Background Determination for the LUX-ZEPLIN Experiment

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UCLA Dark Matter 2023

LZ Collaboration

https://lz.lbl.gov/

@lzdarkmatter

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

UKRI Science and Technology Facilities Council

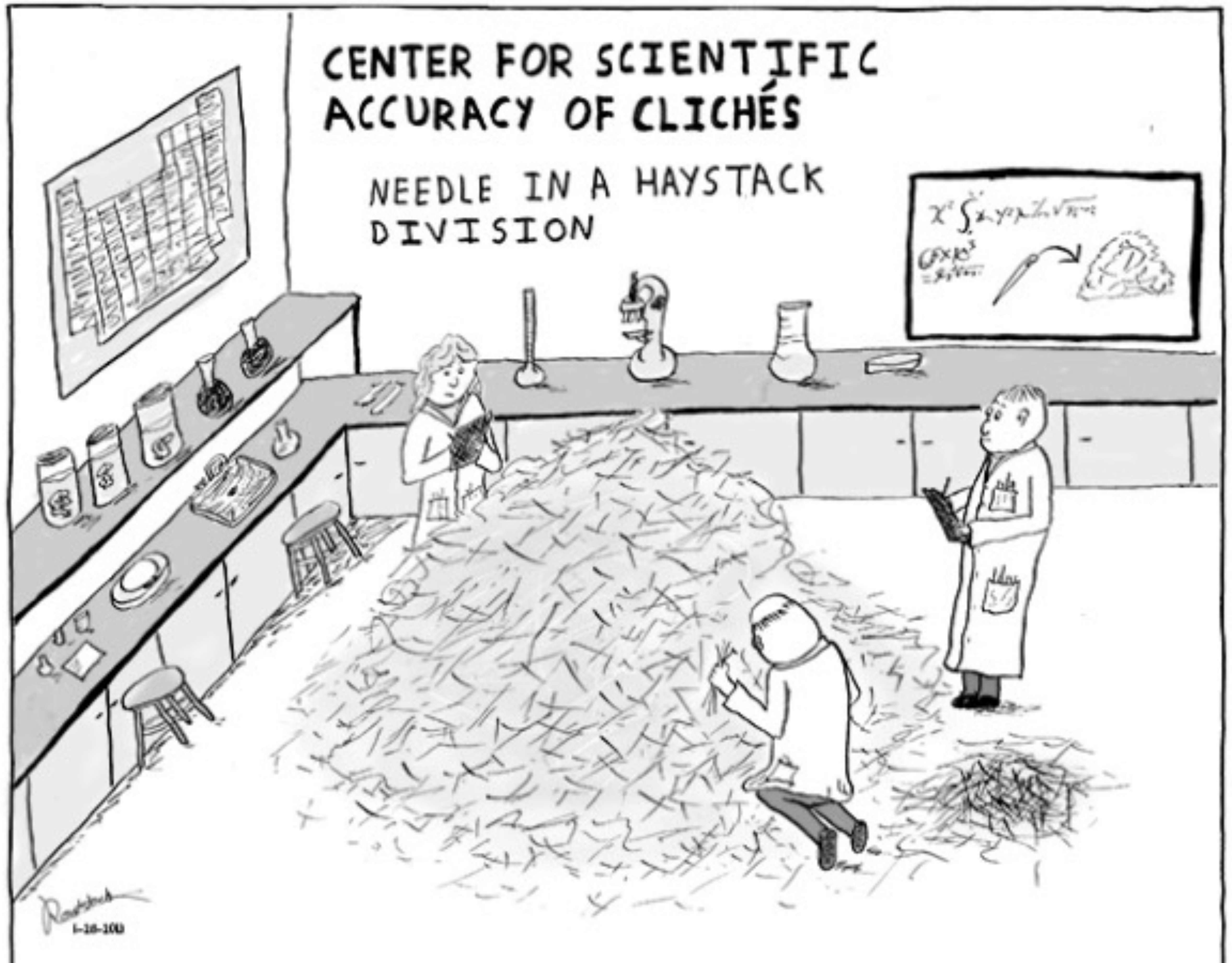
Sanford Underground Research Facility
South Dakota Science and Technology Authority

FCT Fundação para a Ciência e a Tecnologia

ibs Institute for Basic Science

Other LZ talks @ UCLA: 1) WIMP results; 2) Ultra heavy DM; 3) MIGDAL

The Backgrounds Problem



For the first time, scientists were close to determining how difficult it is to actually find a needle in a haystack.

WIMP sensitivities of current experiments

O(1) events/tonne/year

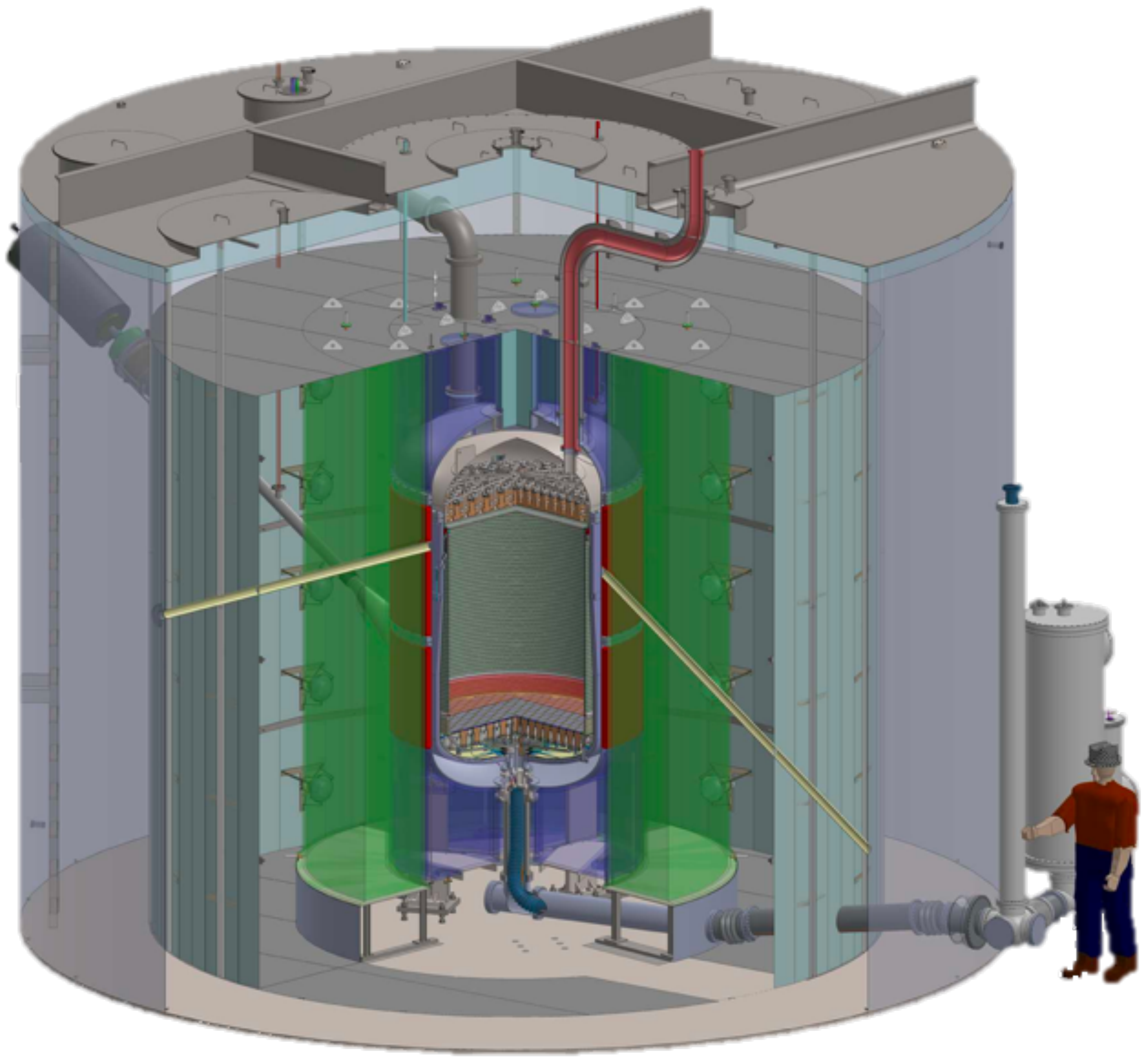
Typical particle detector on the surface

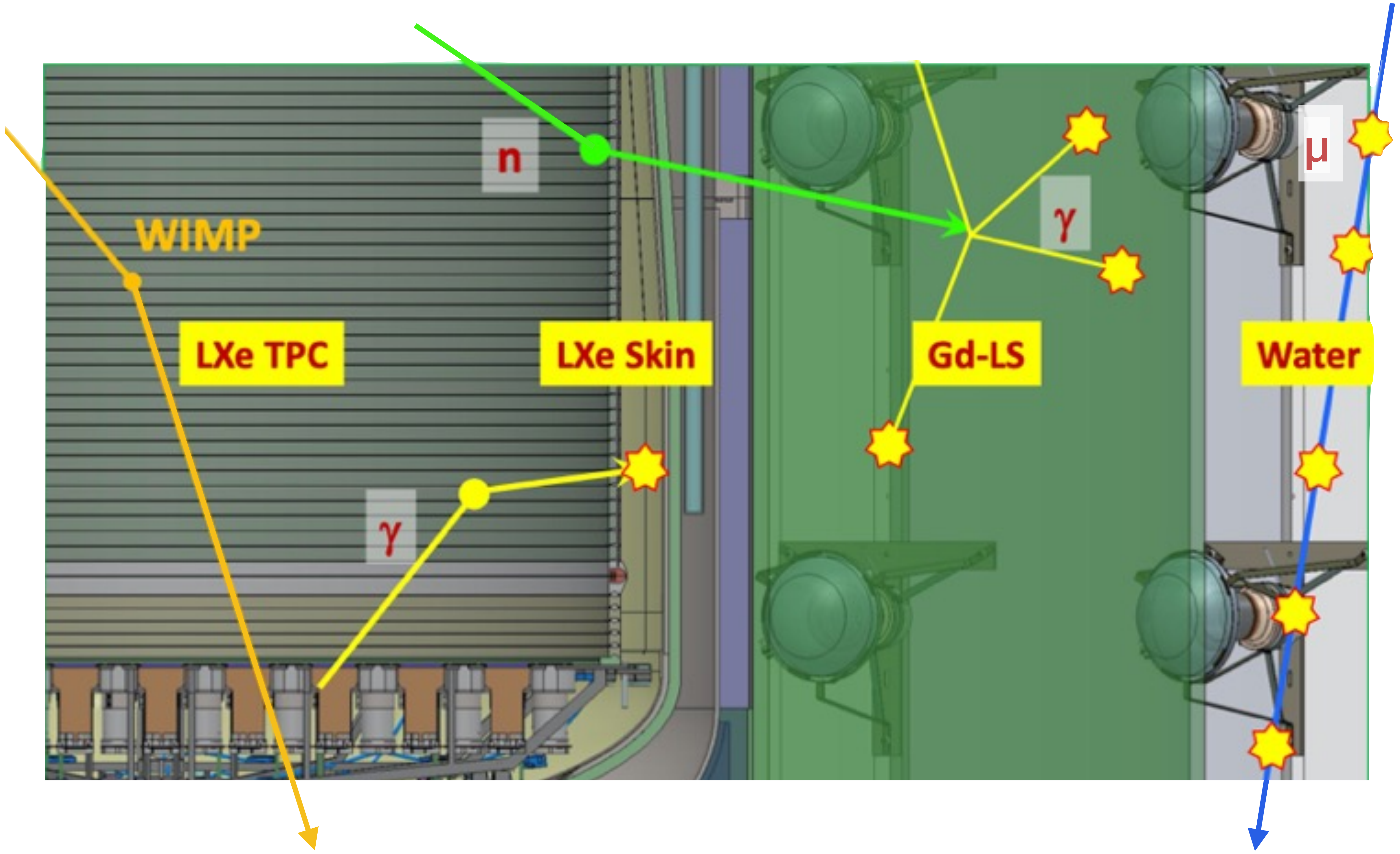
O(10^{12}) events/tonne/year

How can we mitigate backgrounds?

- Discrimination built into design
- Control & cleanliness in construction
- Assessment & reduction in analysis

