Status of LUX-ZEPLIN

WIMP Search 2024

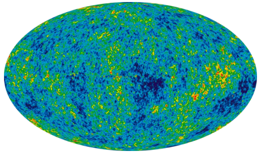
Ewan Fraser
Research Associate

25th September 2024

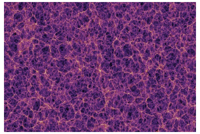
Contents:

Gravitational Interactions & Dark Matter

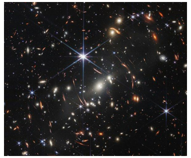
Size



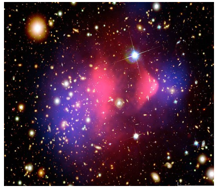
- Cosmic Microwave Background



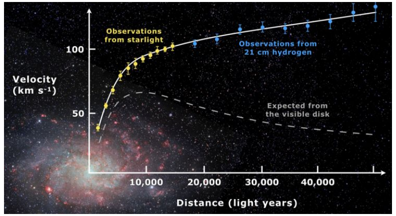
- Large Scale Structure



- Galaxy Clusters

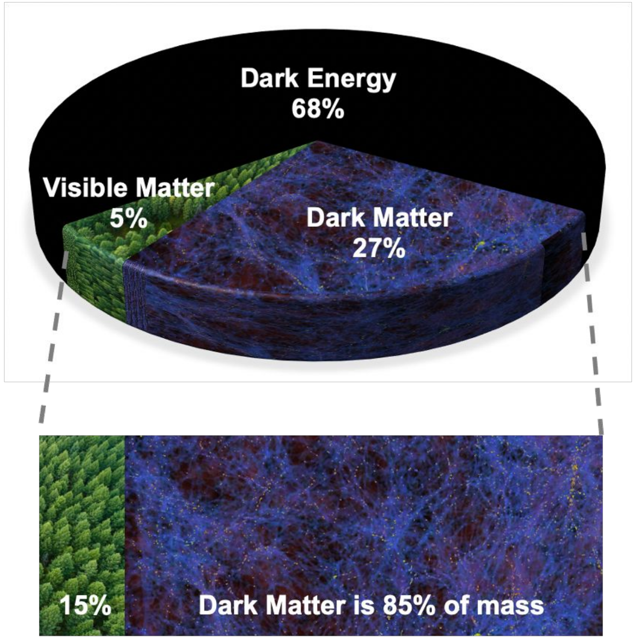


- Bullet Cluster Merger



- Galaxy Rotation Curves

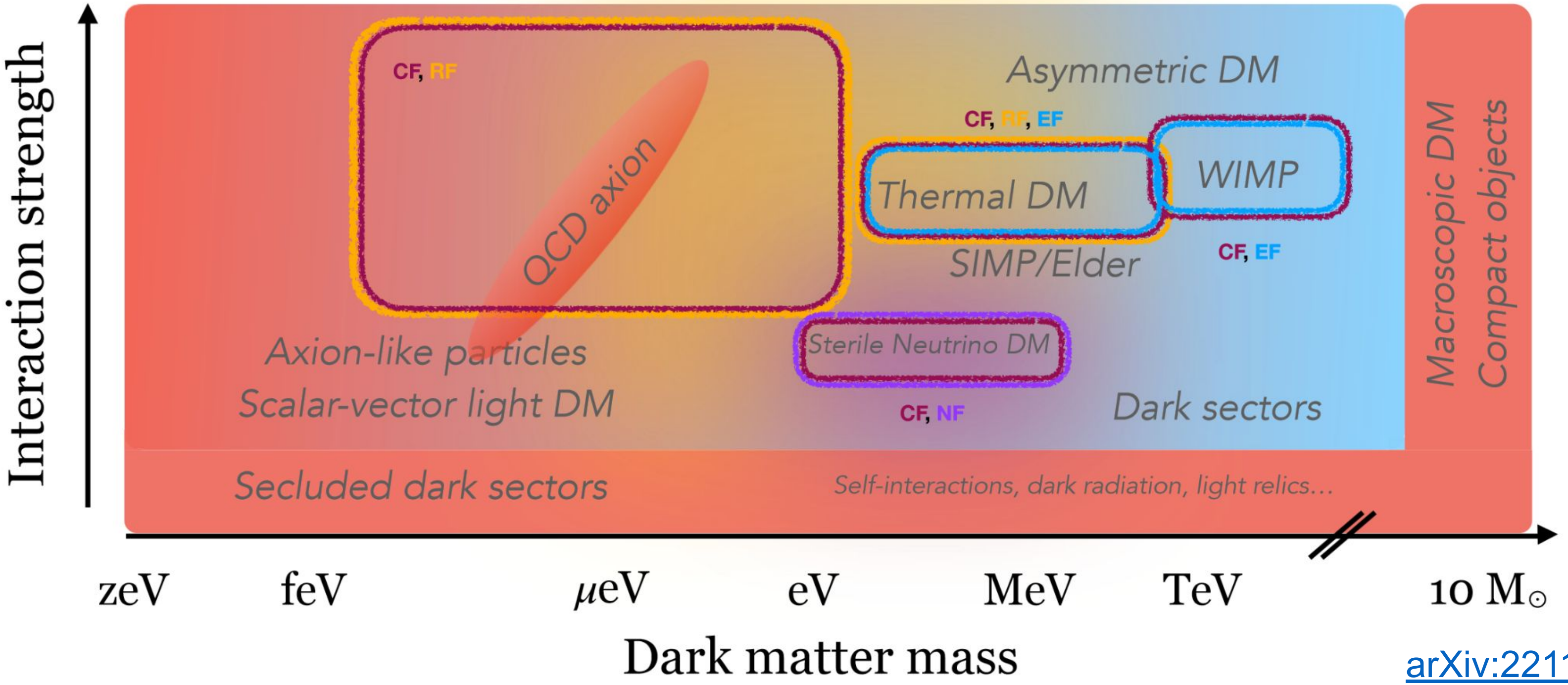
Gravitational Interactions



ΛCDM model of the Universe

Dark Matter Properties

Neutral **Non-Baryonic** **Stable** **Cold** **~Collisionless**

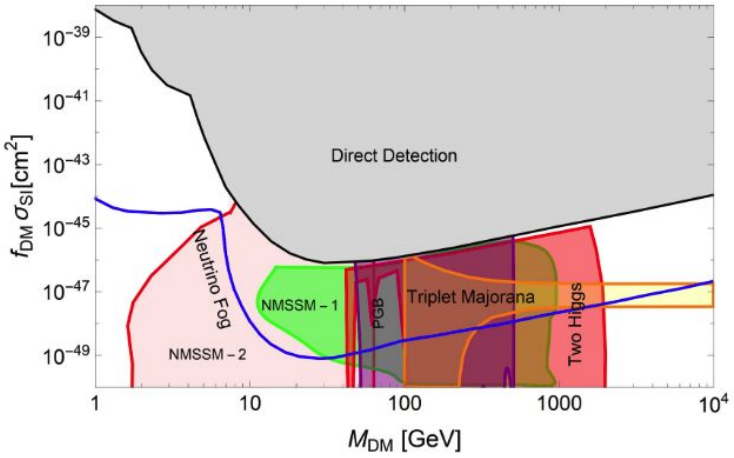


arXiv:2211.07027

"Delve Deep and Search Wide"

WIMP Region specifically

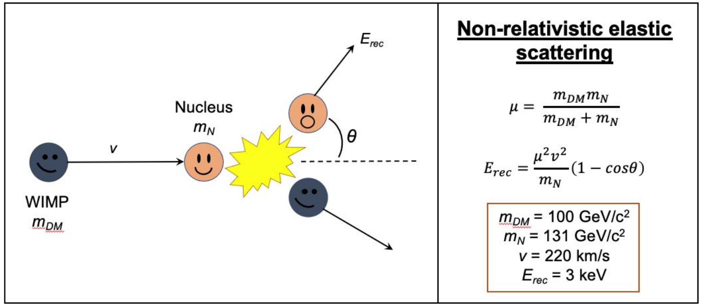
- Well motivated candidate is a “WIMPy” thermal relic
  - MeV - 100 TeV scale particle (cosmological bounds)
  - Weak scale interactions leads to correct relic density
  - Theoretical models independently predict particles with the correct properties



Snowmass CF1-WP1 - arXiv:2203.08084

- Direct Detection
  - Solar System travels through Milky Way’s Dark Matter Halo
  - Billions of WIMPs will pass through us every second
  - Challenge - Interaction is an exceptionally rare process
  - Challenge - Background radiation is everywhere

Fill a detector with your favorite material and wait for WIMPs to scatter off it



LZ Collaboration - 38 Institutions 250 scientists, engineers, and technical staff

- 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 Zürich

US Europe Asia Oceania

Science and Technology Facilities Council

Swiss National Science Foundation

FCT Fundação para a Ciência e a Tecnologia

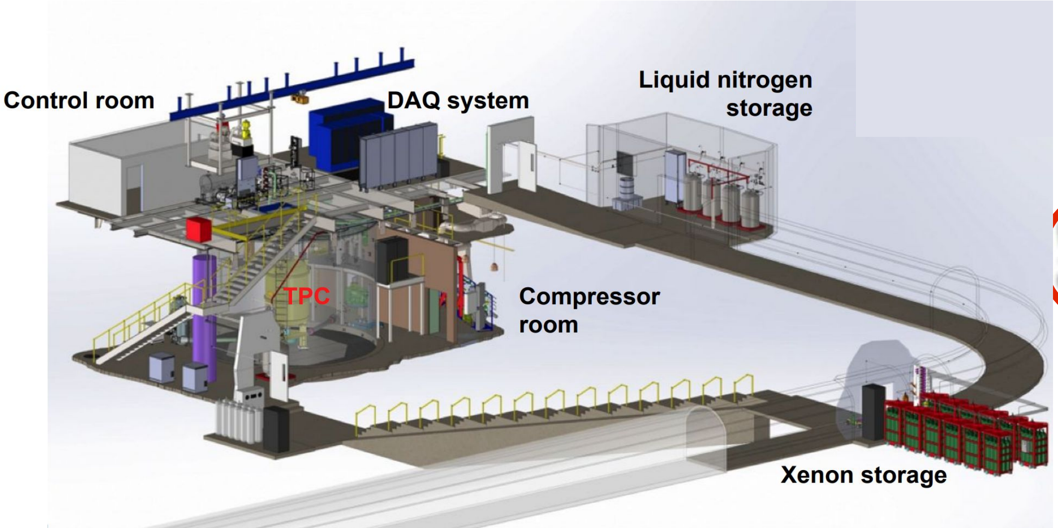
SANFORD UNDERGROUND RESEARCH FACILITY

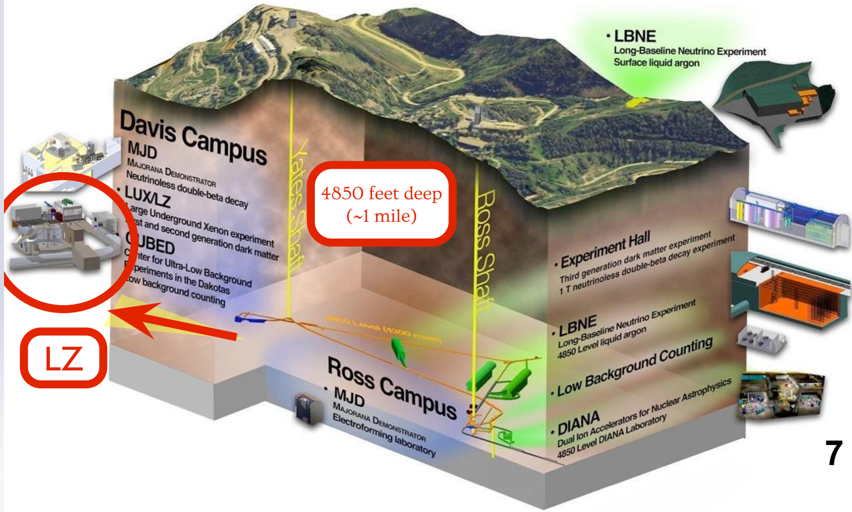
Institute for Basic Science

Thanks to our sponsors and participating institutions!

