New constraints on multiply-interacting ultra-heavy dark matter from the LUX-ZEPLIN (LZ) experiment

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TeVPA

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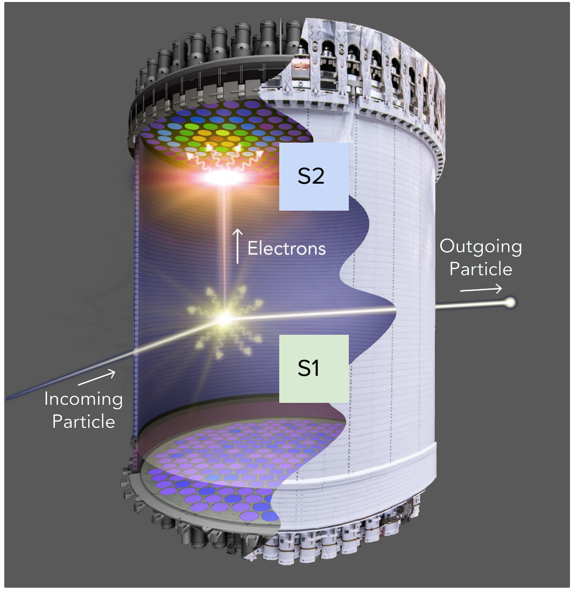
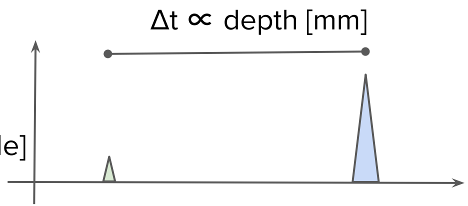
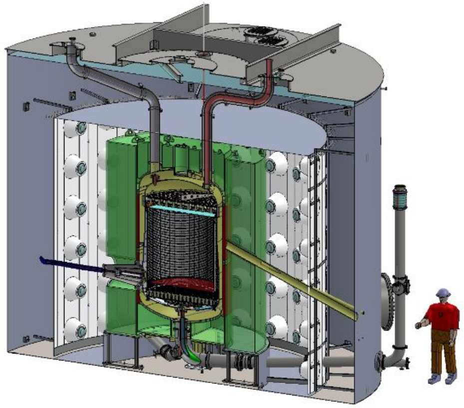
LUX-ZEPLIN



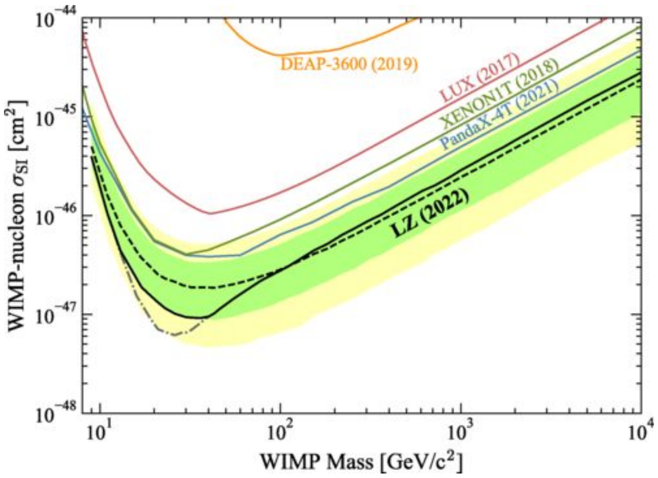
[Credit: LZ Collaboration]



See V. Kudryavtsev's presentation (Wed. 9:45)



NIM A 953, 163047 (2020)

