University of BRISTOL

# Going beyond SI searches with LUX-ZEPLIN

**Sam Eriksen**, on behalf of the LZ Collaboration

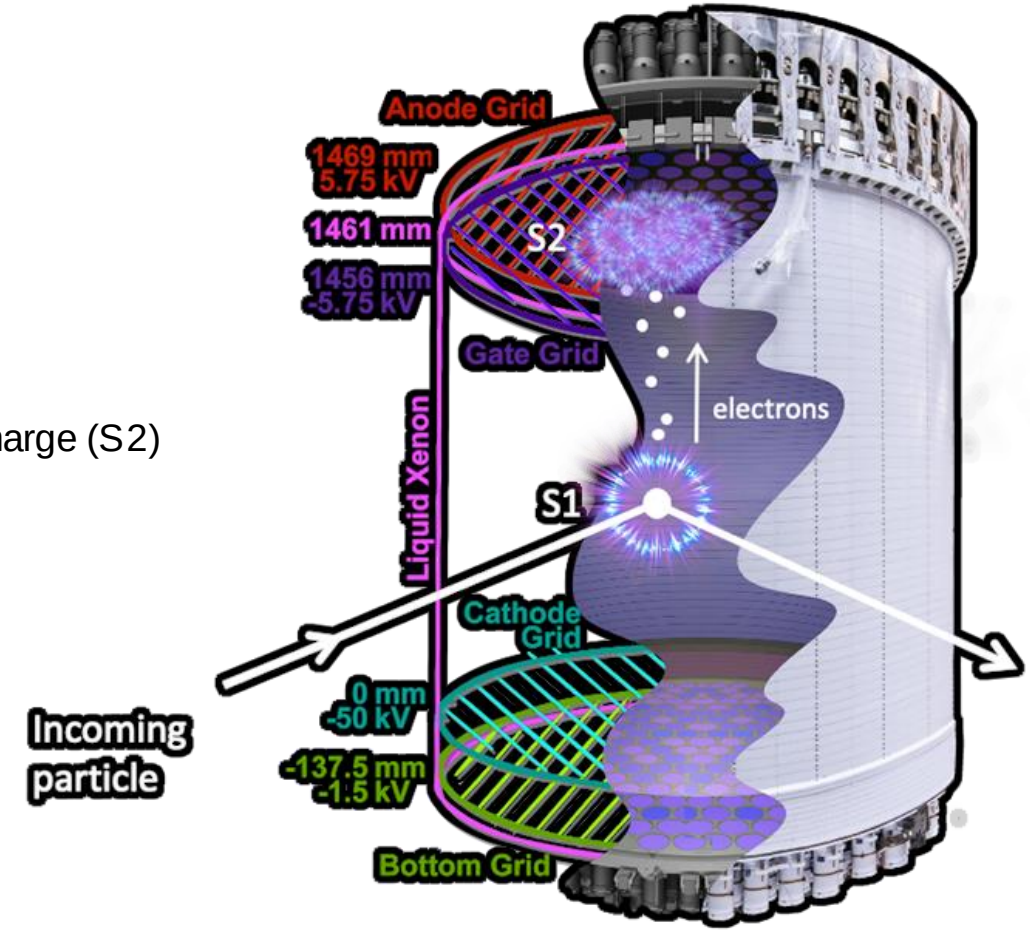
EPS-HEP 2023

25th August 2023

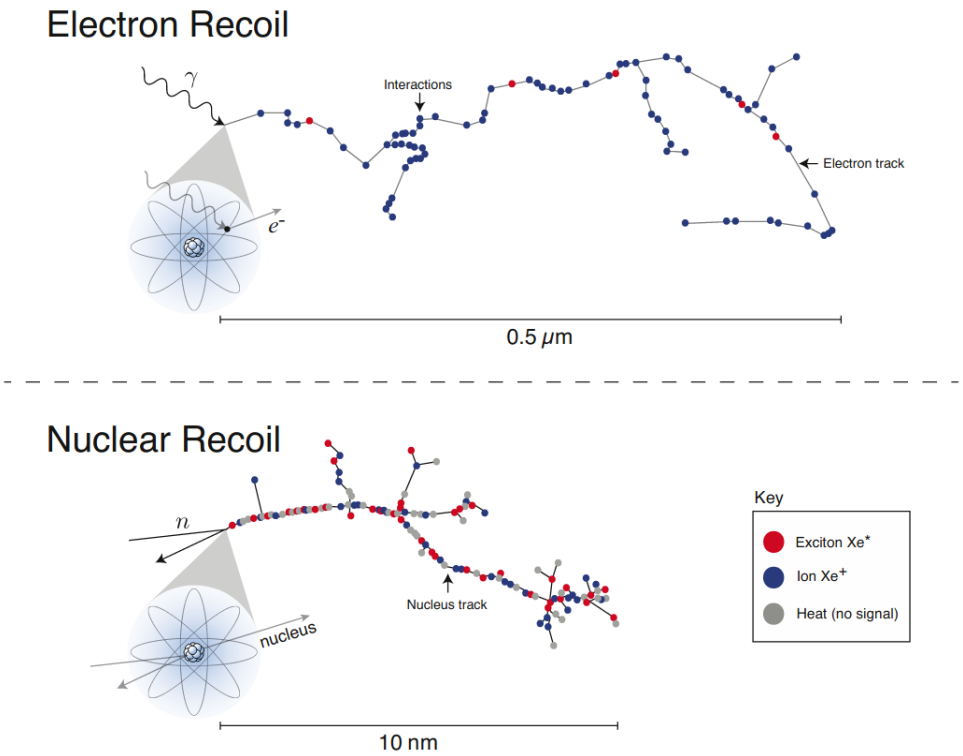
# The LUX-ZEPLIN Detector

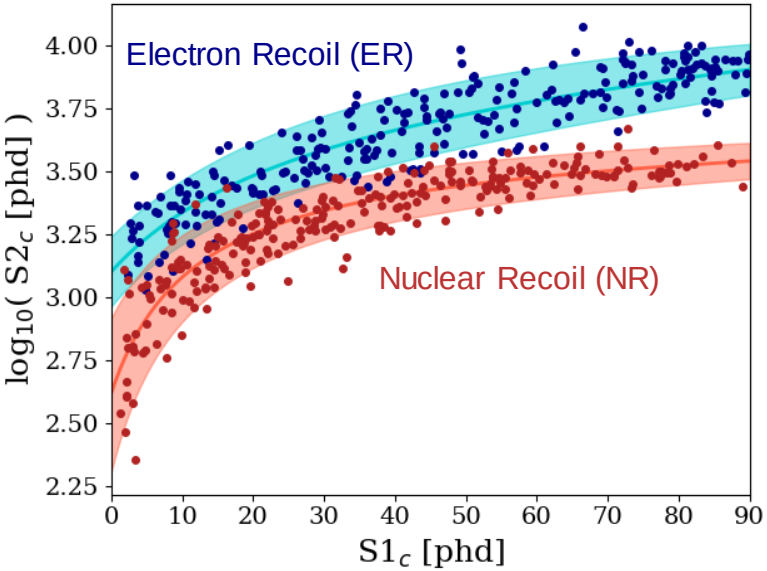
**Dual Phase Time Projection Chamber**

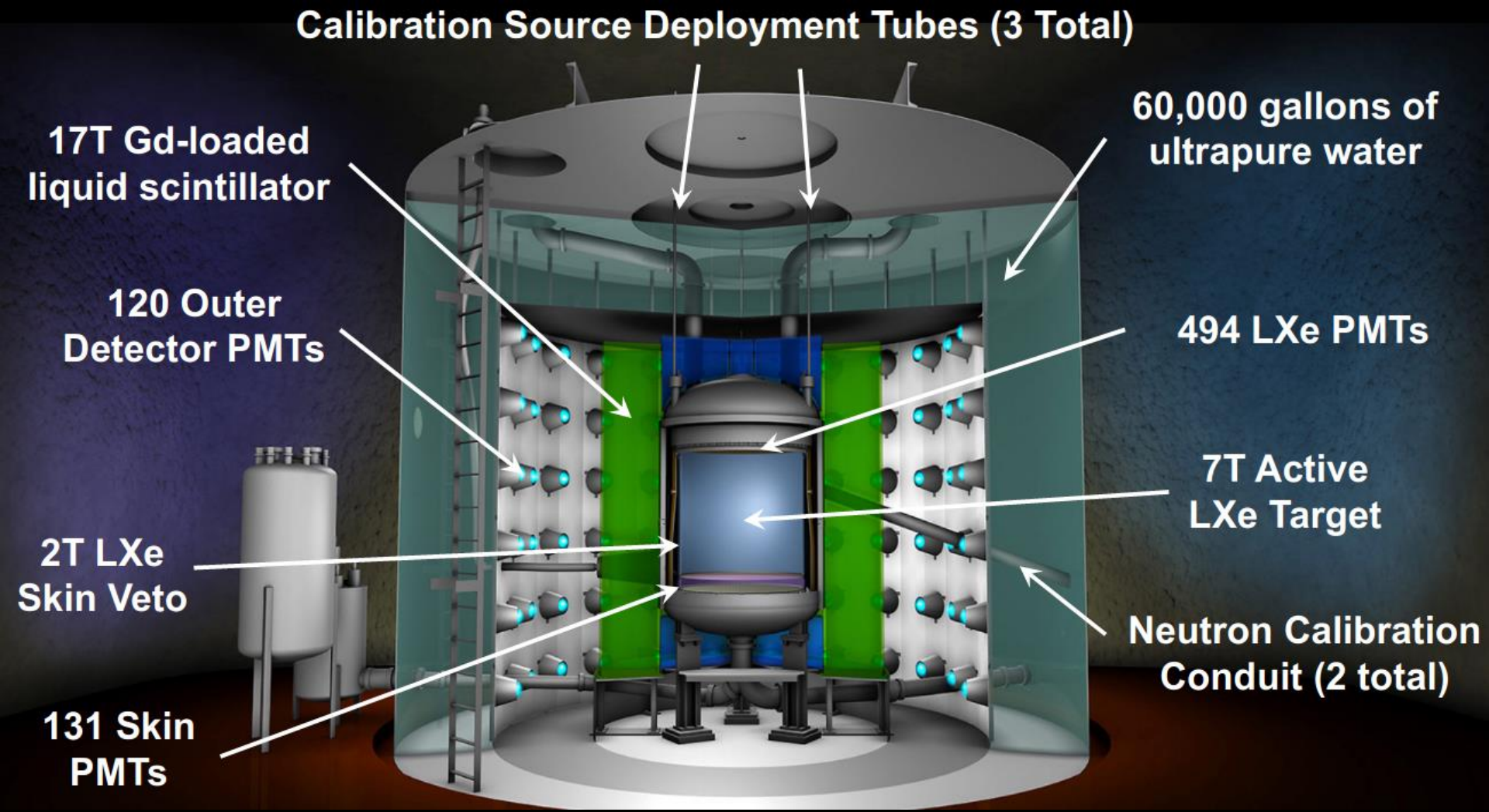
- Primary scintillation light (S1)
- Secondary scintillation induced from free charge (S2)
- 3D reconstruction allows for fidualisation
- ER/NR discrimination from S1:S2 ratio



# The LUX-ZEPLIN Detector



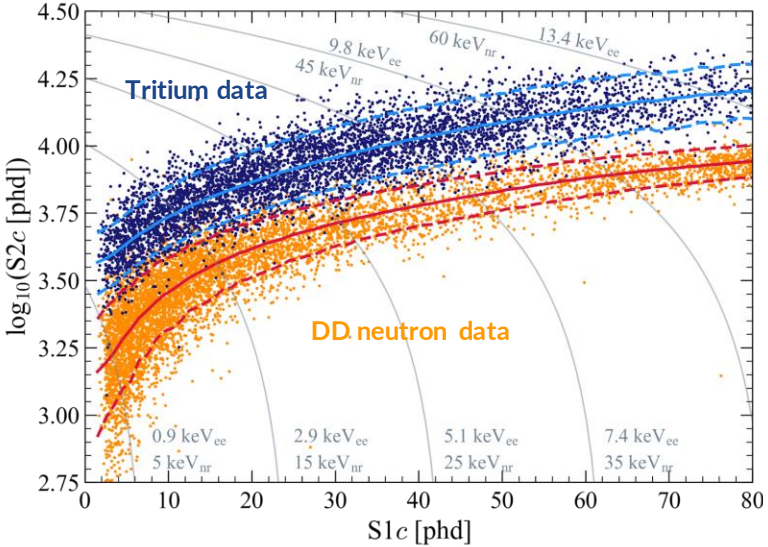

Calibration Source Deployment Tubes (3 Total)
17T Gd-loaded liquid scintillator
60,000 gallons of ultrapure water
