Particle DM Experimental Overview: WIMPs, Light DM

Shingo Kazama

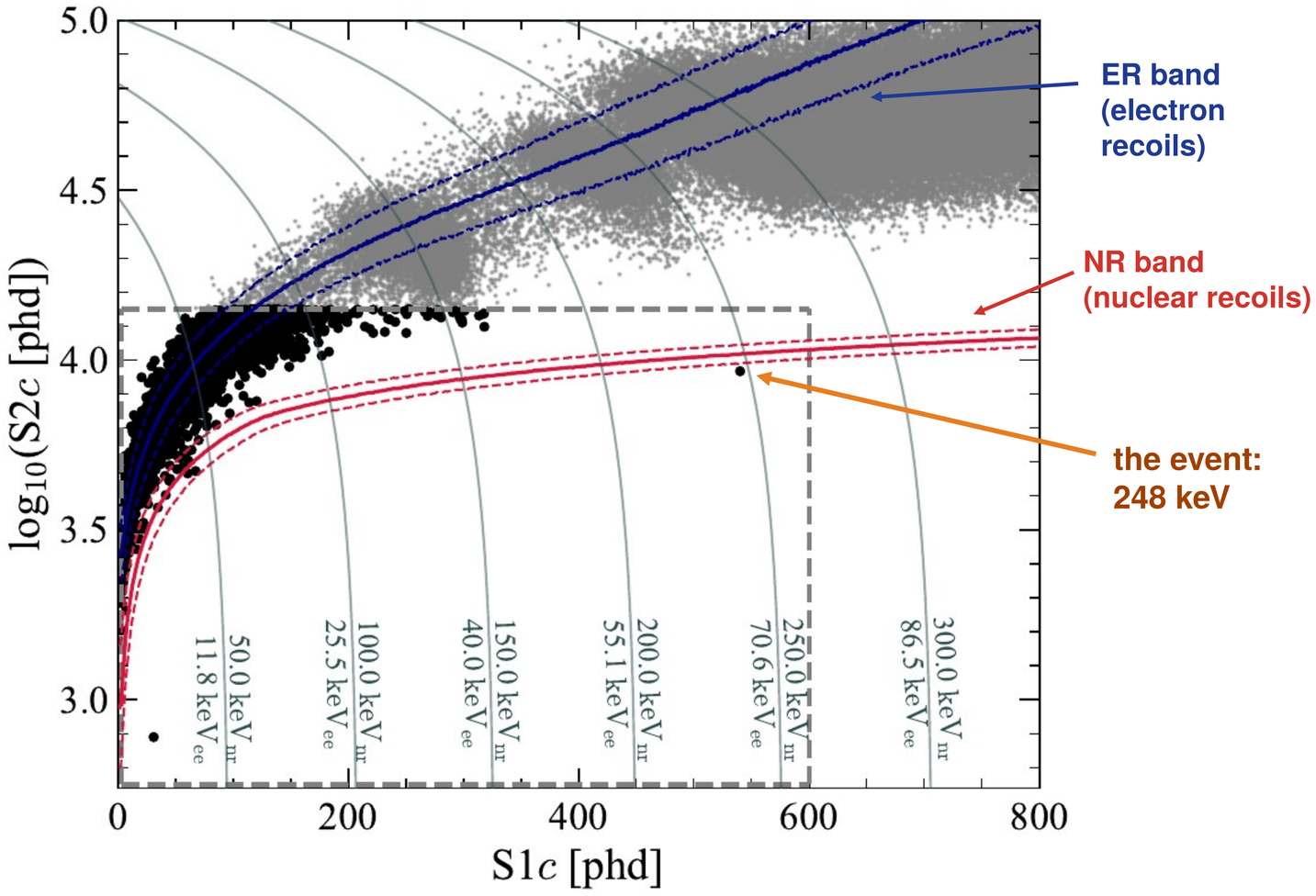
Institute of Science Tokyo





ICFA Seminar 2026, Toyama, 5 November 2026

Introduction



LZ, arXiv:2609.02823

September 2026: LZ reported **one nuclear-recoil-like event at 248 keV**, far above the usual WIMP window. Near its energy, only ≈ 0.01 BG events were expected.

In only two months, **more than 150 papers** on arXiv have cited it.

It may be the first sign of **inelastic scattering of the Higgsino**, with a mass splitting $\delta \approx 350$–380 keV.

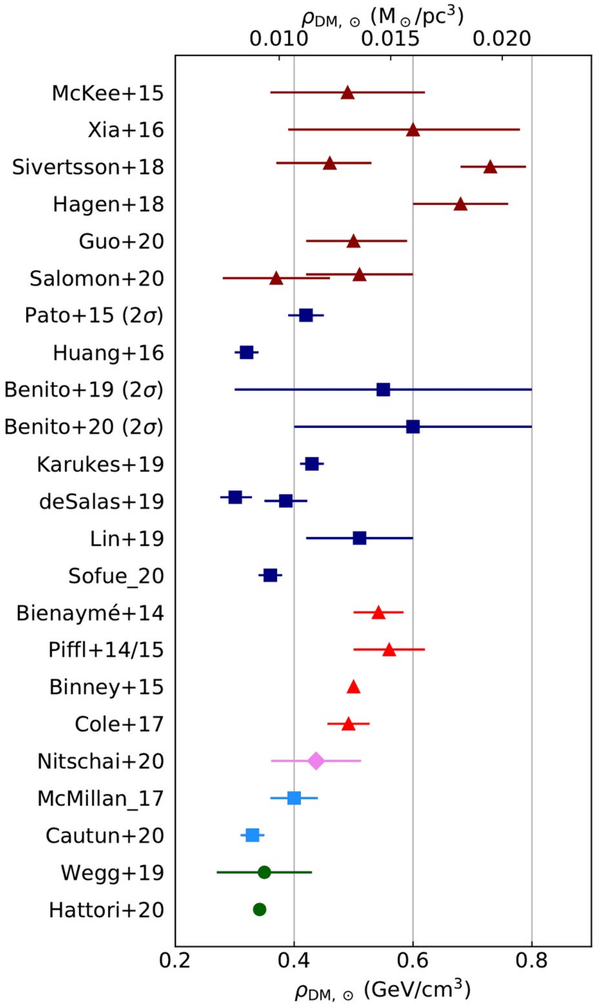
This talk

1. Basics: DM in the Galaxy, elastic and inelastic scattering
2. Status of WIMP and light-DM searches
3. The LZ event: detector, BGs, interpretations, tests
4. The next step: XLZD

Note: I am a member of XENONnT, not LZ. The LZ results in this talk are from LZ's paper and public talks.

Dark Matter in the Galaxy: Density and Velocity

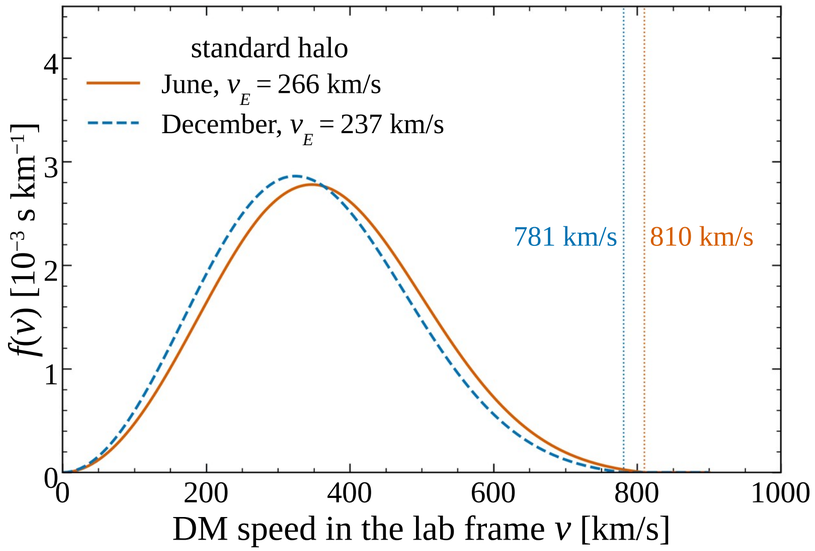
local DM density ρ_0



de Salas & Widmark, Rep. Prog. Phys. 84, 104901 (2021)

- Measured from the **motion of stars**
- ▲ local: stars near the Sun
  → 0.4–0.6 GeV/cm^3
- ■ global: rotation curve
  + mass model → 0.3–0.5 GeV/cm^3
- Experiments use $\rho_0 = 0.3$ GeV/cm^3 by convention

DM velocity distribution in the lab frame



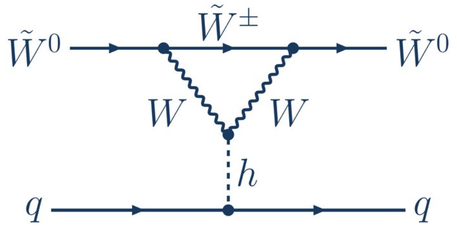
- **Not measured directly** → standard halo model: a Maxwellian whose parameters are measured with stars
  - $v_0 = 238 \pm 1.5$ km/s: rotation speed of the Galaxy at the Sun
  - $v_{esc} = 544$ km/s: escape speed, from the fastest halo stars (485–580 km/s)
  - the Earth moves at v_E = 237–266 km/s
    → **nothing faster than ≈ 800 km/s** in the lab

The rate scales with ρ_0. For the LZ event as a Higgsino with $\delta \approx 350$–380 keV, only DM at the very end of the distribution can scatter

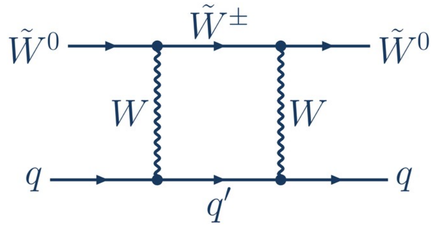
Elastic and Inelastic Scattering

Elastic $\chi N \to \chi N$

wino: Higgs exchange via a W loop



wino: W box



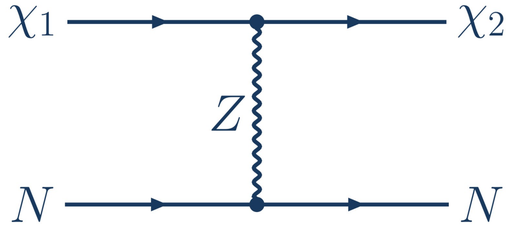
- Pure wino: **no tree-level coupling**, only loop diagrams, which partly cancel (thermal ≈ 3 TeV, $\sigma_n \approx 2 \times 10^{-47}$ cm^2)

lowest DM speed for E_R:

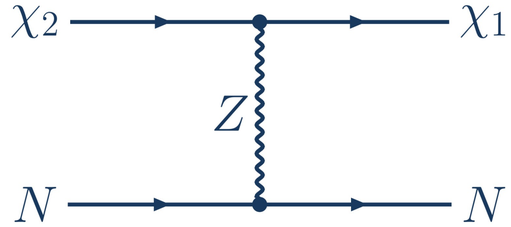
$$v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_N^2}}$$

Inelastic $\chi_1 N \leftrightarrow \chi_2 N$

endothermic: $\chi_1 N \to \chi_2 N$



exothermic: $\chi_2 N \to \chi_1 N$



- Up-scattering $\chi_1 \to \chi_2$ costs $\delta > 0$ (**endothermic**)
- Down-scattering $\chi_2 \to \chi_1$ releases $|\delta|$ (**exothermic**, $\delta < 0$)

lowest DM speed for E_R:

$$v_{\min} = \frac{1}{\sqrt{2 m_N E_R}} \left| \frac{m_N E_R}{\mu_N} + \delta \right|$$

The event rate has the same form; only $v_{\min}(E_R)$ differs:

$$\frac{dR}{dE_R} = \frac{\rho_0}{m_\chi m_N} \int_{v > v_{\min}(E_R)} v\, f(\vec{v}) \frac{d\sigma}{dE_R} d^3 v, \qquad \frac{d\sigma}{dE_R} = \frac{m_N \sigma_n A^2}{2\mu_n^2 v^2} F^2(q)$$

particle physics

m_χ: DM mass

σ_n: DM–nucleon cross-section

μ_n, μ_N: reduced masses (nucleon, nucleus)

nuclear physics

m_N, A: nucleus mass, mass number

$q = \sqrt{2 m_N E_R}$: momentum transfer

$F(q)$: nuclear form factor

astrophysics

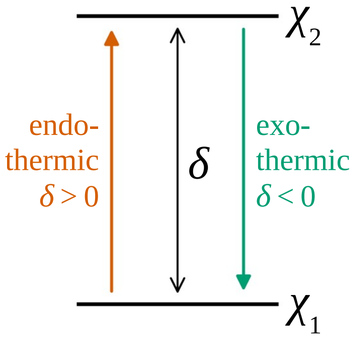
ρ_0: local DM density

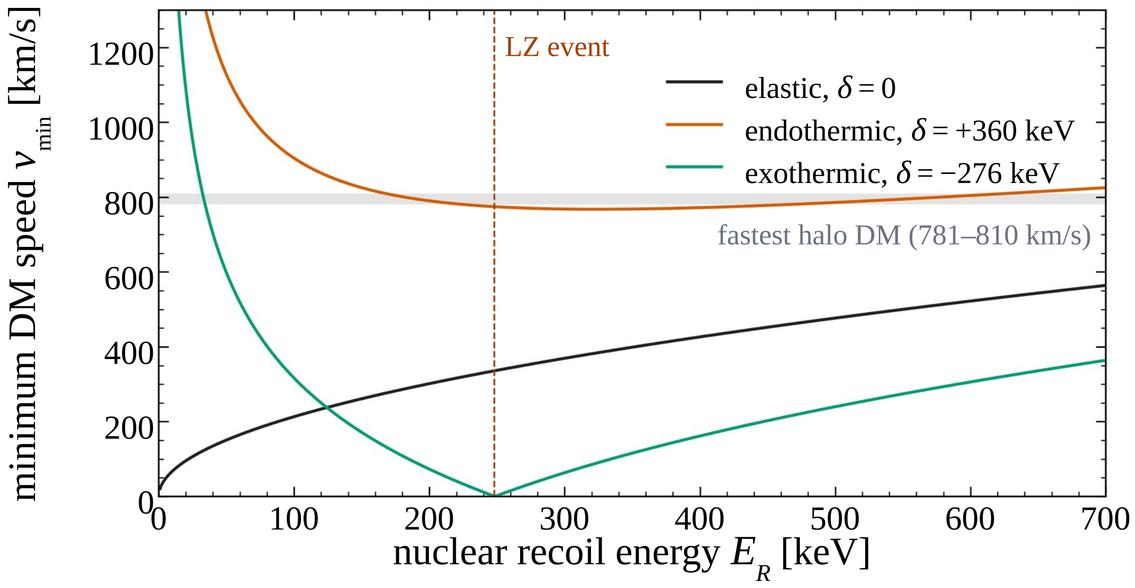
$f(\vec{v})$: velocity distribution (lab)

$v_{\min}$: lowest speed for recoil energy E_R

Inelastic Dark Matter: Endothermic

minimum DM speed for each recoil energy (1.1 TeV DM on xenon)





kinematics

$$v_{\min}(E_R) = \frac{1}{\sqrt{2 m_N E_R}} \left| \frac{m_N E_R}{\mu_N} + \delta \right|$$

lowest at $E^* = \frac{\mu_N}{m_N} |\delta| \approx 0.9\,|\delta|$

$$v_{\min}(E^*) = \sqrt{2\delta/\mu_N}\ \ (\delta > 0), \qquad 0\ \ (\delta < 0)$$

μ_N: DM–nucleus reduced mass, ≈ 110 GeV here

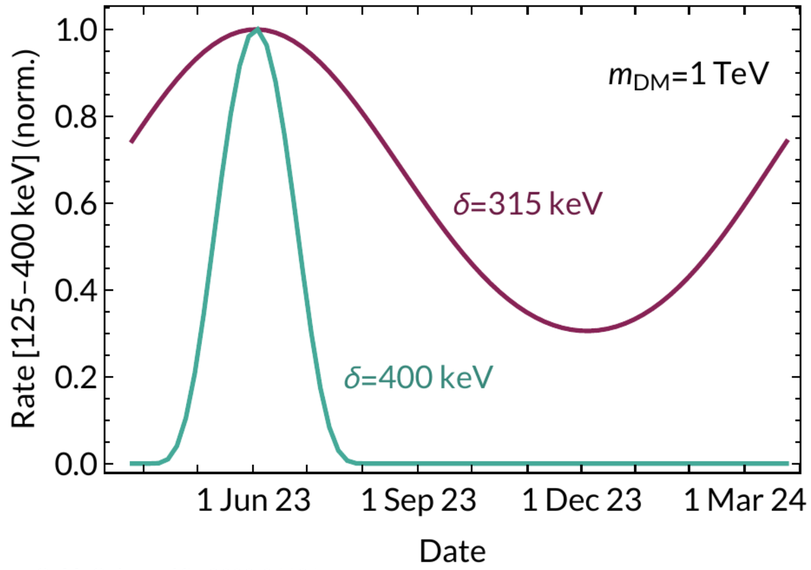
Endothermic, $\delta > 0$: $\chi_1 N \to \chi_2 N$

- Making the heavier χ_2 costs δ → DM needs $v > v_{th} \approx 770$ km/s for $\delta = 360$ keV
- DM in the lab (standard halo) reaches only 781–810 km/s, just above v_{th}

  → **only the fastest DM can scatter for $\delta = 360$ keV**

  → recoils are all at high energy (≈ 170–630 keV): **no low-energy recoils**
- 810 km/s in June, 781 km/s in December → with v_{th} this close, a **strong seasonal change:** at $\delta = 400$ keV the rate is zero for ≈ 2/3 of the year

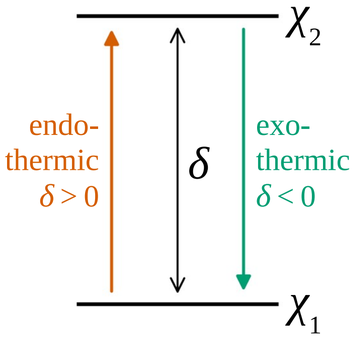
signal rate during one year (1 TeV)

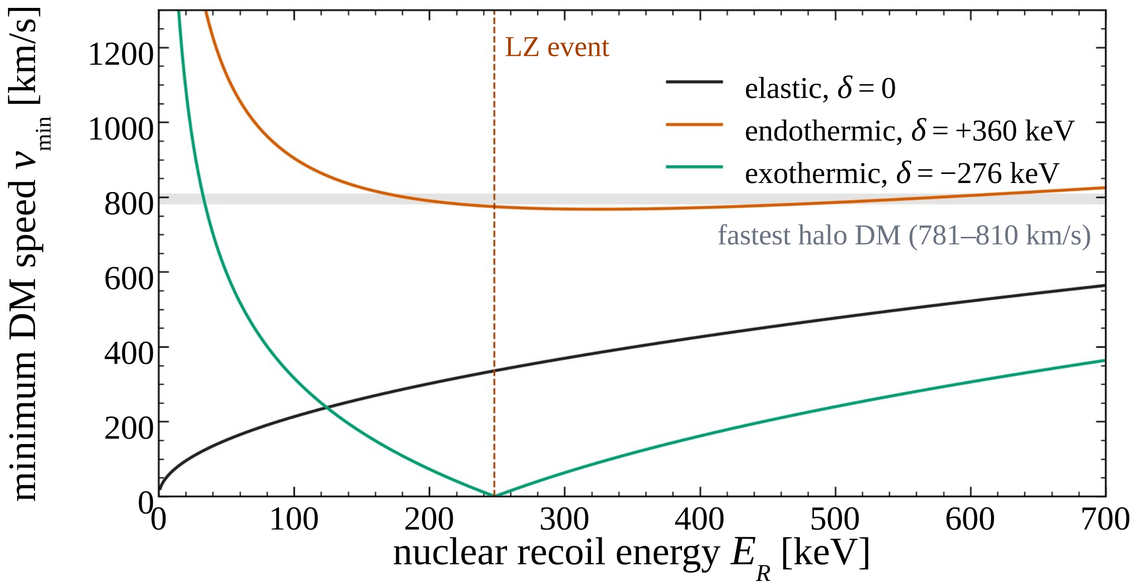


C. McCabe, arXiv:2609.04181

Inelastic Dark Matter: Exothermic

minimum DM speed for each recoil energy (1.1 TeV DM on xenon)





kinematics

$$v_{\min}(E_R) = \frac{1}{\sqrt{2 m_N E_R}} \left| \frac{m_N E_R}{\mu_N} + \delta \right|$$

lowest at $E^* = \frac{\mu_N}{m_N} |\delta| \approx 0.9\,|\delta|$

$$v_{\min}(E^*) = \sqrt{2\delta/\mu_N}\ \ (\delta > 0), \qquad 0\ \ (\delta < 0)$$

