New dark matter results from Xenon experiments

CIPANP 2022
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Outline

- Overview of LXe technology
- The LZ and XENONnT Detectors
- The XENON1T Excess
- First results from LZ (WIMP search)
- First results from XENONnT (Testing the Excess)
- Outlook

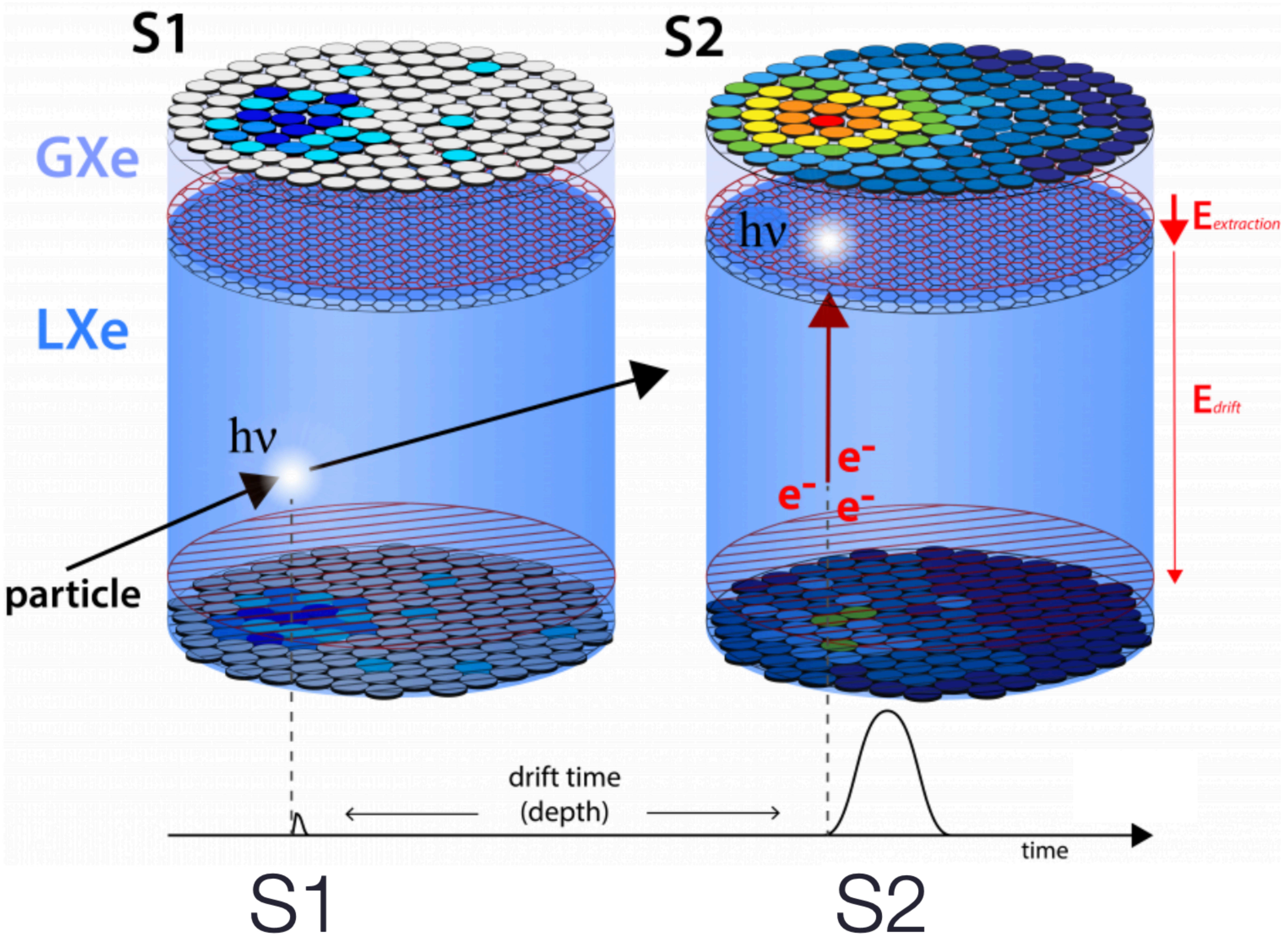
The dual-phase Time Projection Chamber (TPC)

Signal 1: LXe Scintillation

…electron drift (order-100μs)

Signal 2: GXe light emission
(after e-extraction)

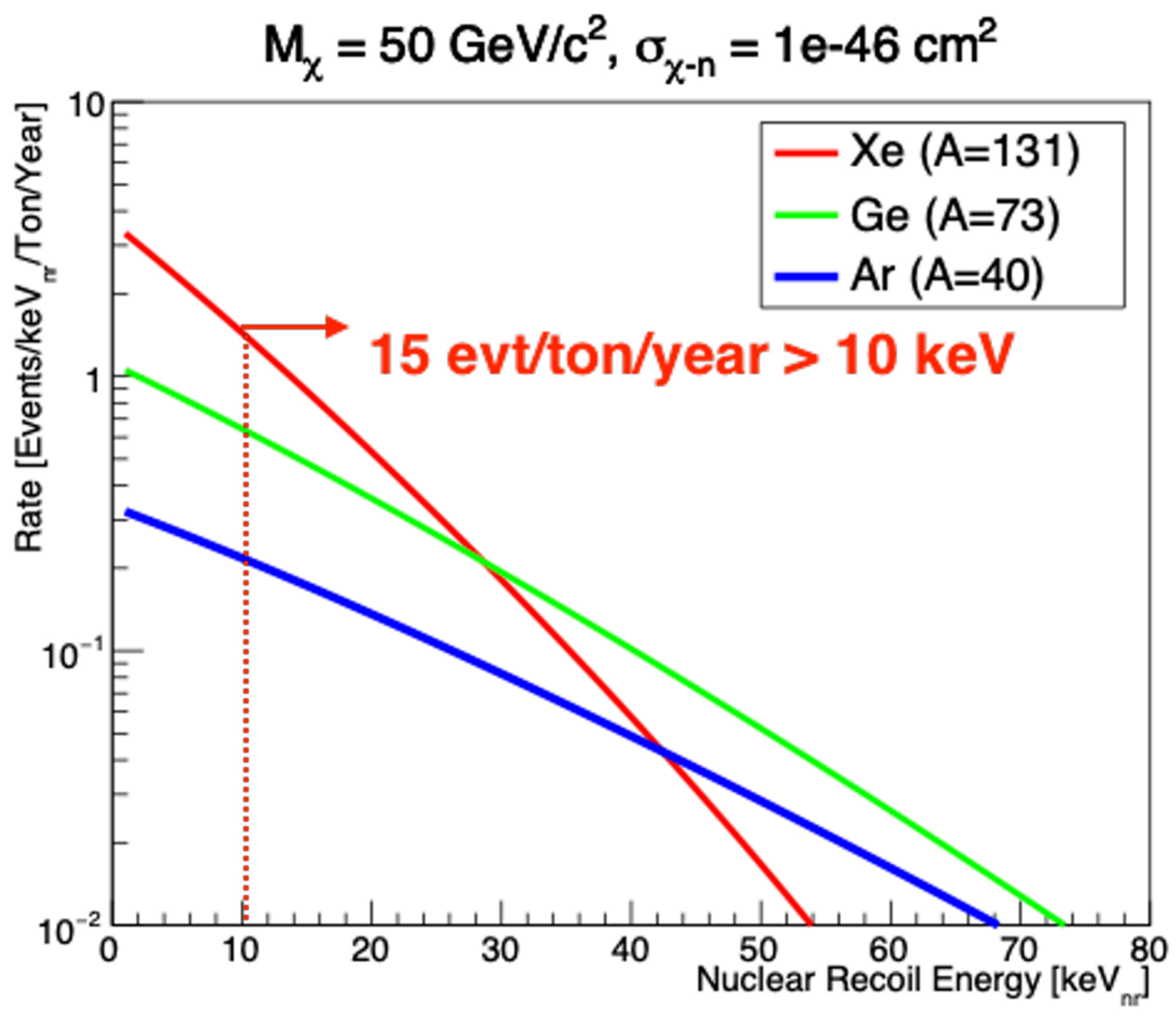
Result: full xyz position information
mm-scale in xy (better in z)



Advantages of LXe technology (I)

1. Coherent scattering cross section

Cross section scales as ~A^2,
and Xe is a high-number nucleus.

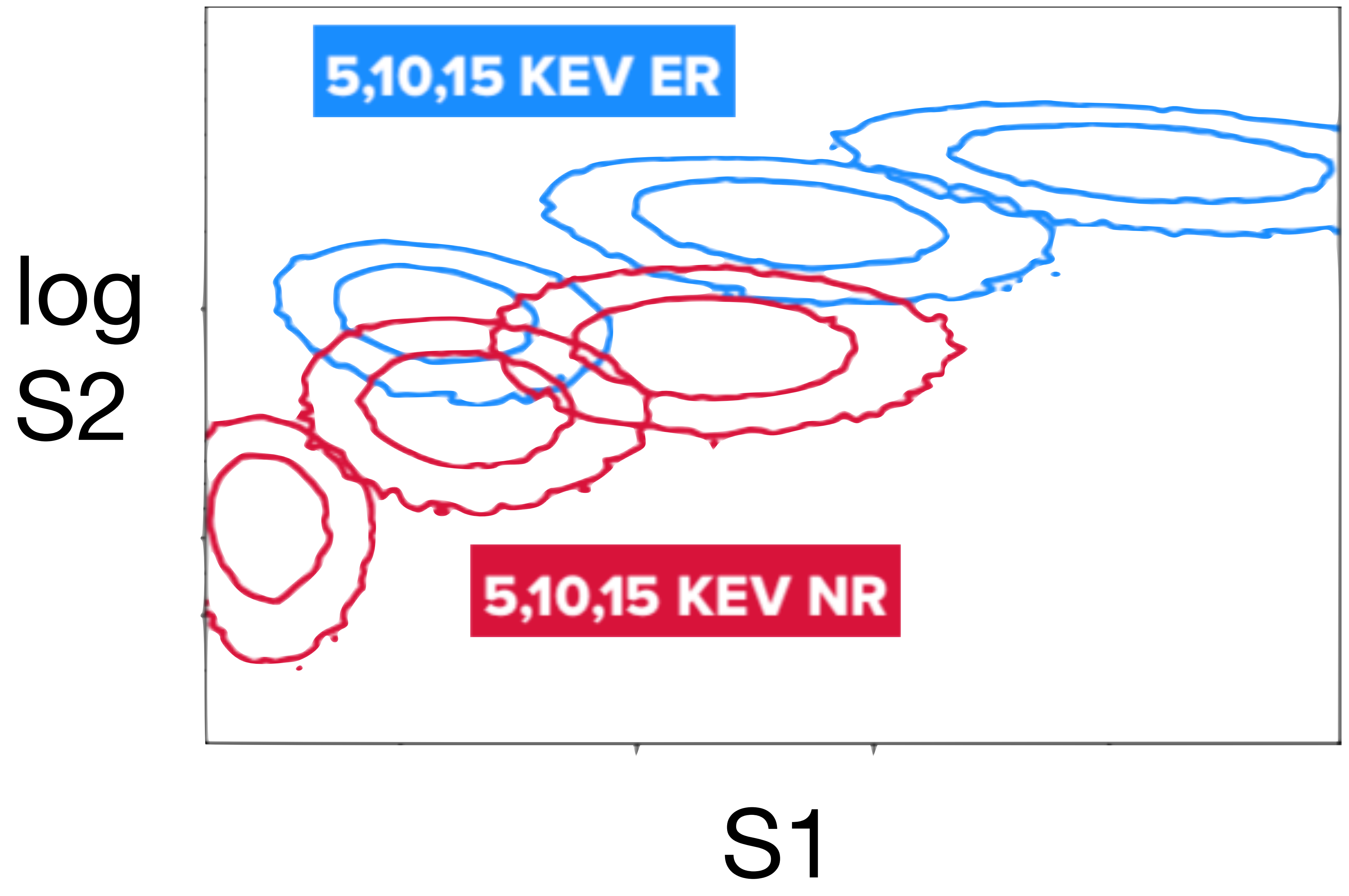


2. Discrimination and threshold

few-photon S1 threshold: few-keVnr

[S2:S1] ratio distinguishes signal vs bkgd.
(nuclear recoil vs electron recoil)

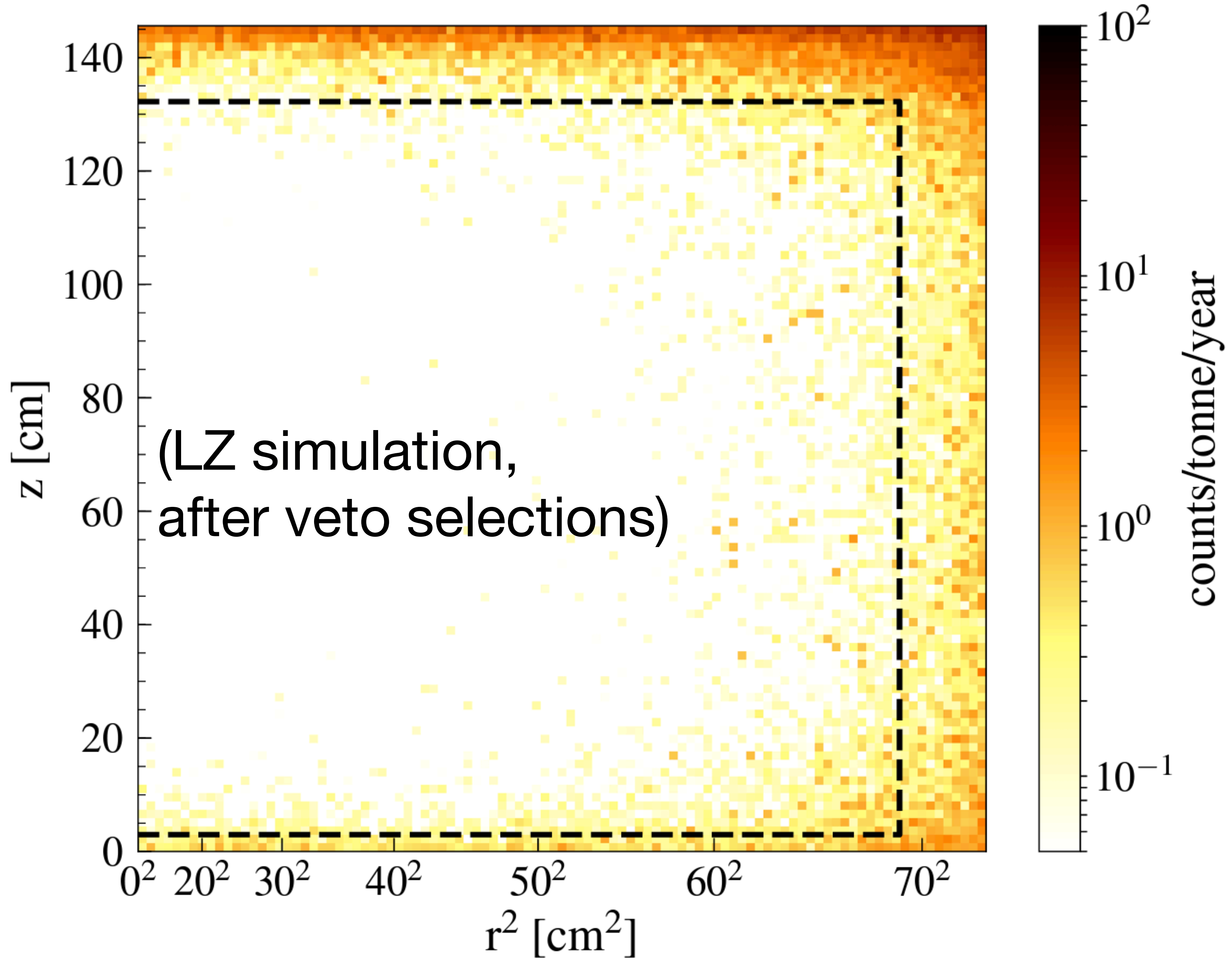
Discrimination excellent down to S1 threshold



Advantages of LXe technology (II)

3. Self-shielding of external backgrounds

Gamma mean free path: few-cm scale
(Again, because Xe is high-Z)



4. Extreme radiopurity of target

The Xe itself: Many isotopes, but remarkably, none is a long-lived beta decay (none is a 'problem')

Non-noble radioisotopes: straightforward to remove continuously via circulation/purification

All that remains: **non-Xe noble radioisotopes**

Primary concern: Rn222 (daughter: Pb214)

