Status of the LUX-ZEPLIN (LZ) dark matter experiment

Aiham K. Al Musalhi
(on behalf of the LZ collaboration)

ATHEXIS, June 2024

Illustration by Sandbox Studio, Chicago with Ana Kova

The LZ collaboration

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

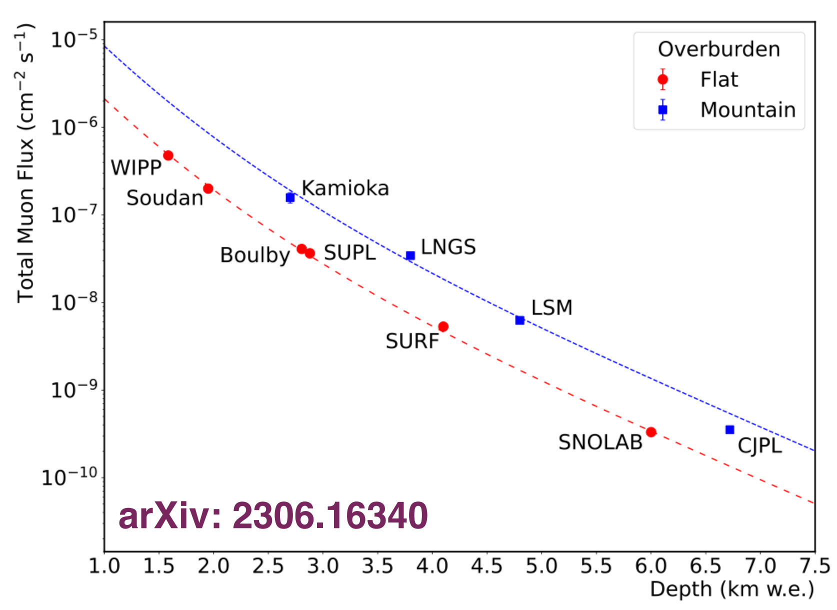
@lzdarkmatter

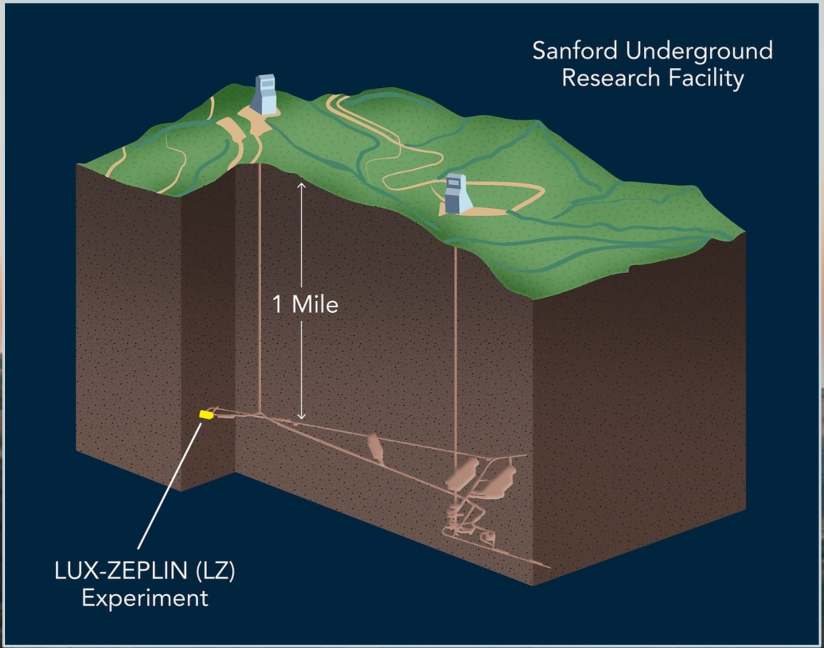
38 institutions, with over **250** scientists, engineers, and technical staff

LZ collaboration meeting at SURF, June 2023

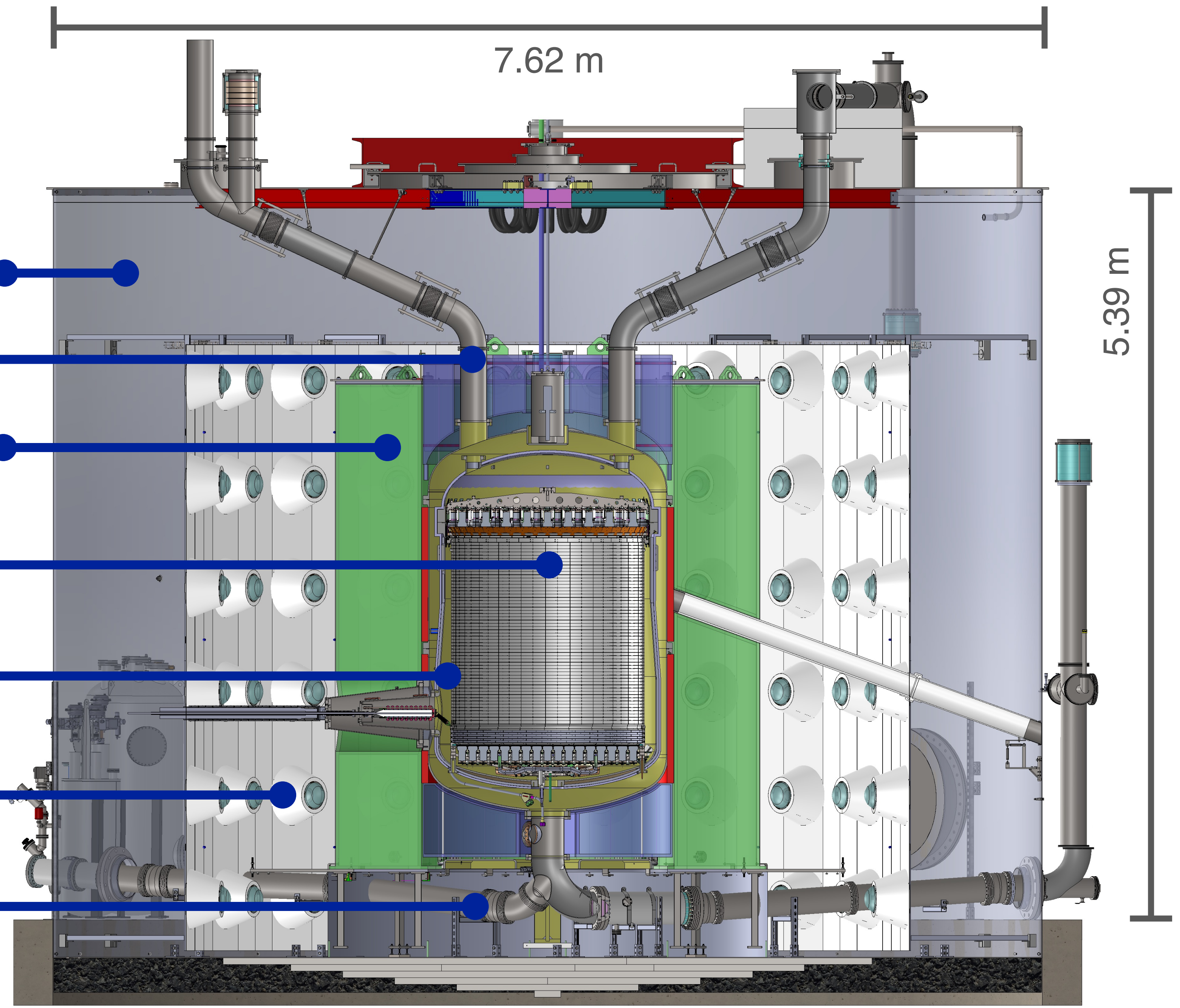
The LZ experiment

- Situated in Davis Cavern, **1480 m underground** in Lead, South Dakota
- 1100 m (4300 m.w.e) rock overburden
  ⇒ muon flux attenuated by a factor of **3×10^6**





The LZ detector



J. NIM A953, 163047 (2019)

The time projection chamber (TPC)

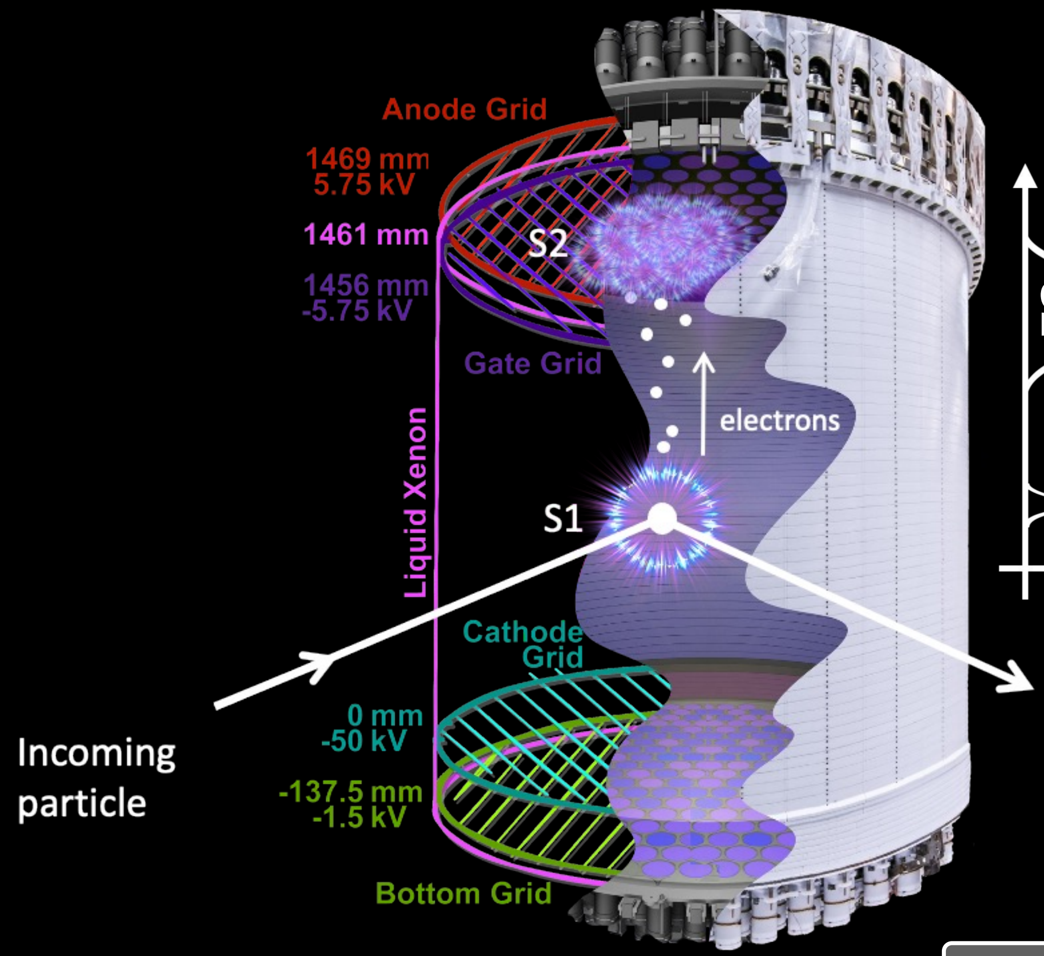
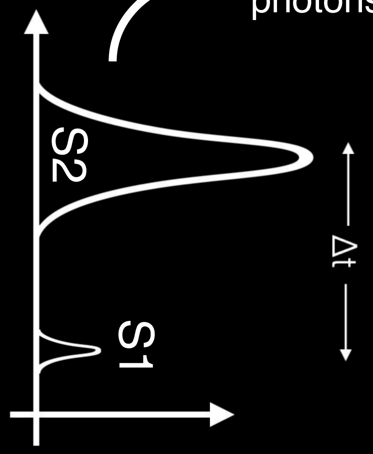
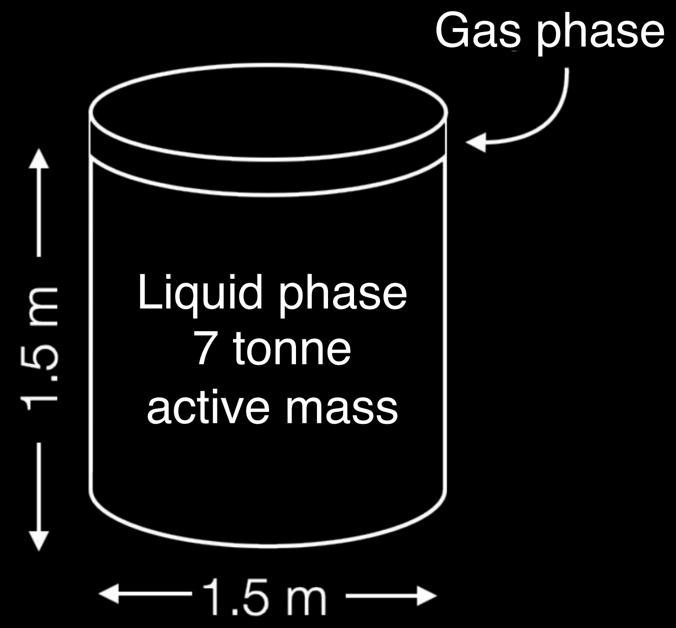


Figure courtesy of Nicolas Angelides (Imperial College London)

S1 & S2 sizes measured in "photons detected" (phd)





Scatter in liquid xenon

S1: prompt scintillation signal

S2: secondary electroluminescence signal

Light detected by photomultiplier tube (**PMT**) arrays

The time projection chamber (TPC)

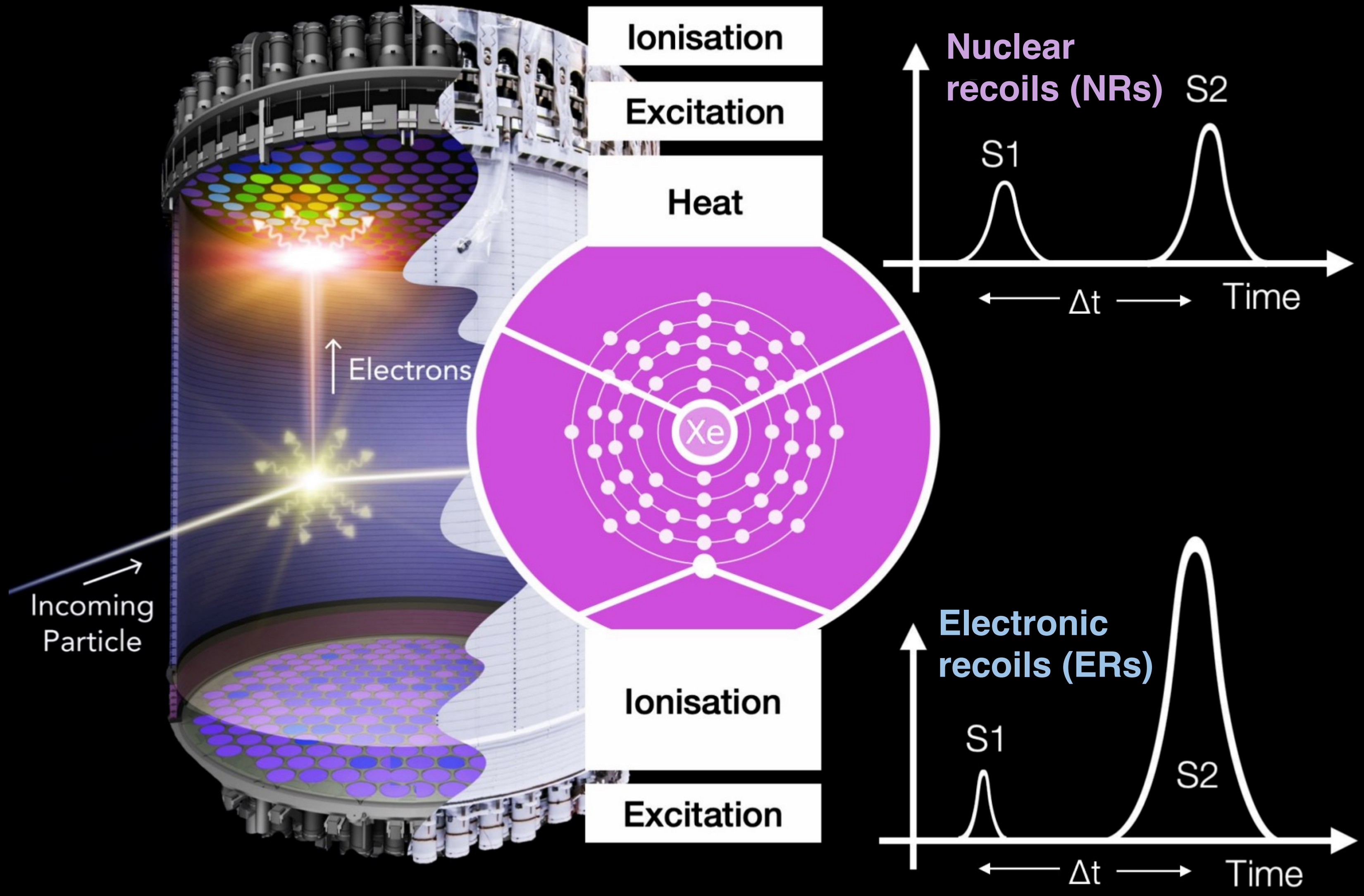


Figure courtesy of Nicolas Angelides (Imperial College London)

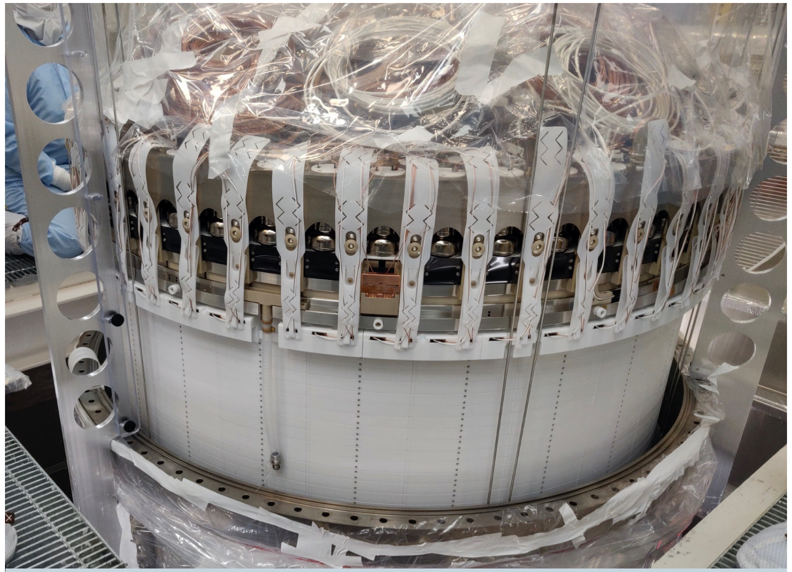
Discrimination between signal-like NRs and background-like ERs via ratio of observables (S1, S2)

Position reconstruction from top-array hit map (x, y) and drift time (z)

Veto detector subsystems

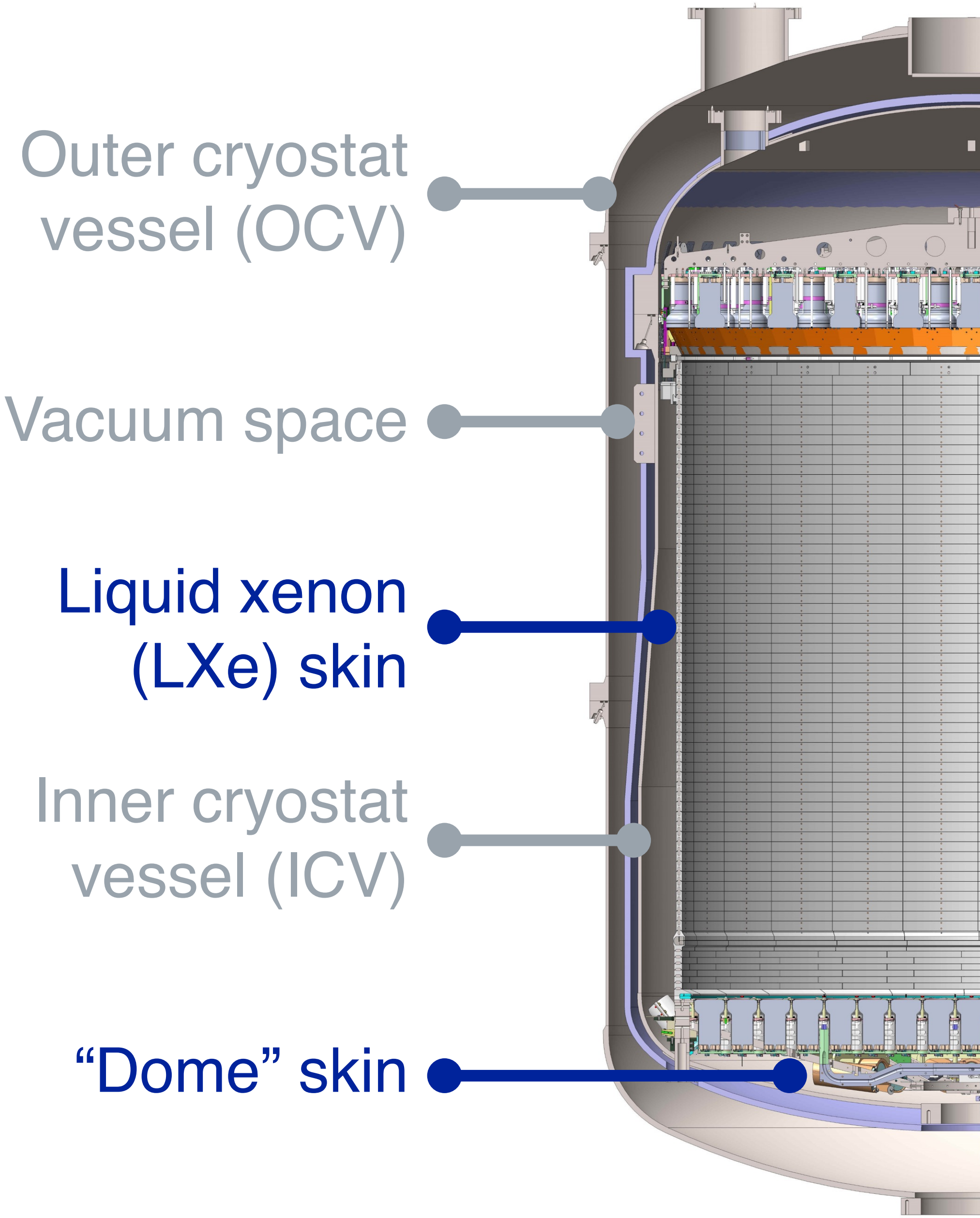
Instrumented LXe skin

- Positioned between TPC and ICV
- Contains approximately **2 tonnes** of xenon
- Mainly tags **γ-ray energy deposits**



