FIRST WIMP SEARCH RESULTS FROM THE LUX-ZEPLIN EXPERIMENT

Amy Cottle, University of Oxford

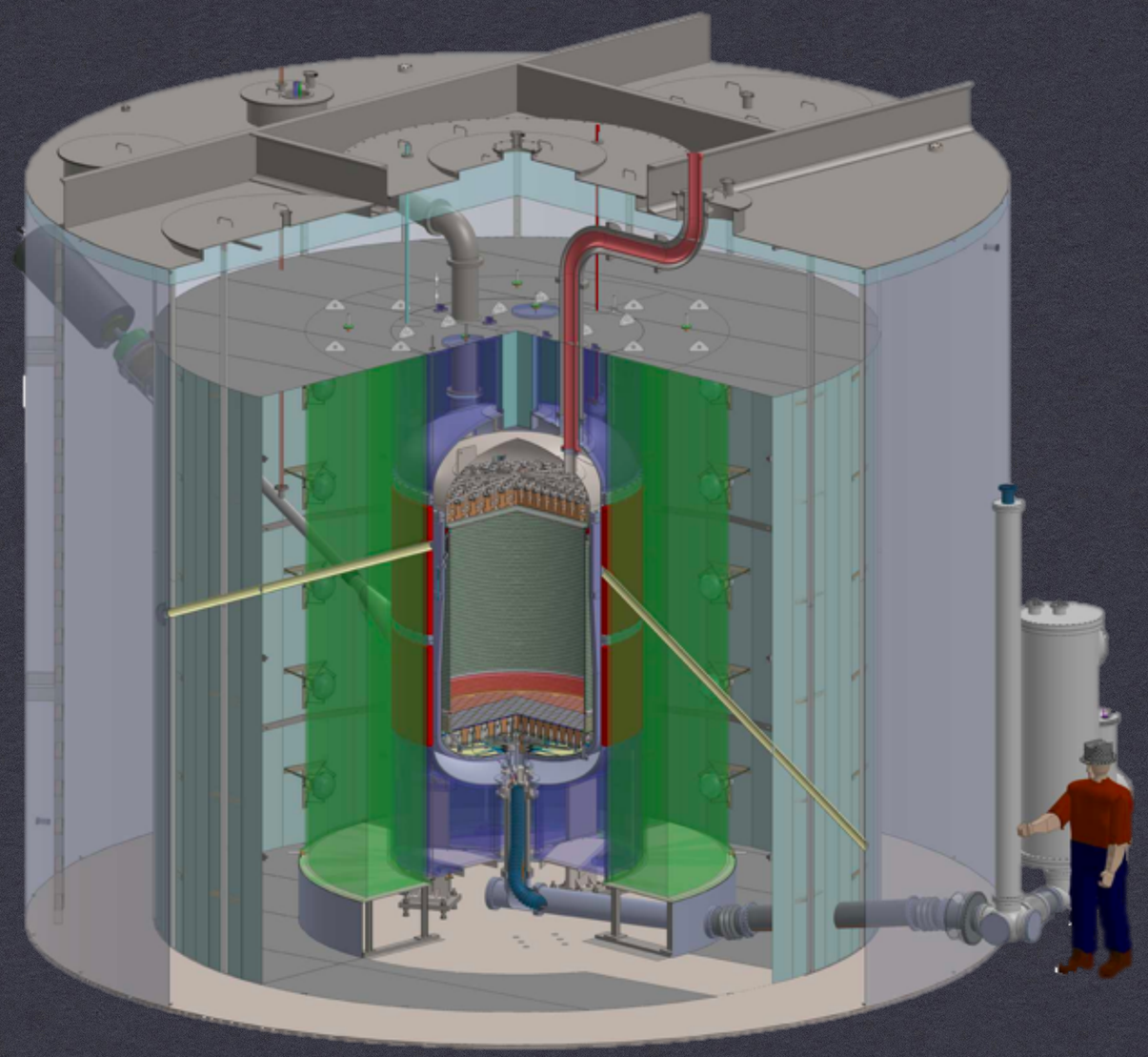
COLLABORATION

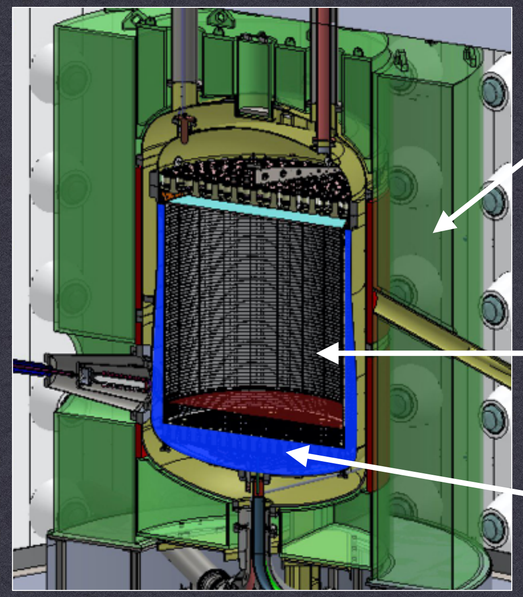
@lzdarkmatter

https://lz.lbl.gov/

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

INTRODUCTION TO LZ



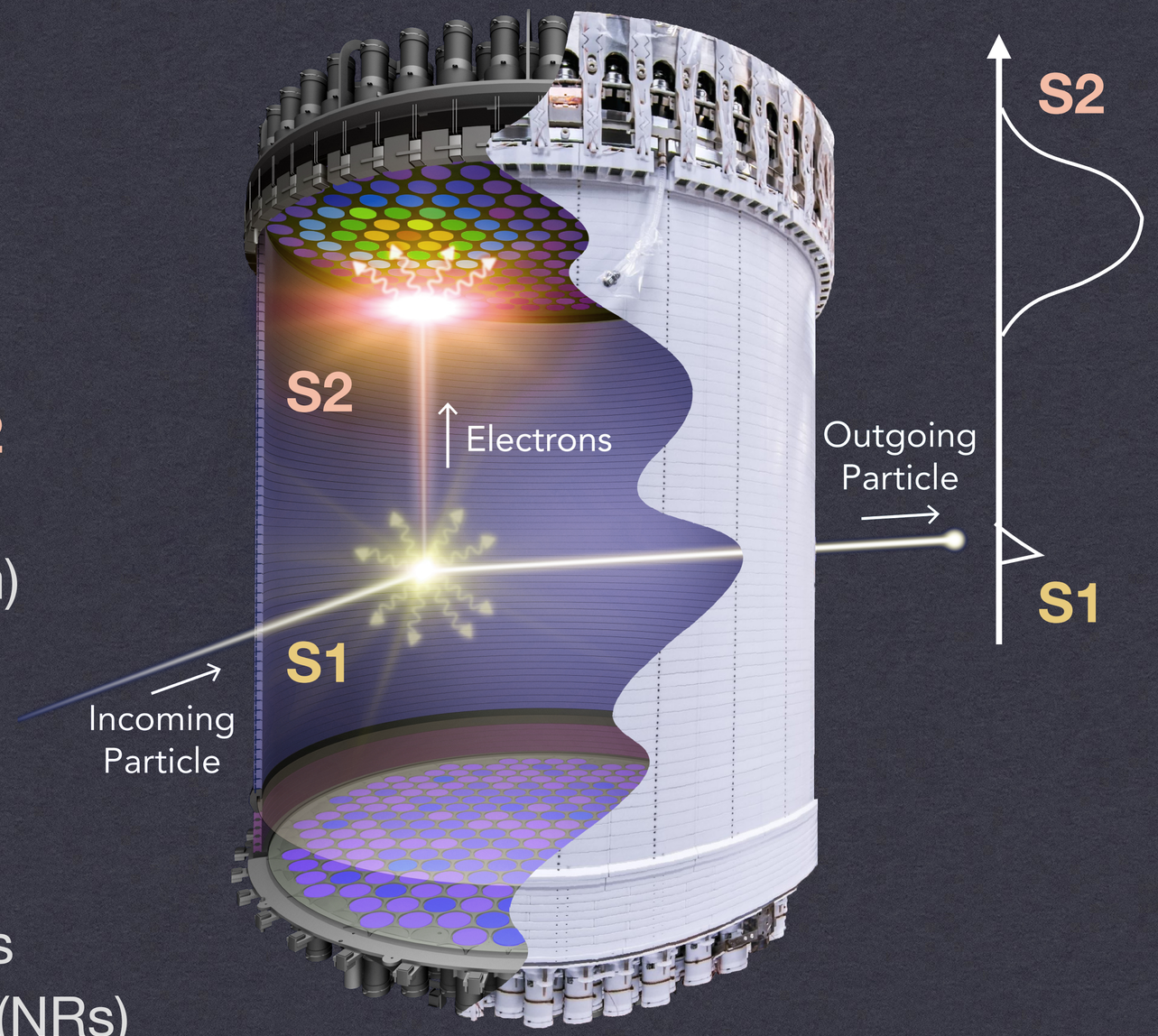


- Based at the Sanford Underground Research Facility (SURF) in Lead, SD
- Dual-phase xenon time projection chamber (TPC) with 7 t active xenon
- Skin & outer detector (OD) veto systems

NIM A, 163047 (2019)

