XENONnT experiment
- First results on electronic recoil events -

KOBAYASHI MASATOSHI , IBS-KMI JOINT WORKSHOP 2022/08/04

XENON
NAGOYA UNIVERSITY
ISEE Institute for Space-Earth Environmental Research
DMNet

XENON Collaboration

~170 scientists, 27 institutions from 12 countries

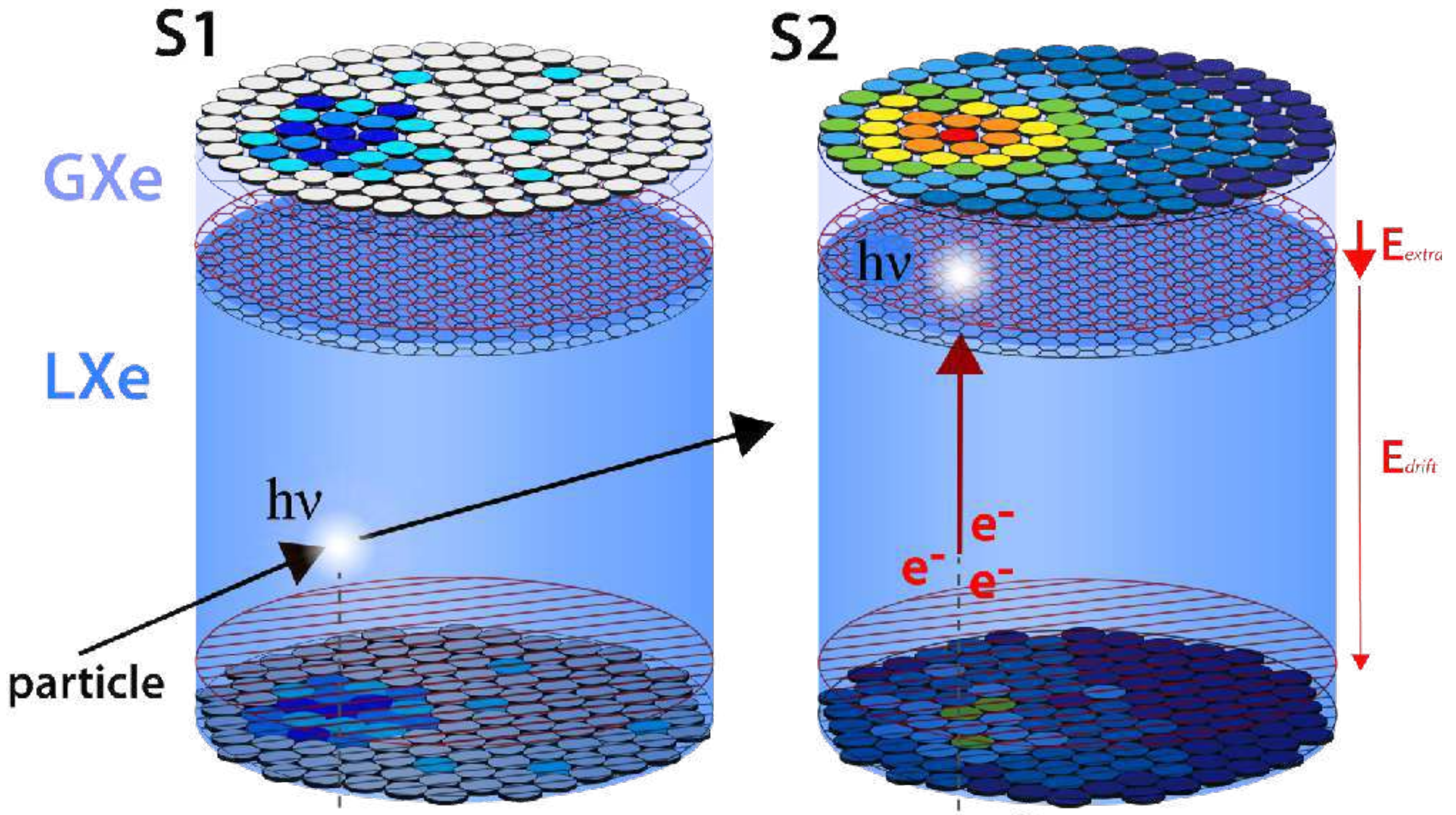
Columbia · KIT · Nikhef · Muenster · Stockholm · Mainz · MPIK, Heidelberg · Freiburg · Zurich

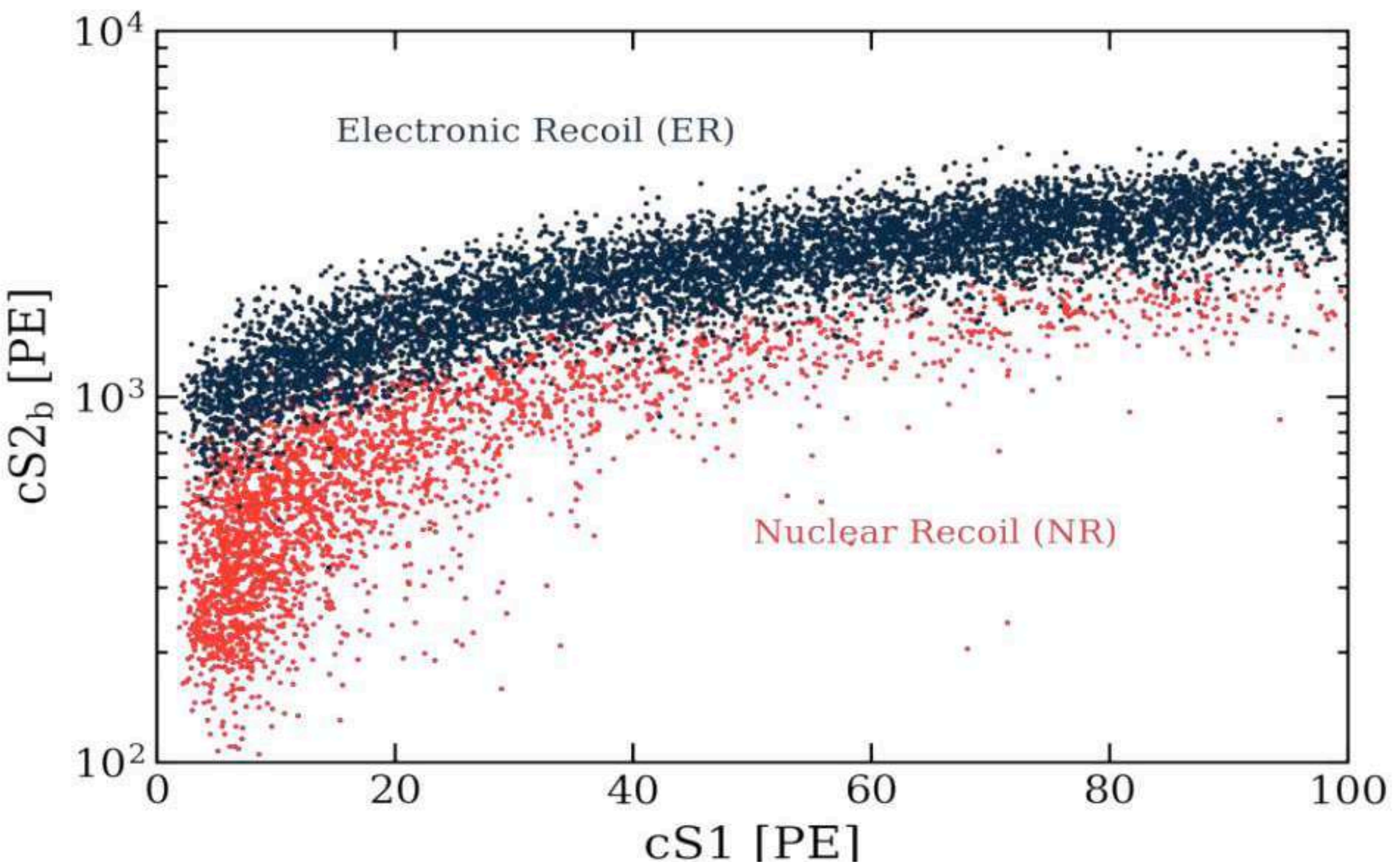
Chicago · UCSD · Rice · Purdue

Tsinghua · Tokyo · Nagoya · Kobe

Subatech · Coimbra · LPNHE · Torino · Bologna · L'Aquila · LNGS · Napoli · Weizmann · NYUAD

Liquid Xenon Time Projection Chamber





- Dual phase detector: LXe and GXe
  - Using PMTs to detect photons
  - Electric field is applied to drift electrons generated
- DM and BG particles generate signals in LXe
  - S1 signal: Scintillation photon
  - S2 signal: Ionization electrons

- S1/S2 depends on the type of interaction
  - Electric recoils: γ ray, β ray, Axion,...
  - Nuclear recoils: Neutron, WIMPs,...
- ER events have larger S2 than NR events
  - BG rejection for WIMPs

XENON projects

- The main target of XENON project: Direct DM detection (WIMPs, ALPs, …)
- Also other important physics: axions, neutrino physics,…

Years	2005 - 2007	2008 - 2016	2012 - 2018	2019 - now
Total Xe mass	25 kg	161 kg	3200 kg	8600 kg
WIMPs sensitivity	~10^{-43} cm^2	~10^{-45} cm^2	~10^{-47} cm^2	~10^{-48} cm^2

XENON projects

- XENONnT, the latest stage of XENON program started taking data since mid. 2021.
- For first science run: WIMPs and Excess in low energy ER events, reported by XENON1T.

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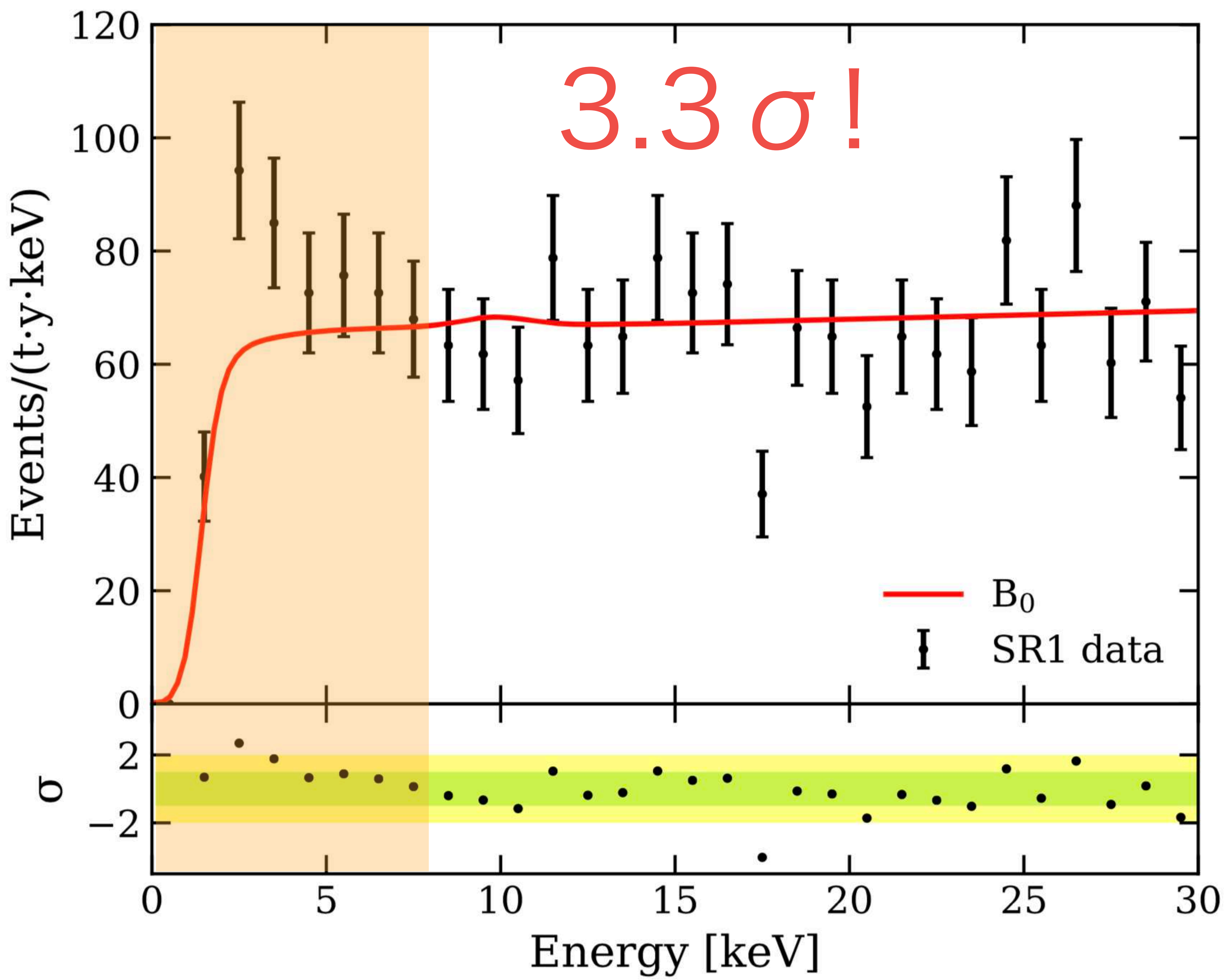
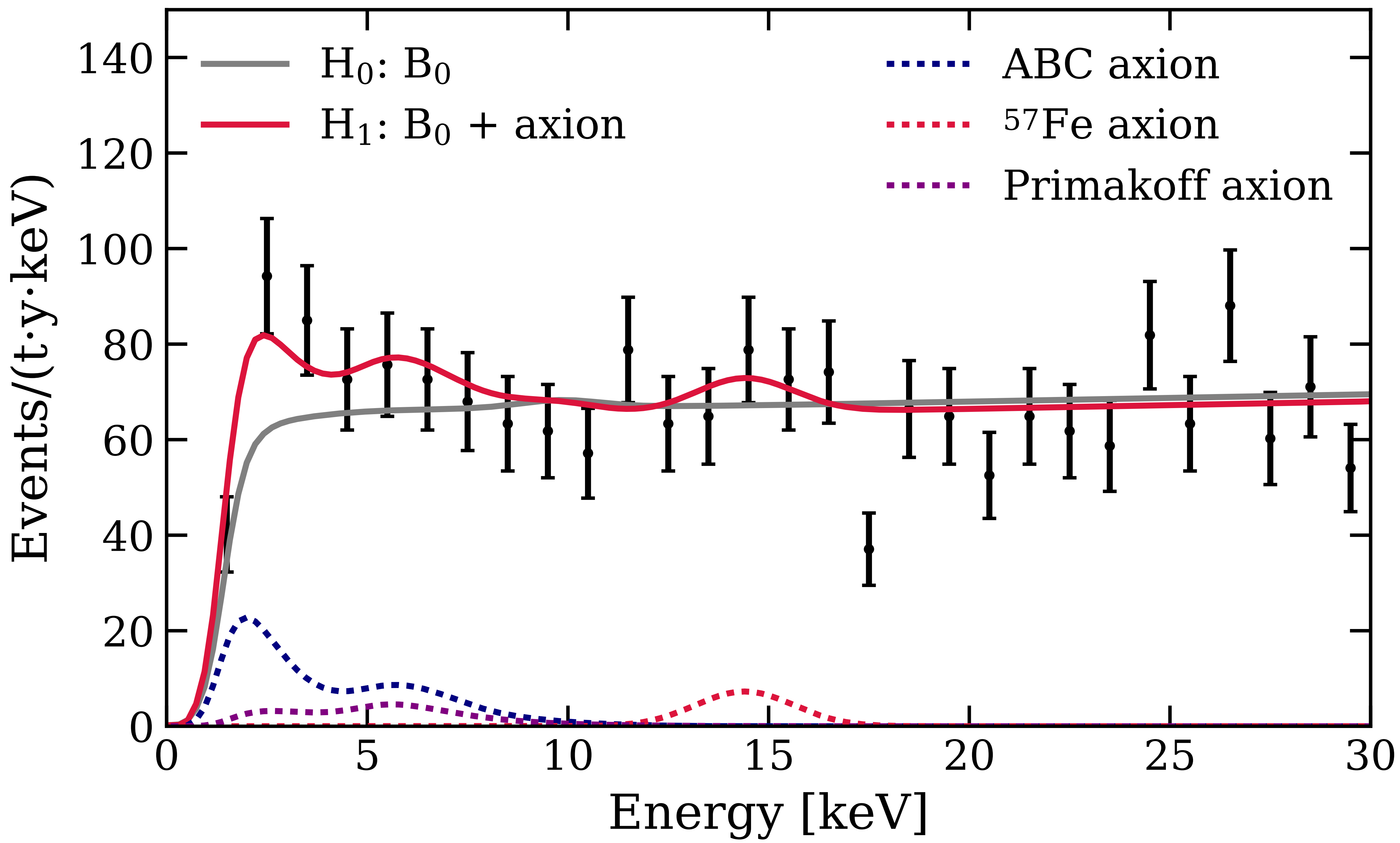
Low-Energy Electronic Recoil Excess in XENON1T



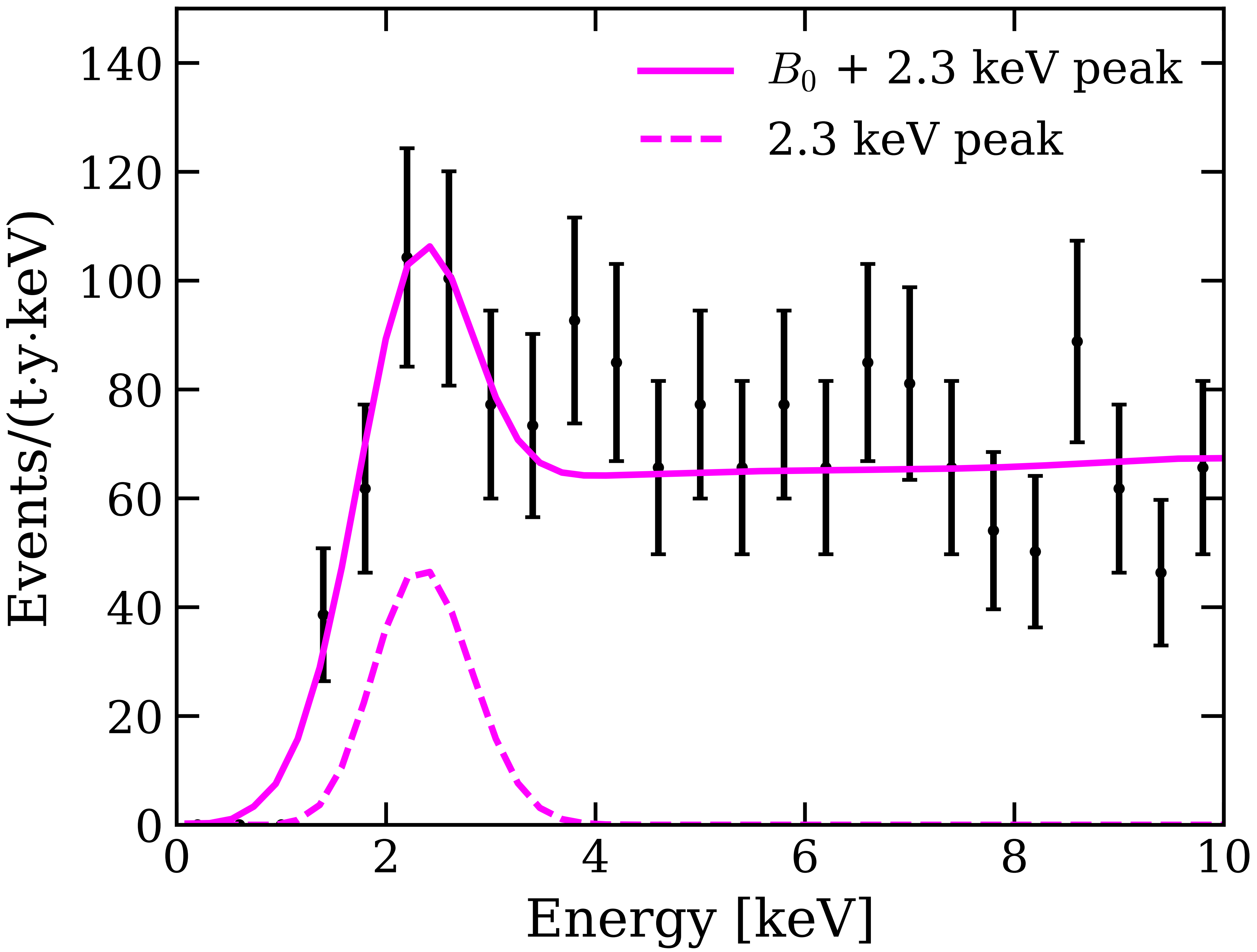
- XENON1T observed an excess in its ER spectrum < 7 keV
  - 285 observed vs 232 ± 15 expected (3.3σ)
- Phys. Rev. D 102, 072004 (2020)

