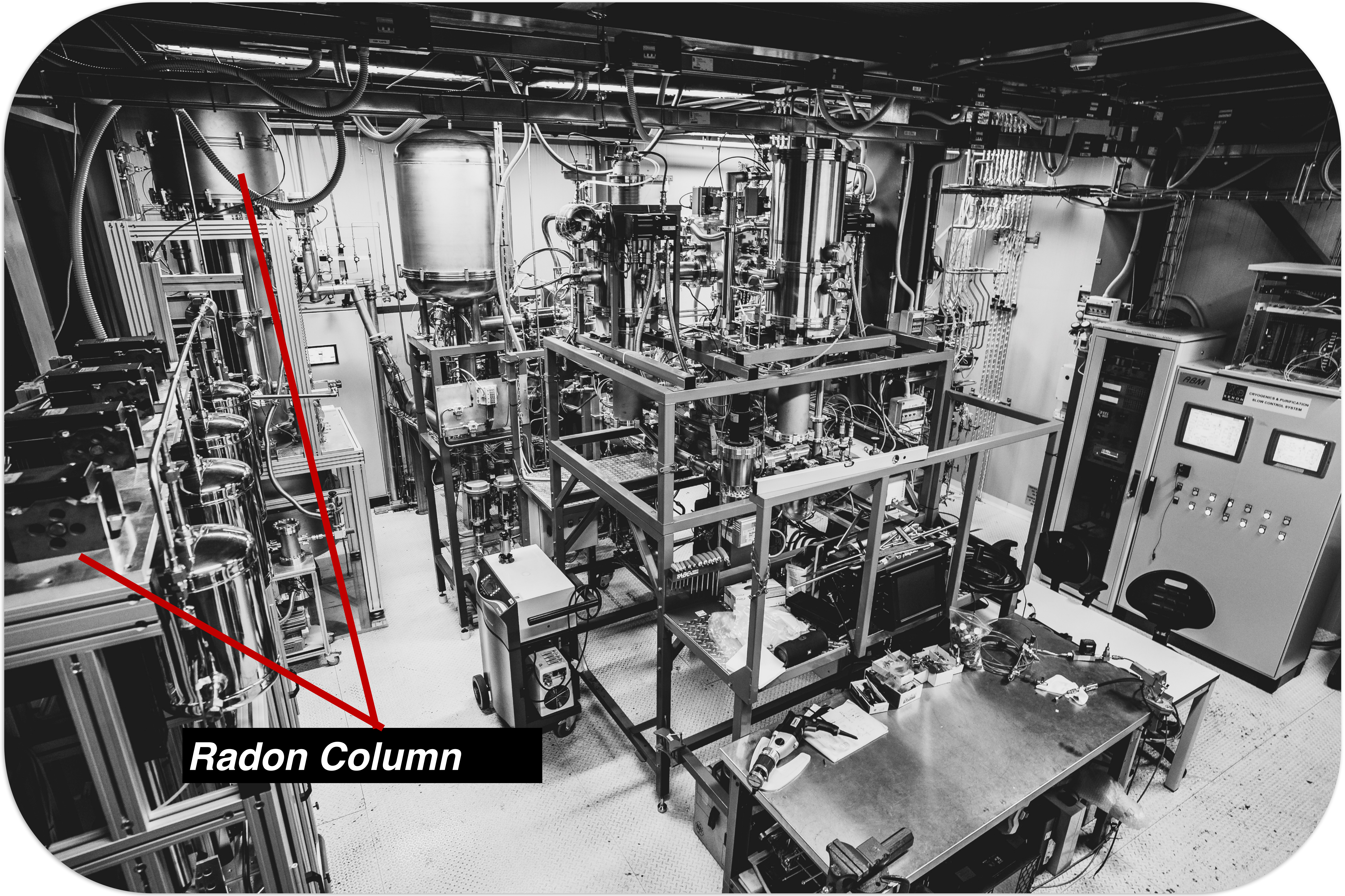
Selected Properties of Xe

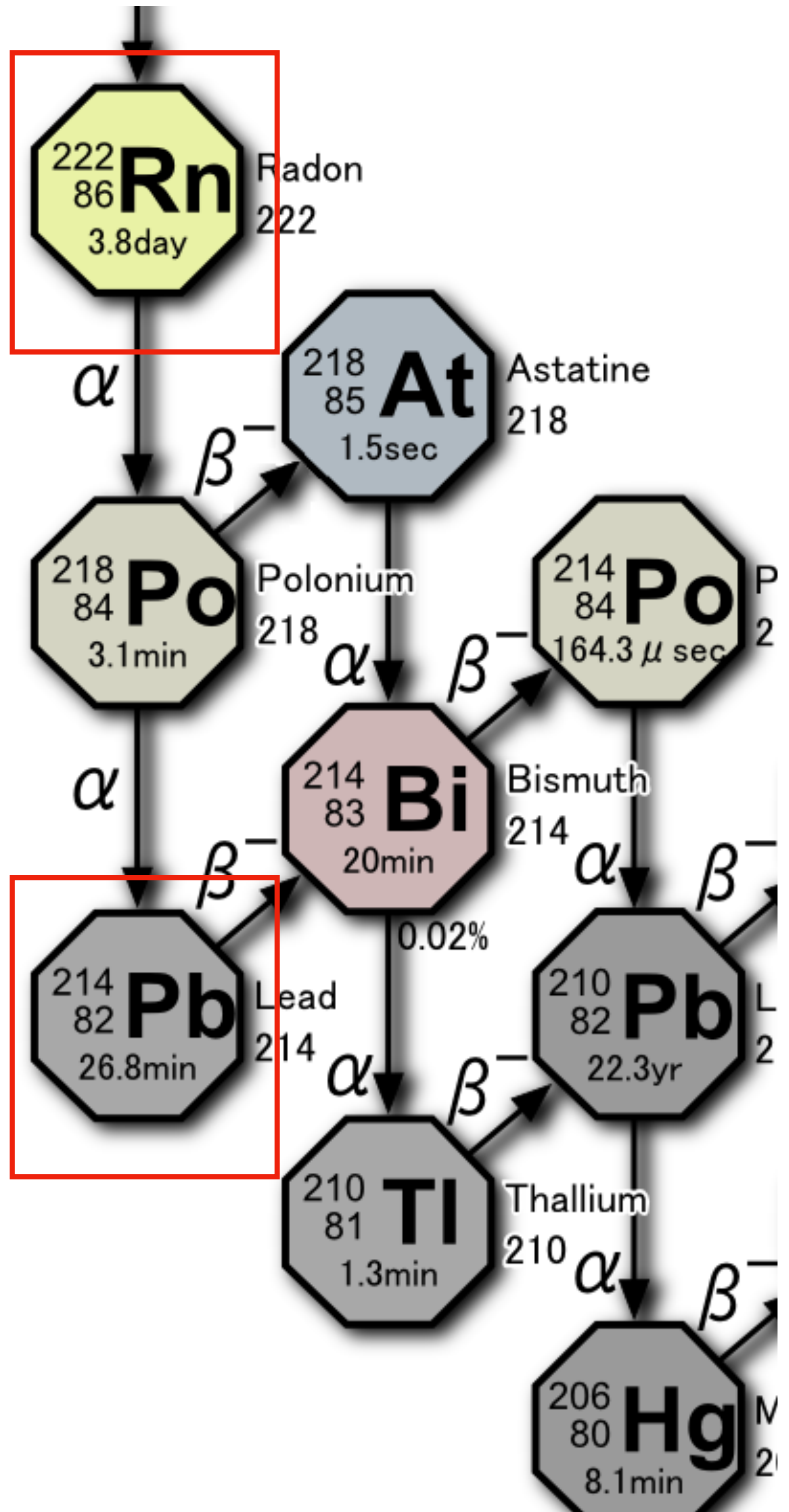
Property	Value
Atomic Number (Z)	54
Atomic Weight (A)	131.30
Number of Electrons per Energy Level	2,8,18,18,8
Density (STP)	5.894 g/L
Boiling Point	−108.1 °C
Melting Point	−111.8 °C
Volume Ratio	519
Concentration in Air	0.0000087 % by volume



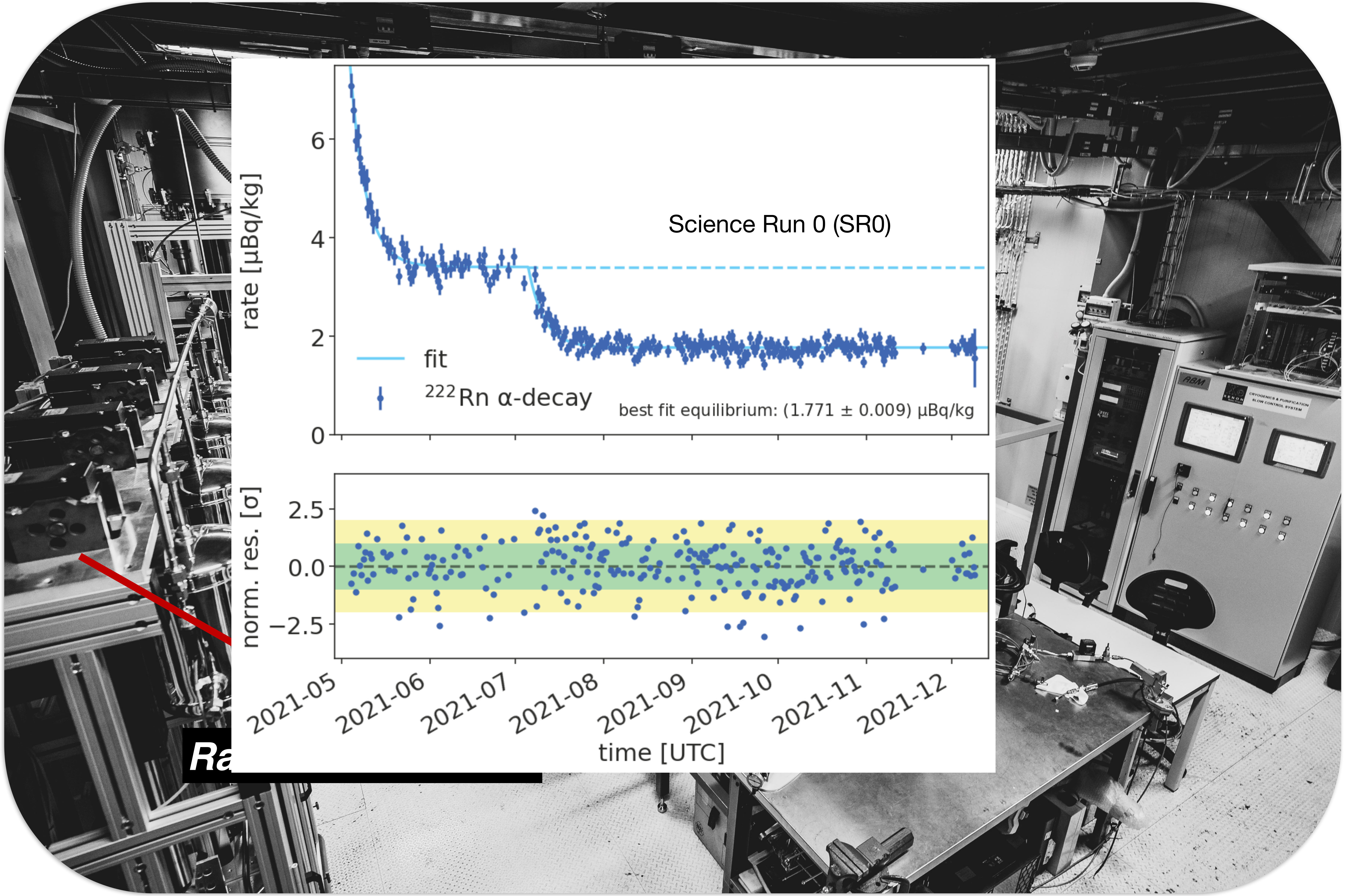
- Heavy
- Scalability & Stability
- Radiopurity

