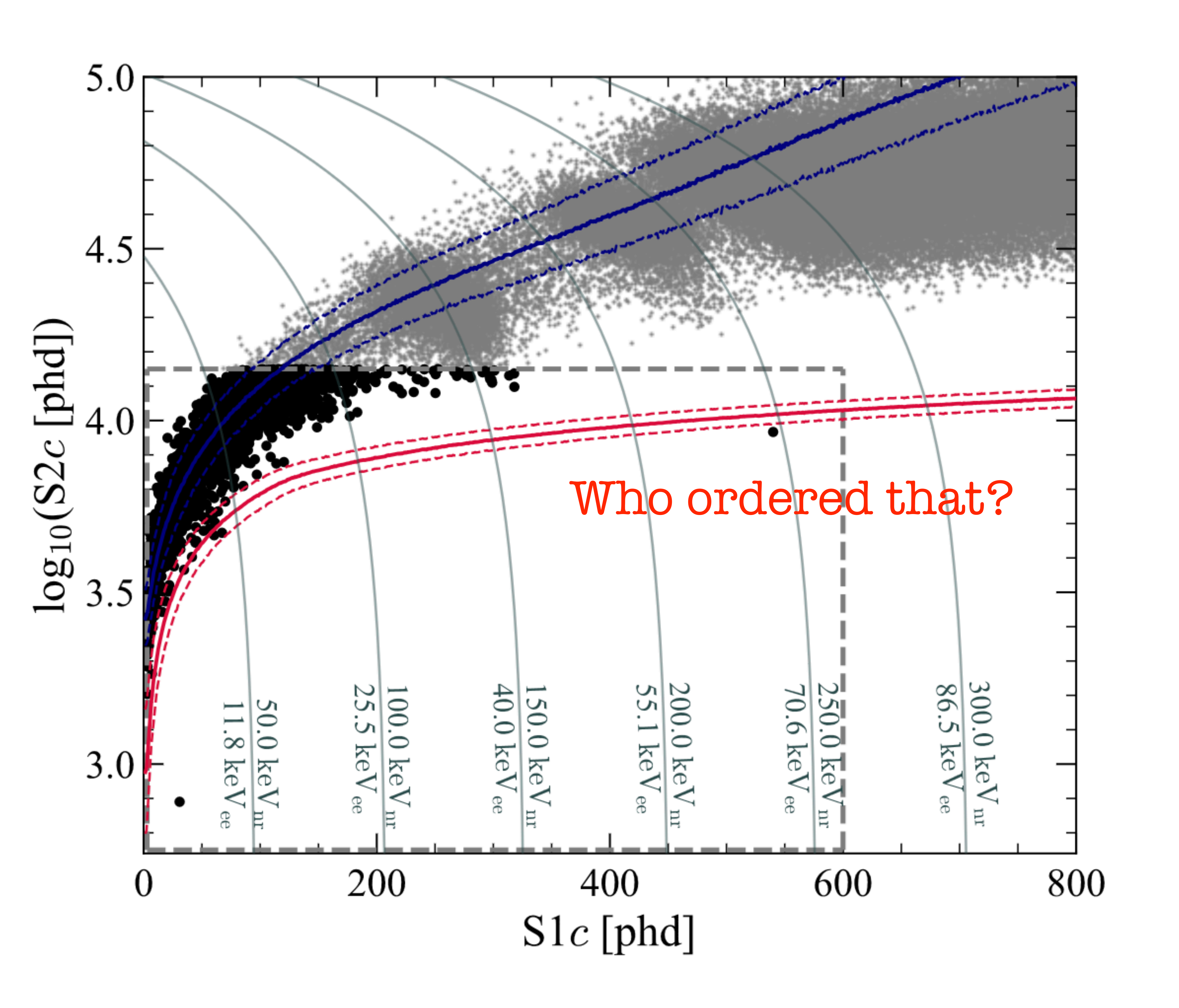
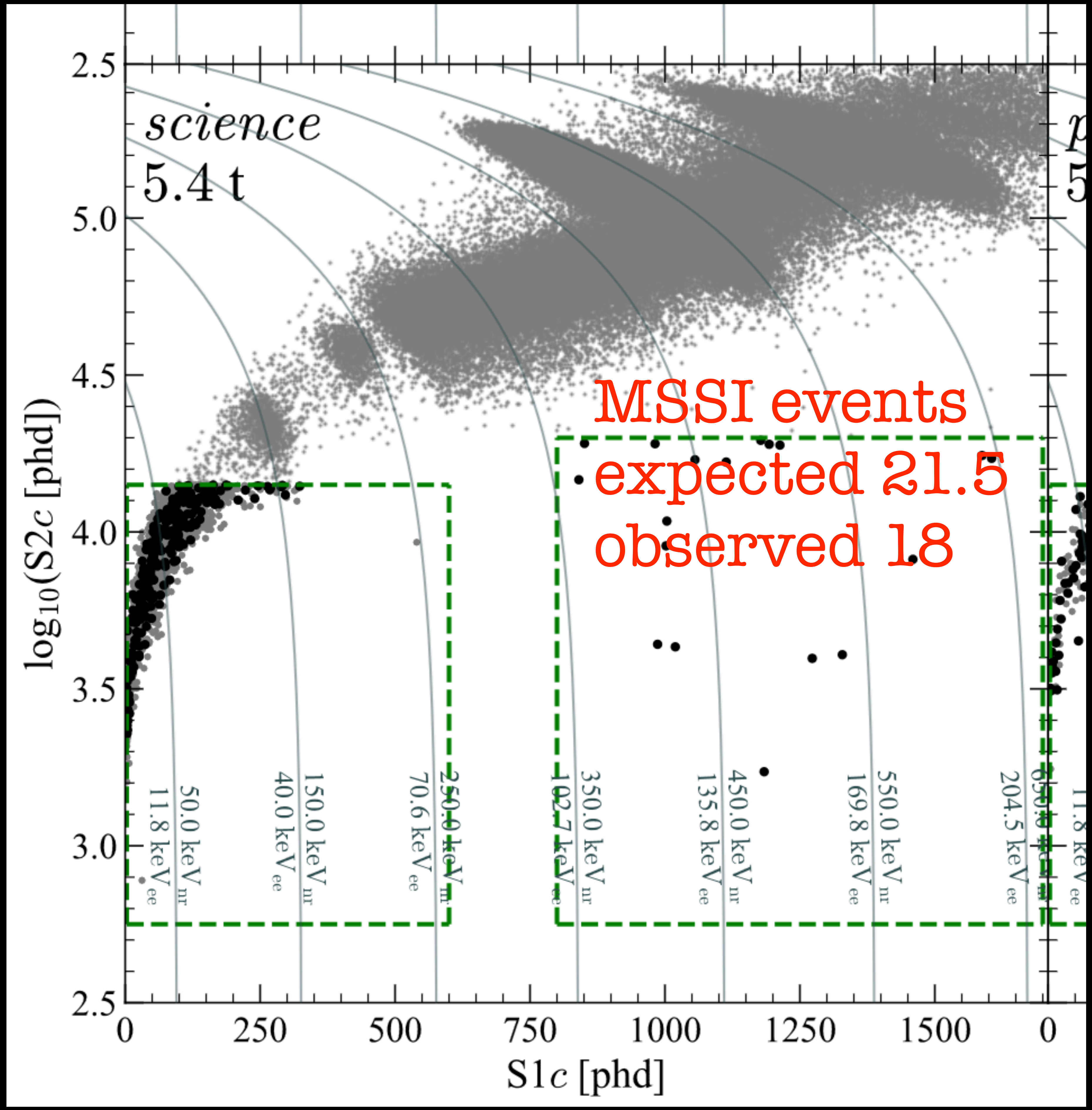
LZ

