

The LZ High-Energy Recoil Candidate: Theoretical Interpretations and Experimental Tests

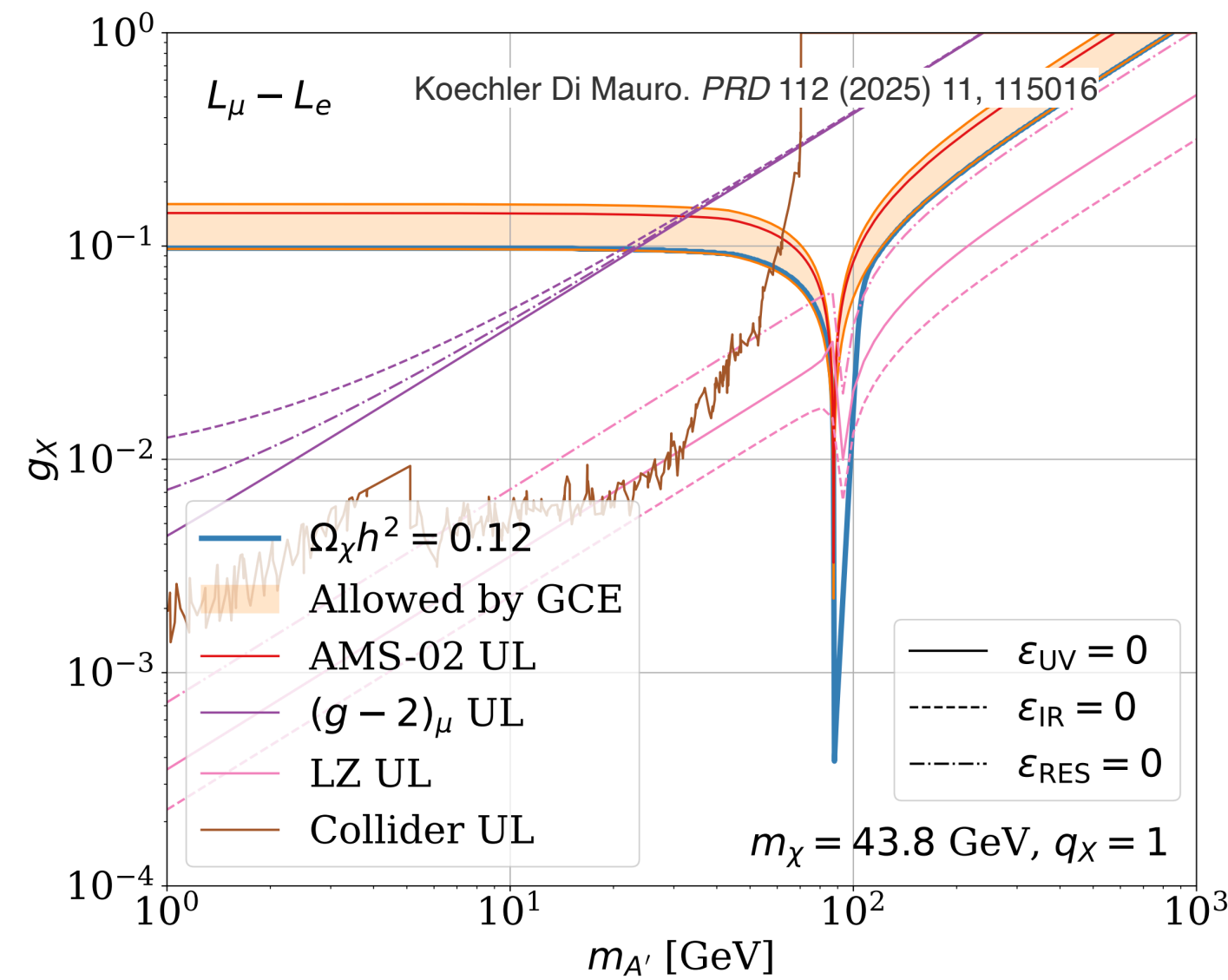
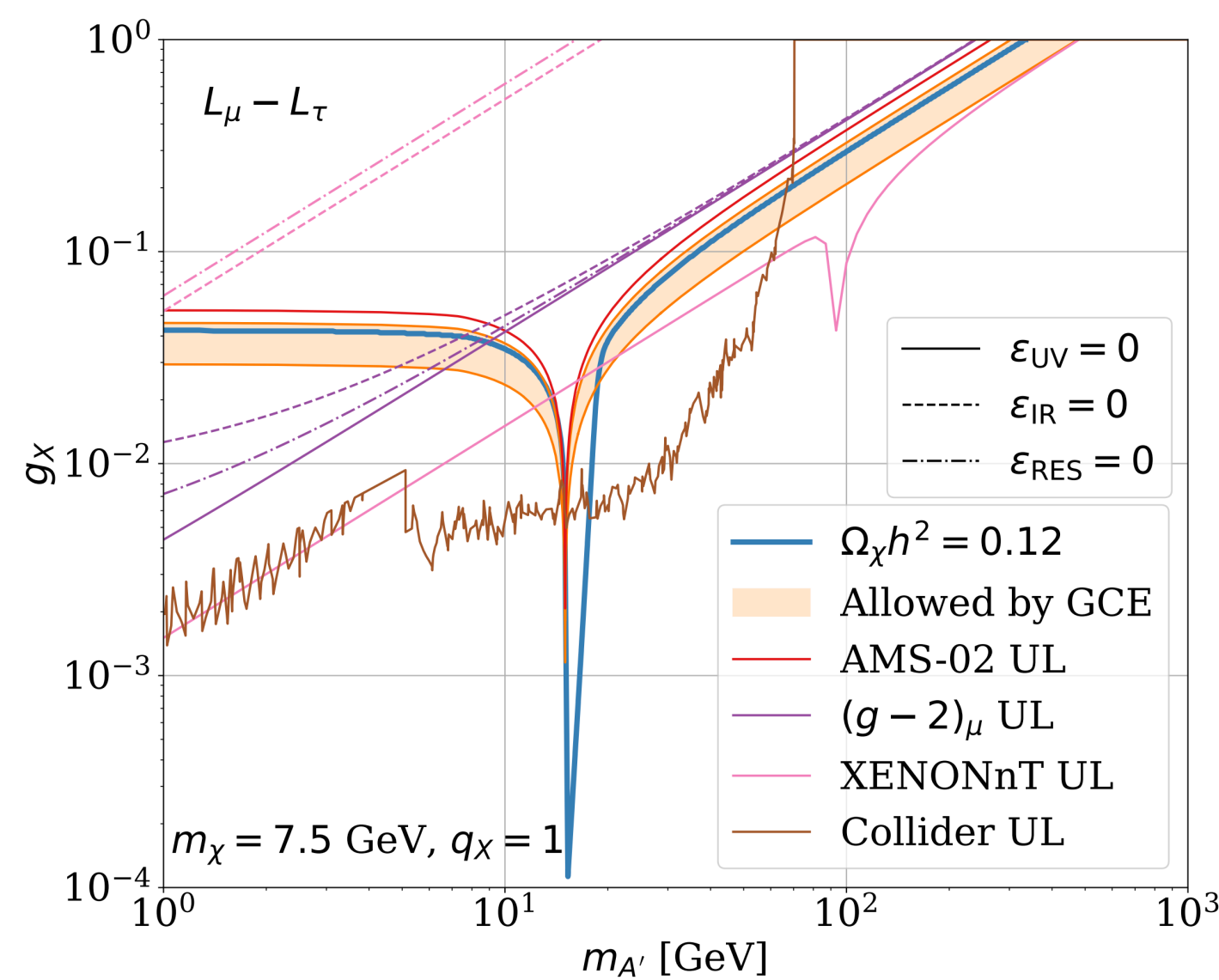
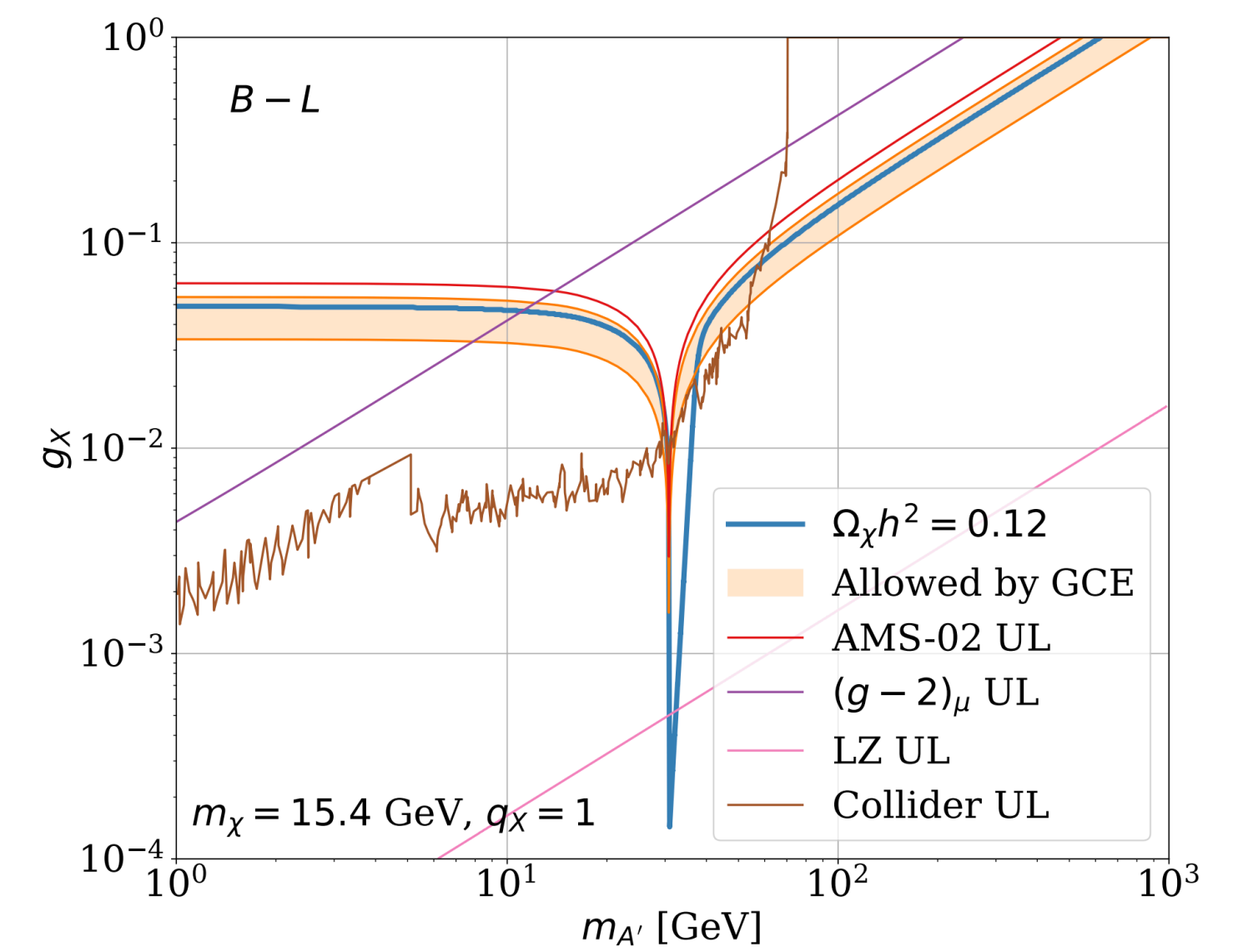
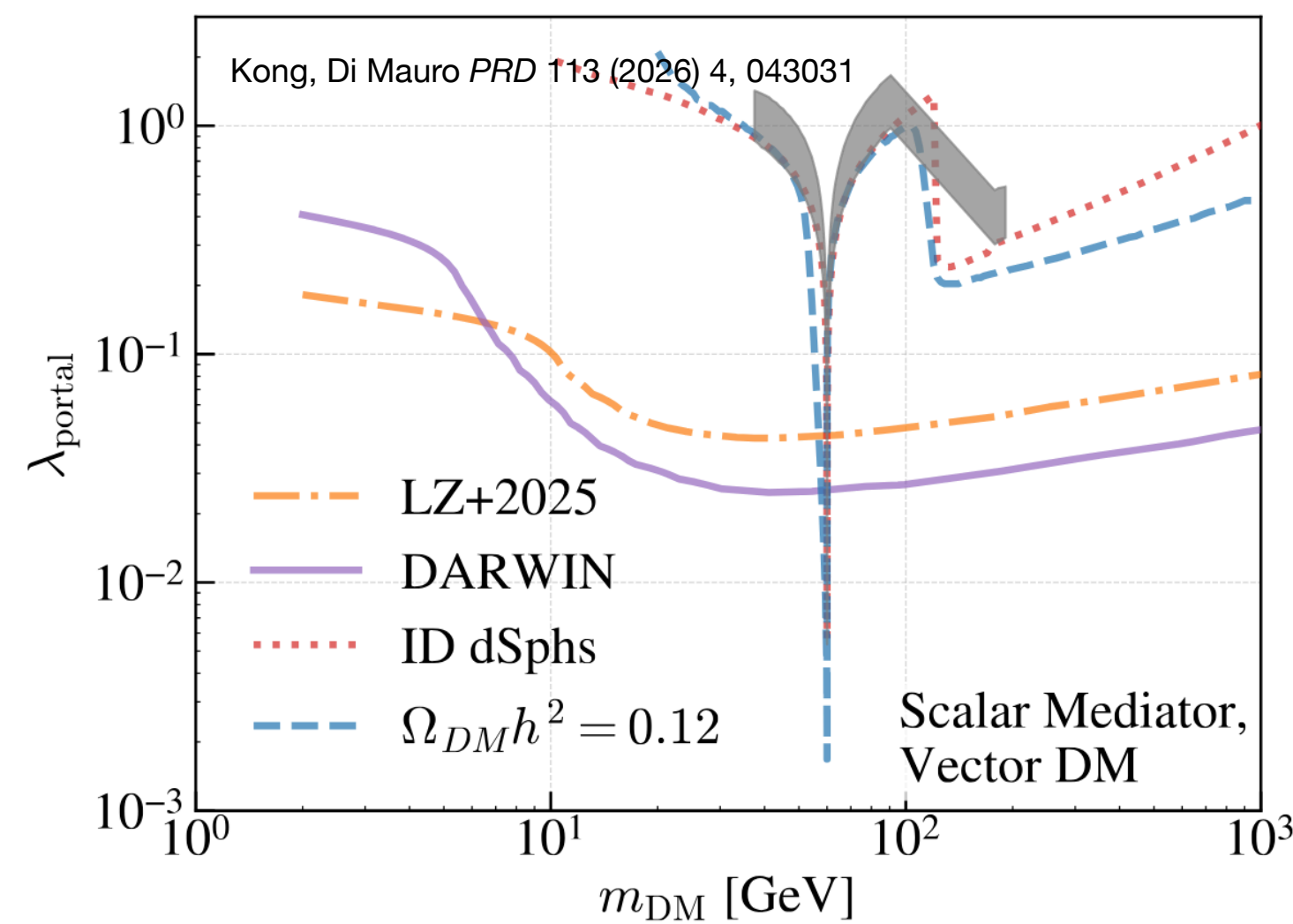
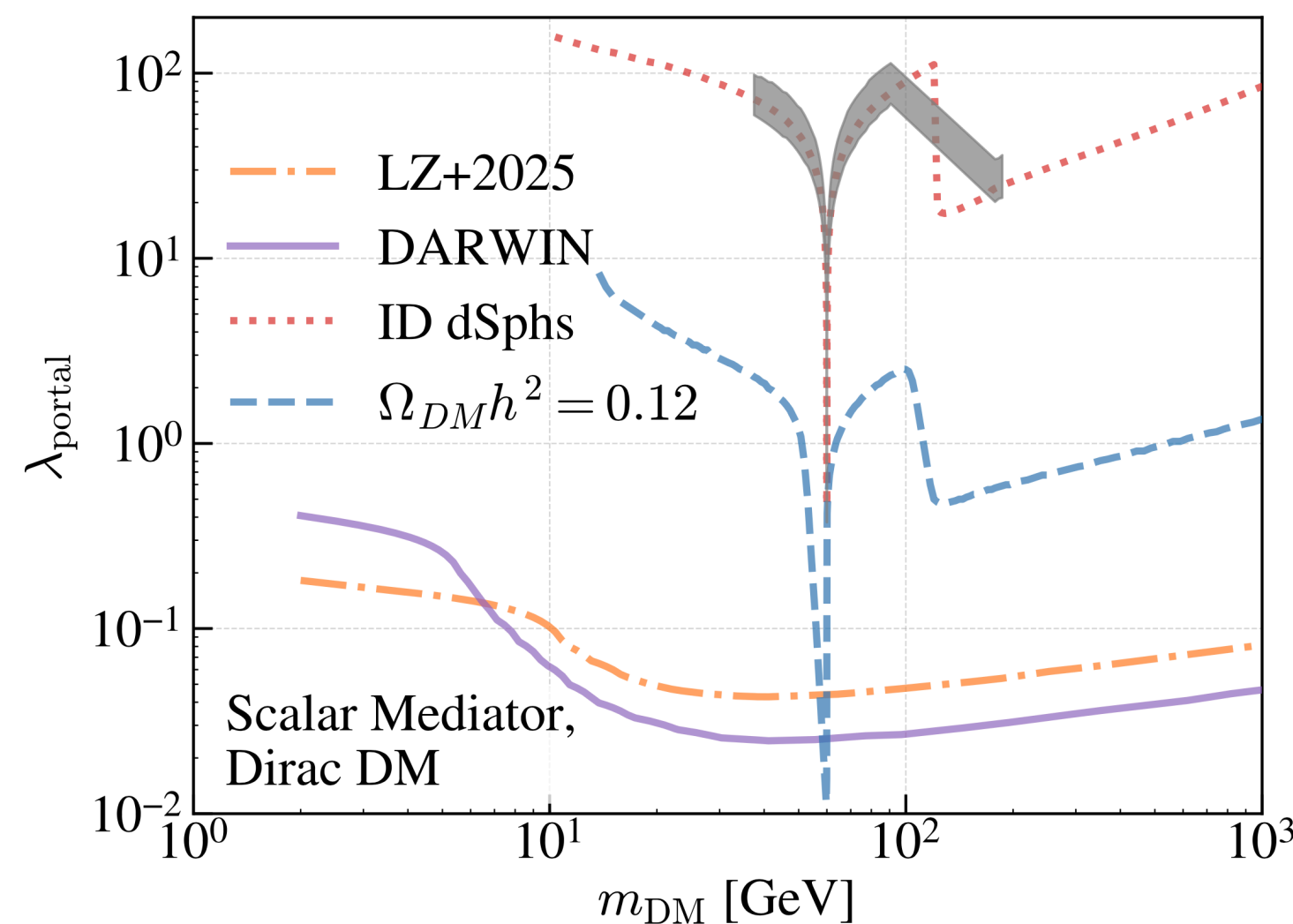
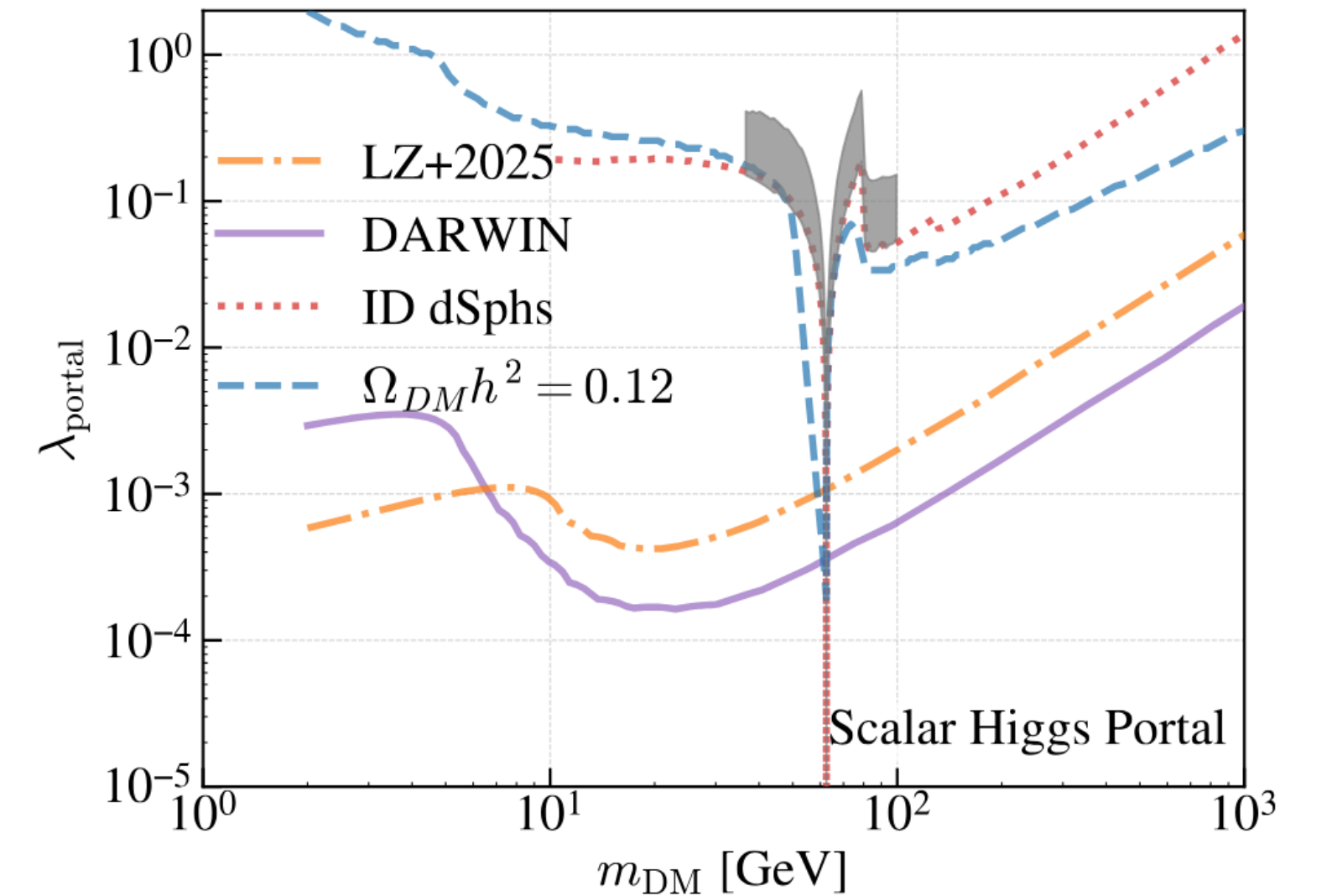
Mattia Di Mauro



**IRN Terascale @ Heidelberg, October 19-21
2026**

Current status of WIMP searches

See also: Arcadi et al., arXiv:2403.15860; Arcadi et al., arXiv:1703.07364; Roszkowski et al., arXiv:1707.06277; Cirelli et al., arXiv:2406.01705; Feng, arXiv:1003.0904; Bertone et al., arXiv:hep-ph/0404175; Jungman et al., arXiv:hep-ph/9506380.



Complementary searches strongly constrain simple WIMP models, while resonant, secluded and suppressed nuclear scattering models preserve viable regions.

LZ high-energy event

High Energy Physics – Experiment

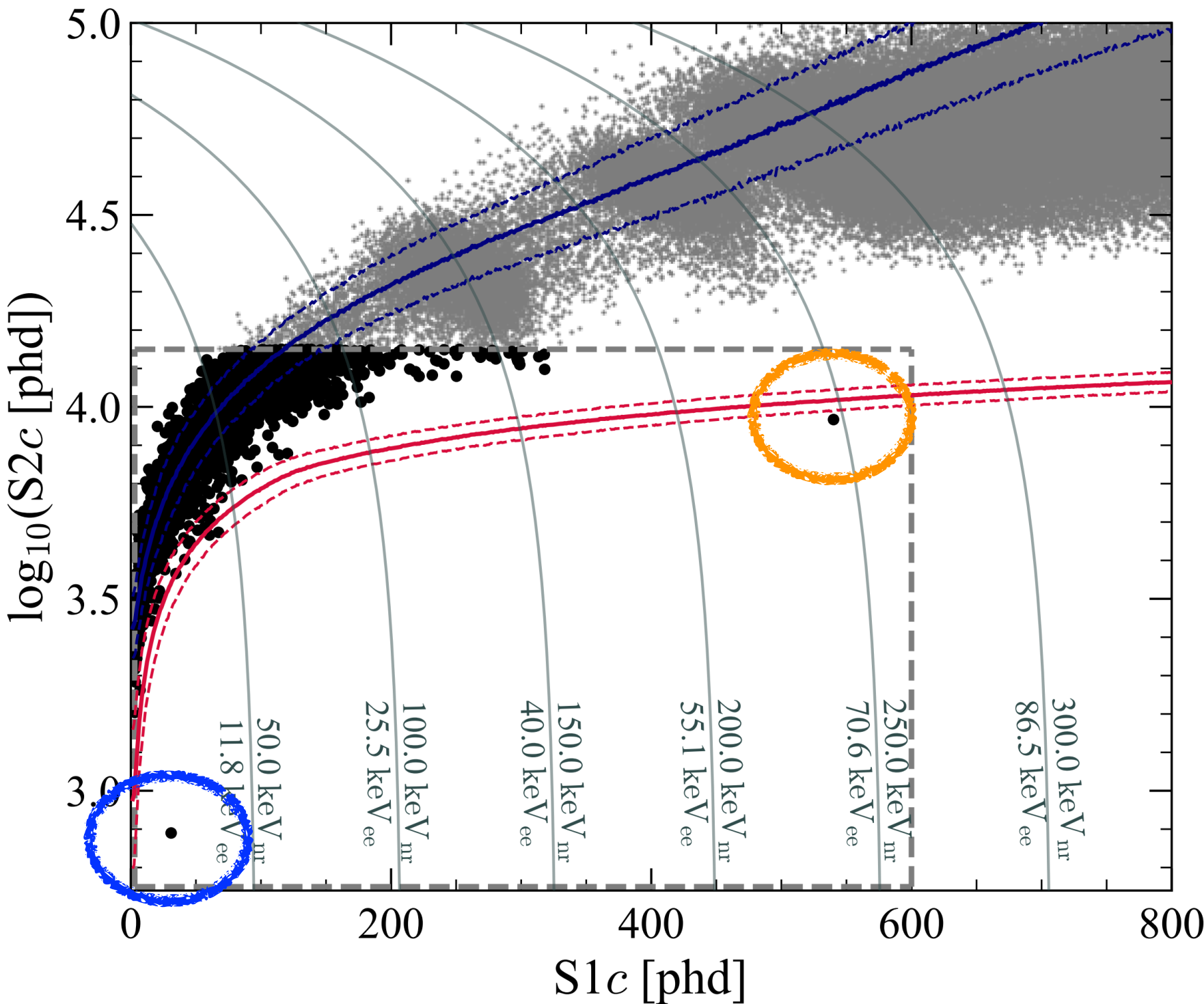
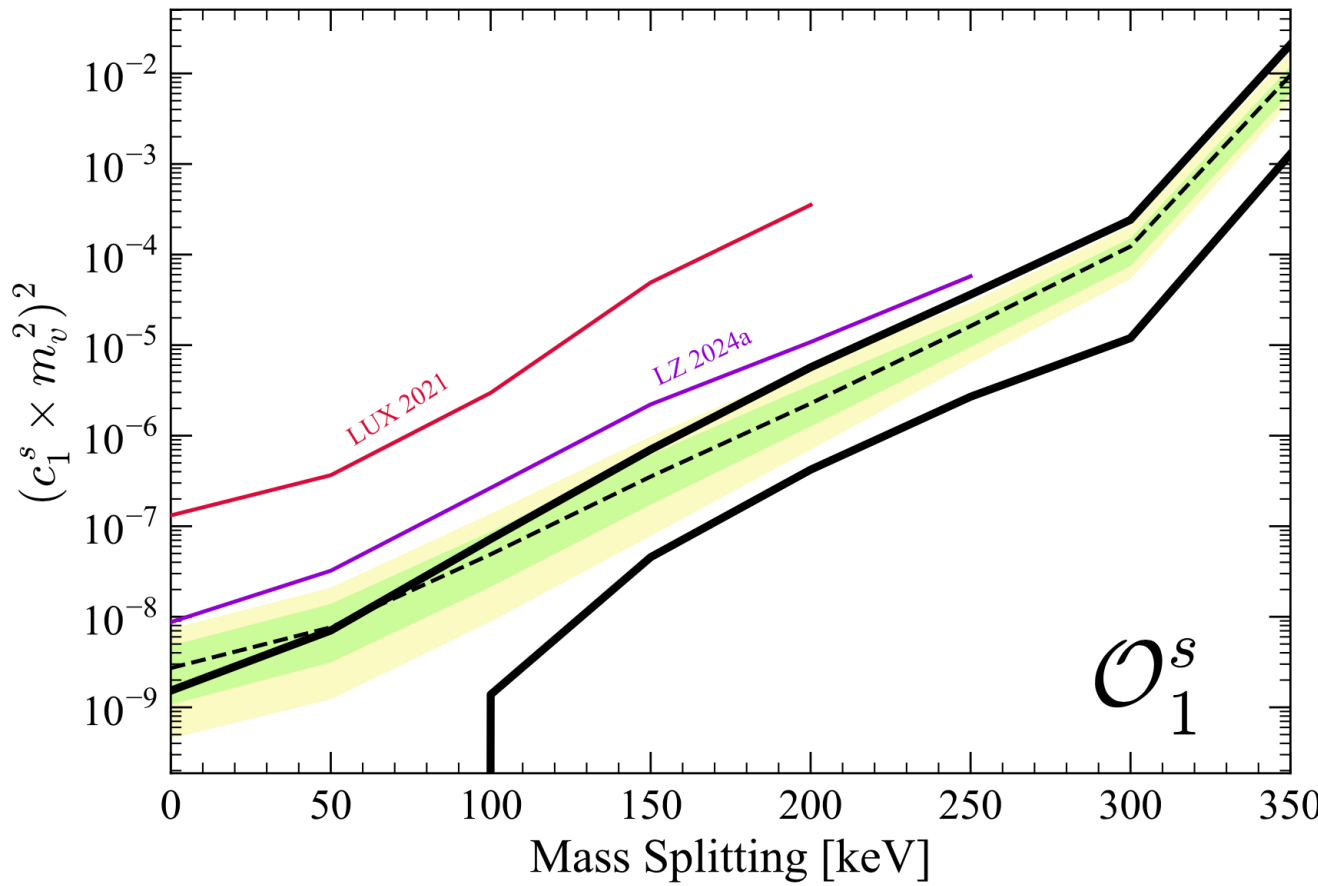
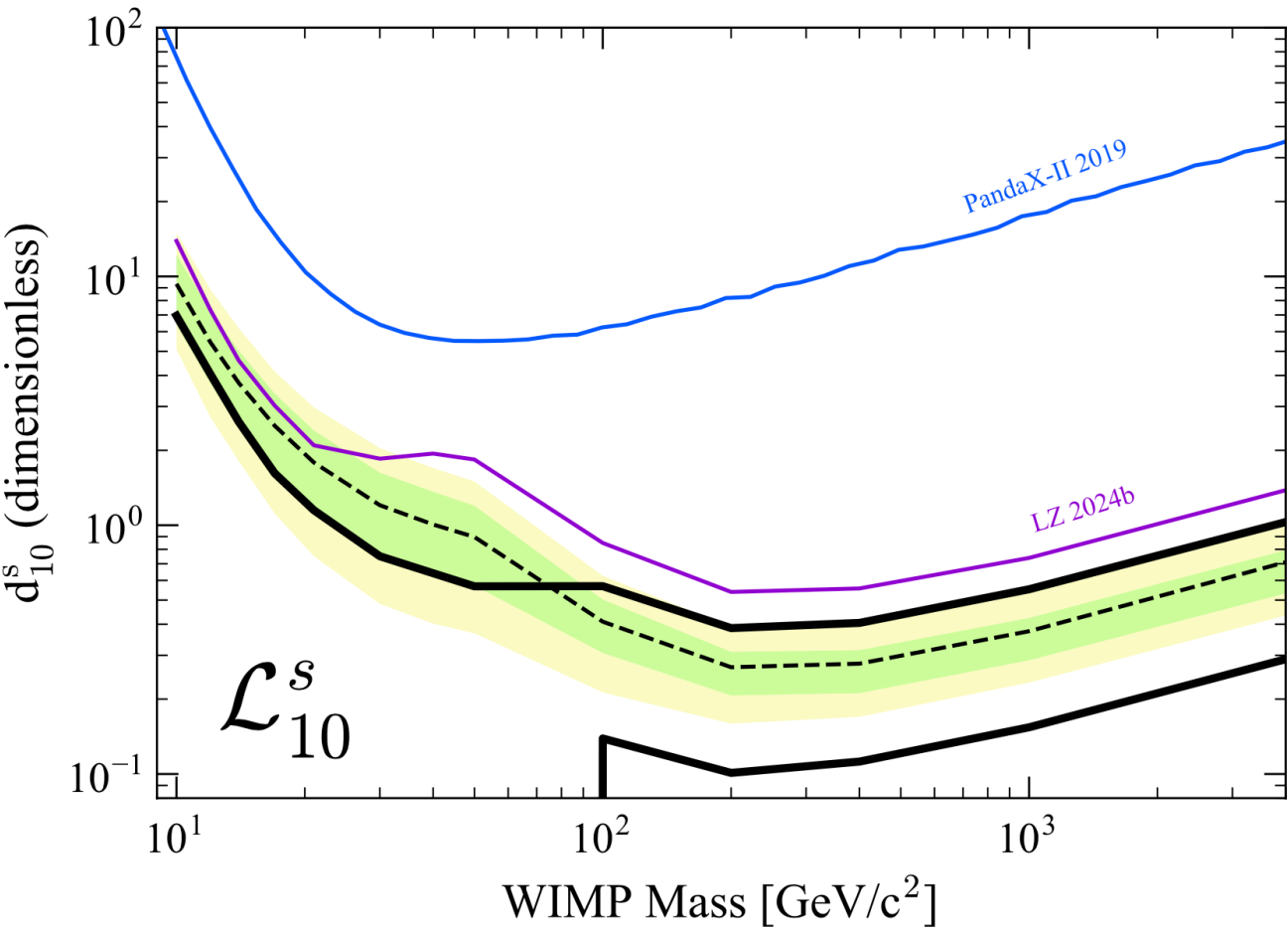
[Submitted on 2 Sep 2026]

Search for dark matter particle interactions in an extended nuclear recoil energy window with the LUX–ZEPLIN (LZ) experiment

D.S. Akerib, A.K. Al Musalhi, B.J. Almquist, C.S. Amarasinghe, A. Ames, T. Anderson, N. Angelides, H.M. Araújo, J.E. Armstrong, M. Arthurs, A. Baker, S. Balashov, J. Bang, J.W. Bargemann, E.E. Barillier, D. Bauer, K. Beattie, A. Beauchene, T.L. Benson, A. Bhatti, T.P. Biesiadzinski, H.J. Birch, E. Bishop, G.M. Blockinger, B. Boxer, C.A.J. Brew, P. Brás, S. Burdin, M.C. Carmona–Benitez, M. Carter, A. Chawla, J.J. Cherwinka, Y.T. Chin, S. Contreras, M.V. Converse, R. Coronel, A. Cottle, C. Coulson, G. Cox, C.E. Dahl, I. Darlington, S. Dave, J. Delgaudio, S. Desai, S. Dey, L. de Viveiros, L. Di Felice, C. Ding, J.E.Y. Dobson, E. Druszkiewicz, S. Dubey, C.L. Dunbar, S.R. Eriksen, S. Fayer, N. Fieldhouse, S. Fiorucci, H. Flaecher, E.D. Fraser, T.M.A. Fruth, P.W. Gaemers, R.J. Gaitskell, A. Geffre, J. Genovesi, C. Ghag, J. Ghamsari, A. Ghosh, S. Ghosh, R. Gibbons, S. Gokhale, J. Green, M.G.D. van der Grinten, J.J. Haiston, C.R. Hall, T. Hall, R.N. Hampp, S.J. Haselschwardt, M.A. Hernandez, S.A. Hertel, G.J. Homenides, M. Horn, T. Horoho, D.Q. Huang, W. Hulse, D. Hunt, E. Jacquet, R.S. James, K.R. Jenkins, A.C. Kaboth, A.C. Kamaha, D. Khaitan, A. Khazov, J. Kim, Y.D. Kim, D. Kodroff, Q.C. Kong, E.V. Korolkova, H. Kraus, S. Kravitz, L. Kreczko, V.A. Kudryavtsev et al. (117 additional authors not shown)

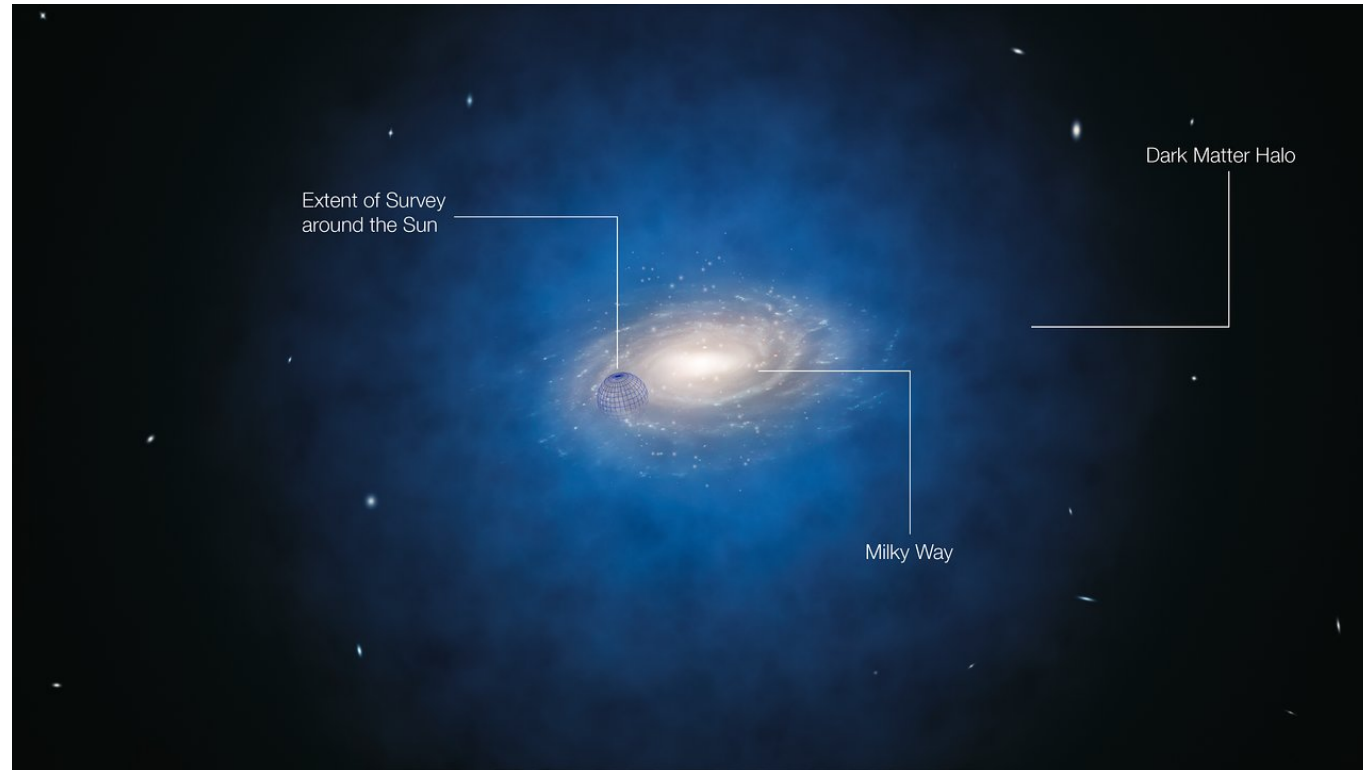
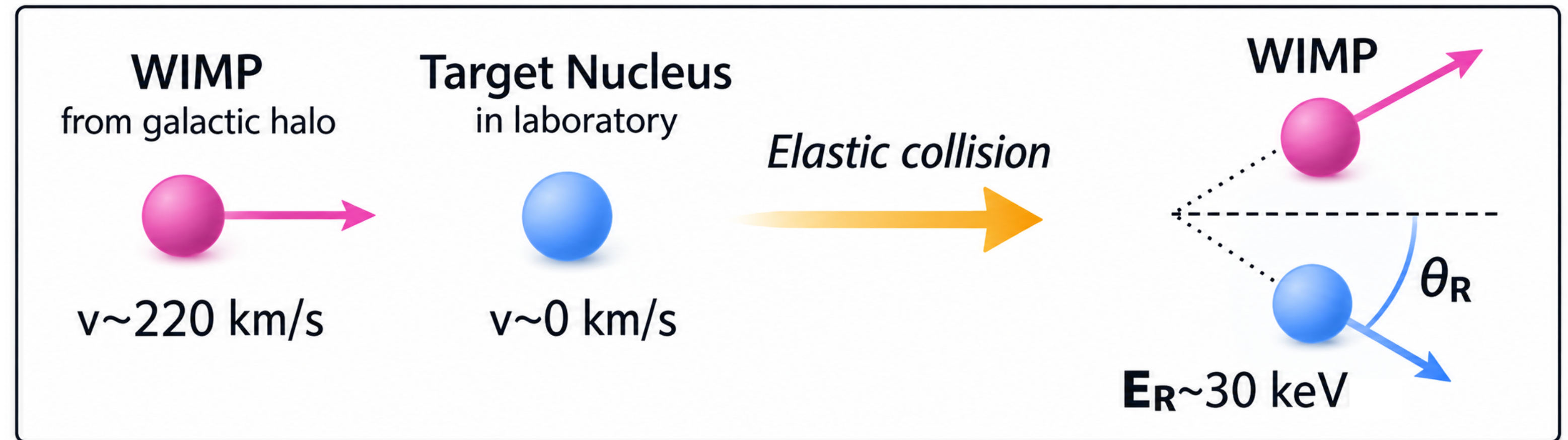
We report on a search for dark matter particles interacting with xenon nuclei in an exposure of 2.84 tonne–years with the LUX–ZEPLIN (LZ) experiment. An extended nuclear recoil energy window up to approximately 270 keV enables searches for effective field theory and inelastic models of dark matter where high-energy recoils account for a larger fraction of the predicted recoil spectrum compared to the nominal spin independent interaction. We observe one event with characteristics consistent with a nuclear recoil of 248 ± 23 (stat) ± 23 (sys) keV, in a region where the known background expectation is low. A profile likelihood ratio test finds tension with the background-only hypothesis at a global significance of 2.6σ when accounting for look-elsewhere effects, with a maximum local significance of 3.4σ across the models tested. We describe the analysis and event of interest, the background model used in the statistical inference, and detail several of the rare background topologies considered.