120 Outer Detector PMTs
494 LXe PMTs
7T Active LXe Target
2T LXe Skin Veto
Neutron Calibration Conduit (2 total)
131 Skin PMTs

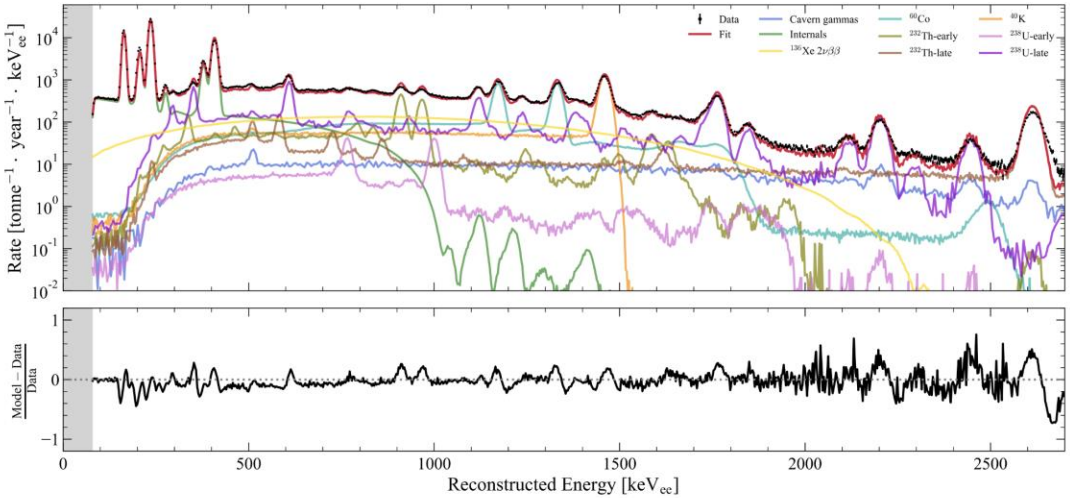
# SR1 Overview

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

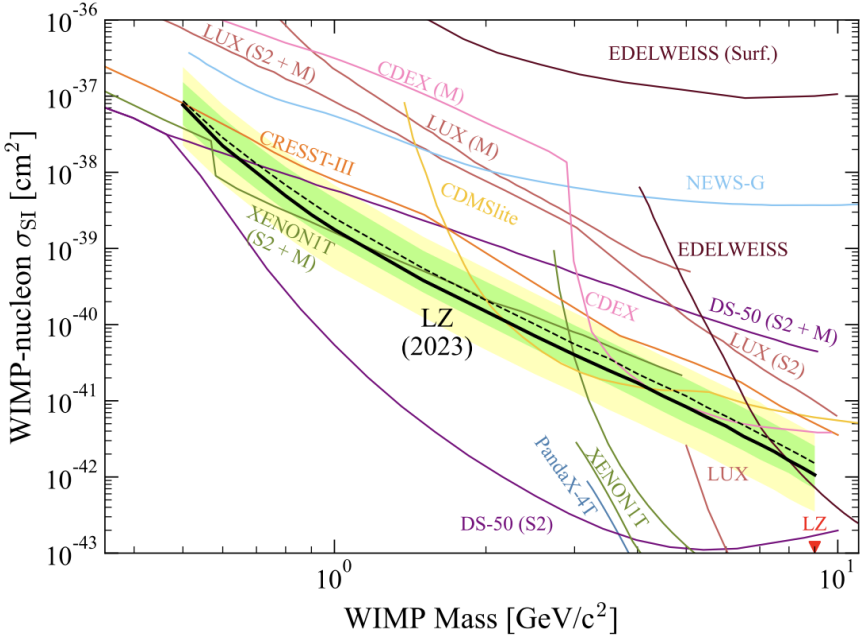
**Dataset**
- Data taken Dec.2022-May.2023
- 60±1 live days
- 5.5±0.2 tonne fiducial volume
- Photon collection efficiency: g1=0.114±0.2 phd/photon
- Charge gain: g2=47.1±1.1 phd/electron

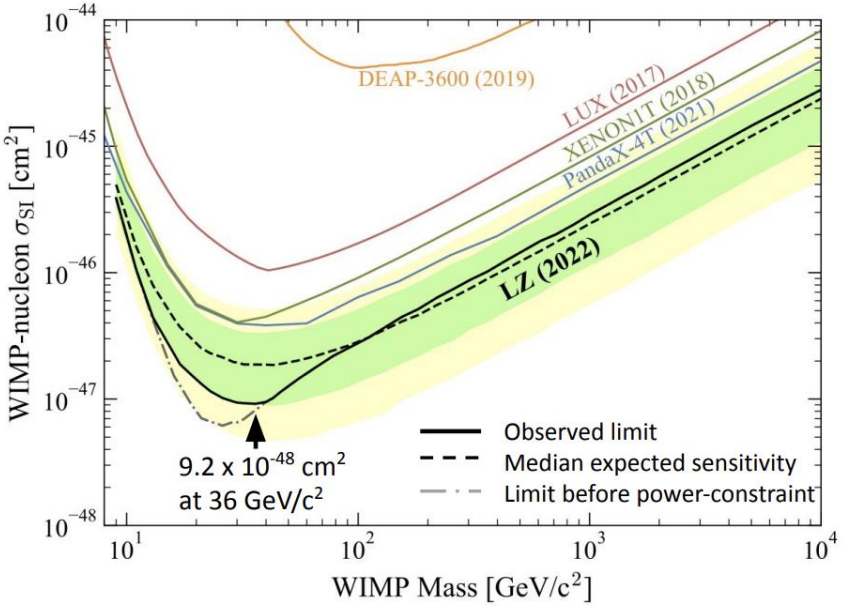
**Analysis**
- ER Calibrations (Tritium)
- NR Calibrations (Deuterium-Deuterium)
- Backgrounds well modelled in energy region (see Phys. Rev. D 108, 012010)
- Unbinned profile likelihood in $\log_{10}(S2_c)-S1_c$
- Paper: Phys. Rev. Lett. 131, 041002