Also: Rn220, Kr85, Ar39, Ar37…

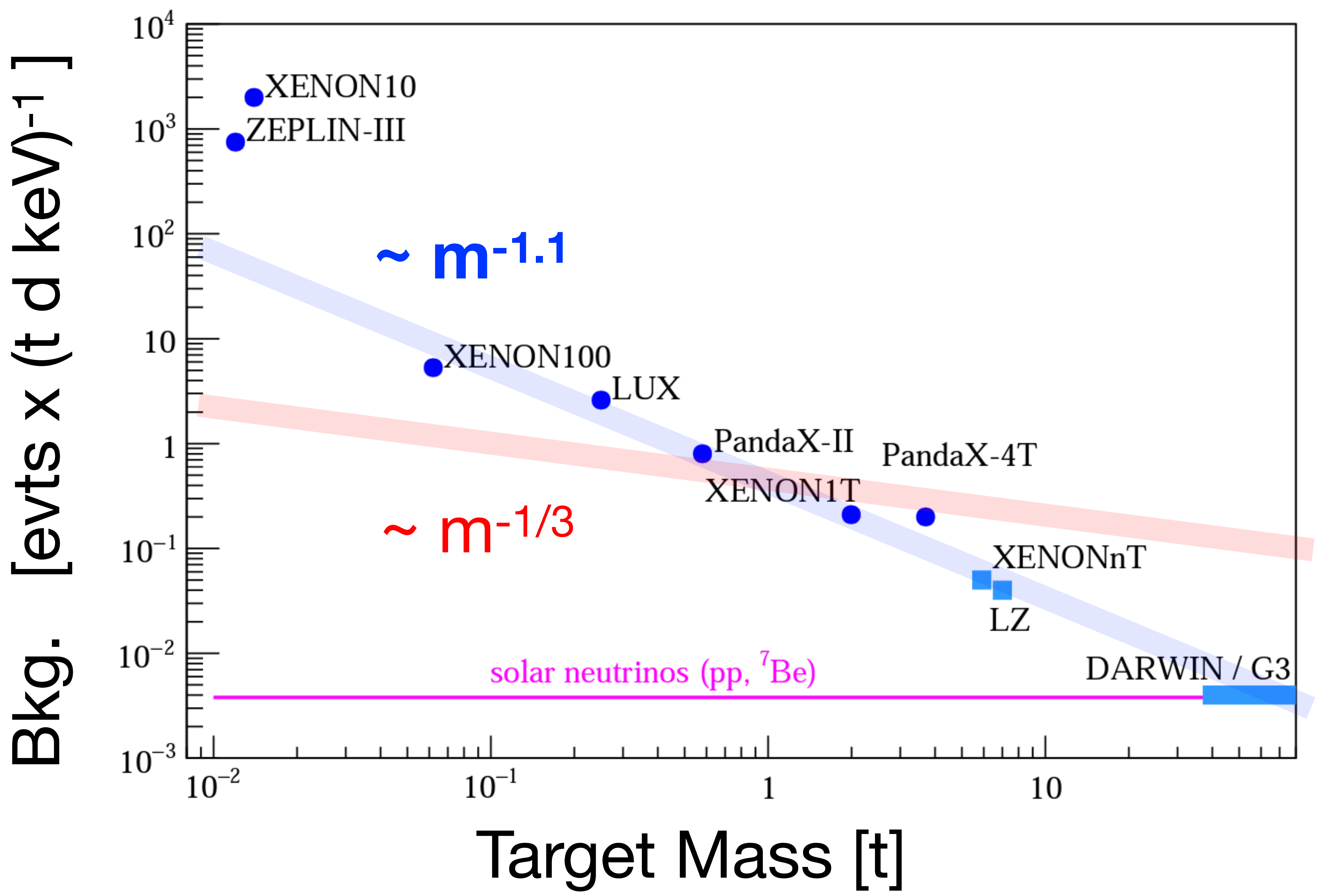
The larger the mass, the lower the backgrounds per mass

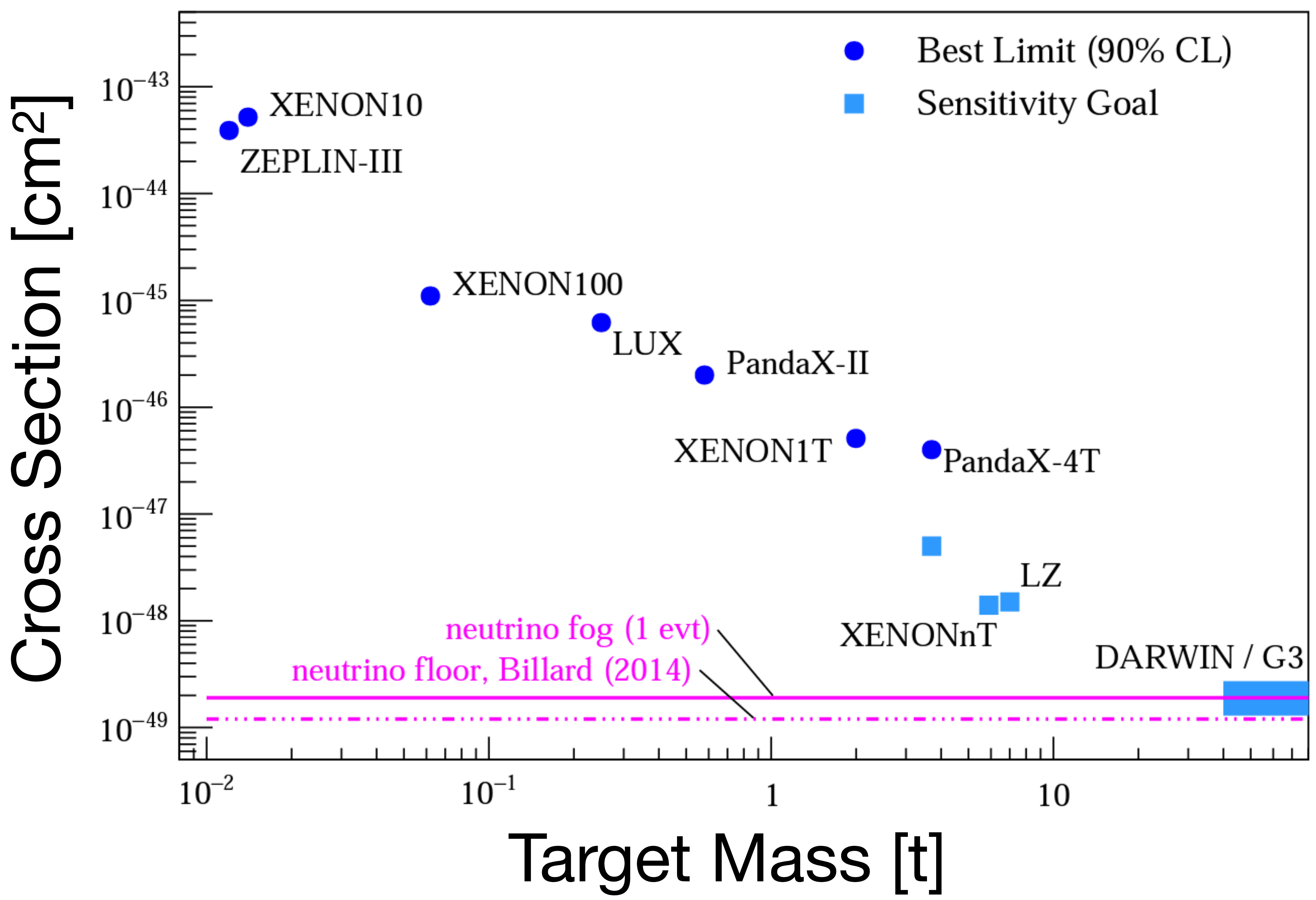
Dominant backgrounds scale with surface area rather than target mass.
(gammas from external sources, radon emanation from vessel)

Background rate per mass:

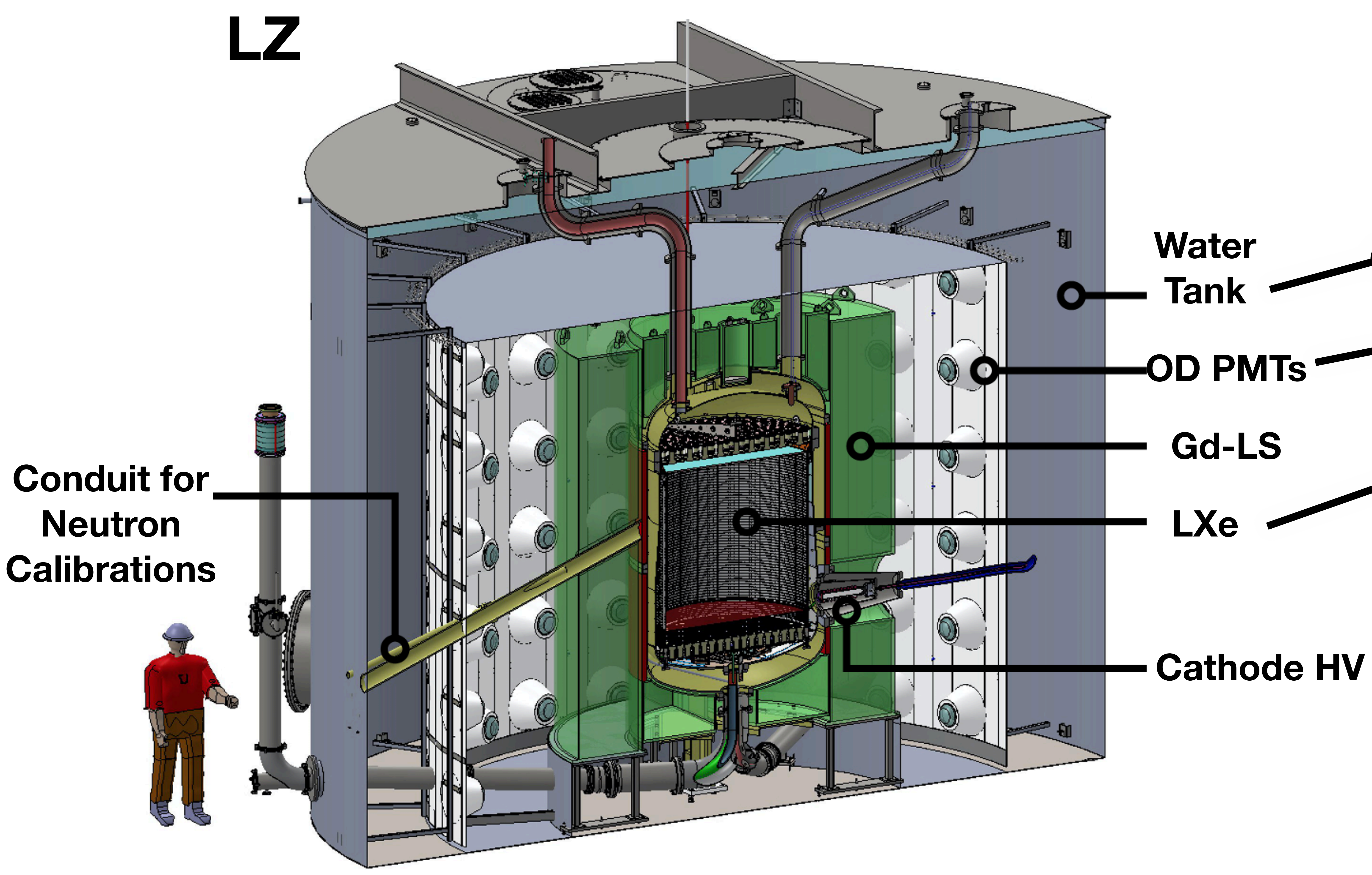
Naive expectation: $\sim r^2 / m = m^{2/3}\, m^{-1} = m^{-1/3}$ *"this technology just wants to work"*

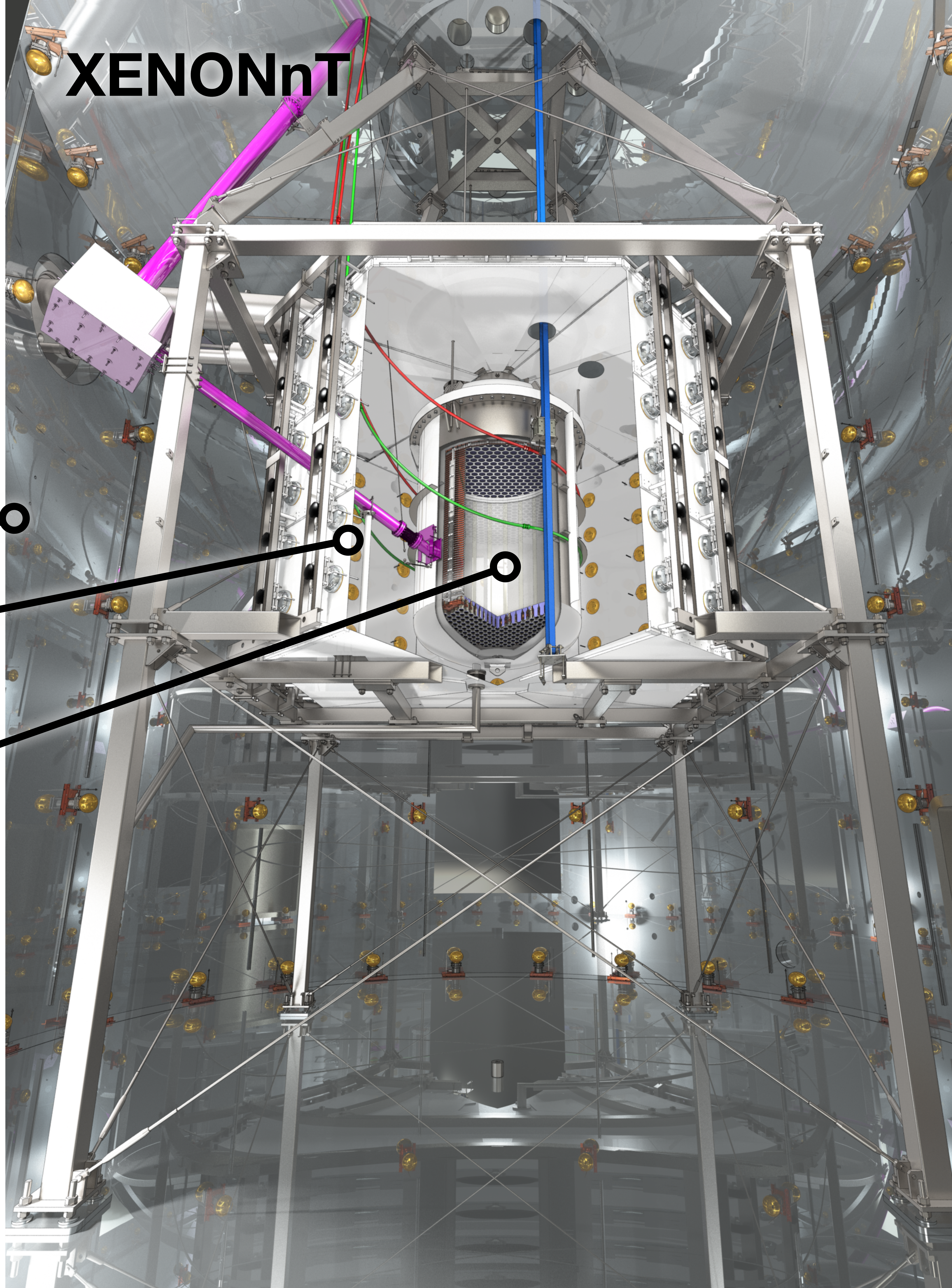
Historical trend: much better, thanks to constant progress reducing Rn222 ($\sim m^{-1}$)





