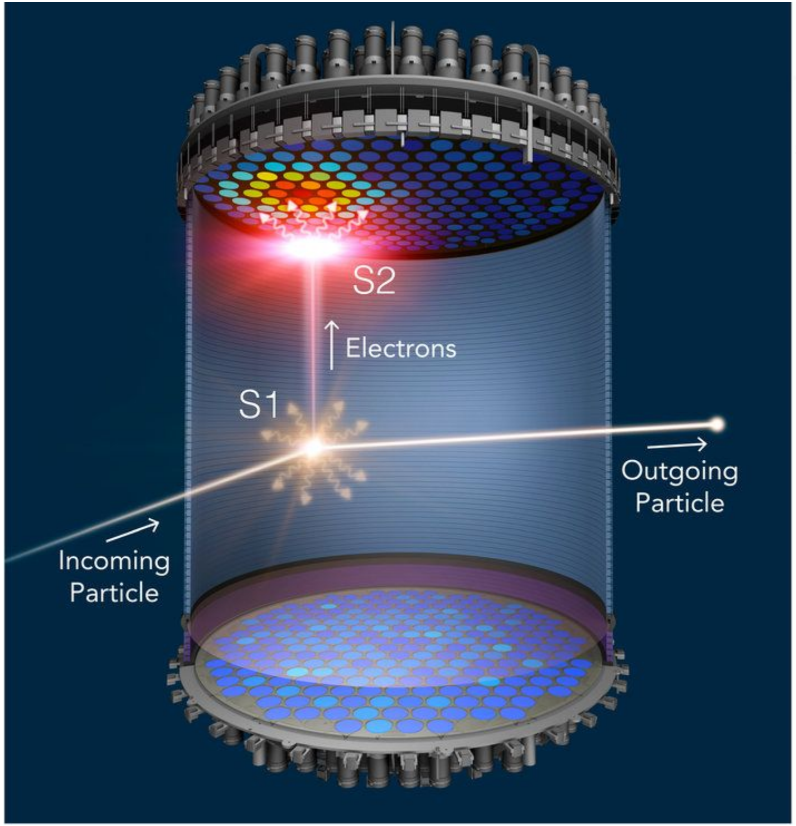
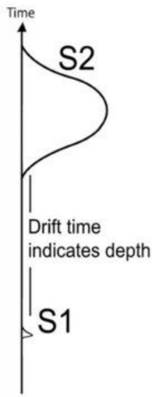
Shining Light on the Dark Matter Problem With LZ

talk given on behalf of the LZ collaboration
Prof. Matthew Szydagis, UAlbany SUNY

The Dual-Phase Xenon Time Projection Chambers (TPCs)

- High scintillation light and ionization charge (e^-) yields
- High Z, A, and density: self-shielding of backgrounds
- Energy reconstruction, across two channels (S1 and S2)
- Robust 3D position reconstruction, mm-cm level
- Relatively easy to purify to a very high degree
- No low-energy, long-lived radioisotopic contaminants
- Long history of TPCs across fields and across the globe



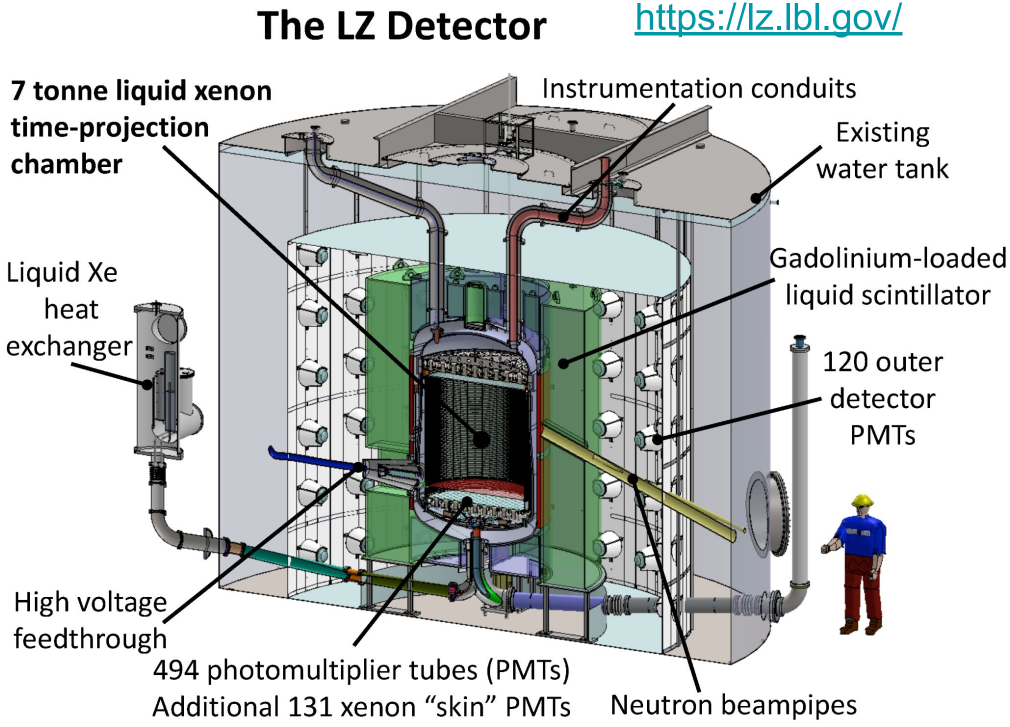


SLAC

LZ is to LUX as CMS and ATLAS are to D0 and/or CDF

How to Avoid a False Positive Detection Claim in LZ

https://lz.lbl.gov/



LZ’s TDR (Technical Design Report)

- Go underground to avoid cosmic rays (huge rock overburden)
  - Especially muon-induced neutrons
  - But rock itself radioactive to a degree!
- Have a water shield for leftover, high-E^{energy} cosmic muons and the rock
  - Used as an active veto (coincidence)
- Put additional layers between the water shield and the LXe TPC
  - Gd-doped liquid scintillator -> neutrons
  - Liquid Xe “skin” (no S2) -> gammas
- Radiopure construction materials
  - Even human sweat is radioactive!
  - Comprehensive paper on cleanliness

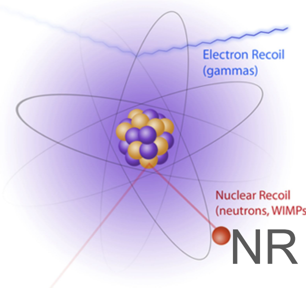
EJPC https://arxiv.org/abs/2006.02506

Photo Credits: SURF, SDSTA

The Sanford Underground Research Facility, in beautiful Lead, SD (site of Homestake gold mine)

More Xenon & LZ Facts !

- 174 nm ultraviolet photons
  - No wavelength shifter needed (compare to LAr)
- Teflon to reflect it (at right)
  - ~100% reflective (diffuse)
- Approximately 5.5 tonne fiducial mass (largest)
  - The outer detector was key
- 99.75 to 99.9% <- not best (cf. LAr) but good enough! discrimination of electronic recoil (ER) backgrounds
  - Depending on *E* spectrum
- A 50% efficiency point @ 5.5 keVnr (nuclear recoil)
  - But non-zero efficiency down to the sub-keV scale
- A US DOE flagship project



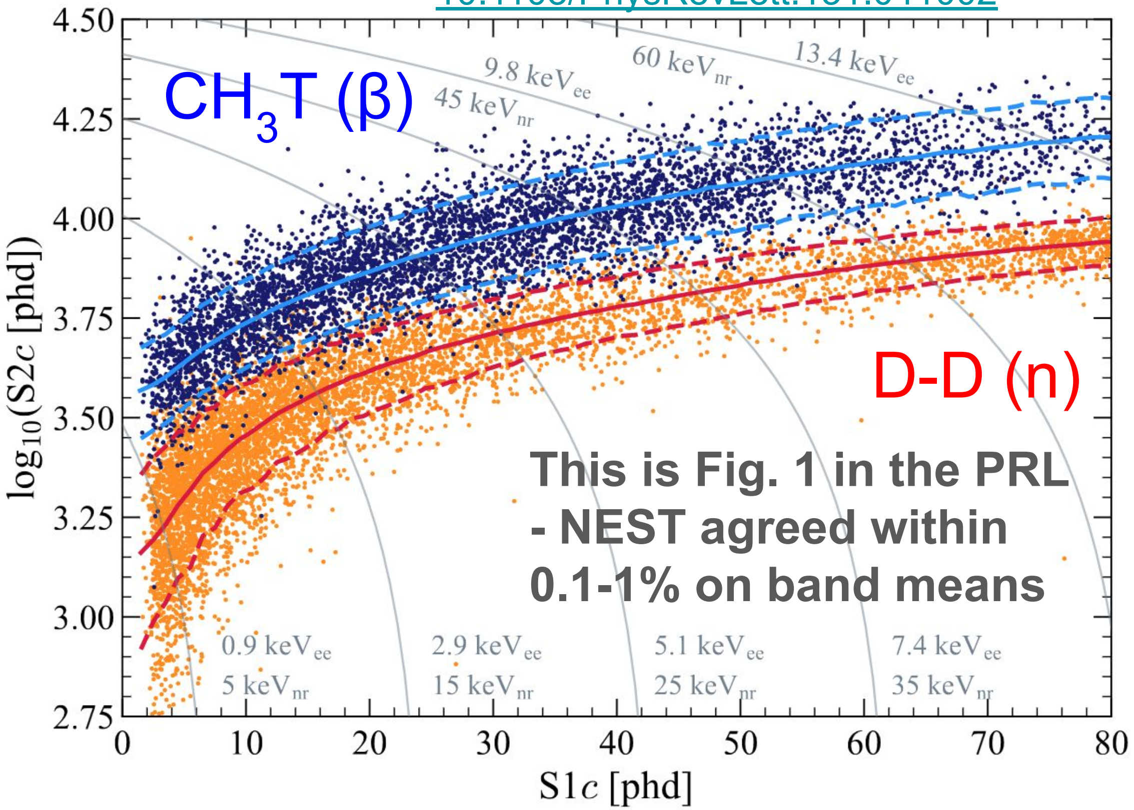
How known? NEST!
https://github.com/NESTCollaboration/nest

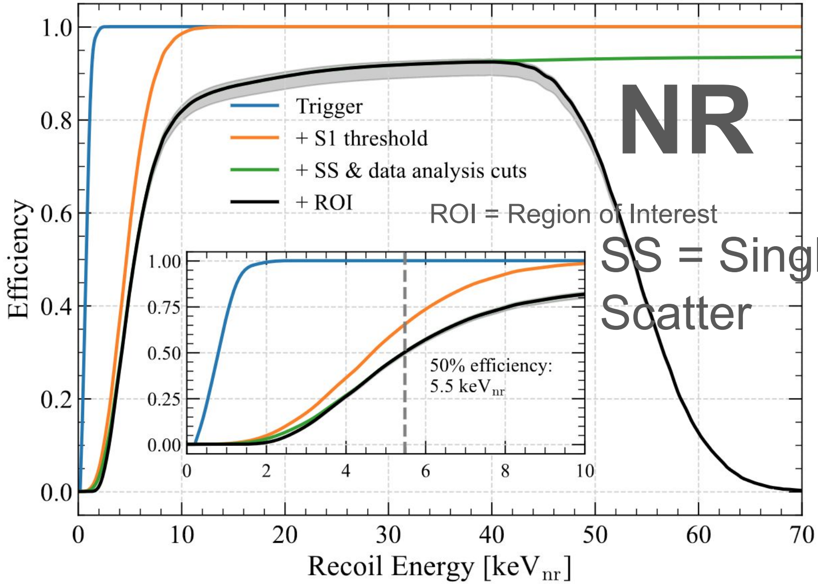
Photo: Matt Kapust

SR = Science Run

LZ's First WIMP-Search Results: SR1 (Published Recently)

https://arxiv.org/abs/2207.03764 or => https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.131.041002





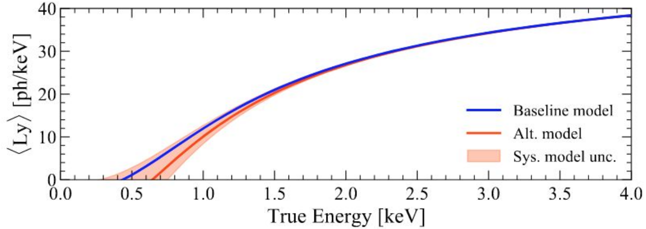
NR

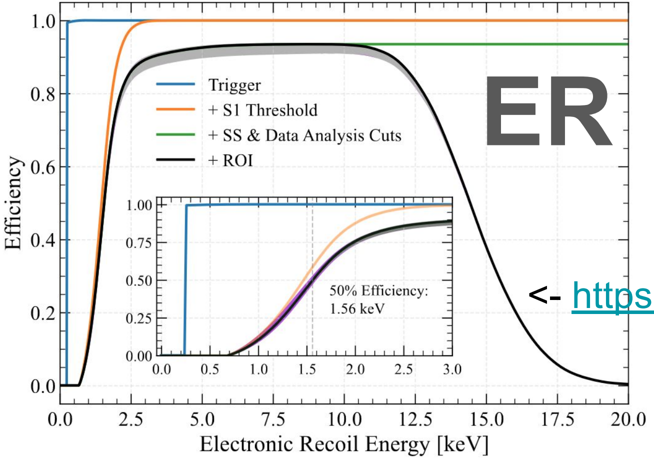
ROI = Region of Interest

SS = Single Scatter

Efficiency of Detection for the Different Basic Particle Types

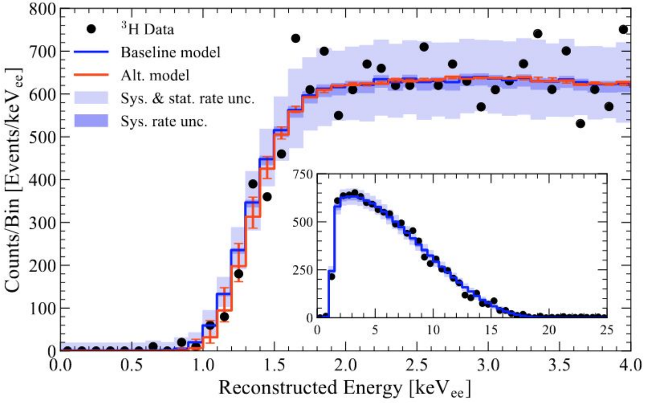
plot at upper left: https://arxiv.org/abs/2207.03764





ER

Parameter	Value
g_1^{gas}	0.0921 phd/photon
g_1	0.1136 phd/photon
Effective gas extraction field	8.42 kV/cm
Single electron	58.5 phd
Extraction Efficiency	80.5 %
g_2	47.07 phd/electron



<- https://arxiv.org/pdf/2307.15753.pdf ->

For BGs! BUT, also different potential signals

3D XYZ Event Distribution

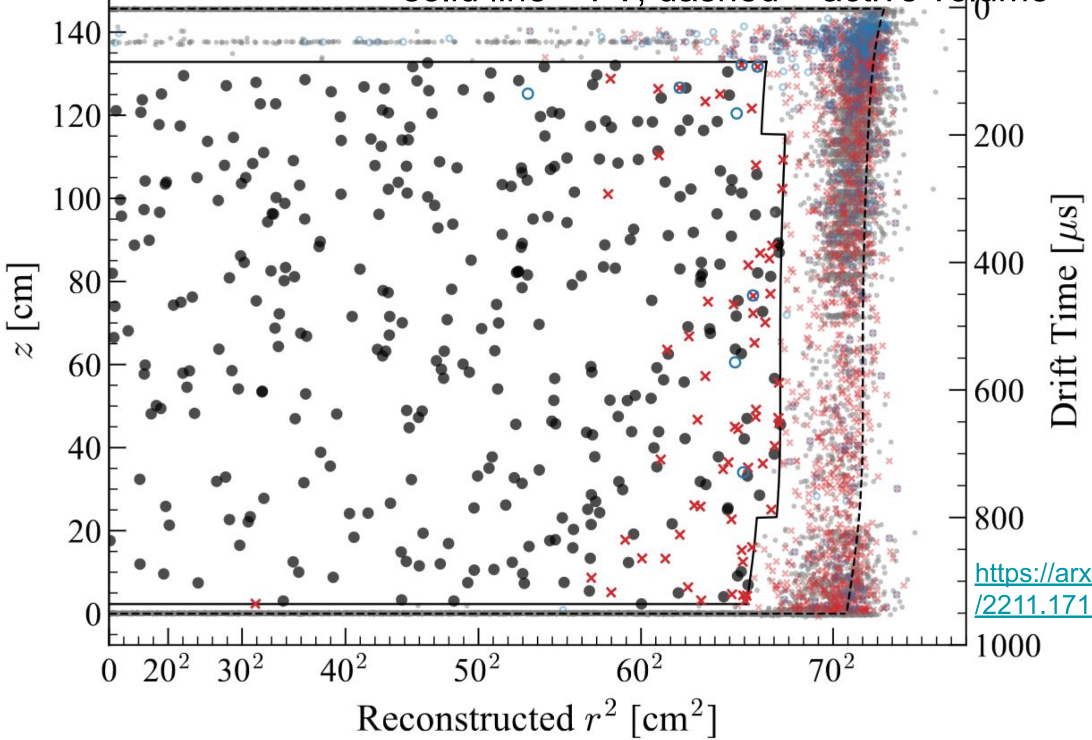
(post all cuts) https://arxiv.org/abs/2207.03764