Insertion of TPC into ICV

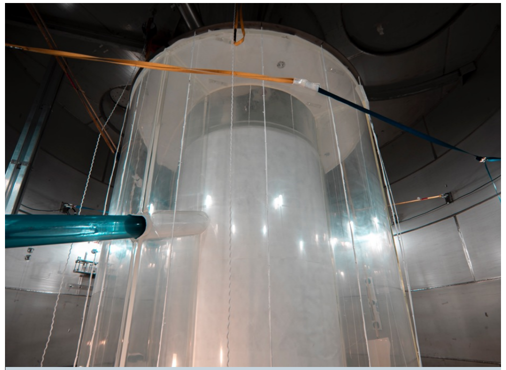
Installation of top skin PMTs

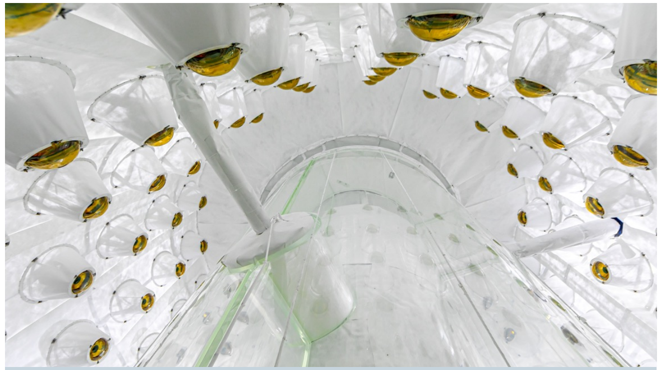


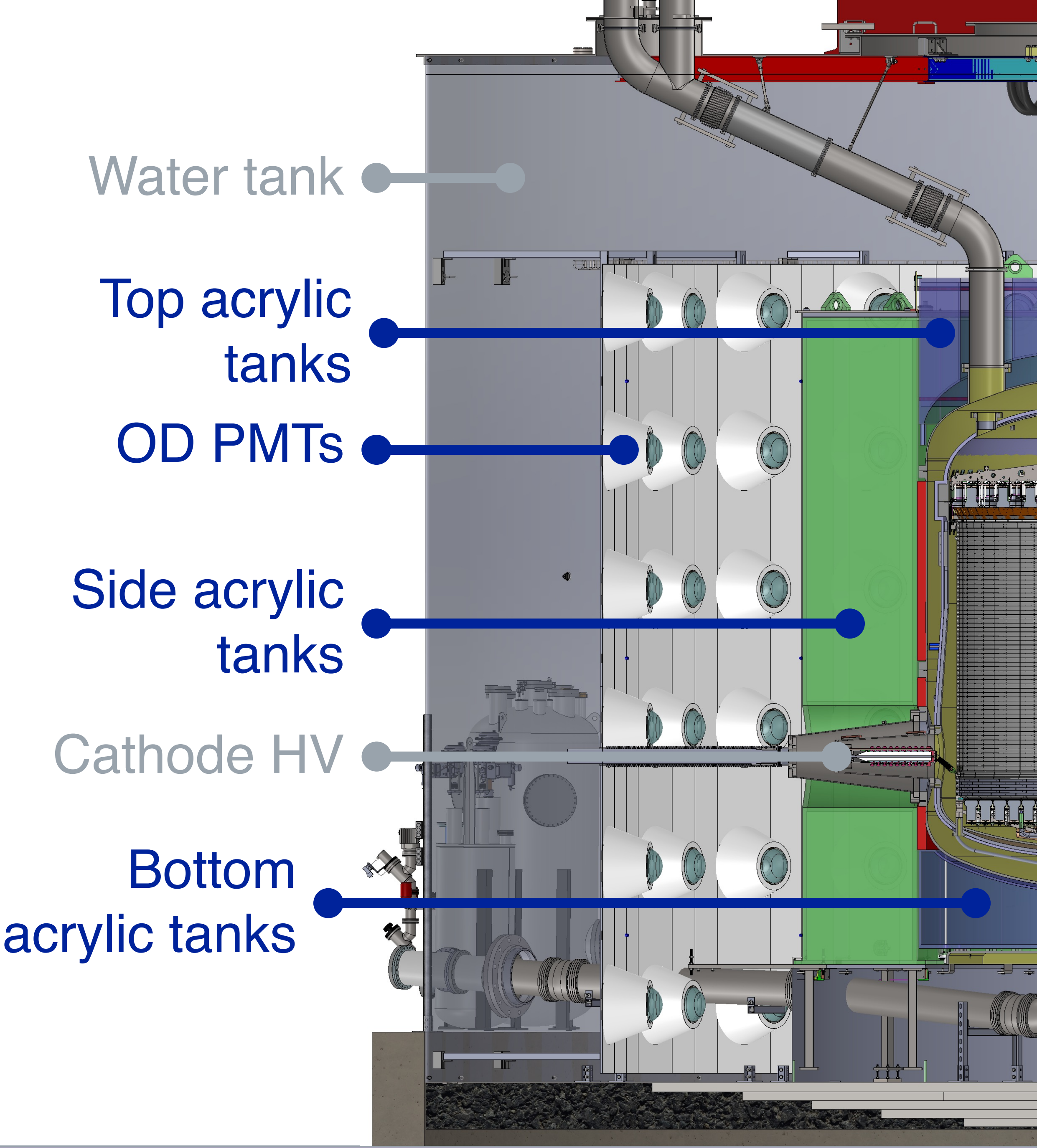
Veto detector subsystems

Outer detector (OD)

- Acrylic tanks containing 17.3 tonnes of Gd-doped liquid scintillator (**GdLS**)
- Primarily tags γ-ray cascades from **neutrons** capturing on Gd (or H)
- All **shielded** within water tank containing 238 tonnes of ultra-pure water


OD installation


Assembled OD

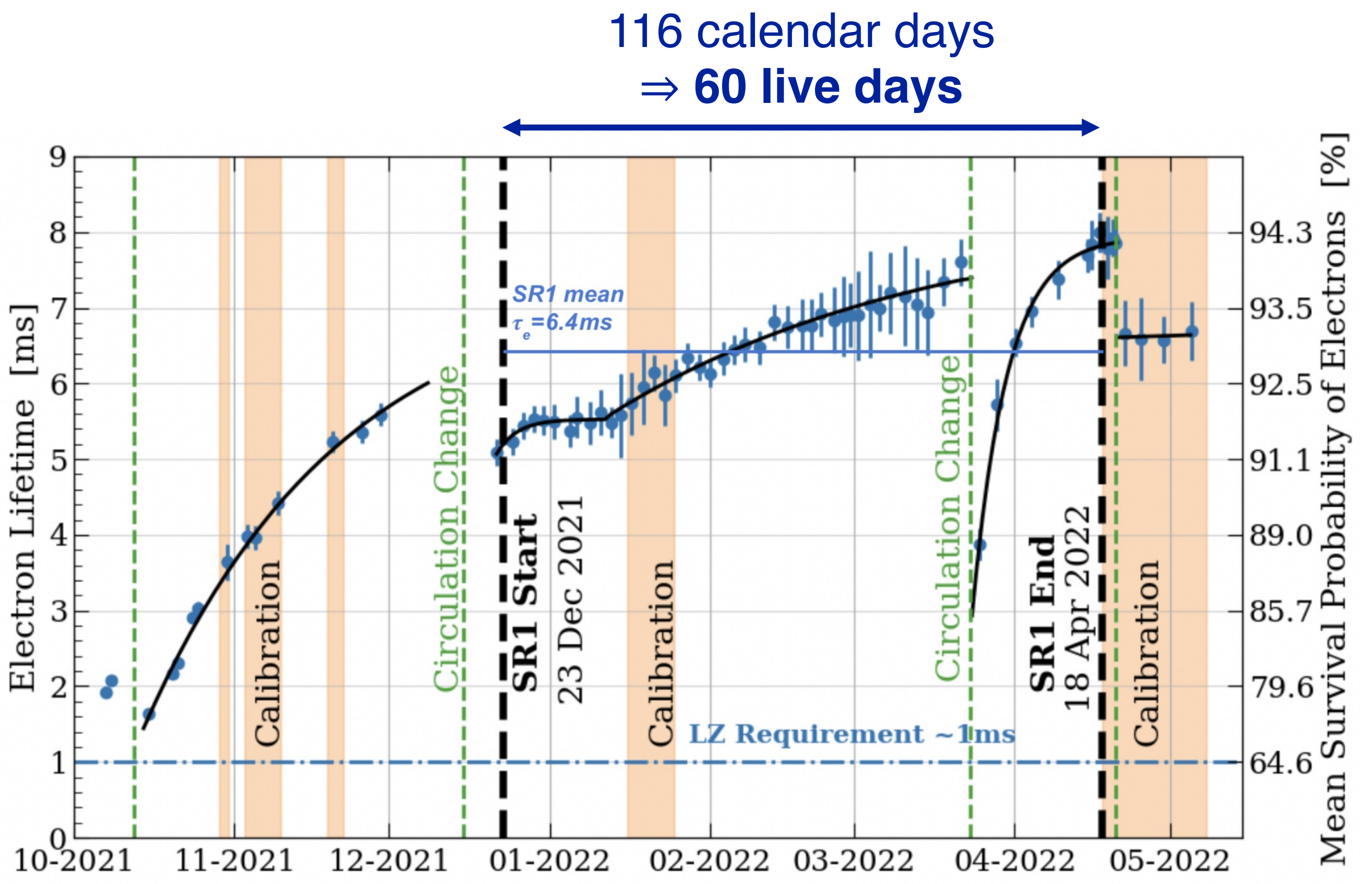


Science Run 1 (SR1)

An unblinded "engineering" run

Stable detector conditions:

- Temperature: 174.1 K
- Gas pressure: 1.791 bar
- Drift field: 193 kV/cm
- Extraction field (gas): 7.3 kV/cm

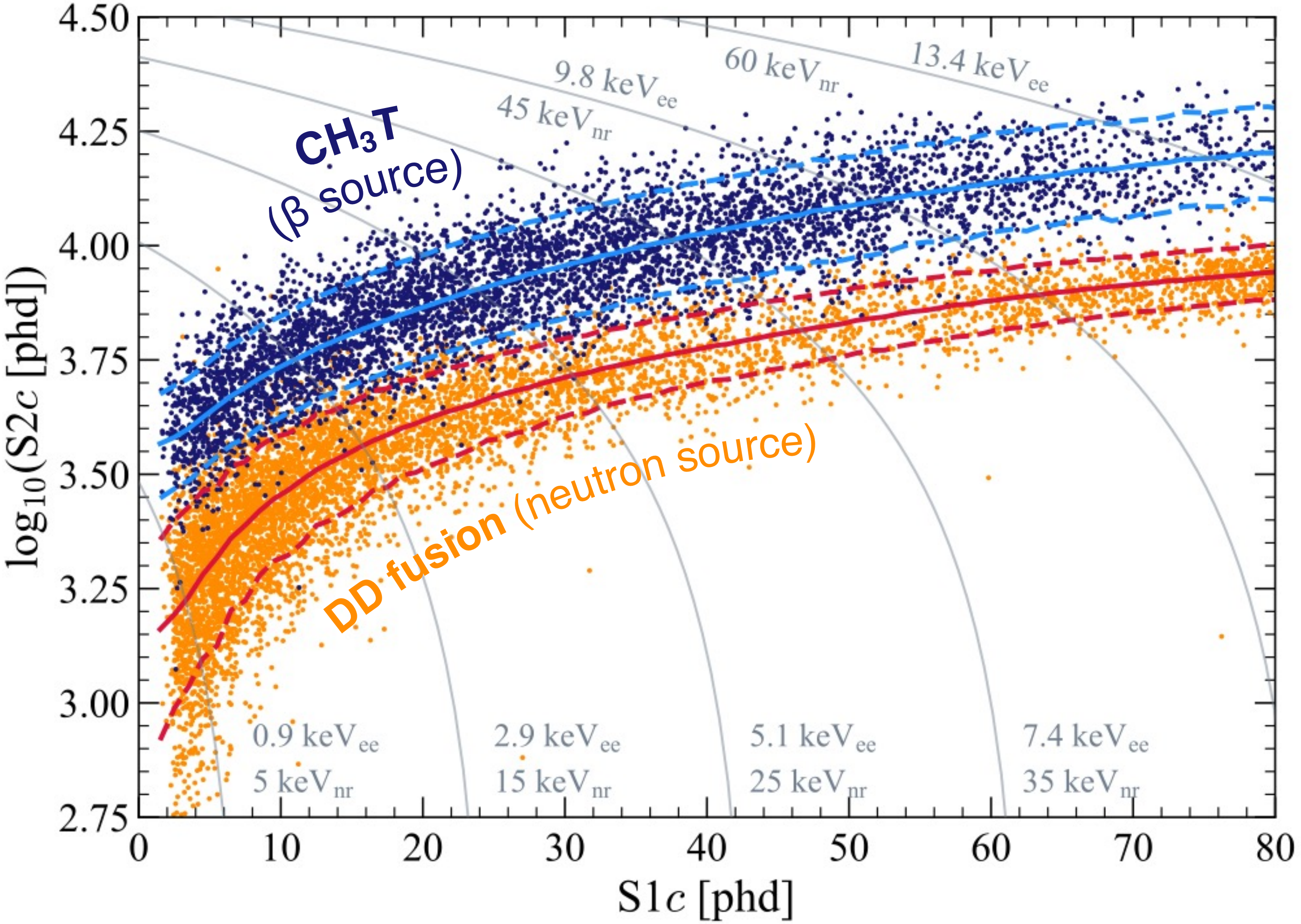


Continuous online purification:

- 3.3 tonnes/day through hot zirconium getter
- Electron lifetime > 5 ms throughout ⇒ **very high detector purity**

Phys. Rev. Lett. 131, 041002 (2023)

TPC calibrations



- Band fits performed using NEST v2.3.7
- **Photon detection efficiency:** $g_1 = (0.114 \pm 0.002)$ phd/photon
- **Effective charge gain:** $g_2 = (47.1 \pm 1.1)$ phd/electron
- **99.9% ER background discrimination** below NR band median

Phys. Rev. Lett. 131, 041002 (2023)

Event selection & data quality

*unblinded analysis, but cuts were developed with calibration data and sideband selections

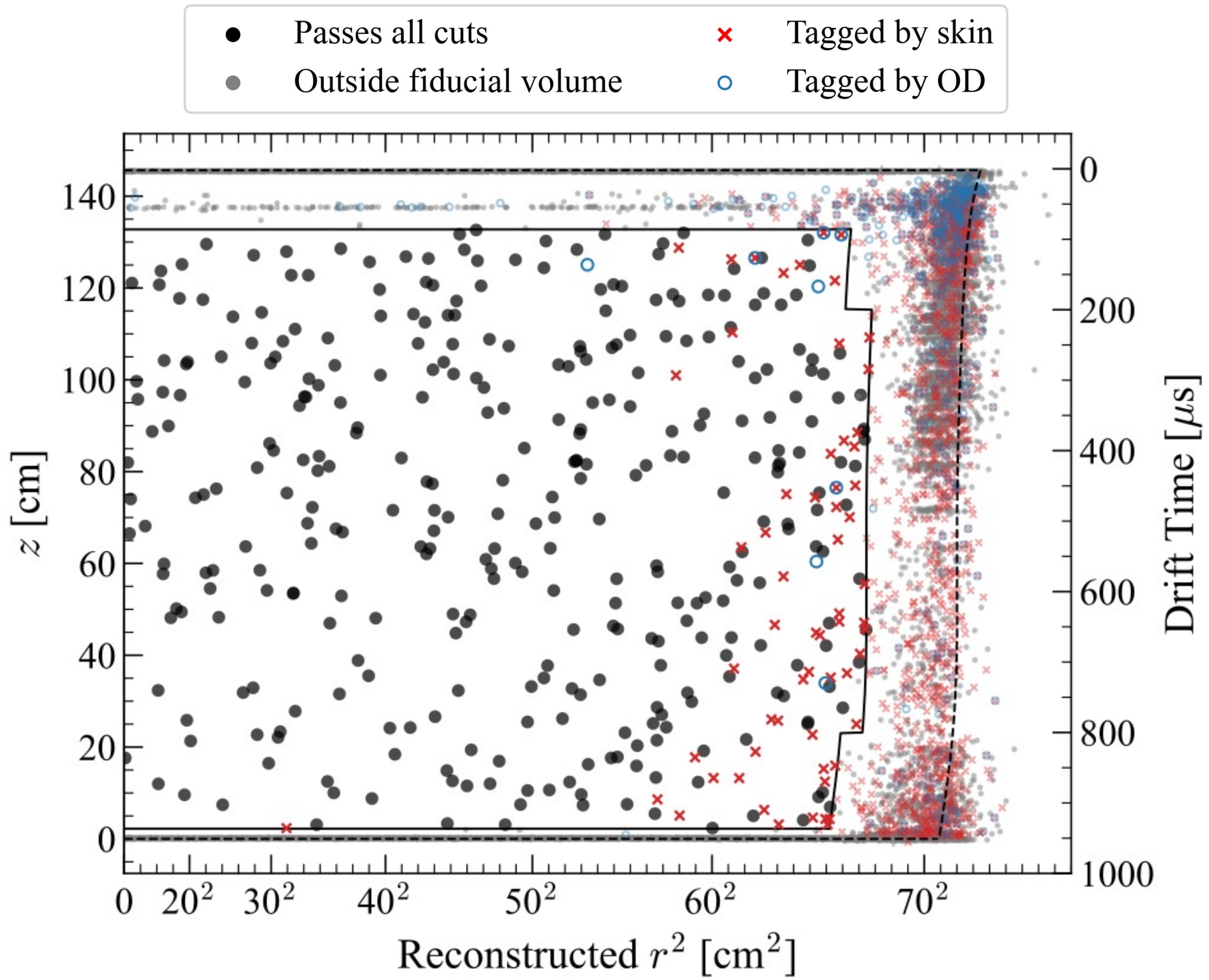
Time exclusion cuts (periods of elevated activity, maintenance, etc.)