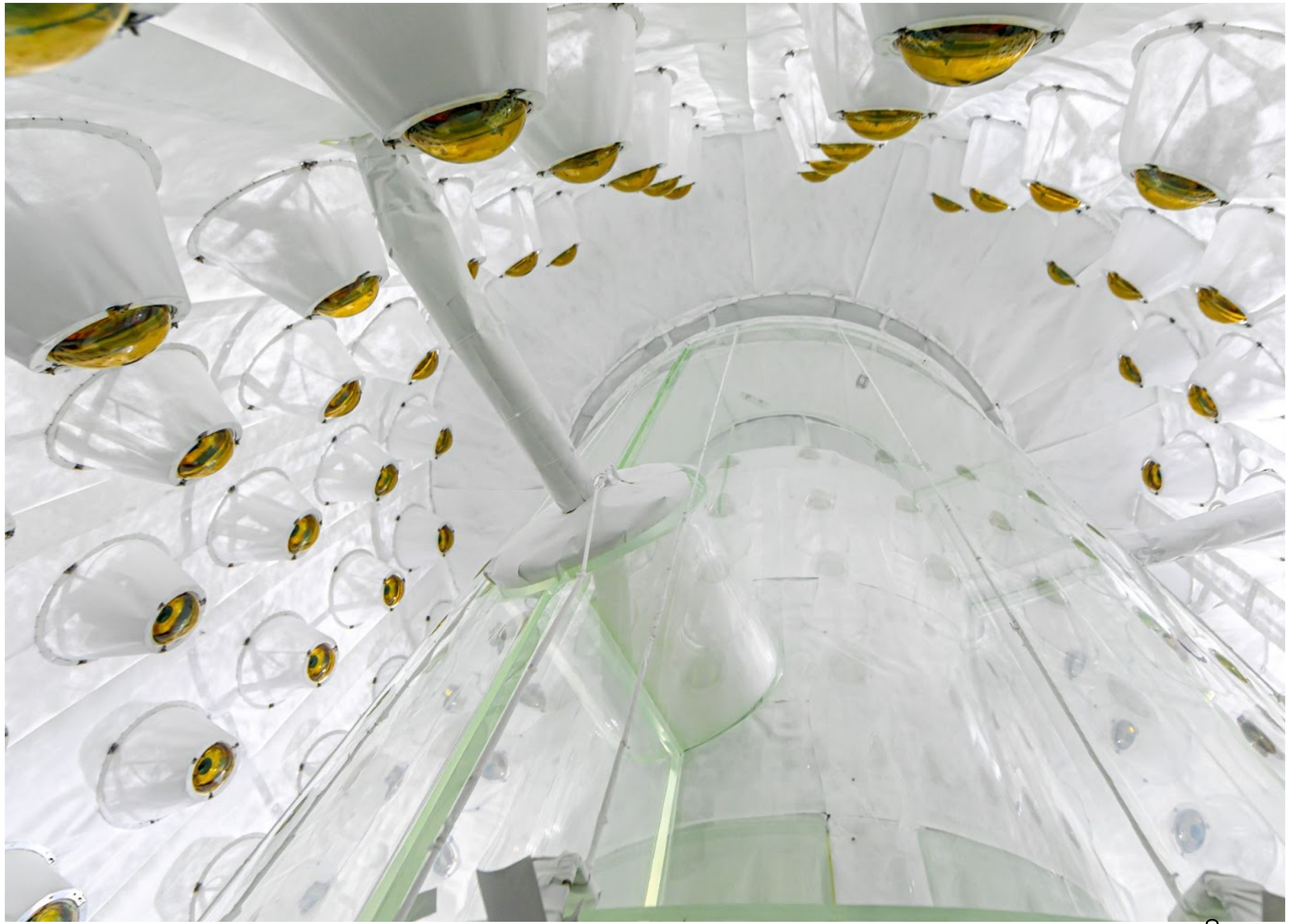
Water Tanks and Outer Detectors



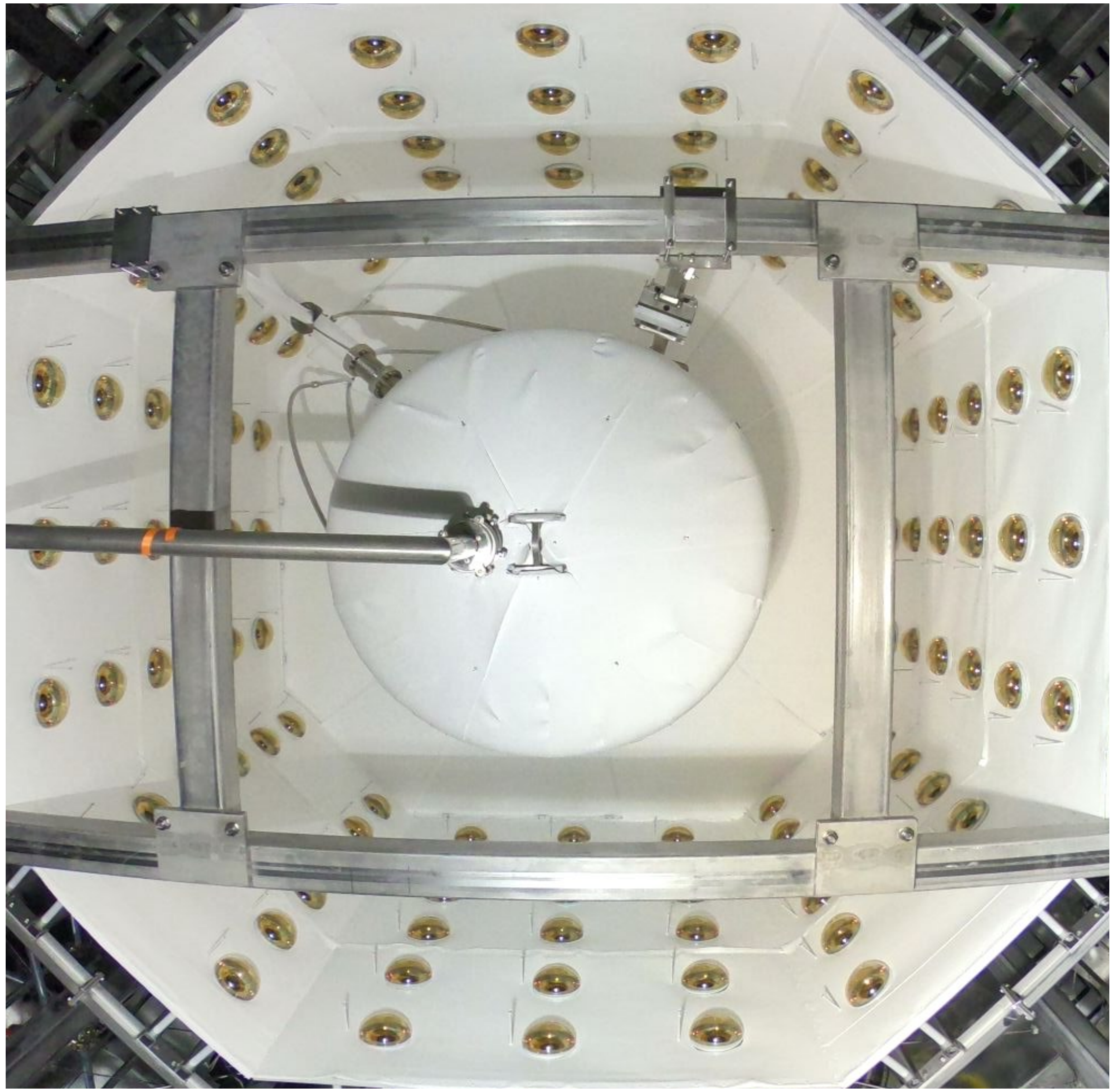


Water Tanks and Outer Detectors

LZ

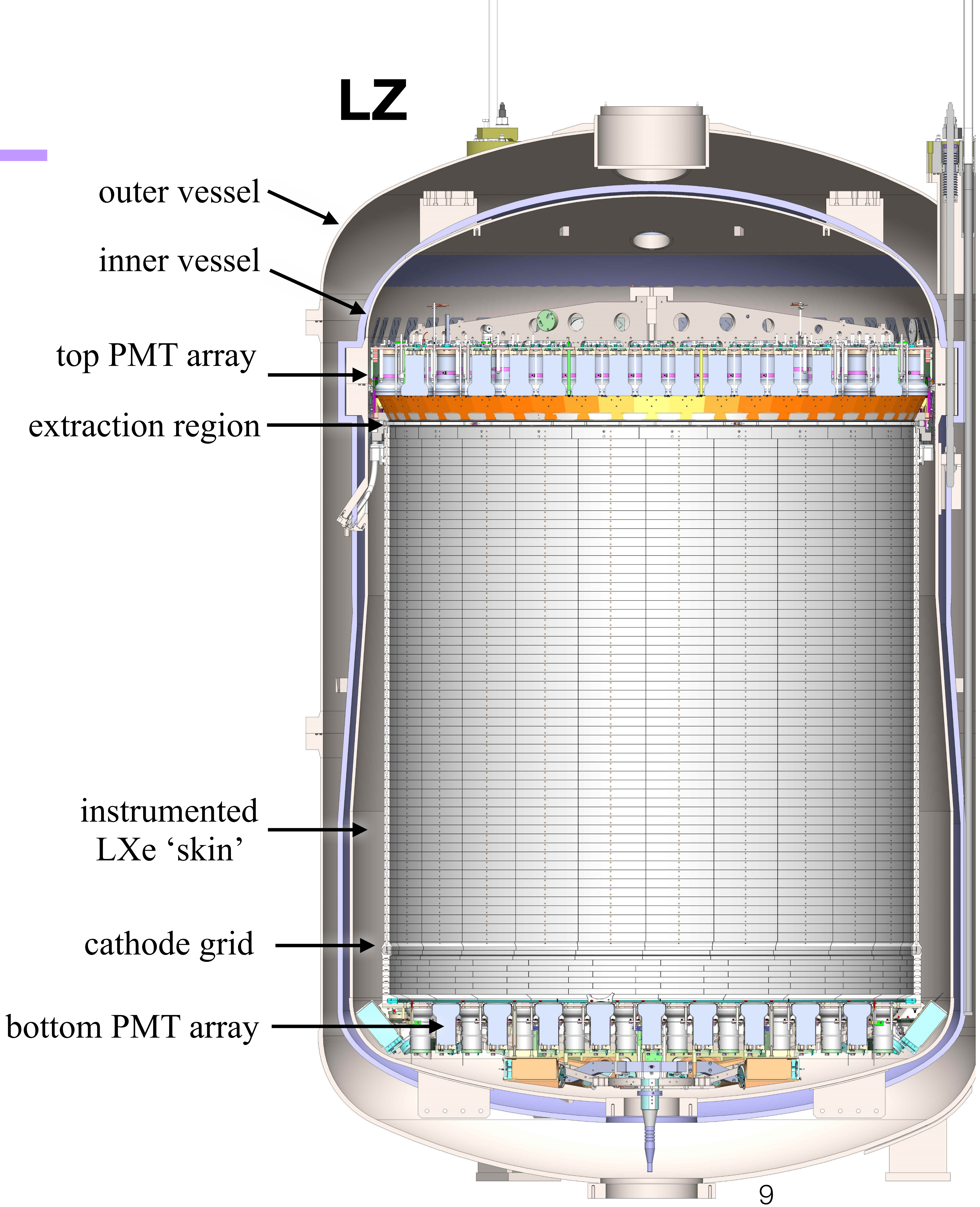


XENONnT

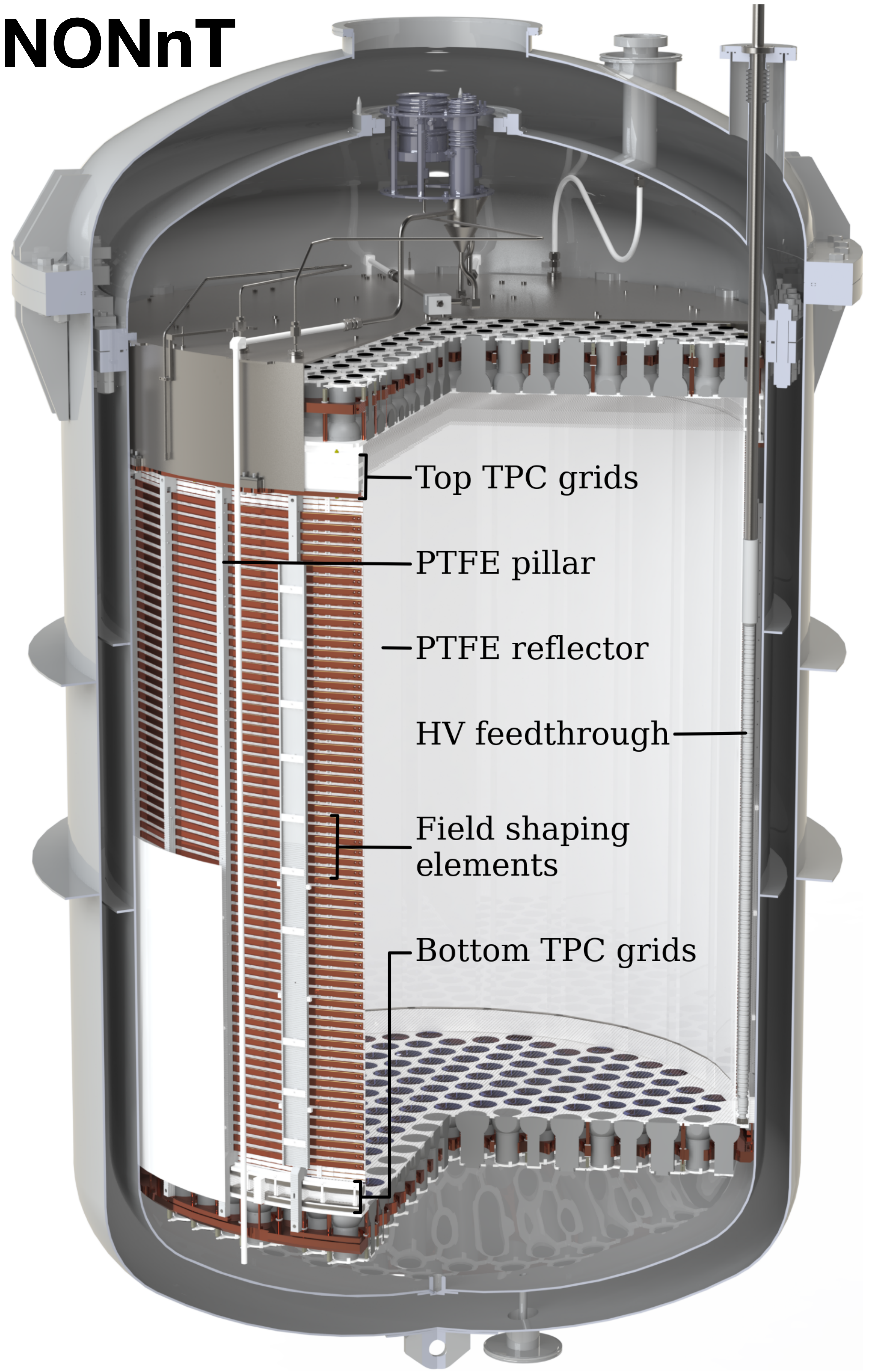


TPCs

LZ



XENONnT



TPCs

LZ

XENONnT

LZ and XENONnT: Complementary Design Choices

	LZ	XENONnT
Outer Detector Technology (neutron tagging)	Gd-doped Liquid Scintillator	Gd-doped Water (not yet doped in first run)
Instrumented LXe 'Skin'	Yes	No
Liquid Level Set Method	Liquid Weir	Gas Belljar
Wire Grids	Woven	Parallel Wires
Field Cage Setpoints	5 (Anode, Gate, Cathode, +two PMT shields)	6 (extra point of voltage control at the top of the field cage)
Neutron Calibration Methods	DD + dedicated low-E sources: AmLi, YBe, DD w/reflector	DD + AmBe low-E source: YBe
Xe circulation/purification	Gas phase pumps, hot Zr getter	Liquid phase pumps, Cu-based purification (+ some gas phase)
Noble Distillation Methods	No onsite distillation (Kr removed offsite)	Two distillation methods (next slide)

Ideal situation for best making future design decisions!

Distillation Columns for separation of noble elements

Significant technological advancements from XENON collaboration
Enables robust removal of noble radioisotopes from Xe “in line”, on site

Rn Column

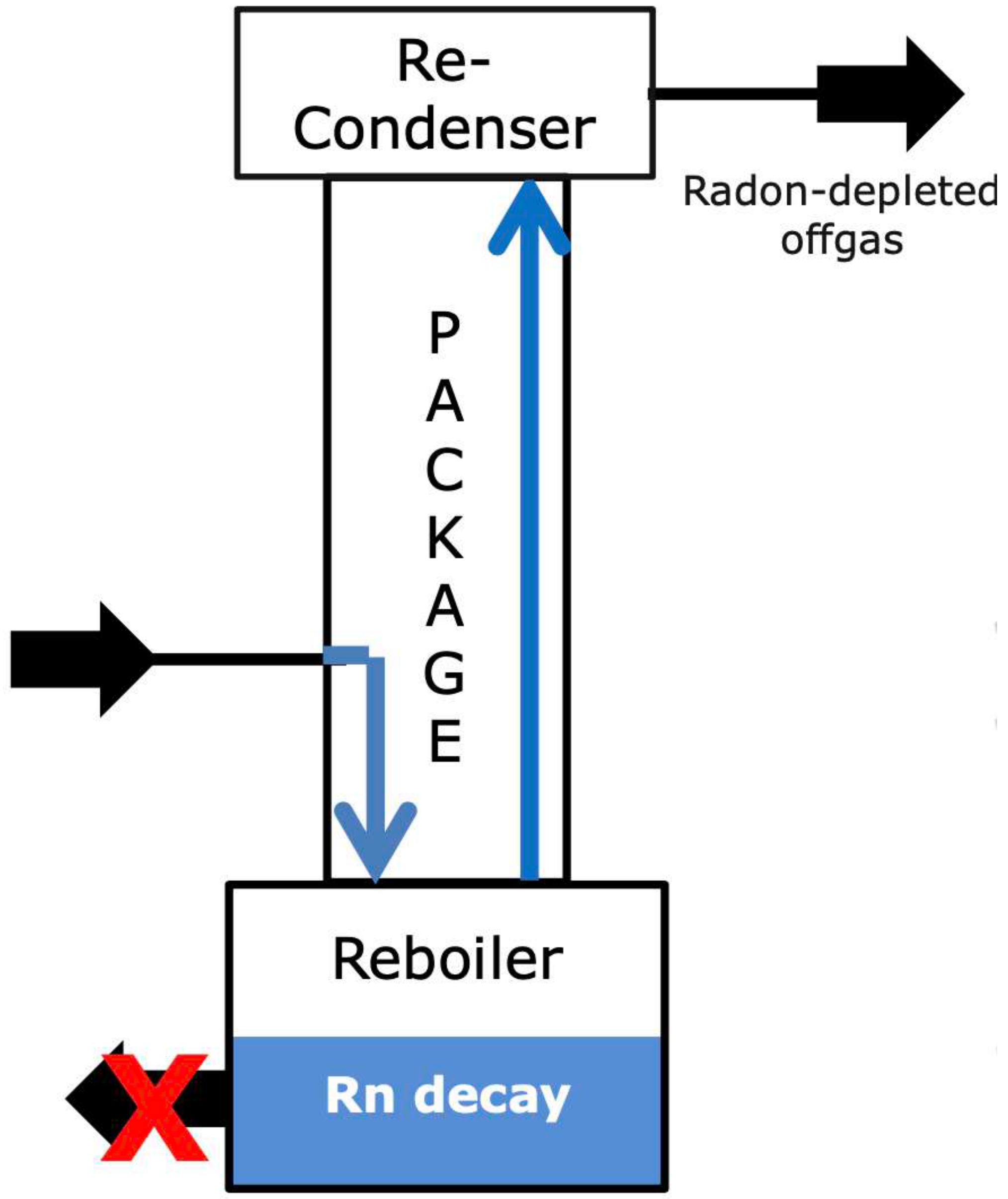
Boiled Xe lower in Rn
(Rn stays in liquid)
Demonstrated <1μBq/kg
(1.7μBq/kg in first run)

