New Dark Matter Search Results from the LUX-ZEPLIN Experiment

Amy Cottle, UCL

LZ COLLABORATION

Thanks to our sponsors and participating institutions!

38 Institutions: 250 scientists, engineers, and technical staff

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- King's College London
- Lawrence Berkeley National Lab.
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- South Dakota Science & Technology Authority
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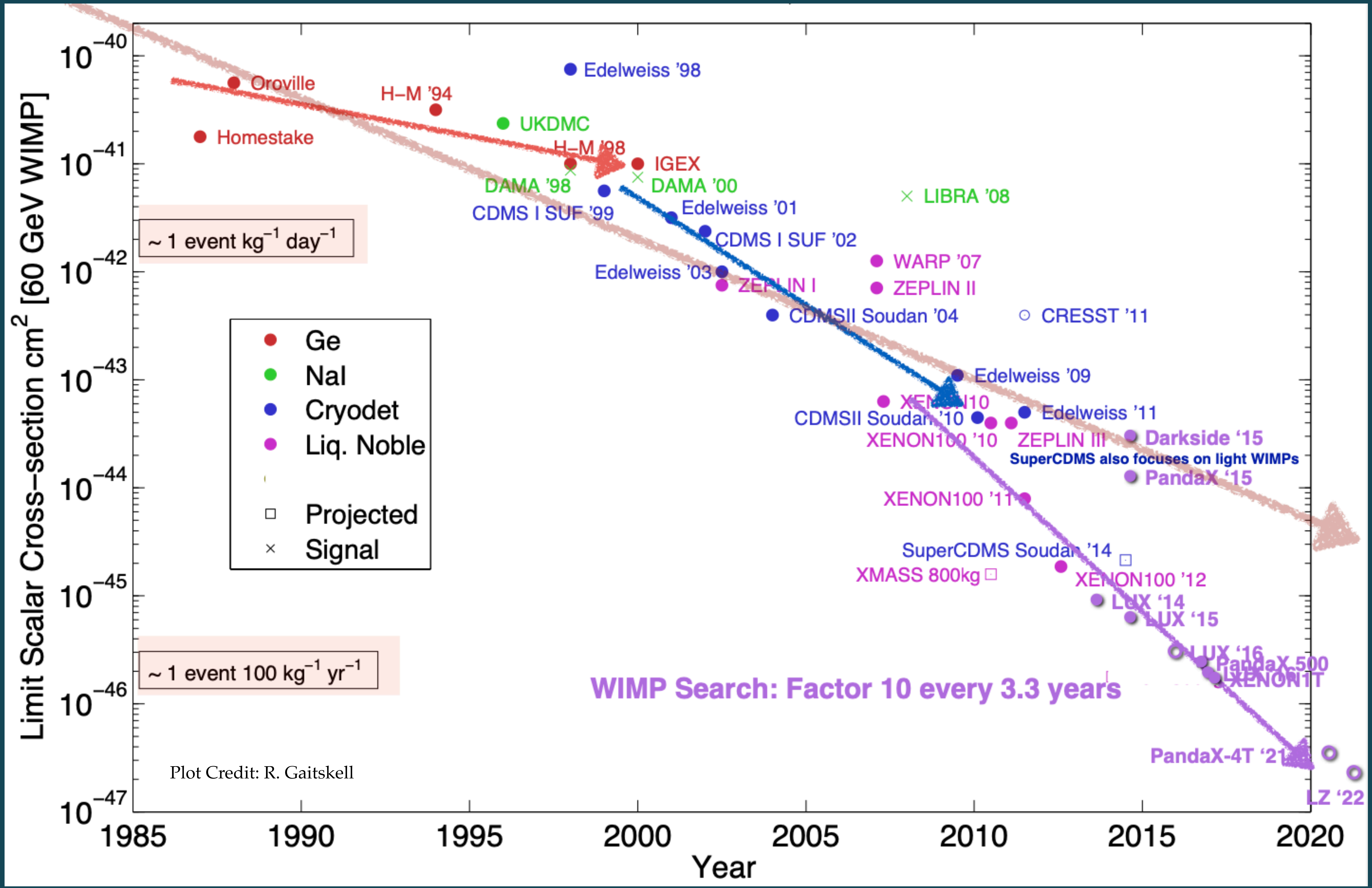
FCT Fundação para a Ciência e a Tecnologia

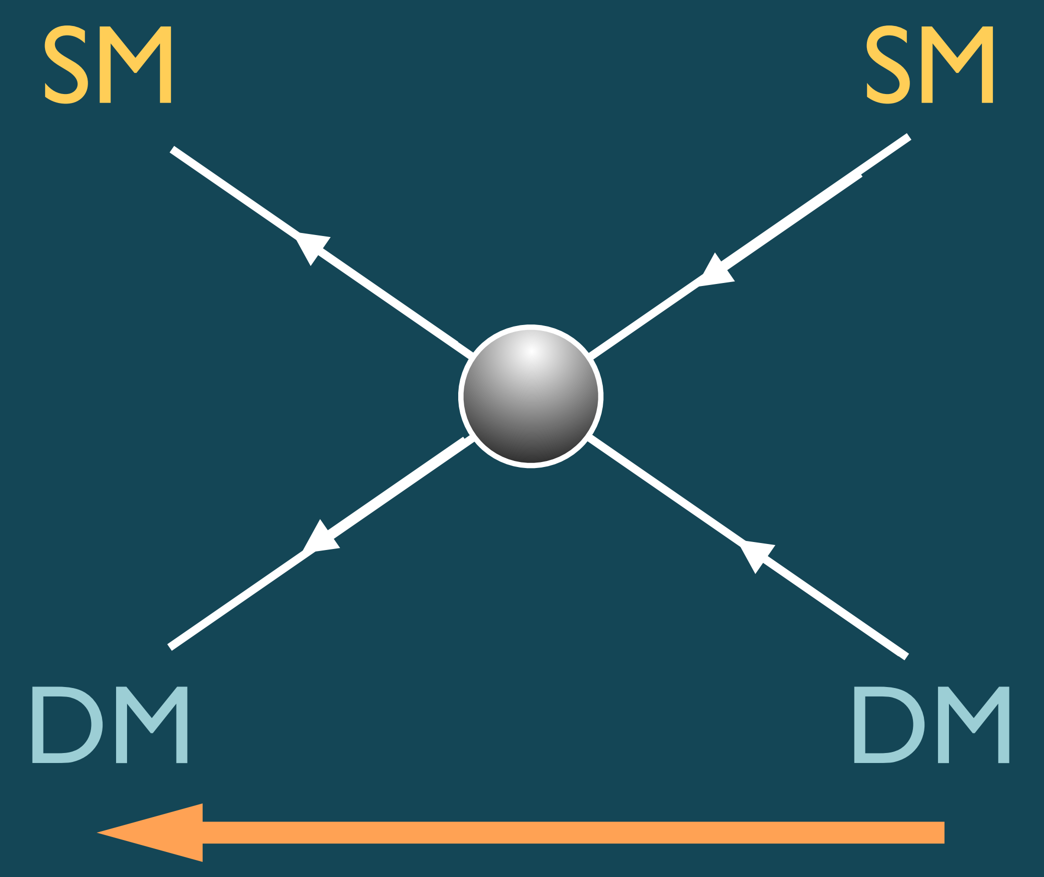
SANFORD UNDERGROUND RESEARCH FACILITY

ibs Institute for Basic Science

DM SEARCHES WITH XENON DETECTORS



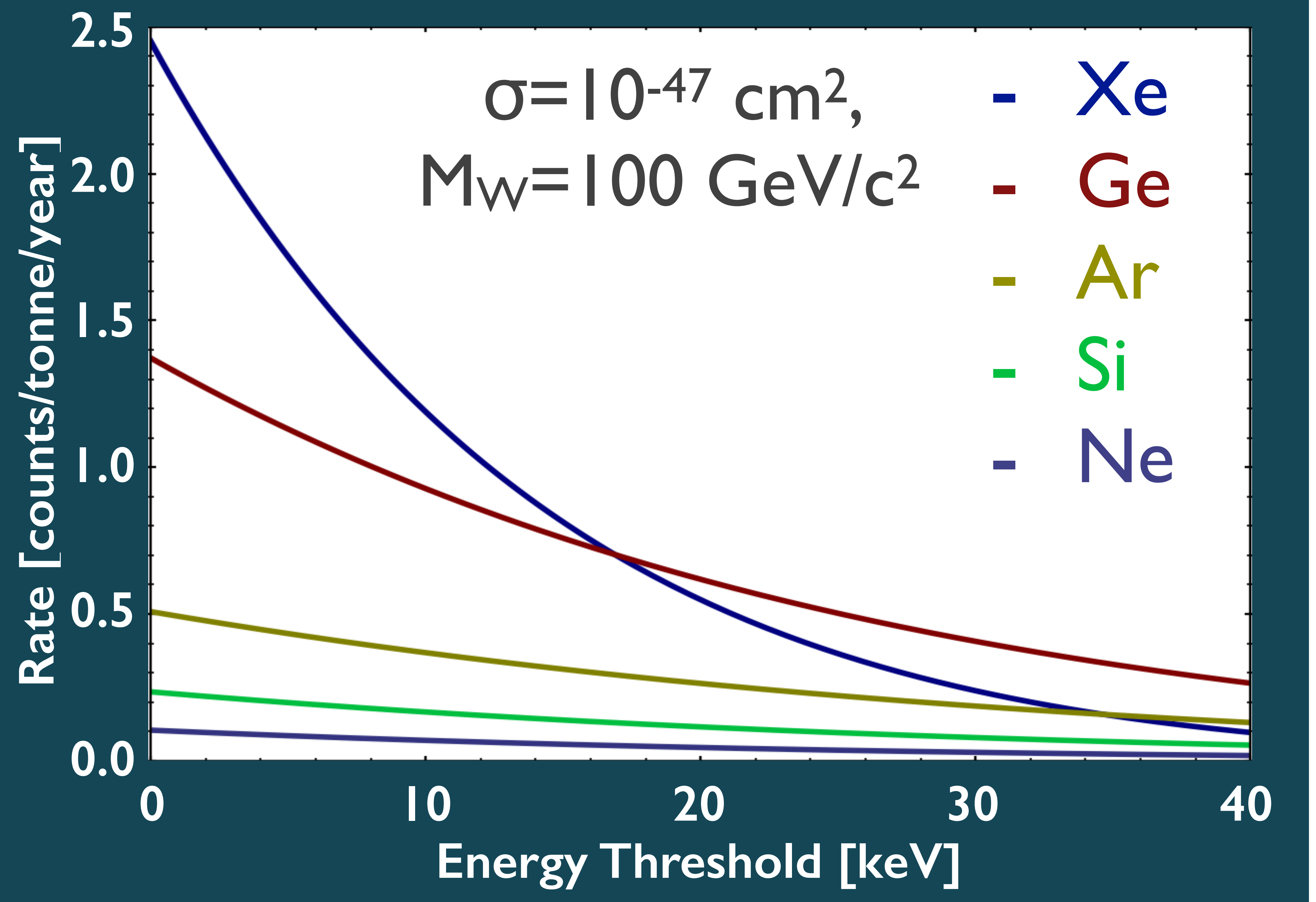
- Weakly Interacting Massive Particles (WIMPs)
  → key galactic DM candidate

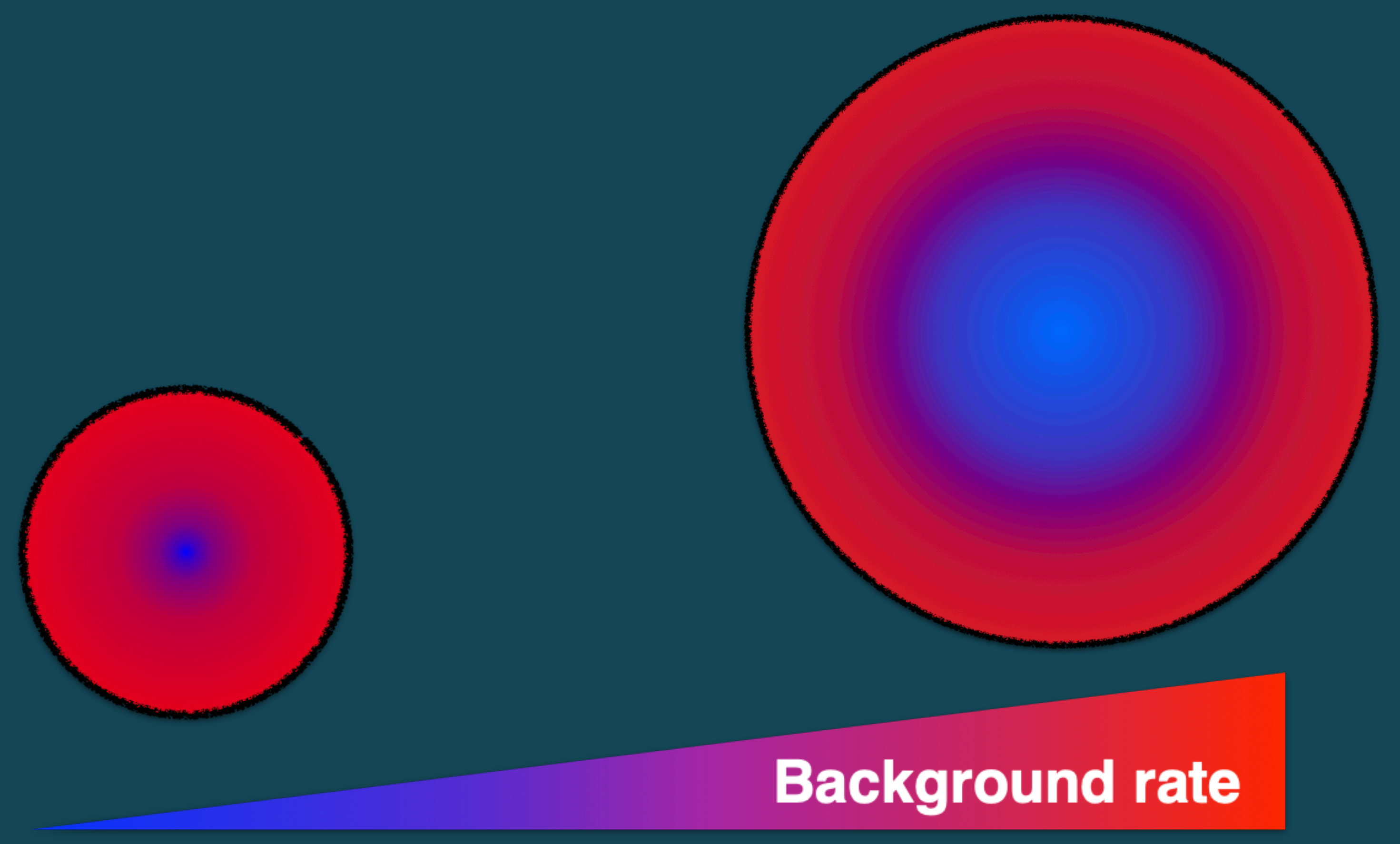


- Direct detection via scatters with target nuclei
- Xe experiments driving sensitivity to WIMPs in last 15 years

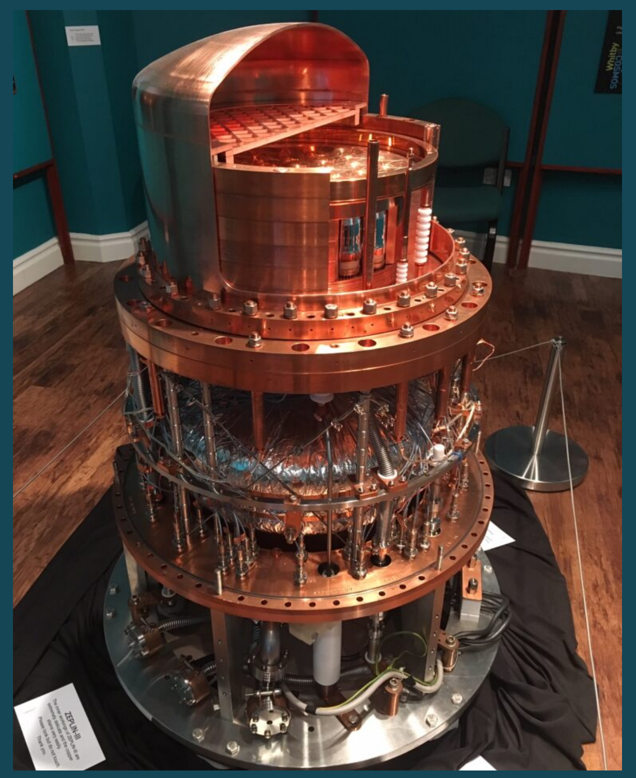
WHY XENON?

- Coherent scalar WIMP-nucleus scattering ($\sigma \propto A^2$)
- Highest charge & light yields of all noble elements
- Commercially available & easily purified
- Dense → short attenuation lengths - self-shielding
- Scalable → potential for large target mass





LZ + Predecessors



ZEPLIN-III

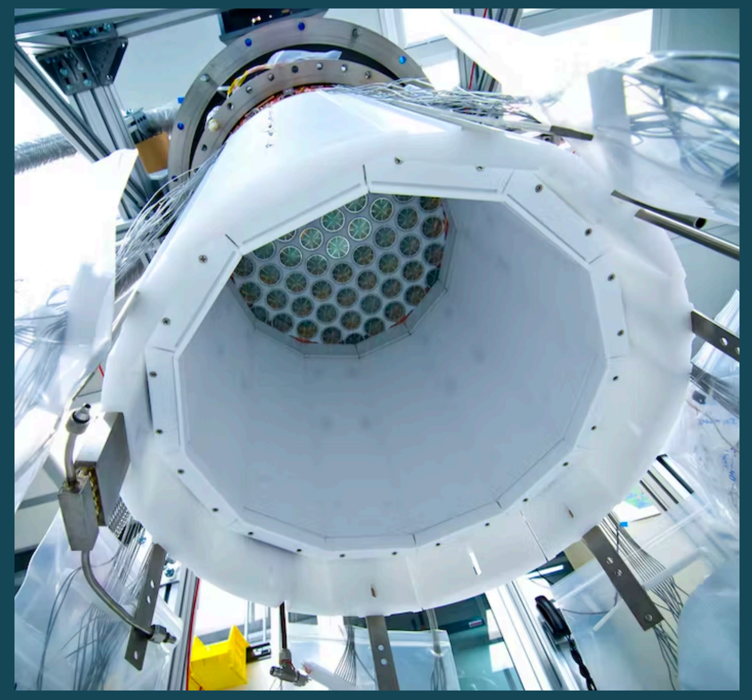
12 kg (7 kg)

2008

LUX

250 kg (100 kg)

2013



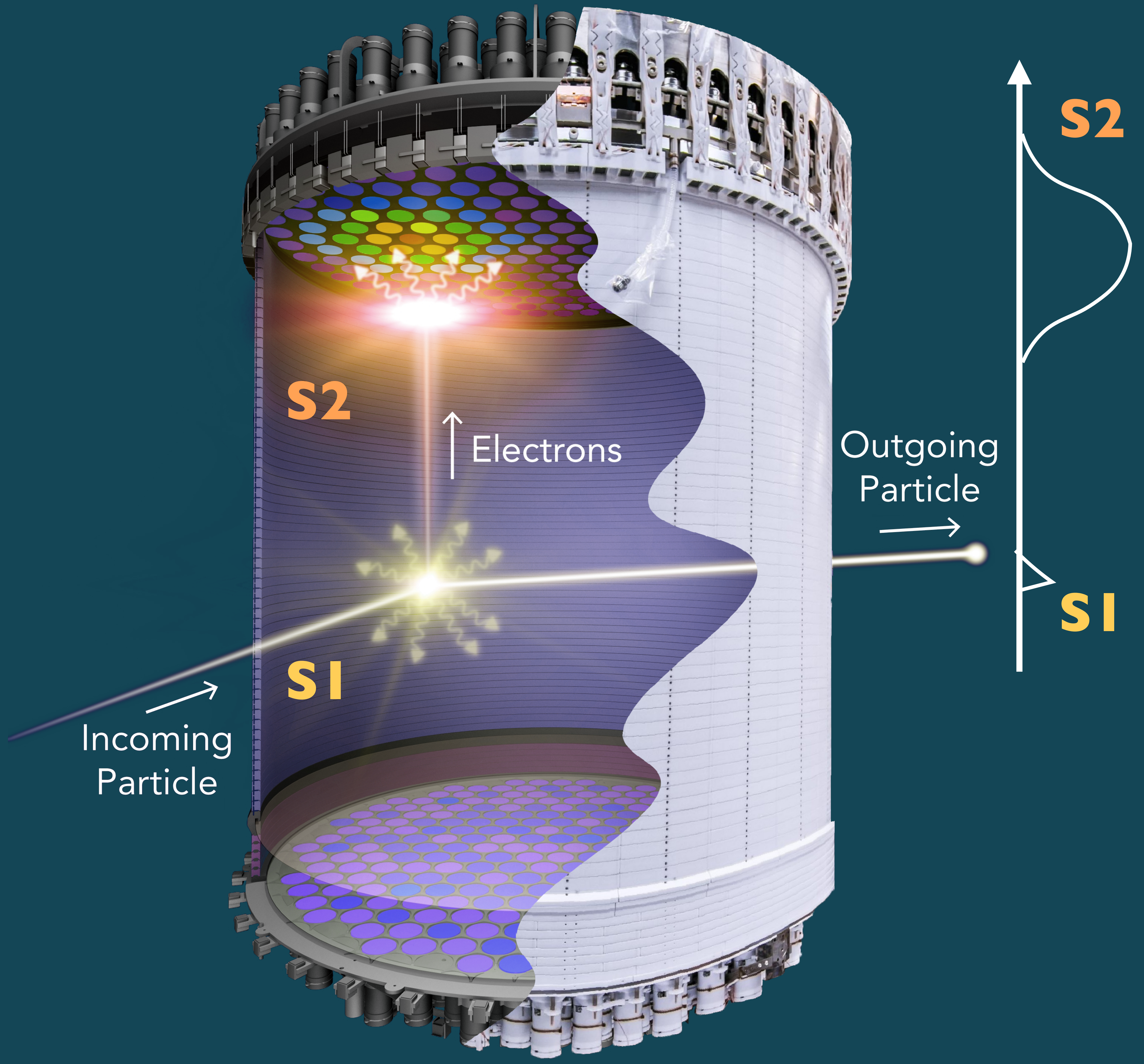
LZ

7000 kg (5500 kg)

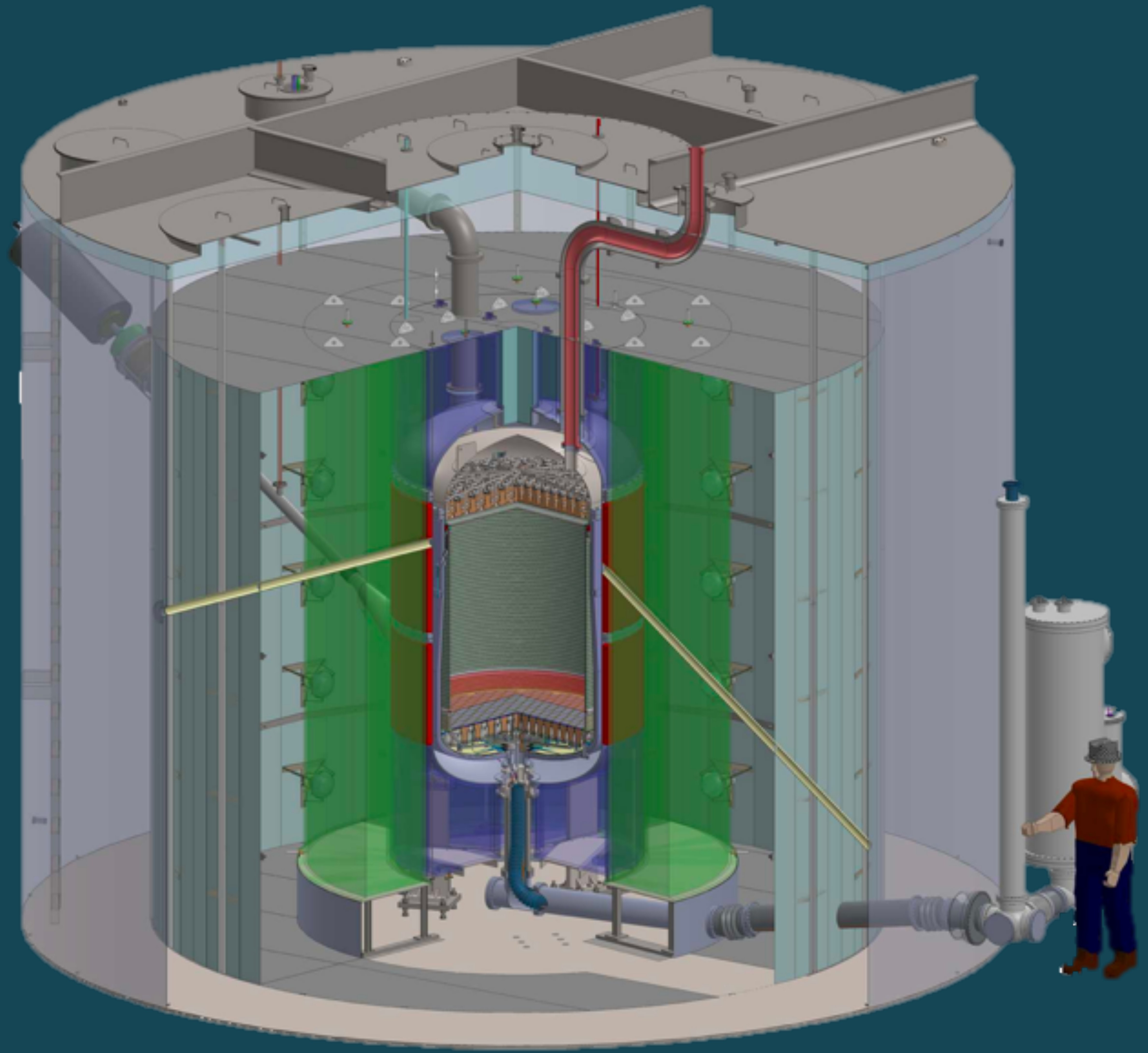
2022-

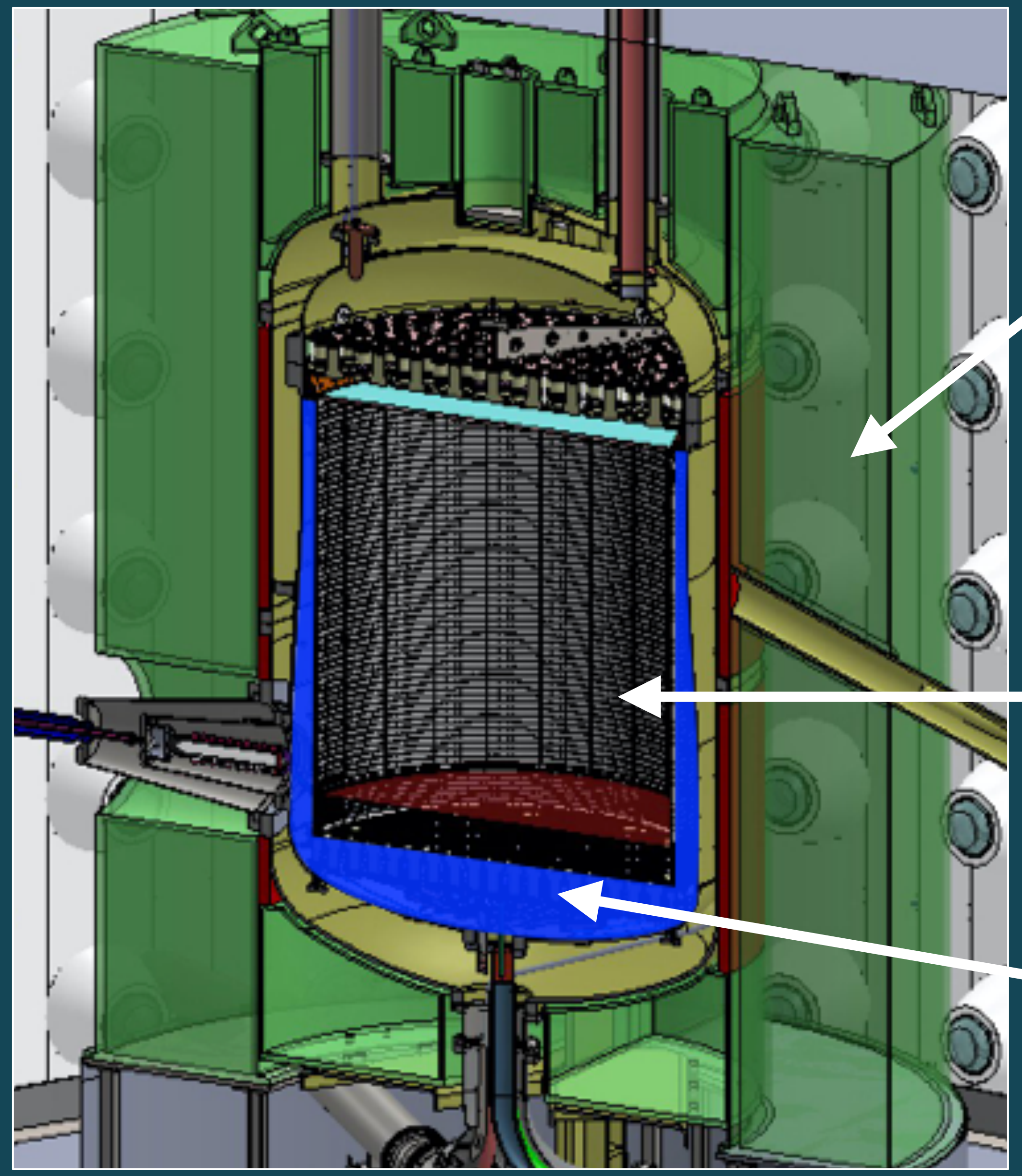
TIME PROJECTION CHAMBER (TPC)

