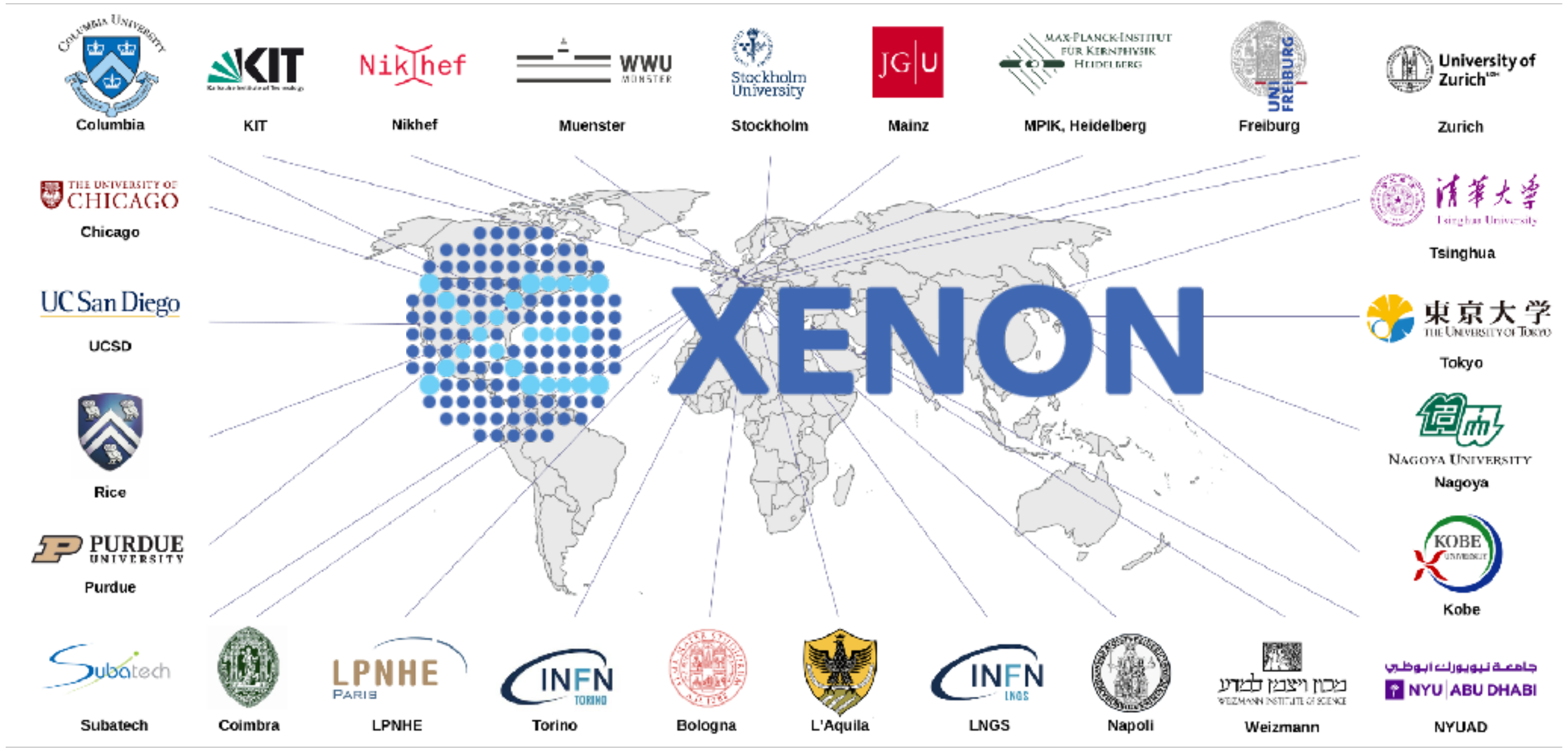
Direct Dark Matter Search with XENON and DARWIN

Shingo Kazama (Nagoya University, KMI)

Symposium on Frontiers of Underground Physics
31st October 2023

The XENON Project @ LNGS



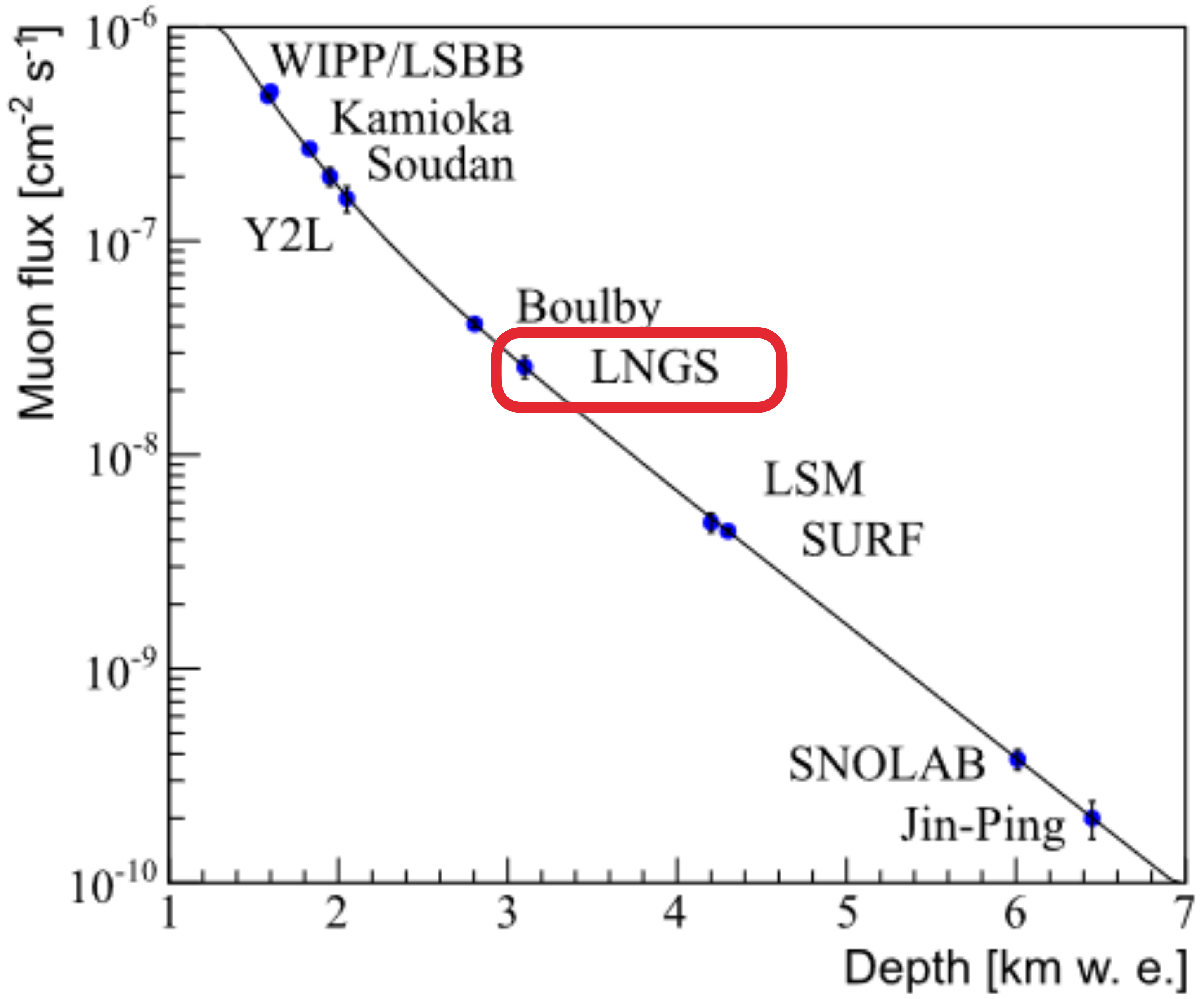
28 institutions
180 collaboration members
in 11 countries

+

西湖大學
WESTLAKE UNIVERSITY

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


Collaboration Meeting in Paris (2023 Sep.)



The XENON and DARWIN Experiment

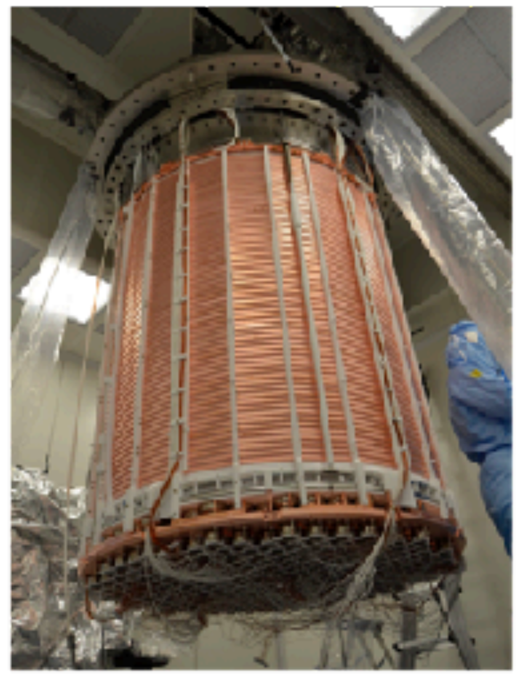
XENON

DARWIN

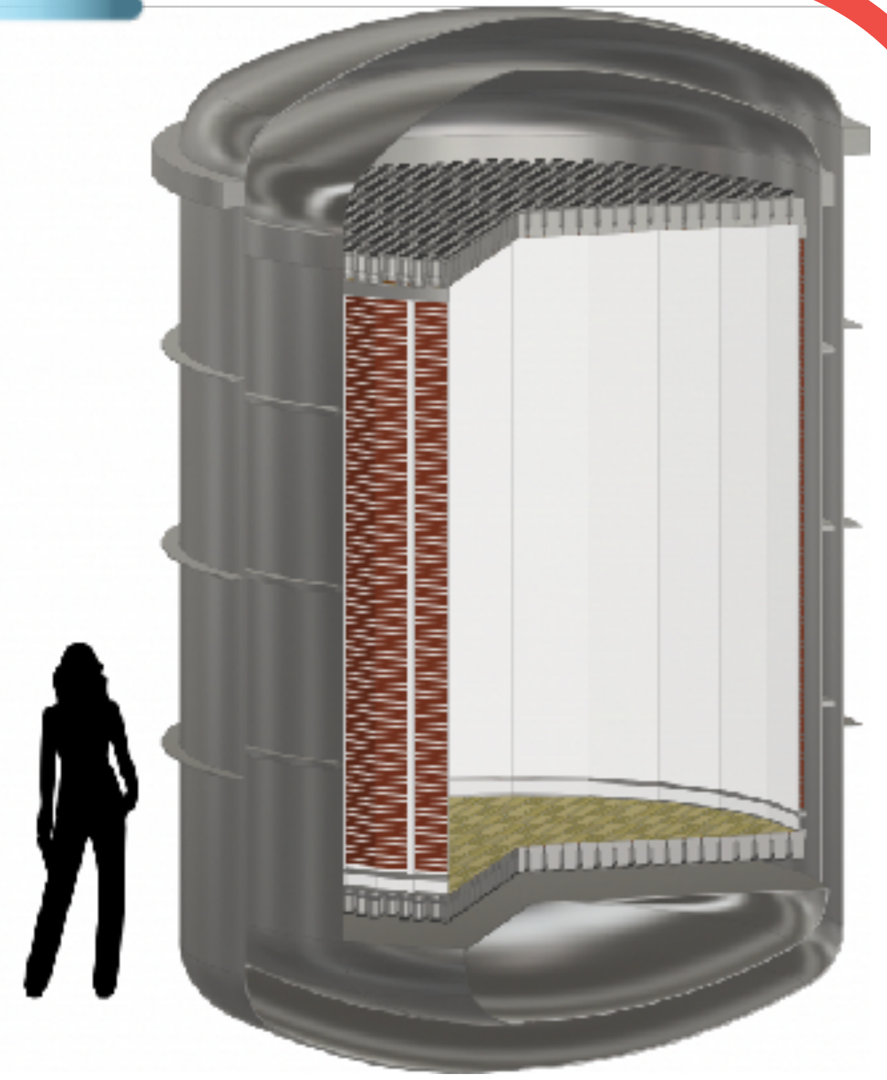
XENON10
Total Xe: 25 kg
Target: 14 kg
Fiducial: 5.4 kg

XENON100
Total Xe: 162 kg
Target: 62 kg
Fiducial: 48 kg

XENON1T
Total Xe: 3.2 ton
Target: 2.0 ton
Fiducial: 1.3 ton



XENONnT
Total Xe: ~ 8.5 ton
Target: ~5.9 ton
Fiducial: ~4 ton



DARWIN
Total Xe: ~50 ton
Target: ~40 ton
Fiducial: >30 ton

XENON10 · XENON100 · XENON1T · XENONnT · DARWIN

2005 · 2010 · 2015 · 2020 · 2027- 2030s

The XENONnT Experiment

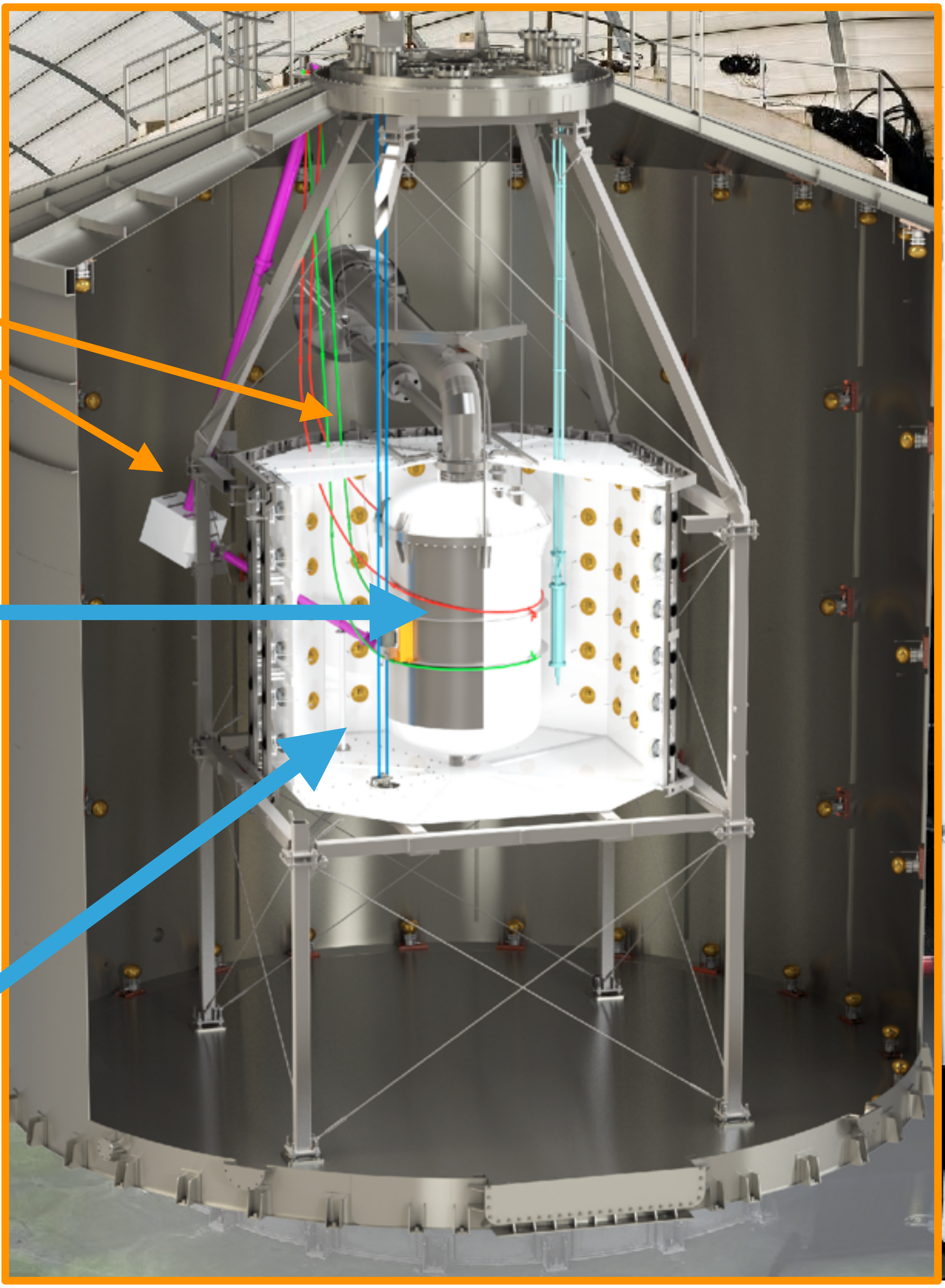
The XENONnT Detector

ER and NR calibration systems

TPC

Active target: 5.9 t
Tota: 8.5 t

Gd-loaded Water Cherenkov neutron veto

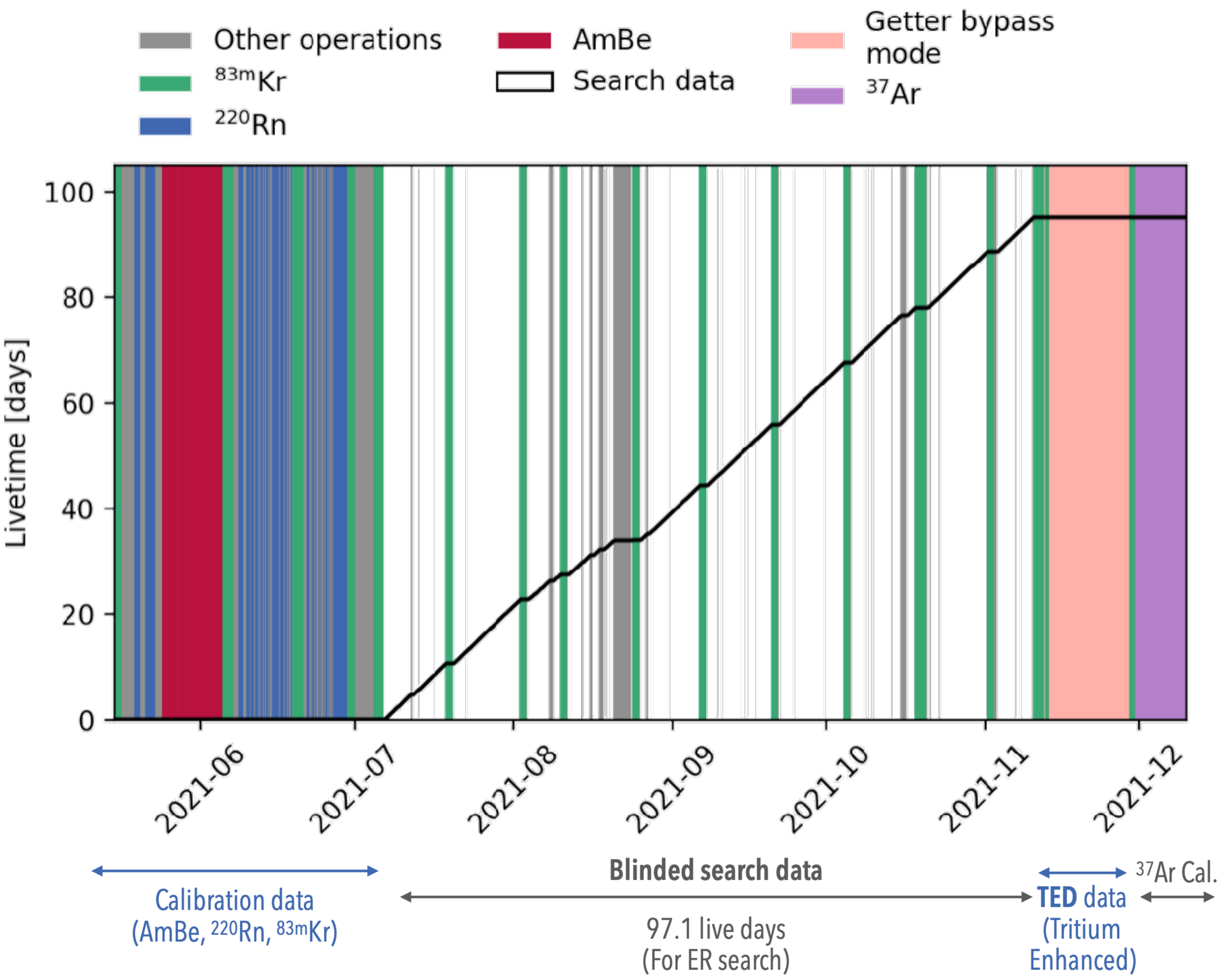


Radon distillation column

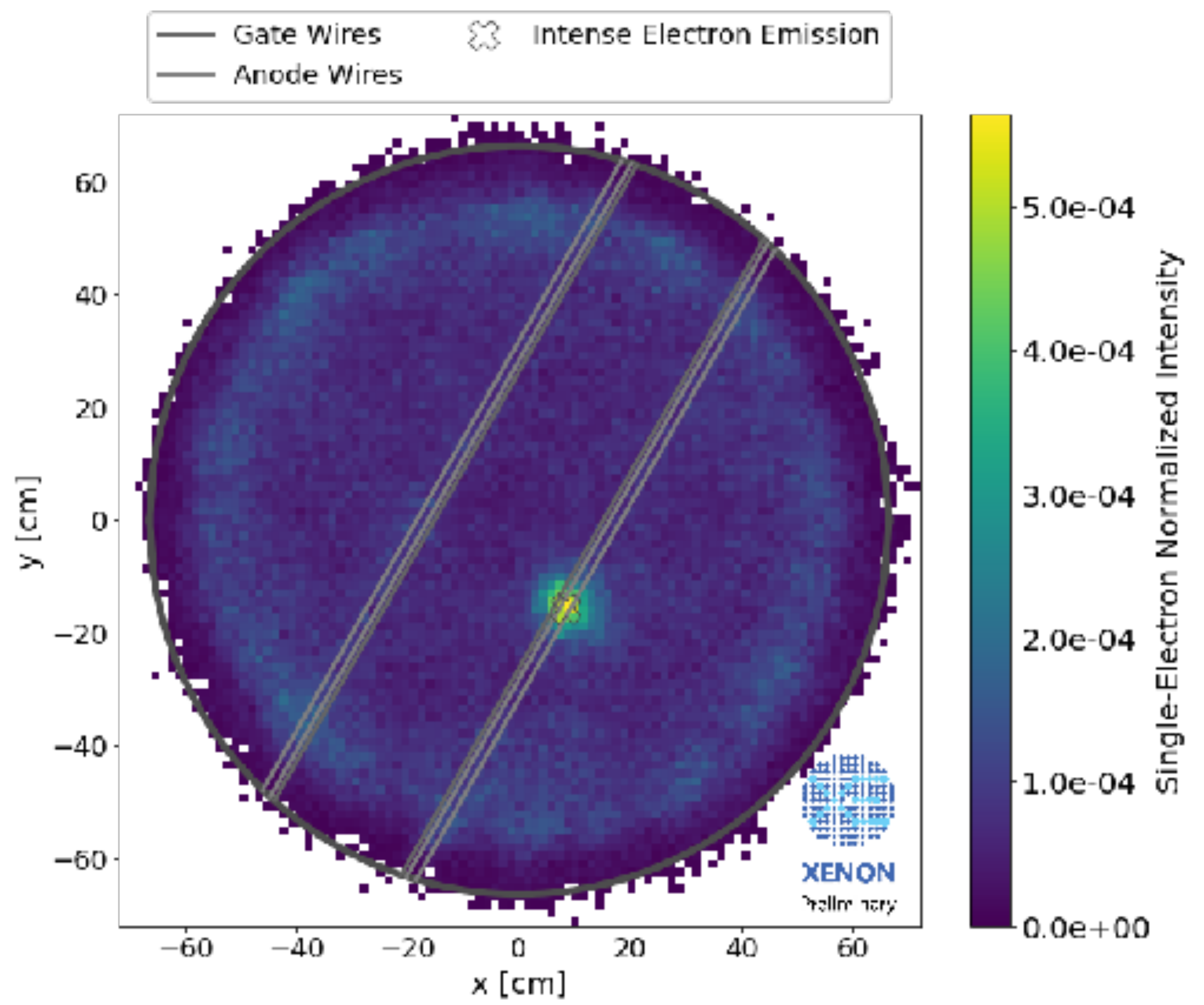
Upgraded DAQ with dedicated high-energy readout

Liquid xenon purification

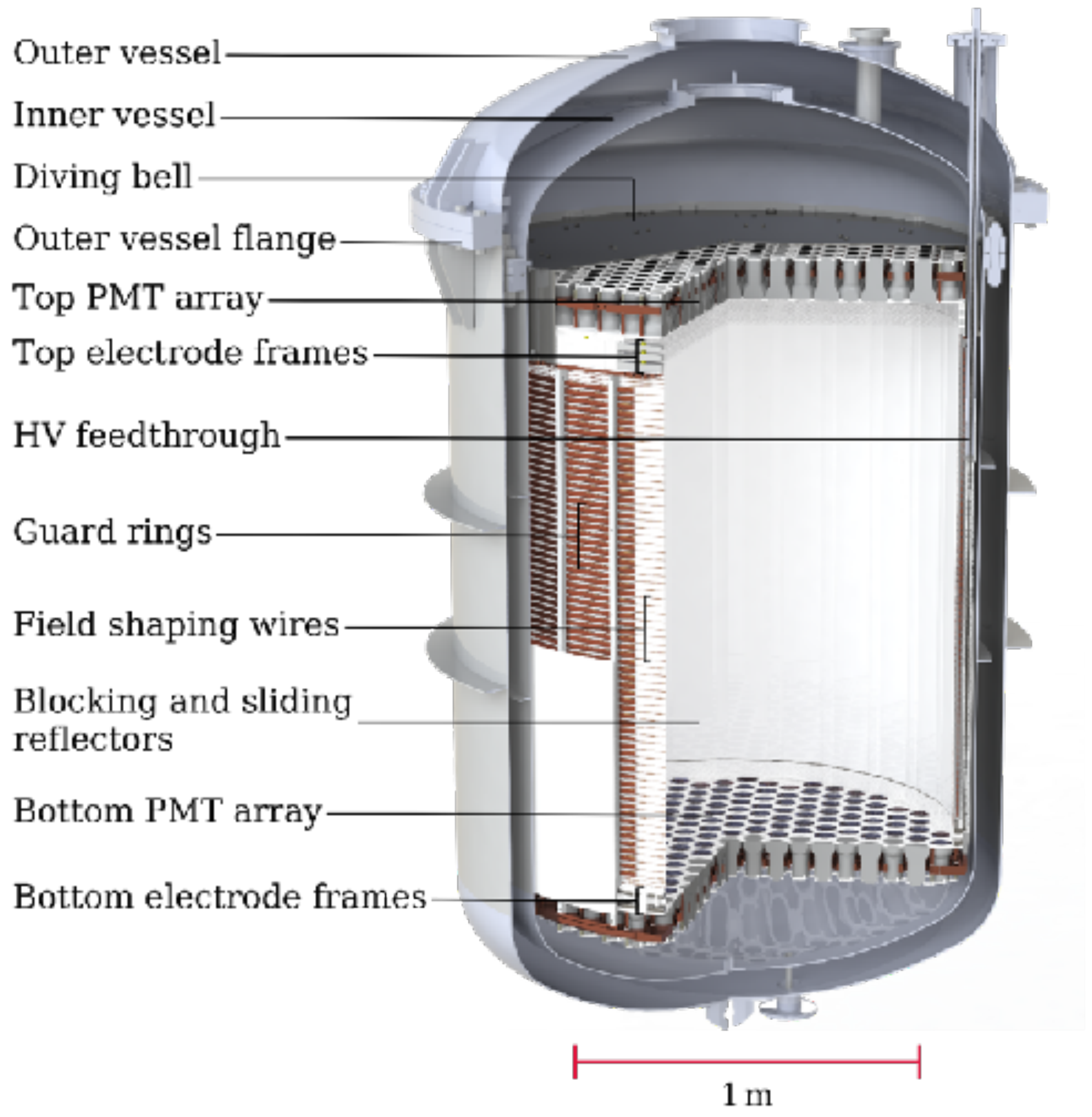
The XENONnT Timeline: Science Run 0

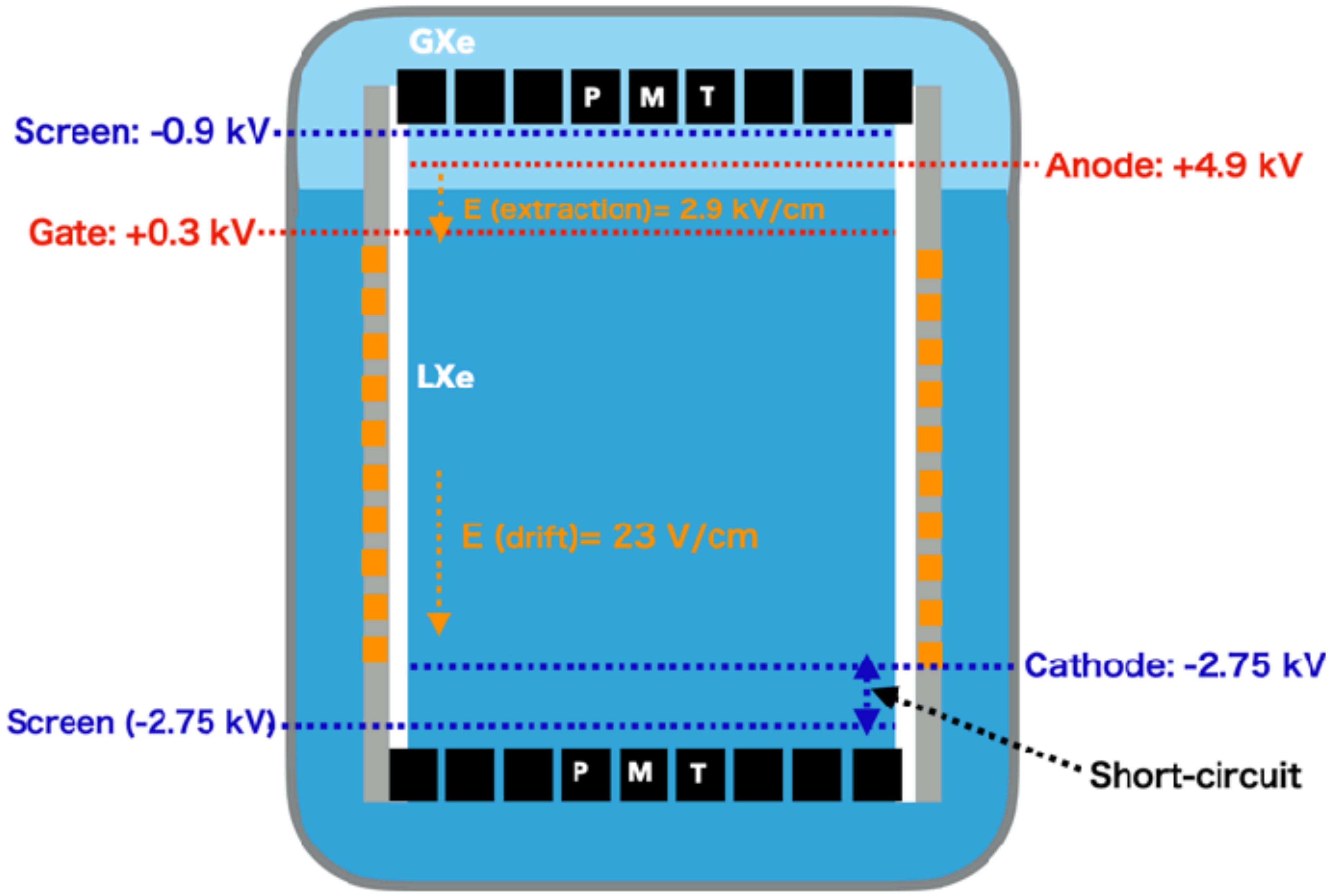


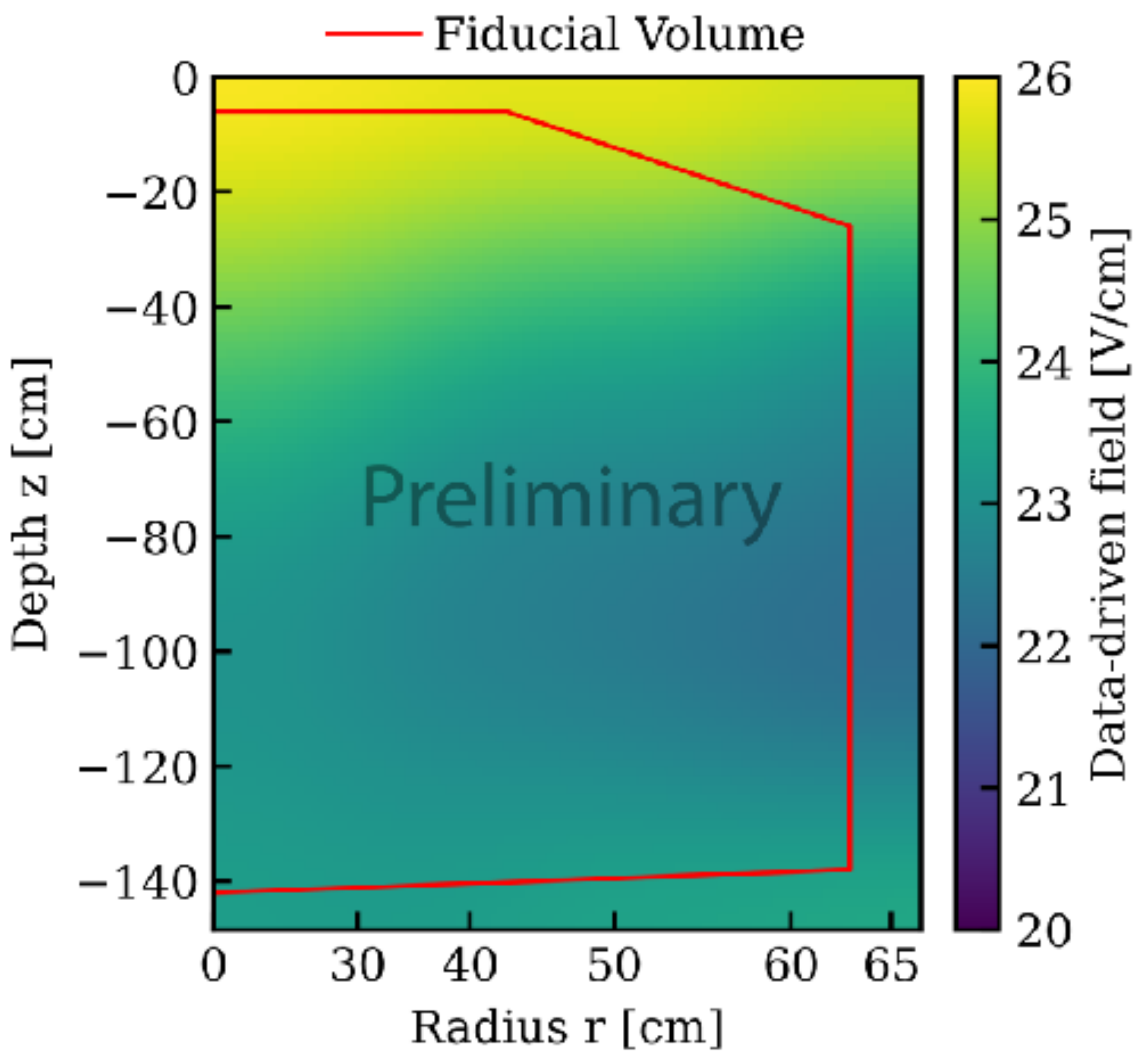
- 97.1 days exposure from Jul. 6th-Nov. 11th 2021
- 95.1 days lifetime corrected
- Rn distillation column in gas-only mode
- All (=494) but 17 PMTs working, gain stable at < 3 %
- Drift E-field: 23 V/cm
- Extraction Field: 2.9 kV/cm
- Localized high single-electron emission occurring seemingly at random, anode ramped down



