FIRST WIMP SEARCH RESULTS FROM THE LUX-ZEPLIN EXPERIMENT

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COLLABORATION

Sanford Underground Research Facility
South Dakota Science and Technology Authority

UKRI Science and Technology Facilities Council

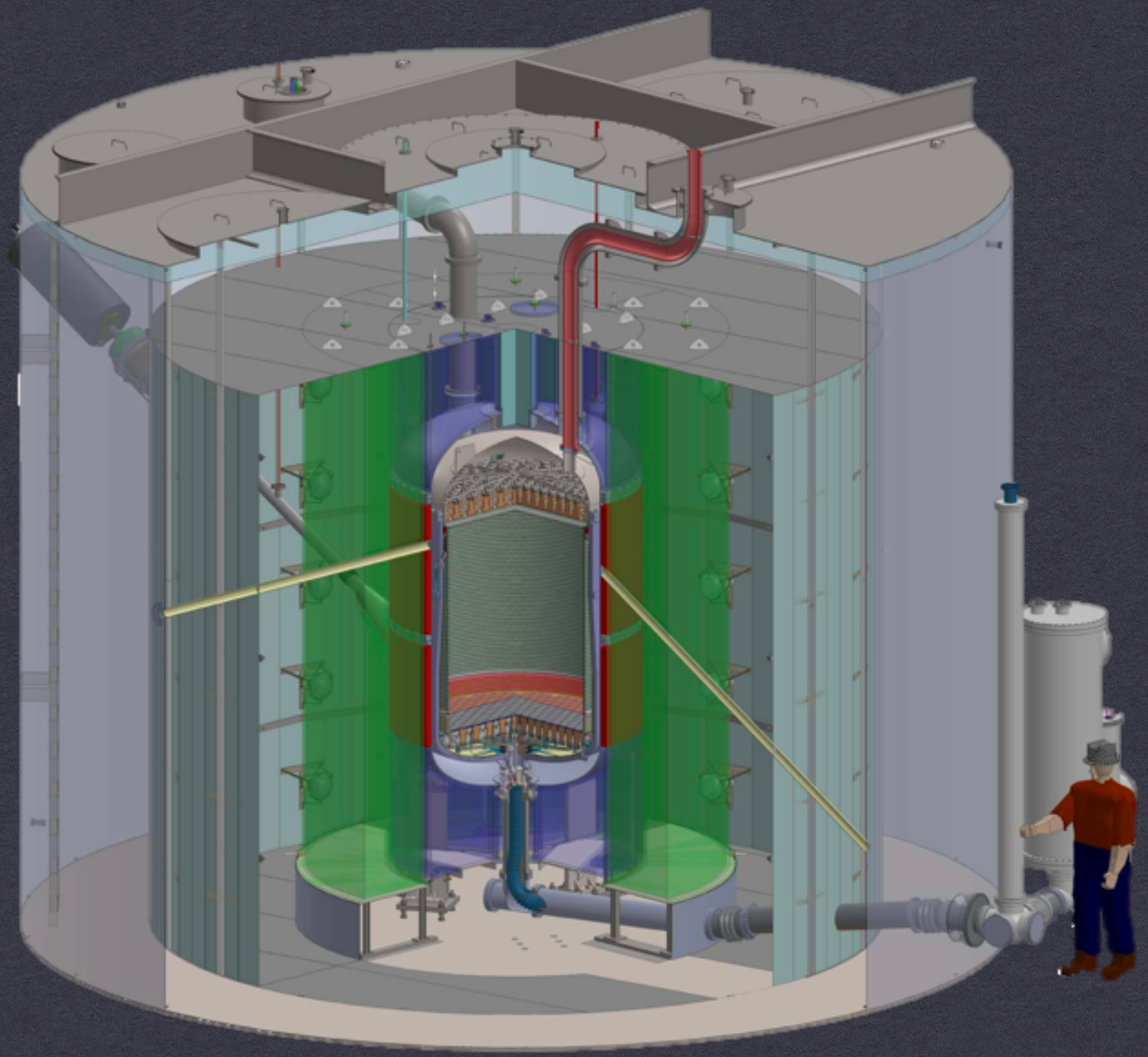
FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

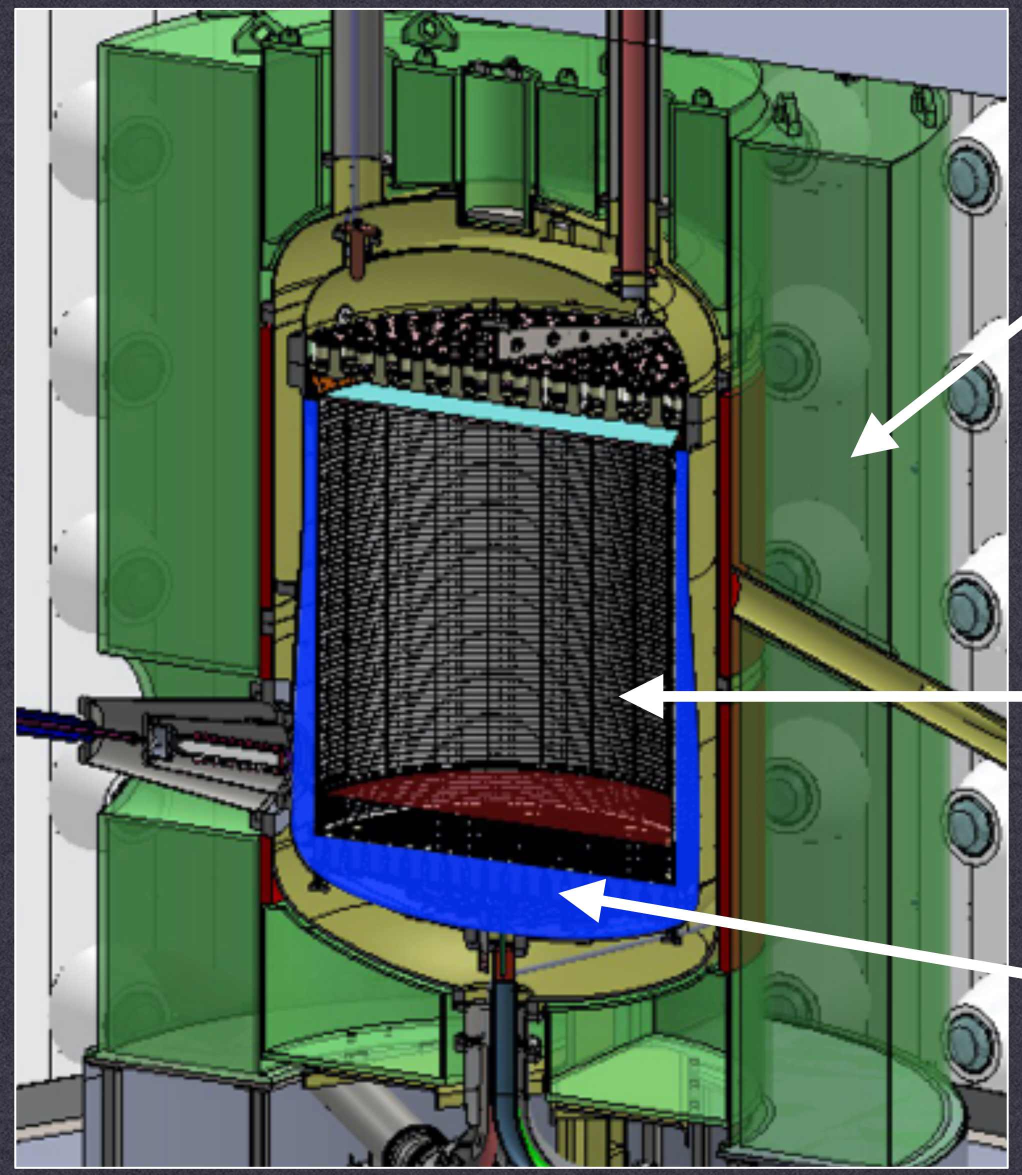
ibs Institute for Basic Science

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

36 Institutions: ~250 scientists, engineers, and technical staff

INTRODUCTION TO LZ



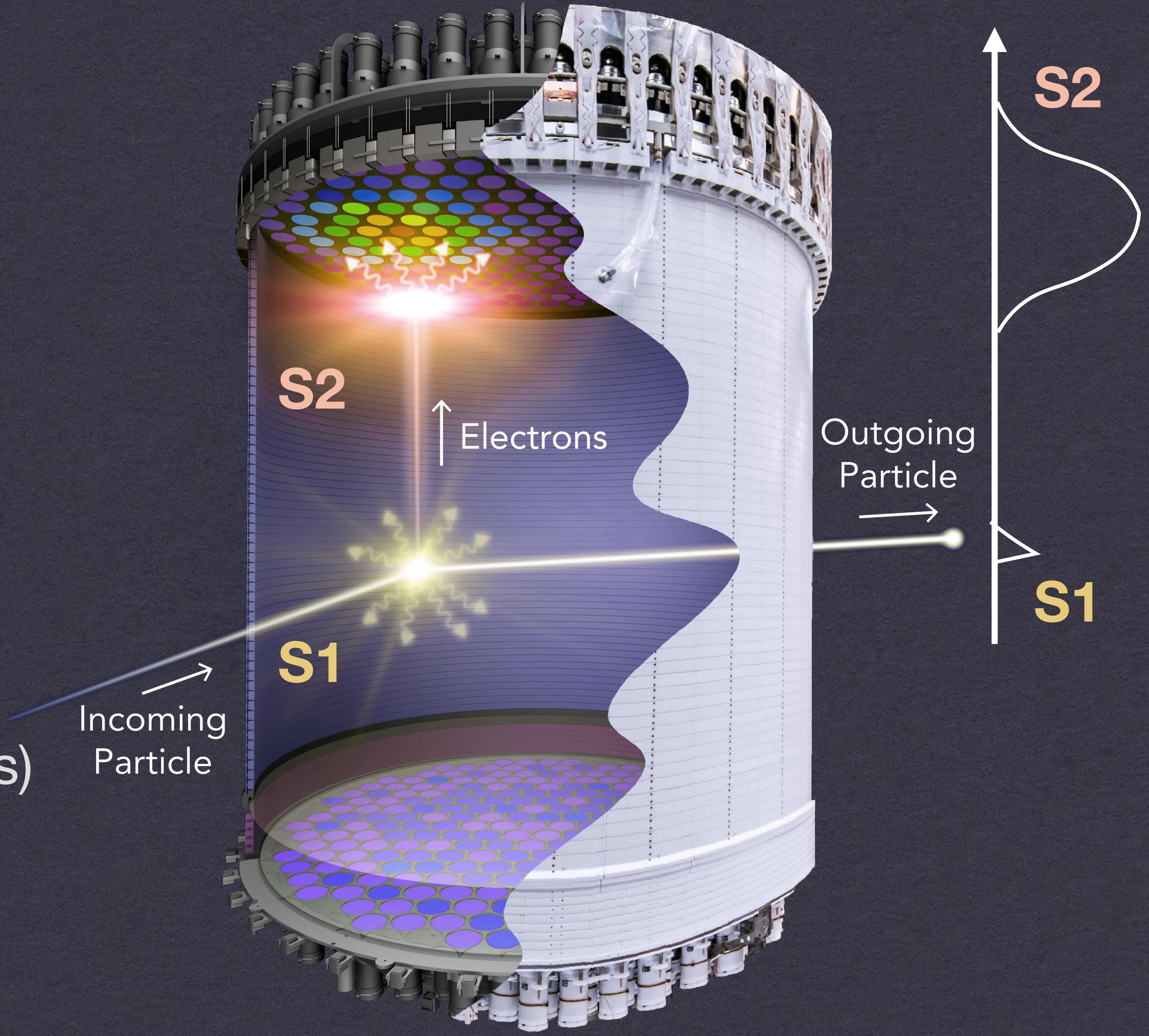


- Based at the Sanford Underground Research Facility (SURF) in Lead, SD
- Dual-phase xenon time projection chamber (TPC) with 7 t active xenon
- Skin & outer detector (OD) veto systems

NIM A, 163047 (2019)

