New constraints on Ultra Heavy Dark Matter from the LZ experiment

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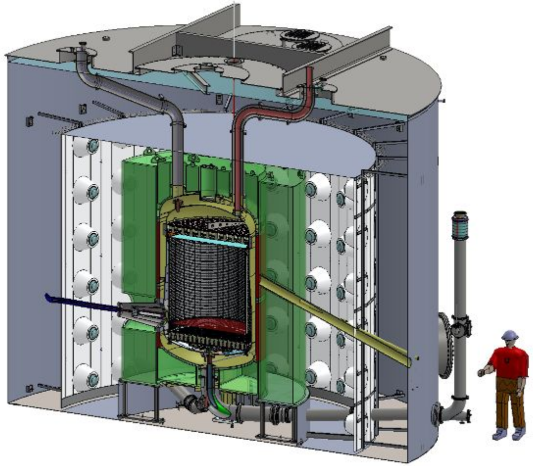
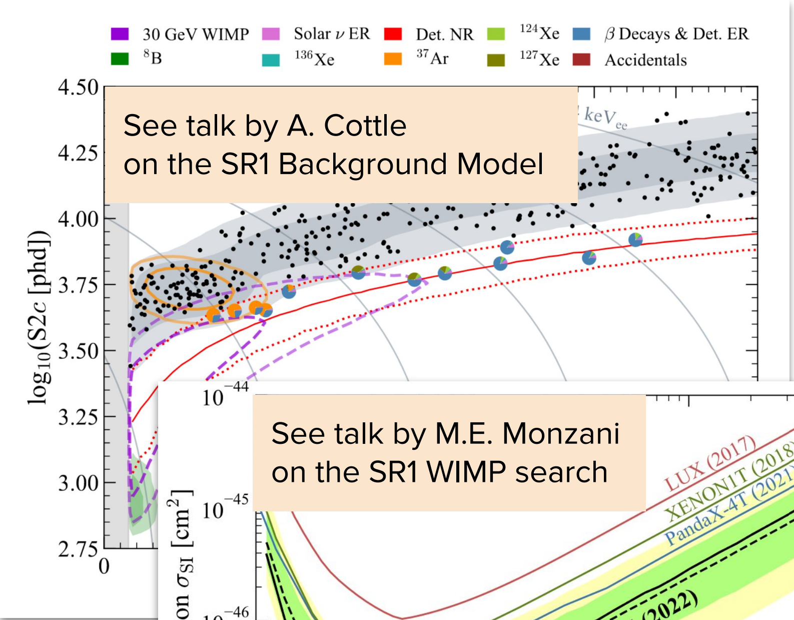
UCLA-DM

03/31/2023

LZ Science Run 1 (SR1)

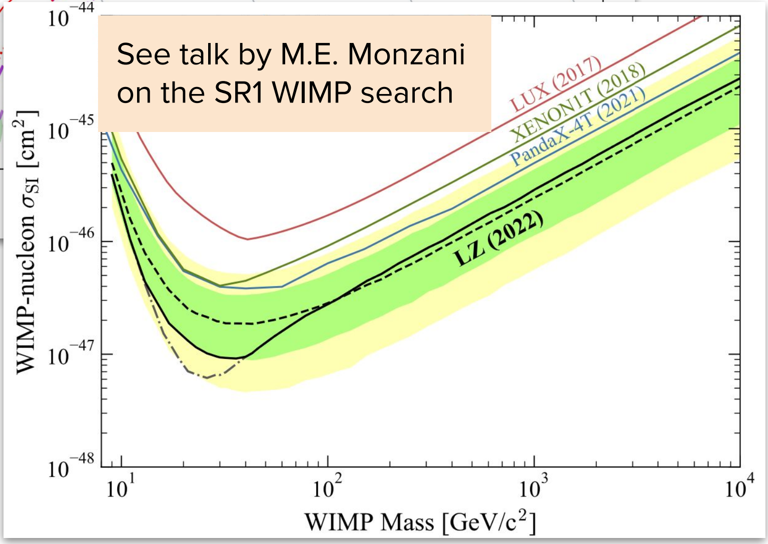


[Akerib et al (2019)]



[arXiv:2211.17120]

