Search for new physics with XENONnT

Carla Macolino

NOW Conference 2022
10.09.22

The XENON collaboration

~170 scientists, 27 institutions

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~170 scientists, 27 institutions

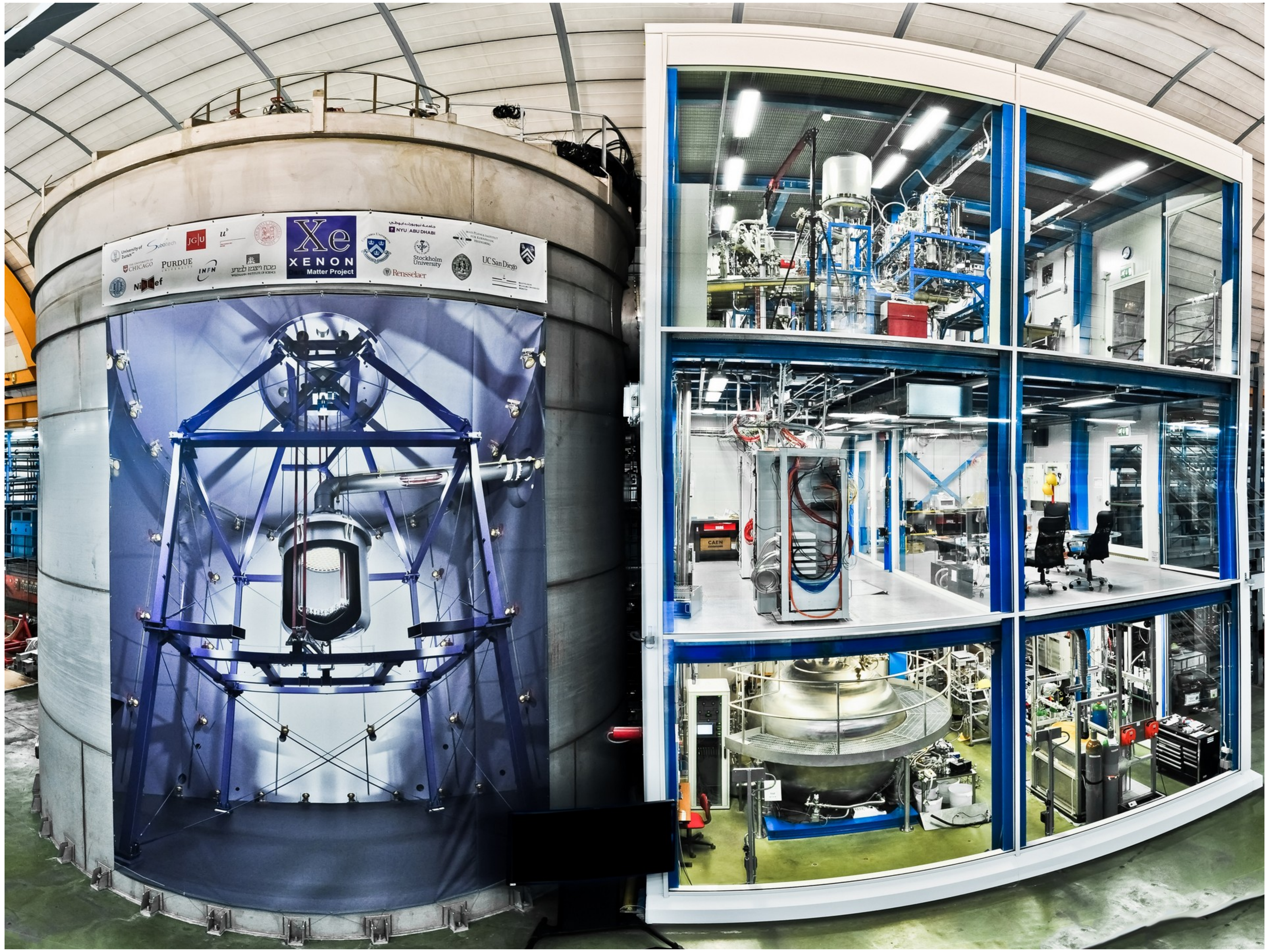
Columbia | KIT | Nikhef | Muenster | Stockholm | Mainz | MPIK, Heidelberg | Freiburg | Zurich

Chicago | UCSD | Rice | Purdue

Tsinghua | Tokyo | Nagoya | Kobe

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

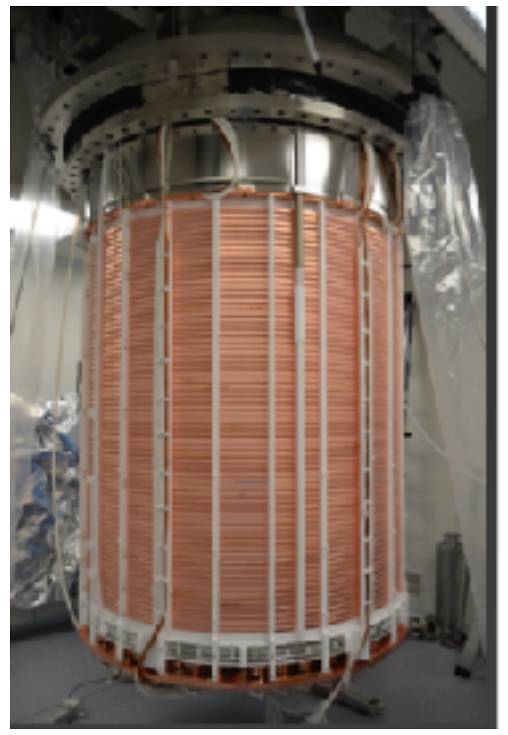
The XENON project at Gran Sasso




XENON10
2005—2007


XENON100
2008—2016


XENON1T
2012—2018


XENONnT
2019—2025

Sensitivity improvement

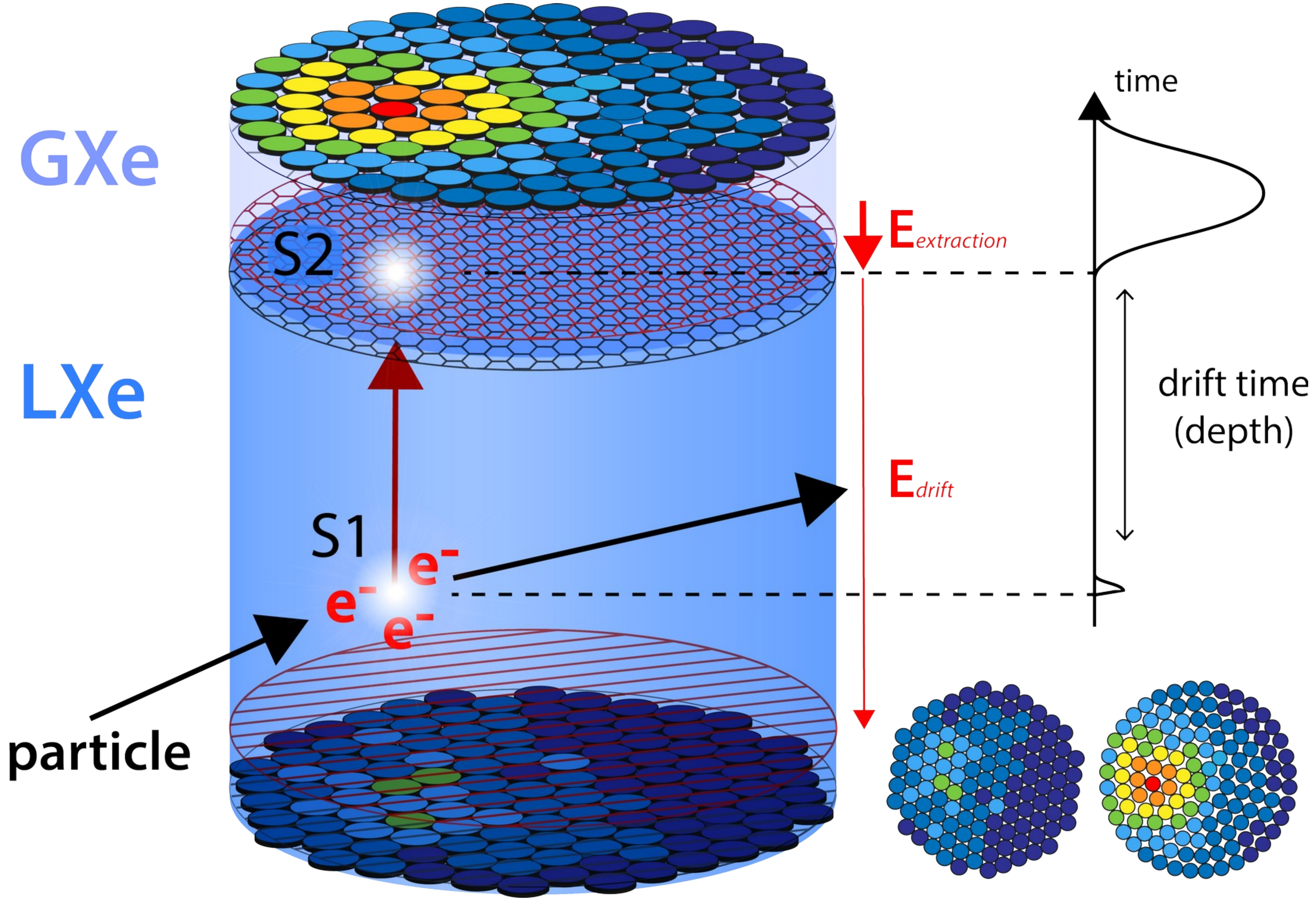
All the detectors of the XENON project located in the Gran Sasso laboratories

1.4 km rock coverage
(3800 m w.e.)

1e6 muon flux reduction

Dual-phase XENON TPC

Optimal technique for detection of dark matter search and rare events



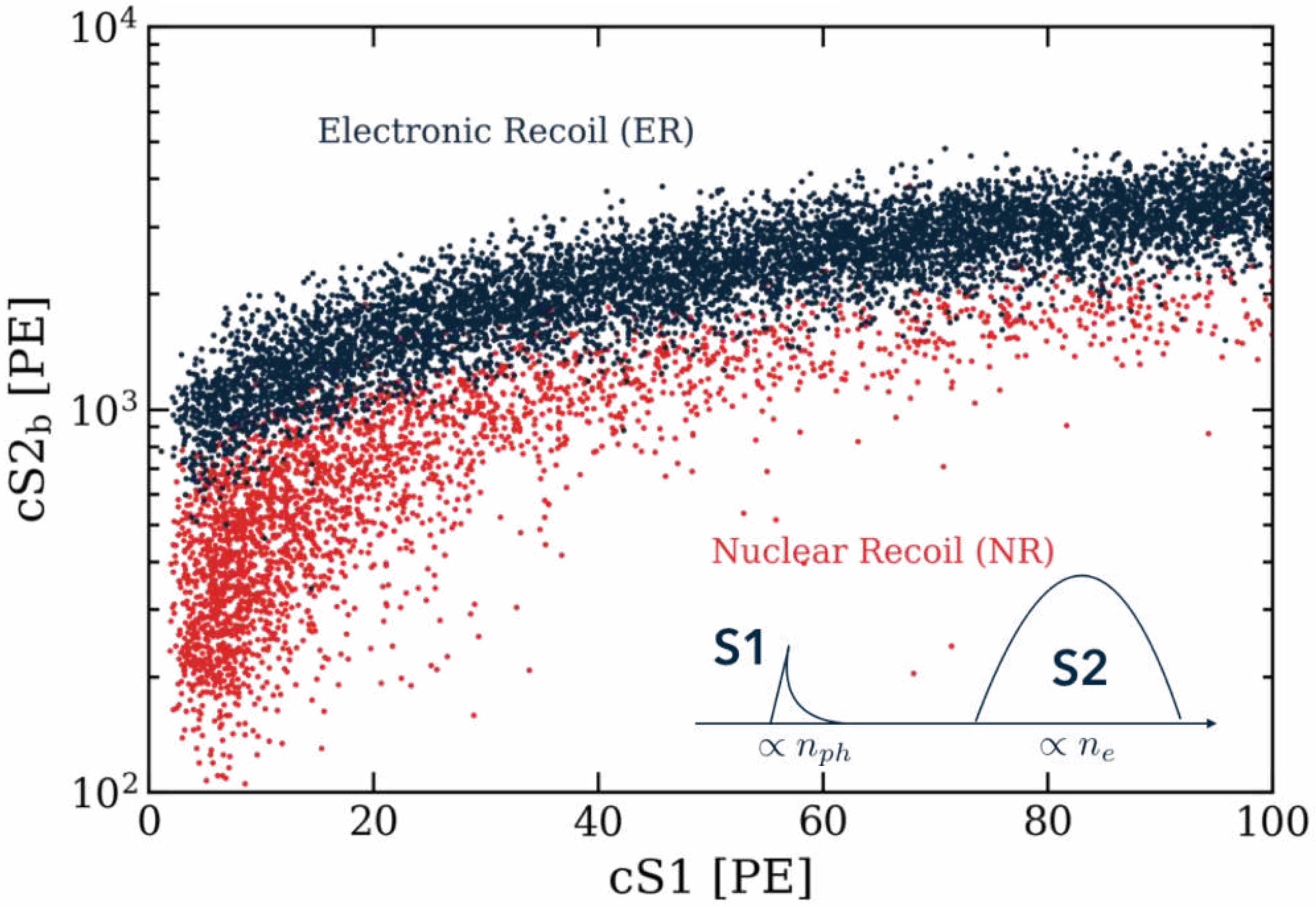
S1 prompt scintillation
S2 proportional to ionization

S2/S1 to discriminate nuclear recoils (NR) from electronic recoils (ER)

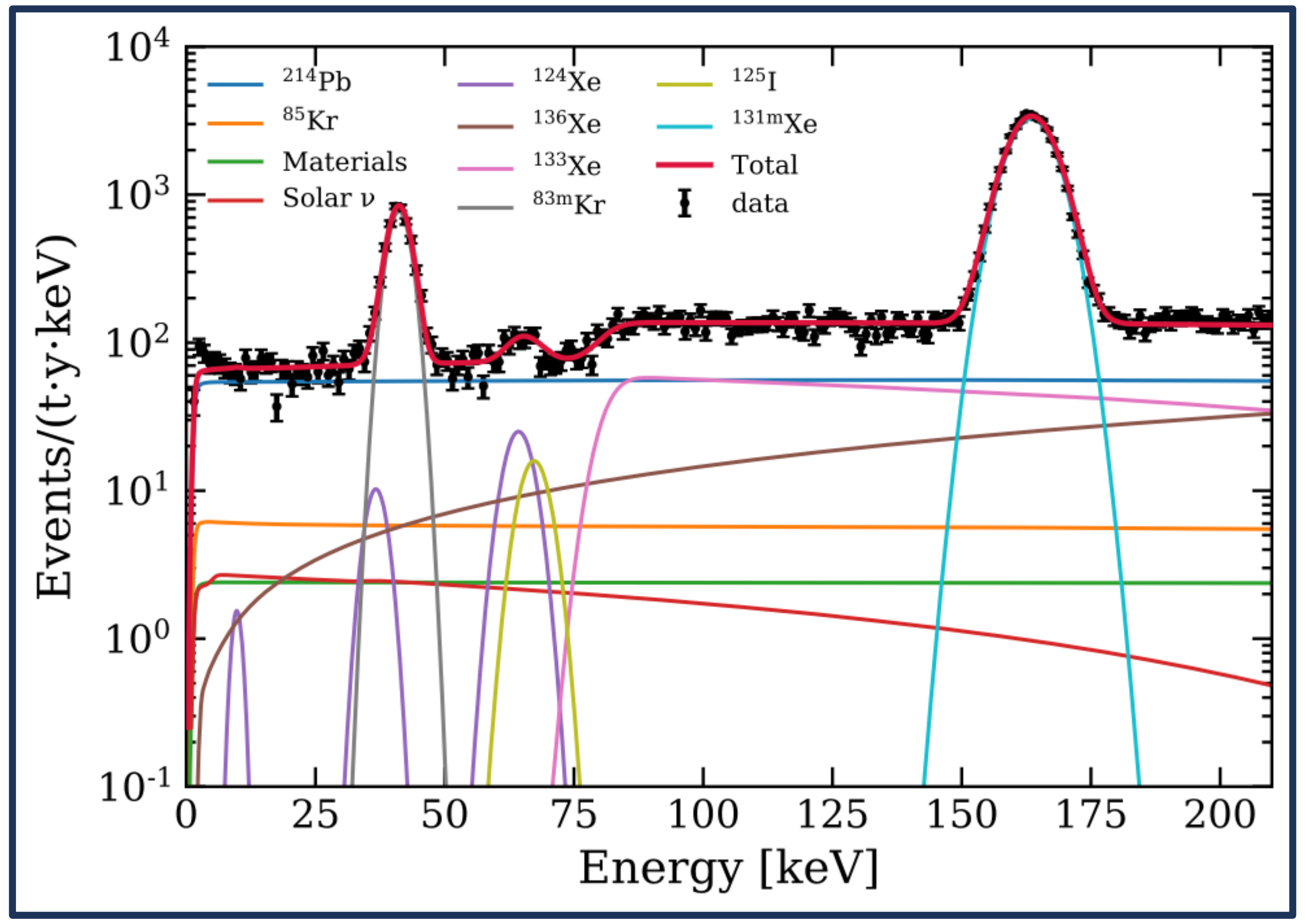
3D position reconstruction

Low energy threshold

Energy reconstruction combining S1 and S2



The XENON1T excess



NEW PHYSICS OR UNEXPECTED BACKGROUND?

Phys. Rev. D 102, 072004

3.2σ TRITIUM BACKGROUND

- Fitted concentration: (6.2±2.0) × 10^{-25} mol/mol ^{3}H/Xe
- We don't expect that much ^{3}H from liquid purity
- Very difficult to confirm or exclude such a tiny abundance

3.4σ SOLAR AXIONS

- Non-null coupling to electrons → ABC and/or Primakoff
- Strong tension with astrophysical constraints
- Axions+^{3}H favoured over ^{3}H-only at 2.1 σ

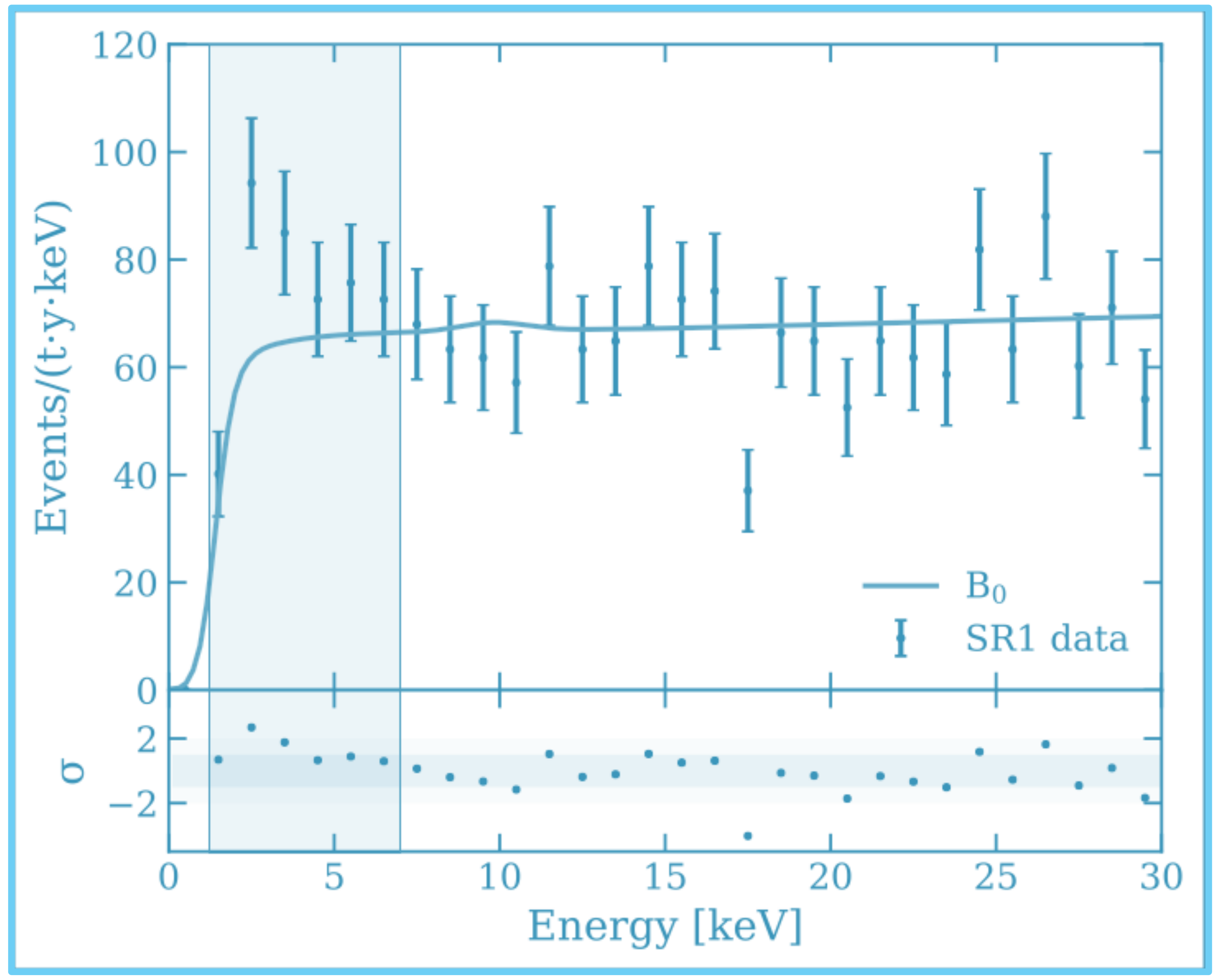
3.2σ NEUTRINO MAGNETIC MOMENT μ_ν

- μ_ν = [1.4, 2.9] × 10^{-11} μ_B
- μ_ν > 10^{-15} would imply neutrinos to be Majorana fermions
- Tension with astrophysical constraints

3.0σ BOSONIC DARK MATTER

- Including pseudo-scalar (ALPS) and vector (dark photons) bosons
- Most restrictive constraints to date set

