

Results from, and Status of, the **LUX-ZEPLIN** Experiment



Amy Cottle, UCL

On behalf of the LZ collaboration



LZ COLLABORATION

Thanks to our sponsors and participating institutions!
38 Institutions: 250 scientists, engineers, and technical staff

- Black Hills State University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics
- **Edinburgh University**
- Fermi National Accelerator Lab.
- **Imperial College London**
- **King's College London**
- Lawrence Berkeley National Lab.
- Lawrence Livermore National Lab.
- **LIP Coimbra**
- Northwestern University
- Pennsylvania State University
- **Royal Holloway University of London**
- SLAC National Accelerator Lab.
- South Dakota School of Mines & Tech
- South Dakota Science & Technology Authority
- **STFC Rutherford Appleton Lab.**
- Texas A&M University
- University of Albany, SUNY
- University of Alabama
- **University of Bristol**
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- University of California Berkeley
- University of California Davis
- University of California Los Angeles
- University of California Santa Barbara
- **University of Liverpool**
- University of Maryland
- University of Massachusetts, Amherst
- University of Michigan
- **University of Oxford**
- University of Rochester
- **University of Sheffield**
- **University of Sydney**
- University of Texas at Austin
- University of Wisconsin, Madison
- **University of Zürich**

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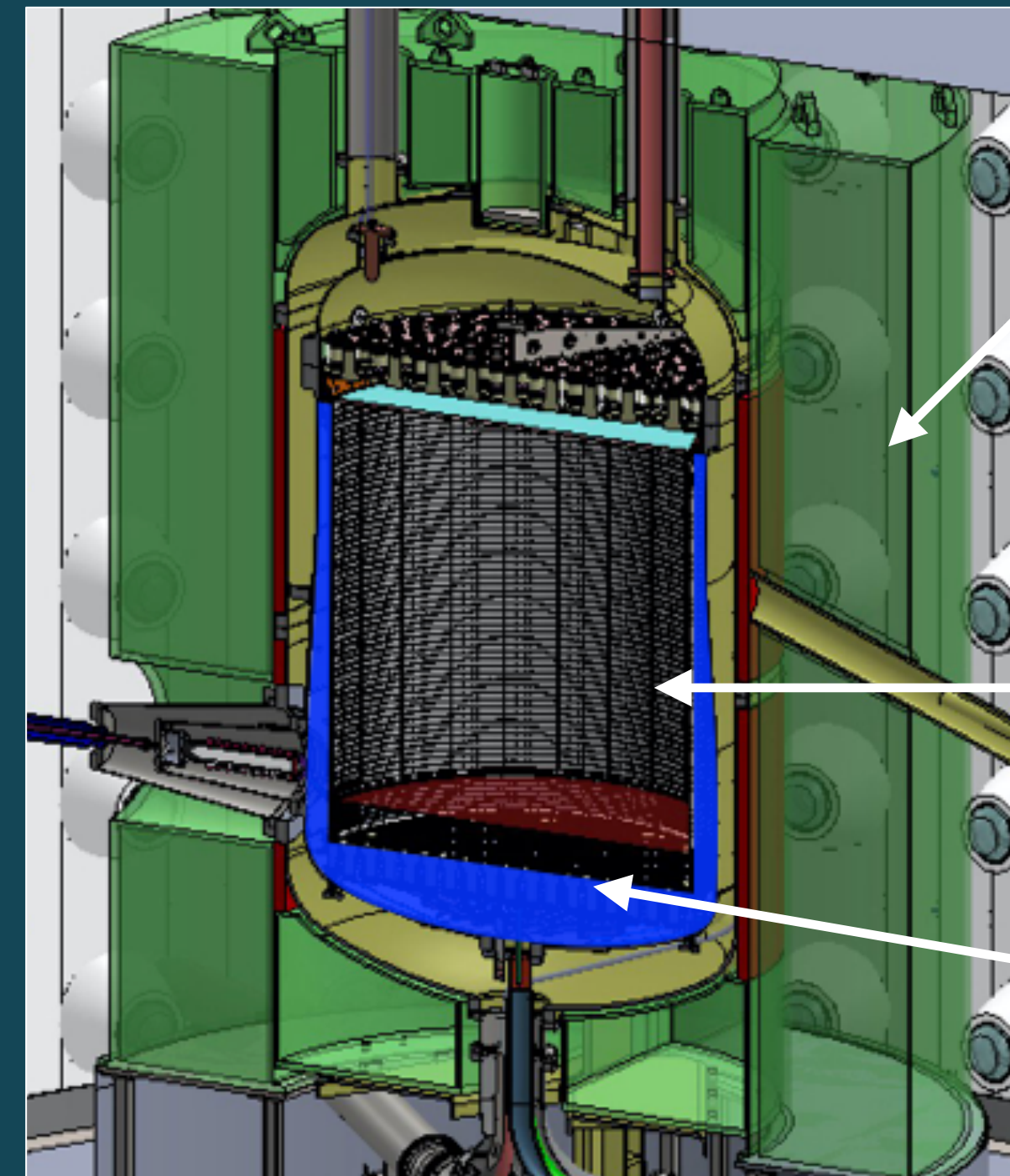
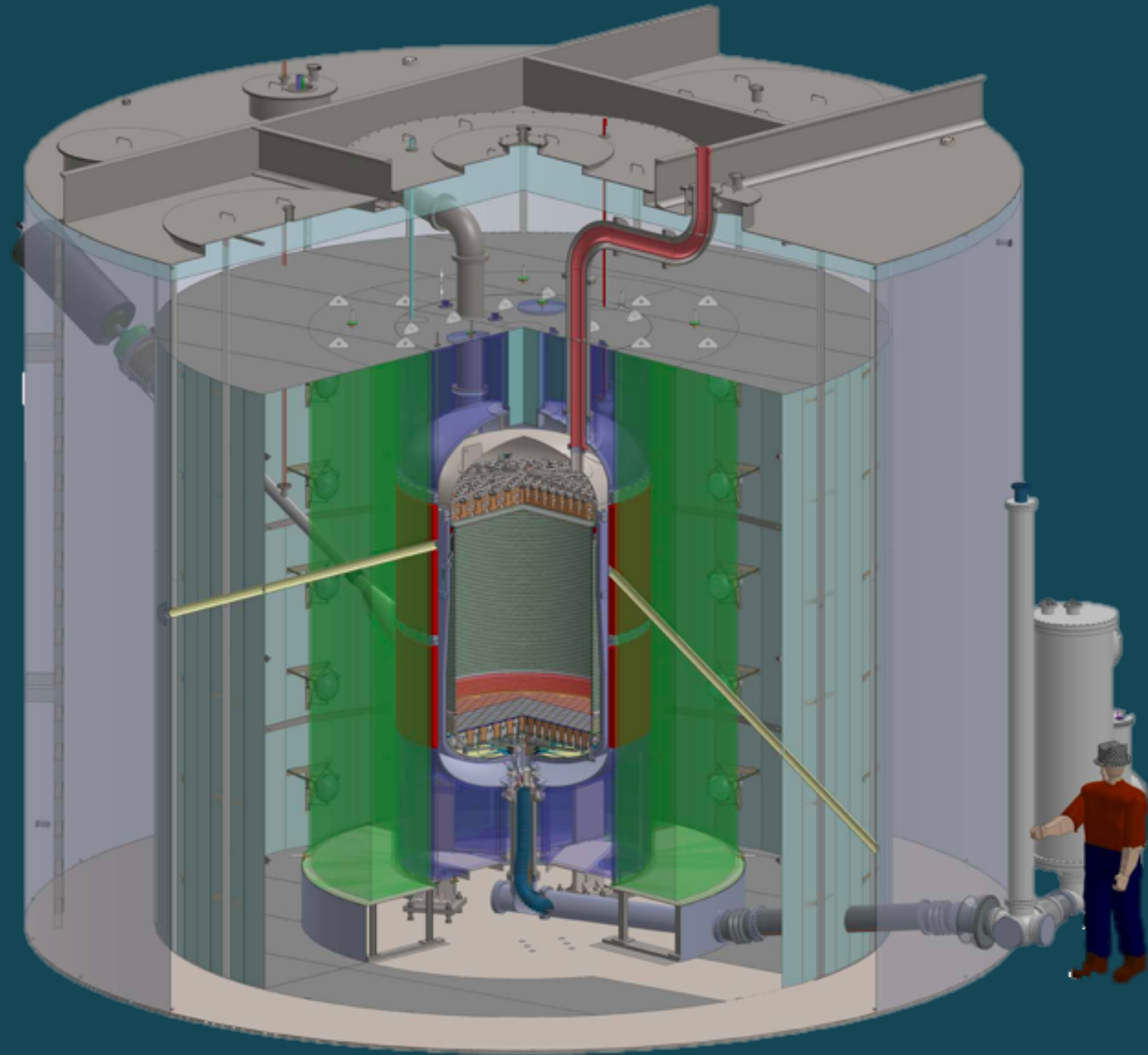


**SANFORD
UNDERGROUND
RESEARCH
FACILITY**

ibS Institute for
Basic Science

ARC CENTRE OF EXCELLENCE FOR
**DARK
MATTER** PARTICLE PHYSICS

THE LZ EXPERIMENT



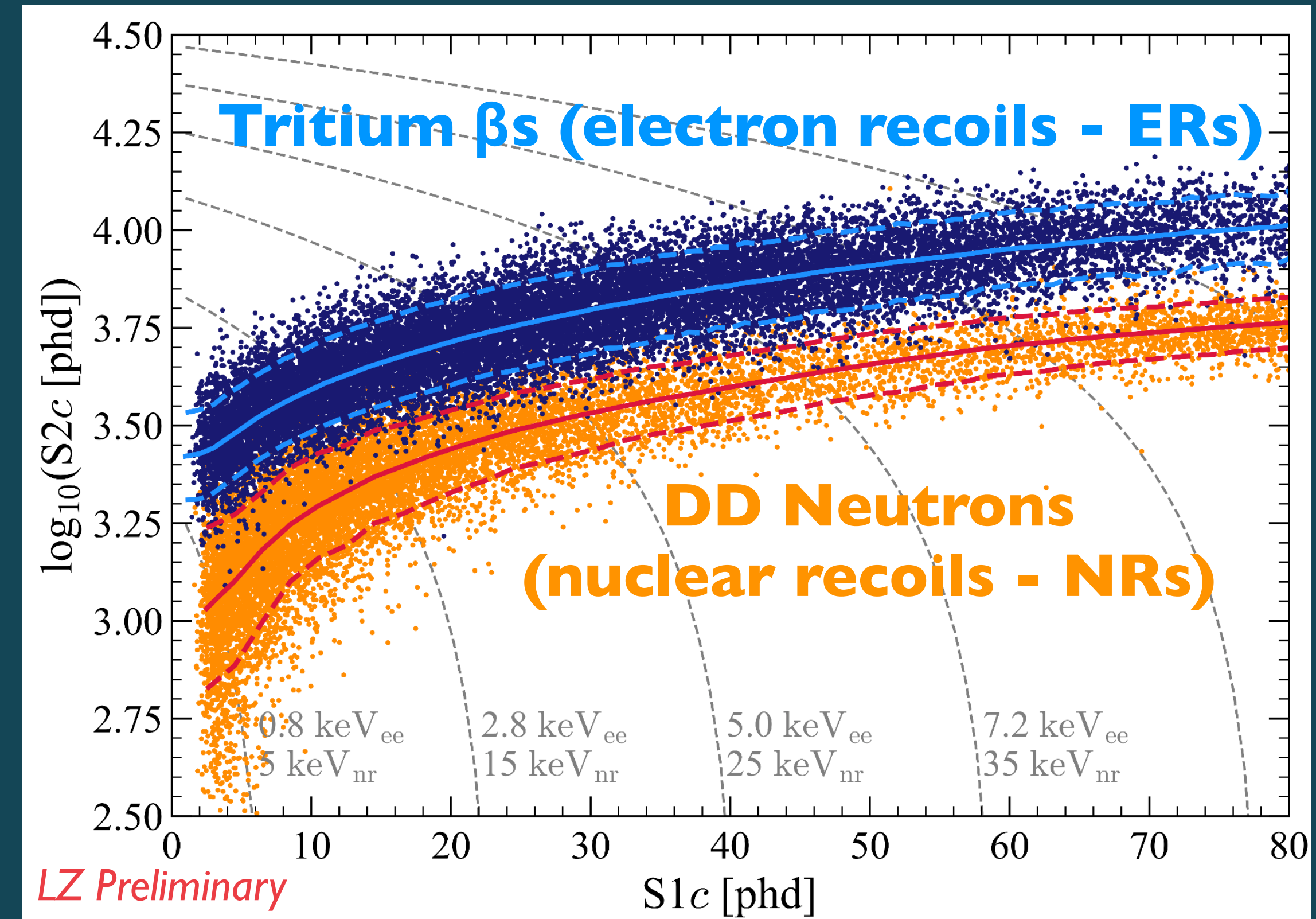
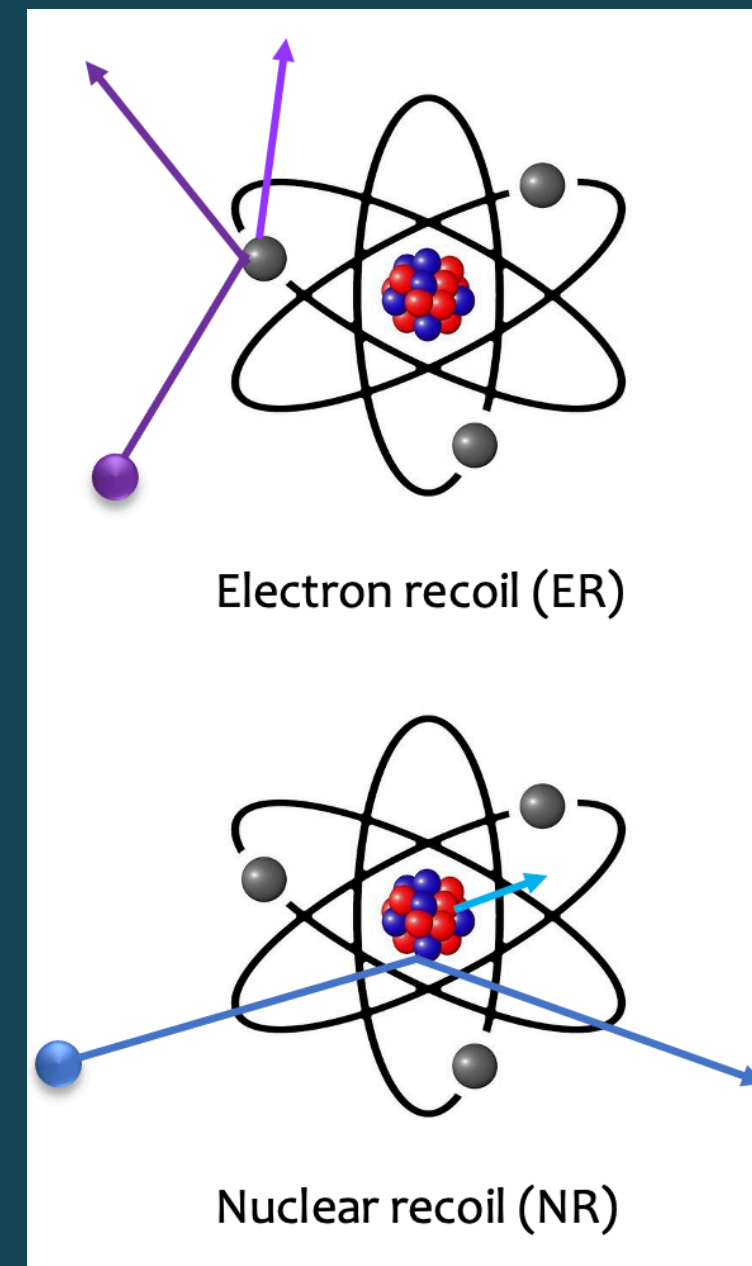
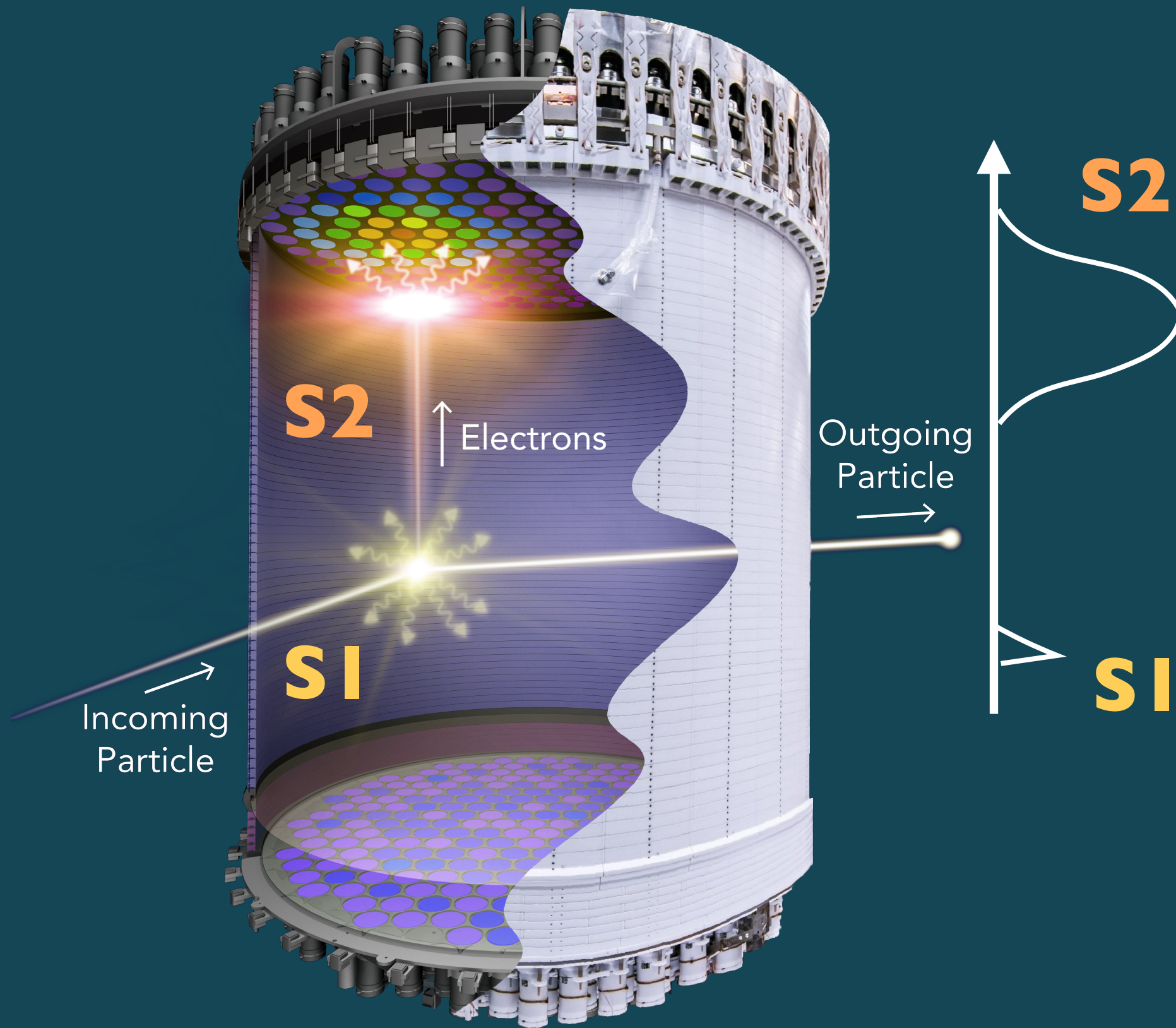
Outer veto
detector: Gd-doped
liquid scintillator

LXe TPC

LXe "Skin" veto
detector

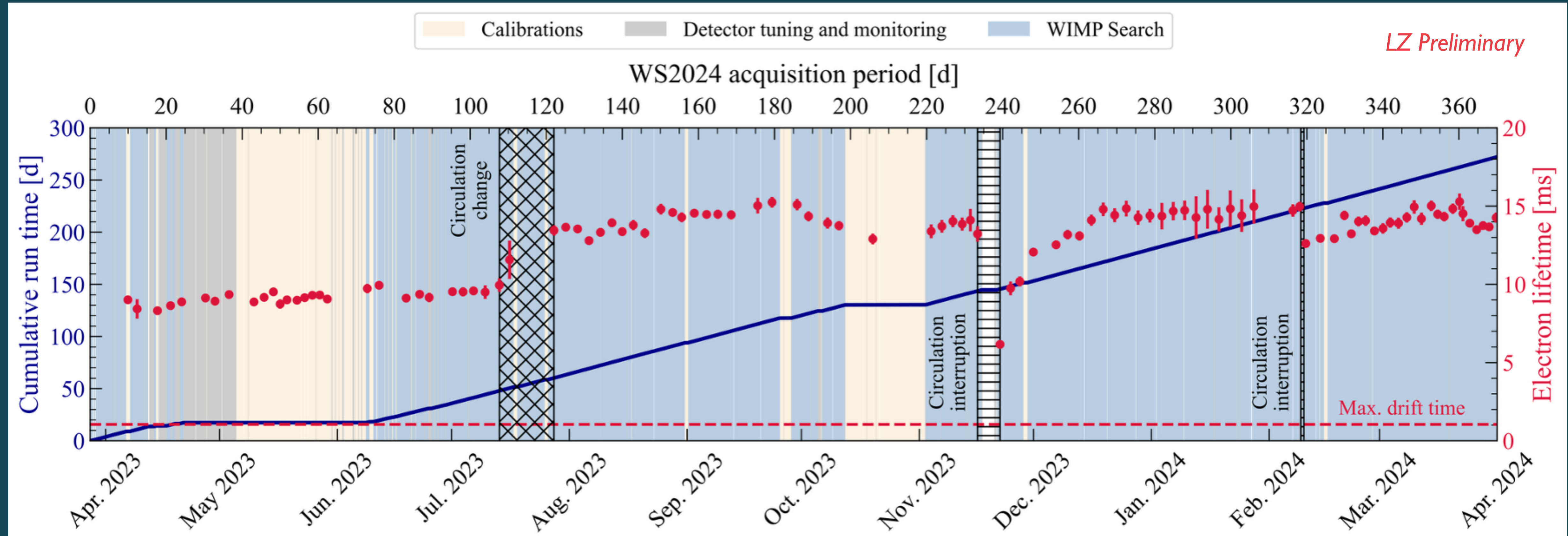
- ~1.5 km underground at the Sanford Underground Research Facility (SURF) in Lead, SD
- Operating world's largest 7 t active dual-phase xenon time projection chamber (TPC)
- TPC nested in Skin & Outer Detector (OD) veto systems → tag neutrons and gamma rays

XENON TIME PROJECTION CHAMBER (TPC)



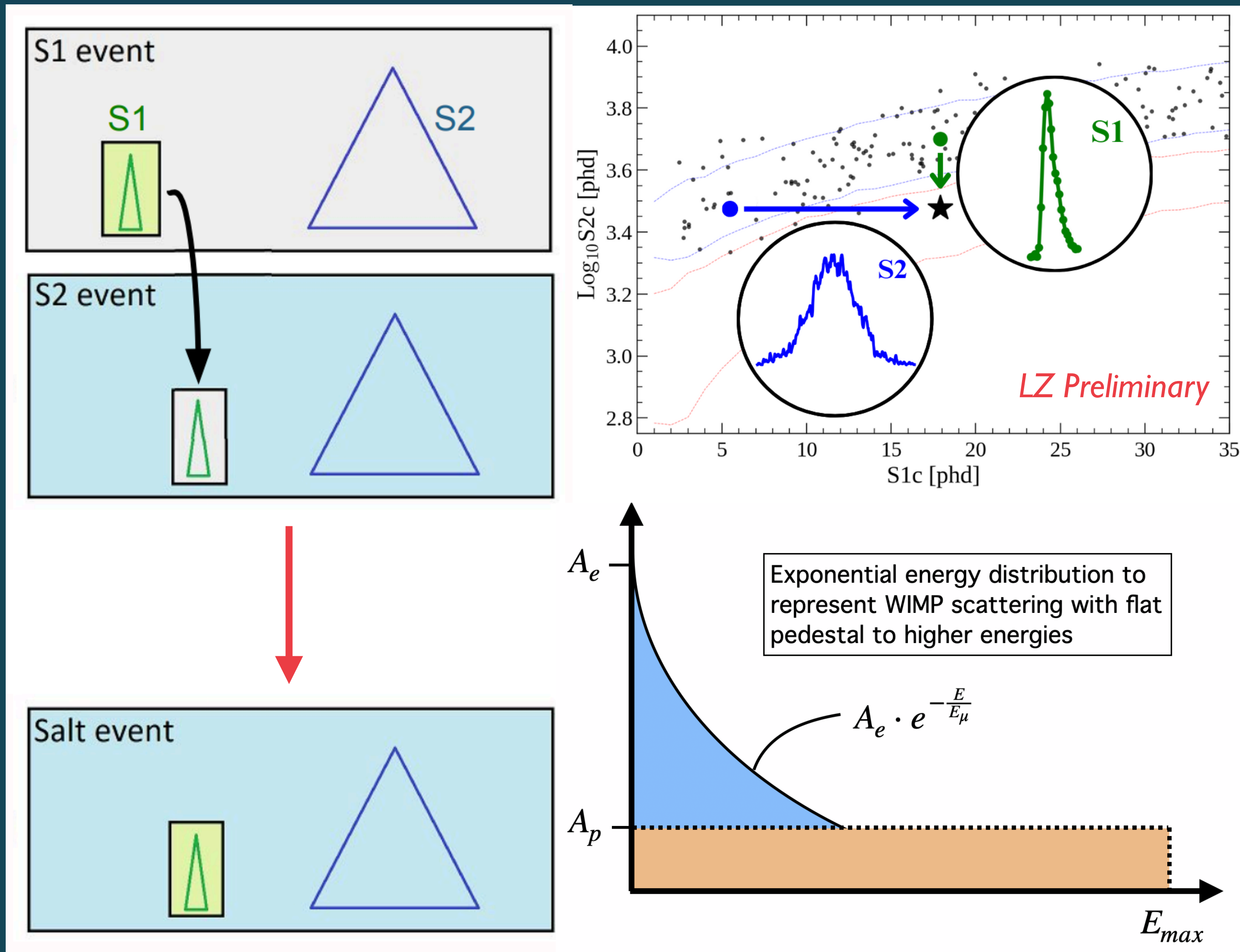
- Interactions give light (prompt scintillation - **SI**) and charge (proportional scintillation - **S2**)
- Excellent 3D position reconstruction ($\sim$ mm) $\rightarrow$ fiducialisation & distinguishing single scatters (SSs)
- Discrimination of electronic recoils (ERs) from potential WIMP nuclear recoils (NRs)

WIMP SEARCH 2024 (WS2024)



- 220 live-day exposure using data from March '23 to end March '24
- Major milestones: bias mitigation (“salting”) began July 3rd; circulation state change July 12th

BIAS MITIGATION



- “Salting” - fake signal events injected randomly during science data-taking
- Salt created using S1s & S2s from sequestered calibration data
- Parent distribution - exponential WIMP recoil spectrum + flat pedestal
- Rate capped by WS2022 cross-section
- Parameters unknown when analysing -
→ unsalting performed after all inputs are defined for statistical inference