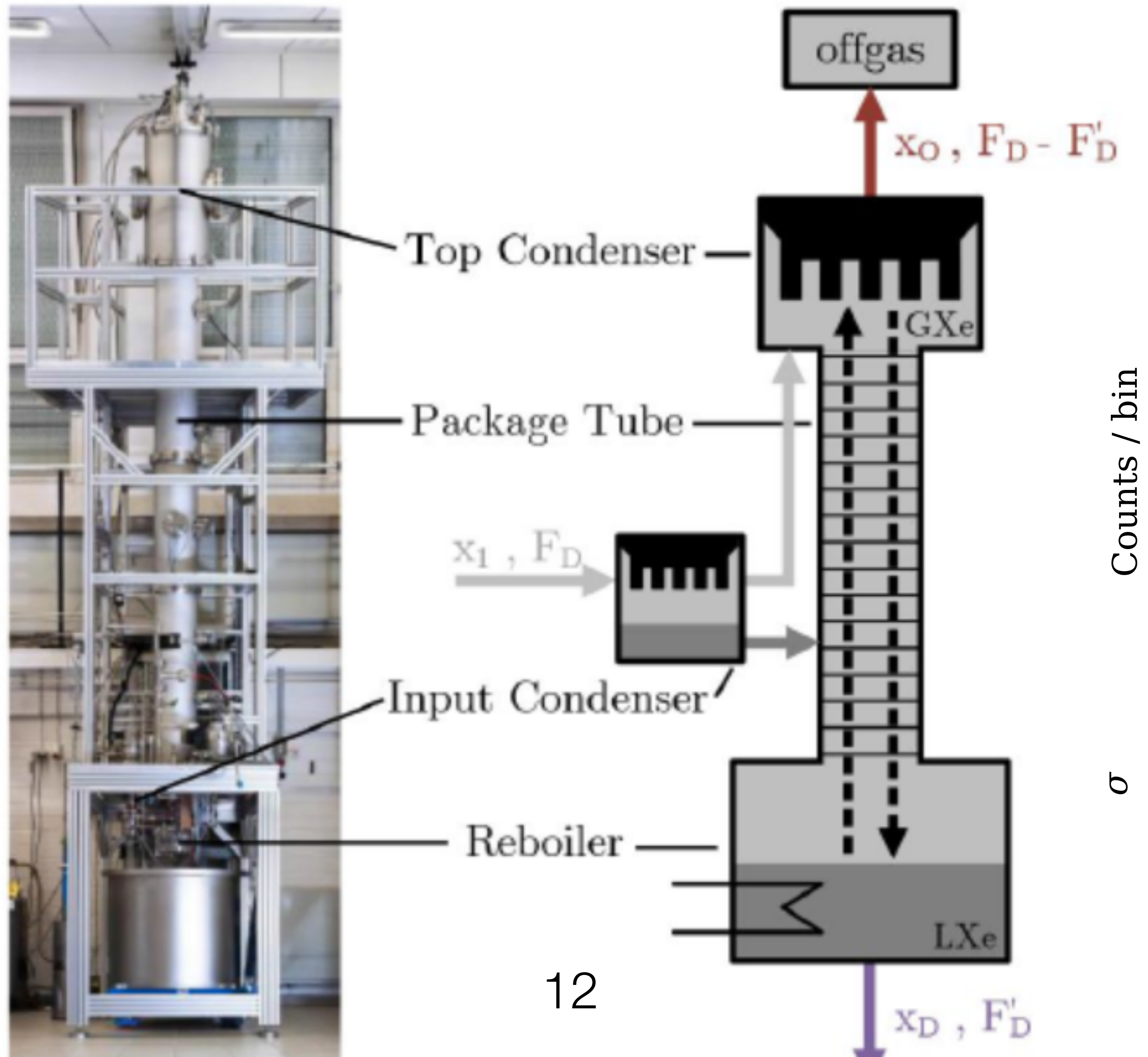
XENON collaboration, Eur. Phys. J. C 77, 358(2017)
M.Murra et al, arXiv:2205.11492

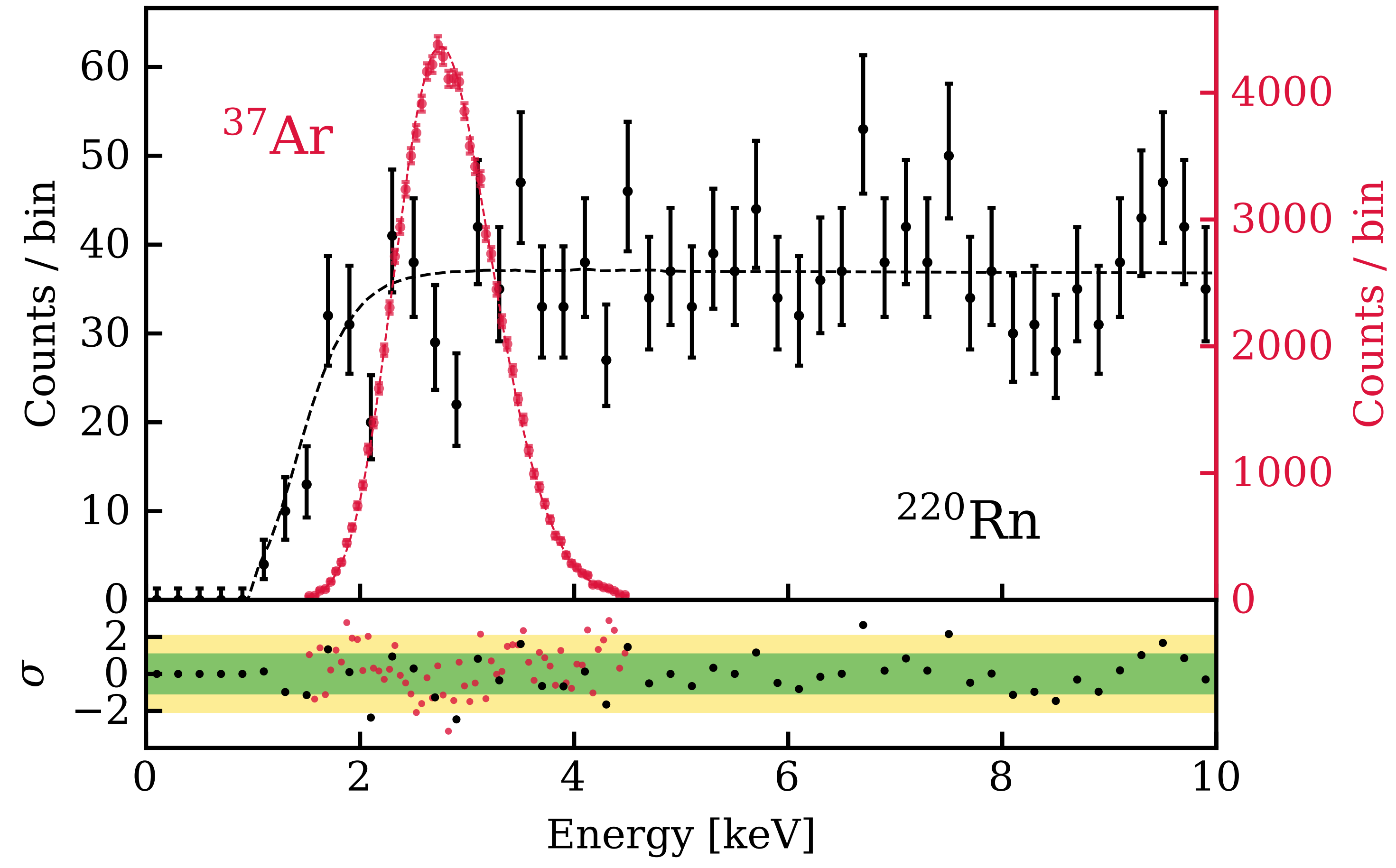
Kr/Ar Column

Similar but with more liquid/gas interfaces, taller
Reverse philosophy: ‘bad’ stuff concentrated at top
Achieved 56±36 ppq ^{nat}Kr in Xe
Enabled powerful Ar37 calibration

XENON collaboration, Eur. Phys. J. C 77, 275 (2017)
XENON collaboration, PTEP Vol 2022, Issue 5, May 2022







The XENON-1T Excess

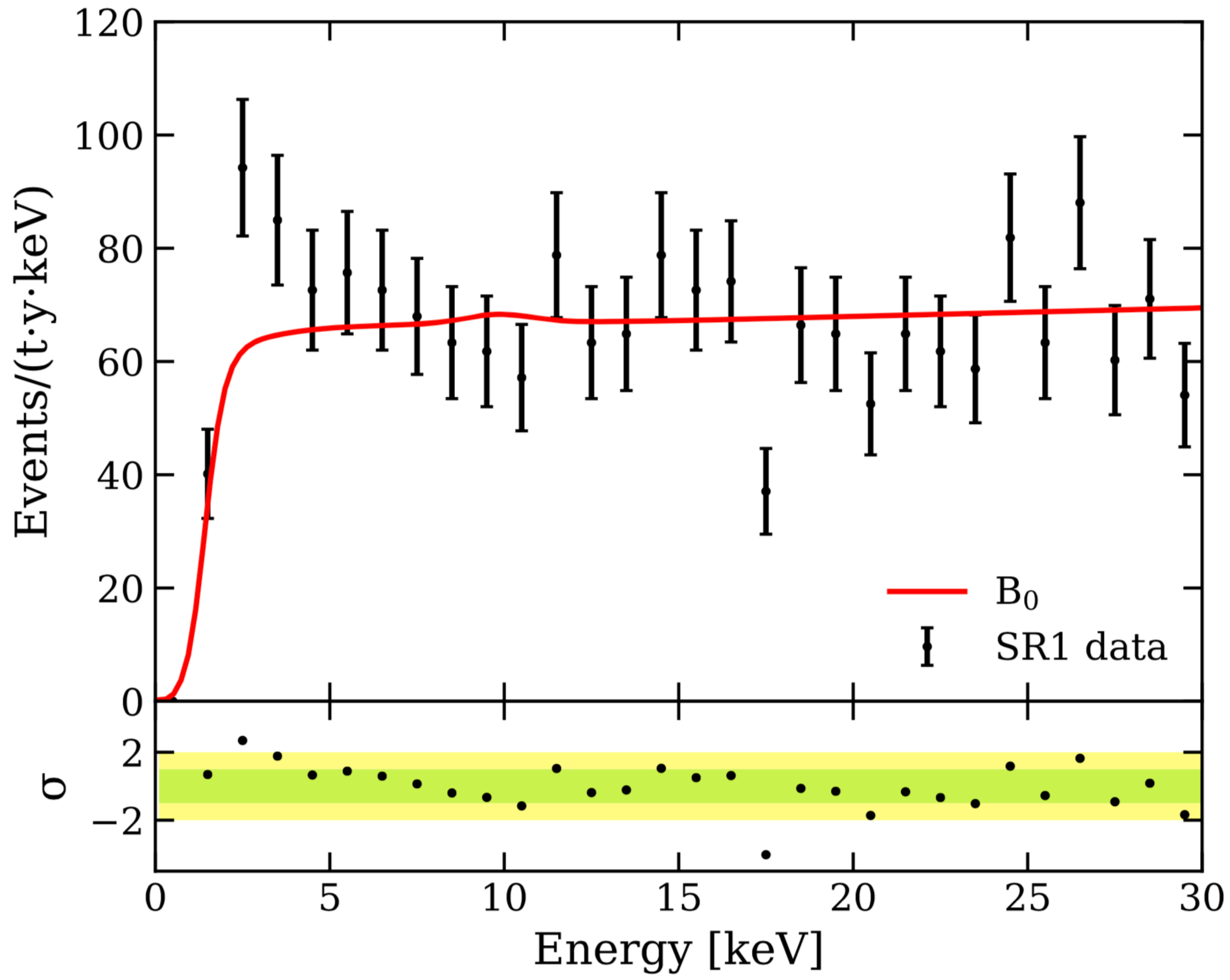
Excess in Electron Recoils

Appears only below ~7keV

Few-sigma significance
(depending on assumed signal)

A challenge to the field since summer 2020.

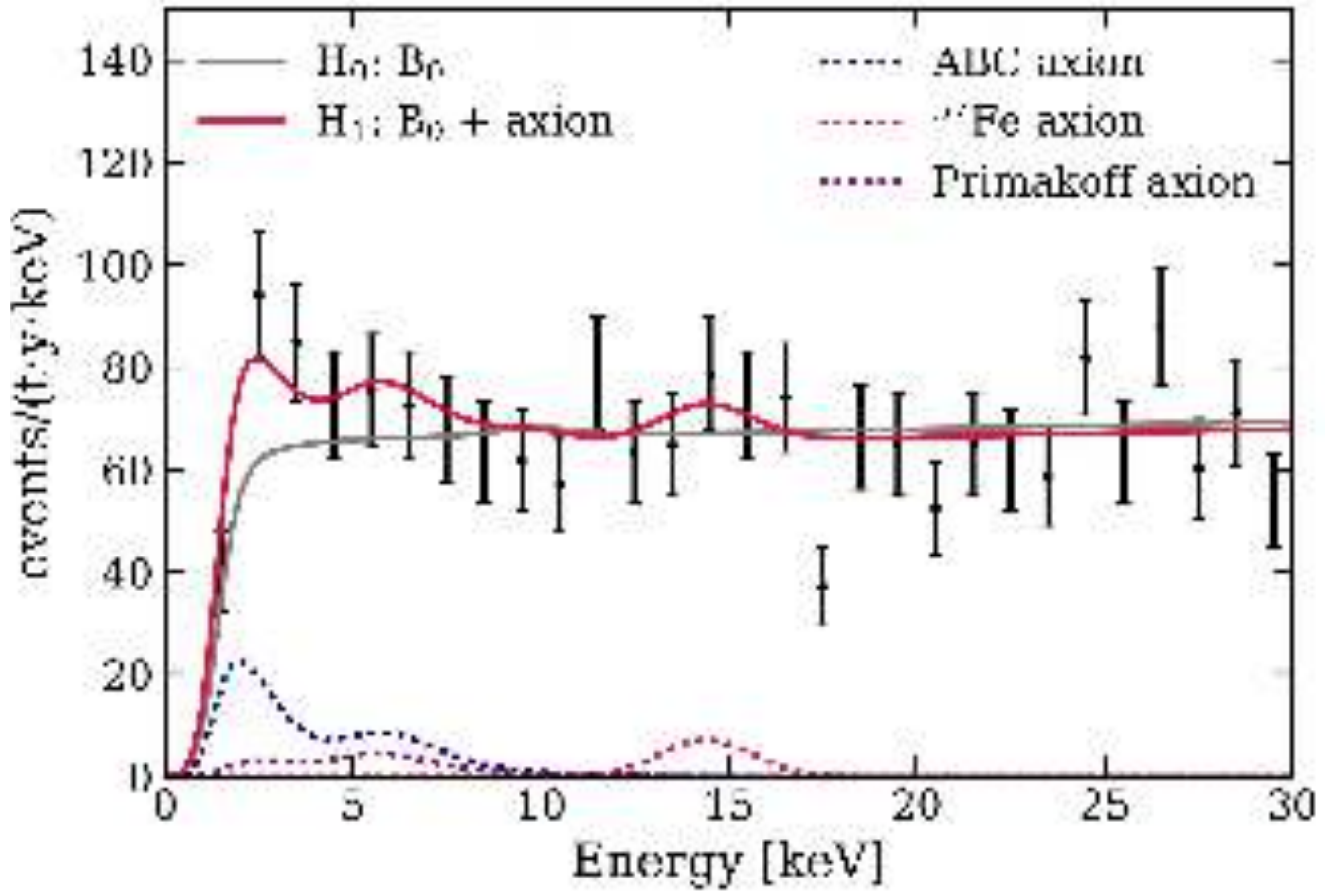
Excess electronic recoil events in XENON1T
Phys.Rev.D 102 (2020) 7, 072004



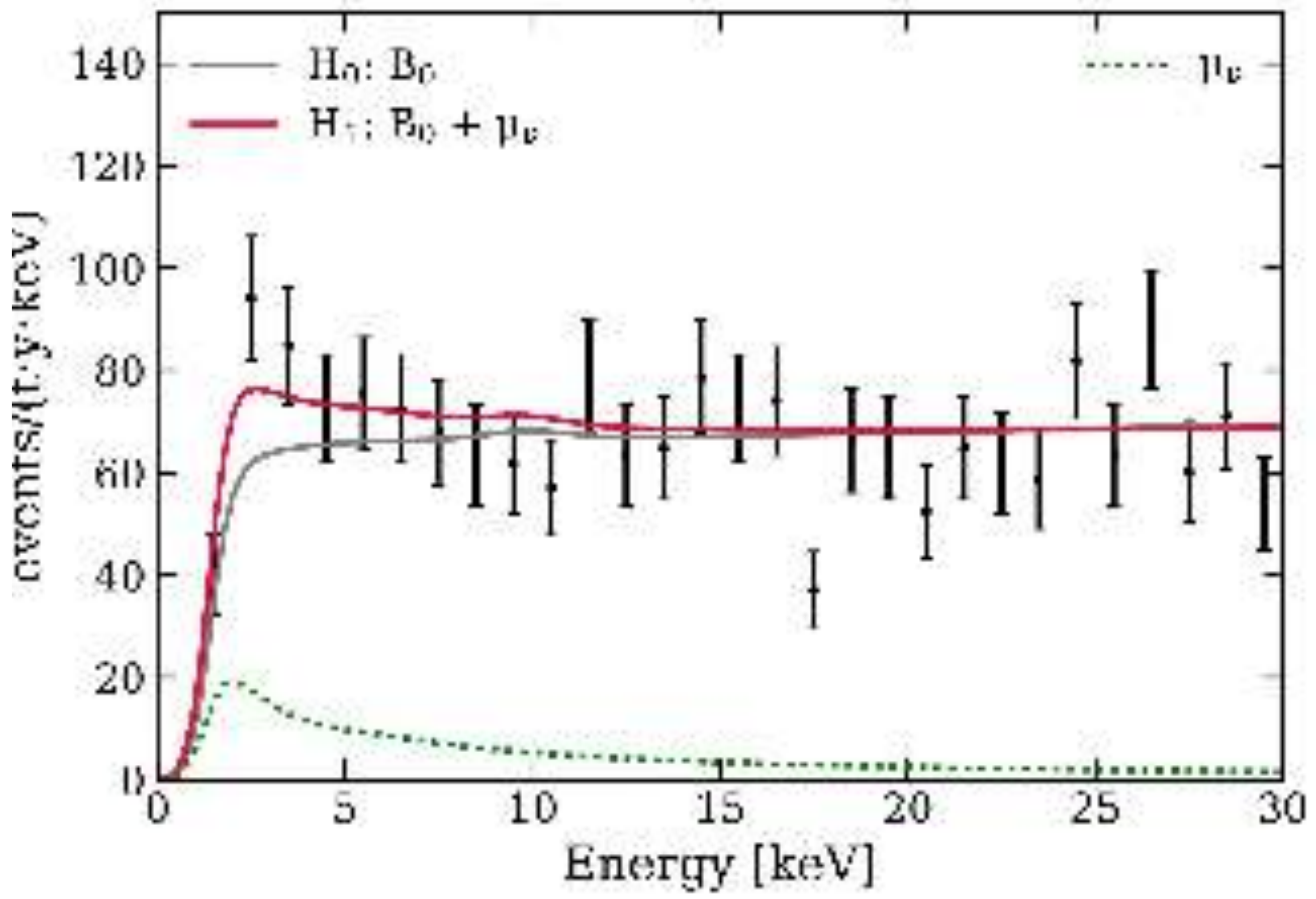
The XENON-1T Excess

New Physics?