Single-scatter (SS) & region of interest (ROI) selections

Data quality cuts (e.g. based on S1 and S2 pulse shapes)

Anti-coincidence veto cuts (i.e. tags from skin and OD)

Fiducial volume cut (removal of wall backgrounds & poor reconstruction)



Phys. Rev. Lett. 131, 041002 (2023)

Background model

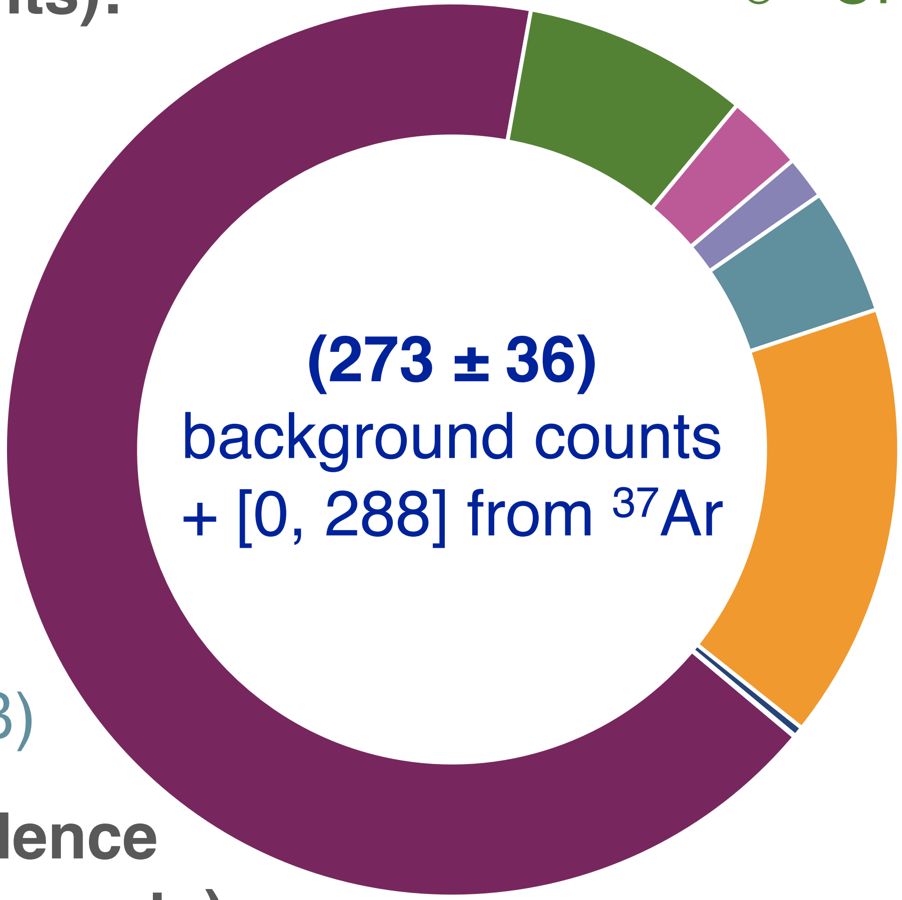
Solar ν:
- *pp*
- ^{7}Be
- CNO

In-depth description of SR1 backgrounds in a complementary paper

Phys. Rev. D 108, 012010 (2023)

Detector material γ rays (< 2 counts):
- ^{40}K
- ^{60}Co
- ^{232}Th
- ^{238}U

β decays:
- ^{214}Pb
- ^{212}Pb
- ^{85}Kr
- ^{136}Xe ($2\nu\beta\beta$)

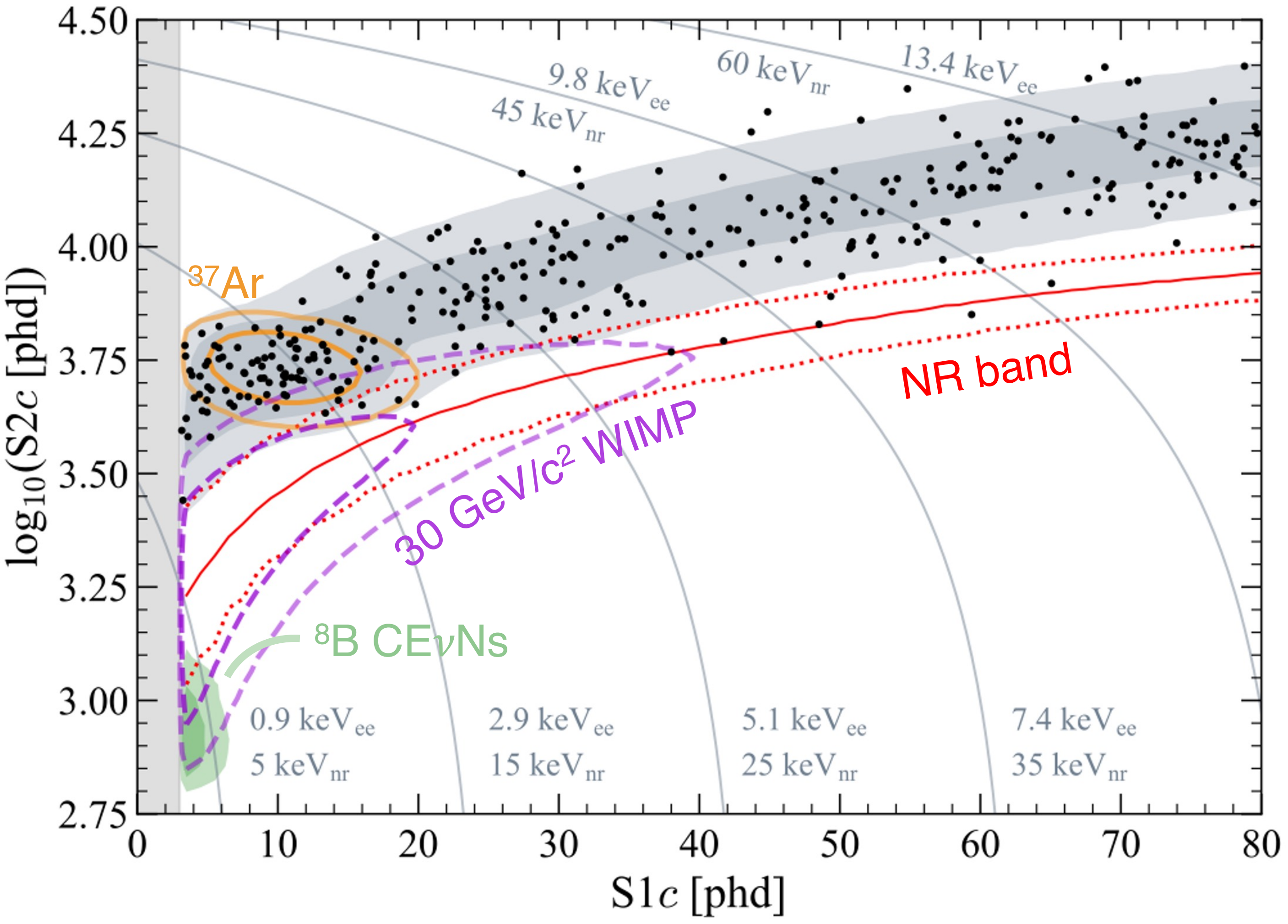


Electron captures:
- ^{37}Ar
- ^{127}Xe
- ^{124}Xe (double)

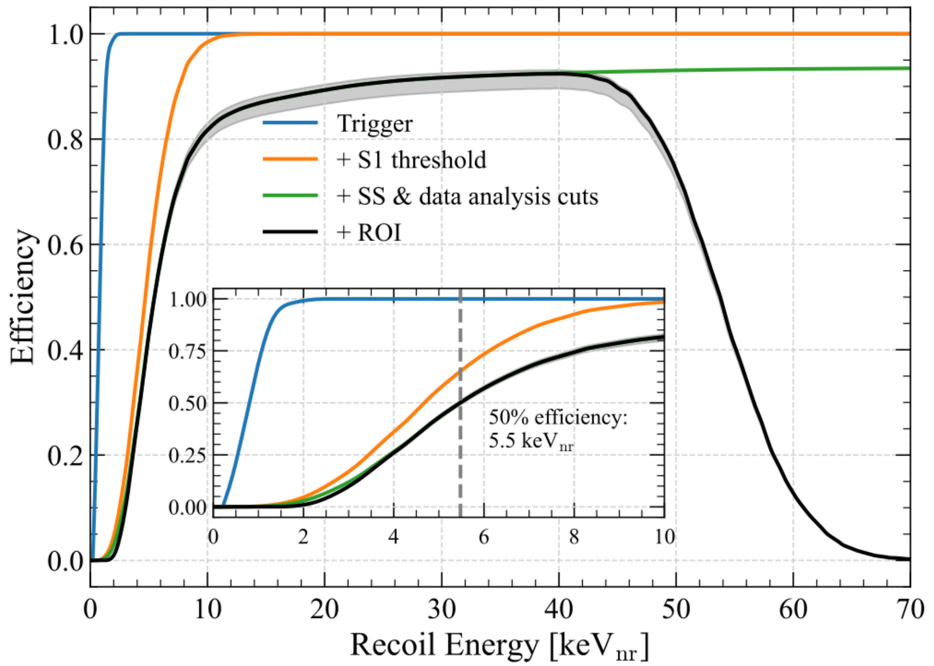
NR backgrounds (0.14 counts):
- ^{8}B CEνNs
- Detector materials; (α, n), spontaneous fission

Accidental coincidence backgrounds (1.2 counts)

First WIMP search results



- **335 events** after all cuts
- **(60.3 ± 1.2) live day** exposure
- **(5.5 ± 0.2) tonne** fiducial mass

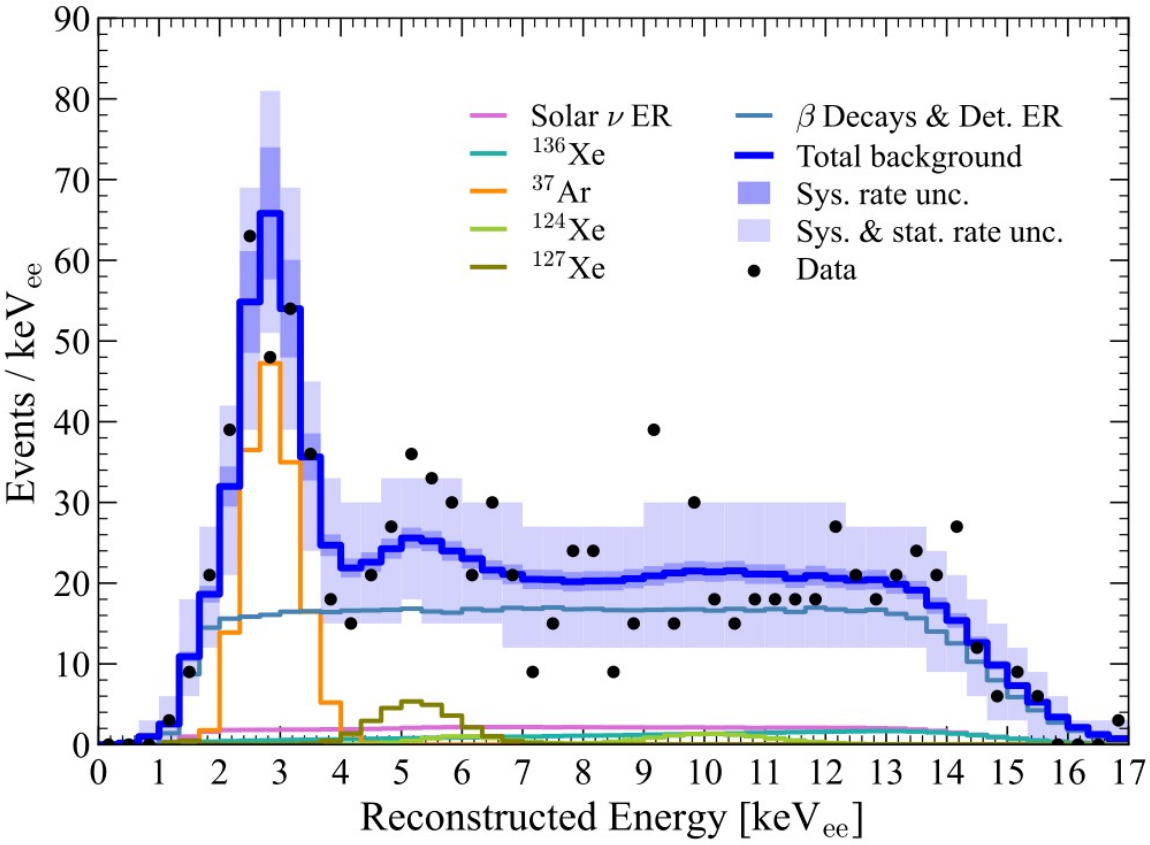


Phys. Rev. Lett. 131, 041002 (2023)

First WIMP search results

- Profile likelihood ratio (PLR) fit in $\log_{10}$(S2c) vs. S1c space ⇒ **0 WIMPs** (so far…)

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

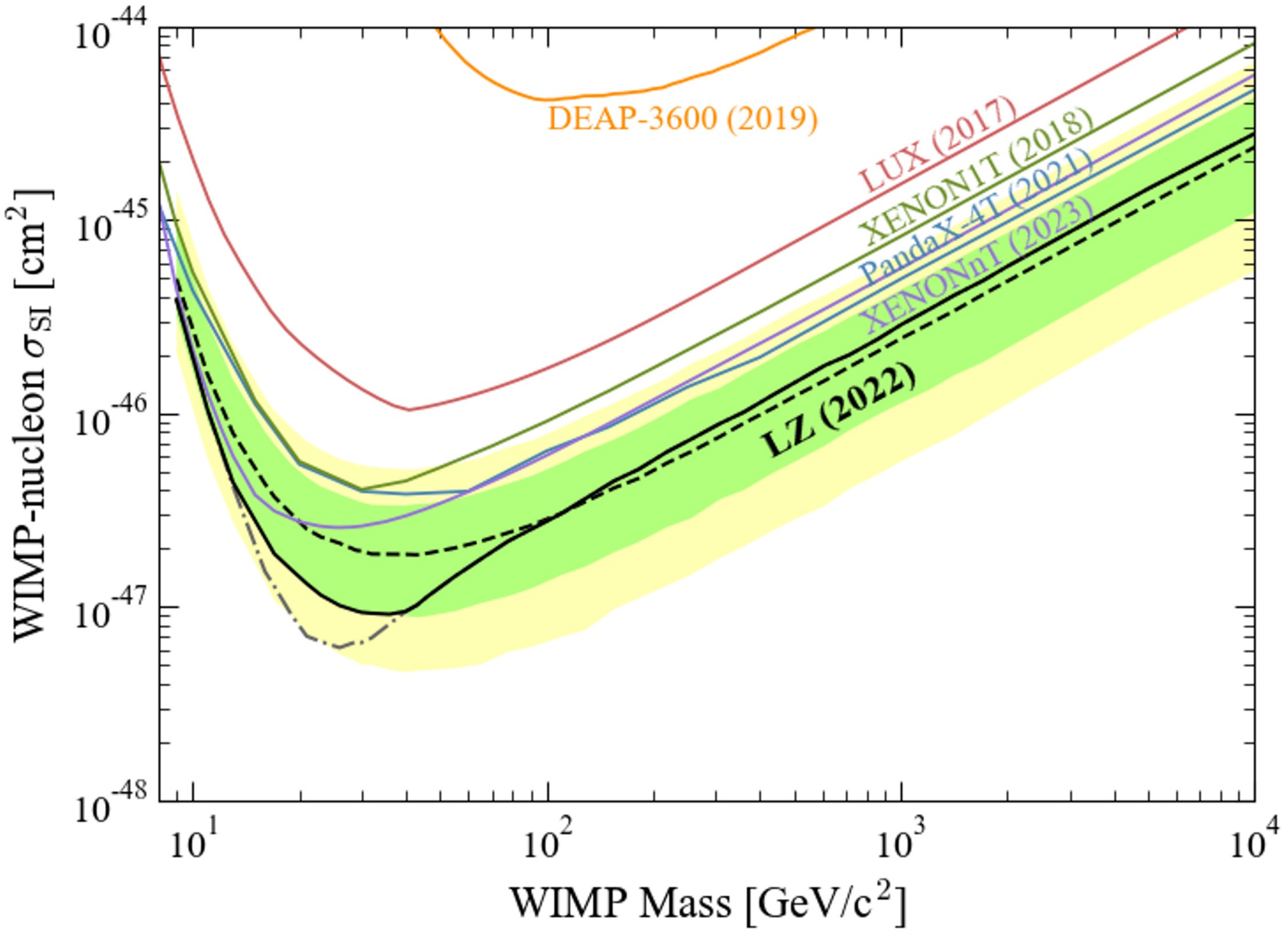


Phys. Rev. Lett. 131, 041002 (2023)

First WIMP search results

Spin-independent (SI) limits:

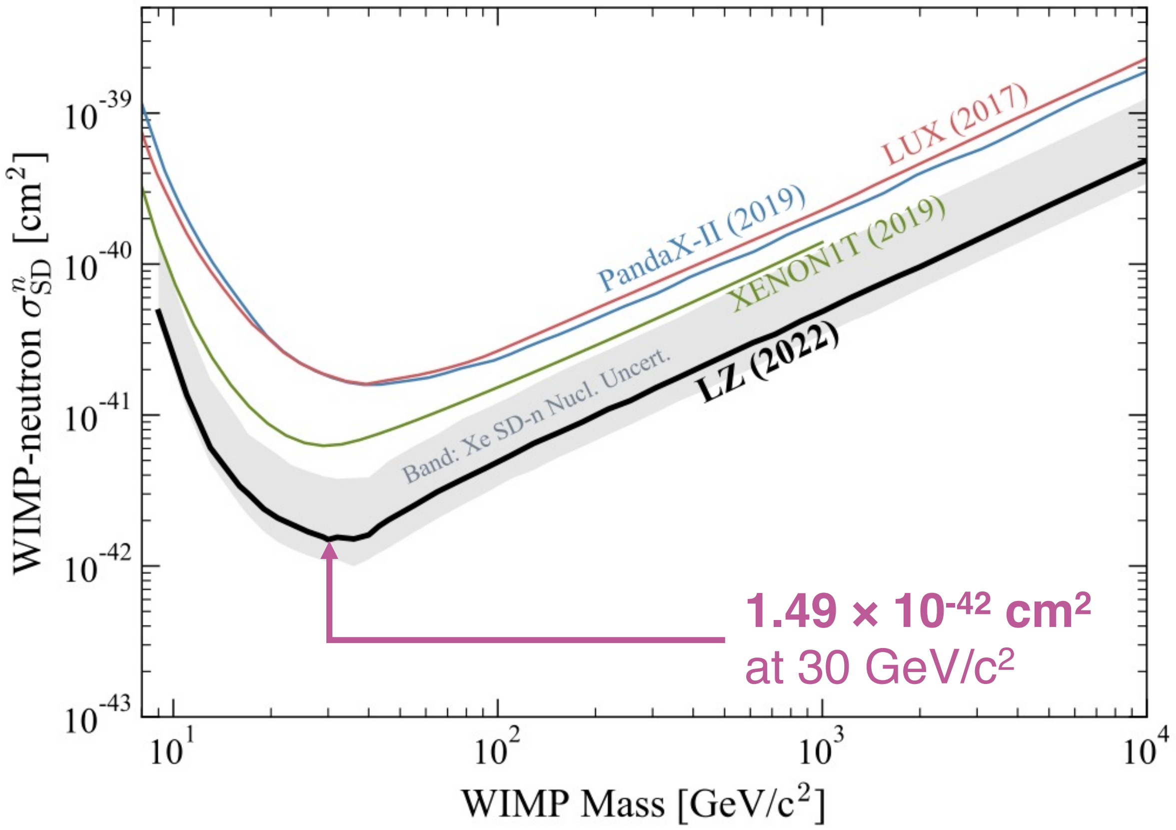
- Two-sided PLR test statistic, **power constrained** to -1σ
- **World-leading** exclusion limit for WIMP masses > 9 GeV/c^2
- Most stringent limit set at **9.2×10^{-48} cm²** for a 36 GeV/c^2 WIMP mass

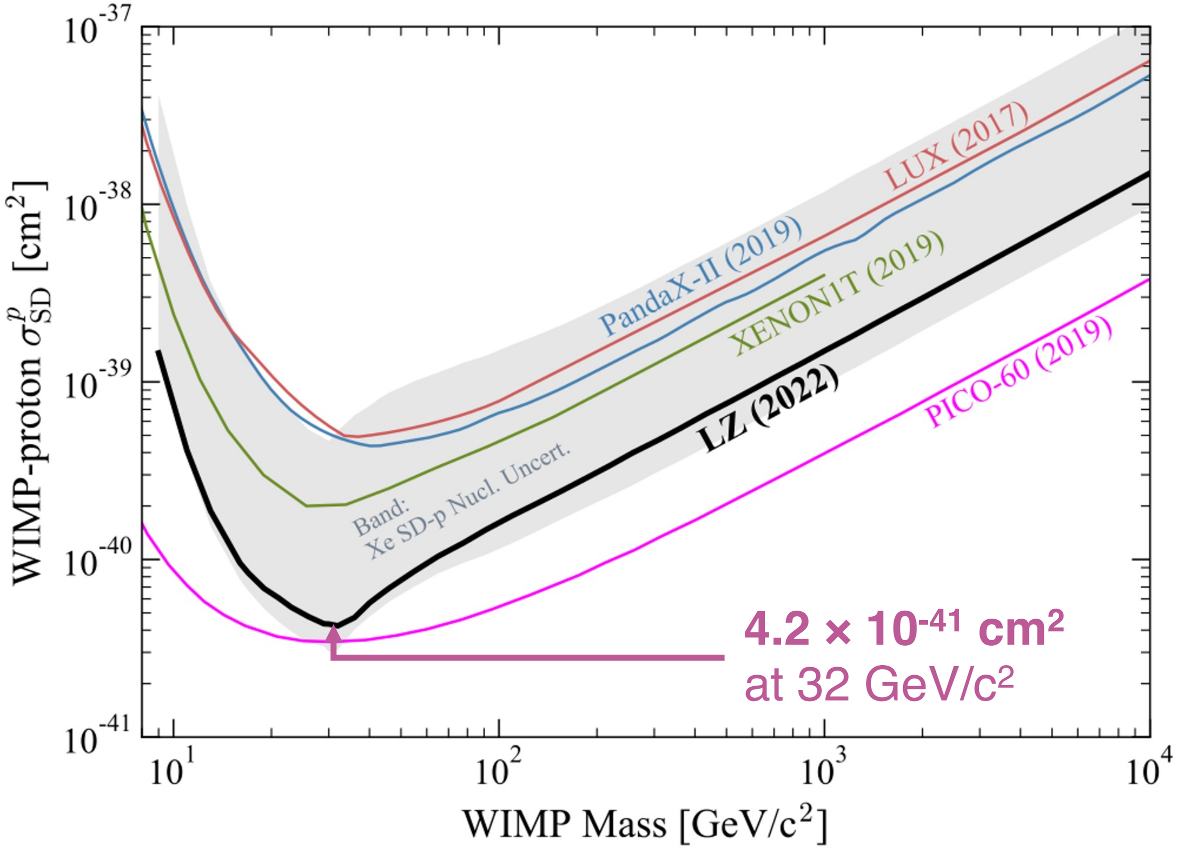


Phys. Rev. Lett. 131, 041002 (2023)

First WIMP search results

Spin-dependent (SD) limits, WIMP-neutron and WIMP-proton scattering





Phys. Rev. Lett. 131, 041002 (2023)

Current status

Longer **salted** run is **ongoing**; expect release of **new** WIMP search results by the end of **2024**!