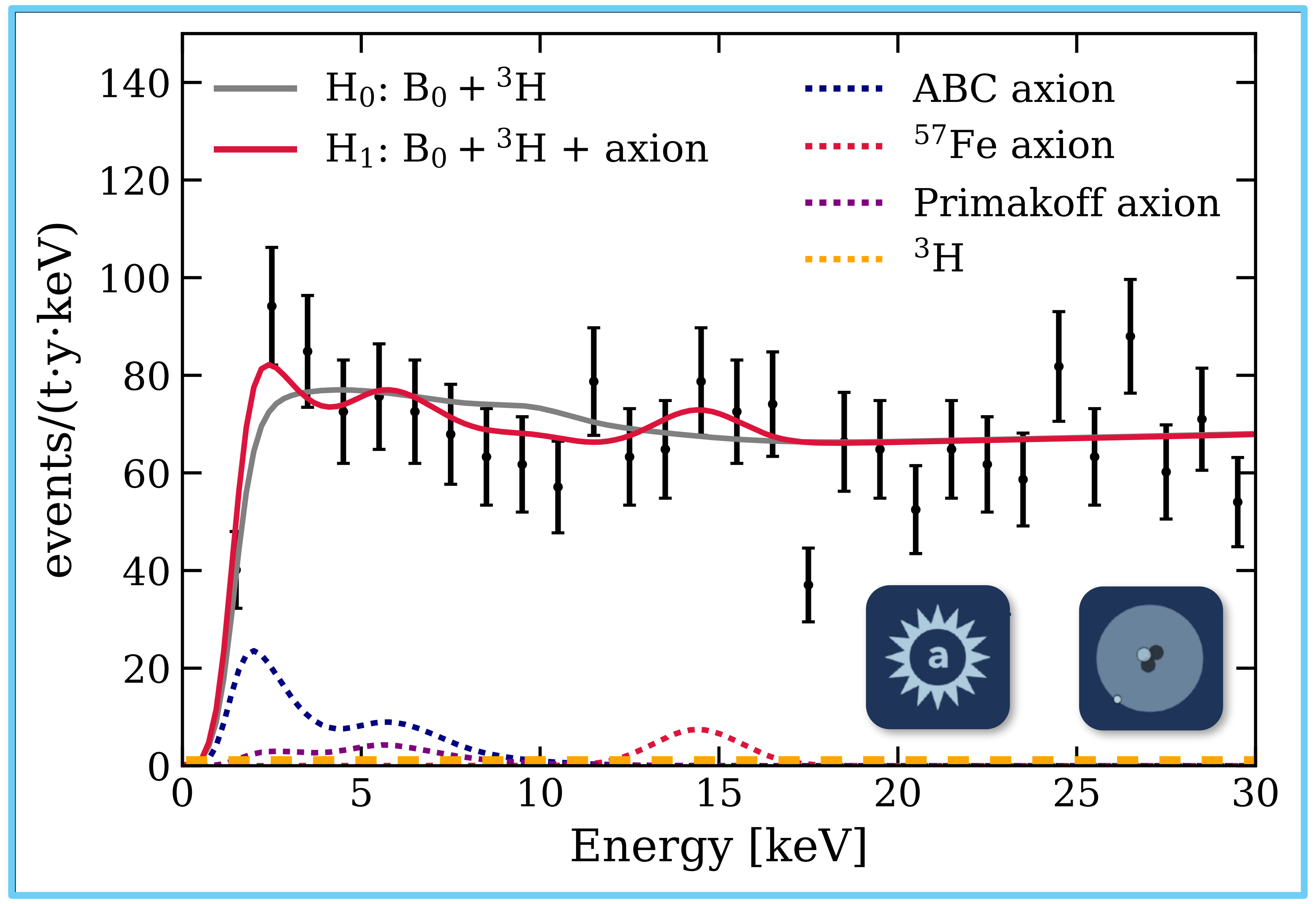
- ^{37}Ar would be removed by the online Kr distillation. The necessary air leak to explain the excess is > 13 l/year, while the upper limit from other contaminants (Kr, Rn) is 0.9 l/year

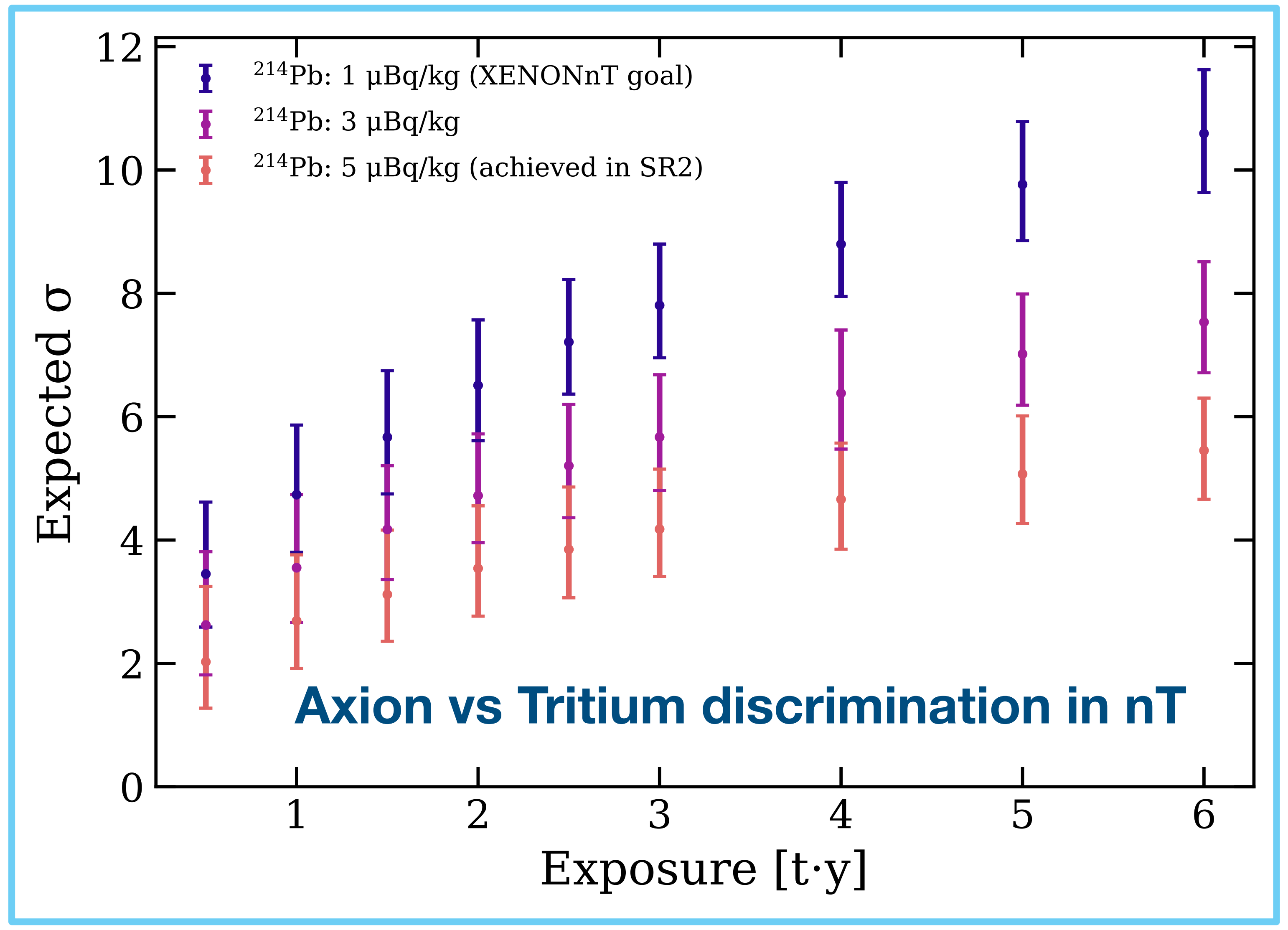


https://arxiv.org/pdf/2112.12231.pdf

Progress of Theoretical and Experimental Physics, Volume 2022, Issue 5, May 2022, 053H01

Solar axions + (unconstrained) ^{3}H fit

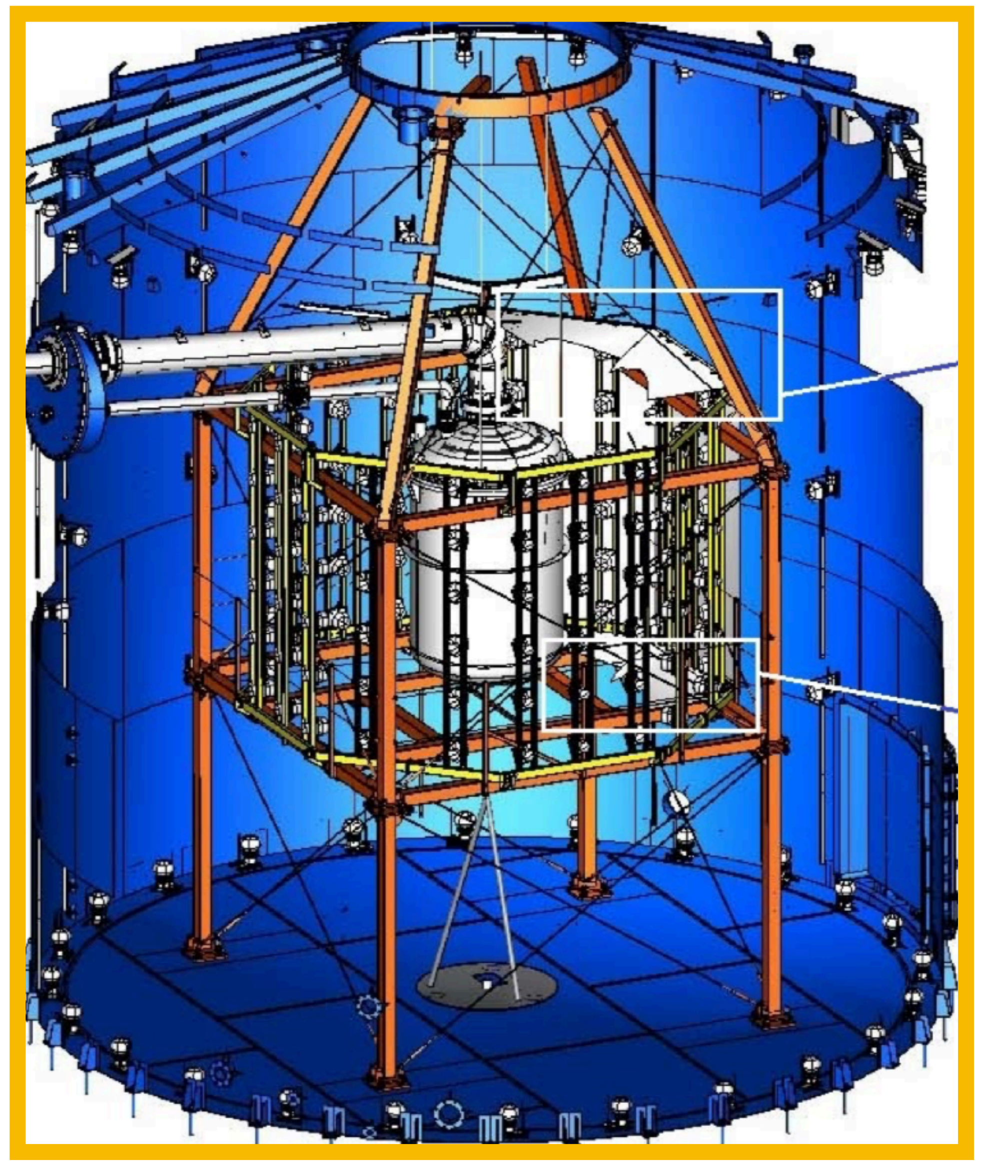




Upgrades for XENONnT

Larger TPC

Total 8.4 t LXe
5.9 t in TPC
~ 4 t fiducial
248 → 494 PMTs

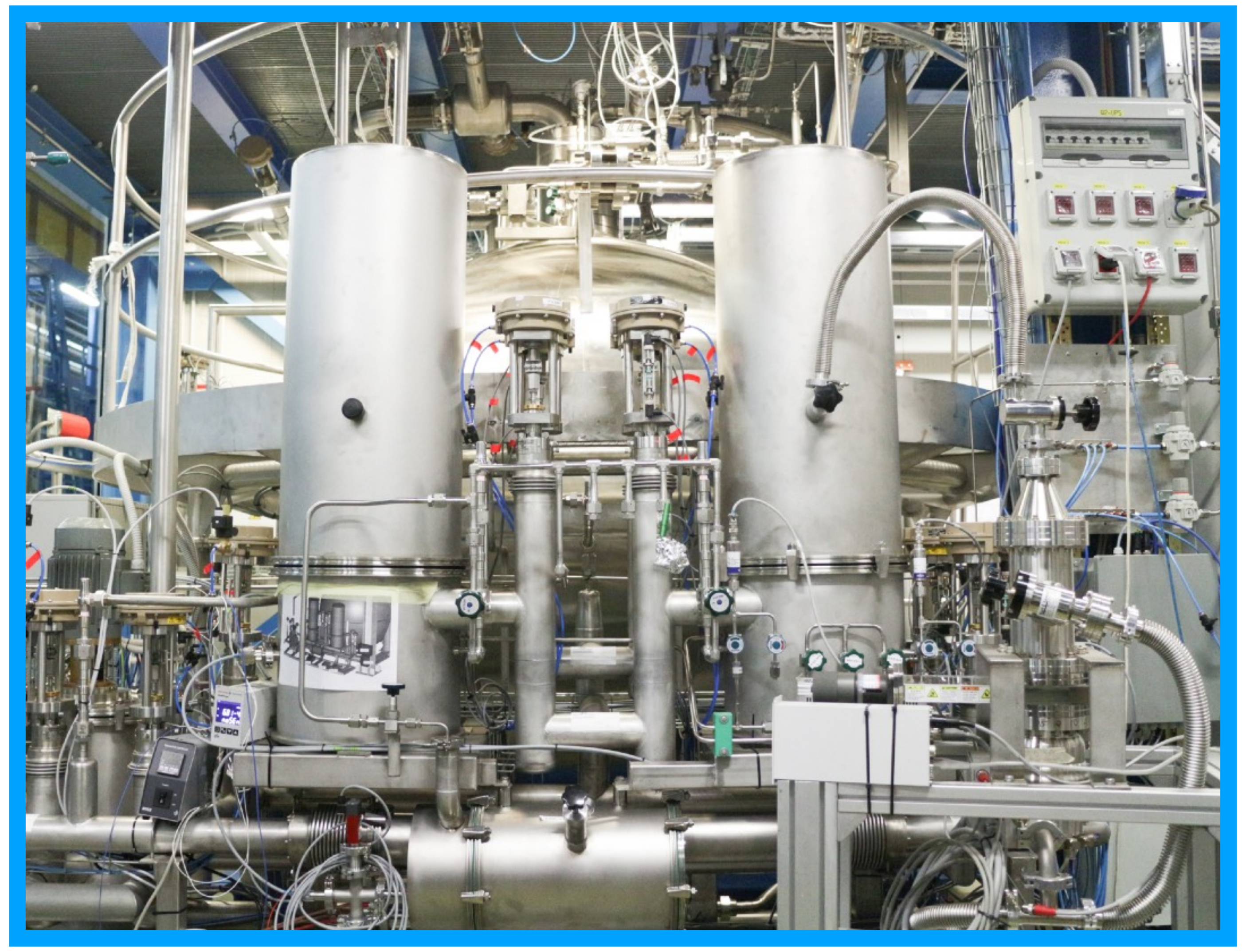


Neutron veto

Inner region of
existing muon veto
optically separate
120 additional PMTs
Gd in the water tank
0.5 % $Gd_2(SO_4)_3$

^{222}Rn distillation

Reduce Rn (^{214}Pb) from
pipes, cables,
cryogenic system
New system,
PoP in XENON1T



LXe purification

Faster xenon cleaning
5 L/min LXe
(2500 slpm)
XENON1T ~ 100 slpm

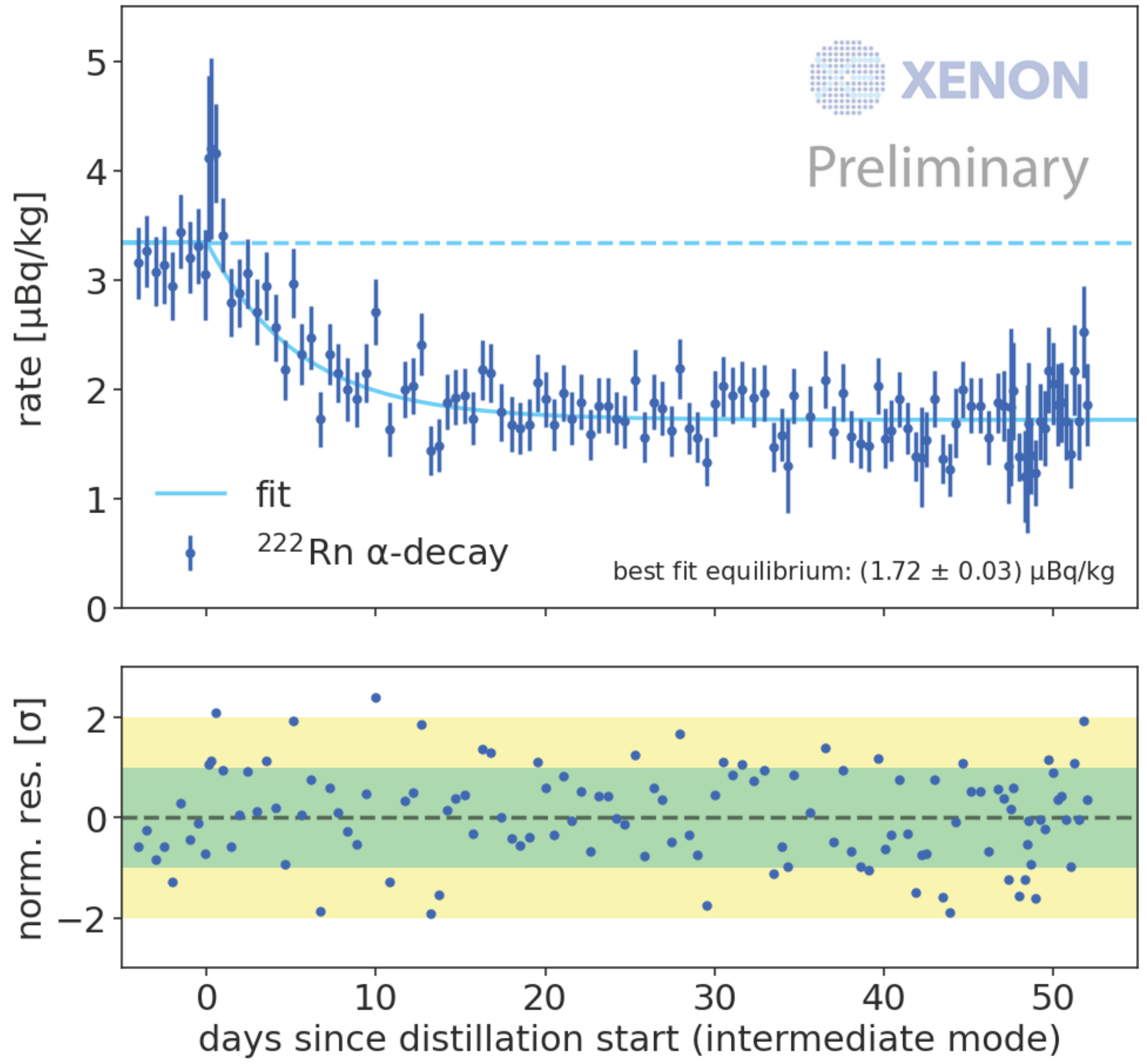
Upgrades for XENONnT

The RADON removal system

Key performance parameter

- liquid xenon inlet and outlet
- flow of 0.4 l/min LXe = 200 SLPM ≈ 70 kg/h
- radon reduction of factor 2 for sources within detector
- further reduction by gas extraction from cryogenics

Basic removal concept proven: EPJ C77 (2017) 358, arXiv:2009.13981



NEW RADON REMOVAL SYSTEM

ER background reduction

- Dedicated Rn cryogenic distillation column
- 1 μBq/kg ^{222}Rn level (goal)
- In XENON1T was
  13 μBq/kg (science run)
  4.5 μBq/kg (latest R&D run)

Large Xe flows using Rn-free compressors and heat exchangers

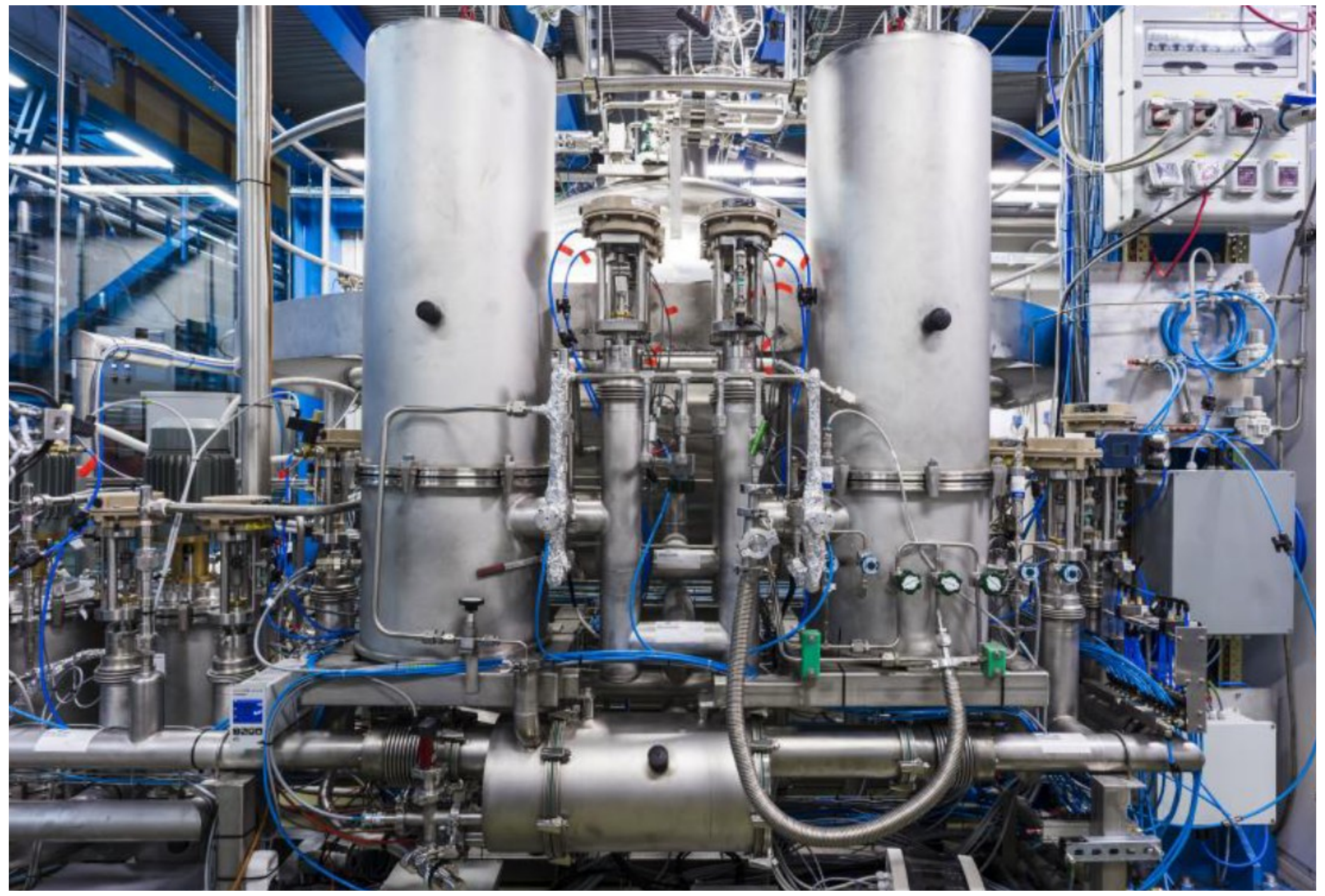
Rn contamination in first SR is 1.7 μBq/kg