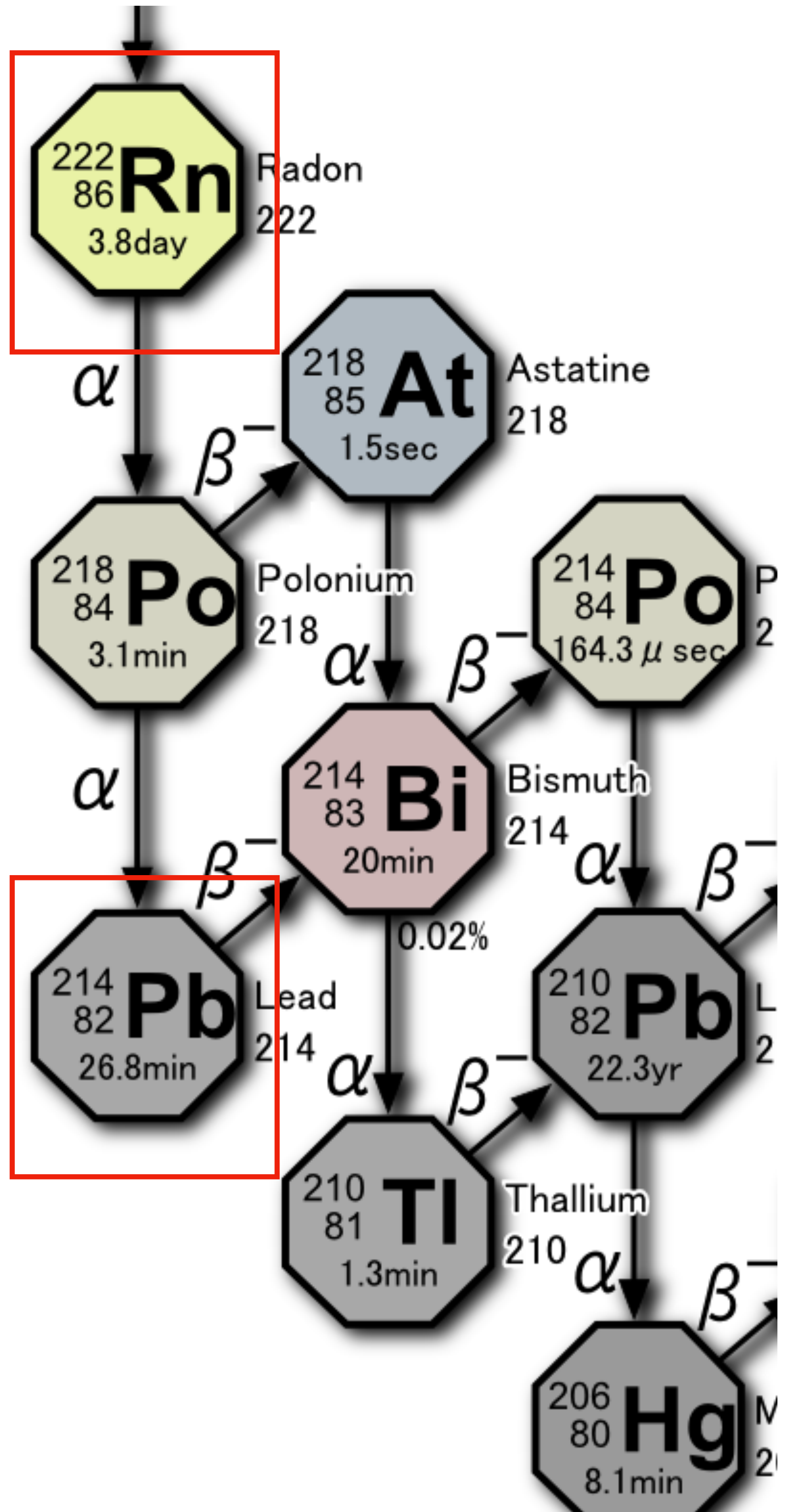
Radon distillation column



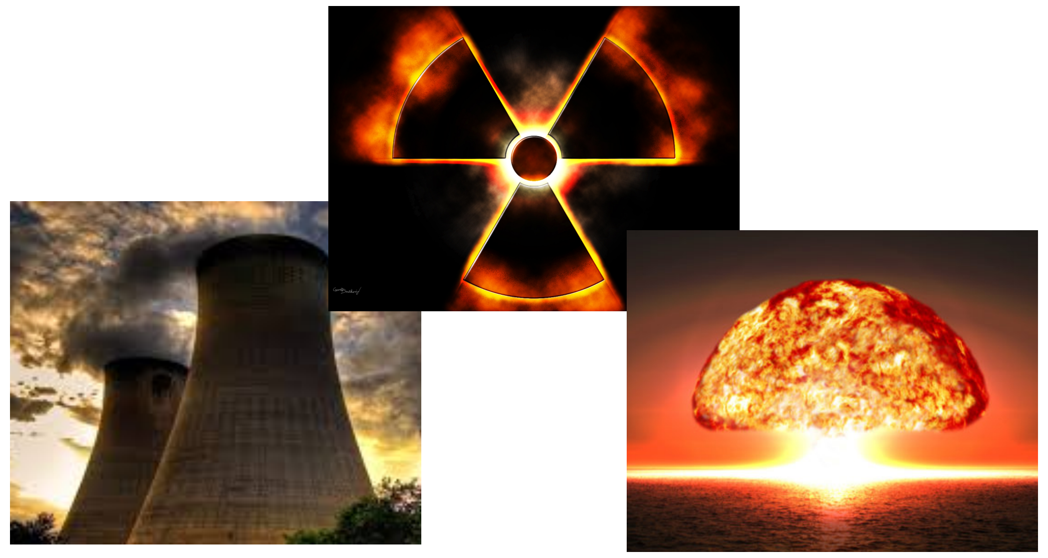


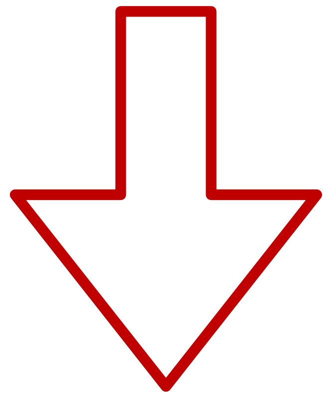
Radon distillation column



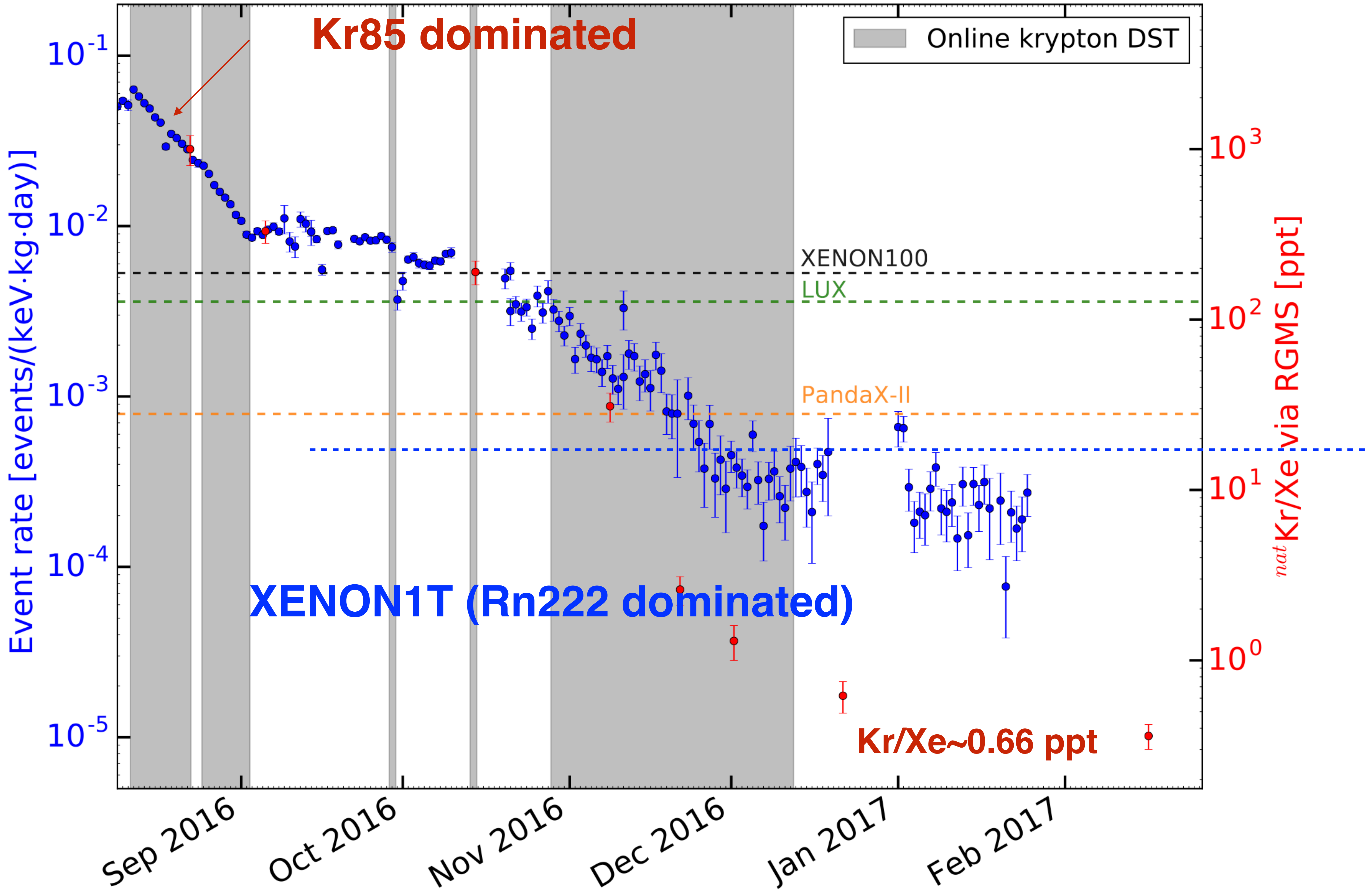


Krypton distillation column



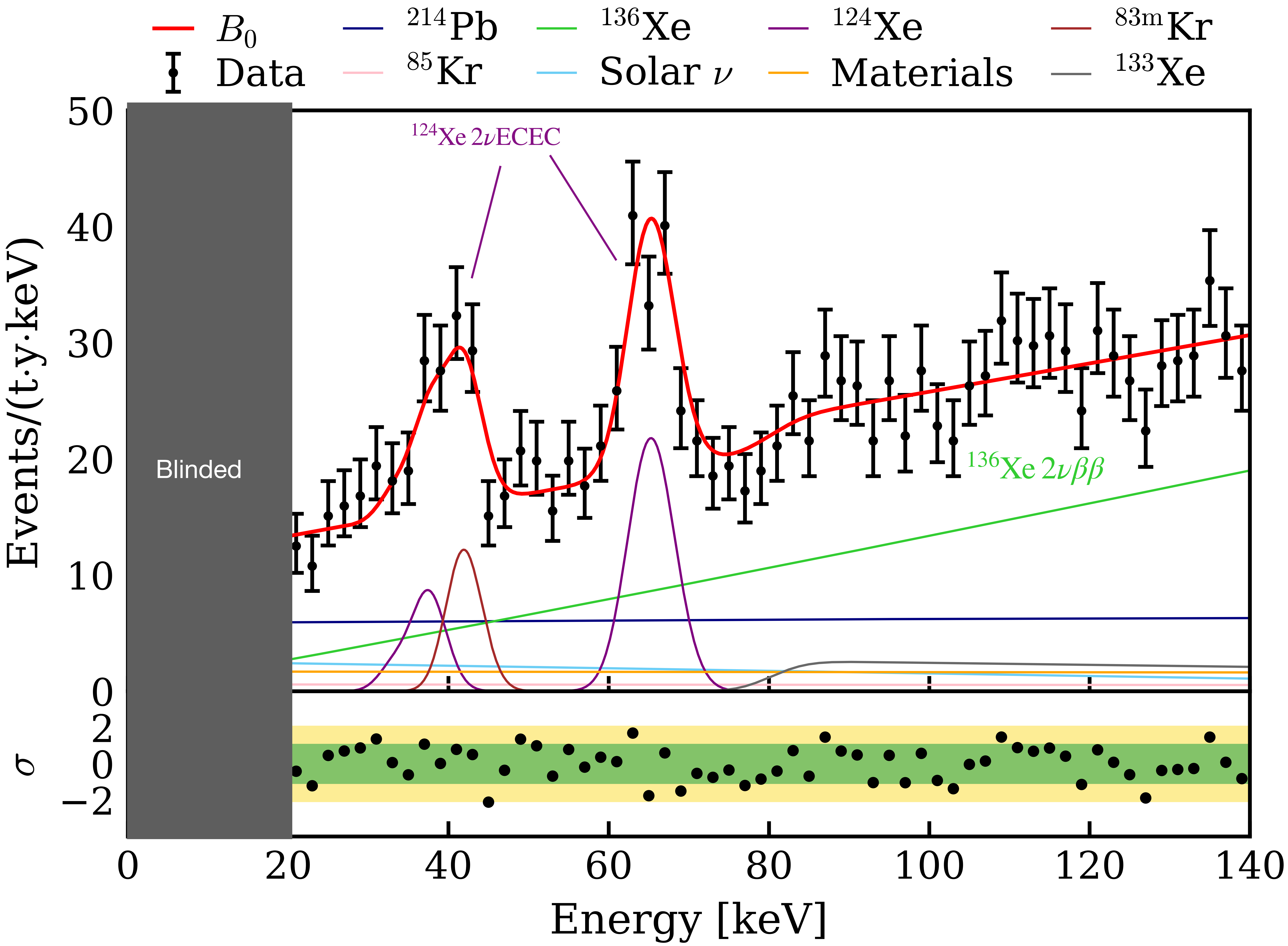


^{85}Kr

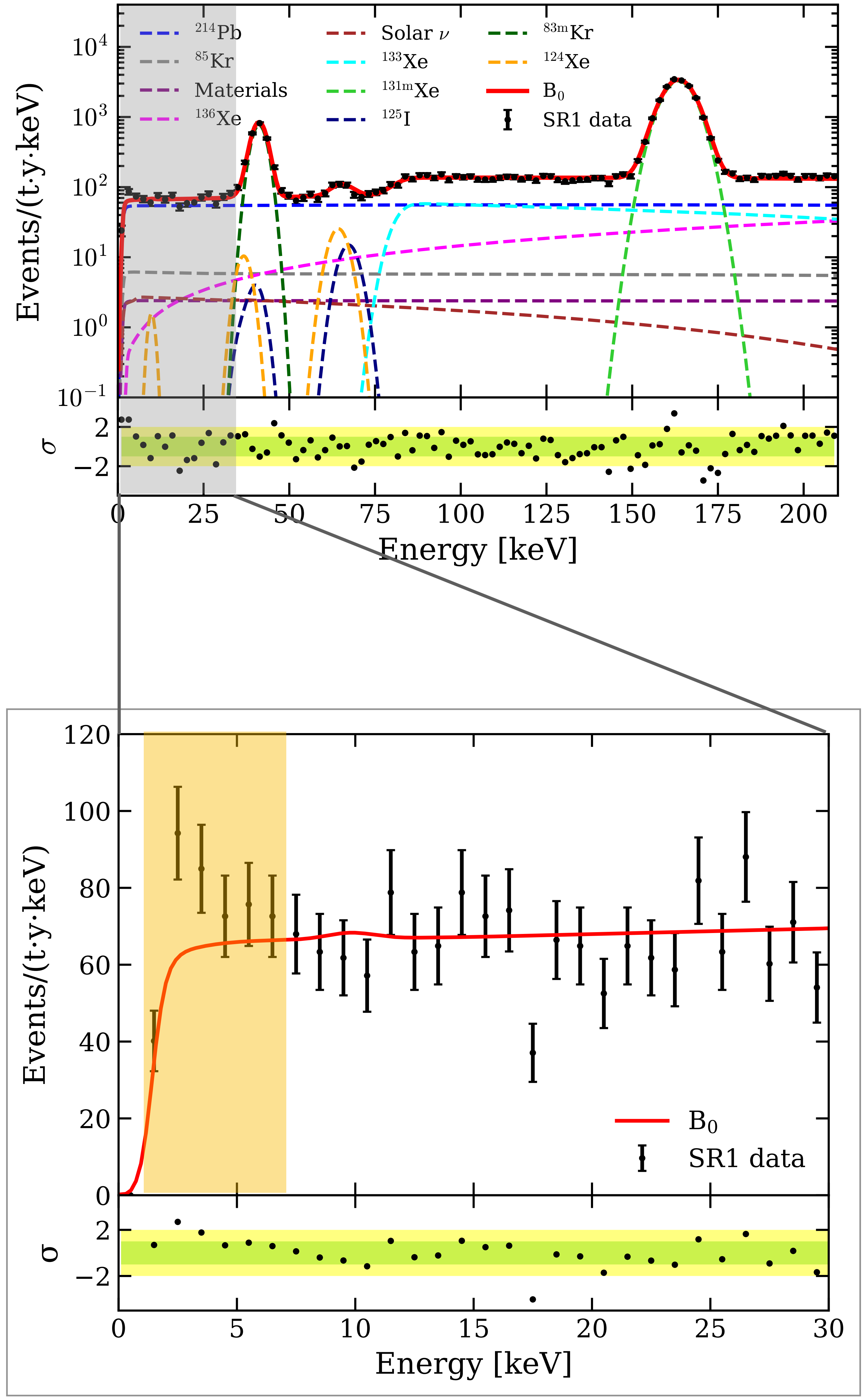


- Decrease krypton concentration by cryogenic distillation
- ^{nat}Kr: (56 ± 36) ppq (XENON1T SR1: (660 ± 110) ppq)

SR0 ER backgrounds



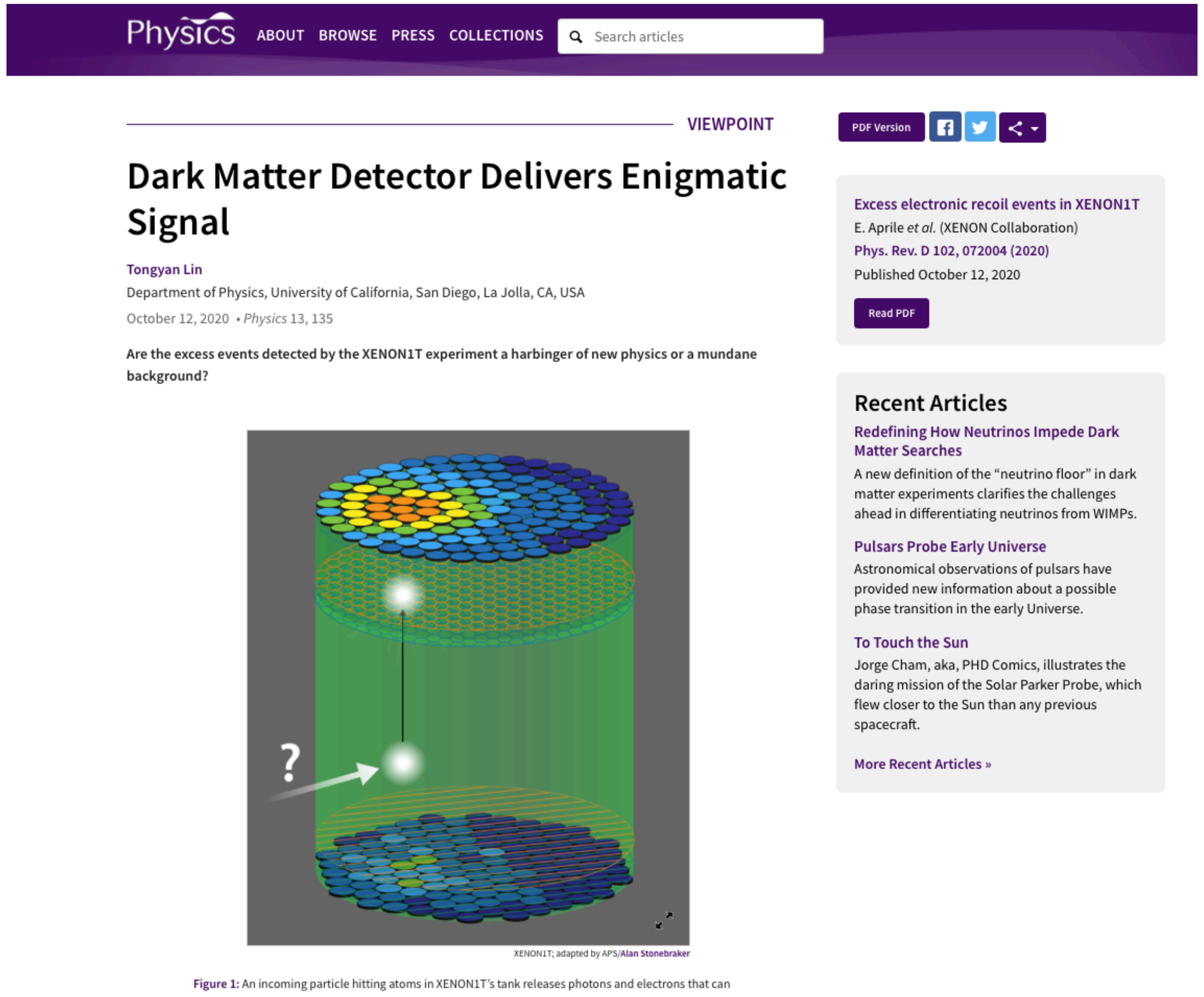
XENON1T Excess



1—7 keV
(reference region)

