Status of the LUX-ZEPLIN (LZ) Experiment's Search for Dark Matter

Scott Kravitz
On behalf of the LZ Collaboration

LIDINE 2023, Madrid, Spain
September 20, 2023

LZ (LUX-ZEPLIN) Collaboration, 37 Institutions

@lzdarkmatter

250 scientists, engineers, and technical staff

https://lz.lbl.gov/

- 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
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Thanks to our sponsors and participating institutions!

The LUX-ZEPLIN Experiment (LZ)

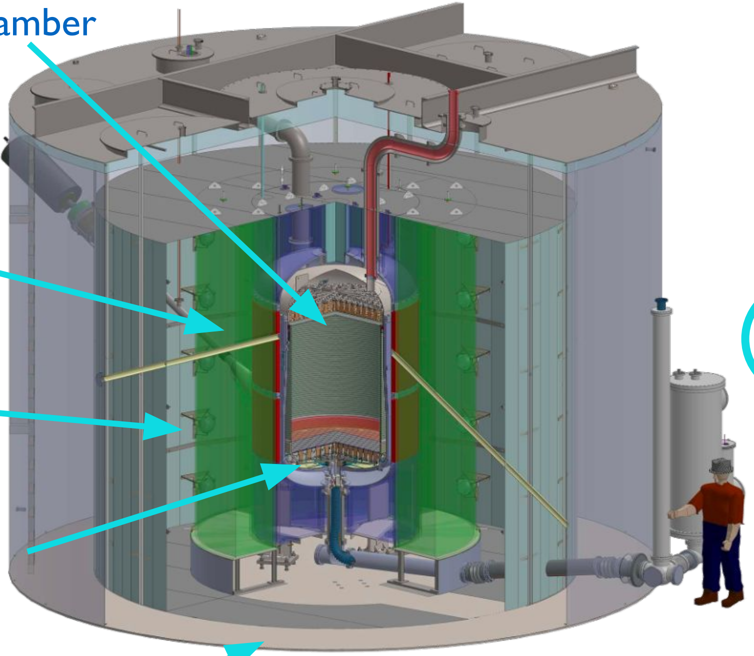
Liquid Xenon (LXe)
Time projection chamber
(TPC)

Outer detector
(veto)

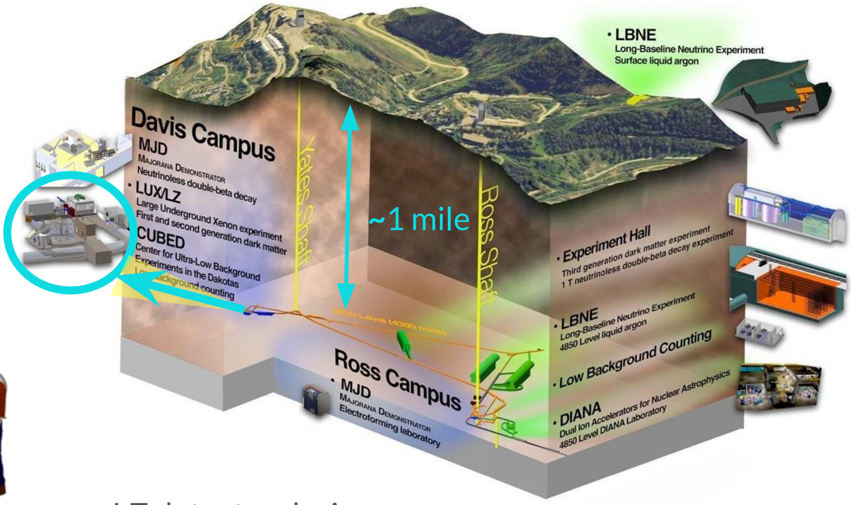
Outer detector
PMTs

LXe Skin (veto)

Water tank



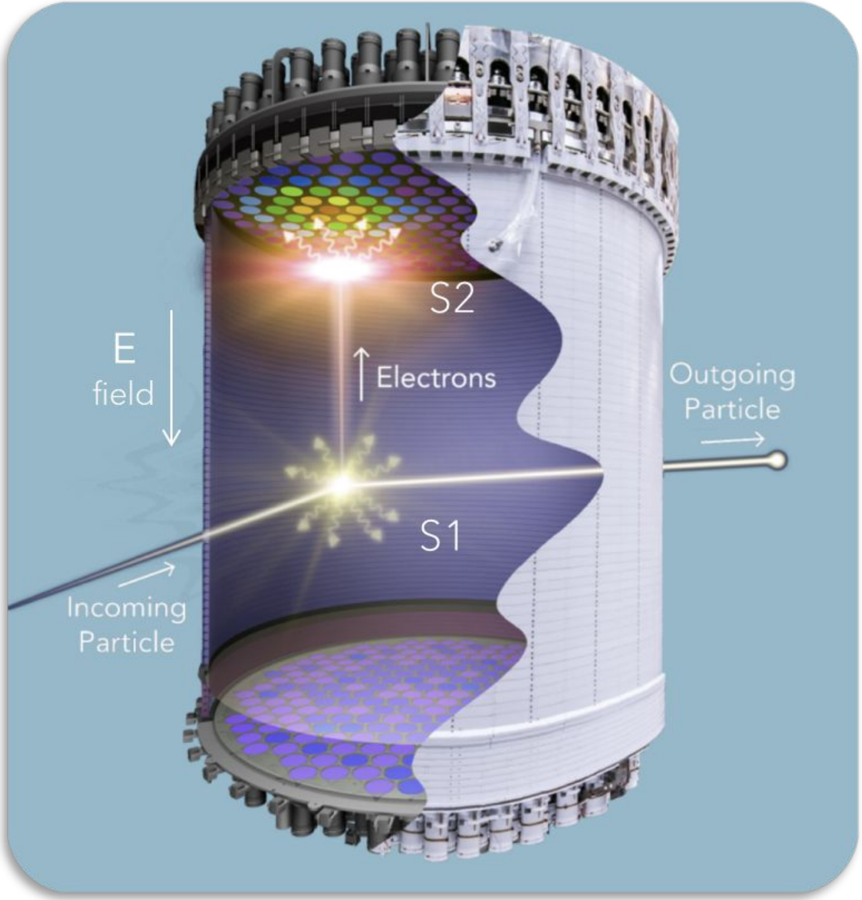
Located 4850 ft. underground at the
Sanford Underground Research Facility (SURF)
in Lead, South Dakota, USA

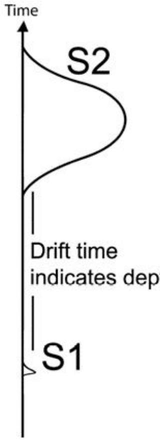


LZ detector design:
[NIM A, 163047 (2020)]

Principle of operation

- Raw data: waveform per PMT
- Typical reconstructed info (for each scatter):
  - **S1** (prompt scintillation) total area
  - **S2** (ionization signal) total area
  - **X, Y position** (from S2 PMT hit pattern)
  - **Z** (from Δt between S1 and S2)
- Weighted sum of S1, S2 gives **E**
- S1/S2 ratio implies **recoil type**
  - Dominant backgrounds are electron recoils (**ER**)
  - WIMP interactions are nuclear recoils (**NR**)

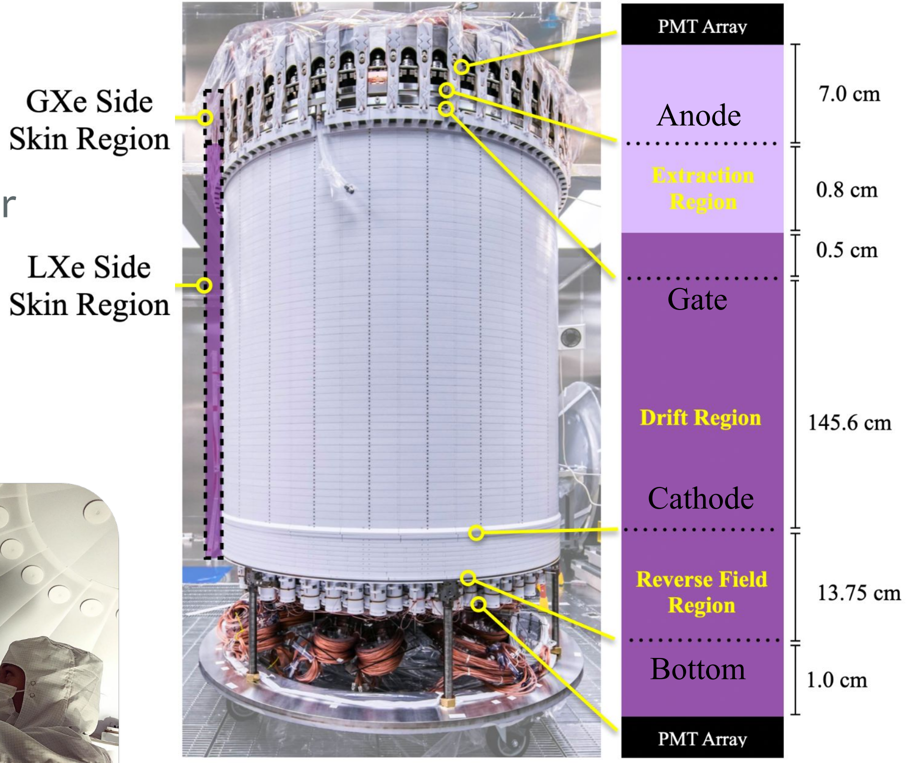




Early LZ Operations

- First science run started late 2021
- First results summer 2022 with ~60 live days
- Past year: extensive calibrations, ongoing longer data-taking run in discovery mode

- Key detector stats:
  - **7 tonnes** active Xe mass
  - TPC dimensions: **1.5 m tall x 1.5 m dia.**
  - **~500 PMTs** in the TPC
  - PTFE walls **~97% VUV reflectivity**
  - 4 woven electrode grids
- First science run parameters:
  - Temperature: **174.1 K**
  - Gas Pressure: **1.79 bara**
  - Drift Field: **193 V/cm**
  - GXe Extraction Field: 7.3 kV/cm (**~80% electron extraction**)
  - Electron lifetime: >5 ms (**82-88% e- survival** at max drift)



LZ electrode grid design:
NIM A, 165955 (2022)

Background reduction - a monumental effort

- Key challenge: reducing backgrounds enough to observe O(1-10) DM events in years of data

- Mitigation techniques in construction and operation:
  - Rock overburden - muons reduced by ~10^6
  - Radiopure detector materials - all materials assayed to reduce γ and (α,n) rates (HPGe, ICPMS, neutron activation)
  - TPC assembled in Rn-reduced cleanroom
  - Xe distilled off-site for Kr removal (<300 ppq)
  - In-line Rn removal with charcoal chromatography

HPGe counters at SURF

Kr removal system at SLAC

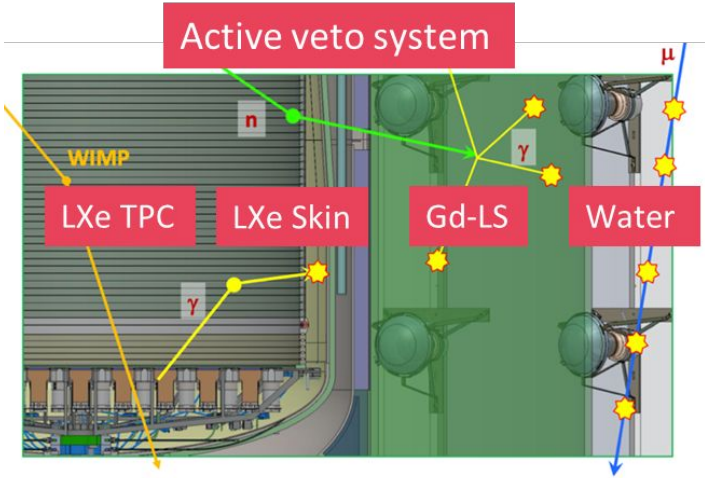
Radioassay and cleanliness: EPJC, Vol 80: 1044 (2020)

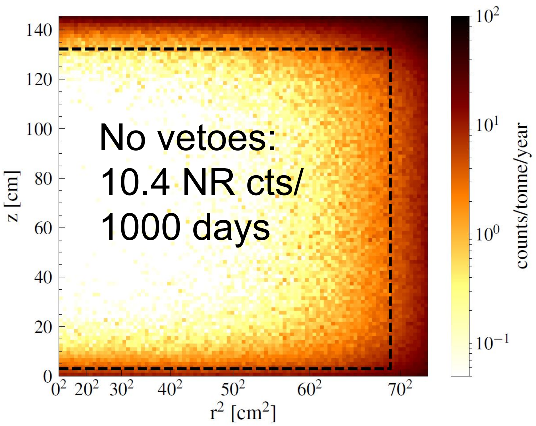
Ultrapure titanium: Astropart. Phys. 96, 1 2017

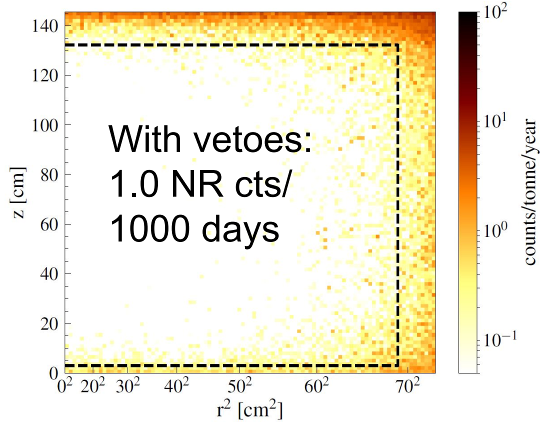
Background reduction - analysis techniques

- Only **1 in 10^9** events are of interest: extreme needle in a haystack problem!
- Fiducialization - xenon self-shields from external γ
- Highly efficient veto system:
  - 89% n rejection from OD + skin (AmLi calibration source)
  - 78% γ rejection from skin (^{127}Xe events)

Total Collected Particles	100%	5 Billion
Single Site Interactions	5%	250 Million
Low Energy Transfer	0.4%	1 Million
Detectable Charge Level	10%	100,000
Use Inner Volume Only	5%	5,000
Not Observed in Gadolinium	20%	1,000
Low Charge/Light Ratio	0.5%	5