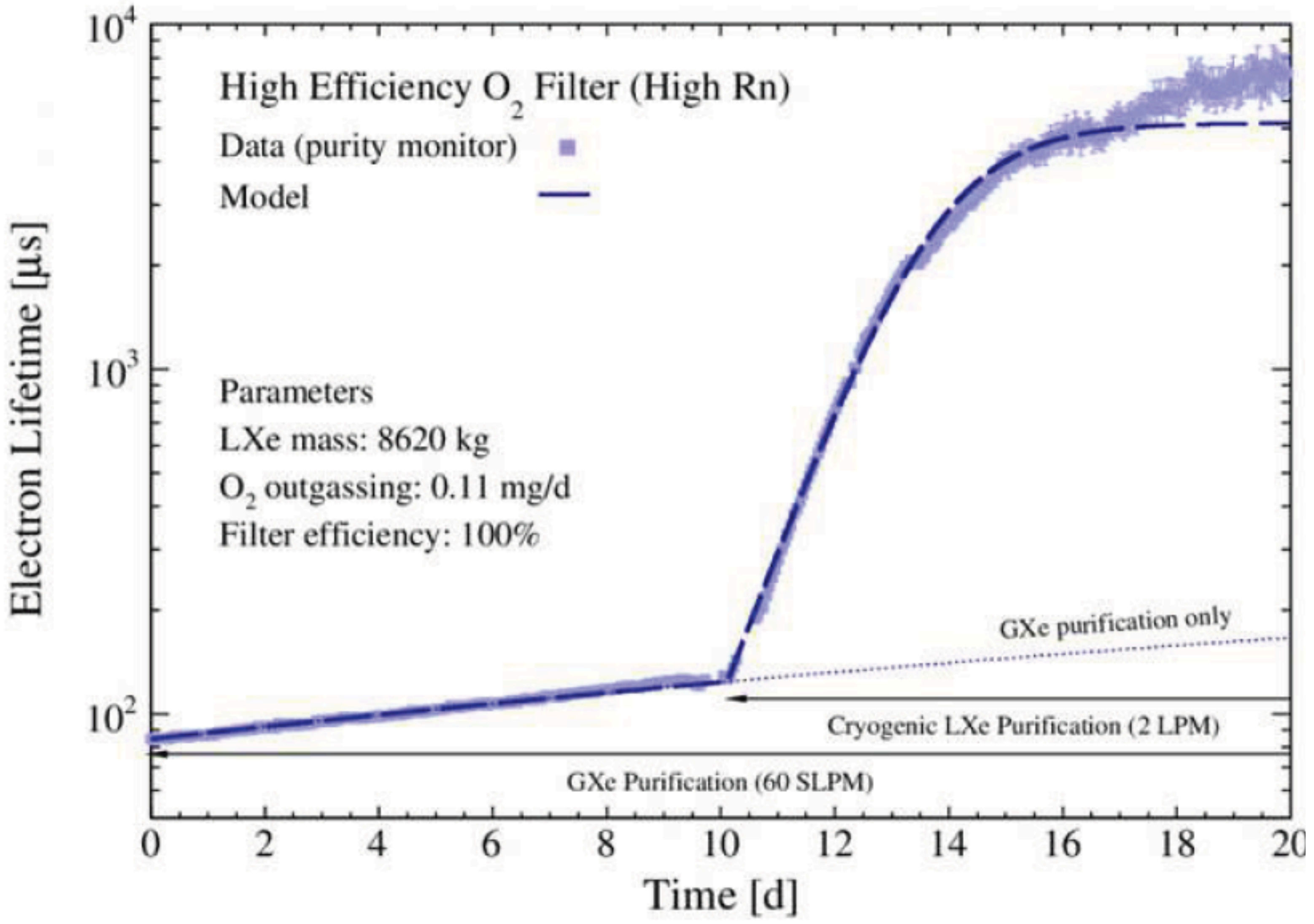
Will be reduced to <1 μBq/kg in next science

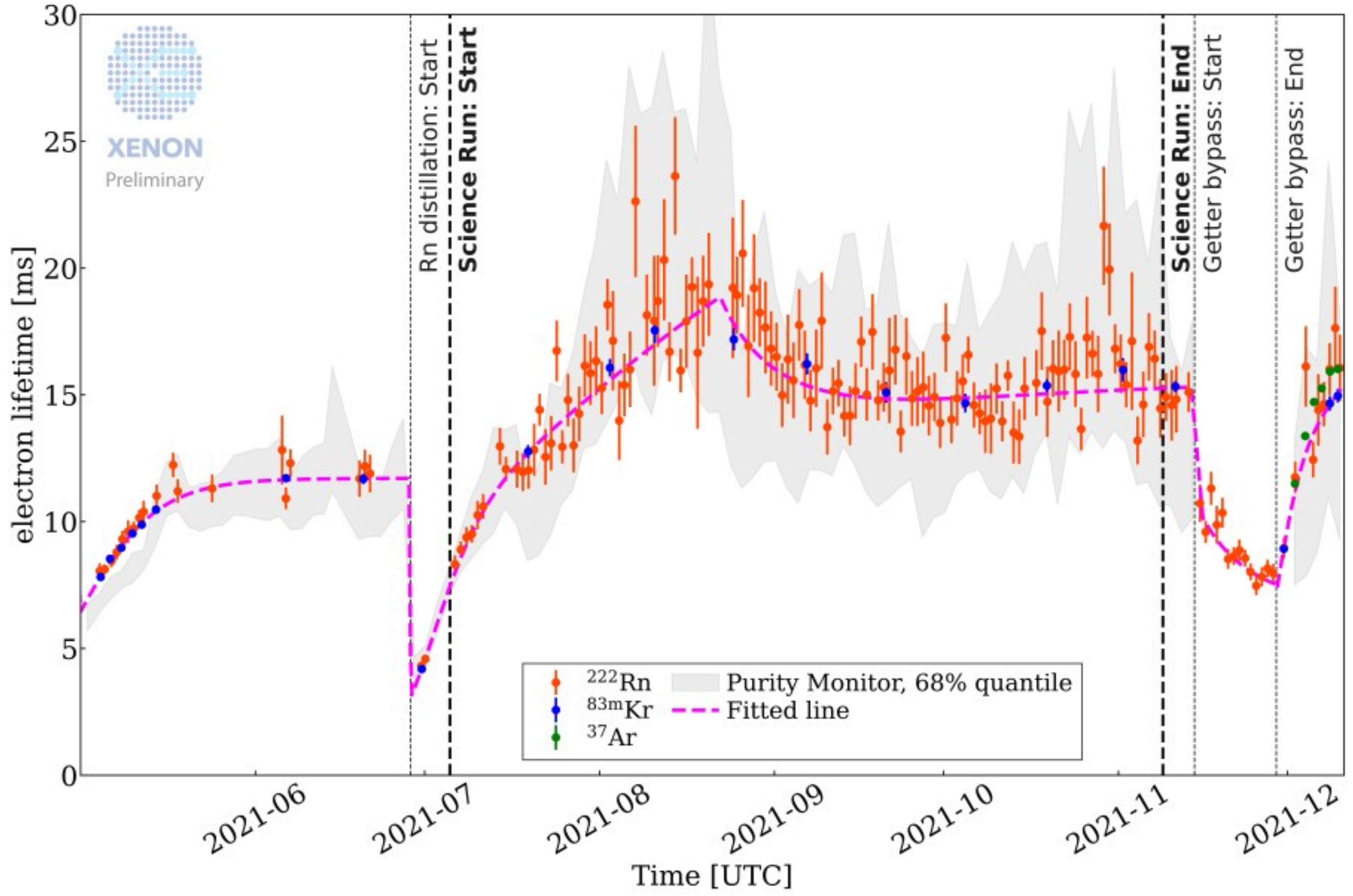
arXiv:2205.11492

Upgrades for XENONnT

The purification system







	Full TPC drift time	electron lifetime	electrons surviving a full drift length
XENON1T	0.67 ms	0.65 ms	30%
XENONnT	2.2 ms	10+ ms	86 % @ 15 ms

Replaceable filter units and low Rn emanation

High flow of 2 liters LXe/min (350 kg/h)

Electron lifetime from 100 μs to 5 ms in 5 days

Electron lifetime > 10 ms in science run (maximum drift time in the chamber is 2.2 ms)

Upgrades for XENONnT

The neutron veto

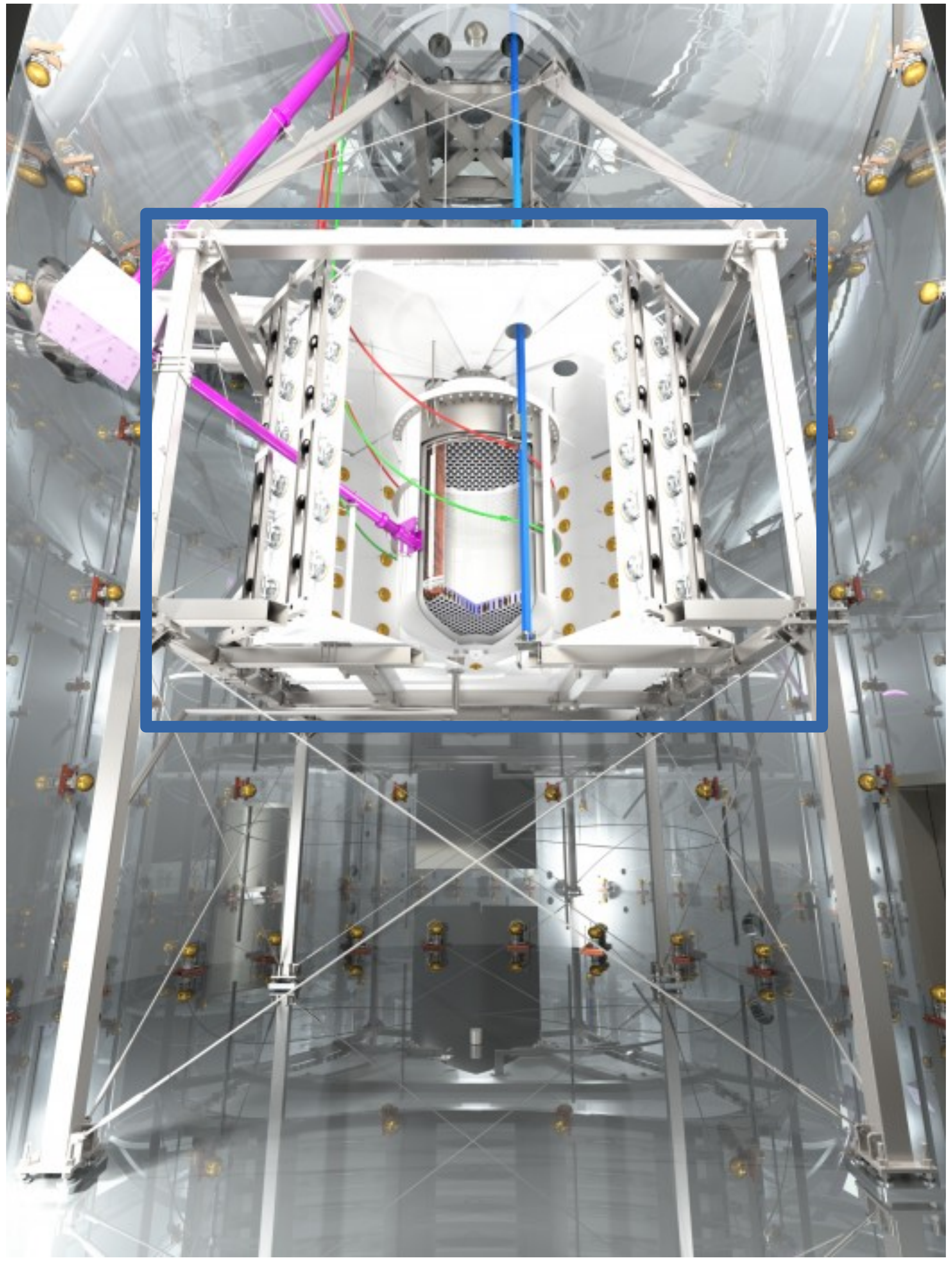
Tag neutrons which contribute to background in WIMP search

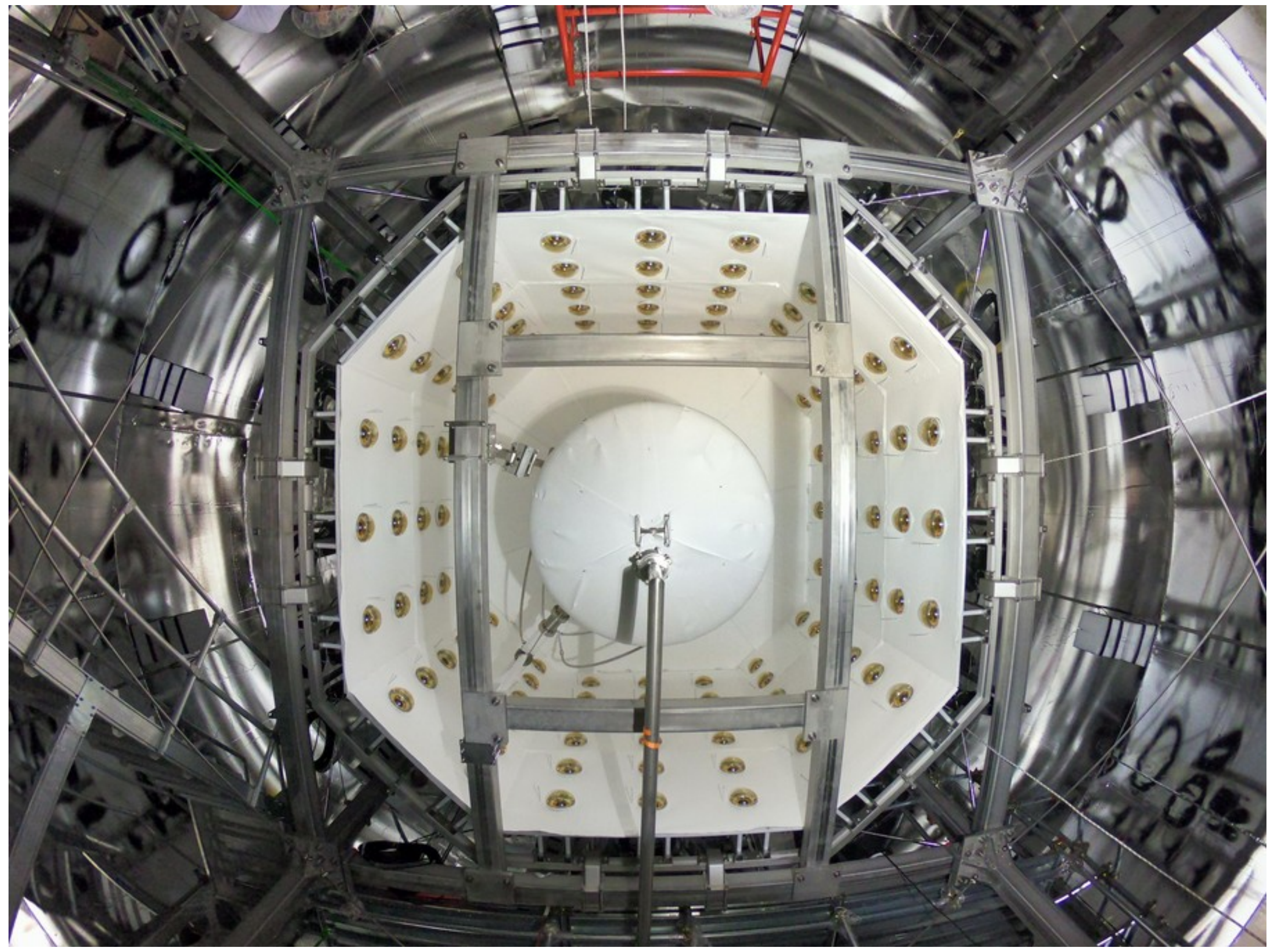
Gd-loaded Water: 0.2% of Gd in mass
 -> 3.4 t of Gd-sulphate-octahydrate;
 (technology from EGADS-SK colleagues)

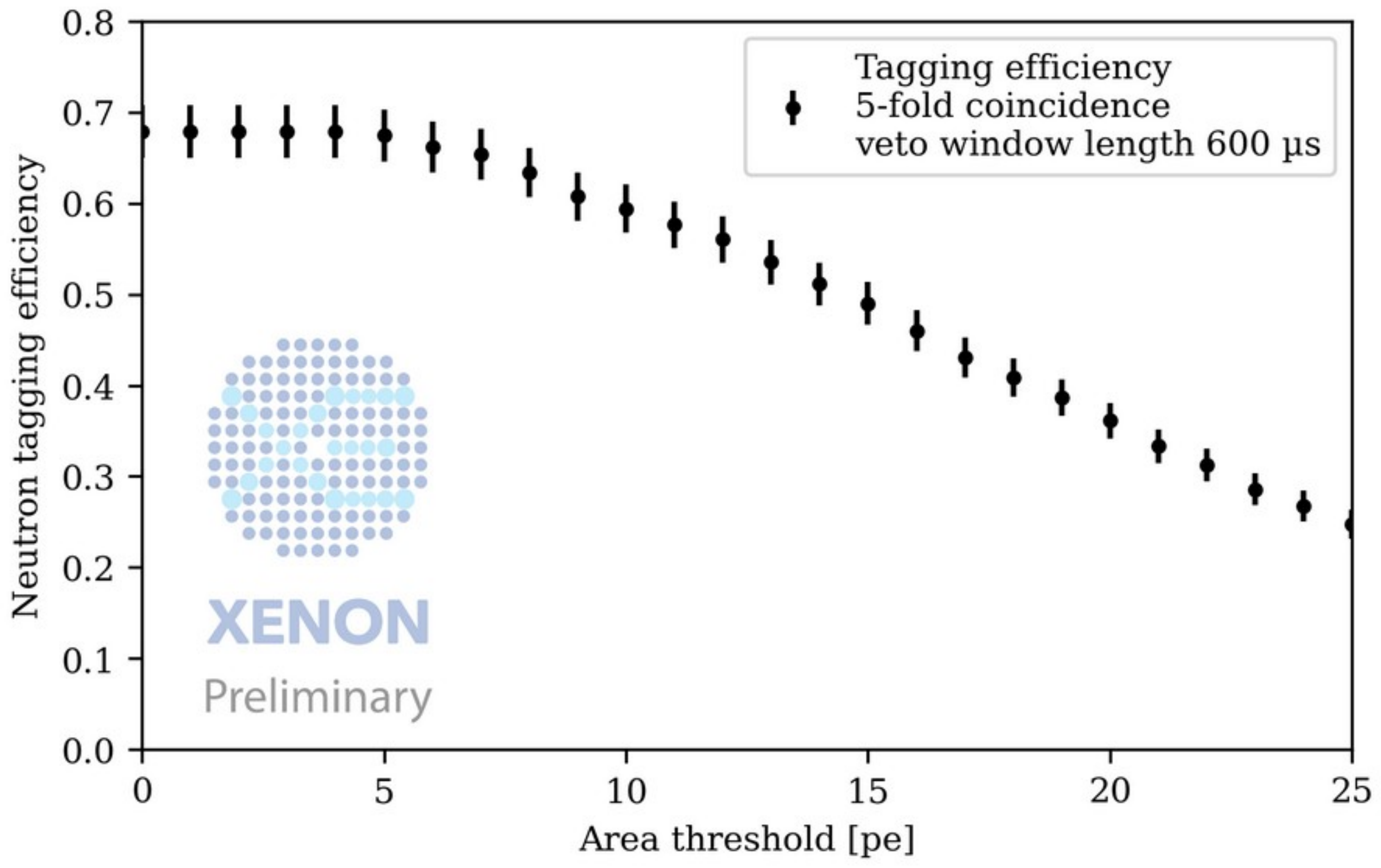
Water cherenkov detector around cryostat with 120 8″ PMTs inside an enclosure of reflective panels

Science Run 0 running with pure water, tagging efficiency was 68%

Gd -doping to increase performances (85% efficiency with 0.2% Gd)