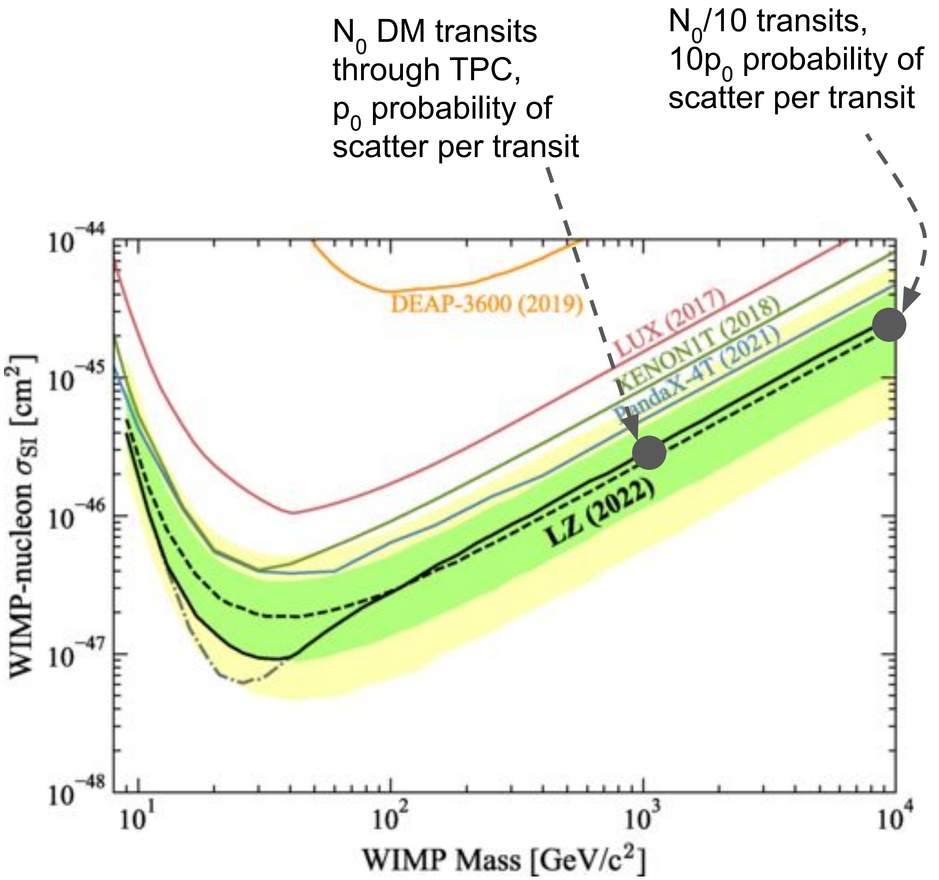


Phys. Rev. Lett. 131, 041002 (2023)

WIMP limits at high mass

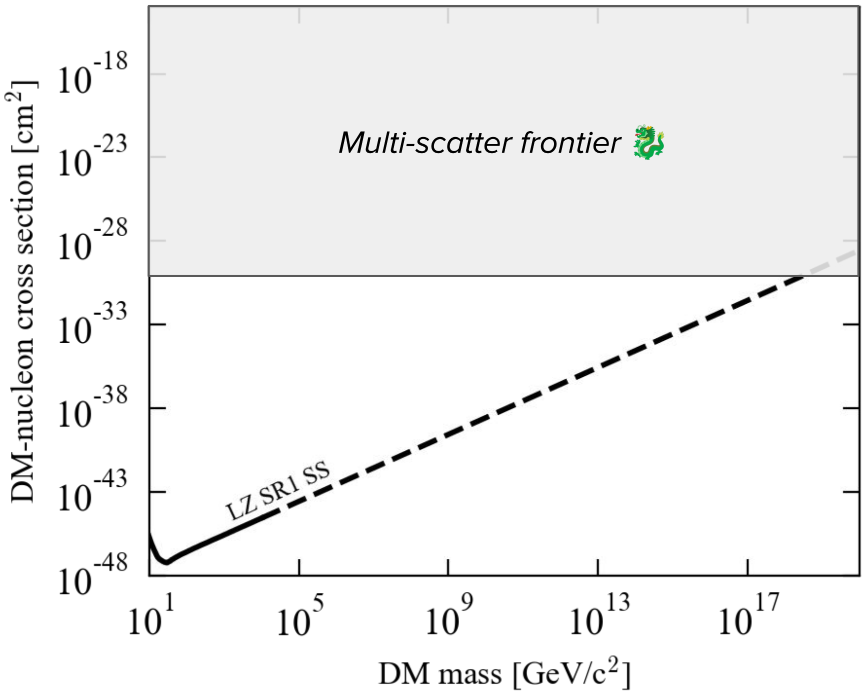
- LZ limit plots are truncated above 10 TeV - for masses much higher than m_{Xe}, the recoil spectrum no longer depends on dark matter mass

$$E_r = \frac{m_\chi^2 m_N v^2}{(m_\chi + m_N)^2}(1 - \cos(\theta))$$



WIMP limits at high mass

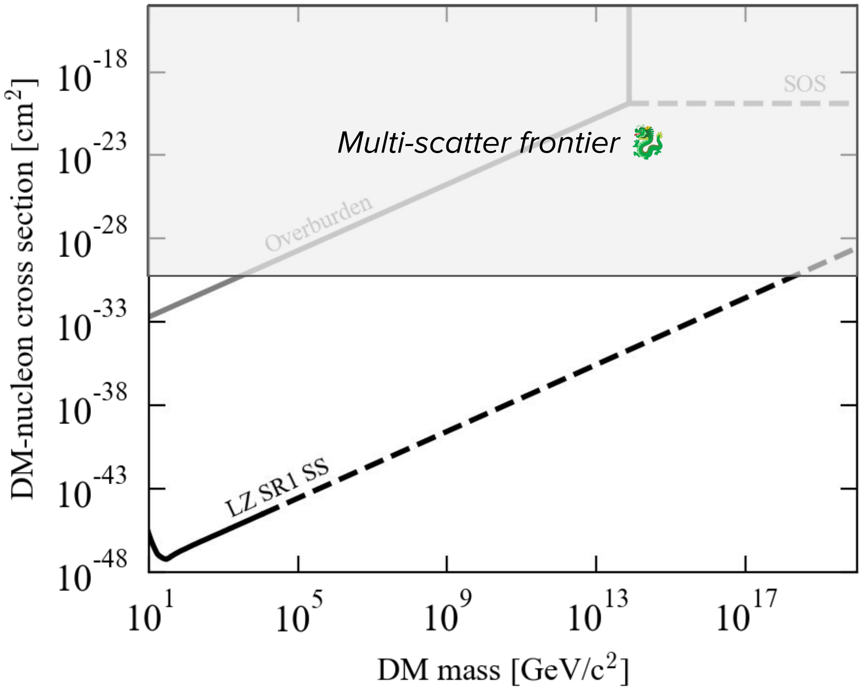
- At high cross section (>10^{-31} cm^2), DM signal no longer consists primarily of single scatters