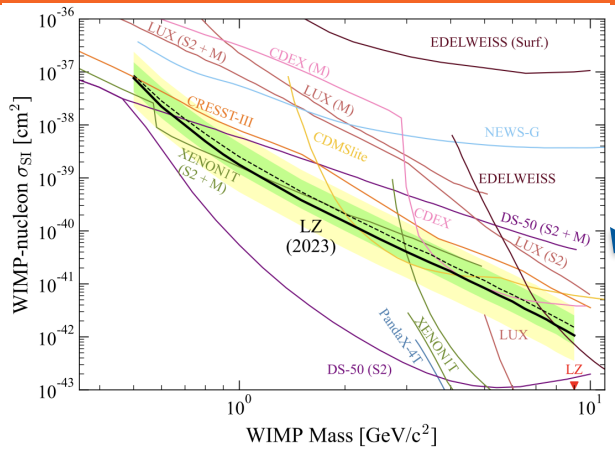



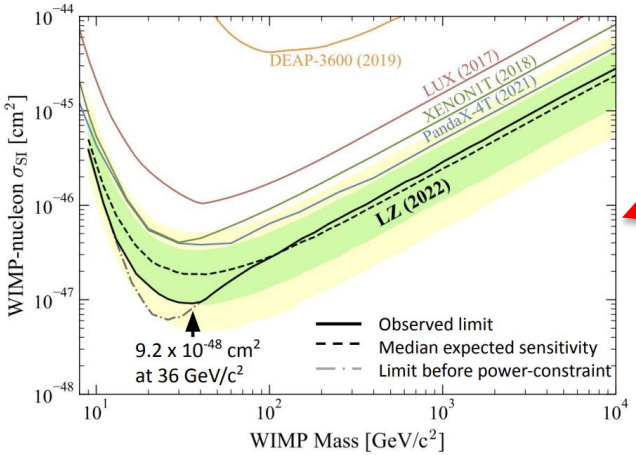
# SR1 Dark Matter Search Results

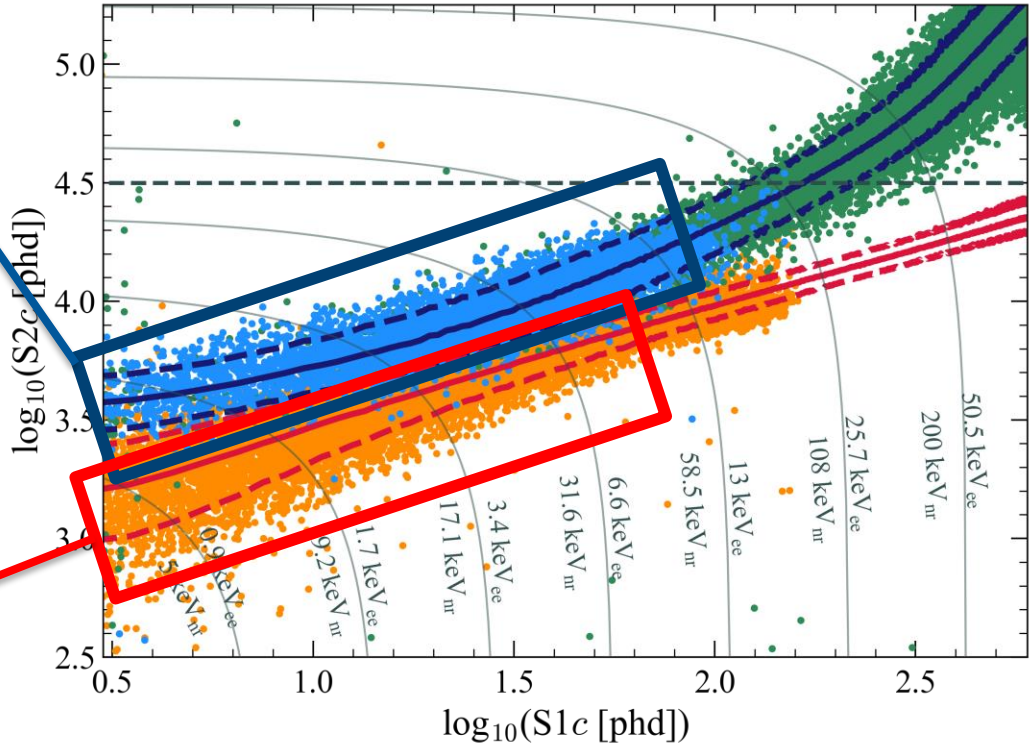


# SR1 Dark Matter Search Results



# Non-Relativistic Effective Field Theory: Operators

- Spin Independent and Spin Dependent interactions rely on the assumption of a zero-momentum transfer. But what if there is some momentum dependency?

- Use an EFT where we treat the WIMP-nucleon elastic scattering as a four-field interaction

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

- 4 Galilean, Hermitian invariants quantities which describe the interaction

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

- We are then left with 15 operators which contribute to the interaction Lagrangian

$$\begin{aligned}\mathcal{L}_{int} &= \sum_i c_i \mathcal{O}_i \\ &= c_1 + ic_3\vec{S}_N\cdot(\vec{q}\times\vec{v}^{\perp}) + c_4\vec{S}_{\chi}\cdot\vec{S}_N \\ &+ ic_5\vec{S}_{\chi}\cdot(\vec{q}\times\vec{v}^{\perp}) + c_6(\vec{S}_{\chi}\cdot\vec{q})(\vec{S}_N\cdot\vec{q}) \\ &+ c_7\vec{S}_N\cdot\vec{v}^{\perp} + c_8\vec{S}_{\chi}\cdot\vec{v}^{\perp} + ic_9\vec{S}_{\chi}\cdot(\vec{S}_N\times\vec{q}) \\ &+ c_{10}\vec{S}_N\cdot\vec{q} + ic_{11}\vec{S}_{\chi}\cdot\vec{q} + c_{12}\vec{S}_{\chi}\cdot(\vec{S}_N\times\vec{v}^{\perp}) \\ &+ ic_{13}(\vec{S}_{\chi}\cdot\vec{v}^{\perp})(\vec{S}_N\cdot\vec{q}) + ic_{14}(\vec{S}_{\chi}\cdot\vec{q})(\vec{S}_N\cdot\vec{v}^{\perp} \\ &+ -c_{15}(\vec{S}_{\chi}\cdot\vec{q})\left((\vec{S}_N\times\vec{v}^{\perp})\cdot\vec{q}\right)\end{aligned}$$

- Differential Recoil Rate in this case

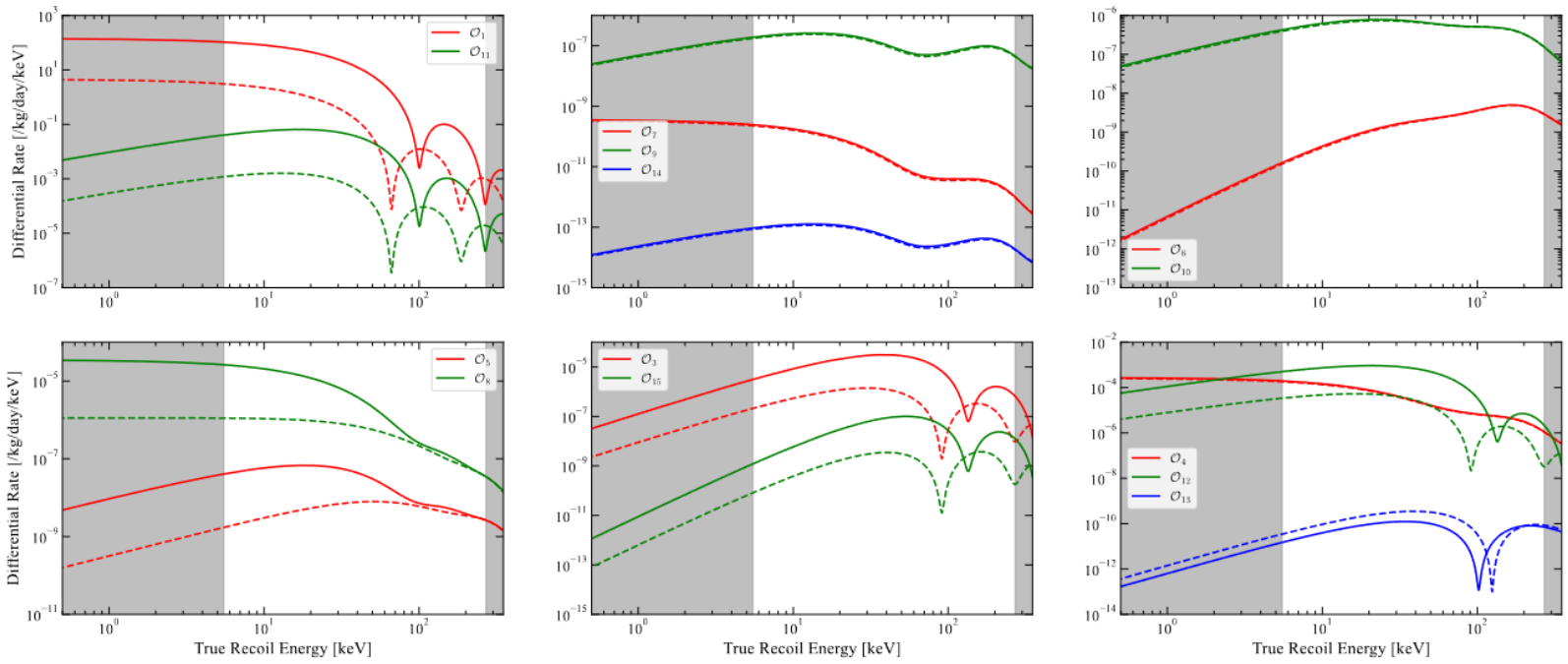
$$\frac{dR}{dE_R} = \frac{\rho_{\chi}}{32\,\pi m_{\chi}^3 m_N^2}\int_{v>v_{min}}^{\infty}\frac{f(\vec{v})}{v}\sum_{i,j=1}^{15}\sum_{a,b=0,1} c_j^a c_i^b F_{i,j}^{a,b} d^3v$$