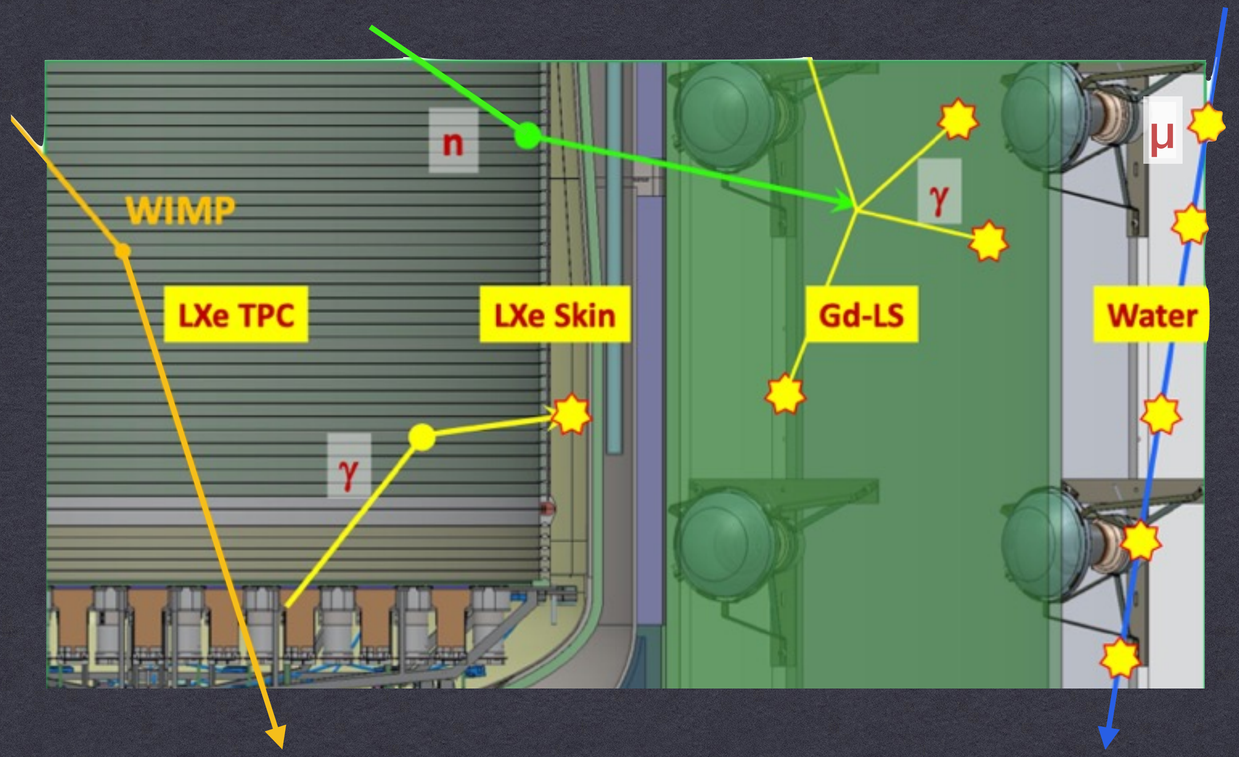
TPC DETECTION PRINCIPLE

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

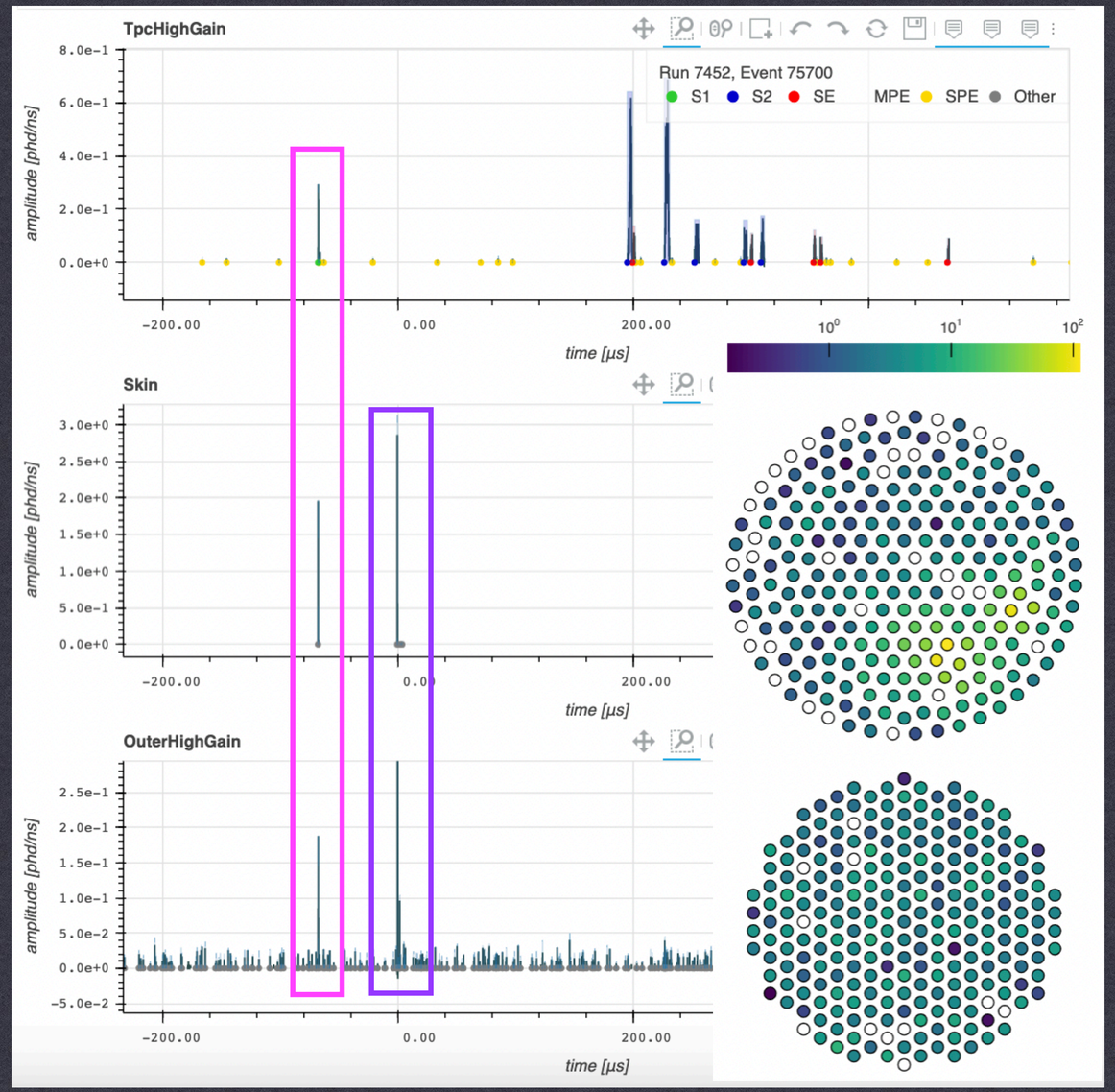


VETO DETECTOR ANTI-COINCIDENCE

- 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

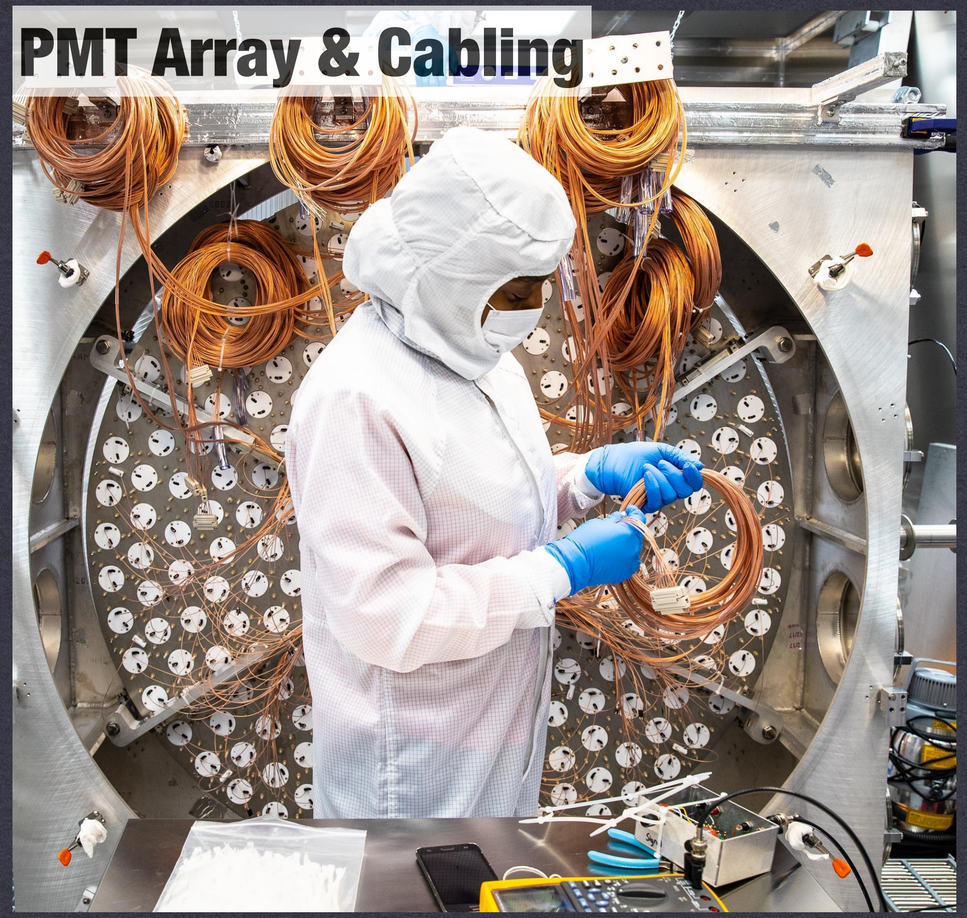


Example Neutron Event



TPC & SKIN ASSEMBLY

TPC Field Cage


PMT Array & Cabling


Bottom Dome Skin PMTs

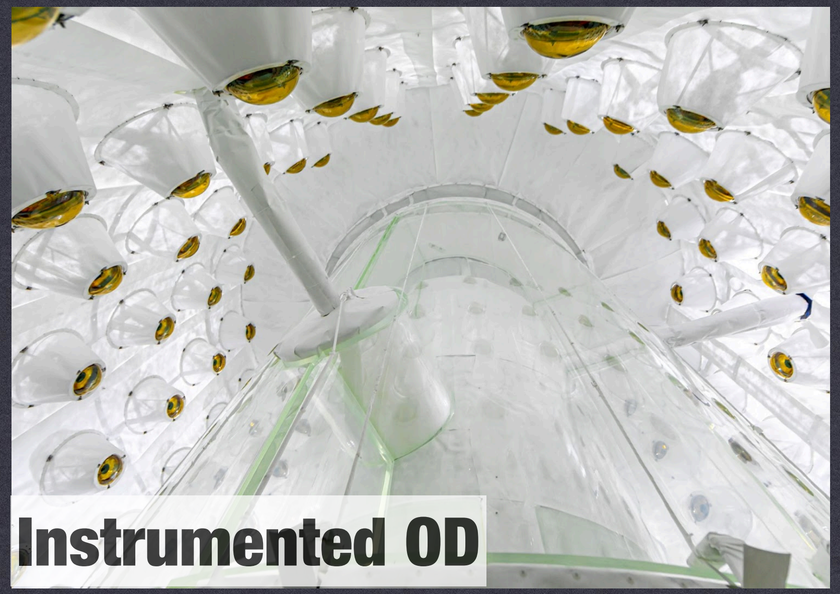

Bottom Side Skin PMTs


UV Inspection

OD CONSTRUCTION & UNDERGROUND INSTALLATION

Water Tank Panoramic

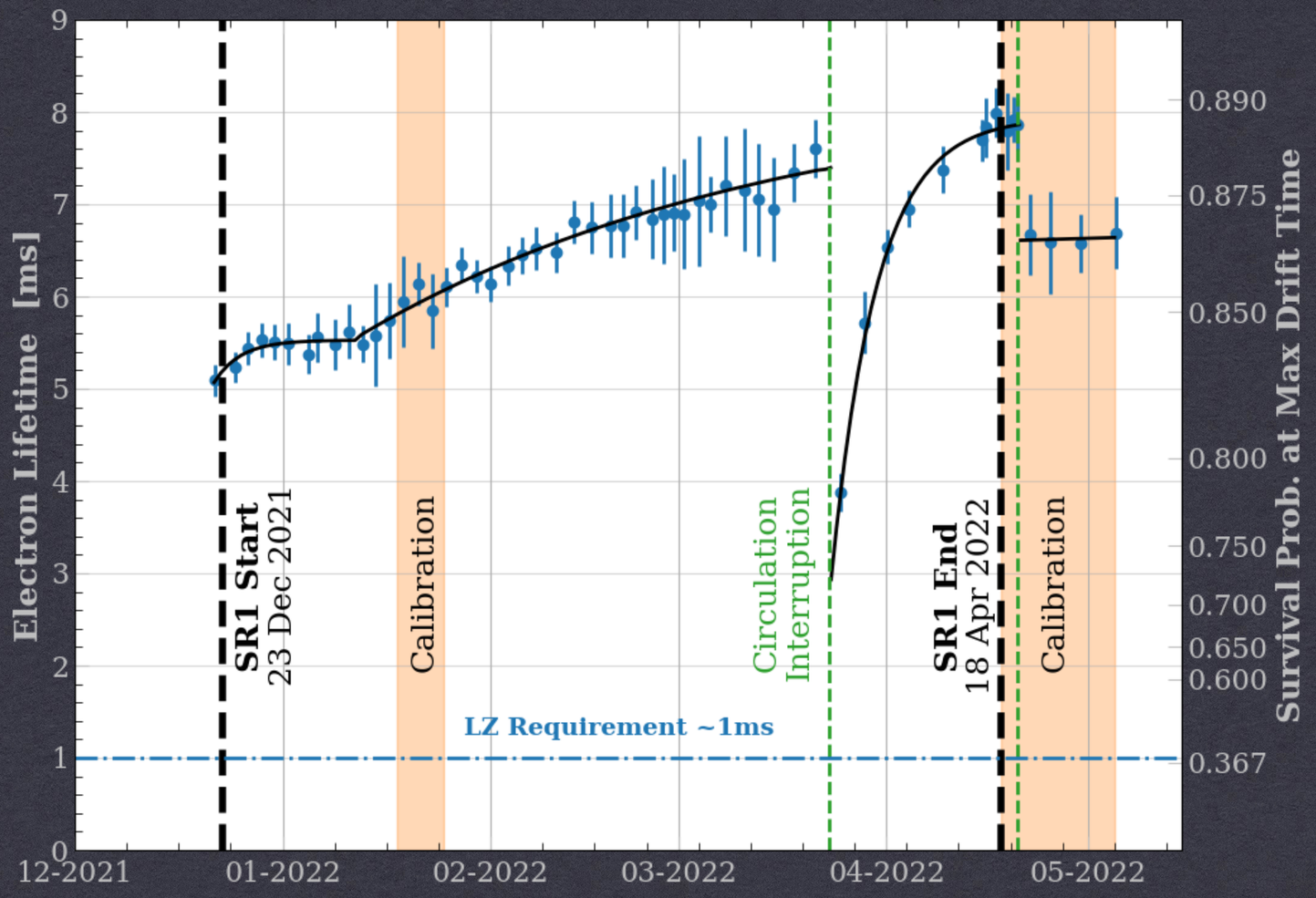
Cryostat Insertion



Instrumented OD

FIRST SCIENCE RUN (SR1)

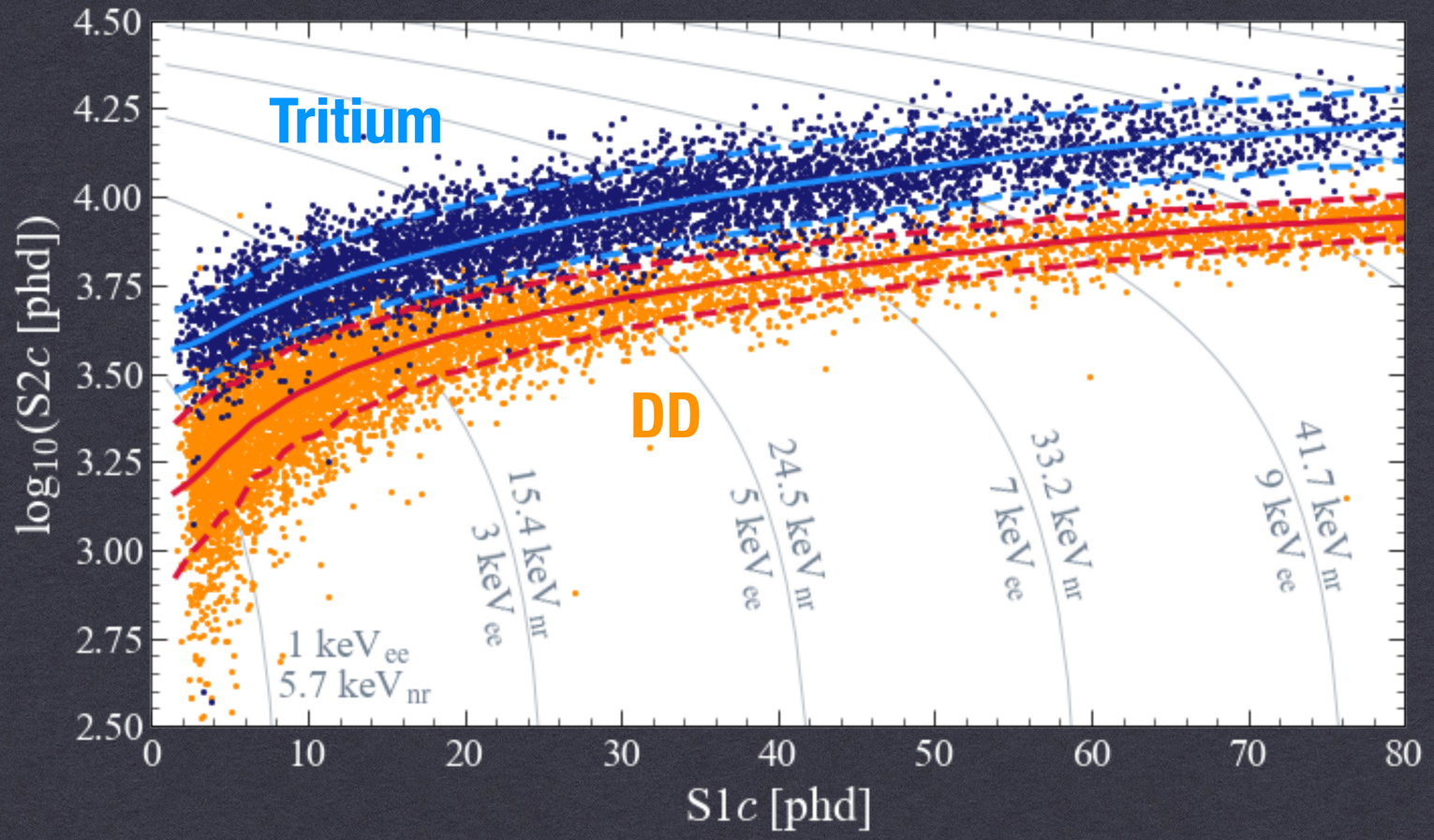
- 116 calendar days -> 89 live days
- Stable detector conditions
  - Temperature of 174.1 K
  - Gas pressure of 1.791 bar
  - Drift field of 193 V/cm
  - Extraction field of 7.3 kV/cm (in gas)
- Continuous purification at 3.3 t/day through hot getter system
- **Demonstration run, not blinded**