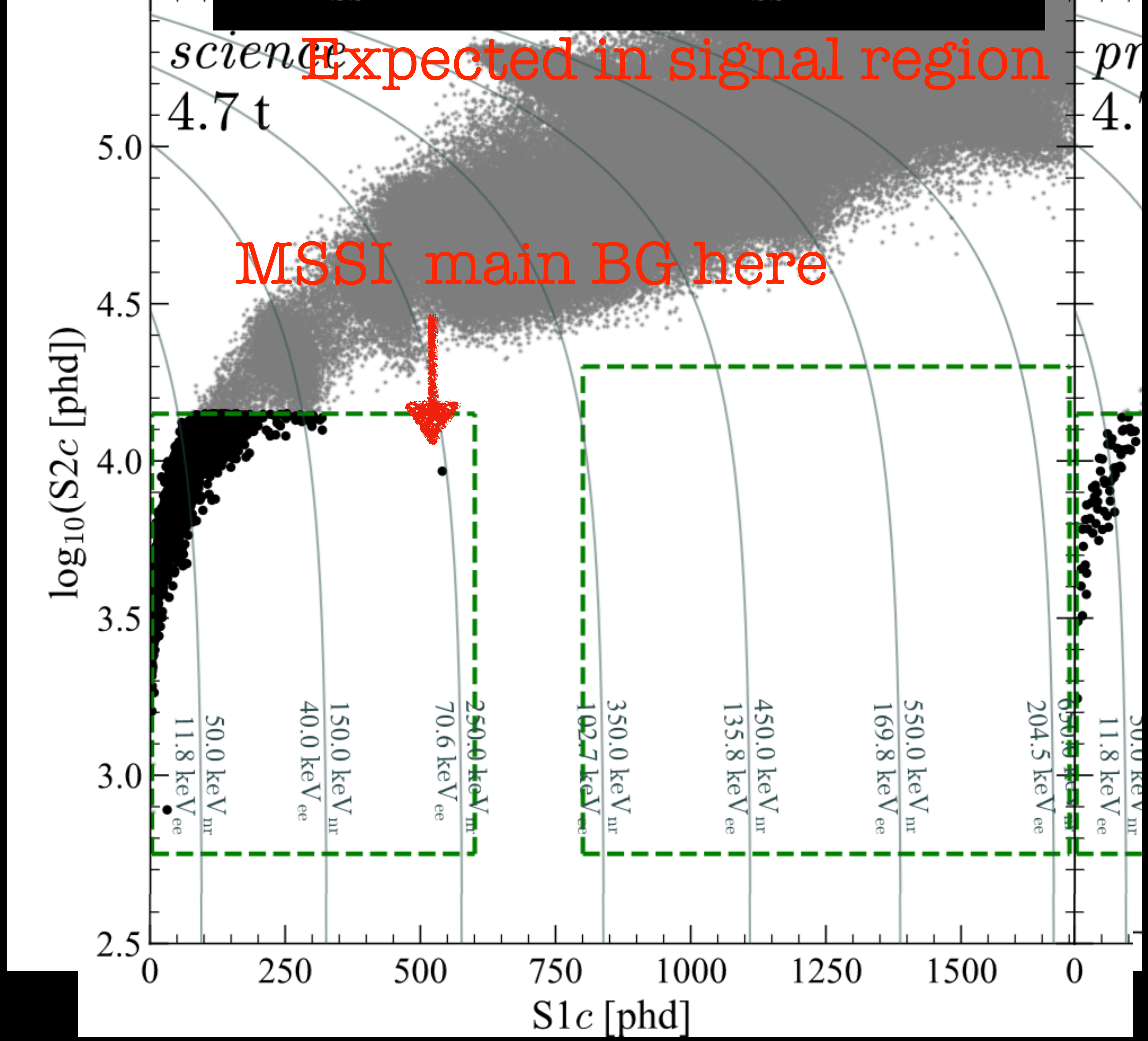
Signal Region



High energy sideband validates MSSI BG



$$N^{\rm wall}_{\rm MSSI} \simeq 0.0048, \qquad N^{\rm RFR}_{\rm MSSI} \simeq 0.0001.$$



