



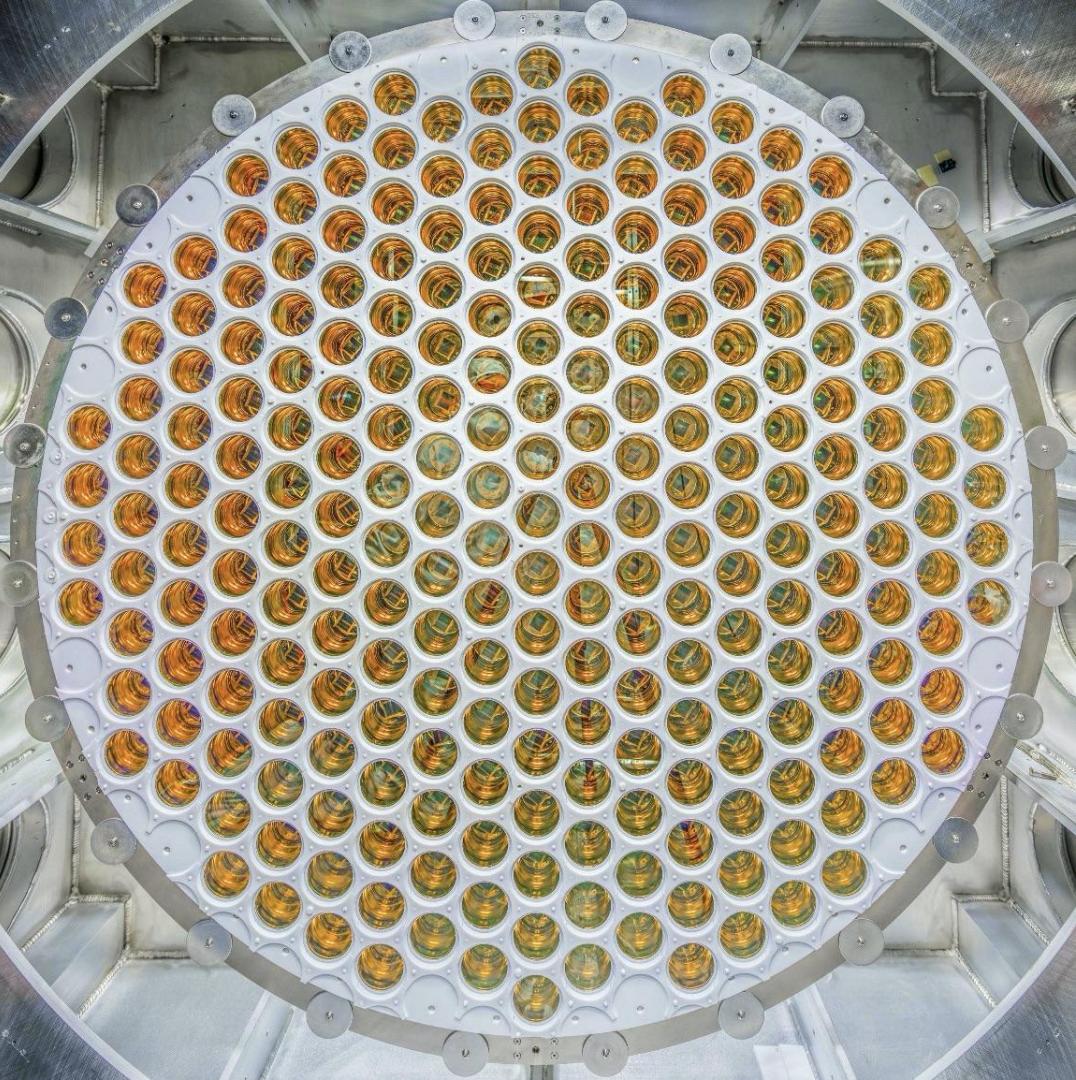
Effective Field Theory Dark Matter Searches with the LZ Detector

Michael Williams

On Behalf of the LZ Collaboration

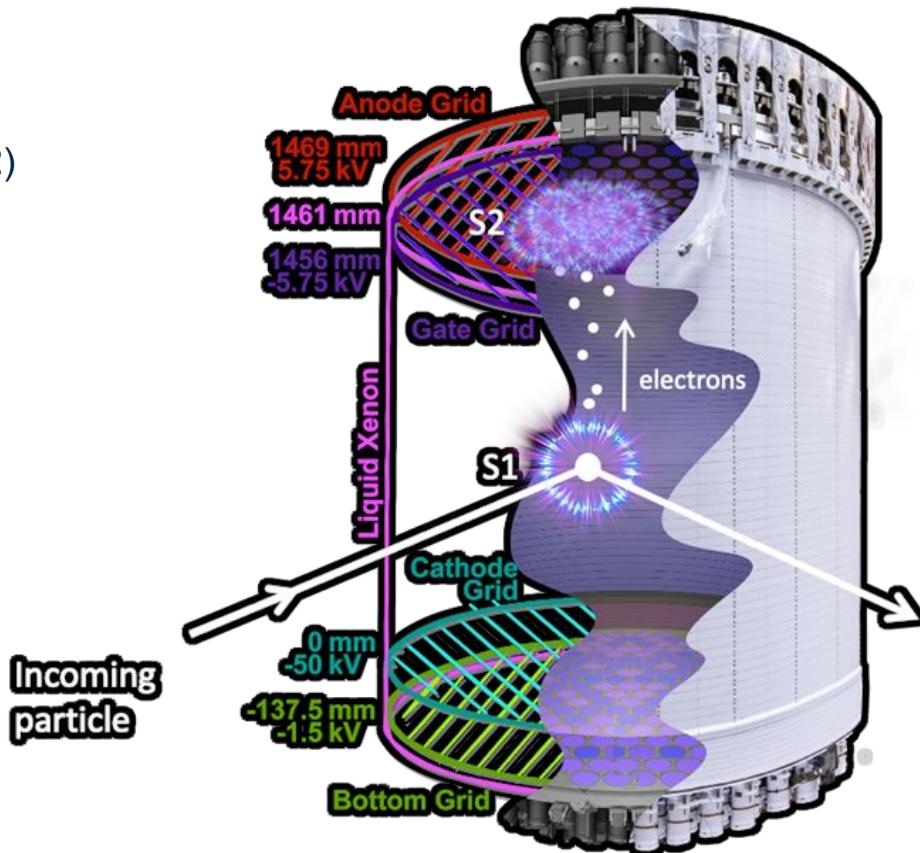
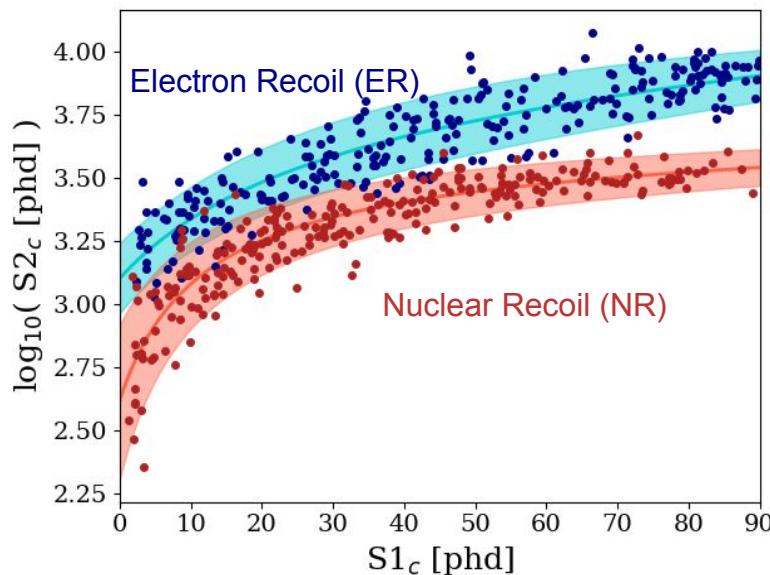
TAUP 2023

