Searching for Dark Matter High and Low with LZ

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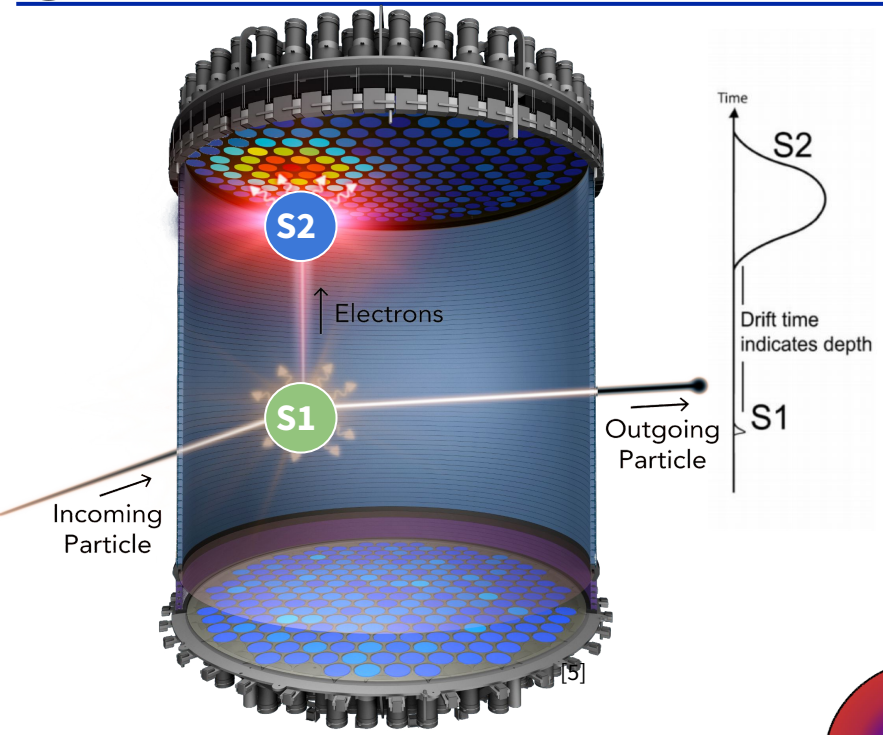
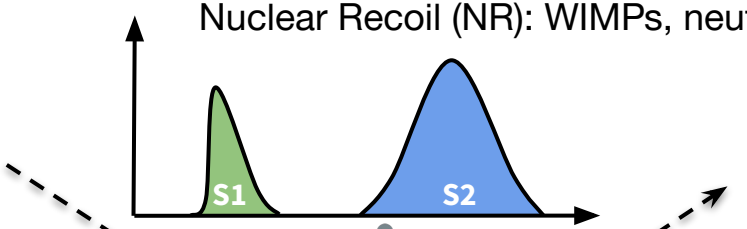
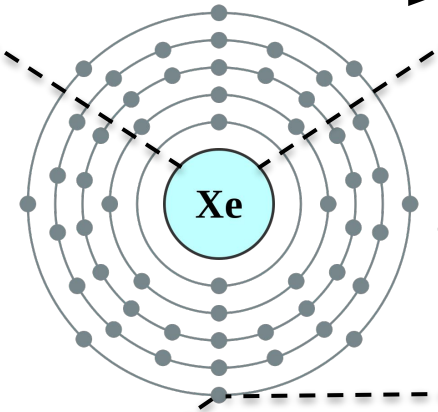


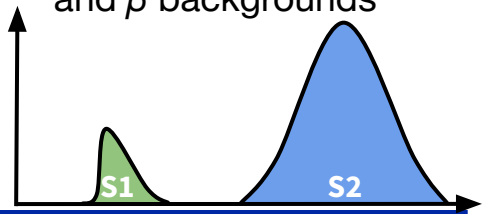
Nuclear Recoil (NR): WIMPs, neutrons



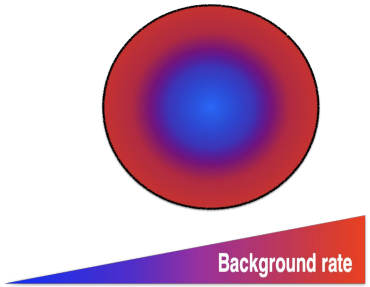


ER/NR discrimination from ratio of S1 and S2

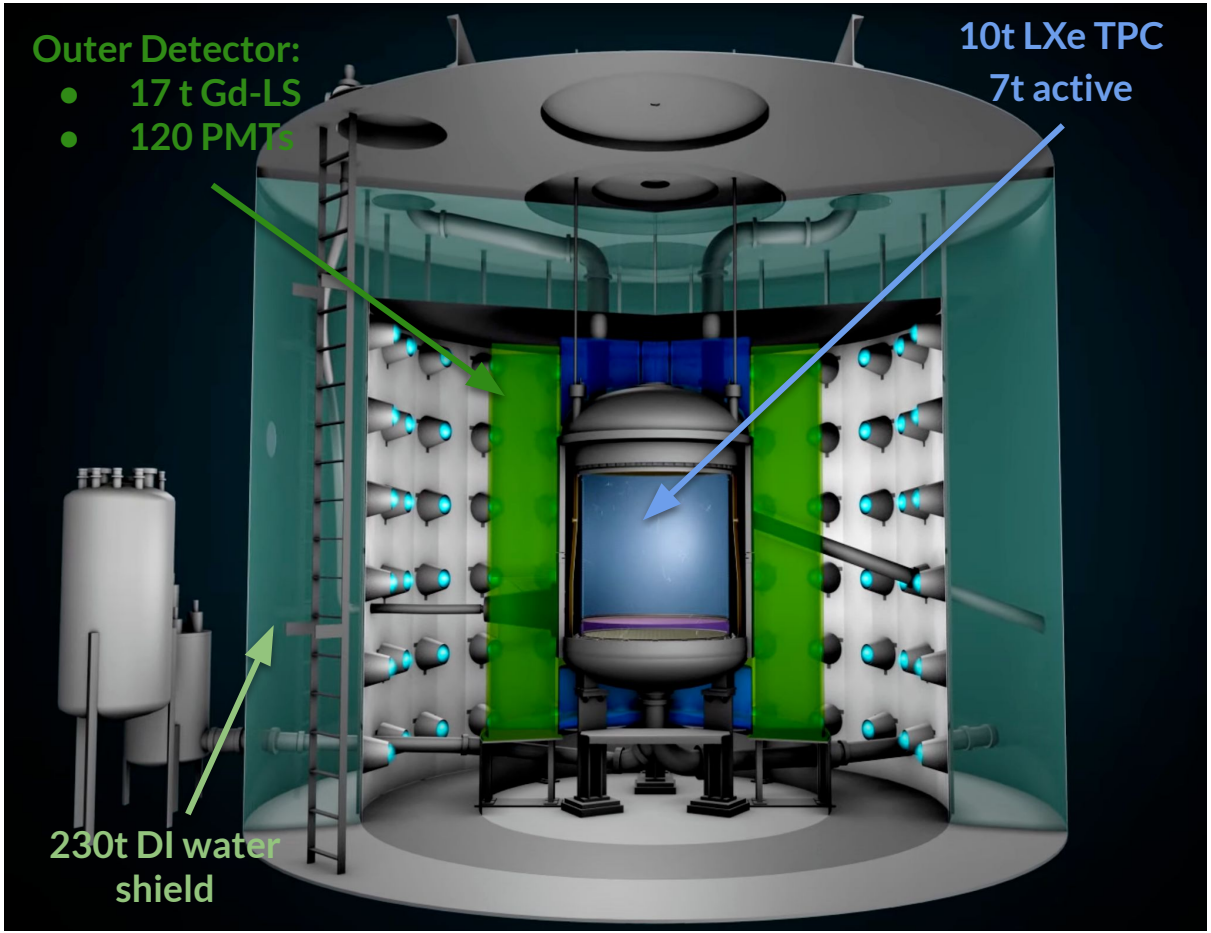
Electron Recoil (ER): γ and β backgrounds



- 3D position reconstruction from PMT hits and Δt
- Self-shielding

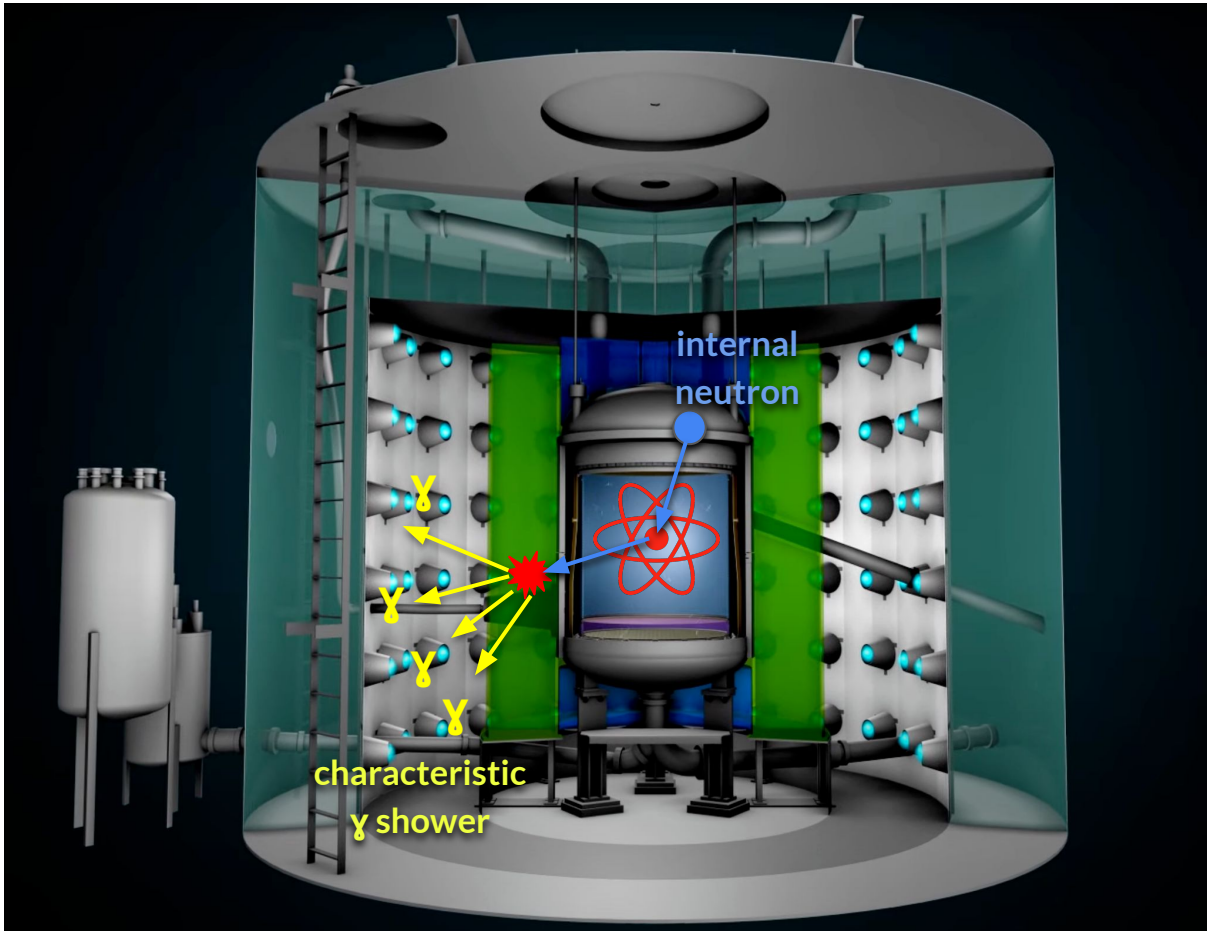


- 10t LXe target mass, **7t active**
  - **1.5m** height
  - **494** TPC PMTs (R11410-22)
  - PTFE field cage
  - 4 HV grids to establish drift field & extraction region
- **Active veto** system



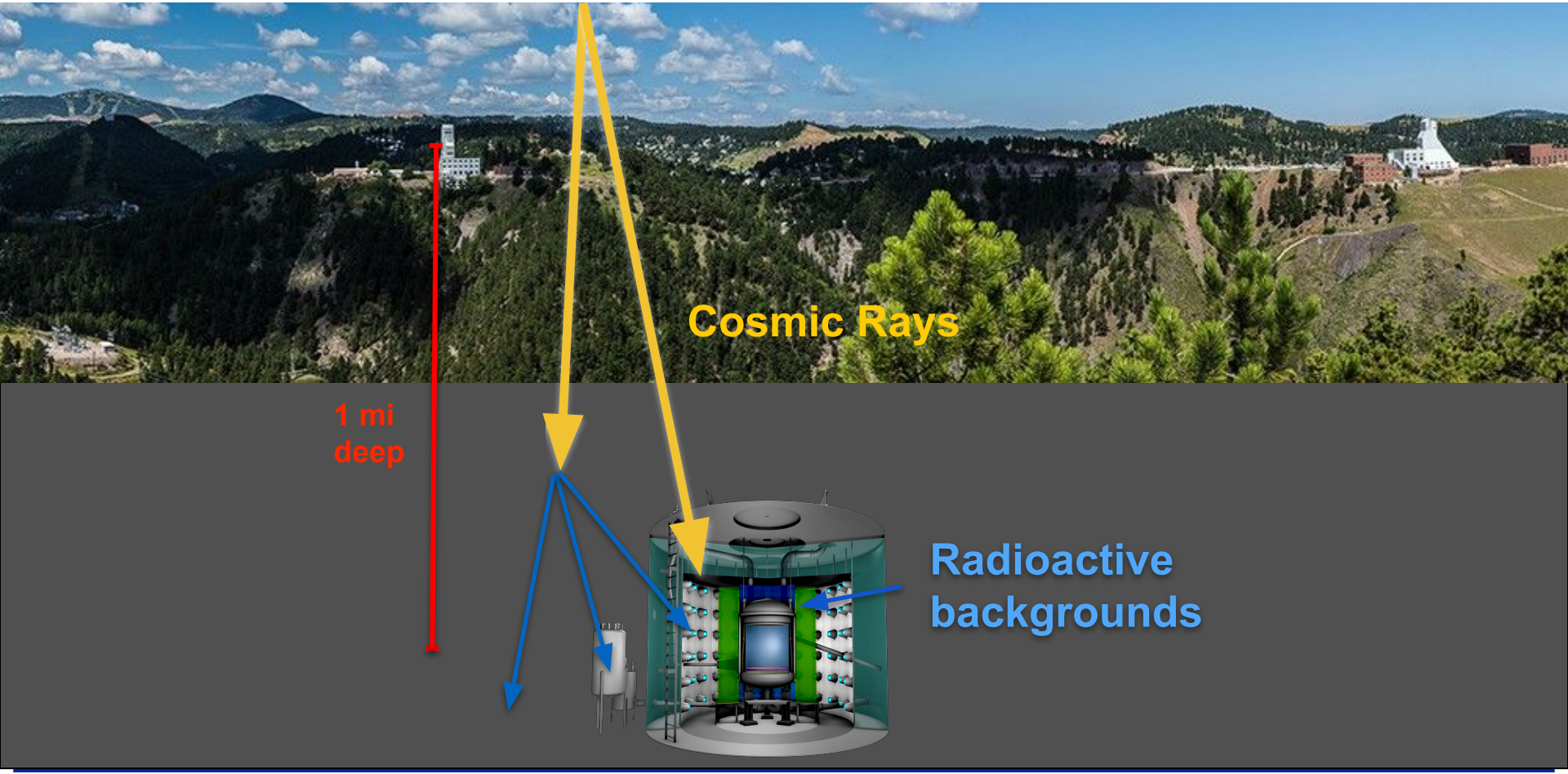
The Outer Detector

- The **Outer Detector** encloses hermetically the TPC
- Using Gadolinium based liquid scintillator (**Gd-LS**)
- OD views Gd-LS using 120 8”-PMTs, surrounded by reflector system
- Capturing neutron created 7.9 MeV cascades of about 3-4γ
- About **doubles** the **fiducial volume**