- Exposure: **2.84 tonne-years.**
- Recoil candidate: **248 ± 23 (stat) ± 23 (sys) keV.**
- Maximum local significance: **3.4σ** ; global significance: **2.6σ** across the models tested.



A single candidate motivates theoretical interpretations but does not establish a dark-matter signal.

Direct detection in a nutshell



$$K = \frac{1}{2}mv^2 = \frac{1}{2}m\beta^2c^2 = 27 \text{ keV}$$

$$v_N \approx \sqrt{\frac{2k_B T}{m_N}} \approx 10^{-7} c$$

$$E_R^{\text{max}} = 2 \frac{\mu^2}{m_N} v^2$$

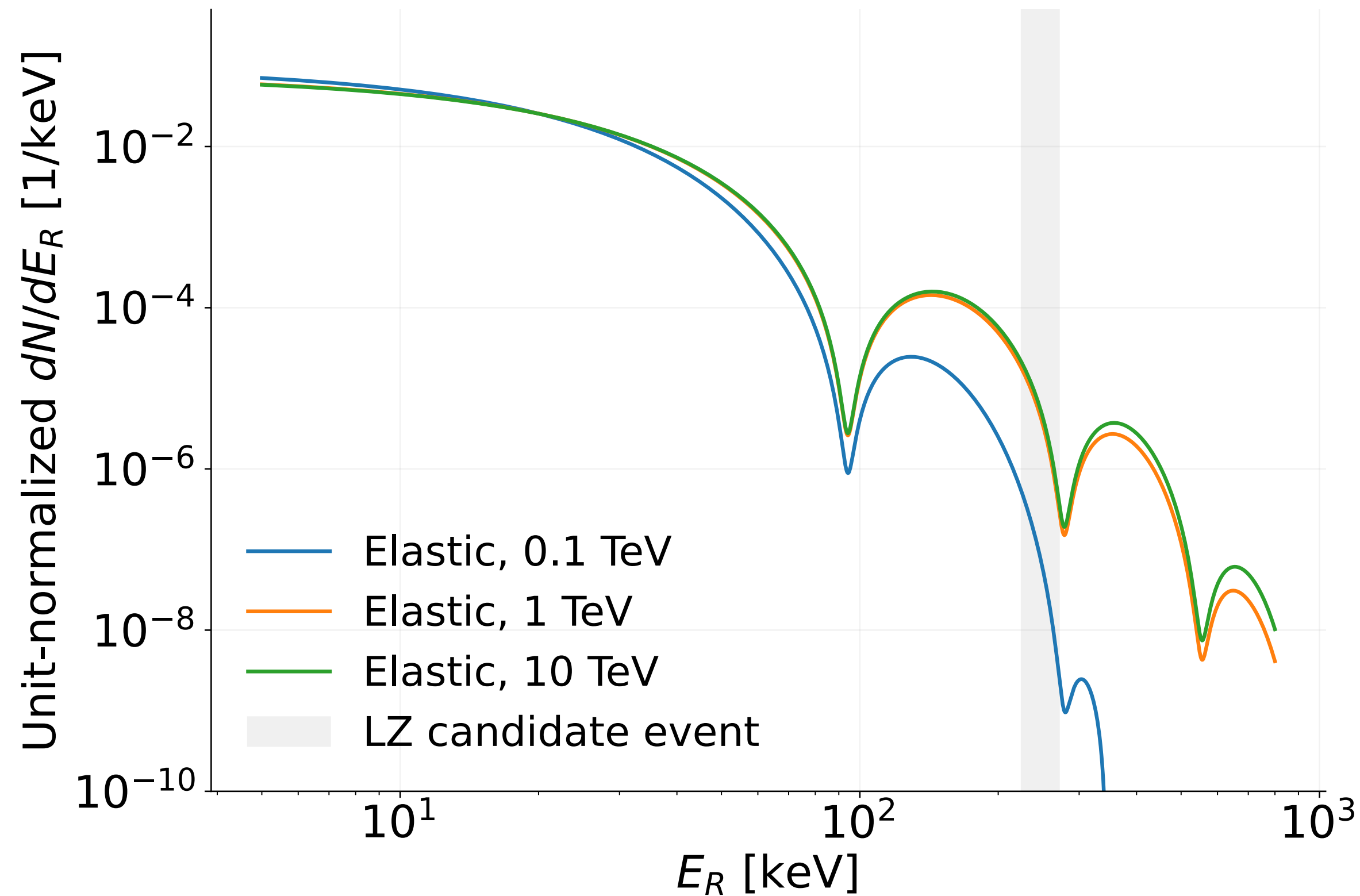
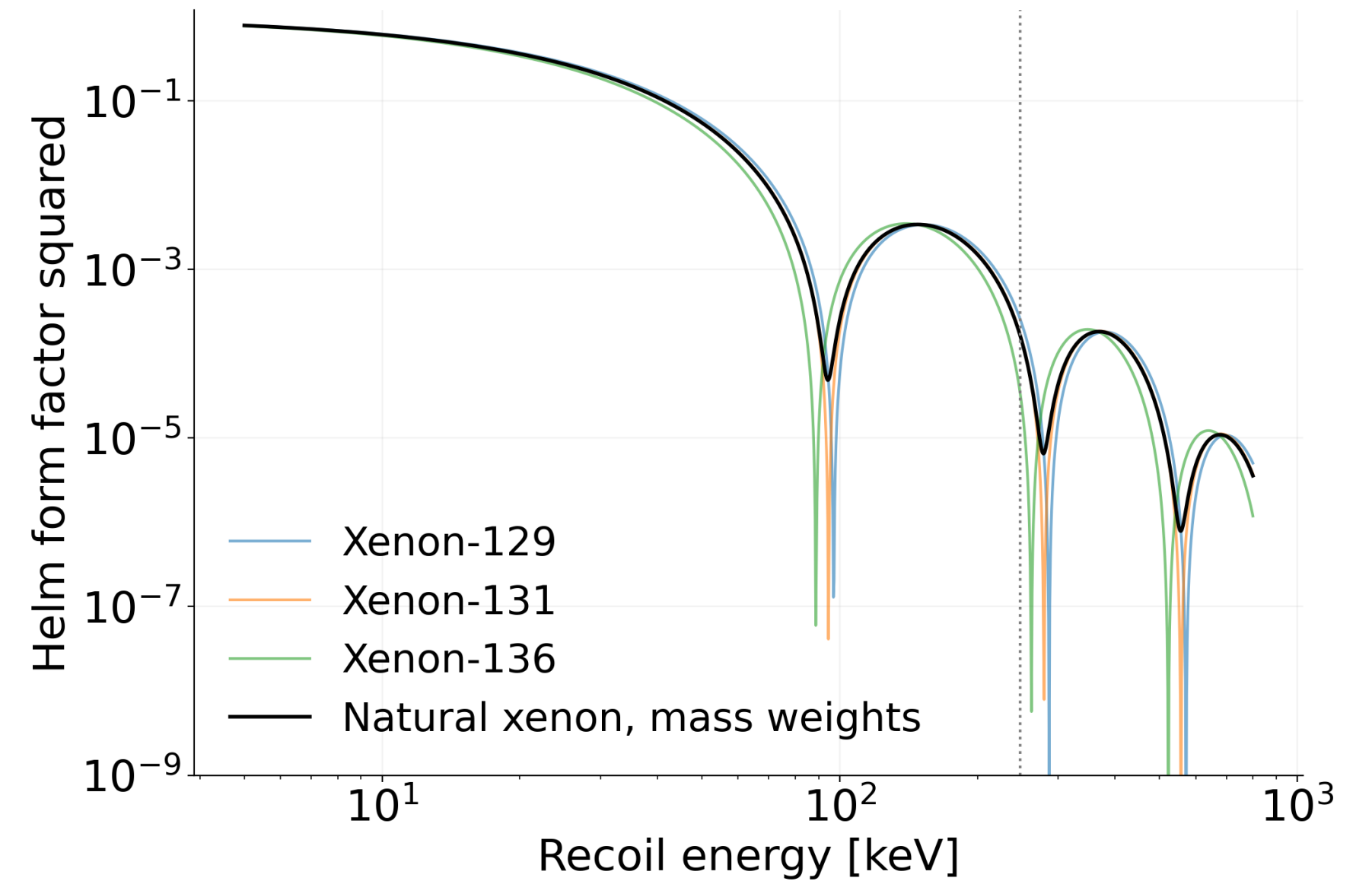
$$\simeq 131 \text{ keV} \left(\frac{m_\chi}{1 \text{ TeV}} \right)^2 \left(\frac{1 \text{ TeV}}{m_\chi + m_N} \right)^2 \left(\frac{v}{220 \text{ km/s}} \right)^2$$

High recoil energies select heavy or fast incident particles, modified interactions, or an additional source of energy.

Why conventional elastic scattering struggles

$$\frac{dR}{dE_{\text{nr}}} = \frac{\rho_0 M}{m_N m_\chi} \int_{v_{\text{min}}}^{v_{\text{esc}}} v f(v) \frac{d\sigma}{dE_{\text{nr}}} dv$$

$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_\chi} \frac{\sigma_N}{2\mu_N^2} \sum_i \xi_i A_i^2 F_i^2(E_R) \eta[v_{\text{min}}(E_R)]$$



$$\frac{N(E_R > 200 \text{ keV})}{N(5.4 < E_R < 300 \text{ keV})} \simeq 1.37 \times 10^{-3}$$

$$N_{5.4-55} \simeq 1.42 \times 10^3$$

Di Mauro ArXiv:2609.02608

Normalizing a conventional spin-independent spectrum to the high-energy candidate generally predicts a much larger low-energy population.

Inelastic dark matter models

Endothermic

$$\chi_1 N \rightarrow \chi_2 N \quad | \quad \delta = m_{\chi_2} - m_{\chi_1} > 0$$

$$v_{\min}(E_R) = \frac{1}{\sqrt{2m_N E_R}} \left(\frac{m_N E_R}{\mu_{\chi N}} + \delta \right)$$

$$E_R^* = \frac{\mu_{\chi N}}{m_N} \delta \quad | \quad v_{\min}^* = \sqrt{\frac{2\delta}{\mu_{\chi N}}}$$

Exothermic

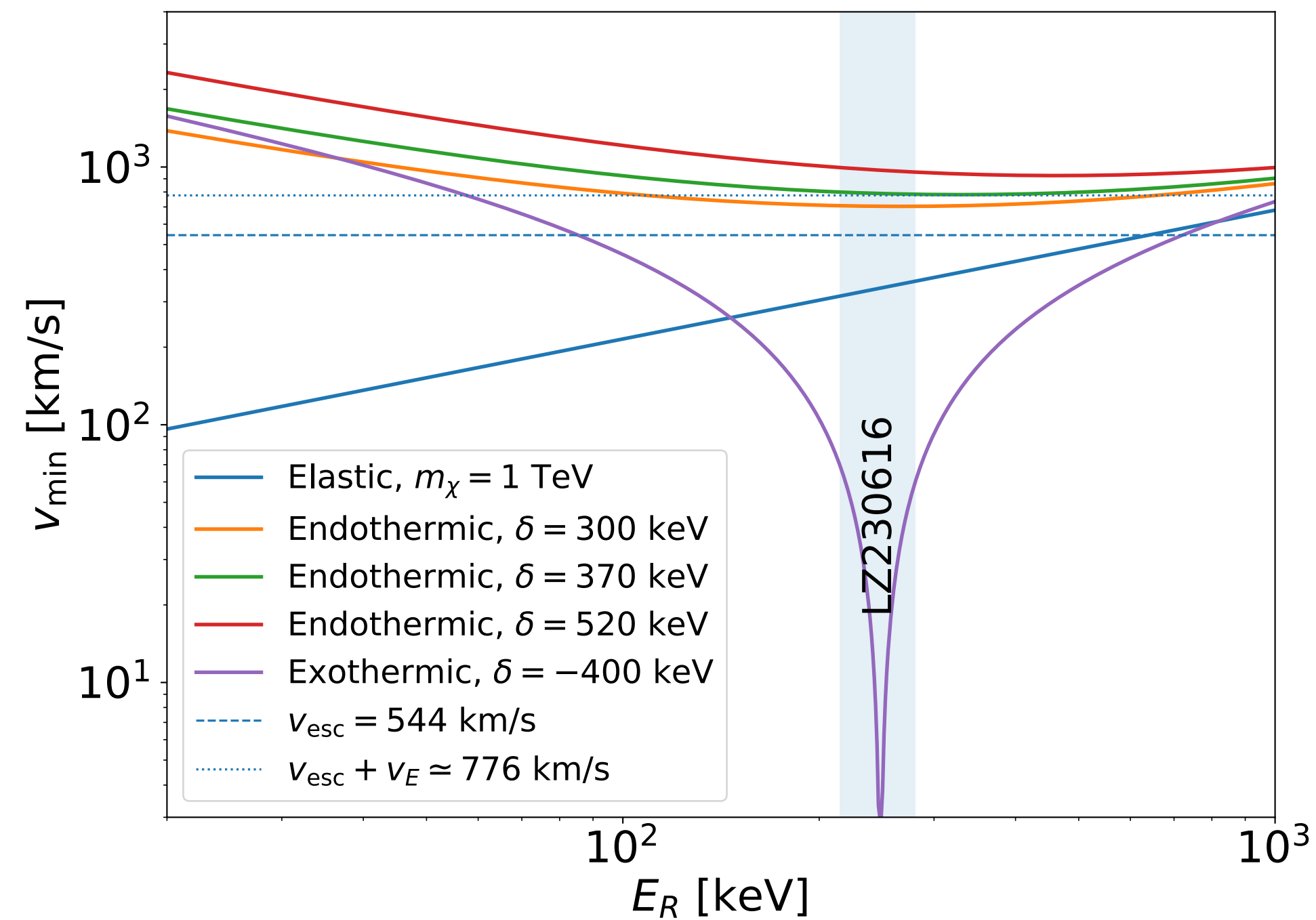
$$\chi_2 N \rightarrow \chi_1 N \quad | \quad \delta = m_{\chi_1} - m_{\chi_2} < 0$$

$$v_{\min}(E_R) = \frac{1}{\sqrt{2m_N E_R}} \left| \frac{m_N E_R}{\mu_{\chi N}} - |\delta| \right|$$

$$v_{\min}^* = 0 \quad | \quad E_R^* = \frac{\mu_{\chi N}}{m_N} |\delta|$$

$$\mu_{\chi N} = \frac{m_{\chi} m_N}{m_{\chi} + m_N}$$

DM-nucleus reduced mass



Endothermic scattering probes the fastest dark matter

Standard Halo Model (SHM) reference parameters

For the baseline analysis we adopt the Standard Halo Model (SHM).

Local circular speed
(of the Milky Way)

$v_0 = 238 \text{ km s}^{-1}$

Galactic escape speed

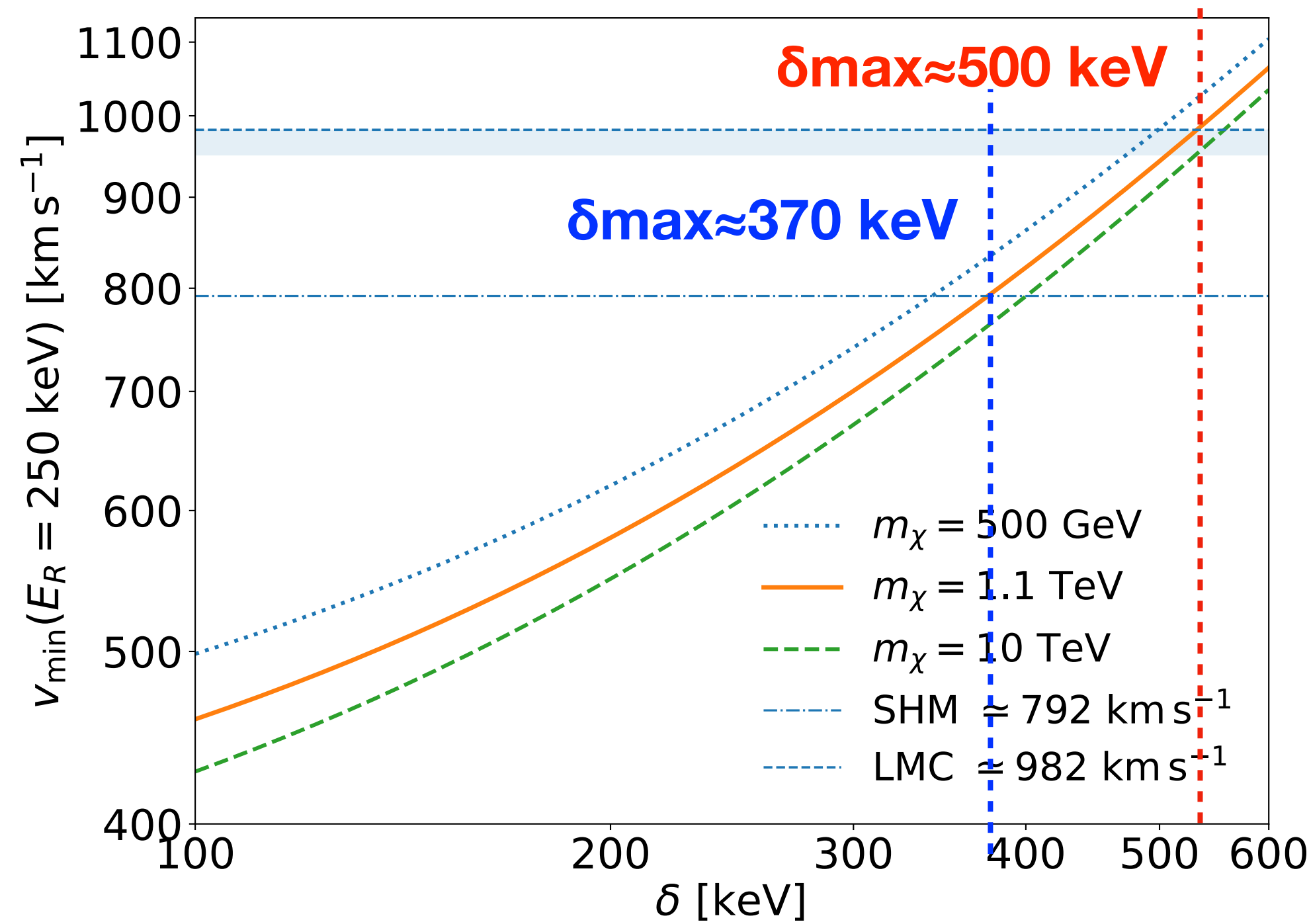
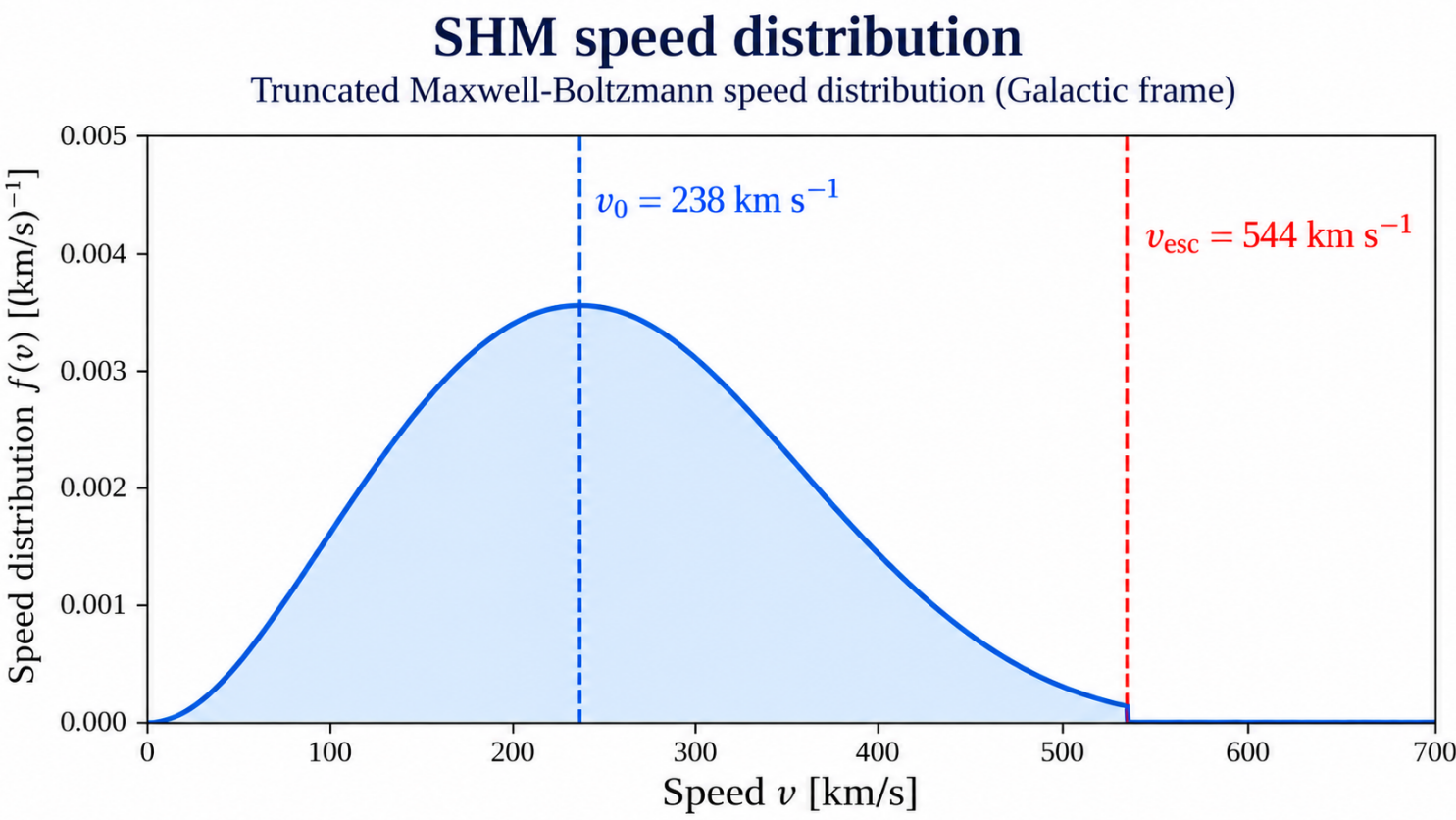
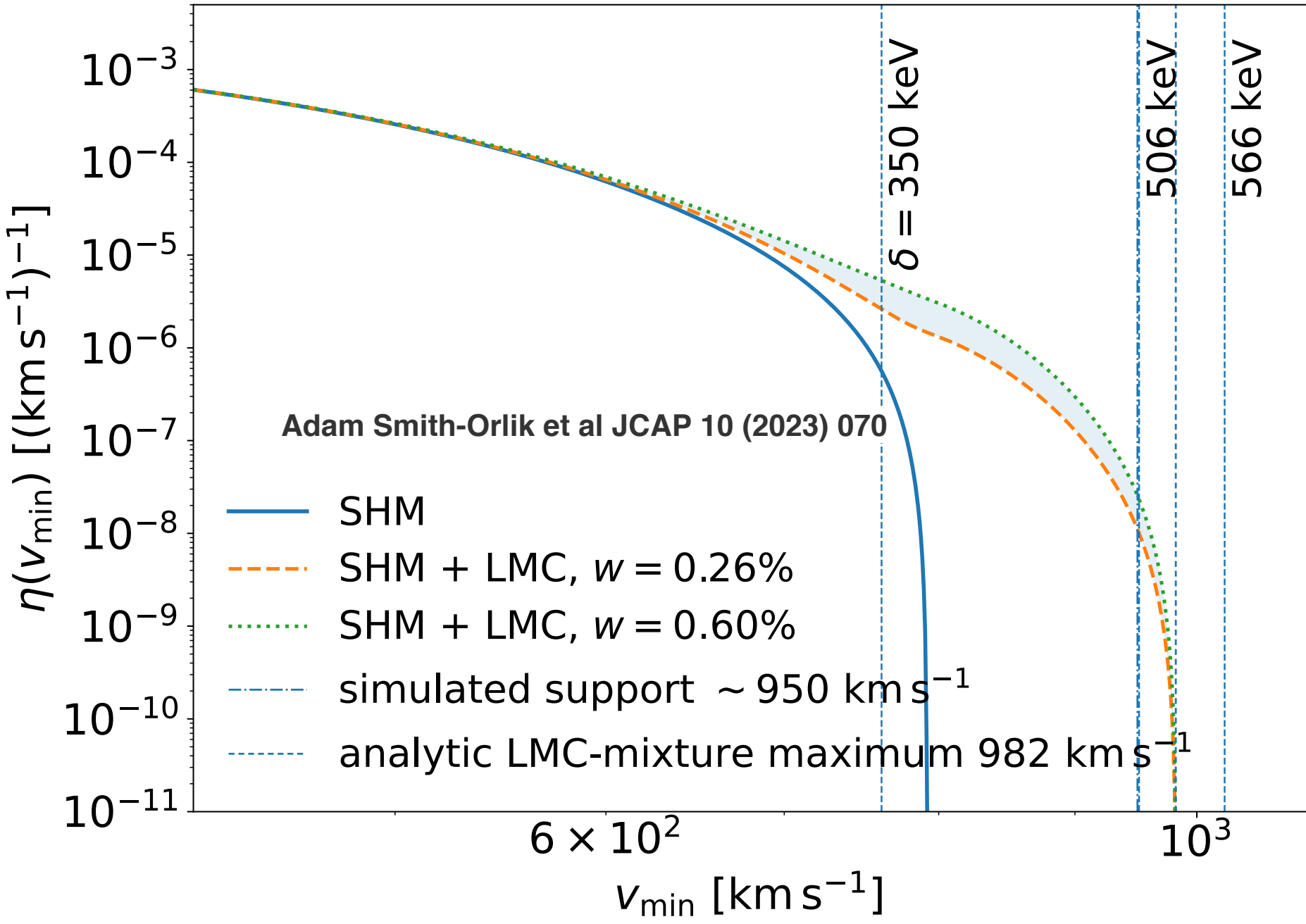
$v_{\text{esc}} = 544 \text{ km s}^{-1}$

Earth speed
(in the Galactic frame)

$v_E = 250.2 \text{ km s}^{-1}$

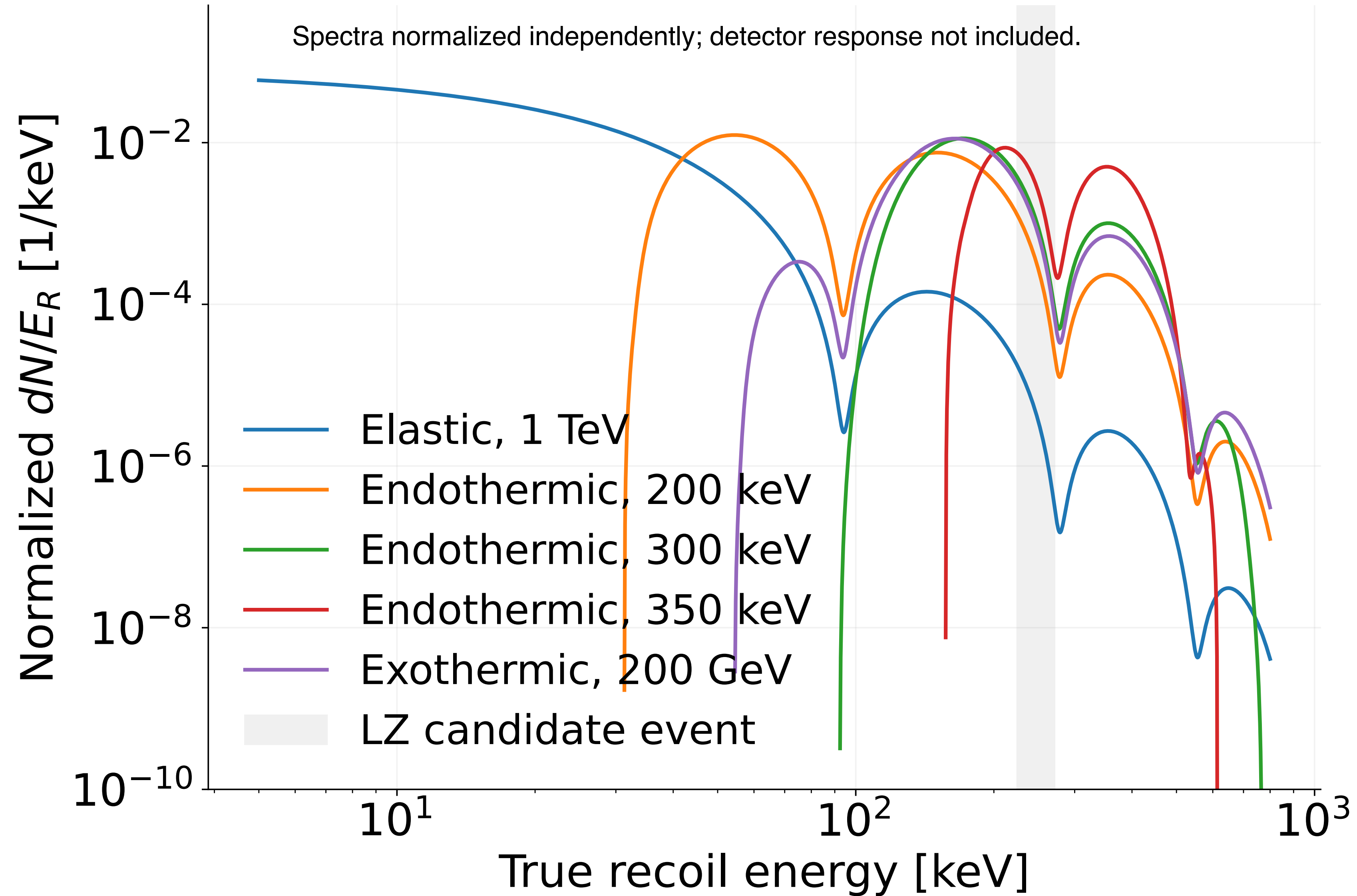
Derived maximum speed:

$v_{\text{max}} = v_{\text{esc}} + v_E \simeq 794.2 \text{ km s}^{-1}$



The high-speed halo population controls the accessible splitting and event rate. An LMC-induced component can extend the endothermic reach.

Different mechanisms produce different recoil spectra



Higgsino Interpretation

The fermionic partners of the two MSSM Higgs doublets transform under $SU(2)_L \times U(1)_Y$ as

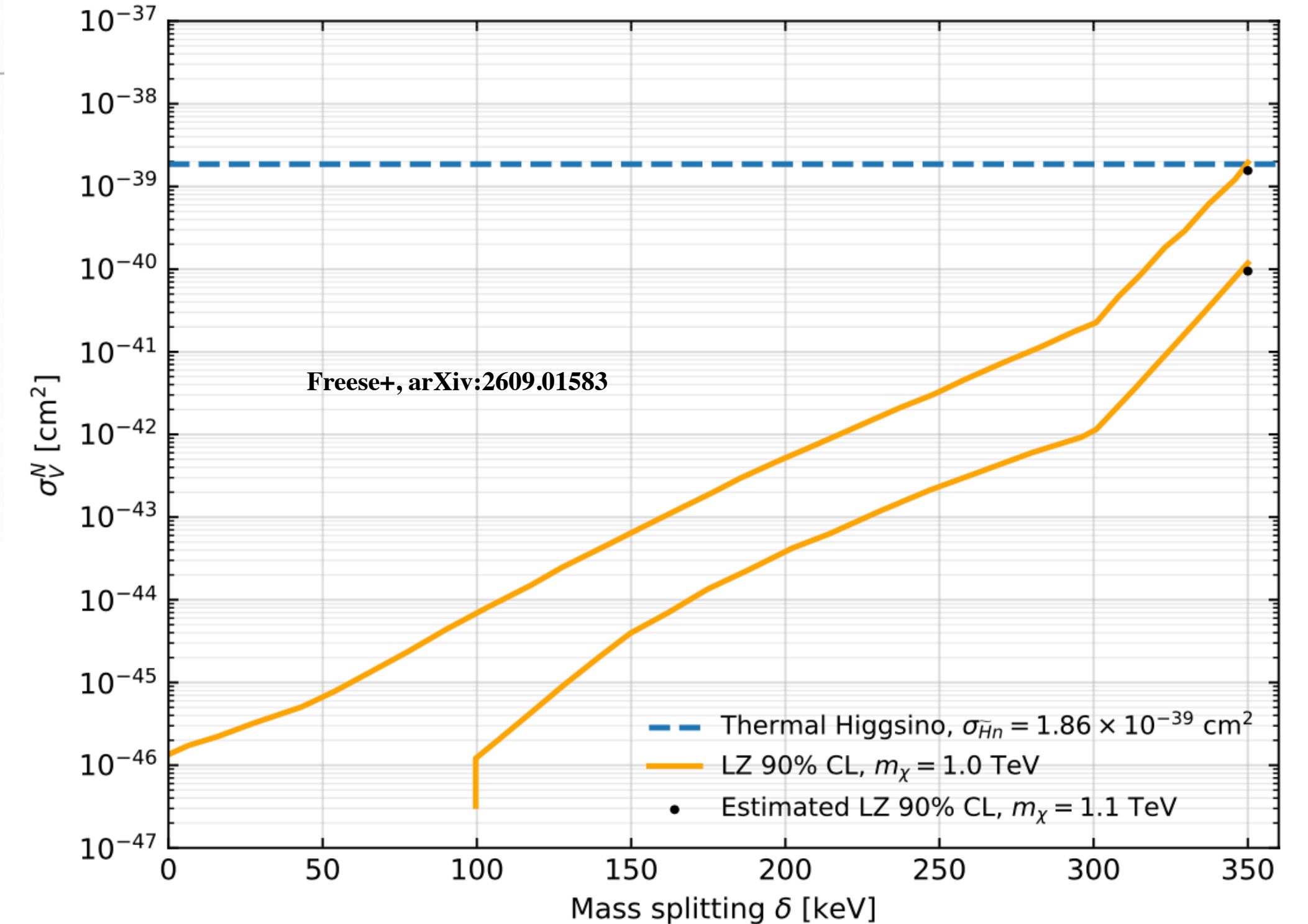
$$\begin{aligned}\tilde{H}_u &\sim (\mathbf{2}, +1/2), & \tilde{H}_d &\sim (\mathbf{2}, -1/2) \\ \mathcal{L}_{\text{mass}} &\supset -\mu \tilde{H}_u \cdot \tilde{H}_d - \frac{1}{2} M_1 \tilde{B} \tilde{B} - \frac{1}{2} M_2 \tilde{W}^a \tilde{W}^a + \text{h.c.}\end{aligned}$$

In the nearly pure Higgsino limit, with $|M_1|, |M_2| \gg |\mu|$, the two neutral Weyl fields form an approximate Dirac fermion protected by an approximate Higgsino-number symmetry. Electroweak symmetry breaking, together with finite M_1 and M_2 , lifts this degeneracy and produces two neutral Majorana eigenstates.

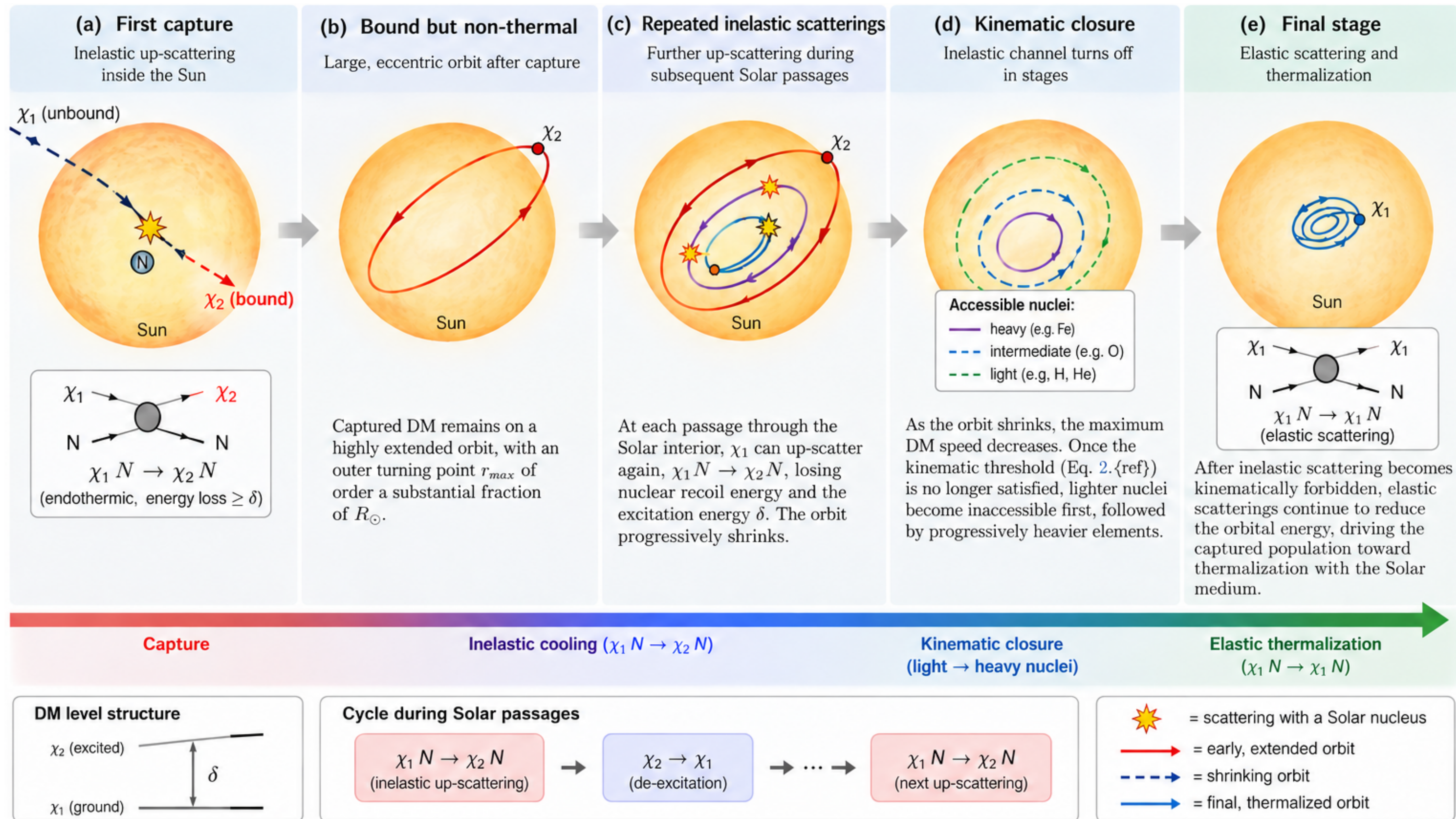
$$m_\chi = 1.1 \text{ TeV}, \quad \delta \simeq 377 \text{ keV}$$

- Standard thermal freeze-out selects a nearly pure Higgsino mass around 1.1 TeV.
- The LZ spectrum and normalization constrain the splitting, with substantial dependence on the halo distribution and detector response.

$$\begin{aligned}\mathcal{L}_{Z\tilde{H}\tilde{H}} &\supset \frac{g}{2c_W} Z_\mu \bar{\tilde{\chi}}_2^0 \gamma^\mu \tilde{\chi}_1^0 + \text{h.c.} \\ \delta &\equiv m_{\tilde{H}_2} - m_{\tilde{H}_1} \simeq m_Z^2 \left(\frac{\sin^2 \theta_W}{M_1} + \frac{\cos^2 \theta_W}{M_2} \right)\end{aligned}$$