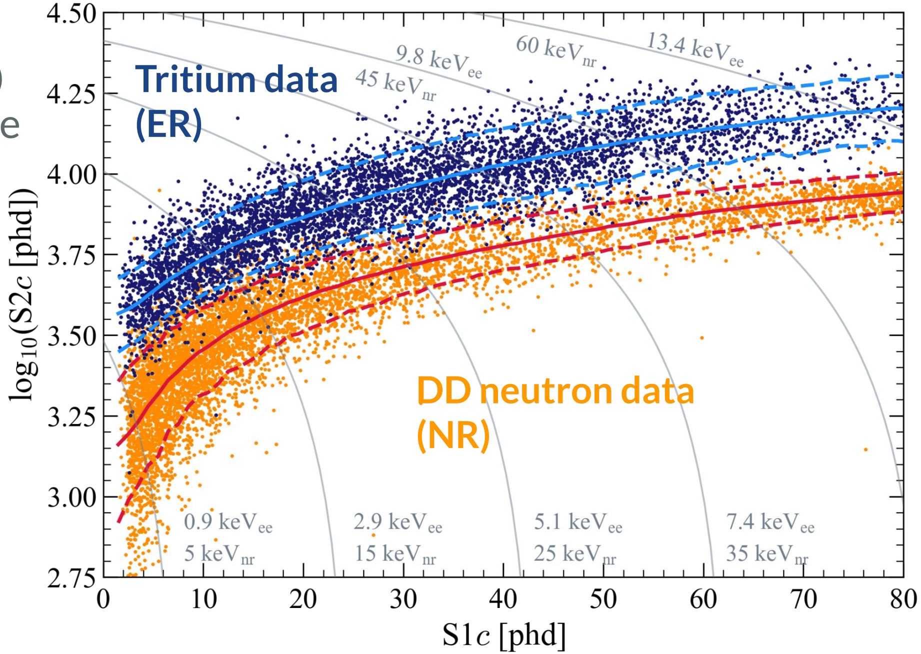


Projected sensitivity: [Phys. Rev. D 101, 052002 (2020)]

Calibration and Simulations

- Principle calibration sources:
  - **CH_3T** (tritium) beta source, ER, dispersed (<18.6 keV)
  - **DD neutron** source, NR, external (2.45 MeV neutrons)
- Many others, such as dispersed ^{83m}Kr and ^{131m}Xe (position, time-dependent signal corrections)

- Calibration data used to tune NEST*-based simulation parameters:
  - Light gain **g1: 0.114** ± 0.002 phd/photon
  - Charge gain **g2: 47.1** ± 1.1 phd/electron
  - Single electron size: **58.5 phd**
- ***99.9% rejection*** of ERs below the NR median
- See Jack Bargemann's talk on light and charge yields of Xe electron captures, Thurs 2 pm



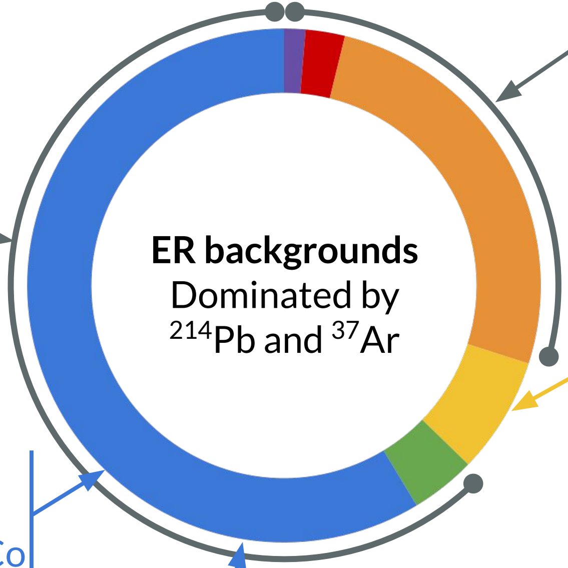
* https://nest.physics.ucdavis.edu/, v2.3.7

LZ simulations: Astropart. Phys. 116 (2020) 102391

Background model

Total expected **ER** counts in ROI in first run: **276** + [0, 291] from ^{37}Ar

Total expected **NR** counts in ROI in first run: **0.15**



Dissolved e-captures (mono-energetic x-ray/Auger cascades):

- ^{37}Ar
- ^{127}Xe
- ^{124}Xe (double e-capture)

Dissolved β-emitters

- ^{214}Pb (^{222}Rn daughter)
- ^{212}Pb (^{220}Rn daughter)
- ^{85}Kr
- ^{136}Xe ($2\nu\beta\beta$)

Solar neutrinos (ER)

- pp + ^{7}Be + ^{13}N

Includes γ-emitters in detector materials

- ^{238}U chain, ^{232}Th chain, ^{40}K, ^{60}Co

NR backgrounds

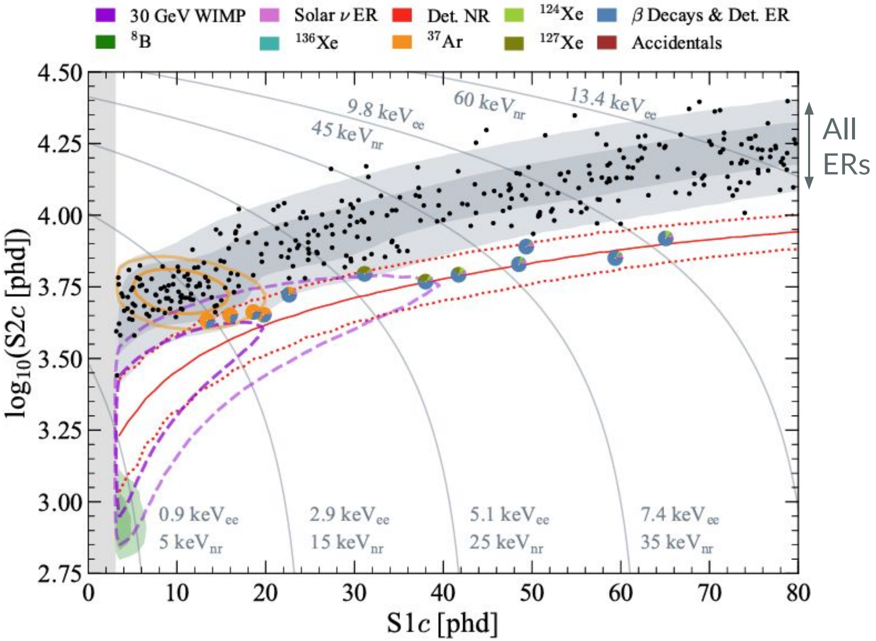
- Neutron emission from spontaneous fission and (α,n)
- ^{8}B solar neutrinos

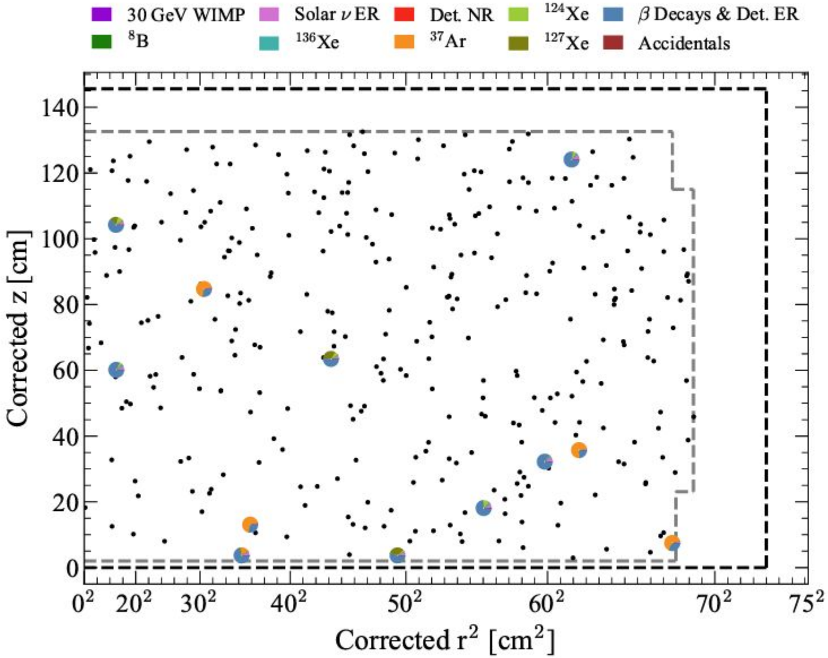
Accidental coincidence backgrounds

- 1.2 events expected

LZ backgrounds: Phys. Rev. D **108**, 012010

Data from first science run





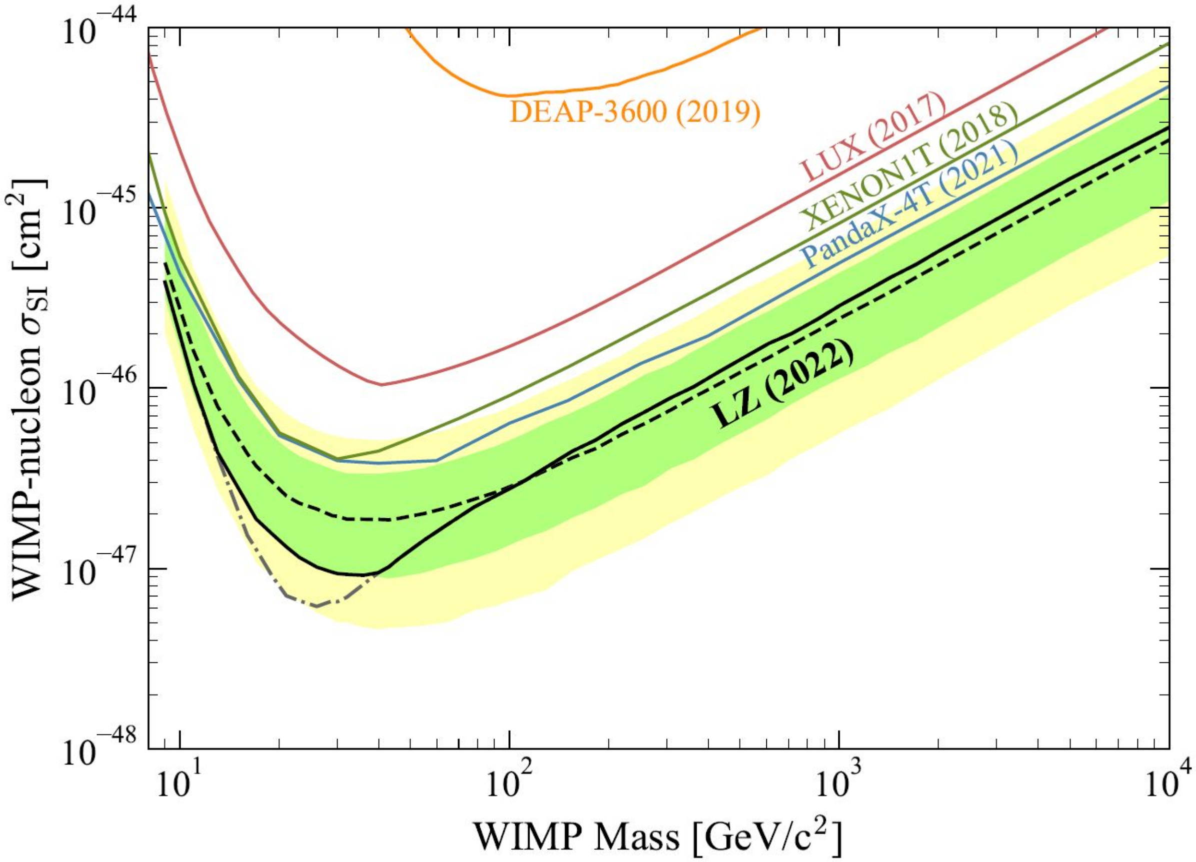
- Data are fit to simulated models for each background and signal in the 2D space of {$\log_{10}$(S2c), S1c}
- Statistical inference done using a profile likelihood ratio (PLR) analysis in this space
- **Best fit finds no WIMP signal**
- Events within 2σ NR contour have pie charts indicating best fit contributions from each component

Dark matter limits

Phys. Rev. Lett. **131**, 041002

- Curves:
  - Dot-dashed gray: observed limit
  - Dashed-black: median expected sensitivity
  - **Solid black: observed limit after power constraint**
  - Green (yellow) band: +/- 1 (2) σ sensitivity

- No evidence of WIMPs at any mass
- Minimum exclusion limit is 9.2×10^{-48} cm^2 at 36 GeV
- Compared to next strongest limits:
  - **x3.0 improvement at 36 GeV (XENONnT)**
  - **x1.7 improvement above 1 TeV (PandaX-4T)**

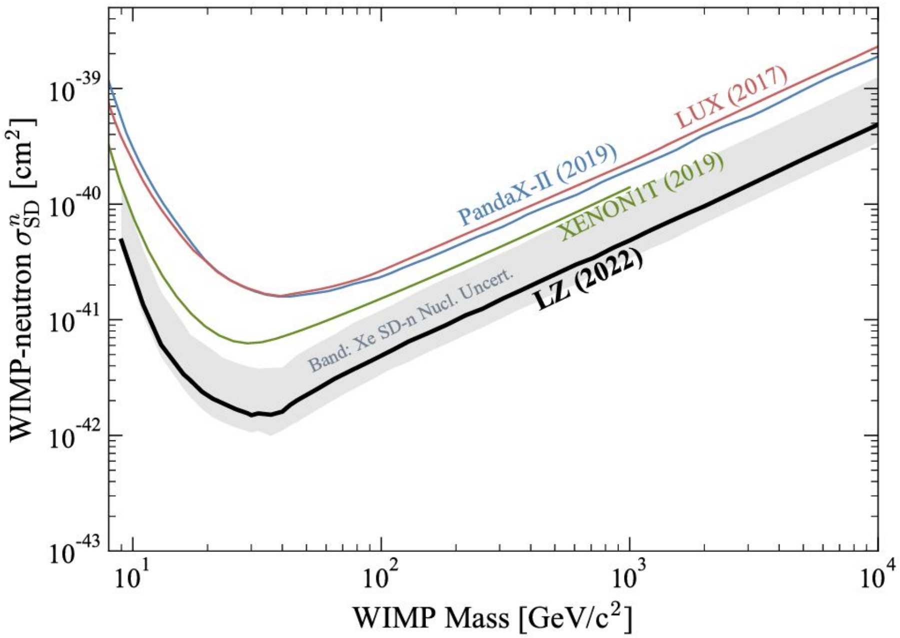


World-leading across 3+ orders of magnitude in WIMP mass with only 60 days of data