μ_N: DM–nucleus reduced mass, ≈ 110 GeV here

Exothermic, $\delta < 0$: $\chi_2 N \to \chi_1 N$

- Long-lived heavier χ_2 turns into χ_1 and releases $|\delta|$ → no threshold speed:

  χ_2 of any speed can scatter (for the Higgsino, $\tau(\chi_2) \approx 0.02$ s, so no χ_2 is left today)

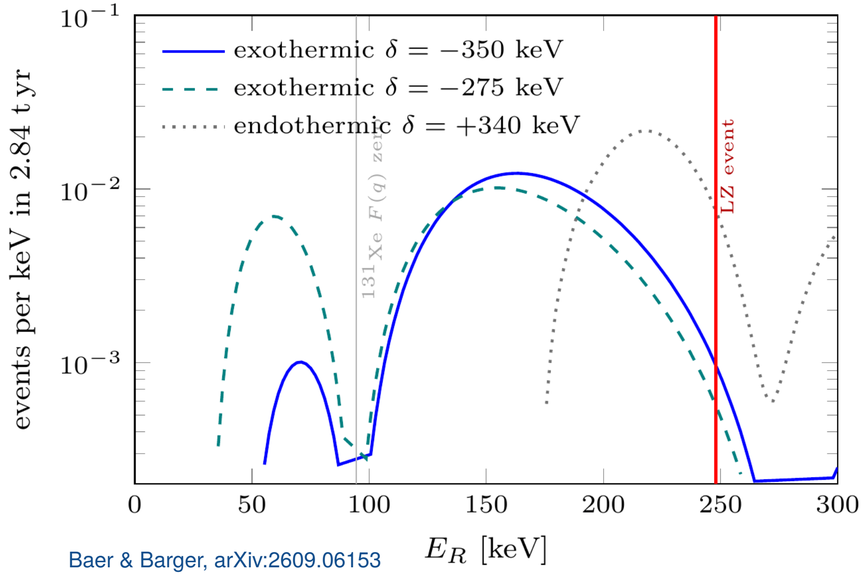
- Slow DM also scatters → **little seasonal change**

- Without the form factor, the spectrum would peak at $E^* = (\mu_N/m_N)\,|\delta|$.

  For the δ that fits the LZ event, E^* is near a zero of the xenon form factor (≈ 280 keV) → the spectrum moves lower: **many events below 248 keV**

xenon recoil spectra: exothermic vs endothermic

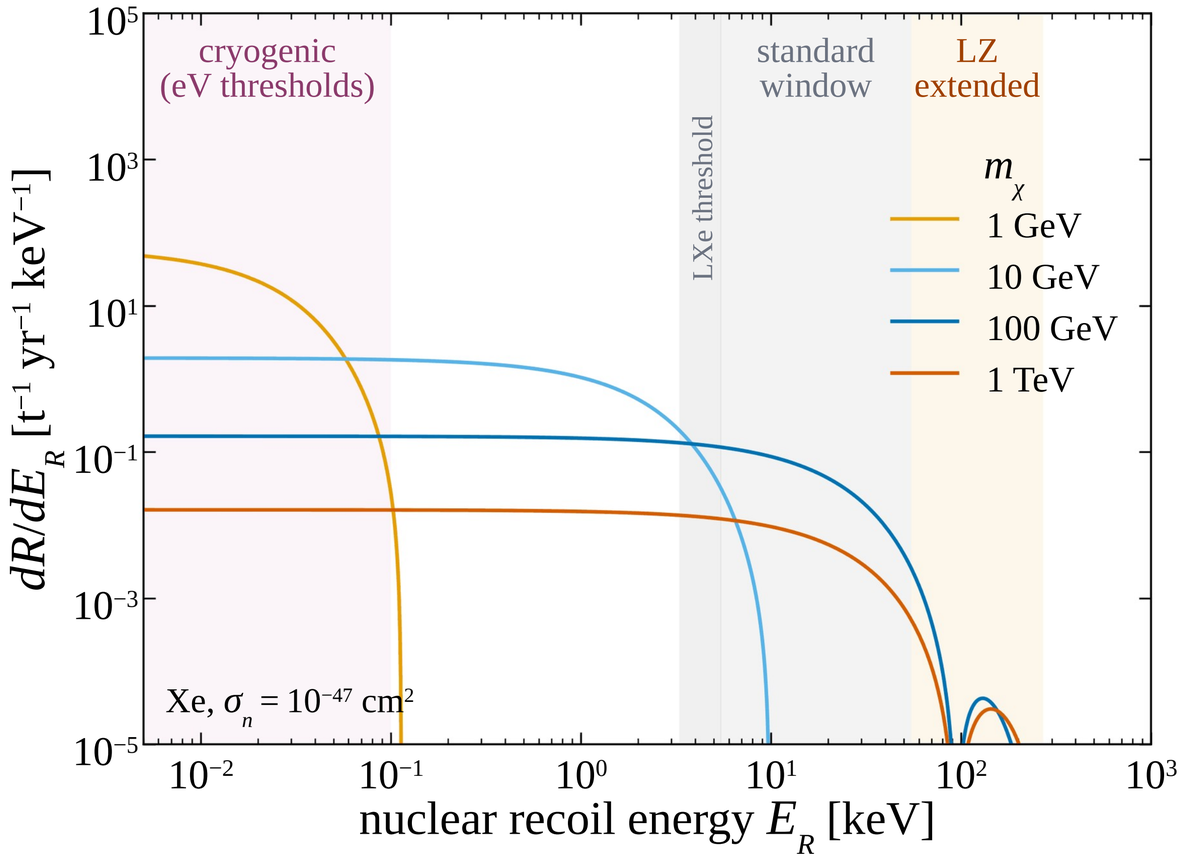
xenon, $m_\chi = 500$ GeV, each normalised to one event



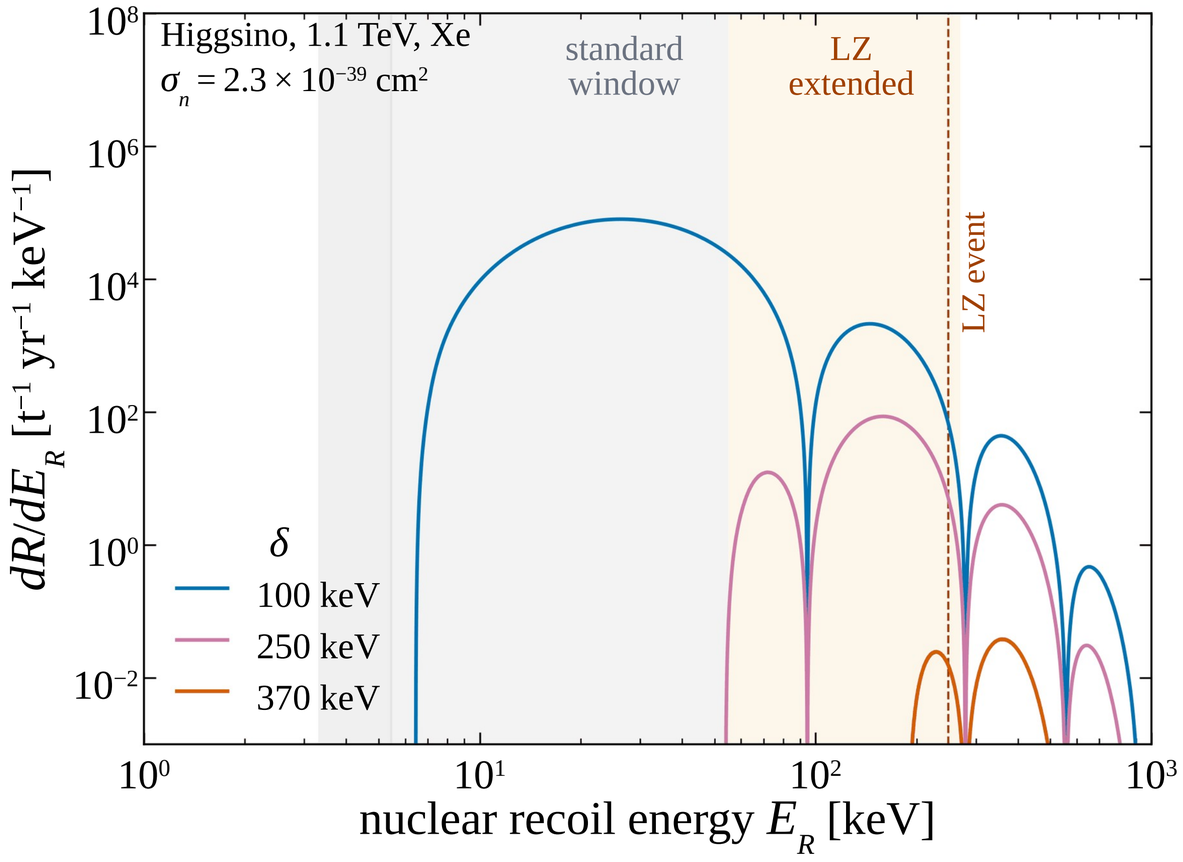
Baer & Barger, arXiv:2609.06153

Which Recoil Energies to Search

Elastic: four DM masses



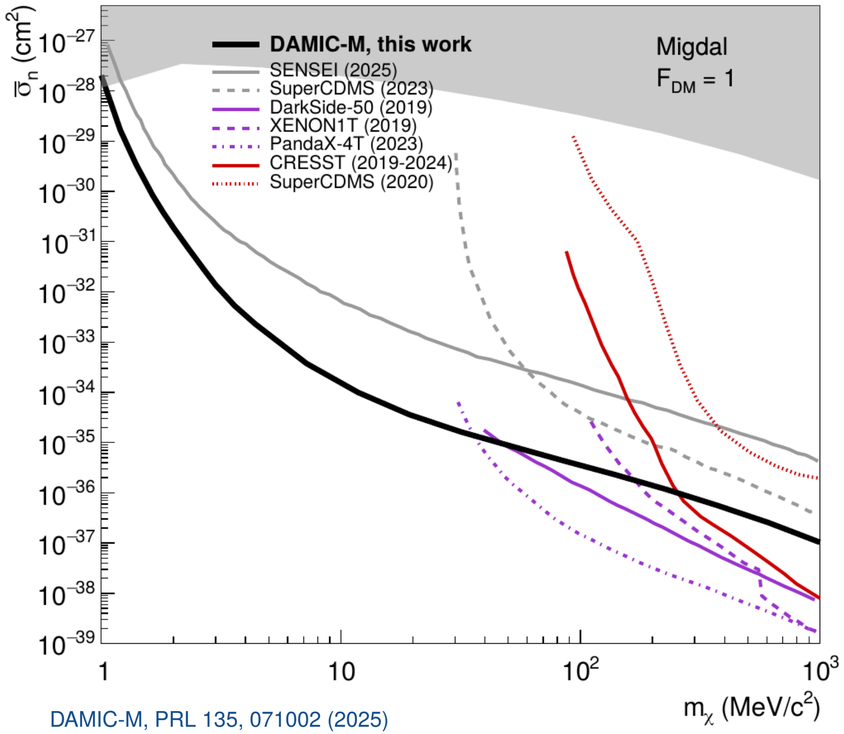
Inelastic: Higgsino, several δ



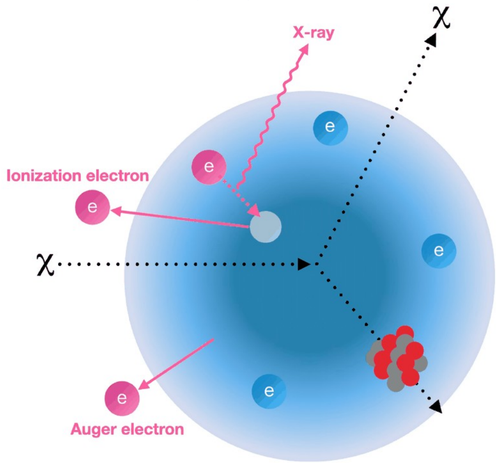
- Light DM: tiny recoils (≈ 0.1 keV at 1 GeV) → needs **eV thresholds**: cryogenic detectors (CRESST, SuperCDMS, TESSERACT, EDELWEISS)
- Heavy WIMPs, elastic: most recoils below tens of keV → standard windows end at 55–100 keV
- Inelastic: larger δ moves the recoils to **higher energy**: at $\delta = 370$ keV only ≈ 190–590 keV. **So LZ searches up to 270 keV**

Status: Light Dark Matter

DM–nucleon limits: Migdal and standard NR



DAMIC-M, PRL 135, 071002 (2025)



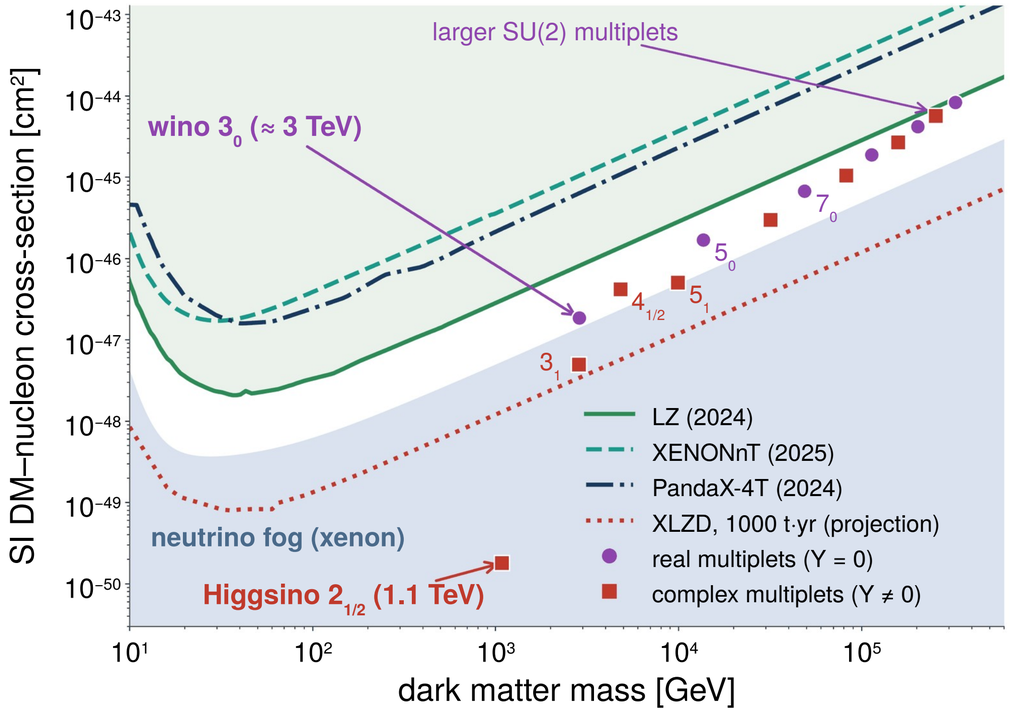
adapted from XENON1T, PRL 123, 241803 (2019)

light-DM searches today

experiment	target / signal	threshold	leading mass range
CRESST-III	$CaWO_4$ crystals, phonons + light	30 eV_{nr} (Si-on-sapphire: 6.7 eV)	≈ 0.07–0.8 GeV (NR)
TESSERACT	Si, phonons	1.5 eV	≈ 0.04–0.09 GeV (NR)
SuperCDMS	Ge / Si, phonons + charge	16 eV (Si, phonons only); SNOLAB from 2026	≈ 0.5–10 GeV from 2027
DAMIC-M, SENSEI	Si skipper CCDs	single electron	DM–electron scattering, ≈ 1–50 MeV
DarkSide-50	liquid argon, charge only	0.6 keV_{nr} (4 e^-)	≈ 0.8–3.5 GeV (NR)
XENONnT, PandaX-4T	liquid xenon, charge only	0.3–0.5 keV_{nr}	≈ 3–8 GeV (NR); Migdal: to ≈ 0.03 GeV; DM–e: > 50 MeV

- Light DM ($\lesssim$ 5 GeV): xenon recoils fall below the ≈ 3–5 keV (S1 + S2) threshold. Cryogenic phonon detectors with eV thresholds lead below ≈ 1 GeV for standard NRs; silicon skipper CCDs lead for DM–electron scattering below ≈ 50 MeV
- Migdal effect: the nucleus is kicked suddenly and its electron cloud cannot follow at once → the atom can be ionised (probability ≈ 10^{-5}–10^{-4}). First observed in 2026 with neutrons in a gas detector (Yi et al., Nature 649, 580 (2026))
- Why this is useful for xenon: the electron and the following X-ray / Auger electrons give an electron recoil of up to a few keV, without quenching. A 0.5 GeV DM particle gives a nuclear recoil below 0.03 keV, but a visible Migdal signal → reach from ≈ 3 GeV down to ≈ 0.03 GeV

Status: Heavy WIMPs



multiplets: Bloch et al., JHEP 08 (2025) 216; XLZD: collaboration projection

LUX-ZEPLIN



SURF, 7 t

XENONnT



LNGS, 5.9 t

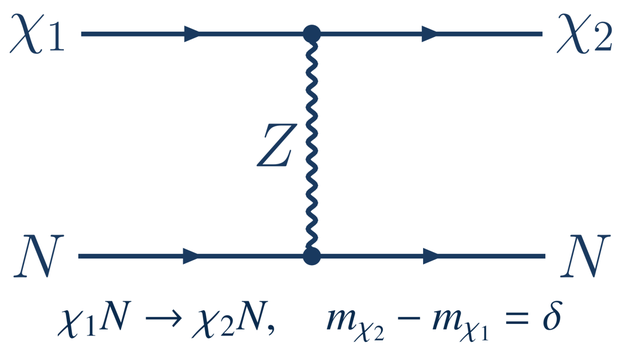
PandaX-4T



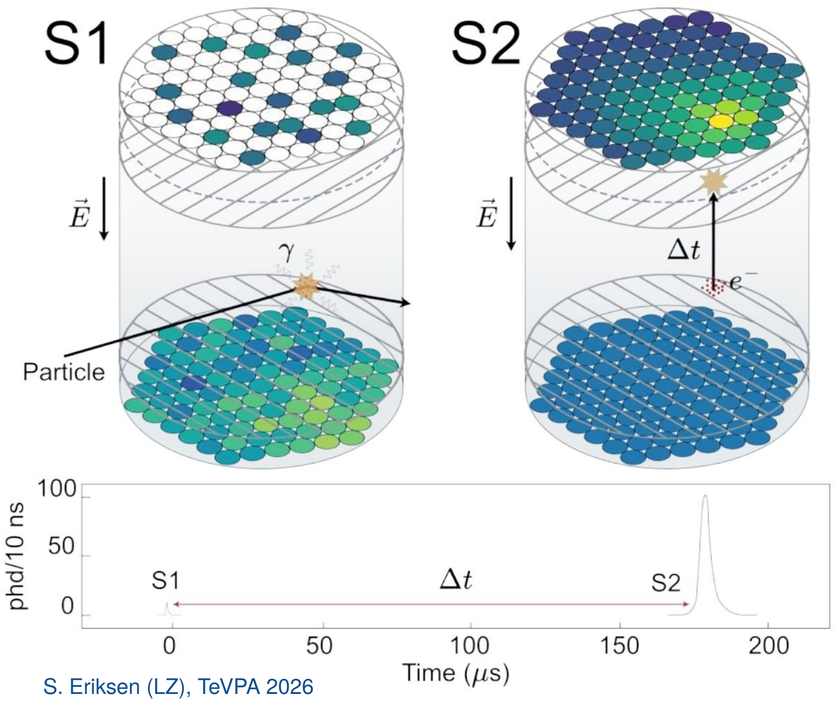
JinPing, 3.7 t

	site	xenon total / active	WIMP exposure	limit, 30–40 GeV
LZ	SURF (US)	10 t / 7 t	4.2 t·yr	2.2×10^{-48} cm²
XENONnT	LNGS (IT)	8.6 t / 5.9 t	3.1 t·yr	1.7×10^{-47} cm²
PandaX-4T	CJPL (CN)	5.6 t / 3.7 t	1.54 t·yr	1.6×10^{-47} cm²