Low-Energy Electronic Recoil Excess in XENON1T

Solar-axion



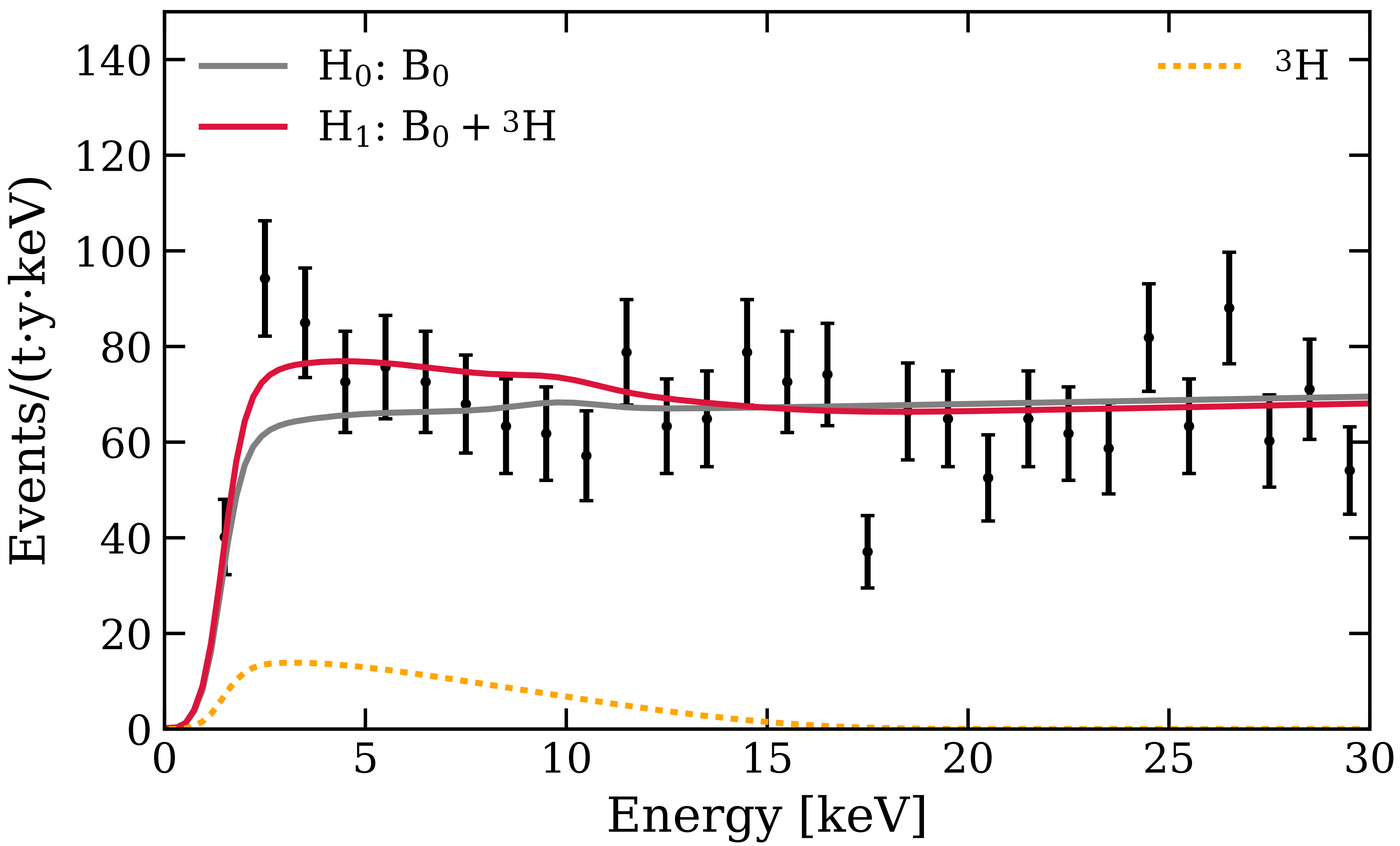
ALPs/Dark Photon



- The Excess was compatible with new physics scenarios:
  - Solar axions, ALPs, dark photons, a neutrino magnetic moment and many more

Low-Energy Electronic Recoil Excess in XENON1T

Tritium

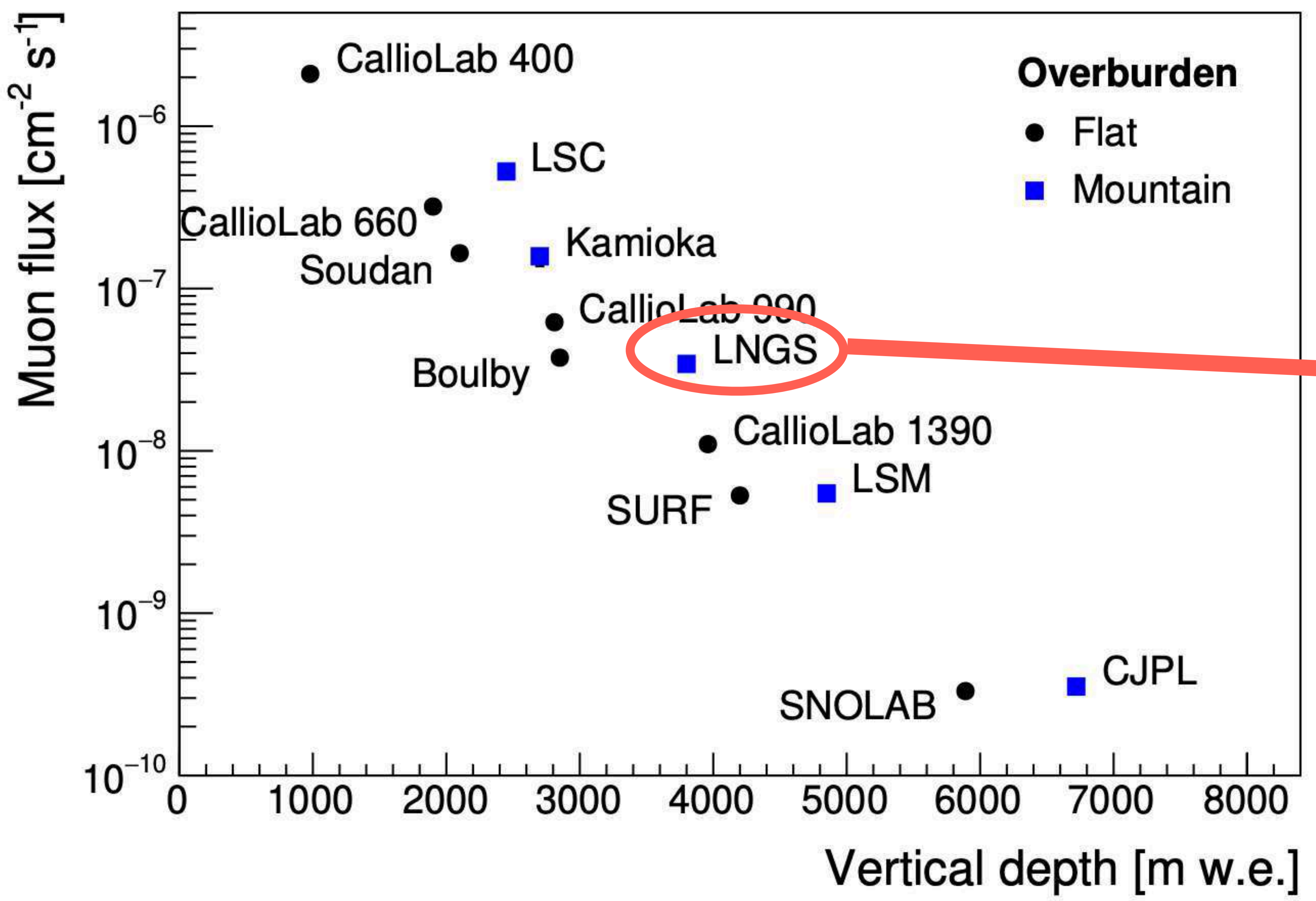


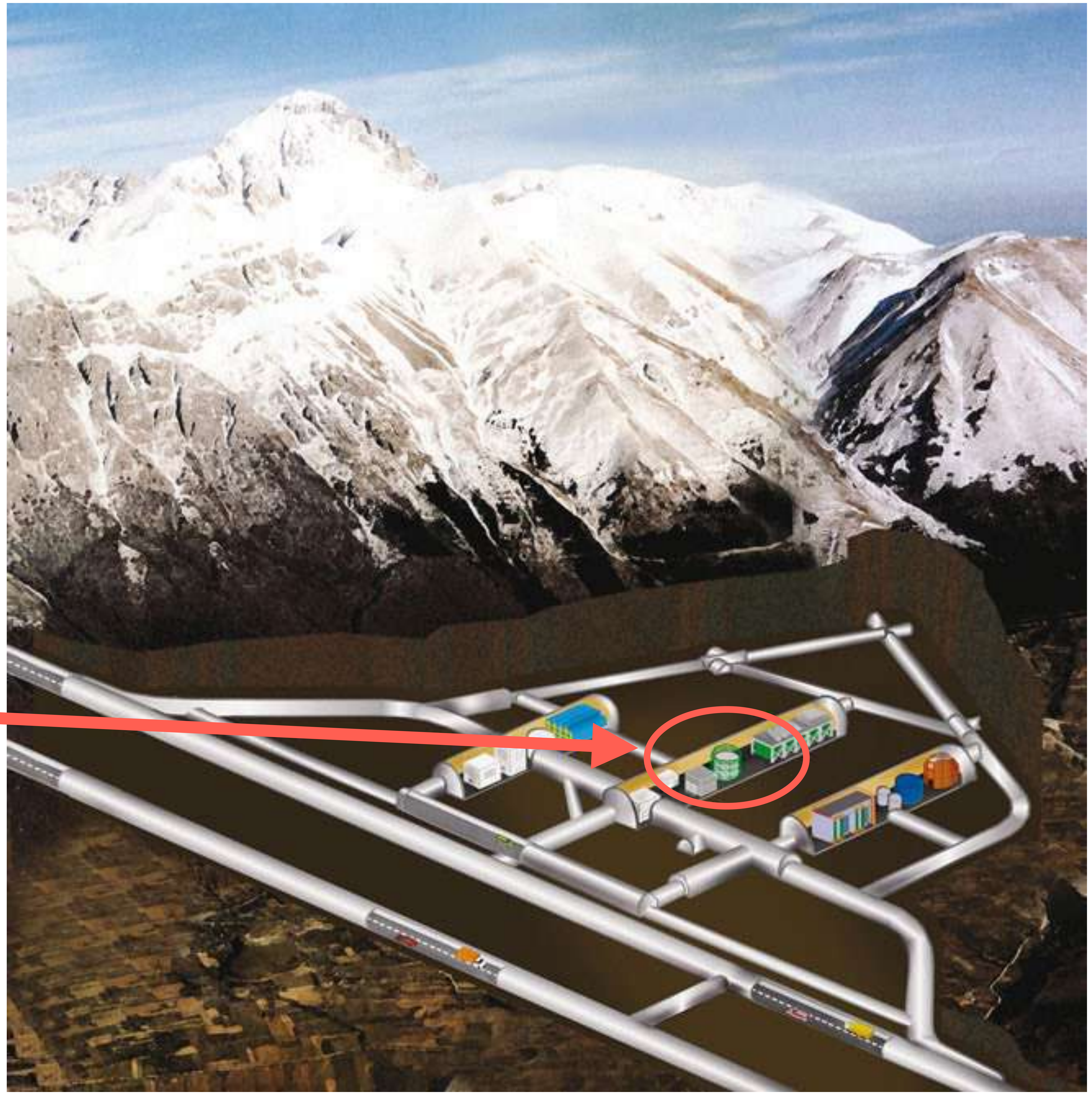
- However, also consistent with tritium β ray (Q=18keV)
  - The significance of solar axion goes down to 2.0 σ with tritium
- Using first XENONnT data, we would answer for this excess!

The XENONnT: detector and subsystem

The XENONnT

- The XENONnT detector is located at Laboratori Nazionali del Gran Sasso (LNGS), Italy
- Underground area: suppress muon background
  - 1500 m of rock ~ 3600 m.w.e
  - Suppress muon flux to 10^{-6} of surface area