- Interactions in the xenon create
  - Light - prompt scintillation - **S1**
  - Charge - electrons drifted and extracted into gas → proportional scintillation - **S2**
- Time separation between S1 & S2 = drift time
- Excellent 3D position reconstruction (~mm)
- Distinguish between single scatter (SS) and multiple scatter (MS) interactions
- S2:S1 ratio - discriminate electronic recoils (ERs) from potential WIMP nuclear recoils (NRs)



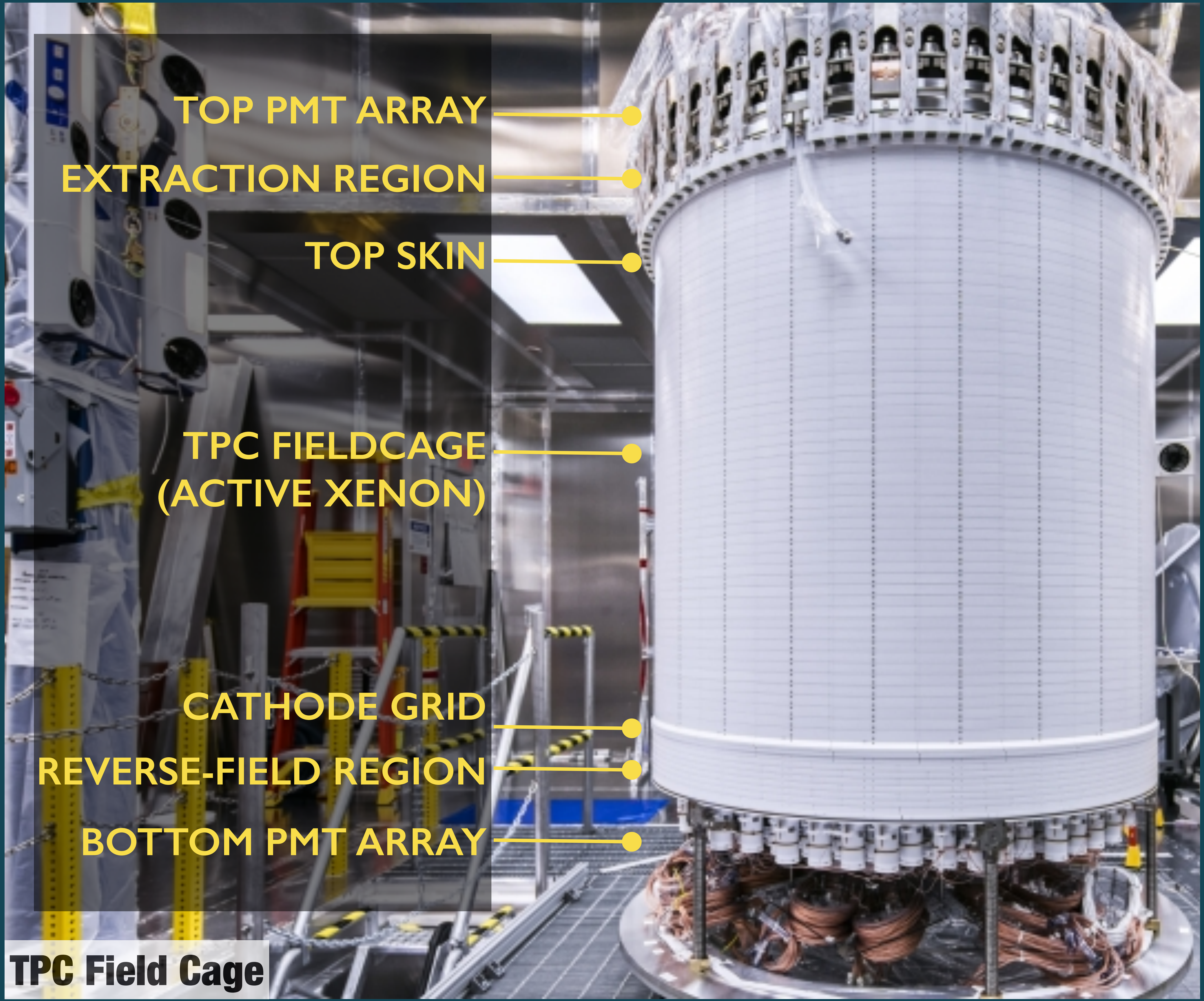
THE LZ EXPERIMENT

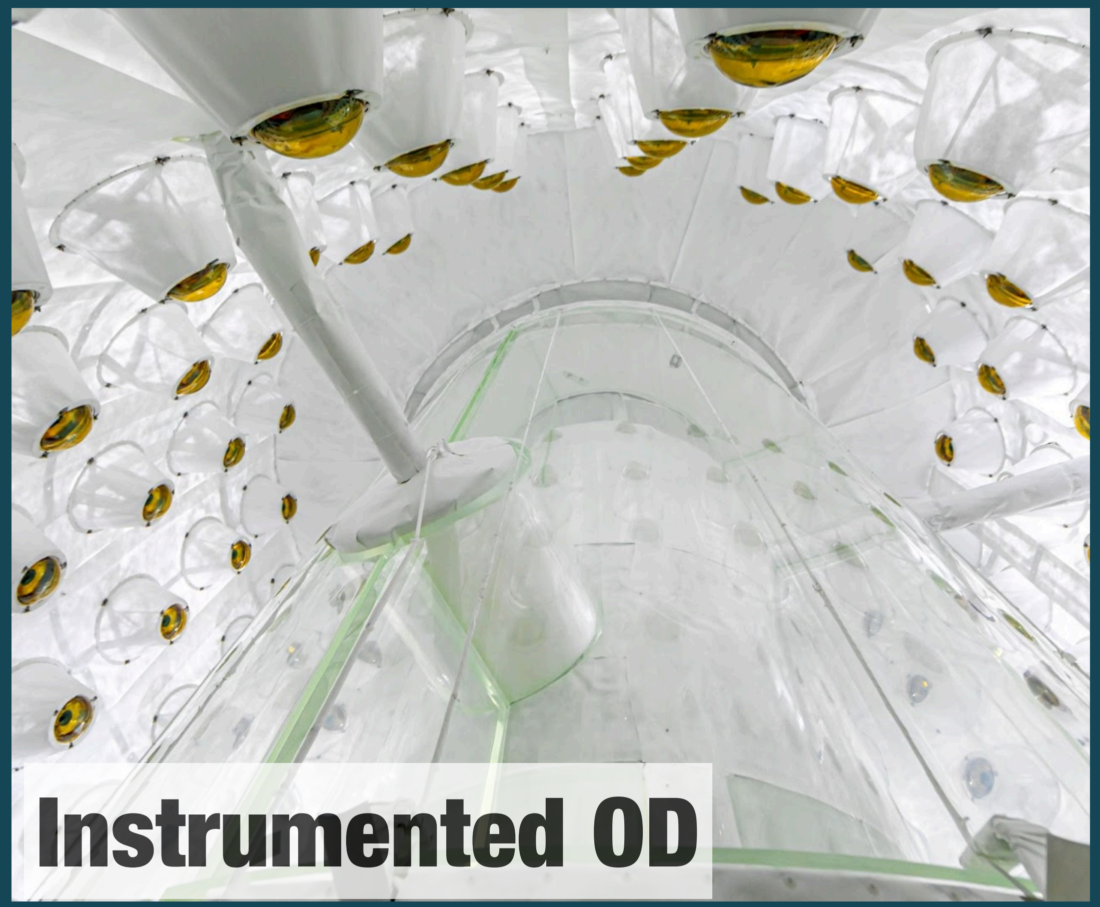




- Based at the Sanford Underground Research Facility (SURF) in Lead, SD
- 7 t active dual-phase xenon TPC
- Skin & outer detector (OD) veto systems → tag gamma rays & neutrons

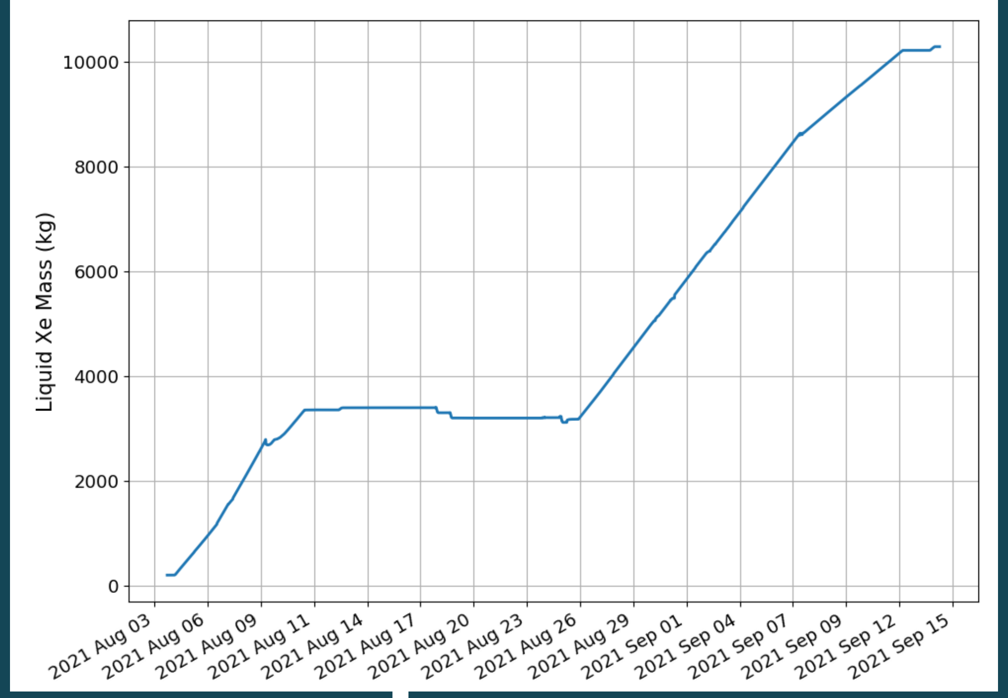
THE LZ EXPERIMENT





LZ TIMELINE

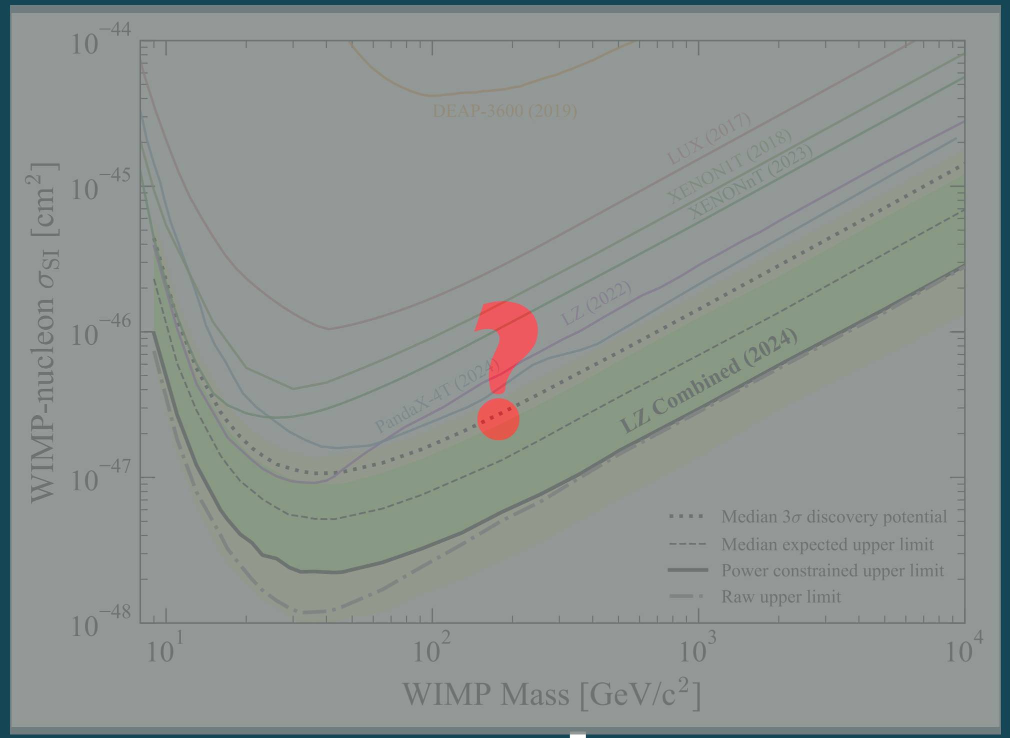
TPC Underground



Commissioning Begins

WS2024 Starts

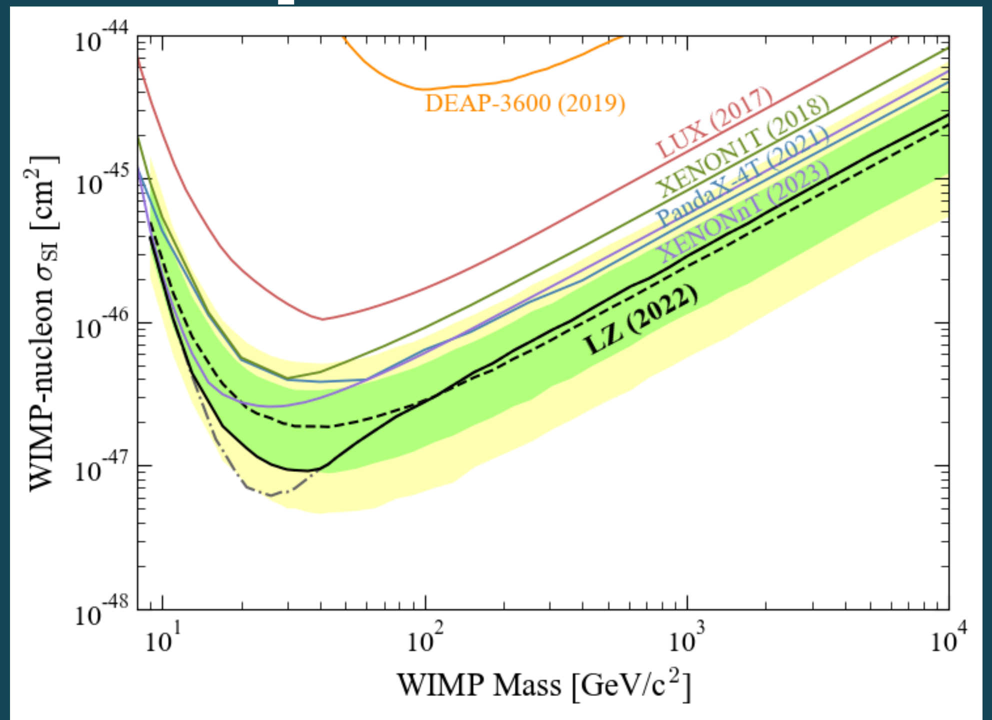
New WIMP Search Results (WS2024+WS2022)



2020 2021 2022 2023 2024

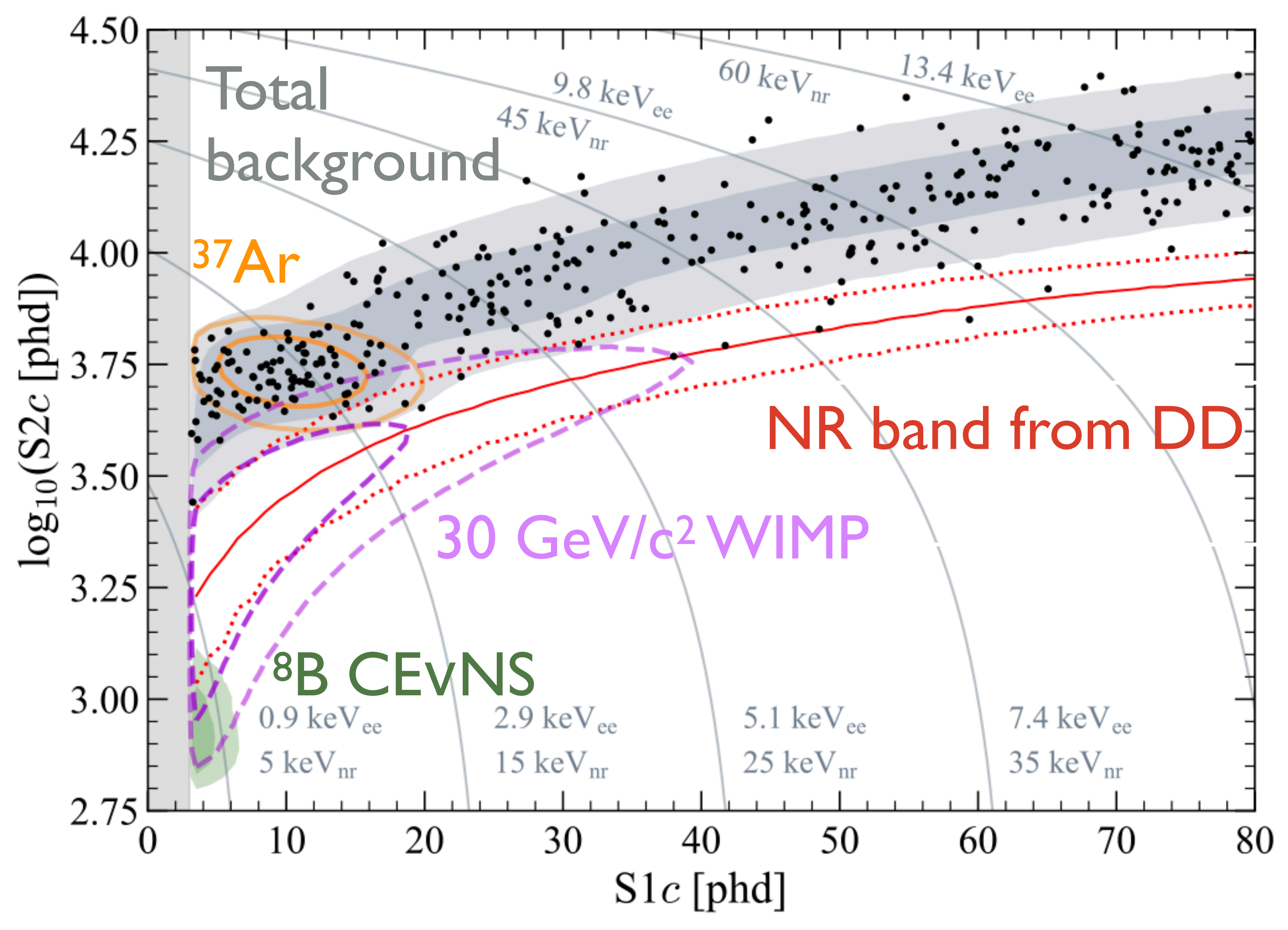
Installation Complete

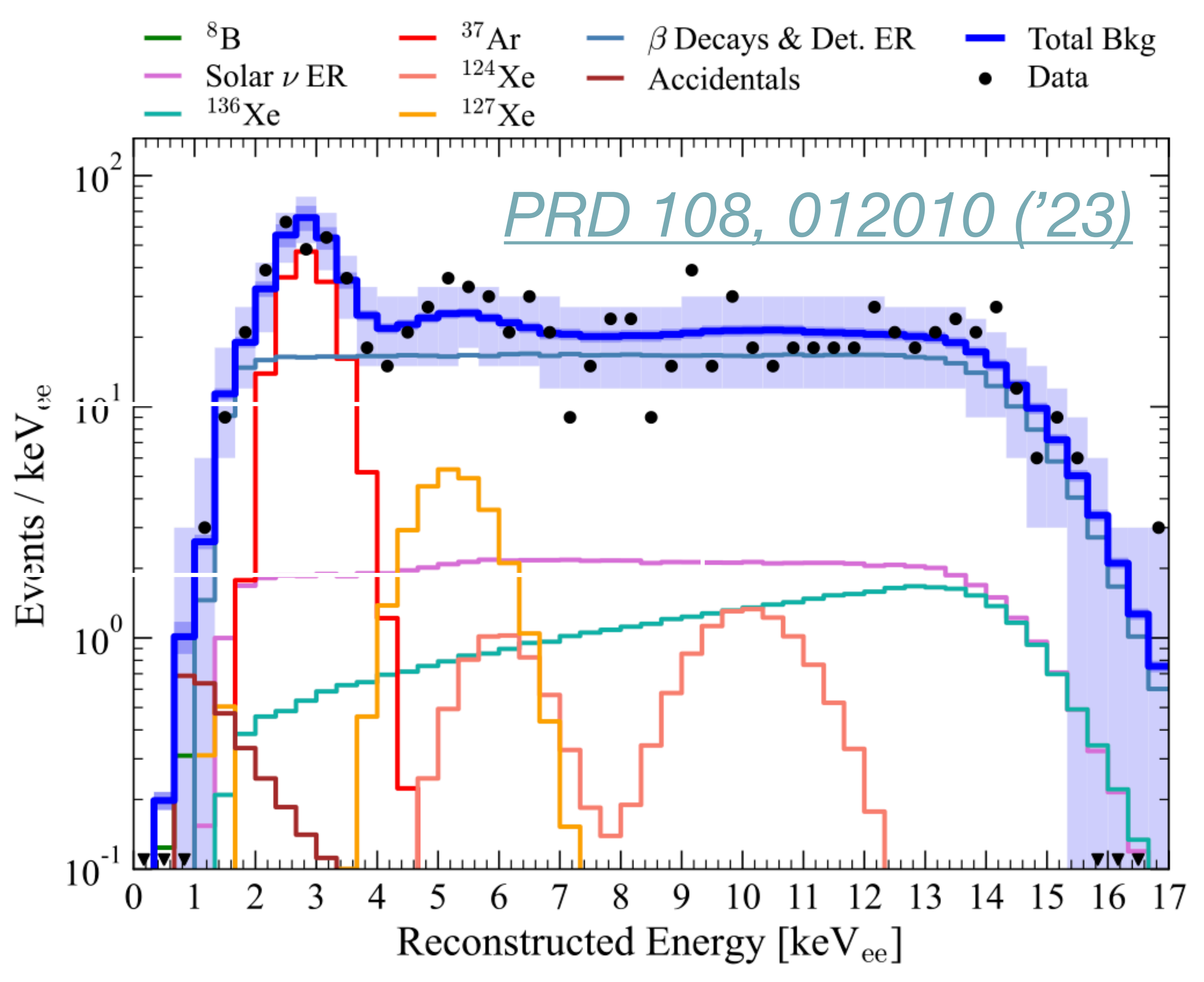
WS2022 Starts

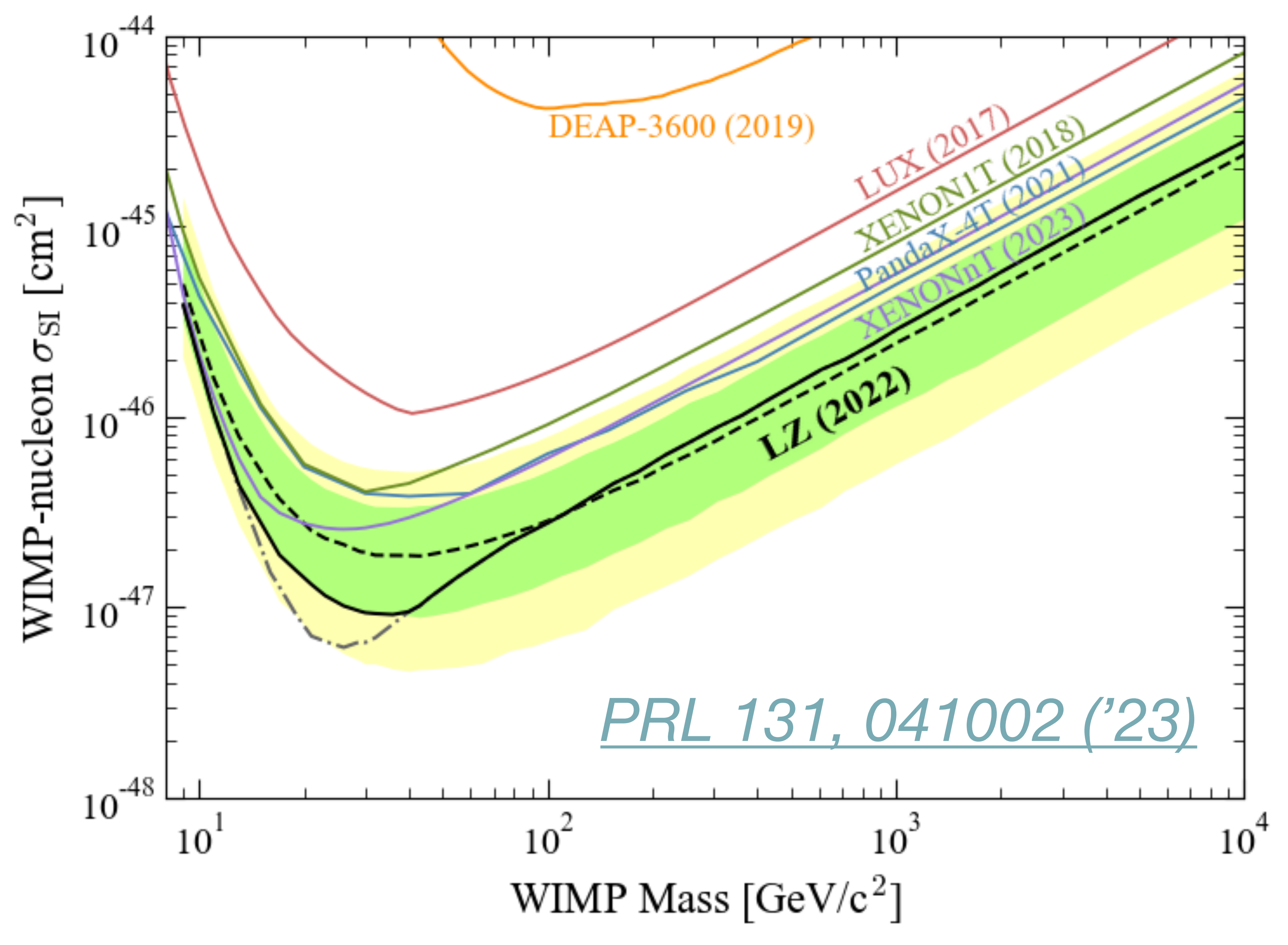


First WIMP Search Results (WS2022)