The positions of the events

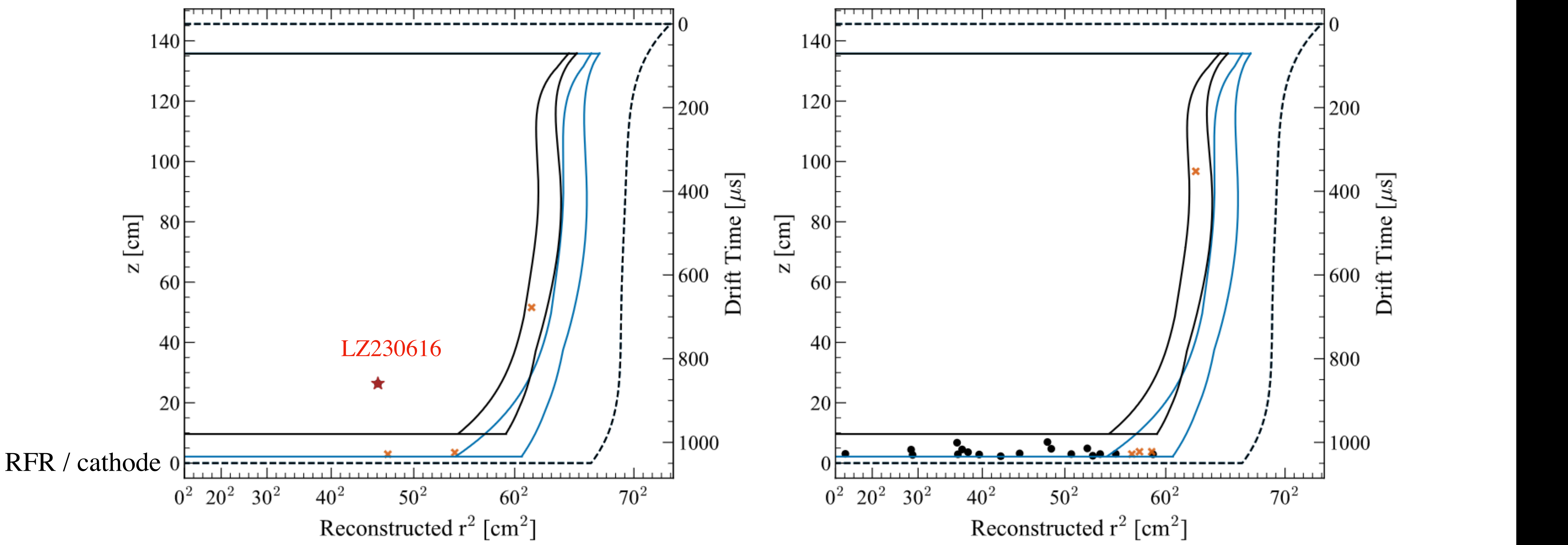
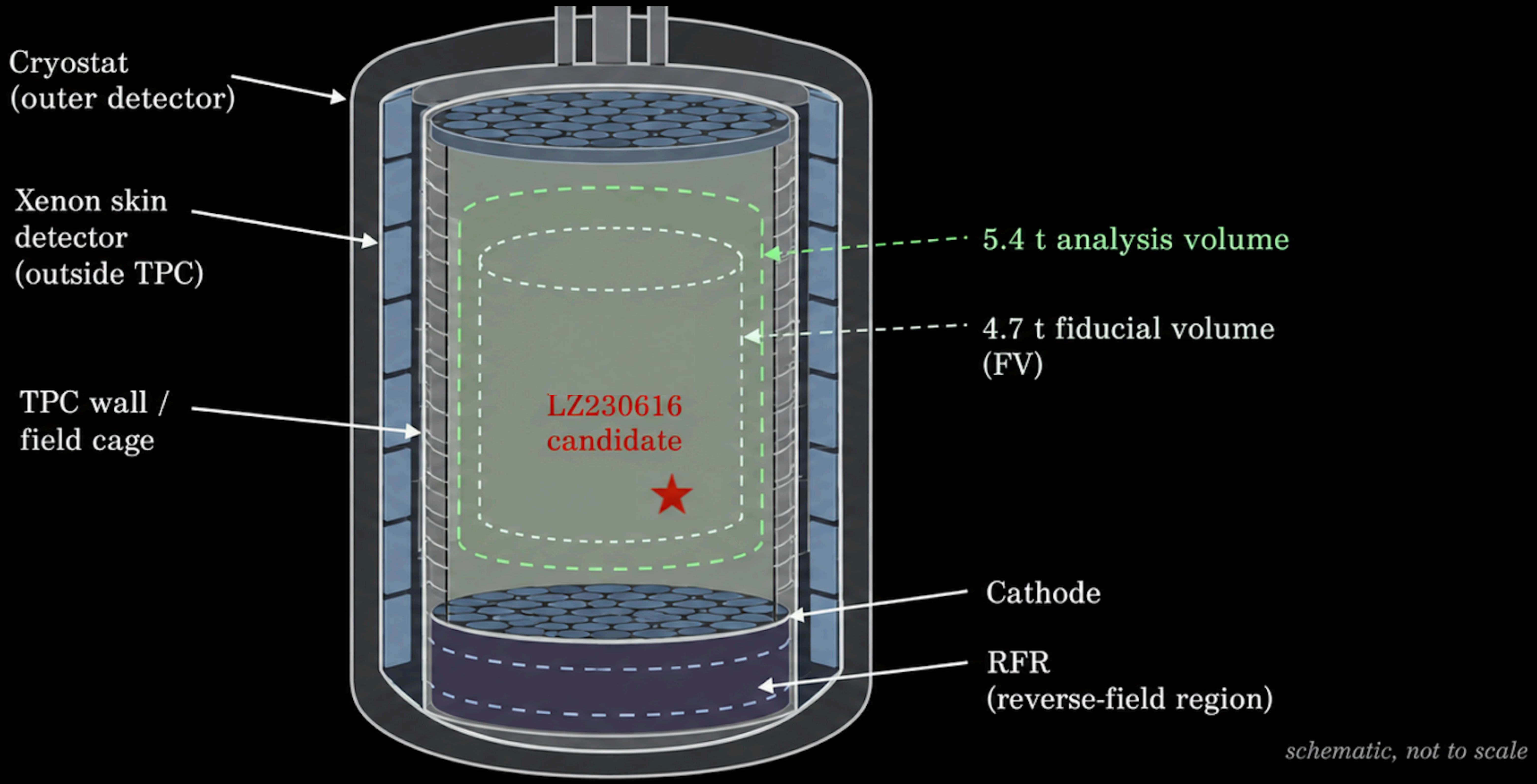


FIG. S5. Reconstructed $r^2 - z$ projections for the two analysis regions: WS ROI of the main analysis (left) and the high energy sideband (HE SB) used to validate the MSSI model (right). The *science* and *prompt veto* samples are denoted by black circles or orange crosses, respectively. In the WS ROI, the events shown are 5σ or greater from the ER band, with the event of interest shown as the brown star. The dashed line indicates the reconstructed wall, averaged over azimuth, indicating the active volume. The solid lines indicate the minimum and maximum radial extent of the 4.7 t (black) and 5.4 t (blue) analysis volumes.

The positions of the events

+ One isolated NR-like event at very high recoil: ER =248±23stat ±23sys keV
+ Ordinary elastic SI scattering struggles spectrally
+ The event is geometrically clean
+ Multiple scintillation single ionisation (MSSI) is possible in principle, but requires an unusual topology
+ One event local significance 3.4 σ, global 2.6σ



Candidate reconstructs well inside the 4.7 t FV; wall/RFR MSSI is disfavored, not excluded.

