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

Amy Cottle, UCL

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
- University College London
- University of California Berkeley
- University of California Davis
- University of California Los Angeles
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- University of Michigan
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- University of Rochester
- University of Sheffield
- University of Sydney
- University of Texas at Austin
- University of Wisconsin, Madison
- University of Zürich

US Europe Asia Oceania

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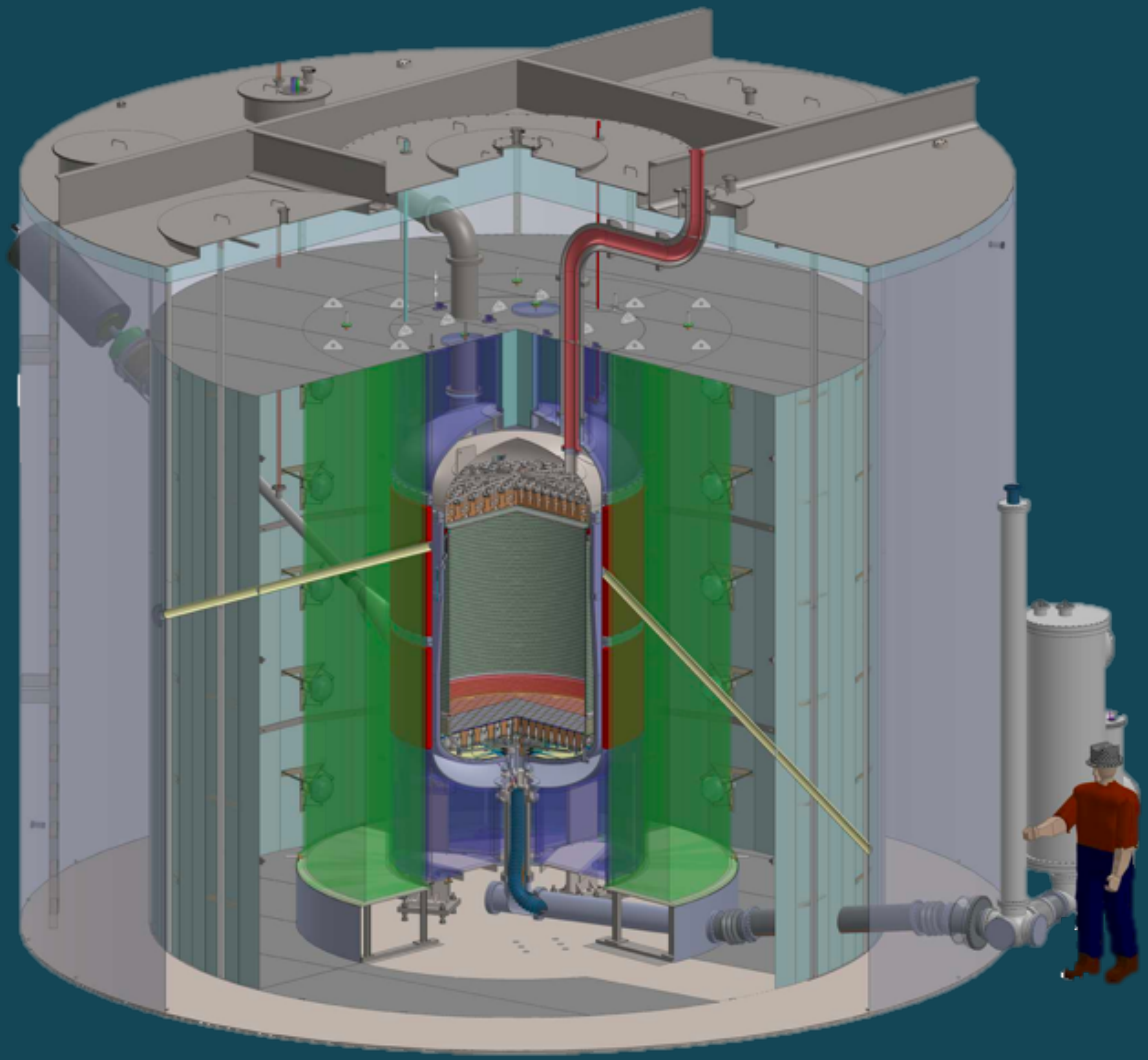
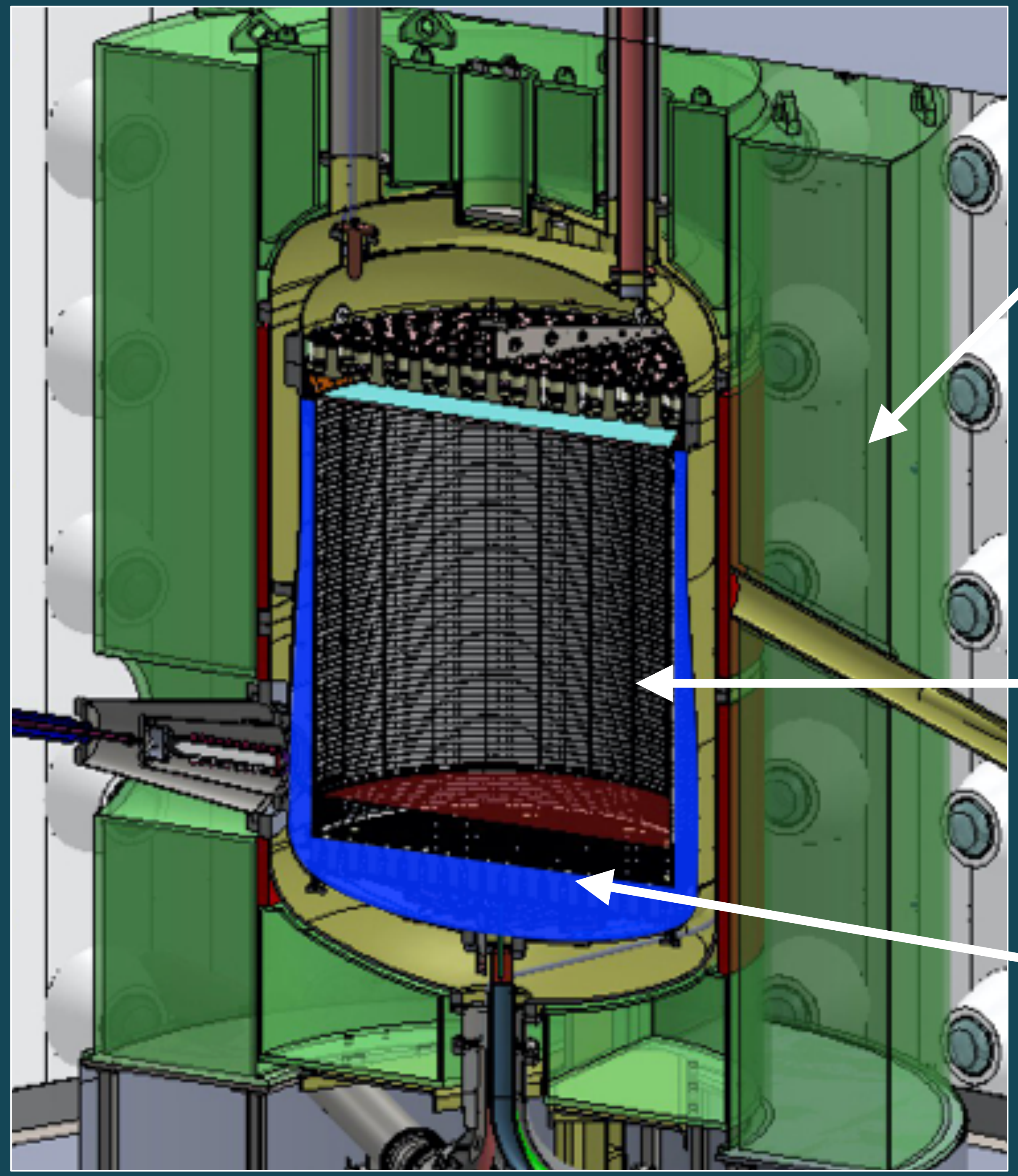
Science and Technology Facilities Council
Swiss National Science Foundation
FCT Fundação para a Ciência e a Tecnologia
Ministério da Educação e Ciência
Sanford Underground Research Facility
ibs Institute for Basic Science
ARC Centre of Excellence for Dark Matter Particle Physics

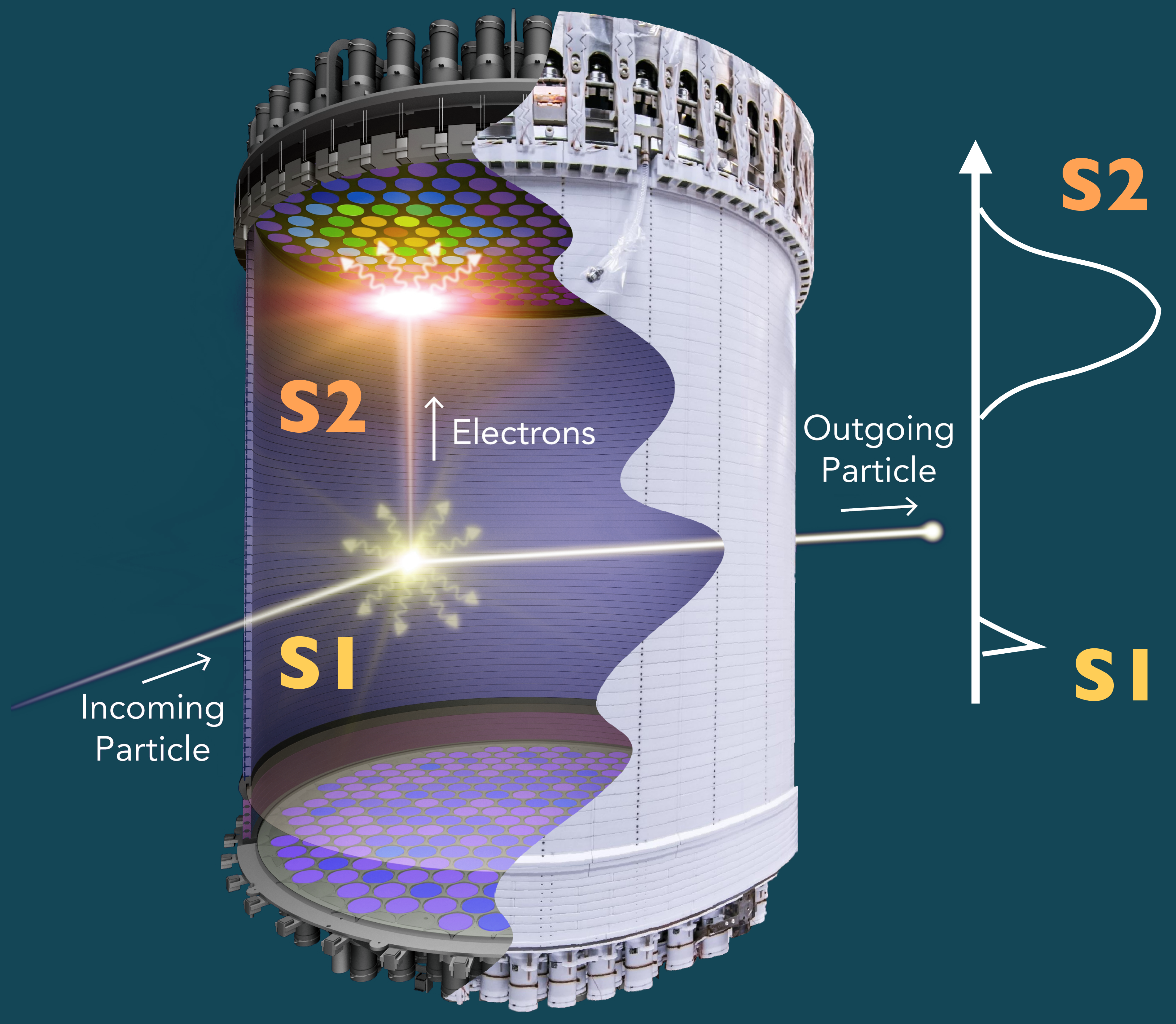
THE LZ EXPERIMENT

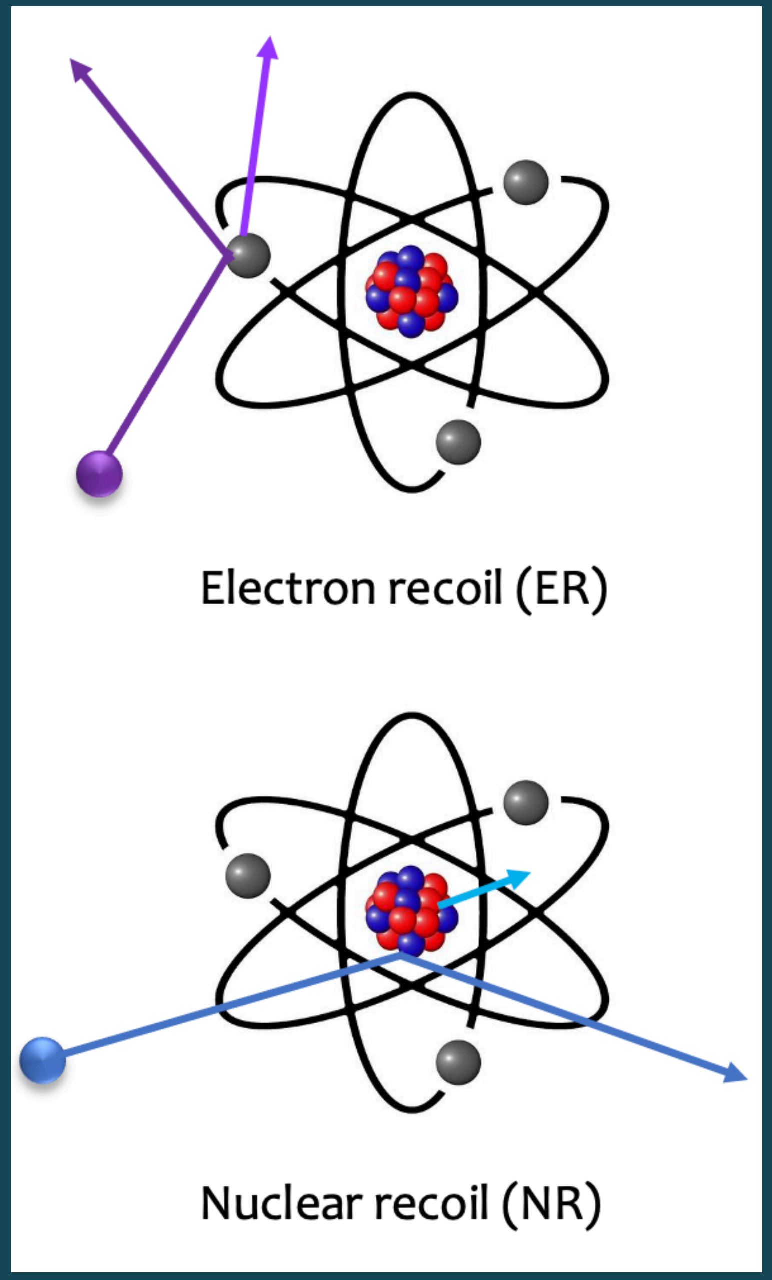


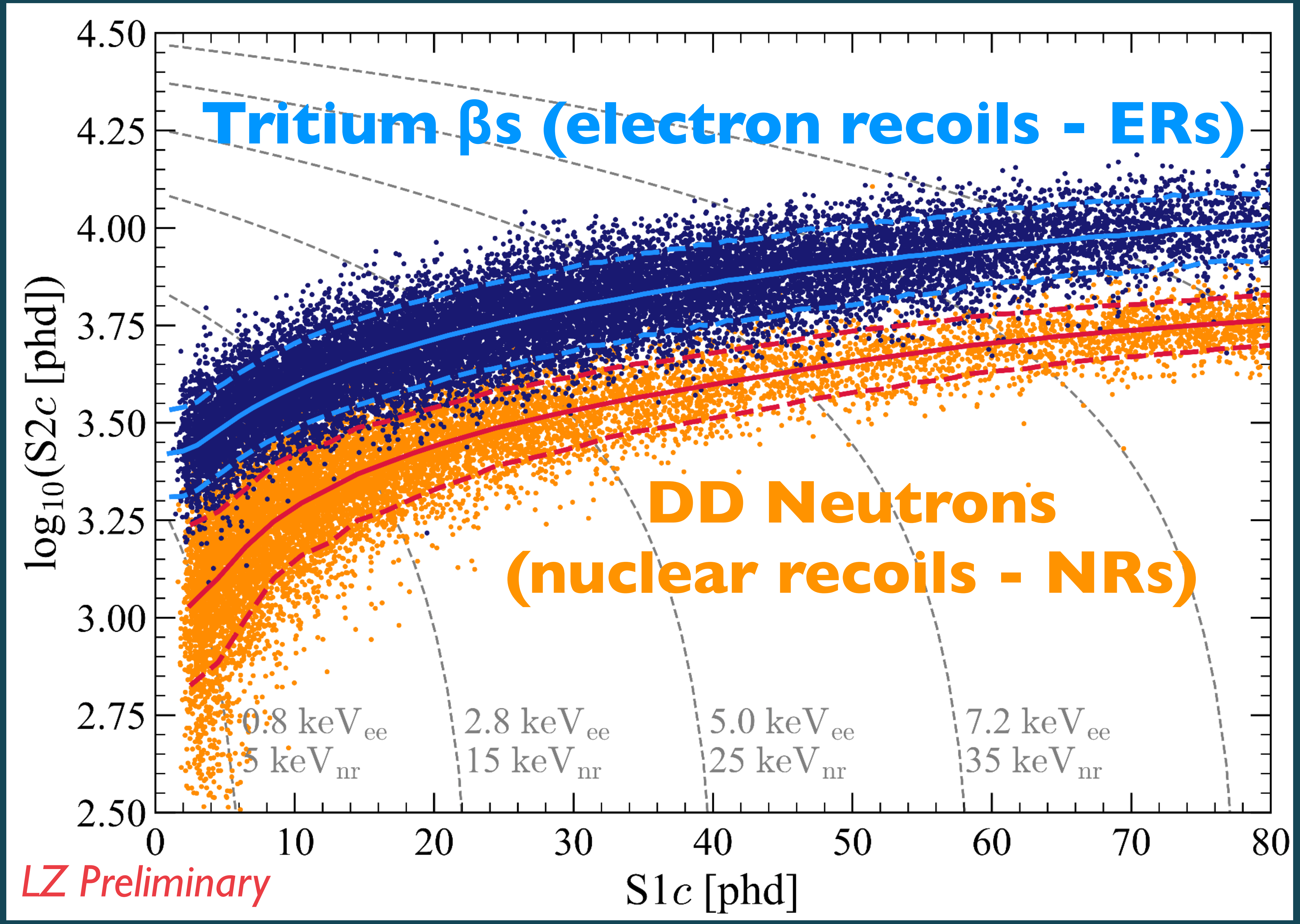


- ~1.5 km underground at the Sanford Underground Research Facility (SURF) in Lead, SD
- Operating world’s largest 7 t active dual-phase xenon time projection chamber (TPC)
- TPC nested in Skin & Outer Detector (OD) veto systems → tag neutrons and gamma rays

XENON TIME PROJECTION CHAMBER (TPC)

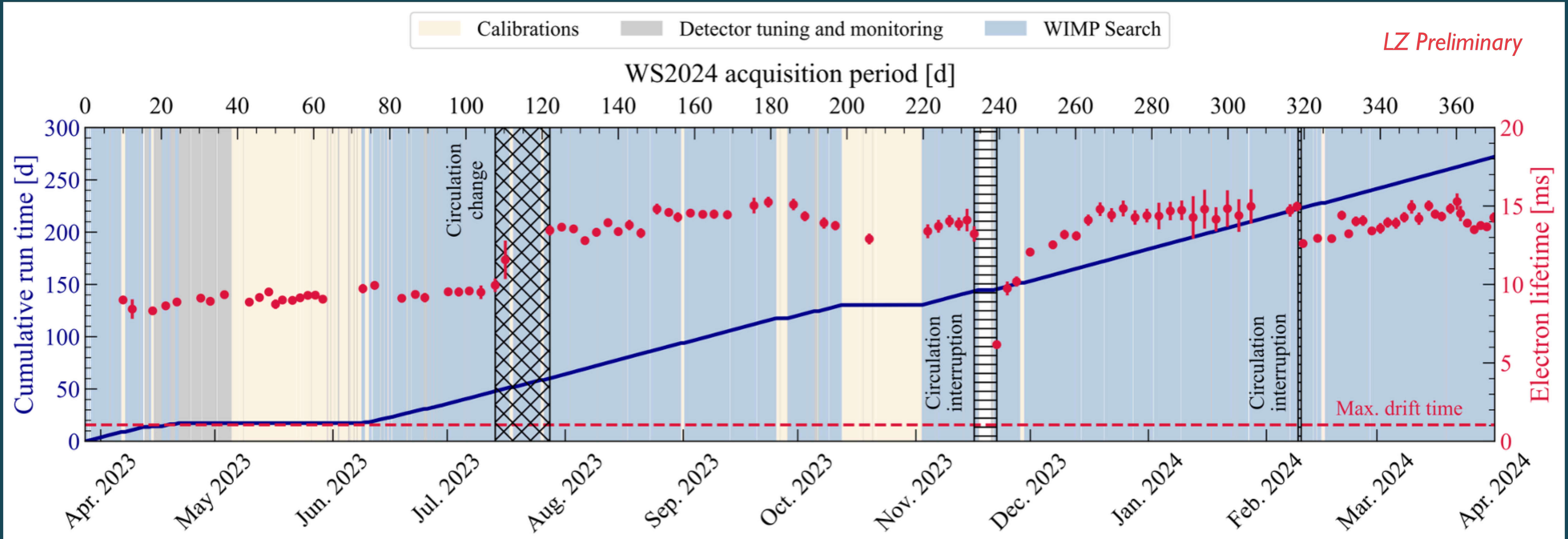






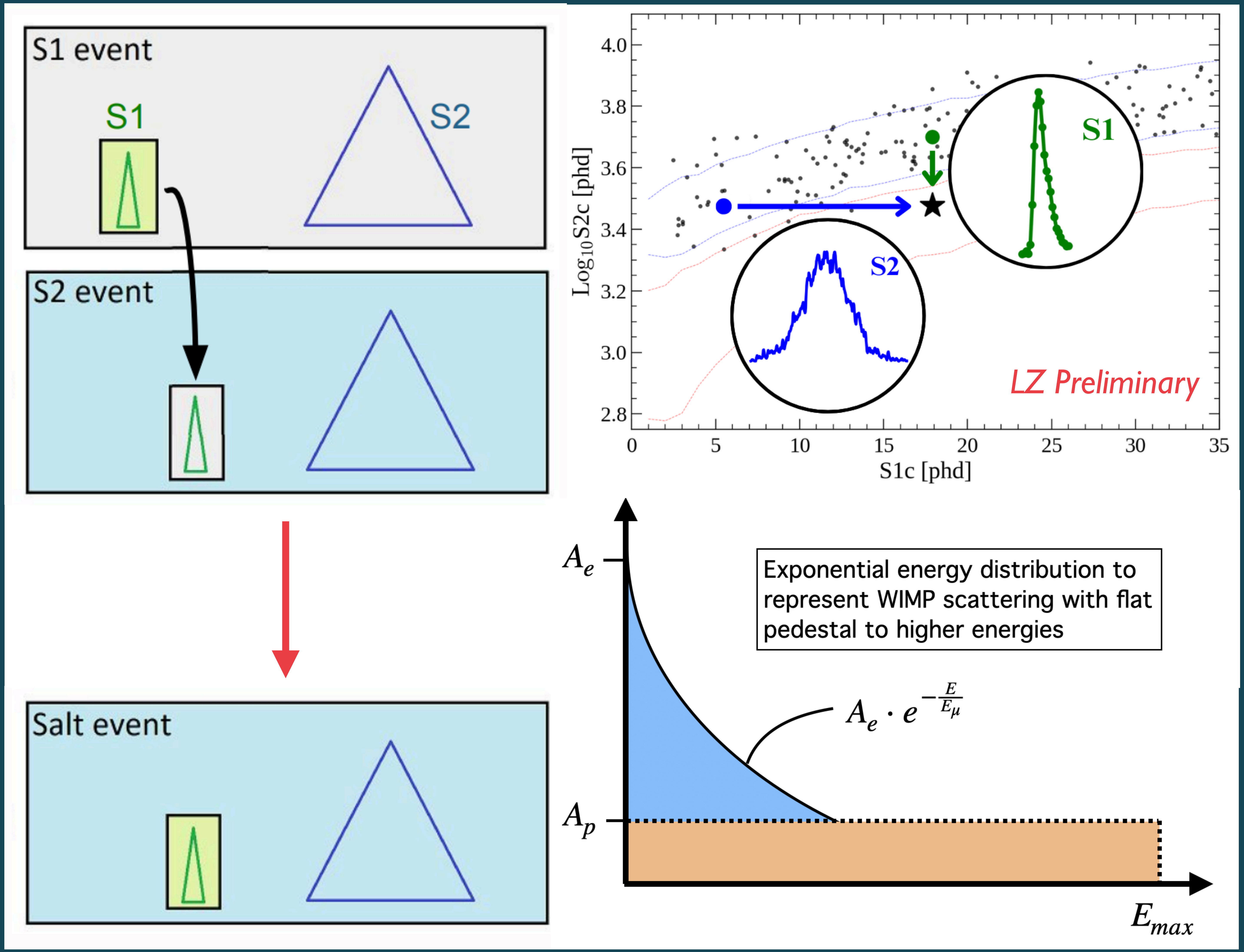
- Interactions give light (prompt scintillation - **S1**) and charge (proportional scintillation - **S2**)
- Excellent 3D position reconstruction (~mm) → fiducialisation & distinguishing single scatters (SSs)
- Discrimination of electronic recoils (ERs) from potential WIMP nuclear recoils (NRs)