RECAP OF WIMP SEARCH 2022 (WS2022)

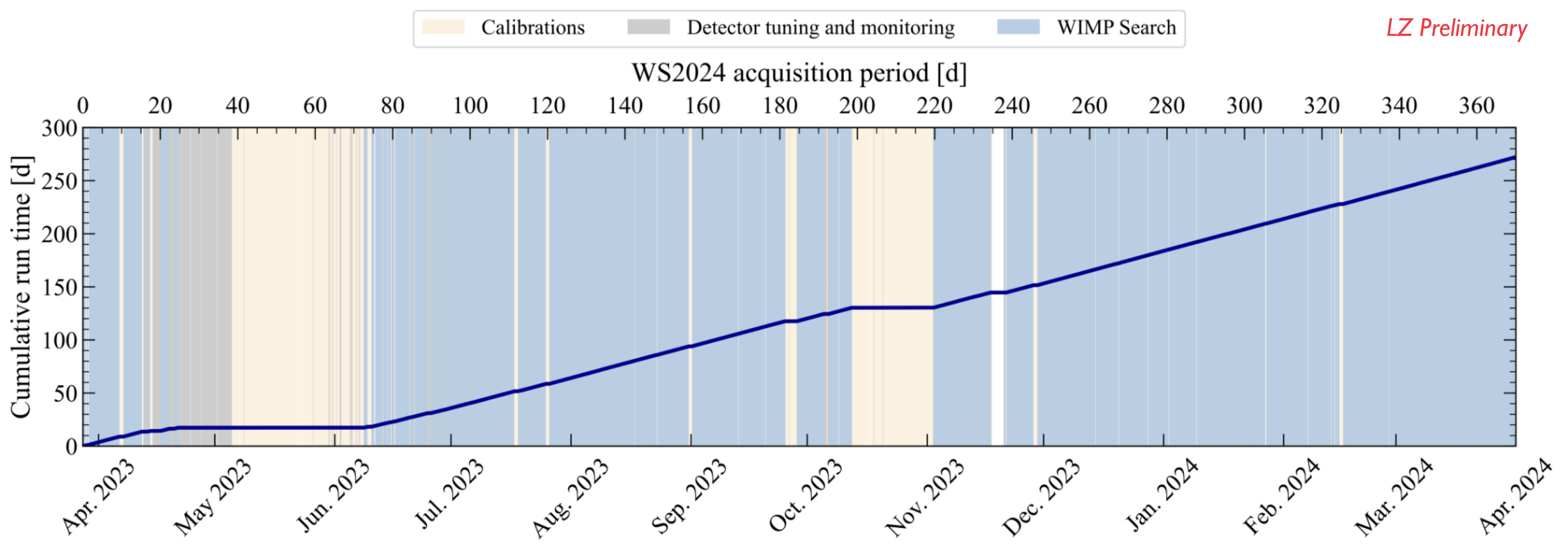






- 60 live-day analysis using data from demonstration run with no blinding or salting
- Backgrounds extensively assessed, with high contribution from cosmogenic activation
- Minimum cross-section of $\sigma_{SI} = 9.2 \times 10^{-48}$ cm^2 for WIMP mass of 36 GeV/c^2

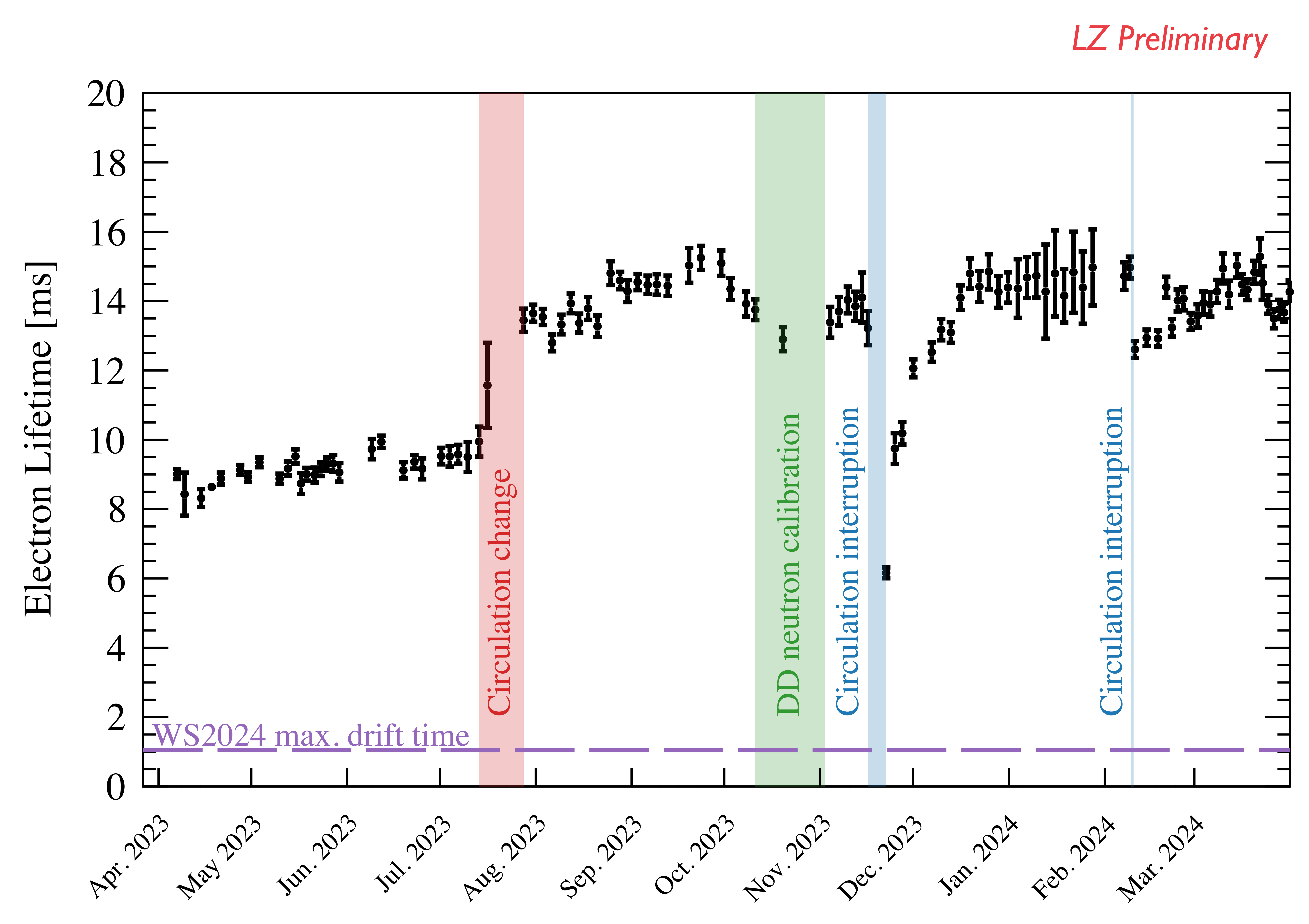
WIMP SEARCH 2024 (WS2024)



- 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

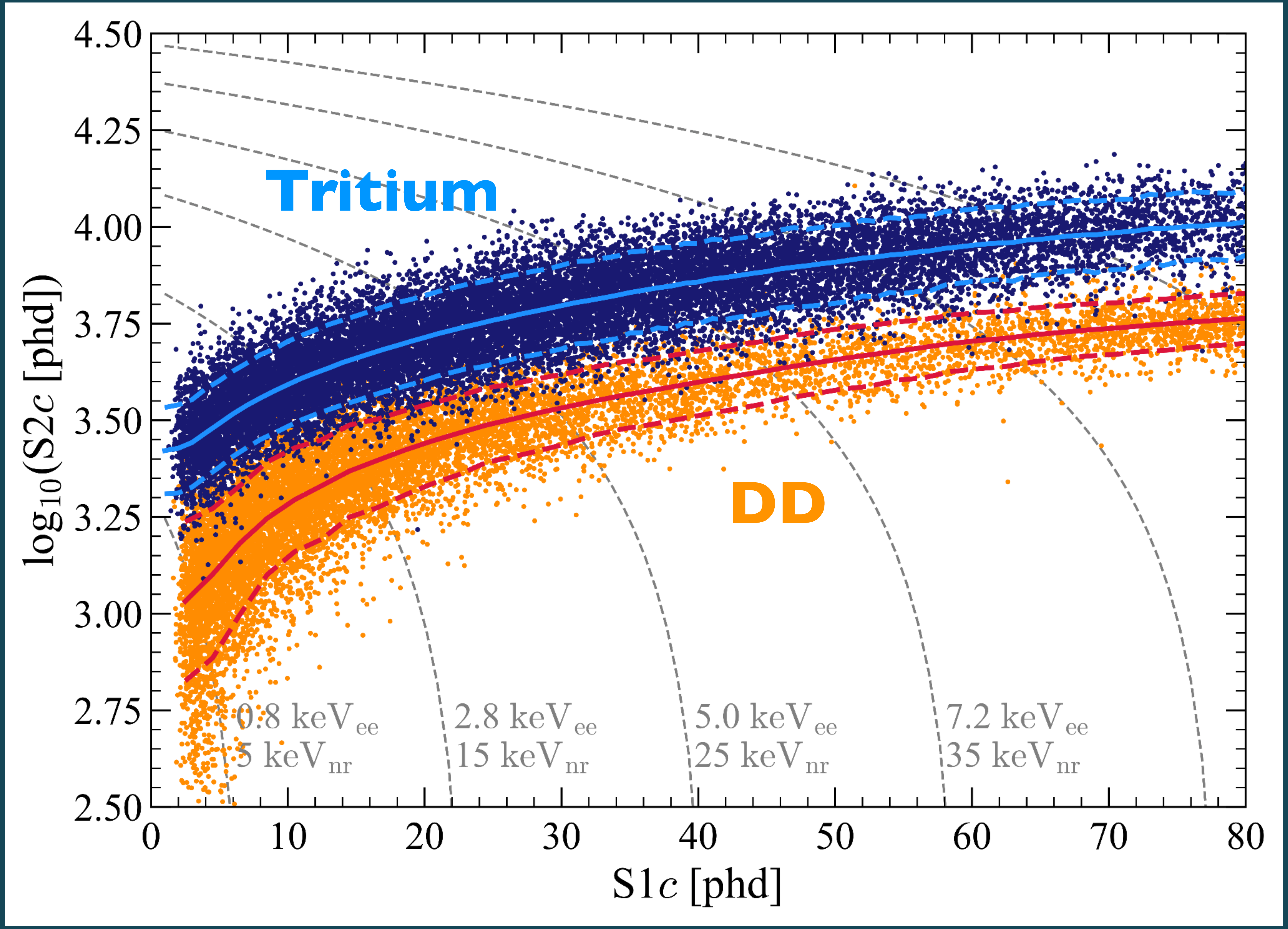
WS2024 SCIENCE RUN CONDITIONS

- Drift field of 97 V/cm
- Extraction field of 3.4 kV/cm (in liquid)
- Continuous purification at 3.3 t/day through hot getter system
- Electron lifetime (measure of purity) at >8 ms for most of the run
- >95% science data-taking efficiency throughout the run
- Science data spatio-temporally corrected using calibrations



CALIBRATIONS

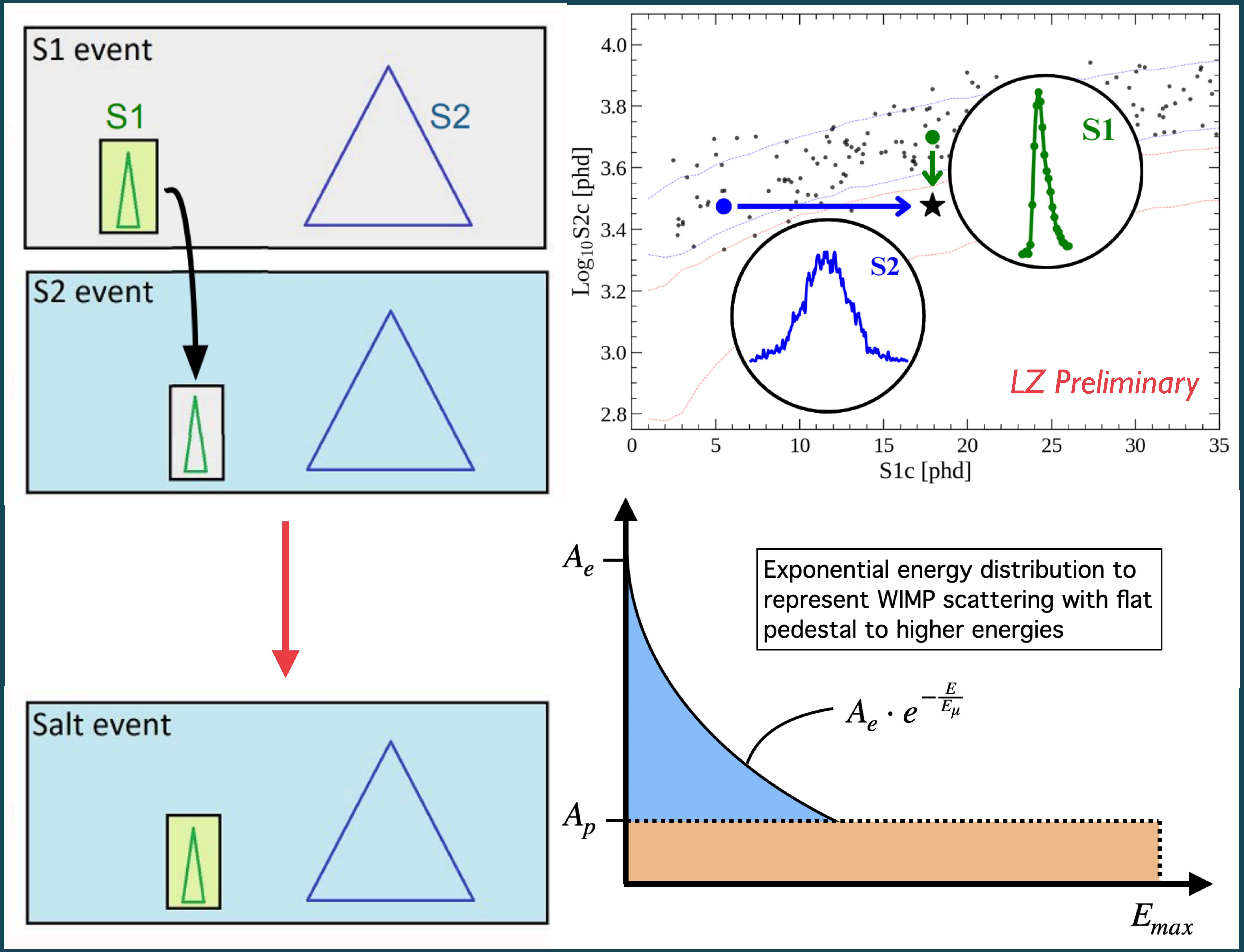
- Backgrounds predominantly ERs; WIMPs produce NRs
- Radiolabelled methane (^3H, ^{14}C) injection to calibrate ER band
  - Spatially homogenous β source
- DD neutron generator (NR band)
  - Mono-energetic 2.45 MeV neutrons
- 99.8% discrimination of beta backgrounds under flat NR band median achieved



g1 (light gain) = 0.112 +/- 0.002 phd/photon

g2 (charge gain) = 34.0 +/- 0.9 phd/e^-

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

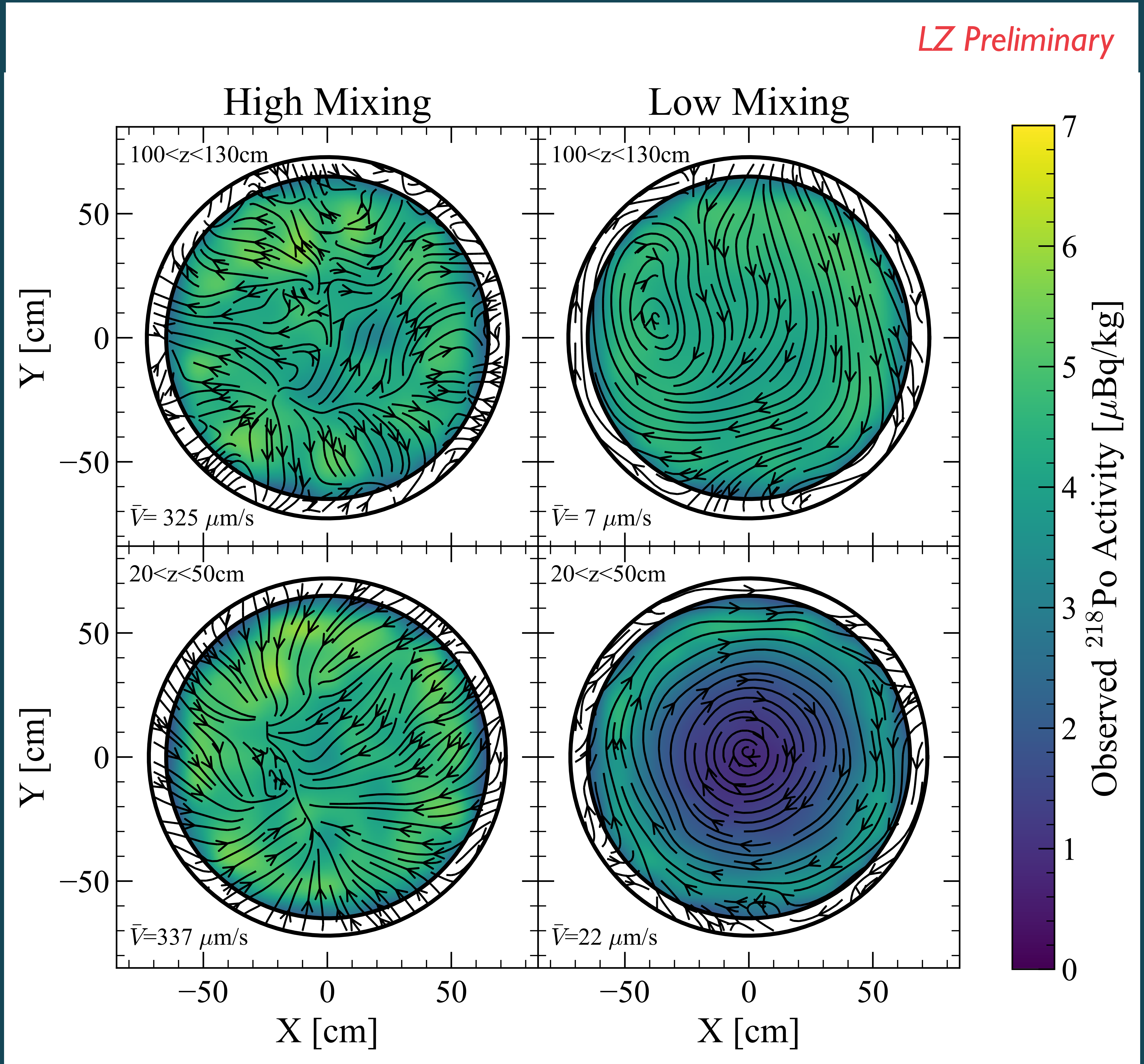
- Circulation & cooling systems allow control of temperature & xenon flow

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

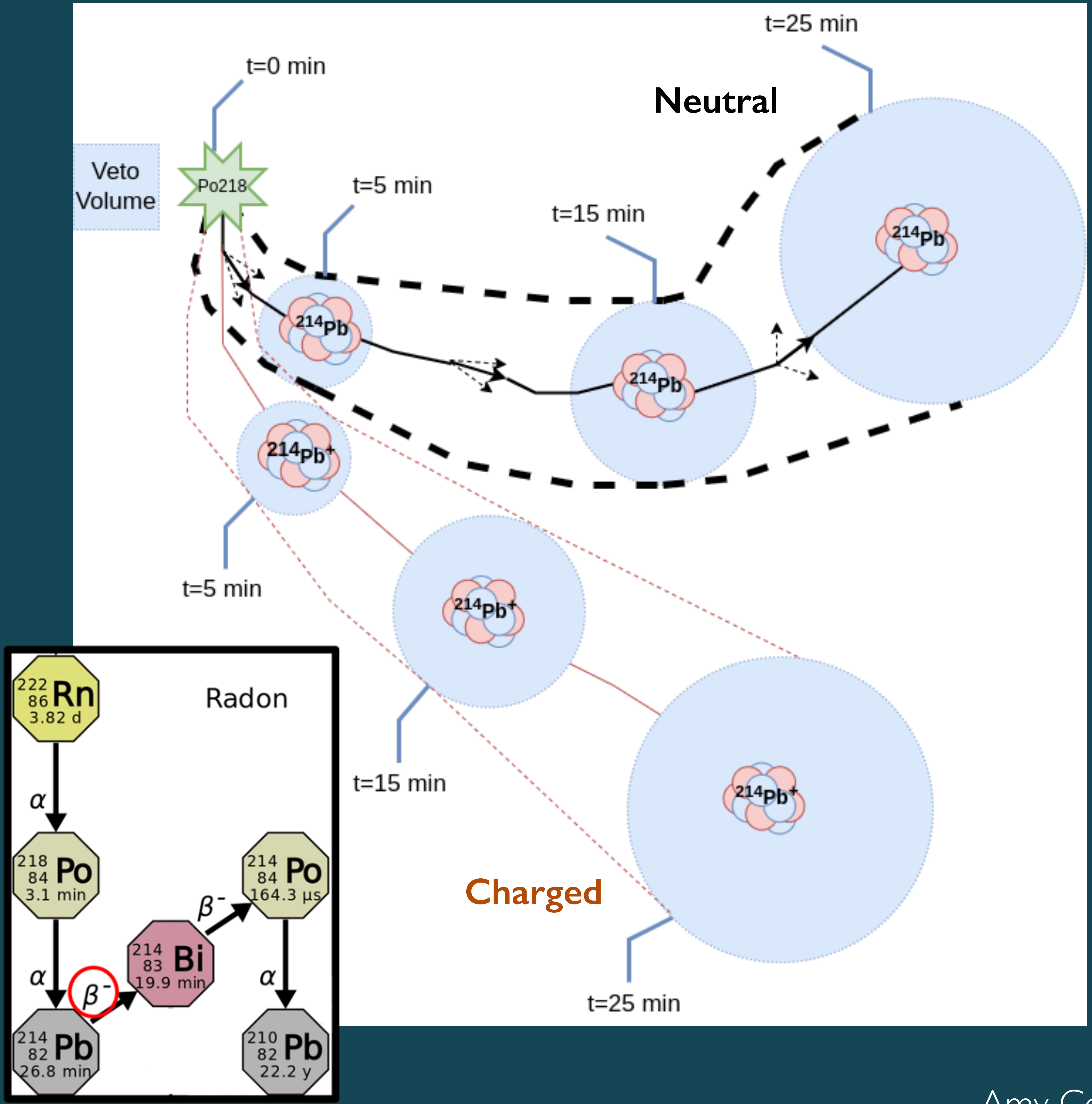
  Low-mixing state
  Slower, laminar flow

- ^{222}Rn emanates from detector materials

- ^{222}Rn-^{218}Po pairs ($T_{1/2}$ = 3.1 min)
  → used to map the flow vectors



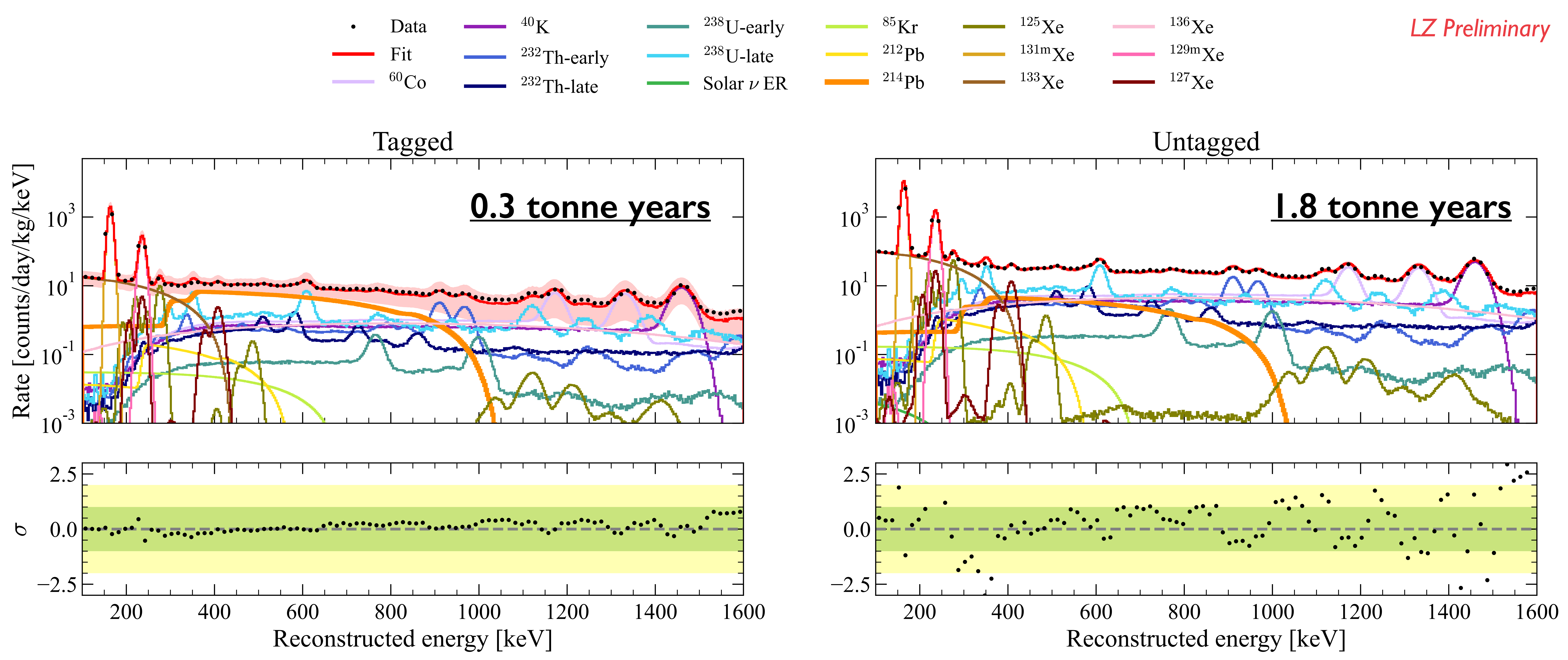
RADON TAG



- "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 $T_{1/2}$)
- Tagged & untagged data both in WIMP analysis

