Search for Solar Axions and ALP Dark Matter with XENONnT

Jingqiang Ye (叶靖强)
The Chinese University of Hong Kong, Shenzhen
On behalf of the XENON Collaboration

Axion Quest@Quy Nhon
August 8, 2024

PRL 129, 161805 (2022)

The XENON Collaboration

29 institutes
~200 scientists

AMERICA

- UC San Diego — San Diego
- Rice (Houston)
- The University of Chicago — Chicago
- Columbia University in the City of New York — New York City
- Purdue University — Lafayette

EUROPE

- Universität Zürich — Zurich
- KIT Karlsruhe Institute of Technology — Karlsruhe
- WWU Münster — Münster
- Uni Freiburg — Freiburg
- JGU — Mainz
- Max-Planck-Institut für Kernphysik — Heidelberg
- Nikhef — Amsterdam
- Stockholm University — Stockholm
- Universidade de Coimbra — Coimbra
- Subatech — Nantes
- LPNHE Paris — Paris
- INFN Torino — Torino
- Alma Mater Studiorum — Bologna
- Università degli Studi dell'Aquila — L'Aquila
- INFN LNGS — Assergi
- Napoli

MIDDLE EAST

- מכון ויצמן למדע Weizmann Institute of Science — Rehovot
- جامعة نيويورك أبوظبي NYU Abu Dhabi — Abu Dhabi

ASIA

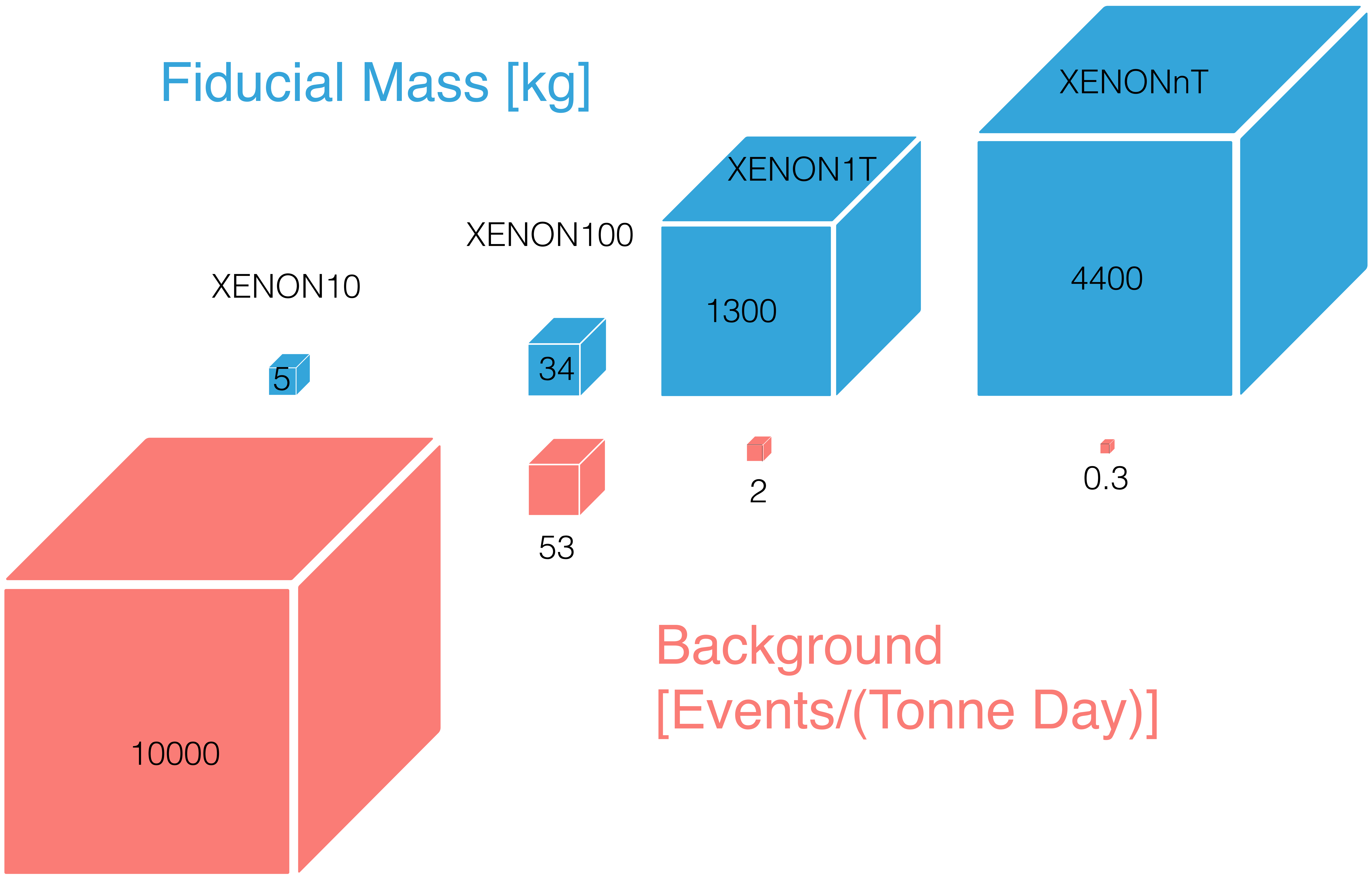
- 清华大学 Tsinghua University — Beijing
- 西湖大学 Westlake University — Hangzhou
- The Chinese University of Hong Kong, Shenzhen — Shenzhen
- 東京大学 The University of Tokyo — Tokyo
- Nagoya University — Nagoya
- Kobe University — Kobe

The evolution of XENON experiments

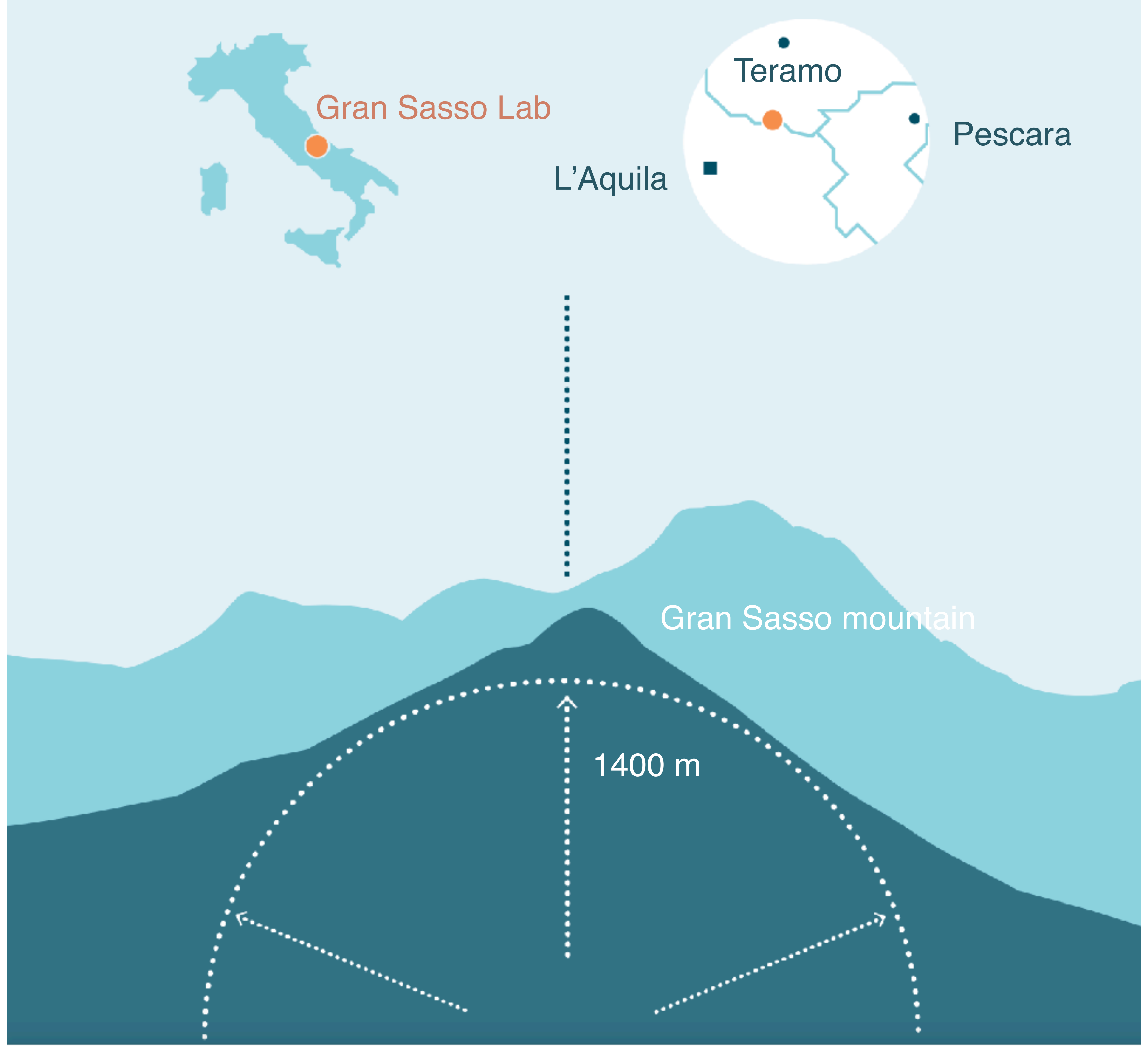


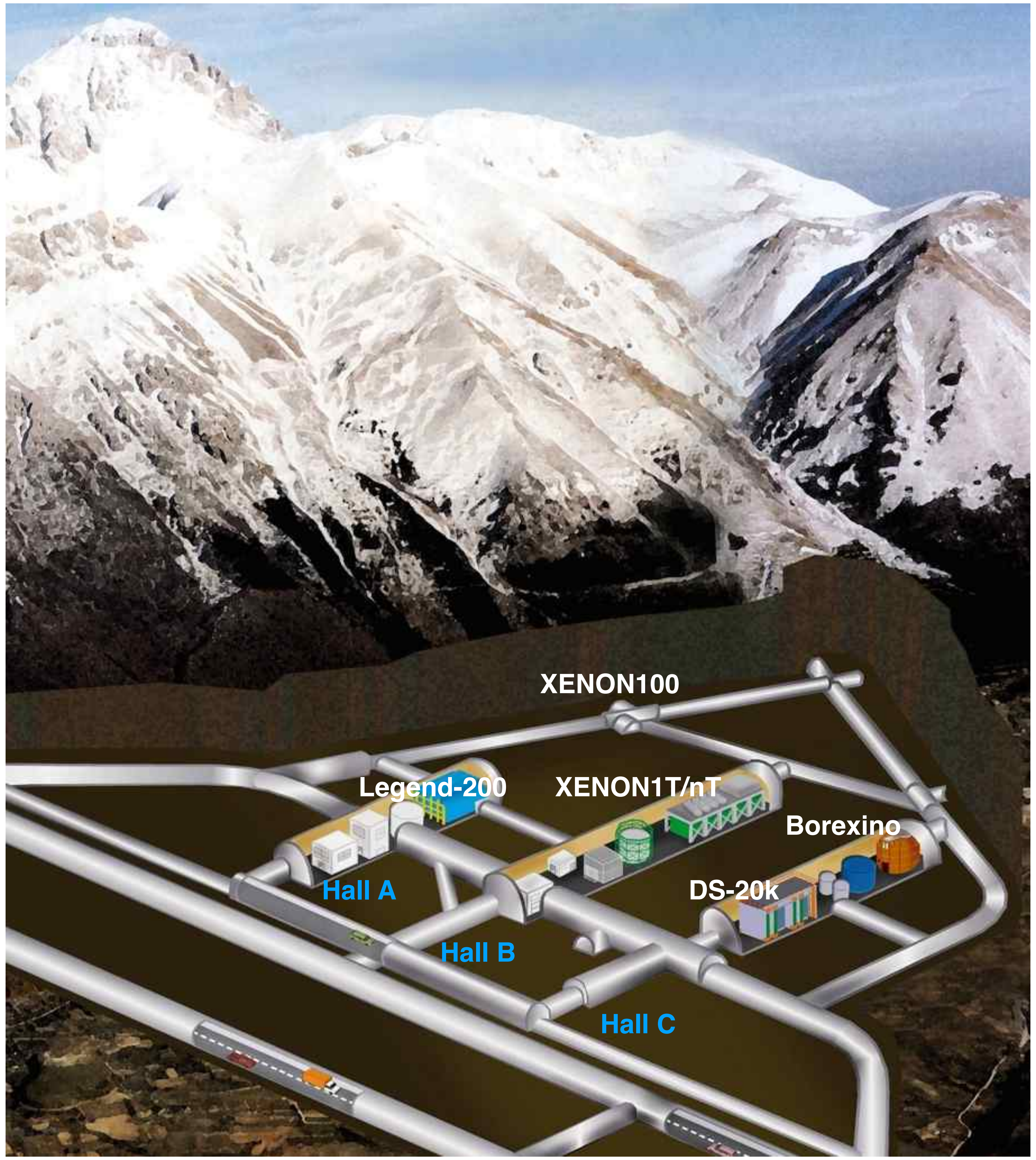

	XENON10	XENON100	XENON1T	XENONnT
Science data taking	2005–2007	2008–2016	2012–2018	2021 —
Xe Target	14 kg	62 kg	2 t	5.9 t
Background	~2000000 ER events/(keV t y)	1800 ER events/(keV t y)	82 ER events/(keV t y)	15.8 ER events/(keV t y)
WIMP sensitivity	$\sim 10^{-43}$ cm^2	$\sim 10^{-45}$ cm^2	4×10^{-47}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

Fiducial mass and background

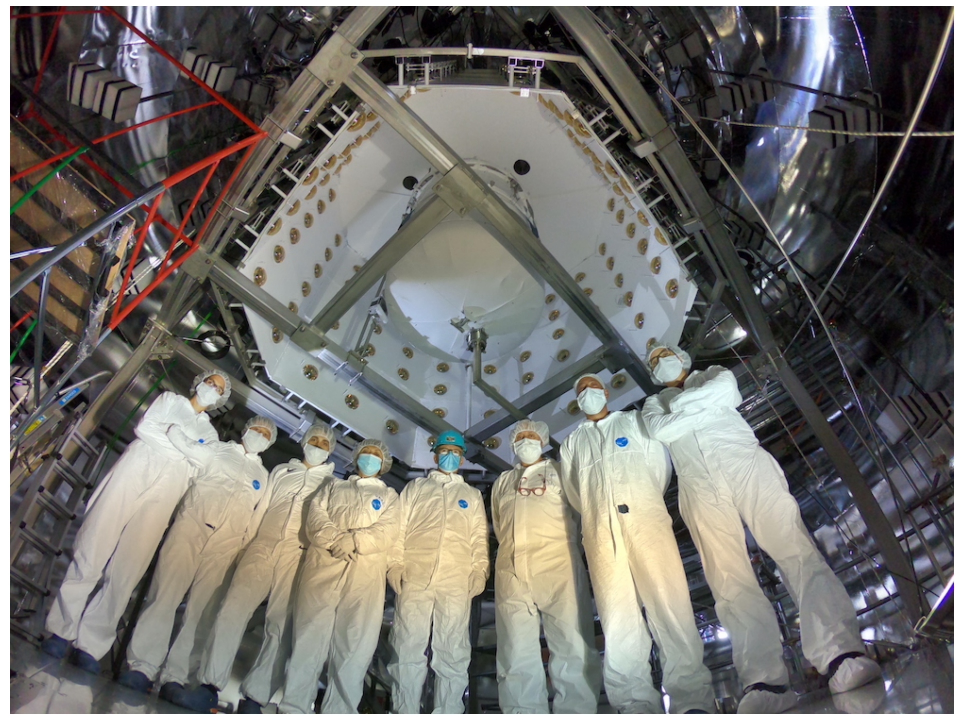


INFN Gran Sasso National Laboratory (LNGS)



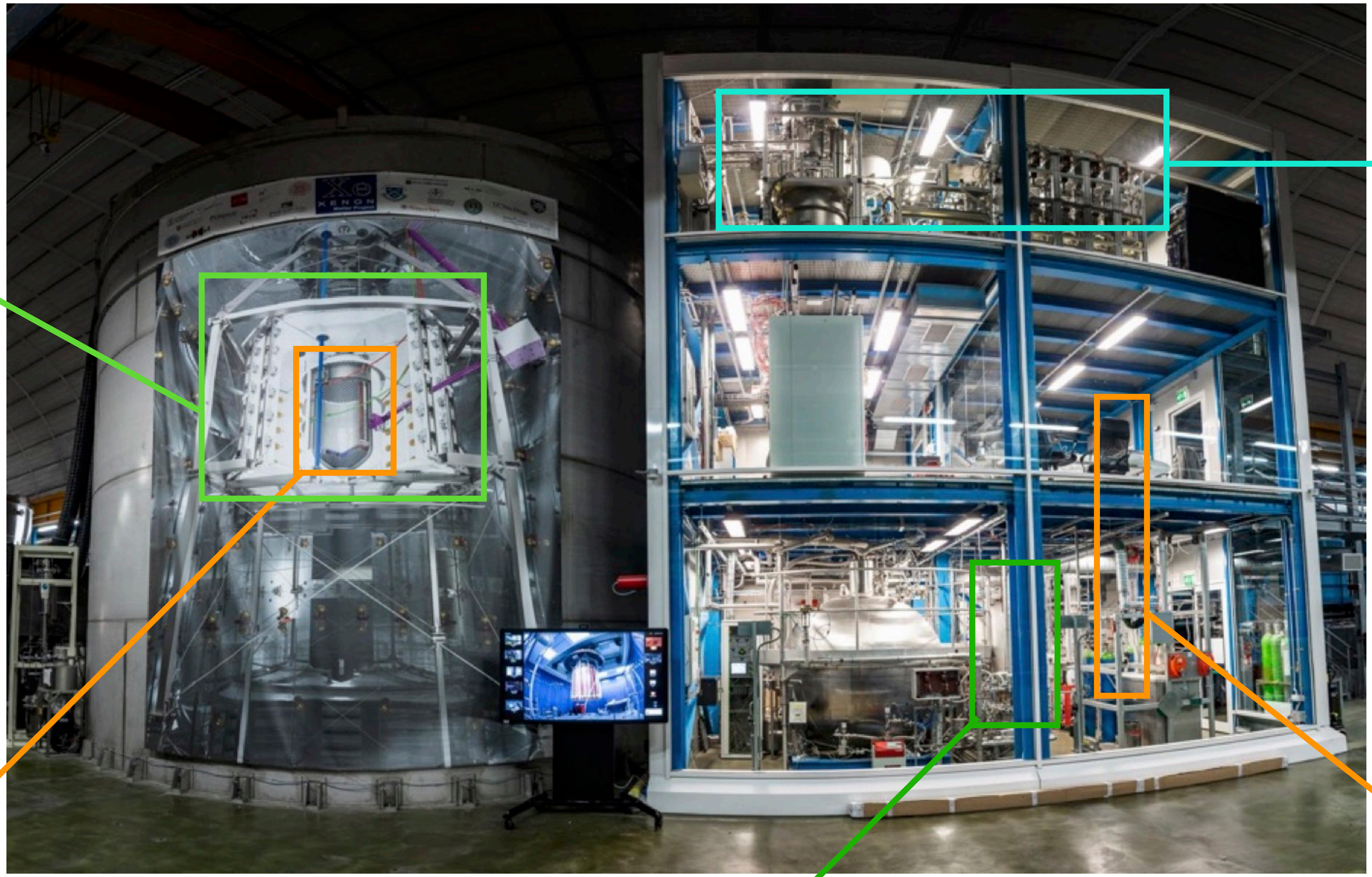


The XENONnT experiment



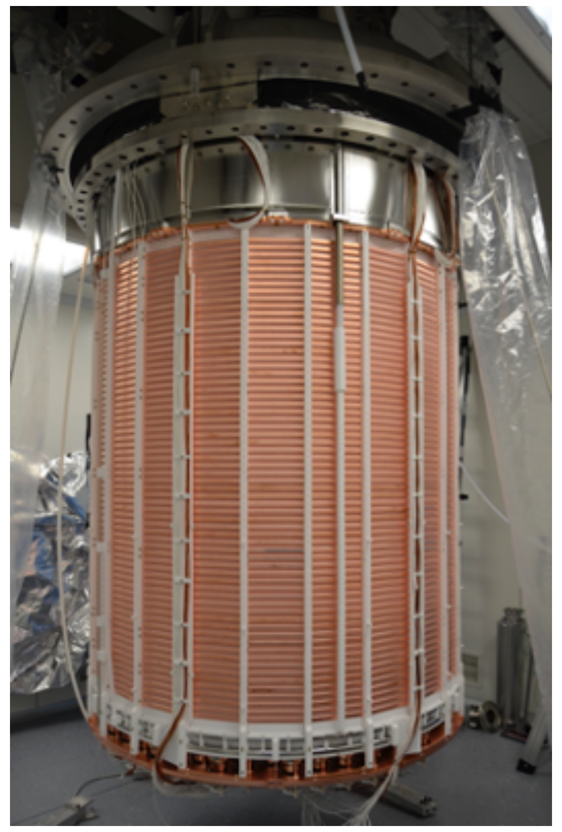
Neutron veto

Wenz, PhD thesis (2023)