Background Mitigation

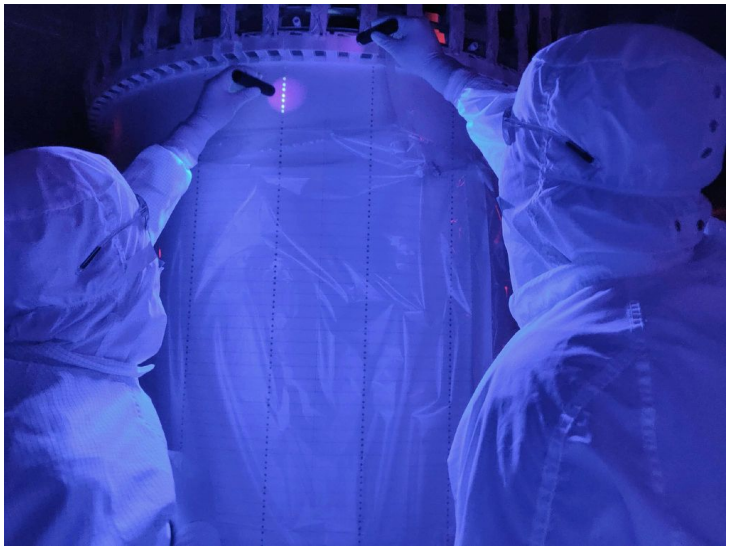
- LZ is located at SURF 1 mile deep
- Historic (and future) place
- Need to go deep to avoid suppress cosmic rays backgrounds


Cosmic Rays
1 mi deep
Radioactive backgrounds

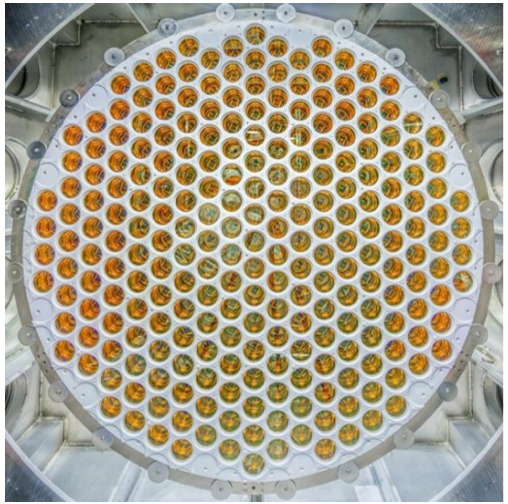
1 Banana = 15 Bq

- Bananas are actually somewhat radioactive due to potassium
  - **15Bq/Banana**
- Our target activity in the Xe: 2 μBq/kg - **1/750,000 Bananas**
- Cleaning, cleaning, cleaning, cleaning!

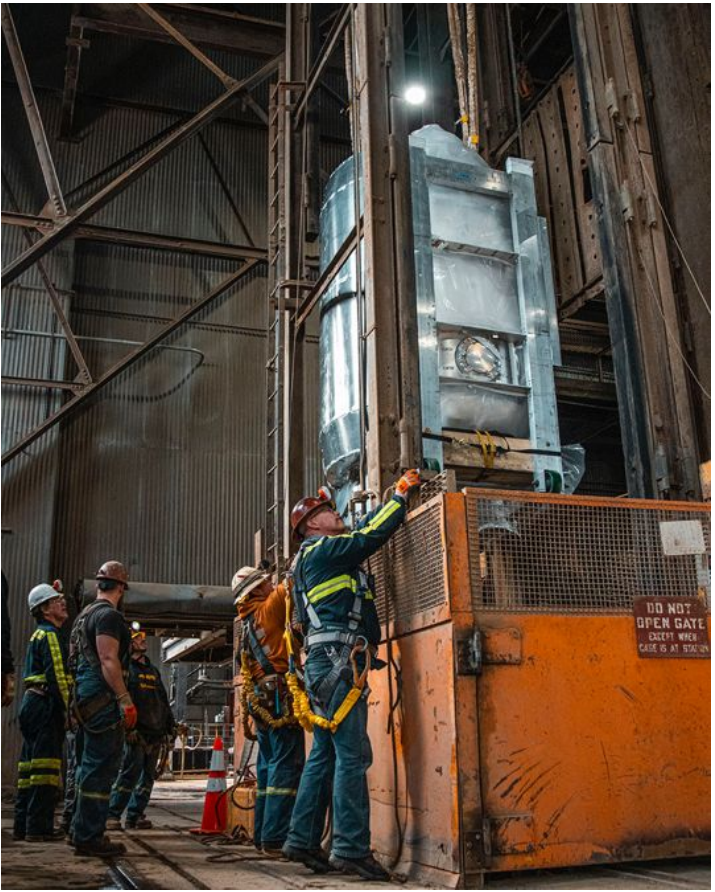
- **Need also to avoid all type of internal contaminants**
  - Use purest materials obtainable, screen all materials
  - Build everything in clean room, reduce dust on surfaces to **O(ng/cm^2)**
  - Keep circulating and purifying target material: aim Xenon contaminants to **O(0.015 ppt)**



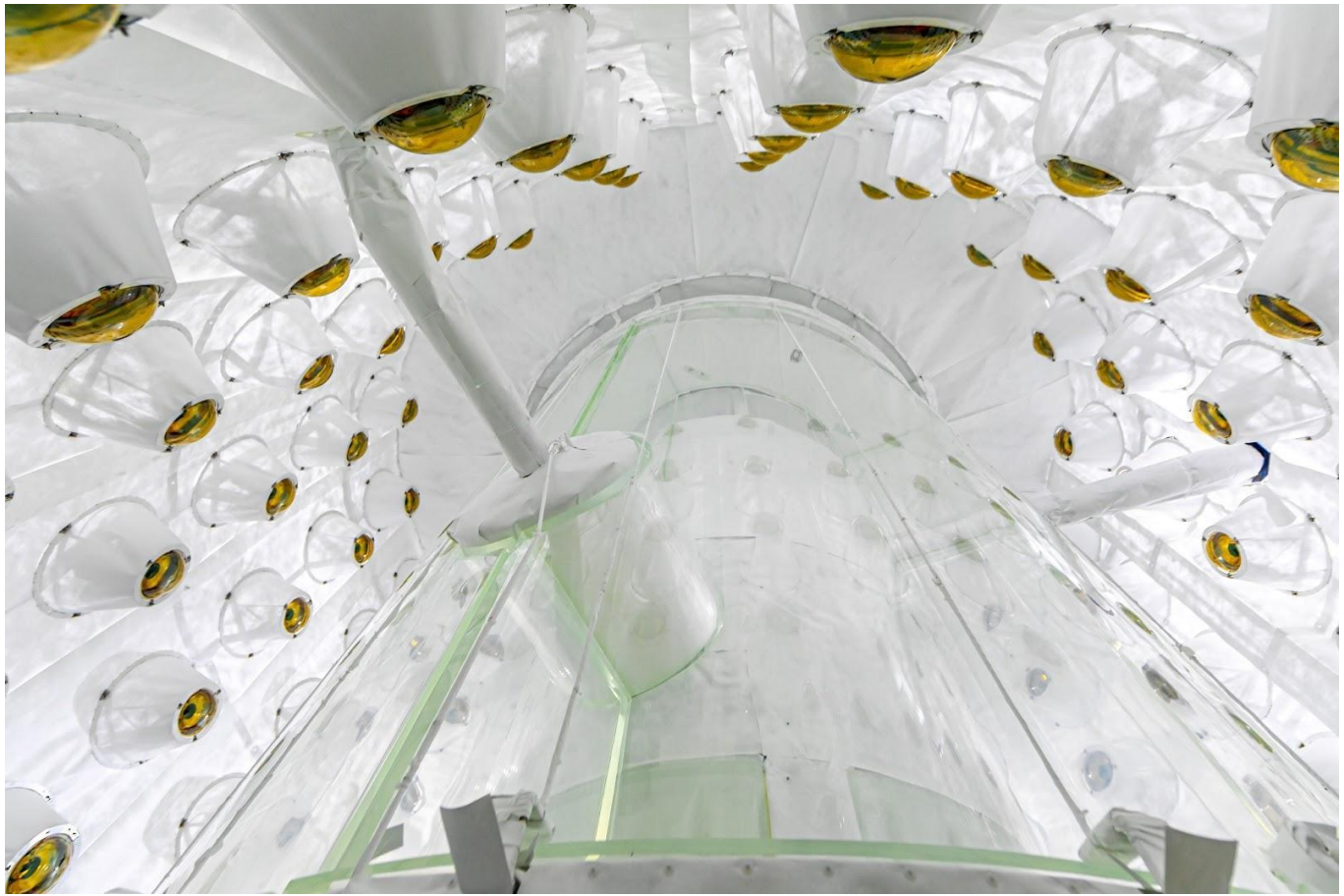
Construction



Underground Transport

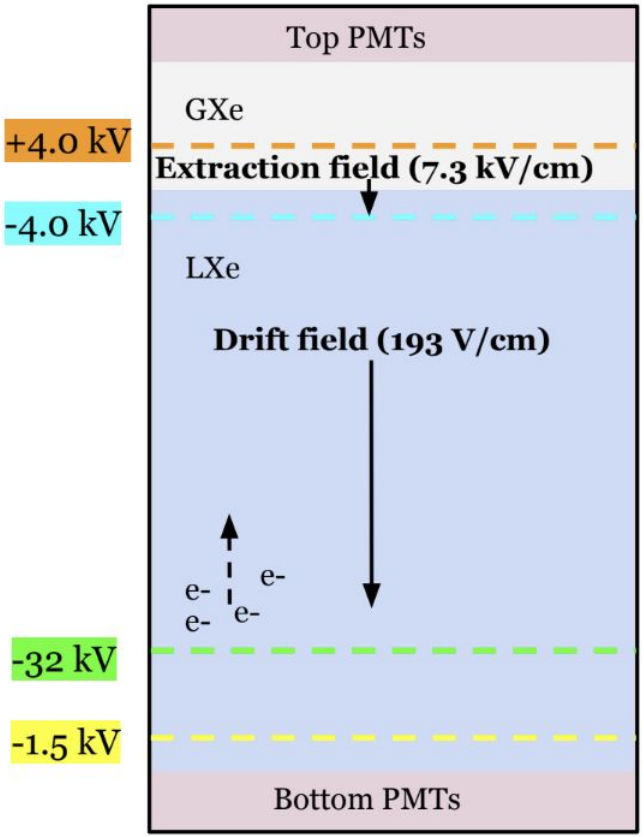


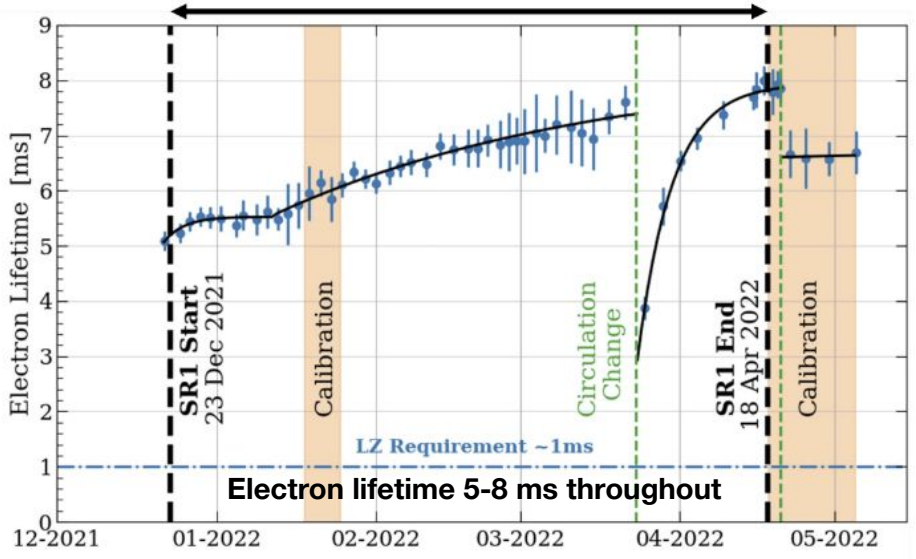
Outer Detector



Outer Detector

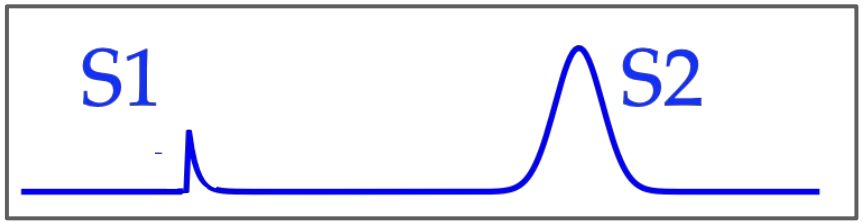
Let’s look at some Data!

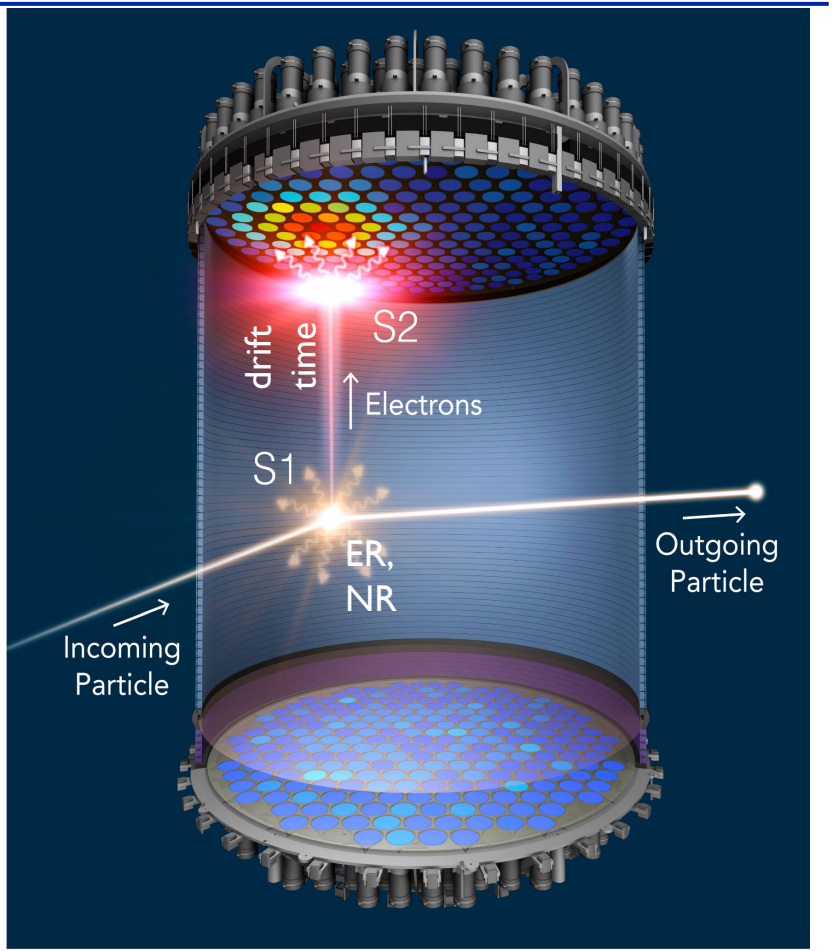




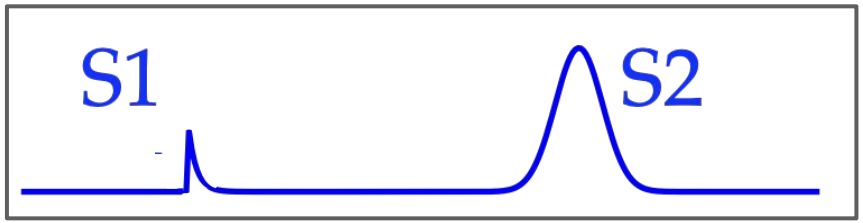
- Stable detector:
  - Temperature= 174.1 K
  - Gas pressure= 1.791 bar
- 97% PMTs operational
- Continuous purification: 3.3 t/day through hot getter system