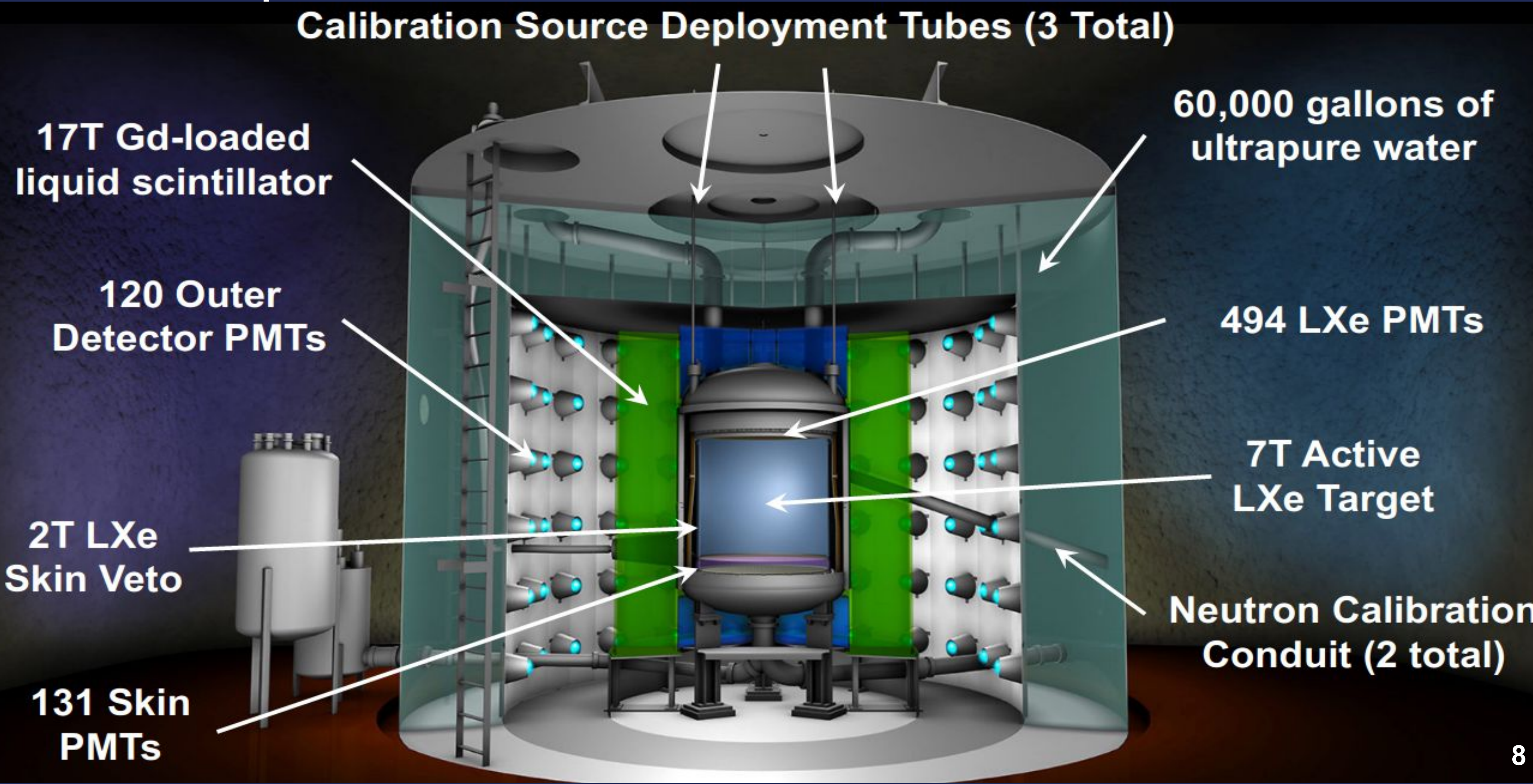
LZ at SURF

- ❑ LUX-ZEPLIN at Sanford Underground Research Facility
  - ❑ SURF - Homestake Mine, Lead, South Dakota
  - ❑ ~1 mile underground, Davis Cavern
  - ❑ Rock overburden reduces cosmic ray muon flux by $O(10^6)$

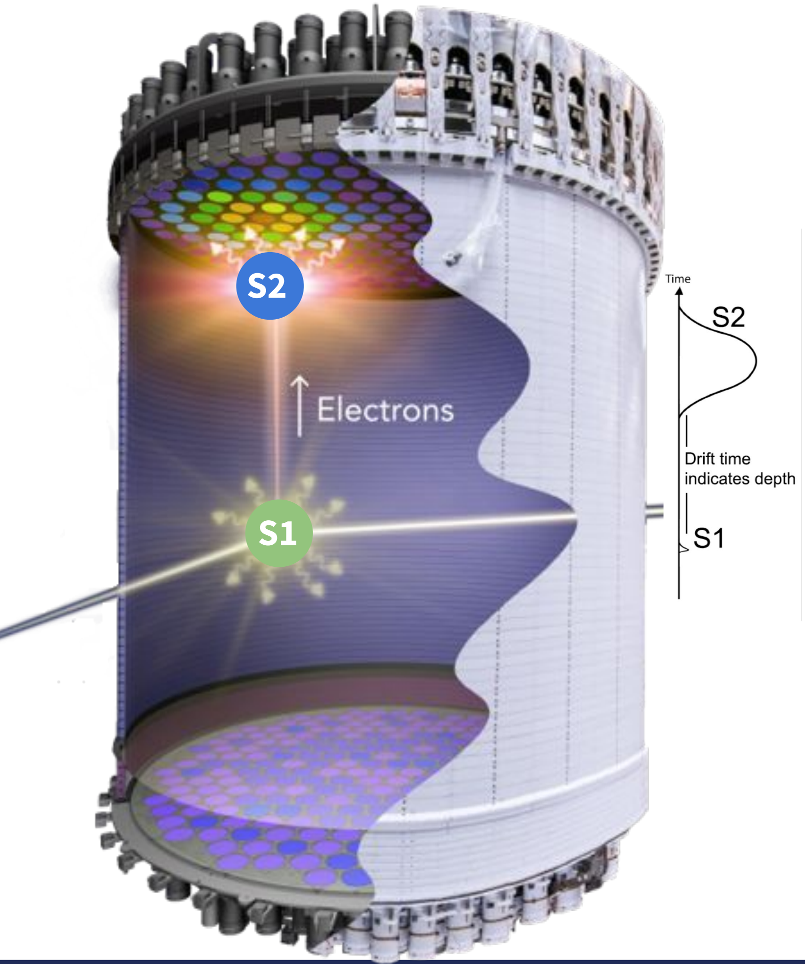




LZ - Experiment for Direct Detection of WIMP Dark

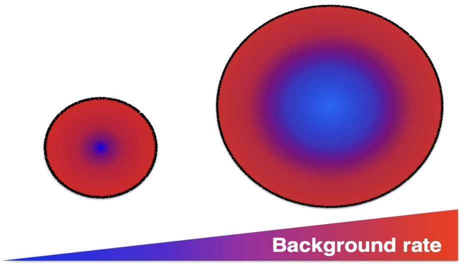


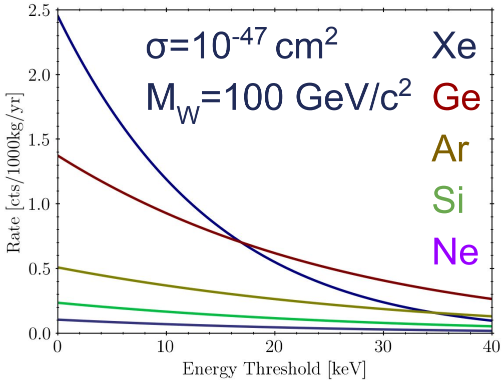
LXe TPC Principles



Why LXe?:

- ❏ 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

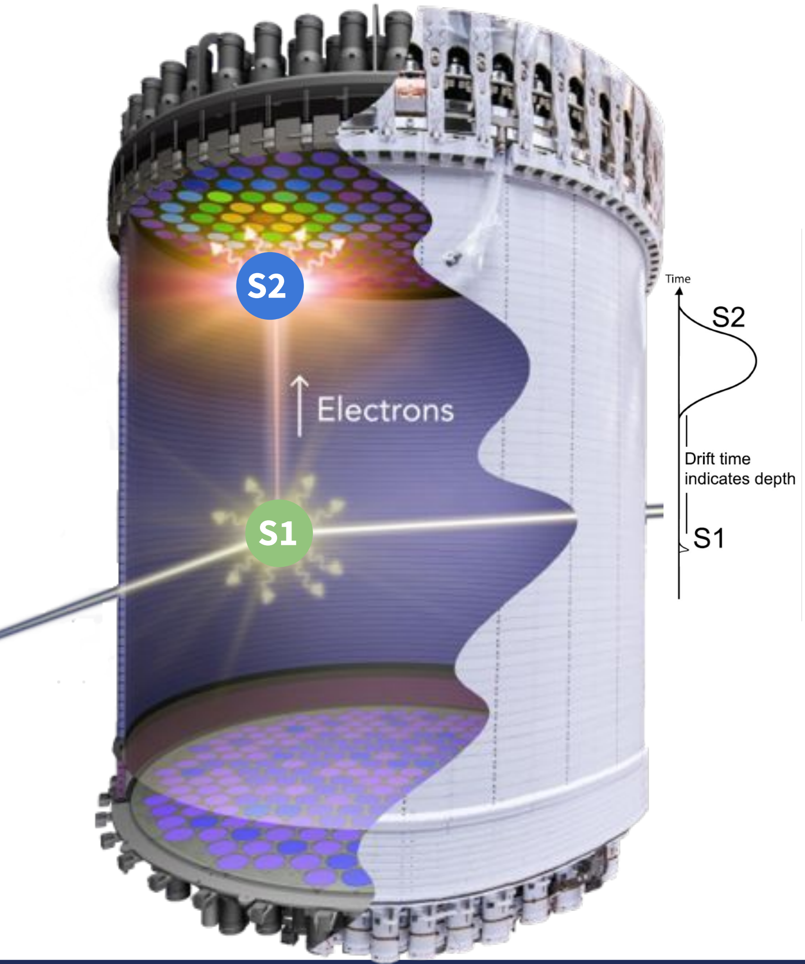


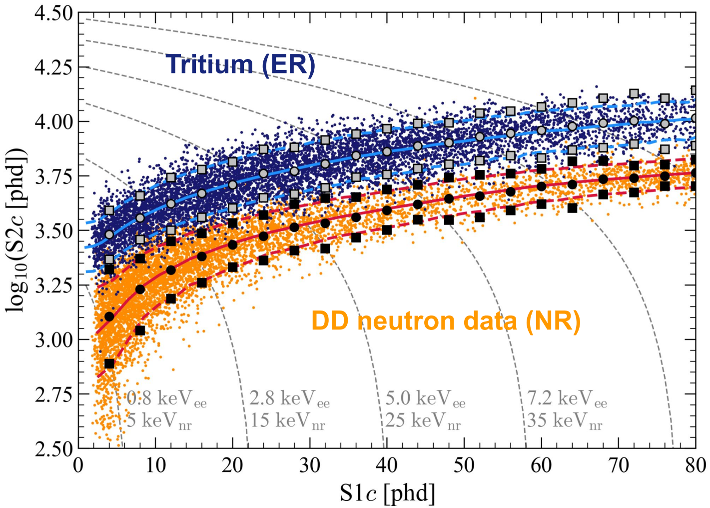


Time Projection Chamber:

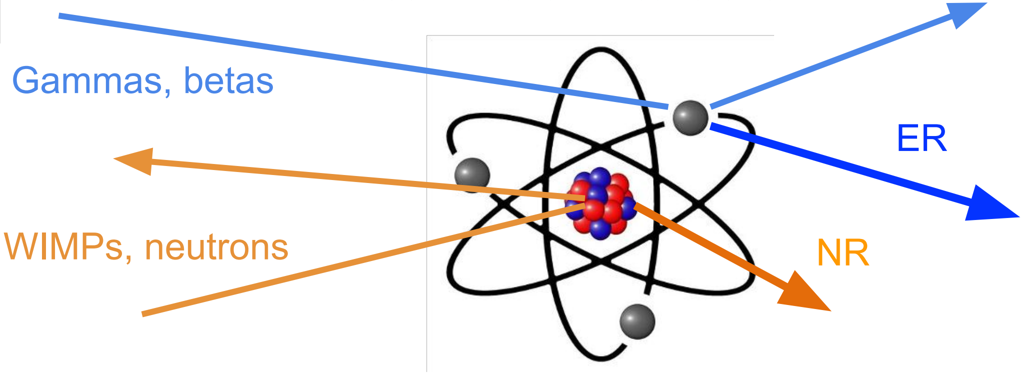
- ❏ S2 hit pattern, Drift Time - (xy, z)
- ❏ Energy deposited reconstructed from - S1, S2
- ❏ Particle discrimination - S1:log(S2)

