Status of the LUX-ZEPLIN Experiment

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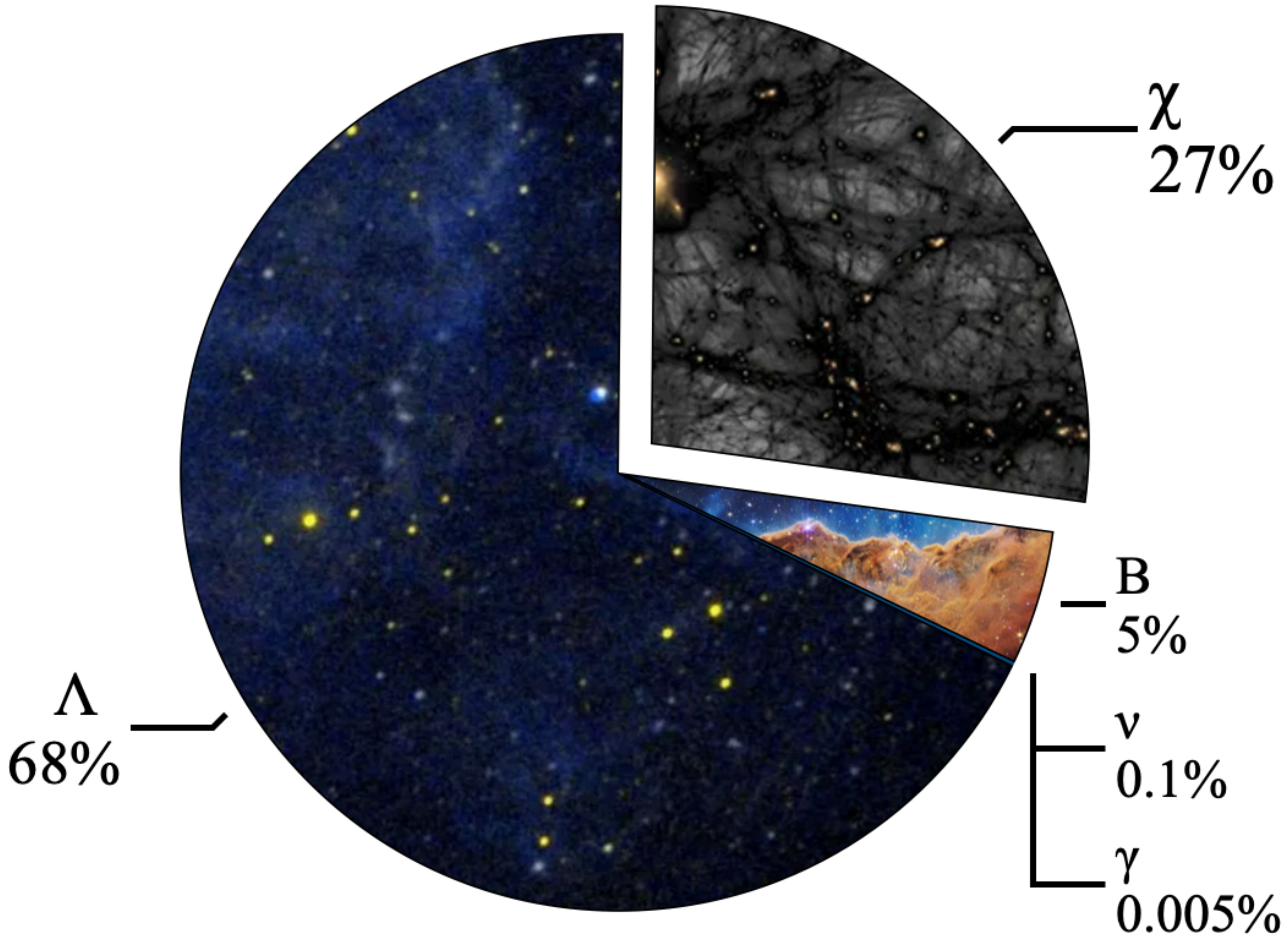
21st July
PASCOS 2025
Durham UK

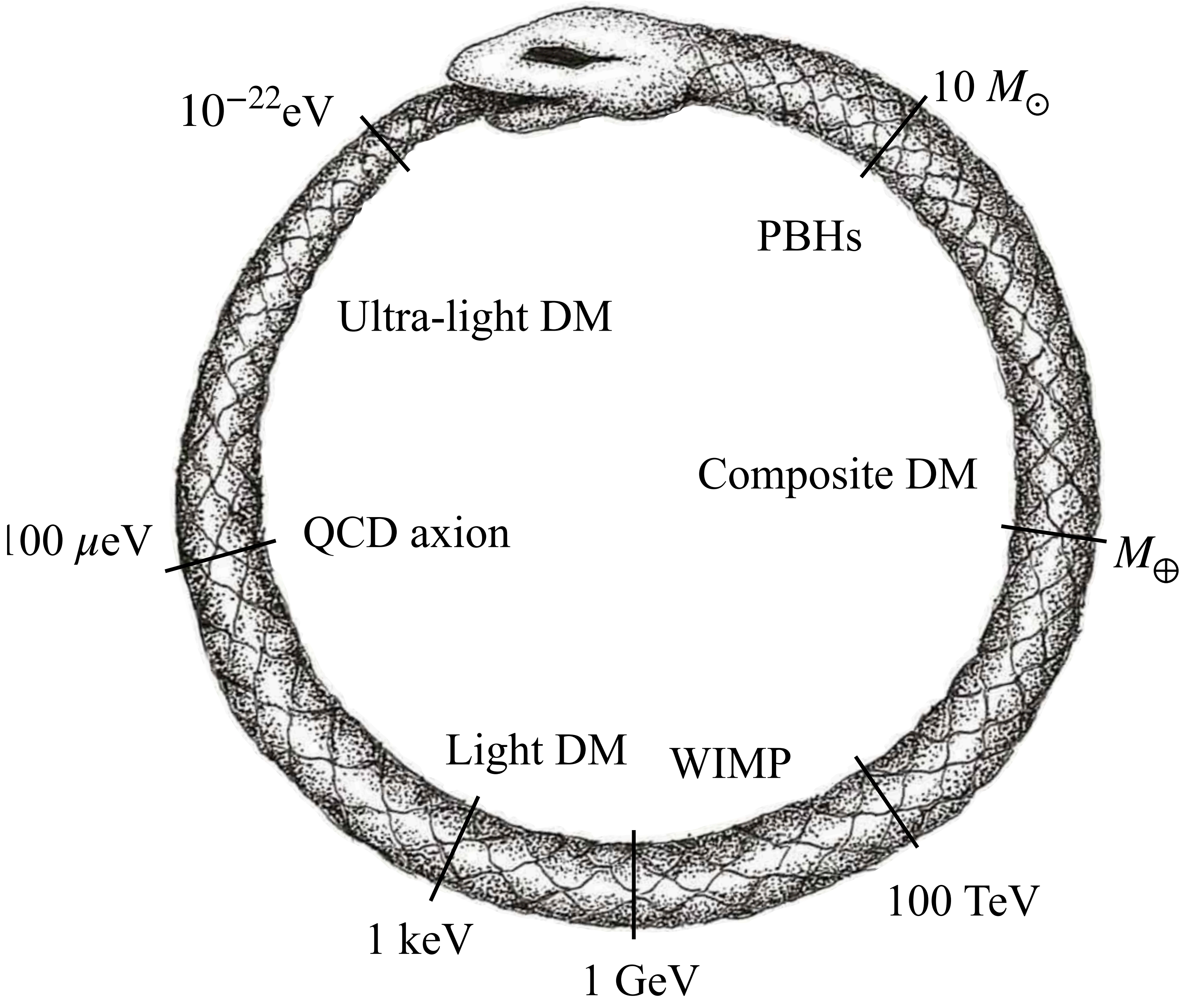
Origin of Dark Matter

- Dark matter: 85% of matter in the Universe
- Diverse candidates, elusive searches
- Could potentially scatter ordinary matter

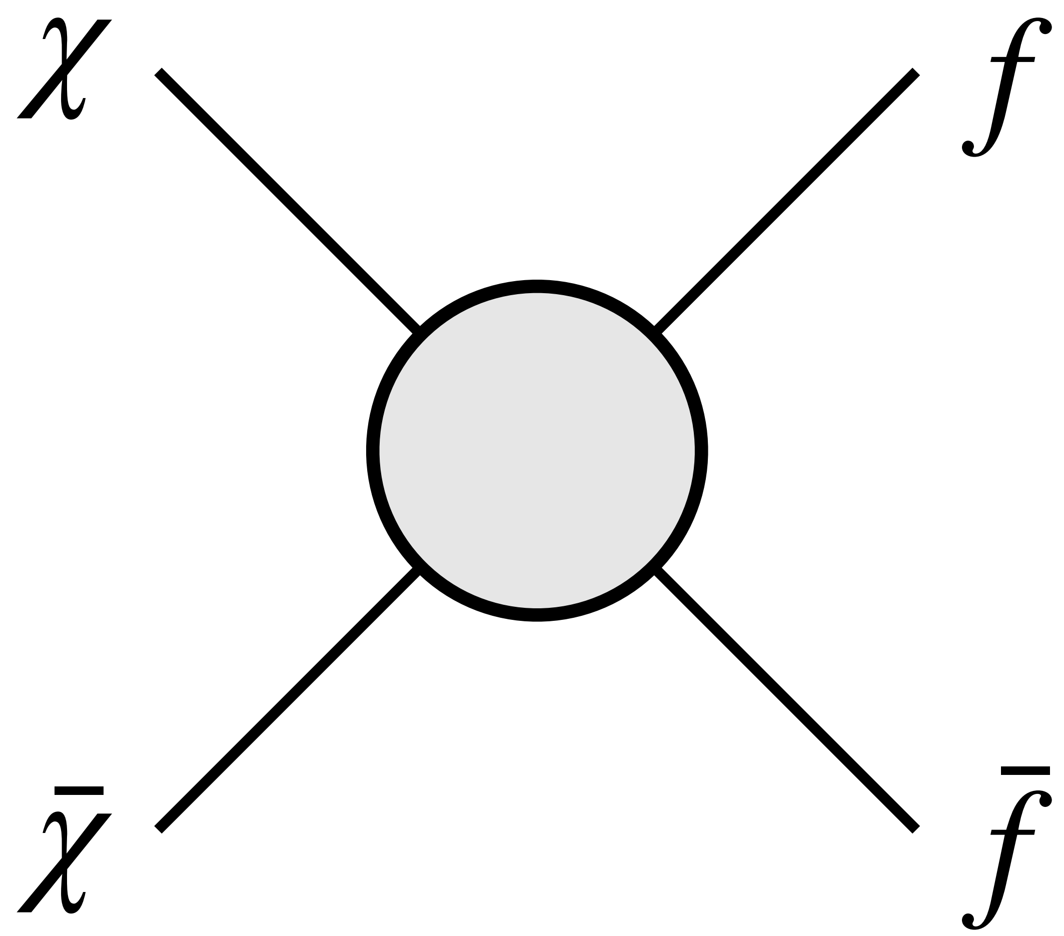


Planck 2018, A&A 641, A6 (2020)

ΛCDM Universe Components



“Dark Matter Ouroboros”

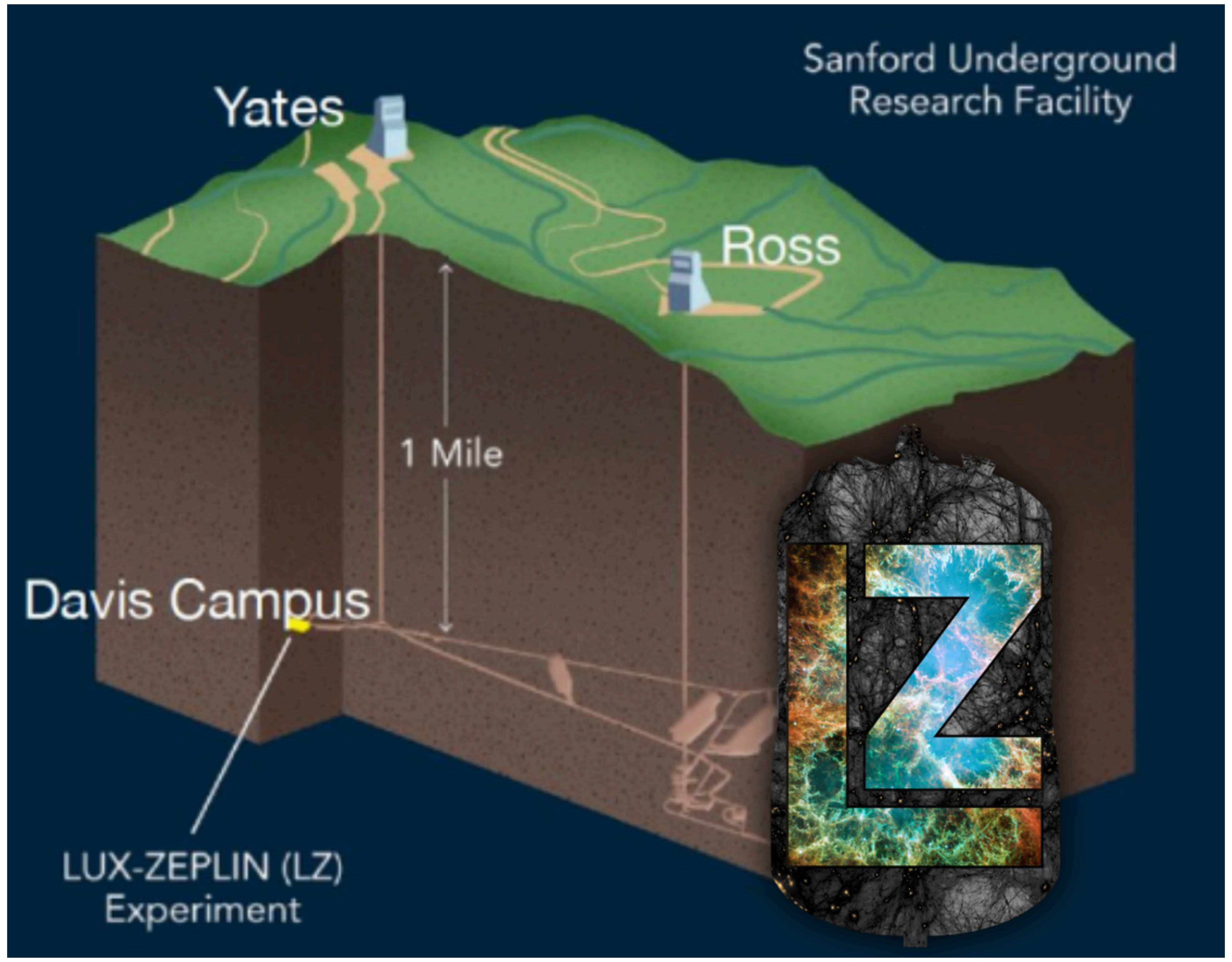


WIMP Feynman Diagram

LUX-ZEPLIN (LZ) Experiment

- Located 1.5 km (4850 ft) underground at Sanford Underground Research Facility (SURF), South Dakota, USA
- Shielded by rock, water, and active veto system
- 7-tonne liquid xenon detector for dark matter search

