Gravity-Mediated Dark Matter Annihilation in the Randall-Sundrum Model

[1706.07540], Hewett, Rizzo, TDR

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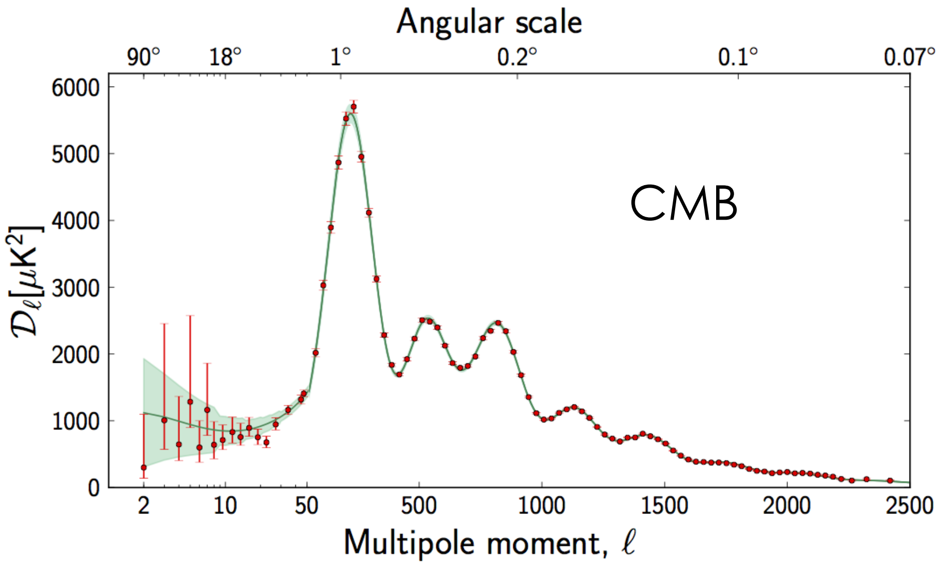
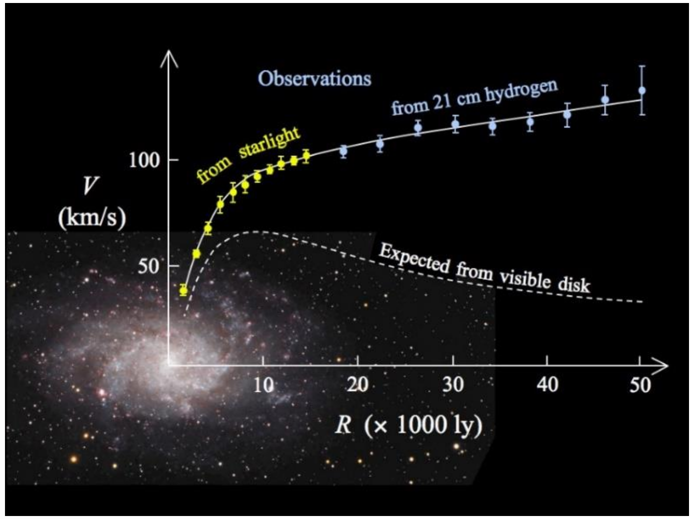
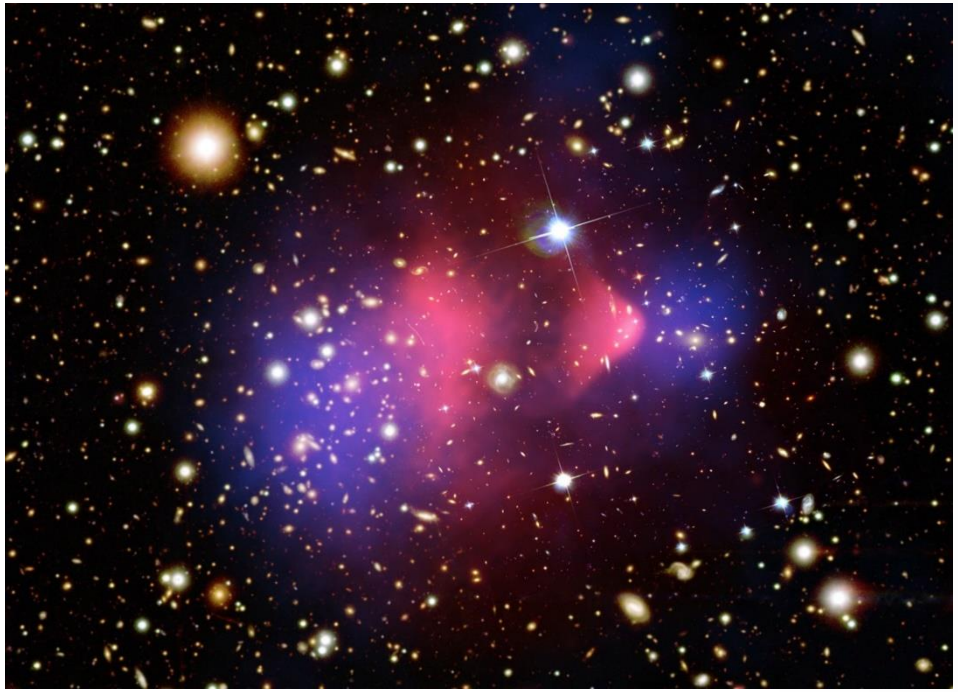
Evidence for Dark Matter