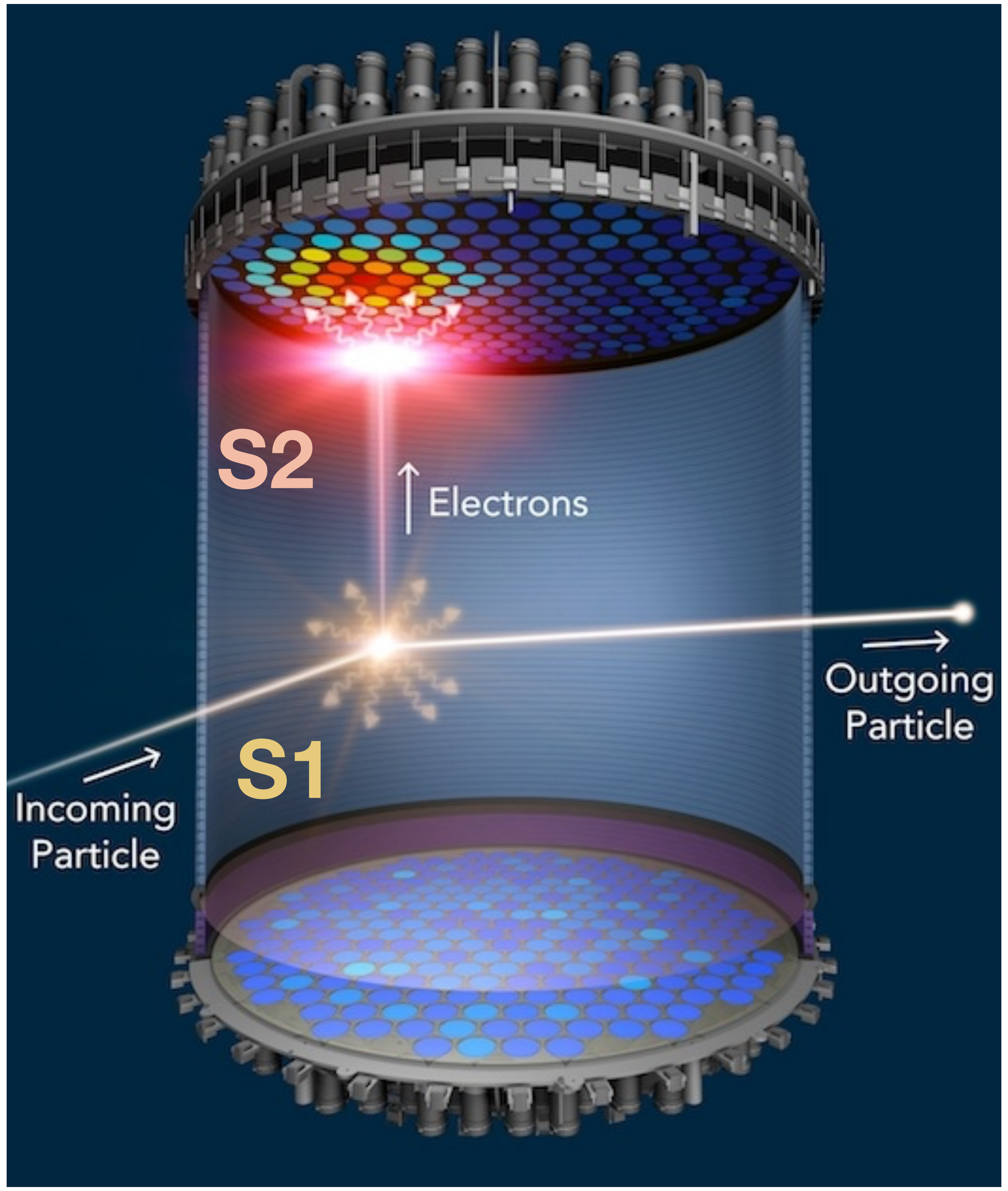
Designing a Low Background Experiment

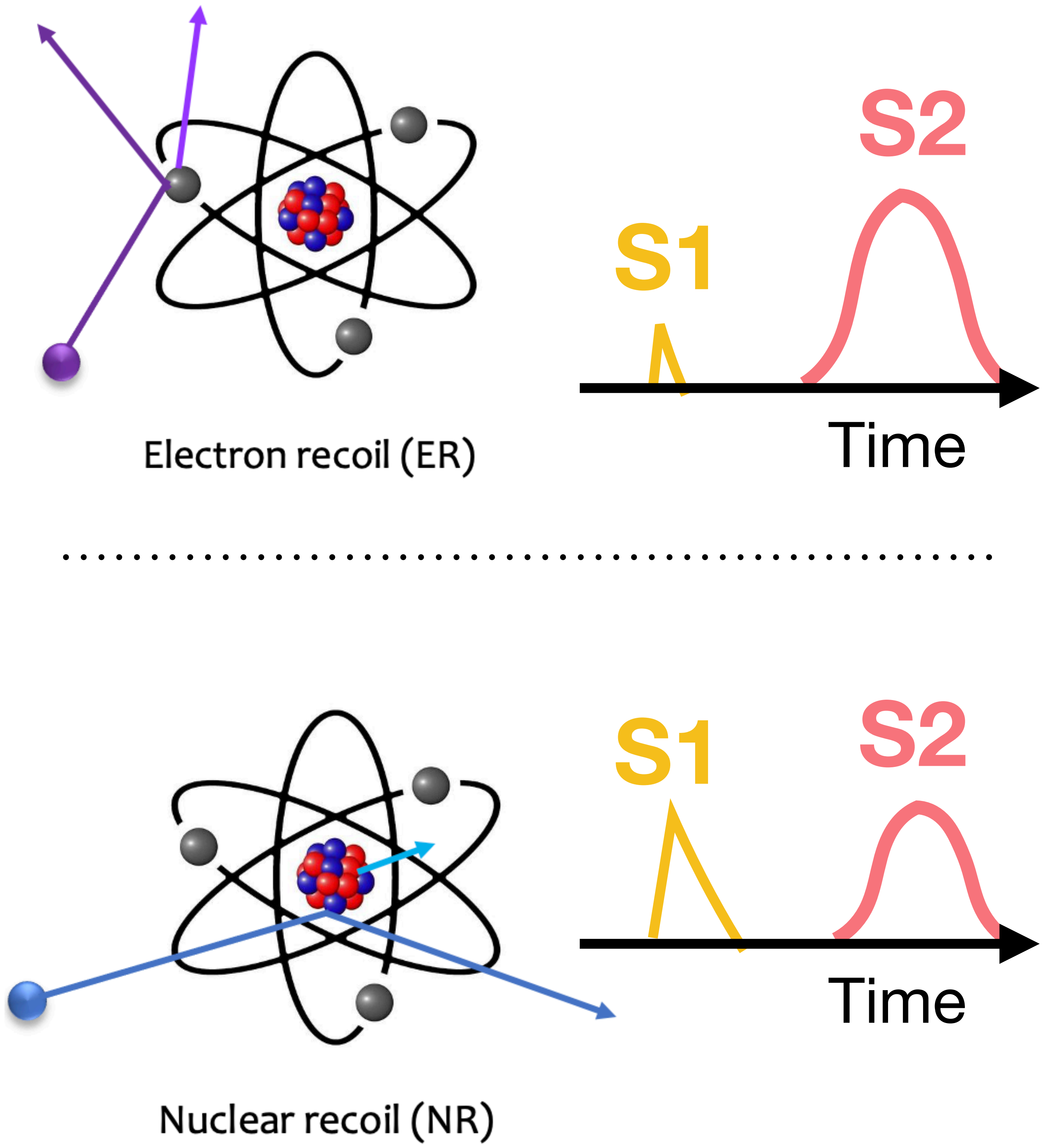


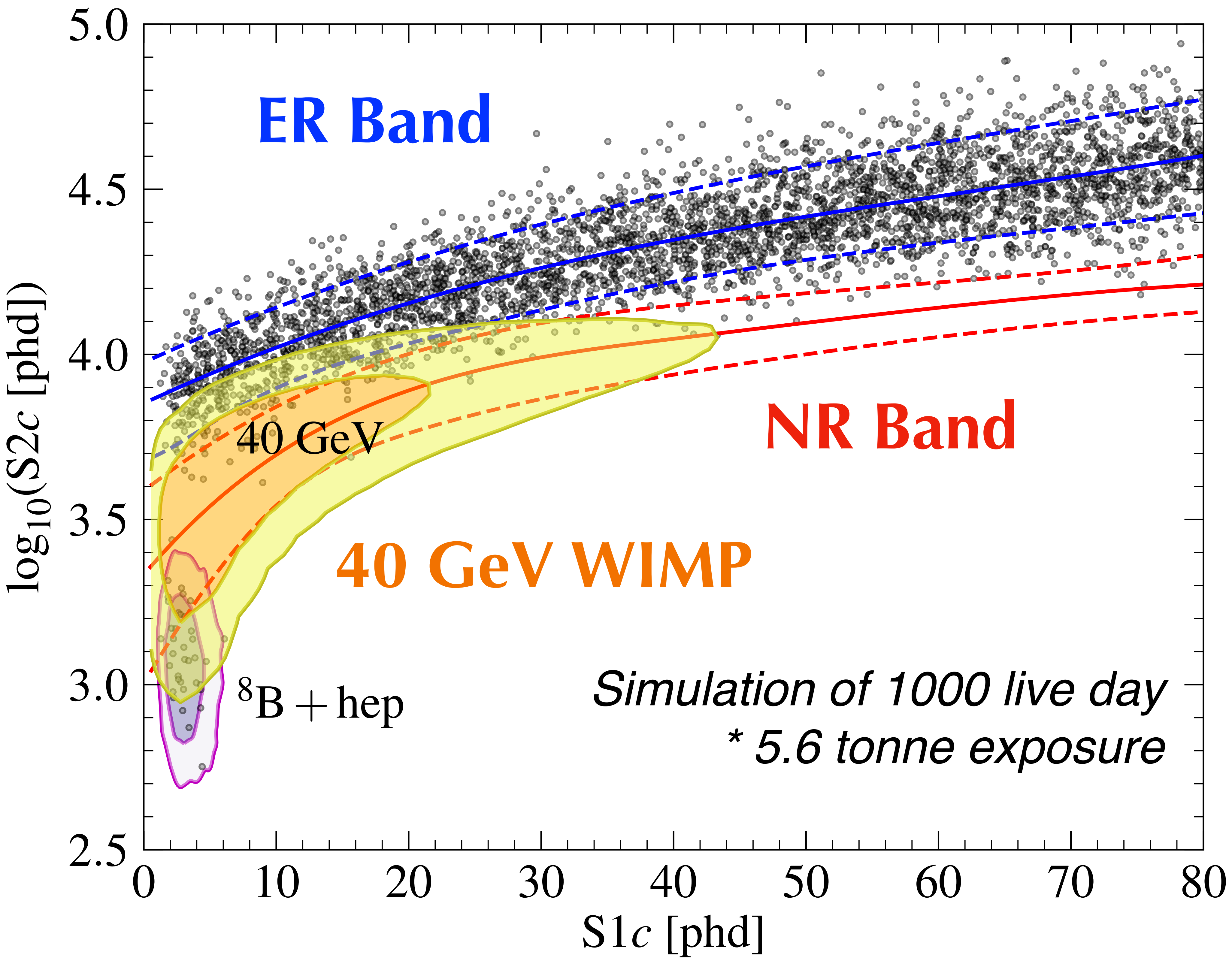


- LZ hosted underground in Davis Cavern @ SURF → ~10^6 muon flux reduction
- Built with radiopure materials, selected based on ~2000 radioassays [EPJC, Vol 80: 1044 (2020)]
- Tri-detector system: Skin & Outer Detector around TPC to tag external γ-rays and neutrons

Designing a Low Background Experiment







- S2/S1 ratio → discrimination between WIMP (NR) & β-particle or γ-ray (ER) events
- Self-shielding xenon + 3D position reconstruction → background-light fiducial volume

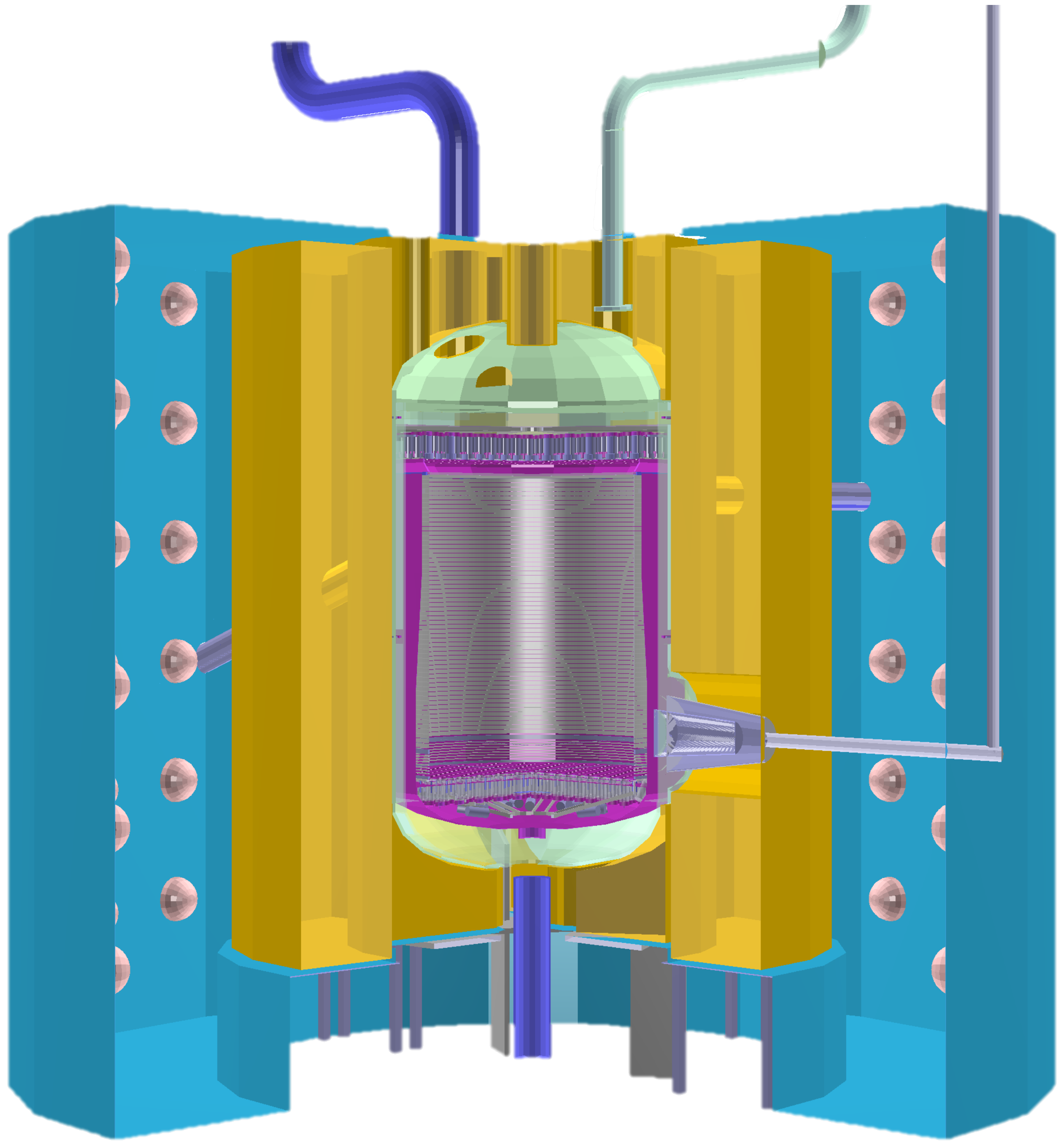
First Science Run (SR1)

- First, world-leading WIMP results achieved with just 60 live days [arXiv:2207.03764]
- Developed cuts with high background rejection, maintaining high signal acceptance
  - 335 events remaining → what are these events?

Building a Background Model

1) Particle & Detector Modelling

- GEANT4-based simulation framework with bespoke features
- Used in sensitivity studies



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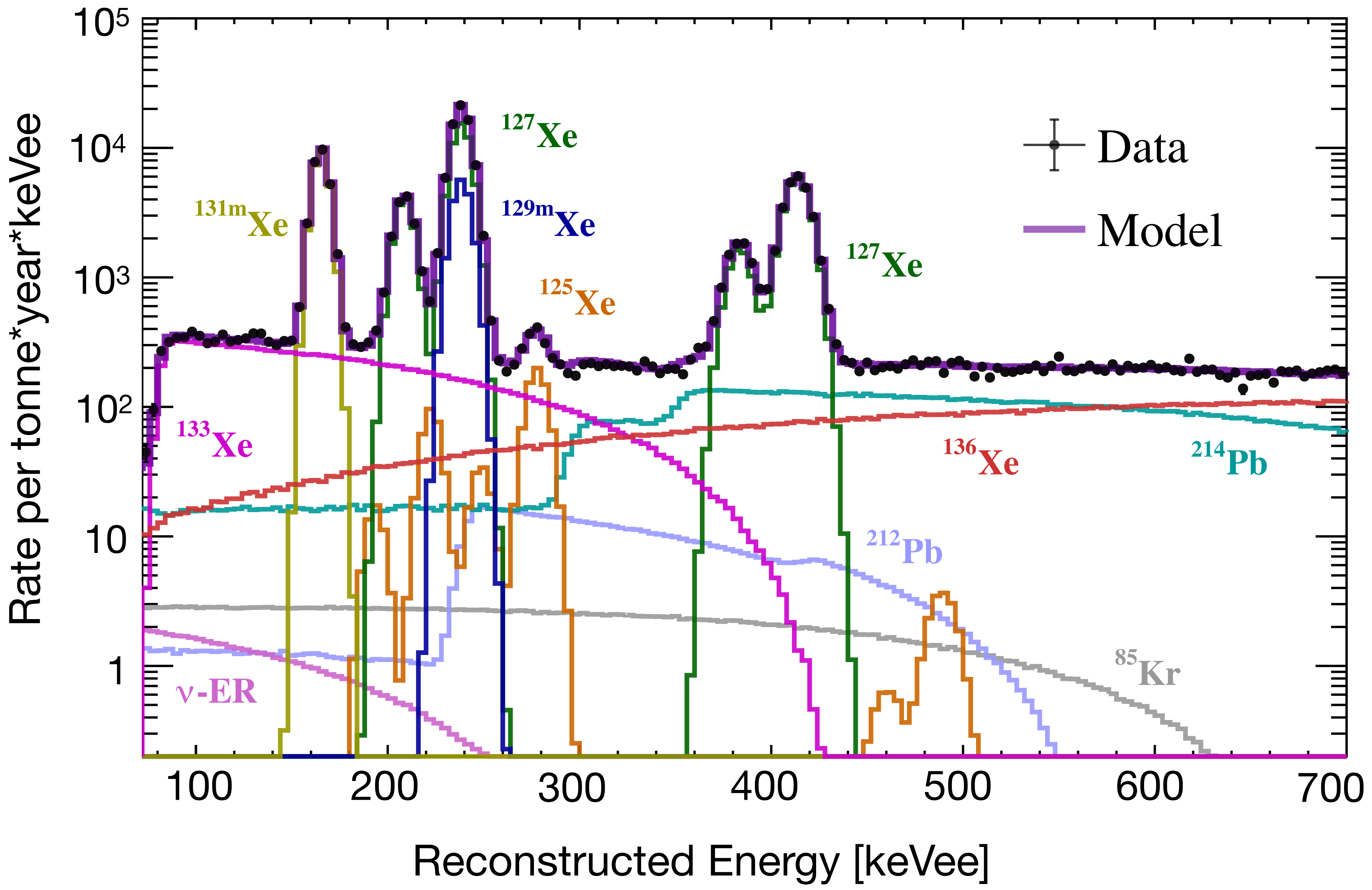
2) In-Situ Background Measurements

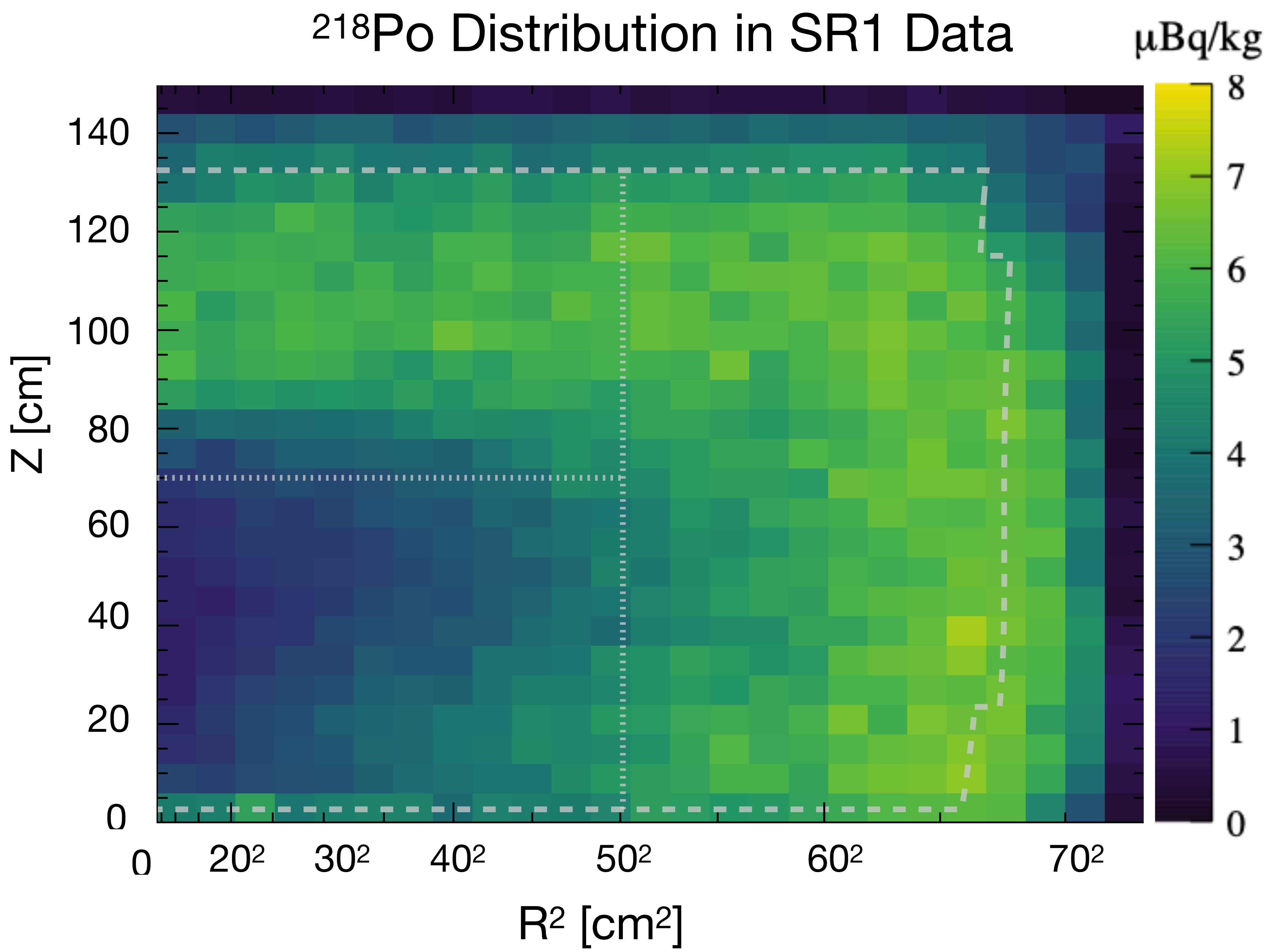
- WIMP sideband analyses
- Energy spectrum fitting at higher energies

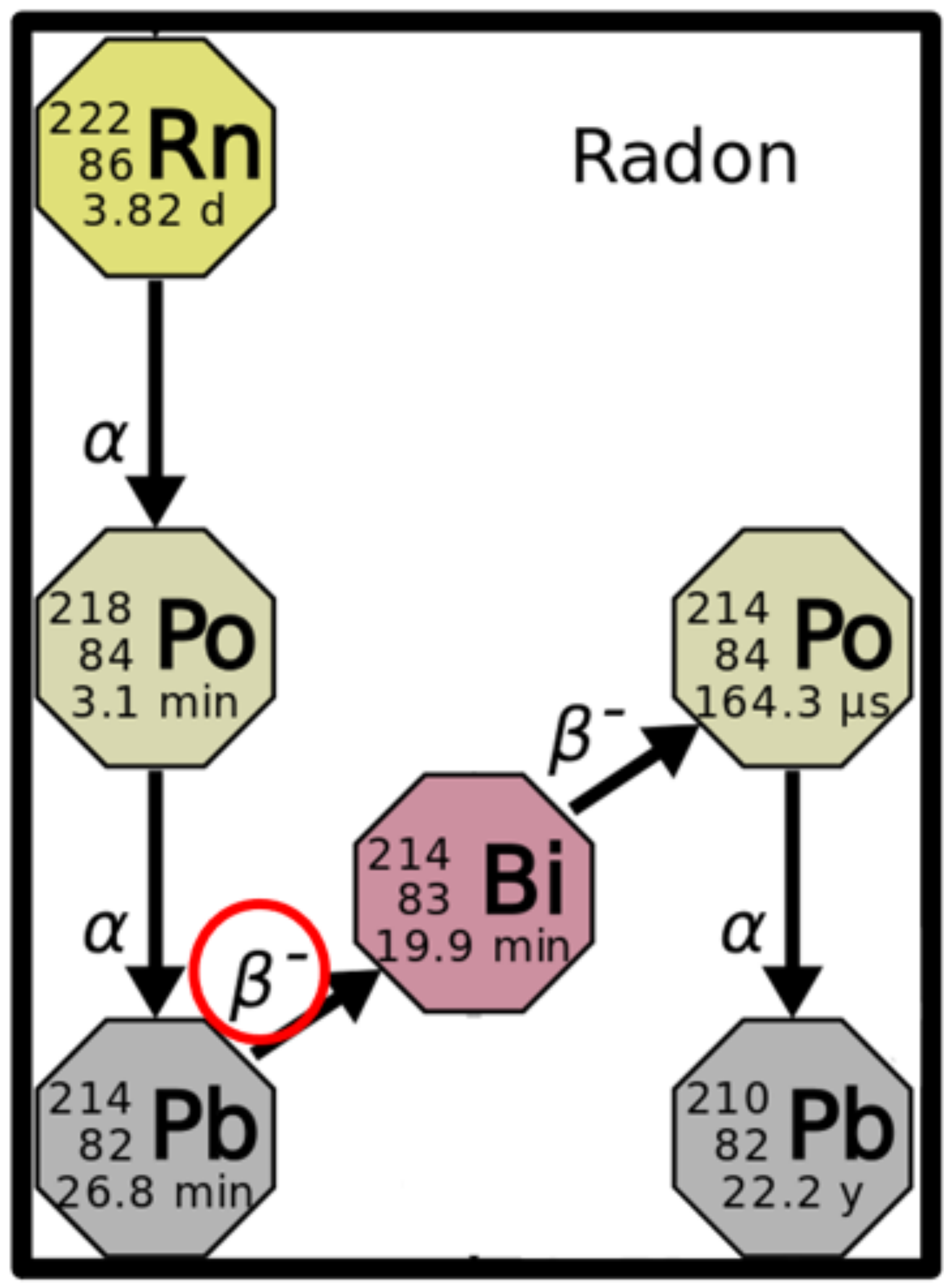


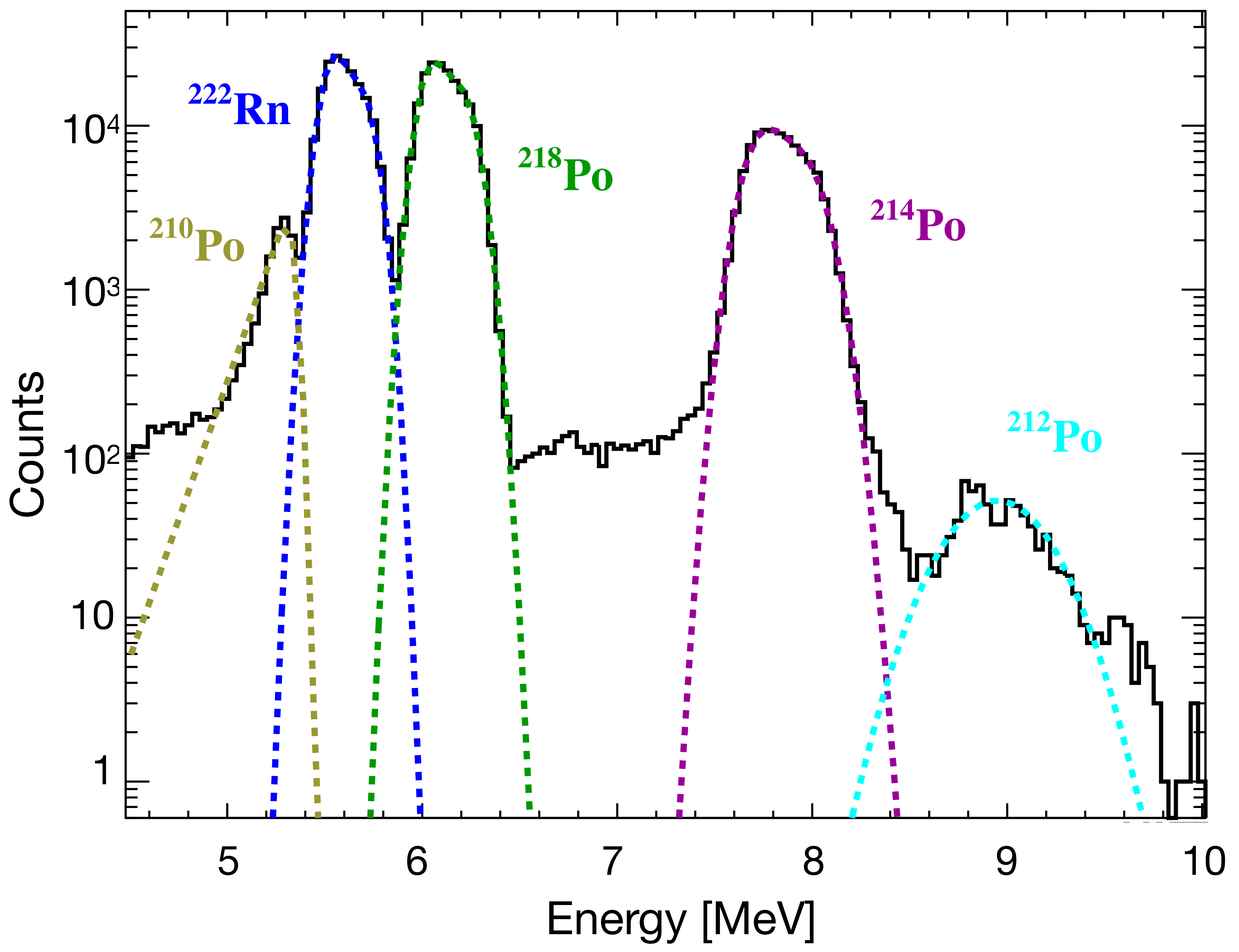
3) Cut Development & Acceptance Assessment

- Fiducial volume, S1 & S2 pulse shape cuts etc.