Dual-Phase Time Projection Chamber

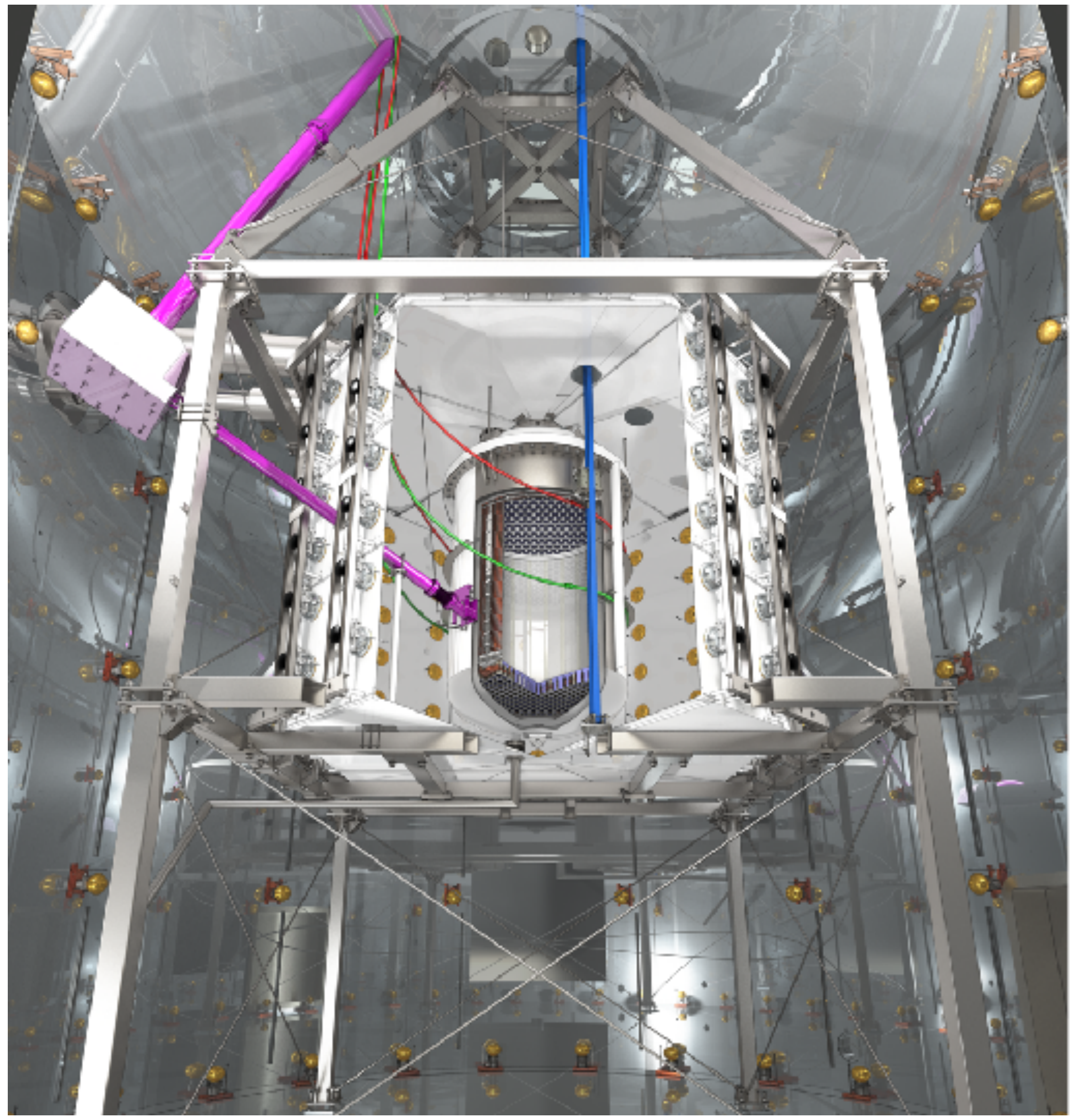


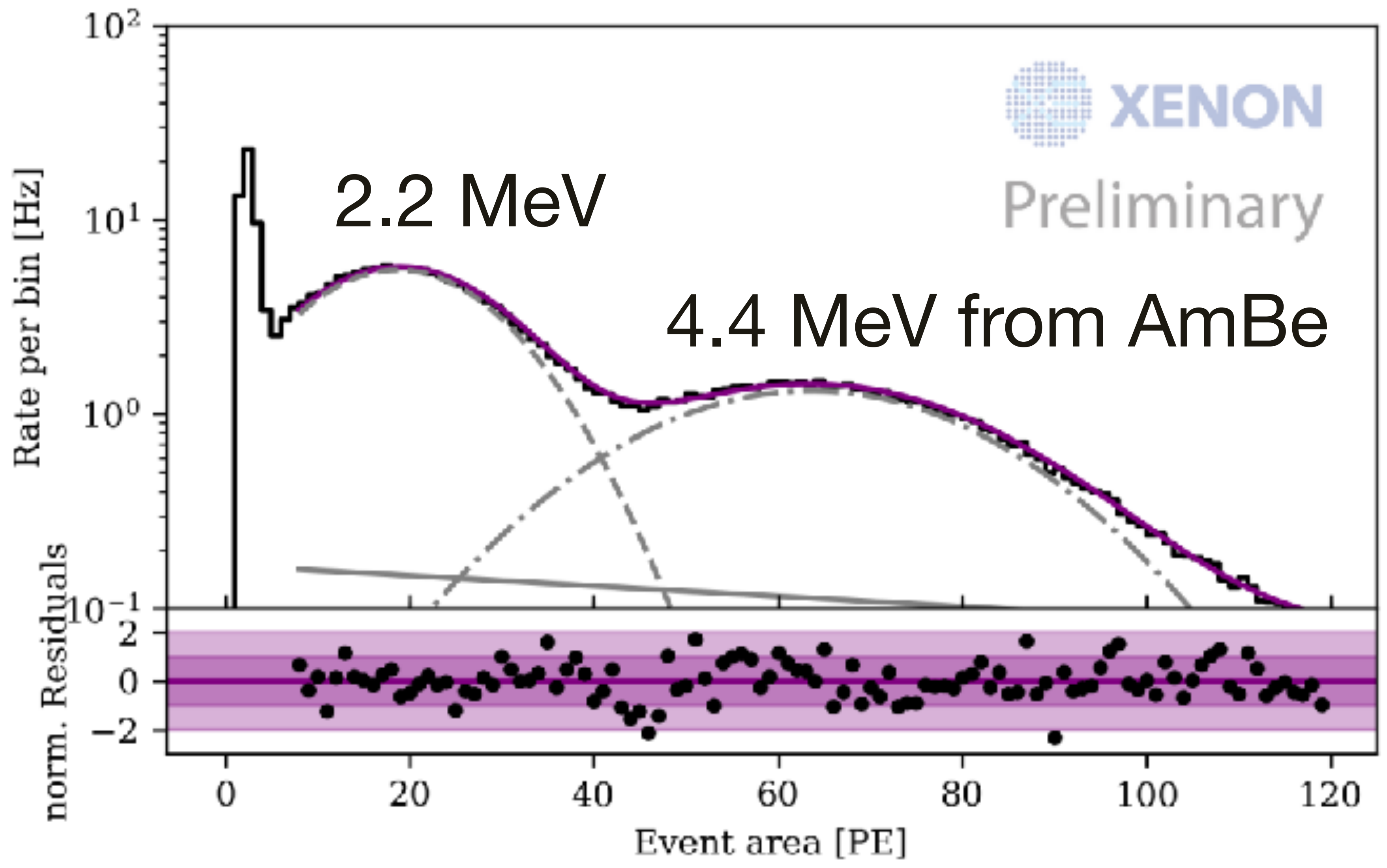


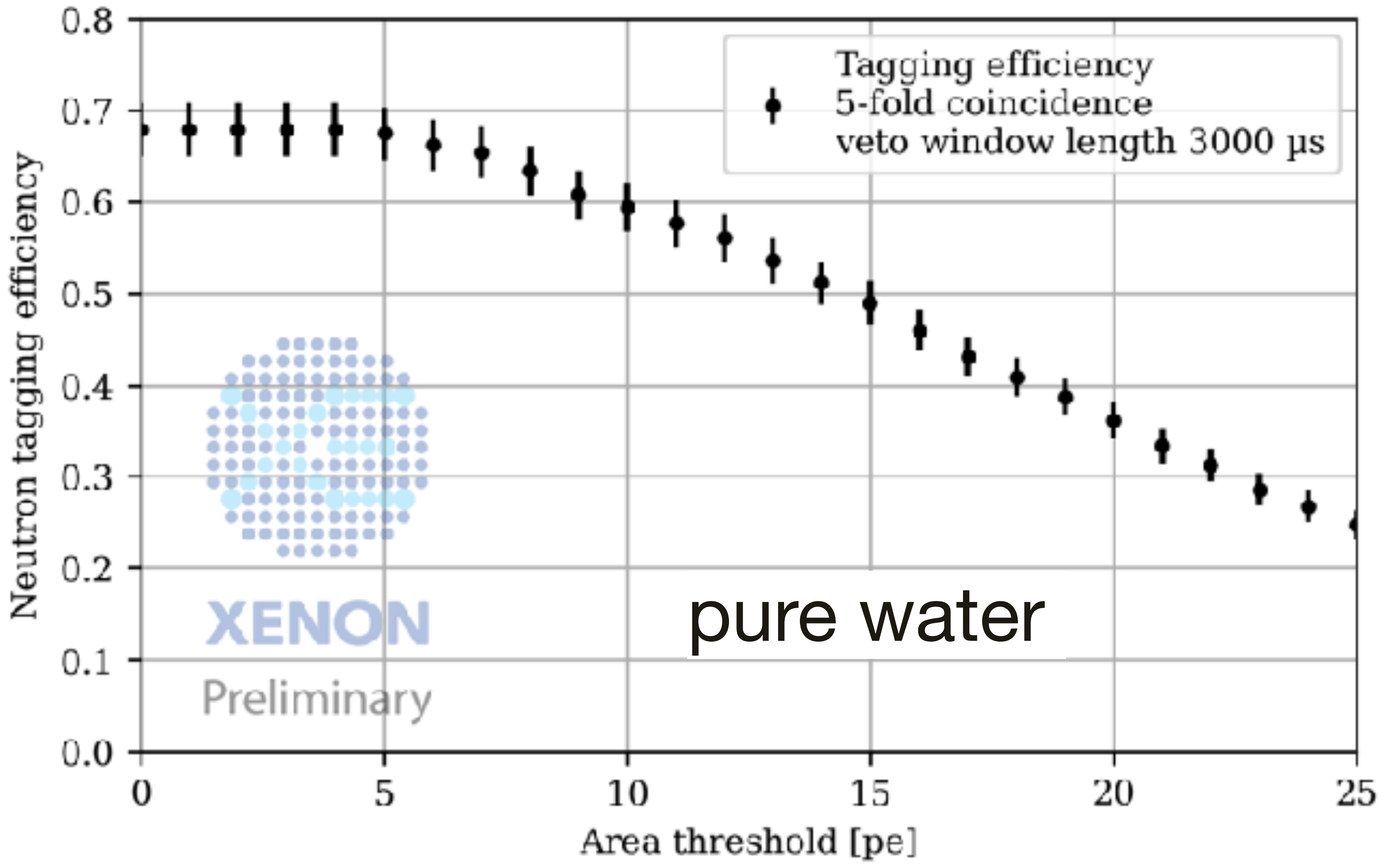


- 1.3 m diameter and 1.5 m height
- 5.9 t xenon instrumented, 8.5 t total xenon
- 5 electrodes and 2 sets of field shaping rings
- PTFE reflectors to maximize light collection efficiency (LCE ~ 36%)
- 494 3” PMTs (R11410-21) in the top/bottom array (QE ~ 34%)
- short-circuit between the cathode and bottom screen limited the cathode voltage to –2.75 kV → E-field at 23 V/cm

Veto Systems



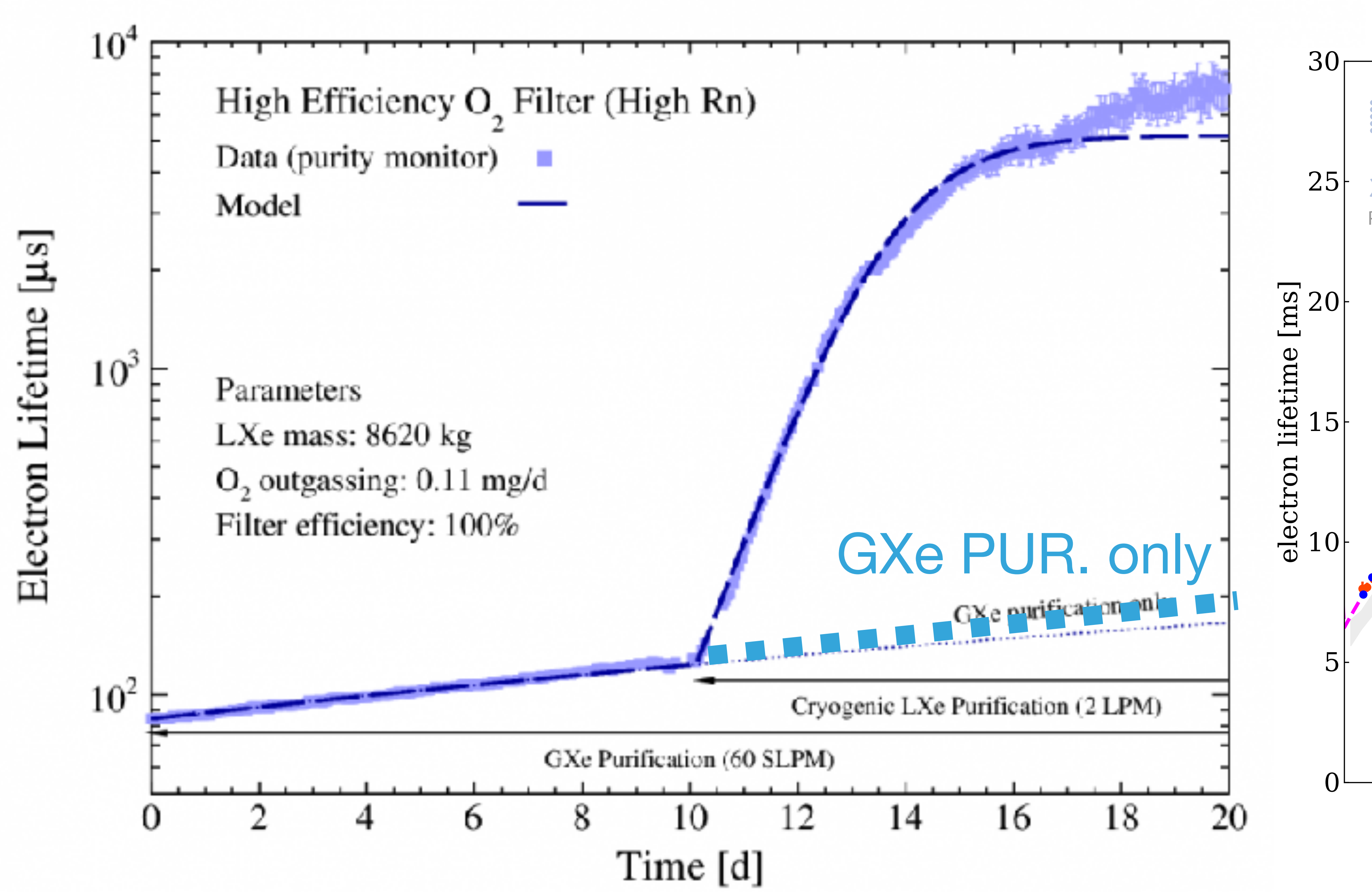


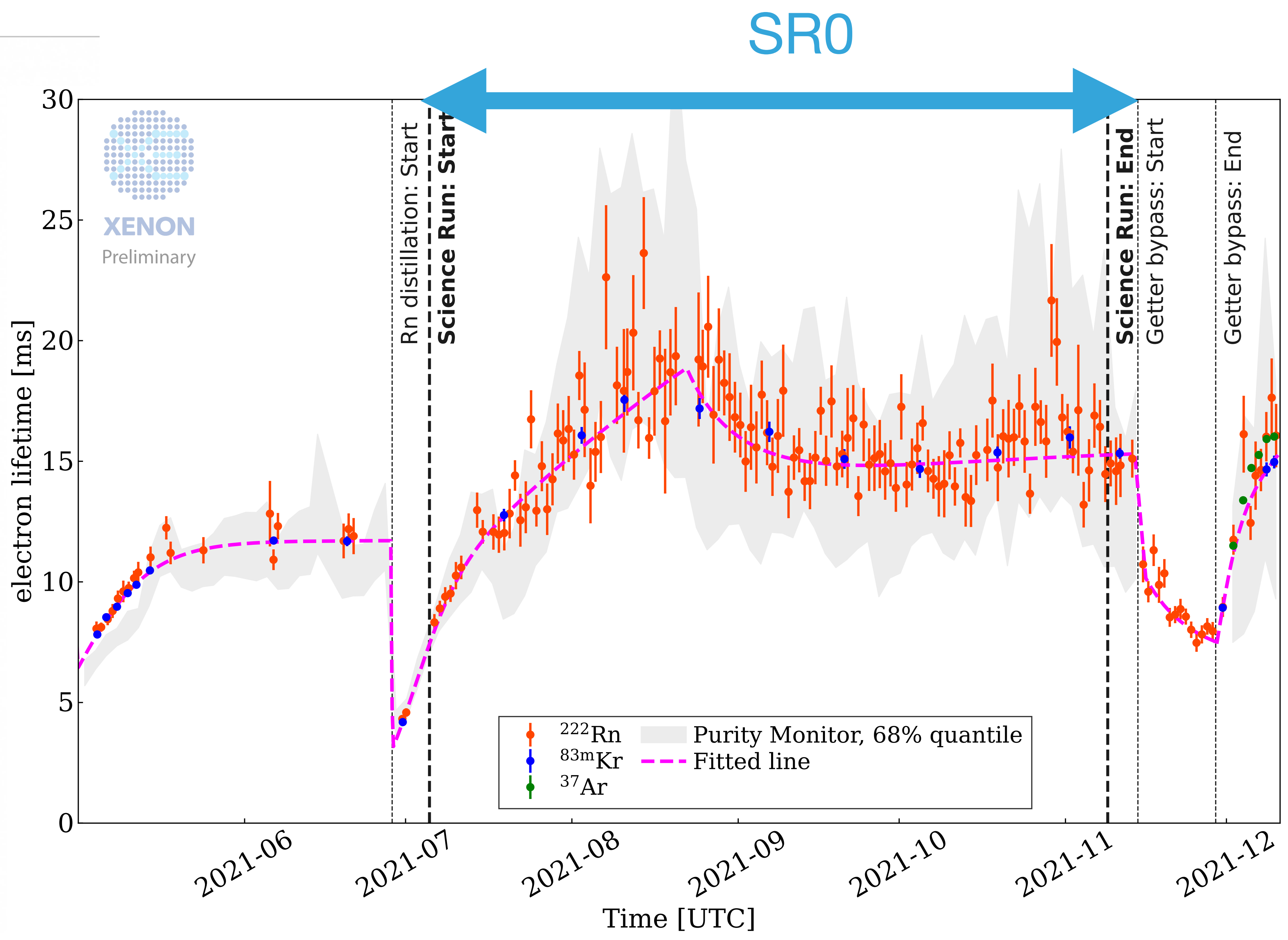


- Gd-Water Cherenkov detector (SuperK/EGADS technology)
- In SR0, operated nVeto with pure-water
- Tag neutrons through the neutron-capture on hydrogen which releases a 2.2 MeV γ-ray
- Covering the entire detector wall with ePTFE (~99% reflectivity)

- Measured (68 ± 3) % tag. efficiency @ 600 μs window and a 5-fold PMT coincidence, and 5 PE threshold
- 53 % tag. efficiency with SR0 configuration (250 μs veto window)
- 0.2 % Gd doping will improve it to 87 % (150 μs, 10-fold)

LXe Purification





◉Direct liquid circulation with cryogenic pump

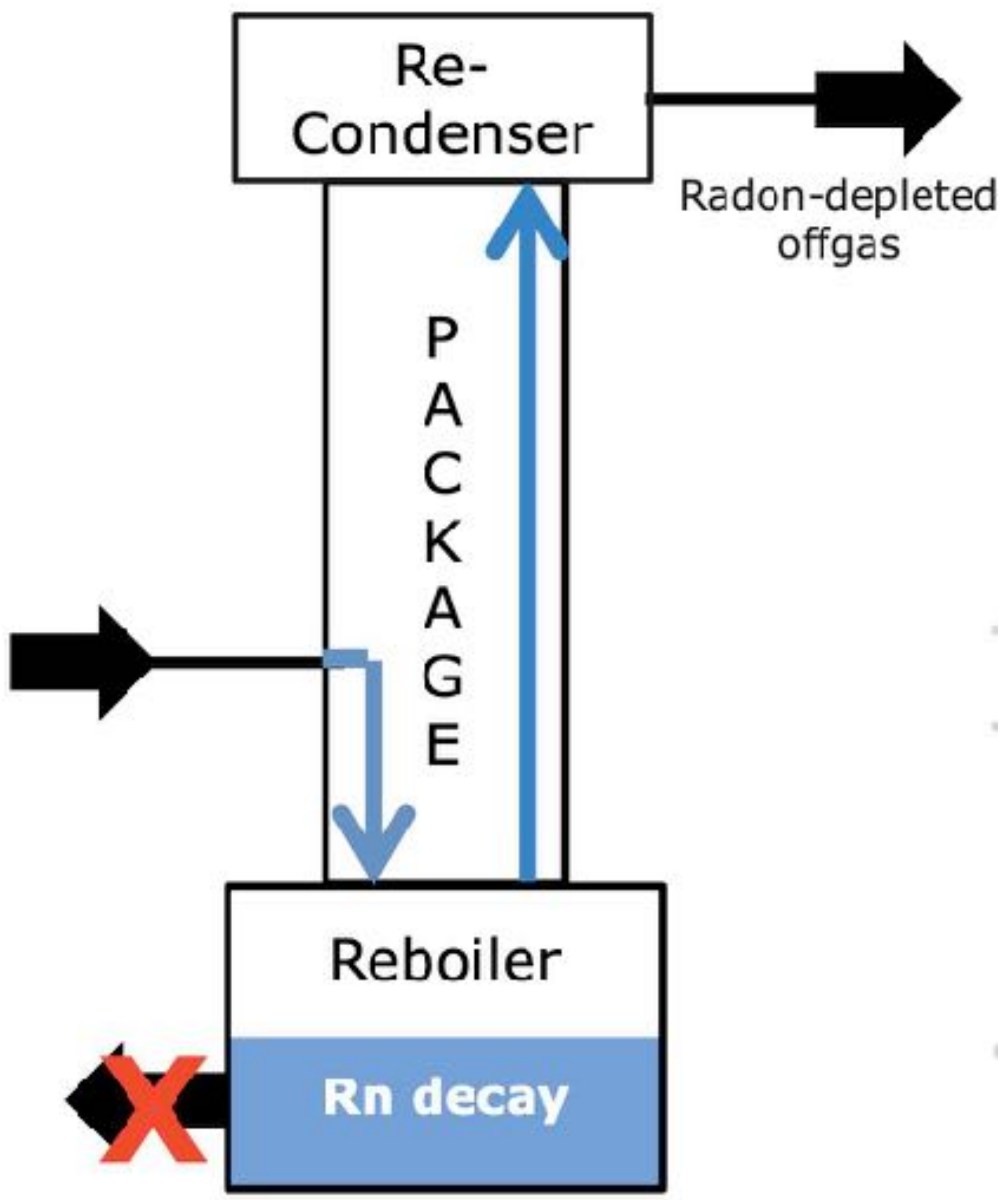
- 2 LPM (18h to exchange the entire volume of 8.5 ton)

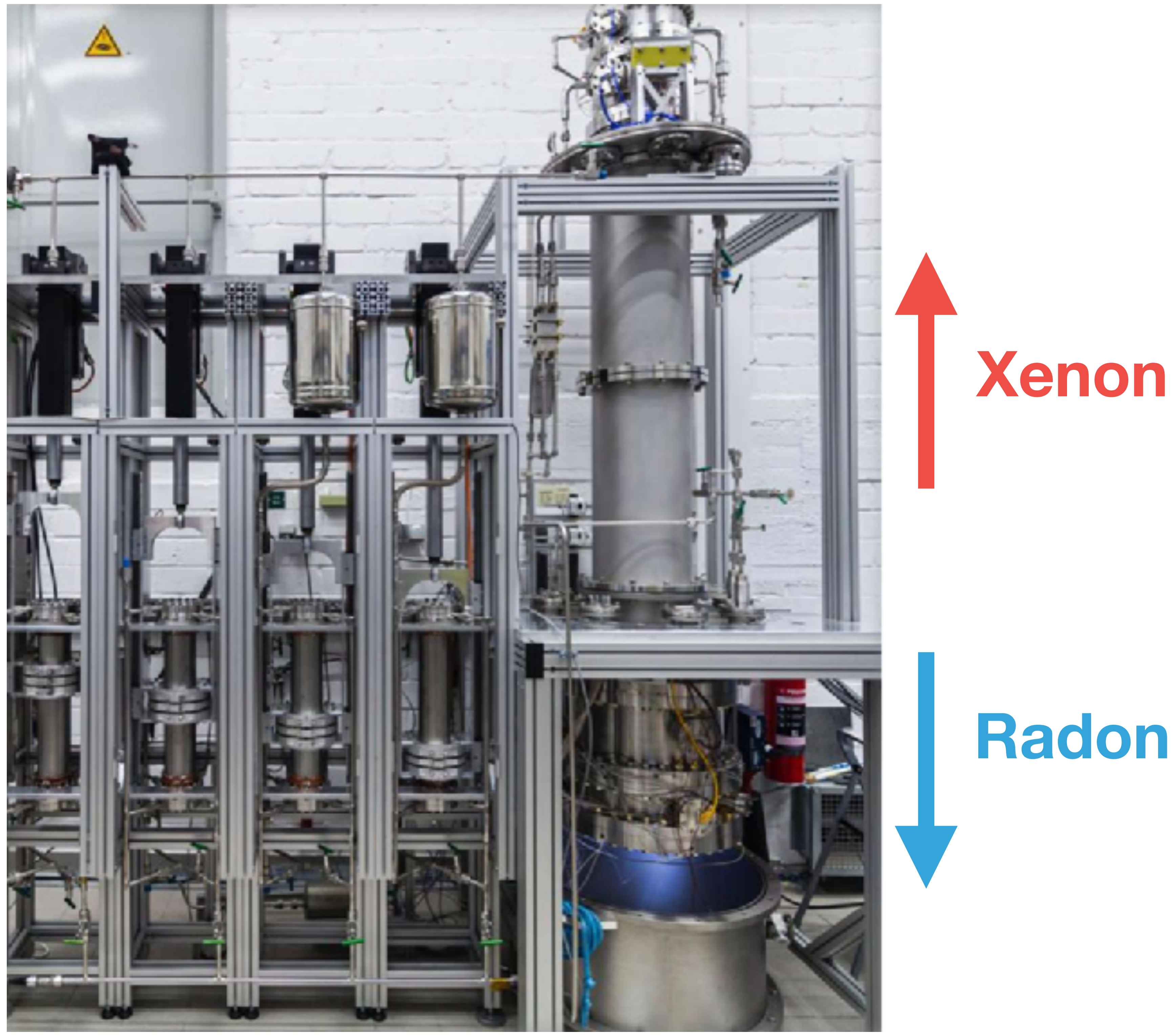
◉Multiple filters

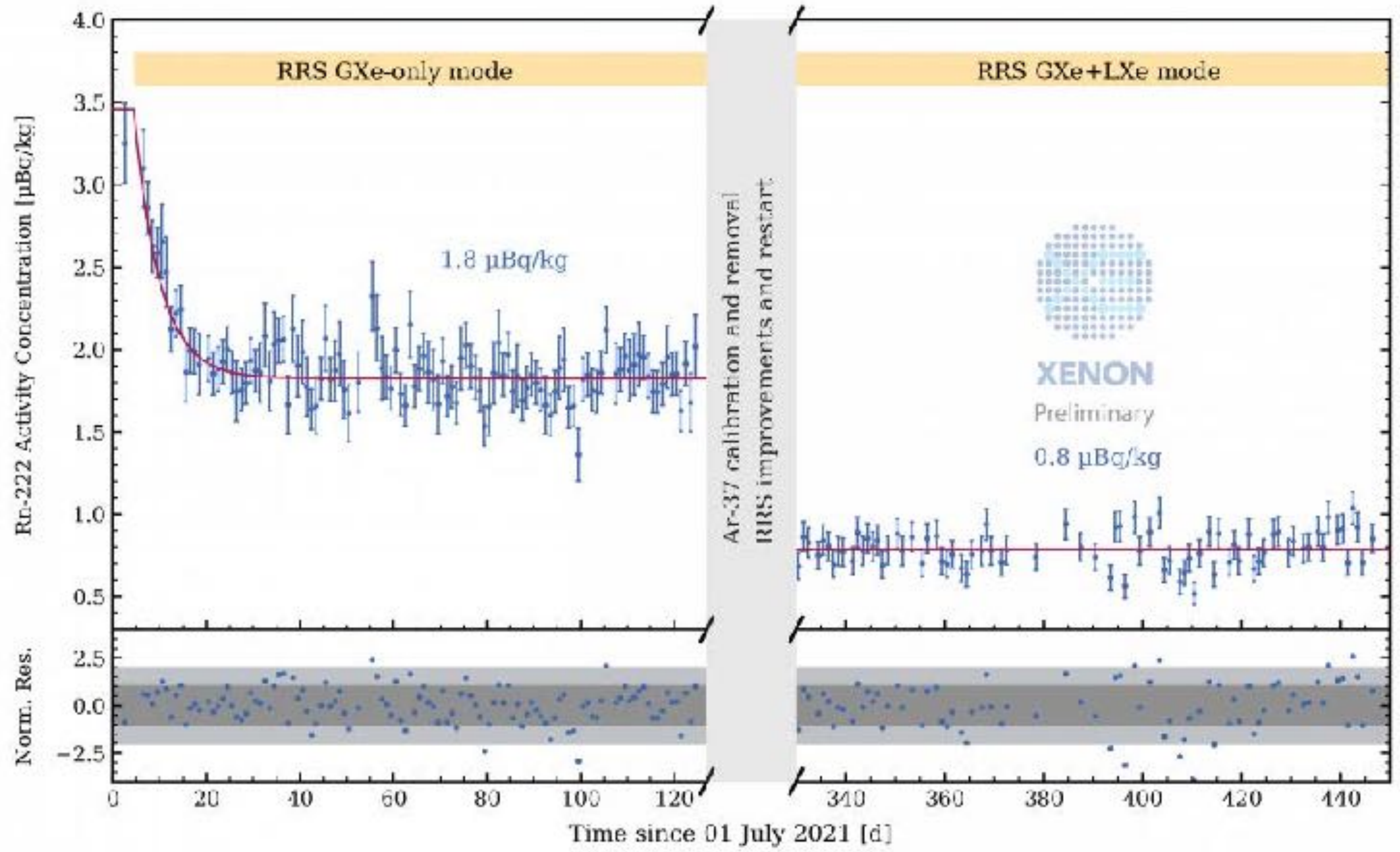
- Engelhard Q5: High eff / High Rn (for fast purification)
- SAES St707 getter pills: Mid eff / Low Rn (for SR0)