Lots of science from **just SR1**:

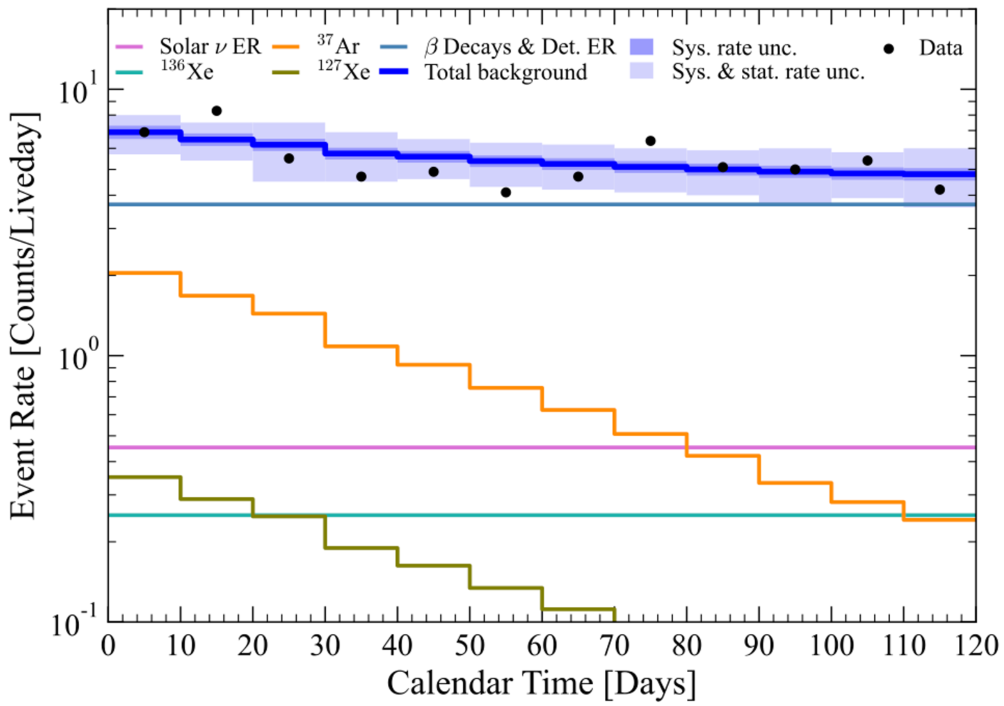
- Low-energy ER searches
- Ultraheavy dark matter searches
- Effective Field Theory (EFT) constraints
- WIMP-pion interactions

Ongoing and upcoming searches:

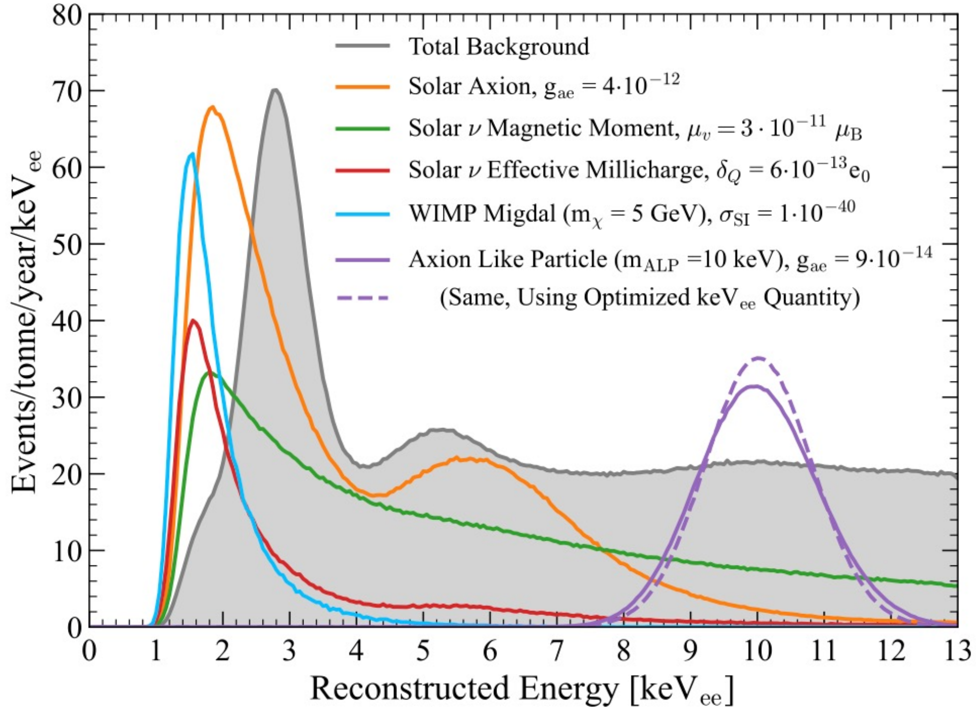
^{124}Xe $2\nu2$EC, ^{136}Xe $0\nu\beta\beta$, S2-only, DD Migdal, ^{8}B CEνNs, and more!

Low-energy ER searches

- **Employs a time-dependent PLR technique** to constrain ^{37}Ar and ^{127}Xe backgrounds



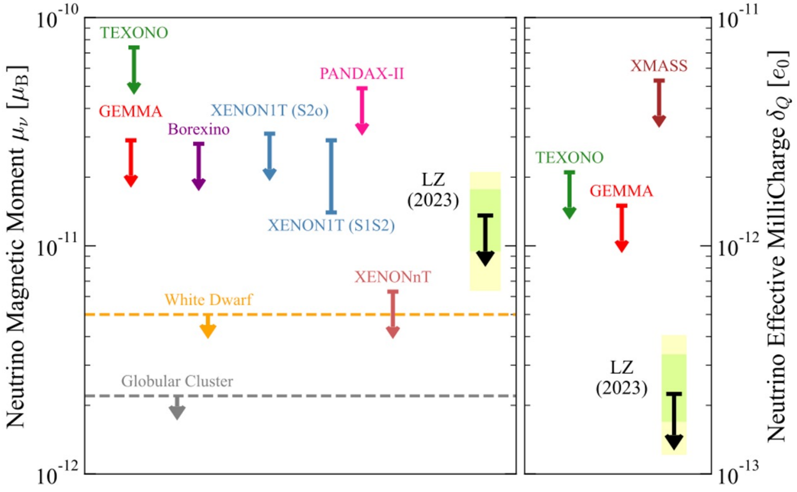
- **Probes for various new phenomena**
  - Solar axions
  - Solar ν magnetic moment and eff. millicharge
  - Axion-like particles (ALPs)
  - Hidden photons (HPs)
  - Low-mass WIMPs via Migdal effect



Phys. Rev. D 108, 072006 (2023)

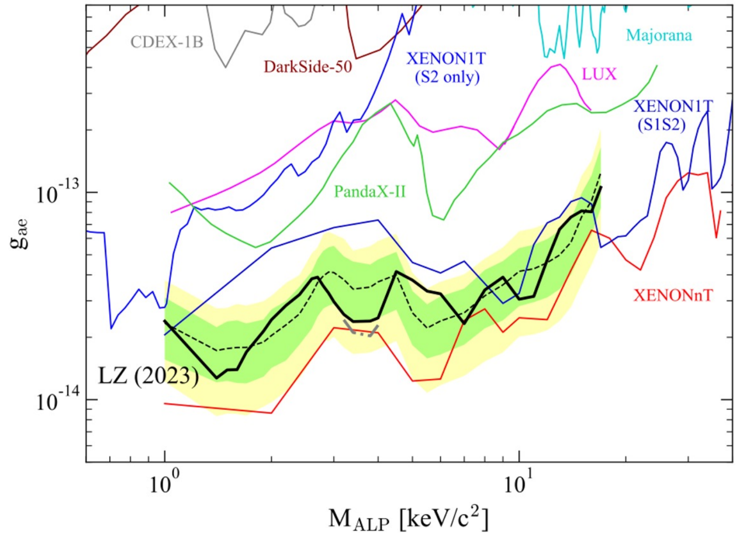
Low-energy ER searches

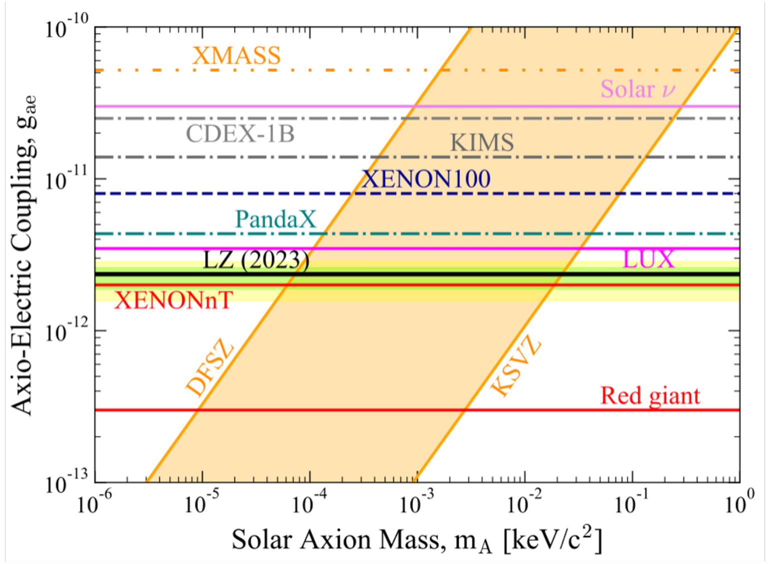
*XENONnT has a **lower ER background**, so there is room for improvement in future iterations



Exotic solar ν properties

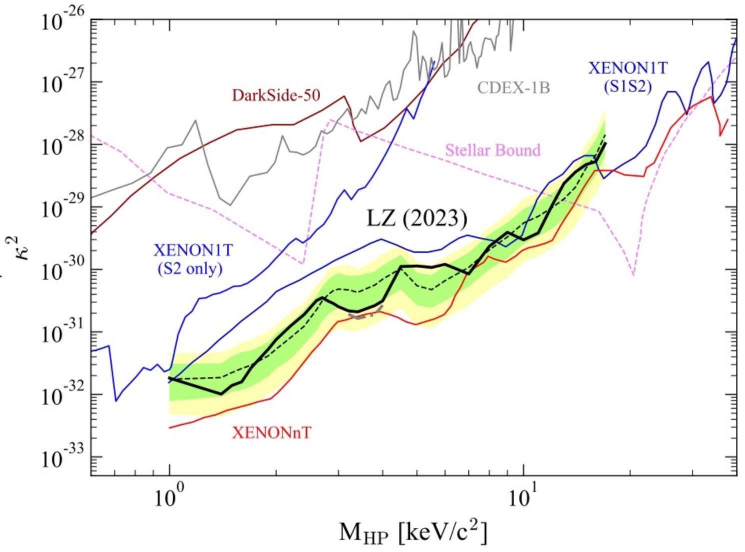
ALP constraints





Solar axion constraints

HP constraints



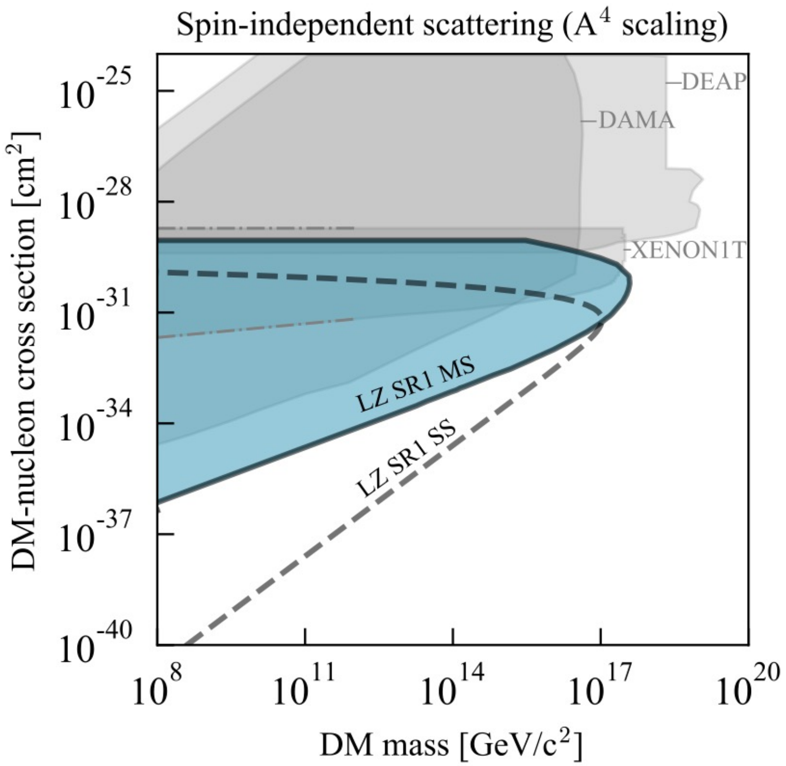
Phys. Rev. D 108, 072006 (2023)

Ultraheavy dark matter searches

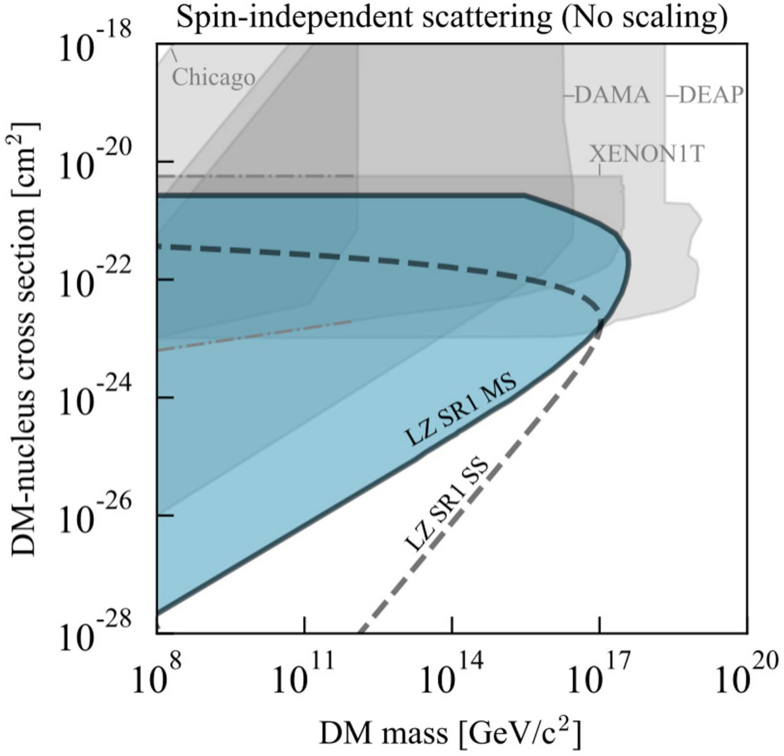
Multiply Interacting Massive Particles (MIMPs)

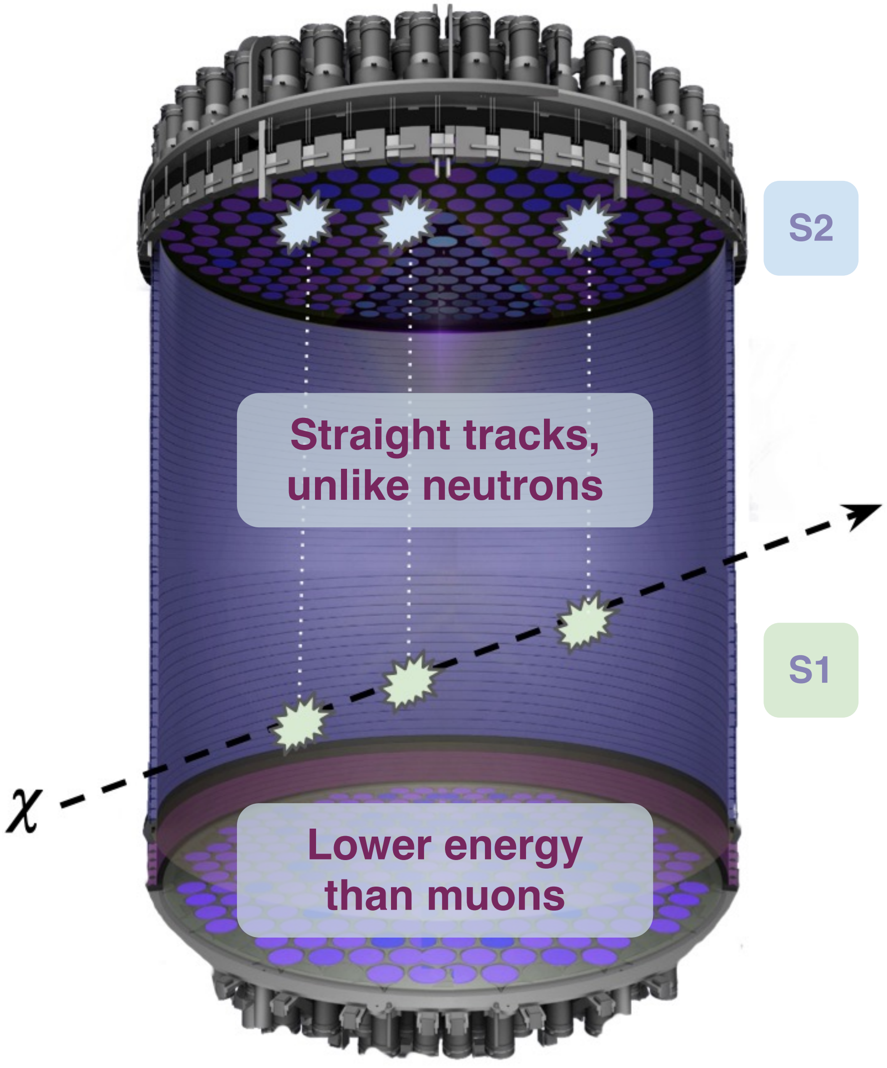
- Higher mass scale (> 10^4 GeV/c^2), unique pathology

(MIMP-**nucleon**)



(MIMP-**nucleus**)

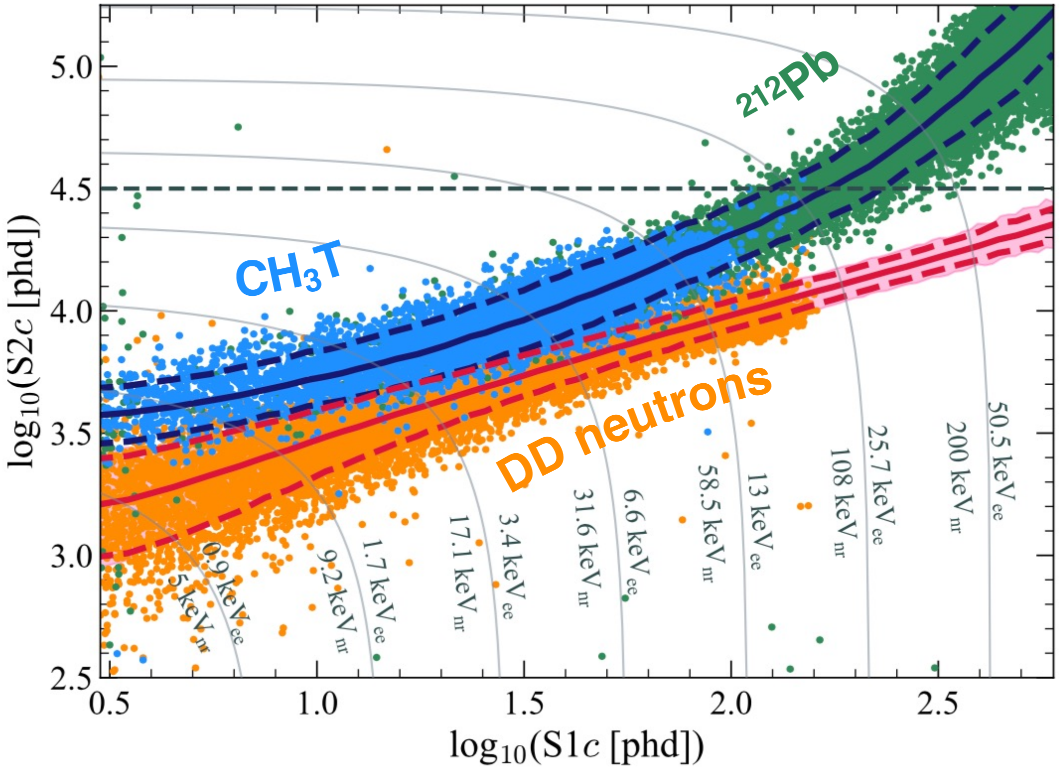


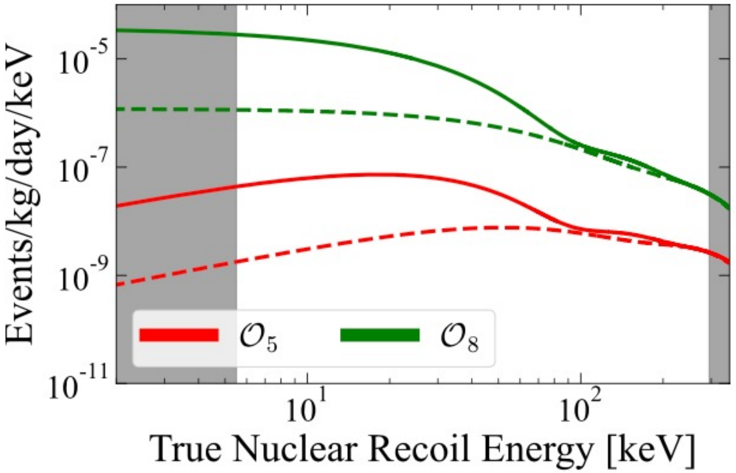


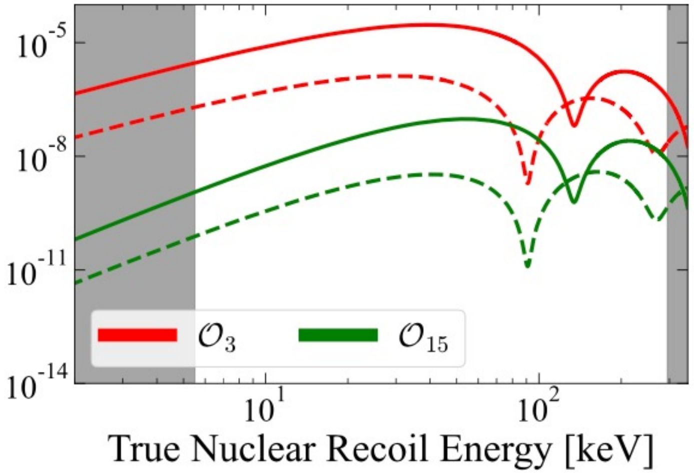
arXiv: 2402.08865

EFT constraints

- Standard SI and SD interactions assume **suppressed momentum dependence**
- **EFT** provides a more generalised (**model independent**) description
- Effective Lagrangian is expanded in terms of dimensionless operators