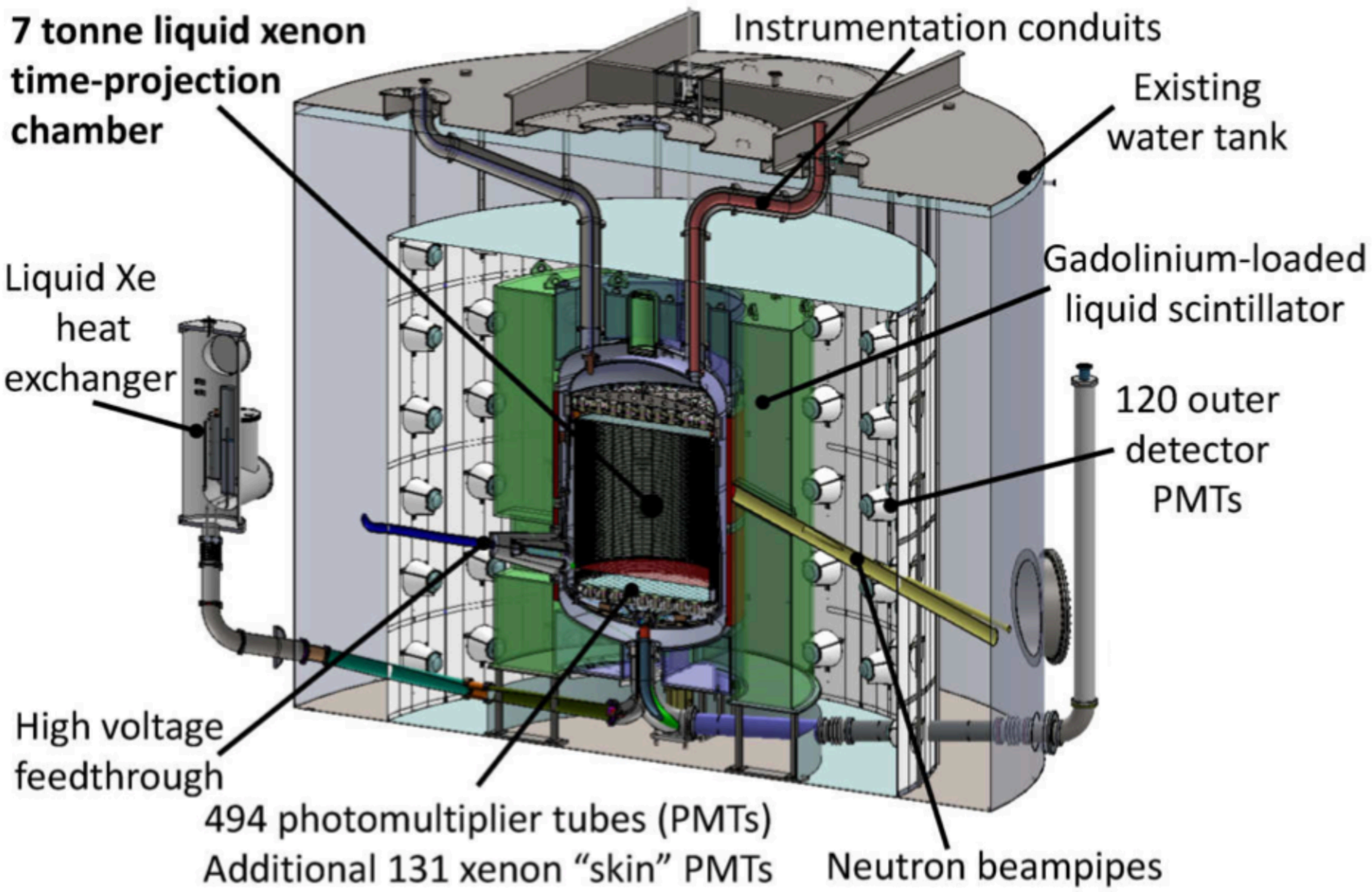
SURF surface and the Black Hills



LZ at Davis Campus

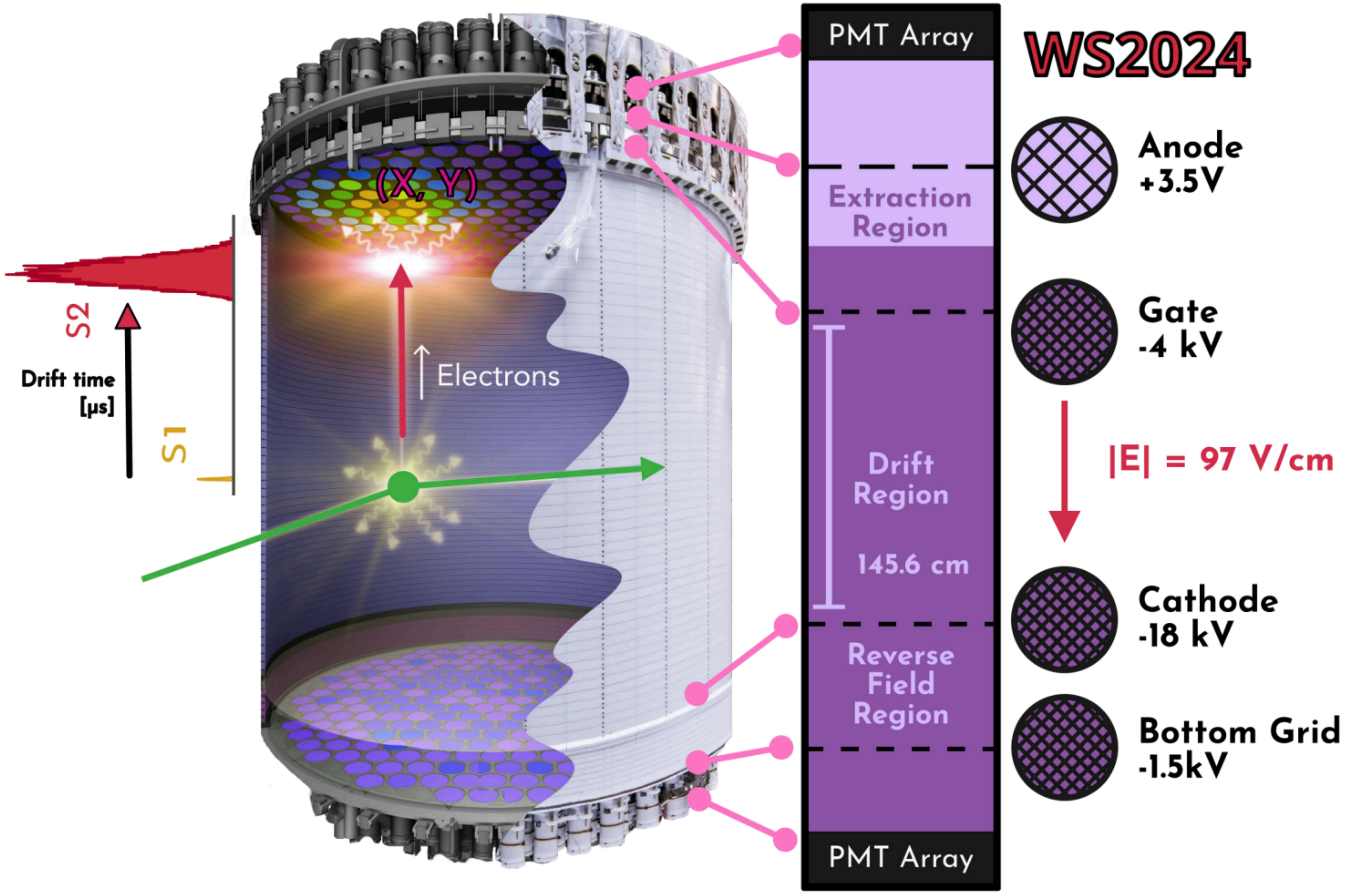
LZ Cryostat

Detector Structure



- TPC
  - 494 3-inch PMTs, 253 top and 214 bottom
  - 7 tonne of liquid xenon as the active region @ 174.1 Kelvin, 1.791 bar
- Skin detector between TPC and cryostat
  - 93 1-inch and 38 2-inch PMTs
- Outer Detector in the acrylic tank
  - 17 tonne of 0.1% Gd-doped LS
- Water Tank
  - 120 8-inch PMTs
  - 238 t of pure water

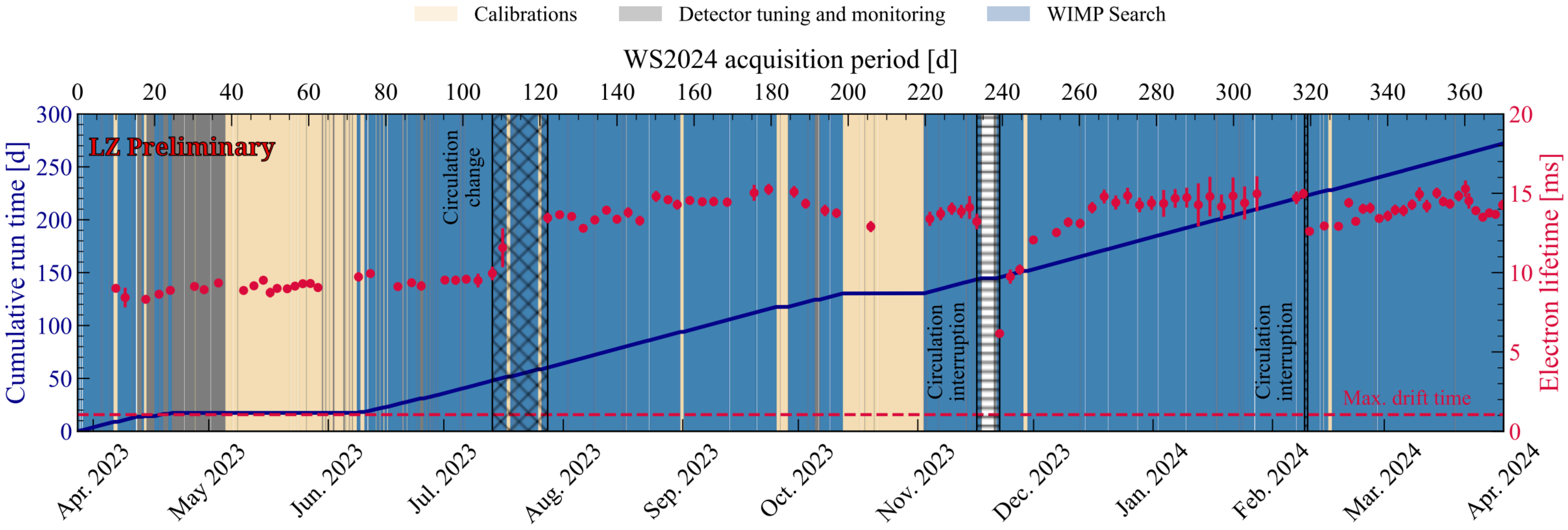
Time Projection Chamber



- Dual-phase liquid xenon time projection chamber
- Nuclear recoil vs electronic recoil discrimination
  - Primary scintillation light signals (S1)
  - Delayed (drifted, extracted, and amplified) ionisation charge signals (S2)
- 3D position reconstruction
  - S2 light pattern on top PMTs
  - S1-S2 timing difference
- 1.5 m diameter × 1.5 m height
  - 7 tonnes total active xenon
  - 5.5 tonnes fiducial xenon
- Woven mesh wire grids for bottom, cathode, gate, and anode electrodes
  - WS2024: 97 V/cm drift field, and 3.4 kV/cm extraction field (below liquid surface)

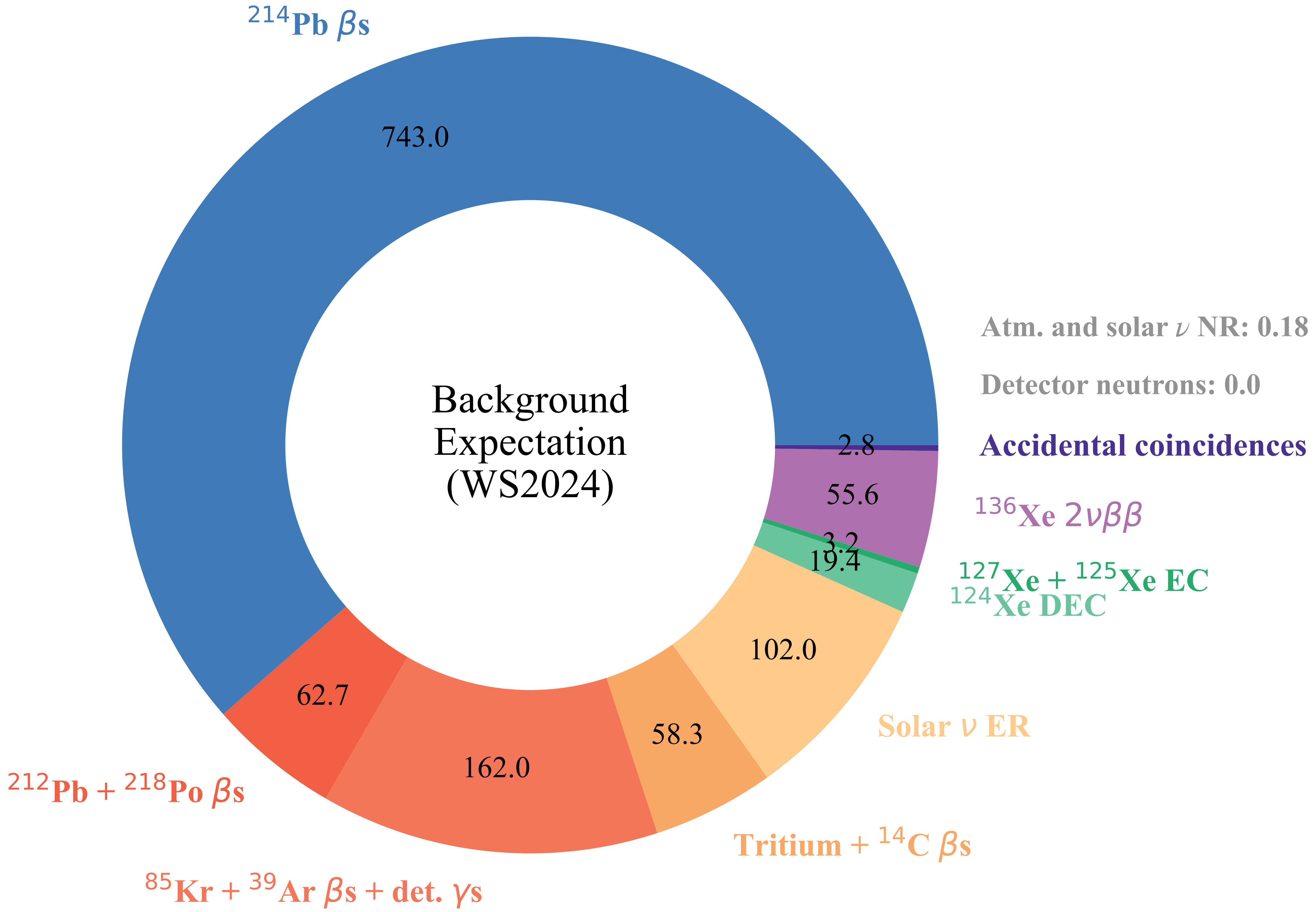
Data Taking Timeline

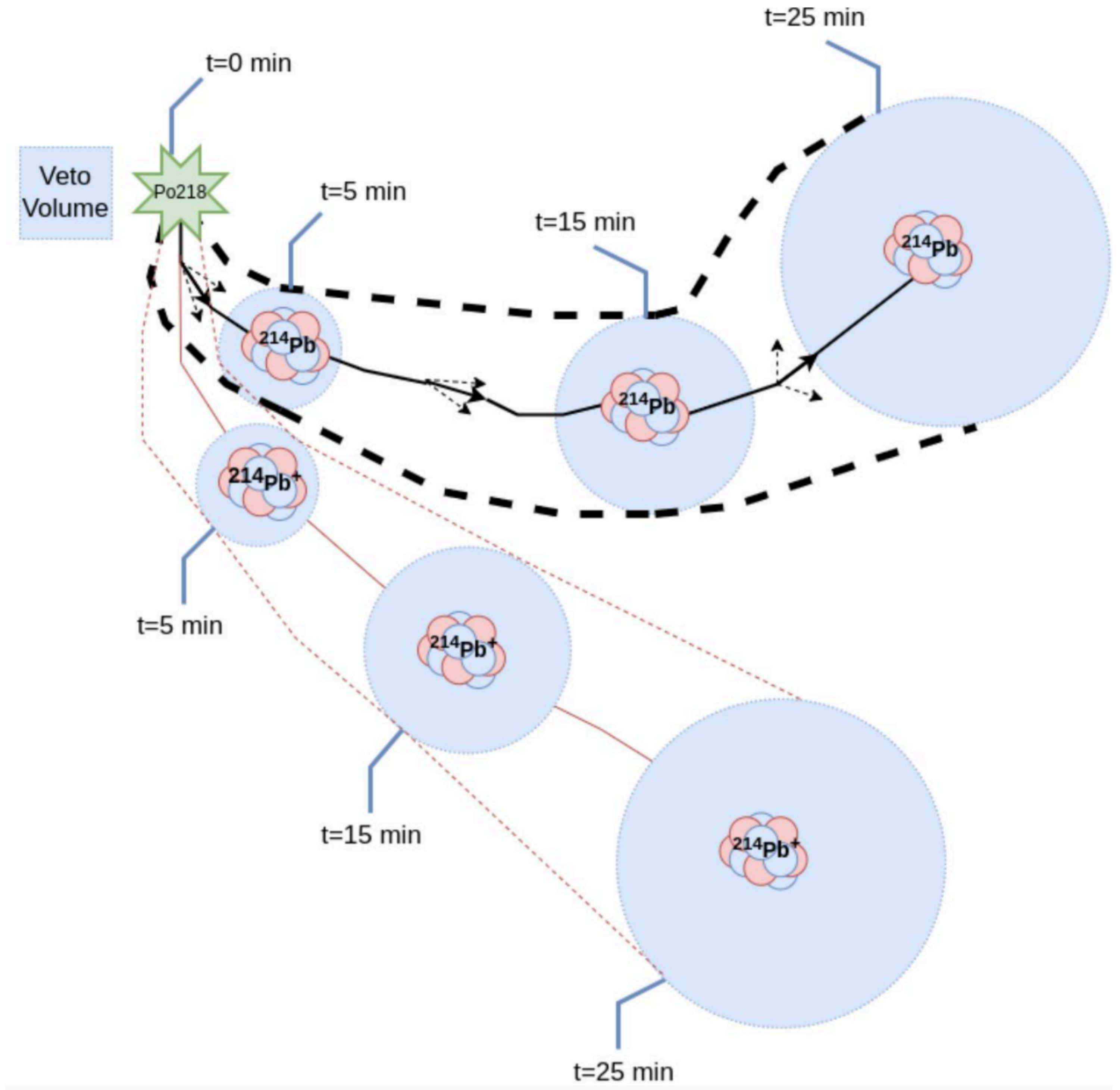
- Construction completed Fall 2021
- First science run (WS2022): Dec 2021 - May 2022, 60 live days exposure, PRL 131.041002
- Detector conditions campaign Dec 2021 - May 2022
- WS2024 data: Mar 2023 - Mar 2024, 220 live days exposure
- Xenon circulation changed in July 2023: lower mixing, improved background rejection

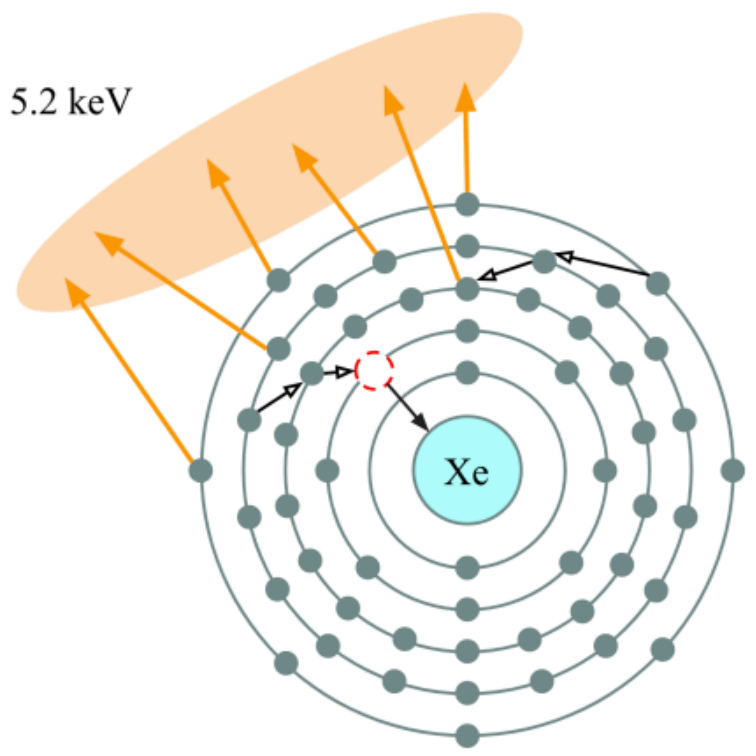


Background Budget

- Pb-214 betas from dissolved Rn-222 daughters contributes to major background
- Background suppression by radon tagging and low-mixing control
- Electron capture decays from Xe isotopes create keV peaks