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

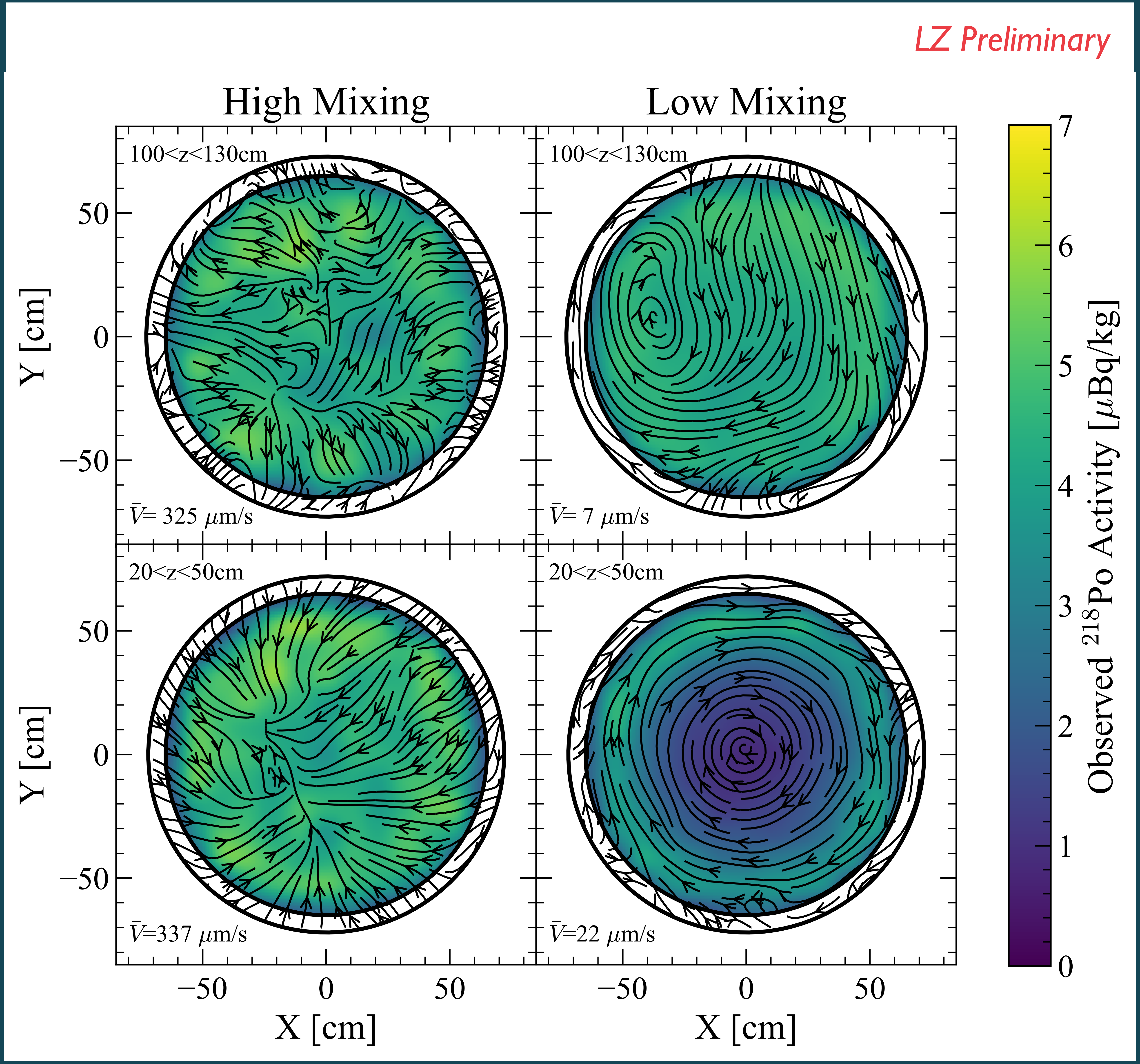
- Circulation & cooling systems allow control of temperature & xenon flow

  High-mixing state
  More turbulent flow → uniform distribution of injected calibration sources

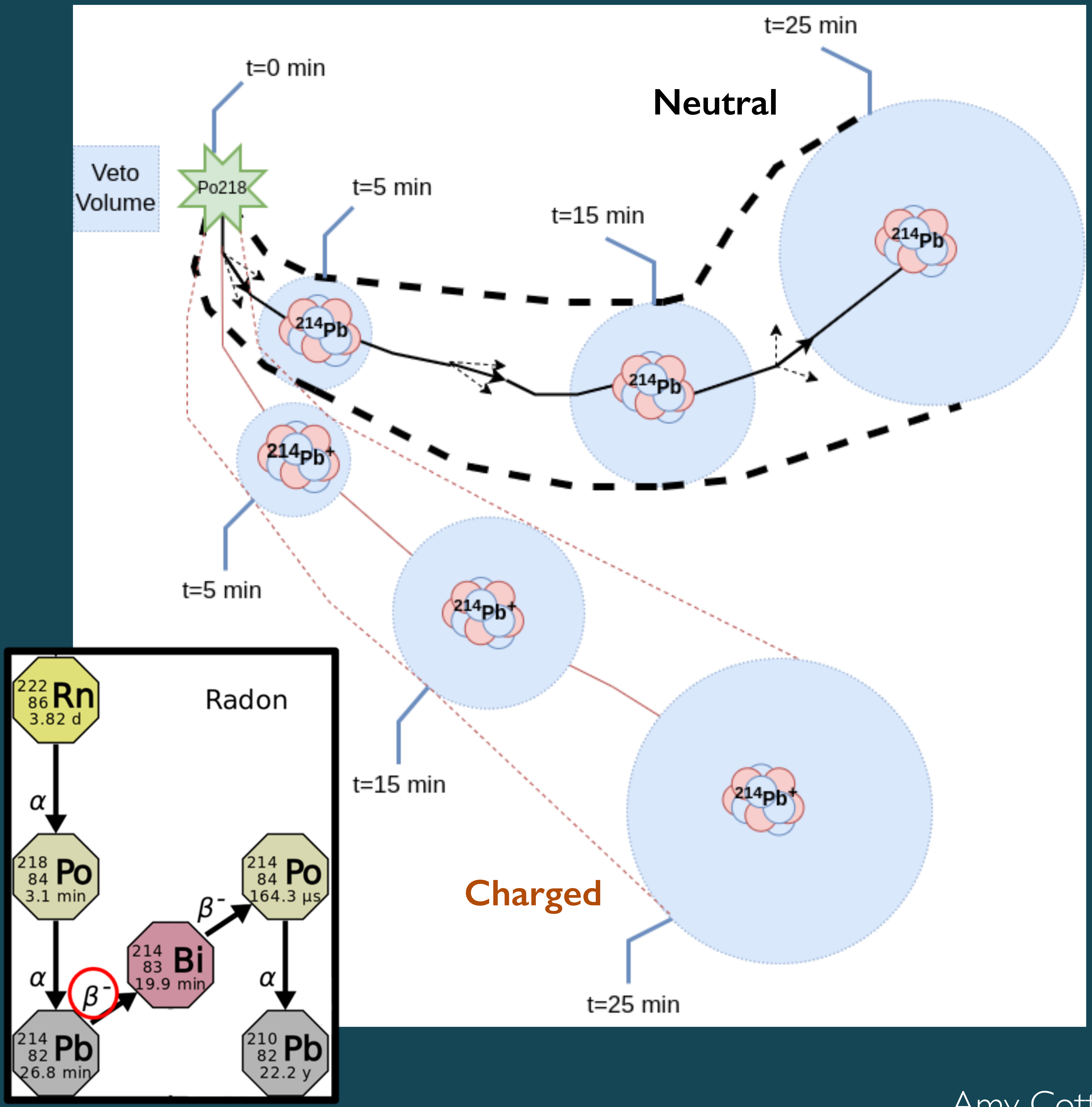
  Low-mixing state
  Slower, laminar flow

- ^{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 (~3x ^{214}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

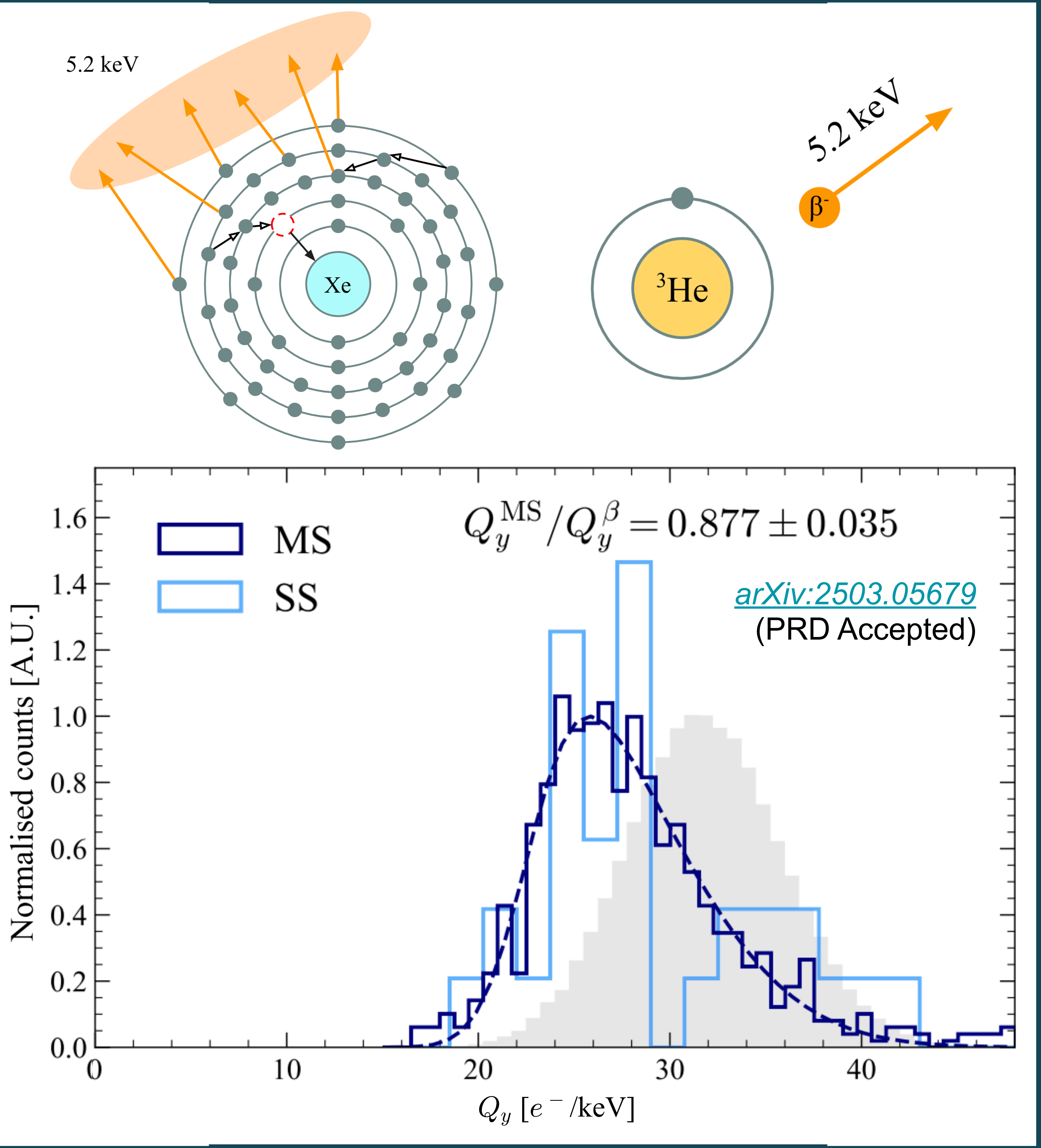
- ^{127}Xe & ^{125}Xe decay by electron capture (EC)

- L-shell EC (5.2 keV) relevant for WIMP search

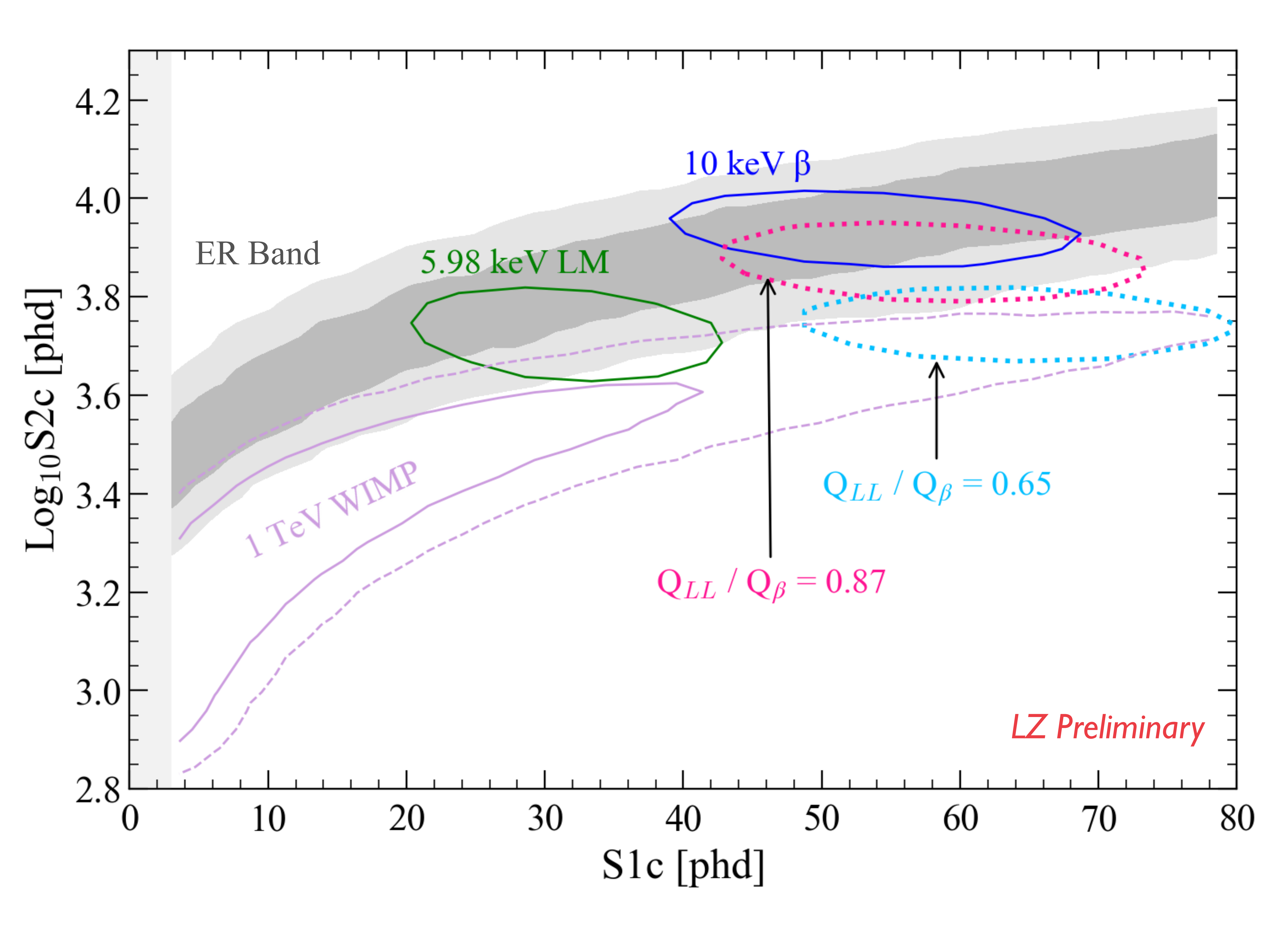
  - Auger/X-ray cascade → more NR-like than β i.e. **enhanced recombination**

  - *In-situ* measurement in LZ for WS2024: **Q_L/Q_β = 0.877 ± 0.035** (arXiv:2503.05679)

- 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

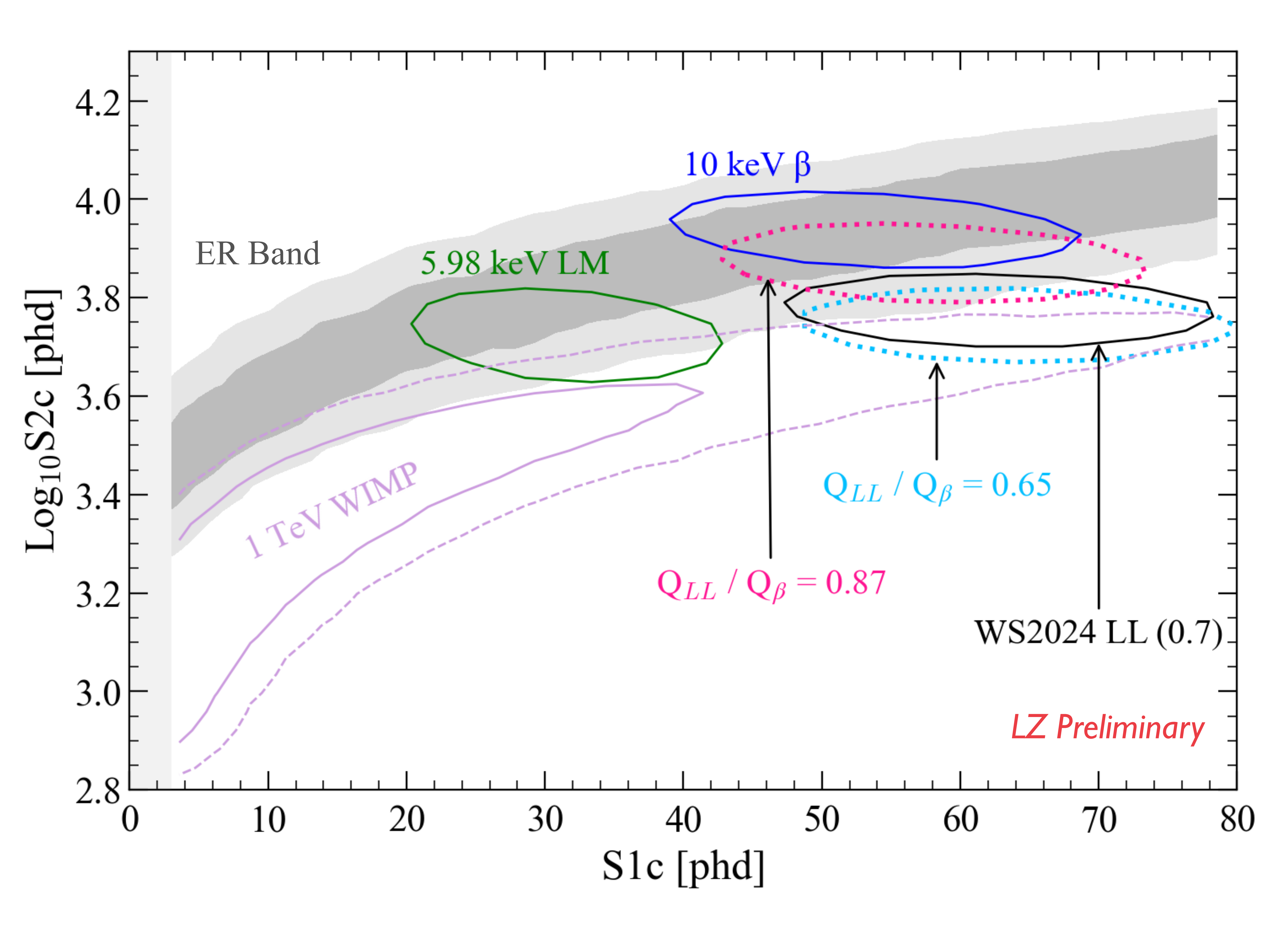


- Expect 7.1 (LM) + 12.3 (LL) = 19.4 counts with 20% uncertainty
- LM modelled with same as single L-shell charge suppression
- LL expected to be further charge-suppressed due to higher ionisation density i.e. $Q_{LL}/Q_\beta < Q_L/Q_\beta$
- **Vary Q_{LL}/Q_β in fitting of our data:**

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

2x L-shell ionization density (0.65) — **Q_L/Q_β** (0.87)

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



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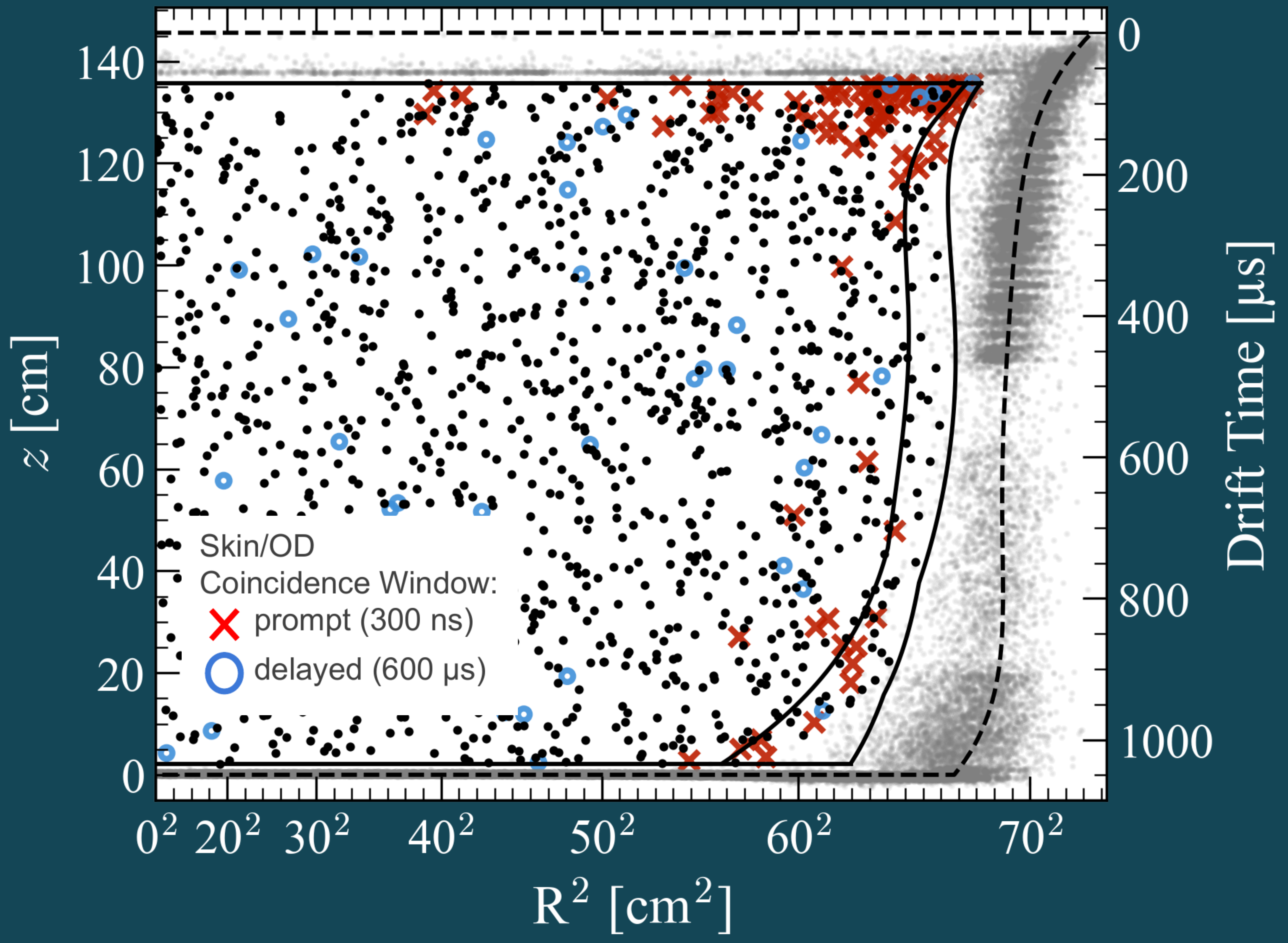
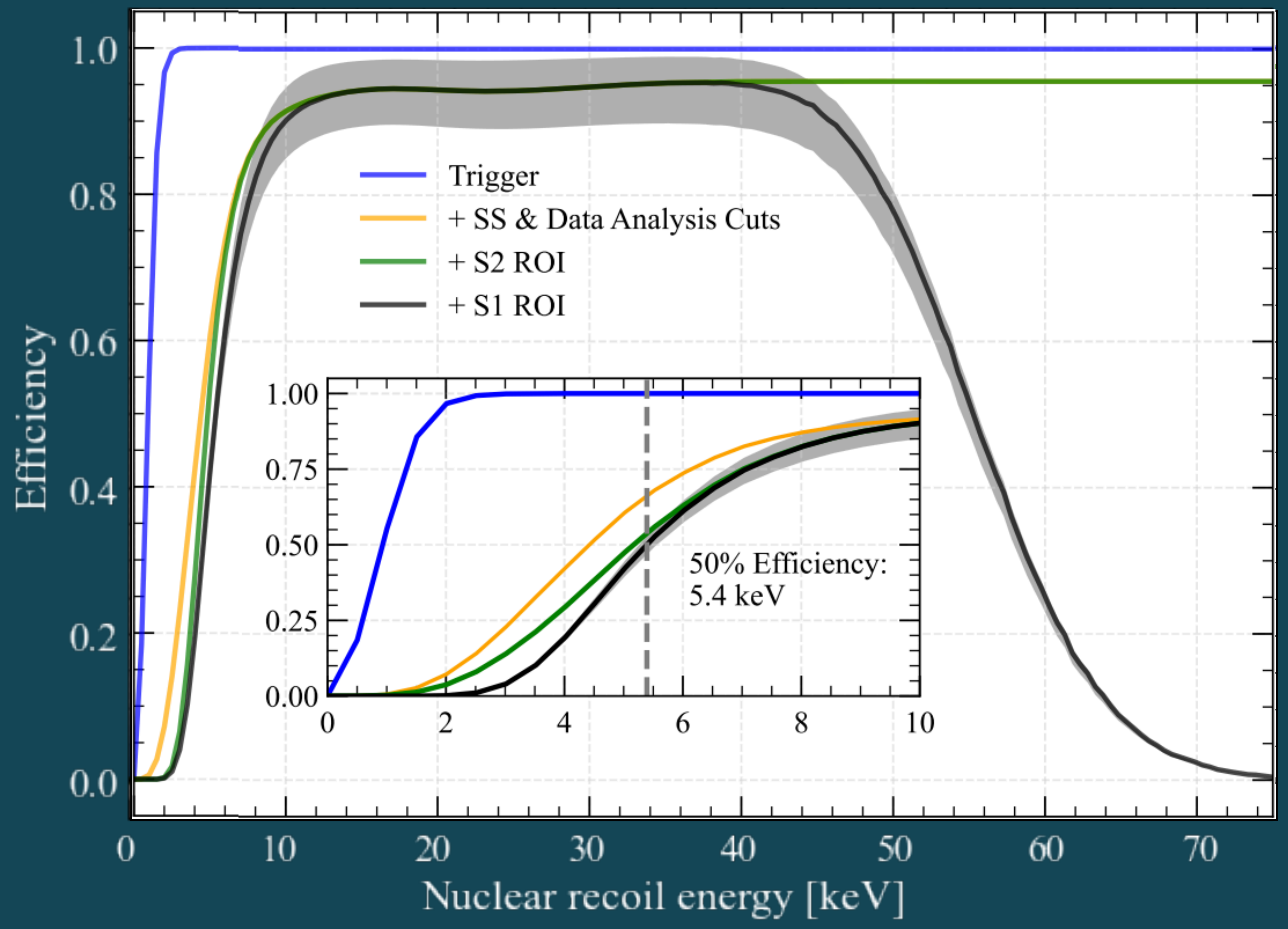
- **Vary Q_{LL}/Q_β in fitting of our data:**