Interpretation classes from over 50 papers

Mechanism	Why 248 keV?	Representative ideas / arXiv	Smoking-gun issue
Endothermic DM $\chi_1 N \to \chi_2 N$, $\delta > 0$	Threshold removes low-E_R events; kinematics piles the spectrum near an endpoint	Higgsino / pseudo-Dirac / EW multiplets / dark photon-vector 2609.01583, 2609.01475 2609.04144, 2609.02868	High-v tail; annual modulation; solar capture; target dependence
Exothermic DM $\chi_2 N \to \chi_1 N$, $\delta < 0$	Internal-state energy supplies the recoil; no high-speed threshold	Down-scattering pseudo-Dirac / dark-photon models 2609.05204, 2609.06153	Survival of excited state; weaker halo dependence; Xe/Ar/Ge comparison
Elastic, hard nuclear response	q- or spin-dependent matrix element suppresses the usual low-E_R spectrum	Pseudoscalar / axion portal; elastic SD / momentum-dependent operators 2609.04186, 2609.02608	Strong target / isotope dependence; no threshold-like seasonal signature
Nonstandard incoming flux	Projectile is much faster than ordinary halo DM	Cosmic-ray / dark-sector boosted DM; atmospheric-ν up-scattering 2609.11600, 2609.06890, 2609.04185	Direction / time / flux correlations; accompanying high-energy population
Absorption / conversion	DM rest energy is converted directly into nuclear recoil energy	Fermionic DM absorption 2609.01592	Sharp mass–energy relation; strong constraints from other detector materials
Neutron disappearance $n \to$ inv. or $\chi n \to$ inv.	Bound-neutron Fermi momentum becomes daughter recoil: $p_F \sim 250$ MeV $\Rightarrow$ $E_R \sim 250$ keV	Aghaie–Strumia: spontaneous or DM-induced disappearance 2609.09037	De-excitation / isomers; "quiet" fraction; isotope + target scaling