- Cartoon waveform:

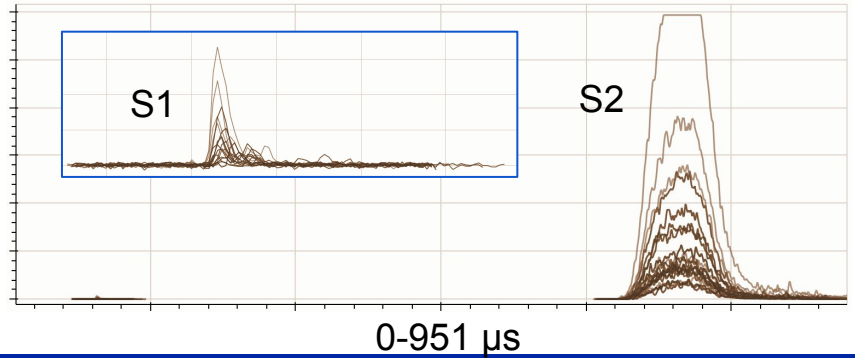


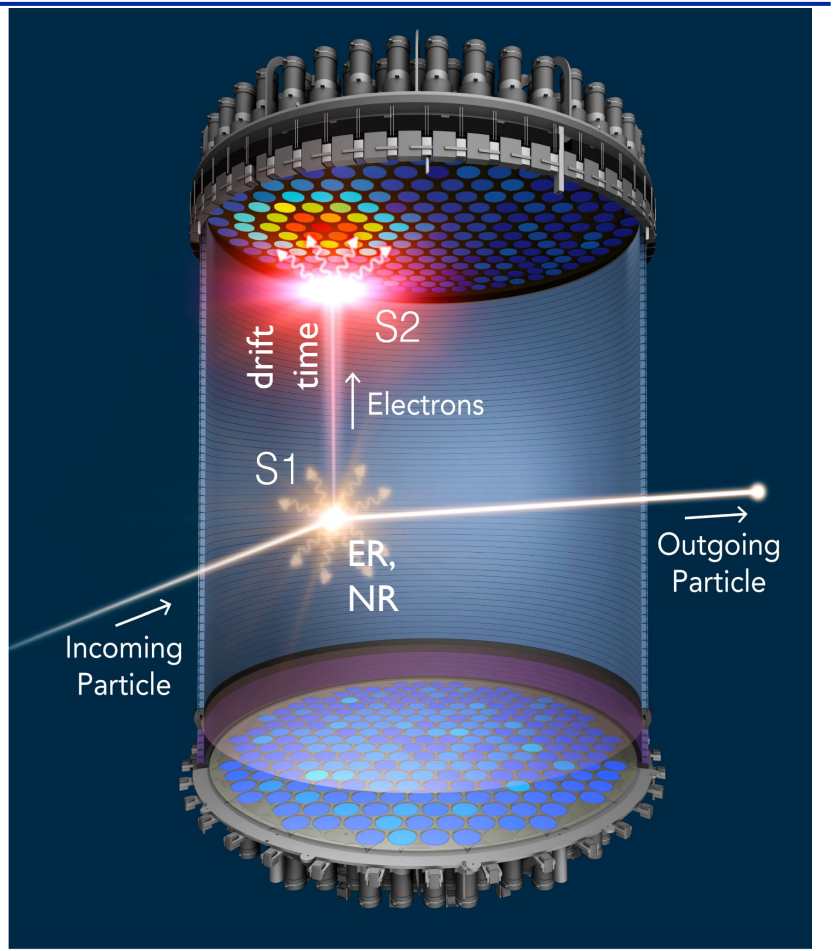


- Cartoon waveform:

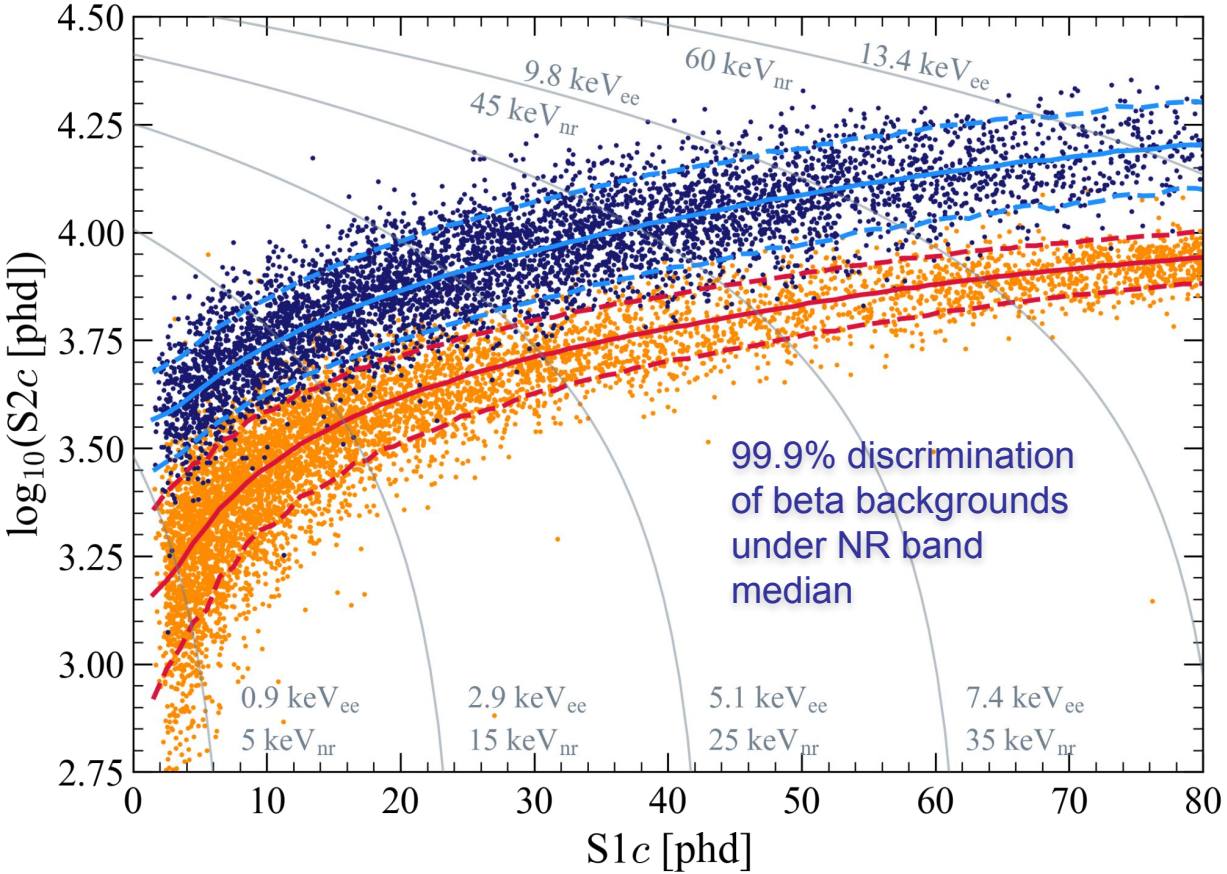


- Actual waveform:

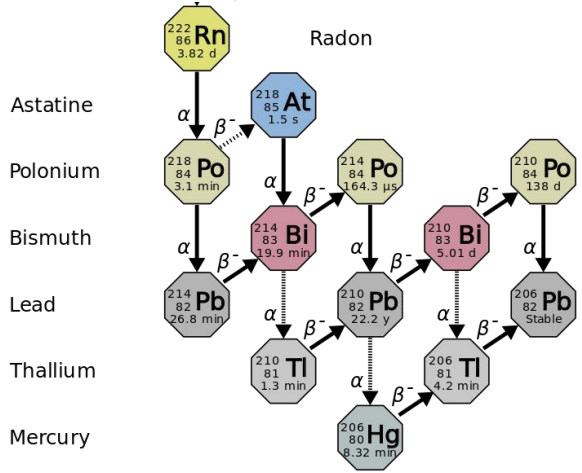


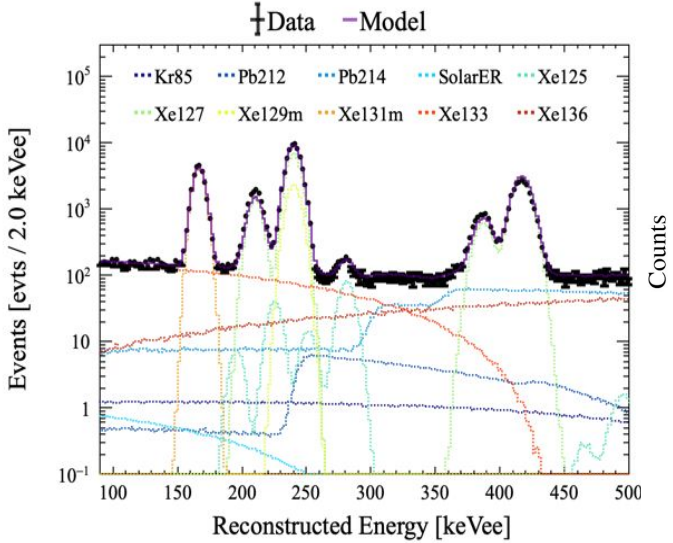


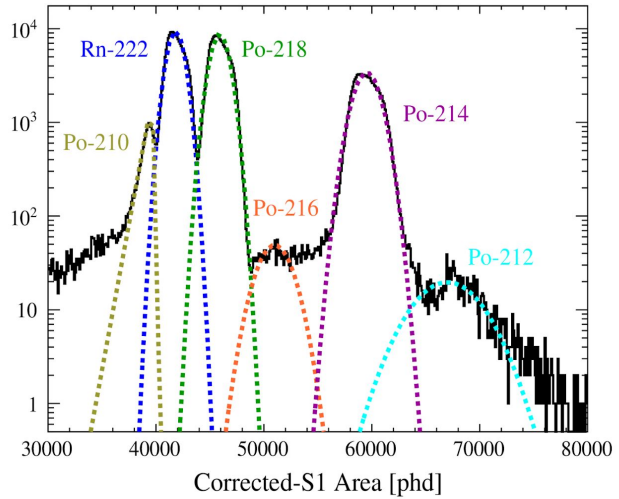
- Backgrounds predominantly ERs, WIMPs produce NRs
- **ER band**: Tritiated methane (CH3T) injection, spatially homogeneous β source
- **NR band**: DD neutron generator (NR band), Monoenergetic 2.45 MeV neutrons
- **Photon** detection efficiency: g1 = 0.114 ± 0.002 phd/ɣ
- **Ionization** channel gain: g2 = 47.1 ± 1.1 phd/e
- 99.9% discrimination



https://arxiv.org/abs/2211.17120



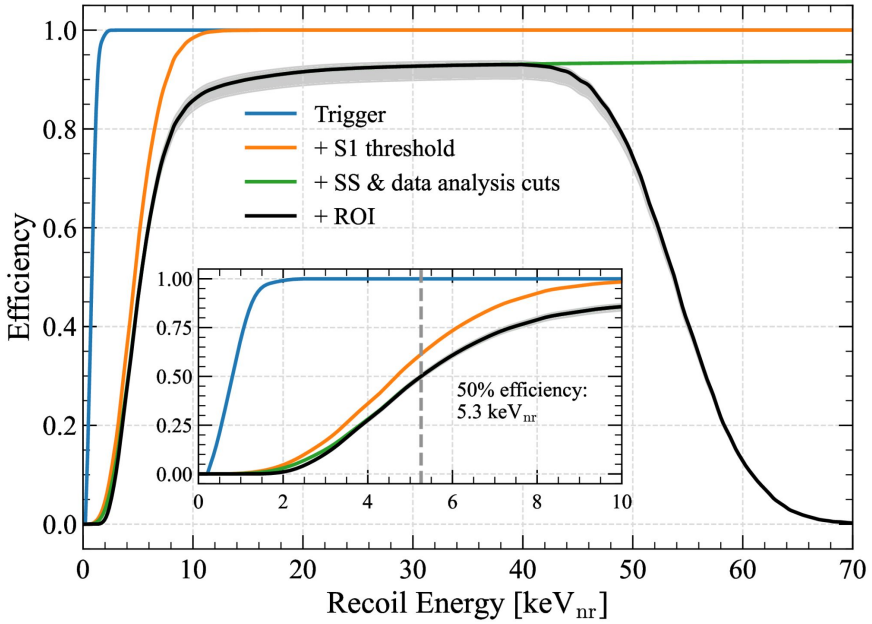


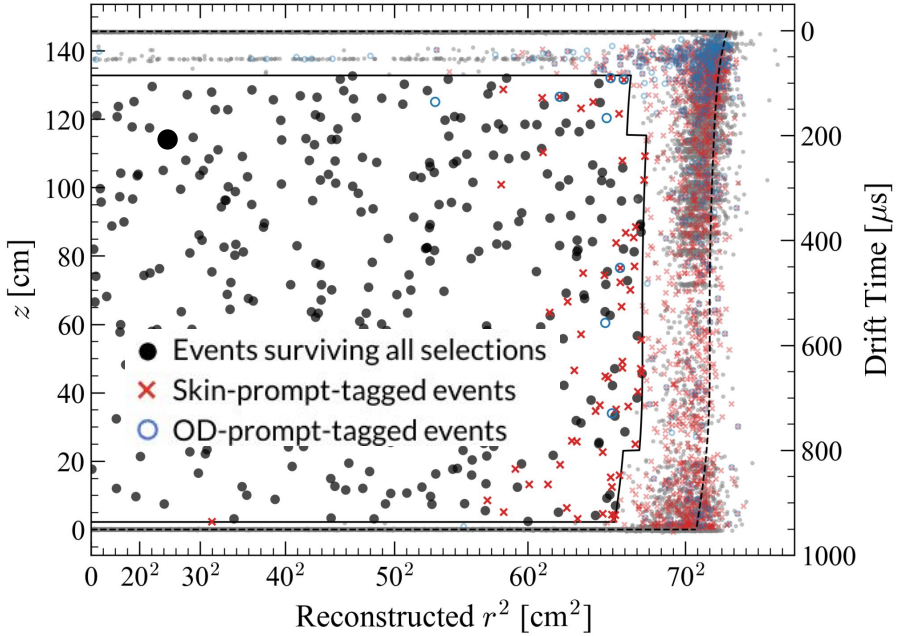


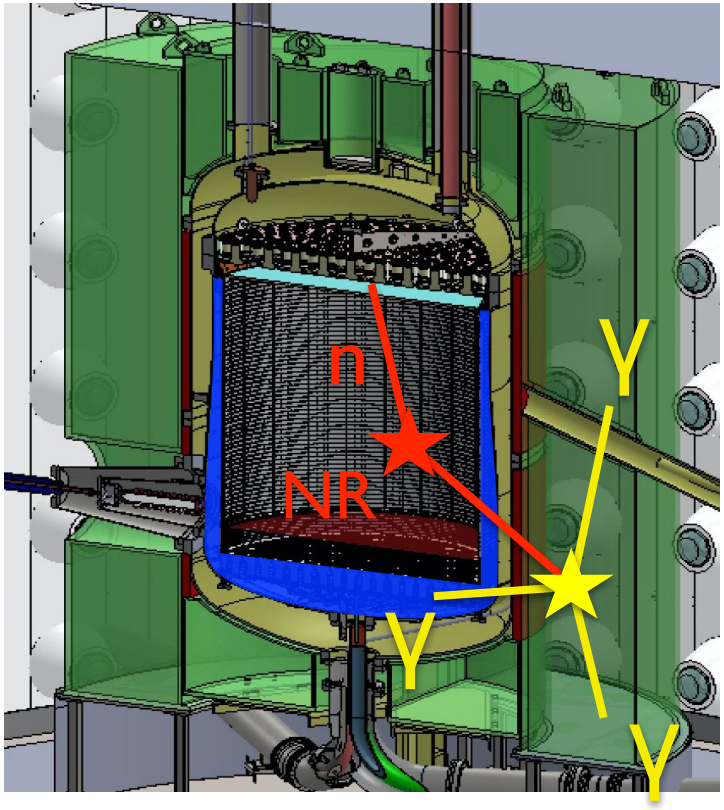
- ‘Naked’ ^{214}Pb β-decays (no-γ) from Rn emanated in Xe are the main ER background
- Constrain β-decay rate by bracketing with Rn-chain α-tagging & spectral fit of all internal background components
- ^{222}Rn activity within assay expectation