XENONnT: Science Run 0

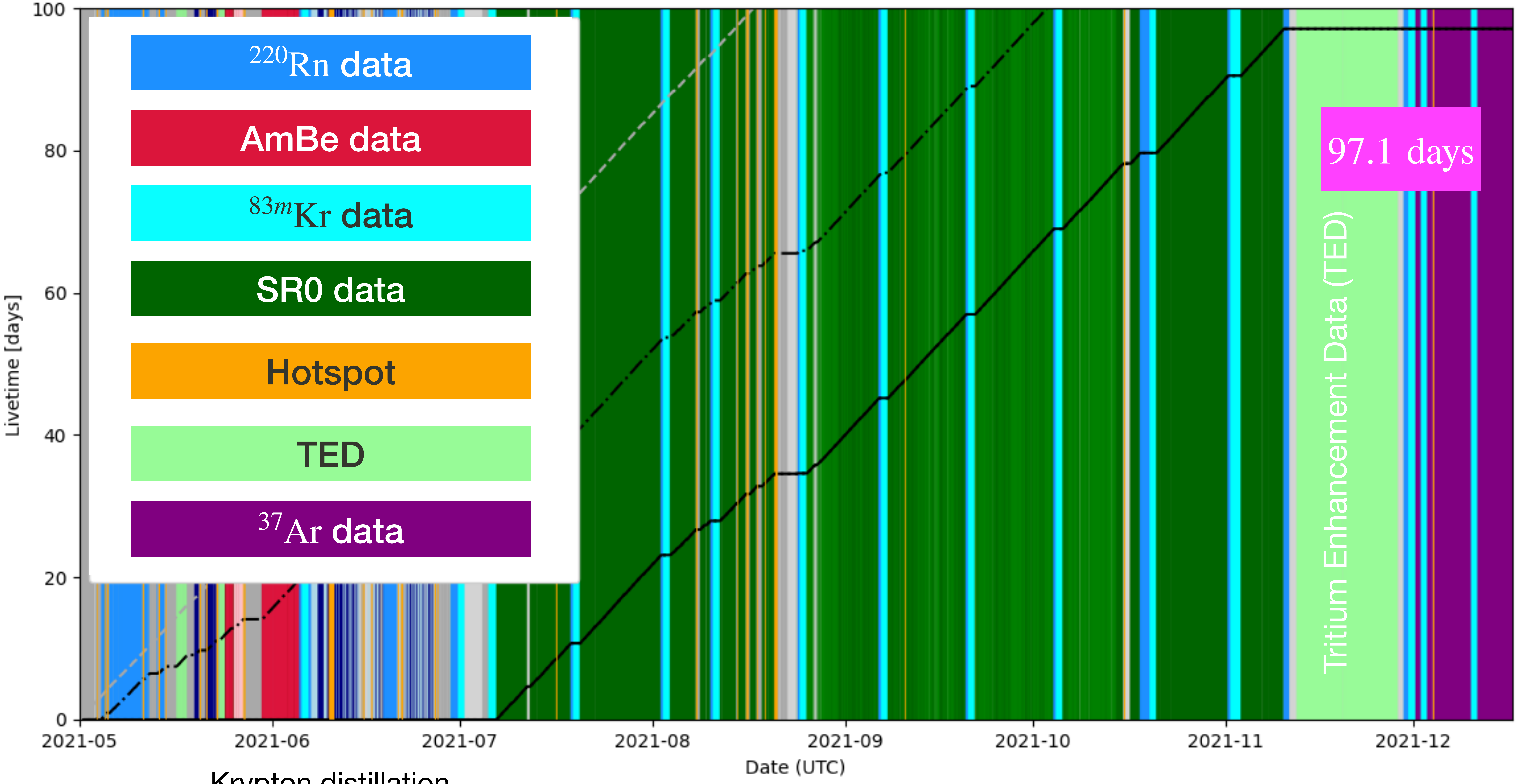
Gain stable at 3%

All PMTs working except 17

23 V/cm drift field
2.9 kV/cm extraction field

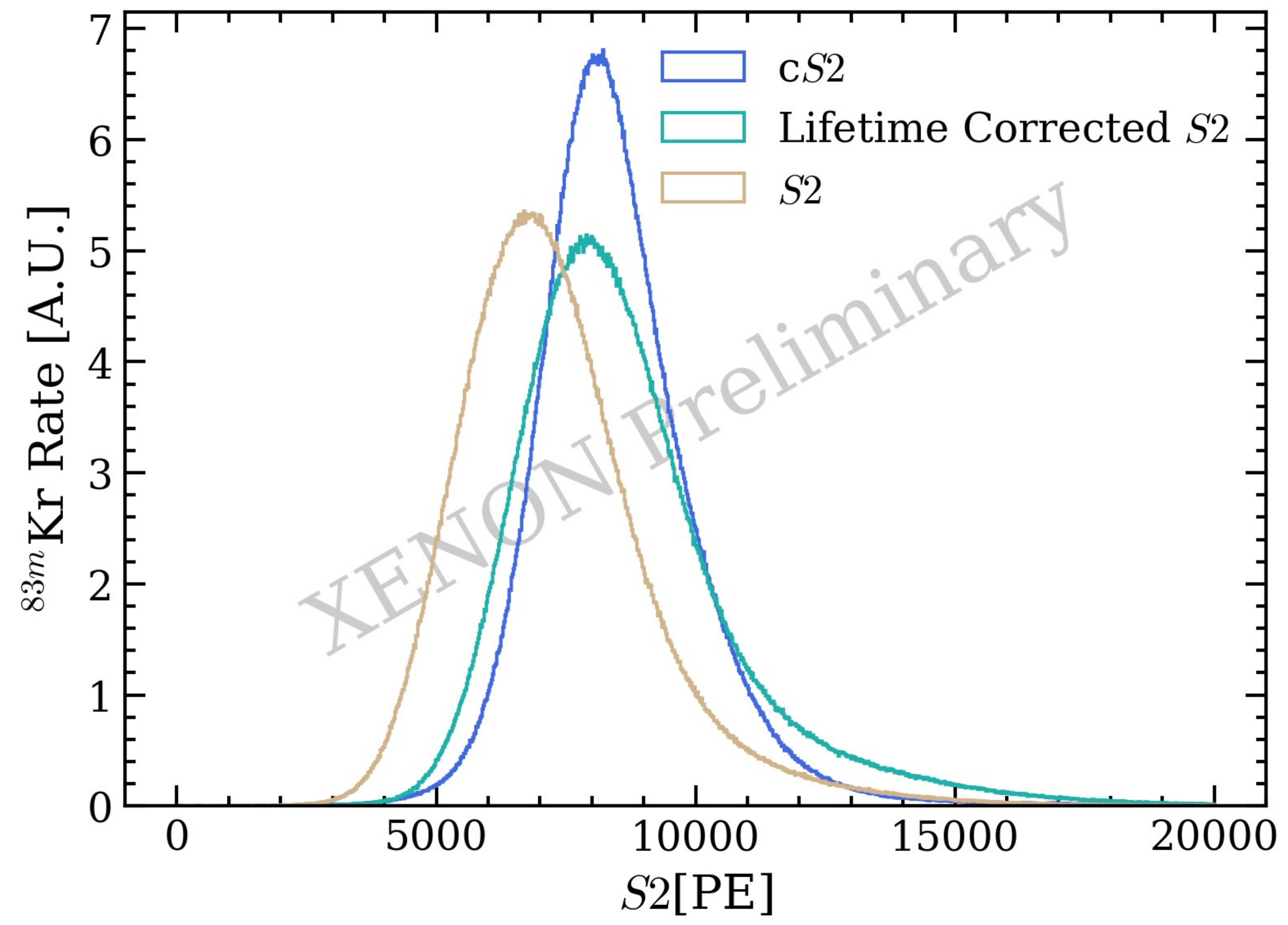
Hot-spots:sporadic ramp-downs of the anode, due to localized, high-rate, bursts of electrons (hot-spots)

97.1 livetime days (from July 6, 2021 to November 10, 2021)



Krypton distillation

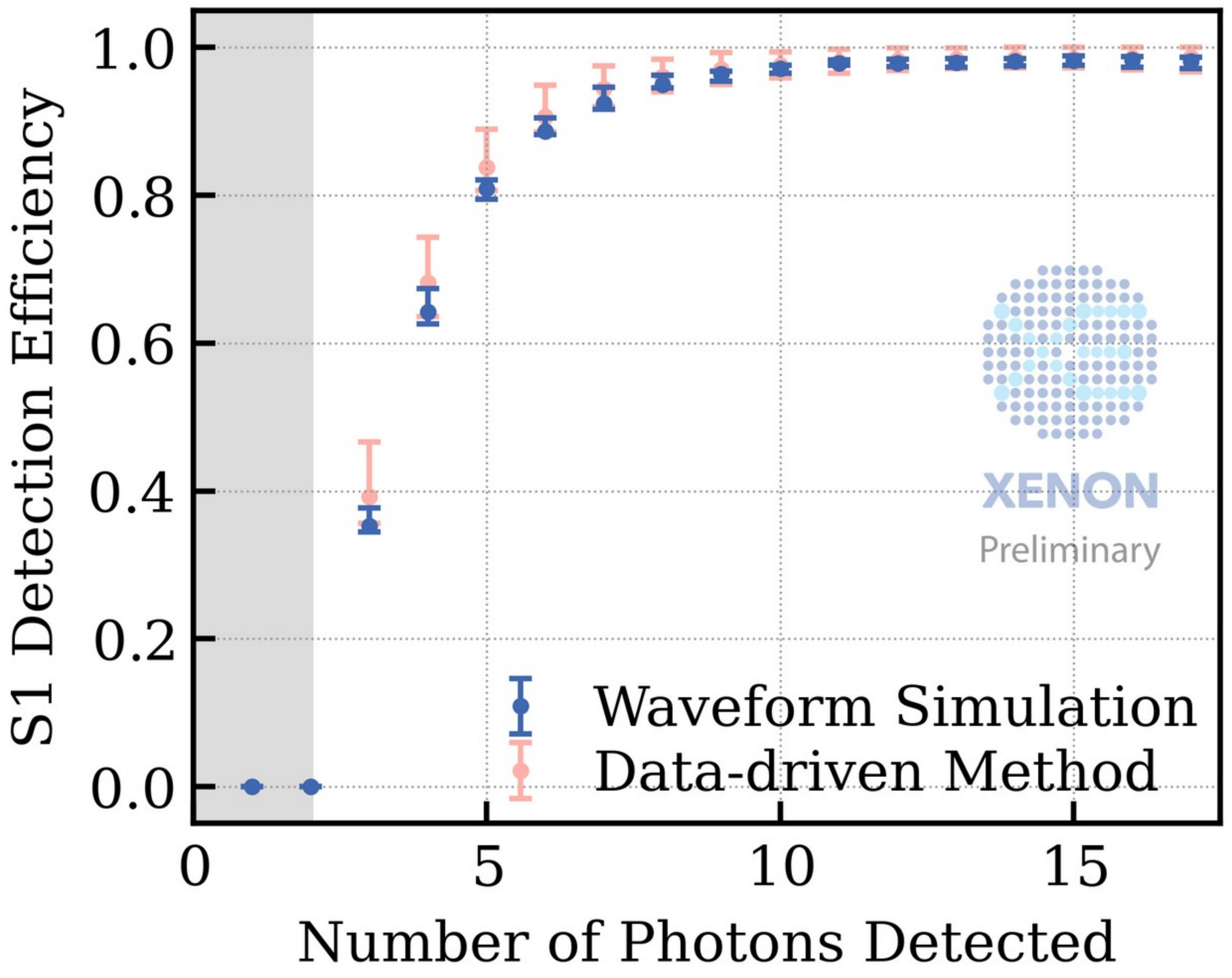
XENONnT: Corrections and efficiencies

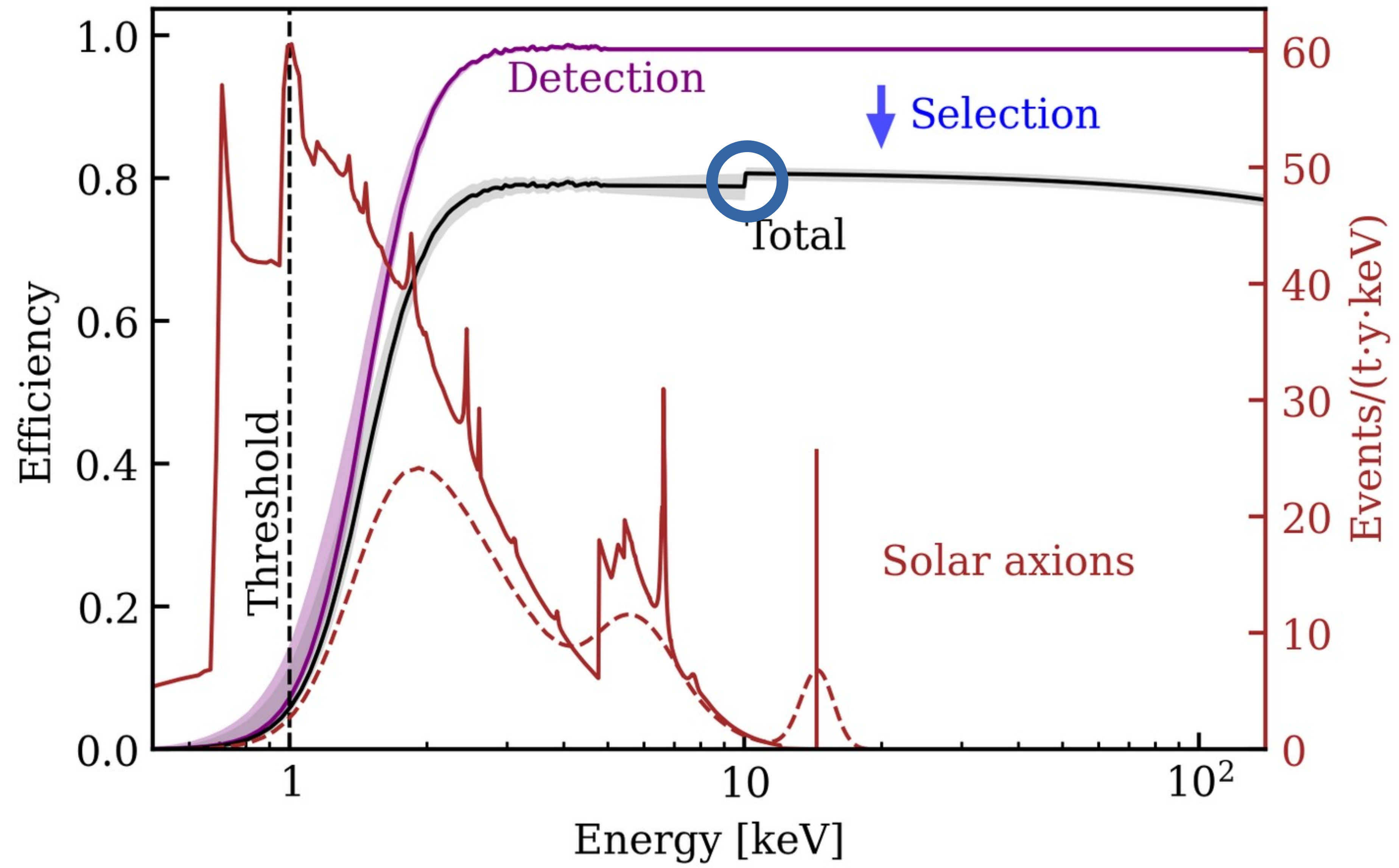


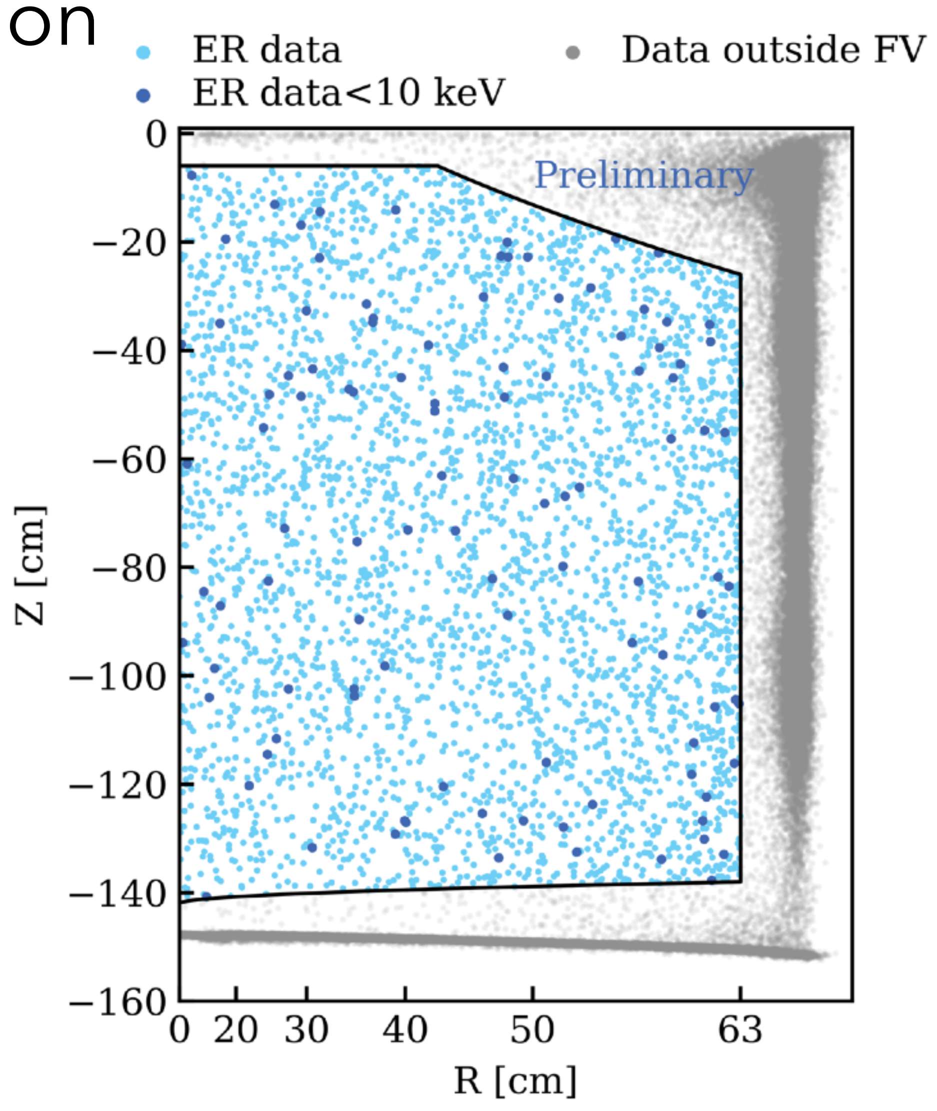
S2 corrected for depth and inhomogeneous response

Waveform simulation and data-driven method (validation) drawing subsamples of photon hits to make up a pulse for S1

Efficiency: probability to reconstruct a peak after reconstruction



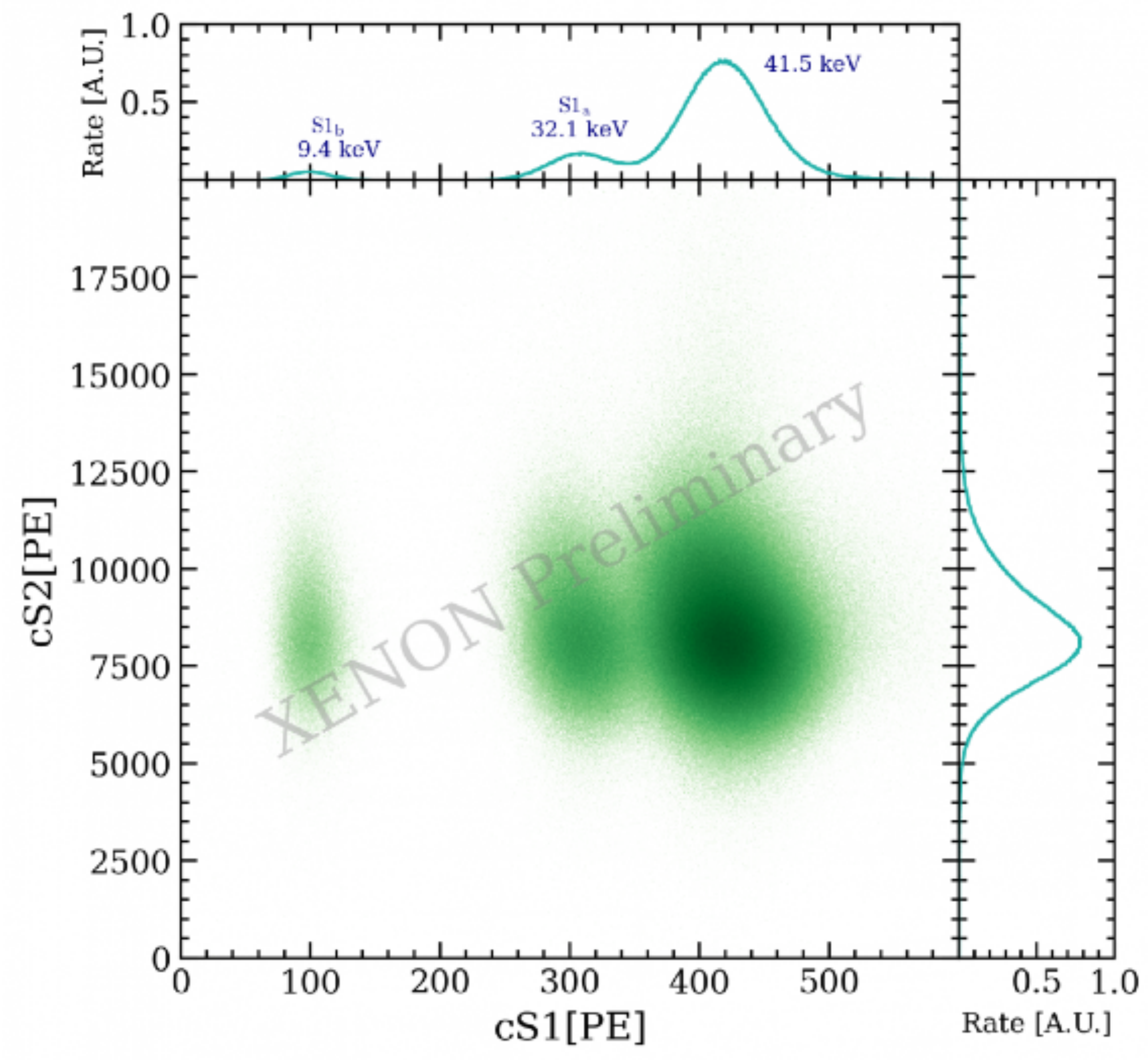




DATA QUALITY CUTS

- Events are required to pass a range of quality cuts:
  - The S1 and S2 peak should each have patterns, top/bottom ratios etc. consistent with real events
  - An S2 width consistent with the expected diffusion
  - An S2 over 500 PE
  - Not within < 300 ns of a neutron veto event
- Events must be within ER band
- Fiducial volume cut selects a mass of (4.37 ± 0.14) tonnes with low backgrounds

XENONnT: Calibrations



^{83m}Kr

-Injected every 14 days

-Used to estimate:

S1 light collection efficiency as a function of position

Position reconstruction distortion due to the field

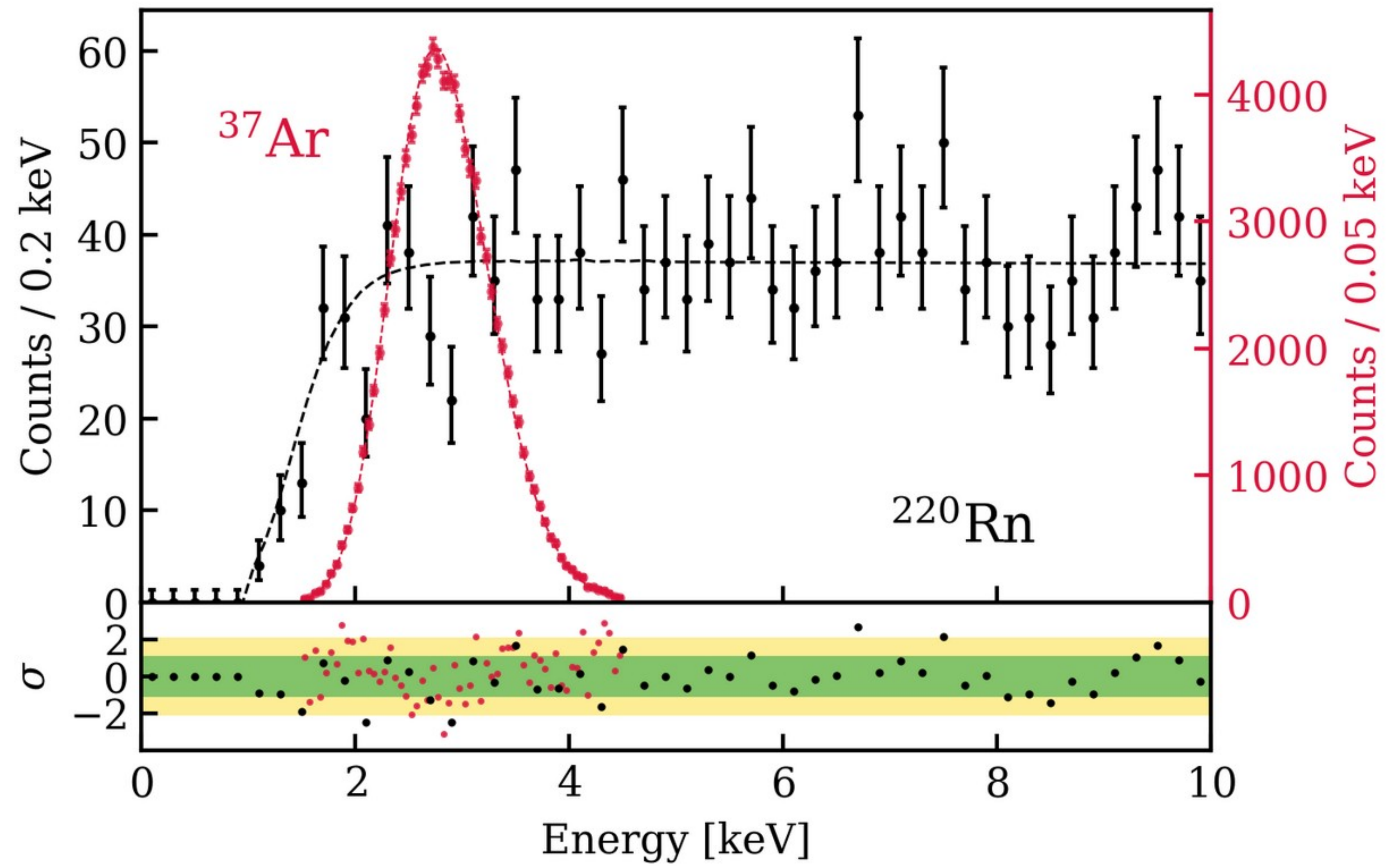
-Validate COMSOL field simulation of the signals ratio S(32.1 keV)/S(9.4 keV)