SD interaction: Elahi & Pedro Schwaller, 2609.08993

E6 UV:Kotlarski, Kamila Kowalska & Enrico Sessolo, 2609.06750

EW interaction: Juri Smirnov & Griffith, Beacom, 2609.04144

Predictive Electroweak Benchmarks

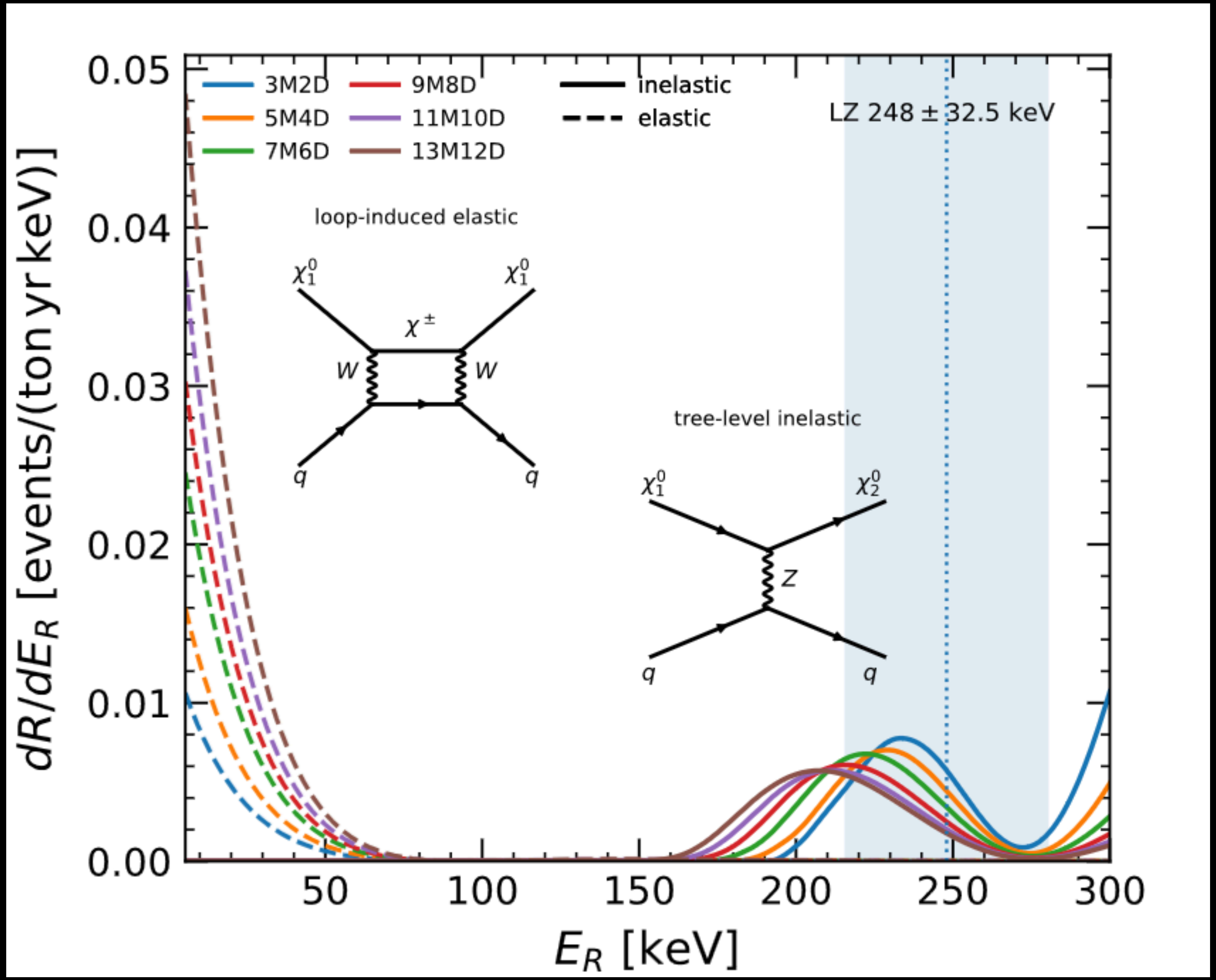


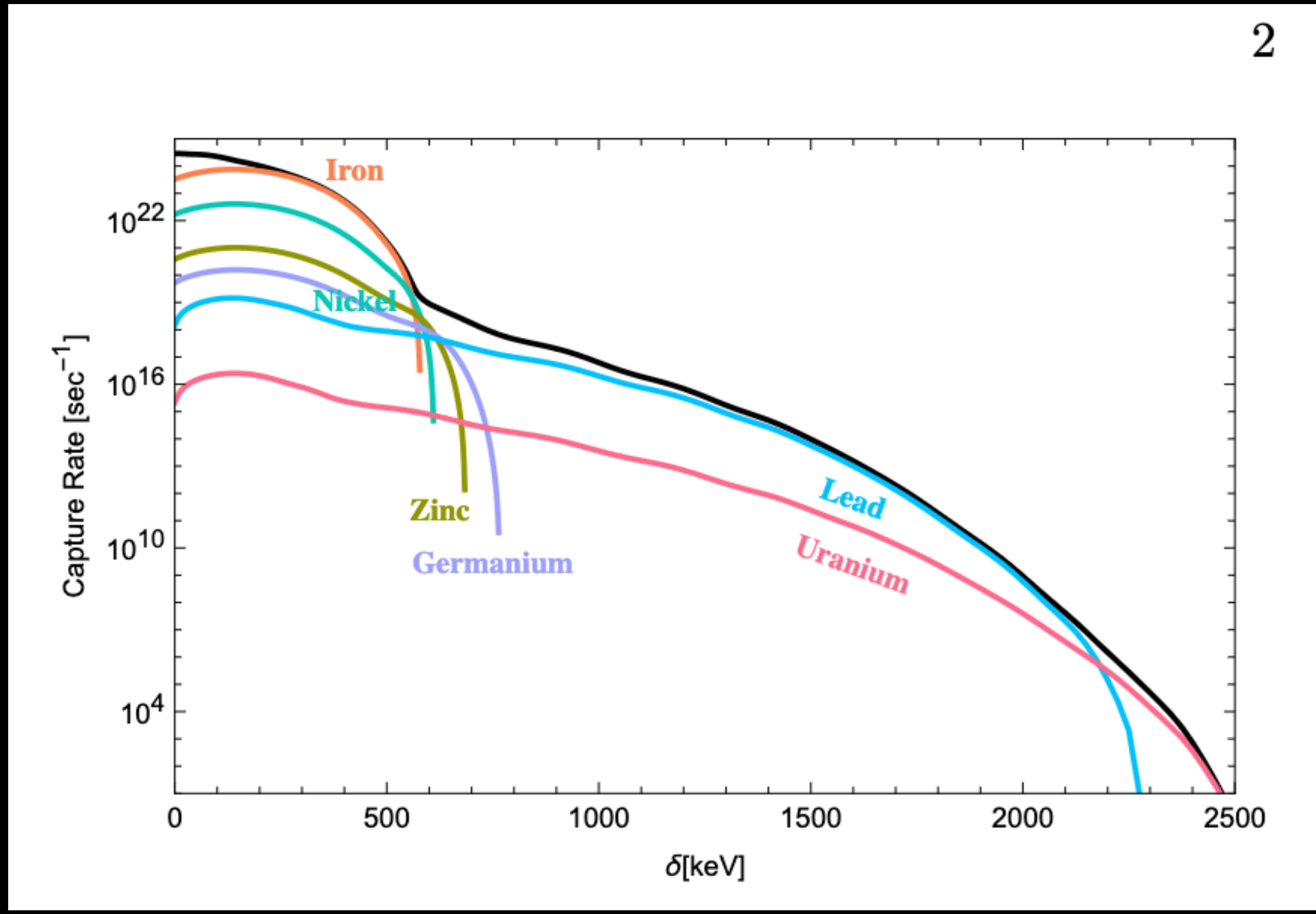
TABLE I. Benchmark points selected by the intersections of the relic trajectories with the LZ rate-matched band. The final column gives the corresponding expected elastic yield.

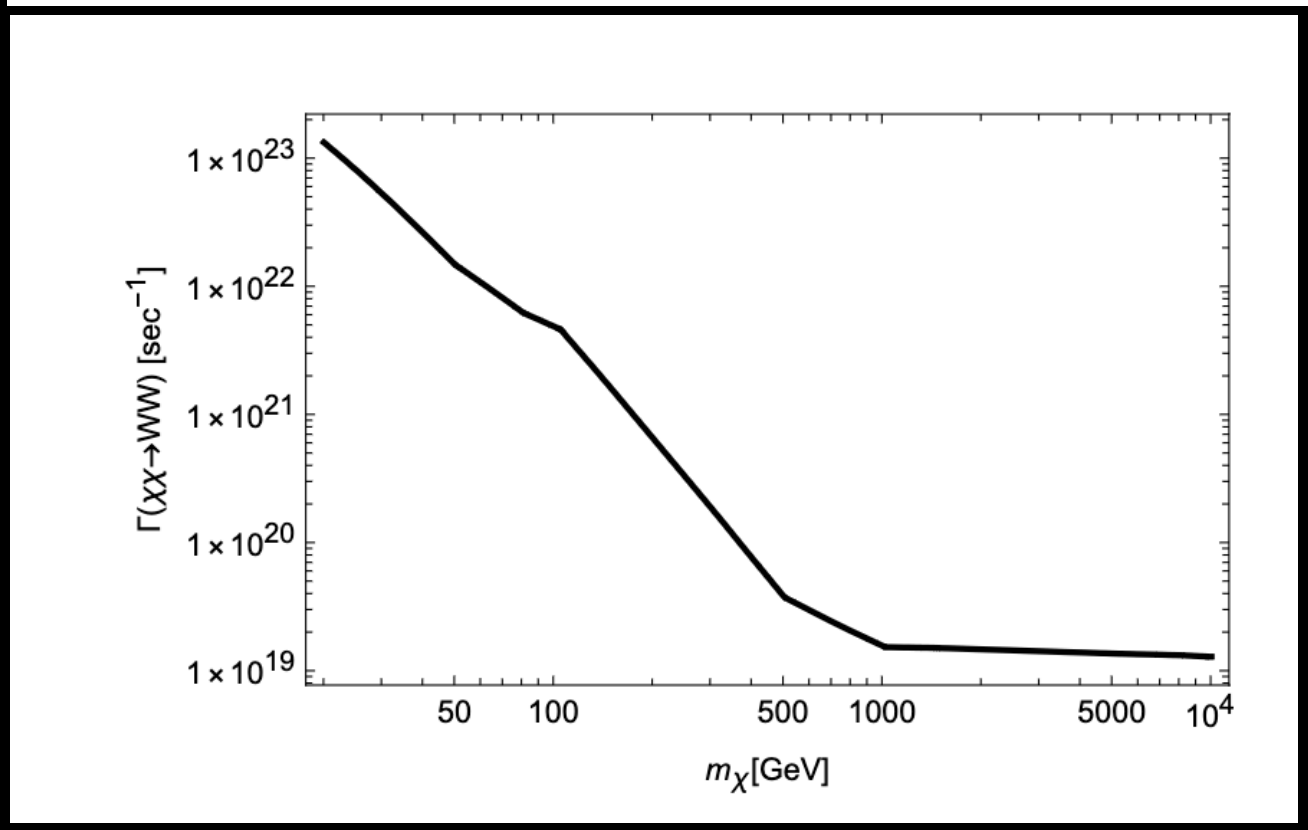
Model	$y_\star$	$m_{\chi,\star}$ [TeV]	$\delta_\star$ [keV]	$\sigma_{\rm SI}^{\rm loop}$ [cm^2]	$N_{\rm el}$
3_M2_D	6.0×10^{-3}	1.4	378	1.3×10^{-47}	0.5
5_M4_D	1.4×10^{-2}	7.7	386	1.1×10^{-46}	0.8
7_M6_D	2.4×10^{-2}	22	382	4.5×10^{-46}	1.2
9_M8_D	3.4×10^{-2}	48	377	1.2×10^{-45}	1.5
11_M10_D	4.5×10^{-2}	82	372	2.6×10^{-45}	1.8
13_M12_D	5.6×10^{-2}	130	368	5.0×10^{-45}	2.4