XENON FLOW

- Circulation & cooling systems allow control of temperature & xenon flow

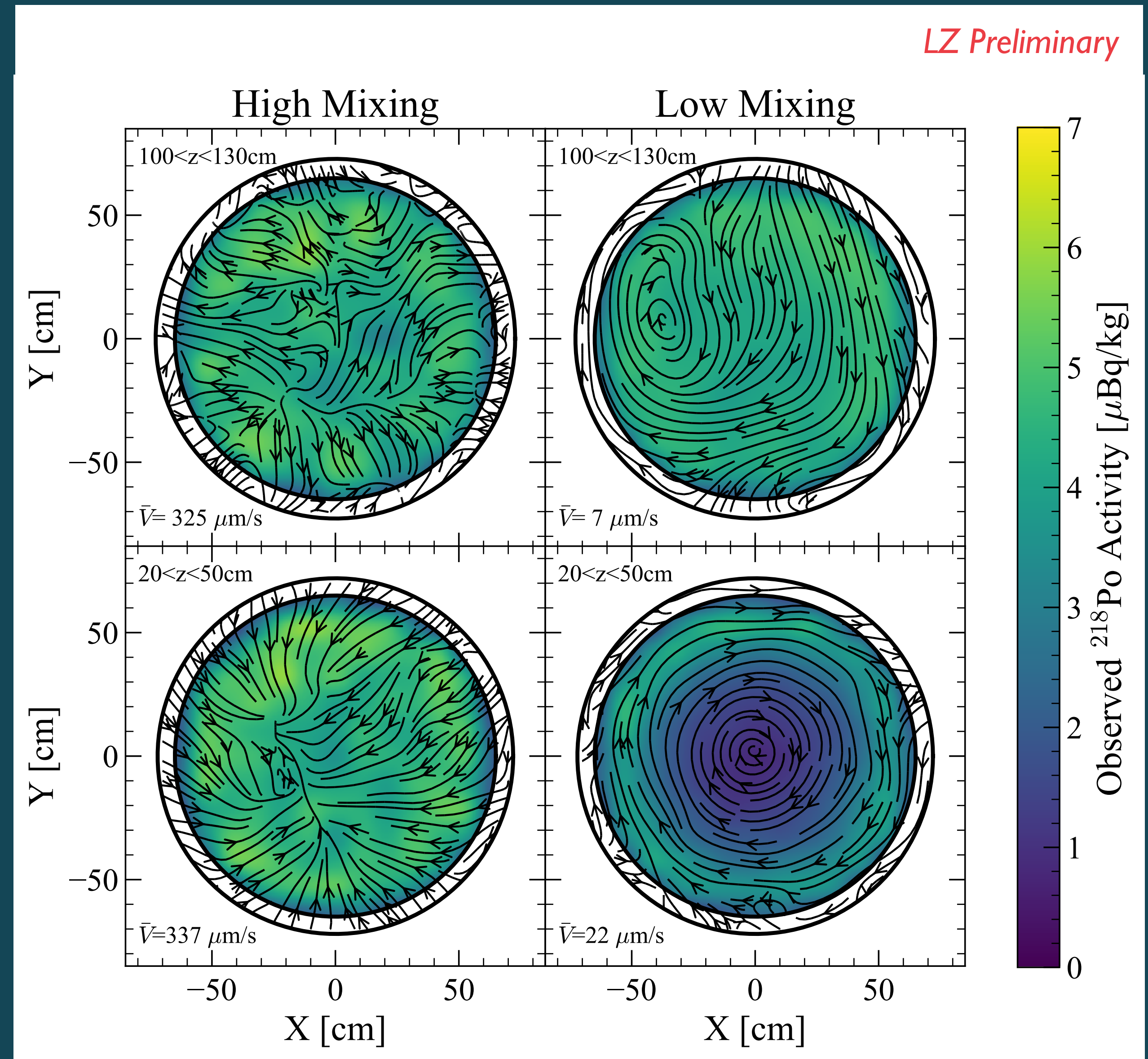
High-mixing state

More turbulent flow → uniform distribution of injected calibration sources

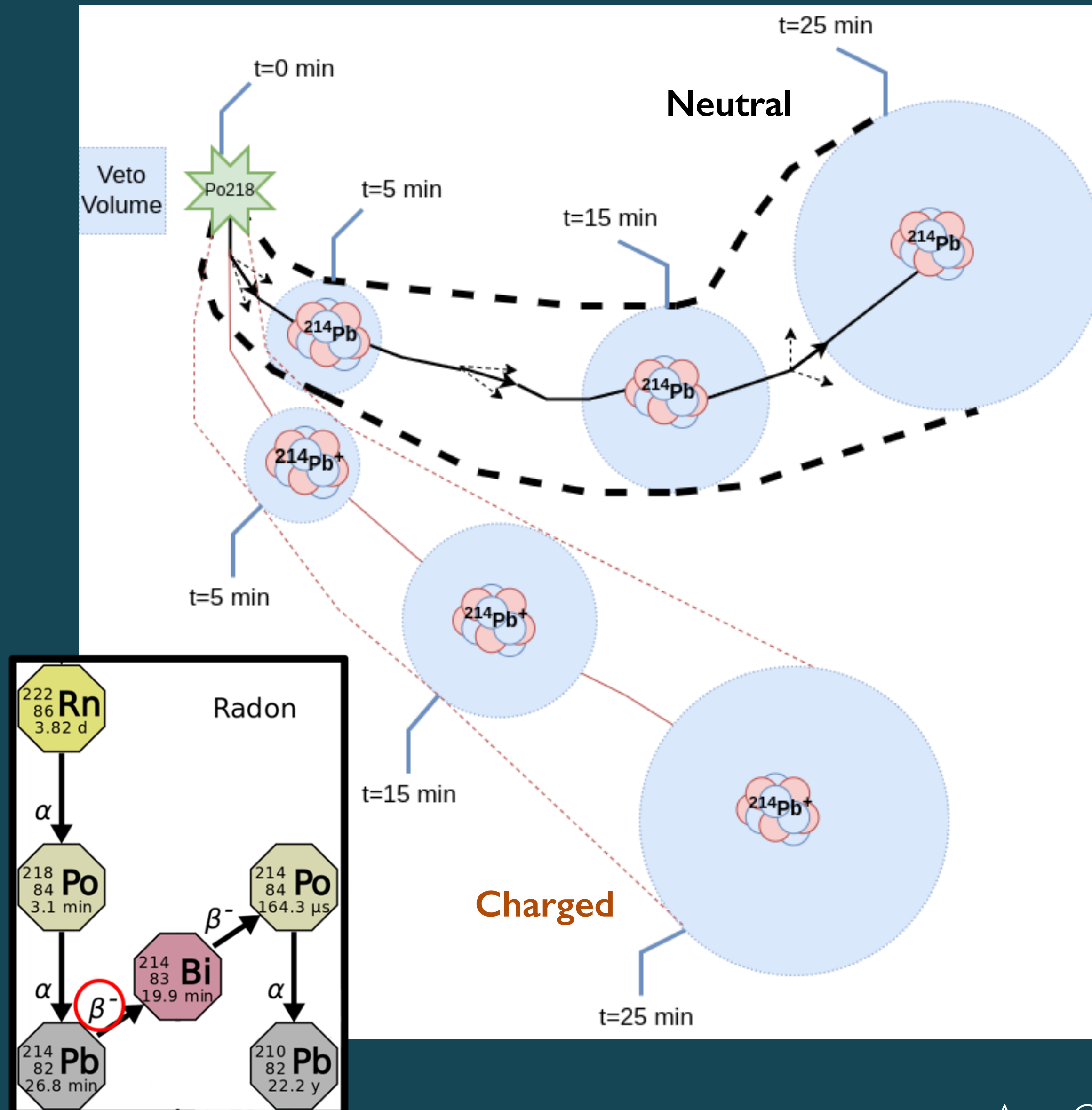
Low-mixing state

Slower, laminar flow

- ^{222}Rn emanates from detector materials
- ^{222}Rn - ^{218}Po pairs ($\tau_{1/2} = 3.1$ min)
→ used to map the flow vectors



RADON TAG

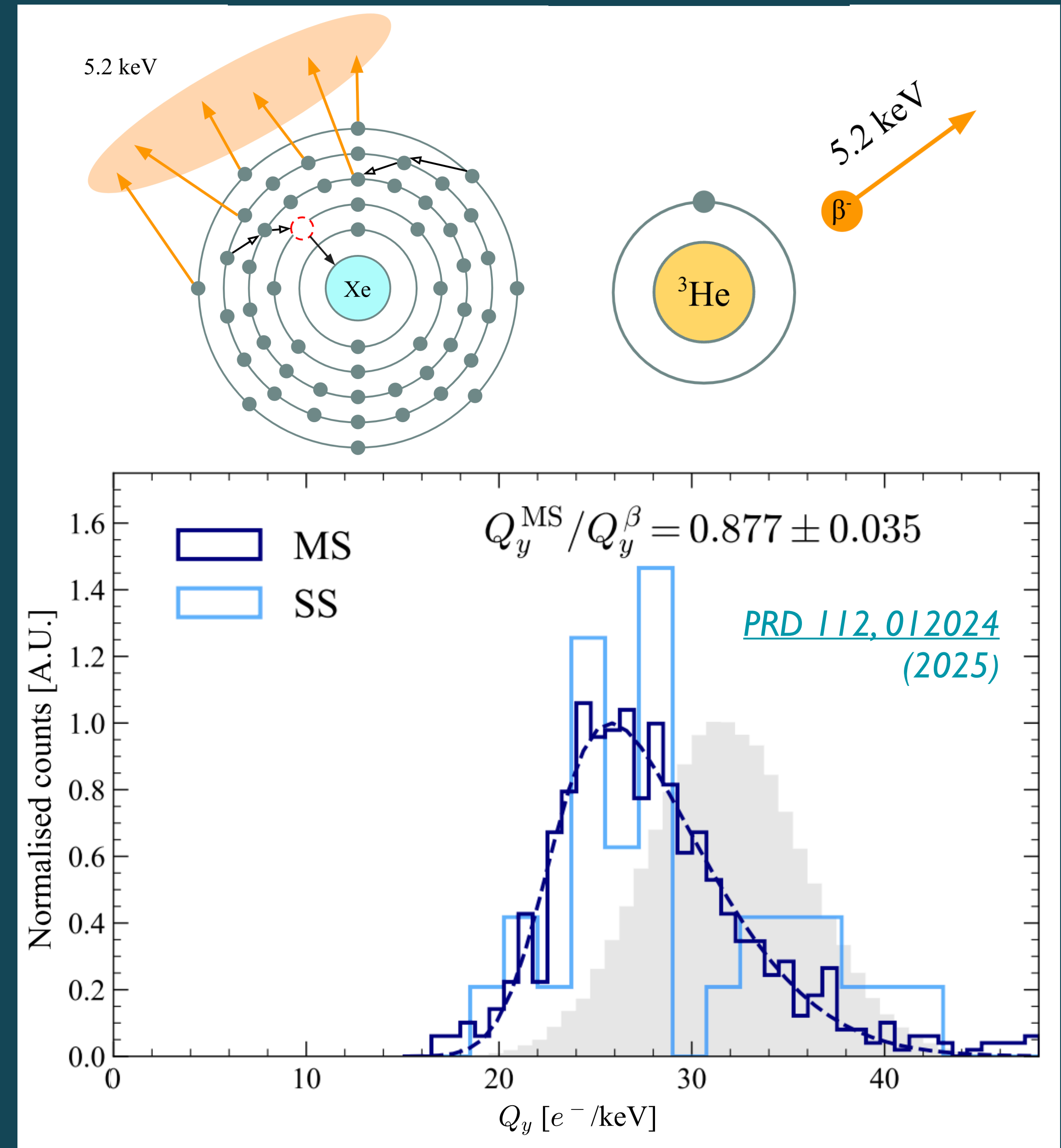


- “Naked” ^{214}Pb β decays = biggest ER background
- Simulations of neutral and charged ^{214}Pb movement using flow and field maps
→ use to create a “radon tag” in low-mixing state
- Define co-moving volumes around “streamlines” where ^{214}Pb is likely to be found
 - Each volume active 81 mins ($\sim 3 \times ^{214}\text{Pb} \tau_{1/2}$)
- Tagged & untagged data both in WIMP analysis

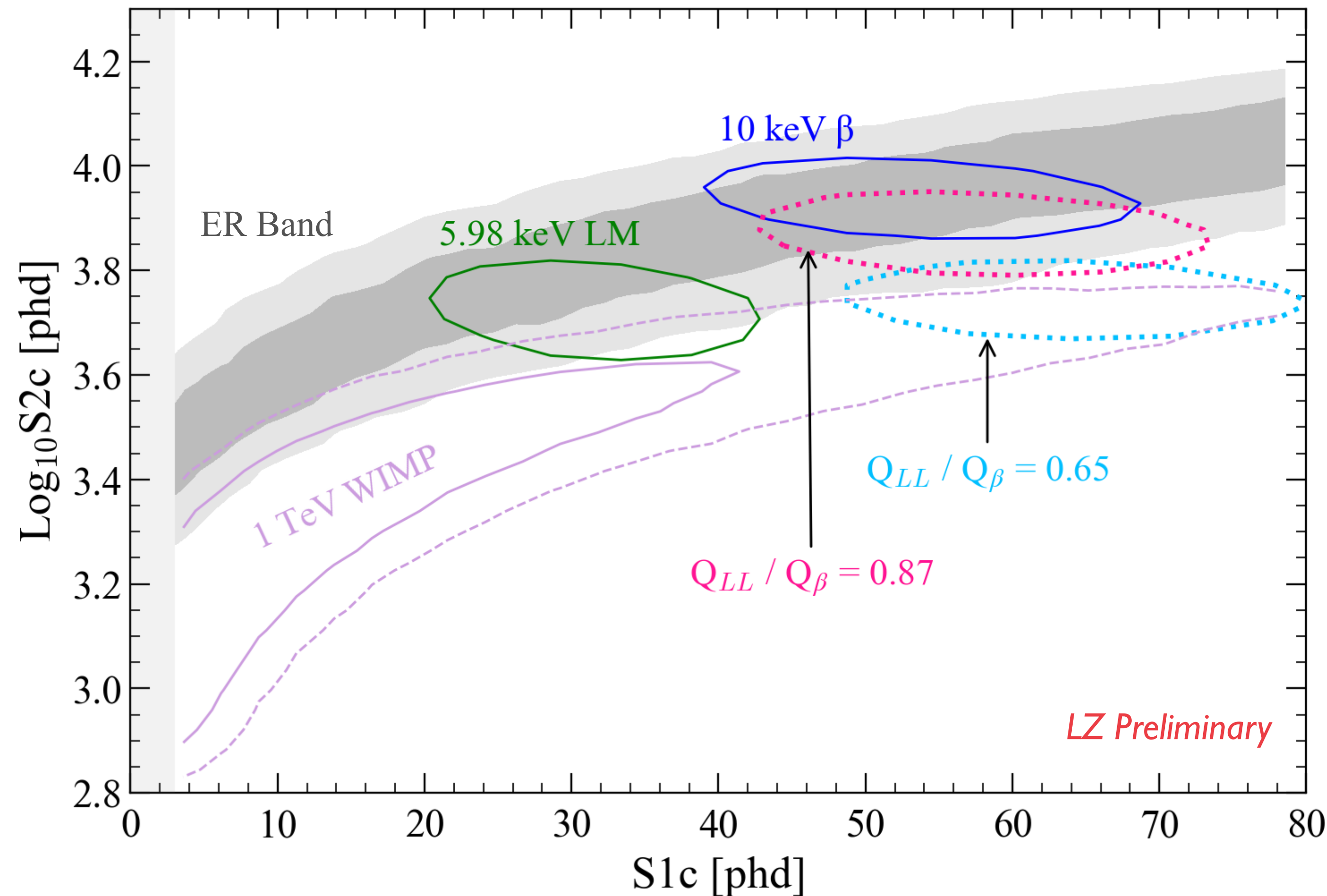
	% ^{214}Pb of Total	% Volume of Total
Tagged	60 ± 4	15
Untagged	40 ± 4	85

ELECTRON CAPTURES

- ^{127}Xe & ^{125}Xe decay by electron capture (EC)
- L-shell EC (5.2 keV) relevant for WIMP search
 - Auger/X-ray cascade $\rightarrow$ more NR-like than β
i.e. **enhanced recombination**
 - *In-situ* measurement in LZ for WS2024:
 $Q_L/Q_\beta = 0.877 \pm 0.035$ (PRD 112, 012024)
- How does this impact ^{124}Xe double electron capture (DEC)? - “world’s rarest decay”
(LM (6.0) & LL-shell (10.0 keV) contributions)



MODELLING ^{124}Xe LM- & LL-SHELL DEC



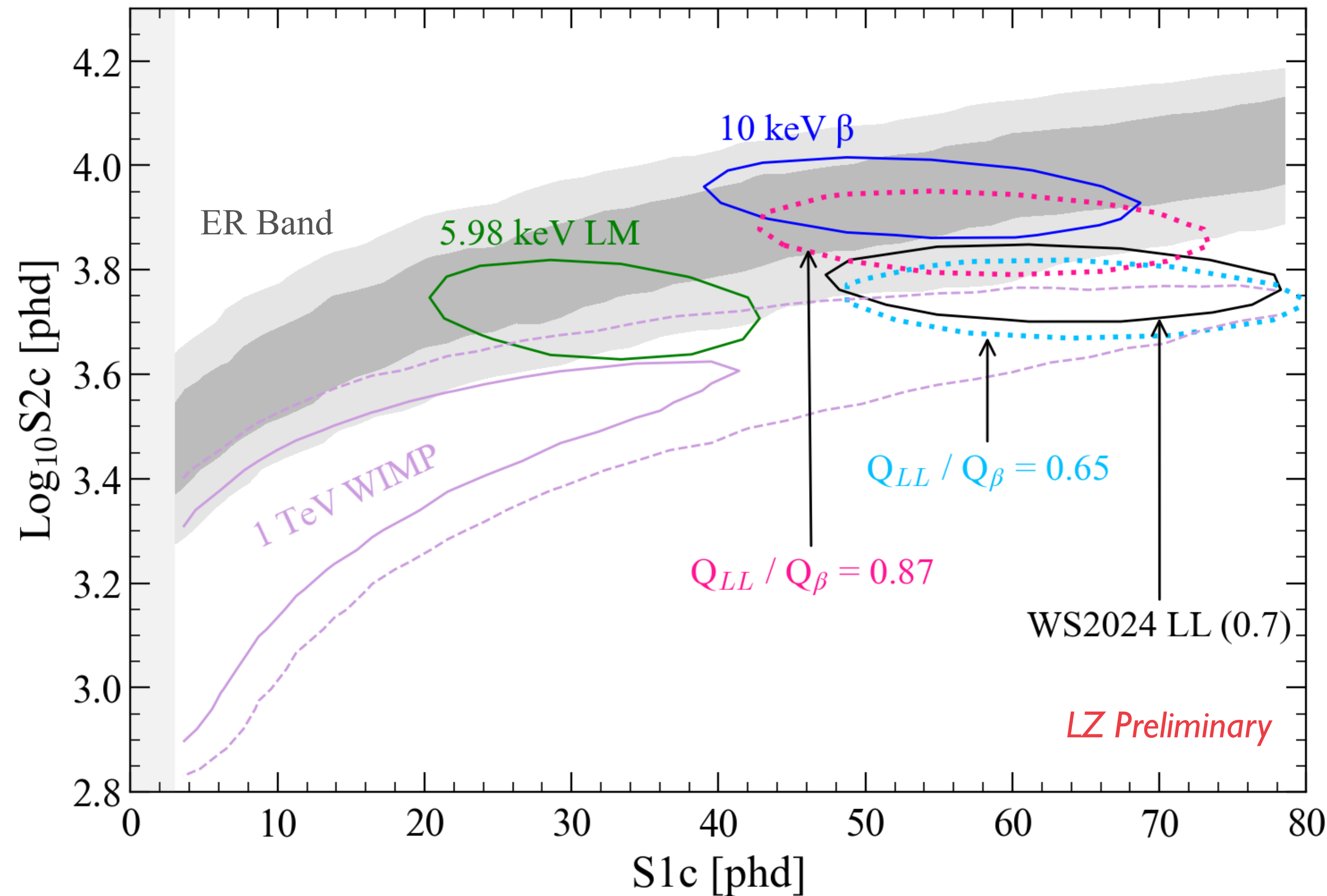
- Expect 7.1 (LM) + 12.3 (LL) = 19.4 counts with 20% uncertainty
- LM modelled with same as single L-shell charge suppression
- LL expected to be further charge-suppressed due to higher ionisation density i.e. $Q_{LL}/Q_{\beta} < Q_L/Q_{\beta}$
- Vary Q_{LL}/Q_{β} in fitting of our data:

$$0.65 < Q_{LL}/Q_{\beta} < 0.87$$

2x L-shell ionization density

Q_L/Q_{β}

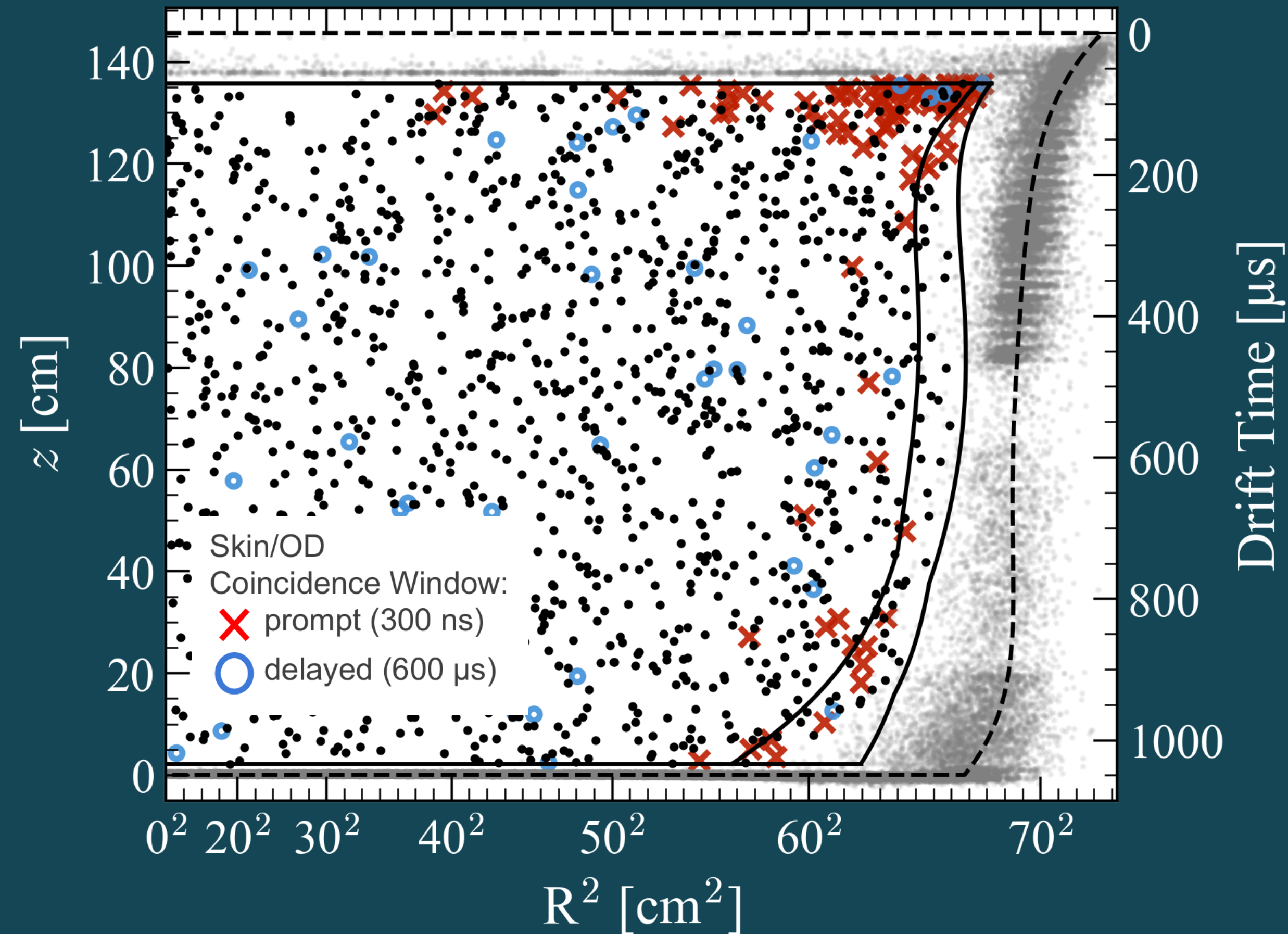
MODELLING ^{124}Xe LM- & LL-SHELL DEC



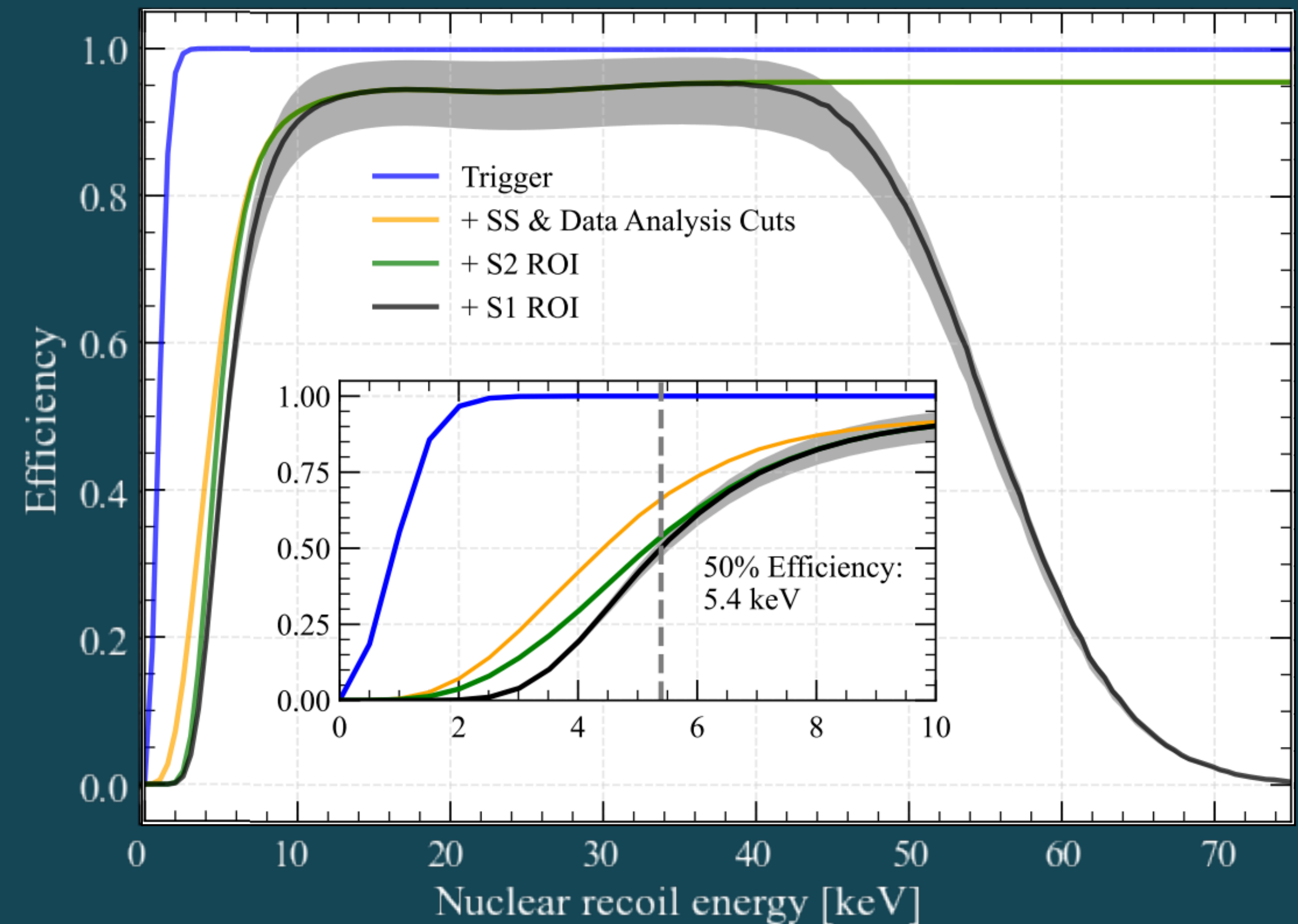
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- Vary Q_{LL}/Q_{β} in fitting of our data:
 $0.65 < Q_{LL}/Q_{\beta} < 0.87$