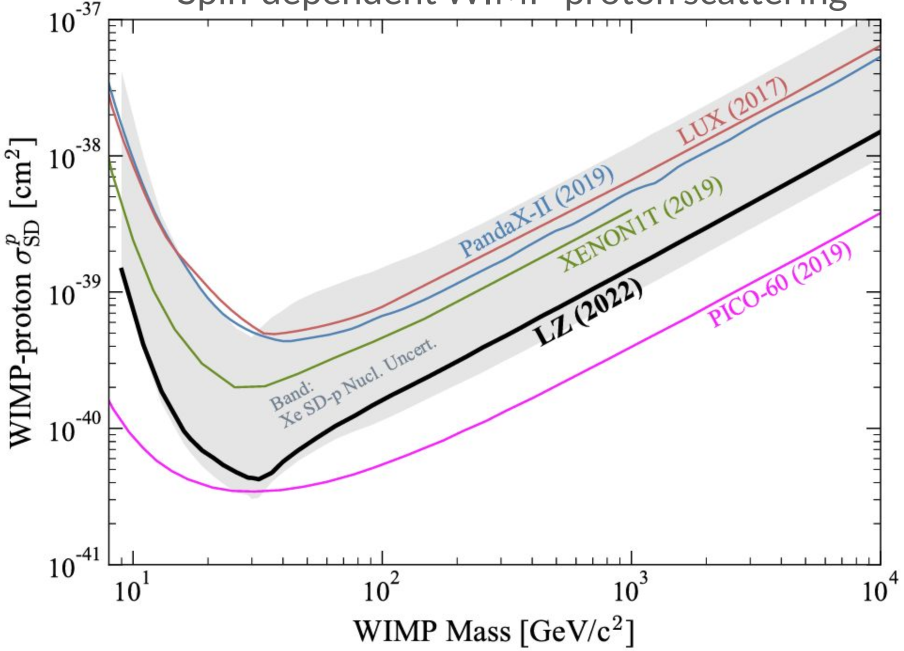
Dark matter limits - spin dependent

Phys. Rev. Lett. **131**, 041002

Spin-dependent WIMP-neutron scattering



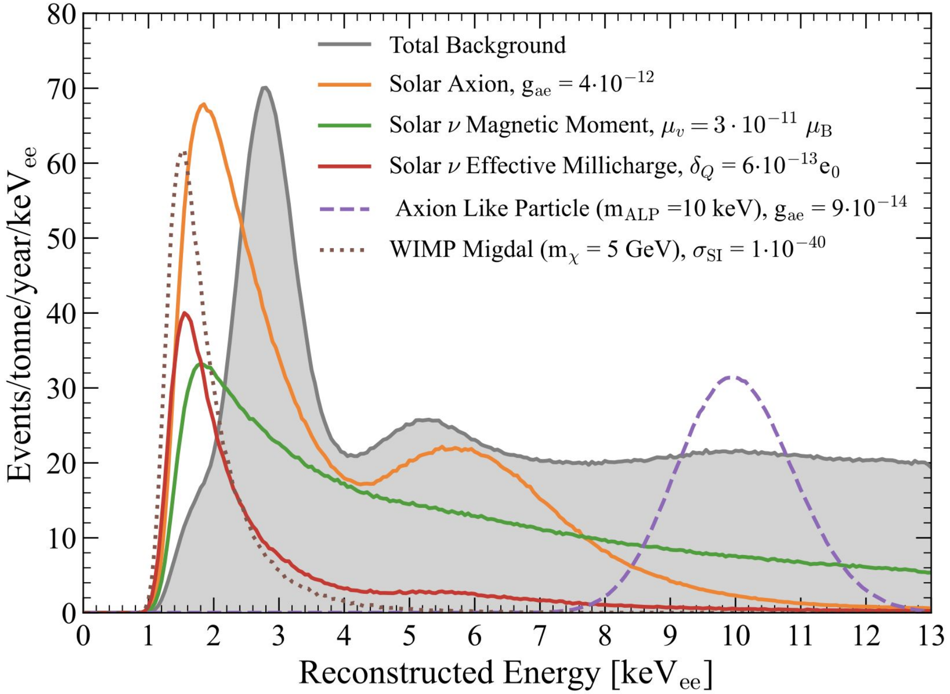
Spin-dependent WIMP-proton scattering



- Curves:
  - **Solid black: observed limit after power constraint**
  - Gray band: theoretical uncertainty from differing estimates of xenon nuclear structure factors

New physics searches in low energy ERs

- New analysis of ER interactions
  - Same data as WIMP search
  - Same cuts
  - Same background simulations
- Time-dependence added to fit (^{37}Ar + ^{127}Xe; both half-lives ~35 days)

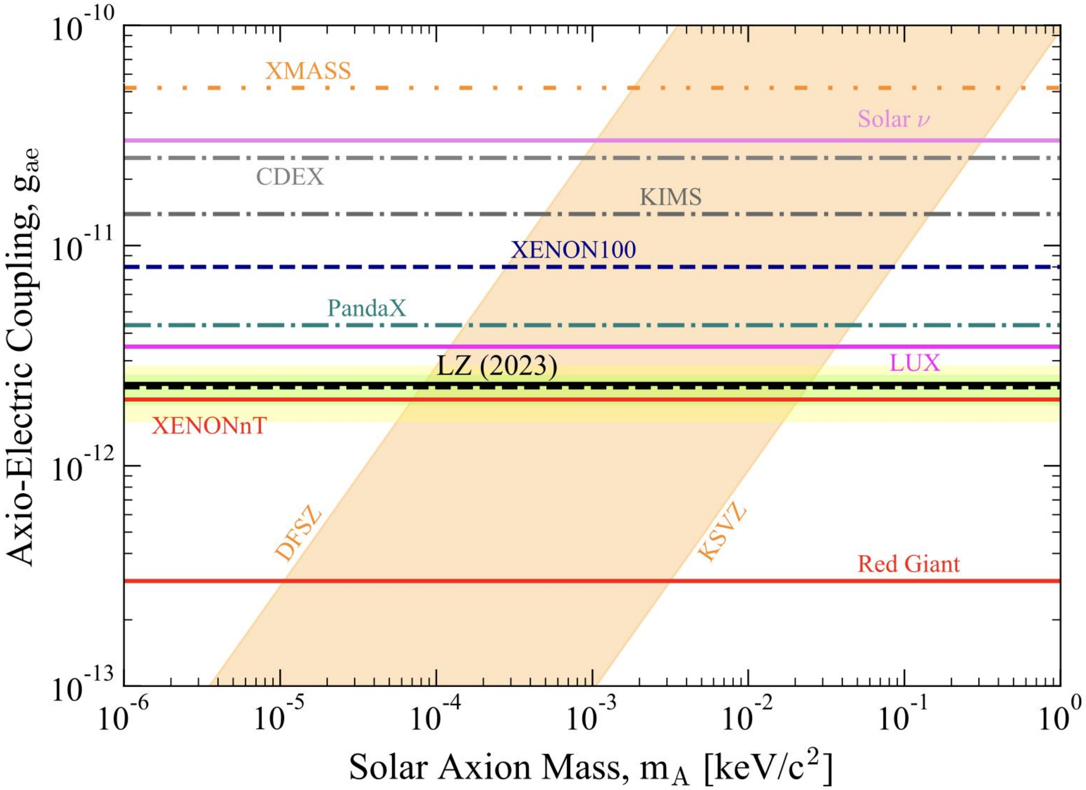


Signal strengths scaled for ease of viewing on same plot

arXiv:2307.15753, accepted to PRD

Solar axions

- Production within Sun
- Interaction in Xe via axio-electric effect
- 90% C.L. on $g_{ae} = 2.35 \times 10^{-12}$
- Strongest limit: cooling rate measurements of red giant stars



arXiv:2307.15753, accepted to PRD

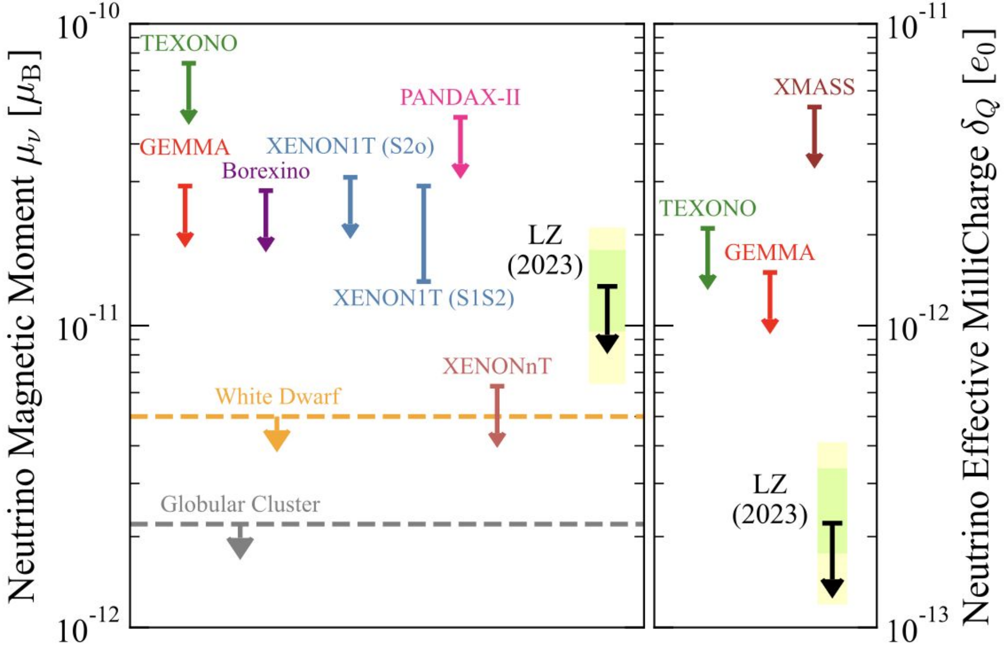
Neutrino interactions

- A non-zero neutrino magnetic moment or effective millicharge would increase the rate of solar neutrino ER interactions

- 90% C.L. $\mu_\nu = 1.36 \times 10^{-11}\ \mu_B$
- Strongest limits: cooling rates of white dwarf stars, precision photometry of red giants in globular clusters

- 90% C.L. $\delta_Q = 2.24 \times 10^{-13}\ e_0$

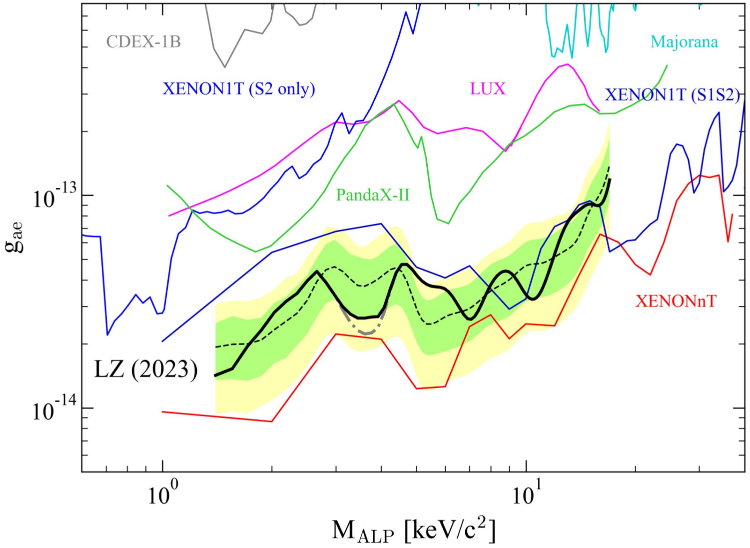
World-leading!



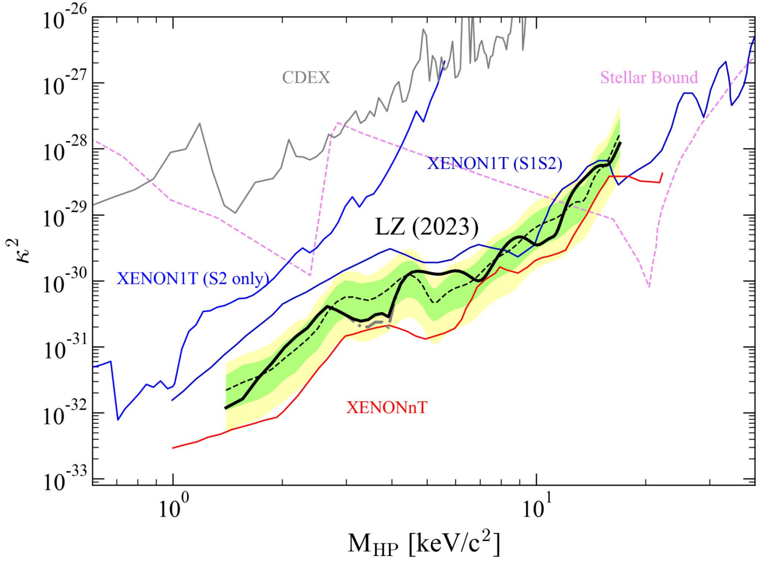
arXiv:2307.15753, accepted to PRD

Mono-Energetic Signals: ALPs + Hidden Photons

- Axion-Like Particles (ALPs):
  - Gauge pseudo-scalar boson from BSM global symmetry breaking