Expected: 232
Observed: 285

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

PDF Version

Dark Matter Detector Delivers Enigmatic Signal

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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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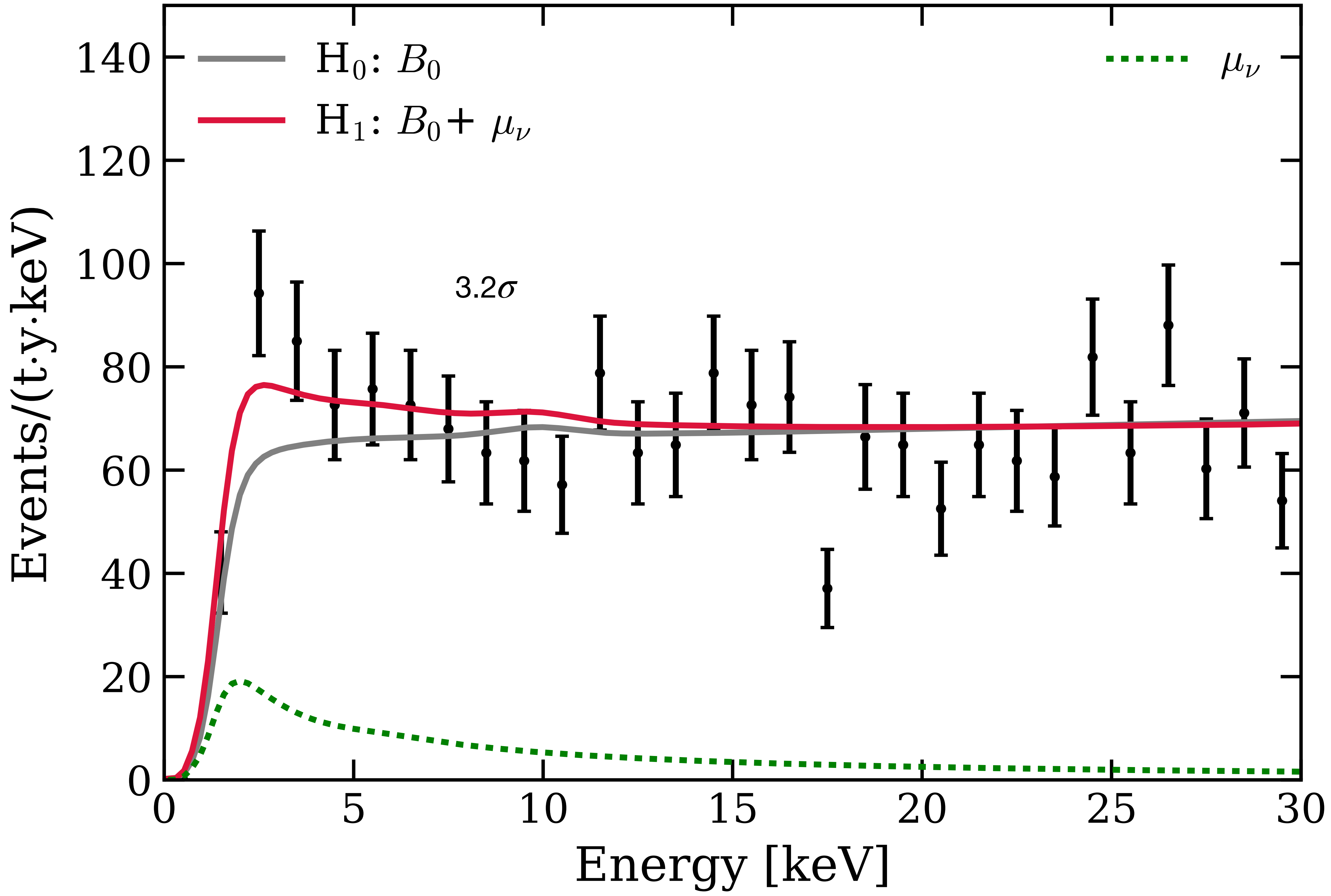
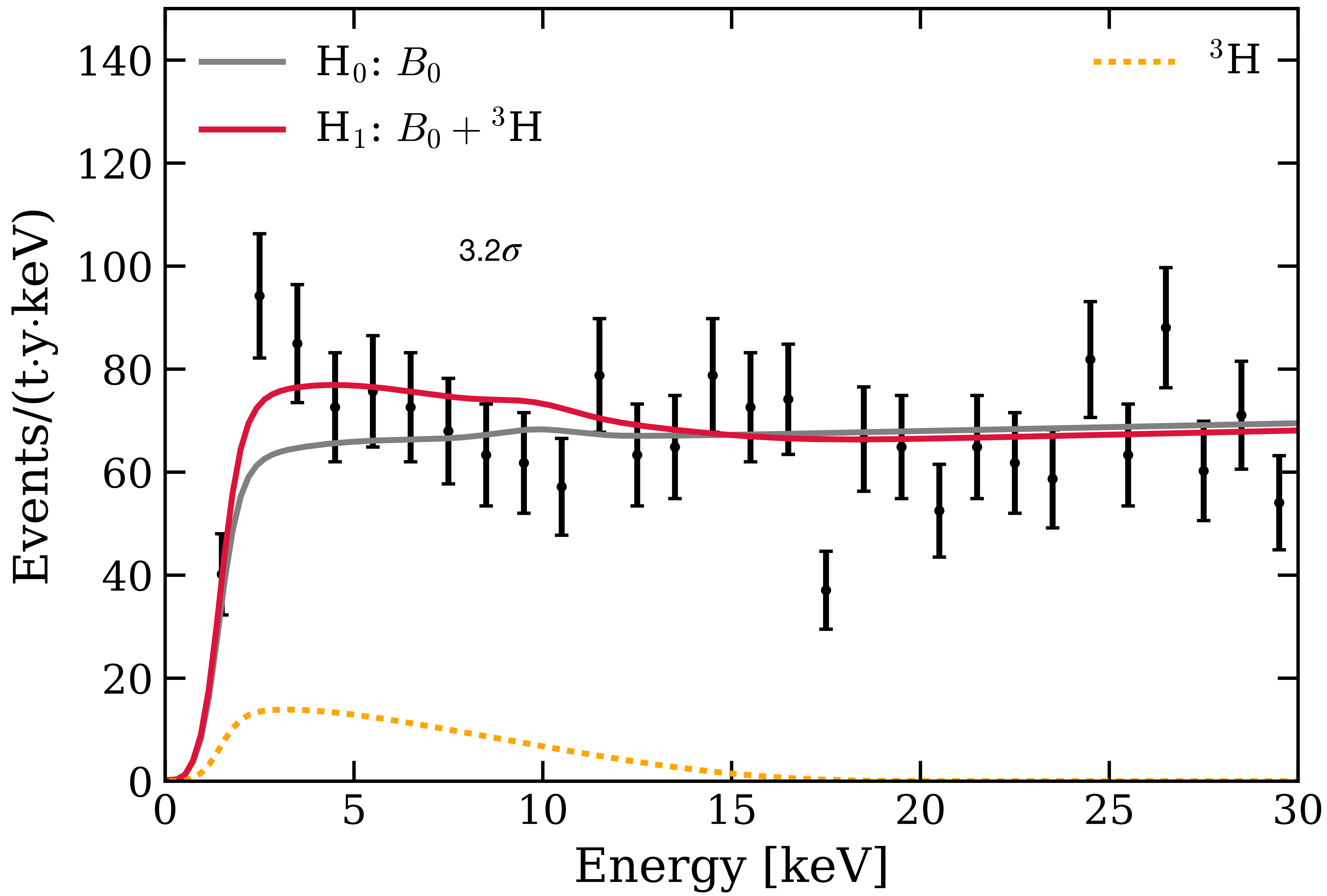
New physics or background?



Neutrino magnetic moment

Enhance solar pp neutrino elastic scattering with electrons

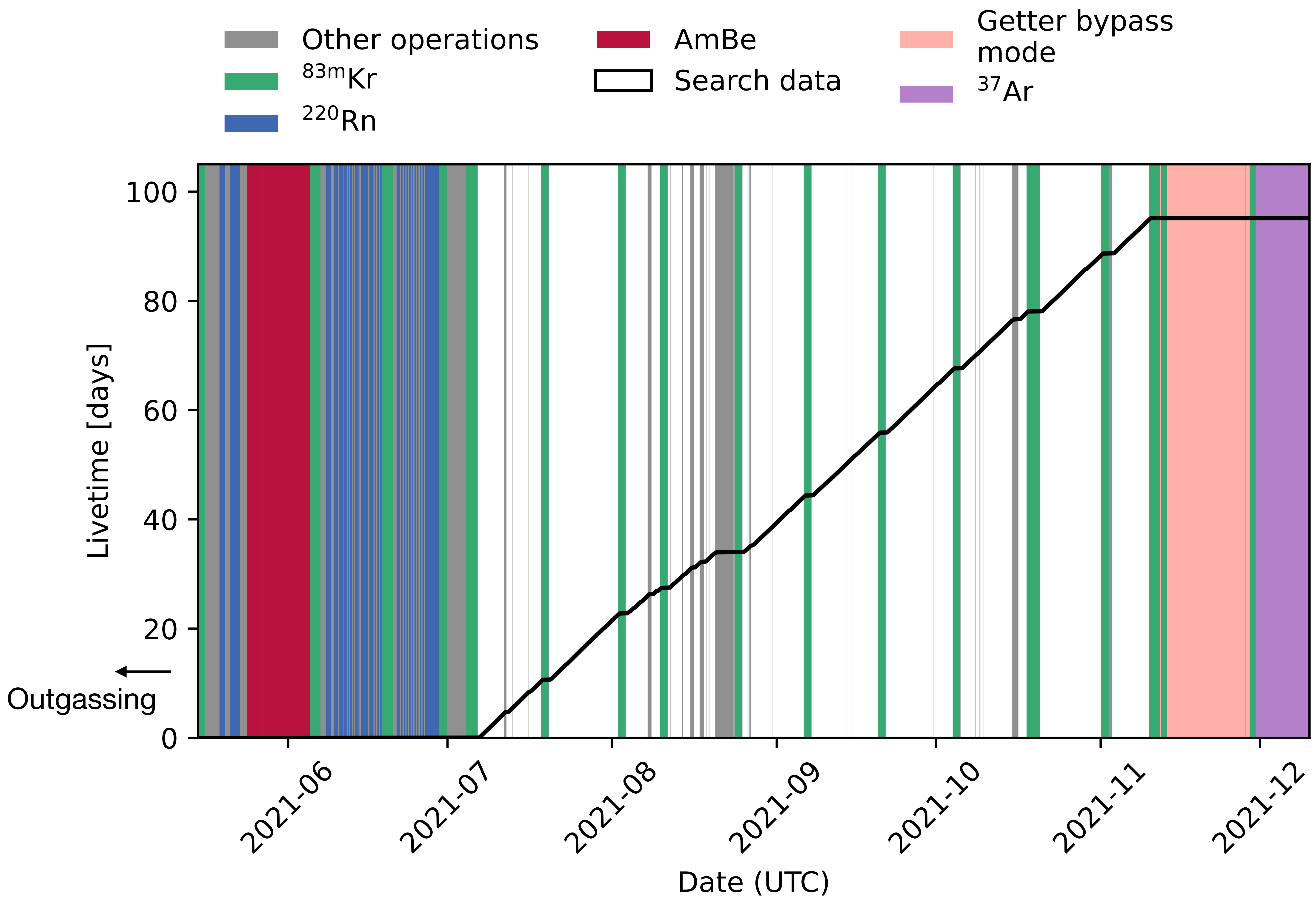


Tritium

- Can be introduced to an underground detector in the forms of HT and/or HTO
- No external constraint on the amount of tritium, in particular HT

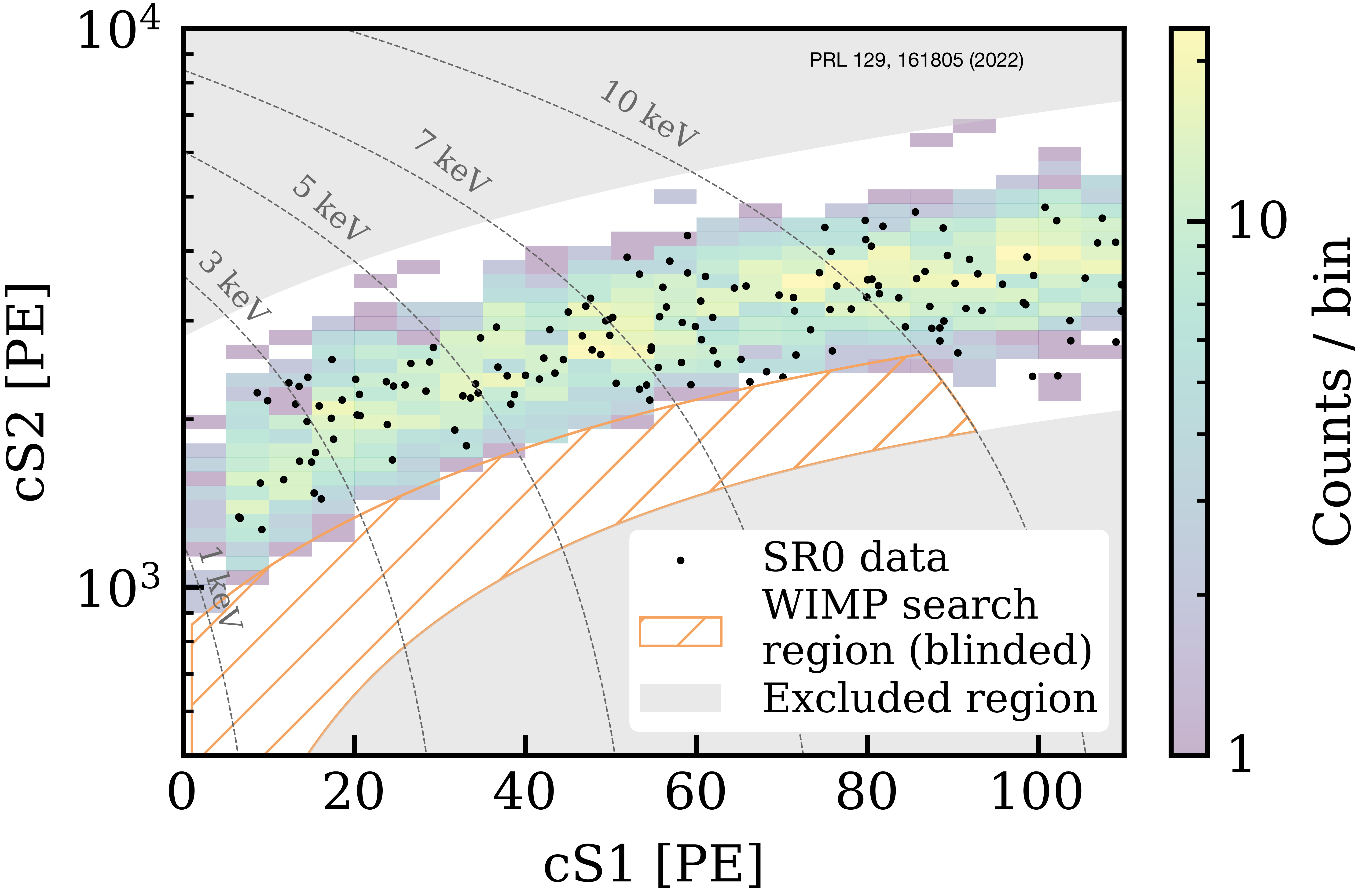
PRD 102, 072004 (2020)

XENONnT SR0



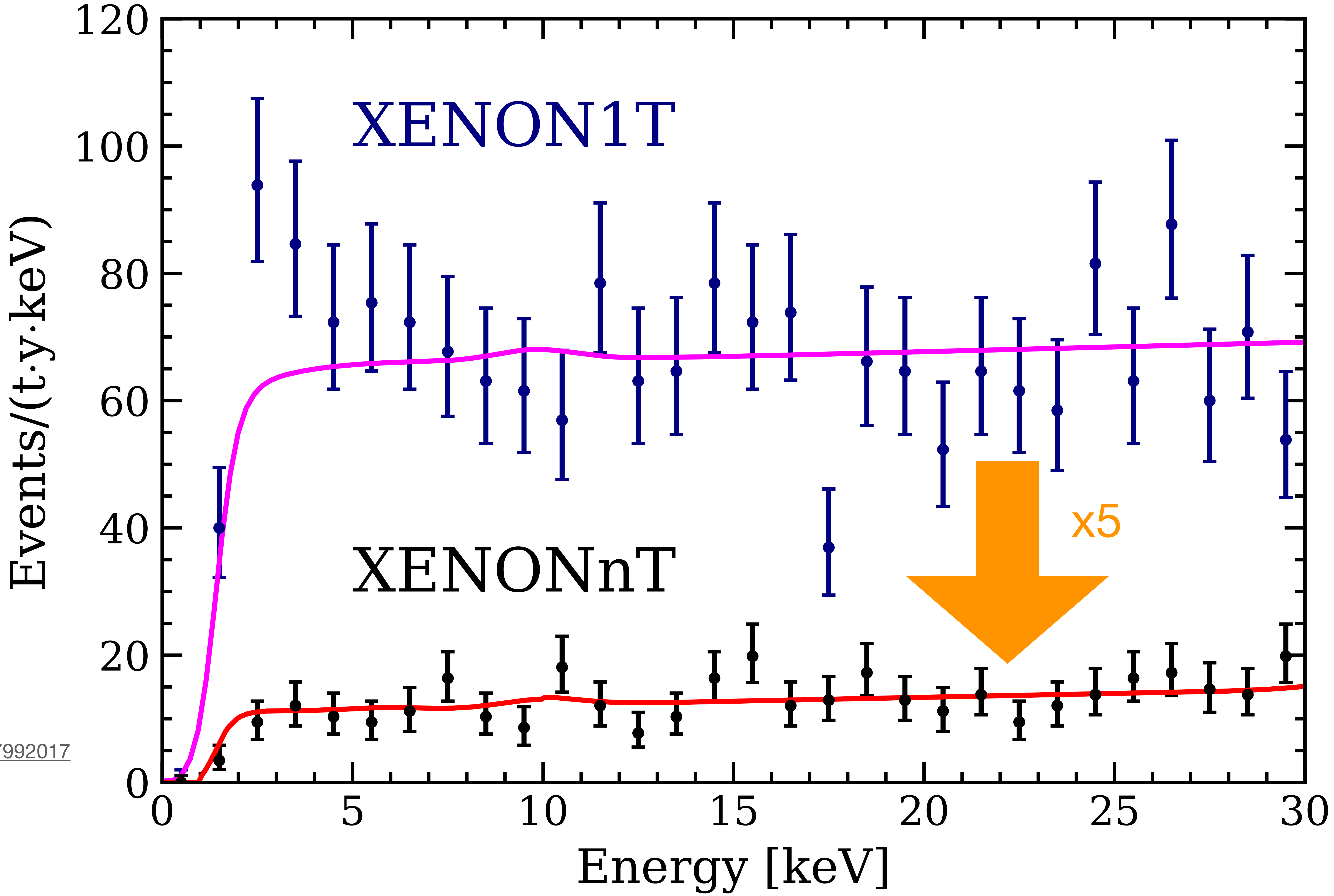
- The first science run length is defined to decipher the XENON1T excess
- Livetime: 97.1 days
- Exposure: $(1.16 \pm 0.03)\,\mathrm{tonne} \cdot \mathrm{year}$
- TPC outgassed for ~3 months before filling GXe to reduce HTO/HT (~10 days in XENON1T)