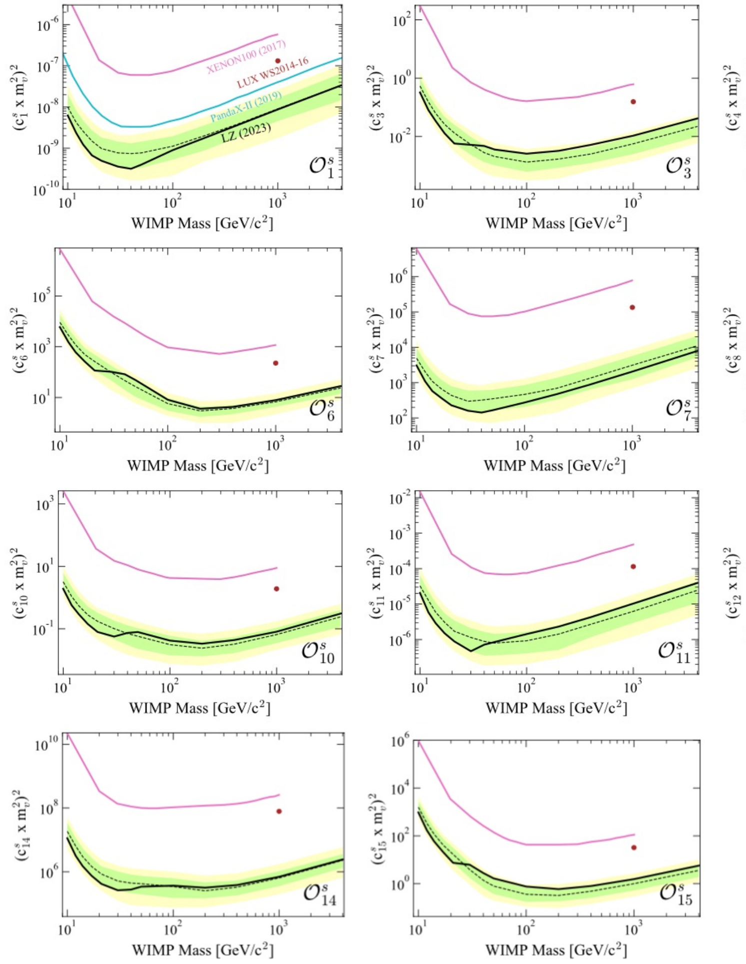
$$\mathcal{O}_1 = 1_\chi 1_N, \quad \mathcal{O}_2 = \left(v^\perp\right)^2, \quad \mathcal{O}_3 = i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right),$$
$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N, \quad \mathcal{O}_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right),$$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

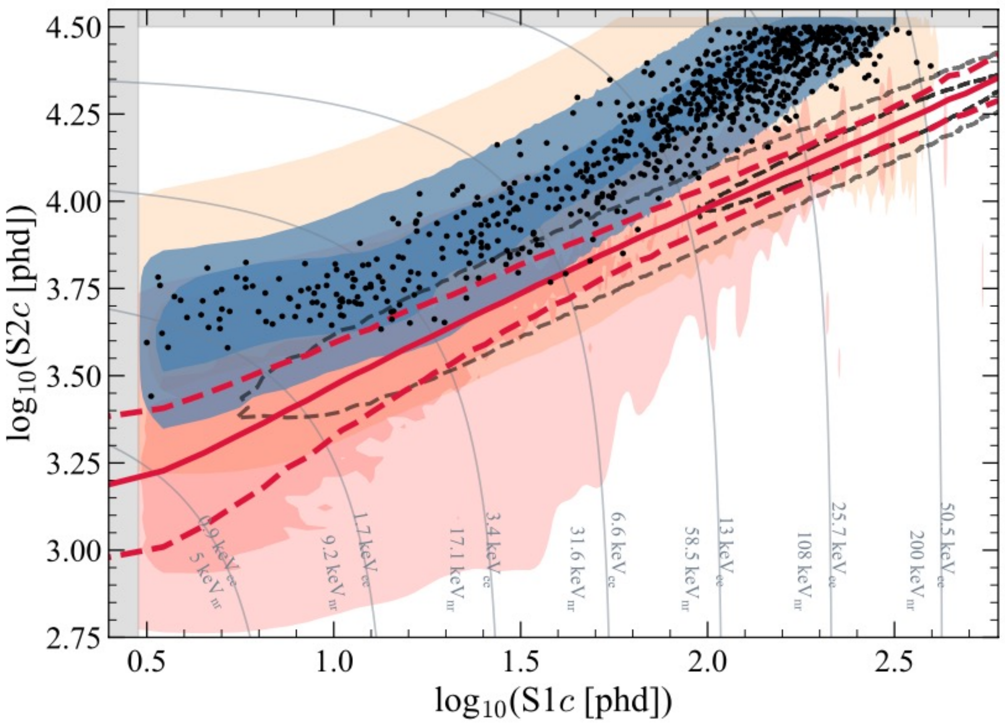
EFT constraints

***Two** SR1 EFT publications so far!

Phys. Rev. D 109, 092003 (2024)

arXiv: 2404.17666

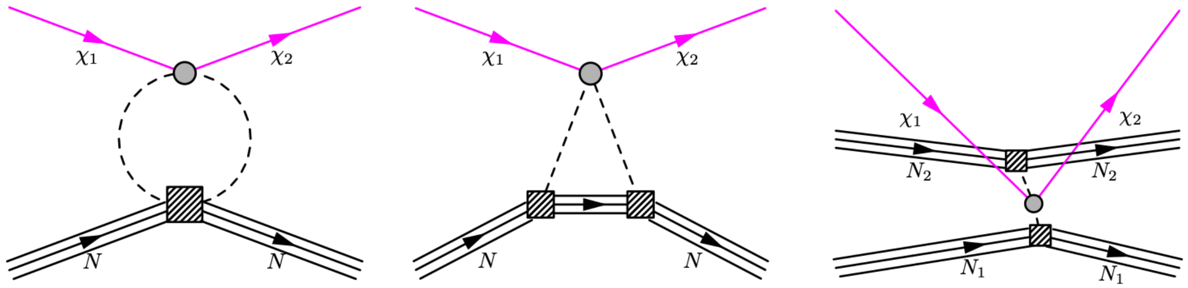


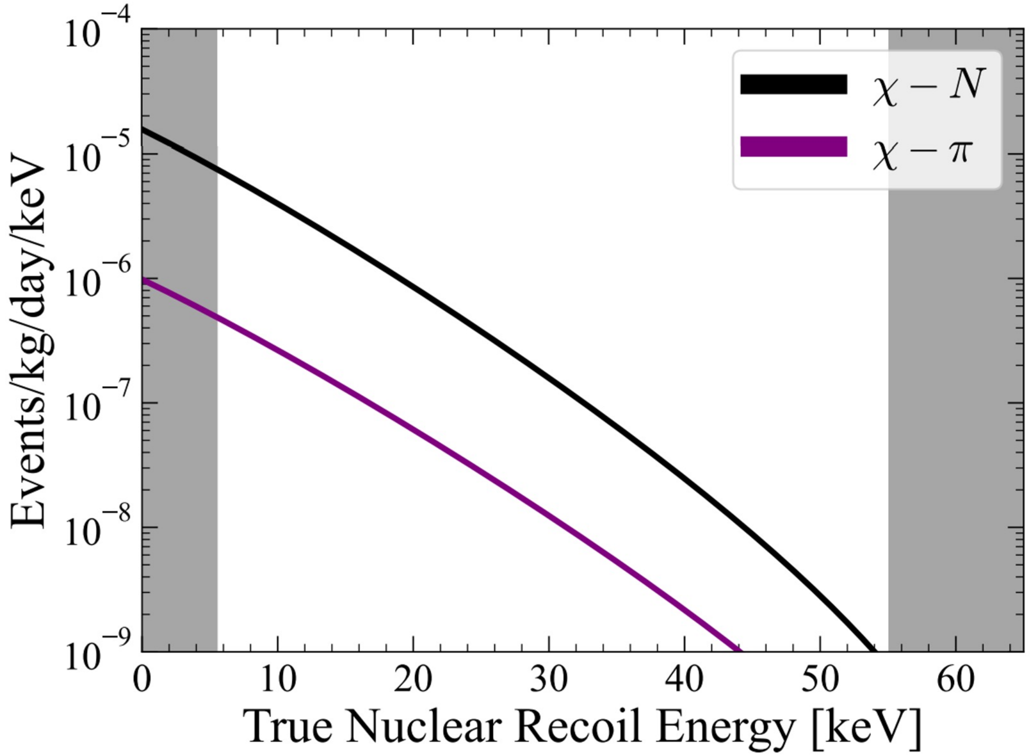


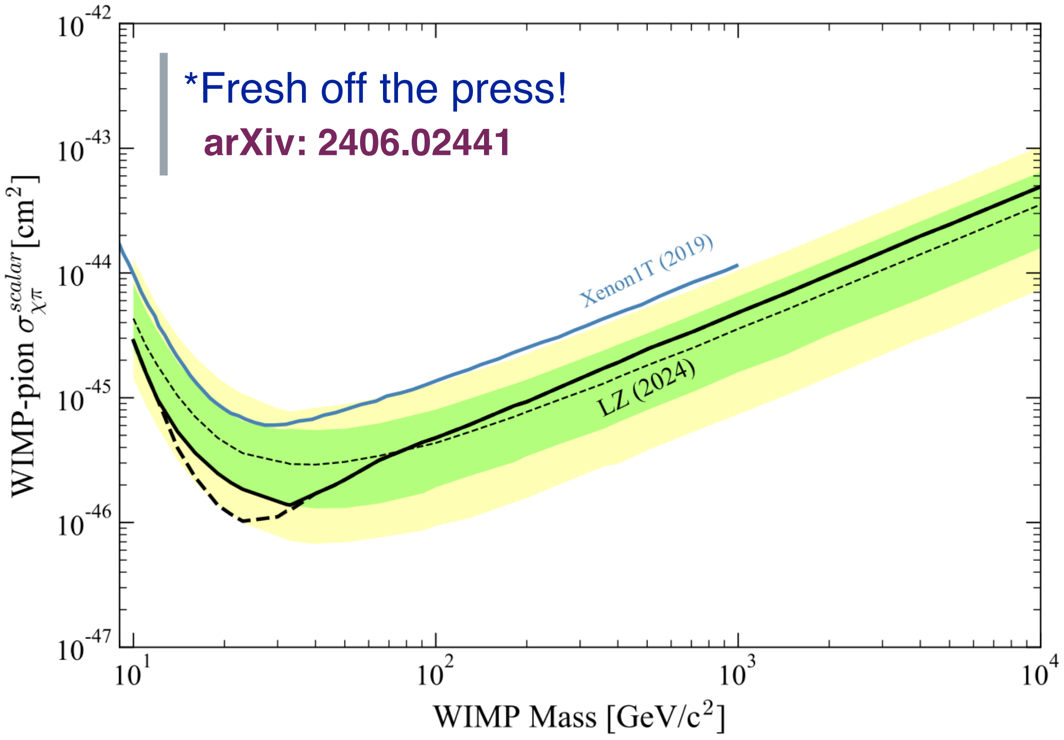
- EFT searches extend up to **higher energies**; new backgrounds are introduced
- **No excesses** observed, but **several world-leading constraints** set on different operator couplings

WIMP-pion interactions

- Probes for interactions between WIMPs and **virtual pions** exchanged between nucleons
- No excess observed; upper limit set at **1.5 × 10^{-46} cm^2** for a 33 GeV/c^2 WIMP mass







What's next?

xlzd.org

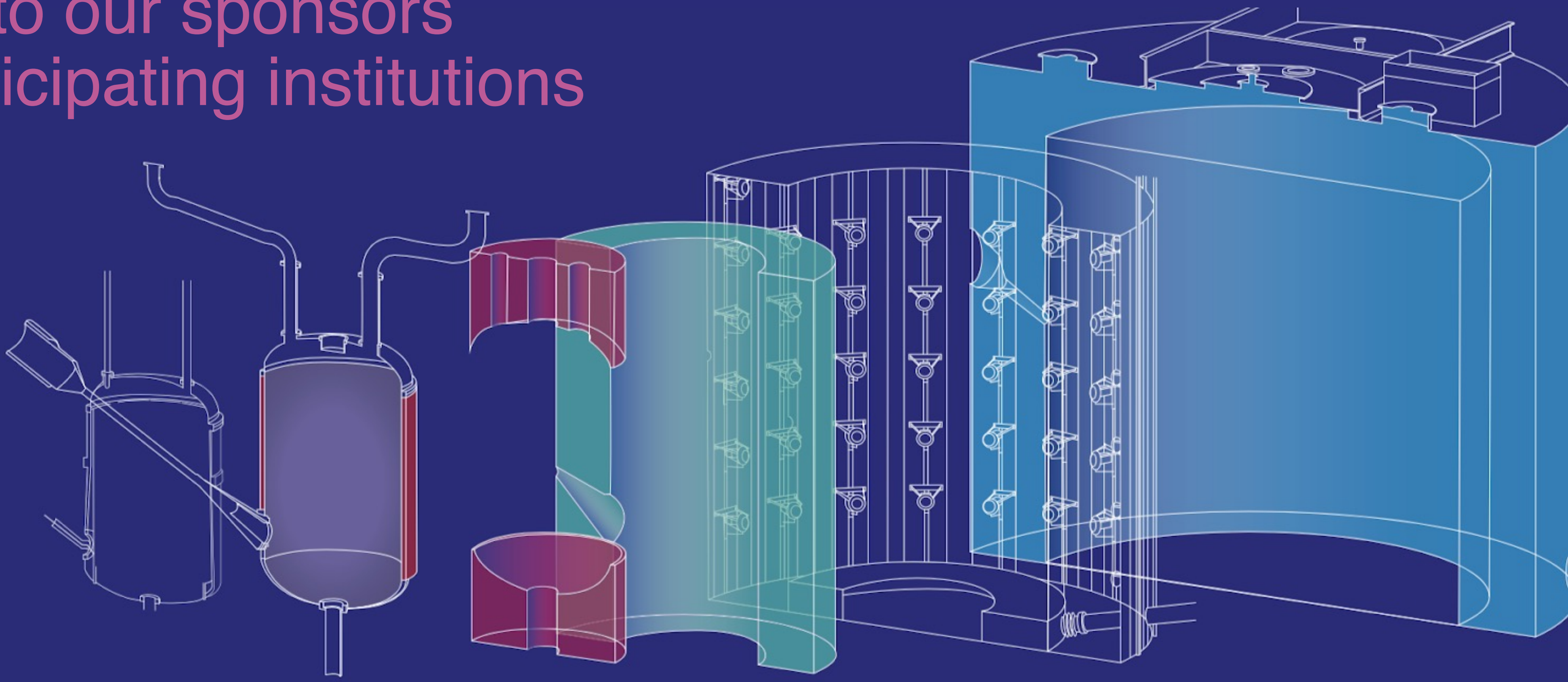
J. Phys. G: Nucl. Part. Phys. 50 013001 (2022)

- **XLZD consortium** formed between XENON, LZ, and DARWIN collaborations
- Goal is to build a **definitive WIMP detector and rare event observatory** (60-80 t of LXe)

XLZD consortium meeting at RAL, April 2024

Thanks for listening!

and to our sponsors
& 38 participating institutions



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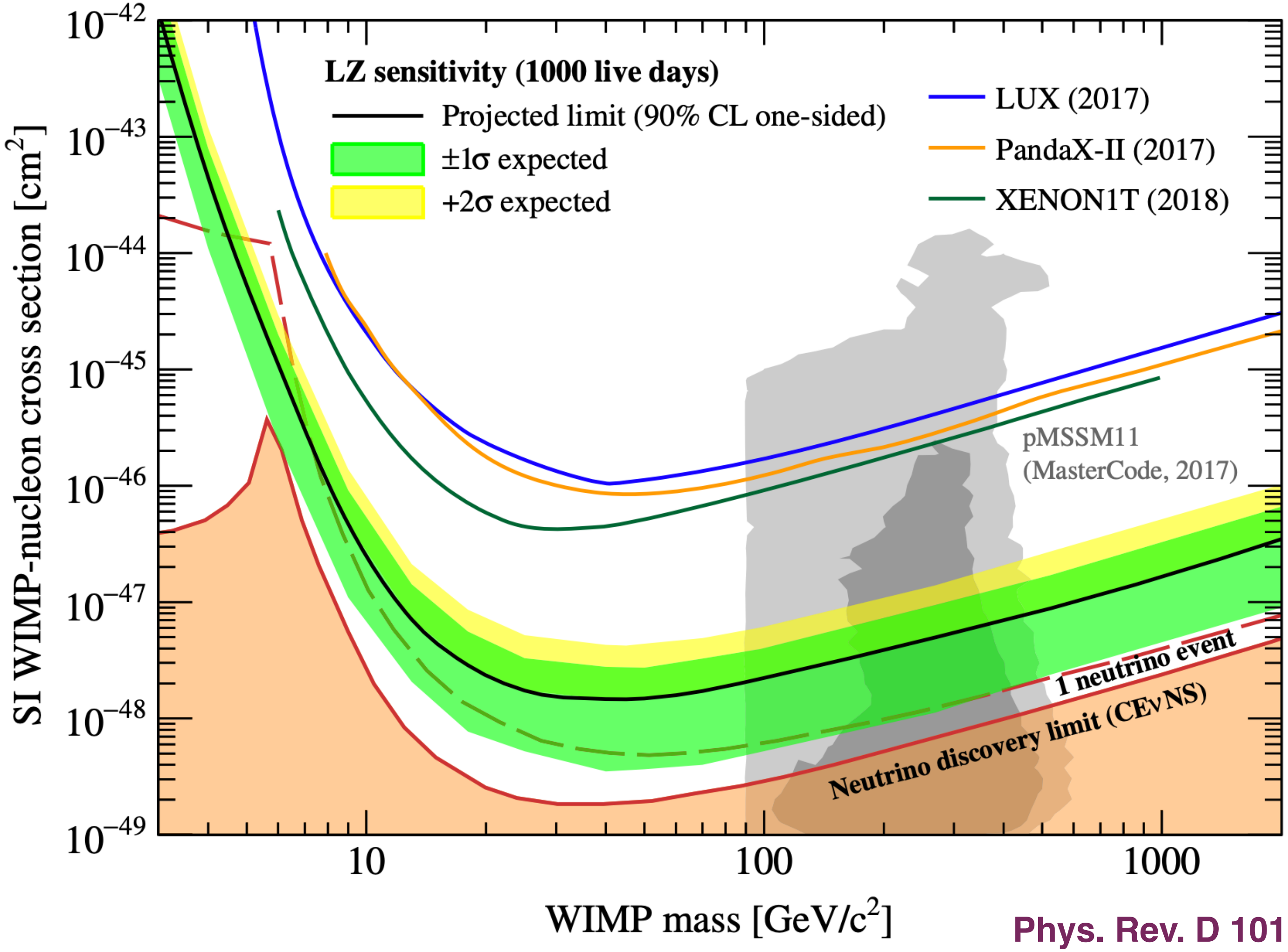
Supplementary slides

