



Signatures of gravity-mediated dark matter interaction in theories with large extra dimensions

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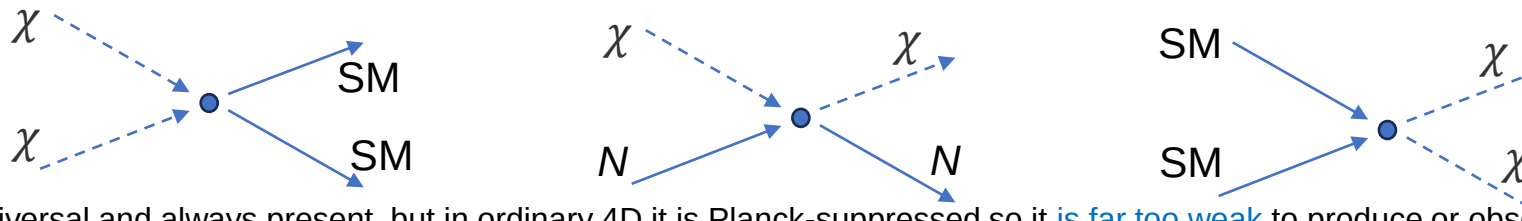


Motivations and Background

- WIMP remains dominating candidate for DM particles χ
- The likely mass range:

$$O(1)\text{GeV} < m_\chi < O(100)\text{TeV}$$

- Standard search channels: relic freeze-out / indirect detection, nuclear recoil direct detection, and collider missing-energy



- Gravity is universal and always present, but in ordinary 4D it is Planck-suppressed so it is far too weak to produce or observe WIMPs.:

$$A_{\text{grav}} \sim M_{\text{Pl}}^{-2}$$

- ADD changes this logic: gravity propagates in $D = 4 + n$ dimensions, the fundamental scale M_D may be much lower than M_{Pl} , and the KK tower enhances short-distance gravitational interactions. [Arkani-Hamed, Dimopoulos, Dvali, Phys. Lett. B 429, 263 (1998)]
- Question addressed here: do present direct- and indirect-detection data constrain the parameter space when gravity is the only interaction portal?

$$\{m_\chi, M_D, n\}$$

Assumptions

- χ is stable, localized on the brane, and saturates the dark-matter abundance.
- The direct-detection analysis allows χ to be elementary or sufficiently compact and composite; the indirect analysis is specialised to elementary scalar χ .

Arkani-Hamed–Dimopoulos–Dvali (ADD) model

Phys. Lett. B 429, 263 (1998)

- Gravity can propagate in compact **extra dimensions** while the matter lives in 4D space-time (brane)
- R is the **size of compact extra dimensions**, it can be as large as $O(1) \mu\text{m}$

- 4D Planck constant $M_{\text{Pl}} \approx 10^{19} \text{ GeV}$ is related to the $D=4+n$ dimensional one

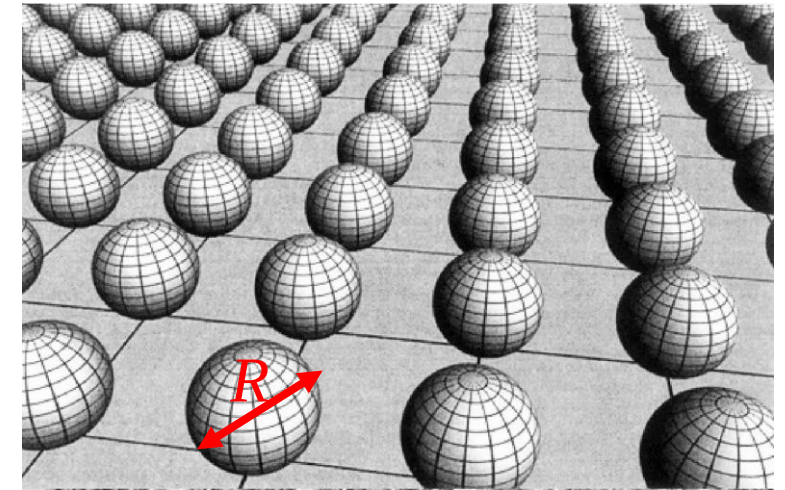
$$M_{\text{Pl}}^2 \sim M_D^{n+2} R^n$$

- **Small-distance modification of the Newton's law of gravity:**

$$V(r) = \begin{cases} -\frac{G m_1 m_2}{r}, & \text{for } r \gg R \\ -\frac{G m_1 m_2 R^n}{r^{n+1}}, & \text{for } r \ll R \end{cases}$$