Best-fit value of $Q_{LL}/Q_{\beta} = 0.70 \pm 0.04$

ANALYSIS CUT SUMMARY

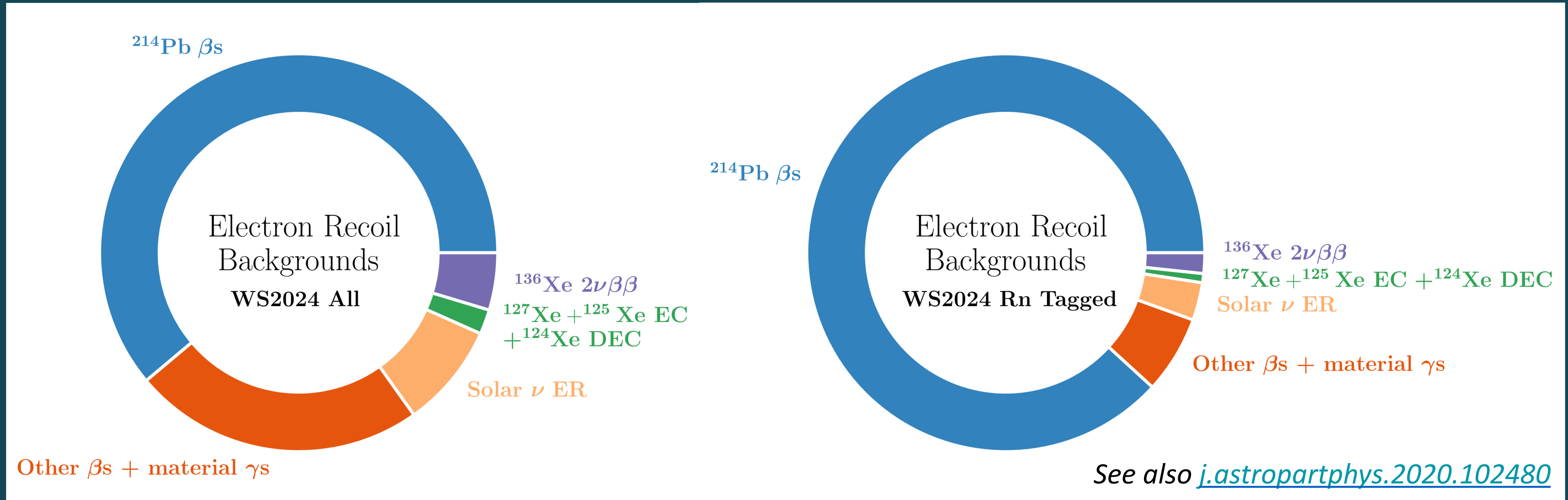


- Fiducial volume (5.5 ± 0.2 t)
- Veto detector anti-coincidence



- WIMP S2-SI region of interest
- SI- & S2-based cuts (target accidentals)

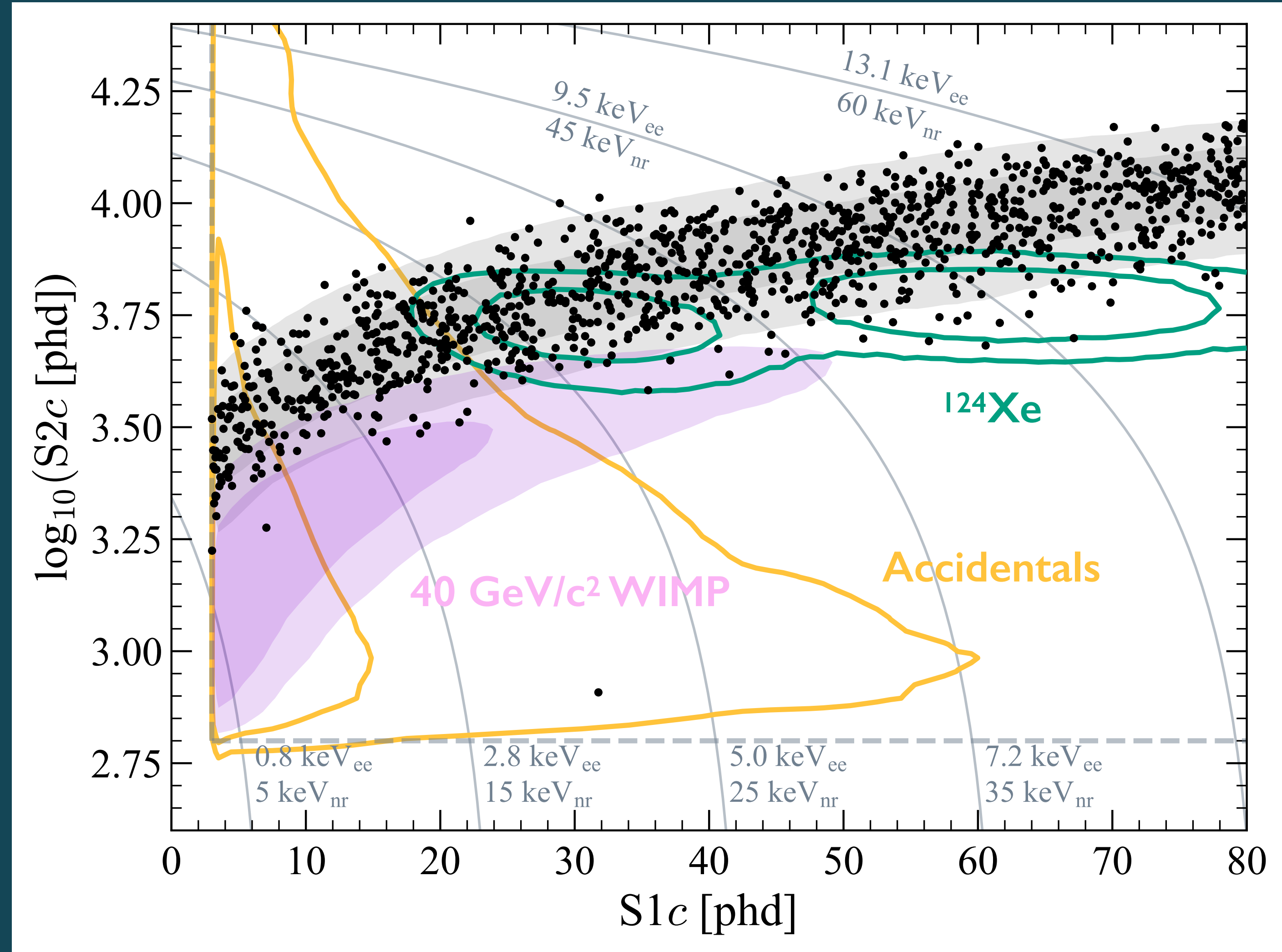
BACKGROUNDS MODEL EXPECTATIONS



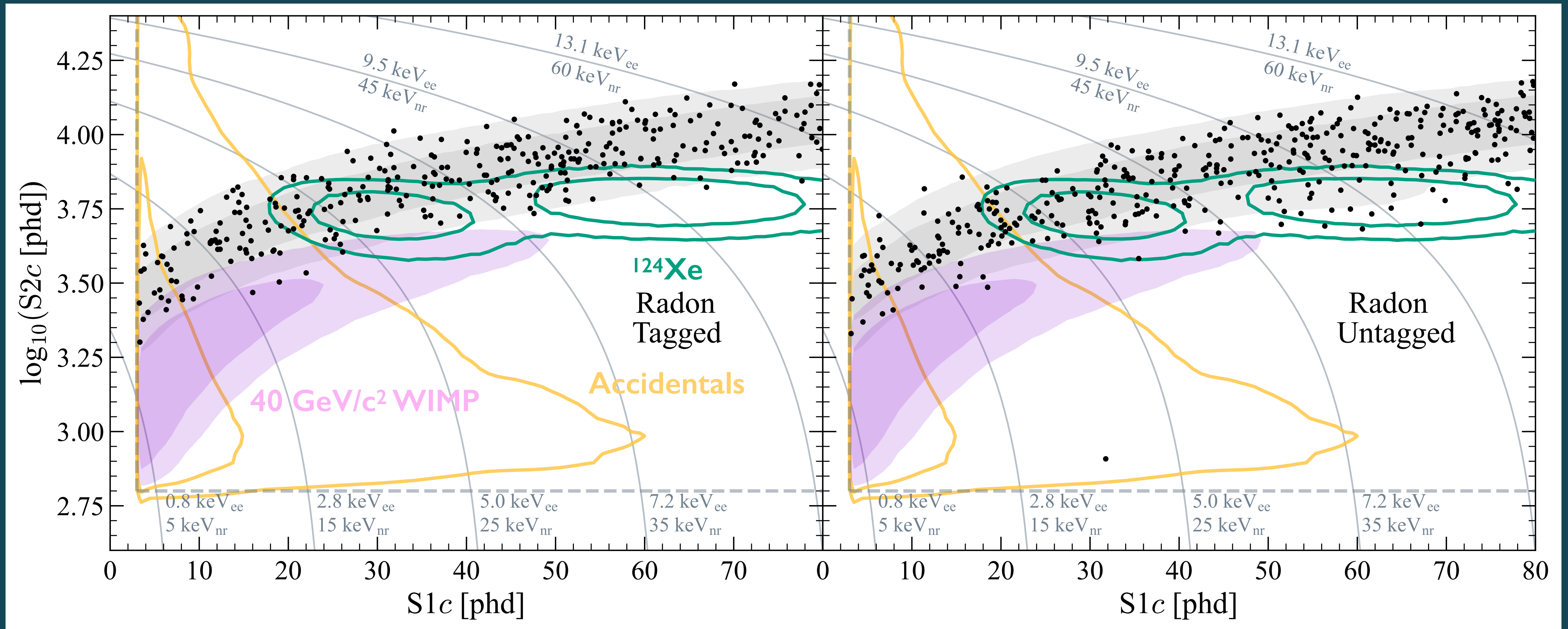
- Total expected **ER** counts for WS2024: **1207** (60% ^{214}Pb) (**327**/88% ^{214}Pb in radon-tagged data)
- Total expected **NR** counts in WS2024: **0.18** from CEvNS (no neutrons - *in-situ* fit constraint)
- **Accidentals** (fake pairs of S1- and S2-identified pulses) controlled with cuts to 2.8 ± 0.6 counts

WS2024 DATA

- Final exposure of
220 live days * 5.5 tonnes
= **3.3 tonne years**
- 7 salt events pass all analysis cuts out
of 8 total injected in WS2024
→ inline with evaluated signal efficiency
- **1220 events** remain after unsalting
- Statistical analysis of these data in
observed $\log_{10}(S2c)$ - $S1c$ space
→ no post-unsalting changes to model



WS2024 DATA - RADON TAGGED VS UNTAGGED

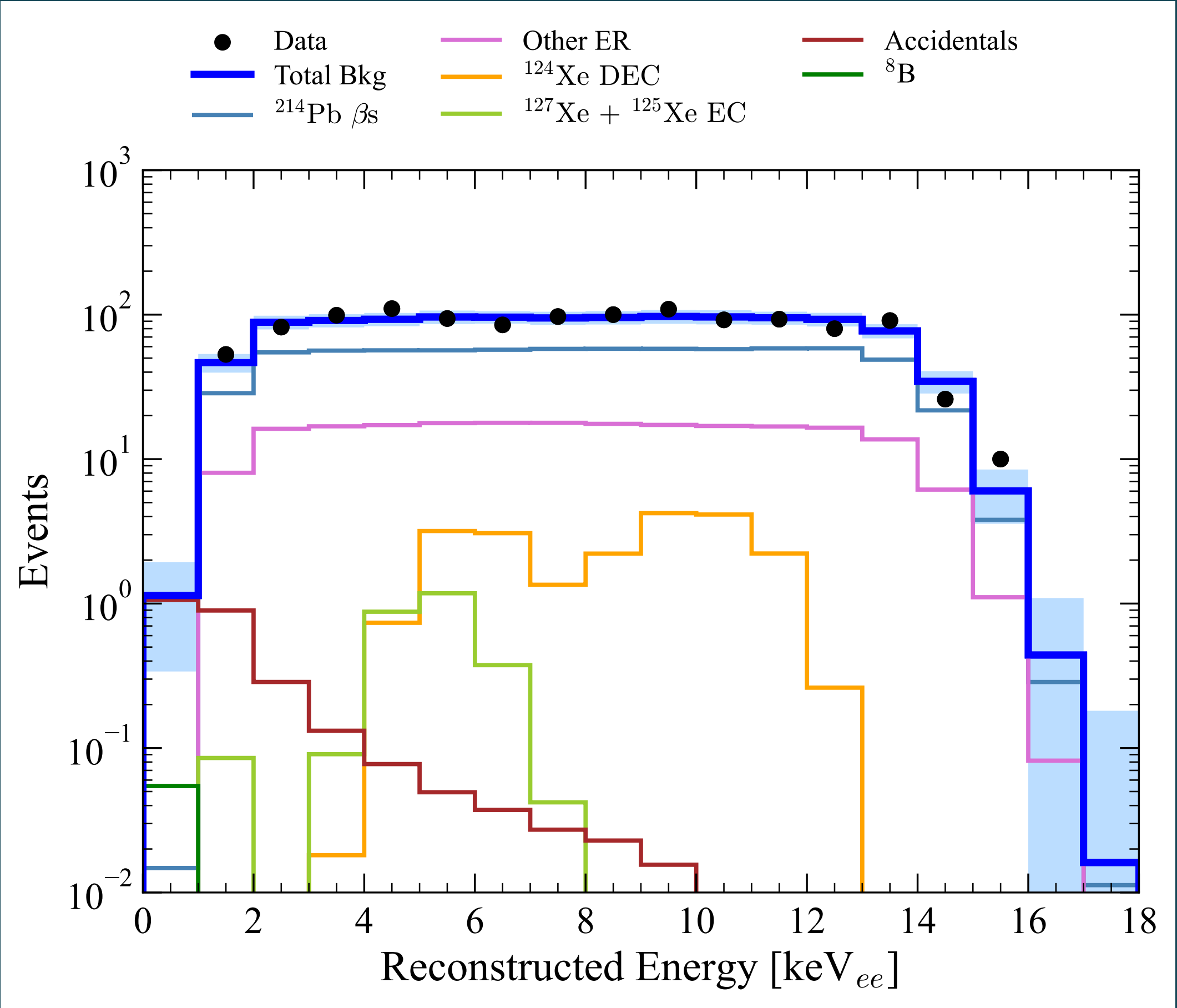


0.3 tonne years

1.8 tonne years

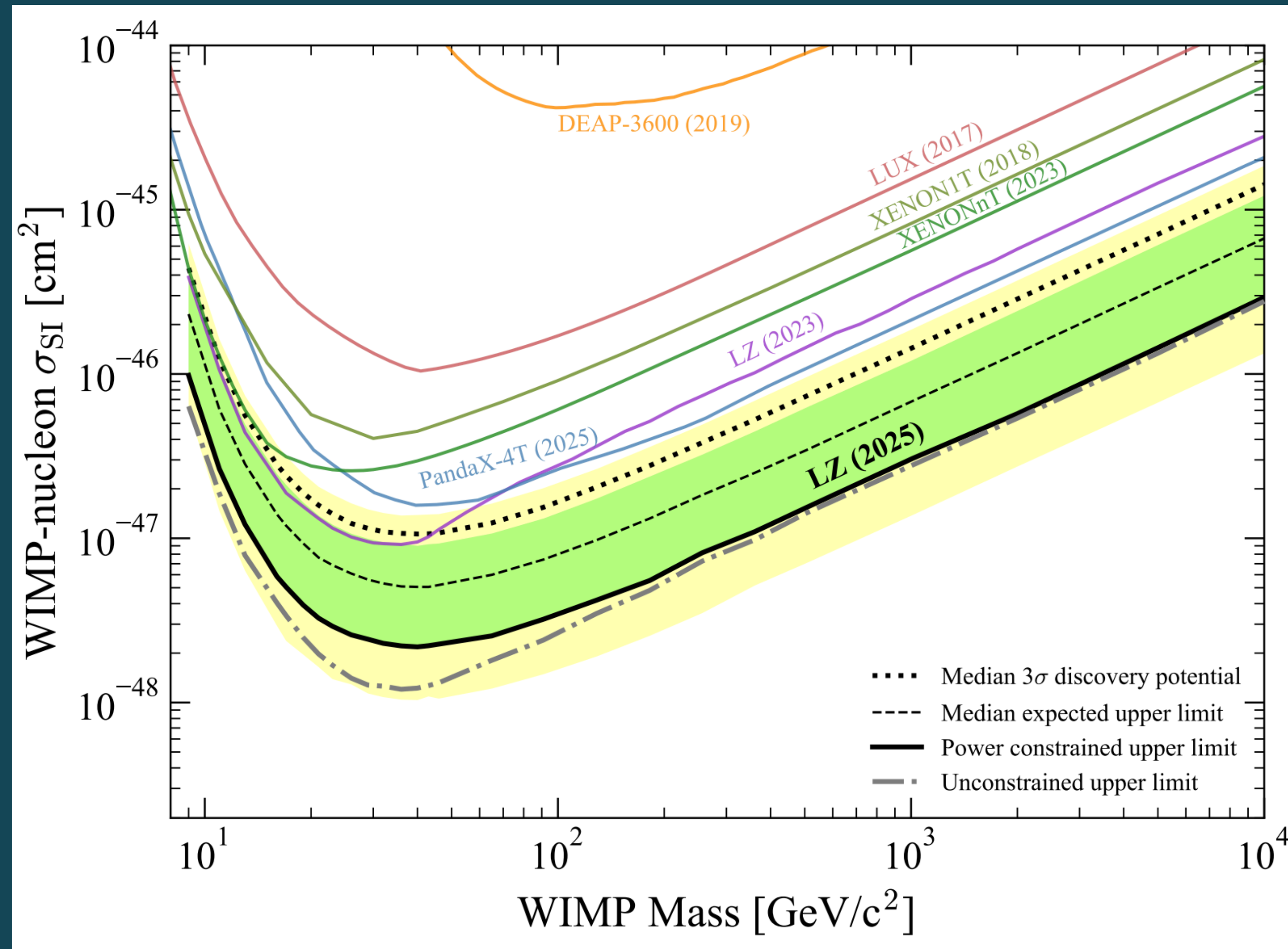
WS2024 FIT RESULTS

Component	Expected Events	Best Fit Events
^{214}Pb β decays	743 ± 88	733 ± 34
$^{85}\text{Kr} + ^{39}\text{Ar} + \text{detector } \gamma\text{s}$	162 ± 22	161 ± 21
Solar ν ERs	102 ± 6	102 ± 6
$^{212}\text{Pb} + ^{218}\text{Po}$ β decays	62.7 ± 7.5	63.7 ± 7.4
$^3\text{H} + ^{14}\text{C}$ β decays	58.3 ± 3.3	59.7 ± 3.3
^{136}Xe $2\nu\beta\beta$ decay	55.6 ± 8.3	55.9 ± 8.2
^{124}Xe DEC	19.4 ± 2.5	20.4 ± 2.4
$^{127}\text{Xe} + ^{125}\text{Xe}$ EC	3.2 ± 0.6	2.7 ± 0.6
Atm. ν CEvNS	0.12 ± 0.02	0.12 ± 0.02
$^8\text{B} + \text{hep } \nu$ CEvNS	0.06 ± 0.01	0.06 ± 0.01
Det. Neutrons		$0.0^{+0.2}$
Accidentals	2.8 ± 0.6	2.6 ± 0.6
Total	1210 ± 91	1202 ± 41



- Best fit of zero WIMPs at all masses tested ($9 \text{ GeV}/c^2 - 100 \text{ TeV}/c^2$)
- Good agreement with background-only hypothesis in all spaces examined

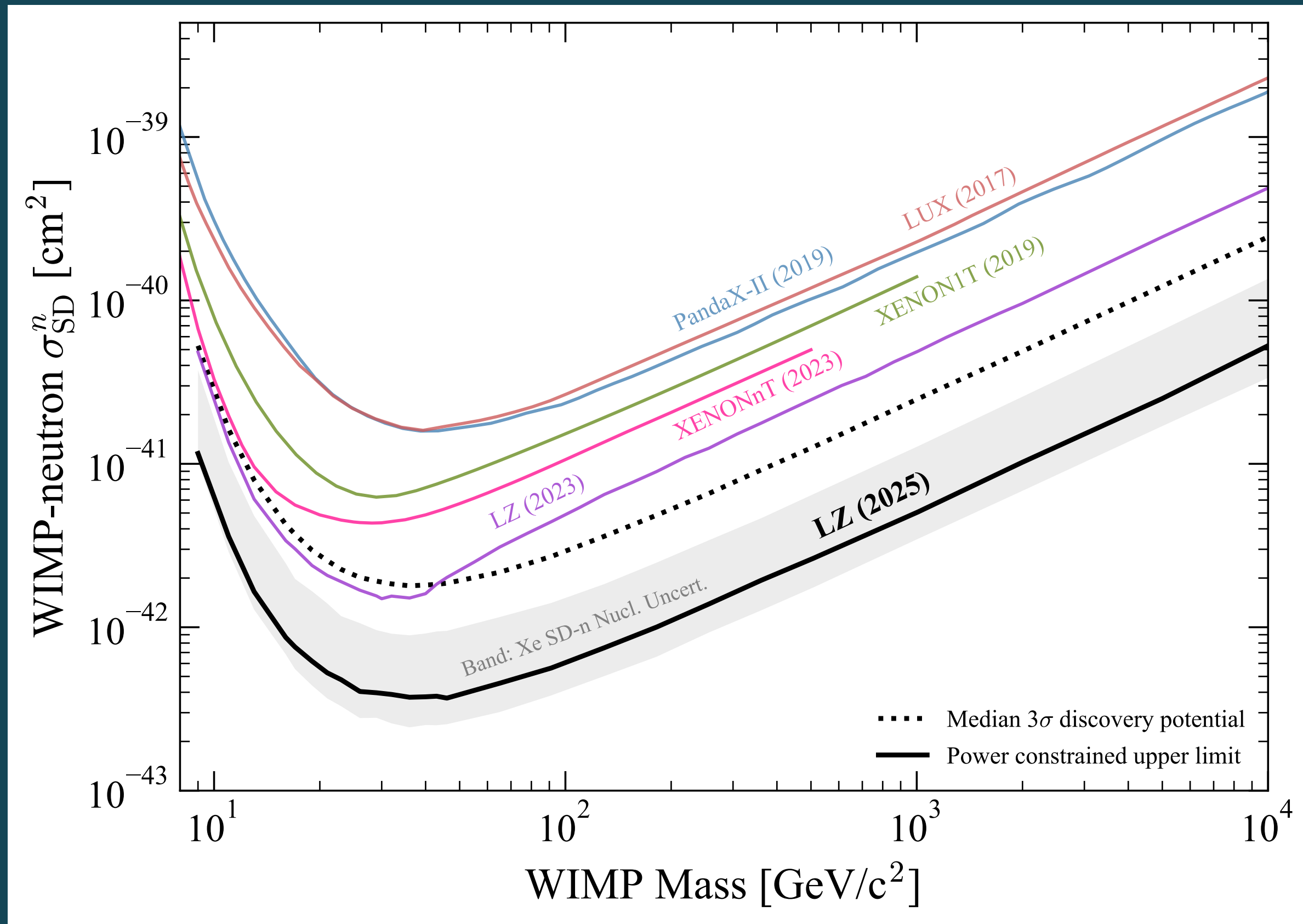
WS2024+WS2022 SPIN-INDEPENDENT LIMIT



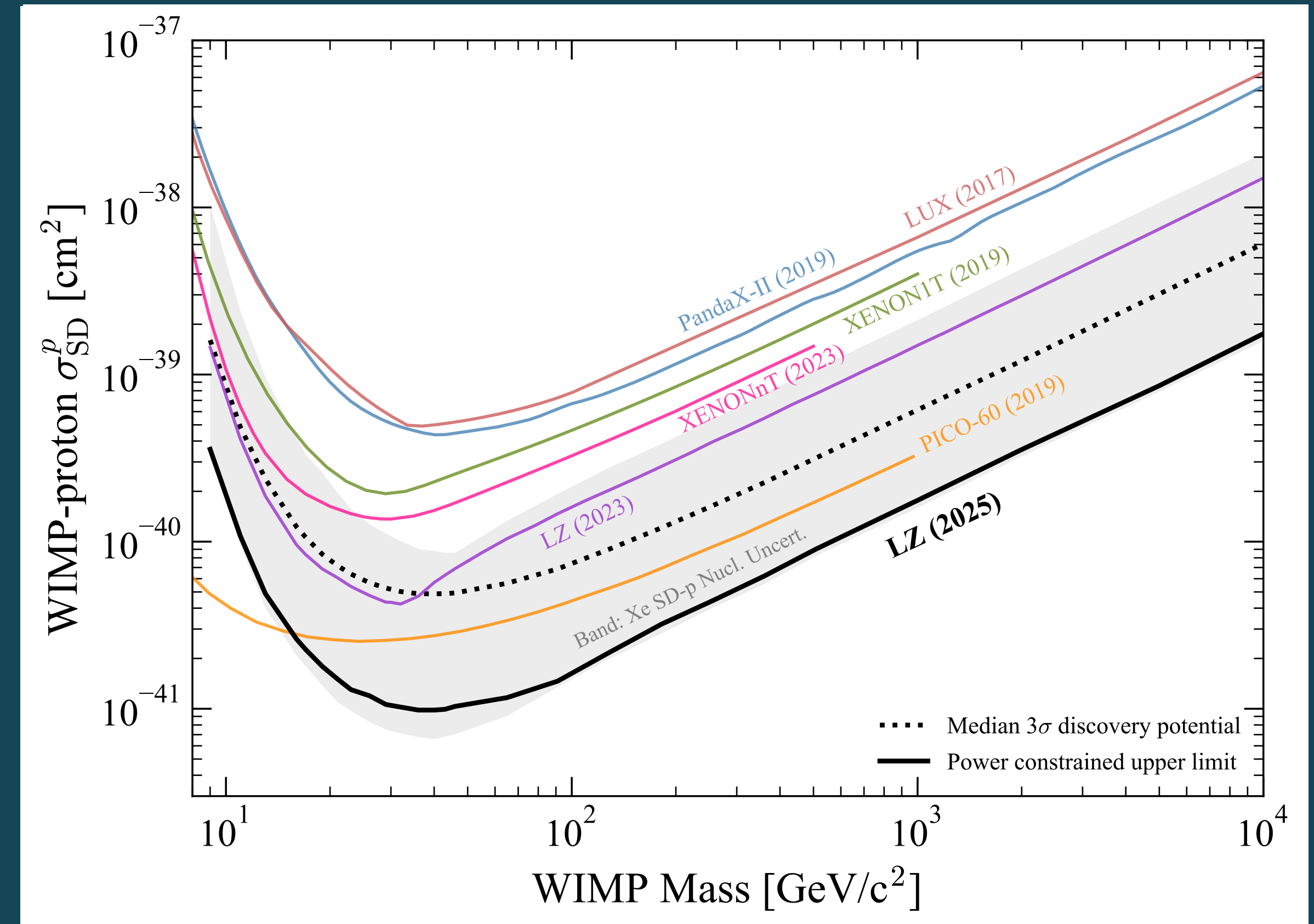
- Combining 60 days of WS2022 with 220 days of WS2024
- Two-sided profile likelihood ratio test statistic
- Power constrained at -1σ as per recommended conventions
[*EPJC* 81, 907 \(2021\)](#)
- Best limit from combined analysis of $\sigma_{\text{SI}} = 2.2 \times 10^{-48} \text{ cm}^2$ for $40 \text{ GeV}/c^2$
- **Results & analysis in paper**
[*PRL* 135, 011802 \(2025\)](#)