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

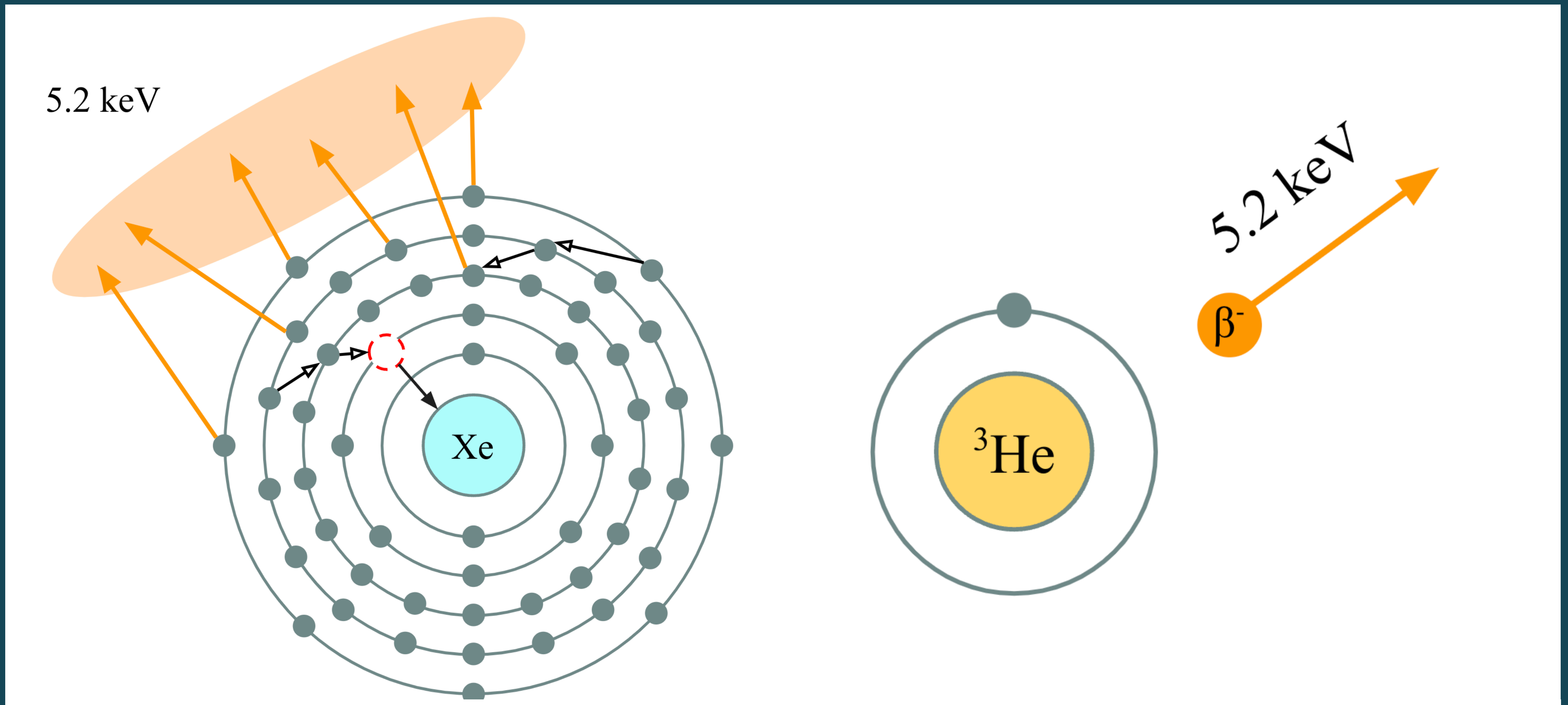
RADON TAGGED HIGH-ENERGY BACKGROUND FIT

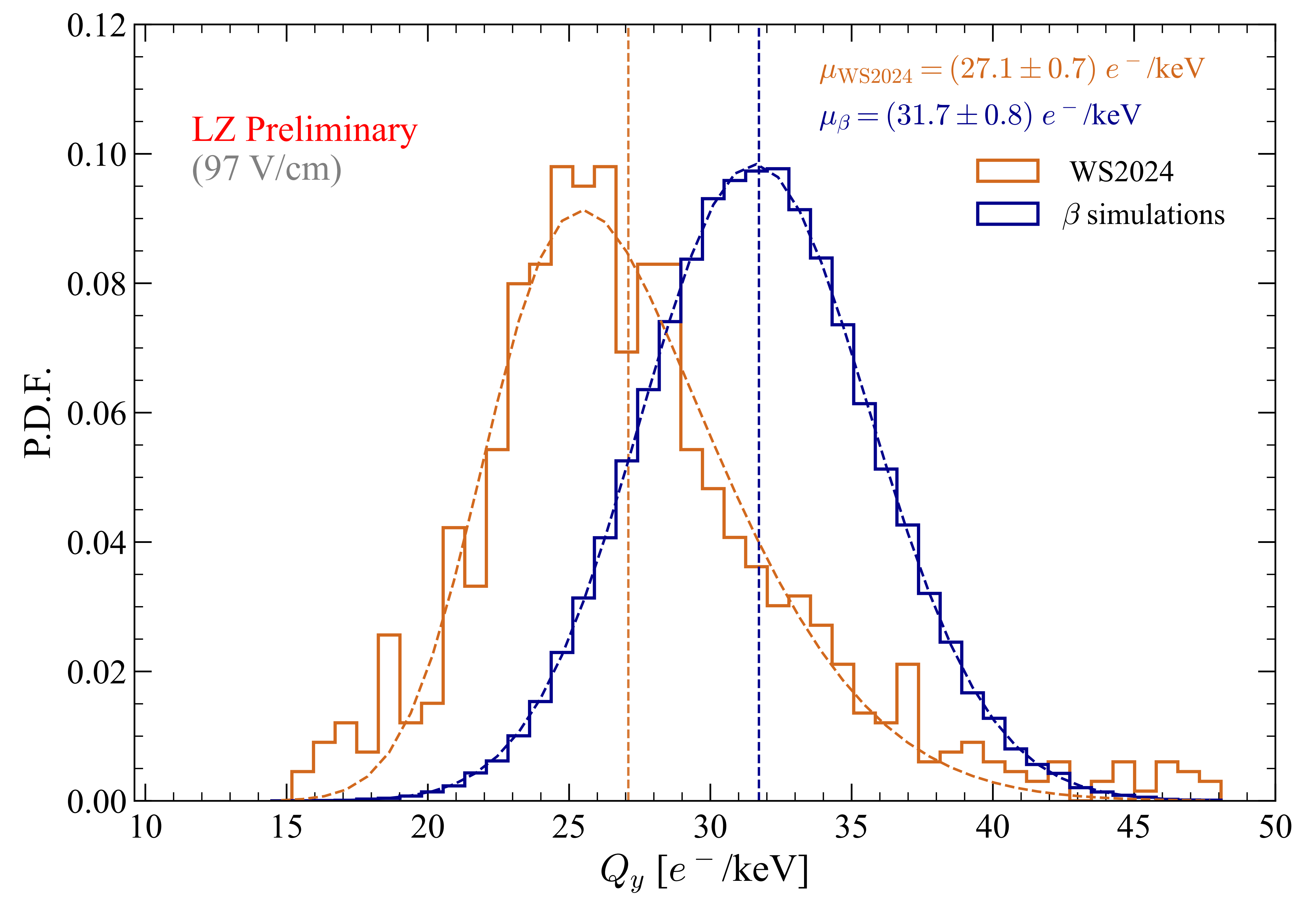


Effective untagged ^{214}Pb activity of 1.8 ± 0.3 µBq/kg (compared to 3.9 ± 0.6 µBq/kg in total exposure)

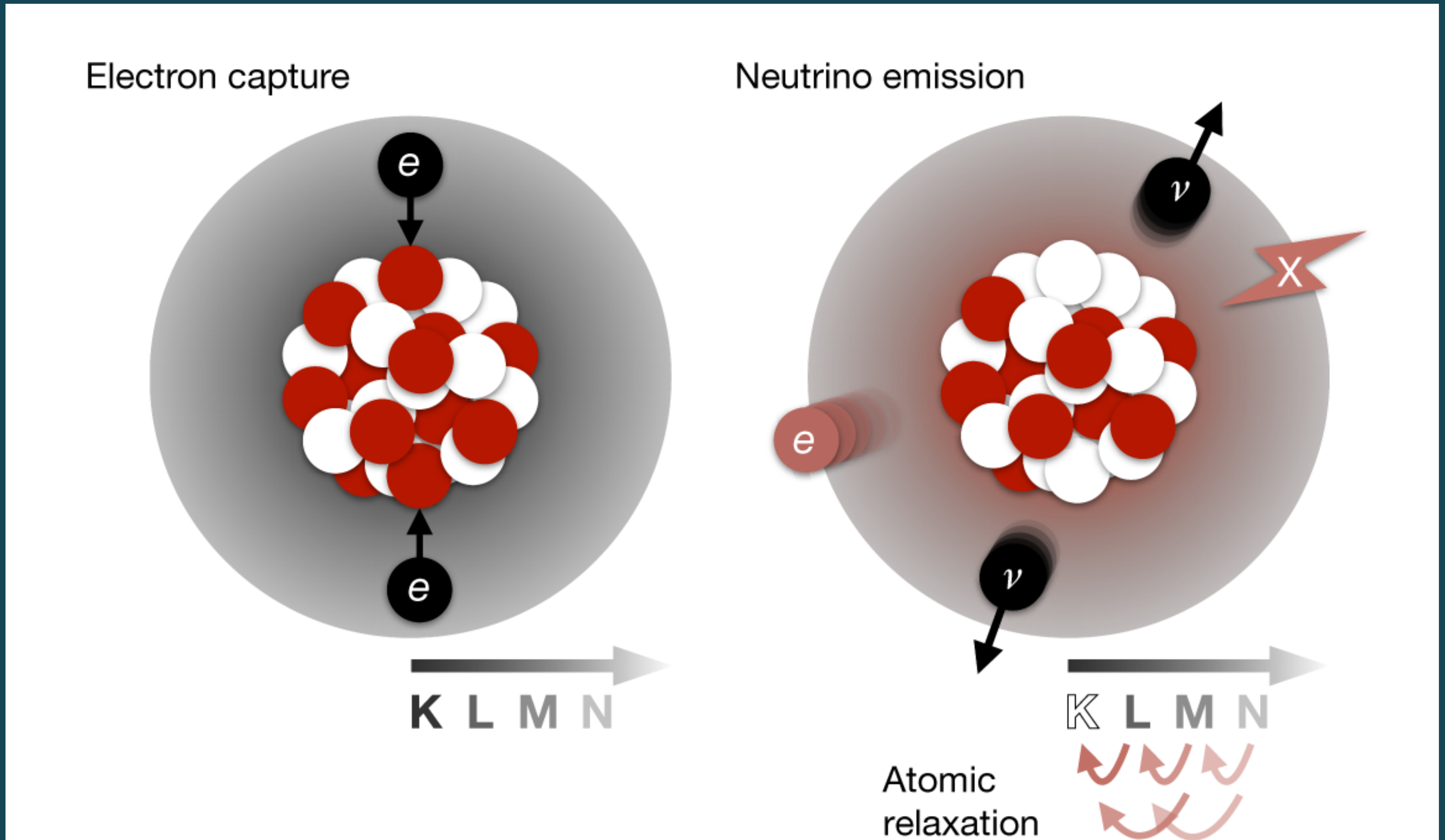
ELECTRON CAPTURES

- ^{127}Xe & ^{125}Xe decay by electron capture (EC)
  - Produced by cosmogenic & neutron activation → much lower activity than WS2022
- L-shell EC (5.2 keV) relevant for WIMP search
  - Auger/X-ray cascade → more nucleated energy deposition than β = more NR-like i.e. **charge-suppressed** ER response
  - Charge suppression first measured in XELDA *PRD 104, 112001 ('21)*
  - *In-situ* measurement in LZ for WS2024: **Q_L/Q_β = 0.86 ± 0.01**

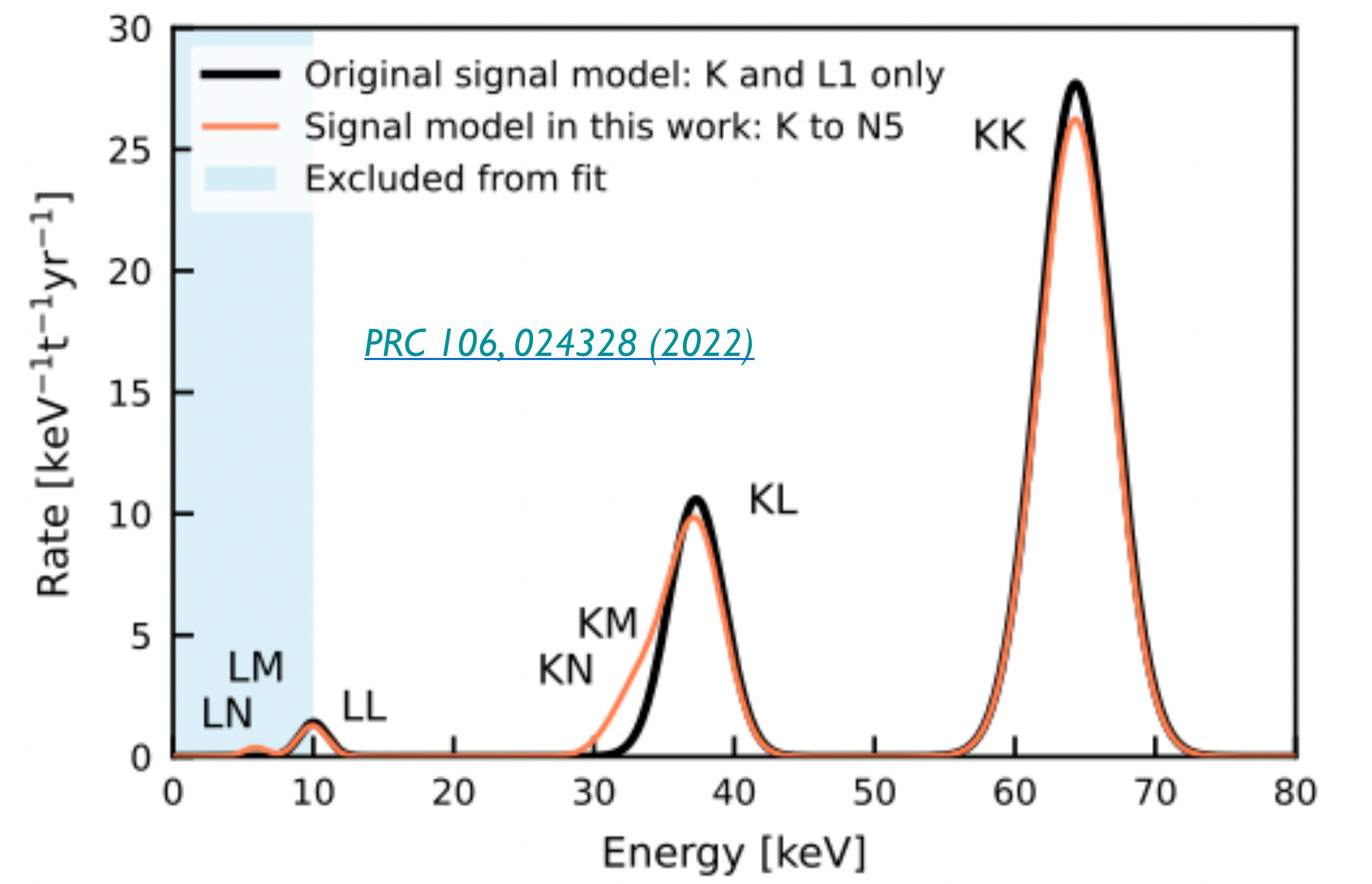




^{124}XE DOUBLE ELECTRON CAPTURE (DEC)



Nature 568, 532–535 (2019)

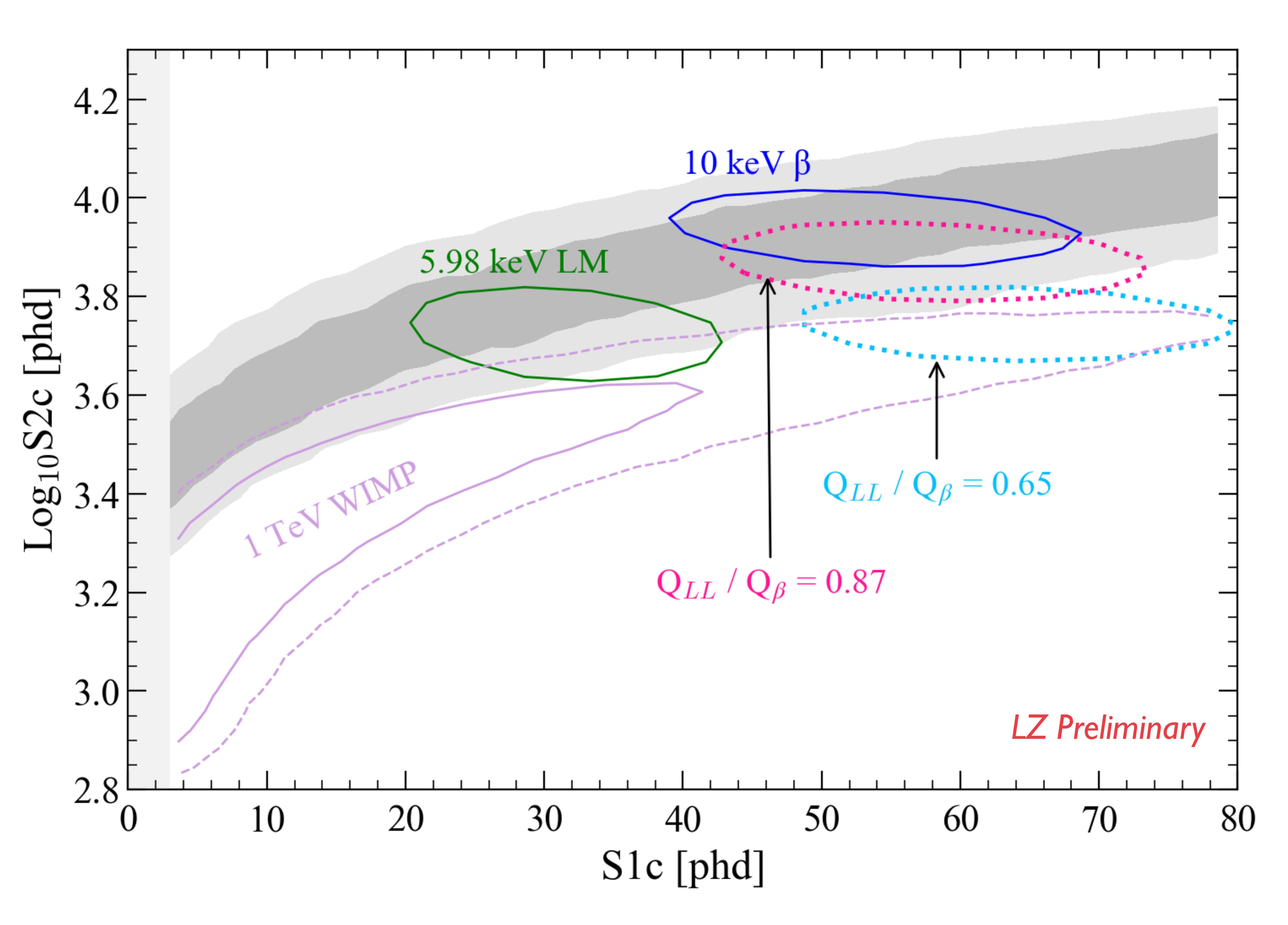


PRC 106, 024328 (2022)

- "World's rarest decay" - $T_{1/2}$ = $(1.09 \pm 0.14_{stat} \pm 0.05_{sys}) \times 10^{22}$ yr (LZ preliminary measurement*)
- KX-shell measured; LM (6.0 keV) & LL-shell (10.0 keV) relevant for WIMP search

*Paper in preparation

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



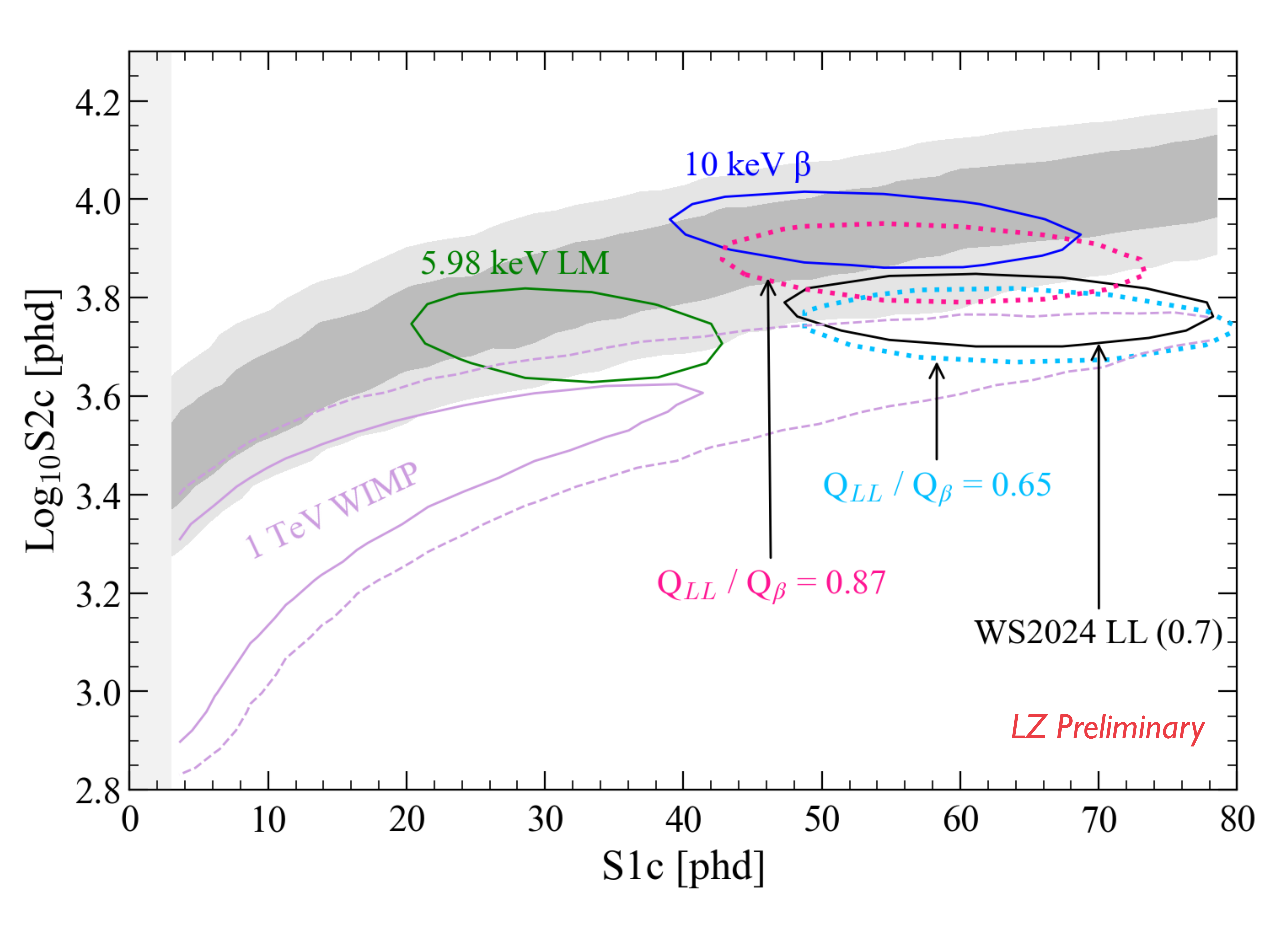
- Expect 7.1 (LM) + 12.3 (LL) = 19.4 counts with 20% uncertainty
- LM modelled with same as single L-shell charge suppression
- LL expected to be further charge-suppressed due to higher ionisation density i.e. $Q_{LL}/Q_\beta < Q_L/Q_\beta$
- **Vary Q_{LL}/Q_β in fitting of our data:**

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

2x L-shell ionization density (→ 0.65)

Q_L/Q_β (→ 0.87)

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



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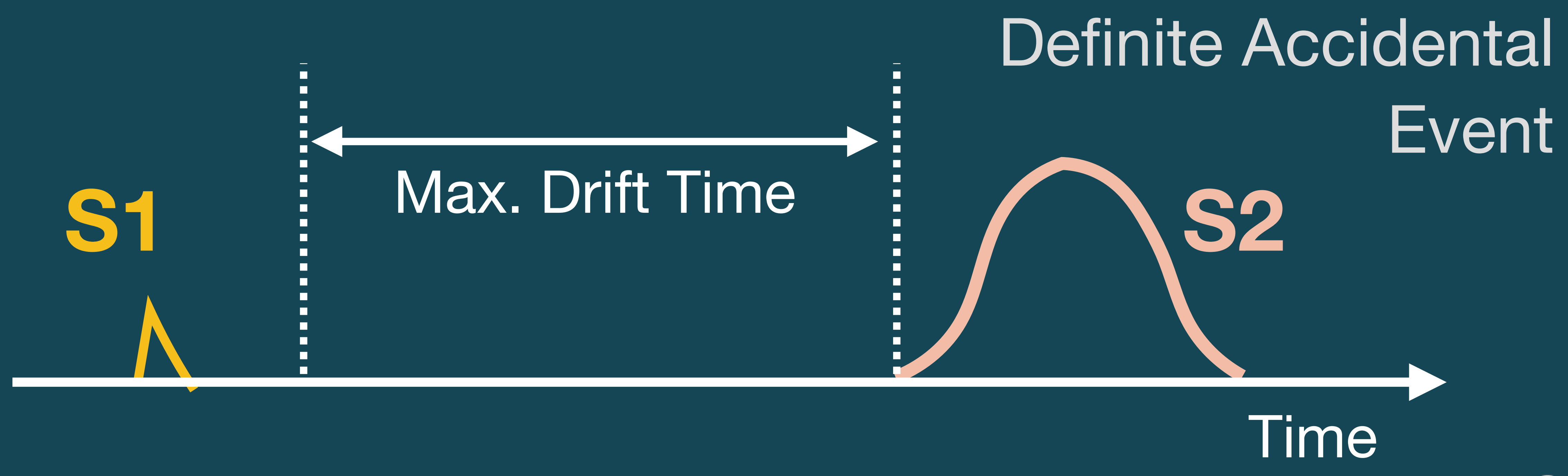
- **Vary Q_{LL}/Q_β in fitting of our data:**