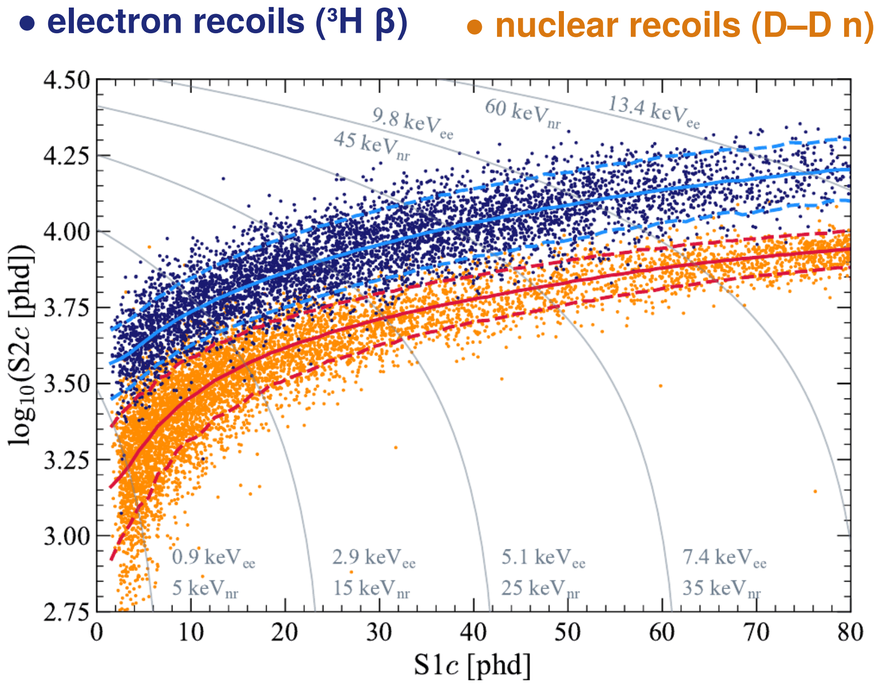
- Heavy WIMPs (≳ 10 GeV): liquid-xenon TPCs lead with **2.2×10^{-48} cm² at 40 GeV** (LZ). No signal yet
- Next: DM with **electroweak charge**. The wino (≈ 3 TeV) is ≈ 4× below the LZ limit, within reach of XLZD
- Exception: the pure Higgsino (1.1 TeV). Elastic only via loops: $\sigma_n \lesssim 10^{-48}$ cm², in the neutrino fog
- But the Z links its two neutral states χ_1, χ_2 at tree level → **inelastic** scattering: a large cross-section; for δ of a few hundred keV, visible only at high recoil energy ($\sigma_n \approx 2.3\times10^{-39}$ cm² (Xe))



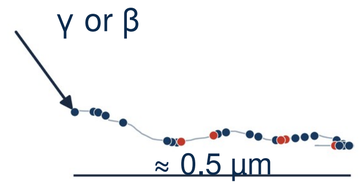
Liquid Xenon TPC



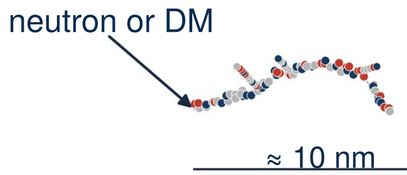
S. Eriksen (LZ), TeVPA 2026



LZ, PRL 131, 041002 (2023)



Electron recoil (ER): sparse, ≈ 0.5 μm

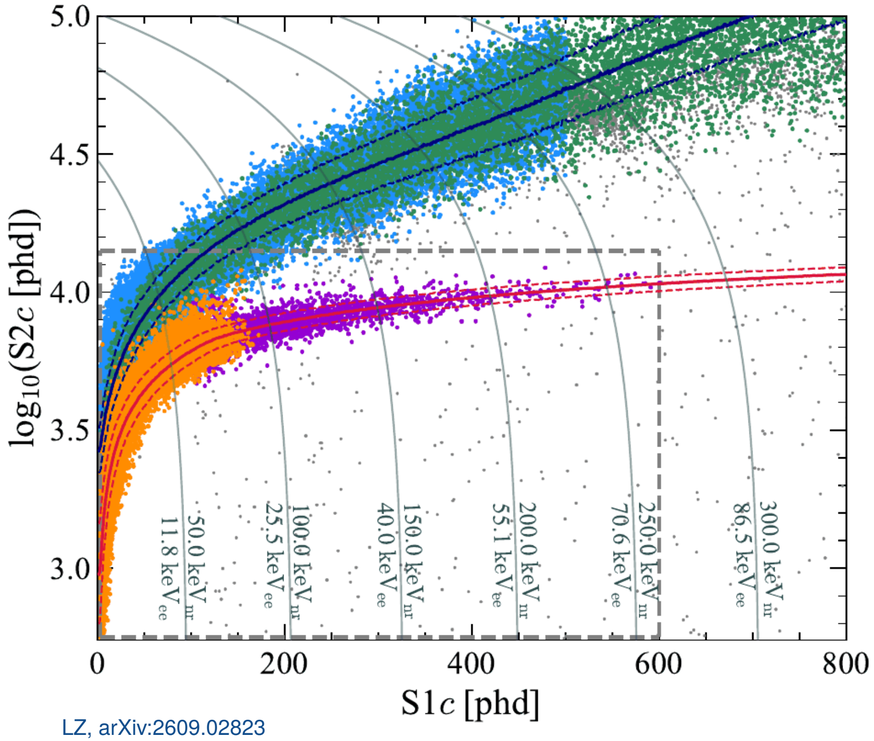


- Xe* → light (S1)
- Xe$^+$ + e$^-$ → charge (S2)
- atomic motion → heat

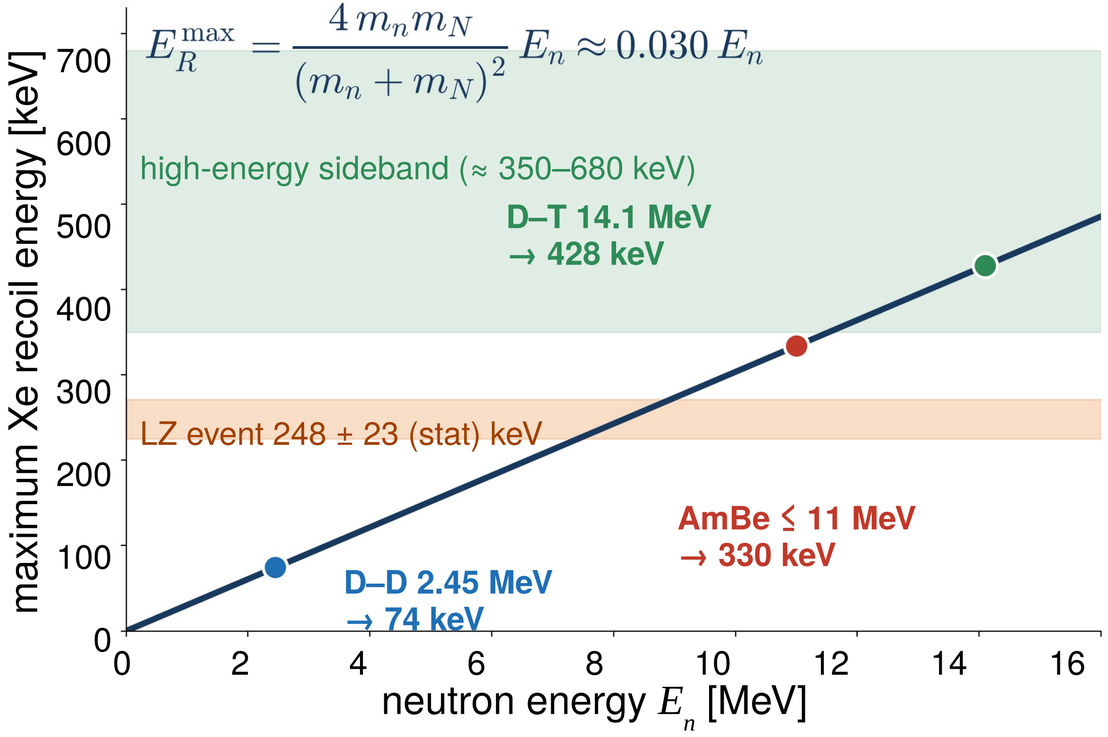
Nuclear recoil (NR): dense, ≈ 10 nm

- Two-phase TPC: liquid xenon with a thin gas layer on top. An interaction gives prompt scintillation (**S1**) and ionisation electrons
- The electrons drift up in an electric field, are extracted into the gas and make **electroluminescence** (**S2**); even a single electron is visible
- S2 pattern on the top PMTs → (x, y); drift time → depth. The inner **fiducial volume**, with low BG, is selected by position
- A nuclear recoil (NR) gives less light and charge per keV than an electron recoil (ER), called **quenching**, and **less charge per light** → two bands; 99.9% of ERs lie above the NR median
- Why: an NR loses part of its energy as heat (atomic motion); its ≈ 50× shorter track gives more recombination. keV$_{nr}$, keV$_{ee}$: NR / ER energy

Search Window and Calibration



LZ, arXiv:2609.02823

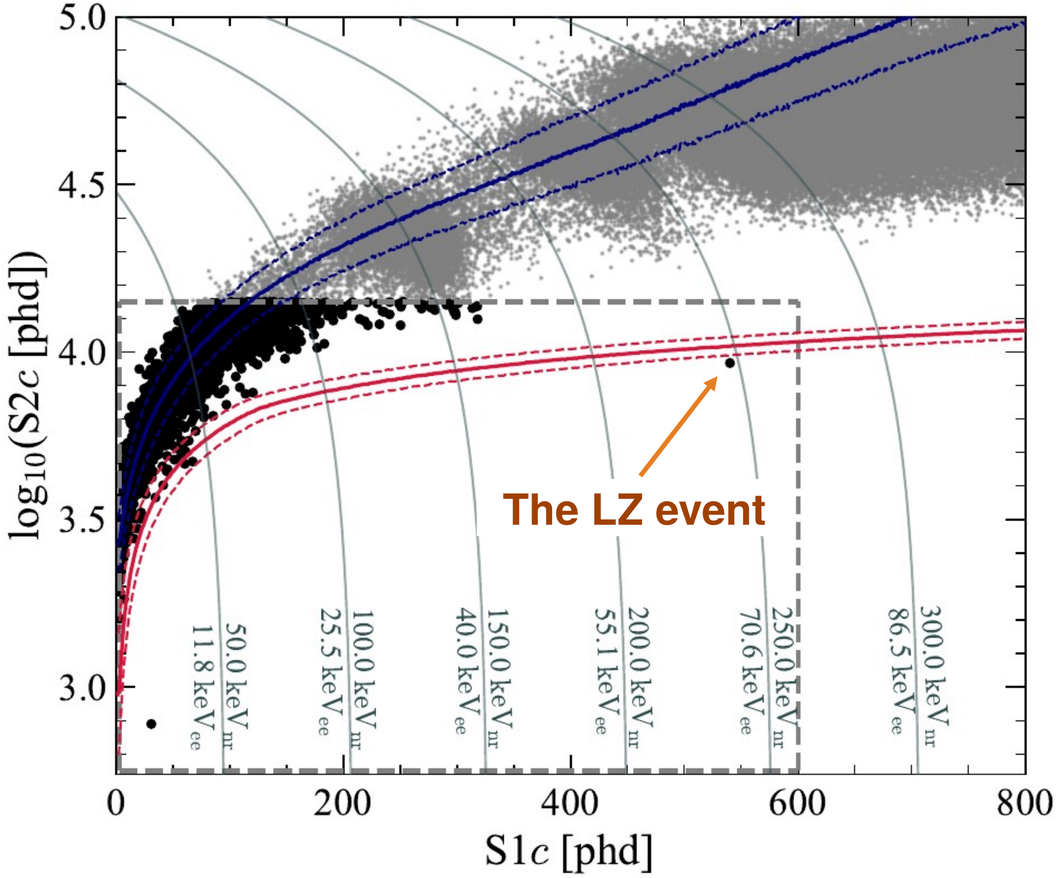


●● ER calibration (^{3}H, ^{14}C, ^{212}Pb) ●● NR calibration (D–D, AmBe)

- The NR band is measured with neutrons: D–D (2.45 MeV) neutron generator reaches 74 keV
  AmBe reaches ≈ 330 keV but gives few recoils above 250 keV
- The LZ window ends at **S1 = 600 phd** (photons detected); for NRs this means 50% efficiency at 270 keV
- **The event (248 keV) is inside the calibrated range, but the high-energy sideband is not**
  → D–T neutrons (14.1 MeV, up to 428 keV) are the next step

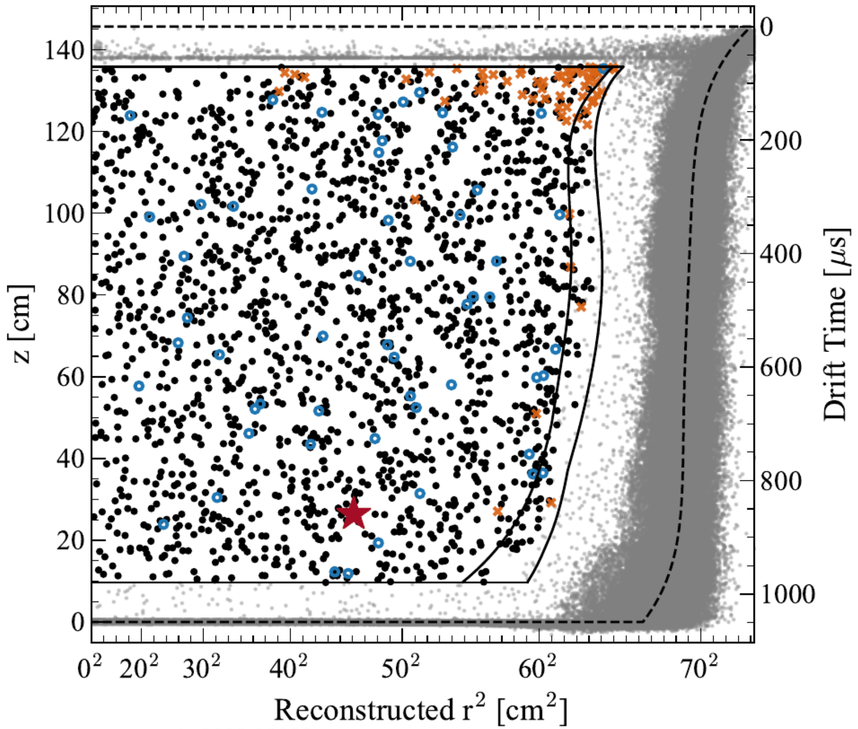
The Candidate Event

untagged events of the search (2.84 t·yr)



LZ, arXiv:2609.02823

position in the detector



LZ, arXiv:2609.02823

★ the event ● untagged events ● outside the fiducial volume
+ veto signal at the same time (prompt veto)
○ veto signal within 600 μs (mostly random)

16 June 2023
S1 = 540 phd, S2 = 9270 phd
1.5σ below the NR median
6.7σ below the ER band
248 ± 23 (stat) ± 23 (sys) keV

data for this search

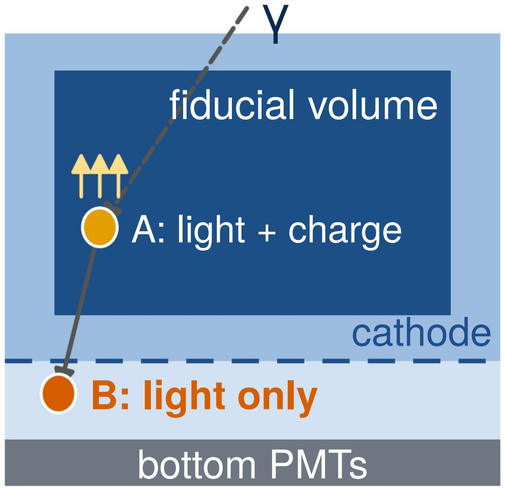
- **220 live days × 4.71 t = 2.84 t·yr**
- single scatters, S1 = 3–600 phd
- NR efficiency 96% (14–250 keV), 50% at 270 keV

- **One NR-like event at 248 ± 23 (stat) ± 23 (sys) keV**, and no excess at lower energy
- It came on **16 June 2023**, close to early June, when DM is fastest in the lab: the best time of year for inelastic DM near the kinematic limit
- A single scatter well inside the fiducial volume; waveform and hit pattern like other single scatters

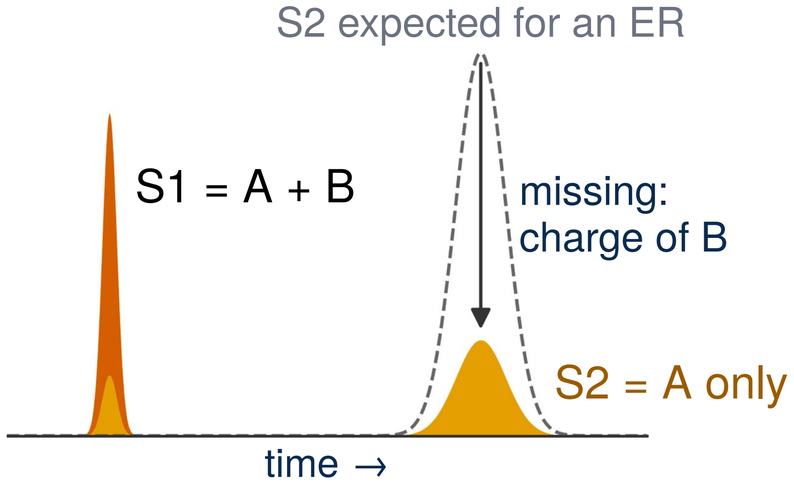
Could It Be a BG?