The XENONnT

The XENONnT

Larger TPC

with 3x active volume

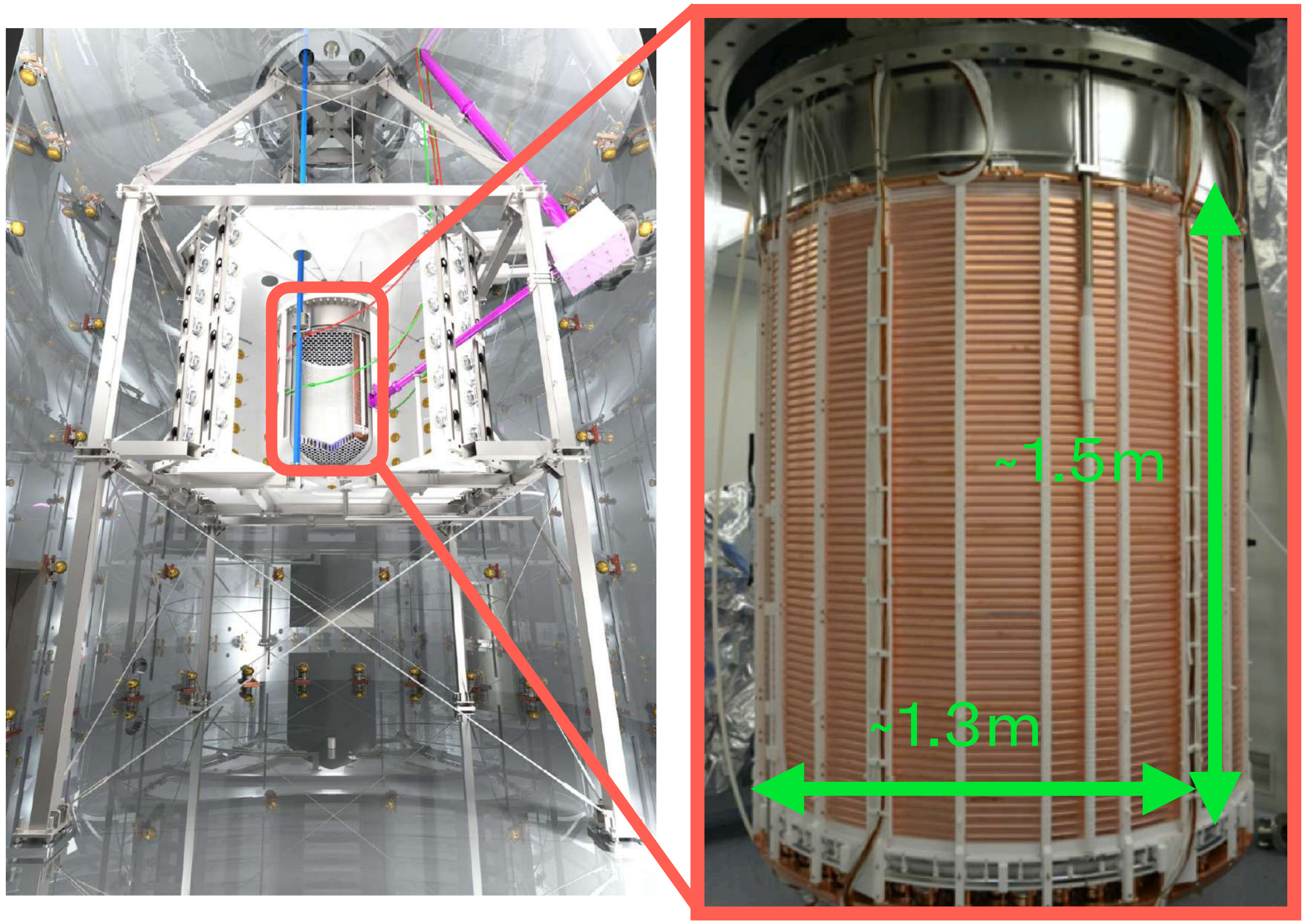
Gd-loaded water Cherenkov neutron veto

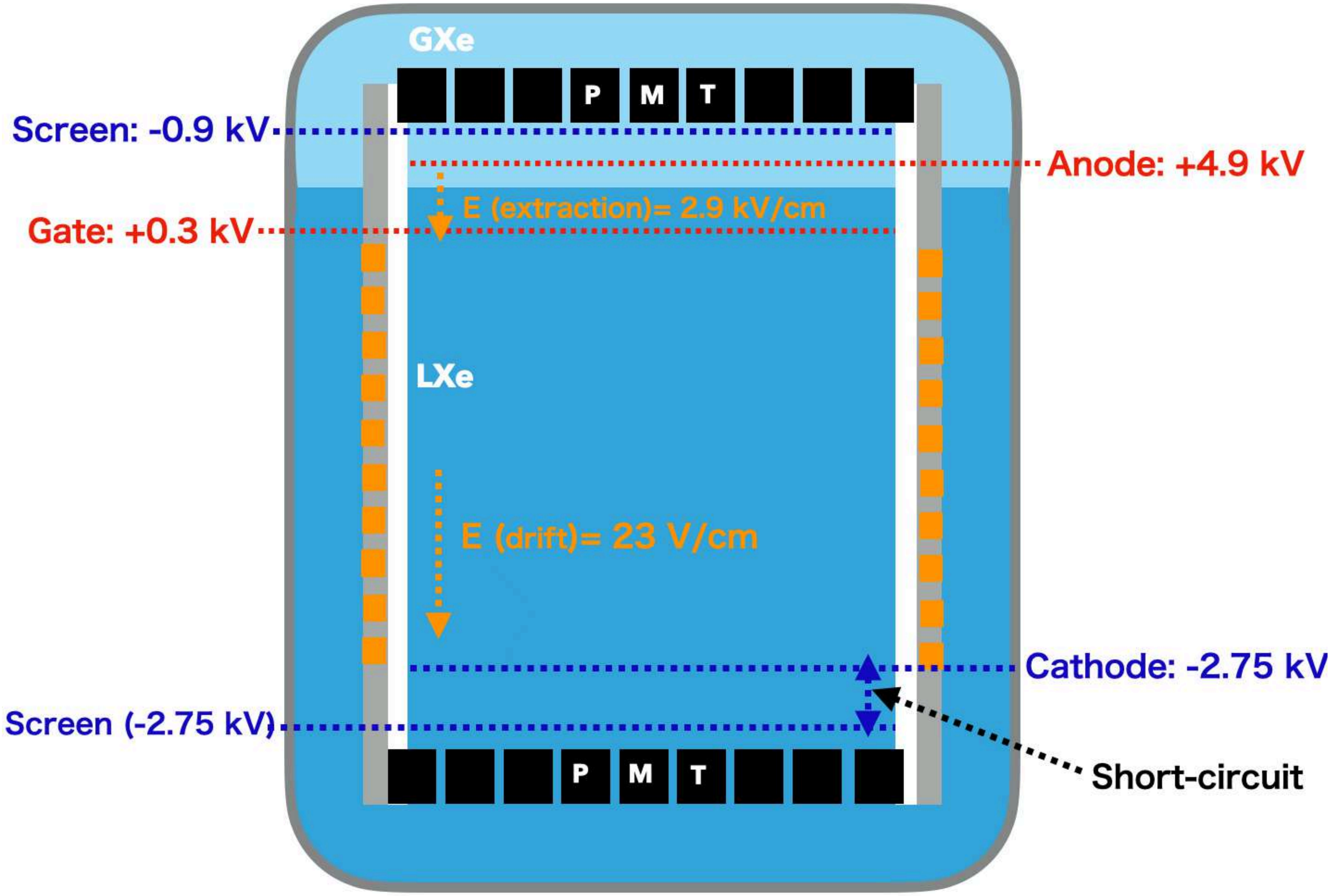
Radon distillation column

Upgraded DAQ with dedicated high-energy readout

Liquid xenon purification

XENONnT TPC

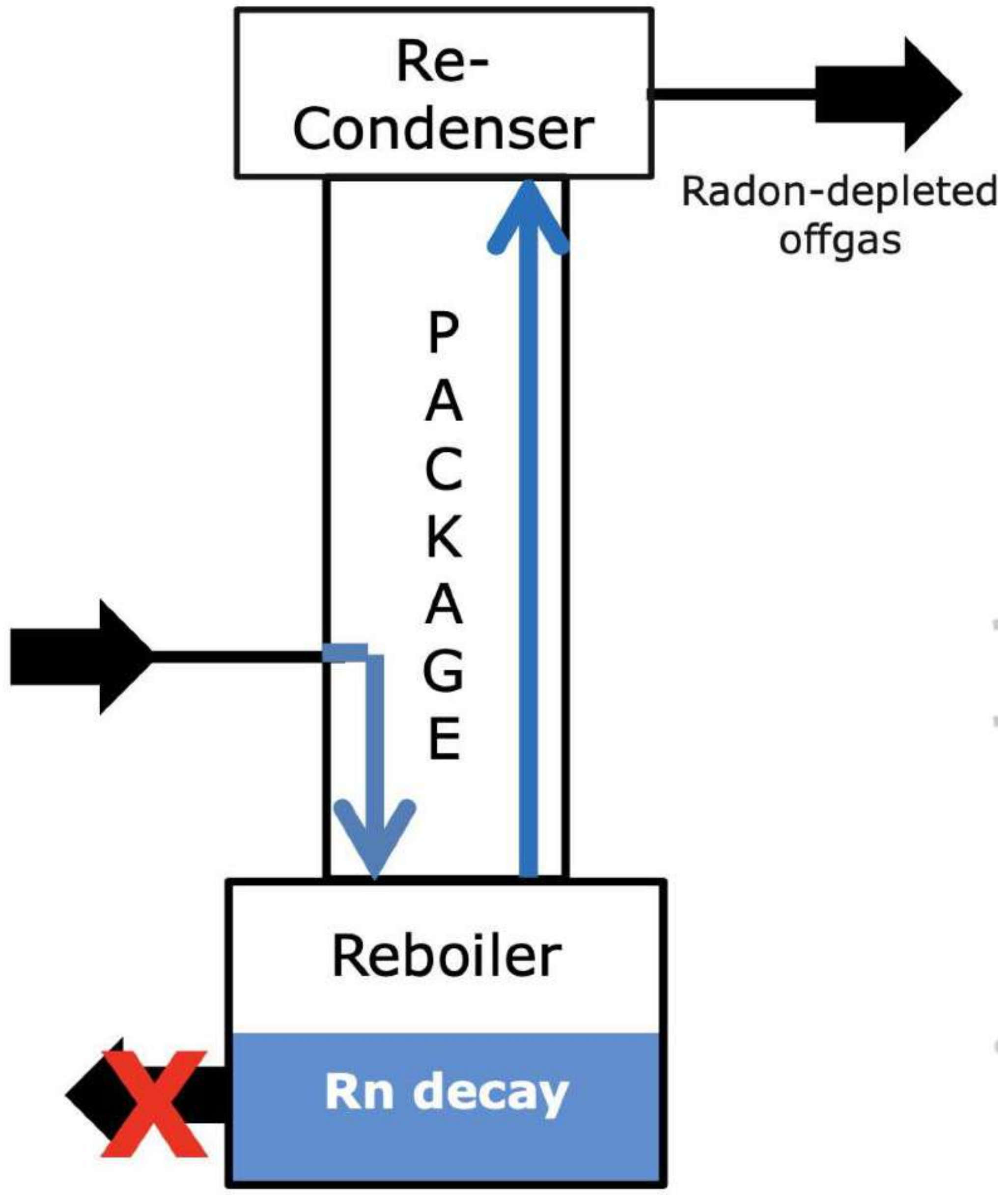




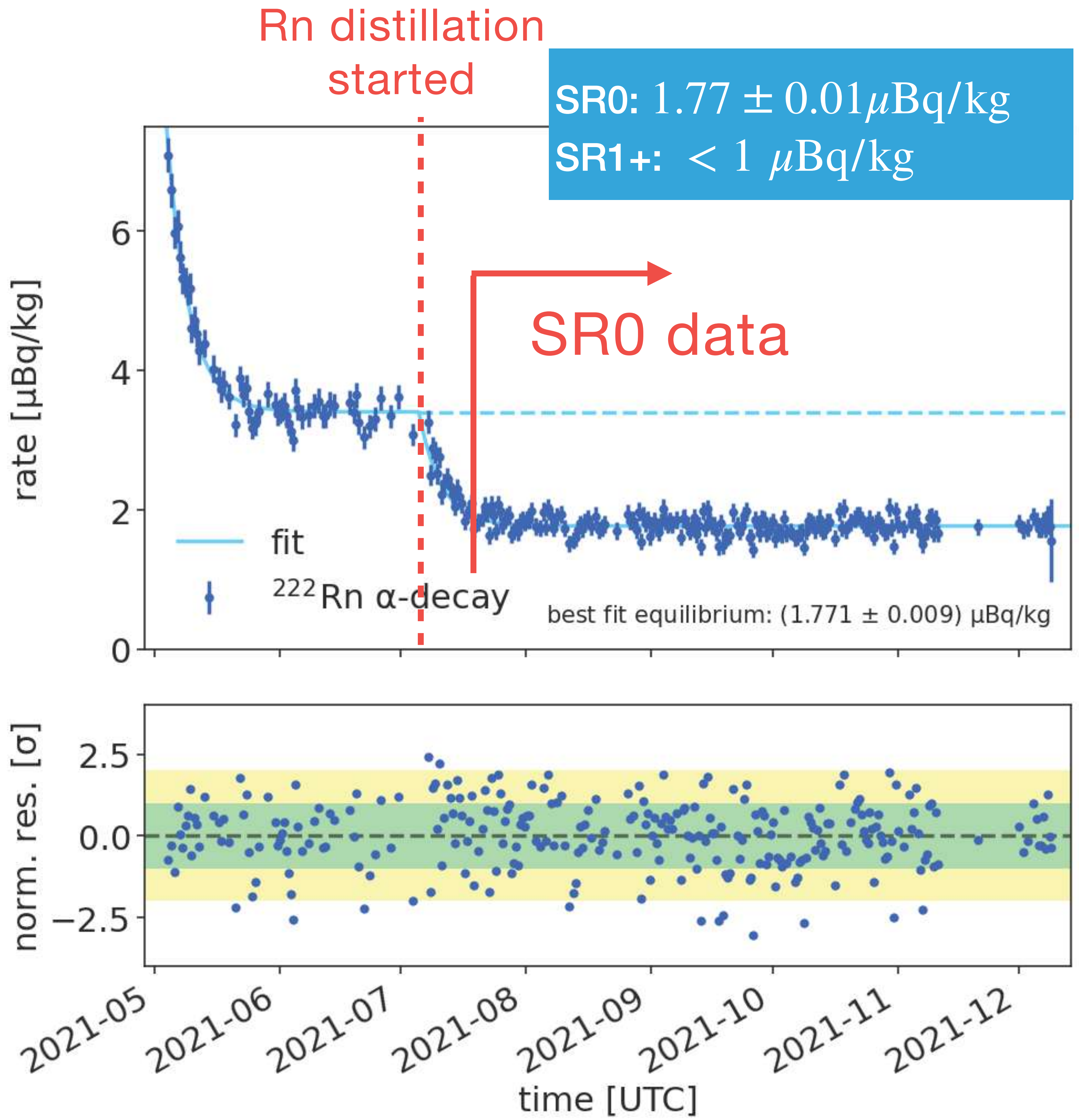
- 1.3 m diameter and 1.5 m height
- 5.9 t xenon instrumented, 8.5 t total xenon
- 5 electrodes and 2 sets of field shaping rings
- PTFE reflectors to maximize light collection efficiency (LCE ~ 36%)

- 494 3" PMTs (R11410-21) in the top/bottom array (QE ~ 34%)
- E-field: 23V/cm
  - Lower than XENON1T: 80V/cm
  - Short-circuit between the cathode and bottom screen limited the voltage to −2.75 kV
- Low field, but sill running stably

Radon Distillation

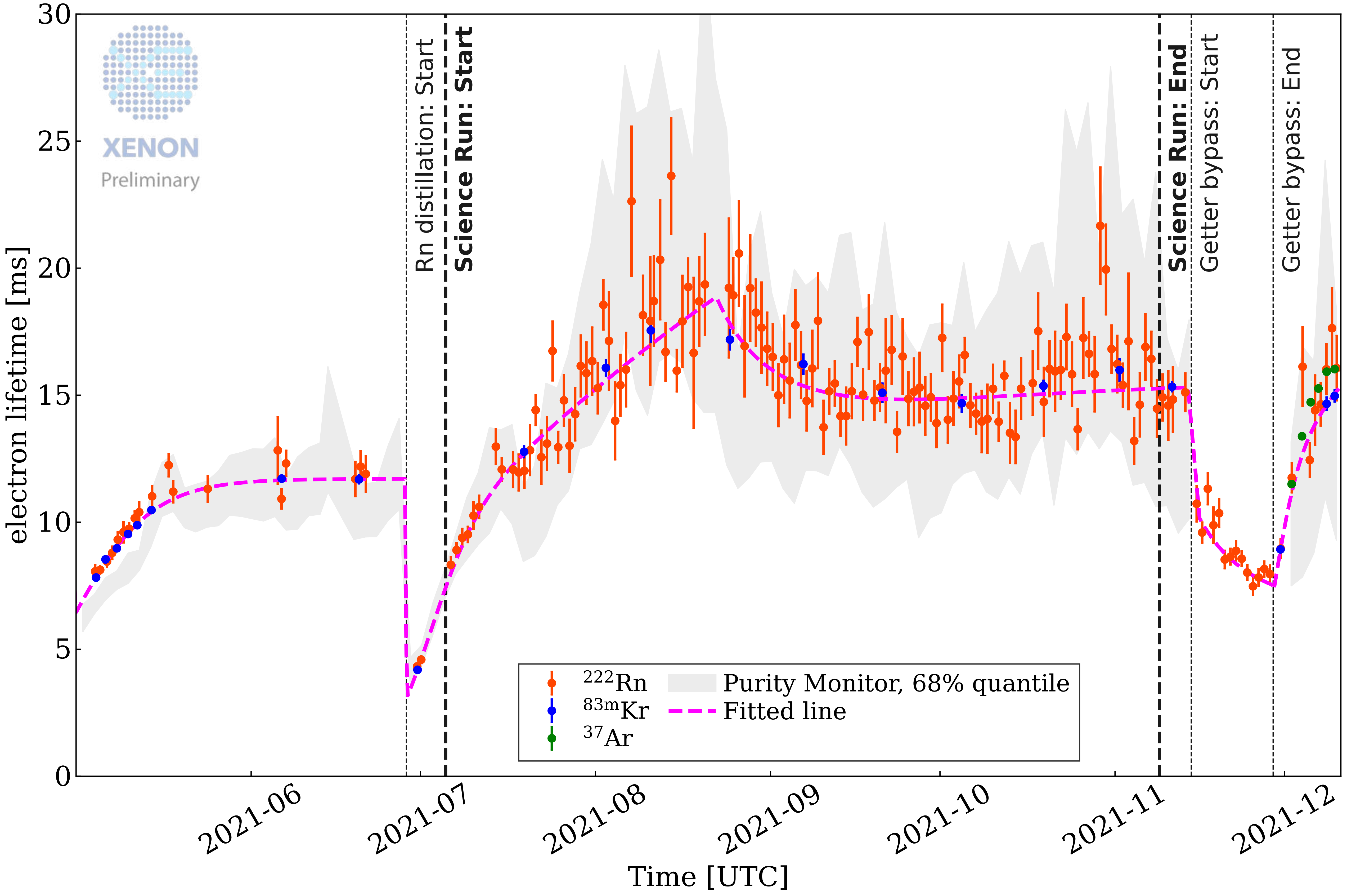


arxiv: 2205.11492



- Rn: main source of BG events in both WIMPs and LowER
  - Target: 1 μBq/kg ^{222}Rn level (XENON1T: 13 μBq/kg)
  - Emanated from materials
- Removal of Rn using difference in vapor pressure of Xe and Rn
  - Rn atom accumulates into LXe more than GXe
- 1.77 ± 0.01 μBq/kg is achieved by GXe-only removal mode (~8 times less BG w.r.t. 1T)
- Additional factor 2 reduction is possible via LXe+GXe removal for SR1