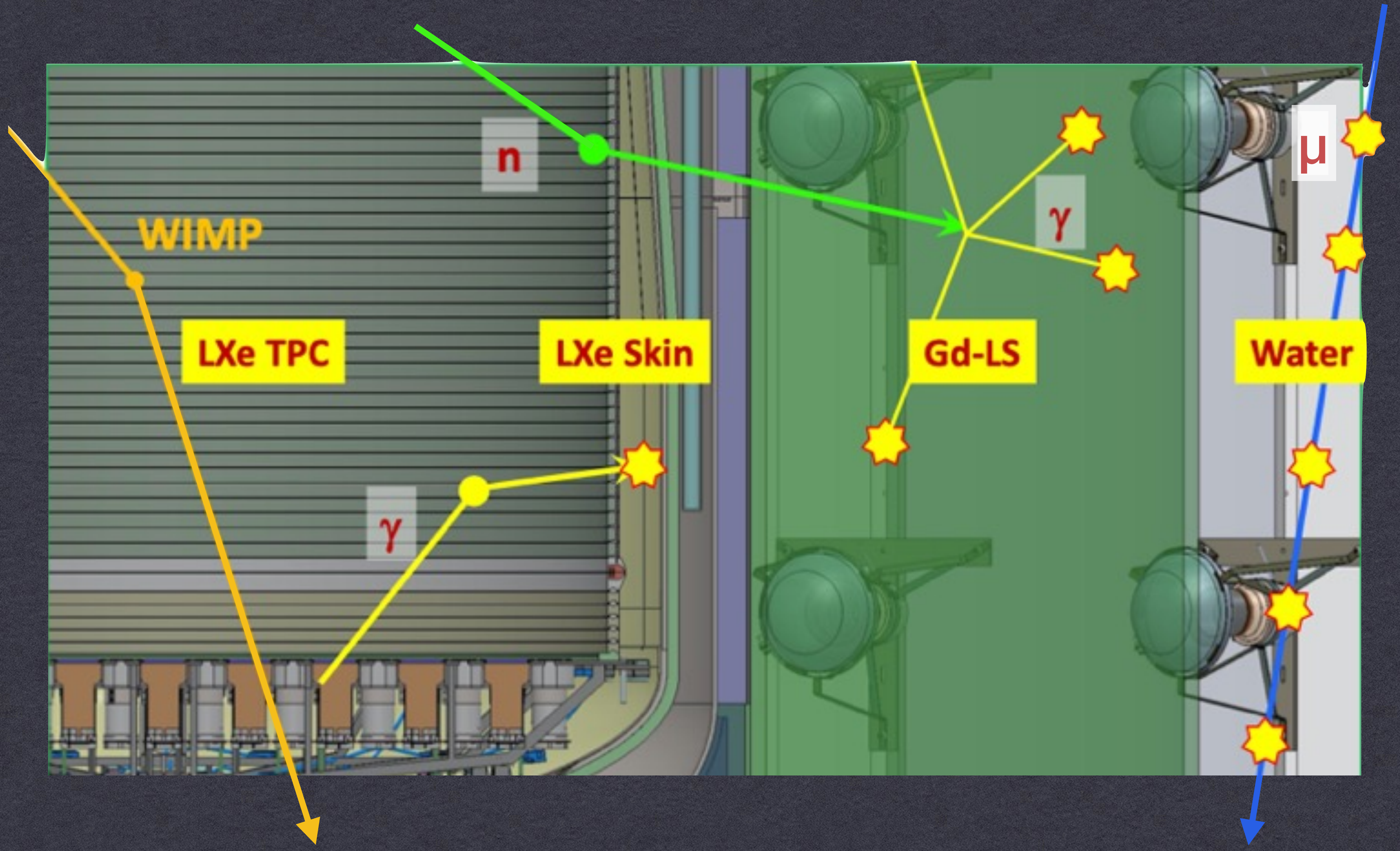
TPC DETECTION PRINCIPLE

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

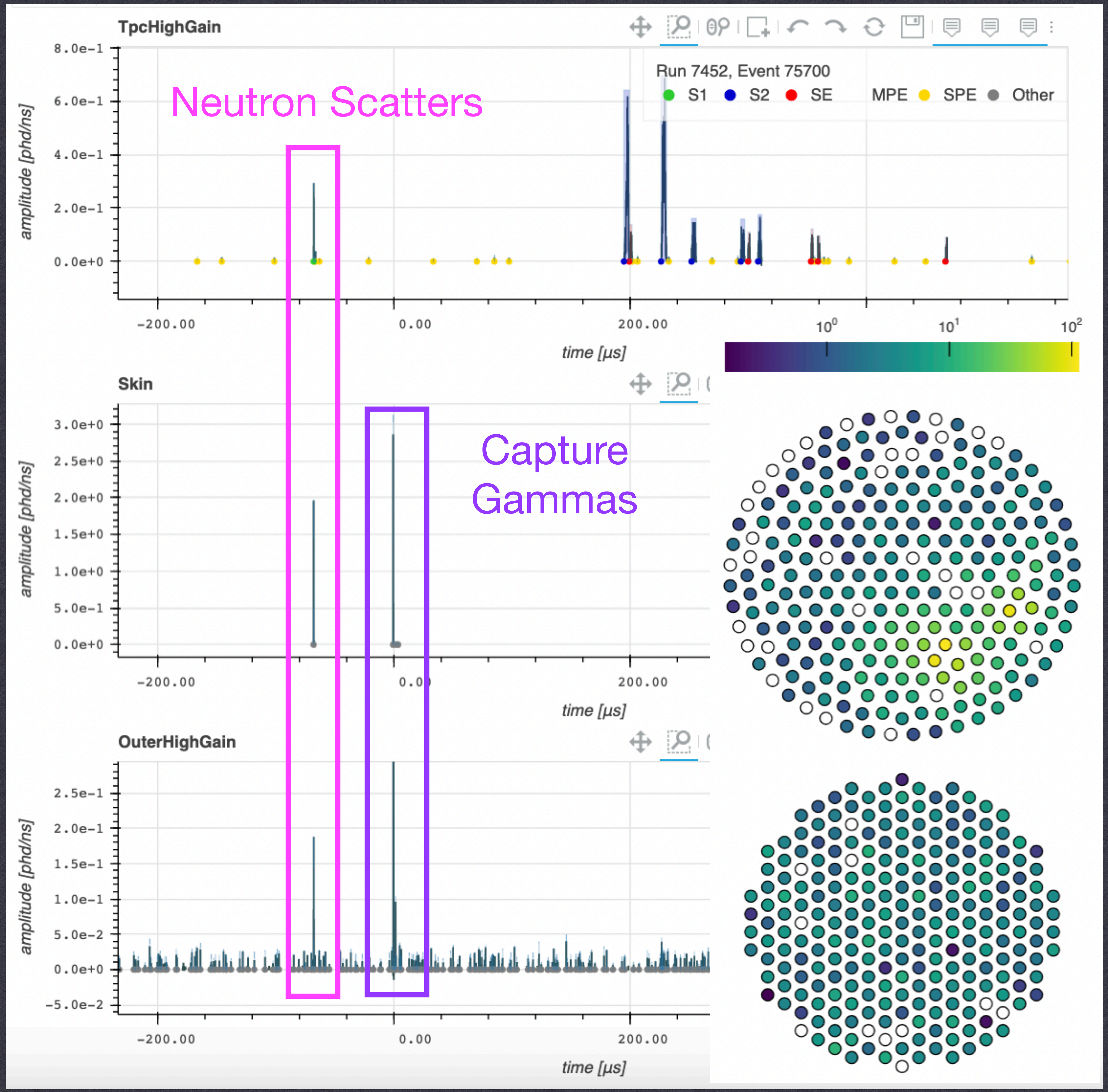


VETO DETECTOR ANTI-COINCIDENCE

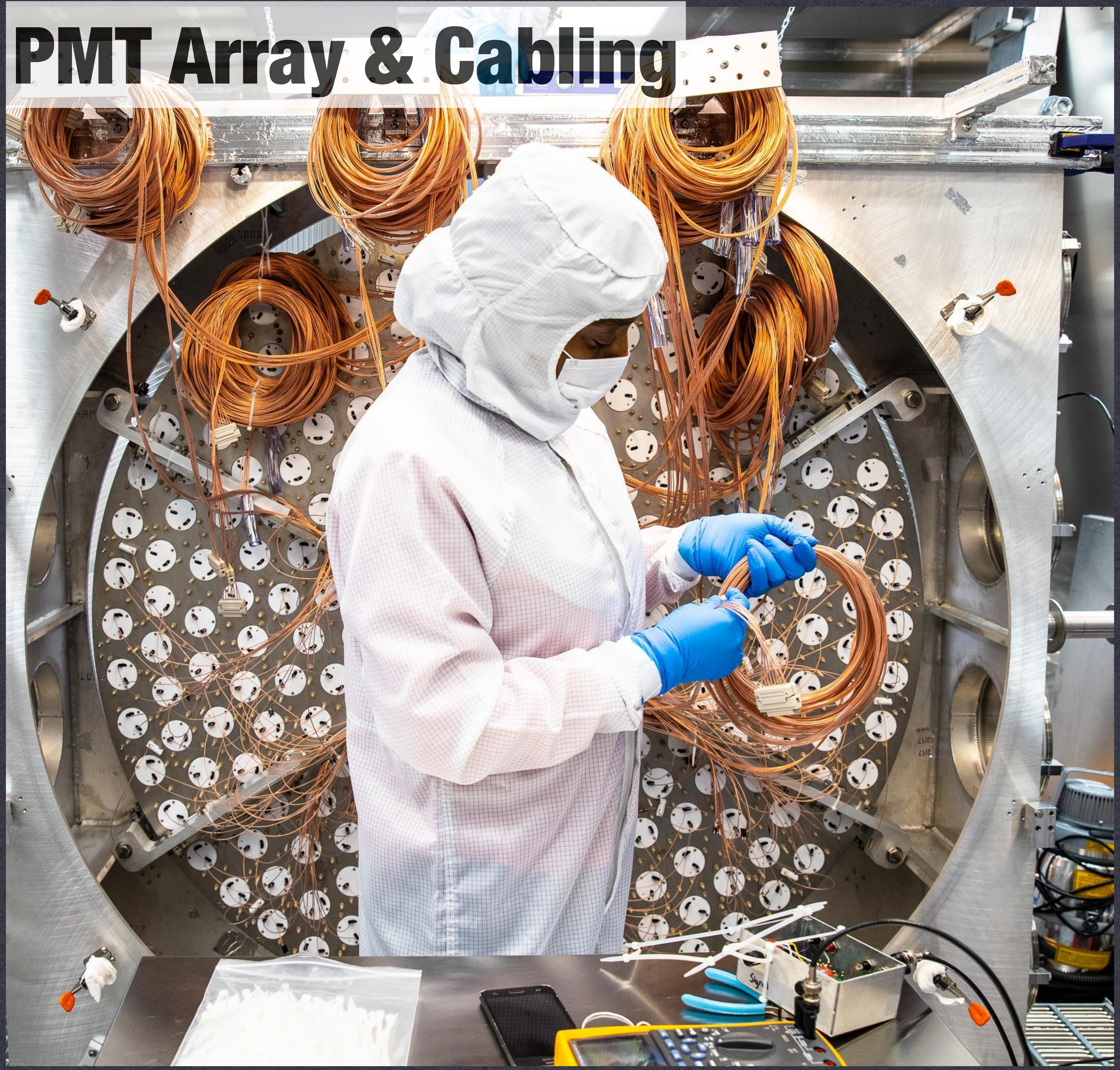
- 17 tonnes Gd-loaded scintillator in OD
  - High thermal neutron capture cross-section
  - Release of ~8 MeV gammas from capture
- Skin LXe detector effective at tagging γ-rays from internal TPC decays, OD neutron captures



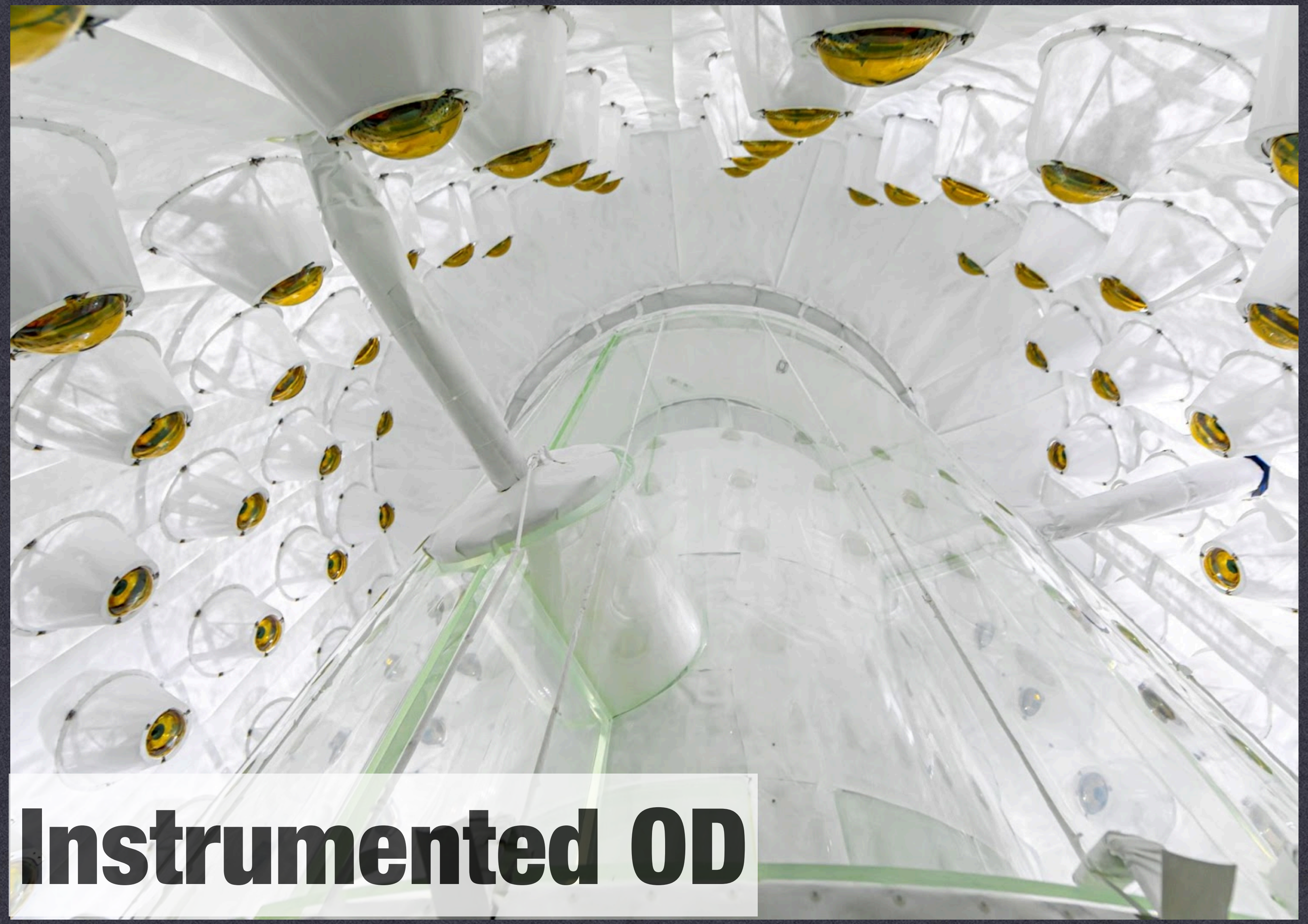
Example Neutron Event



TPC & SKIN ASSEMBLY

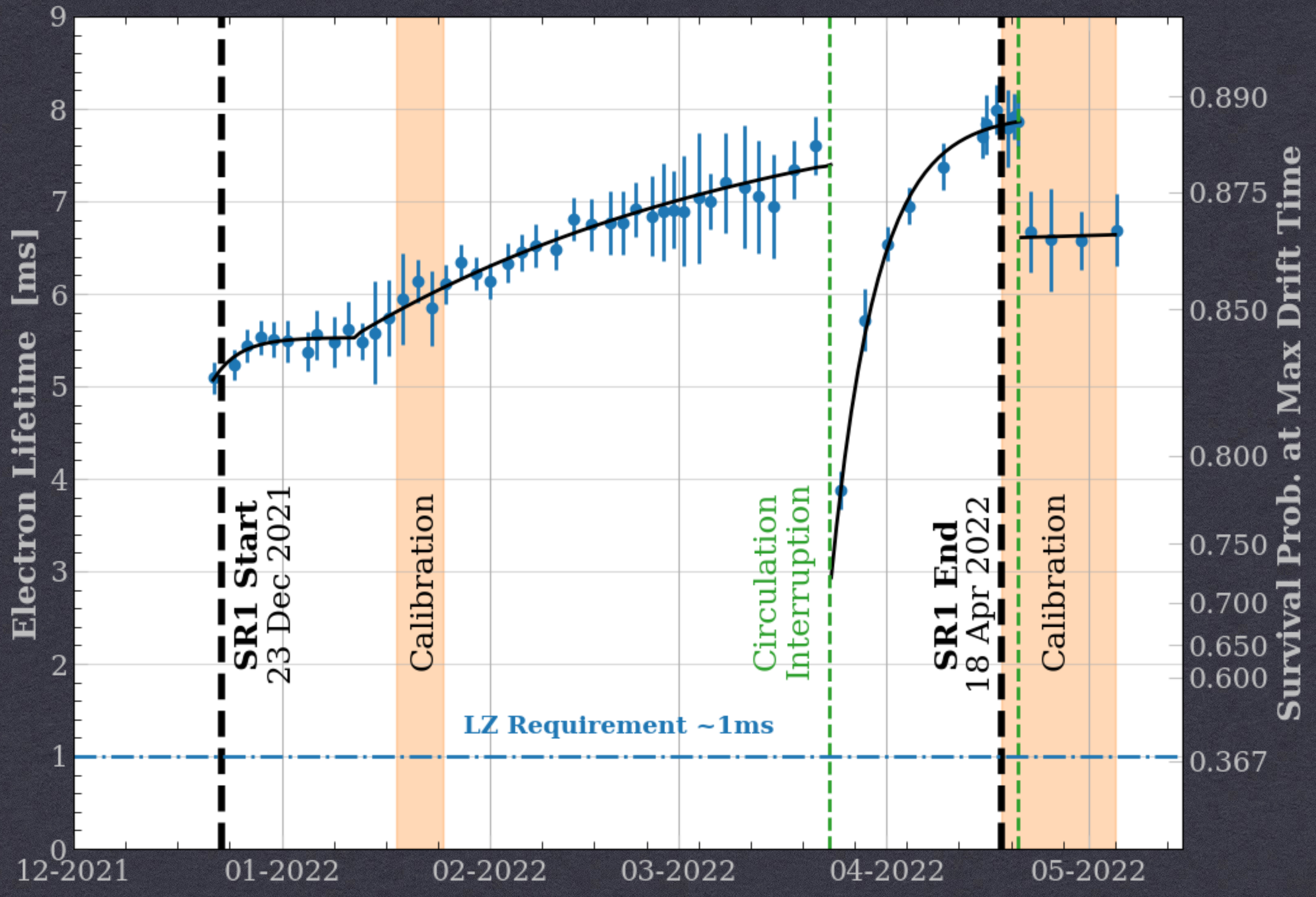


OD CONSTRUCTION & UNDERGROUND INSTALLATION



FIRST SCIENCE RUN (SR1)

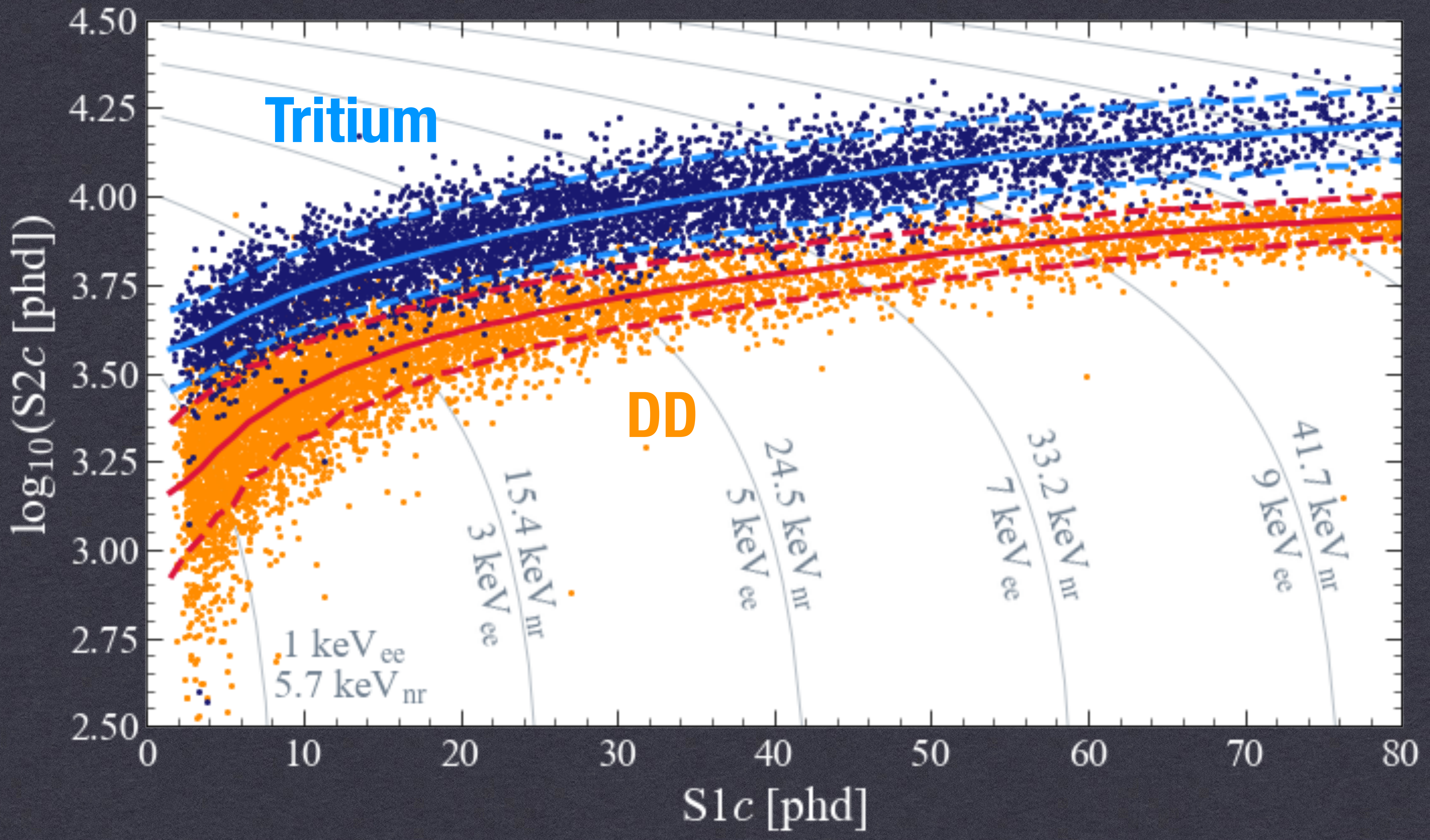
- 116 calendar days -> 89 live days
- Stable detector conditions
  - Temperature of 174.1 K
  - Gas pressure of 1.791 bar
  - Drift field of 193 V/cm
  - Extraction field of 7.3 kV/cm (in gas)
- Continuous purification at 3.3 t/day through hot getter system
- **Demonstration run, no explicit bias mitigation**



Electron lifetime between 5-8 ms throughout

TPC CALIBRATIONS

- Backgrounds predominantly ERs; WIMPs produce NRs
- Tritiated methane (CH_3T) injection to calibrate ER band
  - Spatially homogenous β source
- DD neutron generator (NR band)
  - Monoenergetic 2.45 MeV neutrons
- 99.9% discrimination of beta backgrounds under NR band median achieved