- Hidden (dark) Photons (HPs):
  - Gauge boson of new 'dark' U(1) symmetry

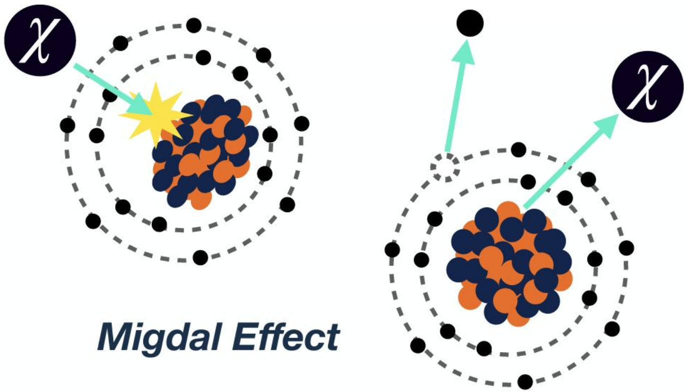


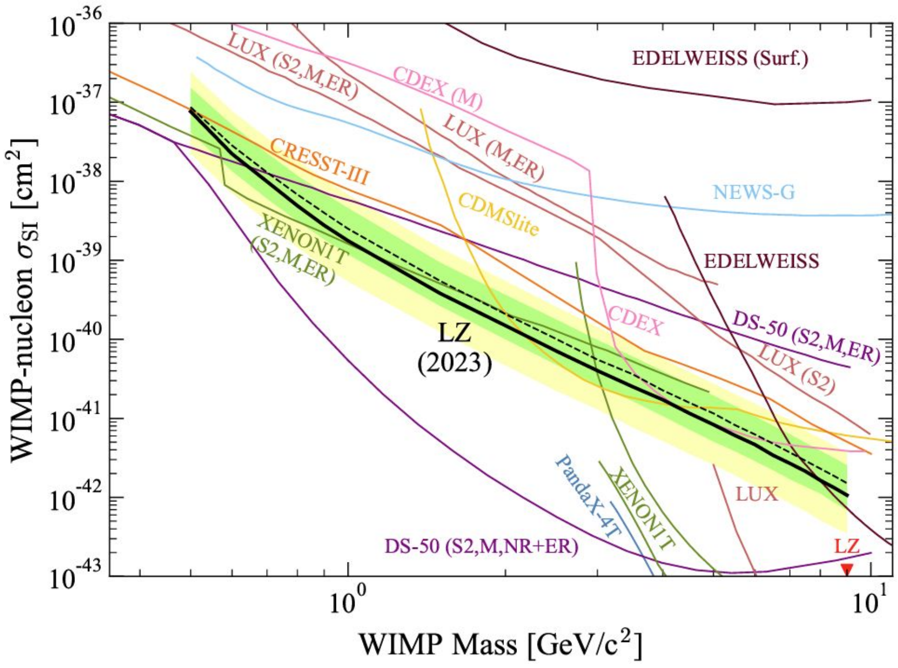
- Both signals manifest as absorption by a Xe electron as in photoelectric effect, but with photon energy replaced with ALP/HP mass

arXiv:2307.15753, accepted to PRD

Migdal effect: spin-independent WIMPs

- Can also search for WIMPs in ER channel:
  - Migdal effect* leads to electron excitation and ionization after nuclear recoil
  - Sub-dominant to pure NR rate except near threshold (1.6 keV for ER vs 5.3 keV for NR)

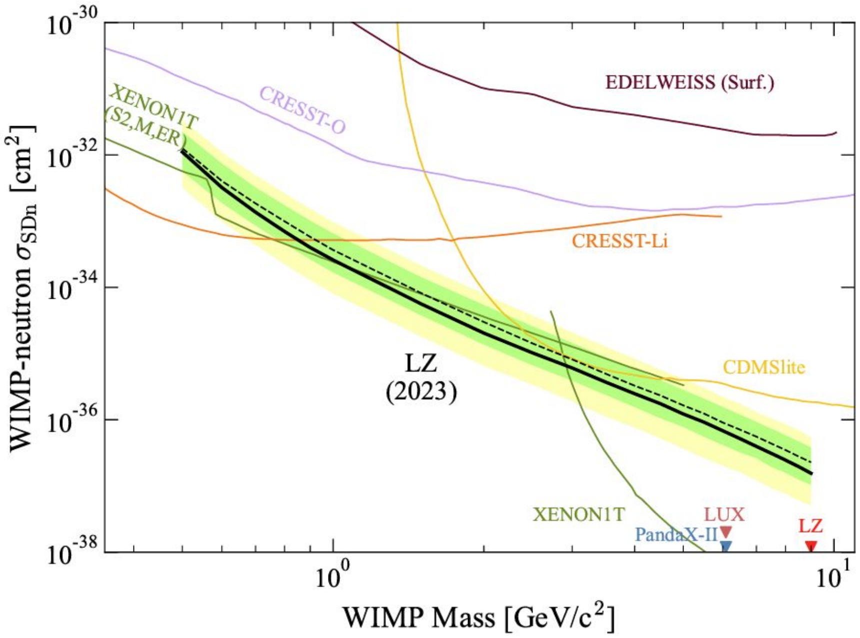


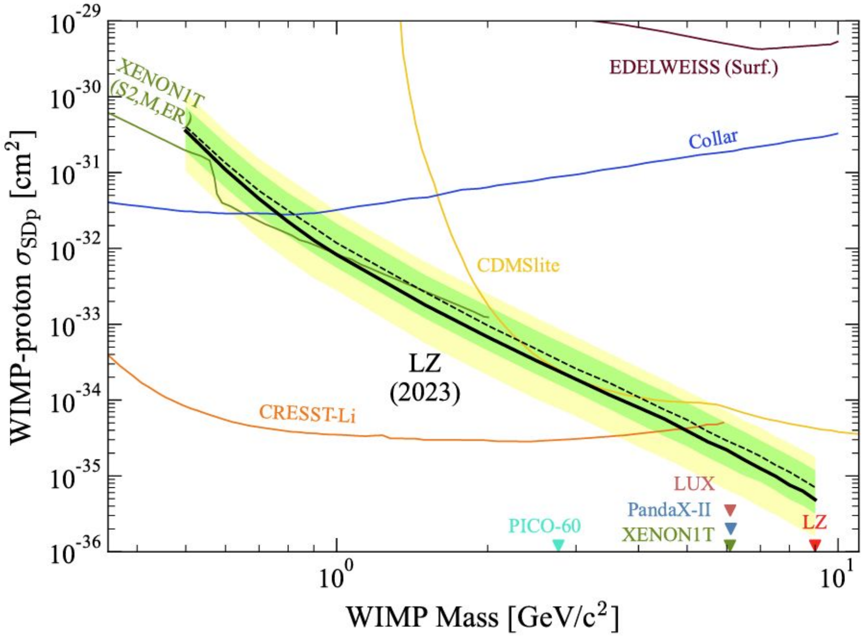


*M. Ibe et al., JHEP03,194 (2018)

arXiv:2307.15753, accepted to PRD

Migdal effect: spin-dependent WIMPs





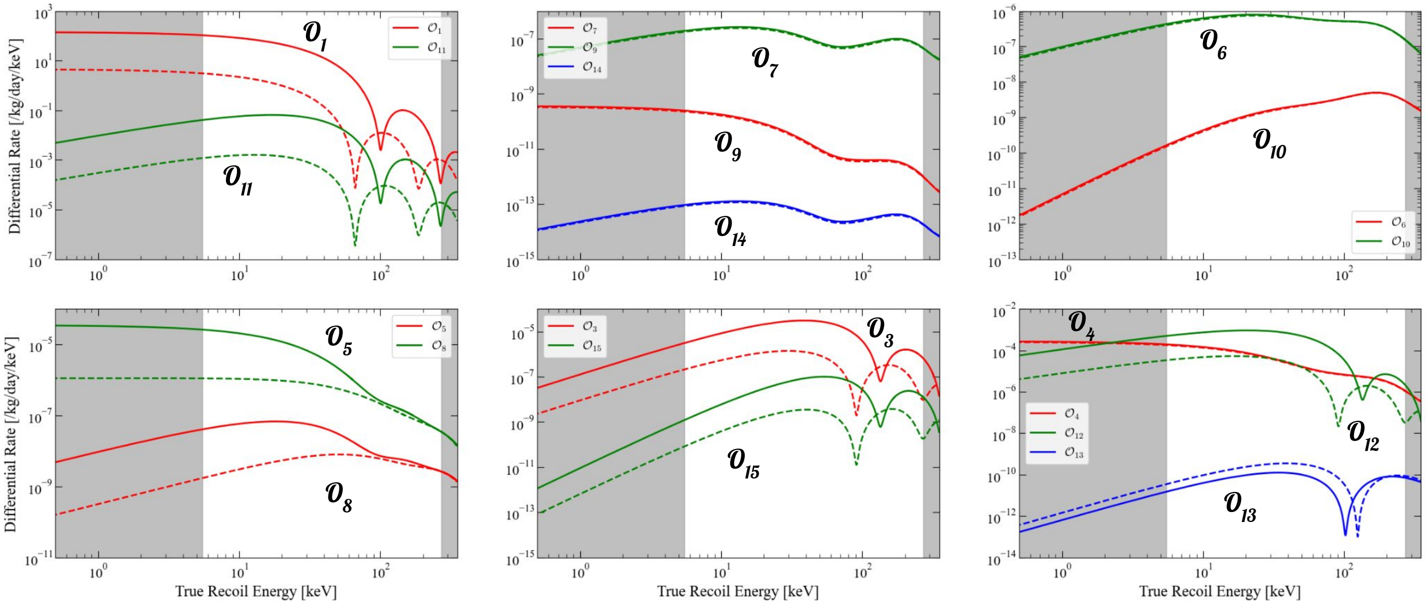
SDn limit world-leading from 1.1 to 3 GeV!

arXiv:2307.15753, accepted to PRD

WIMP-Nucleon Effective Field Theory Couplings

- Consider a broader class of theories than SD or SI WIMPs: all Hermitian, Galilean invariant operators w/ DM spin <= 1
- Total of 15 operators formed by all allowed combinations of spin of nucleon/WIMP, momentum transfer, and WIMP perpendicular velocity

Recoil spectra for 1000 GeV mass



momentum transfer

WIMP velocity perp. to $\vec{q}$

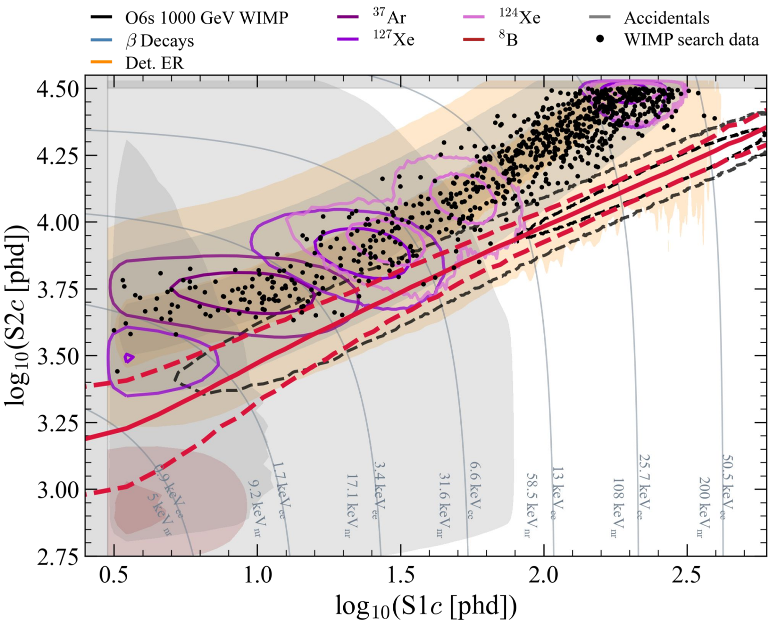
WIMP spin

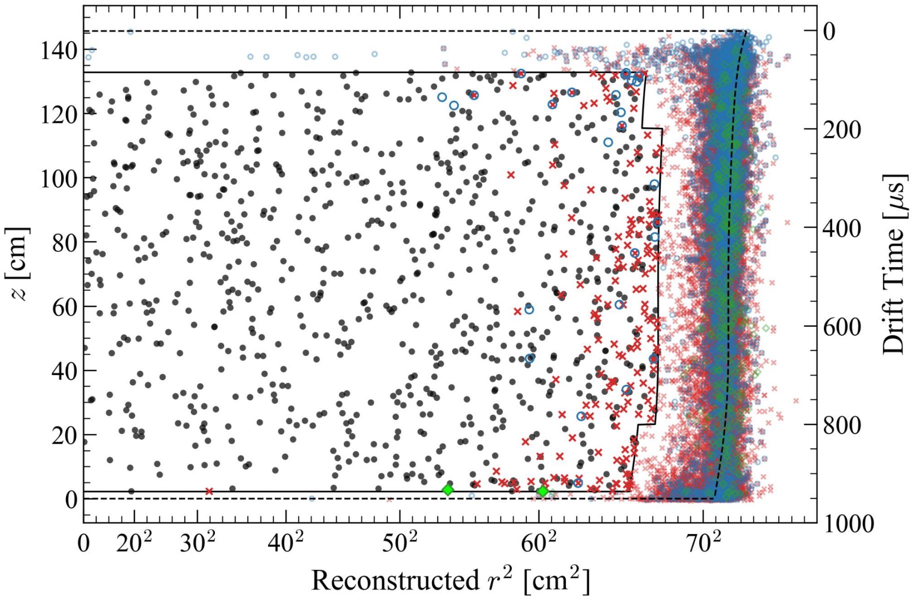
nucleon spin

$$\mathcal{O}_1 = 1$$
$$\mathcal{O}_2 = (v^{\perp})^2$$
$$\mathcal{O}_3 = i\vec{S}_N \cdot (\vec{q} \times \vec{v}^{\perp})$$
$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$
$$\mathcal{O}_5 = i\vec{S}_\chi \cdot (\vec{q} \times \vec{v}^{\perp})$$
$$\mathcal{O}_6 = (\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q})$$
$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^{\perp}$$
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^{\perp}$$
$$\mathcal{O}_9 = i\vec{S}_\chi \cdot (\vec{S}_N \times \vec{q})$$
$$\mathcal{O}_{10} = i\vec{S}_N \cdot \vec{q}$$
$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \vec{q}$$
$$\mathcal{O}_{12} = \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^{\perp})$$
$$\mathcal{O}_{13} = i(\vec{S}_\chi \cdot \vec{v}^{\perp})(\vec{S}_N \cdot \vec{q})$$
$$\mathcal{O}_{14} = i(\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{v}^{\perp})$$
$$\mathcal{O}_{15} = -(\vec{S}_\chi \cdot \vec{q})((\vec{S}_N \times \vec{v}^{\perp}) \cdot \vec{q})$$