0.65 < Q_{LL}/Q_β < 0.87

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

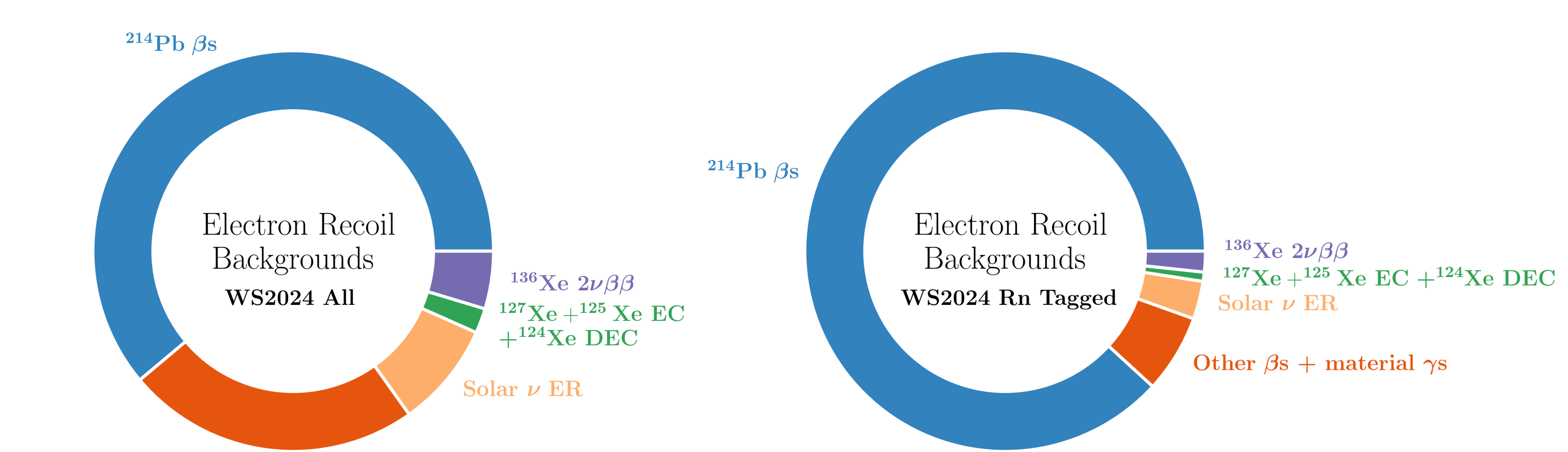
ANALYSIS CUT SUMMARY





- Fiducial volume (5.5 ± 0.2 t)
- Veto detector anti-coincidence
- WIMP S2-S1 region of interest
- S1- & S2-based cuts (target accidentals)

BACKGROUNDS MODEL EXPECTATIONS

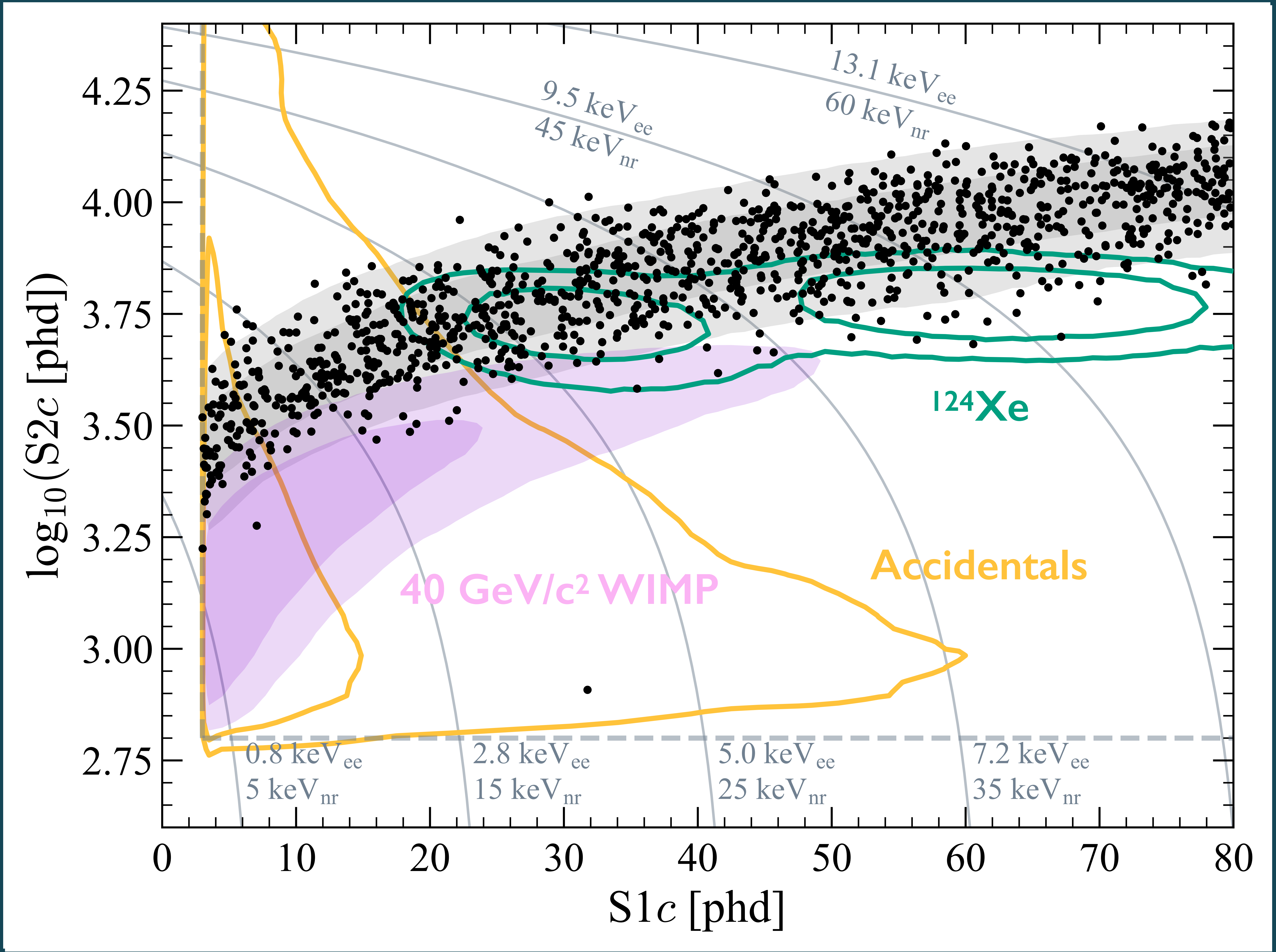


See also j.astropartphys.2020.102480

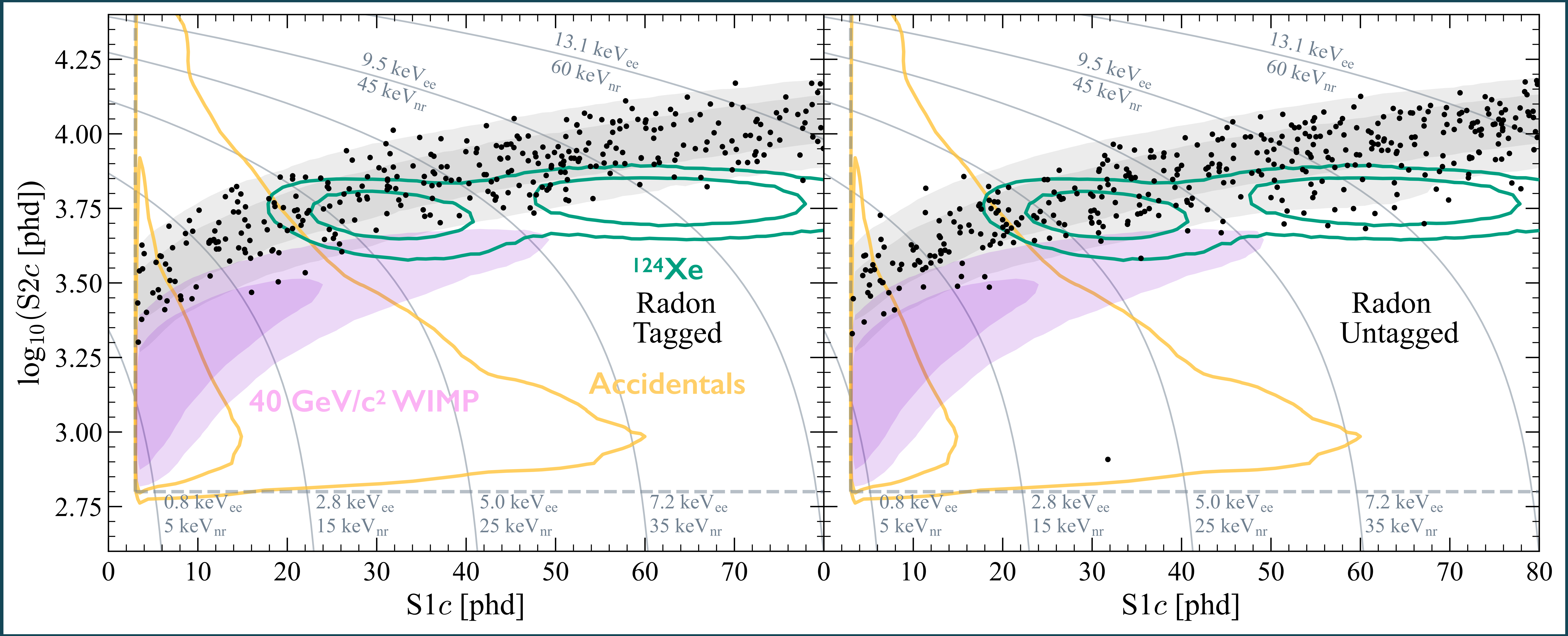
- Total expected **ER** counts for WS2024: **1207** (60% ^{214}Pb) (**327**/88% ^{214}Pb in radon-tagged data)
- Total expected **NR** counts in WS2024: **0.18** from CEvNS (no neutrons - *in-situ* fit constraint)
- **Accidentals** (fake pairs of S1- and S2-identified pulses) controlled with cuts to 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 $\log_{10}$(S2*c*)-S1*c* space
  → no post-unsalting changes to model



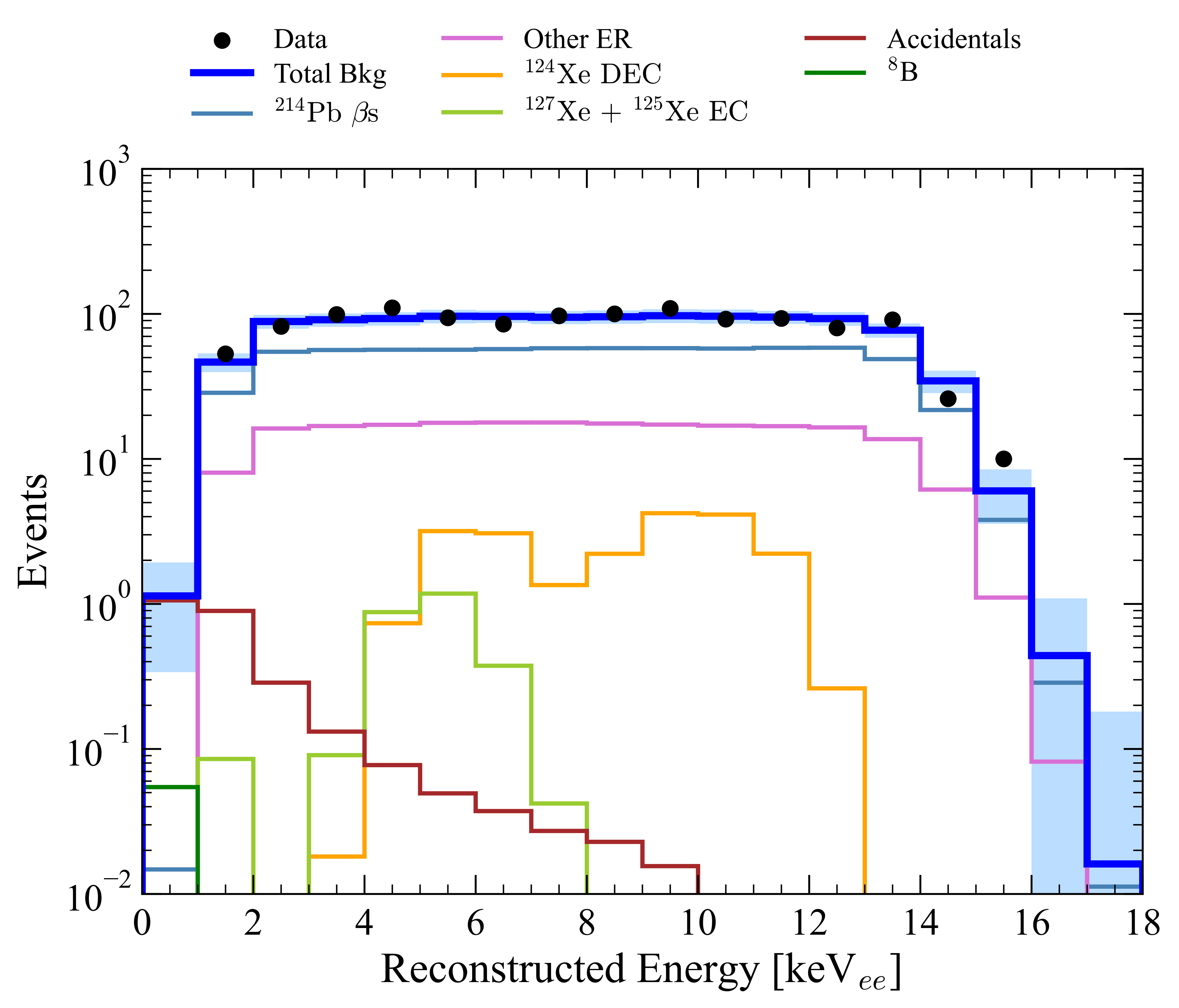
WS2024 DATA - RADON TAGGED VS UNTAGGED



0.3 tonne years **1.8 tonne years**

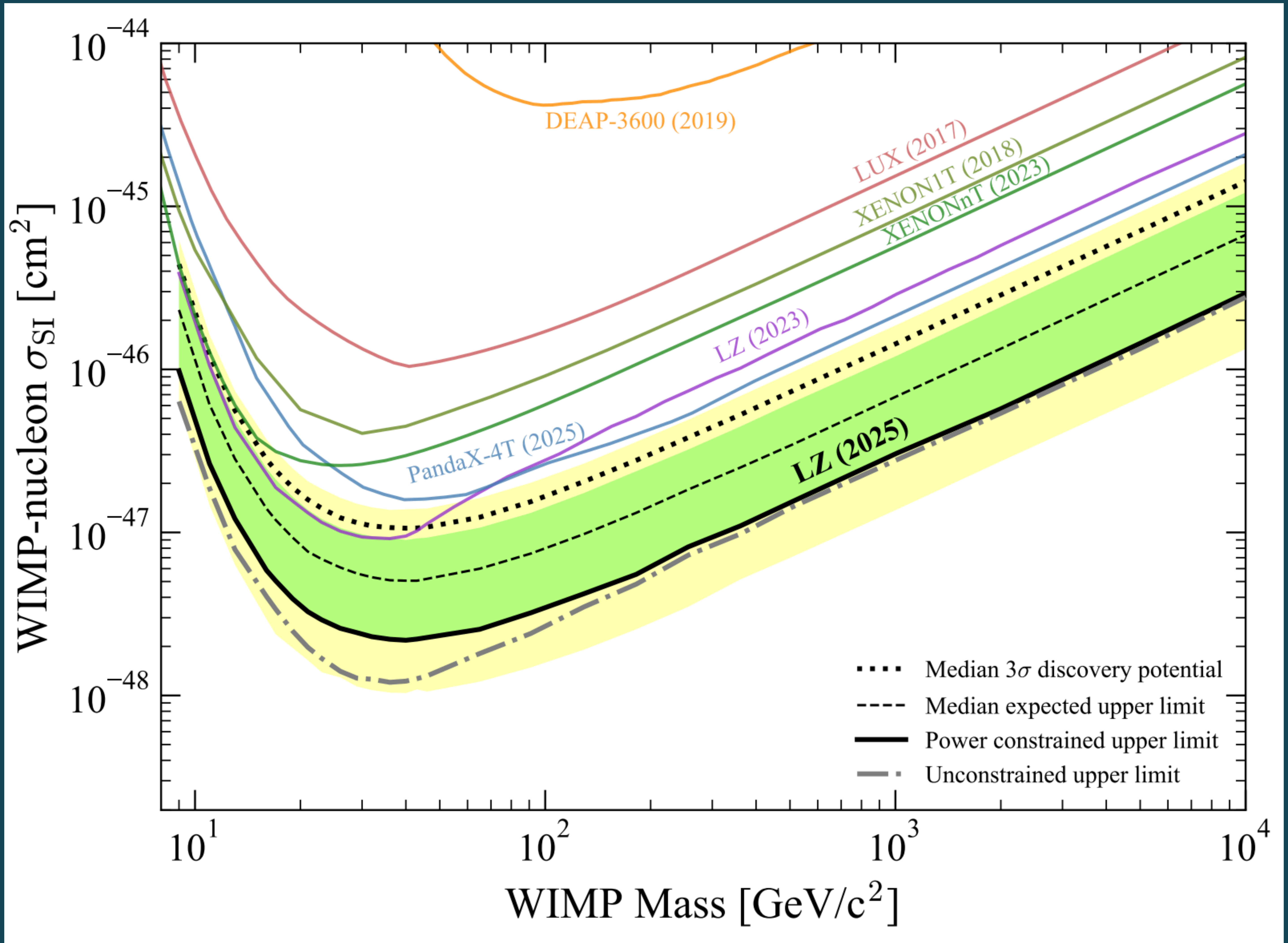
WS2024 FIT RESULTS

Component	Expected Events	Best Fit Events
^{214}Pb β decays	743 ± 88	733 ± 34
^{85}Kr + ^{39}Ar +detector γs	162 ± 22	161 ± 21
Solar ν ERs	102 ± 6	102 ± 6
^{212}Pb + ^{218}Po β decays	62.7 ± 7.5	63.7 ± 7.4
^{3}H + ^{14}C β decays	58.3 ± 3.3	59.7 ± 3.3
^{136}Xe 2νββ decay	55.6 ± 8.3	55.9 ± 8.2
^{124}Xe DEC	19.4 ± 2.5	20.4 ± 2.4
^{127}Xe + ^{125}Xe EC	3.2 ± 0.6	2.7 ± 0.6
Atm. ν CEνNS	0.12 ± 0.02	0.12 ± 0.02
^{8}B + *hep* ν CEνNS	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



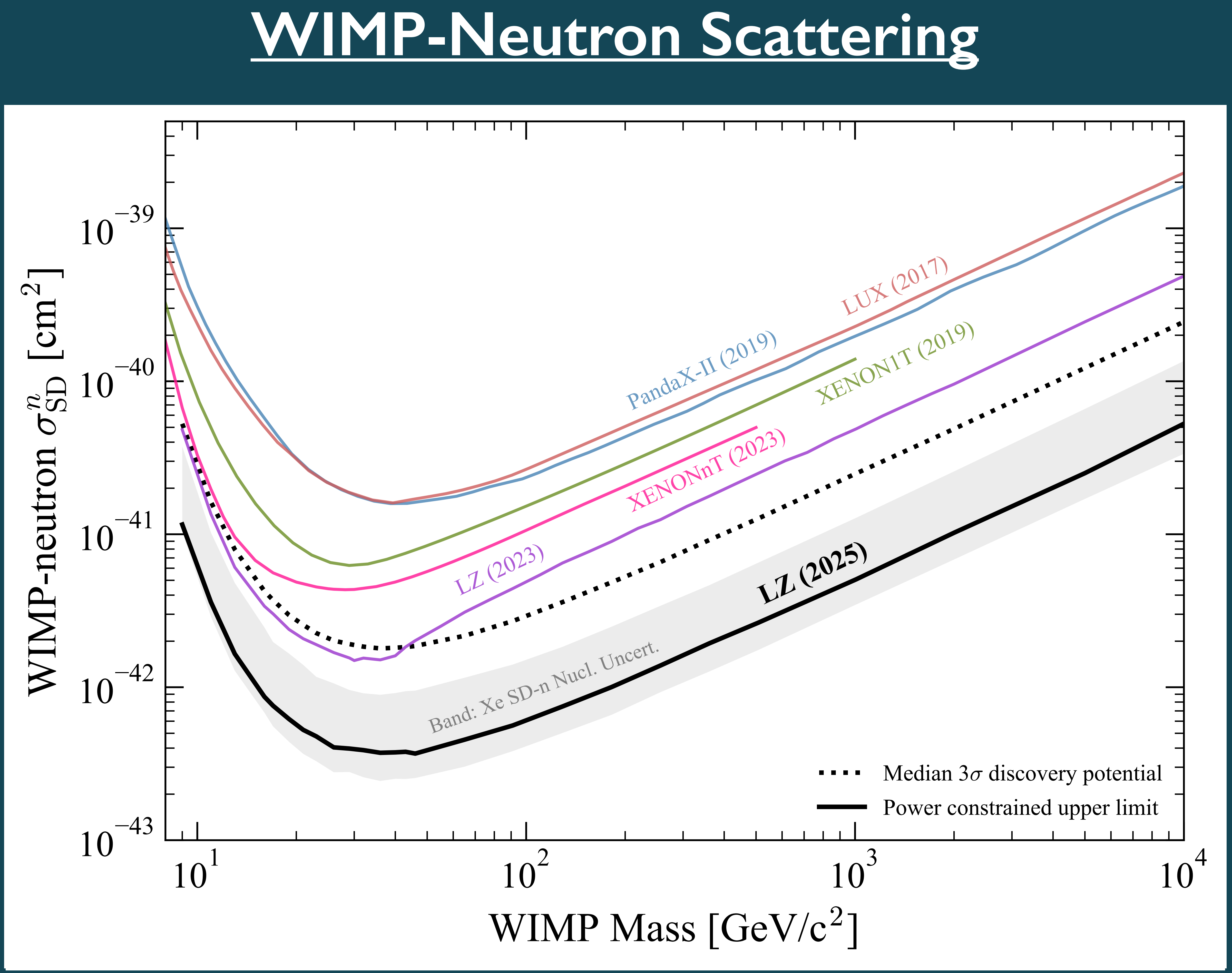
- Best fit of zero WIMPs at all masses tested (9 GeV/c² - 100 TeV/c²)
- Good agreement with background-only hypothesis in all spaces examined

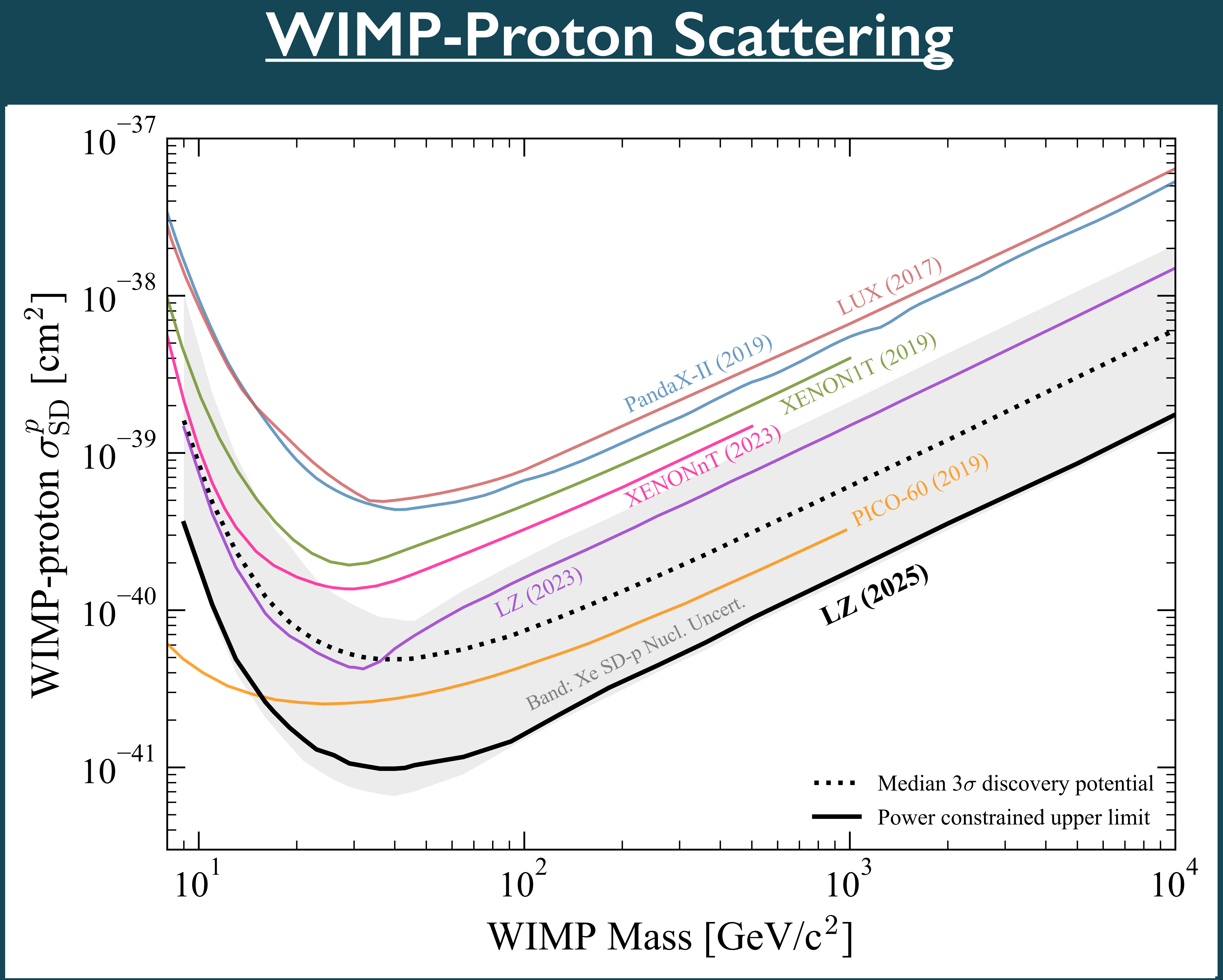
WS2024+WS2022 SPIN-INDEPENDENT LIMIT



- 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 σ_{SI}= 2.2 × 10^{-48} cm^2 for 40 GeV/c^2
- **Results & analysis in paper** ***PRL 135, 011802 (2025)***