MSSI (multiple-scintillation single-ionisation): how one γ-ray can look like an NR

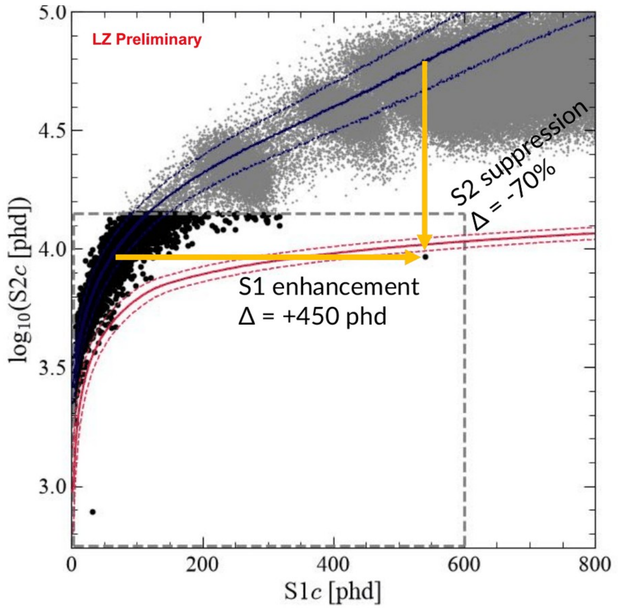
one γ-ray scatters twice



waveform: S2 too small for the S1



what a fake NR would need for the event



S. Eriksen (LZ), TeVPA 2026

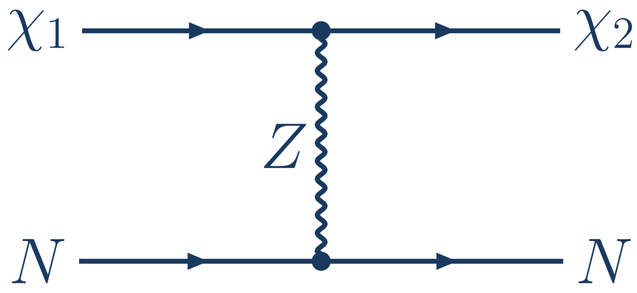
what can fake an NR	expected (whole window)	why it does not explain the event
MSSI (main concern)	0.005 ± 0.005	simulation checked in a larger (5.4 t) volume and with veto-tagged events
neutron (a real NR)	fit: 0–0.12	negligible: needs $E_n > 8$ MeV and would also give smaller recoils; veto tags 92% of detector neutrons
accidental S1 + S2 pairs	2.7 ± 0.6	mostly at low energy; only a tiny tail reaches 248 keV
neutrinos (ν–nucleus scattering)	0.11 (atm.) + 0.06 (solar)	falls steeply with energy; only a tiny tail reaches 248 keV

At the S1 of the event (500–600 phd): **0.0106 ± 0.0008 BG events** → LZ: **up to 3.4σ local, 2.6σ global** (293 signal spectra).

The event is hard to explain with known BGs → next, DM models that can give such an event

Higgsino Interpretation

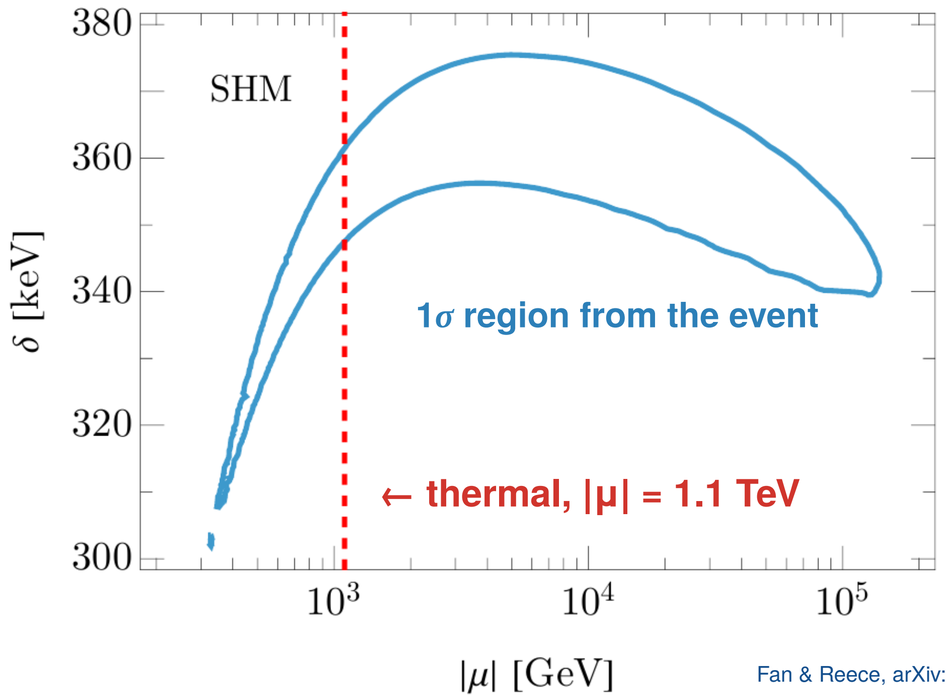
Inelastic scattering via the Z



$\sigma_n \simeq 2.3 \times 10^{-39}\ \mathrm{cm}^2$

- Elastic: loops only; one event at 250 keV would mean ≳ 10^3 events in the standard window → **excluded**
- Inelastic through Z exchange at tree level → σ fixed by the gauge coupling
- For the fitted δ, only the fastest DM scatters → **only high-energy recoils**

δ that fits the event (halo with v_0 = 220 km/s)



Fan & Reece, arXiv:2609.01504

Thermal relic: $m_\chi \approx 1.1$ TeV → at this mass the 1σ region gives **$\delta \approx$ 350–380 keV** (Fan & Reece 2026: ≈ 350; Rodd+ 2026, with 238 km/s: 372–380)

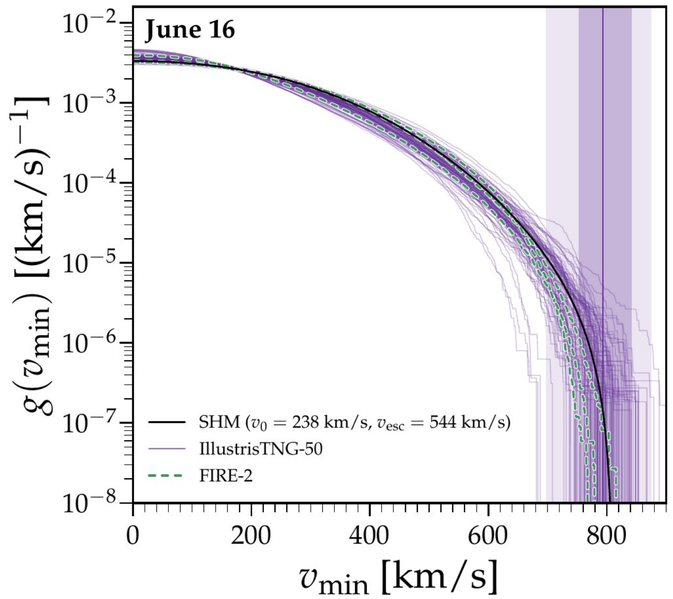
→ δ is set by the gaugino masses: $\delta \simeq m_Z^2 \left(\frac{\sin^2\theta_W}{M_1} + \frac{\cos^2\theta_W}{M_2} \right) \approx 0.35\ \mathrm{MeV}$ for $M_{1,2} \approx 2.4 \times 10^7\ \mathrm{GeV}$

→ this δ needs DM faster than **≈760–790 km/s** in the lab, close to the fastest DM of the standard halo (781–810 km/s)

The thermal Higgsino can explain the event, but only with the fastest DM in the halo

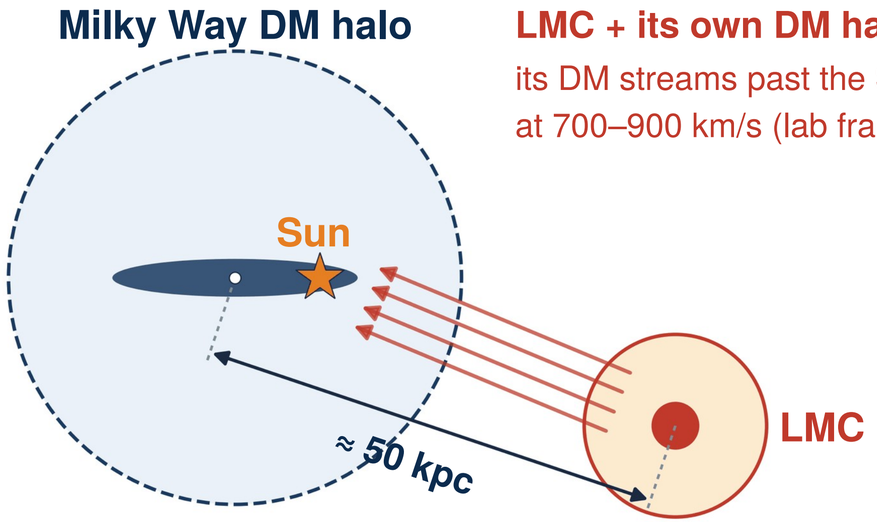
Fastest Dark Matter: Simulated Halos and the LMC

end of $f(v)$ in 101 simulated halos



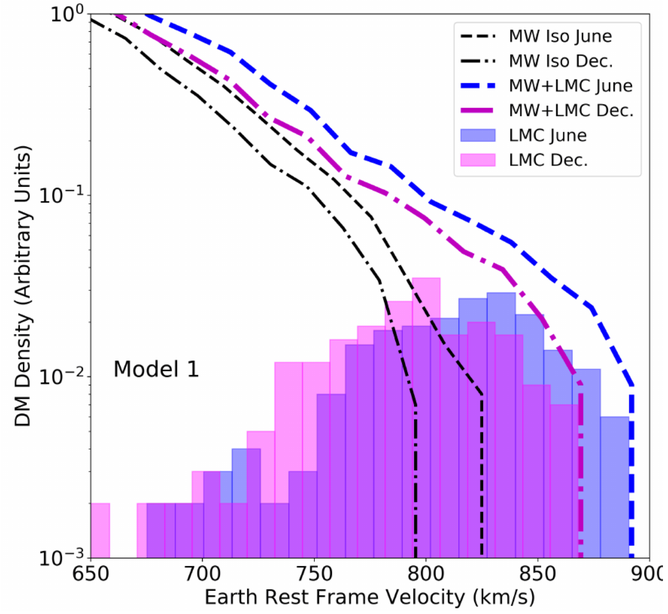
C. O'Hare, arXiv:2609.21444

the Large Magellanic Cloud (LMC) brings its own DM



based on Besla et al., JCAP 11 (2019) 013; Kallivayalil+ 2013

lab-frame speeds with the LMC



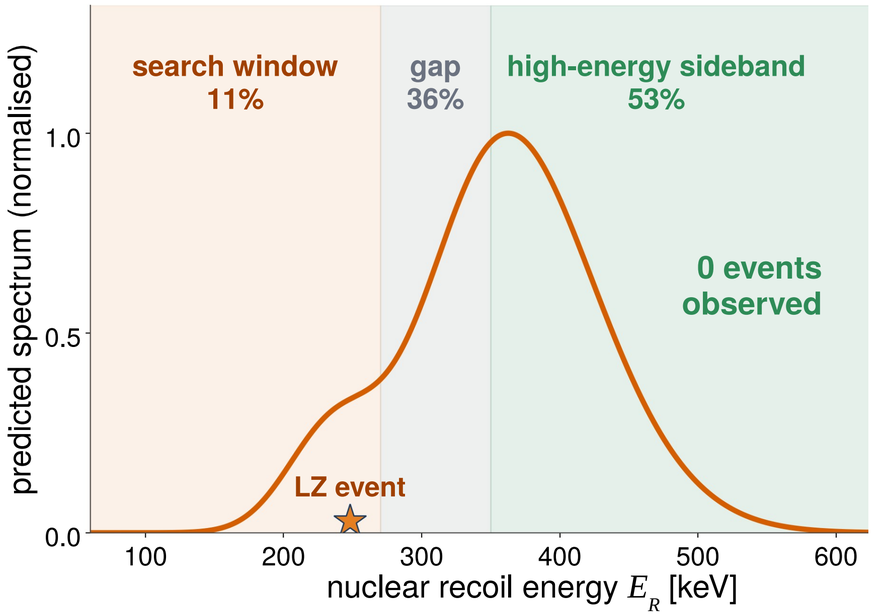
Besla et al., JCAP 11 (2019) 013

- Simulations: 95% of 101 Milky-Way-like halos end at 700–875 km/s → **this end point is uncertain** (O'Hare 2026)
- The LMC is the heaviest satellite of the Milky Way. It came close only ≈ 50 Myr ago, and its gravity has already changed the Milky Way halo (Erkal+ 2019; Shipp+ 2021; Kallivayalil+ 2013; Conroy+ 2021)
- The LMC brings its own DM and also makes the Milky Way DM faster → in the lab, **the fastest DM reaches ≈ 850–980 km/s** (Besla+ 2019; Rodd+ 2026; Zhang+ 2026)
- With faster DM, the fitted δ grows: ≈ 350–380 keV for the standard halo, **up to 514 keV with the LMC** (Fan & Reece 2026; Rodd+ 2026; Ghosh+ 2026)

The tail of the DM speed distribution is not well known → we need tests that depend less on the tail

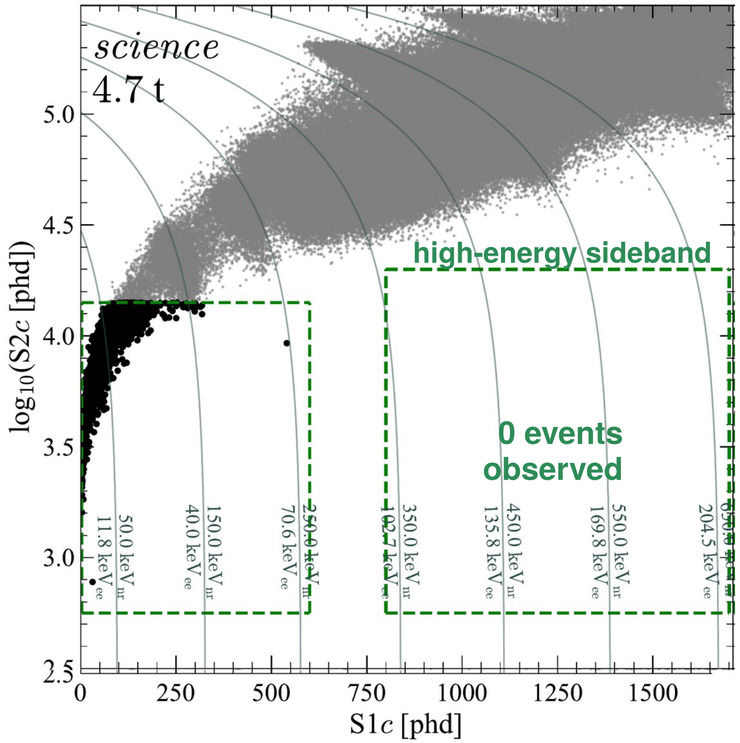
LZ High-Energy Sideband

thermal Higgsino, standard halo: where the events should be



based on Rodd, Safdi, Slatyer, Xu, arXiv:2609.04175

LZ sideband: 0 events



inelastic Higgsino (1.1 TeV)

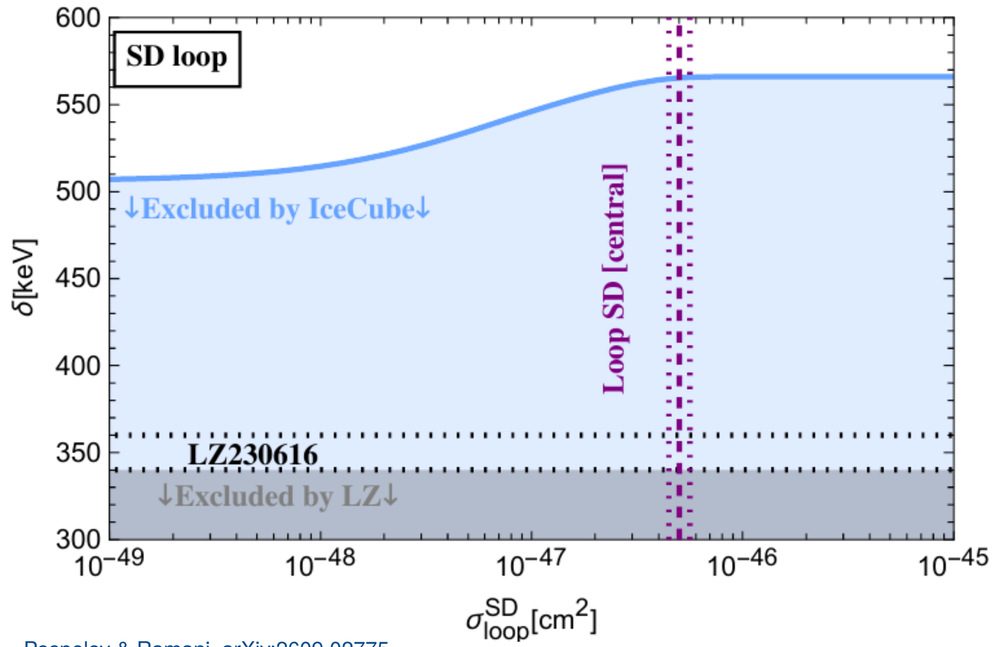
halo model	δ	events in the sideband
standard, $v_{esc} = 544$ km/s	377 keV	4.9
standard, $v_{esc} = 610$ km/s	423 keV	8.8
standard + 0.6% LMC-like DM	492 keV	10.1

Rodd, Safdi, Slatyer & Xu, arXiv:2609.04175

- Benchmark: thermal Higgsino (1.1 TeV), standard halo; one event in the window fixes $\delta = 377$ keV
- This δ is close to the kinematic limit, so most recoils lie above the window:
  11% in the window and 53% in the high-energy sideband (S1 = 800–1700 phd)
- One event in the window means ≈ 5 events in the sideband (if all NRs there are accepted), but LZ saw **0 events**
  → probability ≈ 1%; a faster halo tail predicts even more (≈ 9–10)
- **So, from the sideband, the thermal Higgsino interpretation may be difficult**

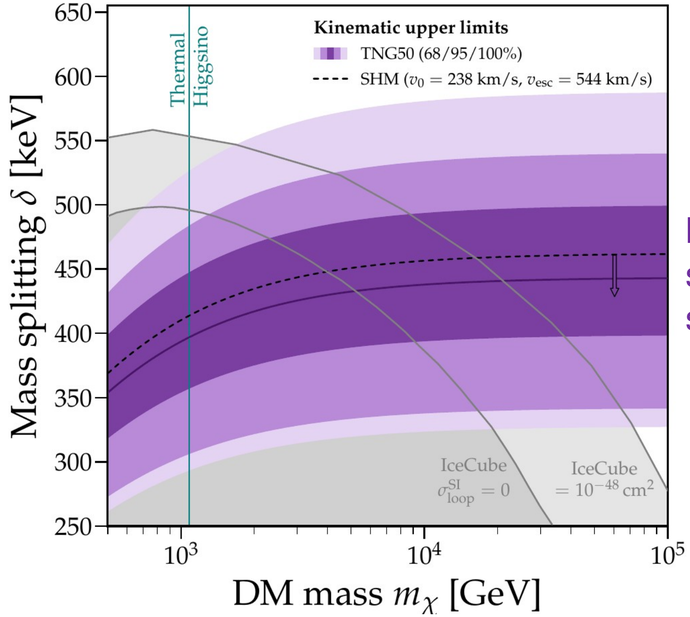
Solar Capture and IceCube

thermal Higgsino (1.1 TeV): IceCube bound on δ



Pospelov & Ramani, arXiv:2609.02775

heavier Higgsinos: IceCube vs kinematic limit



largest δ that xenon can still see, set by the fastest DM in each simulated halo

C. O'Hare, arXiv:2609.21444

- Capture: the Sun's gravity speeds DM up to ≈ 1400 km/s → even slow halo DM scatters and is captured;

  Higgsinos then annihilate into W^+W^-, ZZ → GeV–TeV neutrinos

- Thermal Higgsino: no excess in 10 years of IceCube → $\delta >$ 500–560 keV (Pospelov & Ramani, arXiv:2609.02775).