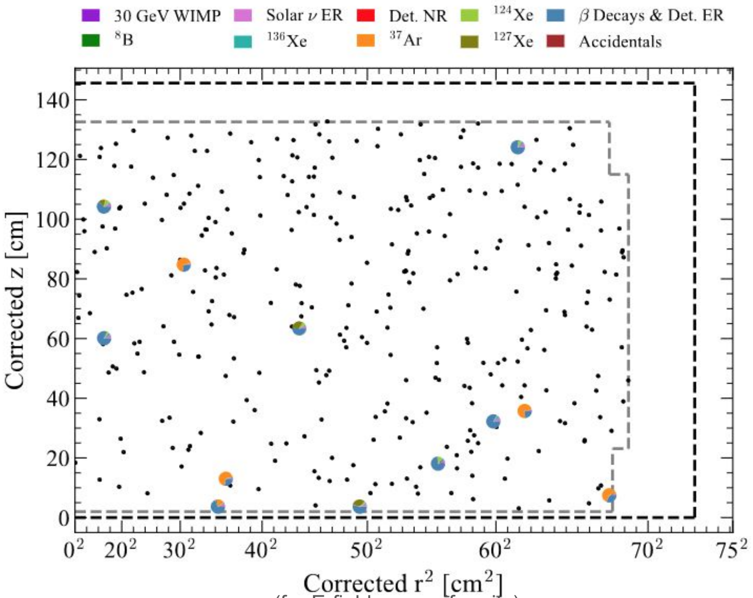
red x <- skin

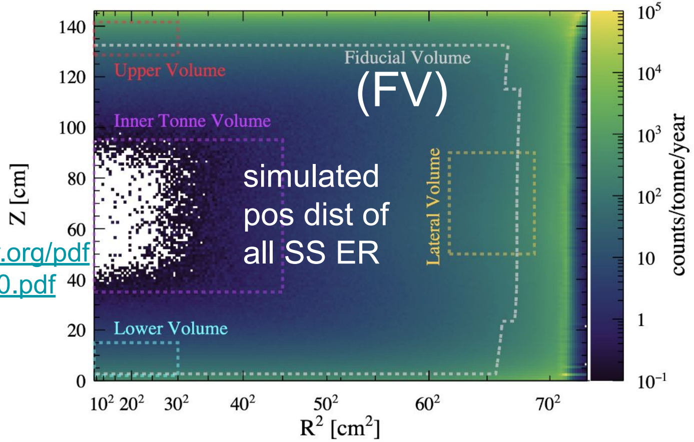
blue circle <- OD vetoed

black (gray) points show the data inside (outside) of the FV.

solid line = FV; dashed = active volume



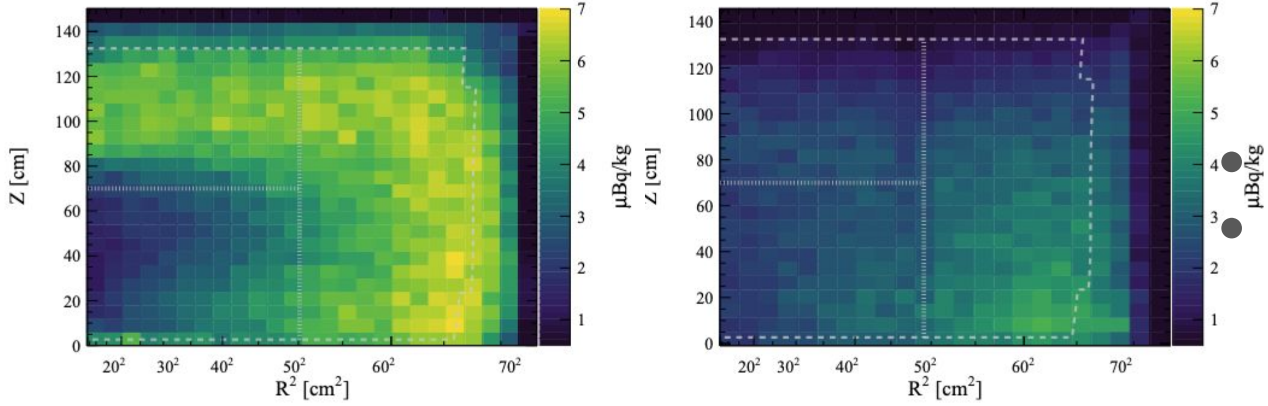




https://arxiv.org/pdf/2211.17120.pdf

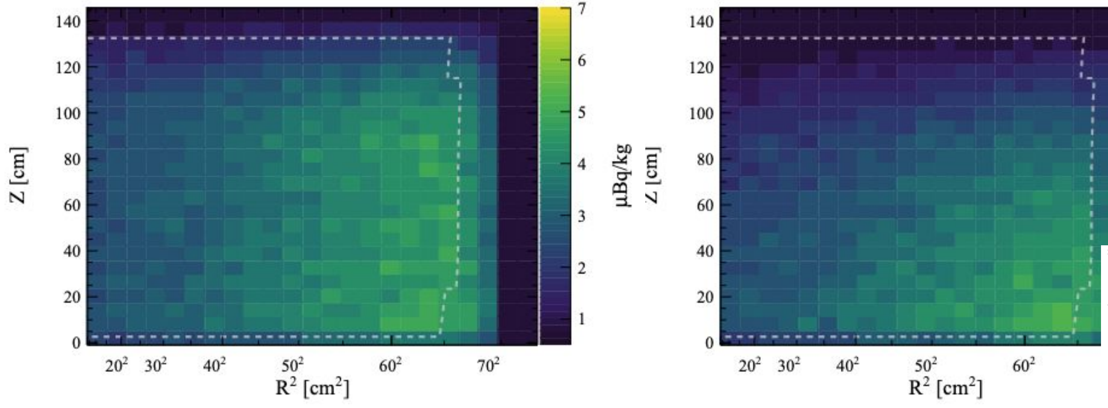
Actual vs. sim distributions<-

- of selected ^{222}Rn daughters
- ^{222}Rn's distribution can be considered to be almost the same as that of ^{218}Po (in a)
- For the observed distributions, two additional dotted lines further separate the FV into upper, lower & outer regions, for the table
  - To quantify non-uniformity



(a) Observed ^{218}Po Distribution (b) Observed ^{214}Po Distribution

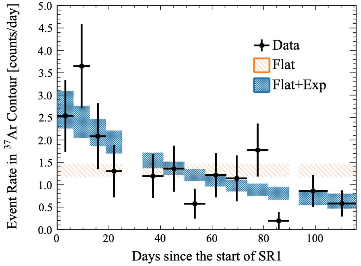
https://arxiv.org/pdf/2211.17120.pdf



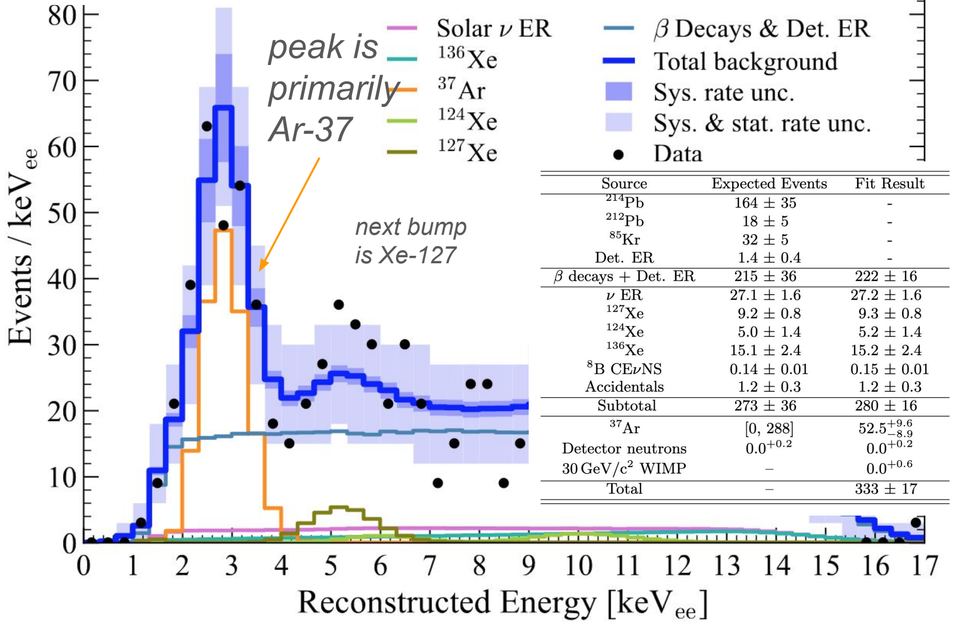
(c) Simulated ^{214}Pb Distribution (d) Simulated ^{214}Po Distributi

Radon Isotope	TPC Rate [µBq/kg]	Single Scatter Efficiency	FV Rate [µBq/kg]	Lower Rate [µBq/kg]	Upper Rate [µBq/kg]	Outer Rate [µBq/kg]
^{222}Rn	4.78 ± 0.33	0.96 ± 0.03	4.62 ± 0.87	2.64 ± 0.60	3.38 ± 0.76	6.32 ± 1.33
^{218}Po	4.82 ± 0.34	0.98 ± 0.03	4.53 ± 0.84	2.64 ± 0.60	3.69 ± 0.83	6.26 ± 1.31
^{216}Po	*$(8.2 \pm 0.6)\cdot10^{-3}$	0.56 ± 0.25	$(4.69 \pm 3.15)\cdot10^{-3}$	$(6.43 \pm 4.39)\cdot10^{-4}$	$(2.48 \pm 1.69)\cdot10^{-3}$	$(7.63 \pm 5.18)\cdot10^{-3}$
^{214}Po	2.65 ± 0.19	$(1.14 \pm 0.38)\cdot10^{-3}$	2.07 ± 0.95	0.76 ± 0.45	1.09 ± 0.65	3.37 ± 1.99
^{212}Po	$(3.7 \pm 0.3)\cdot10^{-2}$	0.34 ± 0.08	$(1.49 \pm 0.73)\cdot10^{-2}$	$(5.72 \pm 2.89)\cdot10^{-3}$	$(1.43 \pm 0.72)\cdot10^{-2}$	$(2.89 \pm 1.44)\cdot10^{-2}$

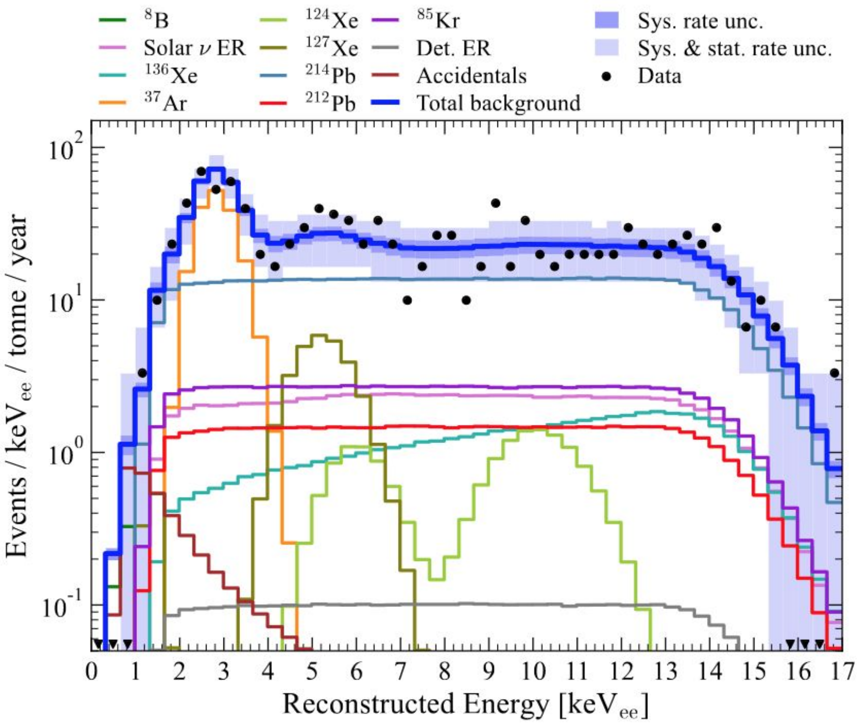
Backgrounds in Science Run 1: *E* (Energy) Histograms



Selection description	Events after selection
All triggers	1.1×10^8
Analysis time hold-offs	6.0×10^7
Single scatter	1.0×10^7
Region-of-interest	1.8×10^5
Analysis cuts for accidentals	3.1×10^4
Fiducial volume	416
OD and Skin vetoes	335

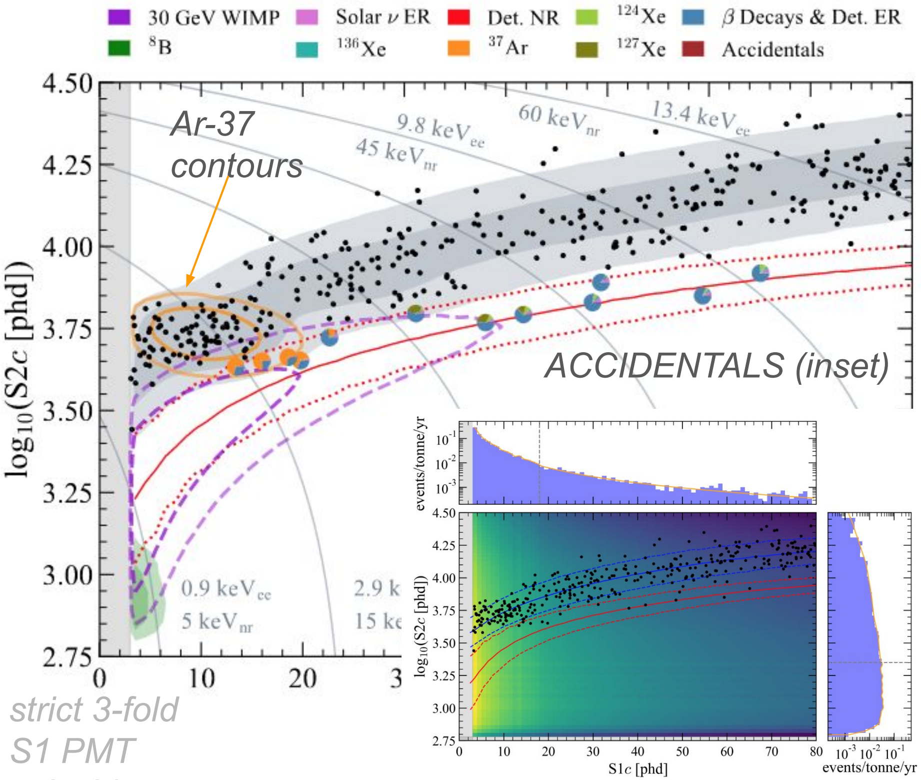


Source	Expected Events	Fit Result
^{214}Pb	164 ± 35	-
^{212}Pb	18 ± 5	-
^{85}Kr	32 ± 5	-
Det. ER	1.4 ± 0.4	-
β decays + Det. ER	215 ± 36	222 ± 16
ν ER	27.1 ± 1.6	27.2 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.1 ± 2.4	15.2 ± 2.4
^{8}B CEνNS	0.14 ± 0.01	0.15 ± 0.01
Accidentals	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



At right, the same information is conveyed, except a bit more, on a log-y scale, and normalized to per tonne per year per keV