Radon

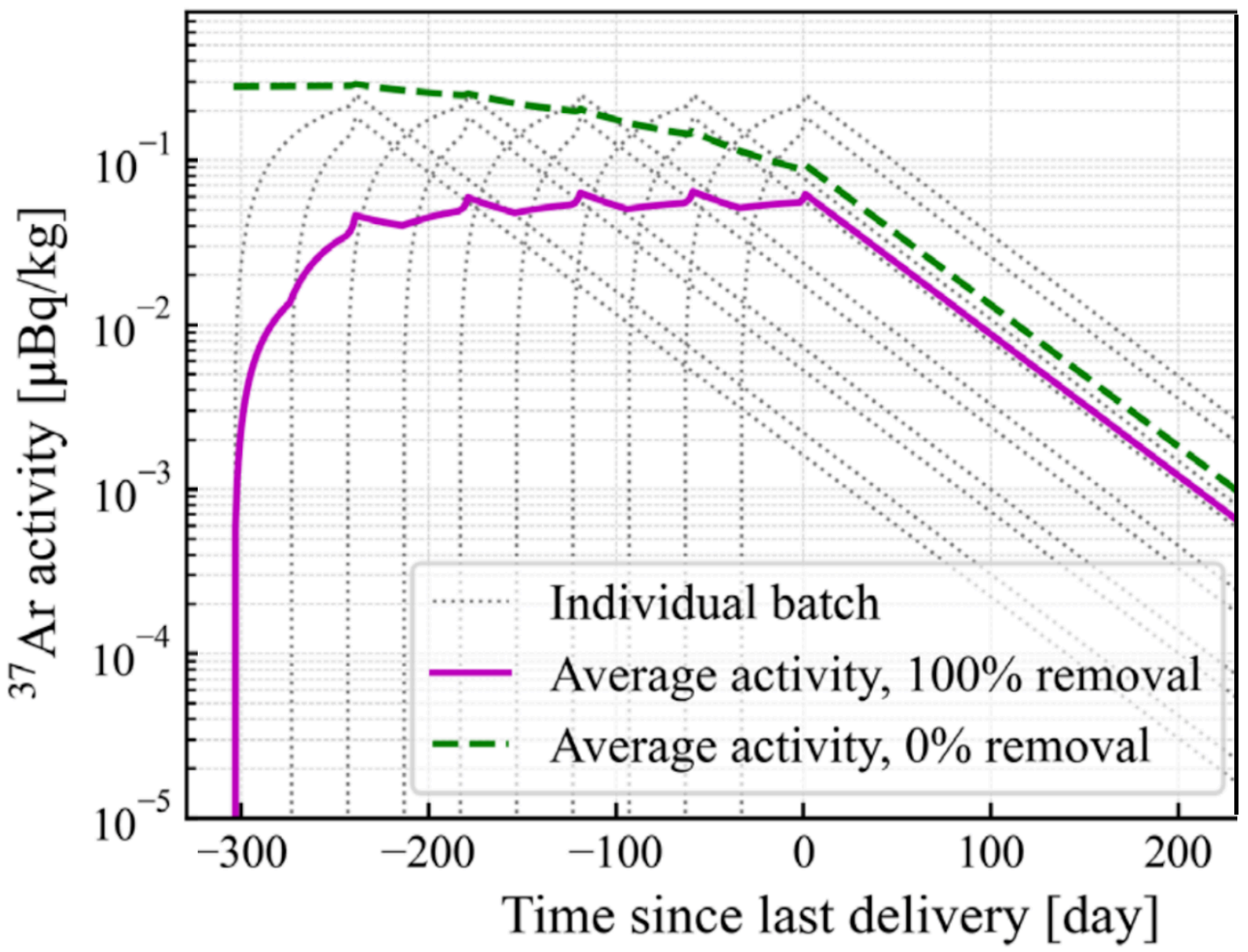


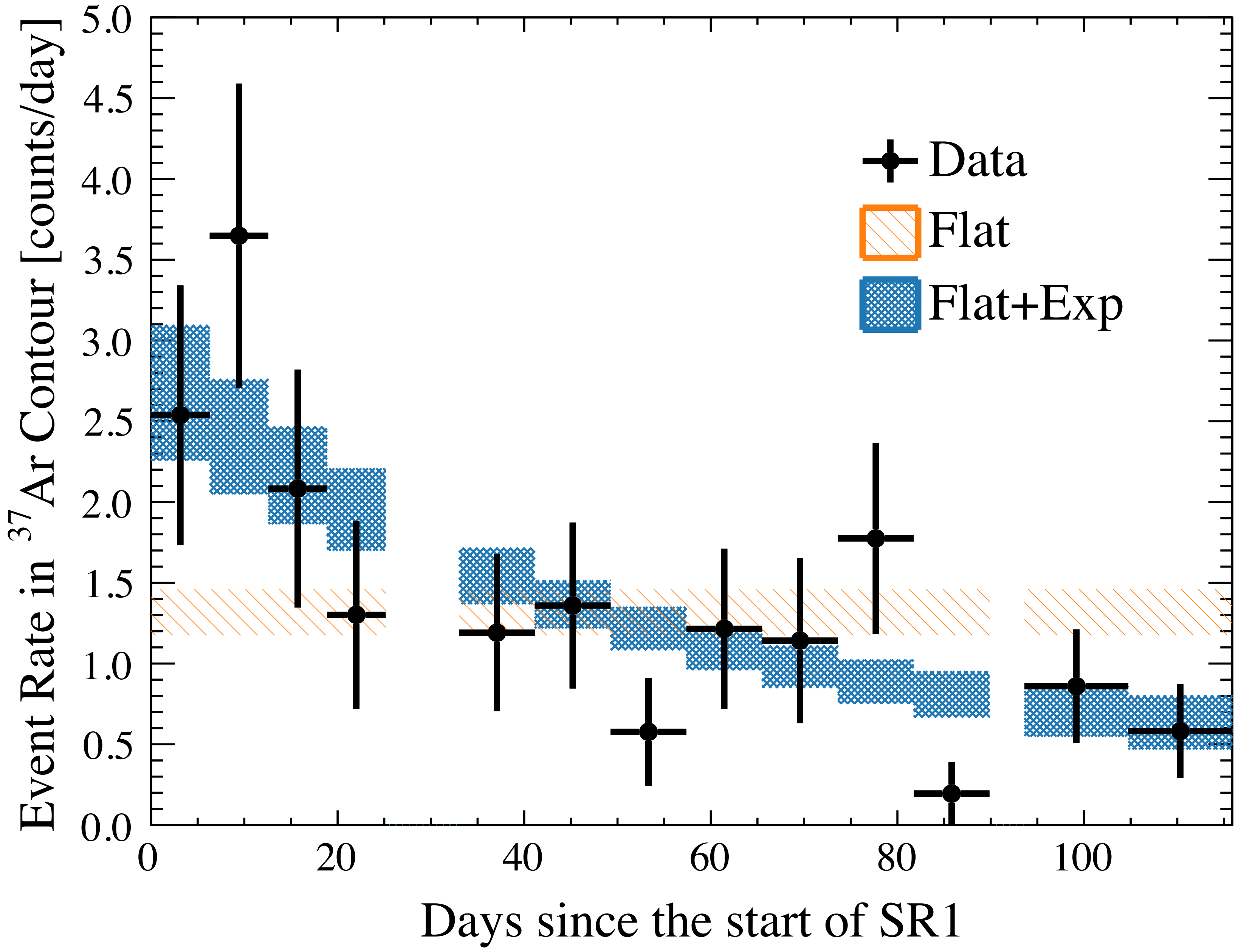


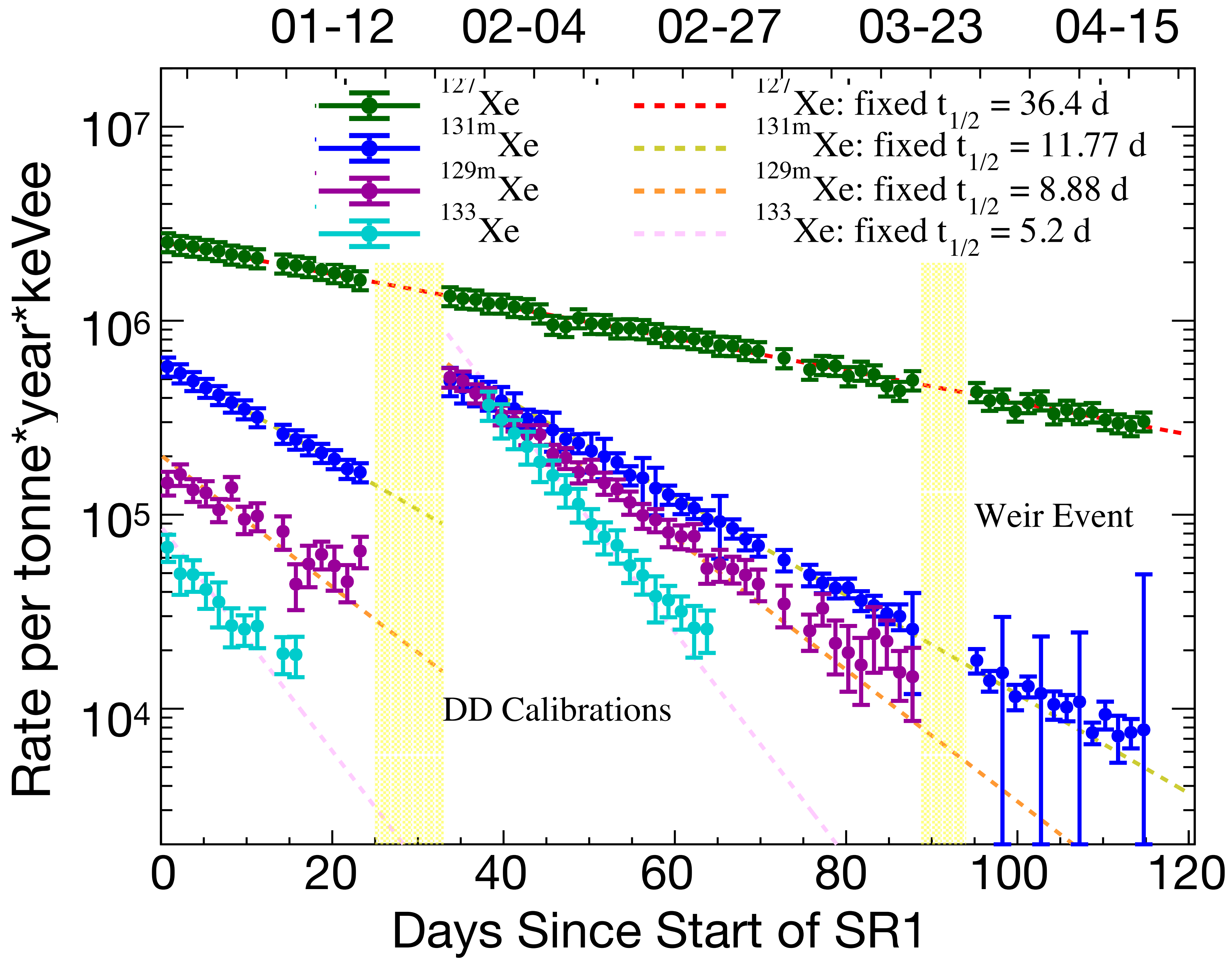


- Radon emanates from detector materials into the xenon
- Non-uniform position distribution due to xenon flow and charged ion movement
- "Naked" ^{214}Pb β decays are the main WIMP background → cannot be directly tagged
  - O(MeV) ^{218}Po & ^{214}Po α signals used to bound ^{214}Pb rate & infer its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

Activation Backgrounds



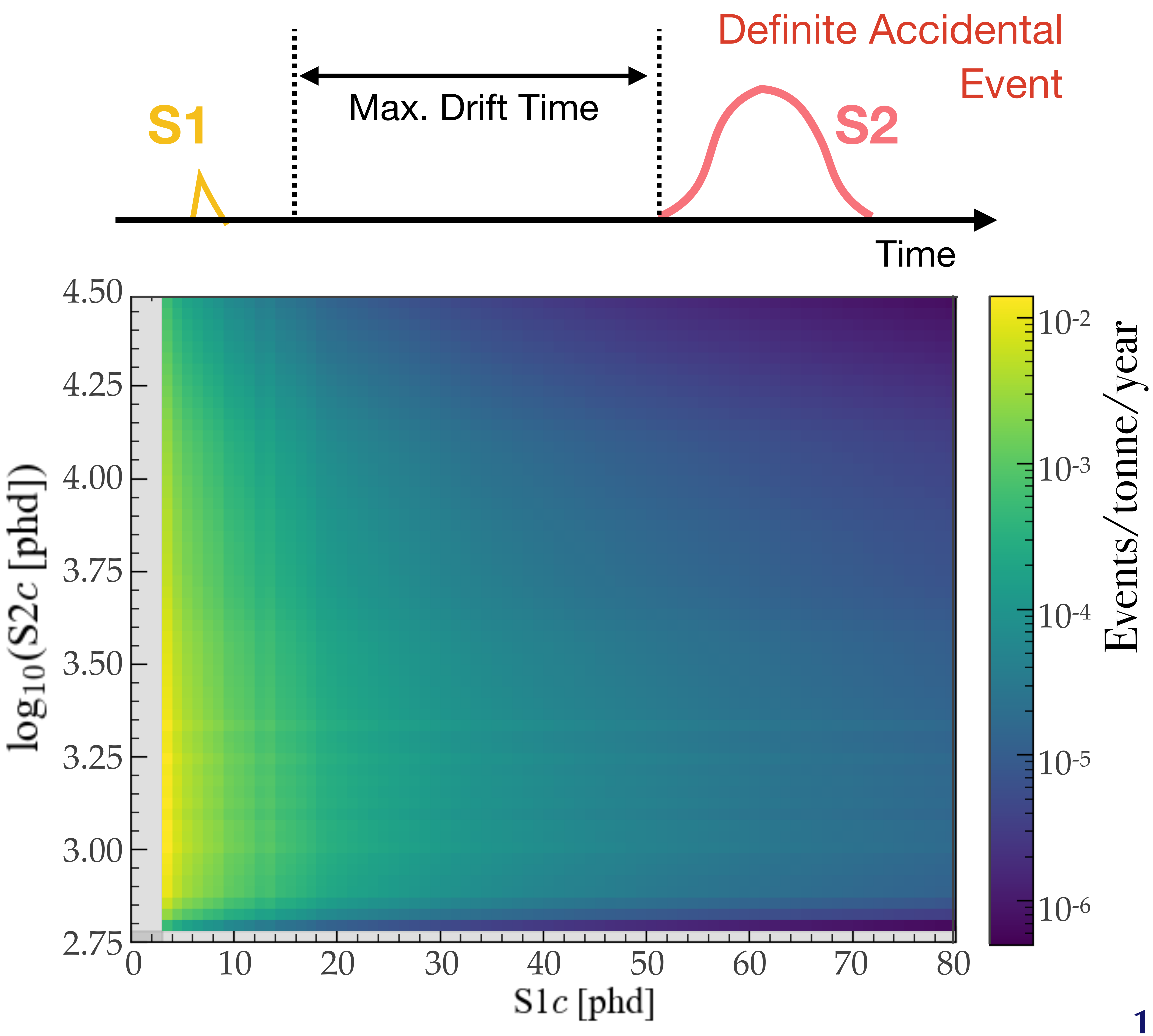




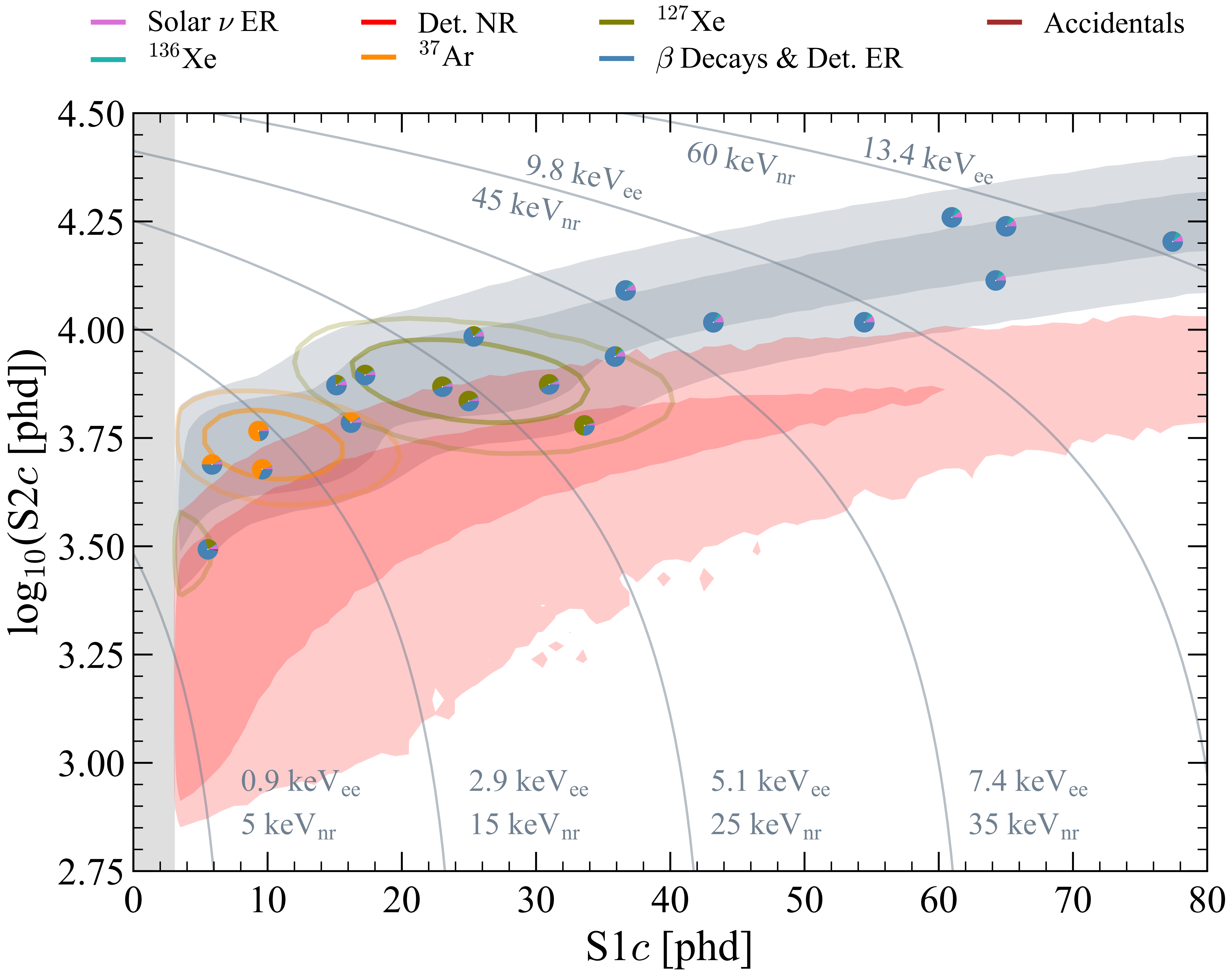
- Cosmogenic activation → decaying xenon isotope & ^{37}Ar contributions during SR1
- ^{37}Ar a significant WIMP search background ($\tau_{1/2}$ = 35 days; monoenergetic 2.8 keV ER)
  - Estimated using ACTIVIA & exposure of the xenon during transport [PRD 105, 082004 (2022)]
  - Fit in data - decaying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