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^-

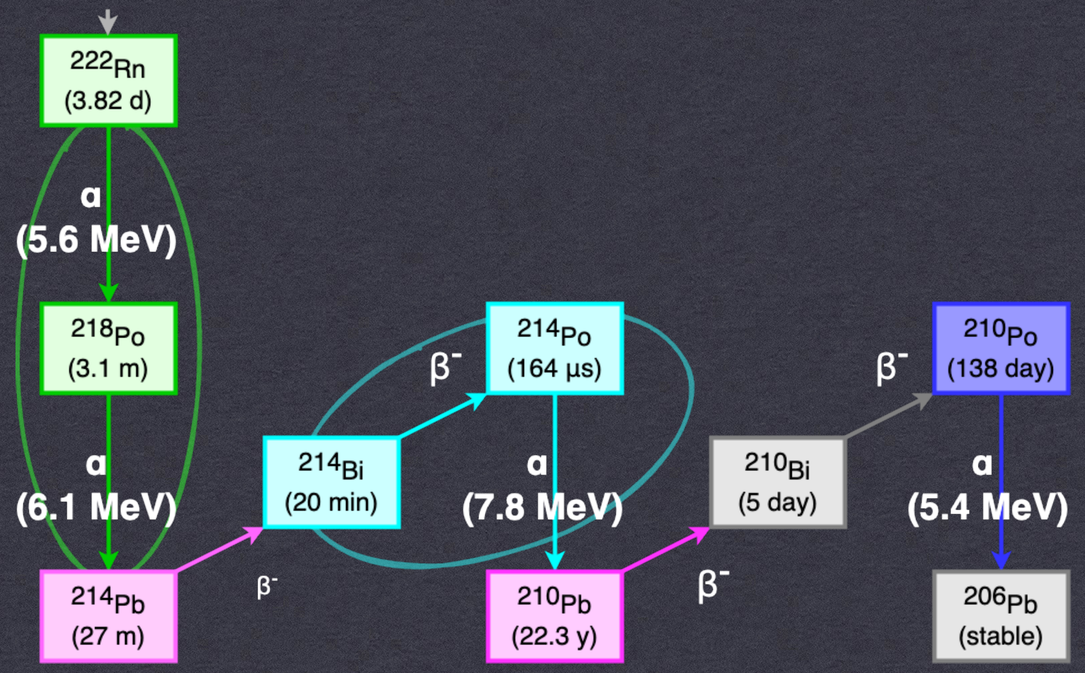
Band fits performed with NEST v2.3.7

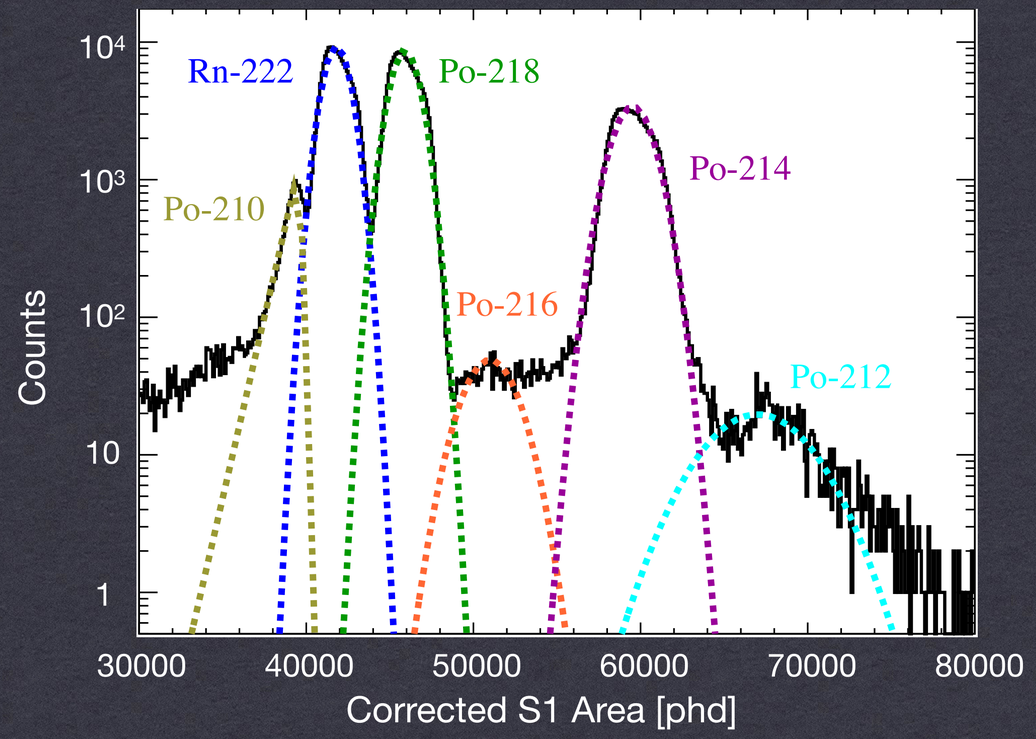
RADON BACKGROUNDS

- Naked Pb β decays **main** WIMP background
  - Produced from emanated Rn in TPC xenon
- Rn-chain alpha tagging measurements performed with S1s at energies >> WIMP ROI

Rn222 (μBq/kg)	Po218 (μBq/kg)	Po214 (μBq/kg)
4.37 ± 0.31	4.51 ± 0.32	2.56 ± 0.21

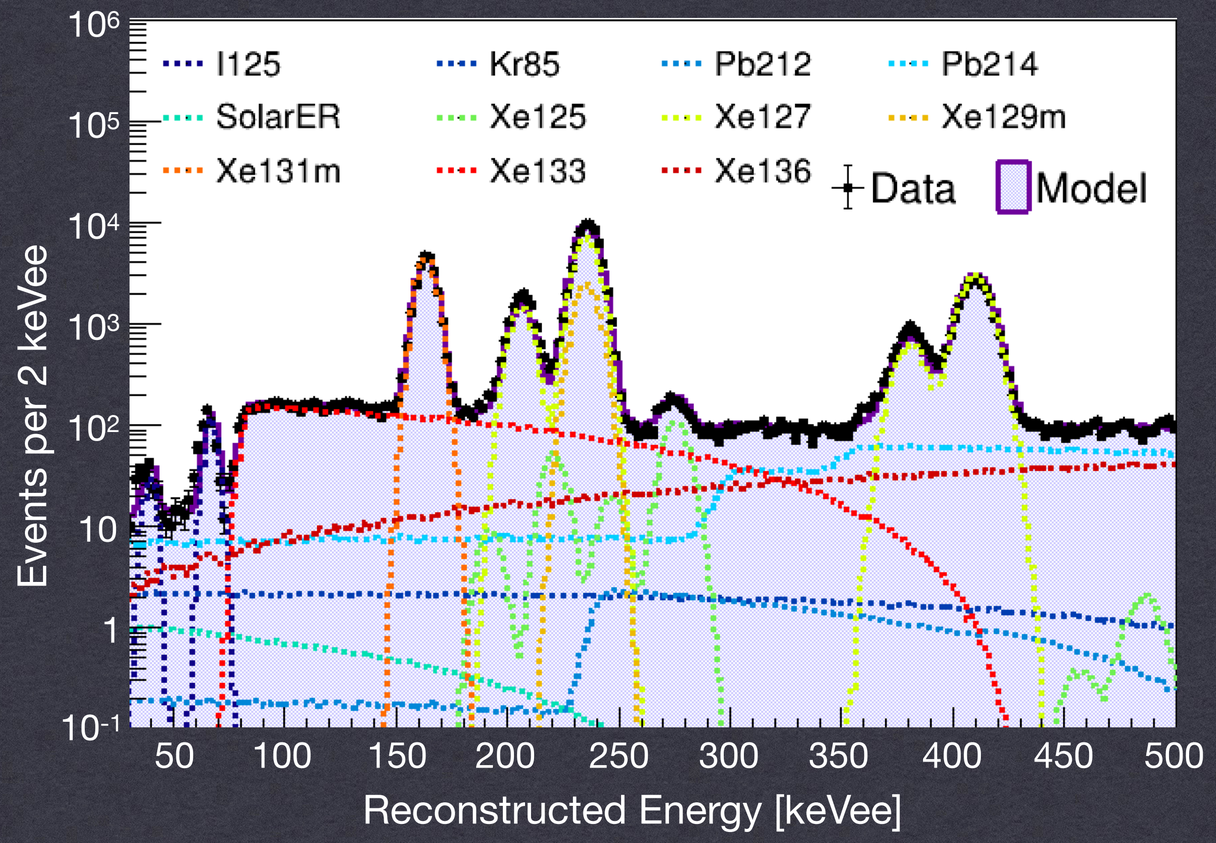
- Rn222 activity within assay expectations
- Po218/Po214 rates bound Pb214 rate

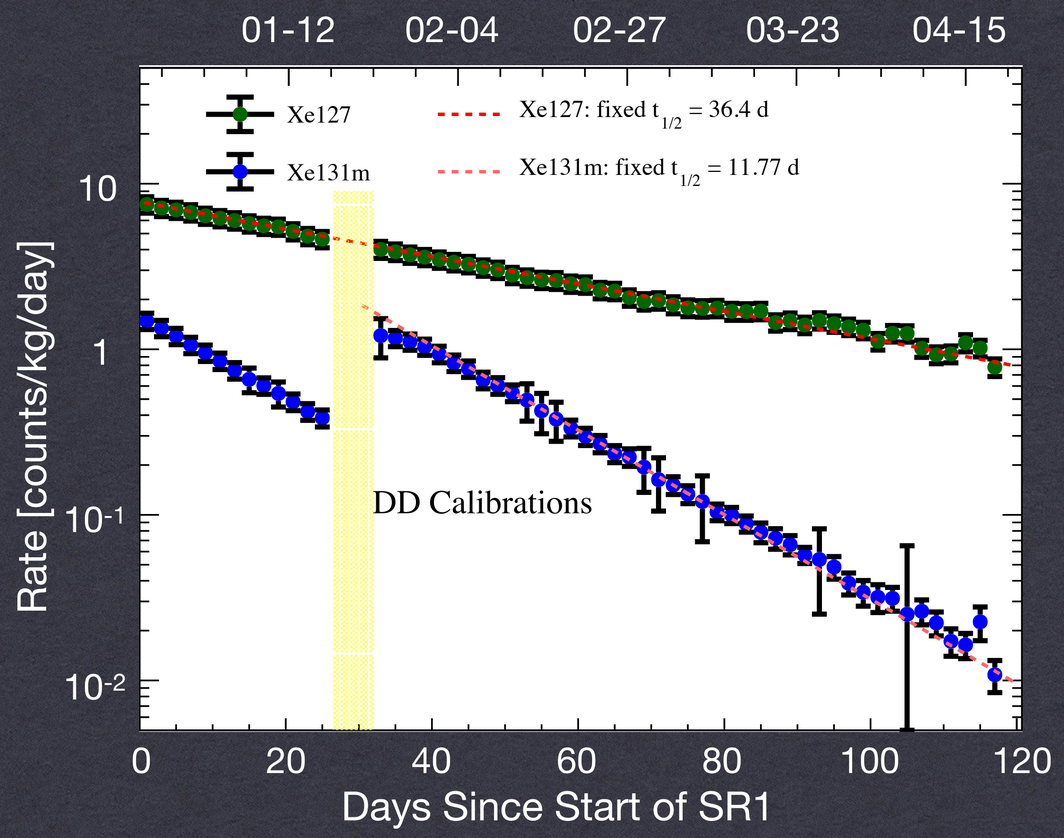




INTERNAL BACKGROUNDS

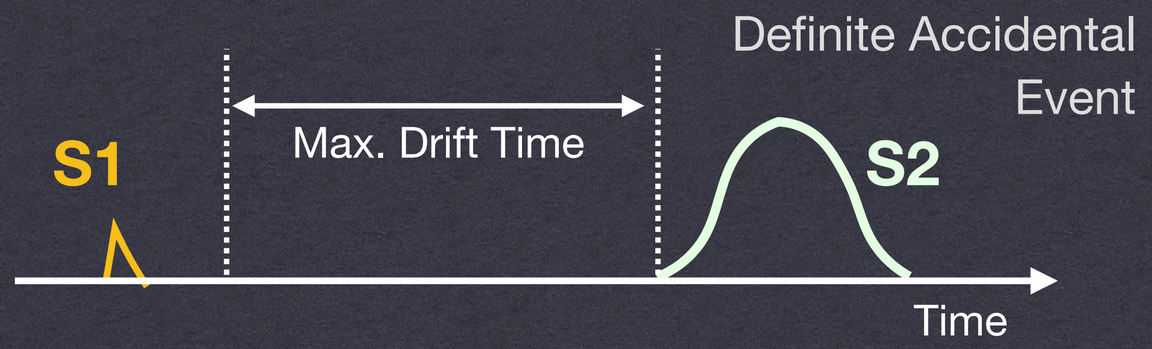
- Activated xenon & contaminant rates informed via energy spectra fits & analyses >40 keV_{ee}
  - Pb214 (3.26 μBq/kg) & Xe127 (36.9 μBq/kg SR1-averaged) constraints for WIMP analysis
- Kr85 constrained by sampling at 144 +/- 22 ppq g/g nat Kr/Xe