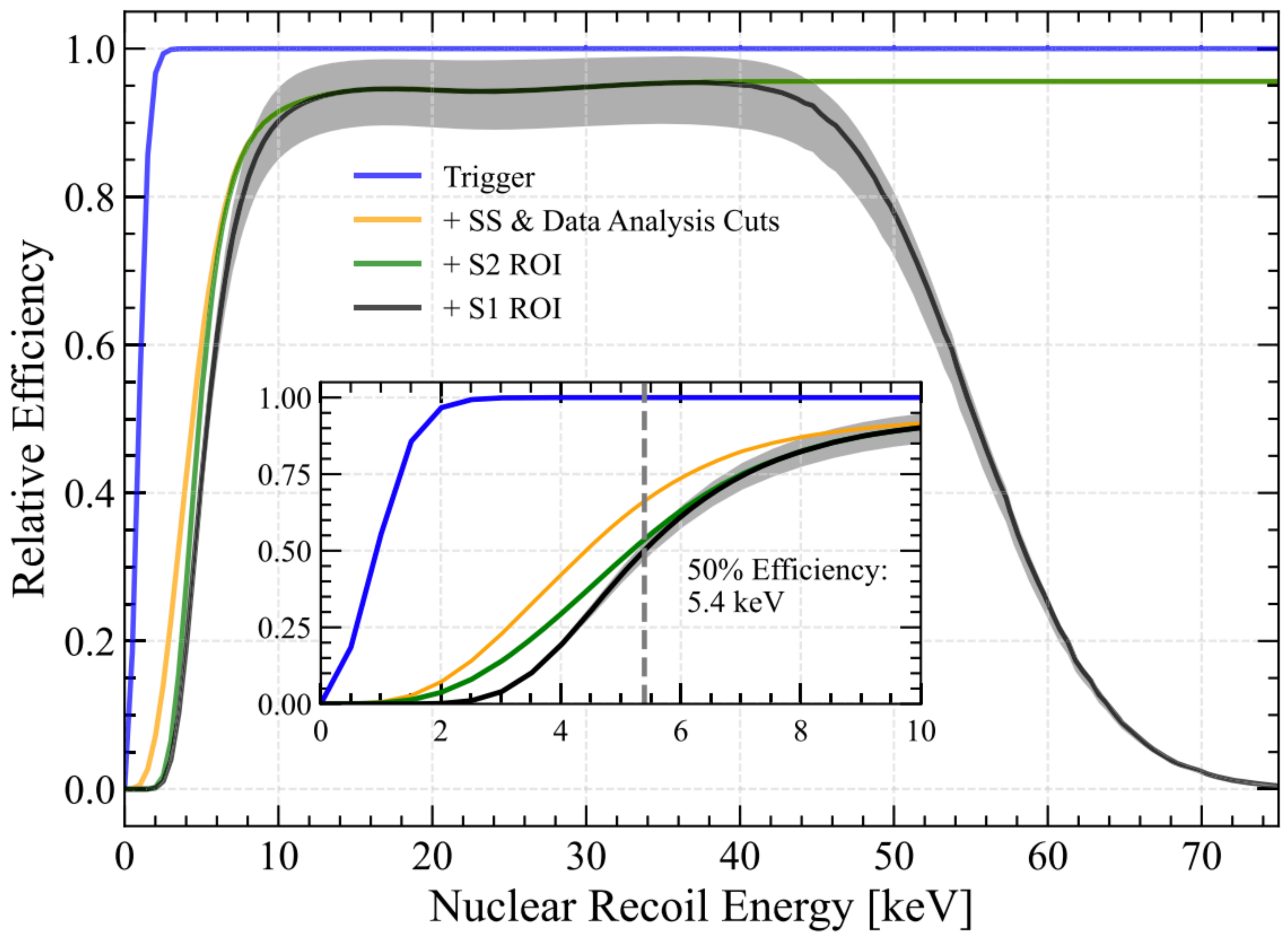


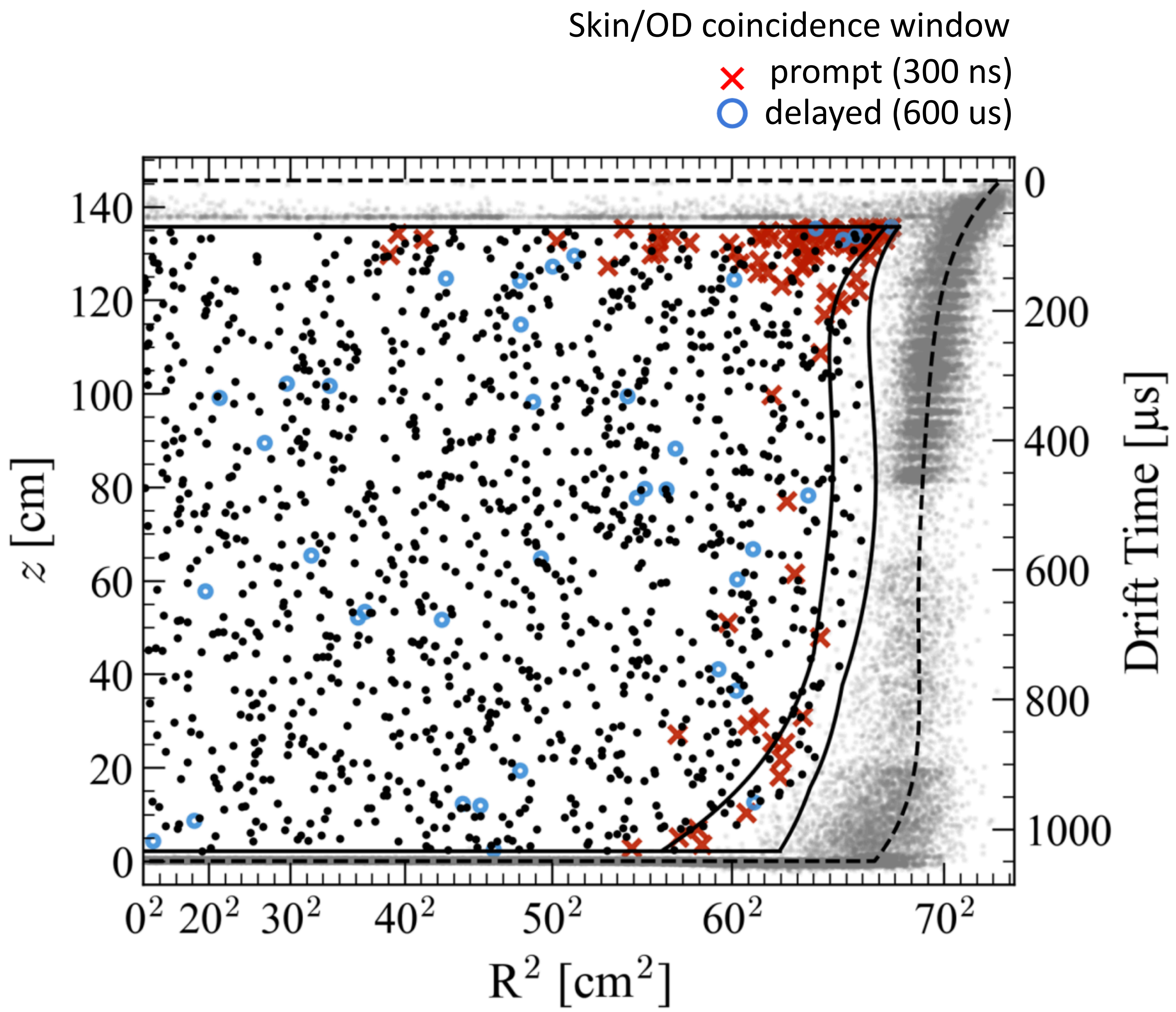


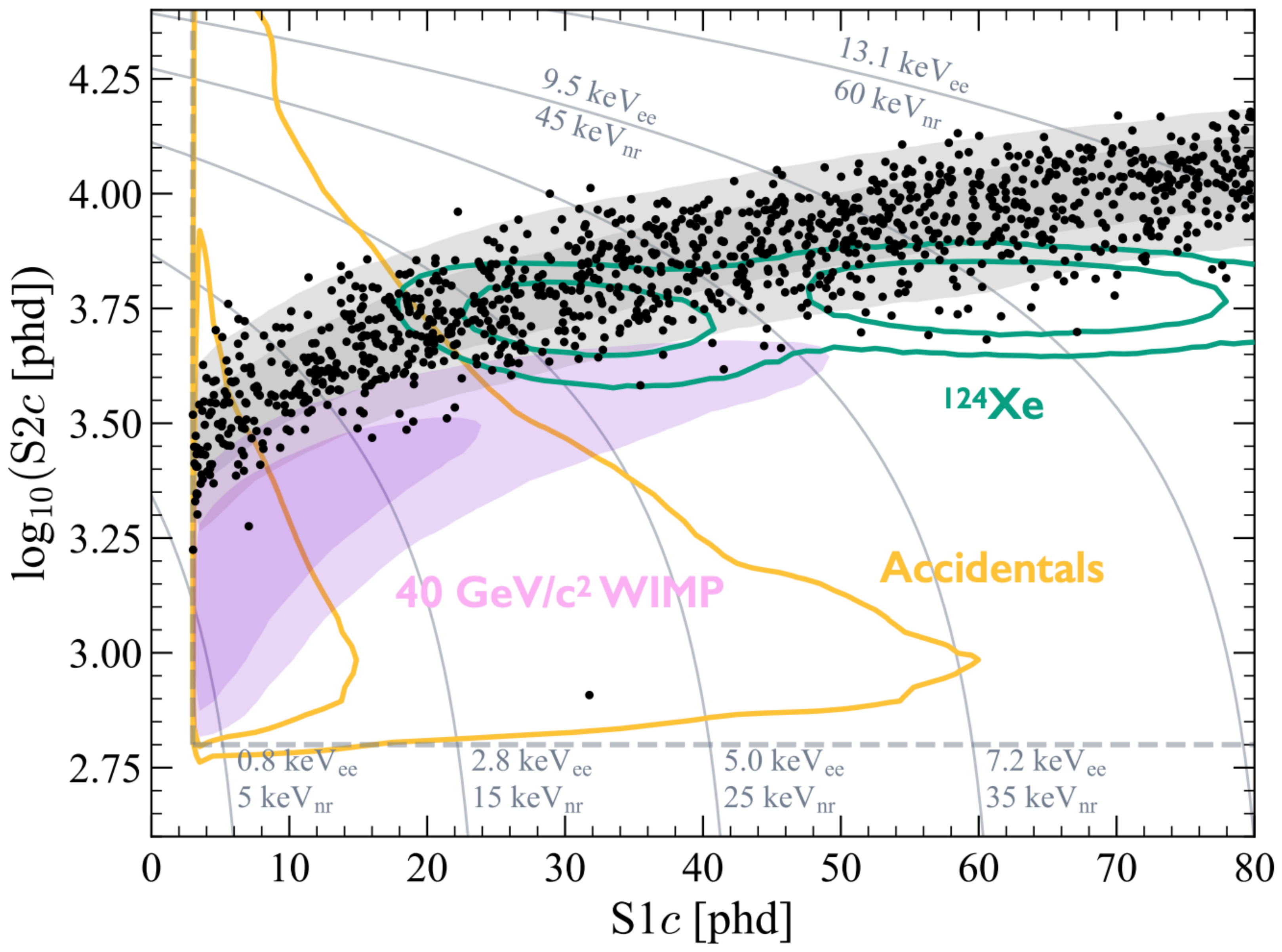


arXiv:2503.05679
PRD accepted

Data Selection







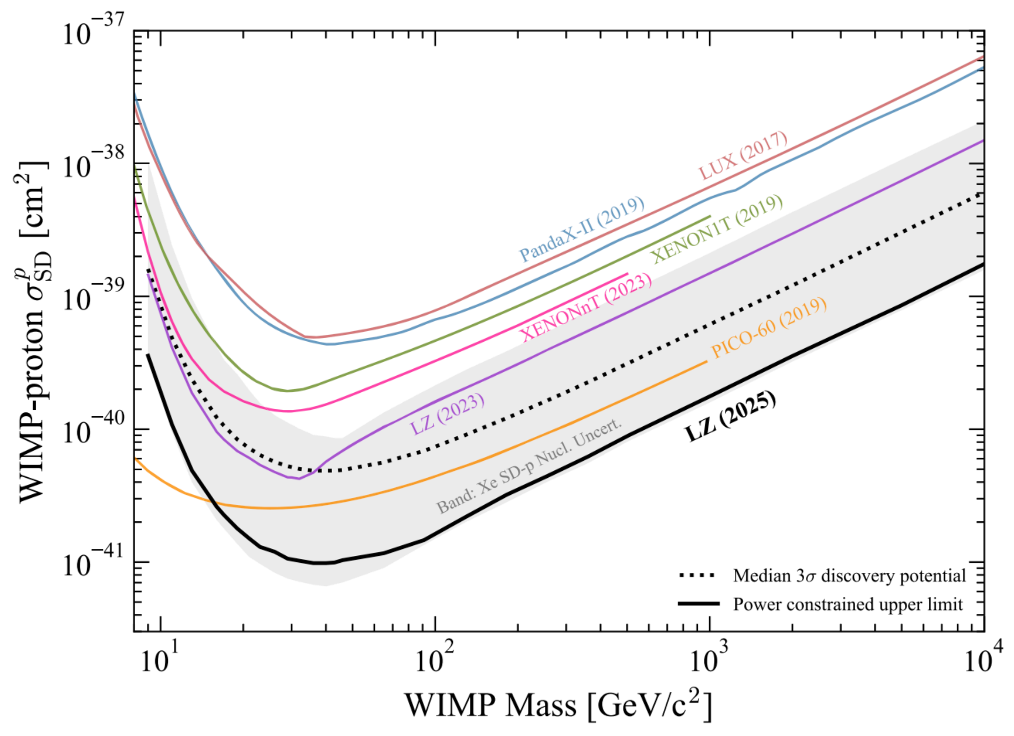
- Trigger efficiency
- Single scattering selection
- Data analysis cuts (see backup)
- 645 < S2c [phd], log10(S2c [phd]) <4.5
- 3 < S1c [phd] < 80

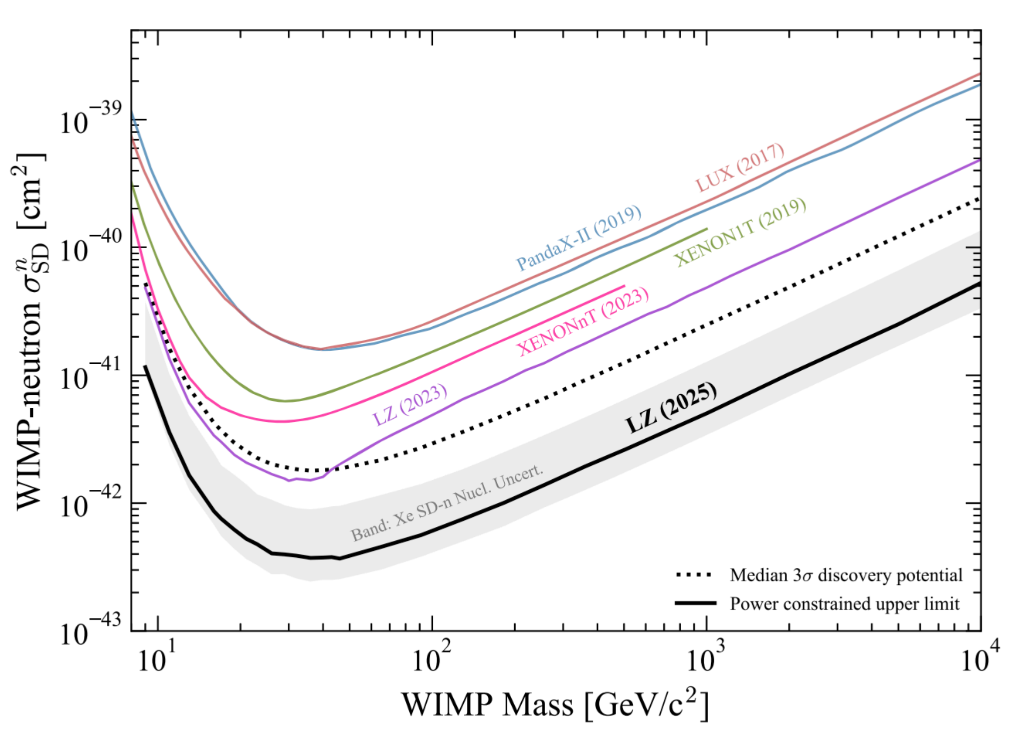
- 5.5 +- 0.2 tonne fiducial volume
- Veto detector anti-coincidence
- Low-mixing background improvement

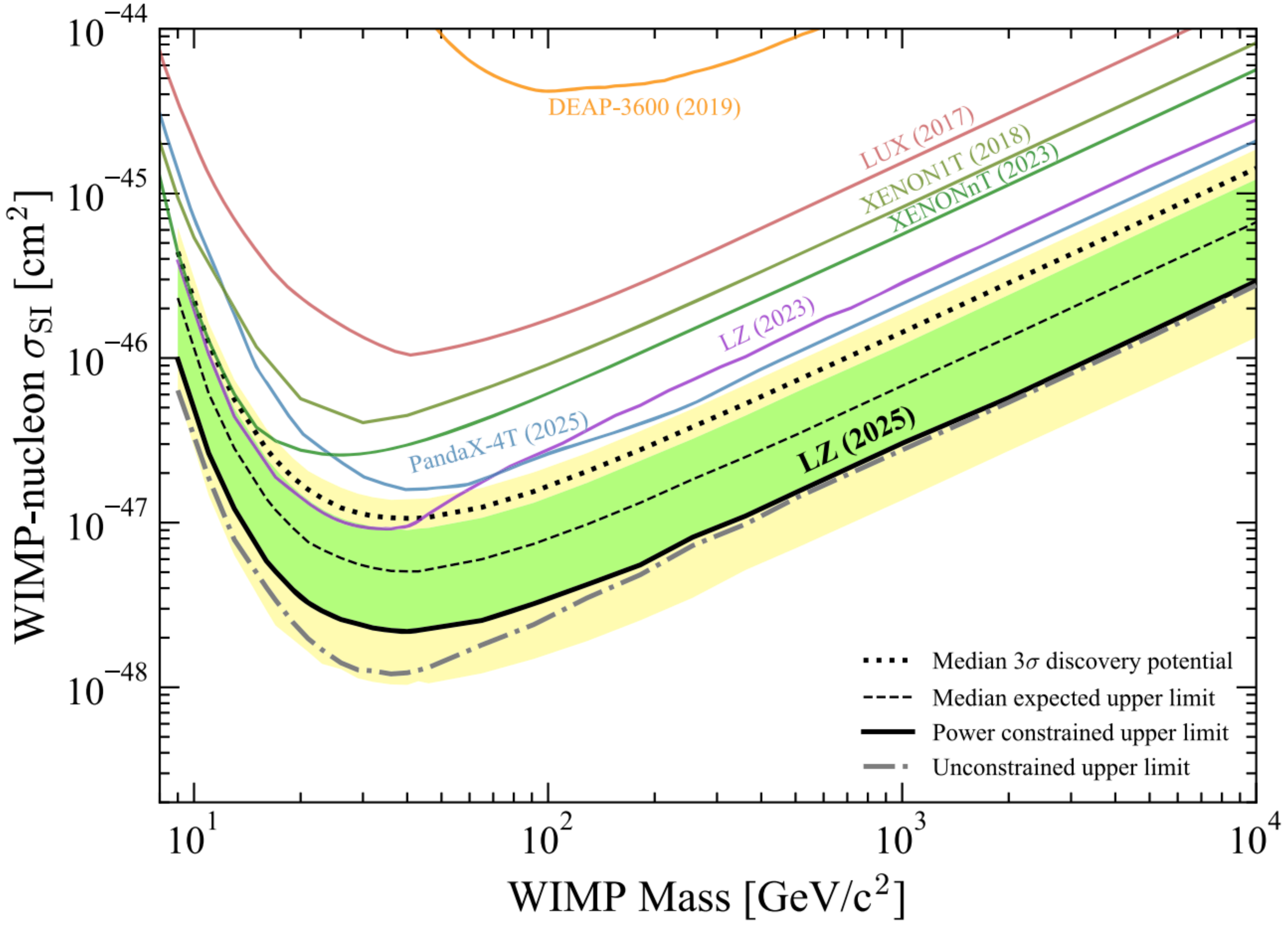
- Agree with background prediction
- No excess events
- No post-unsalting changes