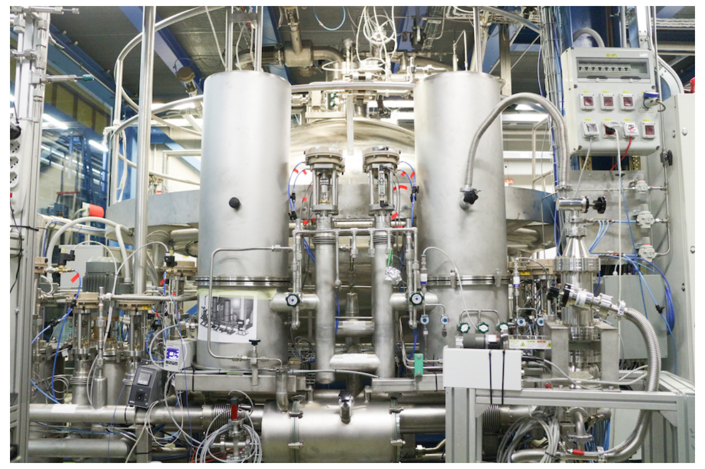
Radon distillation column

Murra et al., JINST 17 P05037 (2022)



Time projection chamber (TPC)

XENON, EPJC 84, 138 (2024)



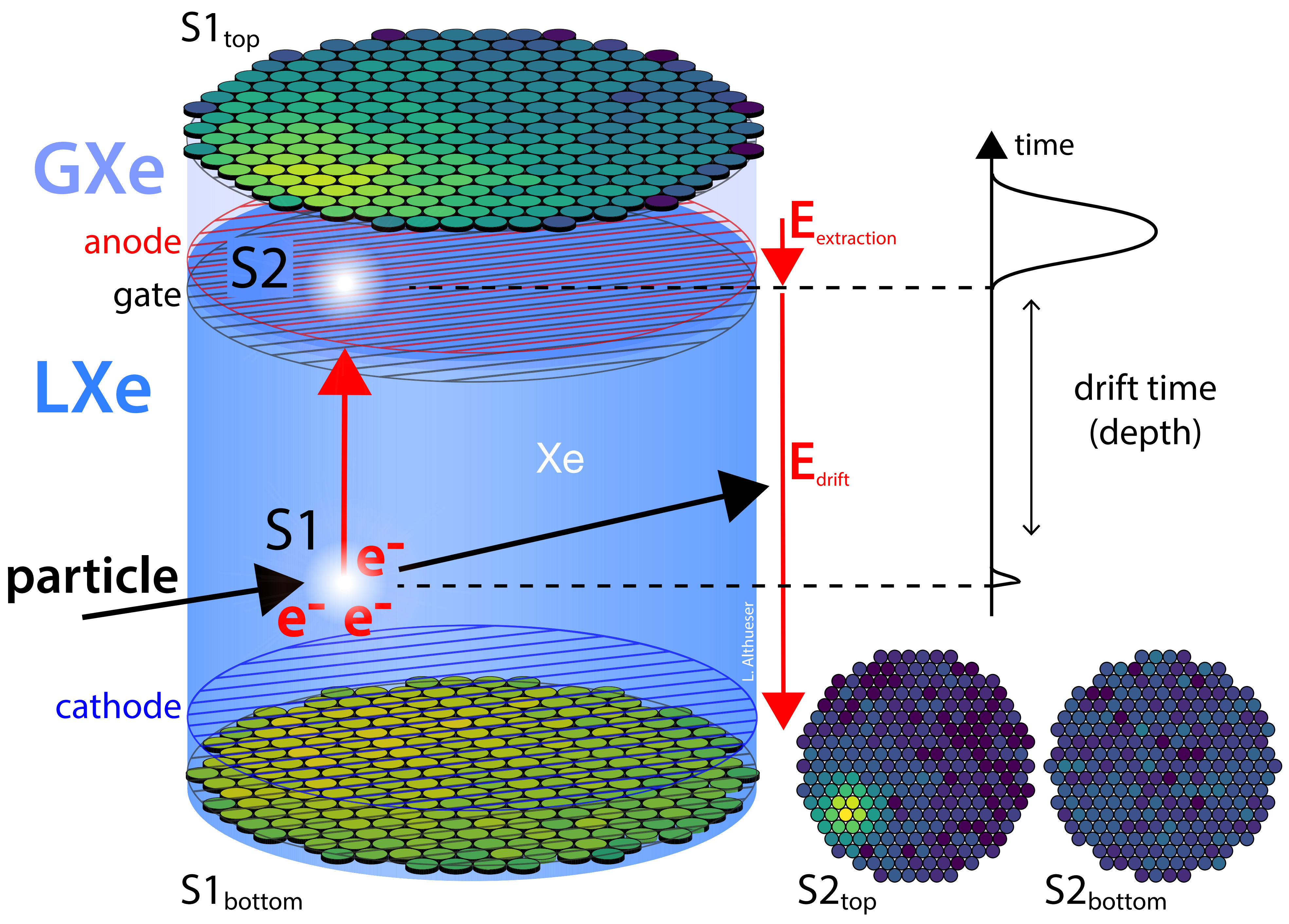
Liquid xenon purification system

Plante et al., EPJC 82, 860 (2022)

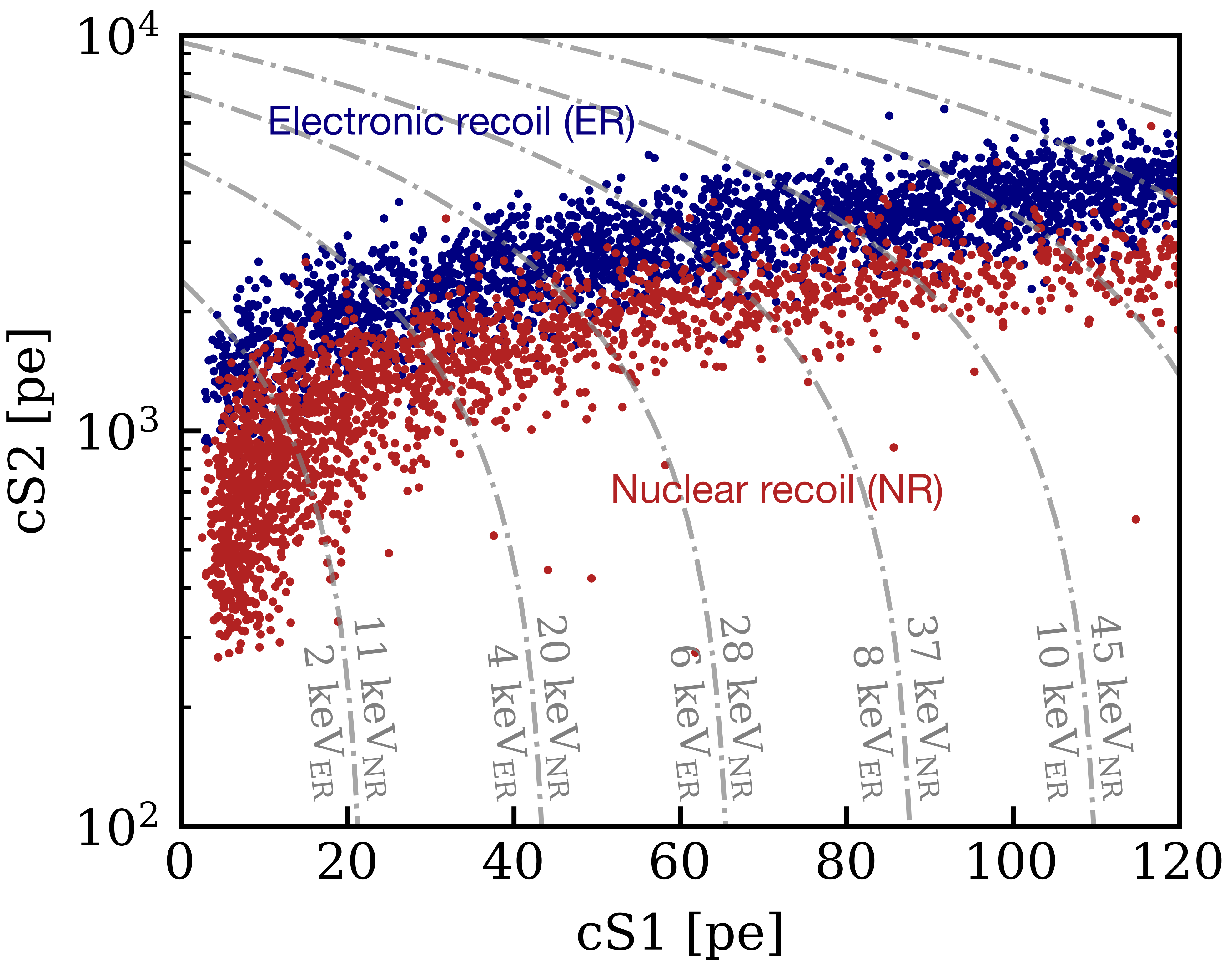
Krypton distillation column

XENON, PTEP 2022 (5) (2022) 053H01

Why TPC?



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



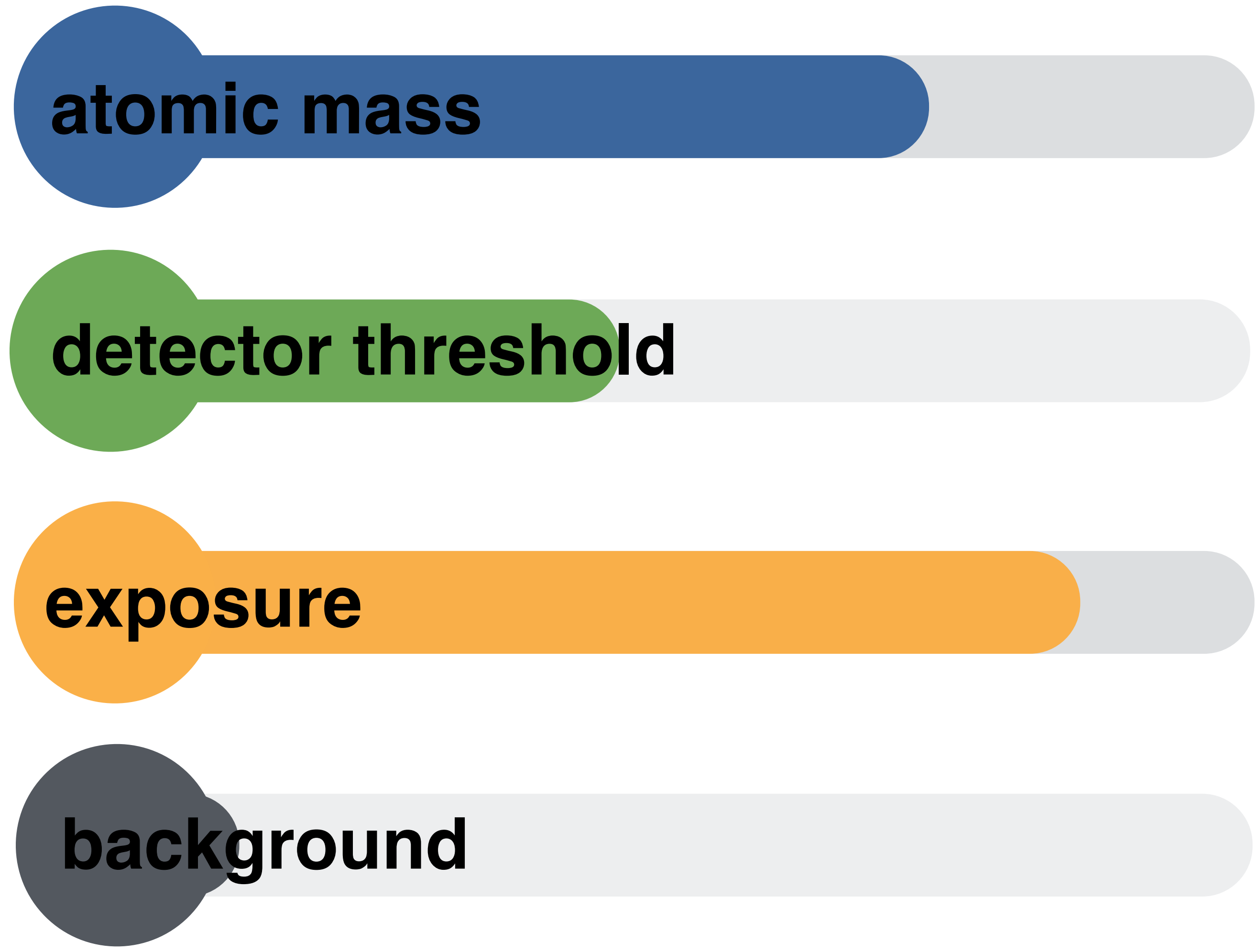
Particle interaction identification

- S2/S1 ratio: ER/NR discrimination

Why xenon?

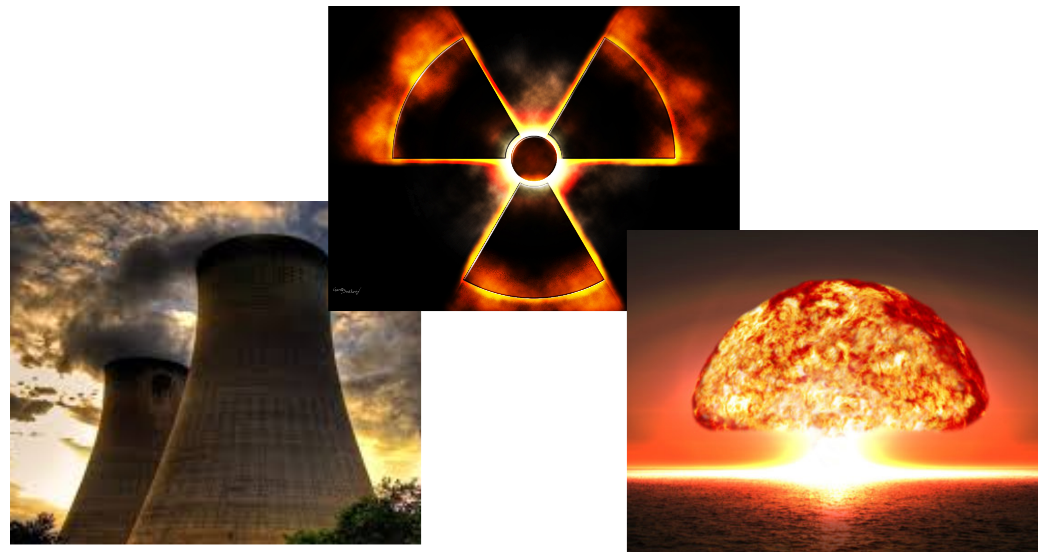
Selected Properties of Xe

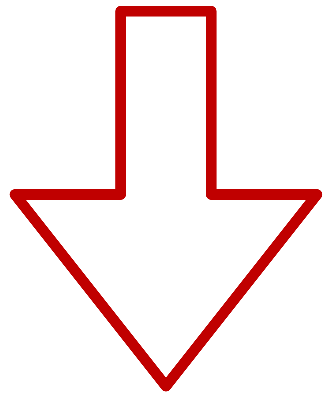
Property	Value
Atomic Number (Z)	54
Atomic Weight (A)	131.30
Number of Electrons per Energy Level	2,8,18,18,8
Density (STP)	5.894 g/L
Boiling Point	−108.1 °C
Melting Point	−111.8 °C
Volume Ratio	519
Concentration in Air	0.0000087 % by volume



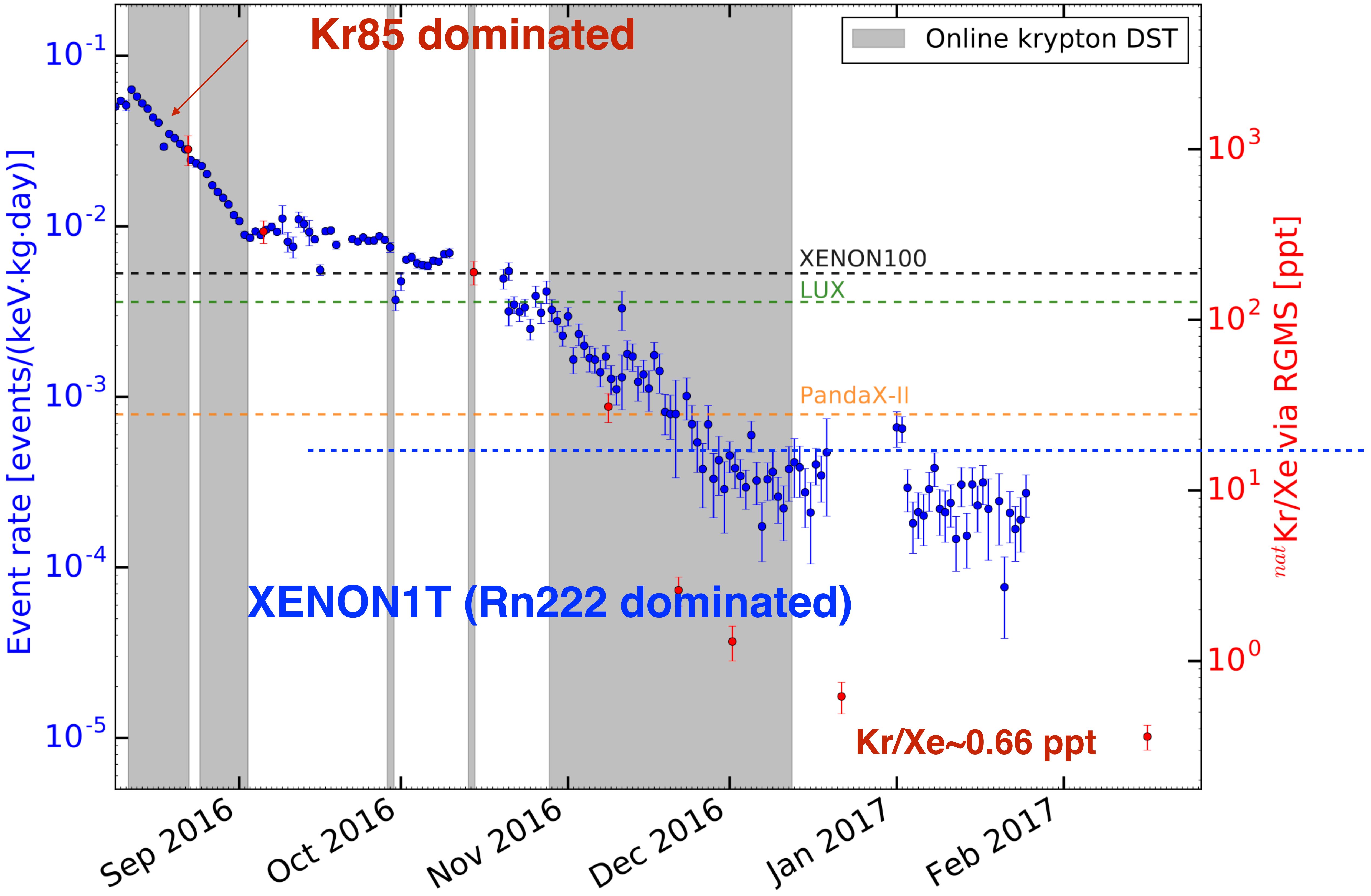
- Heavy
- O(1) keV
- Scalability & Stability
- Radiopurity