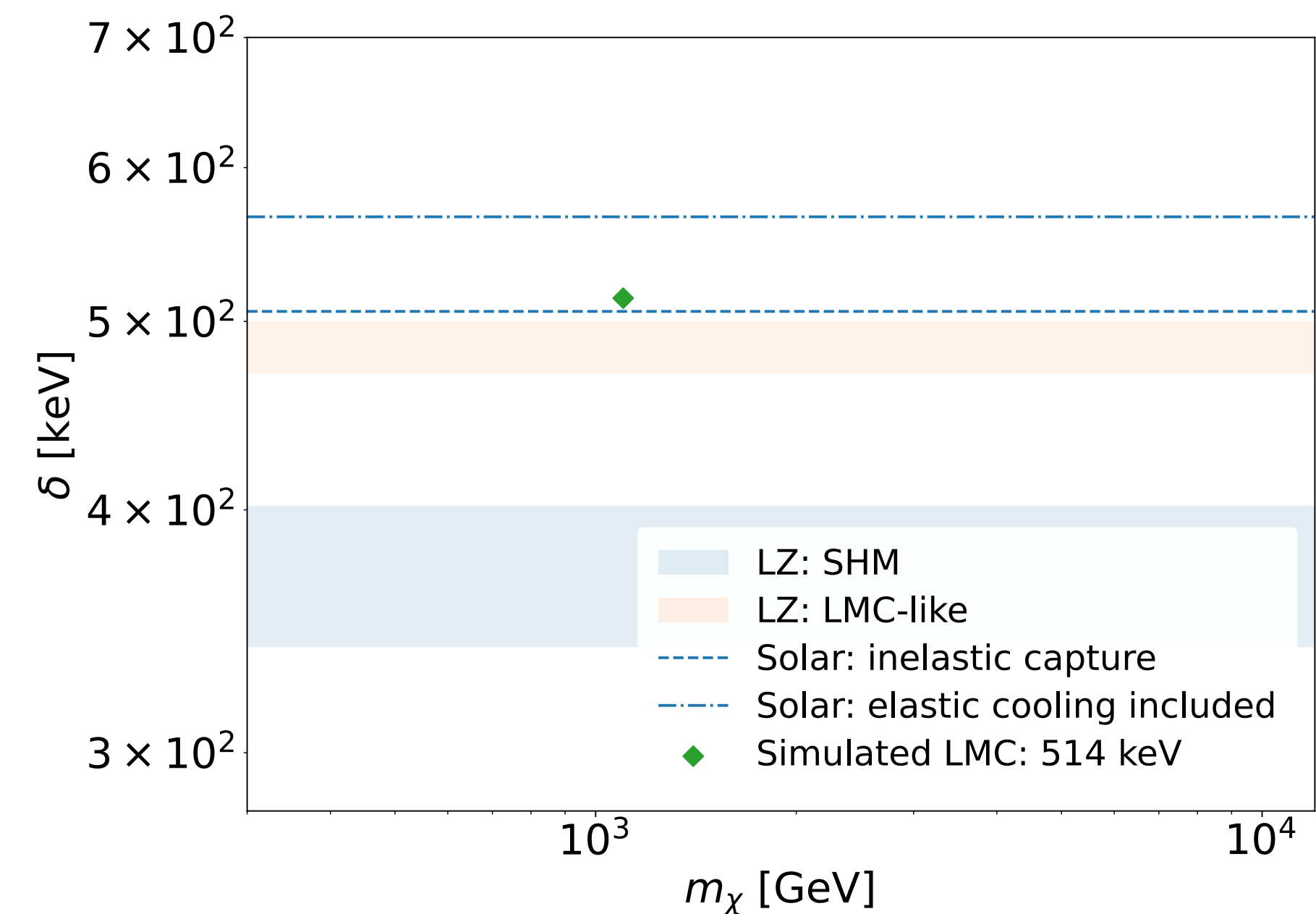
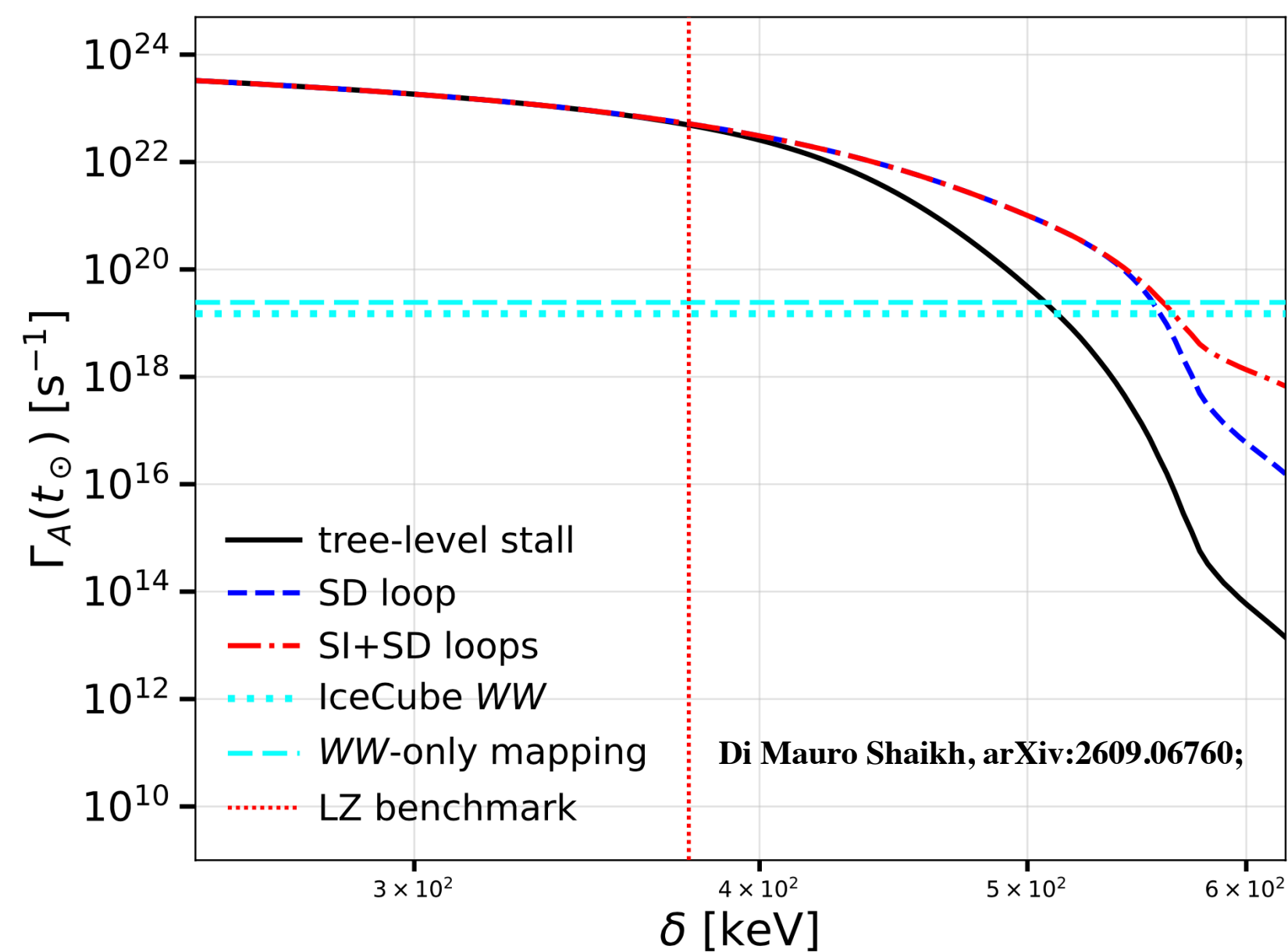
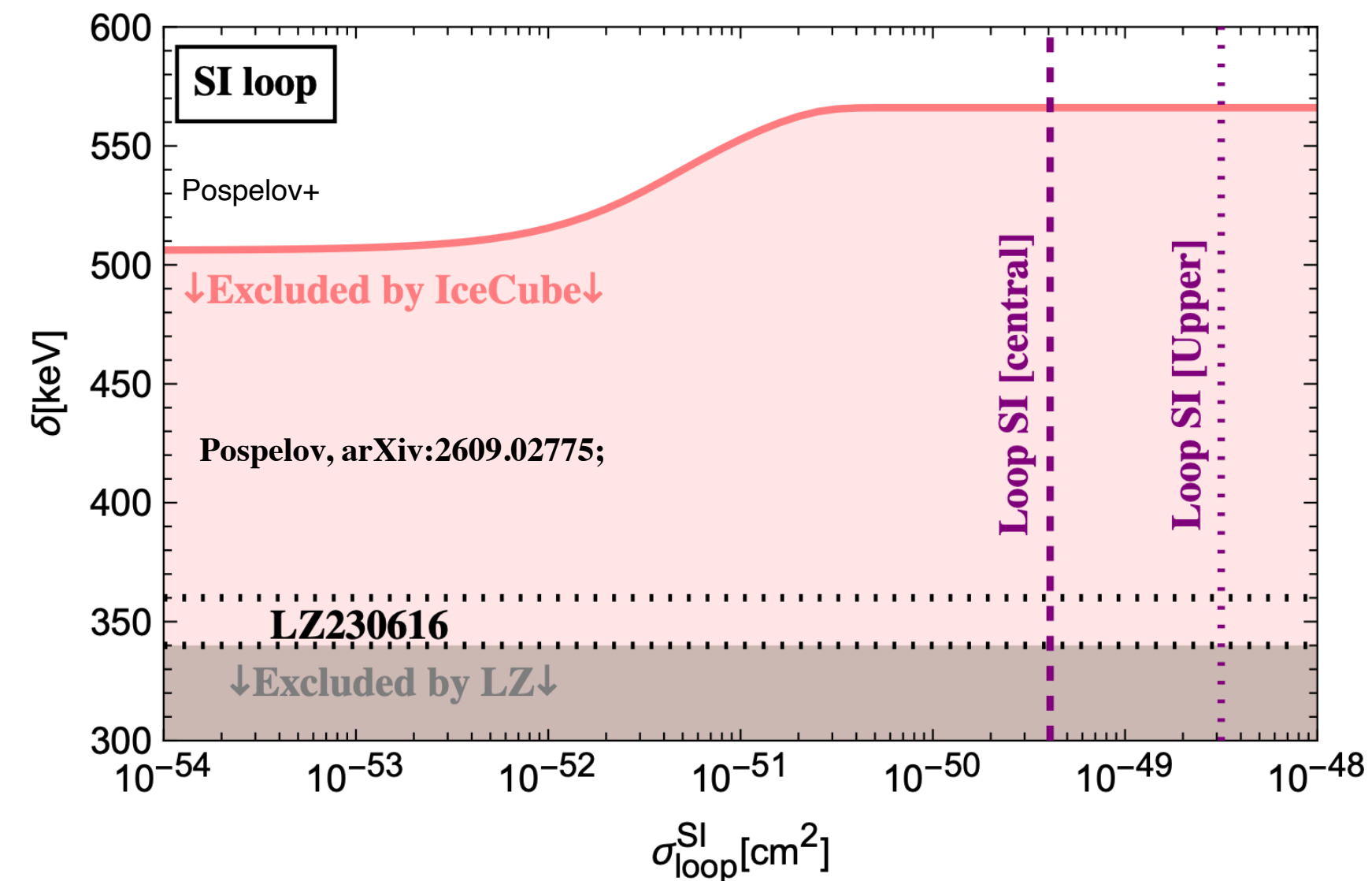


Solar capture mechanism



Bounds from Solar capture

- IceCube limits neutrinos from annihilation of captured dark matter; scattering limits follow after specifying capture and annihilation assumptions.
- Thermal Higgsinos are strongly constrained.
Compatibility depends on solar cooling, the halo distribution and high-energy sidebands.



Higgs-Coupled Minimal Dark Matter

HC-MDM extends the electroweak dark sector by introducing a Majorana multiplet M and a vectorlike Dirac multiplet D in adjacent $SU(2)_L$ representations, allowing a renormalizable interaction with the Higgs field

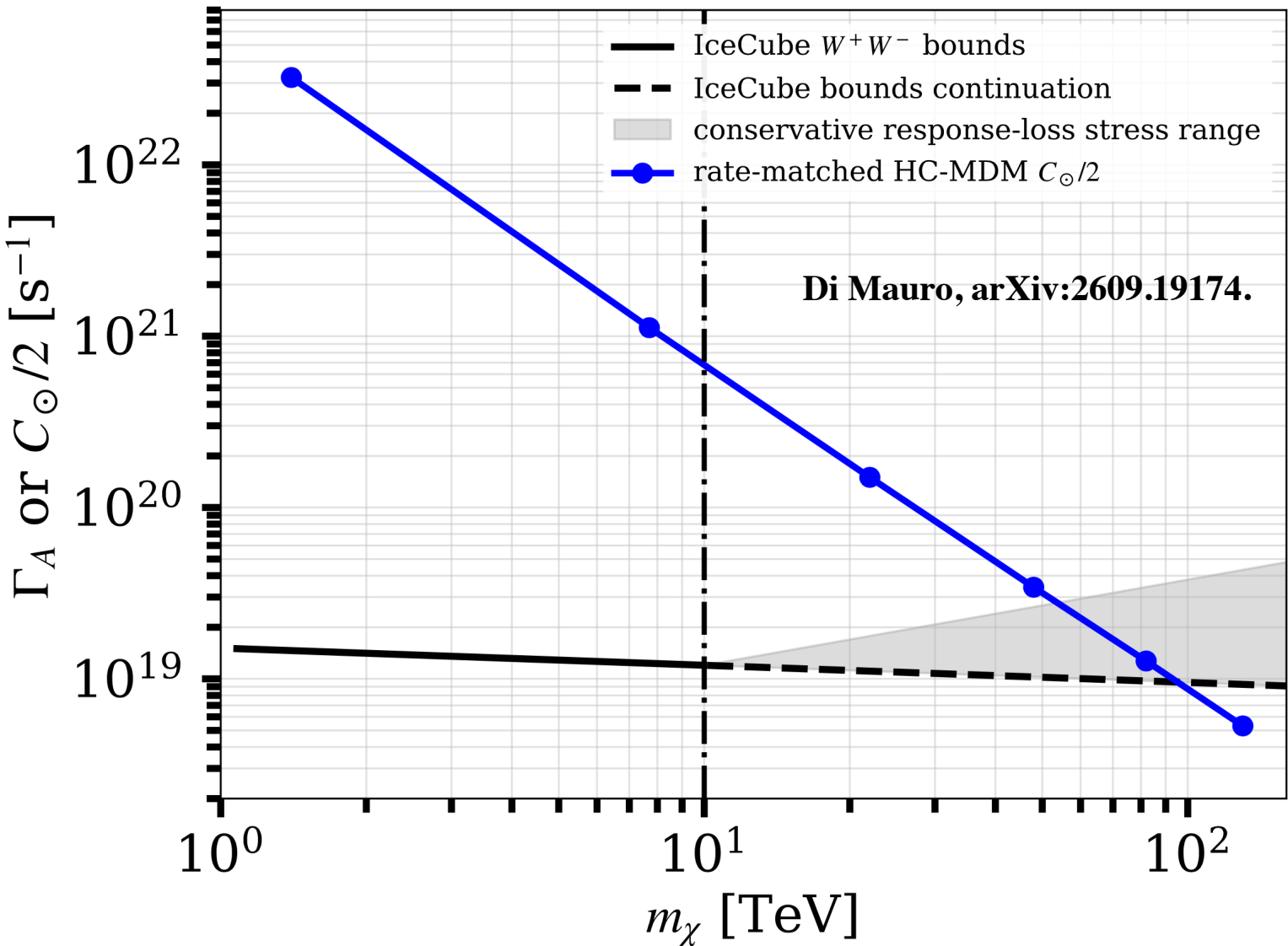
Denoting the two neutral Dirac-sector Weyl fields by ψ^0 and ψ^{e0} ,

$$\mathcal{L} \supset \overline{D} \left(i \gamma^\mu \mathcal{D}_\mu - m_D \right) D + \frac{1}{2} \overline{M} \left(i \gamma^\mu \mathcal{D}_\mu - m_M \right) M \qquad SU(2)_L \times U(1)_Y$$
$$- y_1 D M H^* - y_2 \overline{D} M H + \text{h.c.}.. \qquad M \sim (2n+1, 0), \qquad D \sim (2n, 1/2)$$

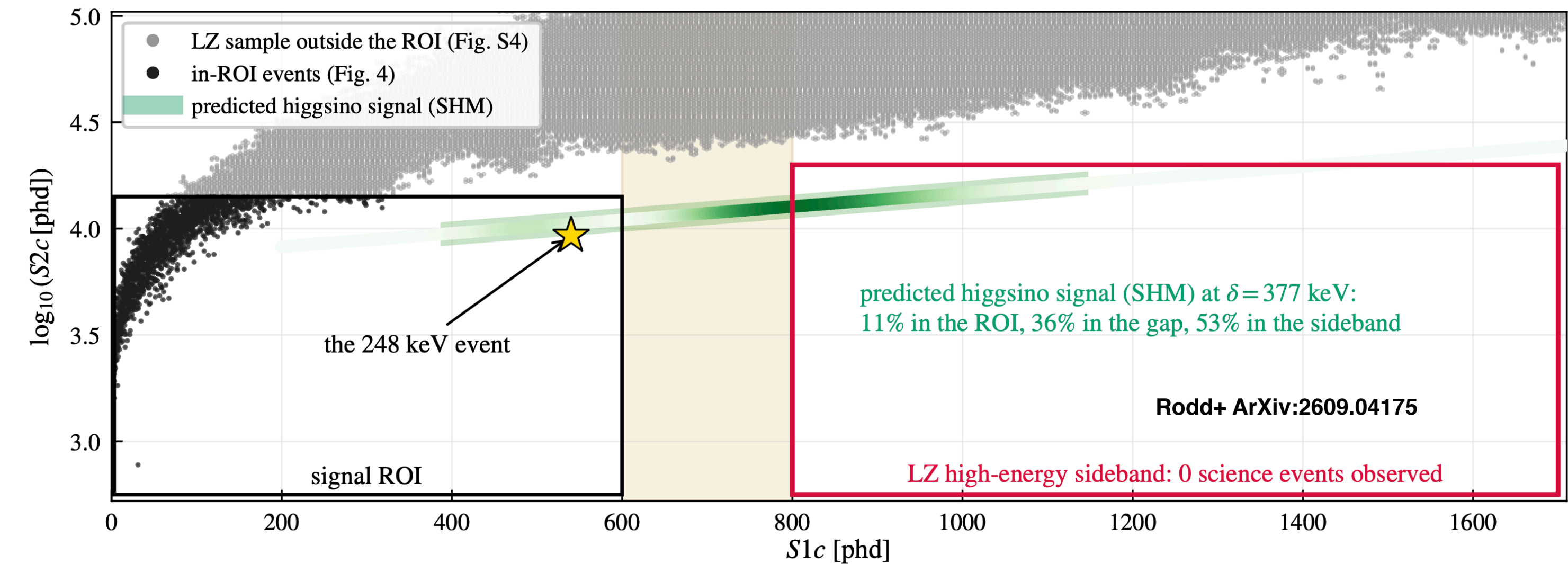
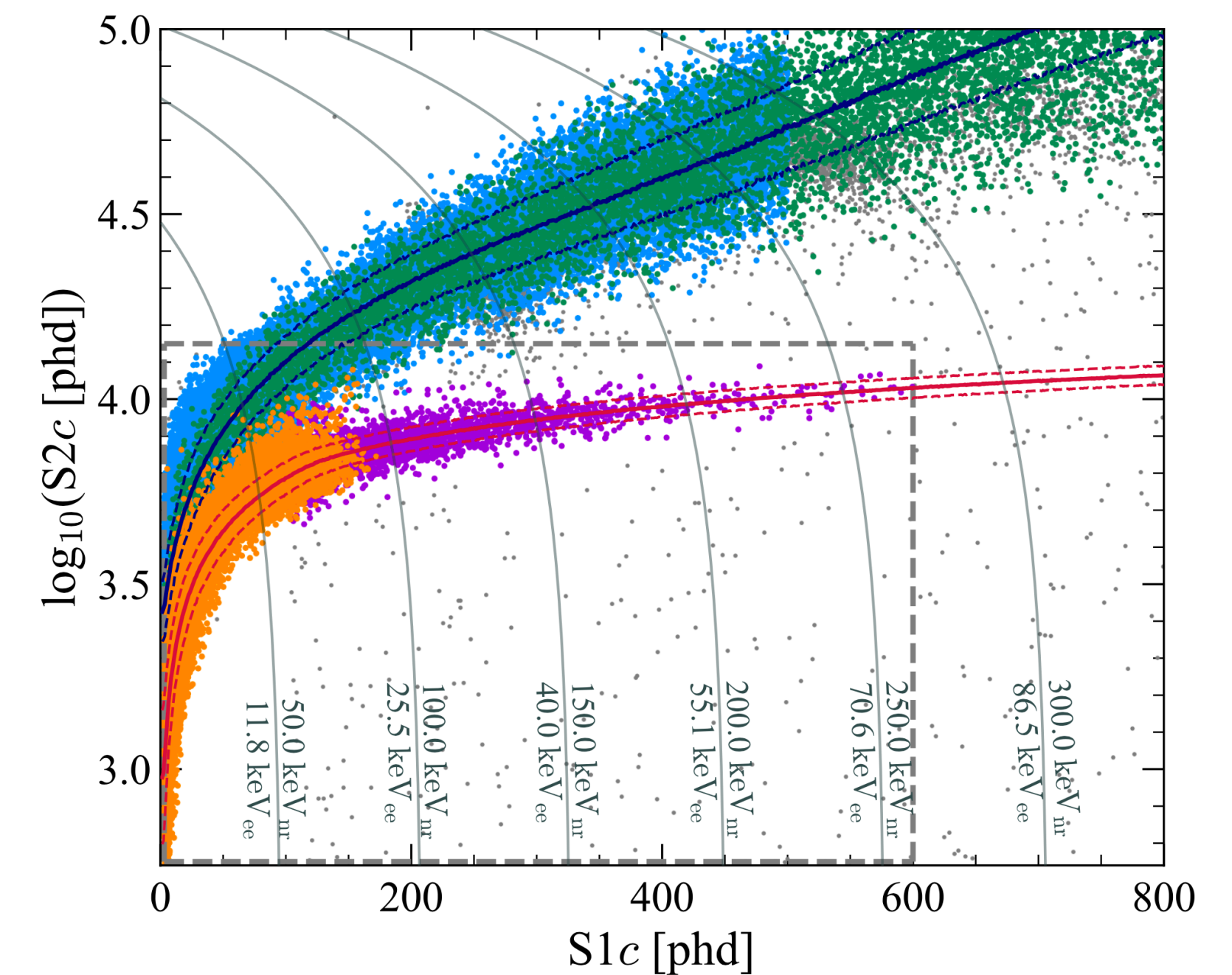
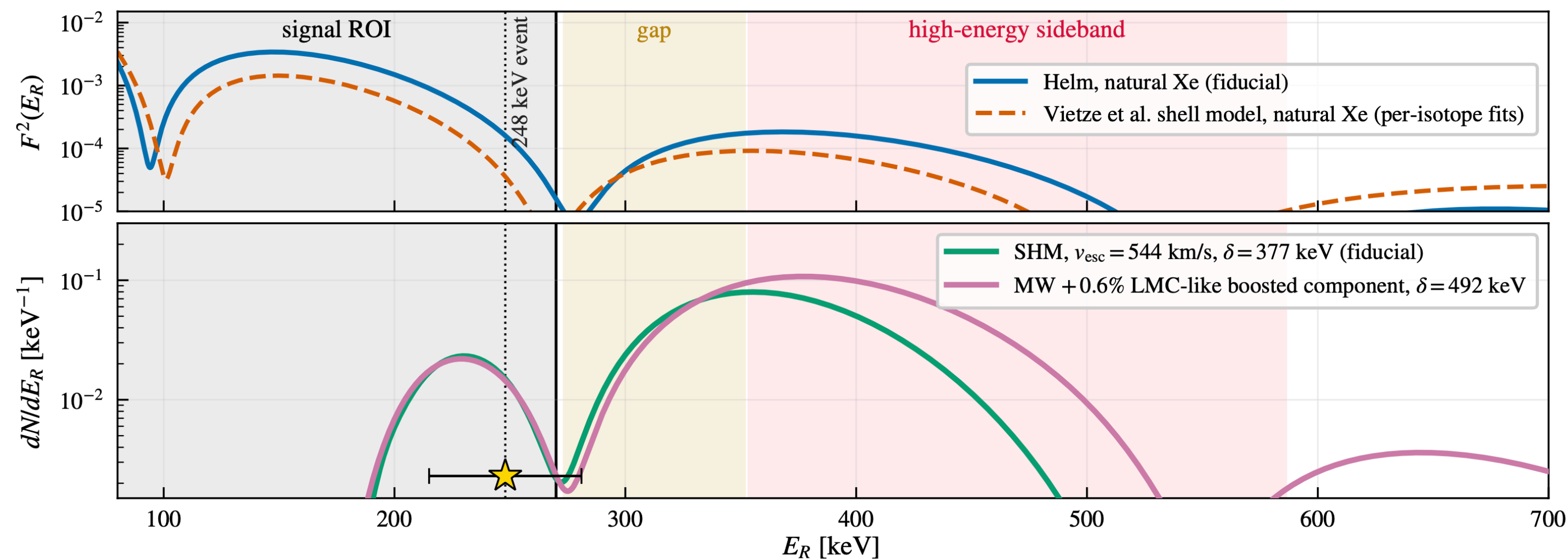
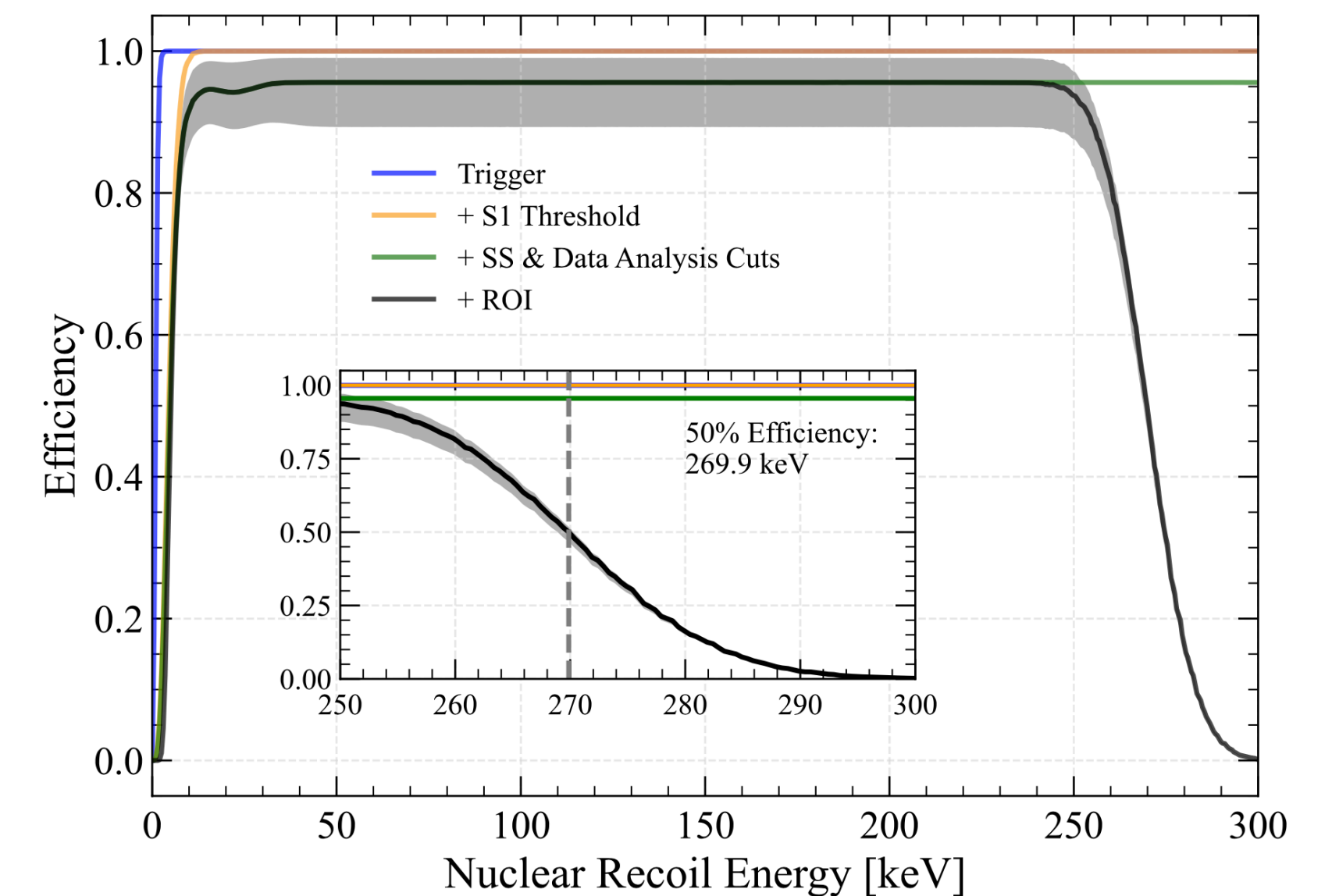
$$D_\pm = \frac{\psi^0 \pm \tilde{\psi}^0}{\sqrt{2}} \qquad \chi_1 = D_+$$

Model	$y_\star$	$m_{\chi,\star}$ [TeV]	$\delta_\star$ [keV]	$\sigma_{\text{SI}}^{\text{loop}}$ [cm ²]	N_{el}	$\Omega_\chi h^2$
$3_M 2_D$	5.92×10^{-3}	1.4	$379.3^{+1.6}_{-1.1}$	1.3×10^{-47}	0.5	0.12
$5_M 4_D$	1.407×10^{-2}	7.7	$389.1^{+3.3}_{-2.7}$	1.1×10^{-46}	0.8	0.12
$7_M 6_D$	2.370×10^{-2}	22	$386.2^{+4.4}_{-3.6}$	4.5×10^{-46}	1.2	0.12
$9_M 8_D$	3.483×10^{-2}	48	$382.3^{+5.3}_{-4.5}$	1.2×10^{-45}	1.5	0.12
$11_M 10_D$	4.529×10^{-2}	82	$378.5^{+6.3}_{-5.5}$	2.6×10^{-45}	1.8	0.12
$13_M 12_D$	5.680×10^{-2}	130	$375.4^{+7.1}_{-6.3}$	5.0×10^{-45}	2.4	0.12

Smirnov, arXiv:2609.04144



High-energy sideband



A successful interpretation must explain the candidate without overproducing events in neighbouring energy regions.

Pseudo-Dirac Vector model

$$\mathcal{L} \supset g_\chi V_\mu \bar{\Psi} \gamma^\mu \Psi + g_q V_\mu \sum_q \bar{q} \gamma^\mu q \quad \Psi = \begin{pmatrix} \xi_\alpha \\ \eta^{\dagger\dot{\alpha}} \end{pmatrix}$$

A small Majorana mass splits one Dirac fermion into two nearly degenerate Majorana states. The vector interaction becomes predominantly off diagonal, enabling inelastic scattering.

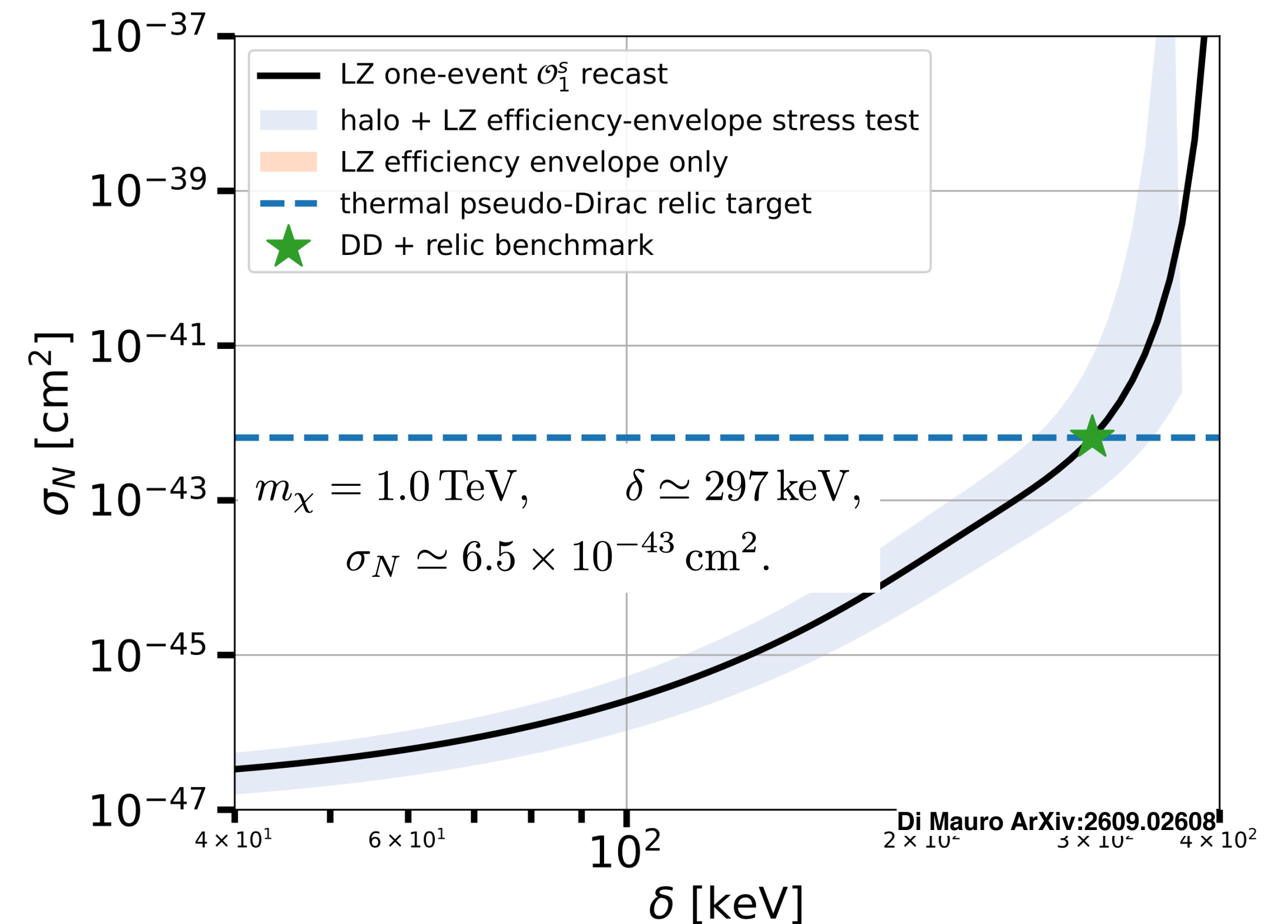
$$\mathcal{L}_{\text{mass}} = -m_D \xi \eta - \frac{1}{2} m_L \xi \xi - \frac{1}{2} m_R \eta \eta + \text{h.c.}$$

$$\delta \equiv m_{\chi_2} - m_{\chi_1} \simeq m_L + m_R$$

$$\bar{\Psi} \gamma^\mu \Psi \longrightarrow i \bar{\chi}_2 \gamma^\mu \chi_1$$

$$\mathcal{L}_{\text{eff}} = i \frac{g_\chi g_q}{m_V^2} (\bar{\chi}_2 \gamma^\mu \chi_1) \sum_q \bar{q} \gamma_\mu q$$

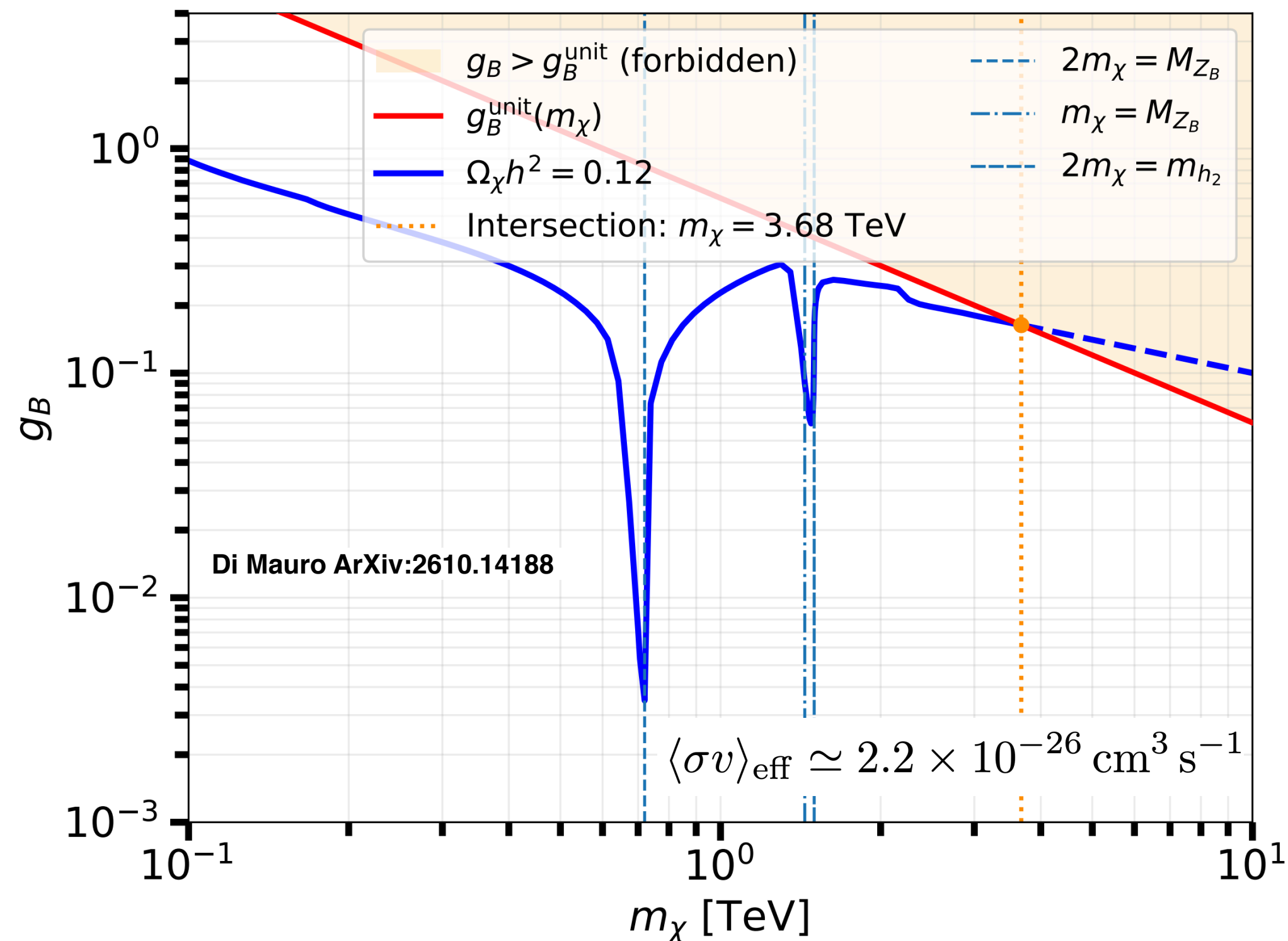
A thermal pseudo-Dirac vector model fits LZ event with a much smaller nuclear cross section wrt the thermal Higgsino



Relic density, indirect detection and solar capture

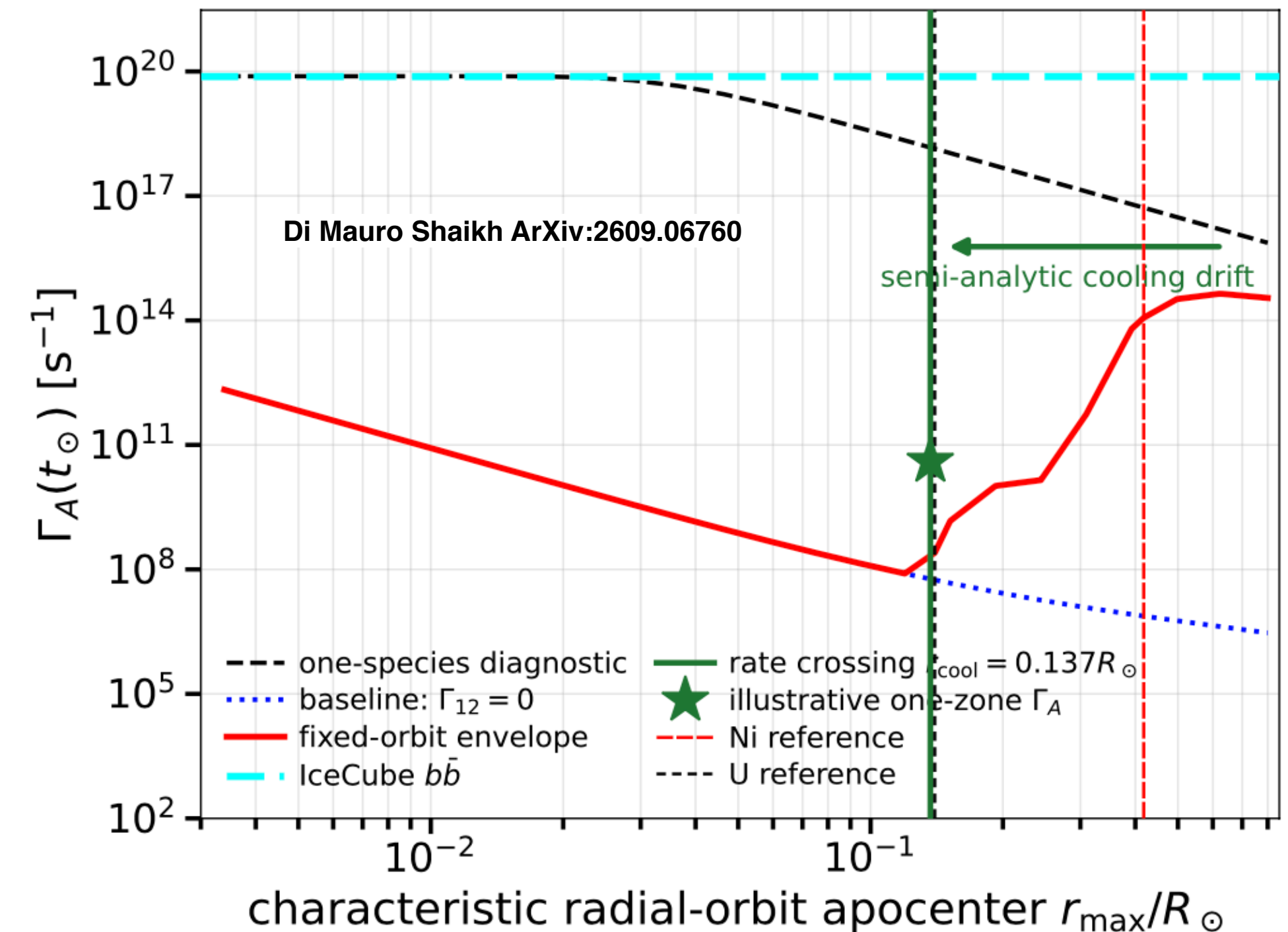
Relic density and Indirect detection

- At freeze-out, both states participate when the splitting is small compared with the temperature.
- Subsequent χ_2 depletion suppresses $\chi_1\chi_2$ annihilation today and ID signal.
- Open $\chi_1\chi_1$ annihilation channels must still be tested against ID limits.



Solar capture

- Track both states after capture, including transitions, decay, cooling and annihilation.
- Two-state kinetics after capture, including the suppression of annihilation caused by the inelastic transitions.
- Repeated excitation/de-excitation cycles and orbital cooling inside the Sun taking into account elastic scatterings.



A UV completion: pseudo-Dirac dark matter with gauged baryon number

$$\mathcal{G} = SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_B$$

Tab. I. Field content beyond the SM. The new fermions are vectorlike under $SU(3)_c \times SU(2)_L \times U(1)_Y$ but chiral under $U(1)_B$. The charge assignment in Eq. (7) cancels all gauge and mixed gravitational anomalies, as shown in App. A.

field	$SU(3)_c$	$SU(2)_L$	Y	B
Ψ_L	1	2	$-1/2$	$-9/2$
Ψ_R	1	2	$-1/2$	$-3/2$
η_R	1	1	-1	$-9/2$
η_L	1	1	-1	$-3/2$
χ_R	1	1	0	$-9/2$
χ_L	1	1	0	$-3/2$
S_B	1	1	0	-3

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{kin}}^{\text{new}} + \mathcal{L}_{\text{Yuk}} - V(H, S_B)$$

$$\begin{aligned} -\mathcal{L}_{\text{Yuk}} = & y_1 \bar{\Psi}_L H \eta_R + y_2 \bar{\Psi}_L \tilde{H} \chi_R \\ & + y_3 \bar{\Psi}_R H \eta_L + y_4 \bar{\Psi}_R \tilde{H} \chi_L \\ & + \lambda_\Psi S_B \bar{\Psi}_L \Psi_R + \lambda_\eta S_B \bar{\eta}_R \eta_L \\ & + \lambda_\chi S_B \bar{\chi}_R \chi_L + \frac{y_\chi}{2} S_B^\dagger \overline{\chi_L^c} \chi_L + \text{h.c.}, \end{aligned}$$

$$\begin{aligned} V(H, S_B) = & -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 \\ & -\mu_B^2 S_B^\dagger S_B + \lambda_B (S_B^\dagger S_B)^2 \\ & + \lambda_{HB} (H^\dagger H) (S_B^\dagger S_B). \end{aligned}$$

$$M_\Psi = \frac{\lambda_\Psi v_B}{\sqrt{2}}, \quad M_\eta = \frac{\lambda_\eta v_B}{\sqrt{2}}, \quad M_\chi = \frac{\lambda_\chi v_B}{\sqrt{2}} \qquad M_{Z_B} = 3g_B v_B \qquad m_M = \frac{y_\chi v_B}{\sqrt{2}}$$

Anomaly-cancelling fermions complete the gauge theory. Symmetry breaking generates the mediator and dark-fermion masses, while a residual symmetry stabilizes dark matter.