WIMP Search Result

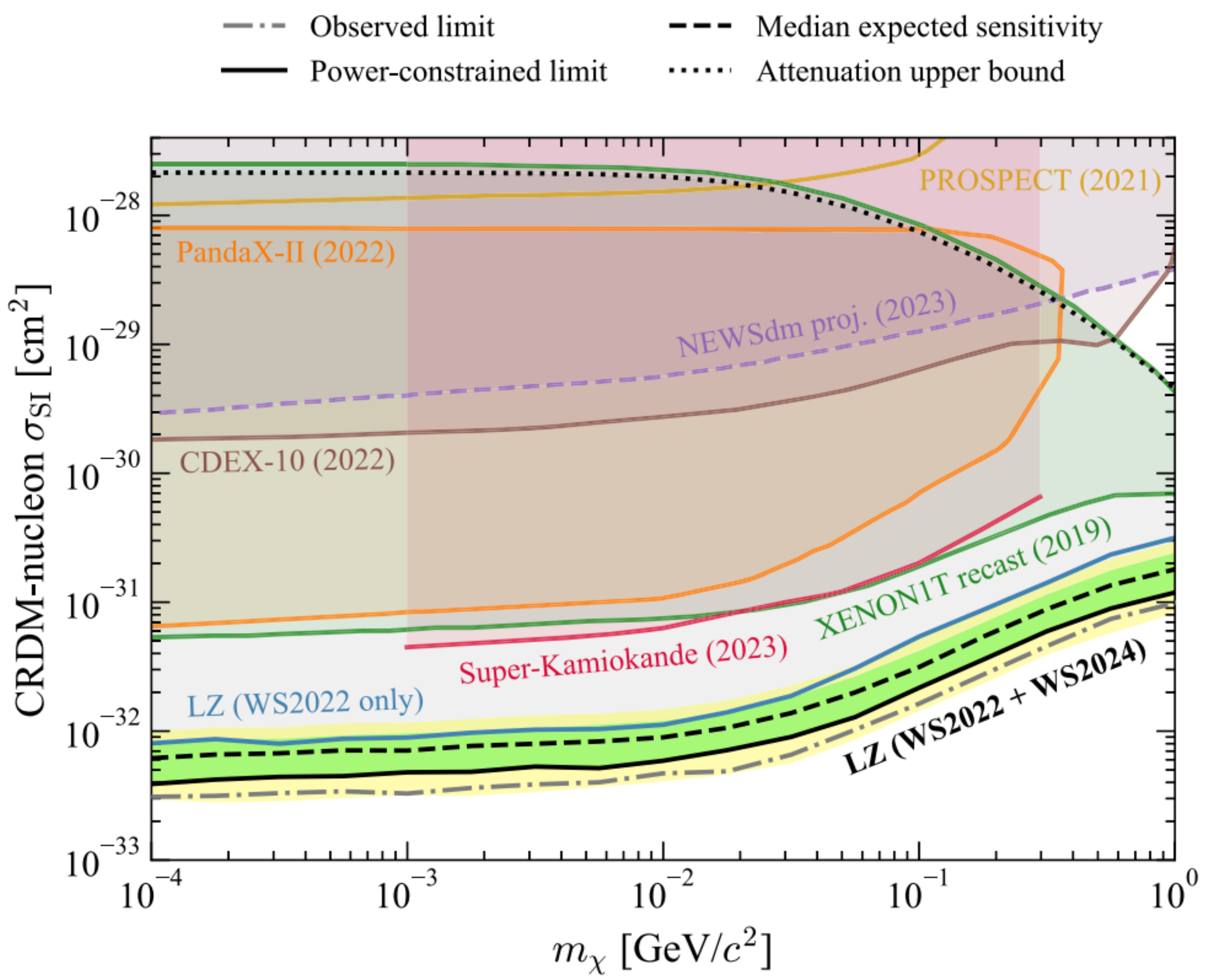
- 1220 events observed
- Two-sided profile likelihood ratio test statistic
- Power constrained at -1 σ [EPJC 81, 907 (2021)]
- Leading limit in 9 GeV - 10 TeV range
- $\sigma_{\mathrm{SI}} = 2.2 \times 10^{-48}$ cm^2 @ 40 GeV/c^2
- PRL 135, 011802 (2025)



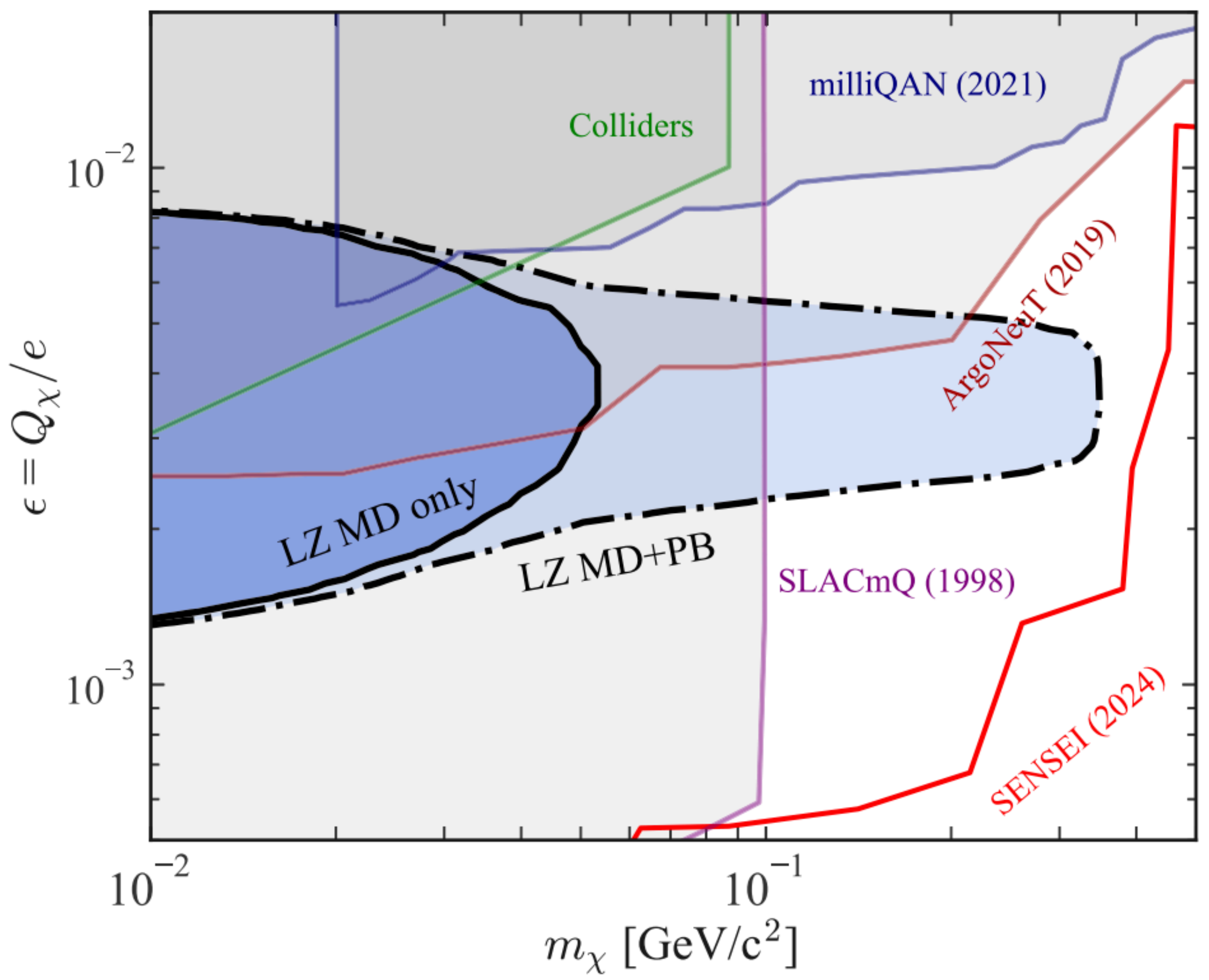




Recent Phenomenological Results

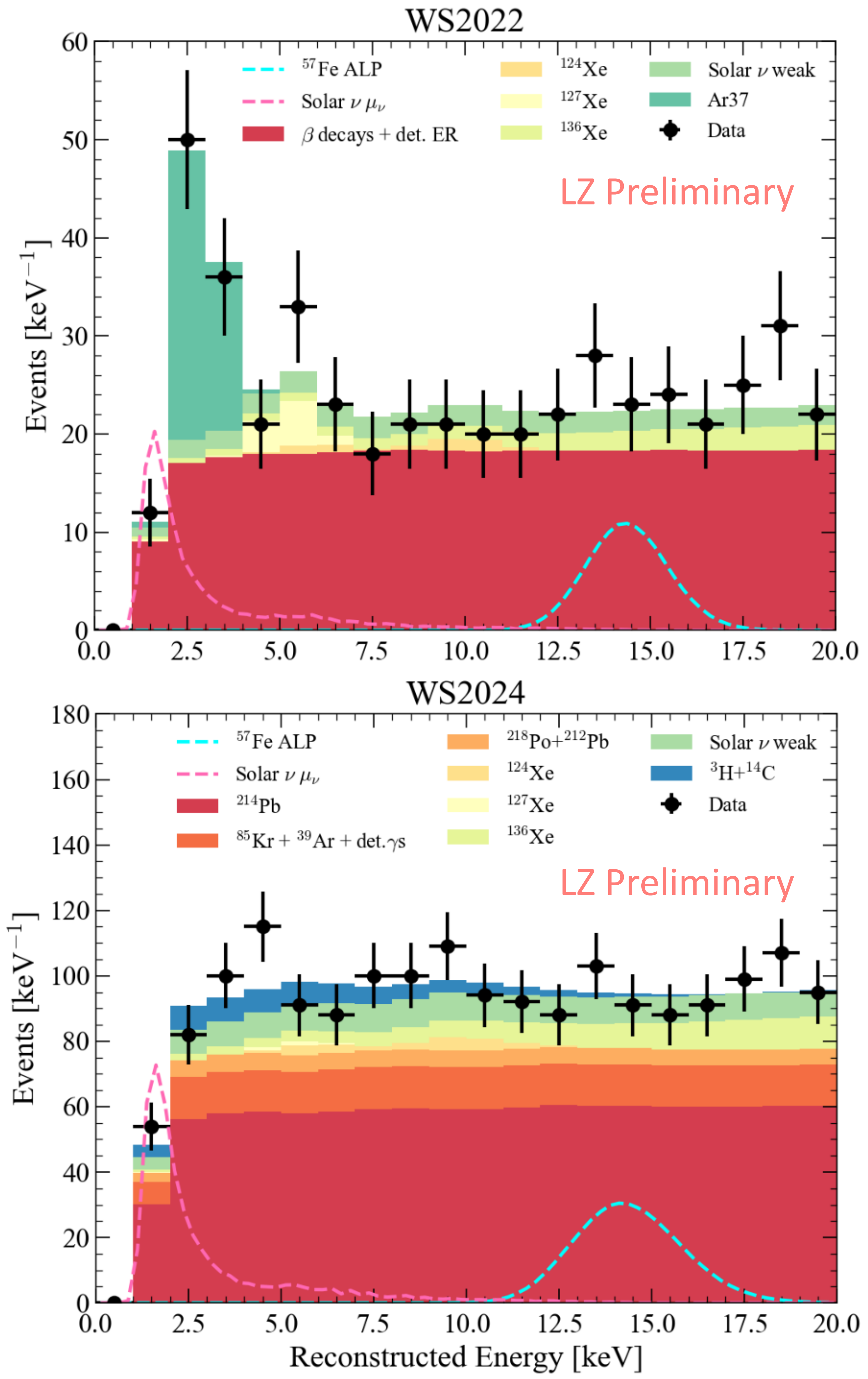


Cosmic Ray Boosted Dark Matter
Phys. Rev. Lett. 134, 241801



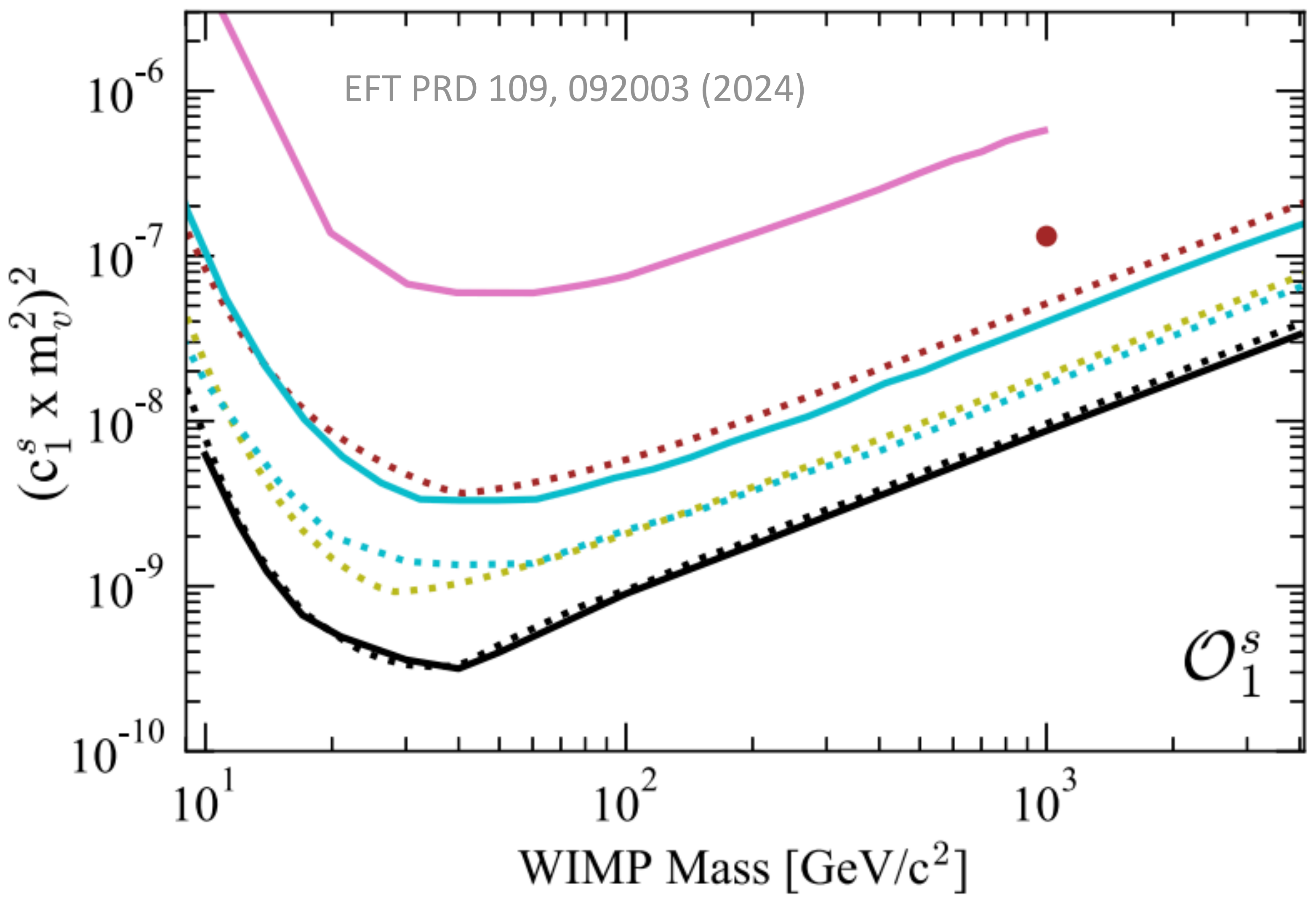
Atmospheric Millicharged Particles
Phys. Rev. Lett. 134, 241802

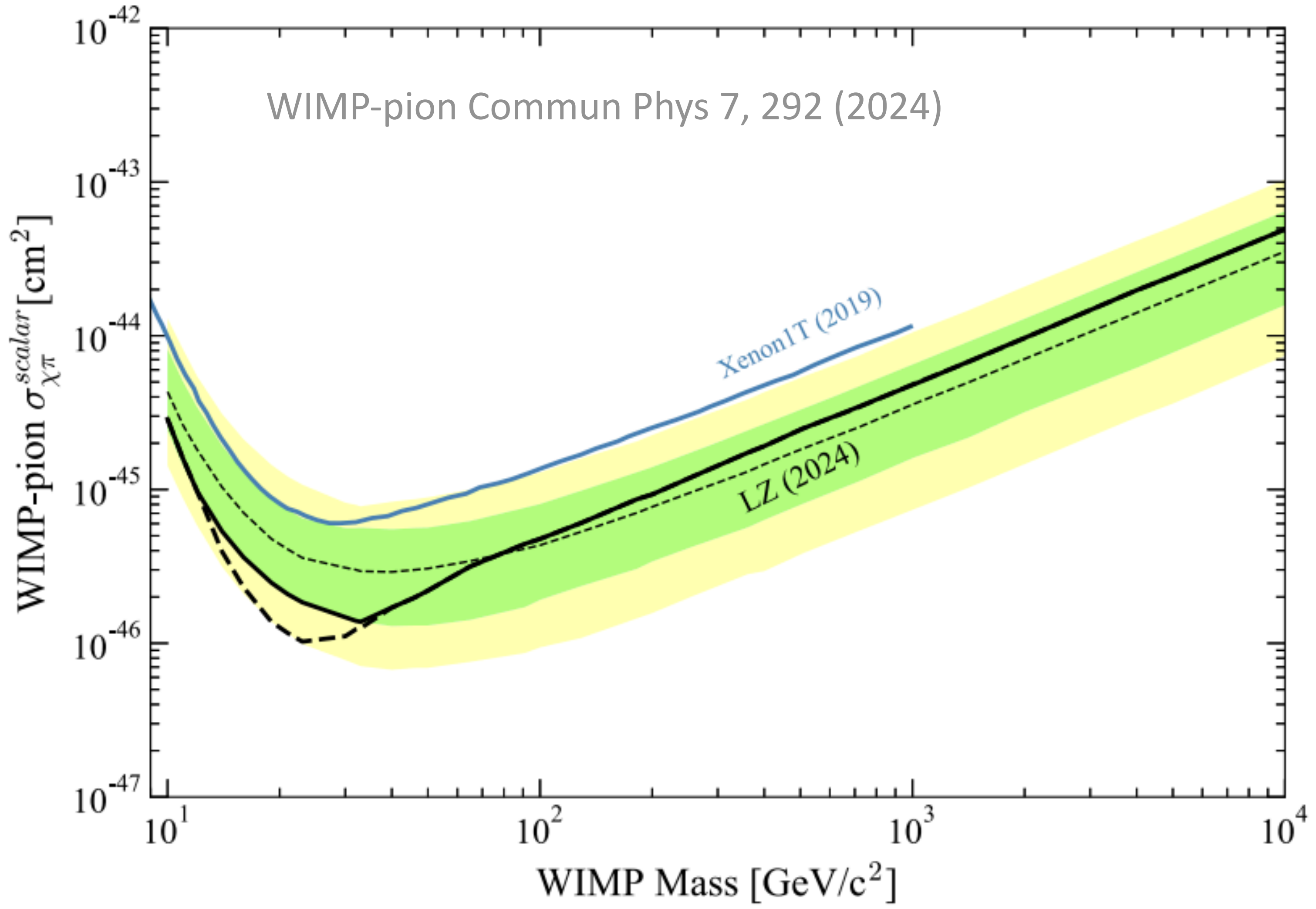
Reconstructed energy spectrum [keVee]