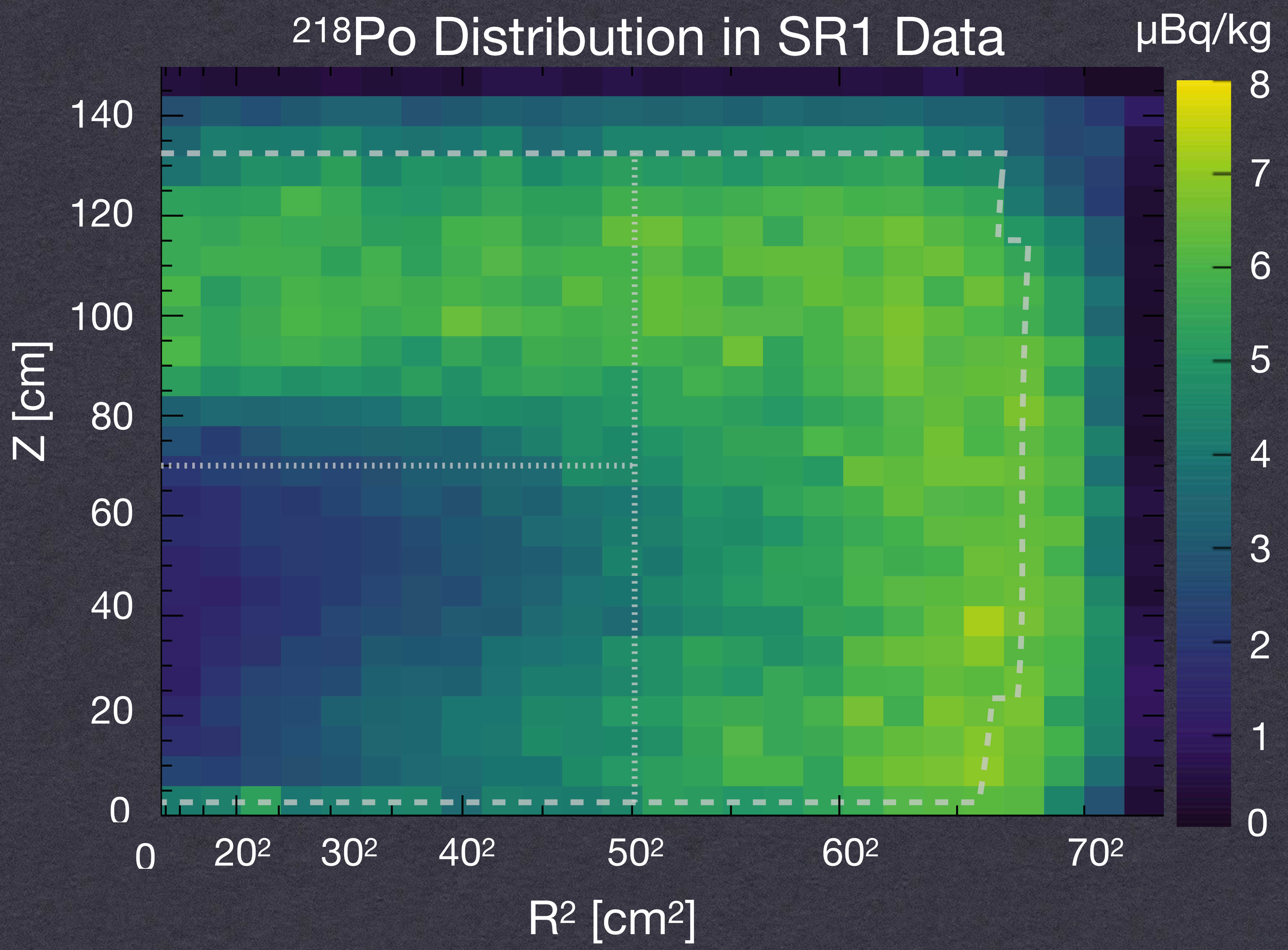


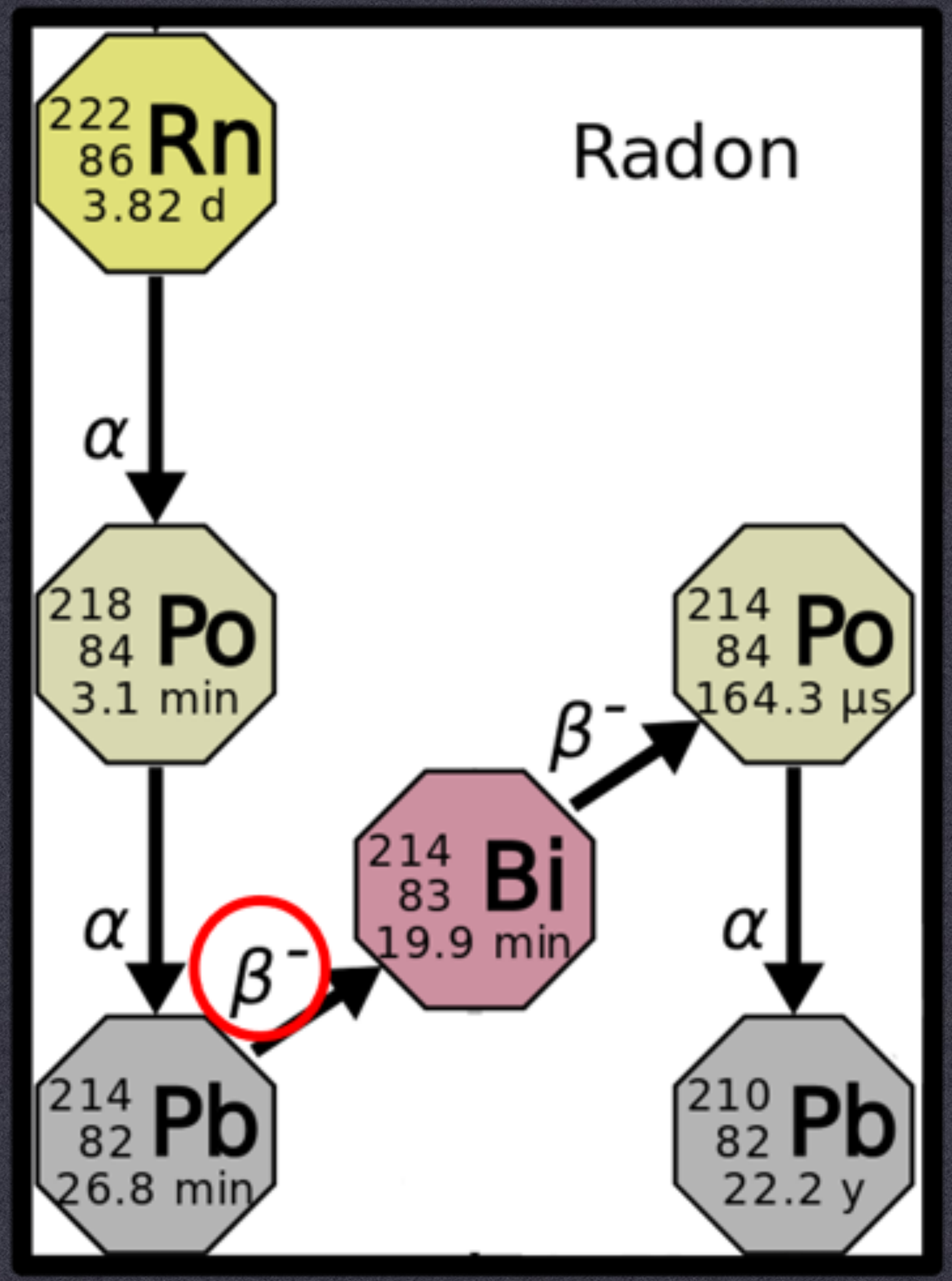
g1 (light gain) = 0.114 +/- 0.002 phd/photon

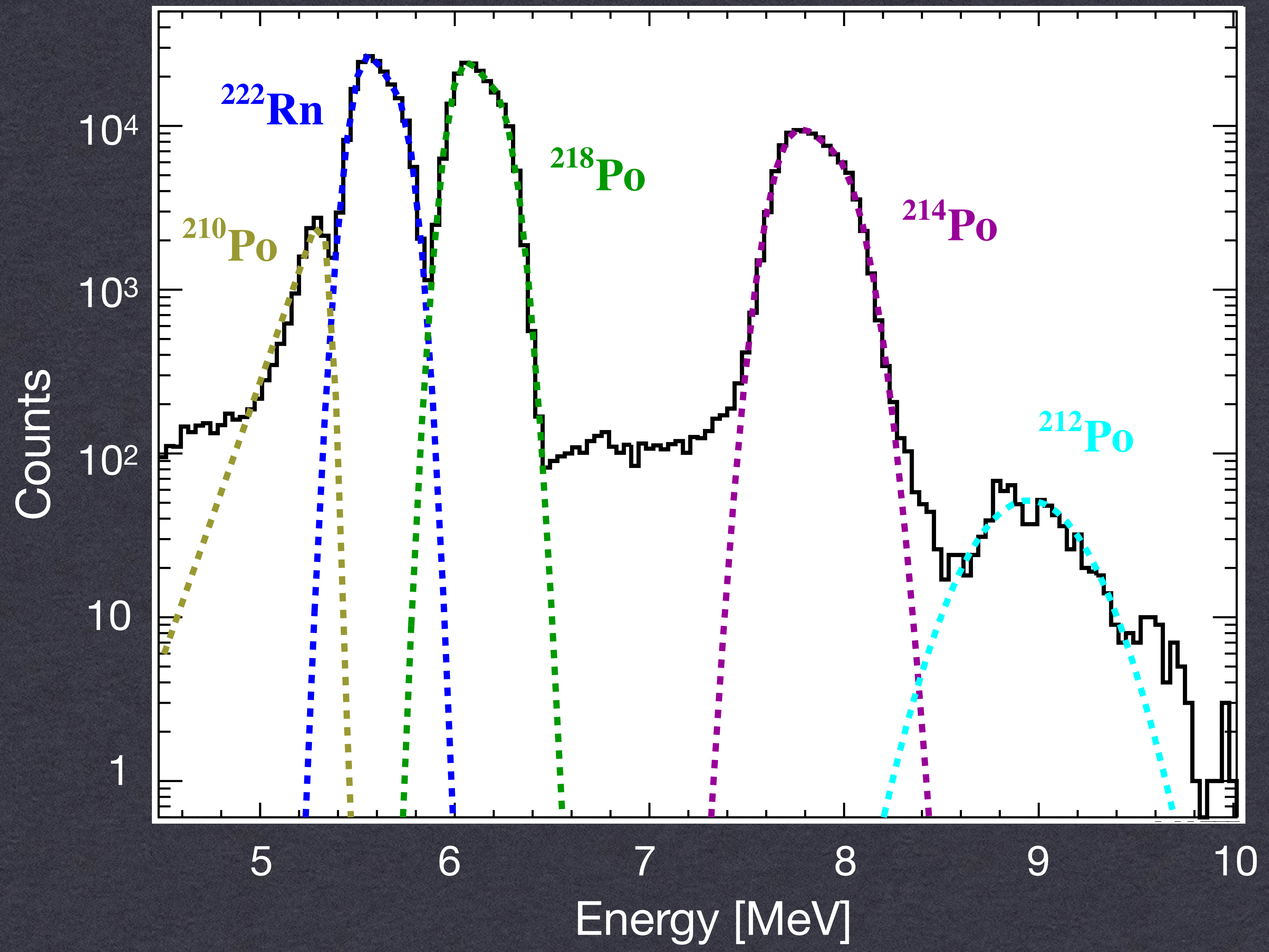
g2 (charge gain) = 47.1 +/- 1.1 phd/e$^-$

Band fits performed with NEST v2.3.7

RADON BACKGROUNDS







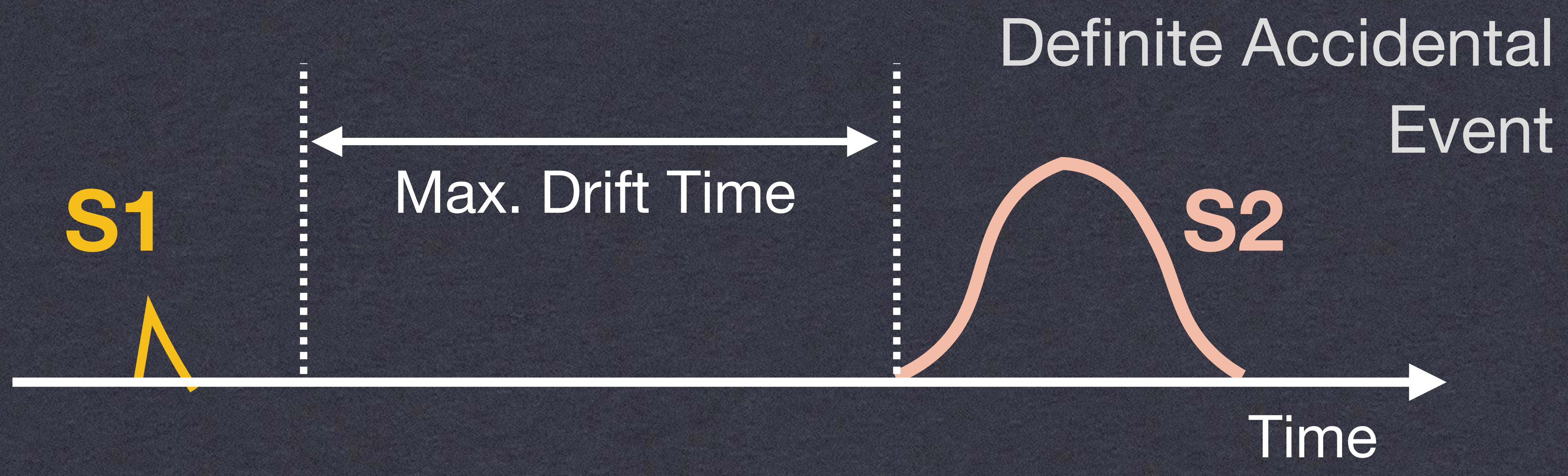
- Radon emanates from detector materials into the xenon
- Non-uniform position distribution due to xenon flow and charged ion movement
- “Naked” ^{214}Pb β decays are the main WIMP background → cannot be directly tagged
  - O(MeV) ^{218}Po & ^{214}Po α signals used to bound ^{214}Pb rate & infer its position distribution

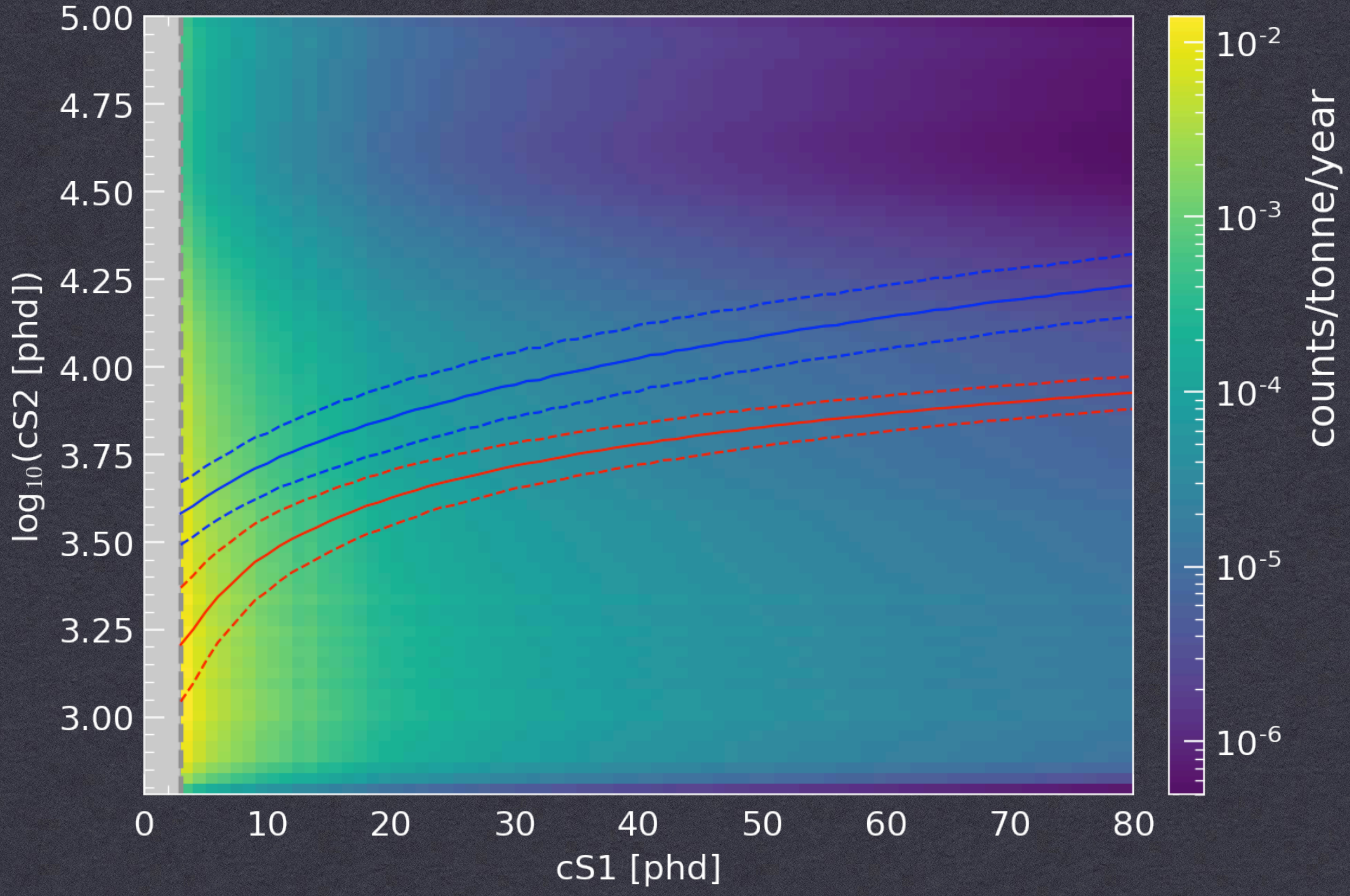
ACTIVATION BACKGROUNDS

- Cosmogenic activation → decaying xenon isotope & ^{37}Ar contributions during SR1
- ^{37}Ar a significant WIMP search background ($\tau_{1/2}$ = 35 days; monoenergetic 2.8 keV ER)
  - Estimated using ACTIVIA & exposure of the xenon during transport [PRD 105, 082004 (2022)]
  - Fit in data - decaying + flat background consistent with data (p-value = 0.43)
- Xenon isotope rates enhanced by neutron activation; measured via energy spectrum fits