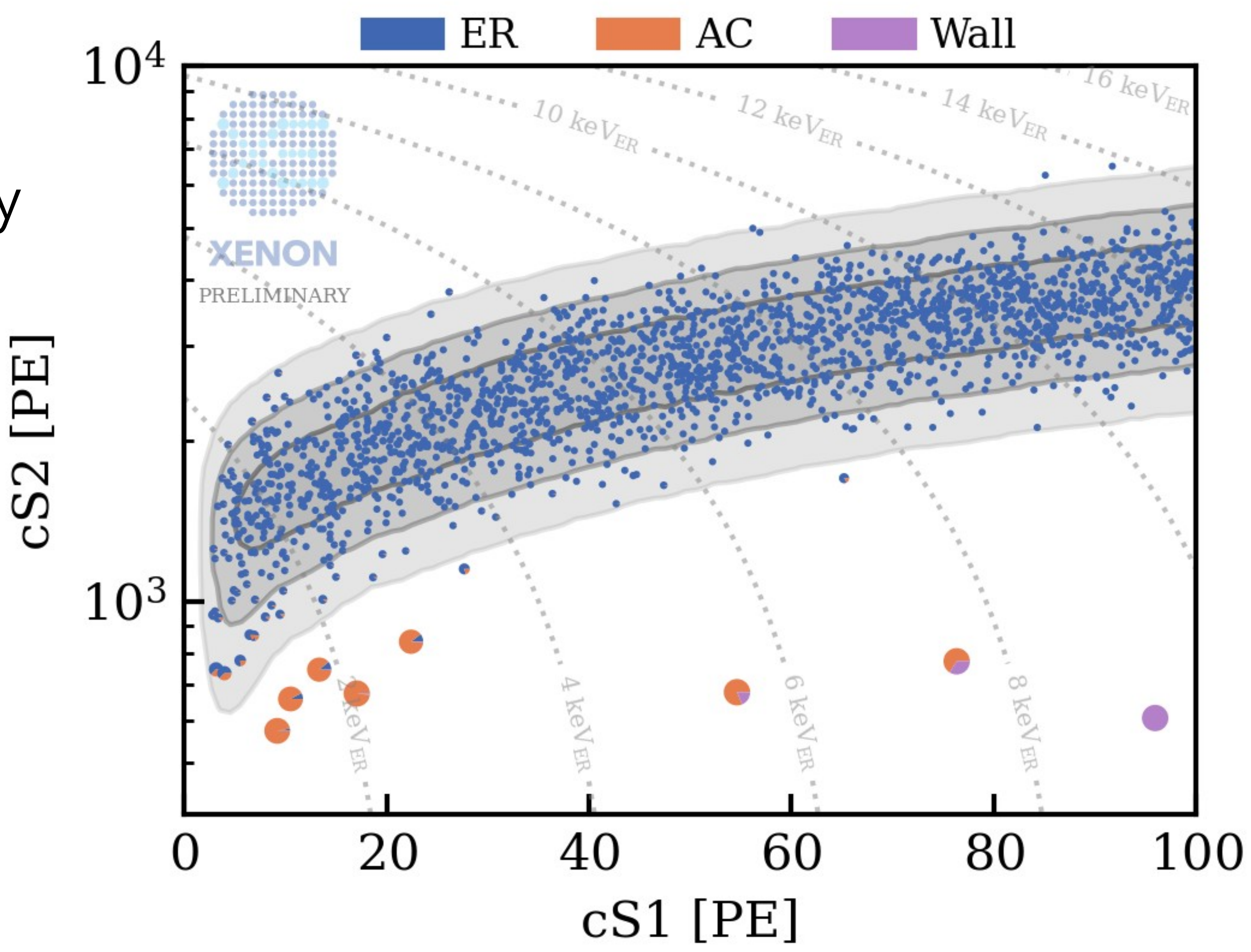
2 calibration sources for Electron Recoils:
^{37}Ar and ^{220}Rn

^{37}Ar: mono- energetic peak at 2.82 keV to set the low-energy response and resolution models

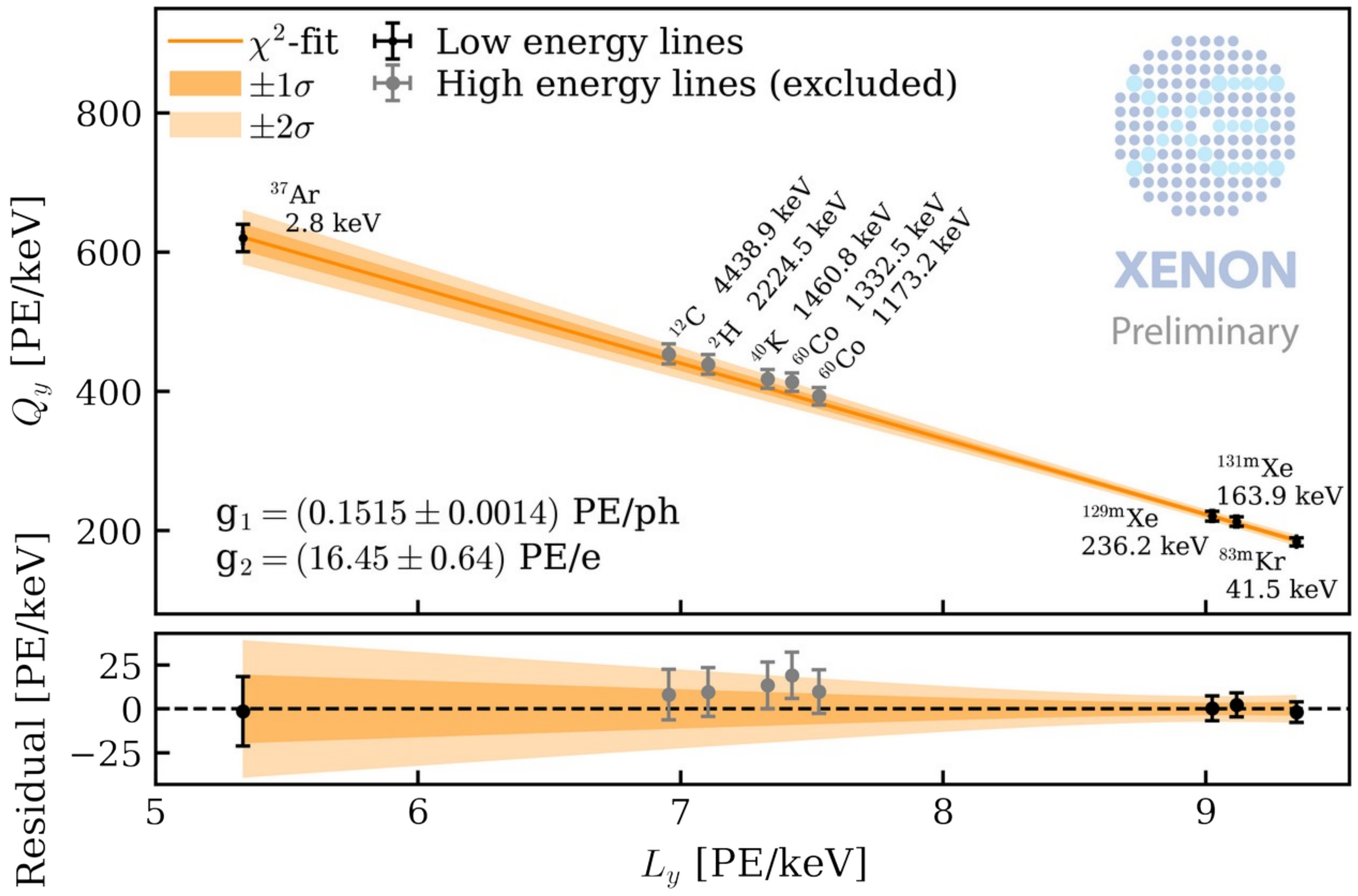
^{220}Rn: ^{212}Pb from ^{222}Rn provides a flat β-spectrum to estimate cut acceptances and validate our energy threshold

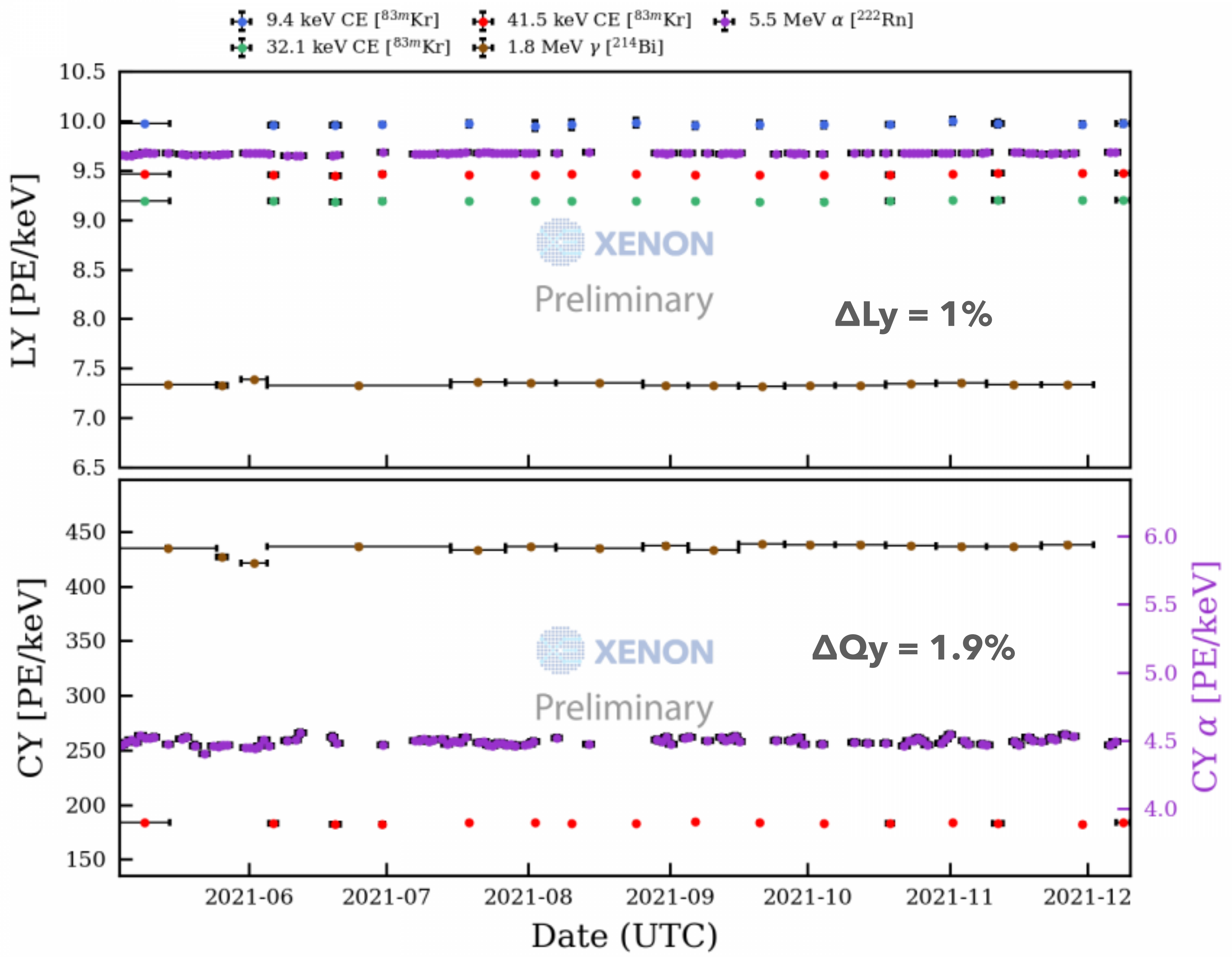
It also defines the ER blinded region





XENONnT: energy scale





For ER sources the entire deposited energy is given by the observable light and charge

$$E = 13.7\ \text{eV}\left(\frac{cS1}{g_1} + \frac{cS2}{g_2}\right)$$

Mono-energetic peaks between 1 and 140 keV from ^{37}Ar, ^{83m}Kr, ^{129m}Xe and ^{131m}Xe

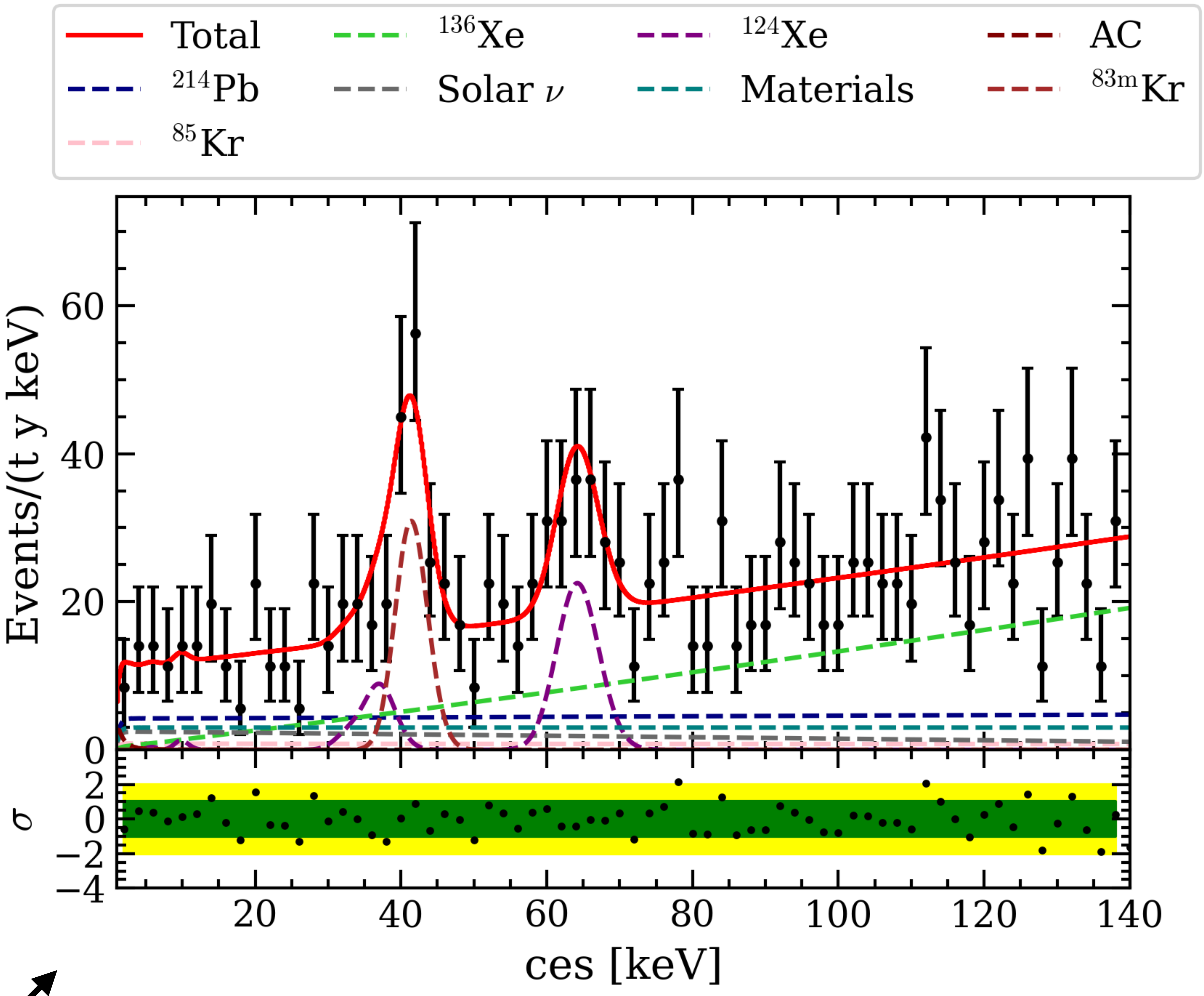
Observed bias in energies between 1-2% included in the modelling

Stability monitored during SR0 from calibration sources, ^{222}Rn α's and materials' γ's

XENONnT: Tritium Enhanced Dataset (TED)

Significant effort to reduce possible sources of a low-energy excess as due to Tritium in XENONnT:

- 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

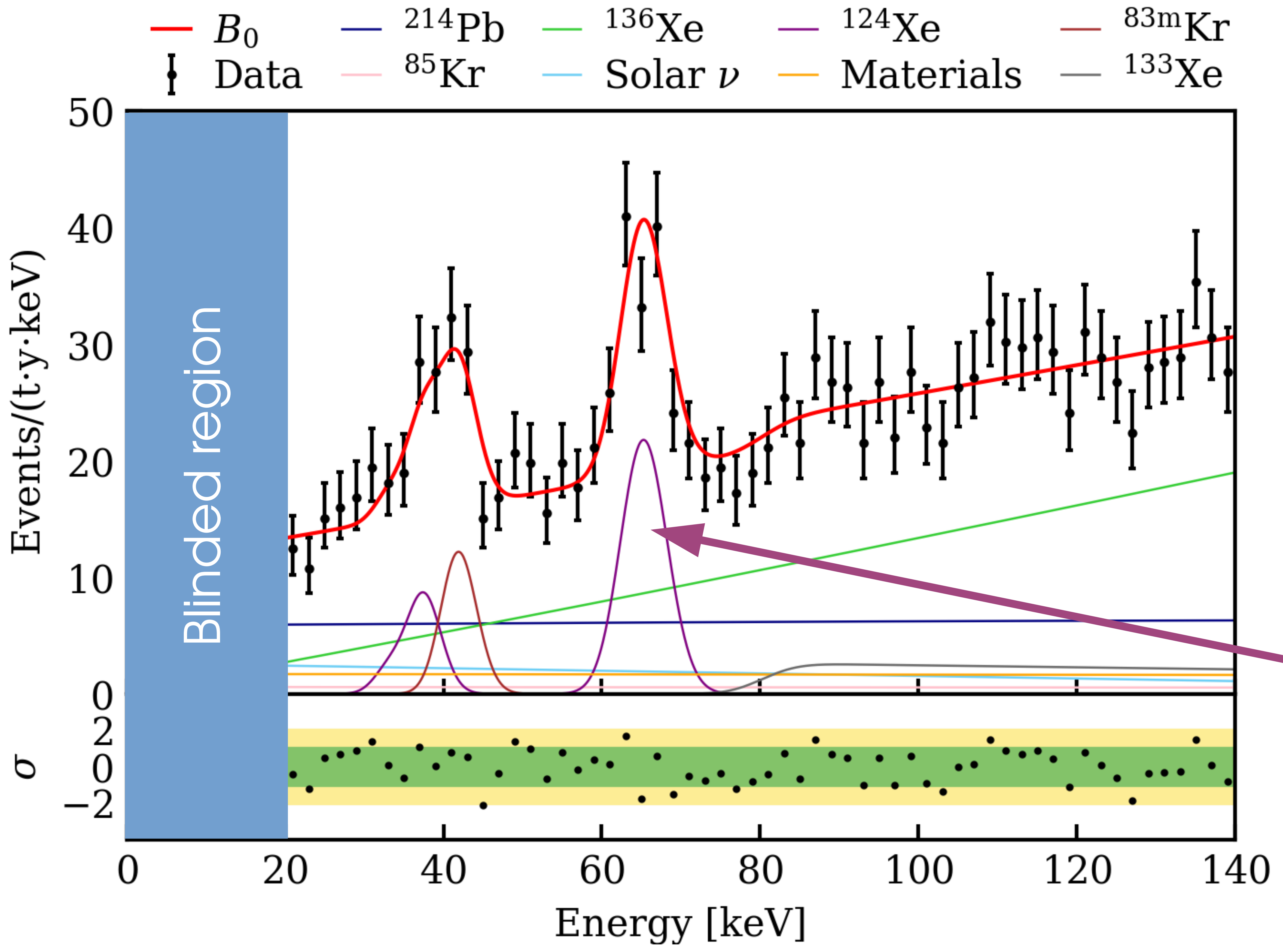


TED: after Science Run 0, the detector was operating bypassing the getters for the gaseous Xe purification during 14.3 days

This enhanced the H2/HT concentration in Liquid Xenon by a factor 10-100

The TED was blinded and after unblinding no tritium-like excess was found

XENONnT: Background



Full blinded analysis with different stages of unblinding

Energy range (1-140) keV

Fiducial mass (4.37±0.14) t Exposure is 1.16 t*y

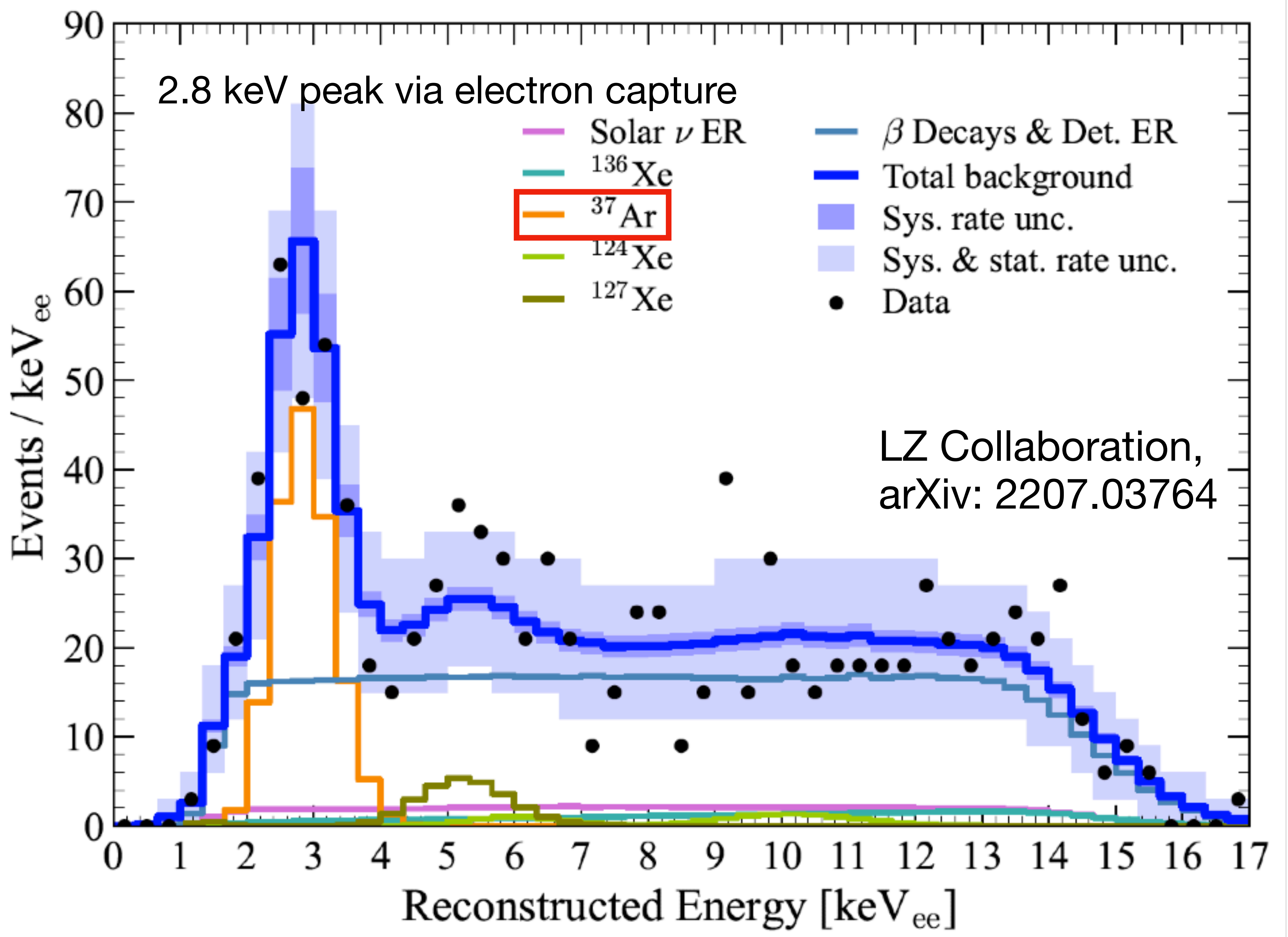
^{222}Rn: ~ 1.7 μBq/kg (XENON1T SR1: ~ 12 μBq/kg)
^{nat}Kr: (56 ± 36) ppq (XENON1T SR1: (660 ± 110) ppq)
^{83m}Kr background is due to leftover of calibrations

Spectral shape dominated by two double-weak decays: ^{136}Xe 2vββ and ^{124}Xe 2vECEC

^{124}Xe 2vECEC the rarest decay ever observed in XENON1T, now also used as a validation of the energy reconstruction

XENONnT: ^{37}Ar

LZ background: ^{37}Ar is observed due to cosmogenic activation during transportation above ground (short half-life: 35 days)



Why not include ^{37}Ar in the background model?