WS2024+WS2022 SPIN-DEPENDENT LIMITS

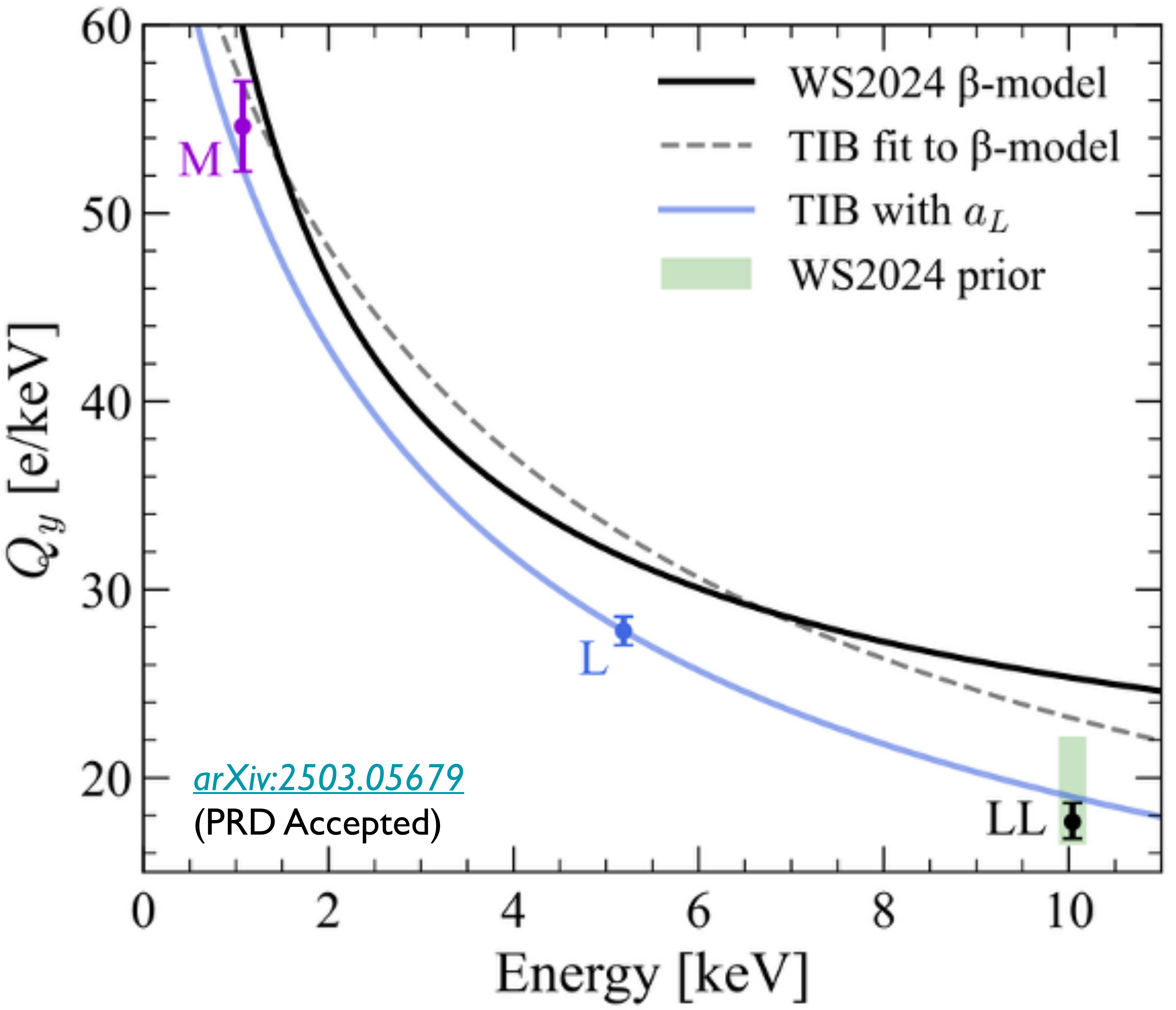




Uncertainty bands represent the theoretical uncertainty on the Xe nuclear structure factor

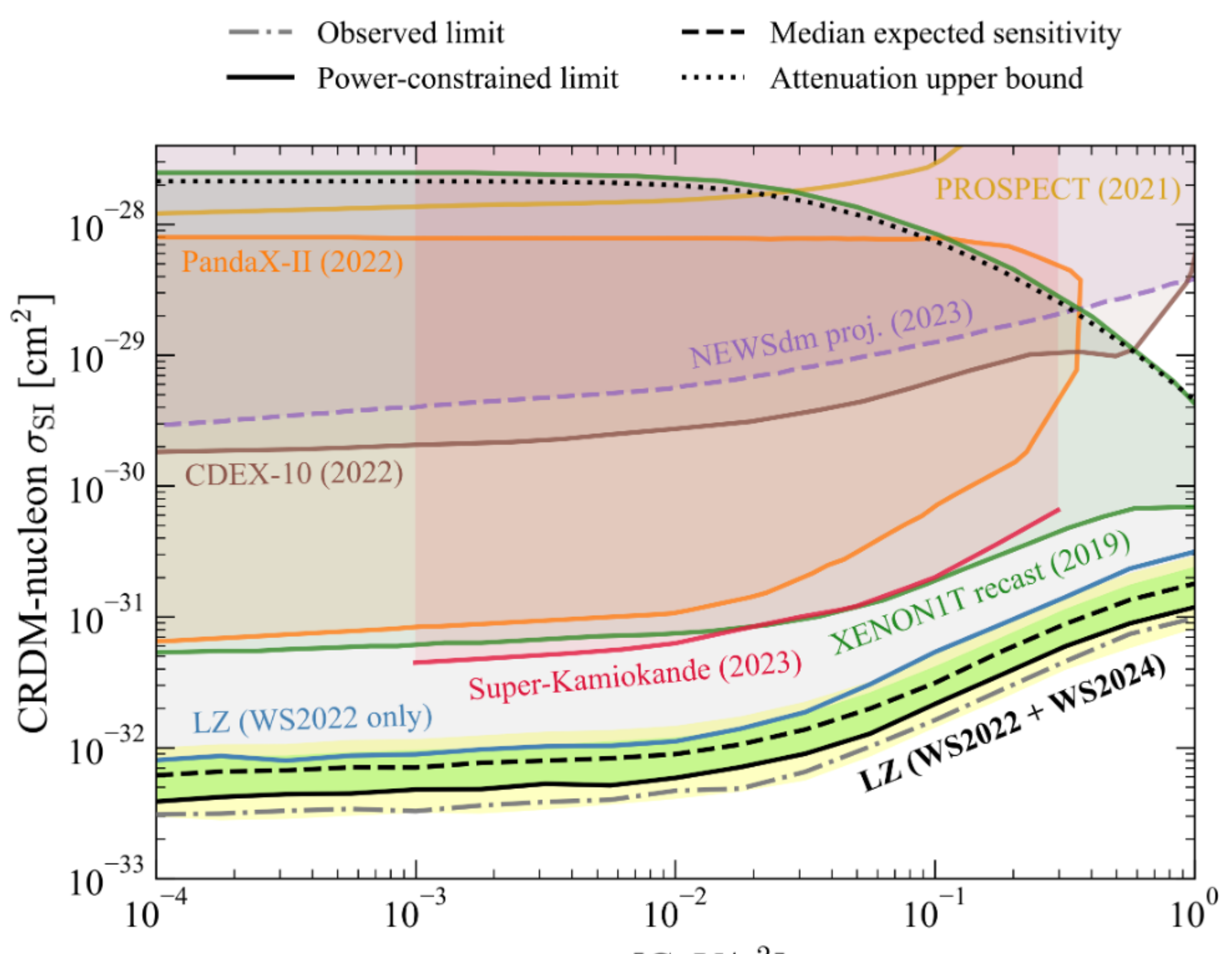
MORE RECENT PUBLICATIONS

Measurements of Enhanced Recombination



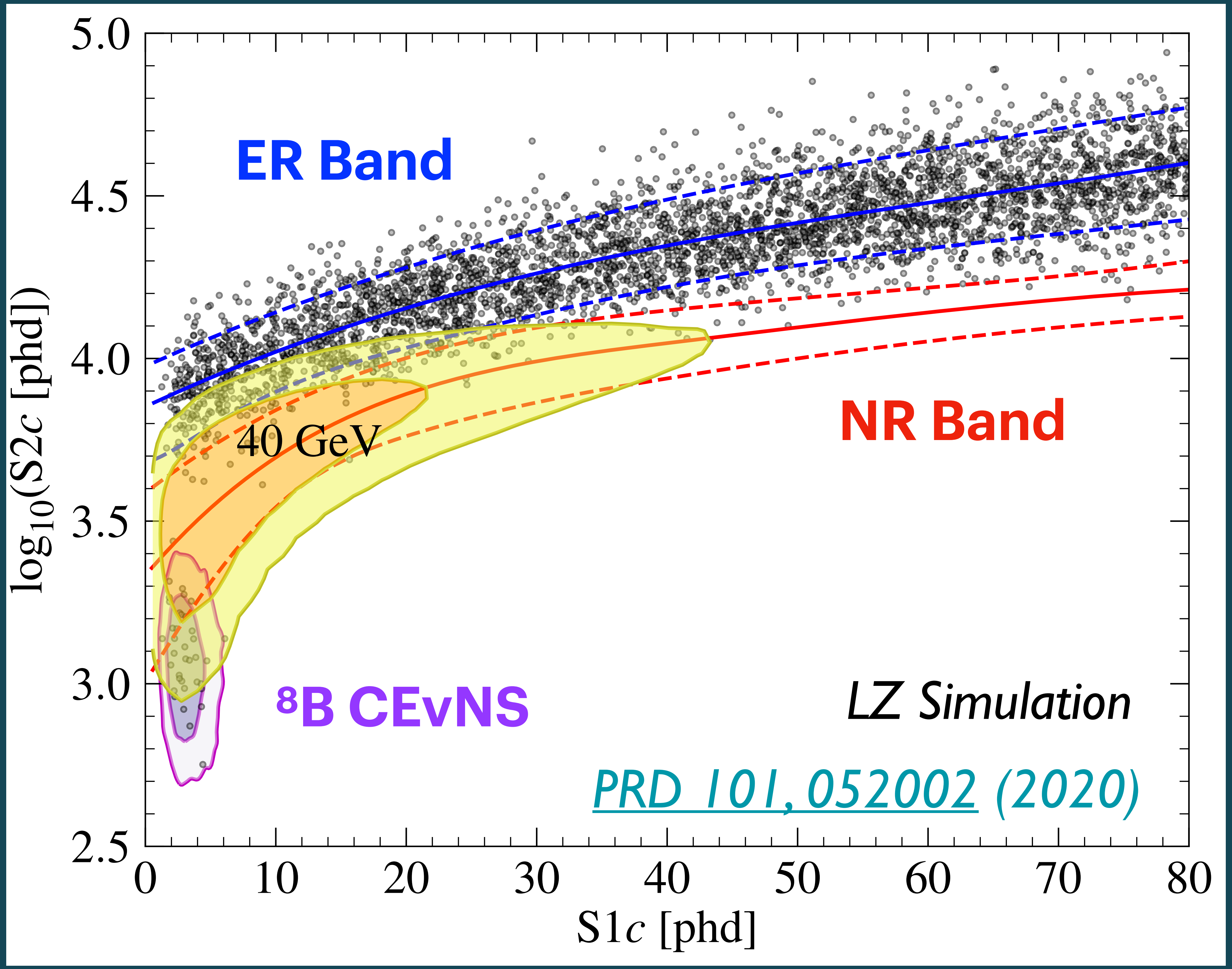
arXiv:2503.05679
(PRD Accepted)

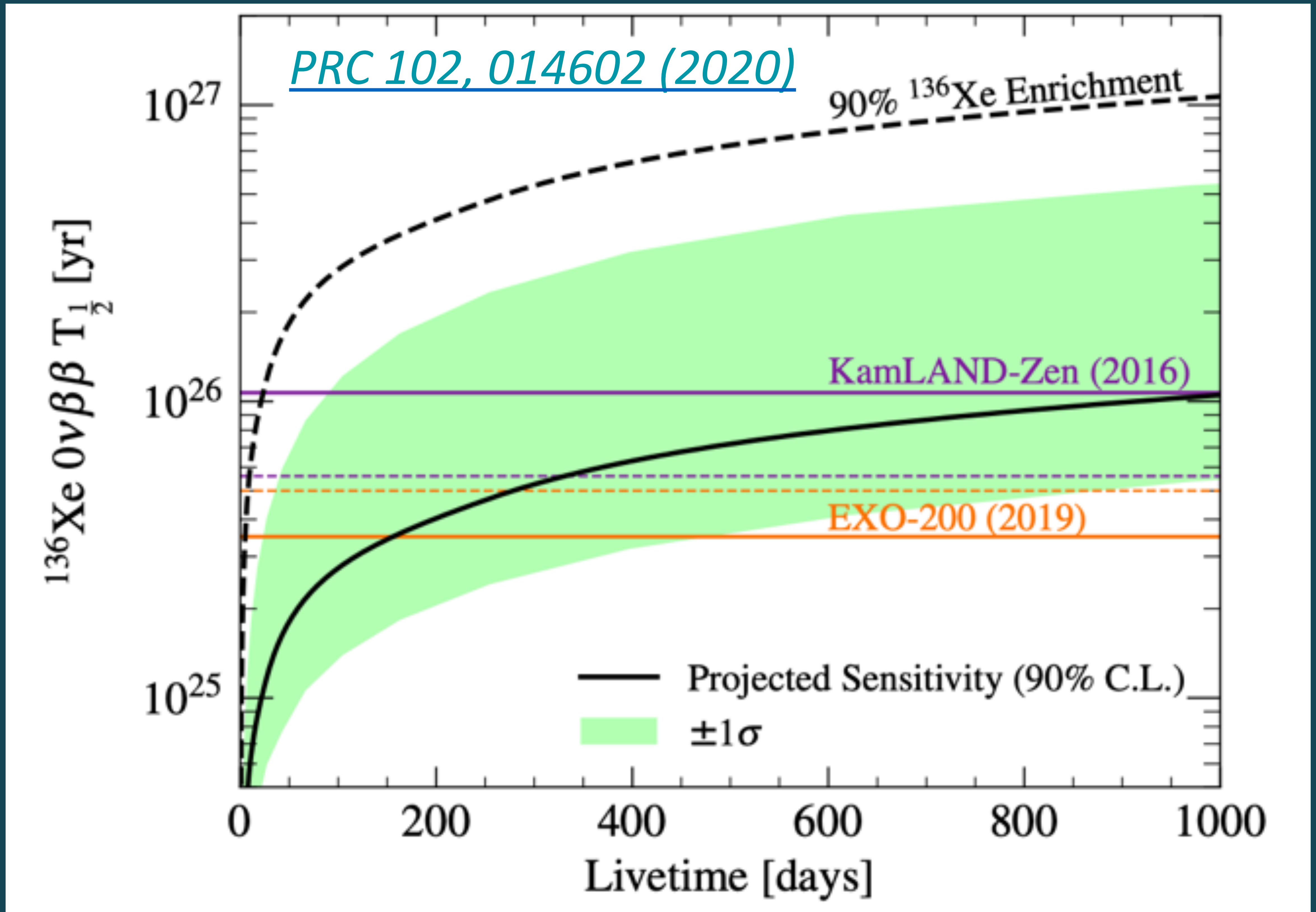
Cosmic Ray-Boosted Dark Matter



PRL 134, 241801 (2025)

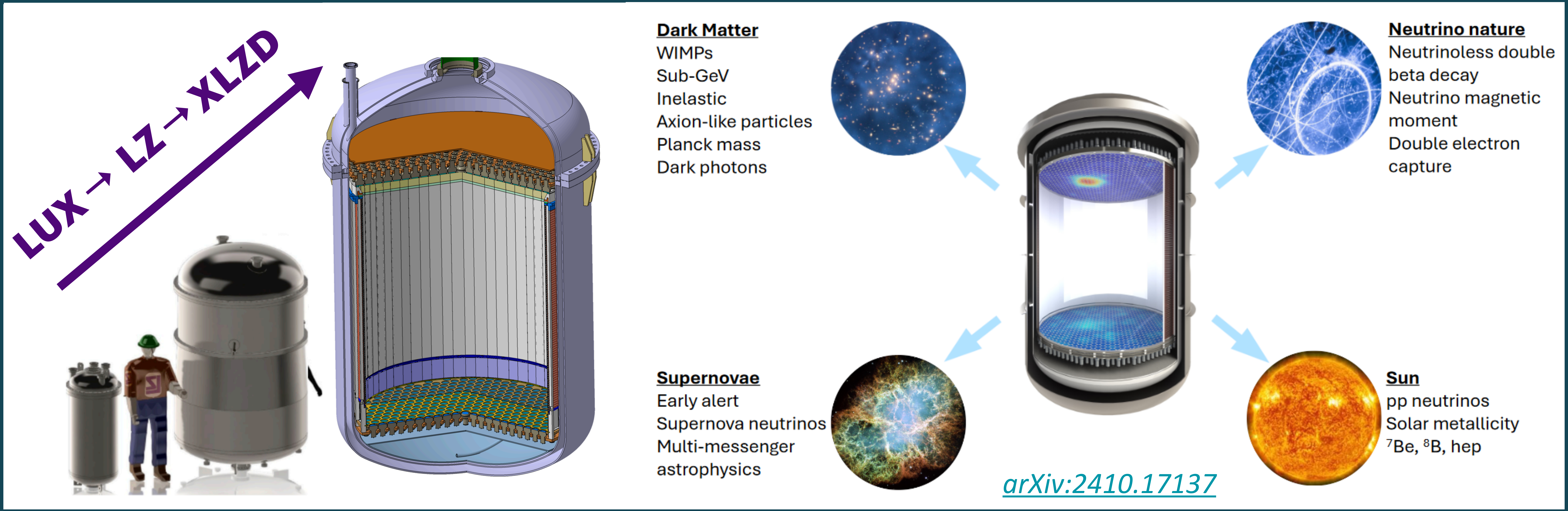
WHAT'S NEXT FOR LZ?





- 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 0νββ decay search - demonstrate competitiveness of this technology

FURTHER INTO THE FUTURE - XLZD



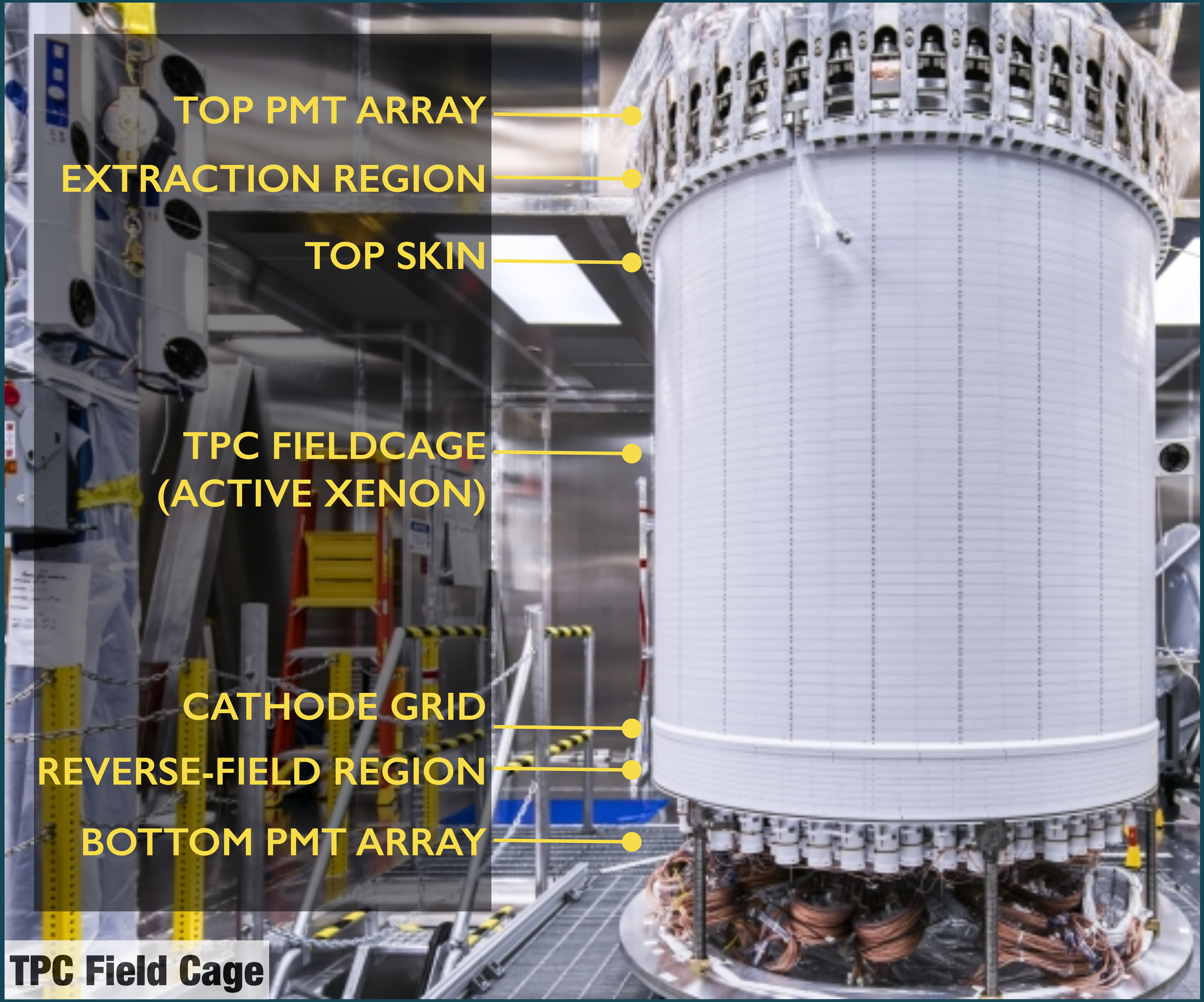
- XLZD will use a 60-80 t xenon TPC (an order of magnitude bigger than current experiments)
- Merger of XENON, LZ, DARWIN → ~500 people in 72 institutions, 17 countries
- A rare-event observatory, more than just the “definitive” WIMP search experiment

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. ^{8}B CEvNS, neutrinoless double beta decay
  - **LZ is discovery-ready for WIMPs**
- Planning and R&D underway for next-generation, XLZD