WIMP limits at high mass

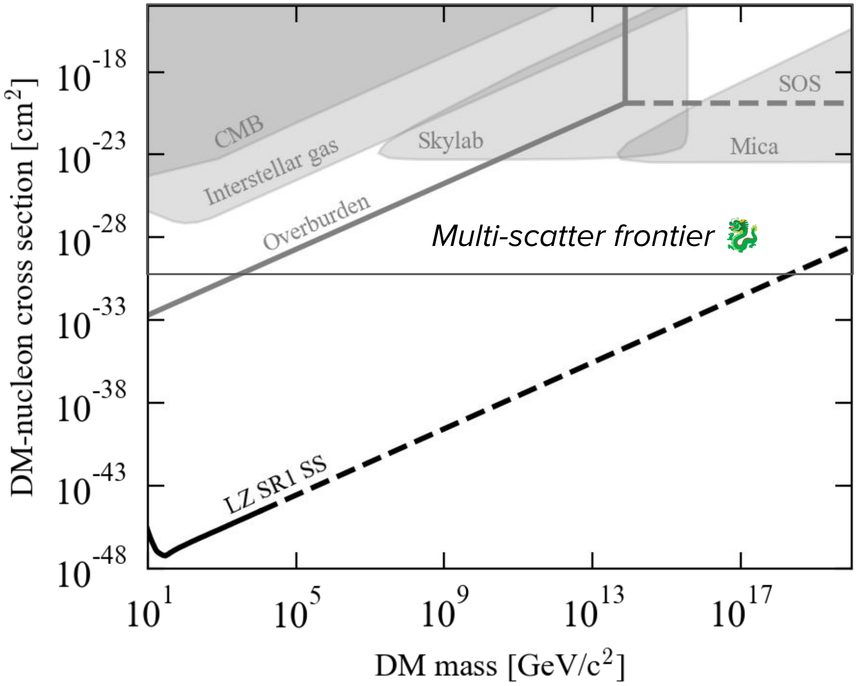
- If dark matter is very heavy, it can penetrate the overburden and reach LZ even if scattering many times
- Saturated overburden scattering (SOS) - for masses above ~10^{14} GeV, can probe arbitrarily high cross sections

[Phys. Rev. D **98**, 083516 (2018)]