28th August, 2023

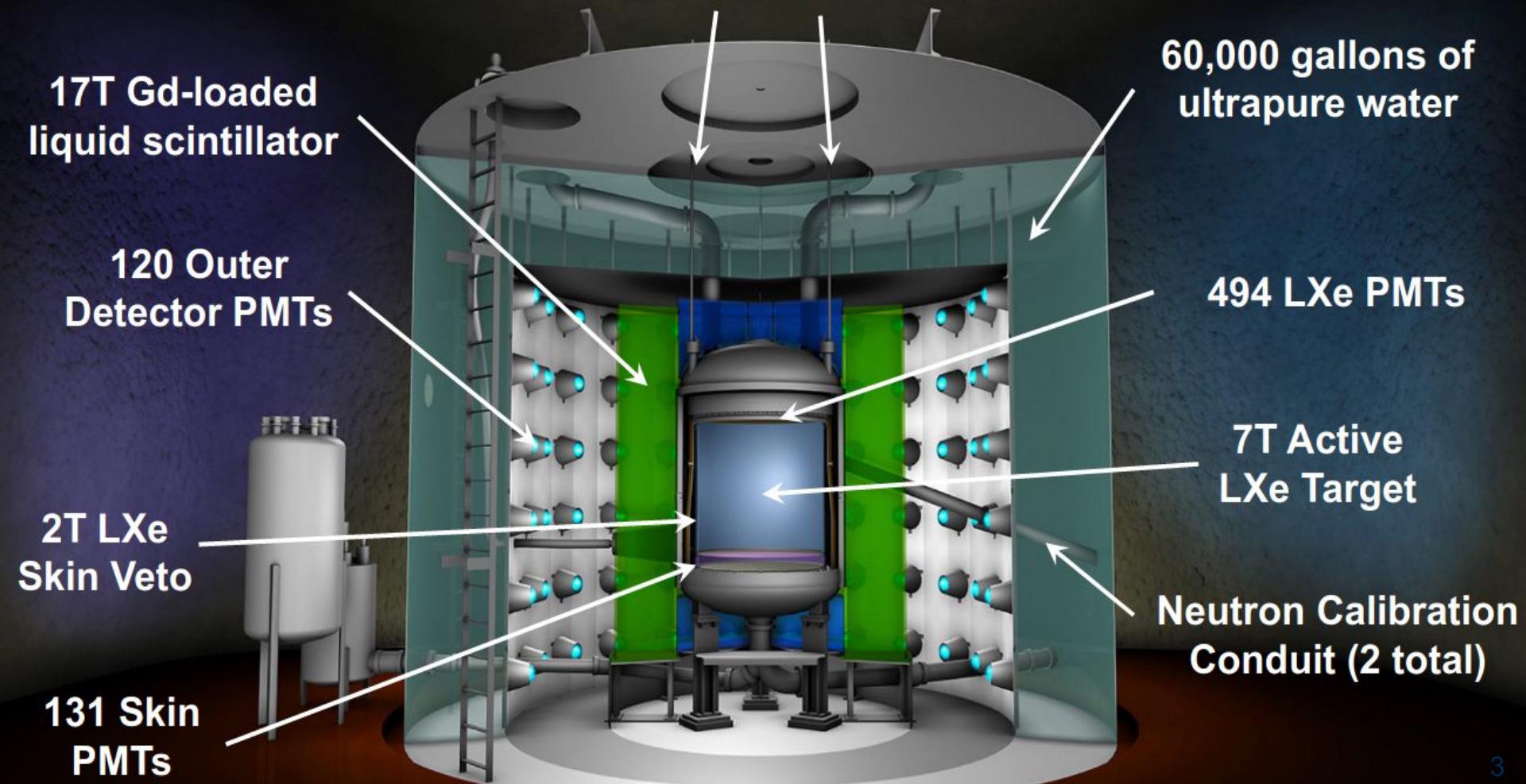


Dual Phase Time Projection Chamber

- Primary scintillation light (S1)
- Secondary scintillation induced from free charge (S2)
- 3D reconstruction allows for fiducialization
- ER/NR discrimination from S1:S2 ratio



Calibration Source Deployment Tubes (3 Total)



Detector Conditions

- Drift field: 193 V/cm
- Extraction field: 7.3 kV/cm in gas
- >97% of PMTs operational
- Liquid temperature: 174.1K
- 3.3 t/day Xe purified through hot getter