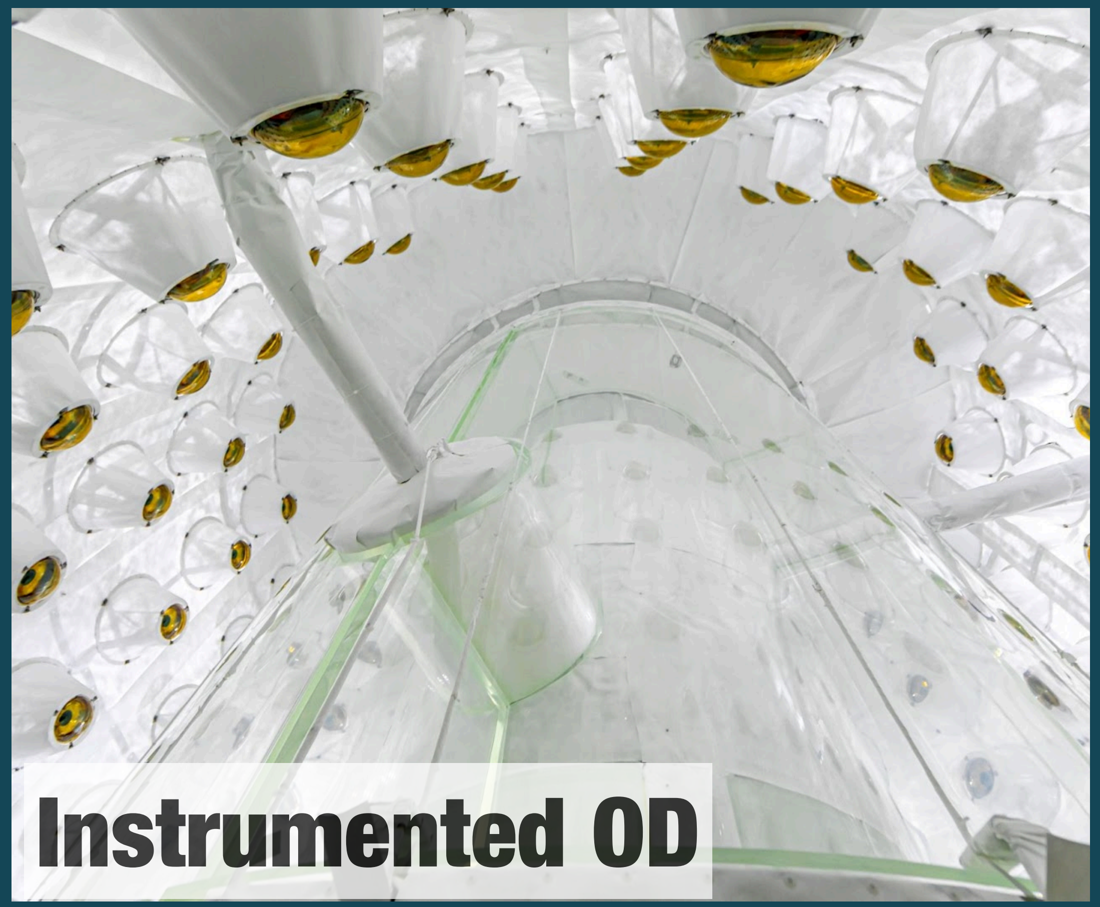
Back Up Slides

THE LZ EXPERIMENT



TPC Field Cage

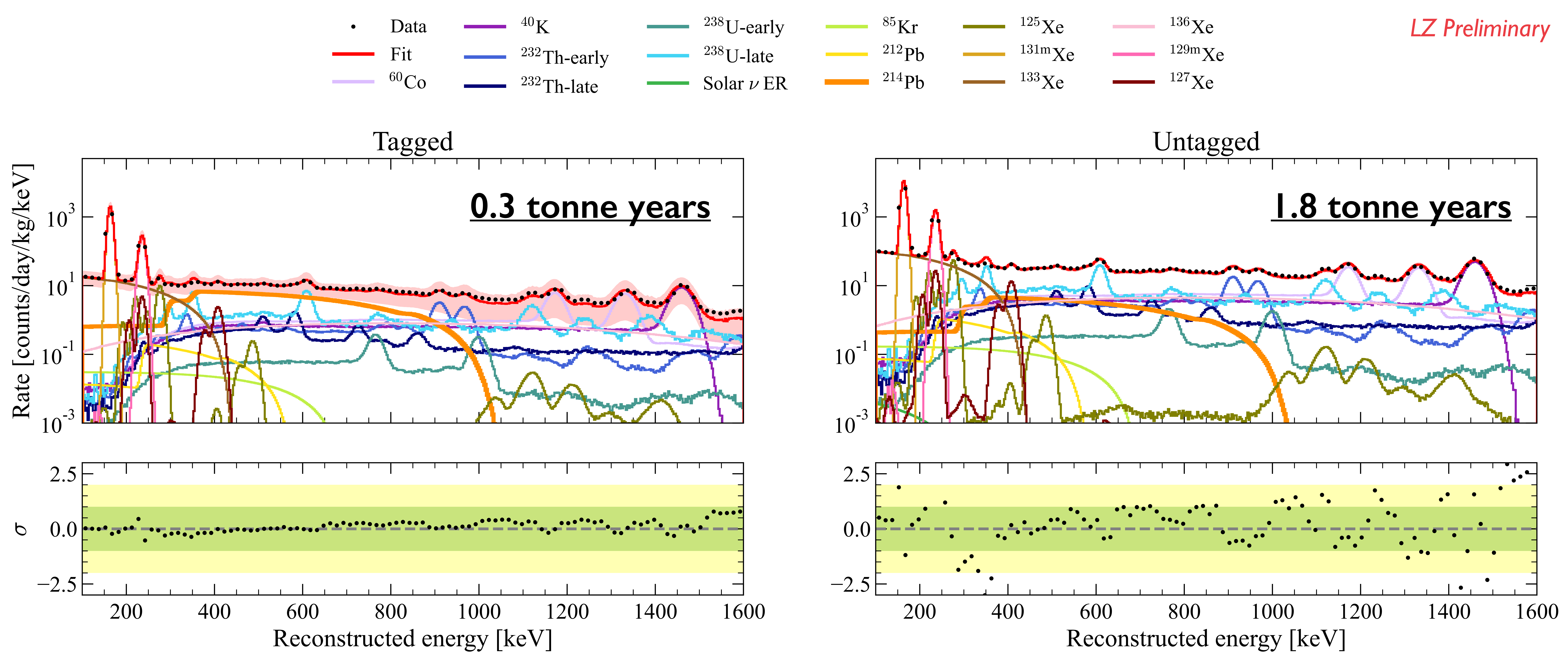

Bottom Side Skin PMTs


Instrumented OD


Bottom Dome Skin PMTs


Water Tank Panoramic

RADON TAGGED HIGH-ENERGY BACKGROUND FIT



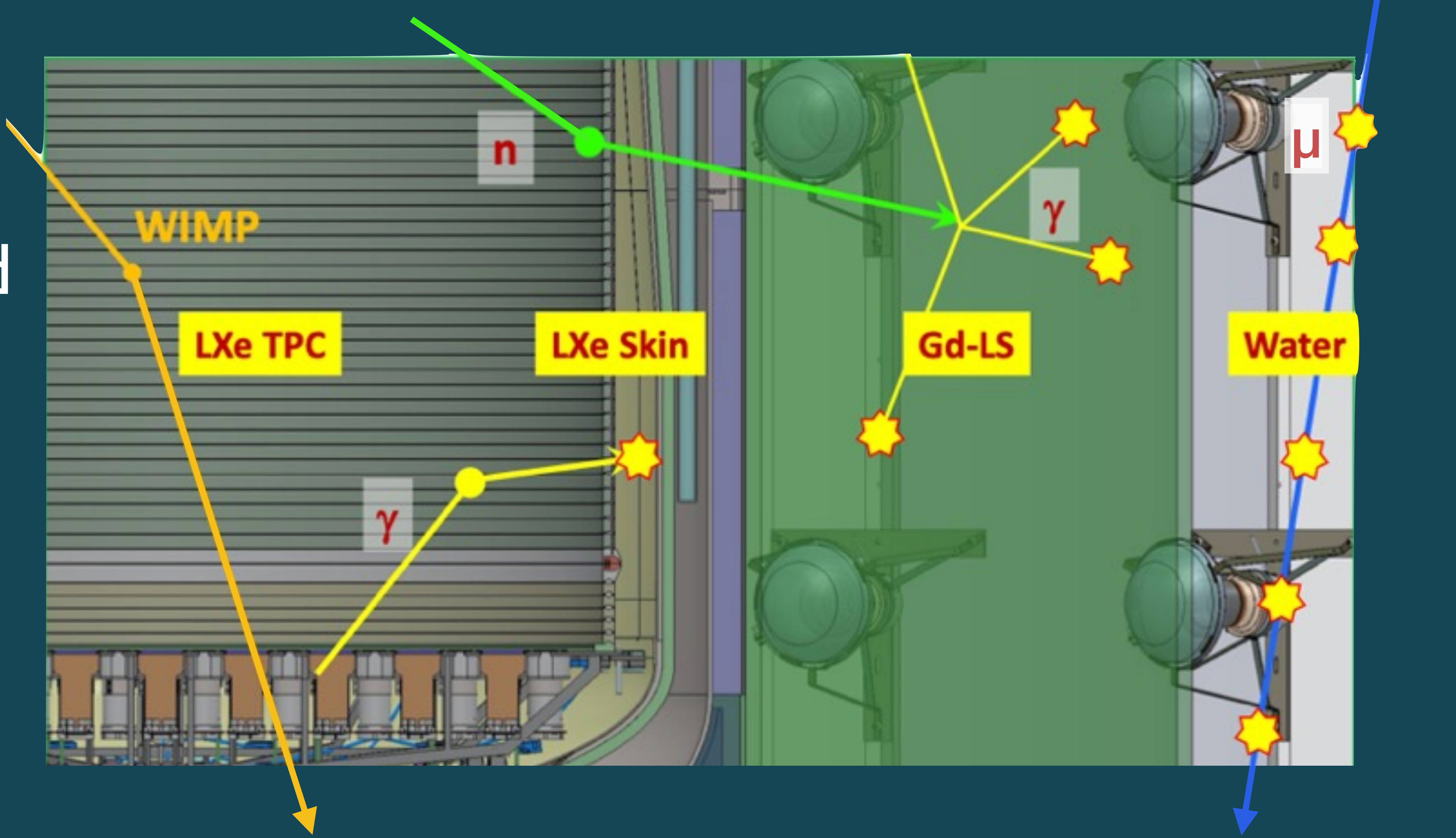
Effective untagged ^{214}Pb activity of 1.8 ± 0.3 µBq/kg (compared to 3.9 ± 0.6 µBq/kg in total exposure)

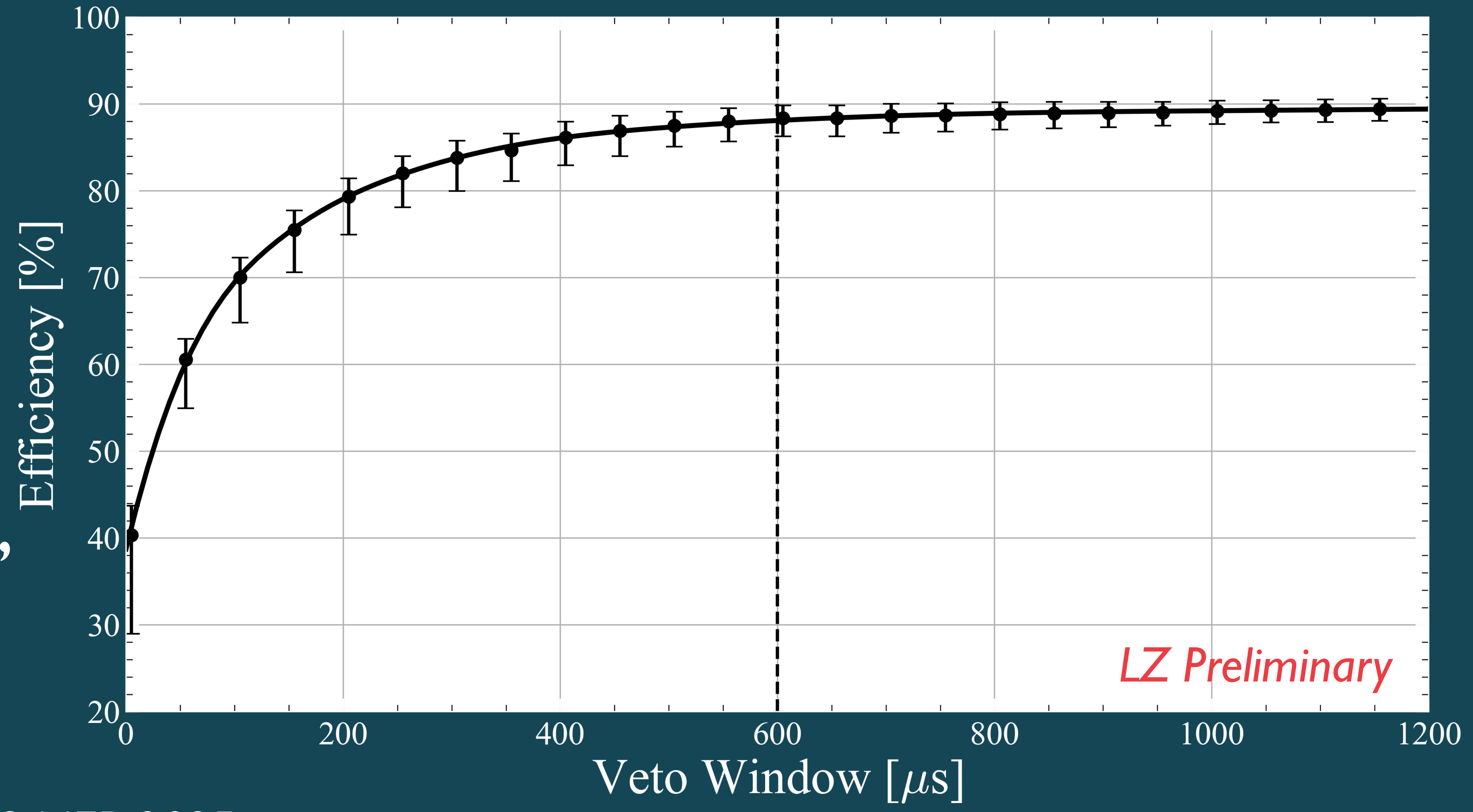
NEUTRONS & OD

- 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

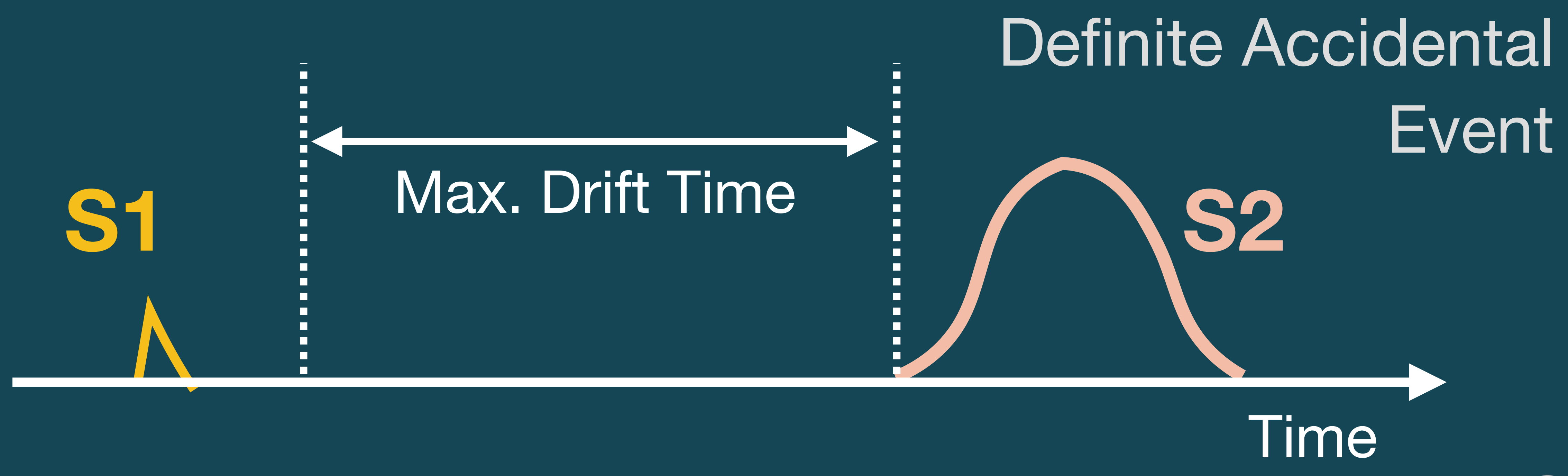
- AmLi neutron calibration-derived neutron veto efficiency = 89 ± 3 %
- Simulated neutron veto efficiency for radiogenic, background neutrons = **92 ± 4 %**
  → used for neutron constraint in final analysis

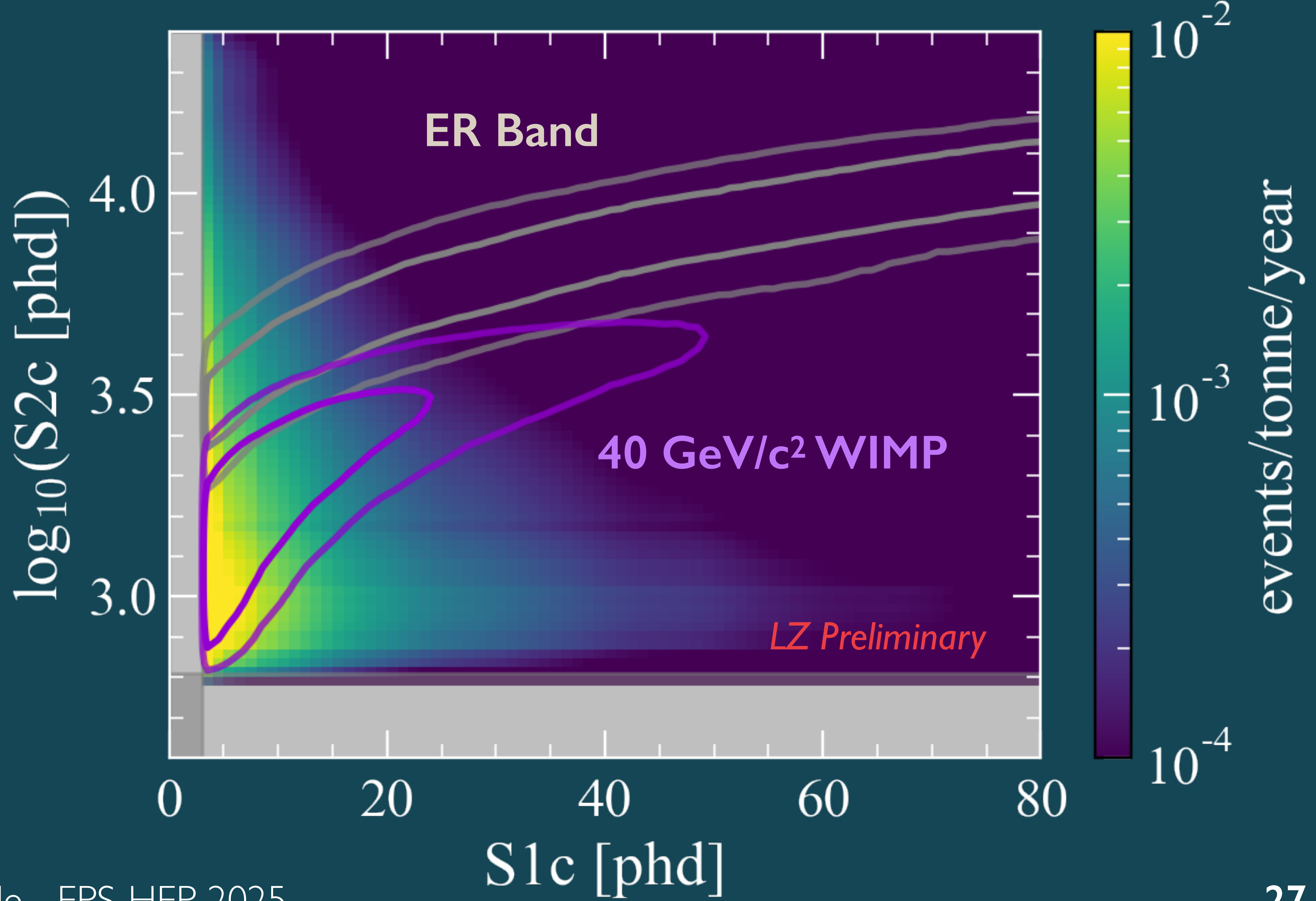




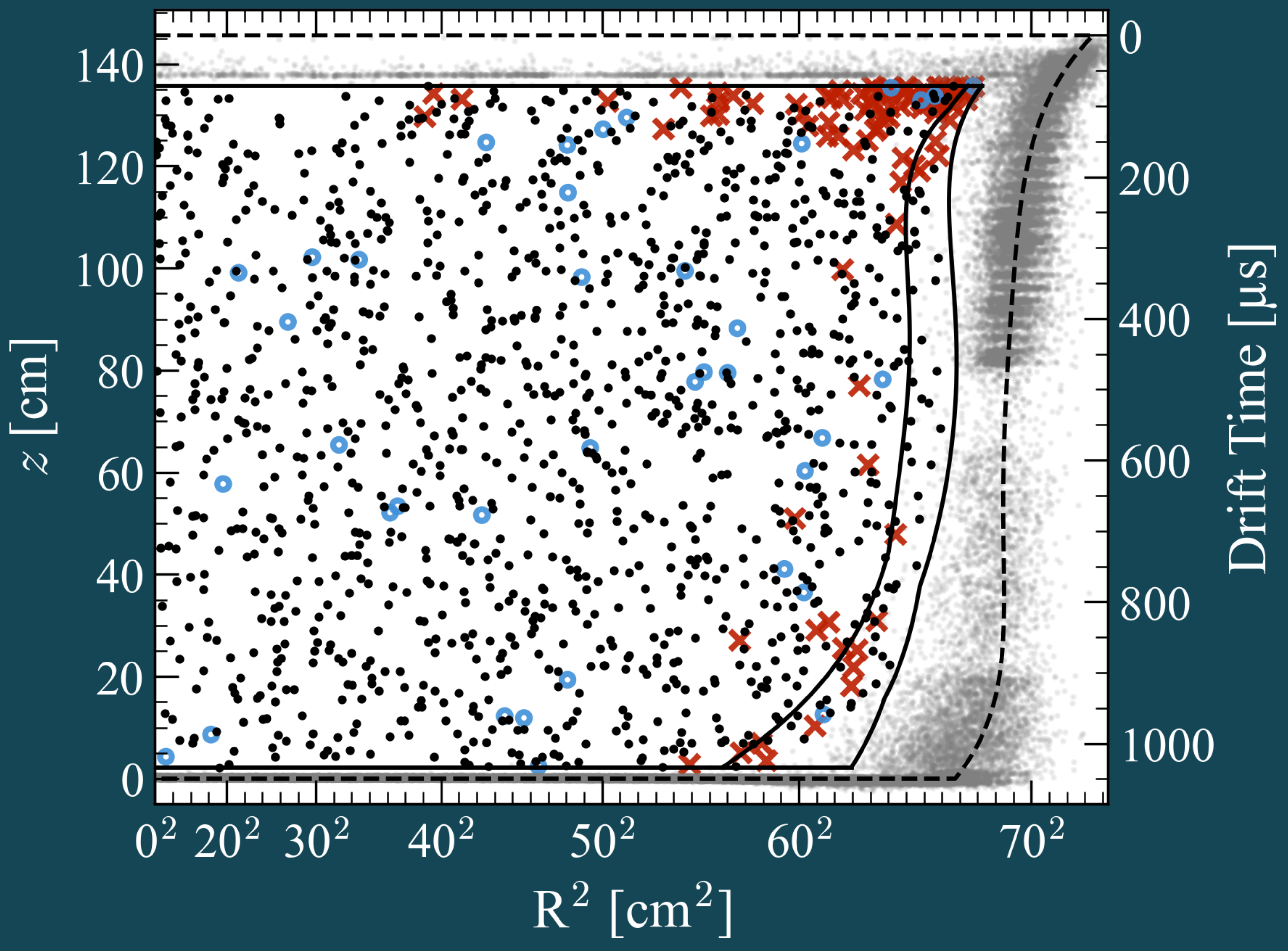
ACCIDENTAL COINCIDENCES

- 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 μs < drift time < 1030 μs
  - Azimuthally & drift time-dependent radial cut chosen to ensure <0.01 wall background counts in the FV
- Calculated fiducial mass of **5.5 ± 0.2 t**

COMBINED LIKELIHOOD

<u>Exposures in Each Sample in Tonne Years</u>

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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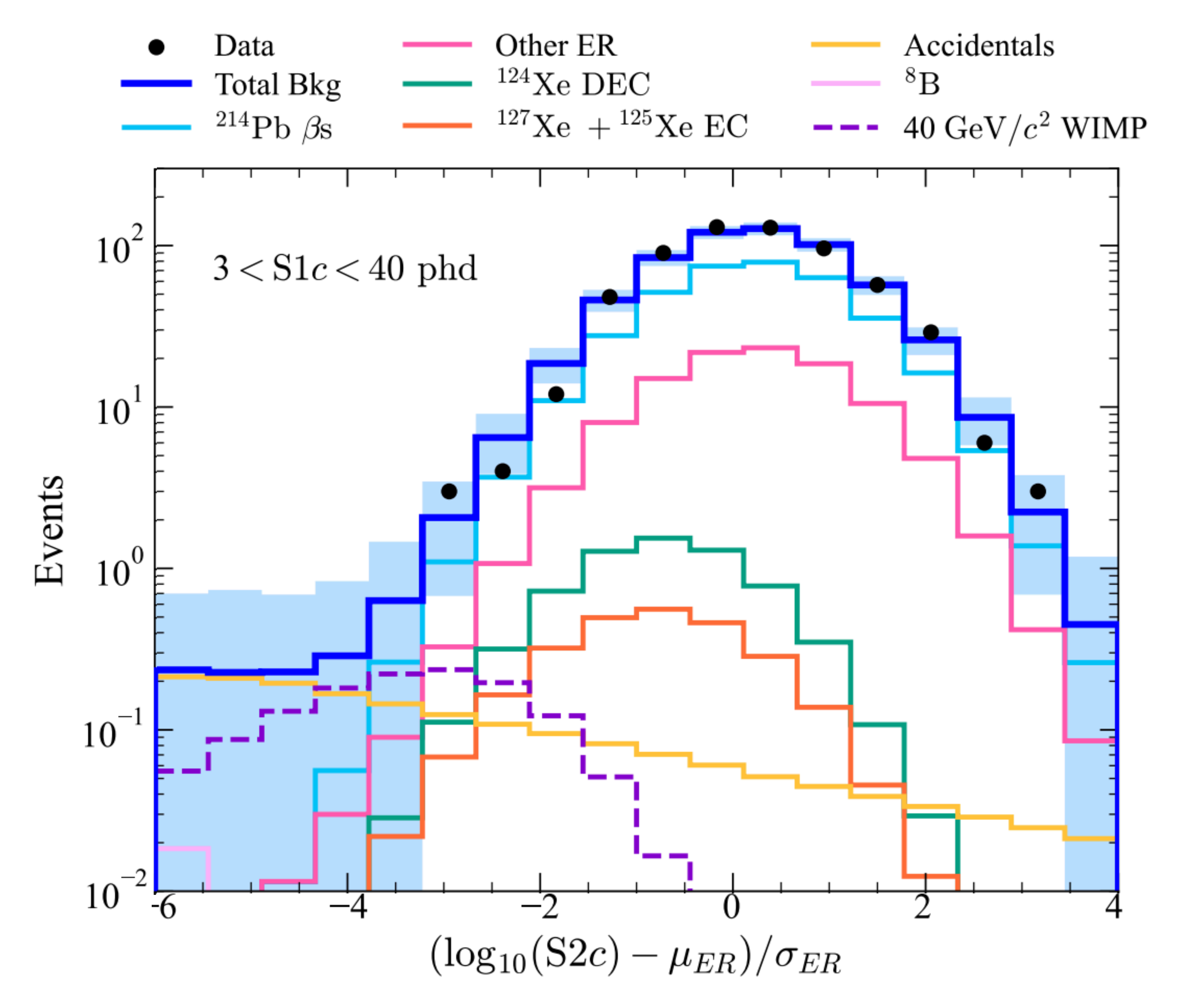
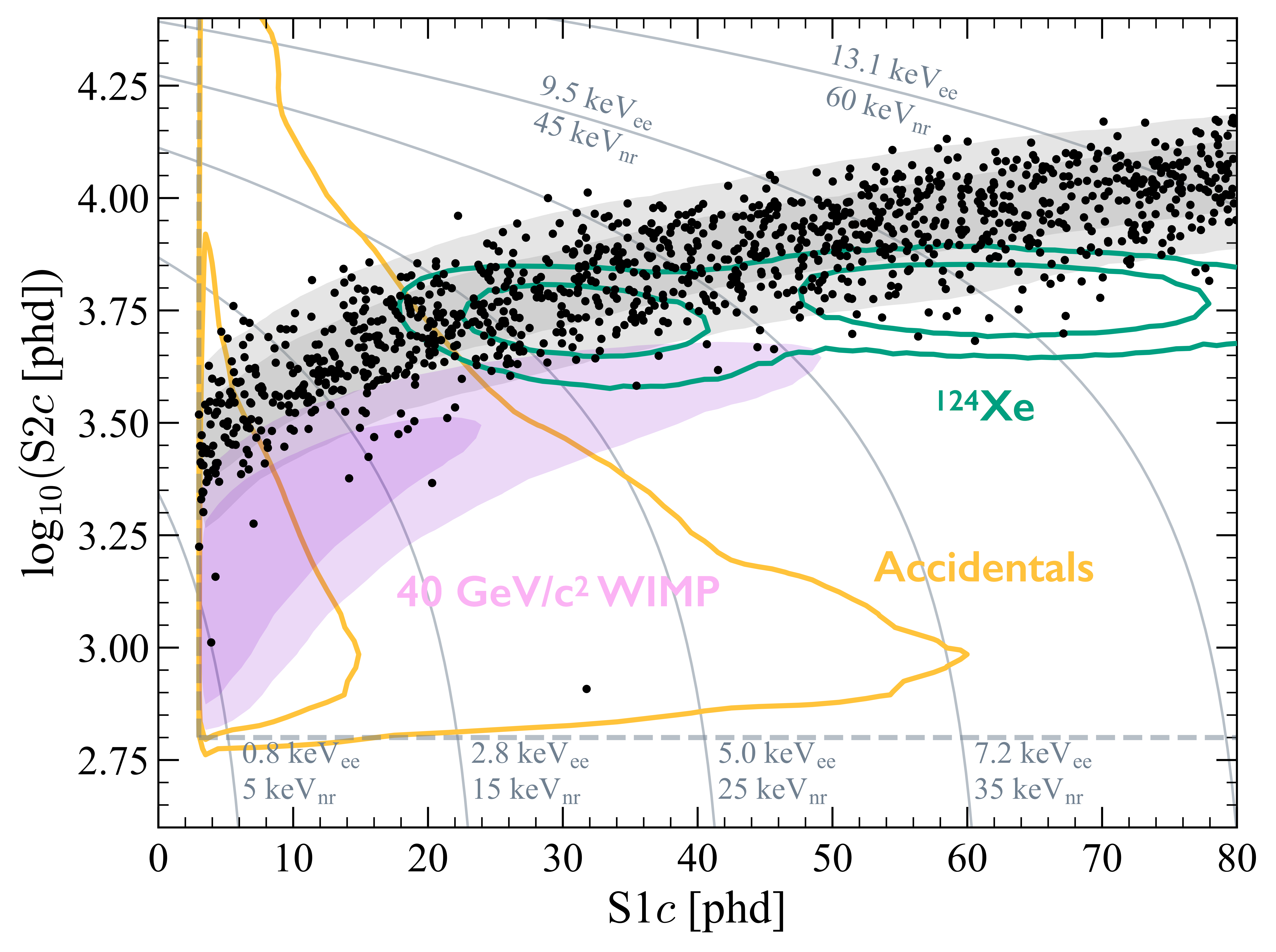