WS2024+WS2022 SPIN-DEPENDENT LIMITS

WIMP-Neutron Scattering



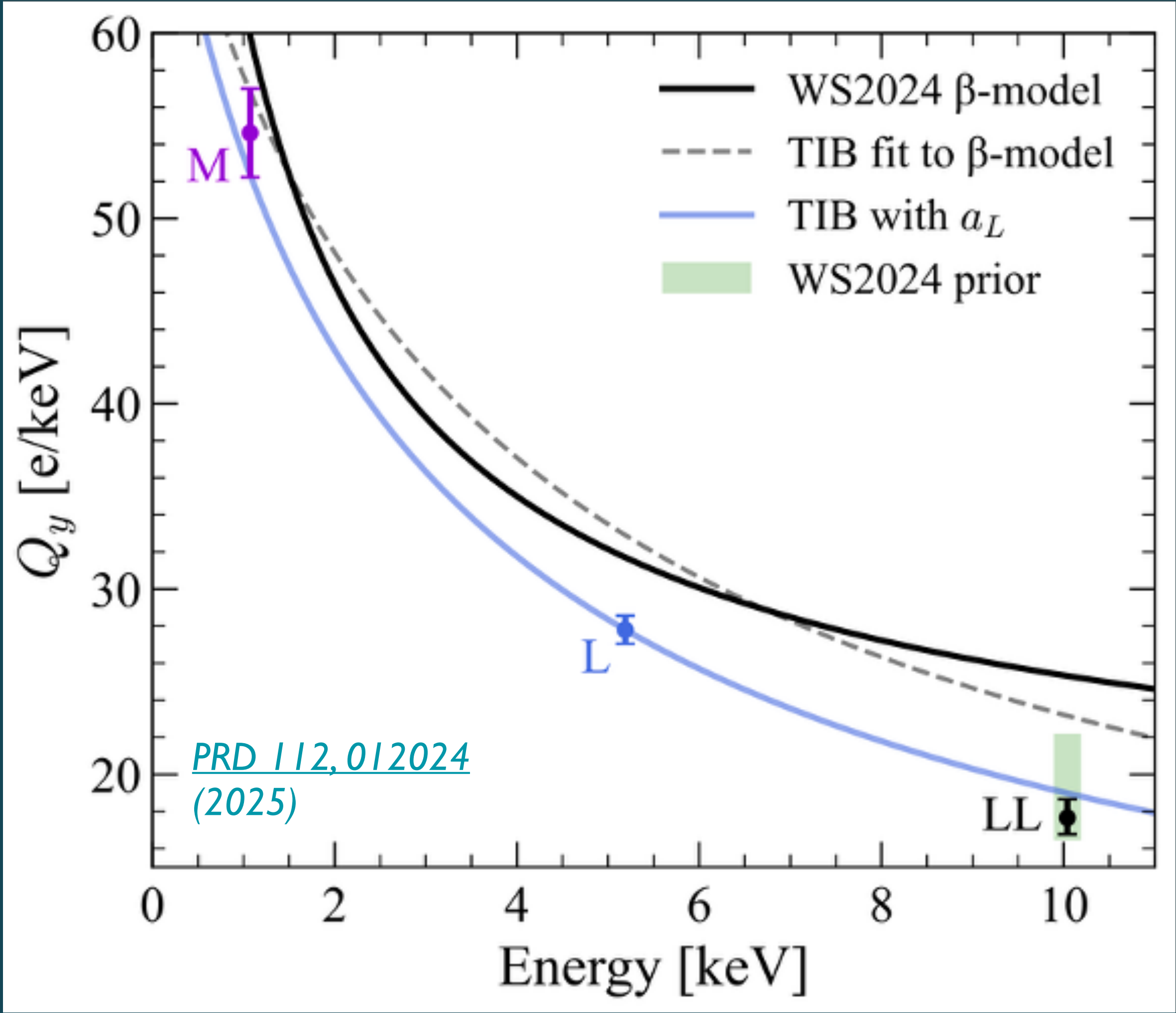
WIMP-Proton Scattering



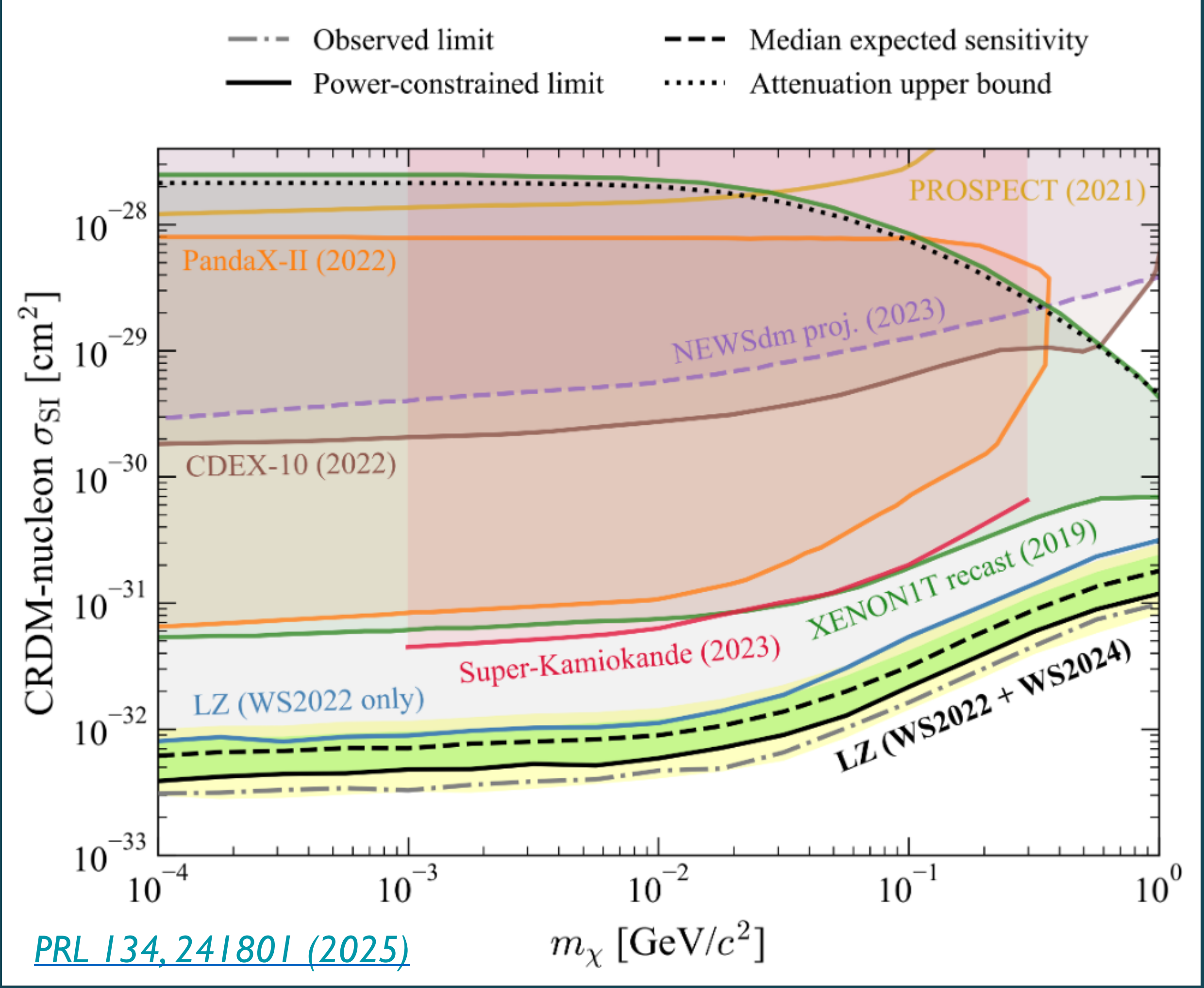
Uncertainty bands represent the theoretical uncertainty on the Xe nuclear structure factor

MORE RECENT PUBLICATIONS

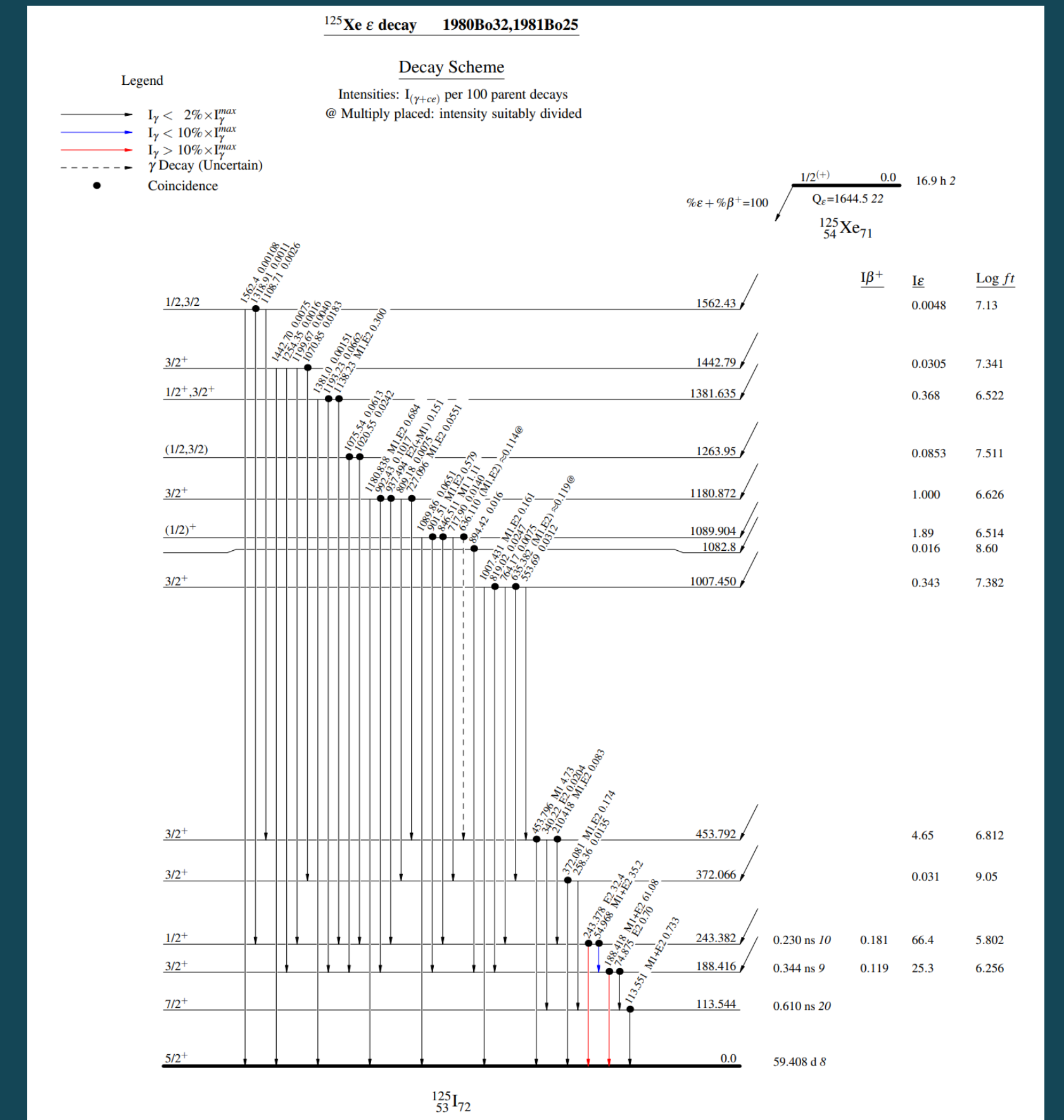
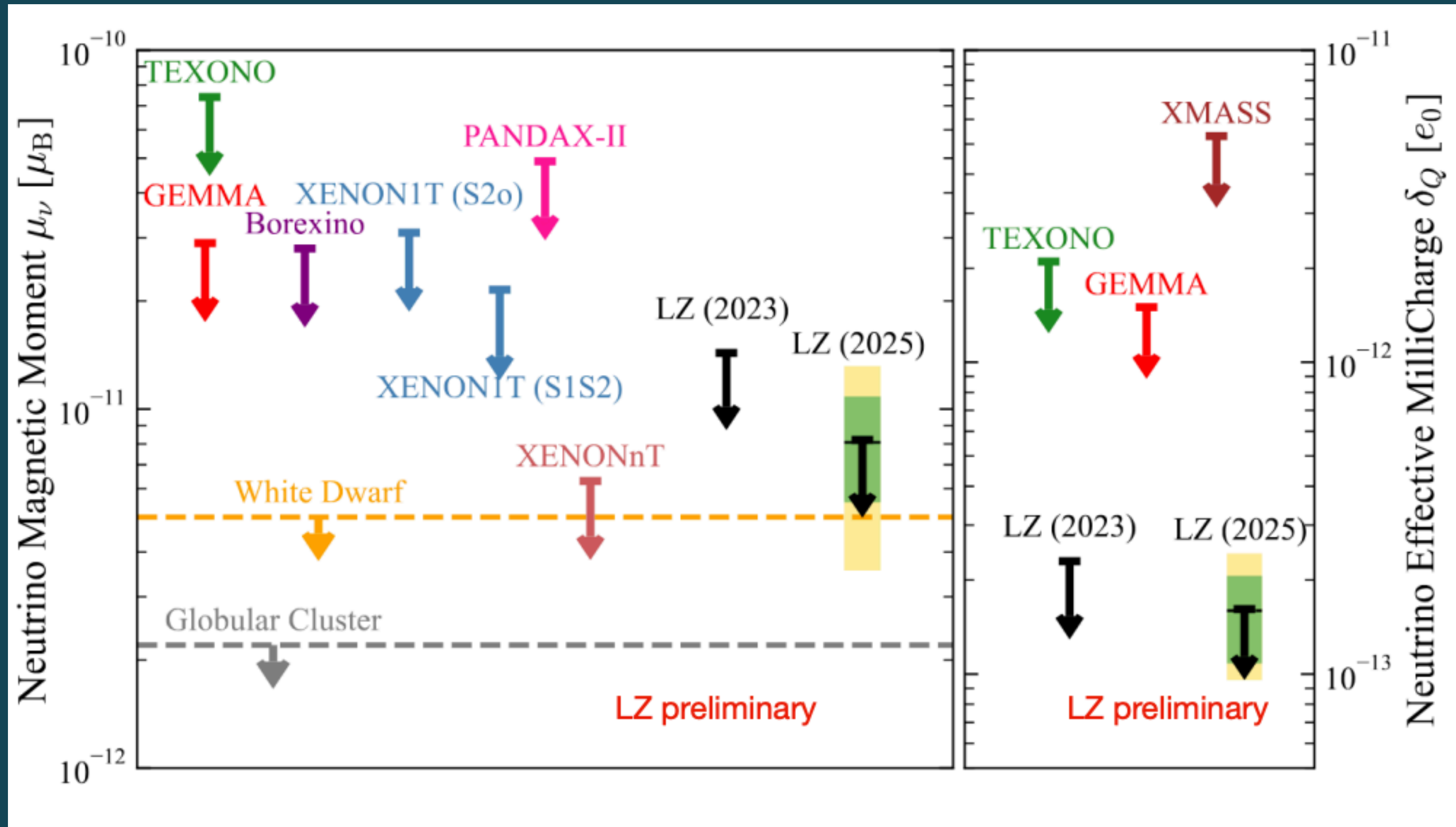
Measurements of Enhanced Recombination



Cosmic Ray-Boosted Dark Matter

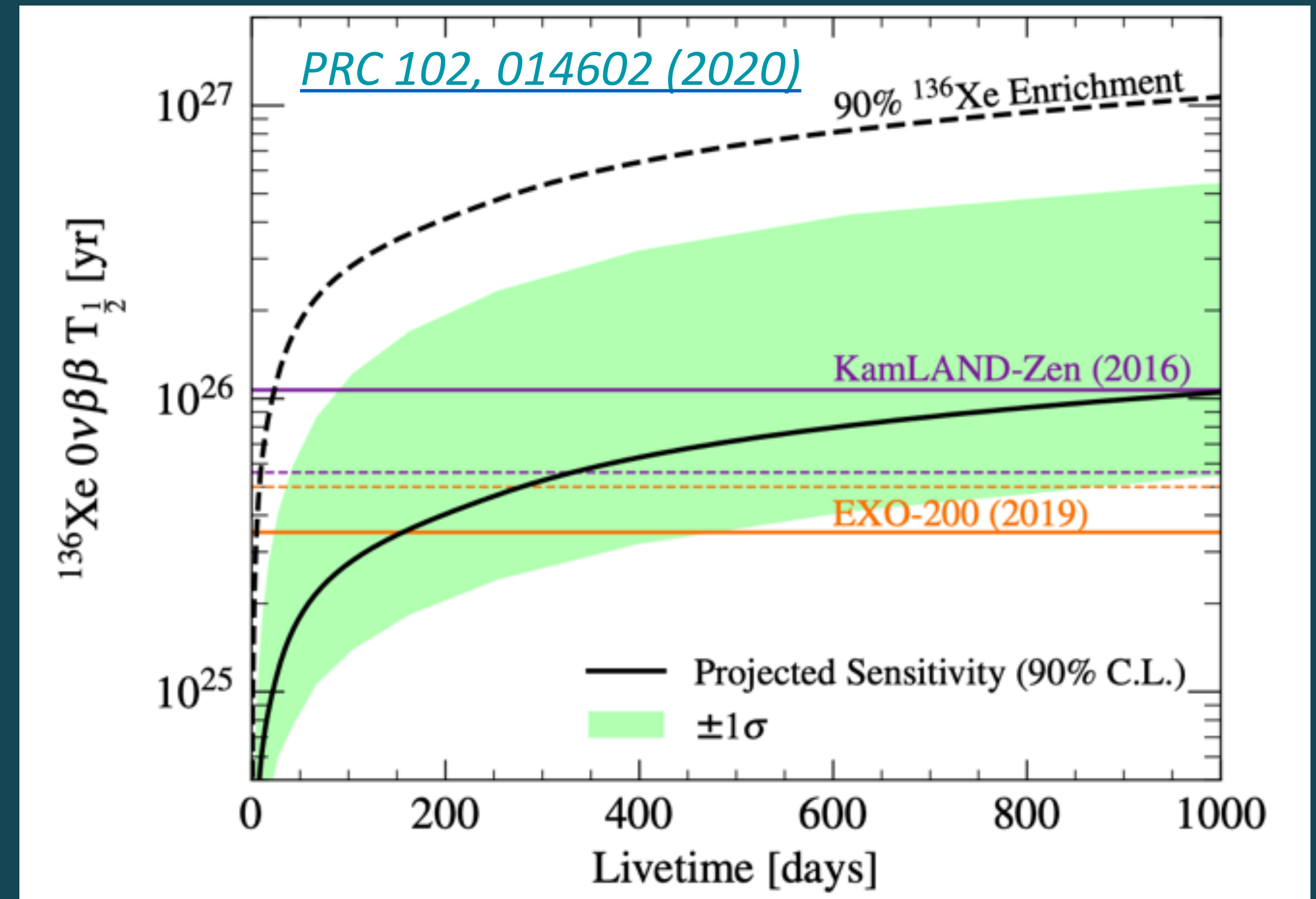
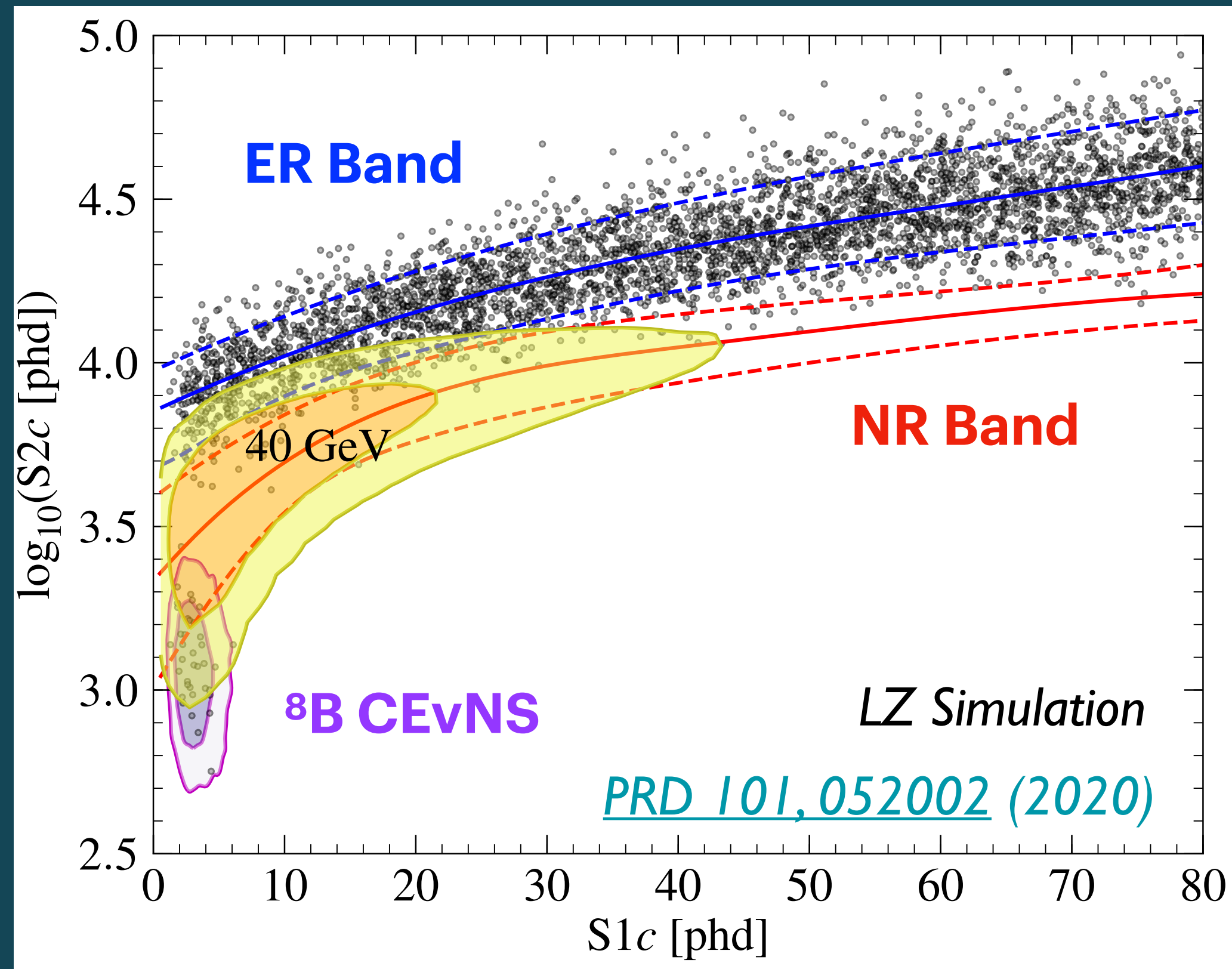


MORE ON LZ AT THIS CONFERENCE



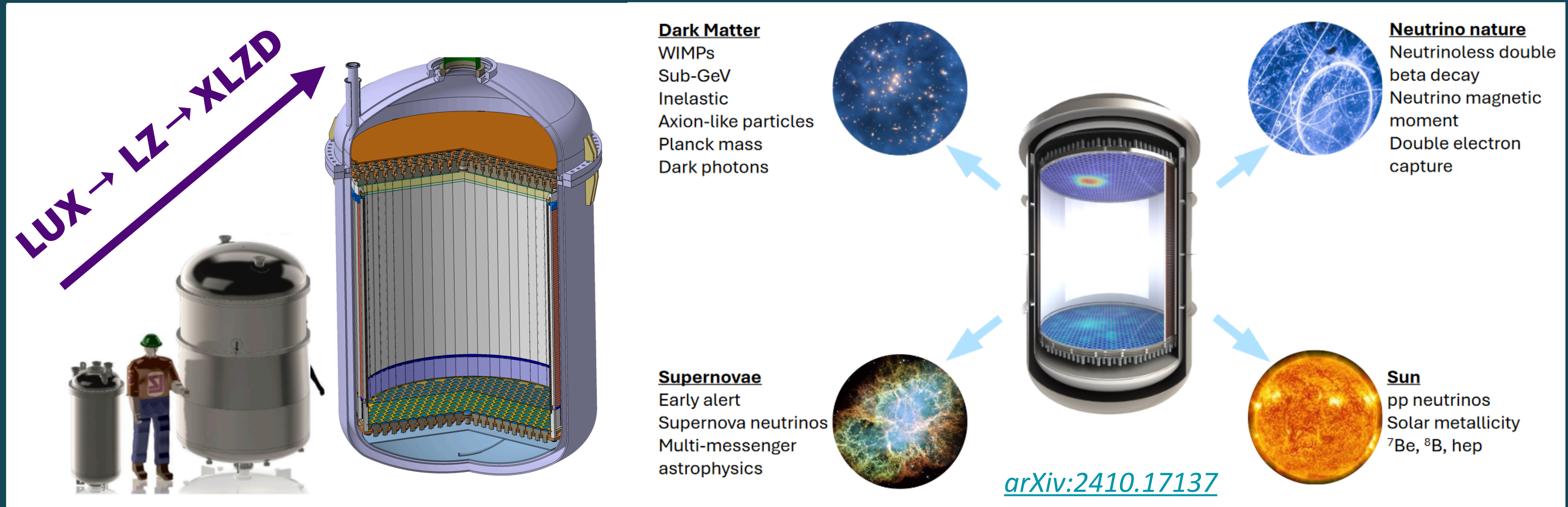
- [Talk from Yongheng Xu](#) on low energy recoil signals (Wed, 16:40) + [poster from Huan Zhang](#)
- [Talk from Miguel Hernandez](#) on ^{125}Xe positron emission decay observation (Thu, 15:20)

WHAT'S NEXT FOR LZ?