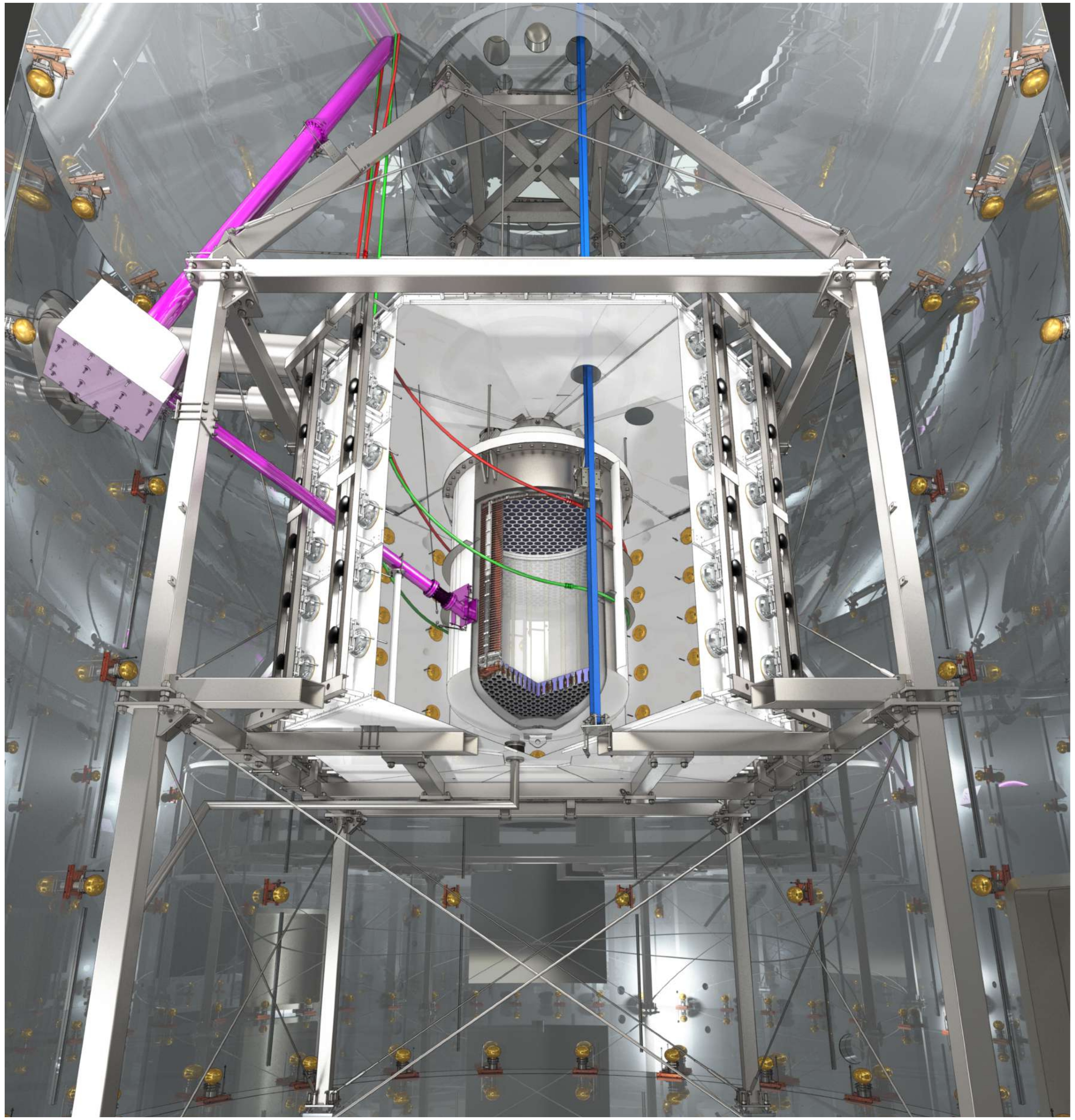
LXe Purification

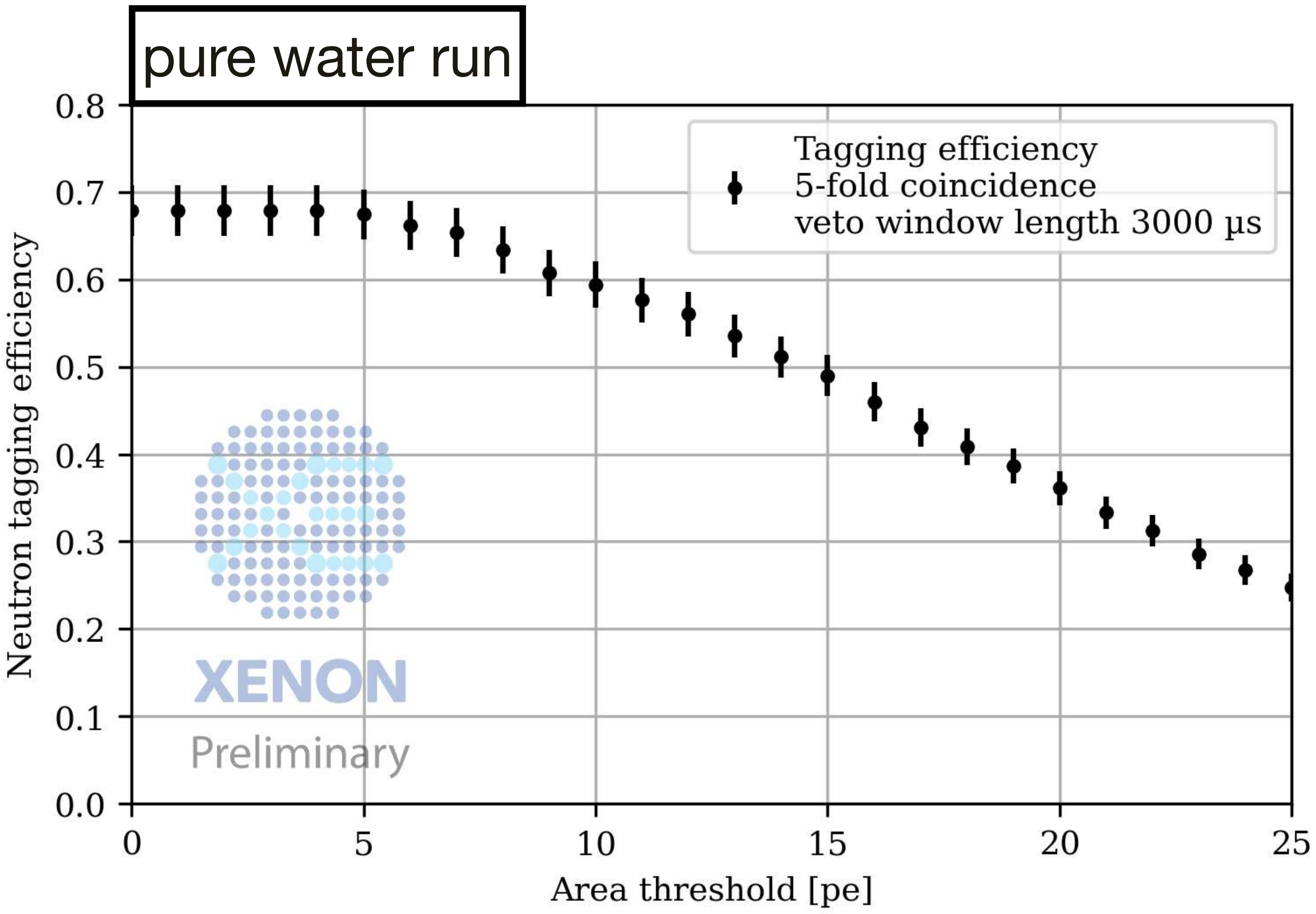


- Impurities (ex.O2, H2O) reduce the signal size
  - Continuous purification of Xe is required
- Direct liquid circulation with cryogenic pump
  - 2 LPM (18h to exchange the entire volume of 8.5 ton)
- Multiple filters (arxiv:2205.07336)
  - Cu: High eff / high Rn (for fast purification)
  - Getter: Mid eff / low Rn (for SR0)

	Full TPC drift time	electron lifetime	electrons surviving a full drift length	O_2 eq. purity
XENON1T	0.67 ms	0.65 ms	30%	~ 1 ppb
XENONnT	2.2 ms	> 10 ms	> 90%	~ 0.02 ppb

Neutron Veto

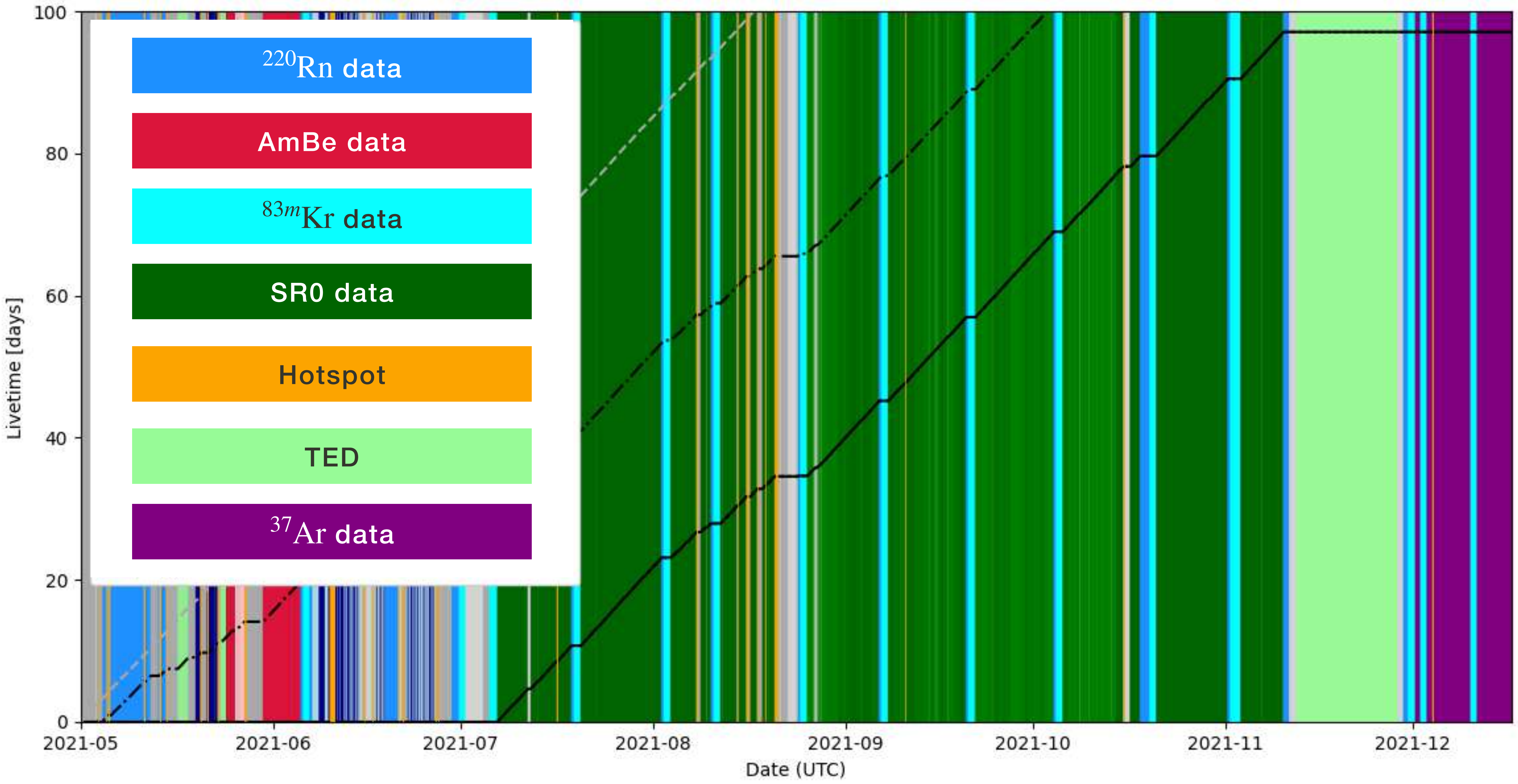




- Gd-Water Cherenkov detector (SuperK/EGADS technology)
- Neutrons are captured by Gd, then produce gammas with total energy of 8MeV
- Covering the entire detector wall with ePTFE with ~99% reflectivity
- 65% neutron tag. eff. In pure water (SR0)
  - Future: ~87% tag. eff with Gd doping

Data analysis and calibrations

First Science Run of XENONnT (SR0)



97.1 days

(July 6 – Nov 11 2021)

×

FV = (4.37 ± 0.14) tonnes

1.16 ton – year

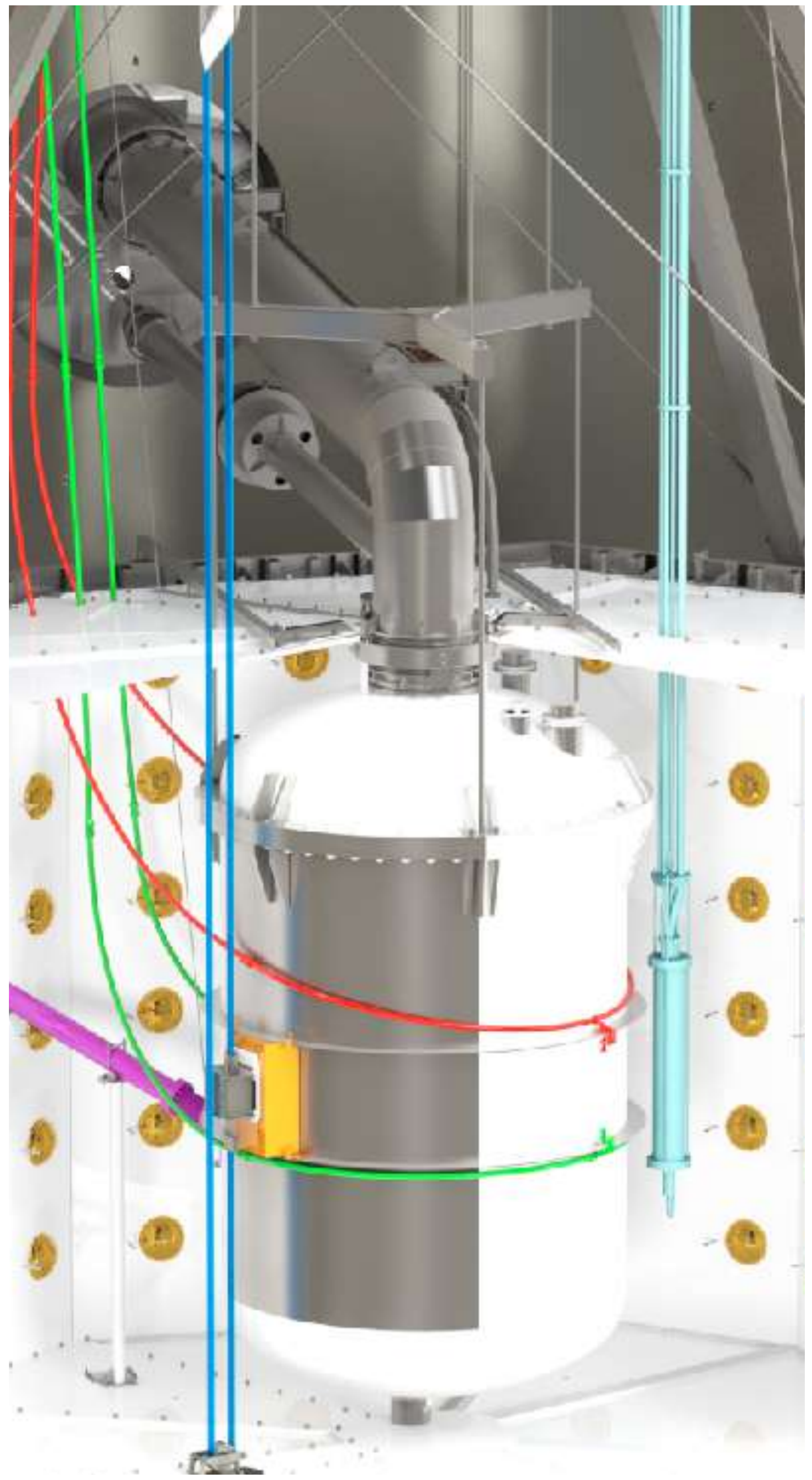
(1T: 0.65 ton-year)

- ^{83m}Kr calibration every two weeks
- ^{220}Rn/AmBe calibration before SR0
- ^{37}Ar calibration after SR0
- Tritium-enhanced data (TED) after SR0 (will be discussed later)

Calibrations in XENONnT

- Internal and external sources
- Calibration for…
  - Energy scale
  - Uniformity
  - Cut efficiency
  - Resolution

	Type	Particle, Energy	Purpose
^{83m}Kr	Internal	e^-: 32 keV + 9 keV	Uniformity, energy scale, etc
^{220}Rn	Internal	e^-: Q=570keV	Low-energy ER
^{37}Ar	Internal	Xray, 2.82 keV	Uniformity, energy scale, threshold
$^{241}AmBe$	External	NR, O(1) MeV Gamma from n-activation	Low-energy NR, Gammas from activation



Energy Calibration

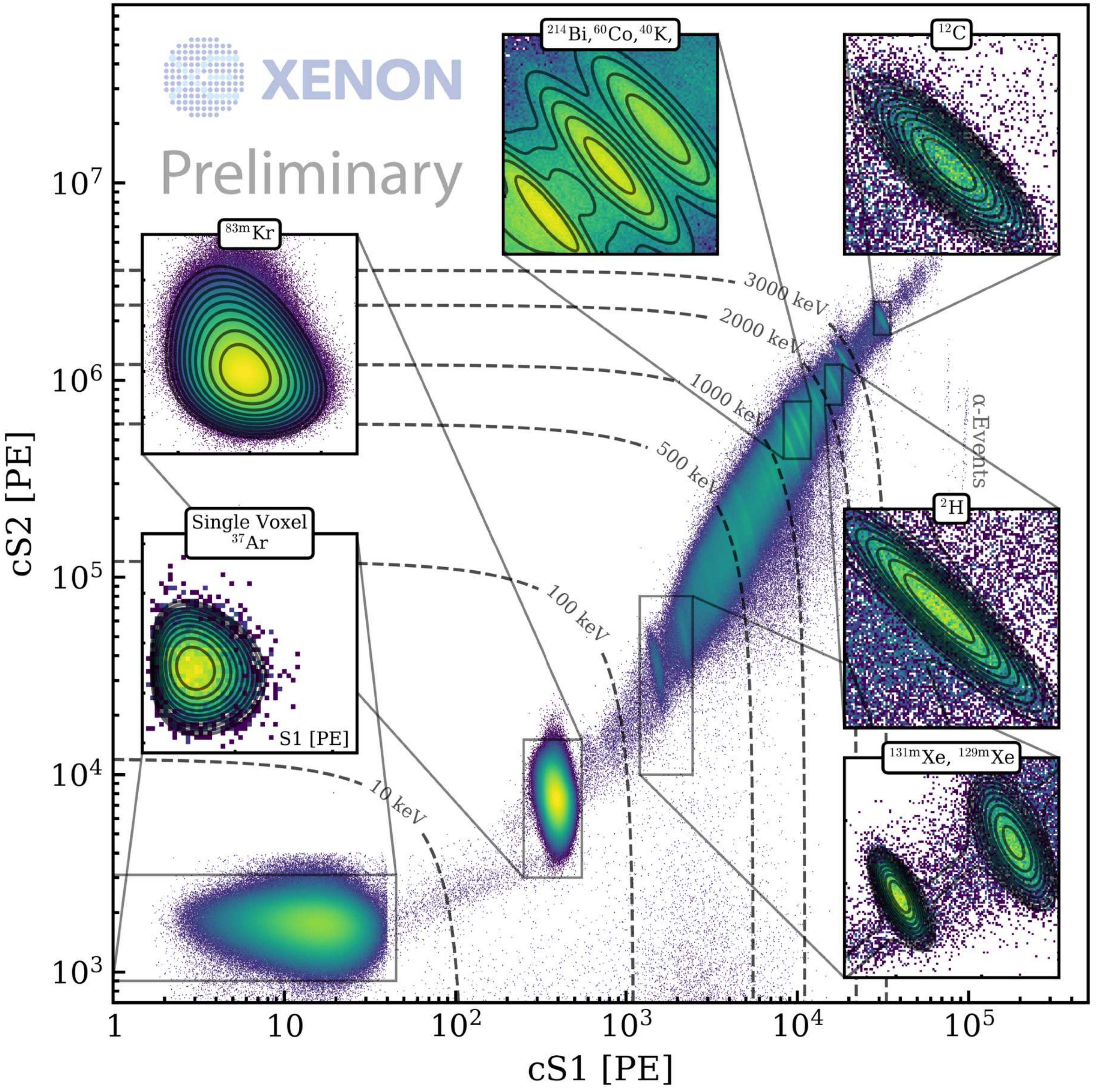
$$E = (n_{ph} + n_e) \cdot W = (\frac{cS1}{g1} + \frac{cS2}{g2}) \cdot 13.7(\text{eV})$$

- cS1, cS2; “corrected” the detector uniformity

- g1 and g2: detector-specific gain constant
  - Extracted from calibration data

$$Q_y = -\frac{g2}{g1} \cdot L_y + \frac{g2}{W} \quad (Q_y = cS_2/E, \quad L_y = cS_1/E)$$