Phys. Rev. C 89, 065501 (2014)

# NREFT Operator Signals

Evaluate the scattering amplitude assuming a single operator

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




$m_\chi$=1000 GeV/$c^2$

**Solid lines:** isoscalar

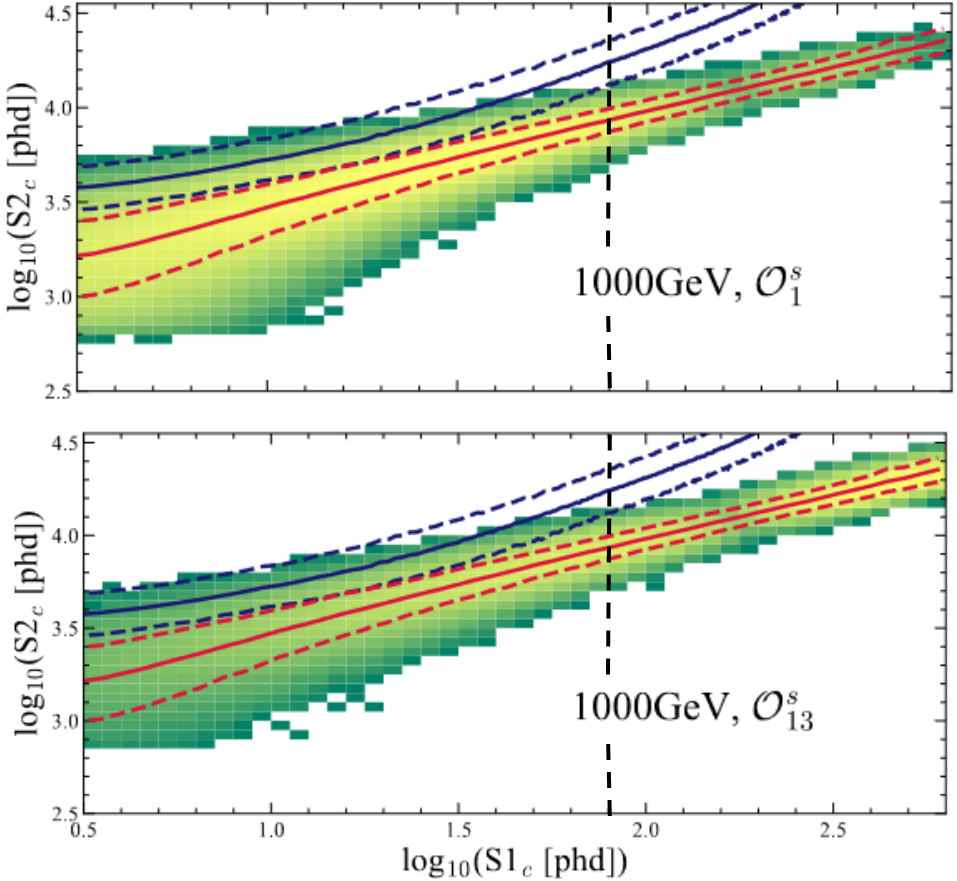
**Dashed lines:** isovector

**Shaded region:**

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

After all cuts and ROI selection

# NREFT Operator Signals



# Lagrangians

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

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

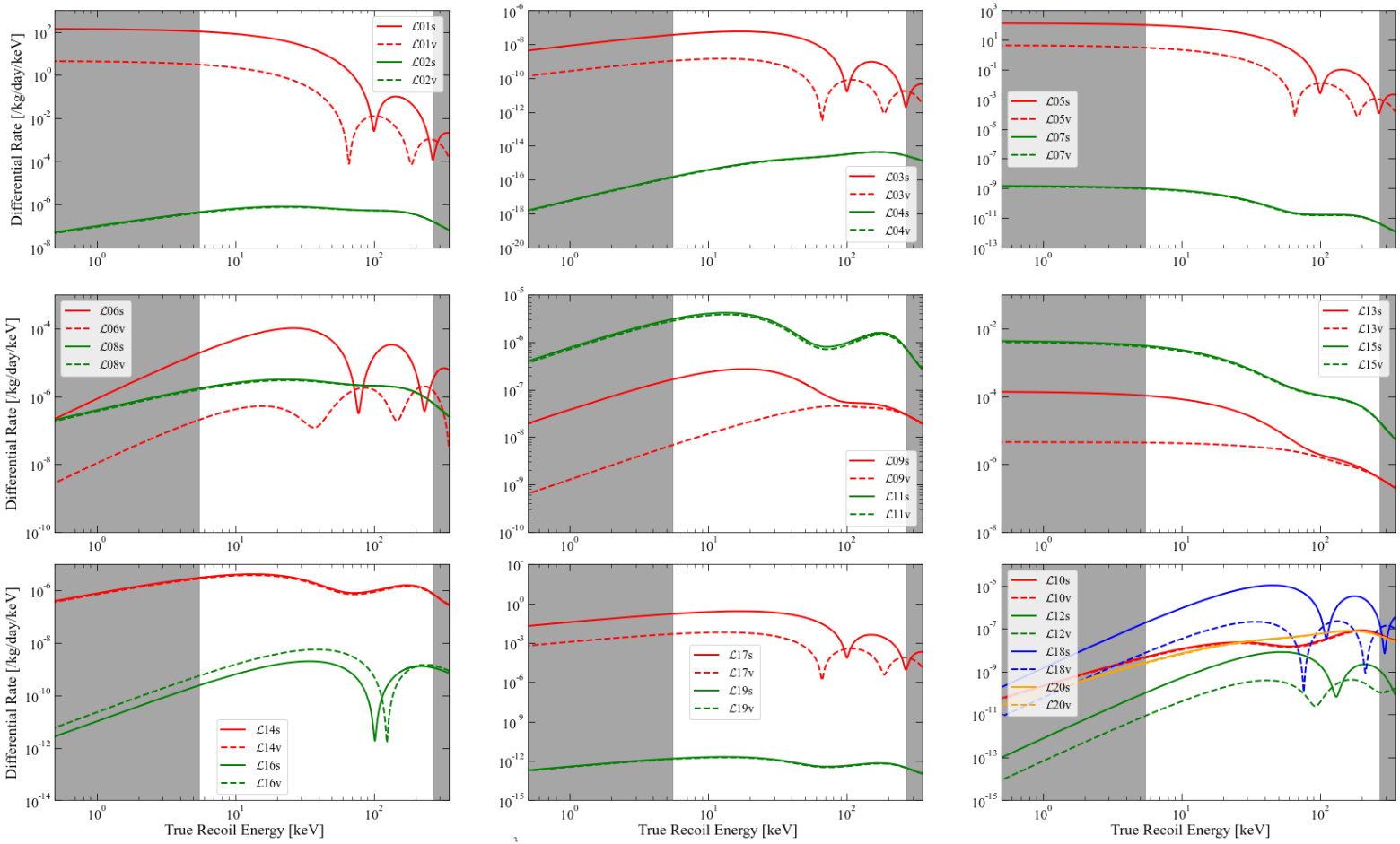
$d$ = operator construct coupling

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

Phys. Rev. C 89, 065501 (2014)