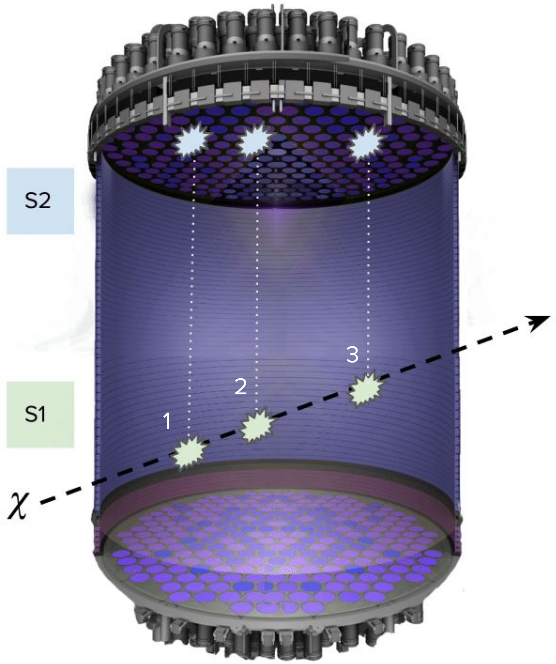
WIMP limits at high mass

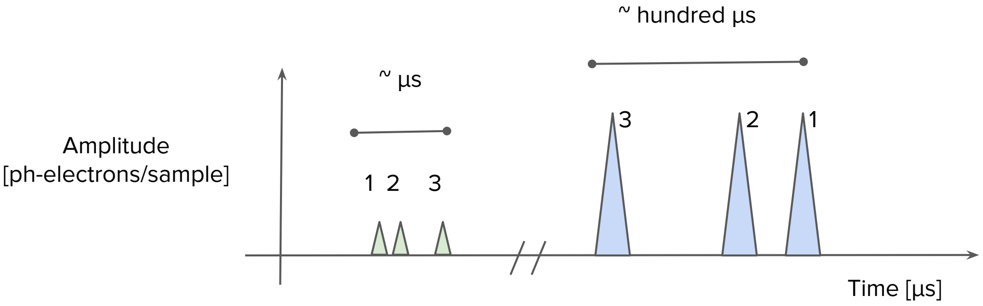
- Direct detection experiments like LZ sensitive to high cross sections unconstrained by astrophysical limits and passive detectors
- Various production scenarios for ultra-heavy dark matter have been proposed [see Snowmass 2021 white paper]



MIMP signals in LZ

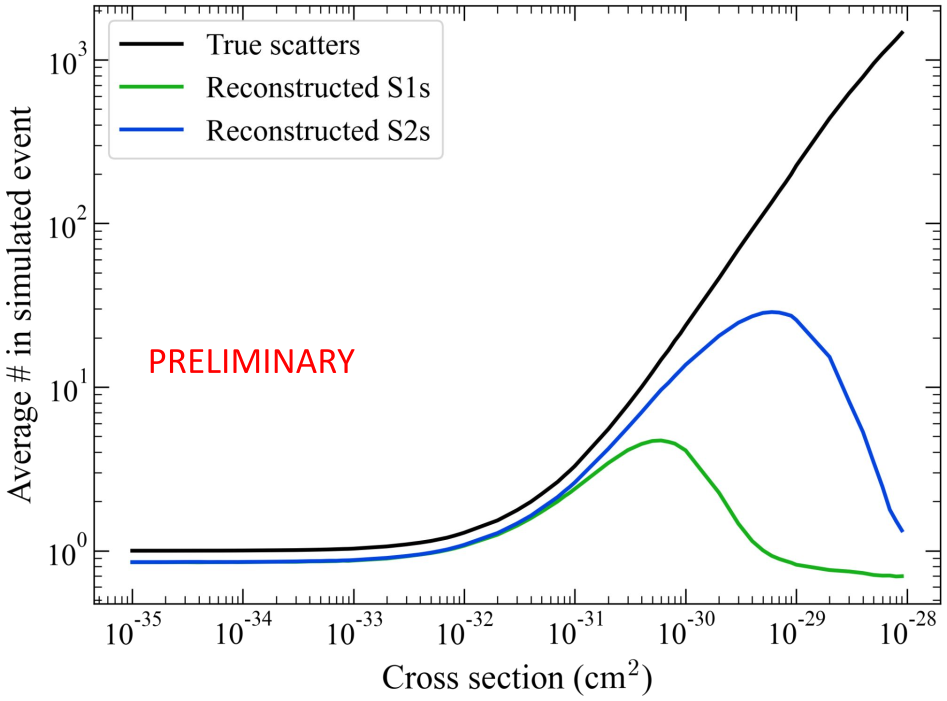
- High cross section dark matter can produce multiple scatters in a single transit, arranged along a straight line for ultra-heavy candidates





Multiplicity

- S2s are better resolved than S1s in typical MIMP tracks
- At cross sections above 10^{-29} cm^2, we no longer resolve S1s, and this search strategy loses sensitivity



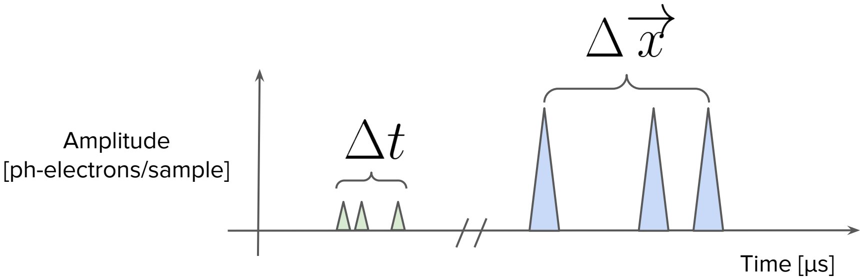
Analysis

- LZ Science Run 1 (SR1) dataset - Dec 12 2021 to May 5 2022, 60 day livetime after base data quality cuts
- Series of cuts tuned to accept simulated MIMP signals
- All SR1 events rejected by cuts