- Best fit of zero WIMPs at all masses tested (9 GeV/c² - 100 TeV/c²)
- Good agreement with background-only hypothesis in all spaces examined

WS2024 DATA - SALTED

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



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- Final exposure of
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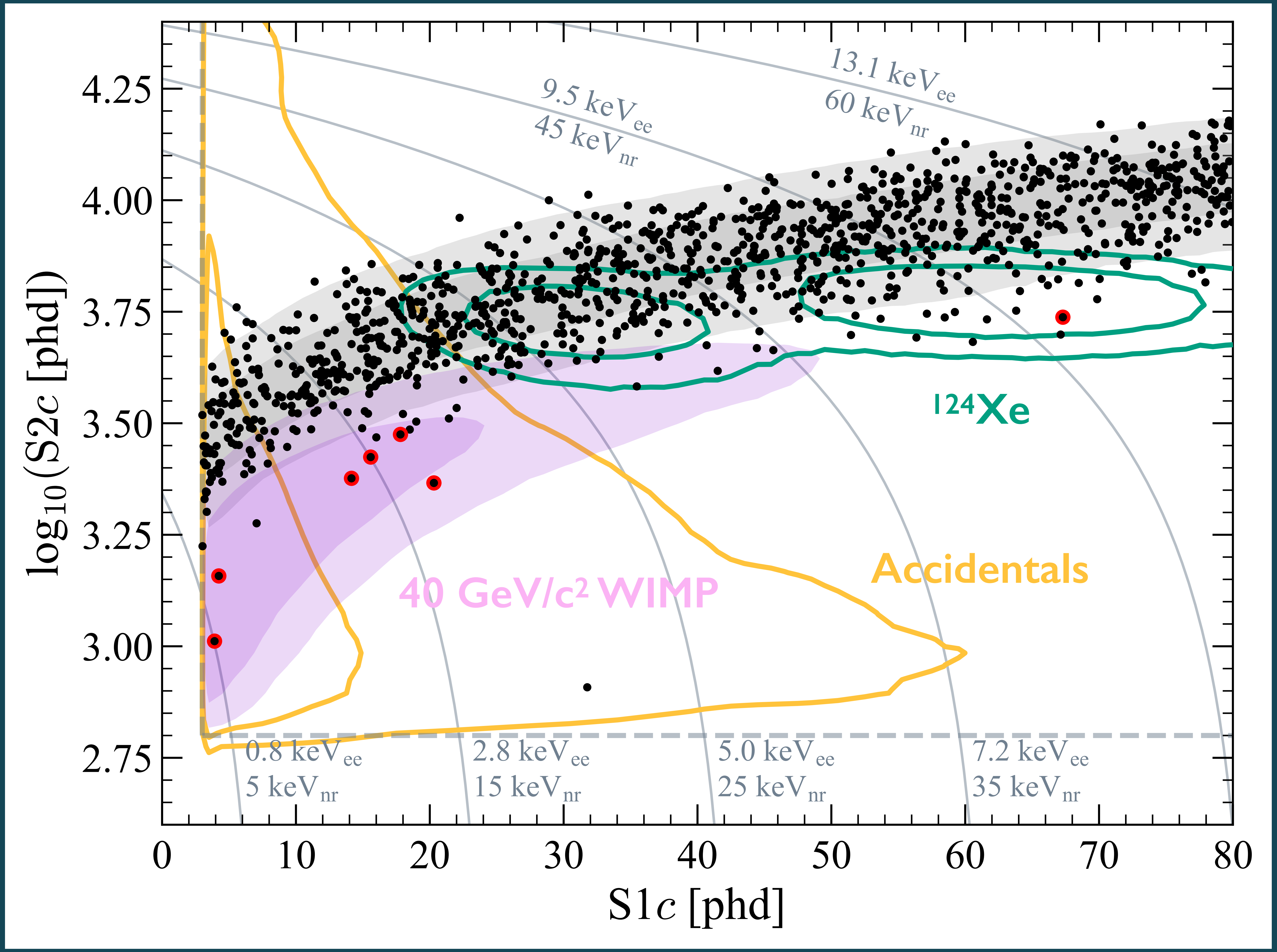
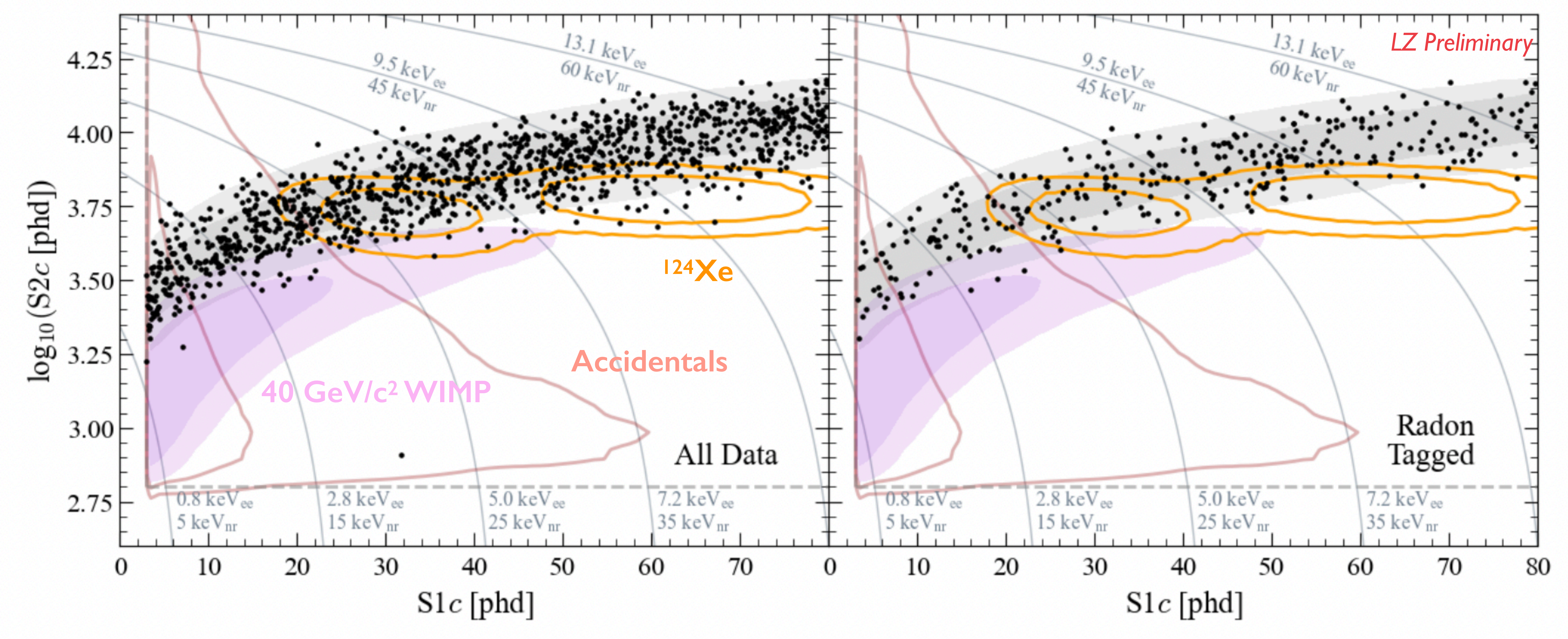
  = **3.3 tonne years**

- 7 salt events pass all analysis cuts out of 8 total injected in WS2024
  → inline with evaluated signal efficiency

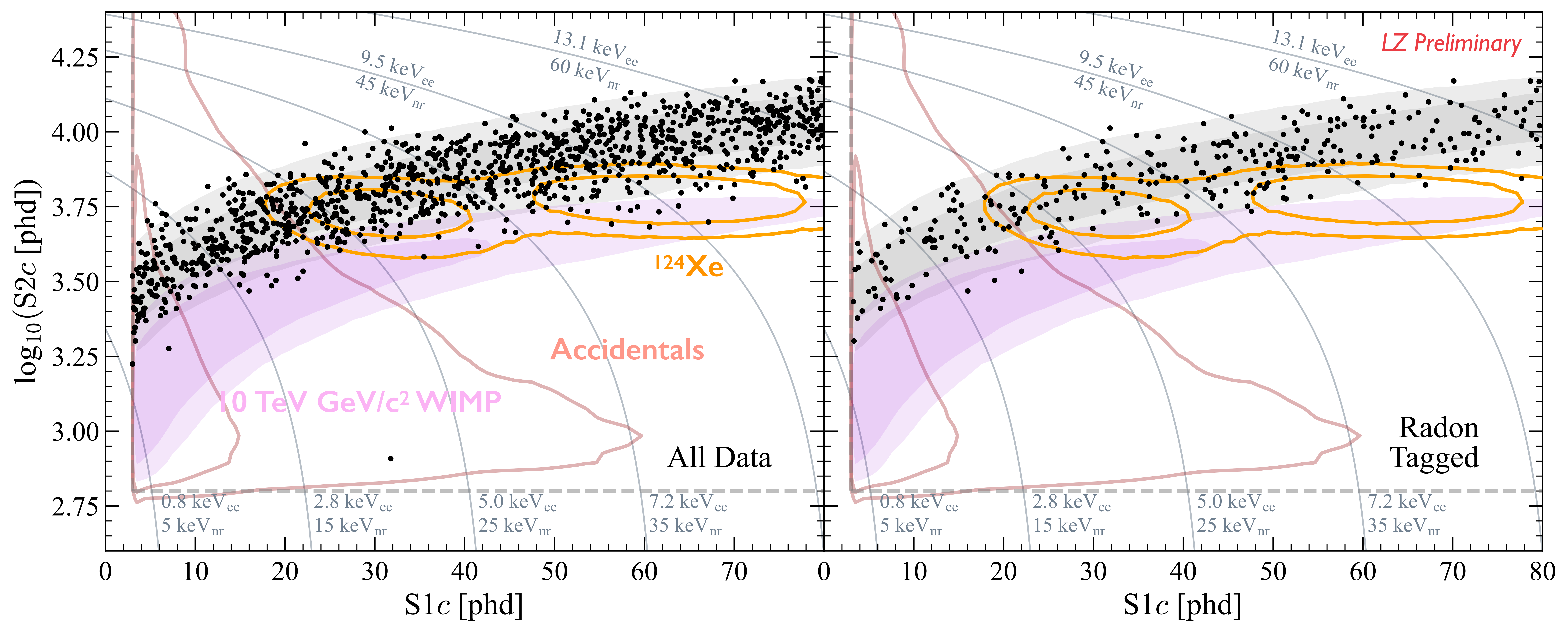


WS2024 DATA - UNSALTED; RADON TAGGED

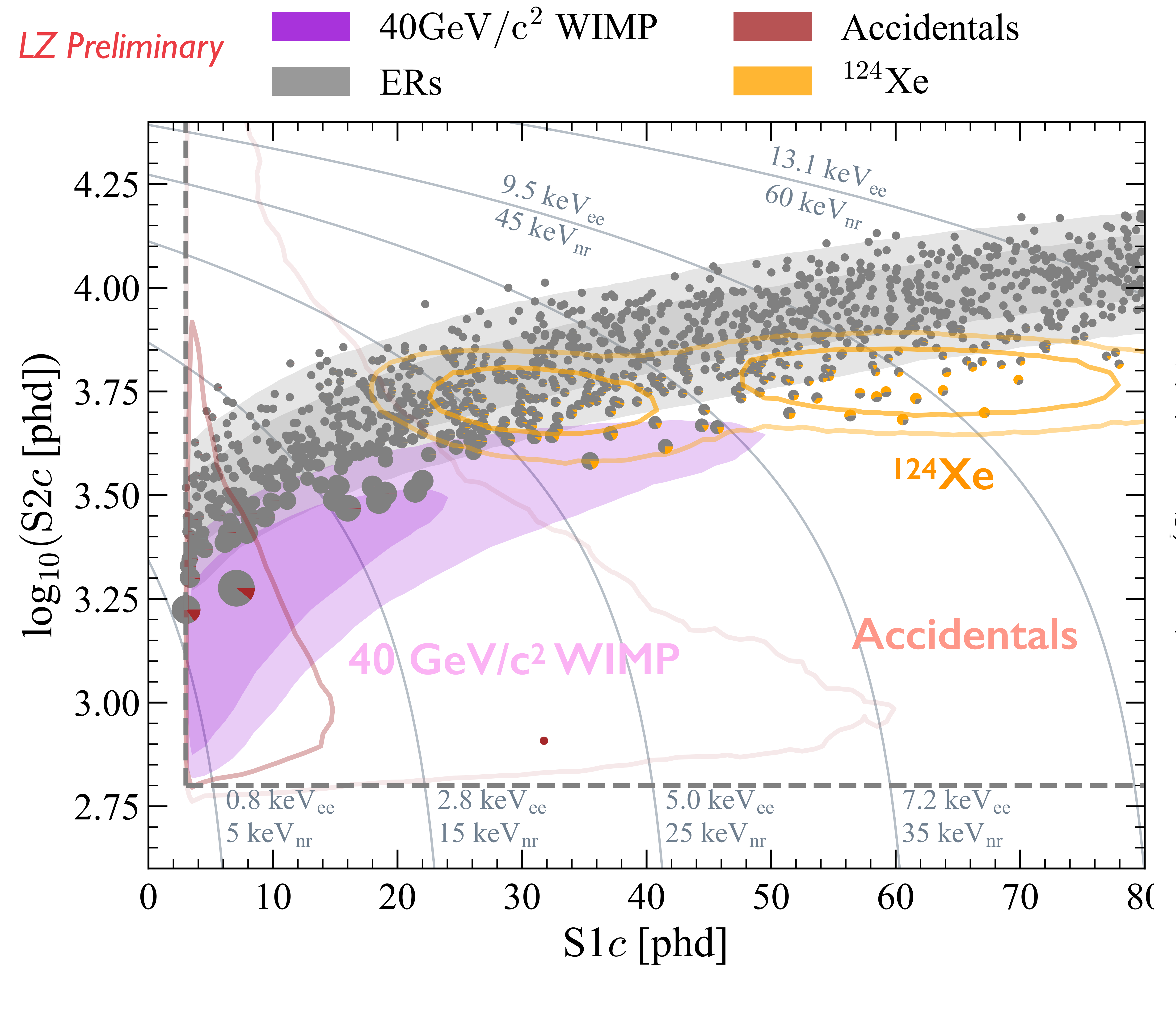


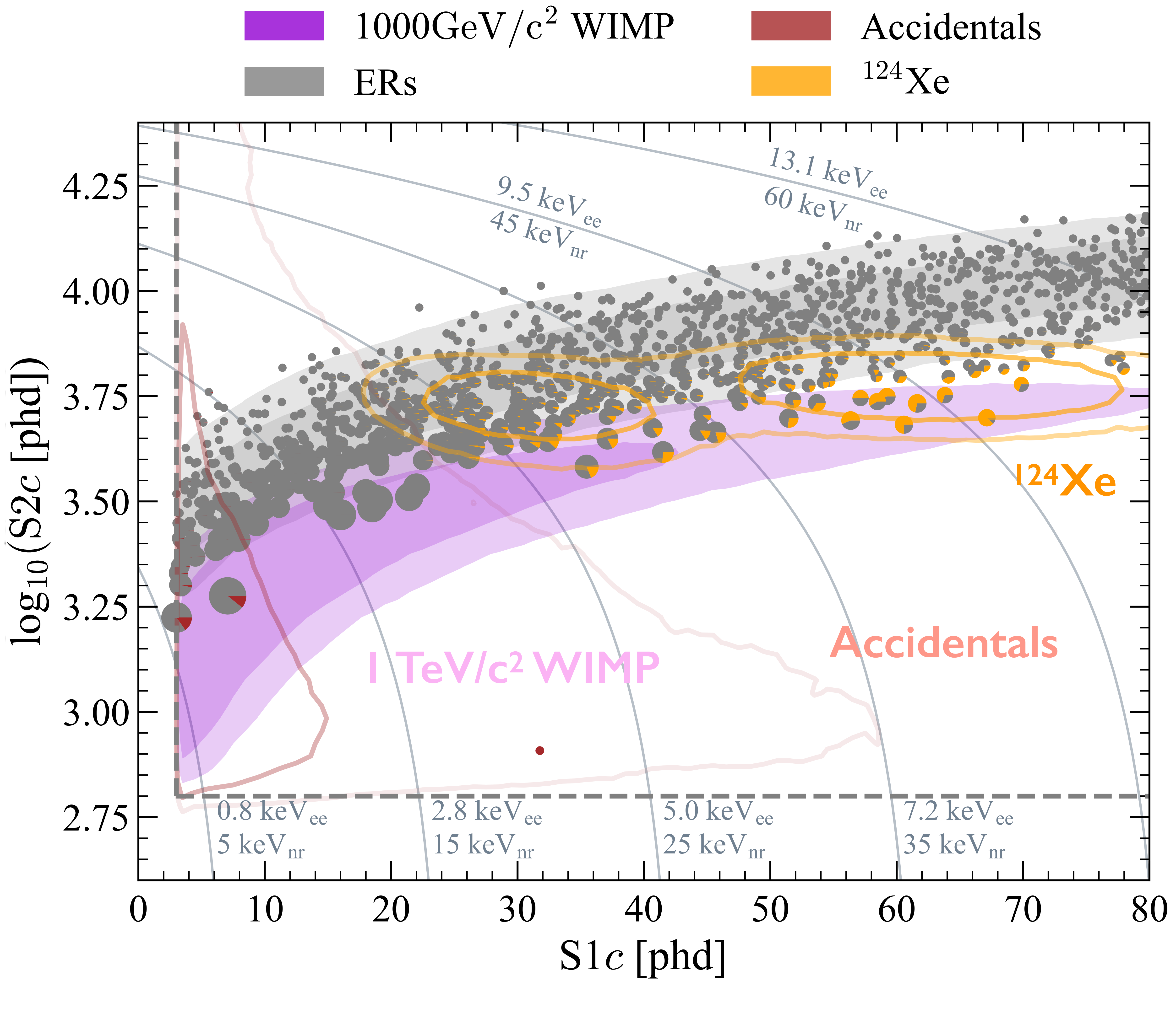
3.3 tonne years **0.3 tonne years**

10 TEV/C² WIMP



WS2024 DATA PIE PLOT

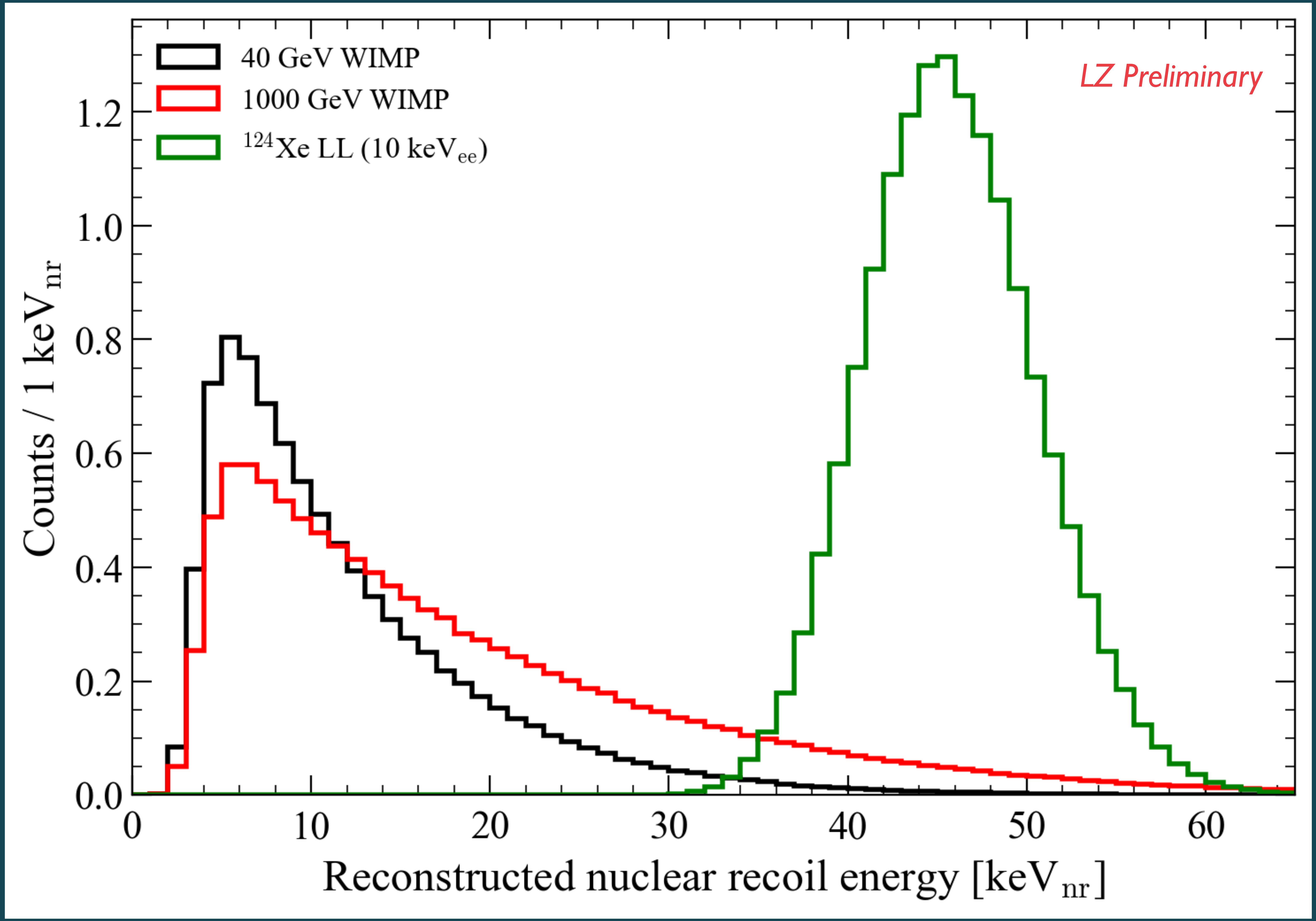




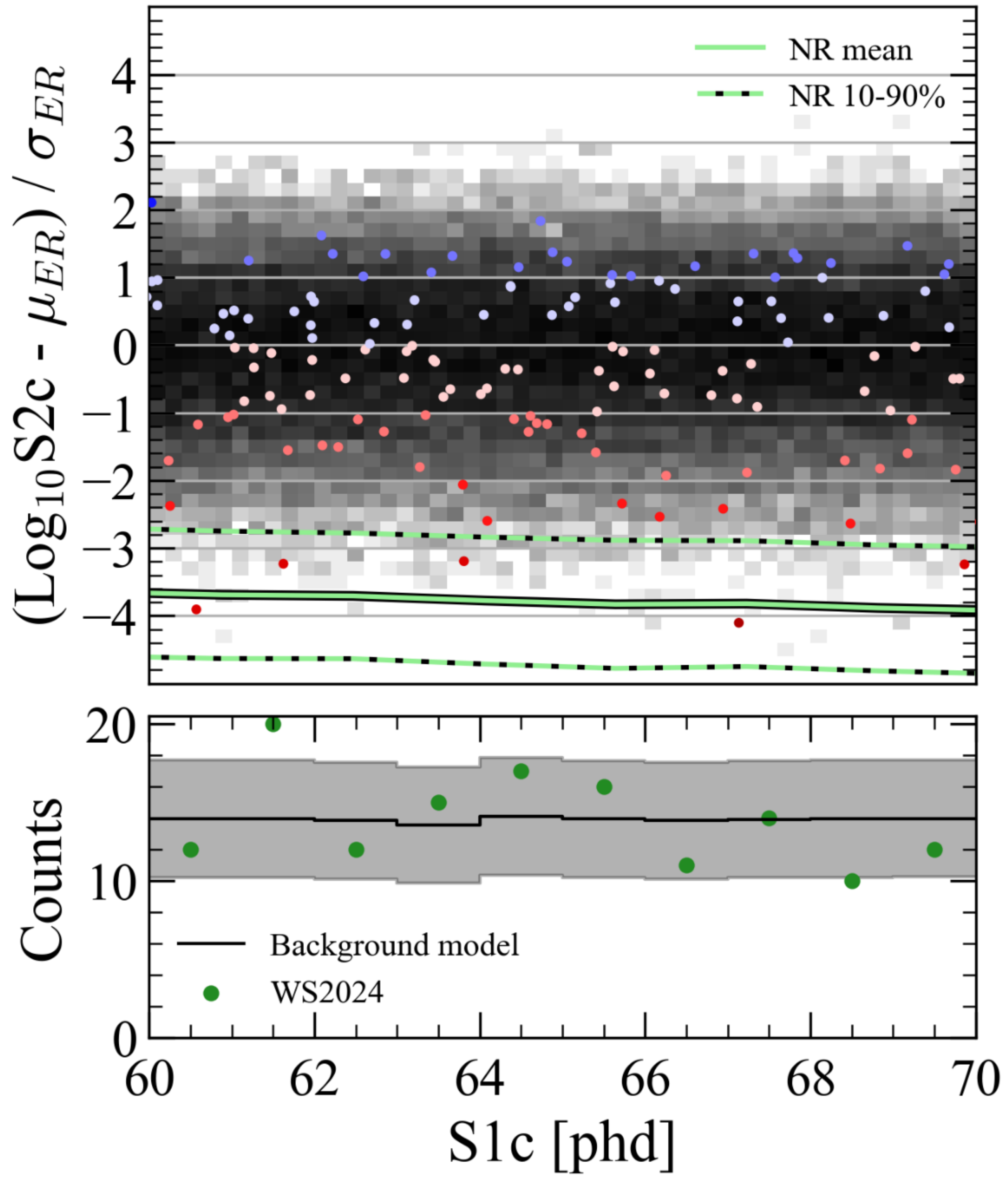
^{124}XE LL-SHELL COMPARED TO DARK MATTER SPECTRA