See talk by A. Cottle
on the SR1 Background Model

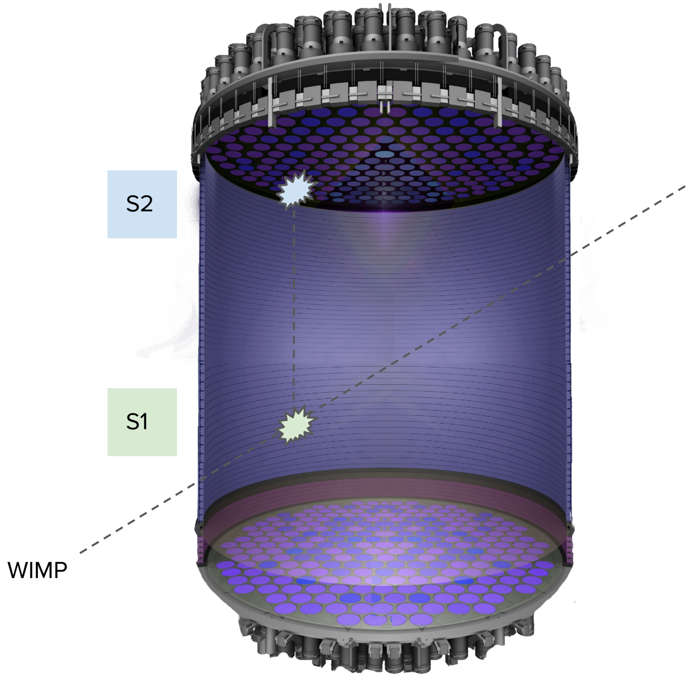


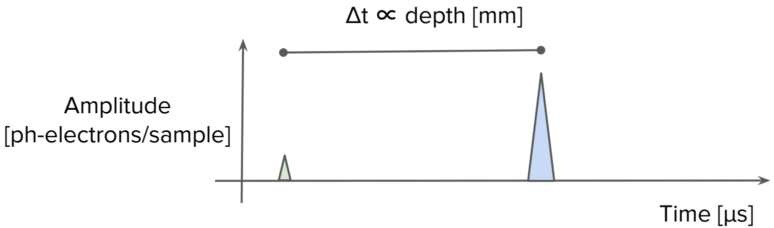
[arXiv:2207.03764]

See talk by M.E. Monzani
on the SR1 WIMP search

WIMP search in LZ

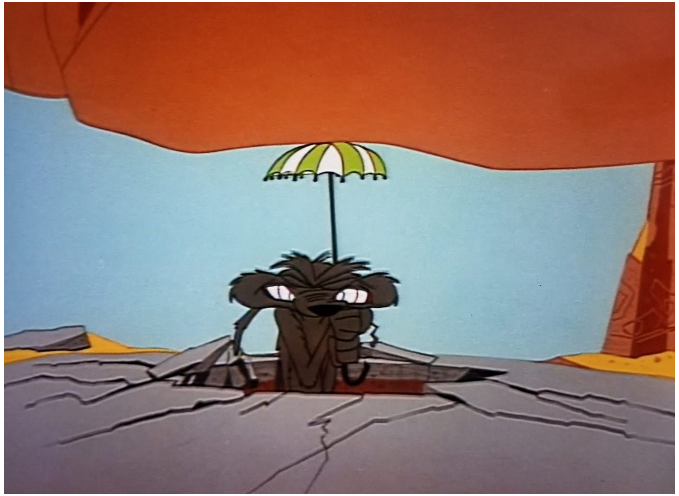
- An event in the TPC is characterized by a prompt scintillation signal in the liquid (**S1**) and a delayed proportional scintillation signal in the gas phase (**S2**)
- Traditional WIMP search:
  - Search for single-scatters (SS) produced by ~GeV/c^2 scale DM
  - Expect many dark matter (DM) transits, but the interaction probability is low → sensitivity scales with *detector's volume*