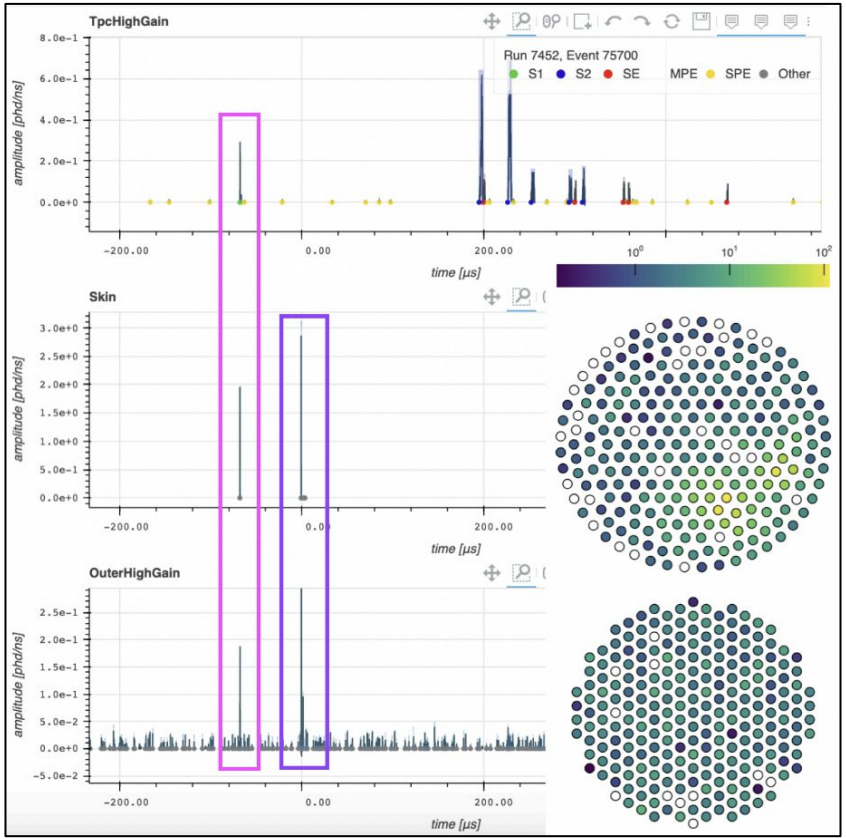
- **Event selection:**
  - S1/S2 shape and topology selection
  - Veto detector, anti-coincidence
  - Fiducial Volume, ROI, single scatter cuts

- Not blind, **but** selection criteria developed on non-WIMP ROI background & calibration data



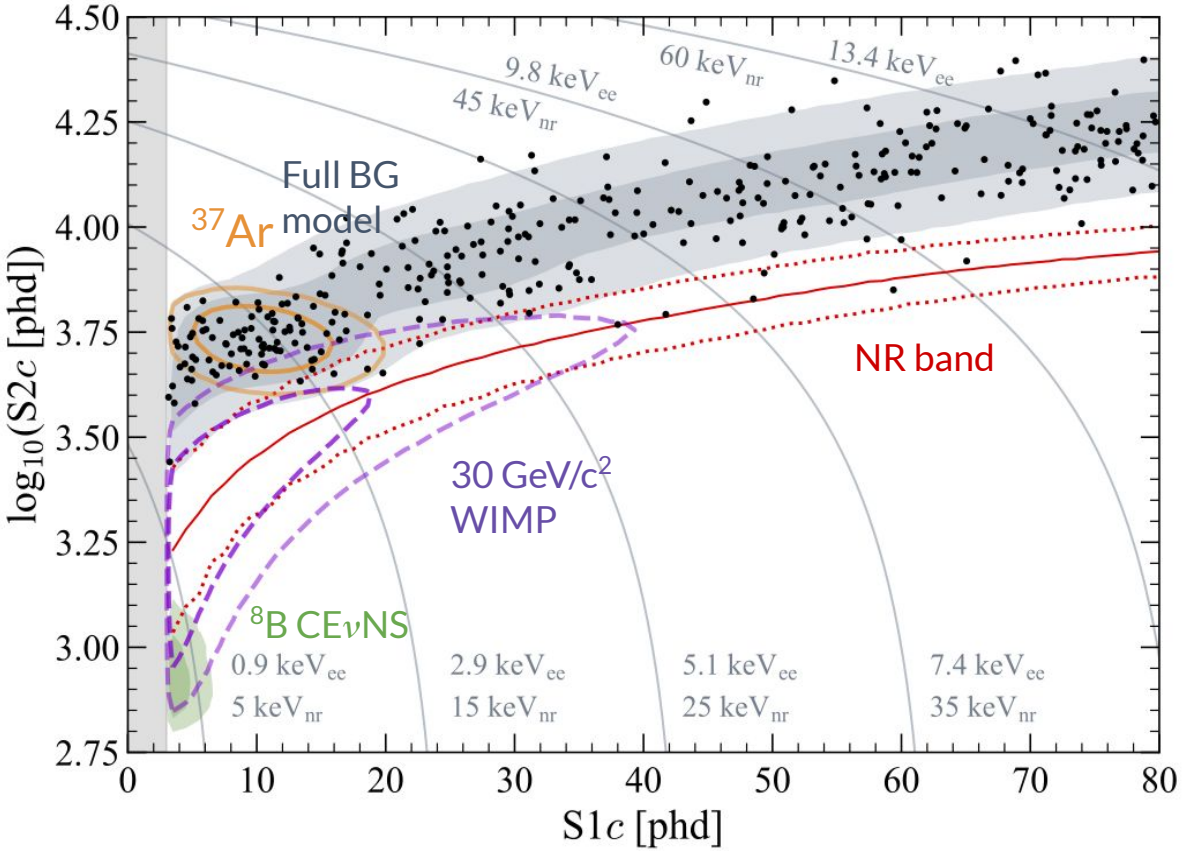


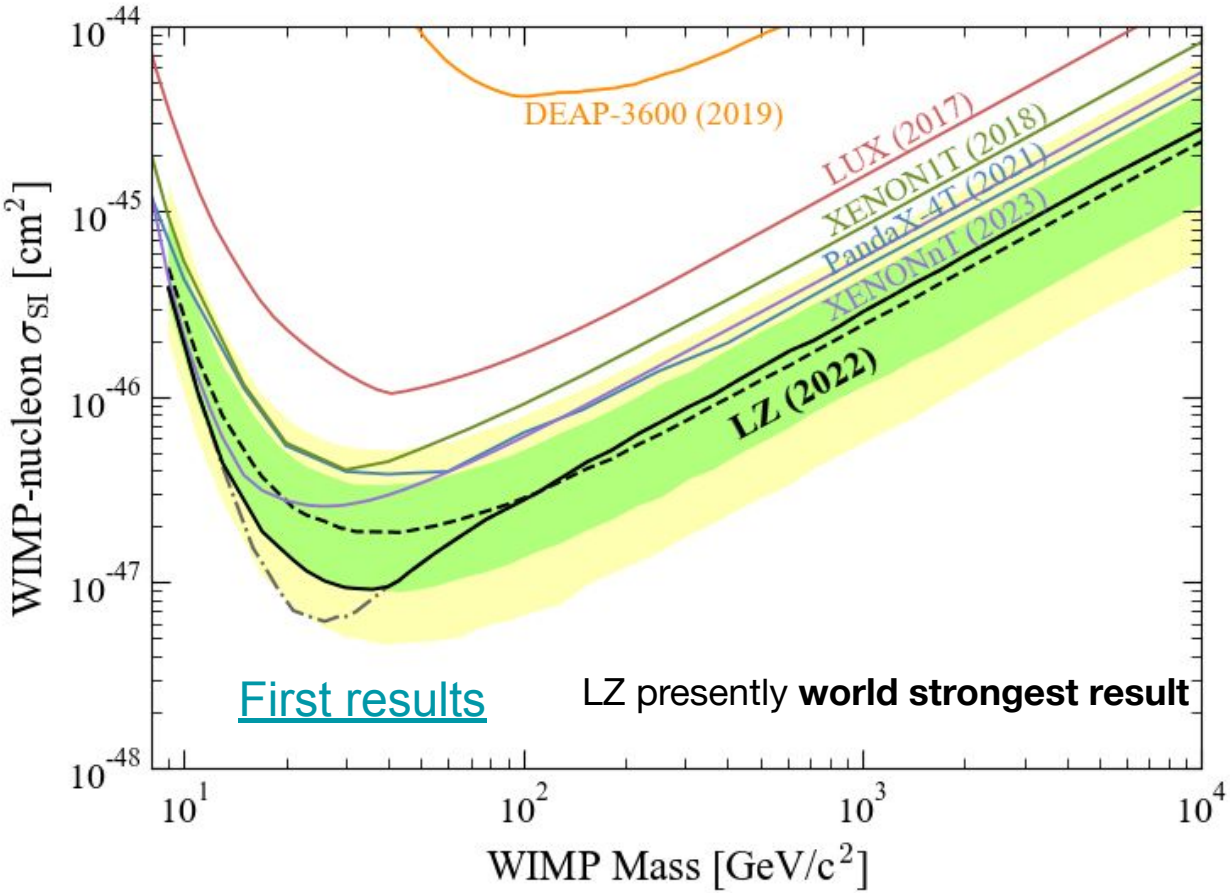




- We actually observed more NR background (now understood) than expected → successfully vetoed by the OD

- **Region-of-interest**:
  - 3 phd < S1*c* < 80 phd, S1 coincidence ≥3
  - S2 > 600 phd ($6e^-$), S2*c* < 10^5 phd
- 335 events in final dataset
- 60 live days, 5.5 ± 0.2 tonne FV