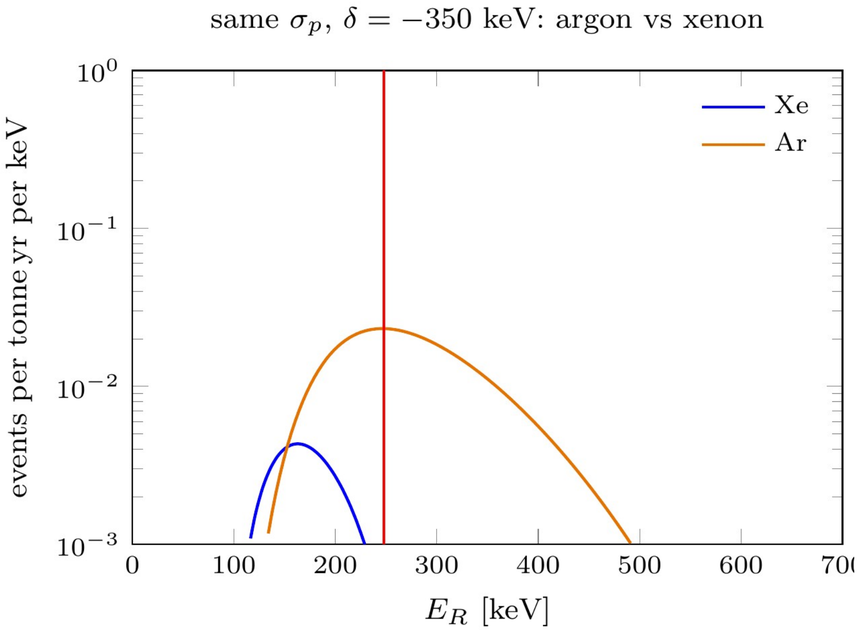
  The LZ event needs $\delta \approx$ 350–380 keV → **the thermal Higgsino is unlikely to explain both the LZ event and IceCube**

- Heavier Higgsinos (10^5–10^6 GeV, non-thermal): similar fitted δ, but the kinematic limit is ≈ 450 keV → **window ≈ sideband ≈ 0.5 events**

- For them, solar capture drops as $1/m_\chi^{\,2}$ → few neutrinos → **the LZ event, the empty sideband and IceCube can all fit** (Langhoff, arXiv:2609.09385)

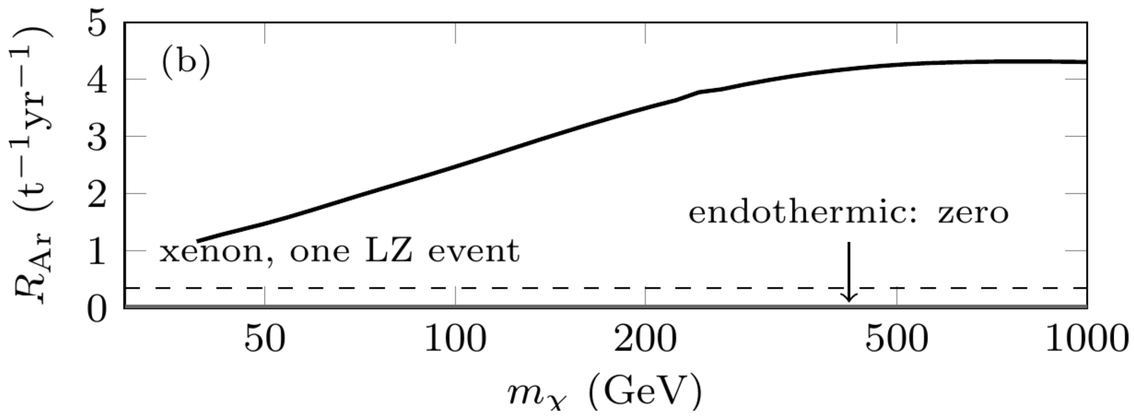
Exothermic Dark Matter: the Argon Test

argon vs xenon, exothermic DM (500 GeV)



Baer & Barger, arXiv:2609.06153

argon rate for one LZ event (exothermic)



Baer & Barger, arXiv:2609.15782

- Argon is lighter: reduced mass $\mu_N = 36$ GeV vs 110 GeV for xenon (1.1 TeV DM) → the relative motion carries 3× less energy
- Endothermic ($\delta \approx 350$ keV): needs $v \gtrsim 1320$ km/s, far above the fastest DM (≈ 800 km/s) → **exactly zero**
- Exothermic: no speed needed, and the argon form factor is large near 300 keV (xenon's is near a zero)
  → **1–4 events / t·yr, 3–12× xenon** ($m_\chi = 40$–1000 GeV)
- DEAP-3600 (3.3 t) data can be re-analysed now; DarkSide-20k (20 t) from ≈ 2030

Argon: exothermic → many events, endothermic → none

Future Tests

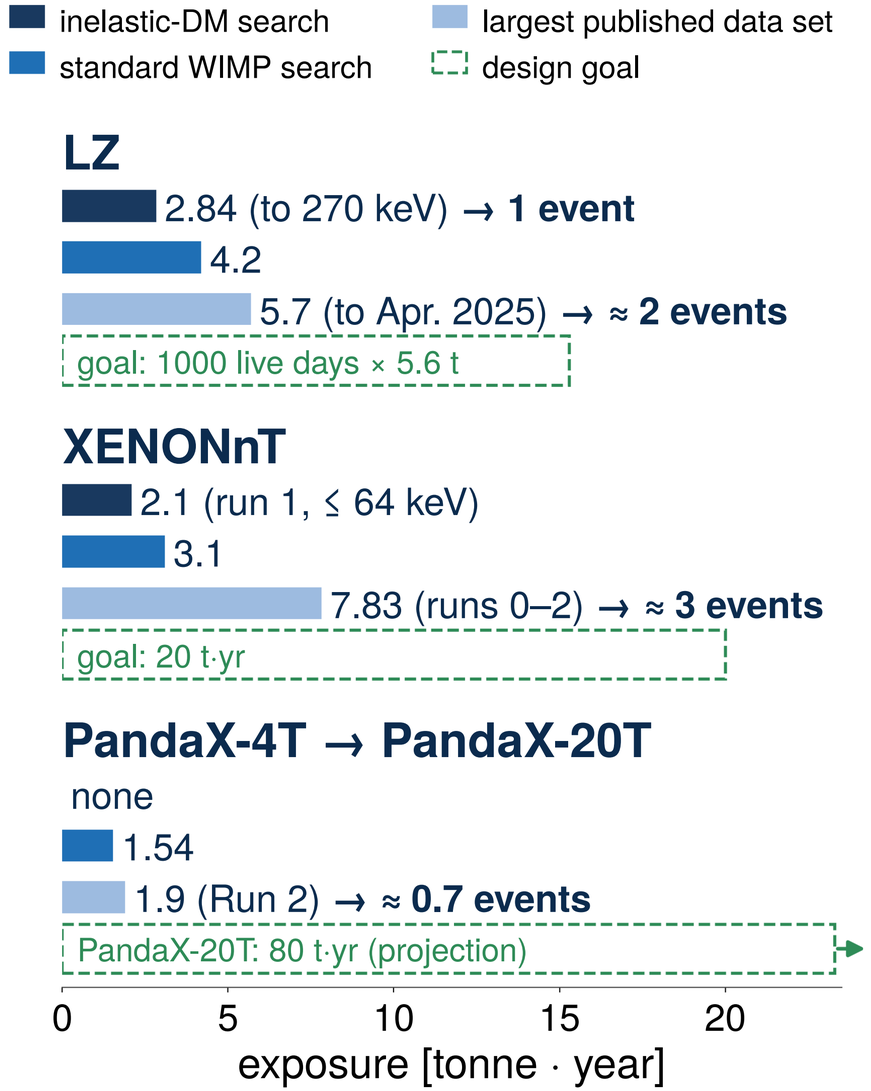
test	endothermic	exothermic	where
recoil energies	a band at high energy, nothing below	mostly below 248 keV	LZ (≈ 4–5 events in 1000 live days), XENONnT, PandaX-20T, XLZD
event dates	strong, peak in June	almost constant	the same xenon TPCs
argon	0 events	1–4 per t·yr	DEAP-3600 (now), DarkSide-20k (≈ 2030)
photon line	χ_2 made in the rock decays: $E_\gamma = \lvert\delta\rvert$	no line: χ_2 lives too long	JUNO, SNO+, KamLAND

- Xenon tests need the NR band above 300 keV → D–T neutrons (14.1 MeV)

- Indirect (thermal Higgsino): annihilation gives a γ-ray line at 1.1 TeV.
  - Fermi-LAT: mild ≈ 2σ hint for a ≈ 1 TeV mass (GeV continuum);
  - **CTAO-North (from 2026): 3σ by ≈ 2031 for the Einasto profile; strongly profile dependent** (Dessert+ 2023; H.E.S.S., arXiv:2608.07234; Abe+ 2026)

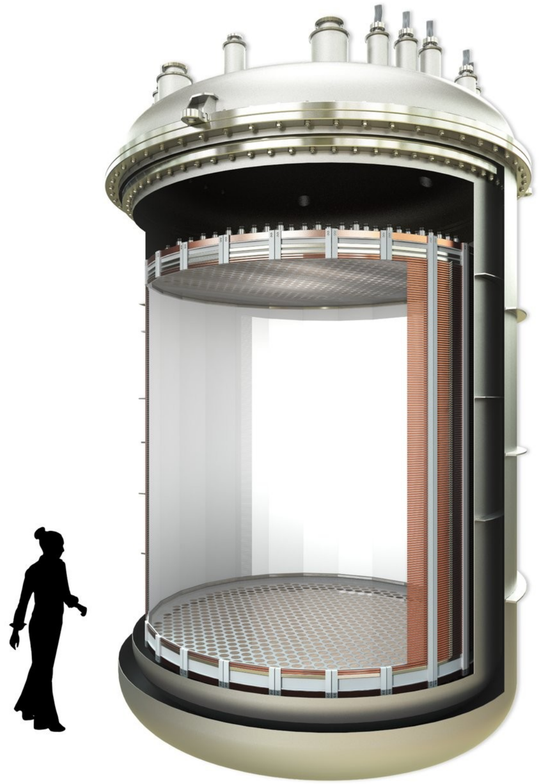
The recoil spectrum gives δ;
event dates and argon can distinguish endothermic from exothermic

exposure and expected events (LZ rate: 1 per 2.84 t·yr)



data already taken: ≈ 5 events in total

XLZD



XLZD Design Book, EPJC 85, 1192 (2025)

candidate sites (Kamioka for comparison)

site	depth [m w.e.]	muon flux [$m^{-2}d^{-1}$]	^{137}Xe [$t^{-1}yr^{-1}$]
SNOLAB (Canada)	5890	< 0.3	0.007
SURF (USA)	4300	4.6	0.142
Boulby (UK)	3330	14.6	0.404
LNGS (Italy)	3800	29.7	0.822
Kamioka (Japan)	2700	128	3.54

events per live year at the LZ rate (0.35 / t·yr)

detector (fiducial)	events / yr
LZ (4.7 t)	1.6
XENONnT (4.0 t)	1.4
PandaX-20T (13 t, 2028–)	4.6
XLZD (48–64 t)	17–22
XLZD, 1000 t·yr total	≈ 350

- XENON + LZ + DARWIN joined in 2024 (> 400 people). **60 t** active xenon (80 t option), 3 m × 3 m TPC
- Goal **200–1000 t·yr**, with every non-neutrino BG below the neutrino rate
- If the LZ event is real: ≈ **350 events in 1000 t·yr** → spectrum, δ and annual modulation

Timeline (public plans, 2025–26)

2024 — collaboration formed

2026 — site choice: Boulby, LNGS, SNOLAB or SURF

2027 — conceptual (early) and technical design reports

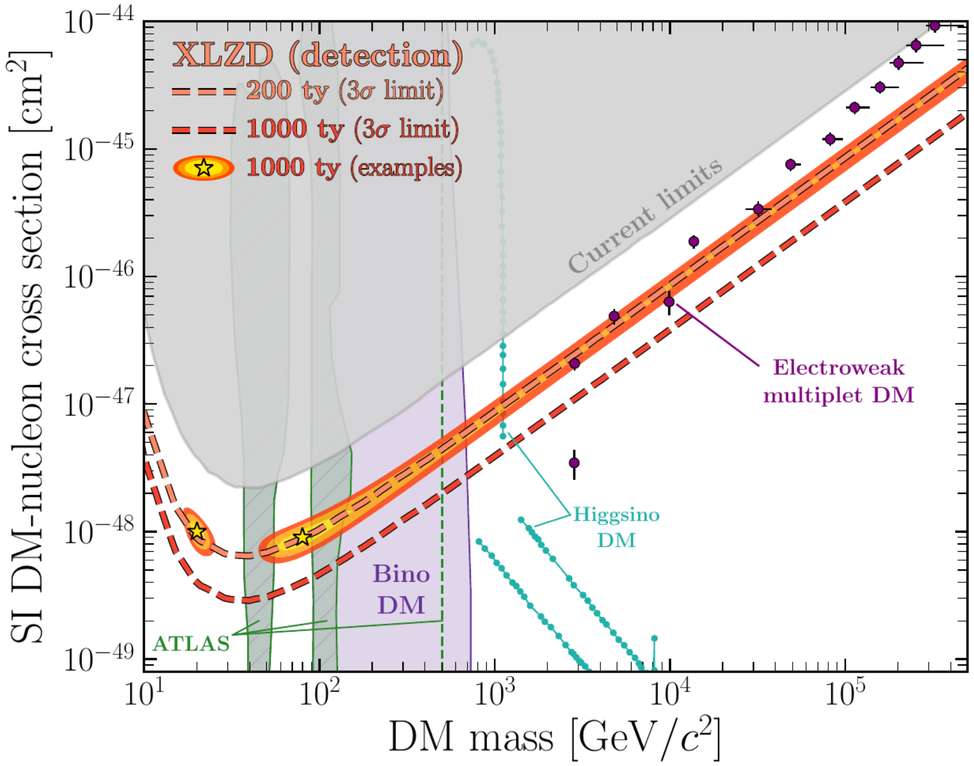
end 2028 — construction starts

2034 — commissioning

2035 — science run

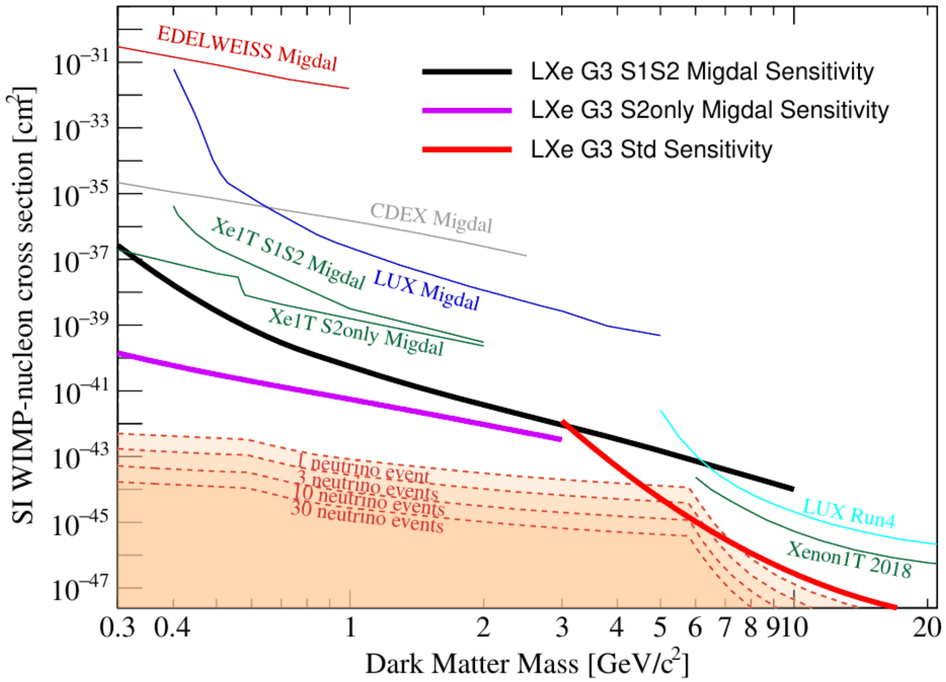
XLZD Physics Reach

electroweak DM: 3σ detection reach



XLZD Design Book, EPJC 85, 1192 (2025)

light DM via the Migdal effect (300 t·yr)



Aalbers et al., J. Phys. G 50, 013001 (2023)

- Electroweak DM: with 200–1000 t·yr, XLZD can see a 3σ signal from **most electroweak-multiplet DM candidates** (XLZD Design Book)
- Thermal wino (≈ 3 TeV, $\sigma_n \approx 2 \times 10^{-47}$ cm², ≈ 4× below LZ): just below the 3σ line for 200 t·yr, above it for 1000 t·yr

  → **3σ evidence needs 200–1000 t·yr; 90% CL exclusion already with ≈ 50 t·yr** (Bloch et al., JHEP 08 (2025) 216)
- Light DM via the Migdal effect: S2-only analyses gain up to ≳ 100× below 1 GeV

Summary

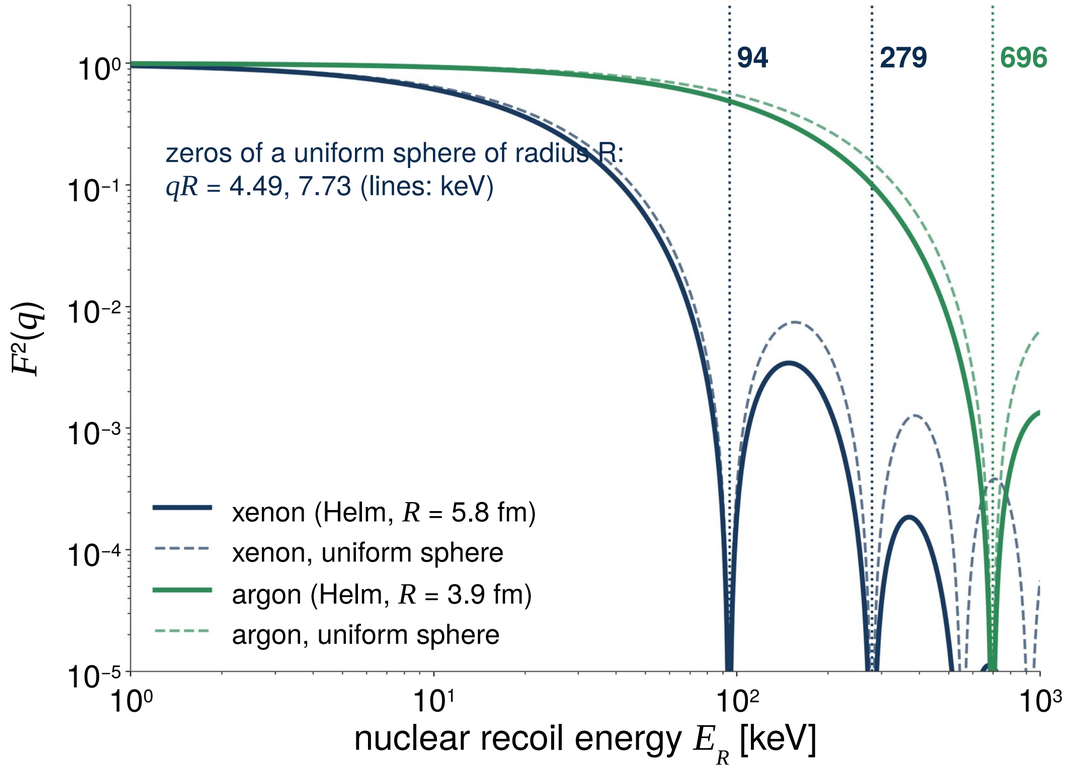
- **Status**: xenon TPCs lead for heavy WIMPs (2.2×10^{-48} cm^2 at 40 GeV), and cryogenic detectors lead for light DM below $\approx$ 1 GeV
- **Observation**: LZ sees one NR-like event at 248 keV, with $\approx$ 0.01 BG events expected near its S1 and no excess at low energy (3.4σ local, 2.6σ global)
- **Interpretation**: standard spin-independent elastic scattering cannot give this spectrum; endothermic inelastic scattering near the kinematic limit can
- **Constraints**: the thermal 1.1 TeV Higgsino is disfavoured by the empty sideband and IceCube. A heavy non-thermal Higgsino or exothermic DM can still fit
- **Next**: more LZ events (energies and dates), NR calibration above 300 keV, argon, and XLZD