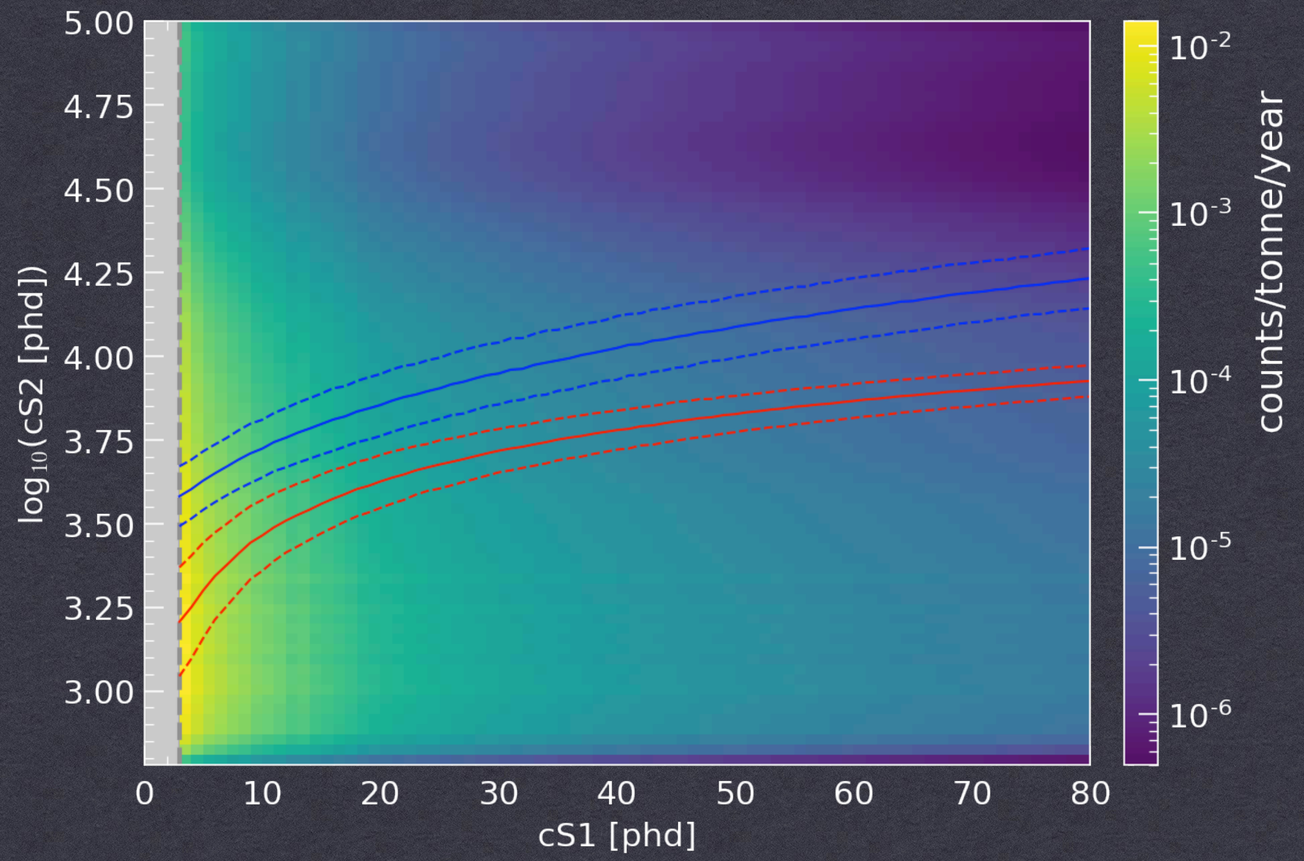




ACCIDENTAL COINCIDENCE BACKGROUNDS

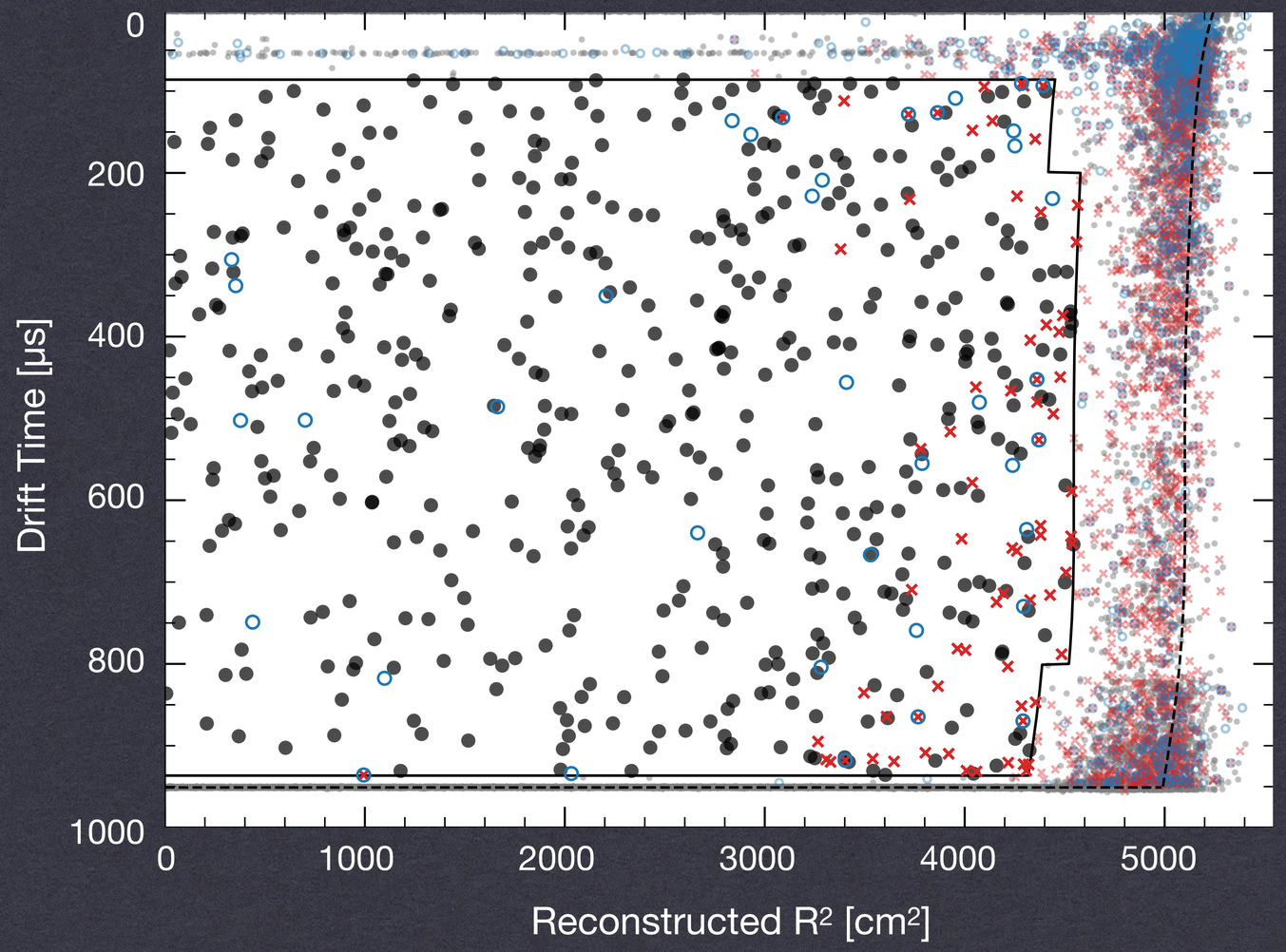
- Lone S1s & S2s can accidentally combine to form WIMP ROI events
- Data-driven estimation of distribution
- Event classification drift time agnostic
  - Drift time >1 ms = definite accidentals
    - Population used to inform rate
- Lone S1 & S2 waveforms extracted and stitched together to form fake events
  - Can produce statistics to assess shape
- Analysis cuts developed to combat observed pulse/event pathologies