Krypton distillation column



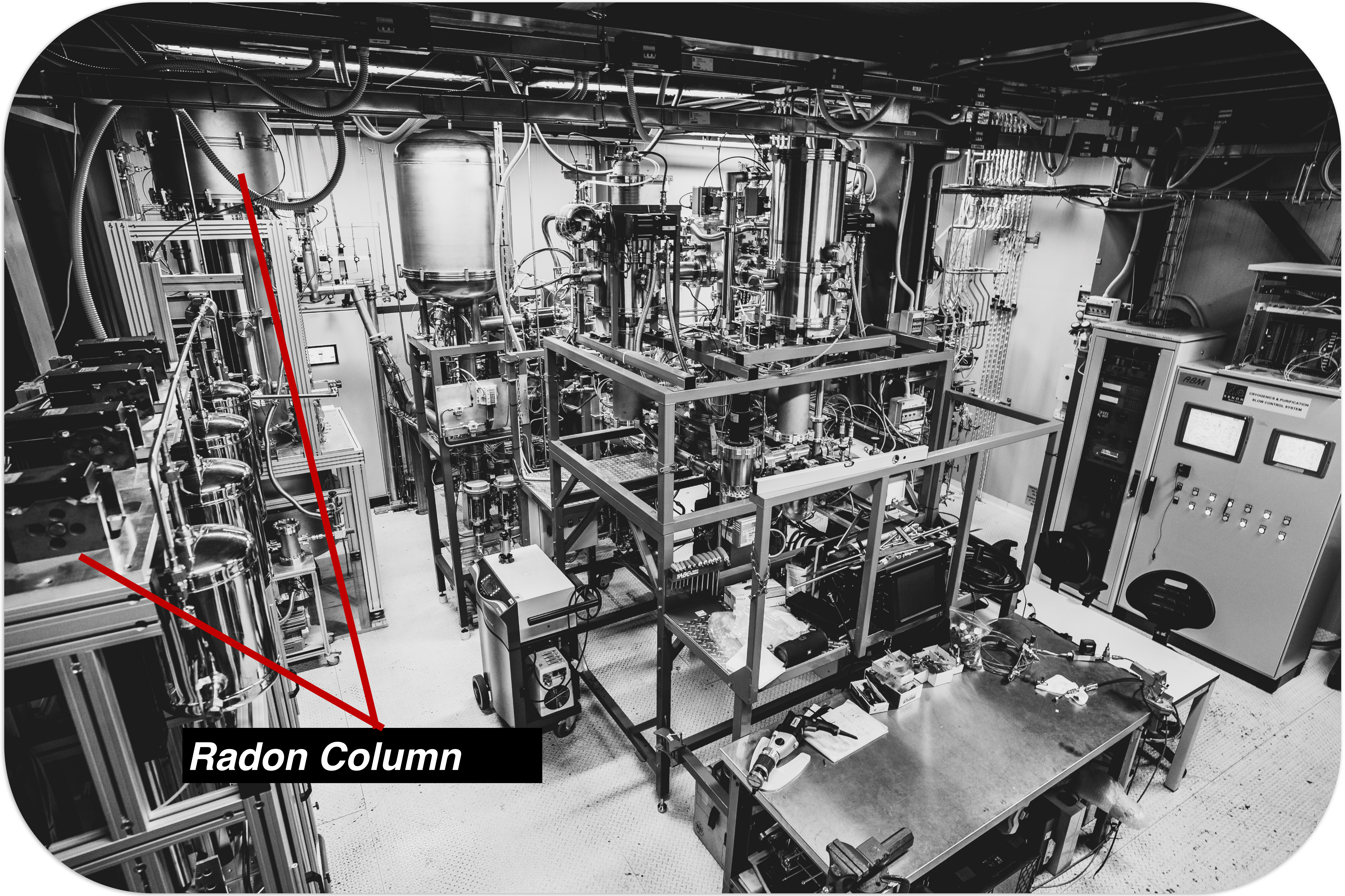


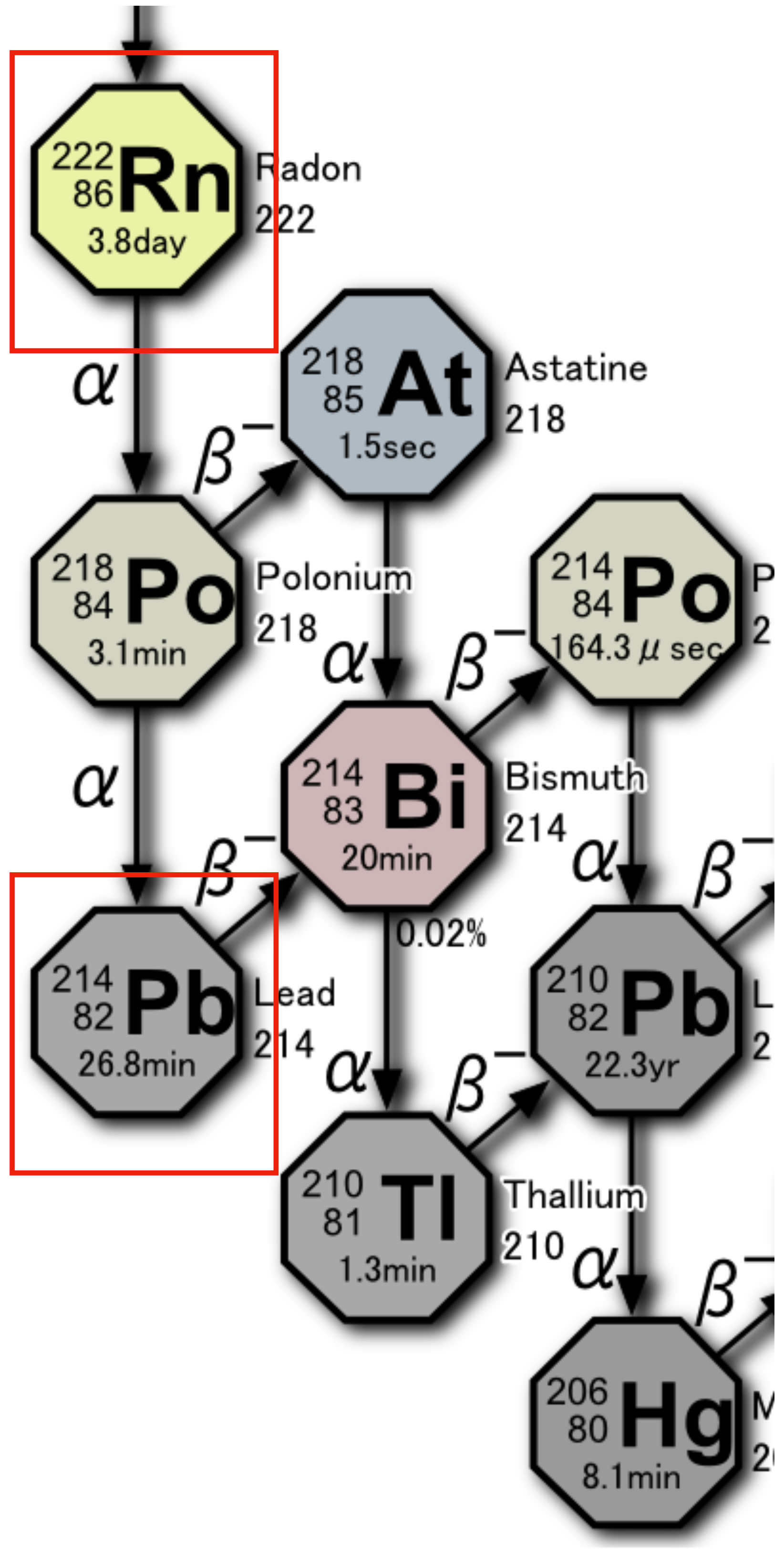
^{85}Kr



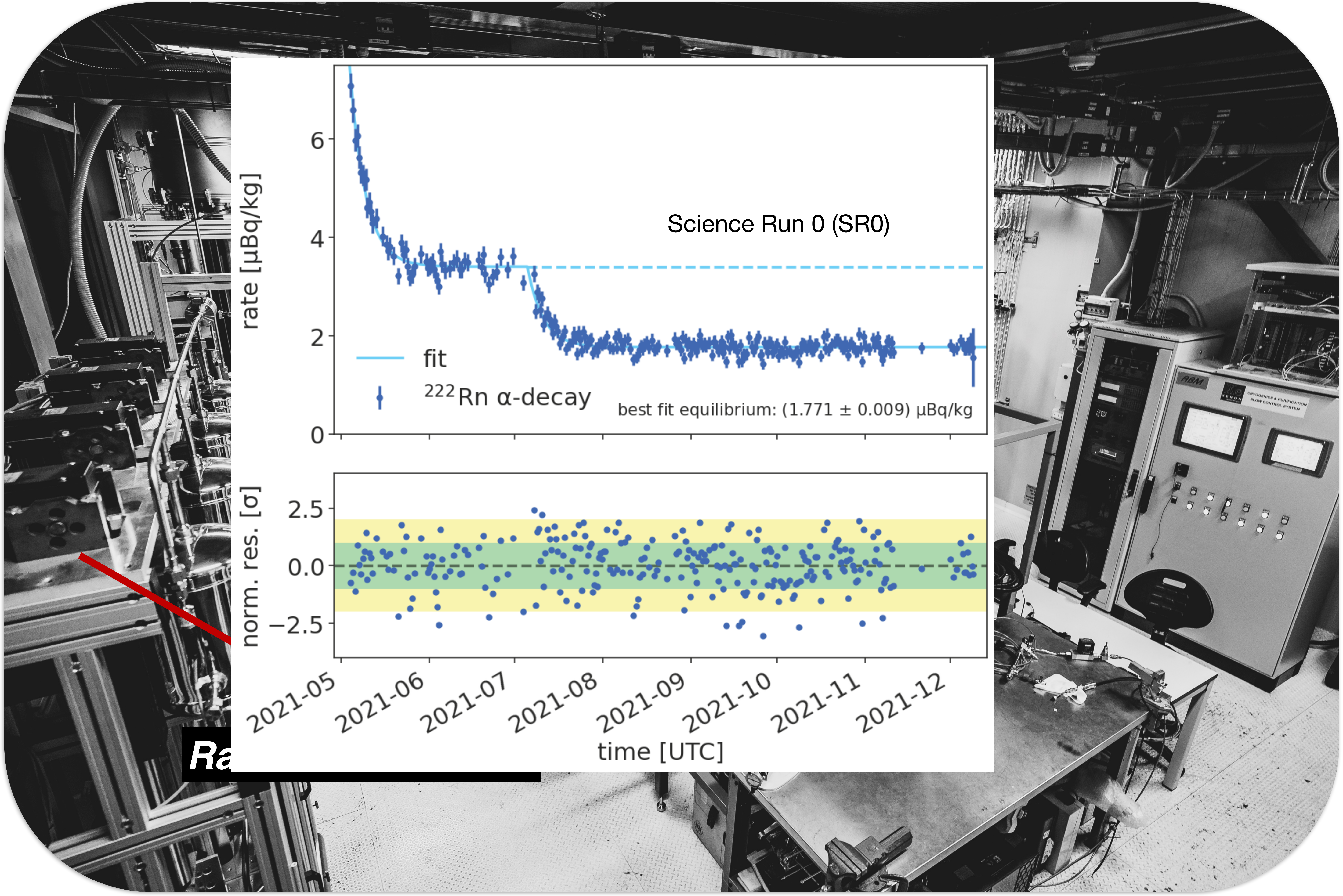
- Decrease krypton concentration by cryogenic distillation
- ^{nat}Kr: (56 ± 36) ppq (XENON1T SR1: (660 ± 110) ppq)

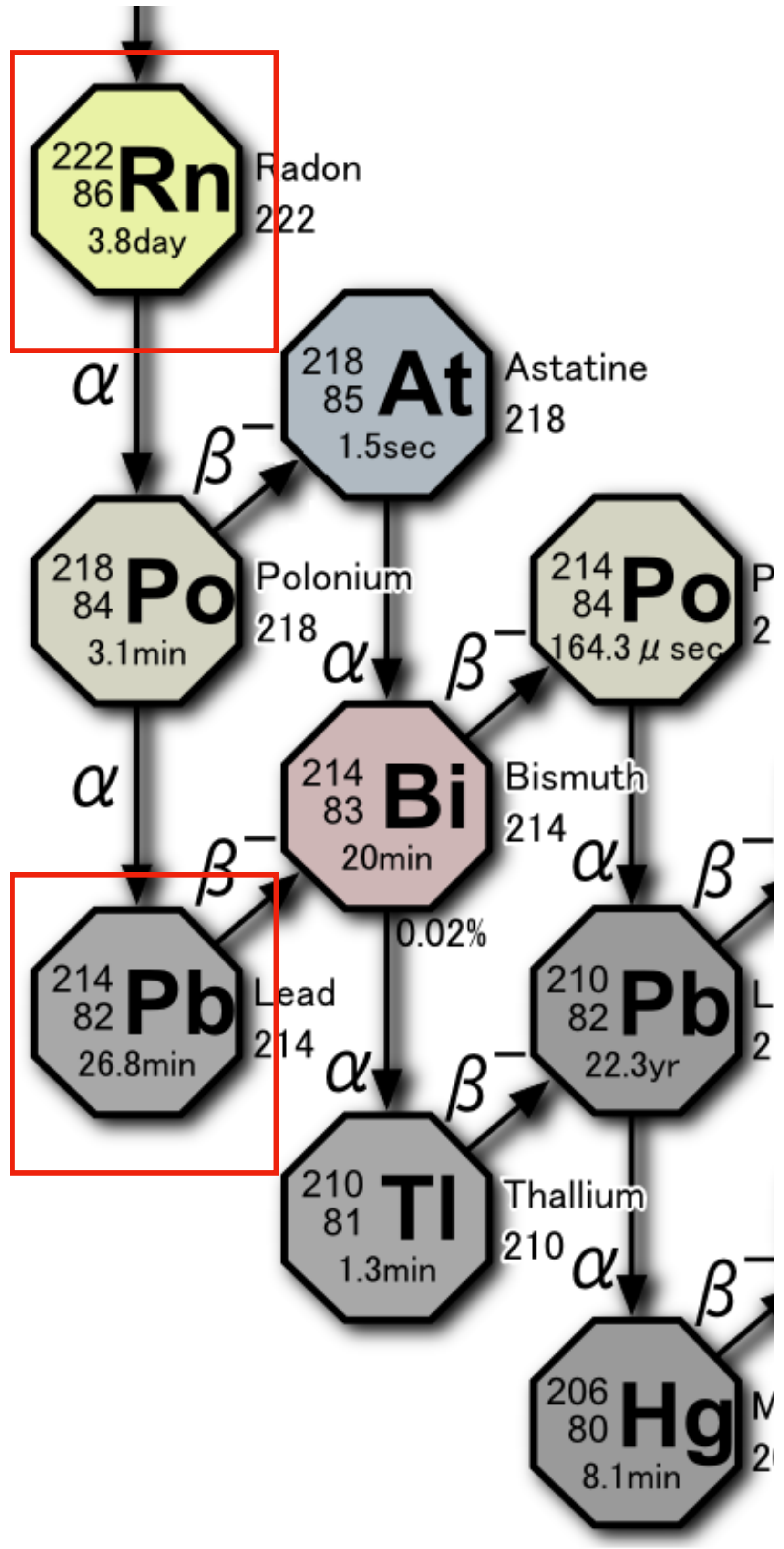
Radon distillation column



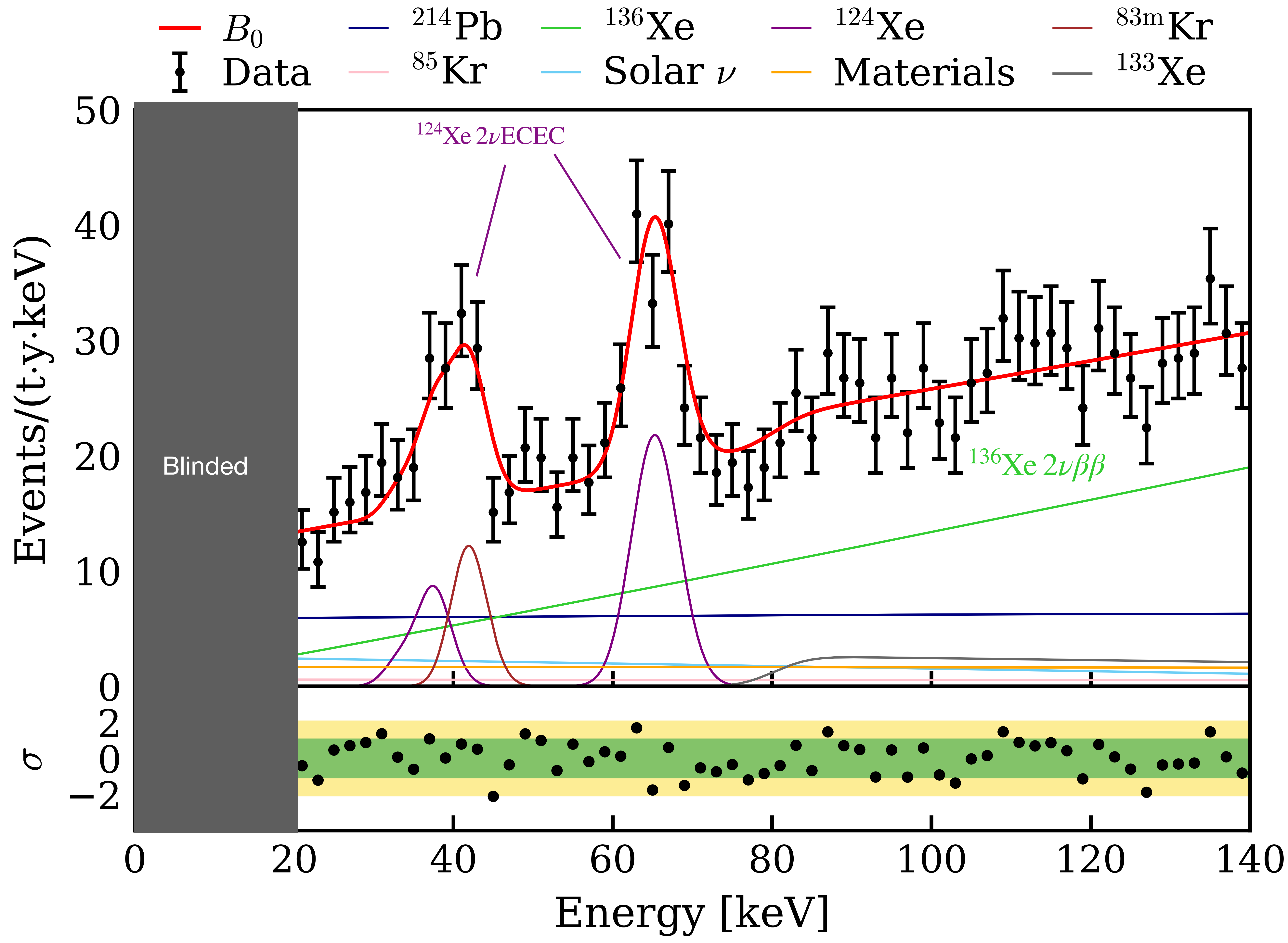


Radon distillation column

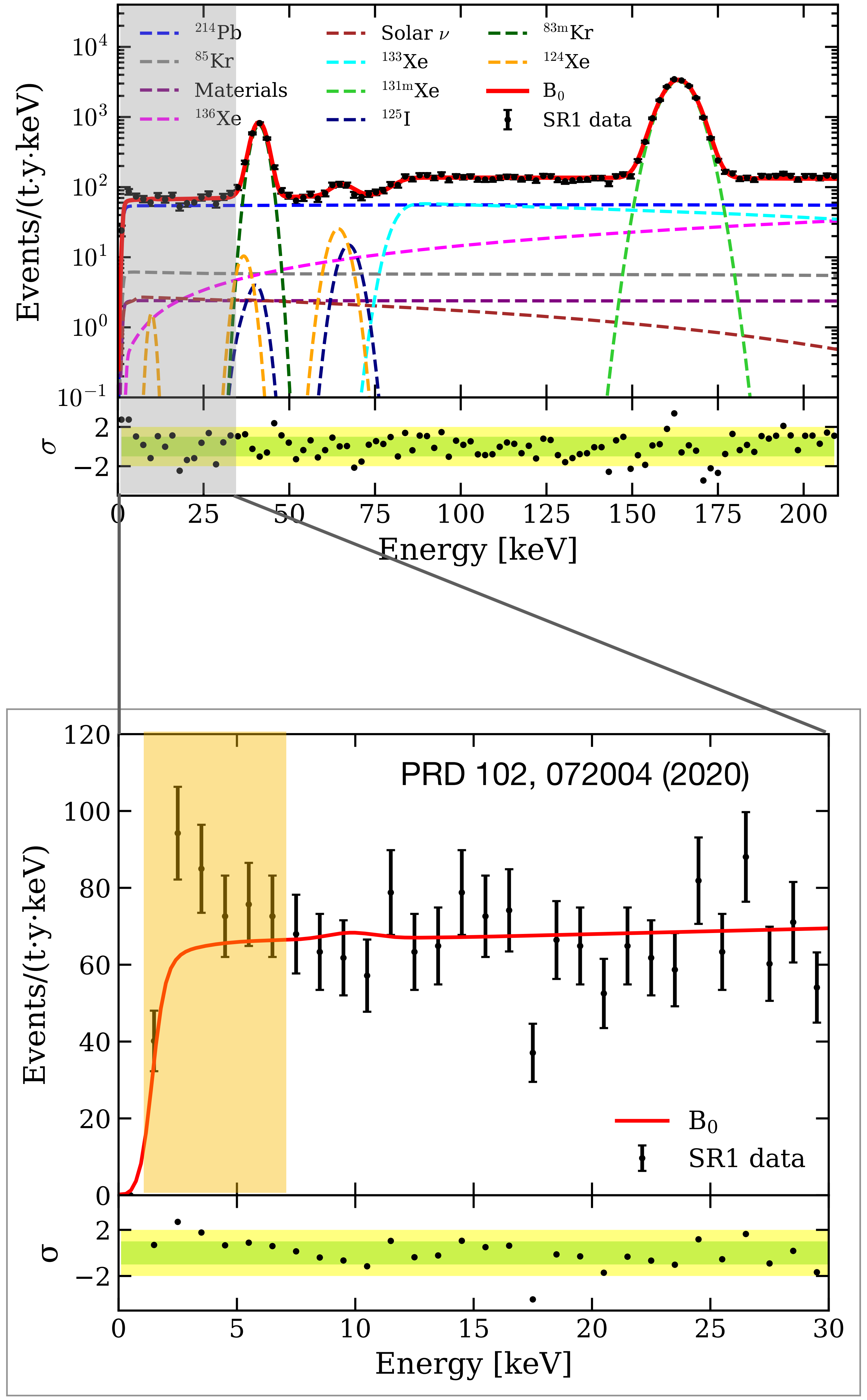




SR0 ER backgrounds



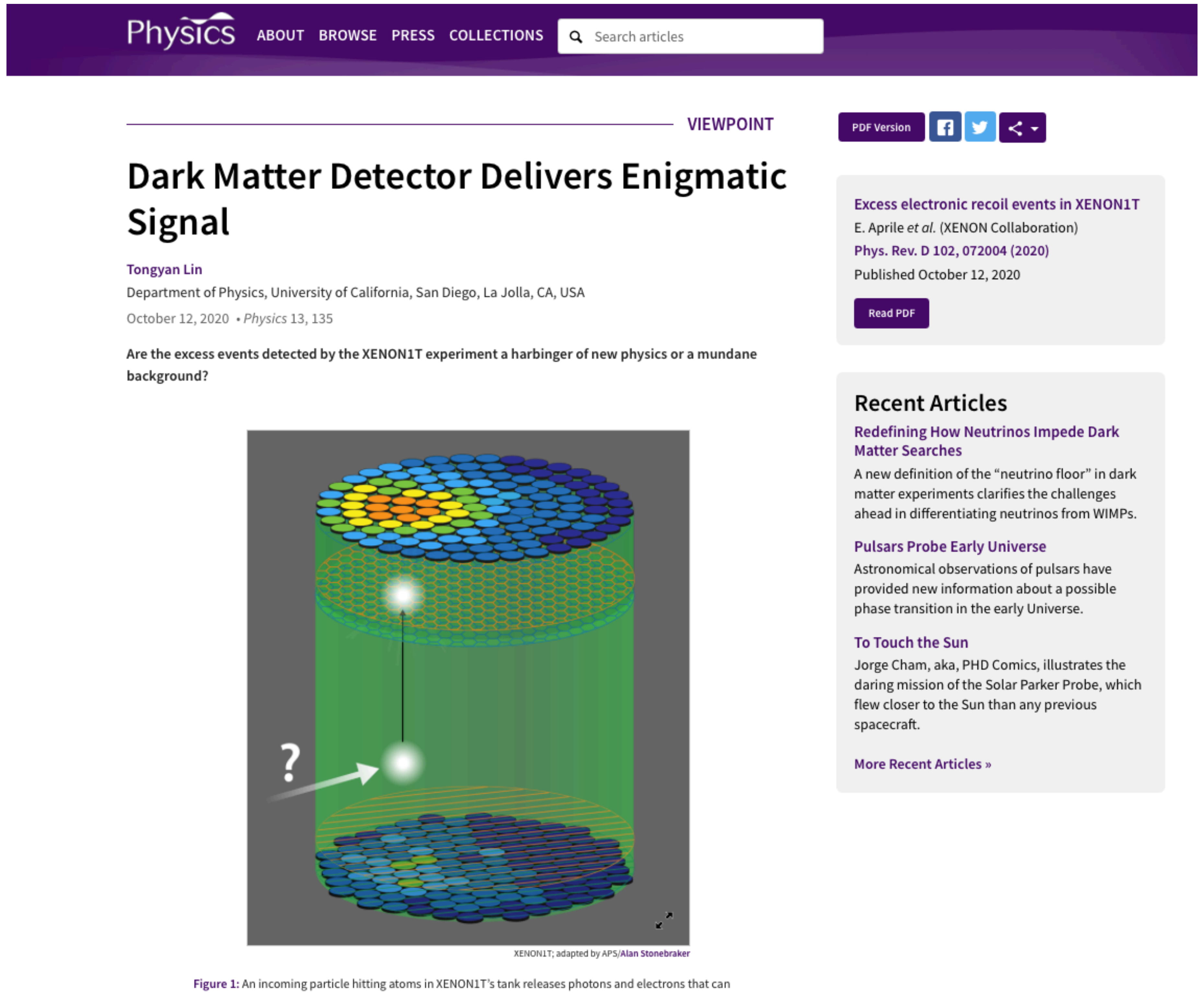
XENON1T Excess



1—7 keV
(reference region)

Expected: 232
Observed: 285

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


Physics ABOUT BROWSE PRESS COLLECTIONS Search articles

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?