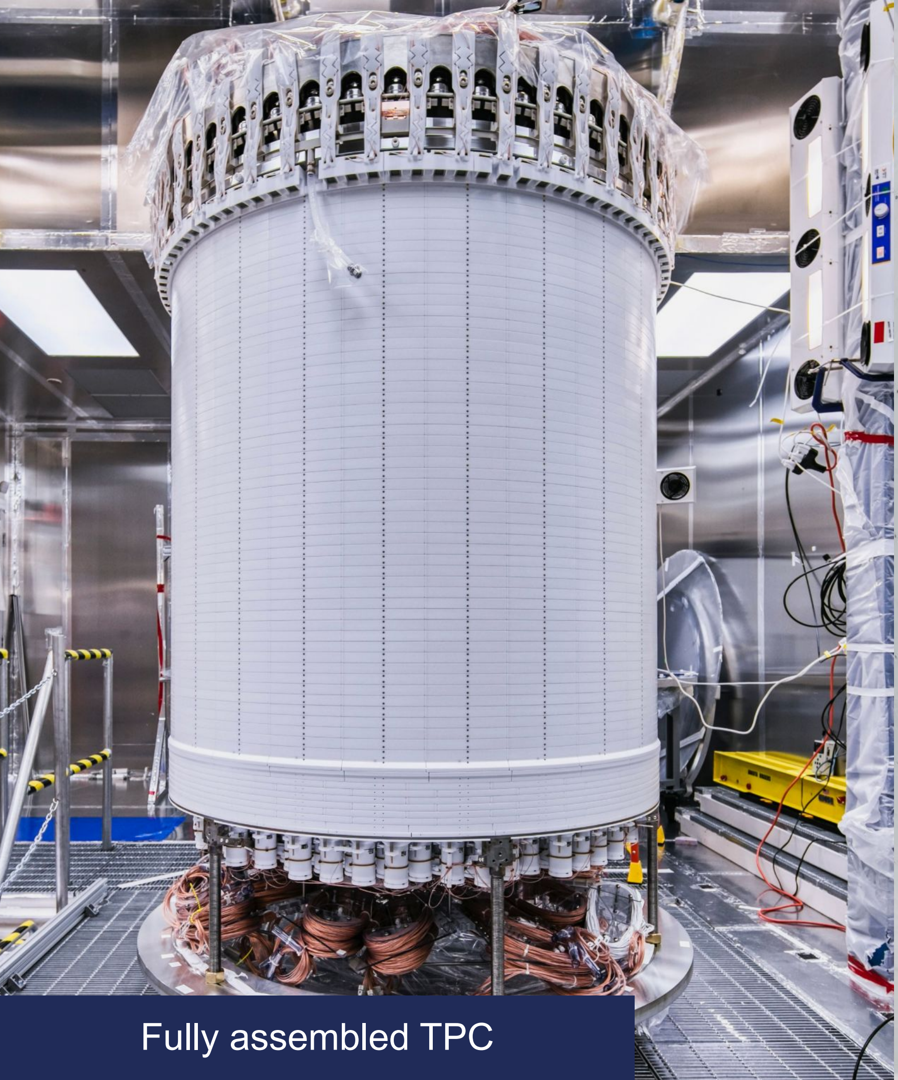
LXe TPC Principles



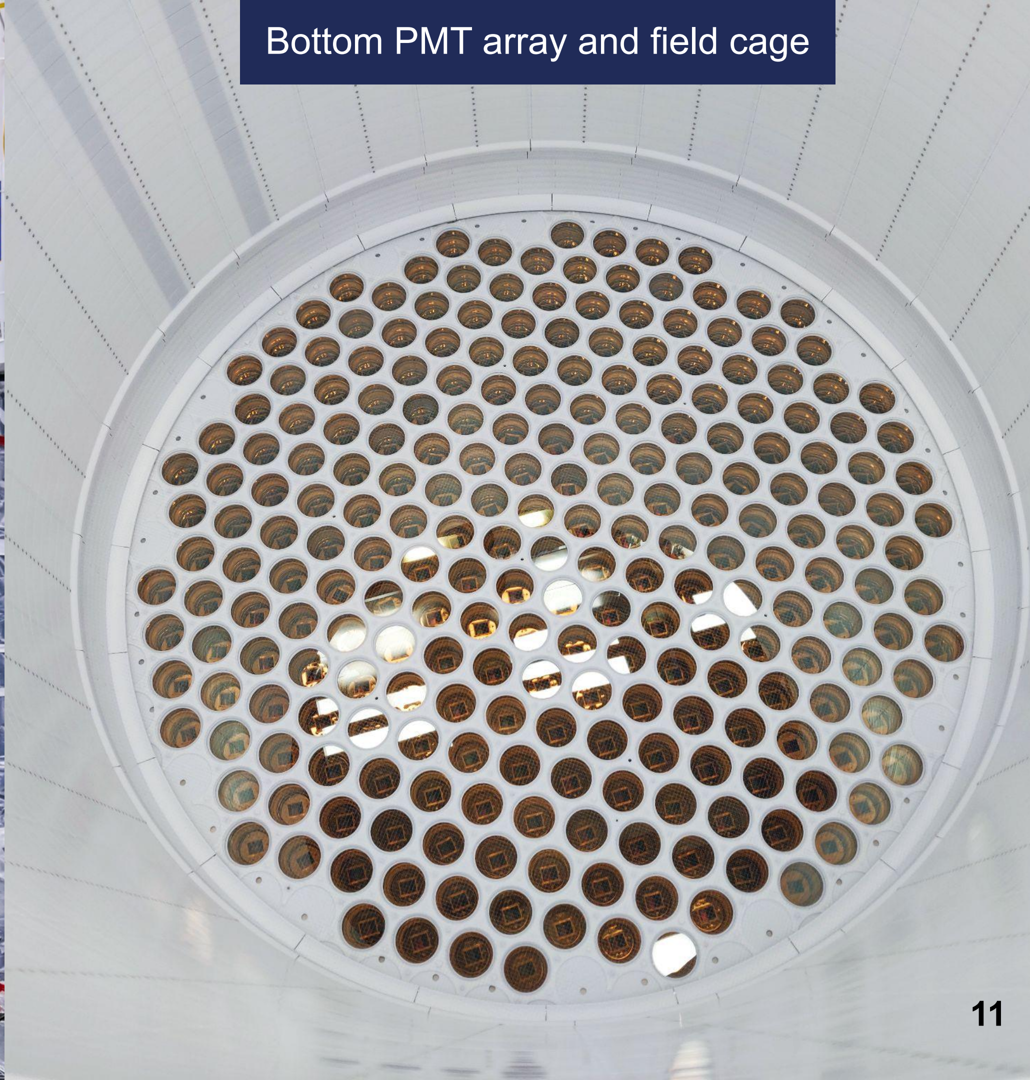


2024 Electronic Recoil (ER) and Nuclear Recoil (NR) discrimination in calibration





Fully assembled TPC



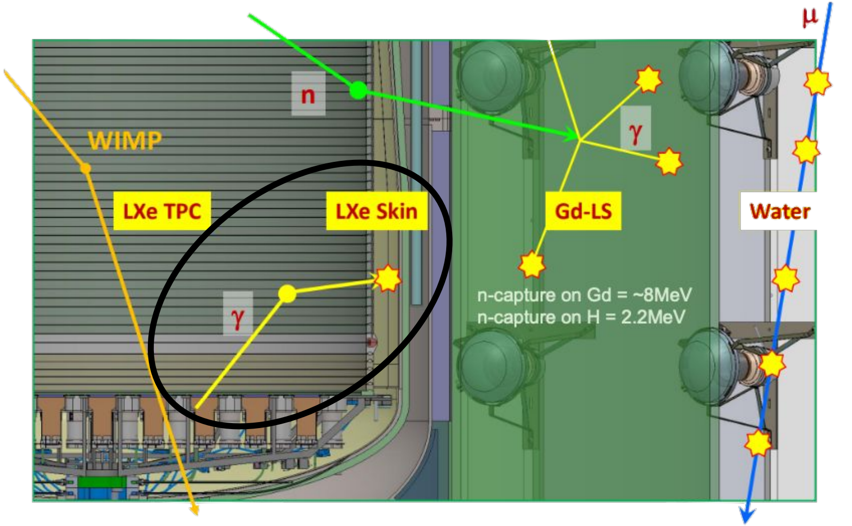
Bottom PMT array and field cage

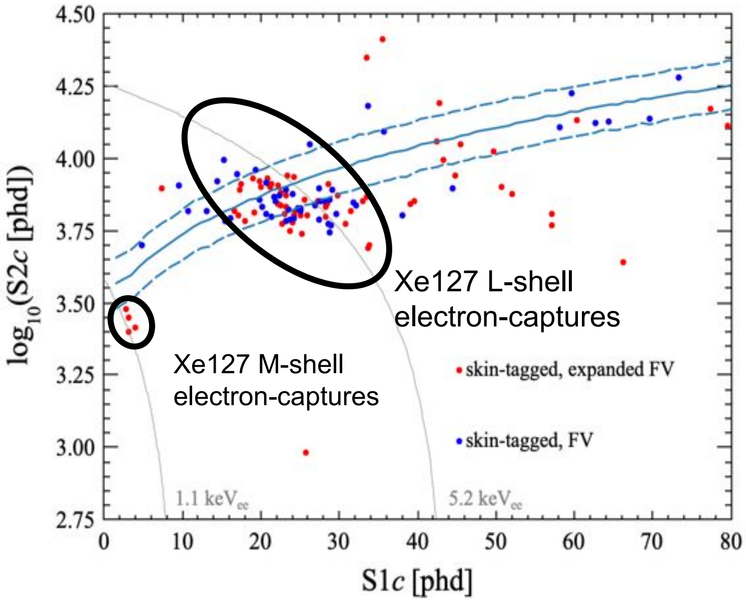
UG TRANSPORTATION

INNER CRYOSTAT INSERTION

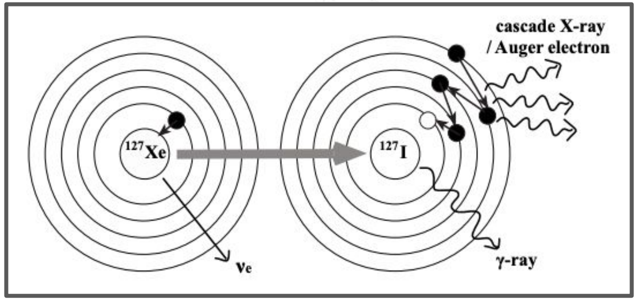
12

LXe Skin



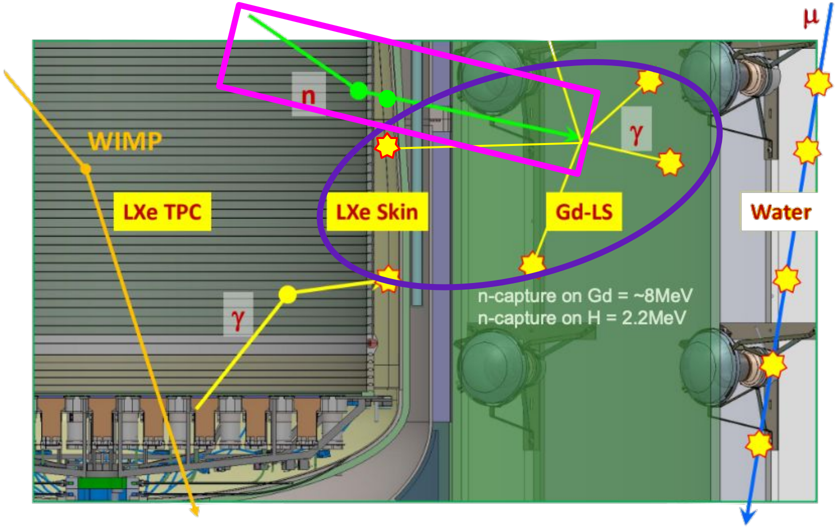


- **2 tonne** of LXe surrounding the TPC
- 131 1" or 2" PMTs
- Anti-coincidence veto for **γ-rays** with **78±5% efficiency**
- Reduction of important ER background rates
  - E.g. ^{127}Xe decay via electron capture



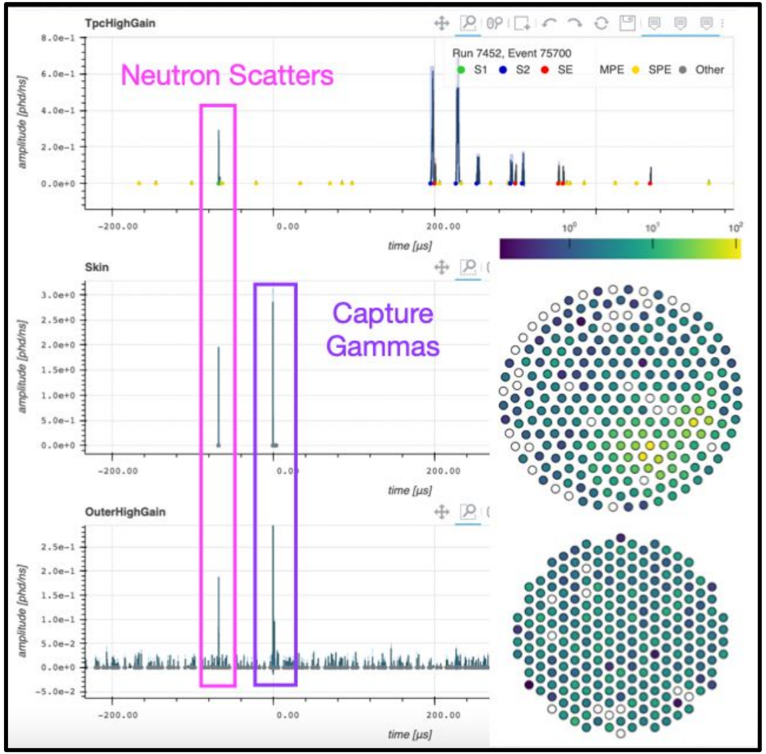
Courtesy of Jack Bargemann APS April 2023