Extending to higher energies

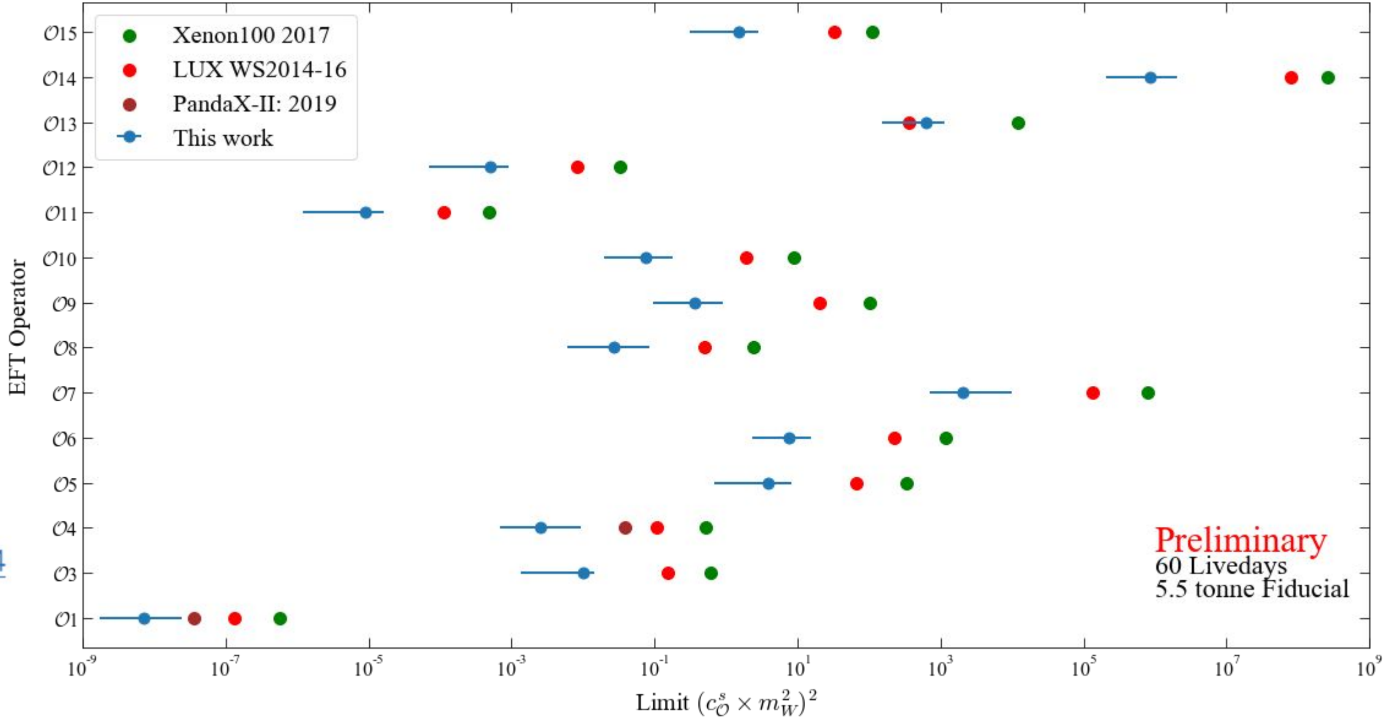
- Principal consequence: energy spectra extend to higher energy
- Models tuned to cover new region using calibration data
- New backgrounds included in model, notably multiple scatter, single ionization (MSSI)
- MSSI low rate becomes negligible after removal with machine learning





EFT operator limits

- mχ = 1000 GeV
- Blue bars: ±2σ expected sensitivity



Comparisons:

Xenon100: Phys. Rev. D 96, 042004

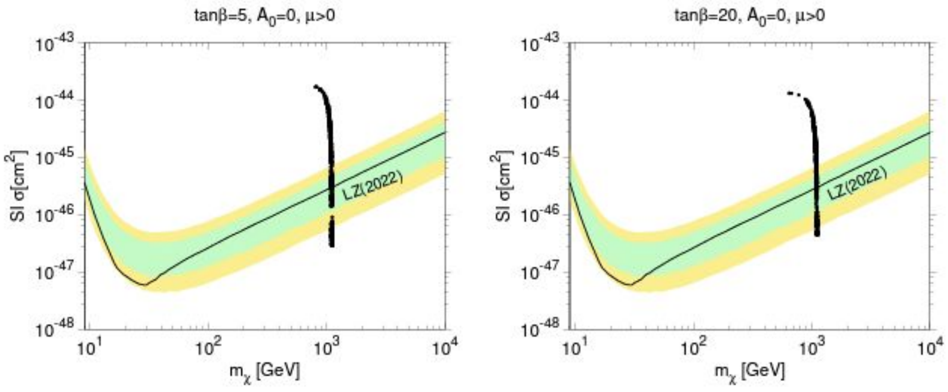
LUX: Phys. Rev. D 103, 122005

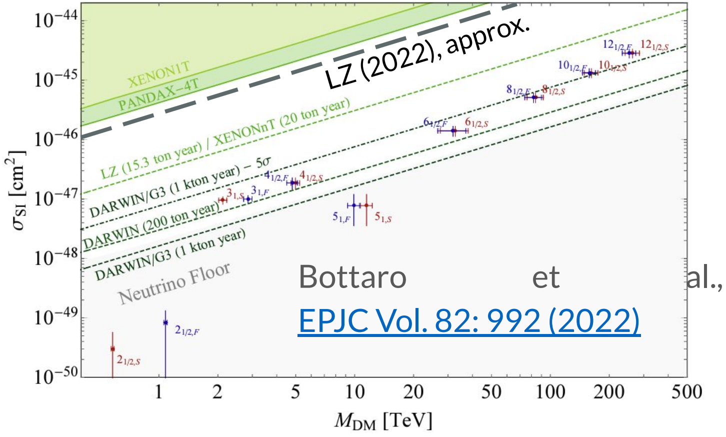
PandaX-II: Physics Letters B 792C

Next up for LZ

- Further exciting analyses, e.g.:
  - Ultraheavy / multiply interacting dark matter
  - Neutrino studies: ^{8}B CEvNS, supernova ν
  - Neutrinoless double beta decay / electron capture
  - DM searches with S2-only channel
- Lots more dark matter searching to do!
  - Anticipate **~15x more data** in the next few years
  - Important theory benchmarks being probed now
  - More are just beyond LZ's reach:
    ~10x to neutrino fog… what then?
  - Long-term limitations:
    exposure, dominant **radon background**

Ellis et al., [EPJC Vol. 83: 246 (2023)]

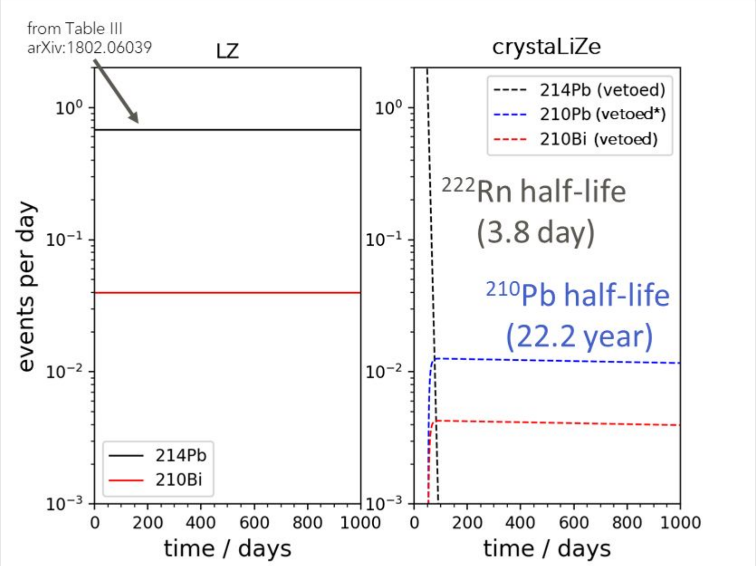




Bottaro et al., [EPJC Vol. 82: 992 (2022)]

Beyond LZ: CrystaLiZe

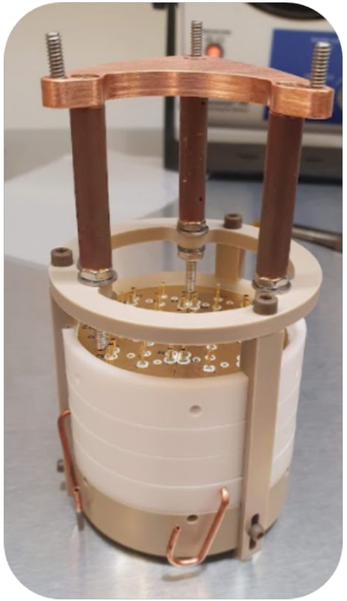
- **Post-LZ ops proposal: freeze LZ**
  Radon emanated from surfaces now **excluded** from solid bulk
- In **CrystaLiZe**, Rn in bulk target from LXe phase would be fixed, decay away in O(100) days
- Reduction in Rn chain daughters of nearly 100x

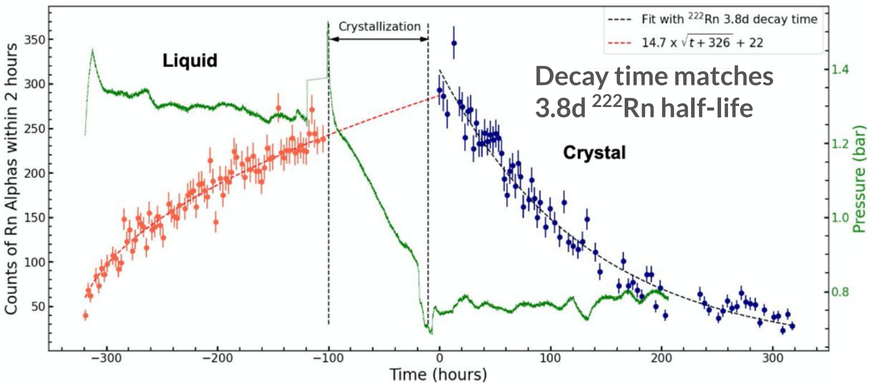


same LZ emanation and dust assumptions

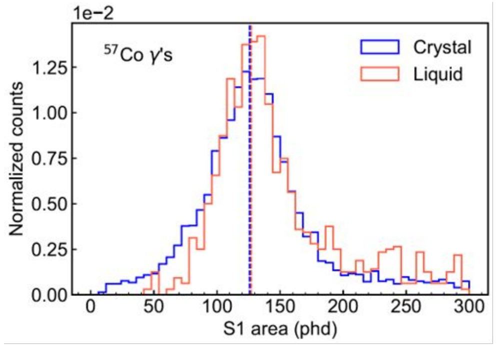
CrystaLiZe status

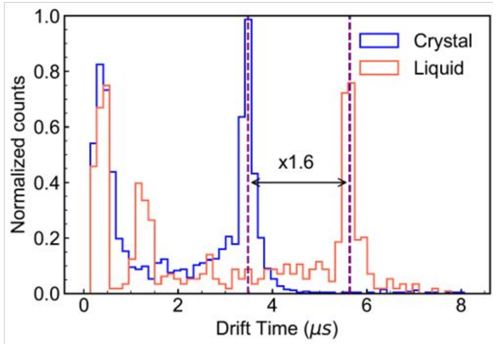
- Dual phase crystal/gas TPC operation established at LBNL (700 g Xe)
  - Detectable signal channels (S1, S2) similar to LXe
  - **Faster** electron drift in crystal by **~1.6-2x**
  - **Radon reduction** as expected
- Is it scalable to LZ at 7000 kg (10^4x bigger)?
  UT Austin group working to establish this - **ask me for details!**
- Possible combination w/ HydroX idea:
  H-doping of LZ for low-mass and spin-dependent WIMP search enhancement





Decay time matches 3.8d ^{222}Rn half-life

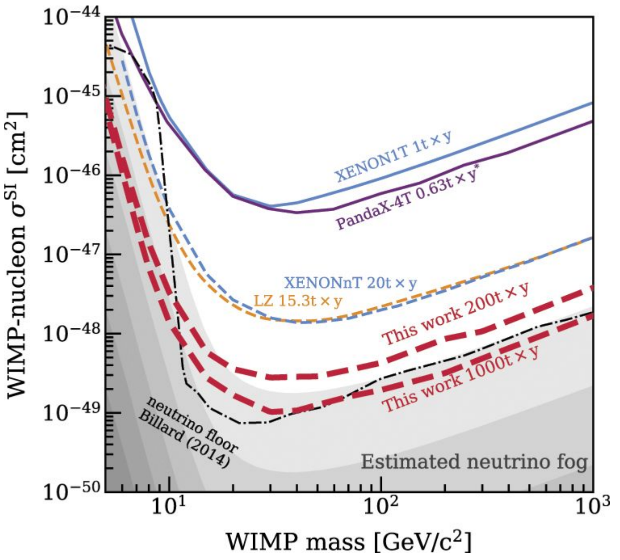




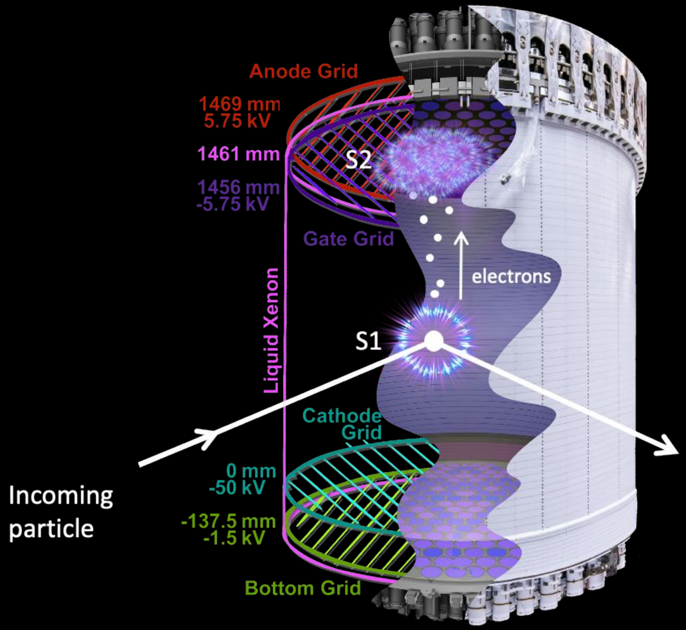
[JINST 17 P04014]

XLZD

- XLZD consortium: XENON, LZ, and Darwin experiments join forces https://xlzd.org/
- Plan for a ~40-80 tonne global xenon experiment
- WIMP search to neutrino fog, neutrinoless double beta decay, solar neutrino physics, and more
- See more details on the website and in the whitepaper: J. Phys. G50, 013001 (2023)



Thank you!