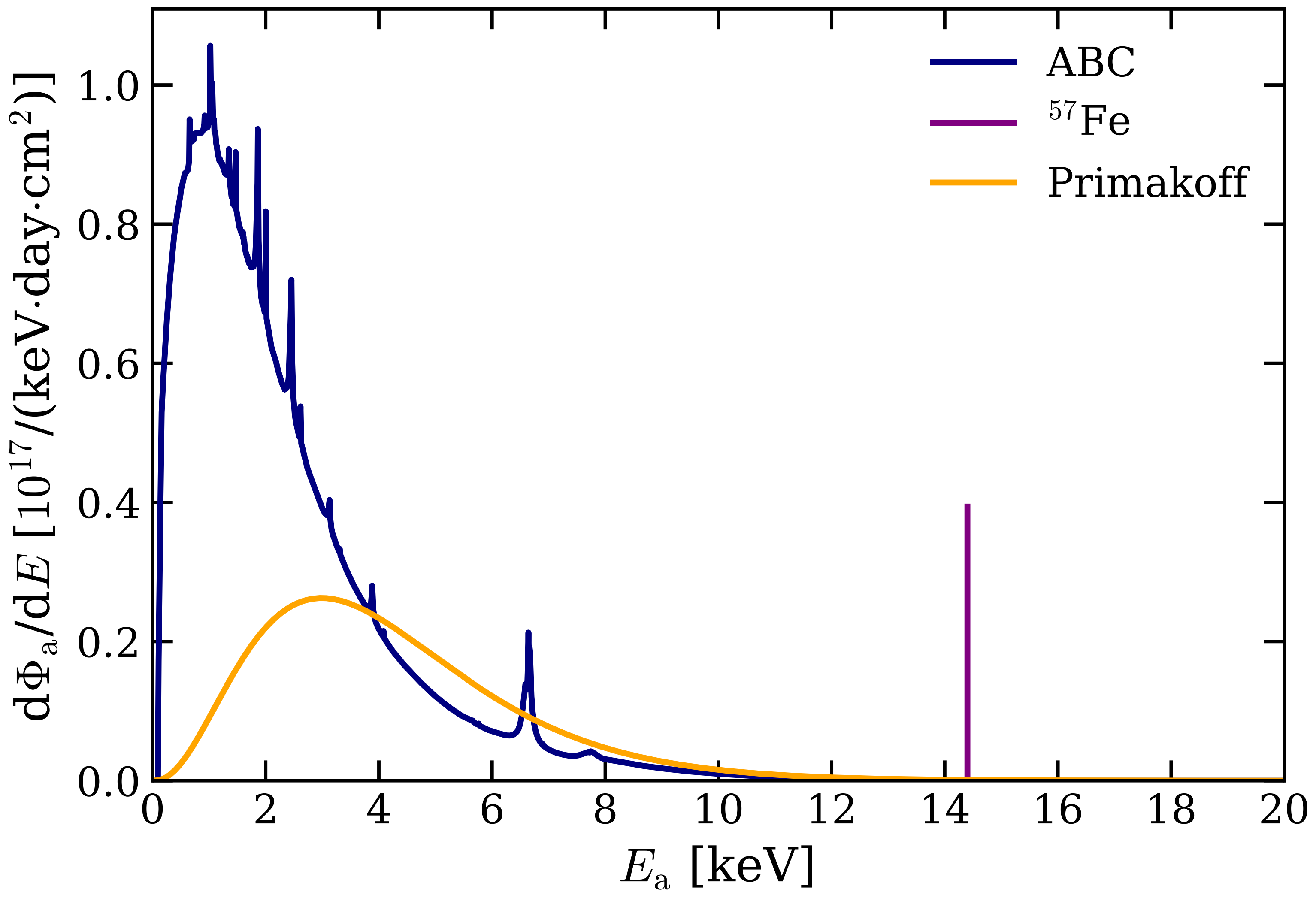
XENON1T; adapted by APS/Alan Stonebraker

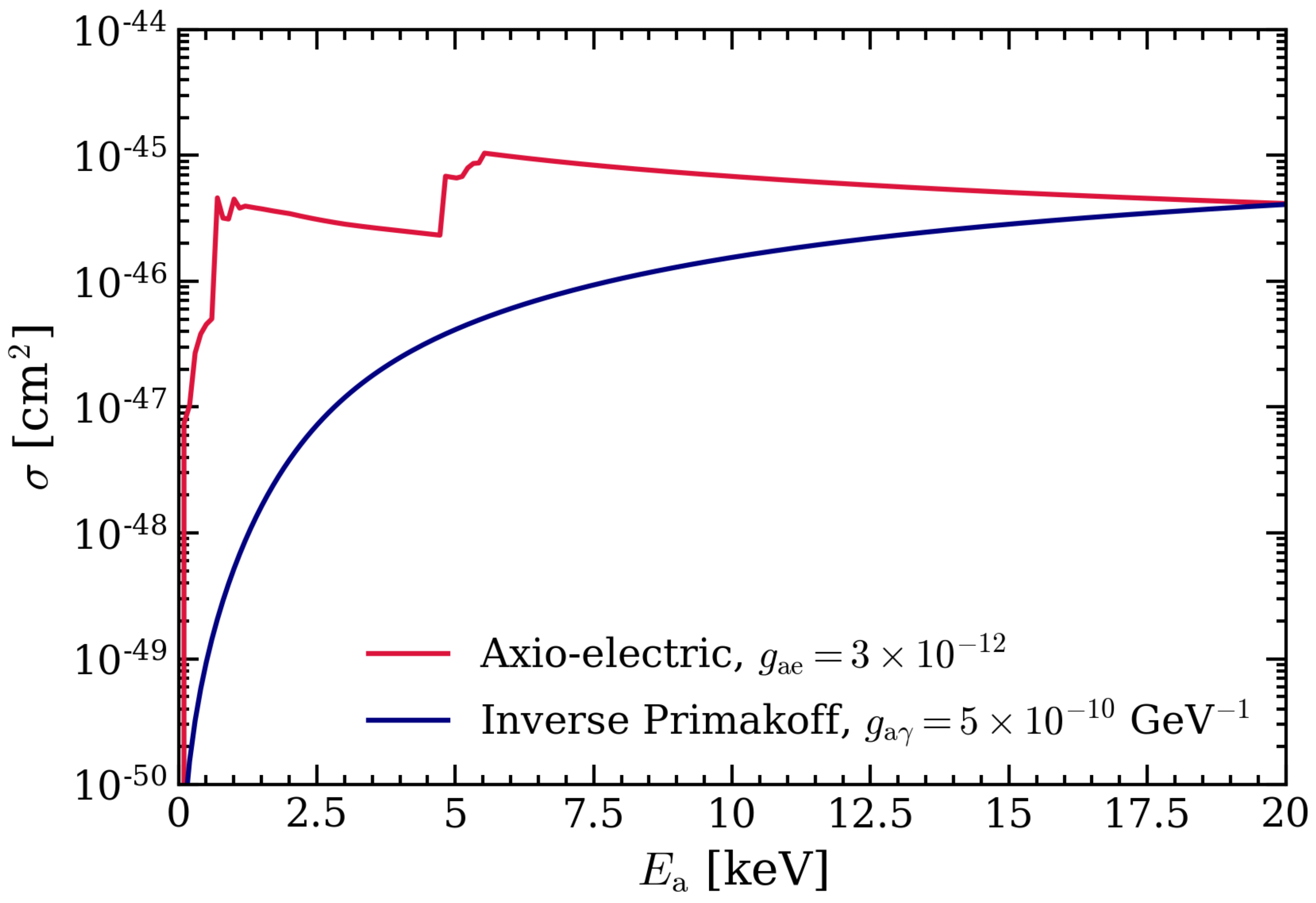
Figure 1: An incoming particle hitting atoms in XENON1T's tank releases photons and electrons that can

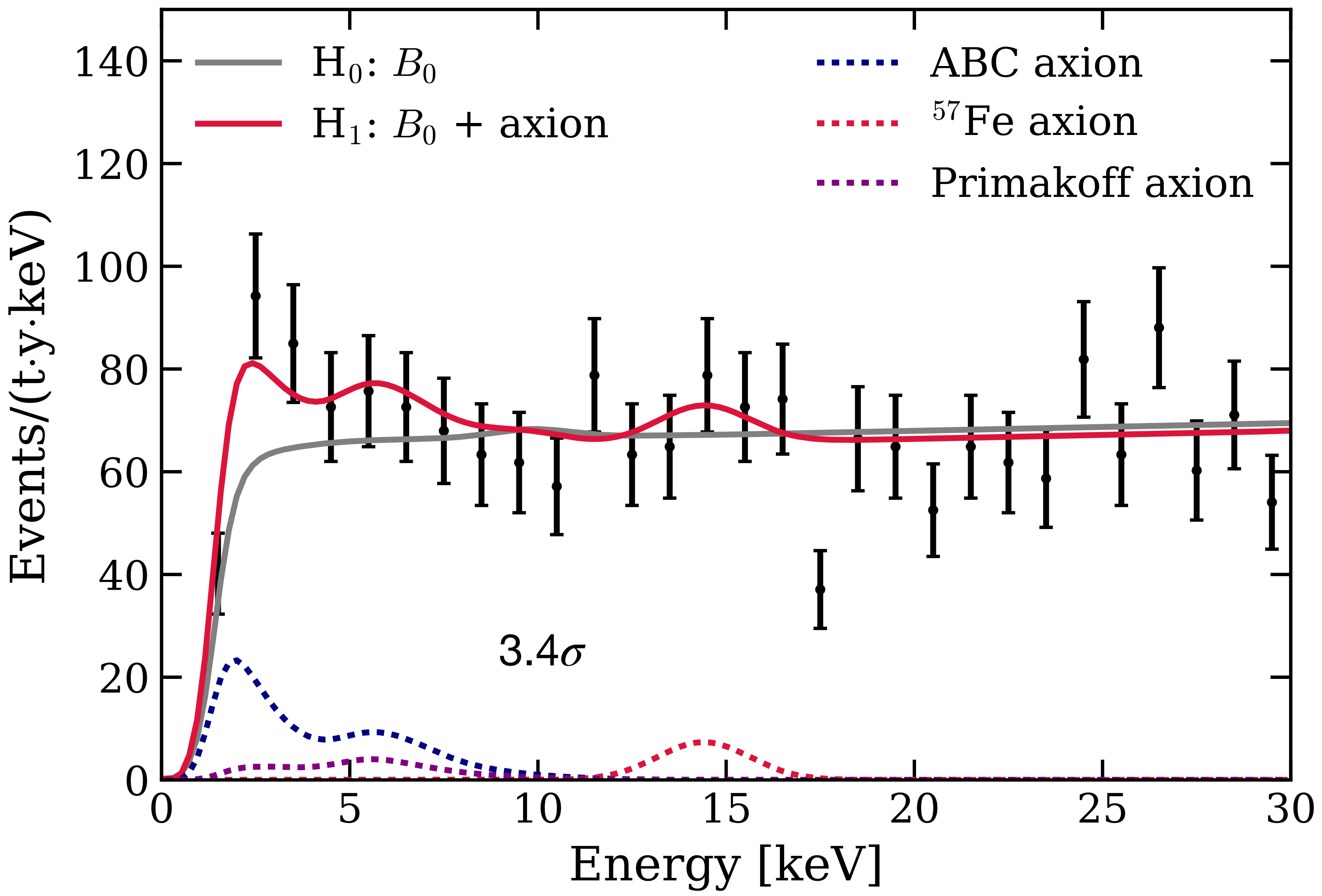
Excess electronic recoil events in XENON1T
E. Aprile *et al.* (XENON Collaboration)
Phys. Rev. D 102, 072004 (2020)
Published October 12, 2020
Read PDF

Recent Articles
Redefining How Neutrinos Impede Dark Matter Searches
A new definition of the "neutrino floor" in dark matter experiments clarifies the challenges ahead in differentiating neutrinos from WIMPs.
Pulsars Probe Early Universe
Astronomical observations of pulsars have provided new information about a possible phase transition in the early Universe.
To Touch the Sun
Jorge Cham, aka, PHD Comics, illustrates the daring mission of the Solar Parker Probe, which flew closer to the Sun than any previous spacecraft.
More Recent Articles »

Solar axion hypothesis







Production:

- ABC process (g_{ae})
- Primakoff ($g_{a\gamma}$)
- Fe57 (g_{an}^{eff})

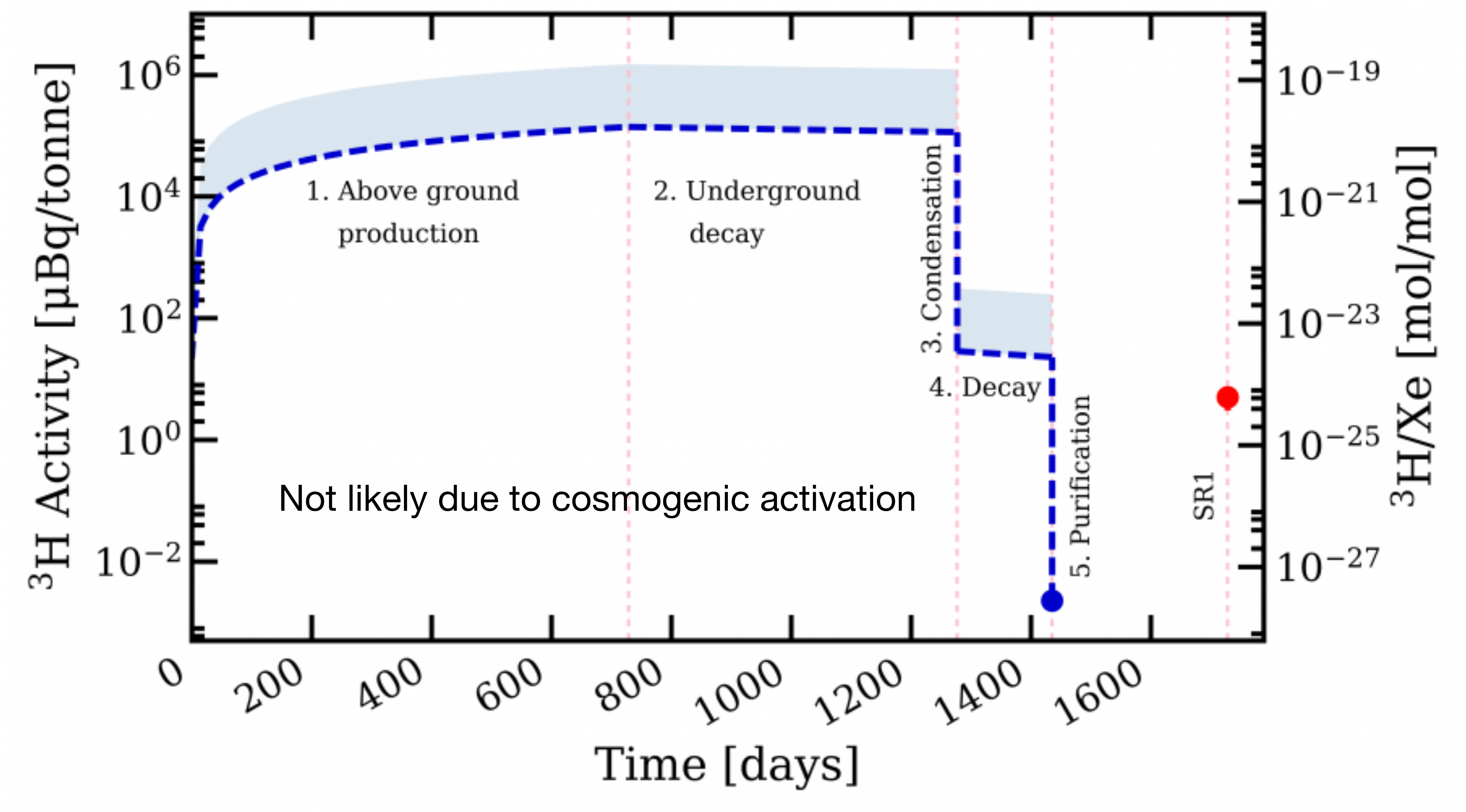
Detection:

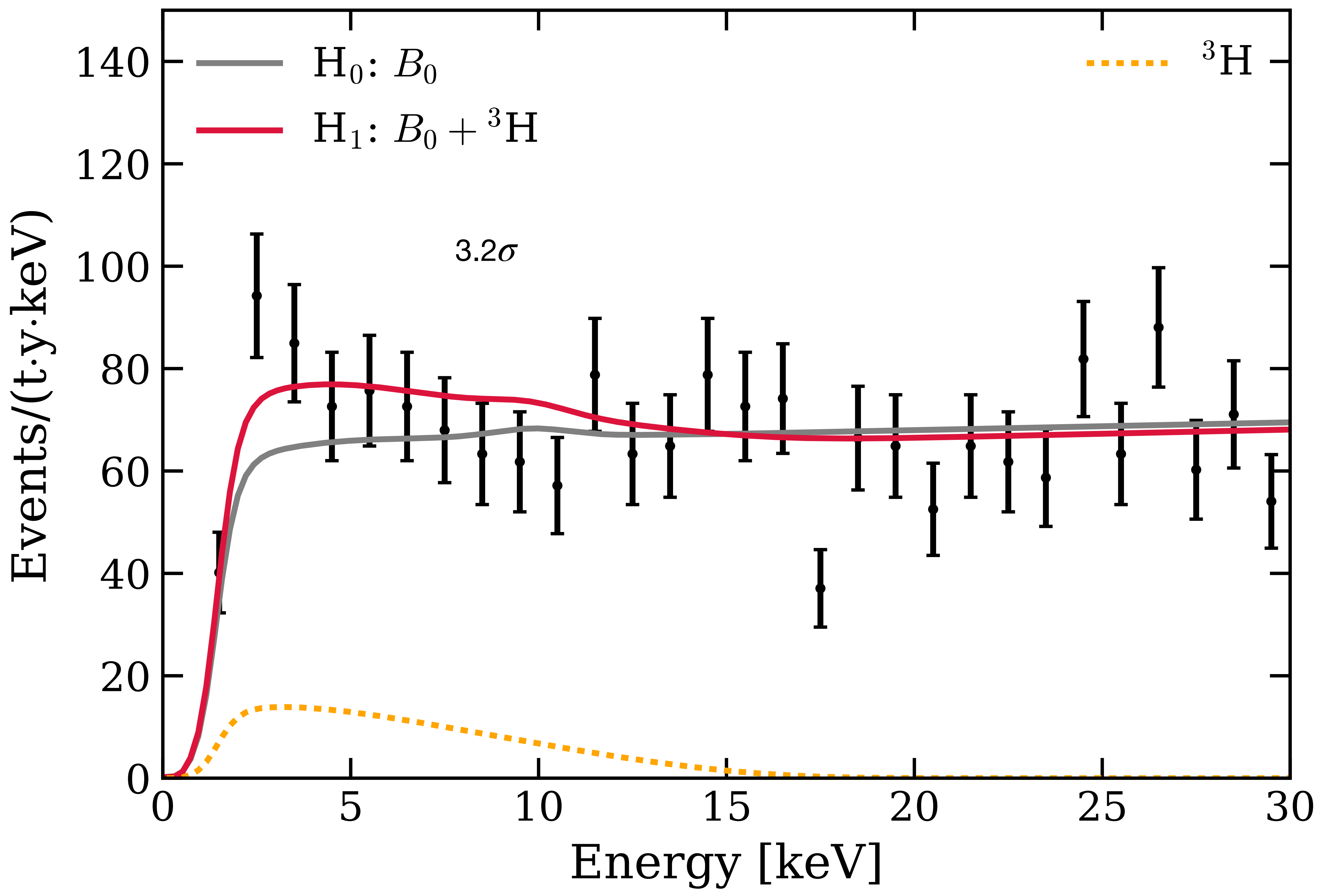
- Axio-electric effect (g_{ae})
- Inverse primakoff effect ($g_{a\gamma}$)
  - Proposed by theorists after the announcement of the excess
  - Not used in XENON1T, but considered in XENONnT