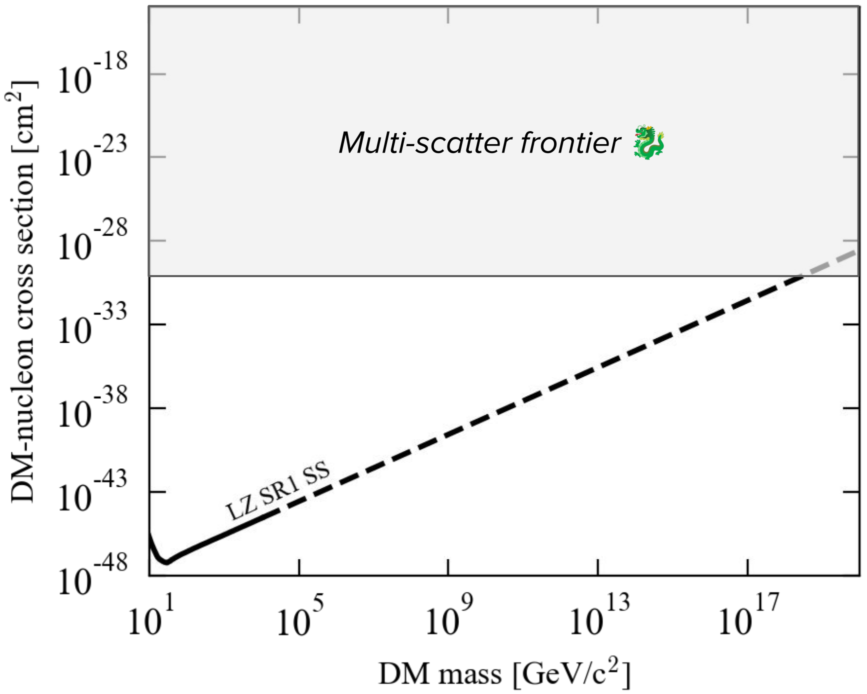
Going heavy

- The WIMP model is valid up to the unitary limit (~10^4 GeV/c^2), above which thermal production mechanism breaks down
- This constraint can be circumvented with **dark sector models** [Petraki & Volkas (2013), Zurek (2014)]
  - The constraint on the mass is relaxed for the freeze-out DM component
- Assuming there is no nuclear bottleneck with the dark nucleon fusion process, large "dark blobs" made up of smaller constituents can be formed progressively until freeze-out [Coskuner et al (2019), Gresham et al (2018)]
  - Enters **Ultra Heavy Dark Matter** (UHDM)



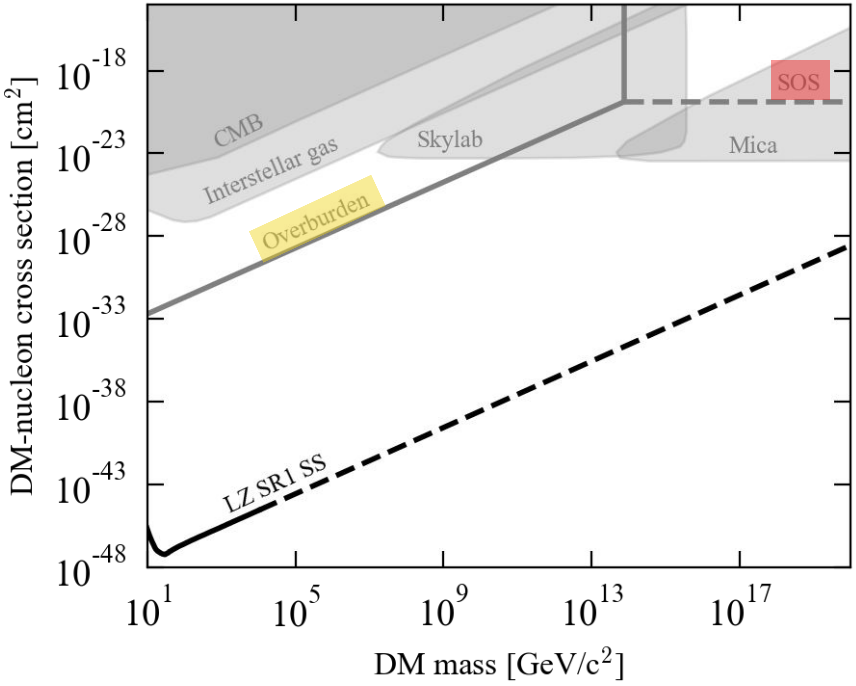
Looking for UHDM

- As we extend the LZ SR1 limit to high masses and cross sections, we enter the "multi-scatter frontier"
  - At such large cross sections, DM is expected to create several scatters in the detector
  - Enters **Multiply Interacting Massive Particles** (MIMPs)
- Searches in this region require a new kind of analysis
  - Search for multiple-scatters (MS) produced by >TeV/c^2 scale DM
  - Expect very few DM transits, but their interaction probability is high ➔ sensitivity scales with *detector's area*