- Using g1 and g2, reconstruct energy of each eve



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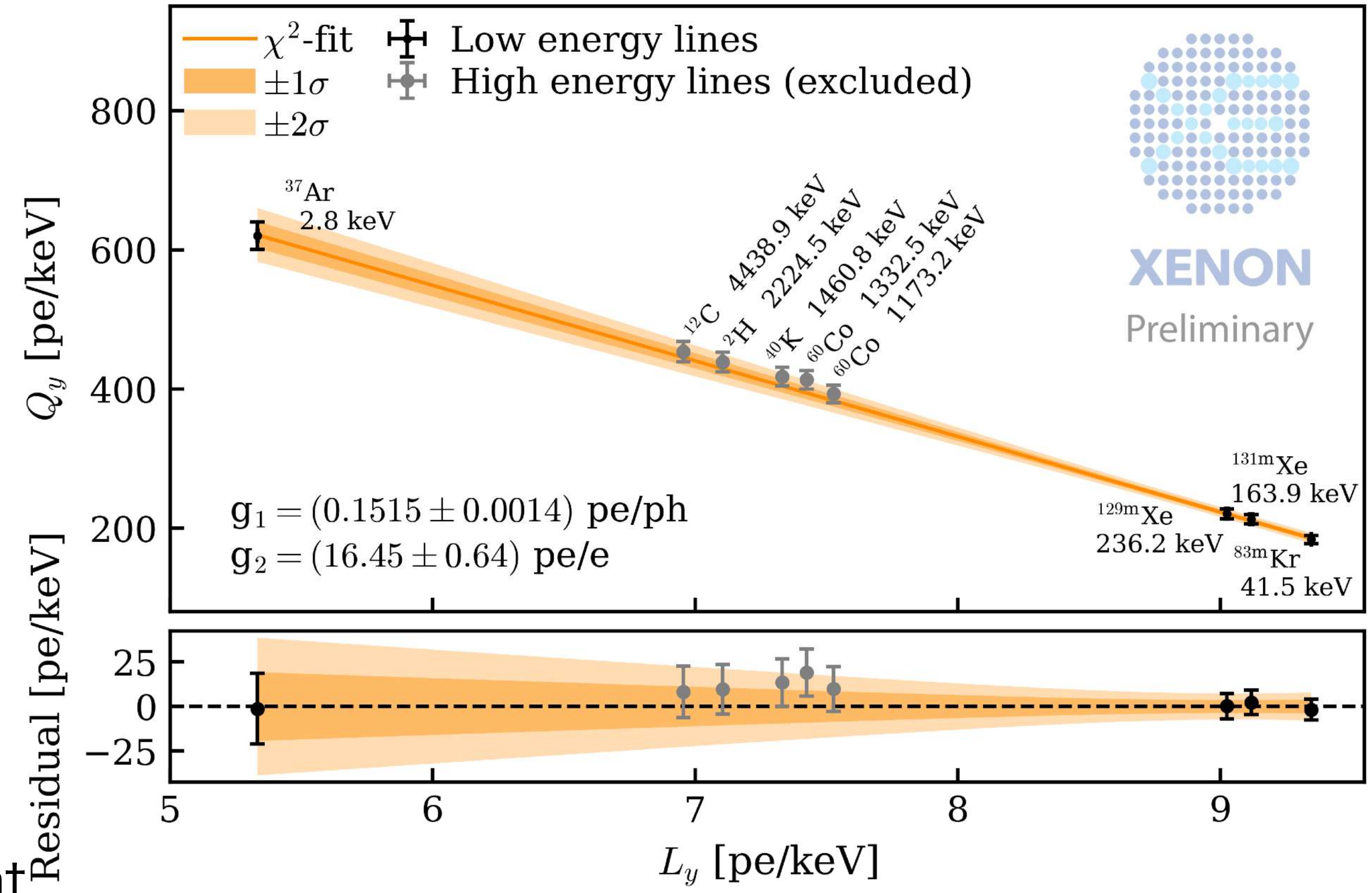
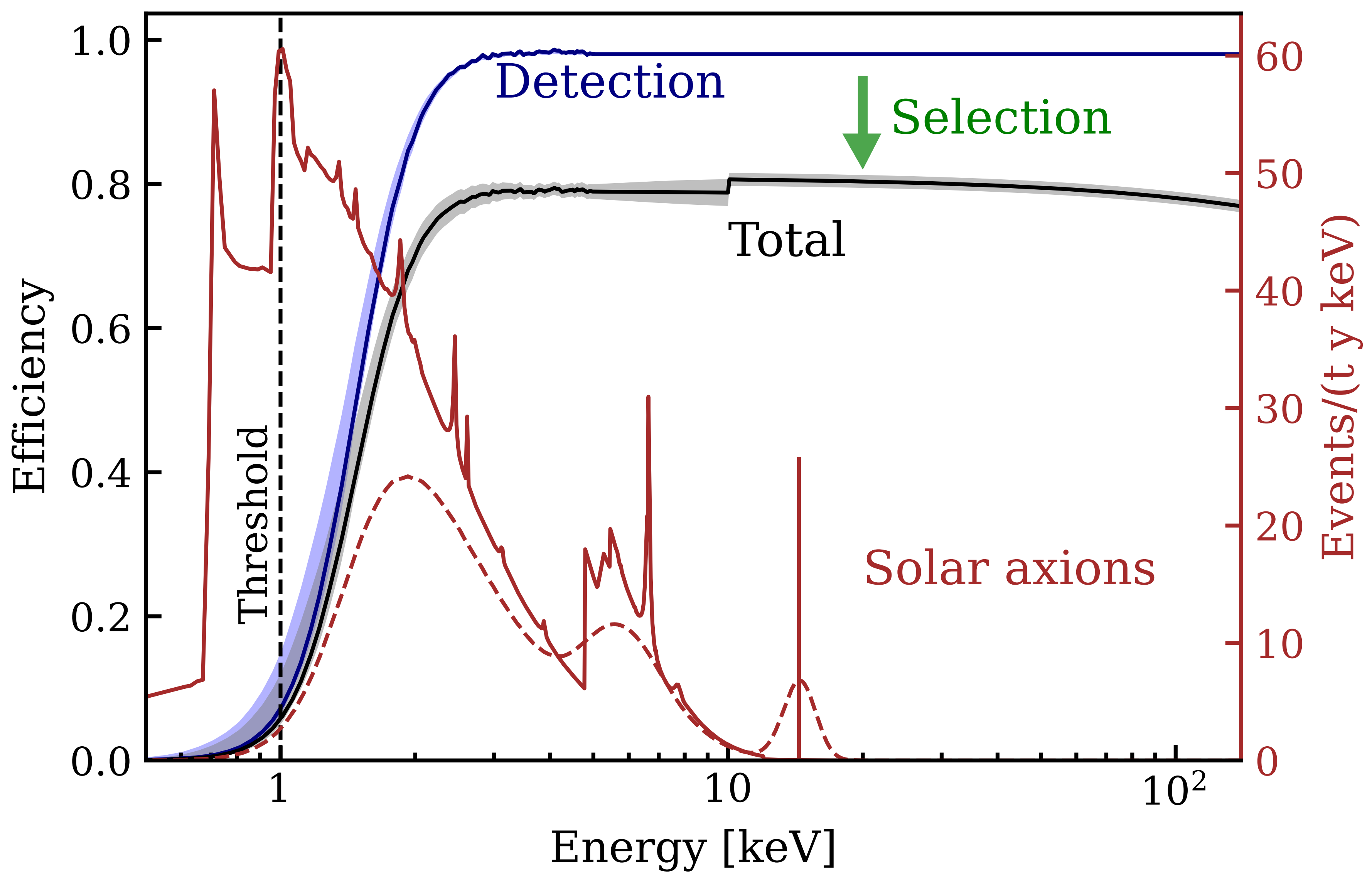
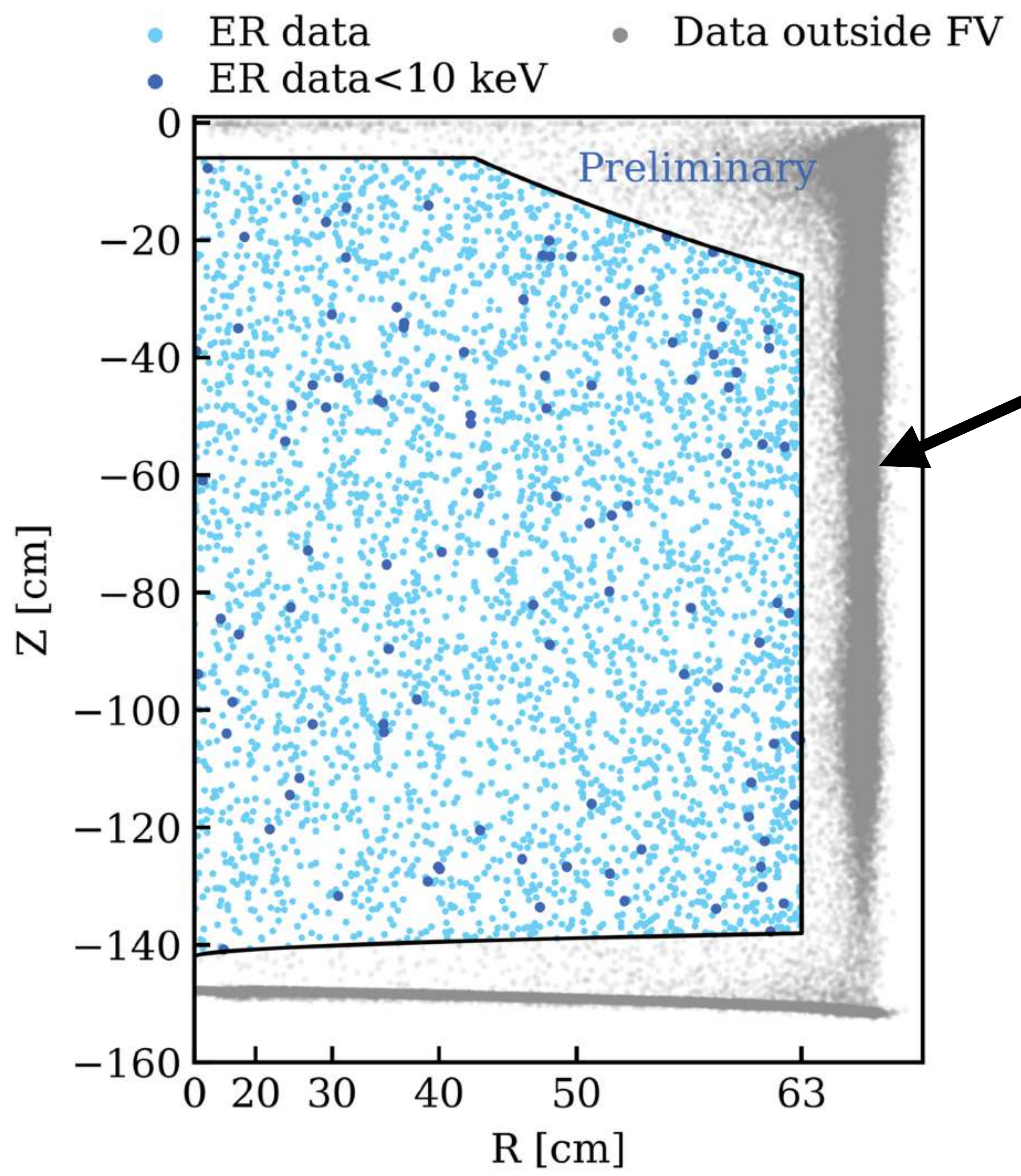


Data-Quality Cuts

- Events are required to pass a range of quality cuts:
  - The S1 and S2 peaks are consistent with real events
    - Patterns, top/bottom ratios, time width, ⋯
  - S1 >= 3 PMTs
  - S2 > 500 PE
  - Not within $< 300\ ns$ of a neutron veto event
  - Events are within ER region of S1-S2 distribution
- Fiducial volume cut selects a mass of (4.37 ± 0.14) tonnes with low backgrounds

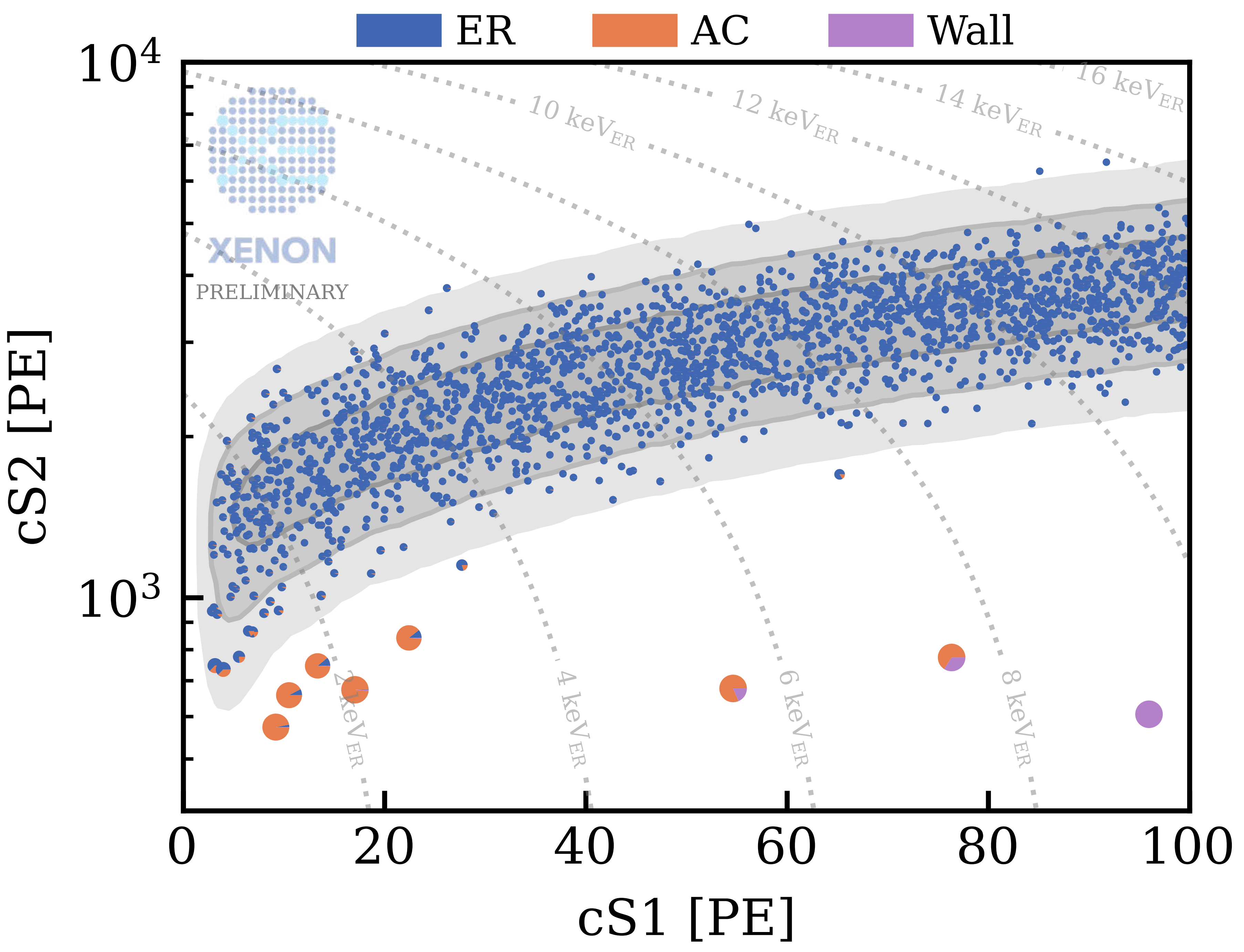
→ 1.16 tonne – year (×2 larger FV w.r.t 1T)

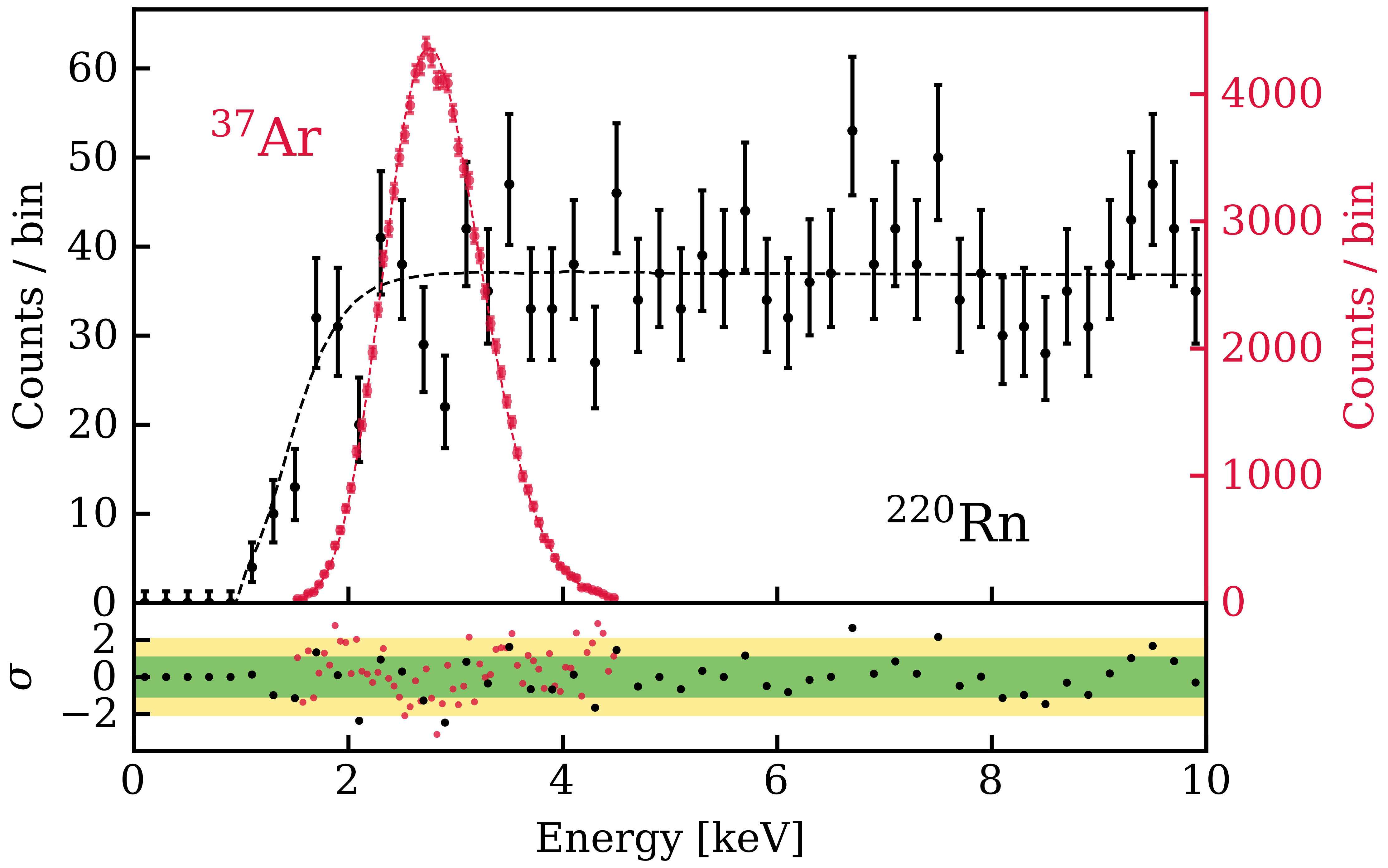




Events passed all the cuts except for the FV cut (gamma-ray from materials)

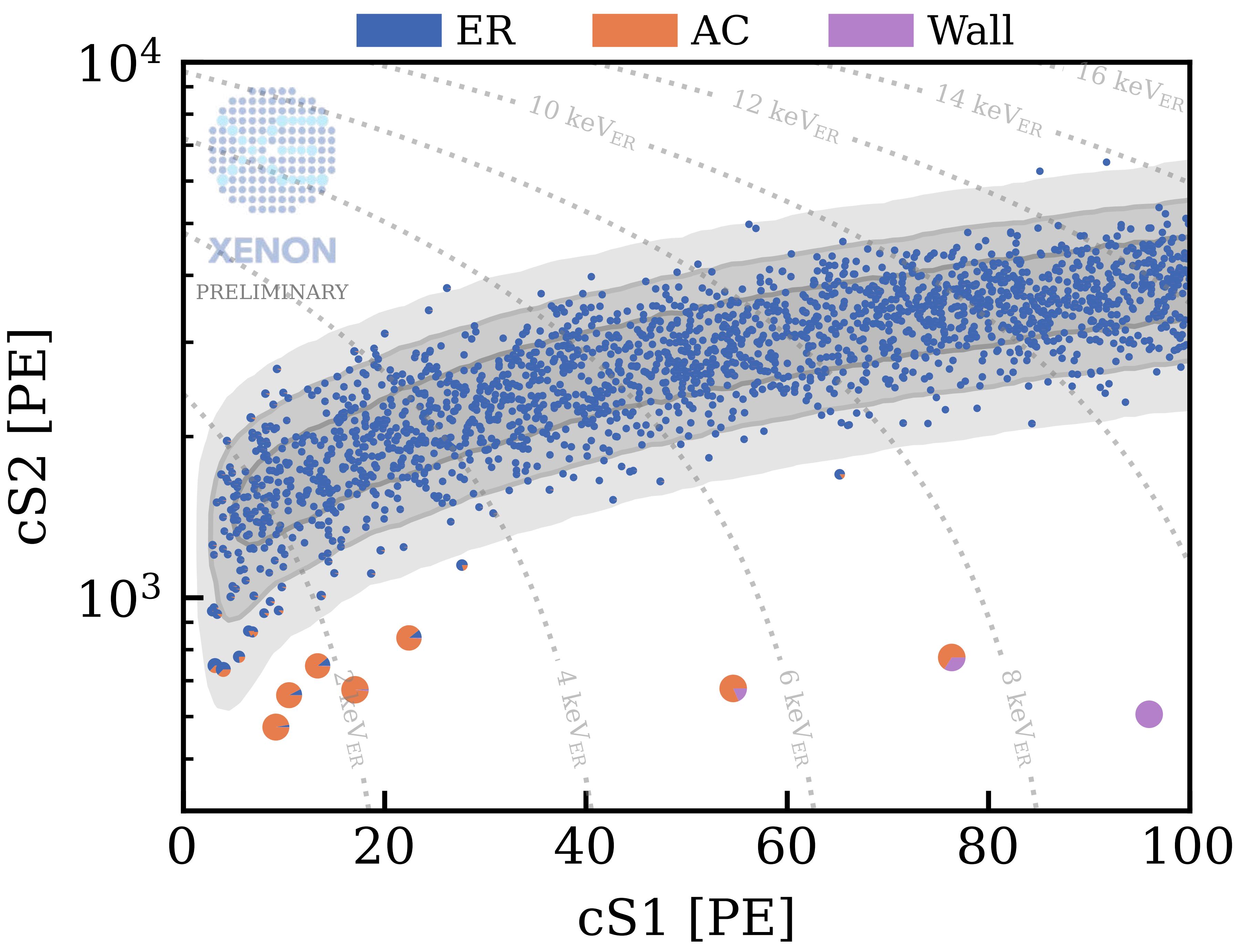
Low-Energy Calibration using ^{220}Rn and ^{37}Ar