- ATLAS lower limits on M_D [Phys.Rev.D 103 (2021) 11, 112006]:

n	2	3	4	5	6
M_D [TeV]	11.6	8.6	7.2	6.4	5.9



Effective short-distance interaction

- At short distance, the gravitational potential may be strong for point-like masses m_1 and m_2 :

$$V(r) = -\frac{\beta}{r^{n+1}}, \quad \beta = \frac{m_1 m_2}{M_D^{n+2}} \quad (r \ll R)$$

- Singularity at the origin is unphysical. It may be regularized by introducing a short-distance **cut-off parameter** r_c :

$$V(r) \rightarrow V_{\text{reg}}(r) = -\frac{\beta}{(r^2 + r_c^2)^{(n+1)/2}}, \quad r_c = M_D^{-1}$$

- Since the regulated potential is dominated by distances much smaller than the nuclear size, it can be replaced by a **contact interaction potential** in the scattering cross section

$$V_{\text{reg}}(r) \rightarrow V_{\text{contact}}(r) = V_n \delta^3(r), \quad V_n = \int V_{\text{reg}}(r) d^3r$$

- Explicitly:

$$V_n = -\frac{\pi^{3/2} m_1 m_2}{M_D^4} \frac{\Gamma(-1+n/2)}{\Gamma((n+1)/2)} \quad (n \geq 3)$$

$$V_2 = -\frac{4\pi m_1 m_2}{M_D^4} \ln \frac{M_D}{q} \quad (n = 2)$$

- Here q^{-1} provides the infrared scale; in xenon recoils q is of order tens of MeV

DM-nucleon scattering cross section

$$V_{\text{contact}}(r) = V_n \delta^3(r)$$

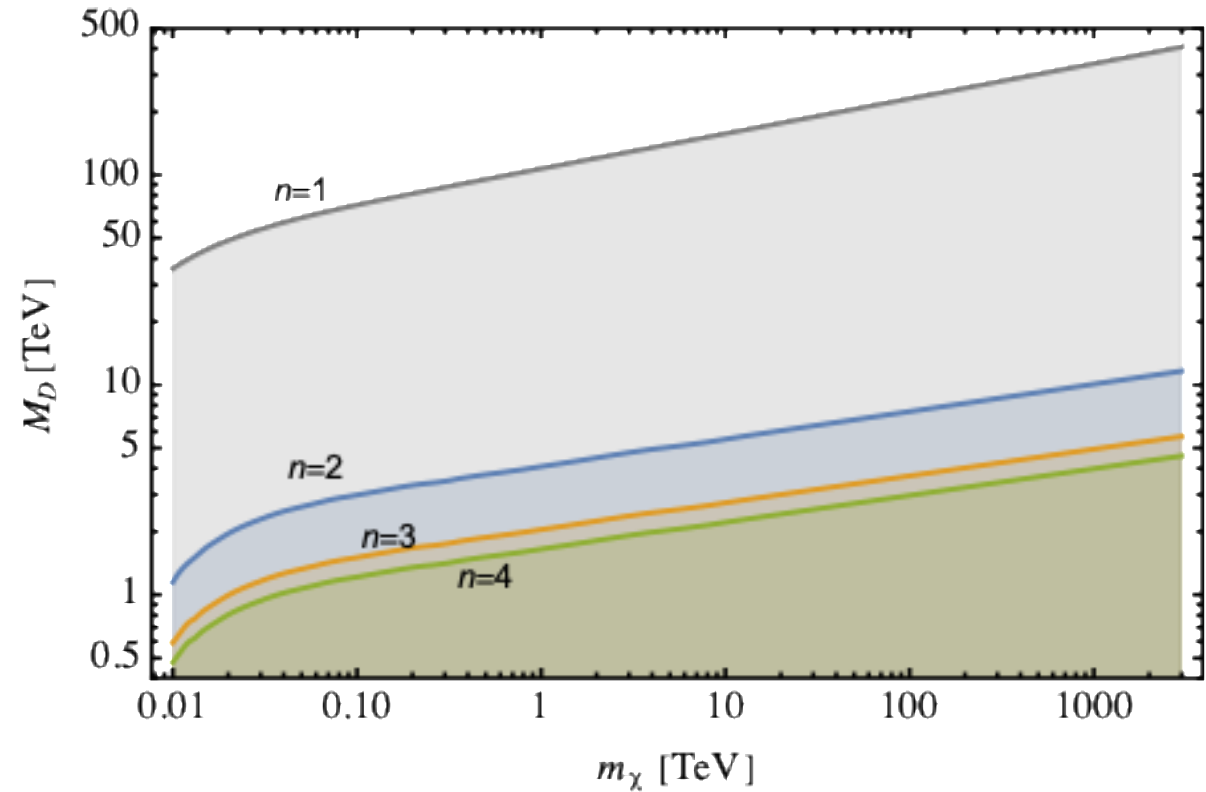
- For contact interaction, non-relativistic DM-nucleon scattering cross section is well known:

$$\sigma_{\chi p} = \frac{\mu_p^2 V_n^2}{\pi}, \quad \mu_p = \frac{m_p m_\chi}{m_p + m_\chi}$$

- As a result, the scattering cross section scales as

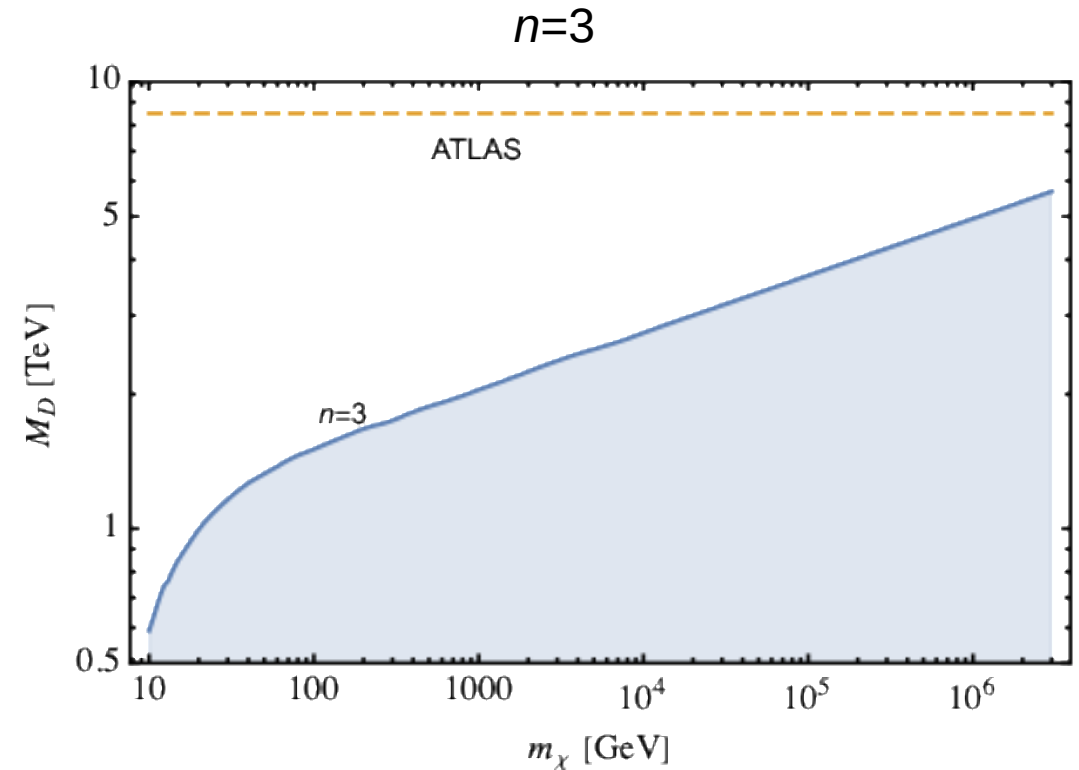
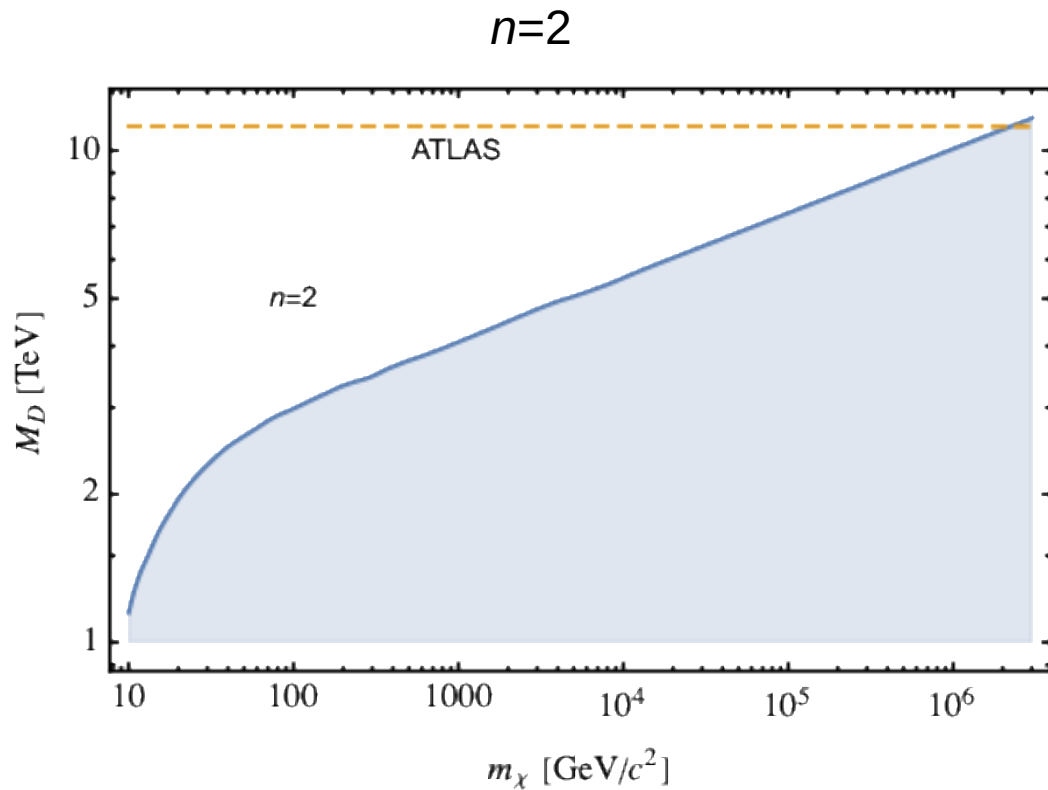
$$\sigma_{\chi p} \propto \frac{m_\chi^2 m_p^4}{M_D^8} \times \begin{cases} \ln^2\left(\frac{M_D}{q}\right) & n = 2 \\ c_n^2 & n \geq 3 \end{cases}$$

- The scattering cross section $\sigma_{\chi p}$ is limited by direct detection experiments, e.g. LZ [[Phys. Rev. Lett. 135, 011802 \(2025\)](#)]



Limits from LZ experiment

- The scattering cross section $\sigma_{\chi p}$ is limited by direct detection experiments, e.g. LZ [[Phys. Rev. Lett. 135, 011802 \(2025\)](#)]
- These limits are comparable with the ATLAS ones for $n=2$



Special case: $n=1$ (one extra dimension)

- For $n = 1$, $V(r) \propto 1/r^2$ is sufficiently long-ranged that the contact-interaction treatment is not applicable.