ACCIDENTAL COINCIDENCE BACKGROUNDS

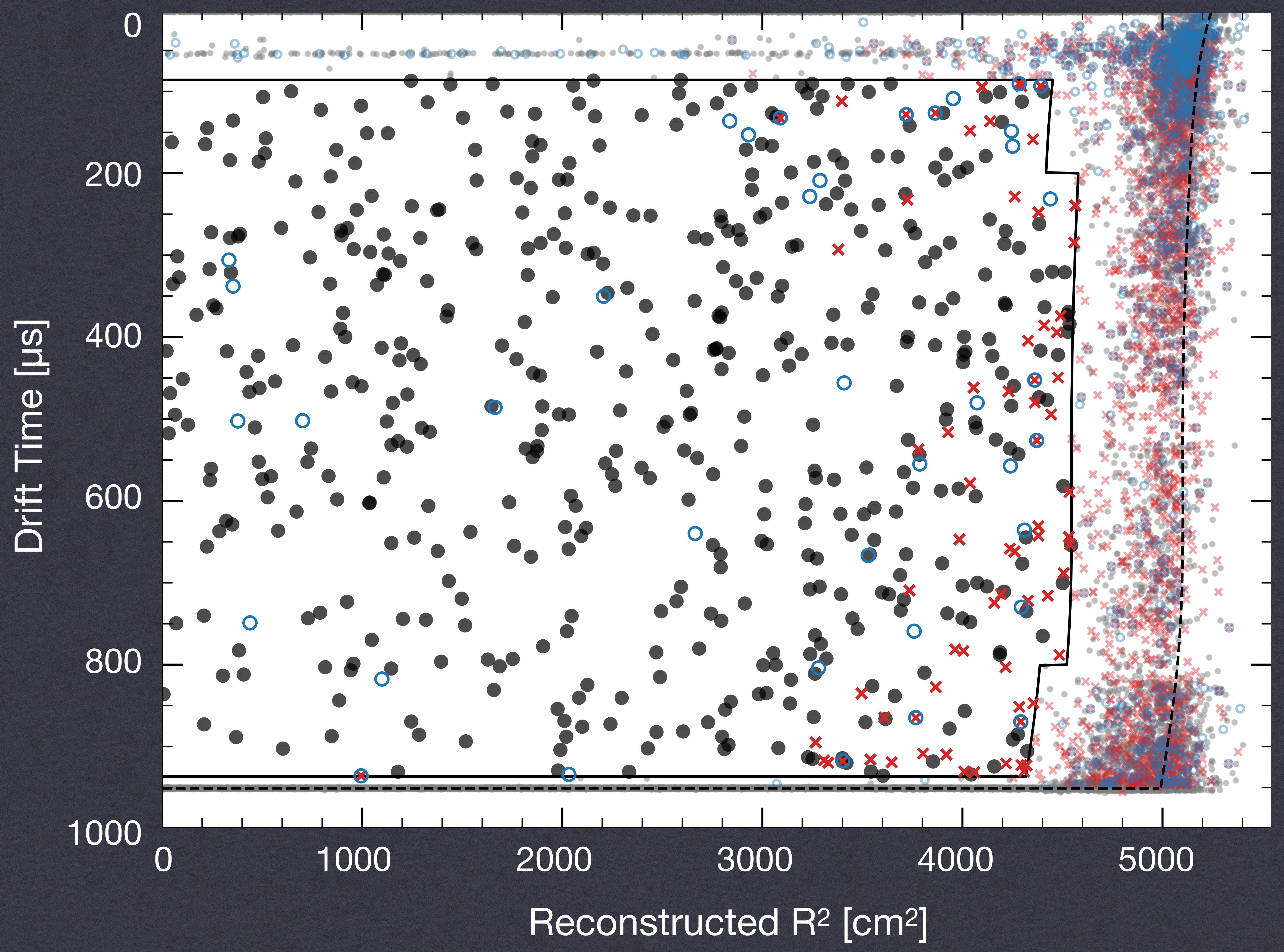
- Unrelated S1s & S2s can accidentally combine to produce single scatter events
- Rate: population of definite accidental events with drift time >1 ms
- Distribution: fake events constructed from lone S1 & S2 pulse waveforms
- Analysis cuts developed to combat observed pulse/event pathologies
  - >99.5% efficiency in removing accidentals
  - SR1 WIMP search counts: 1.2 ± 0.3





WIMP ANALYSIS - ROI & FV

- Region of Interest definition
  - 3 < S1c < 80 photons detected (phd); three-fold PMT coincidence
  - Uncorrected S2 > 600 phd; log10 (S2c) < 5
- Fiducial volume (FV) definition
  - 86 us < drift time < 936.5 us cut to avoid higher background rates at TPC edges
  - Radial cut chosen to ensure <0.01 wall background counts in the FV
- Calculated fiducial mass of 5.5 ± 0.2 t

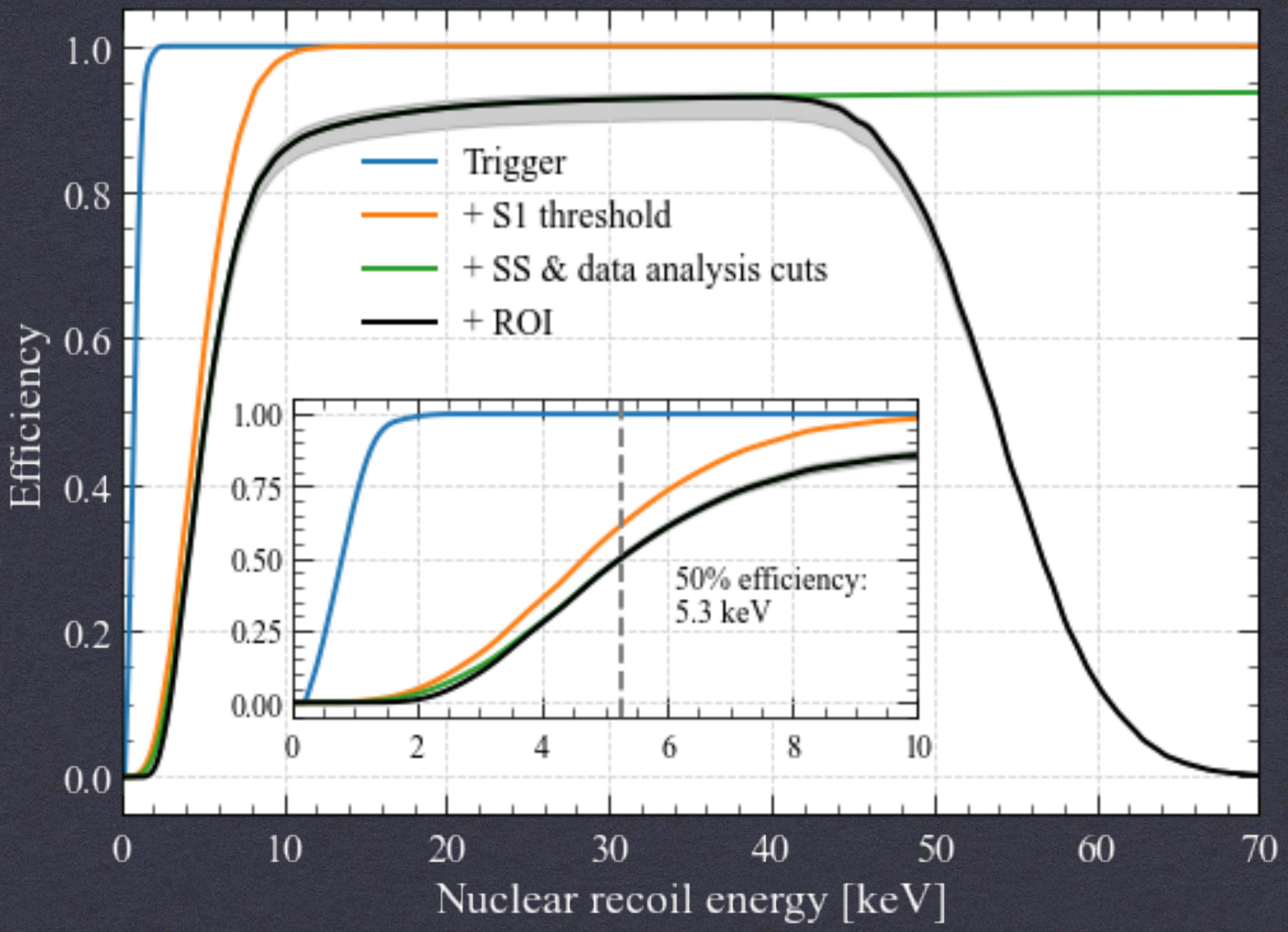


Events tagged by the Skin

Events tagged by the OD

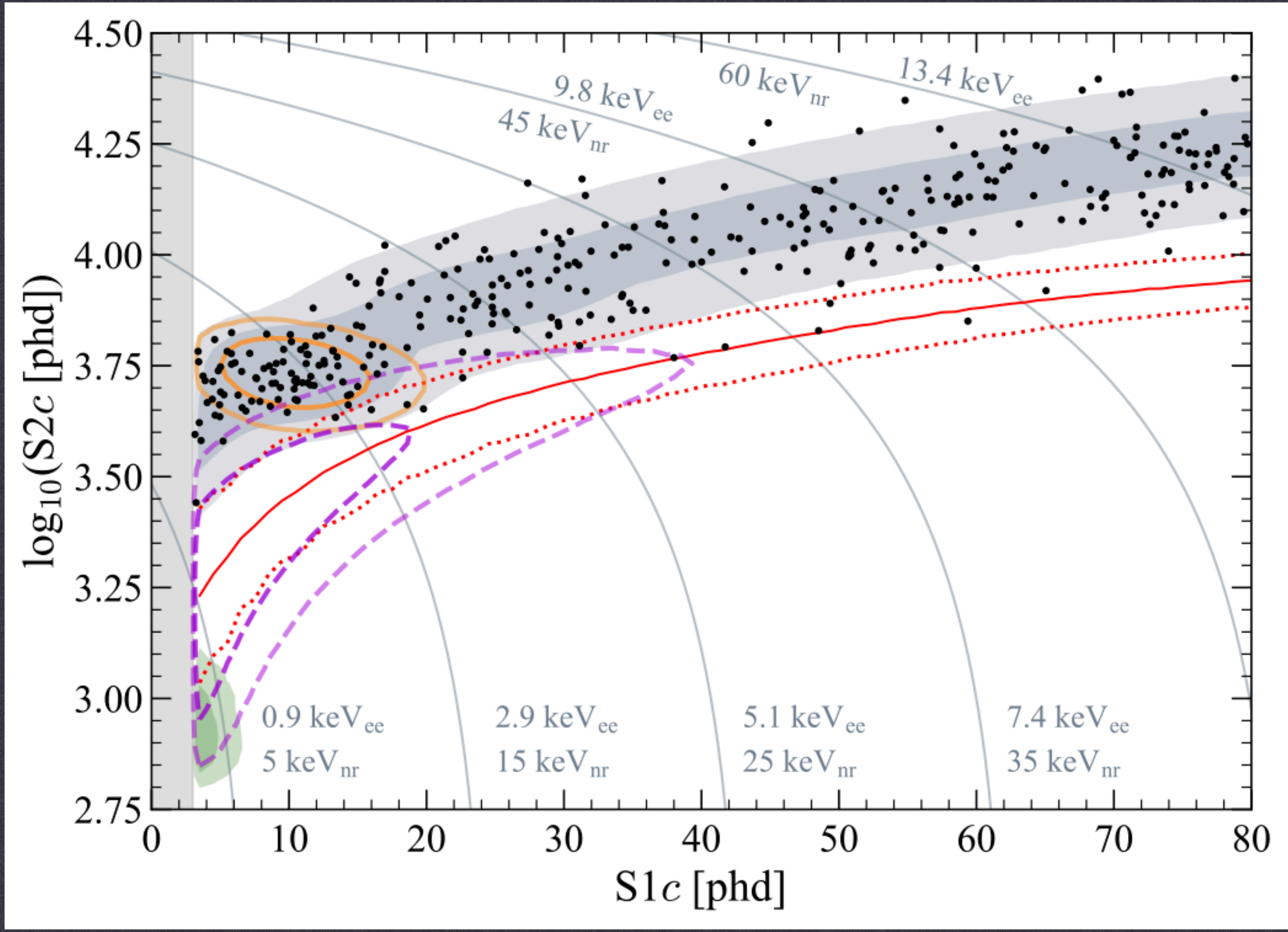
WIMP ANALYSIS - CUTS & DATA QUALITY

- Event selection criteria
  - FV, ROI, single scatter cuts
  - Veto detector anti-coincidence
  - S1/S2 shape cuts
- Cuts developed on non-WIMP ROI background & calibration data
- Rejection of live time with detector instabilities, high TPC pulse rates
  - 60 ± 1 live days



WIMP ANALYSIS - DATA & STATISTICAL INFERENCE

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



Key

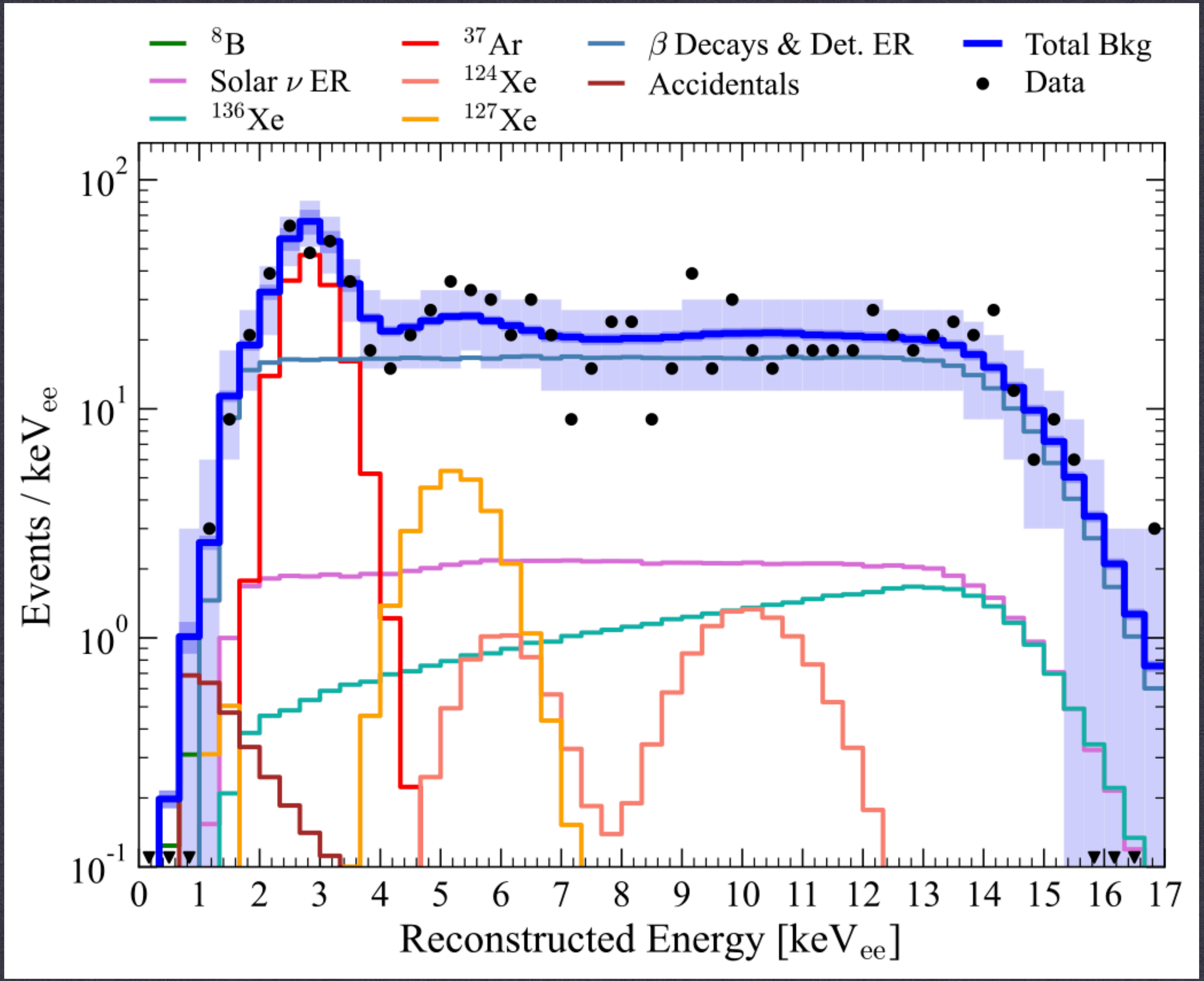
1 & 2-Sigma Contours
- Post-fit total background distribution
- ^{37}Ar
- ^{8}B
- 30 GeV/c^2 WIMP