# NREFT Lagrangian Signals

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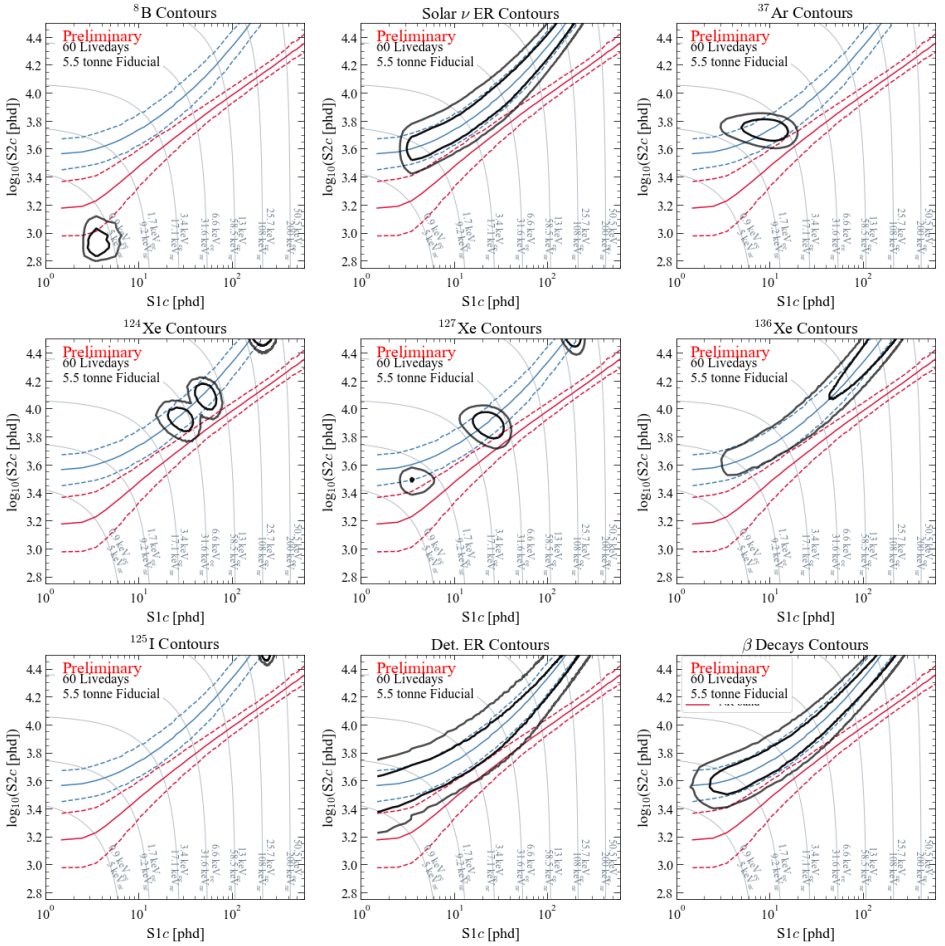
# Backgrounds in an extended energy analysis

All backgrounds relevant to SI WIMP search
Additional backgrounds

- Additional Xe decays
  - ( $^{124}$Xe, $^{133}$Xe, $^{131m}$Xe, $^{127}$Xe)
- Additional ER
- Topologies of more complex interactions (eg multiple scatter signal ionization events)



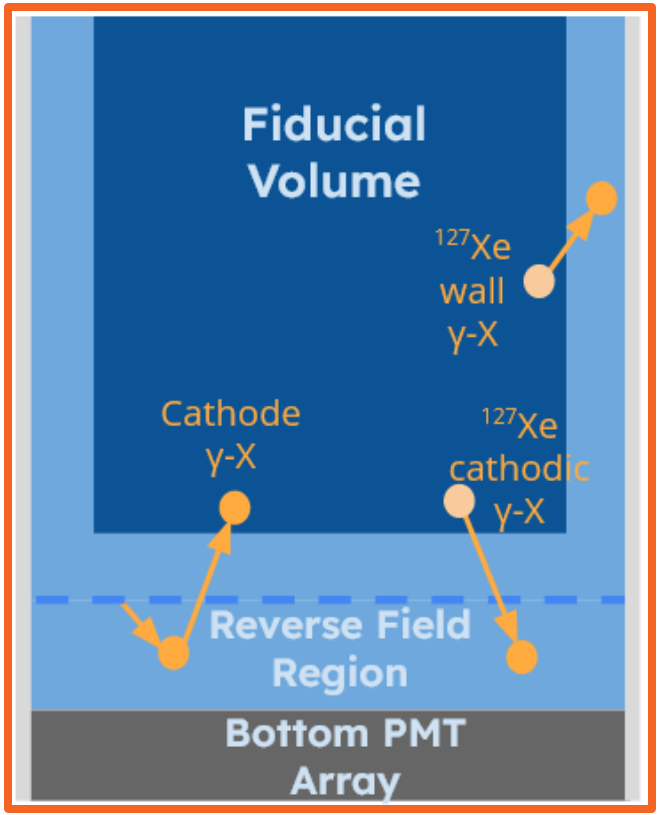
# Multiple Scatter Single Ionisation Events

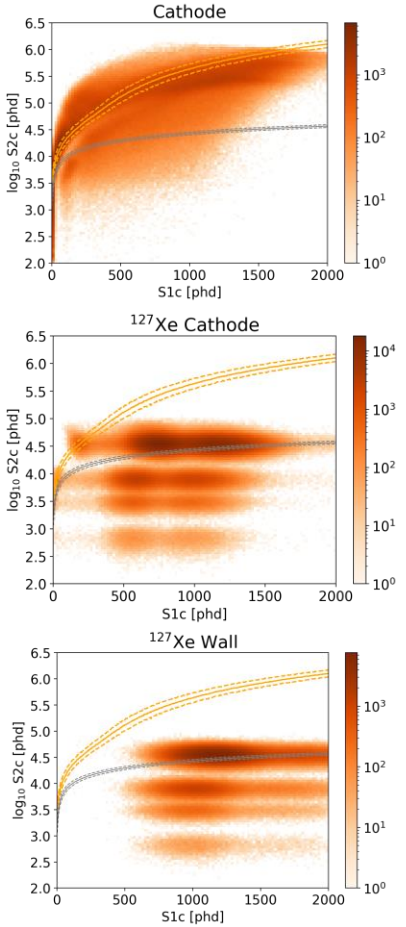
A γ-X event is a multiple-scattering γ where at least one vertex is in a region of incomplete charge collection:

- Reverse field region
- Near the TPC walls

Sources include:

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

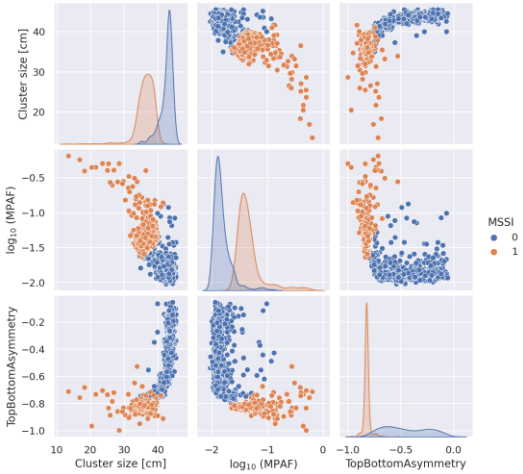


# Machine Learning Boosted Decision Tree for γ-X

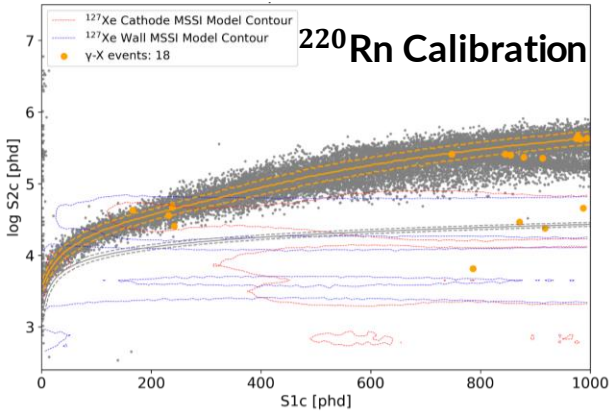
Boosted Decision Tree cut trained on high stats simulations and calibration data

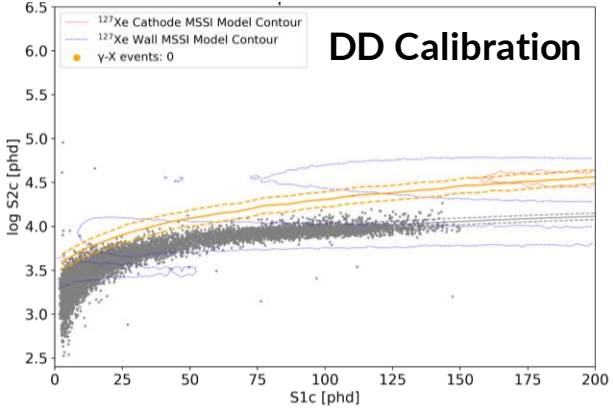
| ↓ P, → T | SS | γ-X |
|---|---|---|
| SS | $99.997 \pm 0.005$ | $0.4 \pm 1.2$ |
| γ-X | $0.003 \pm 0.005$ | $99.6 \pm 1.2$ |