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

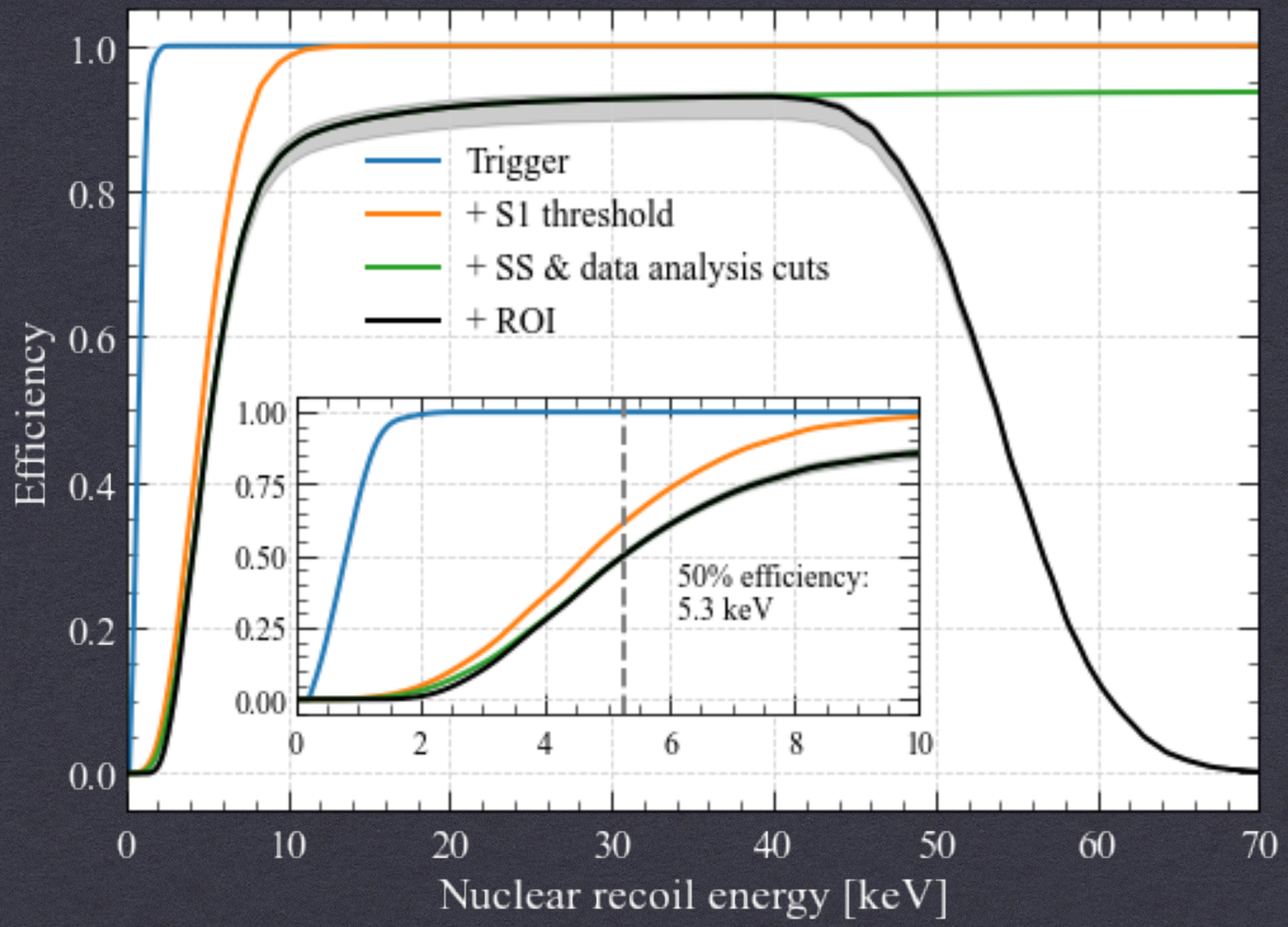


Events tagged by the Skin

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
  - 60.3 ± 1.2 live days



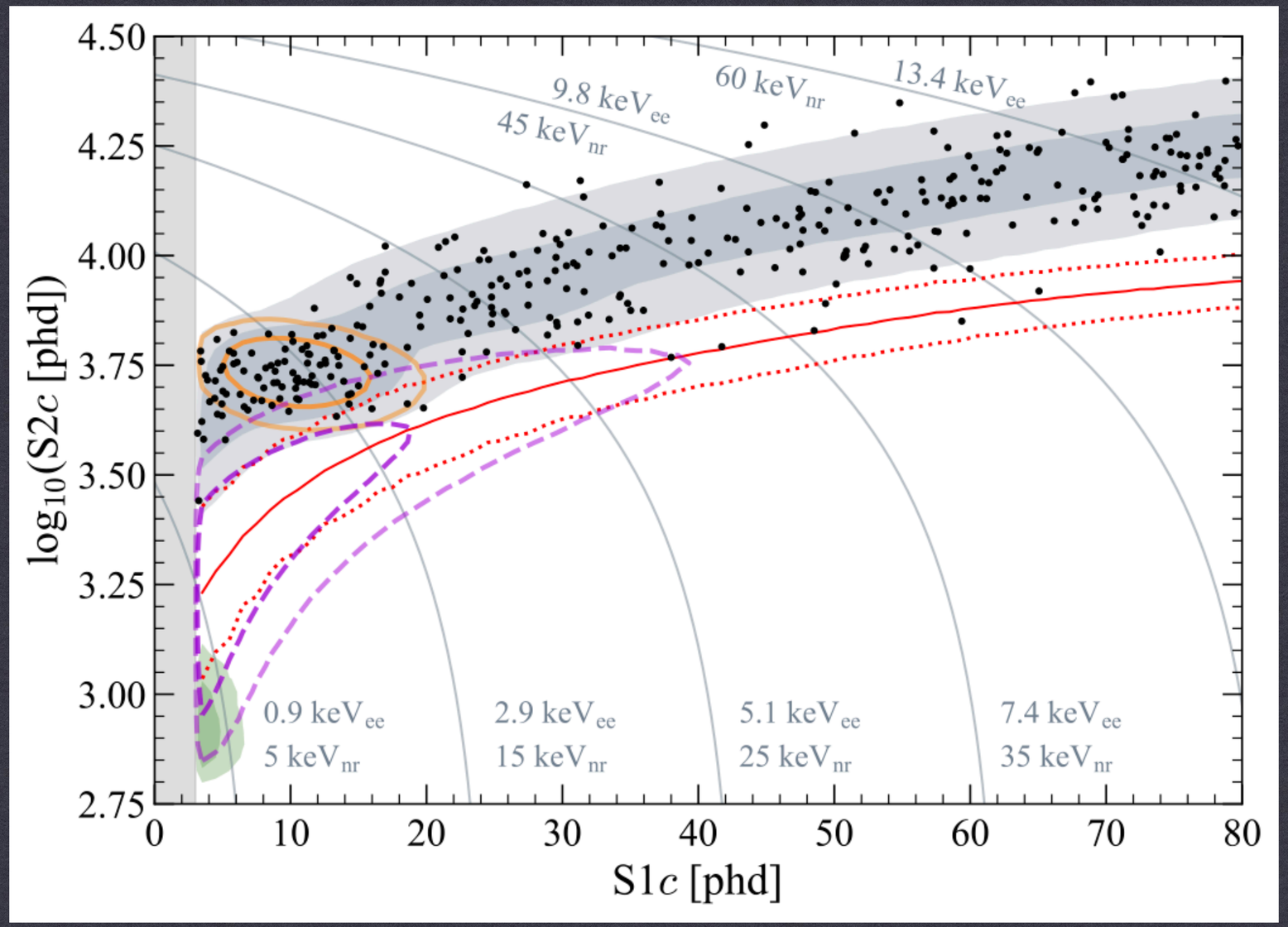
WIMP ANALYSIS - DATA & STATISTICAL INFERENCE

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

Key

1 & 2-Sigma Contours
- Post-fit total background distribution
- Ar37
- B8
- 30 GeV/c² WIMP

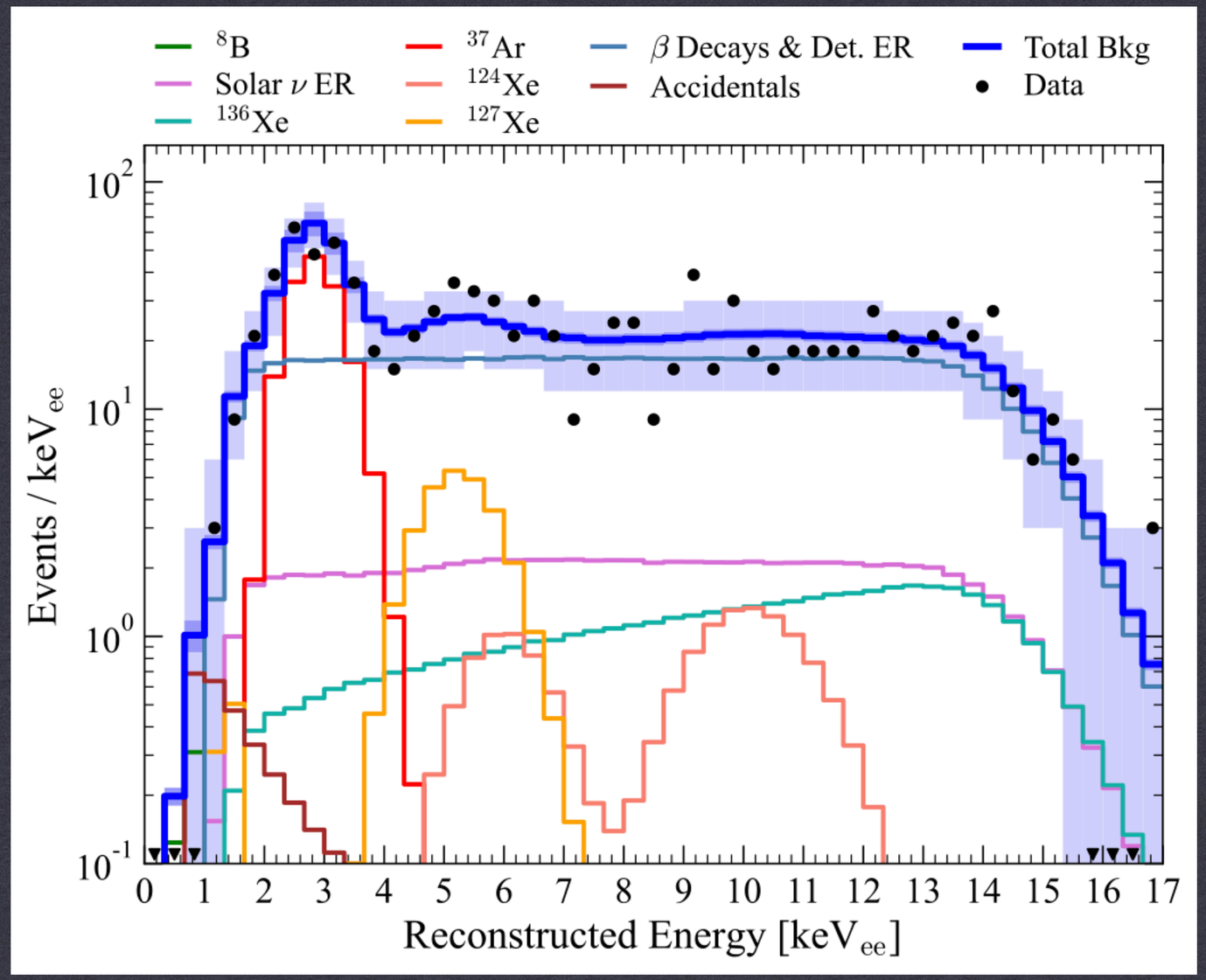
- NR band from DD



* j.astropartphys.2020.102480

WIMP ANALYSIS - BACKGROUNDS & STATISTICAL INFERENCE

Component	Expected Events	Best Fit Events
β decays & detector γs	218 ± 36	222 ± 16
Ar37	[0, 291]	$52.1^{+9.6}_{-8.9}$
Xe127	9.2 ± 0.8	9.3 ± 0.8
Xe124	5.0 ± 1.4	5.2 ± 1.4
Xe136	15.2 ± 2.4	15.3 ± 2.4
Solar ν ERs	27.3 ± 1.6	27.3 ± 1.6
B8 CEvNS	0.15 ± 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	276 ± 36	281 ± 16
Total w/ ^{37}Ar	-	333 ± 17



WIMP ANALYSIS - SR1 LIMIT

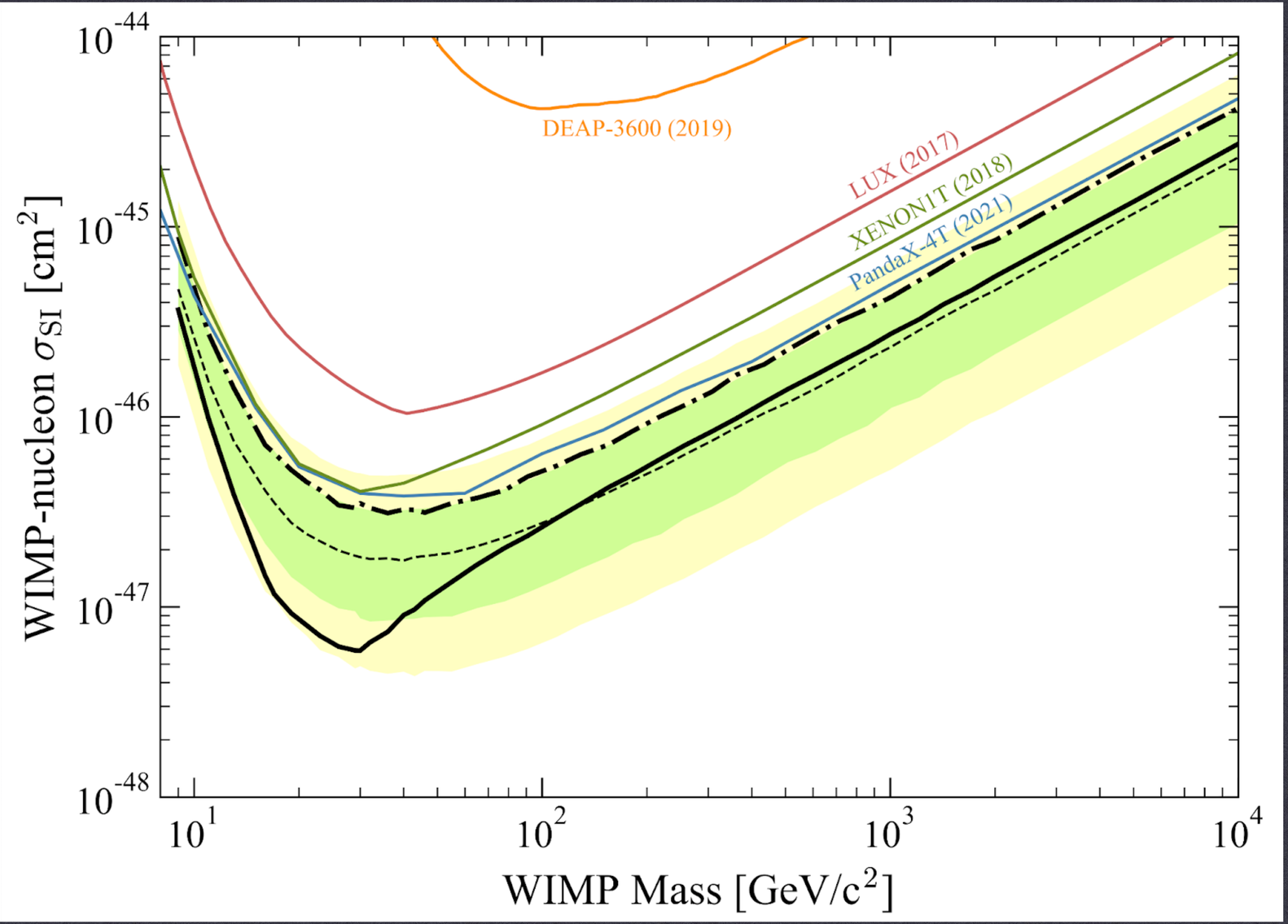
- Two-sided PLR search as per recommended conventions*
- Minimum cross-section of $\sigma_{SI} = 5.9 \times 10^{-48}$ cm^2 for WIMP mass of 30 GeV/c^2
- No evidence for WIMPs

Key

—— Observed limit

- - - Median expected sensitivity

·—· Median 3-sigma evidence



* EPJC 81, 907 (2021)

CONCLUSIONS & FUTURE PLANS

- All LZ systems are performing well
- Background validations proceeding
- World-leading spin-independent WIMP search limit achieved
- Preparing for a year-long run & ultimately 1000 live days of data
  - Detector optimisation & calibrations campaign in motion
- Additional papers in preparation
- XLZD consortium formed, looking towards a next-generation project