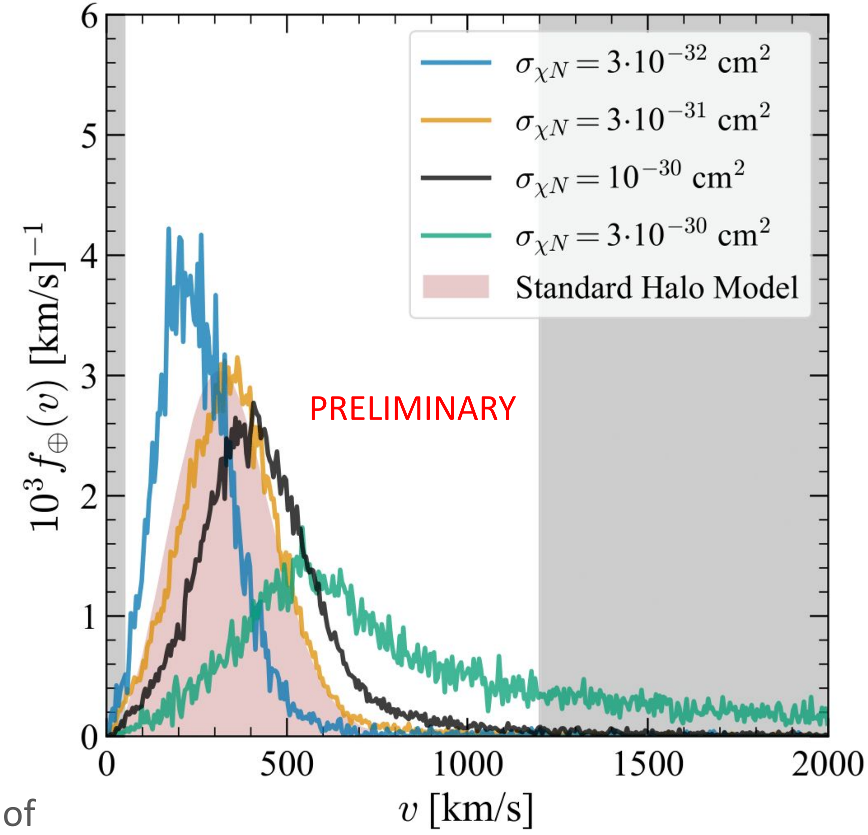
Cut	Survival Fraction
>1 S1, >1 S2	15.2%
Good S1	13.8%
Fiducial	2.7%
Colinearity	2.3%
Uniformity	0.7%
Velocity	0.1%
Region of Interest (ROI)	0%

Velocity reconstruction

- With multiple interactions, DM velocity can be measured for individual events!

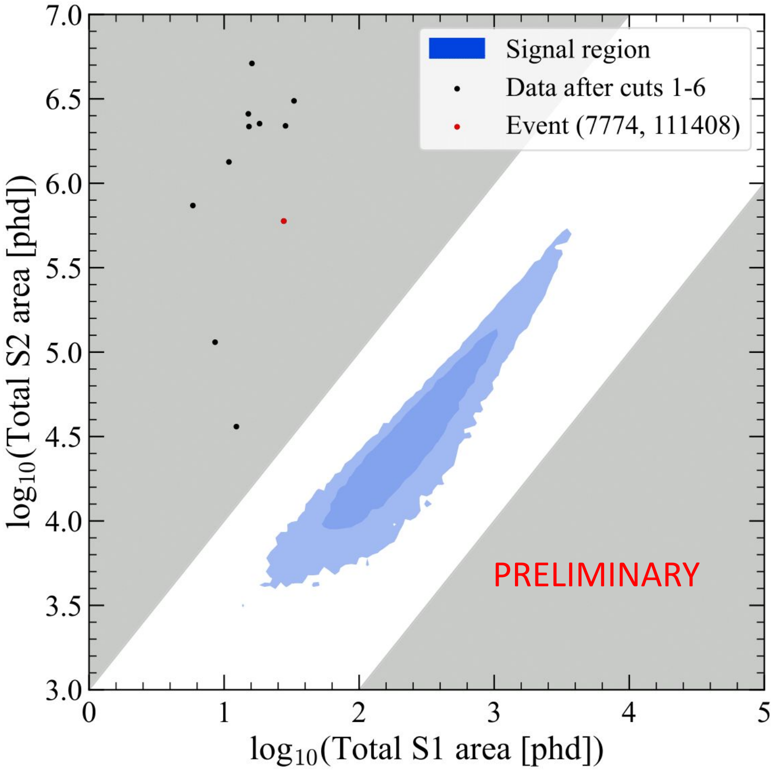


- At high cross sections, merging of pulses causes mis-reconstruction of velocity
- Velocity cut was based on reconstructed distribution for simulated MIMPs with DM-nucleon cross section of 10^{-30} cm^2