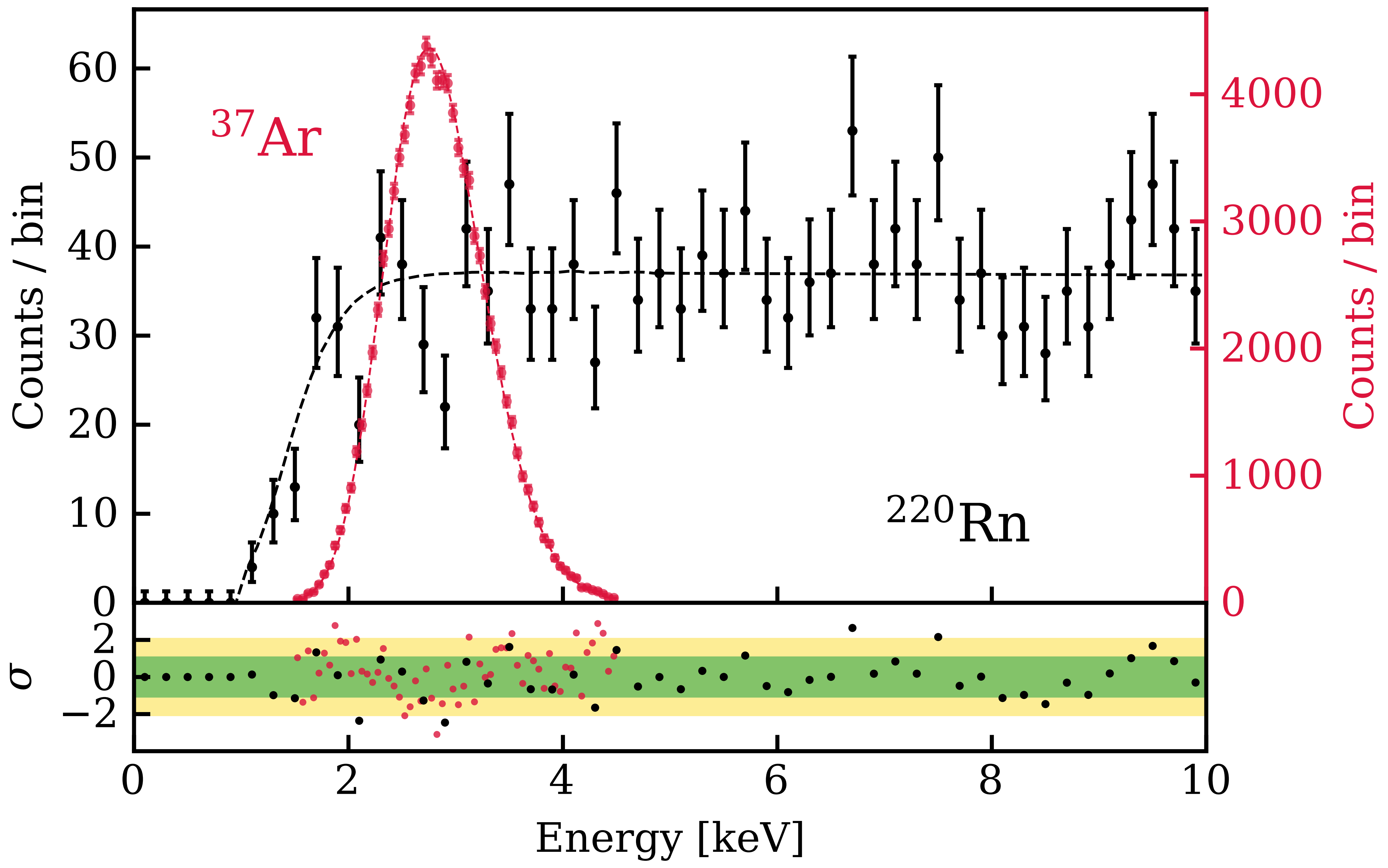




- At low energy, we have two ER calibration sources:
  - $^{37}\mathrm{Ar}$, which gives mono-energetic $2.82\ \mathrm{keV}$peak used to anchor the low-energy response and resolution models with high statistics
  - $^{212}\mathrm{Pb}$ from $^{220}\mathrm{Rn}$ gives a roughly flat β-spectrum to estimate cut acceptances and also validates our threshold.

Low-Energy Calibration using ^{220}Rn and ^{37}Ar





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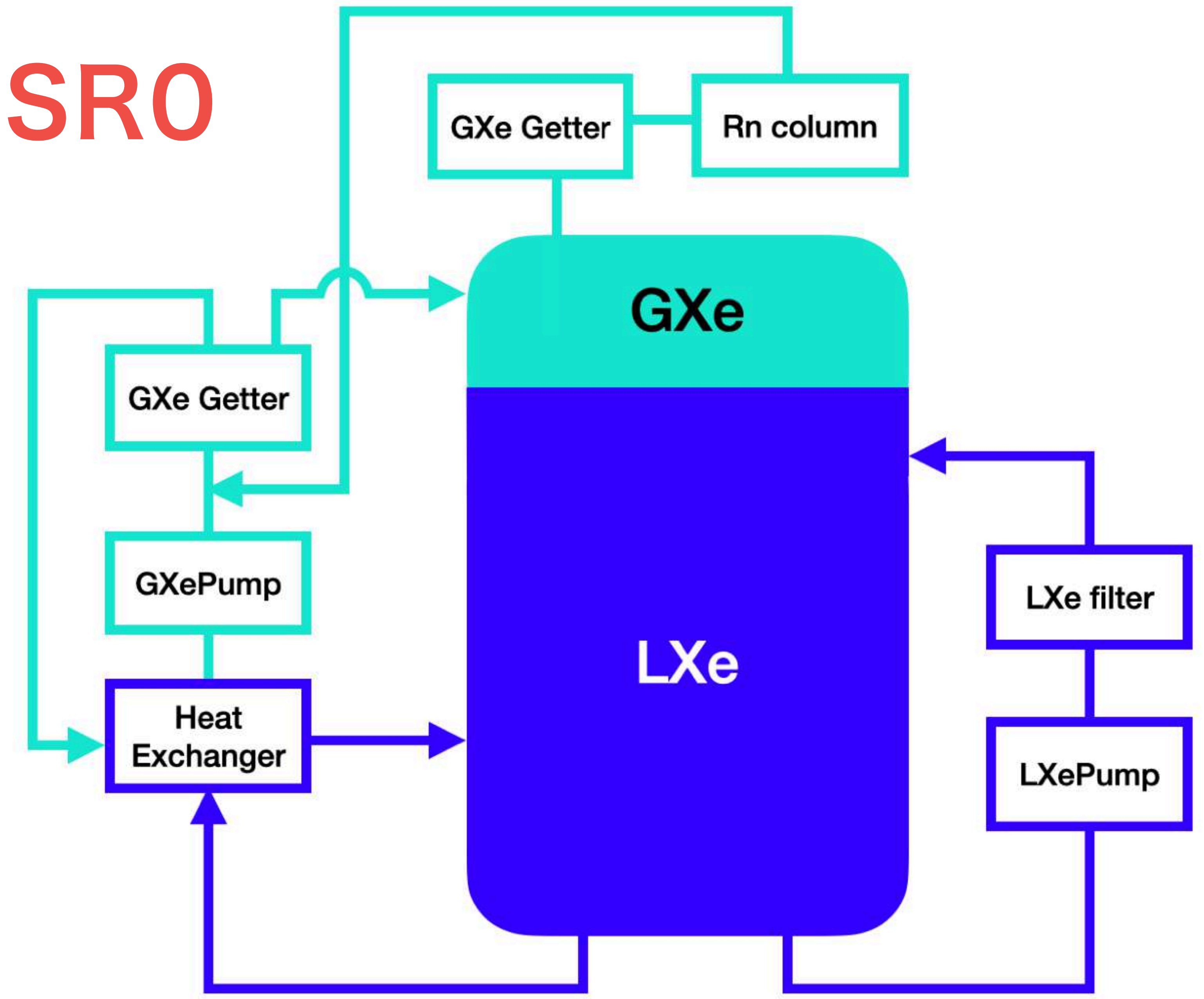
Good agreement between data and our models!

Tritium

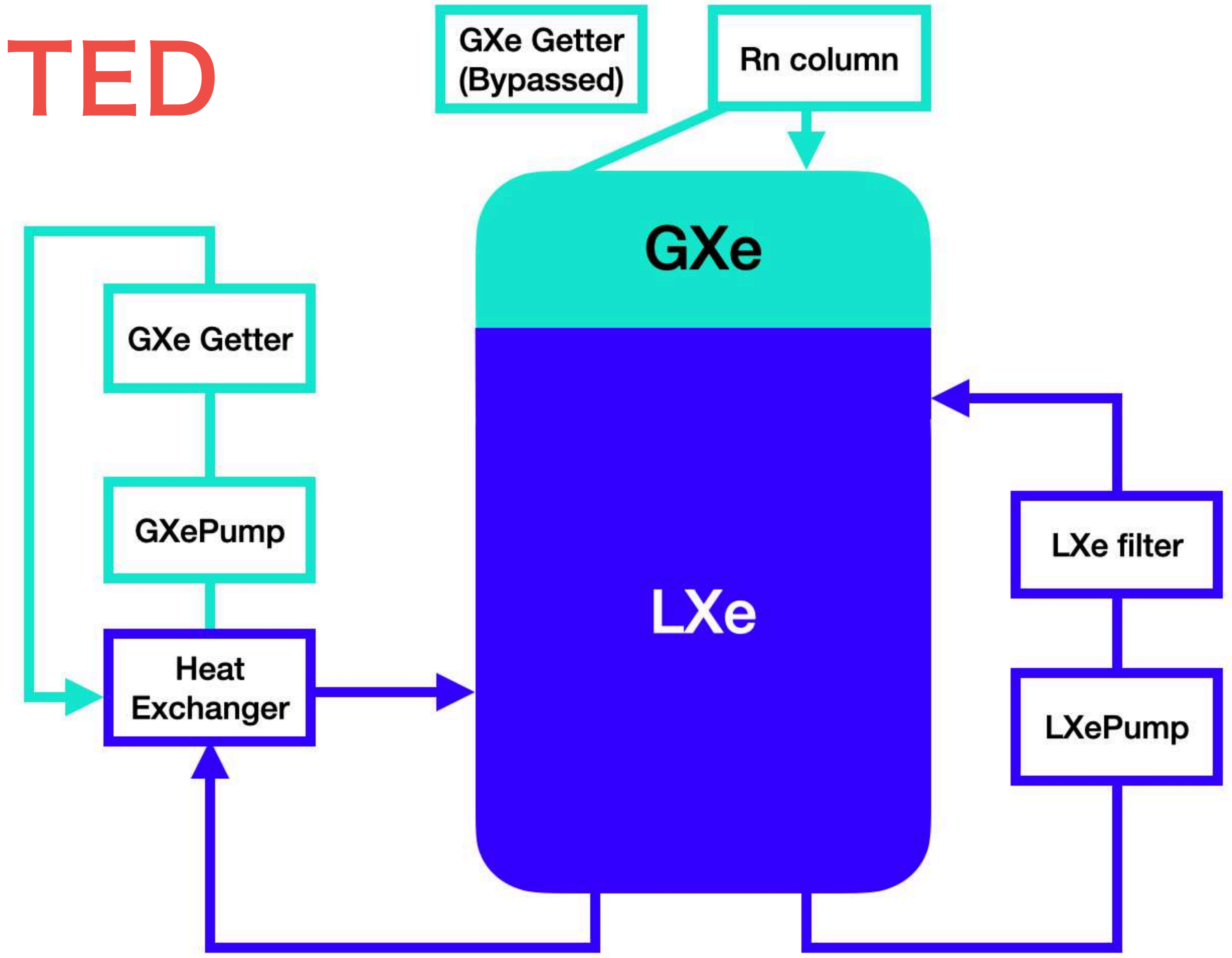
- XENONnT went through significant efforts to reduce possible sources of a low-energy excess
  - Outgassing: 3 months
  - Warm GXe cleaning : 3 weeks
- All new xenon was passed Kr distillation: HT removed too
- GXe was purified with hot getters + H2 removal units at detector filling

SR0



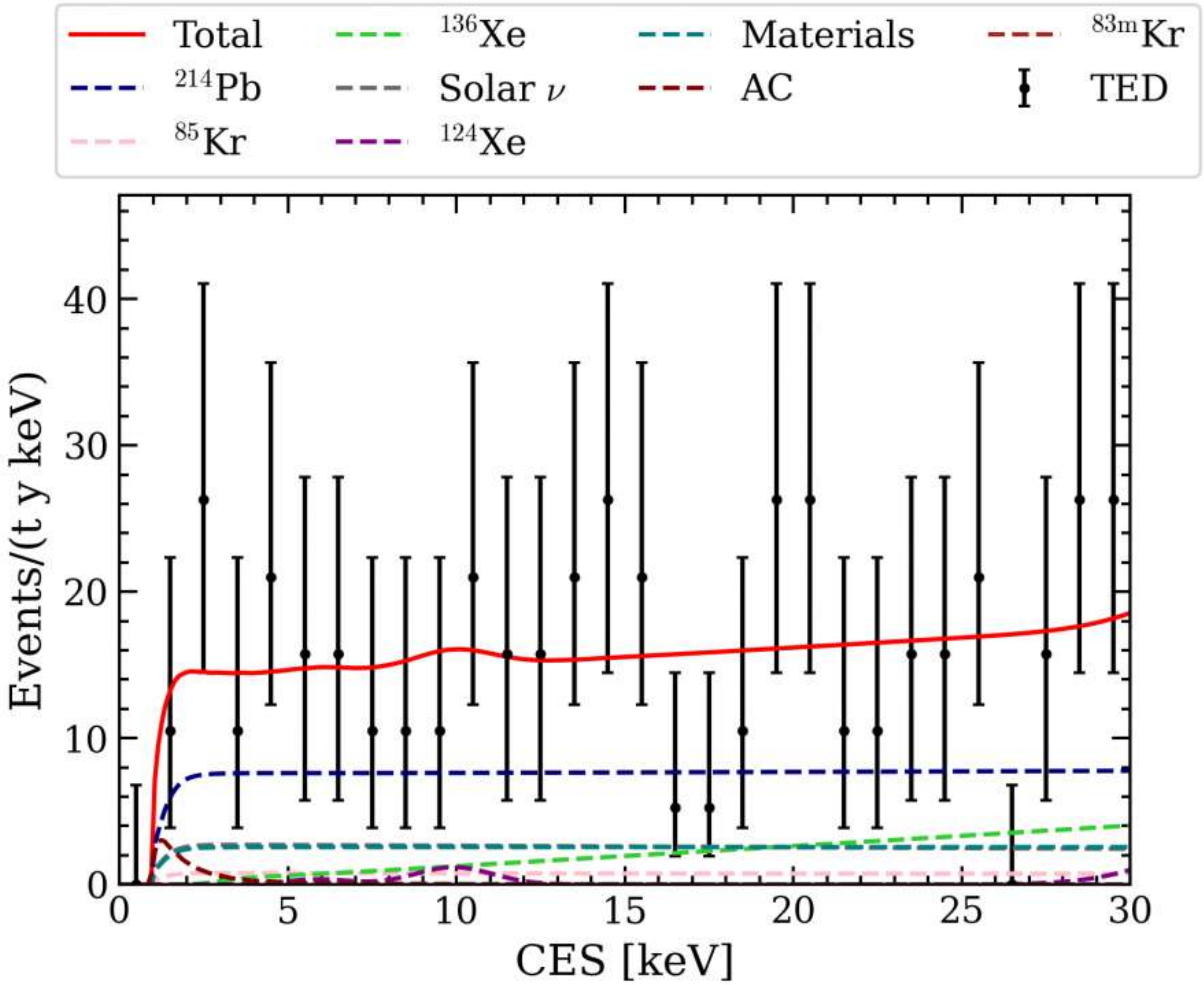
- After the SR0, “Tritium enhanced data” (TED) bypassing getters was taken.
  - orders of magnitude increase in hydrogen concentration (conservative – at least 10x)
- 14.3 days of TED data was analyzed before unblinding SR0

TED

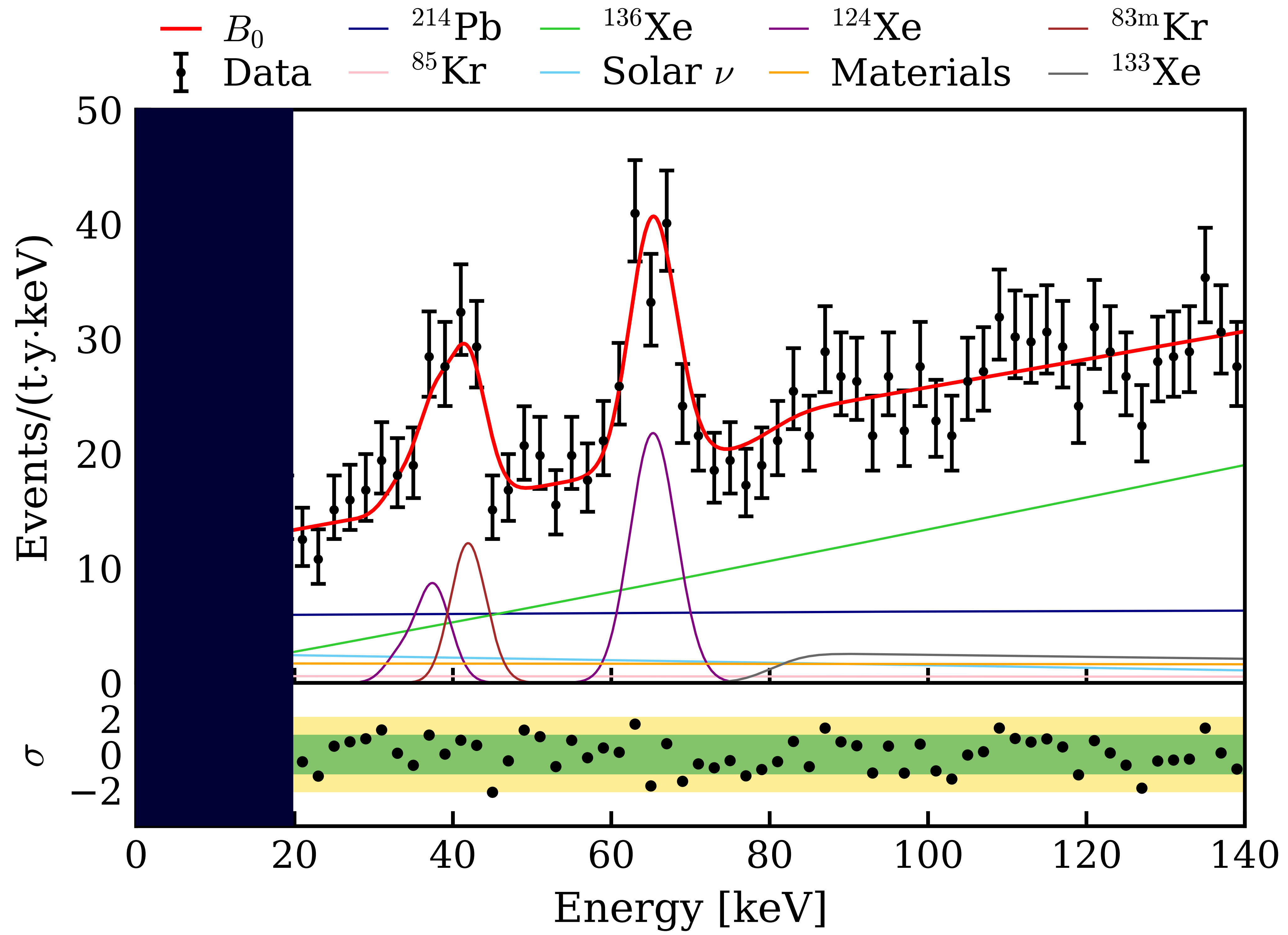


Tritium

- Result of blind TED analysis:
  No tritium observed
- → Tritium is not considered in the BG model