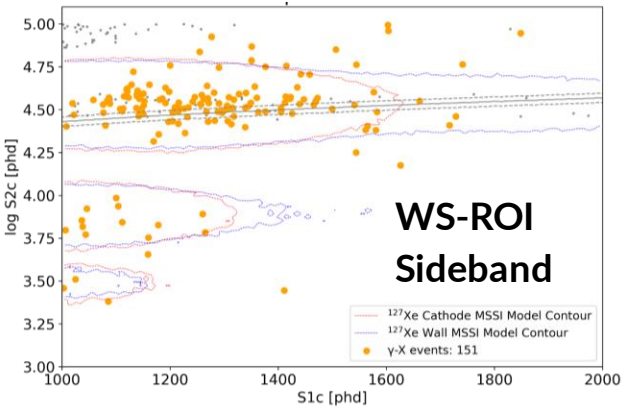



Quantities used in the classification:

- Cluster size (size of the S1 splash on the bottom PMT array)
- Max Peak Area Fraction
- Top Bottom Asymmetry
- S1c
- $\log_{10}$ S2c
- Radius
- Drift Time



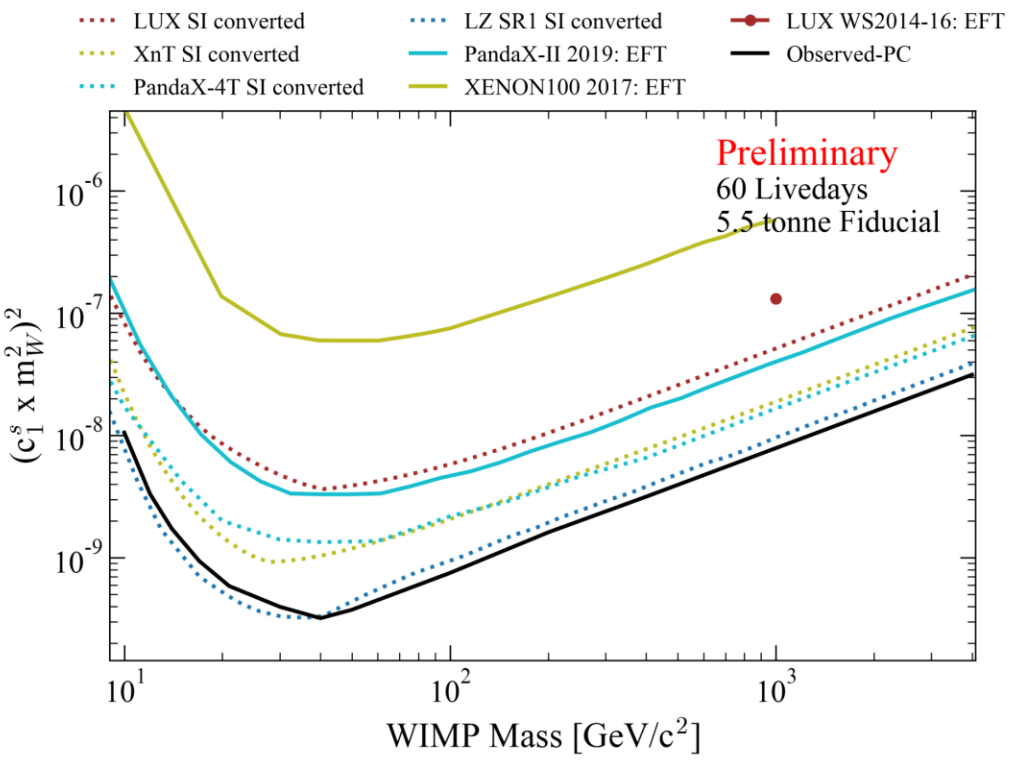



# LZ EFT $\mathcal{O}_1$

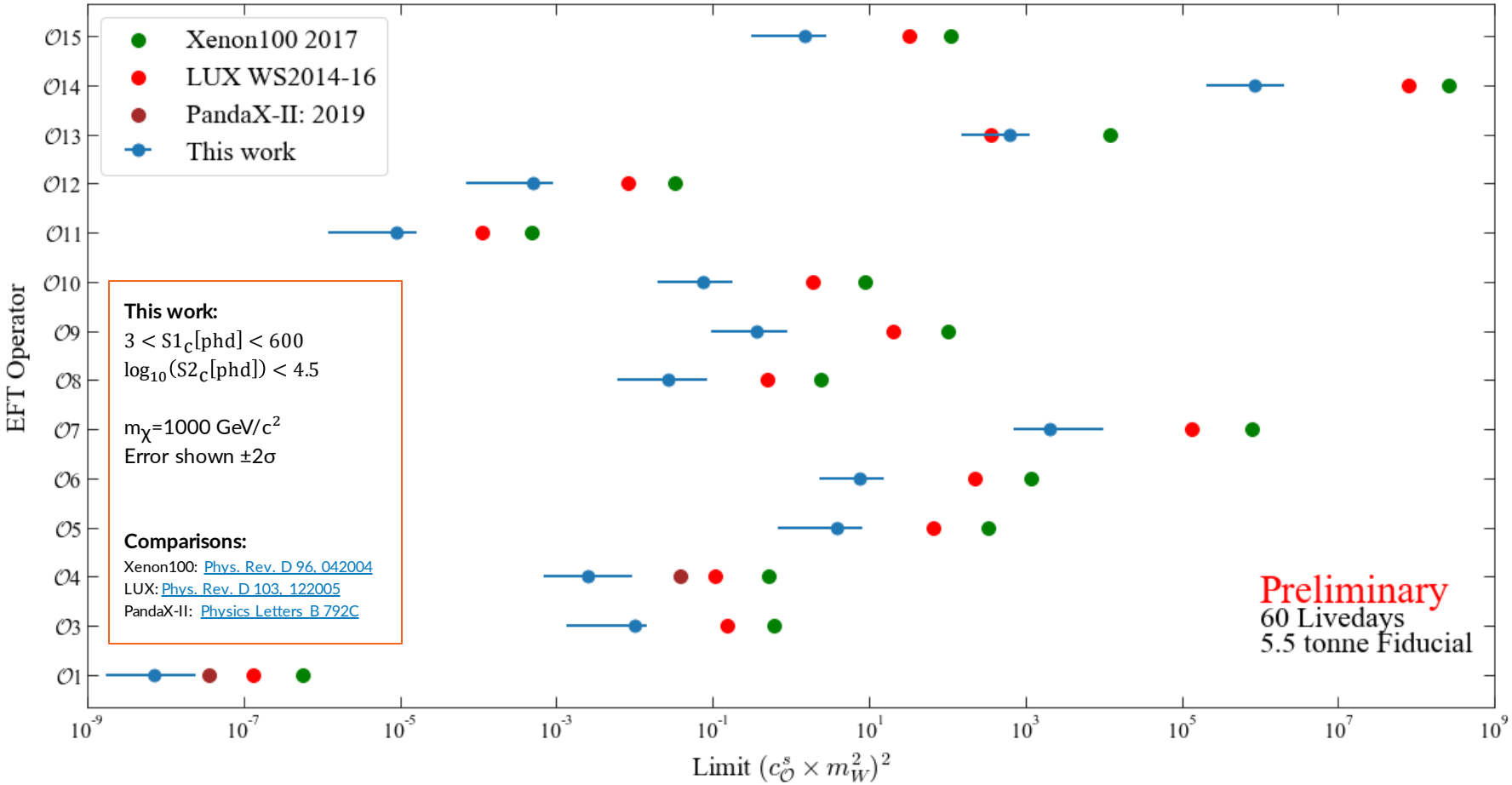
NREFT analyses often have differences in the choices of normalisations

- Representation of isospin
- Dimensionality of the presented result

| | Experiment | Basis | Limit Type | Conversion in plot |
|---|---|---|---|---|
| Phys. Rev. D 96, 042004 | 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 |
| Phys. Rev. D 104, 062005 | LUX: WS2014-16 EFT | $c_0 = (c_p + c_n)$ $c_1 = (c_p - c_n)$ | $(c_1^s \times m_w^2)^2$ | $\frac{1}{4}$ |
| Physics Letters B 792C | PandaX-II: SD EFT | $c_0 = \frac{1}{2}(c_p + c_n)$ $c_1 = \frac{1}{2}(c_p - c_n)$ | $d_5^s\ [\frac{1}{m_w^2}]$ | $(d_5^s)^2$ |
| 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 |
| Phys. Rev. C 89, 065501 | 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 |
| Phys. Rev. Lett. 118, 021303 | LUX: Combined 2017 SI | N/A | $\sigma_{SI}^N$ | $\sigma_{SI}^N \frac{\pi \cdot m_w^4}{(\frac{(\hbar c)}{\mathrm{GeV}})^2 \mu_N^2}$ |
| Phys. Rev. Lett. 127, 261802 | PandaX-4T: 2021 SI | N/A | $\sigma_{SI}^N$ | $\sigma_{SI}^N \frac{\pi \cdot m_w^4}{(\frac{(\hbar c)}{\mathrm{GeV}})^2 \mu_N^2}$ |
| Phys. Rev. Lett. 131, 041002 | LZ: 2023 SI | N/A | $\sigma_{SI}^N$ | $\sigma_{SI}^N \frac{\pi \cdot m_w^4}{(\frac{(\hbar c)}{\mathrm{GeV}})^2 \mu_N^2}$ |
| Phys. Rev. Lett. 131, 041003 | XENONnT: 2023 SI | N/A | $\sigma_{SI}^N$ | $\sigma_{SI}^N \frac{\pi \cdot m_w^4}{(\frac{(\hbar c)}{\mathrm{GeV}})^2 \mu_N^2}$ |