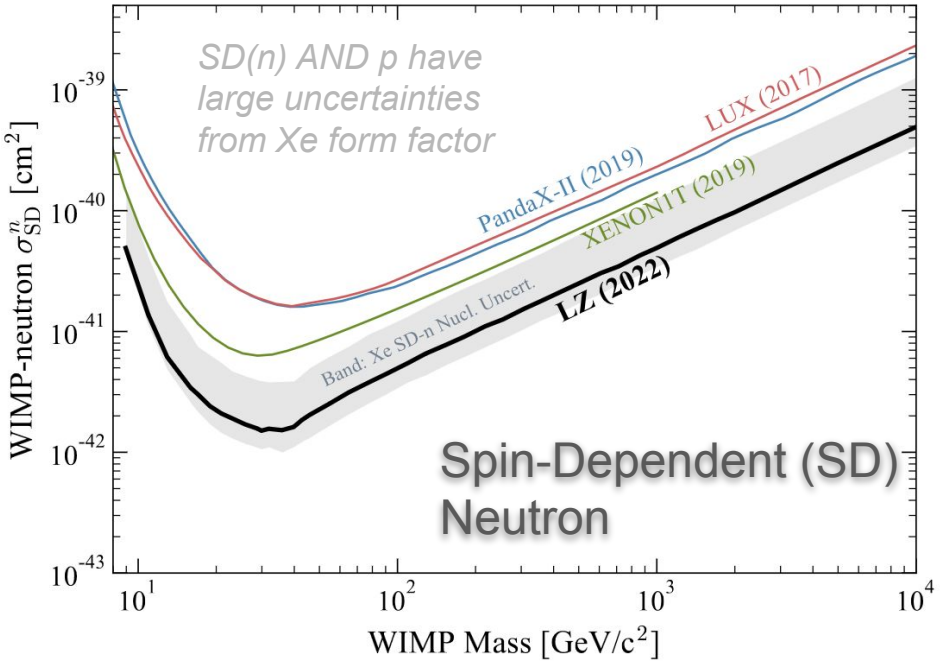


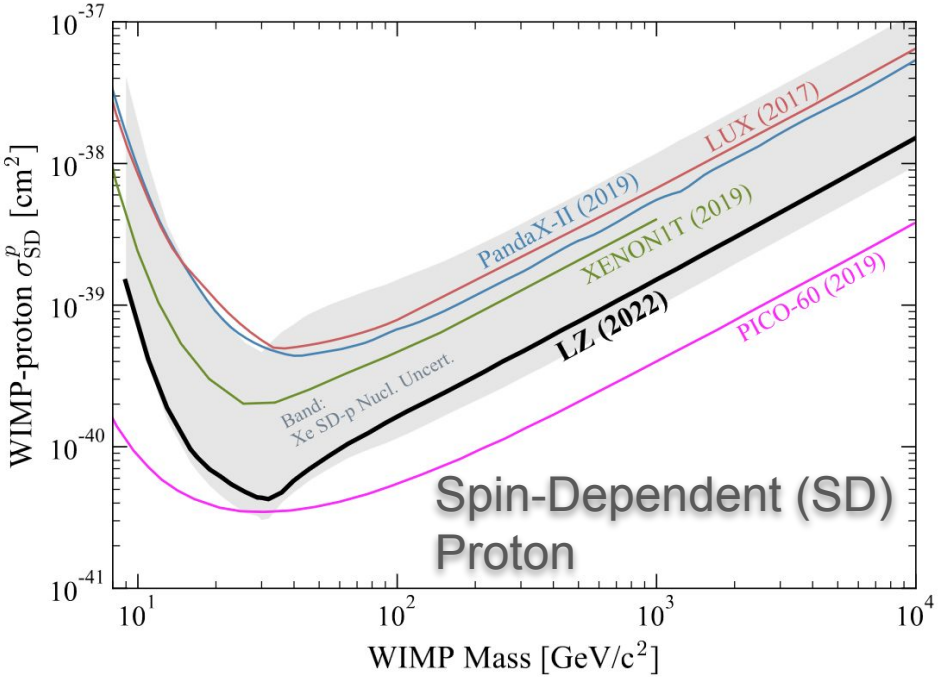


First results

LZ presently **world strongest result**

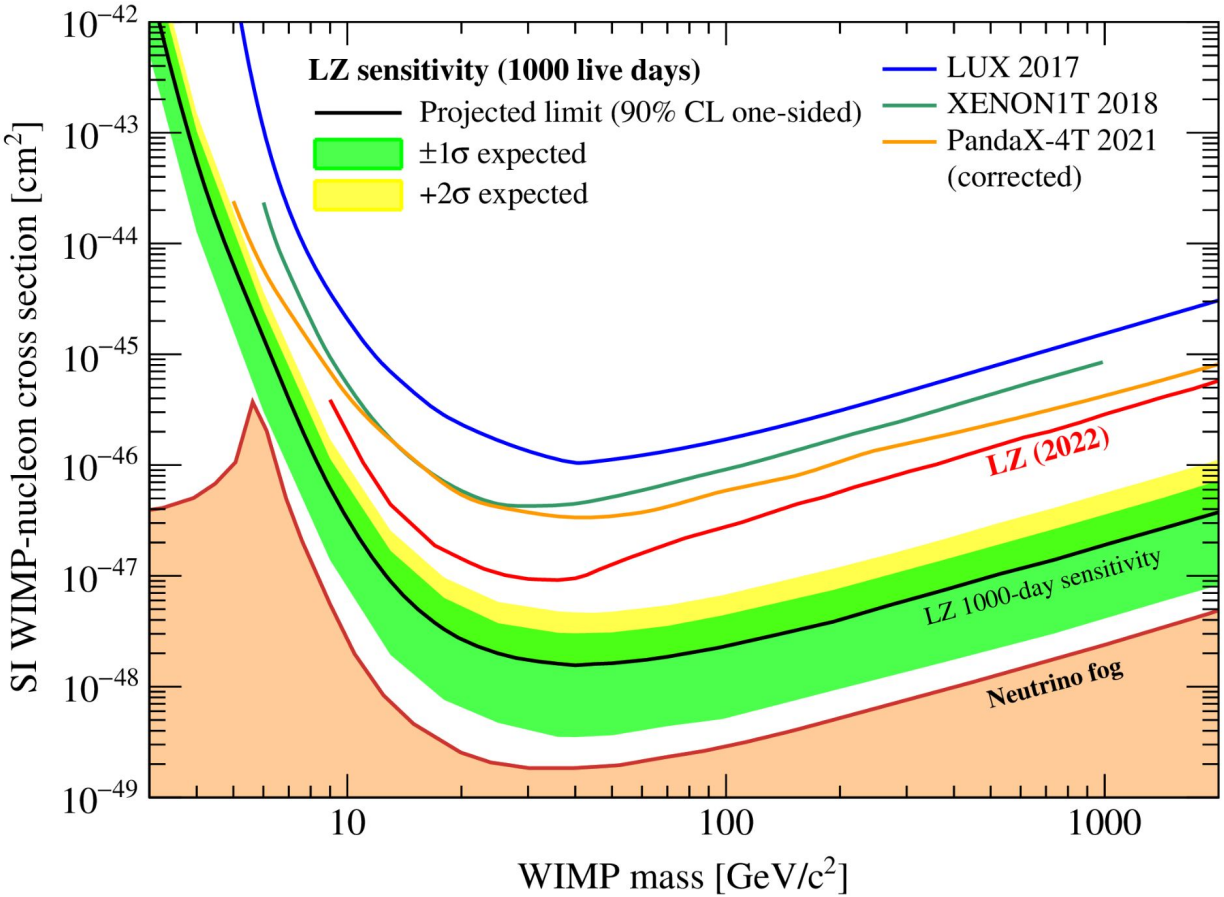
Spin-Dependent Limits





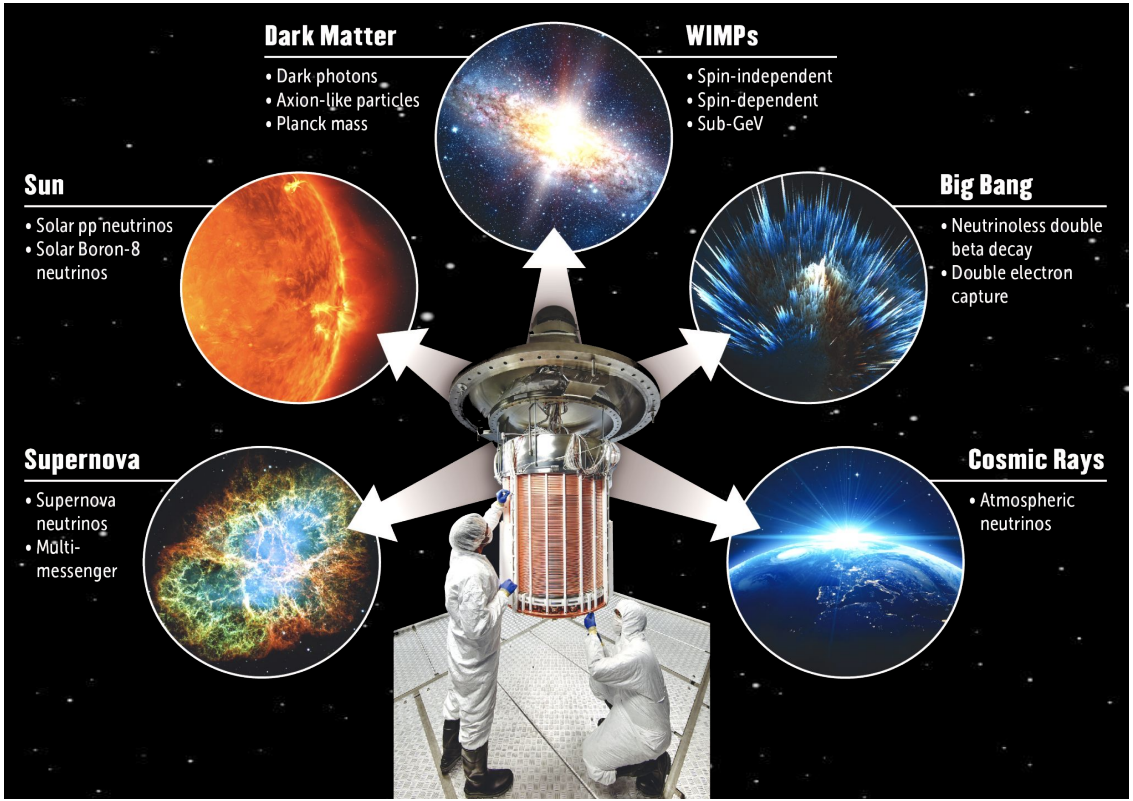
- Only 60 days out of a 1000 days exposure published, considering extension to 2028

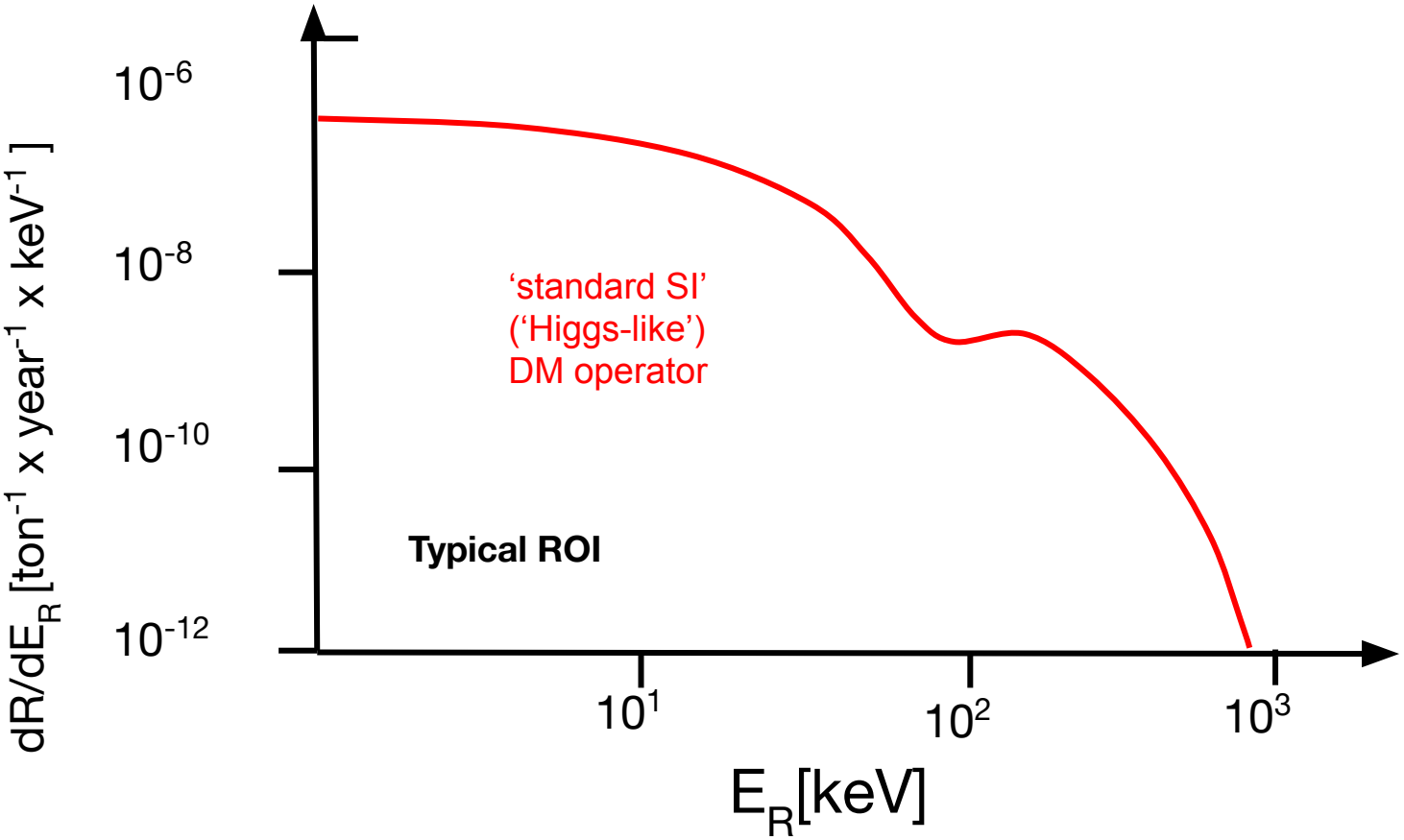
Projected Sensitivity

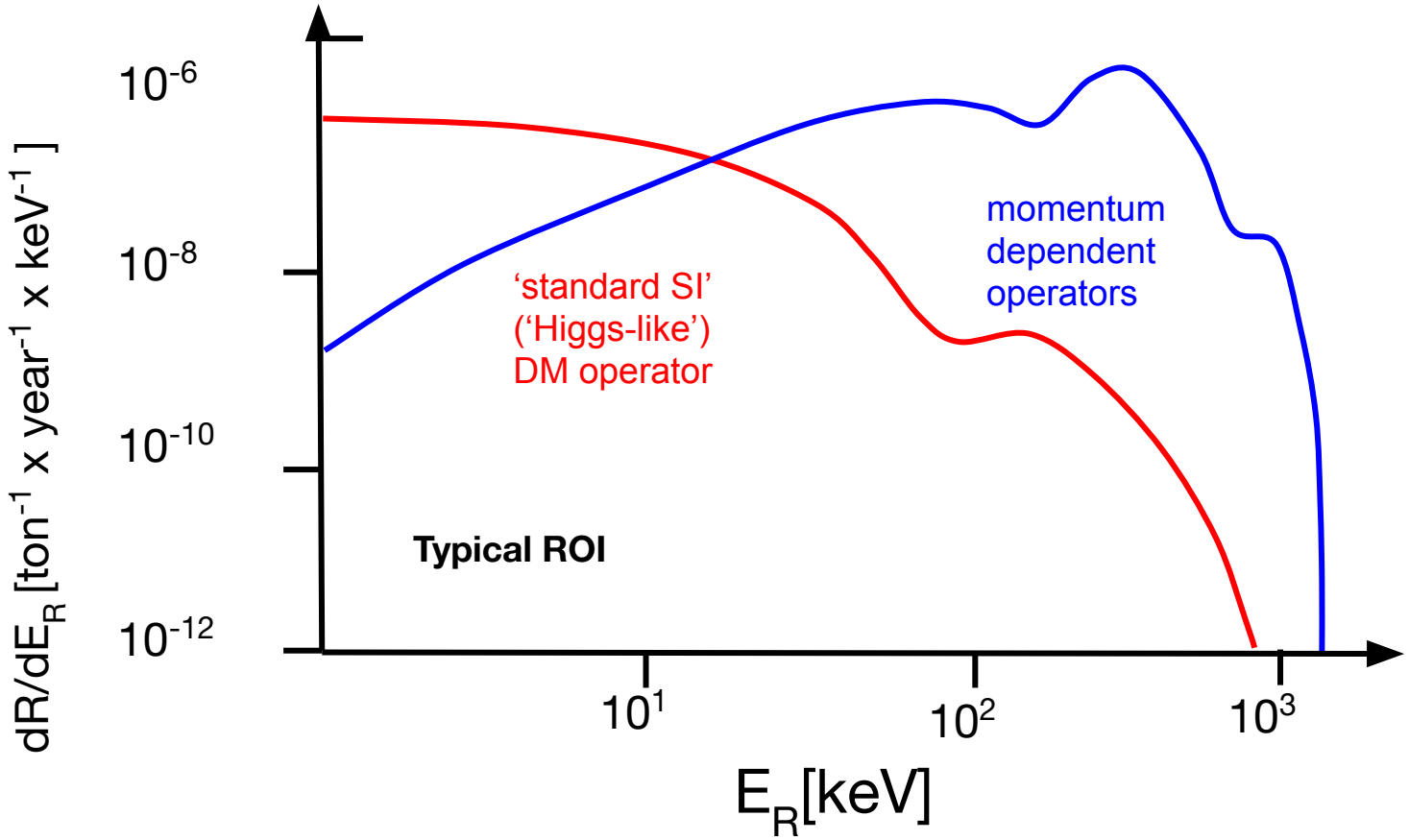


Is that it?

- We can do more than standard WIMP searches
- Multi-purpose detectors for rare/ low E phenomena
- High-energy NR:
  - EFT-motivated searches
- Low-energy ER
  - Axions and ALPs
  - Neutrino physics
  - The Migdal Effect
- Ultra-heavy dark matter




10^{-6}
10^{-8}
10^{-10}
10^{-12}
dR/dE_R [ton^{-1} x year^{-1} x keV^{-1}]
'standard SI'
('Higgs-like')
DM operator
Typical ROI
10^1
10^2
10^3
E_R[keV]


10^{-6}
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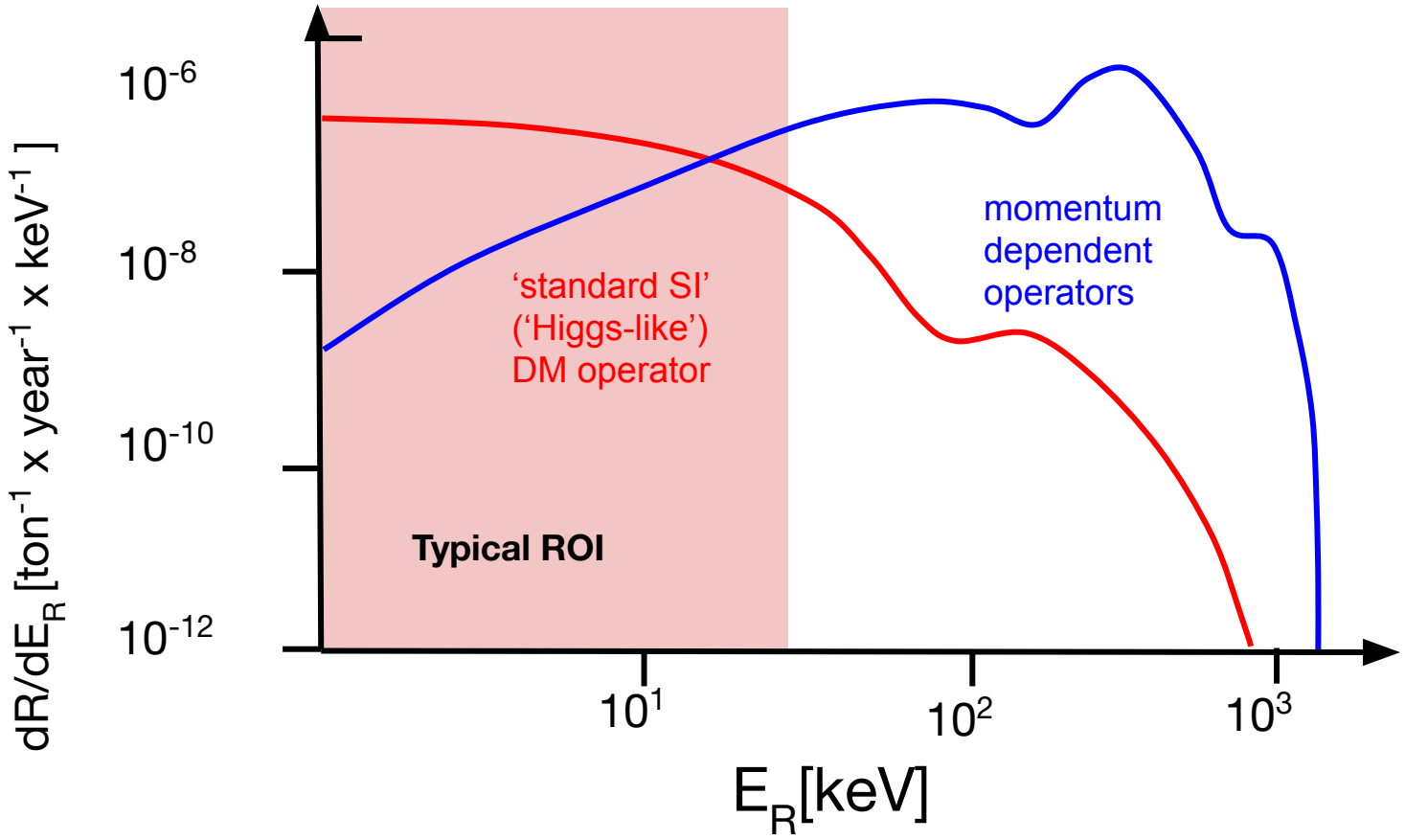
dR/dE_R [ton^{-1} x year^{-1} x keV^{-1}]
'standard SI'
('Higgs-like')
DM operator
momentum
dependent
operators
Typical ROI
10^1
10^2
10^3
E_R[keV]