	Full TPC drift time	electron lifetime	electrons surviving a full drift length	O_2	Purification speed
1T	0.67 ms	0.65 ms	30%	~ 1 ppb	0.65 ms in ~3months
nT	2.2 ms	> 10 ms	> 90%	~ 0.02 ppb	5ms in ~5 days

Radon Removal with Distillation







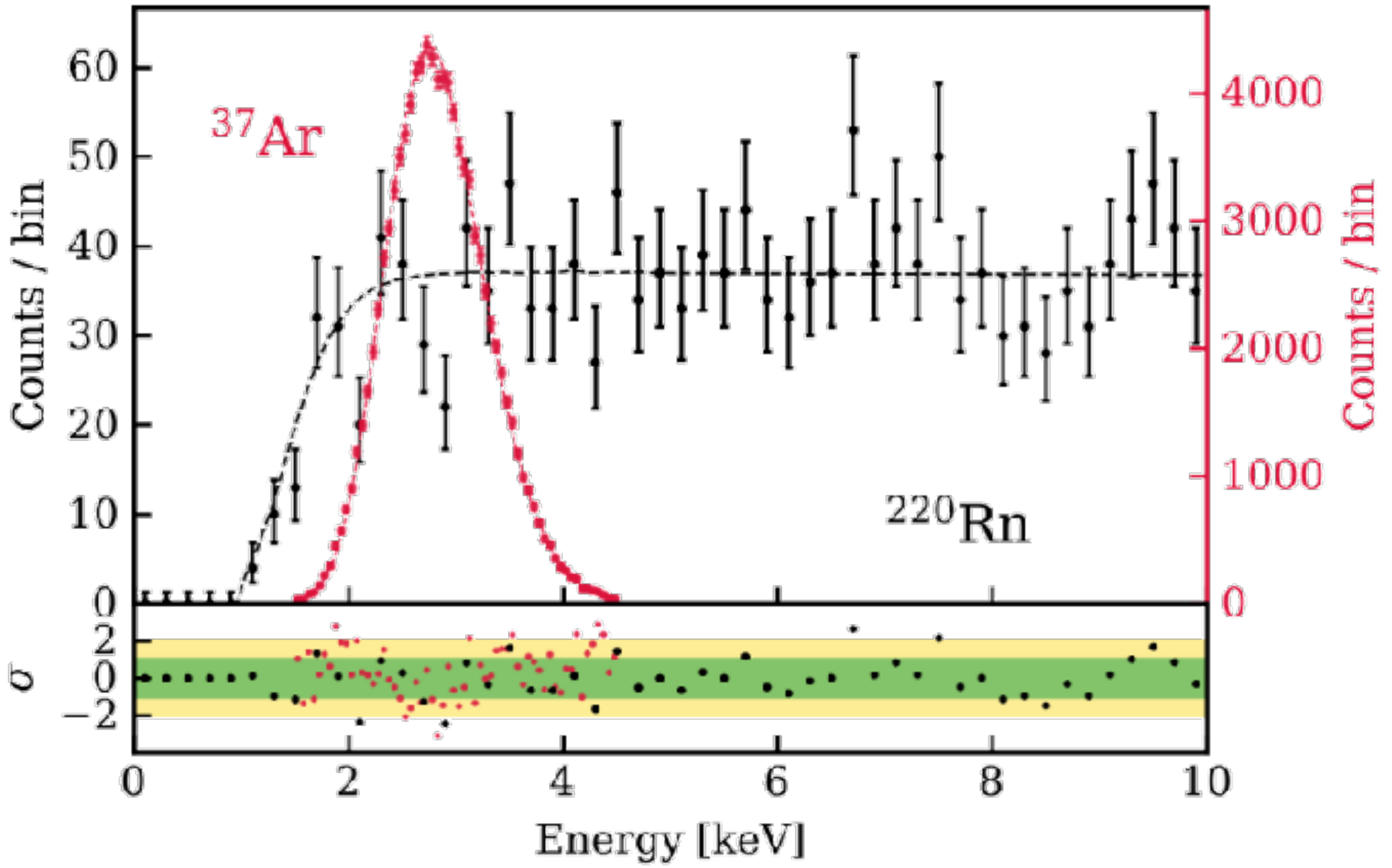
◉Design: 1 μBq/kg ^{222}Rn level (XENON1T: 13 μBq/kg)

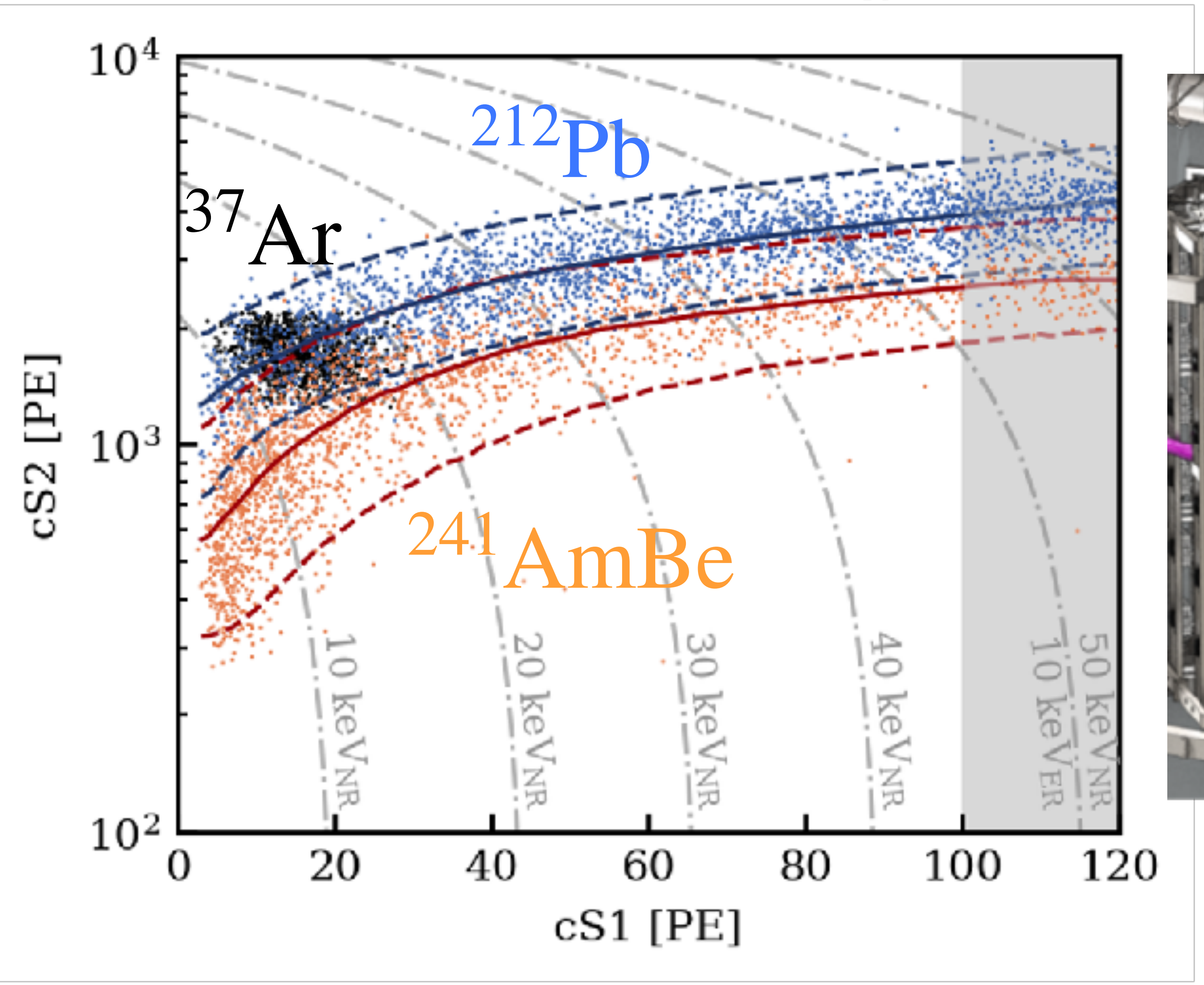
◉Constant removal of emanating Rn using difference in vapor pressure
(Rn atom accumulates into LXe more than GXe)

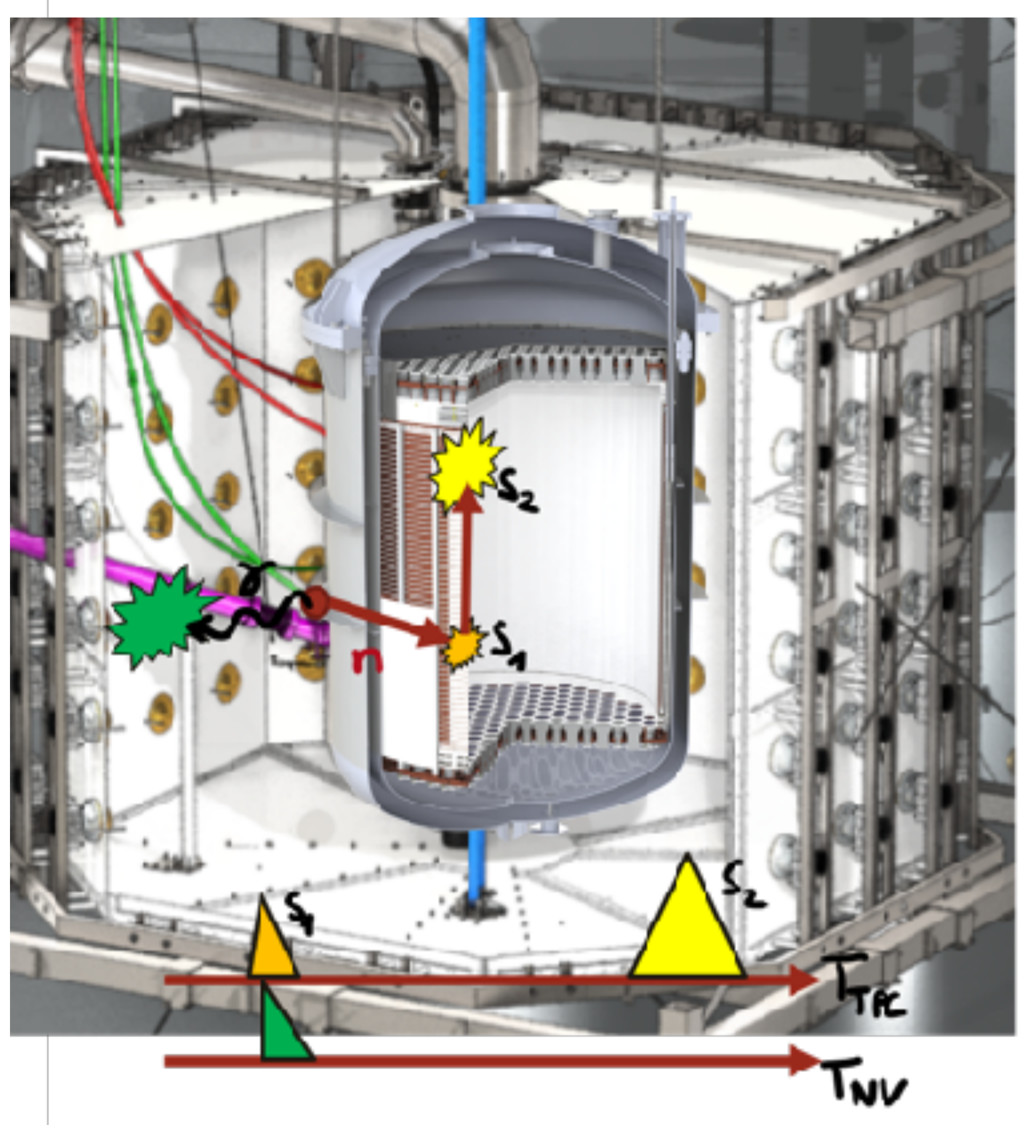
◉Reached equilibrium concentration of 1.8 μBq/kg by gas extraction only (~8 times less BG w.r.t. 1T)

◉Additional factor 2 reduction is possible via liquid extraction for SR1

Detector Calibration







◉Two ER calibration sources at low energy:

- ^{37}Ar, which gives mono-energetic 2.8 keV peak used to anchor the low-energy response and resolution models with high statistics

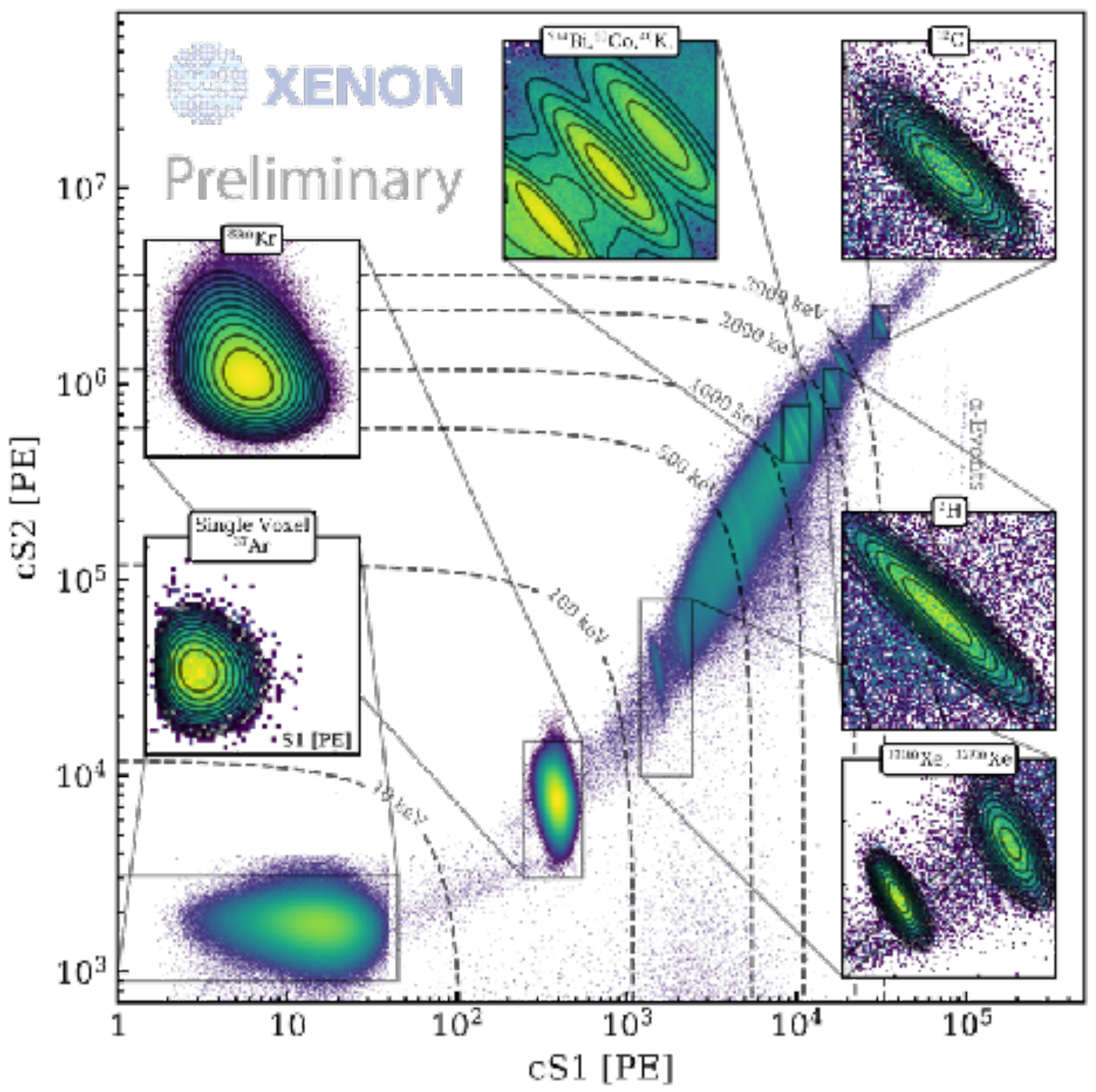
- ^{212}Pb from ^{220}Rn gives a roughly flat β-spectrum to estimate cut acceptances and validates our energy threshold

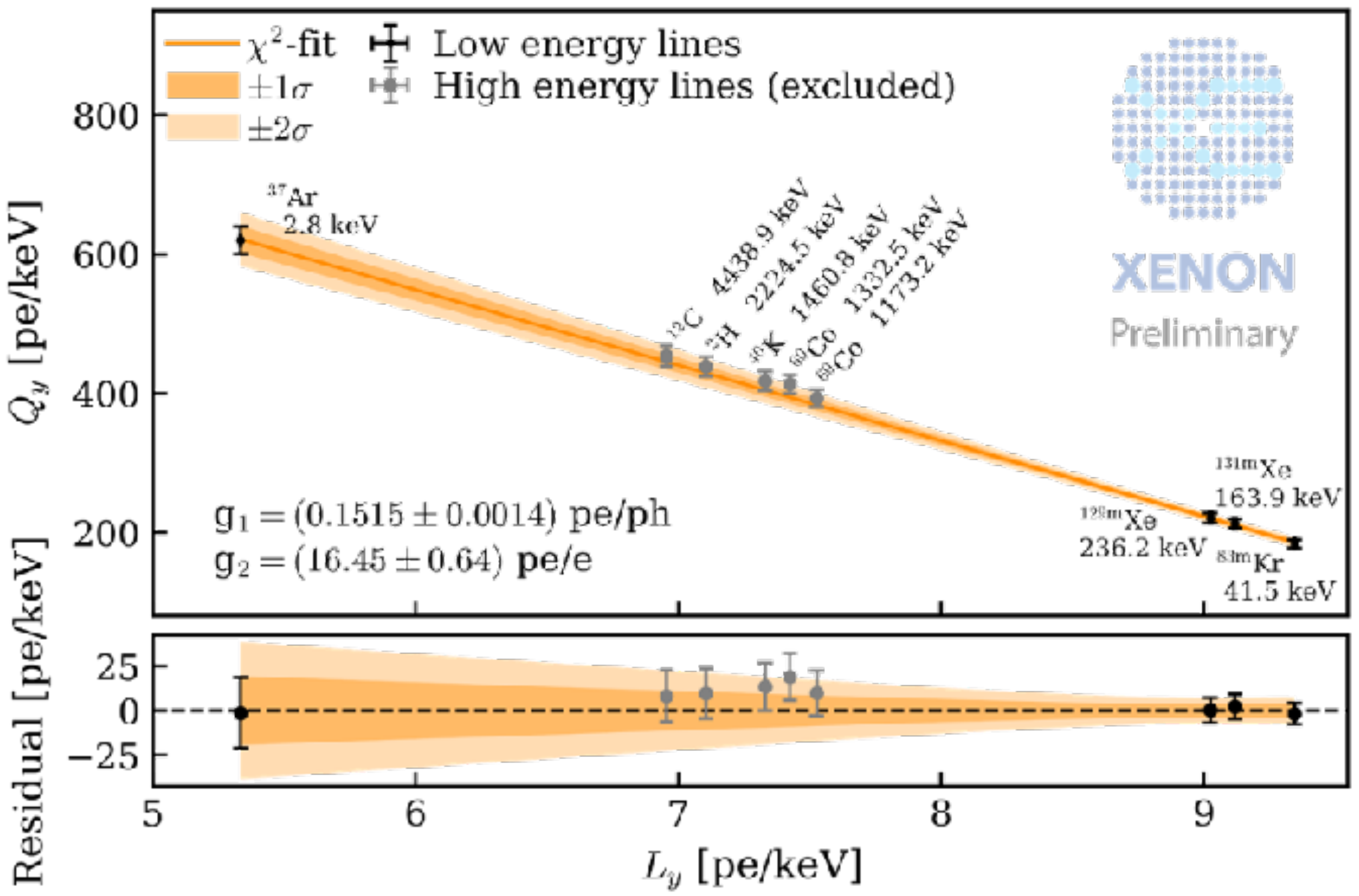
◉One NR calibration in low energies:

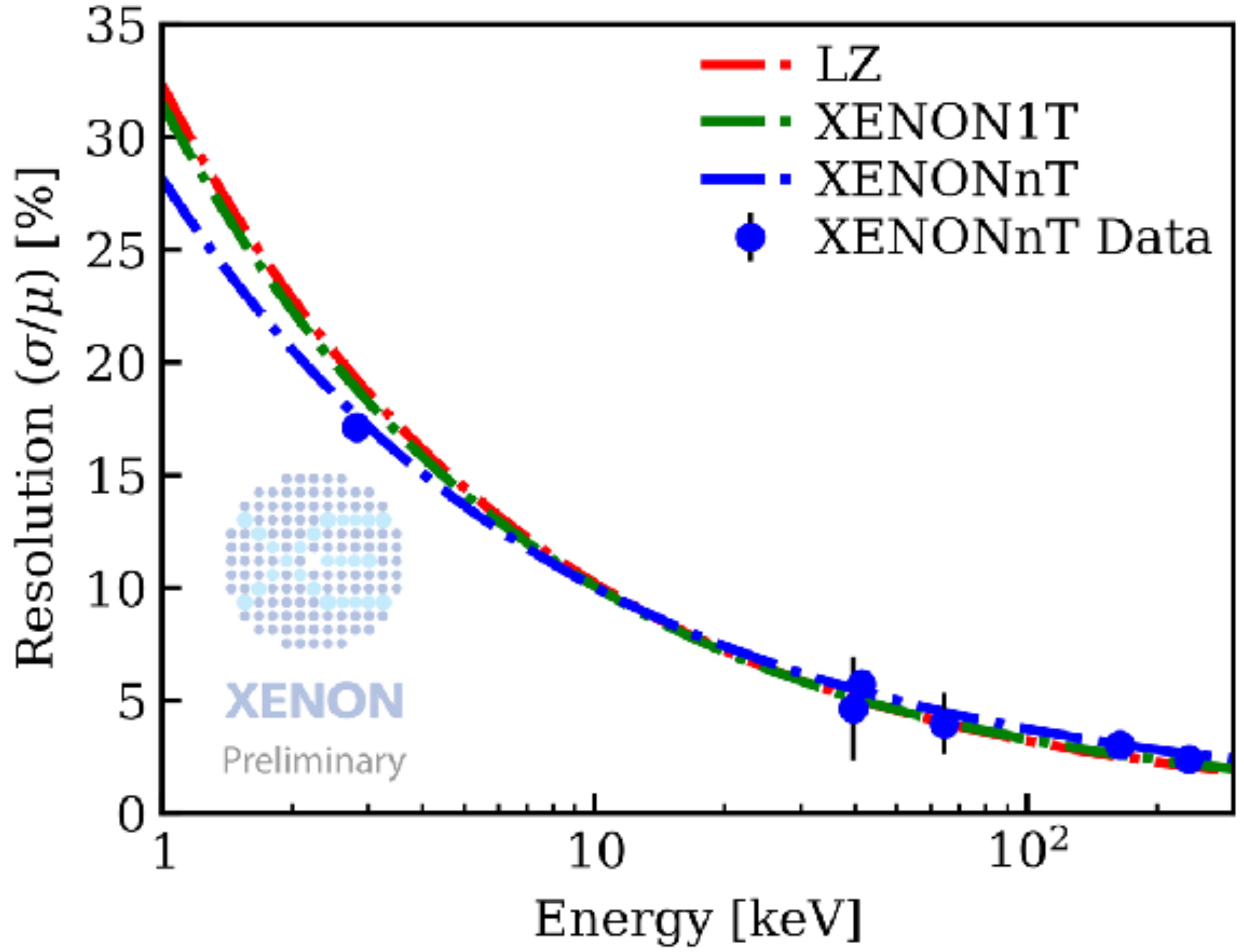
- ^{241}AmBe, external source with clean NR selection via coincident tagging with nVeto which defines the NR response model for LXe

◉ 99% discrimination of ER backgrounds below NR band median achieved

Energy Responss







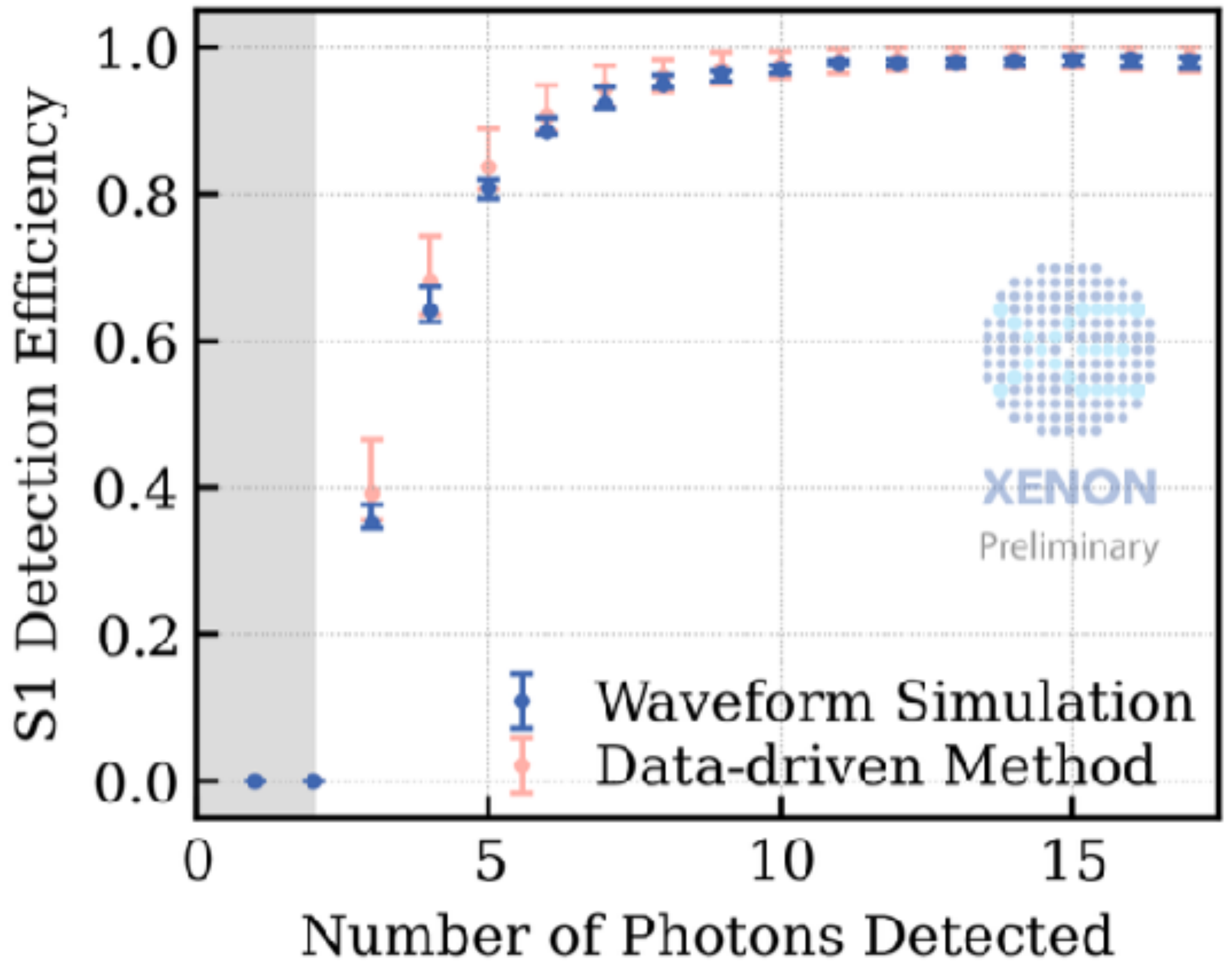
◉Calibrations with various sources including ^{37}Ar, ^{83m}Kr, ^{220}Rn, ^{241}AmBe

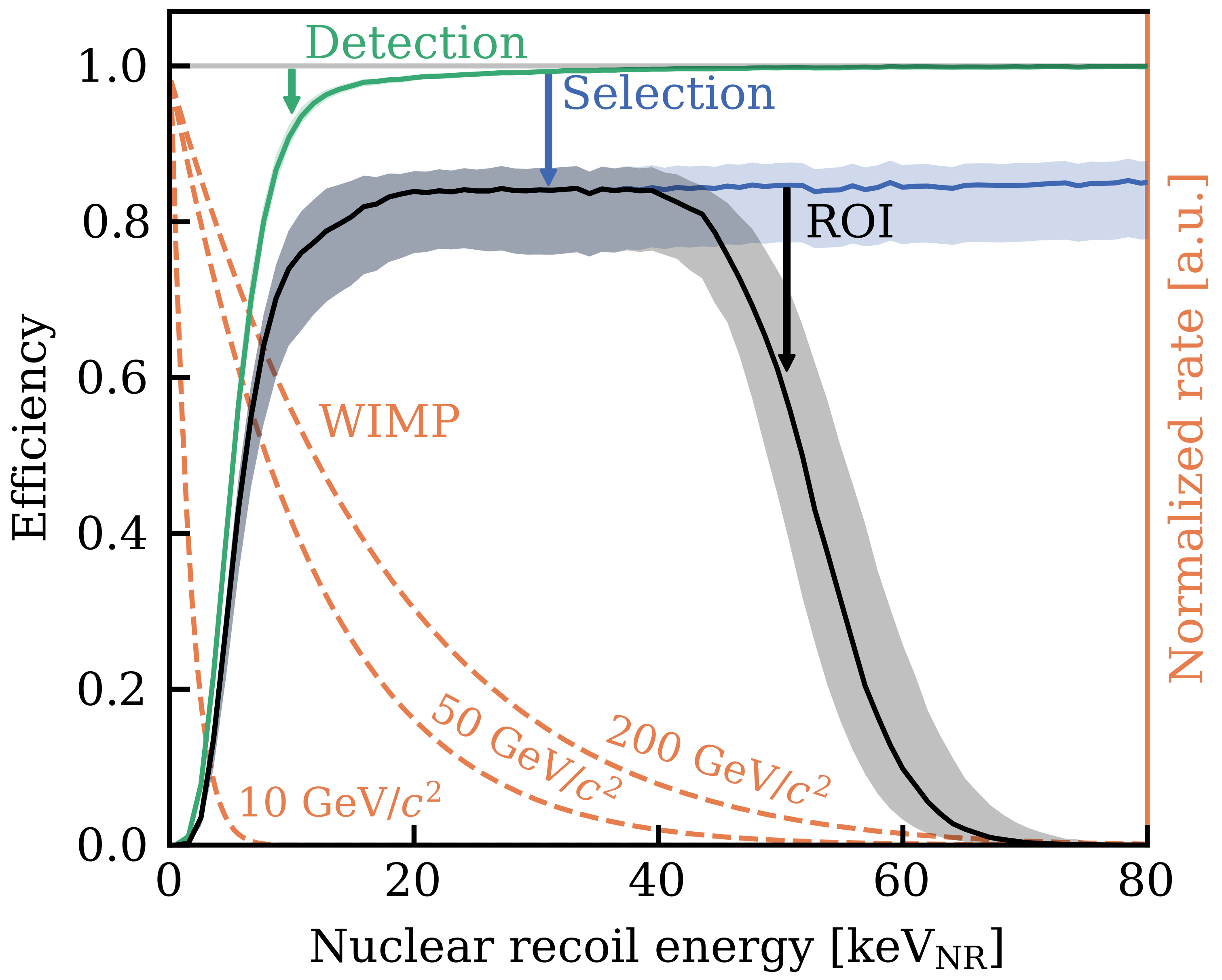
◉Reconstruct energy with g1/g2, validate efficiency/energy threshold with ^{37}Ar, ^{220}Rn (^{212}Pb β-decay)

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

◉Energy resolution at 1 keV is ~30%

Detection and Selection Efficiency for WIMP Searches





◉Detection efficiency:

-threshold driven by a 3-fold PMT coincidence for S1

-Efficiency estimated with two different methods

-simulation-driven: full waveforms

-data-driven method: bootstrapping from ^{83m}Kr and ^{37}Ar S1

◉ROI for WIMP Searches

-cS1: [0 pe, 100 pe]

-cS2 : [$10^{2.1}$ pe, $10^{4.1}$ pe]

◉Event selection for WIMP Searches

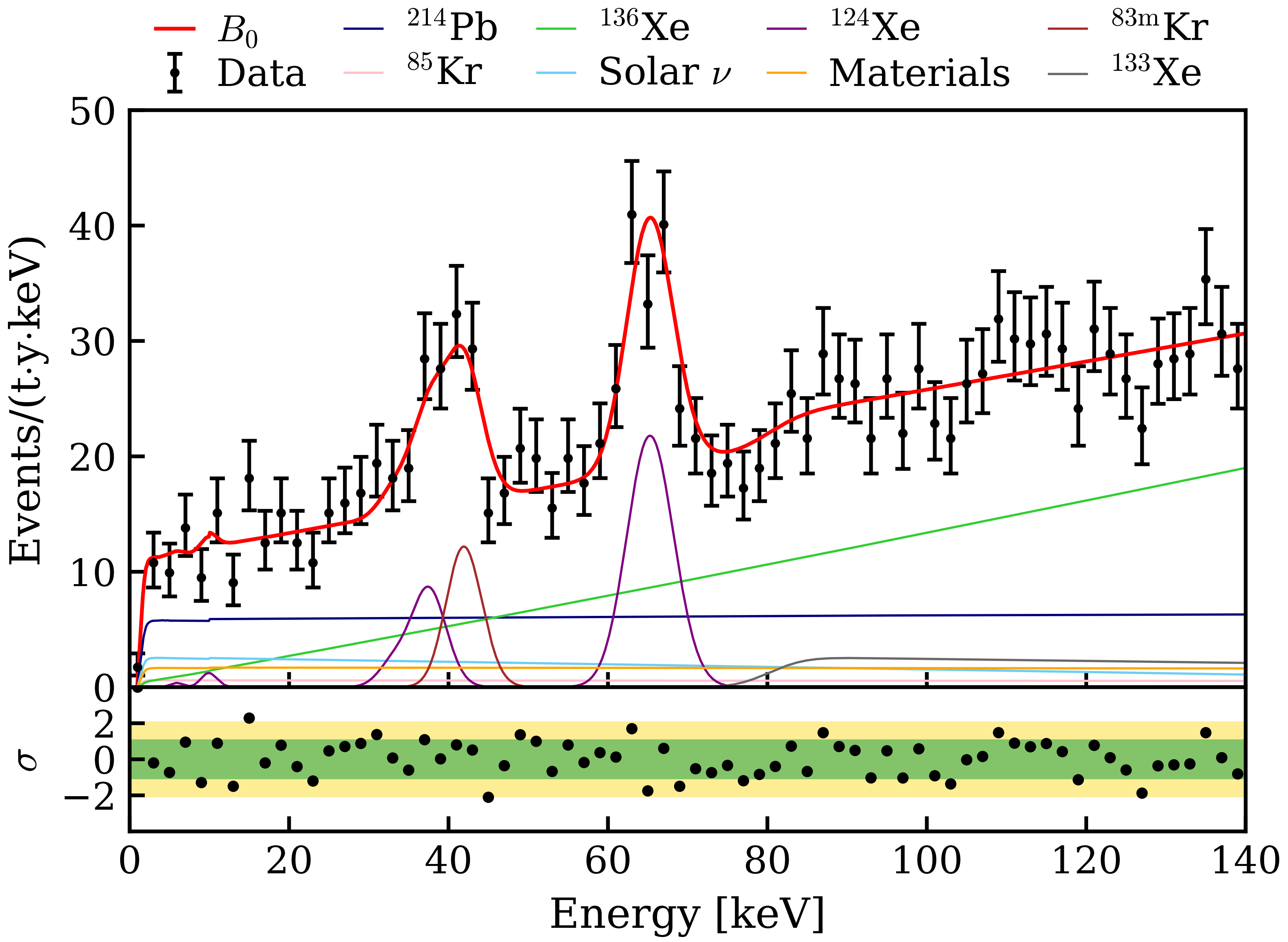
-FV: (4.18 ± 0.13) ton: ~4x larger than in XENON1T

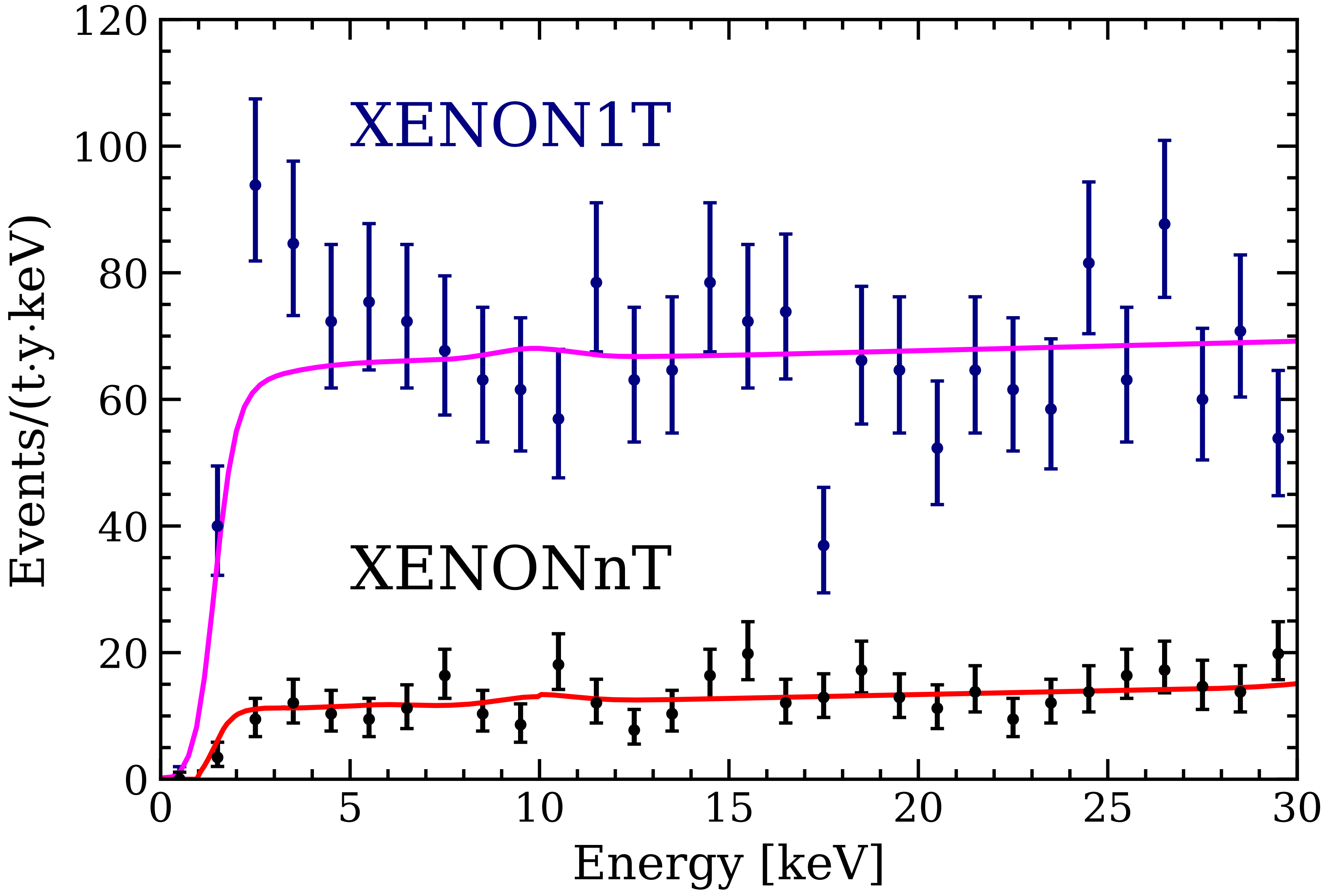
-Veto with events in nVeto within 250μs after S1 signal

-BDT cut to suppress accidental coincidence of isolated S1/S2s

◉Total acceptance > 10% for [3.1 keV$_{NR}$, 60 keV$_{NR}$]

ER Background in XENONnT

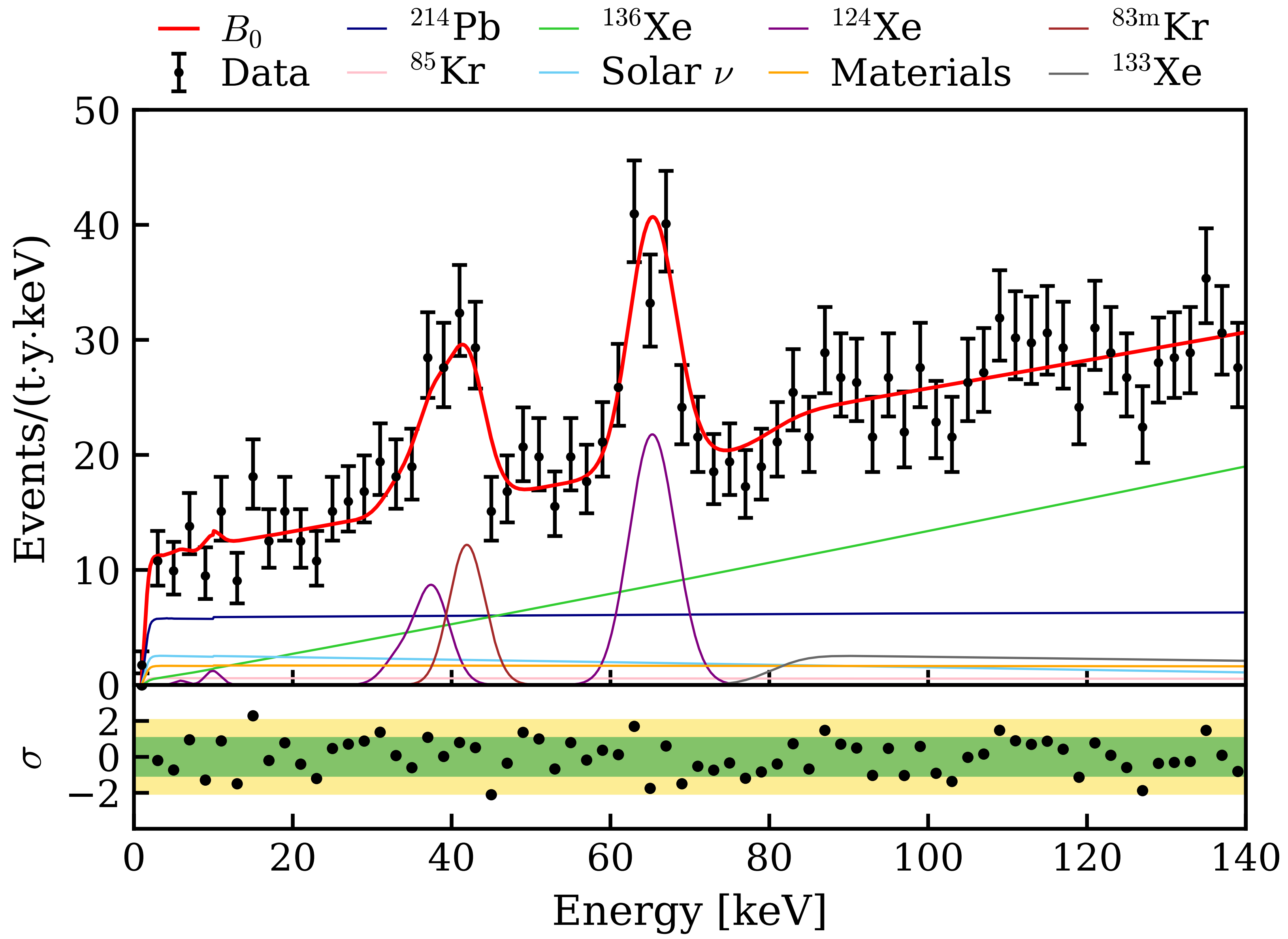


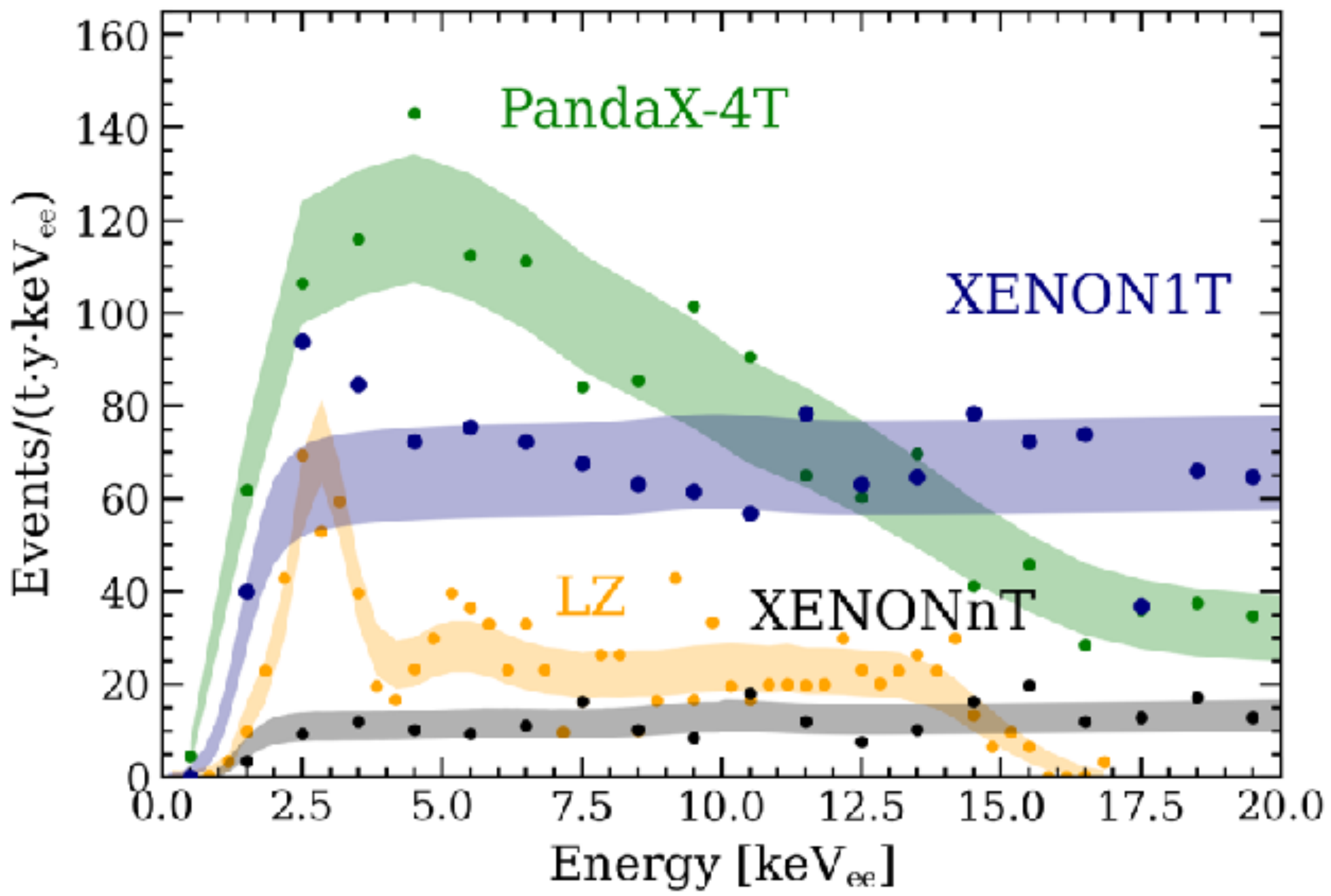


	(1, 10) keV	(1, 140) keV
^{214}Pb	56 ± 7	980 ± 120
^{85}Kr	6 ± 4	90 ± 60
Materials	16 ± 3	270 ± 50
^{136}Xe	8.7 ± 0.3	1520 ± 50
Solar v	25 ± 2	300 ± 30
^{124}Xe	2.6 ± 0.3	260 ± 30
AC	0.70 ± 0.03	0.71 ± 0.03
^{133}Xe	-	160 ± 60
^{83m}Kr	-	80 ± 16

- Main BG = ^{214}Pb (daughter of ^{222}Rn)
- Total ER background below 30 keV: (15.8±1.3) events/(t y keV): ~ 0.2 x XENON1T
- **Lowest background achieved in a DM detector**
- **Solar neutrinos: second largest background below 10 keV**
- No ER excess observed

ER Background in XENONnT





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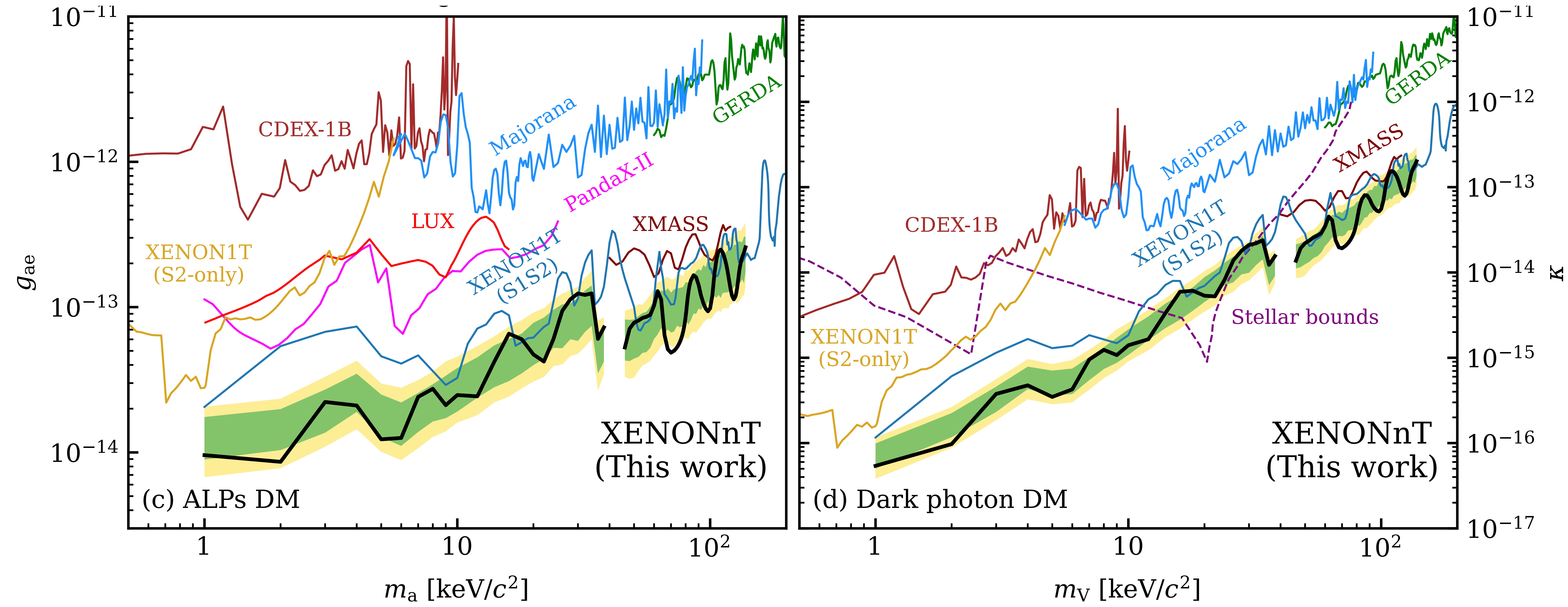
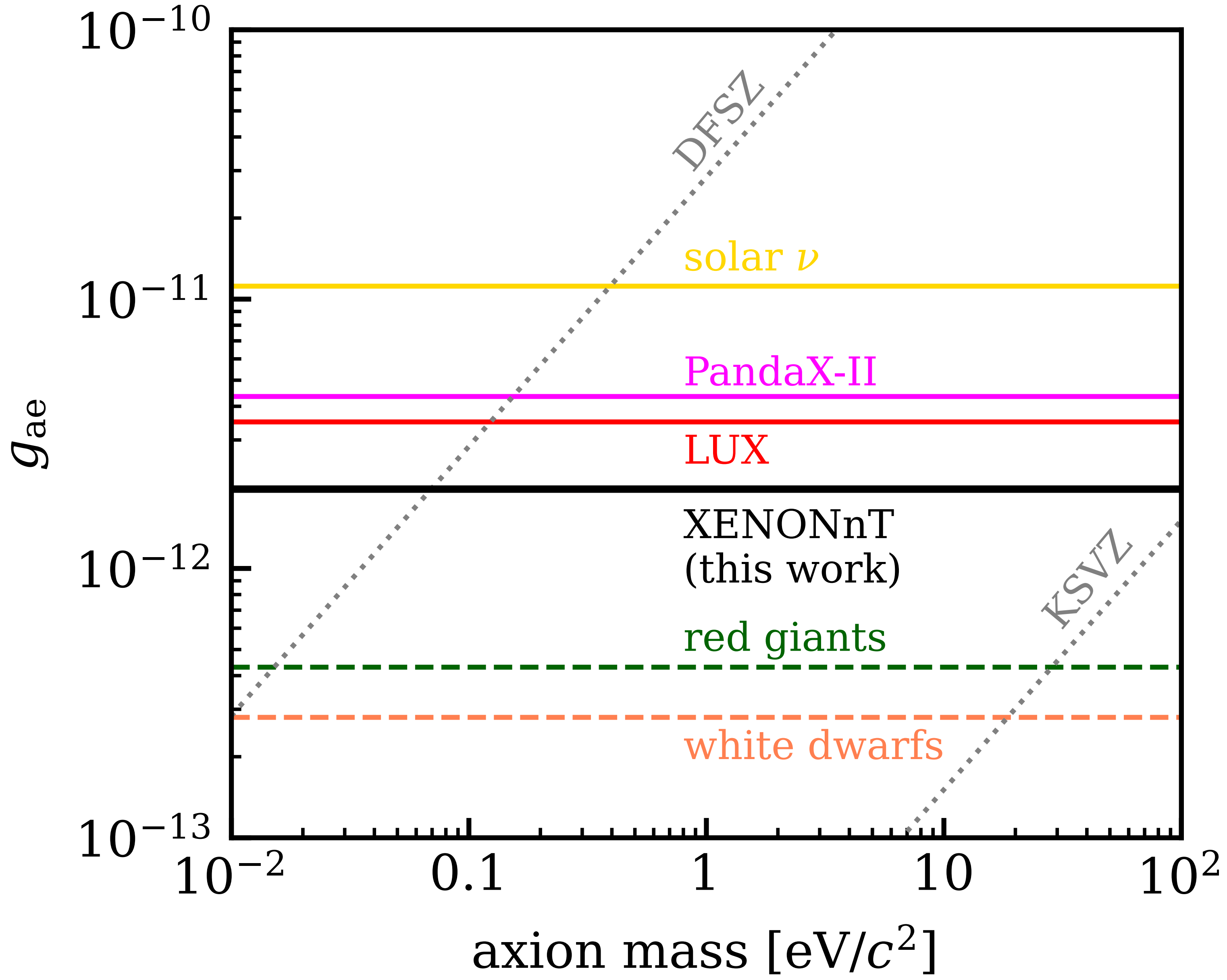
Constraints on Bosonic Dark Matter/Axions

ALPs

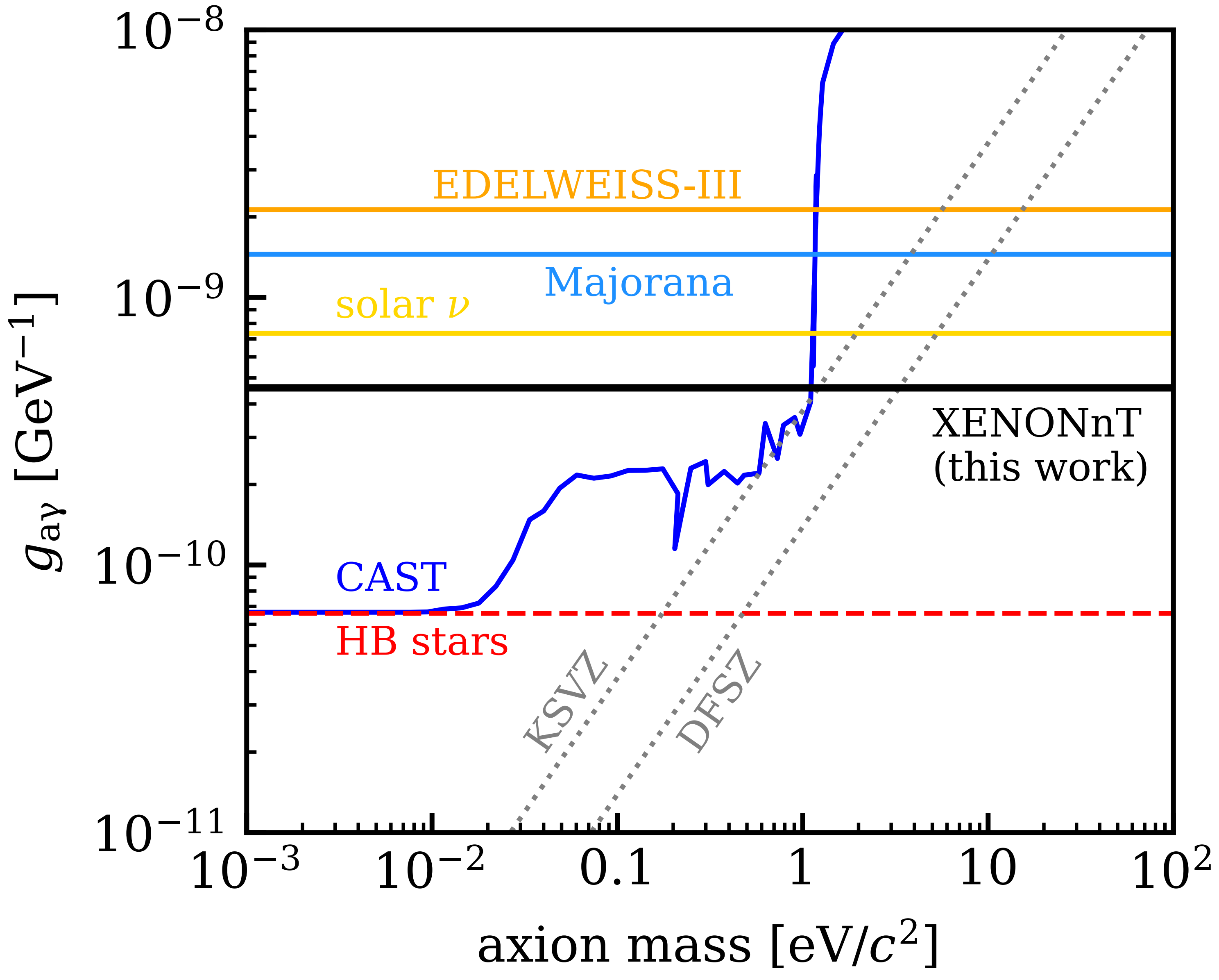
Dark Photon



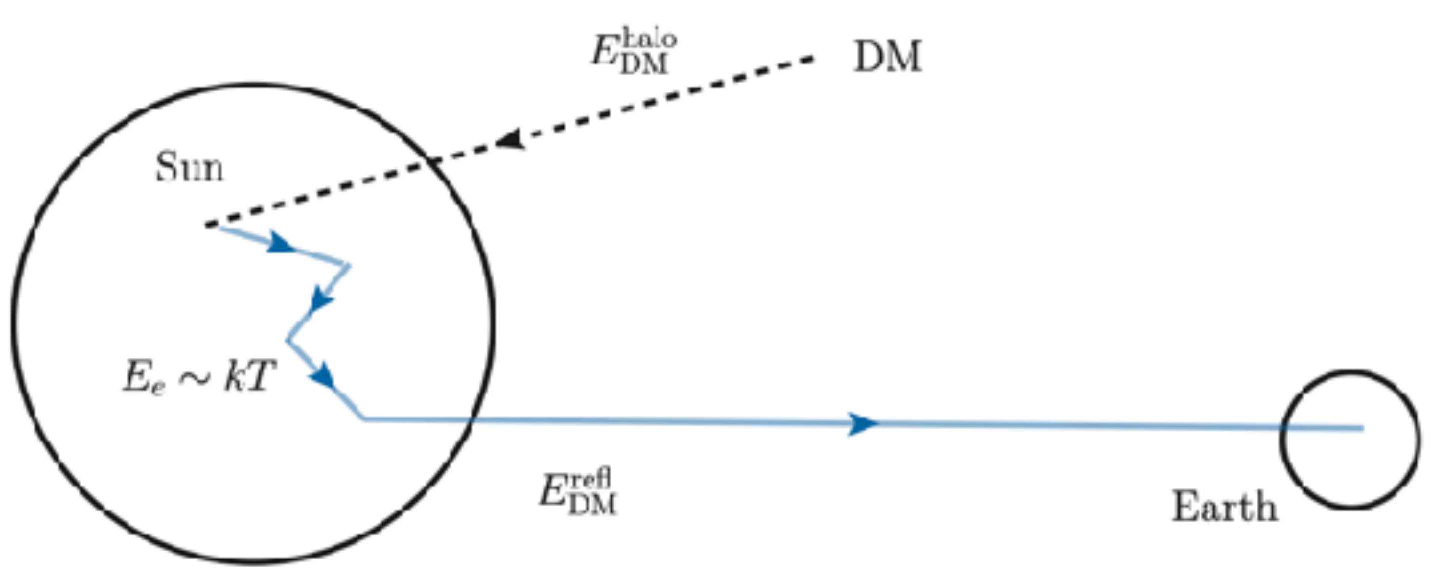
Axion(g_{ae})



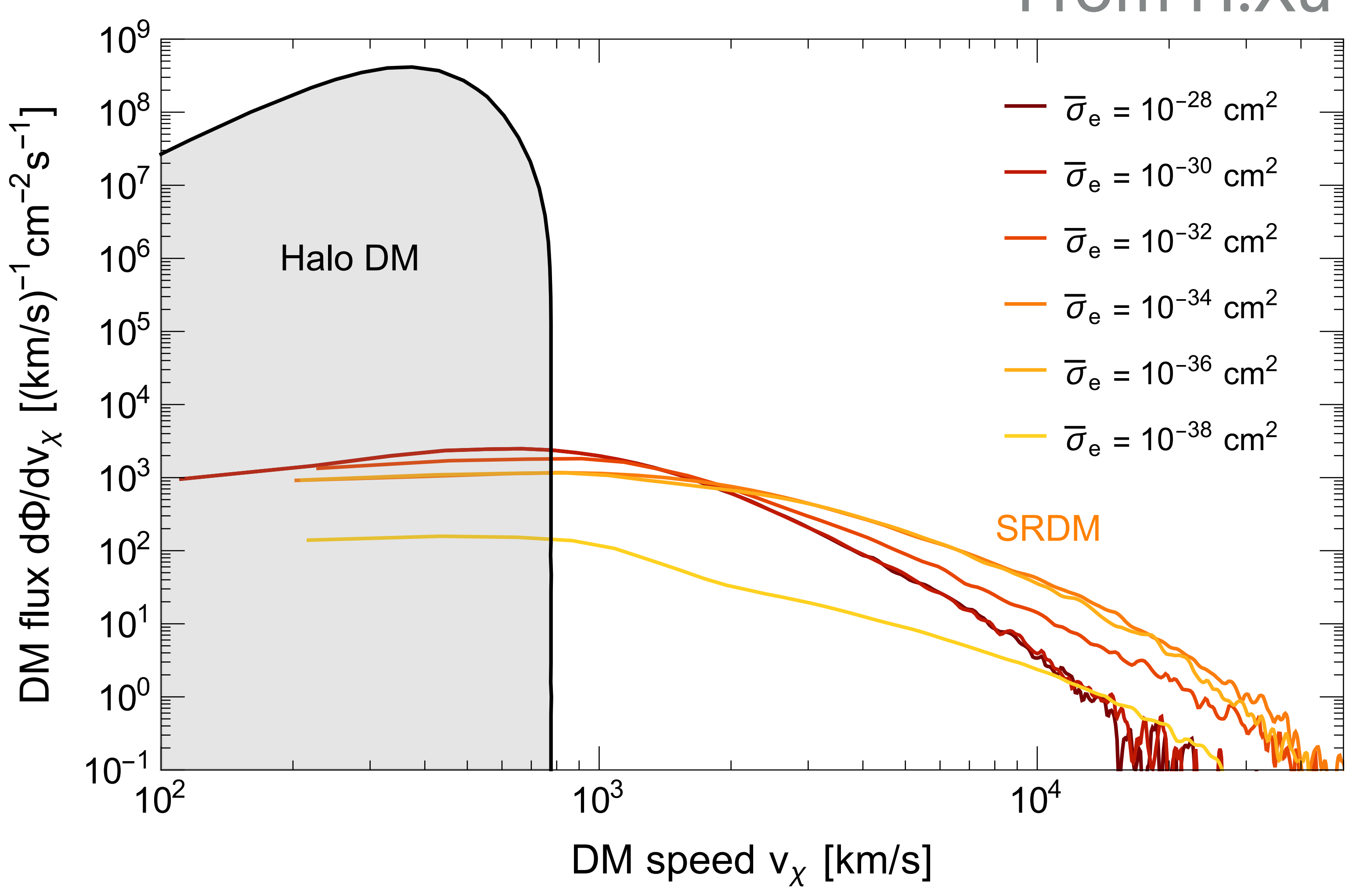
Axion($g_{a\gamma}$)