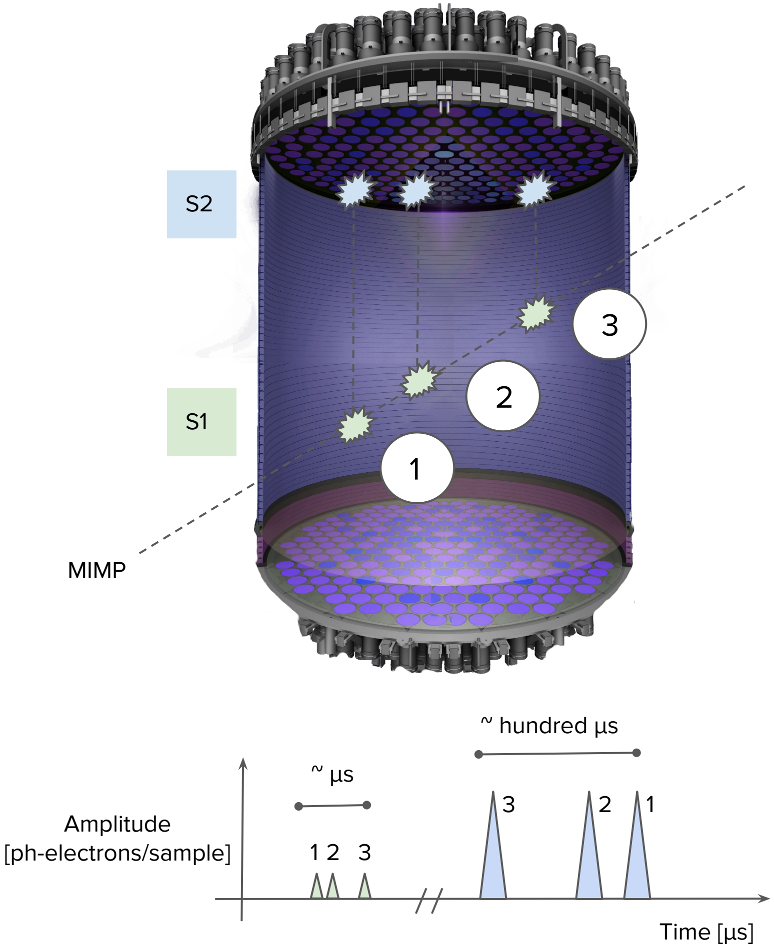
Looking for UHDM

- Astrophysical and experimental constraints exist: interstellar gas cloud heating, CMB distortions, ancient mica…
- For an underground experiment, there is an upper limit on the cross section that can be probed constrained by the overburden.
- Above a certain cross section, MIMPs are expected to interact with every nucleus along its path ➔ **Saturated Overburden Scattering** (SOS) [Bramante et al (2018)]
- A large region of the parameter space still remains open for experimental search!



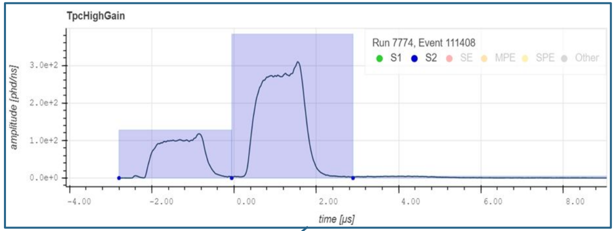
MIMP search in LZ

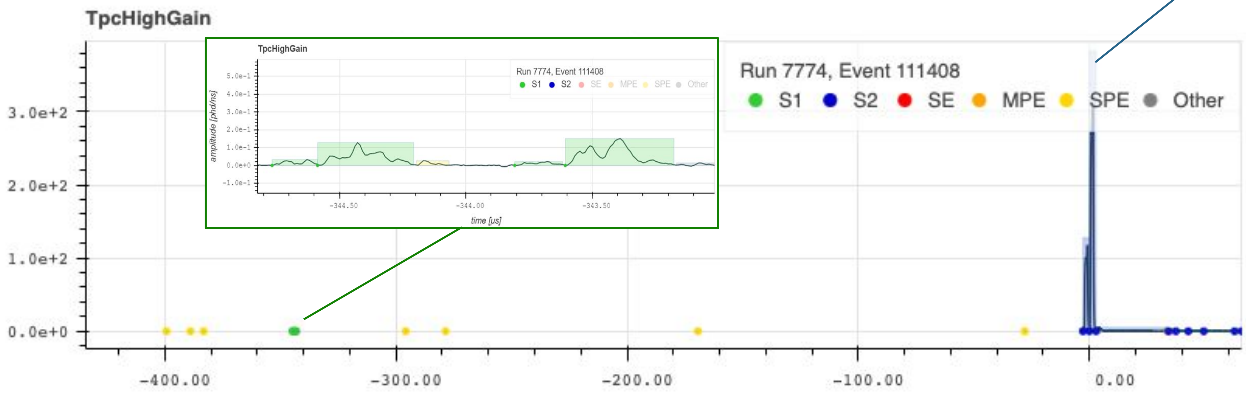
- Because MIMPs are so massive and have such large cross sections, that they will form a straight line (a “track”) as they cross the TPC
  - **Event signature:** multiple S1s happening in a short period of time (few µs) followed by multiple S2s with longer time separations (few hundreds µs)
- The velocity of the MIMP can be reconstructed on an event-by-event basis!
  - **Δ**t: time difference between the last and first S1 pulses
  - Length: distance between the last and first hits of the reconstructed track