10^{-6}
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dR/dE_R [ton^{-1} x year^{-1} x keV^{-1}]
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10^1
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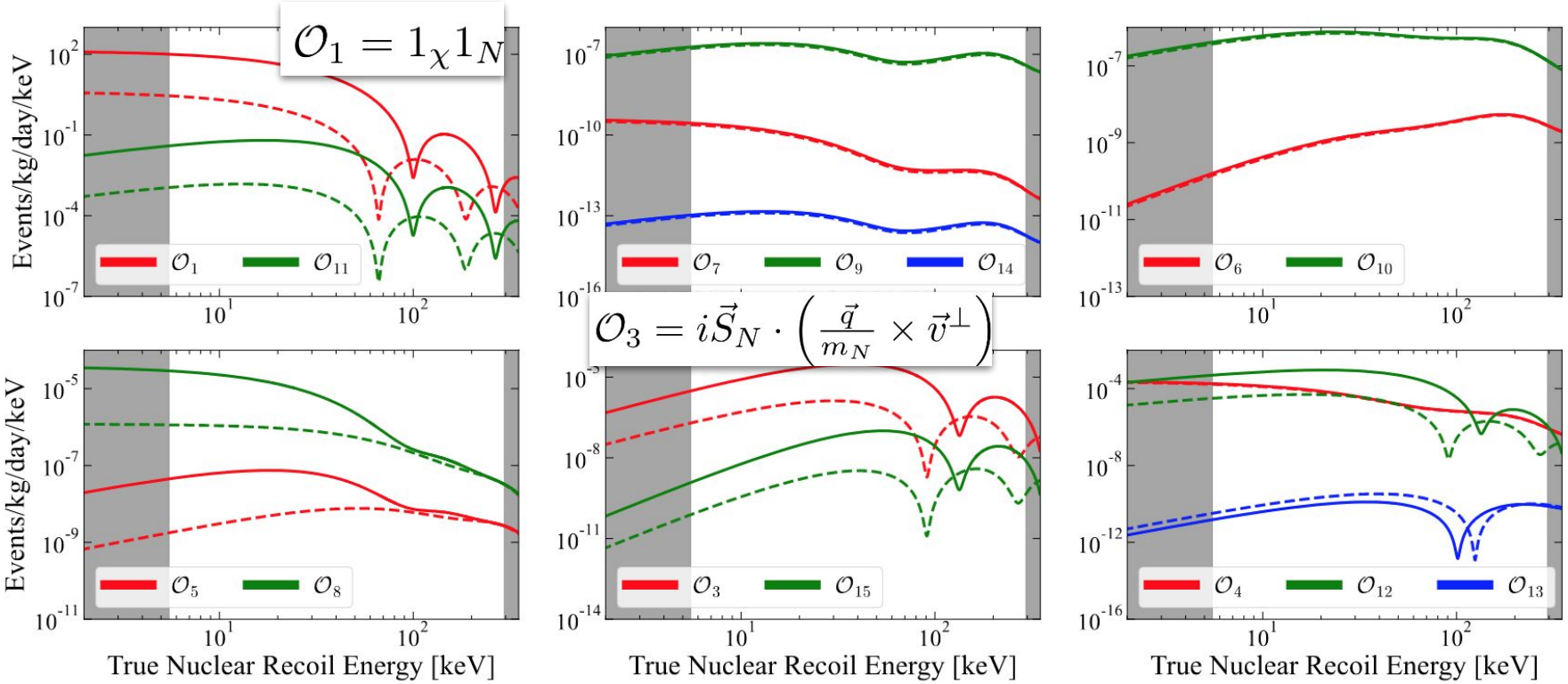
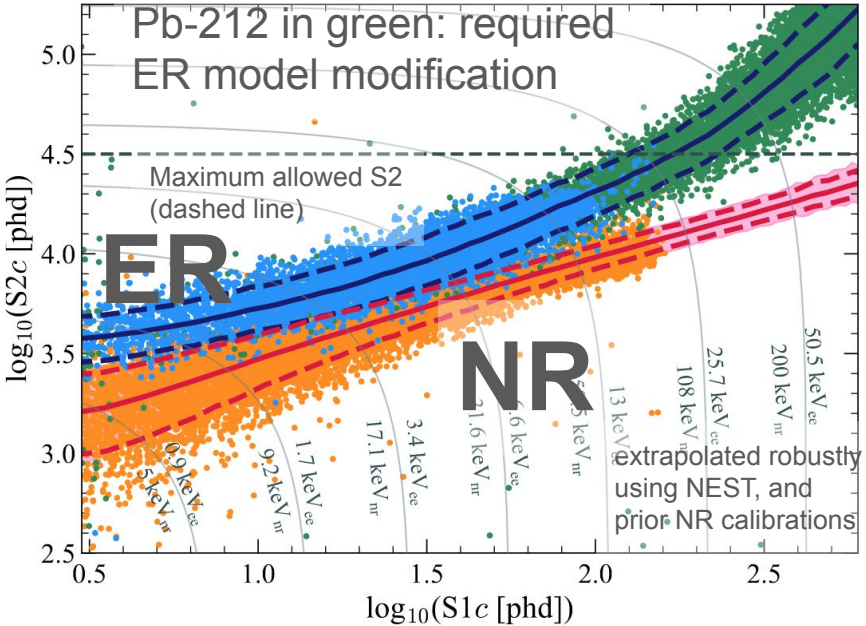
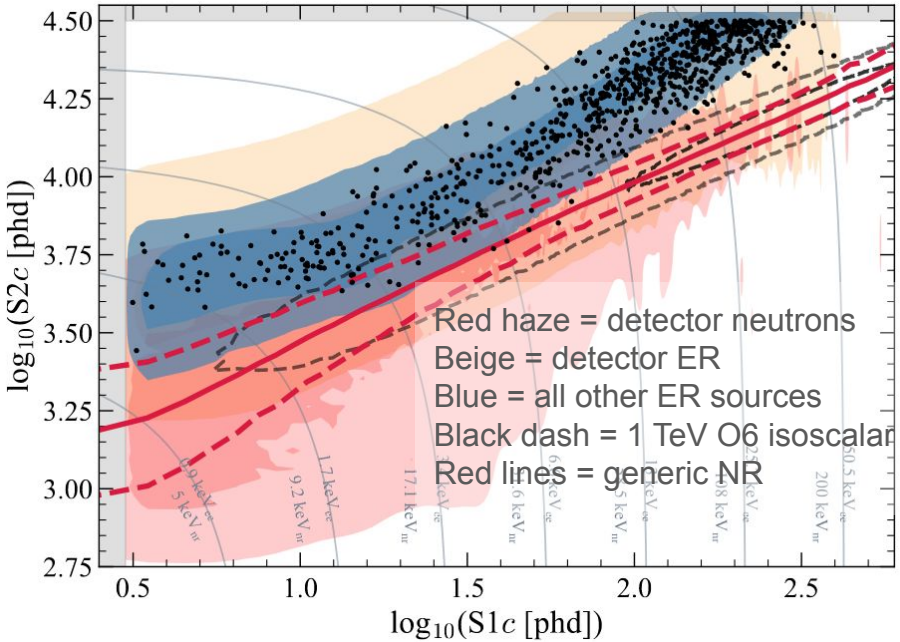


- Effective Field Theory (EFT): Lagrangian written in terms of 16 operators, 15 being non-relativistic

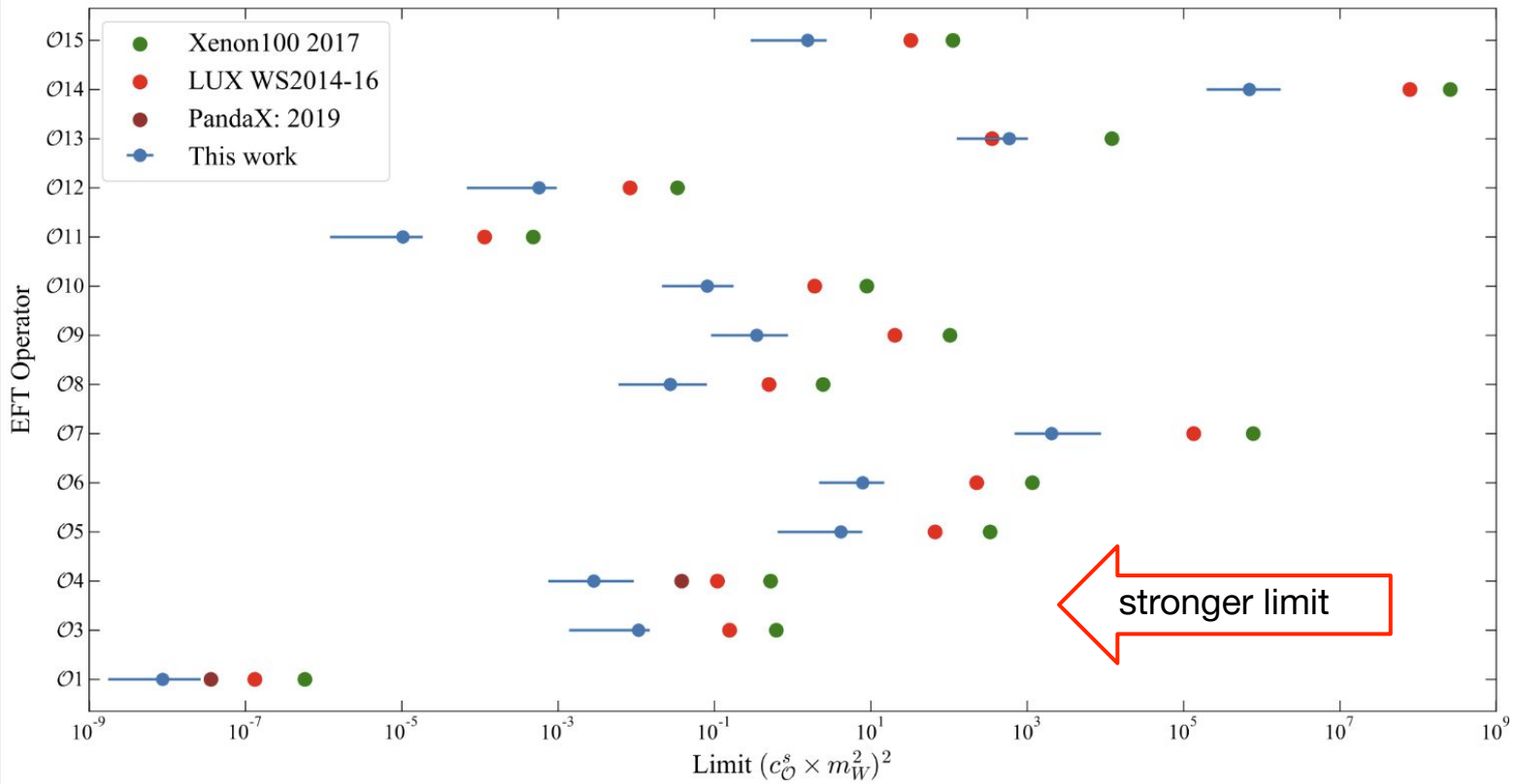
https://arxiv.org/pdf/2312.02030.pdf



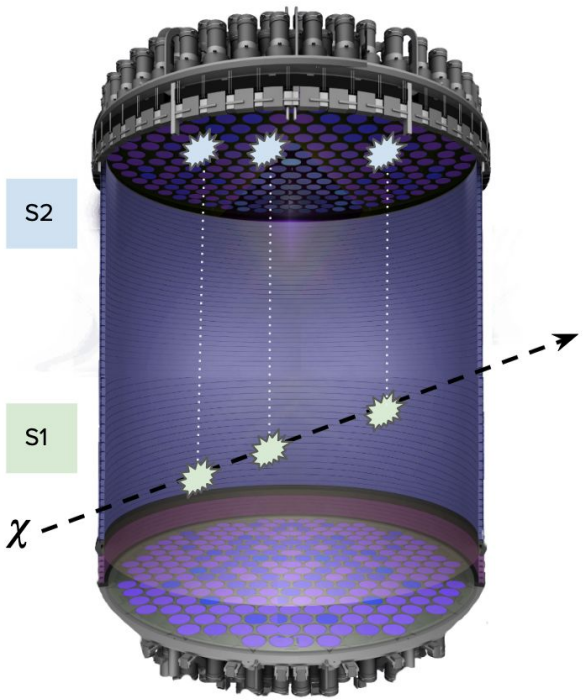


- Effective Field Theory (EFT): Lagrangian written in terms of 16 operators, 15 being non-relativistic
- **Extended analysis region by factor 7.5**, new calibrations, new backgrounds, signals etc