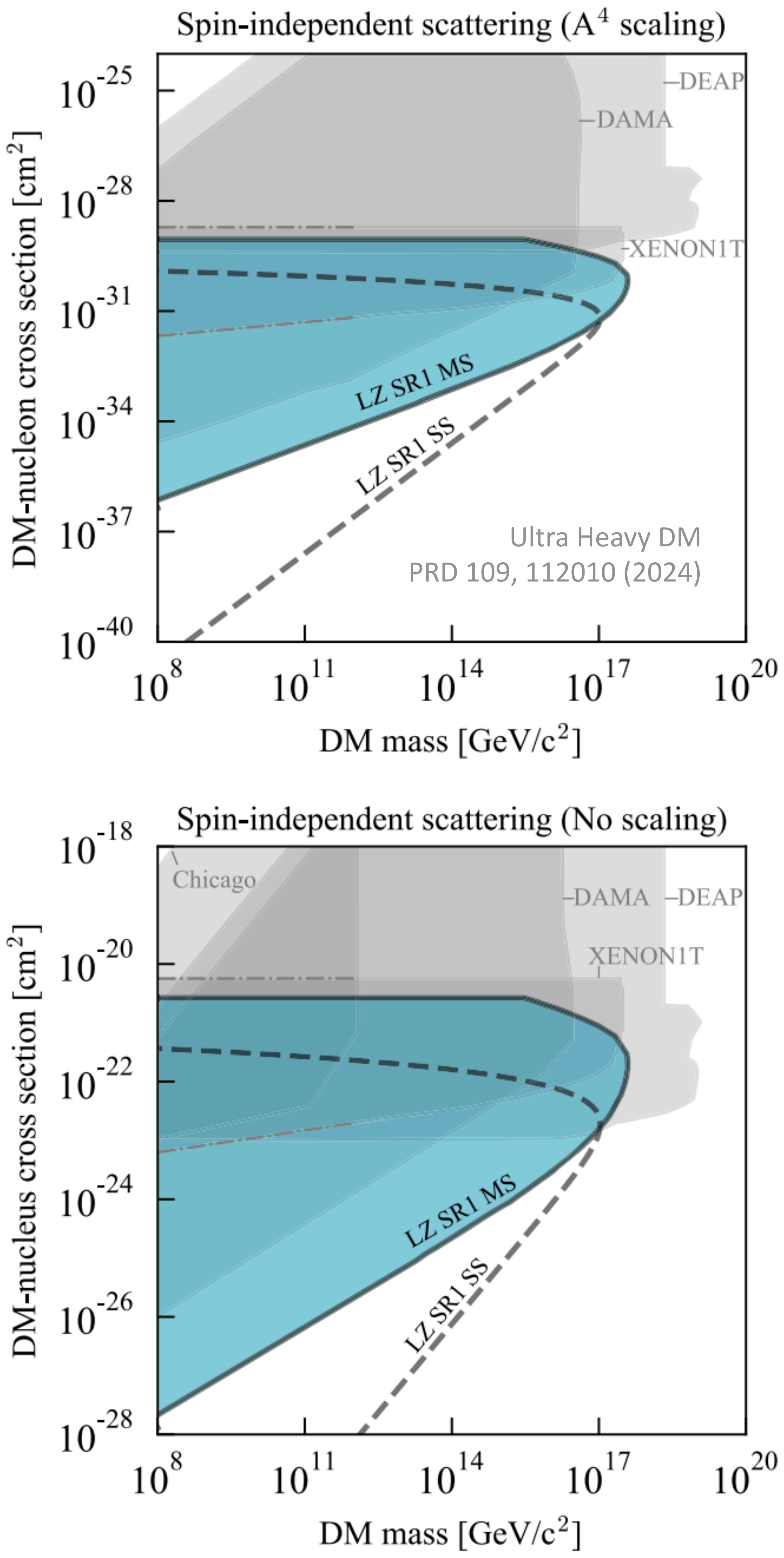


- Agree well on reconstructed energy (keVee) spectrum
- Ar-37 decayed away for WS2024
- Constrain on cosmic ray boosted dark matter, ALPs (see backup), and new physics phenomena

Recent Phenomenological Results

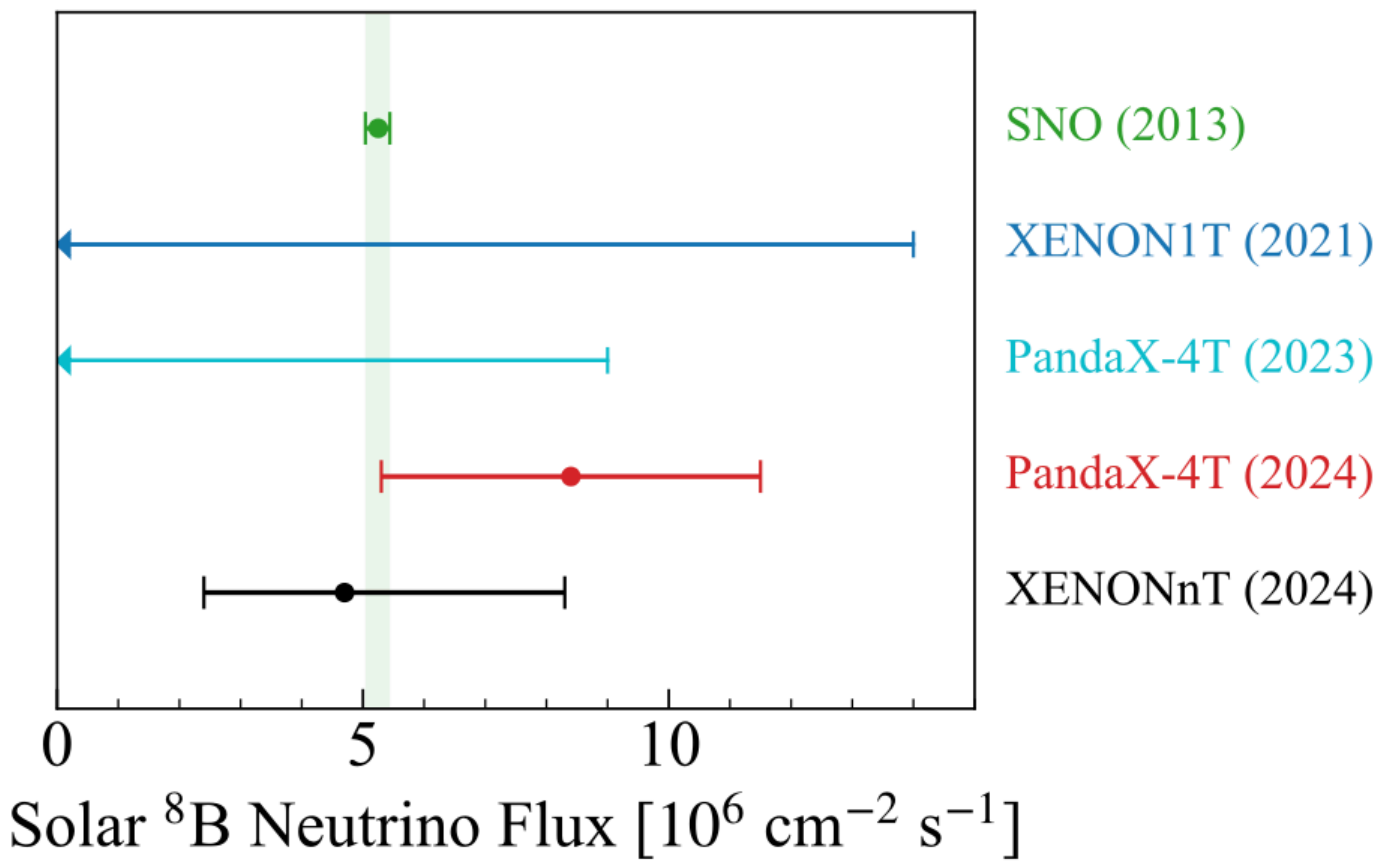


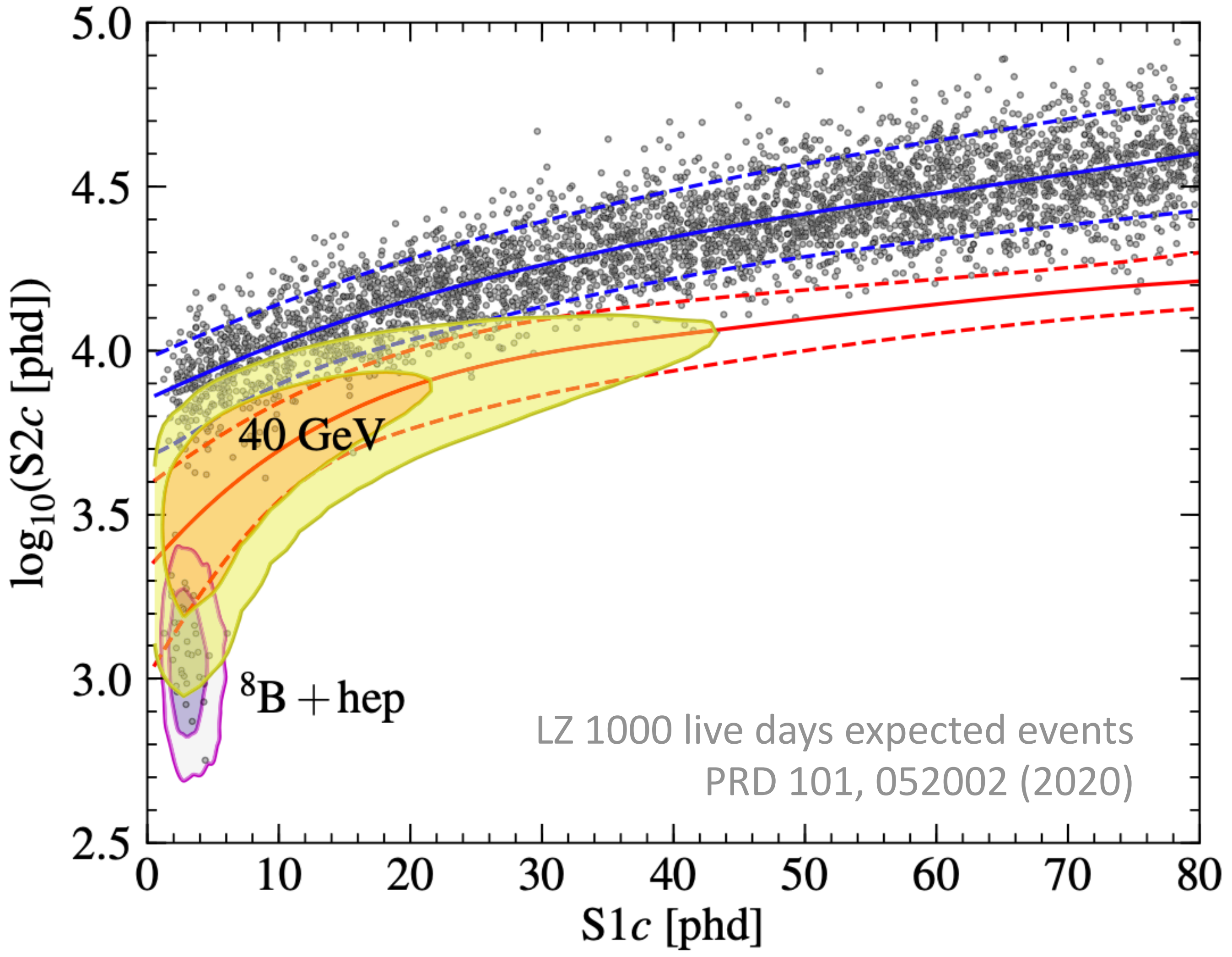


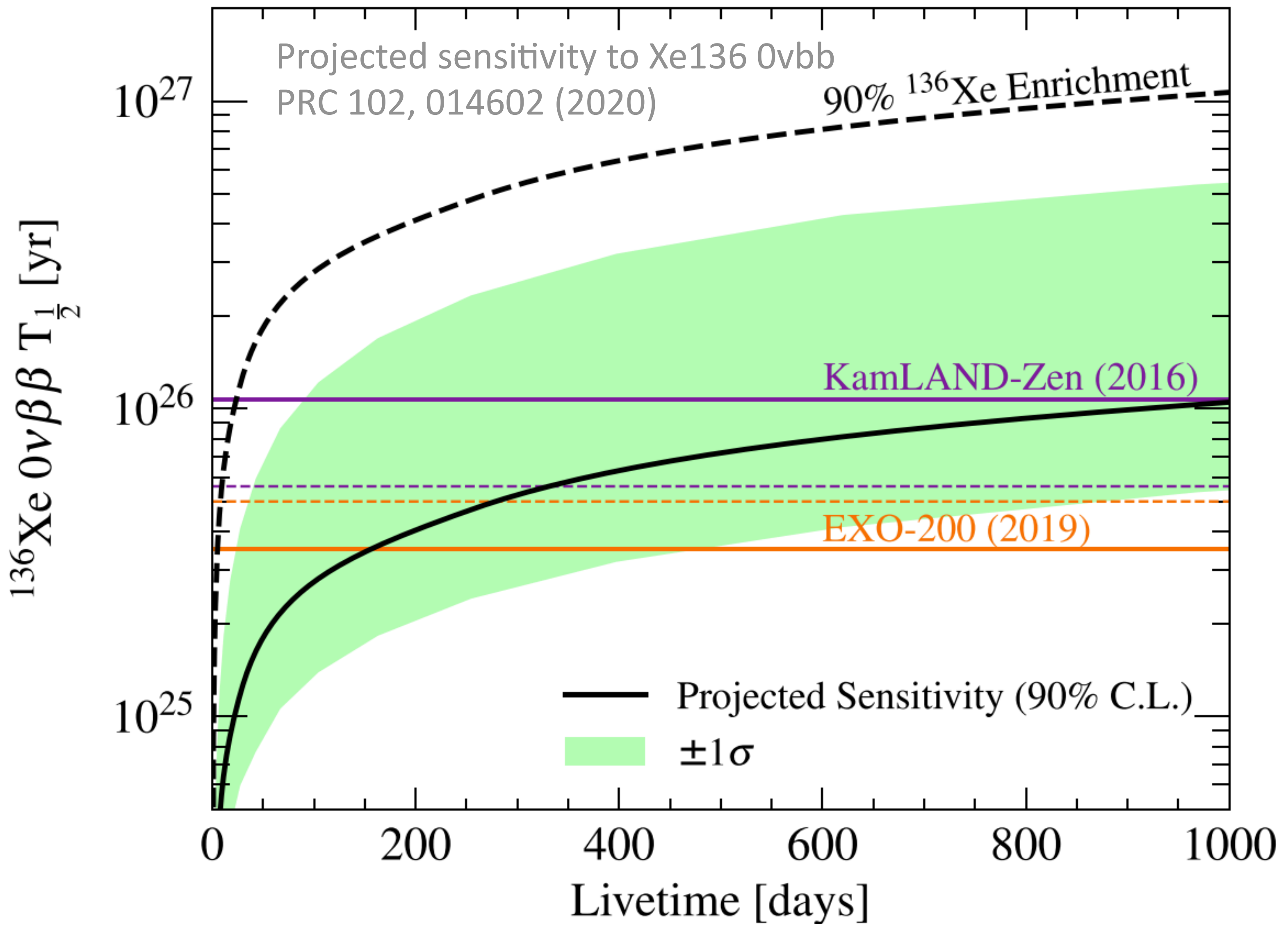


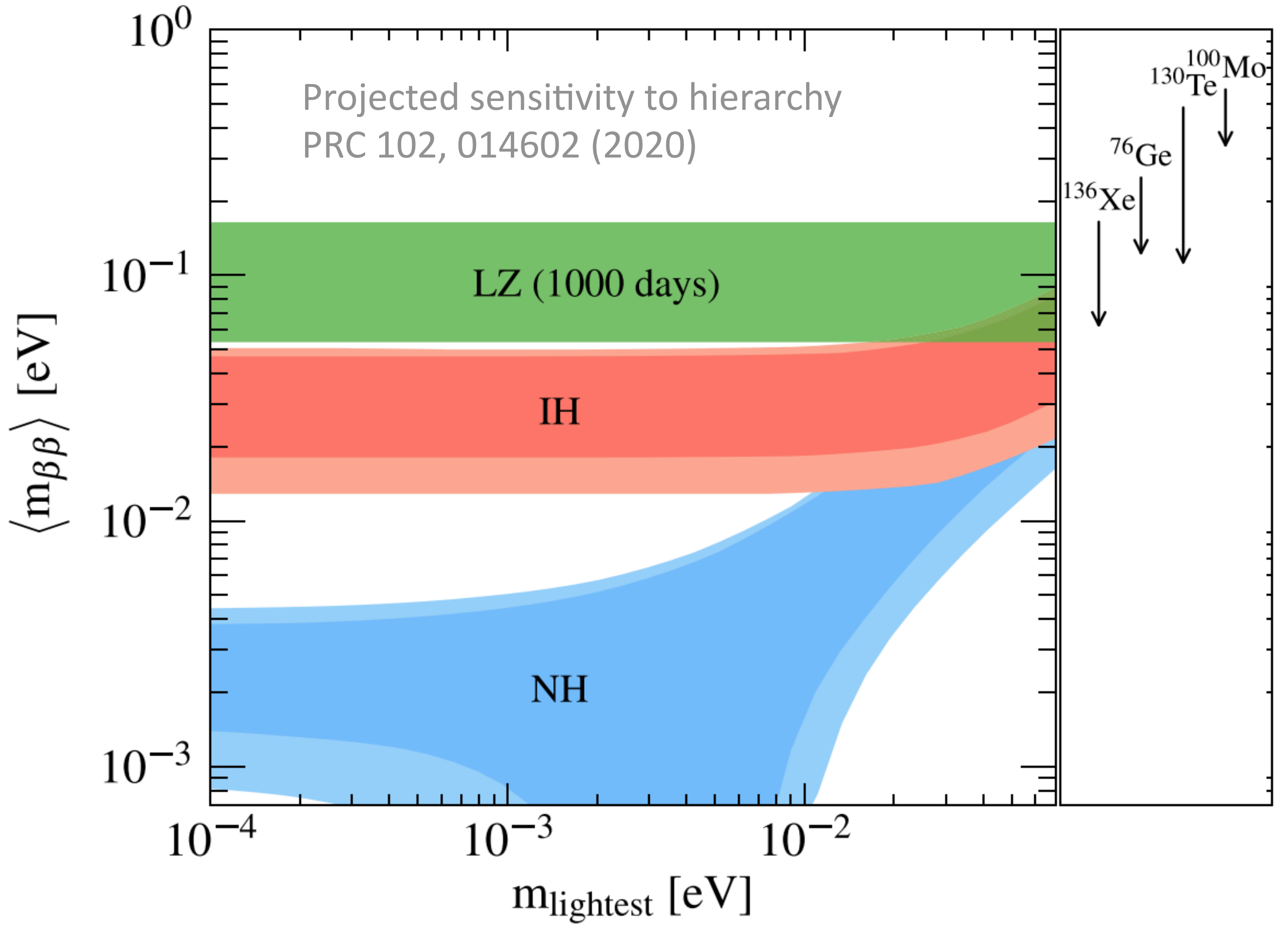
- EFT: systematically analyse O_1–O_{15} WIMP–nucleon operators
- WIMP–pion coupling: can dominate when SI or SD channels are suppressed
- Ultra-heavy dark matter: creates multiple-scatter, track-like events in detectors