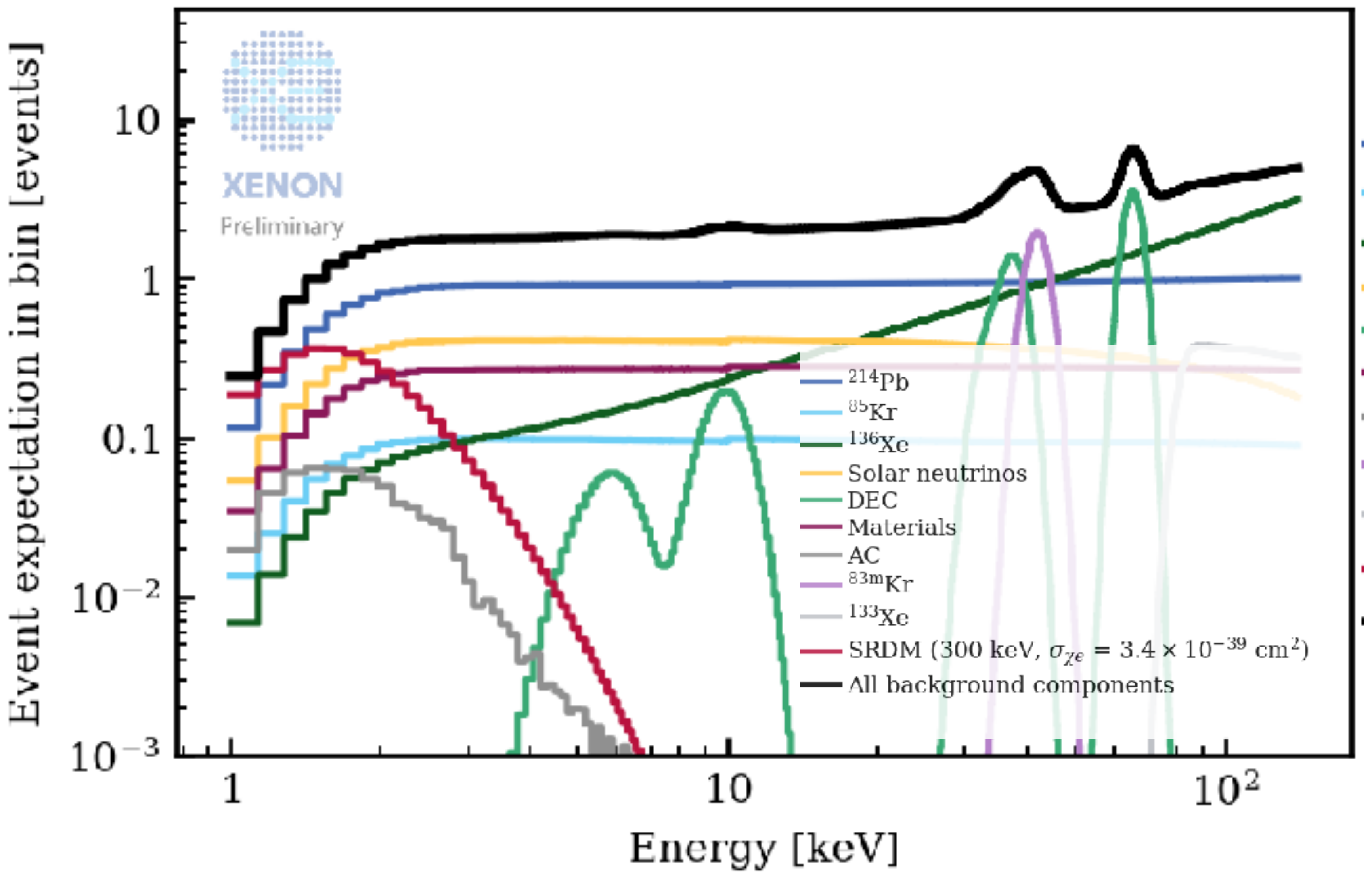


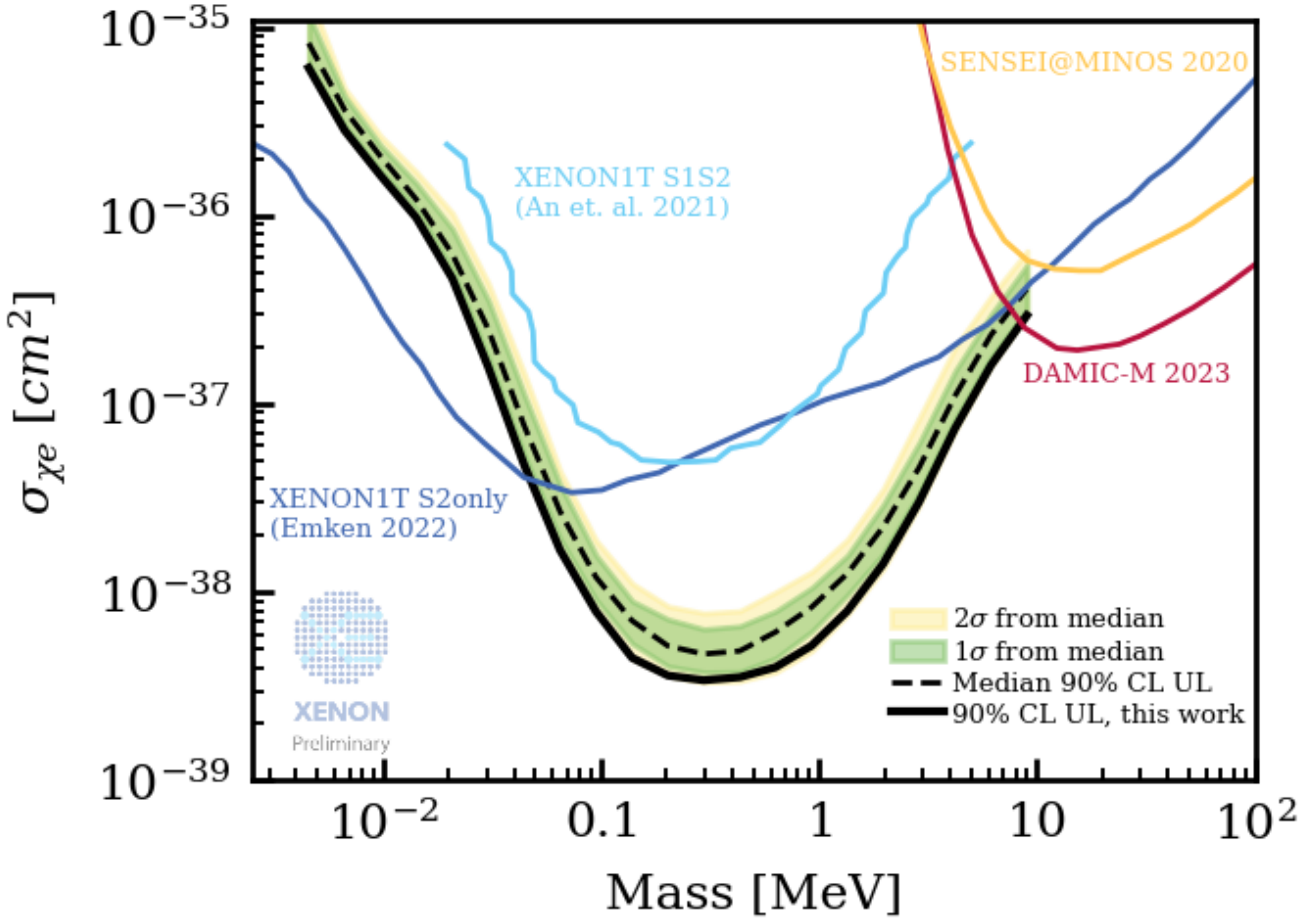
Constraints on Solar-Reflected DM



From H.Xu







- ◉MeV-scale DMs could have a recoil energy of O(1) keV
- ◉Searched for solar-reflected DM using the SR0 ER data
- ◉Obtained new limits on MeV-scale DMs couple to electrons.

Backgrounds for WIMP Searches

ER background

- Dominated by **radon background** (β-decay of ^{214}Pb)

Surface background

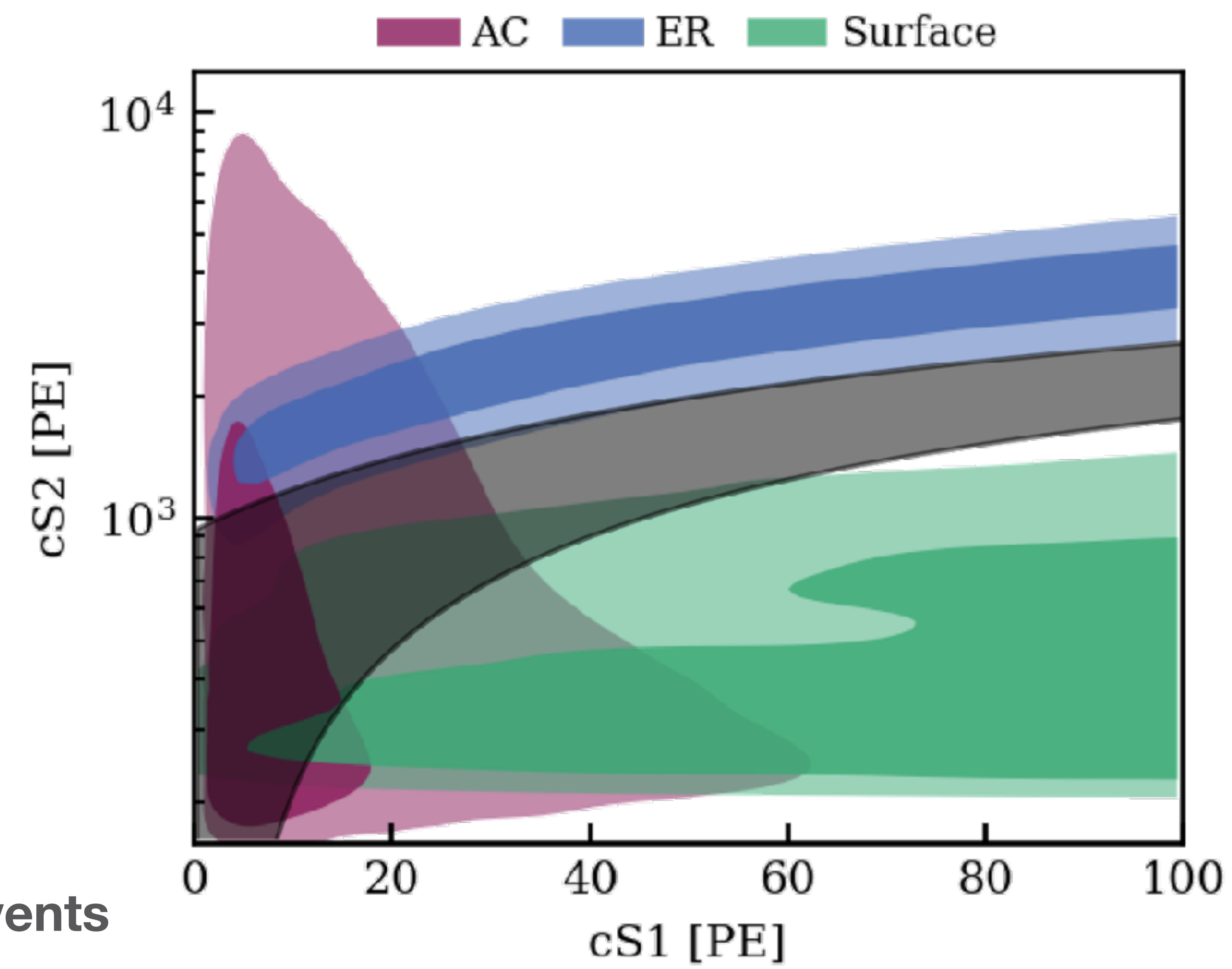
- **^{210}Pb plate-out on the PTFE wall** of the TPC leading to ^{210}Po α-decays with electron loss
- Suppressed by FV cut

Accidental Coincidences (AC)

- **Random pairing** of isolated S1 and S2 signals
- Suppressed by BDT cut based on S2 shape features

NR backgrounds

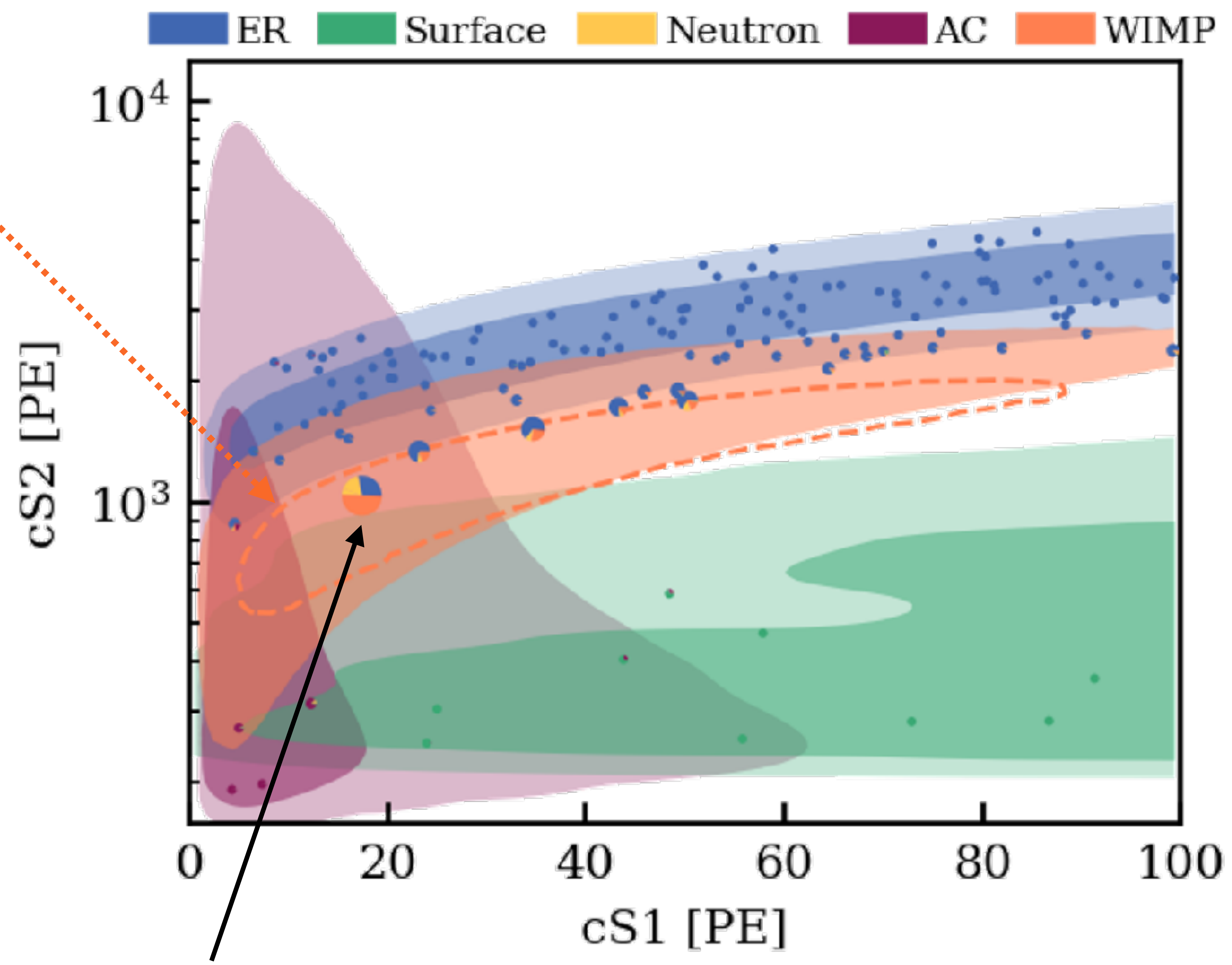
- **Radiogenic neutron** rate prediction from NV tagging: ~ **1.1 events**
- **CEvNS** constrained from solar 8B neutrino flux: ~ **0.2 events**
(CEvNS search based on 2-fold coincidence is ongoing now)



Backgrounds for WIMP Searches

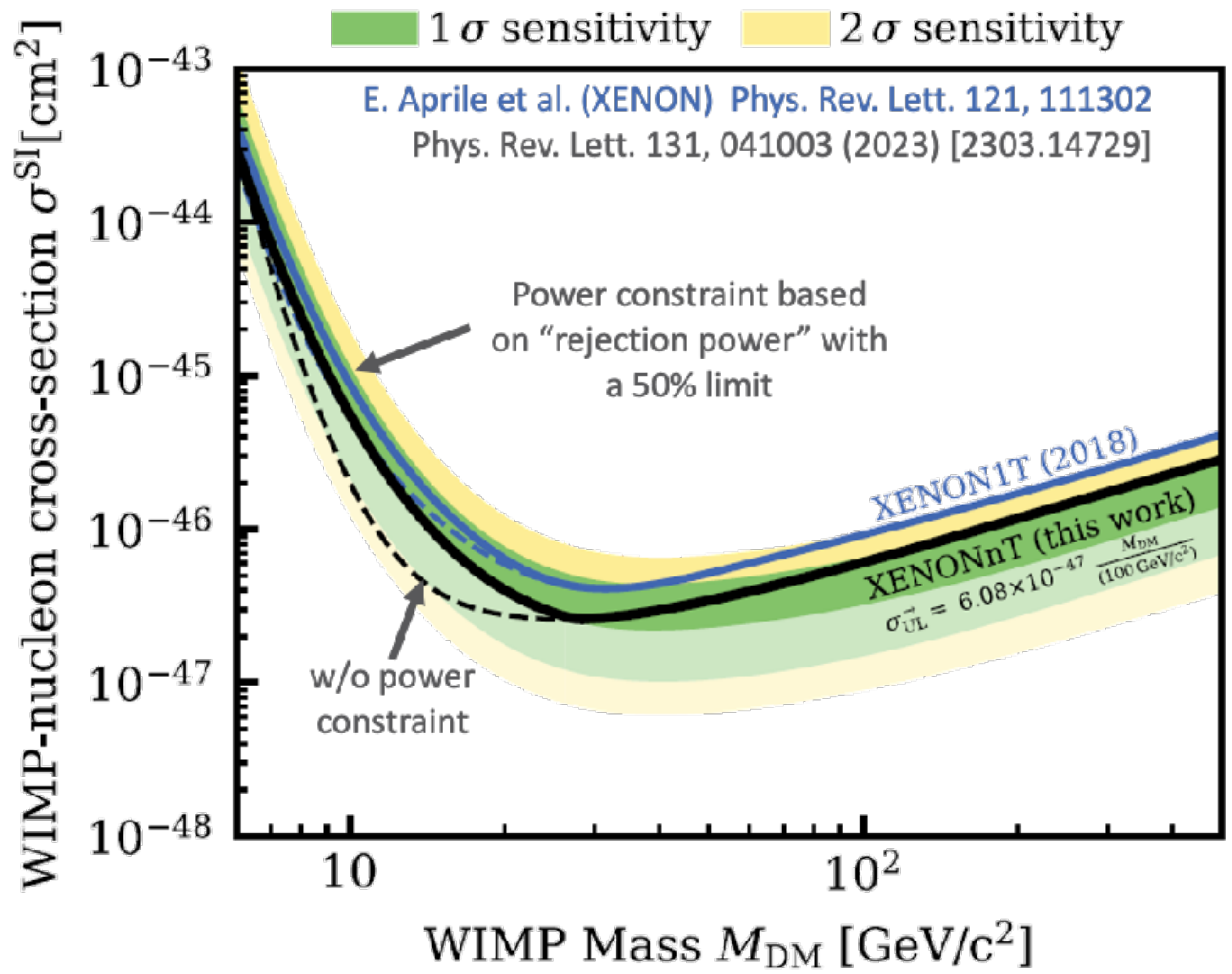
BG	Full	ROI
ER	135^{+12}_{-11}	0.87 ± 0.07
Neutron	1.1 ± 0.2	0.42 ± 0.10
CEvNS	0.23 ± 0.06	0.022 ± 0.011
Accidental Coincidence	4.32 ± 0.15	0.363 ± 0.013
Surface BG	12^{+0}_{-4}	$0.34^{+0.01}_{-0.11}$
Total BG	152 ± 12	$1.95^{+0.12}_{-0.16}$
WIMP (200GeV, 2.7×10^{-47} cm^2)	2.4	1.2
Observation	152	3

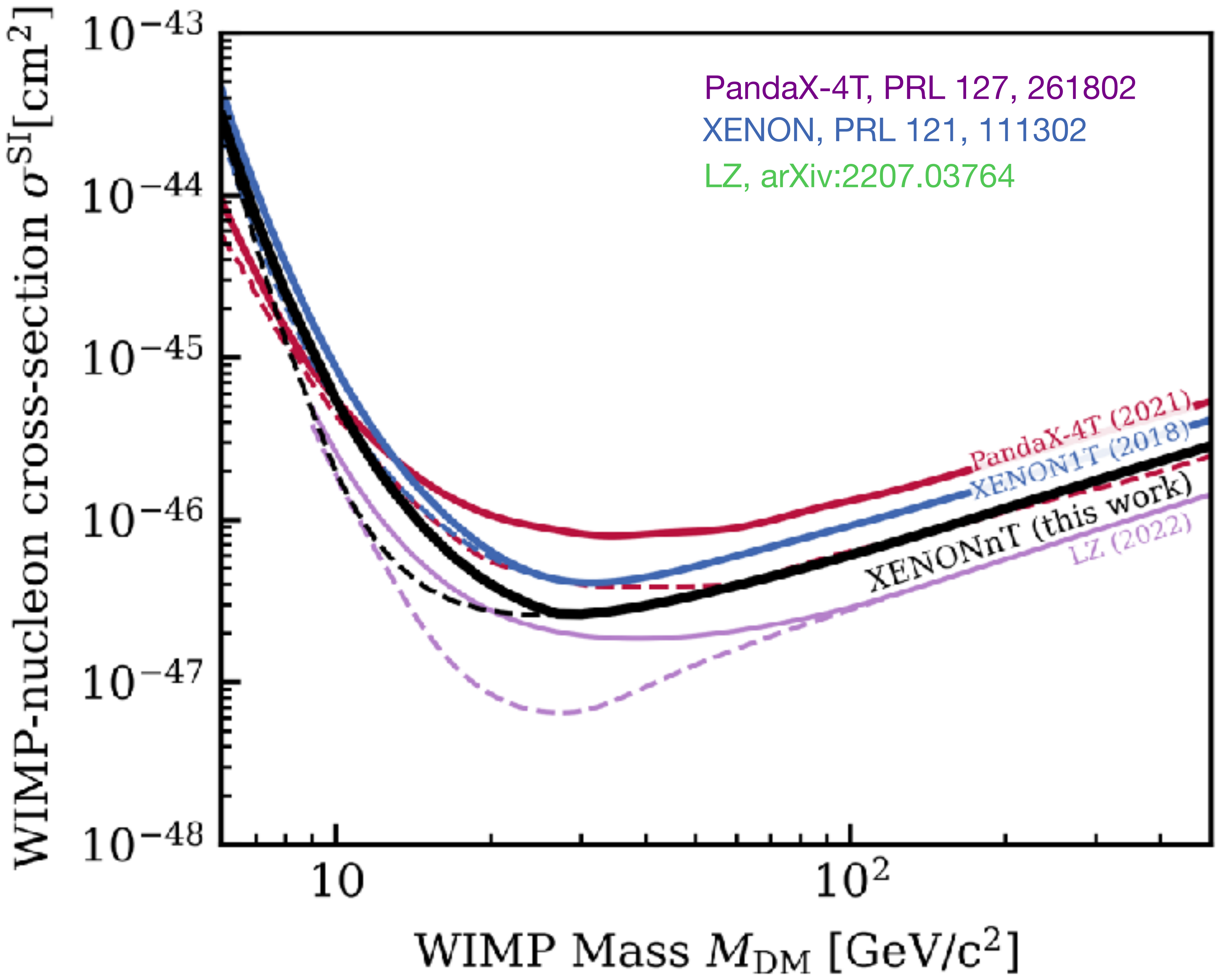
No significant excess above the BG expectation was observed



Component fraction of the best fit model including a 200 GeV/c^2 WIMP evaluated at event position σ = 3.22×10^{-47} cm^2

WIMP Results





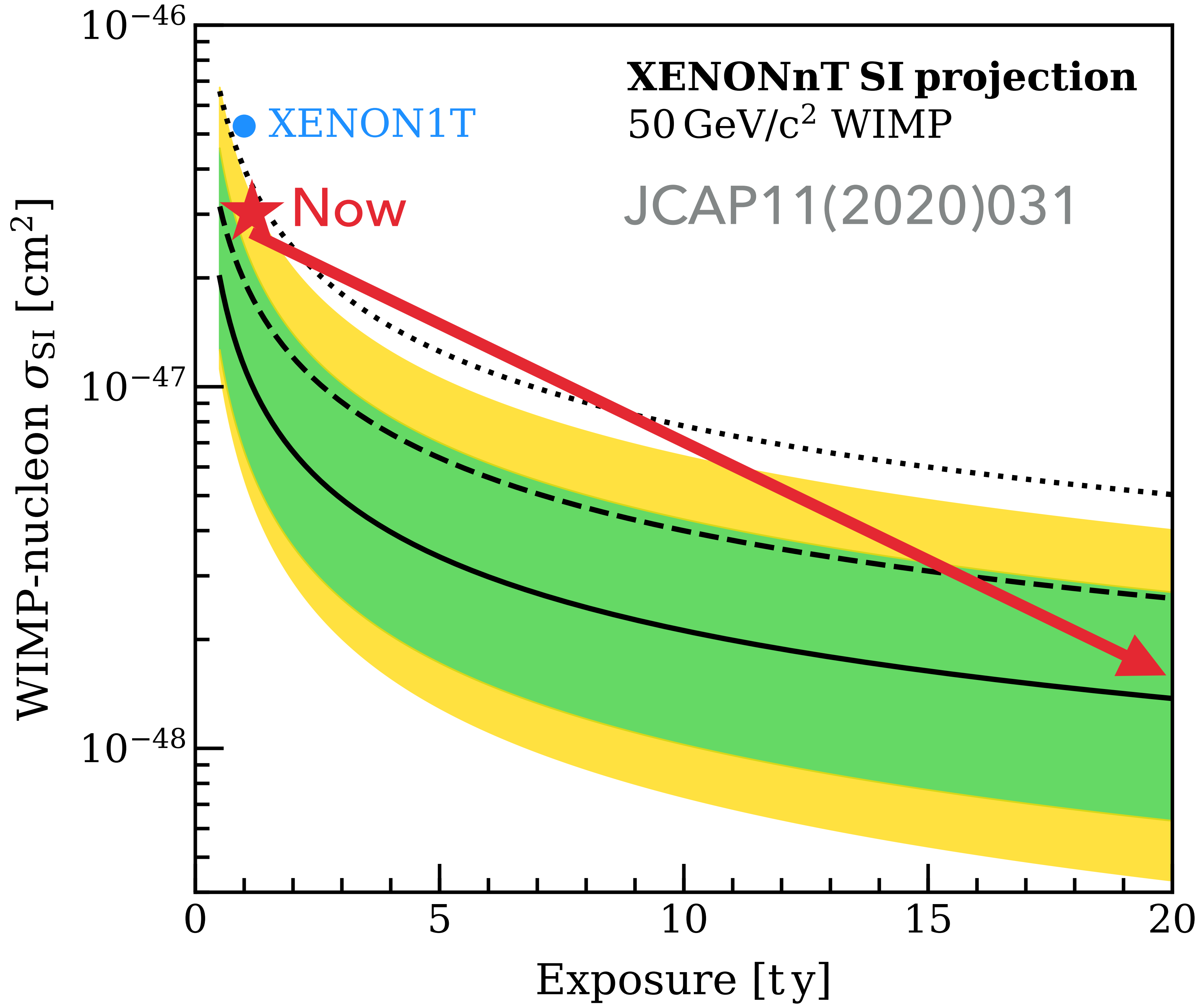
- Blinding analysis
- Strongest limit: 2.58(6.08) $\times 10^{-47}$ cm^2 @ 28(100) GeV
- Factor 1.6 improvement in the upper limit w.r.t. XENON1T (but with considerably shorter livetime)

What's Next for the XENONnT Experiment

- will improve the WIMP sensitivity by a factor of ~10 with 20 t-yr exposure

- Currently our analysis is focusing on ^{8}B CEvNS discovery

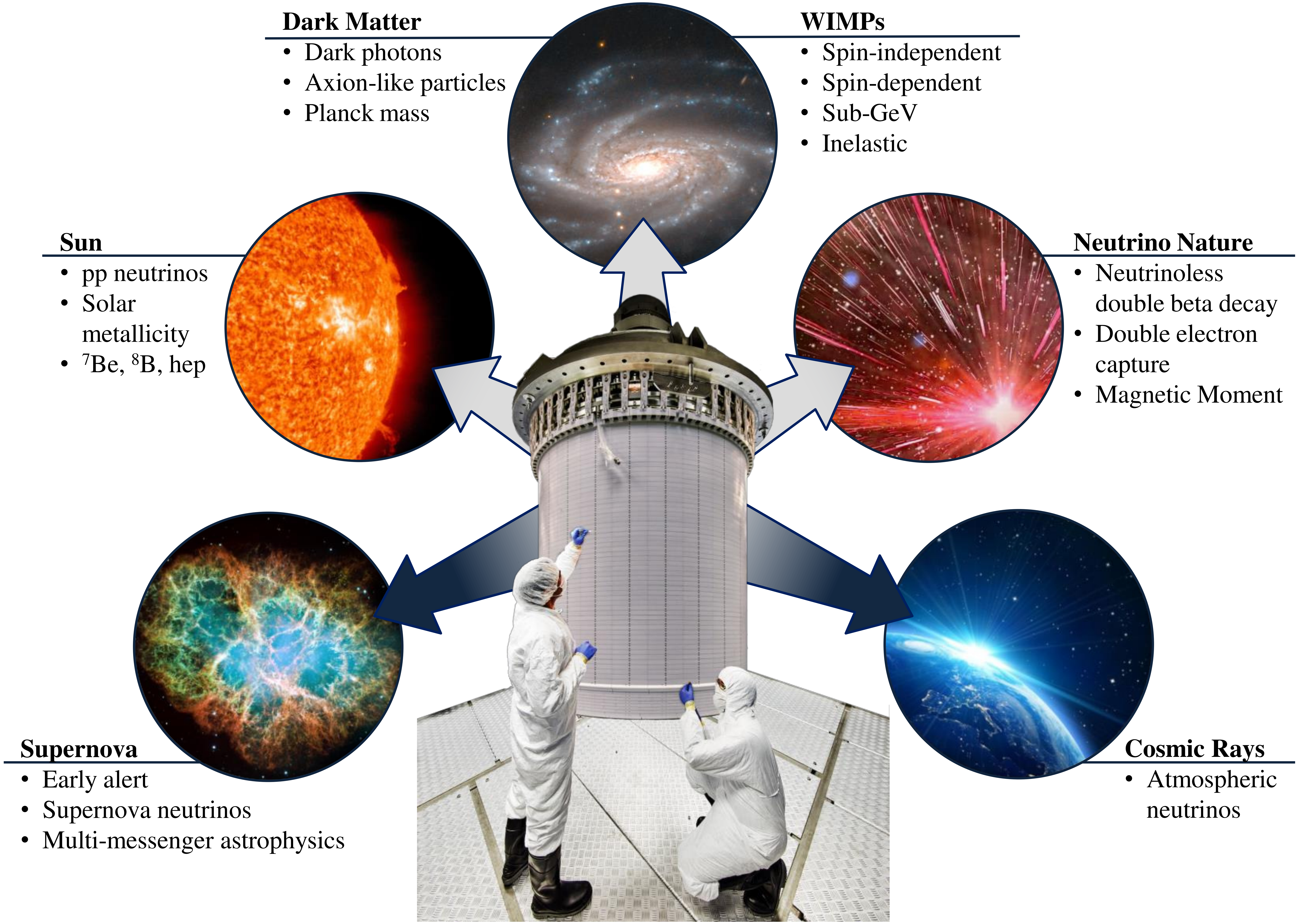
- Data taking ongoing with the improved ER background
  - Further reduction with GXe + LXe radon distillation: 1.8 → 0.8 μBq/kg



- Neutron veto will be loaded with Gd-sulfate octahydrate to increase neutron detection efficiency
  - recently injected small amount of Gd, and gradually increasing the concentration
  - 53% → 87% with a shorter 150 μs tagging window