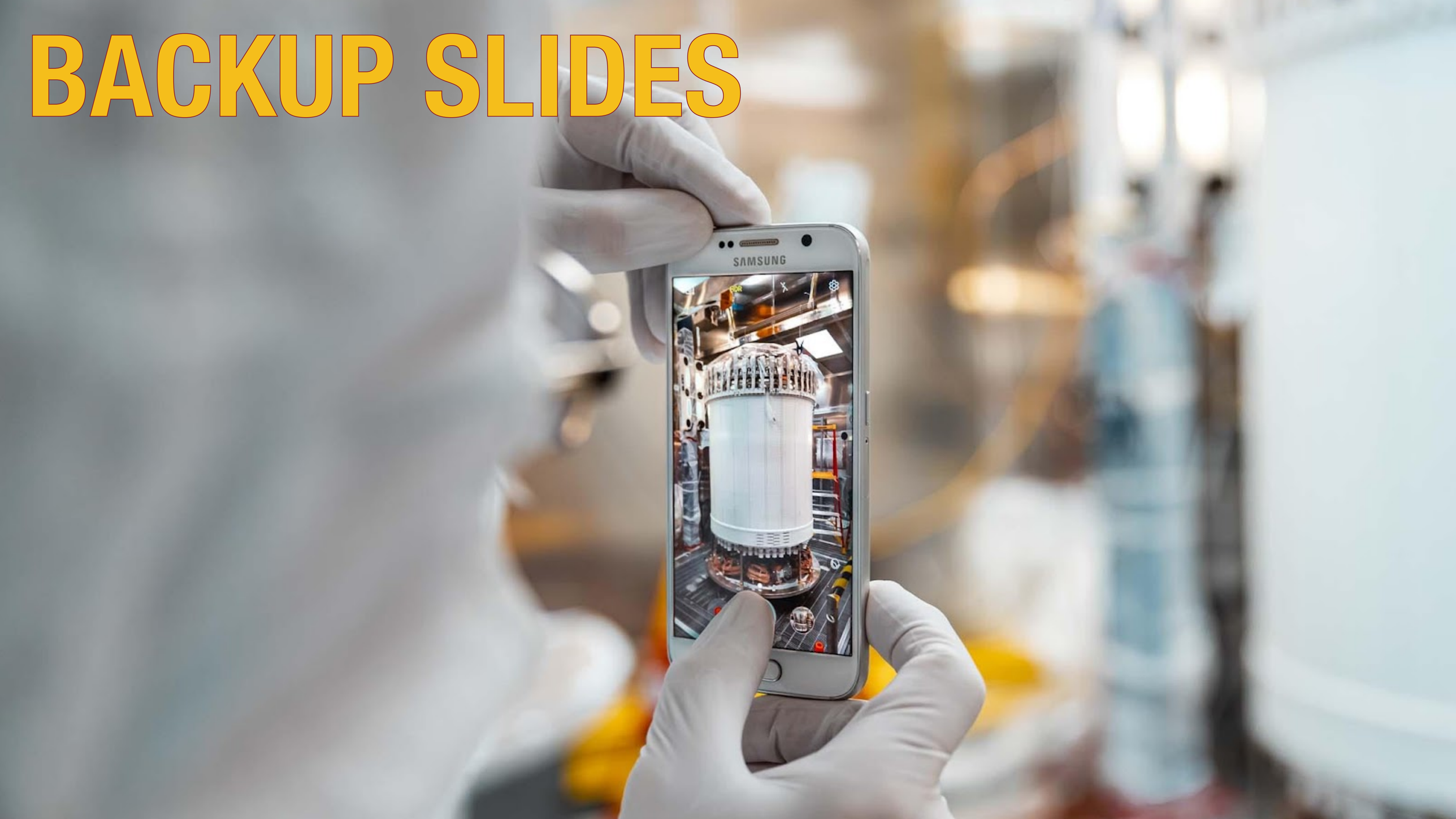
First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment

J. Aalbers,[1,2] D.S. Akerib,[1,2] C.W. Akerlof,[3] A.K. Al Musalhi,[4] F. Alder,[5] A. Alqahtani,[6] S.K. Alsum,[7] C.S. Amarasinghe,[3] A. Ames,[1,2] T.J. Anderson,[1,2] N. Angelides,[5,8] H.M. Araújo,[8] J.E. Armstrong,[9] M. Arthurs,[3] S. Azadi,[10] A.J. Bailey,[8] A. Baker,[8] J. Balajthy,[11] S. Balashov,[12] J. Bang,[6] J.W. Bargemann,[10] M.J. Barry,[13] J. Barthel,[14] D. Bauer,[8] A. Baxter,[15] K. Beattie,[13] J. Belle,[16] P. Beltrame,[5,17] J. Bensinger,[18] T. Benson,[7] E.P. Bernard,[13,19] A. Bhatti,[9] A. Biekert,[13,19] T.P. Biesiadzinski,[1,2] H.J. Birch,[3,15] B. Birrittella,[7] G.M. Blockinger,[20] K.E. Boast,[4] B. Boxer,[11,15] R. Bramante,[1,2] C.A.J. Brew,[12] P. Brás,[21] J.H. Buckley,[22] V.V. Bugaev,[22] S. Burdin,[15] J.K. Busenitz,[23] M. Buuck,[1,2] R. Cabrita,[21] C. Carels,[4] D.L. Carlsmith,[7] B. Carlson,[14] M.C. Carmona-Benitez,[24] M. Cascella,[5] C. Chan,[6] A. Chawla,[25] H. Chen,[13] J.J. Cherwinka,[7] N.I. Chott,[26] A. Cole,[13] J. Coleman,[13] M.V. Converse,[27] A. Cottle,[4,16] G. Cox,[14,24] W.W. Craddock,[1] O. Creaner,[13] D. Curran,[14] A. Currie,[8] J.E. Cutter,[11] C.E. Dahl,[16,28] A. David,[5] J. Davis,[14] T.J.R. Davison,[17] J. Delgaudio,[14] S. Dey,[4] L. de Viveiros,[24] A. Dobi,[13] J.E.Y. Dobson,[5] E. Druszkiewicz,[27] A. Dushkin,[18] T.K. Edberg,[9] W.R. Edwards,[13] M.M. Elnimr,[23] W.T. Emmet,[29] S.R. Eriksen,[30] C.H. Faham,[13] A. Fan,[1,2,*] S. Fayer,[8] N.M. Fearon,[4] S. Fiorucci,[13] H. Flaecher,[30] P. Ford,[12] V.B. Francis,[12] E.D. Fraser,[15] T. Fruth,[4,5] R.J. Gaitskell,[6] N.J. Gantos,[13] D. Garcia,[6] A. Geffre,[14] V.M. Gehman,[13] J. Genovesi,[26] C. Ghag,[5] R. Gibbons,[13,19] E. Gibson,[4] M.G.D. Gilchriese,[13] S. Gokhale,[31] B. Gomber,[7] J. Green,[4] A. Greenall,[15] S. Greenwood,[8] M.G.D.van der Grinten,[12] C.B. Gwilliam,[15] C.R. Hall,[9] S. Hans,[31] K. Hanzel,[13] A. Harrison,[26] E. Hartigan-O'Connor,[6] S.J. Haselschwardt,[13] S.A. Hertel,[32] G. Heuermann,[3] C. Hjemfelt,[26] M.D. Hoff,[13] E. Holtom,[12] J.Y-K. Hor,[23] M. Horn,[14] D.Q. Huang,[3,6] D. Hunt,[4] C.M. Ignarra,[1,2] R.G. Jacobsen,[13,19] O. Jahangir,[5] R.S. James,[5] S.N. Jeffery,[12] W. Ji,[1,2] J. Johnson,[11] A.C. Kaboth,[12,25,†] A.C. Kamaha,[20,33] K. Kamdin,[13,19] V. Kasey,[8] K. Kazkaz,[34] J. Keefner,[14] D. Khaitan,[27] M. Khaleeq,[8] A. Khazov,[12] I. Khurana,[5] Y.D. Kim,[35] C.D. Kocher,[6] D. Kodroff,[24] L. Korley,[3,18] E.V. Korolkova,[36] J. Kras,[7] H. Kraus,[4] S. Kravitz,[13] H.J. Krebs,[1] L. Kreczko,[30] B. Krikler,[30] V.A. Kudryavtsev,[36] S. Kyre,[10] B. Landerud,[7] E.A. Leason,[17] C. Lee,[1,2] J. Lee,[35] D.S. Leonard,[35] R. Leonard,[26] K.T. Lesko,[13] C. Levy,[20] J. Li,[35] F.-T. Liao,[4] J. Liao,[6] J. Lin,[4,13,19] A. Lindote,[21] R. Linehan,[1,2] W.H. Lippincott,[10,16] R. Liu,[6] X. Liu,[17] Y. Liu,[7] C. Loniewski,[27] M.I. Lopes,[21] E. Lopez Asamar,[21] B. López Paredes,[8] W. Lorenzon,[3] D. Lucero,[14] S. Luitz,[1] J.M. Lyle,[6] P.A. Majewski,[12] J. Makkinje,[6] D.C. Malling,[6] A. Manalaysay,[11,13] L. Manenti,[5] R.L. Mannino,[7] N. Marangou,[8] M.F. Marzioni,[17] C. Maupin,[14] M.E. McCarthy,[27] C.T. McConnell,[13] D.N. McKinsey,[13,19] J. McLaughlin,[28] Y. Meng,[23] J. Migneault,[6] E.H. Miller,[1,2,26] E. Mizrachi,[9,34] J.A. Mock,[13,20] A. Monte,[10,16] M.E. Monzani,[1,2,37] J.A. Morad,[11] J.D. Morales Mendoza,[1,2] E. Morrison,[26] B.J. Mount,[38] M. Murdy,[32] A.St.J. Murphy,[17] D. Naim,[11] A. Naylor,[36] C. Nedlik,[32] C. Nehrkorn,[10] H.N. Nelson,[10] F. Neves,[21] A. Nguyen,[17] J.A. Nikoleyczik,[7] A. Nilima,[17] J. O'Dell,[12] F.G. O'Neill,[1] K. O'Sullivan,[13,19] I. Olcina,[13,19] M.A. Olevitch,[22] K.C. Oliver-Mallory,[8,13,19] J. Orpwood,[36] D. Pagenkopf,[10] S. Pal,[21] K.J. Palladino,[4,7] J. Palmer,[25] M. Pangilinan,[6] N. Parveen,[20] S.J. Patton,[13] E.K. Pease,[13] B. Penning,[3,18] C. Pereira,[21] G. Pereira,[21] E. Perry,[5] T. Pershing,[34] I.B. Peterson,[13] A. Piepke,[23] J. Podczerwinski,[7] D. Porzio,[21,‡] S. Powell,[15] R.M. Preece,[12] K. Pushkin,[3] Y. Qie,[27] B.N. Ratcliff,[1] J. Reichenbacher,[26] L. Reichhart,[5] C.A. Rhyne,[6] A. Richards,[8] Q. Riffard,[13,19] G.R.C. Rischbieter,[20] J.P. Rodrigues,[21] A. Rodriguez,[38] H.J. Rose,[15] R. Rosero,[31] P. Rossiter,[36] T. Rushton,[36] G. Rutherford,[6] D. Rynders,[14] J.S. Saba,[13] D. Santone,[25] A.B.M.R. Sazzad,[23] R.W. Schnee,[26] P.R. Scovell,[4,12] D. Seymour,[6] S. Shaw,[10] T. Shutt,[1,2] J.J. Silk,[9] C. Silva,[21] G. Sinev,[26] K. Skarpaas,[1] W. Skulski,[27] R. Smith,[13,19] M. Solmaz,[10] V.N. Solovov,[21] P. Sorensen,[13] J. Soria,[13,19] I. Stancu,[23] M.R. Stark,[26] A. Stevens,[4,5,8] T.M. Stiegler,[39] K. Stifter,[1,2,16] R. Studley,[18] B. Suerfu,[13,19] T.J. Sumner,[8] P. Sutcliffe,[15] N. Swanson,[6] M. Szydagis,[20] M. Tan,[4] D.J. Taylor,[14] R. Taylor,[8] W.C. Taylor,[6] D.J. Temples,[28] B.P. Tennyson,[29] P.A. Terman,[39] K.J. Thomas,[13] D.R. Tiedt,[9,14,26] M. Timalsina,[26] W.H. To,[1,2] A. Tomás,[8] Z. Tong,[8] D.R. Tovey,[36] J. Tranter,[36] M. Trask,[10] M. Tripathi,[11] D.R. Tronstad,[26] C.E. Tull,[13] W. Turner,[15] L. Tvrznikova,[19,29,34] U. Utku,[5] J. Va'vra,[1] A. Vacheret,[8] A.C. Vaitkus,[6] J.R. Verbus,[6] E. Voirin,[16] W.L. Waldron,[13] A. Wang,[1,2] B. Wang,[23] J.J. Wang,[23] W. Wang,[7,32] Y. Wang,[13,19] J.R. Watson,[13,19] R.C. Webb,[39] A. White,[6] D.T. White,[10] J.T. White,[39,‡] R.G. White,[1,2] T.J. Whitis,[1,10] M. Williams,[3,18] W.J. Wisniewski,[1] M.S. Witherell,[13,19] F.L.H. Wolfs,[27] J.D. Wolfs,[27] S. Woodford,[15] D. Woodward,[24,§] S.D. Worm,[12] C.J. Wright,[30] Q. Xia,[13] X. Xiang,[6] Q. Xiao,[7] J. Xu,[34] M. Yeh,[31] J. Yin,[27] I. Young,[16] P. Zarzhitsky,[23] A. Zuckerman,[6] and E.A. Zweig[33]

(The LUX-ZEPLIN (LZ) Collaboration)