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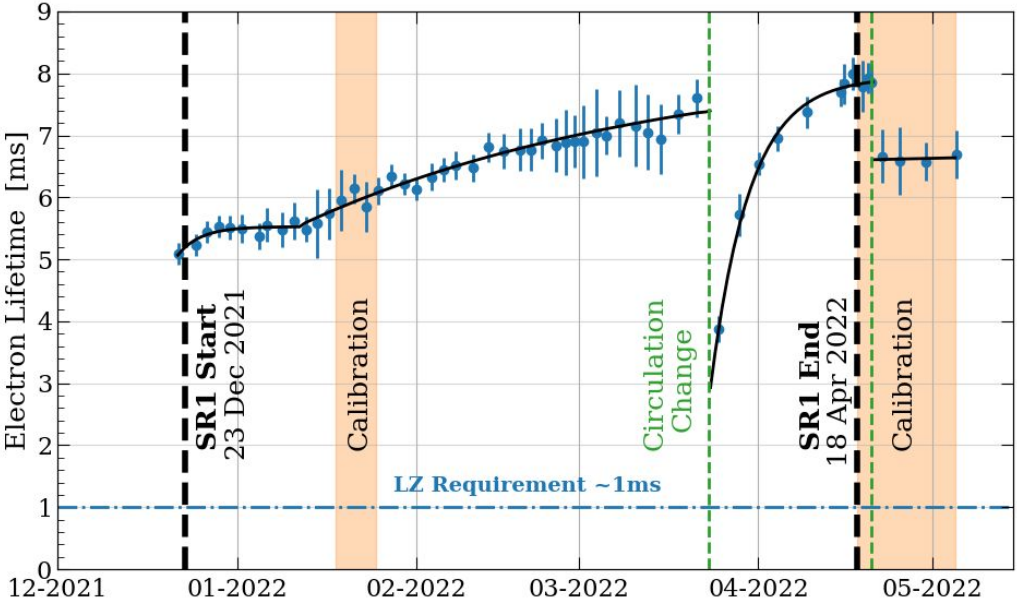
Backups

Electron lifetime



- Drifting electrons can become trapped on impurities like O_2
- Purity is quantified by electron lifetime: mean time a free electron will live before becoming trapped
- LZ requirement: > 1ms (i.e. the maximum drift time from cathode to liquid surface)
- During SR1, e-lifetime consistently greater than 5ms

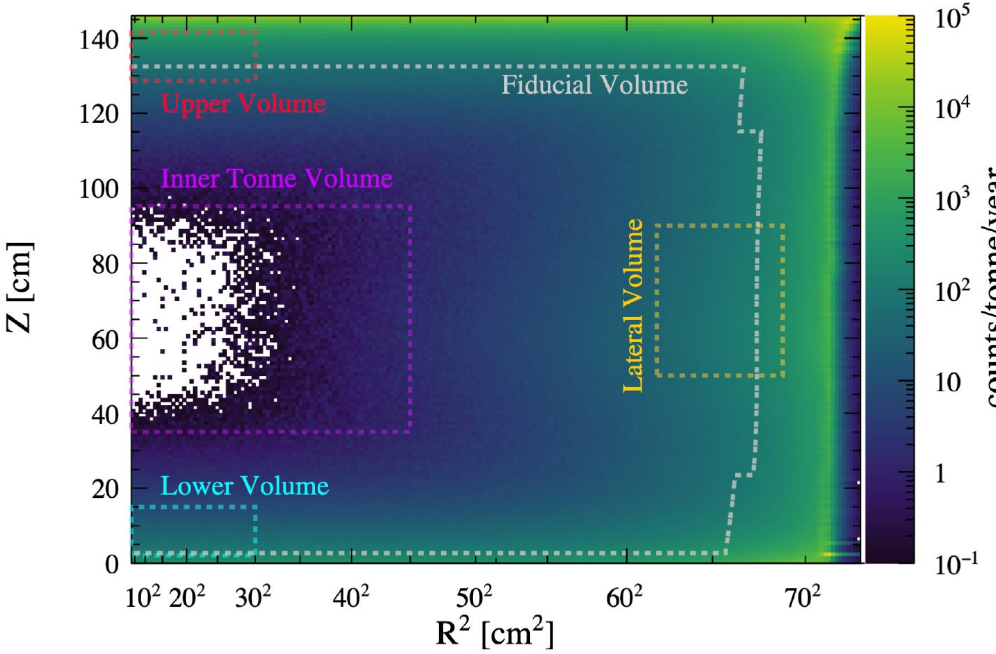
Calibration sources

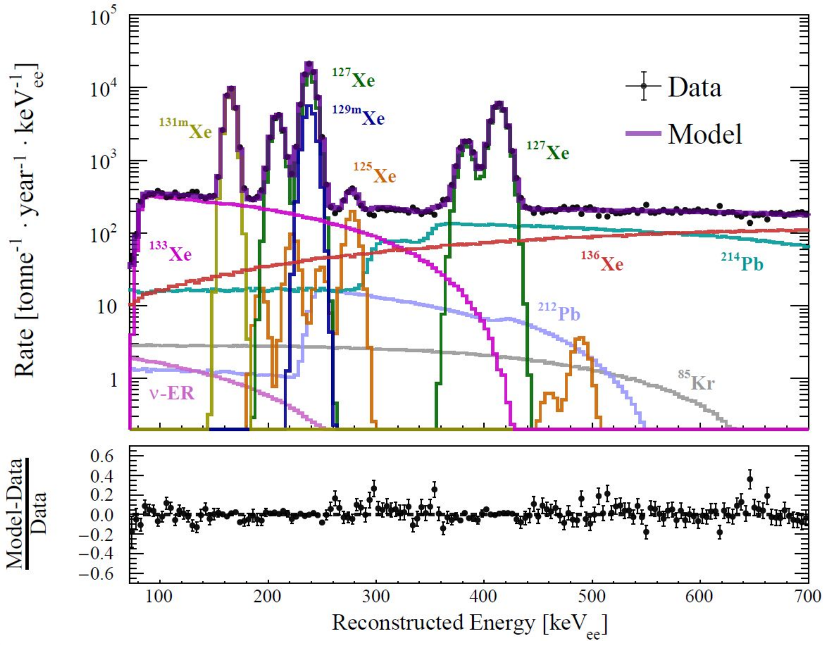
Comprehensive set of dispersed and external radioactive sources to calibrate detector response of TPC, skin, and OD

- ^{83m}Kr: monoenergetic ERs, 32.1 keV and 9.4 keV
- ^{131m}Xe: monoenergetic ER, 164 keV
- CH_3T (tritium): continuum betas, 18.6 keV
- Activation lines

- Deuterium-deuterium (DD): triggered 2.45 MeV neutrons
- AmLi: continuum neutrons, isotropic
- Alphas
- And more (^{220}Rn, YBe, ^{252}Cf, ^{22}Na, ^{228}Th, etc)

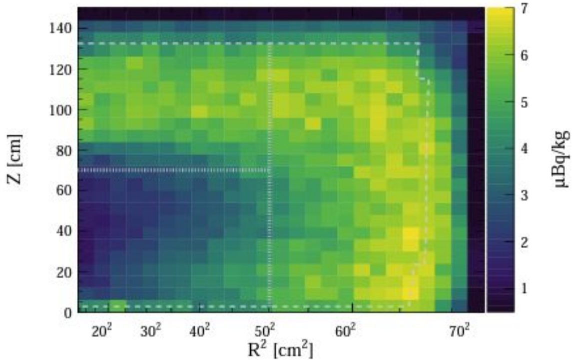
Background model - fitting at higher energy



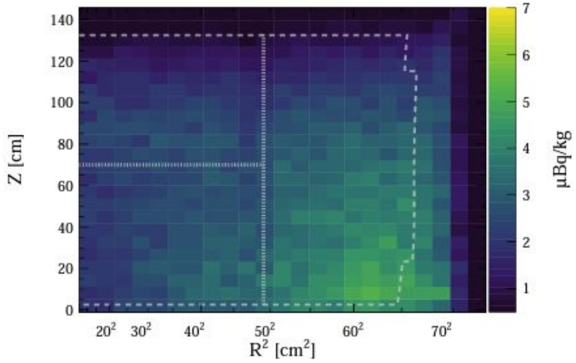


LZ backgrounds: [Phys. Rev. D **108**, 012010]

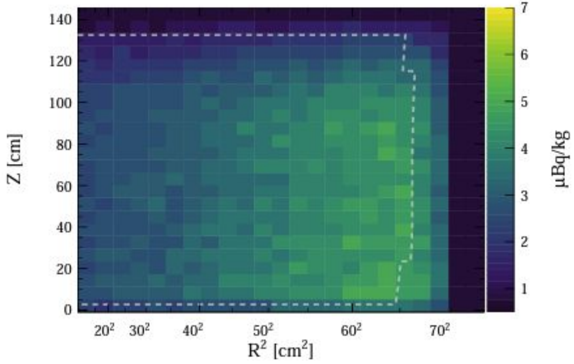
Radon chain positions



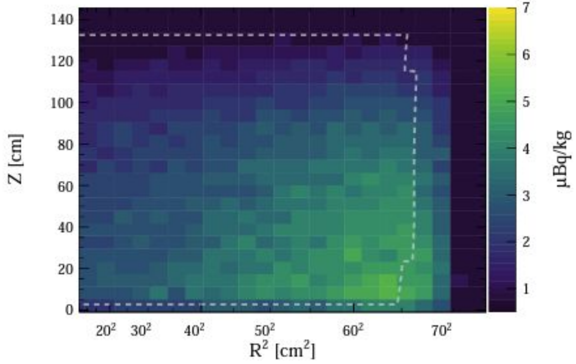
(a) Observed ^{218}Po Distribution



(b) Observed ^{214}Po Distribution



(c) Simulated ^{214}Pb Distribution



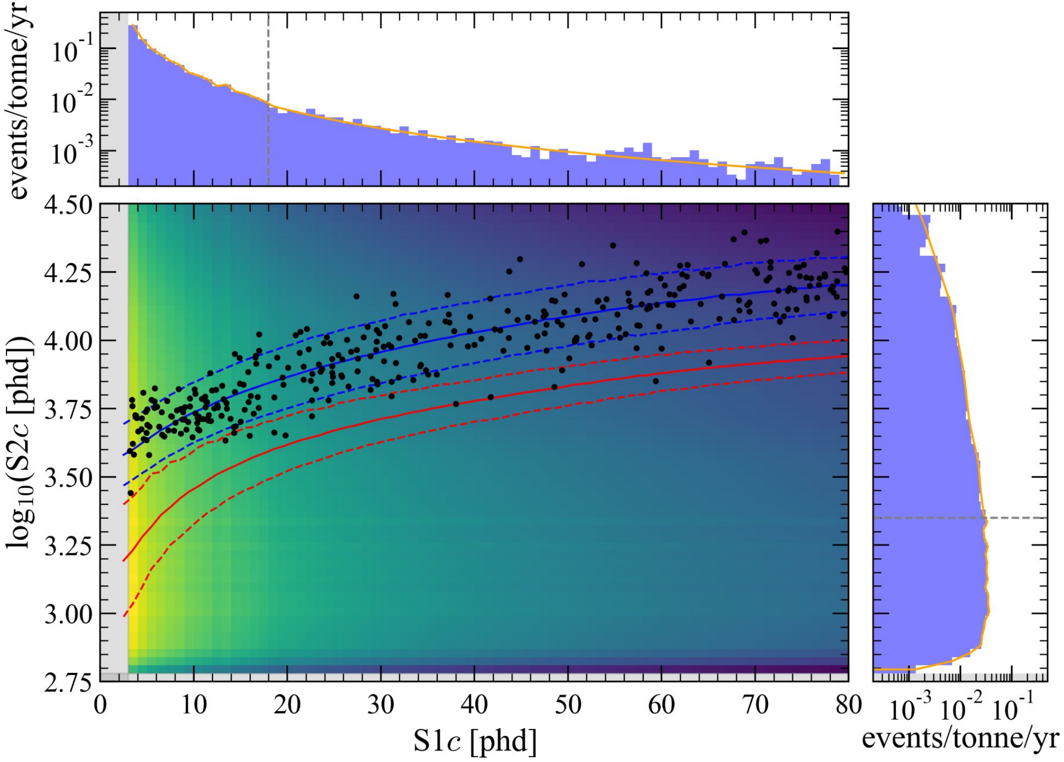
(d) Simulated ^{214}Po Distribution

LZ backgrounds: Phys. Rev. D **108**, 012010

Accidental coincidences

Shape from stitching together isolated S1s and S2s from real data

Rate from a model informed by UDT events

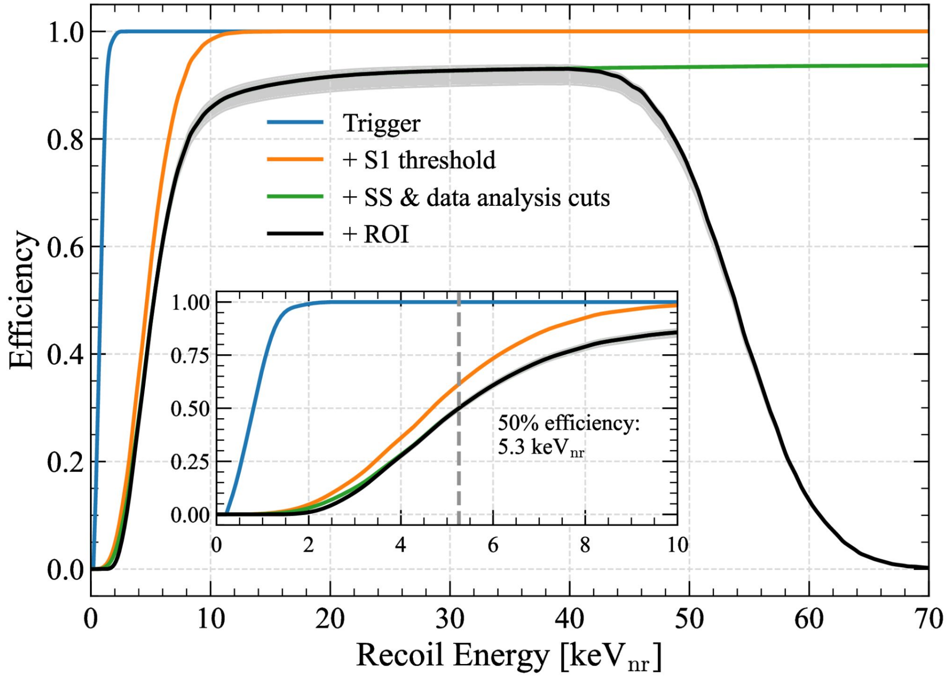


LZ backgrounds: [Phys. Rev. D **108**, 012010]