- NR band from DD

* j.astropartphys.2020.102480

WIMP ANALYSIS - BACKGROUNDS & STATISTICAL INFERENCE

Component	Expected Events	Best Fit Events
β decays & detector γs	215 ± 36	222 ± 16
^{37}Ar	[0, 288]	$52.5^{+9.6}_{-8.9}$
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.1 ± 2.4	15.2 ± 2.4
Solar ν ERs	27.1 ± 1.6	27.2 ± 1.6
^{8}B CEvNS	0.14 ± 0.01	0.15 ± 0.01
Det. Neutrons	$0.00^{+0.02}$	$0.00^{+0.02}$
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Total w/o ^{37}Ar	273 ± 36	280 ± 16
Total w/ ^{37}Ar	-	333 ± 17



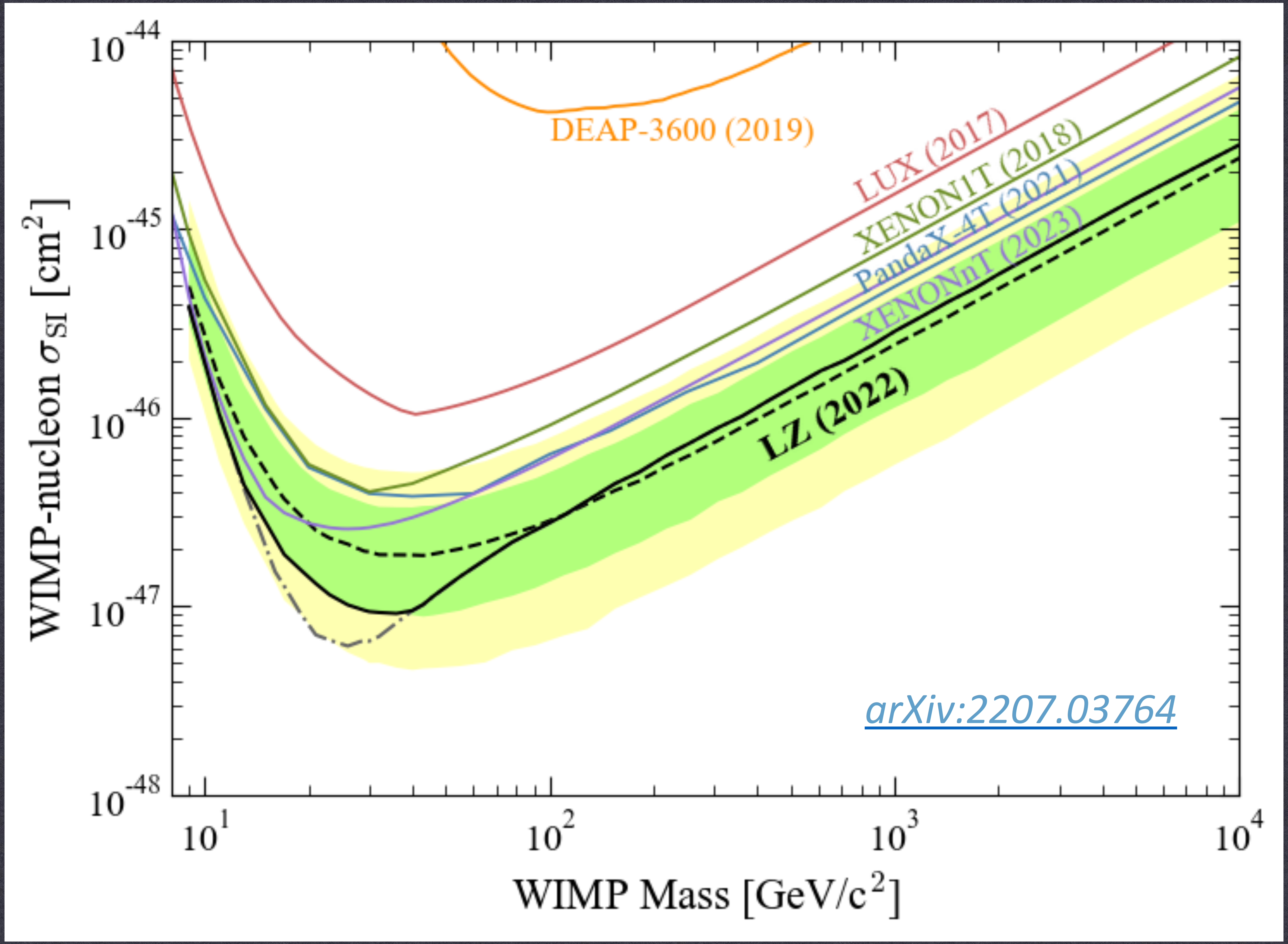
WIMP ANALYSIS - SR1 SPIN-INDEPENDENT LIMIT

- 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

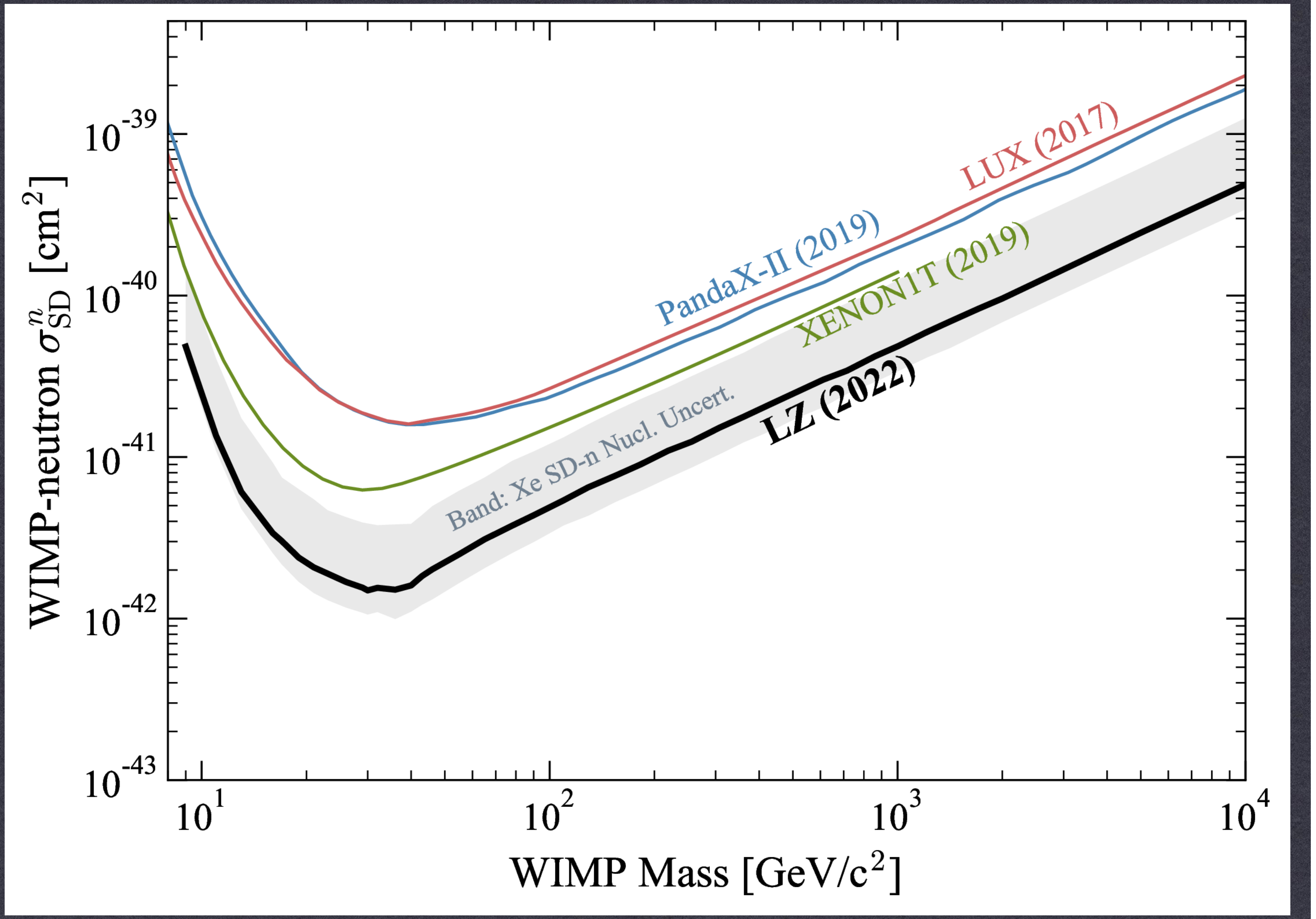
- - - Median expected sensitivity



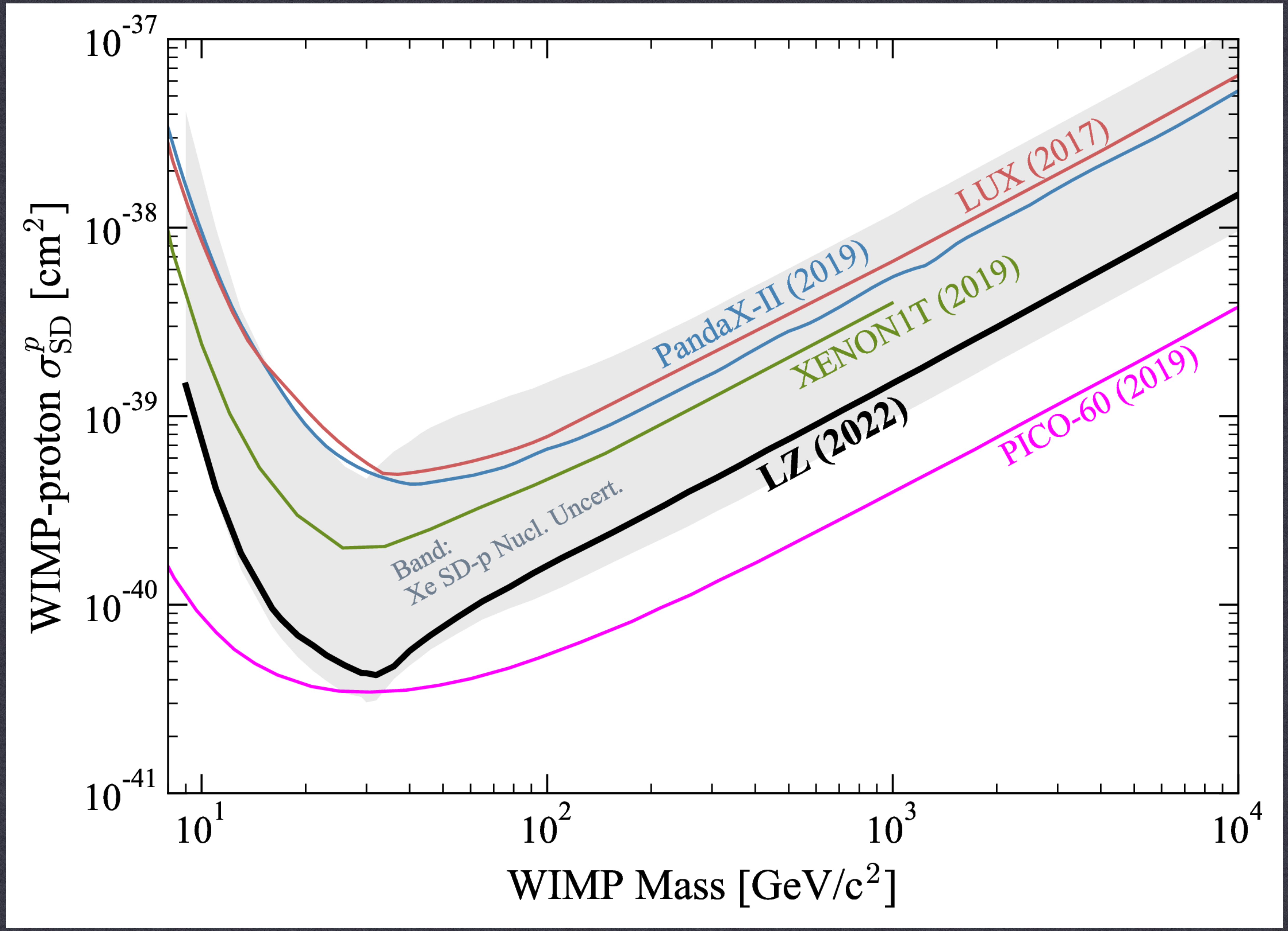
EPJC 81, 907 (2021), arXiv:1105.3166

WIMP ANALYSIS - SR1 SPIN-DEPENDENT LIMITS

WIMP-Neutron Scattering



WIMP-Proton Scattering



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

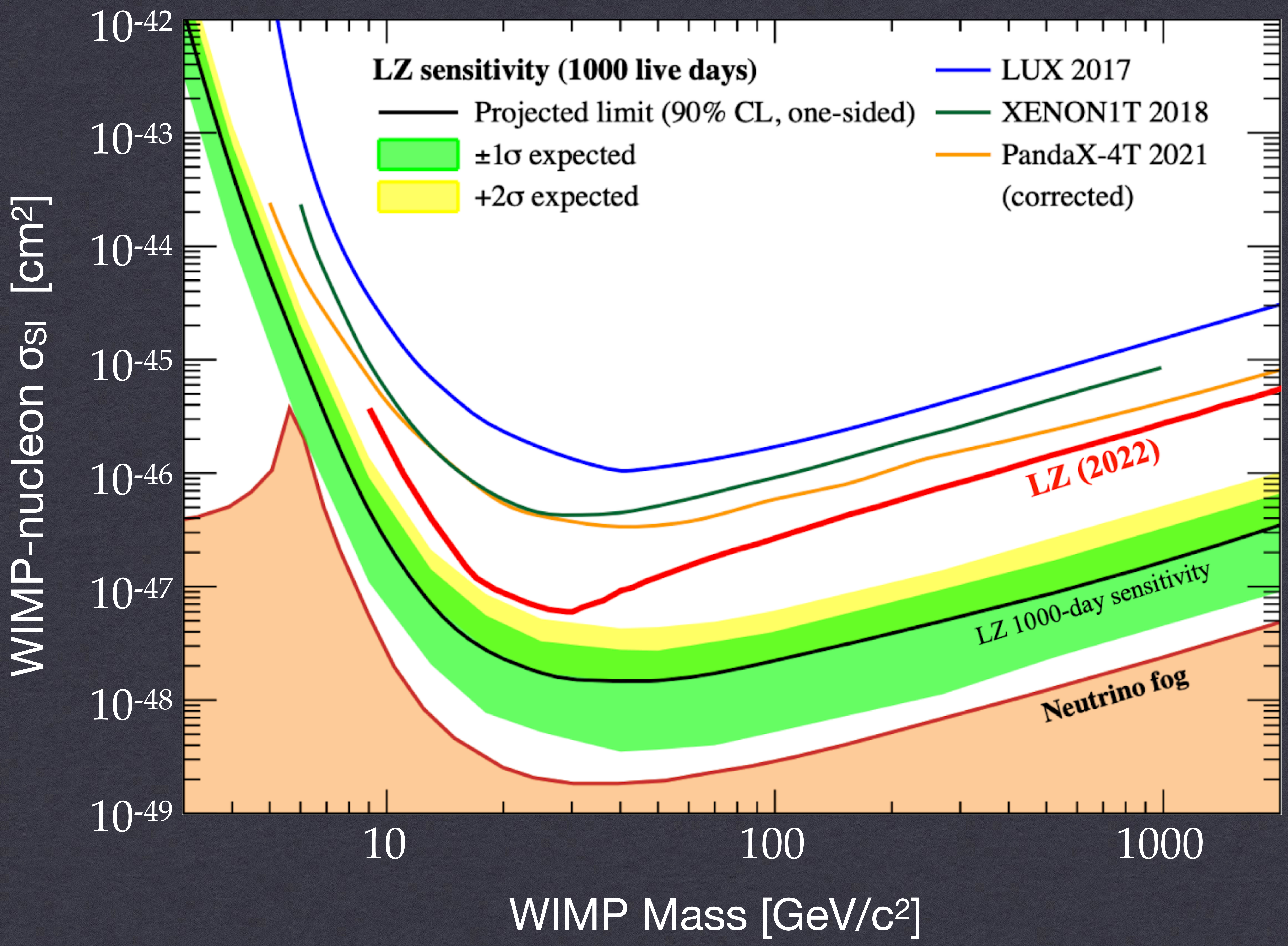
arXiv:2207.03764

WIMP SEARCH PROSPECTS

- SR1 covers just 6% of planned full exposure of 1000 live days
  - Still a lot of parameter space explorable with LZ
  - 1000-day projected sensitivity:

90% CL minimum:
1.4×10^{-48} cm² at 40 GeV/c²

PRD 101, 052002 (2020)