https://arxiv.org/pdf/2609.04144

Electroweak interaction, only representation as free parameter

Solar Constraints





Reps	SHM benchmark δ [keV]	SHM benchmark Γ_{WW} [s^{-1}]	high-v benchmark δ [keV]	high-v benchmark $v_{\min}$ [km s^{-1}]	high-v benchmark Γ_{WW} [s^{-1}]
$3_M 2_D$	378	$\sim 9 \times 10^{21}$	570	1020	$\sim 10^{15}$
$5_M 4_D$	386	$\sim 3 \times 10^{20}$	570	1000	$\sim 5 \times 10^{13}$
$7_M 6_D$	400	$\sim 10^{19}$	–	–	–
$9_M 8_D$	394	$\sim 8 \times 10^{18}$	–	–	–
$11_M 10_D$	392	$\sim 3 \times 10^{18}$	–	–	–
$13_M 12_D$	390	$\sim 10^{18}$	–	–	–

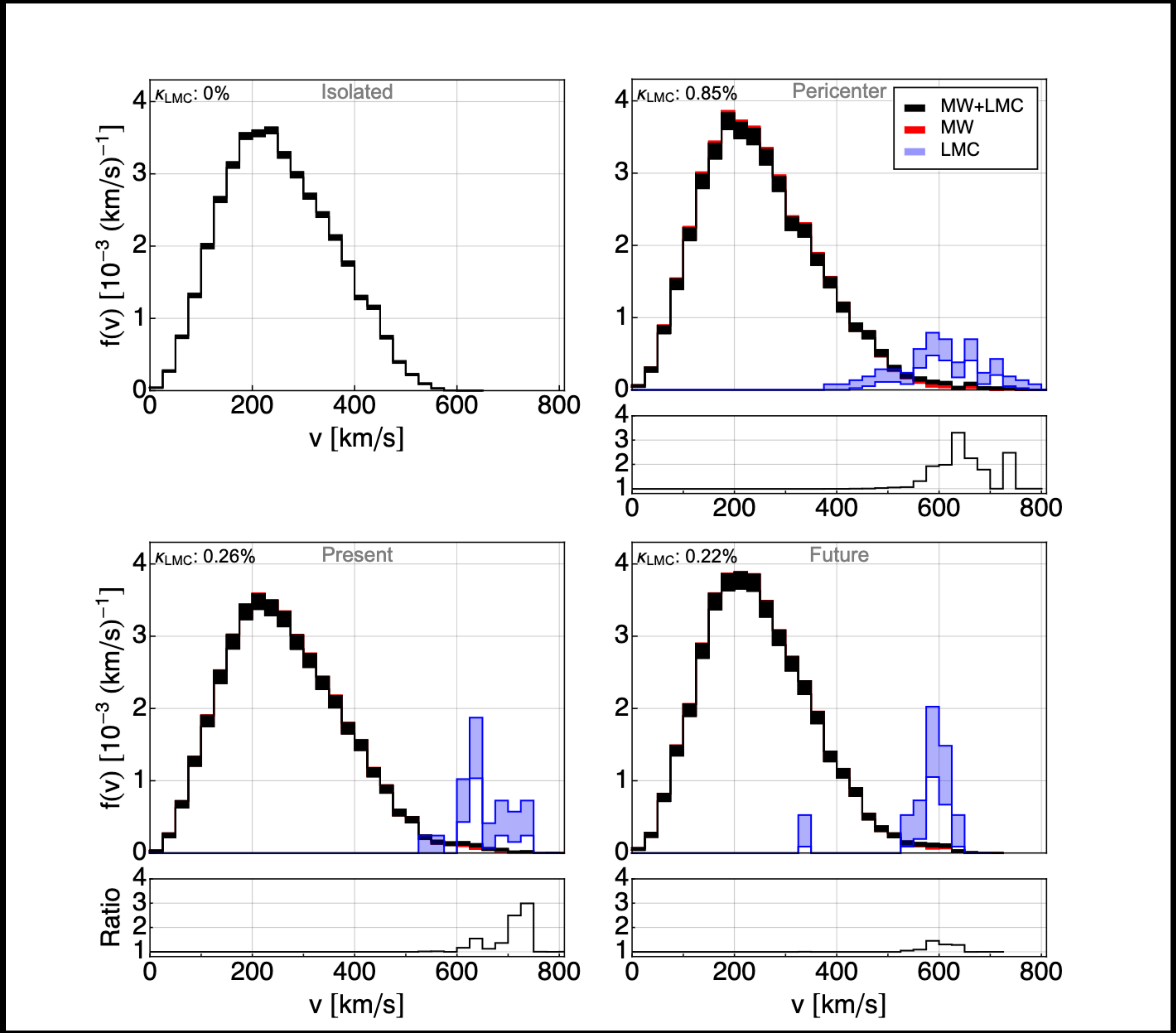
High v and high mass benchmarks are compatible with solar bounds
https://arxiv.org/pdf/2609.04144