Data selection

- Cuts are applied to remove:
  - Periods of high rate
  - Pulses with unusual shapes
  - Poorly reconstructed events
- S1 pulse efficiency dominated by 3-fold PMT coincidence requirement
- Efficiencies measured using various calibration sources and visual inspection of many events
- NR threshold (50% efficiency) measured to be at **5.3 keV**

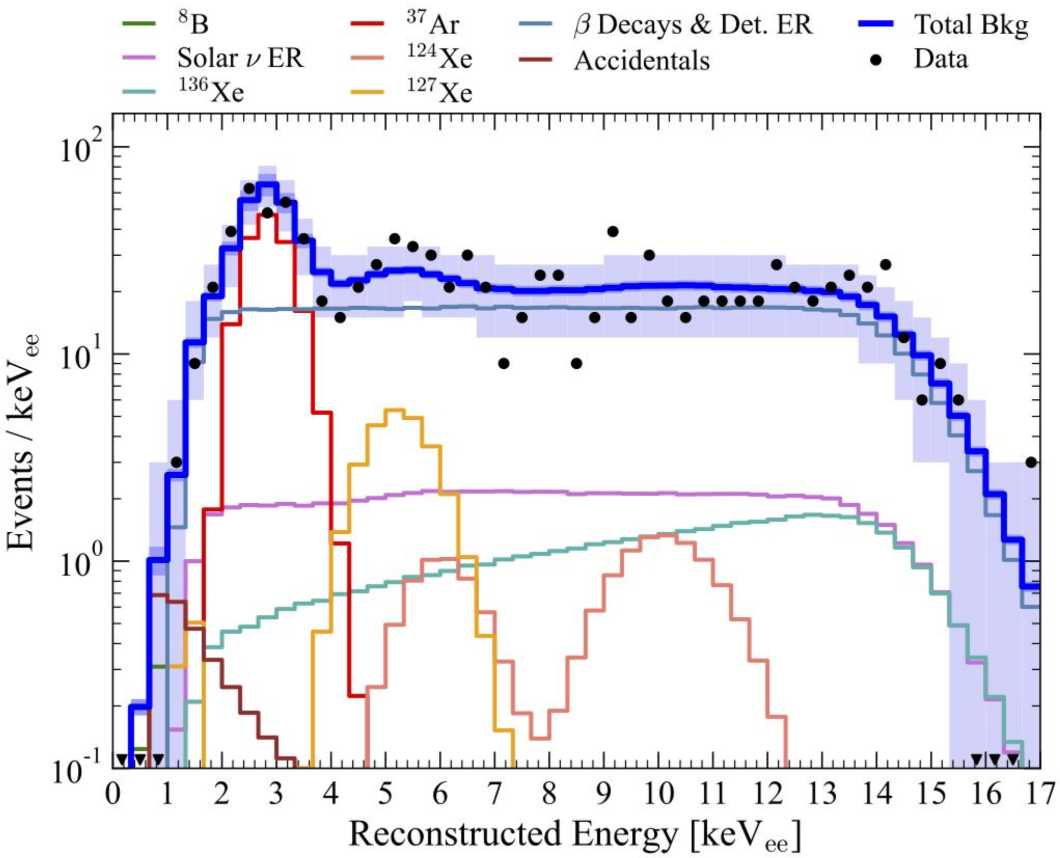
- After cuts, first science run has:
  - **335 events** observed
  - **60.3 ± 1.2 days** of livetime
  - **5.5 ± 0.2 tonnes** fiducial volume



Final SR1 Data

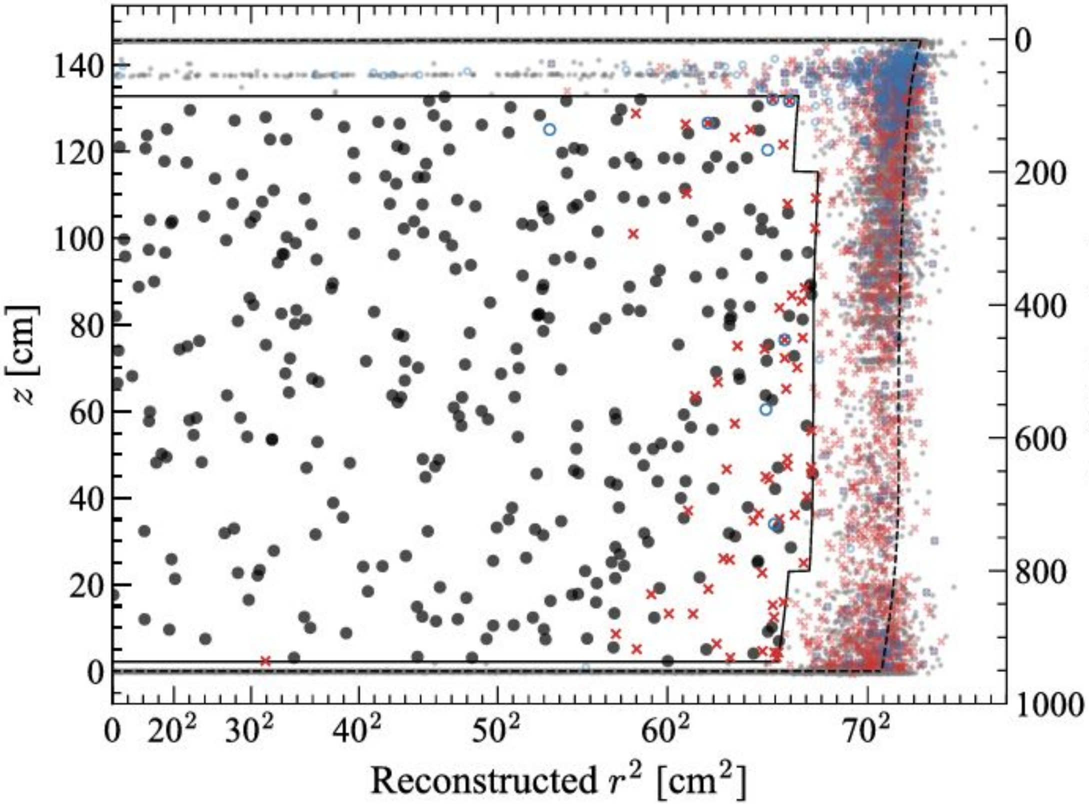
- Projecting onto electronic-equivalent reconstructed energy ("keVee")
- Data histogram shown as black points
- Best fit with no WIMP signal yields **p-value of 0.96**
- Expected range of statistical fluctuations for best-fit: light-blue boxes

Source	Expected Events	Fit Result
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



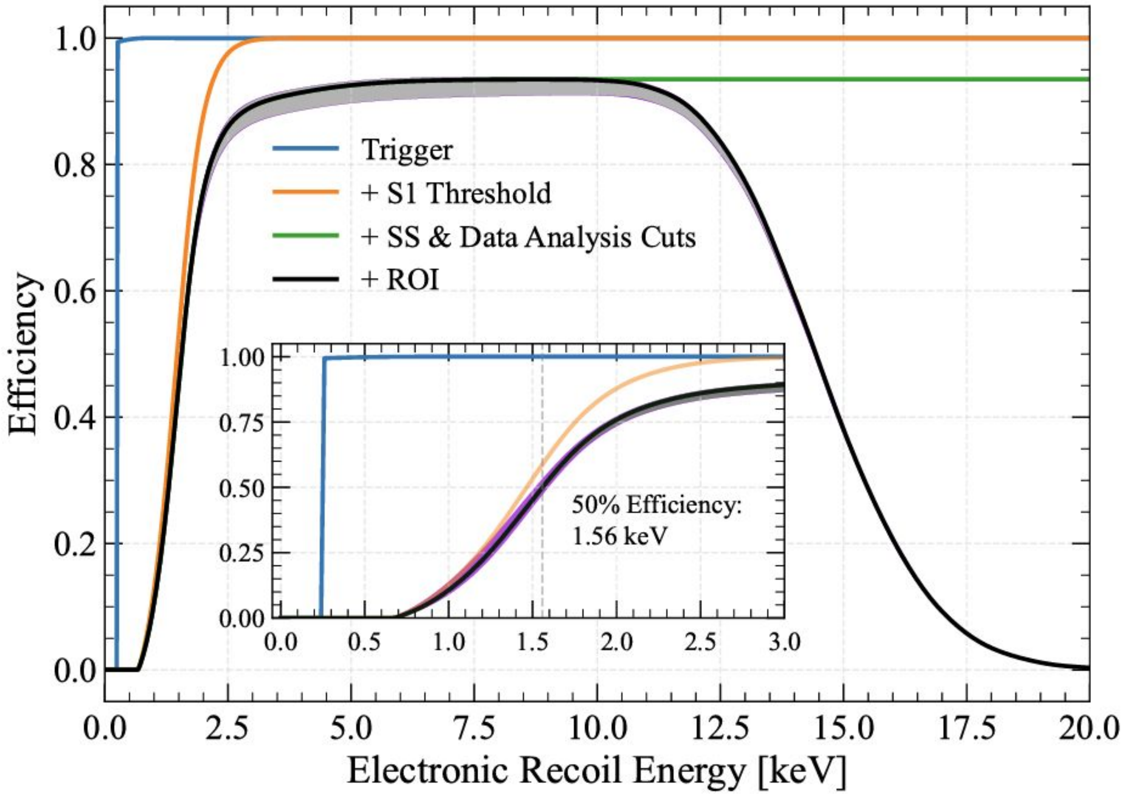
SR1 data - fiducial volume and vetos

- Events passing all cuts
- Events outside of fiducial volume
- Events vetoed by skin (mostly ^{127}Xe)
- Events vetoed by OD



ER threshold

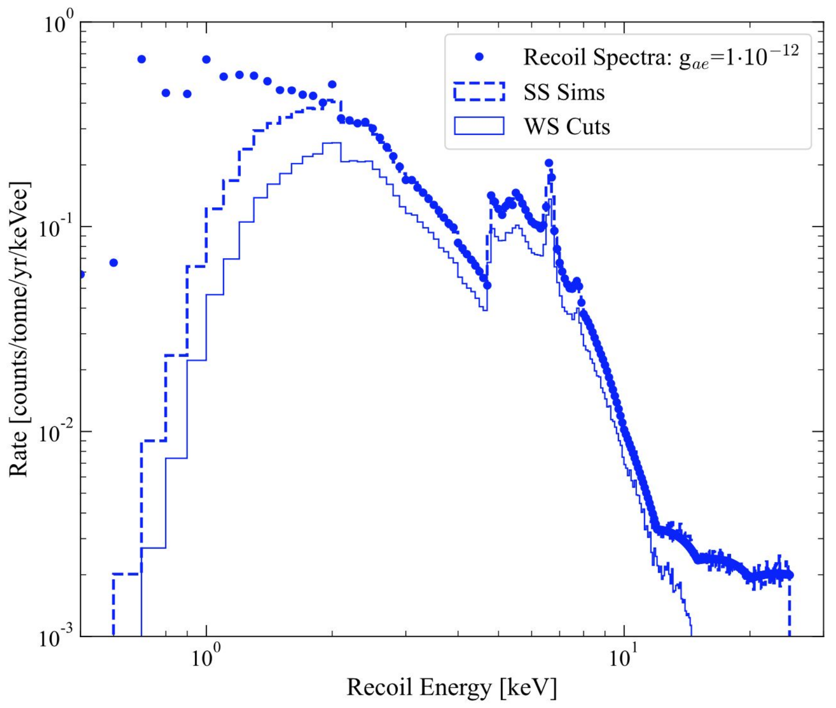
- From low energy ER paper
- 50% efficiency at 1.56 keV



arXiv:2307.15753, submitted to PRD

Solar Axions

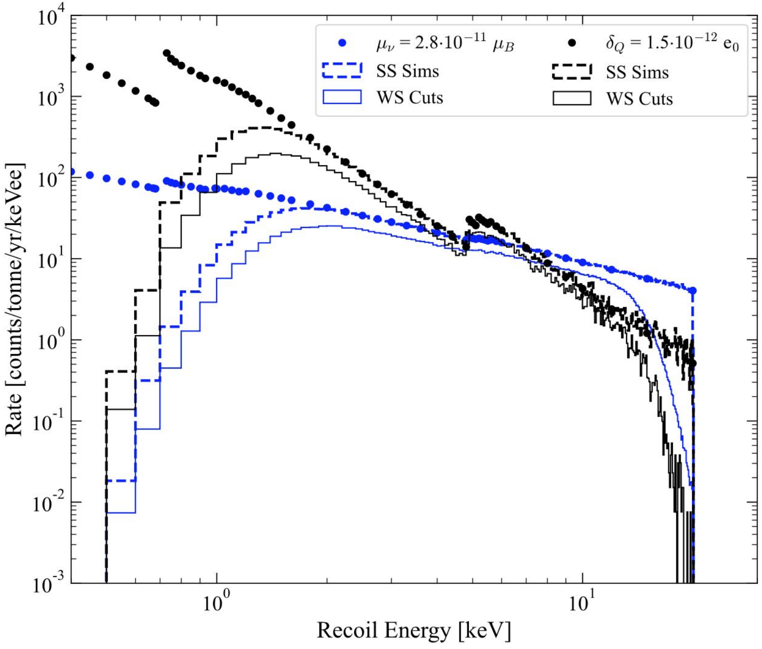
- Axions are bosons that result from spontaneous symmetry breaking of U(1) chiral symmetry as a result of the Peccei-Quinn mechanism to solve strong CP problem in QCD
- Axions in sun can be produced via
  - Axion-electron coupling: Atomic, Bremsstrahlung and Compton (ABC)
  - Axion-nucleon coupling: ^{57}Fe de-excitation
  - Axion-photon coupling: Primakoff effect
- These above methods produce a predicted solar axion flux which would then be axio-electrically absorbed by Xe electrons
  - We consider ABC process → constrain g_{ae}
  - Rate scales with g_{ae}^4
- Axio-electric recoil spectra uses solar flux from Redondo (2013)