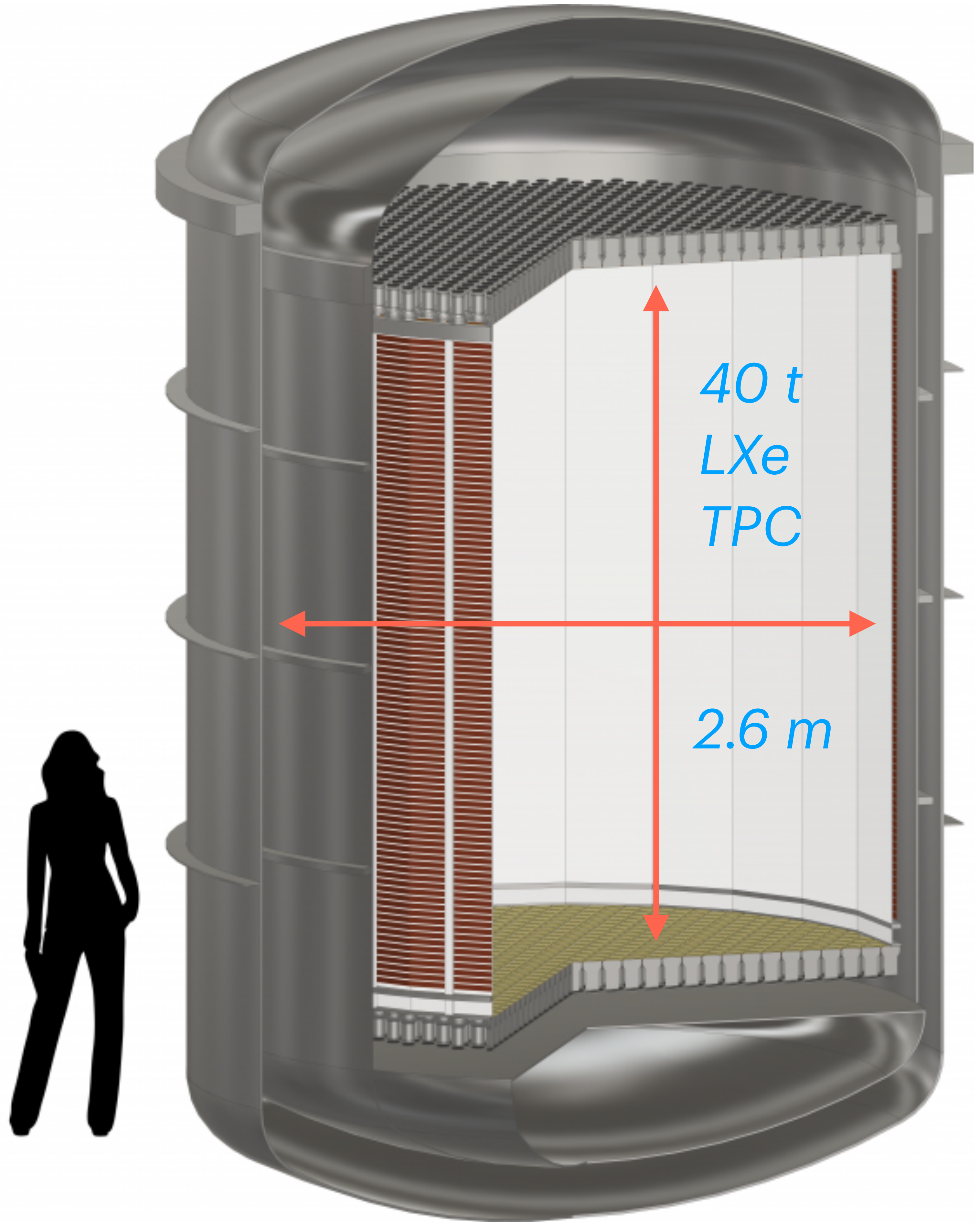
The DARWIN Experiment

Physics Programs @ DARWIN



The DARWIN Detector

- Dual-phase LXe TPC: 2.6 m ø and 2.6 m height
- 50 t (40 t) LXe in total (in TPC)
- Top & bottom arrays of photosensors (e.g., 1800 3-inch PMTs)
- PTFE reflectors and Cu field shaping rings
- Low-background Ti cryostat
- Gd-doped water as n- and μ-vetos
- Alternative designs and photosensors under consideration (details later)



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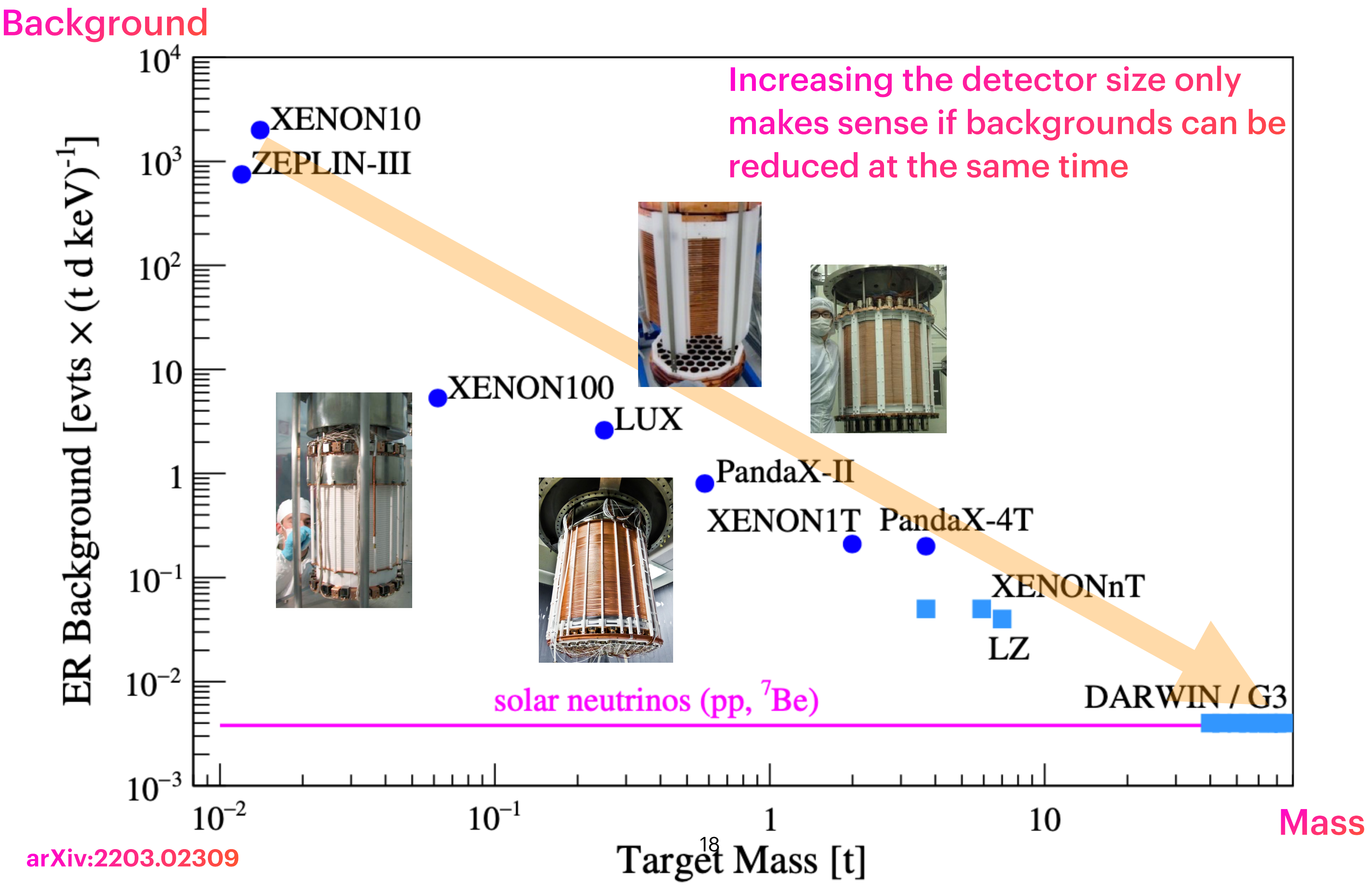
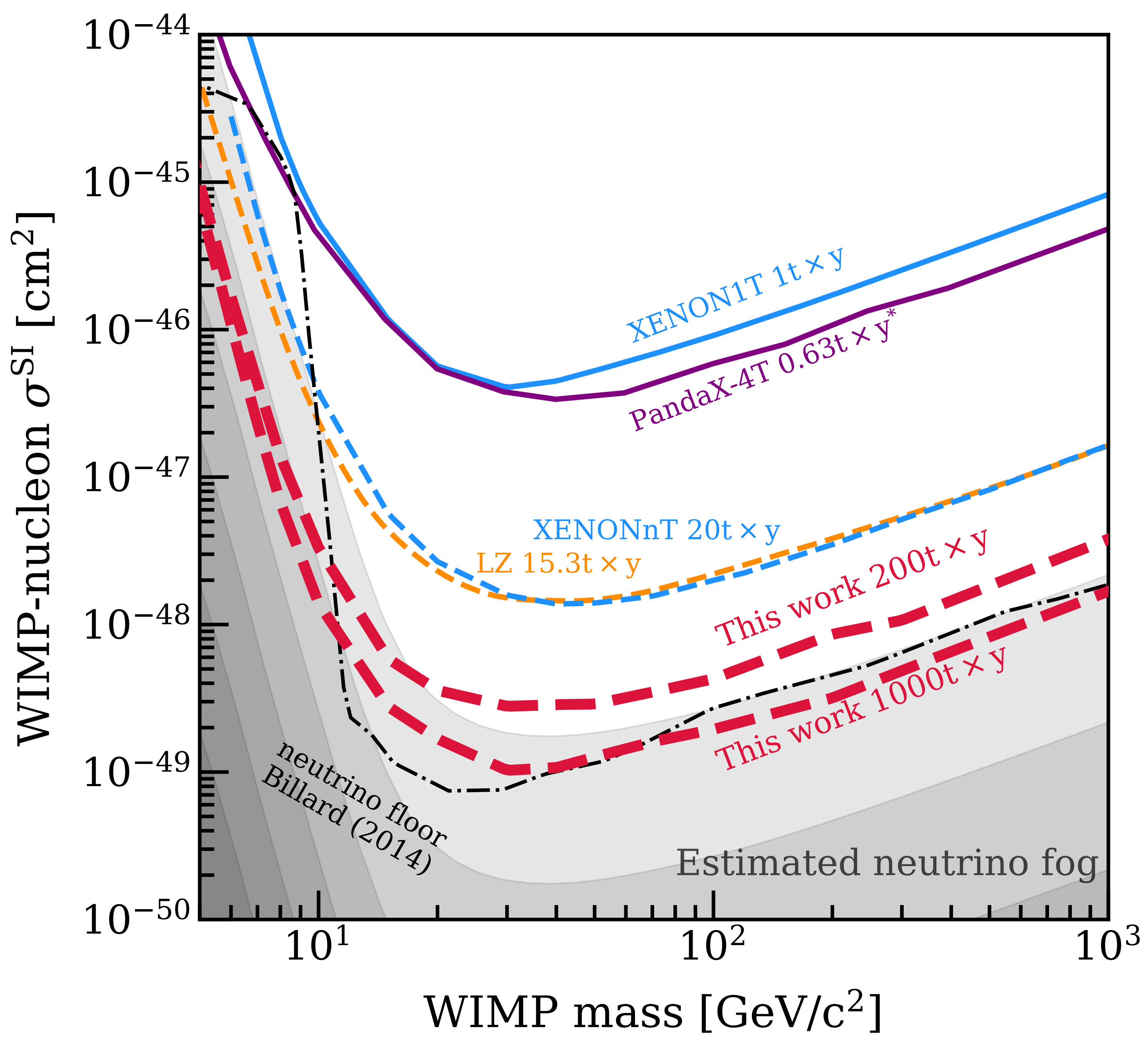
WIMP Sensitivity

- ◉DARWIN will improve the BG level by ×10 w.r.t. LZ / XENONnT
- ◉DARWIN can probe the entire parameter spaces up to neutrino fog
- ◉DARWIN can fully explore DMs with electroweak charges such as 3TeV thermal wino





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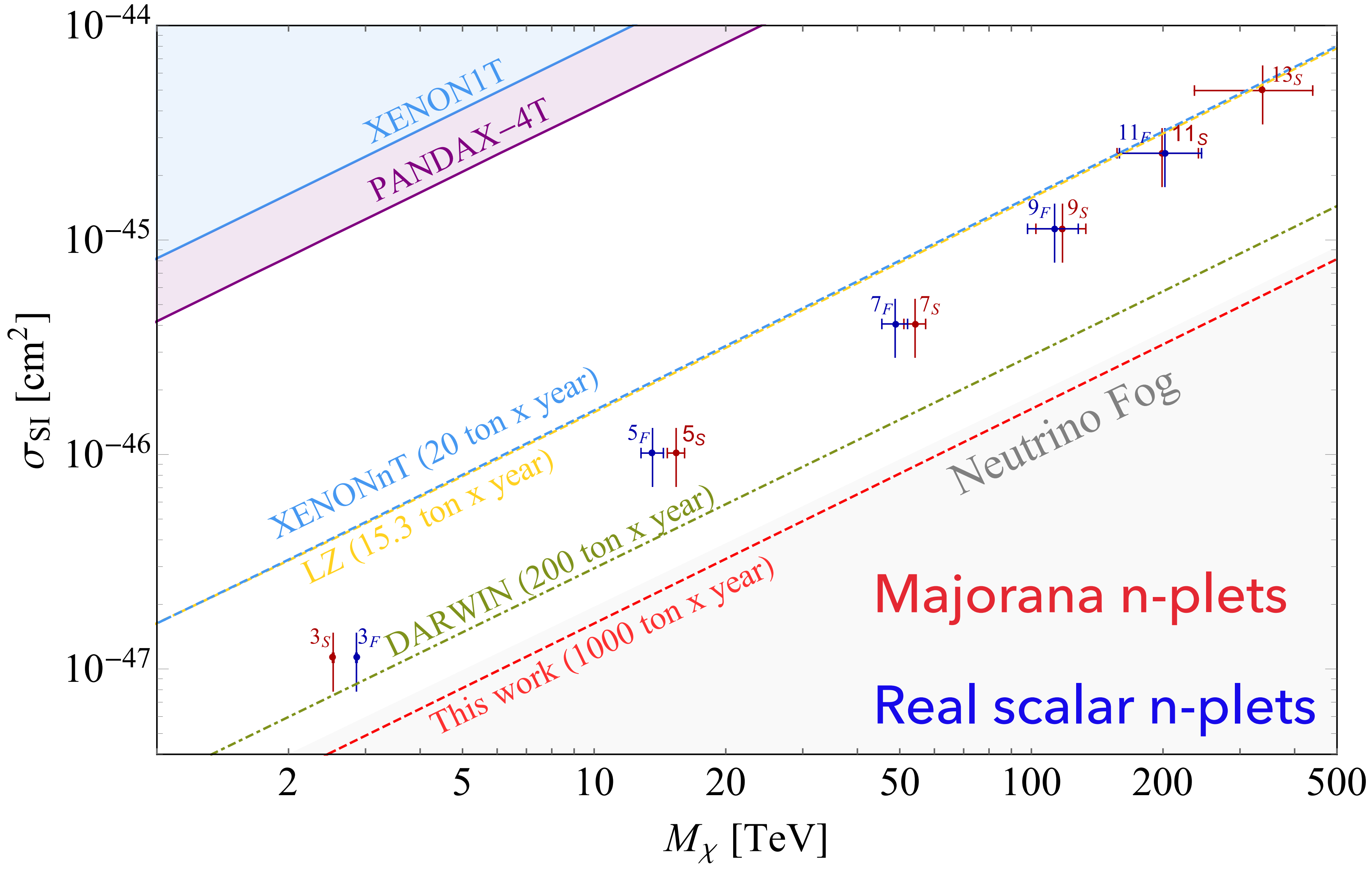
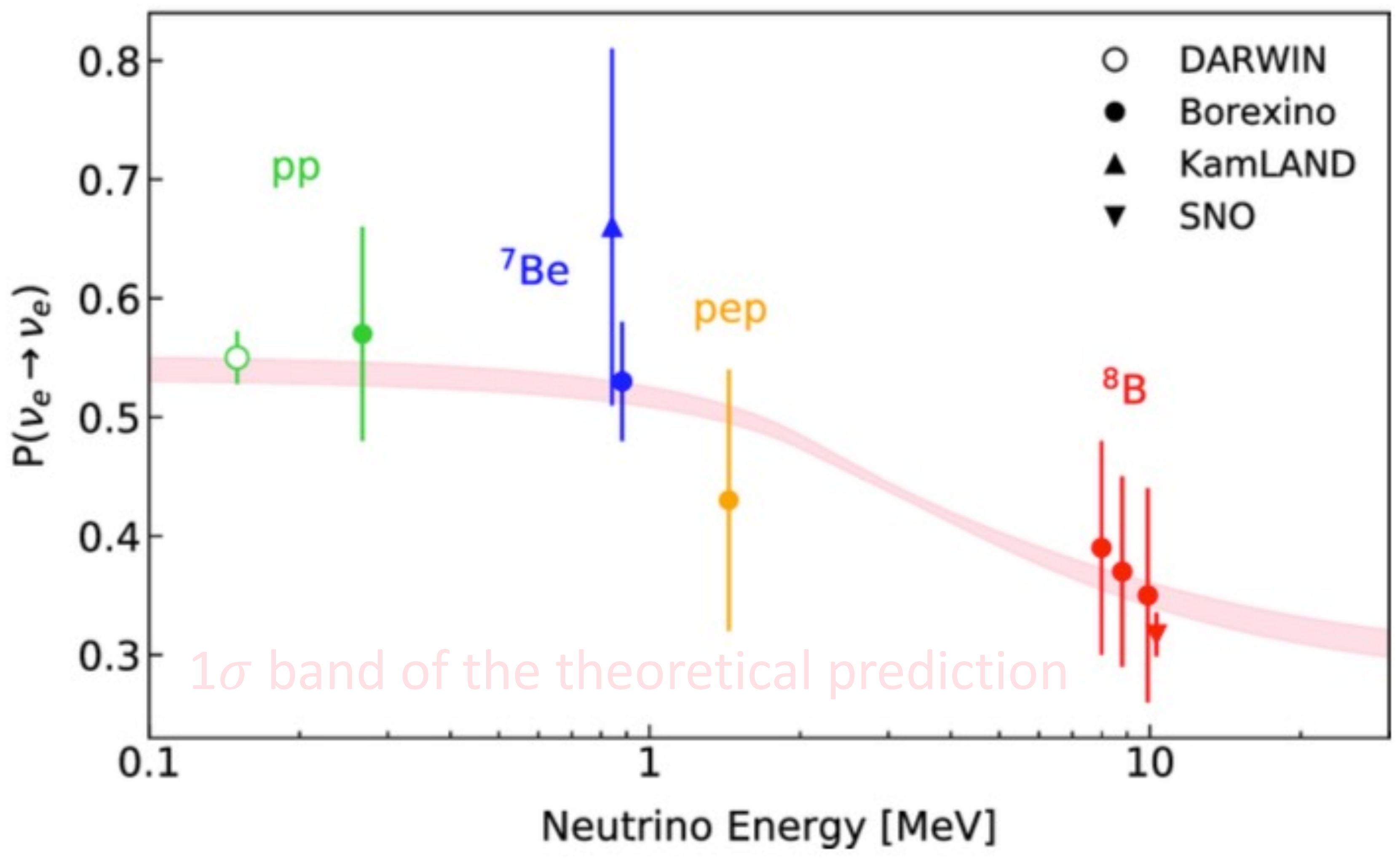


Neutrino Physics @ DARWIN

Low-energy solar neutrinos

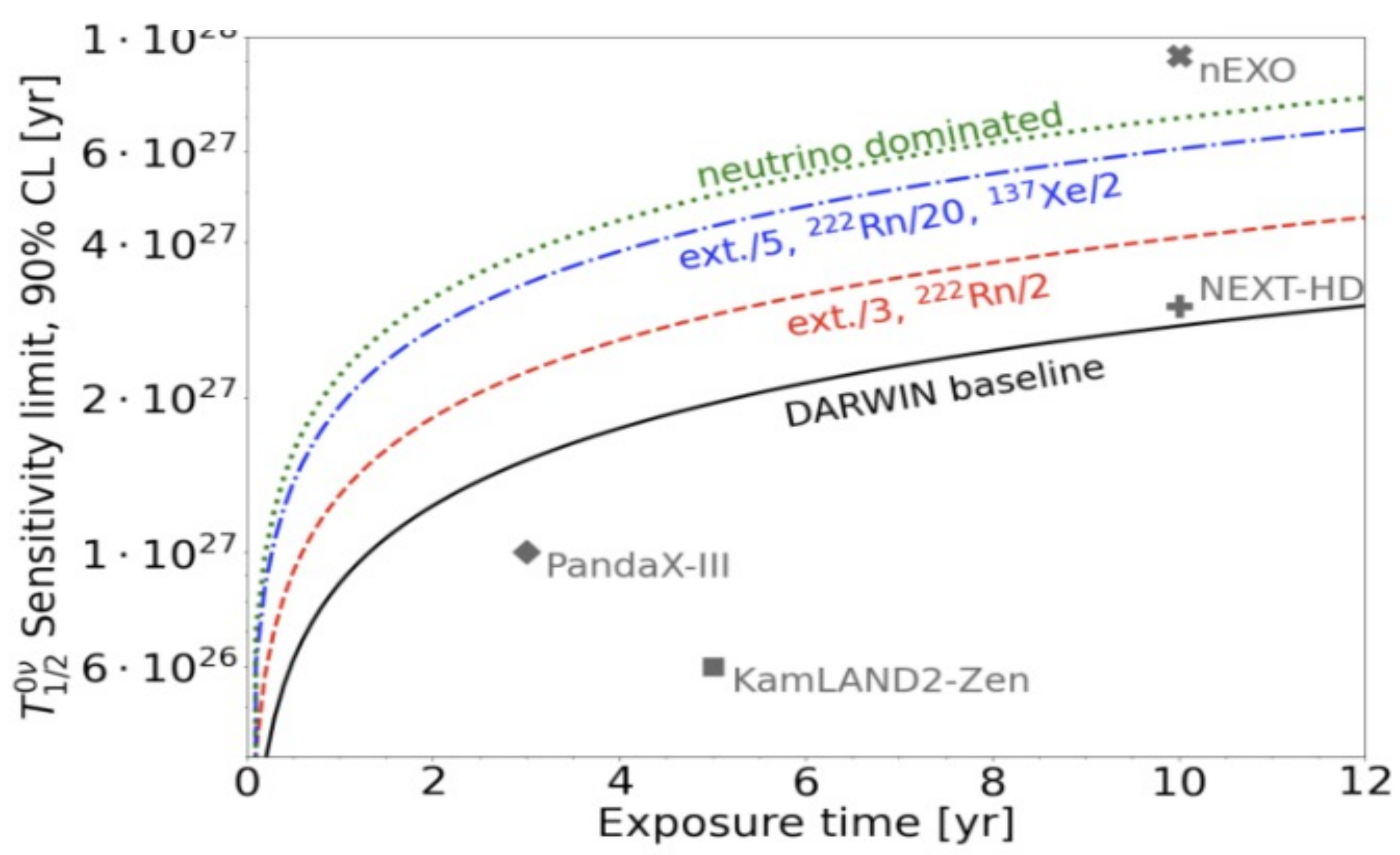
- Measurement of pp, ^{7}Be, ^{13}N, ^{15}O and pep flux
- Constrain the weak mixing angle
- Distinguish high/low metalicity solar models



J. Aalbers et al. Eur. Phys. J. C 80, 1133, 2020

0νββ decay of ^{136}Xe

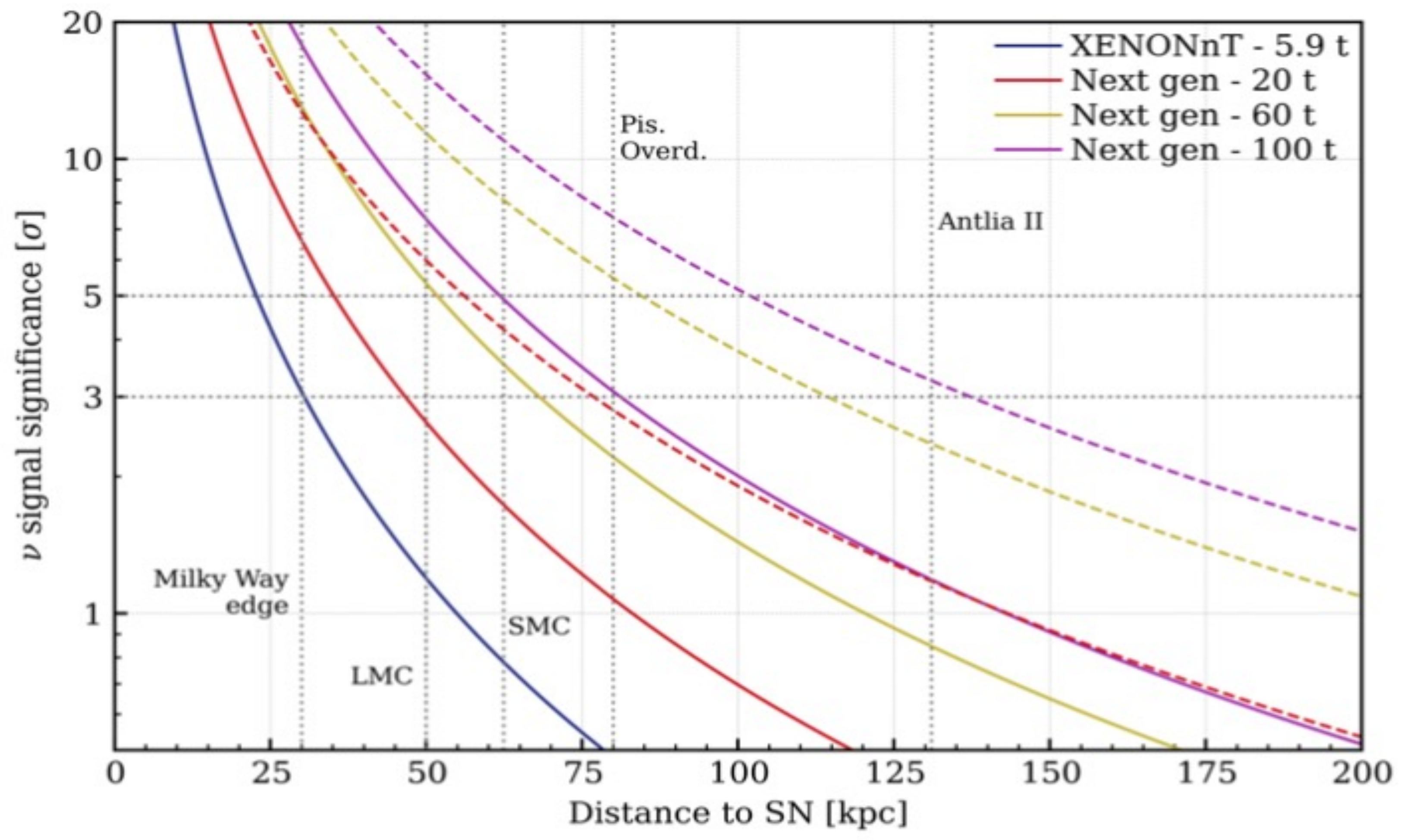
- Probe of the Dirac/Majorana nature of the neutrinos
- Sensitivity: $T^{0\nu\beta\beta} = 3.0 \times 10^{27}$ yr (90% C.L.) after 10 years of data taking



Eur. Phys. J. C 80, 808 (2020)

CEvNS

- Measurement of ^{8}B solar neutrino flux
- Measurement of atmospheric neutrinos
- Multi-messenger astrophysics vis supernovae neutrinos

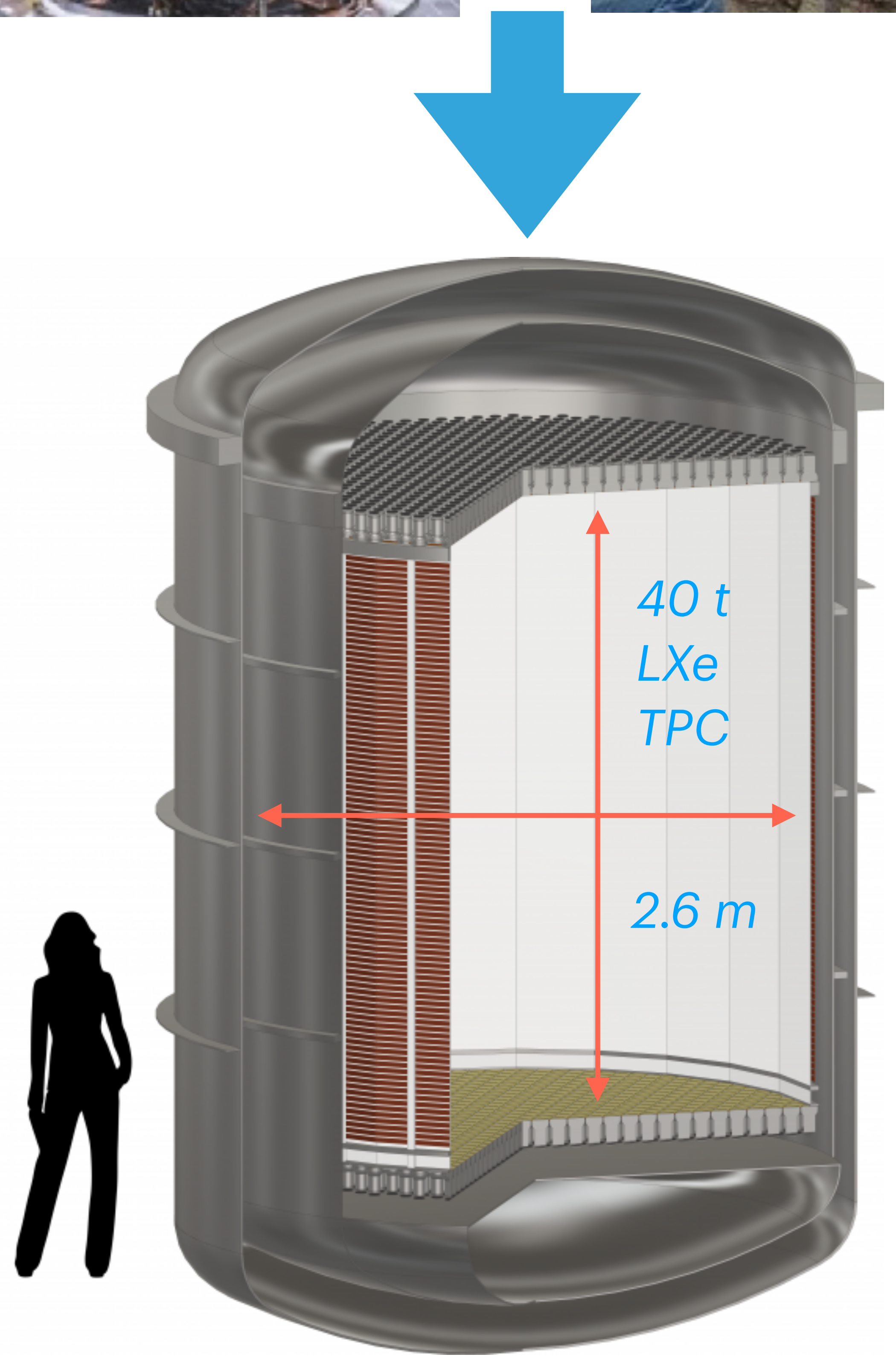


Challenges for Scaling Up

- LUX-ZEPLIN and XENONnT: 1.5 m e- drift and ~ 1.5 m diameter electrodes

DARWIN: 2.6 m ⇒ new challenges

- Design of electrodes: robustness (minimal sagging/ deflection), maximal transparency, reduced e- emission
- Electric field: ensure spatial and temporal homogeneity, avoid charge-up of PTFE reflectors
- High-voltage supply to cathode design, avoid high-field regions
- LXe Purity
- Background mitigation (radon and neutron)



R&D: Full Scale Demonstrator

- Two large-scale demonstrators, in z and in x-y, supported by ERC grants

  - Xenoscope (Zurich): 2.6 m tall TPC
  - Pancake (Freiburg): 2.6 m ø TPC in double-walled cryostats
    - Both facilities available to the collaboration for R&D purposes

JINST 16, P08052, 2021

R&Ds for Radon Reduction

◉Online distillation:

- XENONnT already achieved 0.8 μBq/kg

◉Surface coating

-Trap 222Rn after 226Ra decays

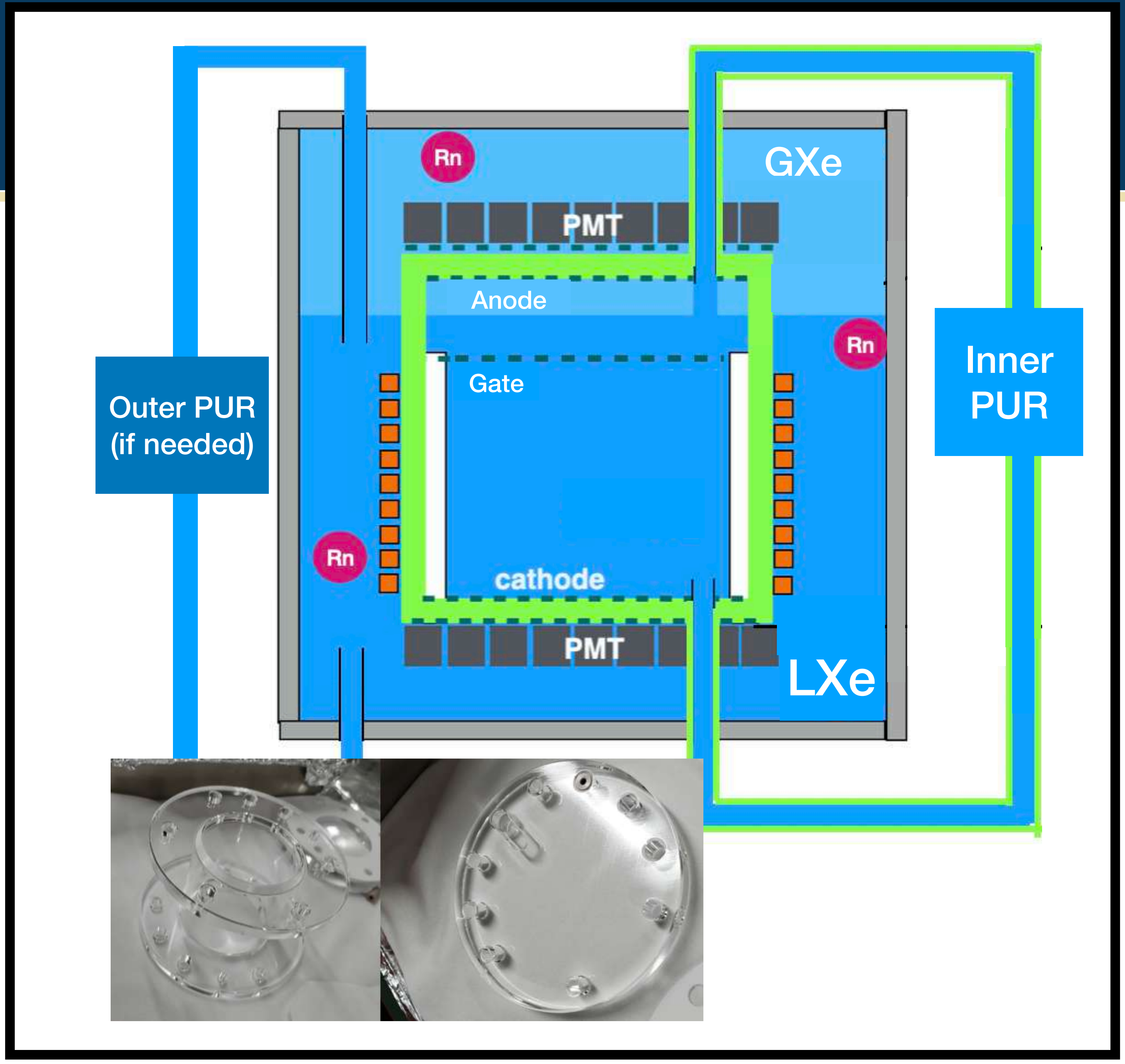
-Avoid Rn emanation

◉Material screening

-Select low-emanation material

◉Hermetic TPC

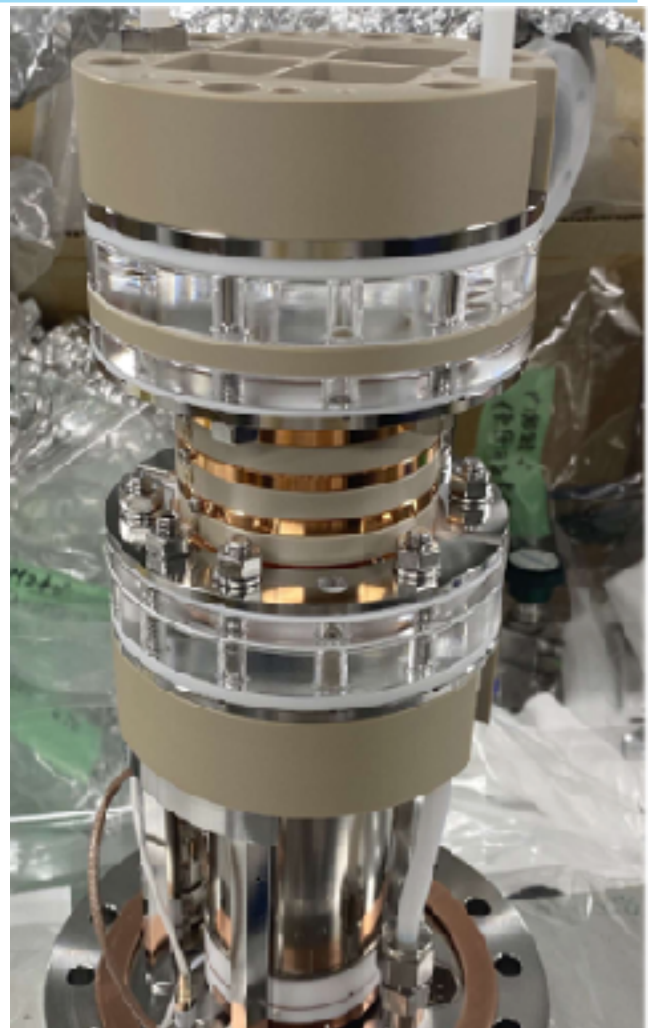
-Inner LXe volume (clean) separated from outer (dirty)



Freiburg

Phys. J. C. 83, 9 (2023)

Nagoya

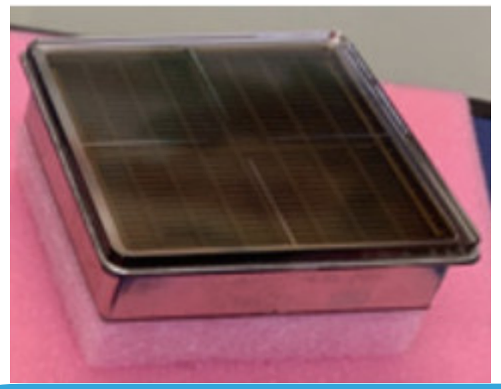


PTEP 2020, 11, 113H02

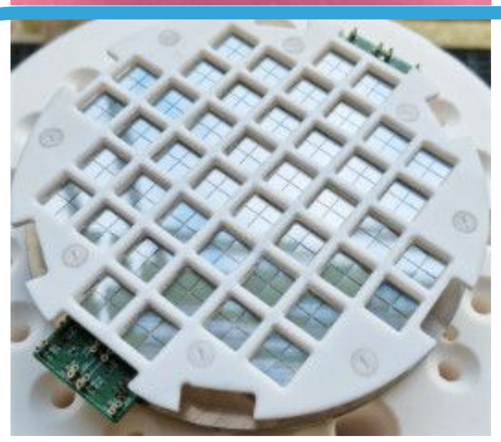
R&Ds for New Photosensors

R11410 **Baseline** *JINST 16 (2021) P08033*
→ improve radioactivity

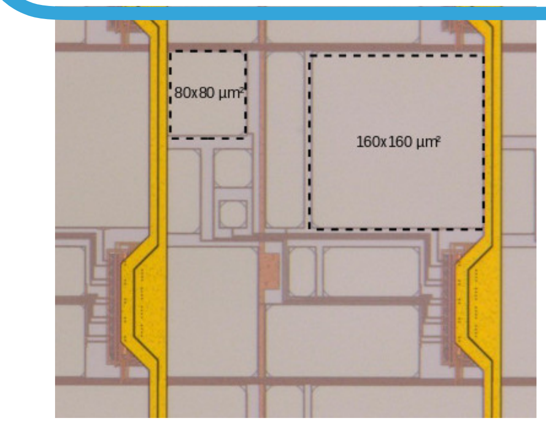
R13111 3“ XMASS *JINST 15 (2020) P09027*
→ curved window



R12699 2“ flat-panel
→ fast, low-radioactivity



SiPM *JINST 18 (2023) C03027, JINST 13 (2018) P10022*
→ lowbackground, DC rate?

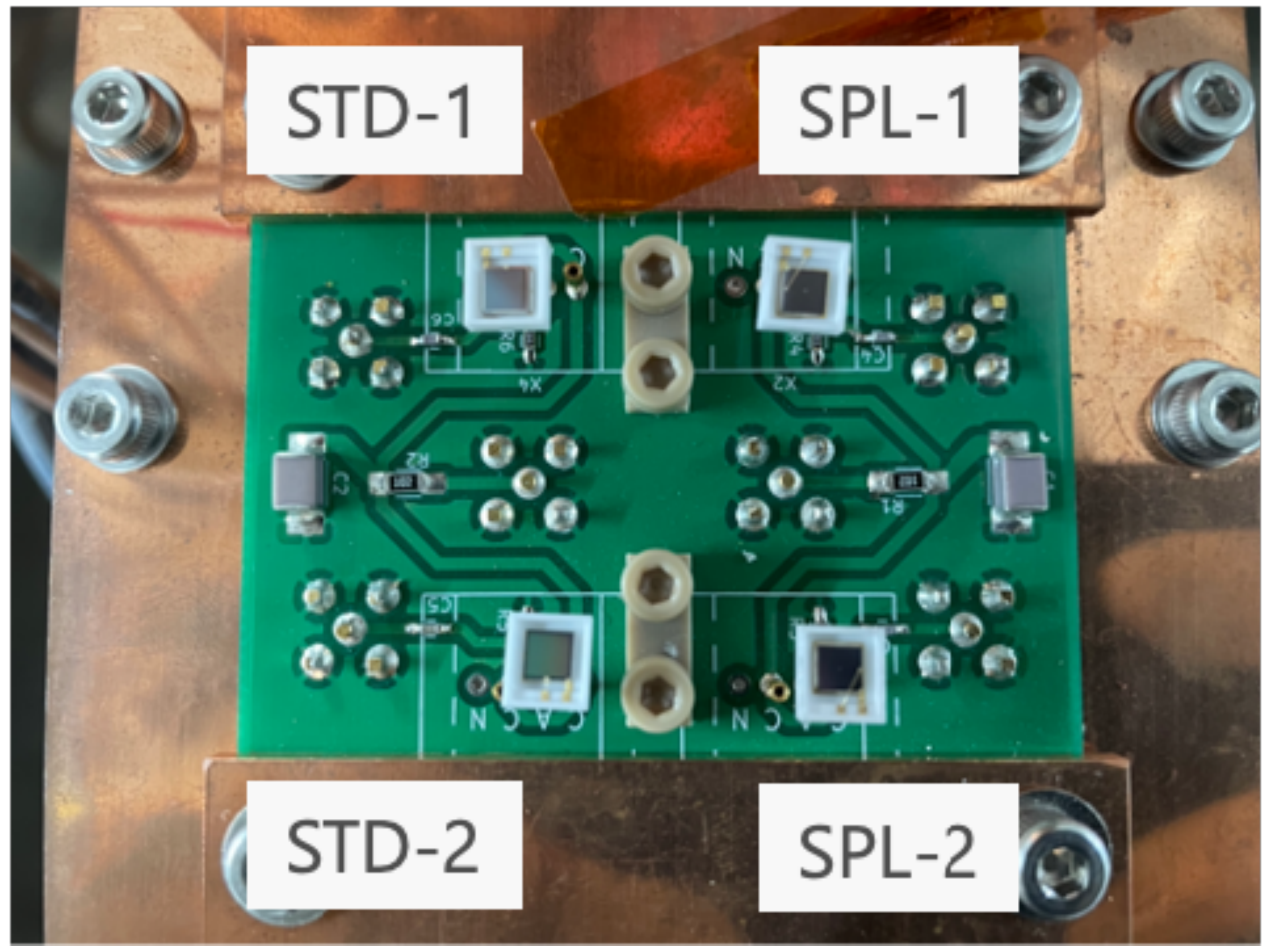


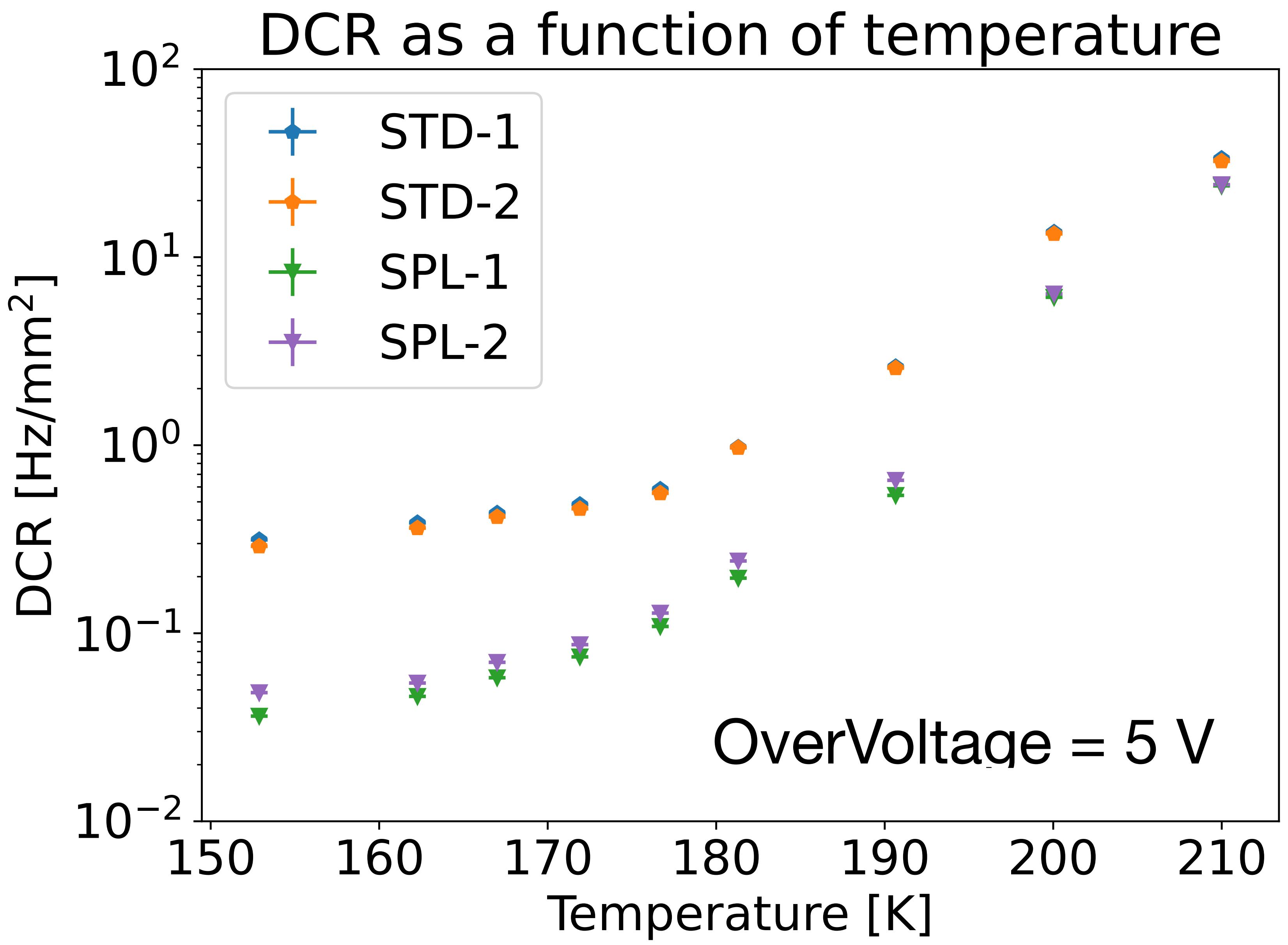
Digital SiPMs
→ goal: DC rate similar to PMTs

Hybrid Detectors: Abalone *NIM A 954 (2020)*
→ low background, HV?

New low-noise VUV SiPMs under study by Nagoya group

SiPM	S13370-3050CN (VUV4, STD)	MPPC-VUV-LDC-050UM-SPL (SPL)	
Operation Voltage	40-50 V	80 - 100 V	
Active Area	3×3 mm^2		
Number of pixels	14400	14400	6400
Pixel size	50×50 μm^2	50×50 μm^2	100×100 μm^2





R&Ds for Alternative Detector Designs

Single-Phase LXe TPC

- Both S1/S2 created in liquid
- No liquid level control is required
- Reduce single-electron emission

◉UCSD

- 10 μm anode wire in the center
- See Kaixuan's talk for more details

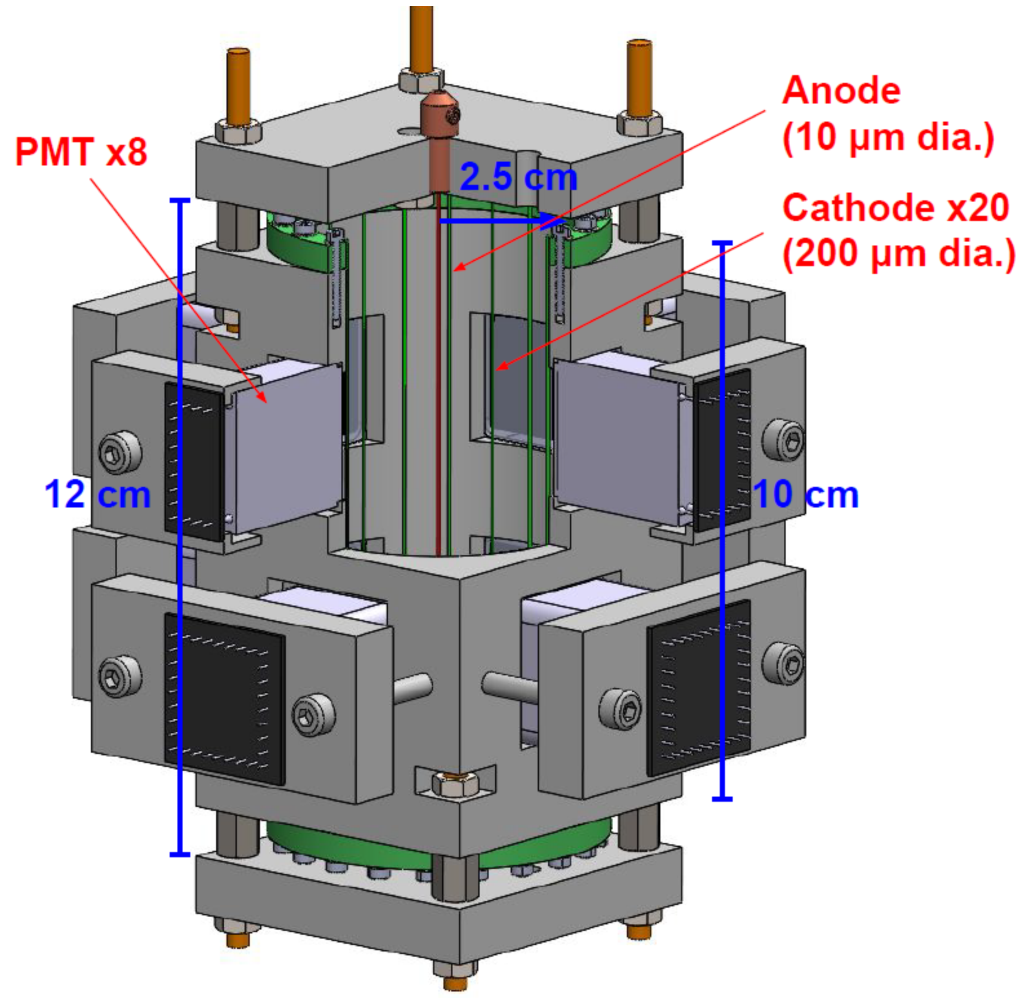
◉Freiburg

- "classical dual-phase" layout with 10 μm anode wire

◉Weizmann (+Nagoya)

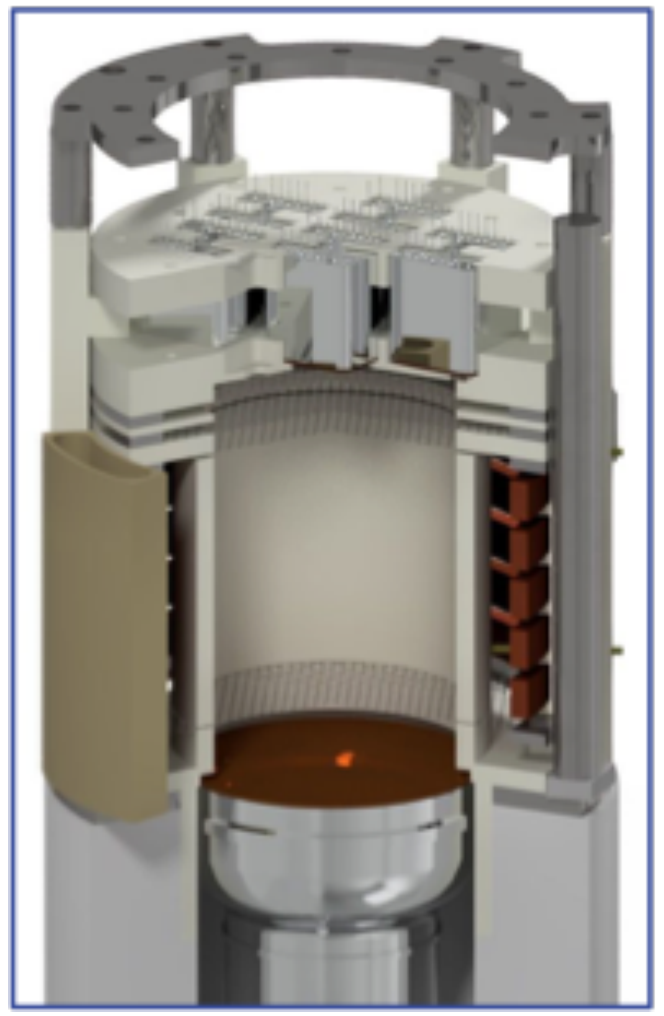
- Microstrip plate coated on a MgF_2/Quartz plate

UCSD



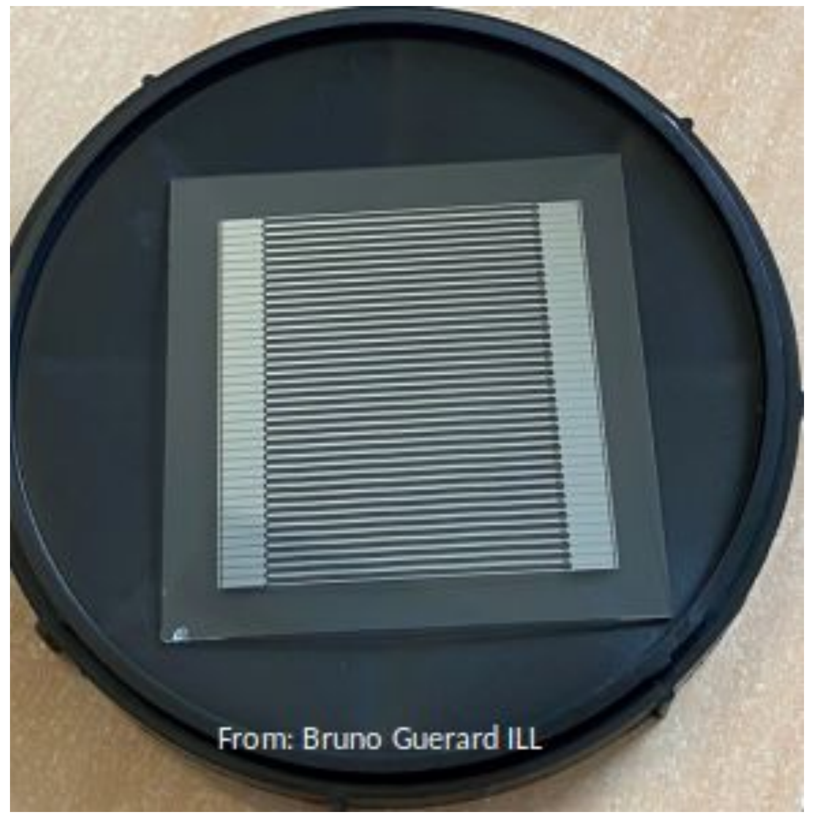
JINST 18 P07027 (2023)

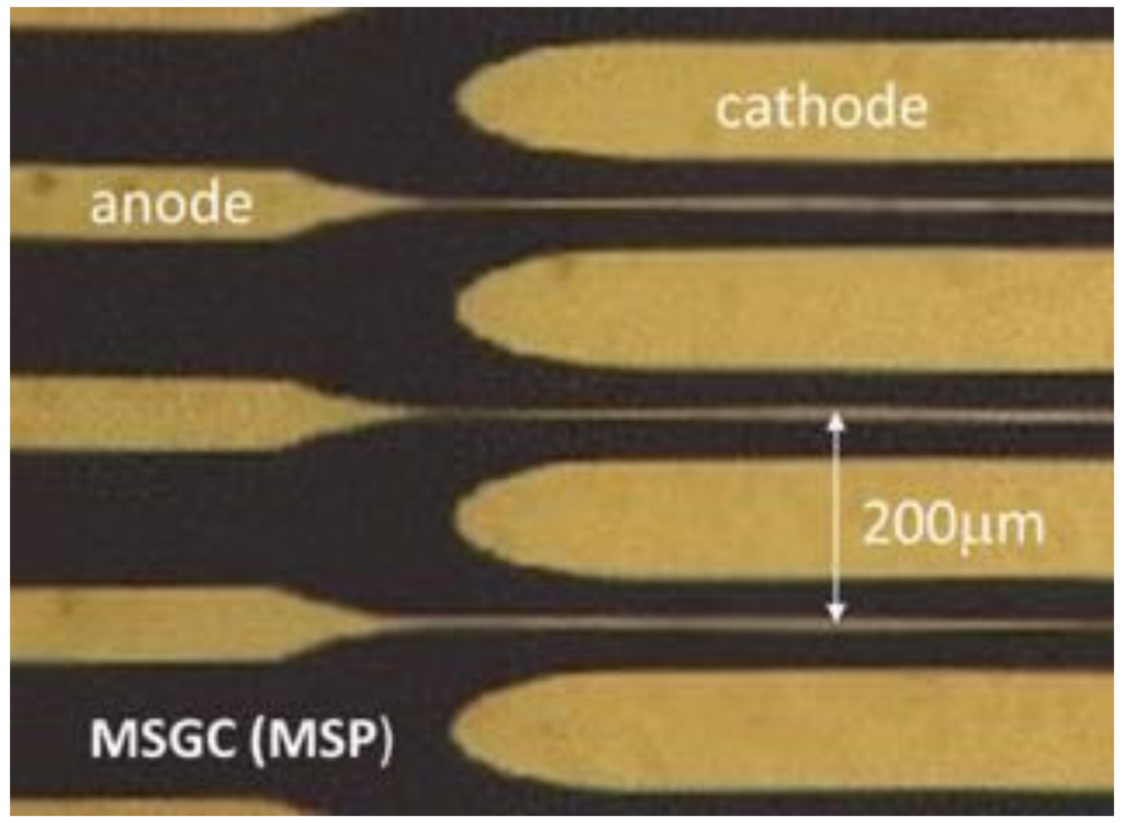
Freiburg



JINST 17 P03027 (2022)

Weizmann





JINST 17 P08002 (2022)

Future: XLZD Consortium

- The XENONnT, LZ & DARWIN have joined forces to build the next generation of LXe dark matter detector

- MoU signed July 6, 2021 by 104 research group leaders from 16 countries

- Seven working groups in place to study science, detector, Xe procurement, R&D etc
  XLZD consortium (xlzd.org) to design and build a common multi-ton xenon experiment

- The XLZD consortium paves the way for a shared future in DM discovery
  → See more details in our white paper: J. Phys. G: Nucl. Part. Phys. **50** 013001 (2023)

Back Up

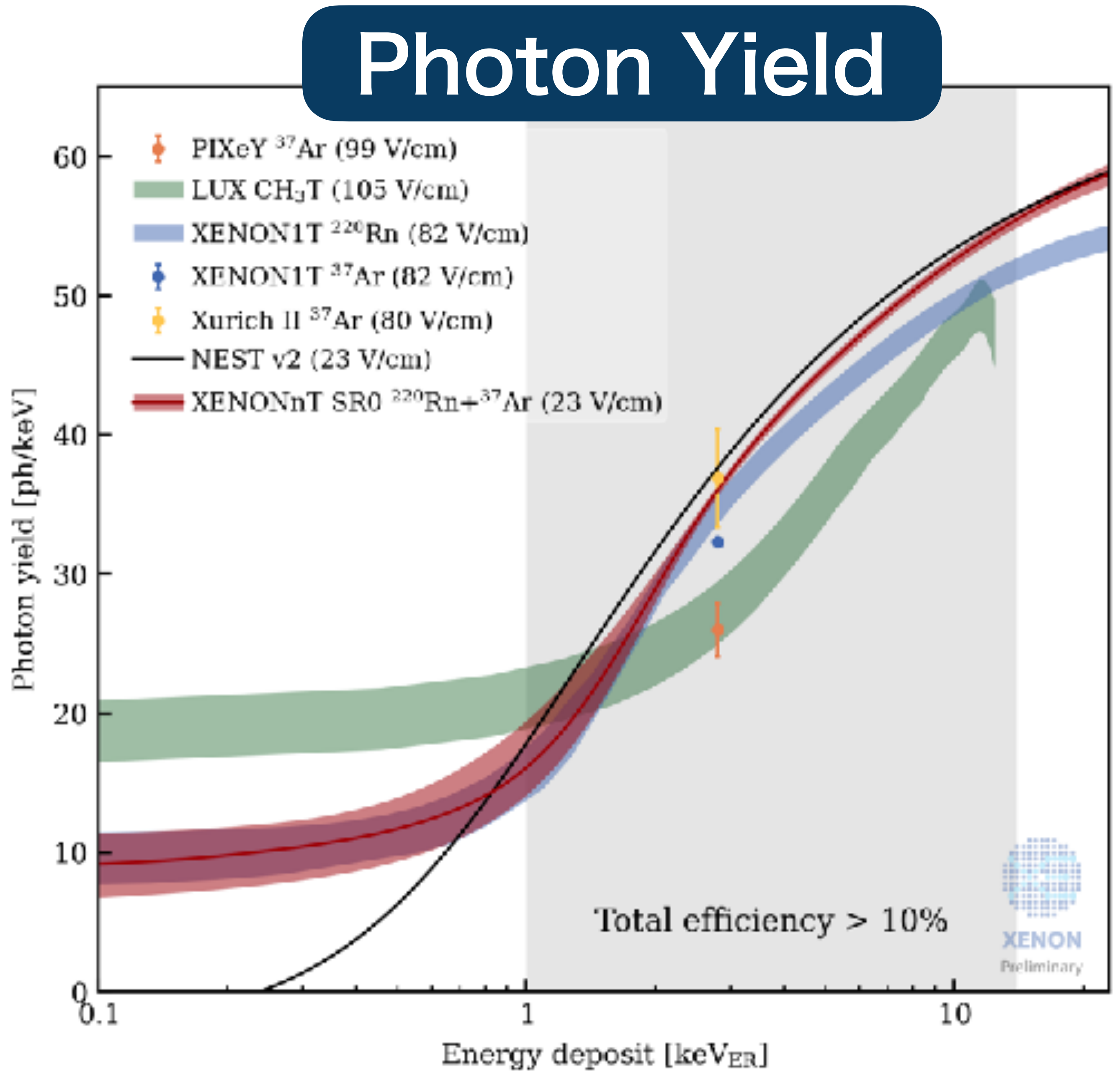
Low Energy ER Calibration

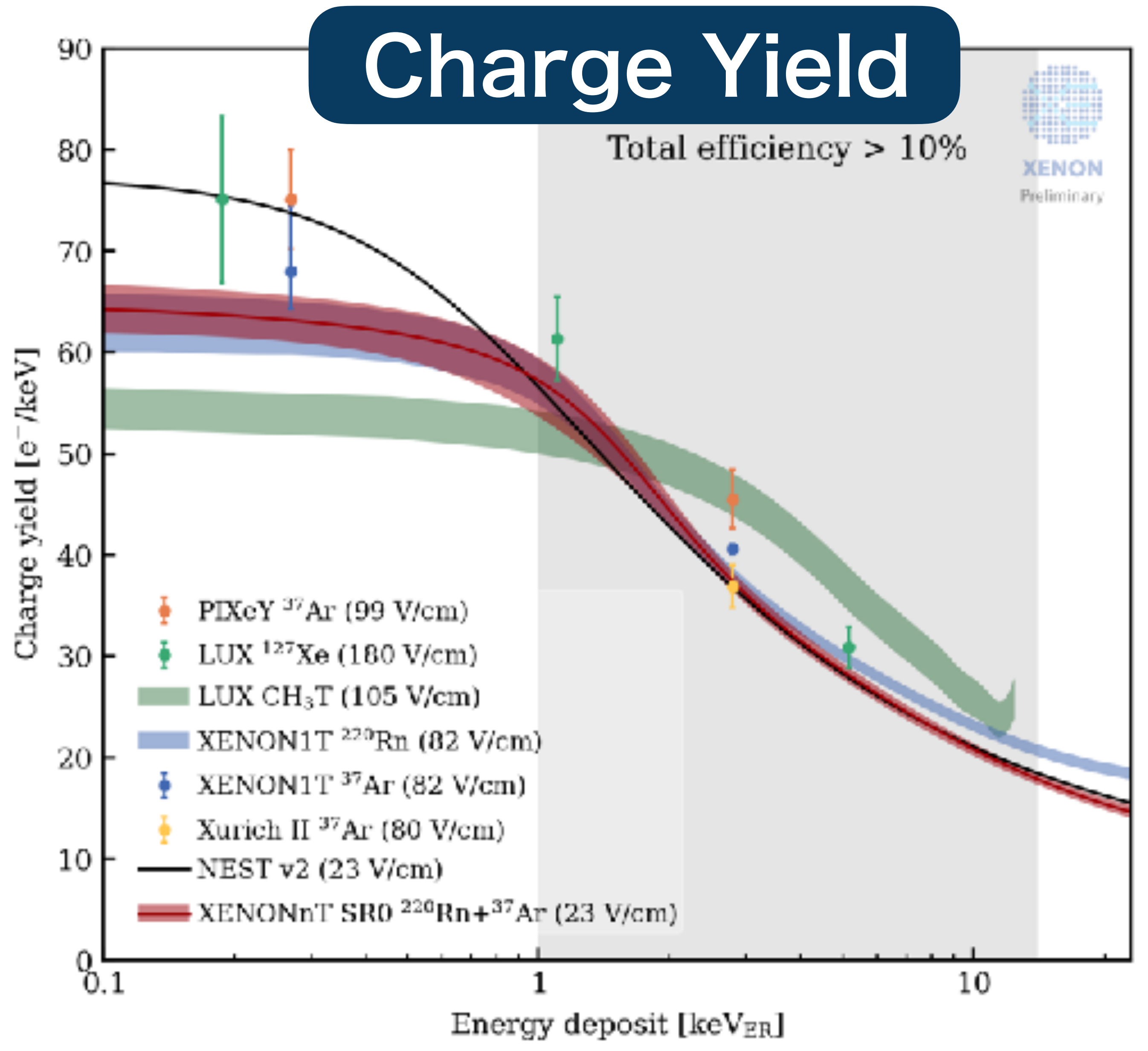
^{212}Pb from ^{220}Rn: β-decay (Q_β = 570 keV)