# LZ EFT Operator Preliminary Results

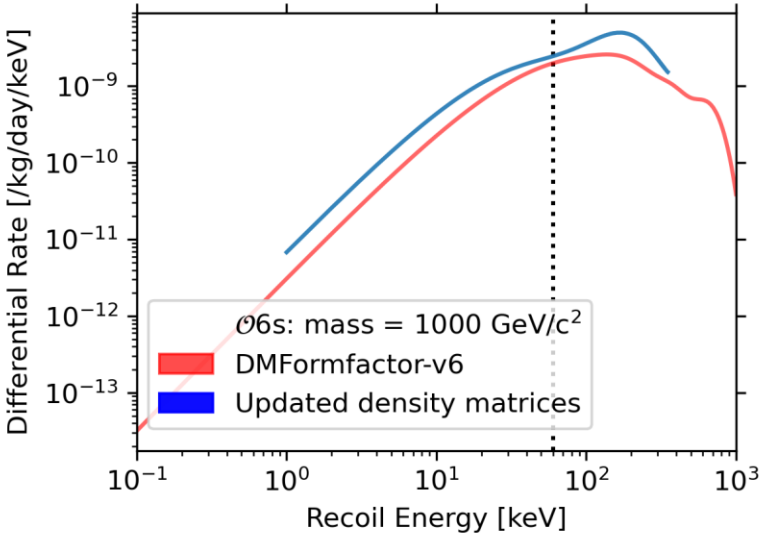


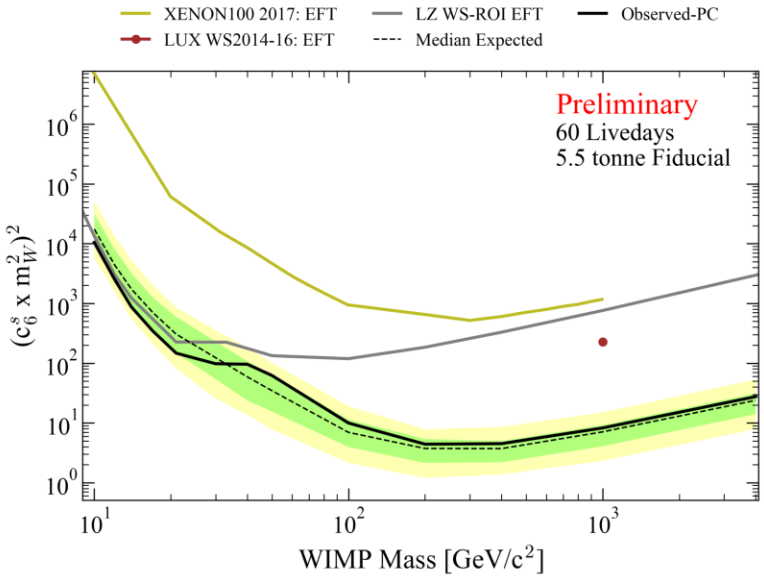

**This work:**
$3 < S1_c[\text{phd}] < 600$
$\log_{10}(S2_c[\text{phd}]) < 4.5$

$m_\chi$=1000 GeV/$c^2$
Error shown ±2σ

**Comparisons:**
Xenon100: Phys. Rev. D 96, 042004
LUX: Phys. Rev. D 103, 122005
PandaX-II: Physics Letters B 792C

# Benefit from an increased energy window




Dashed line indicates the energy at falling edge of the efficiency is 50% with LZ SR1 WIMP-Search ROI:

- $3 < S1_c[\mathrm{phd}] < 80$

Grey:

- $3 < S1_c[\mathrm{phd}] < 80$
- DMFormFactor-v6 signal

Black + Brazilian band (this work):

- $3 < S1_c[\mathrm{phd}] < 600,\ \log_{10}(S2_c[\mathrm{phd}]) < 4.5$
- Updated density matrices for signals

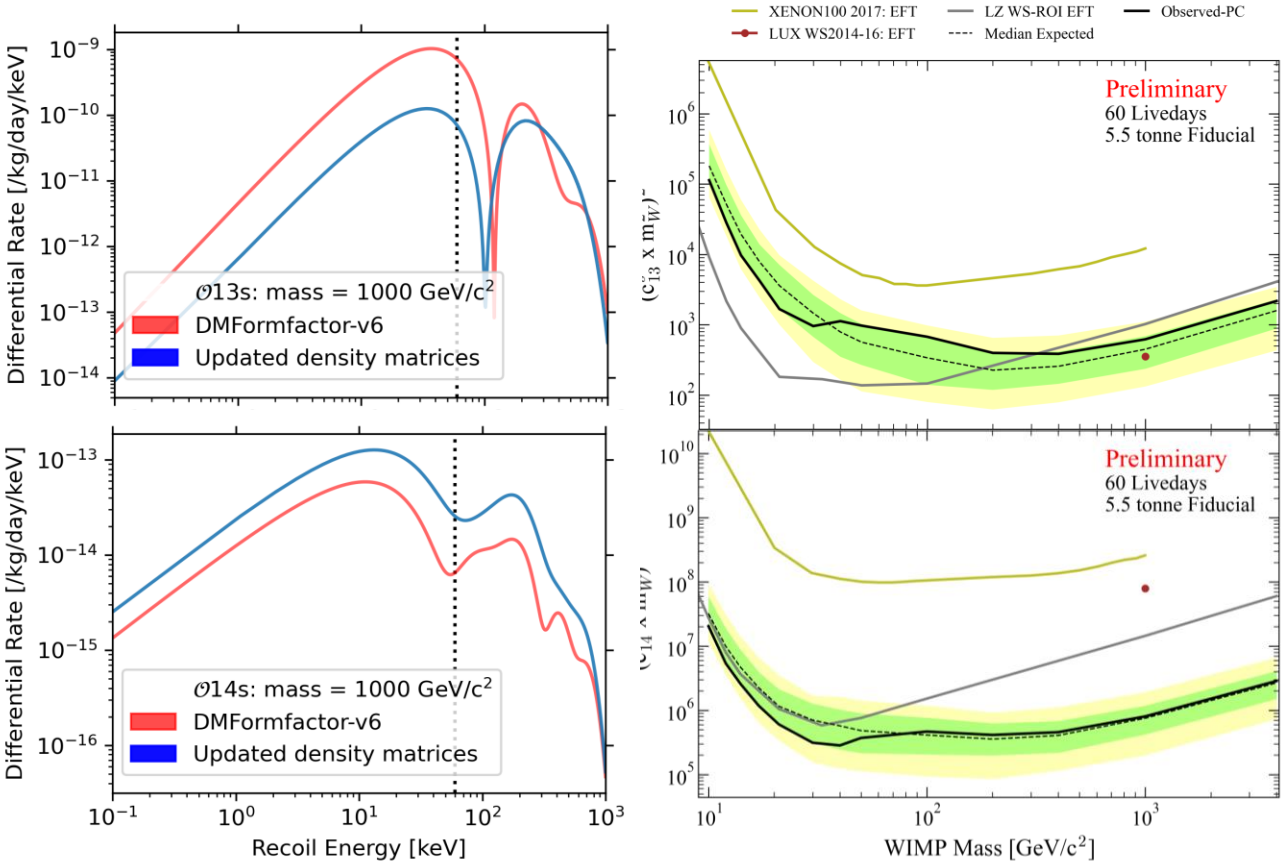
# Impacts from updated nuclear density matrices

Differential recoils used updated GCN5082 ground state to ground state one-body density matrices

These have significant impacts on some operators

$\mathcal{O}_{13}$ differential rate has decreased significantly

$\mathcal{O}_{14}$ has the opposite behaviour



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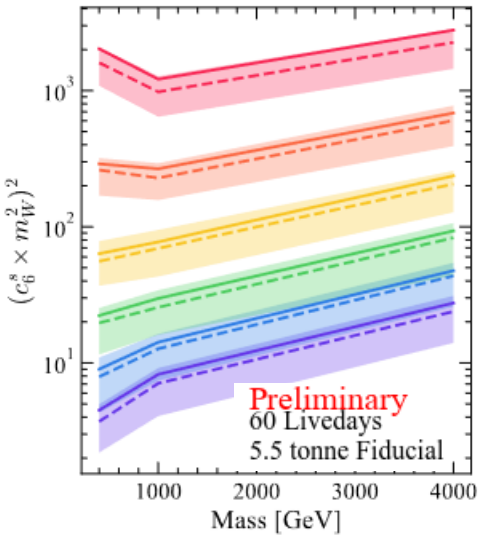
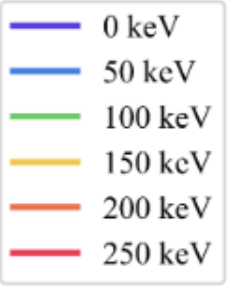