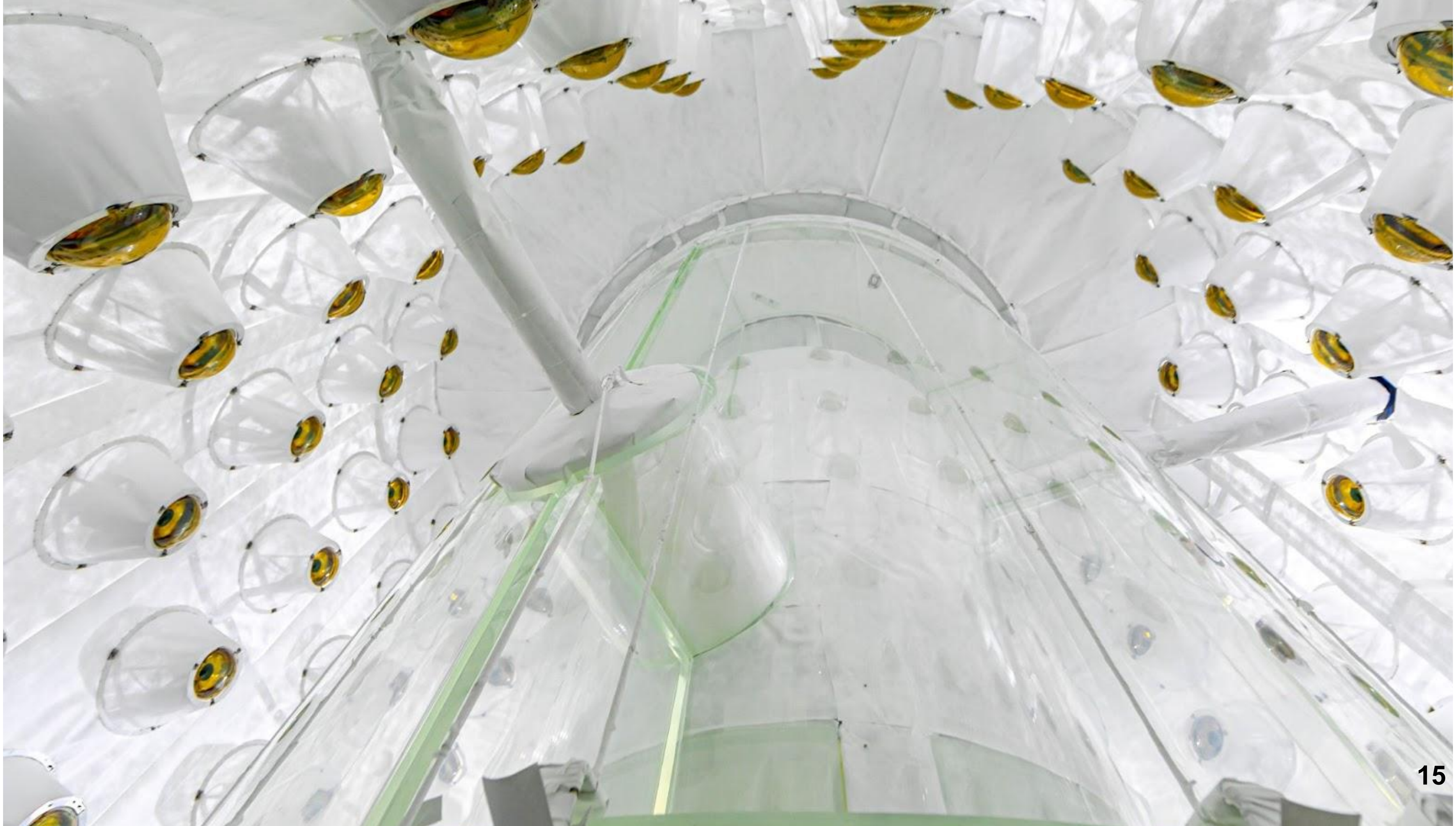
Outer Detector



- **17 tonne** of Gd-loaded liquid scintillator (120 8" PMTs)
- Infinite volume of Gd-LS has a 30us capture time for a thermal neutron
- Expect a n H-capture of Gd-capture ~75% of the time
- ~50Hz of background above 100-200 keV threshold
  - Gd alphas, ^{14}C betas

Waveform example of a tagged neutron multiple scatter:





WIMP Search 2024

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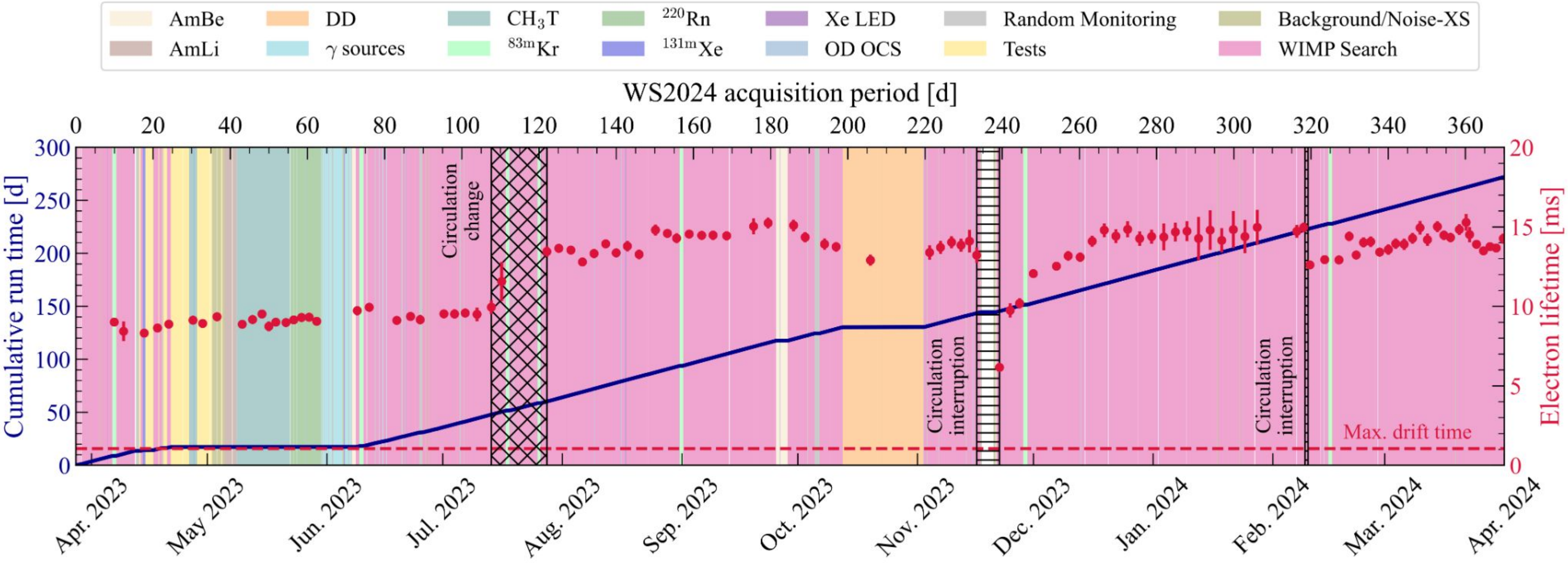
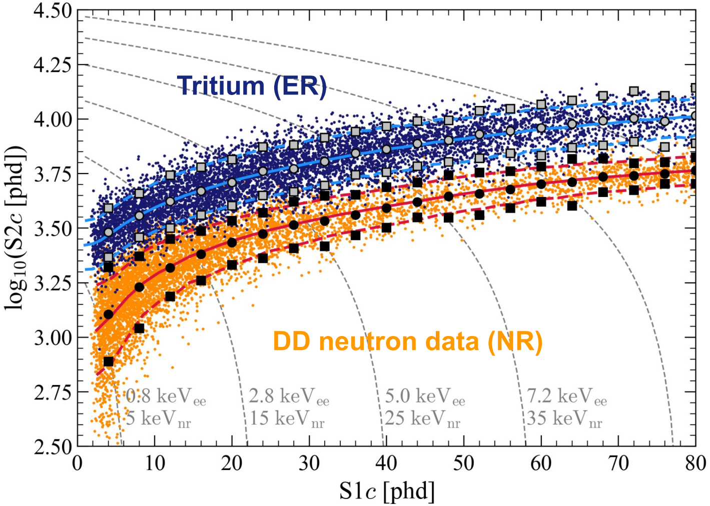


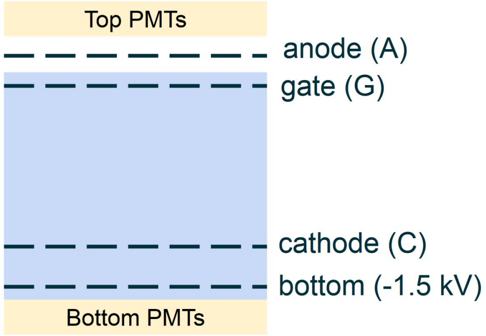
- 220 live-days, one calendar year March ‘23 to March ‘24
- Milestones:
  - Bias mitigation (“salting”) began July 3rd
  - Circulation change July 12th

Calibrations

- ❑ ER calibration: 156k evts radiolabeled methane
  - ❑ ^{3}H (18.6 keV β^-) & ^{14}C (156 kev β^-)
- ❑ NR calibration: 11k neutron evts!
  - ❑ Collimated DD 2.45 MeV & CSD AmLi (α,n)
- ❑ 99.8% discrimination of β^- under flat NR band median
- ❑ Injected ^{83m}Kr, ^{131m}Xe sources, spatial & temporal corrections
  - ❑ (xy, z) resolution at 1σ (<1cm, <1mm)
- ❑ Electron lifetime >8ms (depends strongly on LXe purity)
  - ❑ max e^- drift time ~1ms.

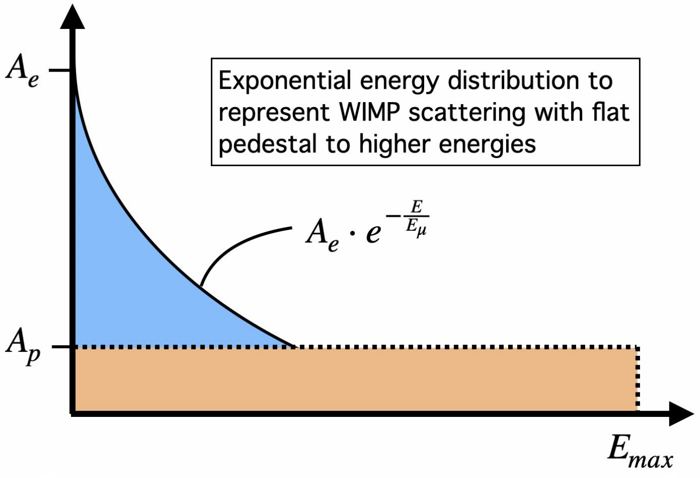


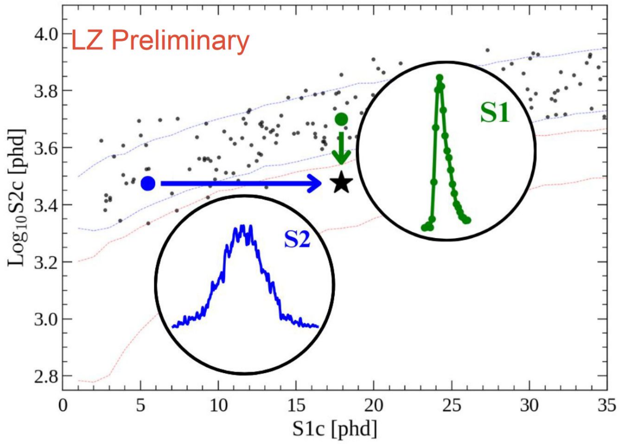
Science Run	C/G/A Voltage [kV]	Drift Field [V/cm]	Analysis live time	g1 (phd/photon)	g2 (phd/e$^-$)
WS2022	-32/-4/+4	193	60	0.114 ± 0.002	47 ± 1.1
WS2024	-18/-4/+3.5	97	220	0.112 ± 0.002	34 ± 0.9