Particle mixing and dark matter splitting

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos \theta_B & \sin \theta_B \\ -\sin \theta_B & \cos \theta_B \end{pmatrix} \begin{pmatrix} h_0 \\ s_0 \end{pmatrix}$$

$$\tan 2\theta_B = \frac{\lambda_{HB} v v_B}{\lambda_H v^2 - \lambda_B v_B^2}$$

$$\mathcal{M}_0^{\text{Dirac}} = \begin{pmatrix} M_\Psi & m_2 \\ m_4 & M_D \end{pmatrix} \begin{pmatrix} \Psi_{L/R}^0 \\ \chi_{L/R} \end{pmatrix} = \begin{pmatrix} \cos \theta_{L/R} & -\sin \theta_{L/R} \\ \sin \theta_{L/R} & \cos \theta_{L/R} \end{pmatrix} \begin{pmatrix} N_{HL/R} \\ N_{LL/R} \end{pmatrix}$$

$$\theta_L = \theta_R = \theta_N = 0.005, \quad \begin{aligned} N_{LL} &\simeq \chi_L - \theta_L \Psi_L^0, \\ N_{LR} &\simeq \chi_R - \theta_R \Psi_R^0 \end{aligned}$$

$$-\mathcal{L}_\chi \supset \lambda_\chi S_B \overline{\chi_R} \chi_L + \frac{y_\chi}{2} S_B^\dagger \overline{\chi_L^c} \chi_L + \text{h.c}$$

$$\mathcal{M}_{\text{light}} = \begin{pmatrix} m_M^{\text{eff}} & m_{N_L} \\ m_{N_L} & 0 \end{pmatrix}$$

$$\mathcal{N}_L = \begin{pmatrix} N_{LL} \\ N_{LR}^c \end{pmatrix}$$

$$\delta_\chi = \frac{y_\chi v_B}{\sqrt{2}} \cos^2 \theta_L$$

$$\delta_\chi \equiv m_{\chi_2} - m_{\chi_1} = m_M^{\text{eff}} = m_M \cos^2 \theta_L$$

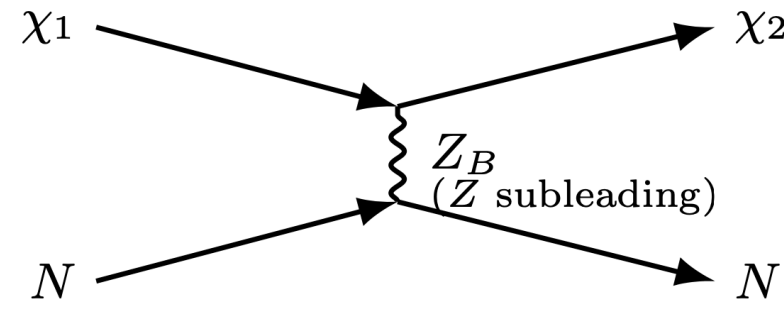
$$m_M^{\text{eff}} = m_M \cos^2 \theta_L$$

$$\chi_{1L} \simeq \frac{i}{\sqrt{2}} (N_{LL} - N_{LR}^c)$$

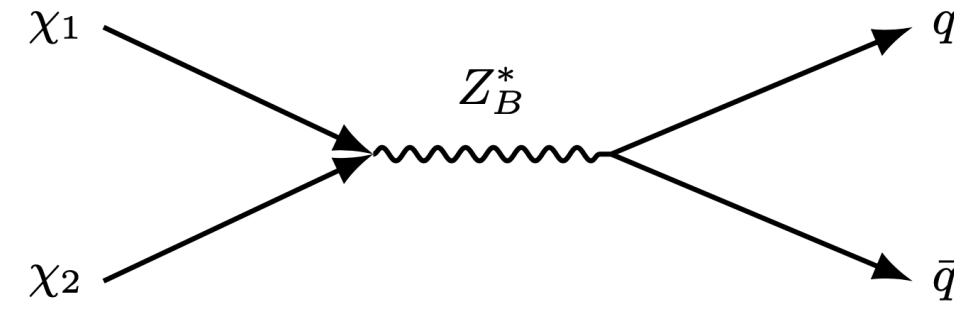
$$\chi_{2L} \simeq \frac{1}{\sqrt{2}} (N_{LL} + N_{LR}^c)$$

The same model links recoil, relic abundance and collider signals

(a) DD and Solar capture

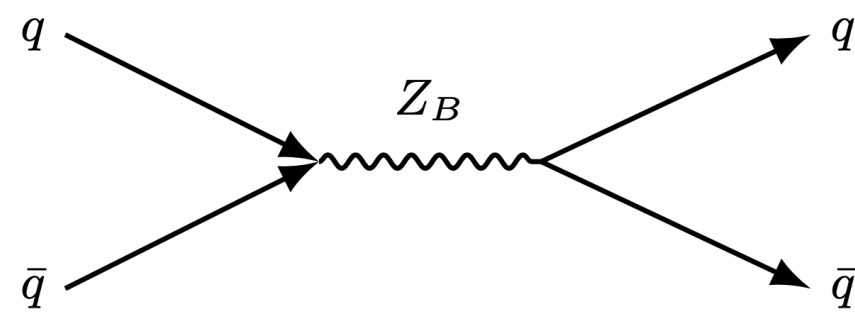


(b) Thermal coannihilation

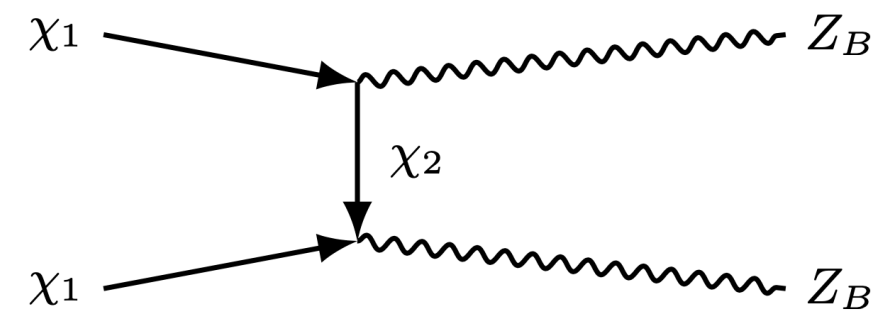


$$\mathcal{L}_Z \supset \frac{g}{4c_W} Z_\mu \bar{N}_L \gamma^\mu \left[\sin^2 \theta_L + \sin^2 \theta_R + (\sin^2 \theta_R - \sin^2 \theta_L) \gamma^5 \right] N_L$$

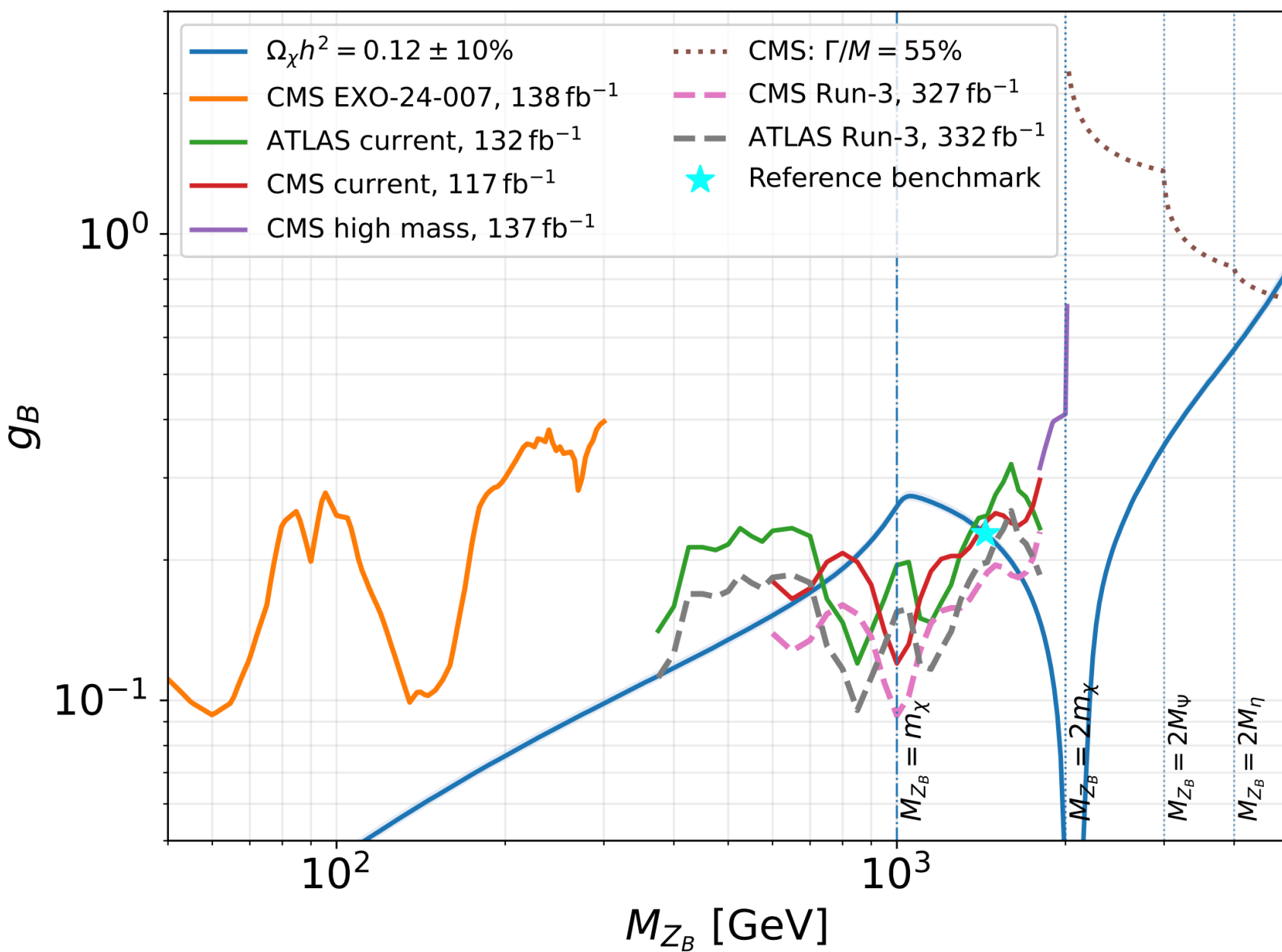
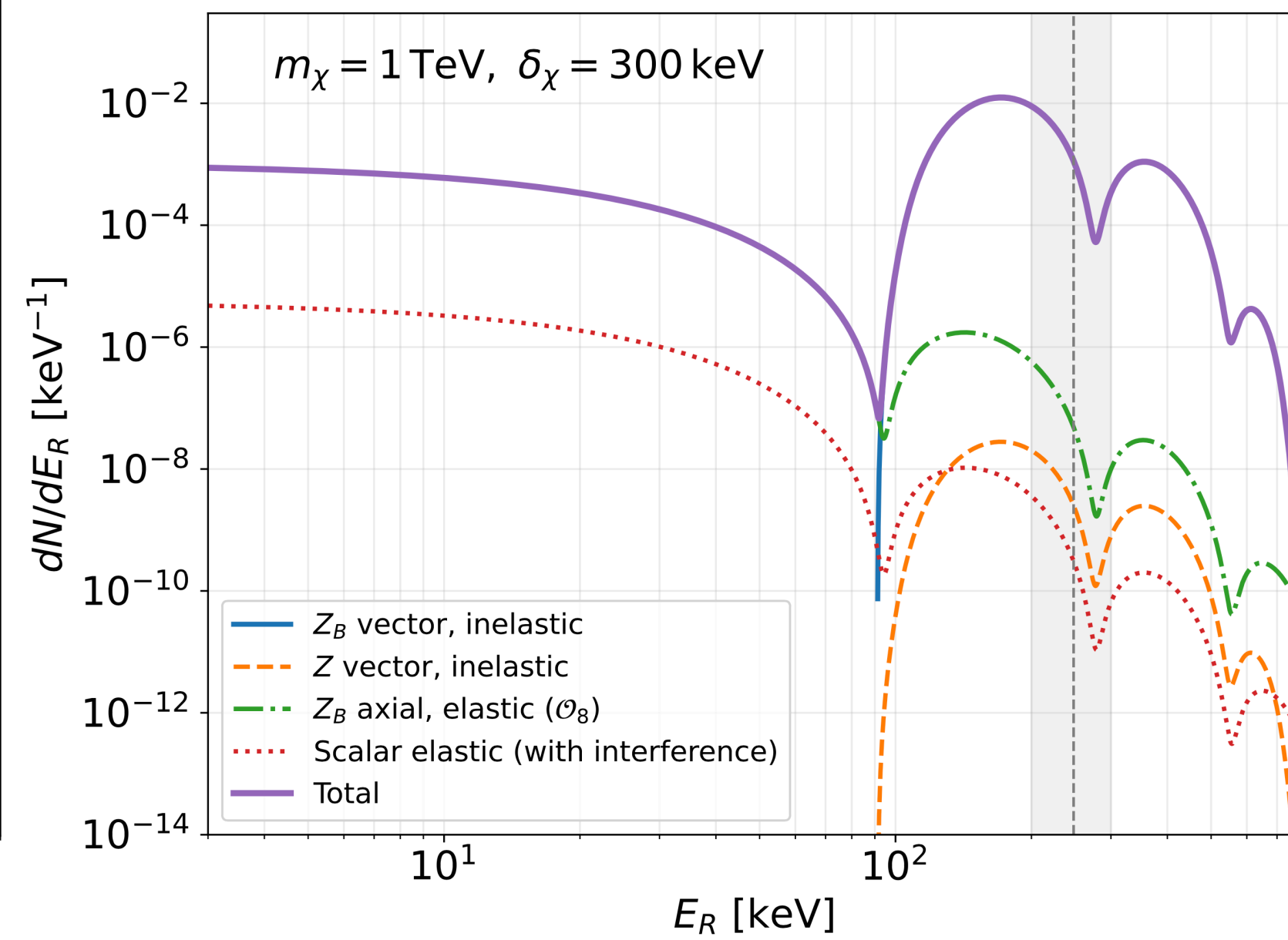
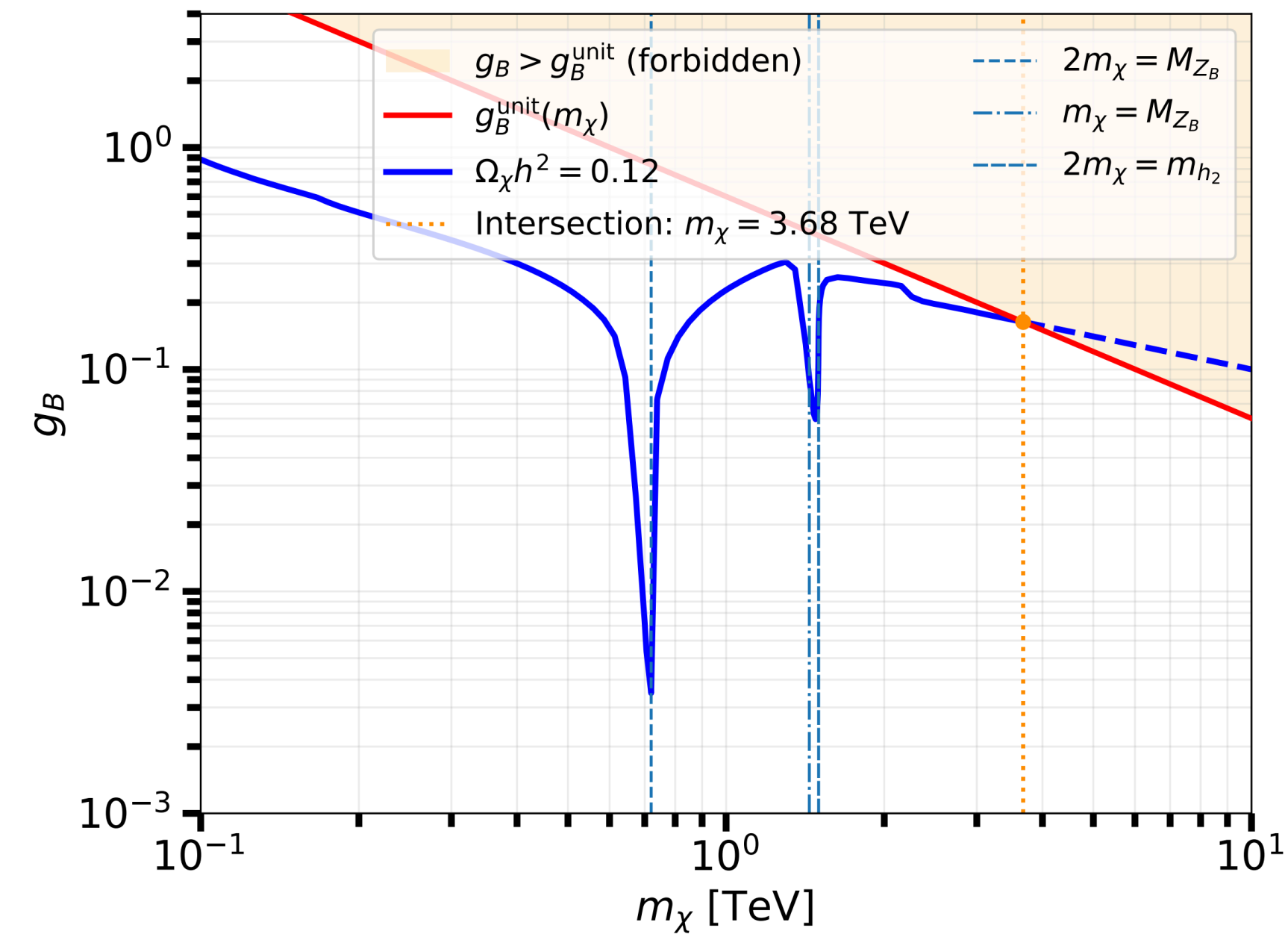
(c) Dijet resonance



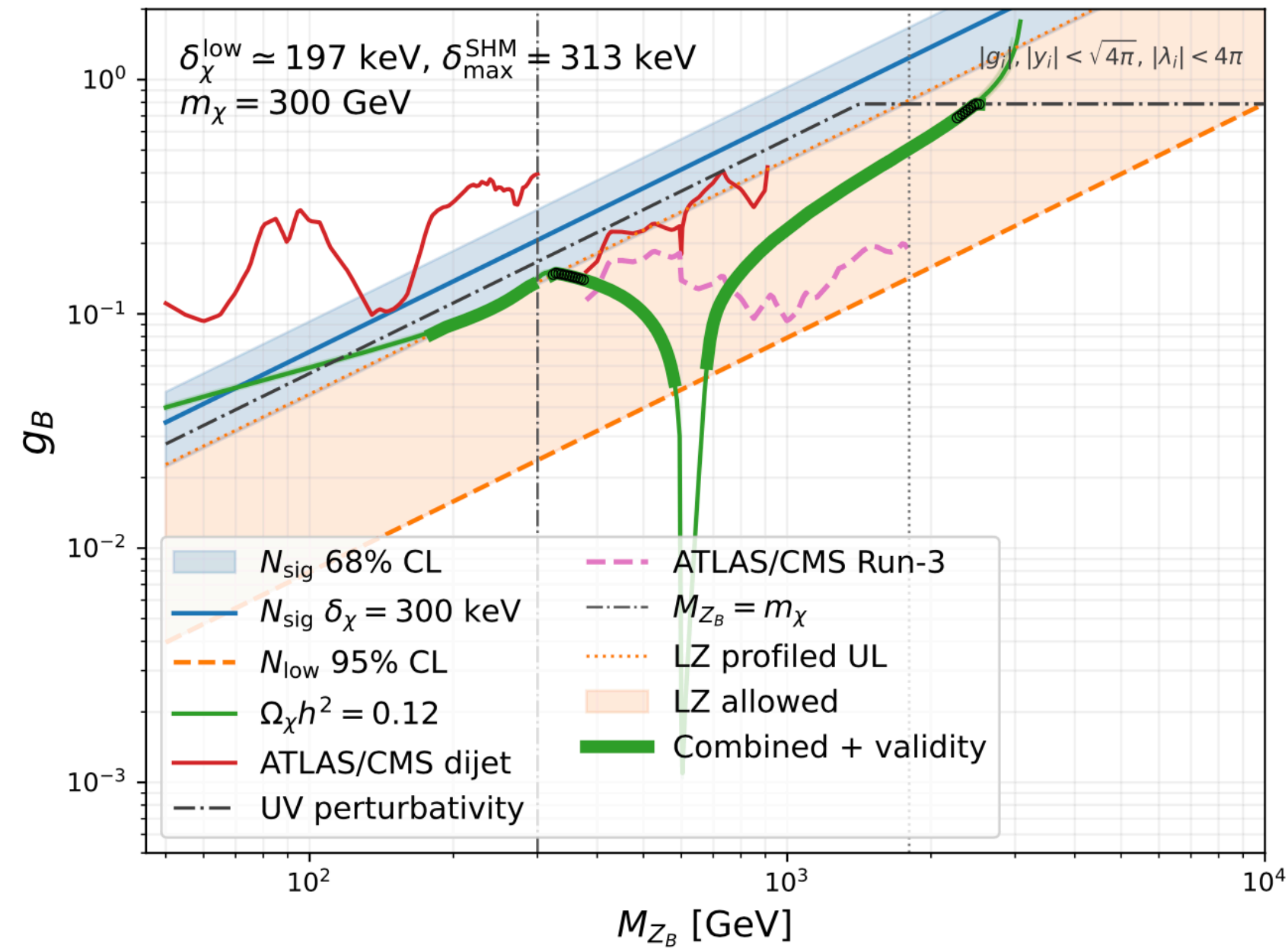
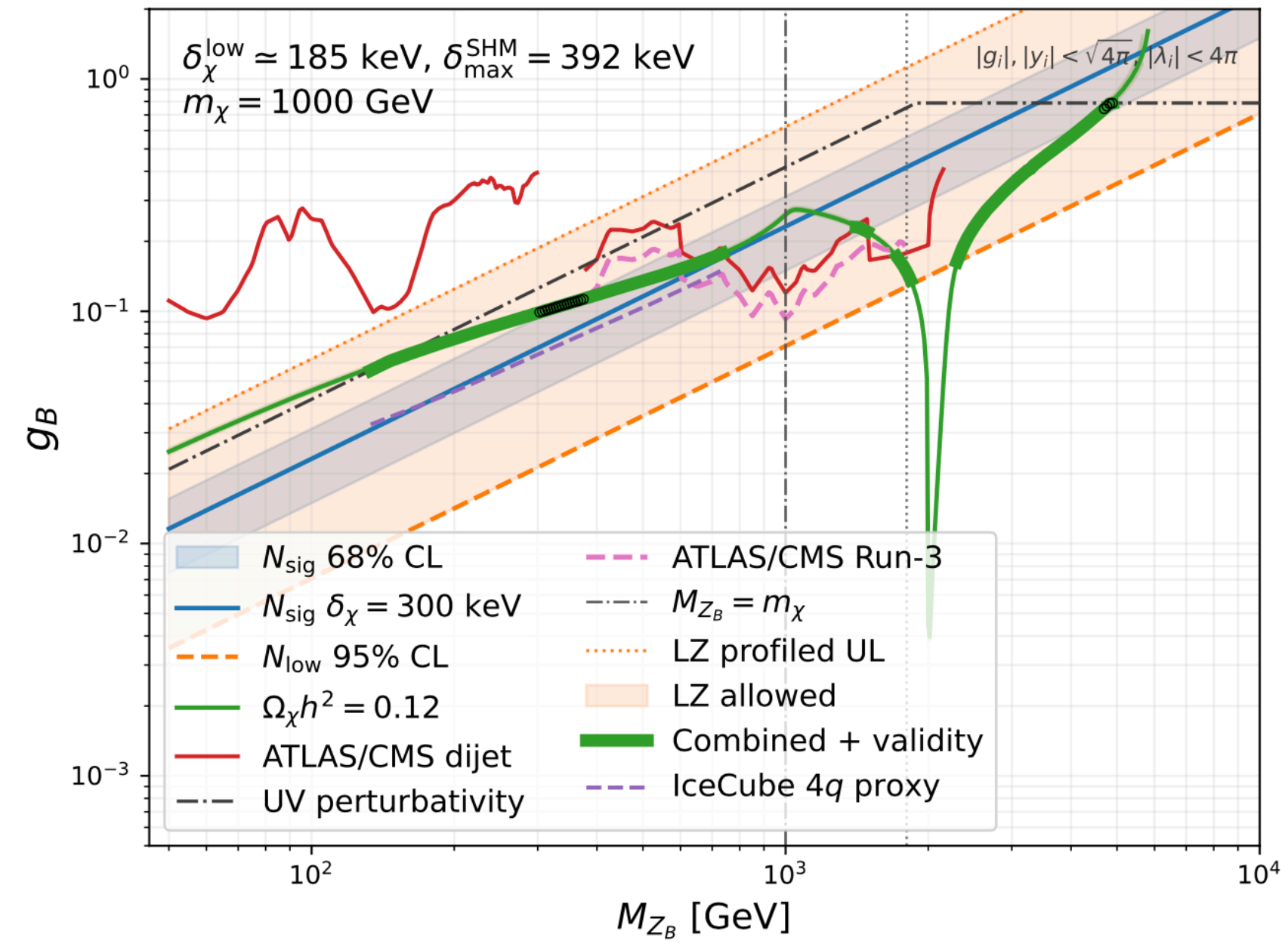
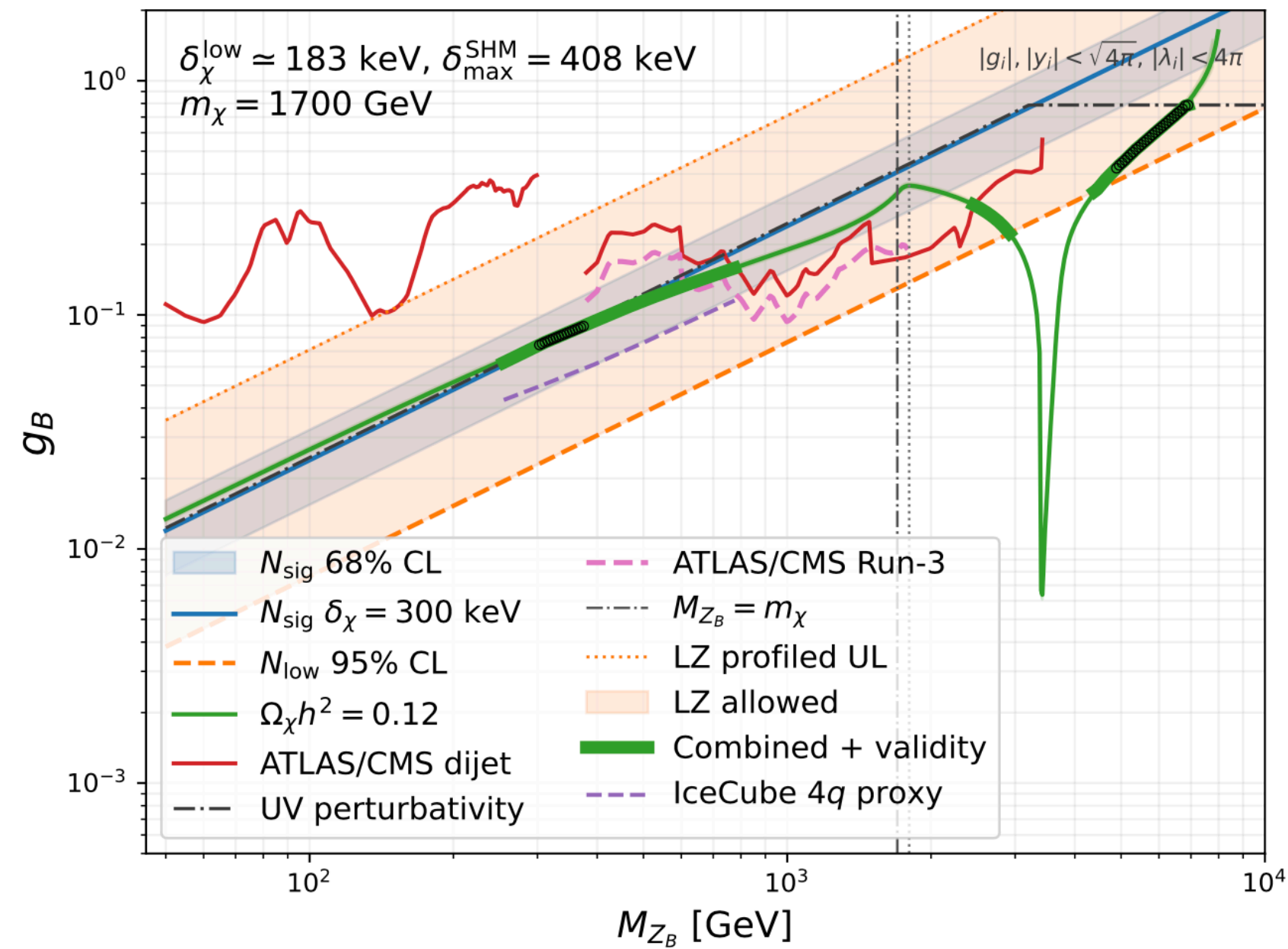
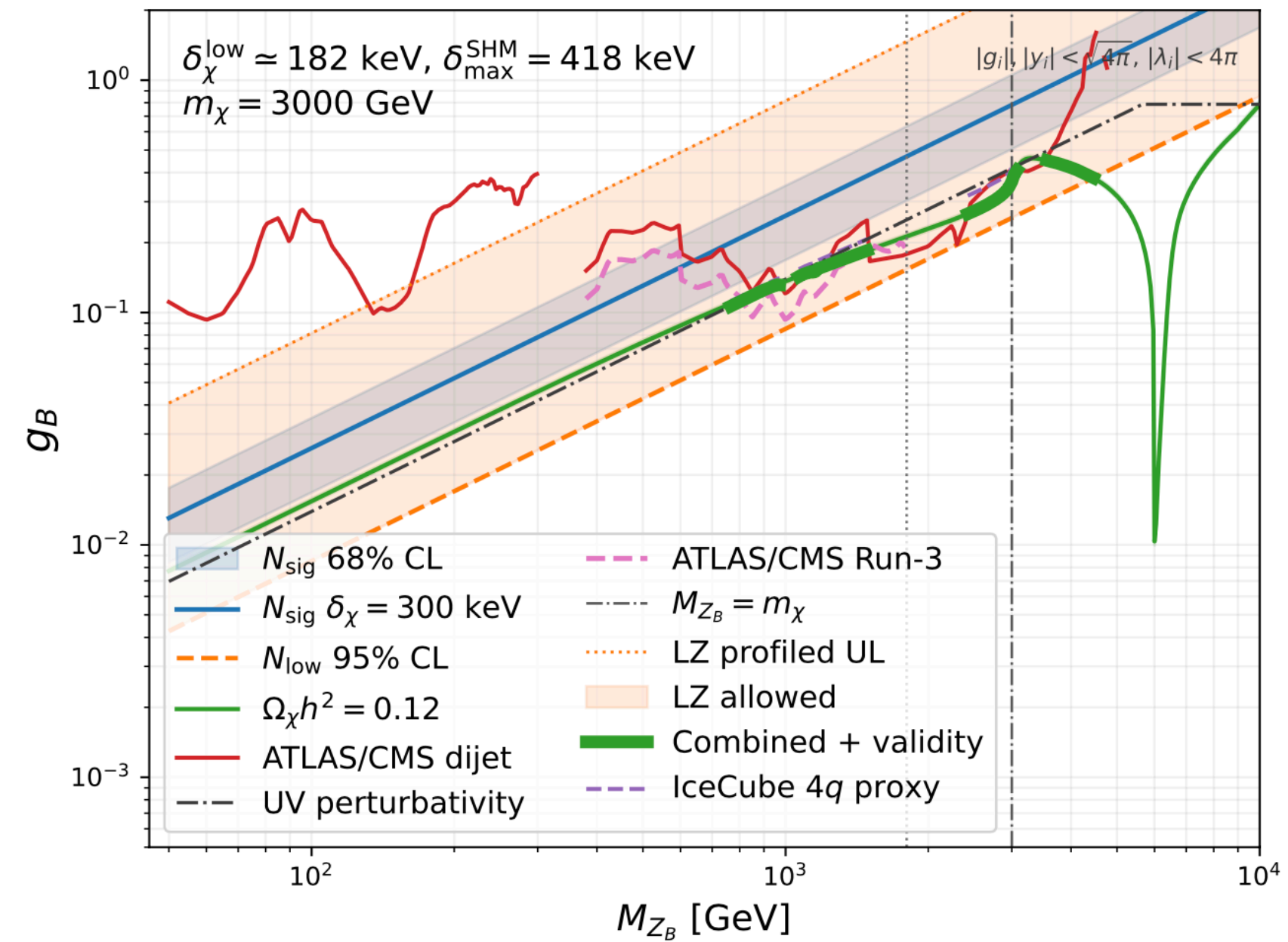
(d) Open-mediator annihilation



$$\mathcal{L}_{N_L Z_B} = g_B Z_{B\mu} \bar{N}_L \gamma^\mu (B_V^{\text{eff}} + B_A^{\text{eff}} \gamma^5) N_L$$



Combined results



Dark-photon-mediated endothermic dark matter

$$\mathcal{L}_{\text{gauge}} \supset -\frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} \\ + \frac{\epsilon}{2c_W}\hat{X}_{\mu\nu}\hat{B}^{\mu\nu} + \frac{1}{2}m_{X,0}^2\hat{X}_\mu\hat{X}^\mu,$$

$$\mathcal{L}_{\chi V} = g_D\hat{X}_\mu\bar{\psi}\gamma^\mu\psi \\ = \frac{ig_D}{\kappa}X_\mu\bar{\chi}_1\gamma^\mu\chi_2 \\ = i(g_{\chi A'}A'_\mu + g_{\chi Z}Z_\mu)\bar{\chi}_1\gamma^\mu\chi_2$$

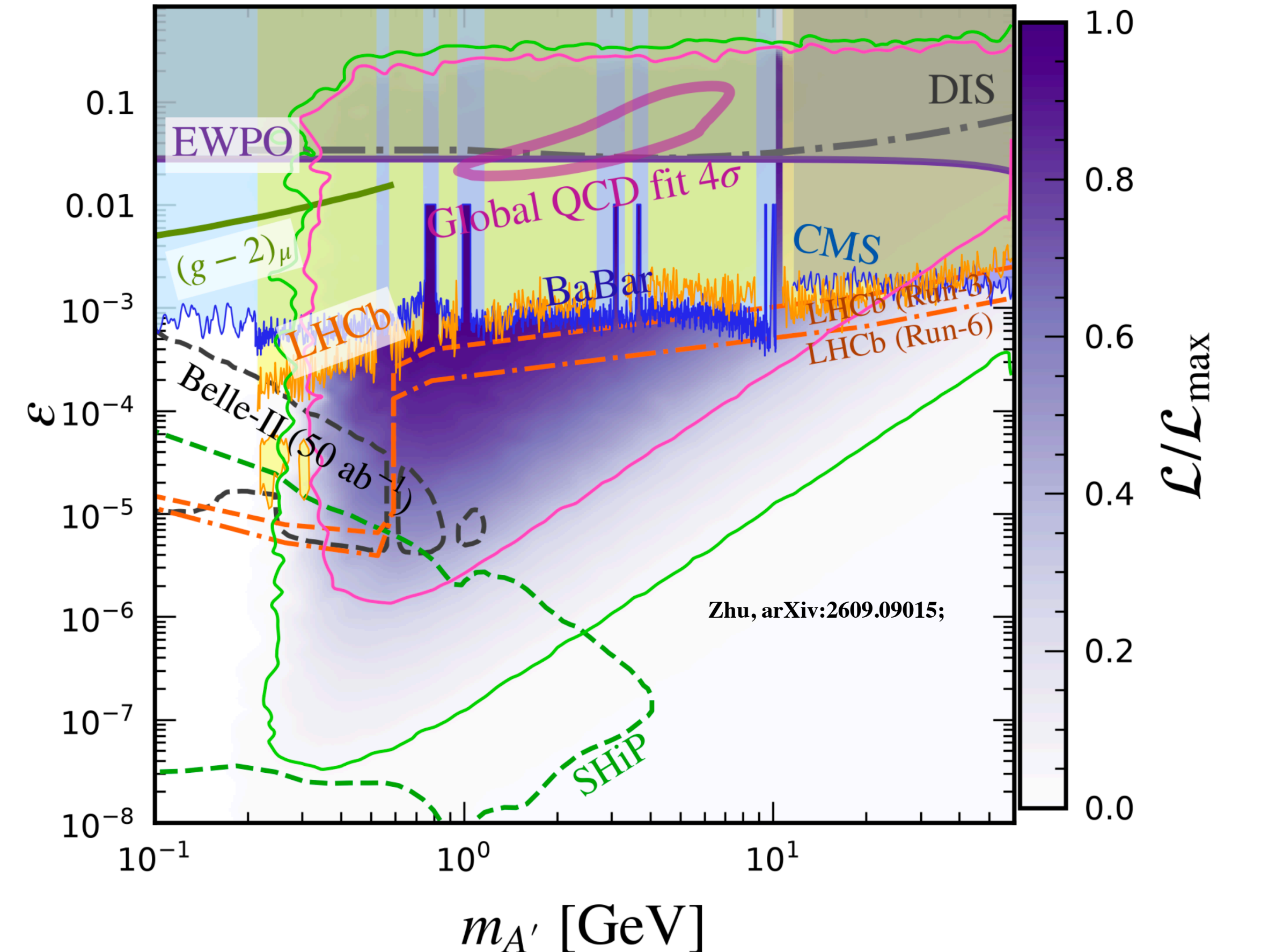
- The freeze-out process occurs in the secluded regime $m_{A'} \ll m_\chi$, so the dominant annihilation channels are $\chi_1\chi_1 \rightarrow A'A'$ and $\chi_2\chi_2 \rightarrow A'A'$.
- The mixed process $\chi_1\chi_2 \rightarrow \text{SM}$ proceeds through s-channel A' and Z exchange and is suppressed by ϵ .
- The $\chi_2 \rightarrow \chi_1 + 3\gamma$ channel is allowed, but its lifetime can exceed the age of the Universe.

$$\chi_2 \rightarrow \chi_1 + 3\gamma$$

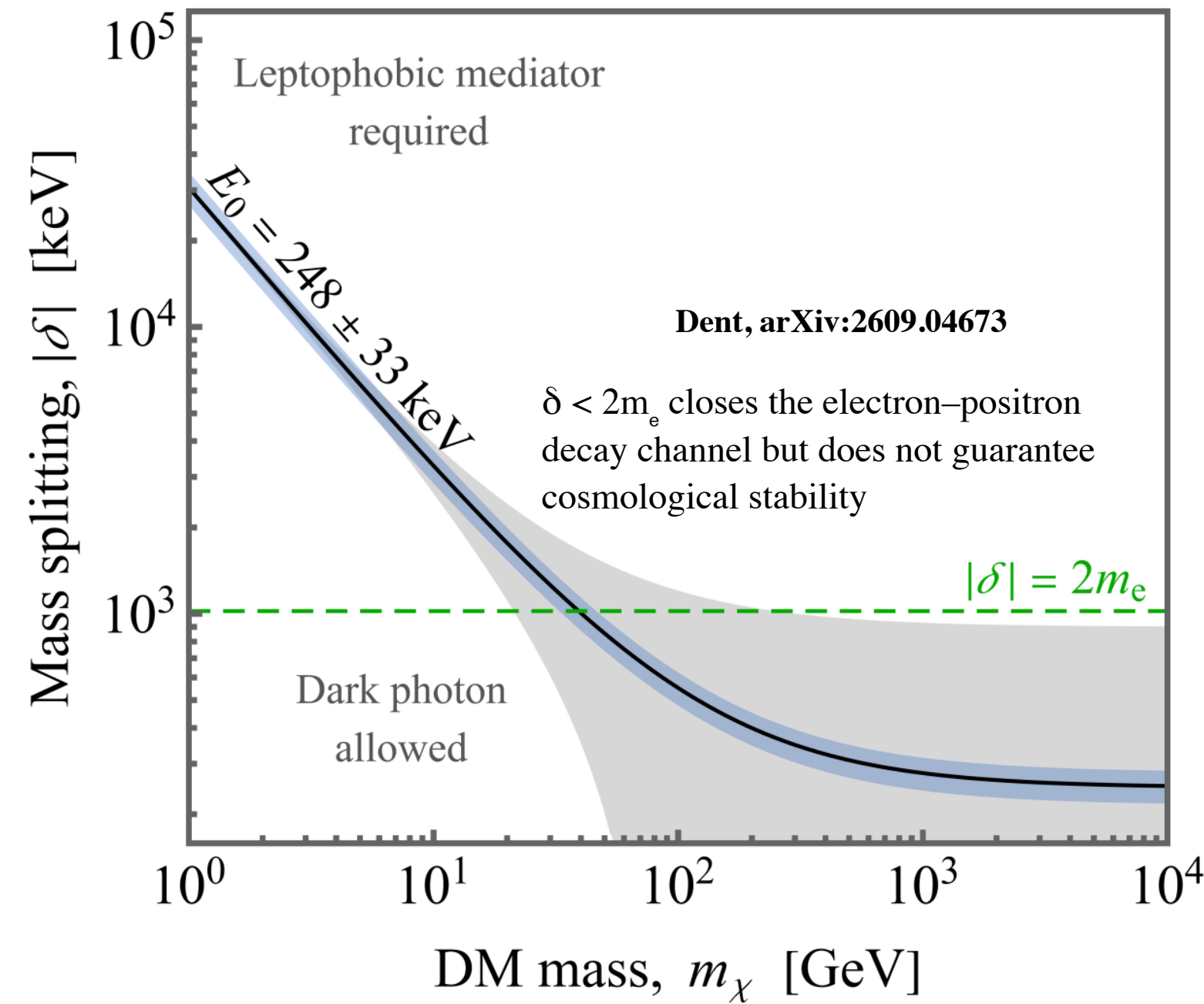
$$\tau_{3\gamma} \sim 10^{18} \text{ s} \left(\frac{300 \text{ keV}}{\delta} \right)^{13} \left(\frac{m_{A'}}{\text{GeV}} \right)^4 \left(\frac{10^{-3}}{\epsilon} \right)^2 \left(\frac{0.02}{\alpha_D} \right)$$

$$\psi = \frac{1}{\sqrt{2}}(\chi_1 + i\chi_2)$$

$$\mathcal{L}_\psi = \bar{\psi}i\gamma^\mu D_\mu\psi - m_D\bar{\psi}\psi - \frac{m_M}{2}(\bar{\psi}^c\psi + \text{h.c.})$$