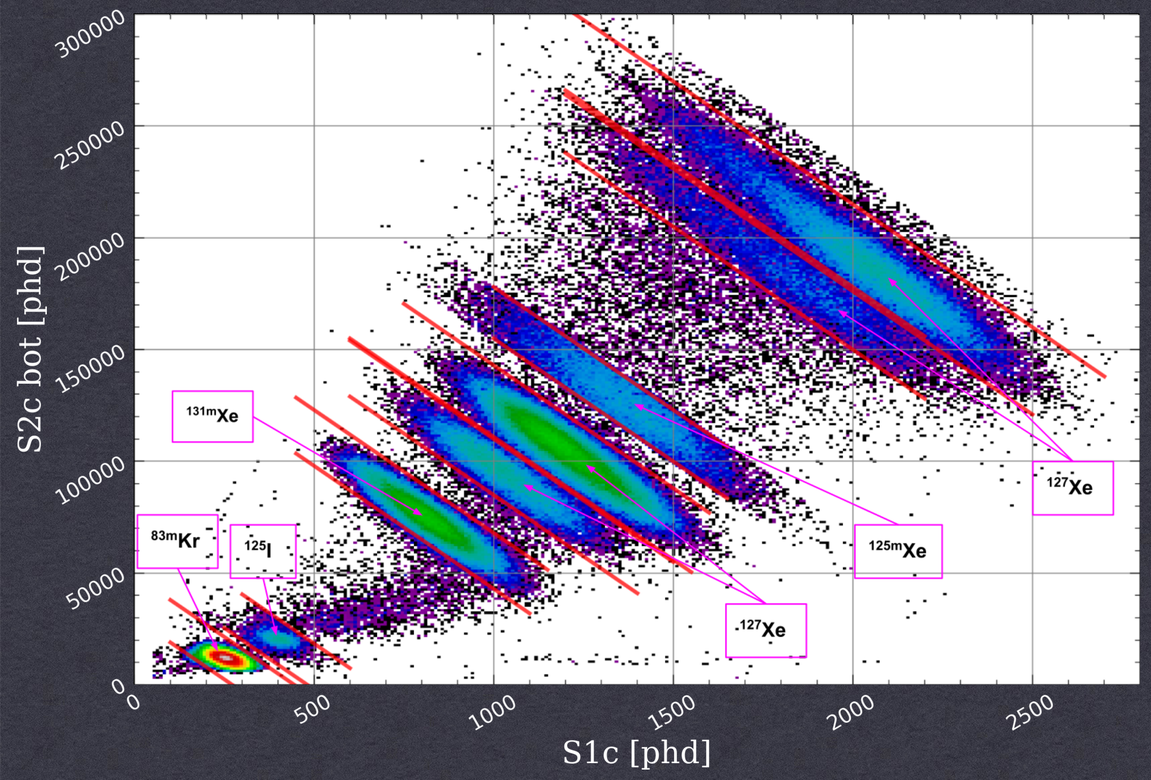
Paper Link

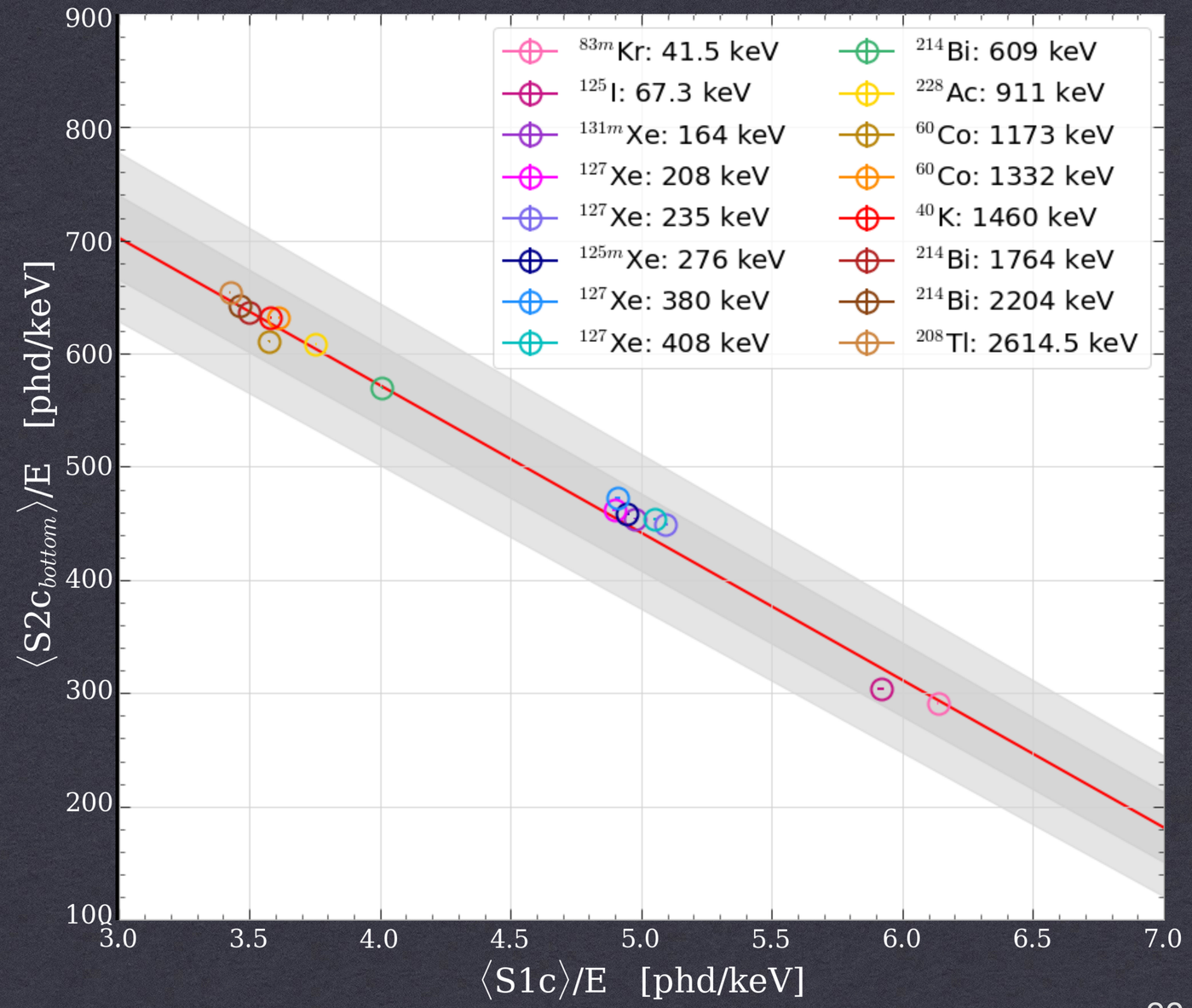
BACKUP SLIDES



TPC ENERGY RESPONSE

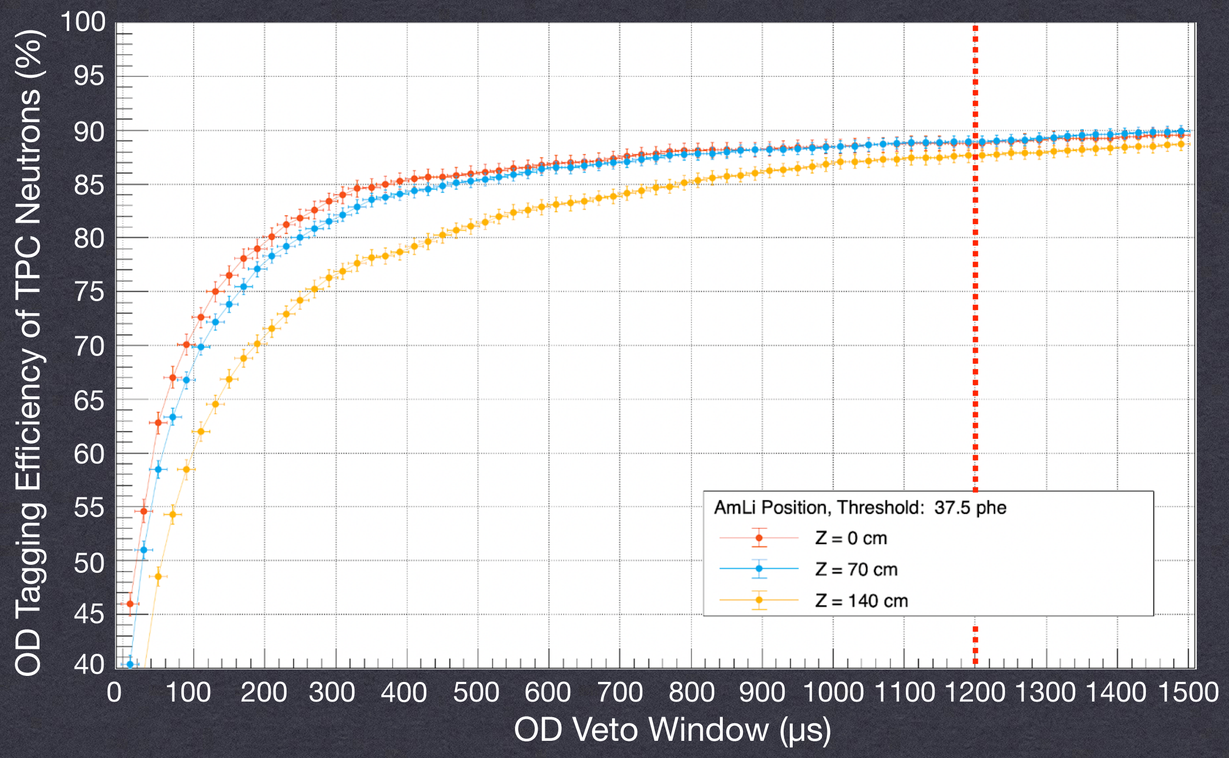
- S1s & S2s position-corrected using ^{131m}Xe background, ^{83m}Kr calibration
- Doke plot constructed with mono-energetic electron recoil peaks

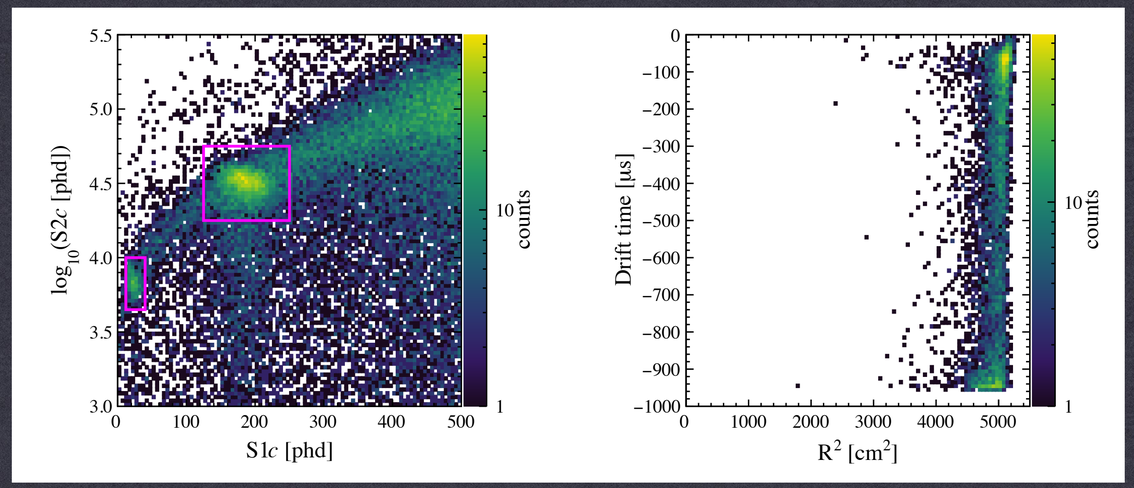




VETO DETECTOR RESPONSE

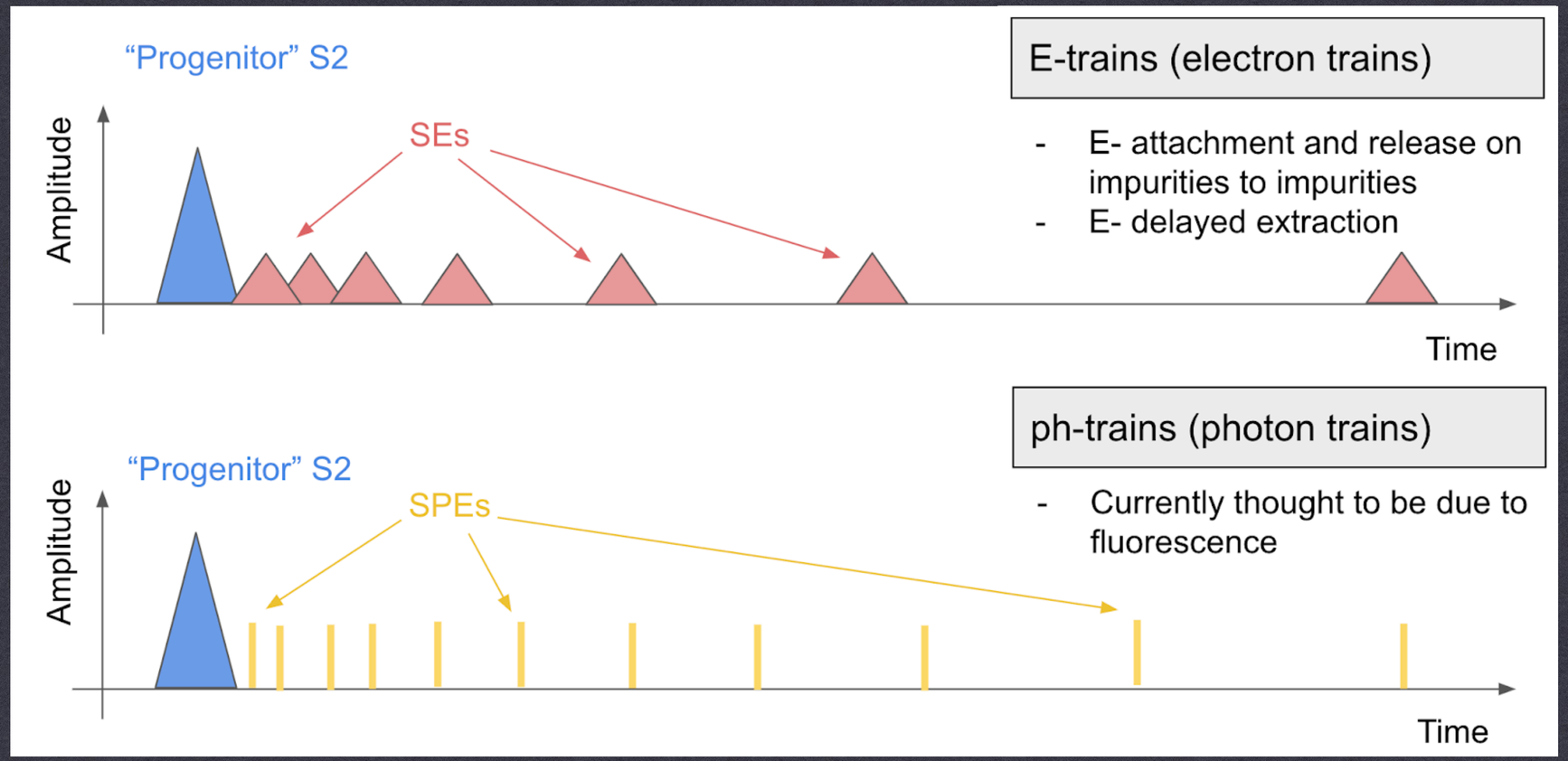
- Skin & OD response and inter-detector timings calibrated
  - OD optical calibration system
  - External γ-ray & neutron sources (e.g. ^{22}Na; DD, AmLi, ^{252}Cf)
- ^{127}Xe Skin tagging efficiency of 78 ± 5% based on K-shell analysis
- OD tagging efficiency of TPC-interacting neutrons of 89 ± 1% (AmLi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