The Backgrounds in Science Run 1: S2 versus S1



strict 3-fold
S1 PMT
coincidence

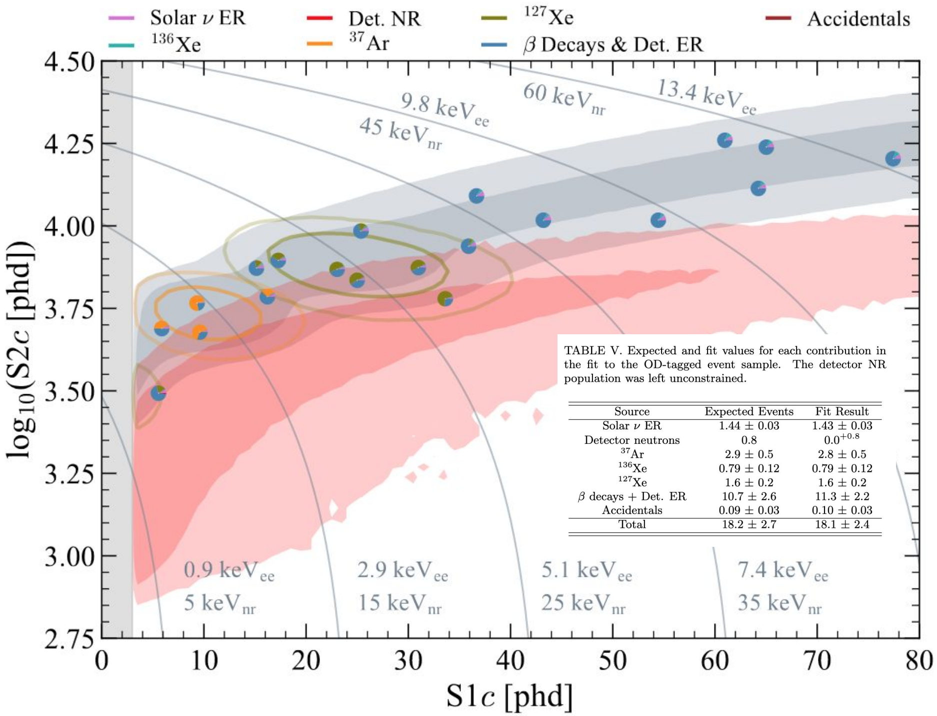
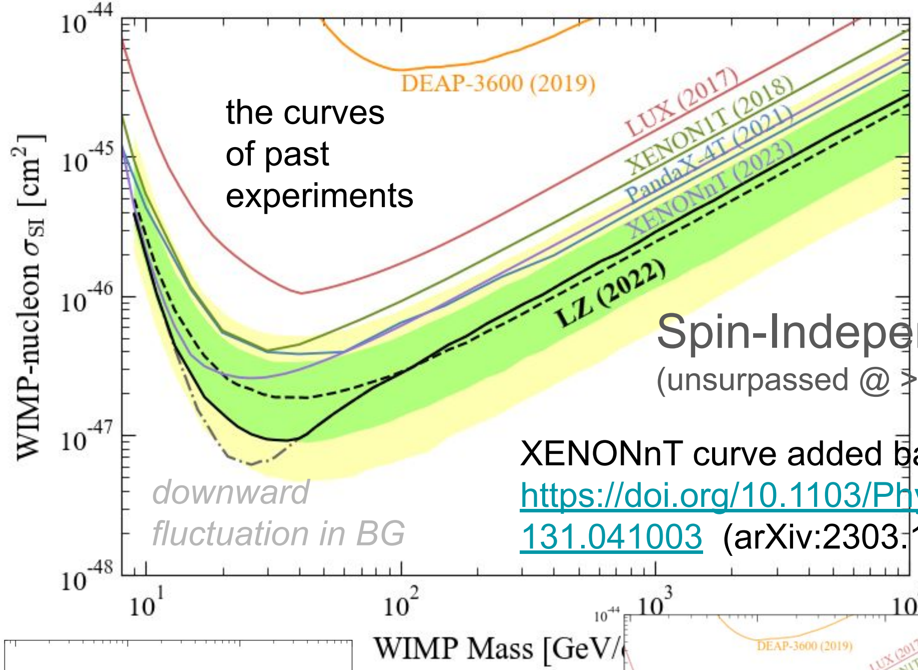


TABLE V. Expected and fit values for each contribution in the fit to the OD-tagged event sample. The detector NR population was left unconstrained.

Source	Expected Events	Fit Result
Solar ν ER	1.44 ± 0.03	1.43 ± 0.03
Detector neutrons	0.8	$0.0^{+0.8}$
^{37}Ar	2.9 ± 0.5	2.8 ± 0.5
^{136}Xe	0.79 ± 0.12	0.79 ± 0.12
^{127}Xe	1.6 ± 0.2	1.6 ± 0.2
β decays + Det. ER	10.7 ± 2.6	11.3 ± 2.2
Accidentals	0.09 ± 0.03	0.10 ± 0.03
Total	18.2 ± 2.7	18.1 ± 2.4

LZ Constraints on the WIMP Interaction Strengths (SI and SD)



the curves of past experiments

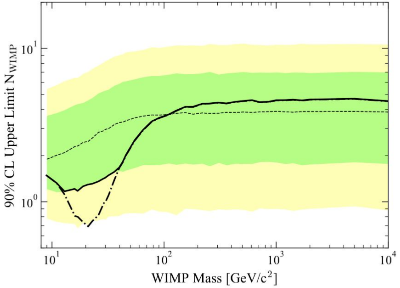
downward fluctuation in BG

<- SI

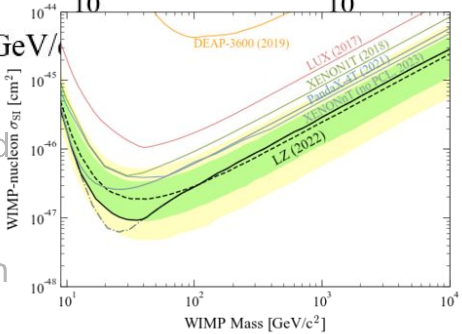
SD –>

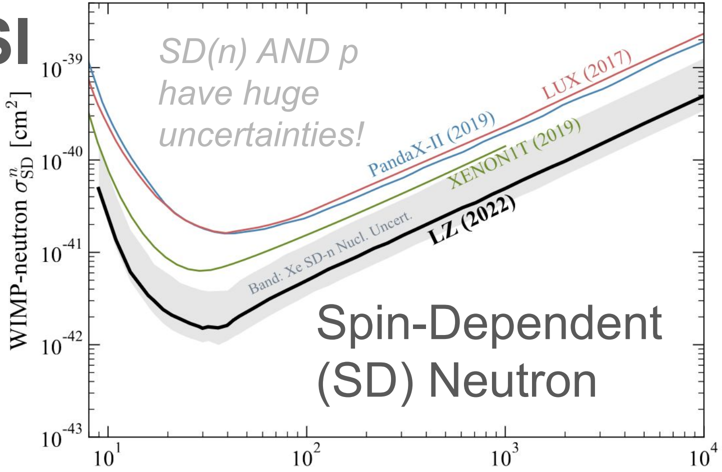
Spin-Independent
(unsurpassed @ >10 GeV)

XENONnT curve added based on https://doi.org/10.1103/PhysRevLett.131.041003 (arXiv:2303.14729)



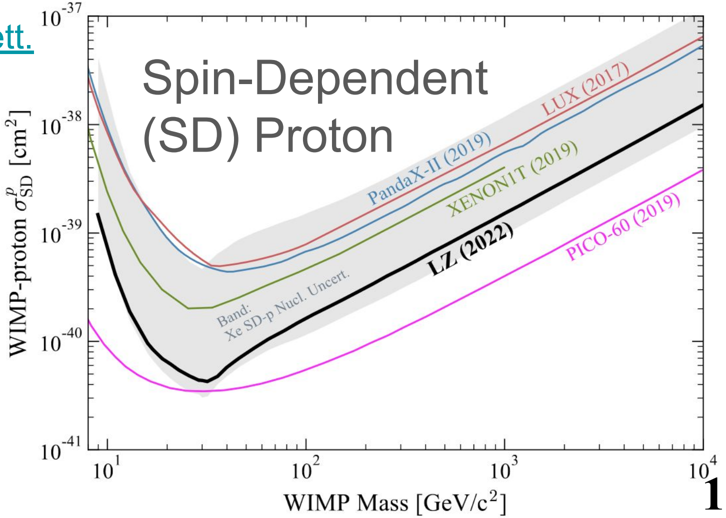
⇒ nT adjusted for more direct comparison





SD(n) AND p have huge uncertainties!

Spin-Dependent (SD) Neutron



Spin-Dependent (SD) Proton

But Wait…There's More! Other LZ Papers

- Energy extension for EFT-motivated dark matter searches (higher-energy NR)
- Low-energy ER
    - Axions and ALPs (axion-like particles)
    - Neutrino physics
    - The Migdal Effect
- High-energy ER
    - Ultra-heavy dark matter

- Ask me questions please, I have plenty of backup slides on these analyses :-)

Conclusions, and Then Q & A

- First off, let us remind ourselves that we are here to make DISCOVERIES
  - Not just set an umpteen number of limits, which can rapidly become very self-reinforcing / sad
- No dark matter conclusively observed yet, but we have to keep on trying, because of mountains of evidence from astronomy, astrophysics, cosmology
  - We're still orders of magnitude away from the neutrino fog
- Null results are extremely valuable: just ask Michelson and Morley for one
- Lack of discovery of vanilla WIMPs in the traditional parameter space motivates looking elsewhere; hence, LZ is conducting searches high and low (in mass)
  - Future work will include, but is not limited to, S2-only limit, WIMP-pion scattering, supernovae..
- LZ running stably for now, with possible future upgrades: HydroX? Crystallize?
- What are (or would be) dark matter particles good for – in practical terms?
  - The same question could have been asked of electricity (Faraday) or of antimatter (PET scans)
  - Right now we're just extending the boundaries of human knowledge, as with Higgs physics
- But we'll have to find it first!! LUX-ZEPLIN is boldly going into new territories

LZ (LUX-ZEPLIN) Collaboration, 38 Institutions

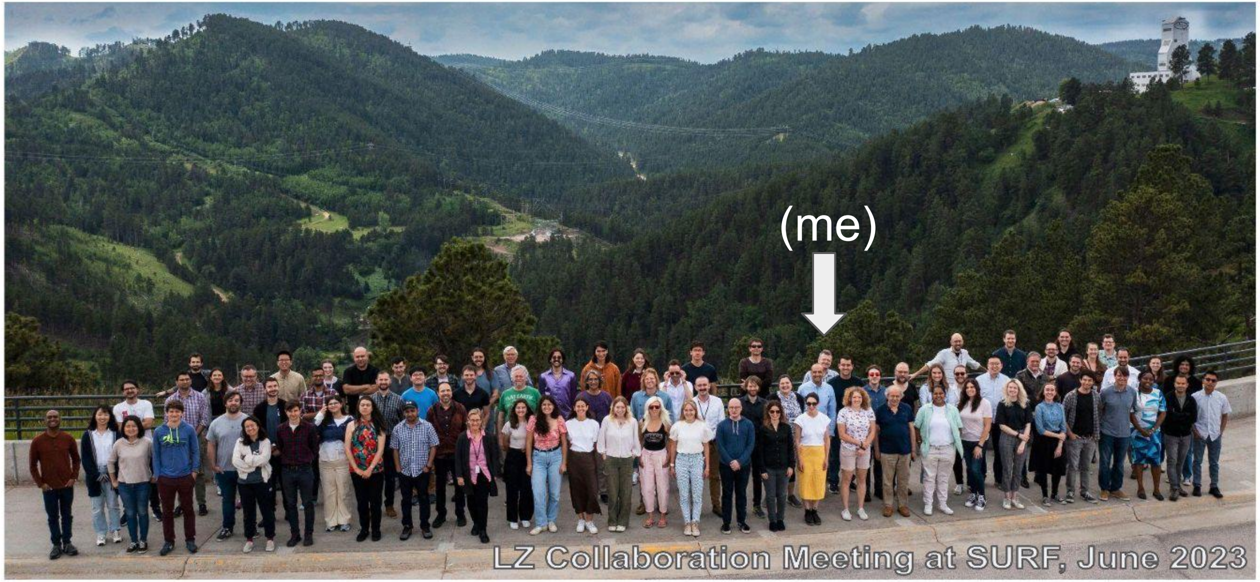
@lzdarkmatter

https://lz.lbl.gov/

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 (me)
- 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

FCT Fundação para a Ciência e a Tecnologia

Sanford Underground Research Facility
South Dakota Science and Technology Authority

Institute for Basic Science

Thanks to our sponsors and participating institutions!

For I dipped into the future, far as human eye could see, Saw the Vision of the world, and all the wonder that would be.

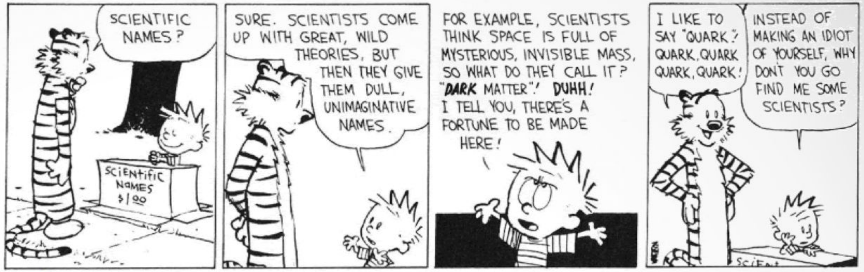
~ Alfred Lord Tennyson

(backup slides to follow)

BACKUP

Dark Matter

= ??????????



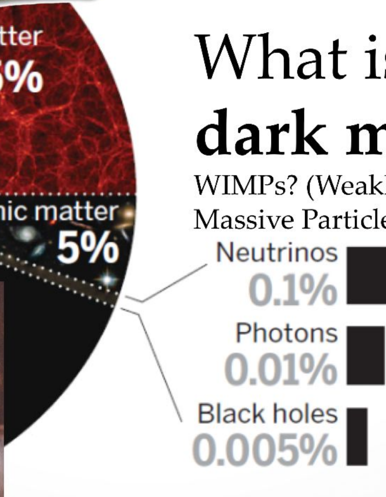
Calvin & Hobbes, by Bill Watterson

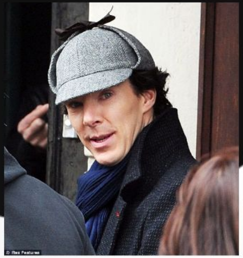
The multiple components that compose our universe

Current composition (as the fractions evolve with time)

MONNDDD

(zombie)

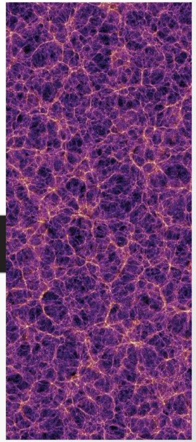




BBC

A Big Hole in Our Knowledge

The Millennium Simulation of Large Scale Structure



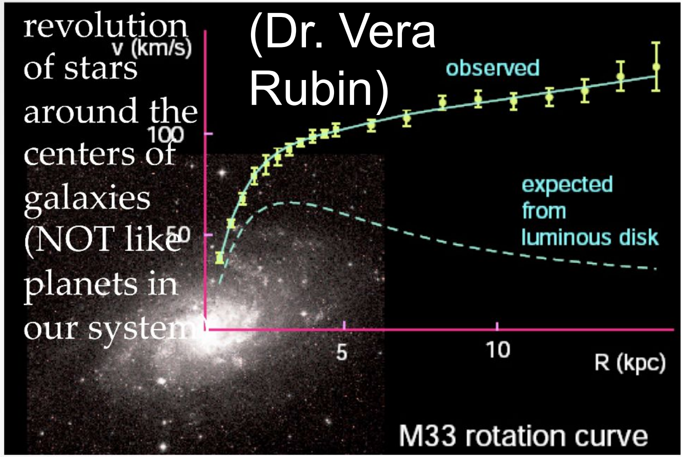
What is this
dark matter?