Dent et al., Phys. Rev. Lett. 125, 131805 (2020)
Gao et al., Phys. Rev. Lett. 125, 131806 (2020)

Solar axion hypothesis is favored by XENON1T data at 3.4σ

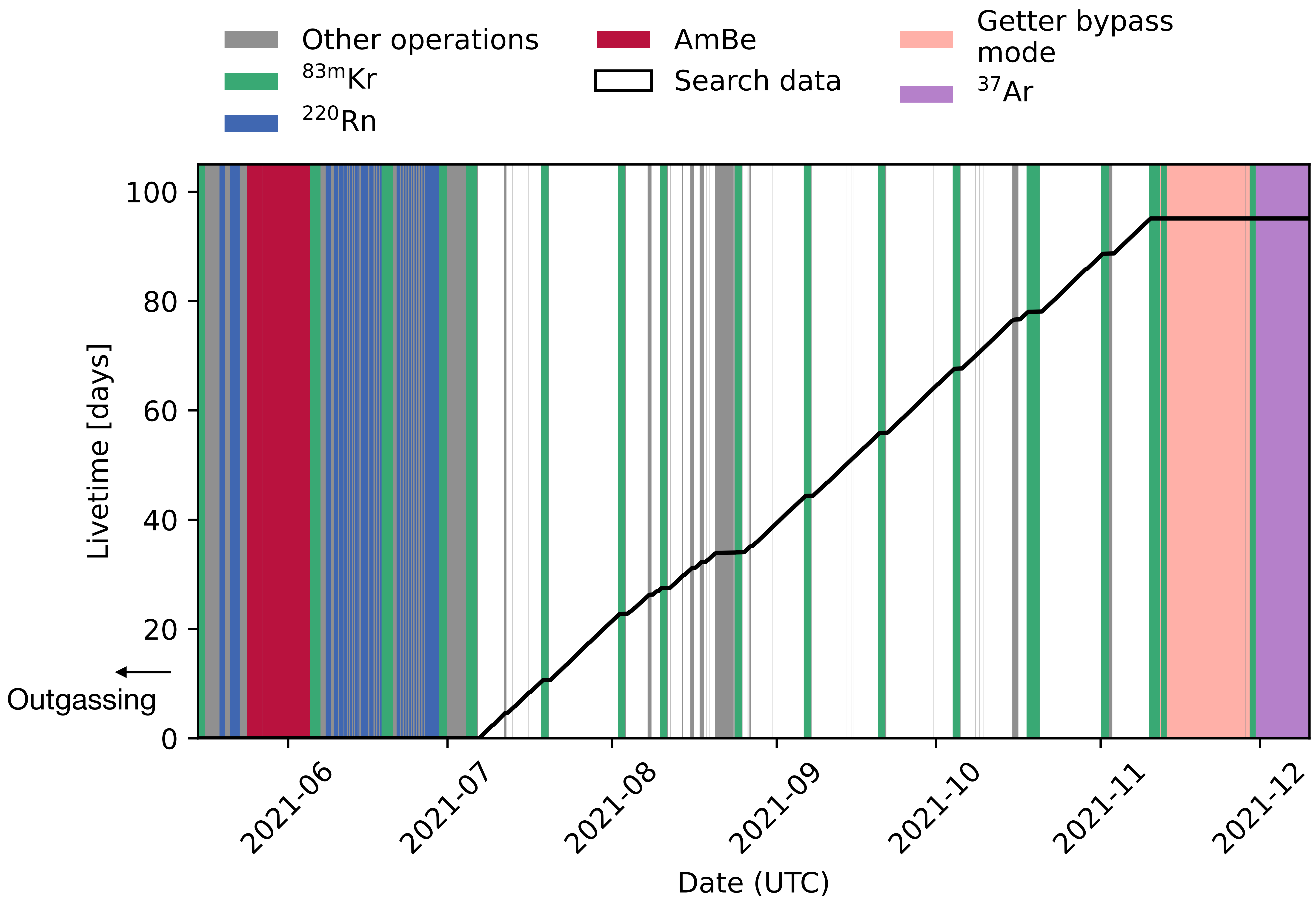
Tritium background





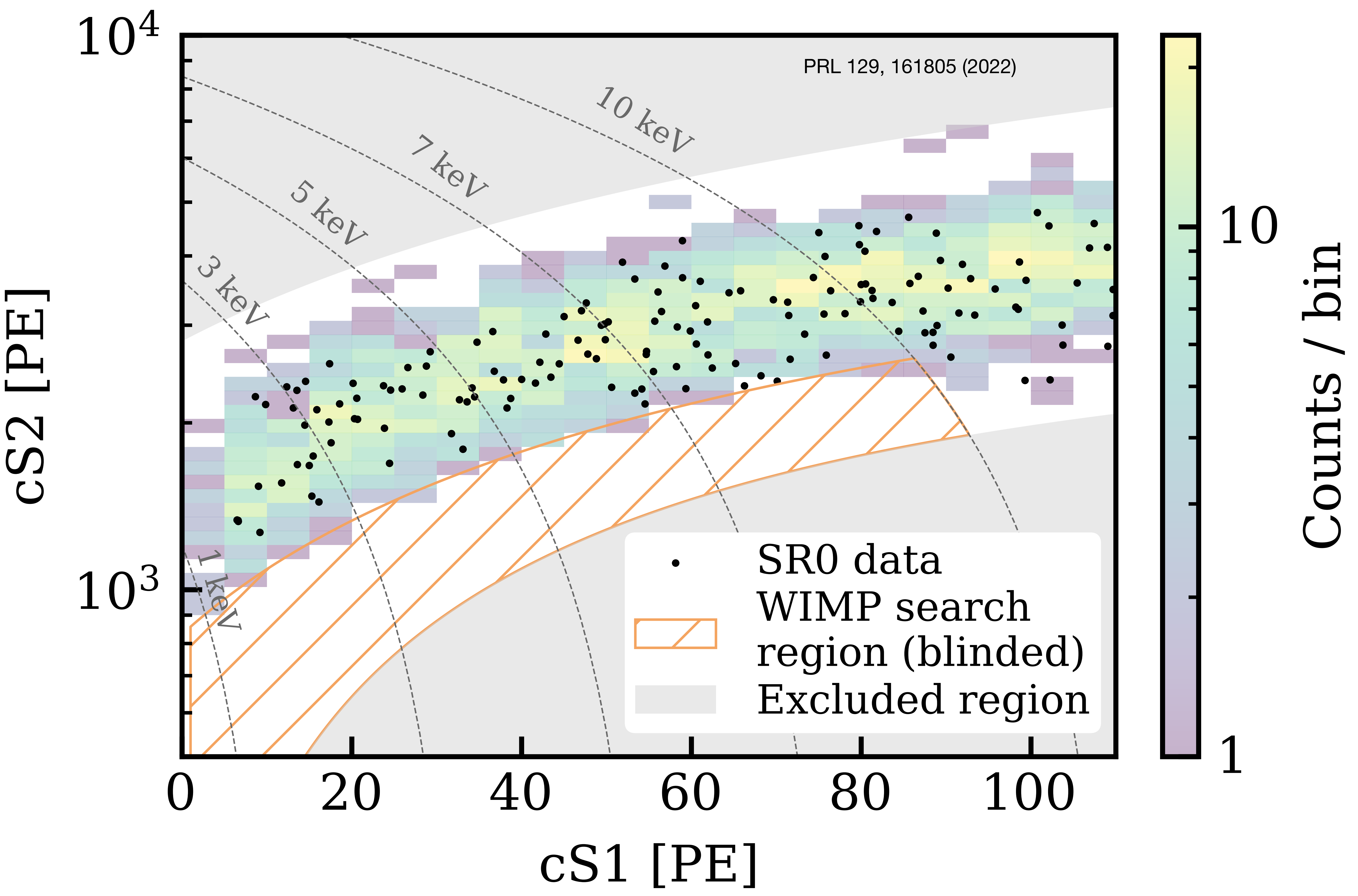
- Can be introduced to an underground detector in the forms of HT and/or HTO
- No external constraint on the amount of tritium, in particular HT

XENONnT SR0



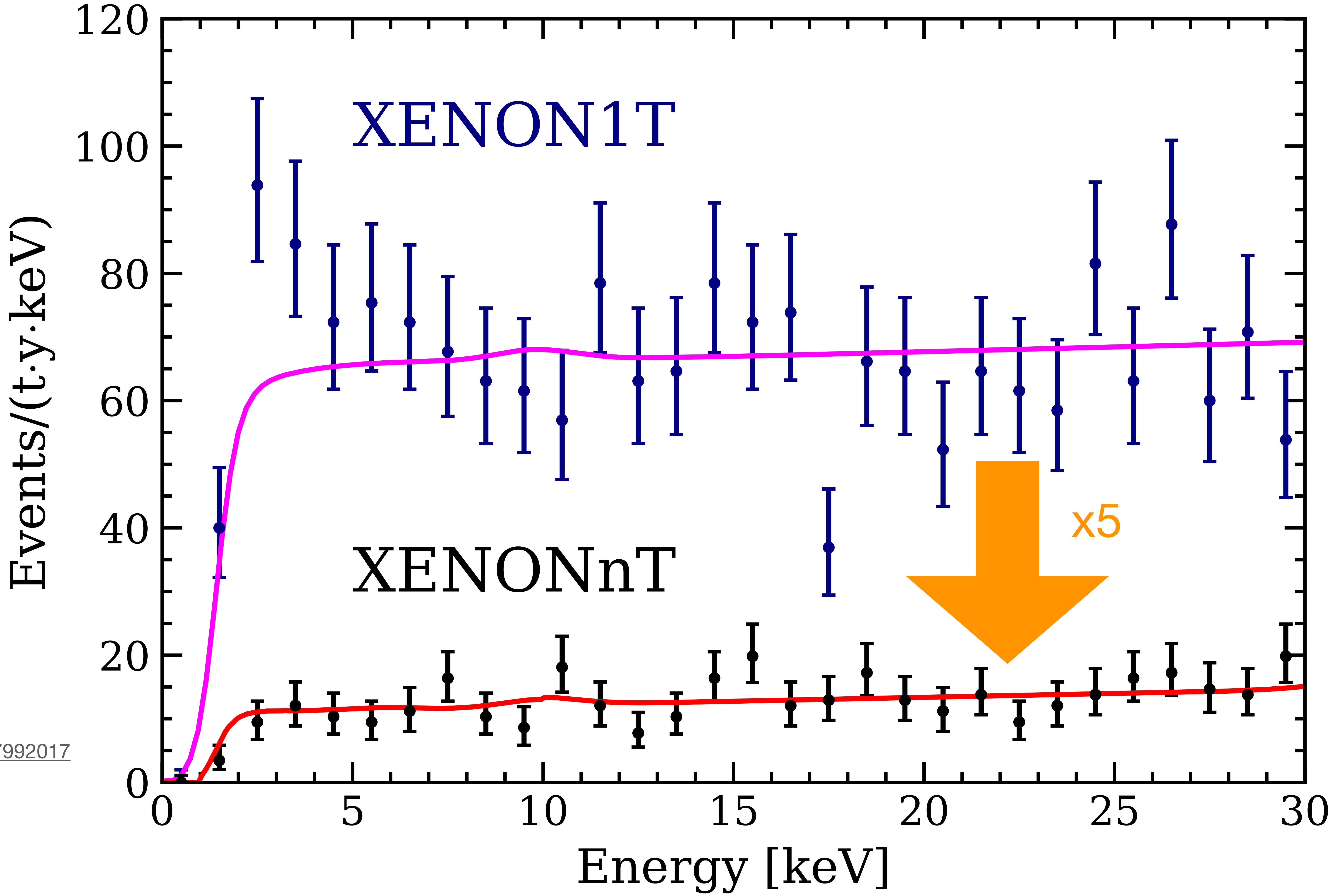
- The first science run length is defined to decipher the XENON1T excess
- Livetime: 97.1 days
- Exposure: (1.16 ± 0.03) tonne $\cdot$ year
- TPC outgassed for ~3 months before filling GXe to reduce HTO/HT (~10 days in XENON1T)

Unblind SR0 ER Data



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

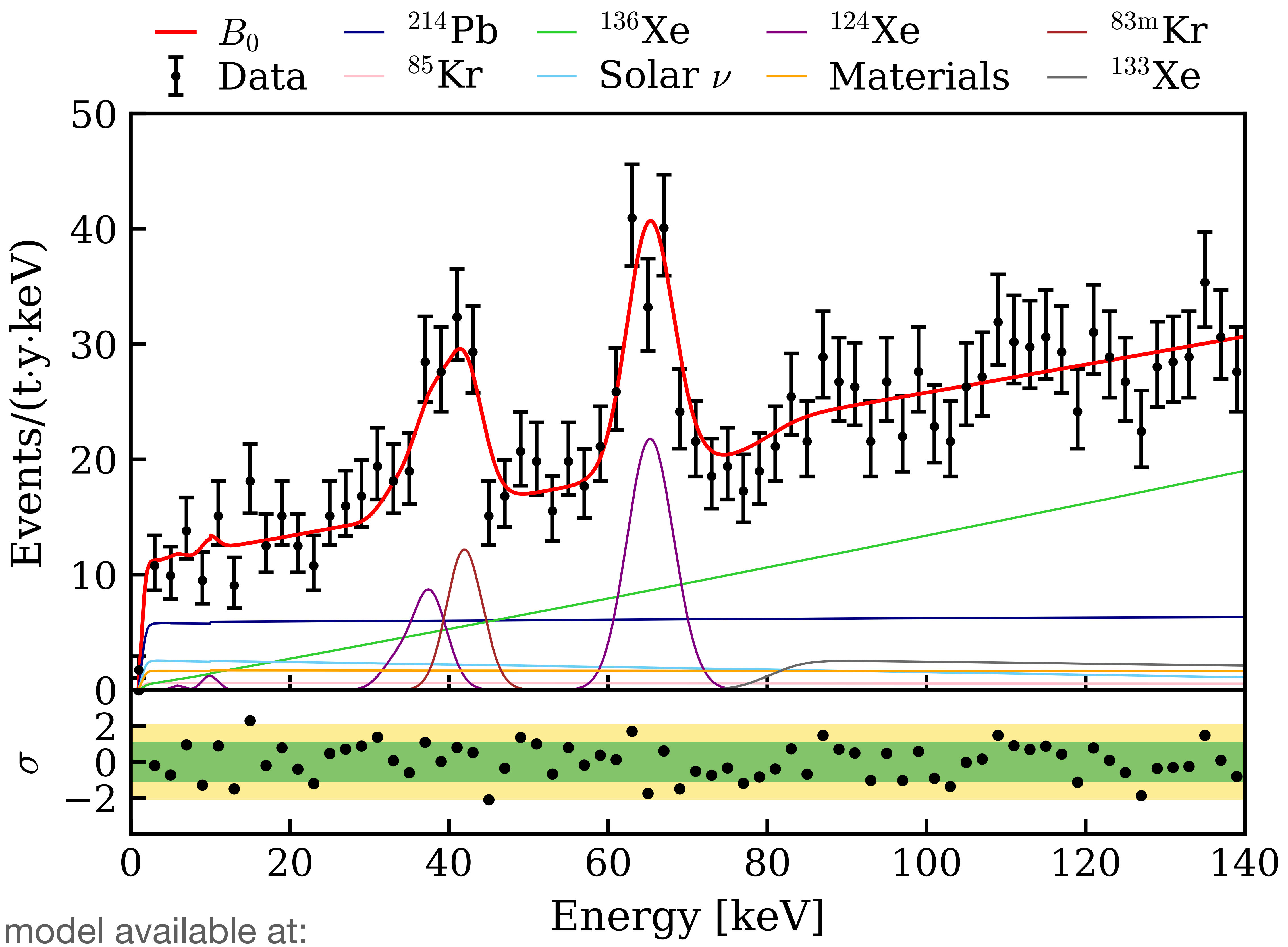
XENONnT ER results



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

XENONnT ER results

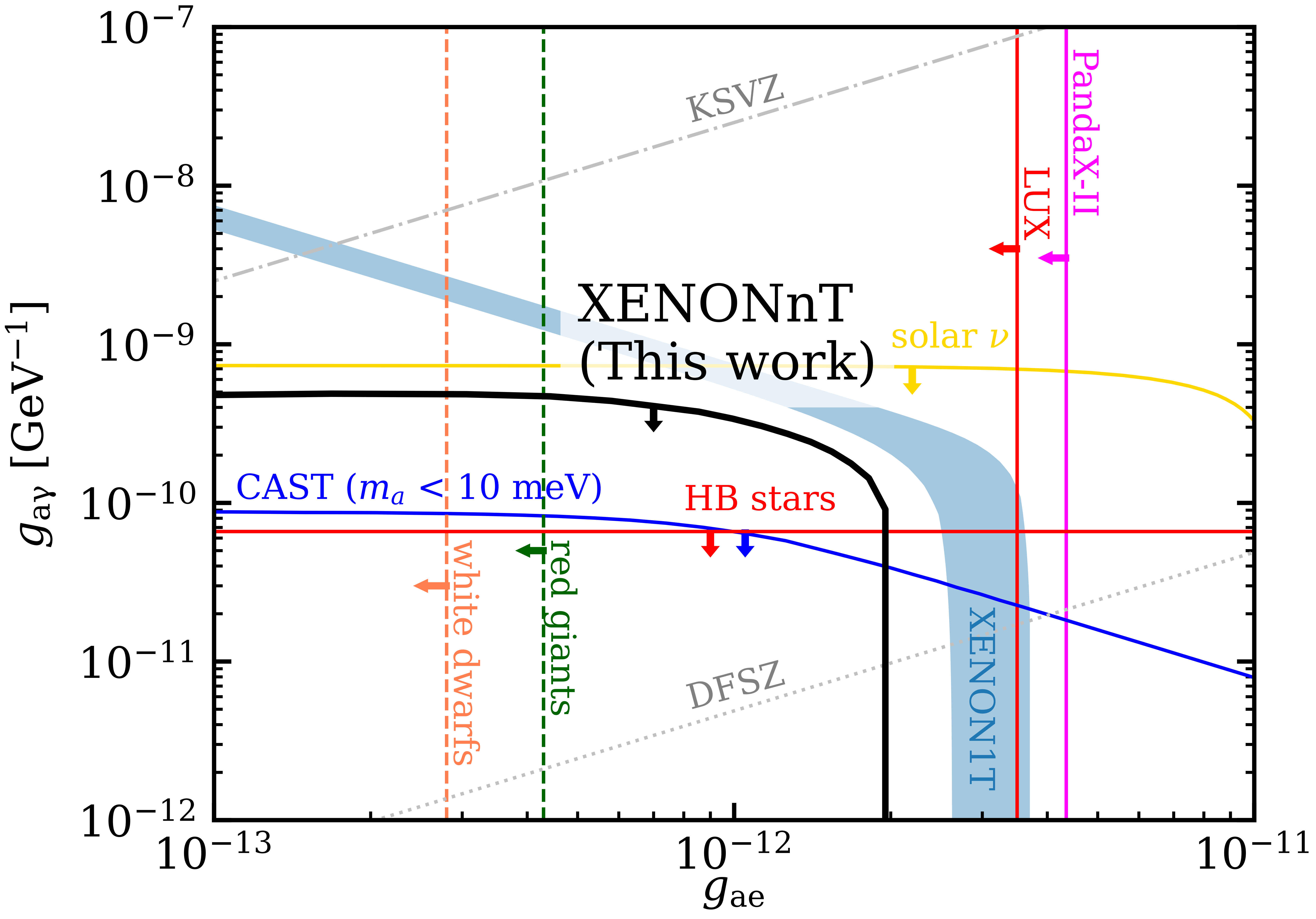


Data and background model available at: https://zenodo.org/records/7992017

SR0	(1, 10) keV	(1, 140) keV
^{214}Pb (^{222}Rn)	55 ± 7	960 ± 120
^{85}Kr	6 ± 4	90 ± 60
Materials	16 ± 3	270 ± 50
^{136}Xe	8.8 ± 0.3	1550 ± 50
Solar pp 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