Unblind SR0 ER Data



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

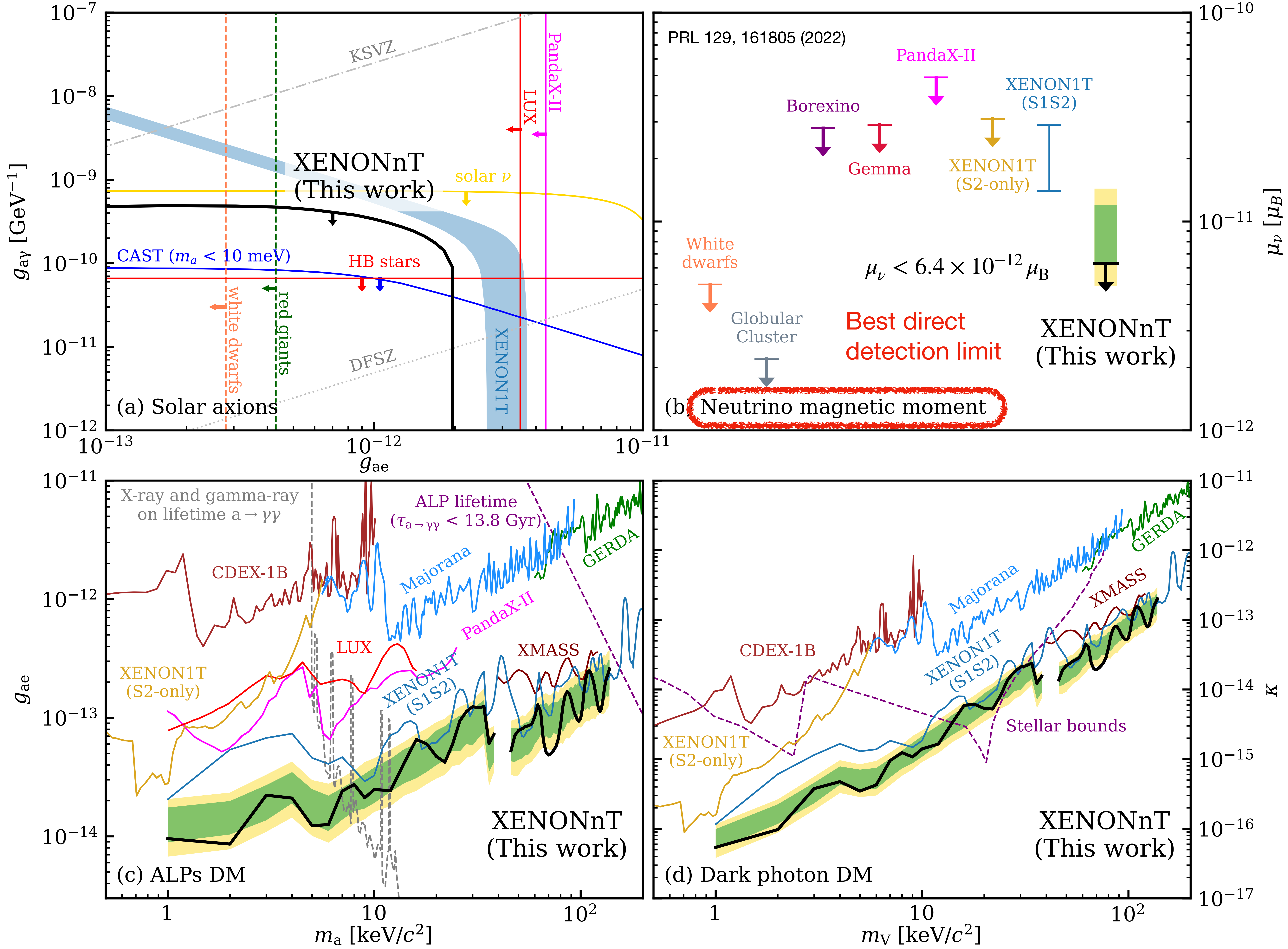
XENONnT ER results



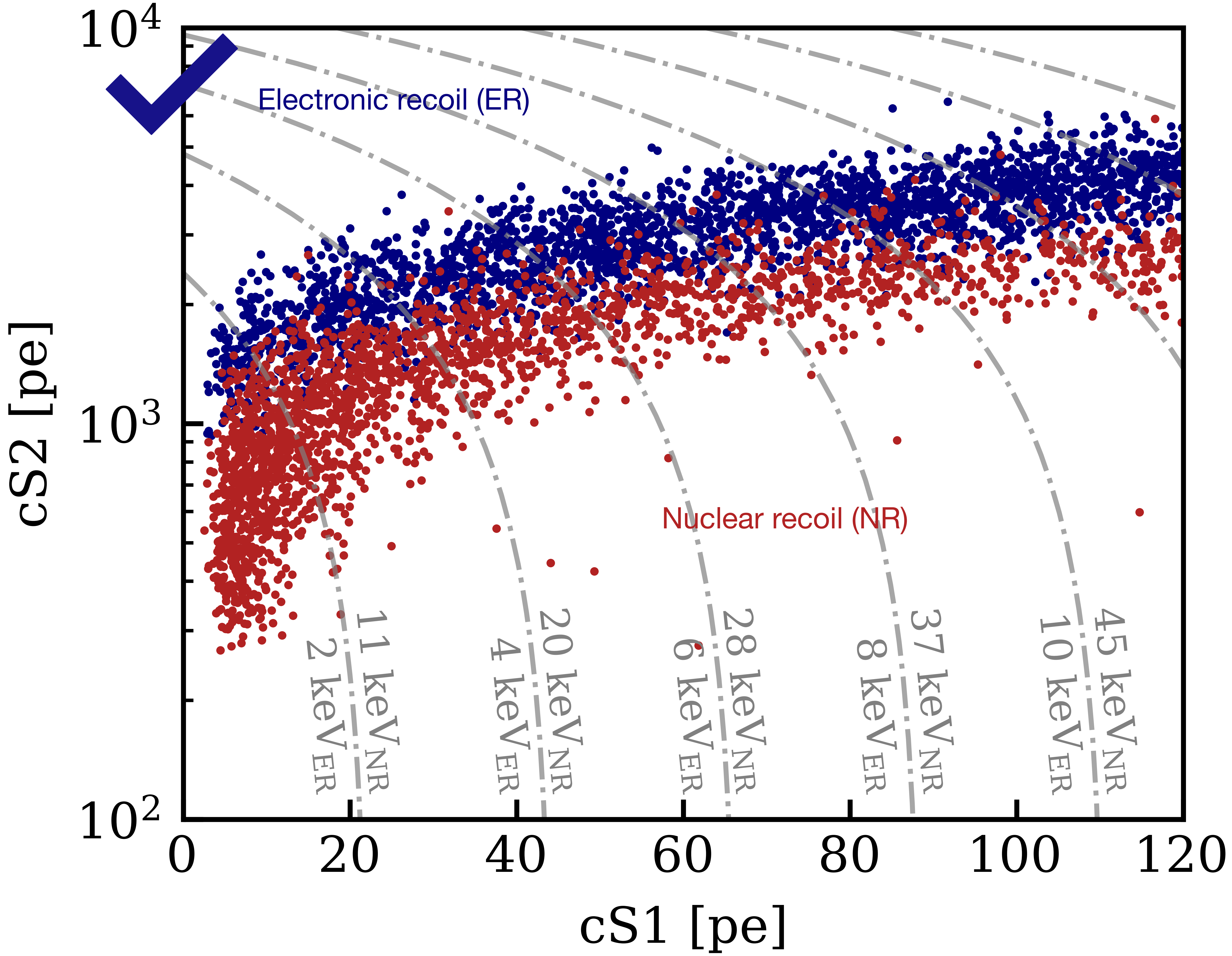
Data and background model available at: https://zenodo.org/records/7992017

- No ER excess is found in XENONnT, which rejects new physics interpretations of the XENON1T excess.
- The XENON1T excess was likely to be caused by trace amount of tritium

Limits on new physics

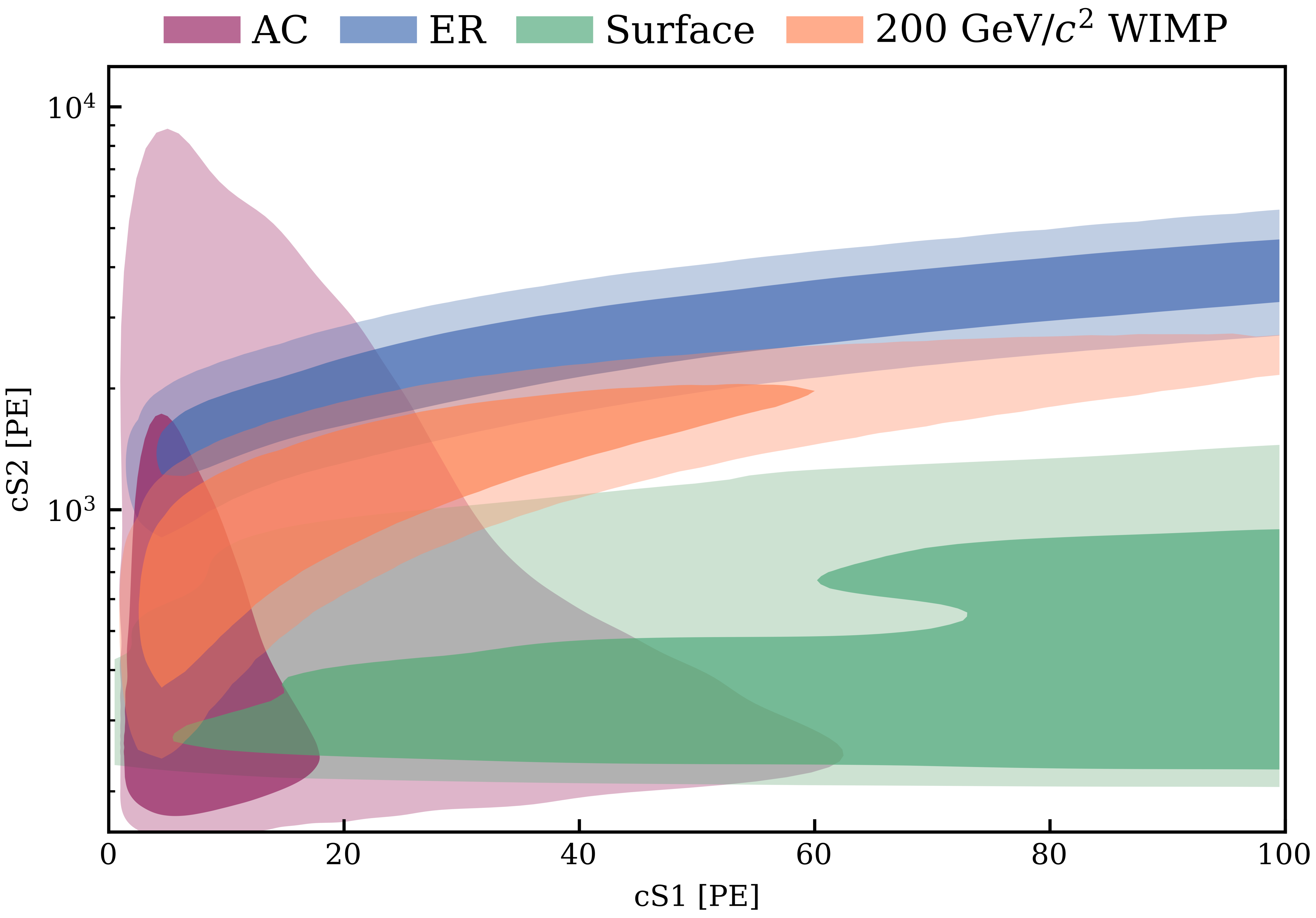


From ER search to NR search



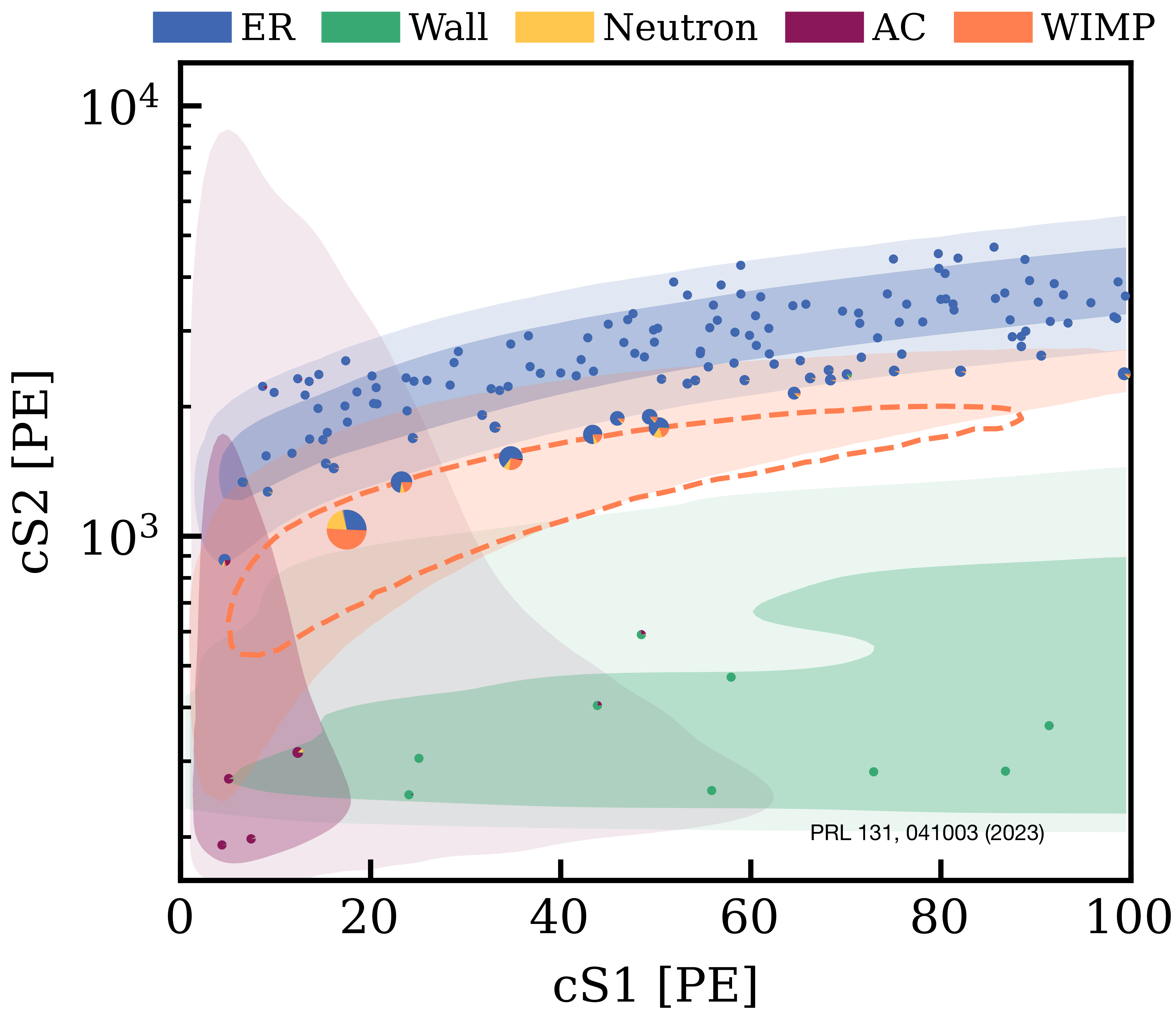
Backgrounds for WIMP search

- **ER**:
  - Dominated by beta decay of ^{214}Pb (daughter of ^{222}Rn)
  - 15.8 events/(t y keV) between 1 and 30 keV
- **Accidental Coincidences (AC):**
  - Random pairing of S1 & S2 signals
  - Suppressed by a dedicated Gradient Boosted Decision Tree (GBDT), using S2 Shape, R and Z information.
- **Surface:**
  - ^{210}Pb plate-out on PTFE walls of the TPC
  - Suppressed by R < 61.35 cm of fiducial volume
- **Nuclear Recoil (NR):**
  - Radiogenic neutron rate prediction from Neutron Veto tagging
  - ^{8}B CEvNS



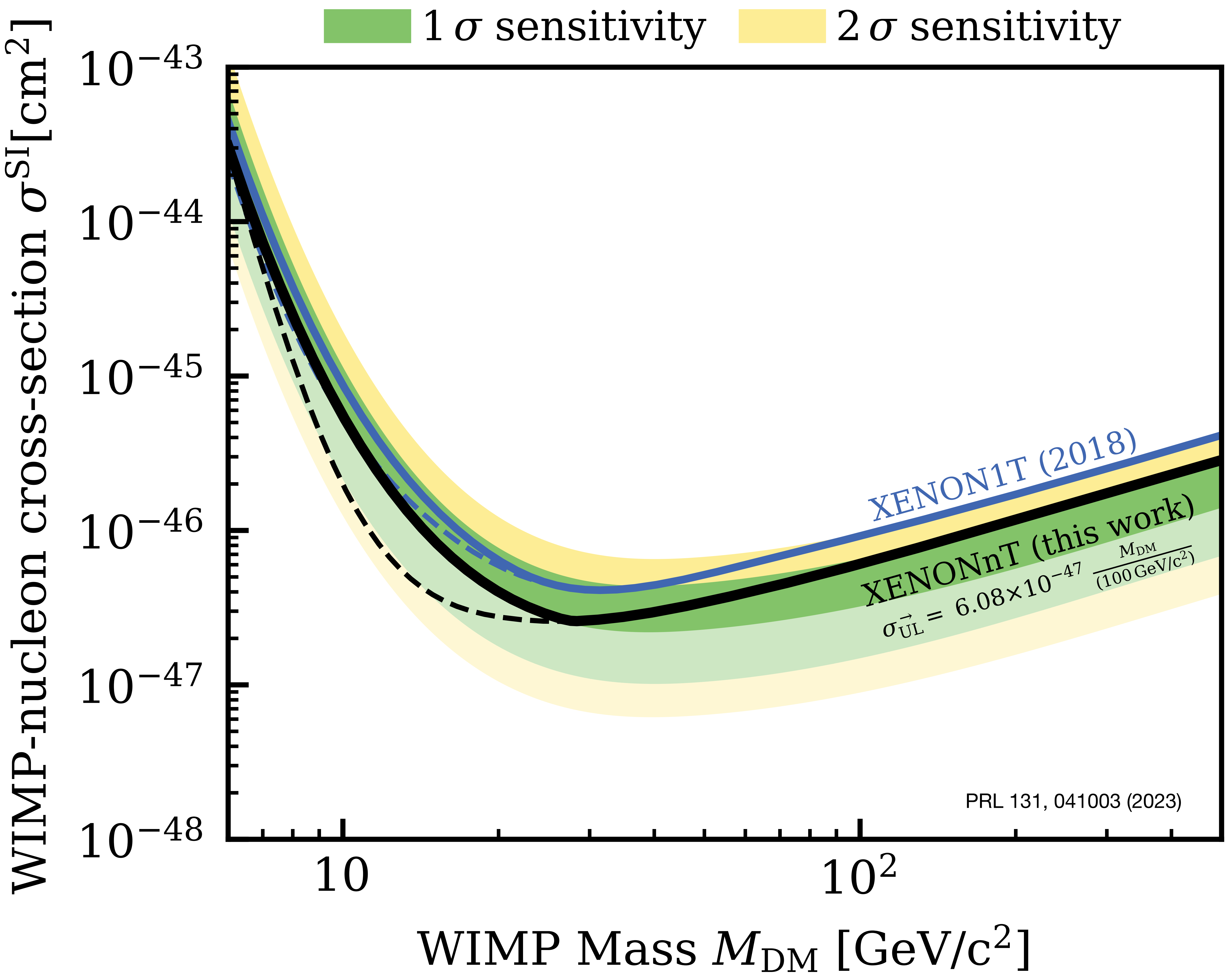
WIMP results

	Nominal	Best Fit	
	ROI		Signal-like
ER	134	135^{+12}_{-11}	$0.86^{+0.08}_{-0.07}$
Neutrons	$1.1^{+0.6}_{-0.5}$	1.1 ± 0.4	0.42 ± 0.17
CEνNS	0.23 ± 0.06	0.23 ± 0.06	0.022 ± 0.011
AC	4.3 ± 0.2	4.32 ± 0.15	0.366 ± 0.013
Surface	14 ± 3	12^{+0}_{-4}	$0.35^{+0.01}_{-0.11}$
Total Background	154	152 ± 12	2.0 ± 0.2
WIMP	-	2.6	1.3
Observed	-	152	3