Accidental Coincidences

- 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

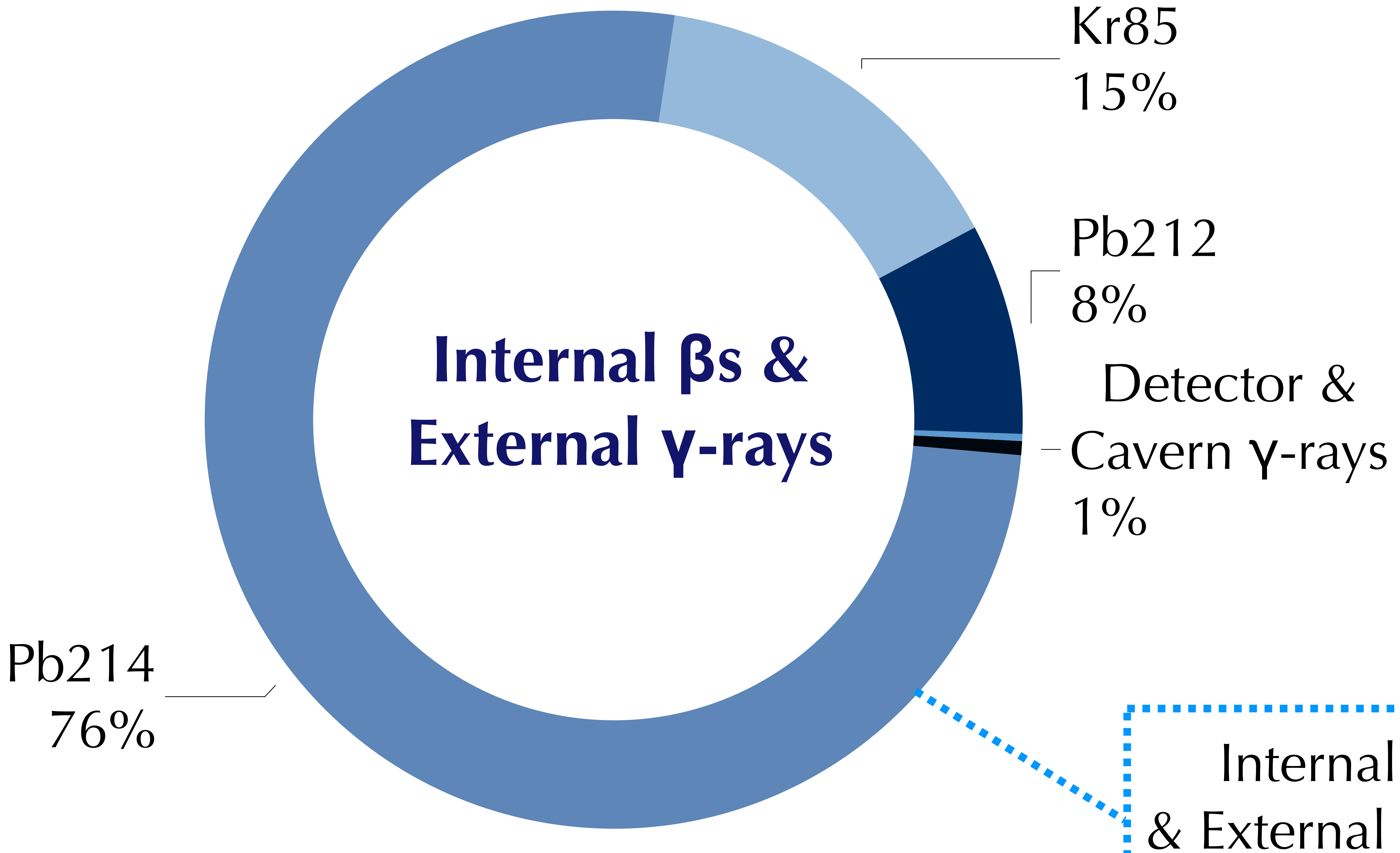


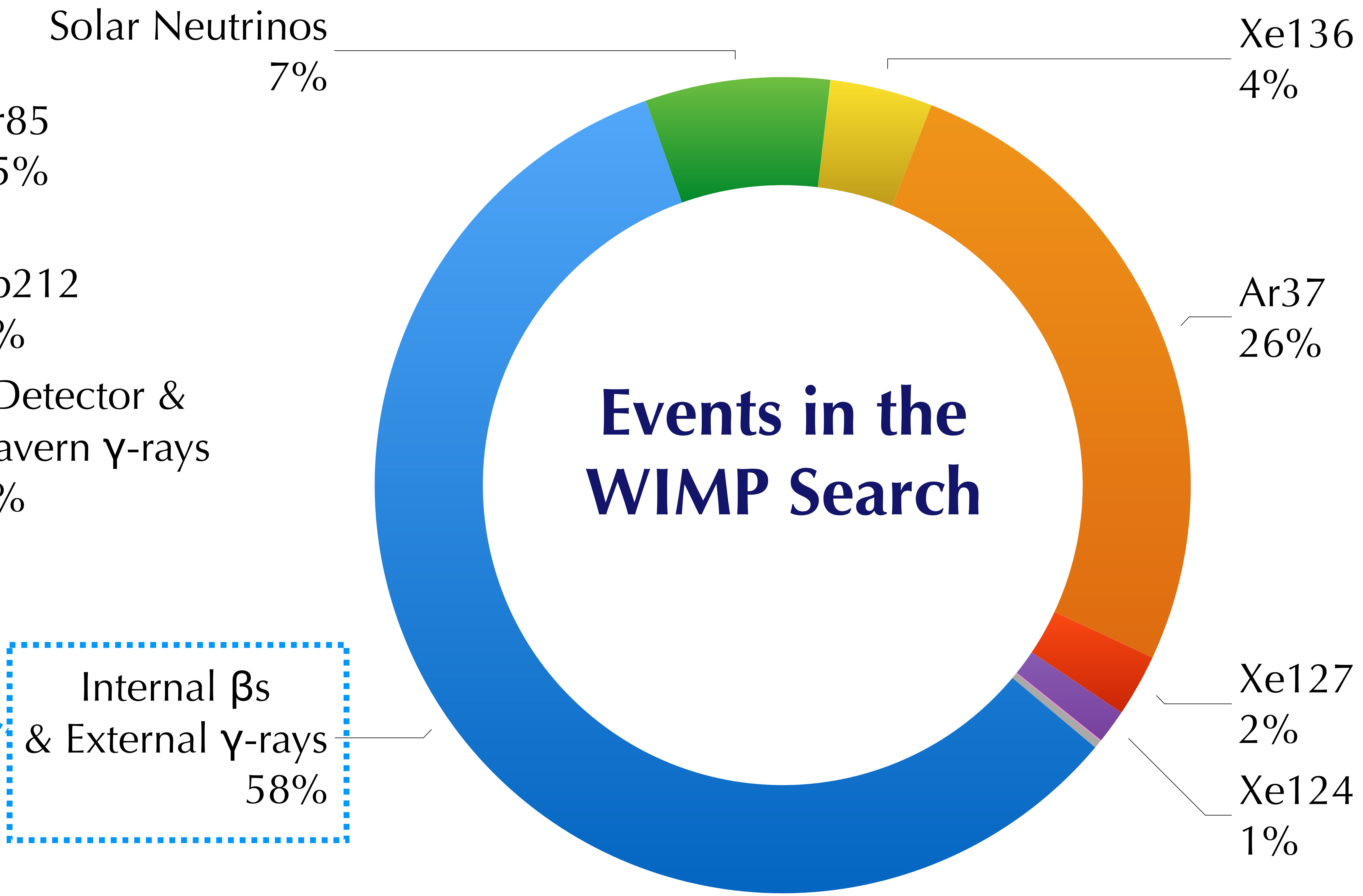
Neutrons



- OD Gd-loaded scintillator - high thermal neutron capture cross-section
  - Measured OD neutron tagging efficiency of 88.5 ± 0.7%
- 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

Background Model Expectations

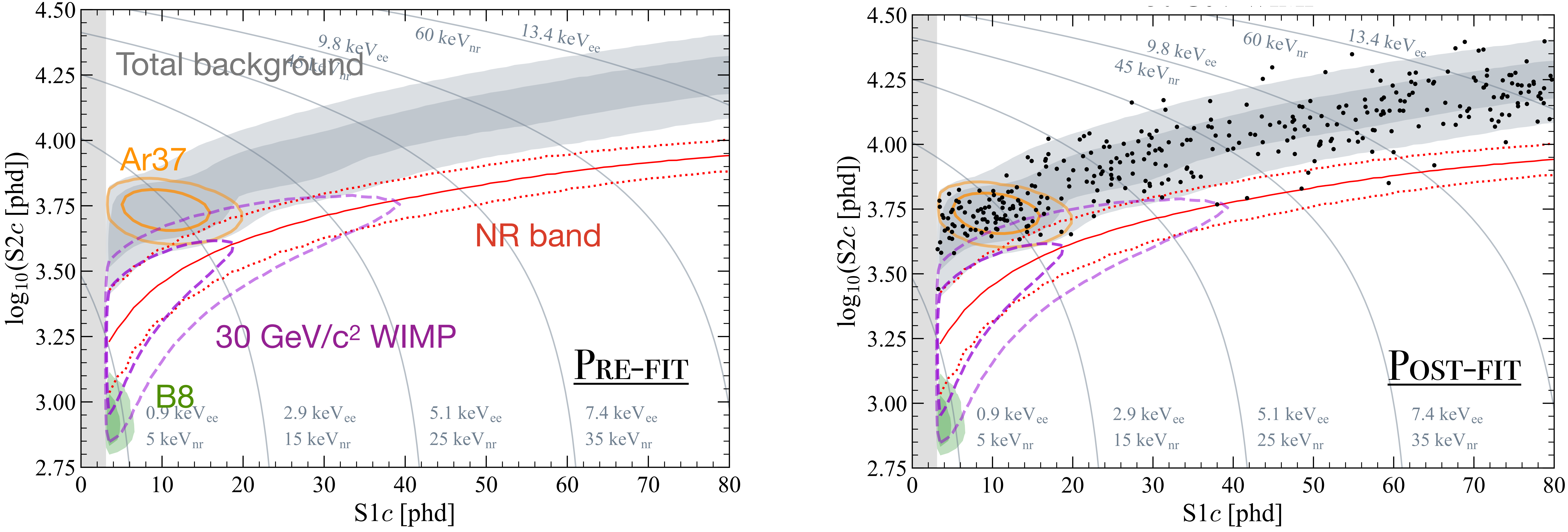




Total expected **NR** counts in SR1 WIMP search: **0.14**

Total expected **ER** counts for SR1 WIMP search: **273** + [0, 288] from ^{37}Ar

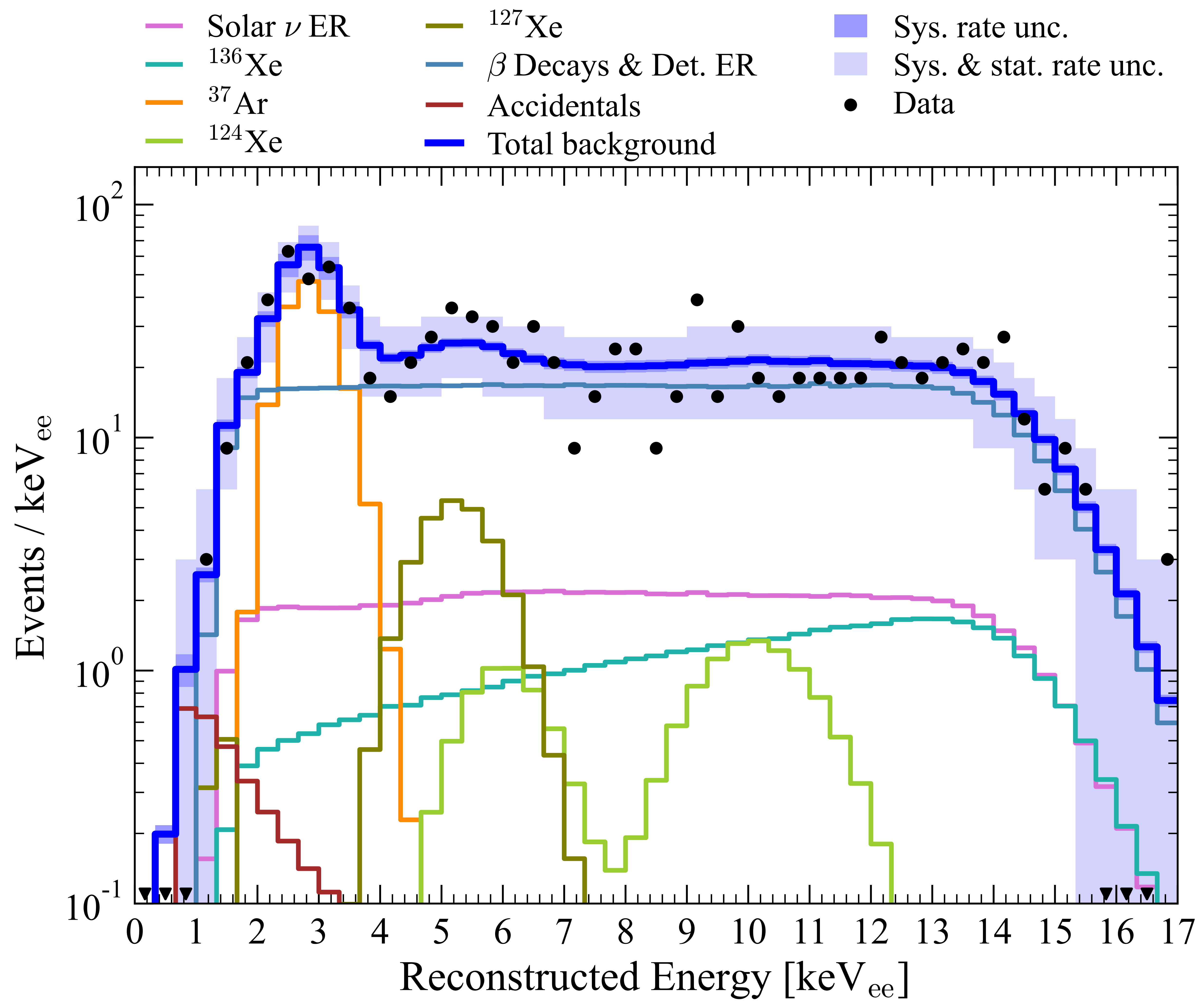
Background Model Fit



- Background PDFs for fit created with energy deposit + detector response simulations
- No visible change in pre- & post-fit total BG contours
  → we predicted our backgrounds well!

Background Model Fit

Source	Expected Events	Fit Result
^{214}Pb	164 ± 35	-
^{212}Pb	18 ± 5	-
^{85}Kr	32 ± 5	-
Det. ER	1.4 ± 0.4	-
β decays + Det. ER	215 ± 36	222 ± 16
ν ER	27.1 ± 1.6	27.2 ± 1.6
^{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
^{8}B CEνNS	0.14 ± 0.01	0.15 ± 0.01
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Subtotal	273 ± 36	280 ± 16
^{37}Ar	[0, 288]	$52.5^{+9.6}_{-8.9}$
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	–	333 ± 17



Best-fit number of zero WIMP events for all masses examined

Conclusions

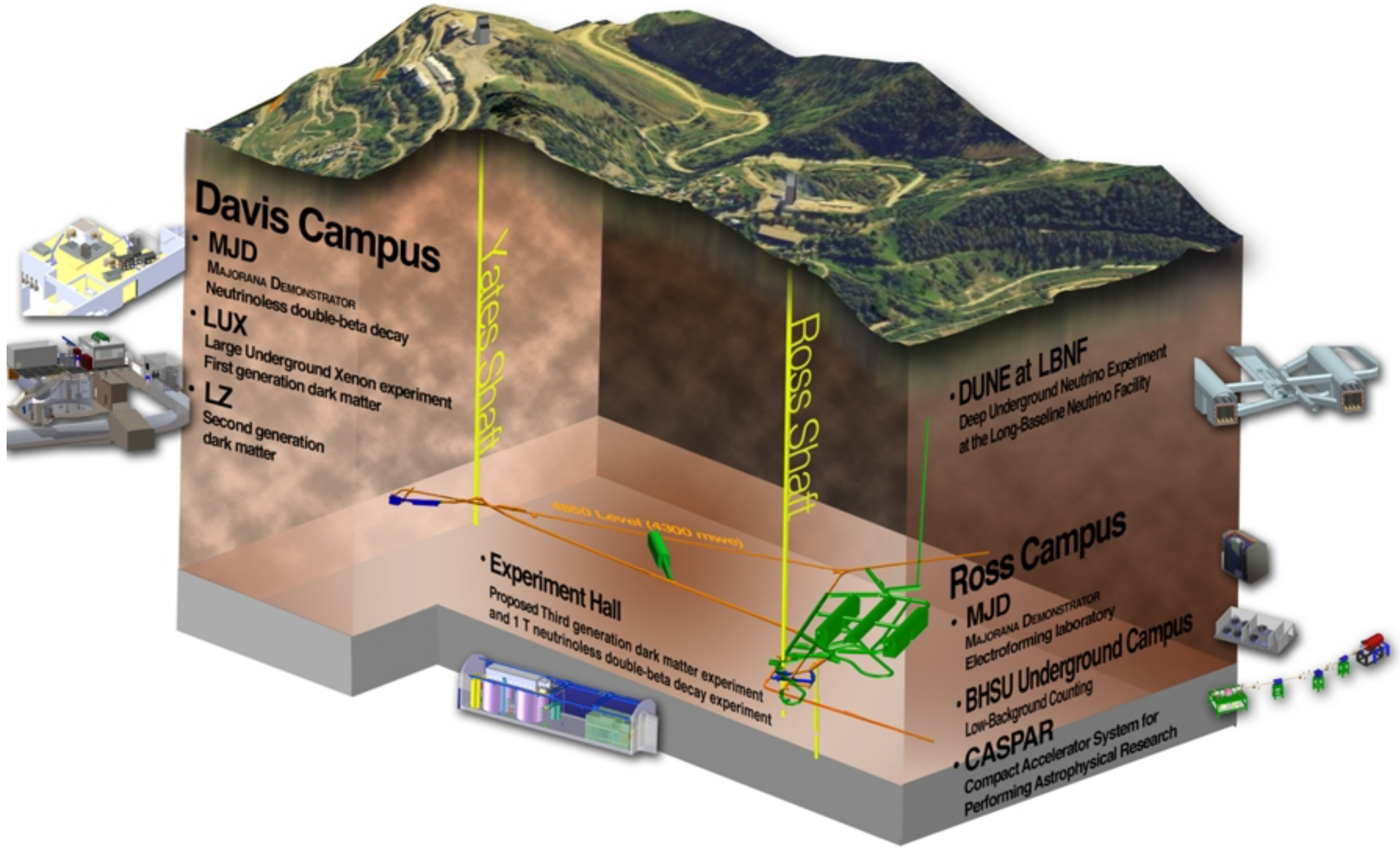
- Successful background model built for SR1 underpinning WIMP search result
- Model extends beyond the WIMP search region of interest to other energy ranges
- Results seen today, and more, can be found in new dedicated paper: arXiv:2211.17120