WIMPs? (Weakly Interacting Massive Particles)

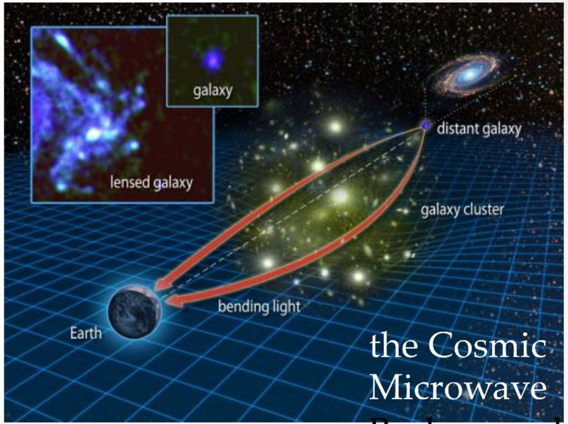
http://cdn.phys.org/newman/gfx/news/hires/2015/thedarksideo.png

The Observational Evidence

revolution of stars around the centers of galaxies (NOT like planets in our system) (Dr. Vera Rubin)

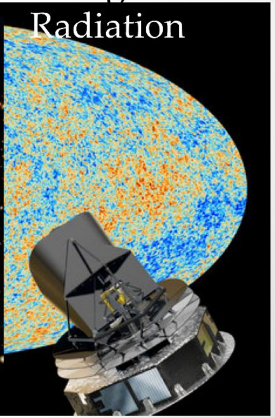


weak gravitational lensing

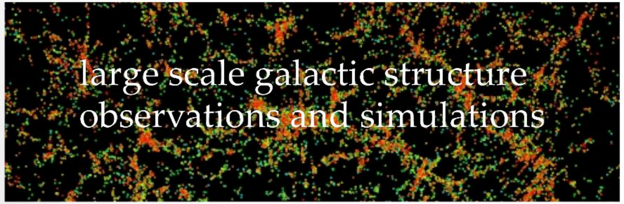


Credit: Karen Teramura, University of Hawai'i Institute for Astronomy

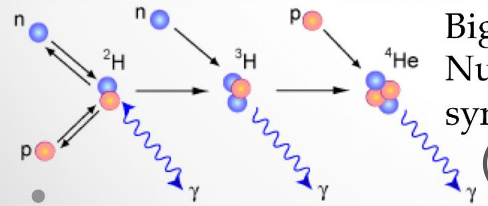
the Cosmic Microwave Background Radiation (CMB)



large scale galactic structure observations and simulations



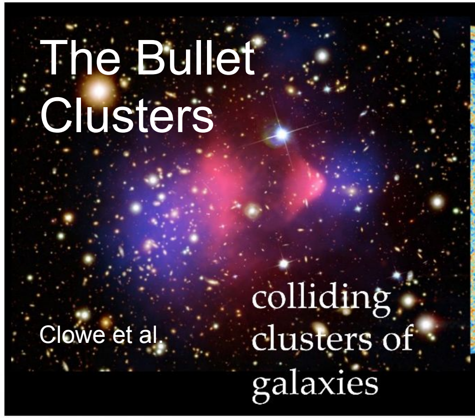
Big Bang Nucleo-synthesis (BBN)



The Bullet Clusters

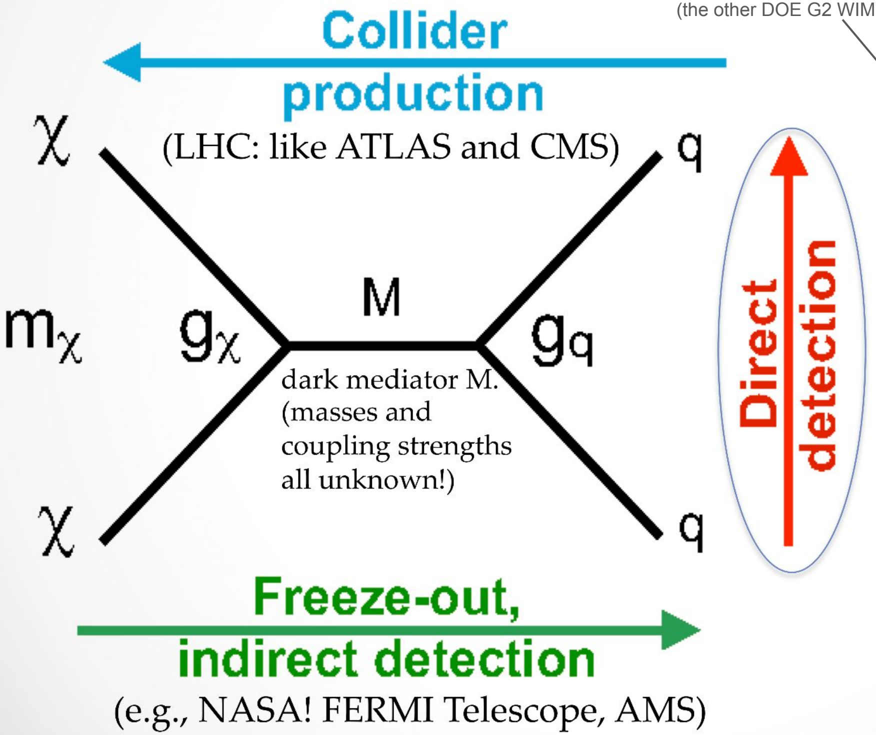
Clowe et al.

colliding clusters of galaxies

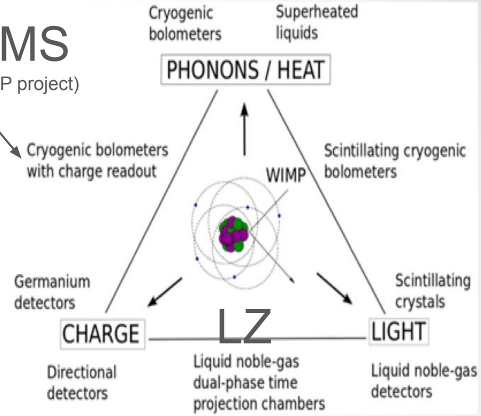


PLANCK

How to Look? Directly



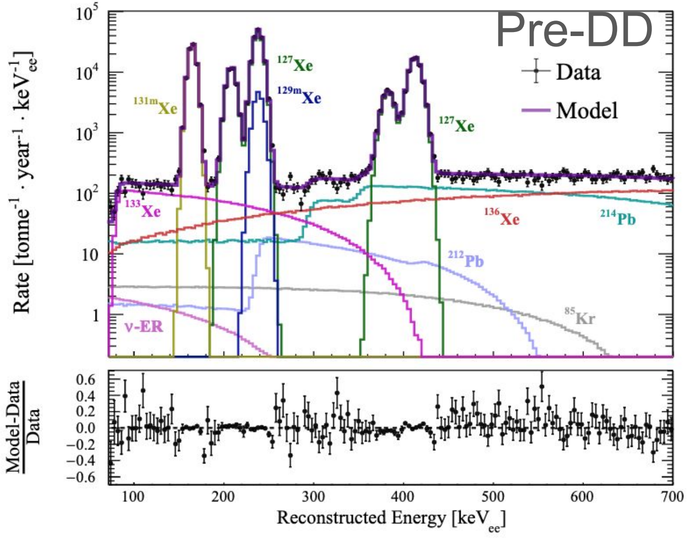
SuperCDMS
(the other DOE G2 WIMP project)

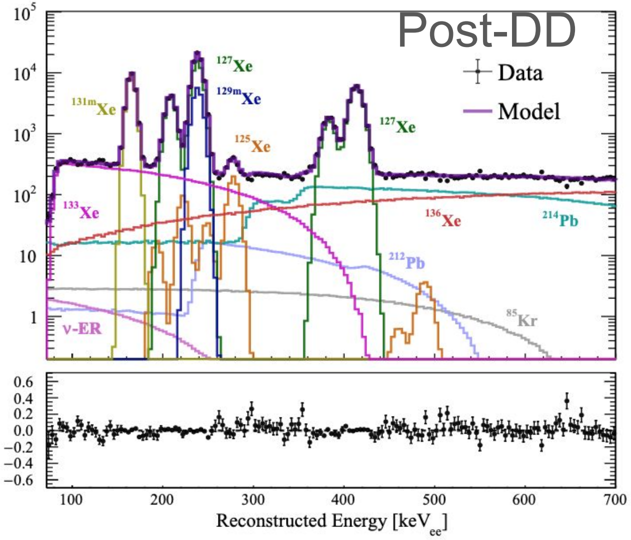


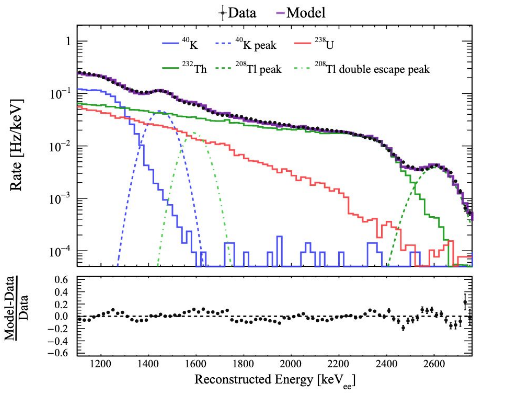
LZ

("billiard ball" collisions. Still need mediator. Higgs perhaps?)

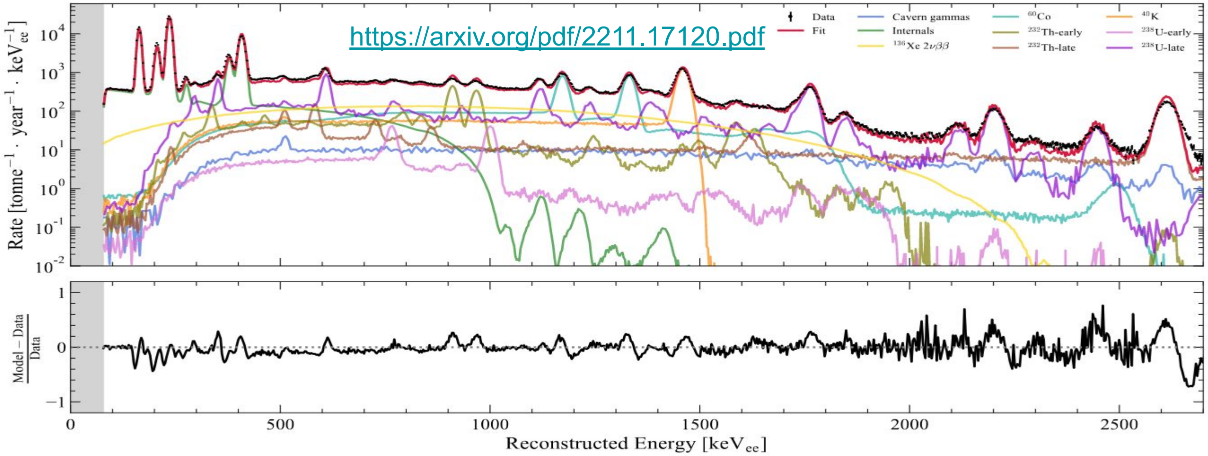
(actual force = ???)







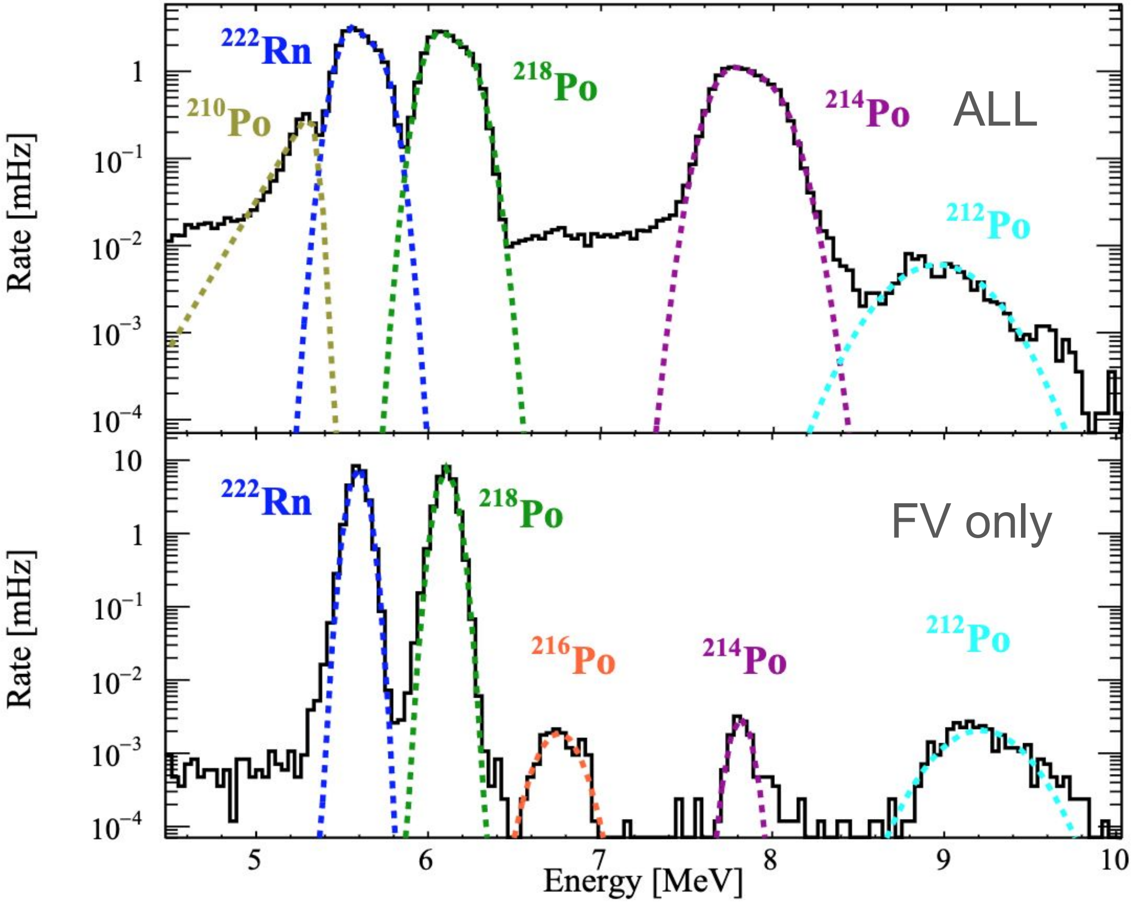
Isotope/ Chain	Predicted Rate (Hz/keV)	Fitted Rate (Hz/keV)	Ratio (Fitted/ Predicted)
^{40}K	4.2 ± 1.1	2.79 ± 0.40	0.67 ± 0.20
^{238}U	3.9 ± 2.0	1.95 ± 0.53	0.49 ± 0.29
^{232}Th	6.1 ± 1.4	4.51 ± 0.43	0.74 ± 0.18



https://arxiv.org/pdf/2211.17120.pdf

- Top left: fit results for the inner 1-tonne TPC region (SR1 exposure)
- Top right: Fit to cavern gamma spectra from technical commissioning
  - when the TPC was filled with GXe and the water tank and OD were empty
- Left: Fitted (SR1) detector component spectra (FV)

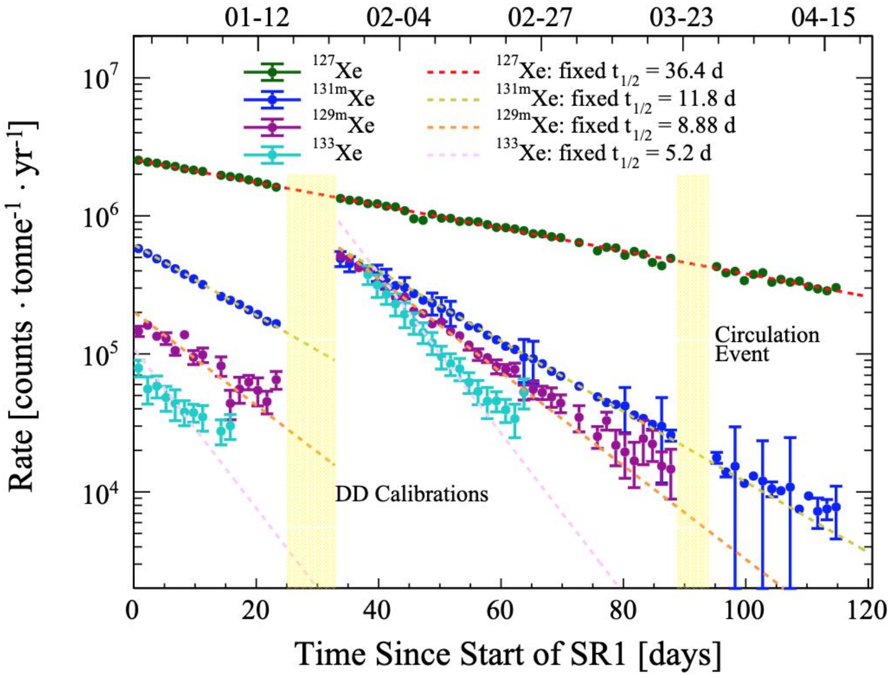
Radon, U, Th,...



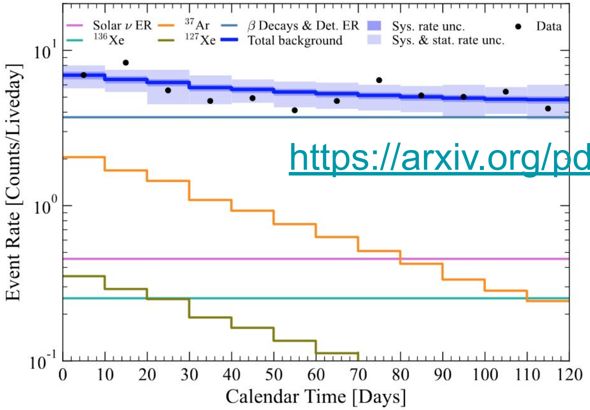
Isotope/ Chain	Region	Screening estimate [Bq]	Best fit [Bq]
^{60}Co	Top	1.13 ± 0.11	1.05 ± 0.11
	Side	1.18 ± 0.12	1.12 ± 1.02
	Bottom	0.81 ± 0.08	1.53 ± 0.19
	Total	3.11 ± 0.18	3.71 ± 1.04
^{40}K	Top	7.63 ± 0.76	2.94 ± 1.66
	Side	2.56 ± 0.26	6.32 ± 0.61
	Bottom	6.54 ± 0.65	5.58 ± 2.19
	Total	16.73 ± 1.04	14.85 ± 2.81
^{232}Th-early	Top	0.28 ± 0.03	0.33 ± 0.29
	Side	0.66 ± 0.07	0.66 ± 0.49
	Bottom	0.22 ± 0.02	0.23 ± 0.17
	Total	1.16 ± 0.07	1.22 ± 0.59
^{232}Th-late	Top	0.25 ± 0.02	0.11 ± 0.16
	Side	1.05 ± 0.10	2.57 ± 1.75
	Bottom	0.30 ± 0.03	0.32 ± 0.27
	Total	1.59 ± 0.11	3.00 ± 1.78
^{238}U-early	Top	2.37 ± 0.24	3.70 ± 1.80
	Side	1.99 ± 0.20	3.92 ± 1.53
	Bottom	1.86 ± 0.19	2.72 ± 1.40
	Total	6.21 ± 0.36	10.34 ± 2.75
^{238}U-late	Top	0.84 ± 0.08	0.63 ± 0.30
	Side	0.54 ± 0.05	3.01 ± 0.61
	Bottom	0.95 ± 0.09	1.28 ± 0.73
	Total	2.32 ± 0.14	4.92 ± 1.00

cumulative source activities for different groupings of sources used in the FV fit. Best fit #s were derived from that: lower left from the last slide.