- 152 events in ROI, 16 in blinded region
- P-value (>0.2) indicates no significant excess

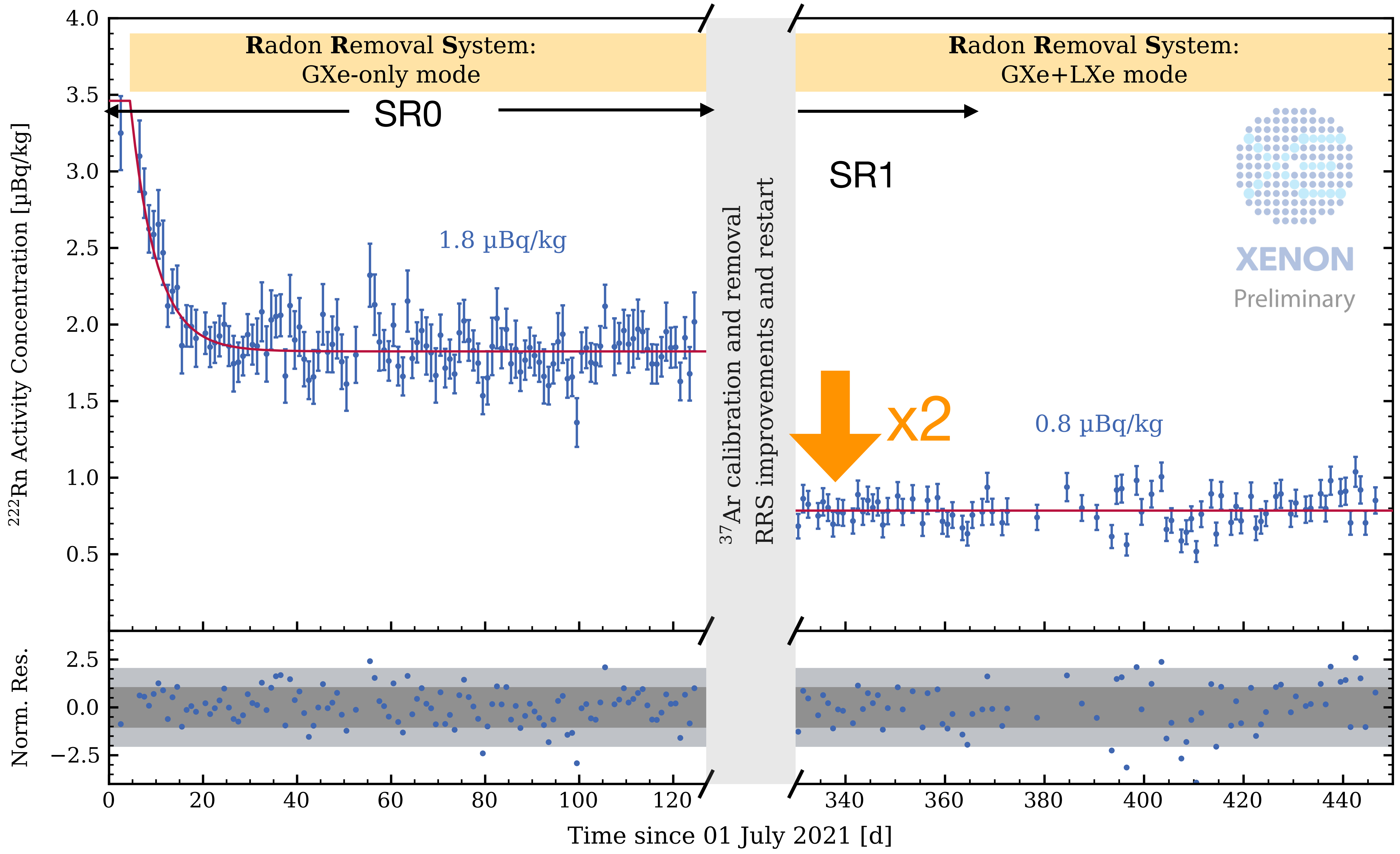
WIMP results



Minimum upper limit for spin-independent (SI) WIMP-nucleon cross sections is $2.58 \times 10^{-47}\,\mathrm{cm}^2$ for a mass of 28 GeV/c^2

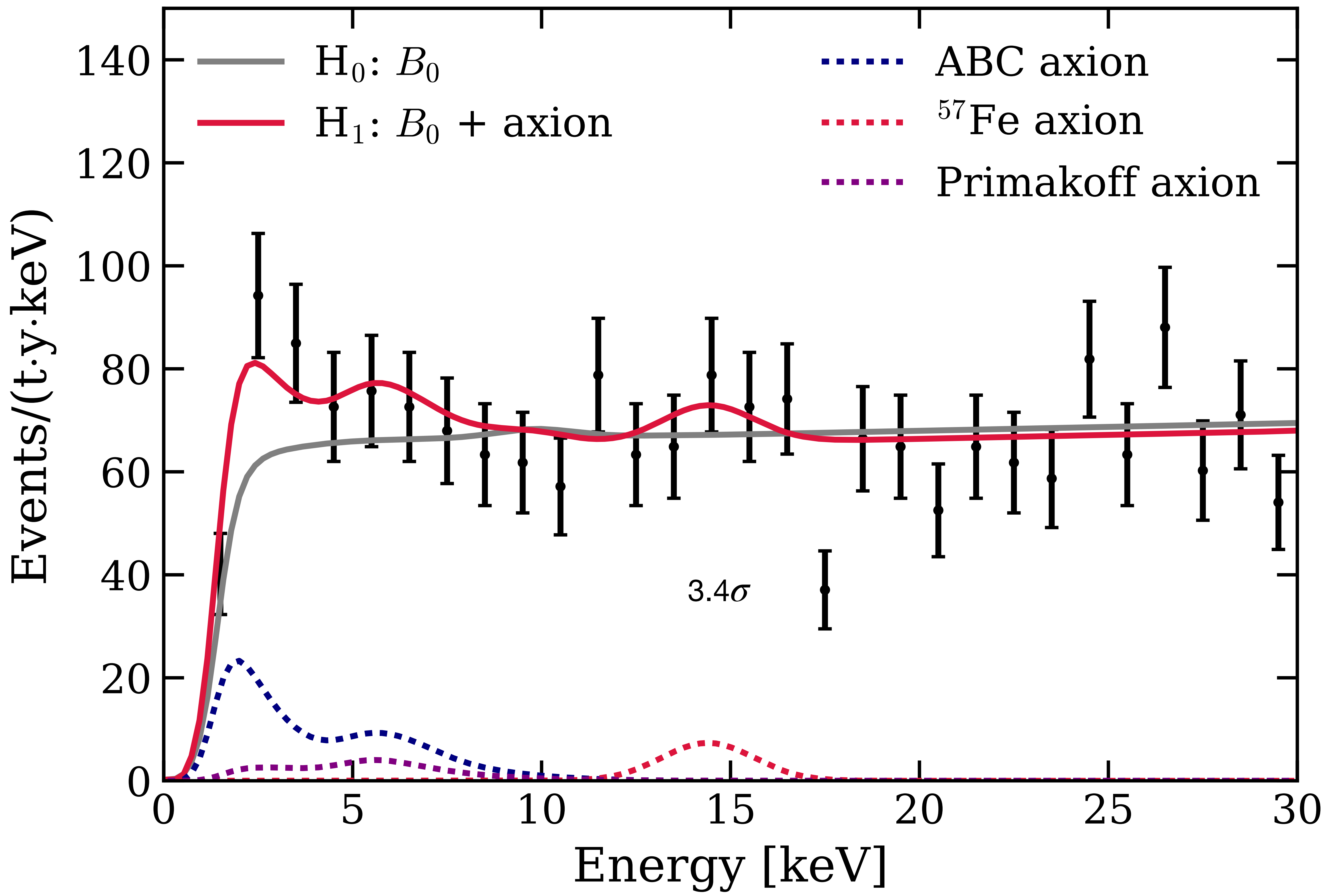
Summary & Outlook

- **SR0** - 1.1 t·yr exposure
- **Unprecedented low ER background** - 15.8 events/(t y keV)
- **Low ER results** PRL 129, 161805 (2022)
  - Deciphered XENON1T excess
  - Best limit on neutrino magnetic moment $\mu_\nu < 6.4 \times 10^{-12}\,\mu_B$
- **WIMP results** PRL 131, 041003 (2023)
  - $2.58 \times 10^{-47}\,\mathrm{cm}^2$ (90% C.L.) at 28 GeV/c^2
- **SR1**
  - ER background further reduced
- **More topics**
  - B-8 CEvNS (NR)
  - Solar pp (ER)
  - Light DM (S2-only)
  - ….



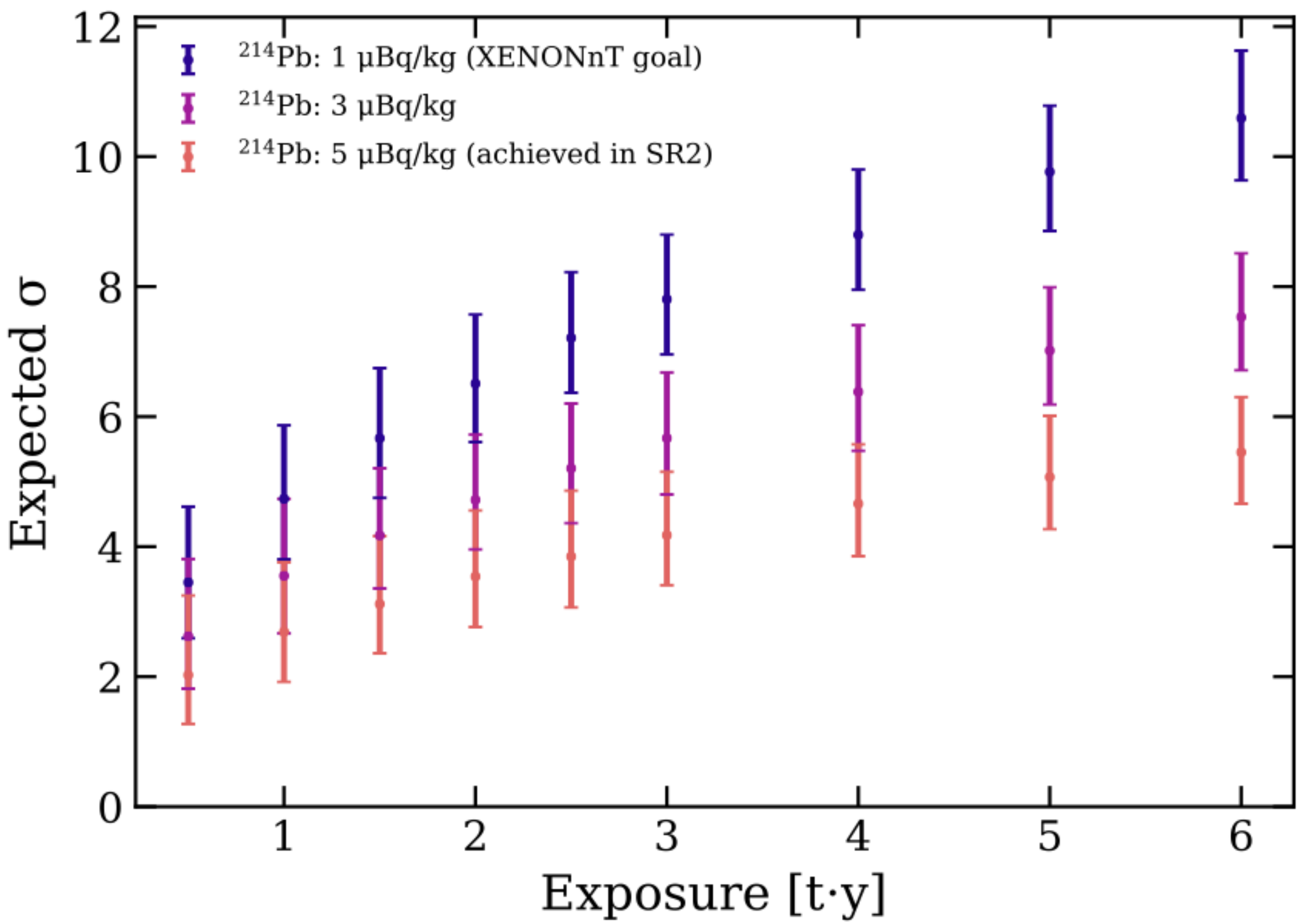
Back up

Solar axion hypothesis



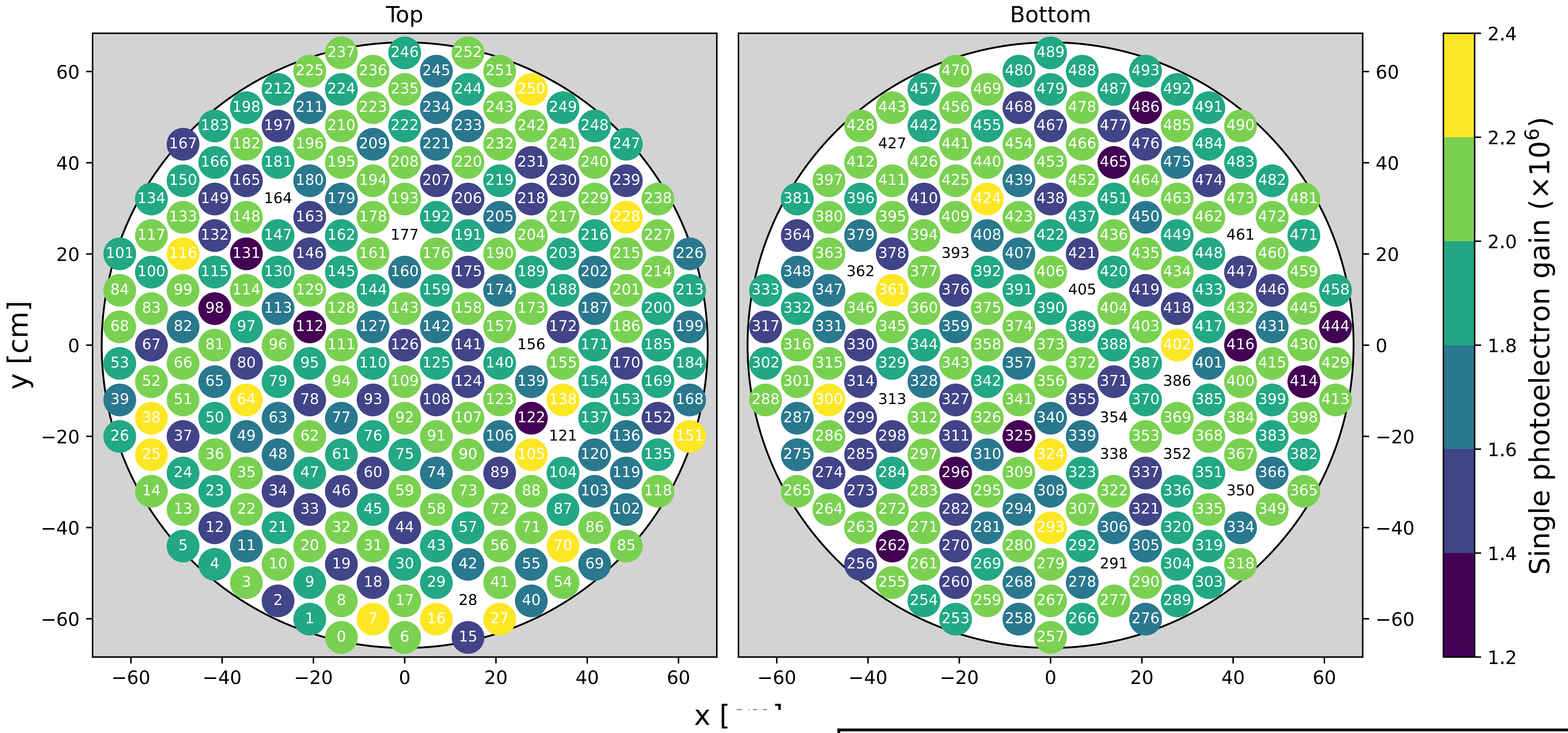
- Axions can be produced in the Sun via its couplings to electrons, photons, and nucleons
- Solar axions can be detected in LXe detectors via axio-electric effect and inverse Primakoff effect, which was not considered in XENON1T but is included in XENONnT
- Solar axion hypothesis is favored by XENON1T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