Backup

Nuclear Form Factor in Elastic and Inelastic Scattering

$$\frac{dR}{dE_R} = \frac{\rho_0}{m_\chi m_N} \int_{v>v_{\min}(E_R)} v\, f(\vec{v})\, \frac{d\sigma}{dE_R}\, d^3v, \qquad \frac{d\sigma}{dE_R} = \frac{m_N \sigma_n A^2}{2\mu_n^2 v^2} F^2(q)$$

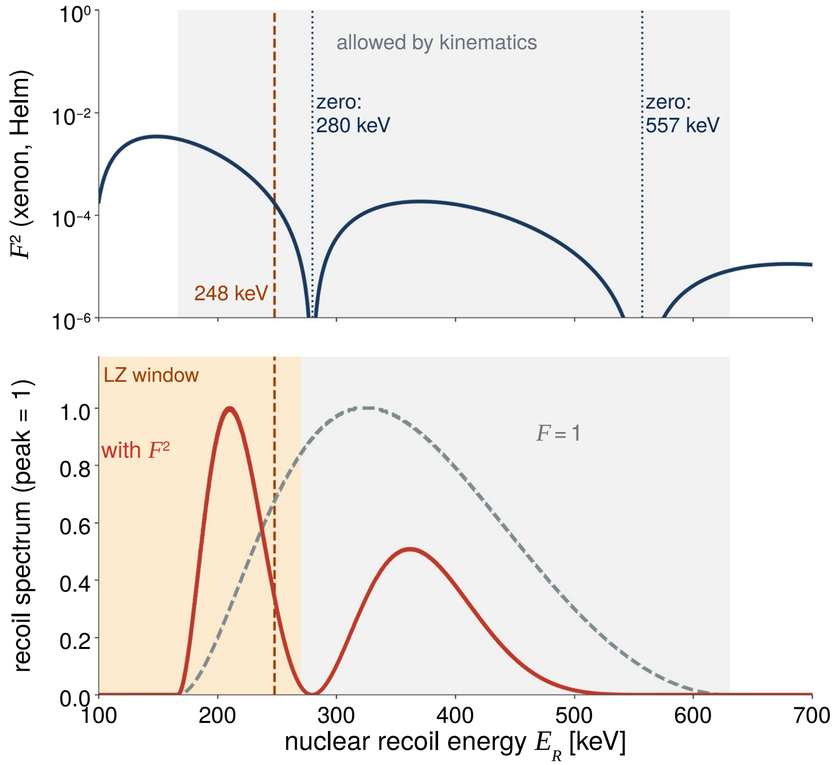
Elastic scattering



based on the Helm form factor with the parameters of Lewin & Smith, Astropart. Phys. 6, 87 (1996)

- Small q: all nucleons scatter coherently, $F \approx 1$, rate $\propto A^2$
- Larger q: waves from the edge and the centre of the nucleus cancel at the zeros (Xe: 94, 279 keV; Ar: ≈ 700 keV)

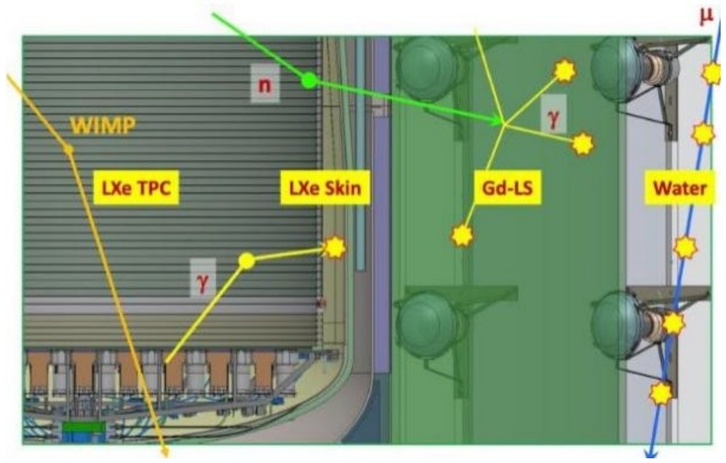
Inelastic scattering



based on the standard halo (June) and the Helm form factor; $m_\chi = 1.1$ TeV, $\delta = 360$ keV

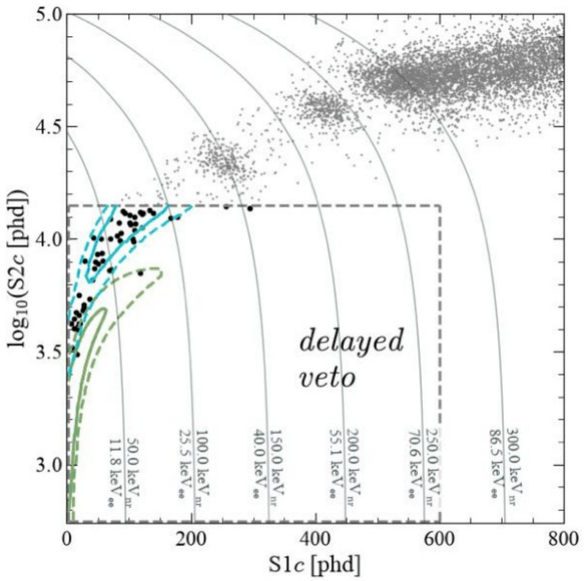
- Same $F(q)$, but for $\delta = 360$ keV only 170–630 keV is allowed: $F^2 \approx 2 \times 10^{-4}$ at the event, so the rate is ≈ 6000× lower
- The zero at 280 keV splits the spectrum: for this δ, more events fall in the LZ window, fewer in the sideband

Veto Detectors and the Three Data Samples



The TPC sits inside a xenon skin and an outer detector (17 t of Gd-loaded liquid scintillator in water). γ-rays and neutrons that scatter in the TPC often leave a signal there too

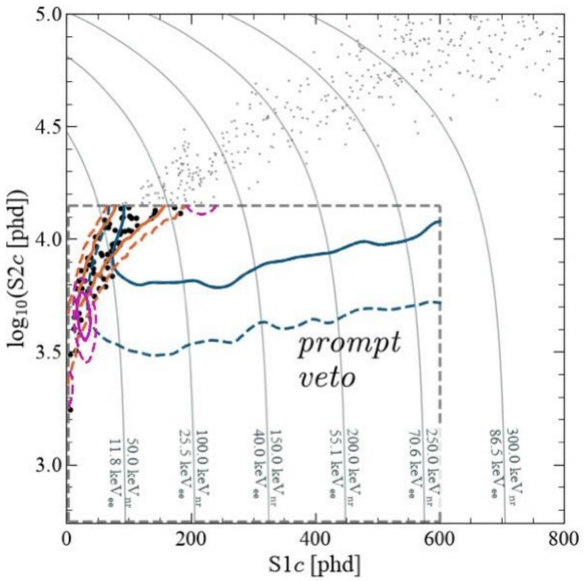
Delayed veto



Contours: Neutrons
ER Backgrounds

skin > 300 keV or outer detector > 200 keV within 600 μs after S1 (neutron capture)

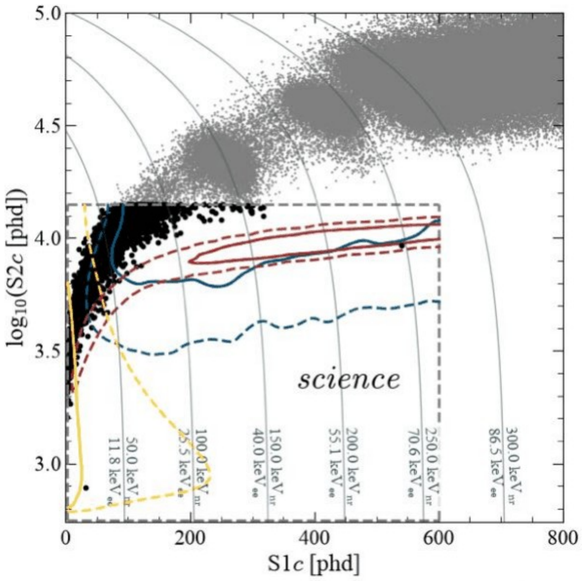
Prompt veto



Contours: Detector ER
^{127}Xe MSSI

skin or outer detector within ≈ ±0.3 μs of S1 (γ-rays and neutrons)

Science



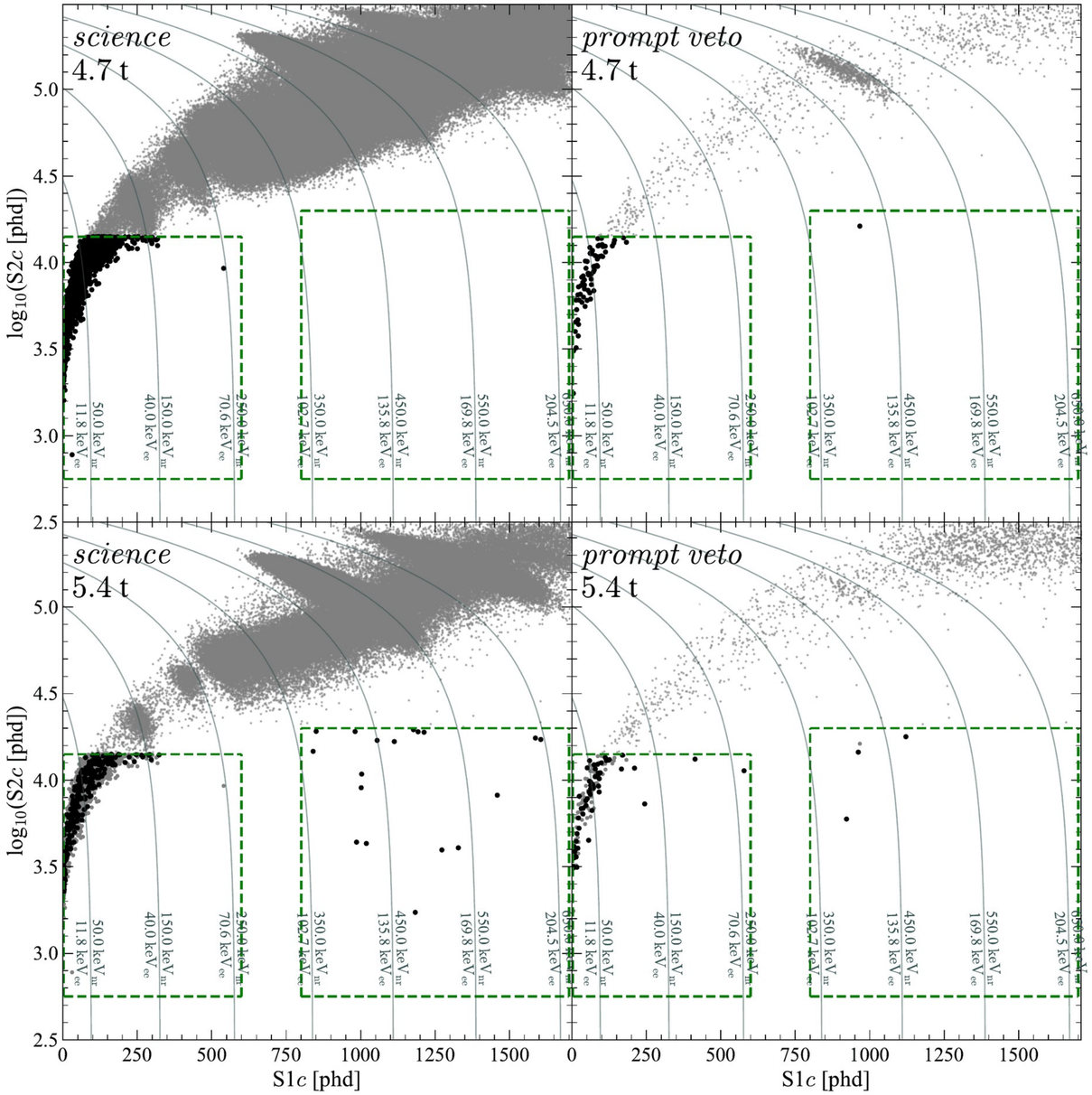
Contours: L10s 1000 GeV/c^2
Accidental Coincidences MSSI

no tag; contains the event. Random vetoes: 0.01% (prompt), 2.86% (delayed)

- The three samples are fitted together, so the tagged samples constrain the γ-ray, neutron and MSSI BGs in the science sample

S. Eriksen (LZ), TeVPA 2026; LZ, arXiv:2609.02823

MSSI Validation in the High-Energy Sideband



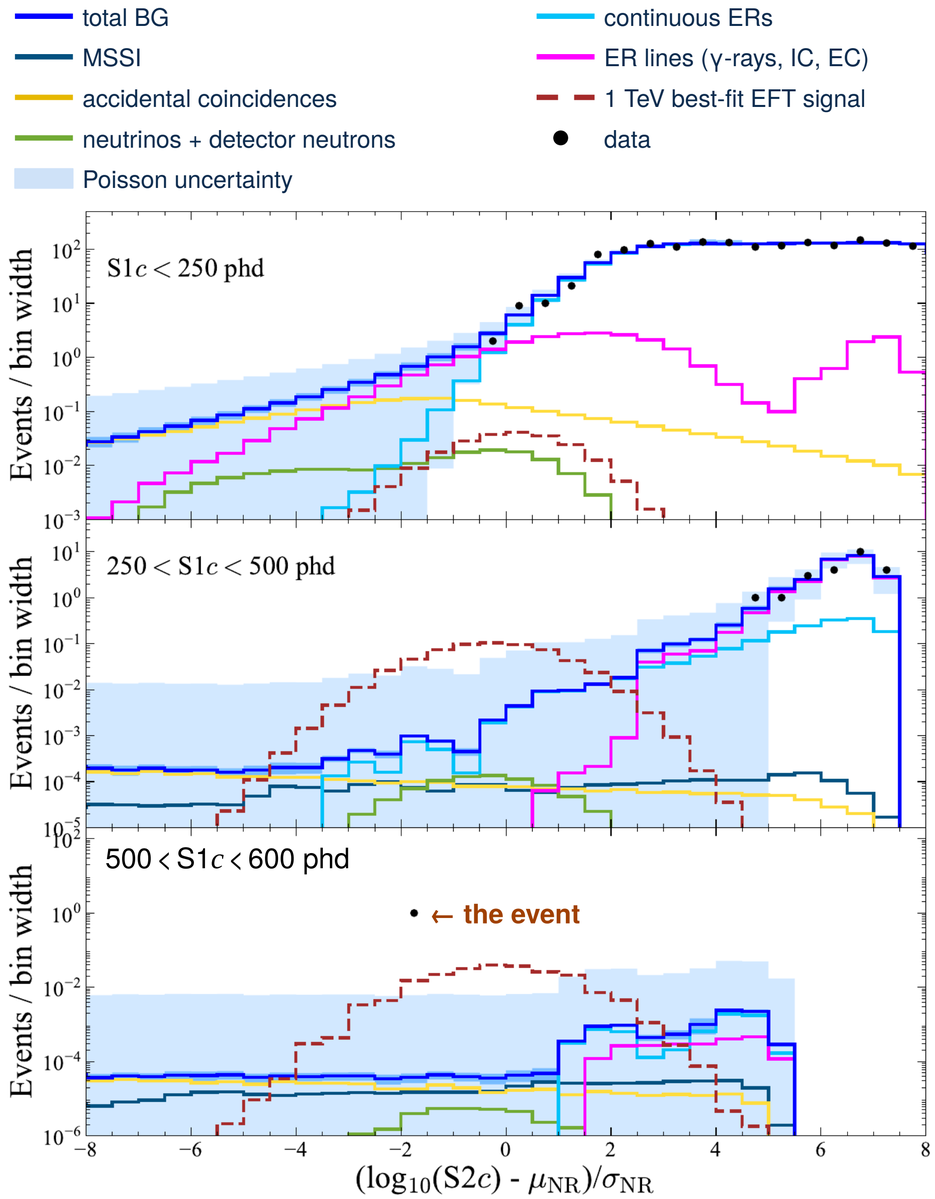
MSSI: a second deposit without charge collection adds light, but no charge

- Sideband: 800 < S1 < 1700 phd, $10^{2.75}$ < S2 < $10^{4.3}$ phd (≈ 350–680 keV_{nr})
- 4.7 t science sample: **0 observed**, 0.6 MSSI expected (wall 0.1 + below cathode 0.5)
- 5.4 t shell around it: 18 observed vs 21.5 expected; 7 of 12 radon-tagged (60% tagging expected); χ^2 p-value 0.7
- Both agree with the MSSI model
- The sideband was defined to test the MSSI model; its NR acceptance is not published

LZ, arXiv:2609.02823 (Suppl. Fig. S4, Table S6)

BG in Three S1 Ranges

data and BG model in three S1 ranges (2.84 t·yr)