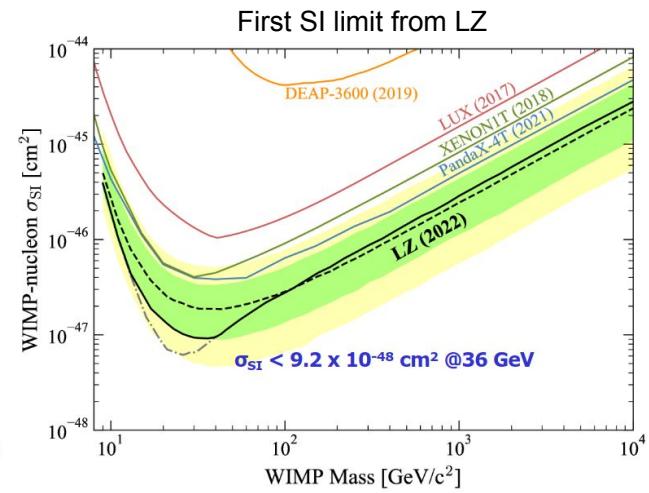
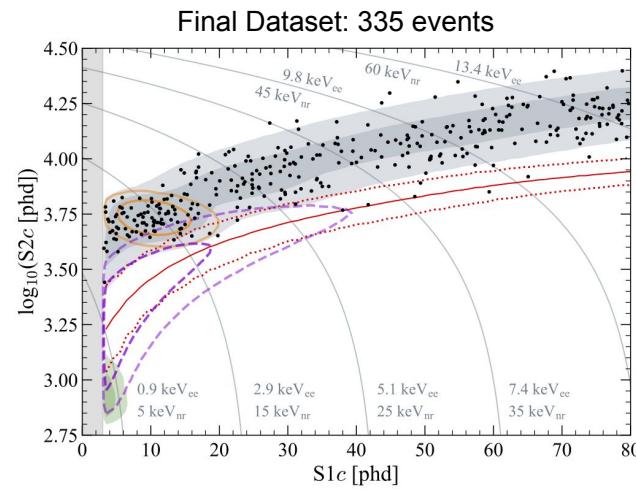
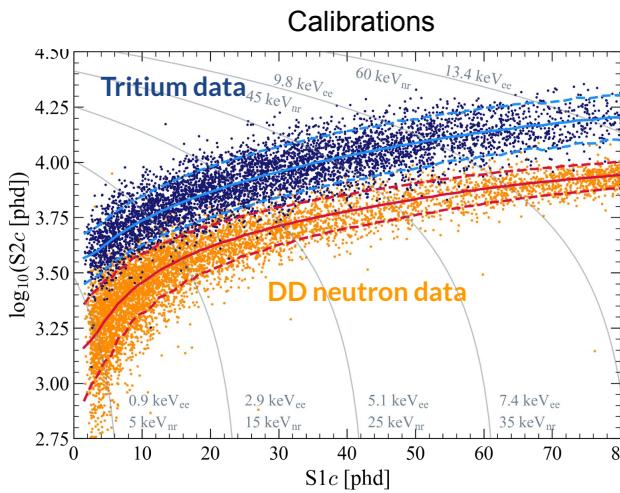
Dataset

- Dec. 2022 - May 2023
- 60 live days
- 5.5 tonne fiducial volume
- $g_1=0.114\pm 0.002$ phd/photon
- $g_2=47.1\pm 1.1$ phd/electron

Analysis

- ER Calibrations - Tritium
- NR Calibrations - DD
- Background model ([Phys. Rev. D 108, 012010](#))
- Unbinned profile likelihood in S1-logS2 space
- Paper: [Phys. Rev. Lett. 131, 041002](#)

More in Billy Boxer's LZ General talk!

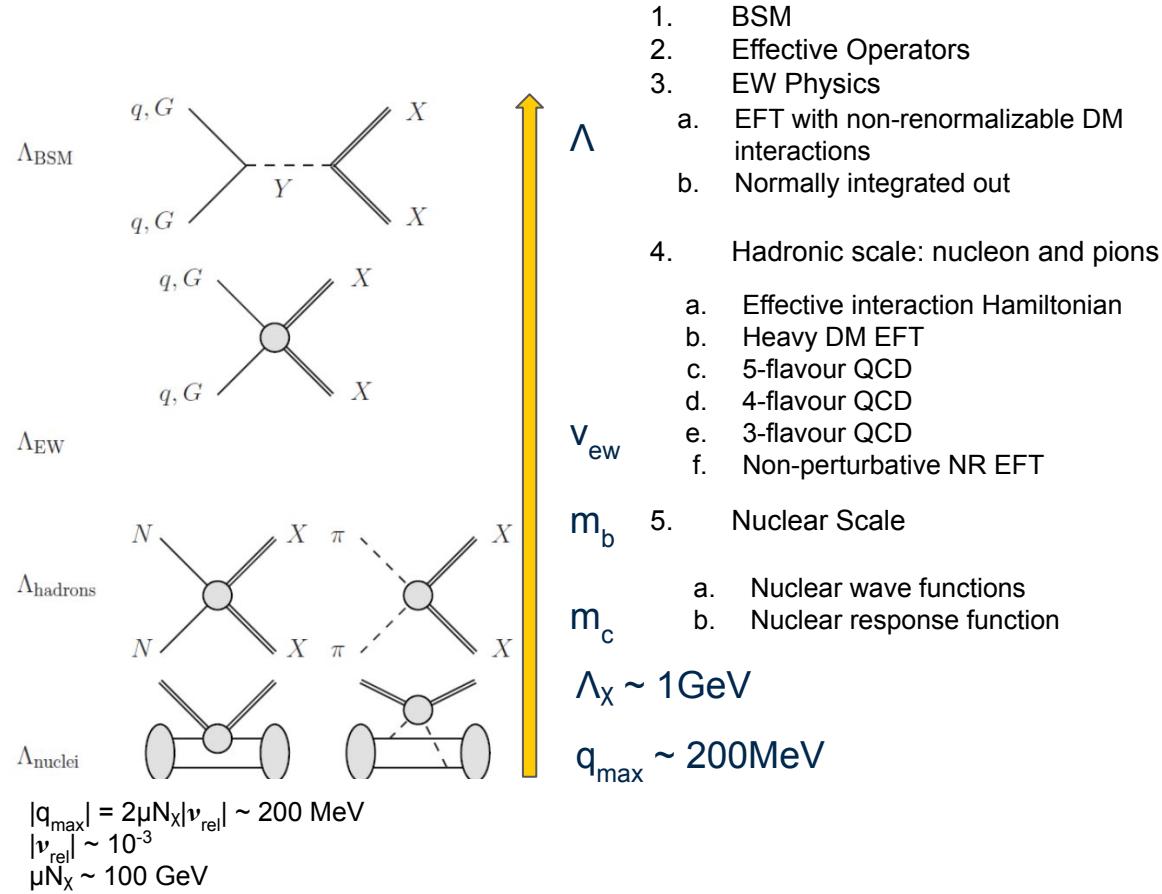


Spin Independent and Spin Dependent interactions rely on the assumption of a zero-momentum transfer.

But what if there is some momentum dependency?

WIMP-nucleon elastic scattering as a four-field interaction

$$\mathcal{L}_{int} = \mathcal{O} \chi^+ \chi^- N^+ N^-$$



Galilean-invariant to quadratic order in momentum transfer

$$i\vec{q}, \vec{S}_\chi, \vec{S}_N, \vec{v}^\perp \equiv \vec{v} + \frac{\vec{q}}{2\mu_N}$$

Spin 1 or less particles

Theory translated to coefficients of an effective operator

These operators can be equated to generic nuclear responses

Possible to reduce covariant interaction Lagrangians to combinations of the operators

$$\frac{dR}{dE_R} = \frac{\rho_\chi}{32 \pi m_\chi^3 m_N^2} \int_{v>v_{min}}^\infty \frac{f(\vec{v})}{v} \sum_{i,j=1}^{15} \sum_{a,b=0,1} c_j^a c_i^b F_{i,j}^{a,b} d^3 v$$

Interactions are linear combinations of 6 independent nuclear responses

Spin Independent

Spin Dependent (transverse)

Spin Dependent (longitudinal)