Back Up

Constructing a Low Background Experiment

1. Underground Location

- LZ hosted in Davis Cavern @ SURF
  →~10^6 muon flux reduction



2. Radiopure Material Selection

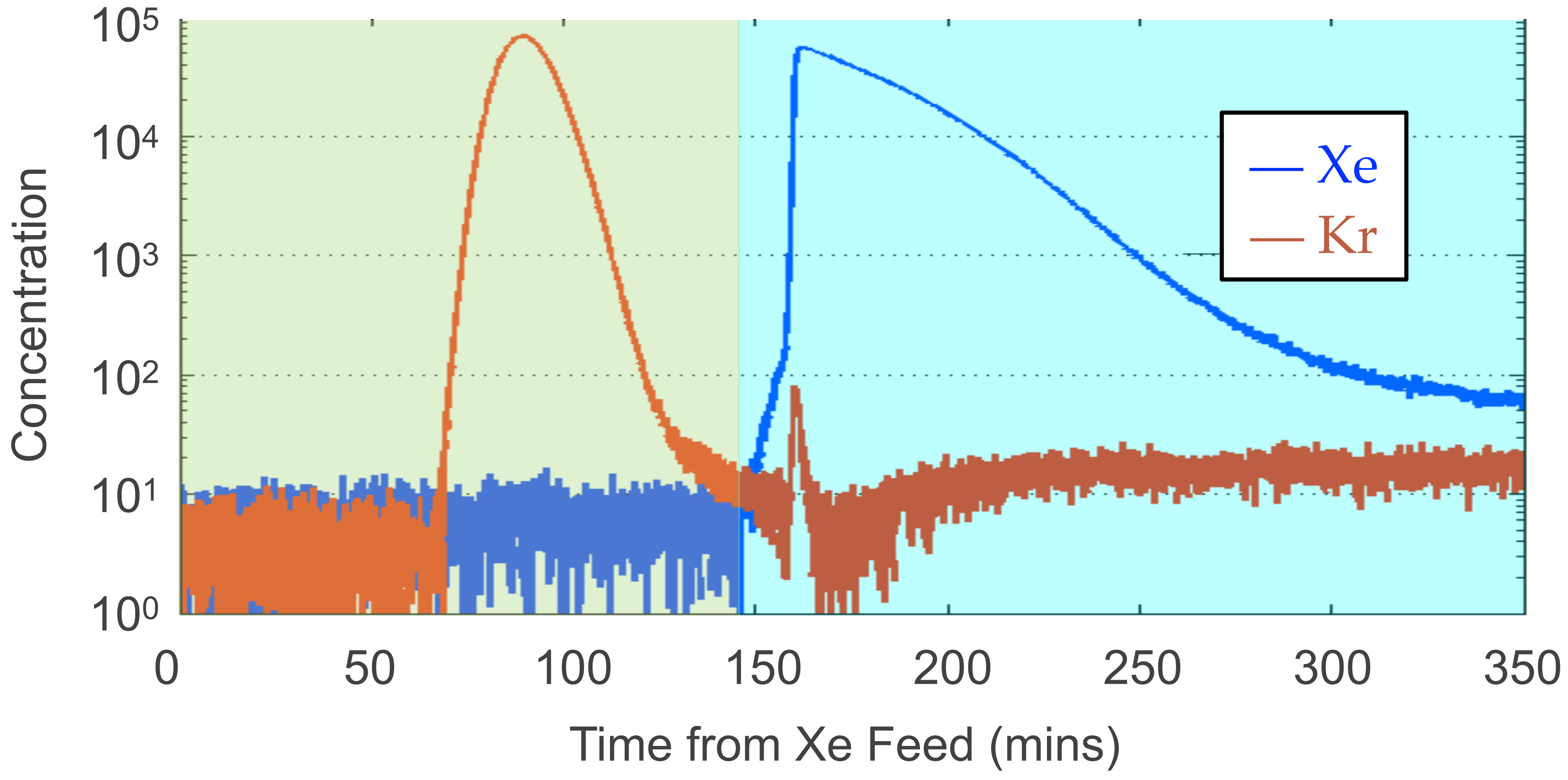
- Based on ~2000 assays with 13 HPGe detectors, ICP-MS, neutron activation analysis

3. Cleanliness Control

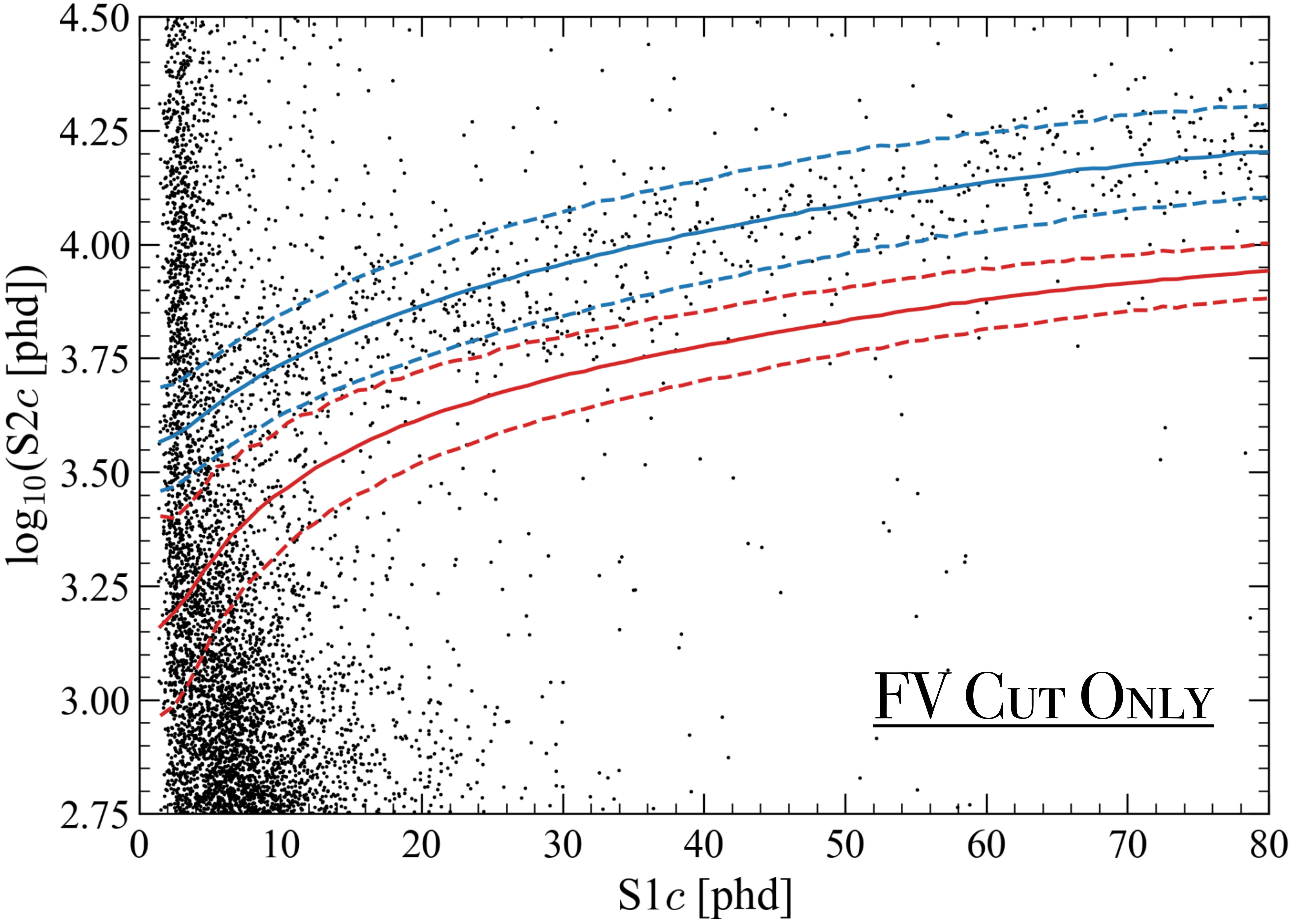
- TPC assembled in Rn-reduced cleanroom
- Dust (<500 ng/cm^3); plate-out (<0.5 mBq/m^2)

4. Xenon Purification

- Chromatography @ SLAC to remove ^{85}Kr, ^{39}Ar
- Online radon reduction system & flow via getter



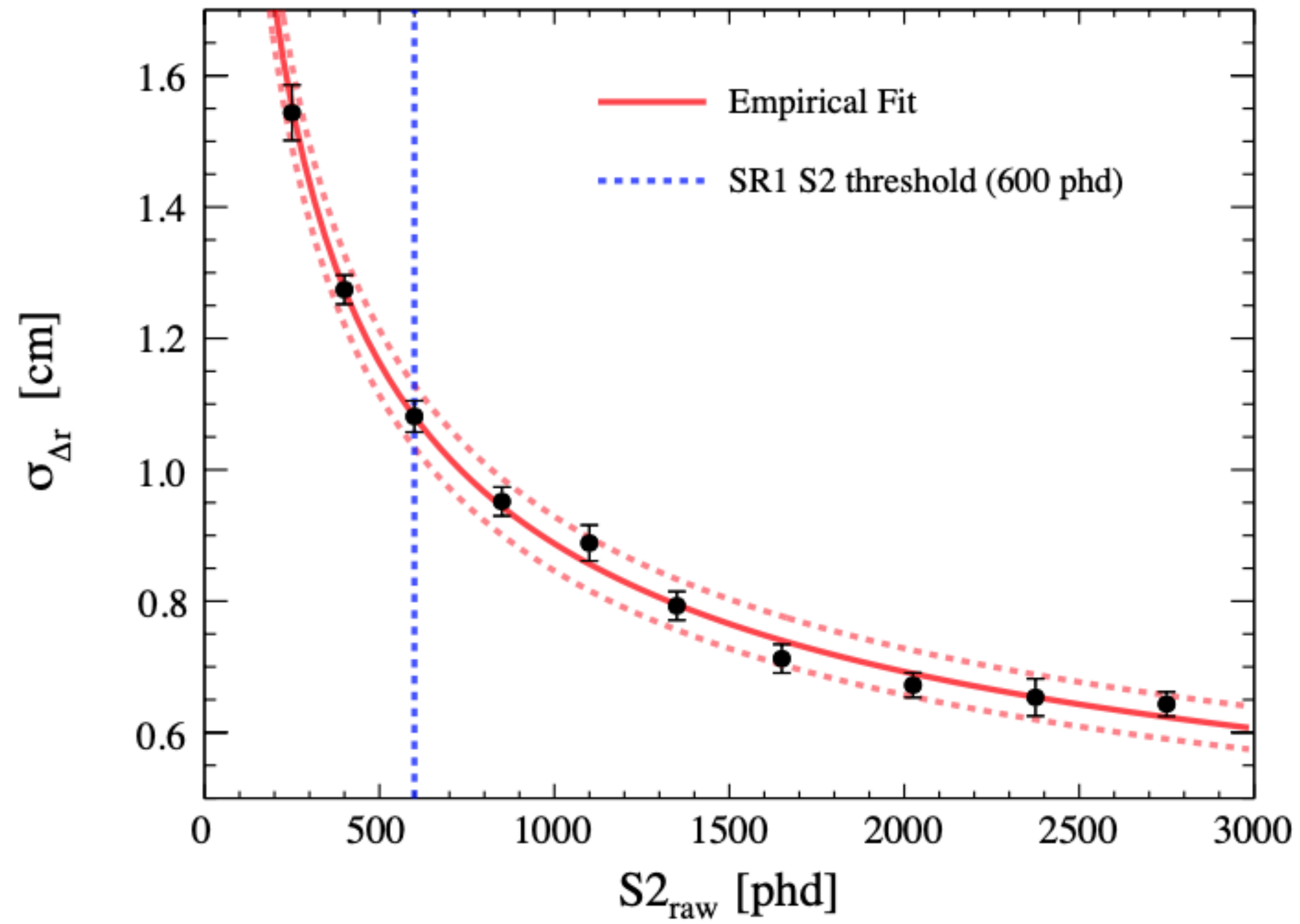
Events After Cuts

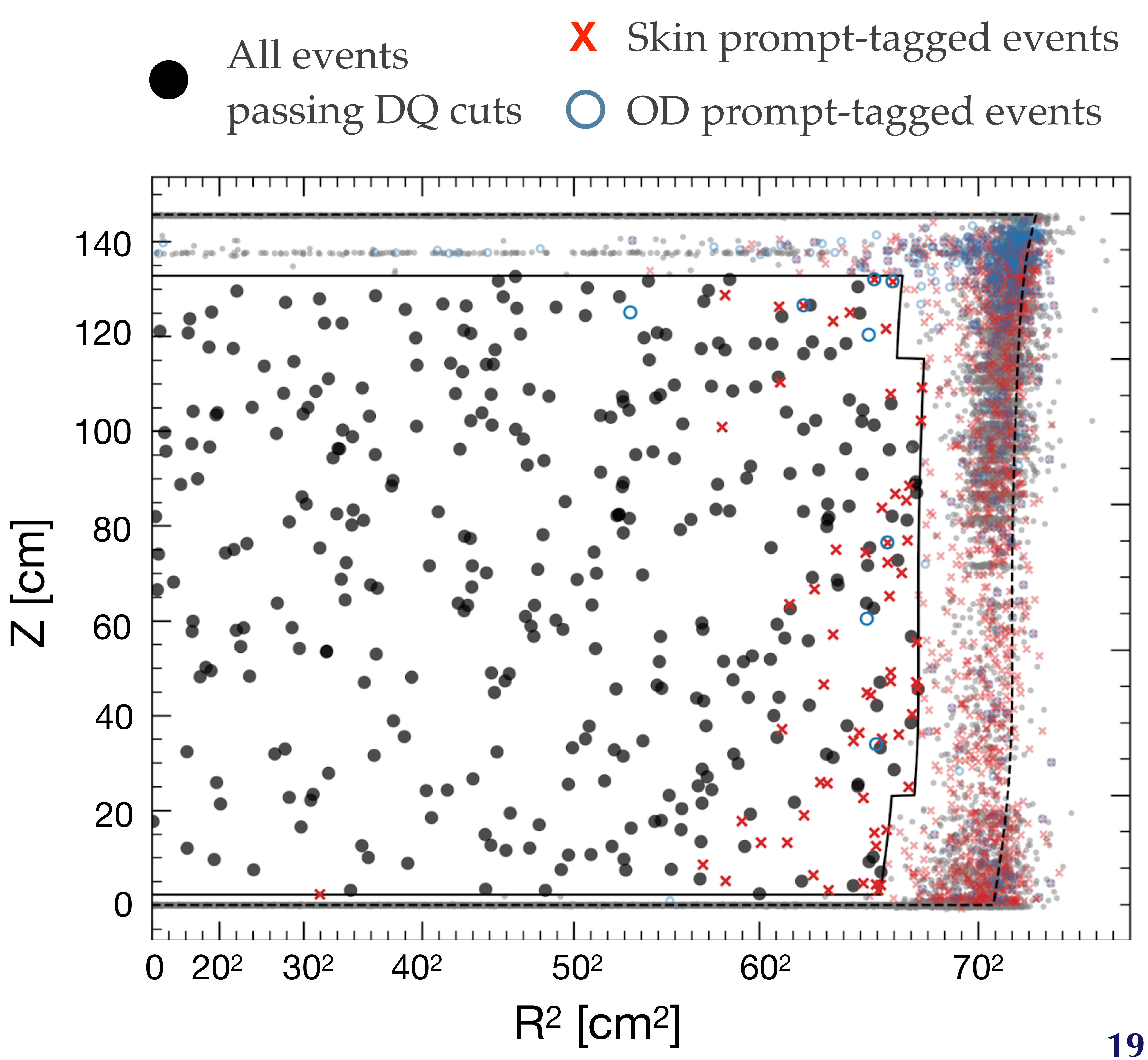


Selection description	Events after selection
All triggers	1.1×10^8
Analysis time hold-offs	6.0×10^7
Single scatter	1.0×10^7
Region-of-interest	1.8×10^5
Analysis cuts for accidentals	3.1×10^4
Fiducial volume	416
OD and Skin vetoes	335

Fiducial Volume Cut

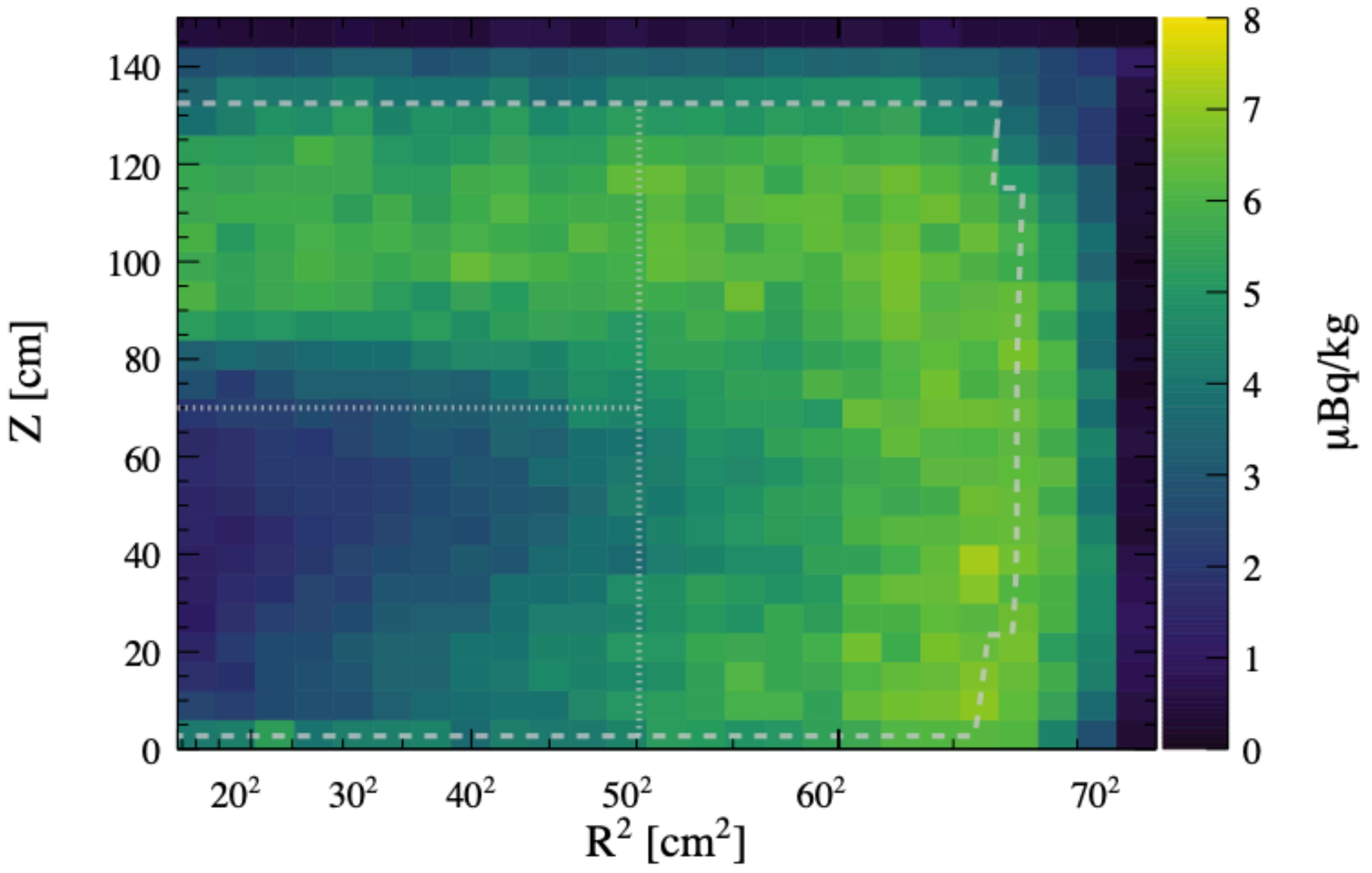
- Vertical cut: 2.2 < Z < 132.8 cm to avoid electrode & surface backgrounds
- Radial cut: R<68.8 cm
  - Partial charge extraction at wall
  - Small S2s -> worse XY reconstruction -> possible leakage radially inwards