- LZ will continue flagship WIMP searches, but also show it is a multi-physics machine
- Observation of boron-8 solar neutrino CEvNS - first for natural neutrinos
- ^{136}Xe $0\nu\beta\beta$ decay search - demonstrate competitiveness of this technology

FURTHER INTO THE FUTURE - XLZD



- XLZD will use a 60-80 t xenon TPC (an order of magnitude bigger than current experiments)
- Merger of XENON, LZ, DARWIN → ~500 people in 72 institutions, 17 countries
- A rare-event observatory, more than just the “definitive” WIMP search experiment

CONCLUSIONS

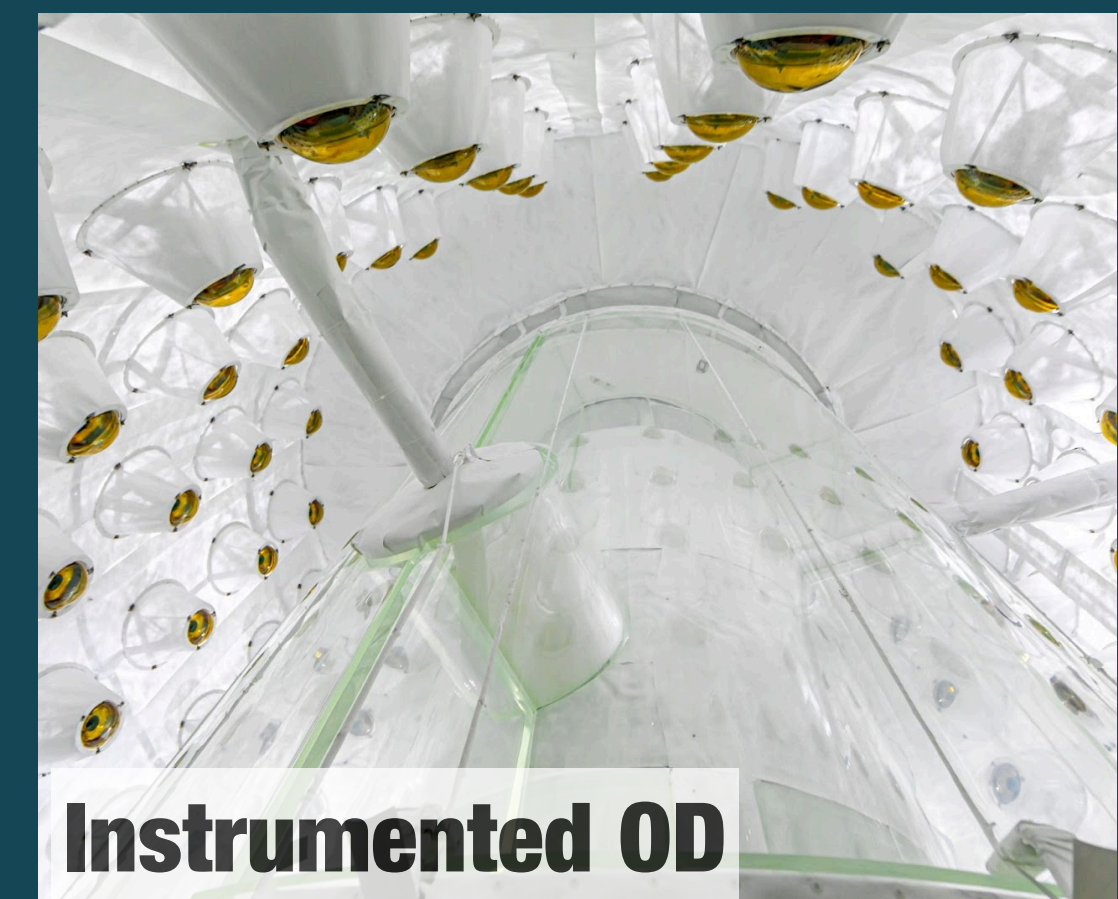
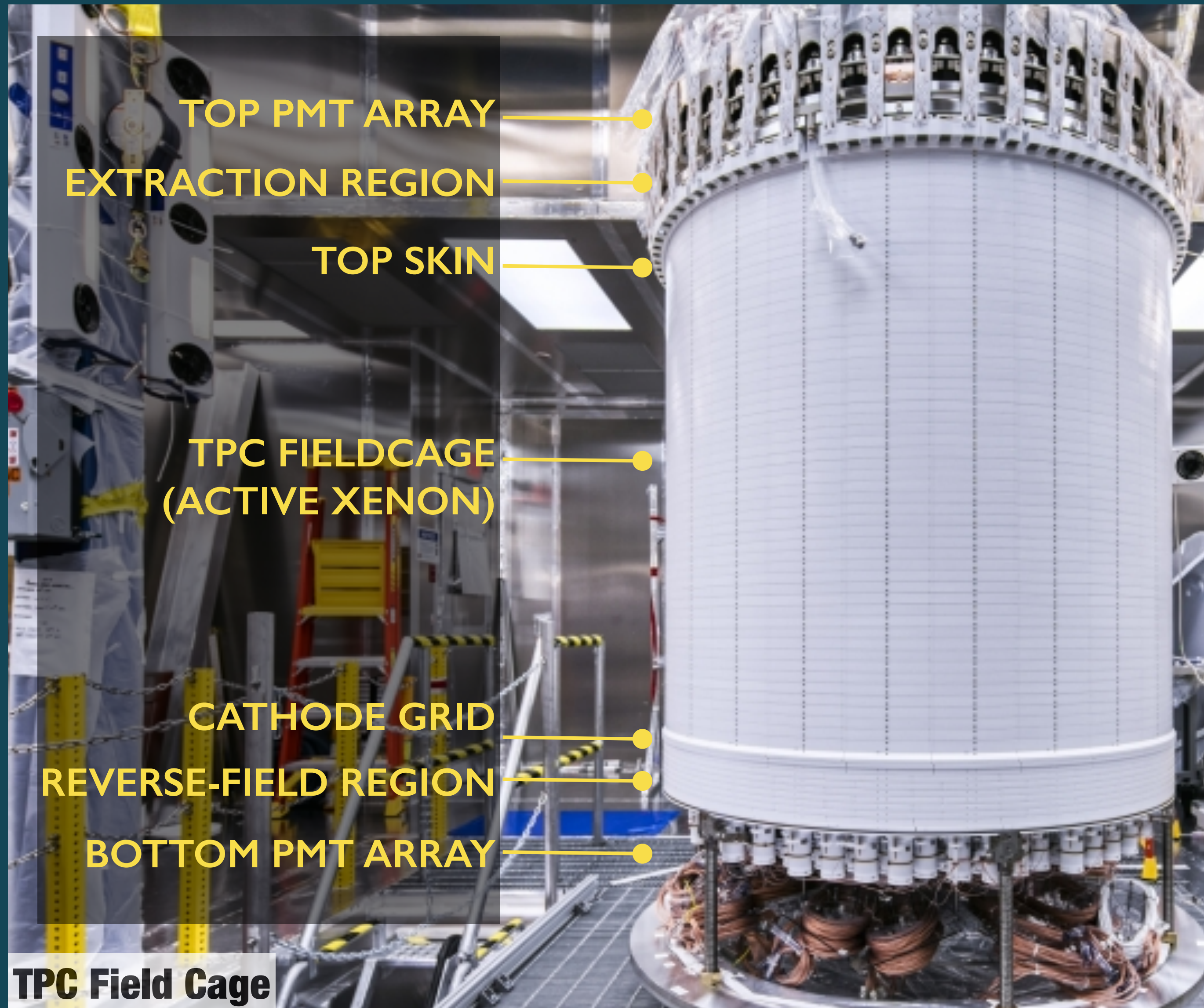
- New world-leading WIMP search limits exceeding previous best constraints by >4 times [[PRL 135, 011802 \(2025\)](#)]
- Radon tag developed and used for the first time:
60% reduction in main ER background
 - First observation of charge-suppressed ^{124}Xe DEC
- LZ will take data until 2028, towards 1000 live days
 - Multiple other physics channels to explore e.g. ^8B CEvNS, neutrinoless double beta decay
 - **LZ is discovery-ready for WIMPs**
- Planning and R&D underway for next-generation, XLZD



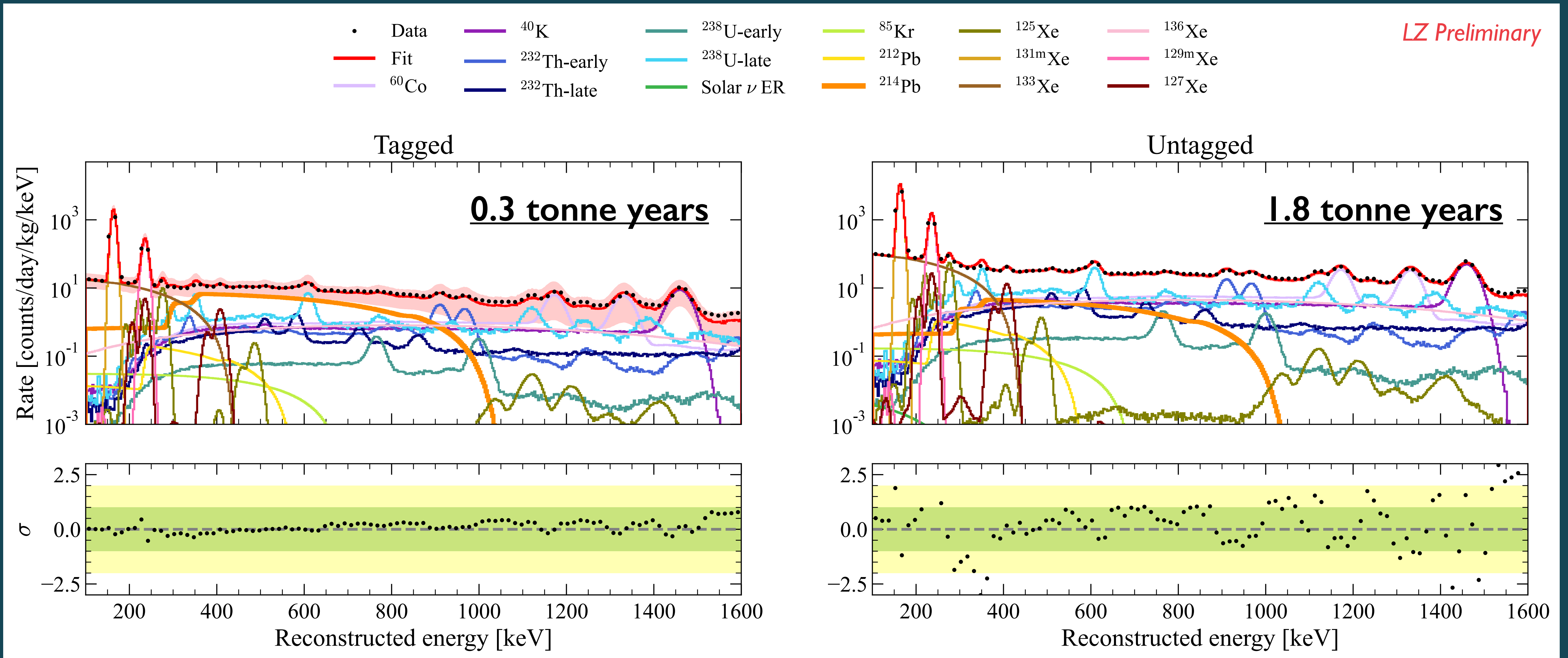
Back Up Slides



THE LZ EXPERIMENT



RADON TAGGED HIGH-ENERGY BACKGROUND FIT



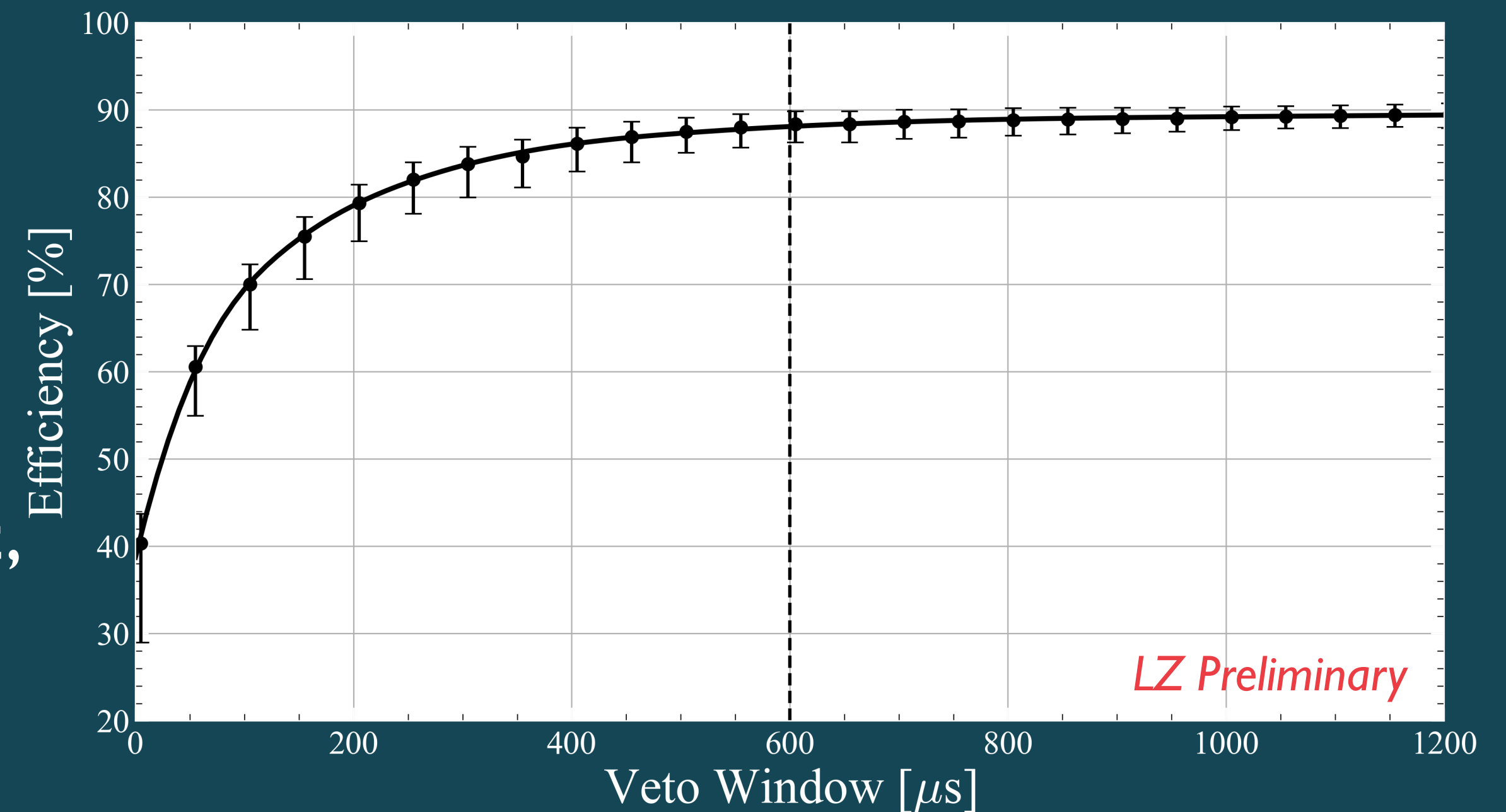
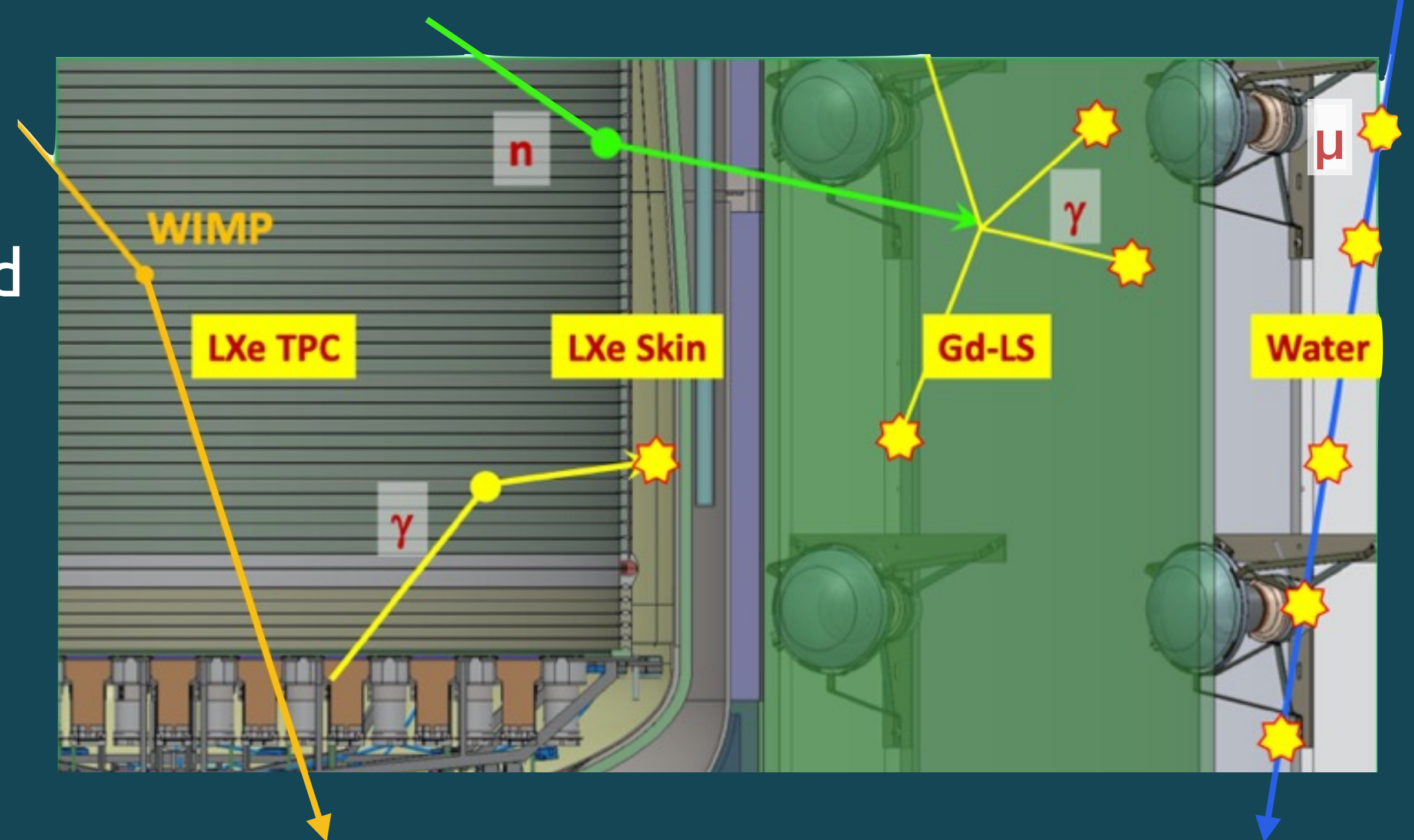
Effective untagged ^{214}Pb activity of $1.8 \pm 0.3 \mu\text{Bq/kg}$ (compared to $3.9 \pm 0.6 \mu\text{Bq/kg}$ in total exposure)

NEUTRONS & OD

- Neutrons induce NRs → dangerous background
- 17 tonnes Gd-loaded scintillator in OD
 - High thermal neutron capture cross-section
 - Release of ~ 8 MeV gammas from capture

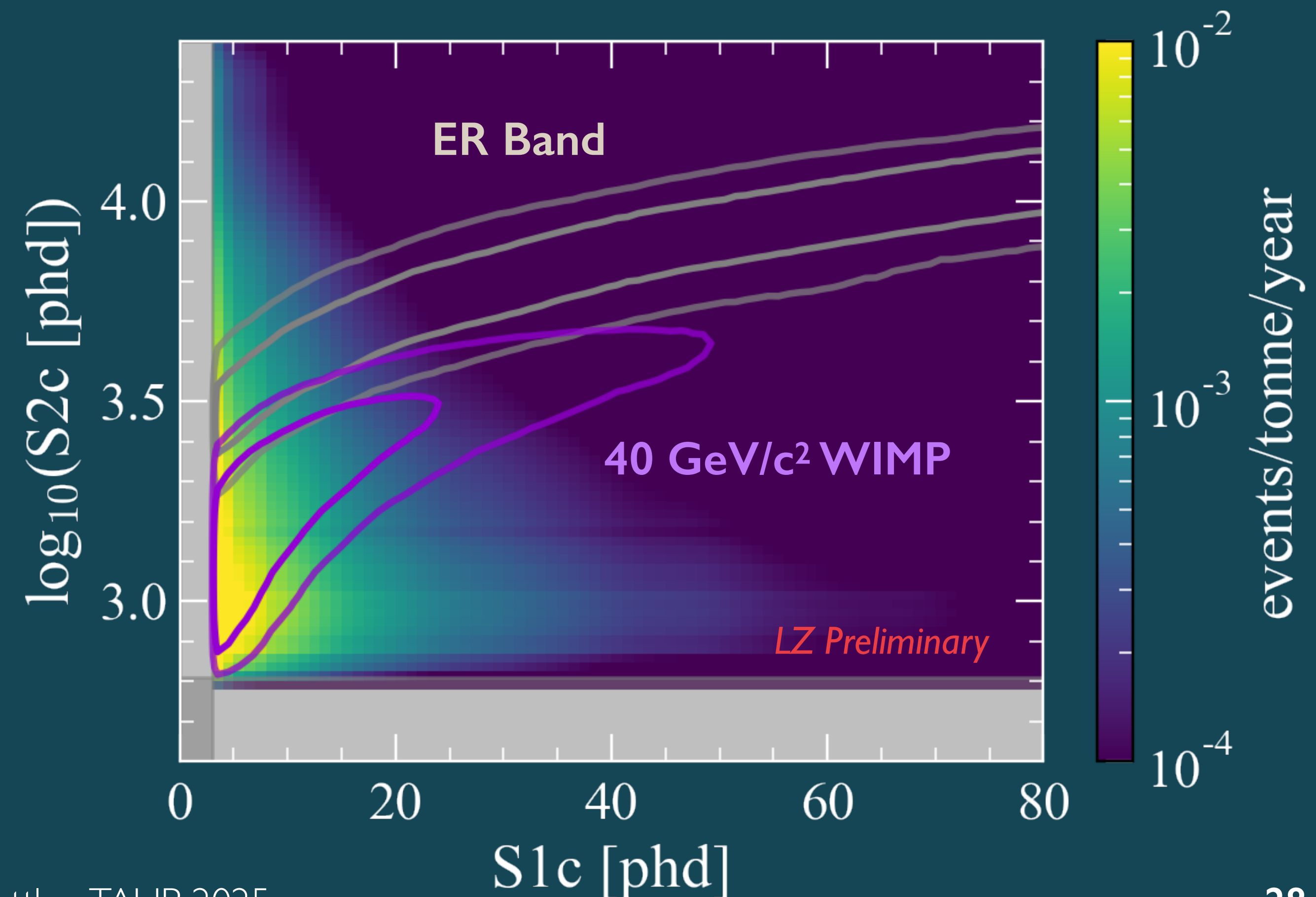
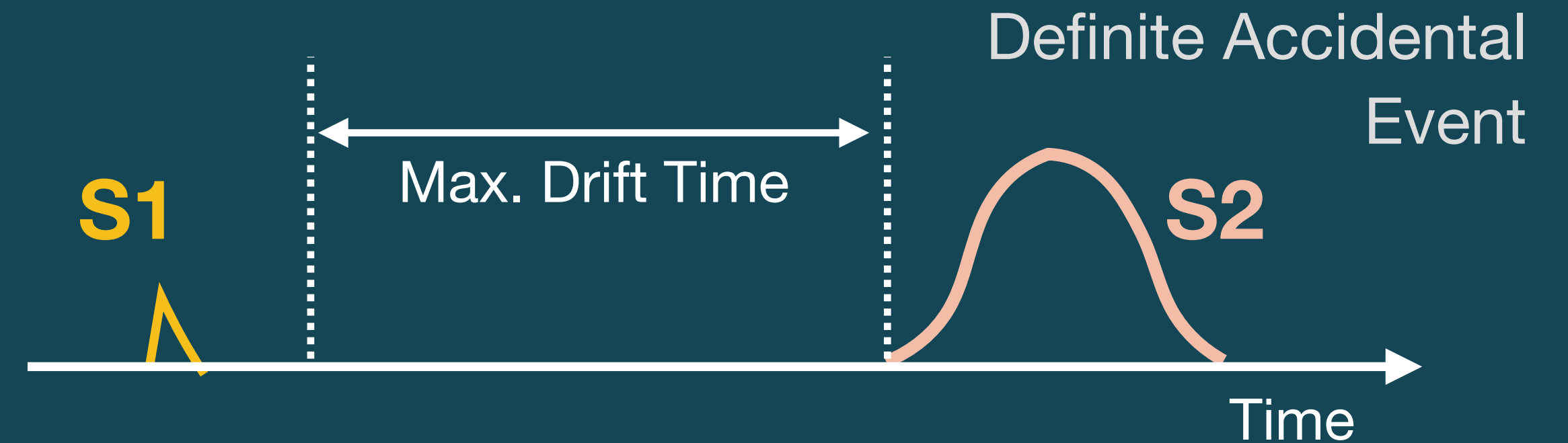
→ delayed OD veto cut to reject neutrons

- AmLi neutron calibration-derived neutron veto efficiency = 89 ± 3 %
- Simulated neutron veto efficiency for radiogenic, background neutrons = 92 ± 4 %
 - used for neutron constraint in final analysis

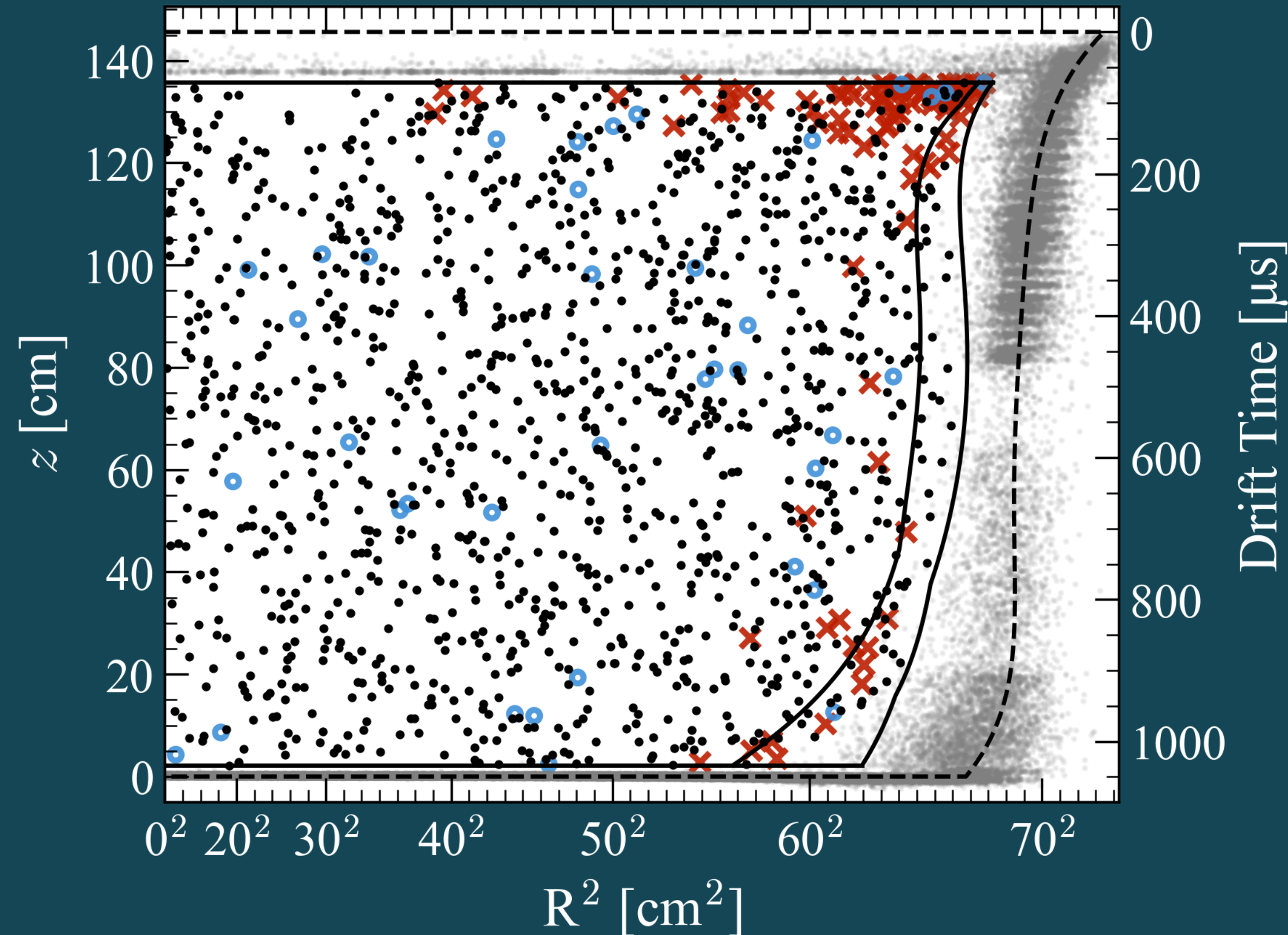


ACCIDENTAL COINCIDENCES

- Unrelated S1s & S2s can accidentally combine to produce single scatter events
→ could mimic a WIMP signal
- Rate: population of definite accidental events with unphysical drift time > 1 ms
- Distribution: fake events constructed from lone S1 & S2 pulse waveforms
- Analysis cuts developed to combat observed pulse/event pathologies
 - $>99.5\%$ rejection efficiency
 - WS2024 counts: 2.8 ± 0.6