Exothermic dark matter

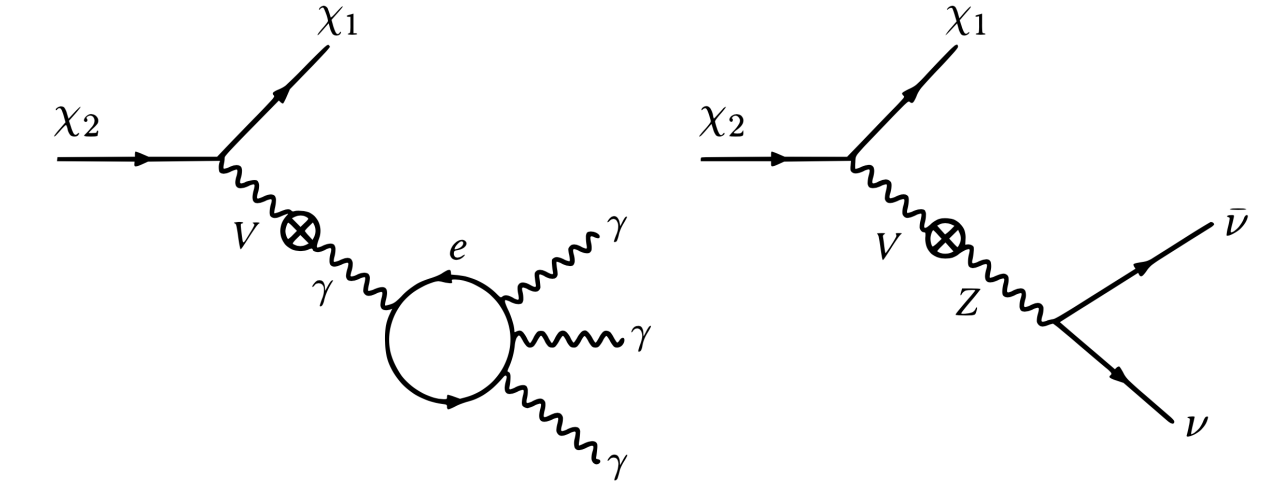
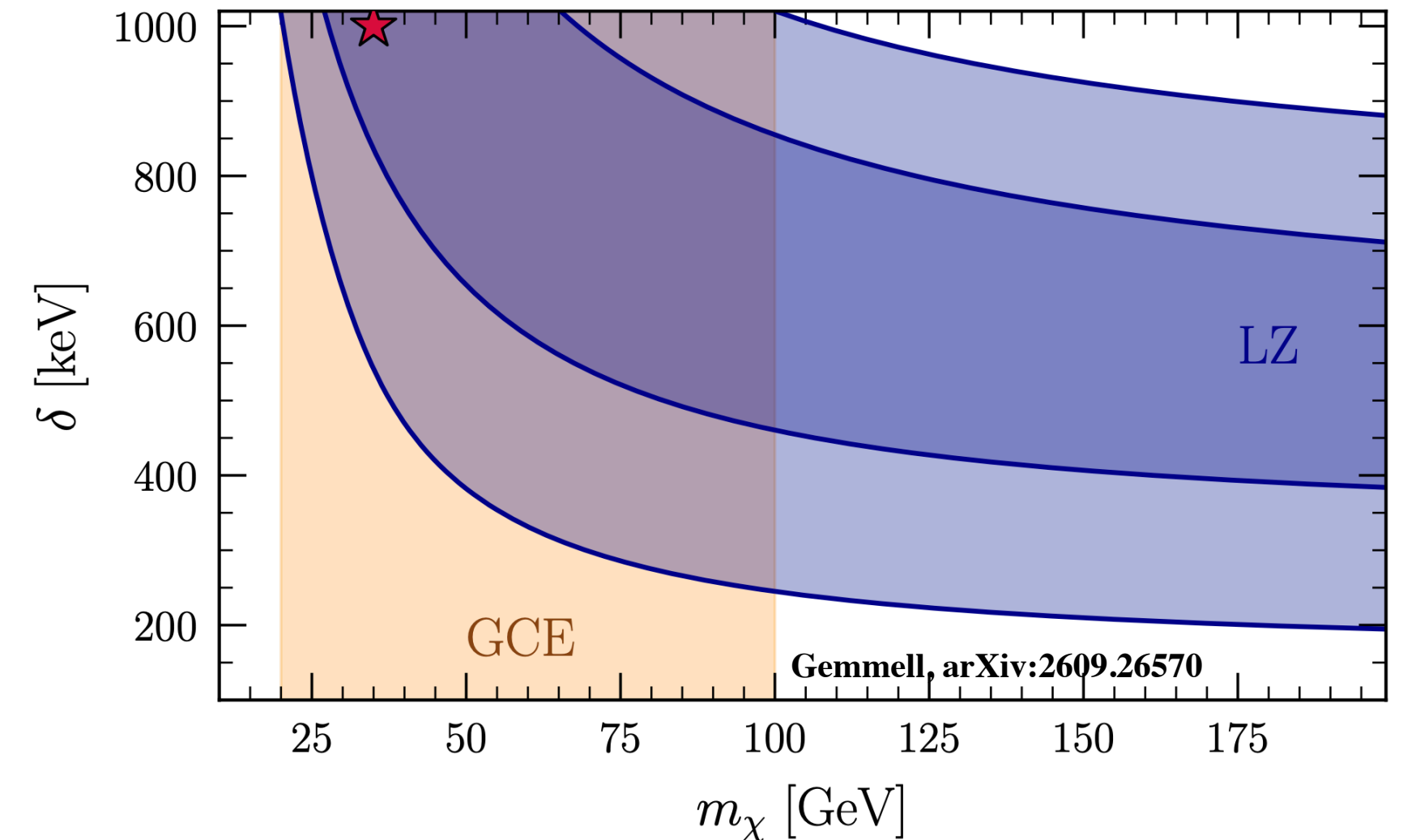


$$\mathcal{G} = SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_B$$

$$\mathcal{L}_{\text{int}} = \frac{1}{2} V_\mu \left(g_\chi \bar{\chi} \gamma^\mu \chi + g_B \sum_q \frac{1}{3} \bar{q} \gamma^\mu q \right)$$

$$\Gamma_{\nu\bar{\nu}}^{\text{KM}} = \frac{\varepsilon_Z^2 g^2 g_\chi^2}{5040 \pi^3 c_W^2} \frac{\delta^9}{m_Z^4 m_V^4} \approx \frac{1}{10^{32} \text{s}} \left(\frac{\varepsilon_Z g_\chi}{10^{-5}} \right)^2 \left(\frac{\delta}{\text{MeV}} \right)^9 \left(\frac{30 \text{ GeV}}{m_V} \right)^4$$

$$\chi_2 \rightarrow \chi_1 \bar{\nu} \nu$$



$$\chi^* \rightarrow \chi e^+ e^-$$

$$\tau_{\chi^*} \approx 4 \times 10^9 \text{s} \frac{1}{f_{\text{PS}}} \left(\frac{\sigma_p}{10^{-45} \text{cm}^2} \right)^{-1} \left(\frac{|\delta|}{2 \text{MeV}} \right)^{-5}$$

Down-scattering releases the excited-state mass splitting, allowing lighter dark matter to produce a high-energy recoil. The signal requires a surviving excited population, determined by decay and state conversion. The same model may generate observable annihilation signals, including a Galactic Center contribution.

Elastic scattering with momentum or velocity suppression

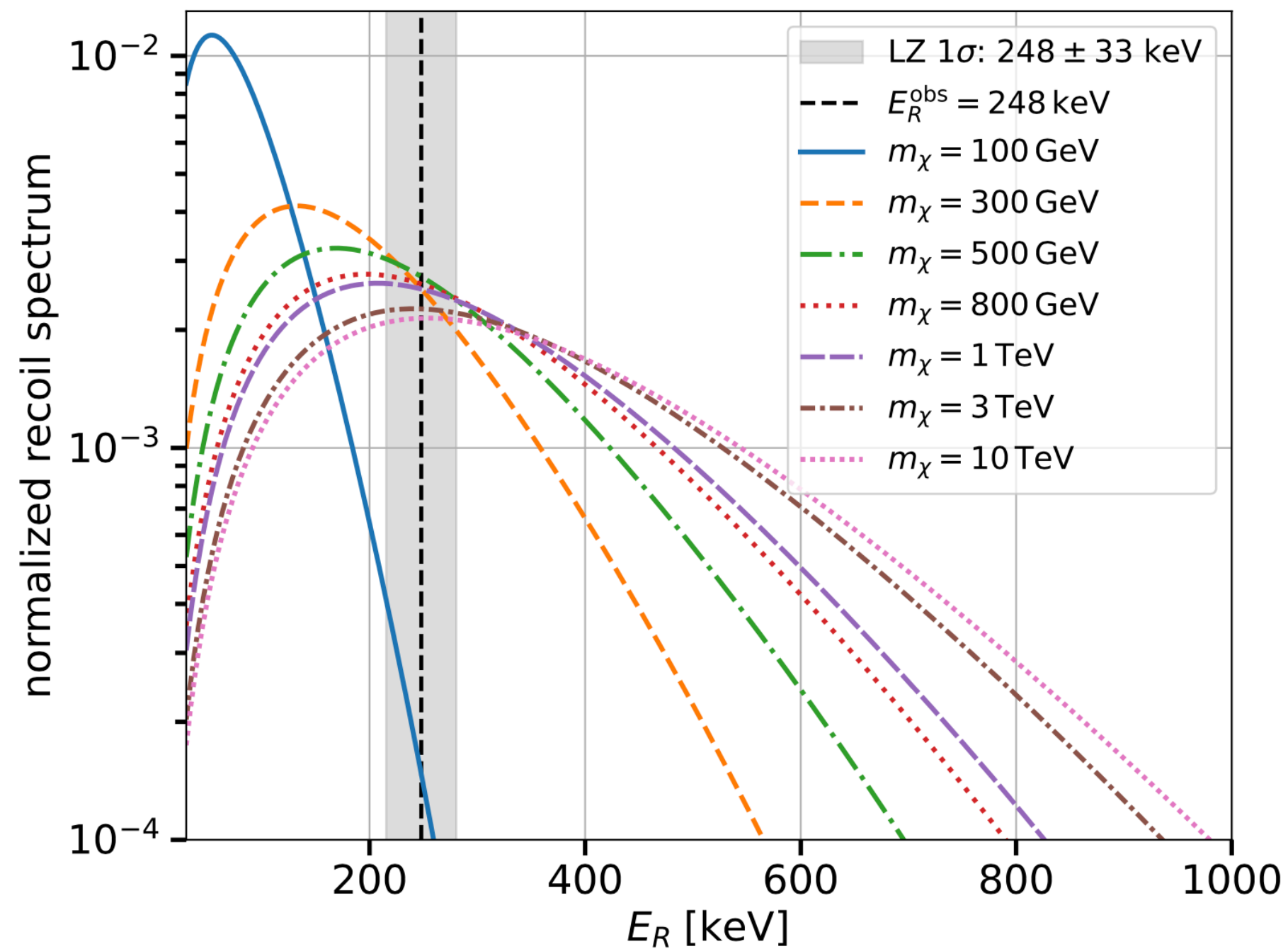
2HD+a model (Arcadi, arXiv:2609.17196;):

The scalar sector is therefore composed of two $SU(2)_L$ doublets, Φ_1 and Φ_2 , together with a pseudoscalar singlet a_0 .

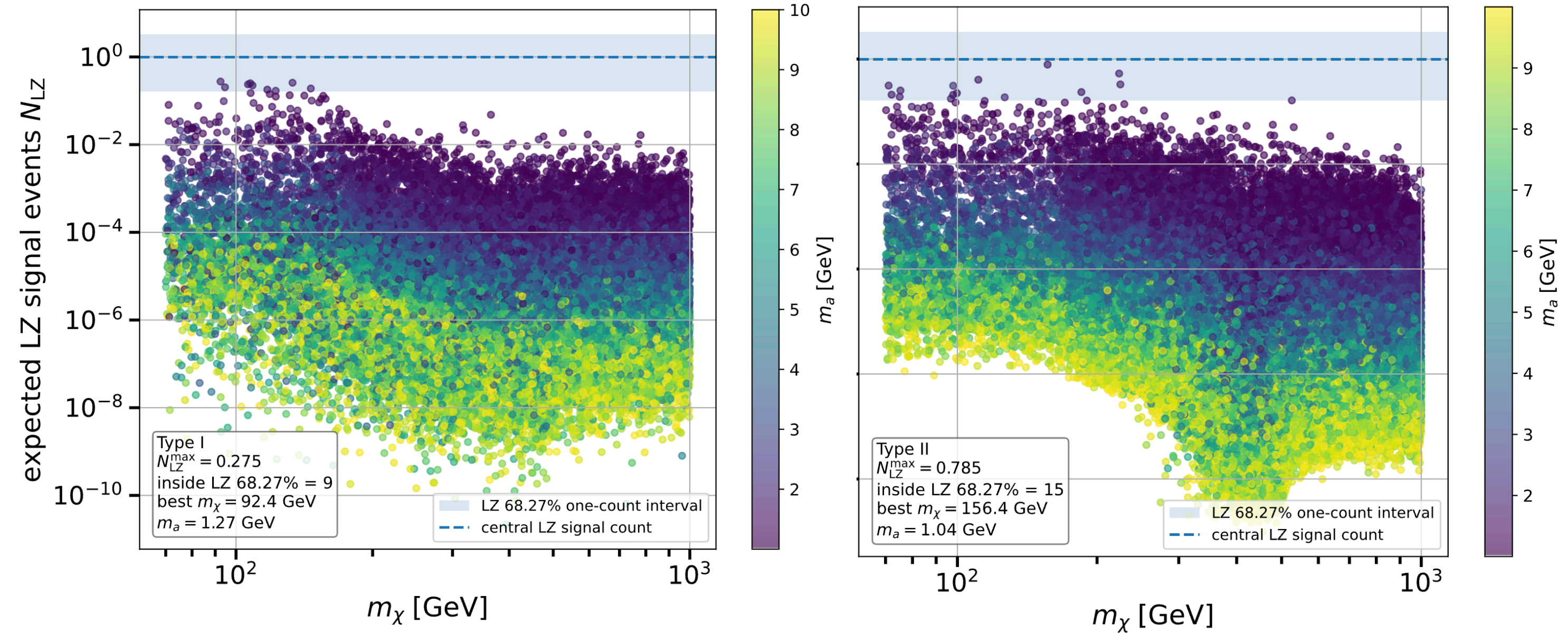
$$V = V(\Phi_1, \Phi_2) + \frac{1}{2}m_{a_0}^2 a_0^2 + \frac{\lambda_a}{4}a_0^4 + \left(i\kappa a_0 \Phi_1^\dagger \Phi_2 + \text{h.c.}\right) + \lambda_{1P}a_0^2 \Phi_1^\dagger \Phi_1 + \lambda_{2P}a_0^2 \Phi_2^\dagger \Phi_2 \quad \mathcal{L}_{\text{Yukawa}} = \sum_f \frac{m_f}{v} \left[g_{hff} h \bar{f} f + g_{Hff} H \bar{f} f - i g_{A_0 ff} \cos \theta A \bar{f} \gamma_5 f + i g_{A_0 ff} \sin \theta a \bar{f} \gamma_5 f \right]$$

$$\mathcal{L}_\chi = i y_\chi \bar{\chi} \gamma_5 \chi (a \cos \theta + A \sin \theta)$$

$$\mathcal{L}_{\text{eff}} = 4c_N(Q^2)\mathcal{O}_6^{\text{NR}} = 4c_N(Q^2)(\mathbf{S}_\chi \cdot \mathbf{Q})(\mathbf{S}_N \cdot \mathbf{Q})$$



Relic density + LZ + Collider + Flavour constraints.

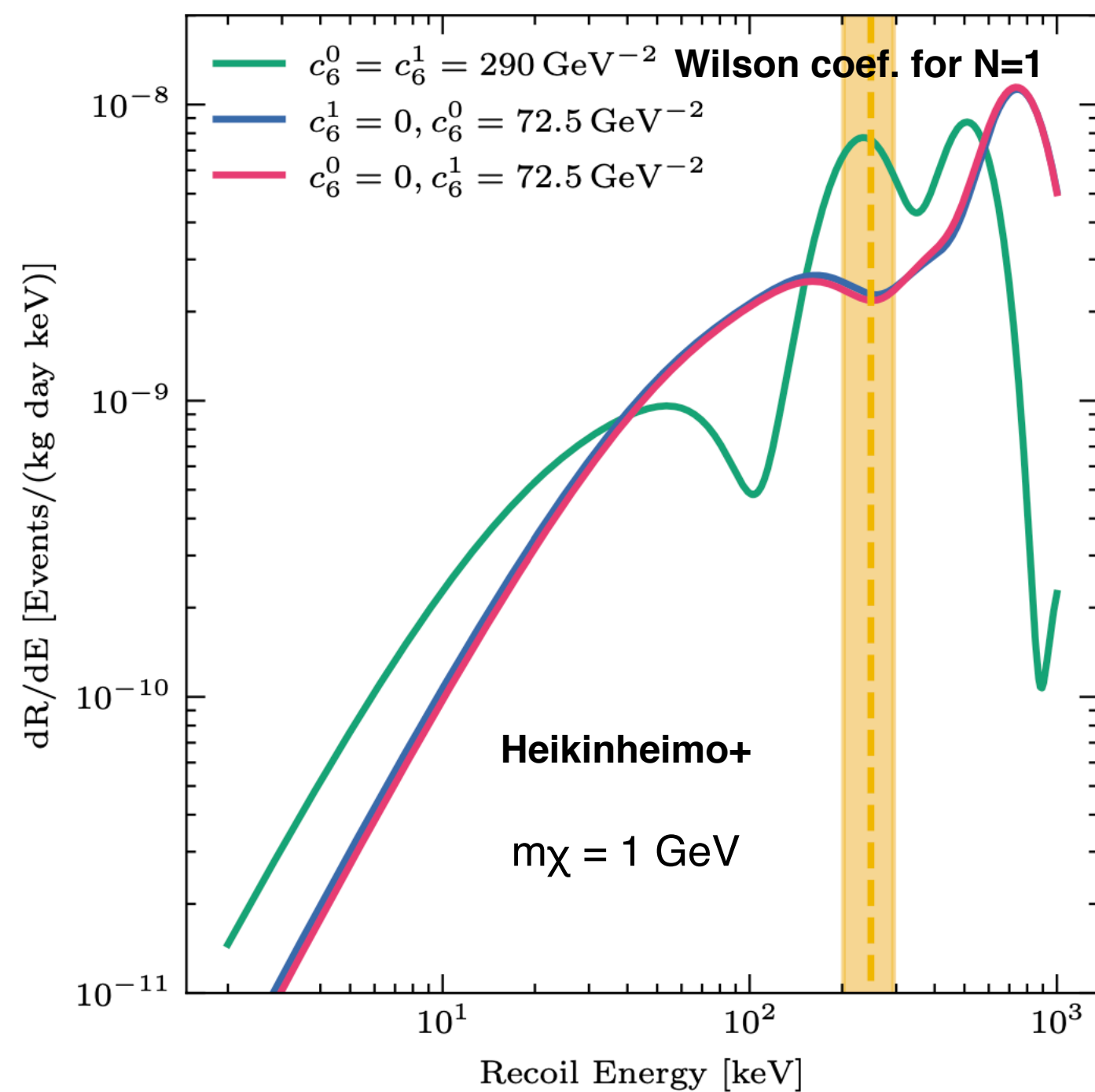
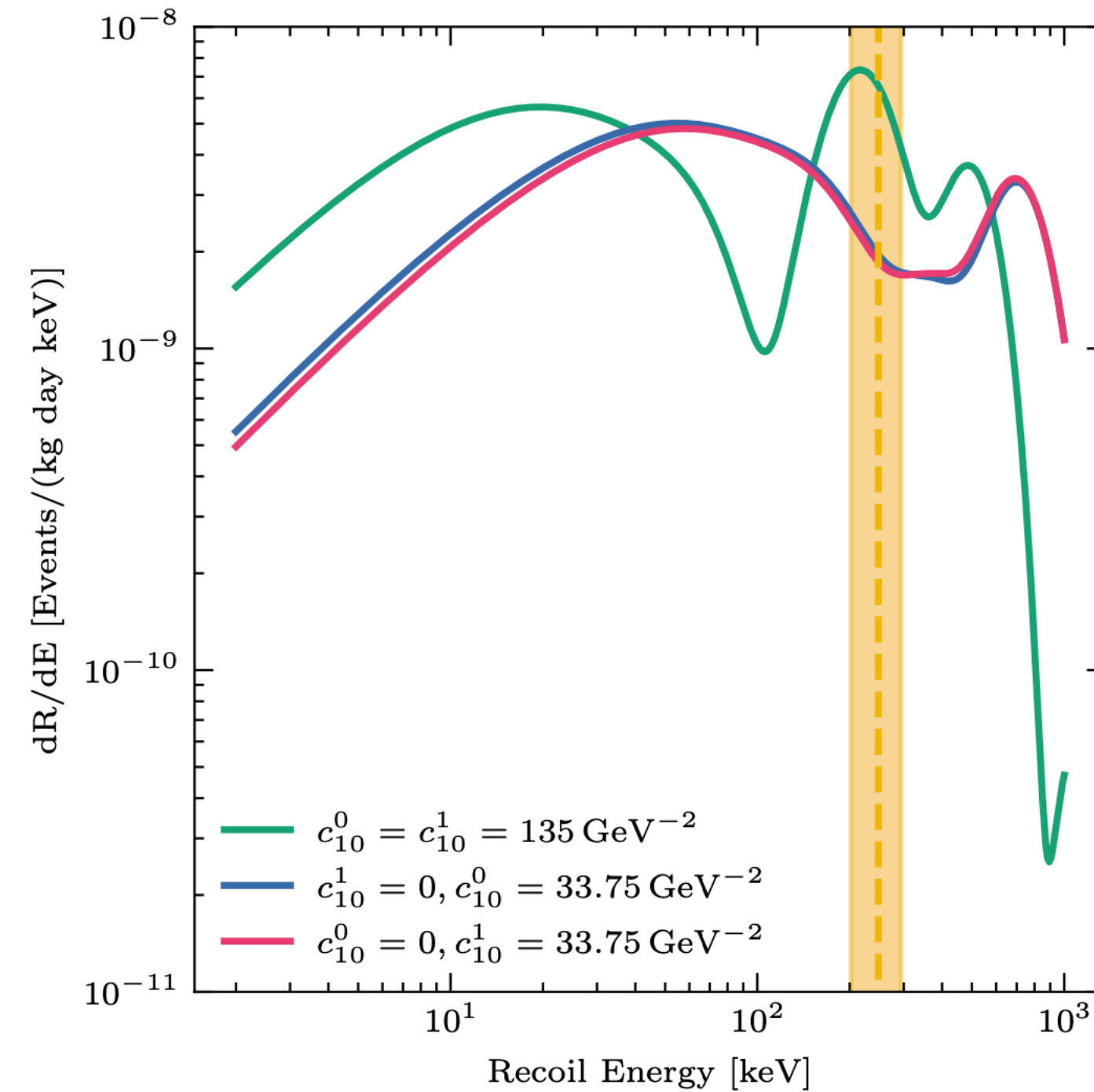
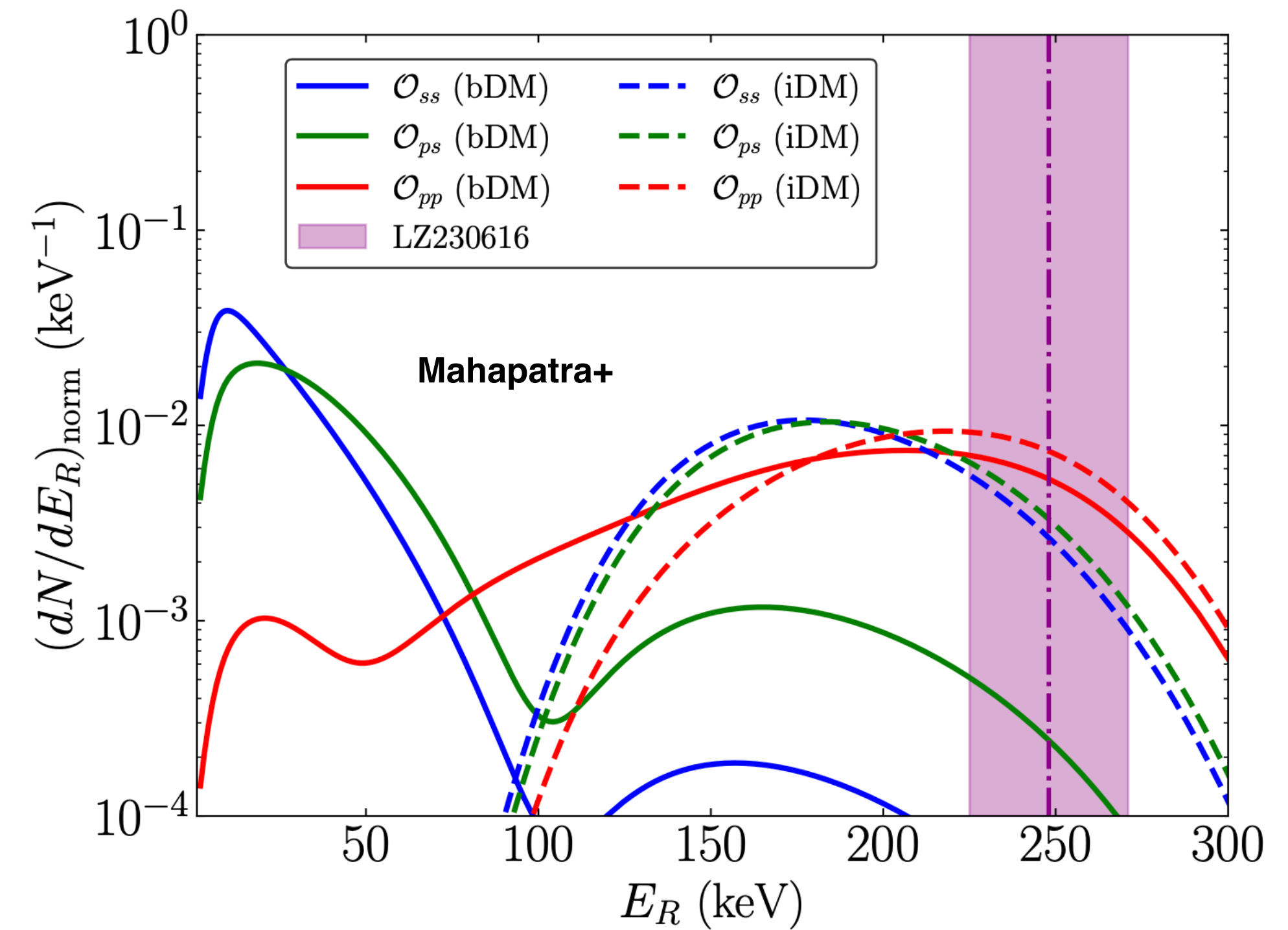


In Type-I, all quarks and charged leptons couple to the same doublet, conventionally chosen as Φ_2 .

In Type-II, up-type quarks couple to Φ_2 , while down-type quarks and charged leptons couple to Φ_1 .

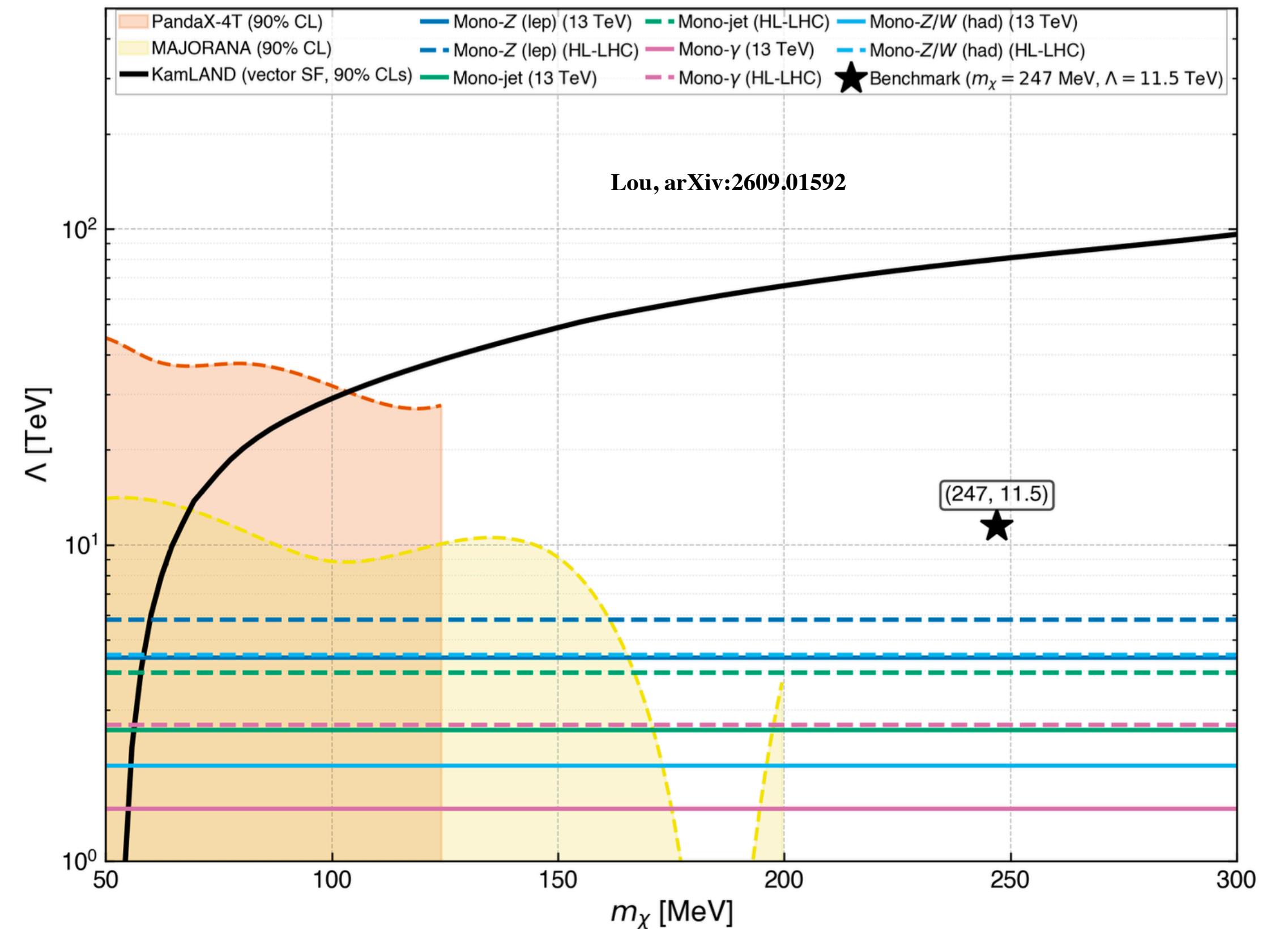
Boosted dark matter

- **Dark-sector production:** Annihilation or decay of a heavier dark-matter component can produce boosted light particles energetic enough to generate the 248-keV recoil.
- **Cosmic-ray acceleration:** cosmic rays transfer energy to initially slow dark matter. Momentum-dependent interactions, such as O6 and O10, can produce a recoil spectrum concentrated near the LZ candidate.



Fermionic DM absorption

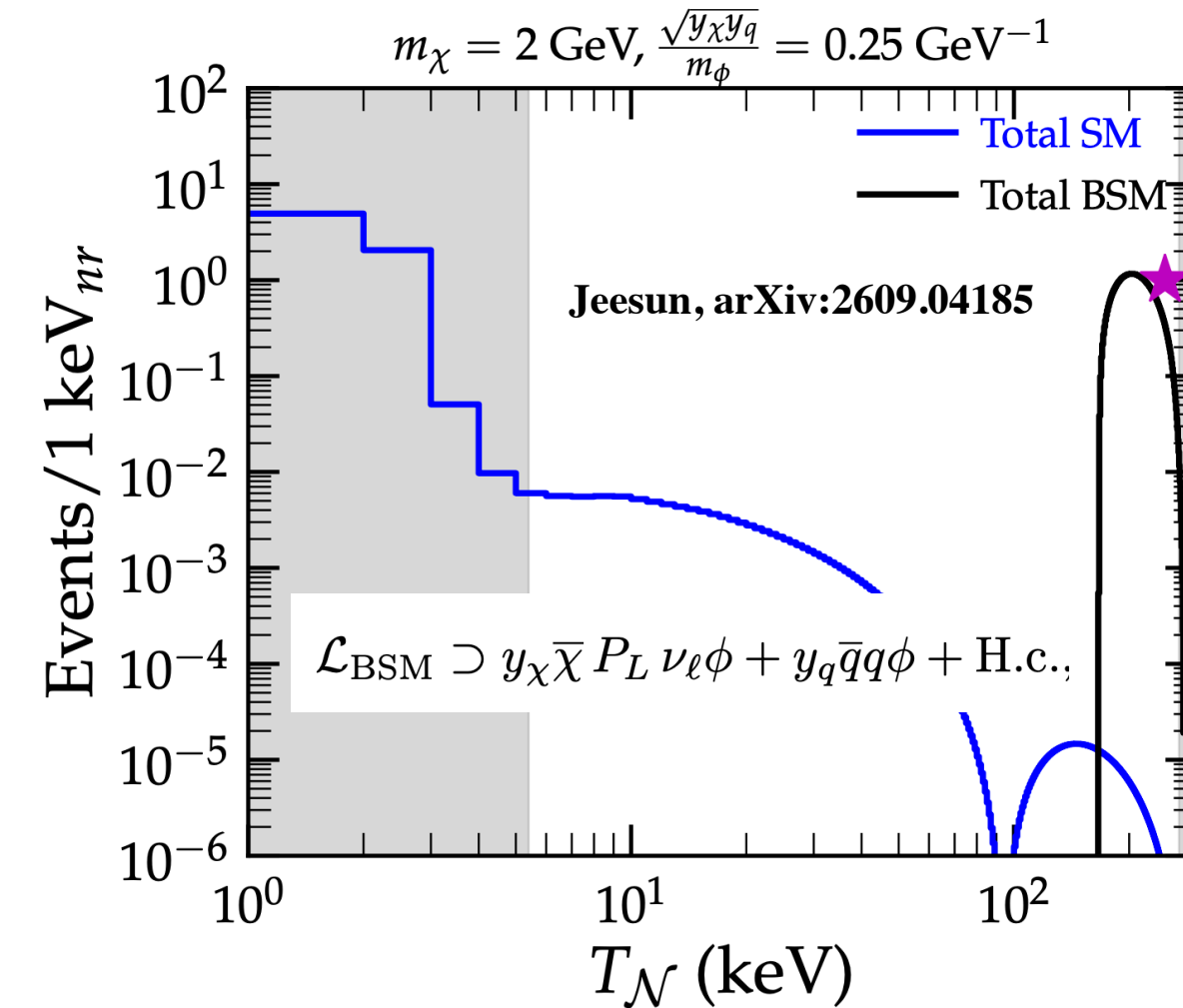
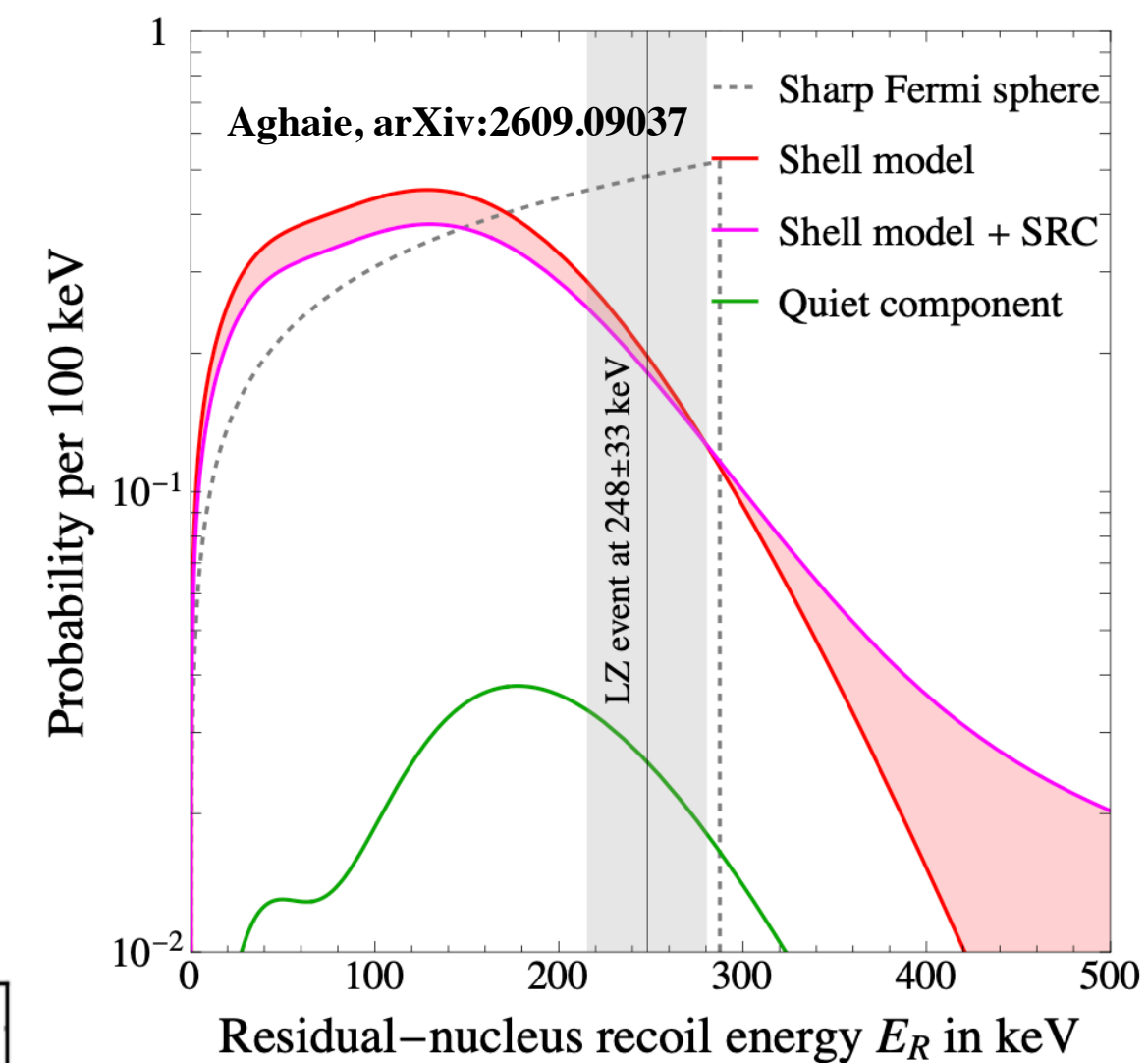
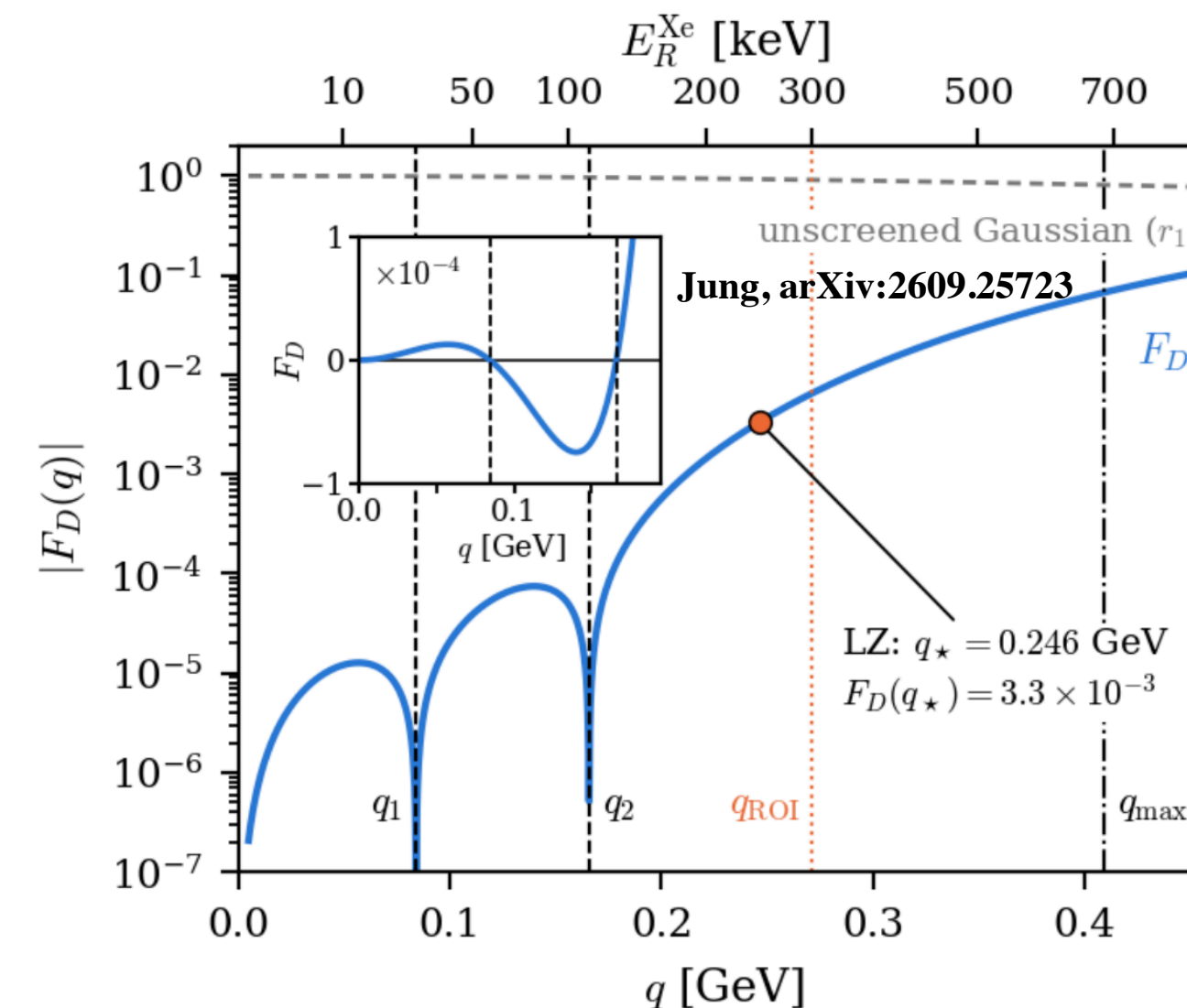
- Fermionic DM absorption: $\chi + (A,Z) \rightarrow \nu + (A,Z)$ converts the DM rest-mass energy into a nuclear recoil. $m_\chi \approx 247$ MeV naturally gives $E_R \approx 248$ keV.
- Fitting the LZ event requires an EFT scale of about $\Lambda \approx 11.5$ TeV.
- KamLAND provides a bound of $\Lambda_V \gtrsim 80$ TeV for the vector operator and $\Lambda_S \gtrsim 73$ TeV for the scalar operator at $m_\chi \approx 247$ MeV.
- The absorption operators also induce mono- X signatures at hadron colliders via associated $\chi\nu^-$ production with initial-state radiation



For the operators shown, the LZ-required interaction is strongly constrained by the KamLAND comparison.