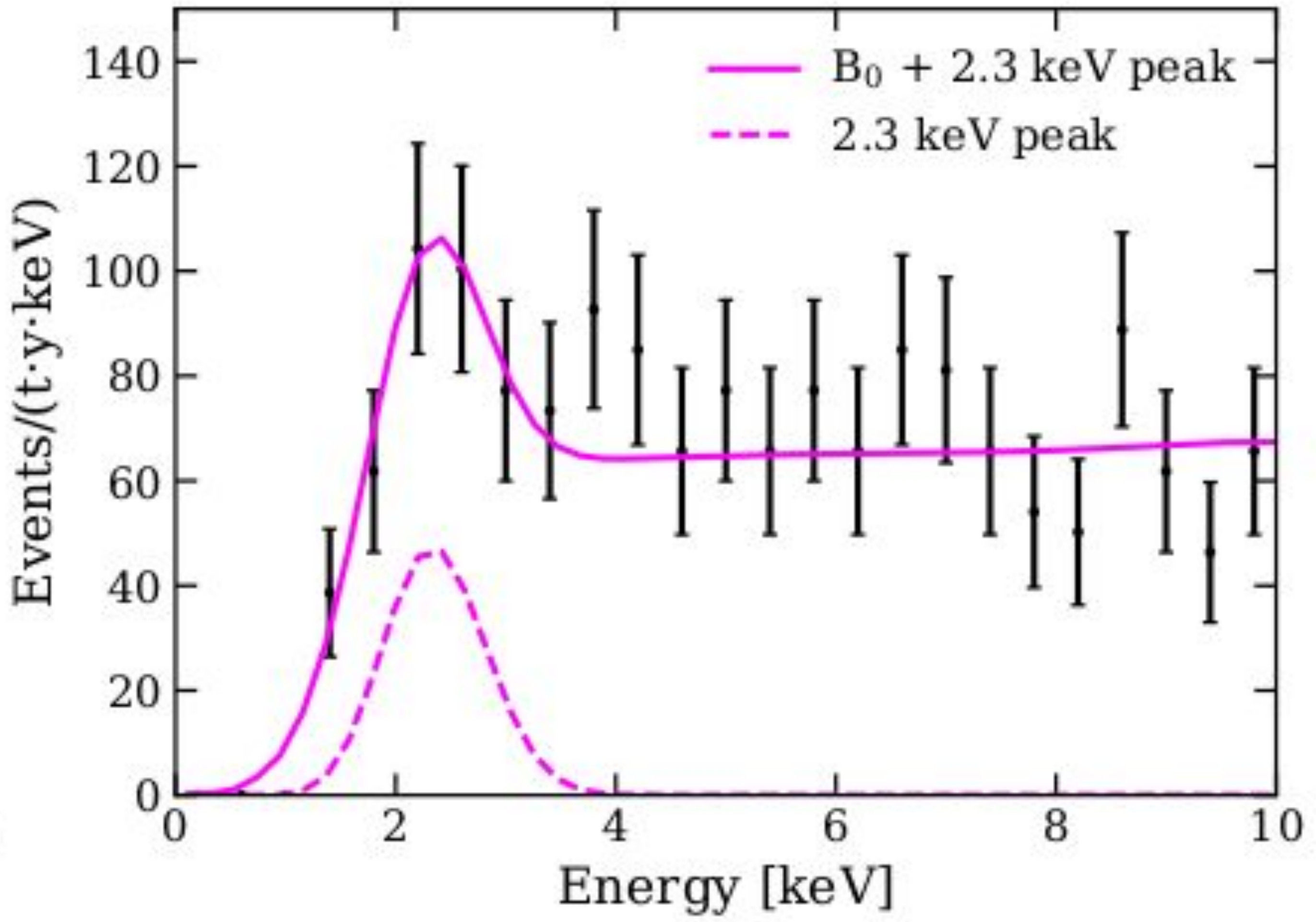
Solar axion: 3.5σ
in tension with stellar constraints



Neutrino Mag. Moment: 3.2σ
in tension with stellar constraints

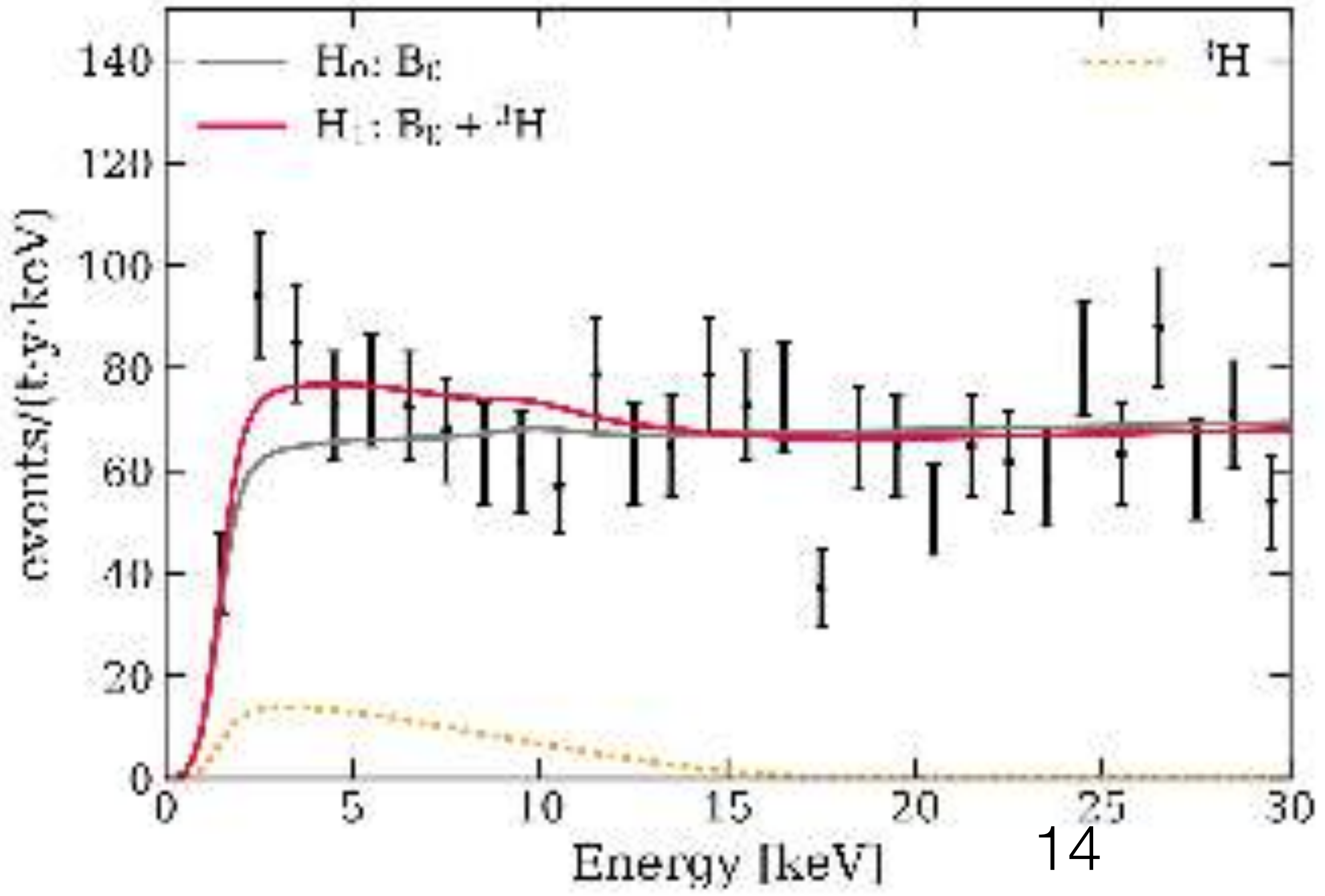


Bosonic DM: 3.0σ (global)
favored mass: 2.3±0.3 keV

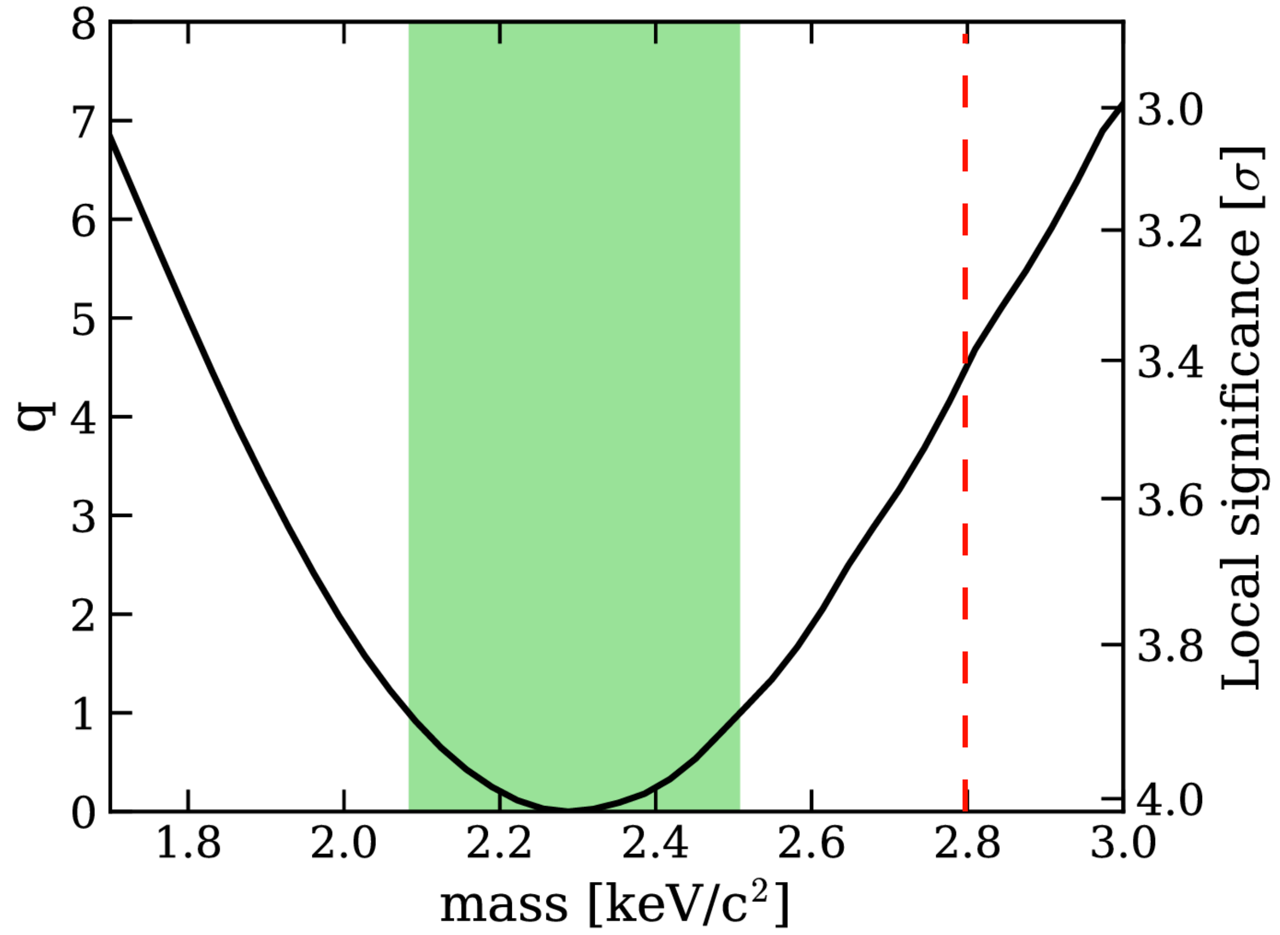


Or Something Less Interesting?

Tritium: 3.2σ
HT emanated by materials



Ar37 (2.8keV peak)
in tension with E-reconstruction, sampling



Looking to LZ and XENONnT for answers

First Exposures of LZ and XENONnT

Near-simultaneous first exposures:

XENONnT "SR0"

July 6- Nov 11, 2021
(97.1 days of lifetime)

4.37t -> 1.16 t-y

Blinded Analyses

LZ "SR1"

Dec 23, 2021 to May 12, 2022
(60 days of lifetime)

5.5t -> 0.90 t-y

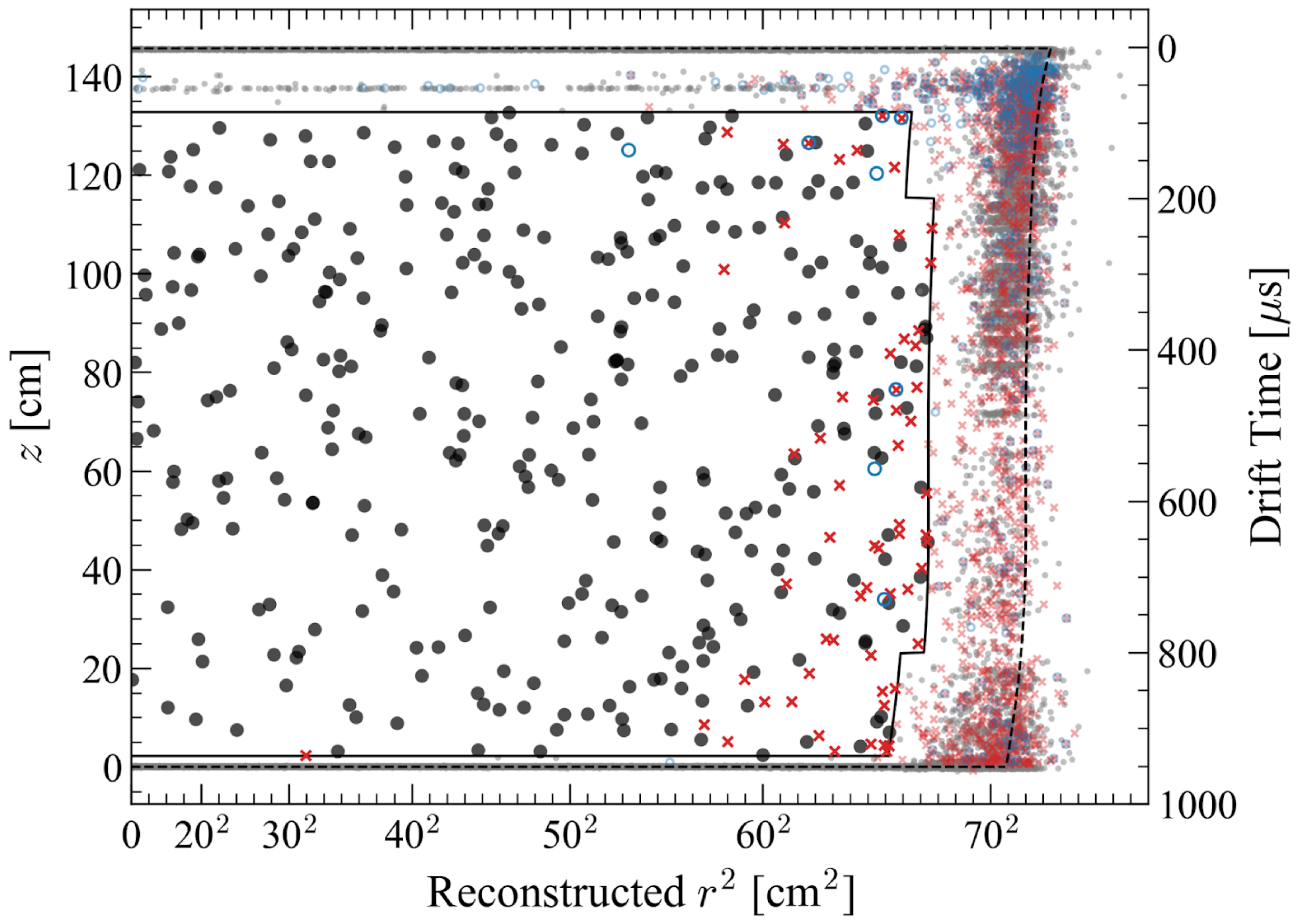
Non-Blinded Analysis (engineering focus)

LZ: Fiducial Volume and Selections

- S2 charge-loss close to TPC wall leads to poor position resolution at radial boundary
  - Choose a central fiducial volume simultaneously with S2 threshold to make wall background leakage negligible for this analysis
  - 5.5 t fiducial mass (measured by uniformly dispersed tritium source)

- Prompt (< 0.5 μs) Skin and OD tag:
  - Reduces naked L-, M-shell Xe127 background by x5 by tagging γ-ray that escapes the TPC