FIDUCIAL VOLUME (FV)



Events prompt-tagged by vetoes

Events delayed-tagged by the vetoes

- FV defined to avoid higher background rates at TPC edges (self-shielding)
- TPC radial edge curved due to electric field
- FV definition:
 - $71 \mu\text{s} < \text{drift time} < 1030 \mu\text{s}$
 - Azimuthally & drift time-dependent radial cut chosen to ensure <0.01 wall background counts in the FV
- Calculated fiducial mass of $5.5 \pm 0.2 \text{ t}$

COMBINED LIKELIHOOD

Exposures in Each Sample in Tonne Years

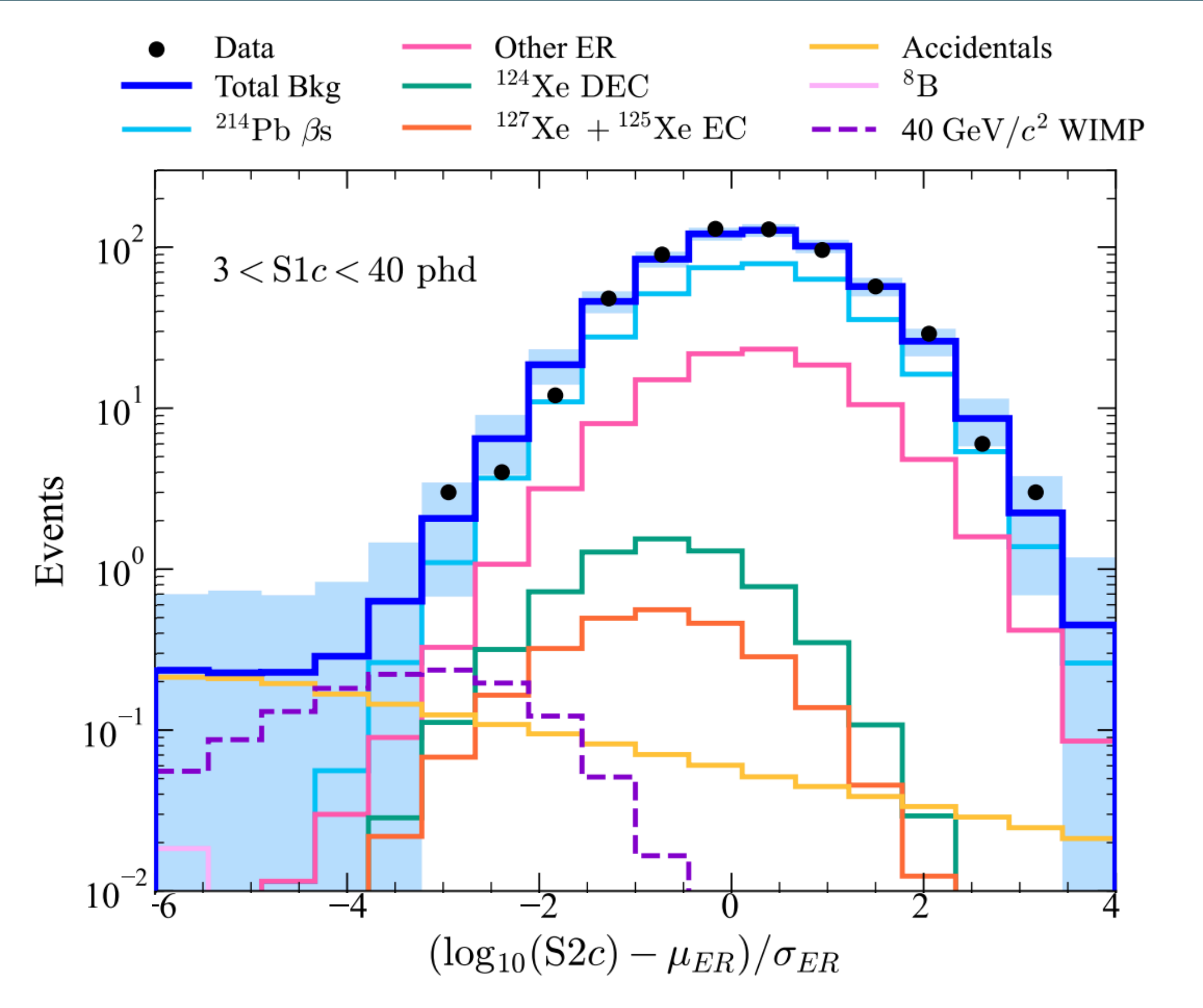
1	2	3	4	5	6
High-Mixing State	Radon Tag Inactive	Radon Tagged	Radon Untagged	Skin/OD Vetoed	WS2022
0.6	0.6	0.3	1.8	n/a	0.9

Six samples combined in likelihood for final statistical analysis

- WS2024 represented by samples 1-4
- Skin/OD vetoed sample (5) - full 3.3 tonne years of WS2024, but failing veto coincidence cuts → provide a direct constraint on the neutron background rate
- WS2022 sample (6) unmodified since first result → push sensitivity further

WS2024 FIT RESULTS

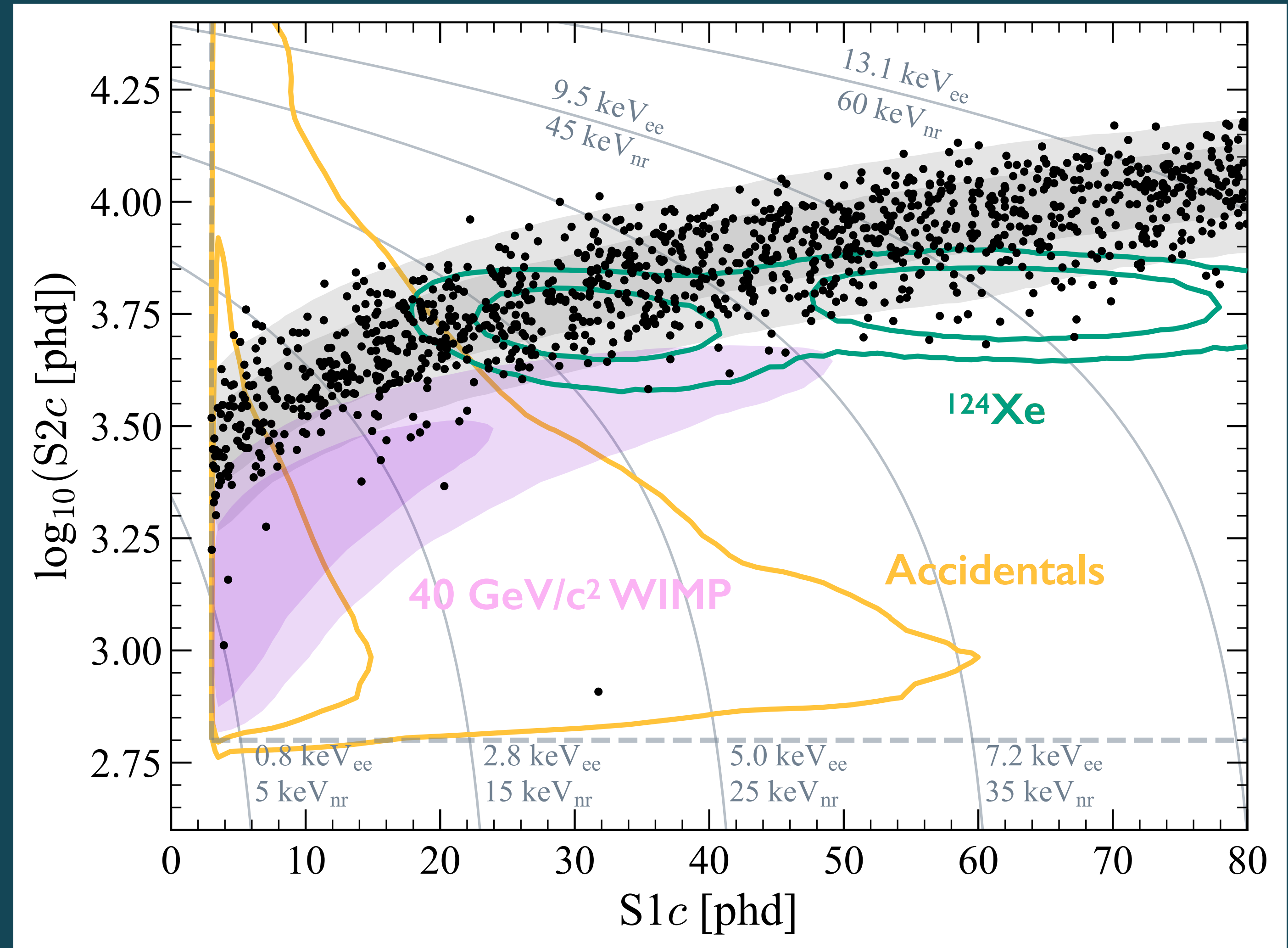
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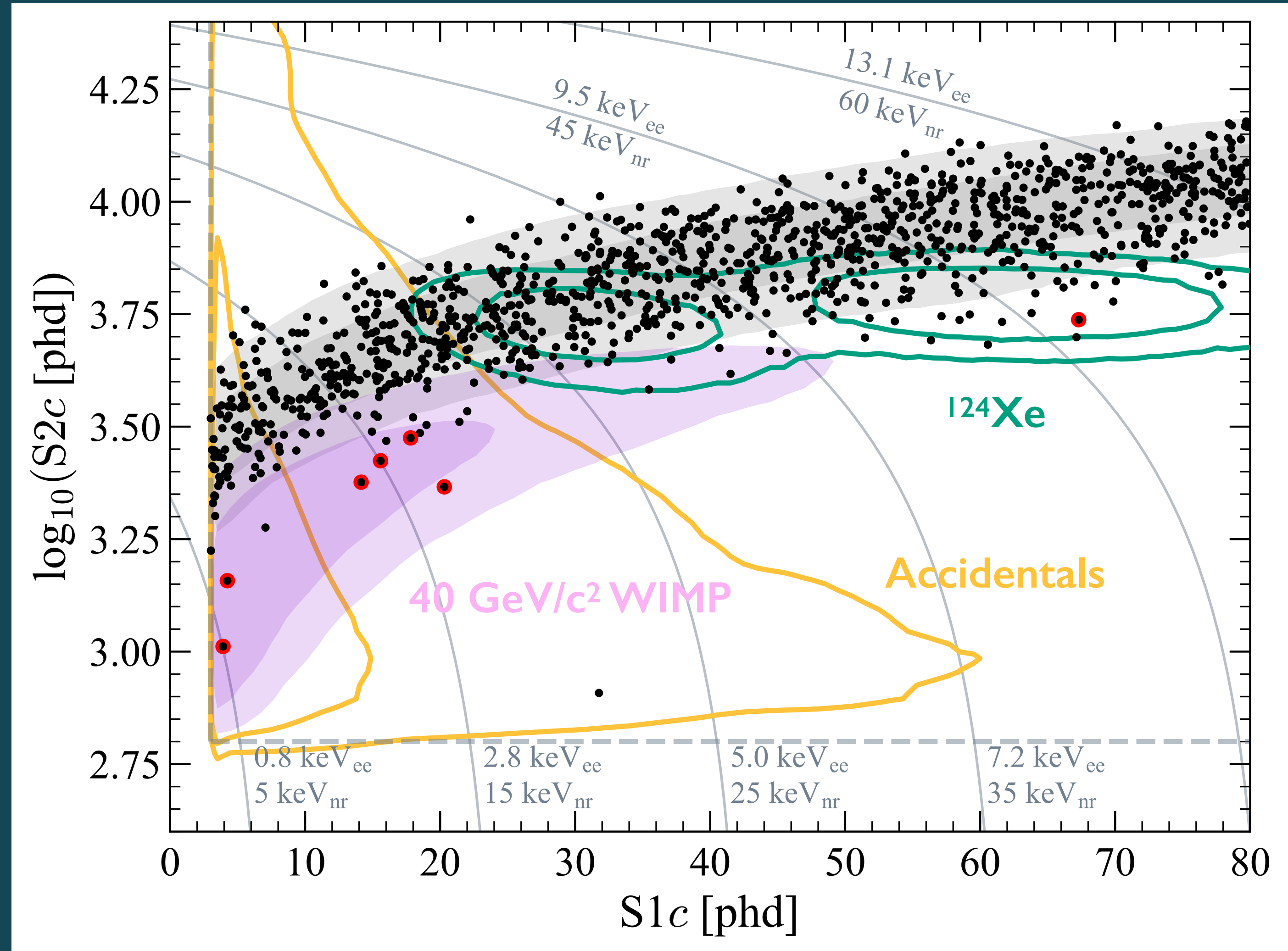
WS2024 DATA - SALTED

- Final exposure of
220 live days * 5.5 tonnes
= **3.3 tonne years**
- **1227 events** remaining

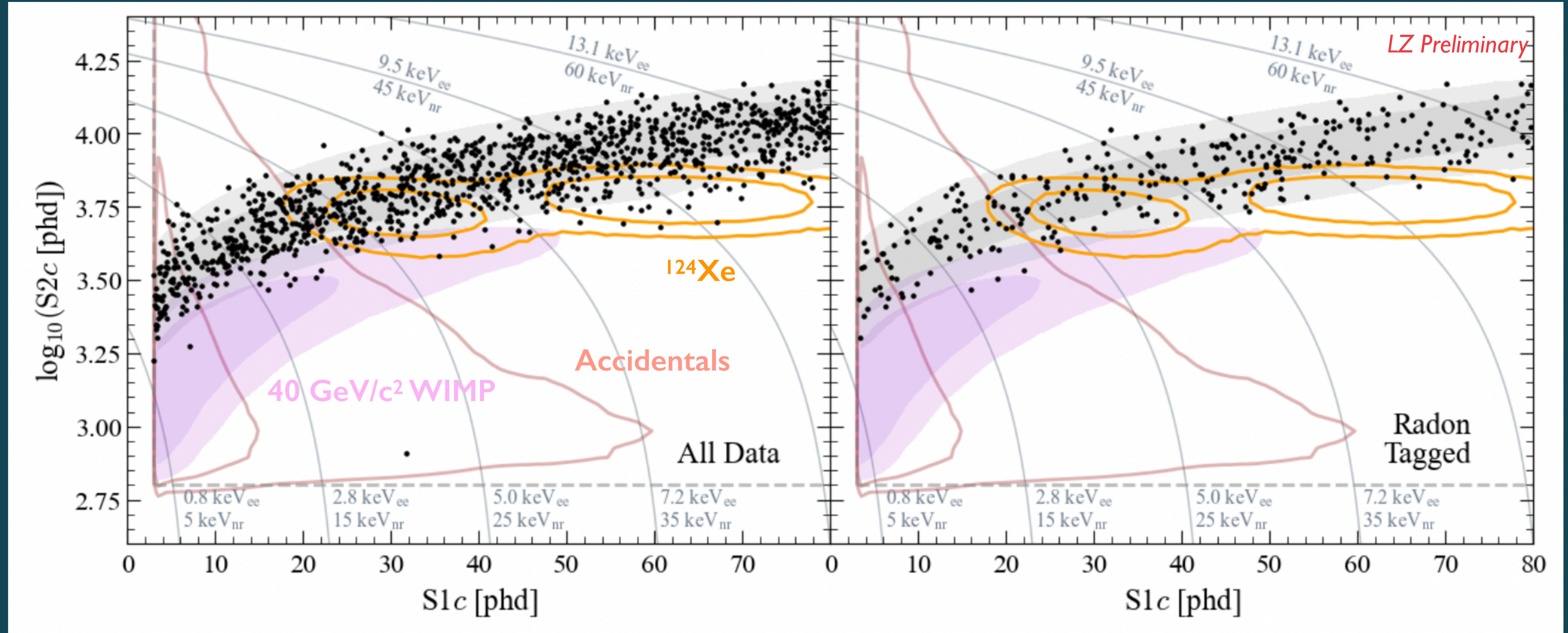


WS2024 DATA - SALTED

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→ inline with evaluated signal efficiency