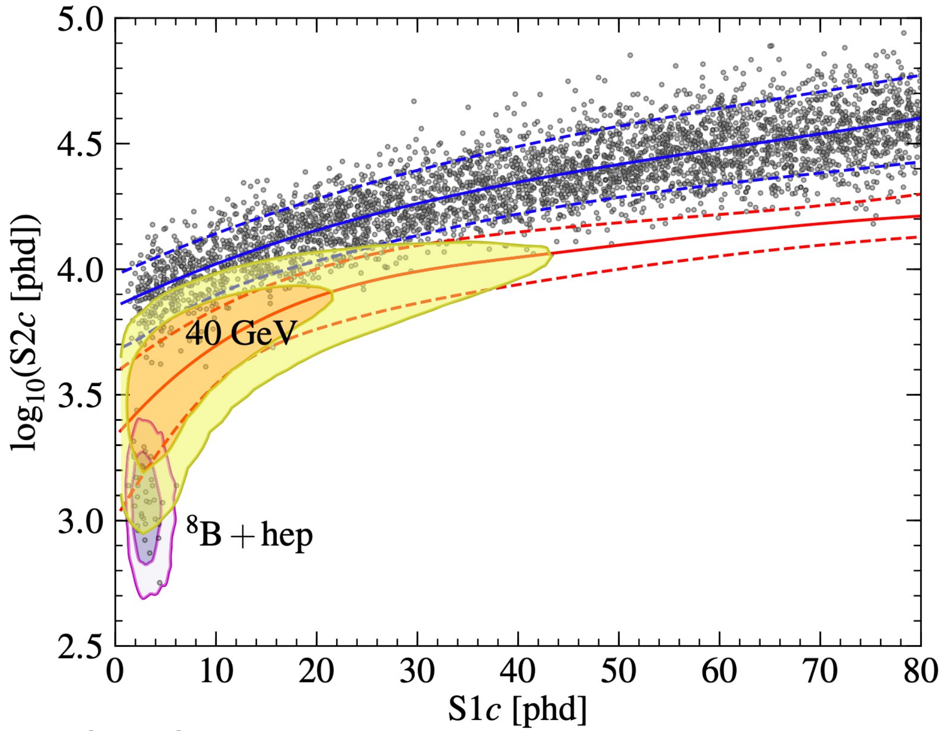
LUX - ZEPLIN

LZ projected sensitivity

SR1 is just **6%** of the planned **1,000 live day exposure**

Expect to achieve **1.4 × 10^{-48} cm^2** for **40 GeV/c^2** WIMPs

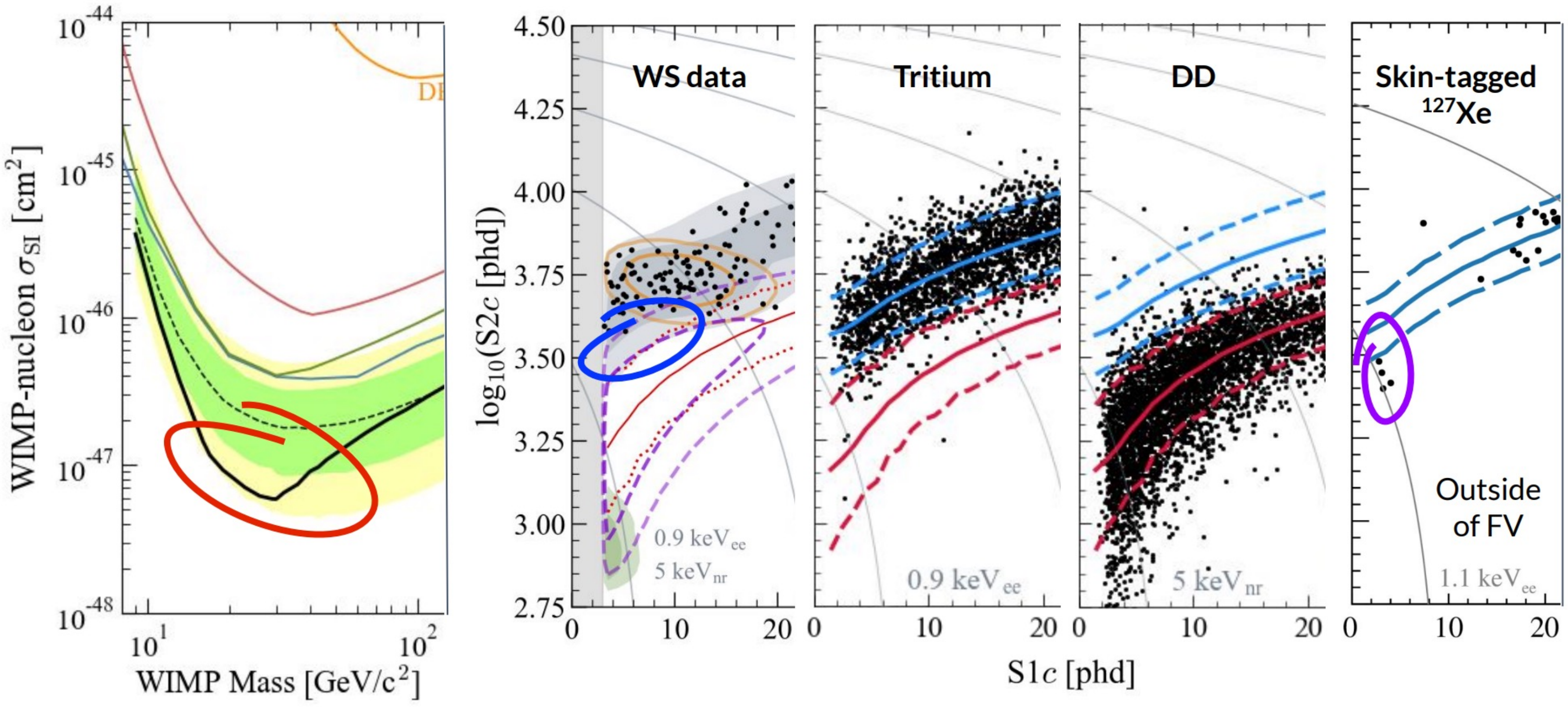




Phys. Rev. D 101, 052002 (2020)

Limit shape

EPJ C 81 907 (2021)

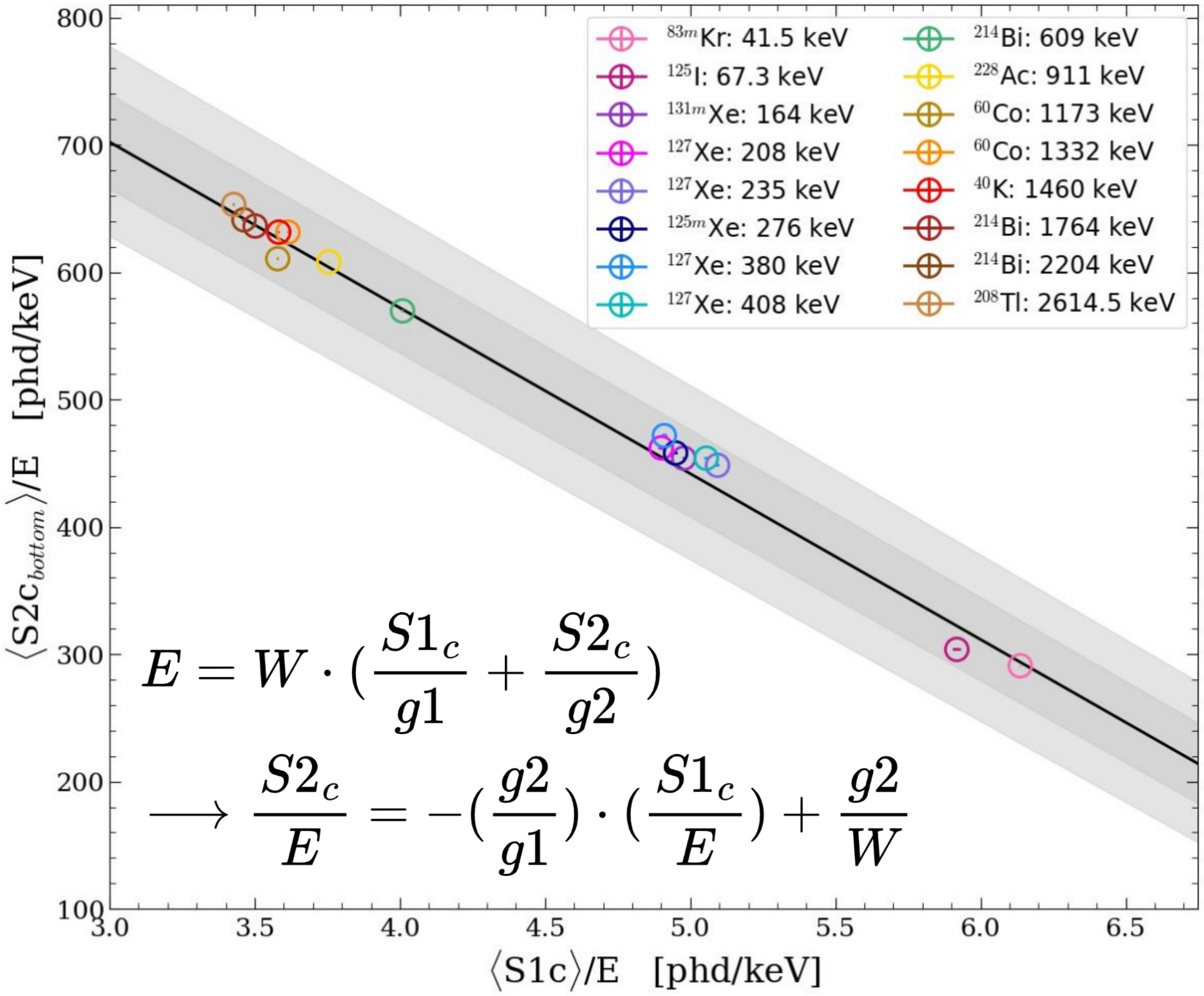


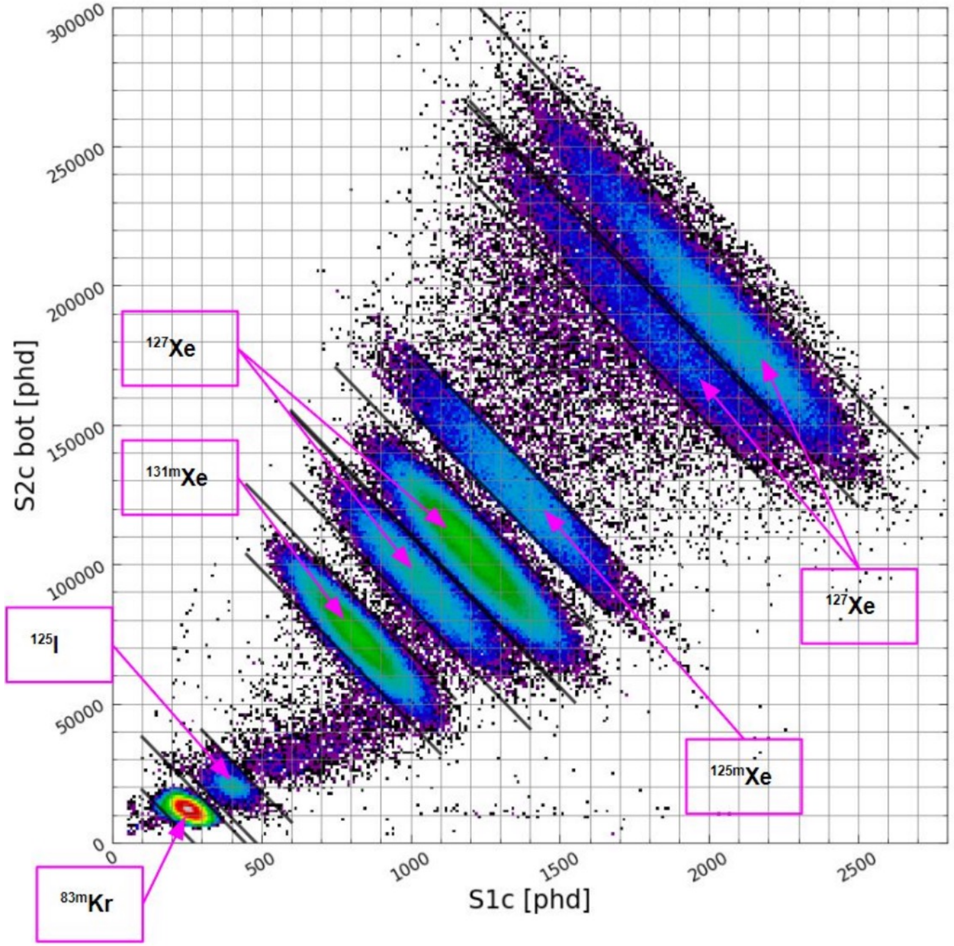
Deficit region is **well-covered by calibration data ⇒ not a signal inefficiency**

Power constraint is applied to the limit (restricts curve to **-1σ contour**, as per **recommended conventions***

Dip in the limit is due to an **under-fluctuation (deficit) in background events** below the ^{37}Ar population

Energy reconstruction

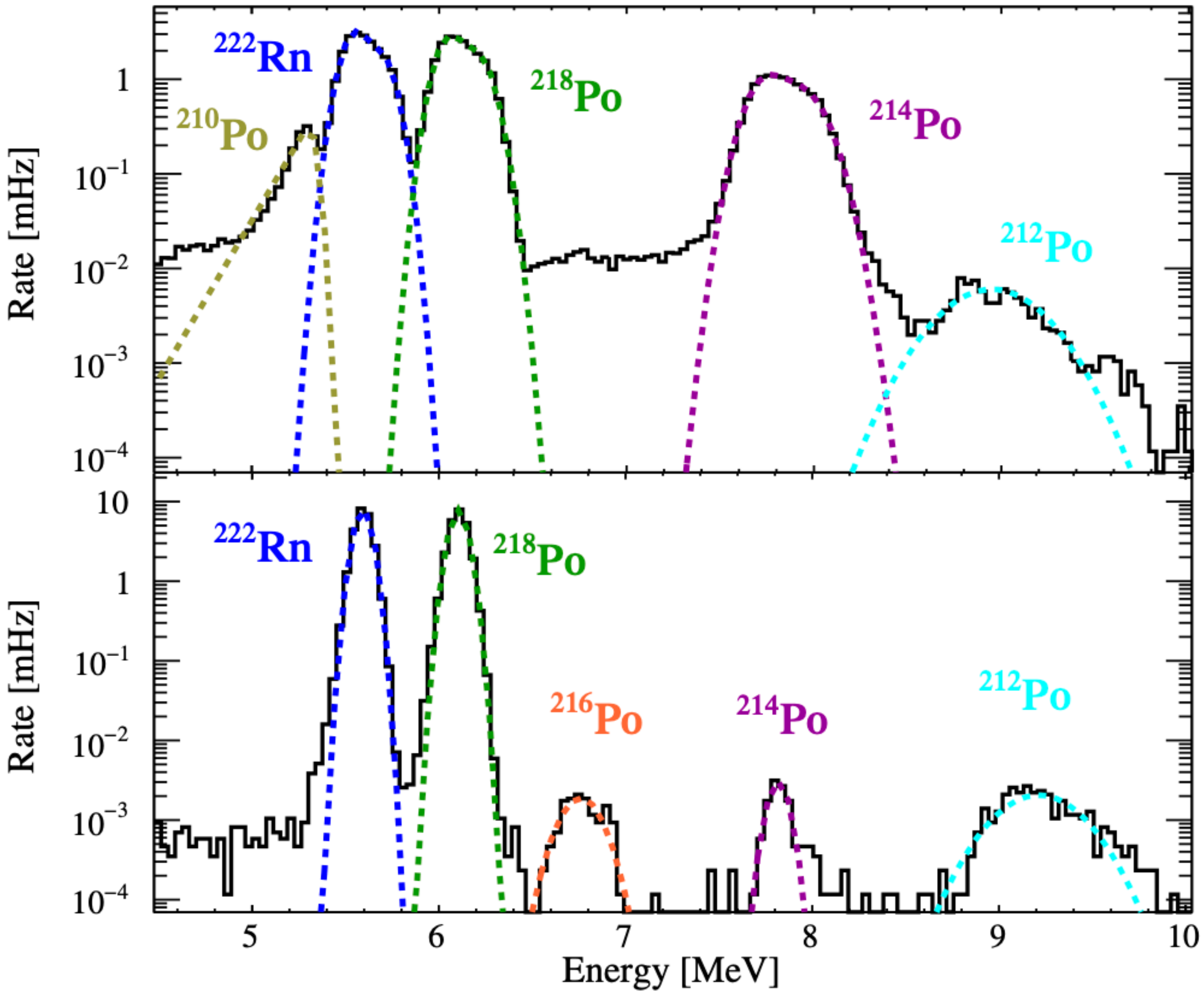


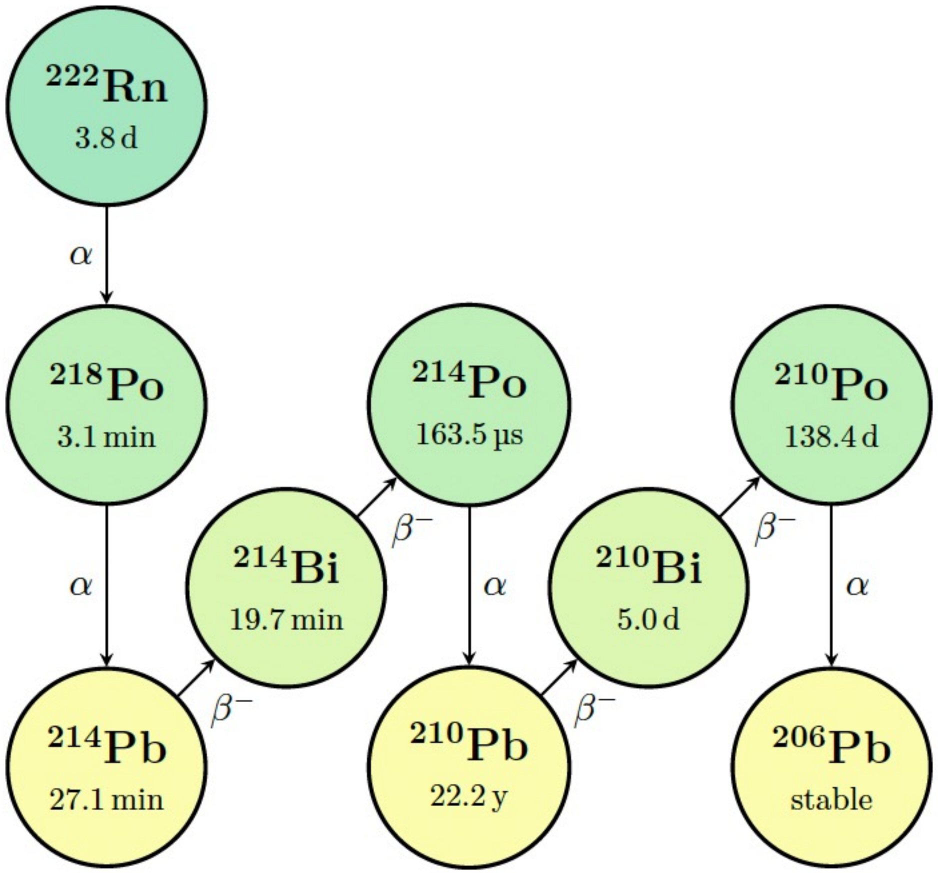


Energy response calibrated with mono-energetic sources via Doke plot method

Backgrounds: radon

Fits to **high-energy spectra** of radon daughters, plus **initial flow mapping**





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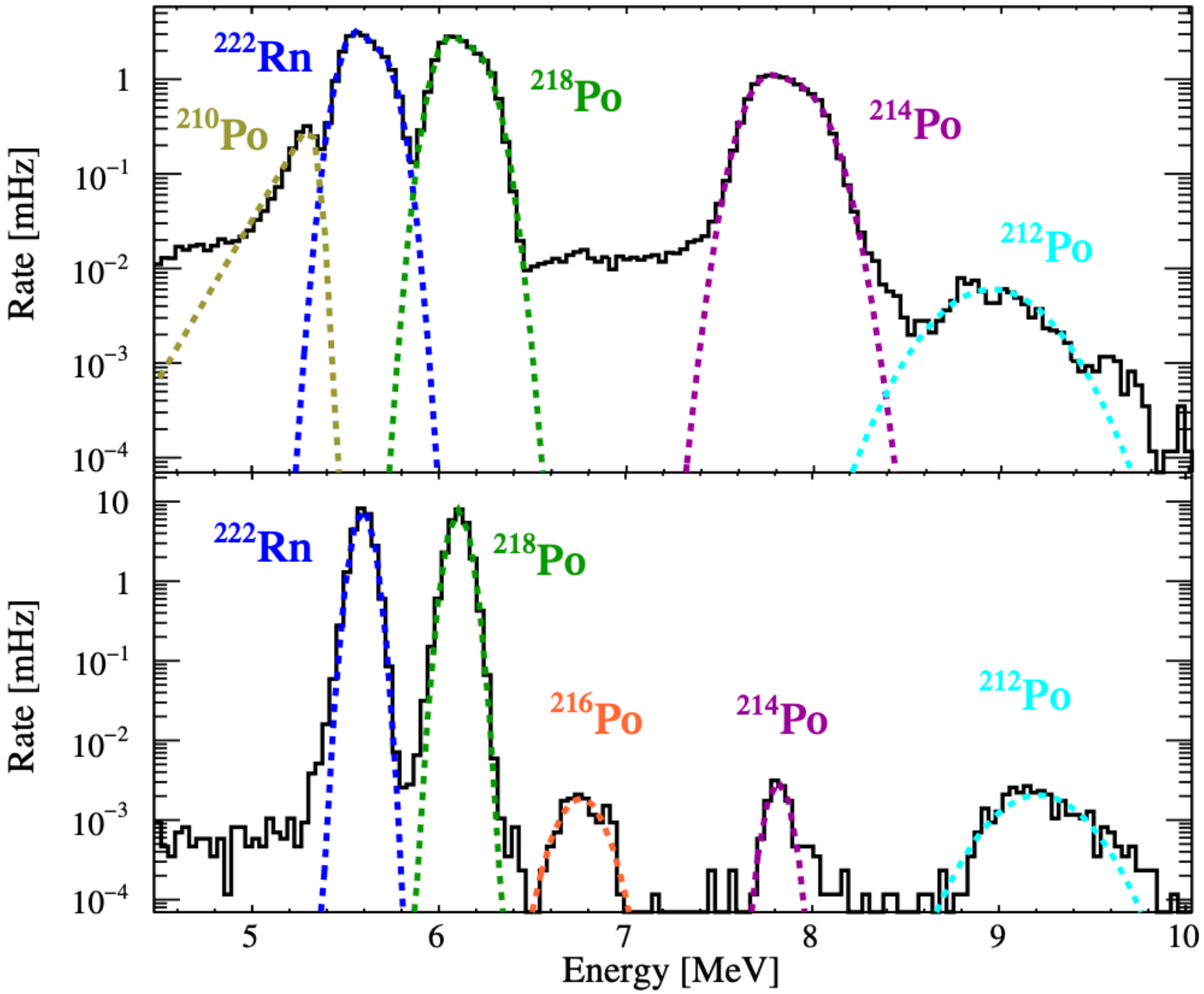
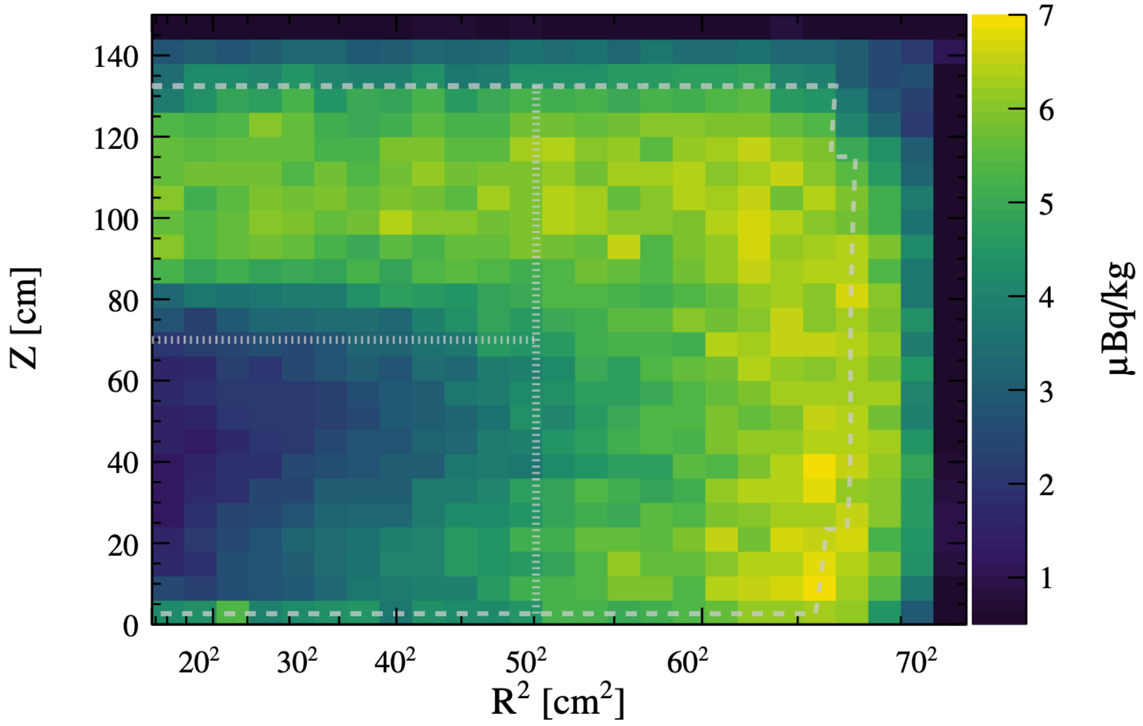
Backgrounds: radon