LZ, arXiv:2609.02823

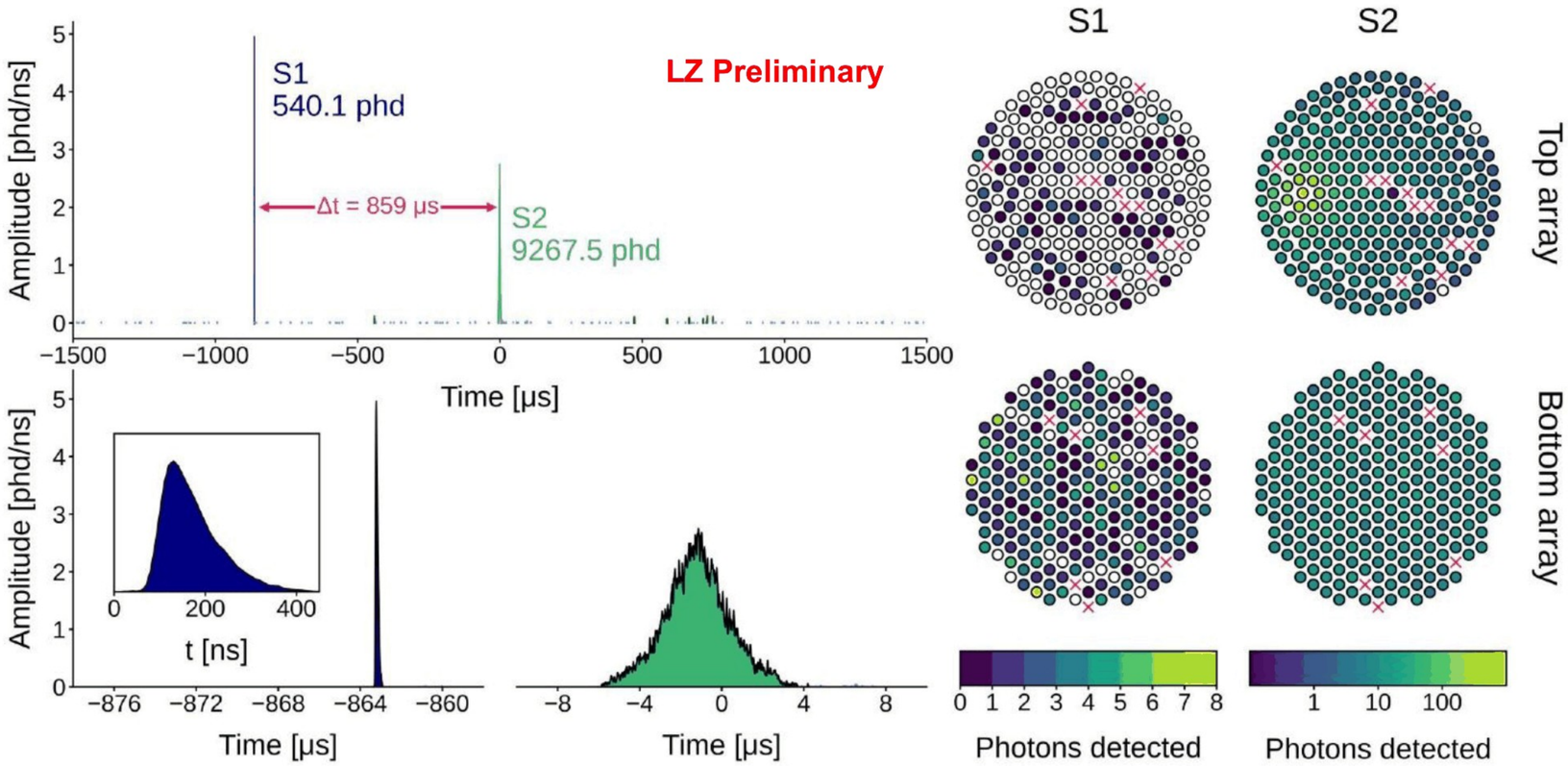
NR-like BGs in the whole search window

BG	expected	how it is known
accidental coincidences	2.7 ± 0.6 (low S1)	isolated S1 and S2 pulses in the data
MSSI	0.005 ± 0.005	simulation; checked in the 5.4 t volume
neutrons from materials	0–0.12 (fit)	veto-tagged samples
neutrinos (ν–nucleus scattering)	0.11 (atm.) + 0.06 (solar)	atmospheric, ^{8}B + hep fluxes

- At higher S1 the ERs move away from the NR band, and the BG falls steeply
- At the event (S1 = 500–600 phd): **0.0106 ± 0.0008 BG events**
- The event is 1.5σ below the NR median, where only accidentals, atmospheric ν and MSSI remain; LZ finds up to 3.4σ local

LZ, arXiv:2609.02823 (Table I, Fig. 5); S. Eriksen (LZ), TeVPA 2026

Waveform and Hit Pattern of the Event

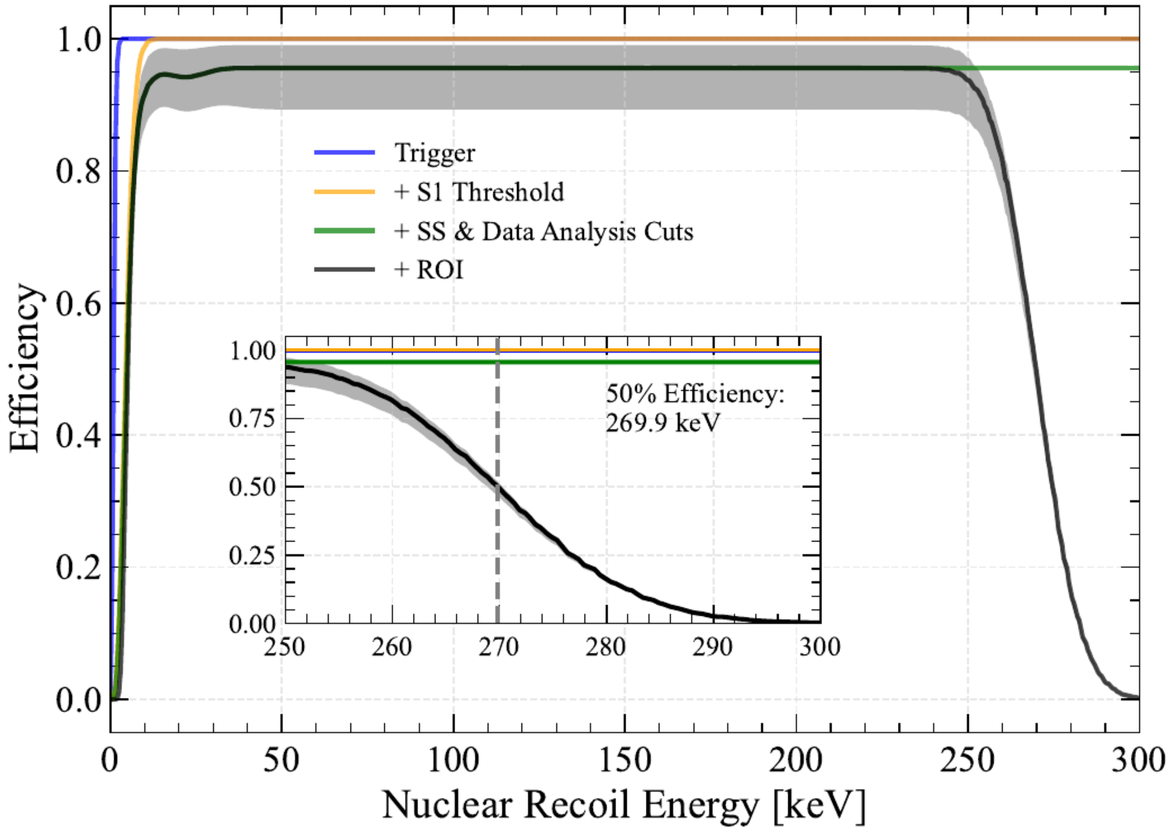


S. Eriksen (LZ), TeVPA 2026

- One S1 and one S2: a single interaction. Drift time 859 μs, i.e. 26 cm above the cathode
- S1 top/bottom light sharing and the S1 hit pattern match single scatters of similar size at that position
- The S2 pulse shape matches single-site α-decay events at the same location
- The rise time is slower than for events near the cathode, and the S1 pattern disagrees with a cathode-MSSI template

- A wall MSSI is not separable by the S1 pattern, but only ≈ 0.005 wall-MSSI events are expected in the whole window
- At S1 ≈ 550 phd the S1 pulse shape cannot tell ER from NR; the classification rests on S2/S1

What Must Be Measured Better



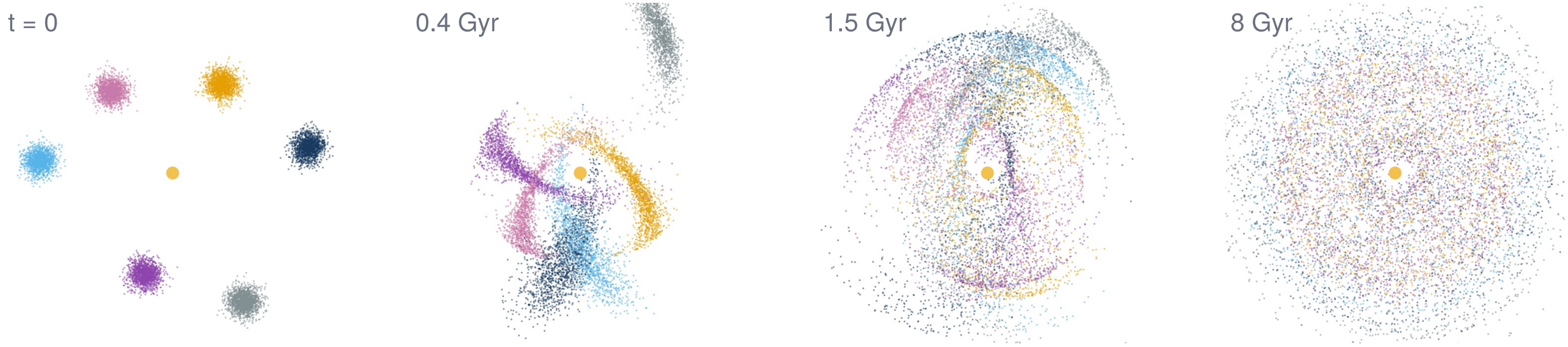
LZ, arXiv:2609.02823

The event (248 keV) sits just below the upper edge of the window, where the efficiency starts to fall (50% at 269.9 keV)

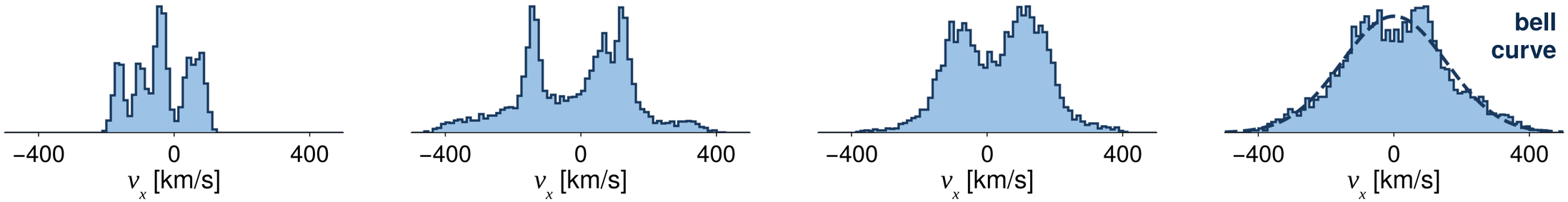
- Energy scale: S1, S2 → keV_{nr} relies on NR yields tuned only up to 330 keV (AmBe): ± 23 keV (sys) at 248 keV, and the sideband is an extrapolation
- NR band above 330 keV sets the acceptance in the high-energy sideband (800–1700 phd); D–T calibration needed
- High-energy BGs: MSSI (light from a second, charge-less deposit; 100% uncertainty), accidentals, ER tails beyond the calibrated range; dedicated control samples needed
- Halo: the fitted δ moves by ≈ 100 keV between the standard halo and an LMC tail (Rodd et al., Table I); Gaia data and simulations will help
- Mass: for $m_\chi \gg m_{Xe}$ the recoil spectrum depends only on δ, so it cannot fix masses above ≈ 1 TeV; the modulation amplitude keeps some mass information (McCabe)

Maxwell Velocity Distribution of a Settled Halo (Toy Model)

1. Start → **2. Fall in** → **3. Mix** → **4. Settled**



velocity of all DM in one direction (v_x)



Cold DM in small clumps; each clump moves as one, so there are only a few velocities

Gravity pulls the clumps in; they move much faster, but each clump in its own direction

Orbits drift apart and overlap (in real halos, merging also changes the gravity); the velocities get mixed

Fully mixed and no longer changing: a bell curve in each direction, i.e. Maxwell

- The standard halo model uses this settled, well-mixed state; it is the simplest halo that also gives a flat rotation curve

based on a 2D toy model: 6 clumps (one colour each) in a fixed potential with circular speed $v_c = 220$ km/s. Binney & Tremaine, Galactic Dynamics (2008), Ch. 4; M. Lisanti, arXiv:1603.03797; MIT 8.902 lecture notes (2023)

LMC: Motivation and Tests

Motivation

- The heaviest satellite: 10–20% of the Milky Way
- It passed close to us very recently; the halo is not in equilibrium
- Its effect on the halo is observed (wake, reflex motion)
- In simulations, the fastest DM near the Sun comes from the LMC

Present knowledge

- Speed: known from the measured LMC orbit
- Density near the Sun: not measured; from simulations only, uncertain by large factors
- Treated as a systematic on the speed tail

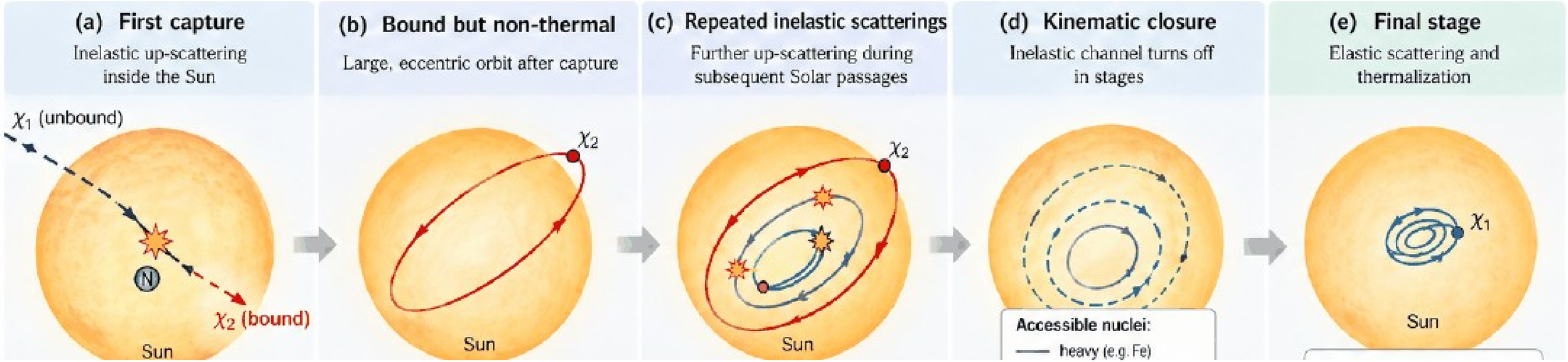
Tests

- Astronomy: LMC mass from stellar streams; response of the halo (Gaia)
- Simulations: many Milky-Way + LMC systems
- Direct detection with more events: dates, end point of the spectrum, a heavier target

- For the thermal Higgsino the LMC does not help much: more sideband events are expected, and δ ($\lesssim 514$ keV) stays below the solar bound of 566 keV

Besla et al., JCAP 11 (2019) 013; Smith-Orlik et al., JCAP 10 (2023) 070; Erkal et al., MNRAS 487, 2685 (2019); Shipp et al., ApJ 923, 149 (2021); Conroy et al., Nature 592, 534 (2021); C. O'Hare, arXiv:2609.21444; Rodd et al., arXiv:2609.04175; Ghosh et al., arXiv:2609.15321

Solar Capture and the IceCube Bound



Di Mauro & Shaikh, arXiv:2609.06760

Capture and annihilation

- The Sun speeds DM up to ≈ 1400 km/s, so even slow halo DM scatters $\chi_1 \to \chi_2$ on Fe, Ni
- Capture rate from the LZ rate: $C \approx 10^{23}$ s^{-1}; captured DM annihilates into high-energy ν
- IceCube sees no excess, ≈ 3000× below the prediction; the thermal Higgsino needs **$\delta > 566$ keV**
- Capture uses slow DM, so the uncertain speed tail hardly matters

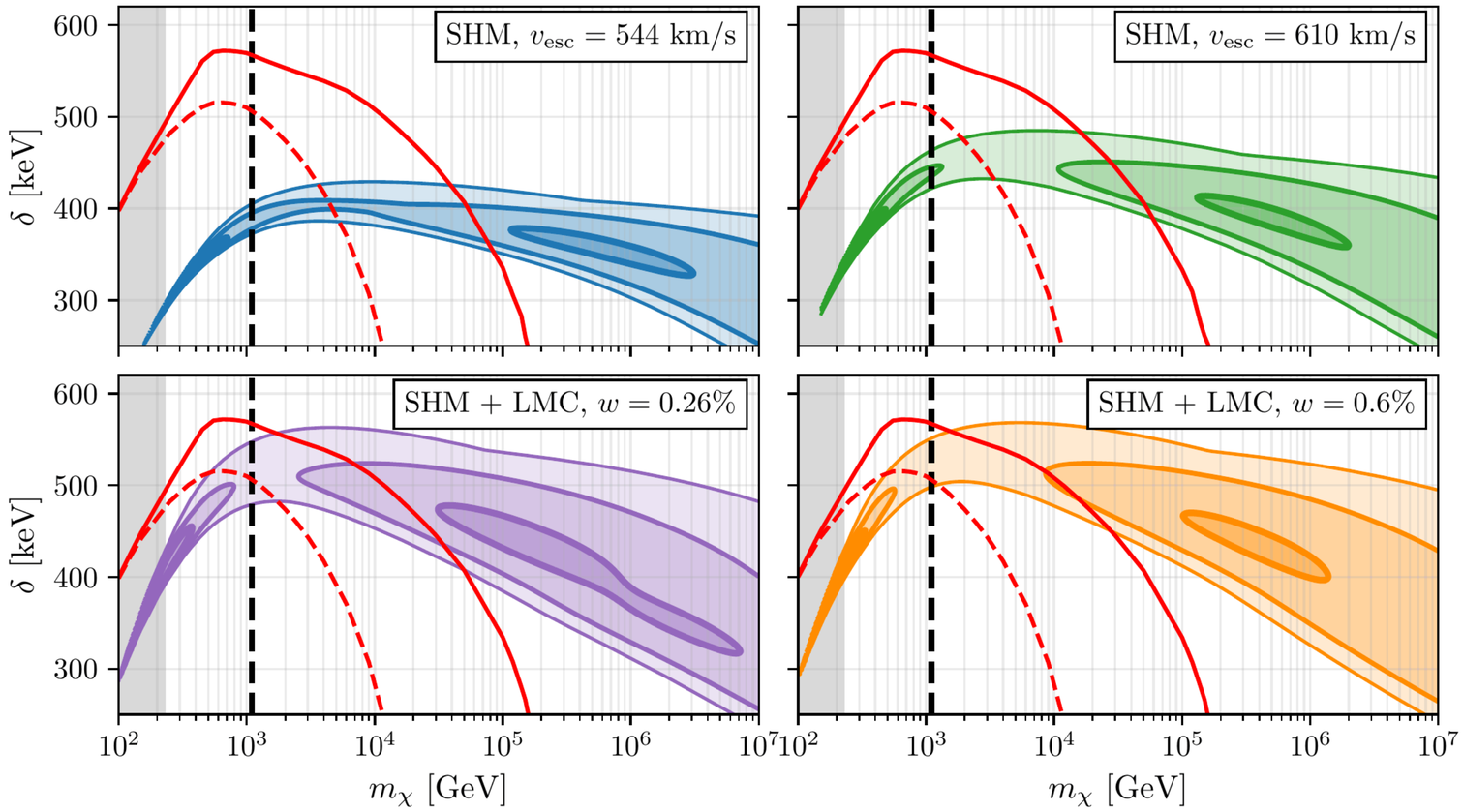
Sinking of captured DM

after capture	IceCube bound
inelastic only: the orbit shrinks only to ≈ 0.2 $R_\odot$	$\delta > 506$ keV
+ elastic scattering (loops): sinks to the core	$\delta > 566$ keV
LZ event	$\delta \approx 350$–380 keV

- Sinking raises the density and the annihilation rate; both bounds are far above the LZ value

Pospelov & Ramani, arXiv:2609.02775; Freese & Theodosopoulos, arXiv:2610.03692; IceCube, arXiv:2507.08457 (10 yr; annihilation rate < 1.5×10^{19} s^{-1} from Pospelov & Ramani)

Lighter and Much Heavier (Non-Thermal) Higgsinos



K. Langhoff, arXiv:2609.09385

colour: fit to the LZ event + empty sideband (4 halo models)
red: lower bound on δ from the Sun (solid, dashed: two treatments of sinking)
dashed line: 1.1 TeV (thermal); grey: LHC