$$V(r) = -\frac{m_\chi m_N}{M_D^3 r^2} \quad \tilde{V}(q) = -\frac{2\pi^2 m_\chi m_N}{M_D^3 q}$$

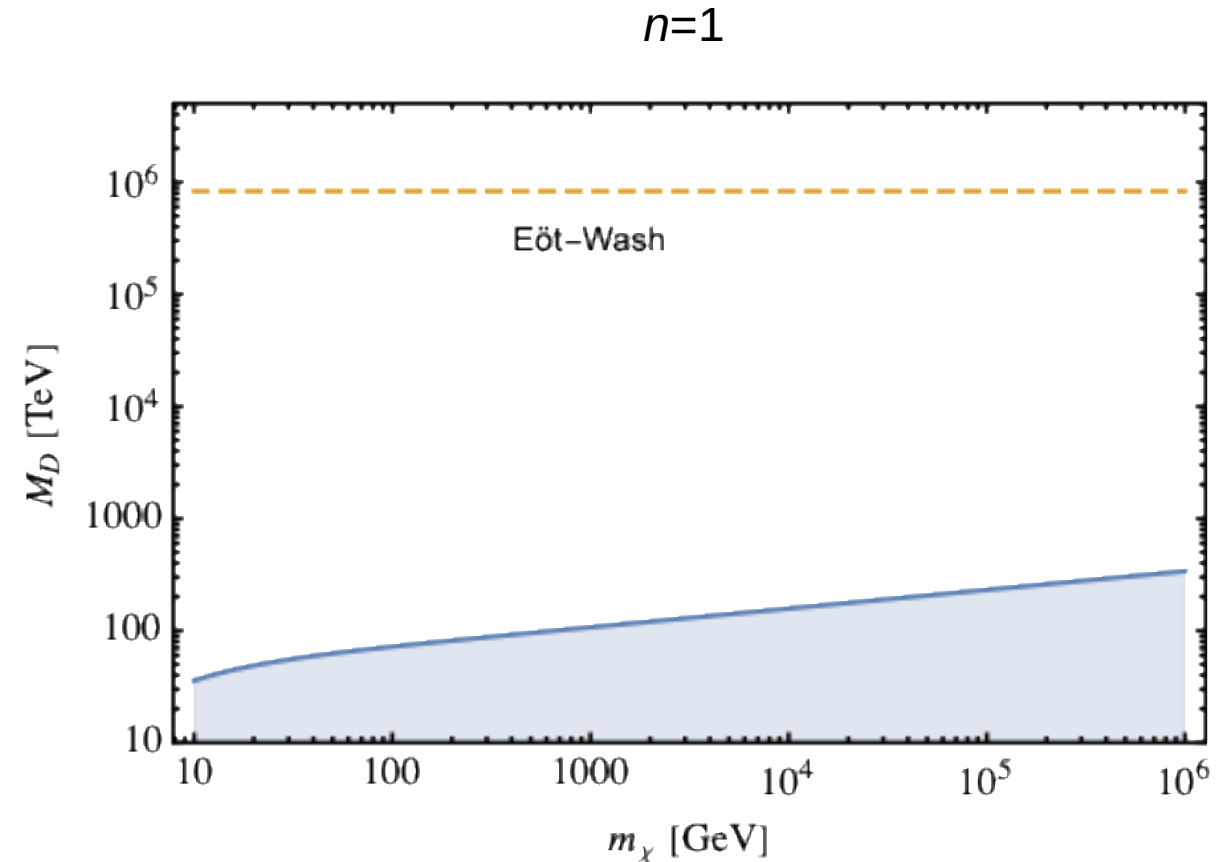
- Differential cross section

$$\frac{d\sigma}{dE_R} = \frac{\pi^3 m_\chi^2 m_N^2}{v^2 E_R M_D^6} F^2(q), \quad q^2 = 2m_N E_R$$

- Event rate for a local density ρ_χ and speed distribution $f(v)$

$$\frac{dR}{dE_R} = \frac{\pi^3 \rho_\chi m_\chi m_N}{M_D^6} \frac{F^2(q)}{E_R} \int_{v>v_{\min}} \frac{f(v)}{v} dv$$