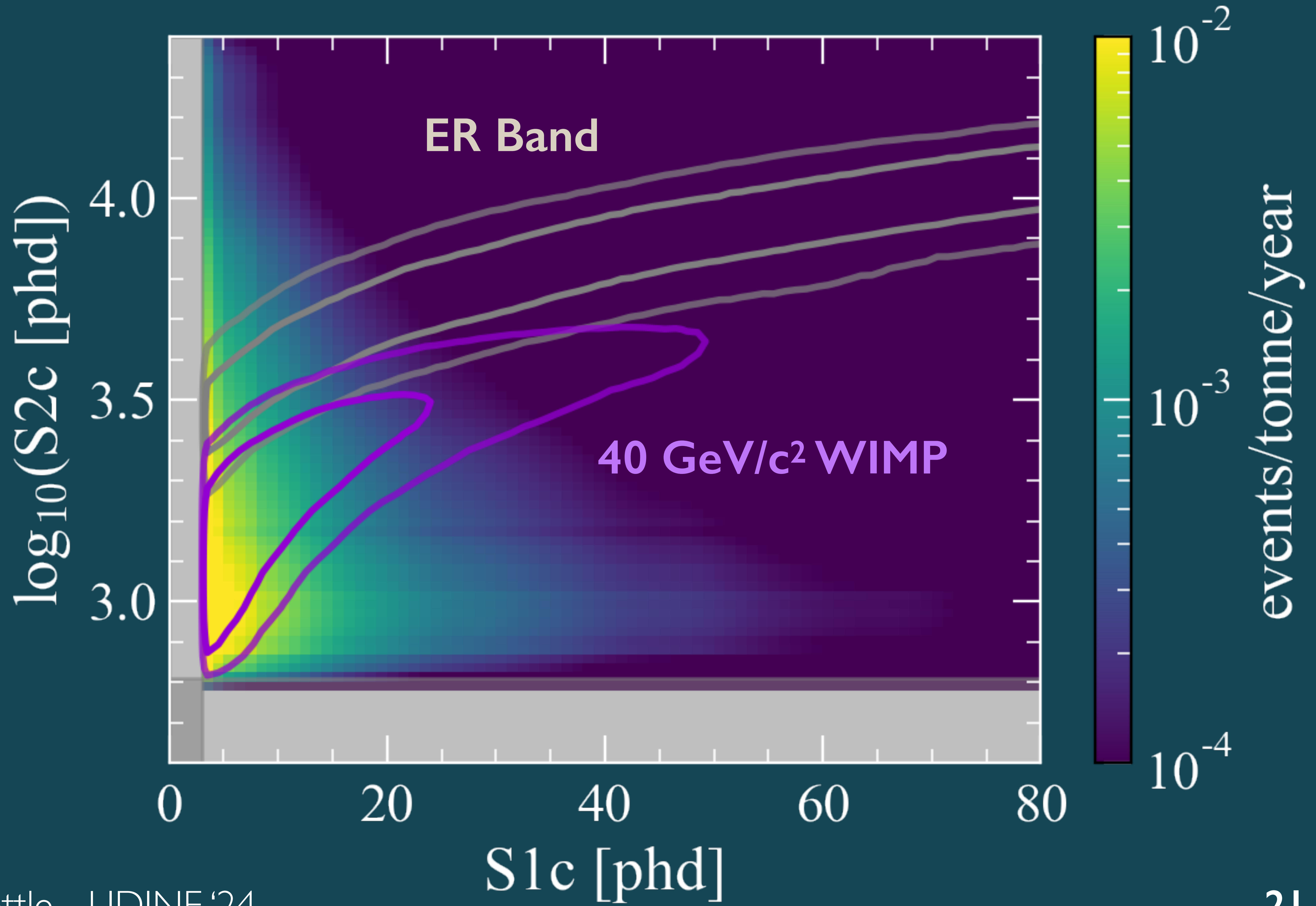
$$0.65 < Q_{LL}/Q_\beta < 0.87$$

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

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



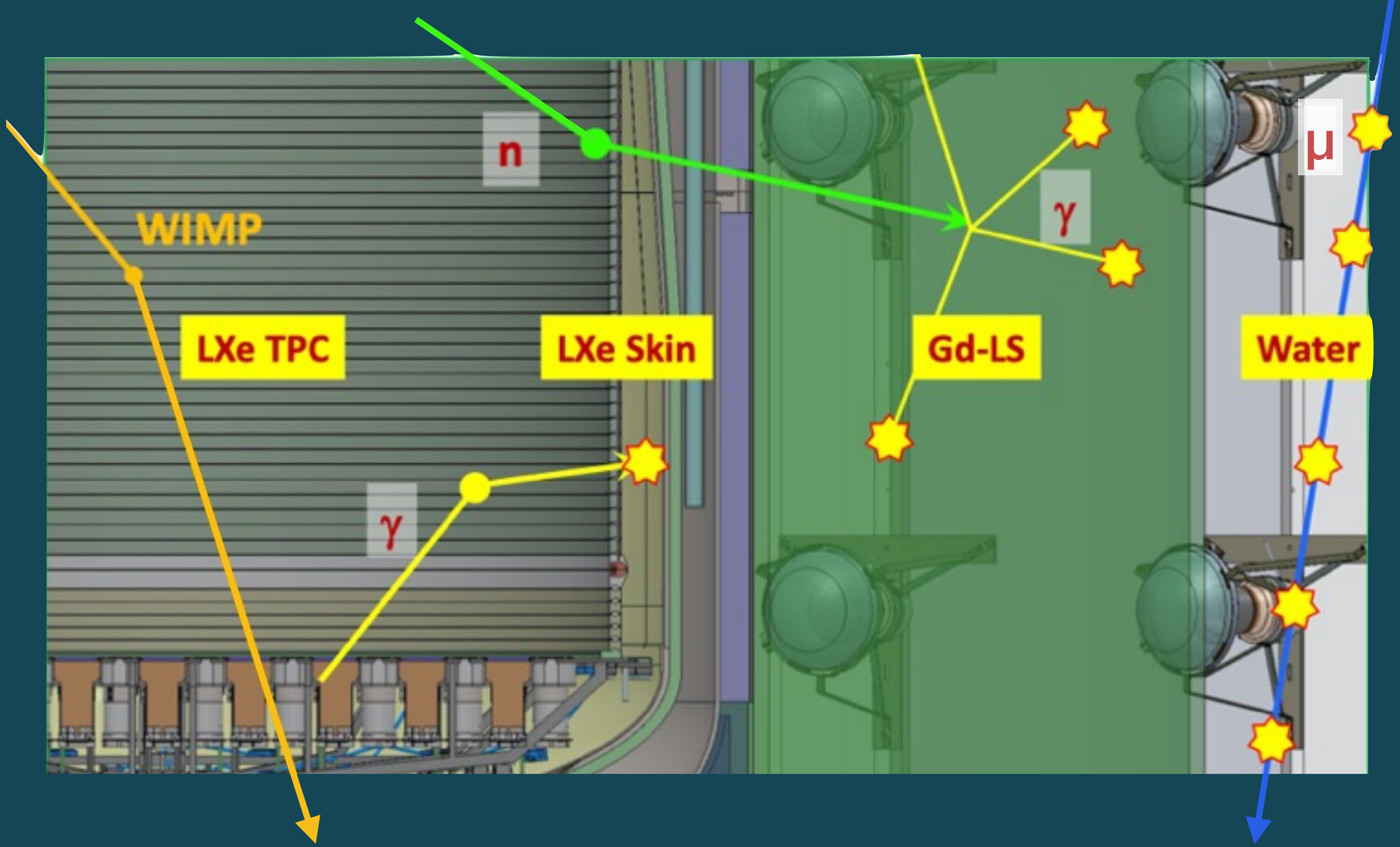


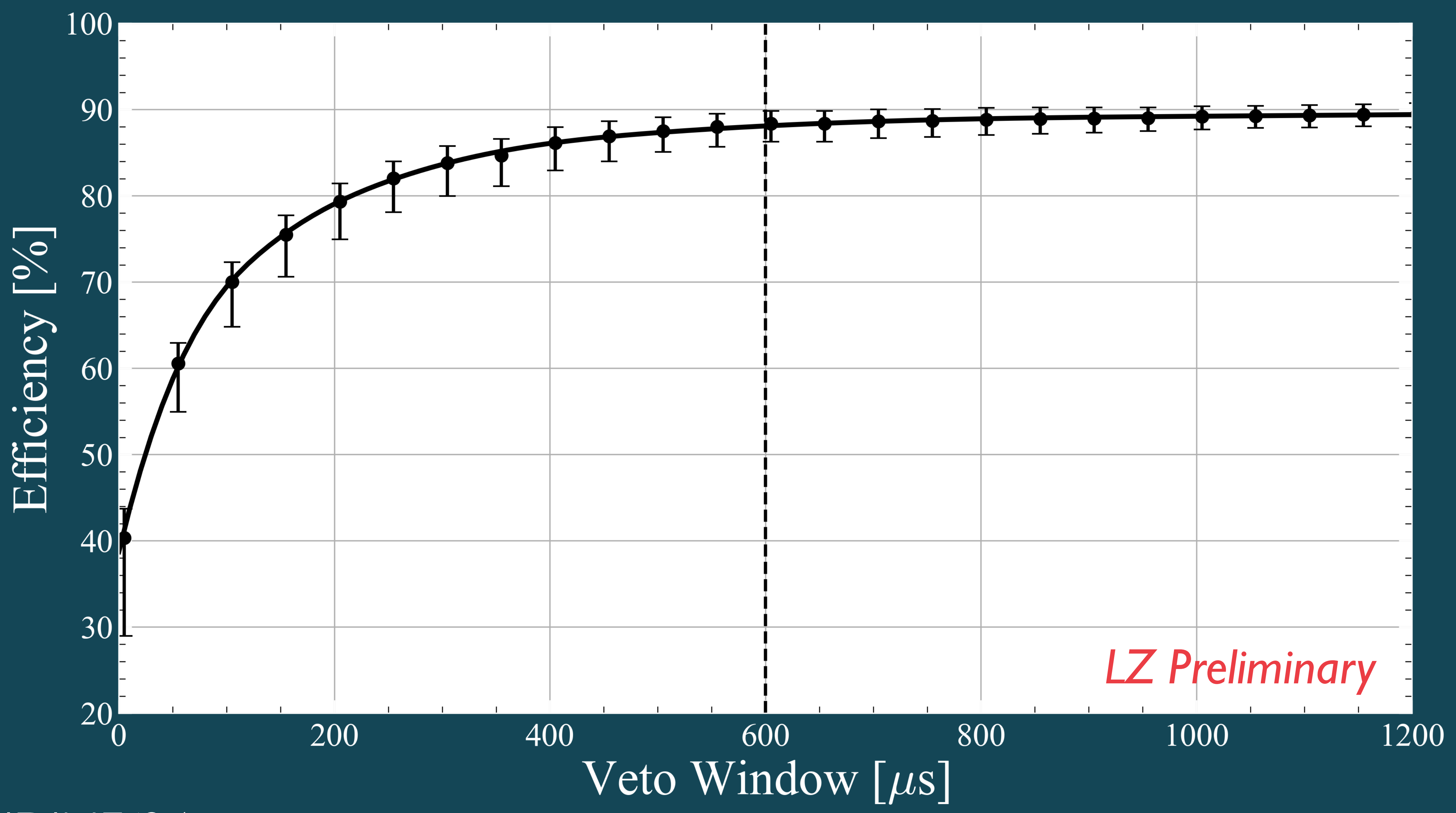
NEUTRONS & OD

- 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

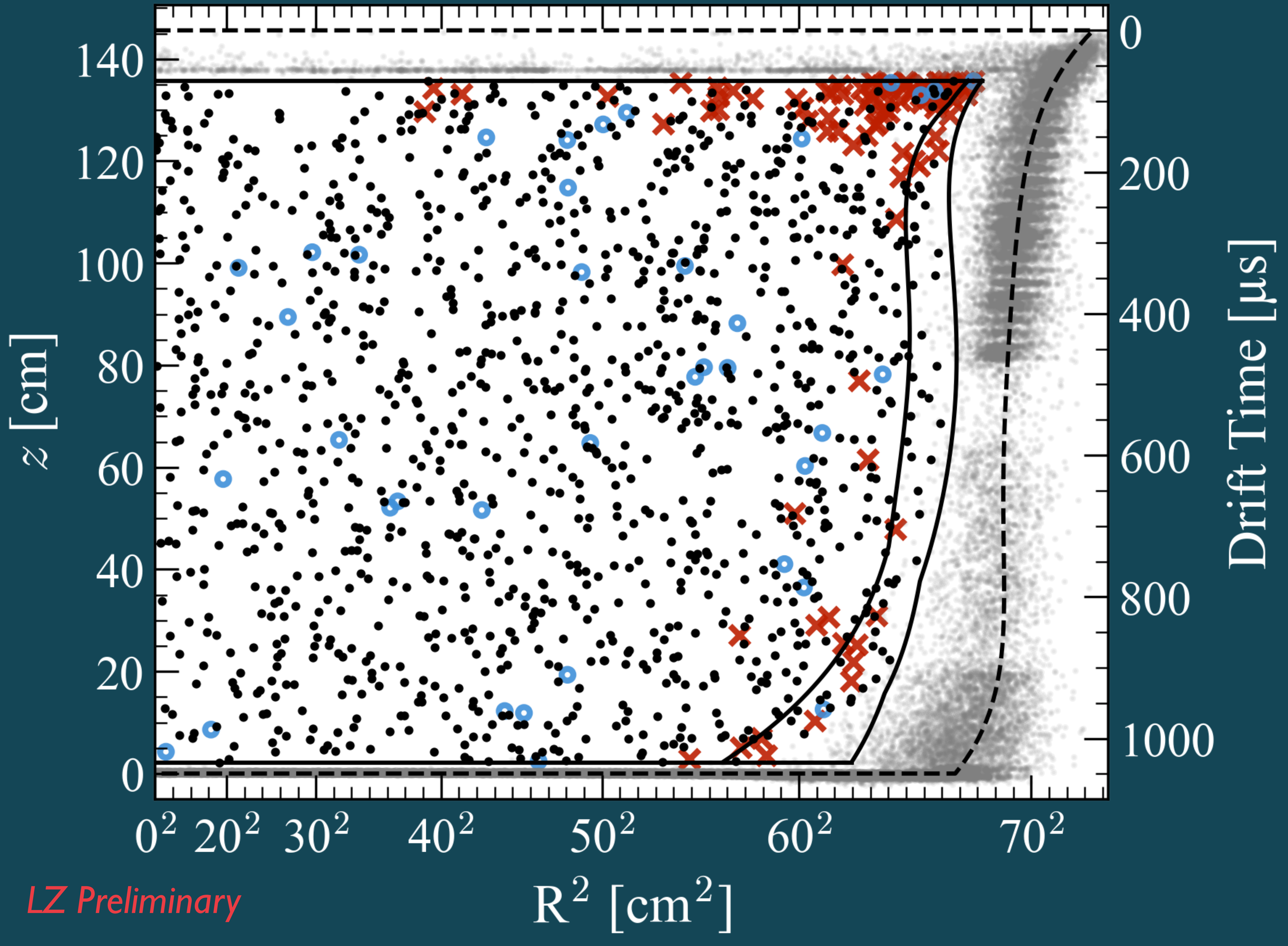
→ delayed OD veto cut to reject neutrons

- 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





FIDUCIAL VOLUME (FV)



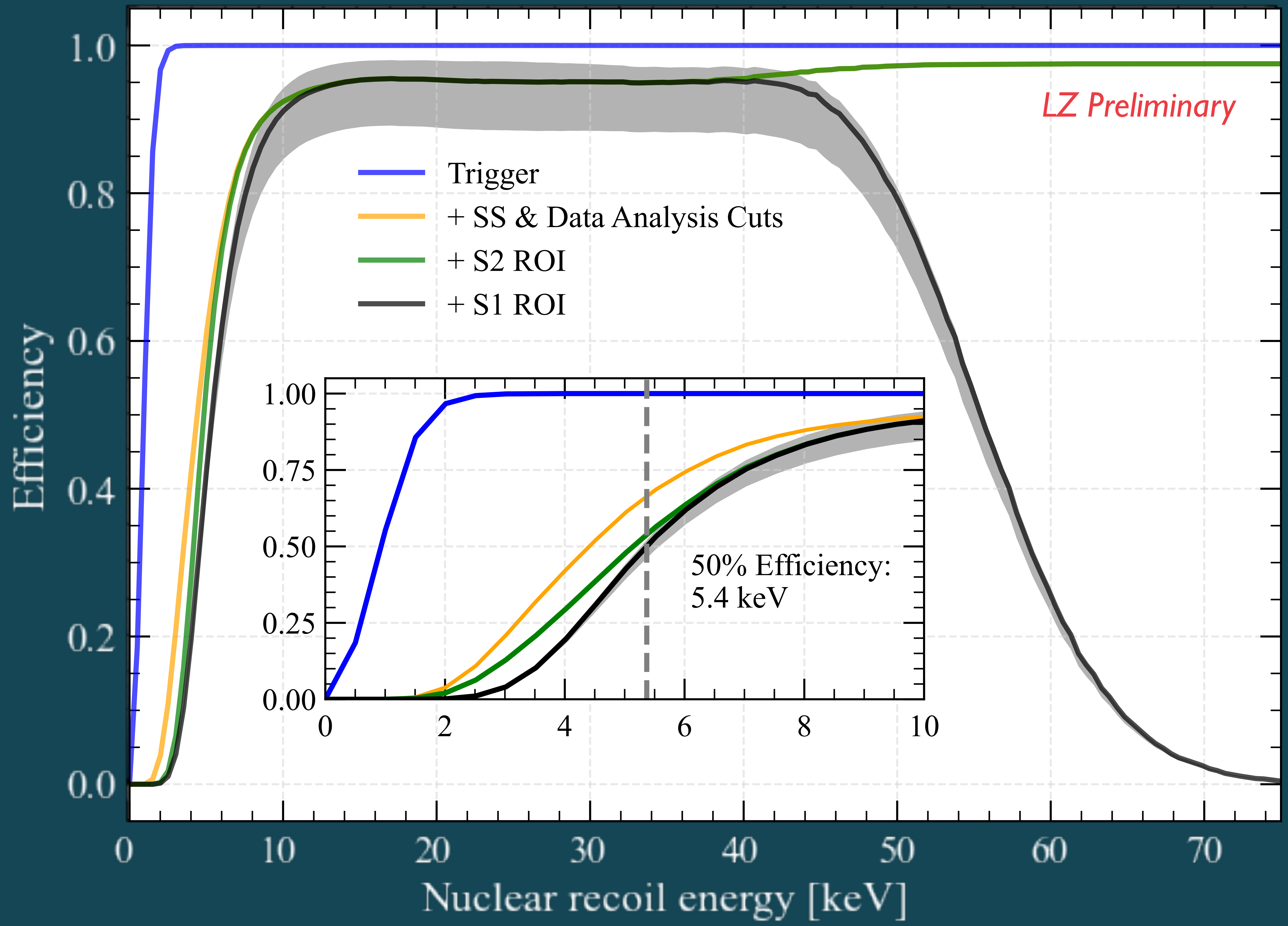
Events prompt-tagged by vetoes

Events delayed-tagged by the vetoes

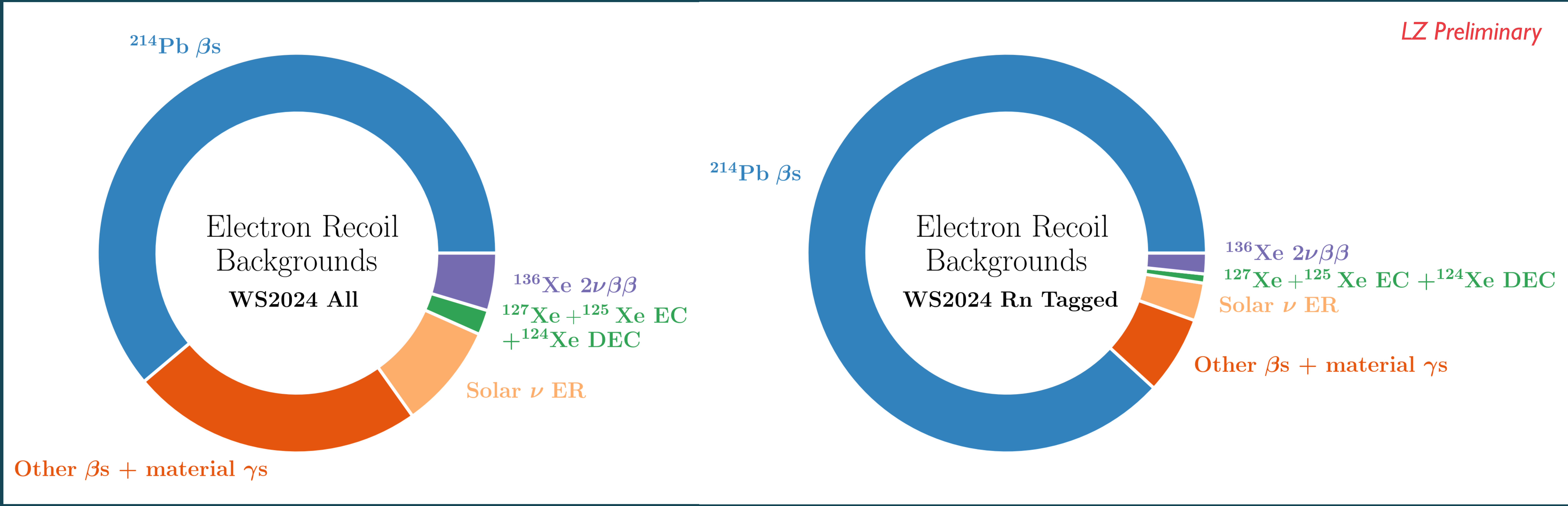
- FV defined to avoid higher background rates at TPC edges (self-shielding)
- TPC radial edge curved due to electric field
  → see Sparshita Dey's talk at 15:55 today
- FV definition:
  - 71 μs < drift time < 1030 μs
  - Azimuthally & drift time-dependent radial cut chosen to ensure <0.01 wall background counts in the FV
- Calculated fiducial mass of **5.5 ± 0.2 t**

ROI & ANALYSIS CUT SUMMARY

- Region of interest (ROI)
  - 3 < S1c < 80 photons detected (phd); three-fold PMT coincidence
  - S2 > 645 phd (14.5 electrons); log10 (S2c) < 4.5
- Cuts developed on non-WIMP ROI data
- Event selection criteria
  - FV, ROI, single scatter cuts
  - Veto detector anti-coincidence
  - S1- & S2-based cuts



BACKGROUNDS MODEL EXPECTATIONS



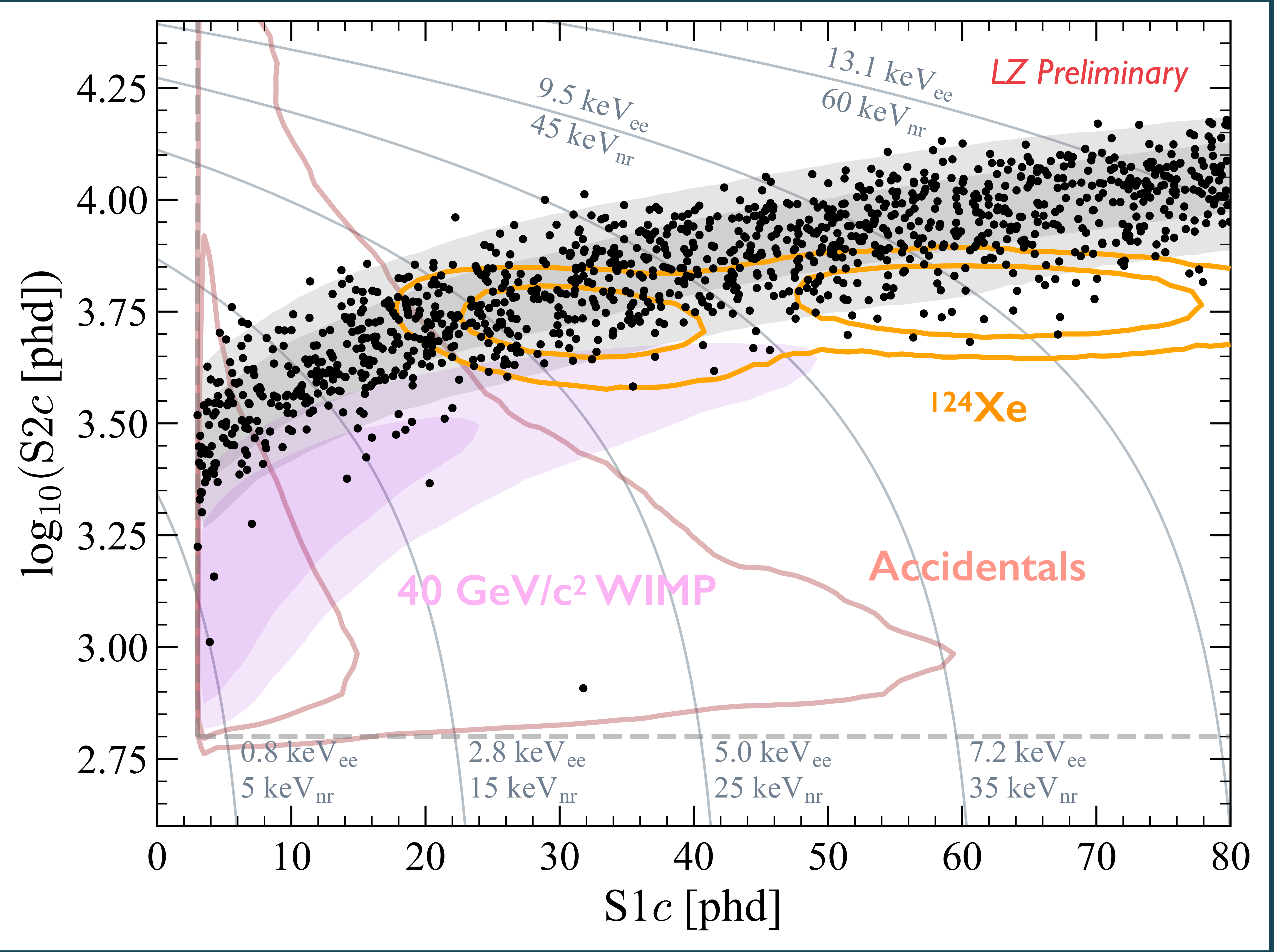
- Total expected **ER** counts for WS2024: **1207** (60% of which are ^{214}Pb)
  - Of which **327** are in the radon tagged data set (88% of which are ^{214}Pb)

- Total expected **NR** counts in WS2024: **0.18** from CEvNS (no neutrons - *in-situ* fit constraint)