ER Backgrounds

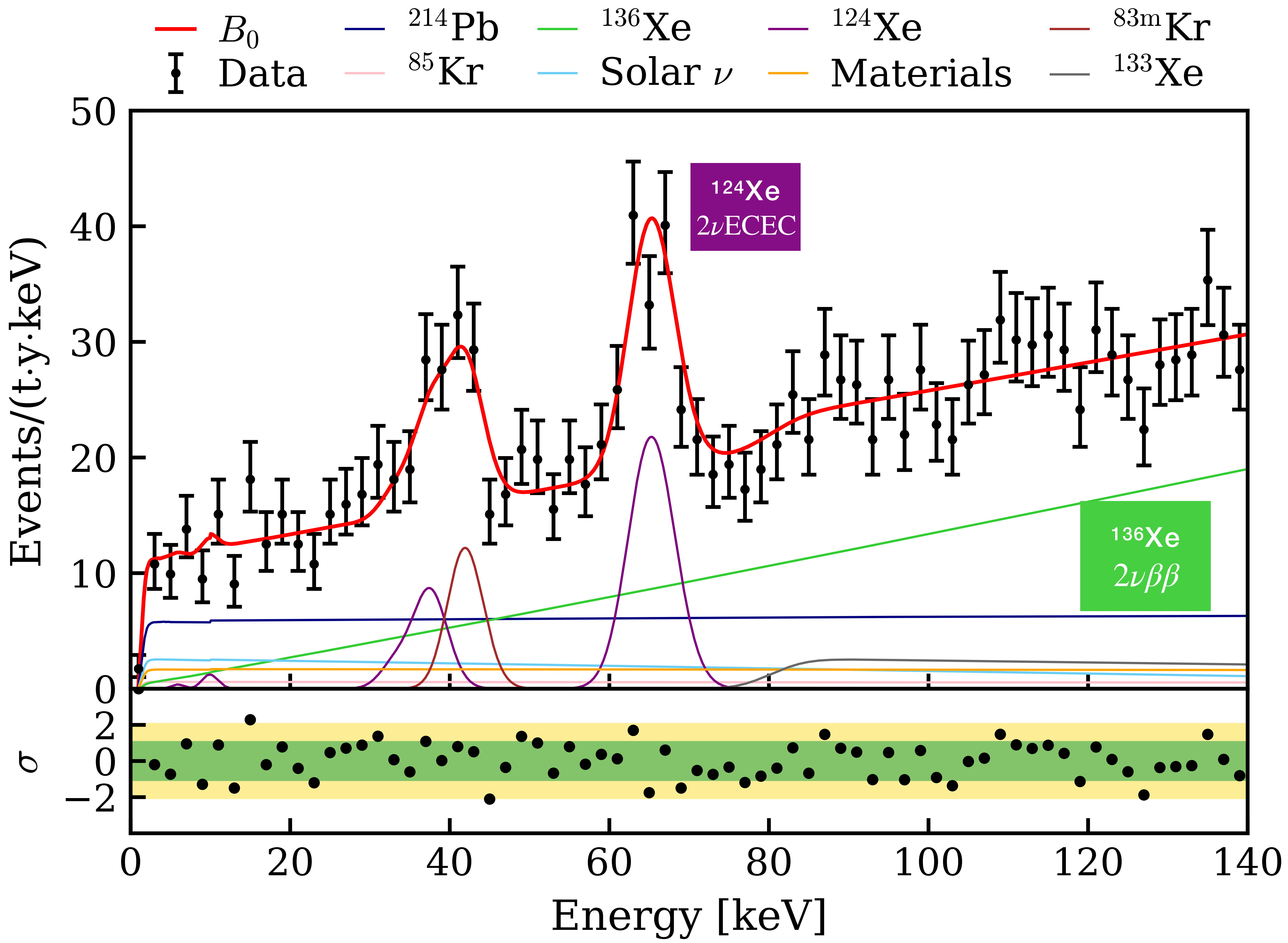


	Number of events in ER band 1-140 keV	Expected < 10 keV
^{214}Pb	980 ± 120	56 ± 7
^{85}Kr	91 ± 58	5.8 ± 3.7
Materials	267 ± 51	16.2 ± 3.1
^{136}Xe	1523 ± 54	8.7 ± 0.3
Solar neutrino	298 ± 29	24.5 ± 2.4
^{124}Xe	256 ± 28	2.6 ± 0.3
Accidental coincidence	0.71 ± 0.03	0.71 ± 0.03
^{133}Xe	163 ± 63	0
^{83m}Kr	80 ± 16	0

- The low-energy ER spectrum is dominated by ^{214}Pb, plus contributions for materials, ^{136}Xe and solar neutrinos.
- External constraints are included for
  - ^{85}Kr, 2×10^{-11} of (56 ± 36) ppq using RGMS
  - material gammas, (2.1 ± 0.4) events/(t × yr × keV) from GEANT4 and screening measurements
  - ^{136}Xe from RGA and $T_{1/2}$ measurements
  - solar neutrinos have a 10% rate uncertainty given the Borexino measurements of the flux.

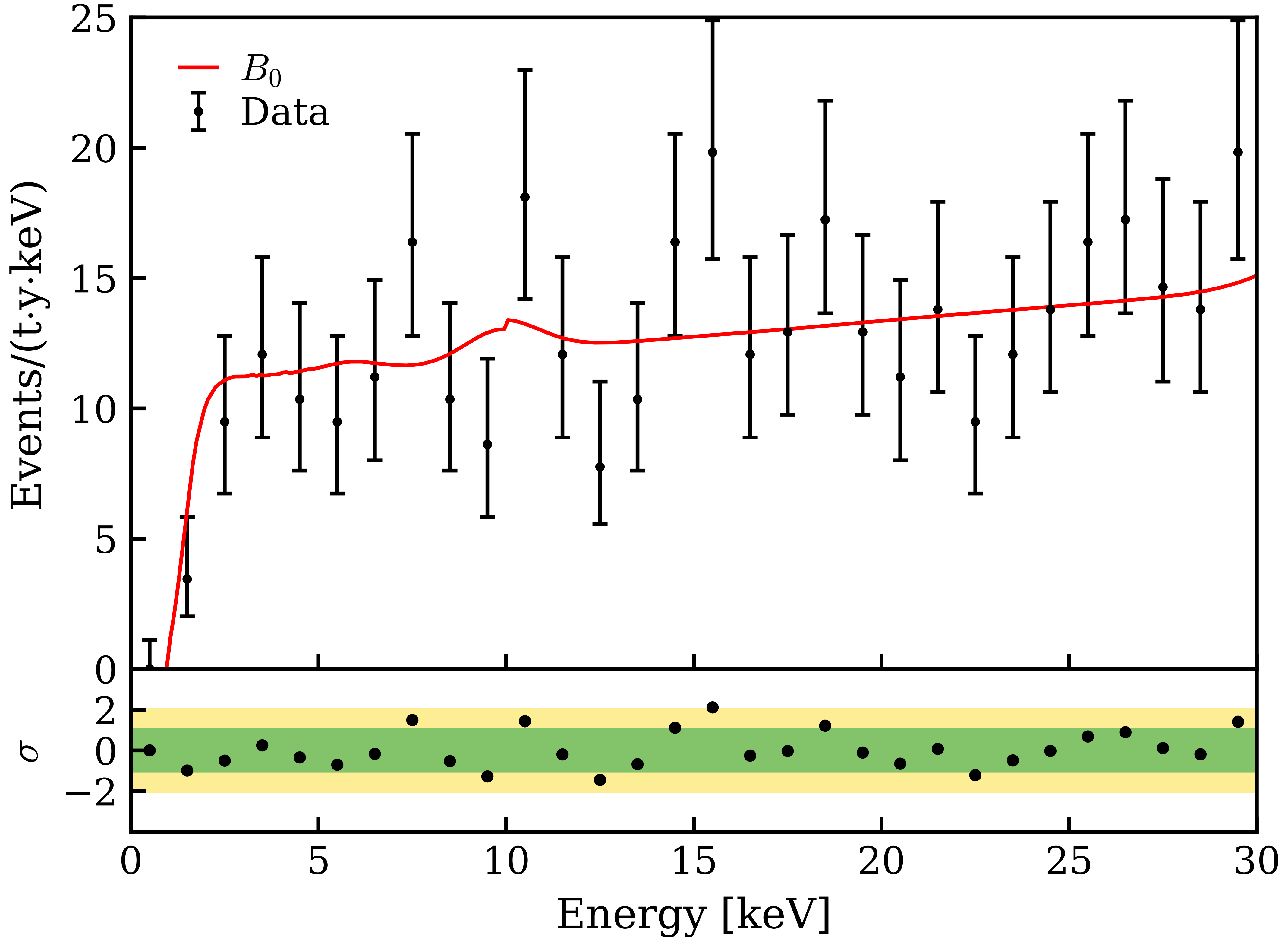
Results of analysis

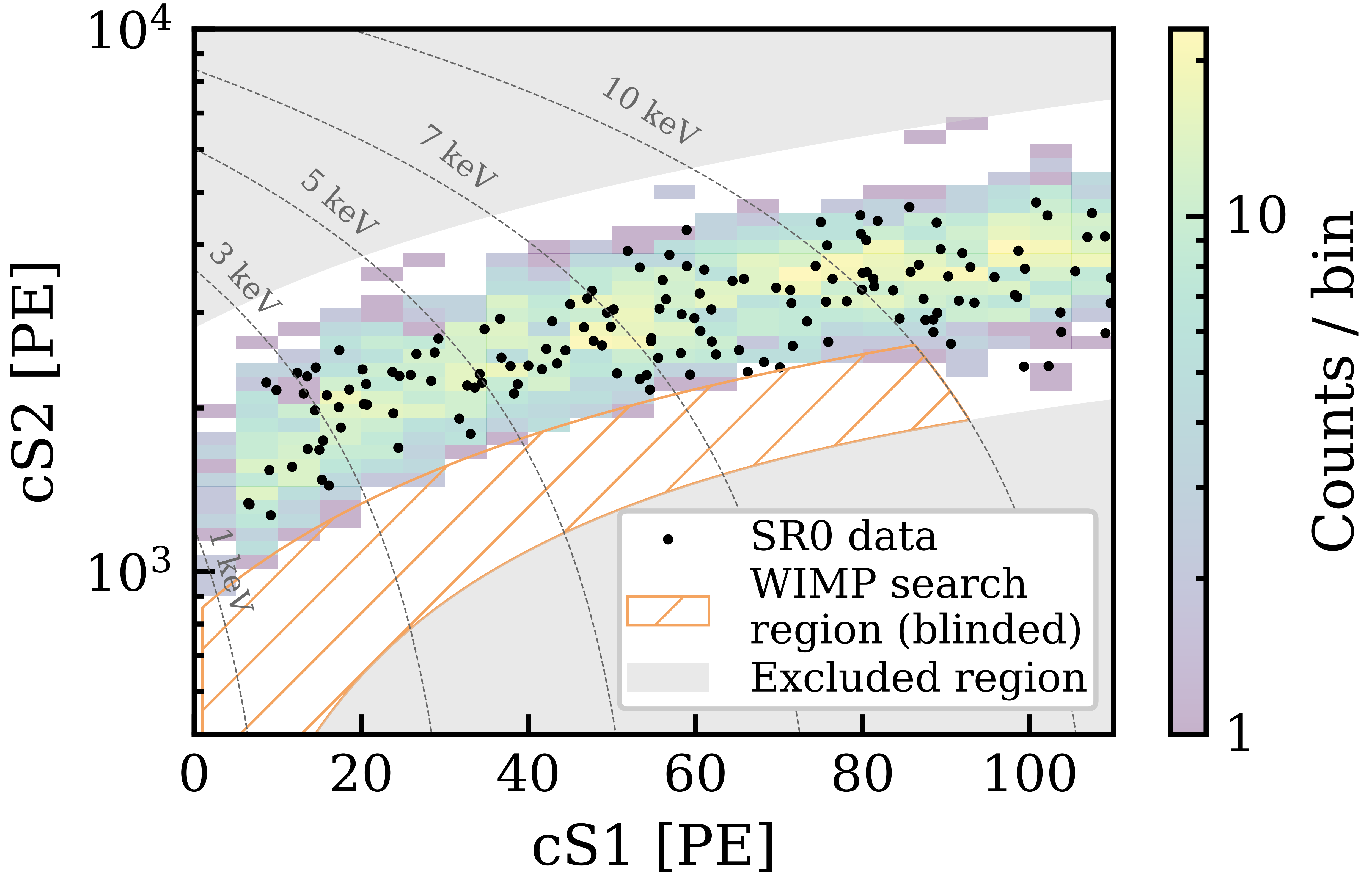
ER Spectrum after Unblinding



- Data agree with background only model in the whole energy range
- No Excess is found in the low energy region!
- Double weak processes from Xe124 and Xe136 start to dominate the background, and useful to validate our models

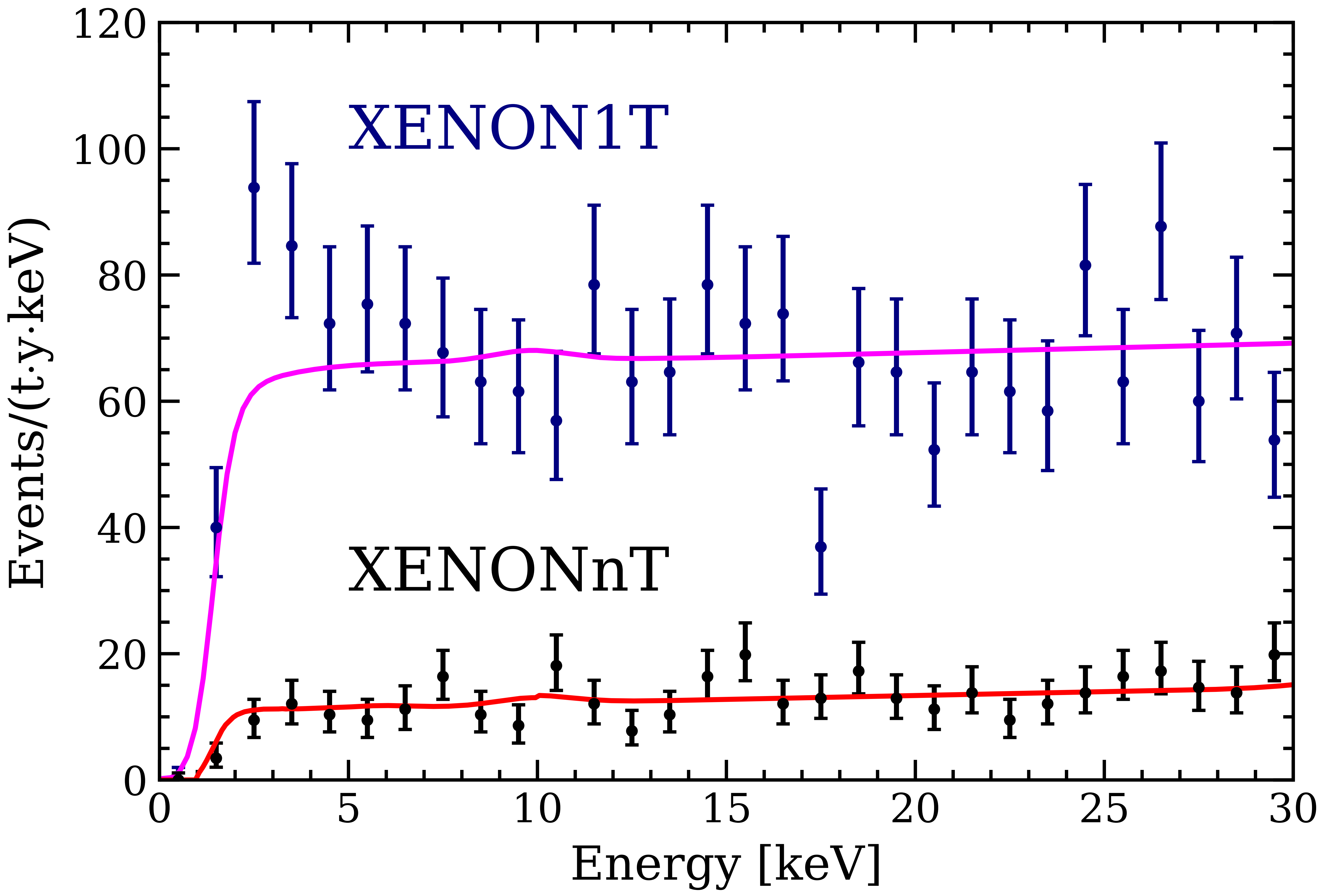
ER Spectrum below 30 keV





- Lowest BG level ever achieved: (16.1 ± 0.3) events/(t × yr × keV)
- WIMP ROI is still blinded

XENONnT vs XENON1T



Exposure:
1.16 tonne – years

$\sim \times 2$ XENON1T ER search (0.65 tonne-years)

Background rate:
(16.1 ± 0.3) events/(t × yr × keV)
in 1-30 keV range

$\sim \times 0.2$ XENON1T

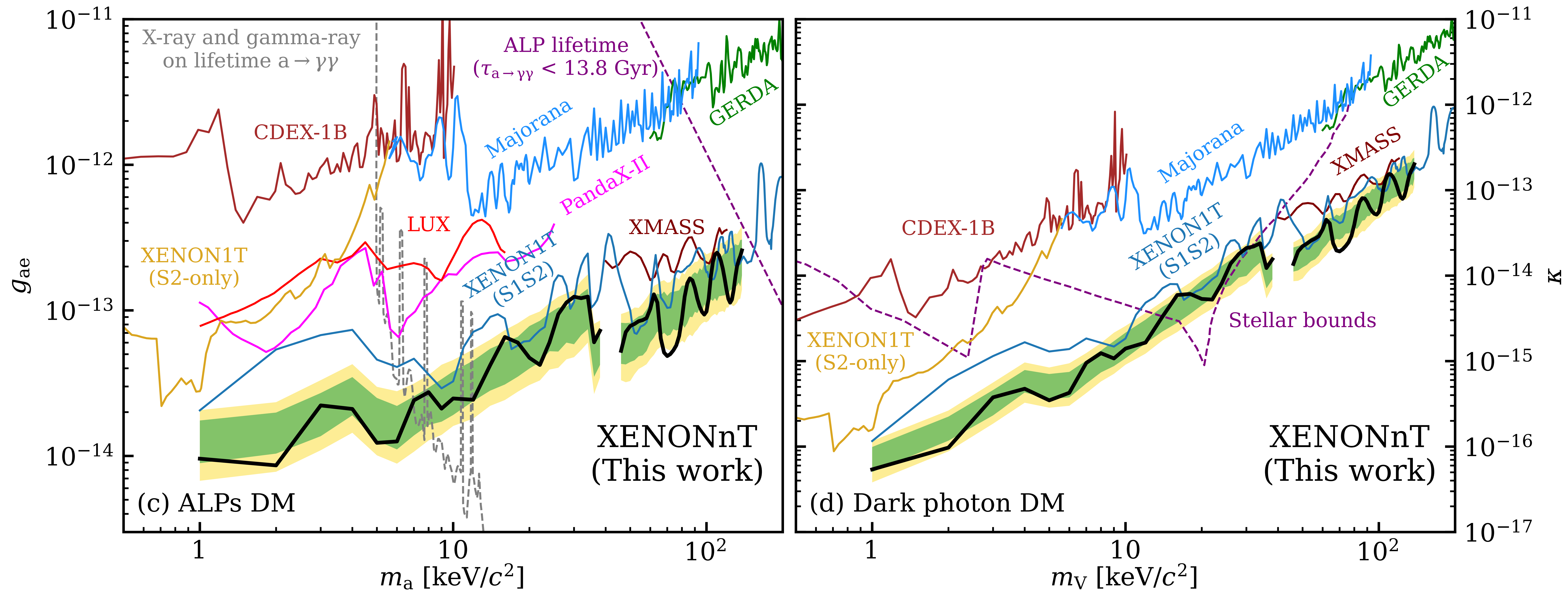
Best-fit signal strength:
0

Exclusion of XENON1T excess (2.3 keV) peak.