$$\eta_s(v_{\min}) \simeq \frac{f_s}{v_s}\Theta(v_s - v_{\min}),$$

$$f_s \sim 10^{-4}\text{–}10^{-3}$$

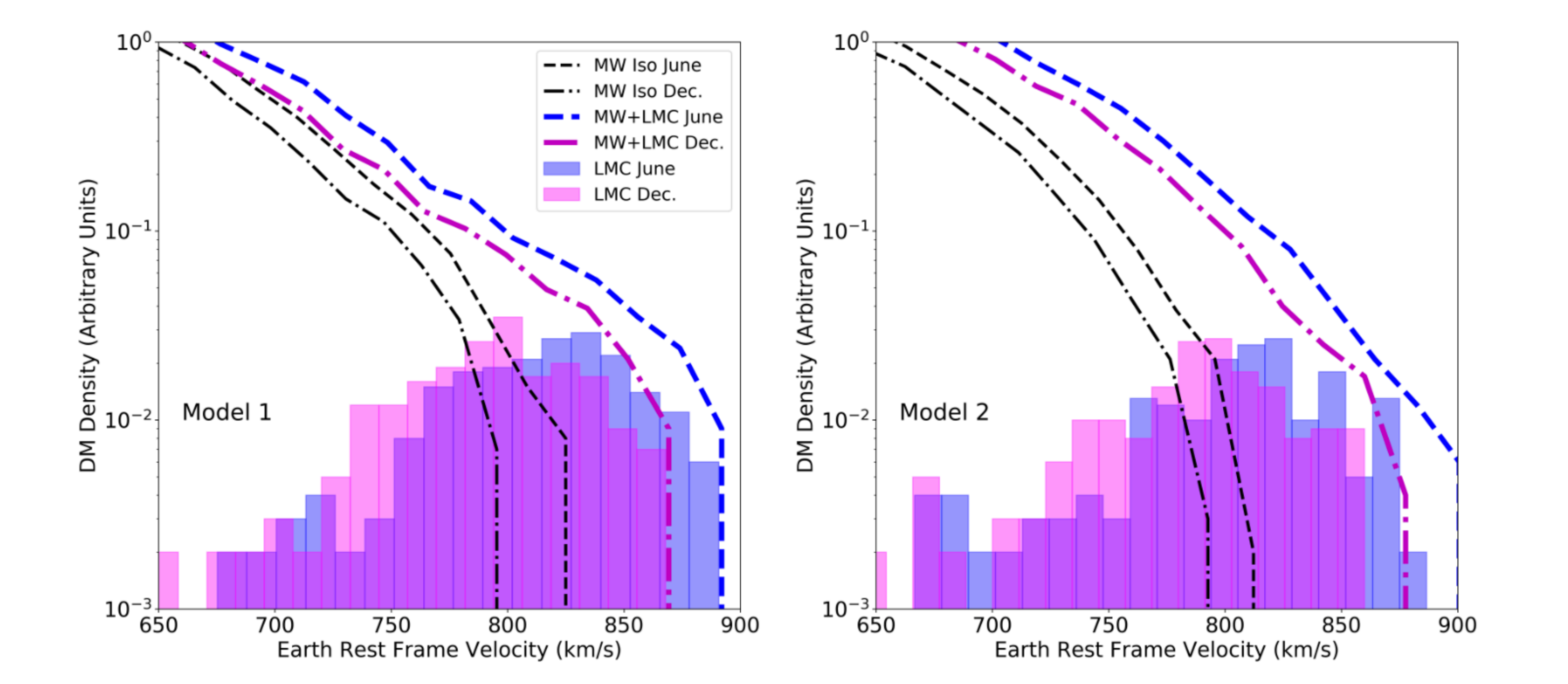
Pospelov's objection
https://arxiv.org/pdf/2609.02775

MW + LMC DM velocity Distribution



https://arxiv.org/pdf/2302.04281

LMC effects and Modulation



https://arxiv.org/pdf/1909.04140

MY FAVORITE LZ EXPLANATION

Pedro Schwaller

based on 2609.08993 with Fatemeh Elahi

LZ fits to DM effective interactions

LZ paper

TABLE S7. Local significance for Lagrangian models tested

L_i	WIMP Mass (GeV/c^2)												
	10	12	14	17	21	30	40	50	100	200	400	1000	4000
L_1^s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
L_1^v	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	1.3	1.2
L_2^s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.4	2.8	2.9	3.0	3.1
L_2^v	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.4	2.5	3.0	3.1	3.1
L_3^s	0.0	0.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.1	1.5	1.7	1.8
L_3^v	0.0	0.0								2.2	2.5	2.6	2.7
L_4^s	0.0	0.0								3.1	3.1	3.1	3.0

… 30 more lines :)

Translation e.g. in Anand, Fitzpatrick, Haxton, 2013

2.7σ for $\mathscr{L}_{15} = \bar{\chi}\gamma_\mu\gamma_5\chi\bar{N}\gamma^\mu\gamma_5 N \rightarrow \mathbf{S}_\chi \cdot \mathbf{S}_N$

Elastic, easy to generate in models

E.g. any Majorana fermion coupled via the Z-boson

Model: Vector-like leptons/Singlet Doublet DM

$$\mathcal{L} \supset -m_\ell \bar{\ell}_L \ell_R - \frac{1}{2} m_0 \bar{\nu}^c \nu - \left(Y_n \bar{\ell}_L \widetilde{H} \nu + Y_n' \bar{\ell}_R \widetilde{H} \nu^c + \text{h.c.} \right)$$

Idea: DM is dominantly singlet ν.

Small mixing into doublet ℓ:

good relic abundance through co-annihilation

DM couplings to SM:

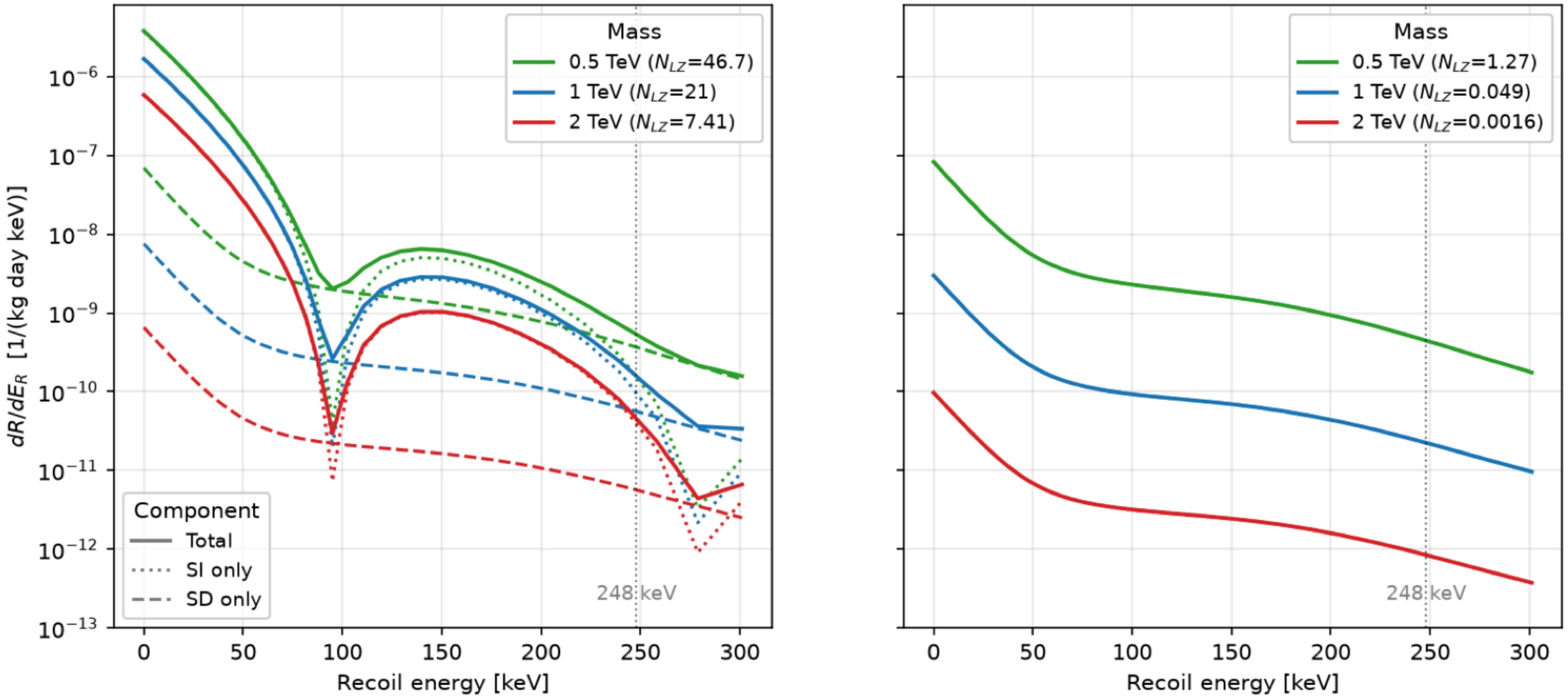
$$\mathcal{L} \supset \frac{g}{4c_W} g_{ZNN} \overline{N}_1 \gamma^\mu \gamma^5 N_1 Z_\mu, \qquad g_{ZNN} = |V_{11}|^2 - |V_{12}|^2. \qquad ✓$$