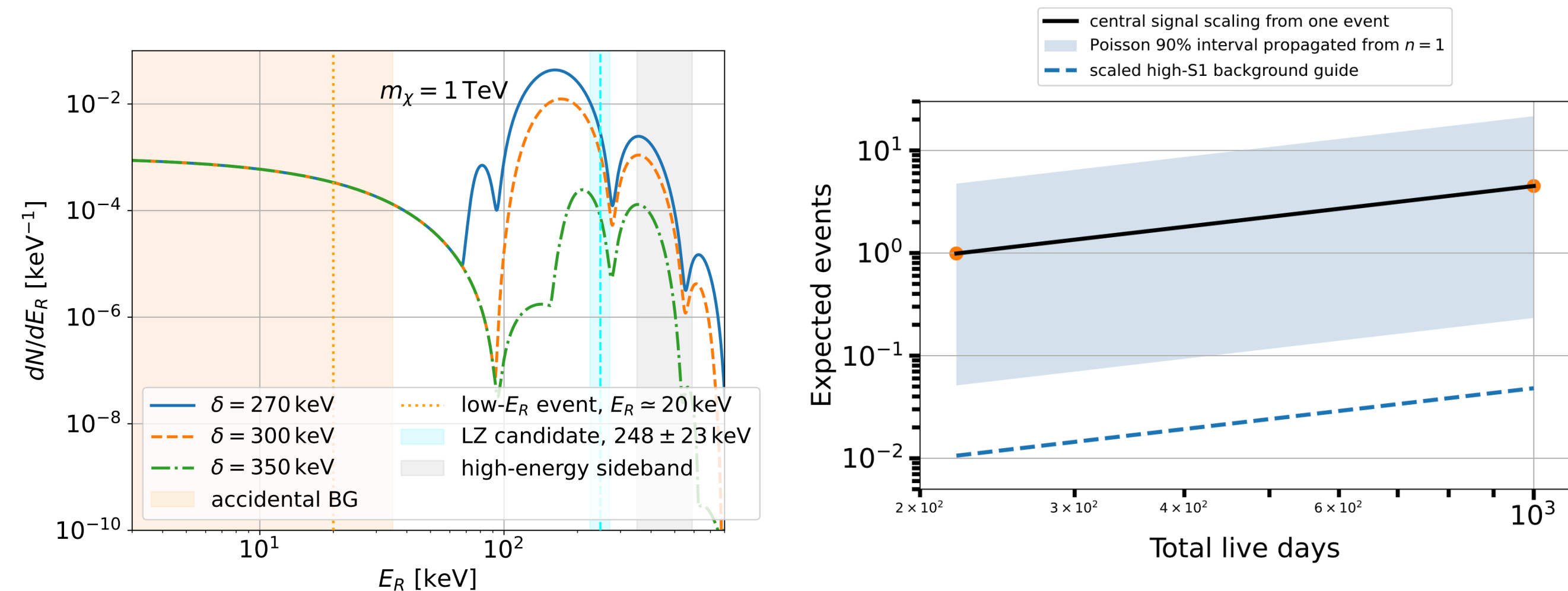
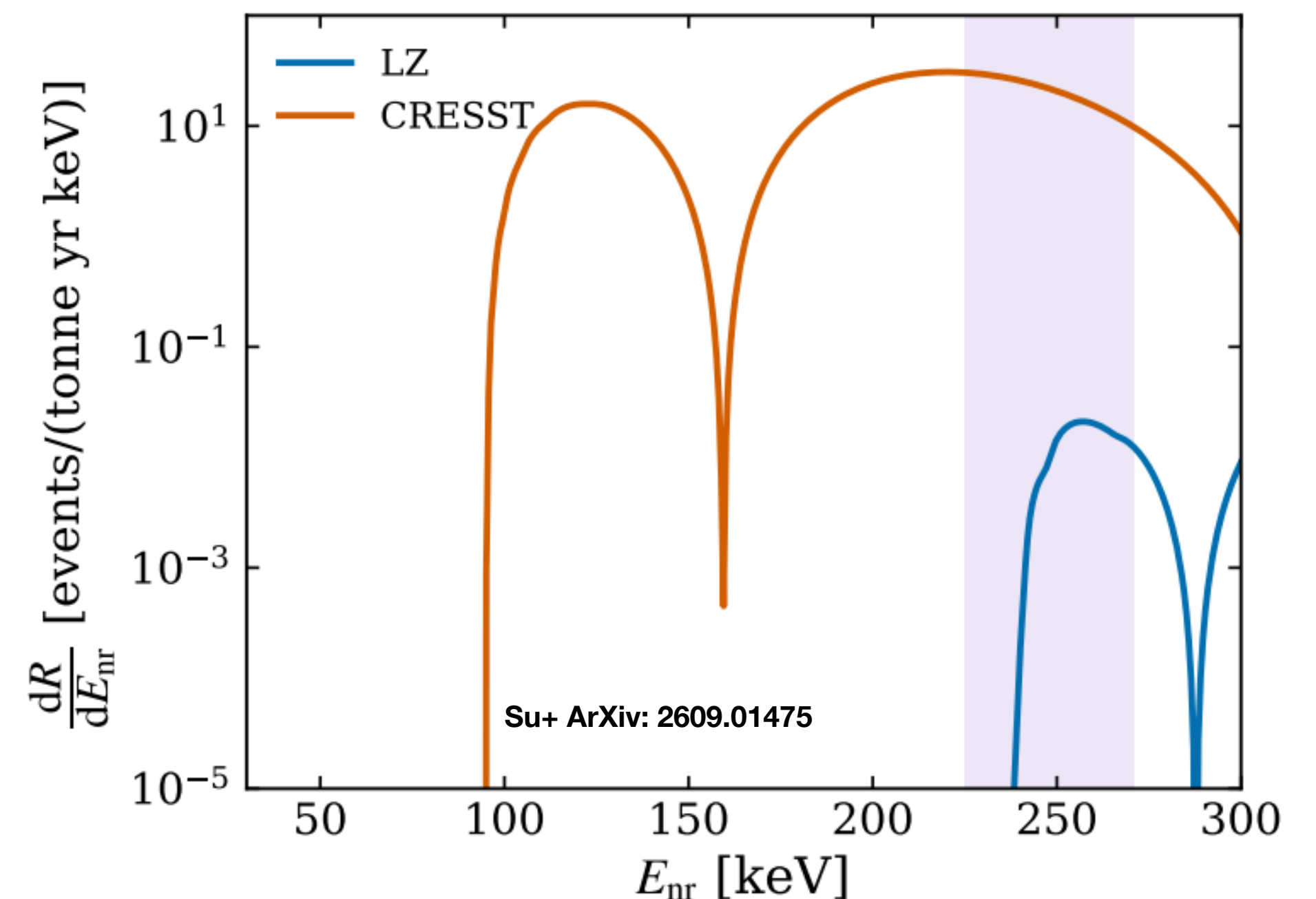
Other interpretations

- **Atmospheric-neutrino up-scattering:** An atmospheric neutrino converts into a massive dark particle through a new mediator, transferring energy to the nucleus $\nu N \rightarrow \chi N$. The signal depends on the neutrino flux and must satisfy accelerator and neutrino-scattering constraints.
- **Invisible neutron conversion:** One or two bound neutrons convert into invisible dark-sector particles, potentially producing narrow, isotope-dependent recoil lines and nuclear de-excitation signals. Viable models must satisfy nucleon-stability and rare-nuclear-process bounds.
- **Composite dark matter:** A neutral bound state of dark quarks scatters through a dark-photon mediator. Screening among constituent charges suppresses the interaction at small momentum transfer. The internal form factor can produce a harder recoil spectrum without a mass splitting or boosted particles.



What's next?

- **More LZ exposure:** 1,000 live days, low-energy data and searches above 300 keV can test predicted spectra.
- **XENONnT:** Extended-energy data can independently test the LZ interpretations.
- **LHC Run 3:** ATLAS and CMS dijet searches can probe viable mediators.
- **IceCube:** Improved solar-neutrino and mediator-cascade searches can test surviving models.
- **Other targets:** Argon, germanium and tungsten can distinguish interactions and inelastic kinematics.
- **Spectra and modulation:** More events can reveal recoil structures and annual variation.
- **Indirect detection:** Gamma rays and charged cosmic particles can test annihilation channels (exothermic).



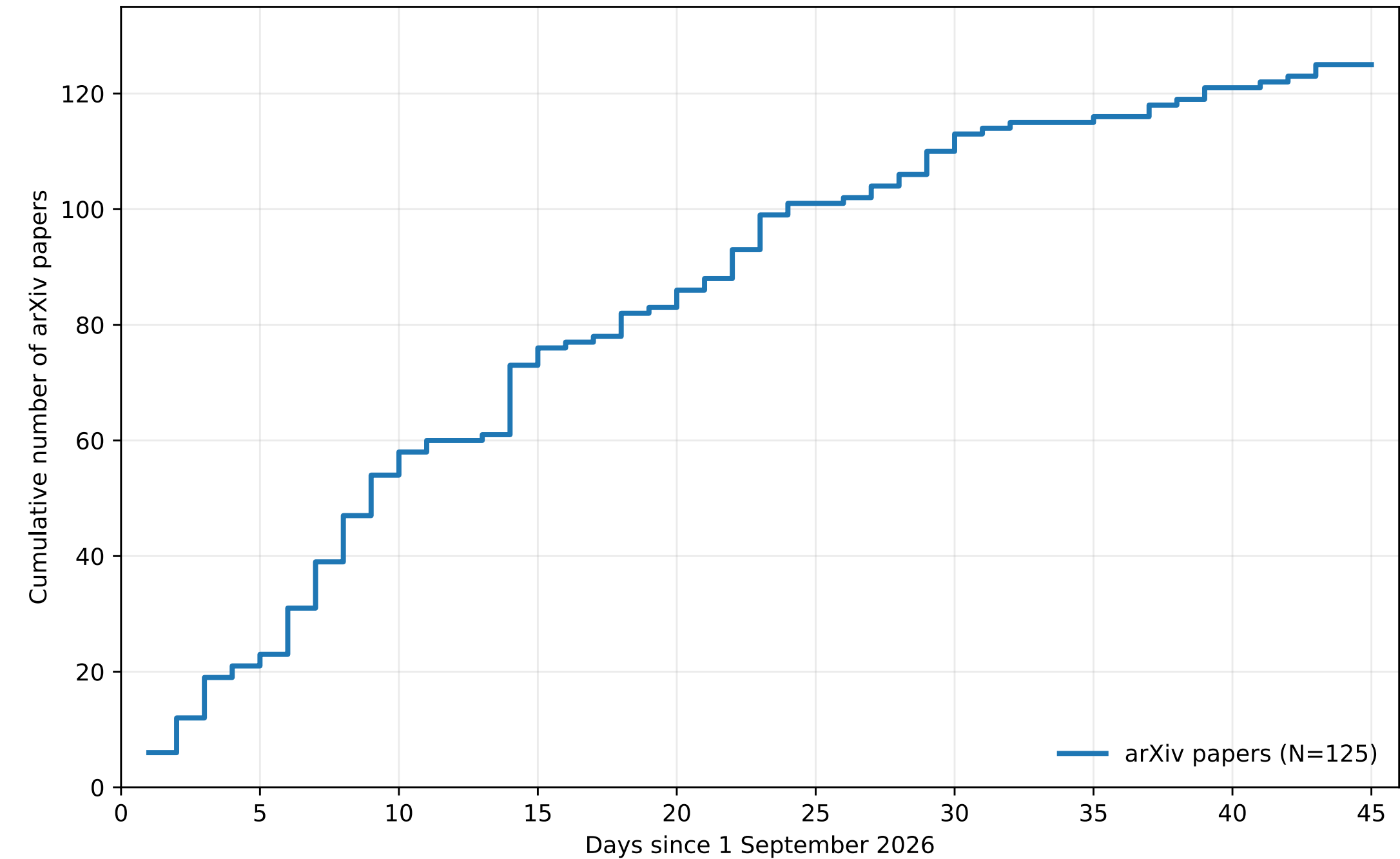
Backup slides

Beyond the simplest elastic WIMP benchmark

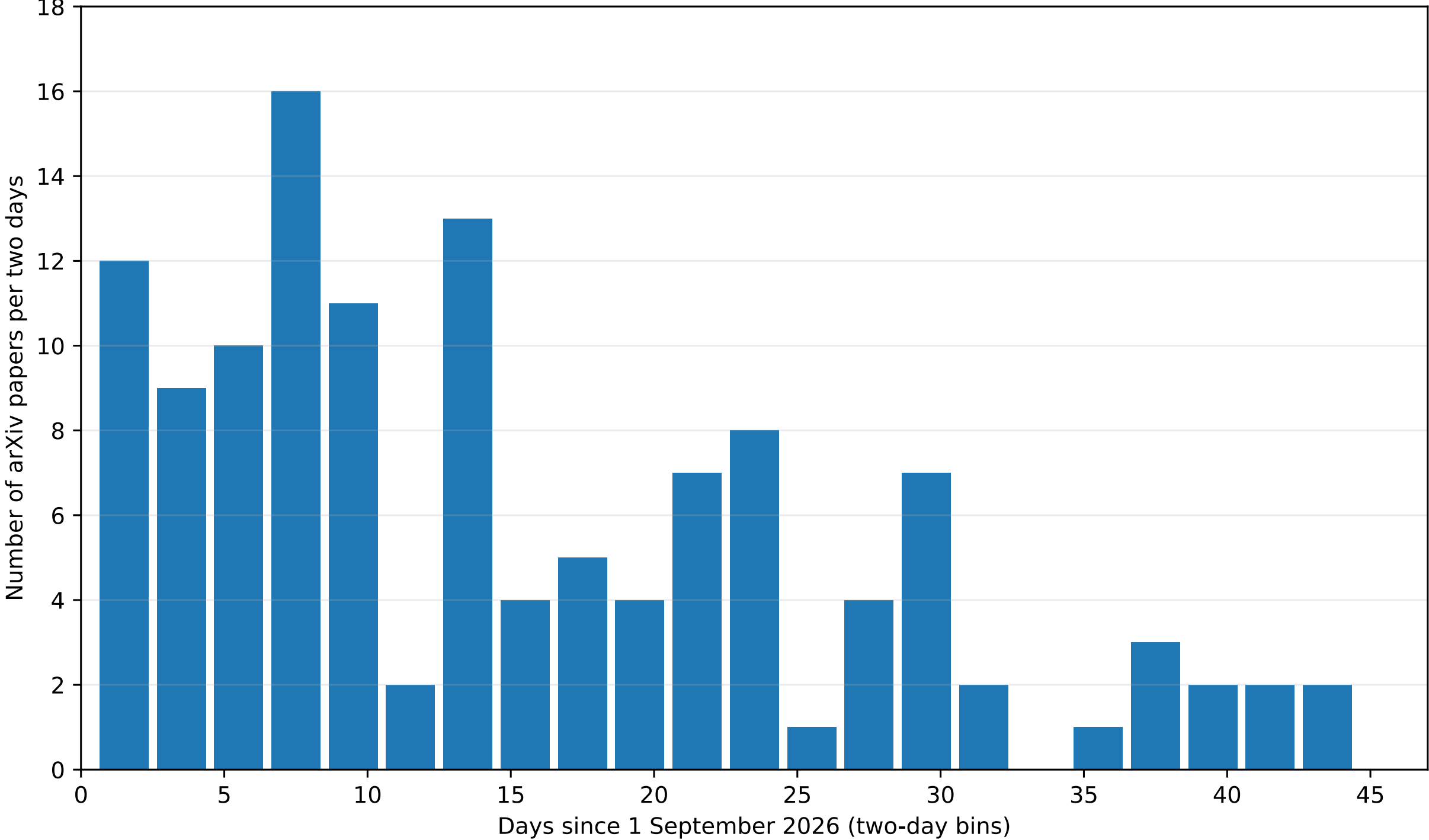
- **Secluded Dark Matter:** Annihilation into dark-sector particles, with suppressed couplings to the Standard Model.
- **Inelastic Dark Matter** (Endothermic/Exothermic): Scattering involving transitions between different dark matter mass states.
- **Non-Thermal Dark Matter** (Freeze-in): Dark matter produced through feeble interactions rather than thermal freeze-out.
- **Direct-Detection-Suppressed Dark Matter:** Models with loop-induced, momentum-suppressed, or velocity-suppressed scattering.
- **Coannihilating Dark Matter:** Relic abundance controlled by interactions involving nearly degenerate dark-sector particles.
- **Resonant Dark Matter:** Efficient annihilation near a mediator resonance, allowing suppressed direct-detection couplings.

Number of paper submitted so far on ArXiv

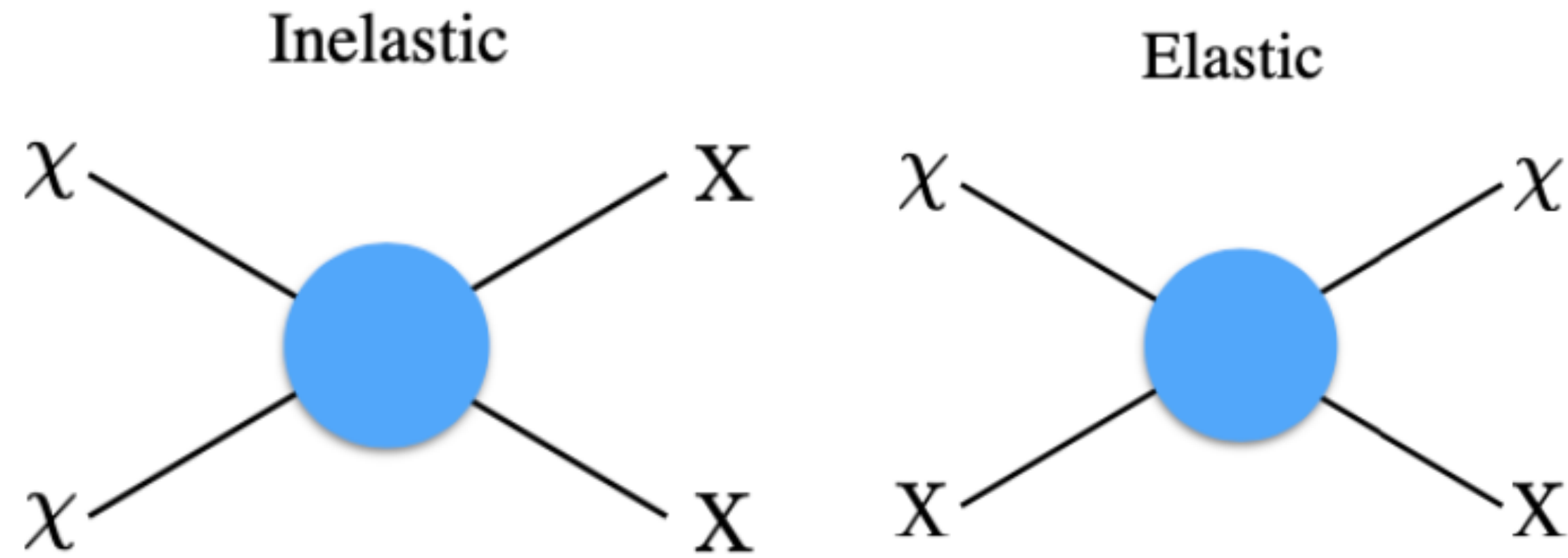
LZ-event literature growth through 15 October 2026



LZ-event papers per two-day interval through 15 October 2026

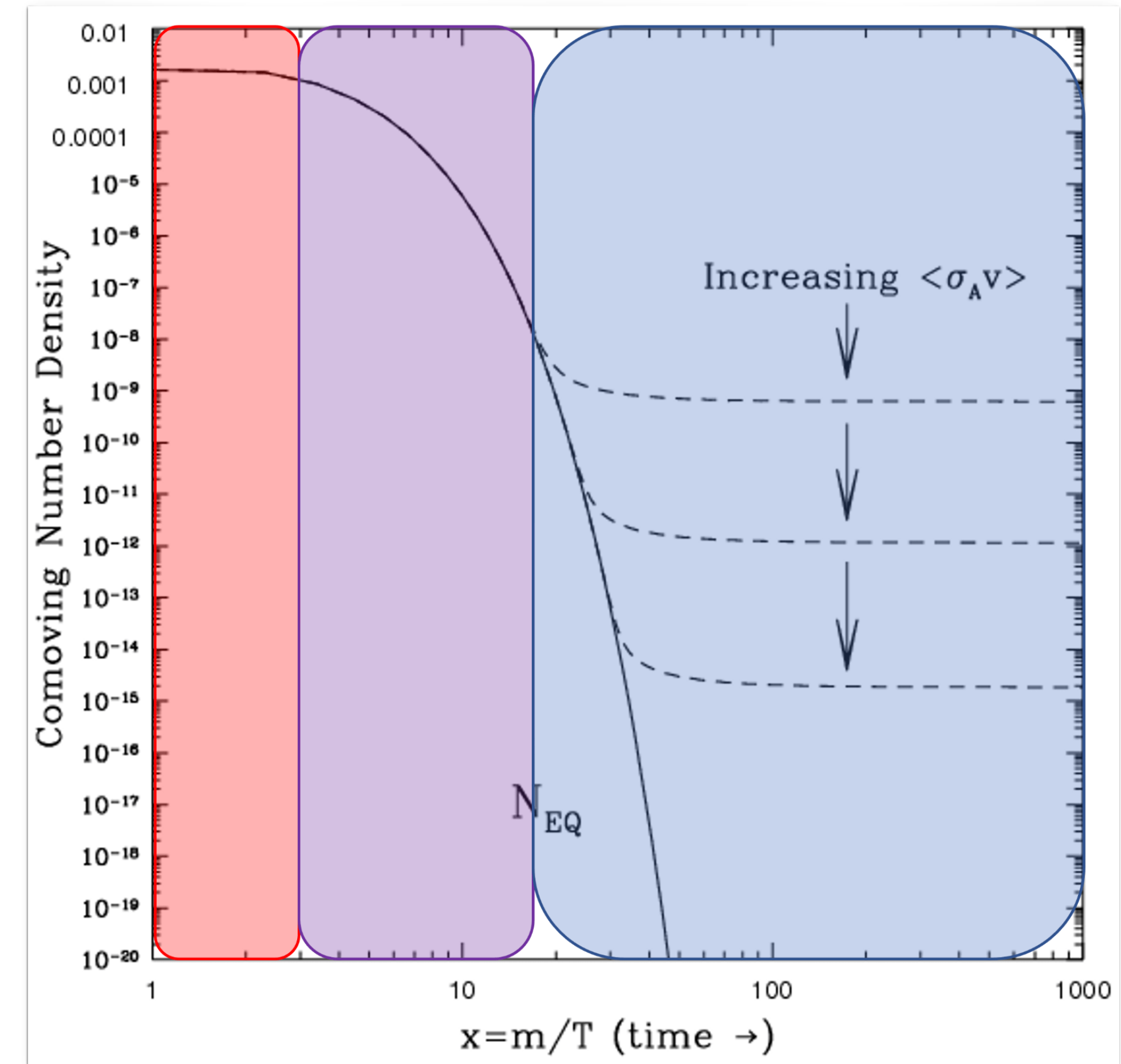


The freeze-out mechanism and WIMP's miracle



$$\Gamma_{\text{inelastic}} = n_{\chi} \langle \sigma v \rangle \sim H$$

$$\dot{n} + 3Hn = \langle \sigma v \rangle (n_{\text{eq}}^2 - n^2)$$

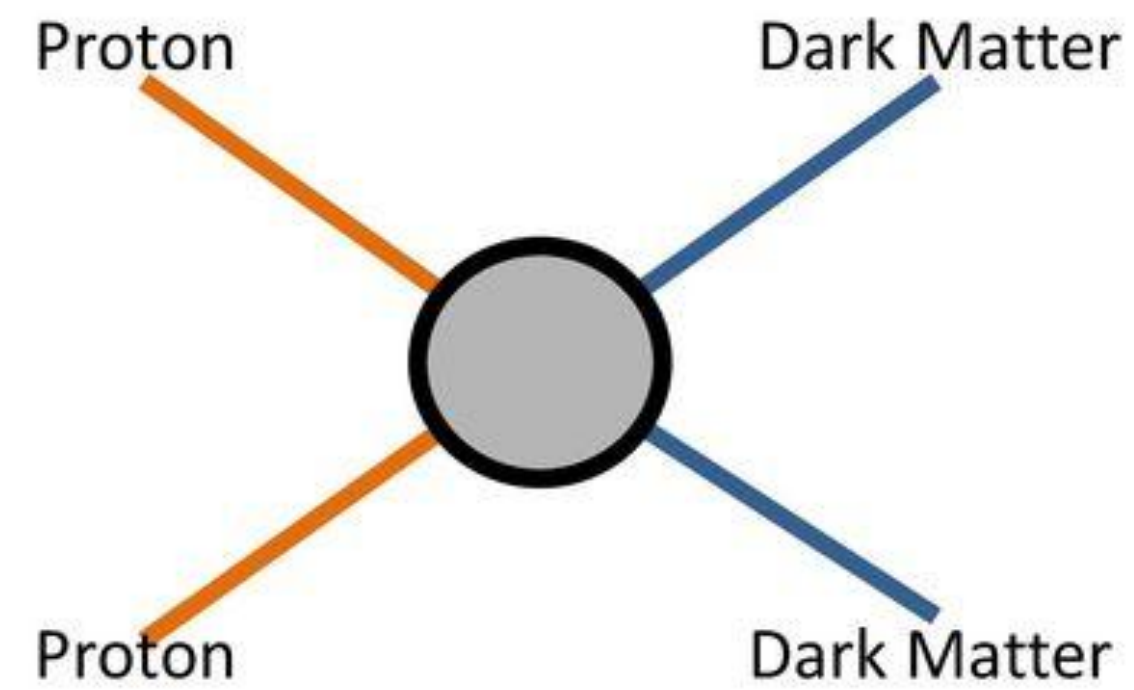


$$\Omega_{\text{DM}} h^2 \sim \frac{10^{-27} \text{cm}^3/\text{s}}{\langle \sigma(\text{DM DM} \rightarrow \text{SM SM})_v \rangle}$$

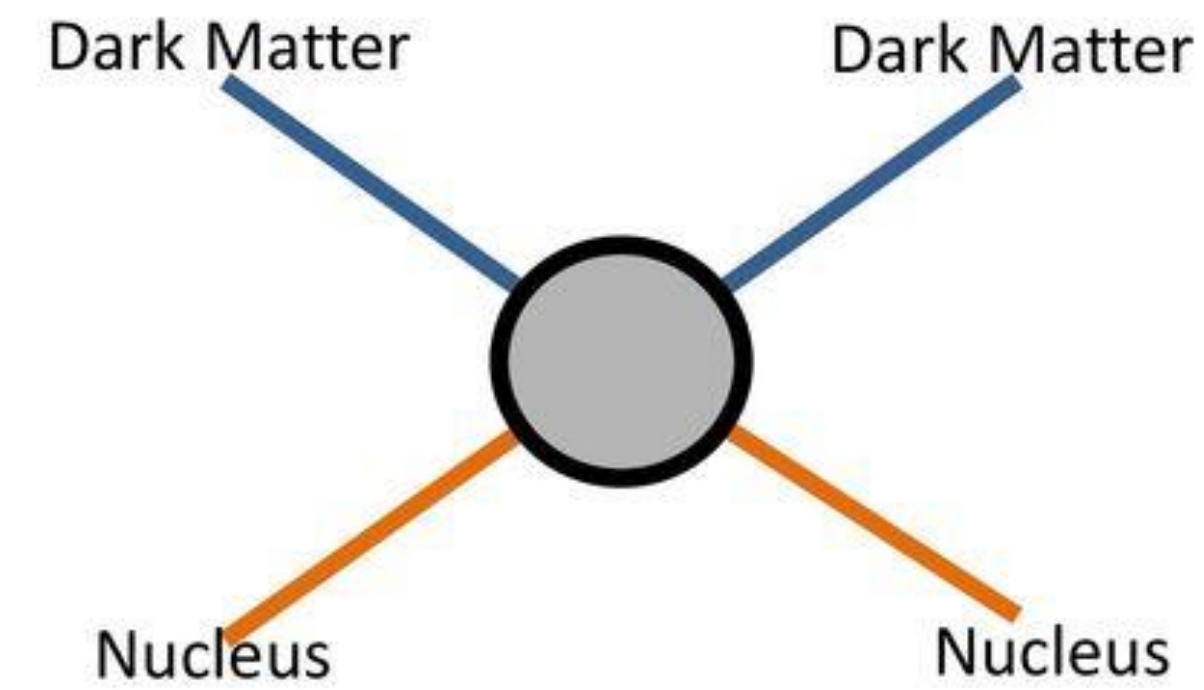
$$\langle \sigma(\text{DM DM} \rightarrow \text{SM SM})_v \rangle \sim 3 \times 10^{-26} \text{cm}^3/\text{s}$$

Dark matter searches

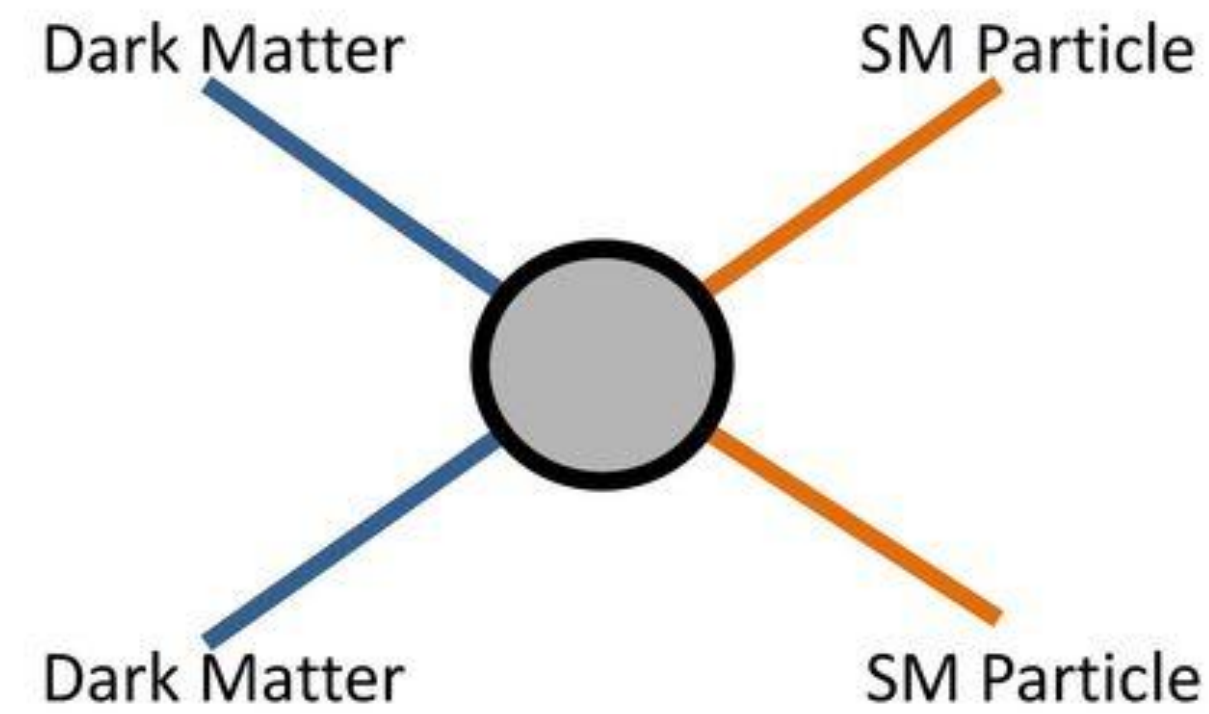
Ways to Detect Dark Matter – *Make, Shake and Break*



Make – collider production



Shake – direct detection scattering



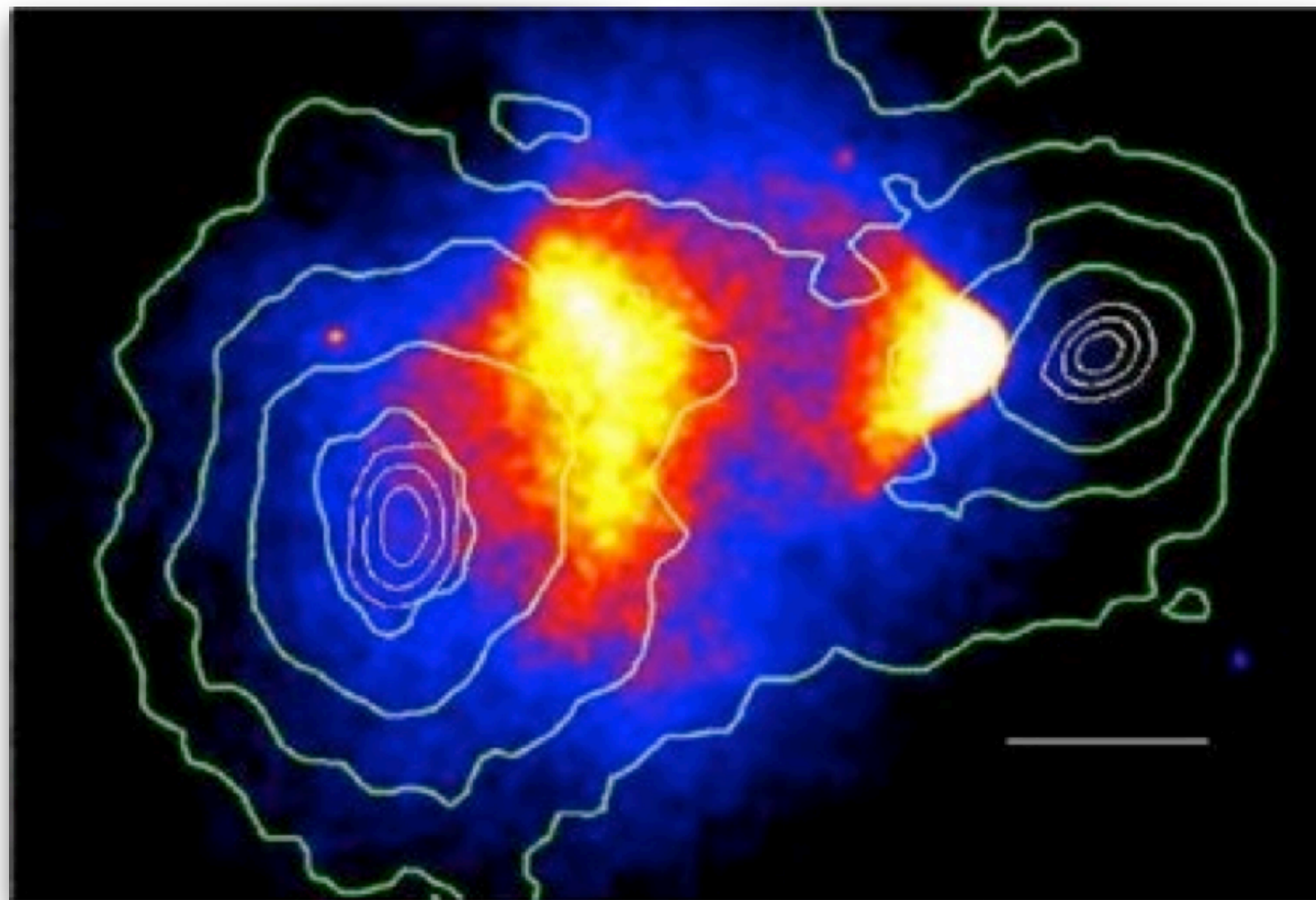
Break – indirect detection of annihilation

Dark matter: gravitational evidence

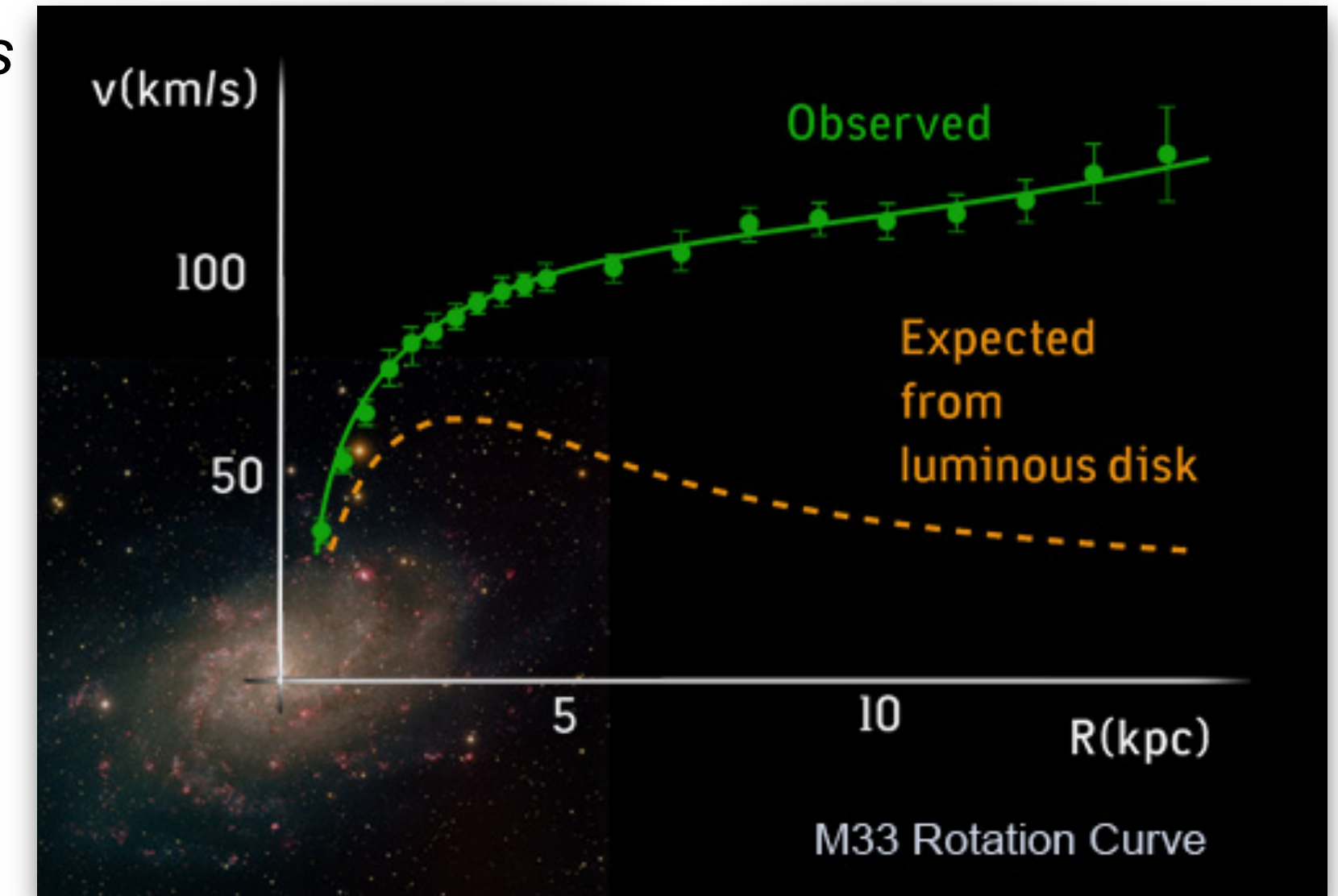
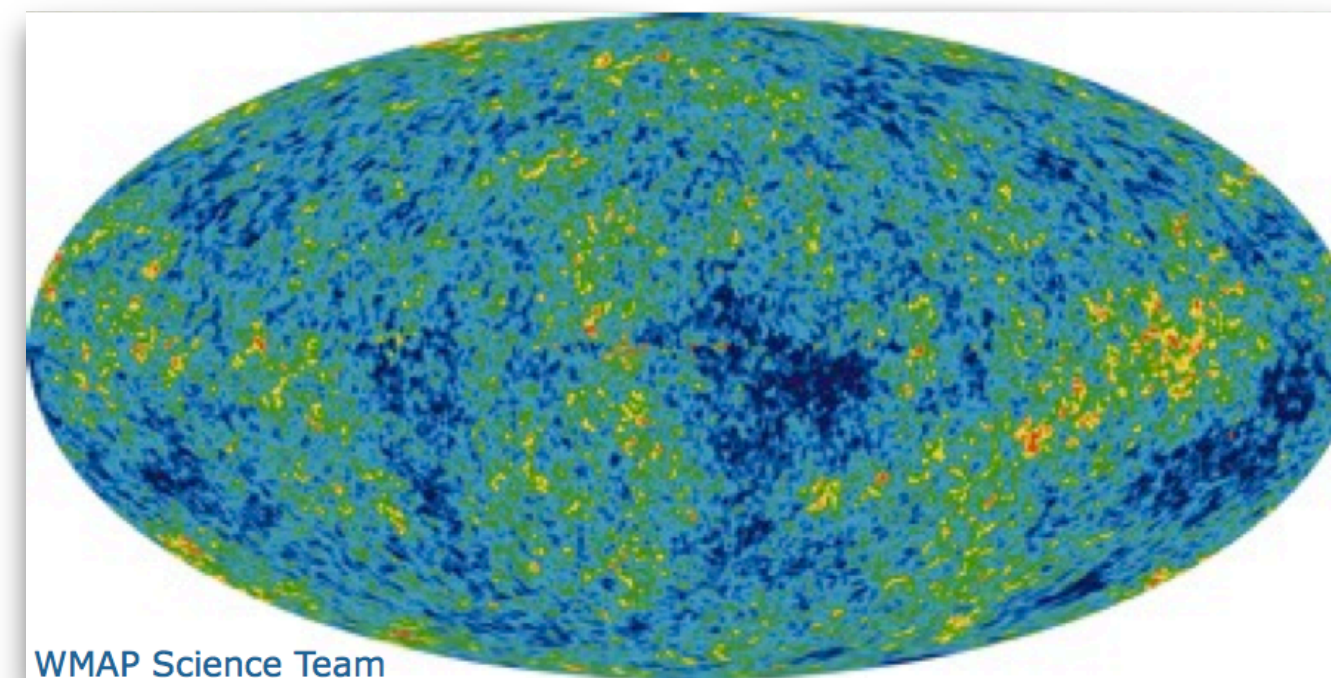
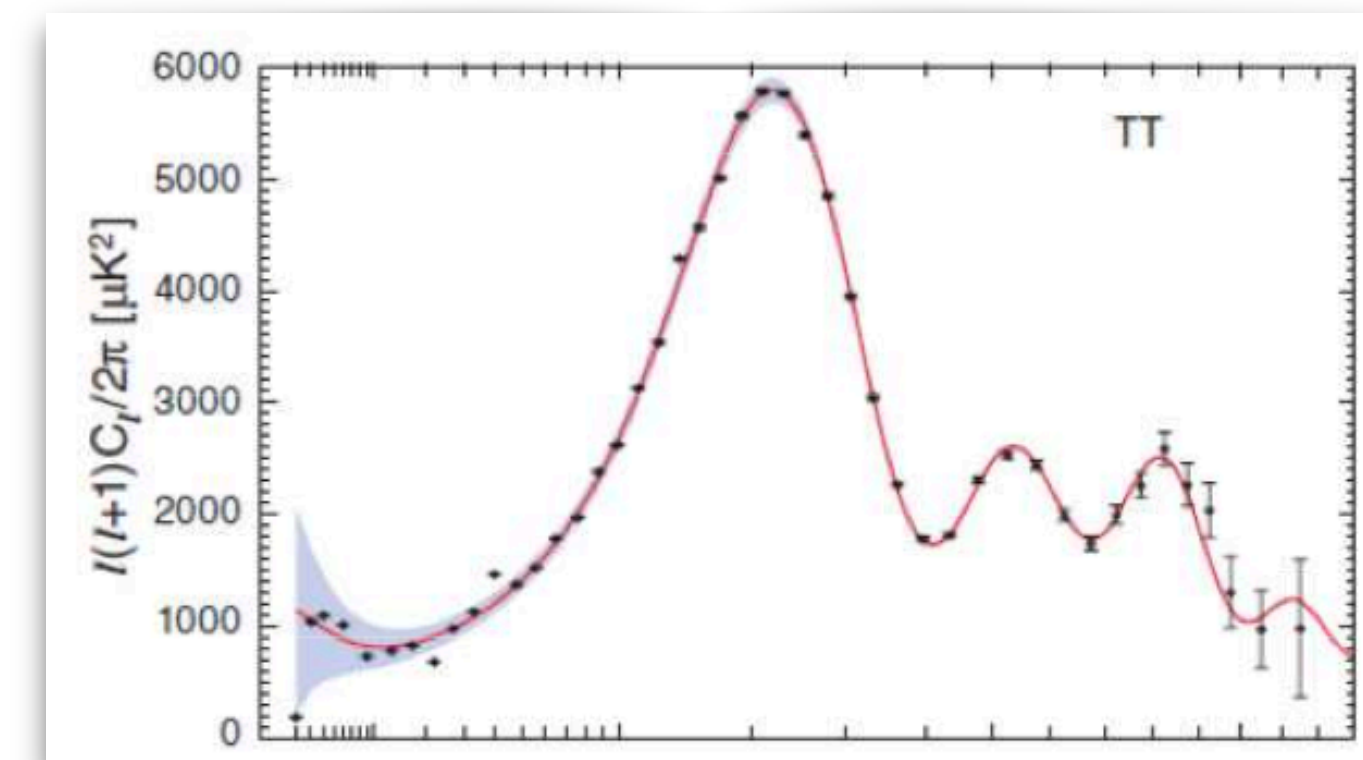