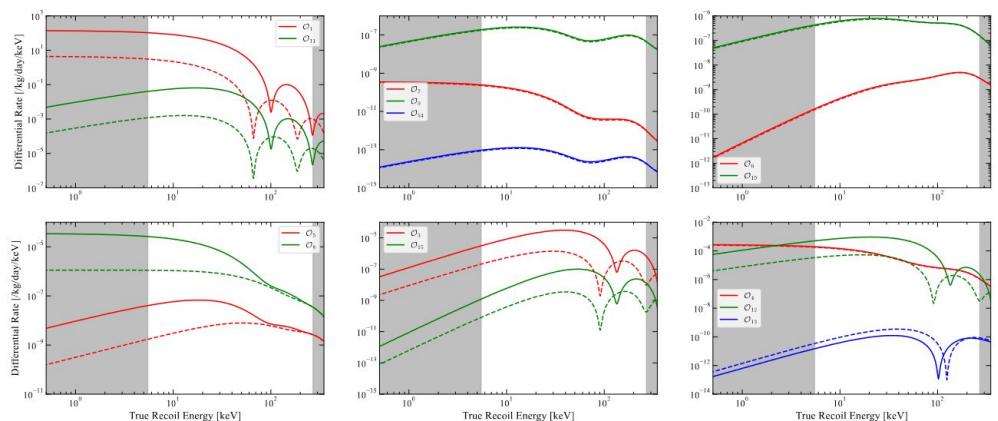
Angular Momentum

Spin Orbit

Tensor spin orbit

Operators give us a sense of the true sensitivity of our detector to different DM-nucleon physics

Phys. Rev. C 89, 065501 (2014)



$m_\chi = 1000 \text{ GeV}/c^2$
Solid lines: isoscalar
Dashed lines: isovector

Shaded region:
Energy where the efficiency for the LZ SR1 WIMP-Search data is <50%
After all cuts and ROI selection

Evaluate the scattering amplitude assuming a single operator

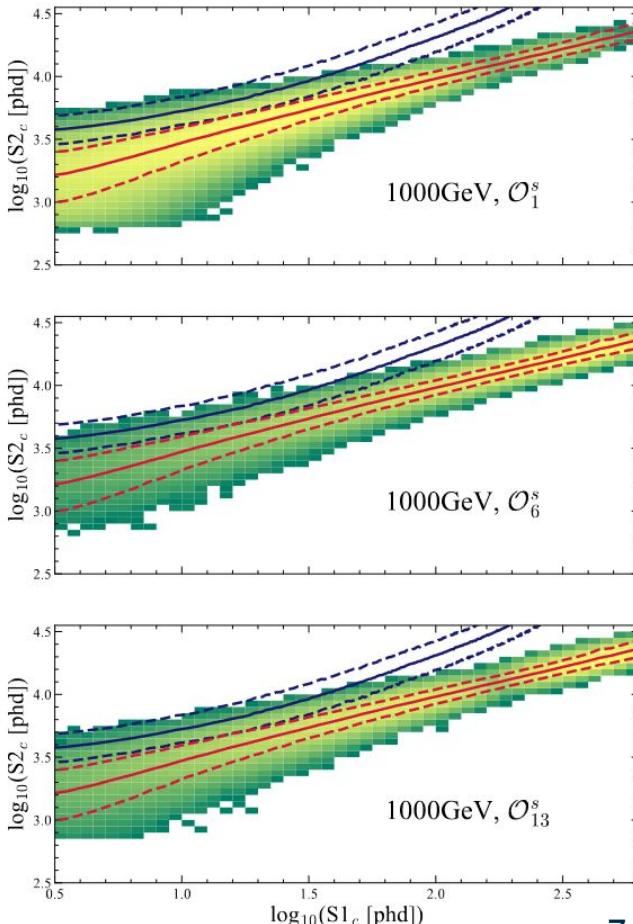
$$\frac{dR}{dE_R} \rightarrow \frac{\rho_\chi c_i^2}{32 \pi m_\chi^3 m_N^2} \int_{v>v_{min}}^\infty \frac{f(\vec{v})}{v} F_{i,i} d^3 v$$

Code used:

DMFormFactor-v6: Used for updating the nuclear response function

WimPyDD: Used to generate final recoils with updated response functions

Using updated GCN5082 ground state to ground state one-body density matrices (supplied by W. Haxton, generated using BIGSTICK)



Can create an effective Lagrangian from combinations of various operators that themselves code in Galilean invariant interactions

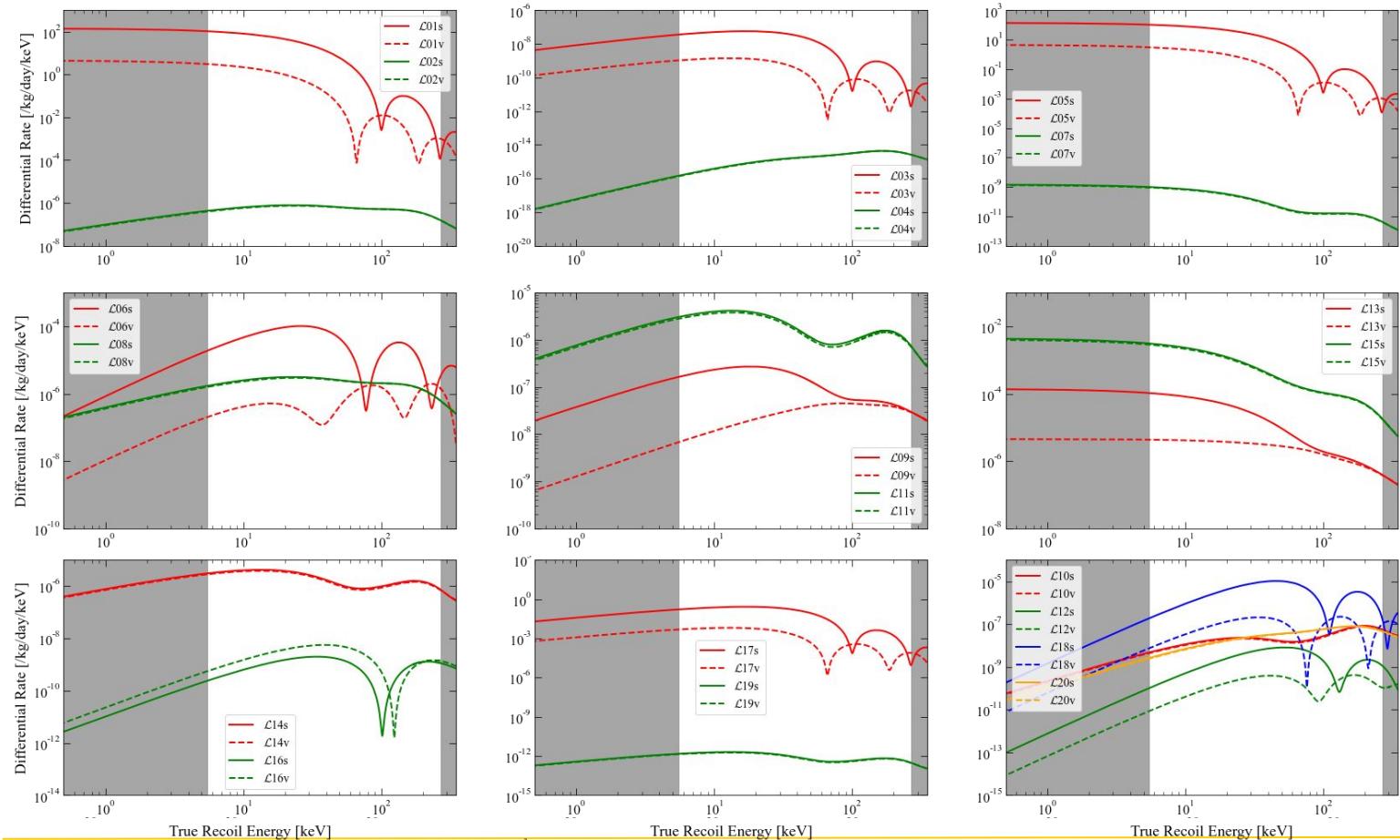
$$\mathcal{L}_{int} = \sum_{N=n,p} \sum_i d_i^{(N)} \mathcal{O}_i \bar{\chi} \chi \bar{N} N$$