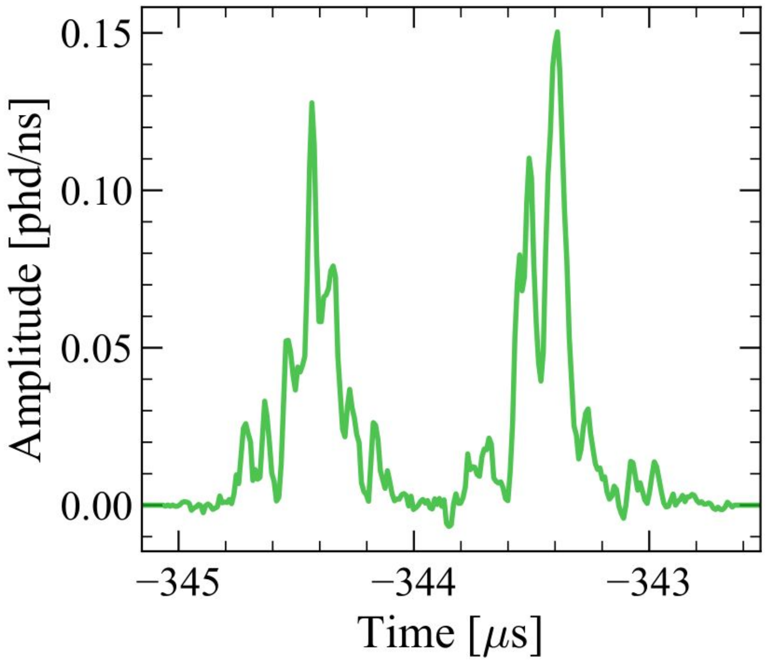


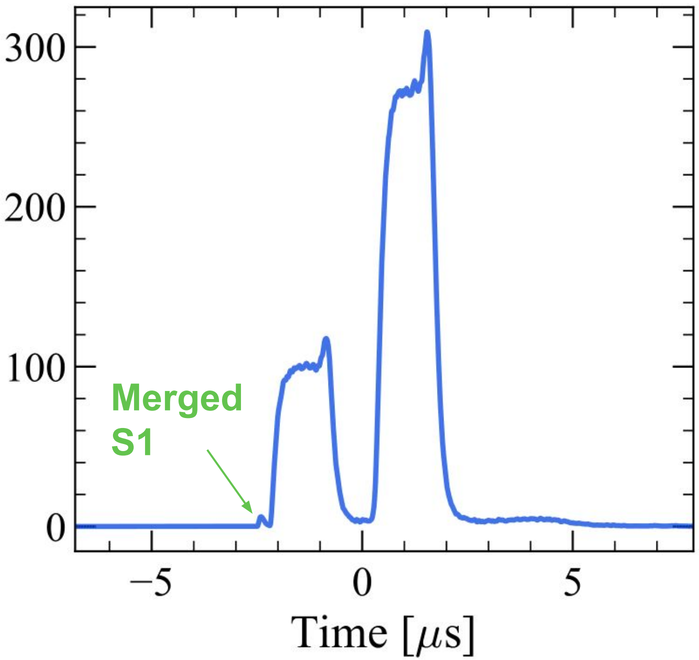
Signal ROI

- Expect scintillation and ionization signals to be positively correlated, with ratio characteristic of nuclear recoils
- Not relying on accurately reconstructing number of scatters - simple conservative cut on ratio of total S2 to total S1
- Backgrounds with S2 area much larger than expected from S1s - characteristic of accidental coincidence



A background event from mis-reconstruction



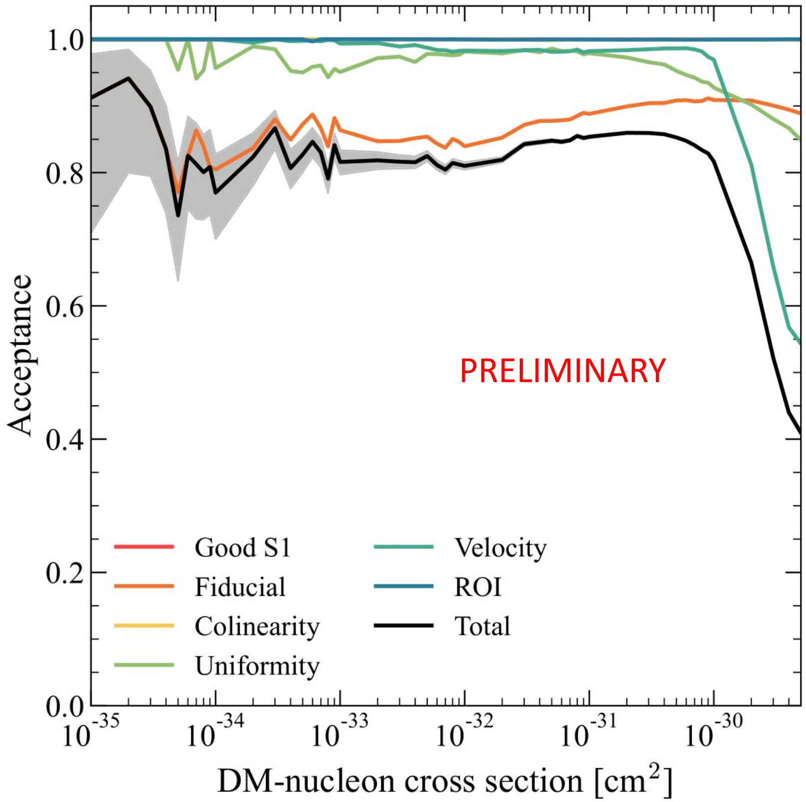


S1s may be misclassified single electron pulses

S2 shape indicates near-surface scatters - pulse finder failed to resolve corresponding S1