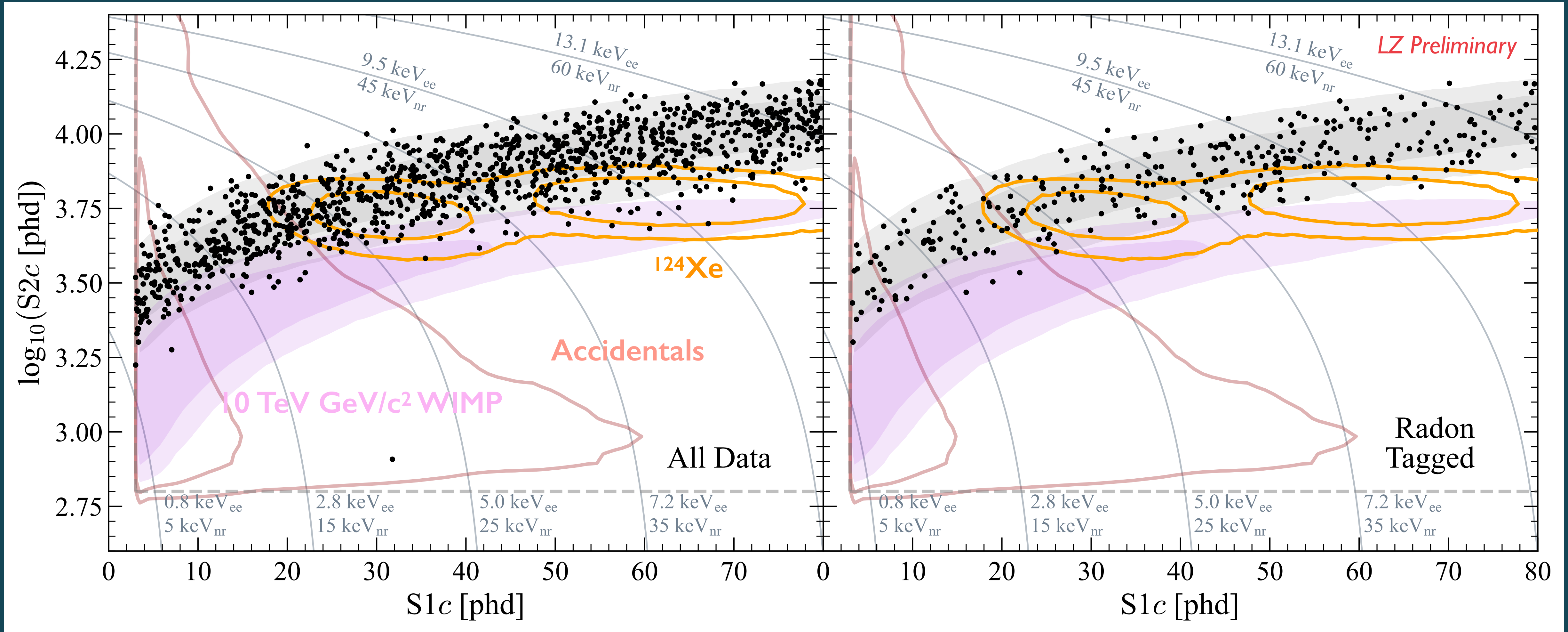
WS2024 DATA - UNSALTED; RADON TAGGED



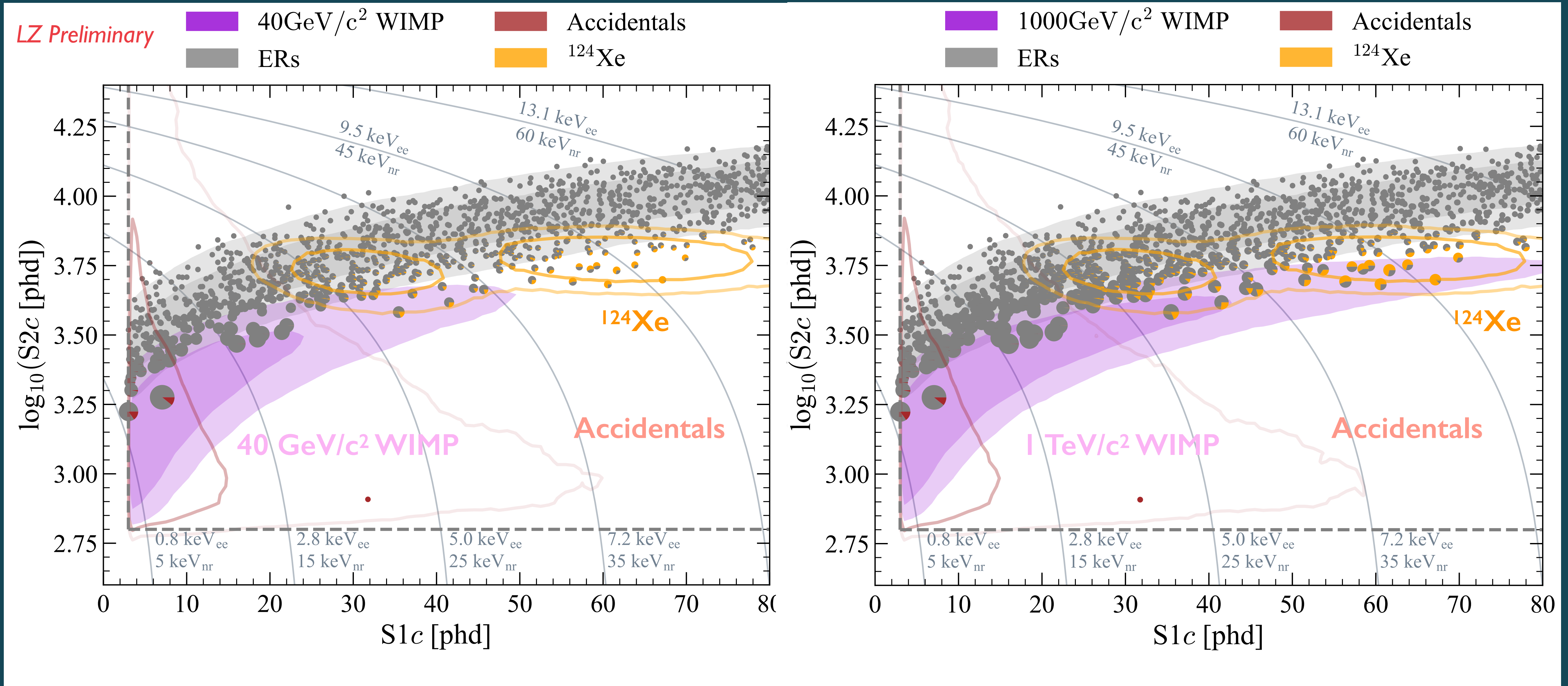
3.3 tonne years

0.3 tonne years

10 TEV/C² WIMP



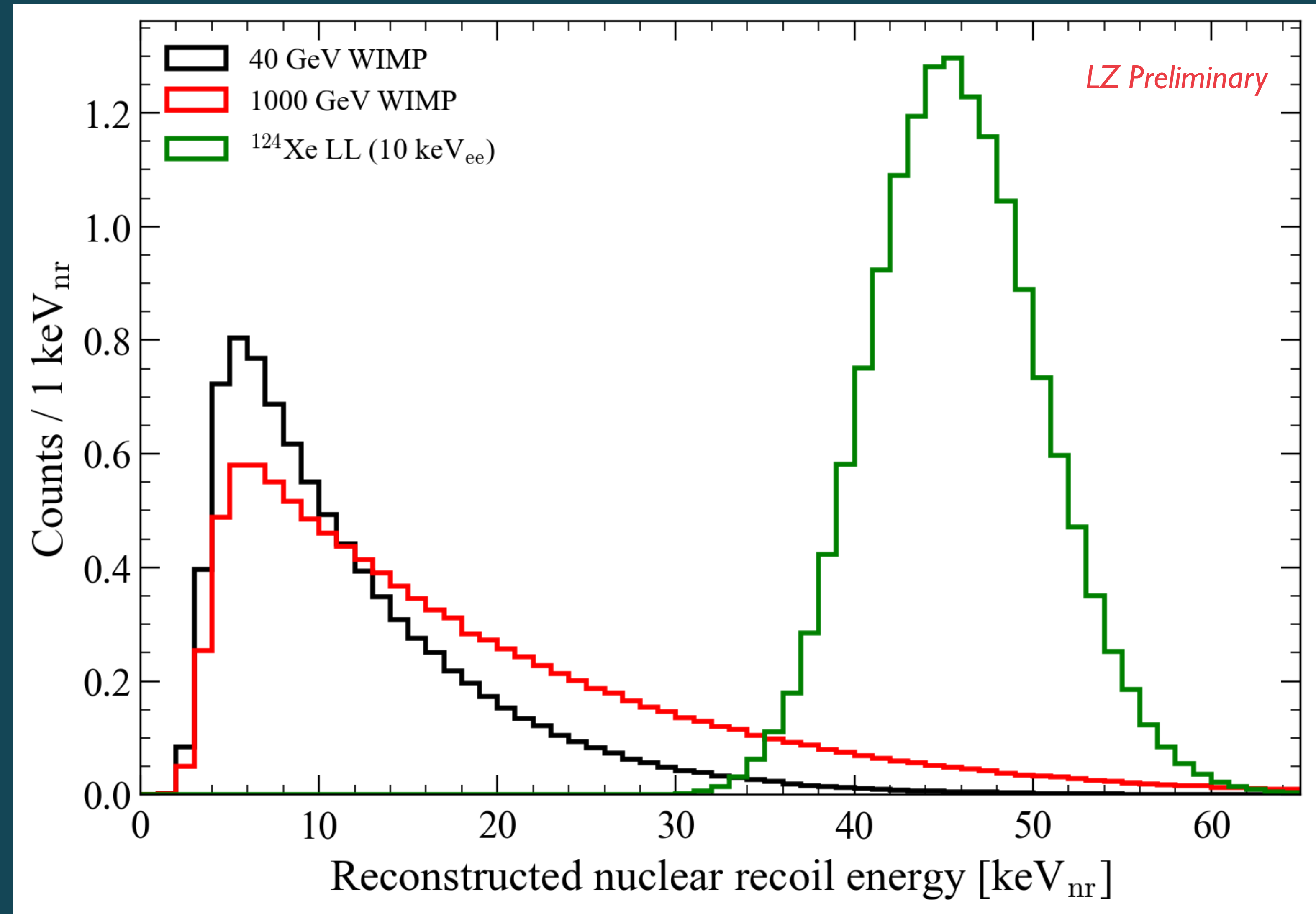
WS2024 DATA PIE PLOT



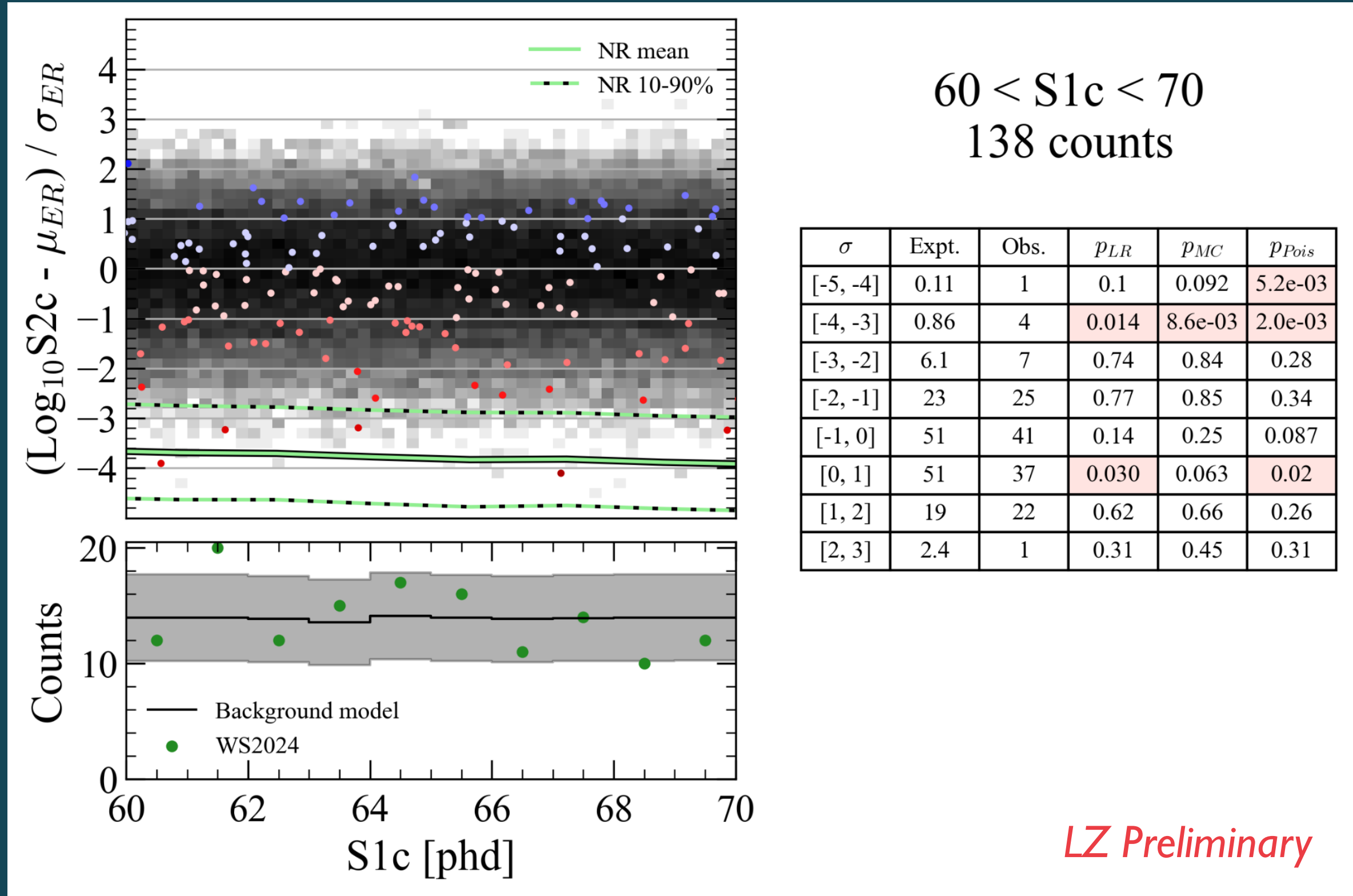
^{124}Xe LL-SHELL COMPARED TO DARK MATTER SPECTRA

WIMP spectra normalised to LZ's 4.2 tonne year median 3σ discovery potential:

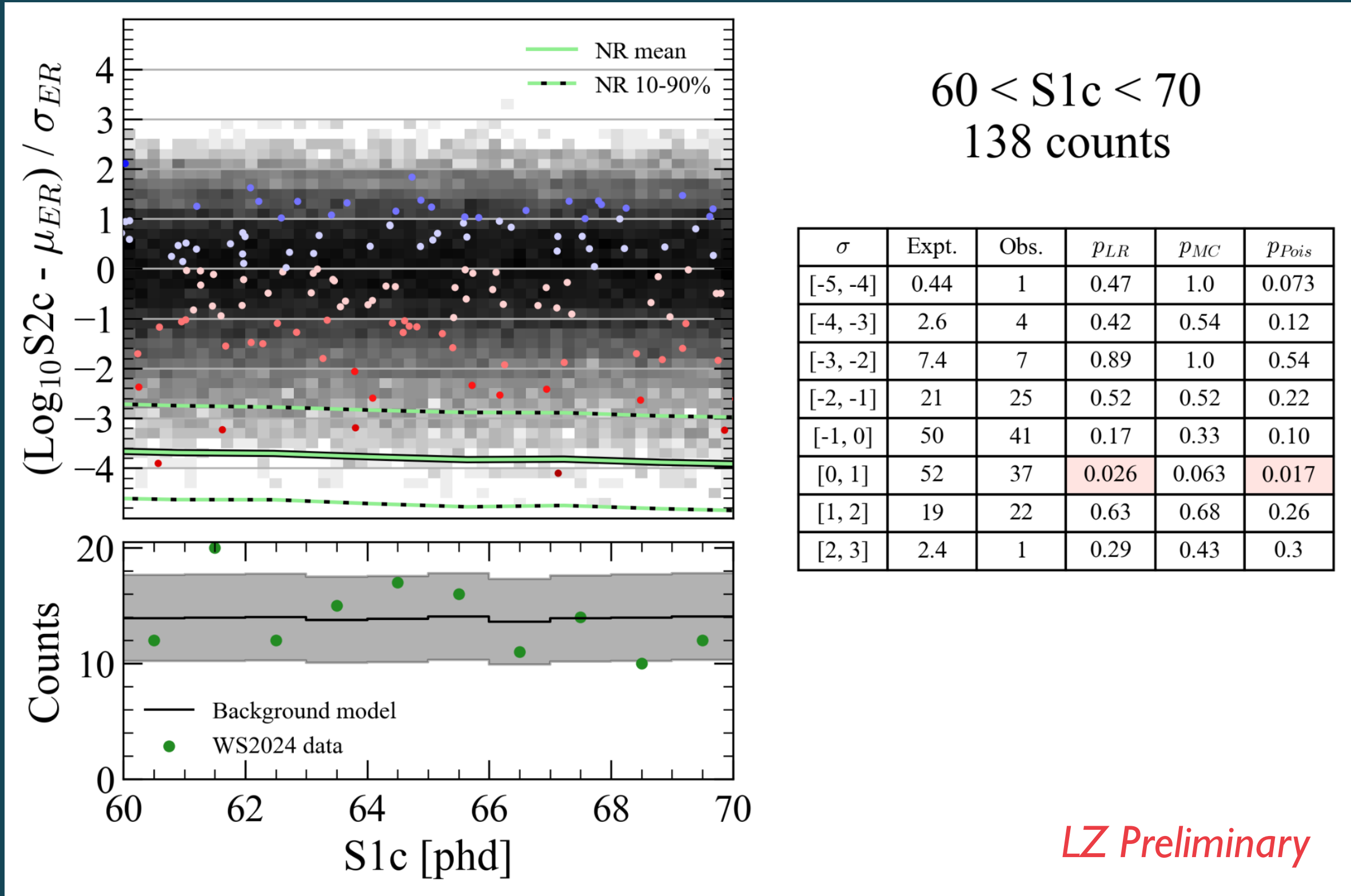
- 9 events @ 40 GeV
- 11 events @ 1000 GeV



GOODNESS OF FITS IN KEY ^{124}Xe REGION



$Q_{LL}/Q_{\beta} = 0.87$
(i.e. L-shell suppression)

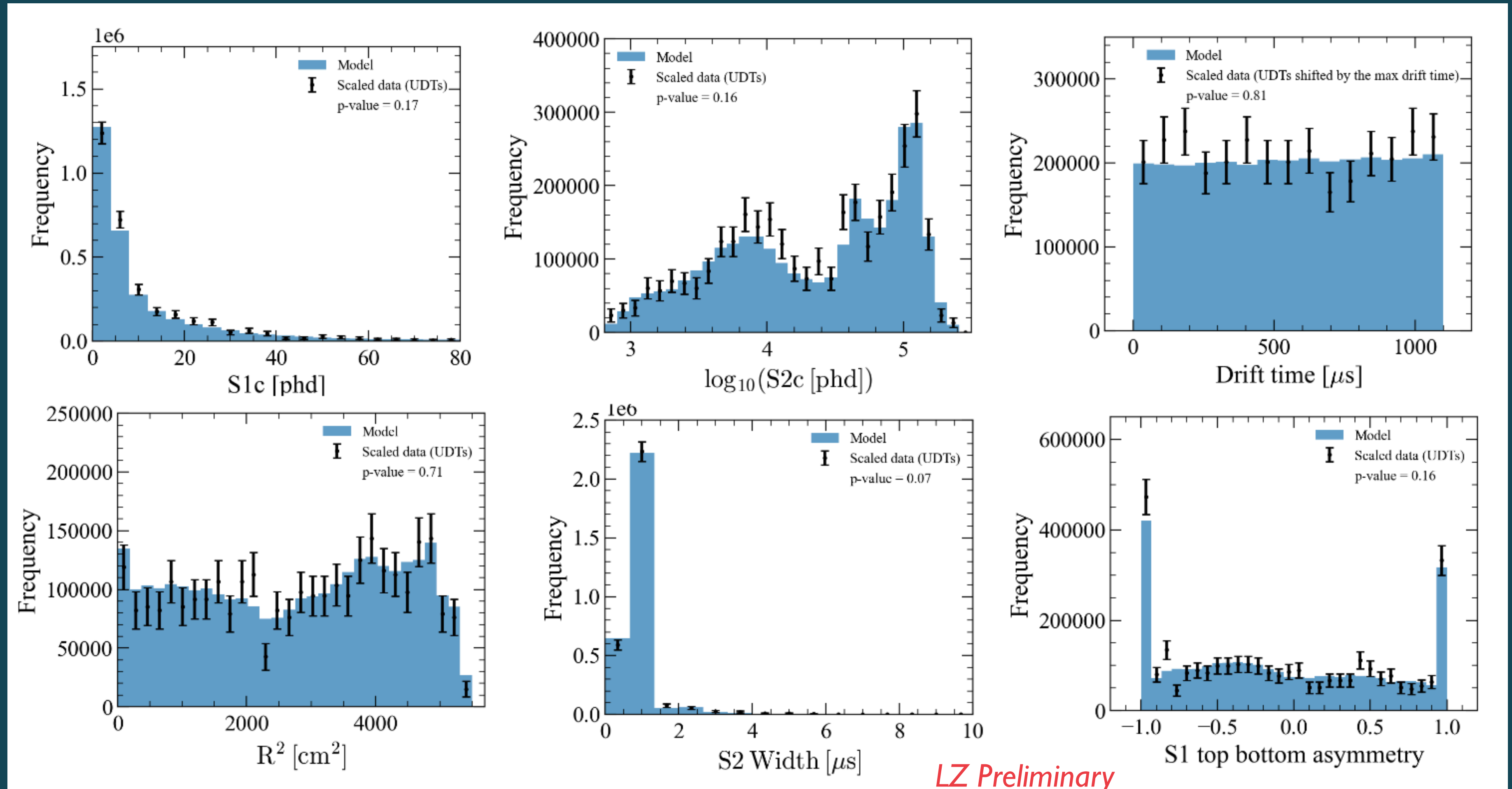


$Q_{LL}/Q_{\beta} = 0.65$
(i.e. double L-shell ionisation density)

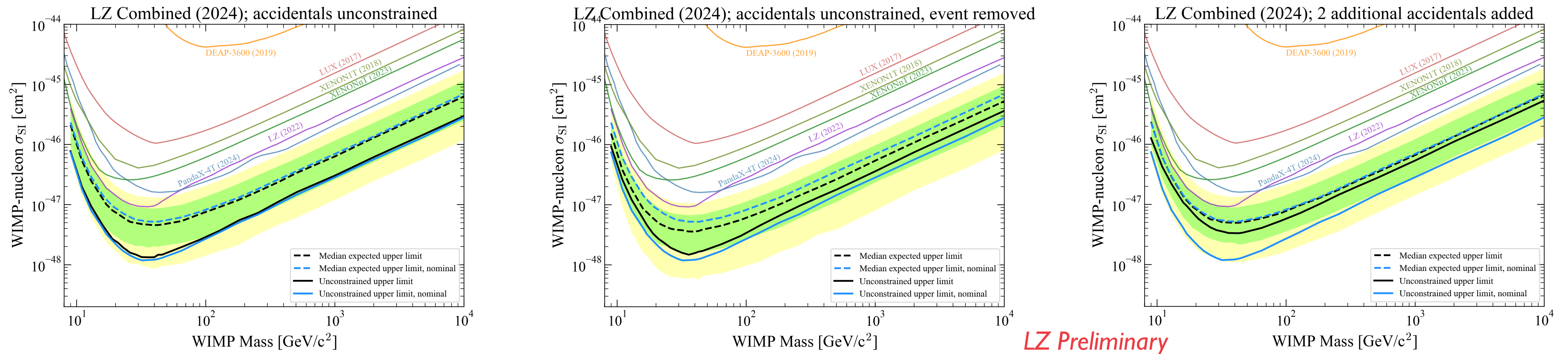
ACCIDENTALS MODEL & SIDEBAND COMPARISONS

Comparing
manufactured
accidental events
and unphysical drift
accidentals

Good agreement
before application of
S1- and S2-based cuts

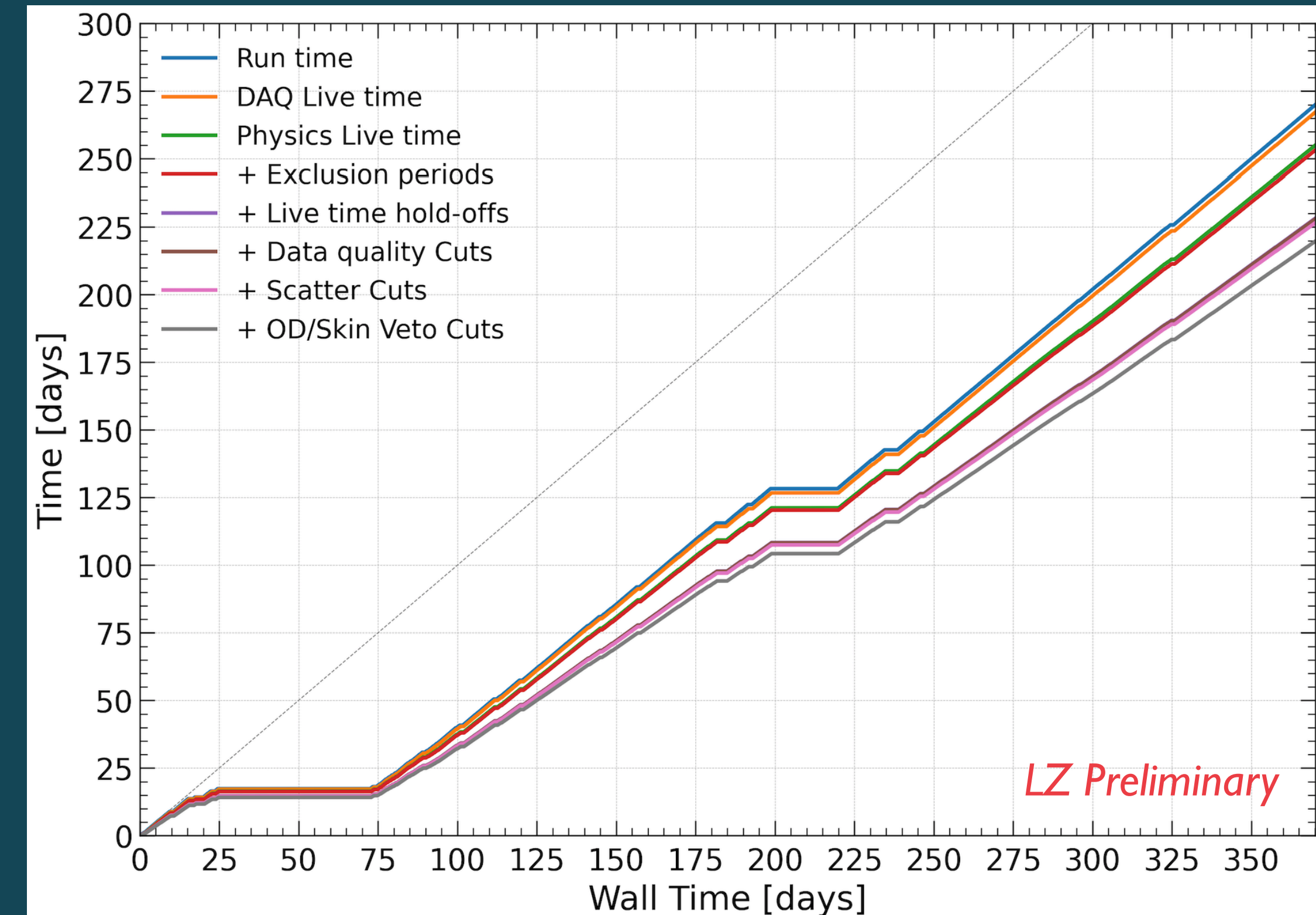
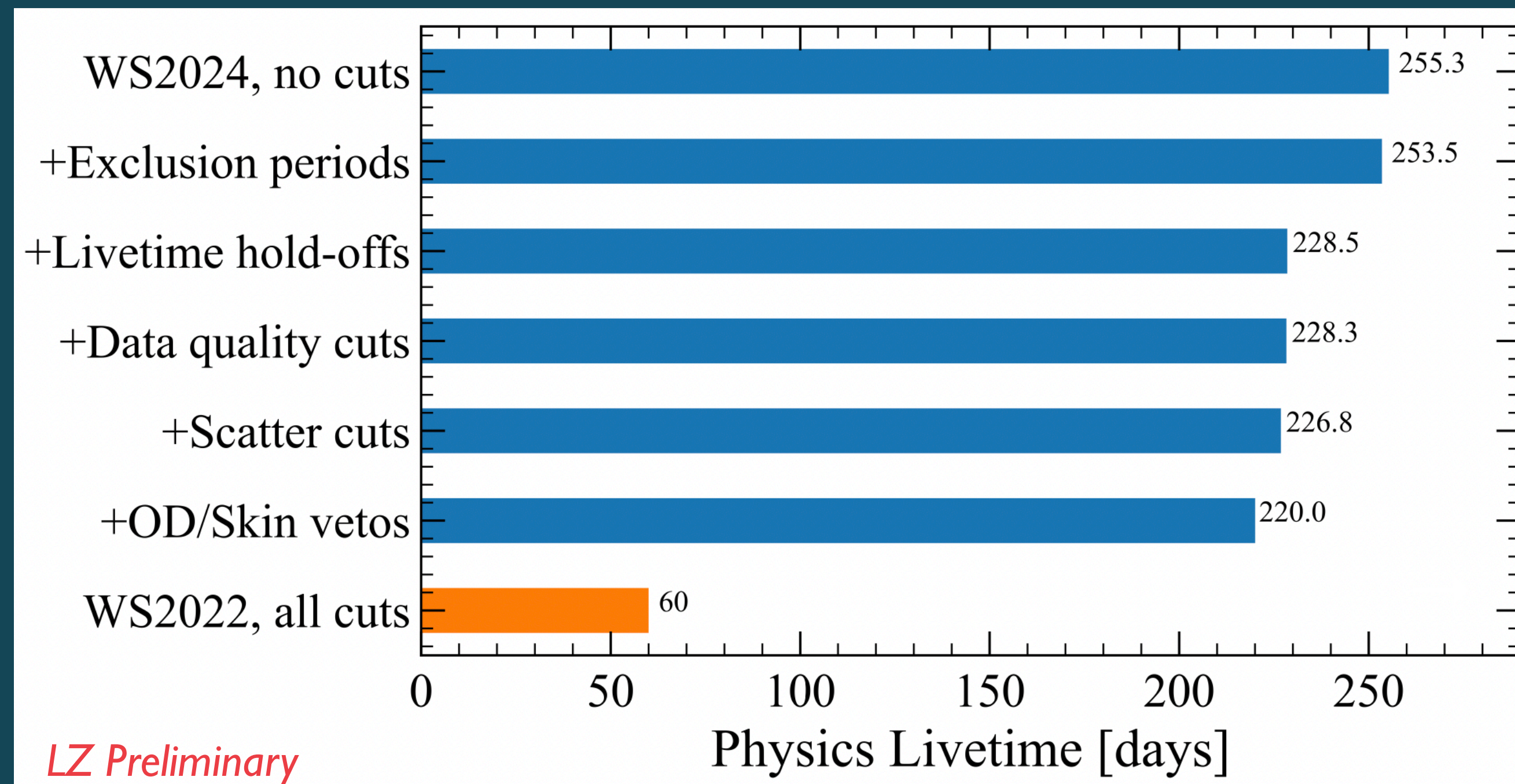


CHECKS OF ACCIDENTALS IMPACT ON LIMIT



1. Remove accidental rate constraint: best fit drops 2.6 $\rightarrow$ 1.4
 2. Remove constraint & outlier event: best fit drops 1.4 $\rightarrow$ 0
 - Outlier event holds model up, over subtracting in the WIMP region
 3. Adding fake events - props limit back up
- $\rightarrow$ under-fluctuation of accidental events in the WIMP region

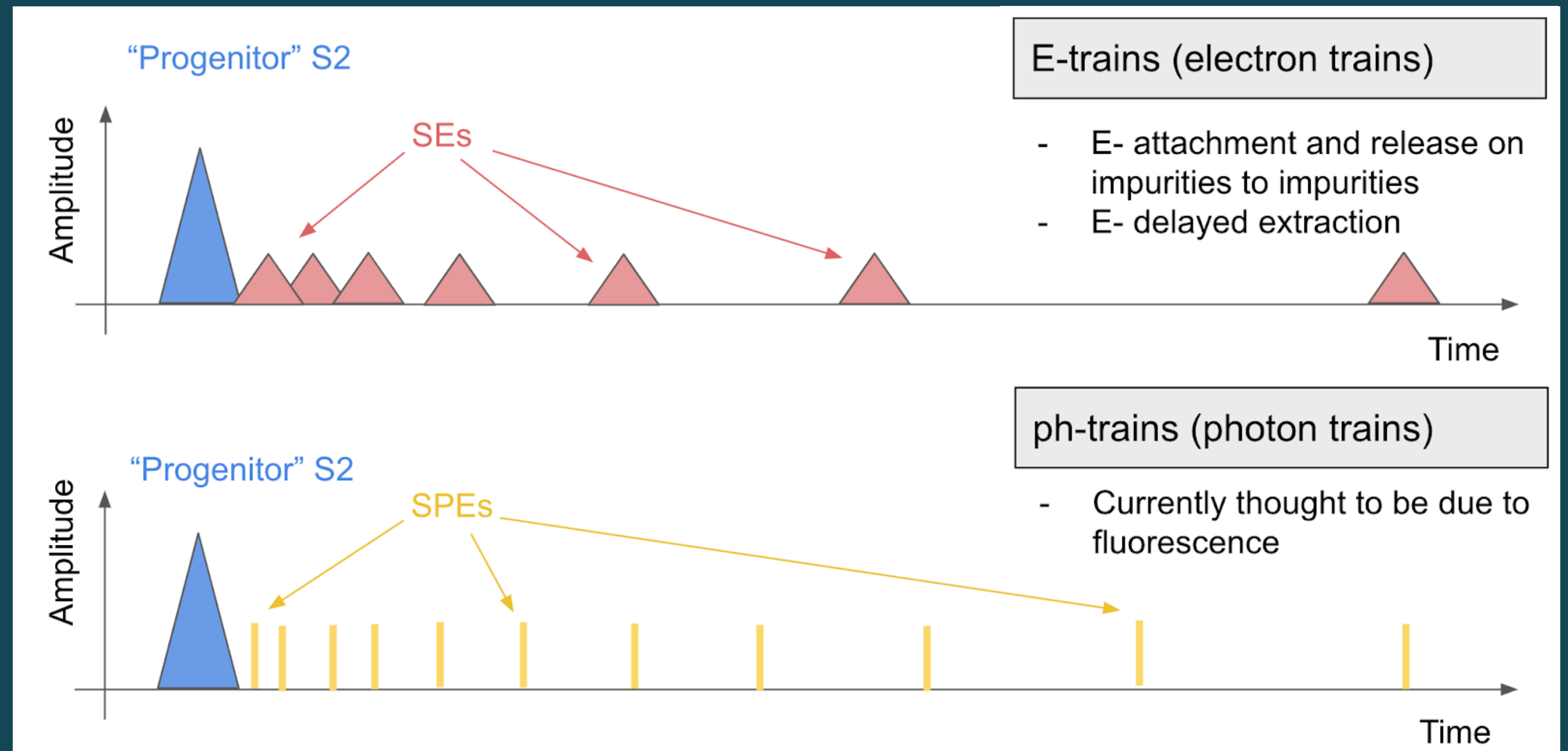
LIVE TIME



- Rejection of live time with detector instabilities, high TPC pulse rates
- 86% live time remaining after all analysis live time exclusions
→ mainly driven by improved live time retention of e-train veto

E-TRAIN VETO

- Large S2s induce pulse "trains" lasting 100s of ms, much longer than the event window
- High pulse rates can lead to piled-up photon or electron pulses that mimic S1s and S2s, thus contributing to accidental coincidence backgrounds
- Removal of periods after S2s (e-/ph trains) excludes ~10% of our live time in WS2024 (compared to ~30% for WS2022)
- Improvement due to optimisations & smaller S2s (= shorter exclusions)