- Requiring that it does not exceed the observed background in LZ and XENON experiments, we find the limits on M_D for $n=1$
- Phenomenologically, $n = 1$ is already highly restricted by tests of Newton's inverse-square law



Resonant annihilation through scalar KK modes

- Heavy DM particles can decay to SM particles via **Kaluza-Klein scalar** modes $\tilde{\phi}_{\vec{n}}$.
- Spin-2 exchange is d-wave suppressed; fermionic dark matter gives p-wave annihilation.

$$\chi^+ \chi \rightarrow \tilde{\phi}_{\vec{n}} \rightarrow (W^+ W^-, ZZ, hh) \rightarrow \gamma$$

- If the center-of-mass energy is sufficiently close to a KK mode mass, then DM annihilation may proceed through a **KK resonance**, significantly enhancing the annihilation rate.
- Near a KK resonance, the **non-relativistic Breit–Wigner cross section** is

$$\sigma_{\vec{n}} = \frac{4\pi}{\vec{k}^2} \frac{\Gamma_{\text{DM}} \Gamma_{\text{SM}} / 4}{(\sqrt{s} - m_{\vec{n}})^2 + (\Gamma_{\text{DM}} + \Gamma_{\text{SM}})^2 / 4}$$

Γ_{DM} is the width of the KK mode decay into the dark-matter pair

Γ_{SM} is the width of the KK mode decay into SM particles

- The total decay width is much smaller than the KK mode spacing for $n \leq 4$. Then, for $\Gamma_{\text{DM}} \ll \Gamma_{\text{SM}}$

$$\sigma_{\vec{n}} = \frac{8\pi^2}{m_{\chi}^2 v^2} \Gamma_{\text{DM}} \delta(\sqrt{s} - m_{\vec{n}}) \quad \Gamma_{\text{DM}} = \frac{\omega^2 \kappa^2 m_{\chi}^3 v}{64\pi} \quad \omega = \sqrt{\frac{2}{3(n+2)}} \quad \kappa = \sqrt{16\pi G}$$

- Summing over KK modes and averaging over the velocity distribution $f(v)$ we find

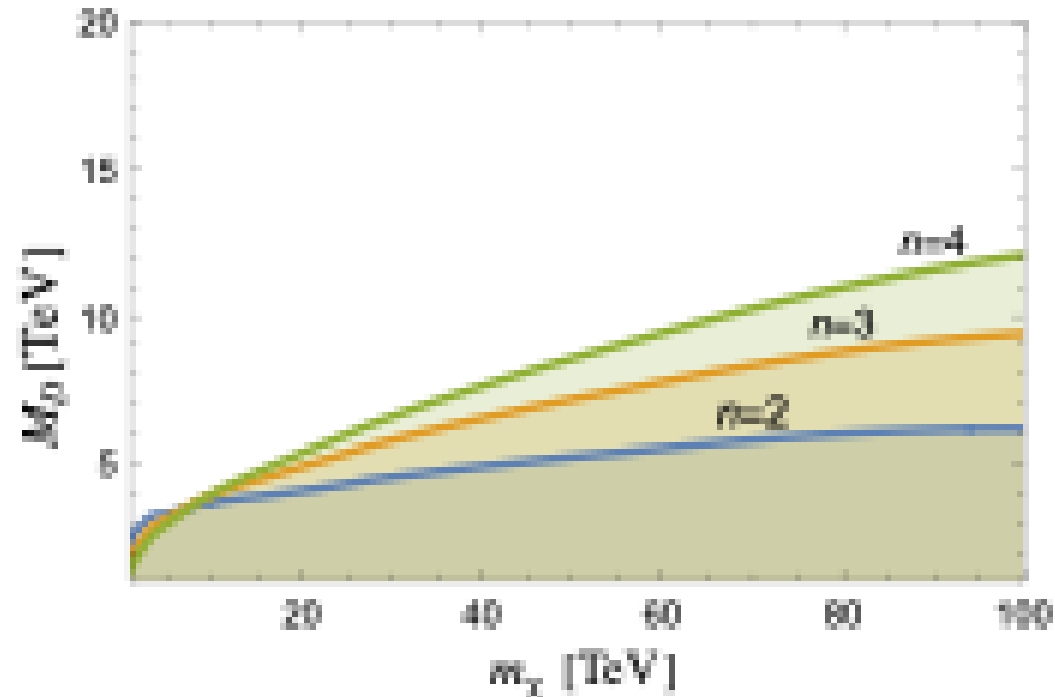
$$\langle \sigma v \rangle = \frac{\alpha_n m_{\chi}^n}{M_D^{n+2}}, \quad \alpha_n = \frac{4\pi^{2-n/2}}{3(n+2)\Gamma(n/2)}$$