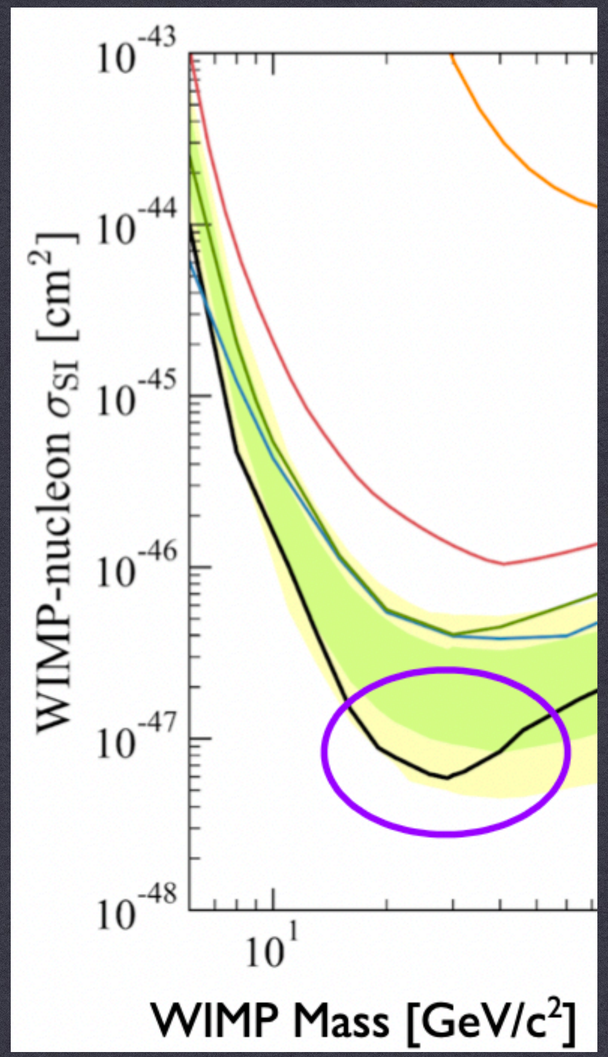
LIVE TIME VETOES

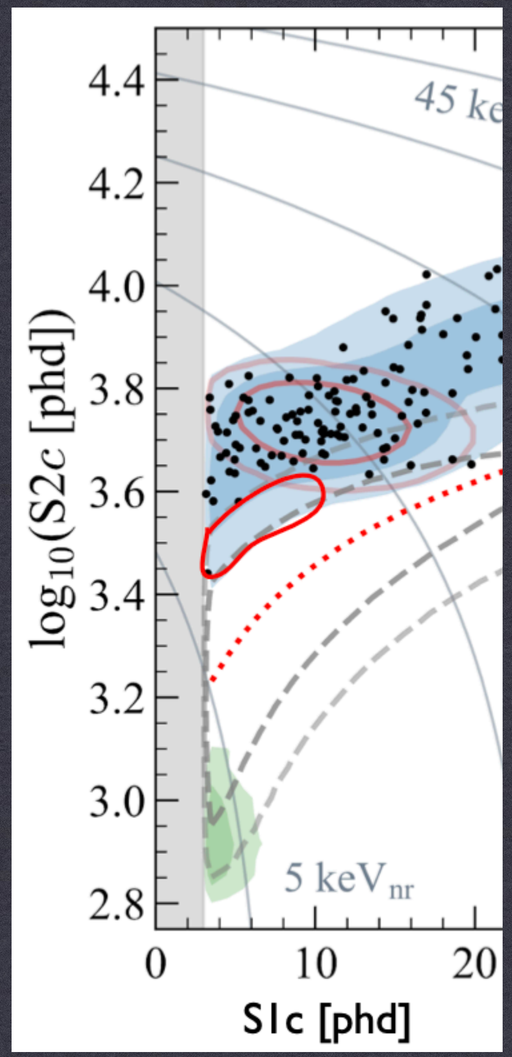
- Large S2s induce pulse "trains" lasting 100s of ms, much longer than the event window
- High pulse rates can lead to piled-up photon or electron pulses that mimic S1s and S2s, thus contributing to accidental coincidence backgrounds
- Removal of periods after S2s (e^-/ph trains) excludes ~30% of our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

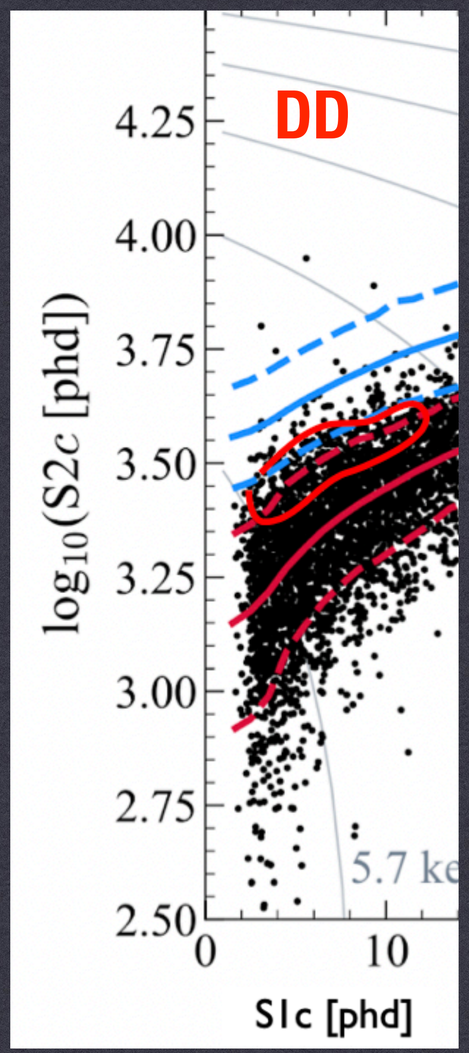


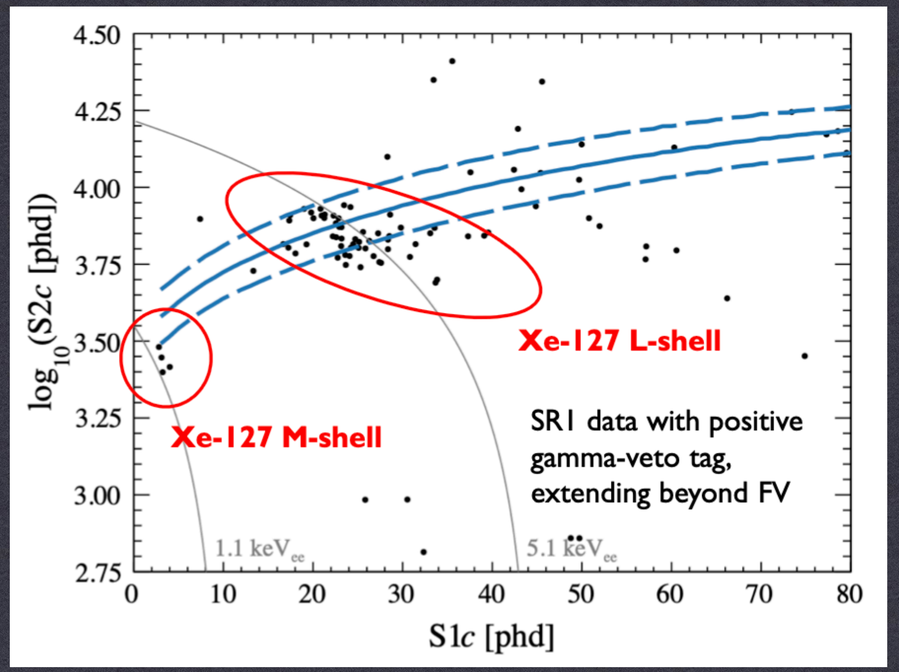
LIMIT SHAPE

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





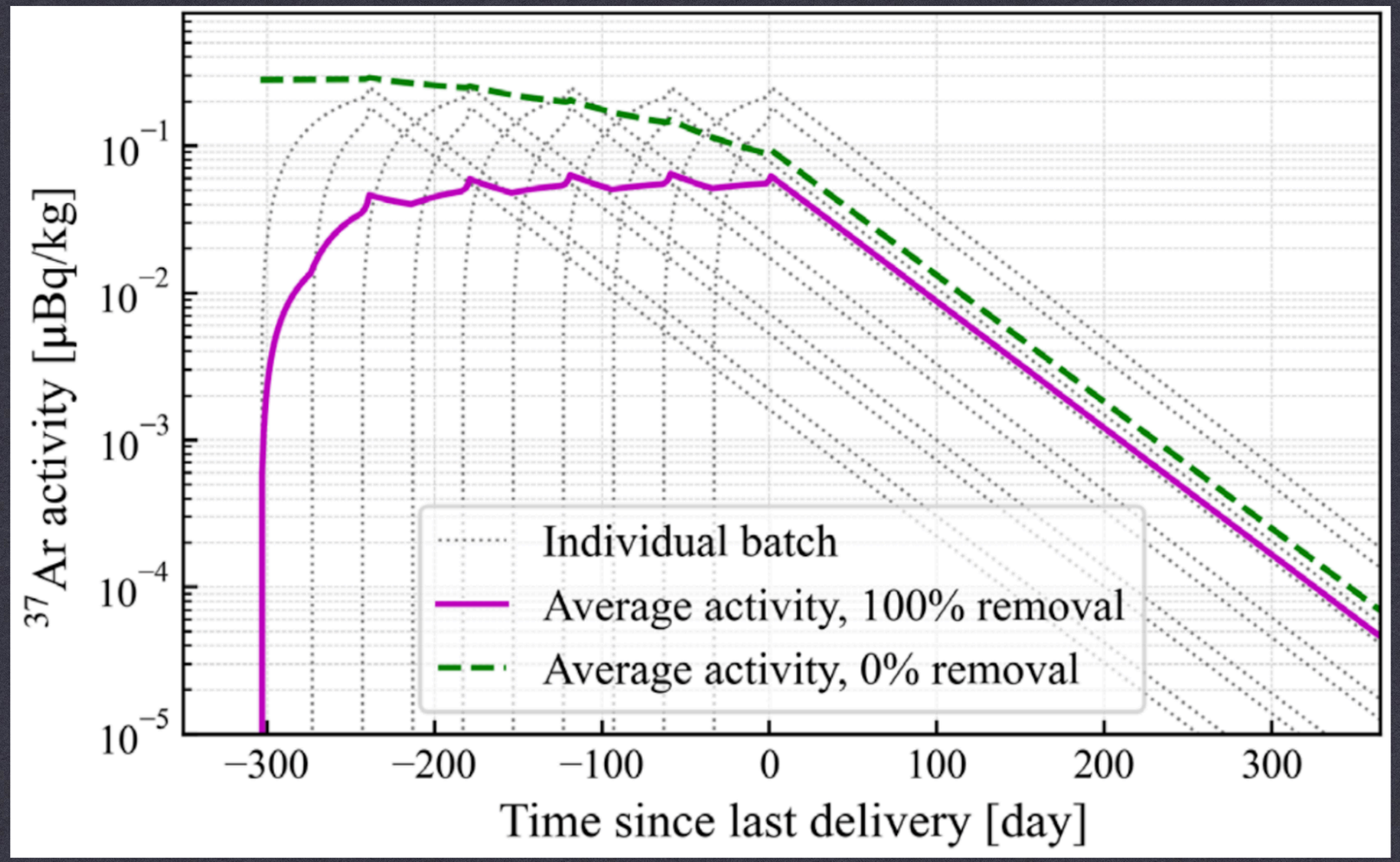




Calibrations and Xe127 M-shell counts as expected under signal acceptance model -> background under-fluctuation

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)*

DETECTOR NEUTRON CONSTRAINT

- Perform fit to events passing all WIMP search cuts except OD anti-coincidence to constrain neutrons
  - Expect ~8 times more neutrons than in the WIMP search due to OD veto efficiency
  - In contrast, only 5% of non-neutron backgrounds should be OD-tagged
- Result of fit -> number of neutrons in SR1 WIMP search is <0.2 events (two-sided constraint)