The Time Dependence of the LZ Backgrounds



https://arxiv.org/pdf/2211.17120.pdf



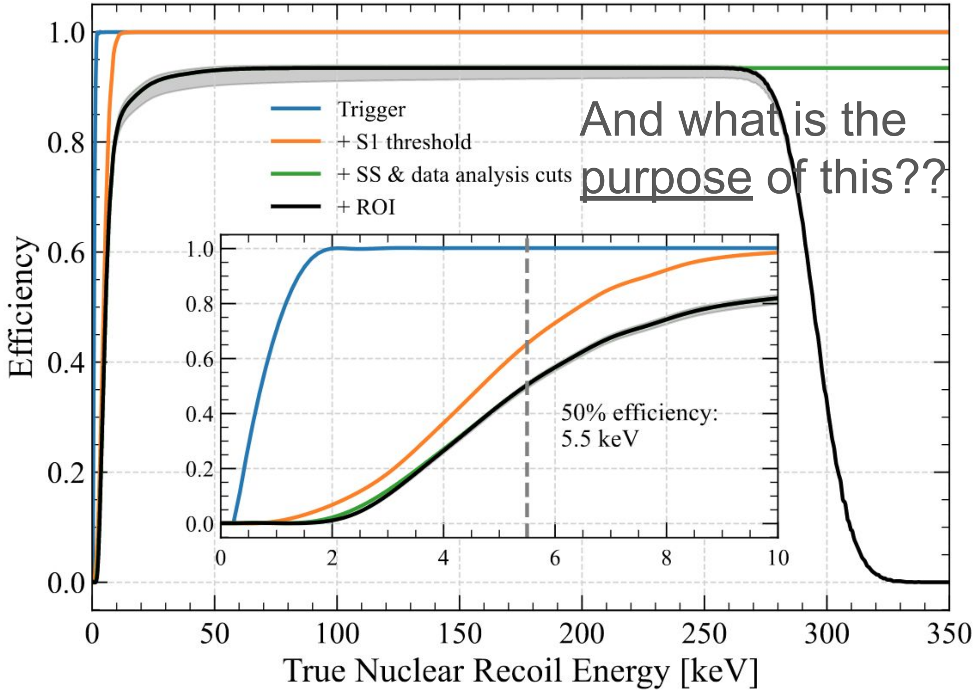
https://arxiv.org/pdf/2307.15753.pdf

Component	Half-life [days]	Pre-DD Fit [µBq/kg]	Post-DD Fit [µBq/kg]
^{127}Xe	36.4	92.88 ± 0.38	89.65 ± 0.48
^{131m}Xe	11.8	18.87 ± 0.13	108.11 ± 0.74
^{129m}Xe	8.9	4.91 ± 0.23	193.04 ± 6.93
^{133}Xe	5.2	2.01 ± 0.11	1467.15 ± 22.21
^{125}Xe[a]	0.7	-	26.70 ± 1.74
^{214}Pb	-	3.05 ± 0.12	3.10 ± 0.10
^{212}Pb	-	0.13 ± 0.01	0.11 ± 0.01
^{136}Xe	-	3.89 ± 0.18	3.96 ± 0.17
^{85}Kr	-	$(4.21 \pm 0.42)\cdot 10^{-2}$	$(4.18 \pm 0.42)\cdot 10^{-2}$

[35] J. Katakura, Nuclear Data Sheets, Vol. 112, 495 (2011).

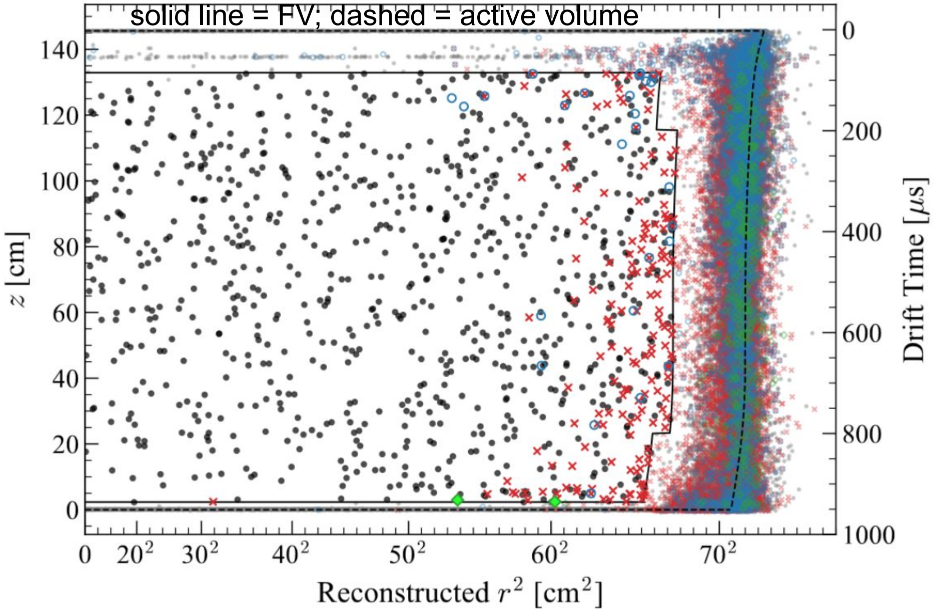
[a] Note that ^{125}Xe has a 16.9 hour half-life and is only measurable in the post-DD period [35]. With little time to homogenize, its distribution was seen to be highly non-uniform following DD calibrations, constrained to the upper third of the TPC, therefore its one-tonne estimate is not representative.

An Extension of the Energy Window



And what is the purpose of this??

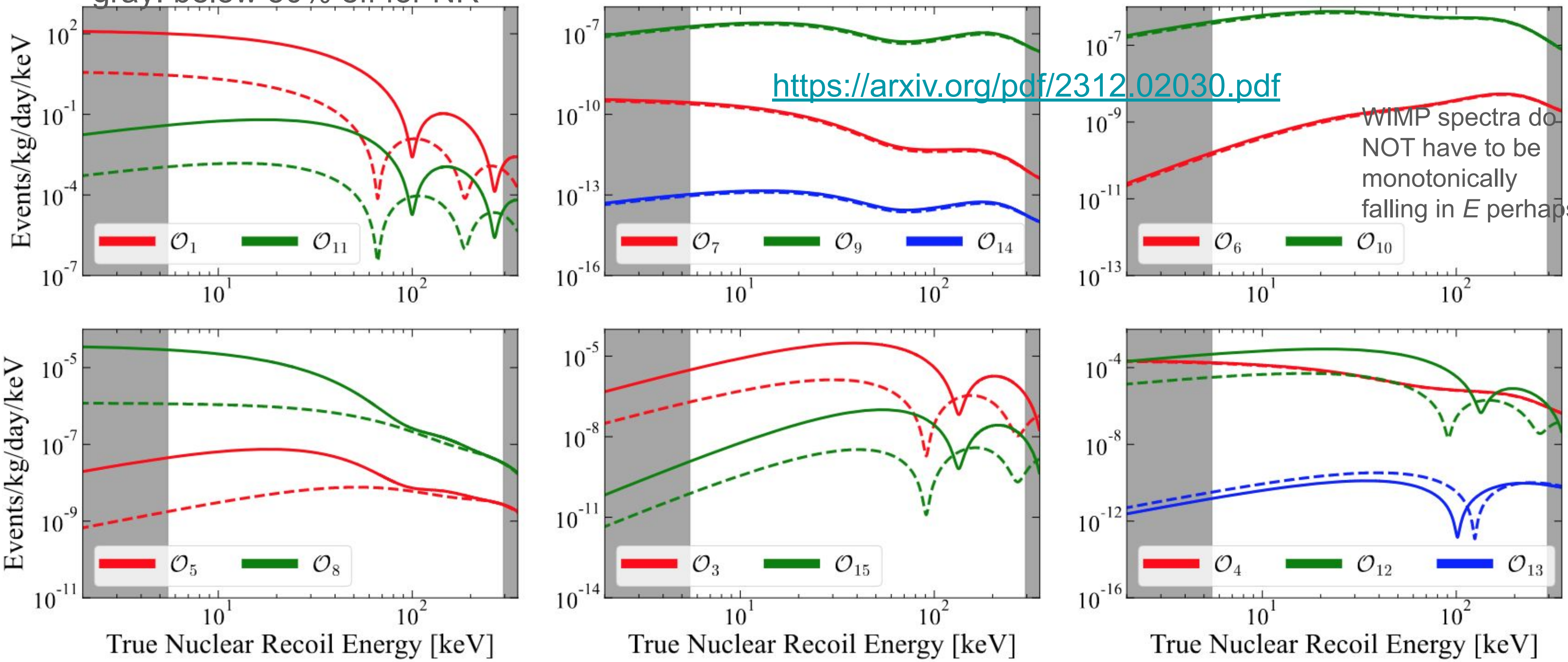
black (gray) points show the data inside (outside) of the FV, after all cuts and vetoes have been applied. red X -> skin-vetoed and blue circles -> OD-vetoed



Solid green diamonds = γ-X BDT-removed post all other cuts
Hollow indicate events outside FV classified as γ-X events

EFT (Effective Field Theory) Operator-Based Searches

gray: below 50% eff for NR

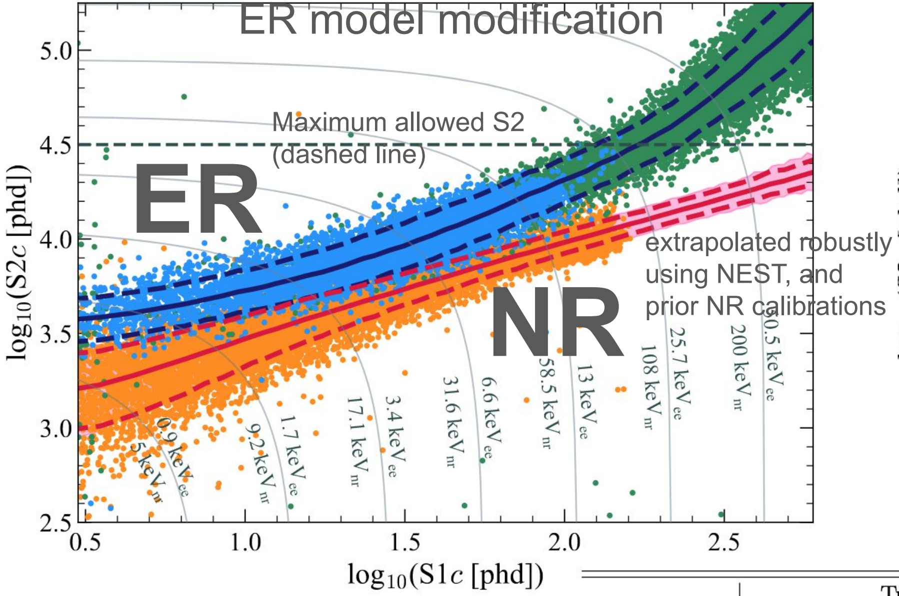


https://arxiv.org/pdf/2312.02030.pdf

WIMP spectra do NOT have to be monotonically falling in *E* perhaps!

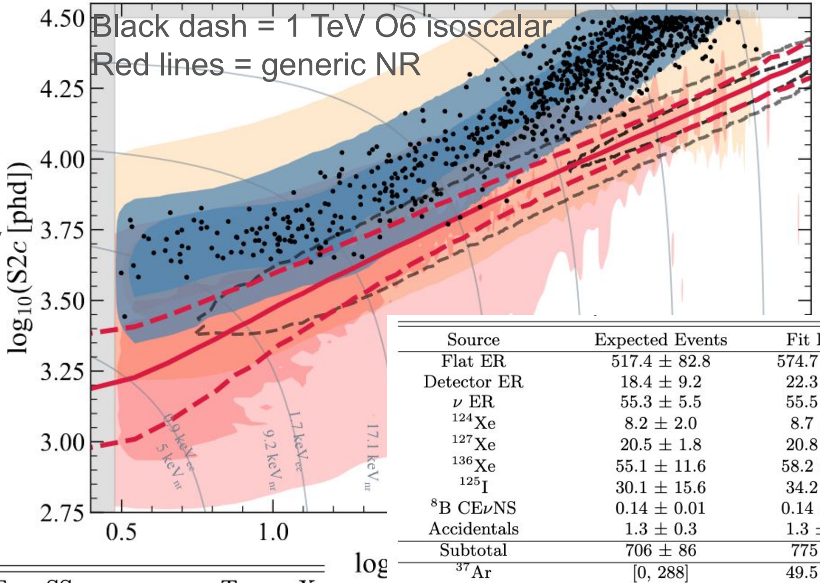
Revised S2 versus S1 Parameter Space: Backgrounds

Pb-212 in green: required ER model modification



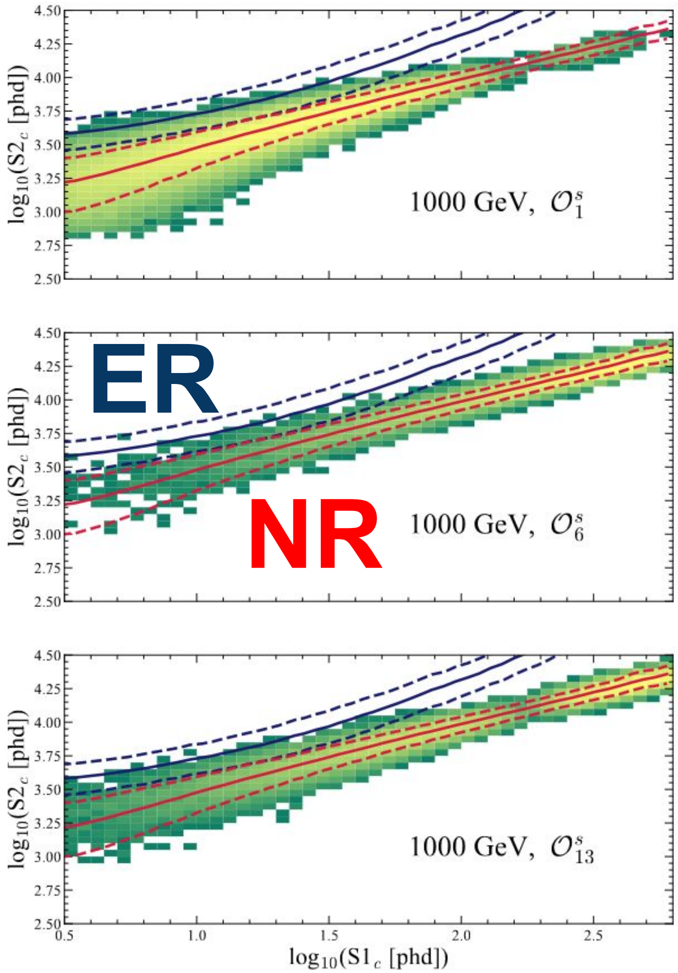
note change of S1 axis to log

Red haze = detector neutrons
Beige = detector ER
Blue = all other ER sources
Black dash = 1 TeV O6 isoscalar
Red lines = generic NR



	True SS	True γ-X
Predicted SS	99.997 ± 0.005	0.4 ± 1.2
Predicted γ-X	0.003 ± 0.005	99.6 ± 1.2

Source	Expected Events	Fit Result
Flat ER	517.4 ± 82.8	574.7 ± 30.2
Detector ER	18.4 ± 9.2	22.3 ± 8.1
ν ER	55.3 ± 5.5	55.5 ± 5.5
^{124}Xe	8.2 ± 2.0	8.7 ± 2.0
^{127}Xe	20.5 ± 1.8	20.8 ± 1.8
^{136}Xe	55.1 ± 11.6	58.2 ± 11.2
^{125}I	30.1 ± 15.6	34.2 ± 8.9
^{8}B CEνNS	0.14 ± 0.01	0.14 ± 0.01
Accidentals	1.3 ± 0.3	1.3 ± 0.03
Subtotal	706 ± 86	775 ± 34
^{37}Ar	[0, 288]	49.5 ± 9.4
Detector neutrons	$0.0^{+0.5}$	$0.0^{+1.8}$
Total	-	825 ± 36



And... Simulated Dark Matter Signals!