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

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



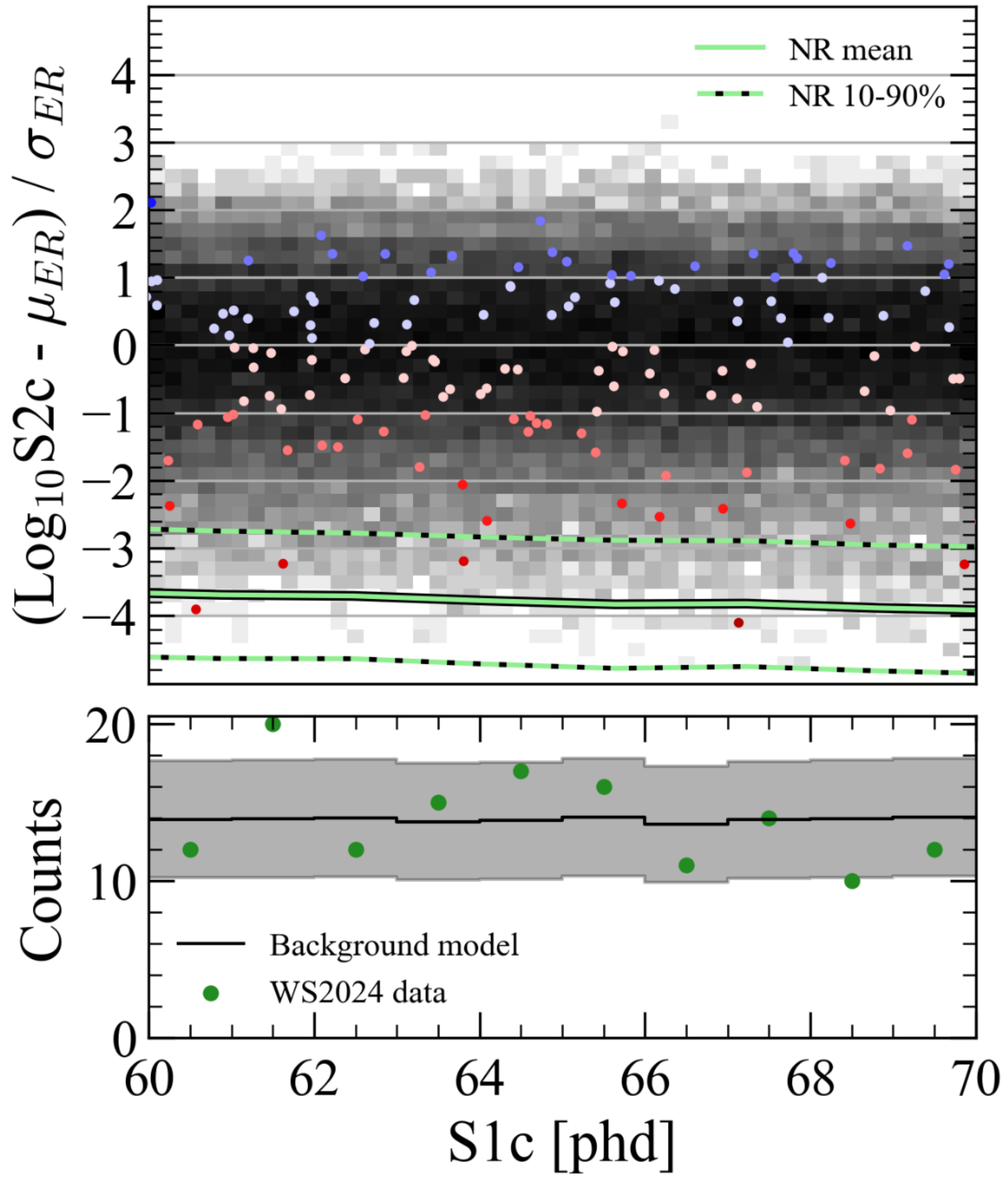
GOODNESS OF FITS IN KEY ^{124}XE REGION



60 < S1c < 70
138 counts

σ	Expt.	Obs.	p_{LR}	p_{MC}	p_{Pois}
[-5, -4]	0.11	1	0.1	0.092	5.2e-03
[-4, -3]	0.86	4	0.014	8.6e-03	2.0e-03
[-3, -2]	6.1	7	0.74	0.84	0.28
[-2, -1]	23	25	0.77	0.85	0.34
[-1, 0]	51	41	0.14	0.25	0.087
[0, 1]	51	37	0.030	0.063	0.02
[1, 2]	19	22	0.62	0.66	0.26
[2, 3]	2.4	1	0.31	0.45	0.31

LZ Preliminary



60 < S1c < 70
138 counts

σ	Expt.	Obs.	p_{LR}	p_{MC}	p_{Pois}
[-5, -4]	0.44	1	0.47	1.0	0.073
[-4, -3]	2.6	4	0.42	0.54	0.12
[-3, -2]	7.4	7	0.89	1.0	0.54
[-2, -1]	21	25	0.52	0.52	0.22
[-1, 0]	50	41	0.17	0.33	0.10
[0, 1]	52	37	0.026	0.063	0.017
[1, 2]	19	22	0.63	0.68	0.26
[2, 3]	2.4	1	0.29	0.43	0.3

LZ Preliminary

Q_{LL}/Q_{β} = 0.87

(i.e. L-shell suppression)

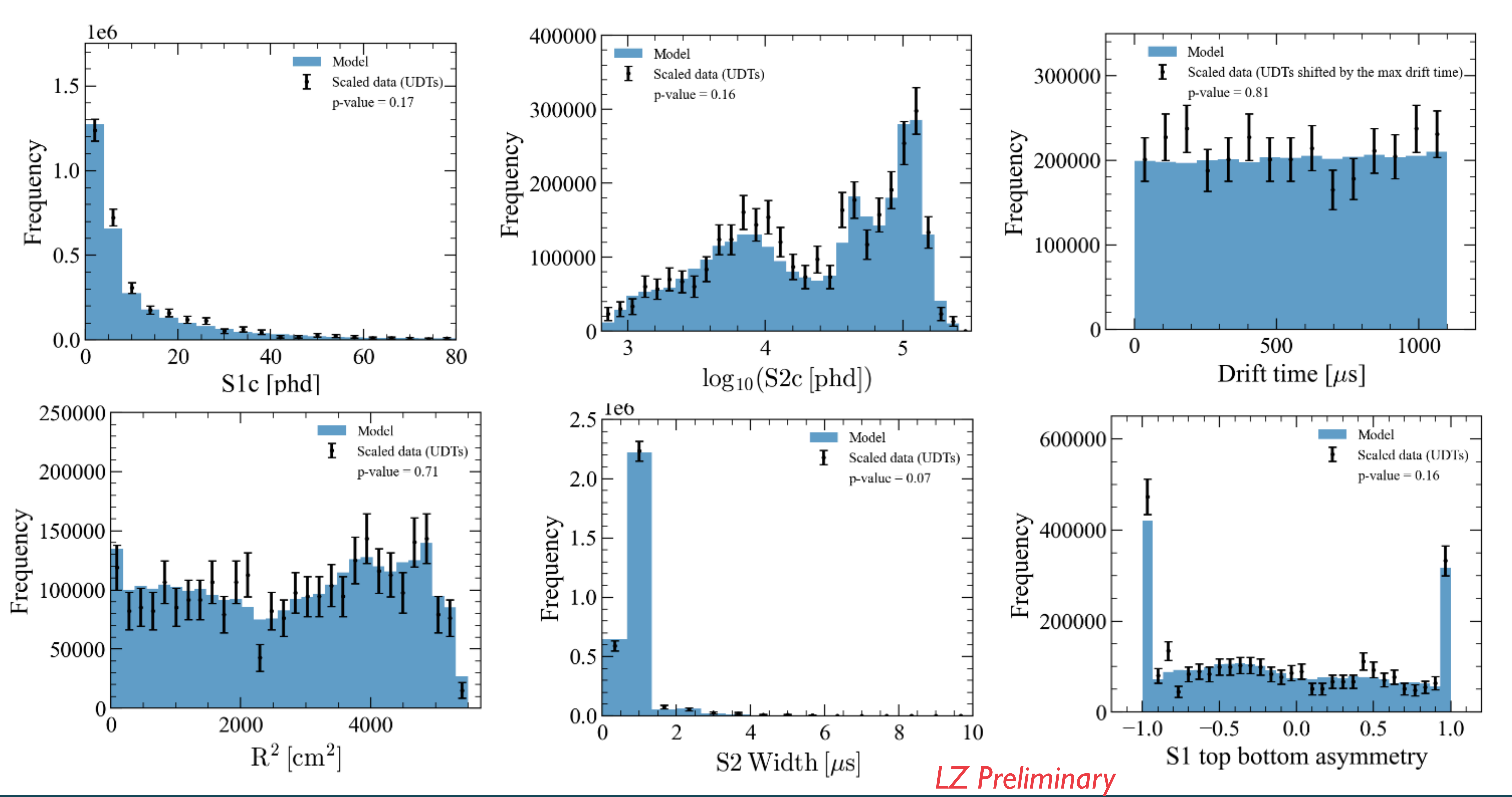
Q_{LL}/Q_{β} = 0.65

(i.e. double L-shell ionisation density)

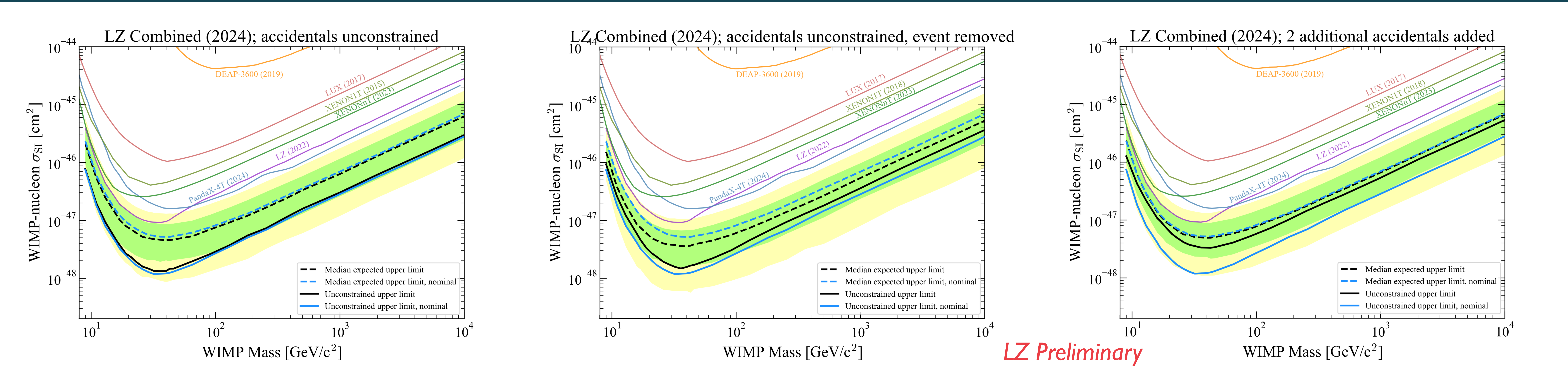
ACCIDENTALS MODEL & SIDEBAND COMPARISONS

Comparing manufactured accidental events and unphysical drift accidentals

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



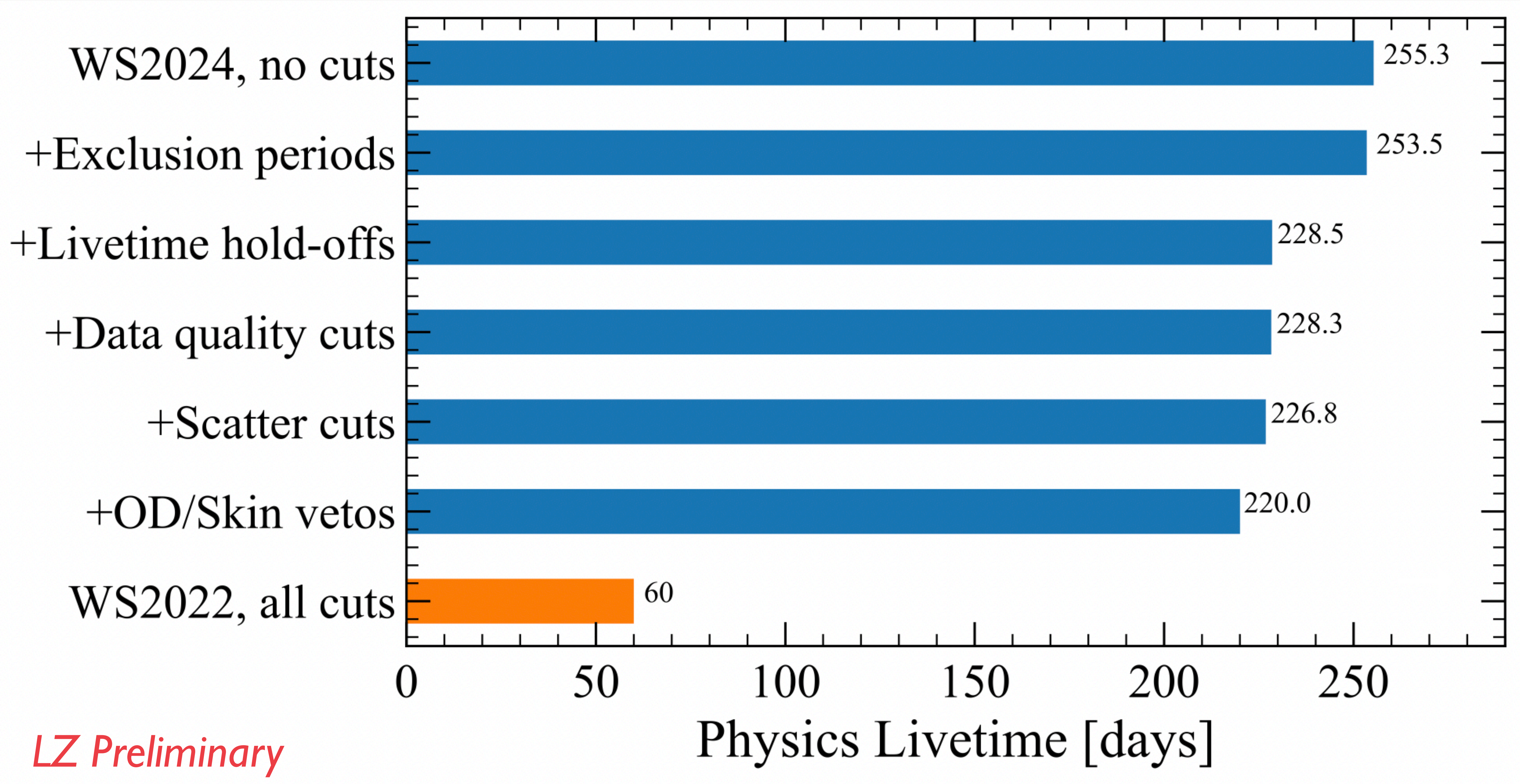
CHECKS OF ACCIDENTALS IMPACT ON LIMIT

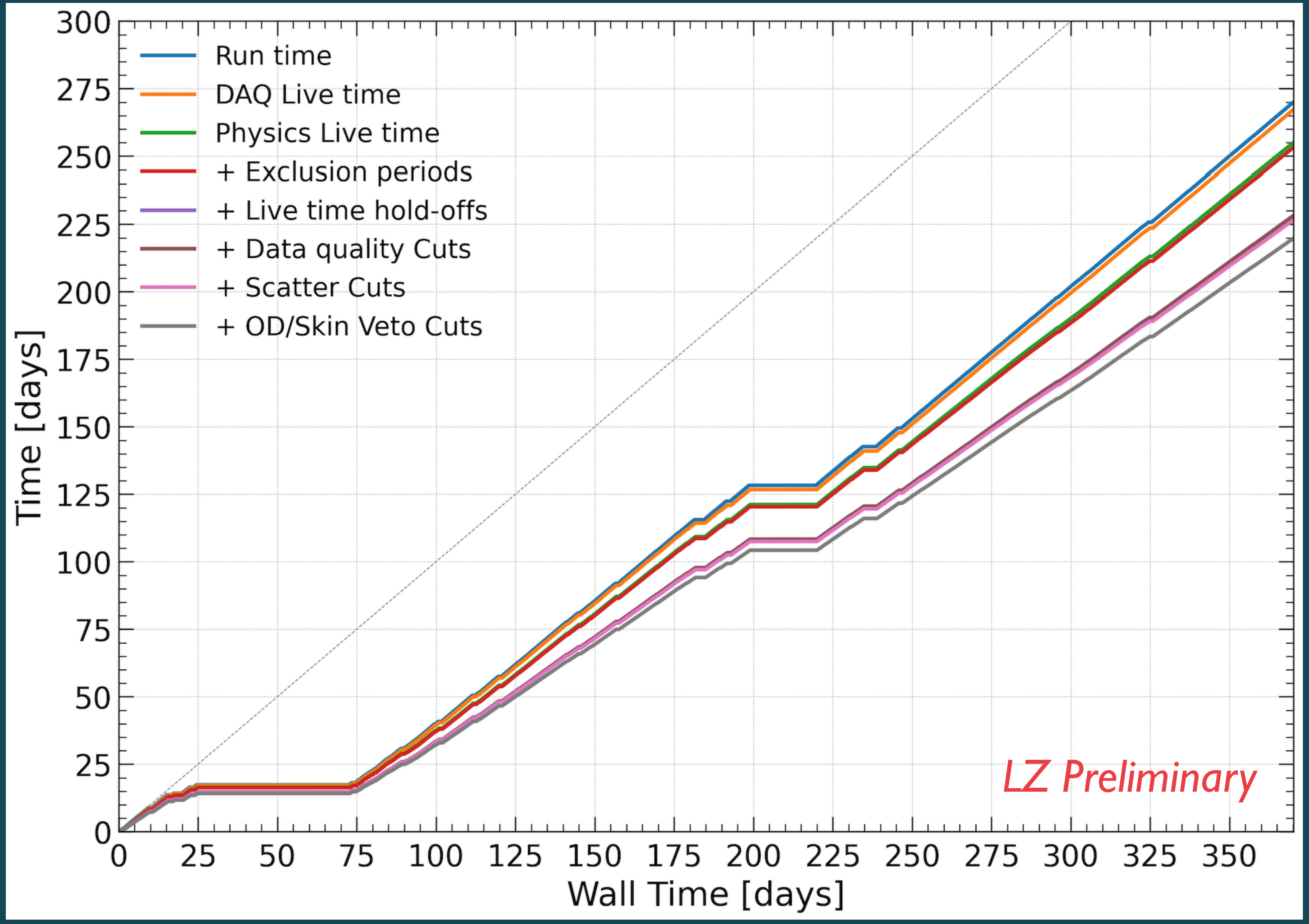


1. Remove accidental rate constraint: best fit drops 2.6 → 1.4
2. Remove constraint & outlier event: best fit drops 1.4 → 0
    - Outlier event holds model up, over subtracting in the WIMP region
3. Adding fake events - props limit back up

→ under-fluctuation of accidental events in the WIMP region

LIVE TIME

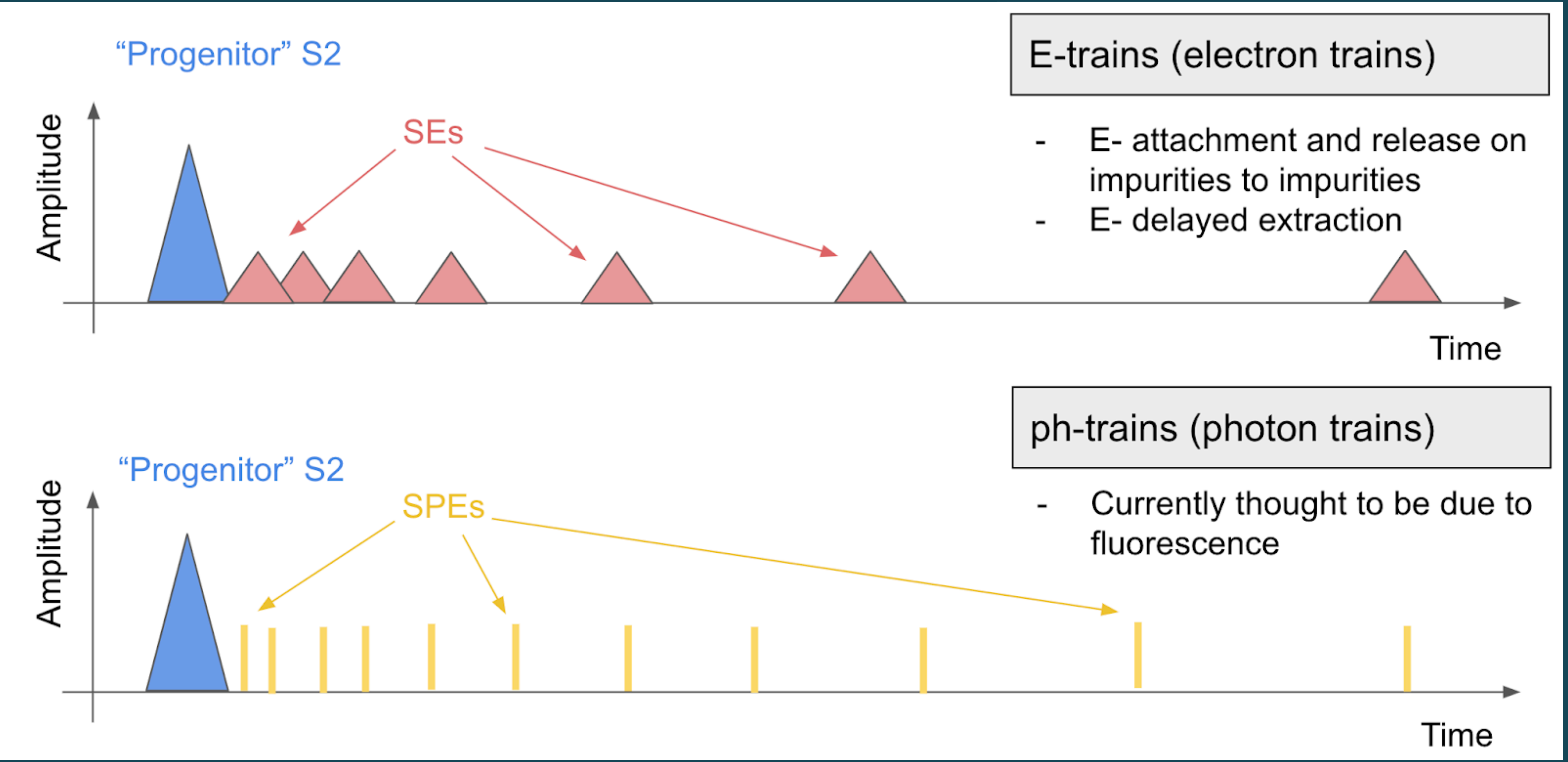




- Rejection of live time with detector instabilities, high TPC pulse rates
- 86% live time remaining after all analysis live time exclusions
  → mainly driven by improved live time retention of e-train veto

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)