Indirect DM detection sensitivity

- Resonant annihilation cross section into SM particles:

$$\langle\sigma v\rangle = \frac{\alpha_n m_\chi^n}{M_D^{n+2}}, \quad \alpha_n = \frac{4\pi^{2-n/2}}{3(n+2)\Gamma(n/2)}$$

- $\langle\sigma v\rangle$ is limited by [Fermi-LAT observations](#) [JCAP 02, 039, arXiv:1601.06590 [astro-ph.HE]]
- This allows us to find additional limits on M_D which are independent of the short-distance cutoff used in elastic scattering



Direct vs indirect probes: different assumptions

	Direct detection	Indirect detection
Process	$\chi N \rightarrow \chi N$	$\chi^+ \chi \rightarrow \text{KK scalar} \rightarrow \text{SM} \rightarrow \gamma$
DM type	Elementary or compact composite	Elementary spinor
Density assumption	Local DM density ρ_χ	Halo annihilation J-factor
Particle symmetry	Not required	Particle–antiparticle symmetry required
UV sensitivity	Logarithmic for $n=2$; power-like for $n \geq 3$	Cutoff independent
Principal scaling	$\sigma_{\chi p} \propto m_\chi^2 m_p^4 M_D^{-8}$	$\langle \sigma v \rangle \propto m_\chi^n M_D^{-n-2}$
Principal final state	Nuclear recoil	W^+W^- , ZZ , $hh \rightarrow \gamma$ rays

The two constraints should not be combined without specifying a particle model and a cosmological history. Their value is complementarity: they interrogate the same ADD scale through independent observables.

Conclusions

- In ADD models, summation over the gravitational KK tower converts a purely gravitational portal into an interaction potentially accessible to current experiments.
- For $n \geq 2$, elastic scattering is effectively contact-like. In the heavy-DM limit, $\sigma_{\chi p} \propto m_\chi^2 M_D^{-8}$
- LZ data provide non-trivial lower limits on M_D . The $n = 2$ result is the strongest and least sensitive to ultraviolet regularisation.
- For fermionic dark matter, annihilation through on-shell scalar KK modes gives $\langle \sigma v \rangle \propto m_\chi^n M_D^{-n-2}$ and can be constrained by gamma-ray observations.
- Direct detection, collider searches, short-distance gravity tests and indirect detection probe different assumptions and should be treated as complementary.
- A complete model must specify the ultraviolet completion, the nature of χ and its non-standard cosmological production history.

Large extra dimensions can make gravity-mediated heavy DM experimentally testable!

Cosmological interpretation and limitations

- The analysis constrains interactions of an assumed dark-matter population; it does not provide a production mechanism for the observed abundance.
- A conventional high-temperature thermal history is problematic in ADD models because excessive production of KK modes requires a low normalcy or reheating temperature, typically well below the electroweak scale.
- Standard WIMP freeze-out at $T_{f.o.} \simeq 0.05 m_\chi$ is therefore not generically available for weak-scale or heavier χ in the minimal ADD cosmology.
- Non-thermal production remains possible, for example through the decay of a sufficiently massive but weakly coupled inflaton.
- For $m_\chi > M^*$, an elementary-particle interpretation is not appropriate. Direct-detection limits may still be applied to compact composite χ provided its size is smaller than q^{-1} .
- For $n \geq 3$, a UV-complete construction is required to determine the order-one relation between the short-distance cutoff and M^* .