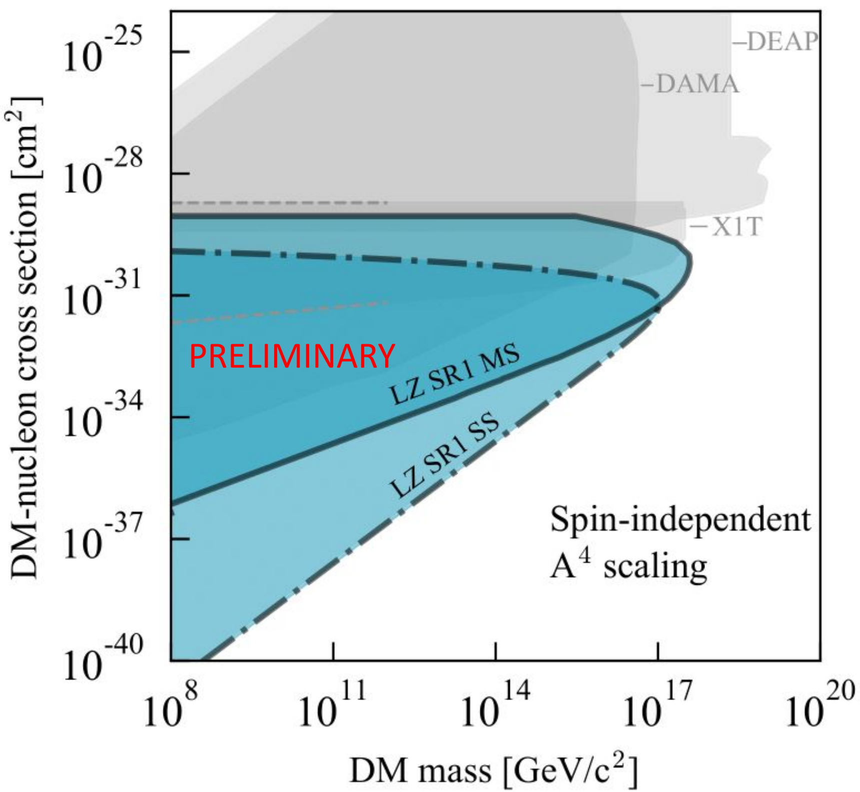
Cut acceptances

- Simulated MIMP signals are accepted with high efficiency, with multiple cuts showing zero loss
- At high cross sections, signal loss due to pulse merging effects is apparent