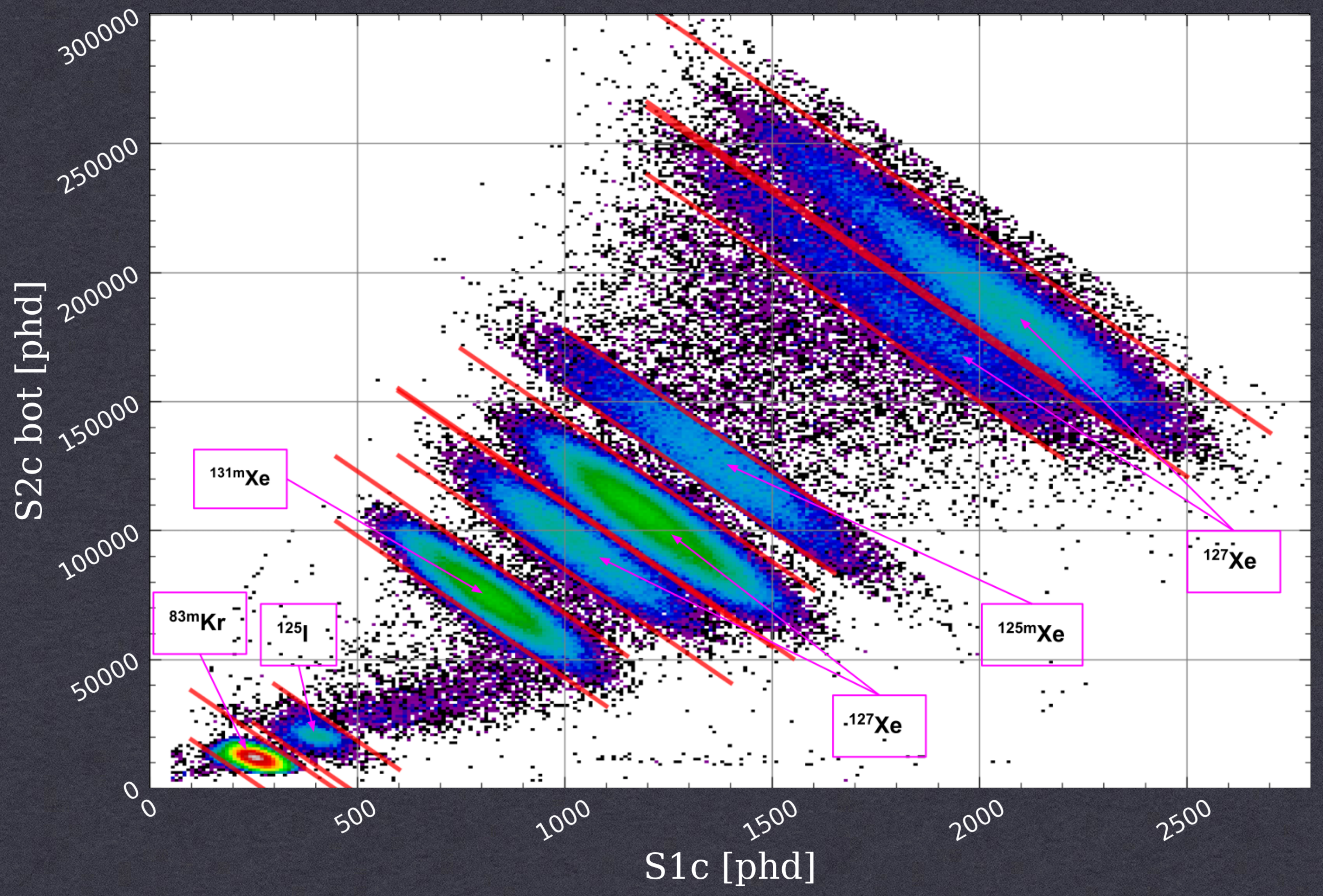
CONCLUSIONS

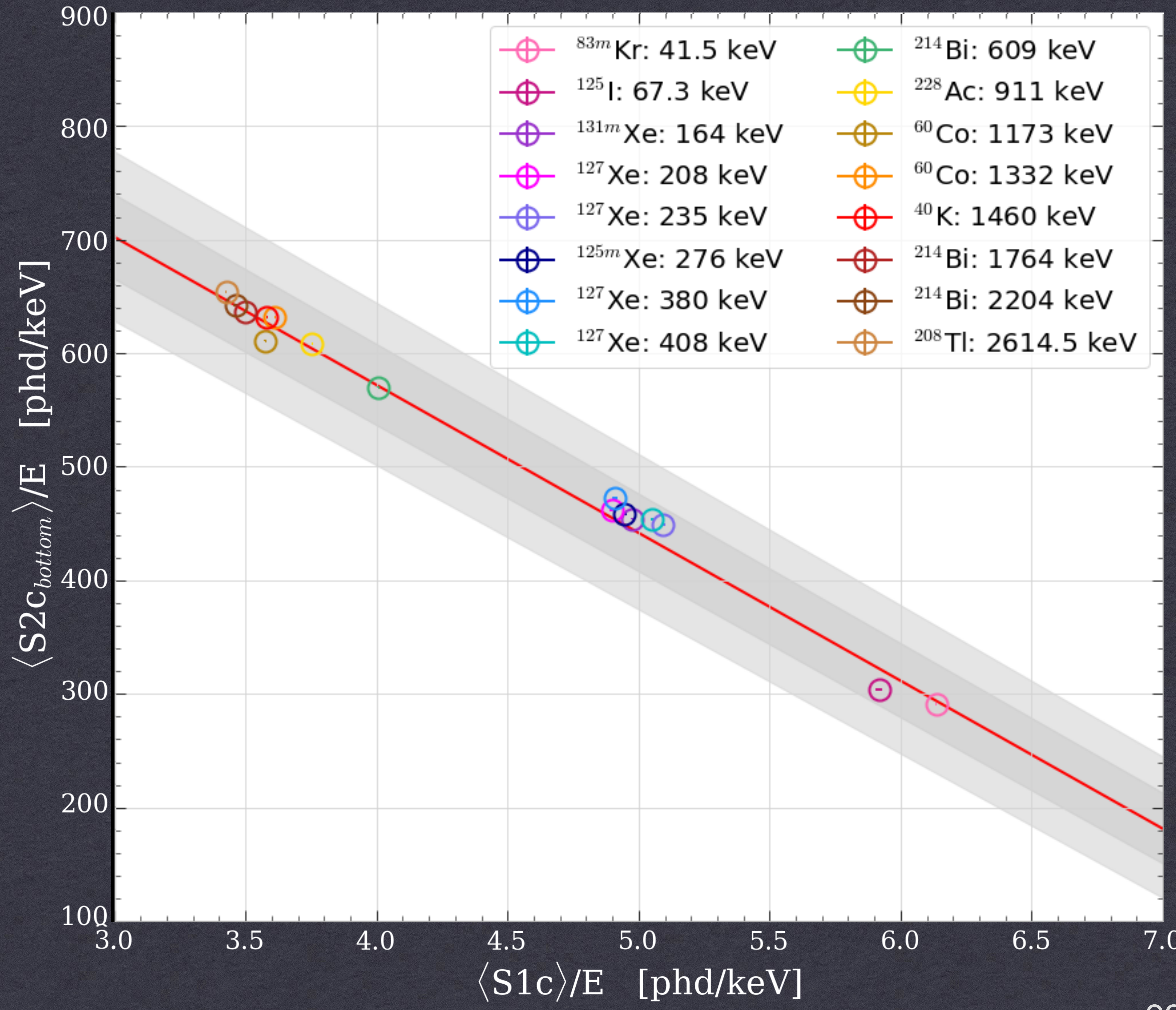
- World-leading spin-independent WIMP search limit achieved with just 6% of planned exposure
  - Now entering discovery parameter space
- Background sources well examined & documented in dedicated paper
- Multiple other physics channels to explore
  - Papers in preparation on SR1 data
- XLZD consortium formed, looking towards the ultimate xenon rare physics observatory

BACKUP SLIDES

TPC ENERGY RESPONSE

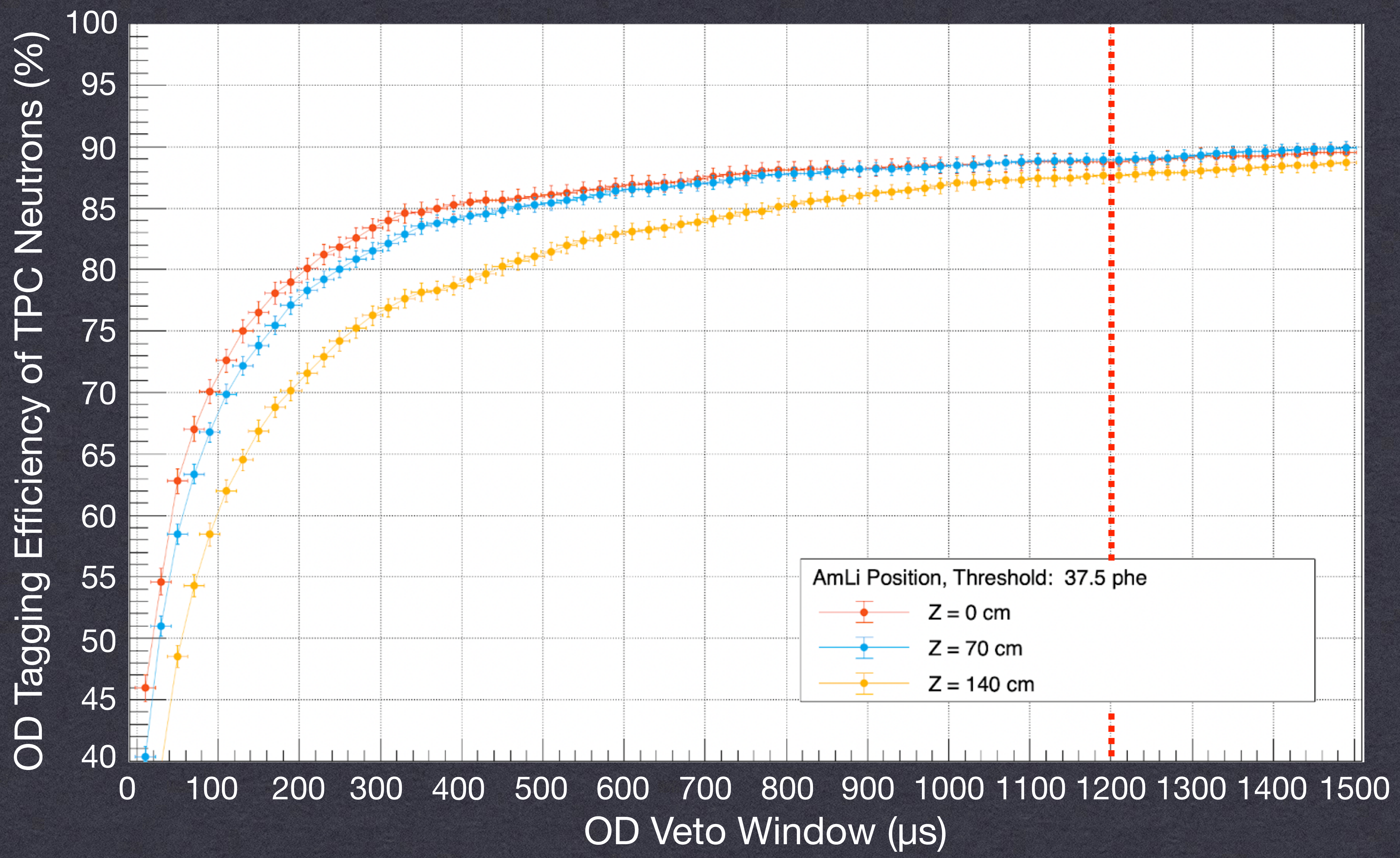
- S1s & S2s position-corrected using ^{131m}Xe background, ^{83m}Kr calibration
- Doke plot constructed with mono-energetic electron recoil peaks

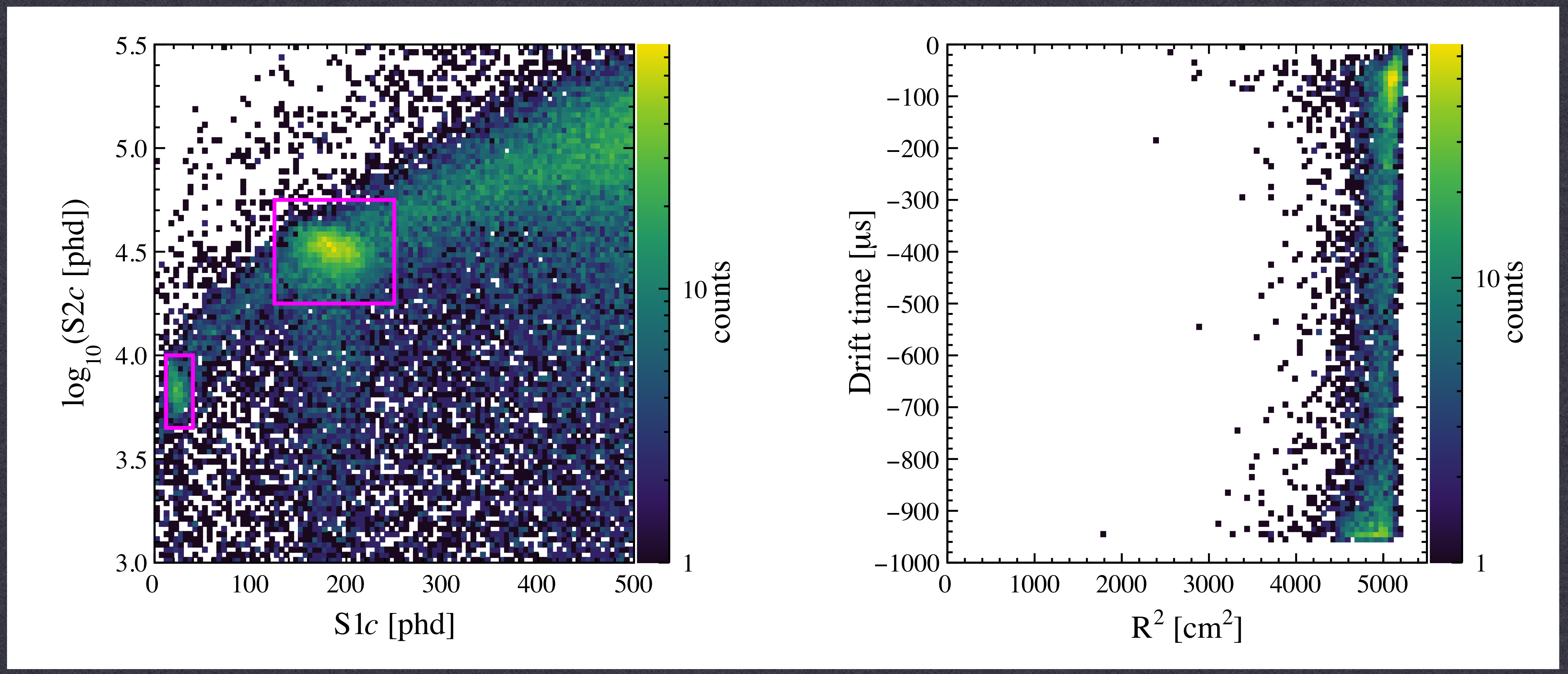




VETO DETECTOR RESPONSE

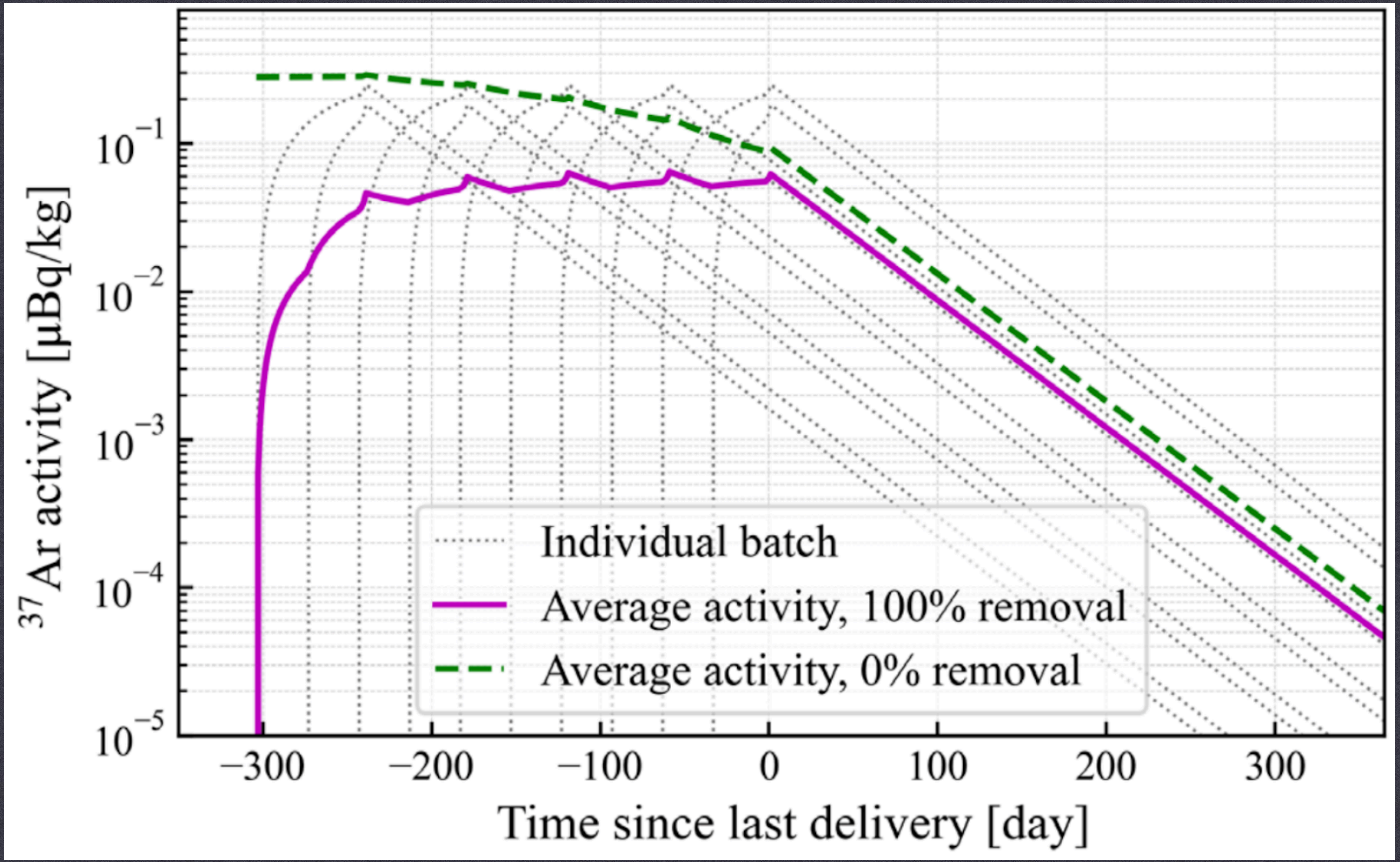
- Skin & OD response and inter-detector timings calibrated
  - OD optical calibration system
  - External γ-ray & neutron sources (e.g. ^{22}Na; DD, AmLi, ^{252}Cf)
- ^{127}Xe Skin tagging efficiency of 78 ± 5% based on K-shell analysis
- OD tagging efficiency of TPC-interacting neutrons of 89 ± 1% (AmLi calibrations)
  - TPC-OD coincidence window: 1200 μs; threshold equivalent to ~200 keV