Neutrino Physics Prospects





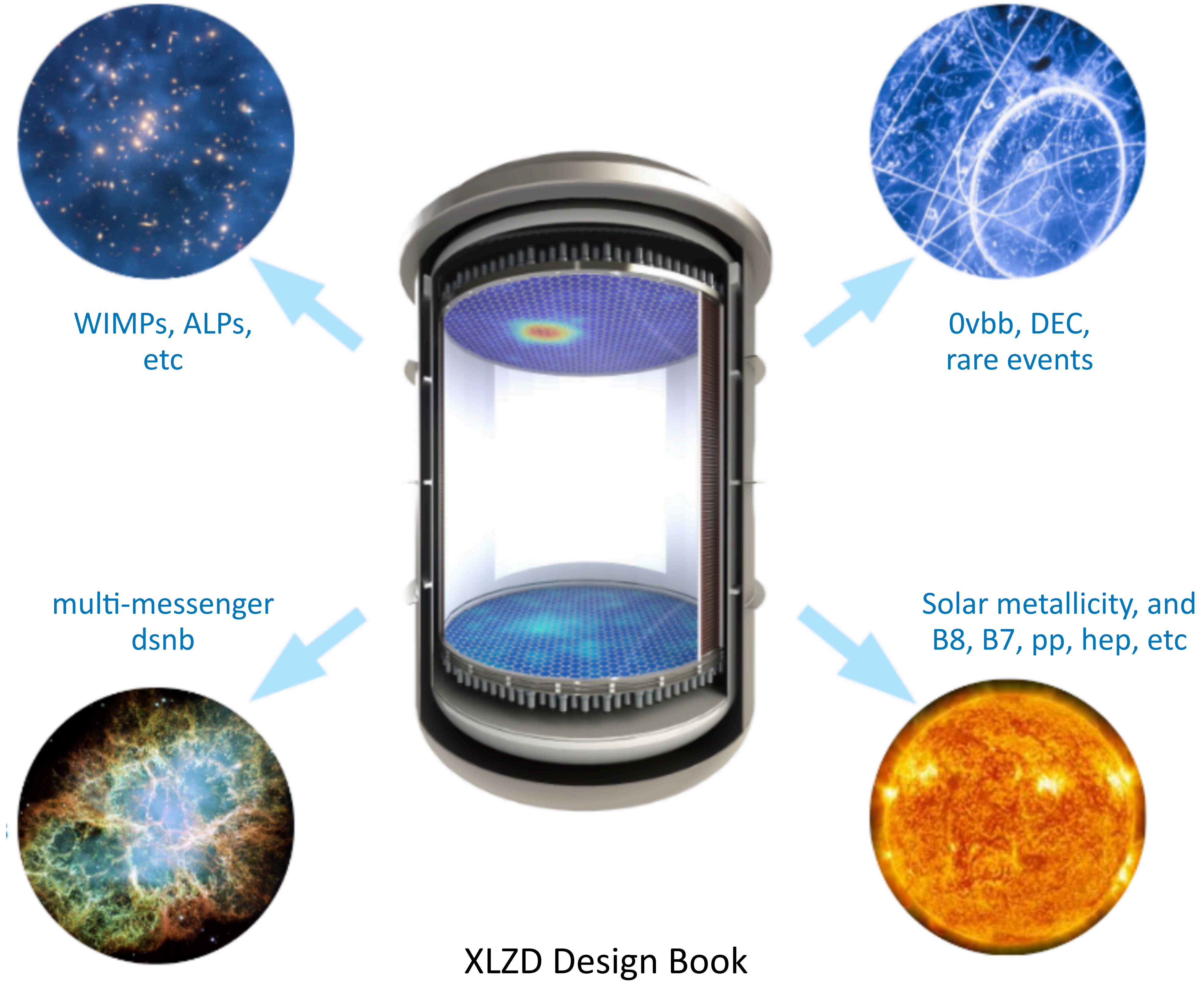




- LZ will continue WIMP search while exploring neutrino physics
- Observation of solar B8 neutrino CEvNS: first for natural neutrinos
- 136Xe 0vbb decay search: probing inverted hierarchy

Next Generation Detector: XLZD

- 60-80 tonne xenon TPC, an order of magnitude larger than current one
- Joint effort of XENON, LZ, Darwin -> ~500 scientists, 72 institutions, 17 countries
- Pursuit dark matter and multi-messenger observables



XLZD Design Book
arxiv:2410.17137

Summary

- New world-leading WIMP search limits, improving previous constraints by over 4 times [PRL 135,011802 (2025)]
- LZ will run until 2028, aiming for 1000 live days to explore multiple physics goals:
  WIMP final run, 8B CEvNS, S2only, 0vbb, ...
- Ongoing planning and R&D for the next generation detector: XLZD

LUX-ZEPLIN Collaboration

250 scientists, engineers, and technical staff from 38 institutions

LZ Collaboration meeting at UCLA, March 2025

- 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
- 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 Zurich

US Europe Asia Oceania

Science and Technology Facilities Council
Fundação para a Ciência e a Tecnologia
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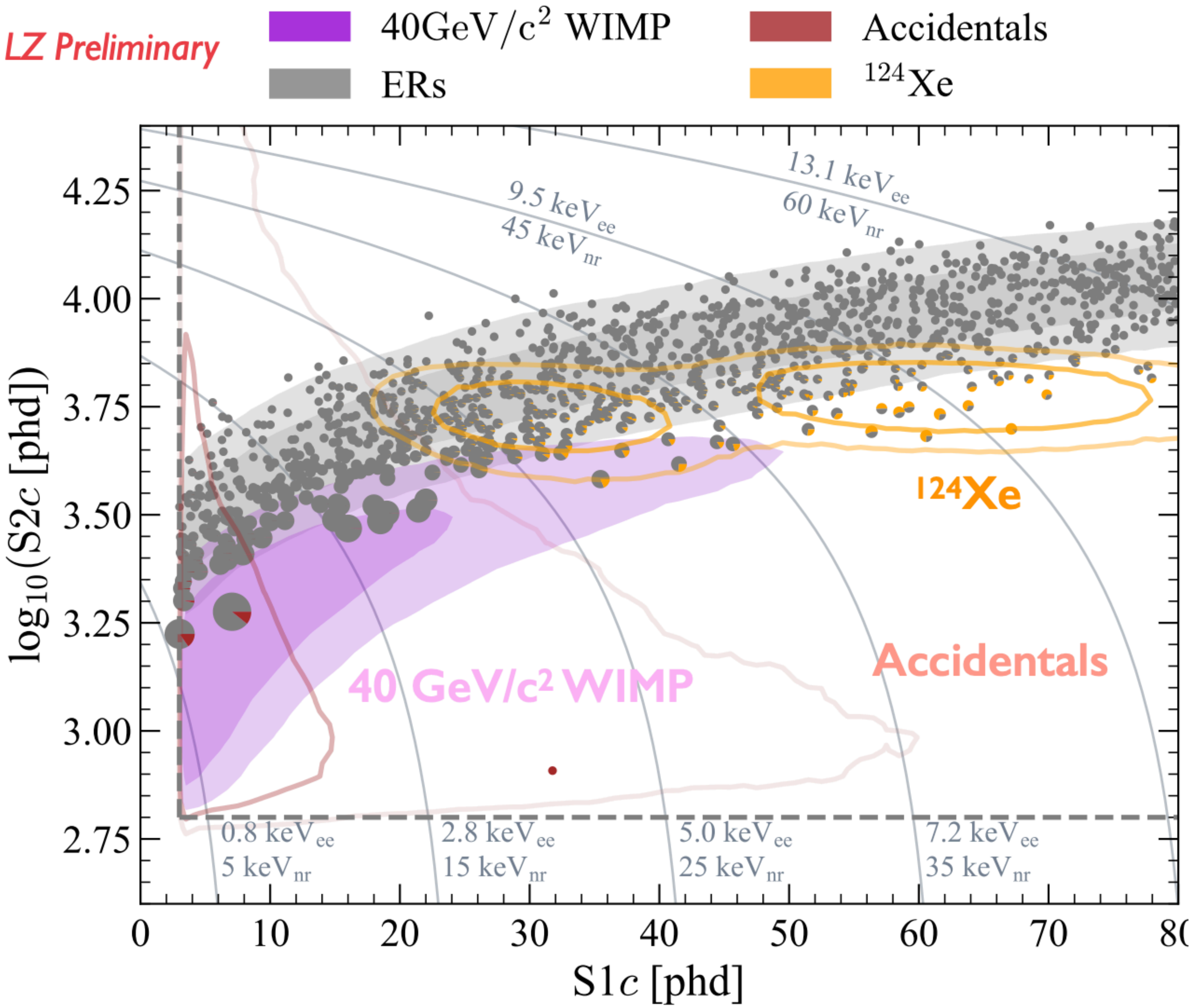
Institute for Basic Science
DARK MATTER