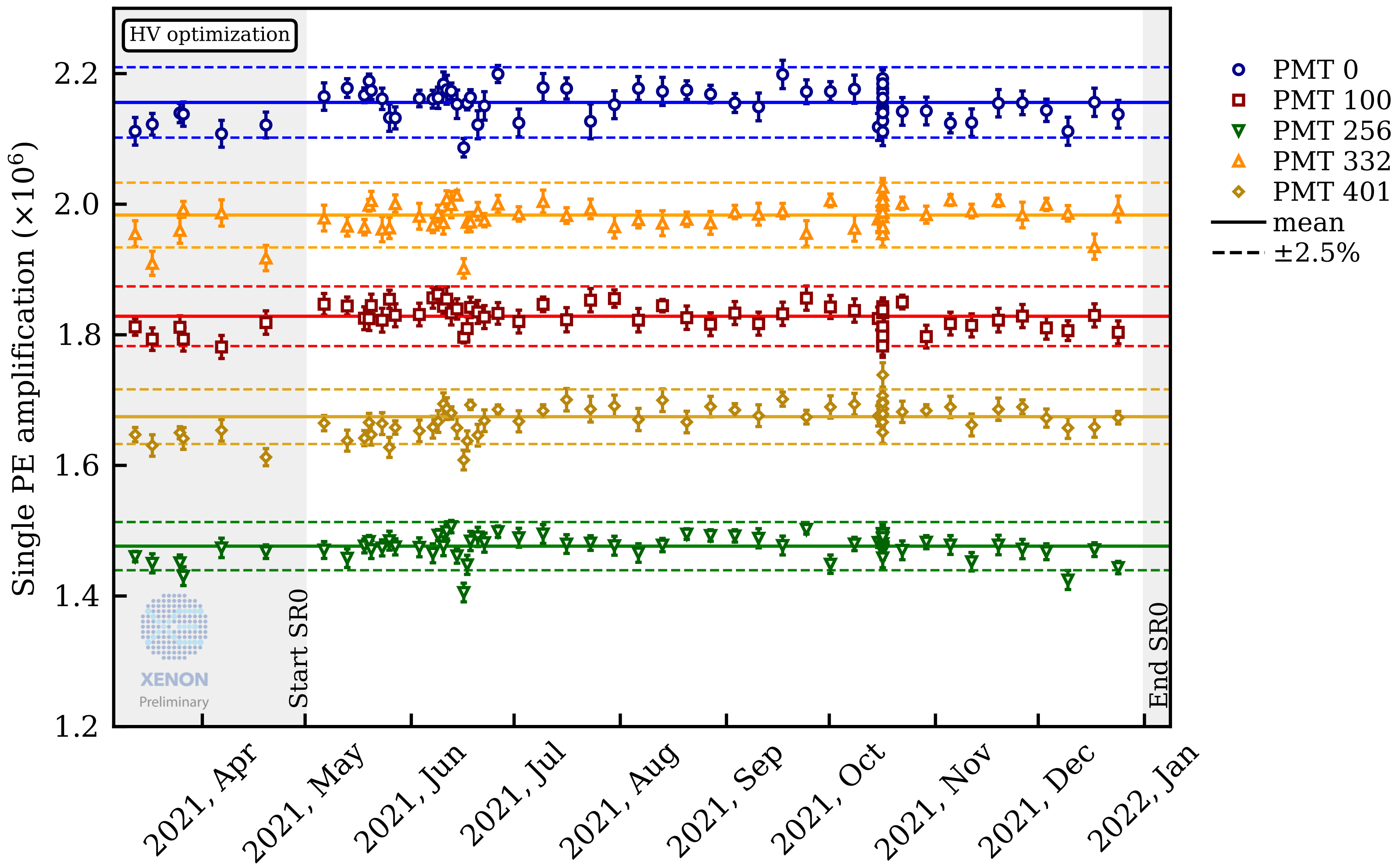
Expected discrimination power in XENONnT



XENONnT should be able to differentiate the excess with a few months of data

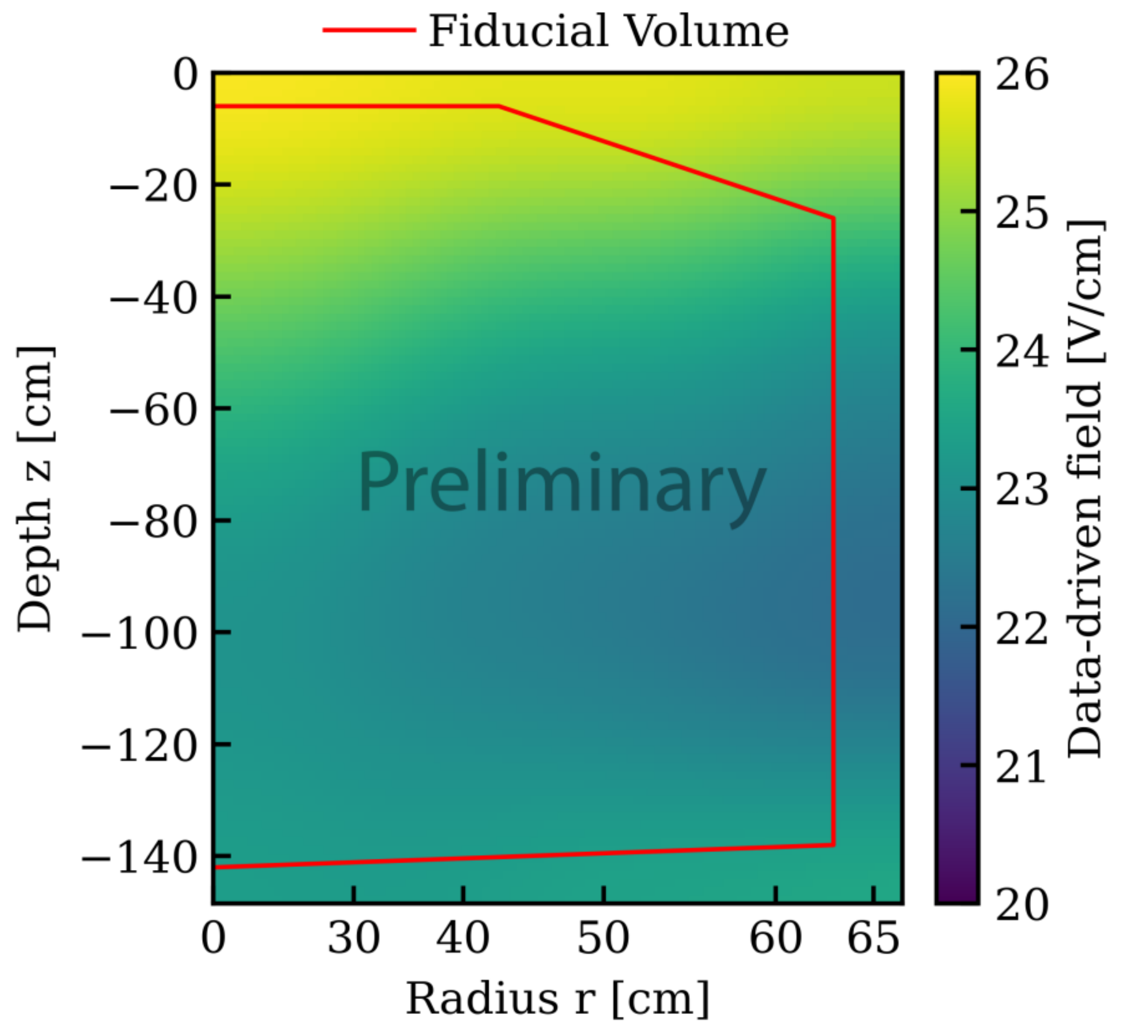
PMT calibration



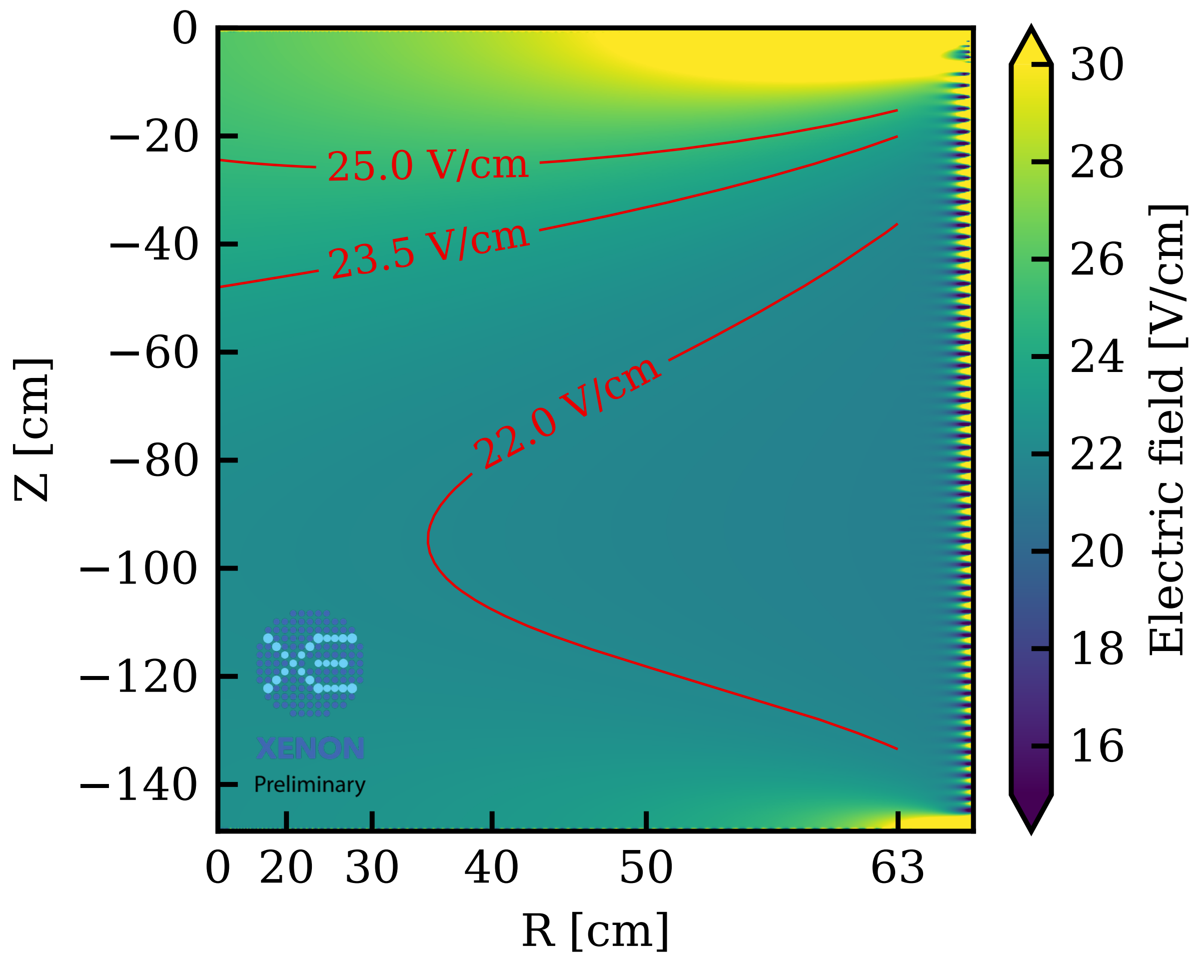


- Weekly PMT calibration using LED light
- 477/494 PMTs working
- Gain stability within 3%