AR37 ESTIMATE

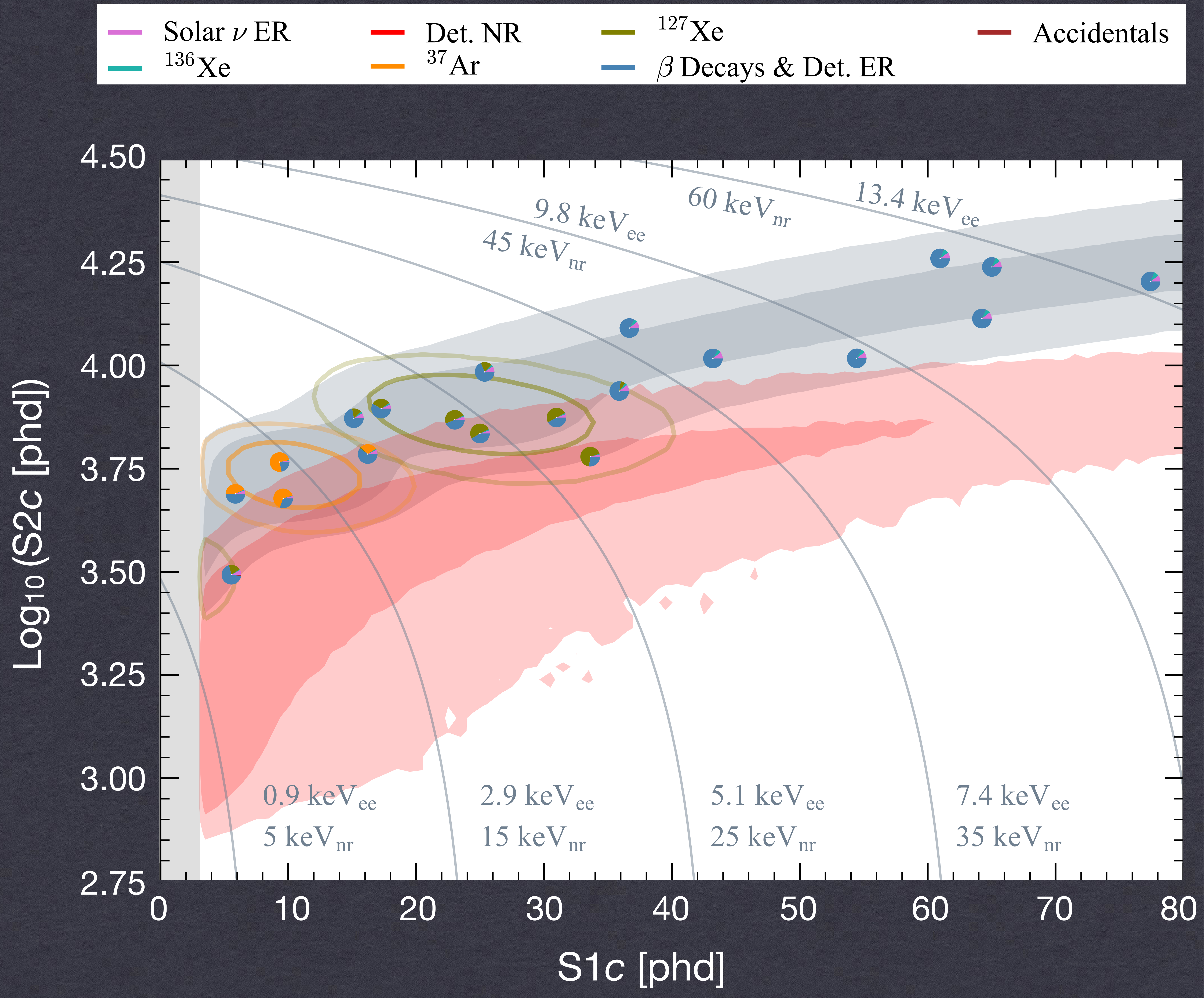
- Ar37 a significant background in early LZ data/SR1 WIMP search
  - K-shell e^- capture -> 2.8 keV
  - $\tau_{1/2}$ = 35 days
- Can be produced via cosmic spallation on xenon
  - Calculated using the ACTIVIA package & estimated exposure of the xenon during transport*
  - Large uncertainties in spallation cross-section



* *PRD 105, 082004 (2022)*

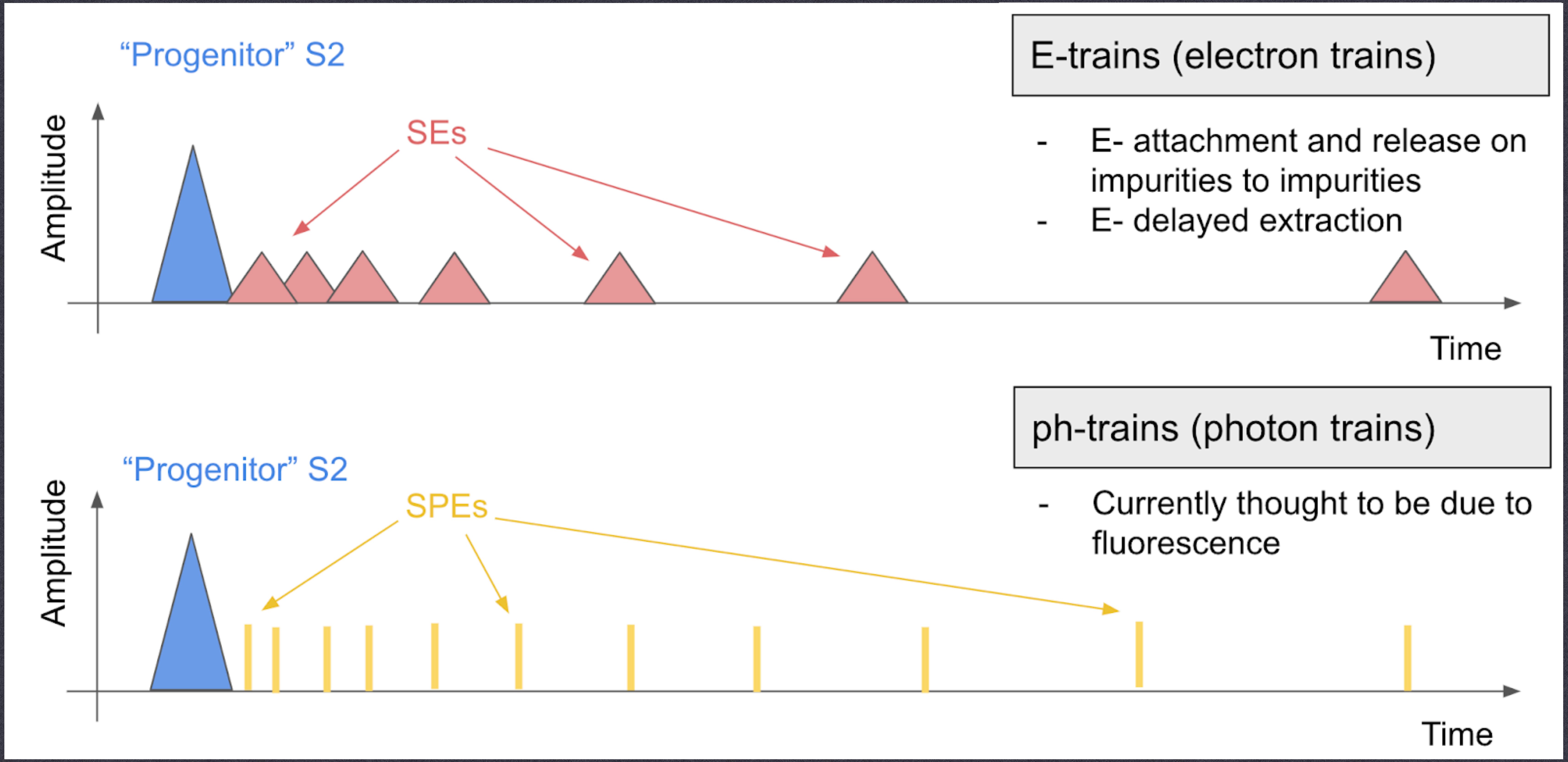
NEUTRONS

- OD Gd-loaded scintillator - high thermal neutron capture cross-section
  - Measured OD neutron tagging efficiency of 89 ± 1%
- Likelihood analysis of sideband of events passing all WIMP search cuts except OD anti-coincidence
  - Constraint in sideband of $0^{+0.8}$ events
  - Constraint on SR1 WIMP search neutron background of $0^{+0.2}$ events



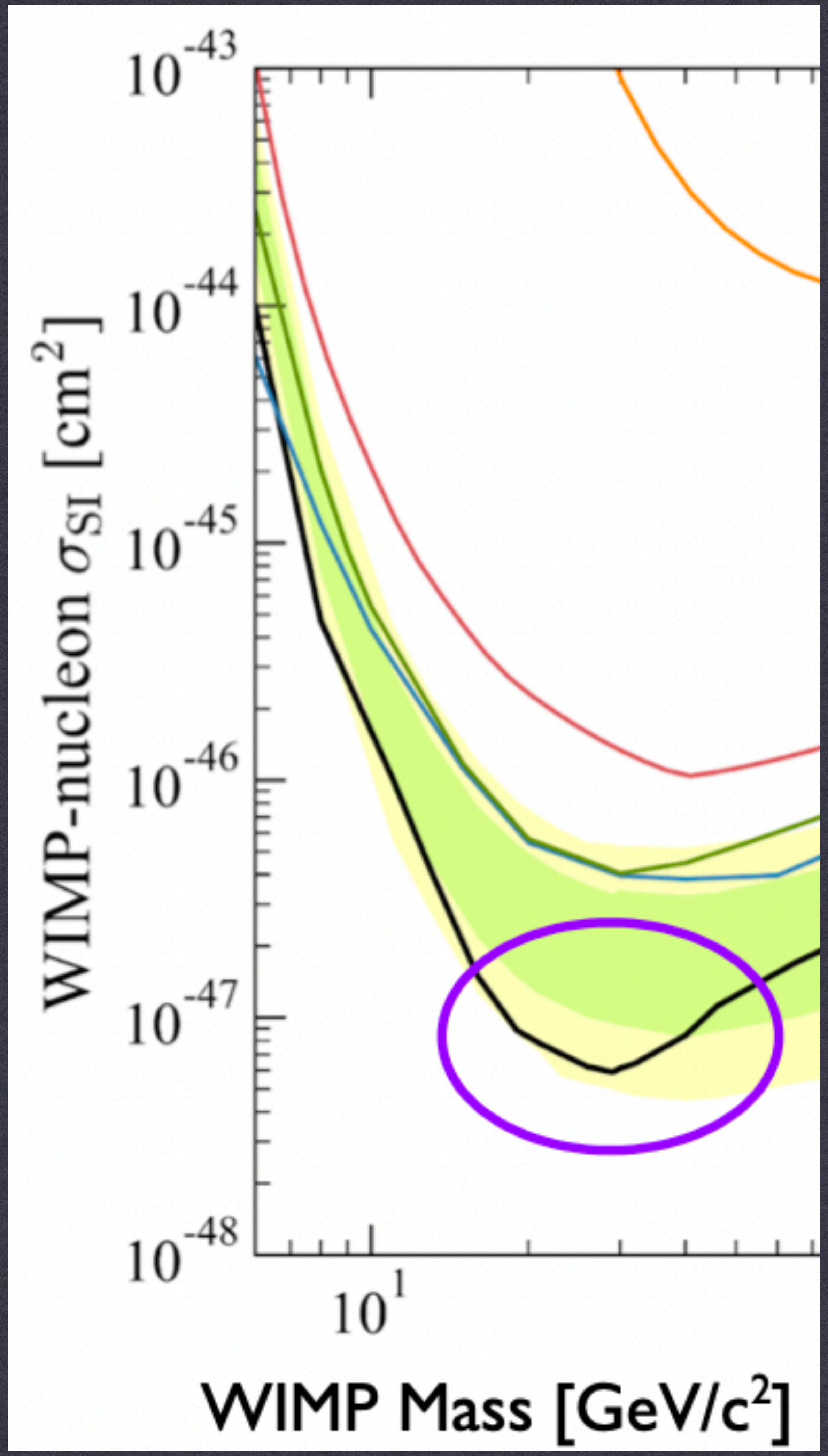
LIVE TIME VETOES

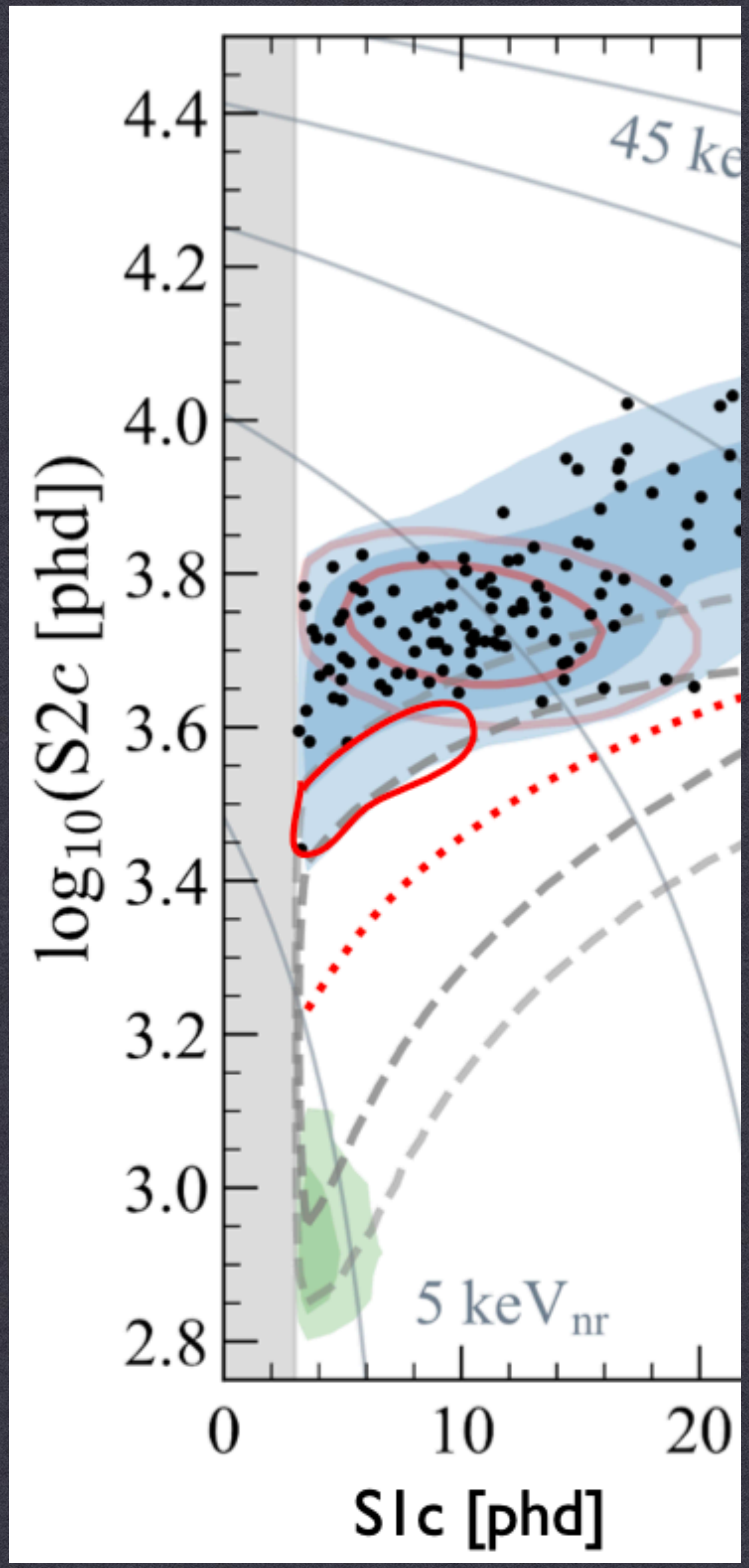
- Large S2s induce pulse "trains" lasting 100s of ms, much longer than the event window
- High pulse rates can lead to piled-up photon or electron pulses that mimic S1s and S2s, thus contributing to accidental coincidence backgrounds
- Removal of periods after S2s (e^-/ph trains) excludes ~30% of our live time
- Working on optimising this live time veto for future runs