$$\mathcal{L} \supset \frac{1}{2} g_{hNN} \overline{N}_1 N_1 h, \quad g_{hNN} = V_{13}(Y_n V_{11} - Y_n' V_{12}). \qquad ✗$$

Model vs EFT: Get correlations among operators

Recoil spectra

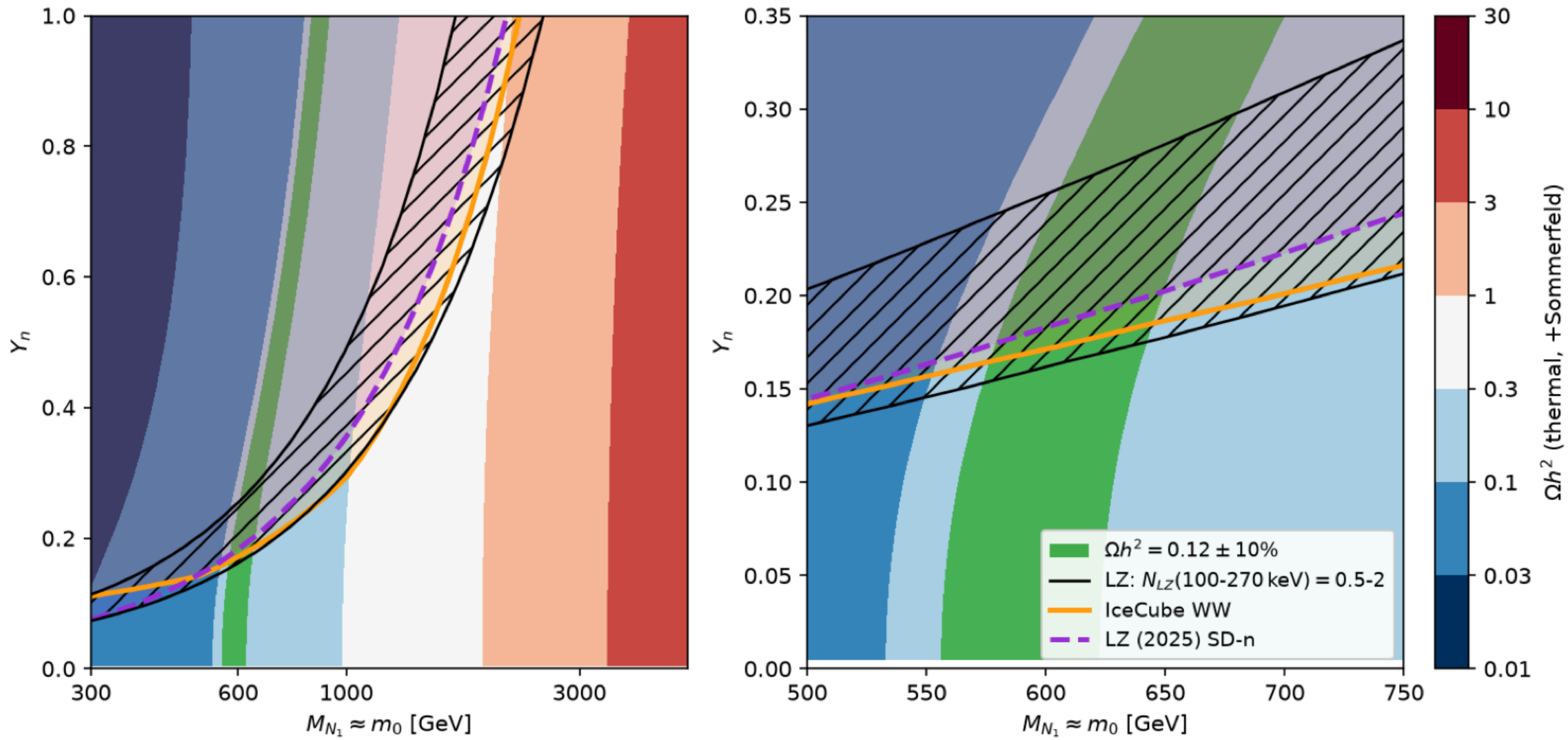
Elahi, PS, 2026



$$\frac{dR}{dE_R} = \frac{\rho_0}{m_\chi}\frac{m_N}{2\mu_{\chi N}^2}\left[\sigma_{SI}^0\, F_{SI}^2(q) + \sigma_{SD}^0\,\frac{S(q)}{S(0)}\right]\eta(v_{min}(E_R))$$

Need to kill the SI contribution, otherwise in tension with zero/few events observed at low recoil -> blind spot!

Parameter space and constraints



Orange: Neutrinos from DM capture in sun (IceCube)

Purple: SD limit from LZ 2025

Green: Good relic abundance :)

Interpretation

+ One event is interesting; a handful would be physics.
+ Elastic companions: simple models often predict them.
+ High-energy sideband: broad spectra predict additional events above 270 keV.
+ Nuclear structure: Helm suppression/diffraction becomes important.
+ Timing: endpoint scattering can have large annual modulation (event in June).
+ Halo structure: the LMC can dominate the relevant high-velocity tail.