WS2024 DATA - SALTED

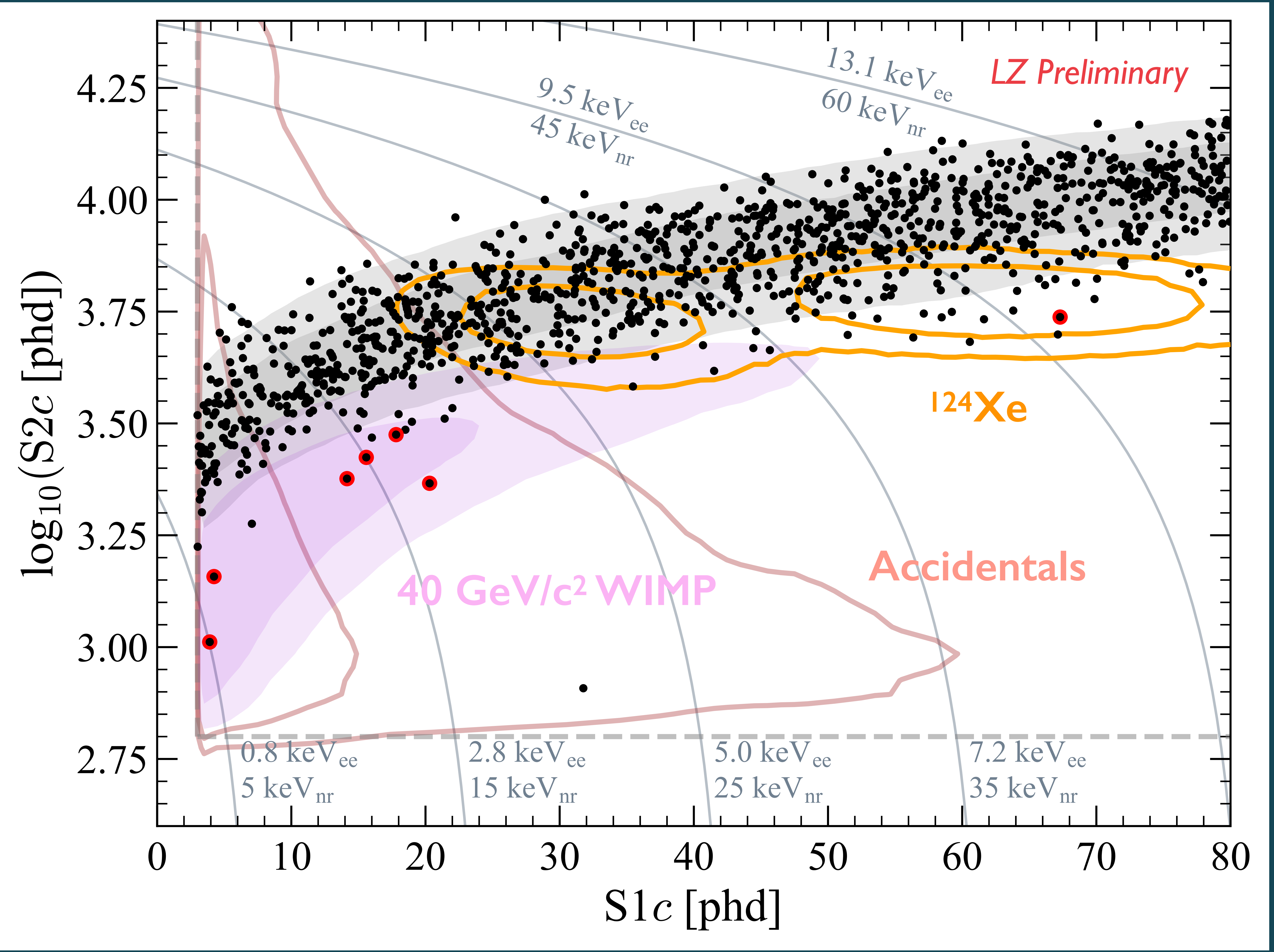
- Final exposure of 220 live days * 5.5 tonnes = **3.3 tonne years**

- **1227 events** remaining



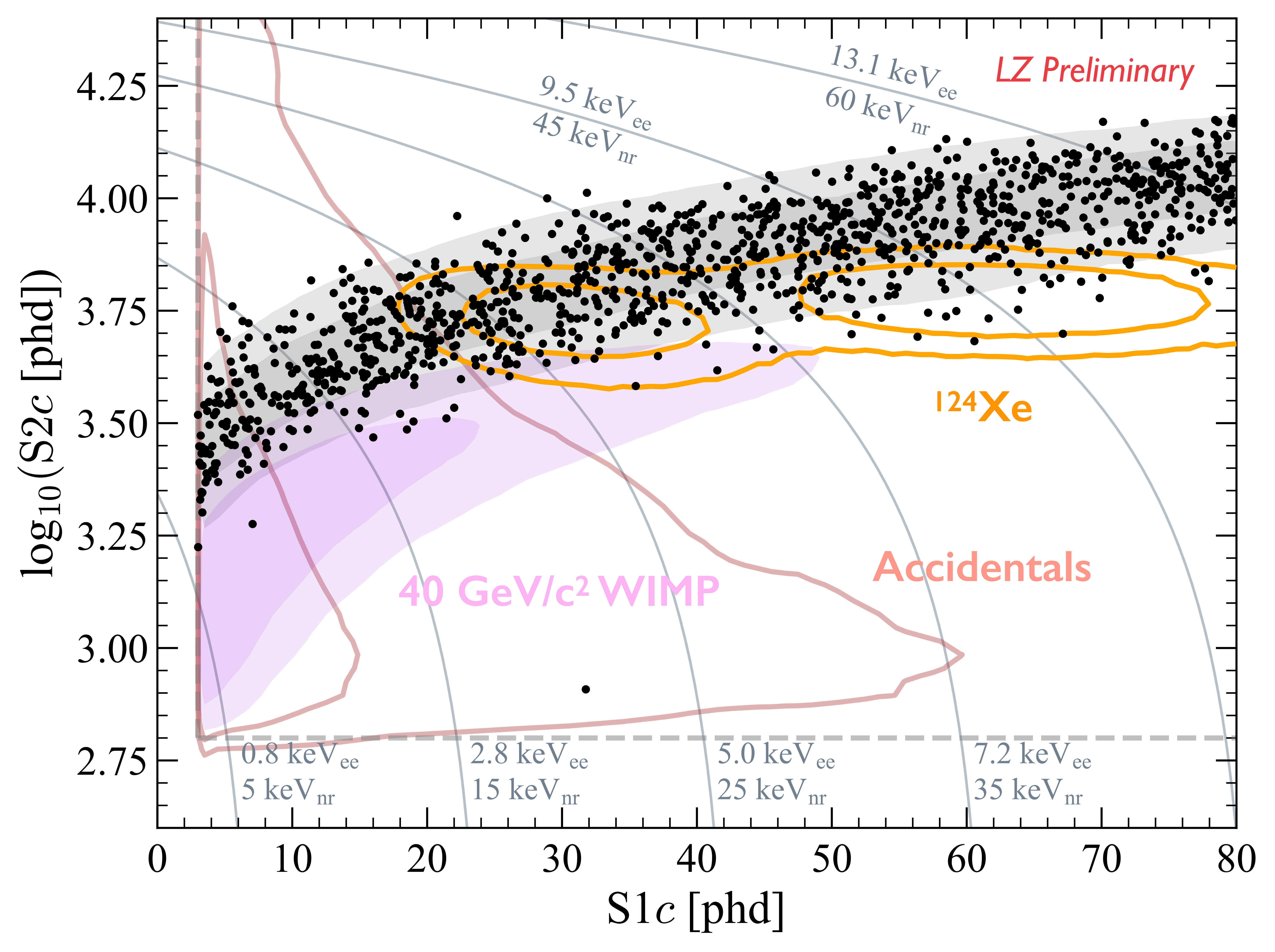
WS2024 DATA - SALTED

- 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

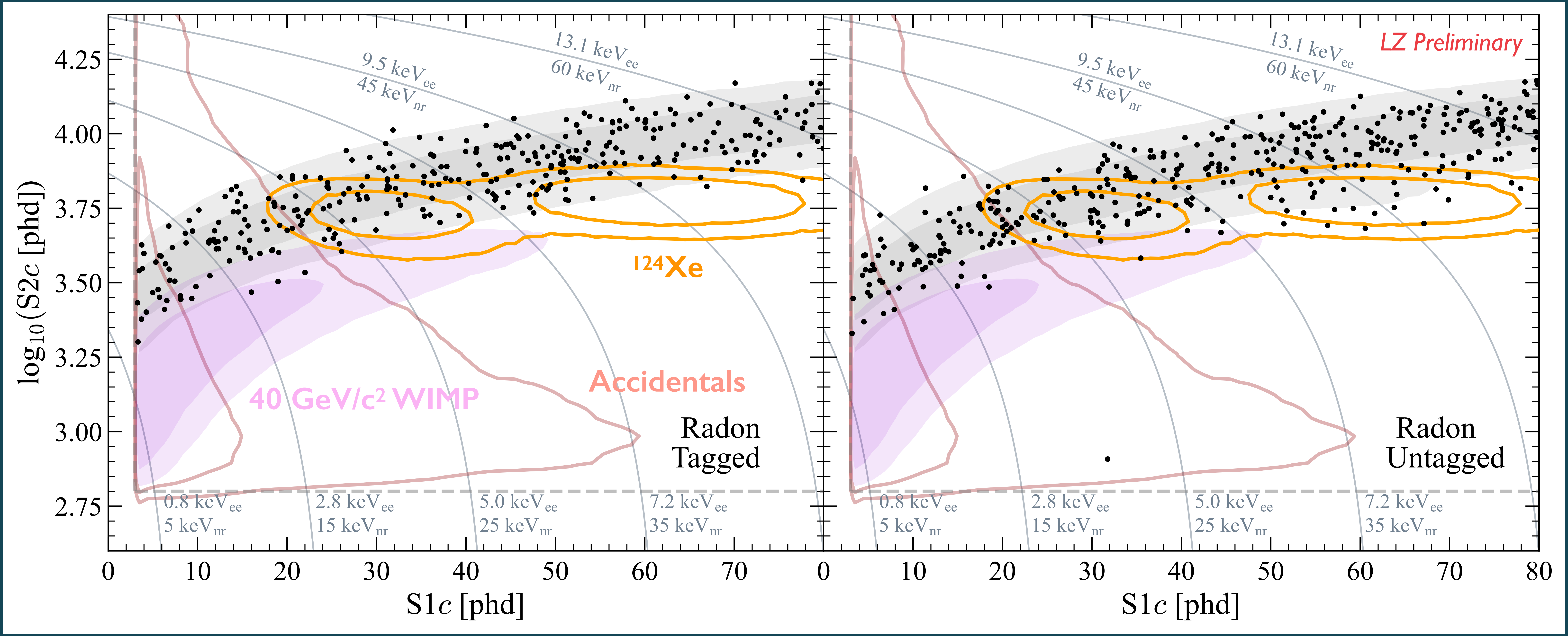


WS2024 DATA - SALTED

- 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**

COMBINED LIKELIHOOD

Exposures in Each Sample in Tonne Years

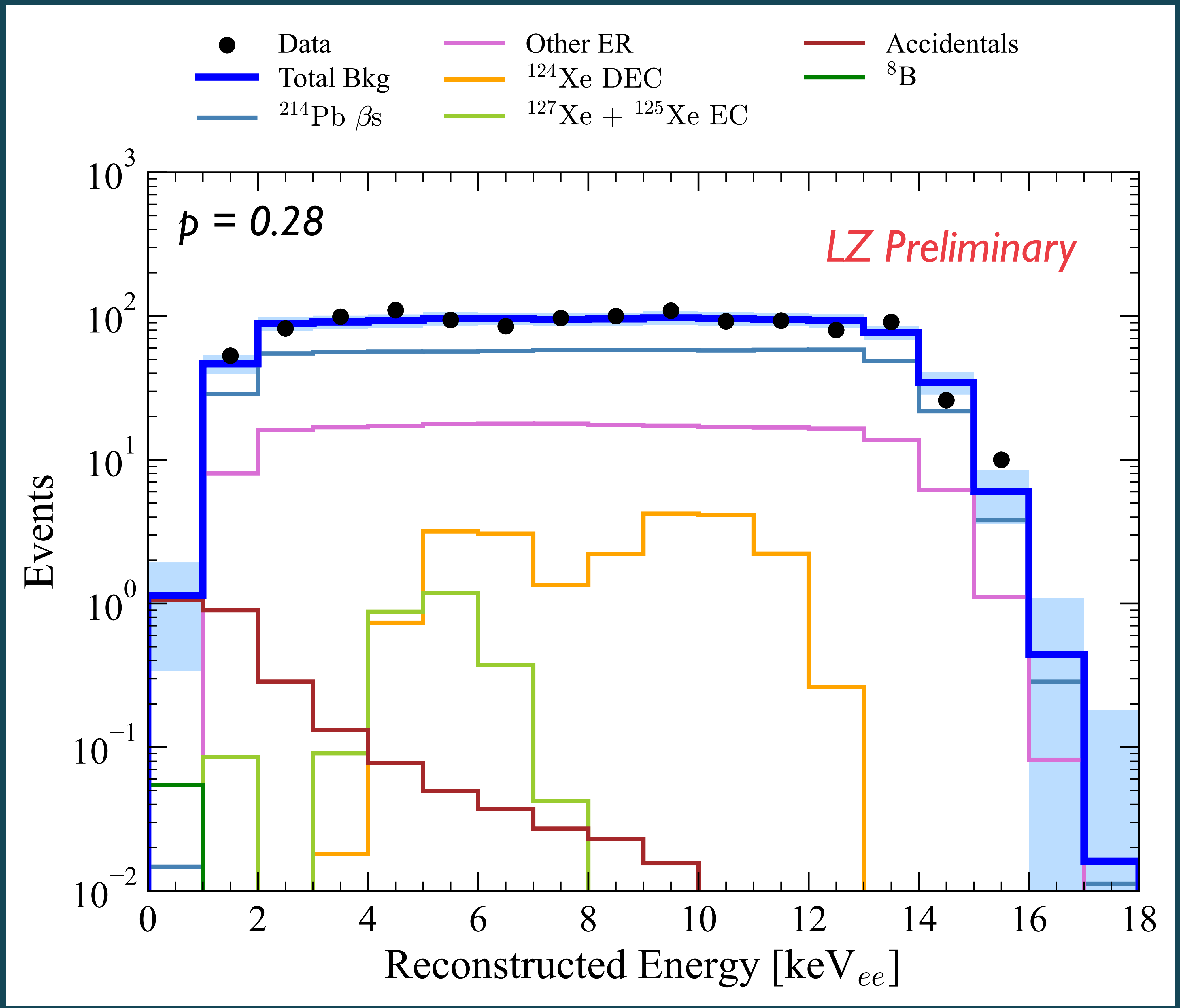
1	2	3	4	5	6
High-Mixing State	Radon Tag Inactive	Radon Tagged	Radon Untagged	Skin/OD Vetoed	WS2022
0.6	0.6	0.3	1.8	n/a	0.9

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

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	55.8 ± 8.2
^{124}Xe DEC	19.4 ± 3.9	21.4 ± 3.6
^{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	1203 ± 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

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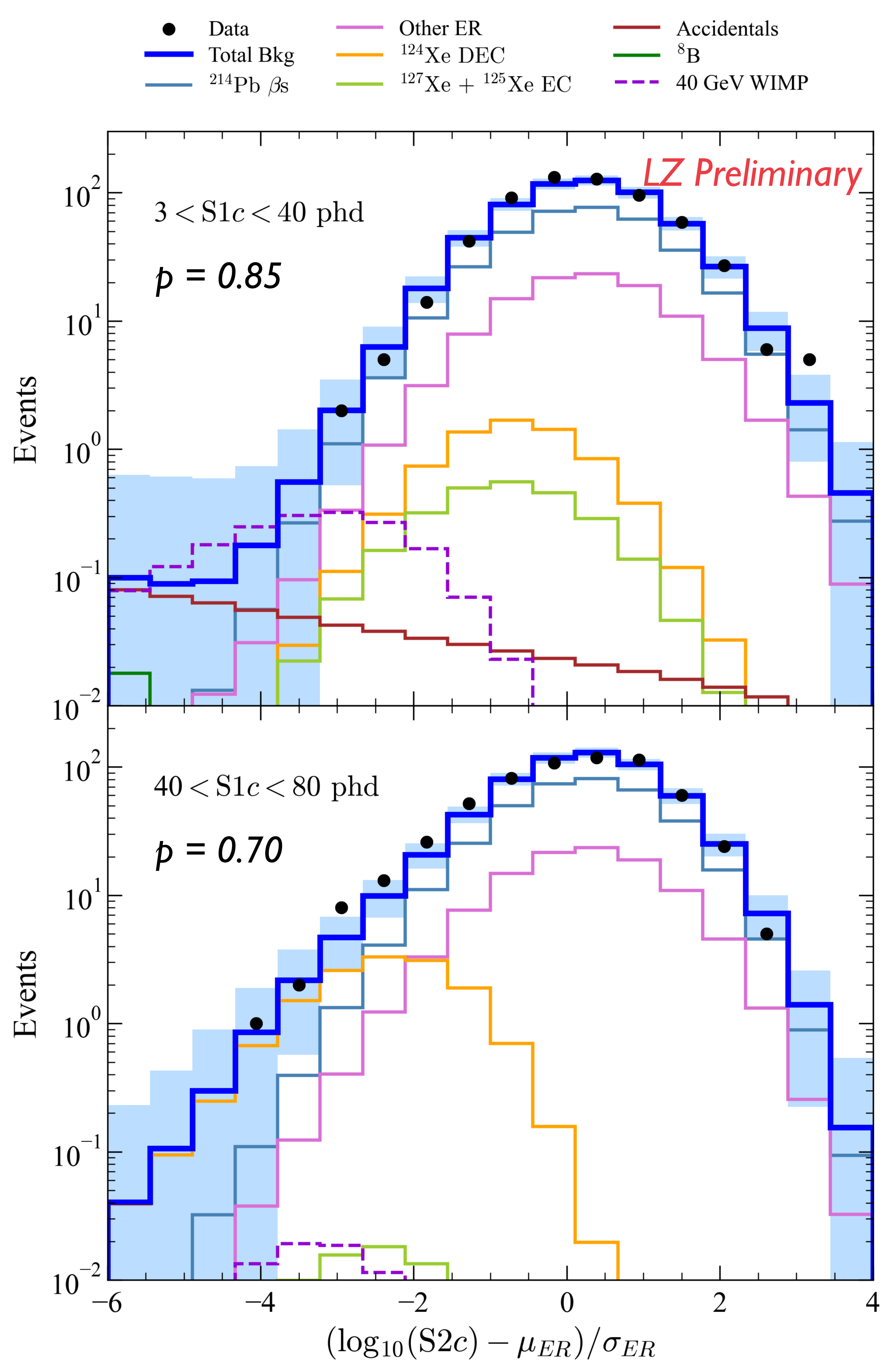
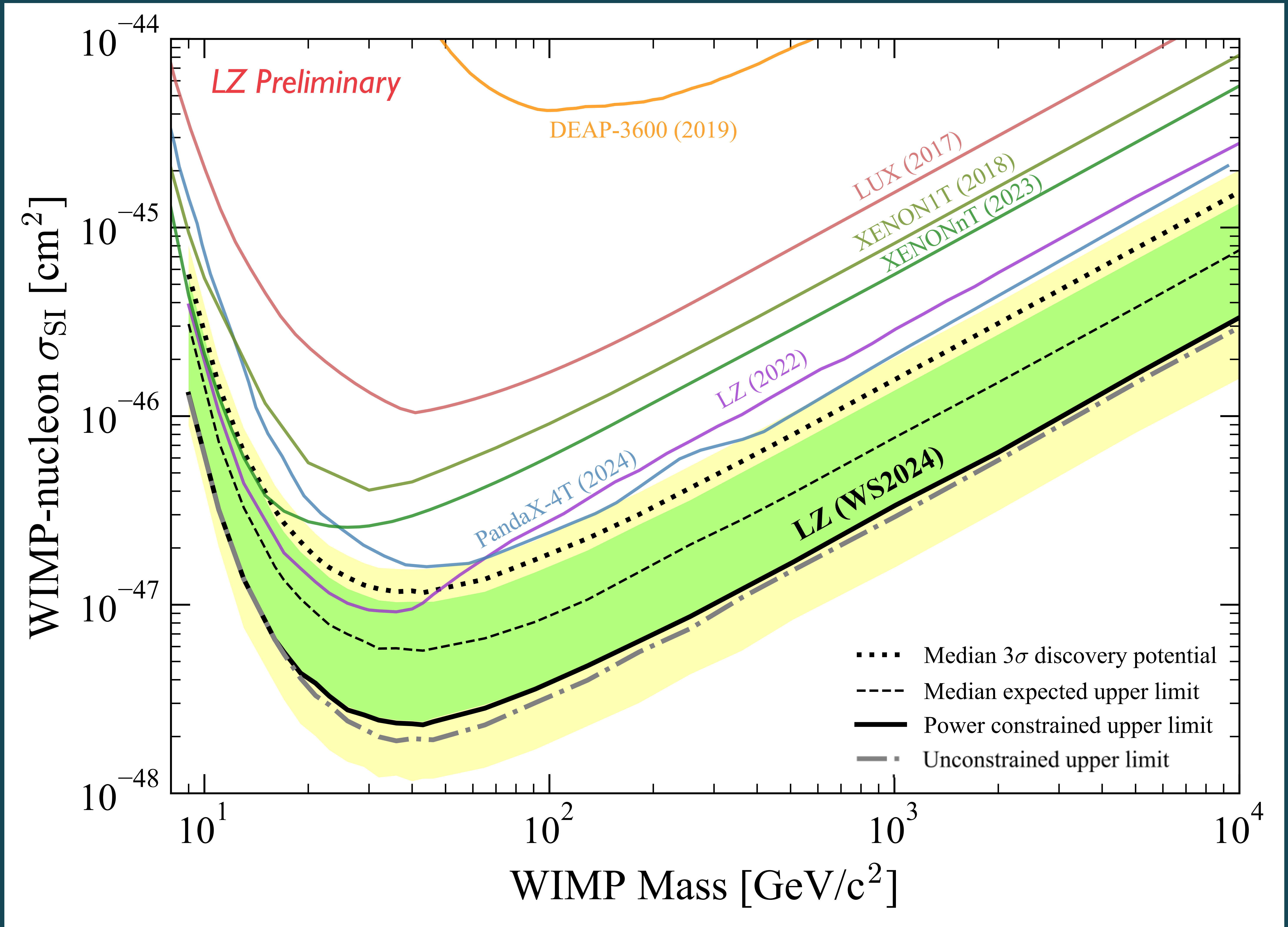
Solar ν ERs	102 ± 6	102 ± 6
^{212}Pb + ^{218}Po β decays	62.7 ± 7.5	63.7 ± 7.4
^{3}H + ^{14}C β decays	58.3 ± 3.3	59.7 ± 3.3
^{136}Xe 2νββ decay	55.6 ± 8.3	55.8 ± 8.3
^{124}Xe DEC	19.4 ± 3.9	21.4 ± 3.6
^{127}Xe + ^{125}Xe EC	3.2 ± 0.6	2.7 ± 0.6
Atm. ν CEνNS	0.12 ± 0.02	0.12 ± 0.02
^{8}B + *hep* ν CEνNS	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	1203 ± 41

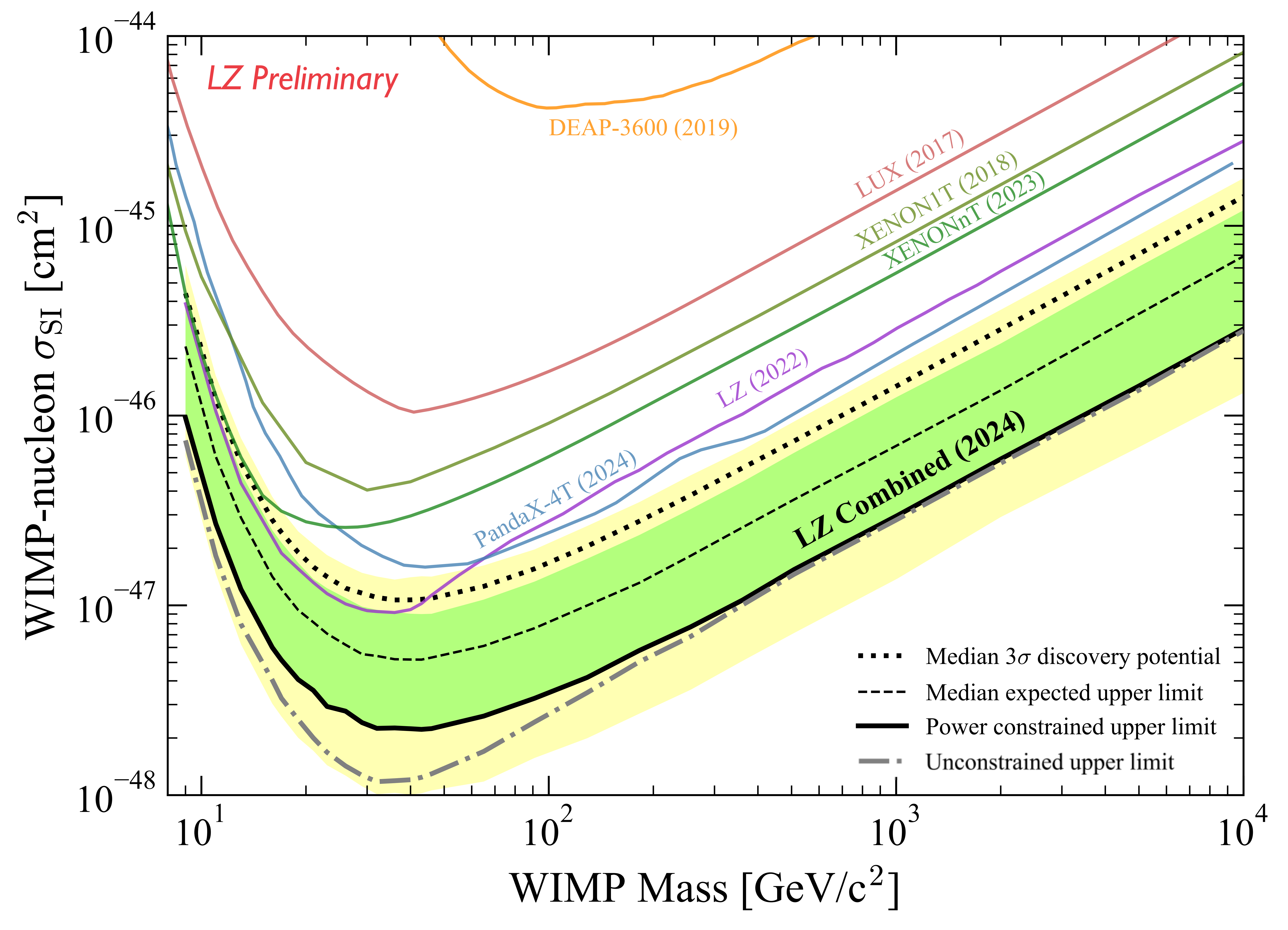


WS2024-ONLY SPIN-INDEPENDENT LIMIT



- Two-sided profile likelihood ratio test statistic
- Power constrained at -1σ as per recommended conventions
  EPJC 81, 907 ('21)
- Under-fluctuation in accidental backgrounds in the region of largest overlap with WIMP signal PDF
- WS2024-only best limit of $\sigma_{SI} = 2.3 \times 10^{-48}$ cm^2 at 43 GeV/c^2