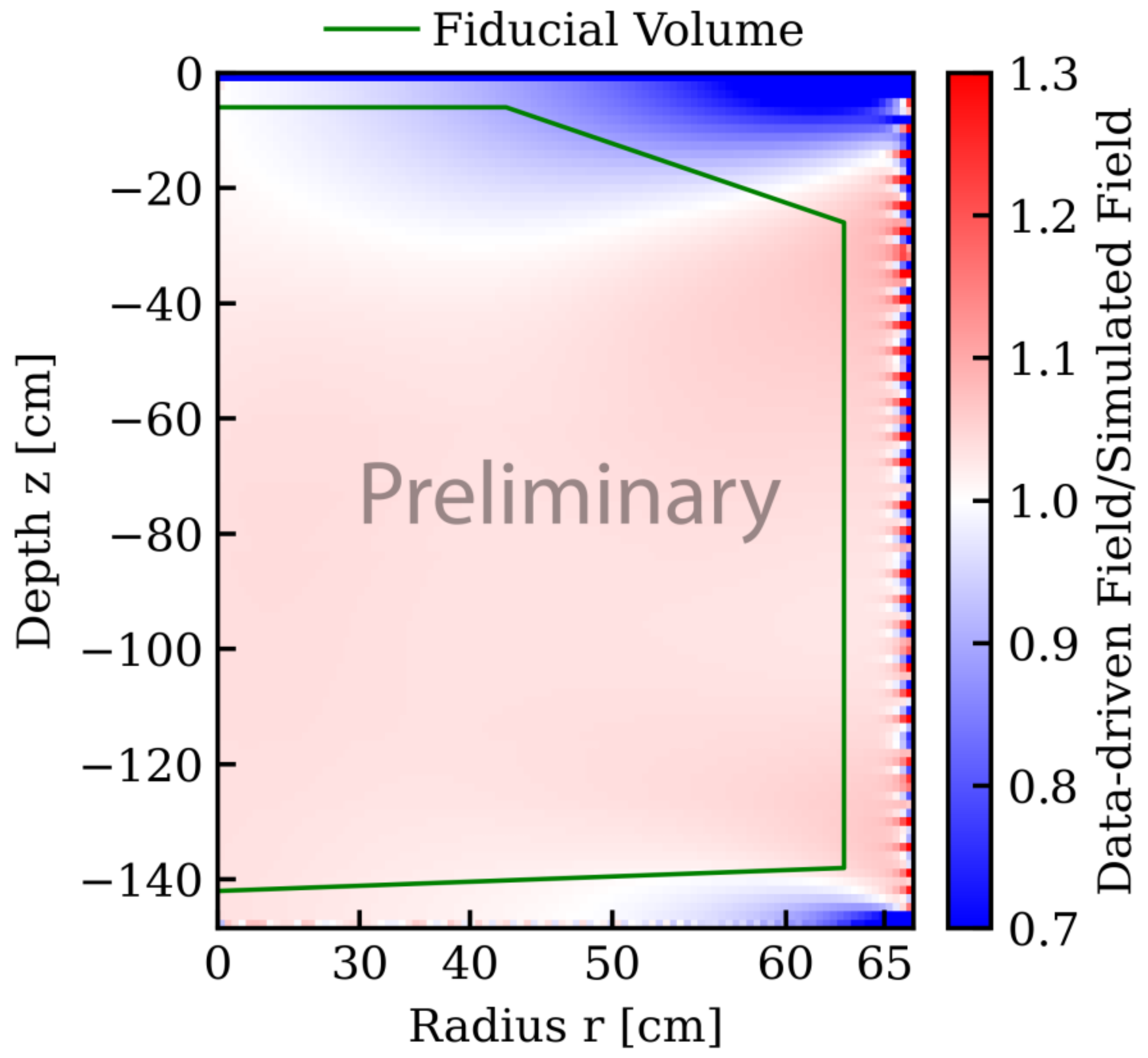
Drift field



Data-driven based on ratio of ^{83m}Kr S1a and S1b

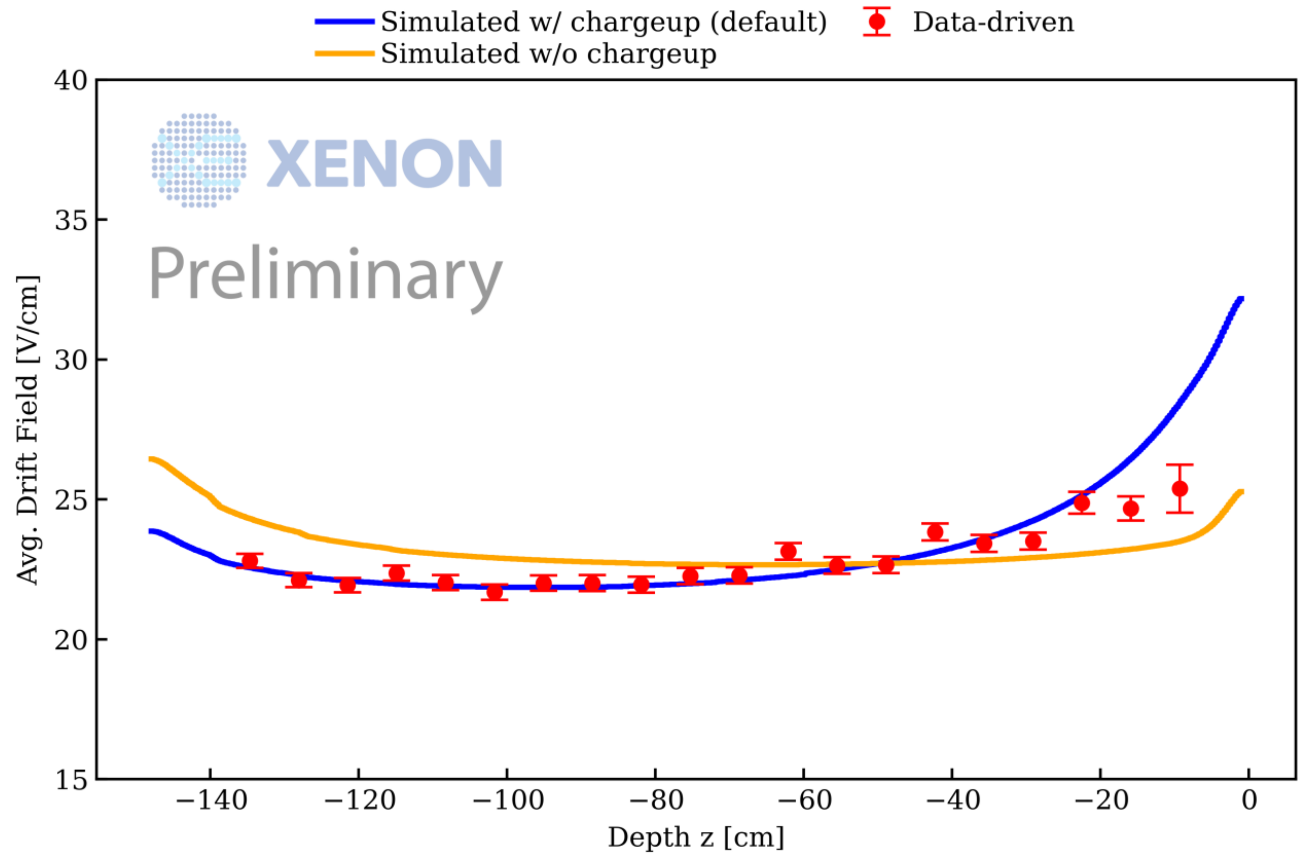


Simulation with charge-up the teflon surface

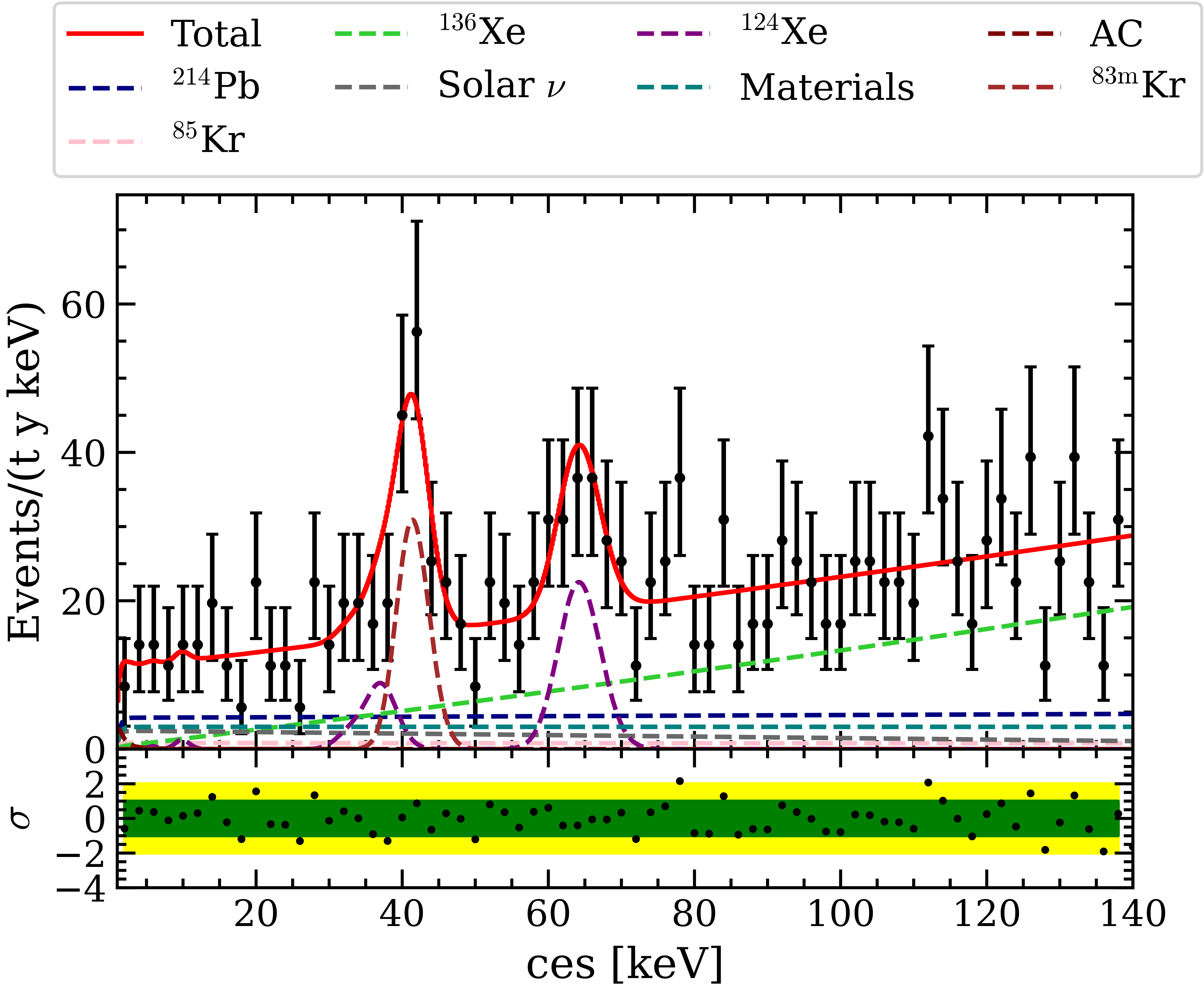


Data-driven and simulated maps agree well

Drift field: $23^{+5.5}_{-1.5}$ V/cm in the fiducial volume

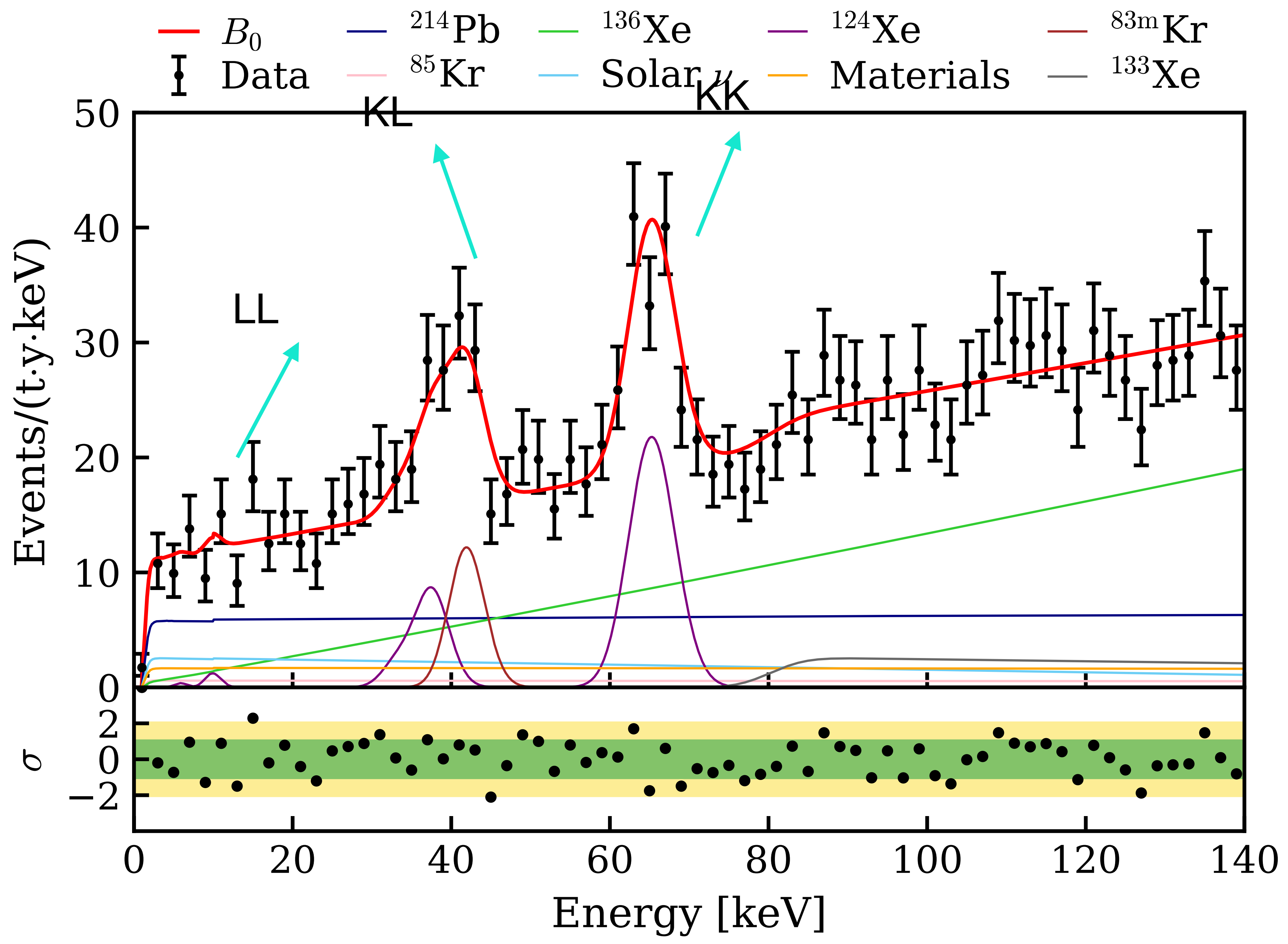


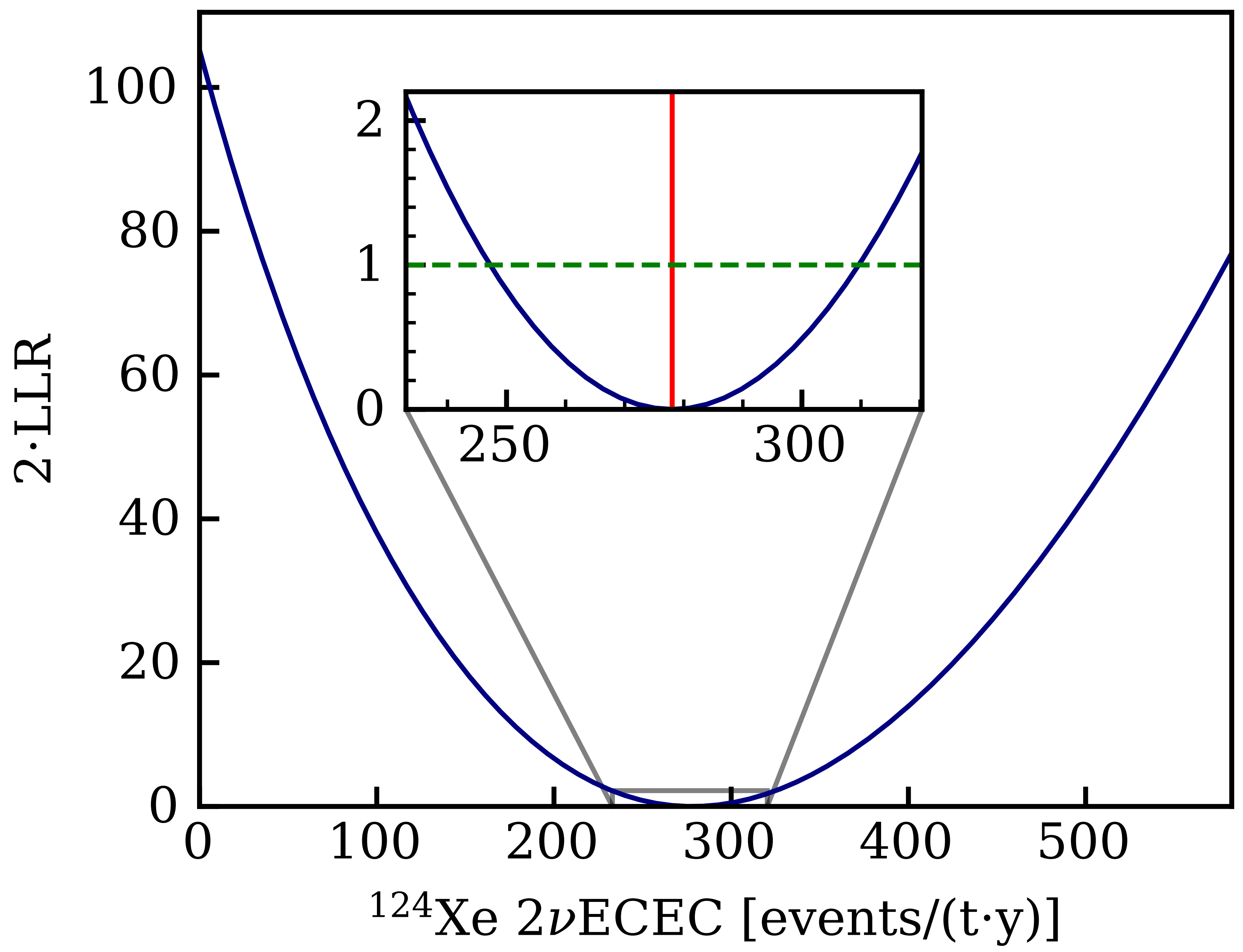
Tritium Enhanced Data (TED)



- 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

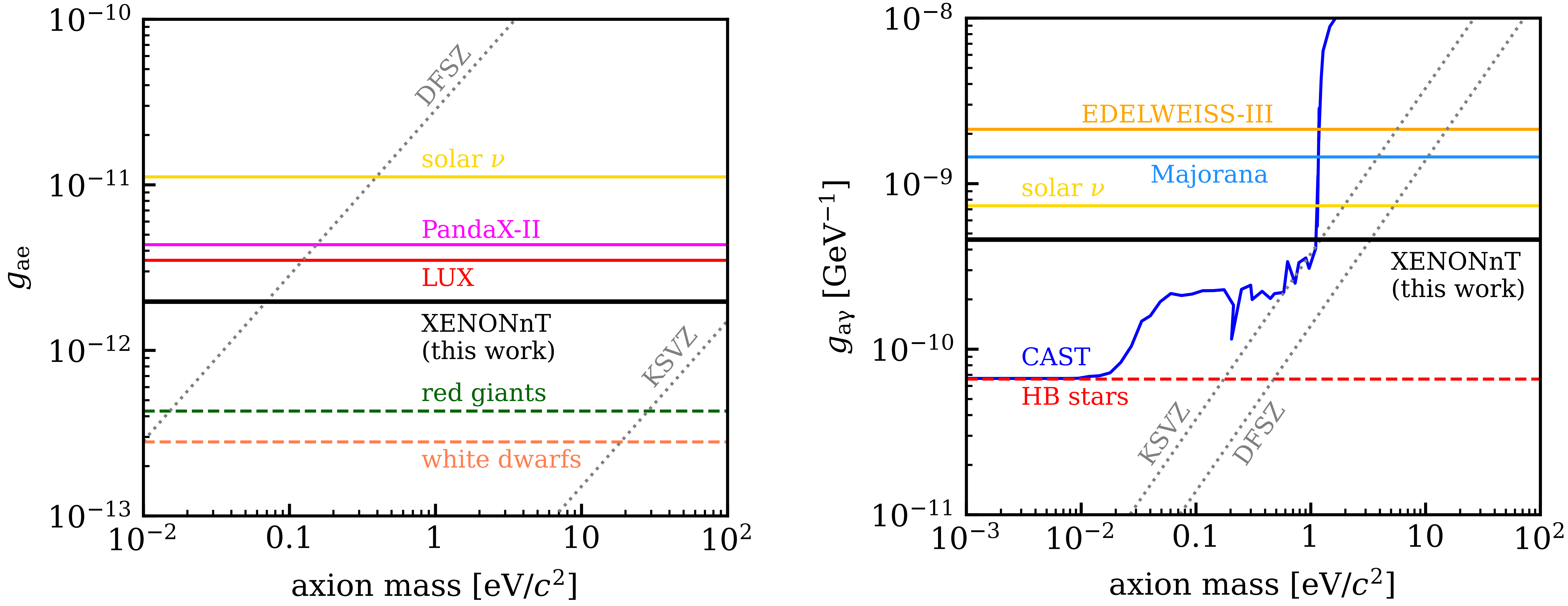
^{124}Xe 2νECEC





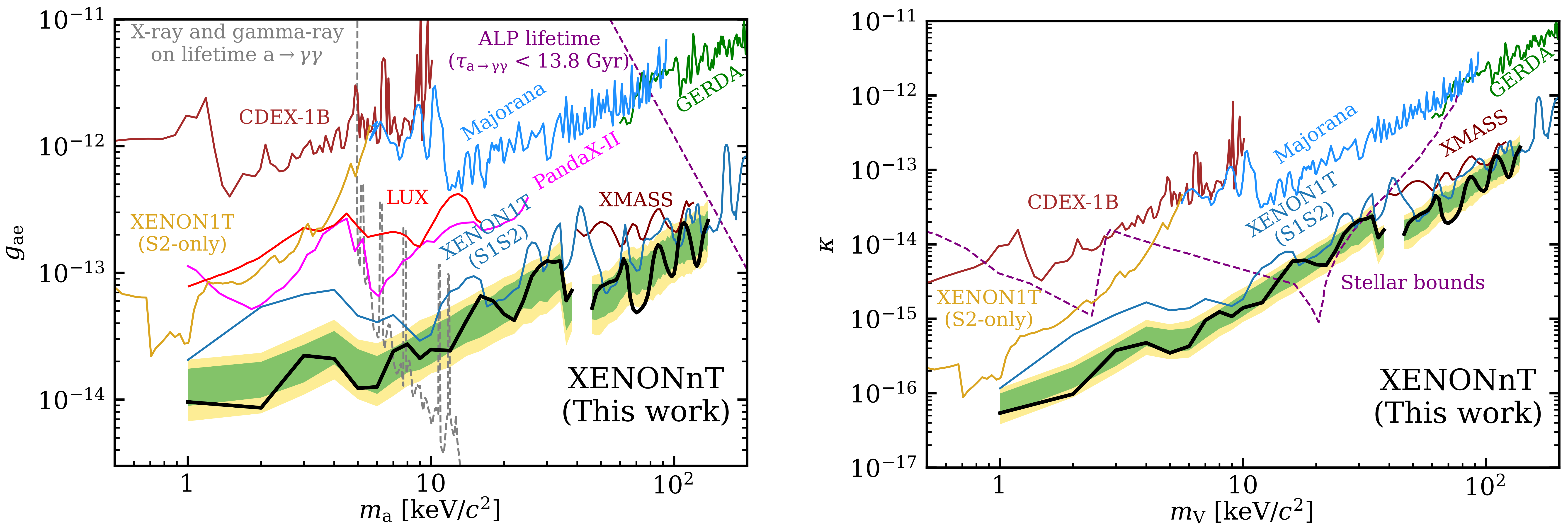
- ^{124}Xe 2νECEC rate is unconstrained in the entire analysis; BRs are fixed
- Stand out in the energy spectrum due to the ultra-low background
  - LL peak is visible even with only ~1% BR
  - KL & KK peaks are used for calibration purpose (energy resolution)
- The measured half-life $T_{1/2}^{2\nu ECEC} = (1.15 \pm 0.13_{stat} \pm 0.14_{sys}) \times 10^{22}$ 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