Comprises **majority of mass** in Galaxies
Missing mass on Galaxy Cluster scale
(Zwicky (1937))

Almost **collisionless**
Bullet Cluster



Large **halos** around Galaxies
Rotation Curves
Rubin+(1980)



Non-Baryonic

Big-Bang Nucleosynthesis,
CMB Acoustic Oscillations
WMAP(2010), Planck(2015)

Dark matter particles

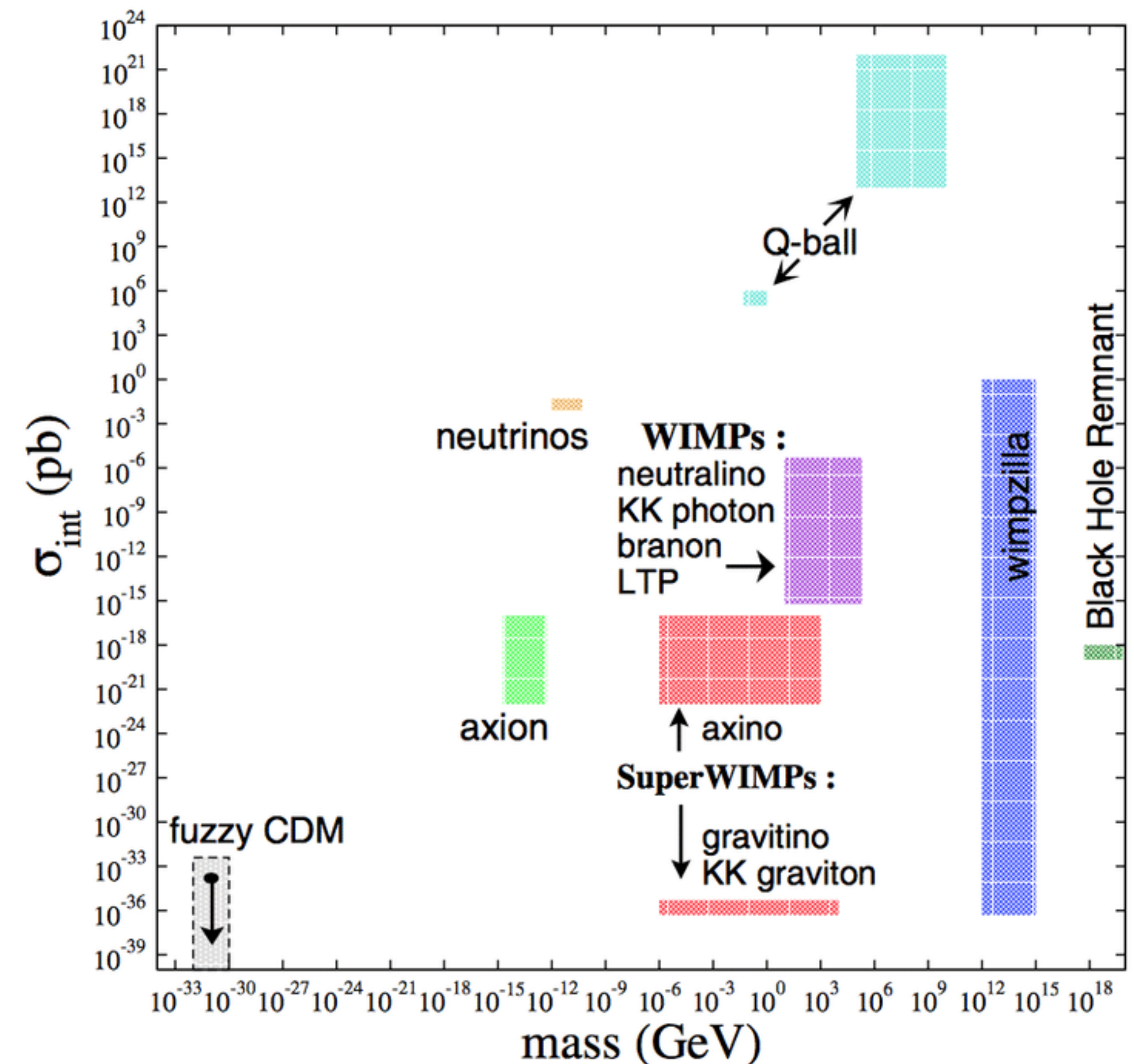
- No Standard Model particle matches the known properties of dark matter
- Weakly interacting massive particle, or WIMP, among the most popular candidate

$$\Omega_\nu h^2 \simeq \frac{\sum m_\nu}{93.14 \text{ eV}},$$

$$\sum m_\nu = m_{\nu_1} + m_{\nu_2} + m_{\nu_3}$$

$$\Omega_\nu h^2 \simeq \frac{0.1 \text{ eV}}{93.14 \text{ eV}} \approx 0.001.$$

KATRIN analysis of tritium β -decay results in an upper limit of $m_\nu < 0.45 \text{ eV}$.



Neutrino flux from dark matter Solar capture

For a one-species population, the most general one-zone evolution equation relevant here is

$$\frac{dN}{dt} = C(t) - C_E(t)N - C_A(t)N^2$$

$$\Gamma_A(t) = \frac{C}{2} \tanh^2 \left(\frac{t}{\tau_{\text{eq}}} \right) \quad \tau_{\text{eq}} = \frac{1}{\sqrt{CC_A}} \quad C_A \simeq \frac{\langle \sigma v \rangle}{V_{\text{eff}}}, \quad V_{\text{eff}} = \frac{4\pi}{3} R_\chi^3$$

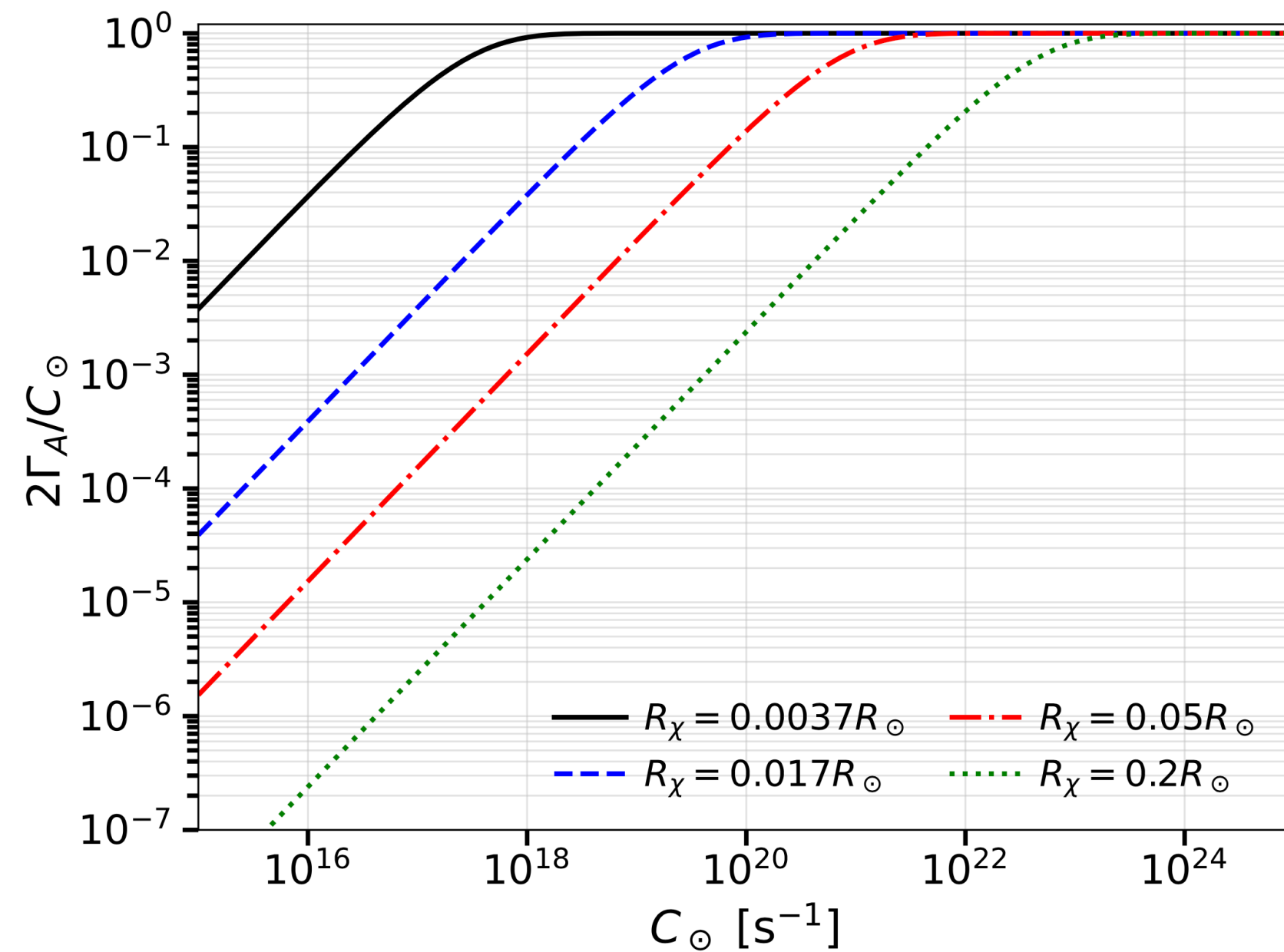


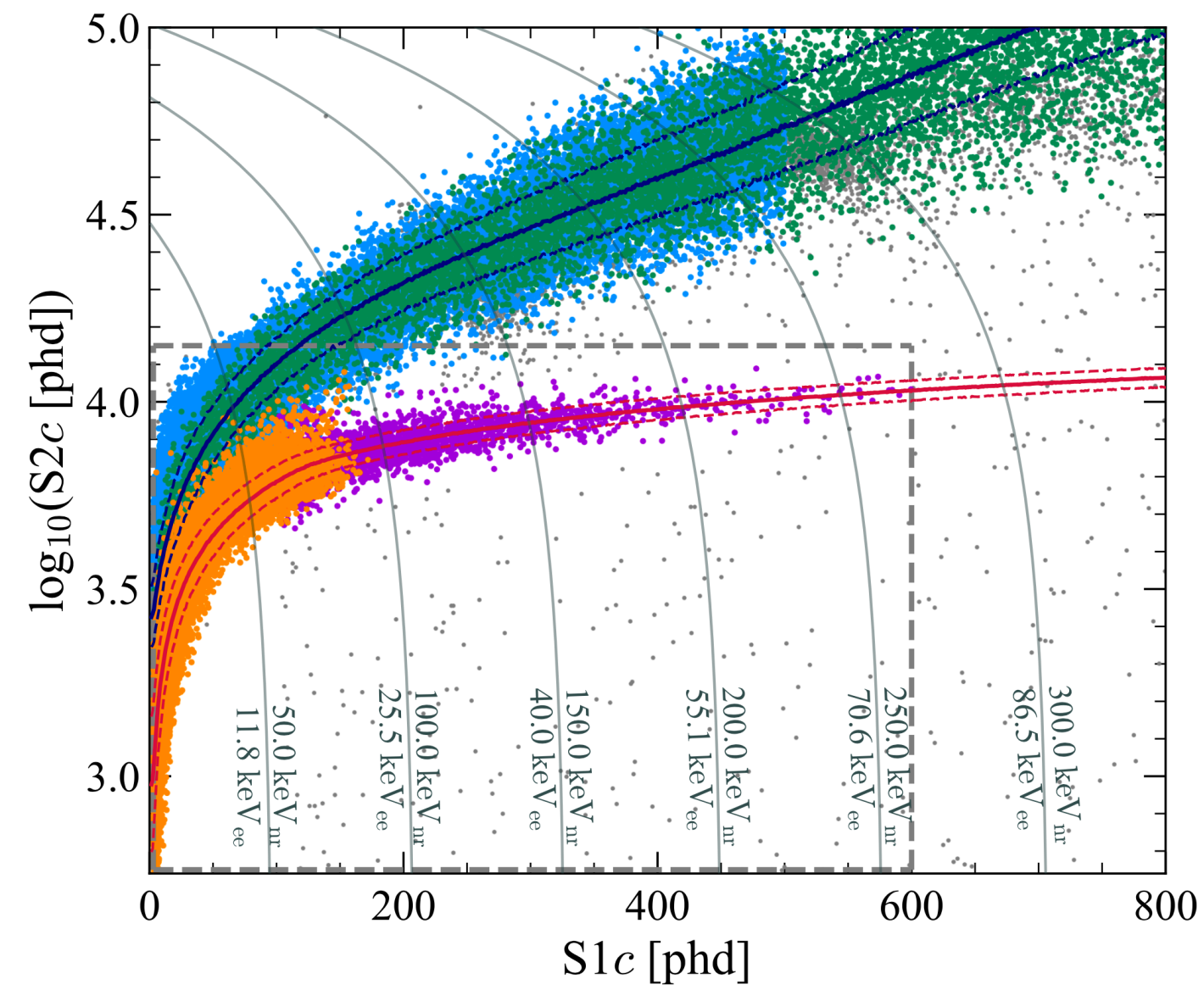
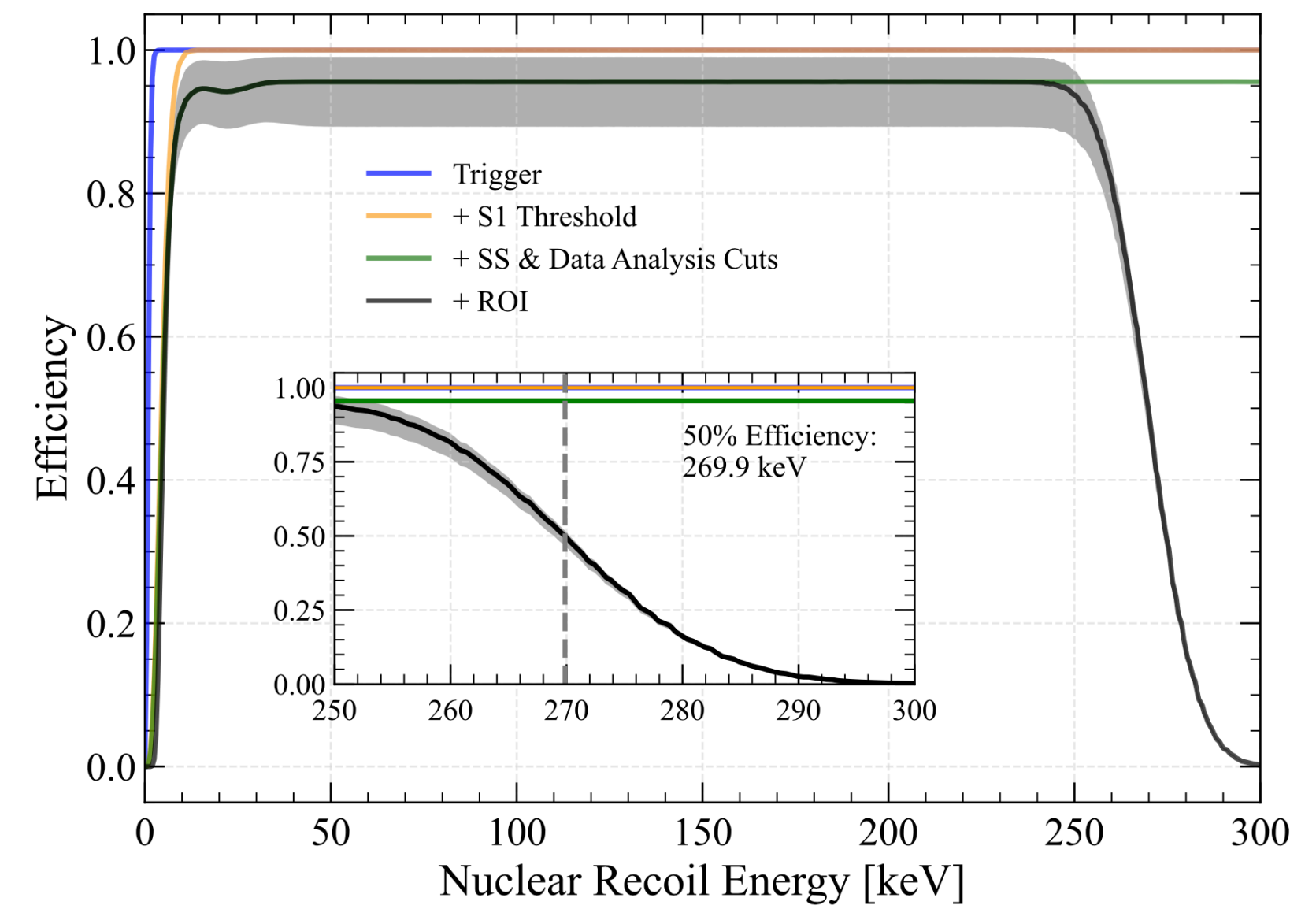
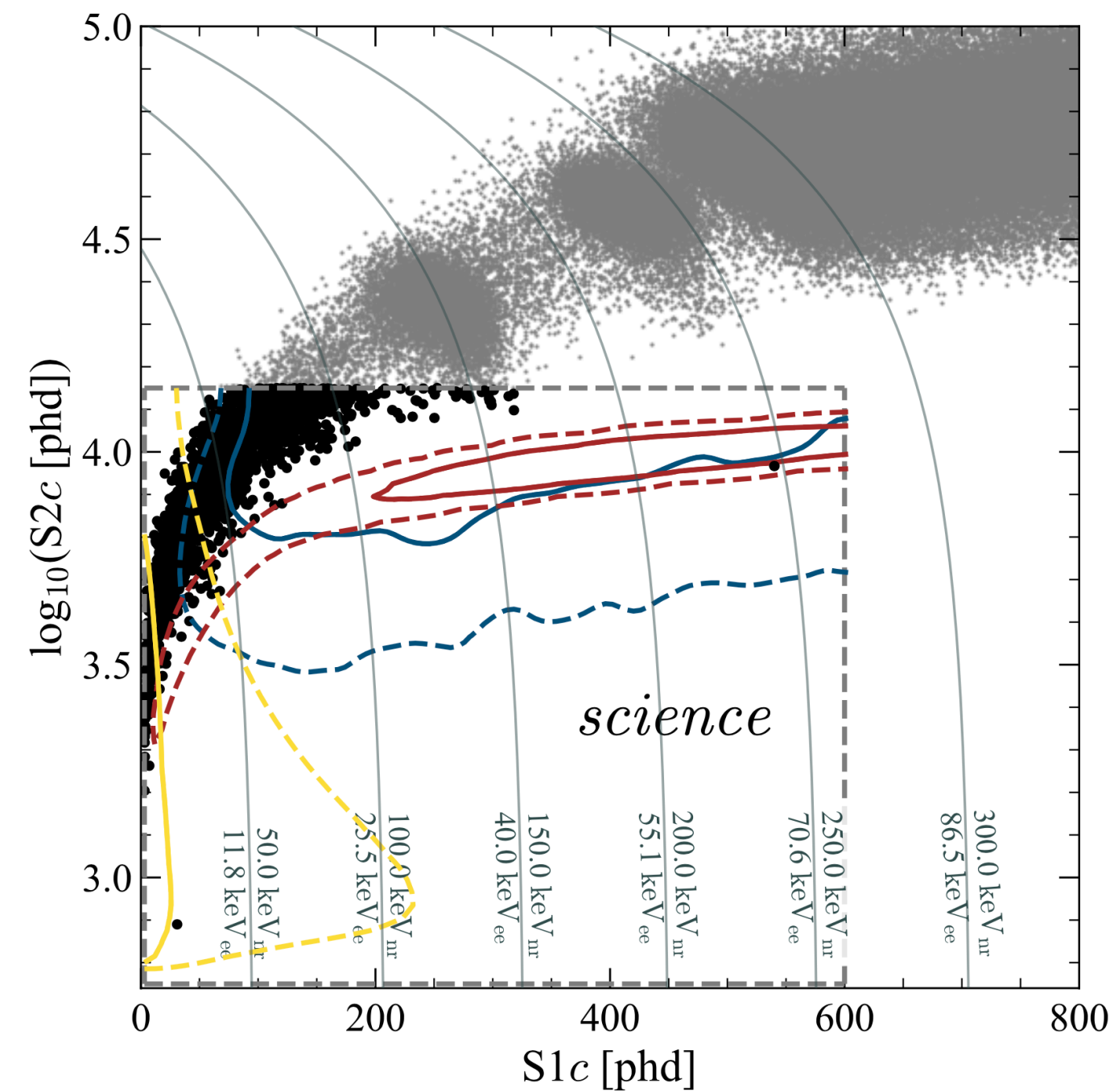
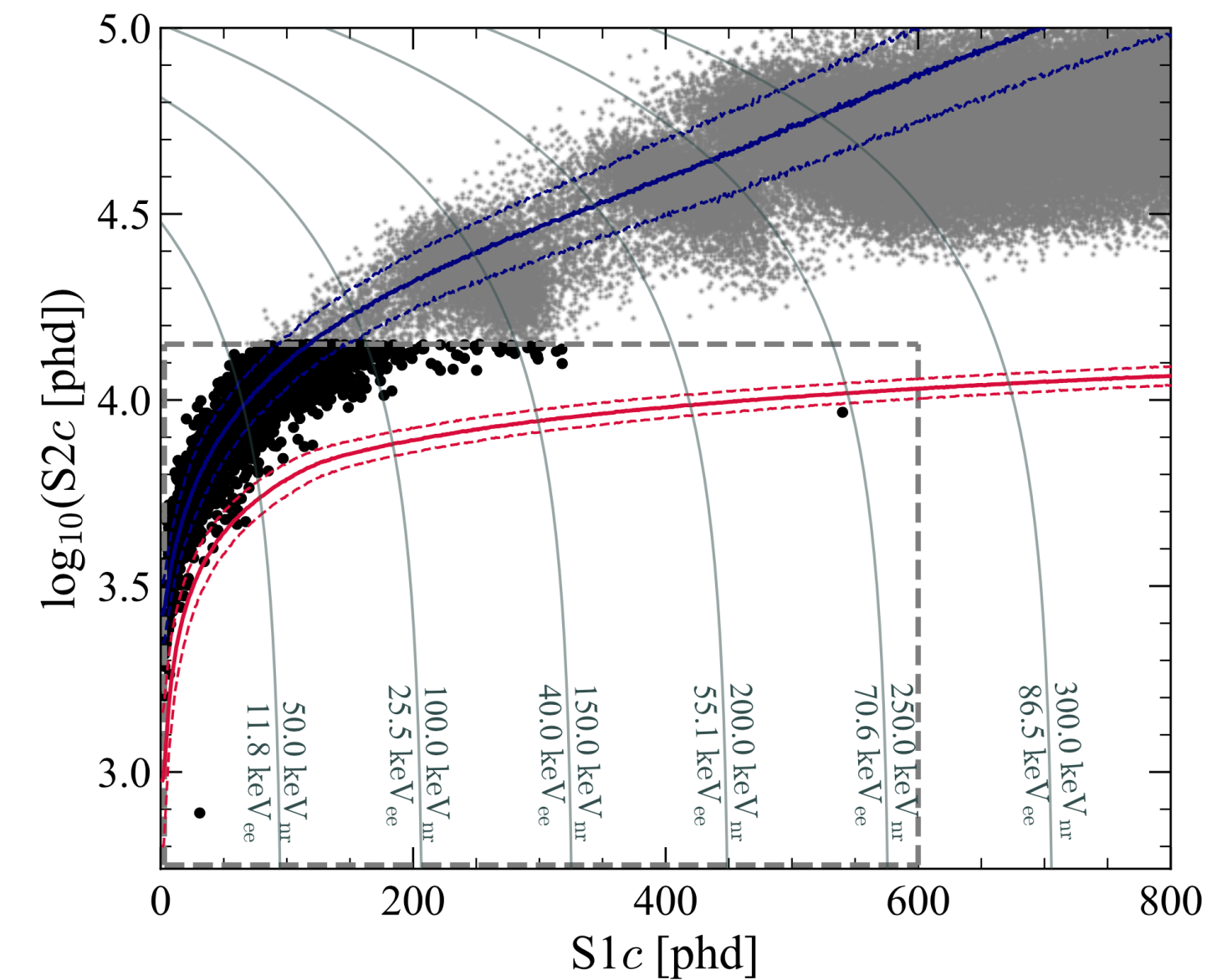
TABLE I. Central mass fractions used in the BS05(AGS,OP)-based capture calculation. H, He, C, N, and O are read directly from the Solar table. The remaining heavy-element values are the adopted surface normalizations multiplied by the common oxygen radial-profile factor at the Solar center.

Species	H	He	C	N	O	Ne	Mg
$X_A(0)$	0.36462	0.62029	7.79×10^{-6}	3.73×10^{-3}	6.06×10^{-3}	1.38×10^{-3}	7.76×10^{-4}
Species	Si	S	Ca	Ti	Cr	Fe	Ni
$X_A(0)$	7.36×10^{-4}	3.43×10^{-4}	7.14×10^{-5}	3.48×10^{-6}	1.85×10^{-5}	1.44×10^{-3}	7.82×10^{-5}
Species	Zn	Ge	Pb	U			
$X_A(0)$	1.92×10^{-6}	2.65×10^{-7}	9.46×10^{-9}	5.57×10^{-11}			

$$r_{\text{Fe}}^{\text{kin}} = 0.438R_\odot, \quad r_{\text{Ni}}^{\text{kin}} = 0.418R_\odot, \quad r_{\text{Zn}}^{\text{kin}} = 0.364R_\odot,$$

$$r_{\text{Ge}}^{\text{kin}} = 0.321R_\odot, \quad r_{\text{Pb}}^{\text{kin}} = 0.151R_\odot, \quad r_{\text{U}}^{\text{kin}} = 0.140R_\odot.$$

LZ detection/efficiency/backgrounds



2HD+a model (Arcadi+)

Model and main Lagrangian

- Two-Higgs-doublet model (2HDM) extended by a light pseudoscalar a and a singlet fermionic dark matter χ .
- A Z_2 symmetry stabilizes χ and controls the couplings of a .

$$\mathcal{L} = \mathcal{L}_{2\text{HDM}} + \mathcal{L}_a + \mathcal{L}_\chi + \mathcal{L}_{\text{int}}$$

2HDM potential: $V_{2\text{HDM}}(\Phi_1, \Phi_2)$ (soft Z_2 breaking)

Pseudoscalar a: $\mathcal{L}_a = \frac{1}{2} \partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2$

Dark matter χ : $\mathcal{L}_\chi = \bar{\chi} (i \not{\partial} - m_\chi) \chi$

Interactions: $\mathcal{L}_{\text{int}} = -ig_\chi a \bar{\chi} \gamma^5 \chi - \sum_f \frac{m_f}{v} y_f^a a \bar{f} i \gamma^5 f$

Scalar sector and mixing

- After electroweak symmetry breaking, the CP-even states h and H mix with angle α .
- Physical states: h (SM-like, 125 GeV), H (heavy), A (CP-odd from 2HDM) and a (light pseudoscalar).
- The pseudoscalars A and a mix with angle θ .

CP-even mixing (h - H)

$$\begin{aligned} h &= -s_\alpha \text{Re}(\Phi_1^0) + c_\alpha \text{Re}(\Phi_2^0) \\ H &= c_\alpha \text{Re}(\Phi_1^0) + s_\alpha \text{Re}(\Phi_2^0) \\ \tan \beta &= \frac{v_2}{v_1} \end{aligned}$$

CP-odd mixing (A - a)

$$\begin{aligned} a_1 &= c_\theta a - s_\theta A \\ a_2 &= s_\theta a + c_\theta A \\ (a_1 &= a \text{ light, } a_2 = A \text{ heavy}) \end{aligned}$$

CP-even

$$\begin{array}{c} \underline{h} \\ \underline{H} \end{array} \quad \begin{array}{l} (125 \text{ GeV}) \\ (\text{heavy}) \end{array}$$

CP-odd

$$\begin{array}{c} \underline{a} \\ \underline{A} \end{array} \quad \begin{array}{l} (\text{light, } 1\text{--}10 \text{ GeV}) \\ (\text{heavy, } \sim \text{EW}) \end{array}$$

Yukawa interactions and 2HDM types

- The pseudoscalar a couples to fermions through the 2HDM Yukawa structure.
- The coupling strength depends on the 2HDM type and $\tan \beta$.
- For DM phenomenology, a light a ($m_a \sim 1\text{--}10$ GeV) is favored.

$$\mathcal{L}_Y \supset - \sum_f \frac{m_f}{v} y_f^a a \bar{f} i \gamma^5 f$$

2HDM type	u-type quarks	d-type quarks	charged leptons
Type I	$\cot \beta$	$\cot \beta$	$\cot \beta$
Type II	$\cot \beta$	$\tan \beta$	$\tan \beta$
Type X (lepton-specific)	$\cot \beta$	$\cot \beta$	$\tan \beta$
Type Y (flipped)	$\cot \beta$	$\tan \beta$	$\cot \beta$

Relevant parameter space for the LZ interpretation

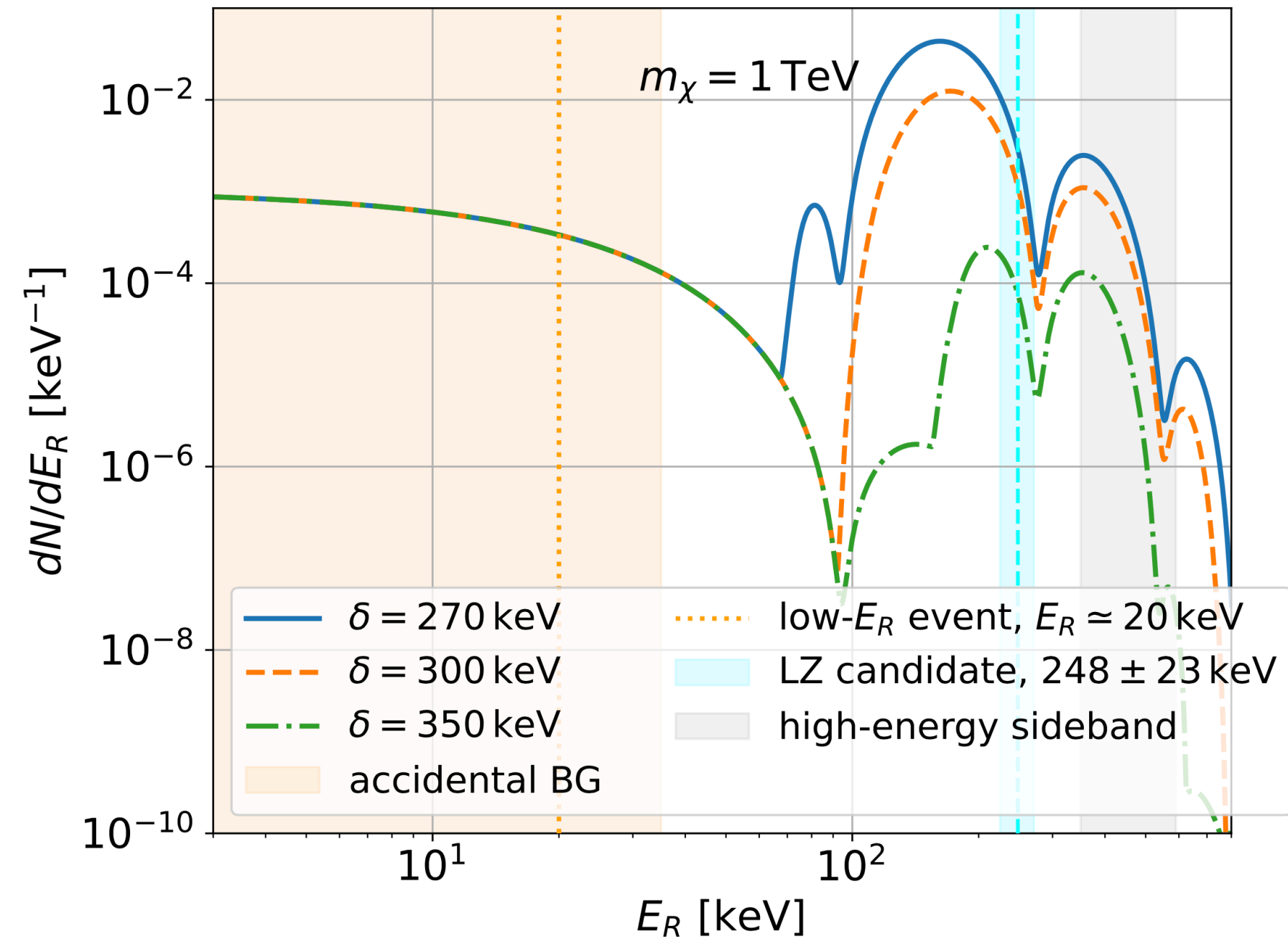
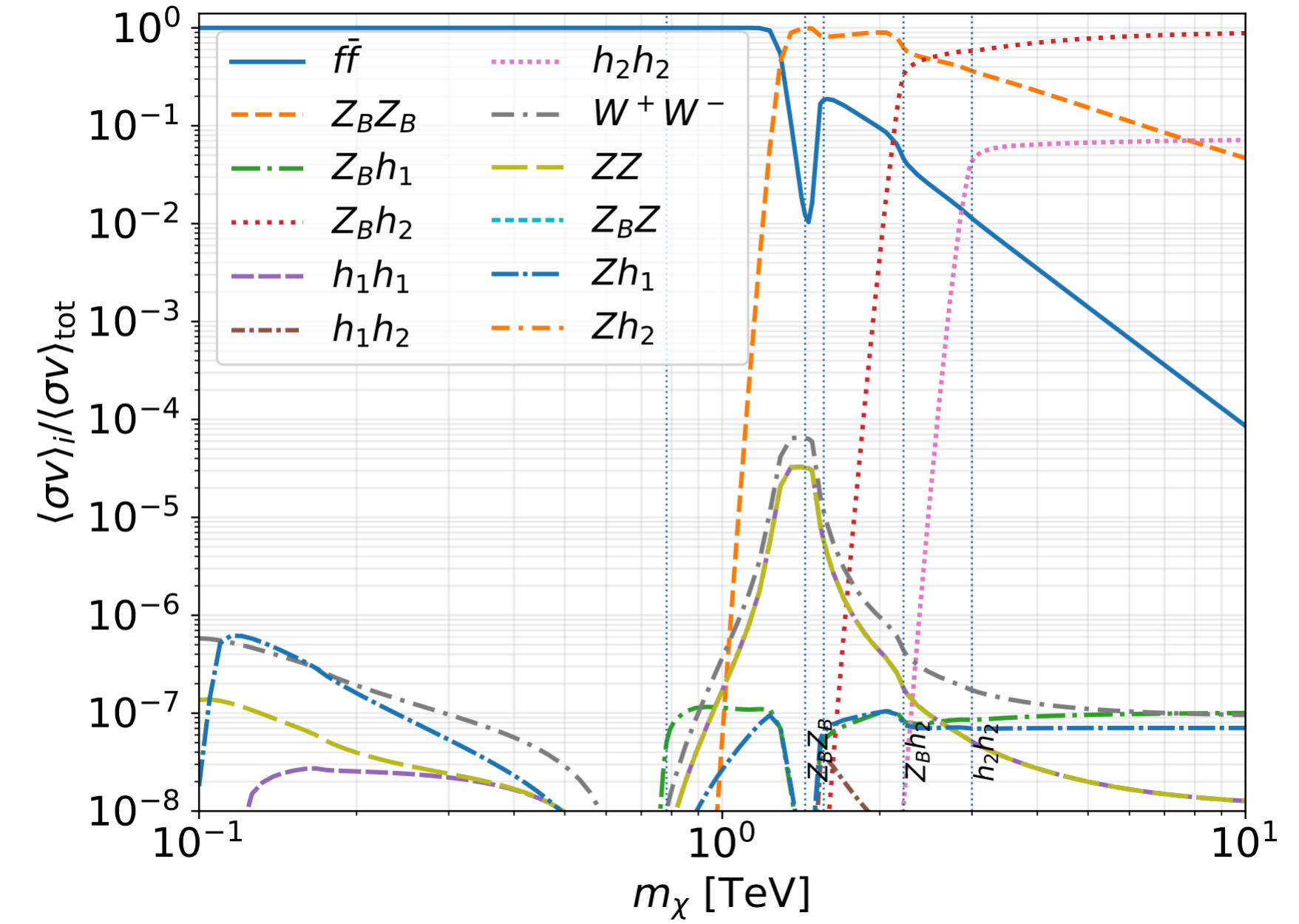
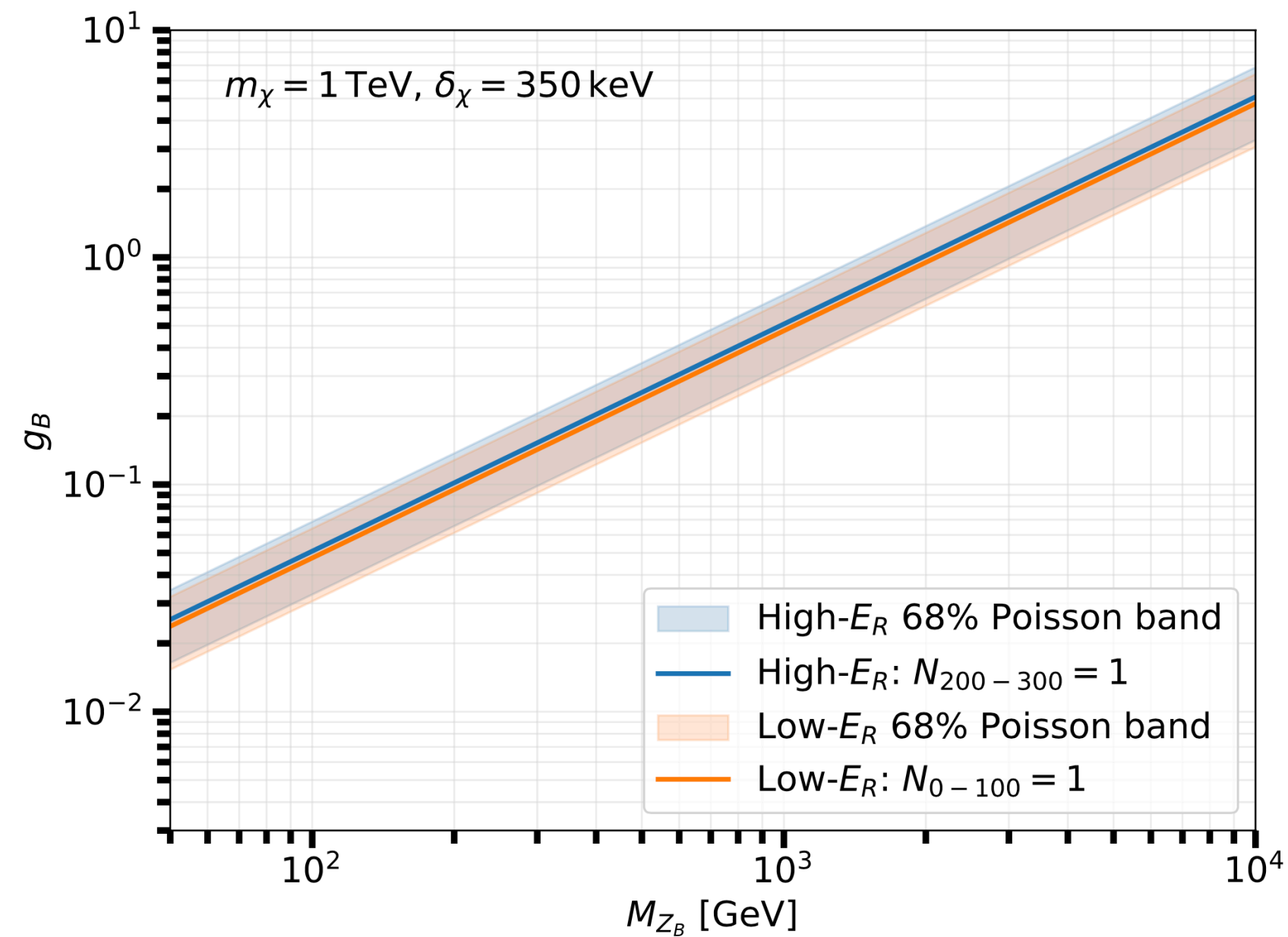
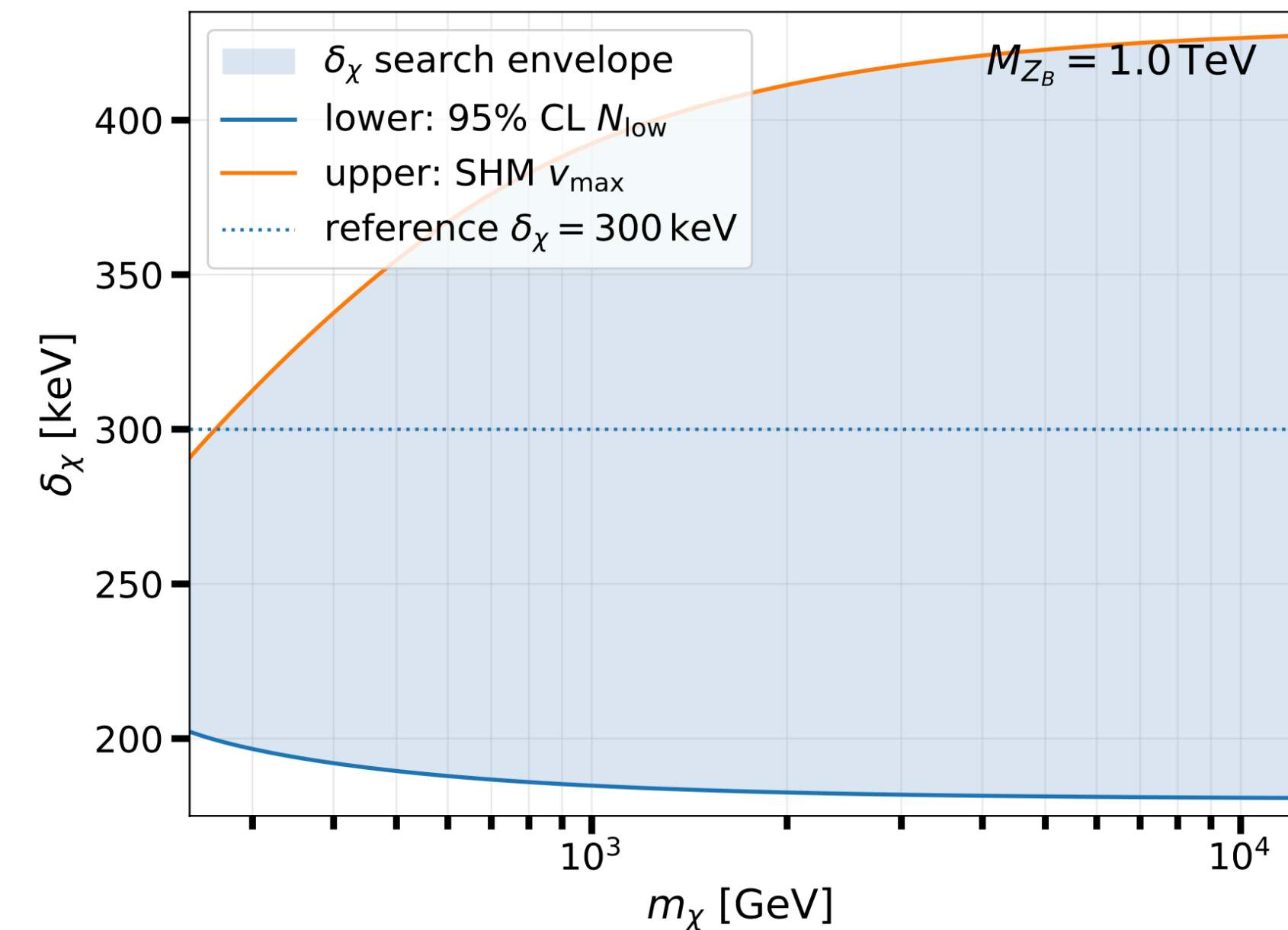
- Fermionic DM with mass $m_\chi \sim$ few hundred GeV.
- Light pseudoscalar a with $m_a \sim 1\text{--}10$ GeV.
- Heavy 2HDM states $H, A, H^\pm$ typically at the electroweak scale or above.