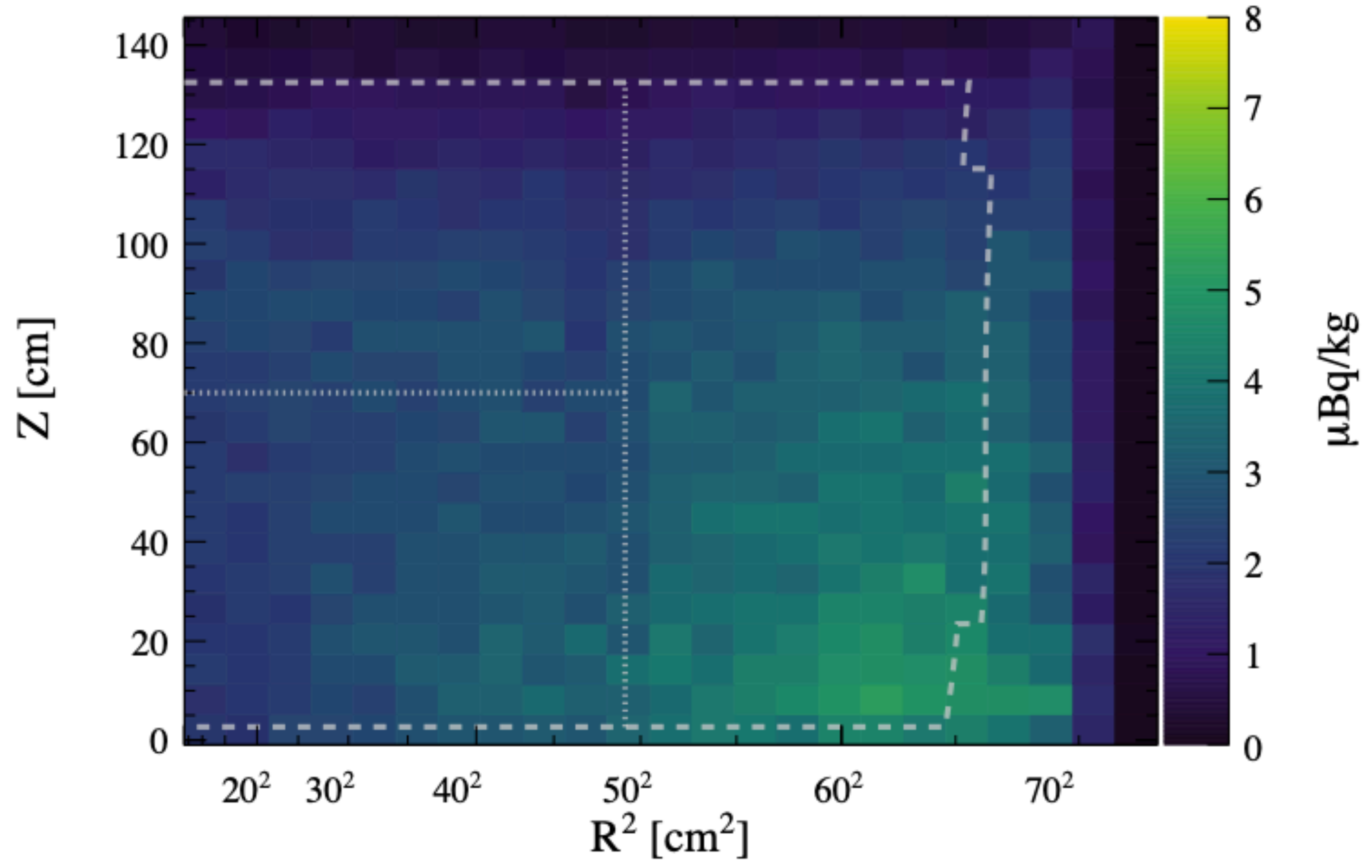


Radon Position Distribution

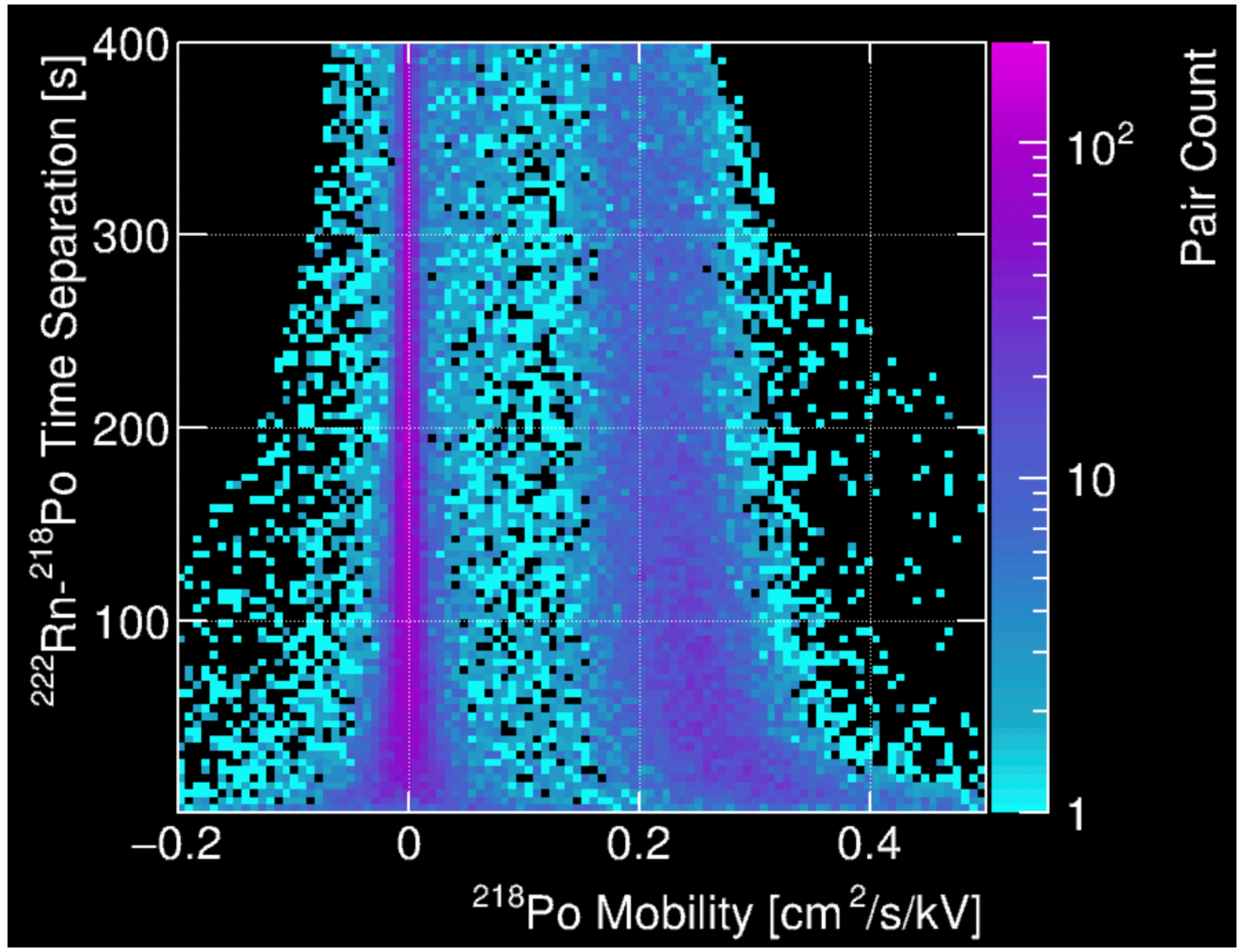
- Radon non-uniform due to slow mixing & thermodynamics

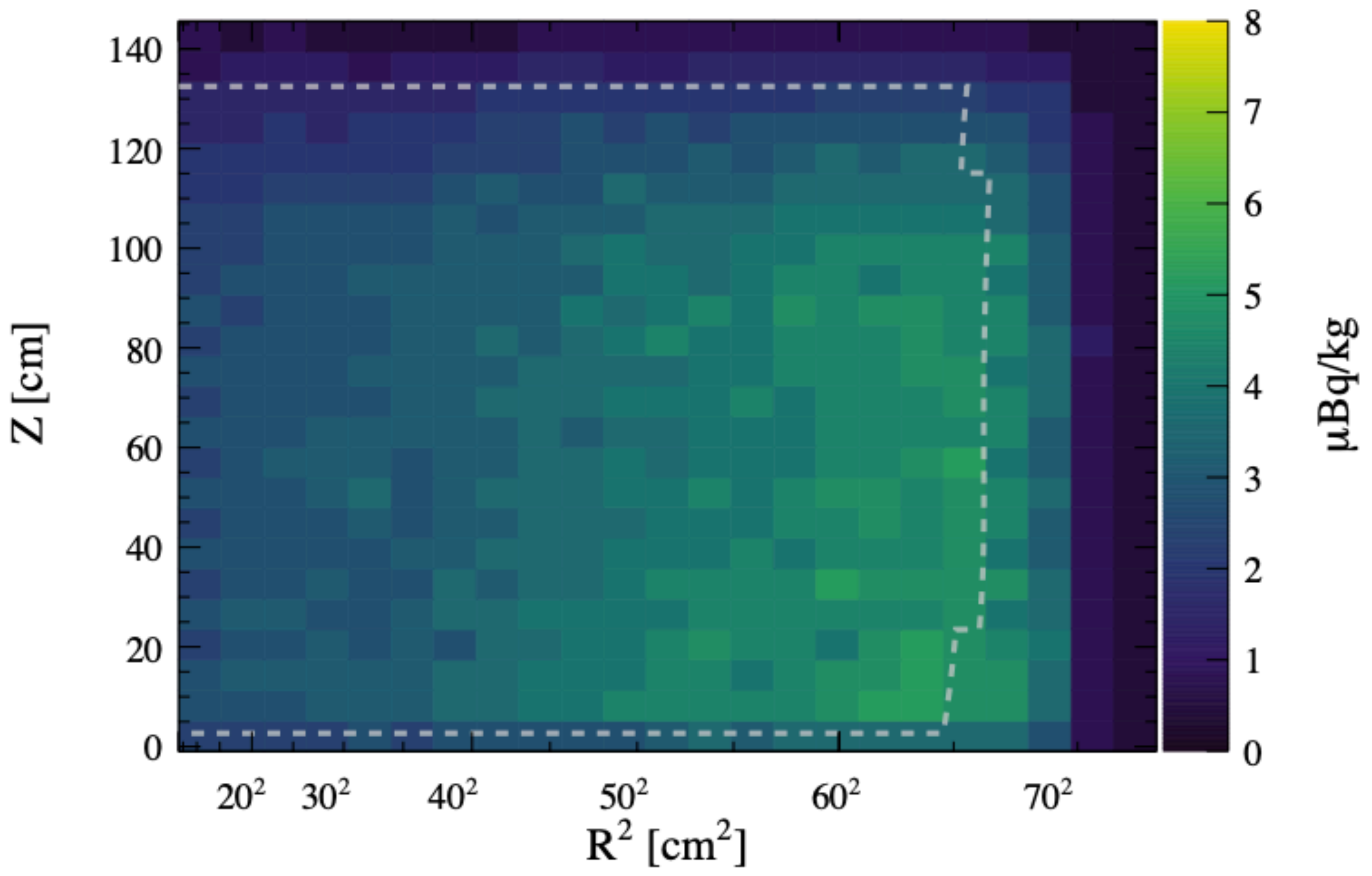


(a) Observed ^{218}Po Distribution

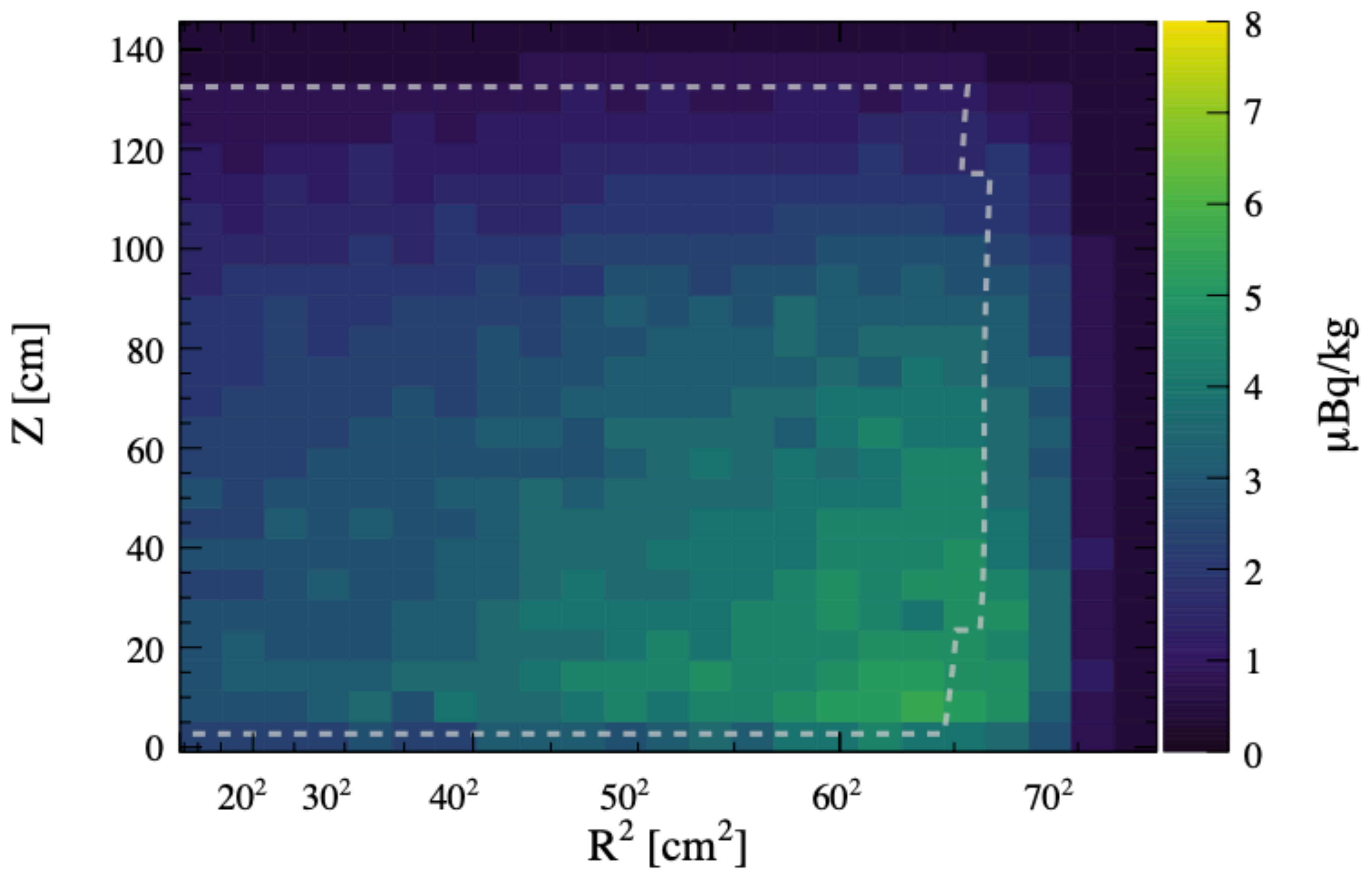


(b) Observed ^{214}Po Distribution





(c) Simulated ^{214}Pb Distribution

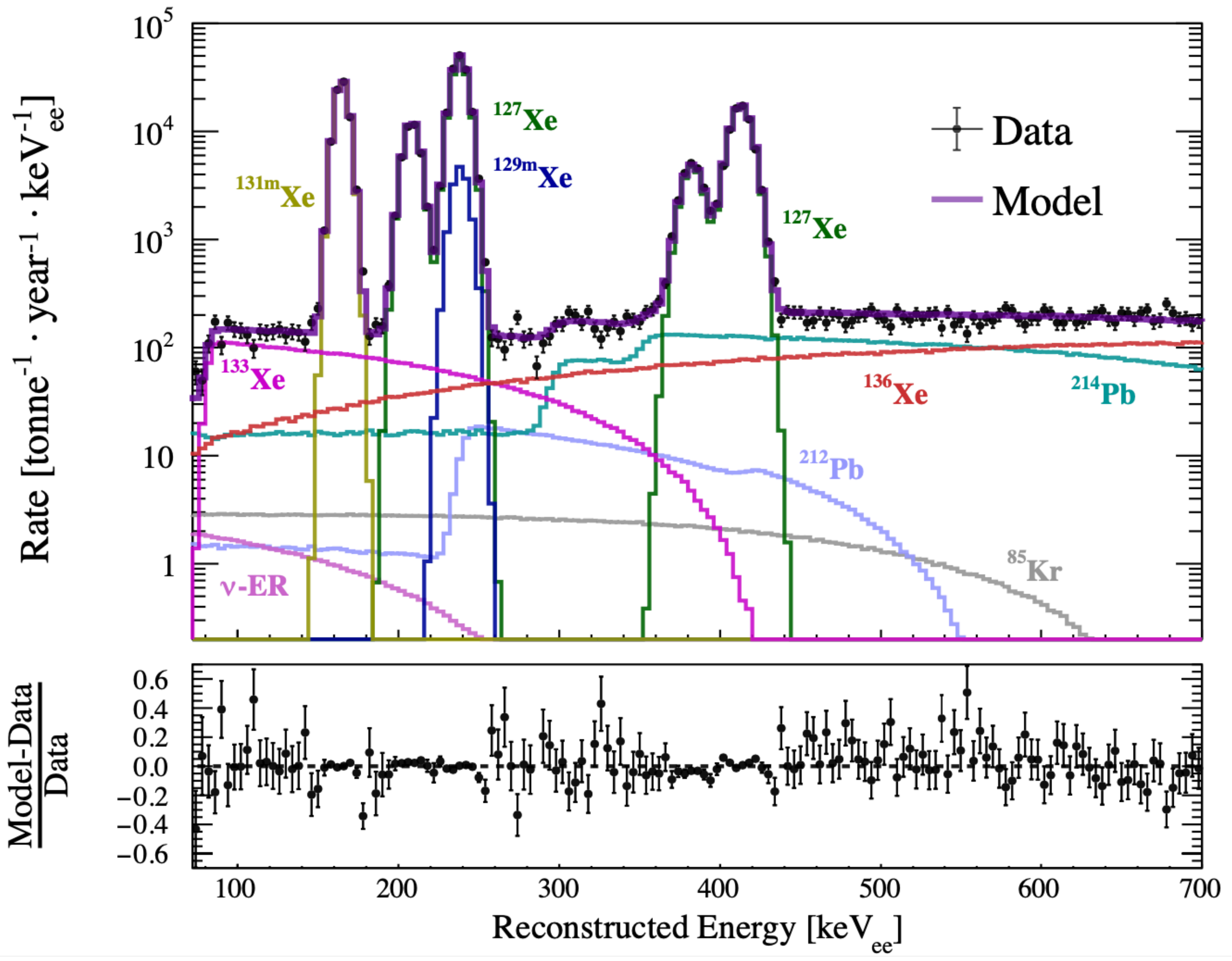


(d) Simulated ^{214}Po Distribution

- Positively charged progeny drift towards the cathode
  - Simulations model this for ^{214}Pb to obtain its distribution