d = operator construct coupling

WIMP magnetic moment: $\mathcal{L}_{int}^9 \rightarrow -\frac{\vec{q}^2}{2m_\chi m_M} \mathcal{O}_1 + \frac{2m_N}{m_M} \mathcal{O}_5 - \frac{2m_N}{m_M} \left(\frac{\vec{q}^2}{m_M} \mathcal{O}_4 - \mathcal{O}_6 \right)$

WIMP electric dipole moment: $\mathcal{L}_{int}^{17} \rightarrow \frac{2m_N}{m_M} \mathcal{O}_{11}$

Lagrangians are a direct probe into possible physics interactions between DM and SM


 $m_\chi = 1000 \text{ GeV}/c^2$
Solid lines: isoscalar

Dashed lines: isovector

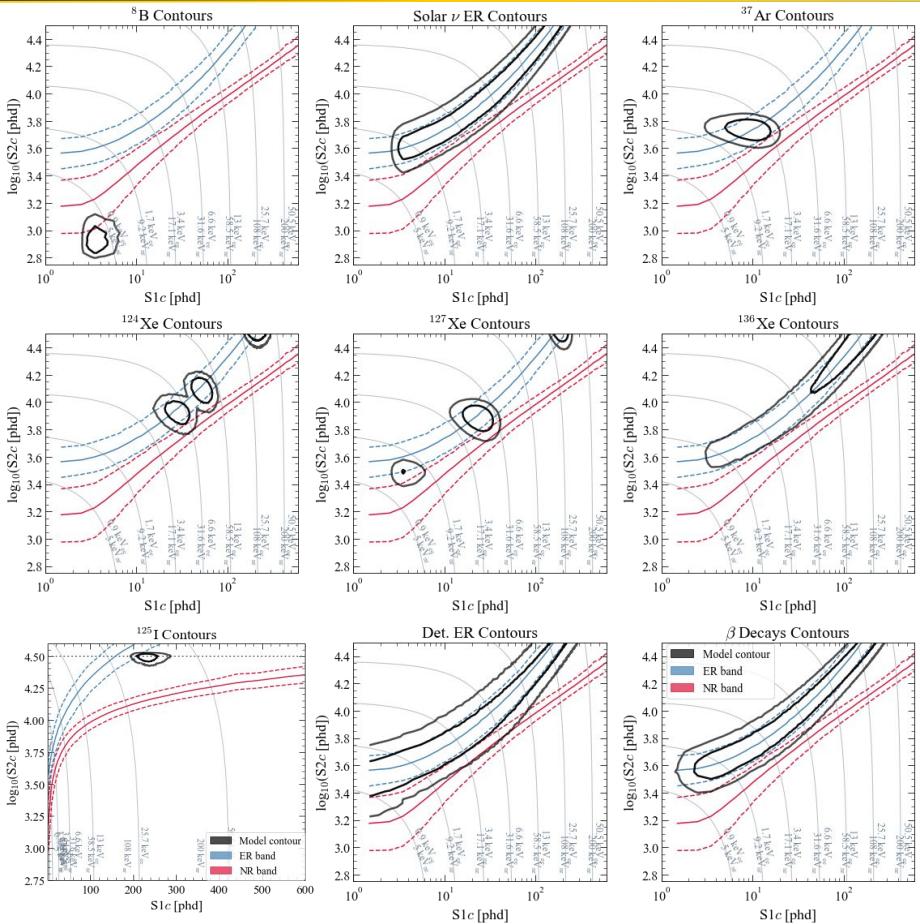
Shaded region:

Energy where the efficiency for the LZ SR1 WIMP-Search data is <50%

After all cuts and ROI selection

All backgrounds relevant to SI WIMP search
Additional backgrounds

- Additional Xe decays
 - ^{124}Xe , ^{133}Xe , $^{131\text{m}}\text{Xe}$, ^{127}Xe
- Additional ER
 - ^{125}I
- MSSI
 - Next slide!

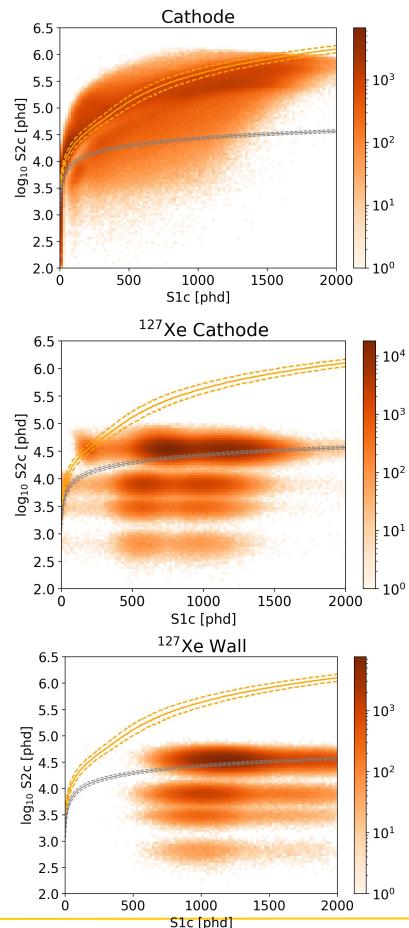
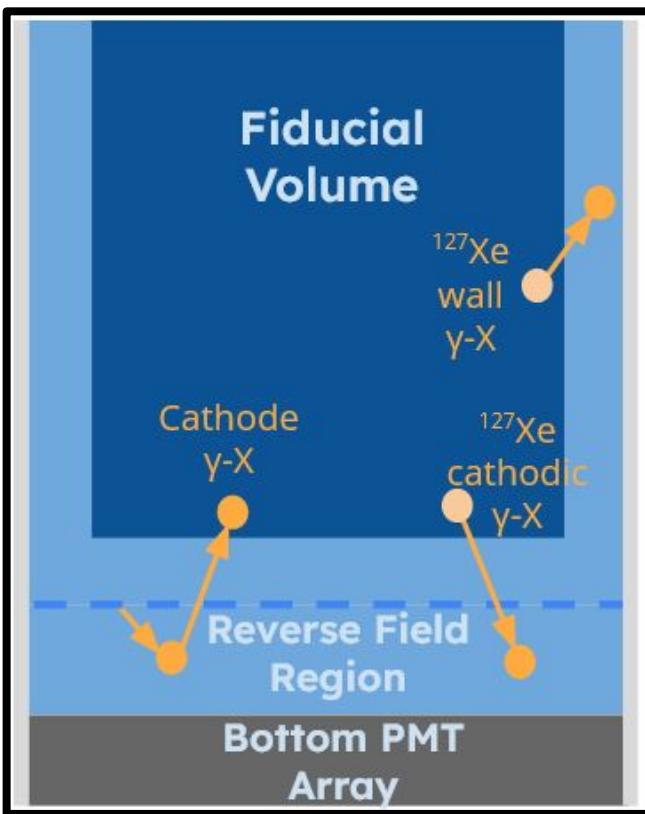