Representative ranges:
 $m_a \simeq 1 - 10 \text{ GeV}$
 $m_\chi \simeq 100 - 800 \text{ GeV}$
 $m_H, m_A, m_{H^\pm} \gtrsim 300 \text{ GeV}$
 $\tan \beta : 1 - 50$
 mixing angle θ : small (light a mostly singlet)

Main constraints used in the analysis

- **Relic density:** $\Omega_\chi h^2 = 0.120 \pm 0.001$ (Planck).
- **Direct detection:** LZ (including the 248-keV event), XENONnT, PandaX-4T.
- **Indirect detection:** limits from gamma rays, cosmic rays and CMB.
- **Collider searches:** LHC searches for heavy Higgs bosons ($H, A, H^\pm$), searches for light pseudoscalars a (e.g. rare B decays, Υ decays, LEP, LHC).
- **Higgs and electroweak precision:** Higgs signal strengths, oblique parameters, flavor observables (e.g. $B \rightarrow Ka$, $B_s \rightarrow \mu^+ \mu^-$), Z and W measurements.
- **Theoretical constraints:** vacuum stability, perturbativity, unitarity.

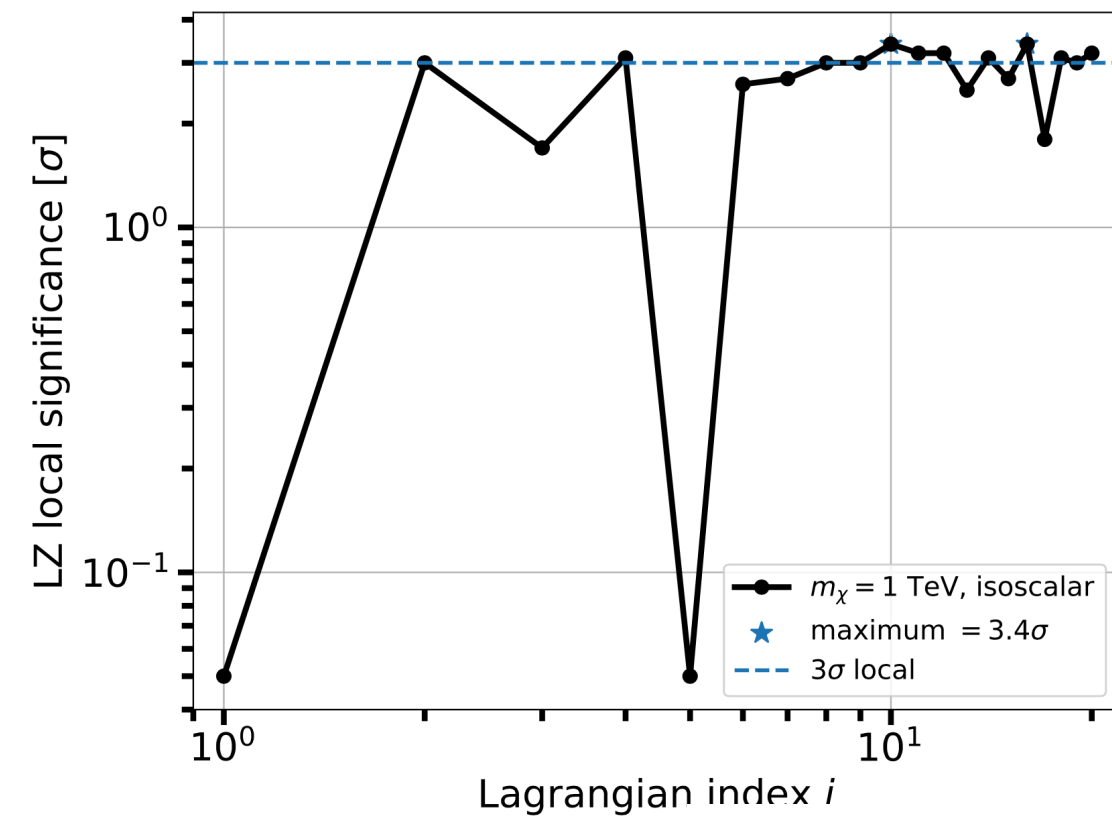
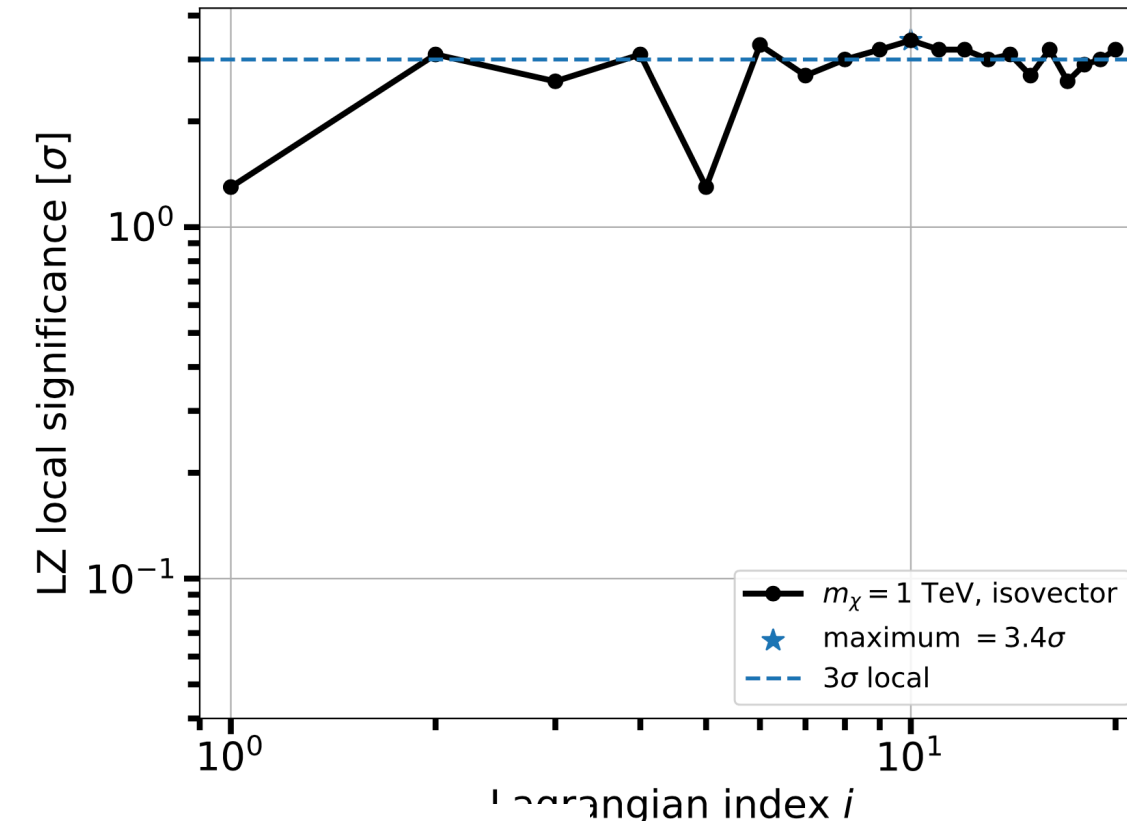
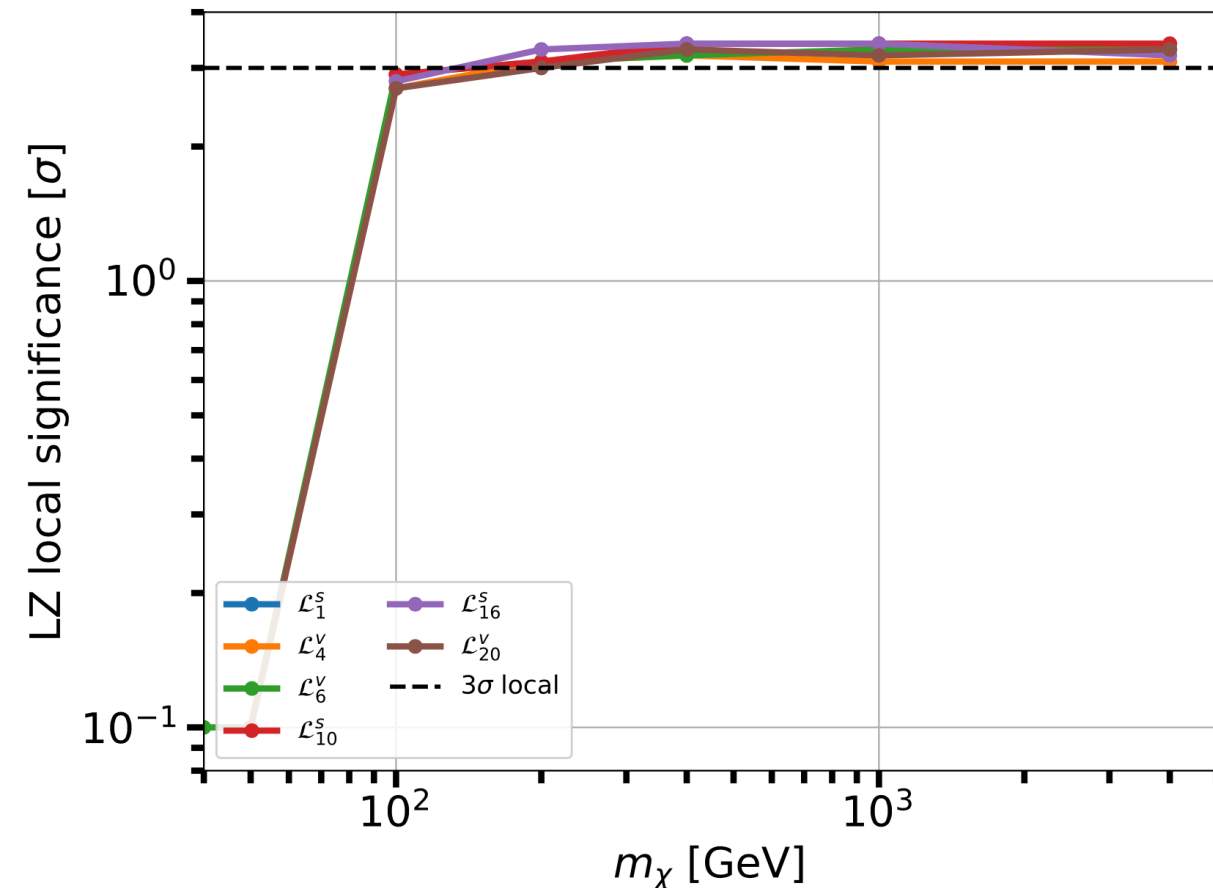
UV Complete model: Pseudo-dirac DM in U(1)_B



LZ model interpretation

TABLE S8. Local significance for $\mathcal{O}_i$ models tested. Dashed entries indicate that the observed event is not physical for those WIMP mass and mass splitting combinations.

Interaction	Mass (GeV/c ²)	Mass-splitting, δ (keV)							
		0	50	100	150	200	250	300	350
$\mathcal{O}_1^s$	400	0.0	0.0	0.8	2.2	2.6	2.9	2.9	-
	1000	0.0	0.0	0.8	2.2	2.7	2.9	3.0	3.3
	4000	0.0	0.0	1.0	2.3	2.7	2.9	3.0	3.3
$\mathcal{O}_1^v$	400	0.8	1.4	2.6	2.8	2.8	2.8	3.1	-
	1000	1.3	1.6	2.6	2.8	2.9	3.0	3.4	3.4
	4000	1.1	1.7	2.6	2.9	2.9	3.1	3.4	3.4
$\mathcal{O}_4^s$	400	2.6	2.7	2.8	3.1	3.2	3.2	3.3	-
	1000	2.7	2.8	2.8	3.0	3.2	3.2	3.4	3.4
	4000	2.8	3.0	3.0	3.1	3.2	3.3	3.4	3.4
$\mathcal{O}_4^v$	400	2.6	2.7	2.8	3.1	3.2	3.2	3.3	-
	1000	2.7	2.8	2.8	3.0	3.2	3.2	3.3	3.4
	4000	2.8	3.0	3.0	3.1	3.2	3.3	3.4	3.4



Local significance

Table S7 contains the local significance of the Lagrangian models tested, and Table S8 shows the same for the $\mathcal{O}_i$ models. A minimum of 30,000 toy distributions were generated for each case. The toys are used to determine the p_0 value of the fit to our data, from Eq. 6 of Ref. [30]. The value in the table is the number of normal-distribution standard deviations (one-sided) that correspond to the observed p_0 for each model and WIMP mass.

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	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	1.5	1.7	1.8
L_3^v	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	2.2	2.5	2.6	2.7
L_4^s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	2.6	3.1	3.1	3.1	3.0
L_4^v	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	2.7	3.1	3.2	3.1	3.1
L_5^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_5^v	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	1.3	1.3
L_6^s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	2.2	2.6	2.6	2.6
L_6^v	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	2.9	3.1	3.2	3.3	3.3
L_7^s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6	2.5	2.7	2.7	2.7
L_7^v	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6	2.3	2.7	2.7	2.8
L_8^s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.3	2.8	2.9	3.0	3.0
L_8^v	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.4	2.9	2.9	3.0	3.0
L_9^s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.1	2.9	2.9	3.0	3.1
L_9^v	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.7	3.0	3.1	3.2	3.1
L_{10}^s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.9	3.1	3.4	3.4	3.4
L_{10}^v	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0	3.2	3.3	3.4	3.4
L_{11}^s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.5	3.0	3.1	3.2	3.2
L_{11}^v	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.5	2.9	3.1	3.2	3.2
L_{12}^s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.4	3.1	3.2	3.2	3.3
L_{12}^v	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.5	3.0	3.2	3.2	3.2
L_{13}^s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	2.4	2.5	2.6
L_{13}^v	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	2.8	3.0	3.0	3.0
L_{14}^s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.5	2.9	3.0	3.1	3.1
L_{14}^v	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.5	2.9	3.0	3.1	3.1
L_{15}^s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	2.3	2.6	2.7	2.7
L_{15}^v	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	2.4	2.6	2.7	2.7
L_{16}^s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.8	3.3	3.4	3.4	3.2
L_{16}^v	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.4	3.2	3.3	3.2	3.2
L_{17}^s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	1.6	1.8	1.8
L_{17}^v	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.1	2.5	2.6	2.7
L_{18}^s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.2	2.9	3.1	3.1	3.1
L_{18}^v	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.2	2.8	2.9	2.9	2.9
L_{19}^s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.2	2.9	3.0	3.0	3.1
L_{19}^v	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.2	2.9	3.0	3.0	3.1
L_{20}^s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	2.7	3.1	3.2	3.2	3.3
L_{20}^v	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	2.7	3.0	3.3	3.2	3.3

PQ origin of inelastic electroweak dark matter

We consider the Standard Model (SM) Higgs doublet H , a complex SM-singlet scalar S that spontaneously breaks the PQ symmetry, two left-handed Weyl doublets D, D^c , a neutral singlet fermion N , and a vectorlike colored KSVZ pair Q, Q^c .

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	X_{PQ}	$\mathbb{Z}_2$
H	1	2	$+1/2$	0	+
S	1	1	0	$+2$	+
N	1	1	0	-1	-
D	1	2	$-1/2$	$+1$	-
D^c	1	2	$+1/2$	-1	-
Q	3	1	$-1/3$	0	+
Q^c	$\bar{\mathbf{3}}$	1	$+1/3$	-2	+

$$\mathcal{L}_{\text{dark}} = -M_D D \cdot D^c - \frac{y_S}{2} S N N - y N H \cdot D + \text{h.c.},$$

The QCD anomaly is generated by the KSVZ fermions through

$$\mathcal{L}_{\text{KSVZ}} = -y_Q S Q Q^c + \text{h.c.},$$

$$\mathcal{L}_{\text{eff}} \supset -M_D D \cdot D^c + \frac{y^2}{2M_N} (H \cdot D)^2 + \text{h.c.},$$

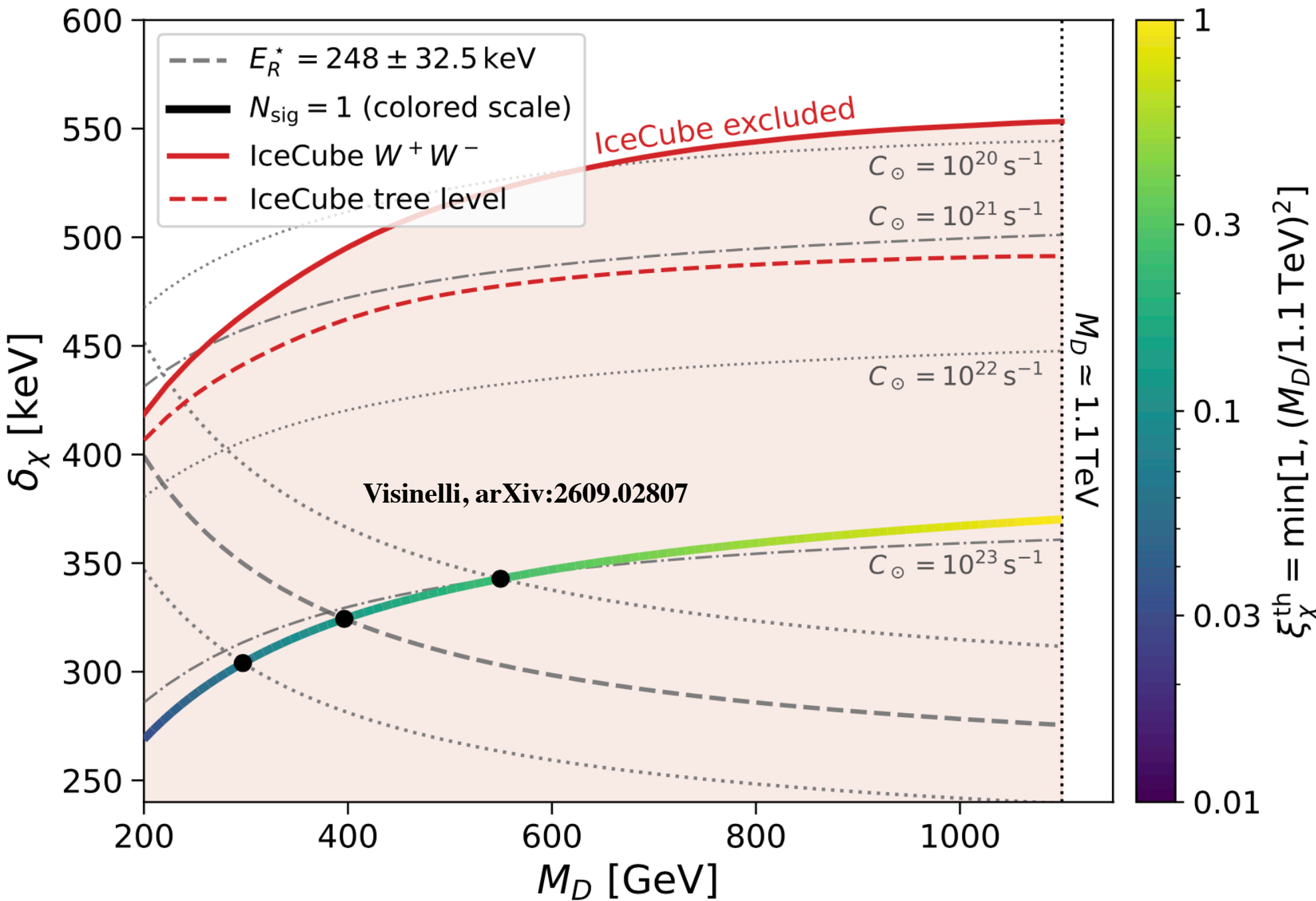
$$\chi_{1L} \simeq \frac{D^0 + D^{c0}}{\sqrt{2}} + \mathcal{O}\left(\frac{m}{M_N}\right) N,$$

$$\chi_{2L} \simeq i \frac{D^0 - D^{c0}}{\sqrt{2}} + \mathcal{O}\left(\frac{m}{M_N}\right) N,$$

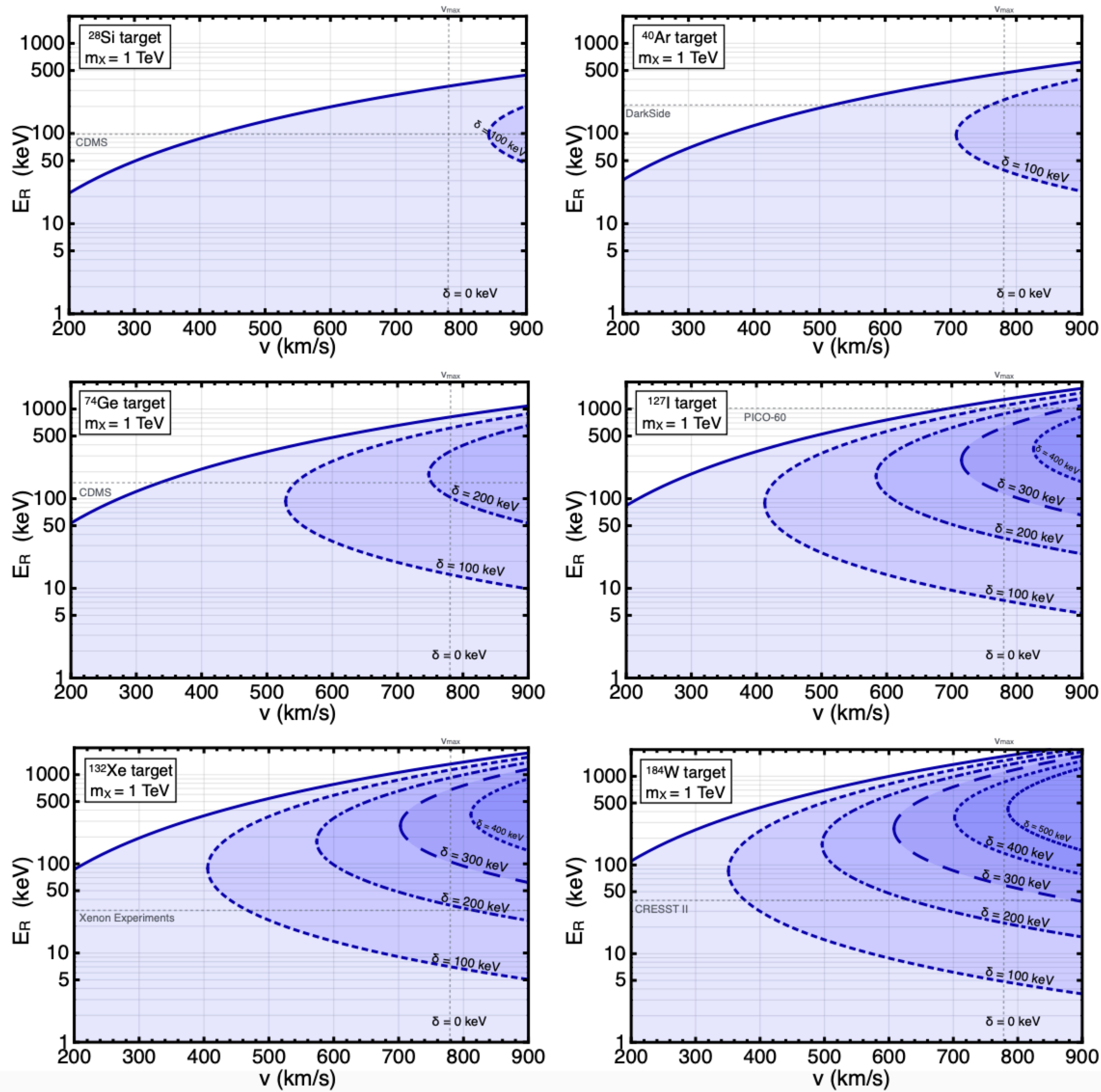
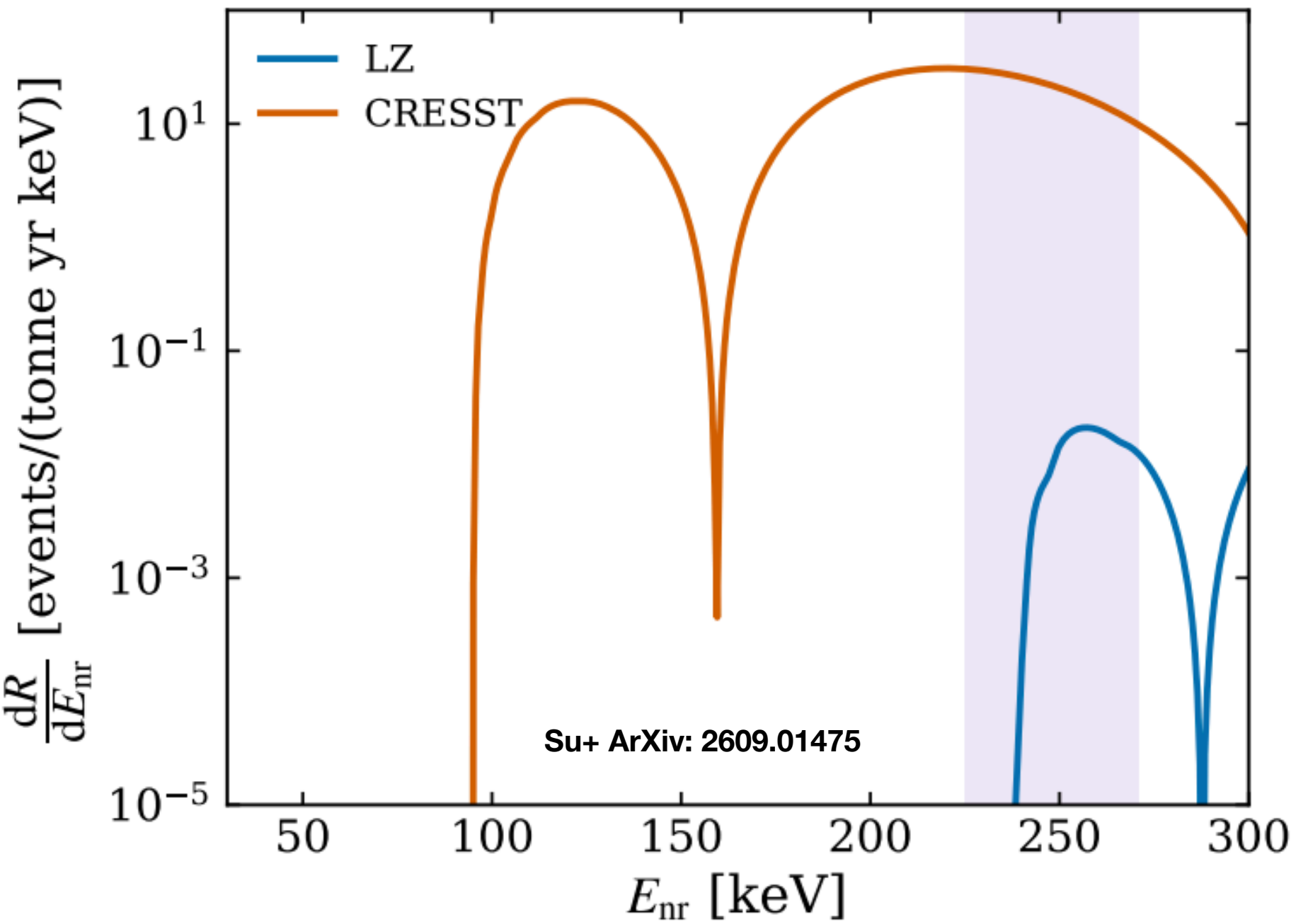
$$\Gamma_{\chi_2 \rightarrow \chi_1 \gamma} \simeq C^2(M_D) \frac{e^2 g^4}{256 \pi^5} \frac{\delta_\chi^3}{M_D^2}$$

$$\tau_{\chi_2} \simeq 1.61 \times 10^{-2} \text{ s} \left(\frac{M_D}{1 \text{ TeV}} \right)^{2.3} \left(\frac{400 \text{ keV}}{\delta_\chi} \right)^3$$

$$\sigma_n^Z = \frac{G_F^2 \mu_{\chi n}^2}{2\pi} \simeq 7.43 \times 10^{-39} \text{ cm}^2$$



Inelastic frontier: Discovering dark matter at high recoil energy

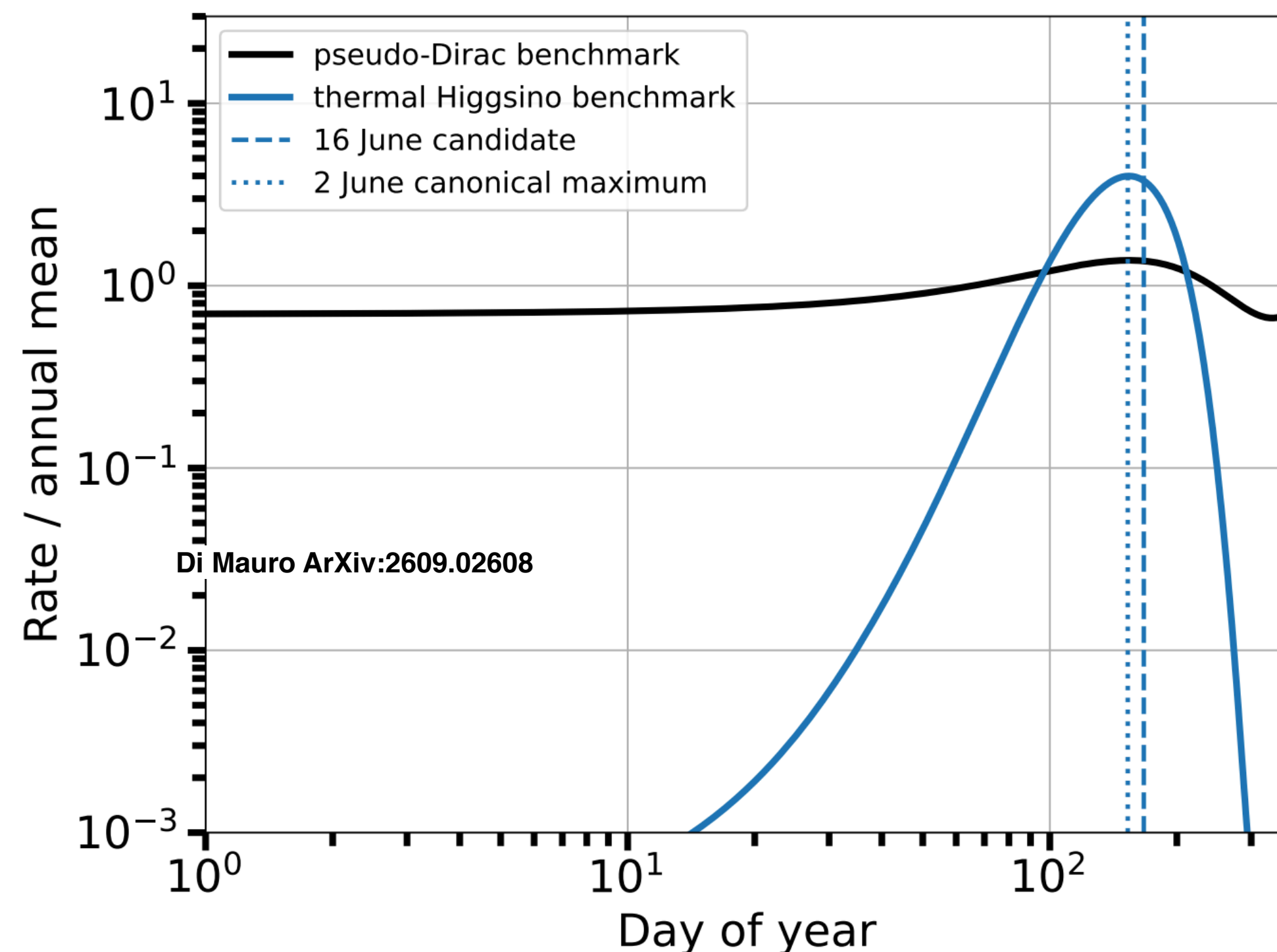
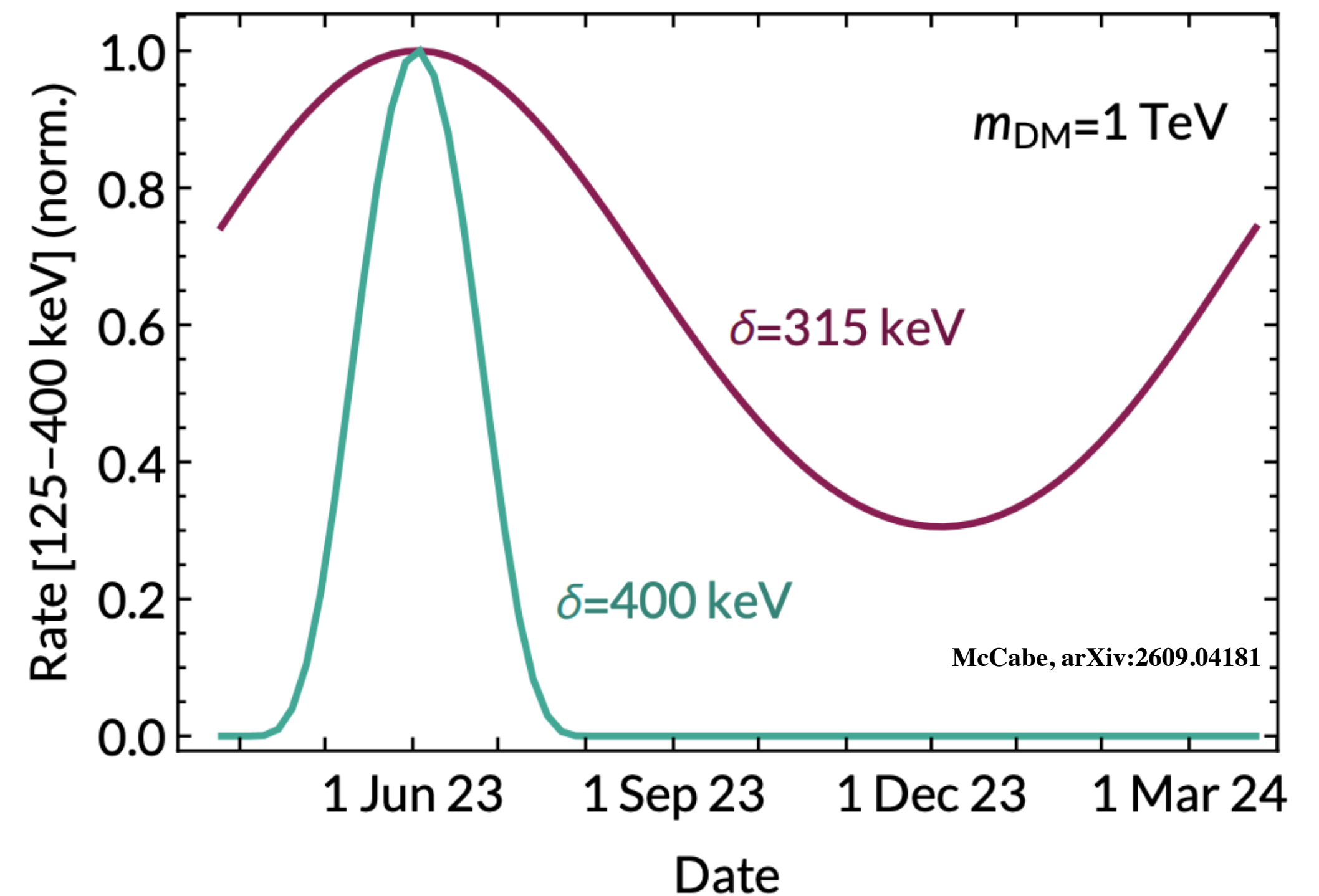


Benchmark: $m_\chi = 1 \text{ TeV}$; maximum laboratory speed $v_{\text{max}} = 800 \text{ km s}^{-1}$.

Target	Endothermic Δ_{max} Any recoil [keV]	Endothermic Δ_{max} $E_R = 248 \text{ keV}$ [keV]	Exothermic Δ range $E_R = 248 \text{ keV}$ [keV]
Argon-40	127.9	105.5	$0 < \Delta \leq 620.0$
Germanium-73	226.7	225.2	$0 < \Delta \leq 754.9$
Xenon-131	387.2	378.2	$0 < \Delta \leq 934.8$
Tungsten-184	521.0	487.5	$0 < \Delta \leq 1068.6$

Annual modulation

- **Annual modulation can be strongly enhanced:** endothermic scattering near threshold probes the fastest halo particles.
- **Large seasonal variations are possible:** some LZ-compatible benchmarks predict modulation above 50%, with the signal disappearing during part of the year.
- **The time dependence can distinguish models:** the studied elastic scenarios typically predict smaller variations.
- **Predictions depend on the halo distribution:** the high-speed tail and possible LMC contribution affect the modulation.
- **Additional events are essential:** the single LZ candidate cannot establish an annual-modulation signal.



Composite dark matter

- **Composite dark matter:** A neutral bound state of dark quarks scatters through a dark-photon mediator.
- **Suppressed low-energy recoils:** Screening among constituent charges suppresses the interaction at small momentum transfer.
- **Enhanced high-energy response:** The internal form factor can produce a harder recoil spectrum without a mass splitting or boosted particles.
- **Distinctive tests:** Diffraction features shift between target nuclei, and additional recoils are predicted above the current LZ energy window.