Backgrounds

- Observing multiple S1s and S2s forming a straight line is an extraordinary signature
  - Most background sources are relativistic; the S1s will occur almost coincident in time
- The sources of background are reduced to cases of pile-up or pulse misreconstruction





Amplitude
[ph-electrons/sample]

Time [µs]

Data analysis

MIMP-specific cuts

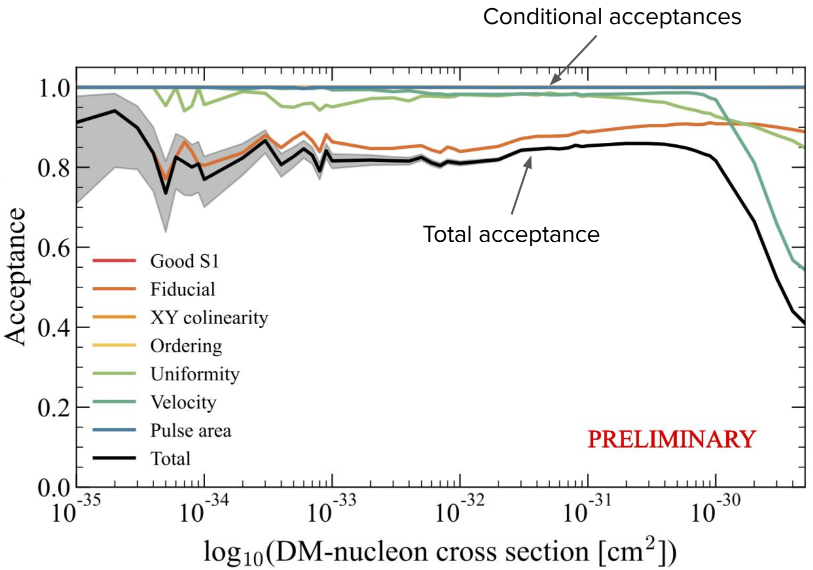
Cuts were loose by design to keep signal acceptance high

Cut name	Description
Multiplicity	Minimum number of S1s and S2s must be greater than 2
Good S1s	S1s cannot have light accumulated on a single PMT or be coincident with an OD signal
Fiducial volume	Define an inner region of the detector with an overall lower background level and check that at least two scatters happened within this region
Colinearity	Check if the reconstructed track in XY is compatible with a straight line
Uniformity	Check if the projected hits along the track are uniformly distributed
Velocity	Check if the reconstructed velocity is compatible with the galactic DM velocity distribution
Pulse area	Check that the total S1 and total S2 areas are correlated as expected from simulation

Data analysis

Acceptances curves

- The signal acceptance for each of the cuts was evaluated on a simulated sample of MIMP-like events
- Above ~10^{-30} cm^2, S1s and S2s start to merge
  - Most events start failing the velocity cut
  - The total cut acceptance is reduced significantly



Data analysis

SR1 dataset [arXiv:2207.03764]

- 60 livedays of data, taken between Dec 12th 2021 and May 5th 2022
- Uniform drift field of 193 kV/cm
- Long e- lifetime of 5–8 ms