Solar Axion Limit



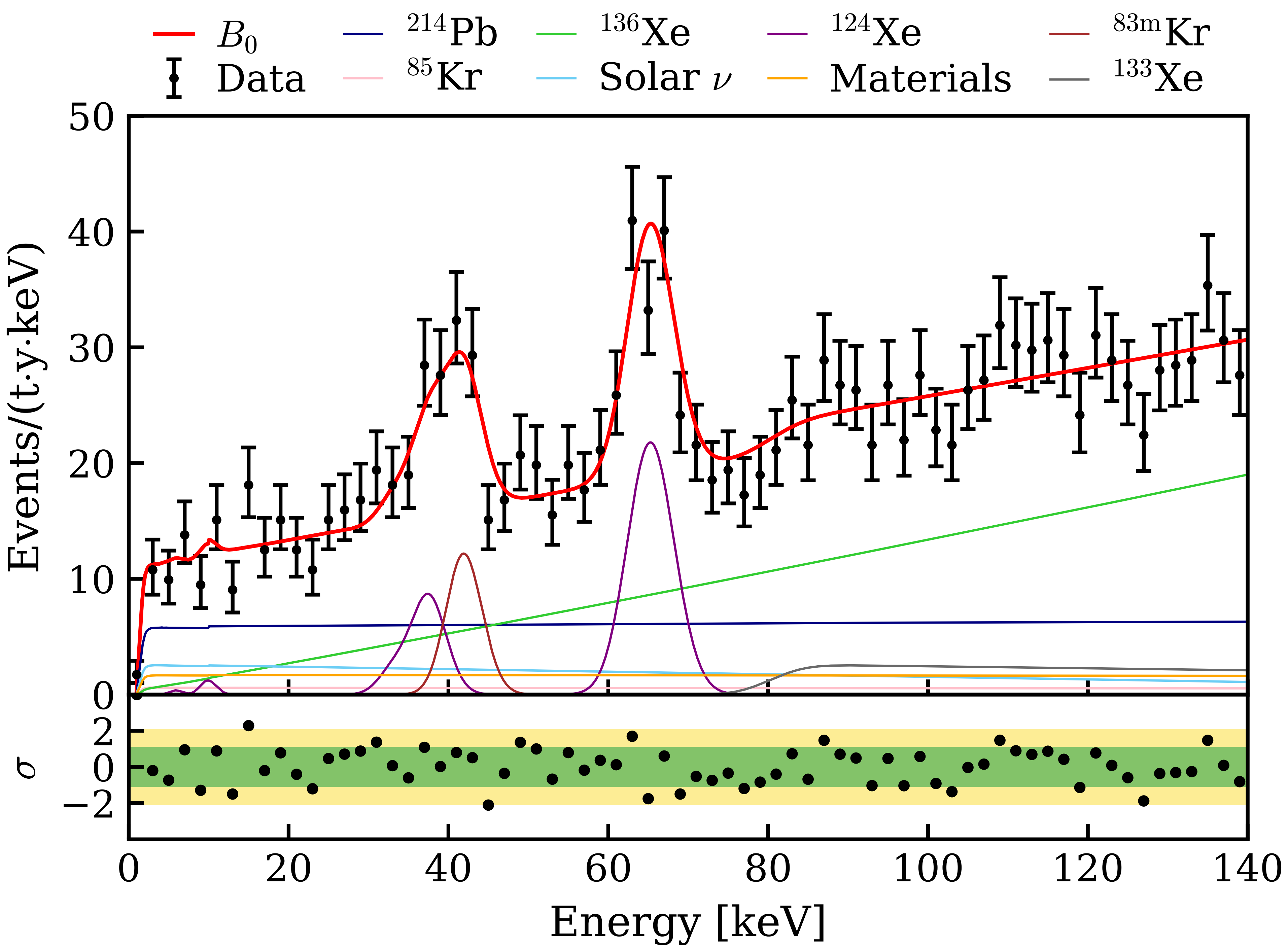
- Valid for axions with mass below 100 eV/c^2
- Best direct detection limit of g_{ae} for axion mass below 100 eV/c^2
- Best direct detection limit of $g_{a\gamma}$ for axion mass between 1 and 100 eV/c^2

Bosonic Dark Matter



- 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

XENONnT ER results



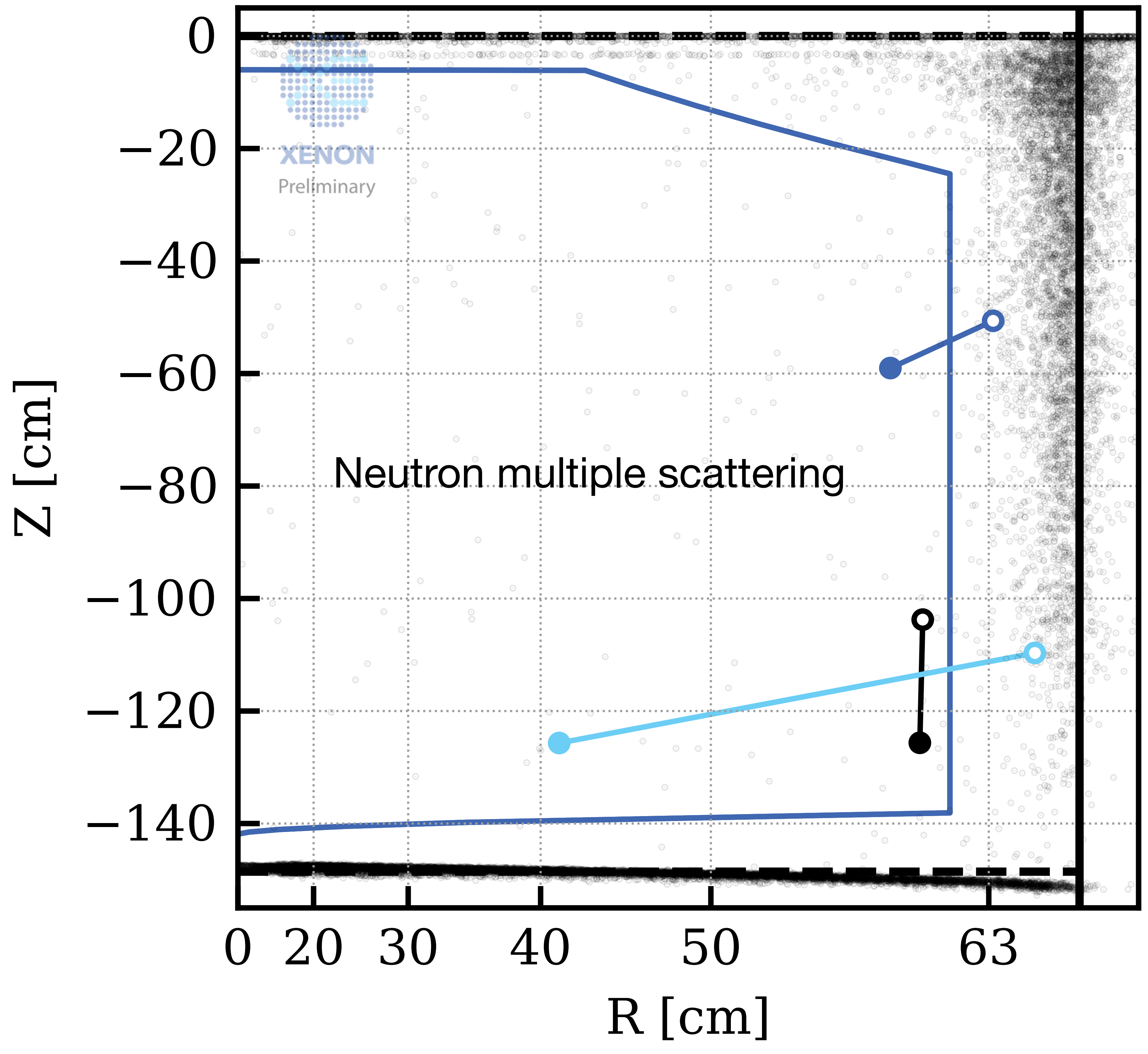
	(1, 10) keV	(1, 140) keV
^{214}Pb	55 ± 7	960 ± 120
^{85}Kr	6 ± 4	90 ± 60
Materials	16 ± 3	270 ± 50
^{136}Xe	8.8 ± 0.3	1550 ± 50
Solar neutrino	25 ± 2	300 ± 30
^{124}Xe	2.6 ± 0.3	250 ± 30
AC	0.70 ± 0.03	0.71 ± 0.03
^{133}Xe	-	150 ± 60
^{83m}Kr	-	80 ± 16

- The total ER rate below 30 keV is $(15.8 \pm 1.3_{\text{stat}})\ \text{events}/(\text{t} \cdot \text{y} \cdot \text{keV})$, the lowest background ever achieved in a dark matter detector, a factor of ~5 lower than XENON1T ER background.
- Solar neutrino: the 2nd largest ER background below 10 keV in SR0
  - Pb-214 background is further reduced by a factor of ~2 in SR1
  - Solar neutrino ER component is similar to Pb-214 background in SR1

NR backgrounds

Two NR backgrounds:

- Coherent Elastic Neutrino Nucleus Scattering (CEvNS) from solar $^{8}\mathrm{B}$ neutrinos
  - Relatively small, $\sim 0.2\,\mathrm{events/(t \cdot y)}$
- Neutrons from spontaneous fission and (α, n) reactions, $\sim 1.1\,\mathrm{events/(t \cdot y)}$

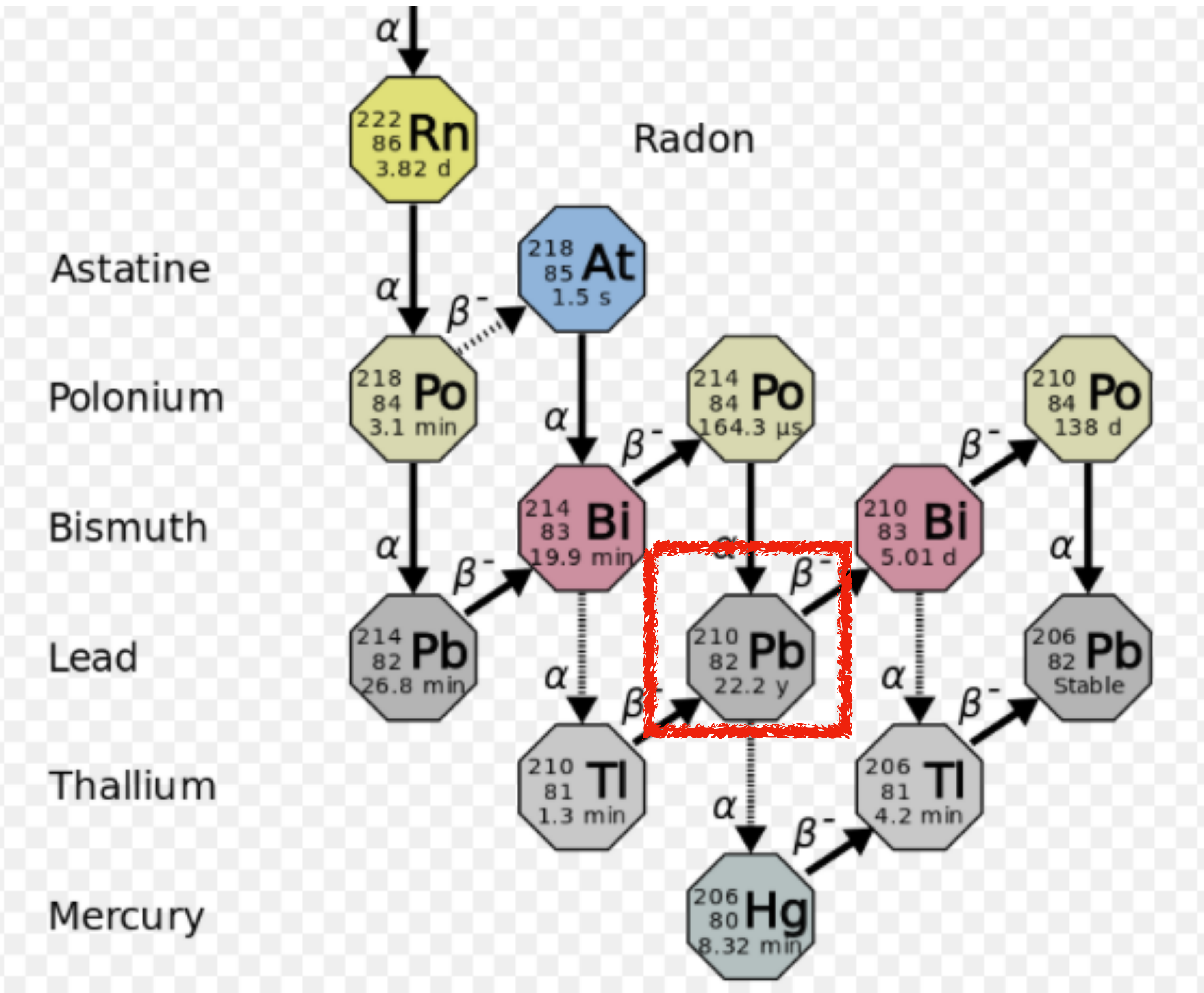


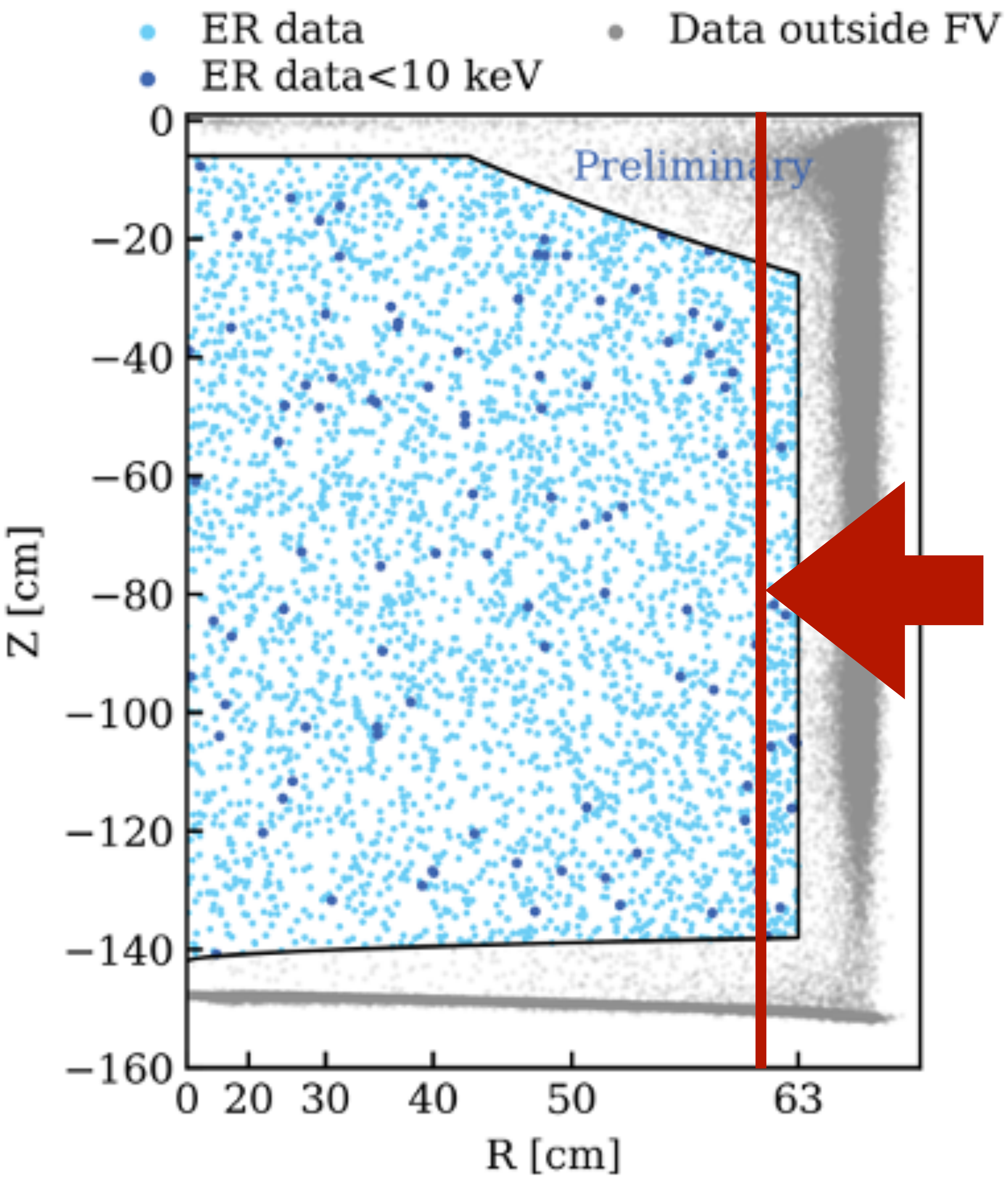
Neutron suppression methods

- Fiducialization
- multiple scatter rejection
- Neutron veto
  - (53 ± 3) % tagging efficiency @ 250 μs window
  - Lifetime loss: 1.6%
- WIMP search livetime: 95.1 days

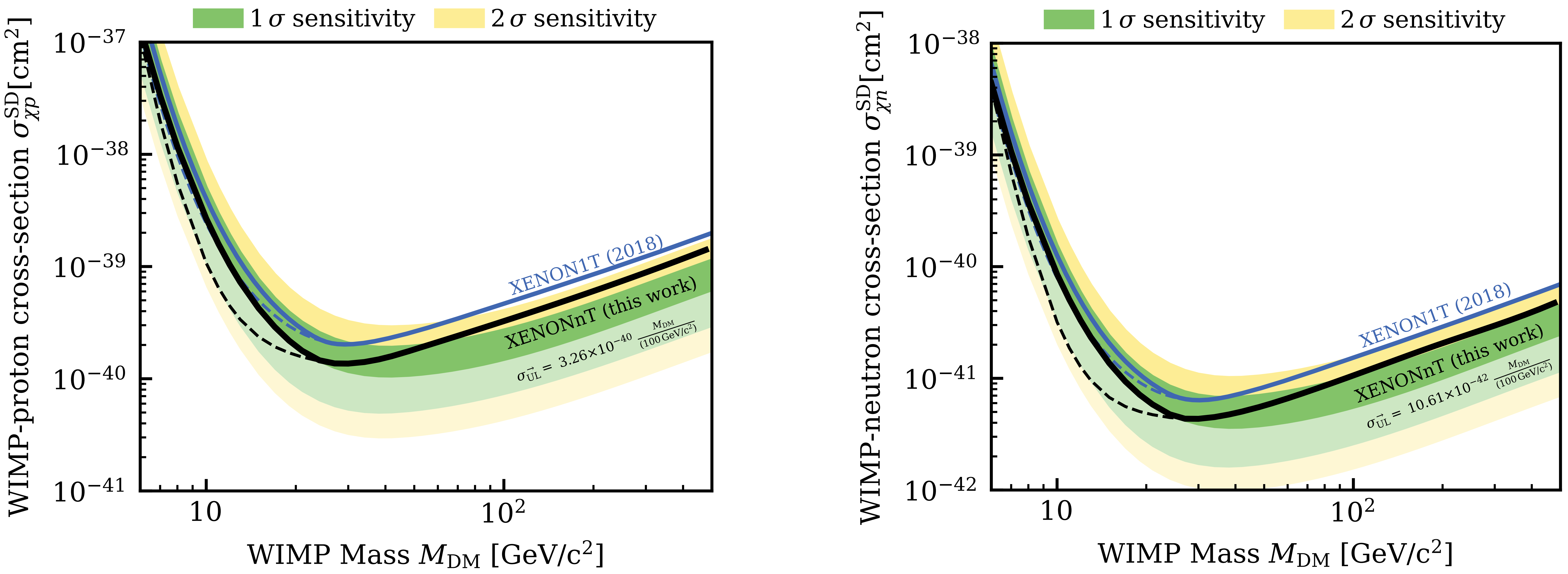
Surface background

- ^{210}Pb plates out on TPC surface (PTFE) due to its long half life of 22 years
- Charges of ^{210}Pb ER events are lost to PTFE, leading to artificially small S2s that overlaps with light WIMPs
- Radius is set at 61.35 cm to reduce surface background





Spin-dependent WIMP results



WIMP results