A γ -X event is a multiple-scattering γ where at least one vertex is in a region of incomplete charge collection:

- Reverse field region
- Near TPC walls

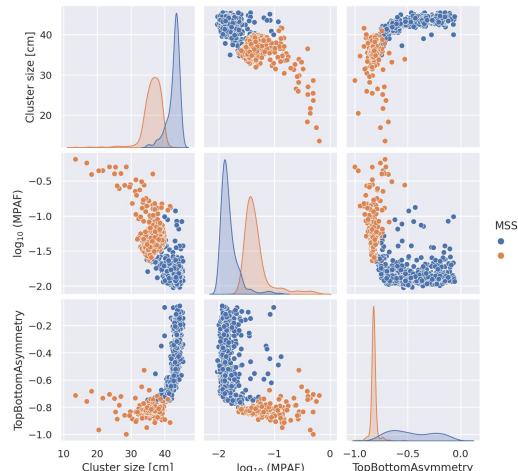
Sources include:

- ^{238}U , ^{232}Th , ^{60}Co , ^{40}K from cathode
- ^{127}Xe near detector edges



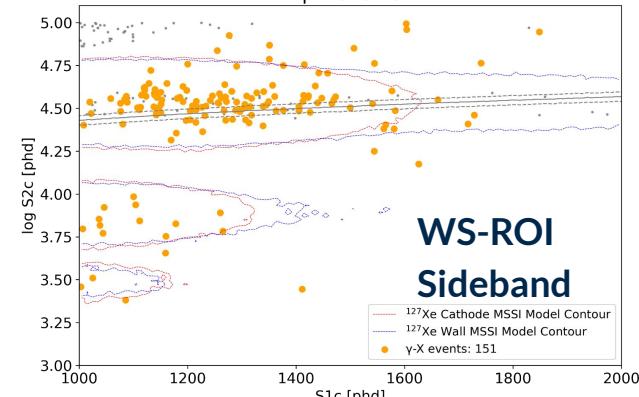
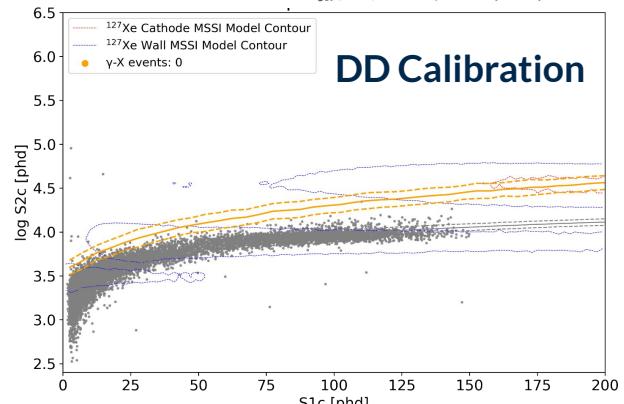
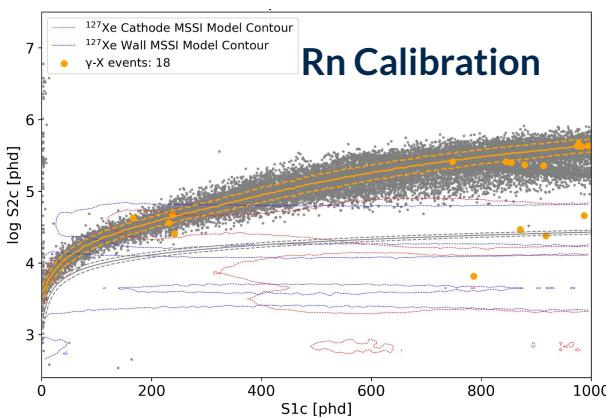
Boosted Decision Tree cut trained on high stats simulations and calibration data

$\downarrow P, \rightarrow T$	SS	γ -X
SS	99.997 ± 0.005	0.4 ± 1.2
γ -X	0.003 ± 0.005	99.6 ± 1.2



Quantities used in classification

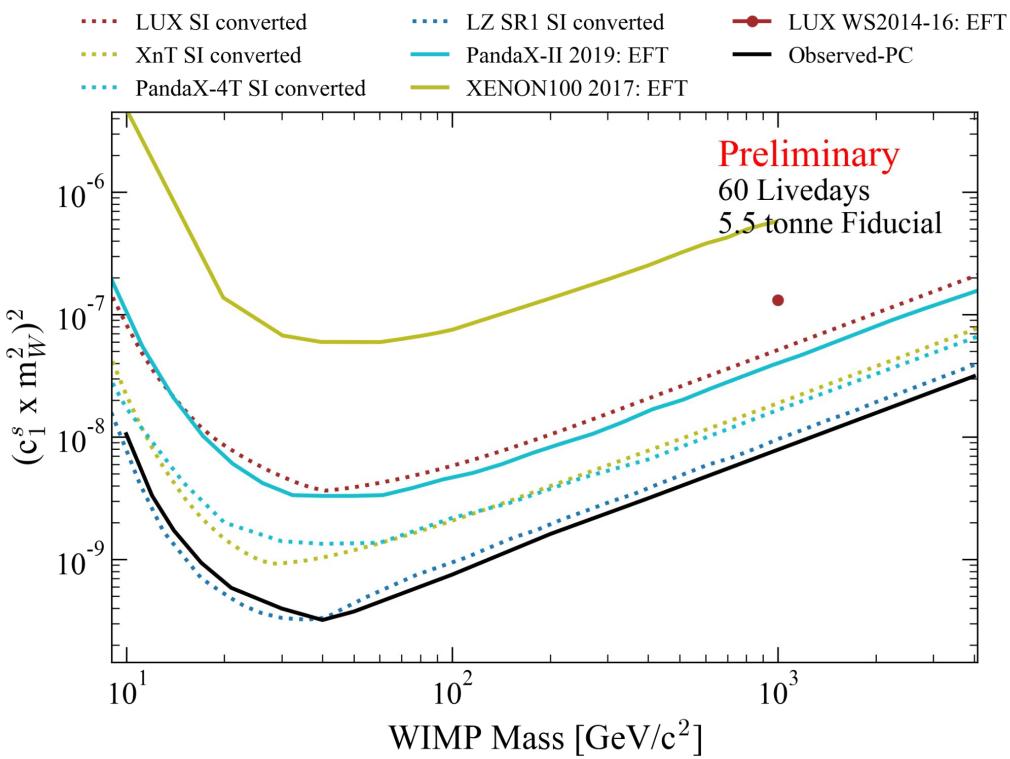
- Cluster size (size of the S1 splash on the bottom PMT array)
- Max Peak Area Fraction
- Top Bottom Asymmetry
- S1c
- LogS2
- Radius
- Drift Time