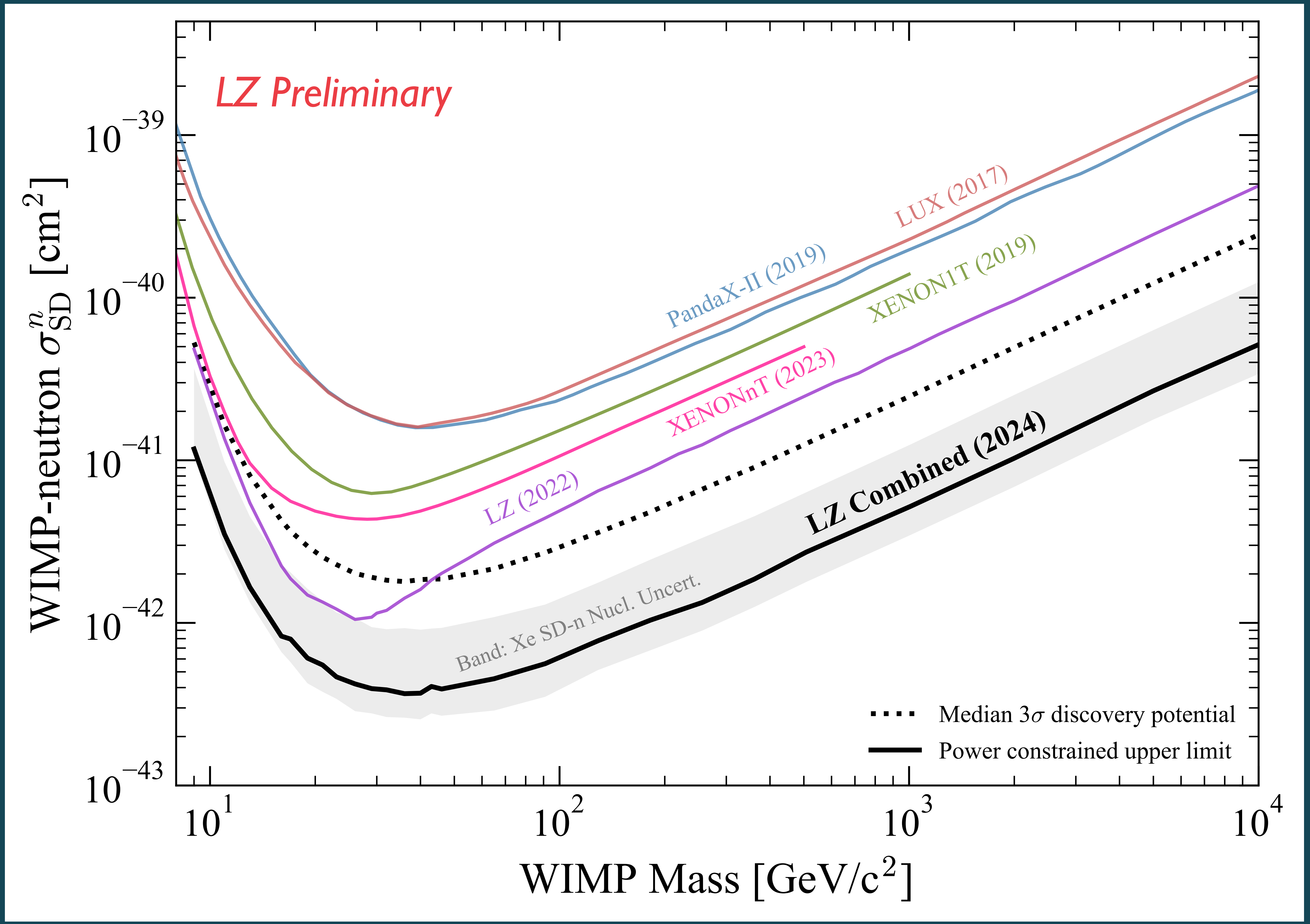
WS2024+WS2022 SPIN-INDEPENDENT LIMIT



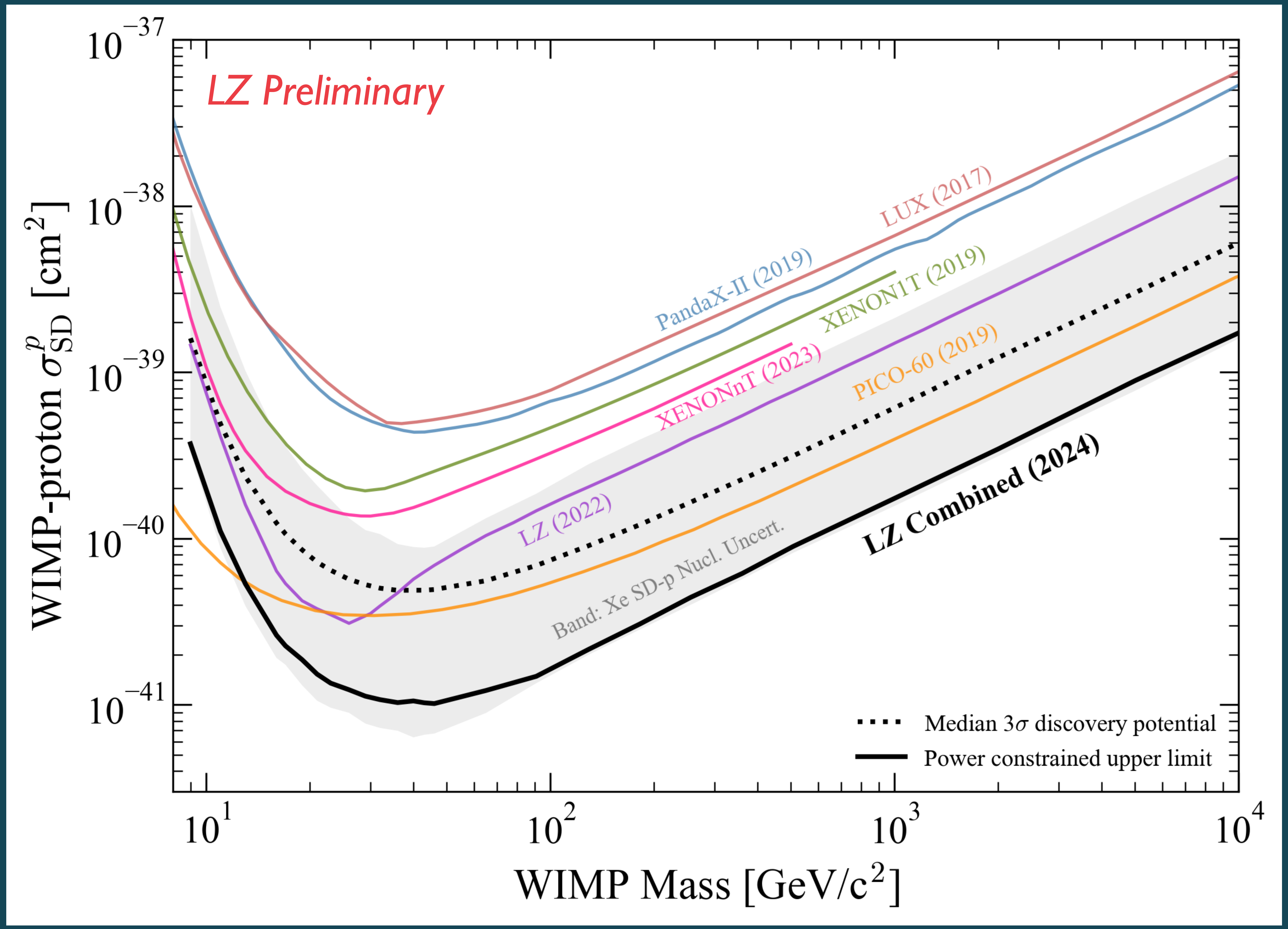
- Two-sided profile likelihood ratio test statistic
- Power constrained at -1σ as per recommended conventions [EPJC 81, 907 ('21)](#)
- Extra under-fluctuation from WS2022 result
- Best limit from combined analysis of $\sigma_{SI} = 2.2 \times 10^{-48}$ cm^2 for 43 GeV/c^2

WS2024+WS2022 SPIN-DEPENDENT LIMITS

WIMP-Neutron Scattering



WIMP-Proton Scattering



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

CONCLUSIONS

- New world-leading WIMP search limits achieved in LZ with WS2024+WS2022 4.2 tonne year exposure exceeding previous best constraints by >4 times
  - 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**

MORE ON LZ

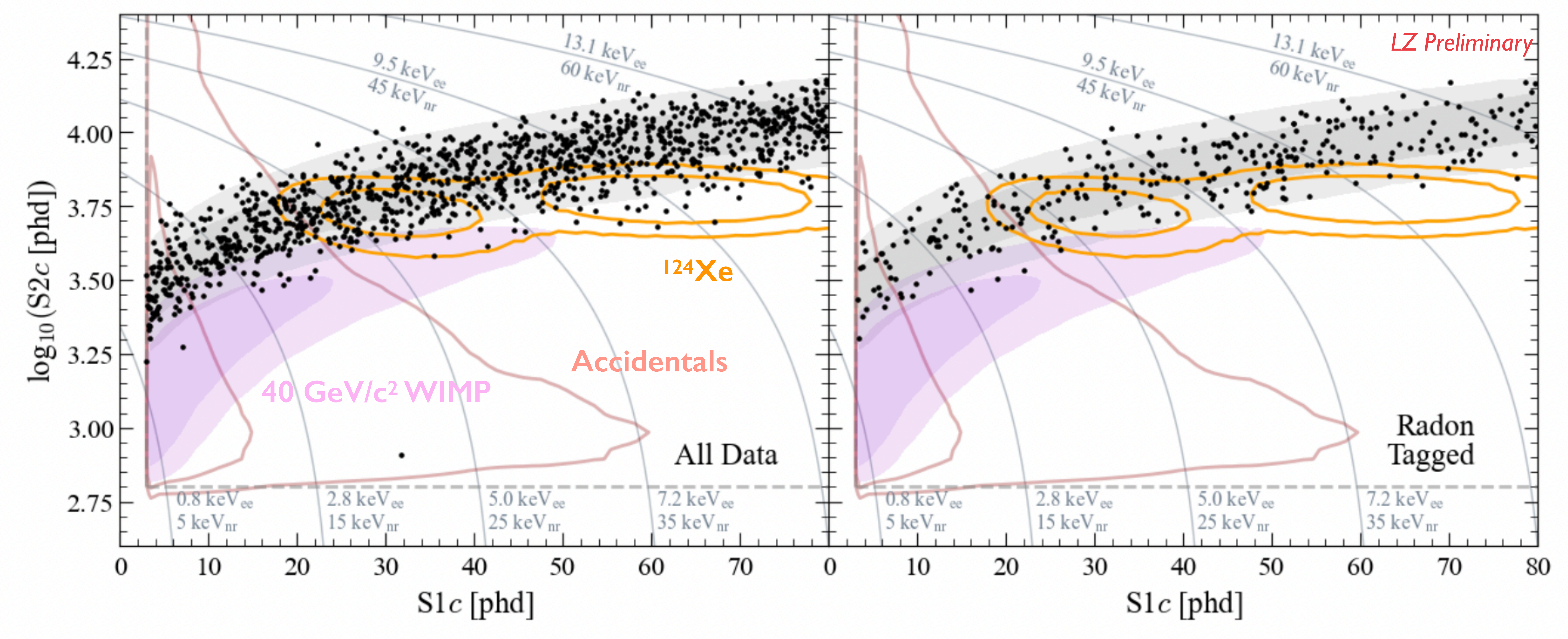
Selected papers already available:

- First dark matter results from the LZ Experiment
  PRL 131, 041002 ('23)
- Background Determination for LZ Dark Matter Experiment
  PRD 108, 012010 ('23)
- Search for new physics in low-energy electron recoils from the first LZ exposure PRD 108, 072006 ('23)
- First Constraints on WIMP-Nucleon Effective Field Theory Couplings in an Extended Energy Region From LZ
  PRD 109, 092003 ('24)

https://lz.lbl.gov/ @lzdarkmatter

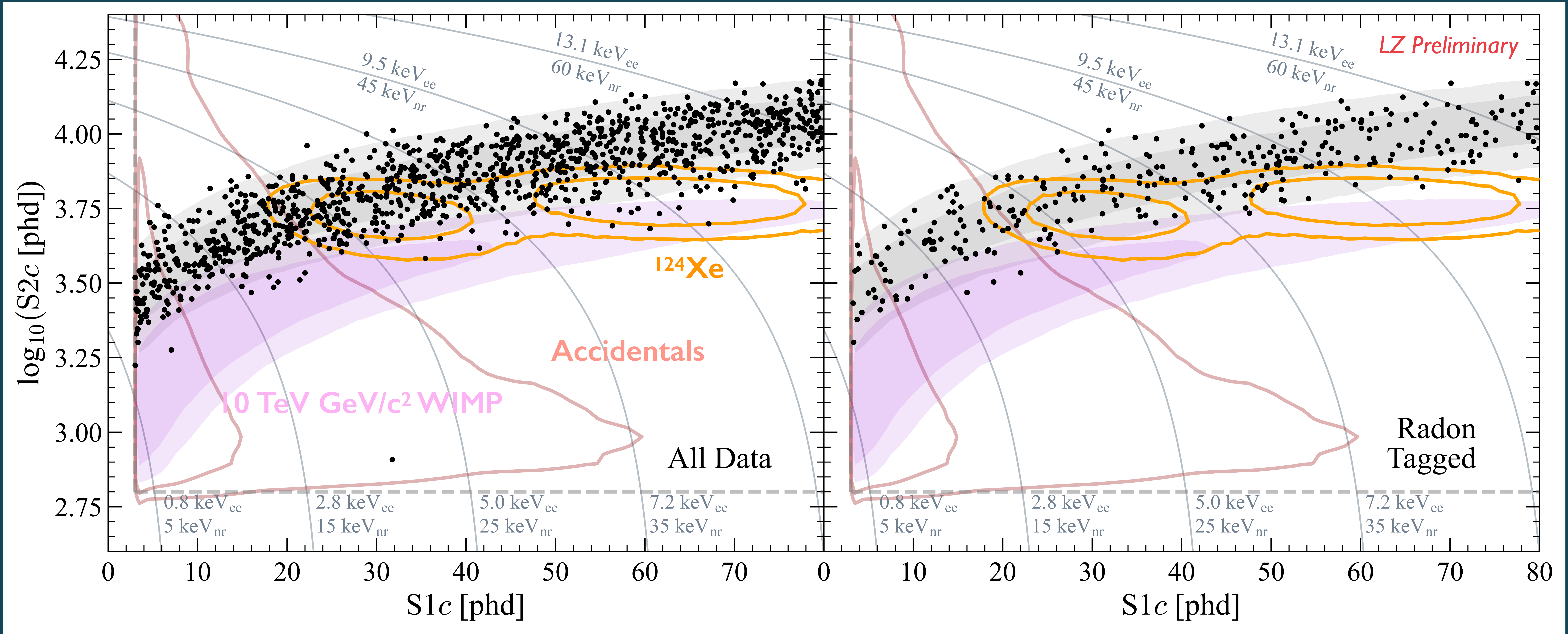
Back Up Slides

WS2024 DATA - UNSALTED; RADON TAGGED

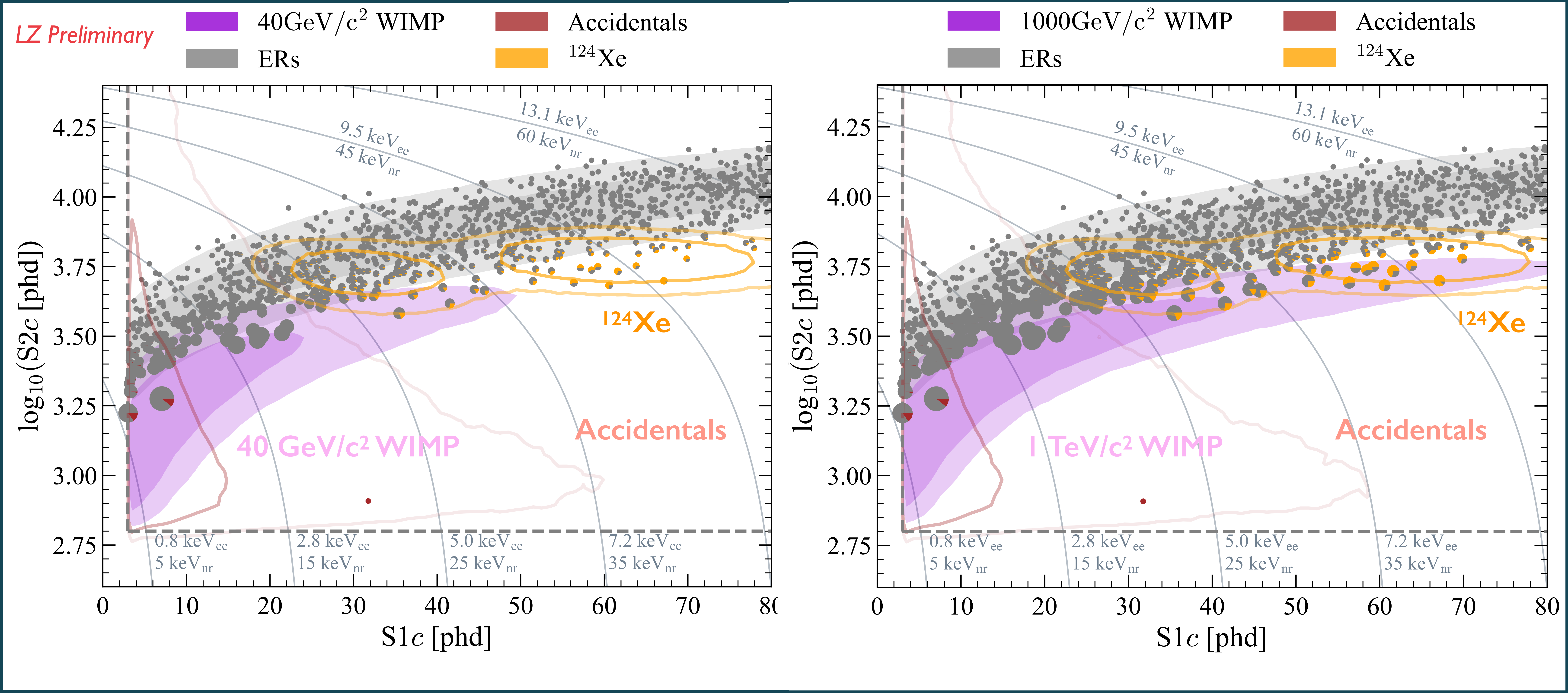


3.3 tonne years | **0.3 tonne years**

10 TEV/C² WIMP



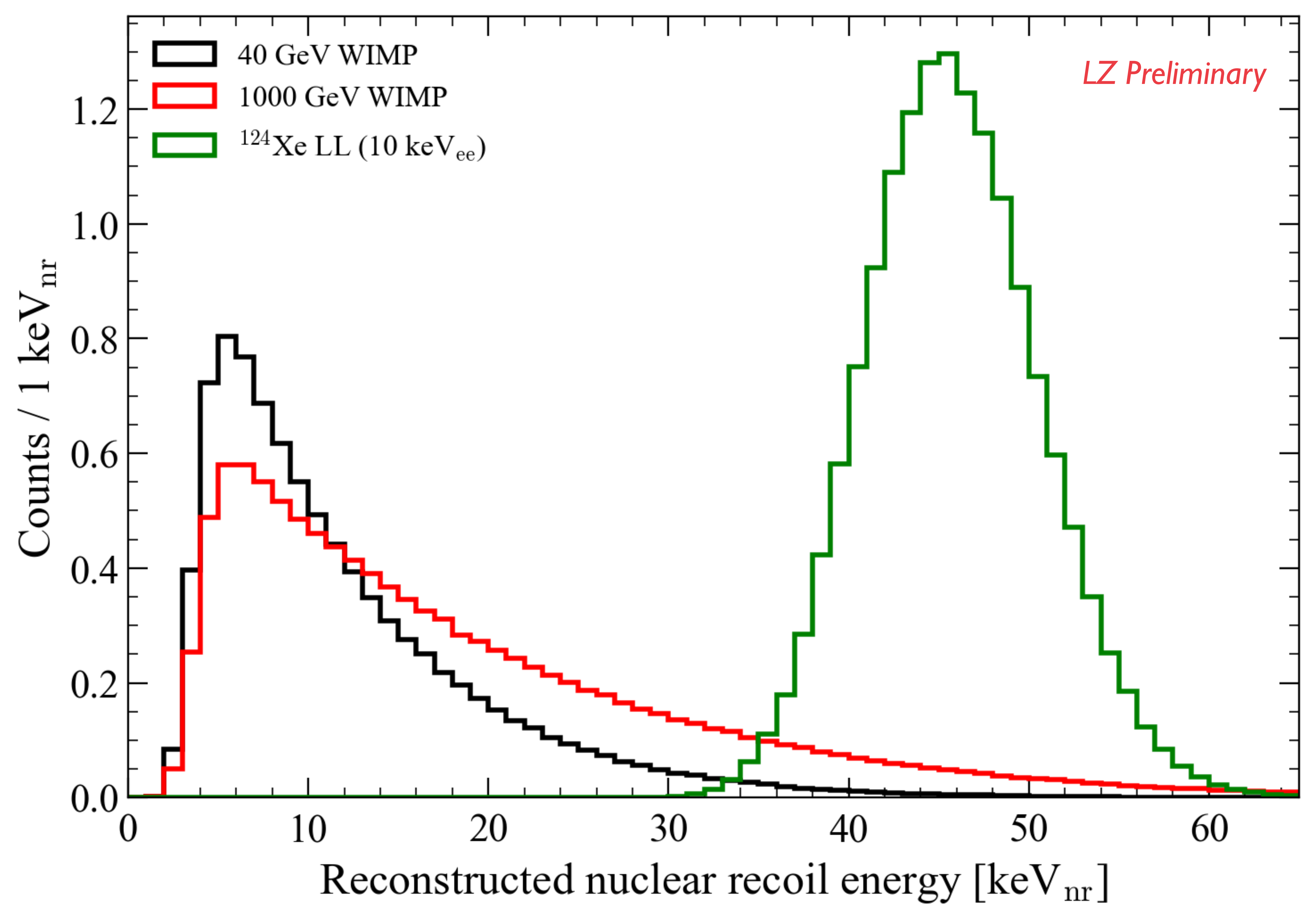
WS2024 DATA PIE PLOT



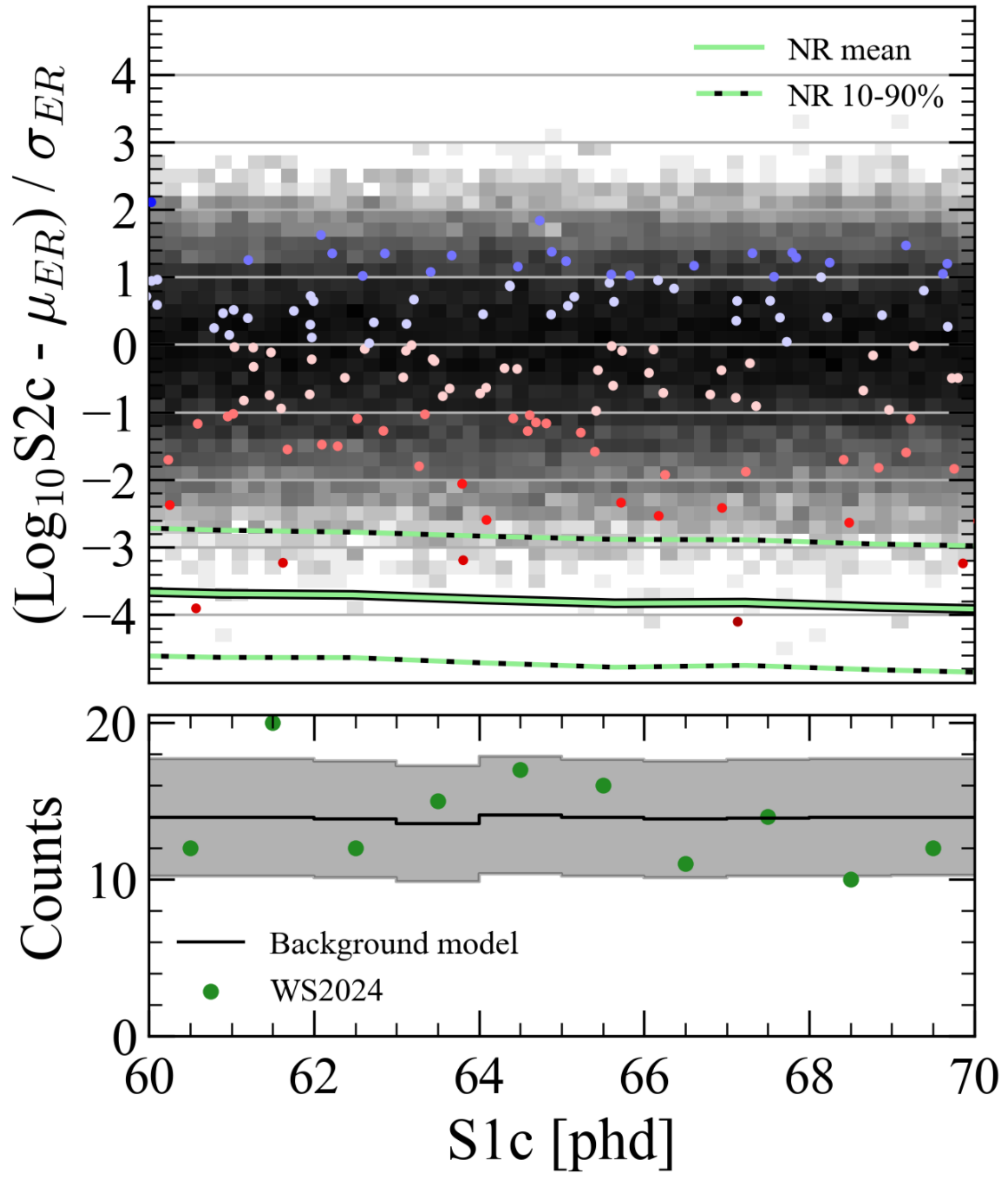
^{124}XE LL-SHELL COMPARED TO DARK MATTER SPECTRA