Neutrino Magnetic Moment and Effective Millicharge

$$\left(\frac{d\sigma_{\nu,e}}{dT_e}\right) \simeq \left(\frac{d\sigma_{\nu,e}}{dT_e}\right)_{\text{weak}} + \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_e} - \frac{1}{E_\nu}\right)\left(\frac{\mu_\nu}{\mu_B}\right)^2 + \frac{2\pi\alpha}{m_e}\left(\frac{1}{T_e^2}\right) q_\nu^2,$$

- Impact of neutrino containing a non-zero magnetic moment (MM) or effective millicharge (mQ) are calculated as enhancements to the Solar ER rate
  - Non-tree level interaction and could imply some BSM physics couplings and/or Majorana nature of neutrino
- Calculated by Hsieh et al (2019) using RRPA method arXiv:1903.06085
- Rate of neutrino magnetic moment and neutrino millicharge scale as μ_ν^2 and q_ν^2, respectively
  - Neutrino MM scales like 1/E
  - Neutrino mQ scales like $1/E^2$



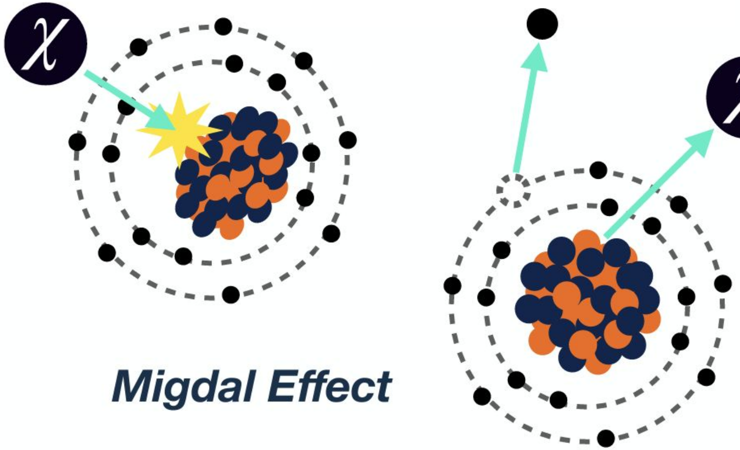
Mono-Energetic Signals

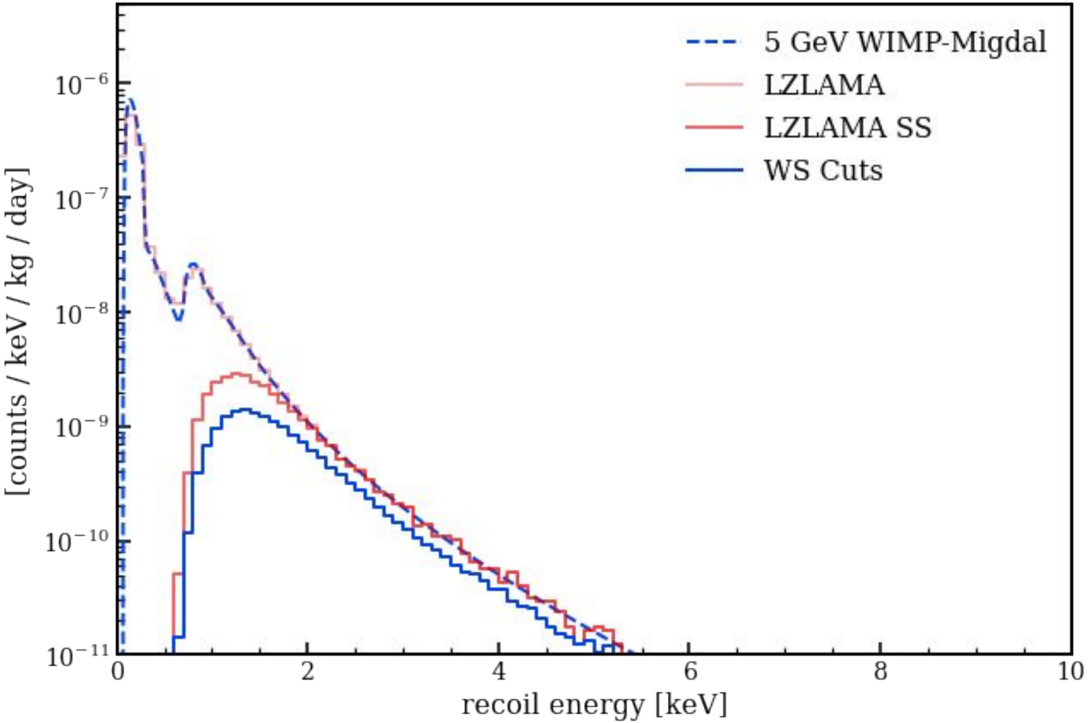
- Axion-Like Particles (ALPs)
  - Gauge pseudo-scalar boson that results from spontaneous symmetry breaking of some BSM global symmetry at a scale f_{ALP}.
  - Not linked to strong CP problem and Peccei-Quinn mechanism as QCD axions e.g. $m_{ALP}f_{ALP}$ parameter space is much wider
- Hidden (dark) Photons (HPs)
  - Gauge vector boson of some ‘dark’ U(1) symmetry, e.g. dark EM, that pops up in some supersymmetric models
- Signal Response
  - Both are absorbed by bound electrons of xenon in process analogous to photoelectric effect, but with photon energy replaced with ALP/HP mass.
  - ALP rate scales with g_{ae}^2 (~$1/f_{\alpha}^2$); HP rate scales with α'/α (often called κ^2)
  - Rates follow prescription in Pospelov et al

$$R_{\mathrm{ALP}} \simeq \frac{1.2\times 10^{19}}{A} g_{\mathrm{Ae}}^2 \sigma_{\mathrm{PE}}\, m_{\mathrm{ALP}} \qquad R_{\mathrm{HP}} \simeq \frac{4\times 10^{23}}{A}\frac{\alpha'}{\alpha}\frac{\sigma_{\mathrm{PE}}}{m_{\mathrm{HP}}}$$

Migdal Effect

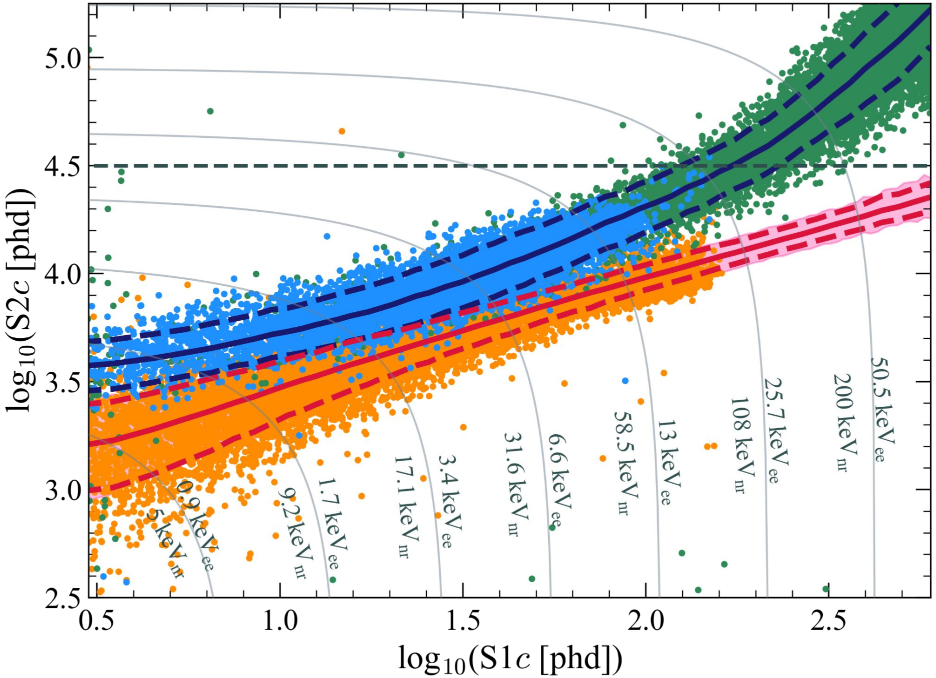
- Electronic excitation/ionization in response to DM interacting with atomic nucleus
- Calculated according to Ibe et al.
  - Restricted to n = 3 & 4 electron shells



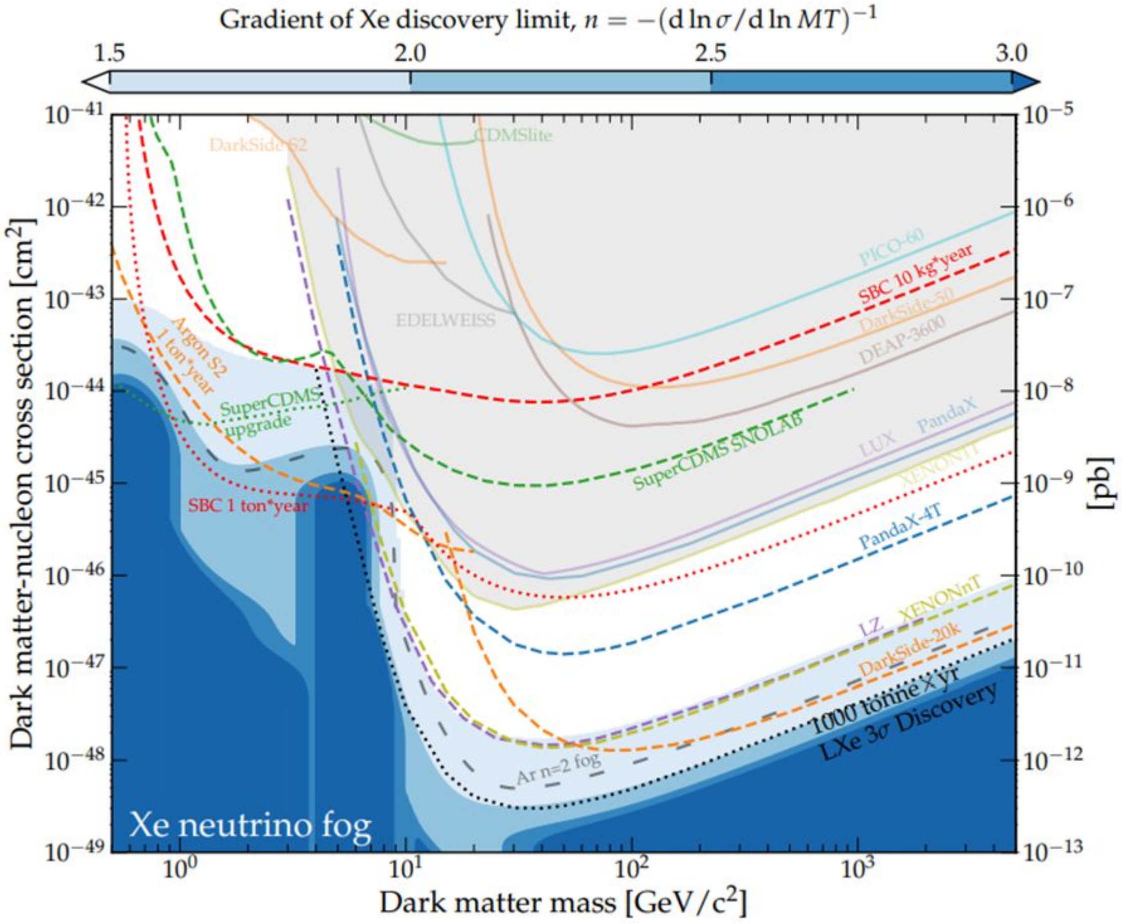


Calibrations out to higher energies

- Flat ER and NR response regions (medians, 90-10 CLs) compared to:
  - ^{3}H (blue)
  - D-D (orange)
  - $^{220}Rn/^{212}Pb$ (green)
- Shaded pink is NR uncertainty

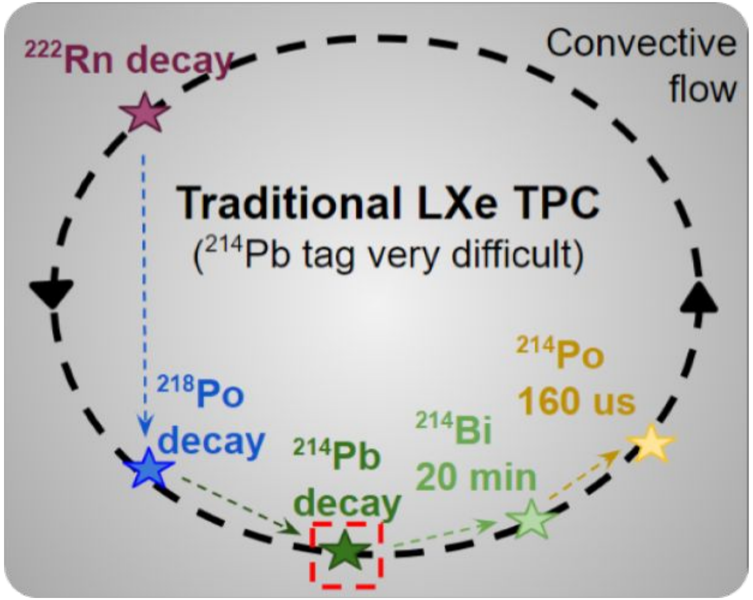


The neutrino fog



O'Hare, [Phys. Rev. Lett. 127, 251802 (2021)]

CrystaLiZe: Radon tagging



- In crystal, radon decay daughters stay at same (x,y,z) as parent
- Allows for tagging/veto
- Limited in liquid due to convection