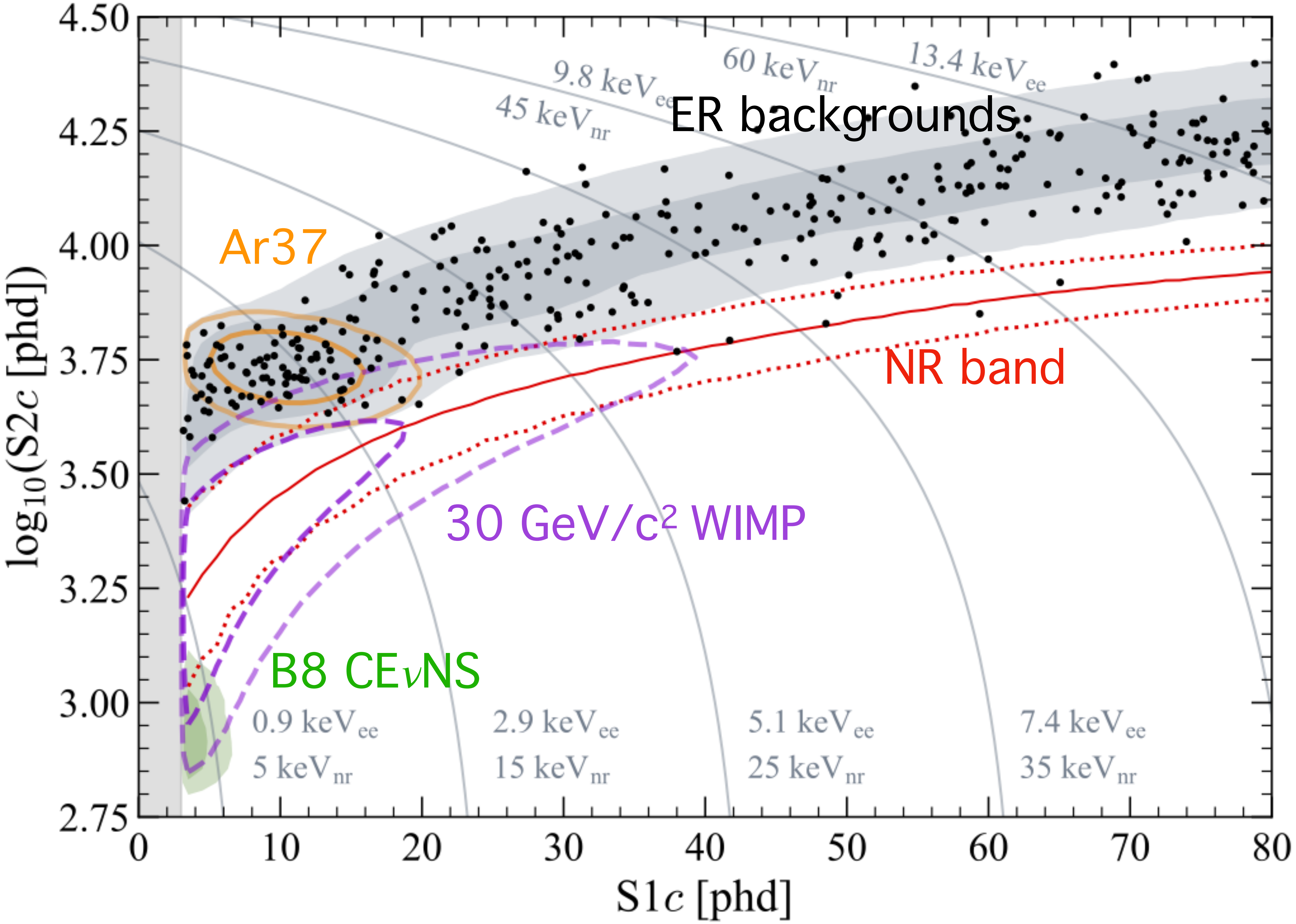
- Delayed OD (and skin) tag:
  - 1200 μs window, ~ 200 keV threshold for n-capture tag - 5% false veto rate
  - Constraint on neutron background $0^{+0.2}$ for this analysis



● = pass all selections (candidates)
● = pass all sections outside fiducial volume
x = skin tagged
○ = OD tagged

LZ: Candidate Events after Selection

- 335 events in final dataset
- Define a Profile Likelihood Ratio (PLR) analysis over the following range:
  - 3 phd < S1c < *80 phd*
  - *S2 > 600 phd (~ 10 extracted electrons)*
  - *S2c < 10^5 phd*



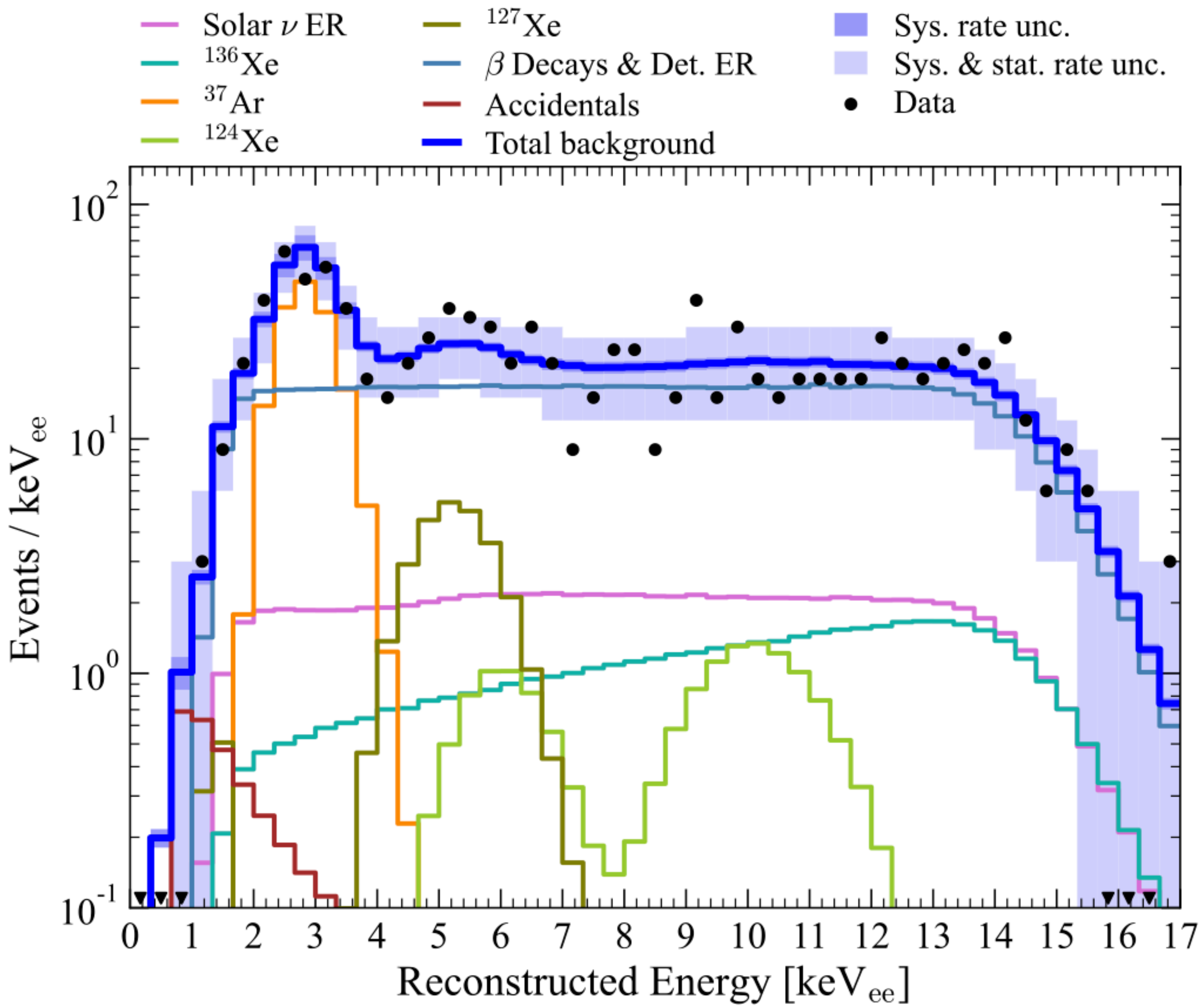
LZ: Best fit model

Best fit of zero WIMP events at all masses, p-value = 0.96

Source	Expected Events	Best Fit
β decays + Det. ER	218 ± 36	222 ± 16
ν ER	27.3 ± 1.6	27.3 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.2 ± 2.4	15.3 ± 2.4
^{8}B CEνNS	0.15 ± 0.01	0.15 ± 0.01
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Subtotal	276 ± 36	281 ± 16
^{37}Ar	[0, 291]	$52.1^{+9.6}_{-8.9}$
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	–	333 ± 17

Expected from background studies (energy sidebands), auxiliary datasets (e.g. measured half lives, rate predictions from other data or simulations)

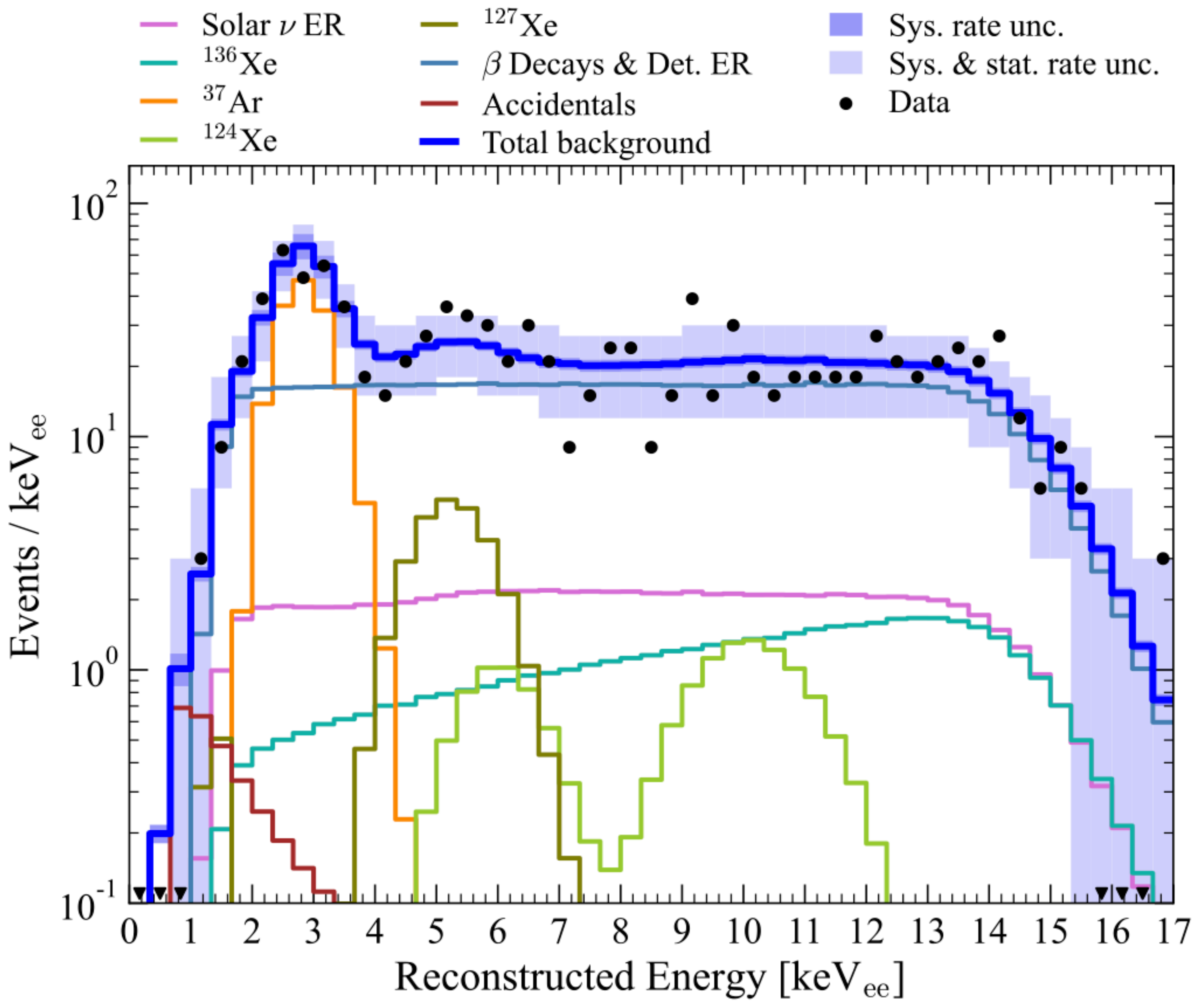
Combined fit to data with expected counts as priors



Several comments on 37Ar

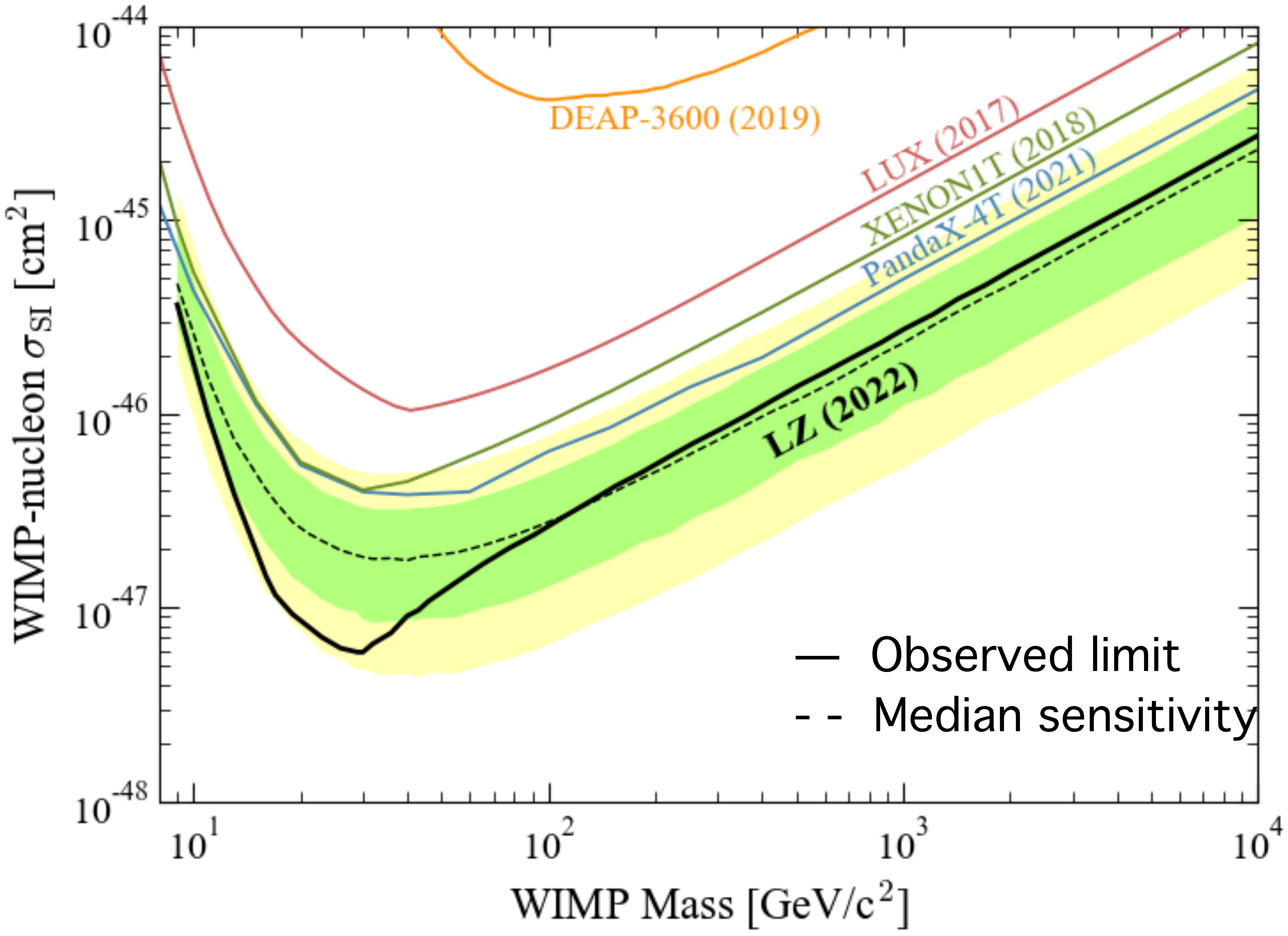
- Difficult for 37Ar to explain XENON1T Excess
  - Constraints on Ar37 from air ingress (w/Kr etc.)
  - Xe stored underground well before run
  - Distillation employed before start of run

- On the other hand: 37Ar ***expected*** in LZ context
  - Significant production of 37Ar in Xe via cosmic spallation while above ground (arXiv:2201.02858)
  - LZ's Xe transported underground shortly before run start (35d half-life)
  - Observed 37Ar rate consistent with expectation
  - ***37Ar will be negligible in future running (same is true for 127Xe, by the way)***