Much heavier Higgsino

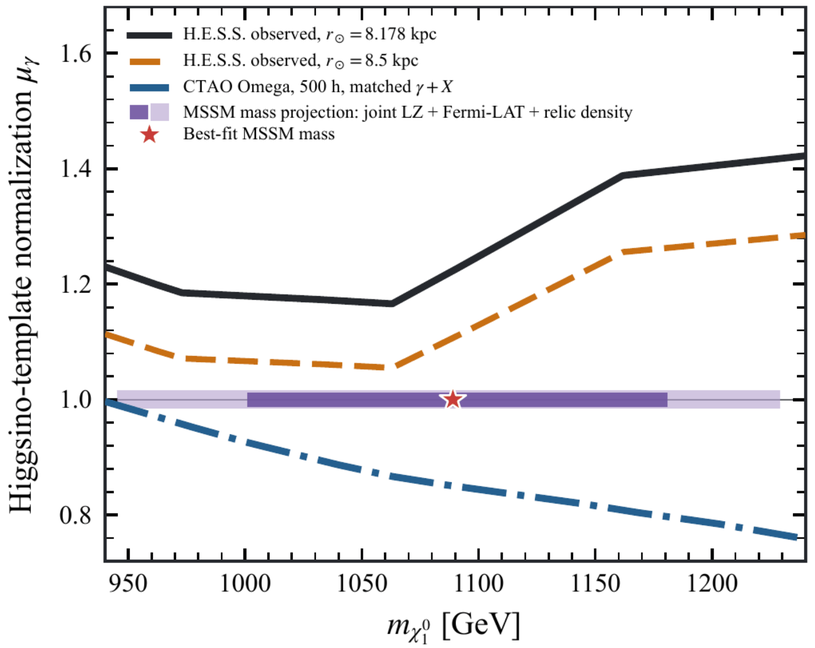
- IceCube: solar capture ∝ 1/m², so few are captured and the bound is avoided
- Sideband: the kinematic limit is higher here (≈ 430–460 keV, standard halo), well above the fitted δ → broad spectrum, similar numbers in window and sideband
- Only a much heavier Higgsino (δ ≈ 330–480 keV) fits all three; not a thermal relic, so non-thermal production is needed

	mass	sideband / window	the Sun
lighter	0.24–0.45 TeV	≈ 0.1–0.2 OK	**excluded**
thermal	1.1 TeV	≳ 5 **too many**	**excluded**
much heavier	10^5–10^6 GeV	≈ 0.8–1 OK	allowed (capture ∝ 1/m²)

The mass above which the Sun allows it differs between analyses: ≳ 10 TeV (Freese & Theodosopoulos; Luengas et al.) to ≈ 10^5 GeV (Langhoff); IceCube limits above 10 TeV are extrapolated

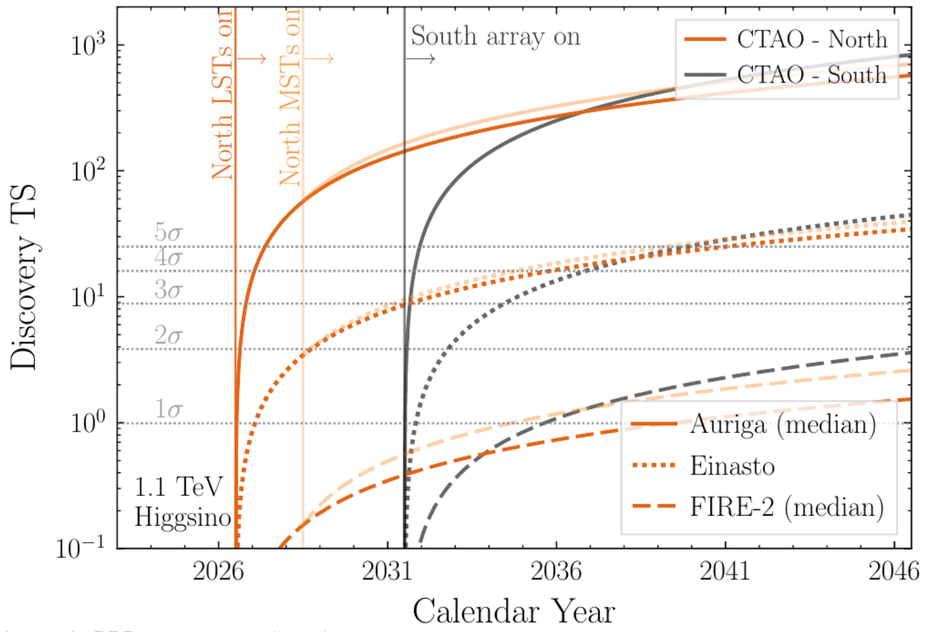
γ-Ray Line Search for the Thermal Higgsino

H.E.S.S. limit (1 = thermal prediction)



Wu, Zhang & Zhu, arXiv:2609.01590

CTAO forecast: discovery TS vs year (100 h/yr)



Abe et al., PRD 114, 023052 (2026)

- Signal: a line at $E_\gamma = m_\chi$, which gives the mass (independent of δ)

Status

- H.E.S.S. (546 h): no line
- Fermi-LAT (14 yr): ≈ 2σ GeV-continuum hint for a ≈ 1 TeV mass
- LST-1 (≈ 40 h): no line

Planned

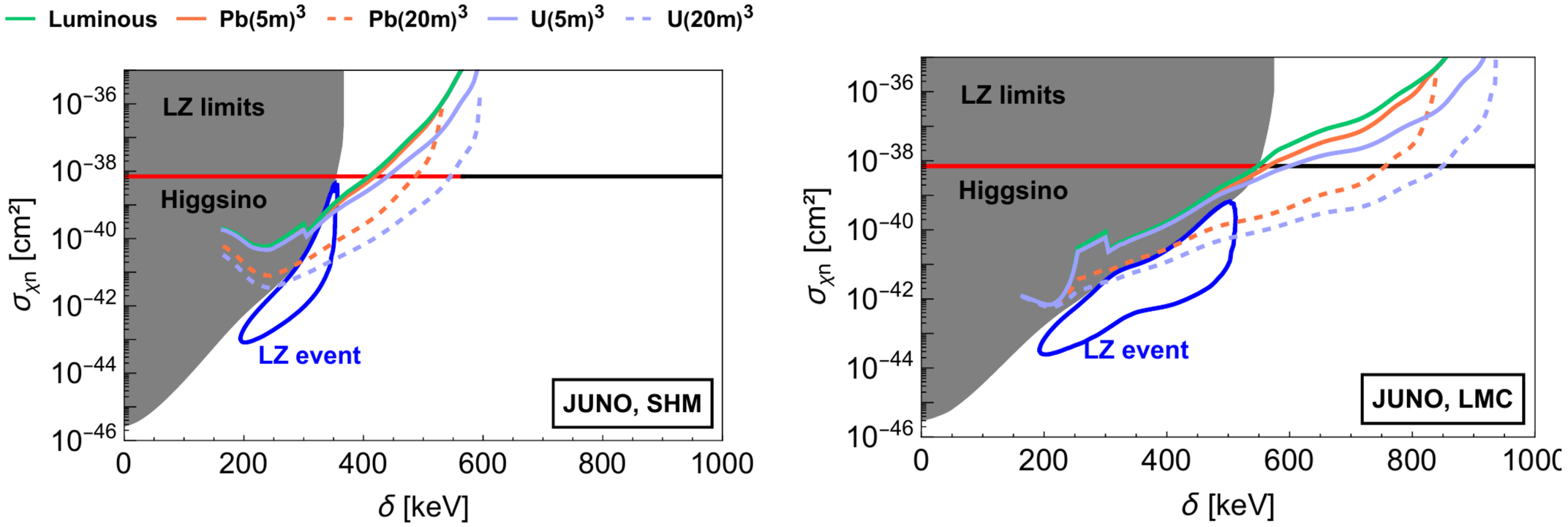
- CTAO-North: 4 LSTs (2026), + 9 MSTs (≈ 2028)
- CTAO-South (Alpha): ≈ 2031

DM profile at the Galactic Center	H.E.S.S. limit today	CTAO reach for the 1.1 TeV thermal Higgsino
Auriga (hydro simulations): much DM	2.9× stronger than for Einasto	already excluded by H.E.S.S.
Einasto (DM-only)	≈ 1.1–1.2 × thermal	North: 3σ ≈ 2031, 5σ ≈ 2040
cored (cNFW); FIRE-2 median of Abe+: little DM	cNFW: 5.8× weaker than for Einasto	FIRE-2 median: < 2σ even in 2046

- J-factors (∫ρ² along the line of sight) of simulated halos differ by > 100×, so the reach depends on the DM profile; for cored profiles no planned instrument reaches 3σ by ≈ 2050

Years read from Abe et al. (Fig. 1): each array alone, ideal BG model; a realistic analysis reaches ≈ 80% of this (Rodd et al., arXiv:2405.13104). J-factors: Abe et al. (Fig. 4). H.E.S.S., arXiv:2608.07234; Dessert et al., PRL 130, 201001 (2023); S. Abe (LST), TeVPA 2026; Safdi & Xu, arXiv:2507.15934

JUNO Search for Photons from Excited DM

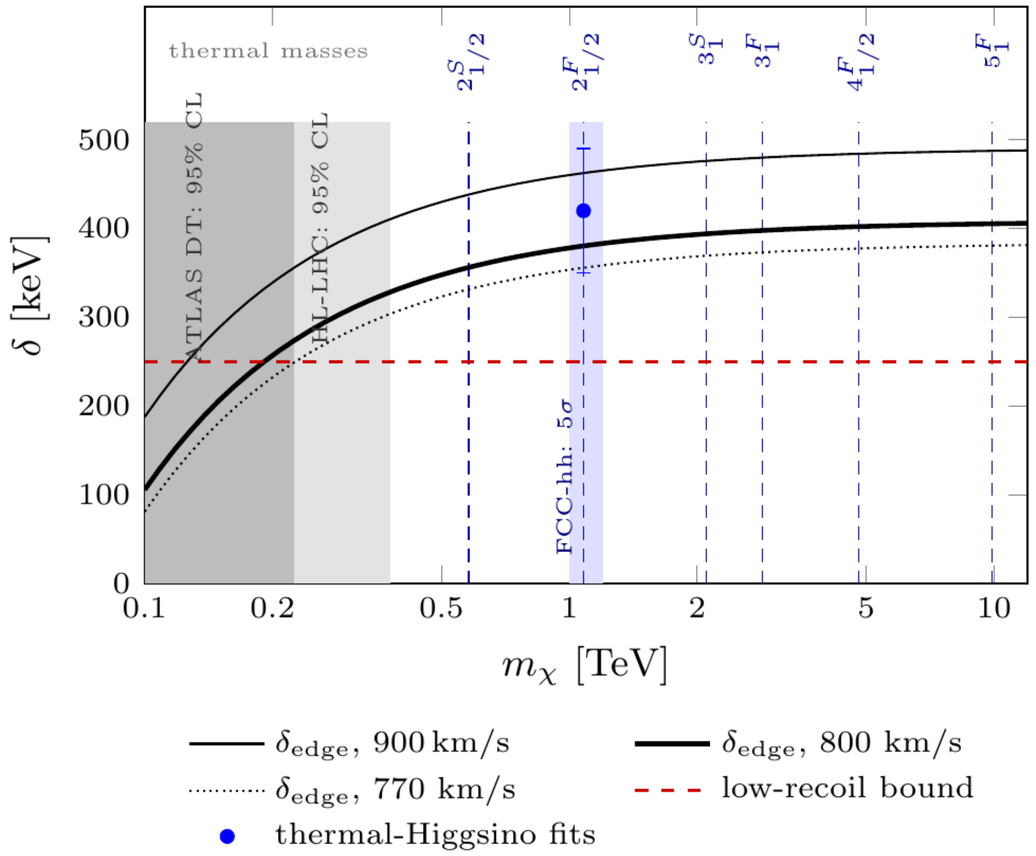


Graham et al., arXiv:2610.21041

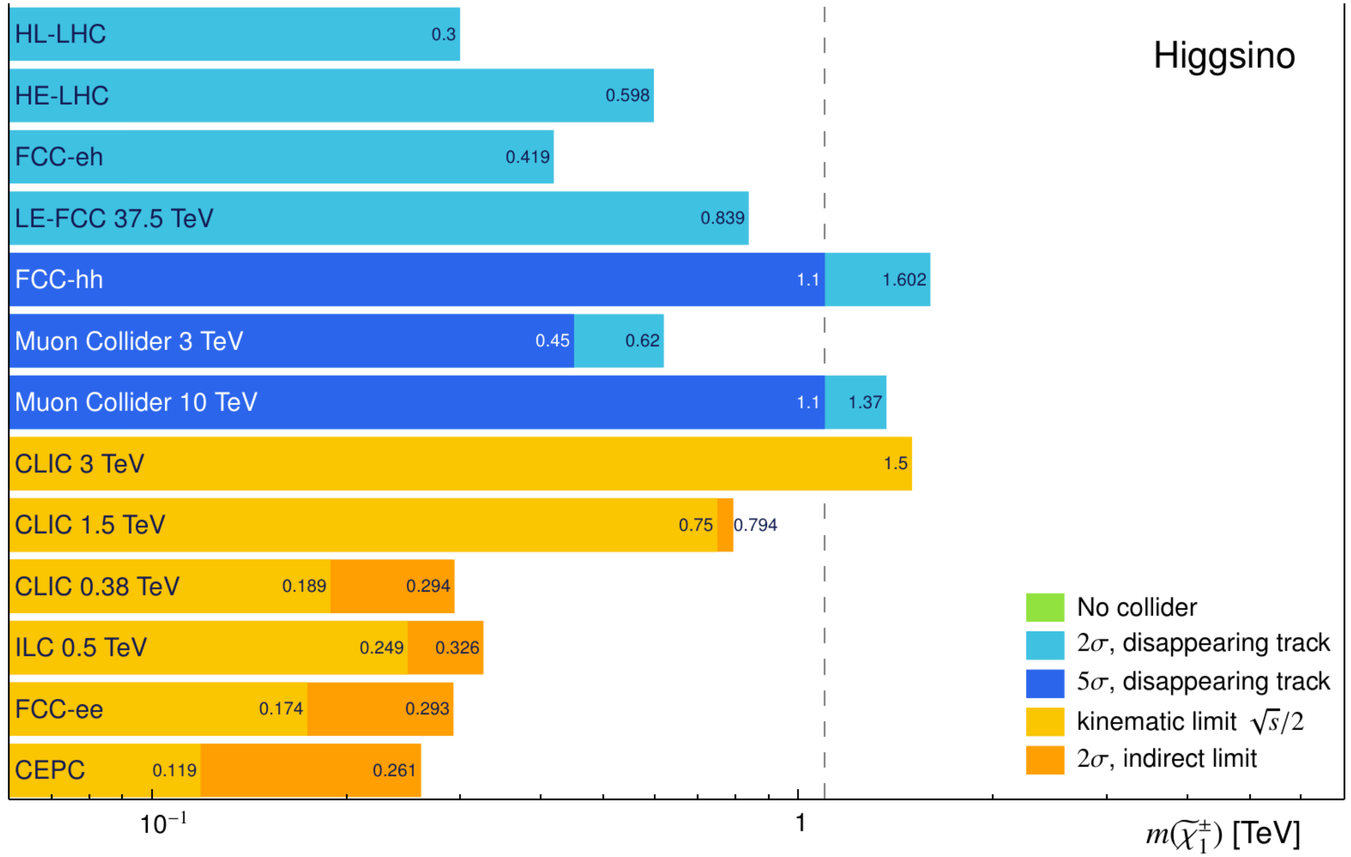
left: standard halo; right: with the LMC. blue: LZ event; grey: excluded; black: Higgsino (Z exchange), red part excluded by the Sun; green: JUNO, rock only; other lines: with a Pb or U block

- DM up-scatters in the rock near JUNO ($\chi_1 \rightarrow \chi_2$), and χ_2 decays inside the detector: $\chi_2 \rightarrow \chi_1\gamma$ with $E_\gamma = \delta$ (decay length ≈ 7.5 km at δ = 400 keV and v = 400 km/s)
- JUNO (running since Aug. 2025) covers part of the LZ region in ≈ 10 years (standard halo); Pb or U around the detector would extend the reach
- Different target and different signal (a γ line at δ), independent of xenon

Collider Searches for the Higgsino



Maier & Spannowsky, arXiv:2609.26870



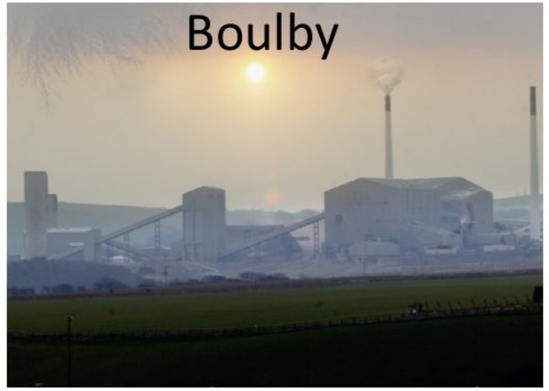
Capdevilla et al., arXiv:2102.11292 (CLIC 3 TeV bar: kinematic limit $\sqrt{s}/2$)

- The charged Higgsino is only ≈ 340 MeV heavier ($c\tau \approx 7$ mm), giving disappearing tracks
- LHC today: $m_\chi^\pm > 225$ GeV (ATLAS); HL-LHC reach ≈ 250–380 GeV (95% CL)
- 1.1 TeV (thermal): FCC-hh ($5\sigma \approx 1.0$–1.2 TeV) or a 10 TeV muon collider (5σ with ≈ 8 ab^{-1}; mono-W ≈ 1.3–1.5 TeV at 95% CL)

Other Interpretations

family	how it gives one event at 248 keV with nothing below	status / what tests it
endothermic two-state DM	threshold; recoils in a band around E* ≈ 0.9 δ (1.1 TeV), reshaped by the form factor; June modulation; thermal Higgsino: only δ free	sideband, halo tail, the Sun (this talk); heavy Higgsino in SUSY GUT: proton decay $p \to K^+\bar{\nu}$ may be within the Hyper-K reach
exothermic two-state DM	χ_2 releases $\lvert\delta\rvert$; no threshold	$\lvert\delta\rvert < 2m_e$, dark photon; argon can test it
momentum-dependent elastic (q^2, q^4)	dipole-type contact operators, pseudoscalar exchange harden the spectrum	LHC monojet limits exist; they depend on the operator (EFT validity assumed)
boosted DM	fast component from annihilation or decay of heavier DM; endothermic versions can peak at 248 keV	needs a flux 10^3–10^4 × canonical; continuum versions put most events below ≈ 200 keV
BGs	neutron, atmospheric ν, ER tail, detector effect	LZ: none found to be likely; ^{3}H/^{14}C calibration stops at S1 = 500 phd (event at 540)

XLZD: Sites and Funding









Key requirements:

Depth for cosmogenic backgrounds

Space for construction

Possibility of transporting large items underground

Site reviews ongoing

Site	Depth (m)	Depth (m w.e.)	μ flux (/(m^2 d))	^{137}Xe rate (/(t year))	SS ROI rate (evt/(t year keV))
SNOLAB	2070	5890	<0.3	0.007	1.29×10^{-6}
SURF	1490	4300	4.6	0.142	2.72×10^{-5}
Boulby	1300	3330	14.6	0.404	7.73×10^{-5}
LNGS	1400	3800	29.7	0.822	1.57×10^{-4}
Kamioka	1000	2700	128	3.54	6.78×10^{-4}

Sites: A. Softley-Brown, IDM 2026. Funding: STFC PPD news (2024); SNOLAB, CAP 2026; R. Gaitskell, IDM 2026

- UK: £8M preliminary award from the UKRI Infrastructure Fund for design work (Sept. 2024); Canada: CFI $1.2M to SNOLAB to advance the XLZD design (Mar. 2026); US: DOE deferred third-generation DM construction until the early 2030s (Dec. 2025)
- Site evaluation to complete "in the coming months" (June 2026); Conceptual Design Report planned for early 2027