- Gives approximately flat energy spectrum
- Used to
  - validate cut acceptances
  - estimate photon/charge yield

^{37}Ar:

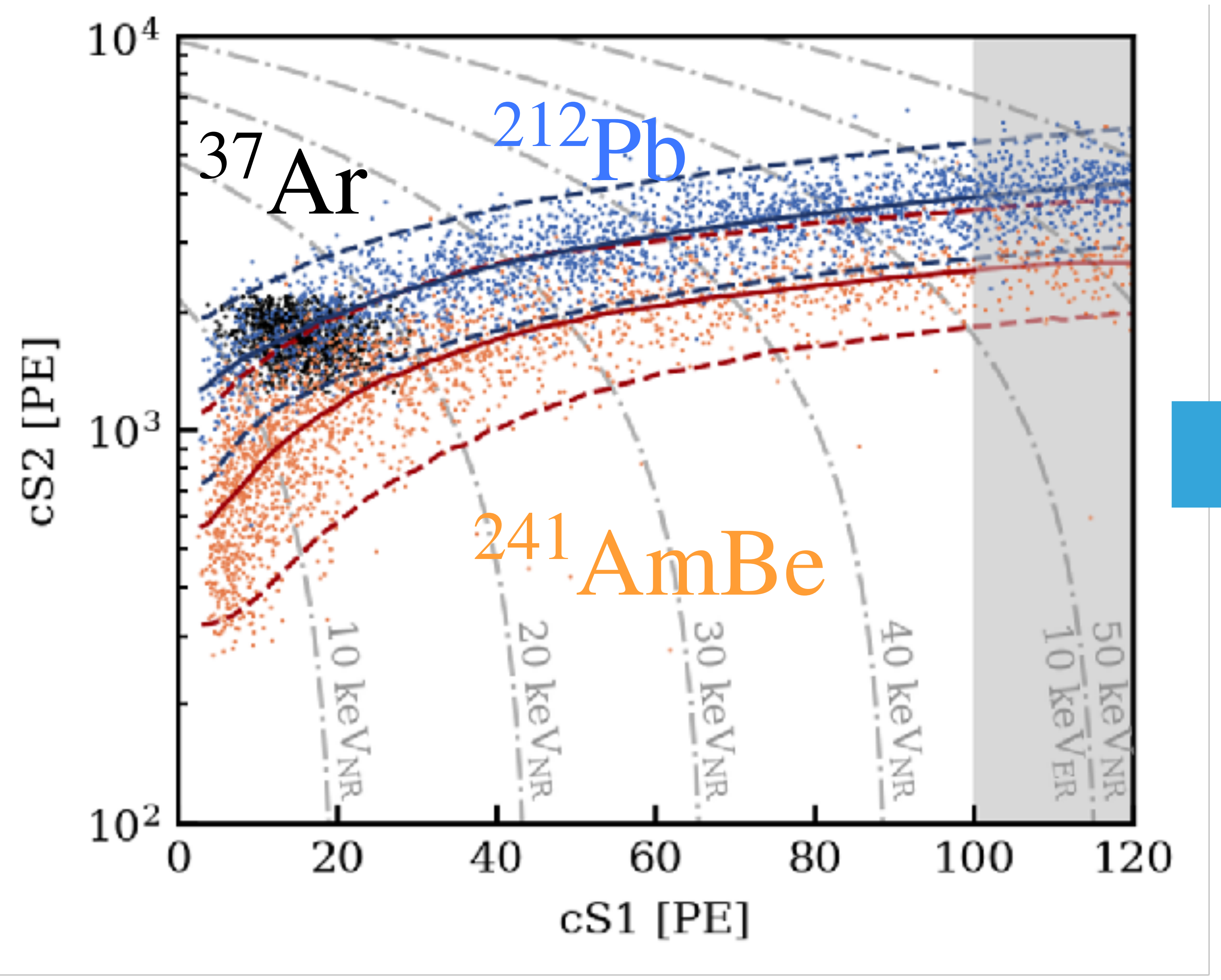
- Mono-energetic line @2.8 keV
- Allows to study performance with high resolution due to high statistics
- Removed via distillation ($T_{1/2} \sim 35$ days)



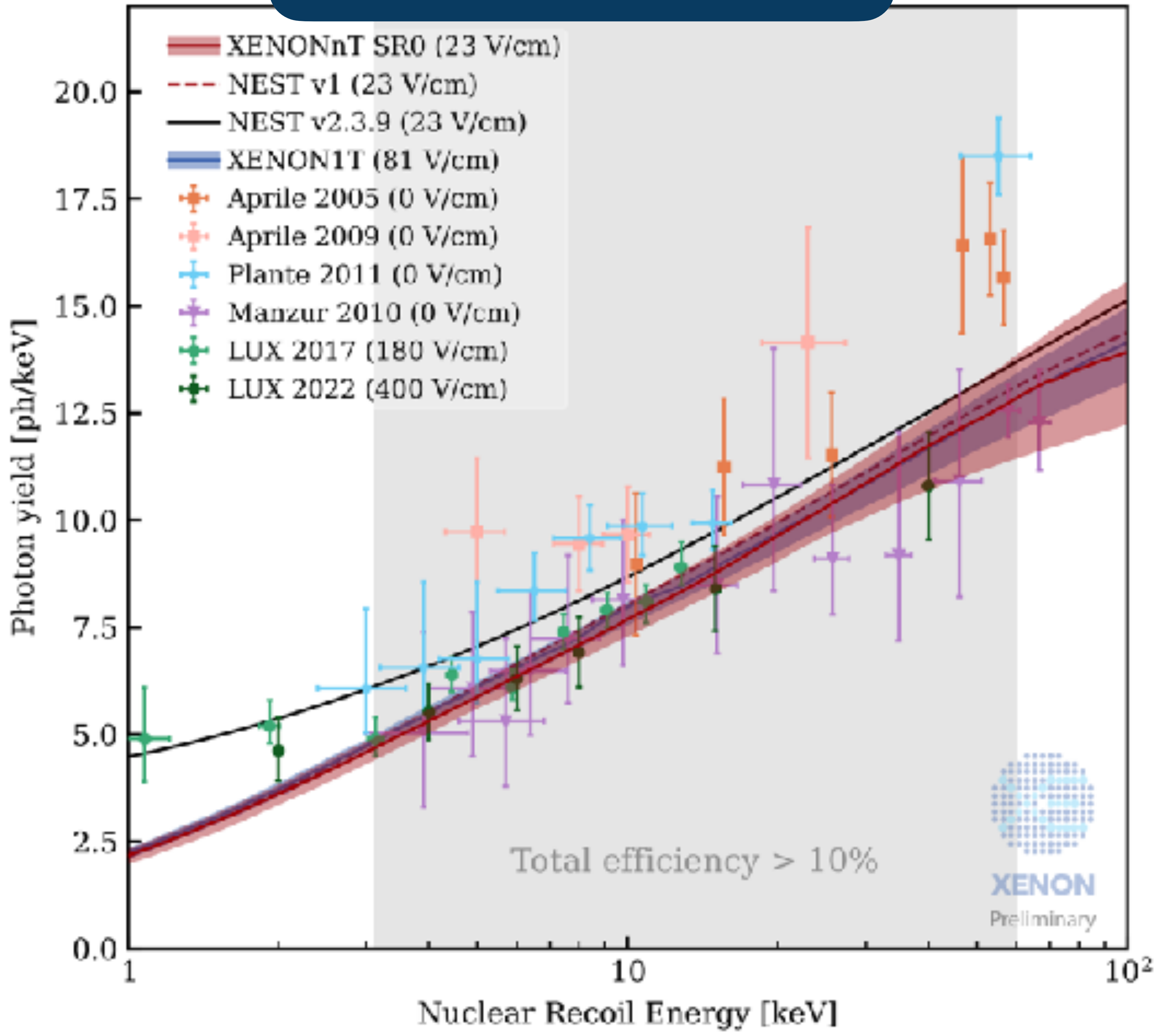


Energy threshold for ER signal is ~ 1keV

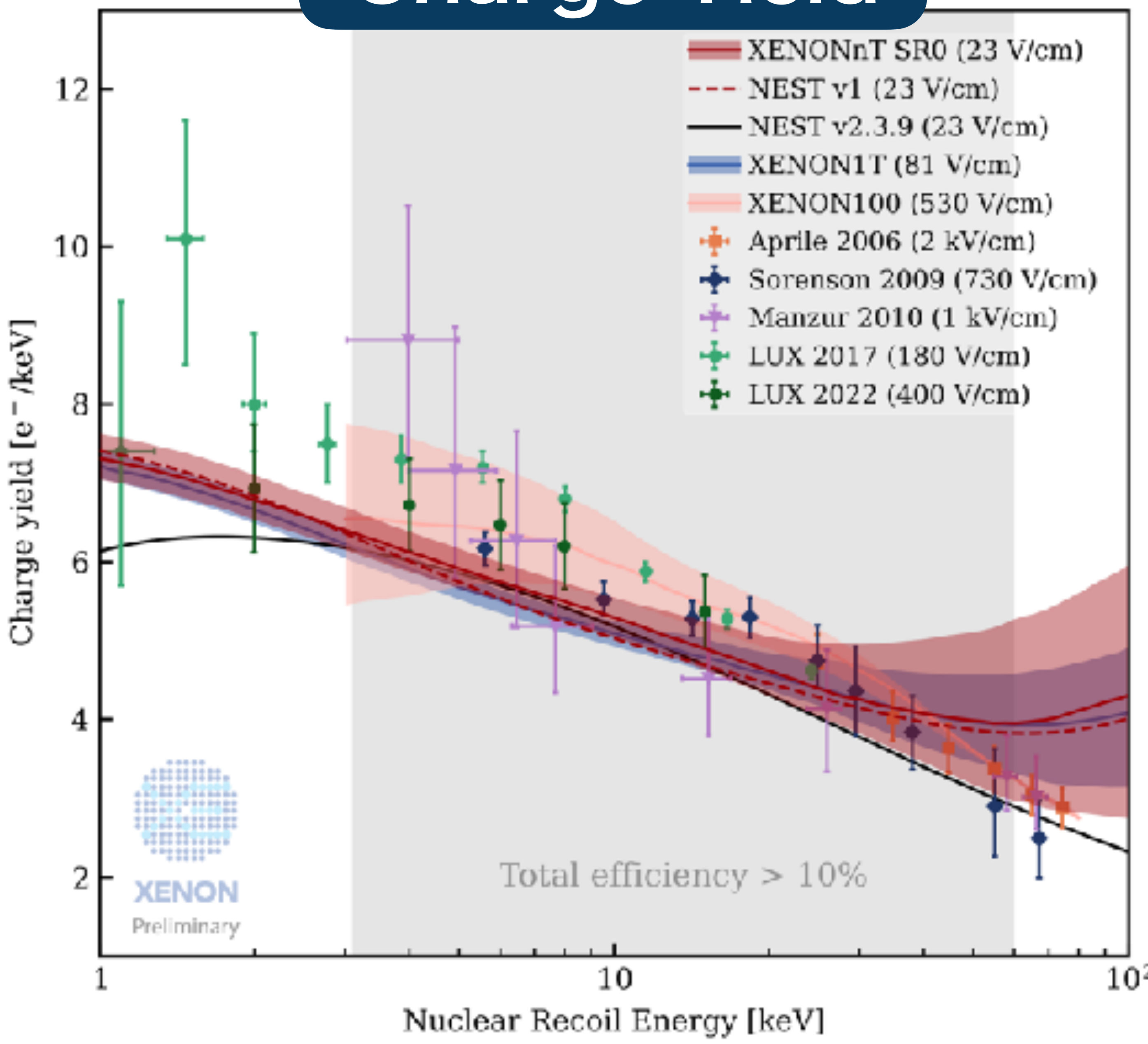
Low Energy NR Calibration



Photon Yield

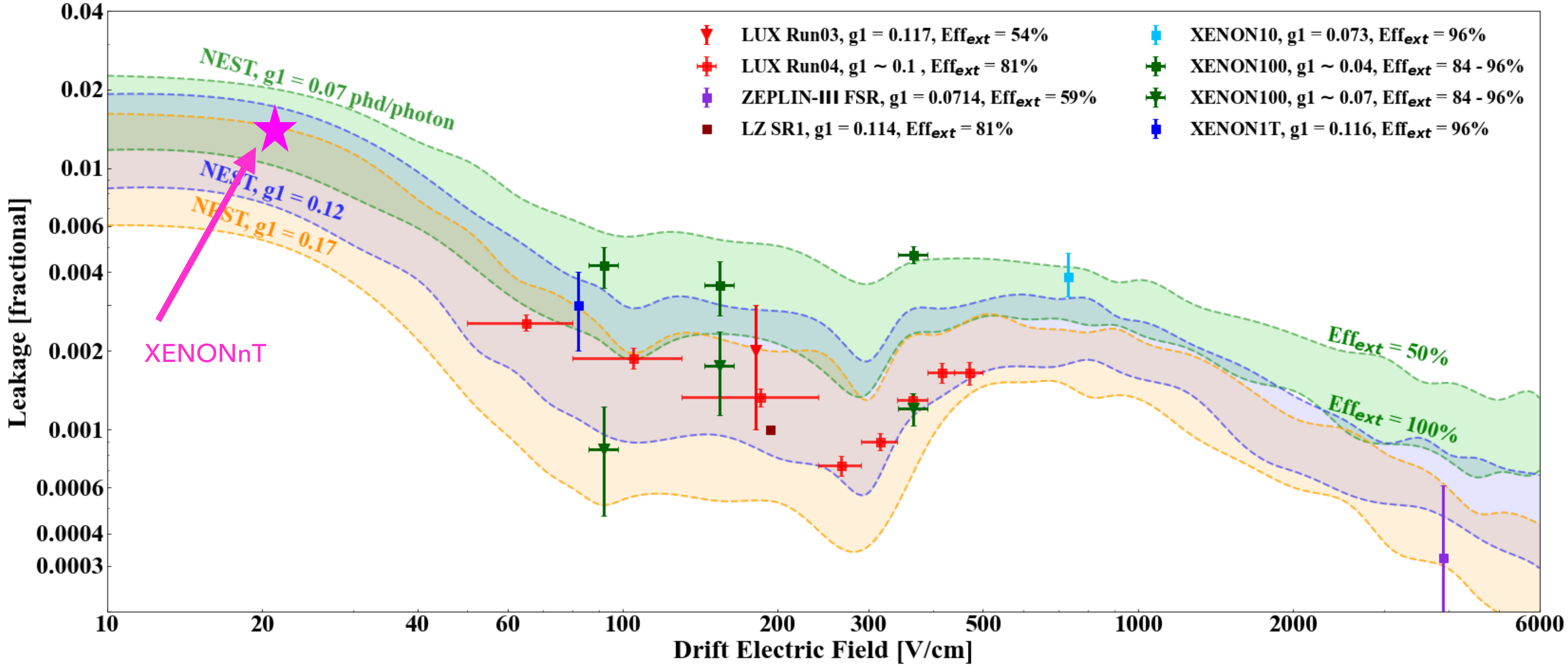


Charge Yield



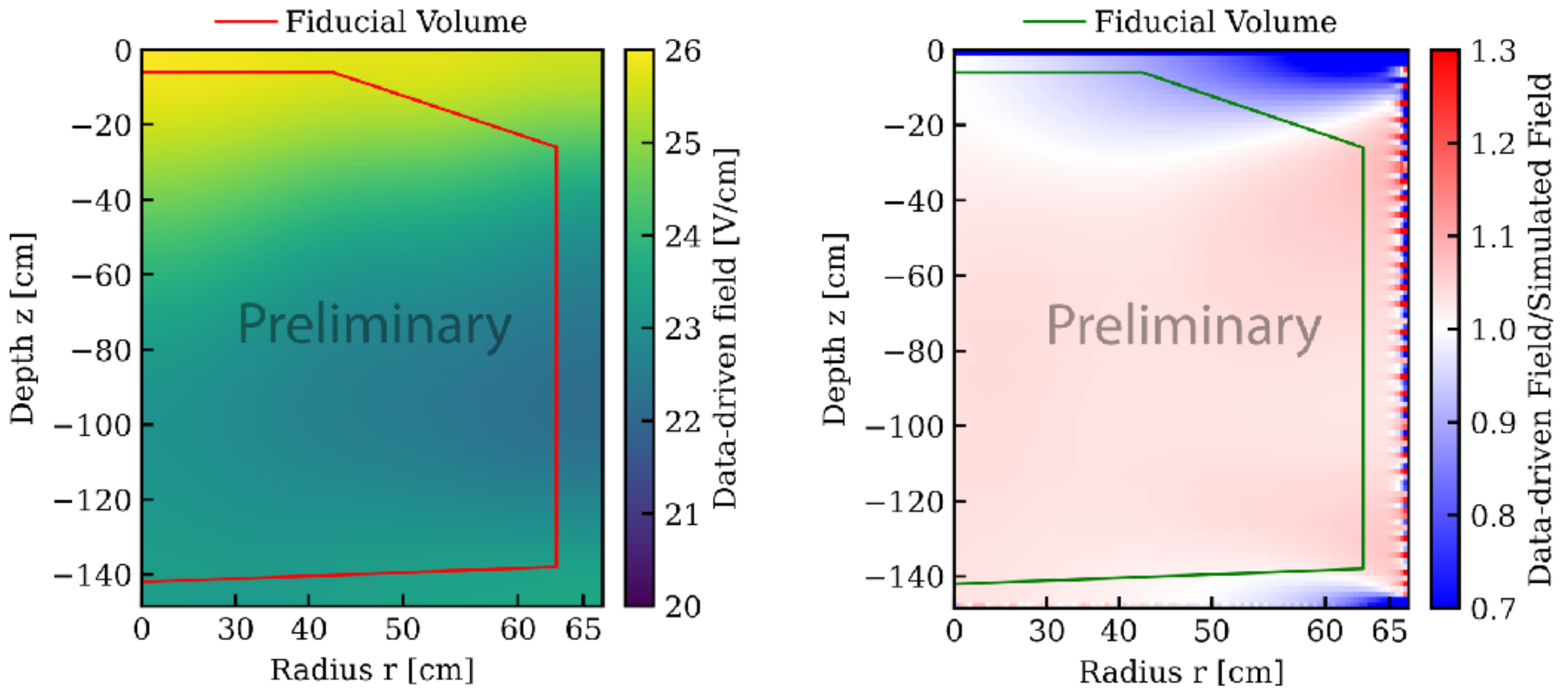
Energy threshold for NR signal is ~ 3keV

ER/NR Separation

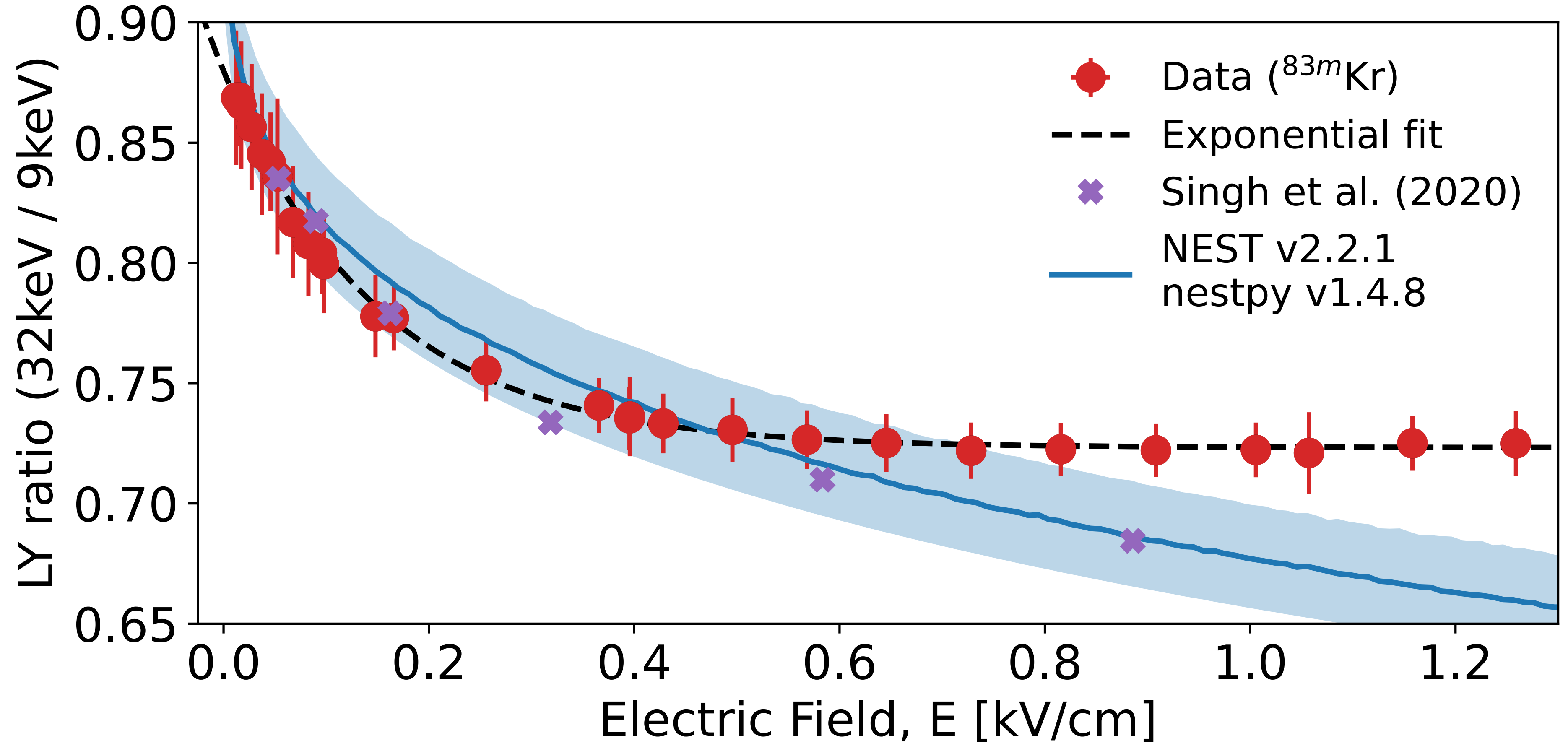


Drift E-fielc Calibration

- Current drift field at ~23 V/cm
- Important to control field non-uniformities
- Calibration with ^{83m}Kr
  - two consecutive lines 32.1 and 9.4 keV
  - ratio of observed amplitudes
    → drift field sensitivity
  - tuning of COMSOL-based field simulation to current detector conditions
- Better than 10% match in fiducial volume for SR0



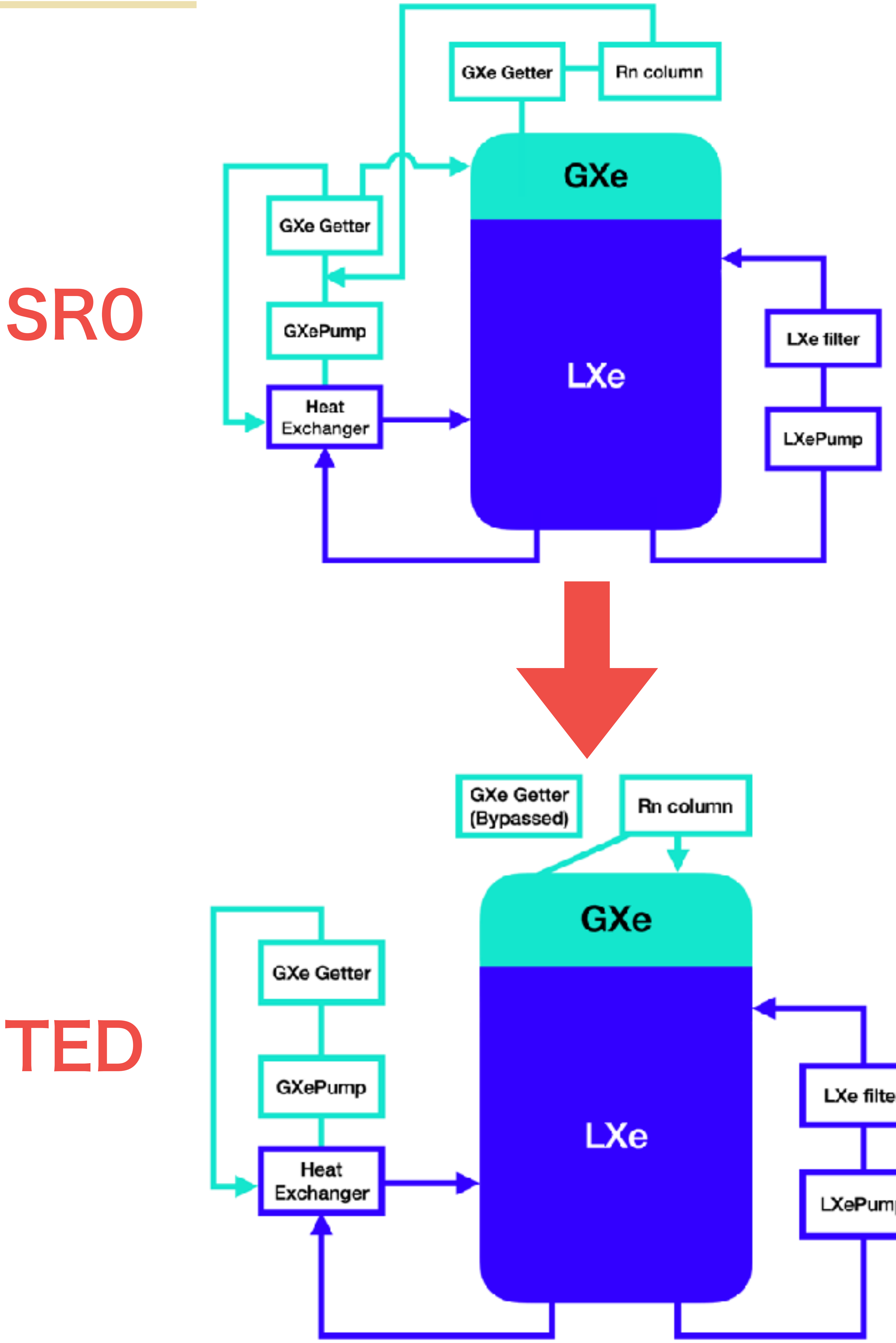
Eur. Phys. J. C 82, 361 (2022)



Tritium Handling @ XENONnT

XENONnT went through significant efforts to reduce possible sources of a low-energy excess

- 3 months of outgassing
- 3 weeks of GXe (warm) cleaning with hot getters
- GXe purified with Kr-removal system during its transfer into the gas storage system, resulting in less HT
- When filling to TPC, GXe was purified with hot getters, which include H2 removal units.



Special mode:

- “tritium enhanced data” (TED) bypassing getters
- orders of magnitude in hydrogen level increase (conservative – at least 10x)
- 14.3 days of TED data

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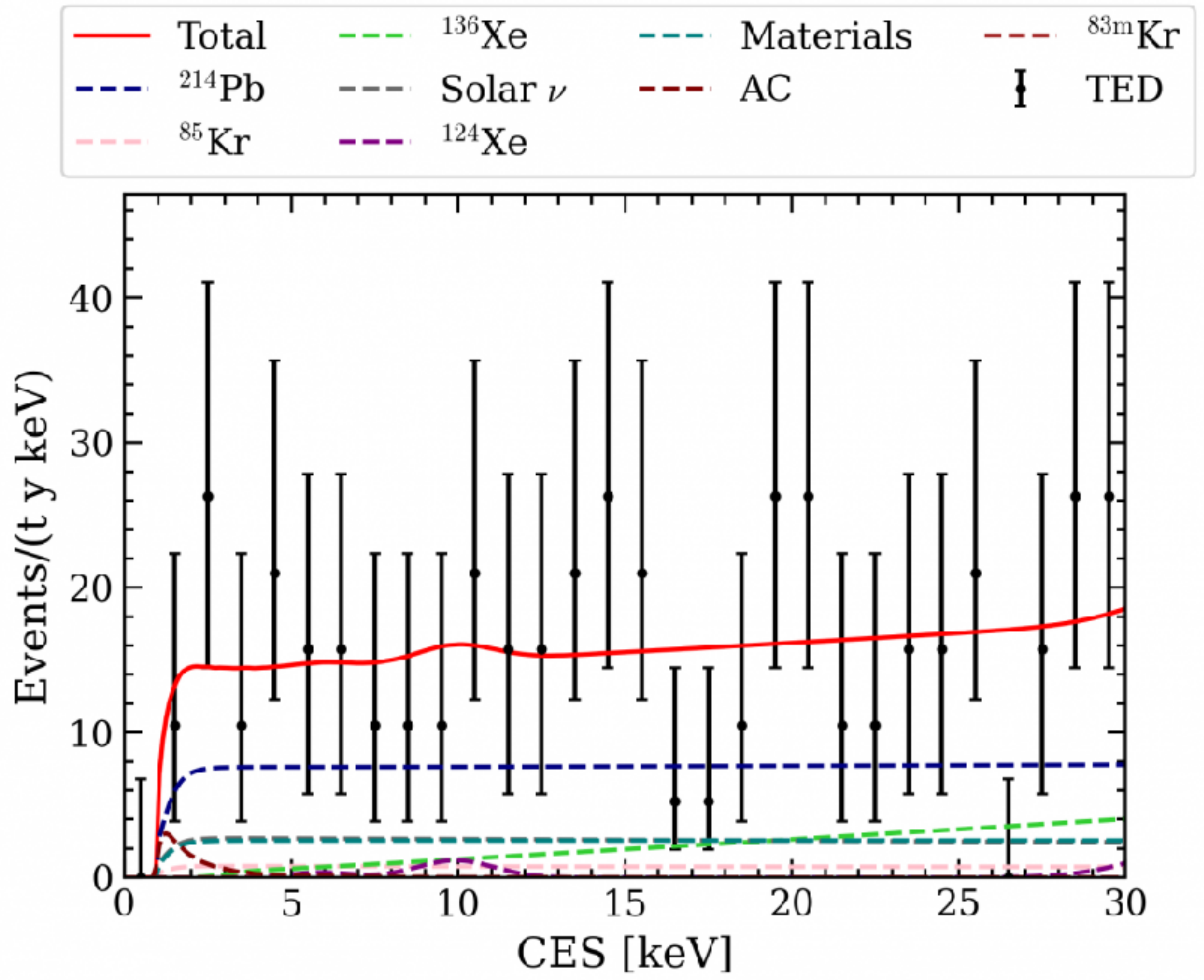

Result of blind TED analysis

→ No tritium excess

→ Tritium is not considered in the BG model