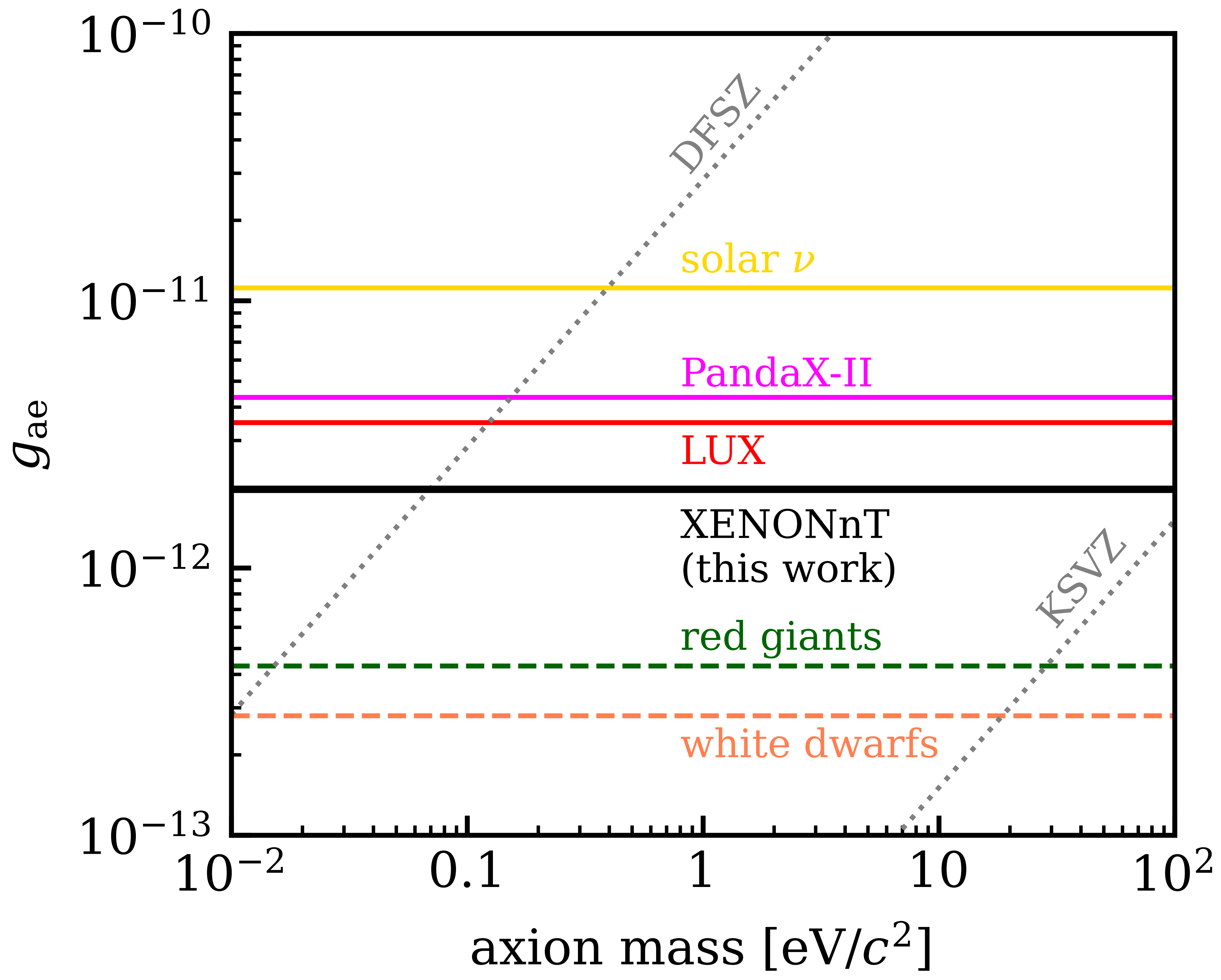
- The total ER rate below 30 keV is $(15.8 \pm 1.3_{stat})$ events/(t · y · keV)
- Solar pp neutrinos
  - the 2nd largest ER contribution below 10 keV in SR0
  - Comparable contribution with ^{222}Rn in SR1

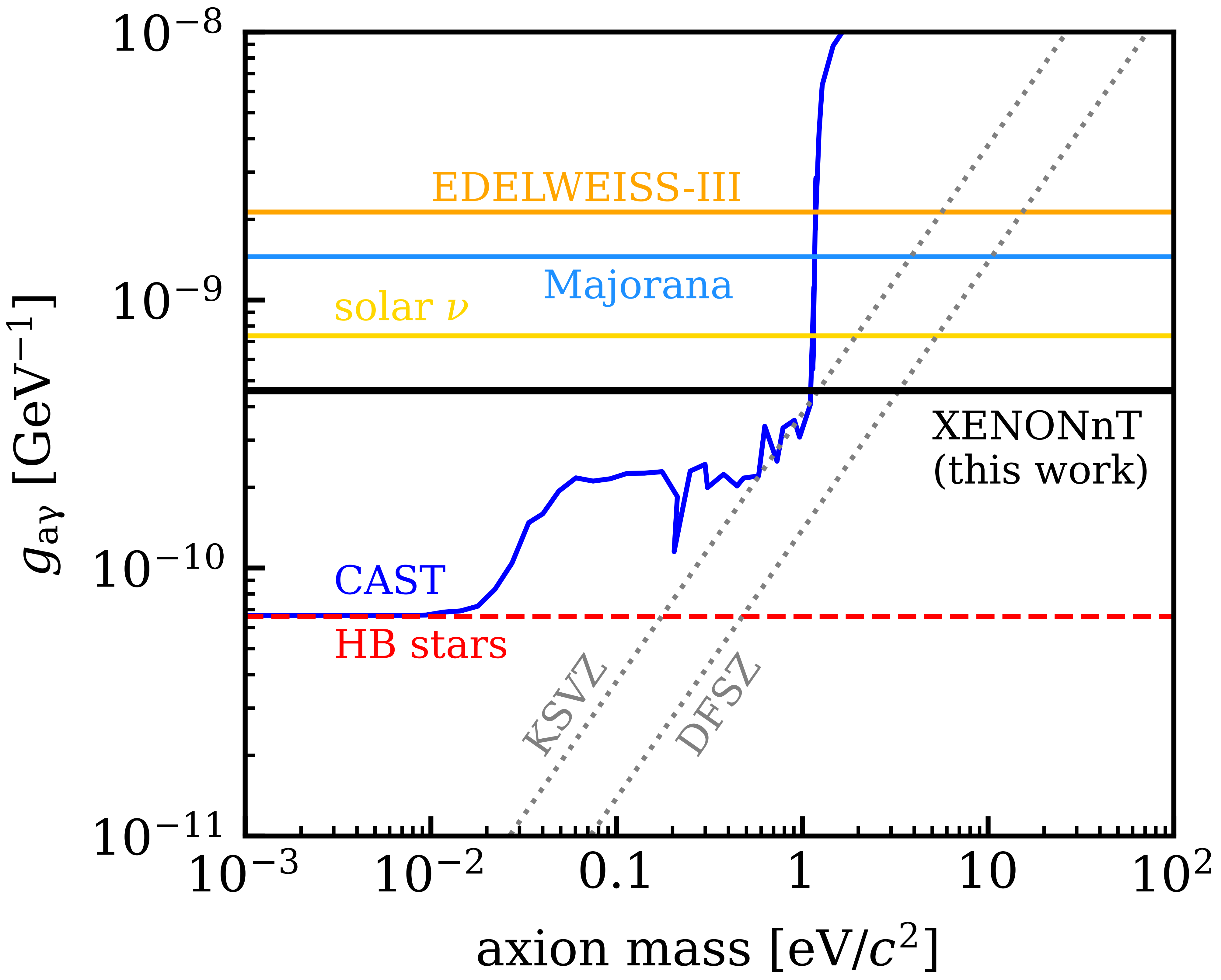
Solar axion result



- 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

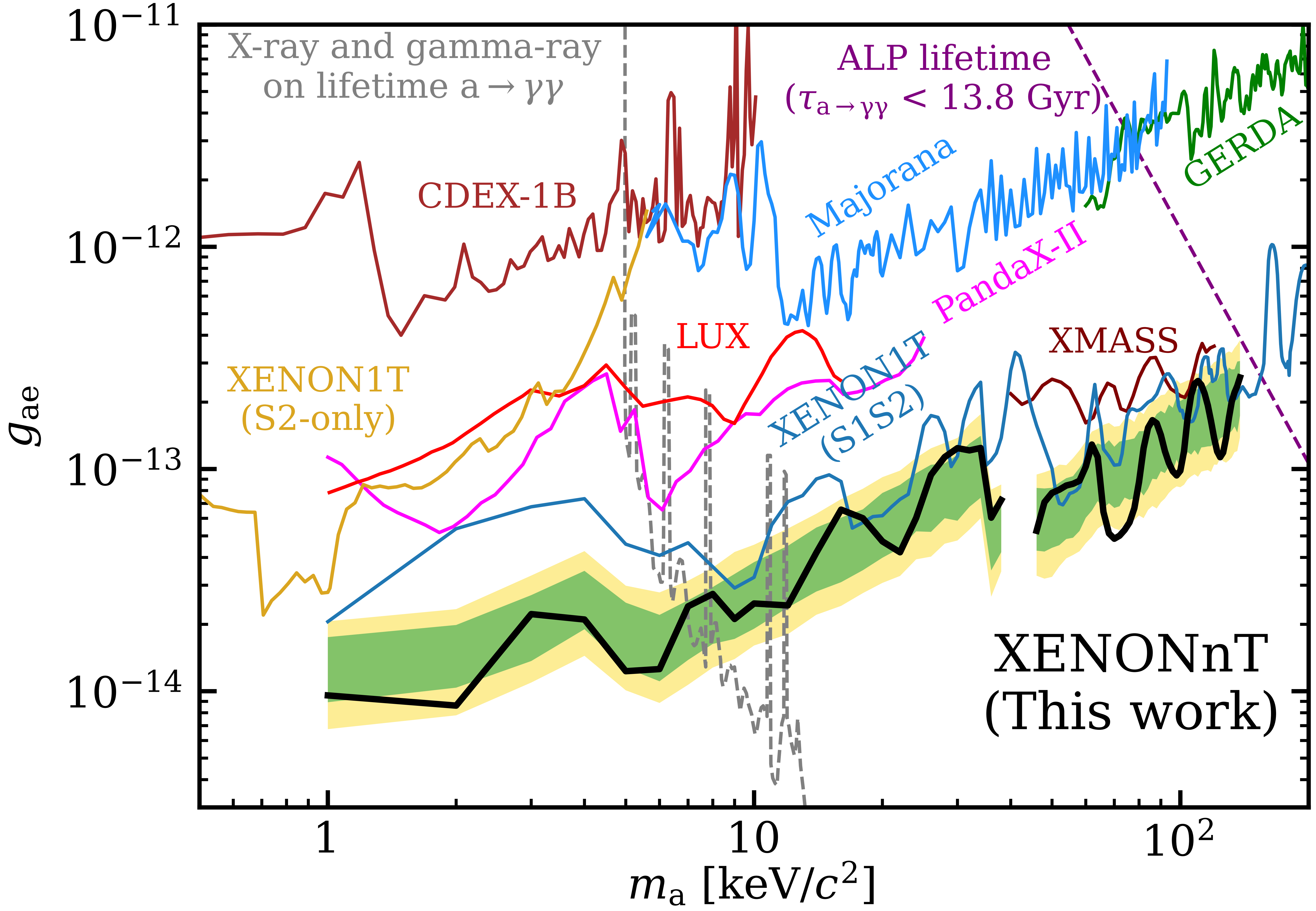
Solar axion result





- 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
- Competitive limits for $g_{a\gamma}$

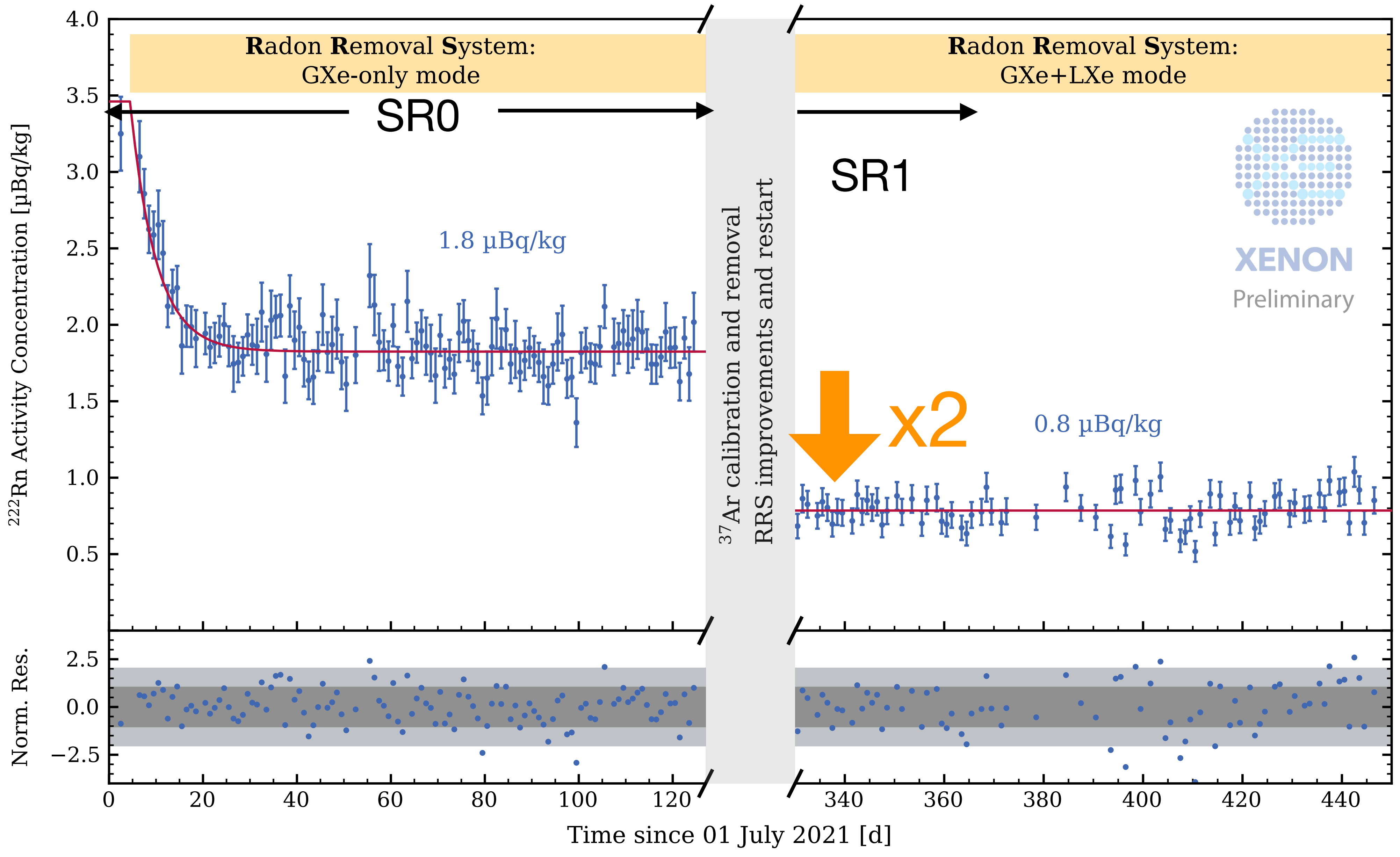
ALP dark matter result



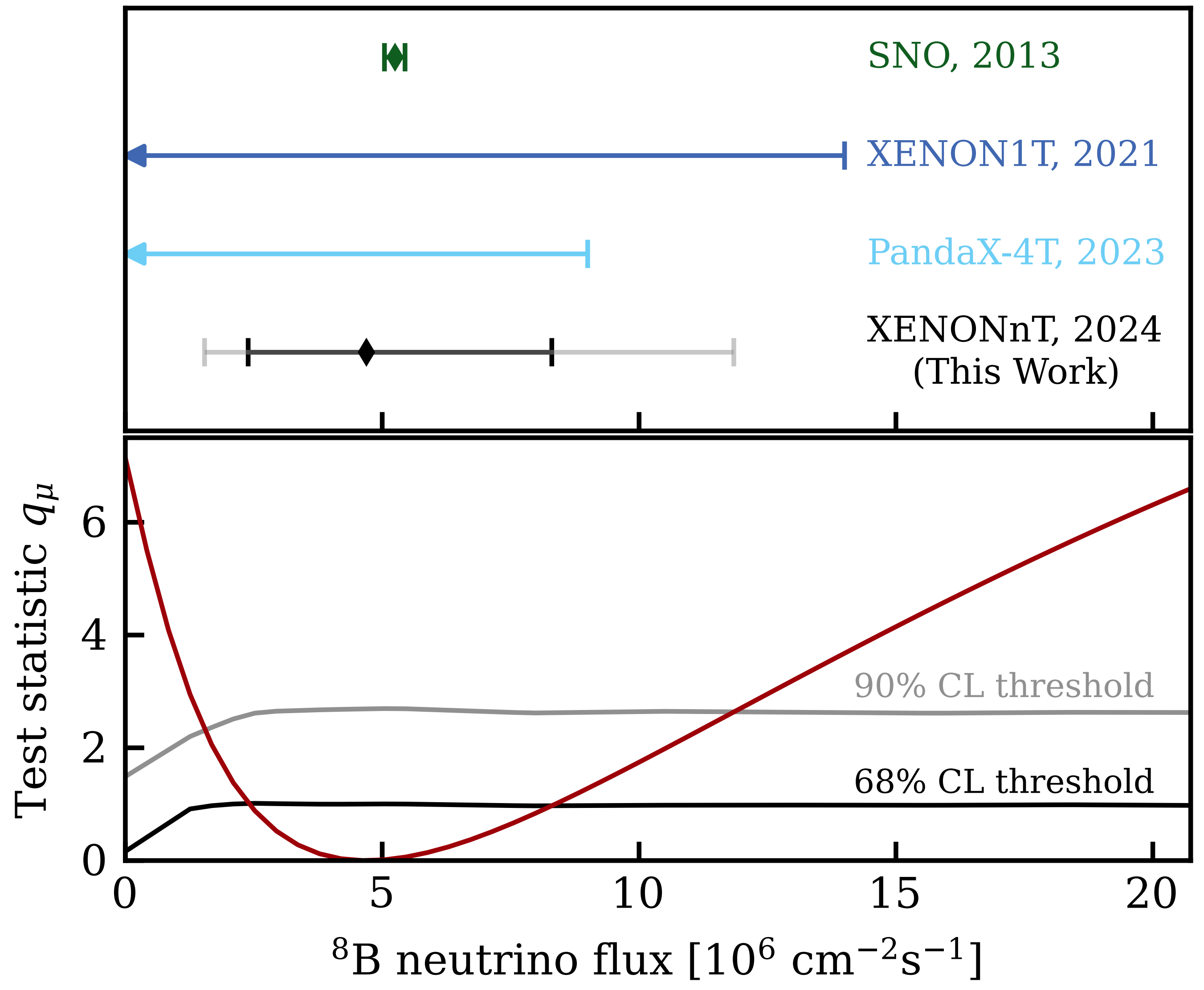
- Competitive limits for mass in (1, 39) and (33, 140) keV/c^2
- The maximum local significance ~1.8 σ at ~109 keV

Summary & Outlook

- **SR0** - 1.16 t·yr exposure
- **Unprecedented low ER background** - 15.8 events/(t y keV)
- **Low ER results**
  - Deciphered XENON1T excess
  - Best limit on g_{ae} with axion mass below 100 eV/c^2
  - Competitive limits for ALPs dark matter with mass below 140 keV/c^2