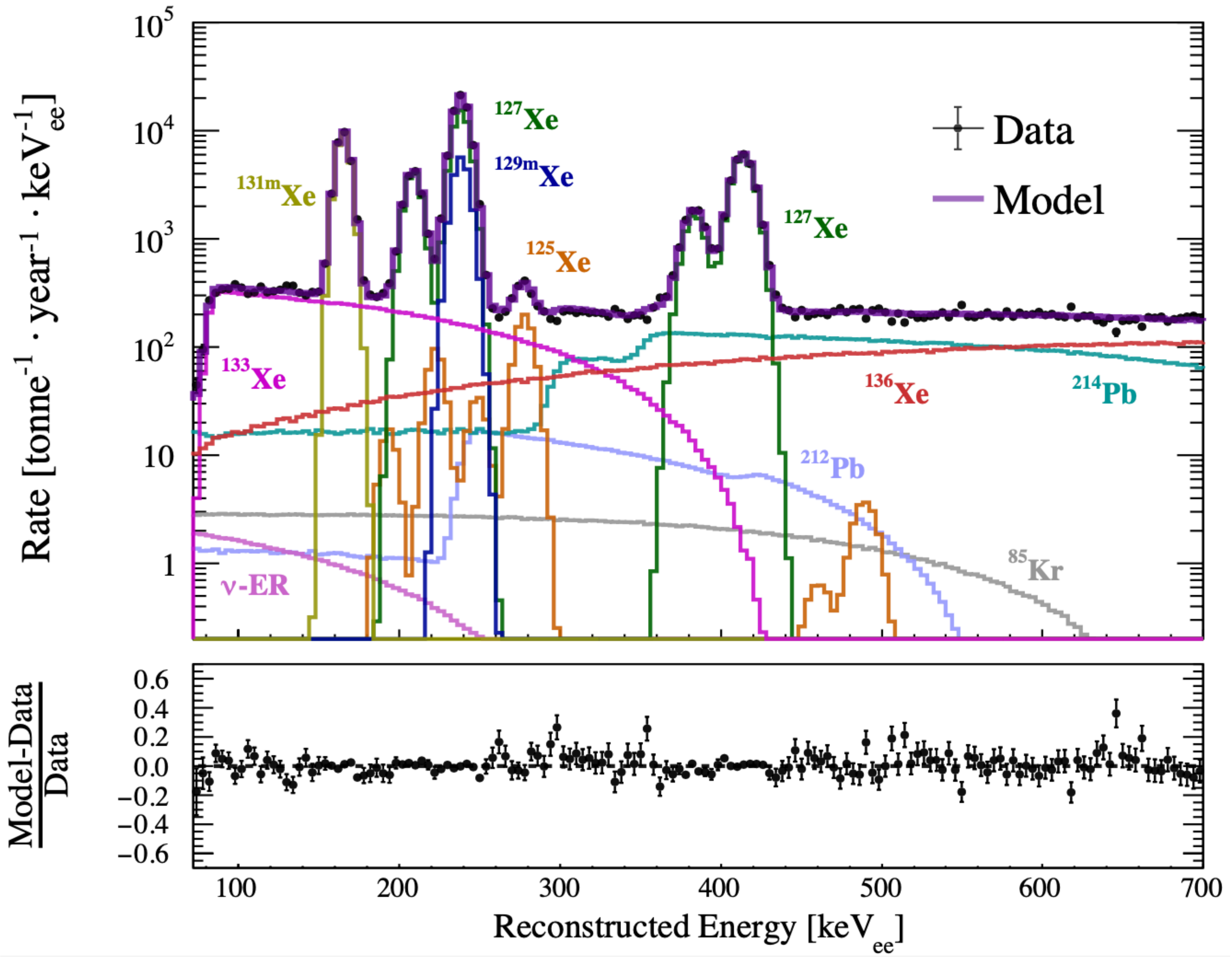
ER Background Fitting

Pre-DD Calibrations



^{214}Pb Rate: 3.05 ± 0.12 μBq/kg

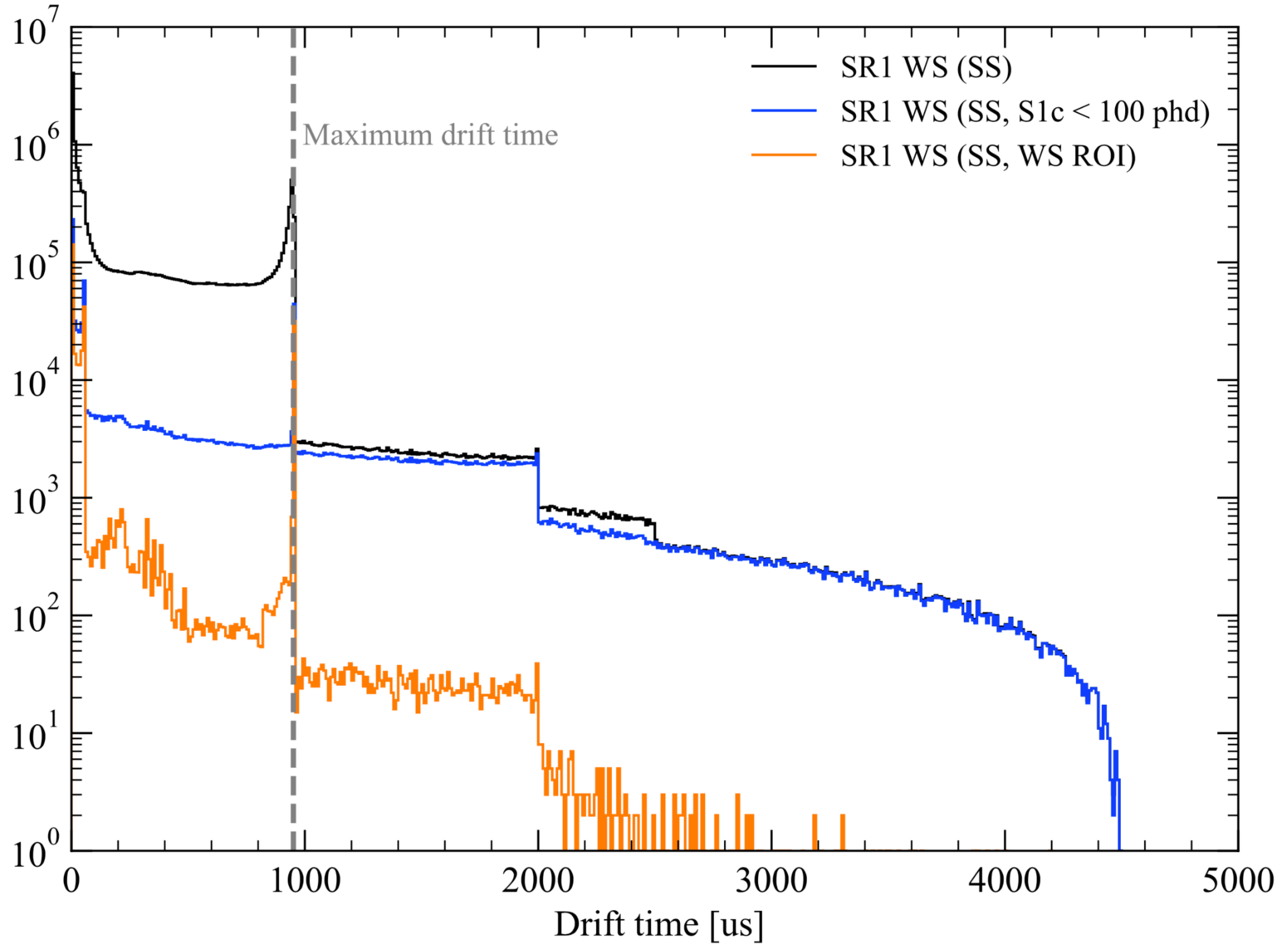
Post-DD Calibrations

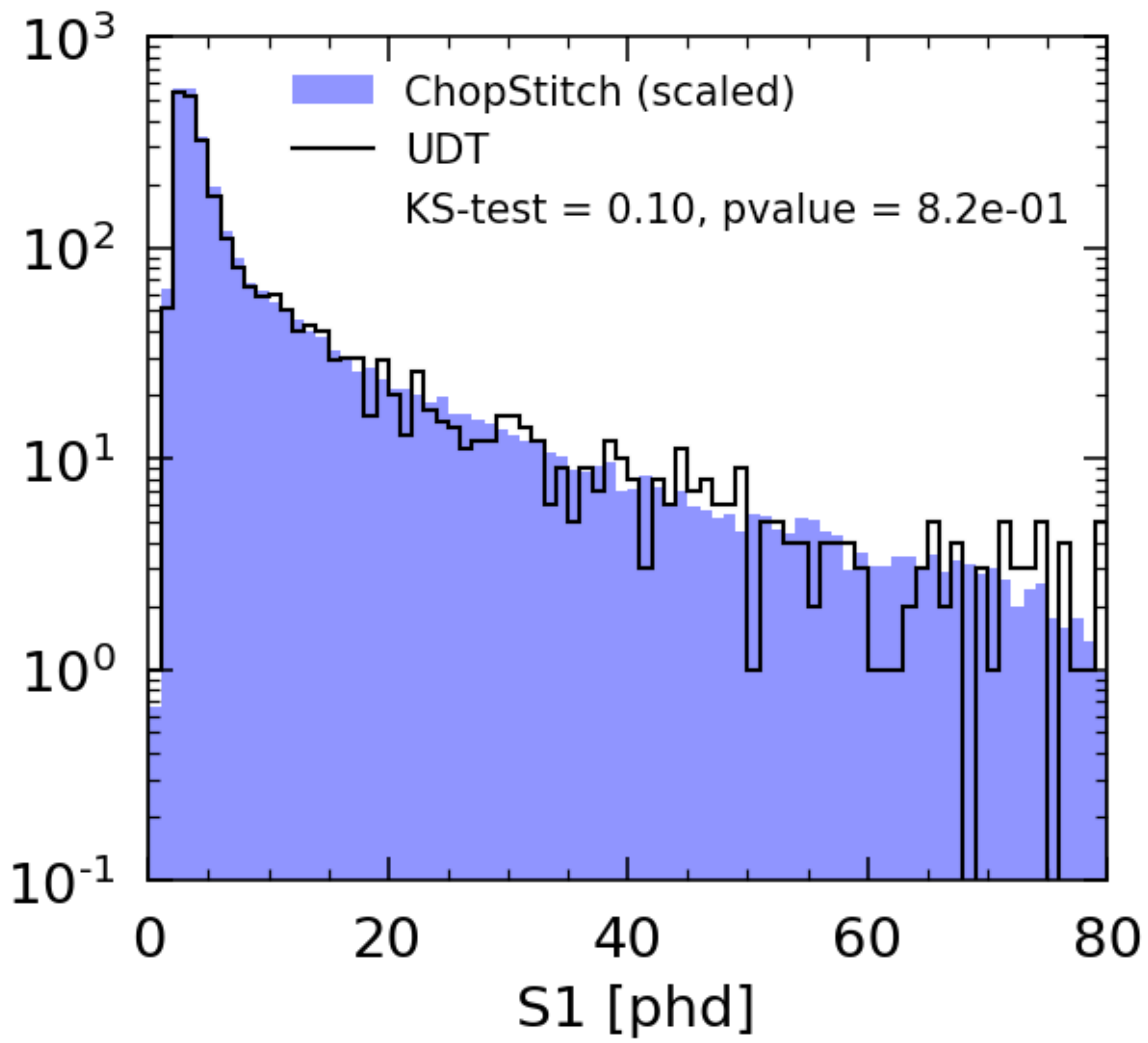


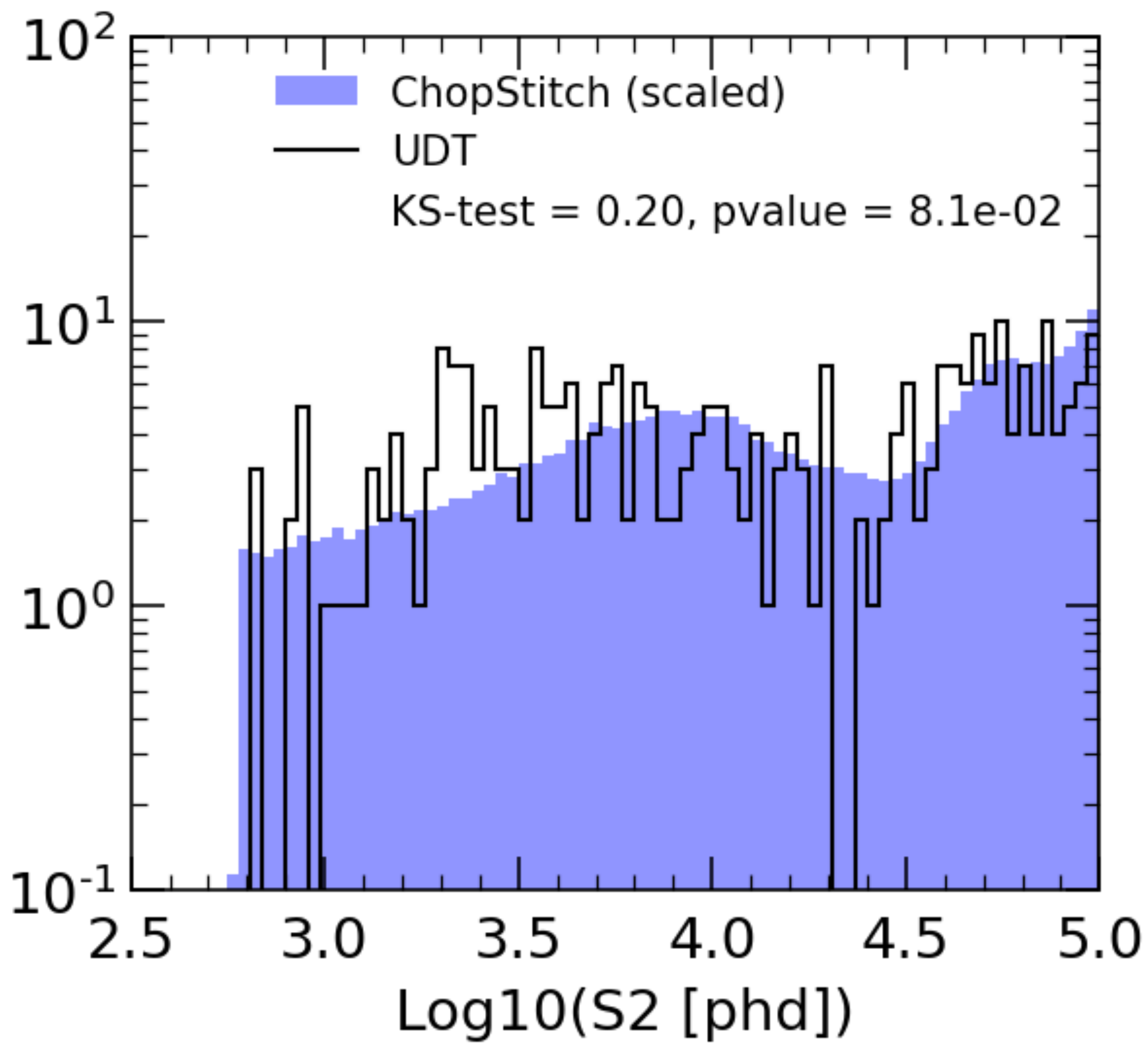
^{214}Pb Rate: 3.10 ± 0.10 μBq/kg

Sources of Isolated Pulses

Accidentals Verification



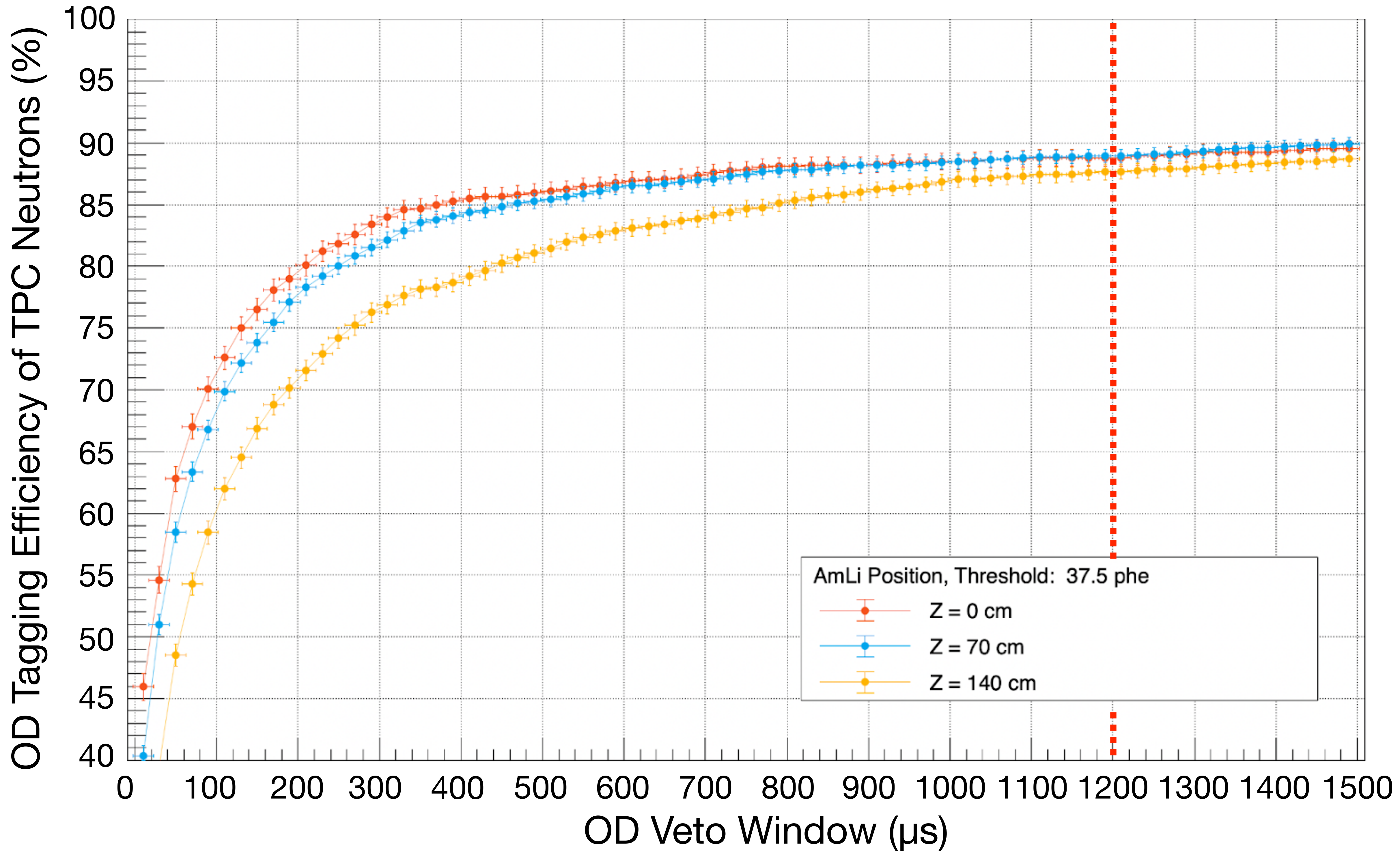


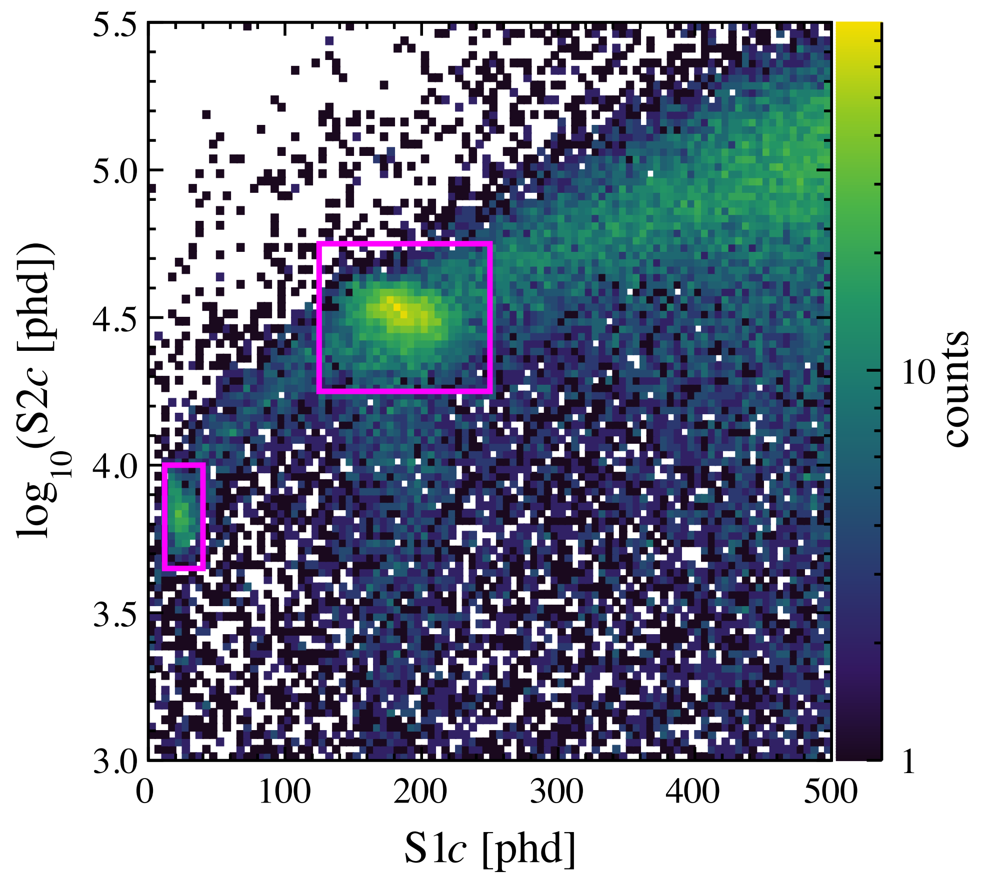


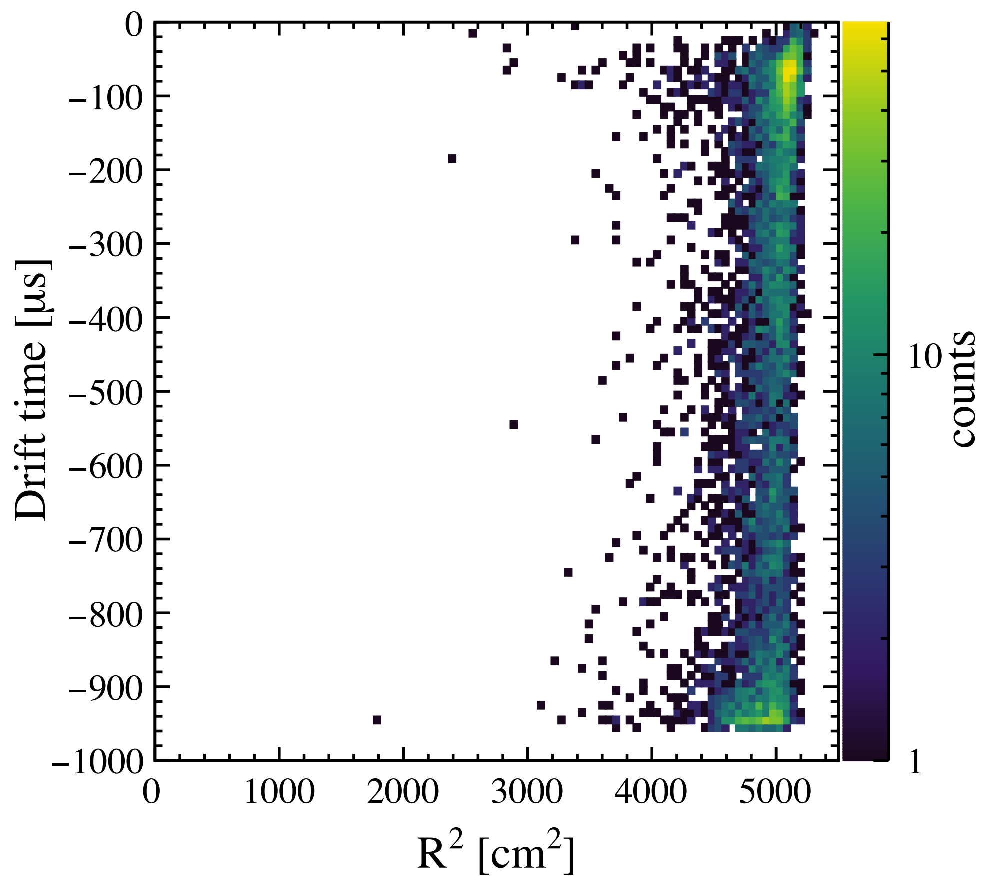
- Unphysical Drift Time (UDT) events: S1 & S2 > one max. drift time apart must be uncorrelated
  - Several checks confirmed the independence of the S1 & S2 variables in UDT data
- Isolated S1 and S2 were combined at the waveform level to form events to probe cut acceptances
  - A good agreement with UDT data was found in several dimensions (pulse size, drift time, etc.)

Veto Detector Responses

- 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 88.5 ± 0.7% (AmLi calibrations)
  - TPC-OD coincidence window: 1200 μs; threshold equivalent to ~200 keV