https://lz.lbl.gov/

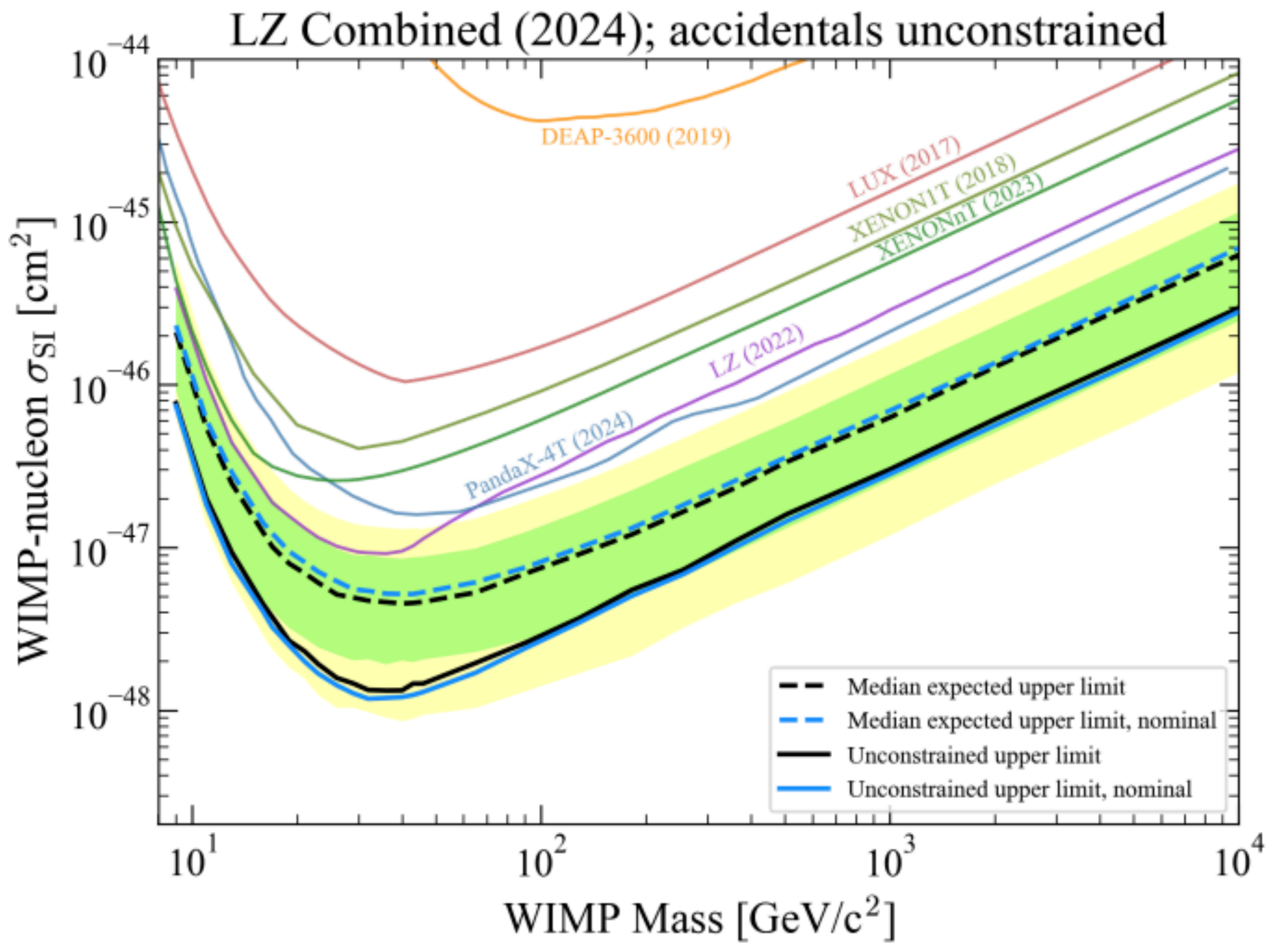
@lzdarkmatter

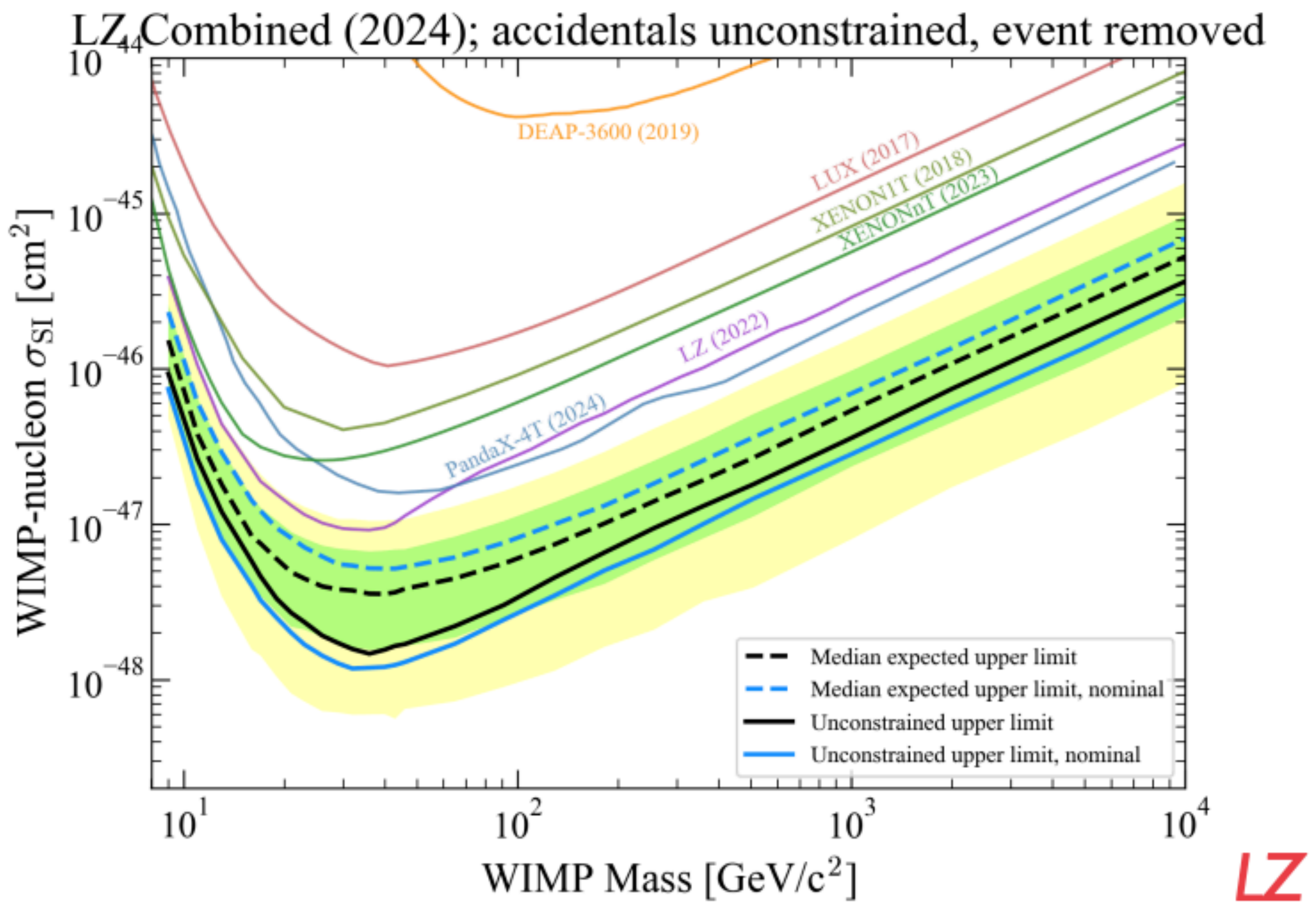
Backups

Candidate Data Pie Chart

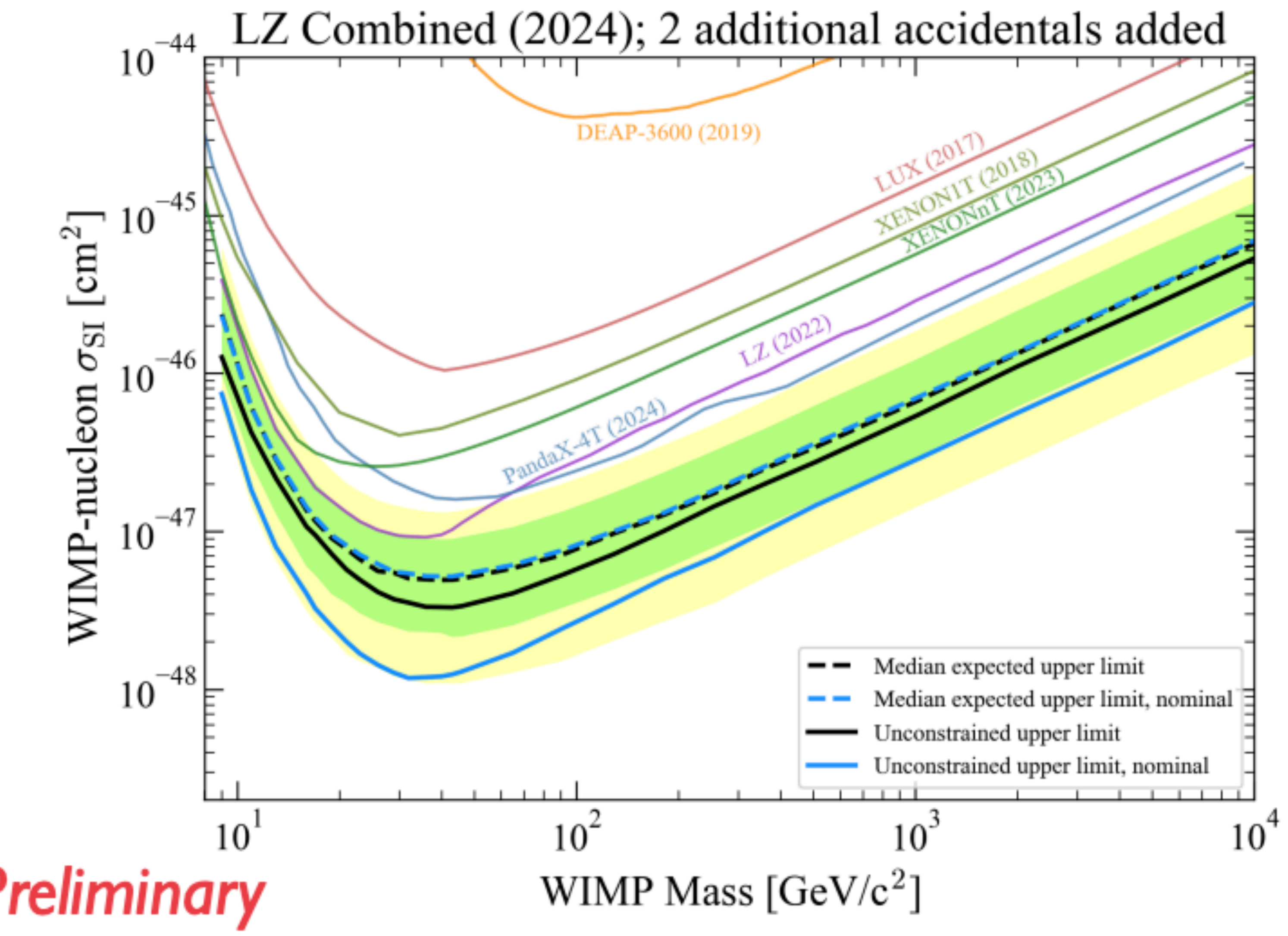


Limit Curve Varying Accidental Background Term





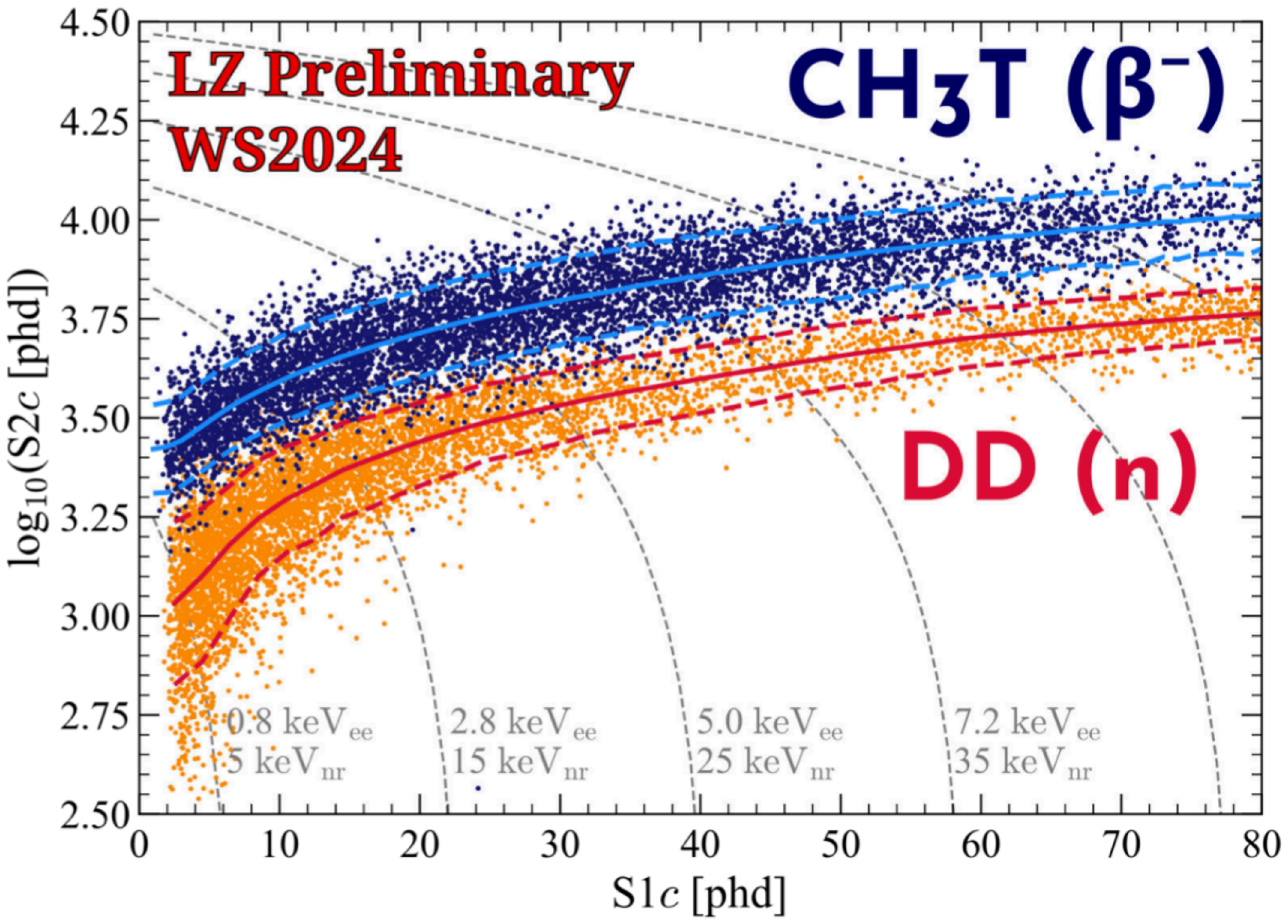
LZ Preliminary



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

Detection Calibration

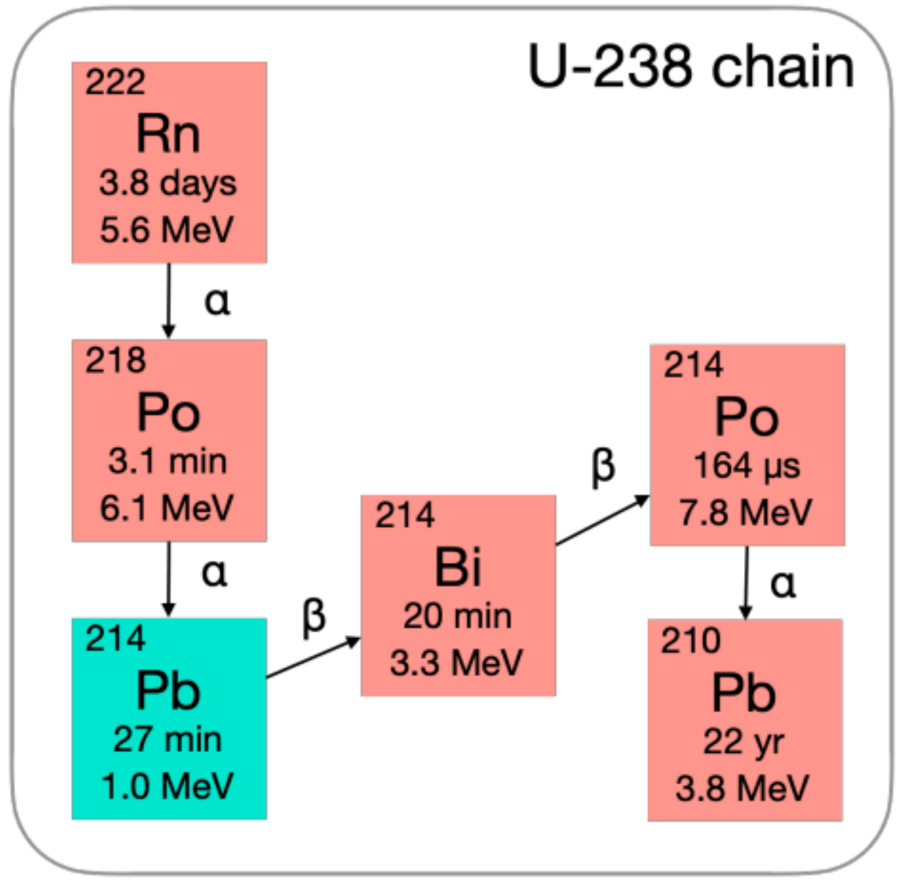
- Electronic recoils
  - Tritium radio-labelled methane & ^{14}C betas
  - Mono-energetic ^{83m}Kr
- Nuclear recoils
  - DD neutron generator (2.45 MeV neutrons)
  - AmLi source for low energy neutrons(<1.5 MeV), deployed at 9 depths
- WS2024 NEST model
  - Light gain (g_1): 0.112 ± 0.002 phd/photon
  - Charge gain (g_2): 34.0 ± 0.9 phd/electron
  - Single electron signal size: 44.5 phd
  - 99.9% ER rejection below 40 GeV WIMP median

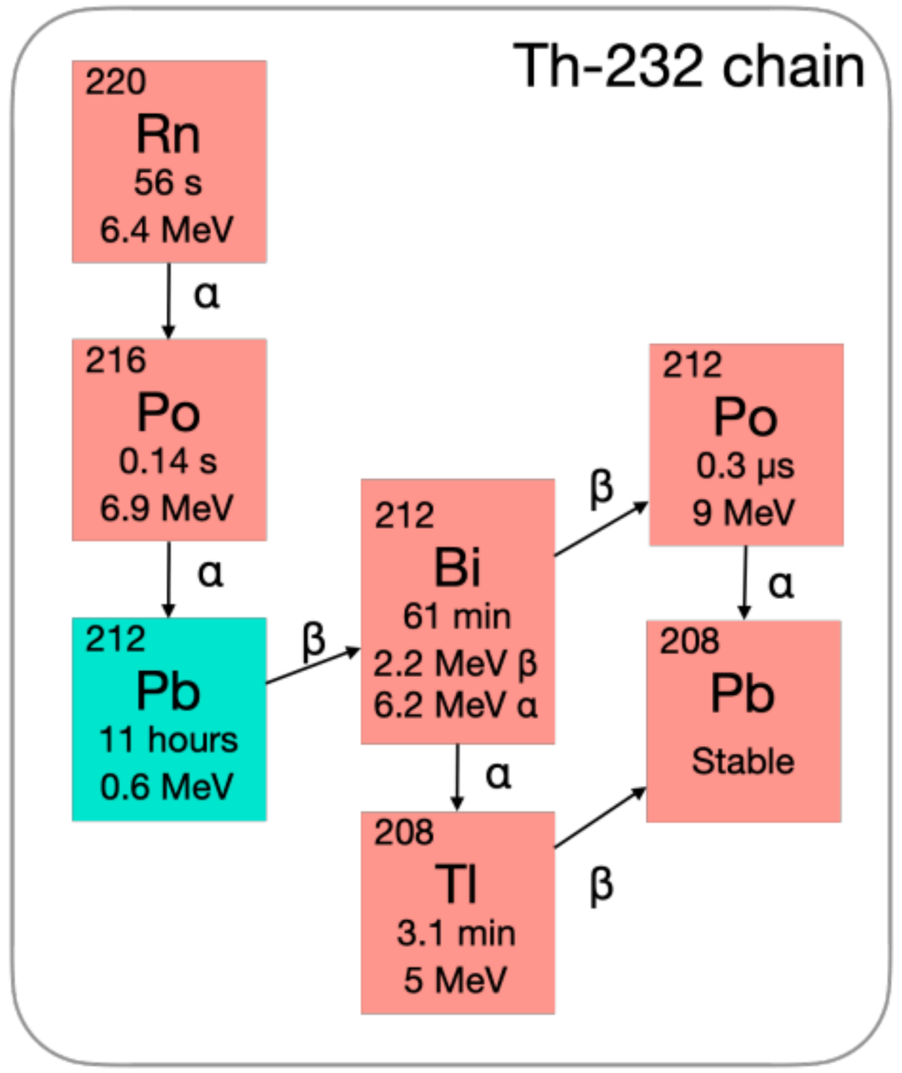


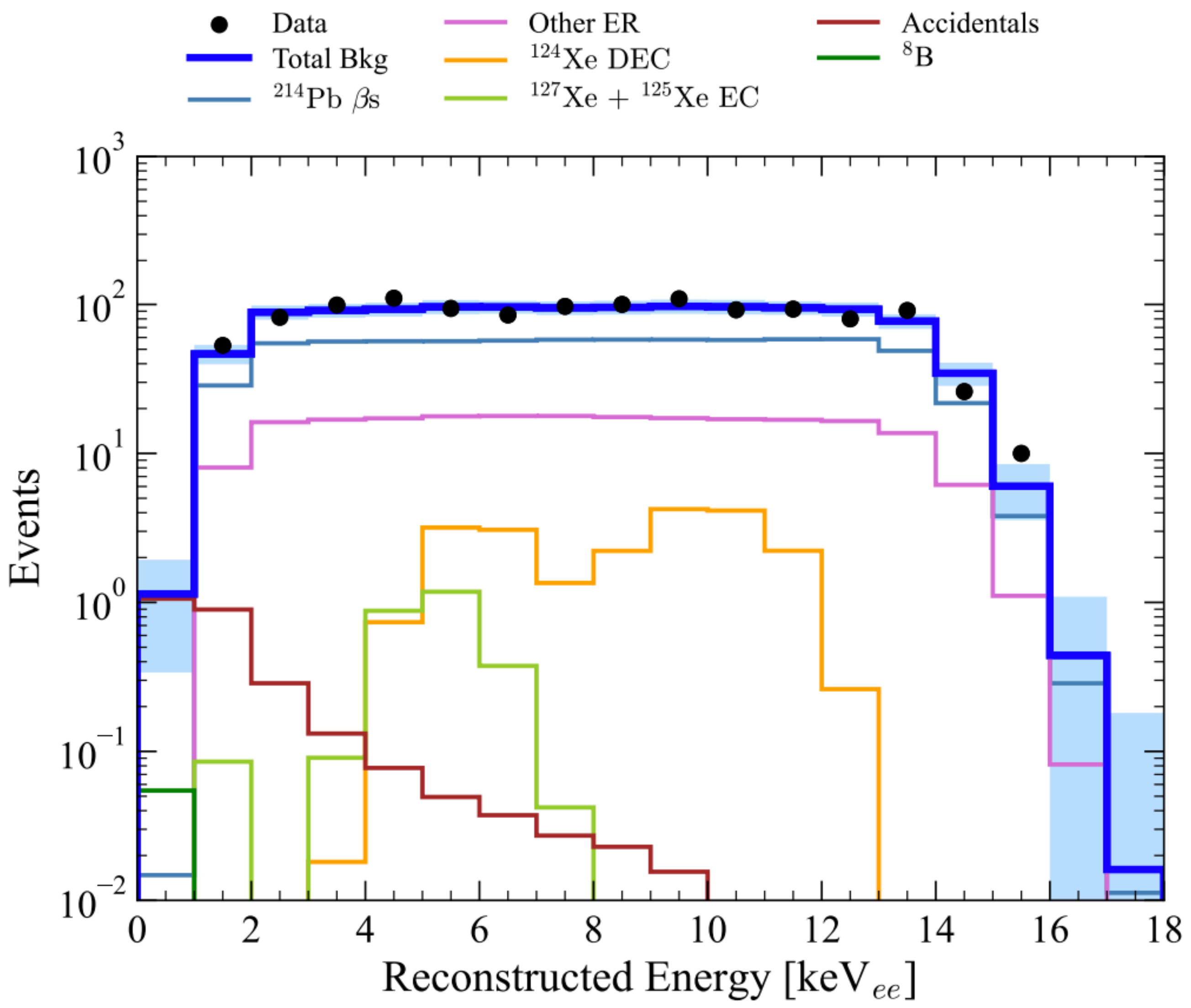
Background Table and Fit Result

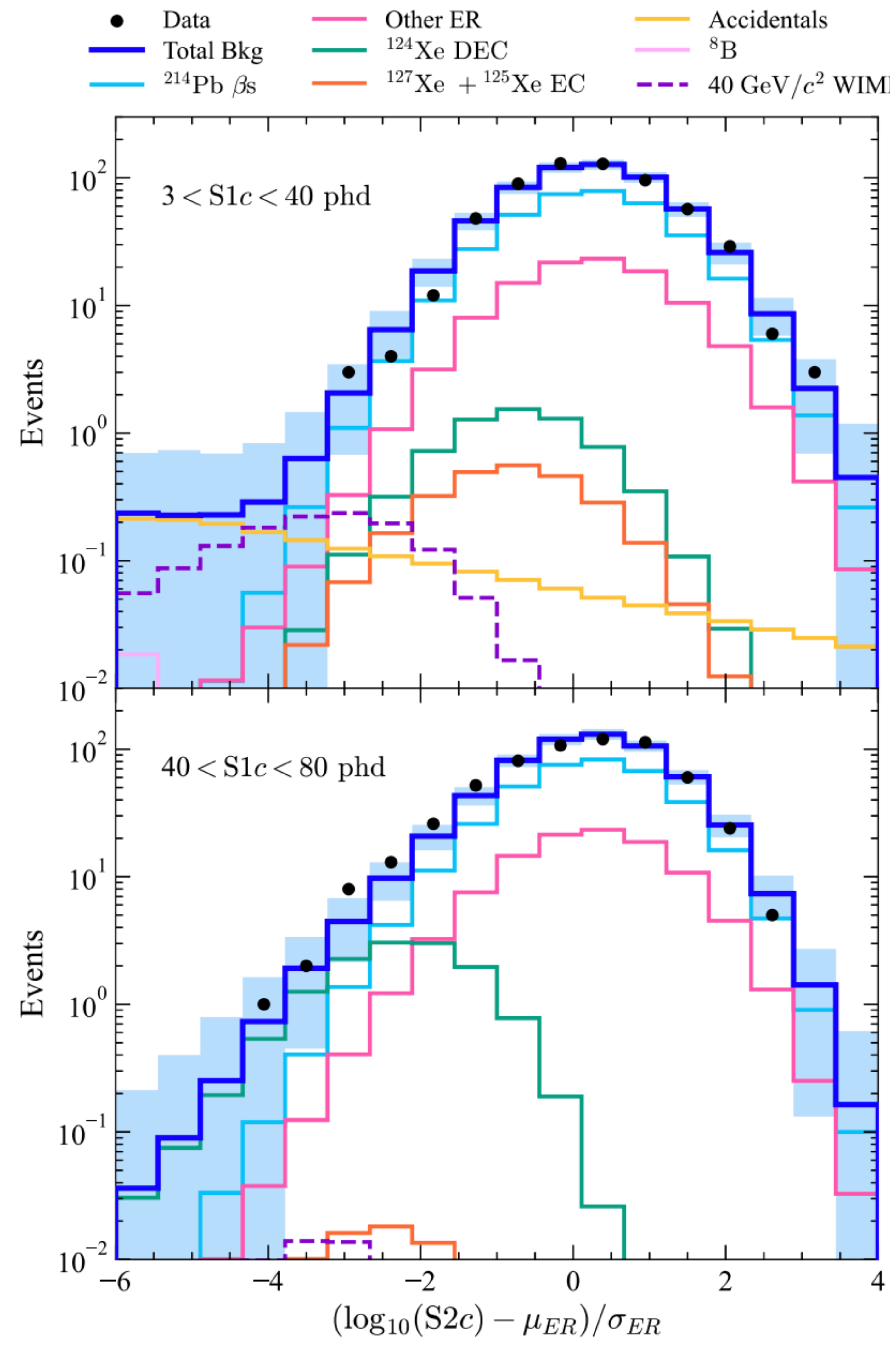
- U-238 and Th232 chains
- Agree well with background only hypothesis
- Tested on keVee and renormalized S2 spectrums
- Fit result adding 40 GeV WIMP: 0.0 + 0.6