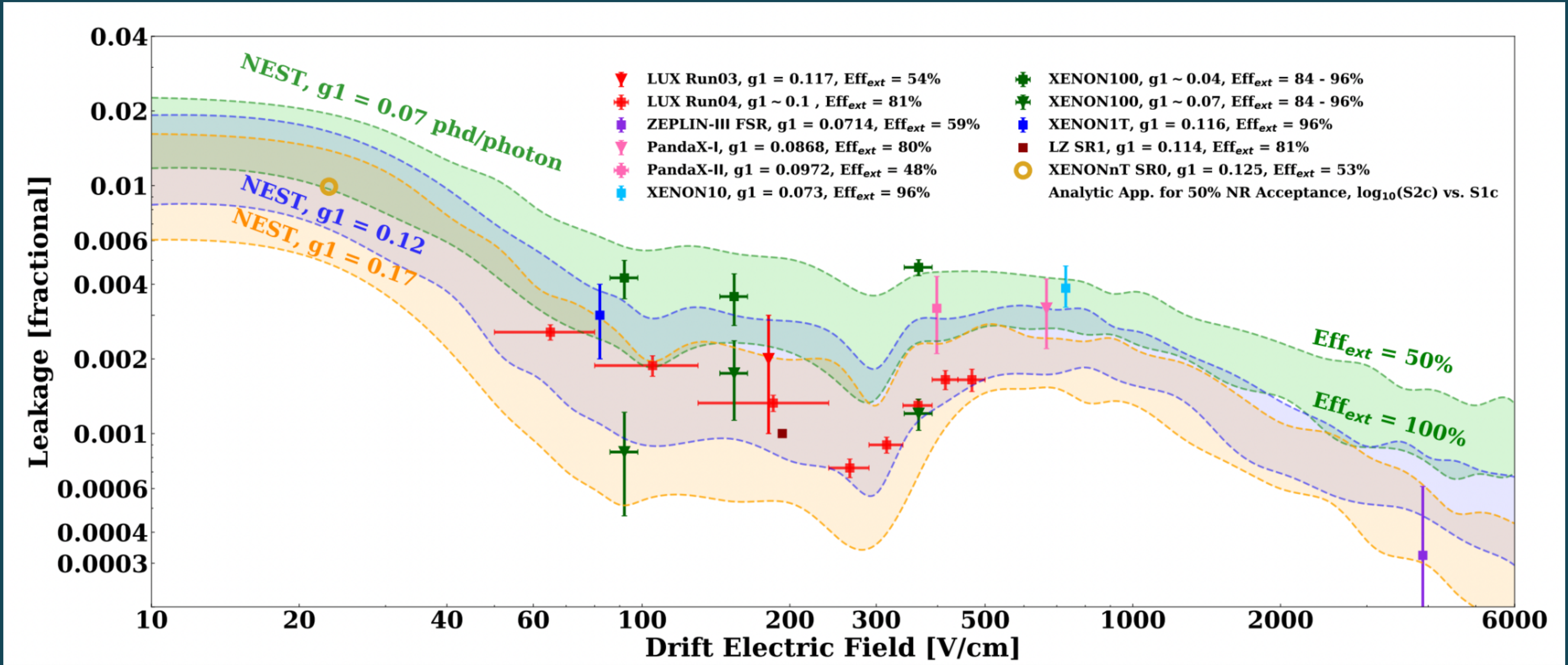


WS2024 VS WS2022 CONDITIONS

	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

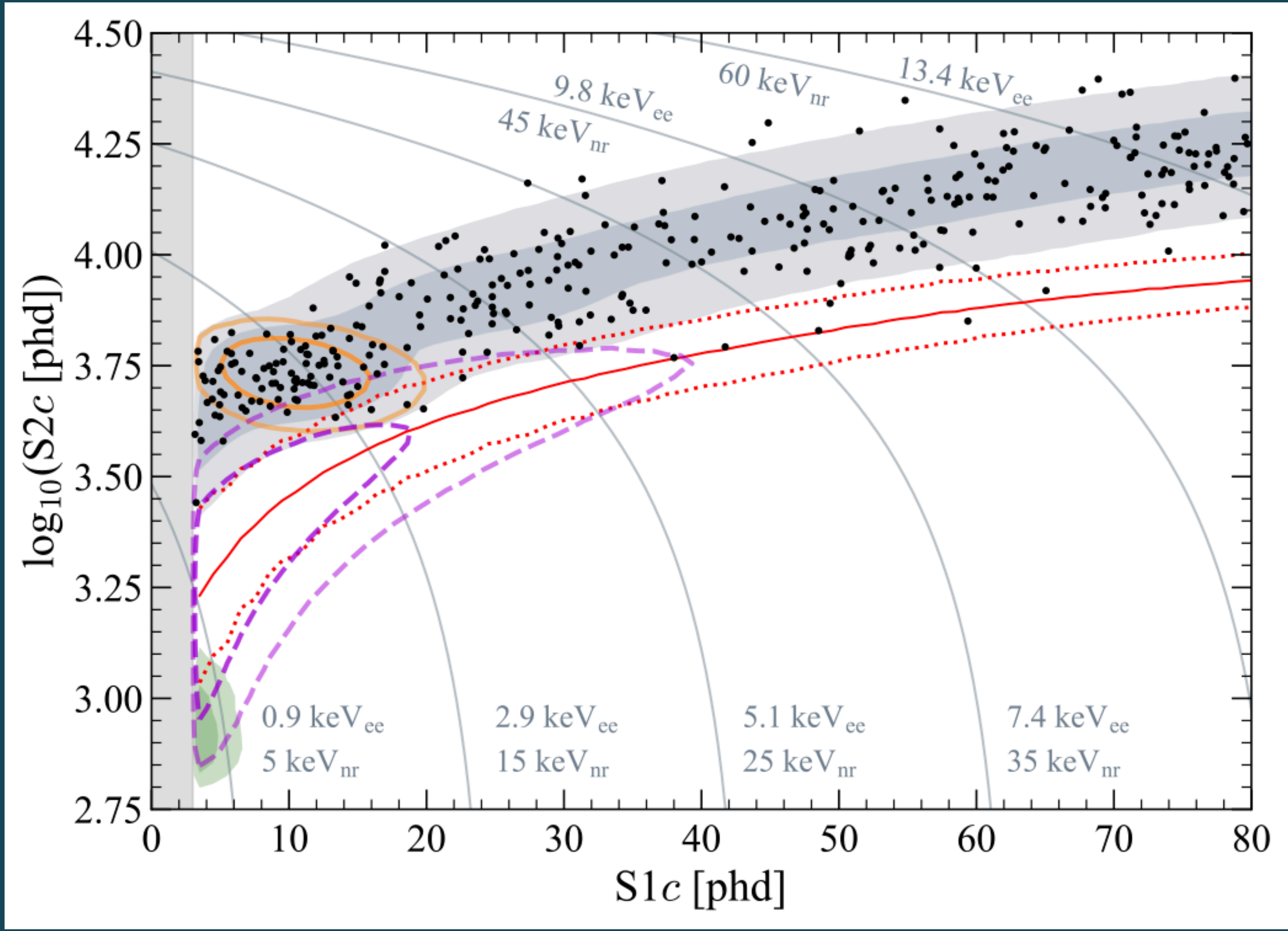
WS2022 DATA

- 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
- ^{8}B
- 30 GeV/c² WIMP

- NR band from DD



*j.astropartphys.2020.102480

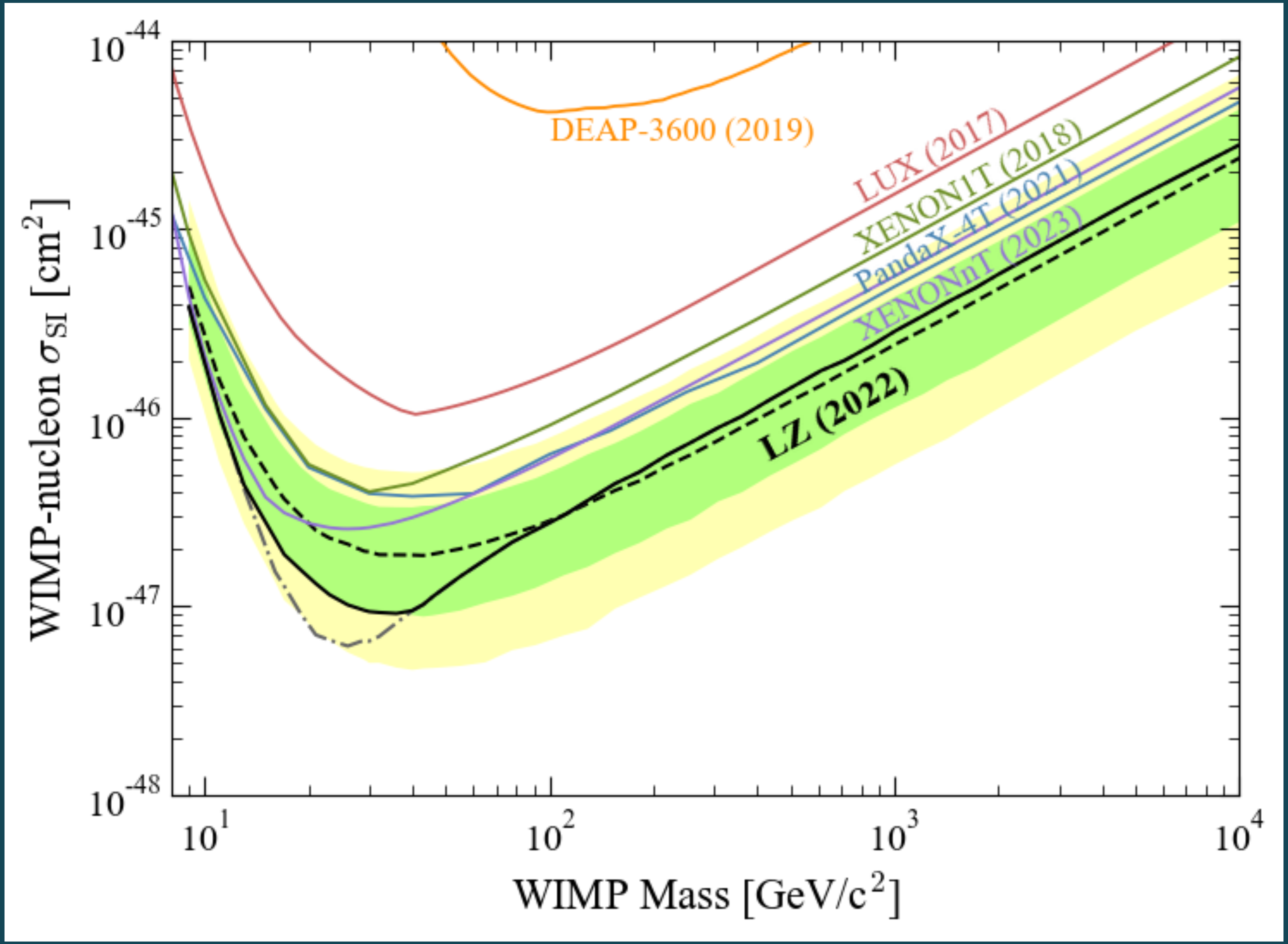
WS2022 LIMIT

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

Key

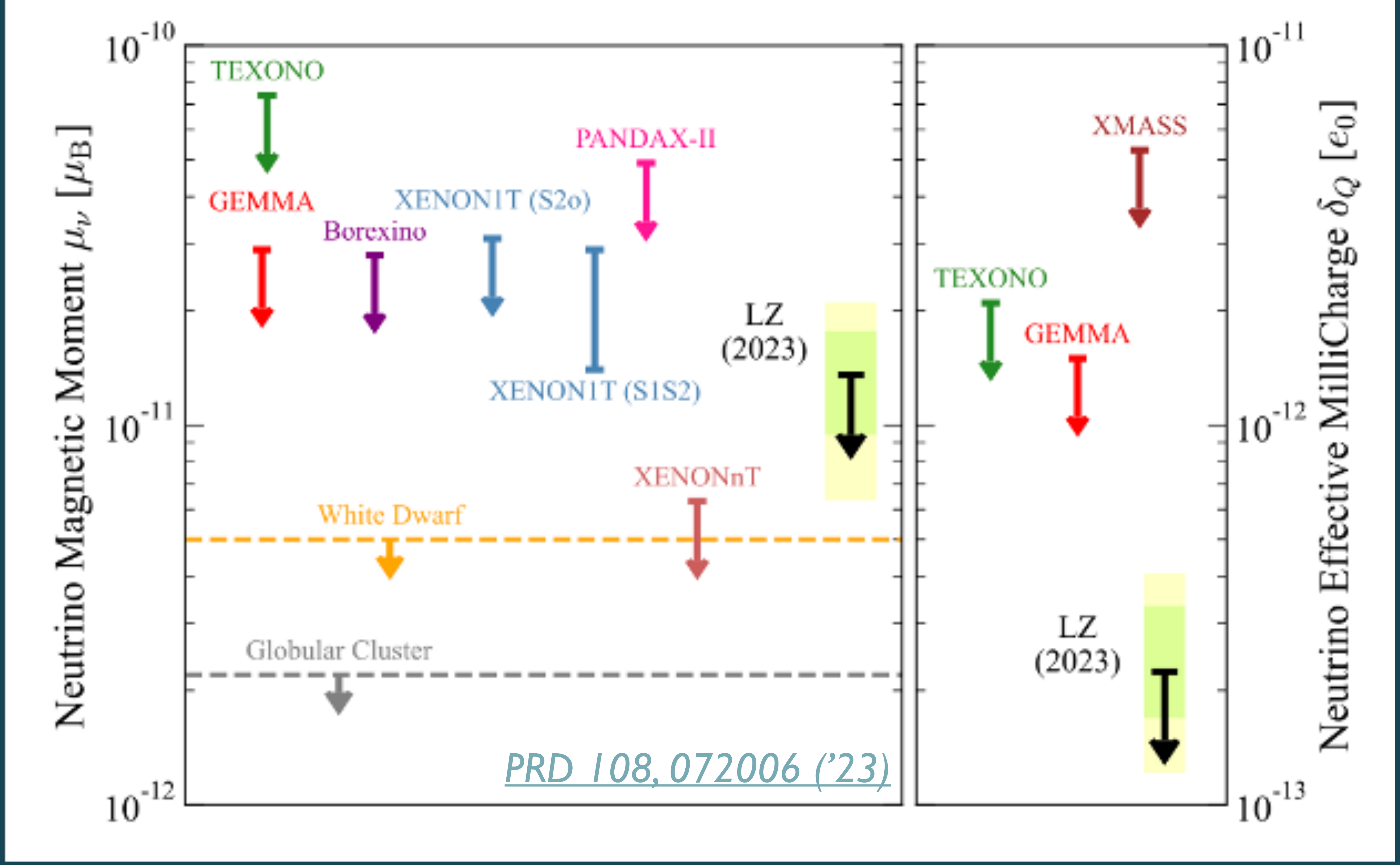
—— Observed limit

- - - Median expected sensitivity

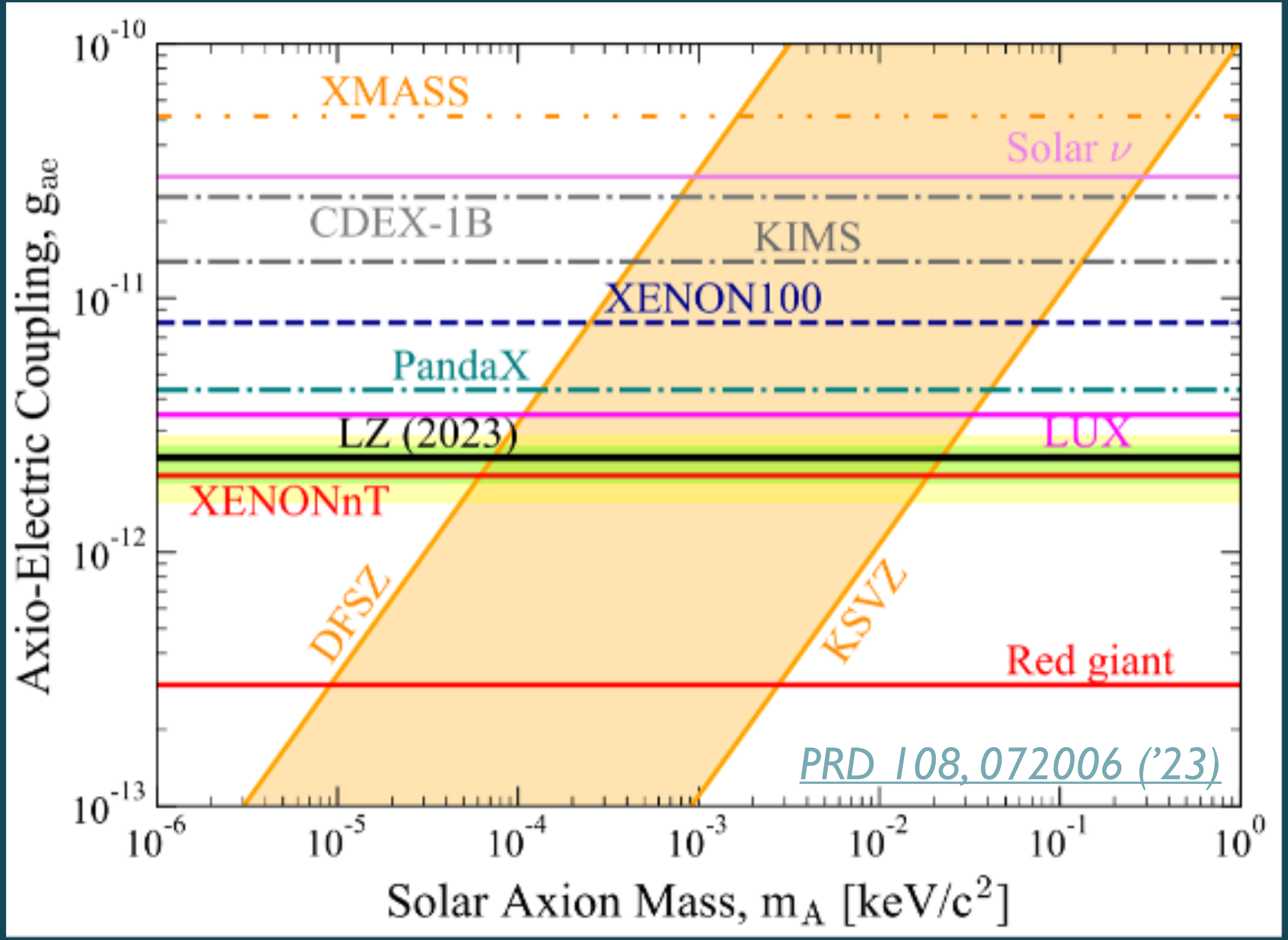


PHYSICS VIA ELECTRON RECOIL CHANNEL

Neutrino Magnetic Moment & Effective Millicharge



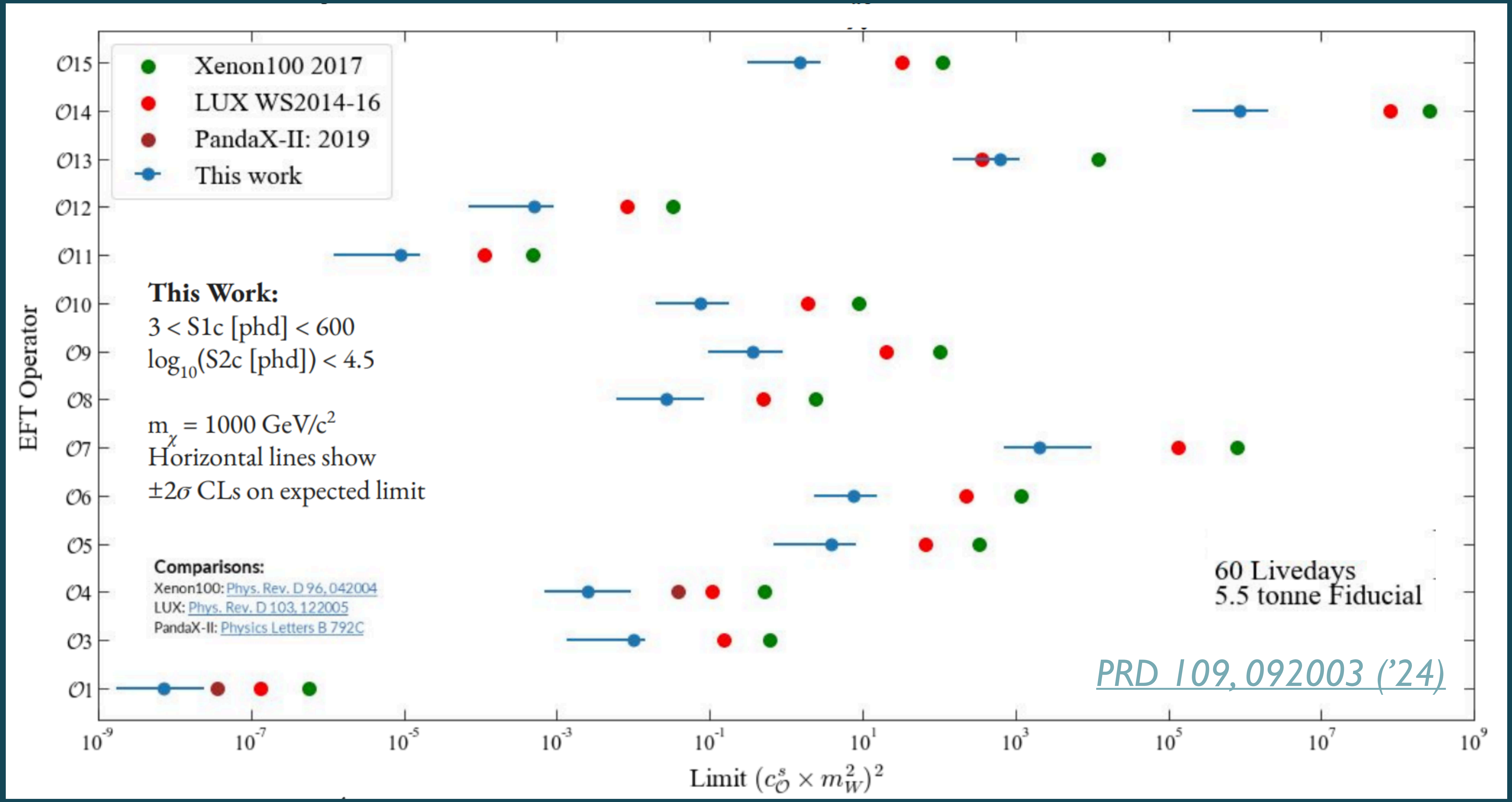
Solar Axion Interactions



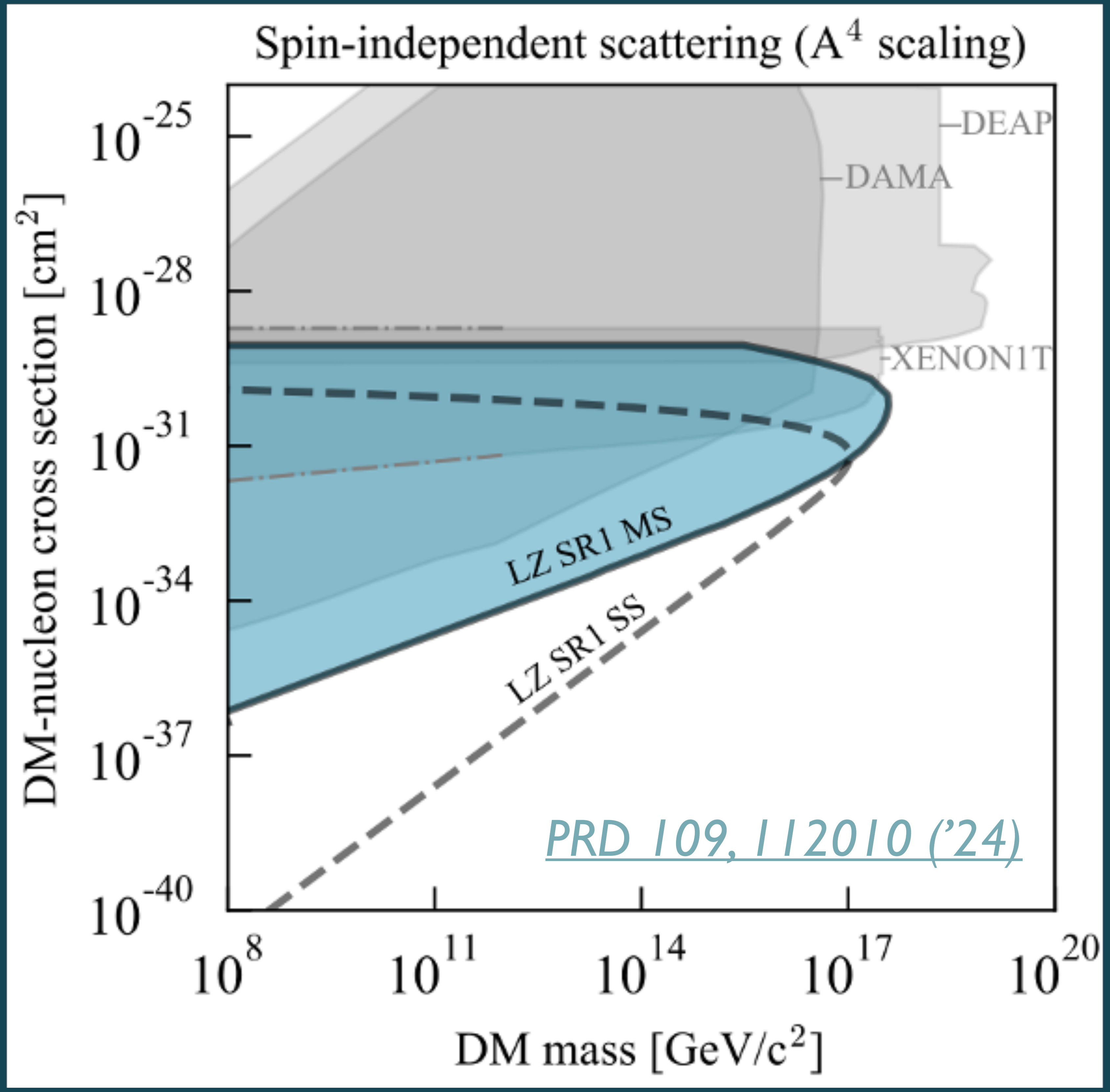
Neutrino interactions & properties; axions and ALPs; rare decays of xenon isotopes

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