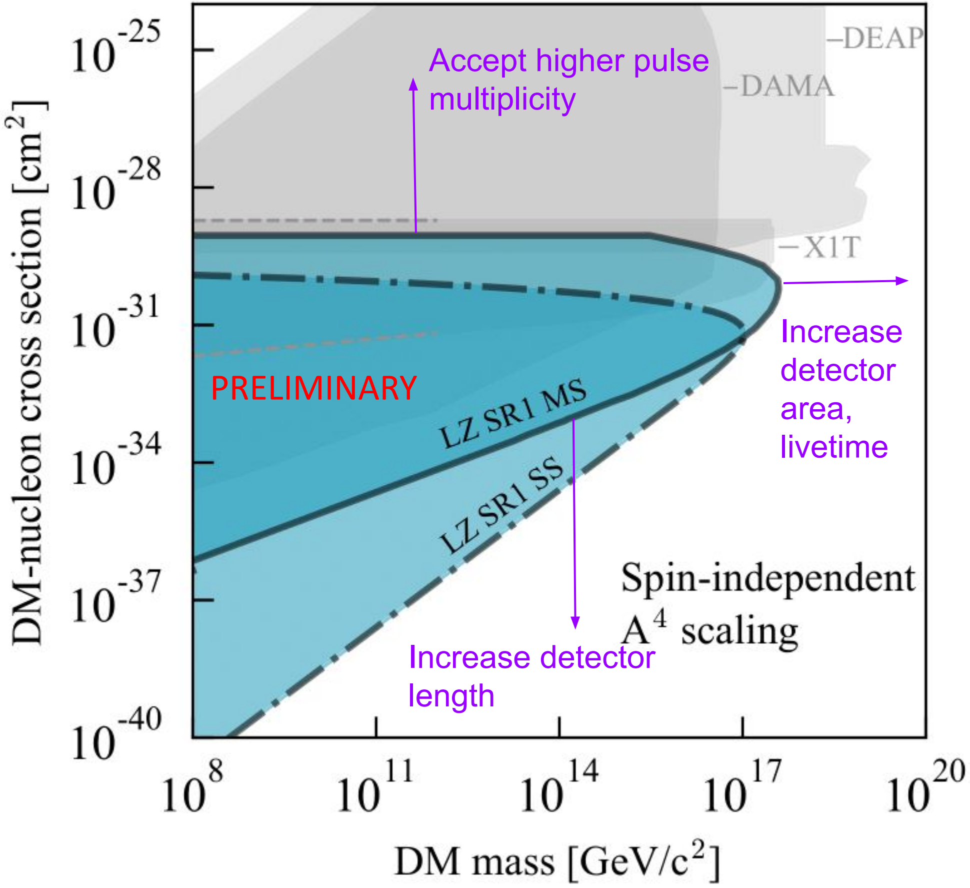


Results

- This search probes cross sections intermediate to LZ WIMP search and previous MIMP searches due to focus on resolved pulses
- Maximum mass sensitivity pushed to $3.9 \cdot 10^{17}$ GeV



Moving forward

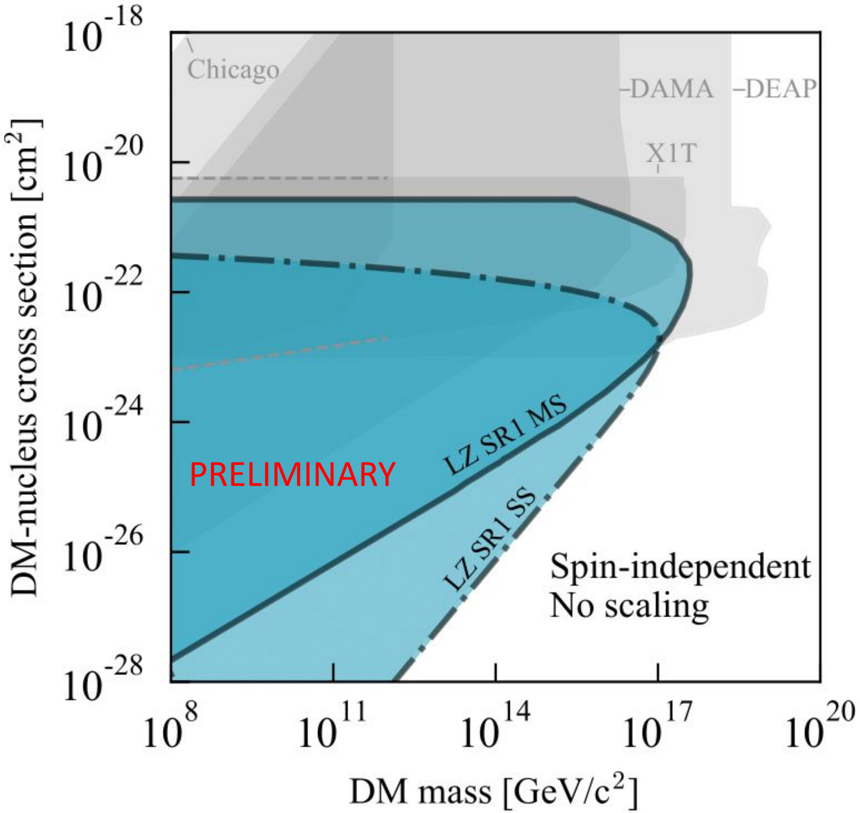


Scaling

- Typical interaction model may not be justified at high cross section [see Phys. Rev. D 100, 063013 (2019)]

$$\sigma_{\chi A}^{(1)} = A^2 \frac{\mu_A^2}{\mu_N^2} \sigma_{\chi N}^{(1)}.$$

- Wide range of alternative models; limits calculated also for recoil cross section independent of A



Conclusions

- We are uncovering new regions of the high mass, high cross section dark matter parameter space with a dedicated multiple-scattering analysis
- The analysis demonstrates the rich information (such as event-level velocity reconstruction) available in the MIMP signal topology
- The multiple-scattering search is a complementary channel to the single scatter search. This unlocks new ways to investigate a possible signal.
- Publication is in progress!

LZ (LUX-ZEPLIN) Collaboration, 37 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
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Backups

Detector parameters

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

$$\langle \text{S1c} \rangle = g_1 \langle n_{ph} \rangle \qquad \langle \text{S2c} \rangle = g_2 \langle n_e \rangle$$

$$g_2 = \langle \text{SE} \rangle \cdot \epsilon_{ext}(\mathcal{E}_{gas}) = g_1^{gas} \cdot Y_e(\mathcal{E}_{gas}, \Delta z_{gas}) \cdot \epsilon_{ext}(\mathcal{E}_{gas})$$