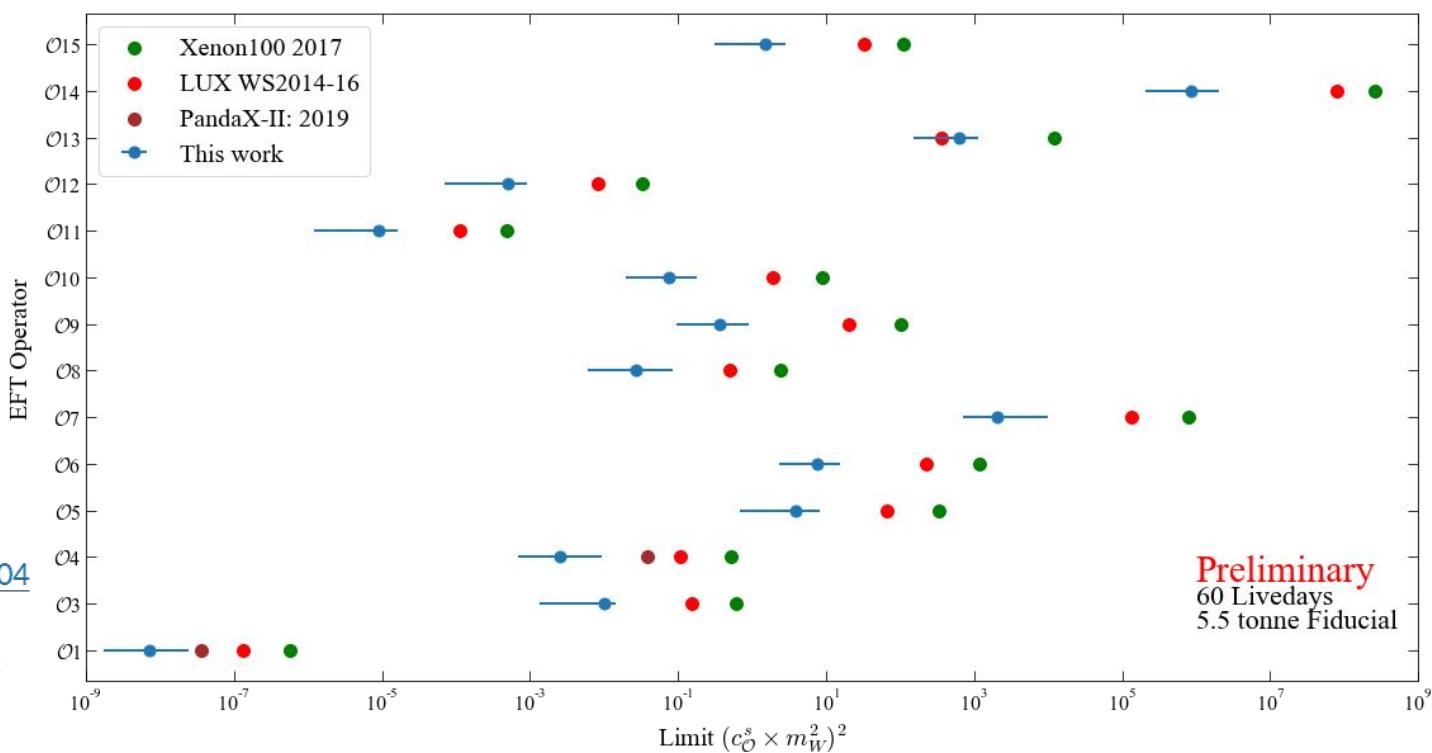


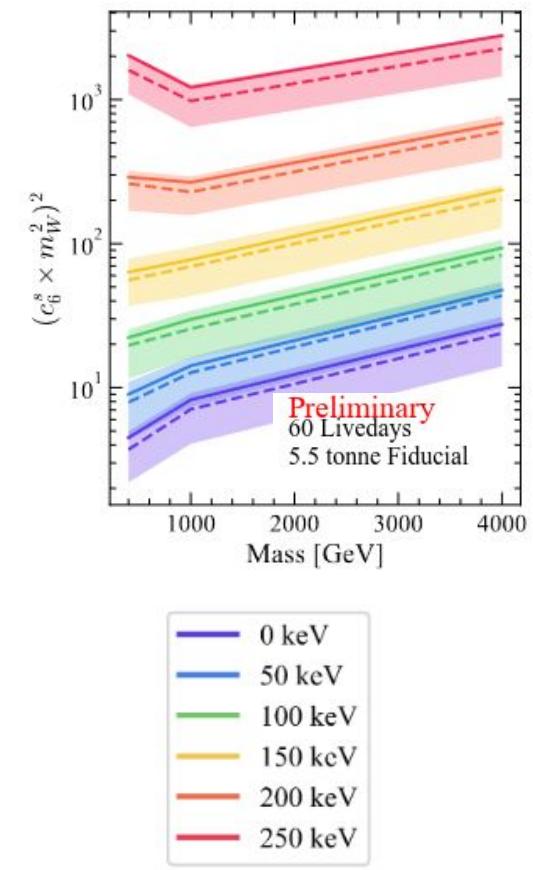
NREFT analyses often have differences in the choices of normalisations