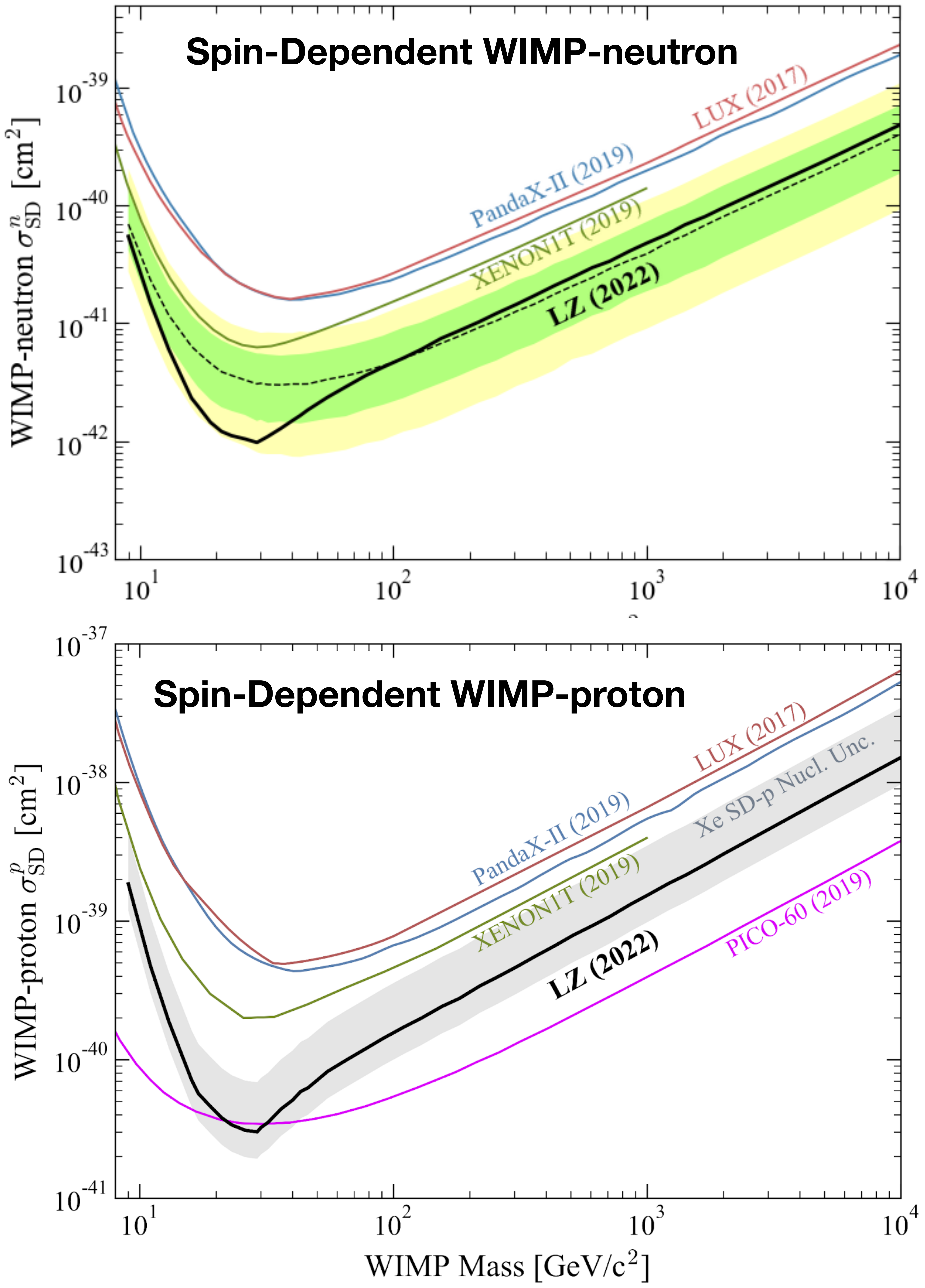
First LZ constraints on WIMP Dark Matter

- Frequentist, 2-sided PLR test statistic
- Following recommendations from community white paper: [Eur. Phys. J. C 81, 907 (2021)]
- **Best limit of σ_{SI} = 5.9 x 10^{-48} at 30 GeV/c^2**
- Green and yellow are the 1σ and 2σ sensitivity bands.
- Assume a spin independent (scalar) WIMP-nucleon interaction

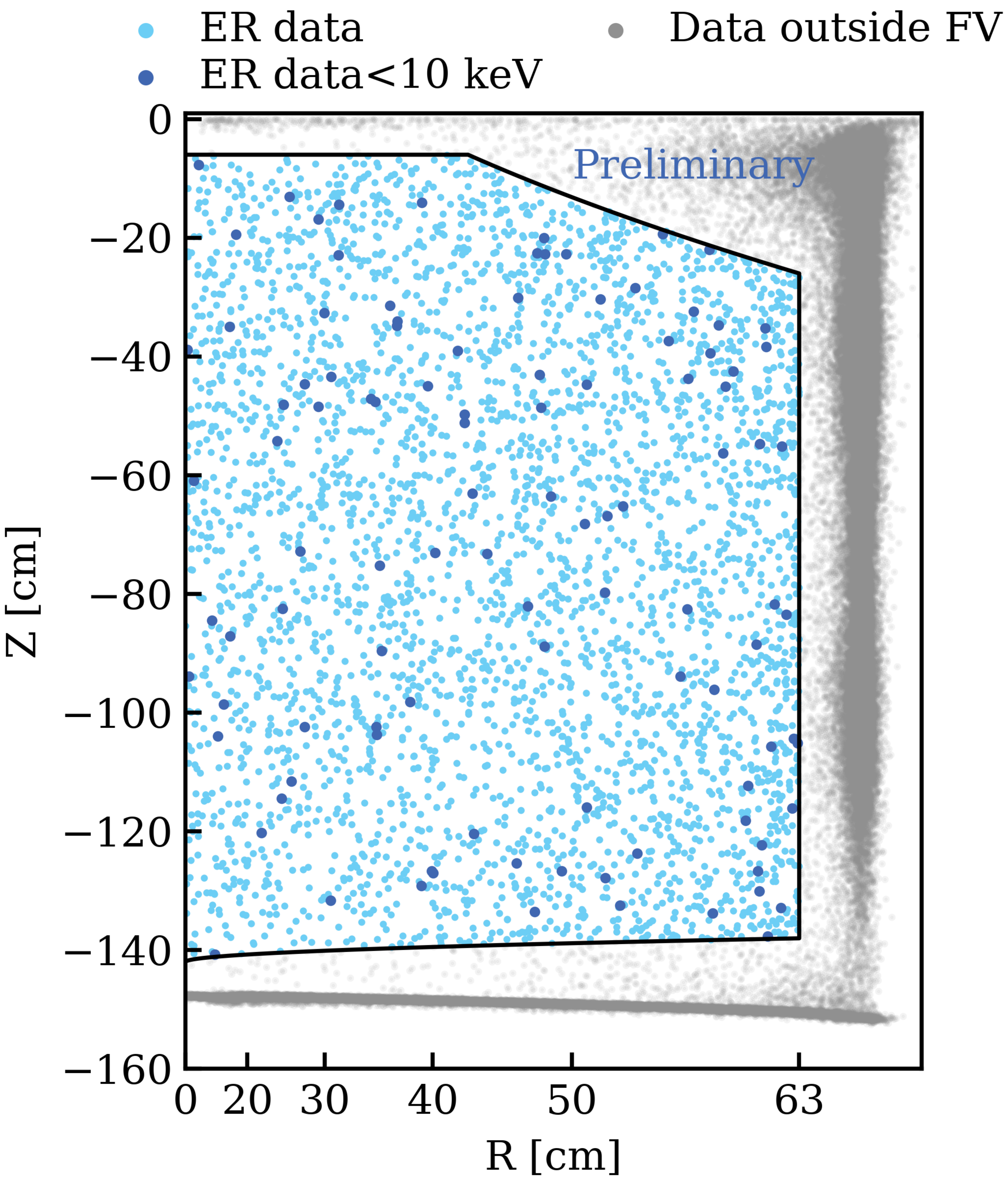


First LZ constraints on WIMP Dark Matter

- Spin-Dependent, assuming either WIMP-proton or WIMP-neutron interactions
- Xe has two isotopes with non-zero nuclear spin (both with unpaired neutrons)
- WIMP-proton sensitivity through higher-order nuclear effects
- Grey uncertainty band due to theoretical uncertainties on nuclear structure factors. A similar uncertainty applies for all other xenon experiments on this plot (i.e. PandaX-II, LUX, and XENON1T).



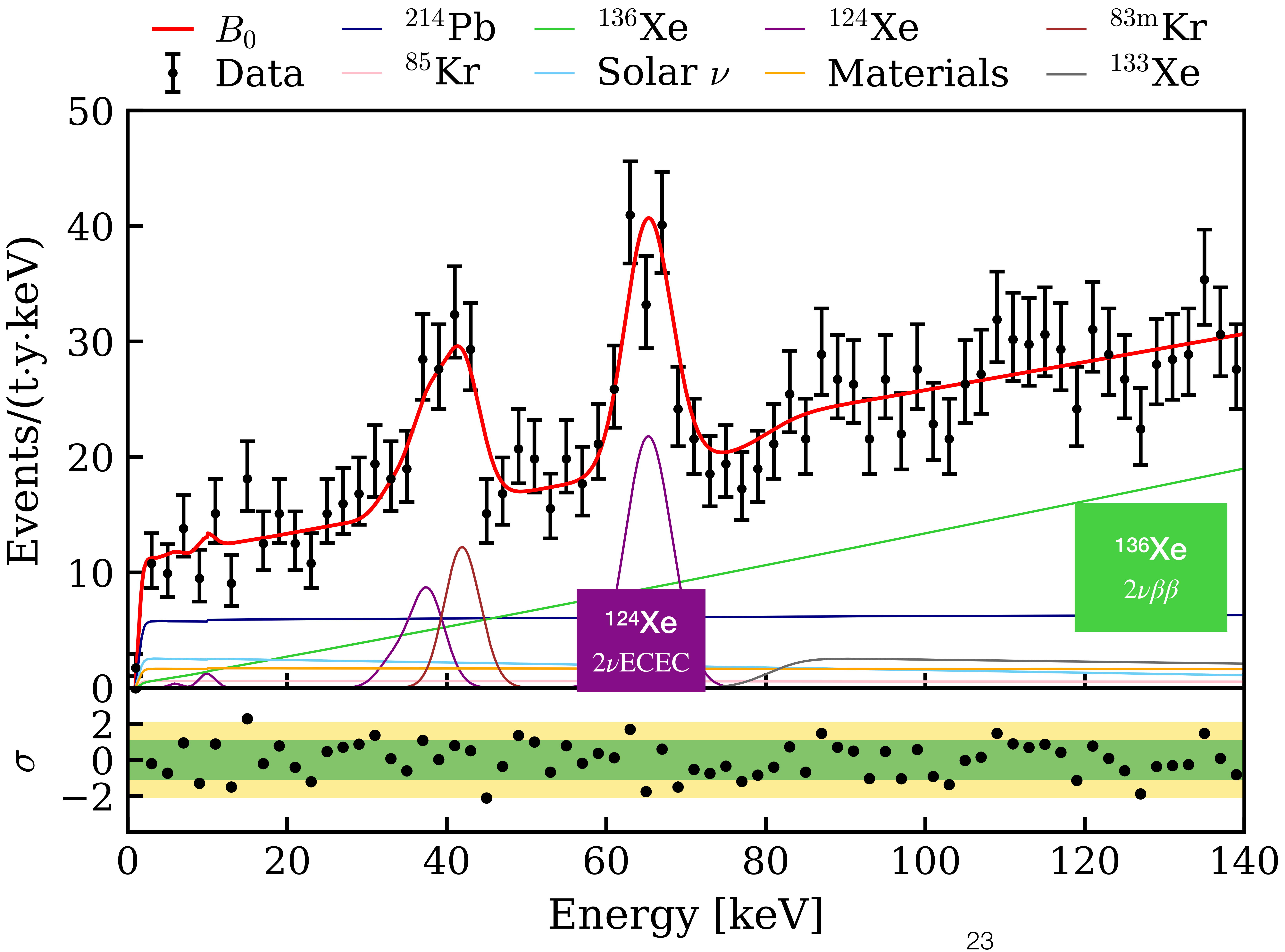
XENONnT: Fiducial Volume and Selections



Switching back to XENONnT

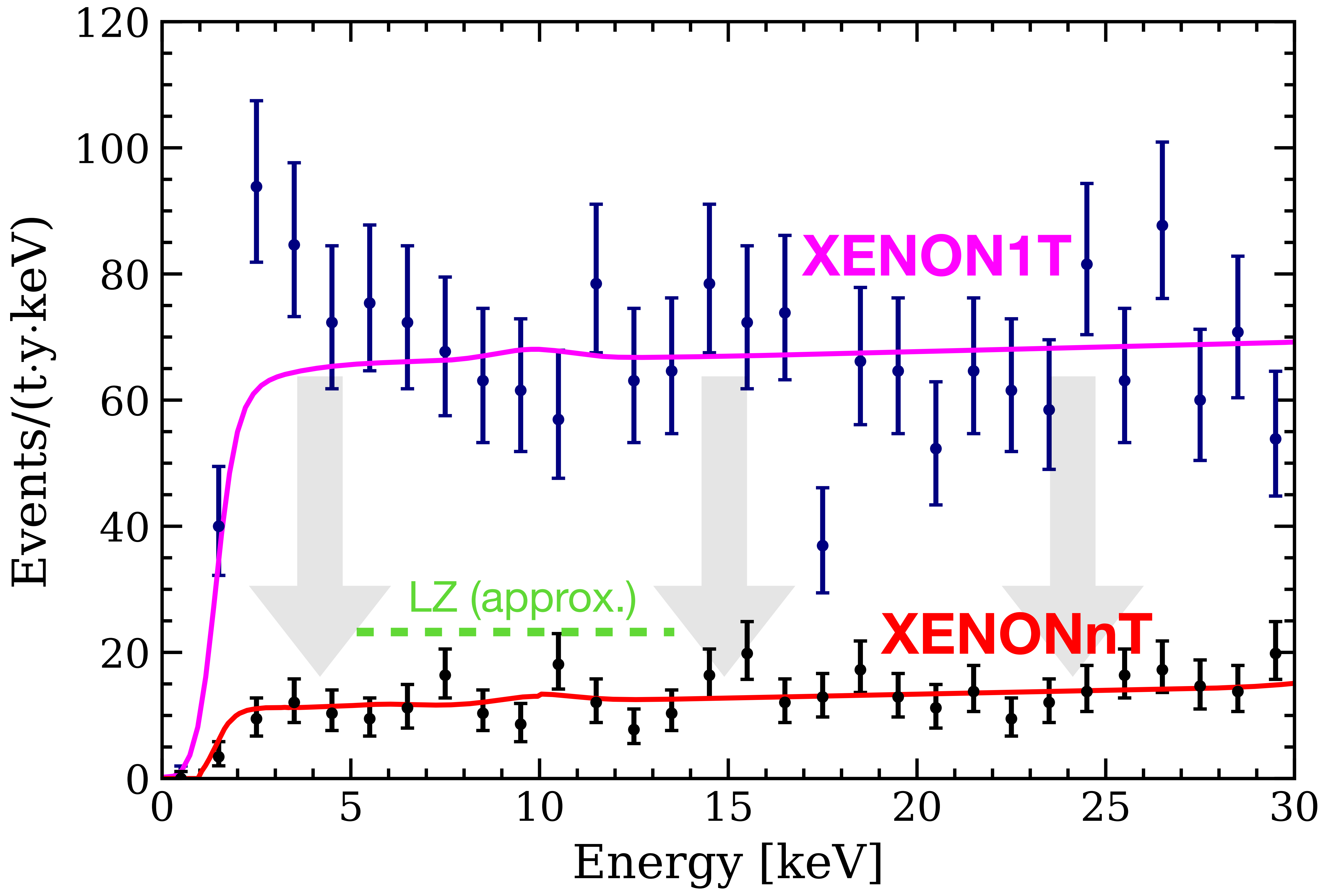
- In addition to quality cuts, events are required to pass a range of quality cuts:
    - An S2 over 500 PE
    - Not within $< 300\ ns$ of a neutron veto event
- Events must be within ER band (NR band blinded for now)
- Fiducial volume cut selects a mass of (4.37 ± 0.14) tonnes with low backgrounds

First Data from XENONnT



- Looking at a wider energy range than LZ, up to 140keV
- At low energies: still dominated by 214Pb
- At higher energies, dominated by two 2nd order weak processes!
  - ^{124}Xe 2νECEC
  - ^{136}Xe $2\nu\beta\beta$

First Data from XENONnT



Zooming in near threshold…

No sign of the excess

(XENON1T: perhaps tritium?)

Lowest background rate ever achieved:

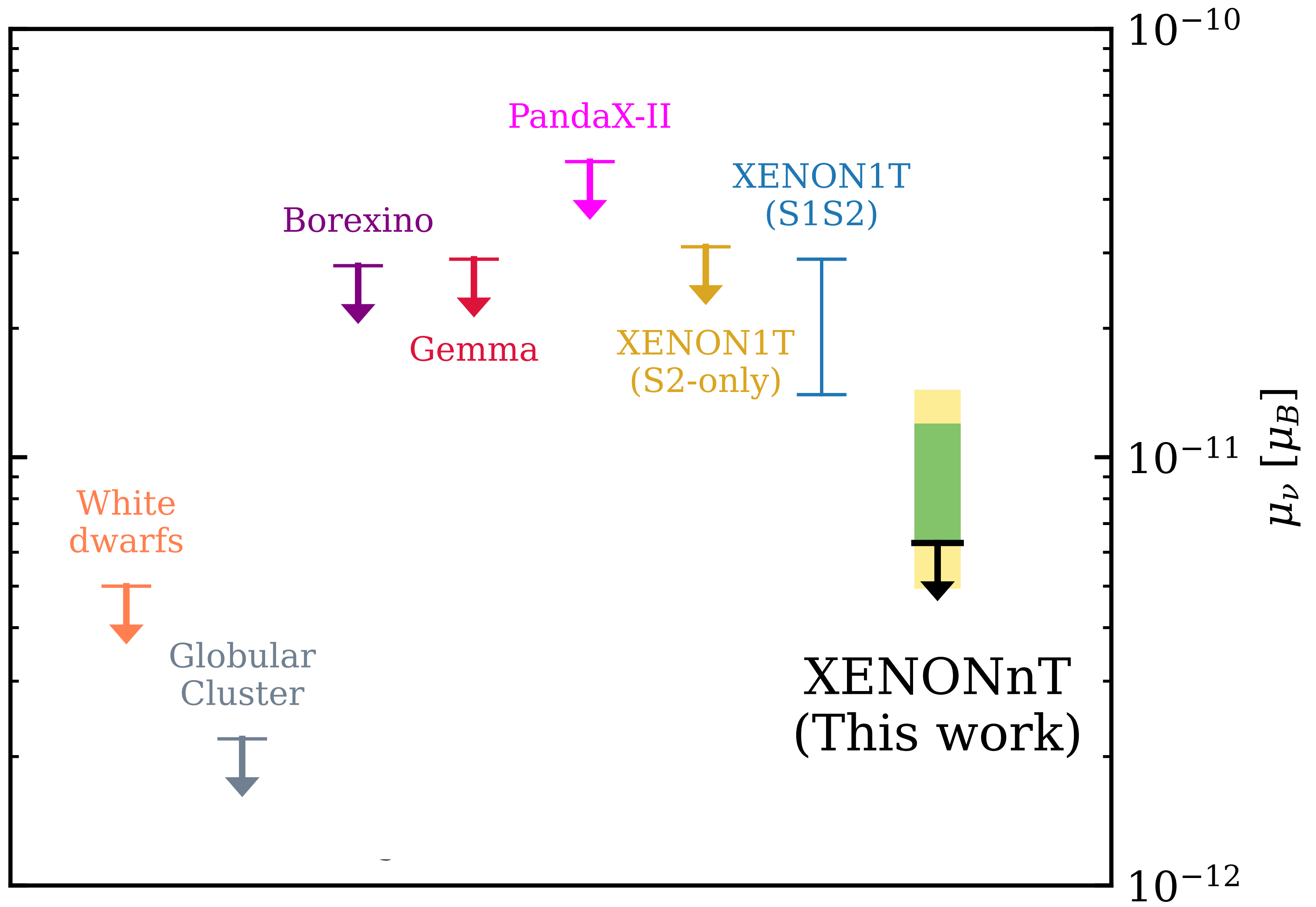
$$(16.1 \pm 0.3)\ \text{events}/(\text{t} \times \text{yr} \times \text{keV})$$

Can set new limits on ER signatures.