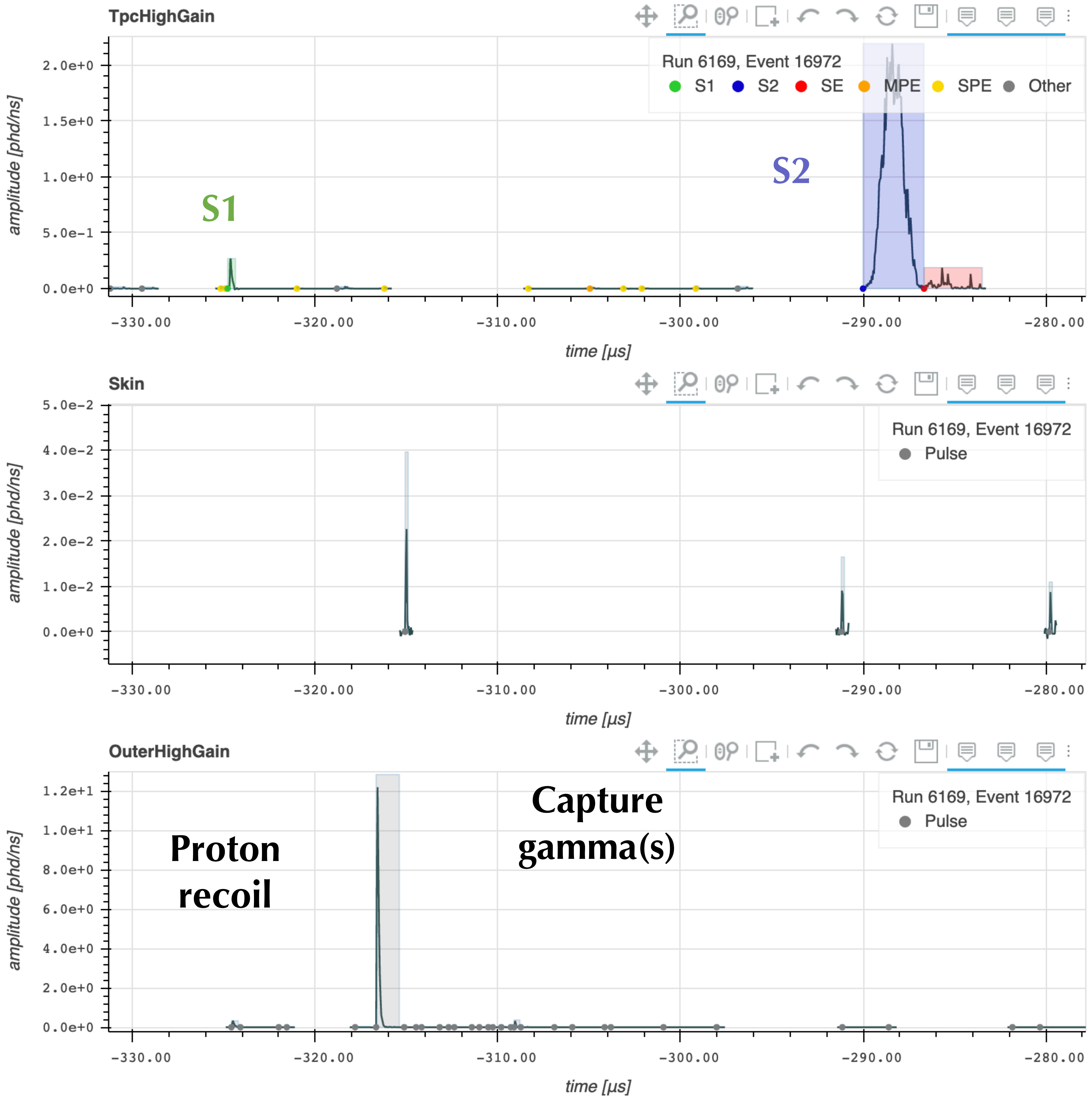


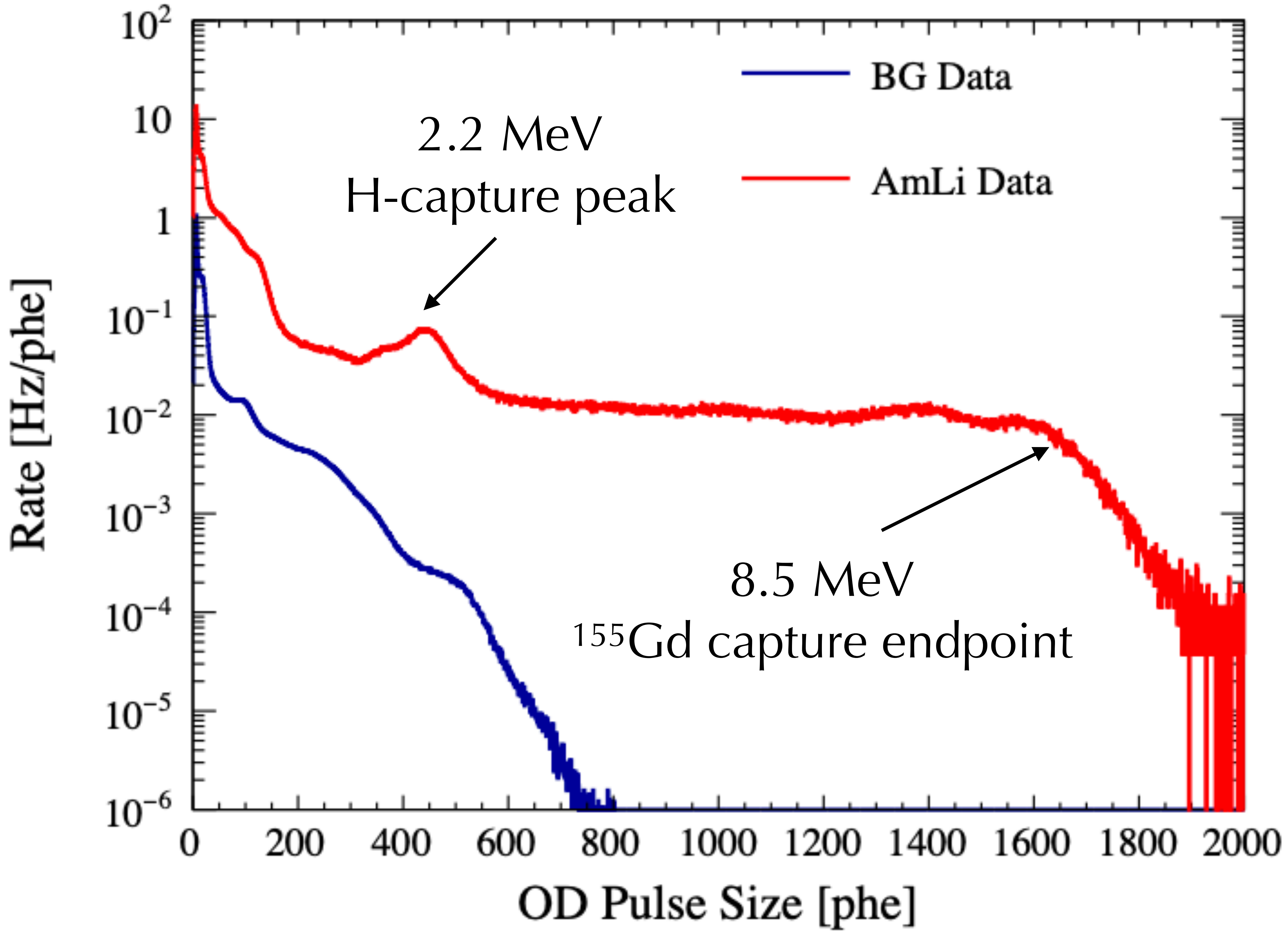




Neutrons in the OD

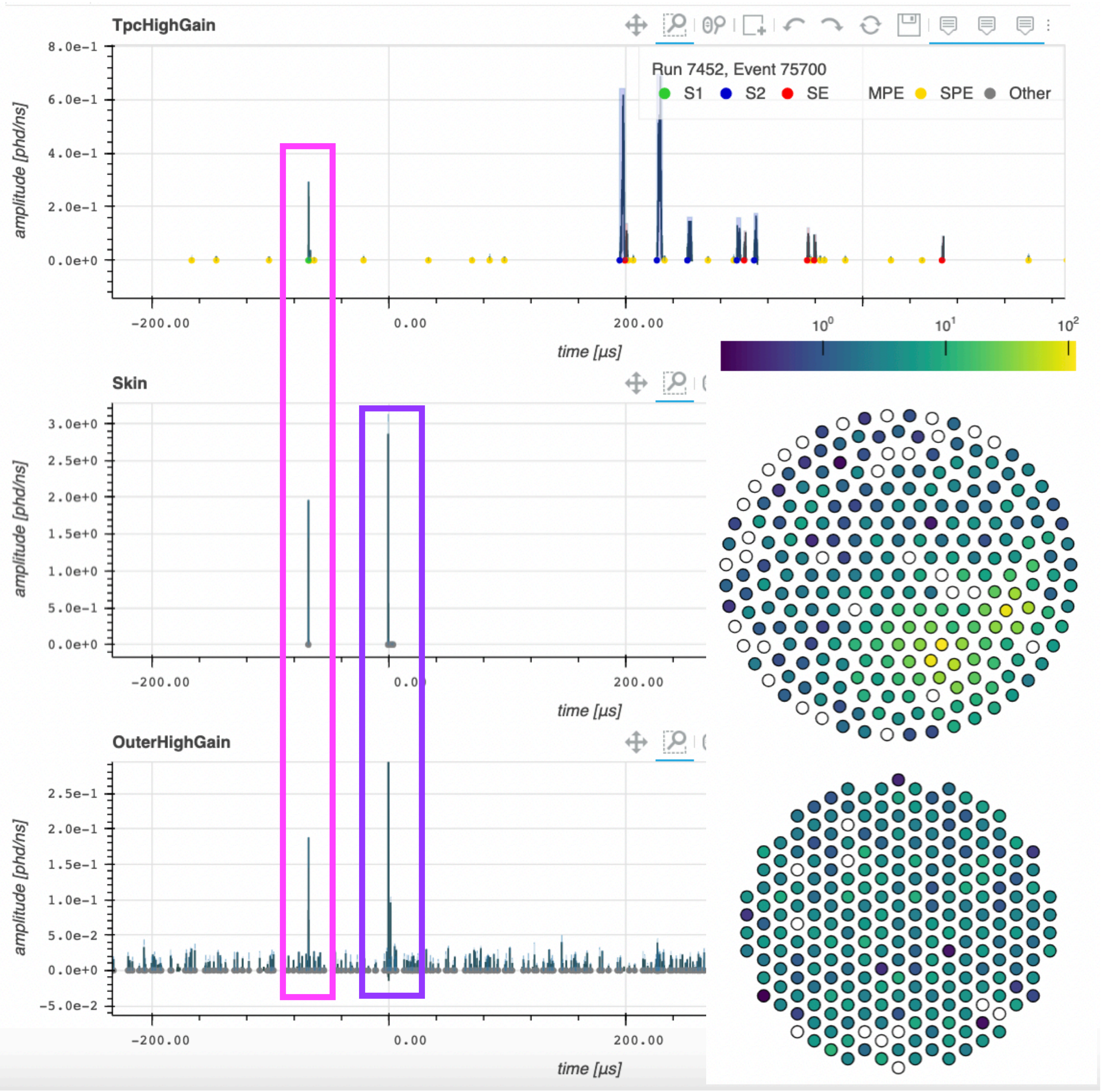
Real LZ AmLi calibration neutron event

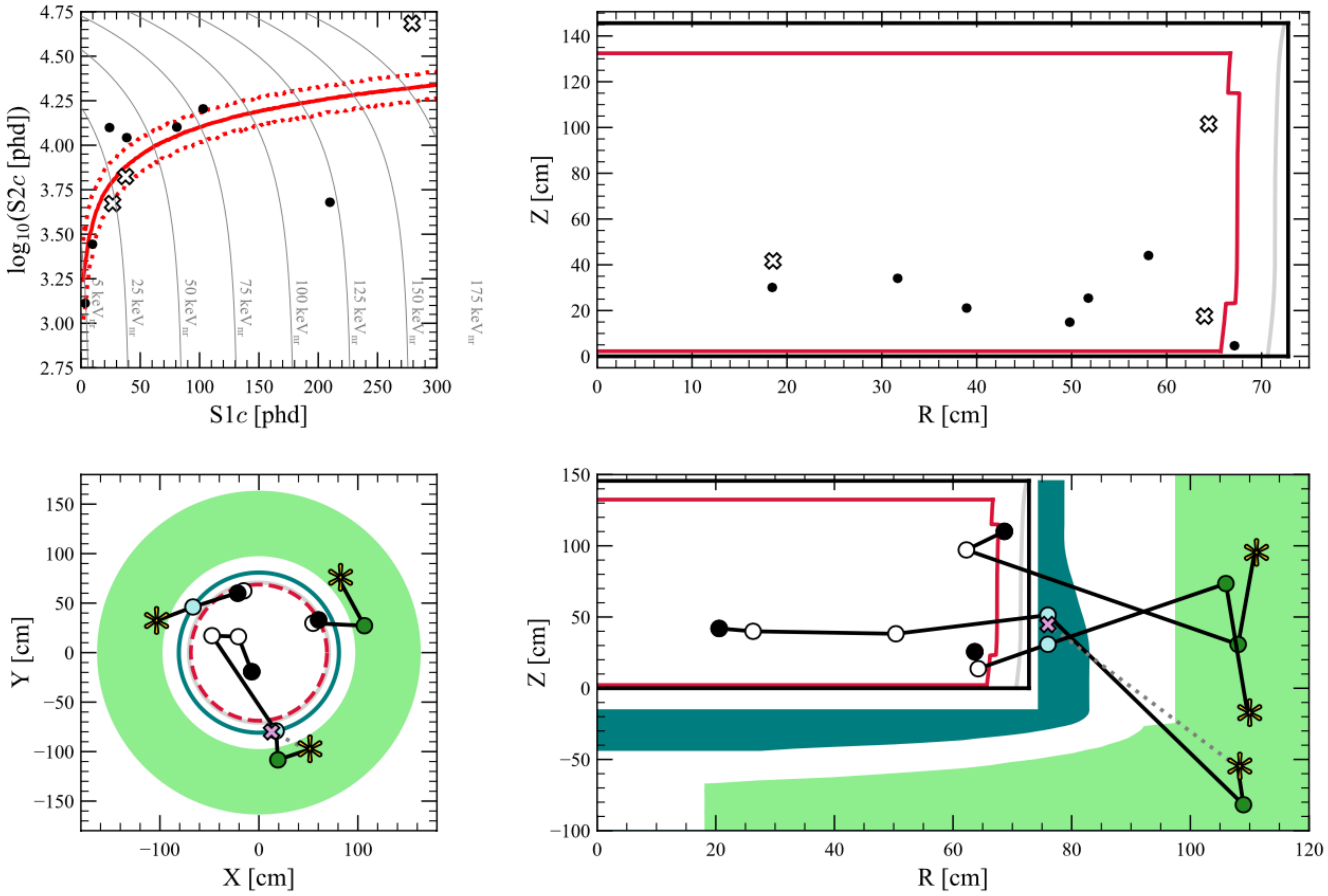




- Neutron capture time on Gd: 30 μs
- Neutron can capture on Gd or H
  - Gd produces 4-5 γ-rays totaling ~8 MeV
  - H produces a 2.2 MeV γ-ray

Neutron Multiple Scatter Events





- Look for multiple scatter events with neutron captures in the OD (>400 phd)
- 10 neutrons found -> suggests none present in the WIMP search data

Neutrino Backgrounds (and Signal)

- Solar neutrinos can produce both ERs from ν-e scatters and NRs from coherent ν-nucleus scatters (CEvNS)
- Rates are predicted from external experimental and theoretical work
- ν-e scatters produce a flat spectrum
- The coherent scattering of solar neutrinos with Xe nuclei (CEνNS) is an irreducible background
  - In SR1, B8 CEvNS gave 0.15 events
    - Mostly excluded via S2 threshold
  - LZ will measure this signal