Bias Mitigation

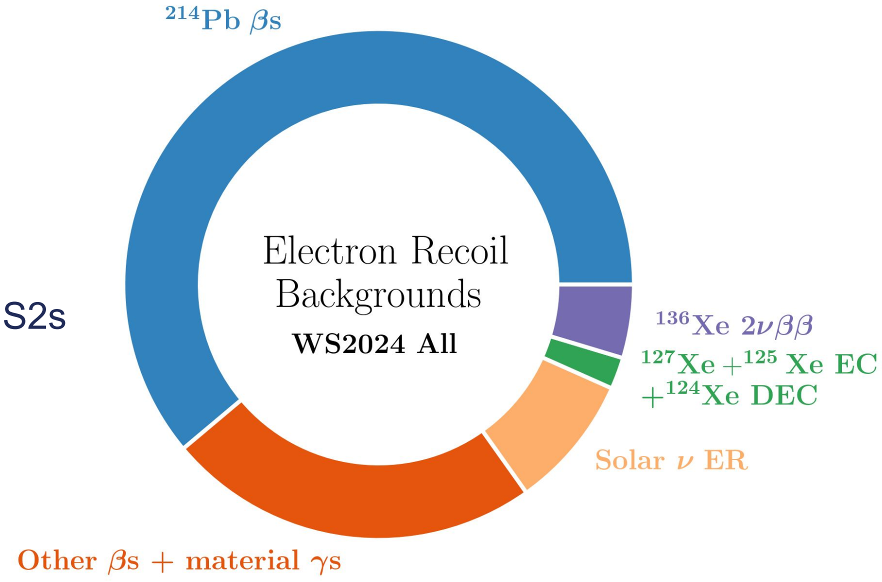
- ❑ "Salting" - fake signal injected randomly
- ❑ Manufactured from sequestered ER & NR calibration data
- ❑ Unknown number of salt events
  - ❑ Rate capped by WS2022 cross-section limit
- ❑ Exponential WIMP recoil spectrum
  - ❑ + flat energy spectrum to cover high energy NR





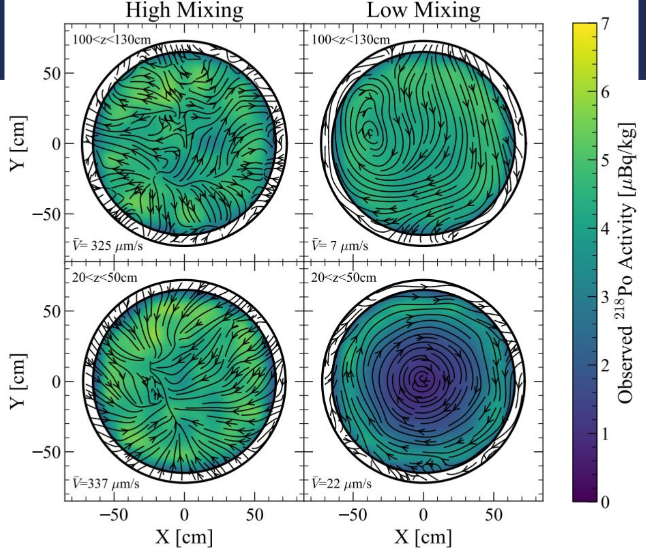
Backgrounds Overview

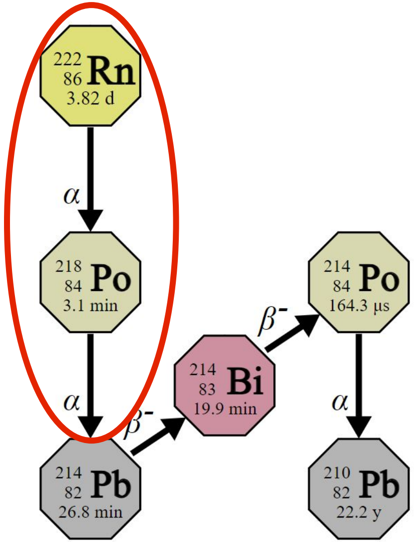
- Dissolved β emitters:
  - ^{214}Pb (^{222}Rn), ^{212}Pb (^{220}Rn), ^{85}Kr, ^{136}Xe (ββ)
- Dissolved EC decays (x-rays/Auger electrons)
  - ^{127}Xe & ^{125}Xe produced by activation from neutron calibration
  - ^{124}Xe (double EC), 0.095% natural abundance
- Solar ν's: ^{8}B (NR), pp+^{7}Be (ER)
- Detector ER, γ emitters from detector materials
  - ^{238}U, ^{232}Th, ^{40}K, ^{60}Co decay chains
- Neutrons from USF and (α,n) in detector materials
- Accidentals - random coincidence of isolated S1 and S2s

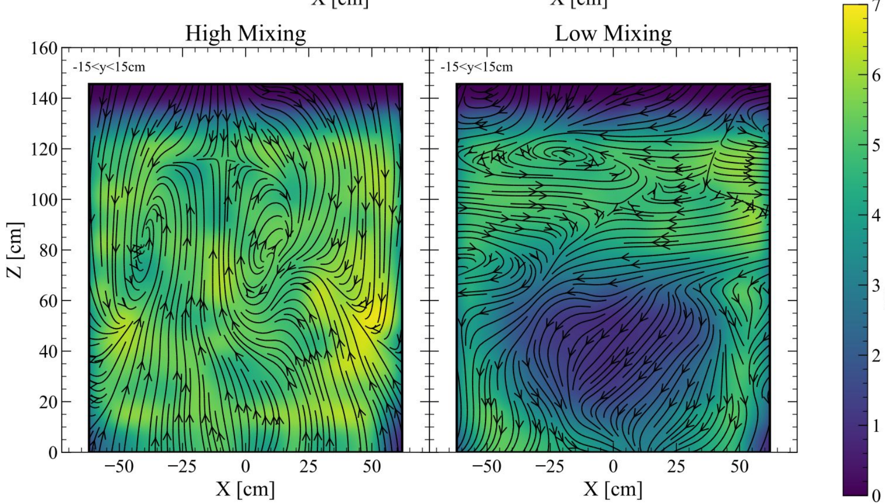


Liquid Xenon Flow

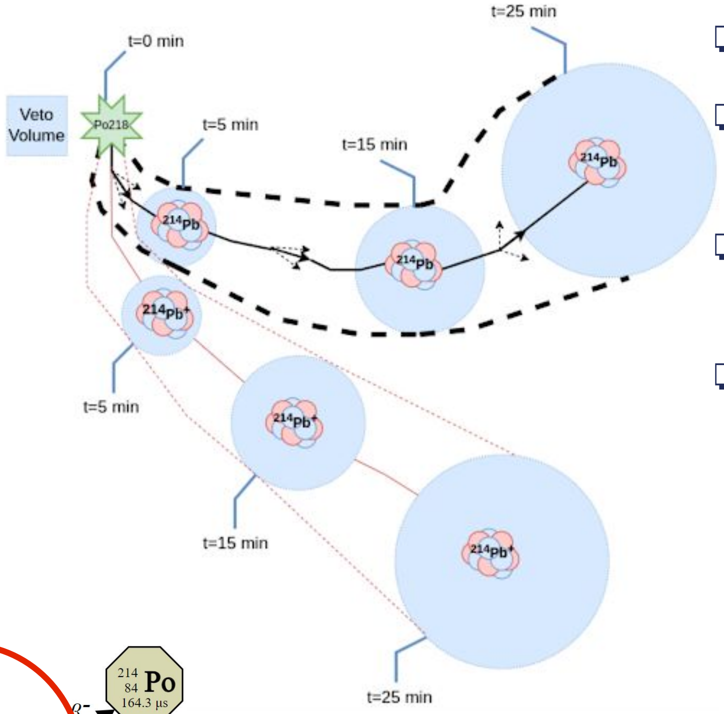
- Fine control of LXe circulation and temperature allows control of LXe flow state
- **High-mixing** state: Turbulent flow, better circulation across TPC, uniform injection of calibration sources
- **Low-mixing** state: Slower, laminar flow. Lower activity in FV, predictable “streamlines”.

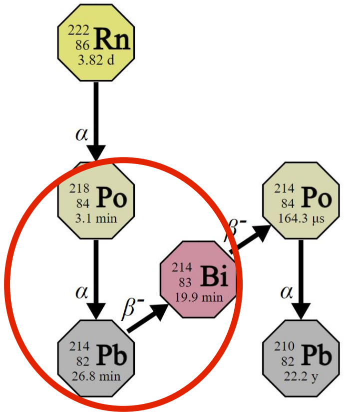






Radon Tag

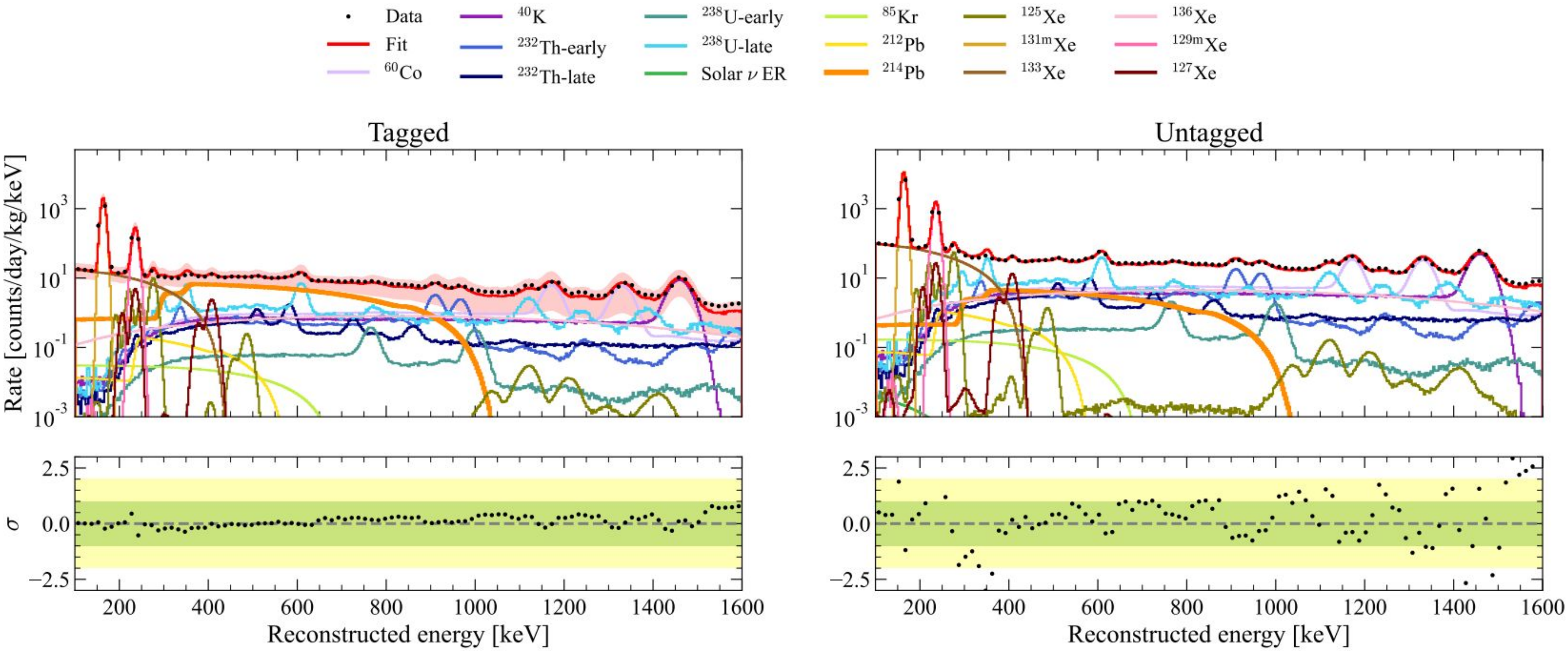




- "Naked" ^{214}Pb β make up majority of ER background
- Combine LXe flow maps & electric field maps to predict volumes likely to contain charged or neutral ^{214}Pb.
- Reduces ^{214}Pb to **1.8 ± 0.3 μBq/kg** in untagged sample
  - 3.9 ± 0.6 μBq/kg in total exposure
- Tagged and untagged samples both fitted for WS2024

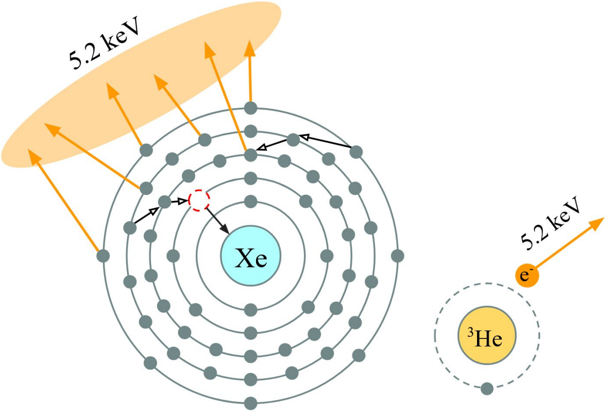
Sample	% ^{214}Pb	% Exposure
Tagged	60 ± 4	15
Untagged	40 ± 4	85

Radon Tagged High Energy Fit

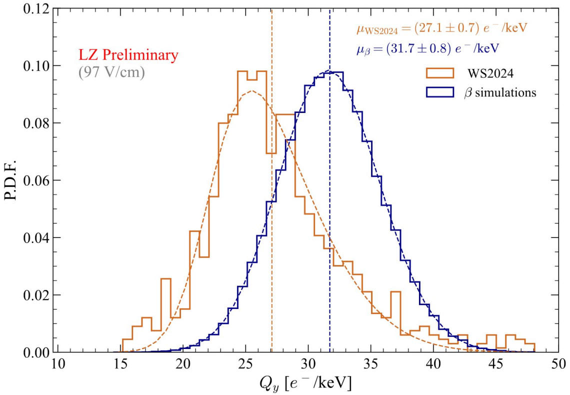


Electron Capture Backgrounds

- ^{125}Xe & ^{127}Xe decay by electron capture (EC)
- Produced by activation from neutrons calibration and cosmogenics
  - Rate in WS2024 << WS2022
- L-shell electron capture (5.2 keV) is a WS background
- Electron capture has a **field-dependent suppressed charge yield**
- Higher ionization density ⟶ increased recombination
- LZ WS2022 (193 V/cm): Q_L/Q_β=0.88±0.01*
- LZ WS2024 (97 V/cm): Q_L/Q_β=0.86±0.01*
- Charge suppression first measured in XELDA
  - [PRD 104, 112001 ('21)]