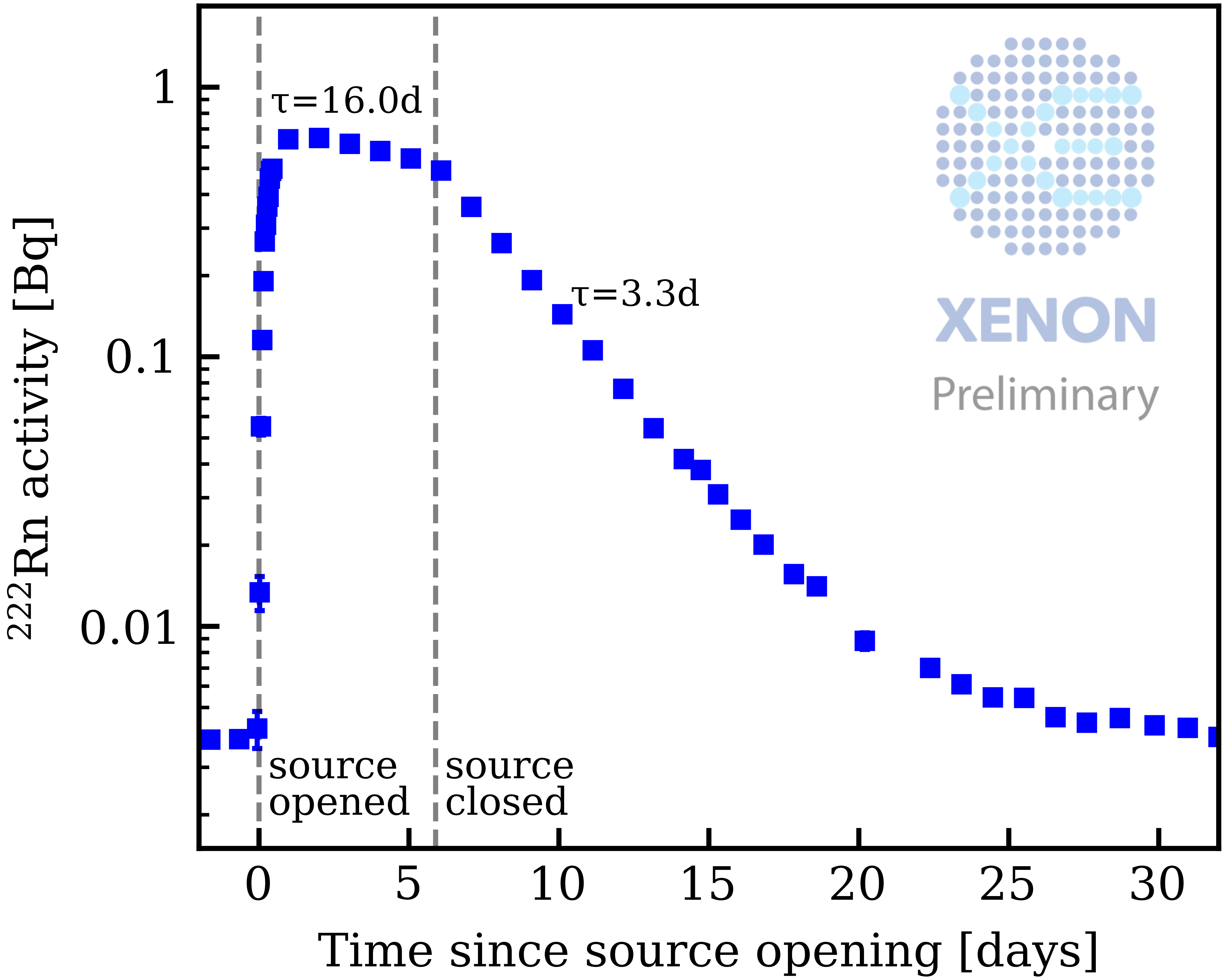


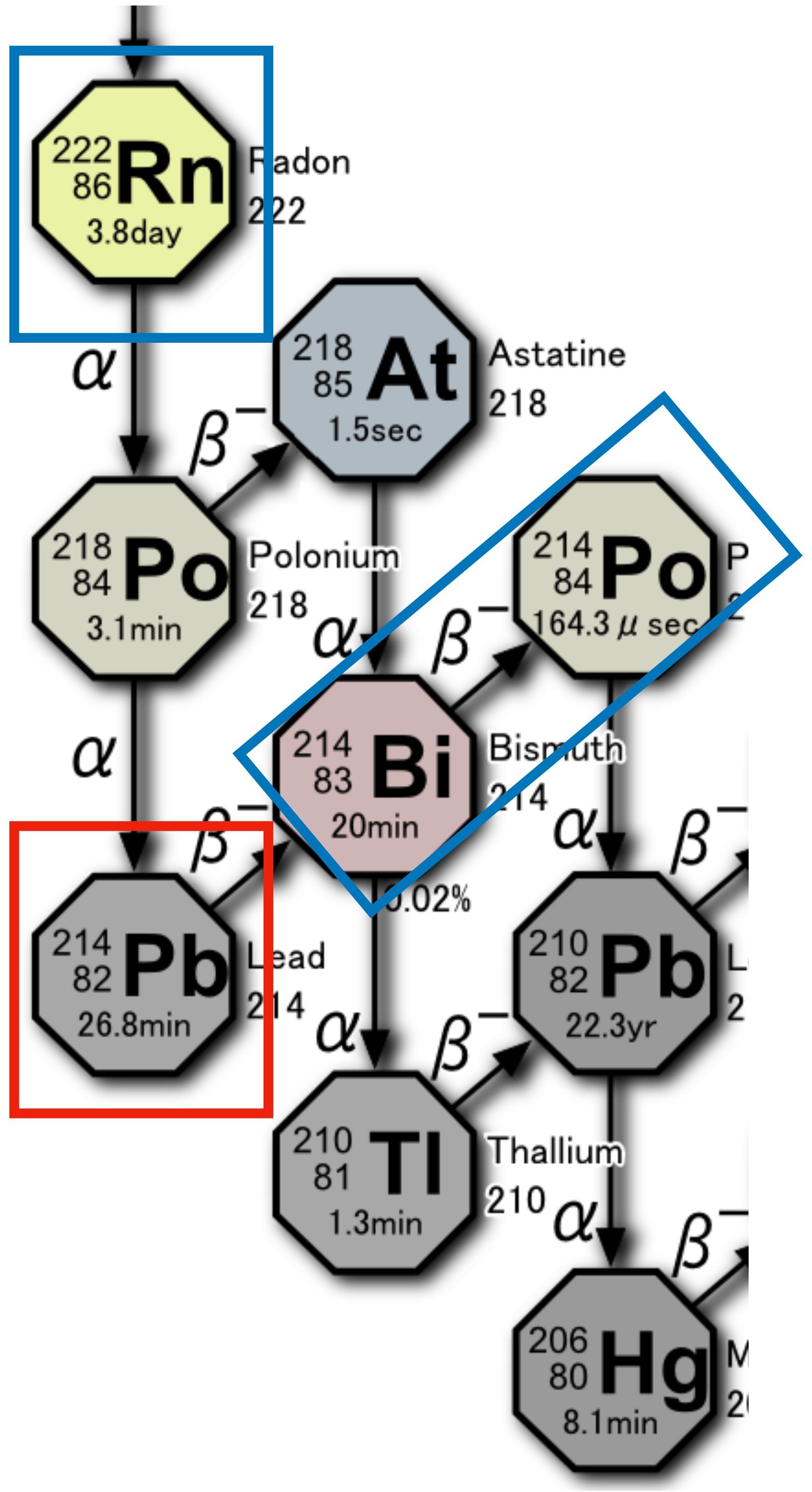
- **SR1**
  - Further reduction of $^{222}\mathrm{Rn}$ ($< 1\mu\mathrm{Bq/kg}$)
  - More topics
    - WIMPs
    - Solar B-8 neutrinos (CEνNS) arXiv: 2408.02877
    - Solar pp neutrinos (elastic ν-e scattering)
    - …



Back up

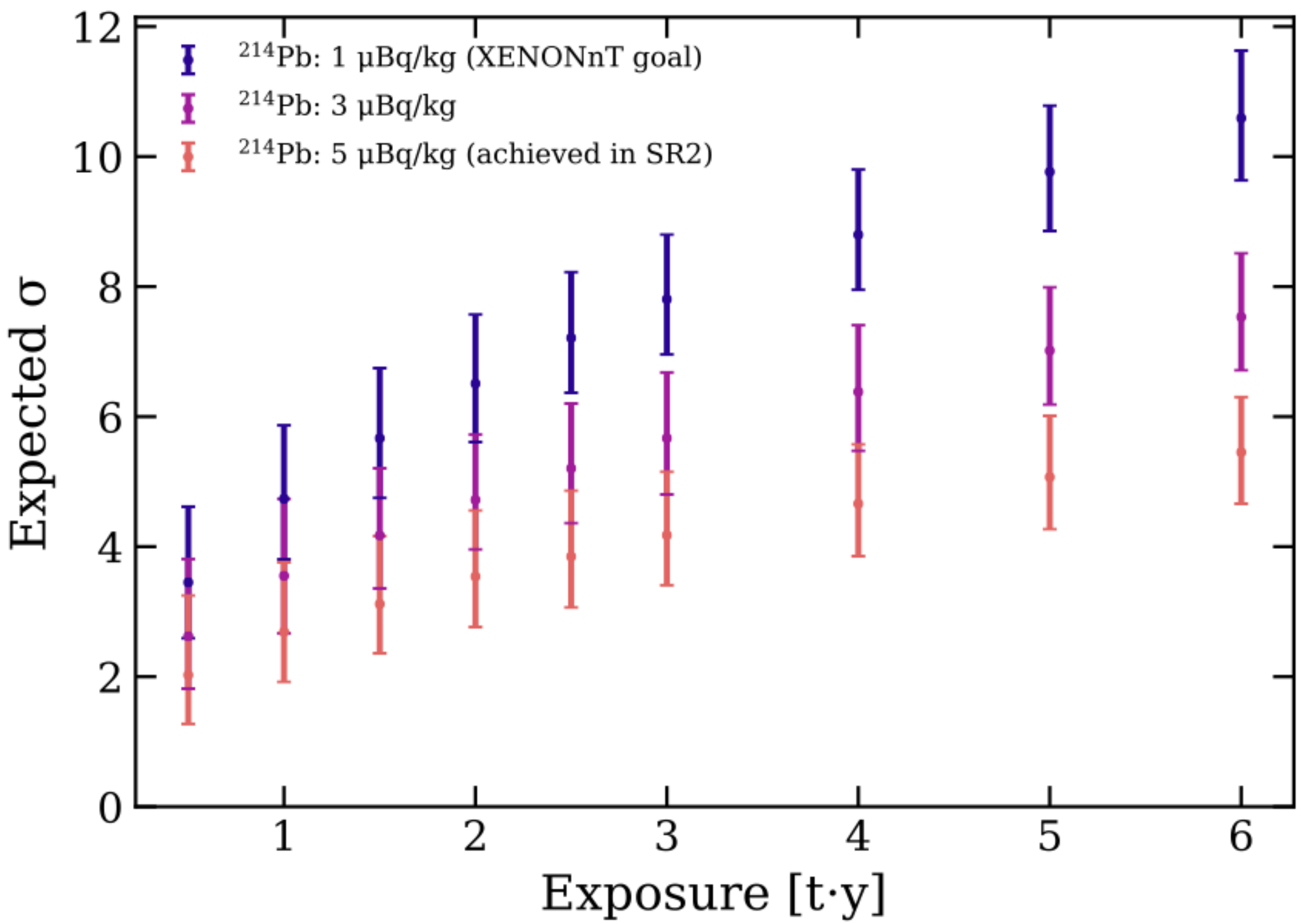
^{222}Rn calibration





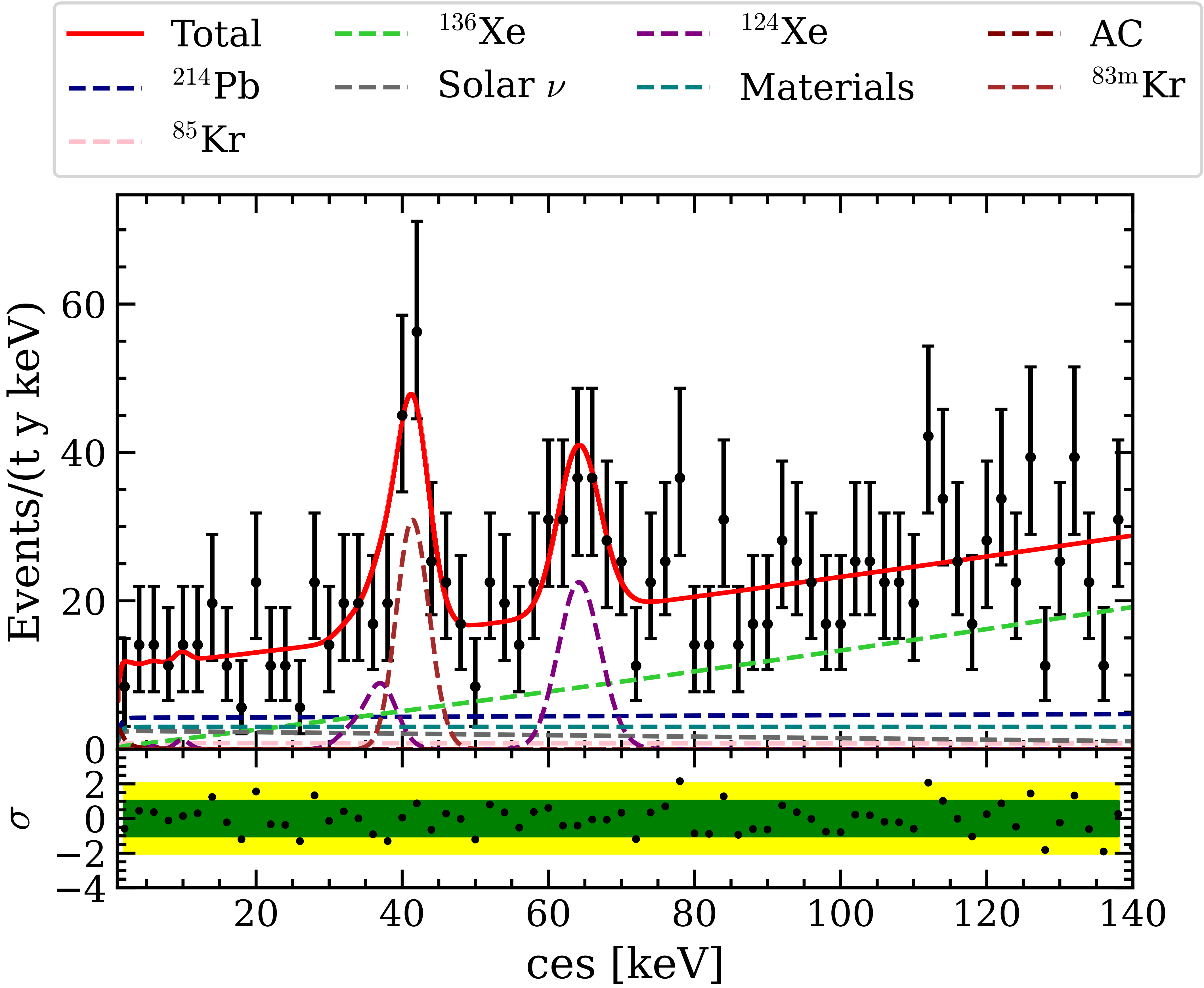
- ^{214}Pb best-fit value: $(1.31 \pm 0.17_{stat})\ \mu$Bq/kg
- Constrain the uncertainty of ^{214}Pb by constraining the ratios between ^{214}Pb and its daughters/parents

Expected discrimination power in XENONnT



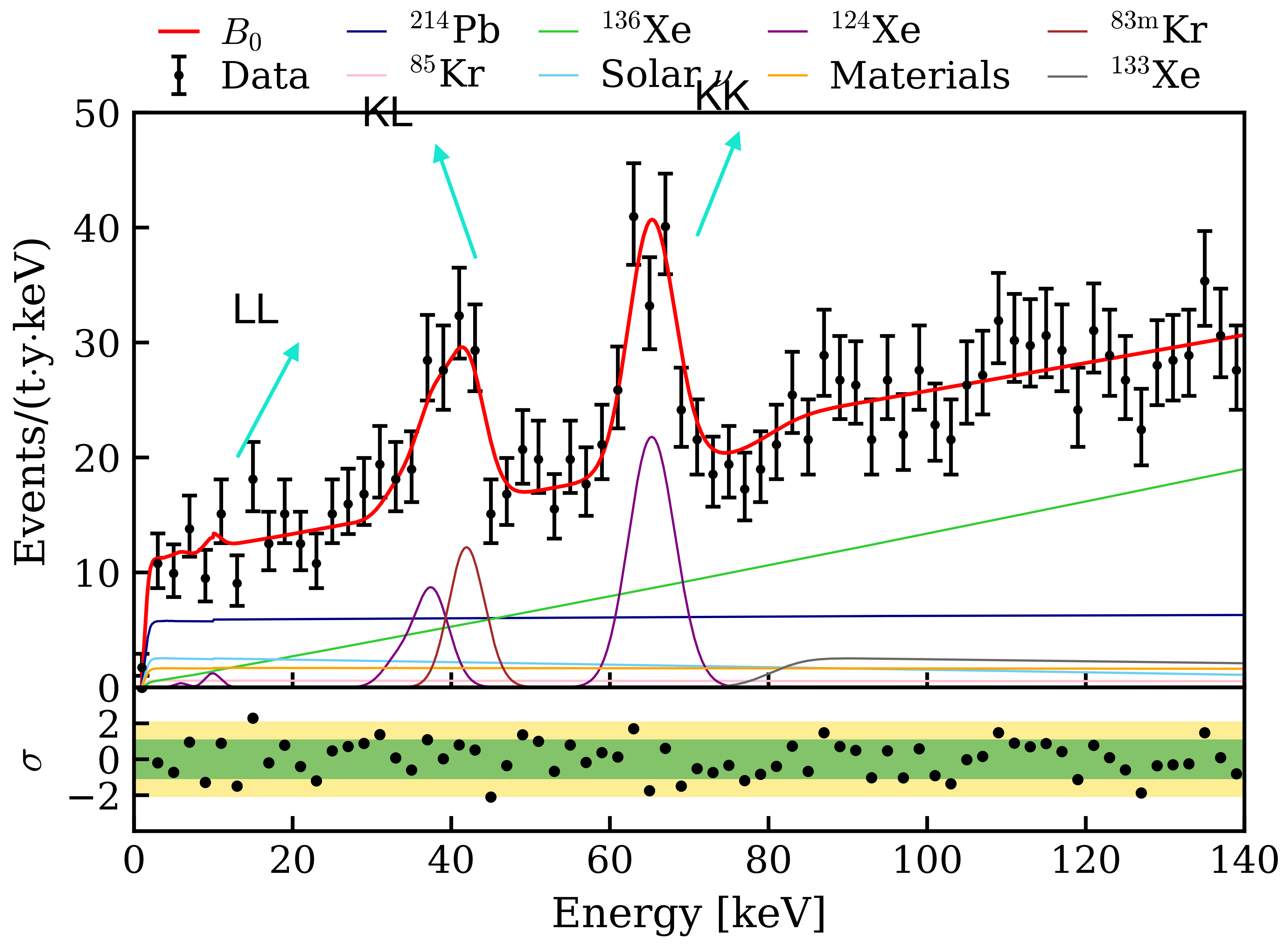
XENONnT should be able to differentiate the excess with a few months of data

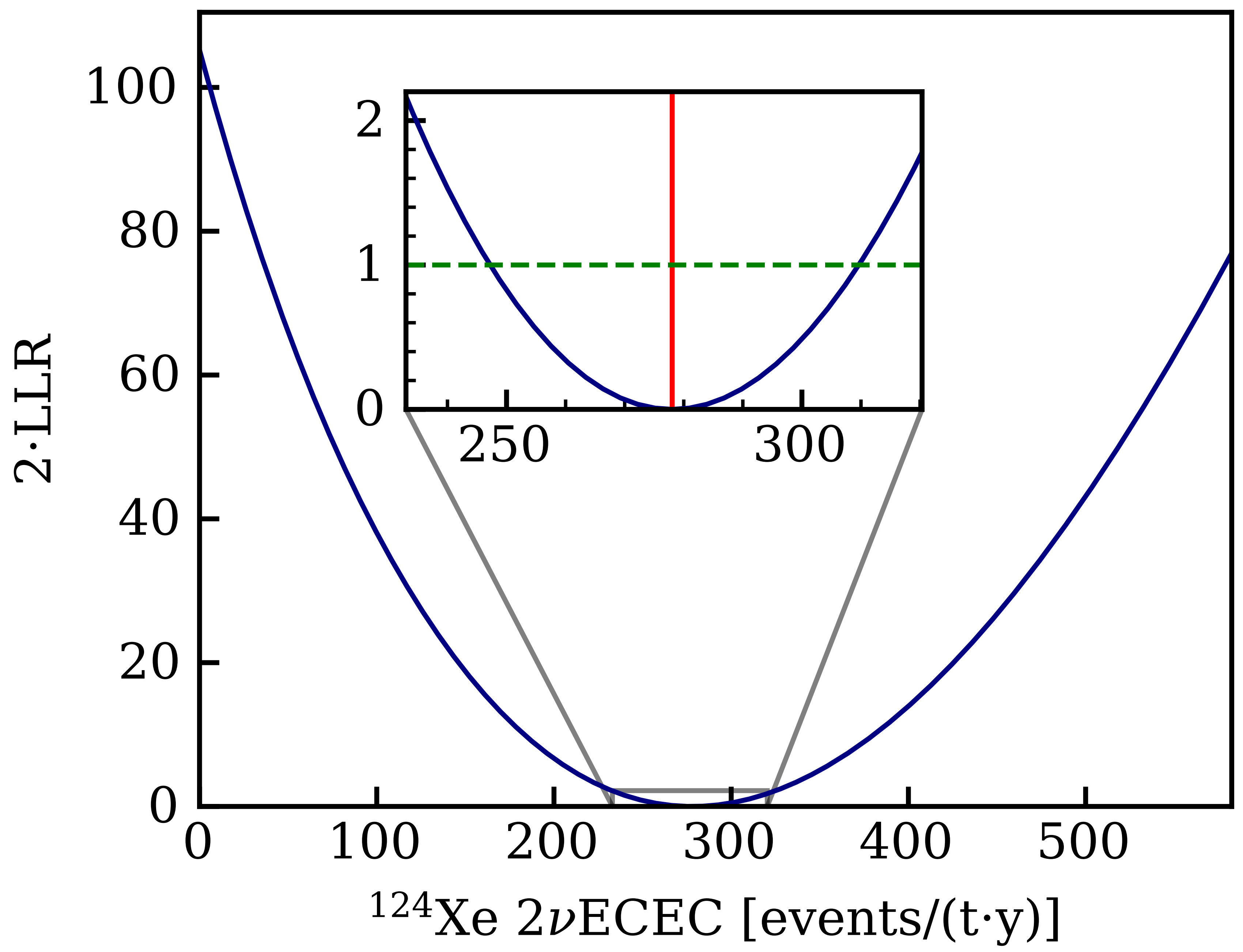
Tritium Enhanced Data (TED)