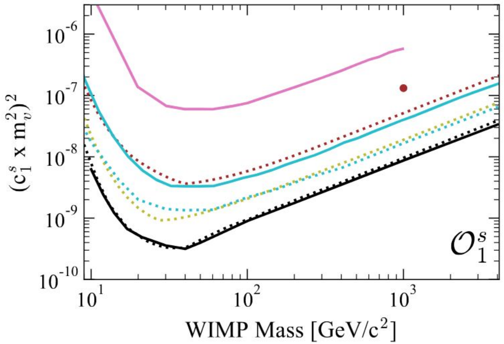
plus, a quick comparison to earlier works

Please see arXiv:2312.02030 for these references []

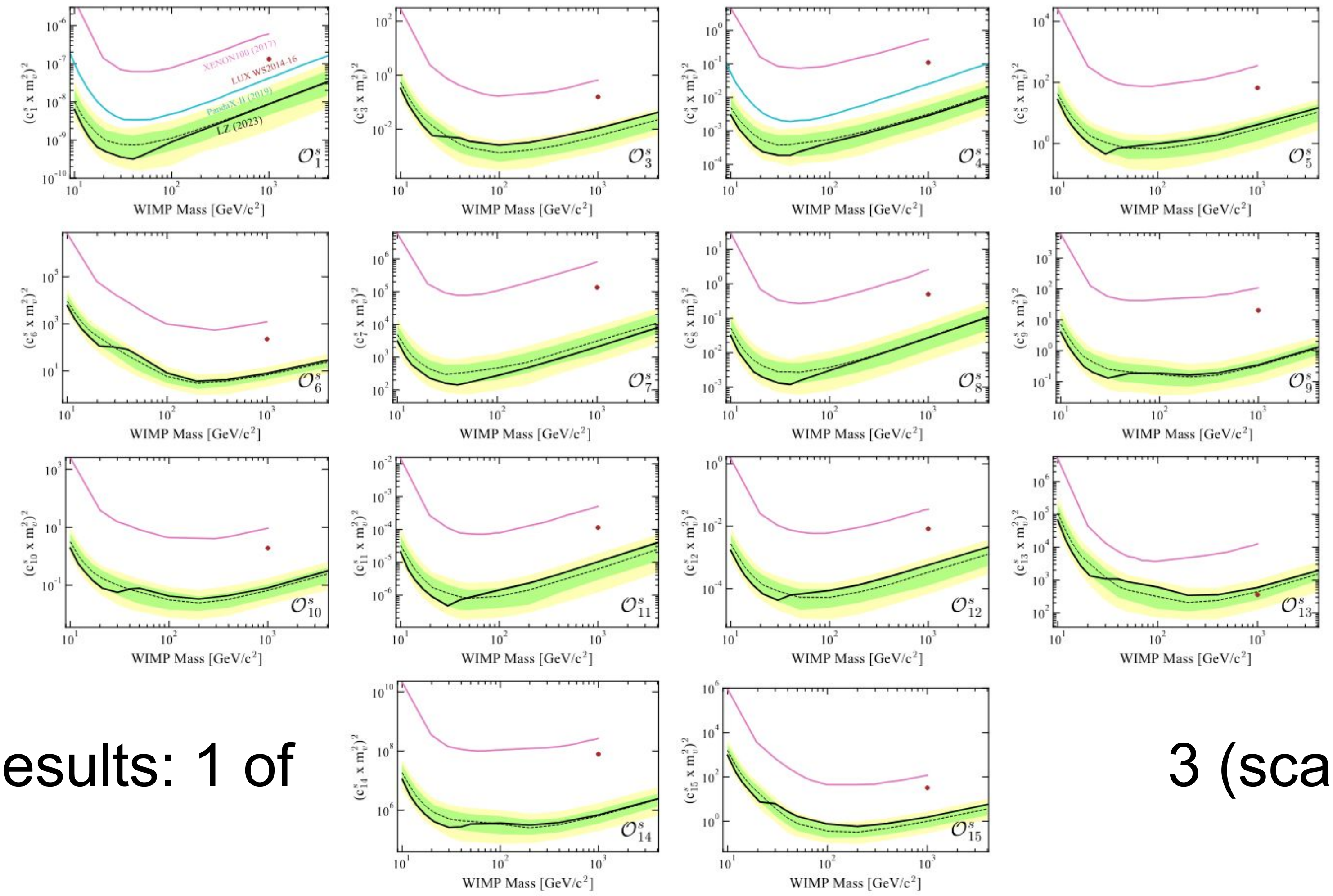
Experiment	Basis	Limit Type	Conversion in plot
Xenon100: 2017 NREFT [10]	$c^s = \frac{1}{2}(c^p + c^n)$ $c^v = \frac{1}{2}(c^p - c^n)$	$(c_i^s \times m_v^2)^2$	None
LUX: WS2014-16 NREFT [9]	$c^s = (c^p + c^n)$ $c^v = (c^p - c^n)$	$(c_i^s \times m_v^2)^2$	$\frac{1}{4}$
PandaX-II: SD EFT [8]	$c^s = \frac{1}{2}(c^p + c^n)$ $c^v = \frac{1}{2}(c^p - c^n)$	$d_5^{s/v}\ [\frac{1}{m_v^2}]$	$(d_5^s)^2$
LZ NREFT (This analysis)	$c^s = \frac{1}{2}(c^p + c^n)$ $c^v = \frac{1}{2}(c^p - c^n)$	$(c_i^{s/v} \times m_v^2)^2$	None
NRET Theory paper [14]	$c^s = \frac{1}{2}(c^p + c^n)$ $c^v = \frac{1}{2}(c^p - c^n)$	N/A	N/A
LUX: Combined 2017 SI [55]	N/A	σ_{SI}^N	$\sigma_{SI}^N \frac{\pi \cdot m_v^4}{(\frac{(\hbar c)}{GeV})^2 \mu_N^2}$
PandaX-4T: 2021 SI [56]	N/A	σ_{SI}^N	$\sigma_{SI}^N \frac{\pi \cdot m_v^4}{(\frac{(\hbar c)}{GeV})^2 \mu_N^2}$
LZ: 2023 SI [1]	N/A	σ_{SI}^N	$\sigma_{SI}^N \frac{\pi \cdot m_v^4}{(\frac{(\hbar c)}{GeV})^2 \mu_N^2}$
XENONnT: 2023 SI [2]	N/A	σ_{SI}^N	$\sigma_{SI}^N \frac{\pi \cdot m_v^4}{(\frac{(\hbar c)}{GeV})^2 \mu_N^2}$

different bases are used by everyone, complicating the ability to make comparisons (LUX no exception, despite ~same people! ;)

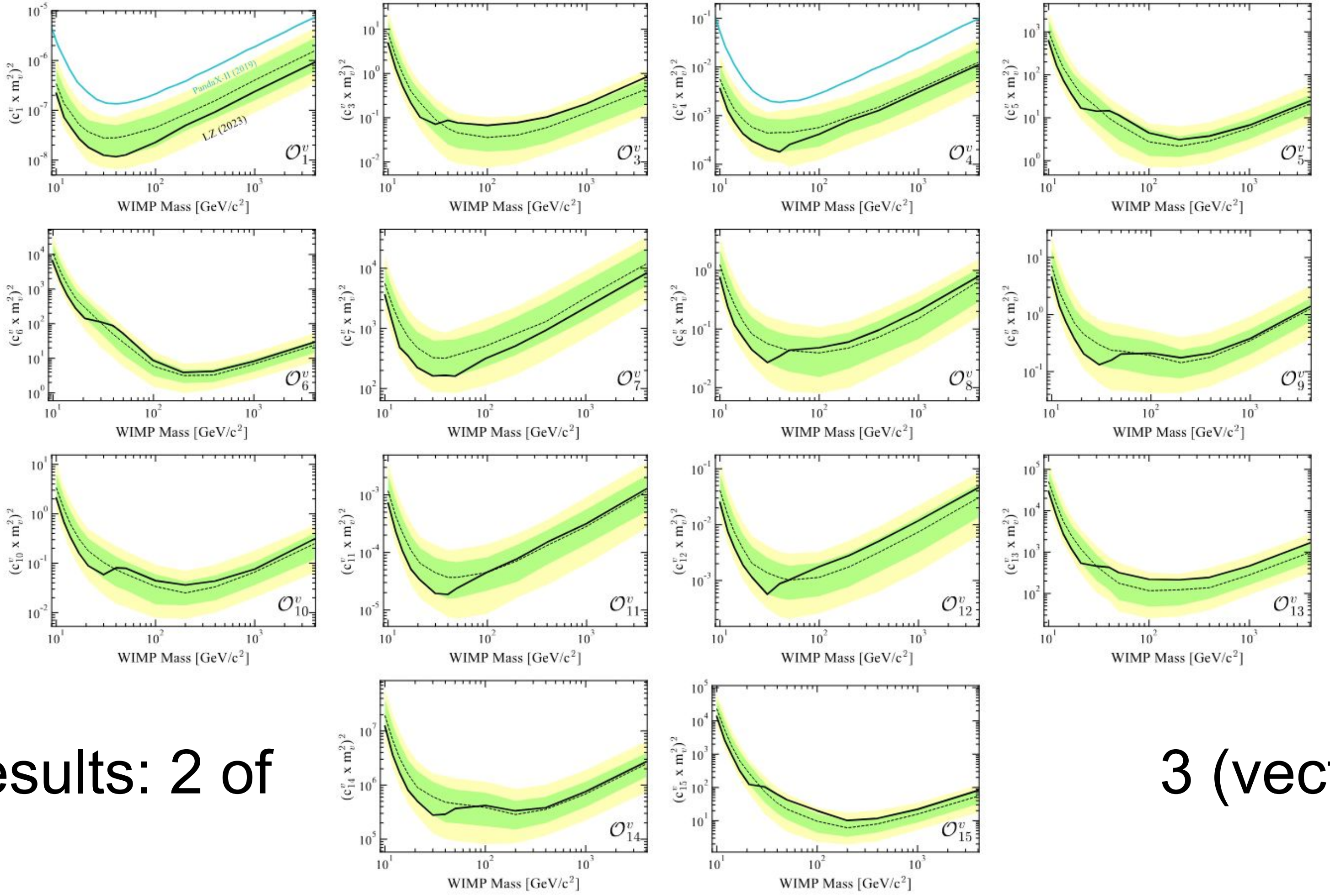
Solid lines represent the limit on O1 isoscalar from NREFT analyses: LZ i.e. this work (black), PandaX-II 2019 (blue), XENON100 (magenta), and LUX WS 2014-16 (brown point). Dotted lines represent recast SI limits, adding XENONnT (yellow dotted) and LUX full exposure (brown dotted). All at the right:

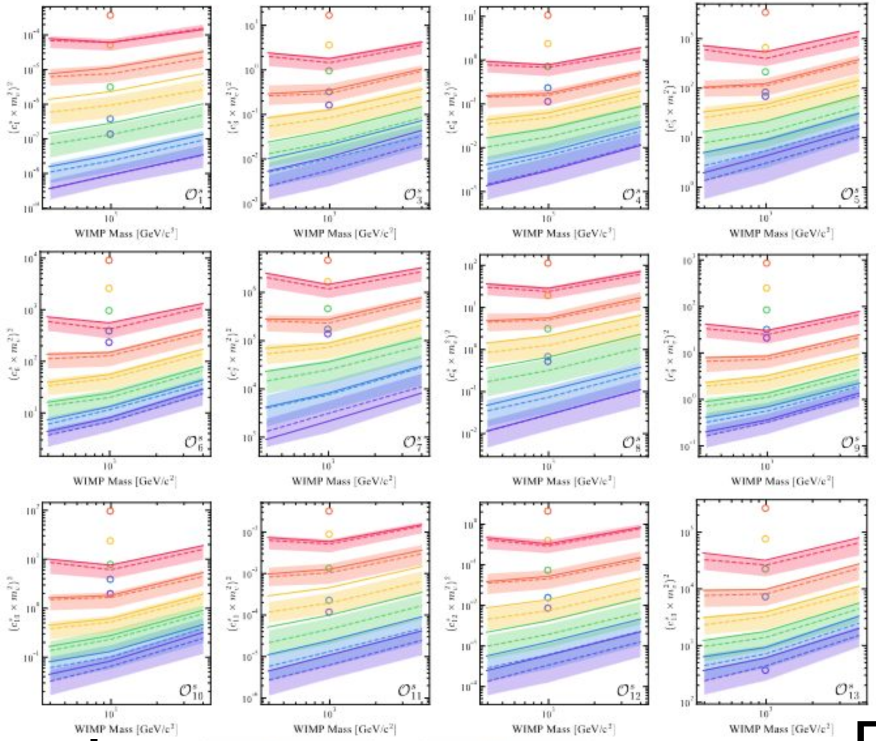


Results: 1 of 3 (scalar)

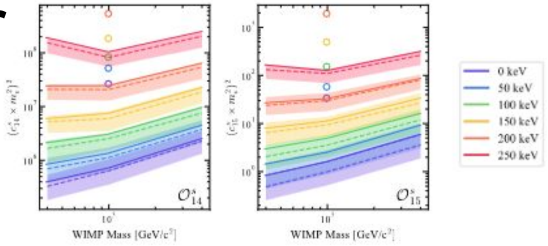


Results: 2 of 3 (vector)



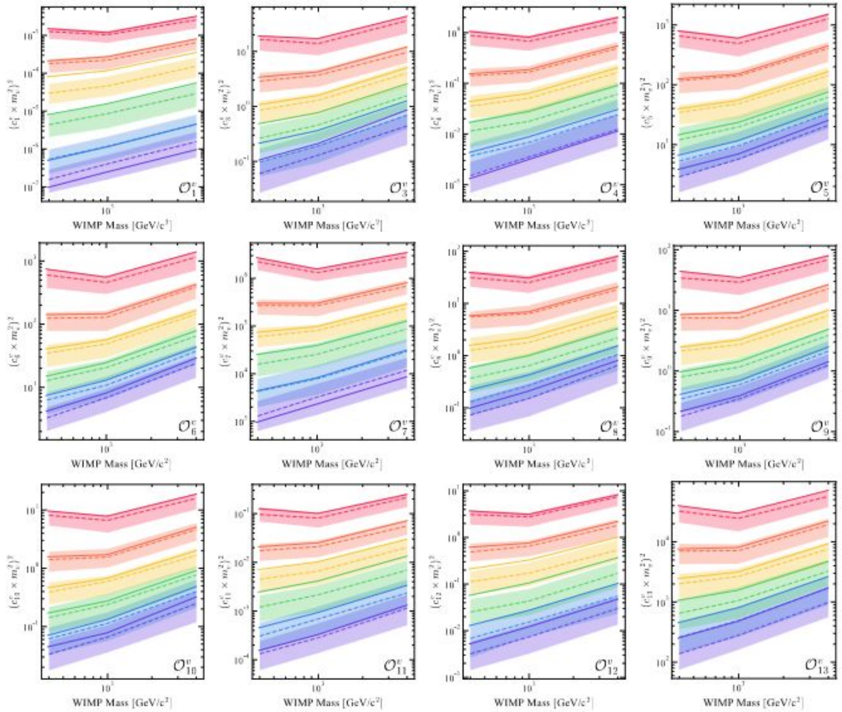


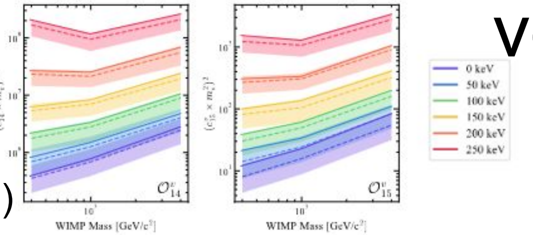
scalar



Results: 3 of 3

(mass splitting)



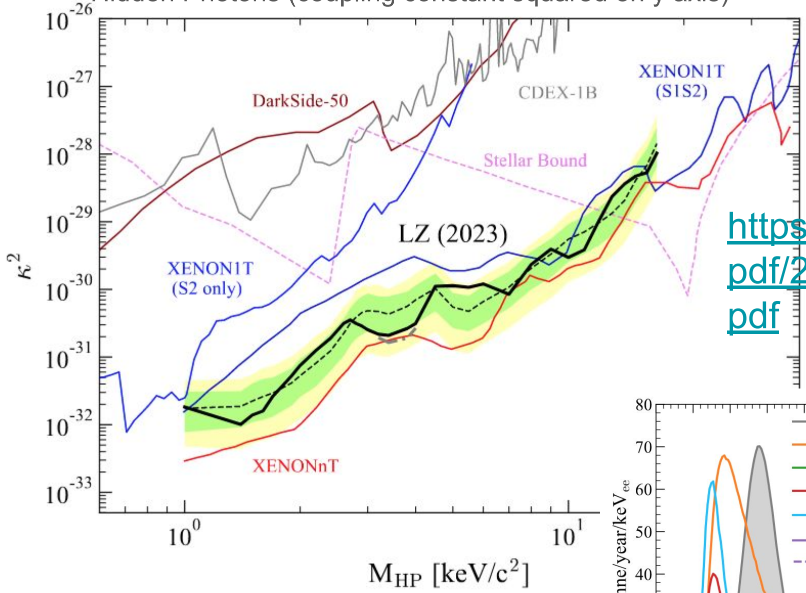


vector

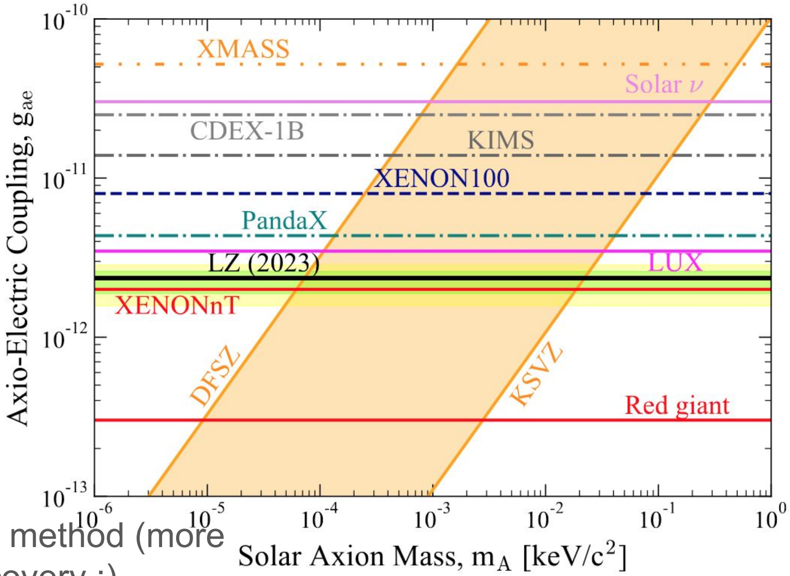
new paper brings even more to the table: https://arxiv.org/abs/2404.17666

So, What About ER?