^{37}Ar leak during the SR0 operation is not possible since:

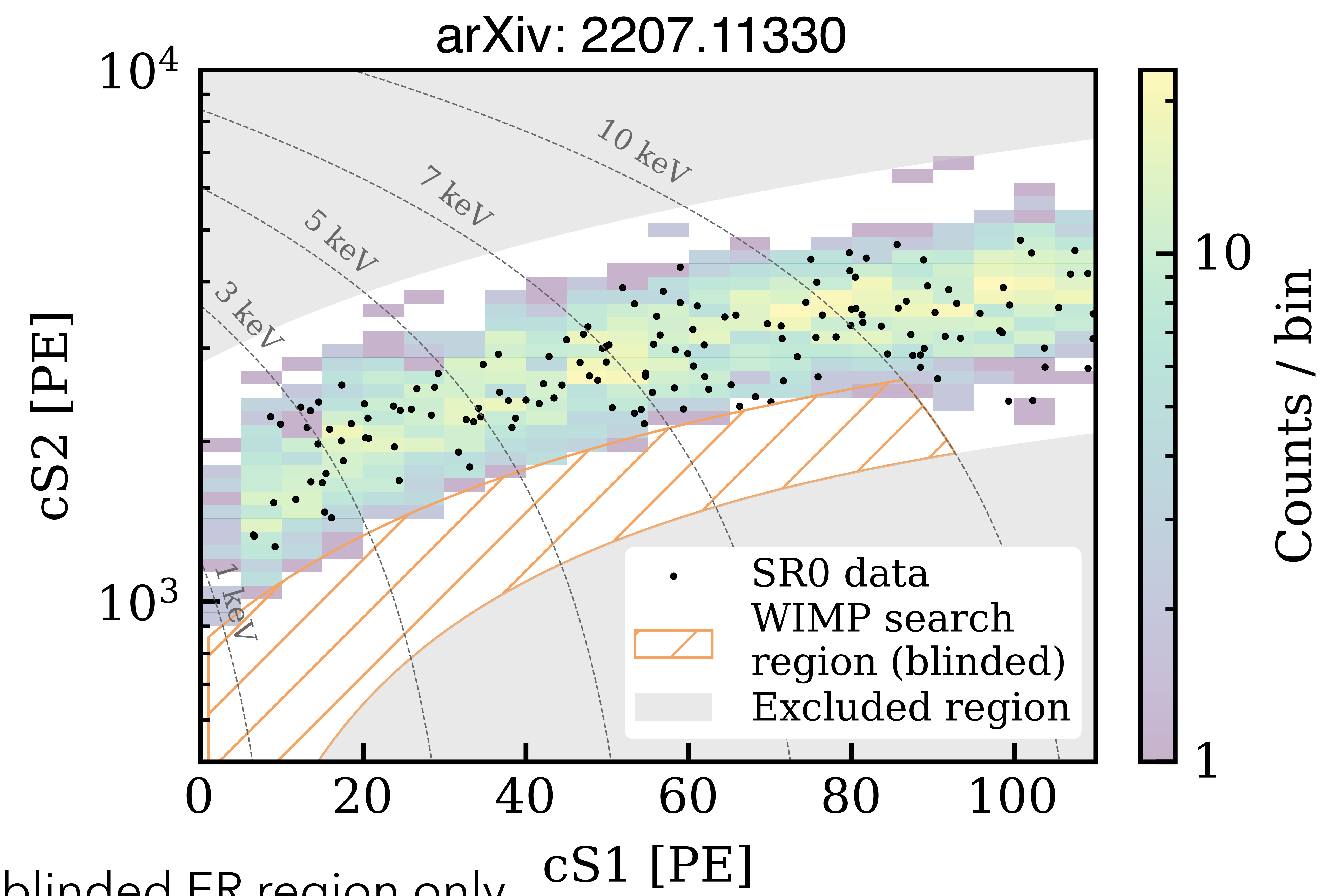
Cosmogenic activation is excluded

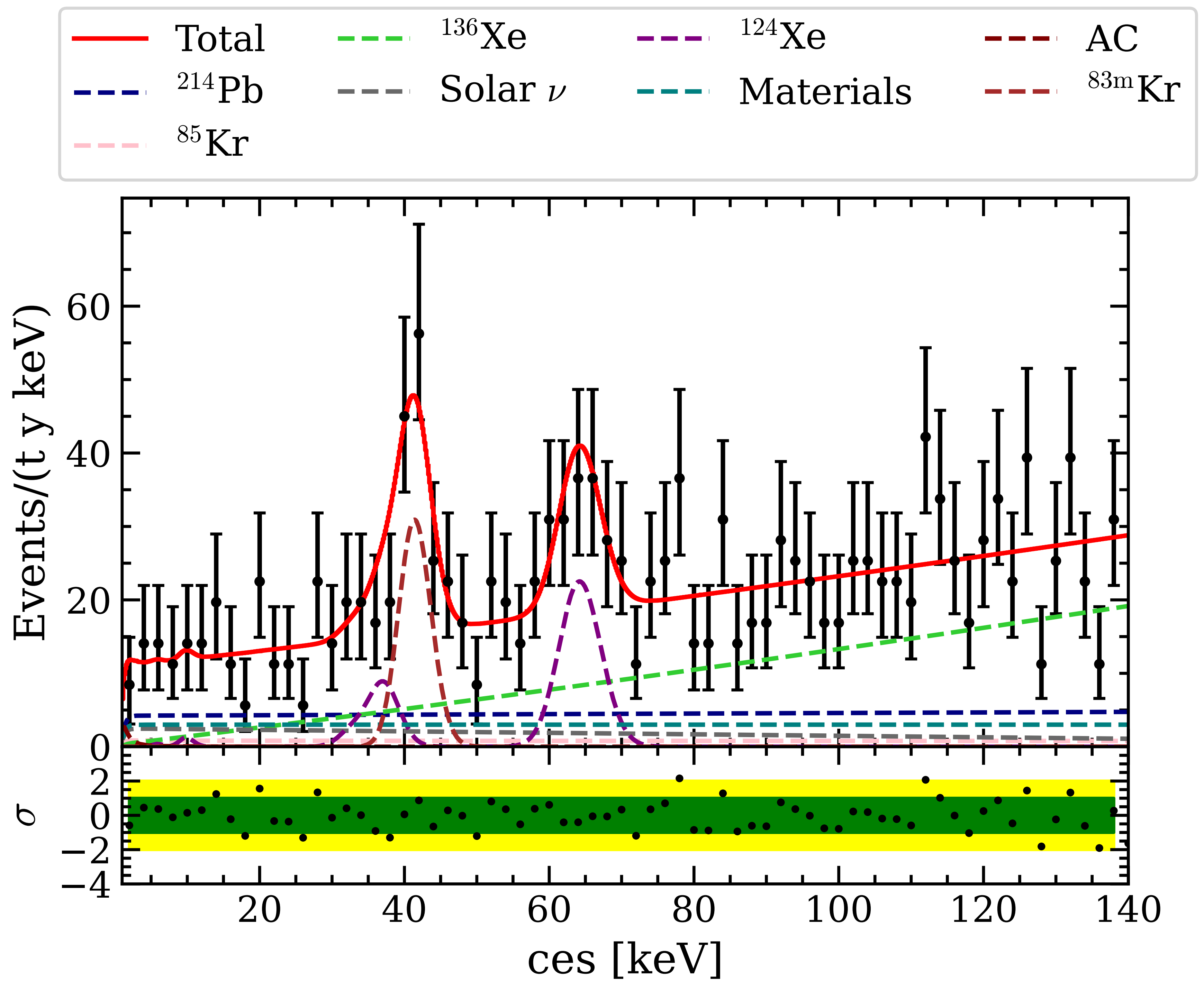
- -Xenon detector has been underground for years
- -Before SR0 data taking the entire xenon inventory has been distilled by the Krypton removal system (XENON Collaboration, PTEP 2022, 053H01)

Leak is excluded

- -natKr variation allows only very small leak to be possible
- -only very small leak is possible when comparing ^{37}Ar activity in the lab air

XENONnT: Unblinding





BEST FIT	(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

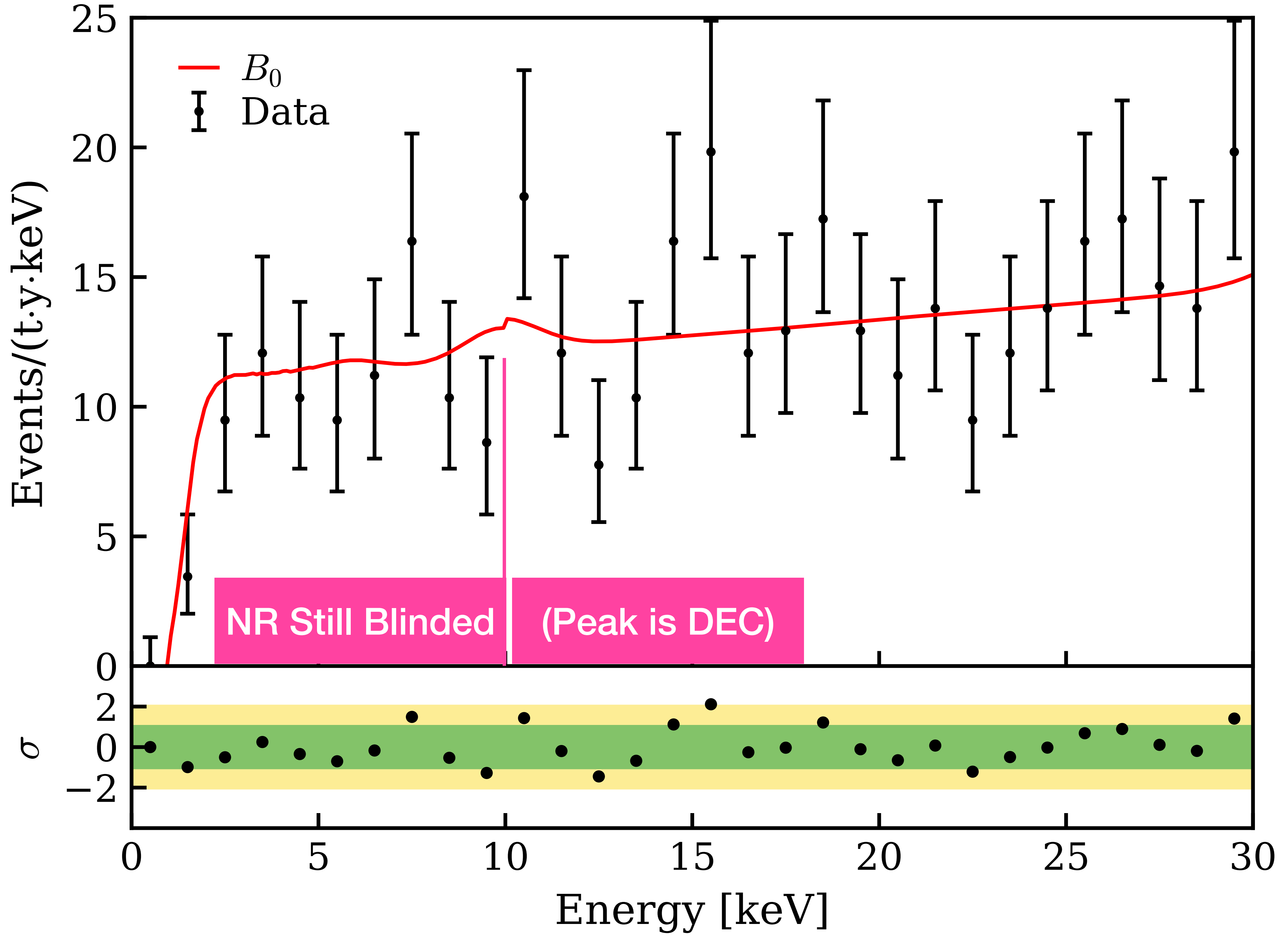
Unblinded ER region only

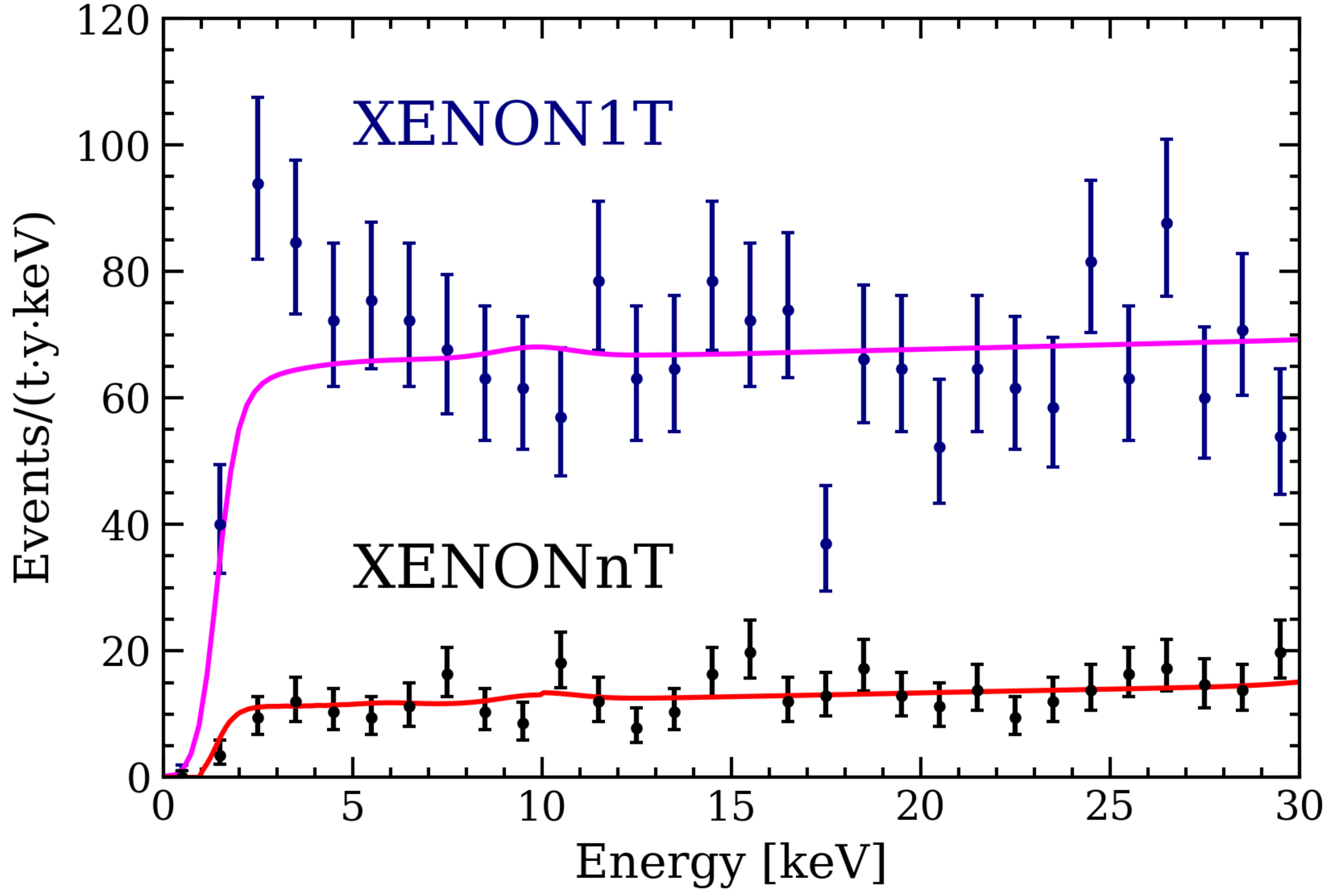
^{214}Pb best-fit rate: (1.36 ± 0.17stat) μBq/kg

Solar neutrino: the 2nd largest ER background below 10 keV

The total ER background below 30 keV is (16.1 ± 1.3stat) events/(t · y · keV), **the lowest background ever achieved in a dark matter detector (~0.2x of XENON1T ER search)**!

XENONnT: Compare with XENON1T





No excess is found in XENONnT!

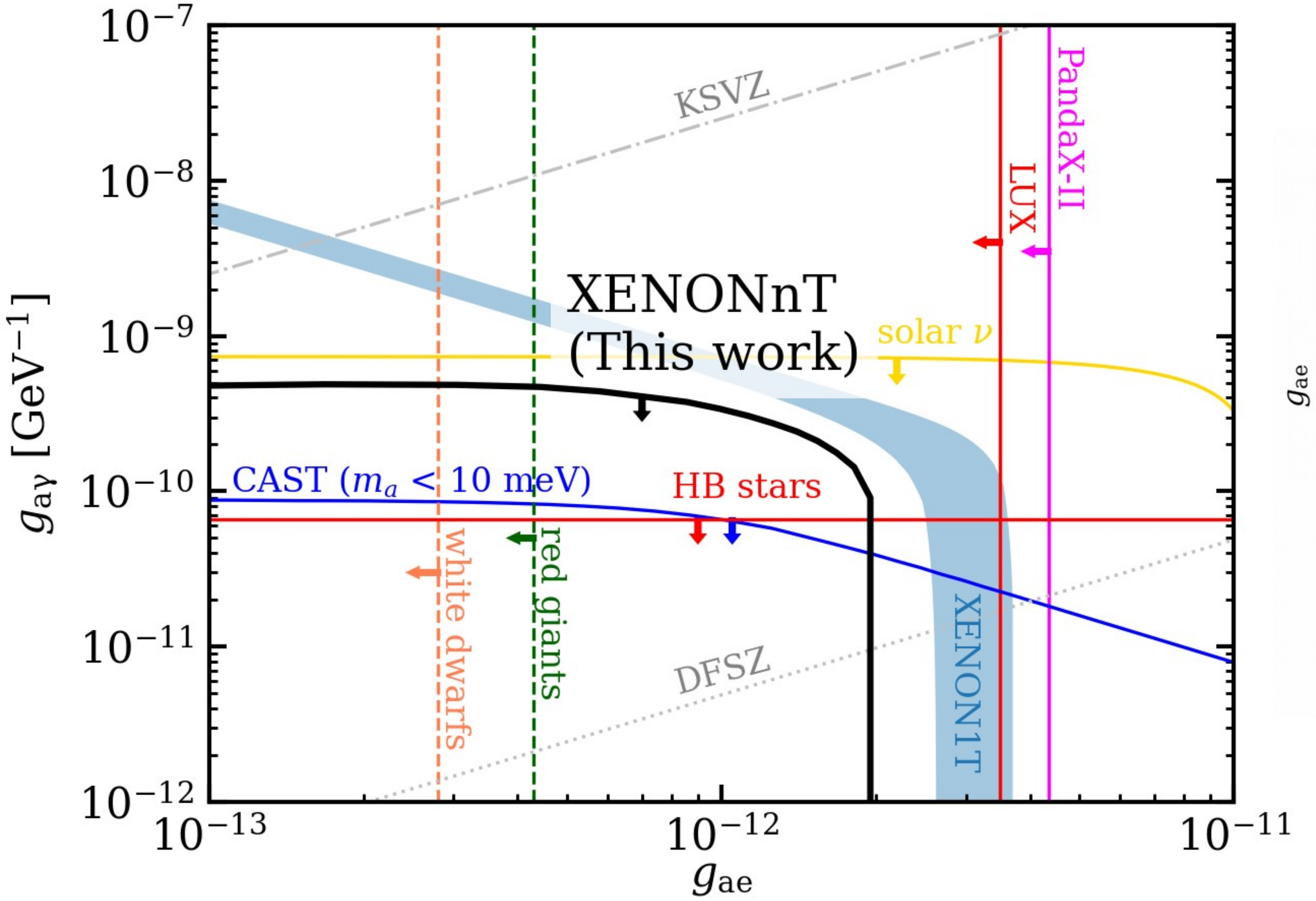
B_0 = (16.1 ± 1.3stat) events/(t*y*keV) in (1,30) keV