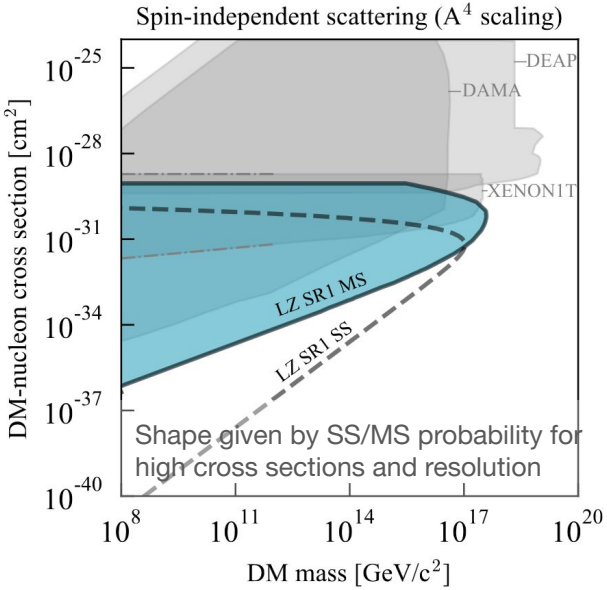
https://arxiv.org/pdf/2312.02030.pdf

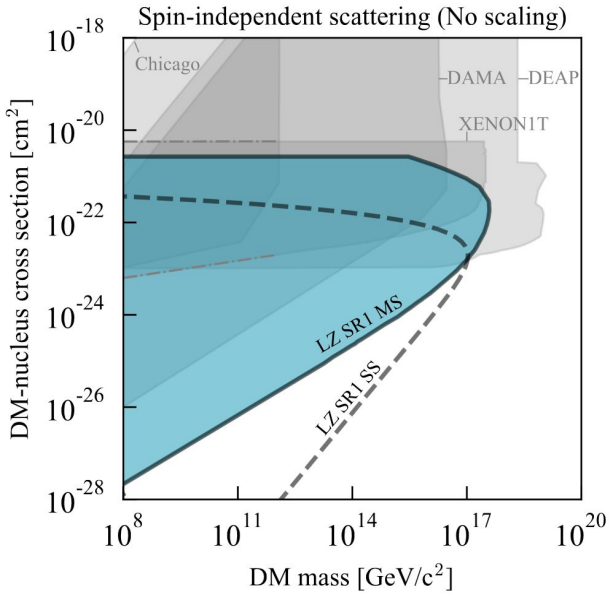


- **LZ provides the strongest upper limits for all but one operator**



https://arxiv.org/pdf/2402.08865.pdf

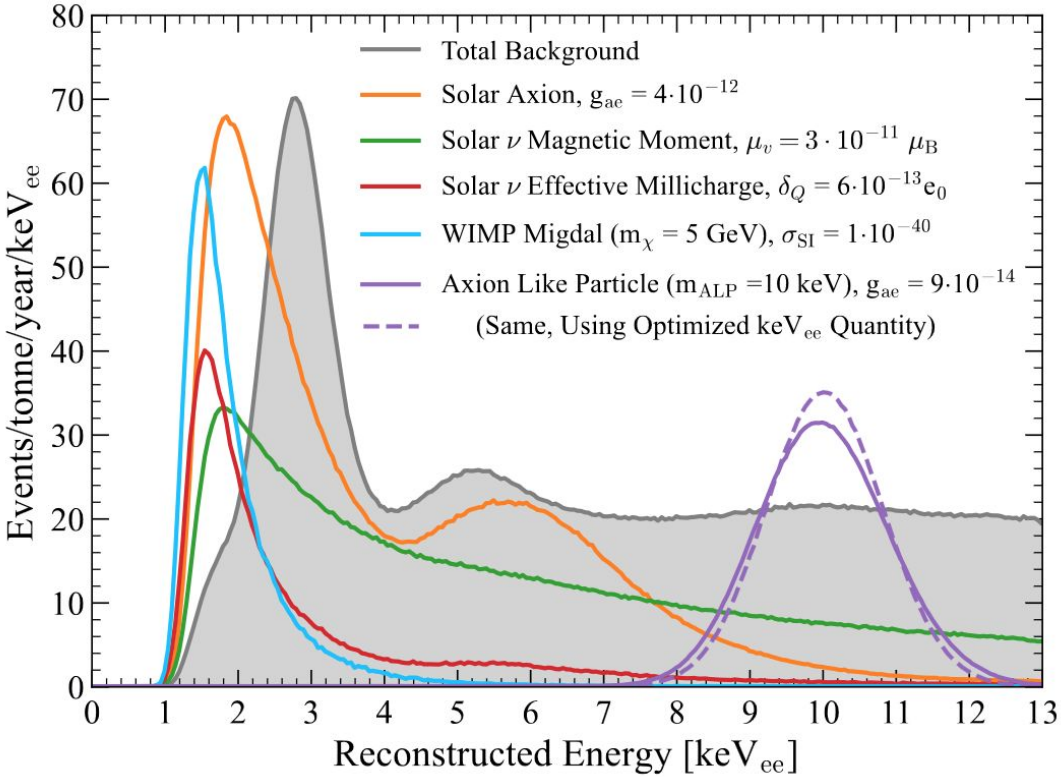




- Multiply Interacting Massive Particles (**MIMPs**):
  - Very heavy mass (> 10^4 GeV)
  - Large cross section (>10^{-31} cm^2)
- **Maximum mass probed by LZ** extended to 3.9 x 10^{17} GeV
- Competitive per-nucleus limits and world-leading per-nucleon limit

https://arxiv.org/pdf/2307.15753.pdf

- **Low energy searches**
  - 1-15 keV_{ee}
- **8 BSM signals** tested with line-features or characteristic spectra
- Same data, selections and background models as WIMP search
- **Time dependence** added to fit ^{37}Ar & ^{127}Xe



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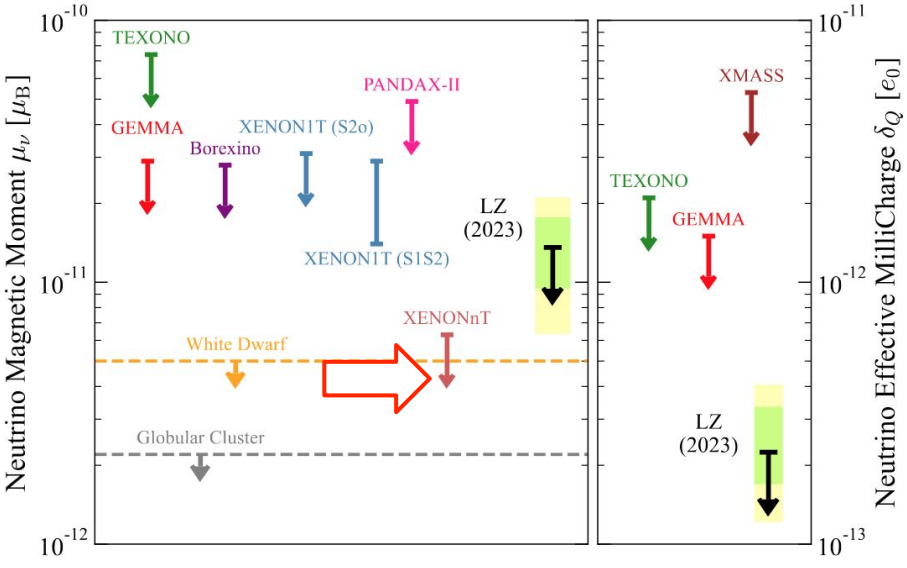
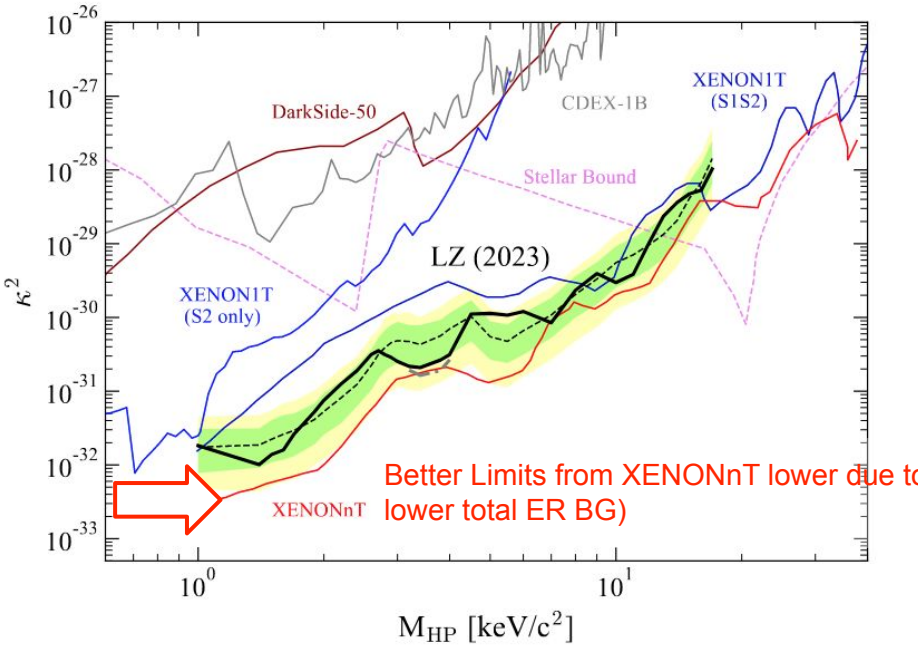
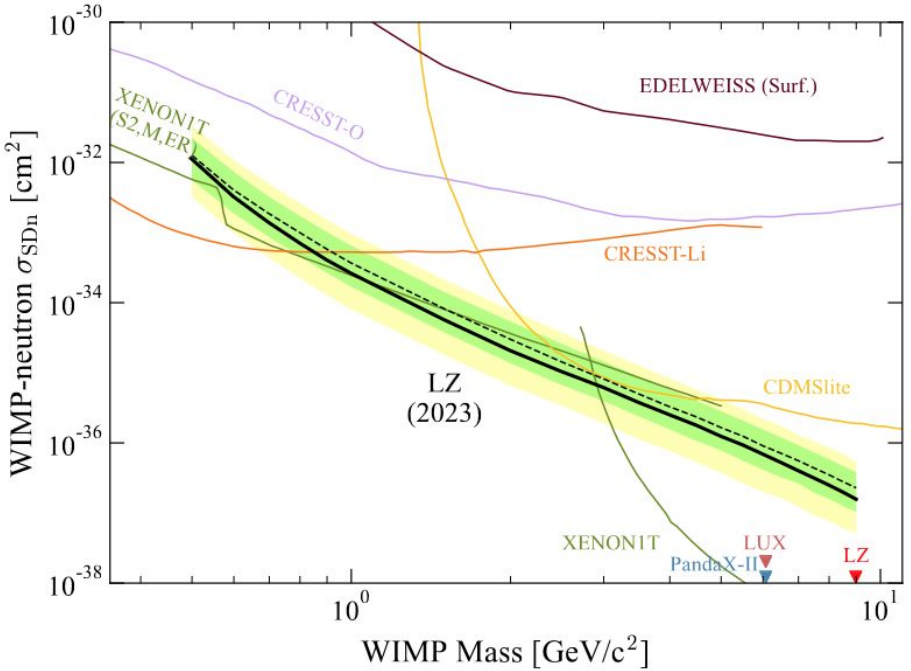


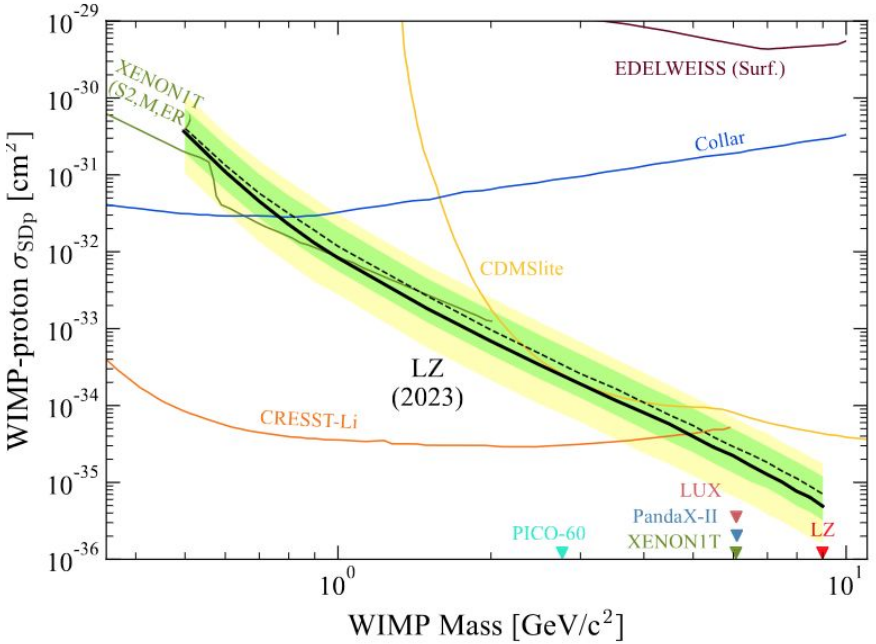


Neutrino magnetic moment
A non-zero neutrino magnetic moment or effective millicharge would increase the rate of solar neutrino ER interactions

Axion, axion-like particle and hidden photon searches:
New boson would induce mono-energetic peak in gauge spectrum

https://arxiv.org/pdf/2307.15753.pdf





- **Extend DM searches** towards lower DM masses
- SI and SD WIMP searches using the Migdal* mechanism

* worldwide calibration effort underway

- **Leading DM experiments come together:** LZD
  - Probing WIMP DM across the entire natural phase space
- Had first meeting in Karlsruhe, LA and Oxford
- White paper published, design and sensitivity paper in preparation
  - https://xlzd.org/
  - White paper (2203.02309)

Summary

- **DM is out there** and will transform our understanding of the universe
- **LZ** has **60 out of 1000 days** of data published
- Continue data taking, stay tuned for larger data sets soon
- Probing new type of DM models, including new masses, new signatures and previously unprobed parameters space
  - A discovery might come any day
- The field is being transformed right now:
  - **Xenon TPCs are the most sensitive detector** today
  - **New low mass DM searches** will within a few years push sensitivities to yet **entirely unprobed energies**
  - **XLZD** preparing **to explore to the neutrino fog**

- 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

38 Institutions, 250 scientists, engineers, and technical staff

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

LZ Collaboration Meeting at SURF, 2023

Science and Technology Facilities Council

Swiss National Science Foundation

FCT Fundação para a Ciência e a Tecnologia

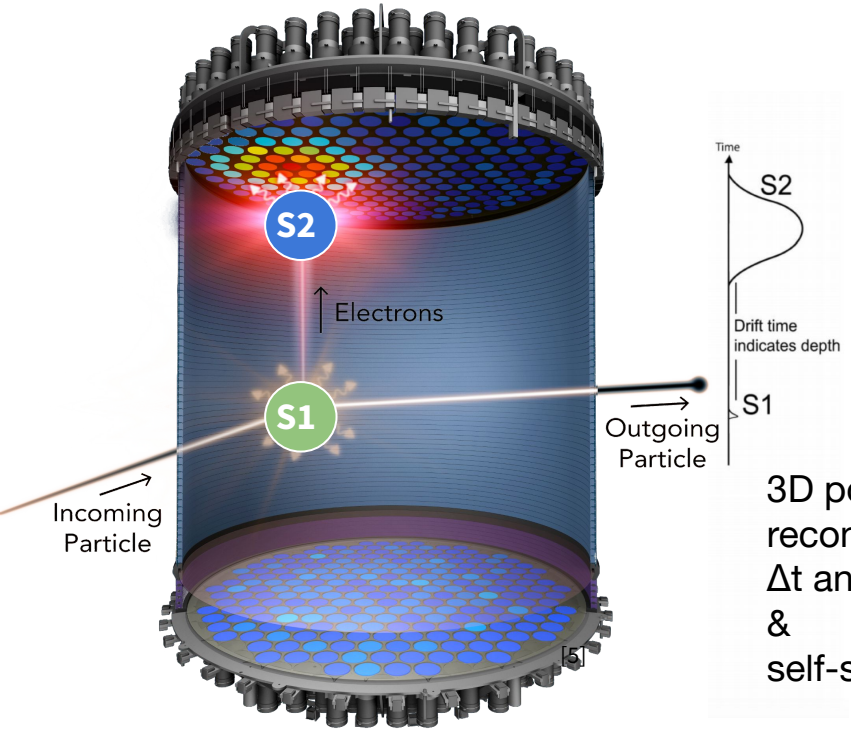
SANFORD UNDERGROUND RESEARCH FACILITY

ibs Institute for Basic Science

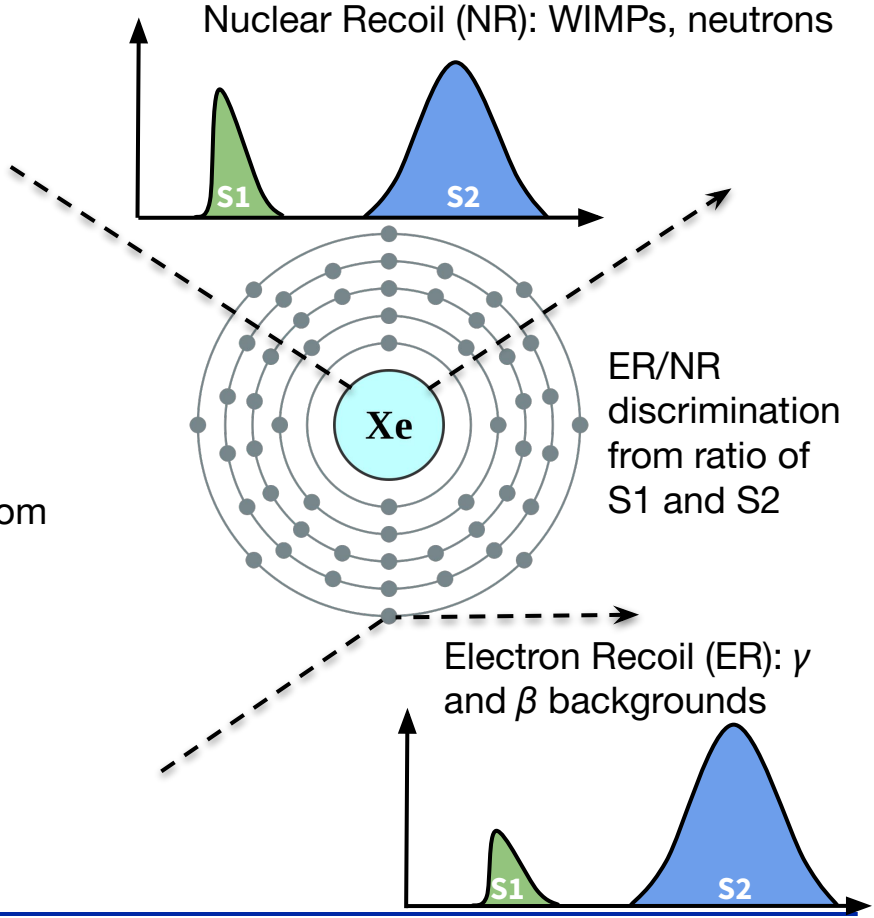
Thanks to our sponsors and participating institutions!