Xe L-shell EC ^3H β^- decay



- Skin tagged Xe L-shell EC
- β simulation

*Preliminary, dedicated publication in progress

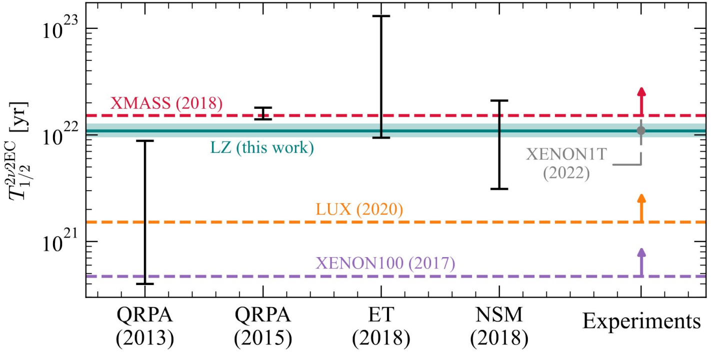
^{124}Xe Double Electron Capture

- ^{124}Xe 2νECEC $T_{1/2}=(1.09\pm0.14^{stat}\pm0.05^{sys})\times10^{22}$ years
  - Worlds longest directly measured half-life
- In-situ $T_{1/2}$ measurement of KK (64.3 keV) captures - (65 ± 5)%
- LL (10 keV) and LM (6 keV) are WS backgrounds
- LM modelled with same as single L-shell charge suppression
  - $Q_{LM}/Q_{\beta} = Q_L/Q_{\beta}$
- For LL expect further charge yield suppression due to higher ionization density.
- Vary Q_{LL}/Q_{β} in fitting of our data $0.65 < Q_{LL}/Q_{\beta} < 0.87$

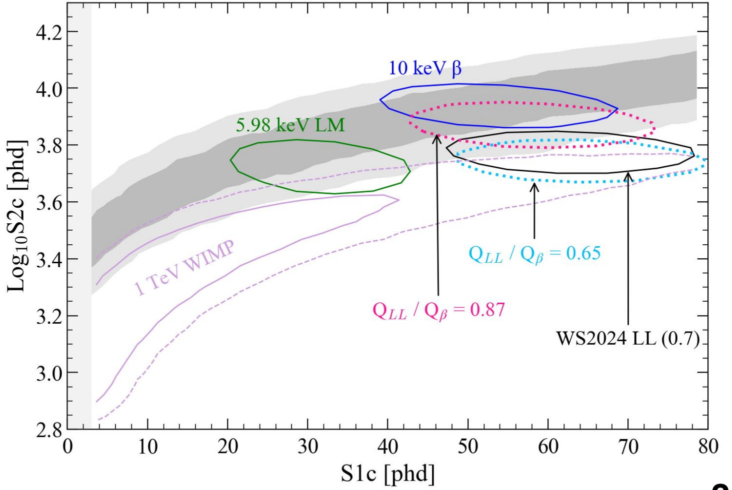
2x ionization density → 0.65

Q_L/Q_{β} → 0.87

- Best fit to WS2024 data: $Q_{LL}/Q_{\beta} = 0.70\pm0.04$

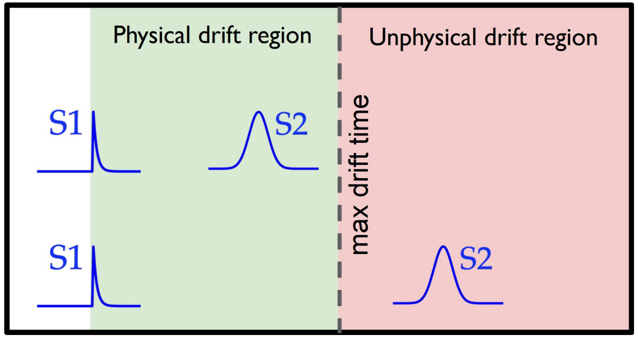


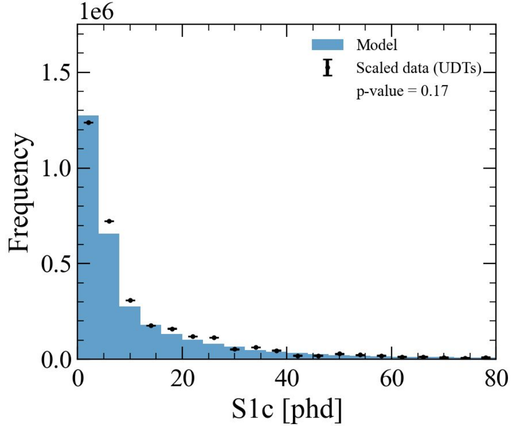
WS2022 arXiv:2408.17391v1

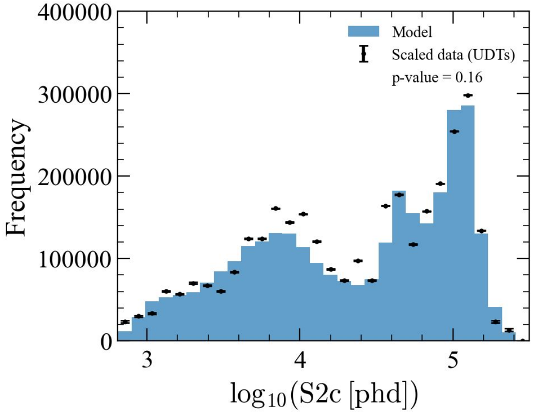


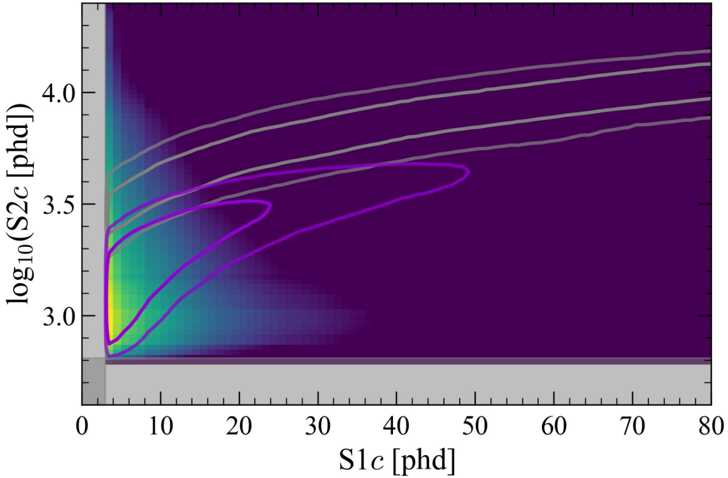
Accidentals Background

- Accidental coincidence of uncorrelated isolated S1 and S2 pulses
- LZ's accidentals model:
  - **Rate:** Measure rate of unphysical drift time (UDT) single scatters. Analysis cut efficiencies analysed using manufactured accidental events.
  - **Shape:** Manufactured by combining isolated S1 and S2 waveforms and applying analysis cut efficiencies.
- Analysis cuts have an 99.5% rejection power



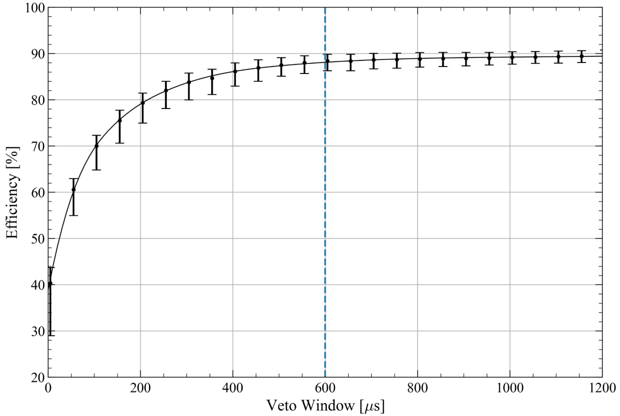


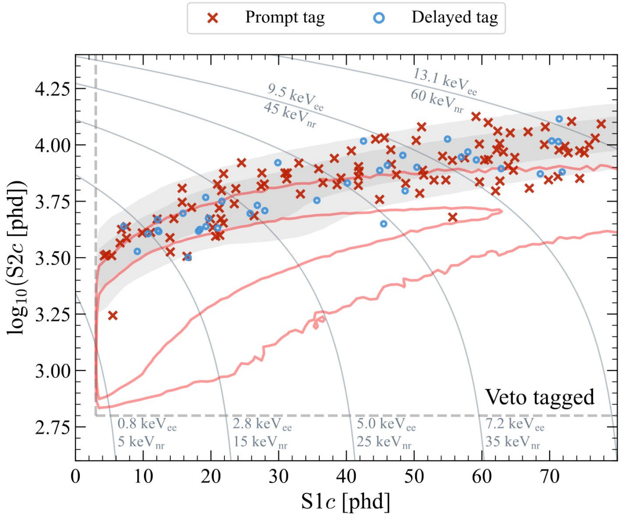




Neutrons & Vetoes

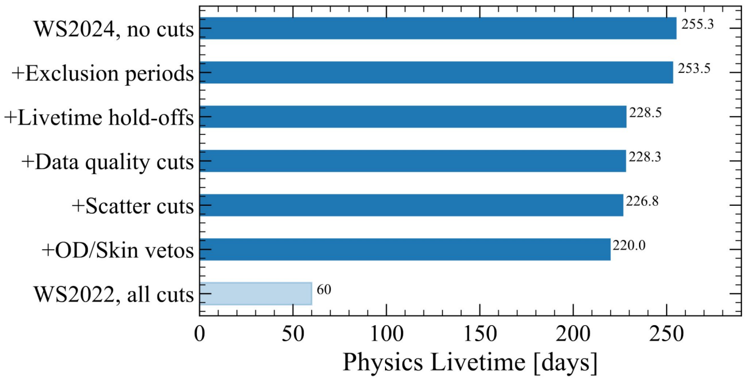
- 89±3% neutron veto efficiency from AmLi calibration
  - 3% deadtime, (false veto rate * veto window length)
- Background simulation suggests higher veto efficiency due to additional gammas from (α,n) and USF - 92±4%
- Determine neutron rate by fitting neutron rich veto tagged single scatter sideband
- Background:
  - Decays with gammas giving a prompt veto signal
  - Random pile-up of TPC decays with delayed veto signal (3% of WS rate)
- Veto sideband fit gives expectation of $0^{+0.2}$ neutrons for WS
- Complimentary multiple scatter analysis predicts 0.3±0.2



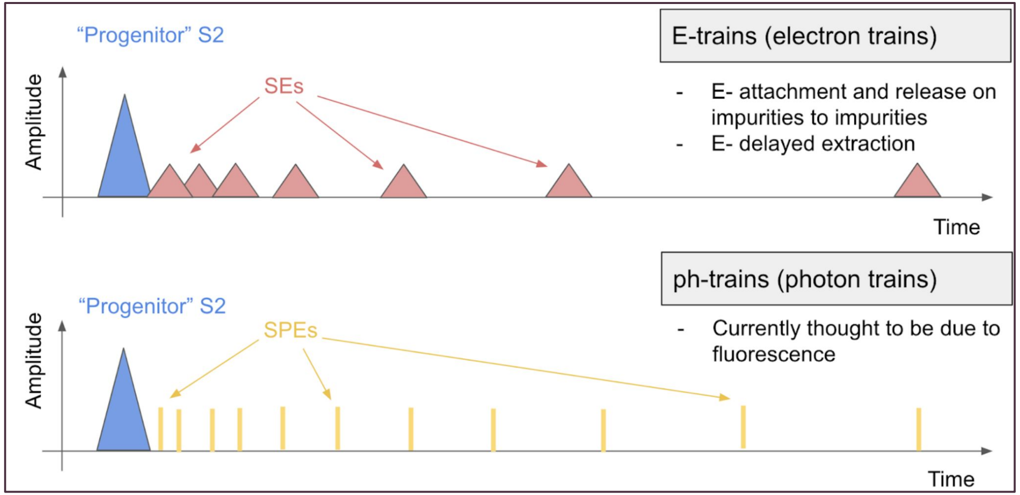


Data Quality

- Contemporaneous and retrospective data quality monitoring
  - Online: Underground Performance Monitor (UPM)
    - Primarily monitors PMT and Trigger health
  - Offline: Physics Readiness Monitor (PREM)
    - Detector health, which data should be included in WS
- Data quality is generally good!