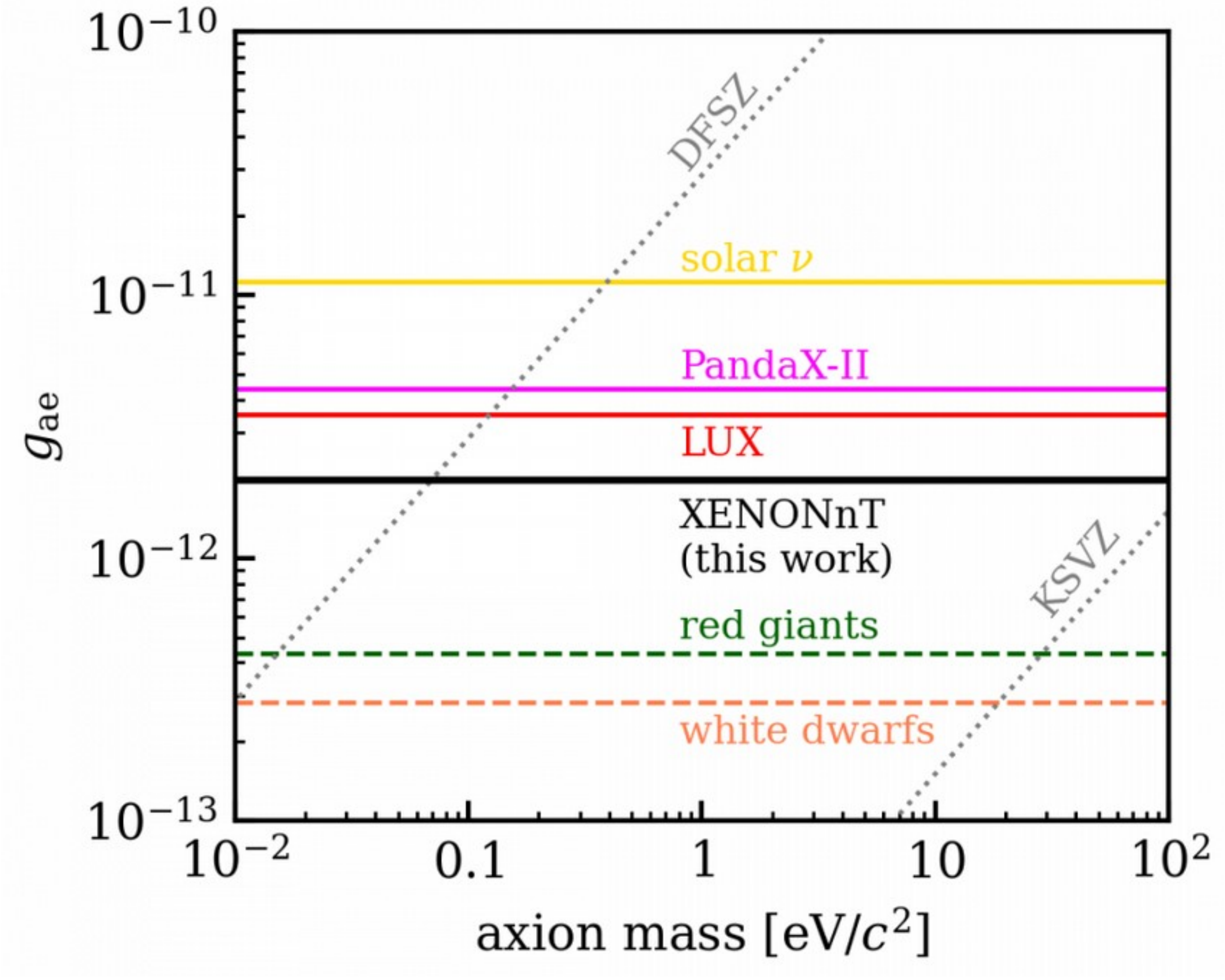
Factor ~5x reduction wrt XENON1T

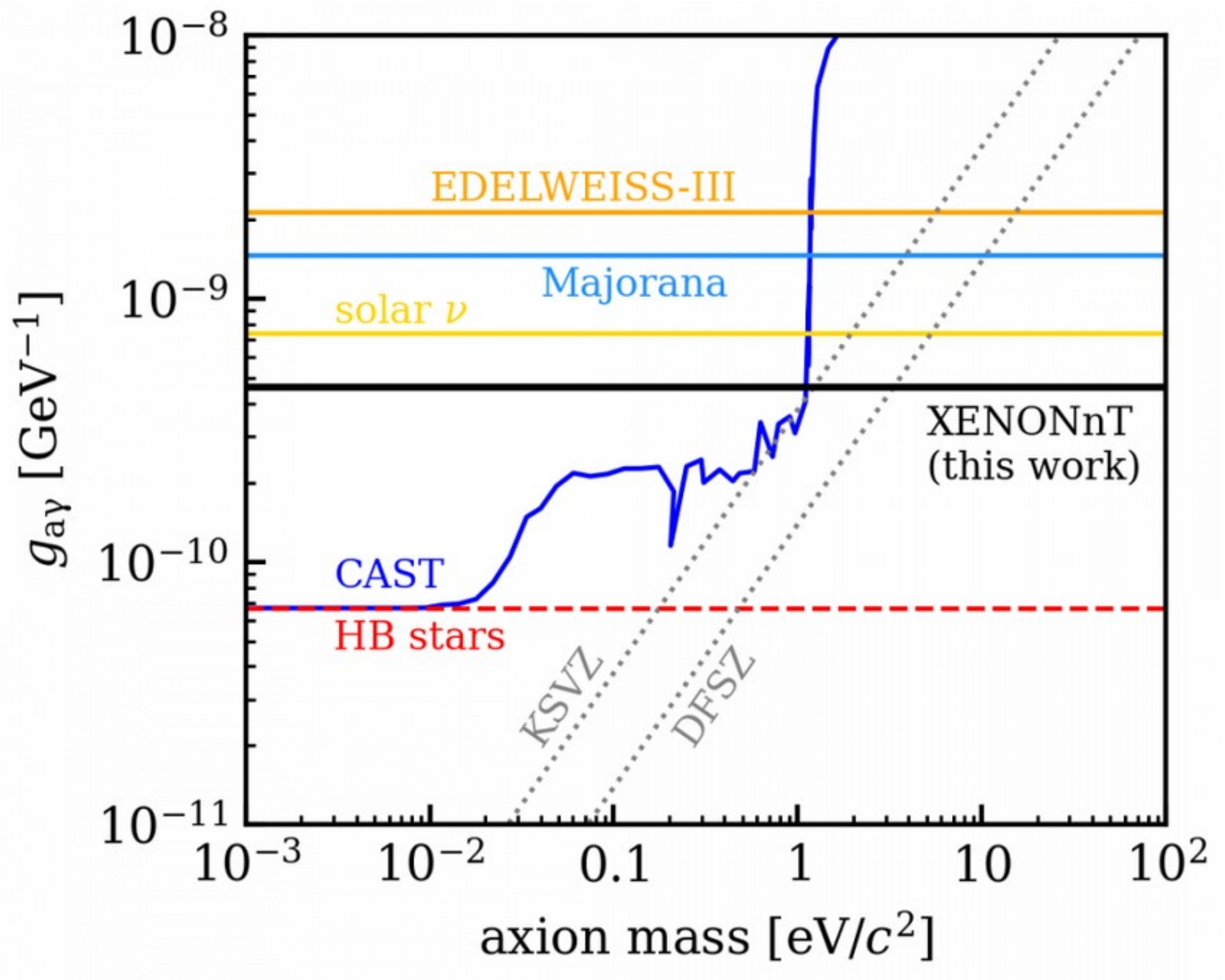
The **excess** observed in XENON1T when modelled as a 2.3 keV mono-energetic peak, is **excluded with a statistical significance of ~4σ**

The **best-fit rate of tritium is 0** and the upper limit (90 % C.L.) is 14 events/(t·y), i.e. to a concentration of 5.4×10^{-26}mol/mol of tritium in xenon.

XENONnT: Solar axions







XENONnT compatible with background-only hypothesis

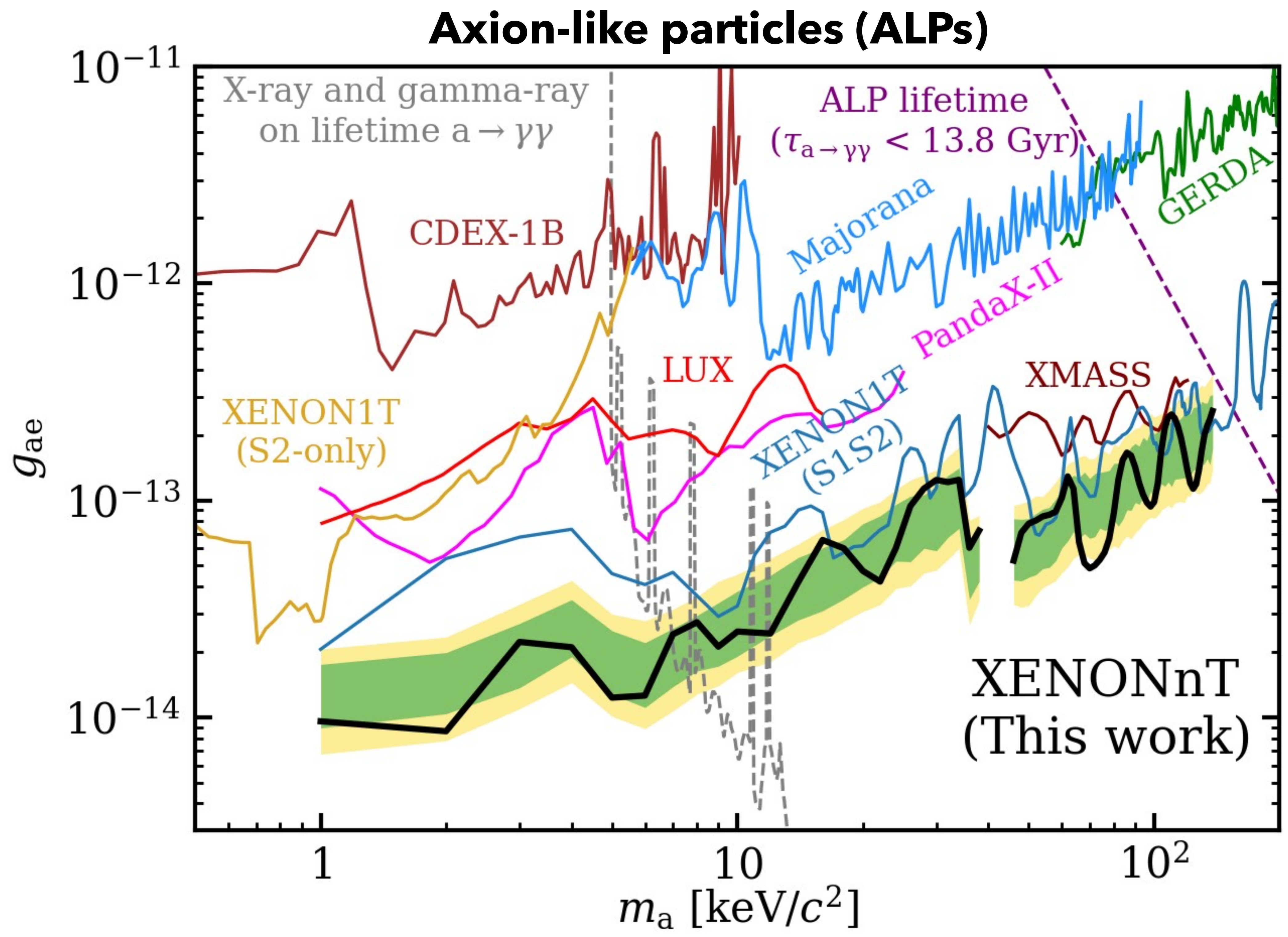
Axion signal assumes axio-electric effect and reverse Primakoff effect

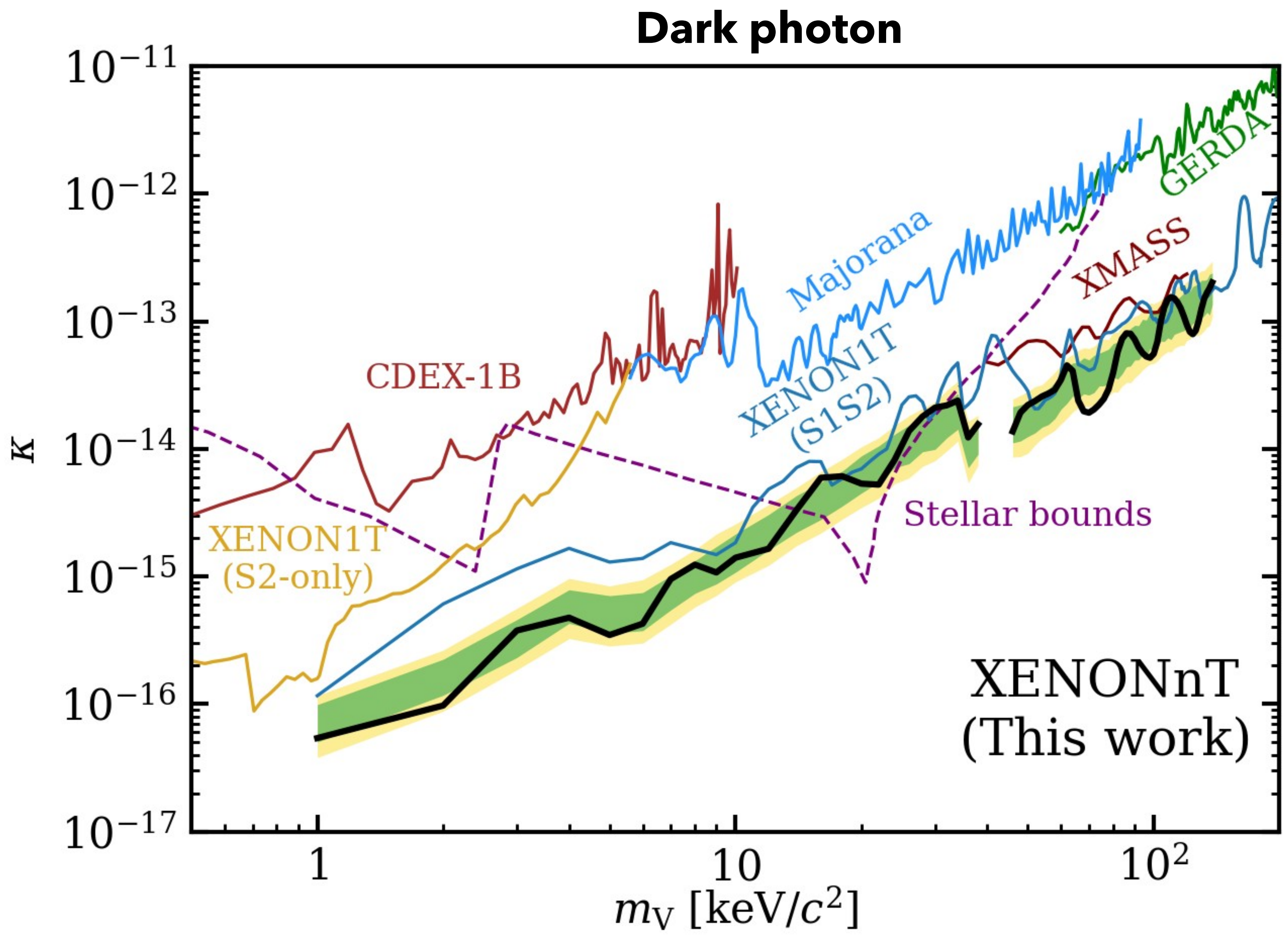
Best direct detection limit of g_{ae} for axion mass below 100 eV/c2

Best direct detection limit of $g_{a\gamma}$ for axion mass between 1 and 100 eV/c2

90% upper limit on 14.4 keV peak from ^{57}Fe solar axion component is 20.4 events/(t yr)

XENONnT: Bosonic DM





Bosonic DM: ALPs and Dark photons

No limit/sensitivity between (39, 44) keV/c2 because ^{83m}Kr background rate is not constrained

Competitive limits for mass in (1, 39) keV/c and (33, 140) keV/c

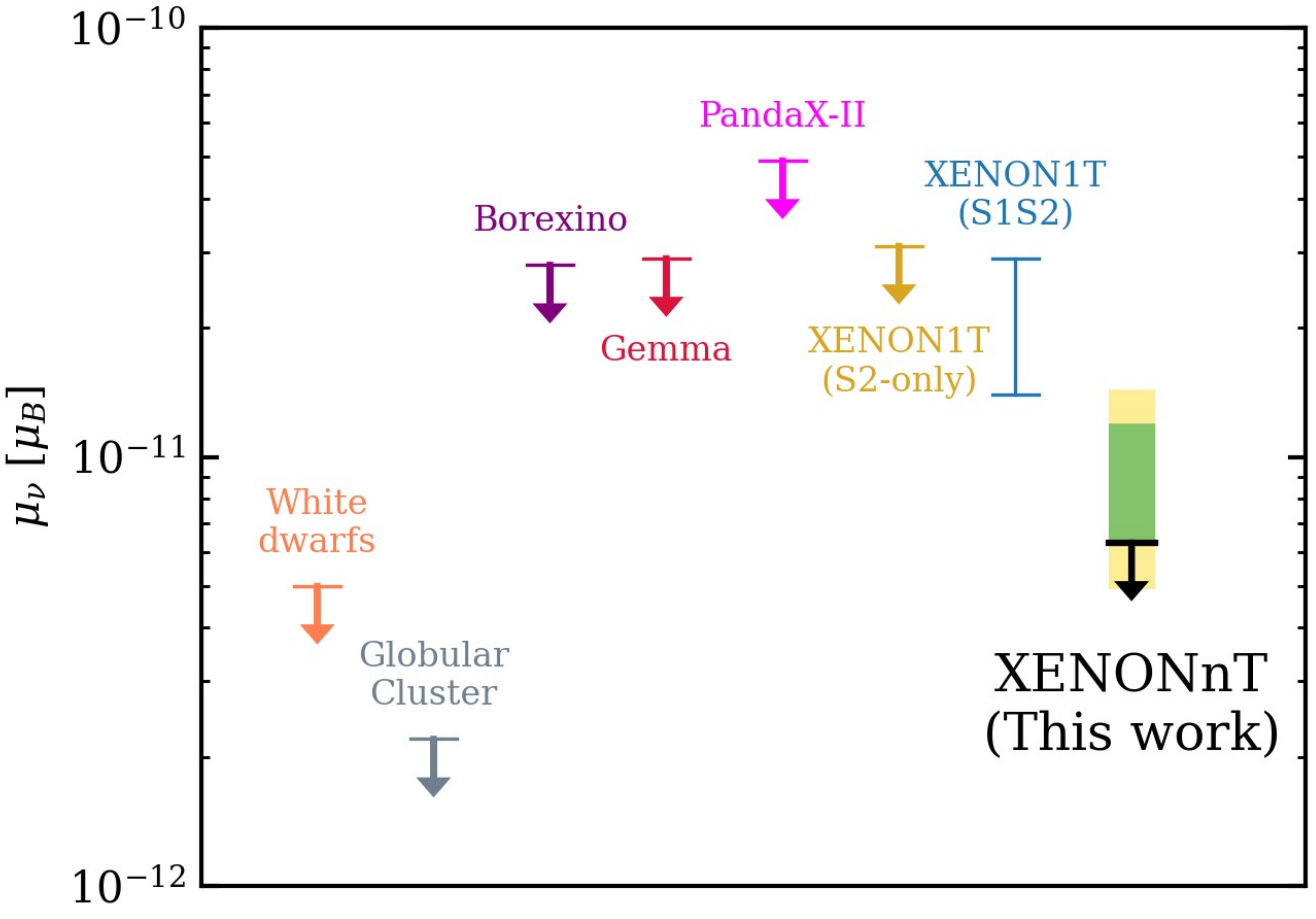
Maximum local significance ~1.8 σ at ~109 keV

XENONnT: Neutrino magnetic moment

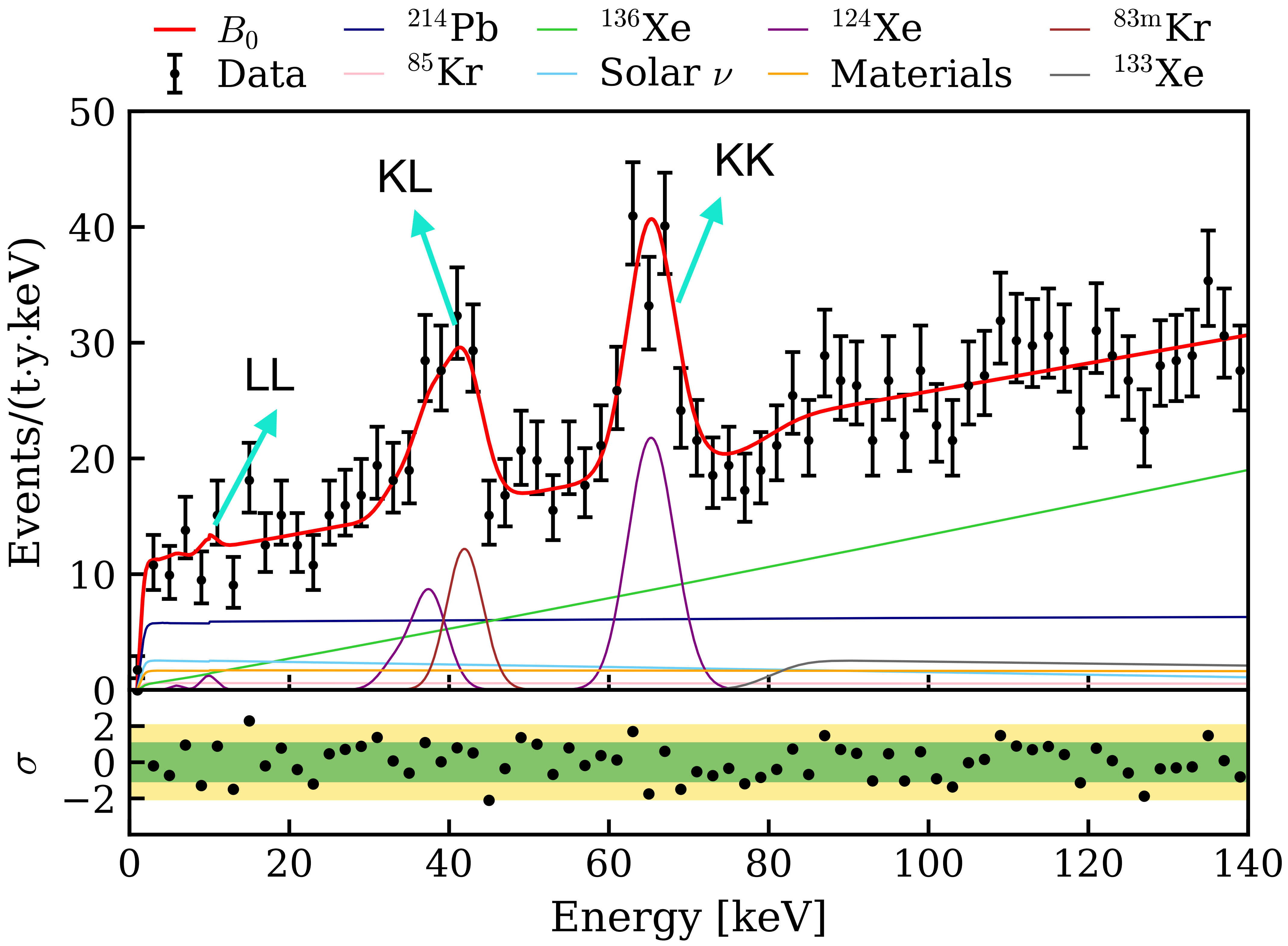
Massive neutrinos imply a not null magnetic moment – if new physics raises this magnetic moment, it may cause an enhanced neutrino scattering rate