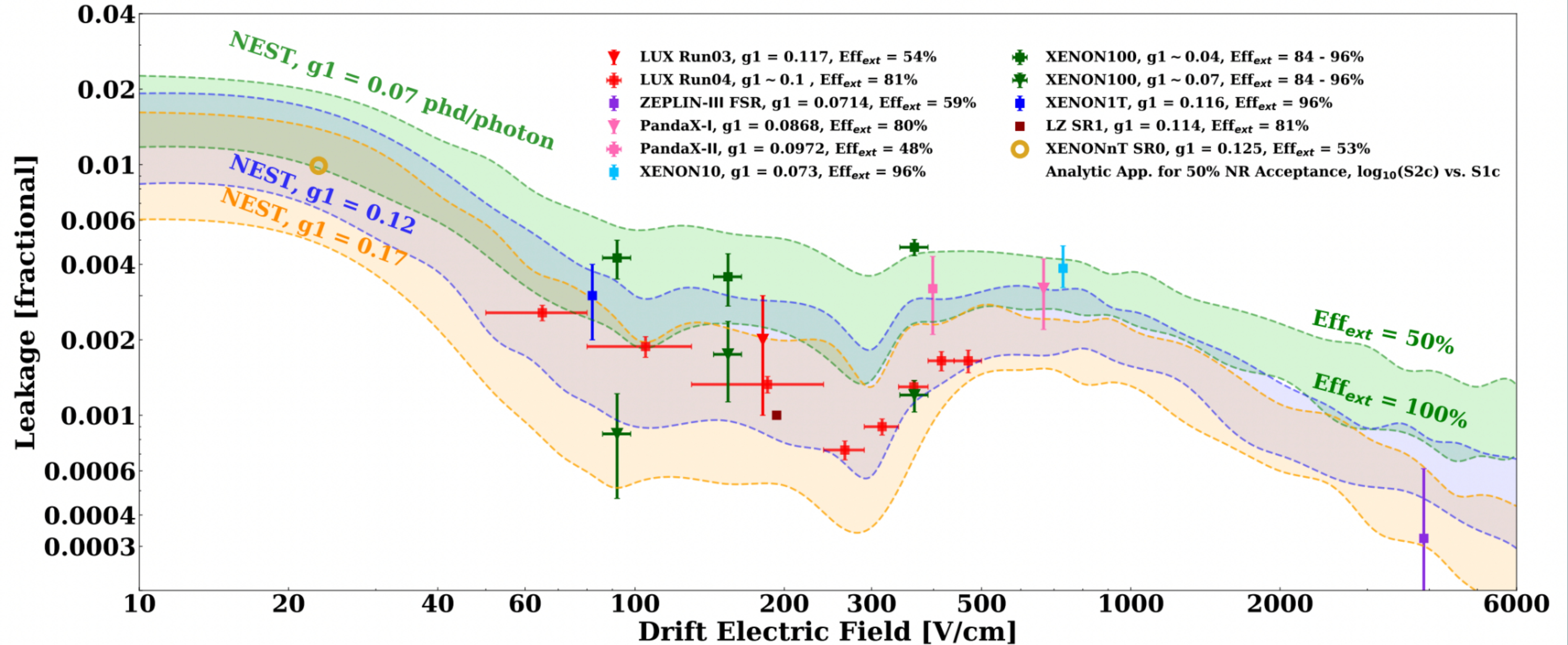


WS2024 VS WS2022 CONDITIONS

	Analysis Live Time (Days)	Drift Field [V/cm]	Extraction Field (in liquid) [kV/cm]	Single Electron Size [phd]
WS2024	220	97	3.4	44.5
WS2022	60	193	4.4	58.5

- Optimisations performed following WS2022: trigger configuration; electrode voltages; circulation
- Lowered gate-anode ΔV by 0.5 kV to reduce spurious electron emissions
- Optimised drift field to 97 V/cm to maintain similar ER/NR discrimination whilst enabling long-term, stable running of the detector

NEST MODEL OF ER LEAKAGE VS DRIFT FIELD



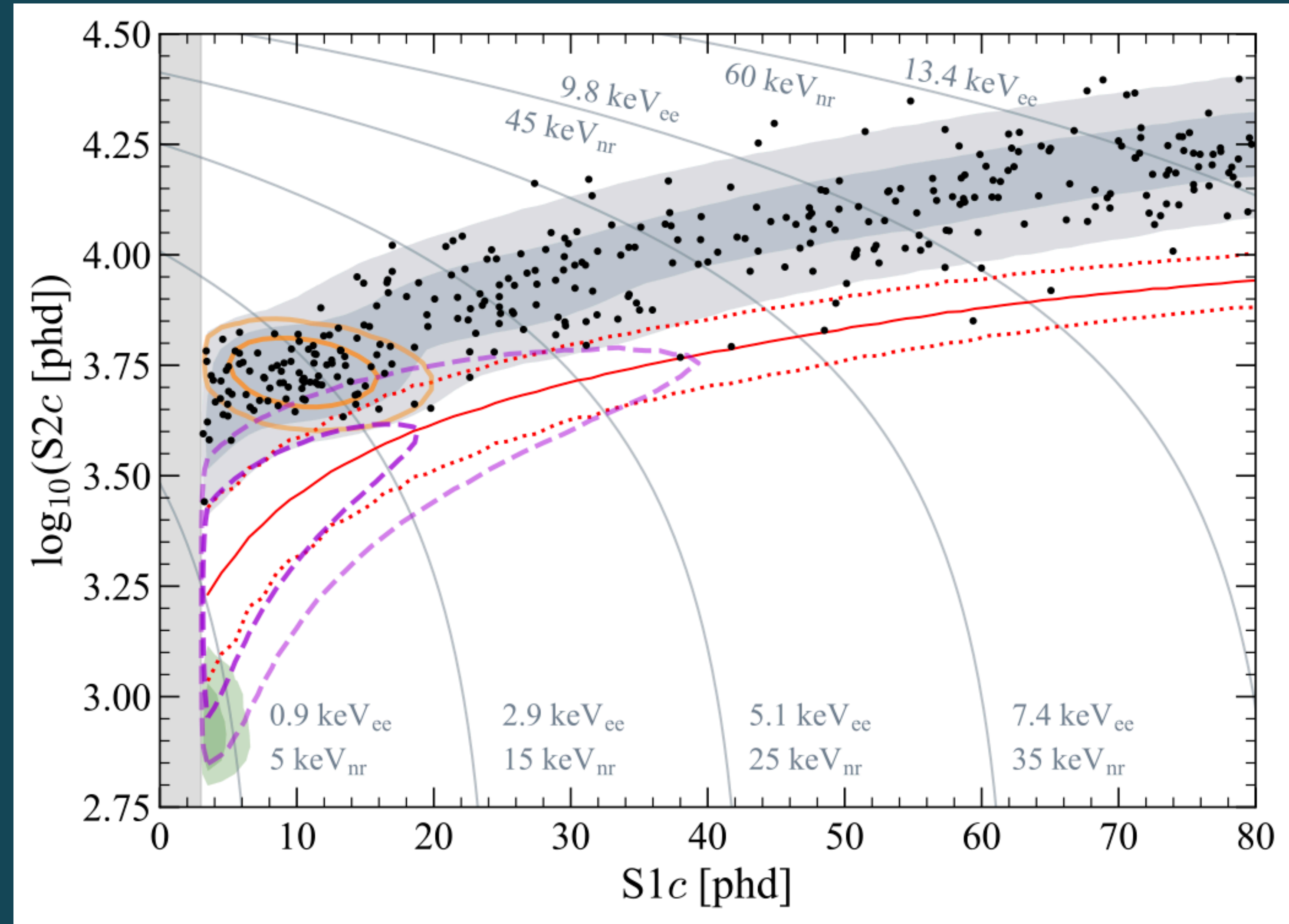
[arXiv:2211.10726](https://arxiv.org/abs/2211.10726)

WS2022 DATA

- 335 events after all cuts
- PDFs created with energy deposit + detector response simulations*
- Profile likelihood ratio (PLR) analysis

Key

- 1 & 2-Sigma Contours
- Post-fit total background distribution
- ^{37}Ar
- ^8B
- 30 GeV/c² WIMP
- NR band from DD

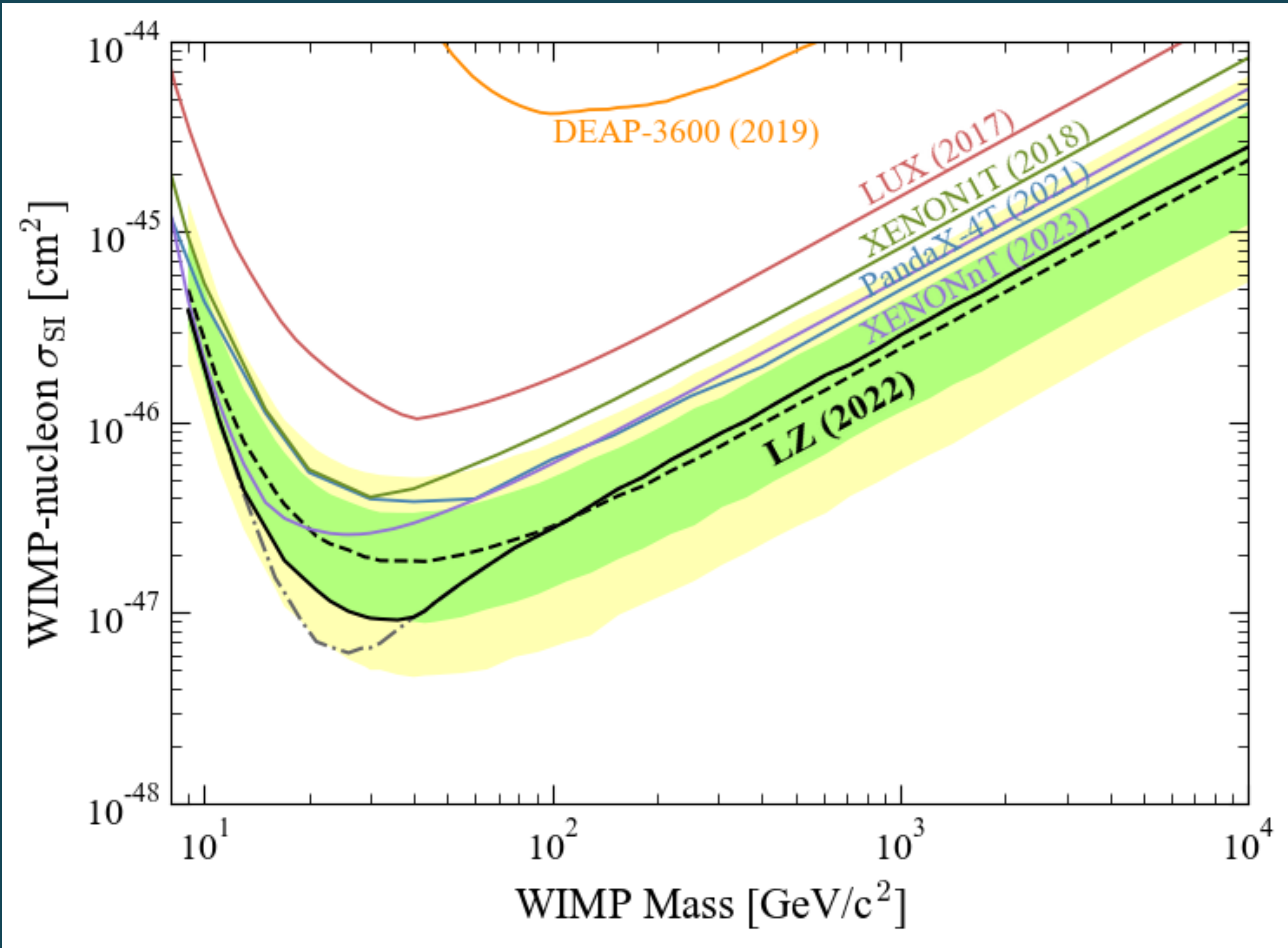


WS2022 LIMIT

- Two-sided PLR search with power-constrained limit defined using rejection power
- Minimum cross-section of $\sigma_{SI} = 9.2 \times 10^{-48} \text{ cm}^2$ for WIMP mass of $36 \text{ GeV}/c^2$
- No evidence for WIMPs

Key

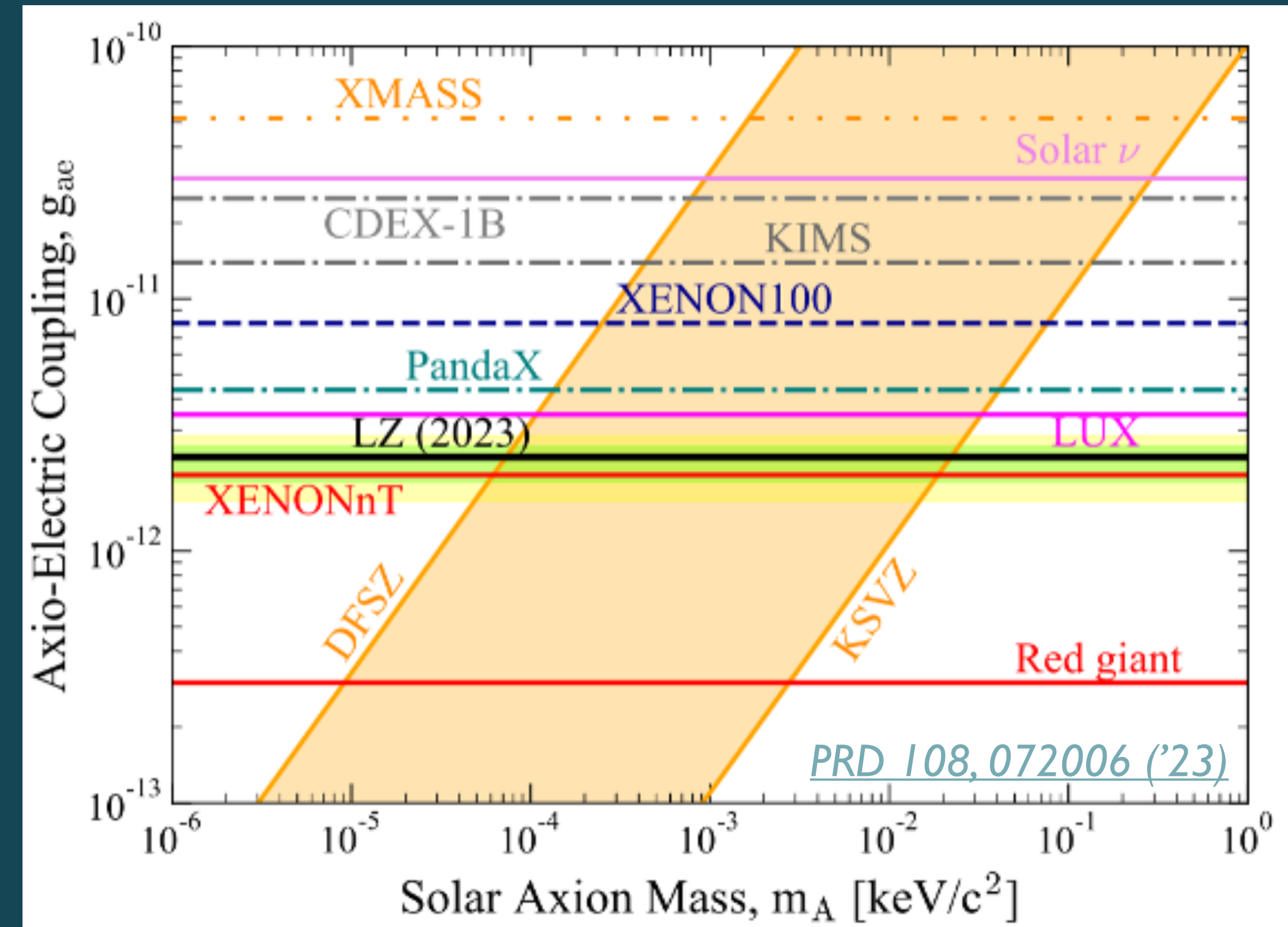
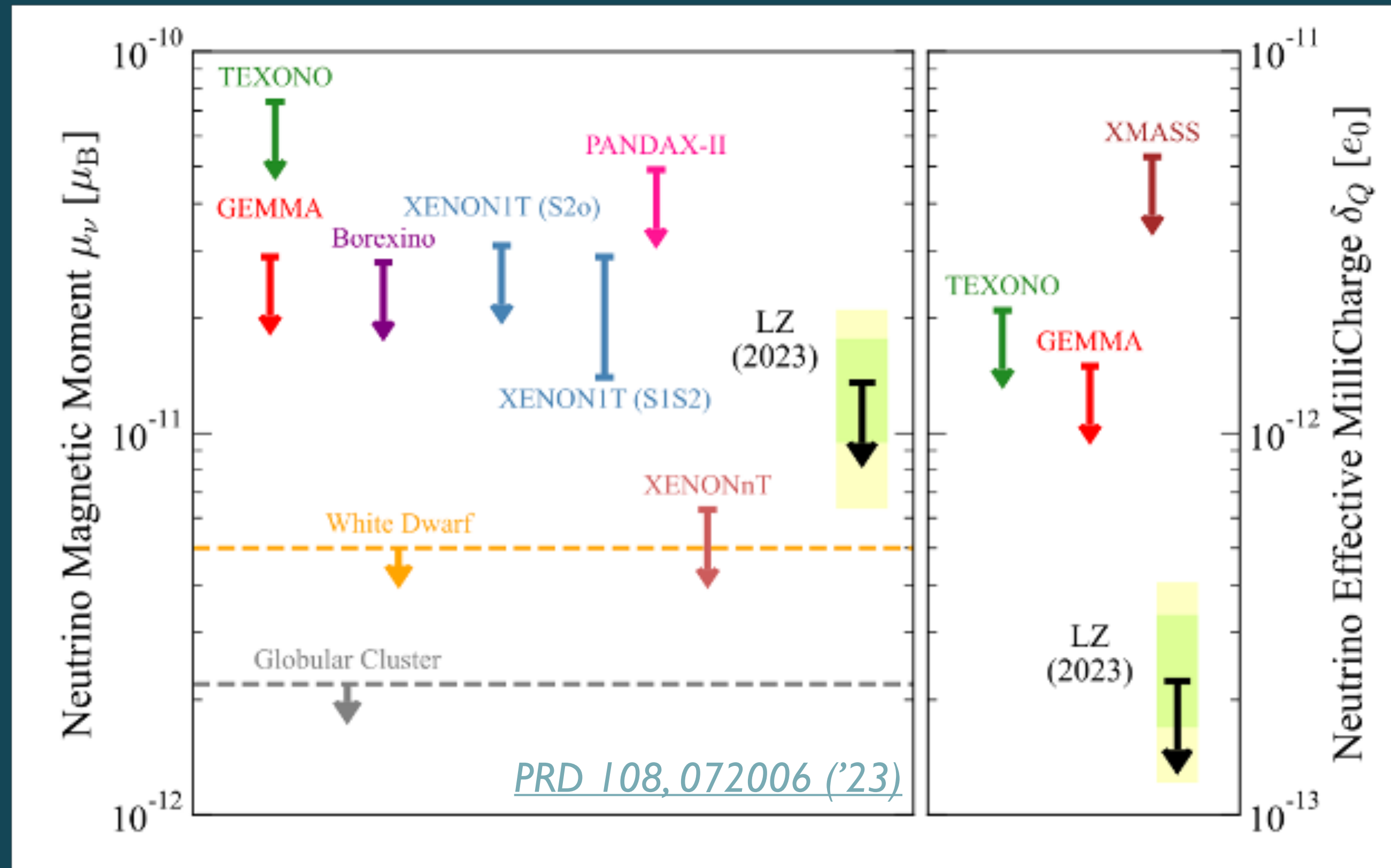
- Observed limit
- - - Median expected sensitivity



PHYSICS VIA ELECTRON RECOIL CHANNEL

Neutrino Magnetic Moment & Effective Millicharge

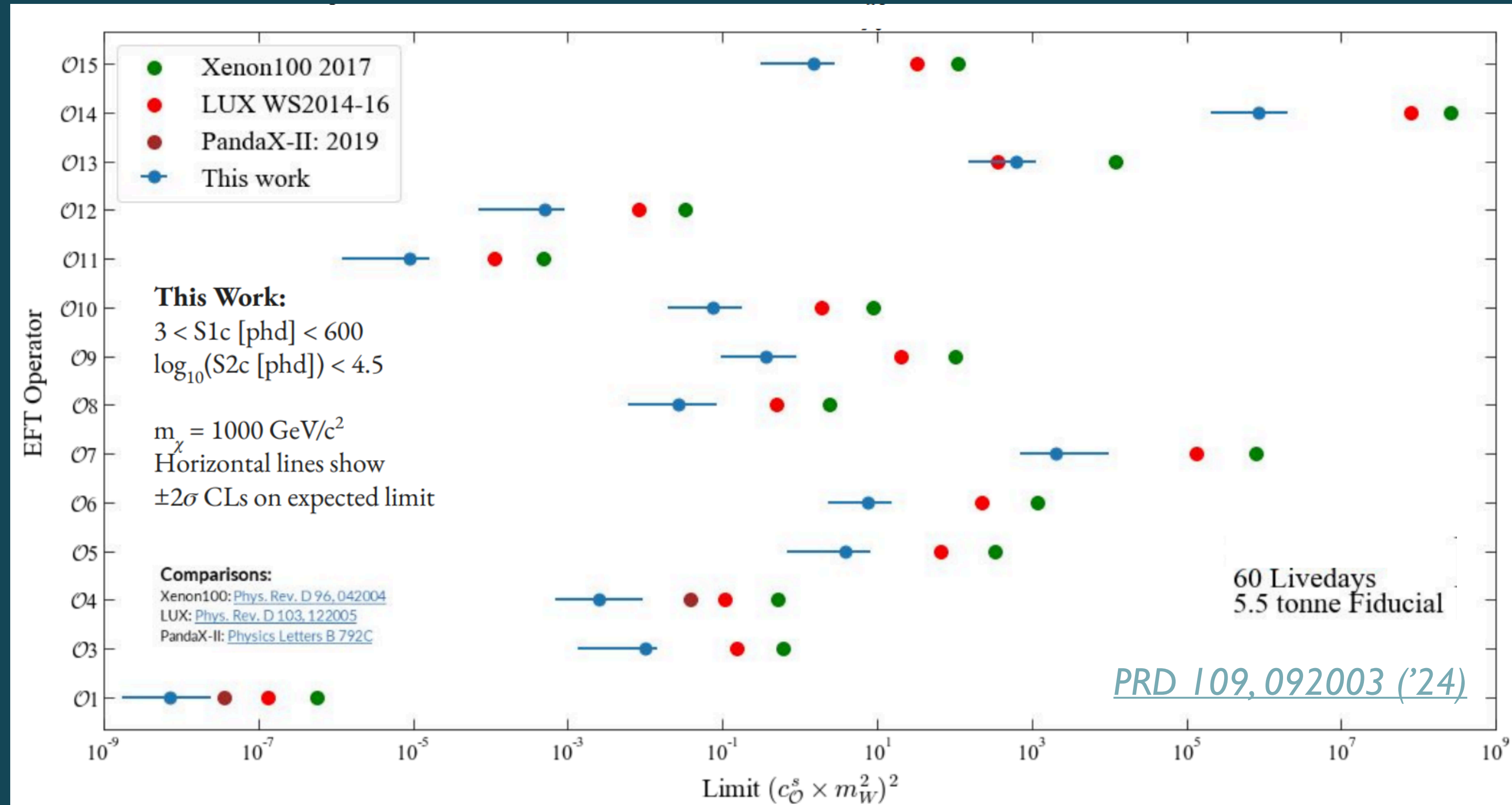
Solar Axion Interactions



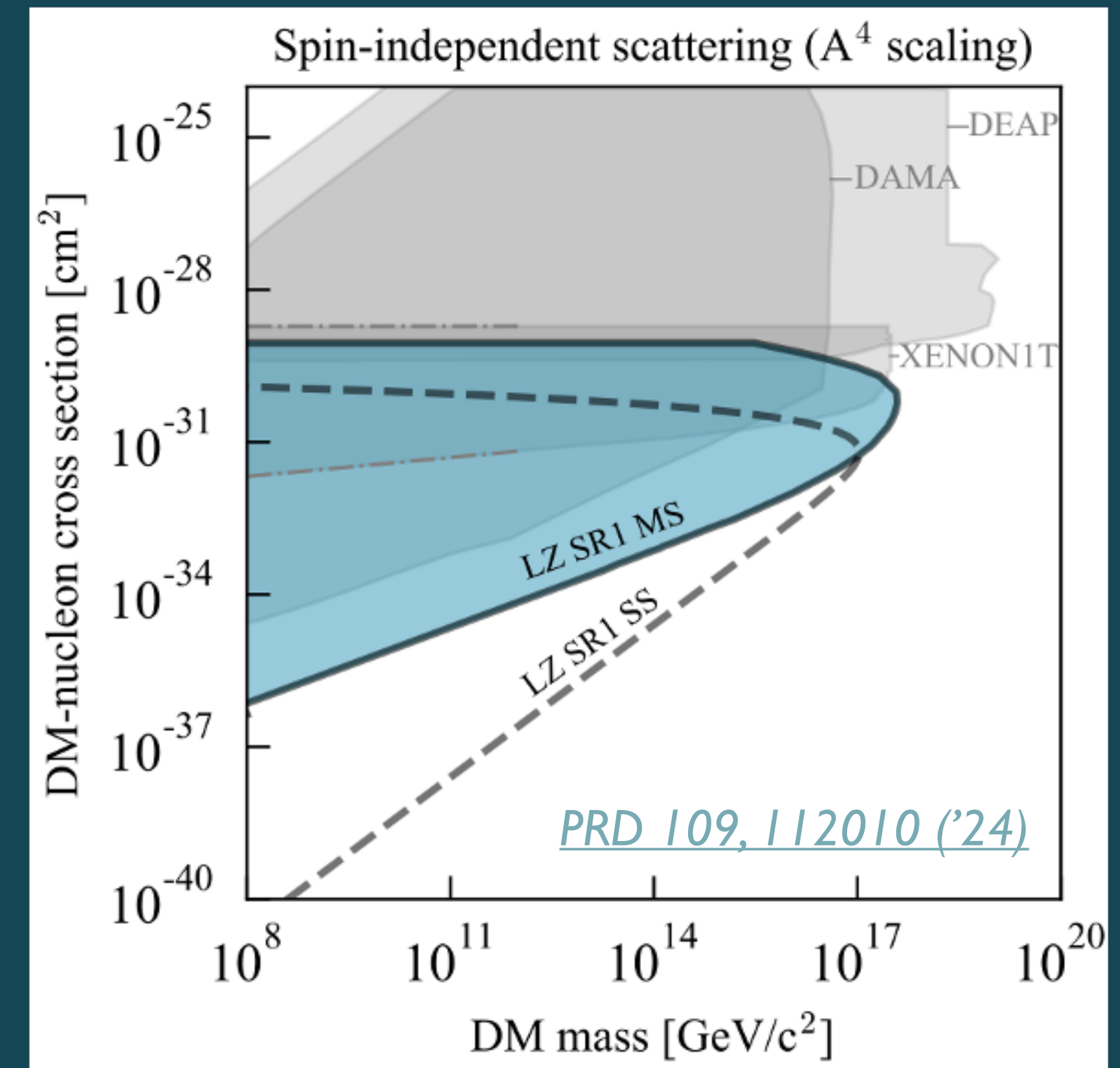
Neutrino interactions & properties; axions and ALPs; rare decays of xenon isotopes

MORE DARK MATTER RESULTS

Effective Field Theory Couplings



Ultra-heavy Dark Matter



New world-leading constraints on several EFT operators; high-energy MIMP interactions
→ broadband detectors, capable of searches across a wide range of candidate masses