Source	Prefit expectation	Fit result
^{214}Pb βs	743 ± 88	733 ± 34
^{85}Kr + ^{39}Ar βs + det. γs	162 ± 22	161 ± 21
Solar ν ER	102 ± 6	102 ± 6
^{212}Pb + ^{218}Po βs	62.7 ± 7.5	63.7 ± 7.4
Tritium + ^{14}C βs	58.3 ± 3.3	59.7 ± 3.3
^{136}Xe $2\nu\beta\beta$	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
Accidental coincidences	2.8 ± 0.6	2.6 ± 0.6
Atm. ν NR	0.12 ± 0.02	0.12 ± 0.02
^{8}B + hep ν NR	0.06 ± 0.01	0.06 ± 0.01
Detector neutrons	$^{a}0.0^{+0.2}$	$0.0^{+0.2}$
40 GeV/c^2 WIMP	$\cdots$	$0.0^{+0.6}$
Total	1210 ± 91	1202 ± 41



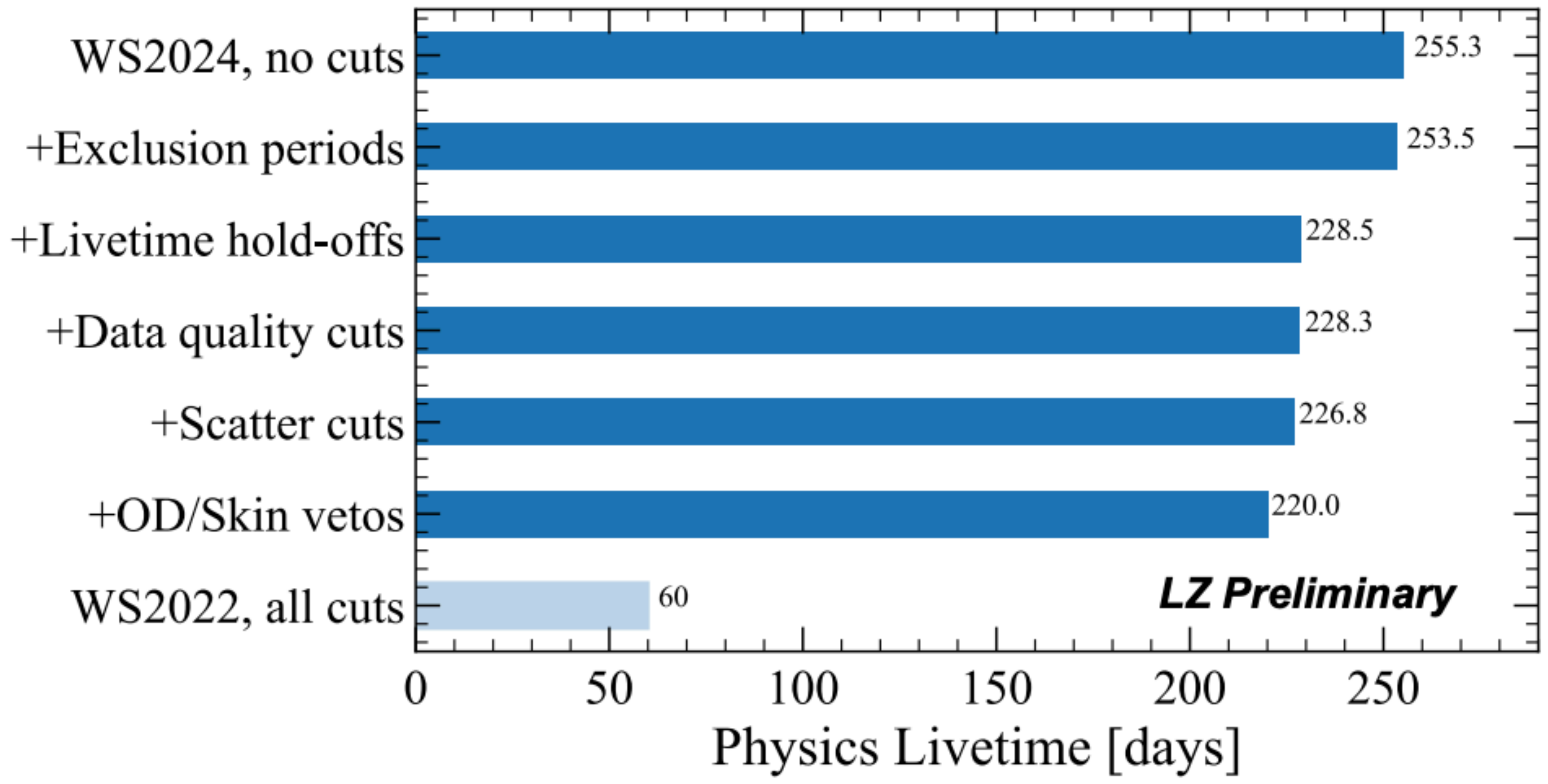


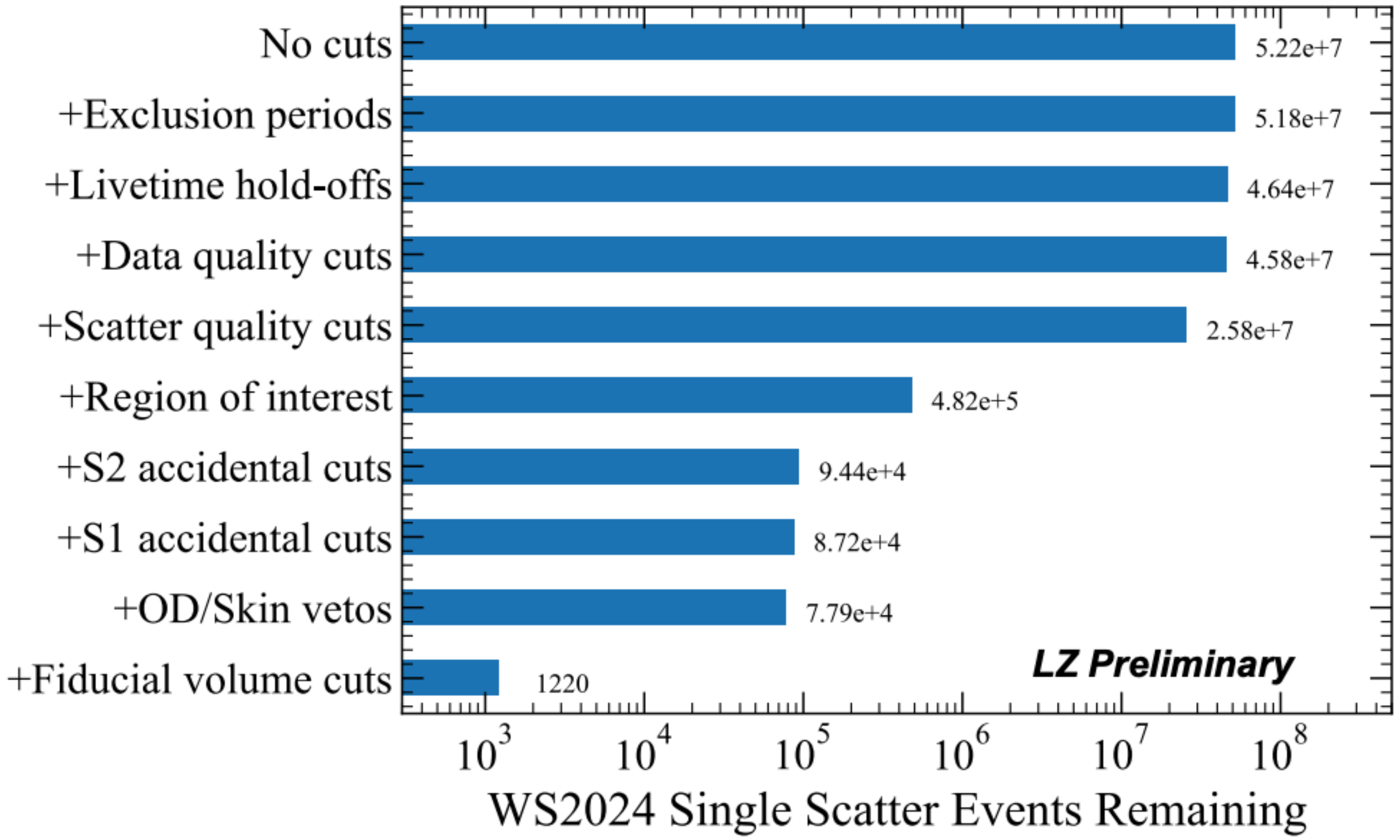




Data Selection

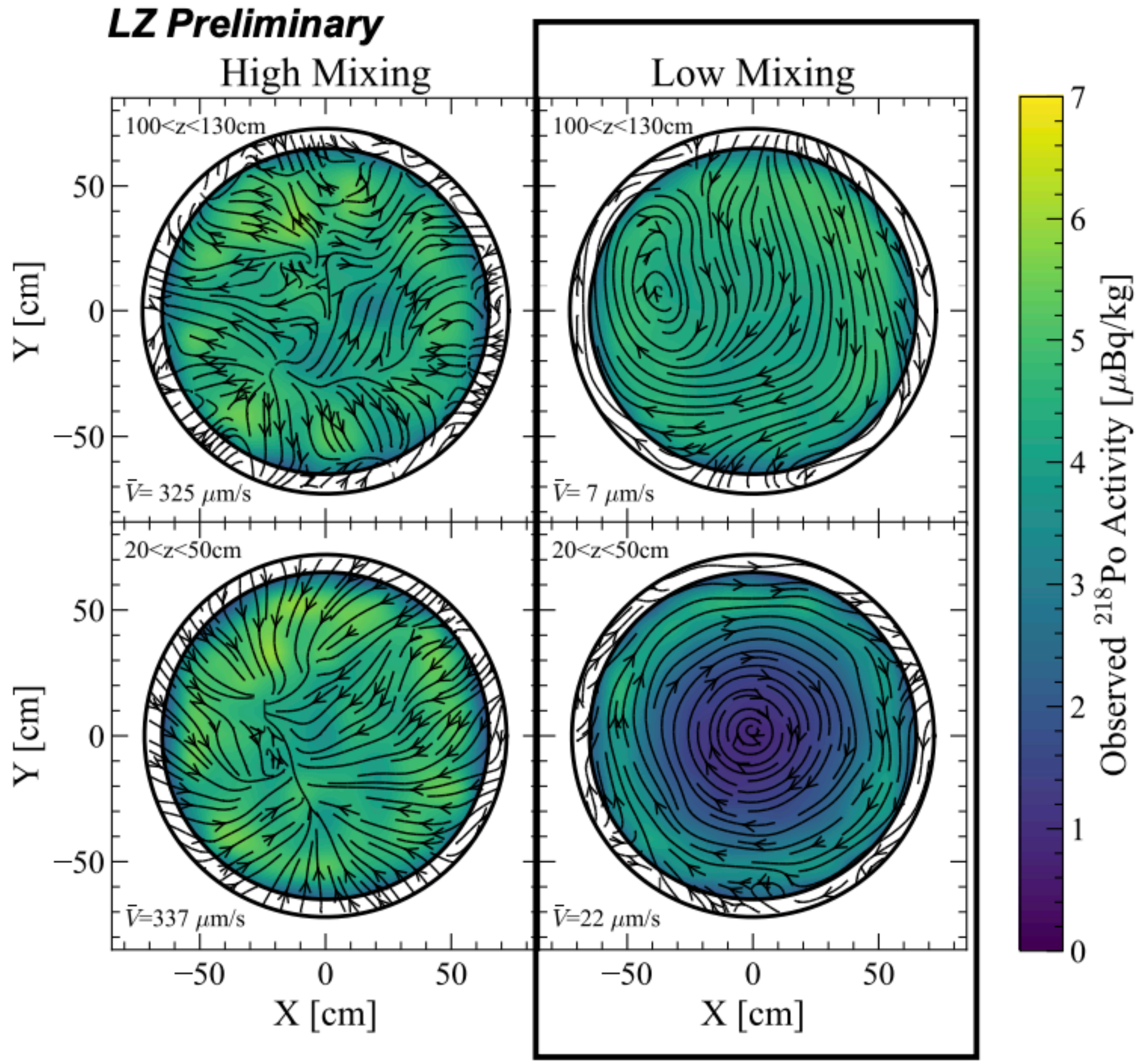
Region of Interest: 3 < S1c [phd] < 80, 645 < S2c [phd], log10(S2c [phd]) <4.5

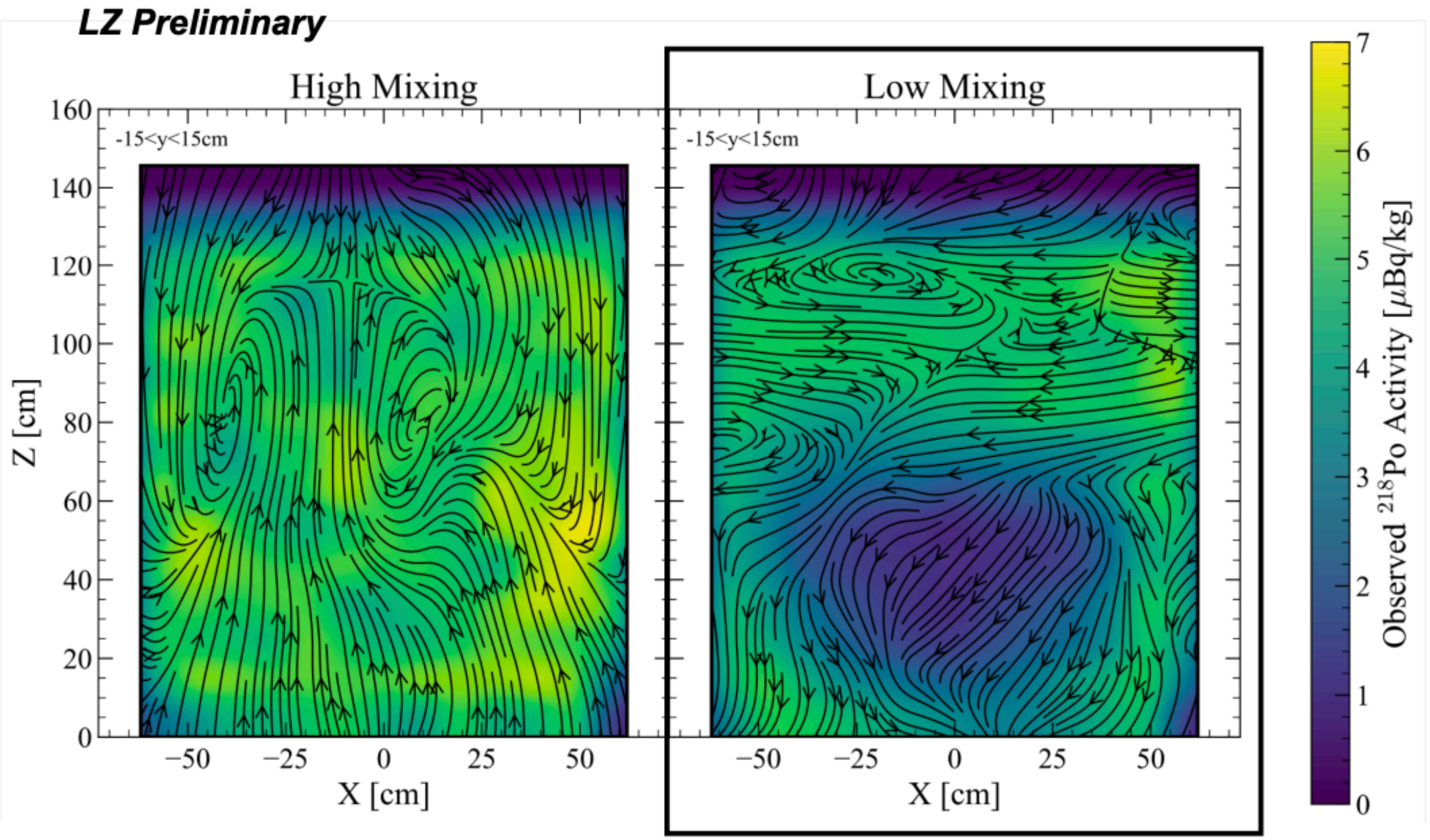




Radon Tagging

- Circulation and cooling systems allow control of temperature and xenon flow
  - High-mixing state: more turbulent flow -> uniform distribution of injected calibration sources
  - Low-mixing state: slower laminar flow
- 222Rn emanates from detector materials
  - 222Rn-218Po pairs (half-life = 3.1 min) used to map the flow vectors





Solar ALPs and Bosonic Dark Matter