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

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



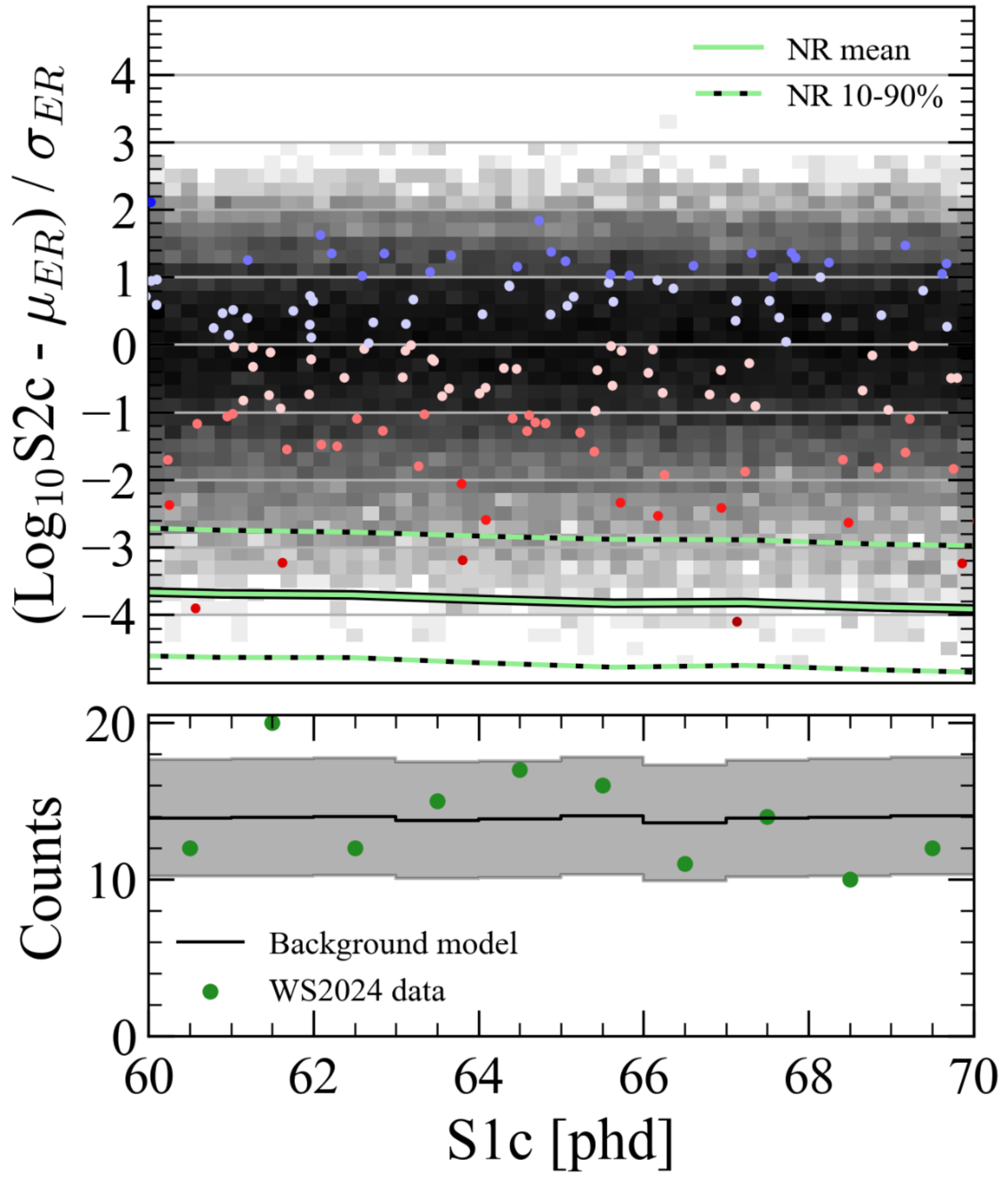
GOODNESS OF FITS IN KEY ^{124}XE REGION



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)

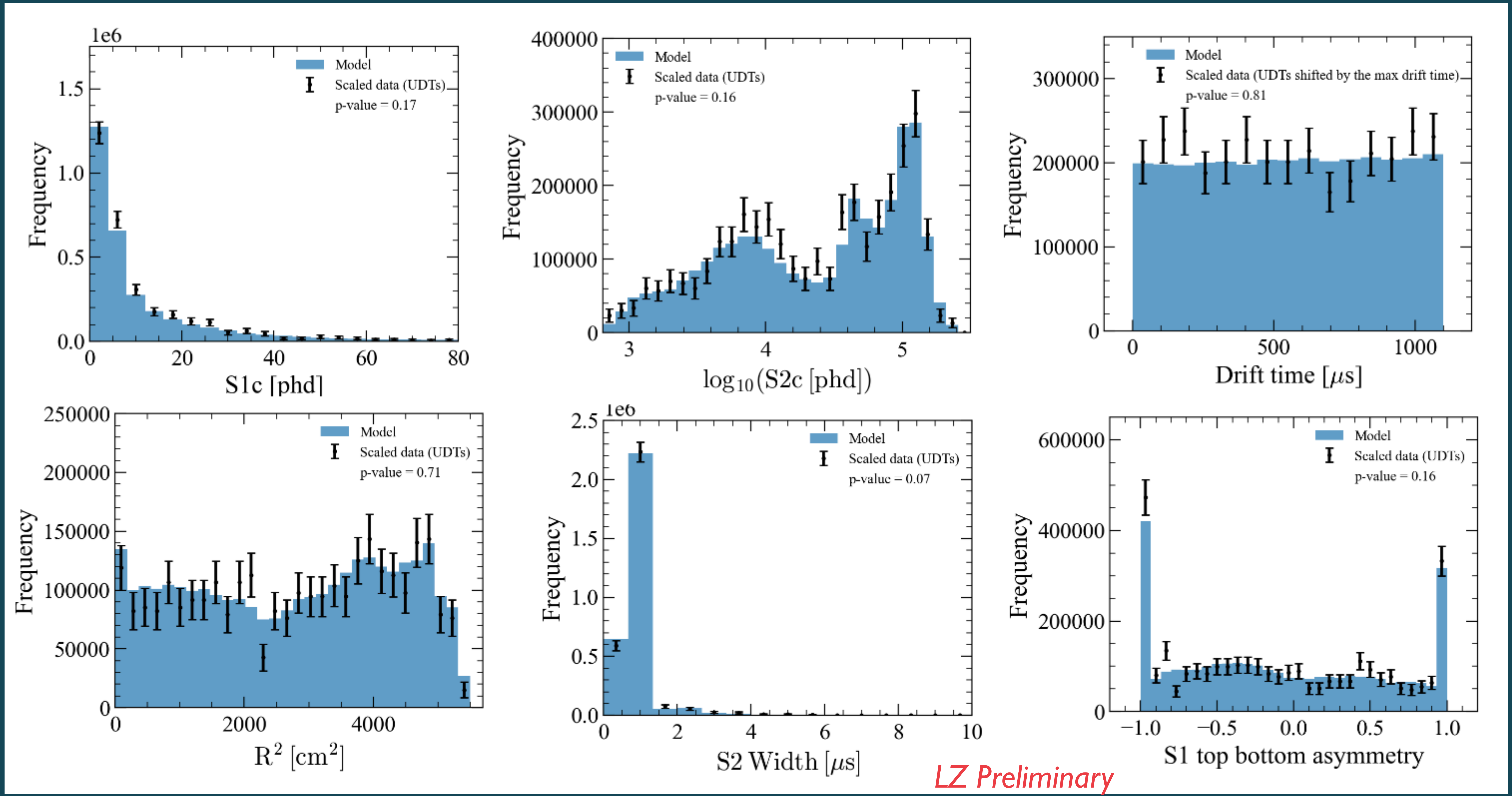
Q_{LL}/Q_{β} = 0.65

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

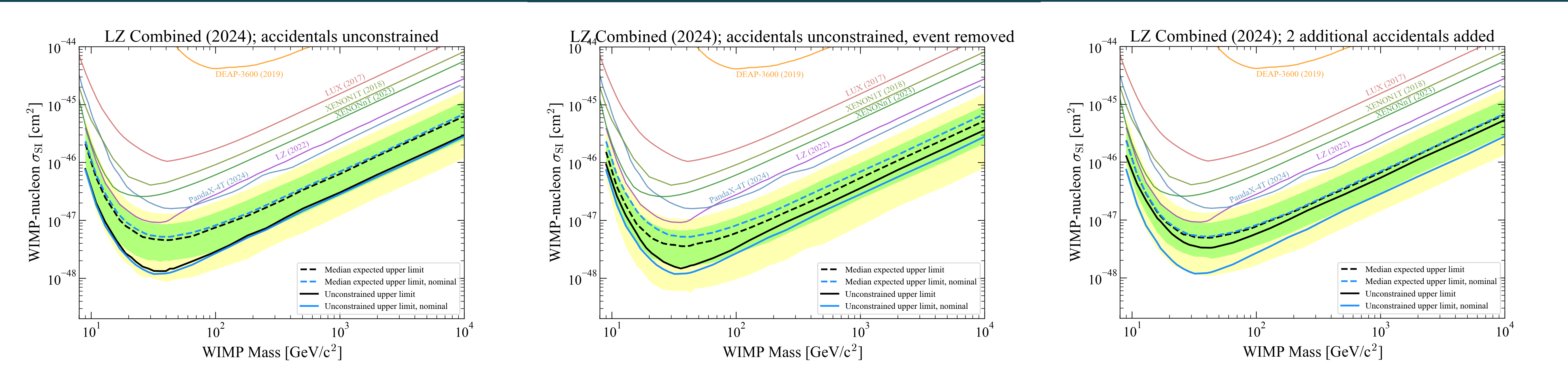
ACCIDENTALS MODEL & SIDEBAND COMPARISONS

Comparing manufactured accidental events and unphysical drift accidentals

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



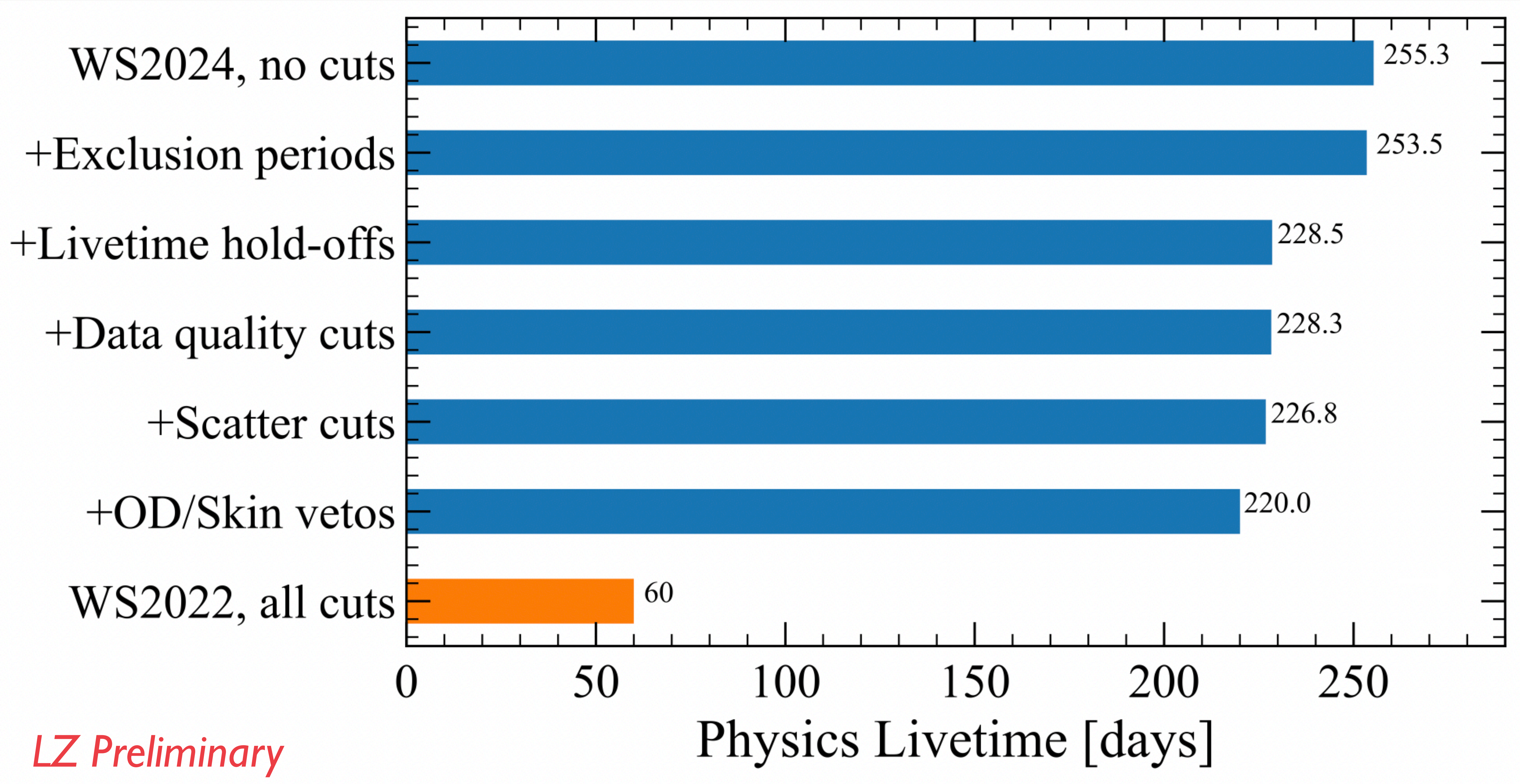
CHECKS OF ACCIDENTALS IMPACT ON LIMIT

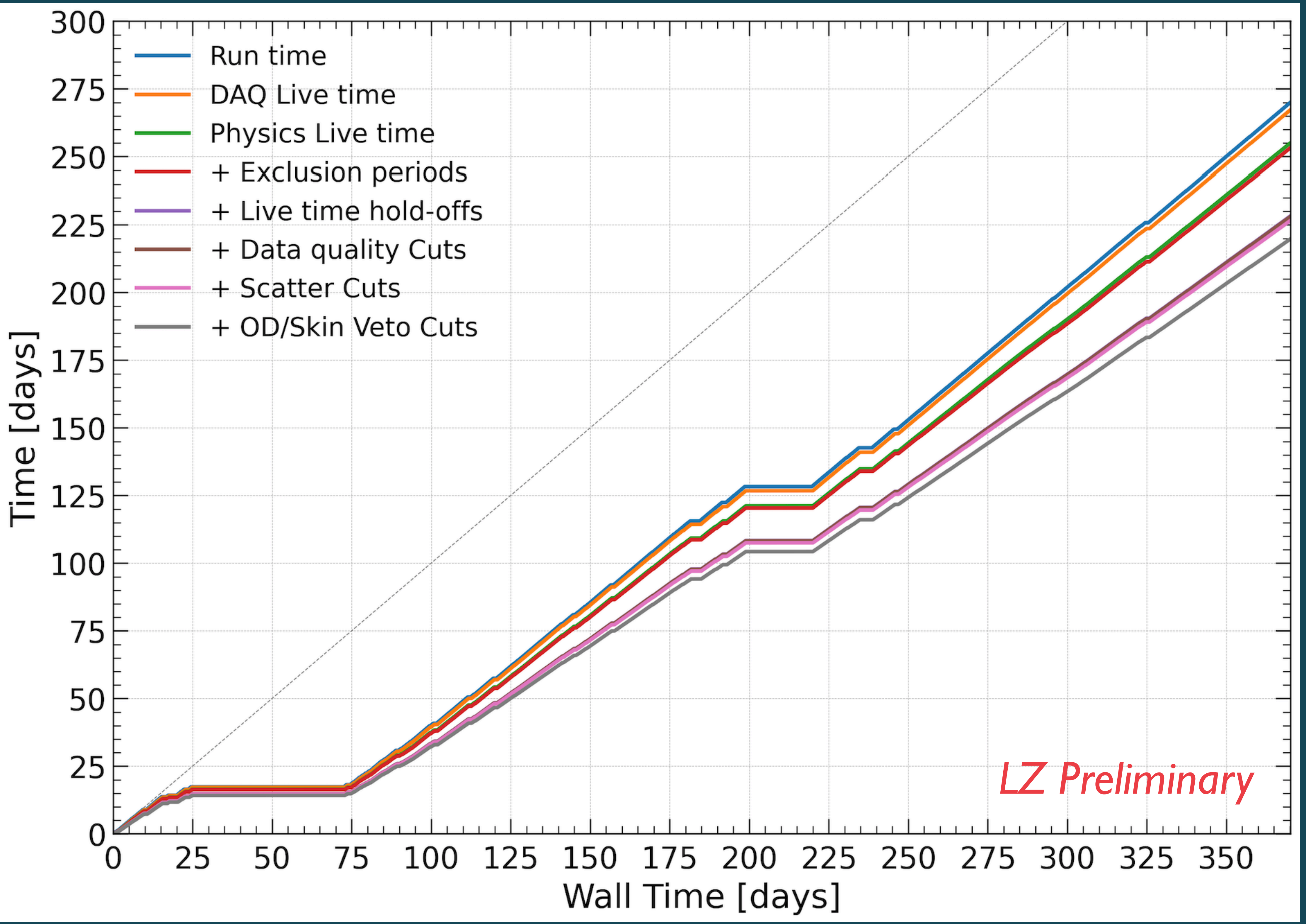


1. Remove accidental rate constraint: best fit drops 2.6 → 1.4
2. Remove constraint & outlier event: best fit drops 1.4 → 0
    - Outlier event holds model up, over subtracting in the WIMP region
3. Adding fake events - props limit back up

→ under-fluctuation of accidental events in the WIMP region

LIVE TIME

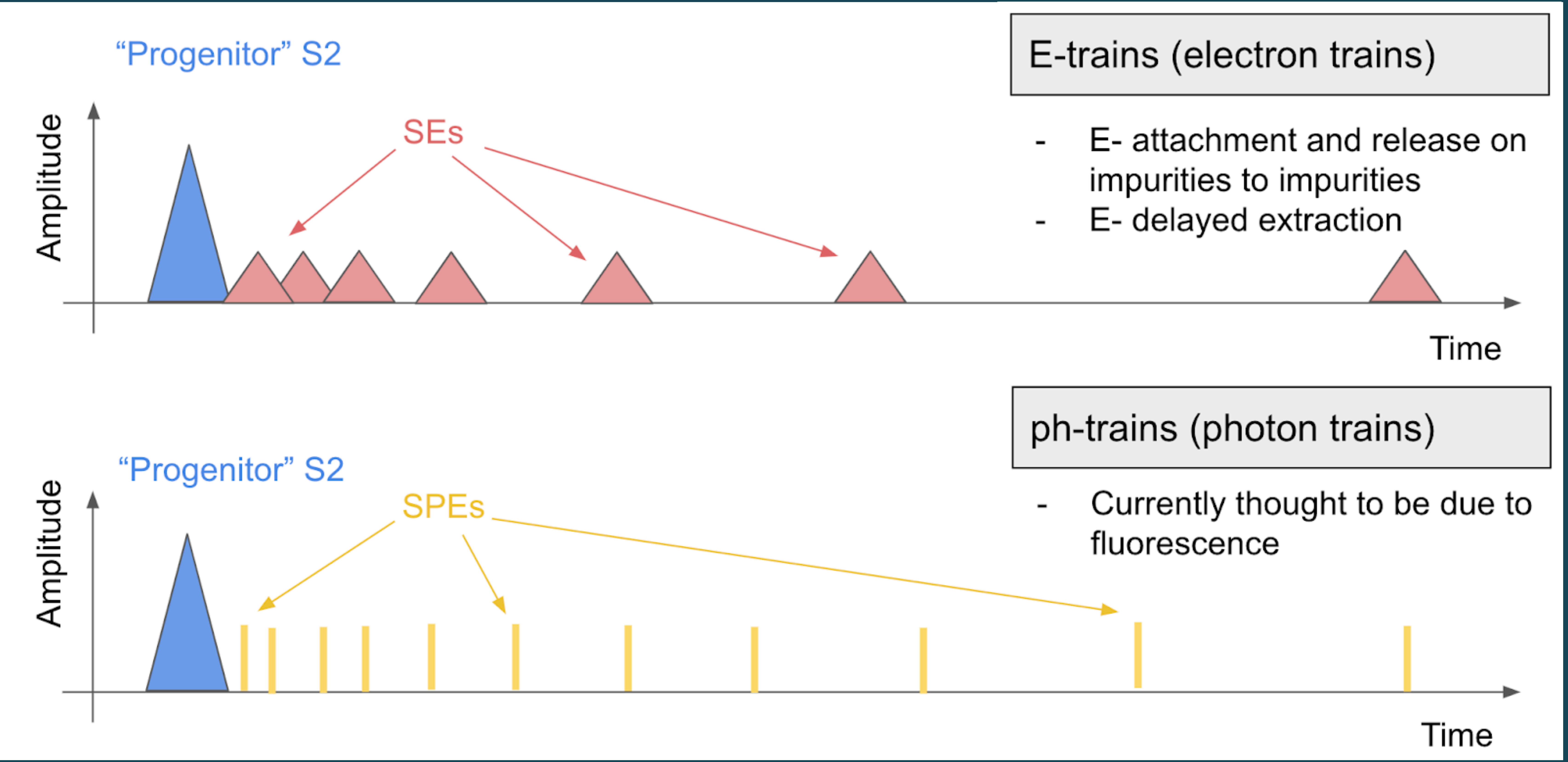




- Rejection of live time with detector instabilities, high TPC pulse rates
- 86% live time remaining after all analysis live time exclusions
  → mainly driven by improved live time retention of e-train veto

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)

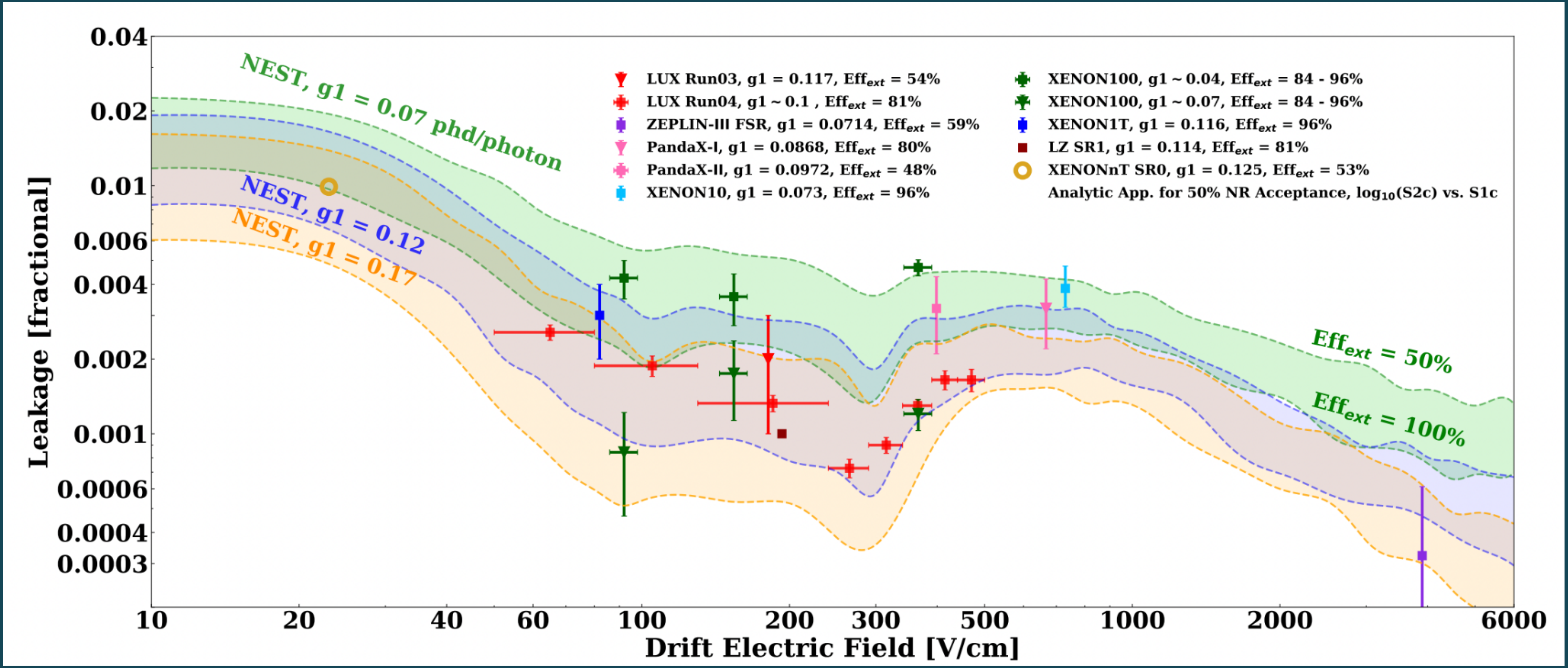


WS2024 VS WS2022 CONDITIONS

	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

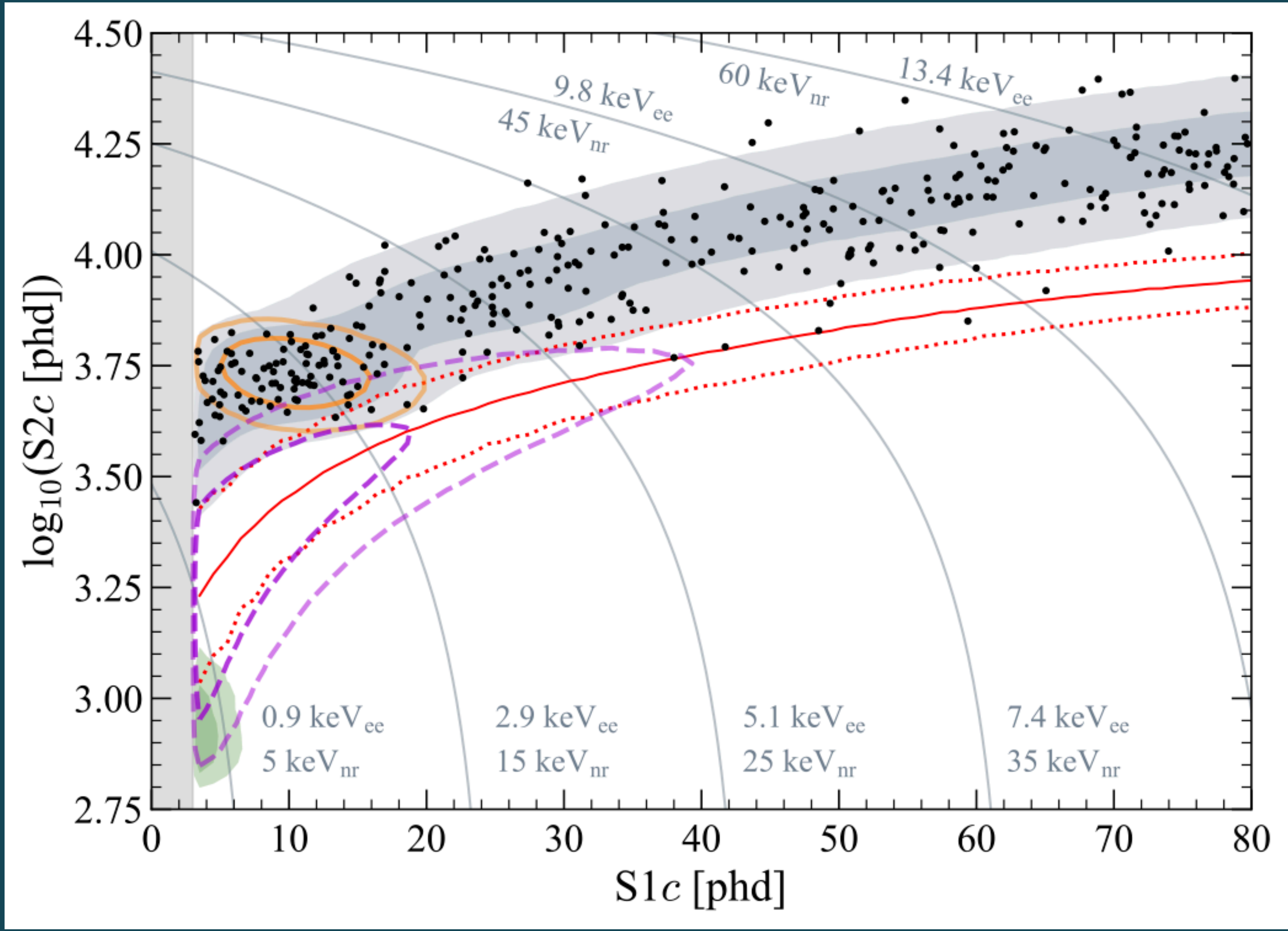
WS2022 DATA

- 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/c^2 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 σ_{SI}= 9.2 × 10^{-48} cm^2 for WIMP mass of 36 GeV/c^2
- No evidence for WIMPs

Key

—— Observed limit

- - - Median expected sensitivity