Hidden Photons (coupling constant squared on y axis)

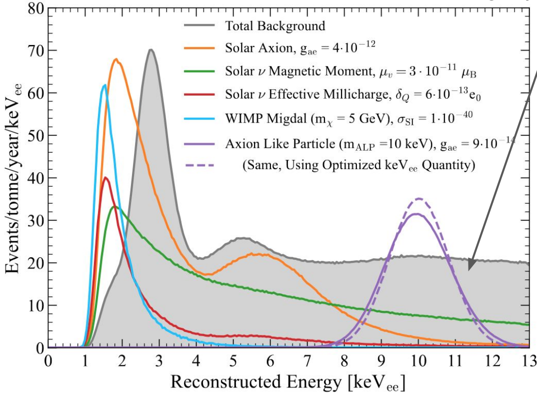


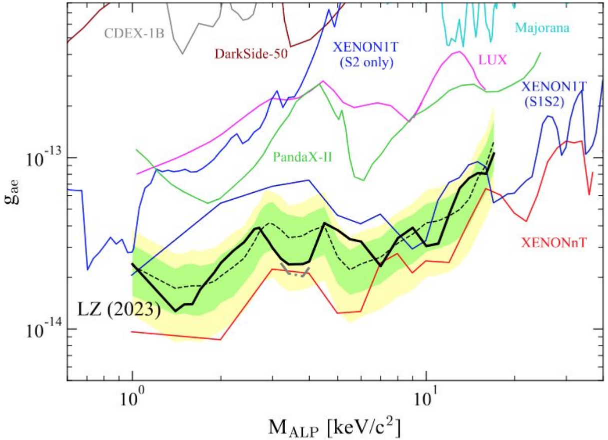
LZ can look for axions as well as axion-like particles (ALPs)



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

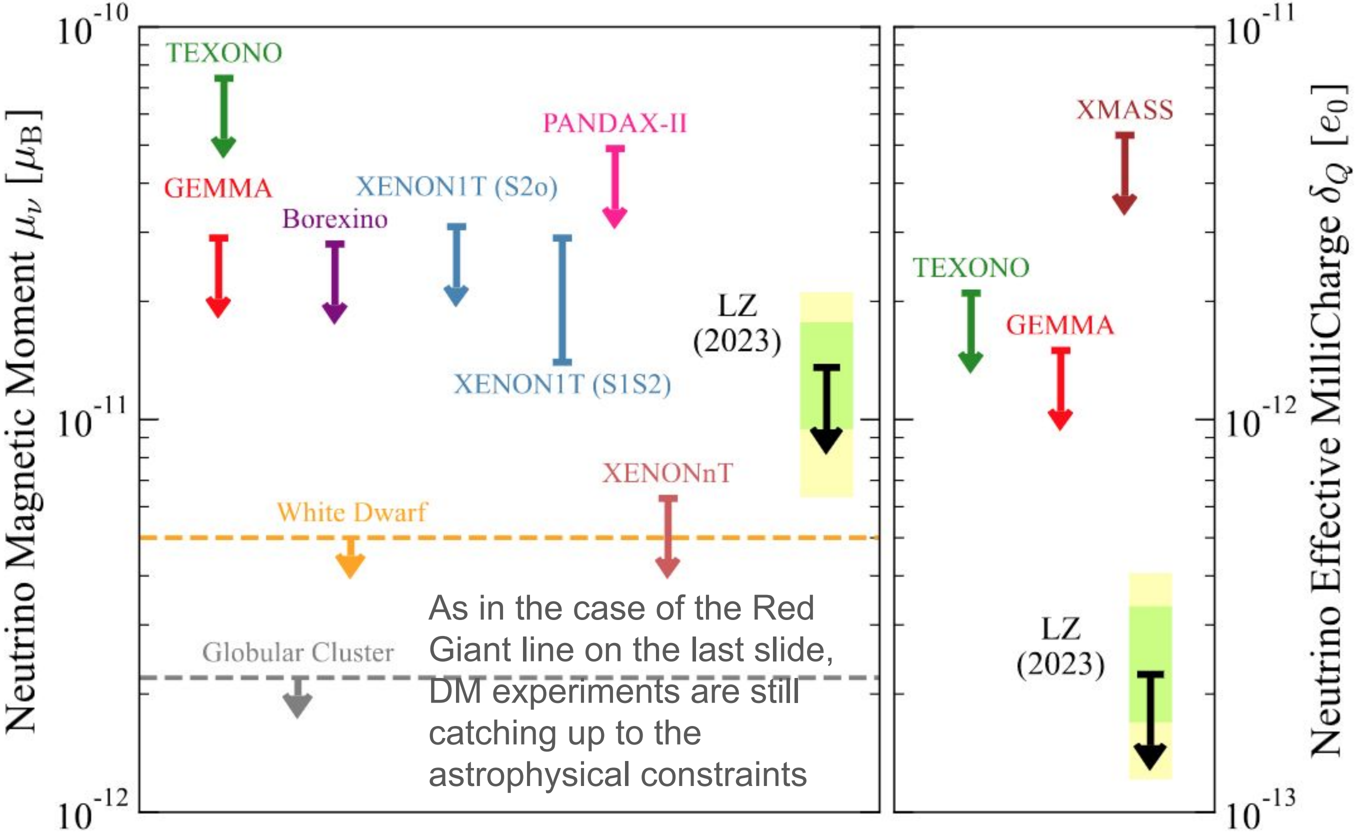
New *E* recon method (more useful in discovery :)





>(Limits from XENONnT lower due to their lower total ER BG)

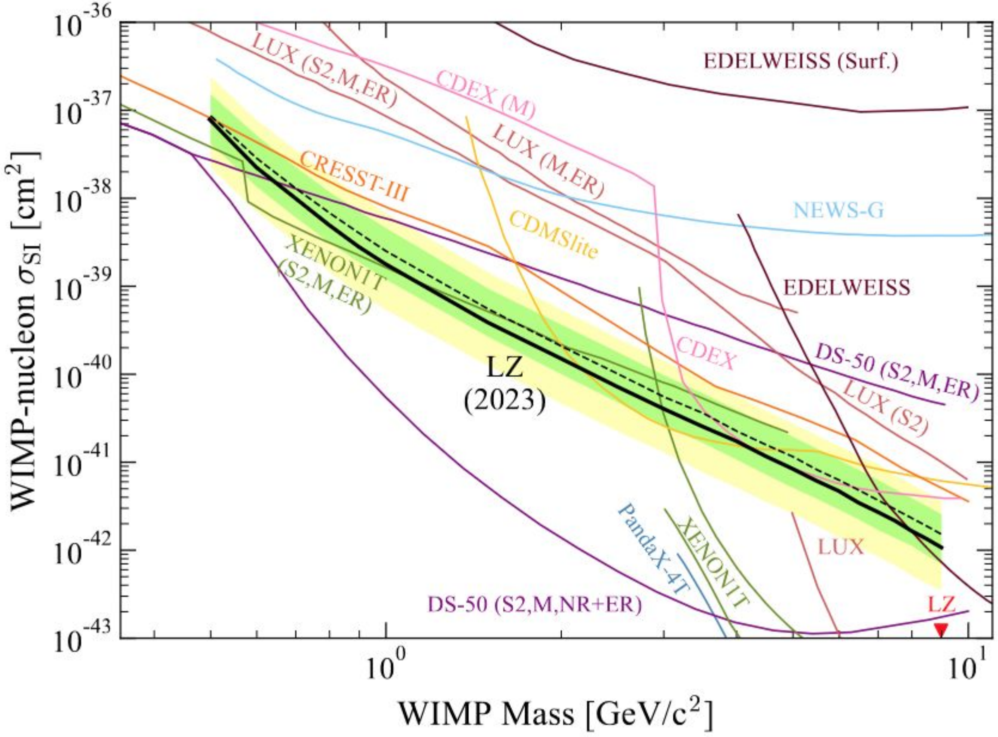
LZ Does More Than Just Dark Matter: Neutrino Physics

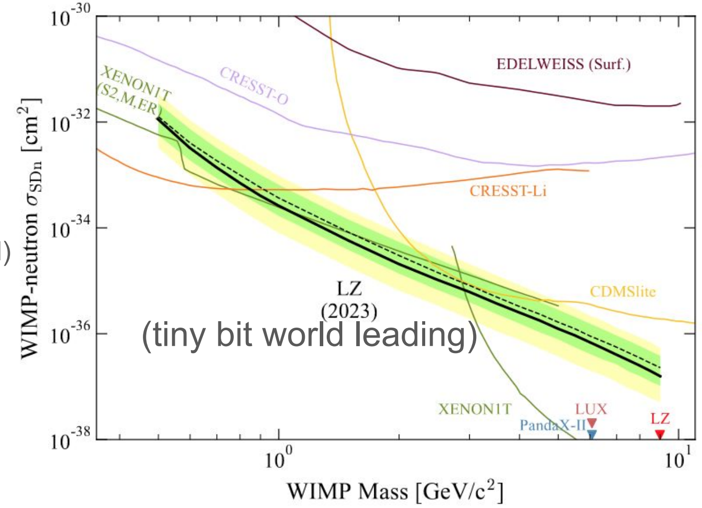


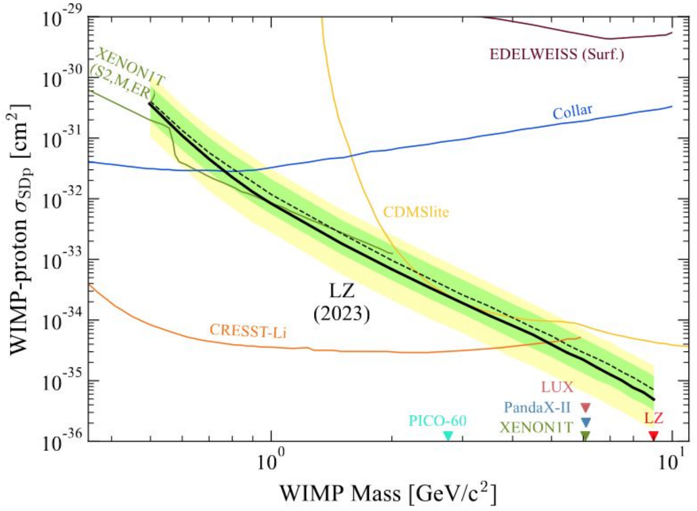
It is a multifaceted i.e. interdisciplinary physics machine (XLZD will be such a detector even more so)

Dark Matter Still the Primary Focus: ER-based in this case

The MIGDAL Effect (calibrations underway across world)





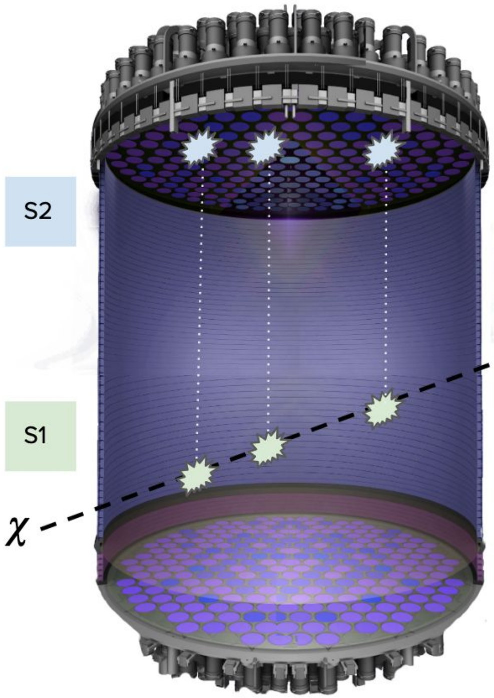


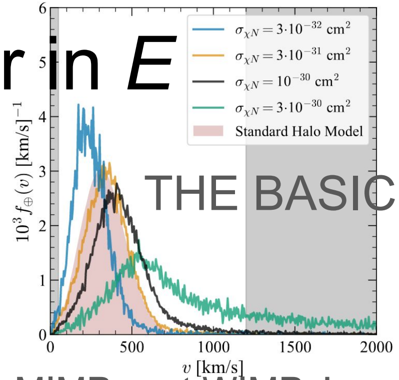
ER, much higher in *E*

Ultra-Heavy Dark Matter

(only a fraction of initial *E* lost; tracks!)

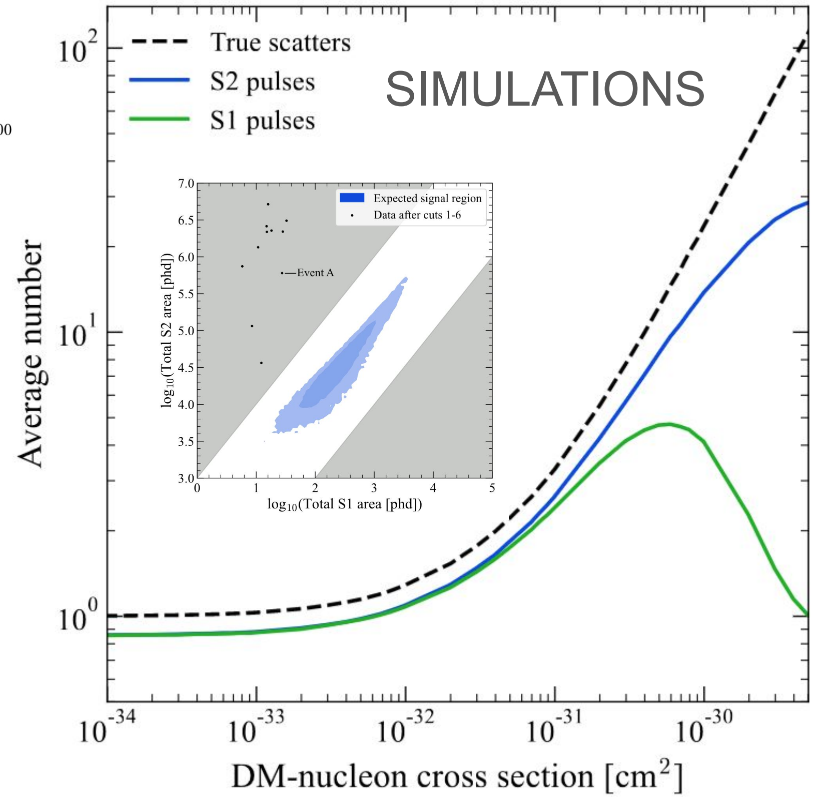
THE BASIC MODEL





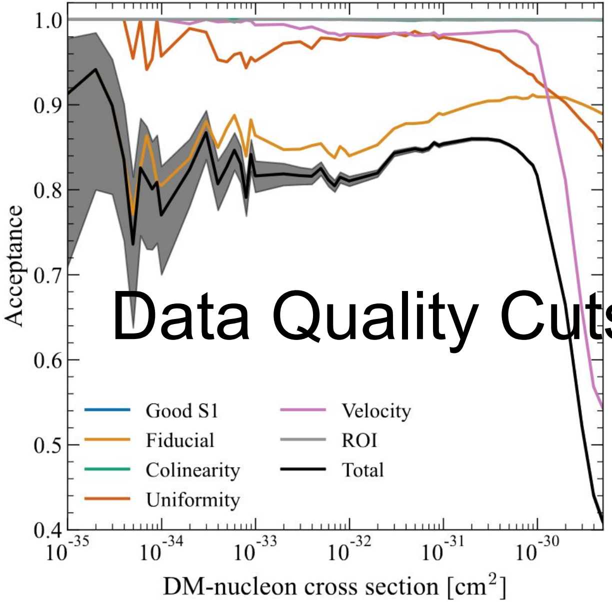
- MIMPs not WIMPs! or, Multiply-Interacting Massive Particles
- Above: MIMP velocity distributions with the SHM in red for comparison to them
- Right: avg. num. of reconstructed pulses in sim data. DM example mass of 10^17 GeV
- Inset: 2D ROI and MIMP events sample