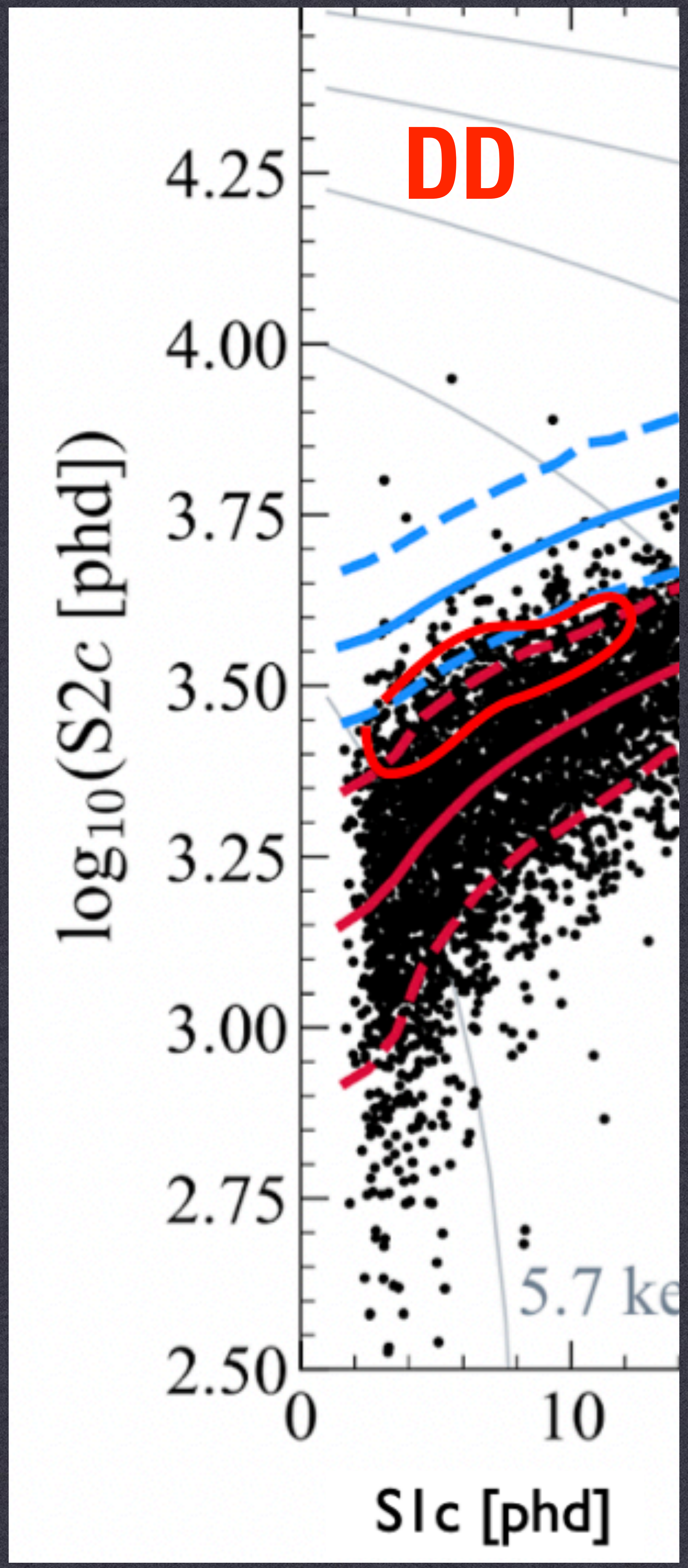


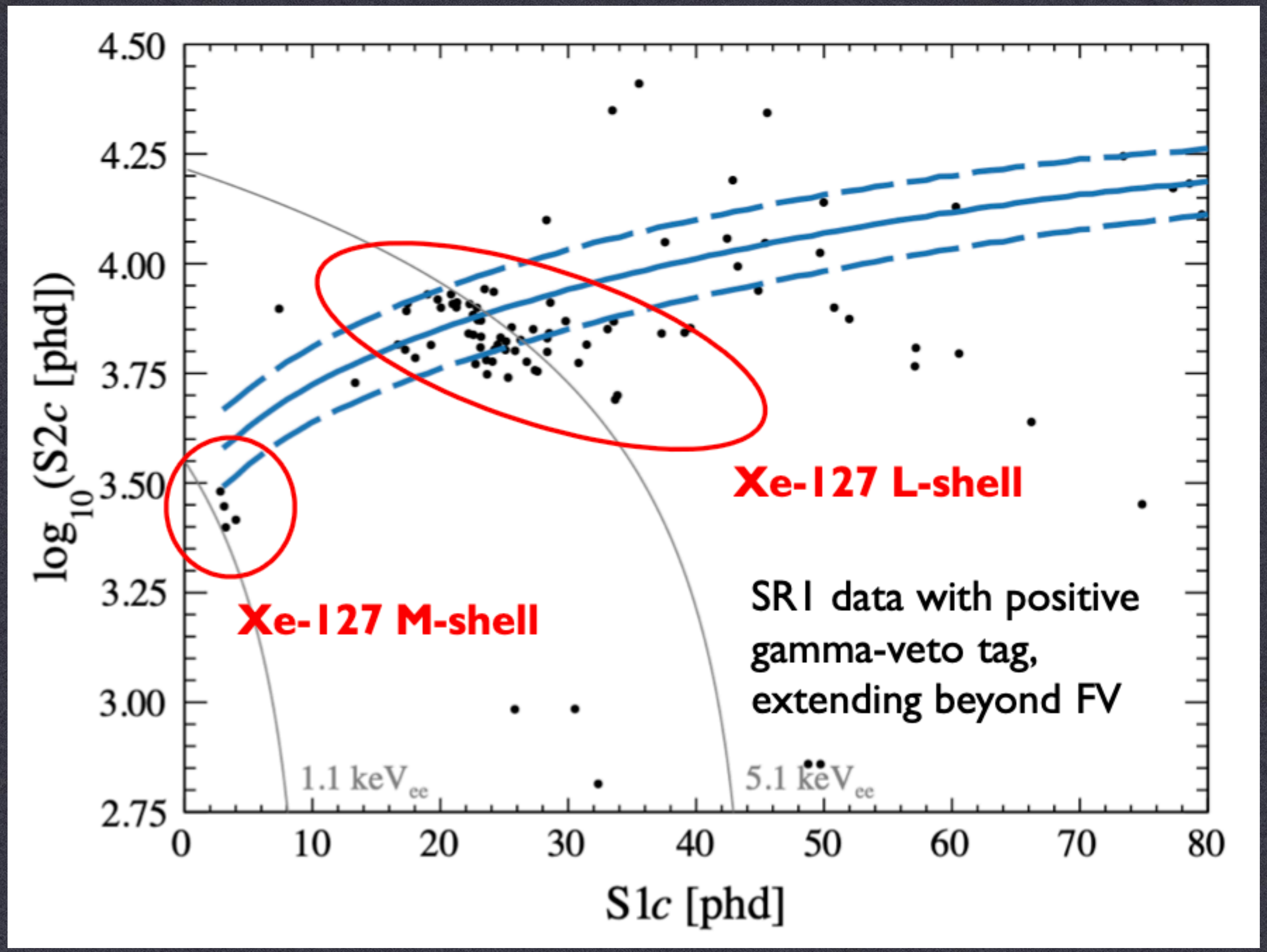
LIMIT SHAPE

Downward fluctuation in limit caused by deficiency of events under Ar37 contour



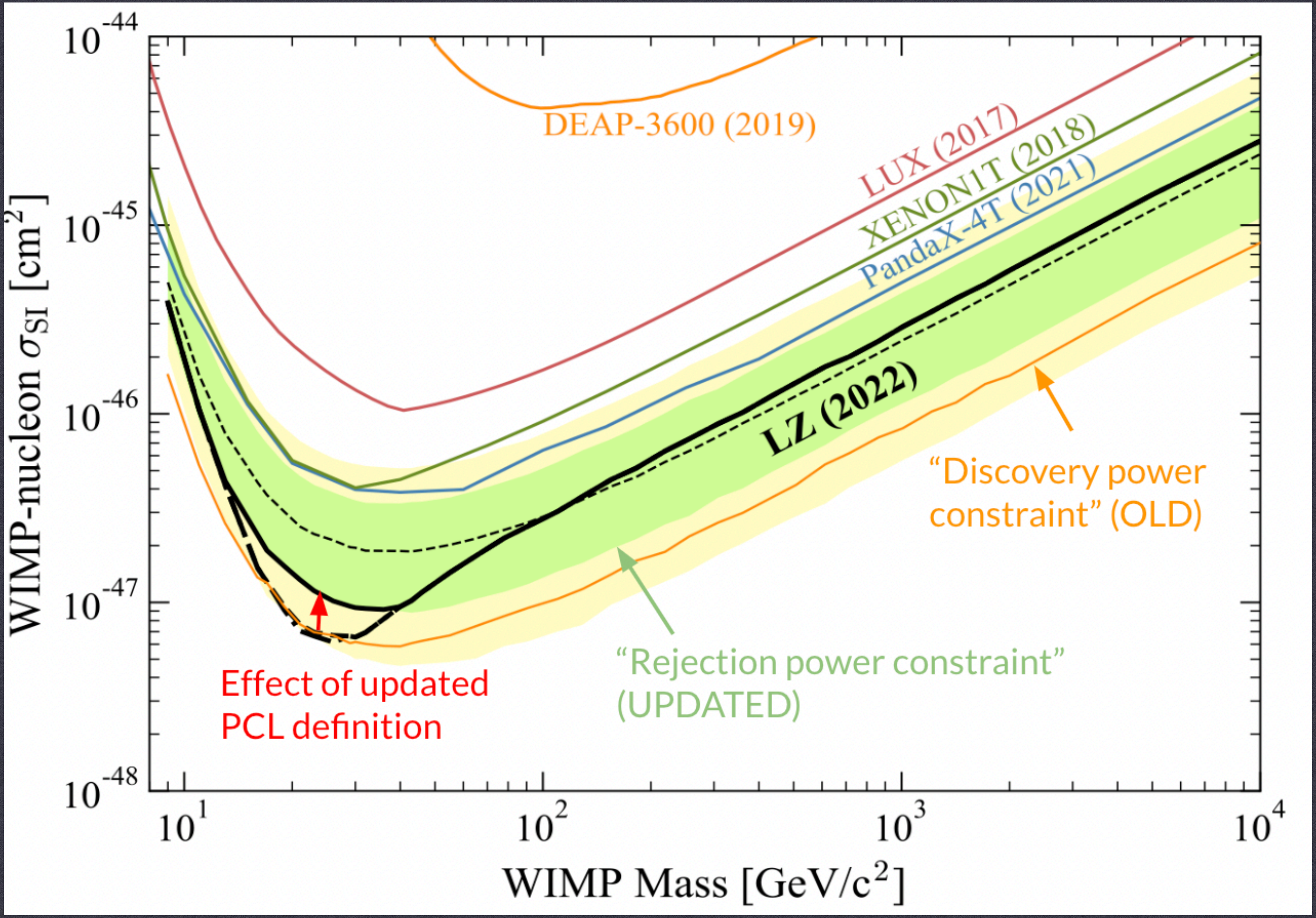






Calibrations and Xe127 M-shell counts as expected under signal acceptance model -> background under-fluctuation

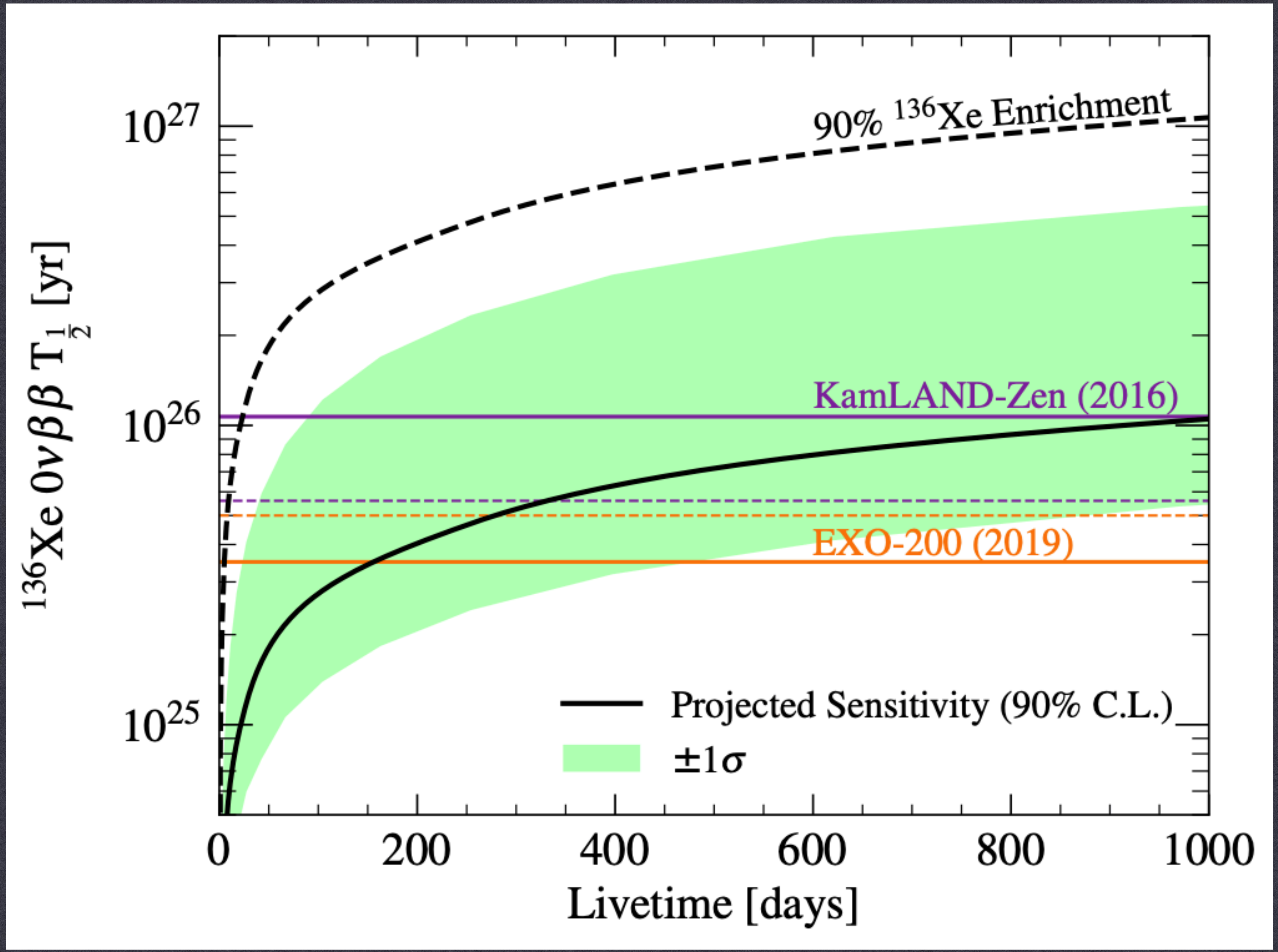
LZ LIMIT UPDATE

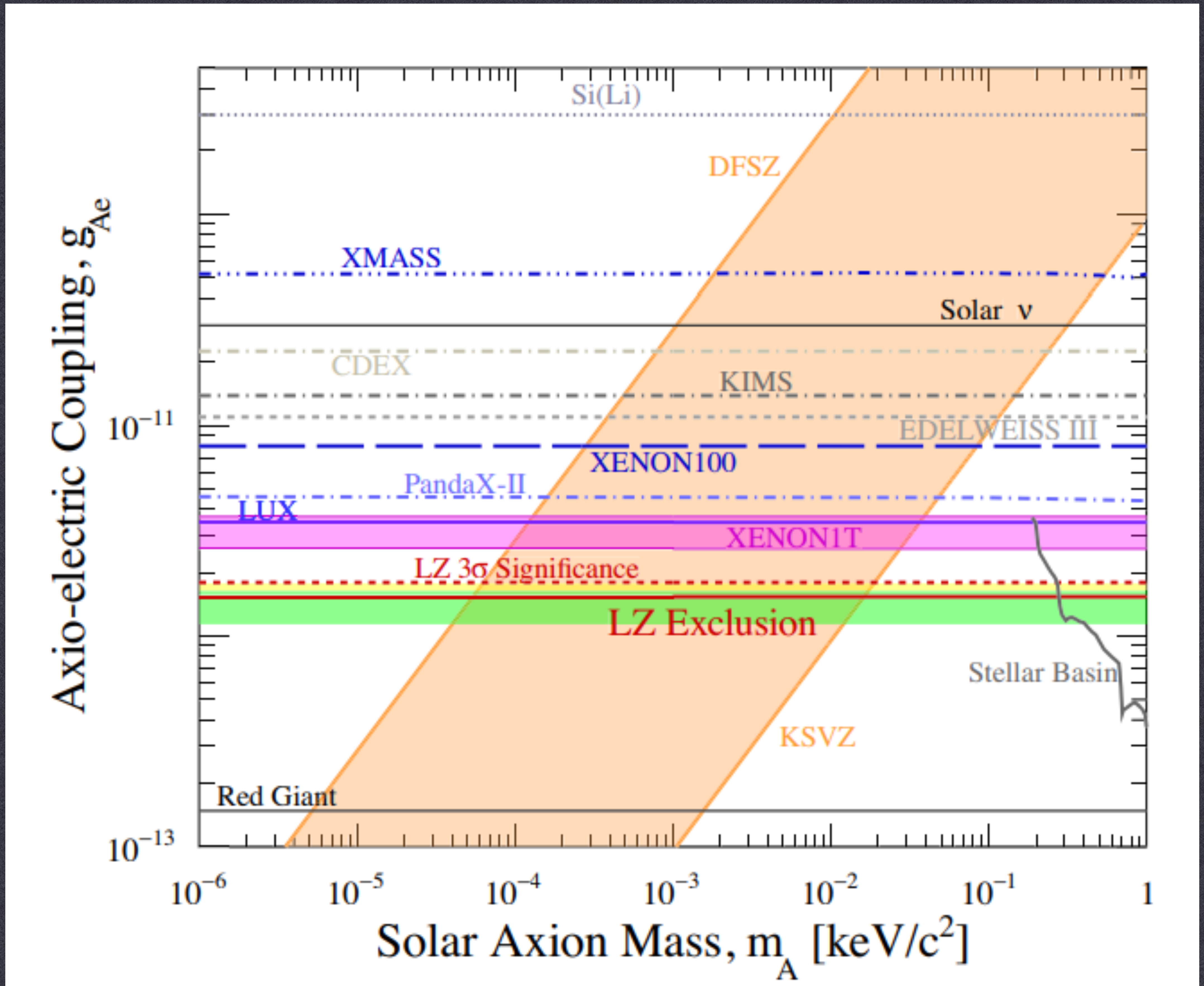


BACKGROUNDS PAPER

- Successful background model built for SR1 underpinning WIMP search result
- Model extends beyond the WIMP search region of interest to other energy ranges
- New dedicated paper: arXiv:2211.17120

WHAT'S NEXT FOR LZ?





- LZ plans to take 1000 live days of data = x17 more exposure than SR1
- Broad physics programme available e.g. neutrinoless double beta decay, solar axions

PRC 102, 014602 (2020), *PRD 104, 092009 (2021)*

BEYOND LZ - XLZD CONSORTIUM

- XLZD consortium formed from the LZ, XENON and DARWIN collaborations
- Coming together to build the ultimate dual-phase multi-ten tonne xenon dark matter detector
- Observatory for other rare physics
- See https://xlzd.org and our joint white paper (arXiv:2203.02309)

XLZD Meeting - UCLA April 2023