Measurements incompatible at ~4σ

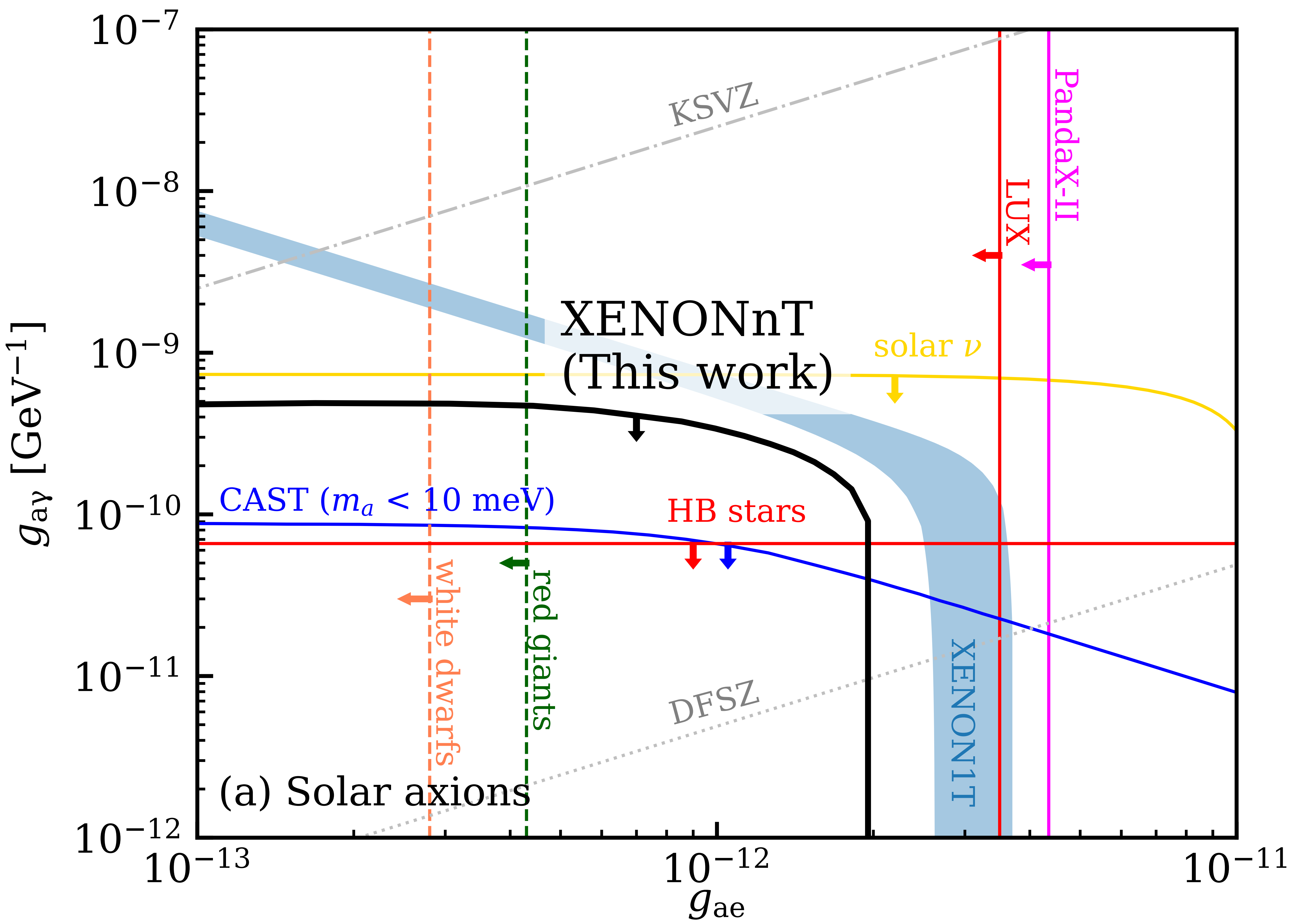
Most likely, the explanation of XENON1T excess is a small tritium contamination.

Limits on Axion-Like Particle & Dark Photon



- A search for a peak from ALP or dark photons sees no significant excess → new stringent limits between 1-140 keV (No limit around 41keV: ^{83m}Kr left unconstrained)
  - Astrophysical limit on ALP: Takahasi et al, Phys. Lett. B 734 (2014) 178; R. Z. Ferreira et al, Phys. Rev. Lett. 128, 221302 (2022)
  - Astrophysical limit on DP: H. An et al, Phys. Lett. B 747, 331 (2015)

Limits on Solar-Axions



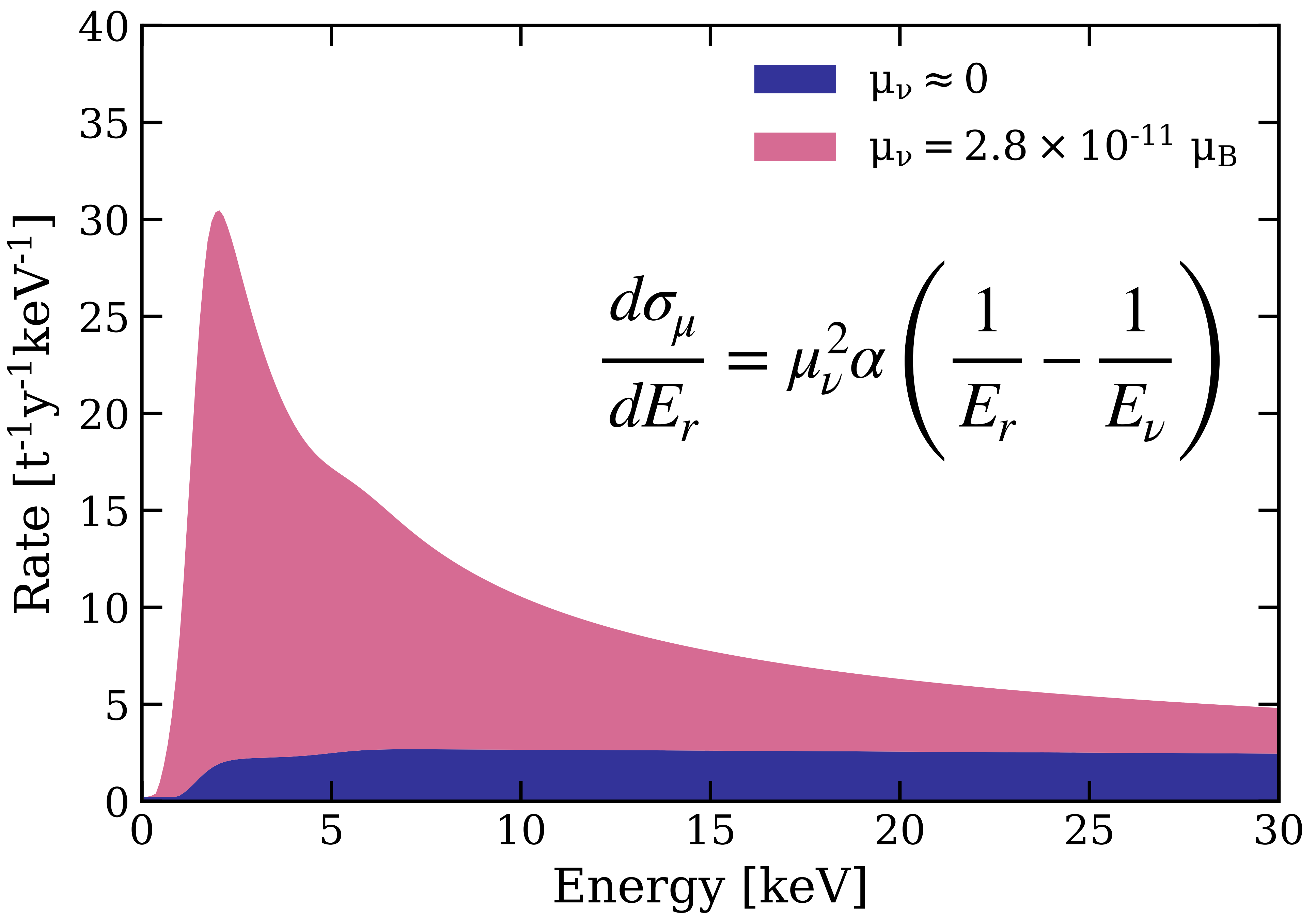
Valid for masses up to ~100 eV

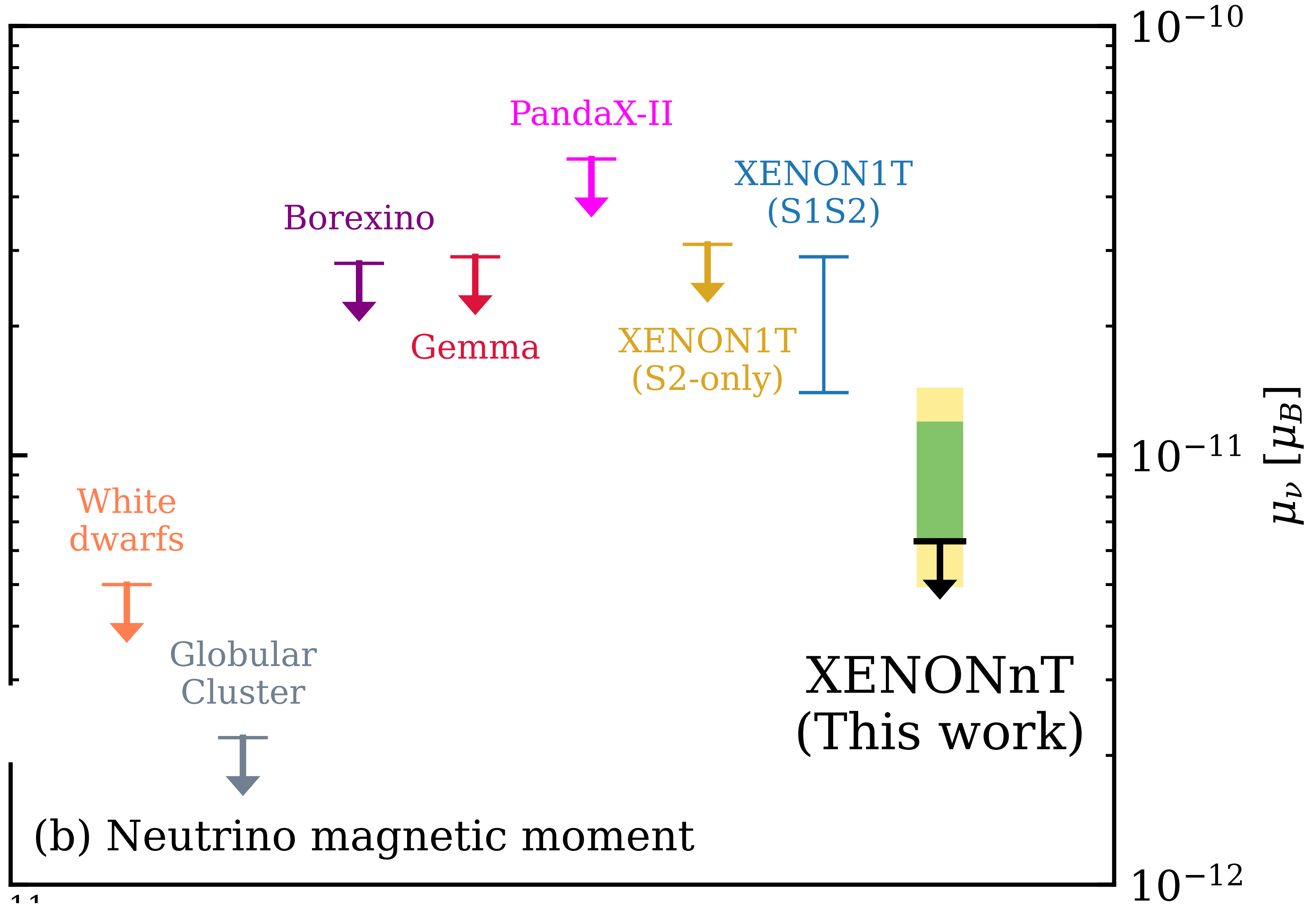
astrophysical constraints from stellar cooling

(arXiv:2003.01100)

- New limits on the axion-electron, γ and nucleon couplings.
  - Detection based on axio-electric effect and Inverse Primakoff effect; described by g_{ae}, $g_{a\gamma}$, g_{an}
- 90% upper limit on ^{57}Fe solar axion component is $20.4\ \mathrm{events/(t \times yr)}$

Limits on Neutrino Magnetic Moment



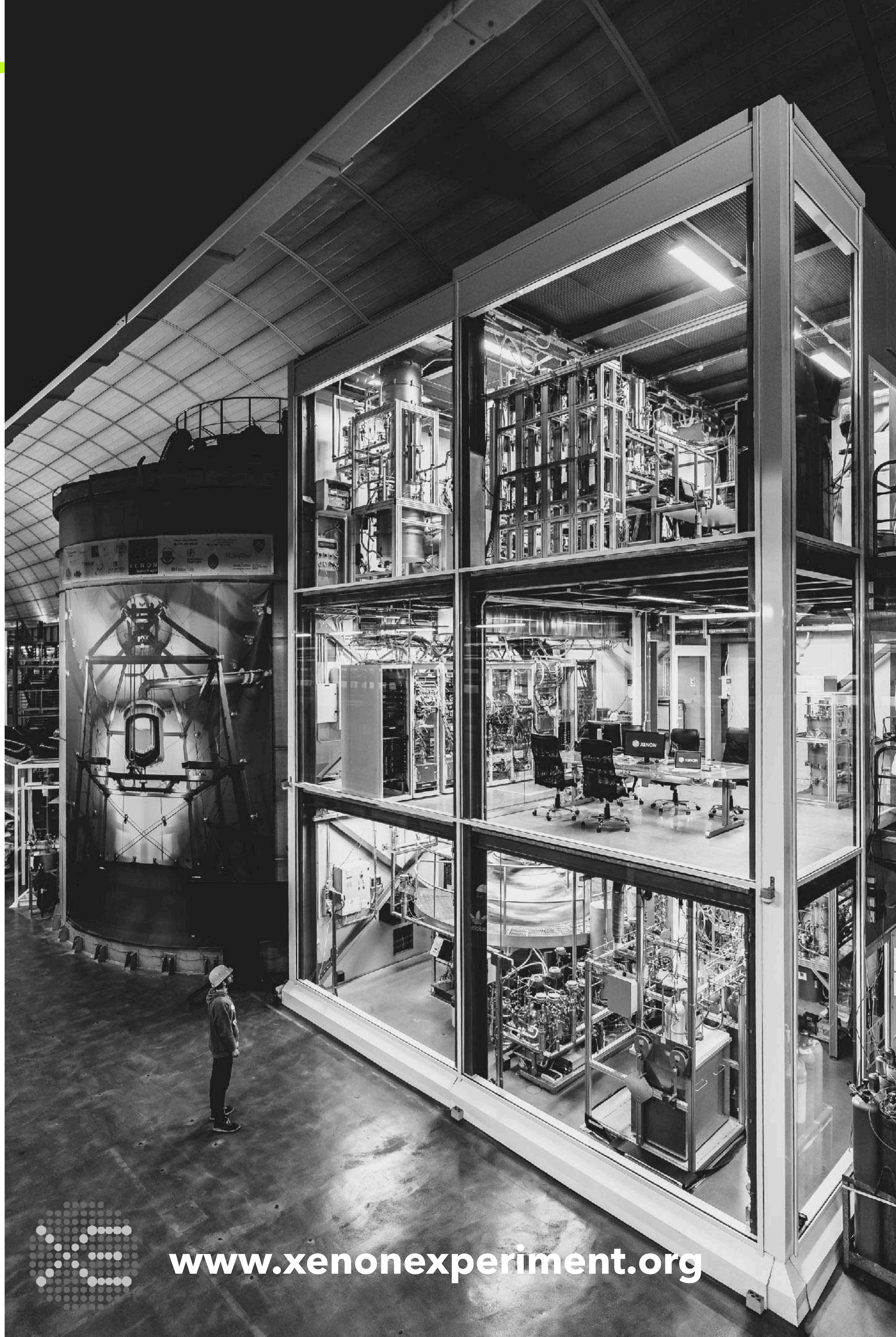


- A magnetic moment is implied by neutrinos being massive ($\mu_\nu \sim 10^{-20}\mu_B$)
- If new physics raises this magnetic moment, it may cause an enhanced neutrino scattering rate
- Upper limit at $\mu_\nu < 6.3 \times 10^{-12}\mu_B$

Summary

- The XENONnT is successfully constructed and commissioned
  - Achieved lowest BG for LXe TPC: (16.1 ± 0.3) events/(t $\times$ yr $\times$ keV)
- Fully blinded analysis of electronic recoil data:
  - No excess observed from 1 to 140 keV
  - Incompatible to XENON1T excess ~4 σ
- New world leading limits on solar-axions, ALPs and DPs as well as neutrino magnetic moment are set
- XENON1T excess is most likely due to the small tritium contamination
- Now the paper is on arXiv: 2207.11330
- NR WIMPs analysis is in progress:

Stay tuned, WIMPs search results to come!



Back Up