Fits to **high-energy spectra** of radon daughters, plus **initial flow mapping**





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Backgrounds: ^{37}Ar

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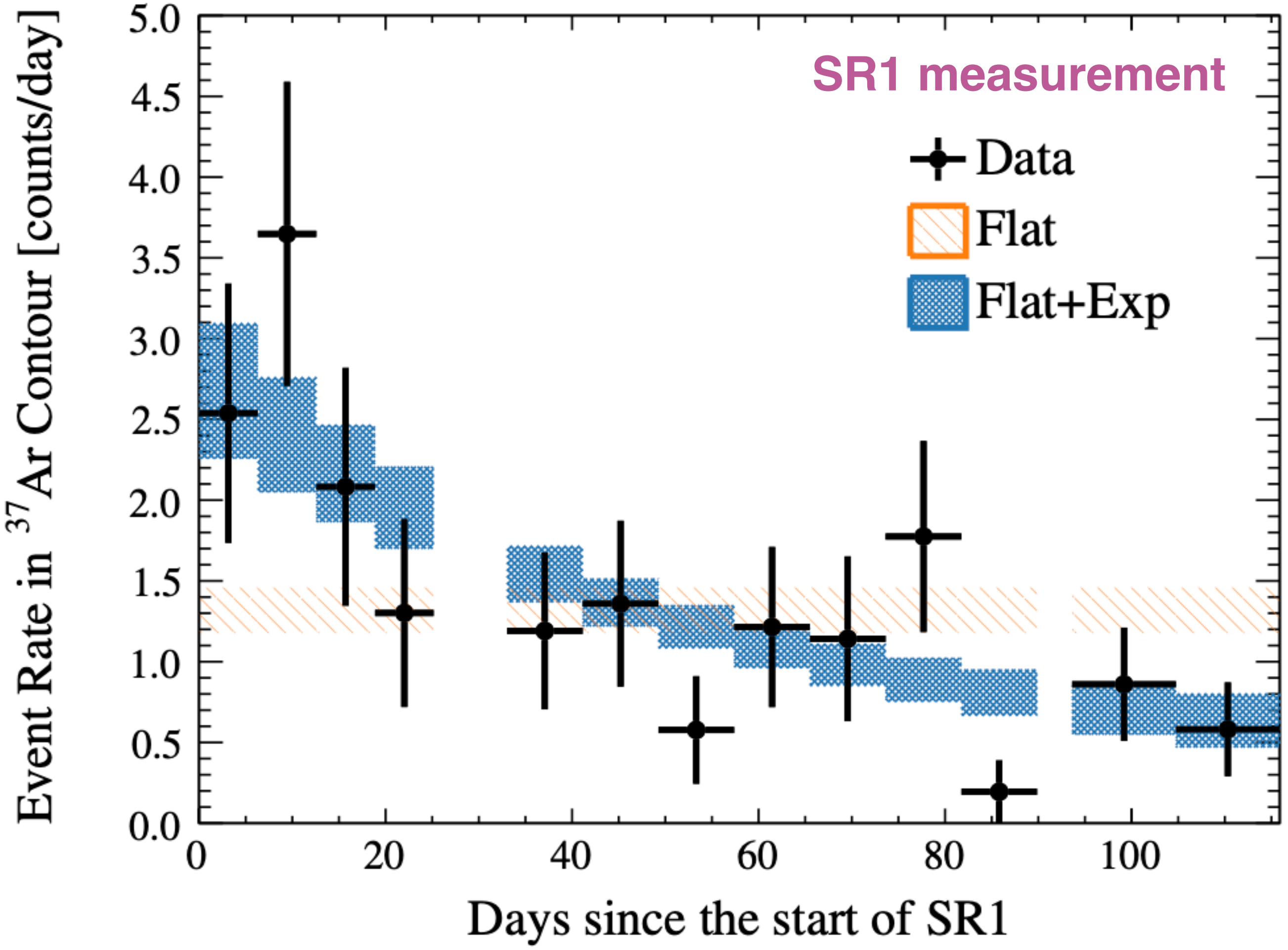

Production of ^{37}Ar through spallation and its gradual decay were **modelled prior to and during SR1**

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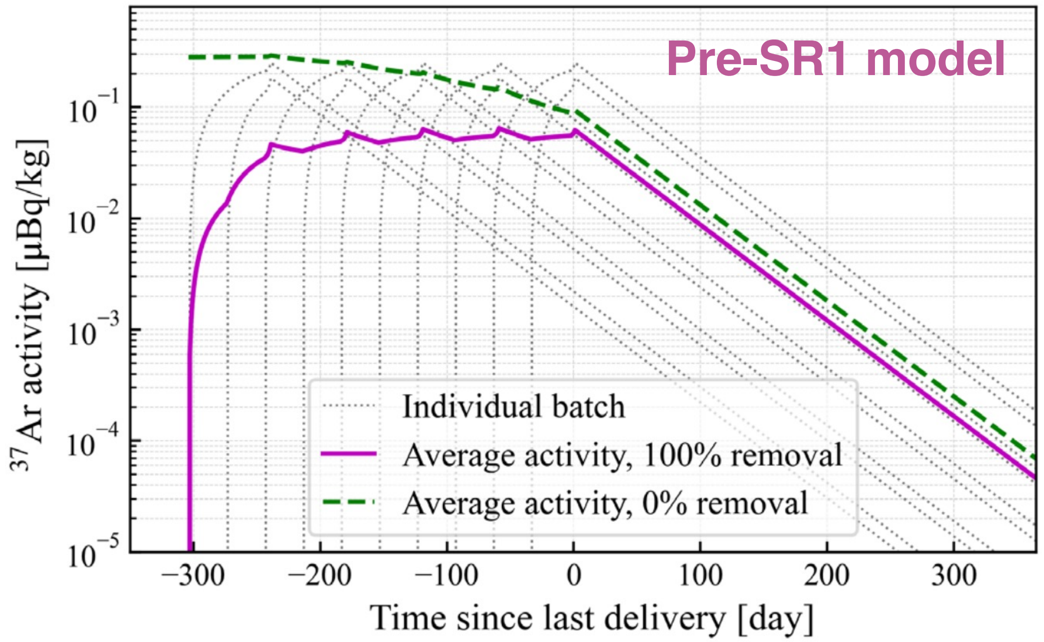
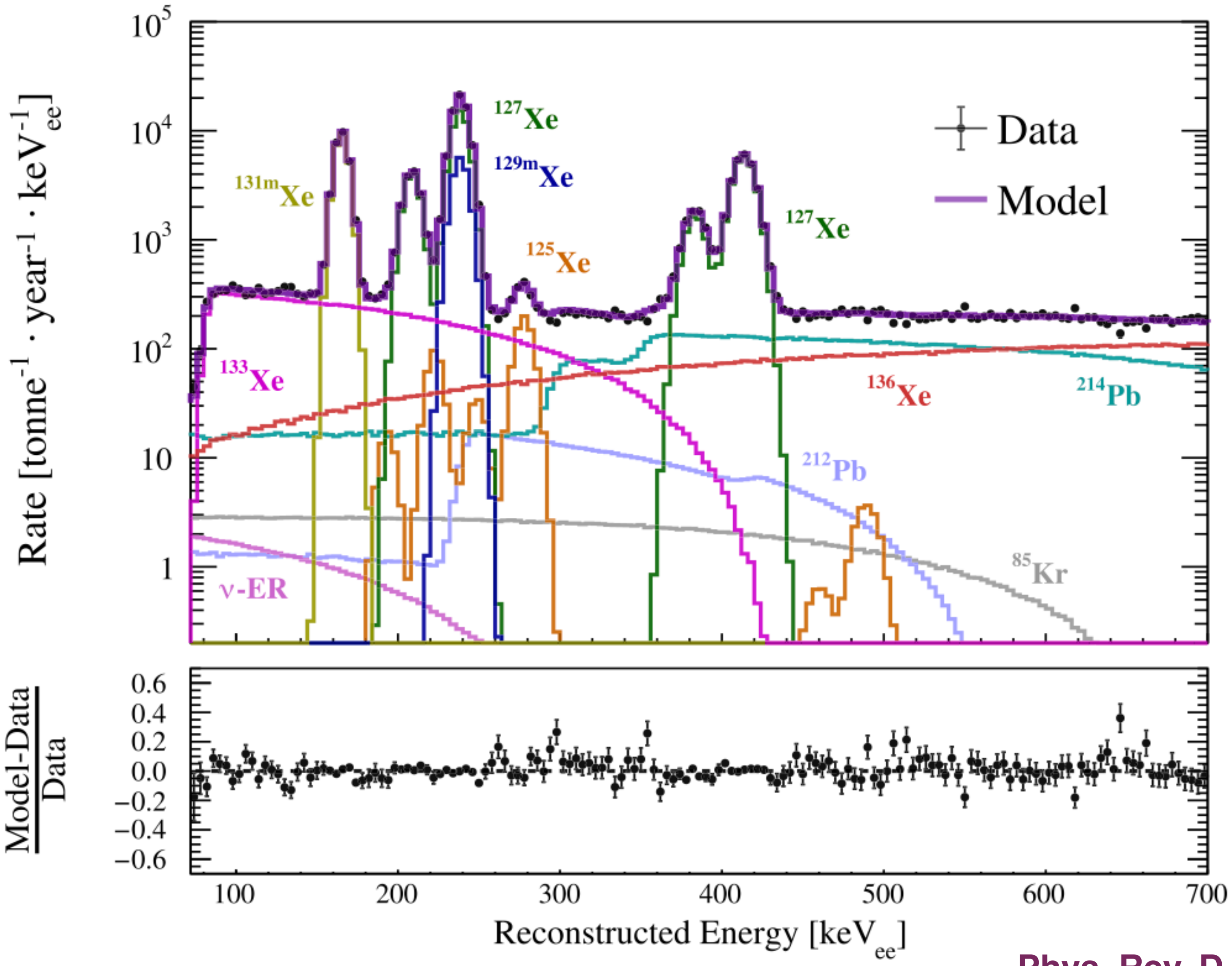
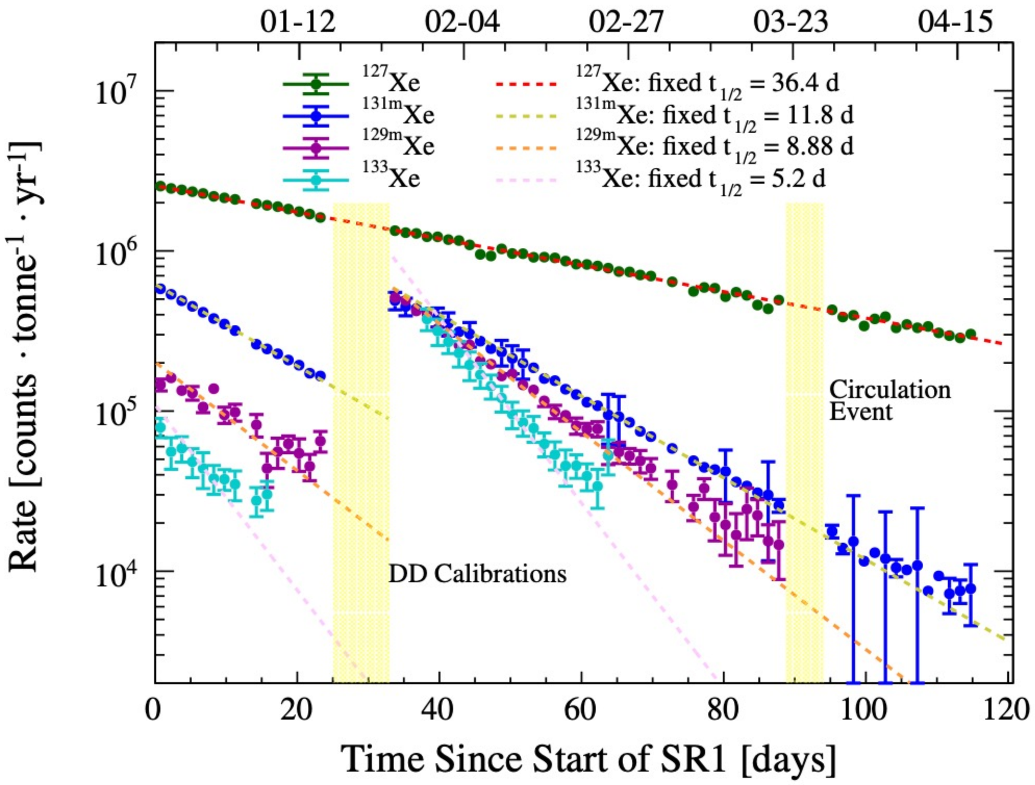


Backgrounds: internals

Constraints of Xe isotopes as activation products from neutron calibrations





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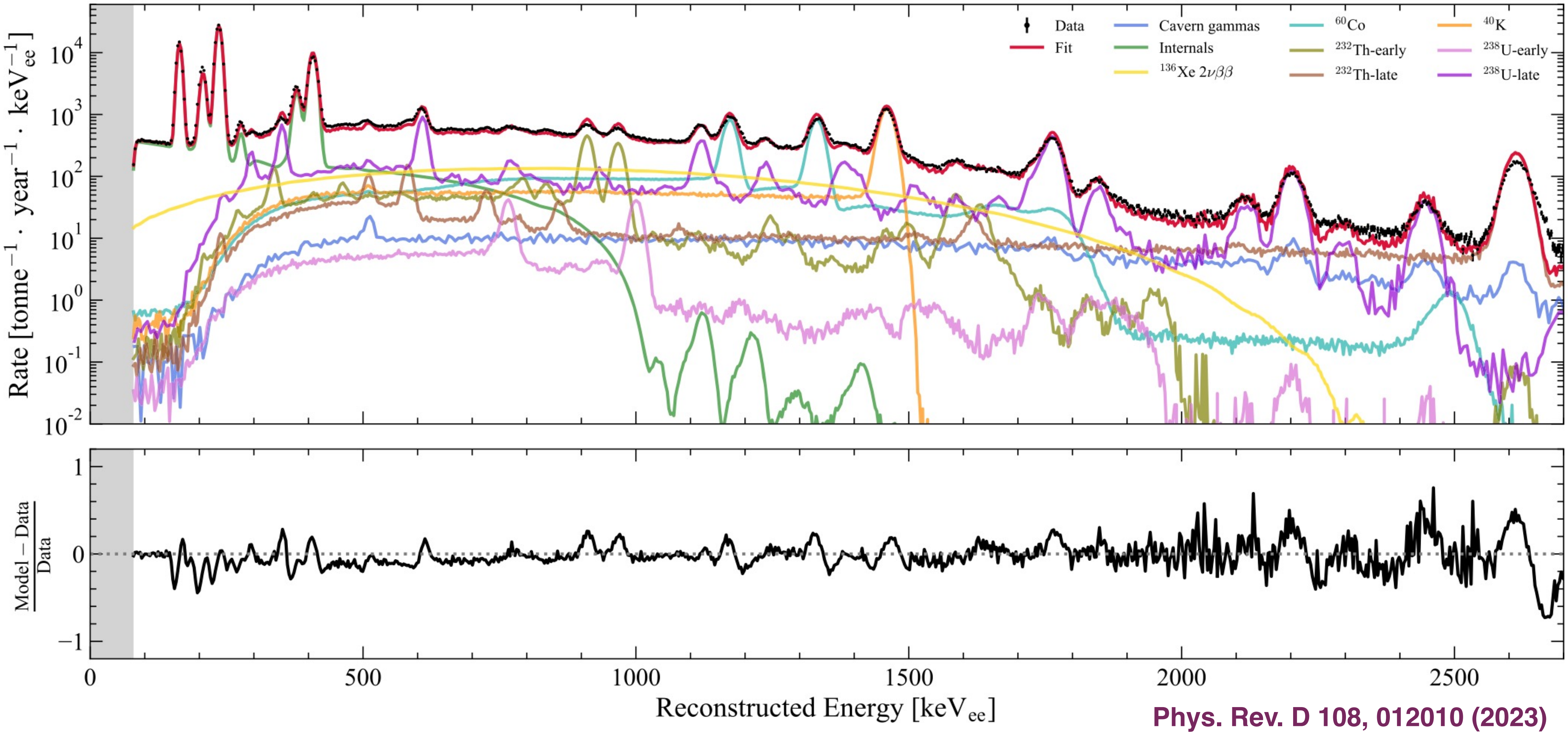
Backgrounds: detector ERs

Fits conducted in several detector sub-volumes



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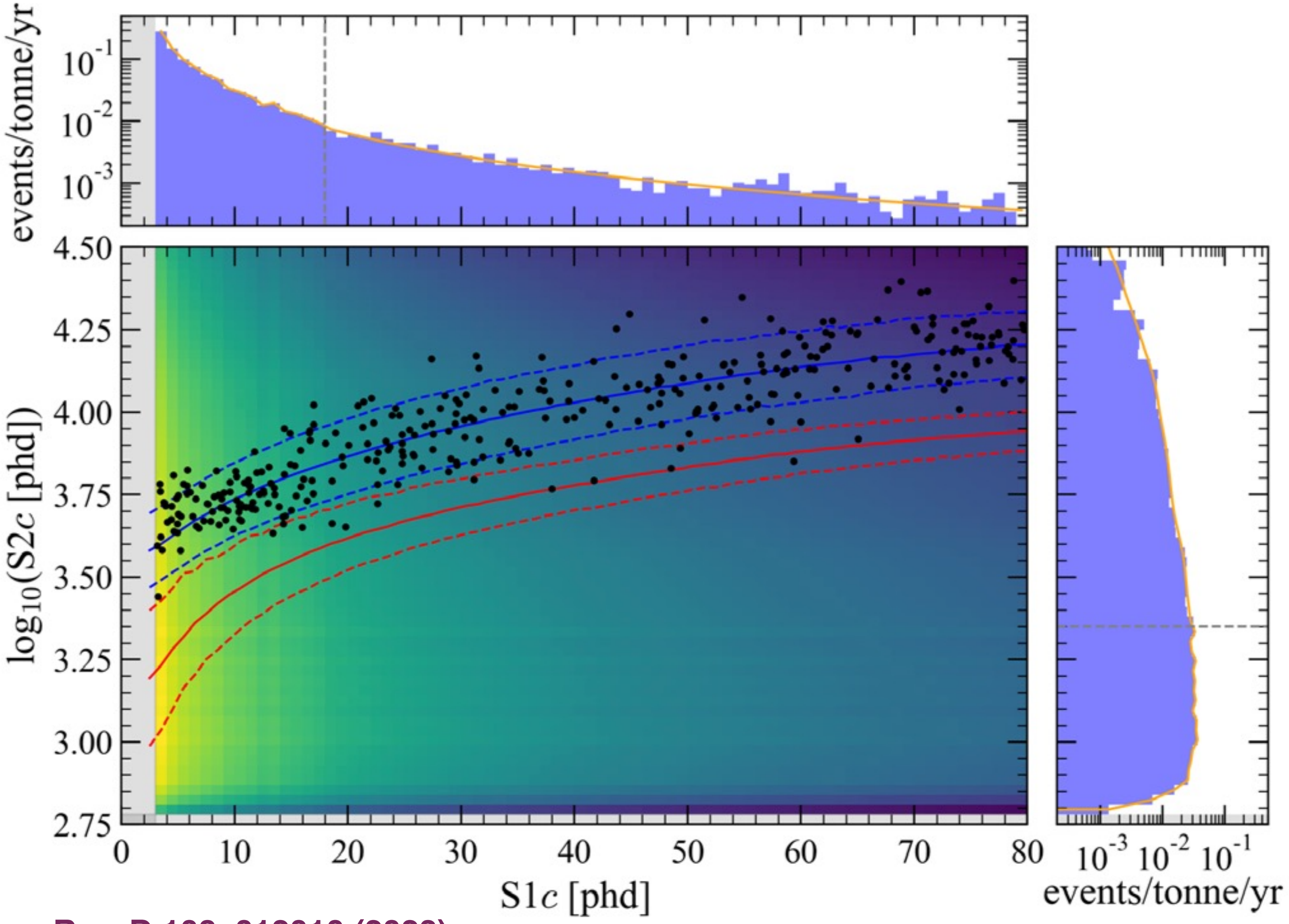
Backgrounds: accidentals