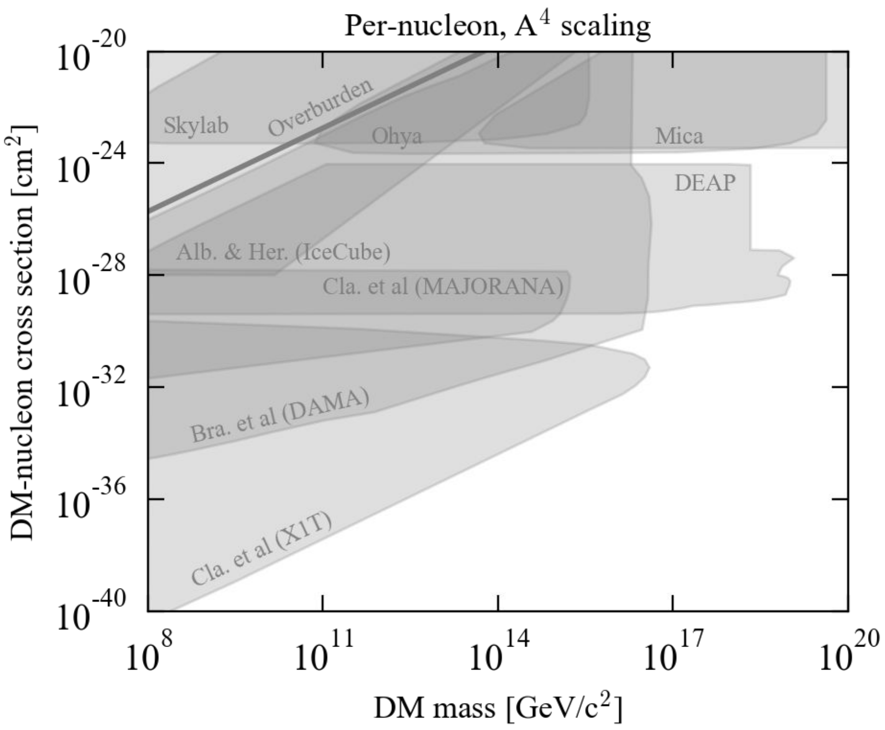
Results

- After careful consideration, we did not expect any event to appear in our region of interest
- Indeed, 0 events passed all cuts
  - This is a background-free search!

Cut name	Cumulative survival of events in the SR1 dataset
Multiplicity	15.17%
Good S1s	13.81%
Fiducial volume	2.65%
Colinearity	2.29%
Uniformity	0.66%
Velocity	0.11%
Total S1 and S2	0%

Exclusion regions

- New constraints have been appearing in this region of the parameter space in the recent years. Most notably:
  - DEAP-3600 collaboration [P. Adhikari et al (2022)]
  - Reinterpretation of DAMA data [A. Bhoonah et al (2021)]
  - Reinterpretation of MAJORANA and X1T data [M. Clark et al (2020)]



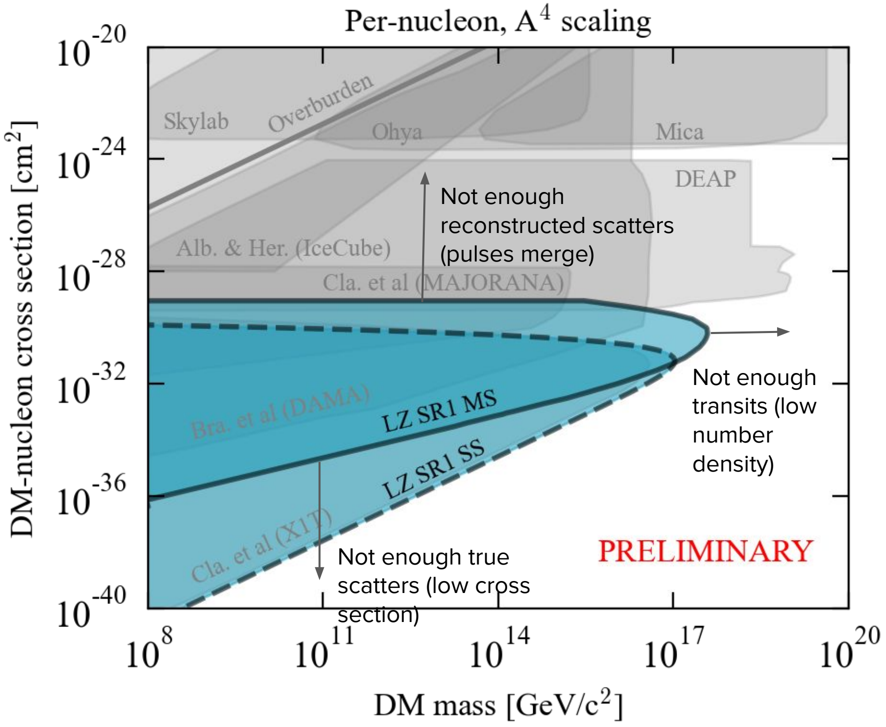
Exclusion regions

Exclusion limits for a background-free experiment were derived following the conventions outlined in [Snowmass2021 CF: UHDM, arXiv:2203.06508]