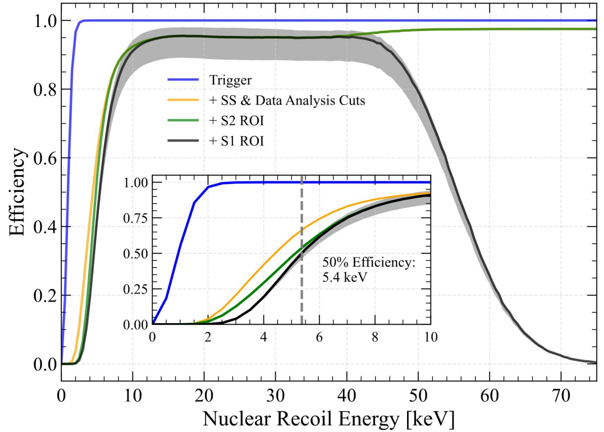


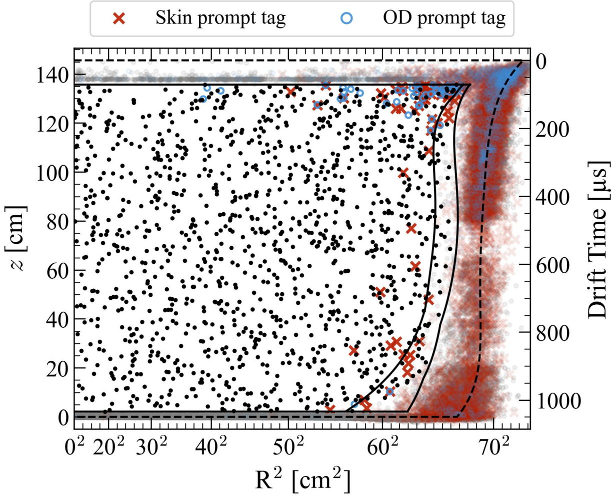
- Largest livetime exclusion is due to e-trains and ph-trains
- 10% livetime loss



Data Analysis

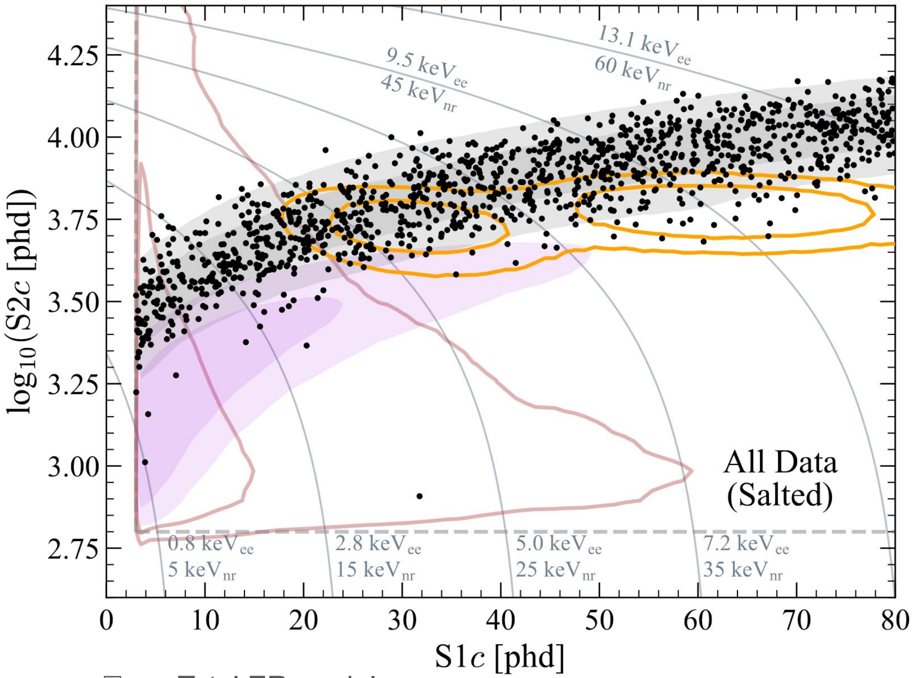
- Region of interest (ROI)
  - 3 < S1c < 80 photons detected (phd)
  - S2 > 14.5 electrons (645 phd)
  - $\log_{10}$(S2c) < 4.5
- Fiducial volume: azimuthally & drift time-dependent
  - < 0.01 charge loss (“wall”) events
  - 5.5 ± 0.2 tonne mass
- Single scatter
- Anti-coincidence Skin & OD vetoes
- Cuts on S1 & S2 parameters to remove accidentals





WS2024 Data - Salted

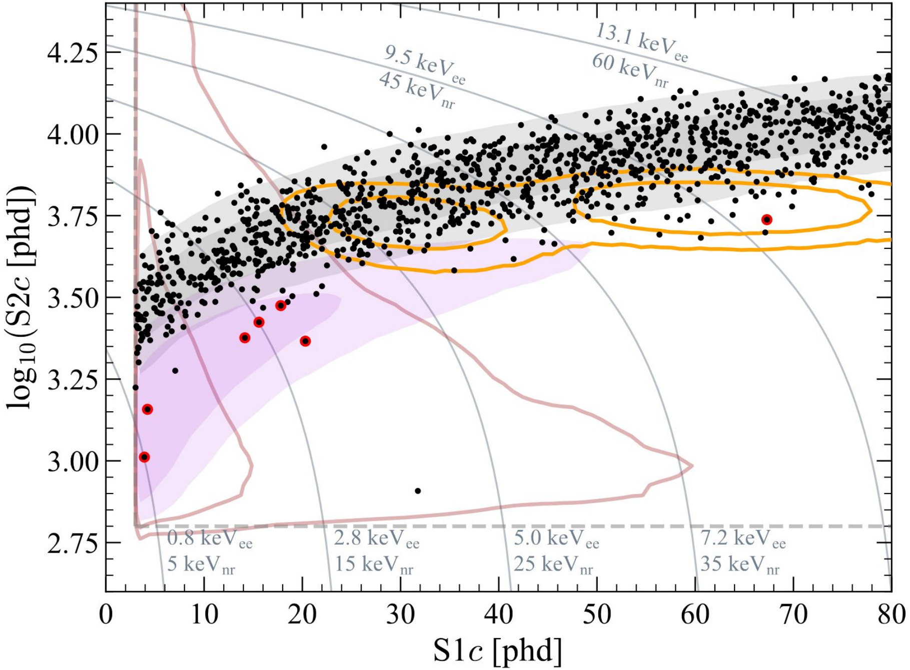
- Final exposure:
  - 220 livedays * 5.5 tonnes = 3.3 tonne years



- Total ER model
- ^{124}Xe model: Q_{LL}/Q_{β} @ best fit
- 40 GeV/c^2 WIMP
- Accidentals model

WS2024 Data - Unsalting

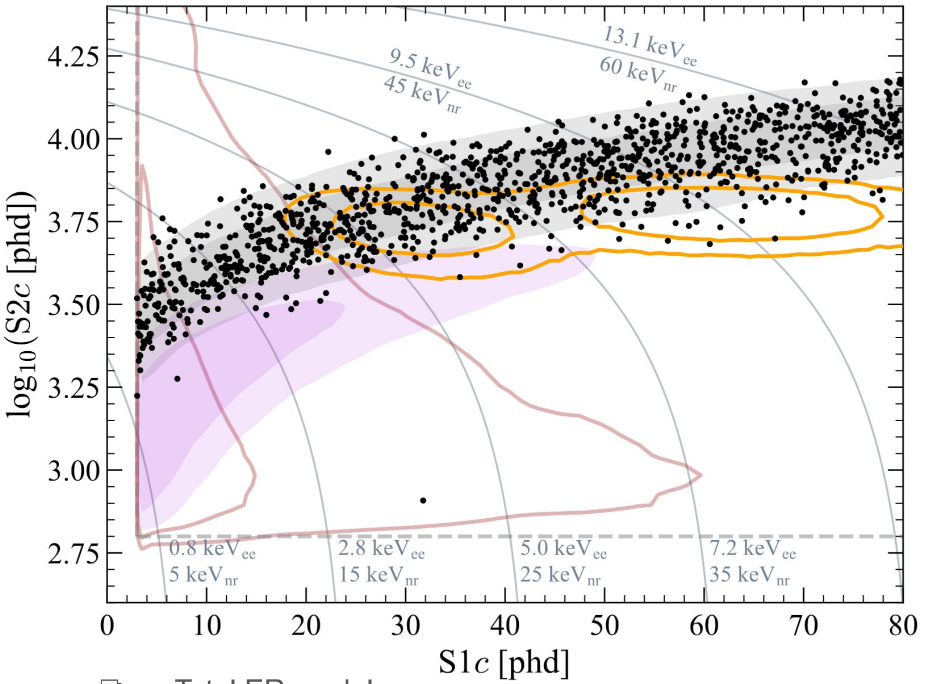
- Final exposure:
  - 220 livedays * 5.5 tonnes = 3.3 tonne years
- 7 salt events present after all cuts
  - 8 injected in WS2024
  - Consistent with evaluated signal efficiency



- Total ER model
- ^{124}Xe model: Q_{LL}/Q_{β} @ best fit
- 40 GeV/c^2 WIMP
- Accidentals model

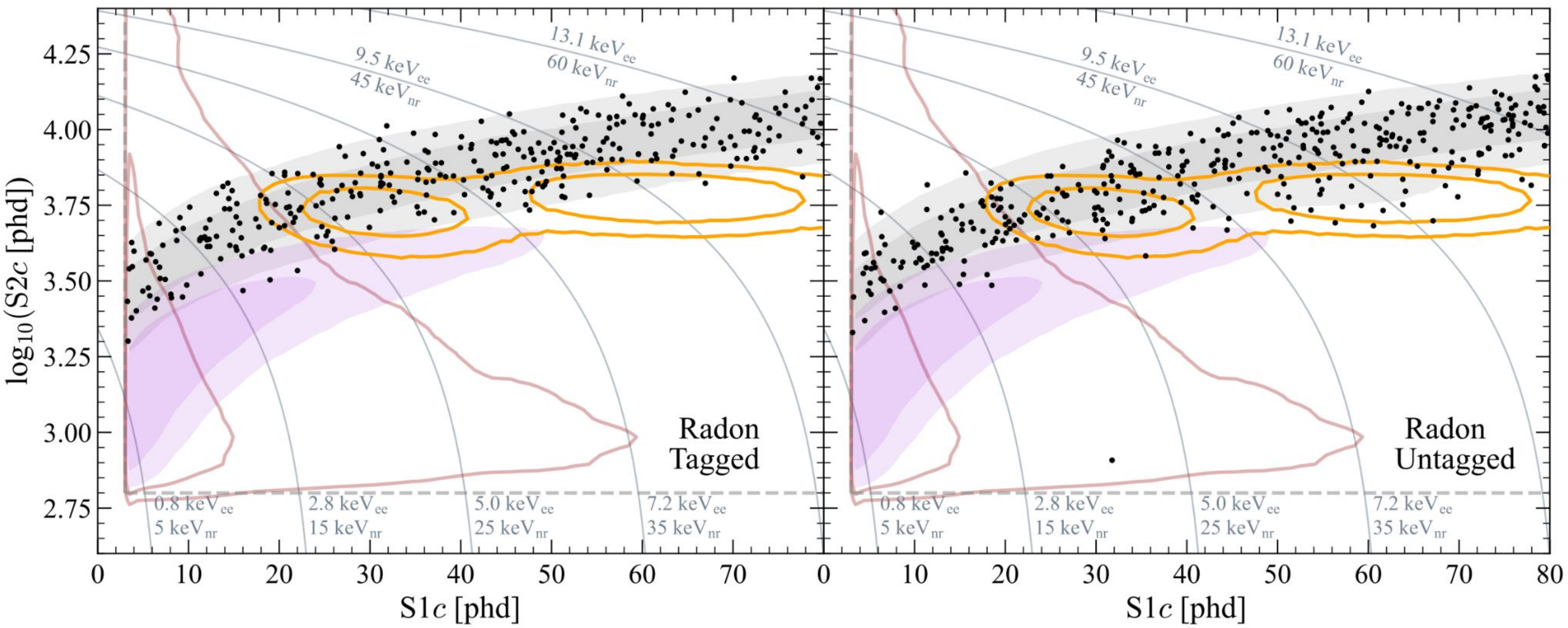
WS2024 Data - Unsalted

- Final exposure:
  - 220 livedays * 5.5 tonnes = 3.3 tonne years
- 7 salt events present after all cuts
  - 8 injected in WS2024
  - Consistent with evaluated signal efficiency
- 1220 events remain after unsalting
- No changes to model required post-unsalting
- Next step: Statistical inference of this data



- Total ER model
- ^{124}Xe model: Q_{LL}/Q_{β} @ best fit
- 40 GeV/c^2 WIMP
- Accidentals model

Radon Tagged vs Untagged



0.3 tonne years

1.8 tonne years

Combined Likelihood

Exposure in each sample [tonne years]