Backup

- LZ is located at **SURF 1 mile underground**
  - SURF has an illustrious history in underground physics
  - Future home of DUNE
- Need to go deep to avoid suppress cosmic rays backgrounds

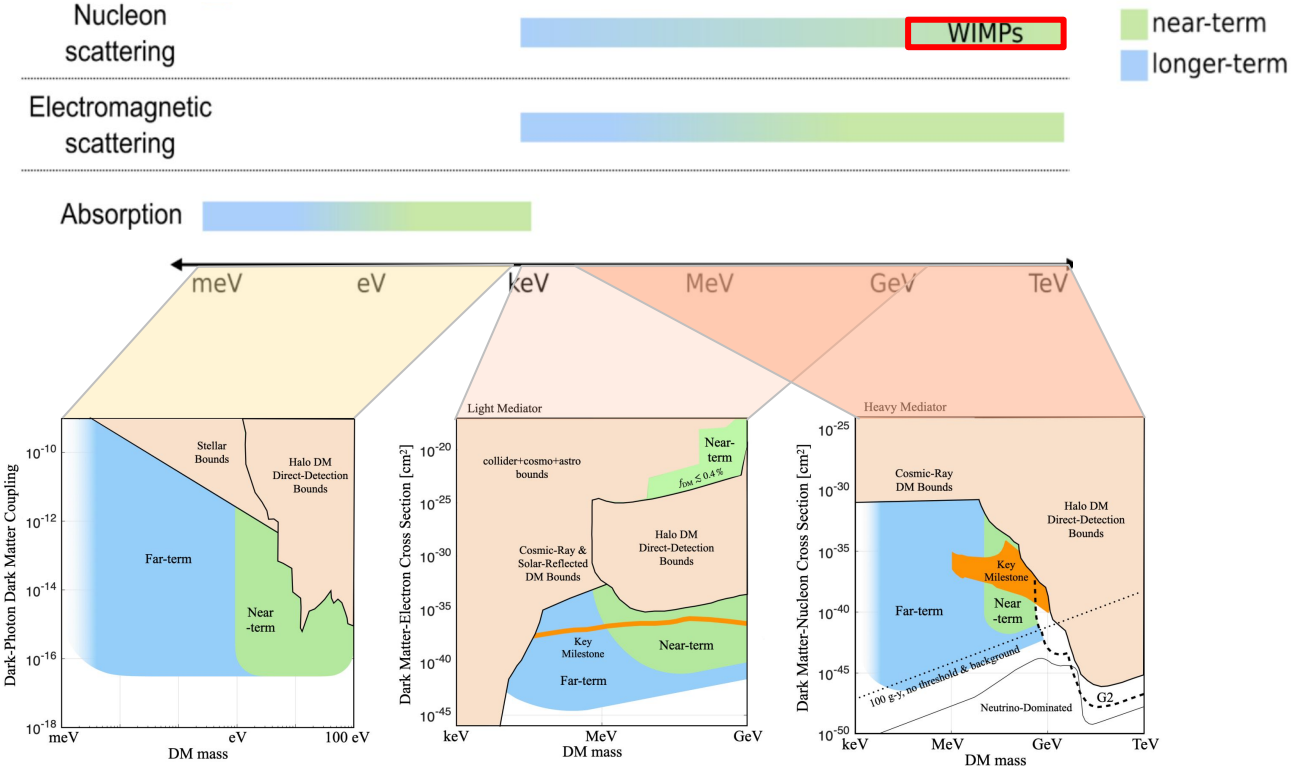


3D position reconstruction from Δt and PMT hits & self-shielding



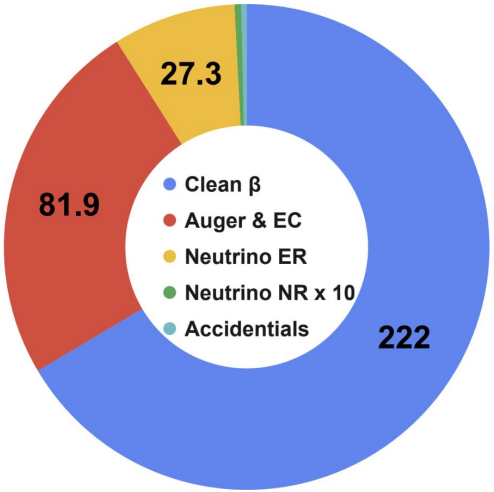
S1 Prompt scintillation light collected by PMTs

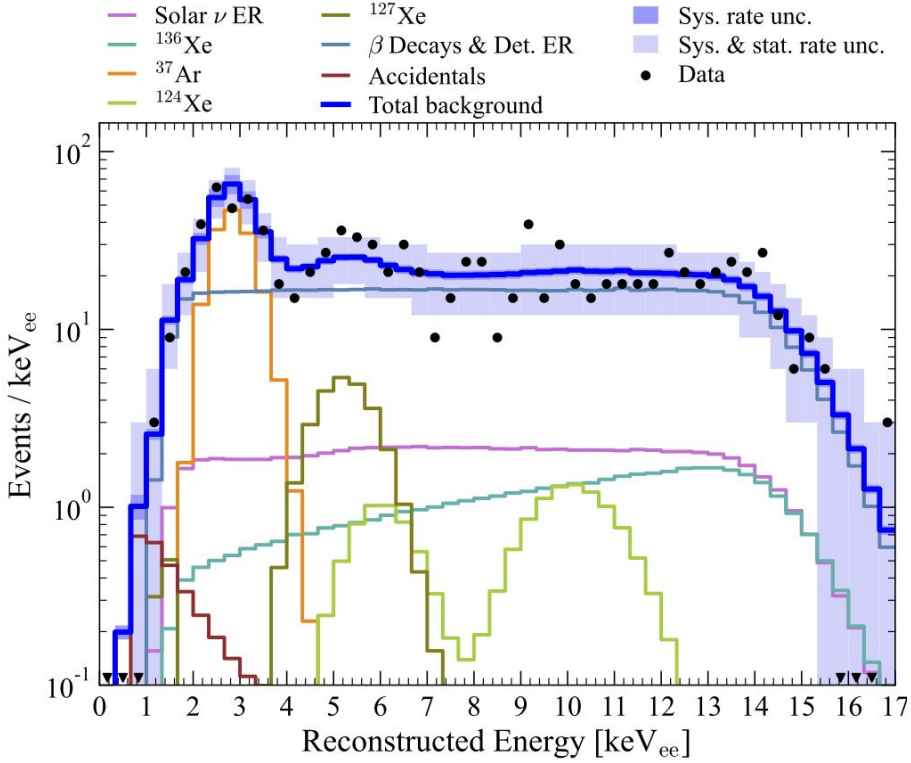
S2 Electroluminescence from liberated electrons extracted into gas layer by uniform electric fields



- Sub-Gev (low mass) DM barely explored
- DM masses in the **MeV regime** and cross sections approaching or below **10^{-40} cm^2** in reach

Results Fit



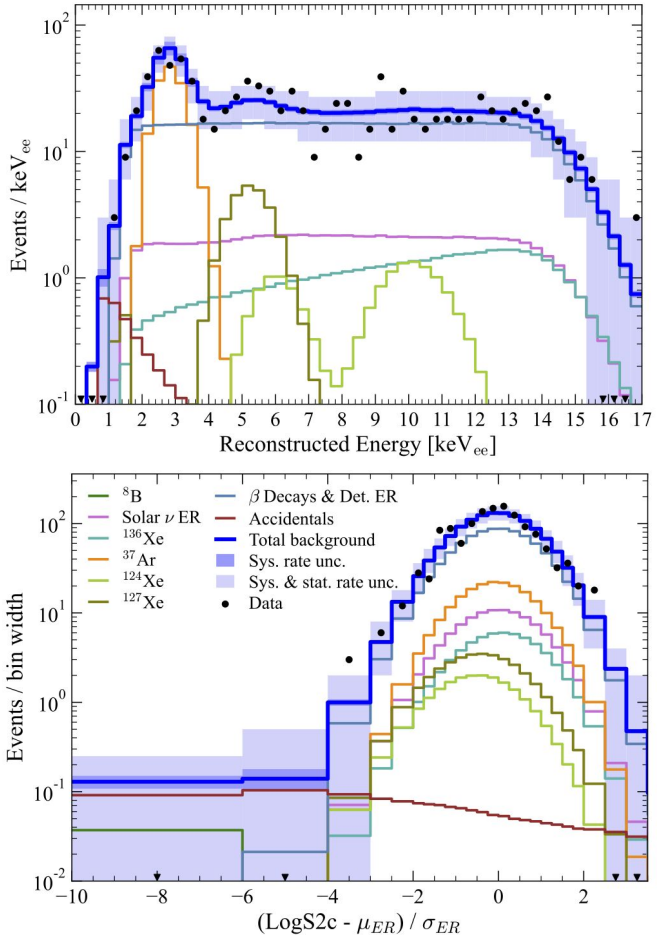


- Electron energy equiv. distribution, systematics are blue band
- Best fit with no WIMP signal

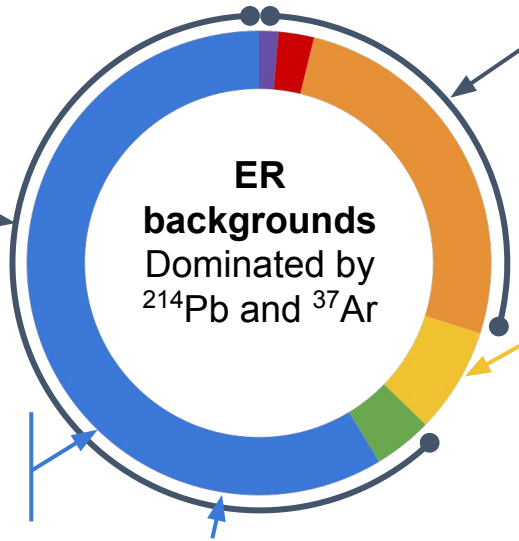
Results Fit

Source	Expected Events	Best Fit
β decays + Det. ER	218 ± 36	222 ± 16
ν ER	27.3 ± 1.6	27.3 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.2 ± 2.4	15.3 ± 2.4
^{8}B CEνNS	0.15 ± 0.01	0.15 ± 0.01
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Subtotal	276 ± 36	281 ± 16
^{37}Ar	[0, 291]	$52.1^{+9.6}_{-8.9}$
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	–	333 ± 17

Best fit with zero WIMP events for all masses



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

Dissolved e-captures (mono-energetic x-ray/Auger cascades):
- ^{37}Ar
- ^{127}Xe
- ^{124}Xe (double e-capture)

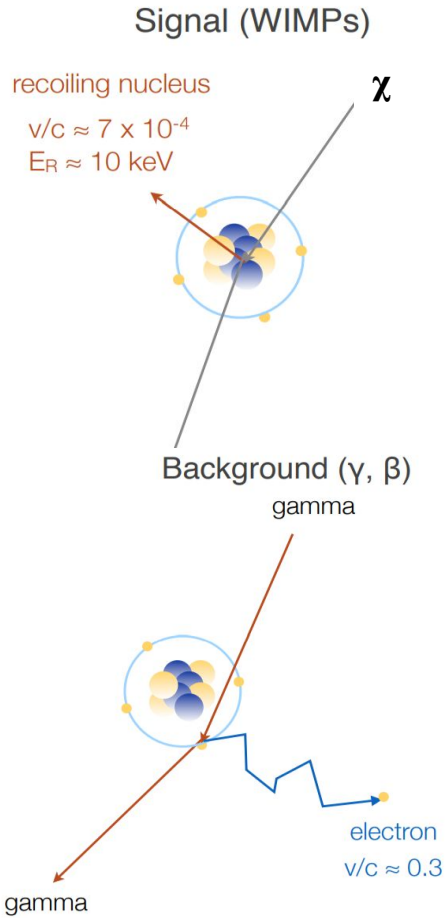
Solar neutrinos (ER)
- pp + ^{7}Be + ^{13}N

Includes γ-emitters in detector materials
- ^{238}U chain, ^{232}Th chain, ^{40}K, ^{60}Co

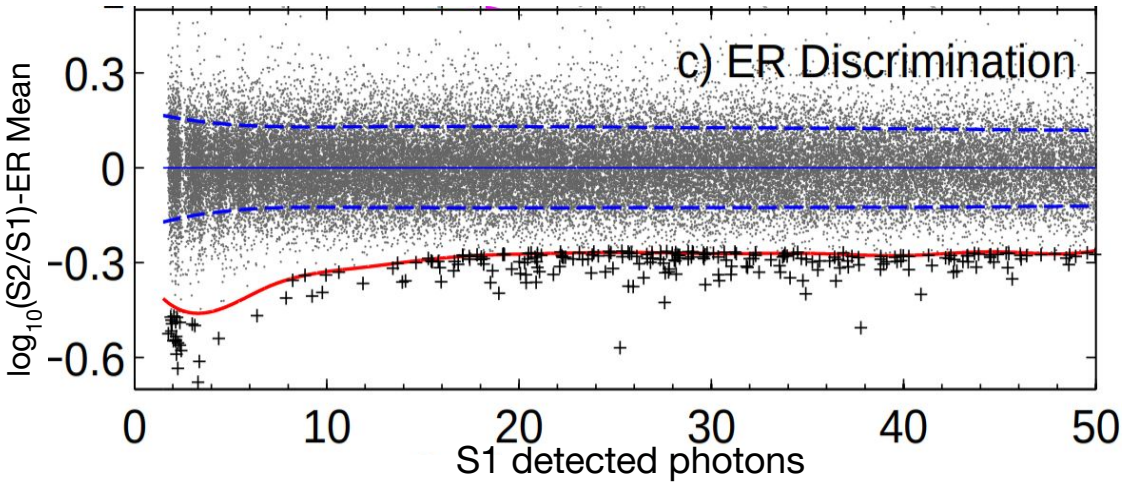
Flat-spectrum (in ROI) ERs

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

Accidental coincidence backgrounds



- Ionization/excitation (charge/light) depends on dE/dx
- Signal ratio allows to **discriminate particles**
  - **Electron** scatter tend to produce **more charge**
  - **Neutron** scatter create **more light**
- Excellent discrimination of signal and most backgrounds: **99.5%** discrimination before statistical methods



- Momentum transfer crucial
- Low mass difficult
- **LXe dual-phase TPCs** demonstrated best sensitivity for WIMP type DM