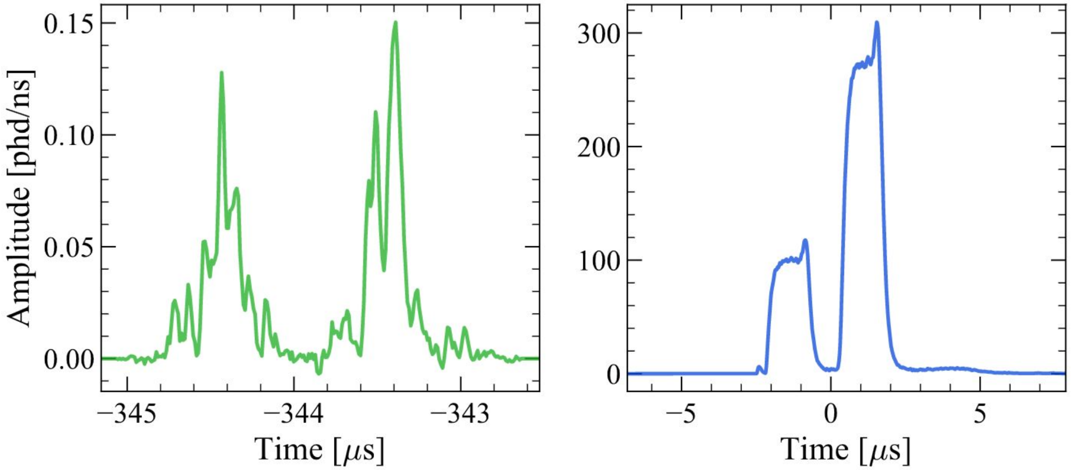
SIMULATIONS



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

Data Quality Cuts

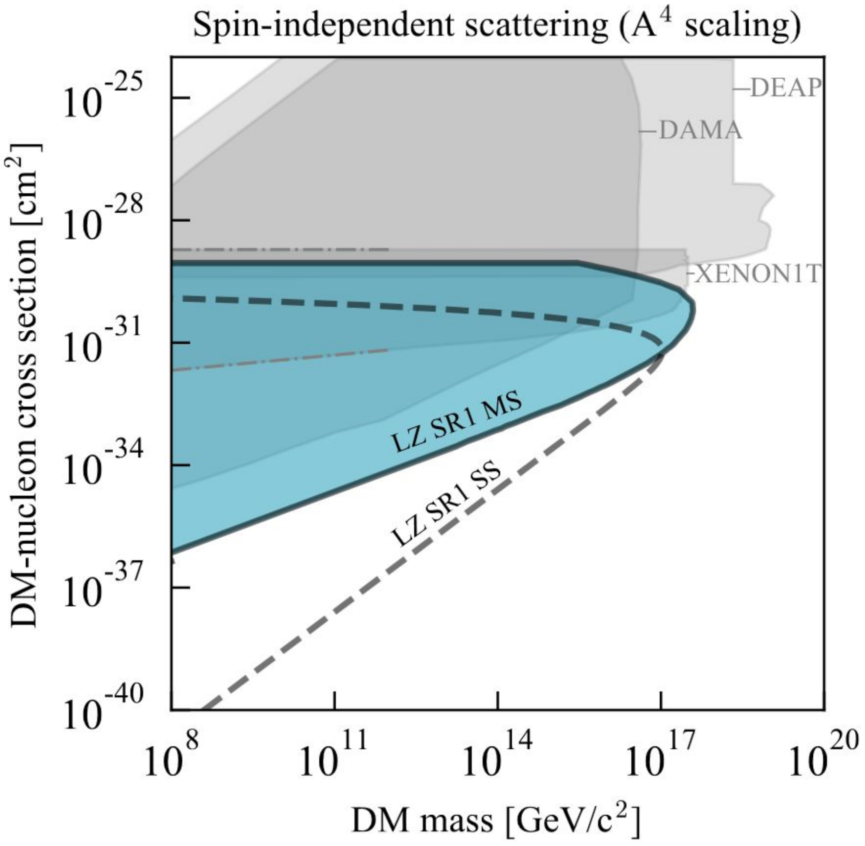


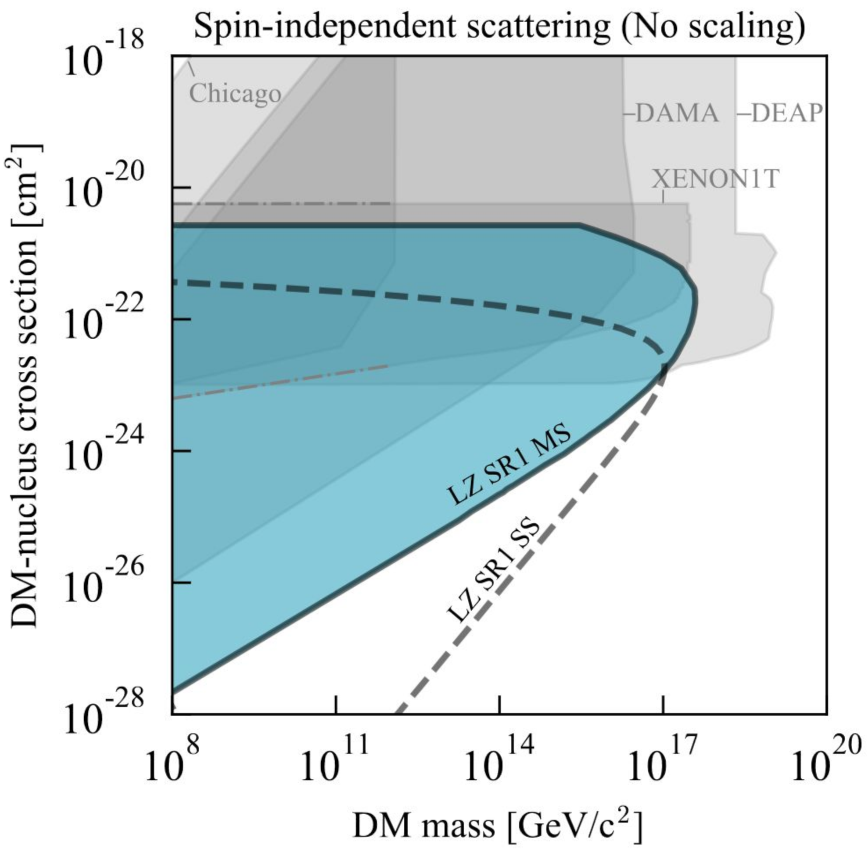


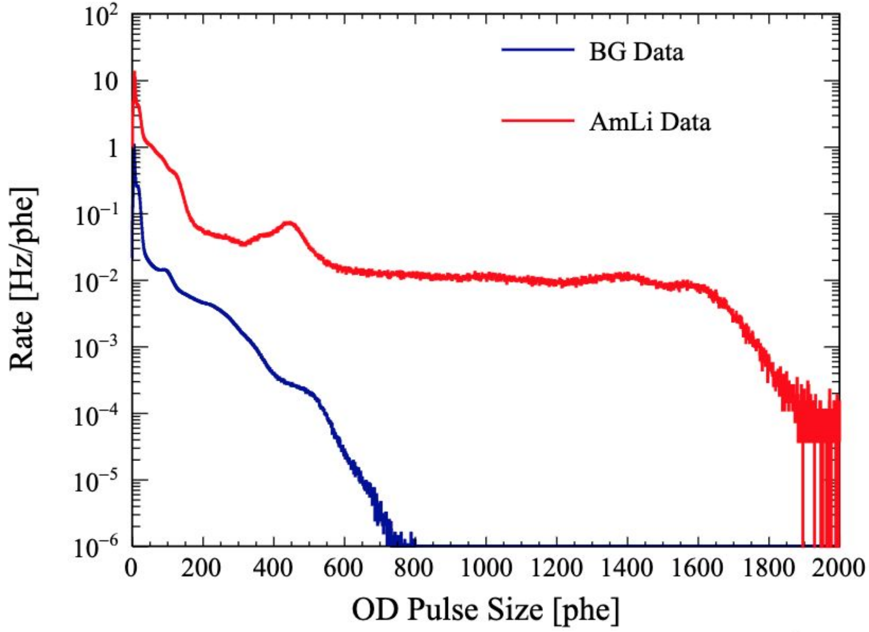
S1 & S2 waveforms for Evt A highlighted in the last slide. Compare the right (blue, S2) to Figure 3 of https://arxiv.org/pdf/1310.1117.pdf

Cut ID	Name	Description	Events
0	*Initial selection*	See Section III (of arXiv:2402.08865)	10137
1	*Multiplicity*	>1 S1s; >1 S2s	1538
2	*Good S1*	No S1s are overly concentrated in one PMT or have a coincident signal in the OD	1400
3	*Fiducial*	$\geq$ 2 S2s with z $\in$ (2, 135) cm and r < 70 cm	269
4	*Colinearity*	Reduced $\chi^2 < 2$; scatters are causally ordered along the track	237
5	*Uniformity*	Scatters are distributed along the track uniformly	67
6	*Velocity*	Reconstructed $v \in$ (50, 1200) km/s	11
7	*ROI*	Total S1 and total S2 area is within signal region	0

The Final Results (SR1)







Total pulse size spectra in the OD for both SR1 background data and an AmLi calibration of duration 7.4 hours

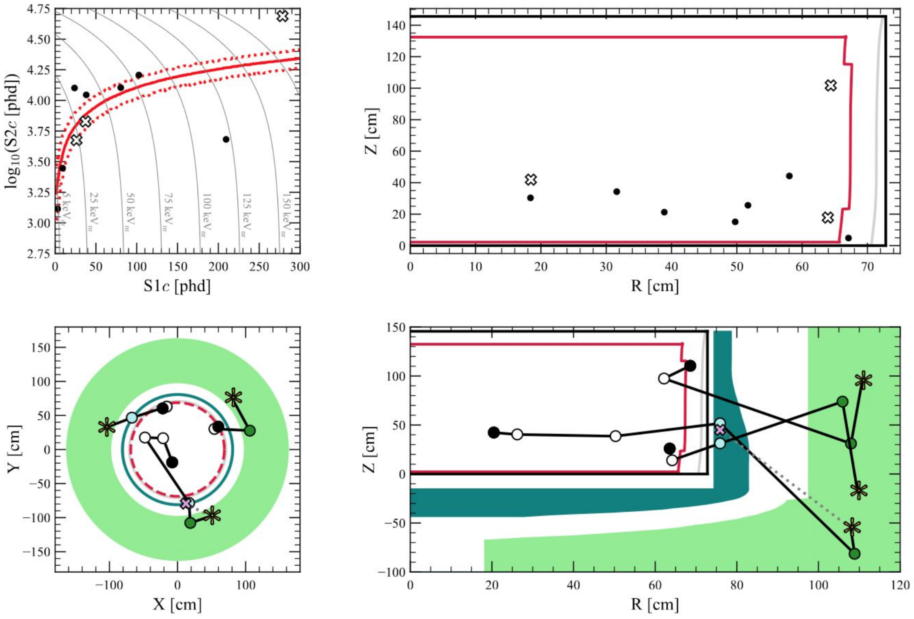
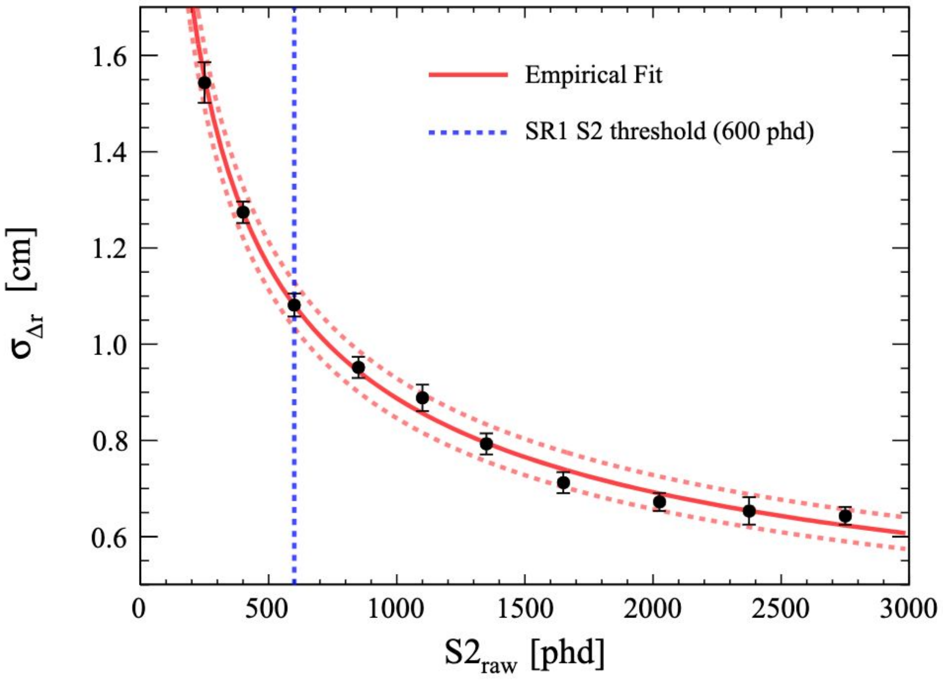


FIG. 9. Locations of MS neutron events identified in the SR1 dataset, correlated across all three detectors. *Top:* Distribution of the 10 identified neutron events in $\log_{10}(\mathrm{S2}c)$-$\mathrm{S1}c$ space overlaid with the MS NR band, as well as their averaged positions in the TPC. White crosses denote three example events displayed in detail on the second row. *Bottom:* Chains of reconstructed scatters demonstrating inter-detector coincidences in tagging neutron events. Working outwards: the red outline indicates the SR1 FV; the gray curve highlights the TPC wall boundary in reconstructed space; the black box indicates the physical edges of the active xenon volume; the teal profile denotes the liquid xenon Skin; the outermost green region represents the OD acrylic tanks containing the GdLS. As the exact chronology of the event could not be determined, interactions were ordered by drift time. Black circles denote the locations of the scatters with shortest drift time in the given neutron MS chain, with empty circles showing the positions of other interactions in the TPC. Scatters in the Skin and OD are shaded in blue and green respectively. Neutron captures in the OD are marked as a $*$, and resulting gamma-ray splashes observed in the Skin are labeled with a pink cross. OD points are randomly assigned radial positions as XY reconstruction there is often biased towards the centre, a correction for which is under development.

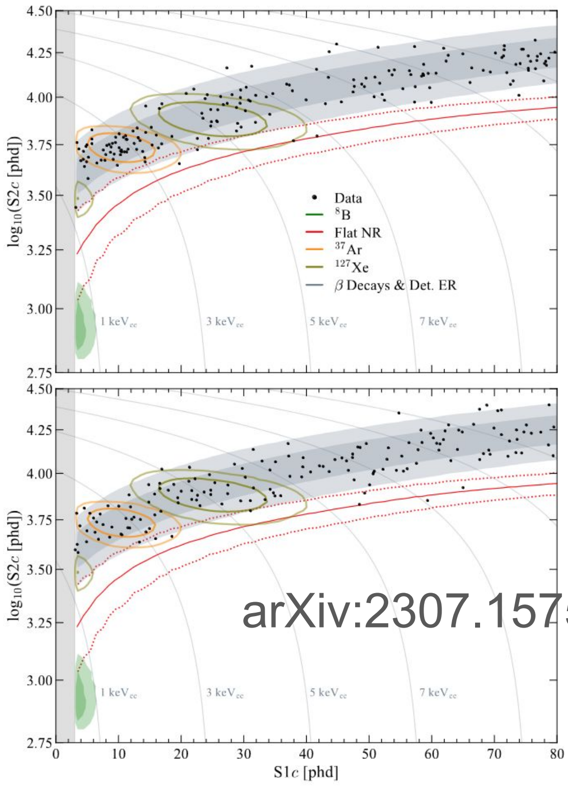
Additional Figures, From the LZ Backgrounds Publication

Wall BG Modeling: The Position Resolution as a Function of the S2 size



Additional Plots from the Low-Energy ER Signals Paper

Figure 1: The SR1 search data (black points) is plotted in the $\{S1c, \log_{10}S2c\}$ space, after all cuts and selections are applied. For illustration purposes, the exposure is shown separated into two periods of equal livetime (top panel is the first half of SR1, bottom panel is the second half). In both panels, the 1σ and 2σ regions are indicated for various background model components: ^{37}Ar (orange contours), ^{127}Xe (green contours), ^{8}B (filled green), and the broad-spectrum ER background encompassing ^{212}Pb, ^{214}Pb, ^{85}Kr, and external gammas (filled gray). The solid red line indicates the median, the dashed the 10% and 90%, quantiles of a flat NR background. Thin gray lines indicate contours of constant ER energy, with a spacing of 2 keV_{ee}. A reduction in ^{37}Ar rate is the dominant change between the two time periods.



arXiv:2307.15753