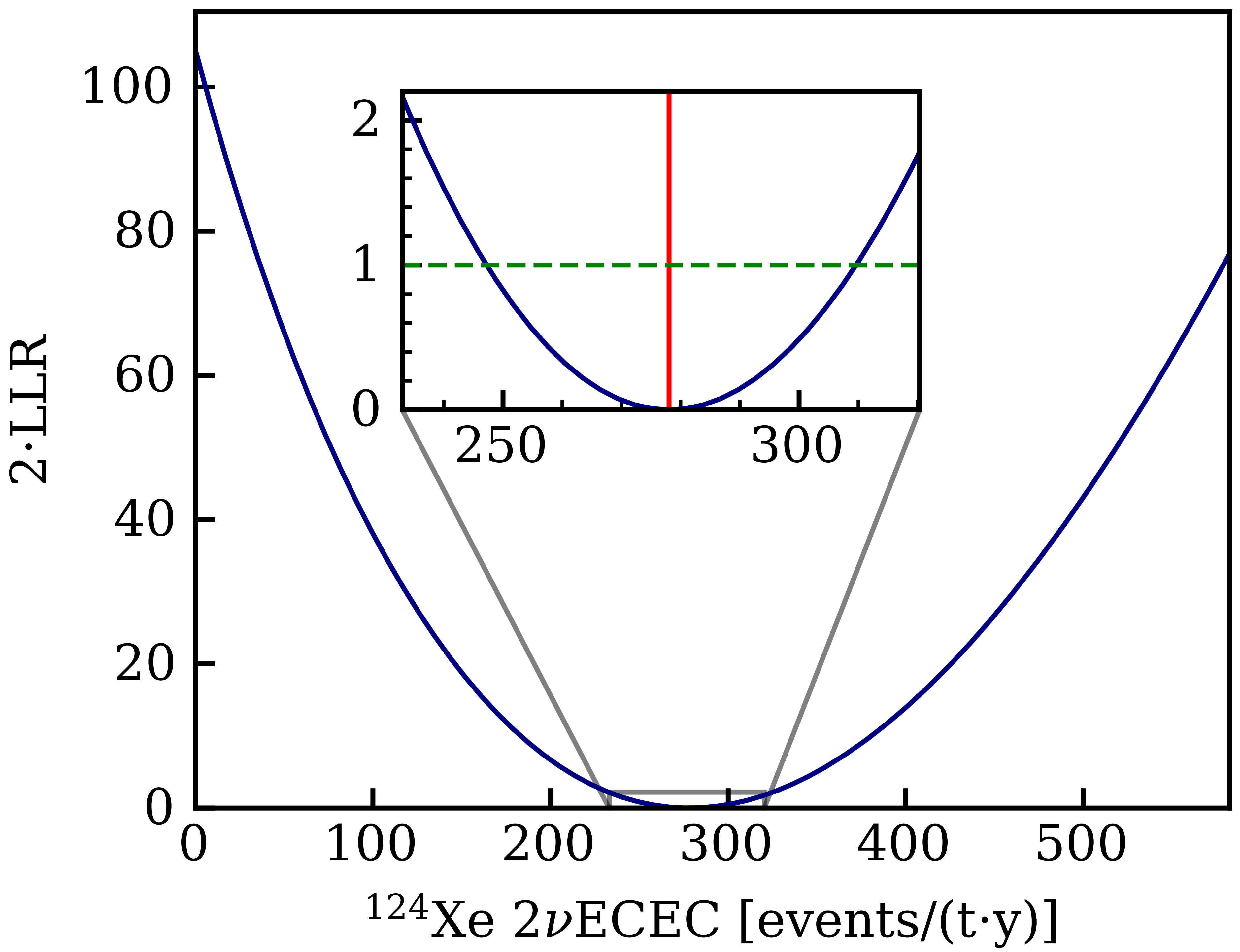
Constraint on neutrino magnetic moment
Upper limit at μv < 6.3*10-12 μB

The most stringent limit in any direct detection experiment



XENONnT: ^{124}Xe 2vECEC





^{214}Xe 2vECEC recognizable in the energy spectrum due to the **ultra-low background**:

- LL peak visible even with only ~1% BR
- KL & KK peaks used for calibration purpose (energy resolution)

The measured half-life T_{2vECEC} = (1.15 ± 0.13 ± 0.14) × 10^{22} yr with a significance of 10σ

Consistent with the previous XENON1T result, T_{2vECEC} = (1.1 ± 0.2 ± 0.1) × 10^{22} yr [XENON Collaboration, Phys. Rev. C 106, 024328]

XENONnT: Conclusions from SR0 ER search

XENONnT performances in SR0:
>10 ms electron lifetime and (1.77 +- 0.01) μBq/kg radon concentration

Exposure 1.16 tonne years (2x XENON1T)
Lowest ER background ever achieved in a DM experiment (0.2x XENON1T):
(16.1 +- 0.3) evts/(t yr keV)

No evidence of ^{3}H, even in the TED

arXiv: 2207.11330

Search for new physics in ER data: best fit signal strength 0, XENON1T peak rejected at 8.6σ

Exclusion of XENON1T excess: measurement incompatible at ~4σ
No evidence of ^{3}H, even in the TED

Most likely explanation of XENON1T excess is a small ^{3}H contamination
Big effort in XENONnT to reduce tritium outgassing

Competitive limits on several new physics models

XENONnT: What next?

Unblinding Nuclear Recoil data soon for WIMP search

A second science run (SR1) with factor 2 lower radon level is ongoing

Follow us at:

xenonexperiment.org

xenon_experiment

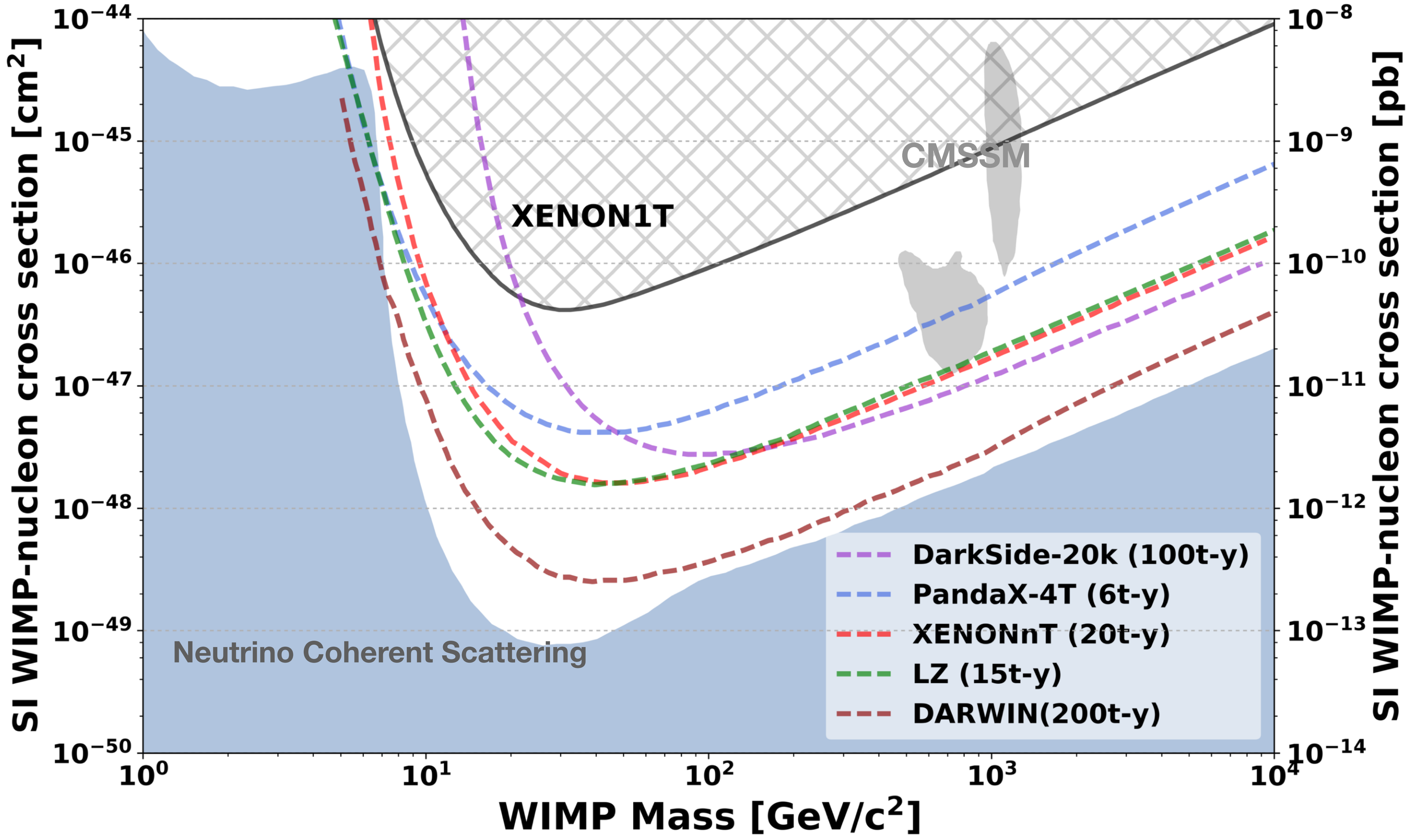
XENONexperiment

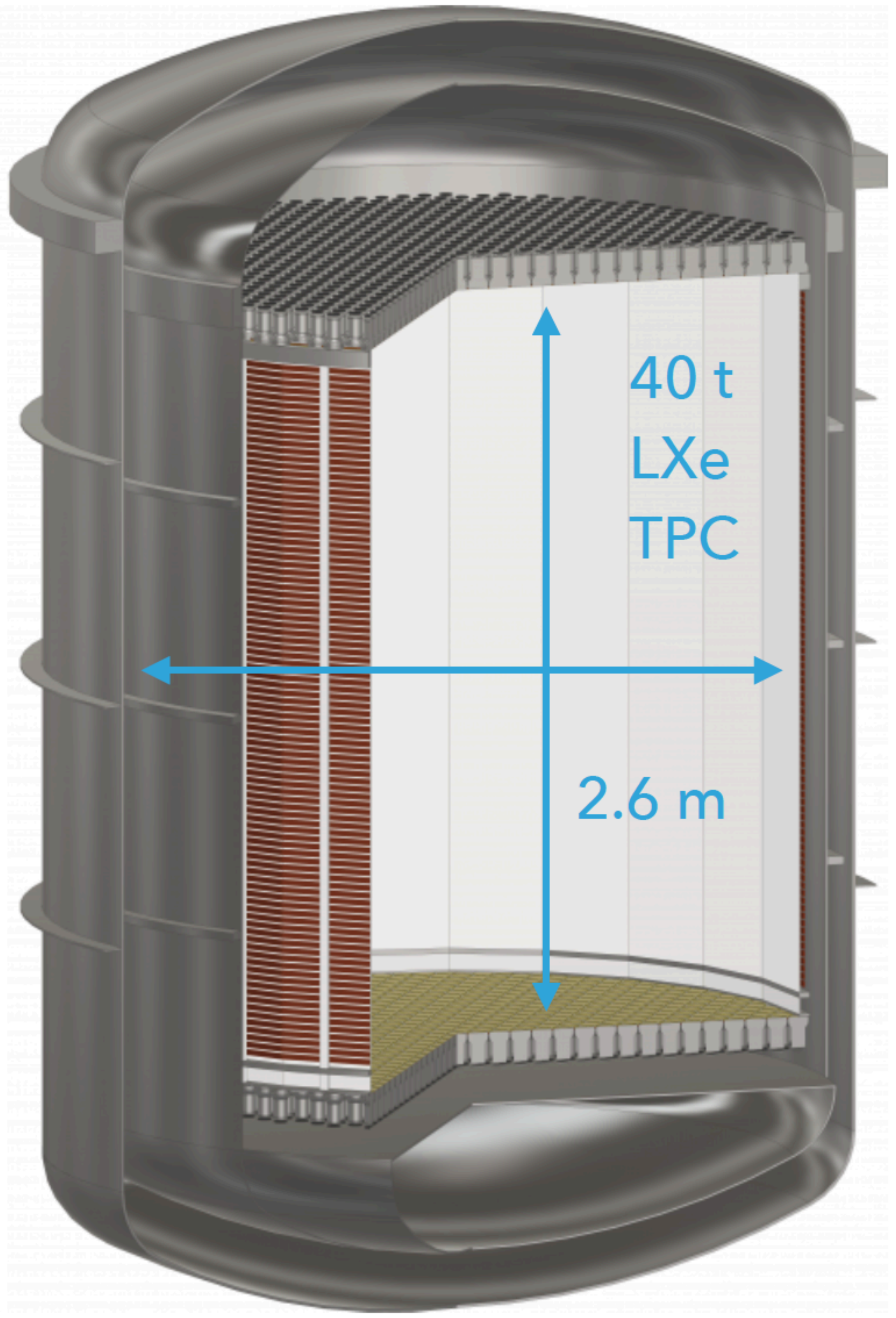
XENON PR Team: xenon-pr@lngs.infn.it

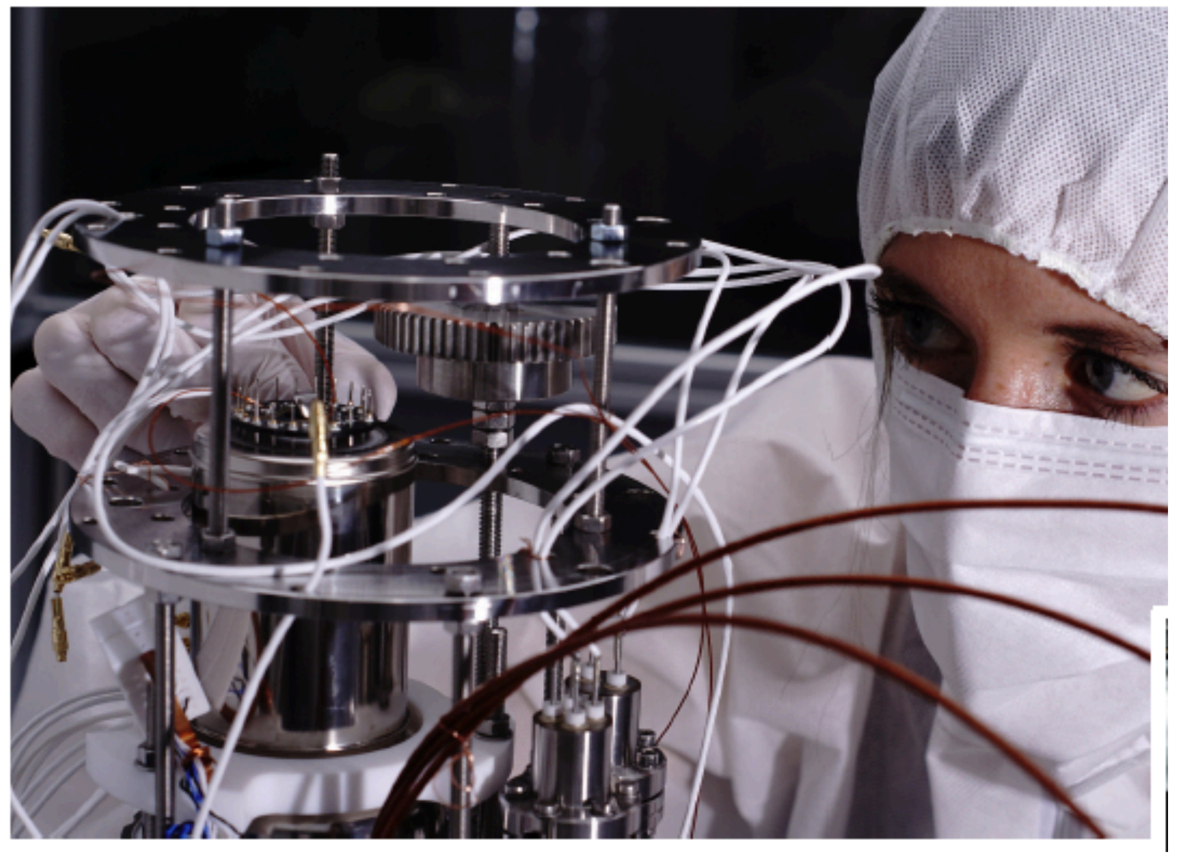
The future: DARWIN

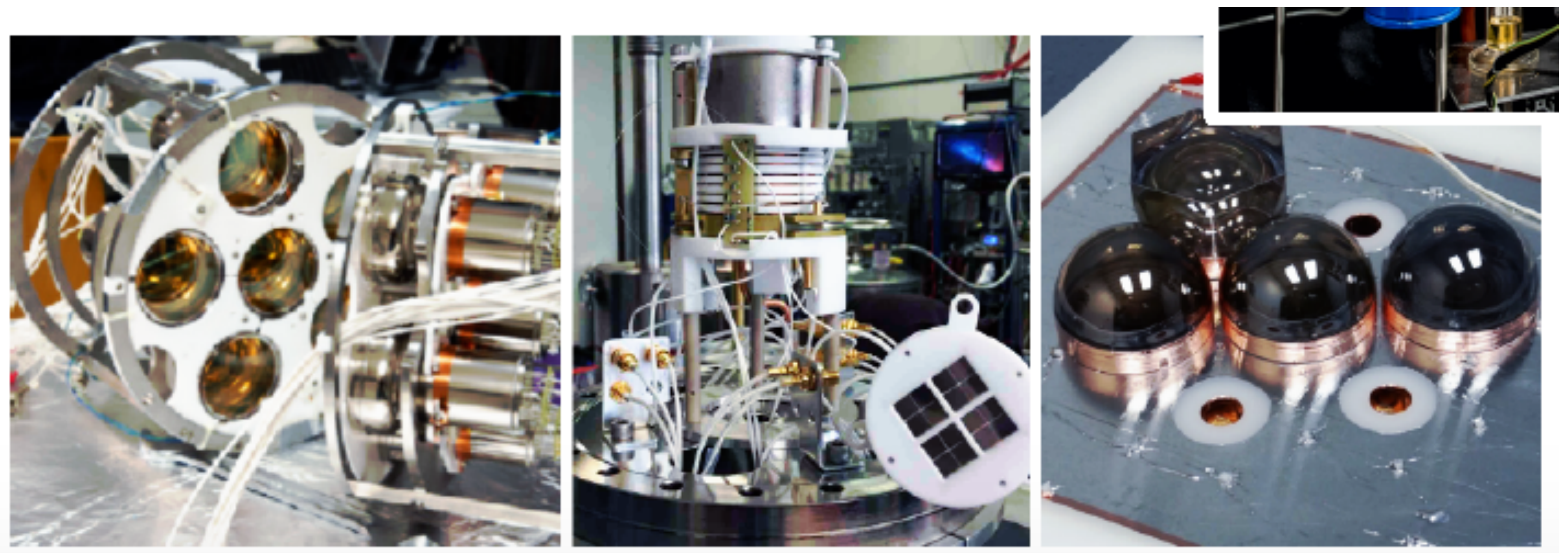
Existing collaboration working on a CDR for a
Larger detector with
Lower background: the irreducible
neutrino background

R&D on electrodes, photosensors



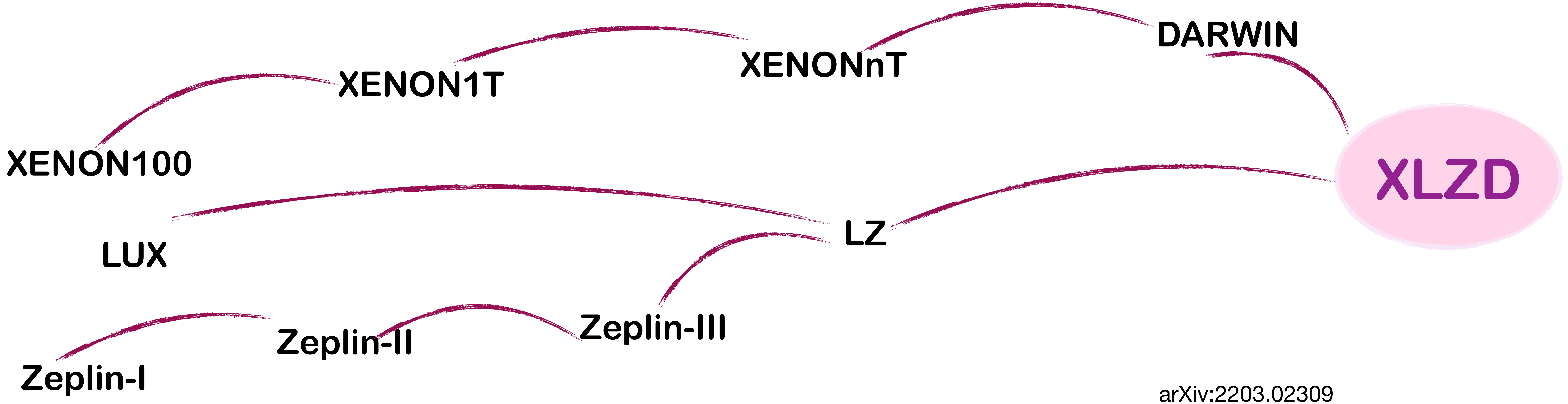






Based on XENON detection techniques but different challenges related to larger and much more radiopure detector

The future: XLZD consortium

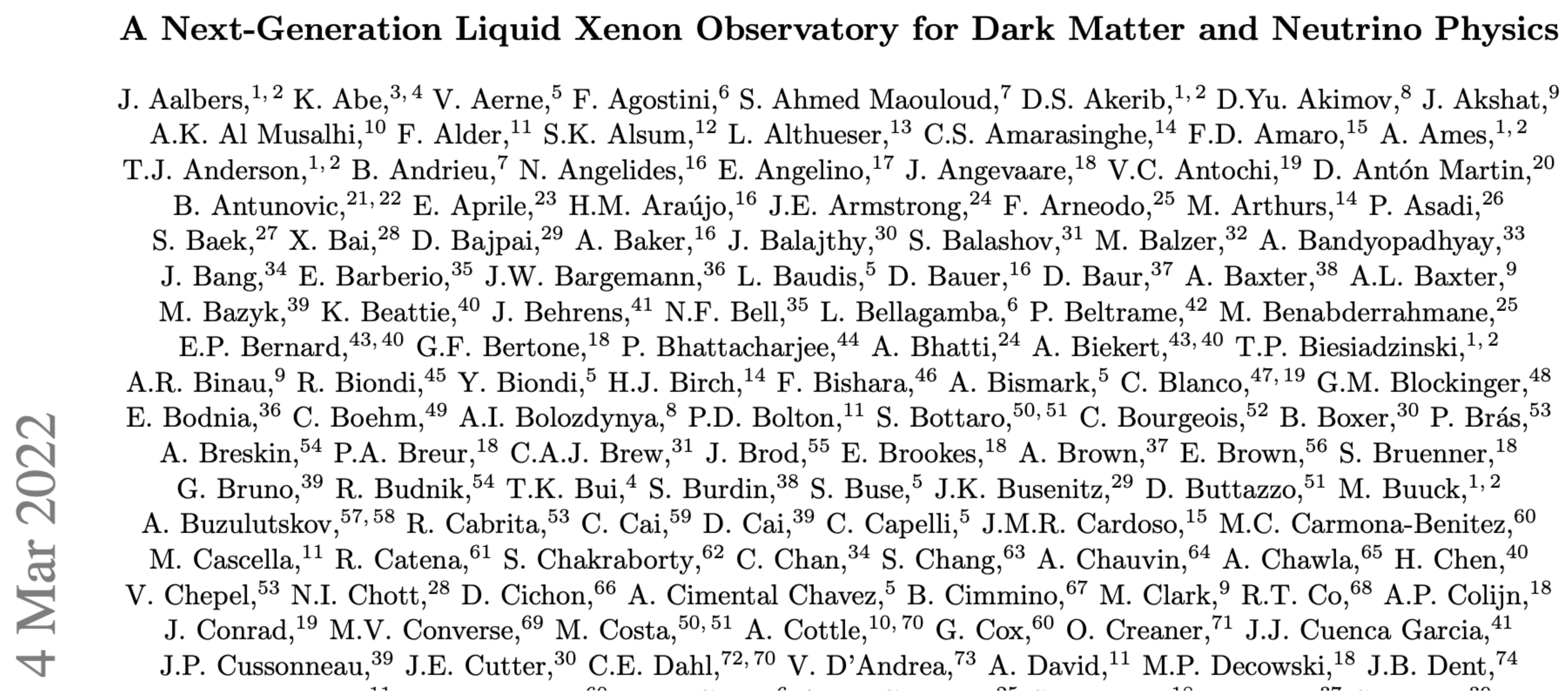


- **Consortium between XENON/DARWIN and LUX-Zeplin (LZ) established on July 2022**

- **Memorandum of understanding** between XENON and DARWIN members to collaborate signed on July 6, 2021 by 104 research group leaders from 16 countries

- **Community whitepaper** with combined science goals, background considerations, priorities posted on arXiv March 2022.

arXiv:2203.02309



4 Mar 2022

A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics

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