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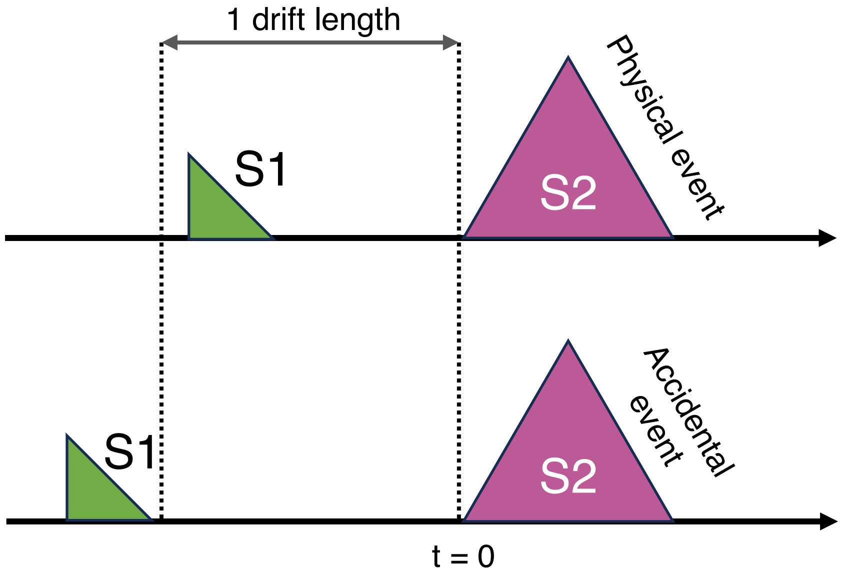
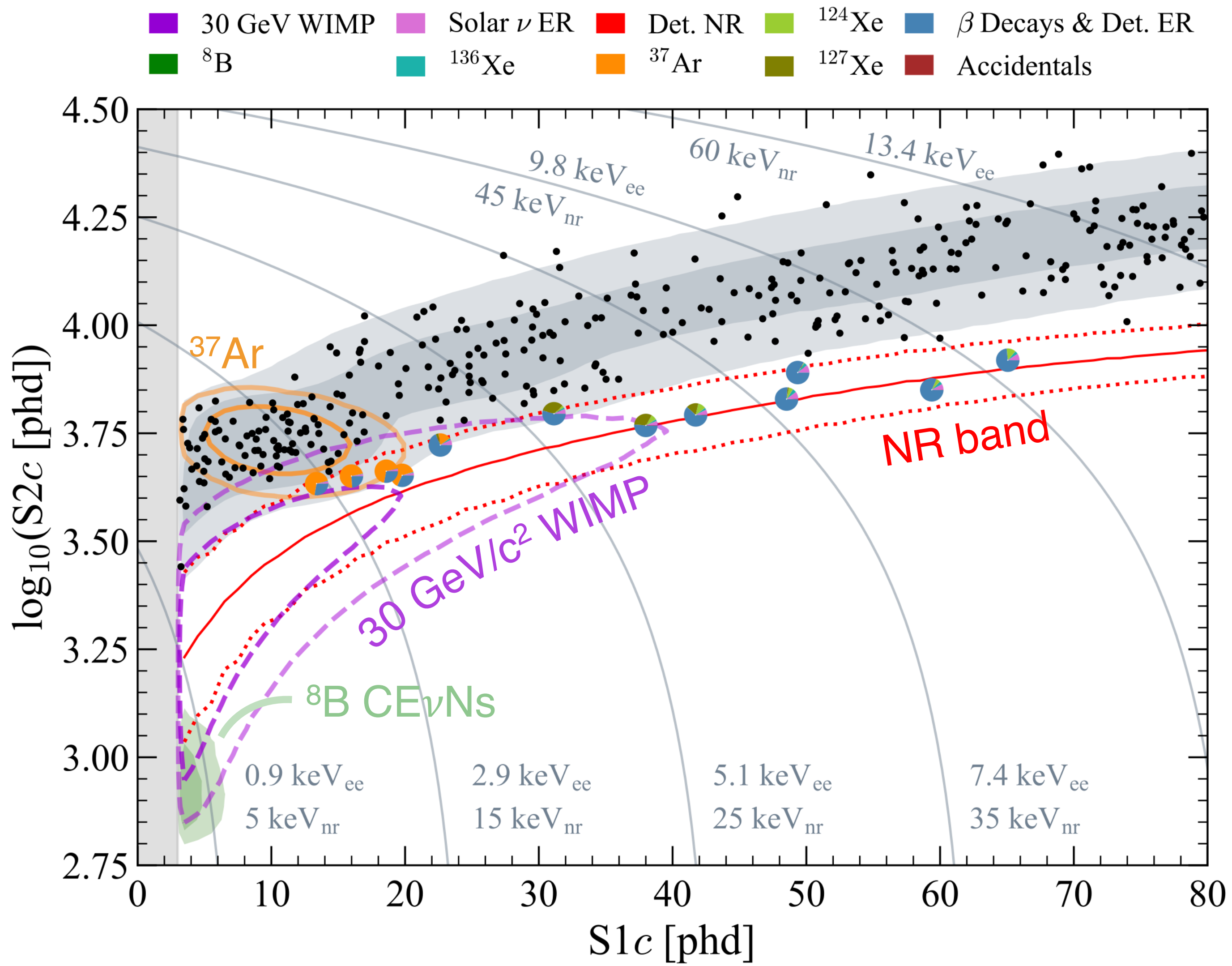
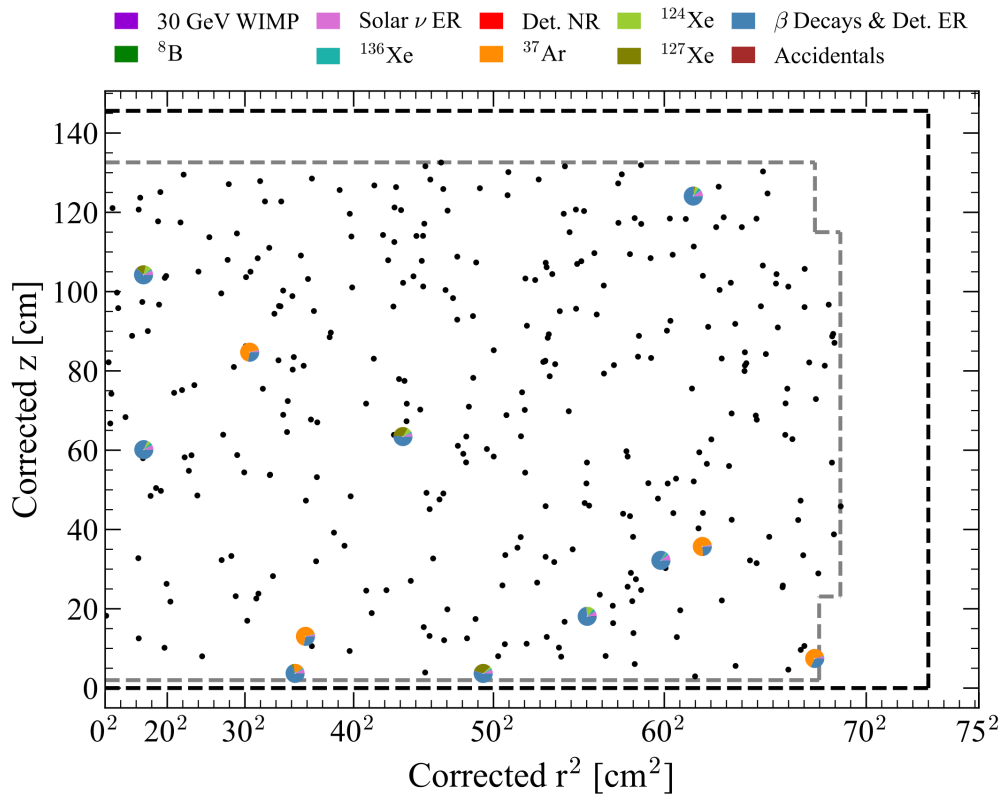
Accidental coincidence backgrounds: false pairings of uncorrelated S1s and S2s



Modelled using artificial events from combined calibration waveforms (“**ChopStitch**”)

Backgrounds: NRs





Pie plots (proxy for probability of seeing a specific source at a given point) for NR band events

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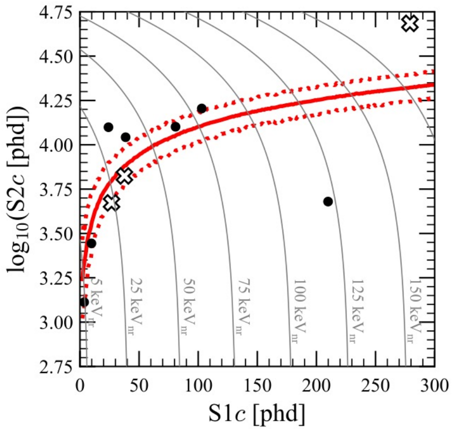
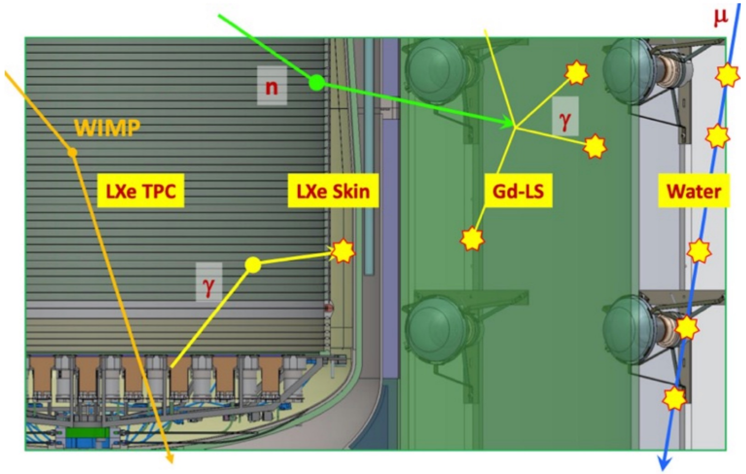
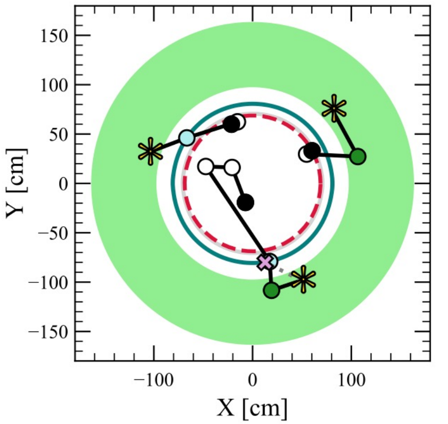
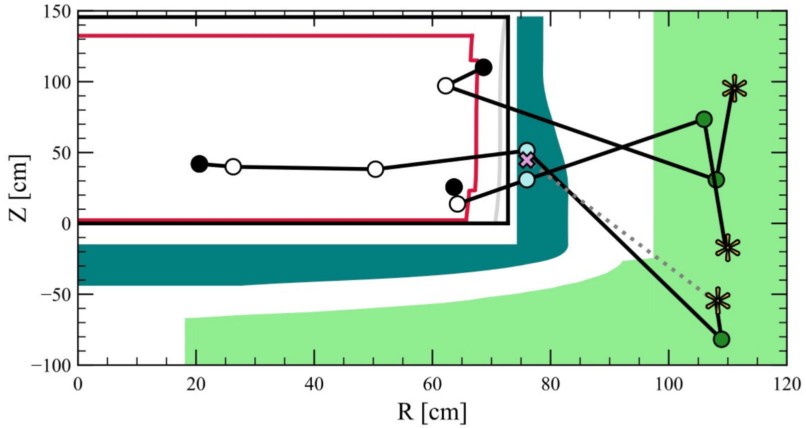
Backgrounds: neutrons

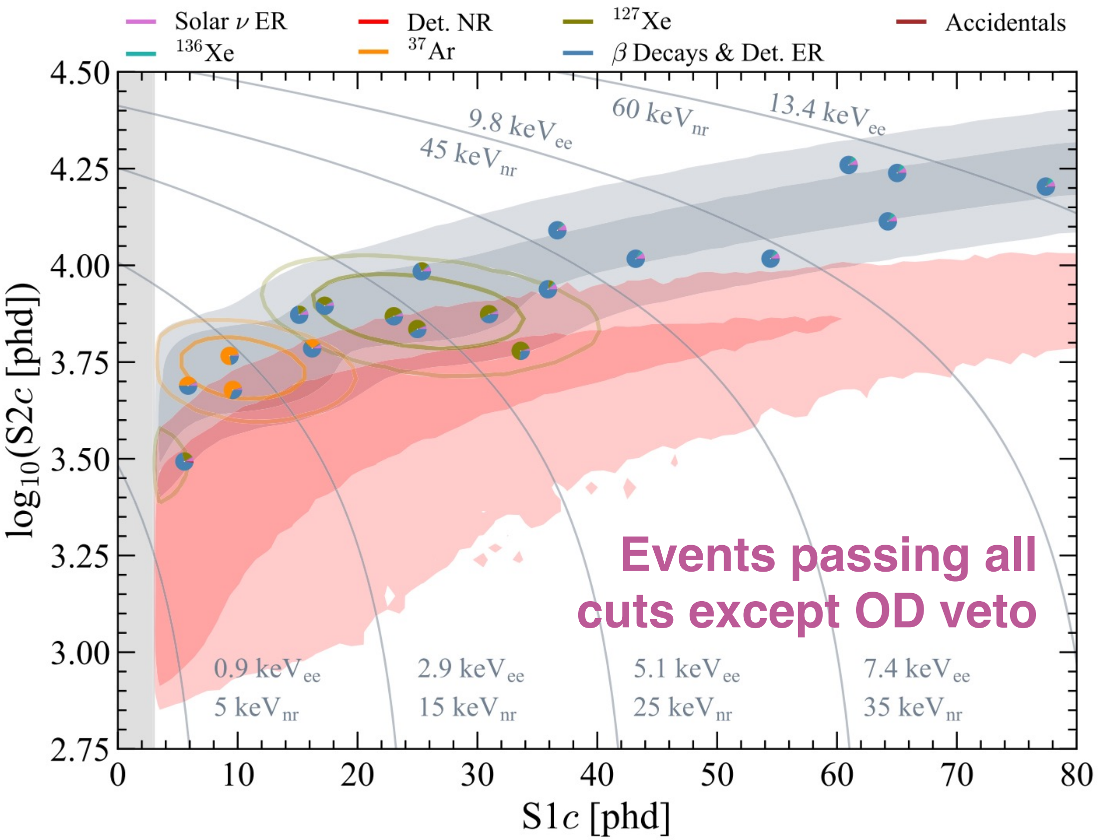
Neutron backgrounds constrained via **OD-tagged sideband** and **multiple scatter (MS) data**; 89% tagging efficiency measured with calibrations and simulations











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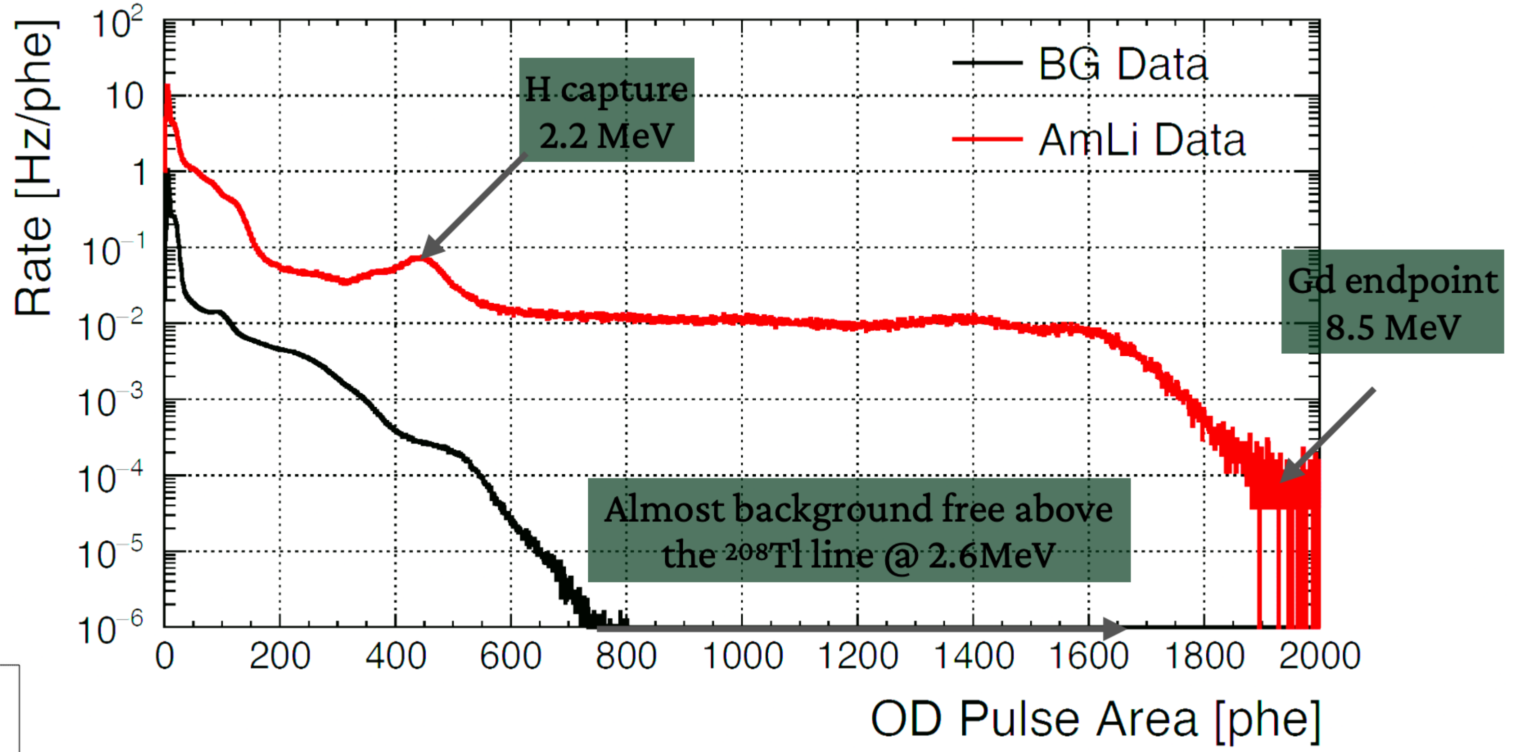
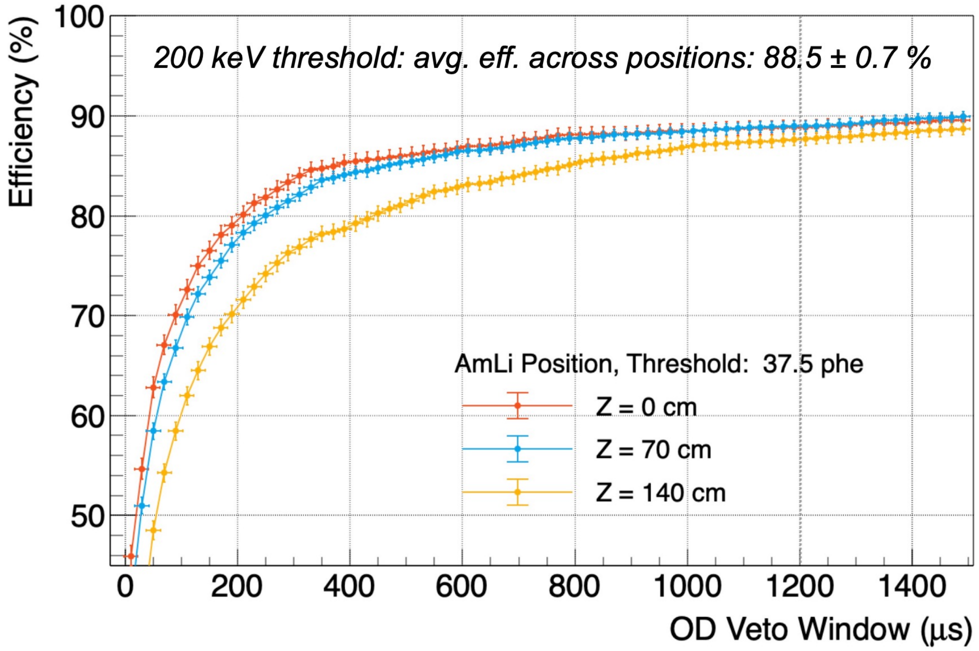
OD veto efficiency

OD efficiency characterised using AmLi calibration source (≤ 1.5 MeV neutrons)





- SS neutron tagging efficiency: **(88.5 ± 0.7) %** for **200 keV threshold** and **Δt ≤ 1200 *µs*** delayed coincidence window
- **5% live time loss** incurred from accidental OD tag (random coincidence)