- 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

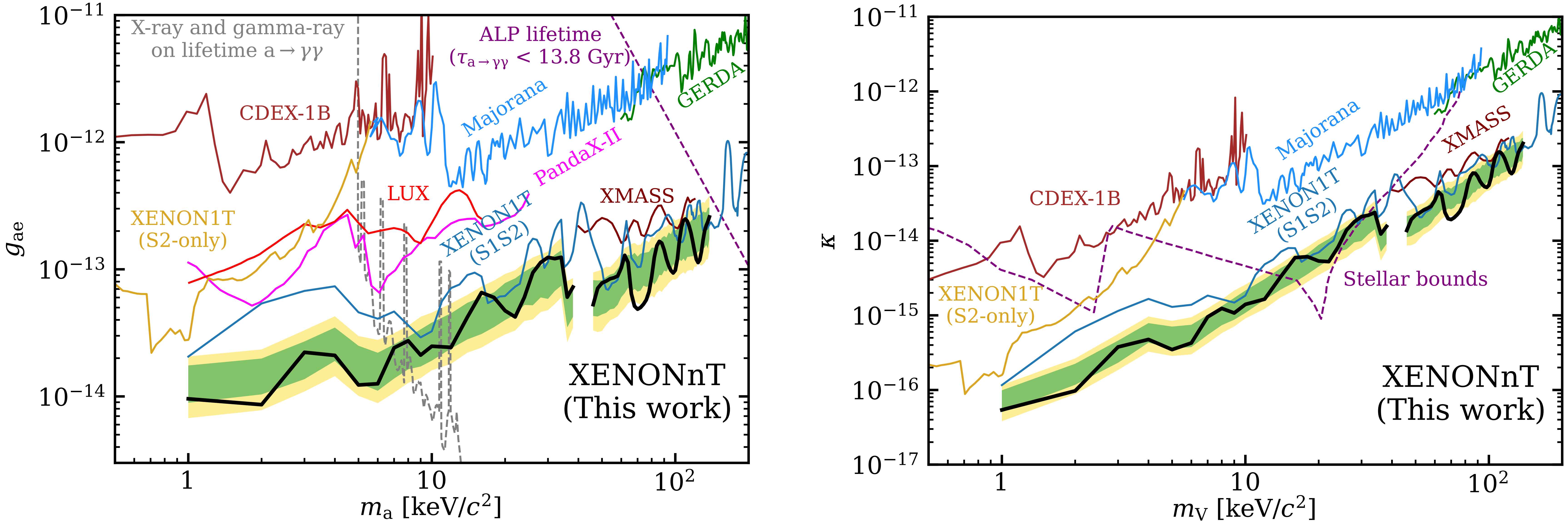
$^{124}Xe\ 2\nu ECEC$





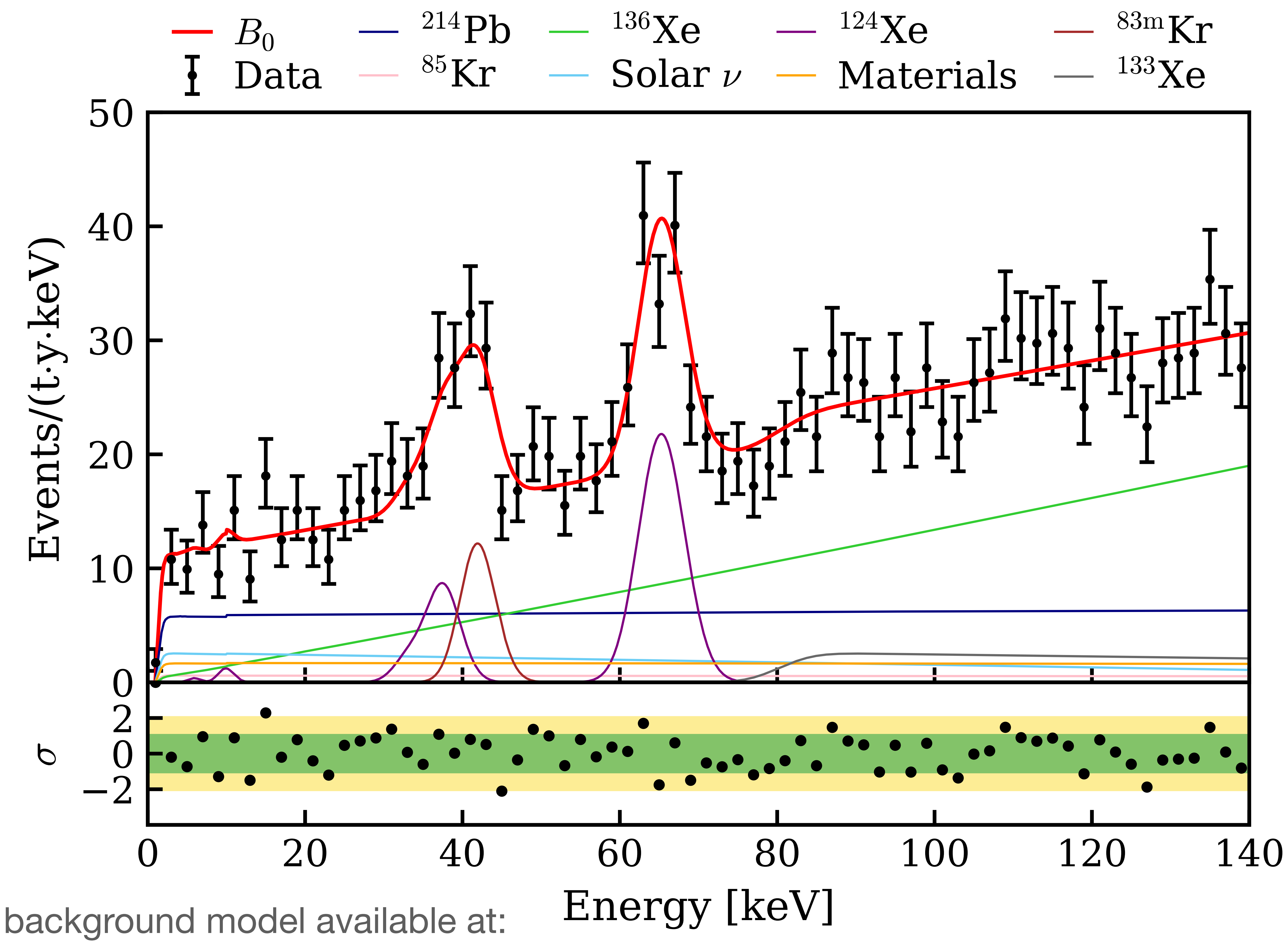
- $^{124}Xe\ 2\nu ECEC$ rate is unconstrained in the entire analysis; BRs are fixed
- Stand out in the energy spectrum due to the ultra-low background
  - LL peak is visible even with only ~1% BR
  - KL & KK peaks are used for calibration purpose (energy resolution)
- The measured half-life $T_{1/2}^{2\nu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

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



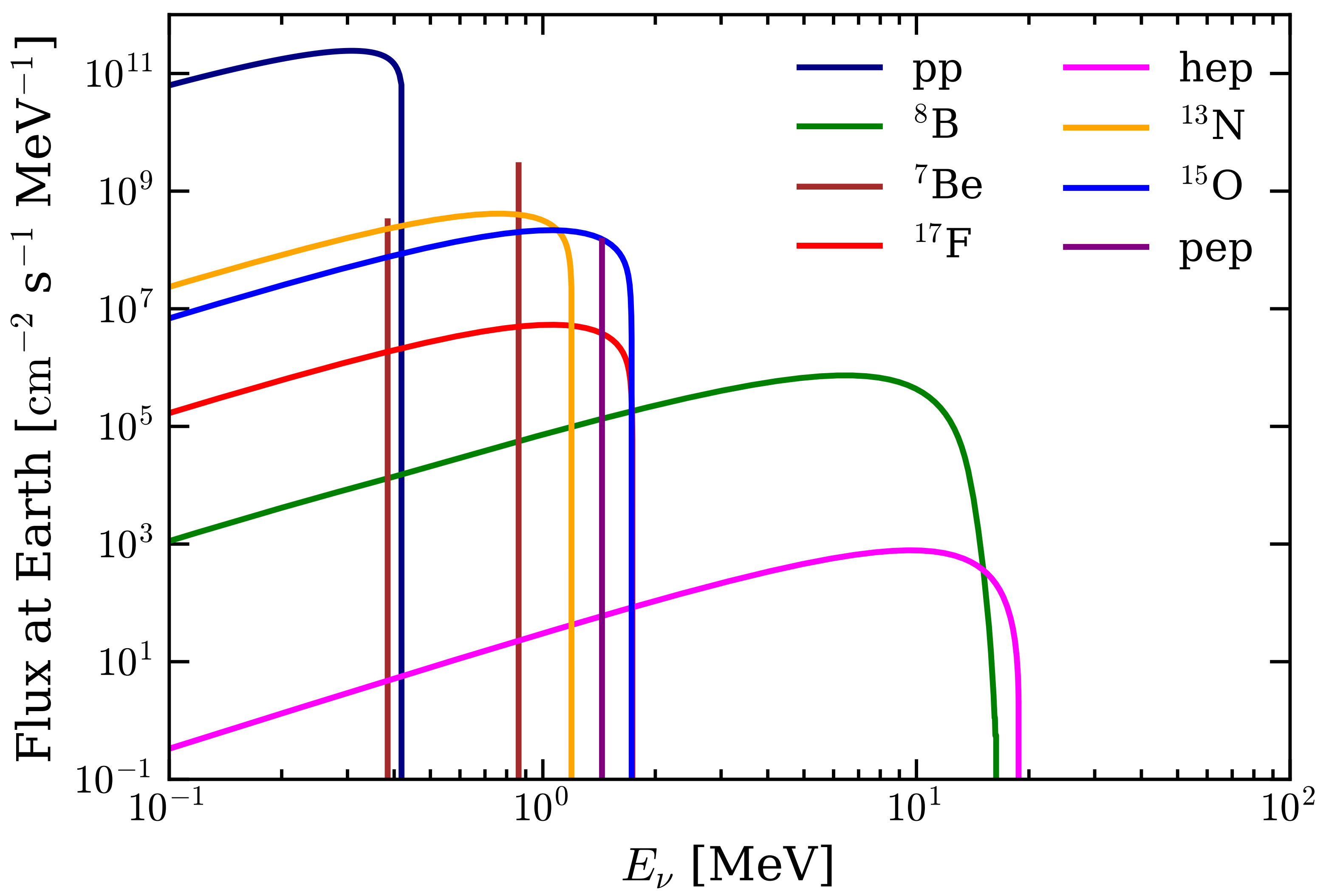
Data and background model available at:
https://zenodo.org/records/7992017

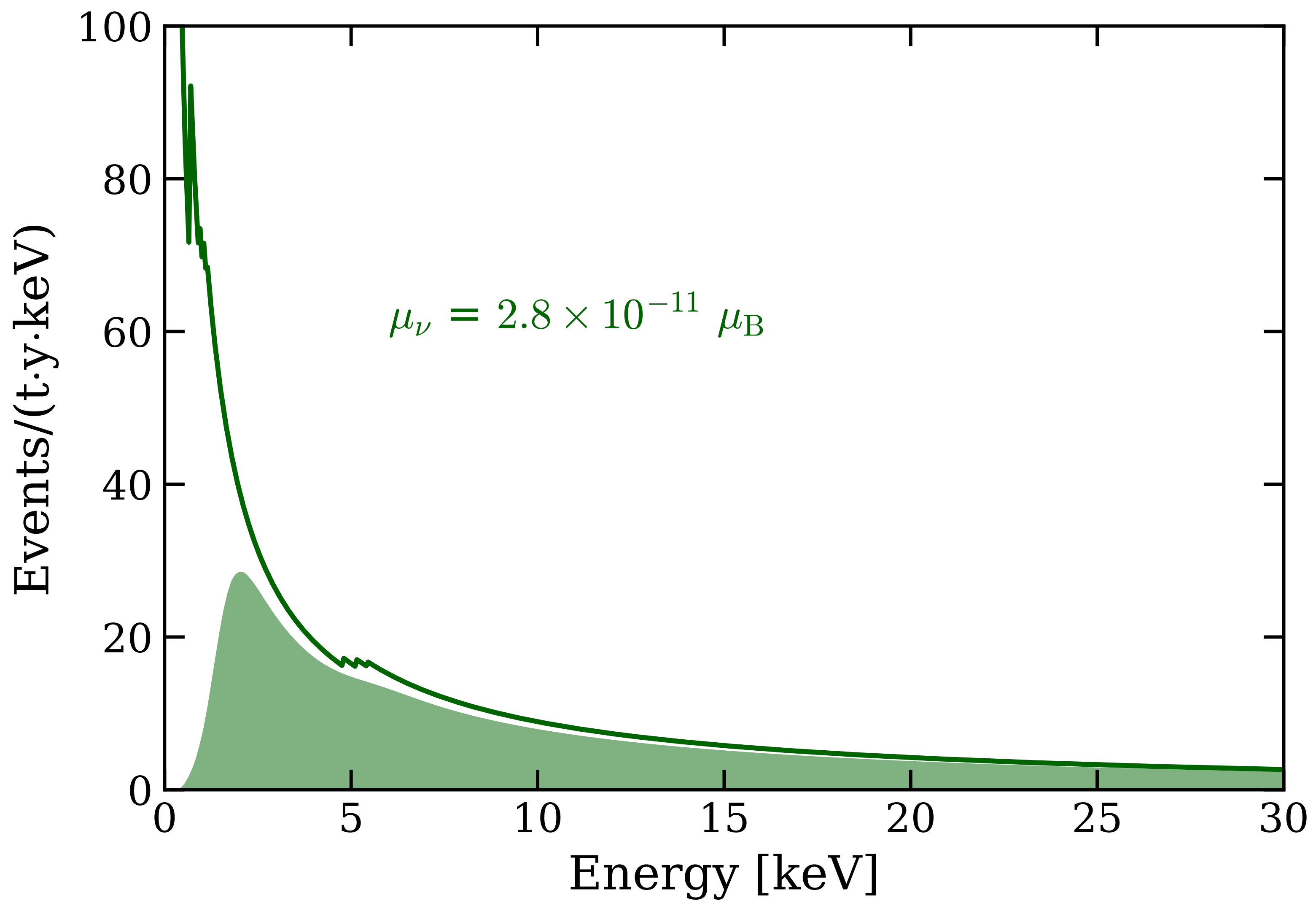
Best-fit values

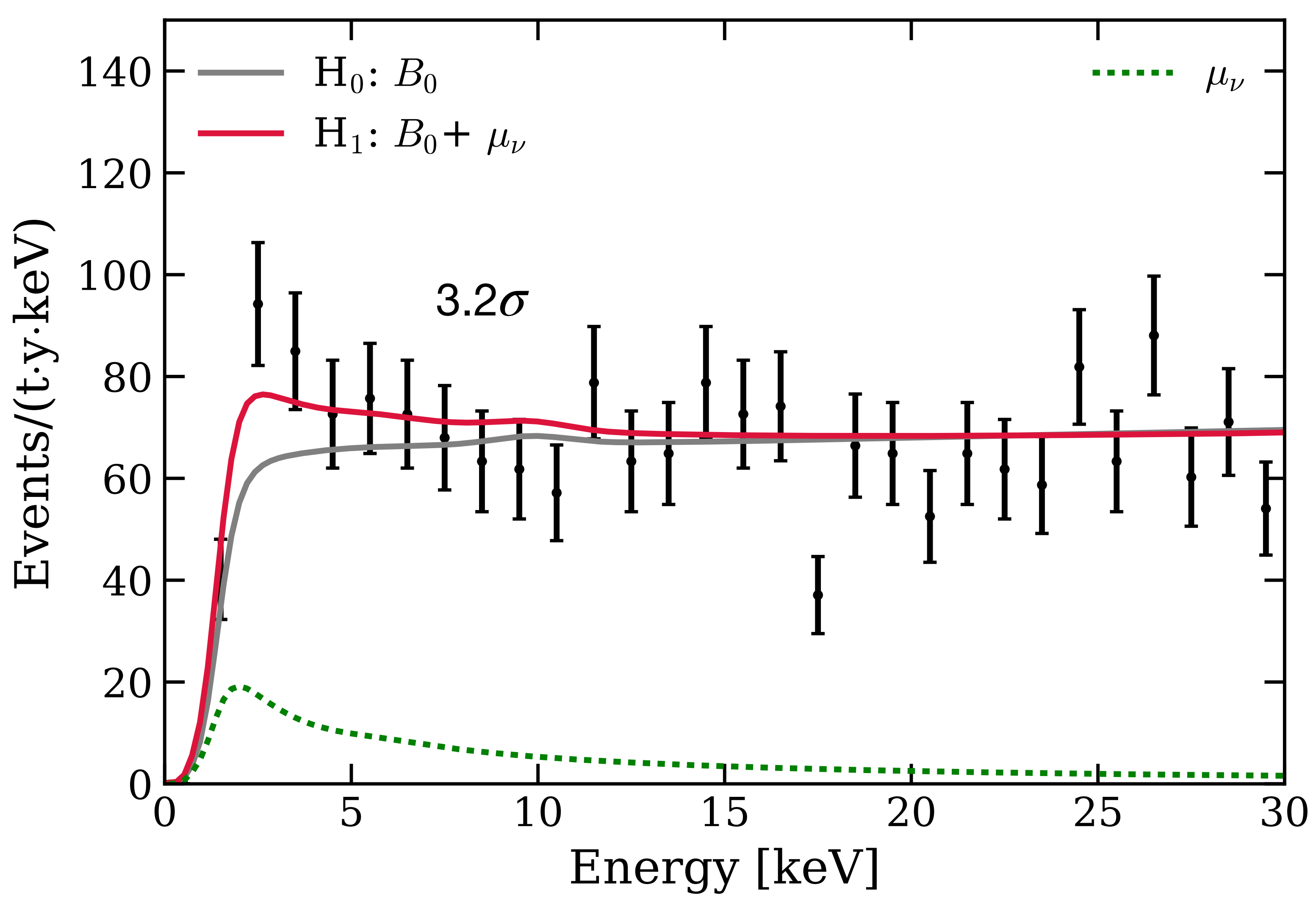
	(1, 10) keV	(1, 140) keV
^{214}Pb (^{222}Rn)	55 ± 7	960 ± 120
^{85}Kr	6 ± 4	90 ± 60
Materials	16 ± 3	270 ± 50
^{136}Xe	8.8 ± 0.3	1550 ± 50
Solar pp neutrino	25 ± 2	300 ± 30
^{124}Xe	2.6 ± 0.3	250 ± 30
AC	0.70 ± 0.03	0.71 ± 0.03
^{133}Xe	-	150 ± 60
^{83m}Kr	-	80 ± 16

- The total ER rate below 30 keV is $(15.8 \pm 1.3_{\rm stat})$ events/$(\rm t \cdot y \cdot keV)$
- ^{214}Pb best-fit value: $(1.31 \pm 0.17_{\rm stat})\ \mu$Bq/kg
- Solar pp neutrino: the 2nd largest ER contribution below 10 keV in SR0

Neutrino Magnetic Moment



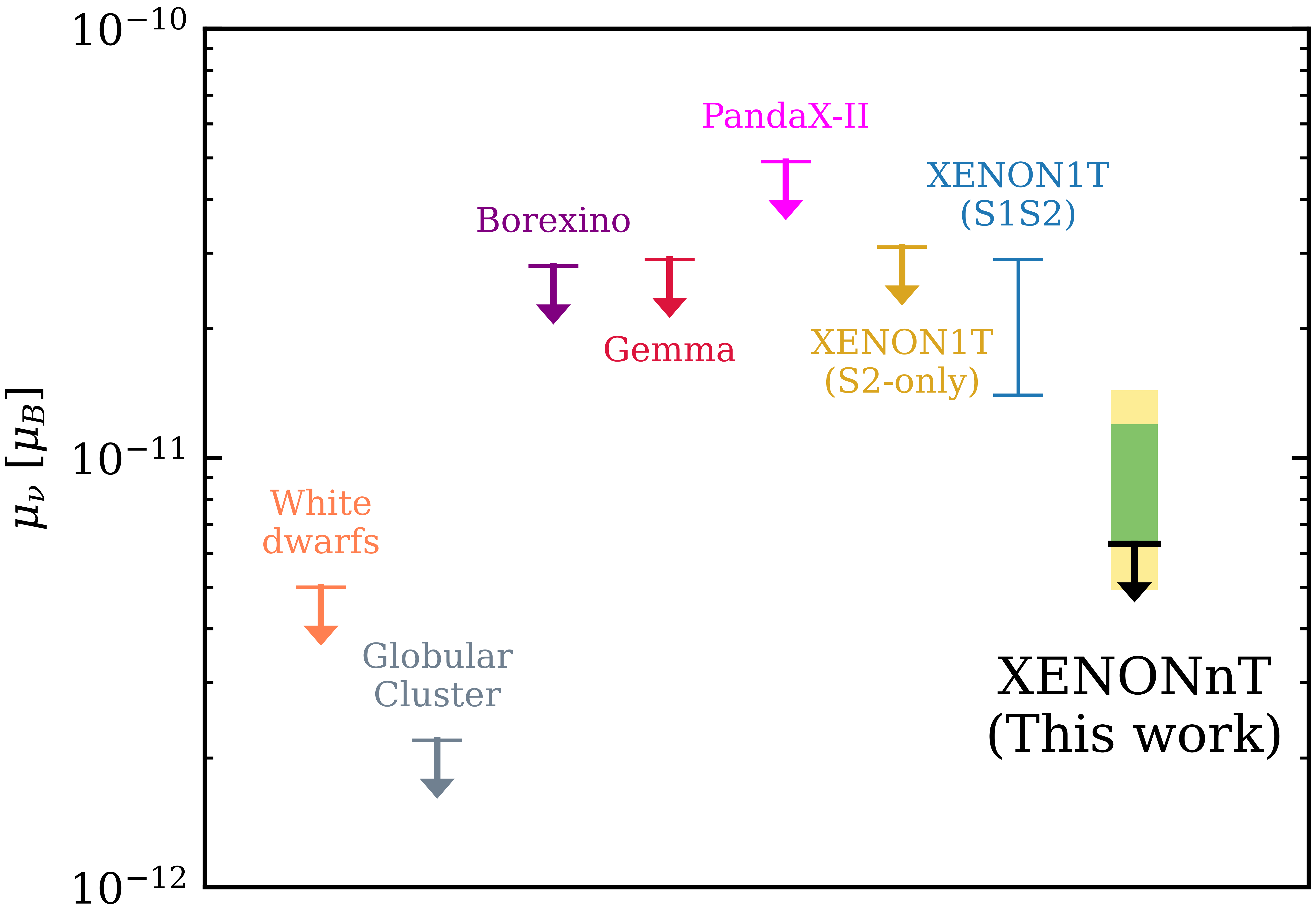




$$\frac{d\sigma_{\mu_\nu}}{dE_r} = \mu_\nu^2 \alpha\left(\frac{1}{E_r} - \frac{1}{E_\nu}\right)$$

- On top of the standard solar neutrino background
- Indication of Majorana nature of neutrinos if an enhanced neutrino magnetic moment ($\mu_\nu > 10^{-15}\,\mu_B$) is observed
- Should the excess is caused by neutrino magnetic moment, $\mu_\nu \in (1.4, 2.9) \times 10^{-11}\,\mu_B$

Neutrino magnetic moment



- Constrain the effective neutrino magnetic moment μ_ν^{eff} using solar neutrinos as LXe detectors are not sensitive to neutrino flavors
- XENONnT result: $\mu_\nu^{\mathrm{eff}} < 6.4 \times 10^{-12}\,\mu_{\mathrm{B}}$ (90% C.L.)

Dark photon dark matter