Model I

- Point-like dark matter interacting via the standard spin-independent scattering with the target nucleus
- An A^4 scaling arises from both a coherent ($\sigma_{\chi A} \propto A^2\sigma_{\chi N}$) and kinematic enhancement ($\mu_A \simeq Am_A$ for $m_\chi \gg m_T$)

$$\sigma_{\chi A}^{(1)} = A^2 \frac{\mu_A^2}{\mu_N^2} \sigma_{\chi N}^{(1)}.$$ [Digman et al (2019)]

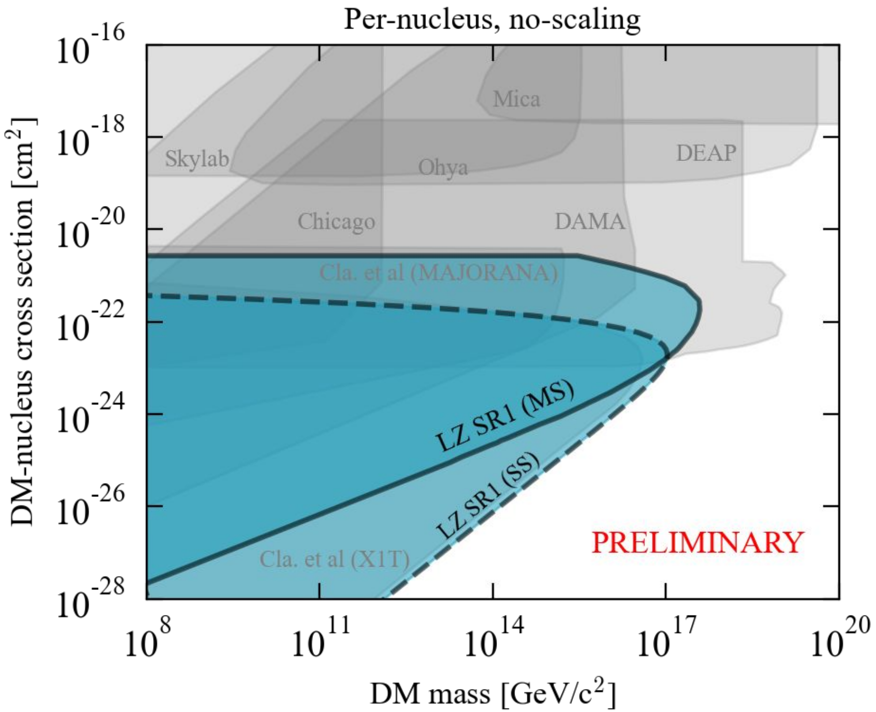


Exclusion regions

Model II

- Billiard ball scattering between DM and the target nucleus
- No scaling from nucleon to nucleus exist
- Limits are reported in a per-*nucleus* basis so results from experiments using different targets can be compared

LZ is uncovering new space in the multi-scatter frontier!



Conclusions

- A new, multi-scatter search for ultra heavy dark matter was conducted with LZ's SR1 data
- New analysis techniques had to be developed since multi-scatters are traditionally deemed as background, not signal
- MIMP events were simulated to evaluate the acceptance of each analysis cut
- New limits were calculated for a background-free search
    - First ever search from a double-phase LXe TPC collaboration!

Publication is in progress
Stay tuned!

Thank you for your attention

@lzdarkmatter
https://lz.lbl.gov

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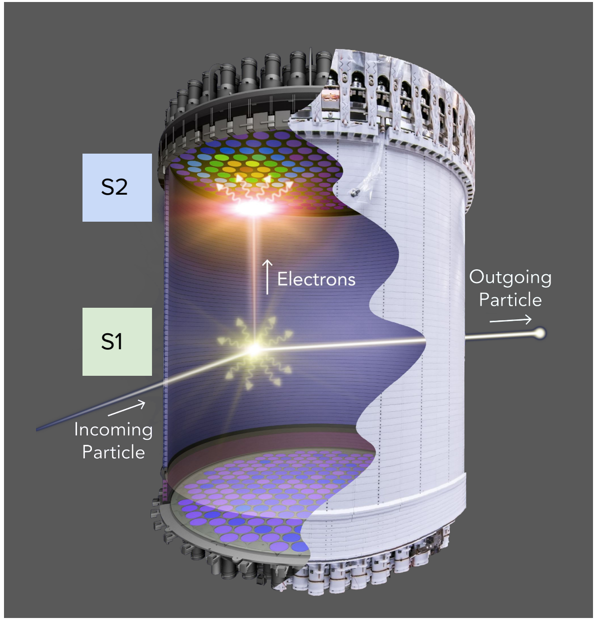
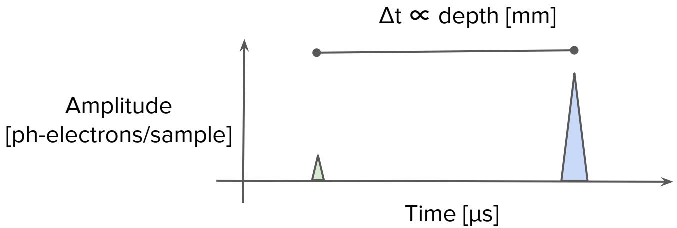
BACK-UP