**Inelastic Operators**

This work:

- $3 < S1_c[\text{phd}] < 600$
- Updated density matrices for signals

$$\delta_m \equiv m_{\chi,out} - m_{\chi,in}$$

$$\delta_m + \vec{v} \cdot \vec{q} + \frac{|\vec{q}|^2}{2\mu_N} = 0$$

$$\vec{v}_{inel}^{\perp} \equiv \vec{v} + \frac{\vec{q}}{2\mu_N} + \frac{\delta_m}{|\vec{q}|^2}\vec{q}$$

**Elastic Lagrangians**

This work:

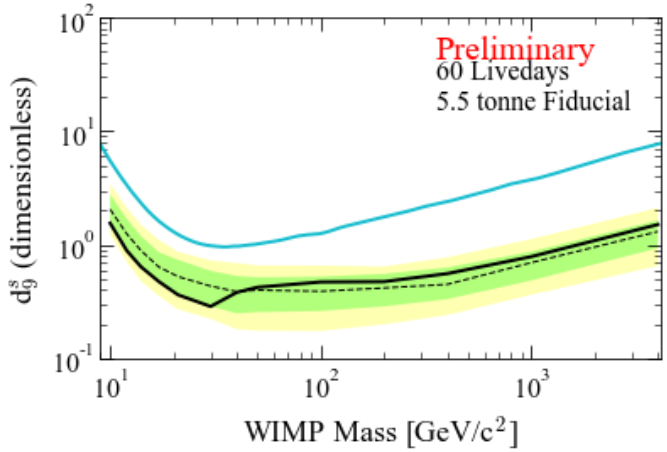
- $3 < S1_c[\text{phd}] < 600$
- Updated density matrices for signals

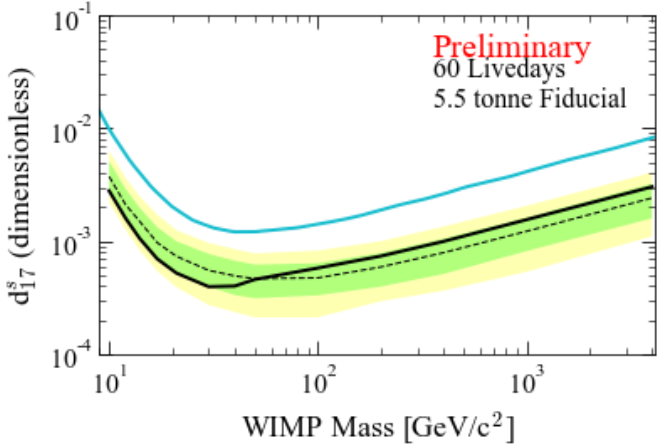
Blue:

- PandaX-II: [Physics Letters B 792C]

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

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



# Summary

- 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 a lot of DM parameter space, eg:
  - 2HDM+a: Phys. D. M. 27, 100351 (2020)
  - DM –photon interactions: Nature **618**, 47 (2023)

**LZ Publications**:

- Detector paper: Nucl. Instrum. Meth. A 953, 163047
- SR1 papers:
  - WIMP-nucleon result: Phys. Rev. Lett. 131, 041002
  - Backgrounds: Phys. Rev. D 108, 012010
  - LowE ER: arXiv:2307.15753
  - this work: paper in progress

University of BRISTOL

LZ

# Questions?


Department of Energy United States of America

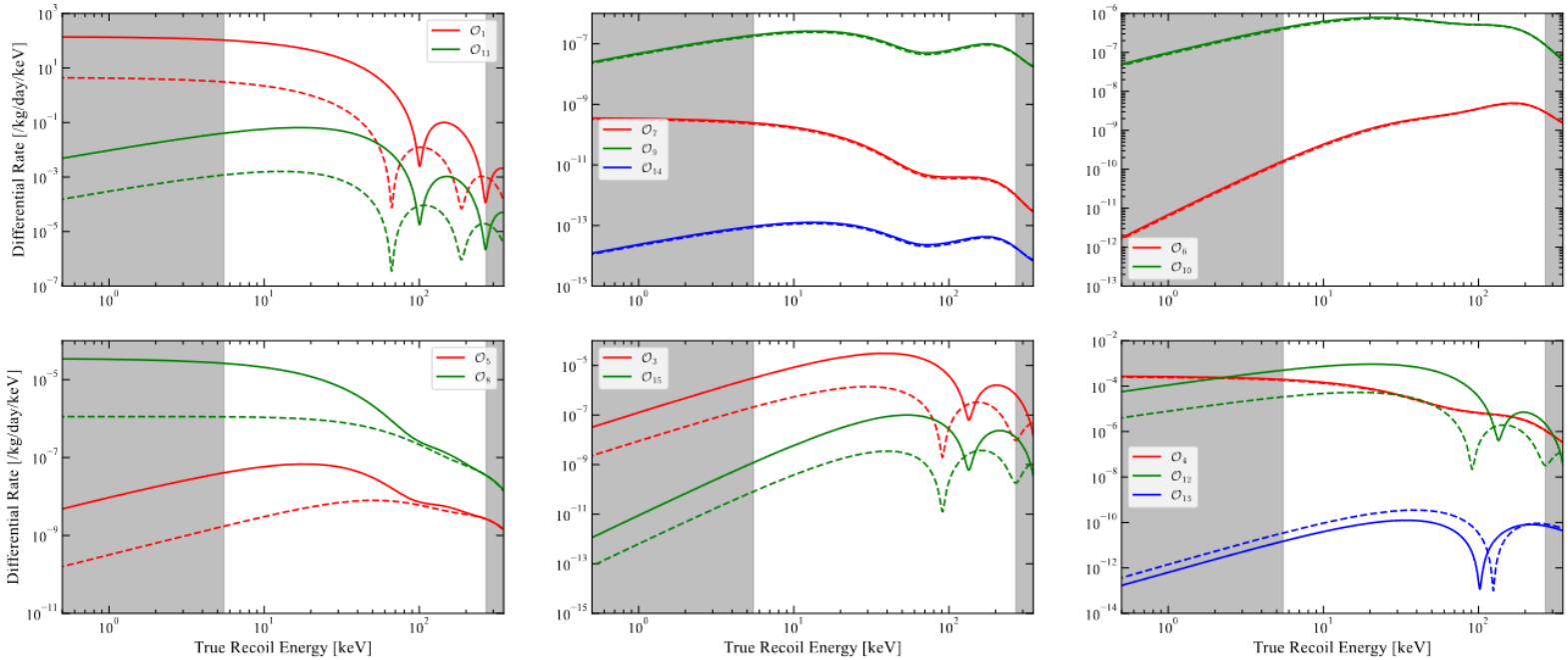
UKRI Science and Technology Facilities Council

Sanford Underground Research Facility
South Dakota Science and Technology Authority

FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

ibs Institute for Basic Science

# NREFT Operator Signals

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**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

**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)

Evaluate the scattering amplitude assuming a single operator

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

# Non-Relativistic Effective Field Theory: Operators

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

$$\begin{aligned}\mathcal{L}_{int} &= \sum_i c_i \mathcal{O}_i \\ &= c_1 + ic_3\vec{S}_N\cdot(\vec{q}\times\vec{v}^\perp) + c_4\vec{S}_\chi\cdot\vec{S}_N \\ &+ ic_5\vec{S}_\chi\cdot(\vec{q}\times\vec{v}^\perp) + c_6(\vec{S}_\chi\cdot\vec{q})(\vec{S}_N\cdot\vec{q}) \\ &+ c_7\vec{S}_N\cdot\vec{v}^\perp + c_8\vec{S}_\chi\cdot\vec{v}^\perp + ic_9\vec{S}_\chi\cdot(\vec{S}_N\times\vec{q}) \\ &+ c_{10}\vec{S}_N\cdot\vec{q} + ic_{11}\vec{S}_\chi\cdot\vec{q} + c_{12}\vec{S}_\chi\cdot(\vec{S}_N\times\vec{v}^\perp) \\ &+ ic_{13}(\vec{S}_\chi\cdot\vec{v}^\perp)(\vec{S}_N\cdot\vec{q}) + ic_{14}(\vec{S}_\chi\cdot\vec{q})(\vec{S}_N\cdot\vec{v}^\perp) \\ &+ -c_{15}(\vec{S}_\chi\cdot\vec{q})\left((\vec{S}_N\times\vec{v}^\perp)\cdot\vec{q}\right)\end{aligned}$$

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

**Interactions are linear combinations of 6 independent nuclear responses**

- $M$ Spin Independent
- $\Sigma'$ Spin Dependent (transverse)
- $\Sigma''$ Spin Dependent (longitudinal)
- $\Delta$ Angular Momentum
- $\Phi''$ Spin Orbit
- $\tilde{\phi}'$ Tensor spin orbit

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

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