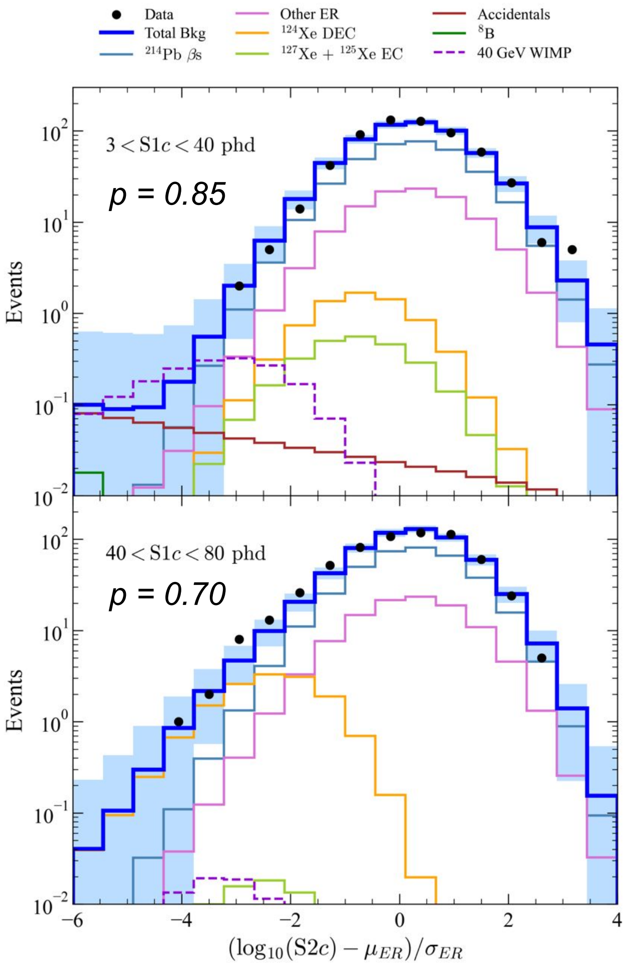
High Mixing State	Radon Tag Inactive	Radon Tagged	Radon Untagged	OD/Skin Vetoed	WS2022
0.6	0.6	0.3	1.8	n/a	0.9

- Likelihood fit contains six samples
- WS2024 represented by first four, totalling 3.3 tonne years
- OD/Skin vetoed - full WS2024 3.3 tonne years - constraint on neutron background
- WS2022 unmodified since original publication → Maximise exposure

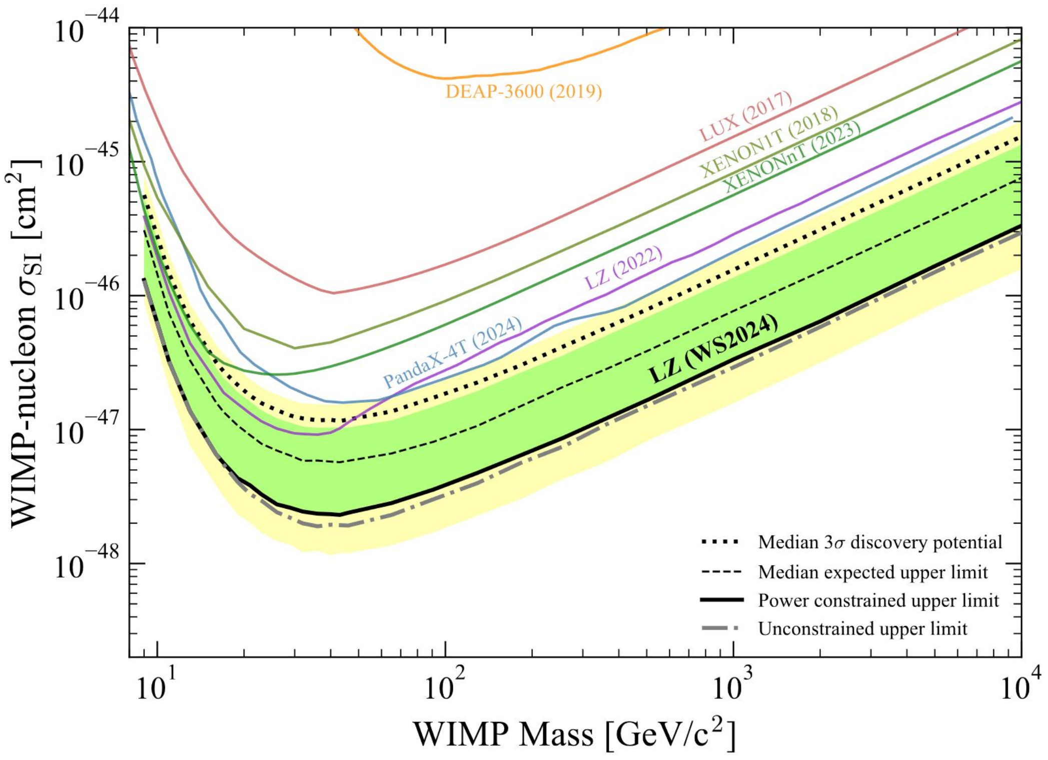
WS2024 Fit Results

Source	Pre-fit Constraint	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	55.8 ± 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
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	–	$0.0^{+0.2}$
40 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	1210 ± 91	1203 ± 42

- Best fit no. of WIMPs is 0 at all tested masses (GeV- 10TeV)
- Strong agreement with background only hypothesis

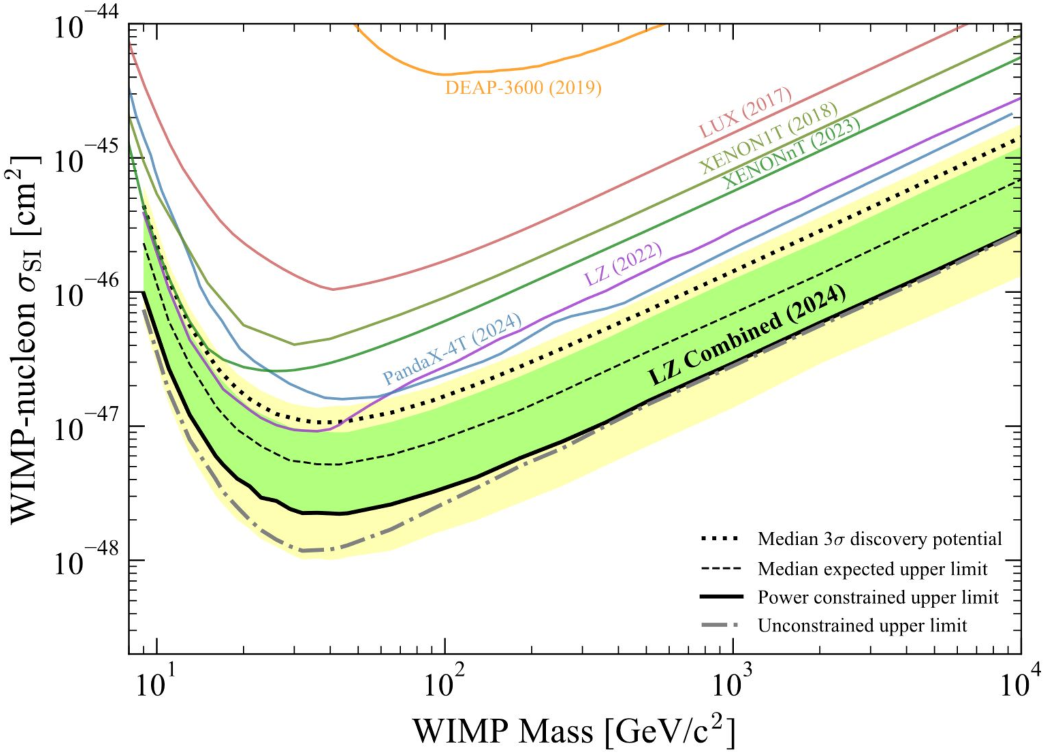


WS2024 Only Sensitivity



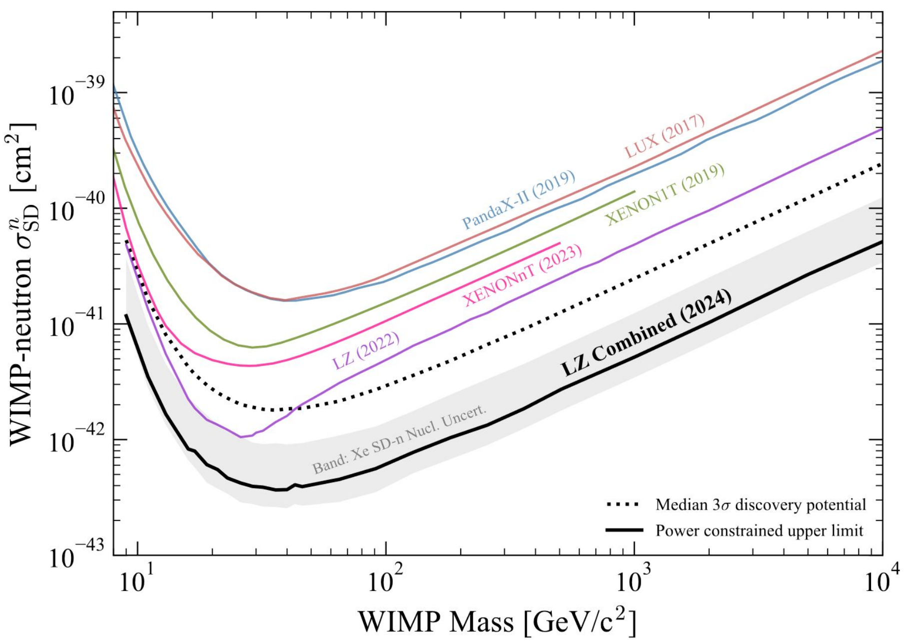
- ❑ Two-sided profile likelihood ratio test statistic
- ❑ Power constrained at -1σ as per recommended conventions EPJC 81, 907 ('21)
- ❑ Under-fluctuation in sensitivity results from arrangement of accidentals background events
- ❑ WS2024-only best limit of σ_{SI}=2.3×10^{-48}cm^2 at 43GeV/c^2

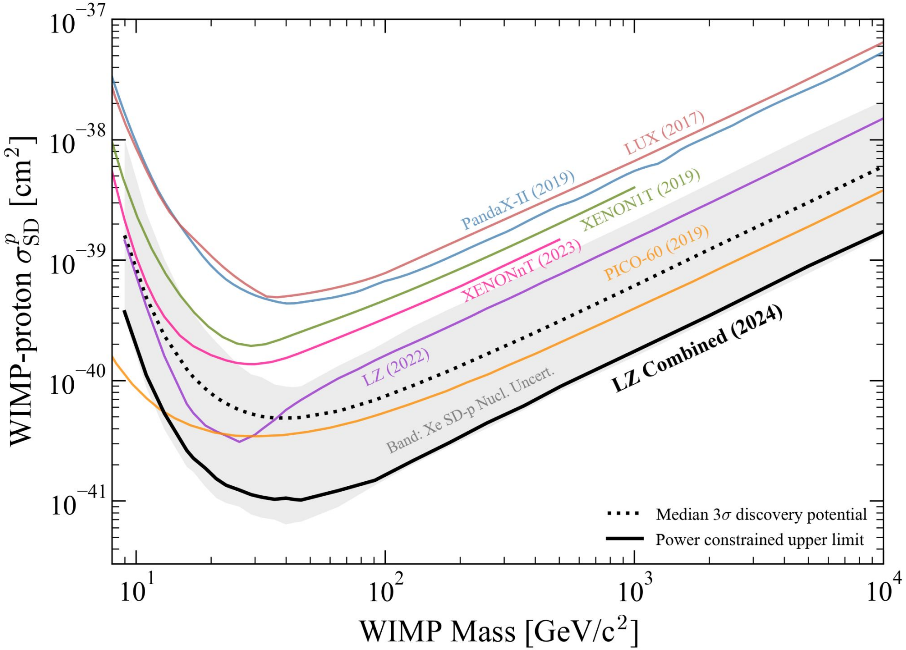
WS2024 + WS2022 Sensitivity



- Two-sided profile likelihood ratio test statistic
- Power constrained at -1σ as per recommended conventions EPJC 81, 907 ('21)
- Further under-fluctuation from WS2022 ER background
- Best limit from combined analysis of $\sigma_{SI}=2.2\times10^{-48}$cm^2 for 43GeV/c^2

Spin Dependent Sensitivity





- Spin-dependent limit using odd Xe isotopes
  - ^{129}Xe, spin 1/2, 26.4% natural abundance
  - ^{131}Xe, spin 3/2, 21.2% natural abundance

Conclusions

- **LZ is the world's most sensitive WIMP direct detection experiment**
  - Total exposure 4.2 tonne-years
  - New constraint exceeds previous best constrain by factor >4
- Radon tag developed and deployed for the first time
  - 60% reduction in main ER background ^{214}Pb
- First observation of suppressed charge yield from LL-shell captures of ^{124}Xe
- LZ will continue to take data until 2028, towards 1000 live days
- Many physics searches on the horizon!:
  - ^{8}B CEνNS, low mass WIMPs, ER based searches, 0$\nu\beta\beta$