LXe TPC technology

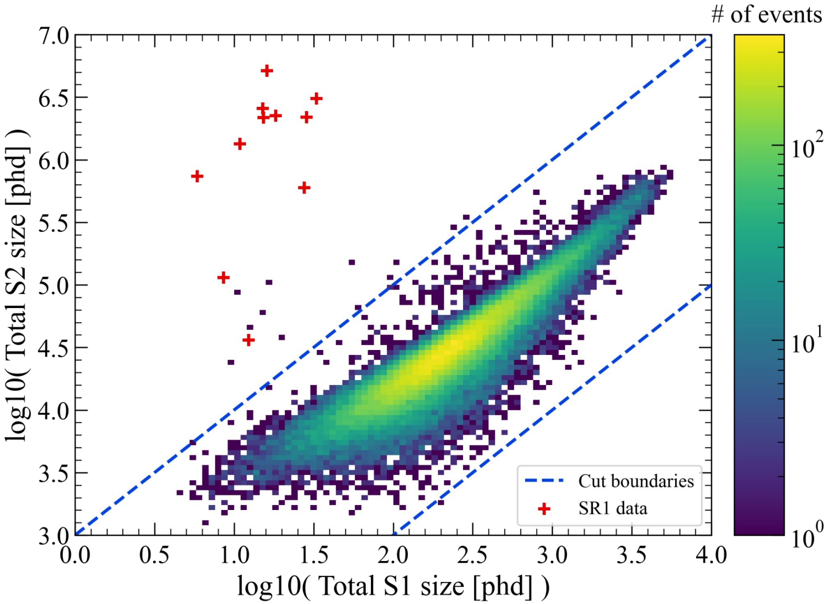
- An event in the TPC is characterized by a prompt scintillation signal in the liquid (**S1**) and a delayed proportional scintillation signal in the gas phase (**S2**)
    - S1 photons are instantly detected
    - Electrons are drifted up by an electric field and extracted into the gas phase, creating S2 photons via electroluminiscense
    - The Δt between the S1 and S2 pulses is directly proportional to the event's depth
    - WIMPs are expected to produce a single-scatter (SS) nuclear recoil event
- Main advantages:
    - 3D event reconstruction
    - Energy reconstruction
    - Excellent discrimination between electron recoils and nuclear recoils

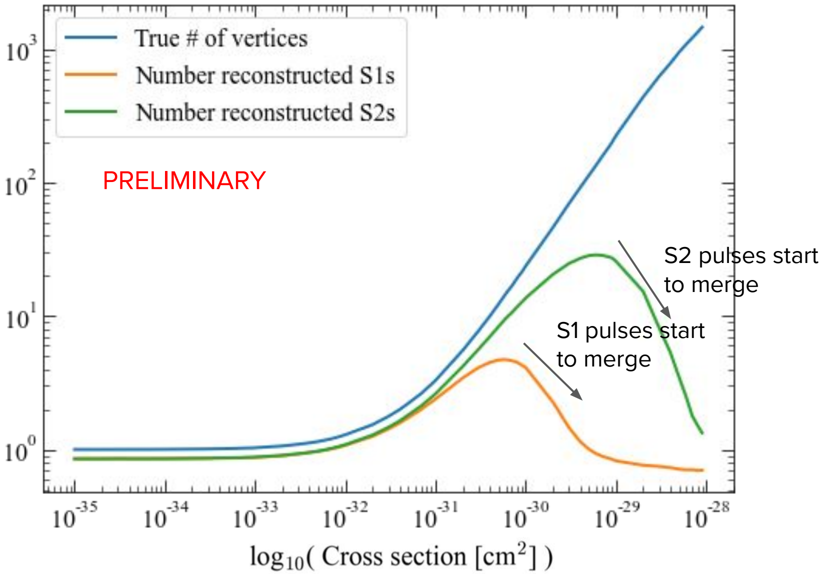


[Credit: LZ Collaboration]



Supplementary plots





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

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

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