- Representation of isospin
- Dimensionality of the presented result

	Experiment	Basis	Limit Type	Conversion in plot
<u>Phys. Rev. D 96, 042004</u>	Xenon100: 2017 EFT	$c_0 = \frac{1}{2}(c_p + c_n)$ $c_1 = \frac{1}{2}(c_p - c_n)$	$(c_1^s \times m_w^2)^2$	None
<u>Phys. Rev. D 104, 062005</u>	LUX: WS2014-16 EFT	$c_0 = (c_p + c_n)$ $c_1 = (c_p - c_n)$	$(c_1^s \times m_w^2)^2$	$\frac{1}{4}$
<u>Physics Letters B 792C</u>	PandaX-II: SD EFT	$c_0 = \frac{1}{2}(c_p + c_n)$ $c_1 = \frac{1}{2}(c_p - c_n)$	$d_5^s \left[\frac{1}{m_w^2} \right]$	$(d_5^s)^2$
Paper in progress	LZ EFT (This analysis)	$c_0 = \frac{1}{2}(c_p + c_n)$ $c_1 = \frac{1}{2}(c_p - c_n)$	$(c_1^s \times m_w^2)^2$	None
<u>Phys. Rev. C 89, 065501</u>	NRET Theory paper	$c_0 = \frac{1}{2}(c_p + c_n)$ $c_1 = \frac{1}{2}(c_p - c_n)$	N/A	N/A
<u>Phys. Rev. Lett. 118, 021303</u>	LUX: Combined 2017 SI	N/A	σ_{SI}^N	$\sigma_{SI}^N \frac{\pi \cdot m_w^4}{(\frac{(hc)}{\text{GeV}})^2 \mu_N^2}$
<u>Phys. Rev. Lett. 127, 261802</u>	PandaX-4T: 2021 SI	N/A	σ_{SI}^N	$\sigma_{SI}^N \frac{\pi \cdot m_w^4}{(\frac{(hc)}{\text{GeV}})^2 \mu_N^2}$
<u>Phys. Rev. Lett. 131, 041002</u>	LZ: 2023 SI	N/A	σ_{SI}^N	$\sigma_{SI}^N \frac{\pi \cdot m_w^4}{(\frac{(hc)}{\text{GeV}})^2 \mu_N^2}$
<u>Phys. Rev. Lett. 131, 041003</u>	XENONnT: 2023 SI	N/A	σ_{SI}^N	$\sigma_{SI}^N \frac{\pi \cdot m_w^4}{(\frac{(hc)}{\text{GeV}})^2 \mu_N^2}$



This work: $3 < S1_C[\text{phd}] < 600$ $\log_{10}(S2_C[\text{phd}]) < 4.5$ $m_\chi = 1000 \text{ GeV}/c^2$ Error shown $\pm 2\sigma$ **Comparisons:**Xenon100: [Phys. Rev. D 96, 042004](#)LUX: [Phys. Rev. D 103, 122005](#)PandaX-II: [Physics Letters B 792C](#)



Inelastic Operators

This work:

- $3 < S_{1C}[\text{phd}] < 600$
- Updated density matrices for signals

$$\begin{aligned}\delta_m &\equiv m_{\chi,\text{out}} - m_{\chi,\text{in}} \\ \delta_m + \vec{v} \cdot \vec{q} + \frac{|\vec{q}|^2}{2\mu_N} &= 0 \\ \vec{v}_{inel}^\perp &\equiv \vec{v} + \frac{\vec{q}}{2\mu_N} + \frac{\delta_m}{|\vec{q}|^2} \vec{q}\end{aligned}$$

Elastic Lagrangians

This work:

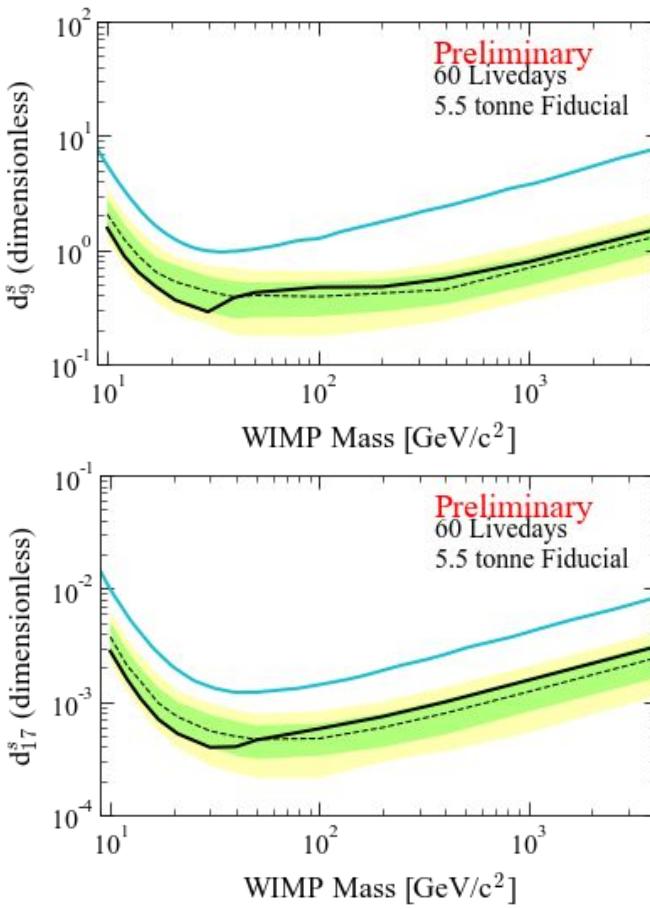
- $3 < S_{1C}[\text{phd}] < 600$
- Updated density matrices for signals

Blue:

- PandaX-II: [arXiv:1807.01936](https://arxiv.org/abs/1807.01936)

$$\mathcal{L}_{int}^9 \rightarrow -\frac{\vec{q}^2}{2m_\chi m_M} \mathcal{O}_1 + \frac{2m_N}{m_M} \mathcal{O}_5 - \frac{2m_N}{m_M} \left(\frac{\vec{q}^2}{m_M} \mathcal{O}_4 - \mathcal{O}_6 \right)$$

$$\mathcal{L}_{int}^{17} \rightarrow \frac{2m_N}{m_M} \mathcal{O}_{11}$$



- Initial science run of LZ has placed stringent limits on both SI and SD WIMP-nucleon interactions
- These models are relatively simplistic, and the inherent nature of interaction may be more complex
- Using an EFT allows us to describe all possible dark matter interactions with nucleons
- Extending energy region is beneficial for EFT analysis
- LZ has set promising EFT limits in SR1 with an extended energy ROI
- With the energy region understood in LZ, we can test more parameter space going forward!
 - 2HDM+a: [Phys. D. M. 27, 100351 \(2020\)](#)
 - DM-photon interactions: [Nature 618, 47 \(2023\)](#)

LZ Publications:

- Technical design report: [arXiv:1703.09144](#)
- Screening paper: [arXiv:2006:02506](#)
- Backgrounds paper: [Phys. Rev. D 108, 012010](#)
- First WIMP-nucleon result: [Phys. Rev. Lett. 131, 041002](#)
- Projected Sensitivities:
 - $0\nu\beta\beta$ ^{136}Xe : [Phys. Rev. C 102, 014602 \(2020\)](#)
 - Low energy ER: [Phys. Rev. D 104, 092009 \(2021\)](#)
 - $0\nu\beta\beta$ ^{134}Xe : [Phys. Rev. C 104, 065501 \(2021\)](#)



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TAUP 2023

28th August 2023

Thank you



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