First XENONnT New Physics Searches

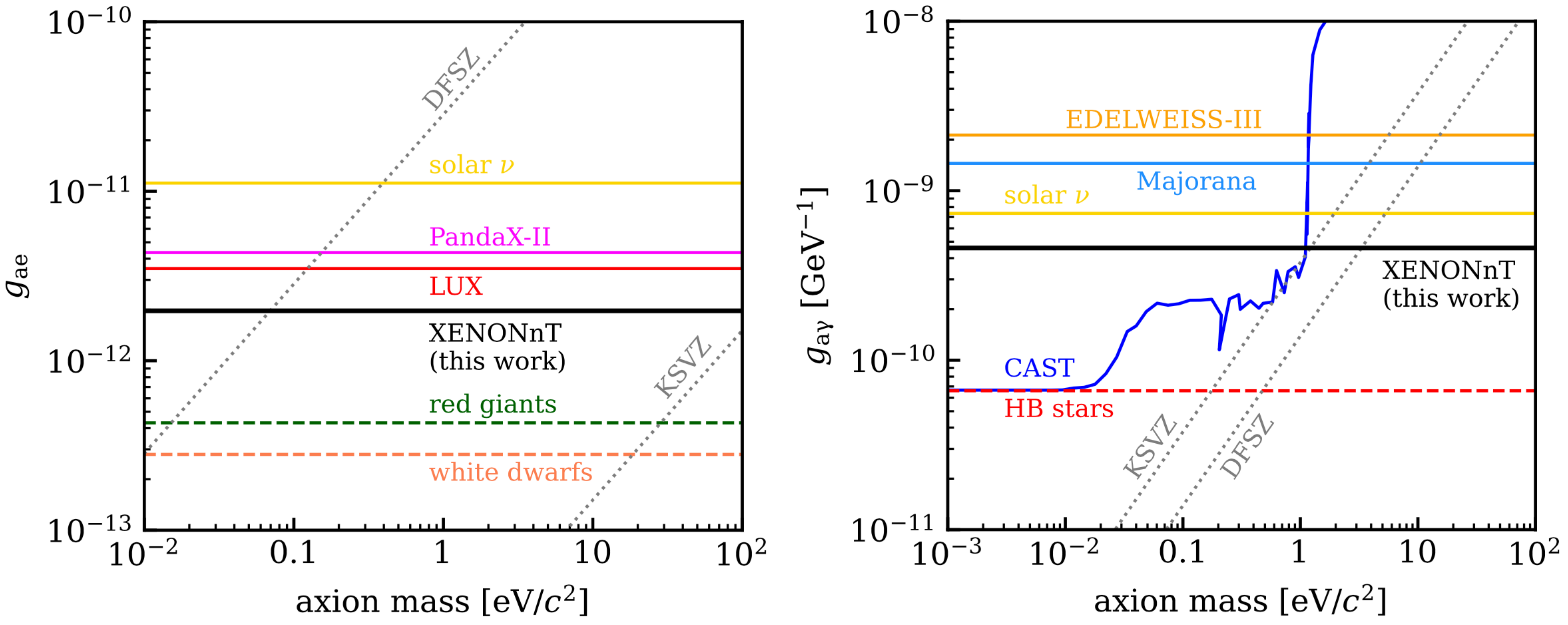
Solar Neutrino Magnetic Moment

$$\mu_\nu < 6.3 \times 10^{-12} \mu_B$$



Solar Axion Couplings

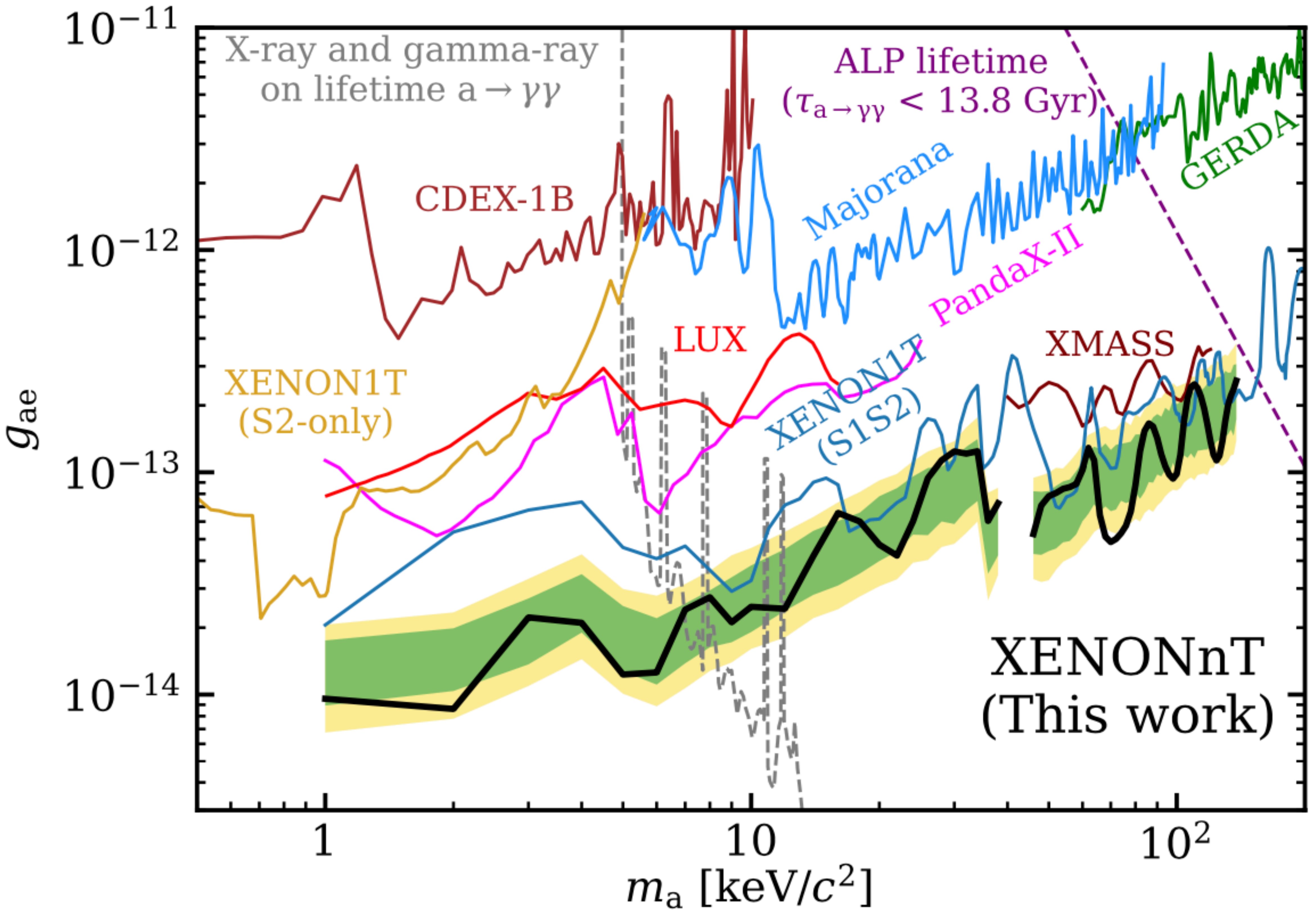
- Valid for axions with mass below 100 eV
- Best direct detection limit on g_{ae} (m<100eV)
- Best direct detection limit on $g_{a\gamma}$ (1<m<100eV)



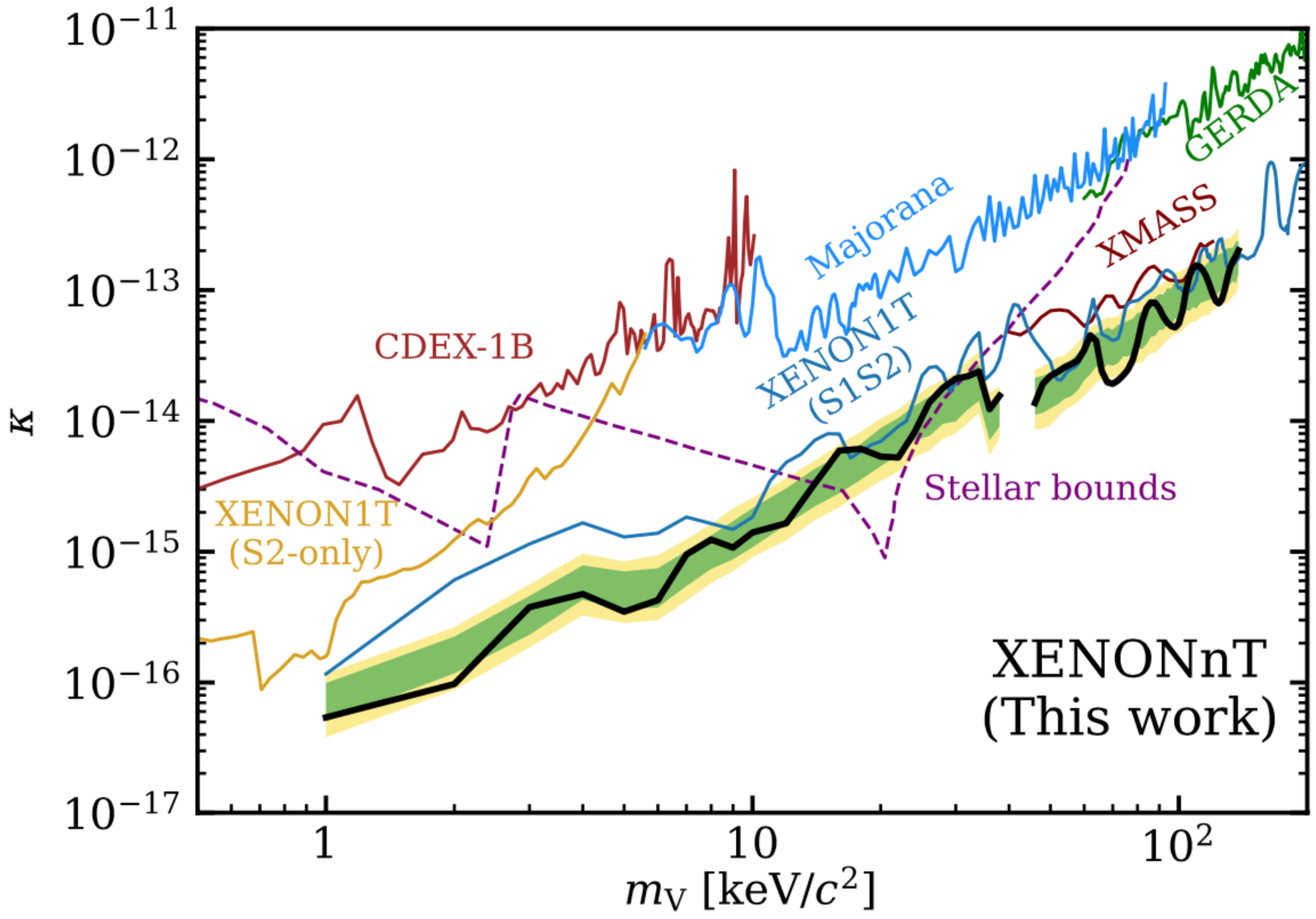
First XENONnT New Physics Searches

- Two searches for Bosonic absorption (mono energetic peaks)
- World-leading across much of the 1-140keV window
- Maximum local significance: ~1.8σ (at ~109keV)

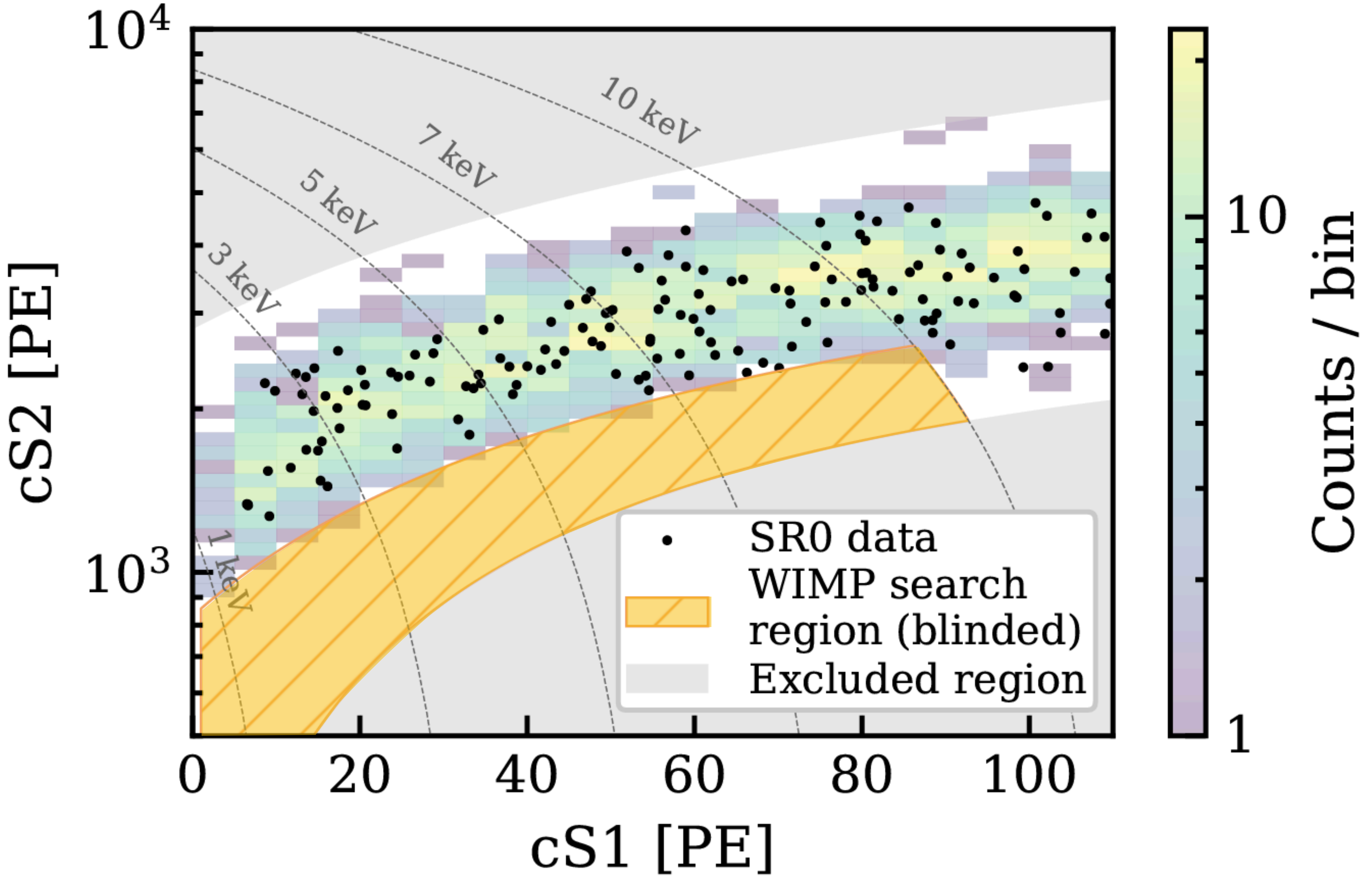
ALP



Hidden Photon



First XENONnT New Physics Searches



Nuclear Recoil region blinded through these ER analyses.

HV issue meant running at unusually low drift voltage (23 vs 193 V/cm), but remember: ***"LXe technology wants to work."***

Looking forward to first WIMP results from XENONnT soon!

Outlook

Next few years: Continue collecting data with existing (newly demonstrated) experiments
Discovery may always be just around the corner.

In parallel: Joining forces to plan a future LXe experiment at the 50-100 t scale

XENON, LZ, DARWIN, and LZ have now formed ‘XLZD Consortium’
Initial meeting 27-29 June 2022 at Karlsruhe Inst. of Technology
See https://xlzd.org and white paper (arXiv:2203.02309)

Outlook

Next experiment: keV regime will be dominated by *neutrinos* (rather than Pb214)

'LXe observatory' with WIMPs as one *part* of a broad portfolio.

The future is bright!