Rotation Curves



Bullet Cluster

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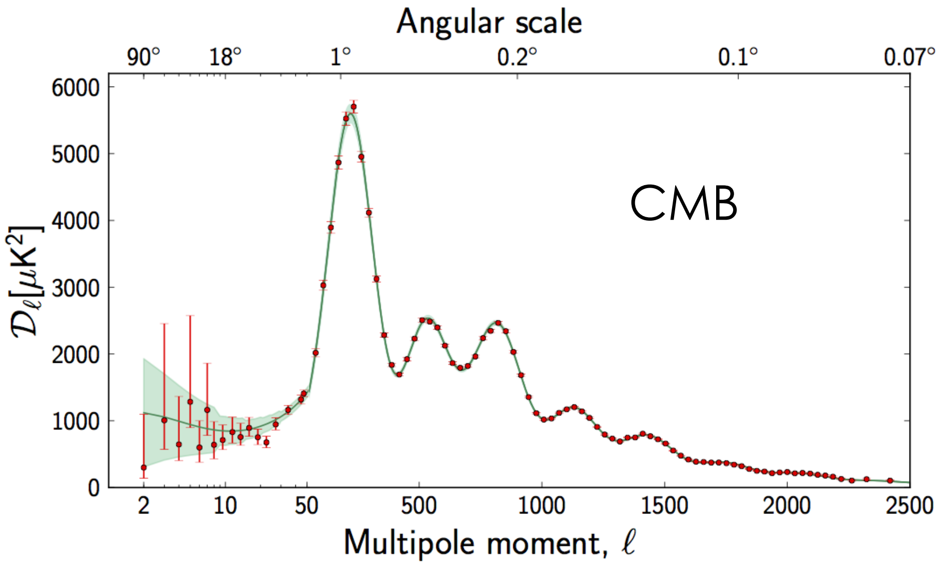

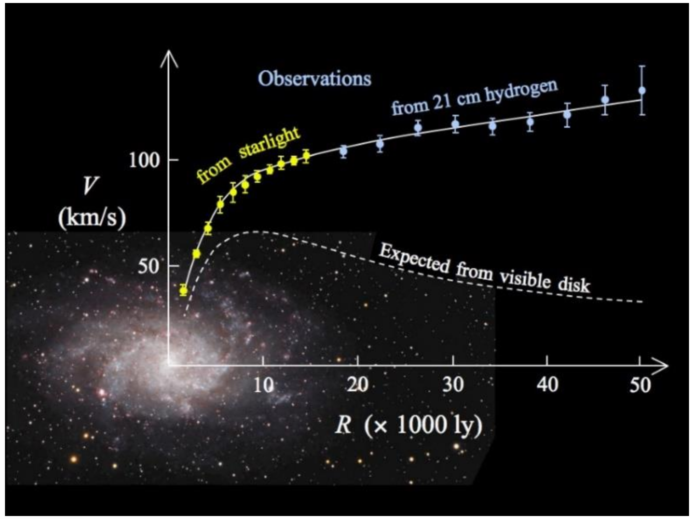

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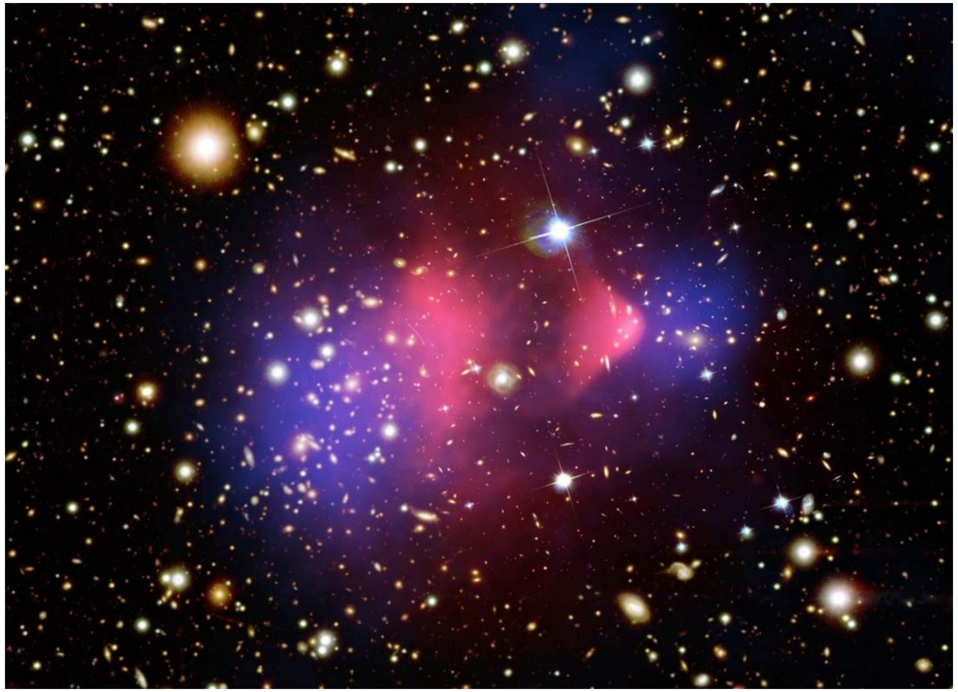

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All of our current evidence for dark matter comes from its gravitational effects.

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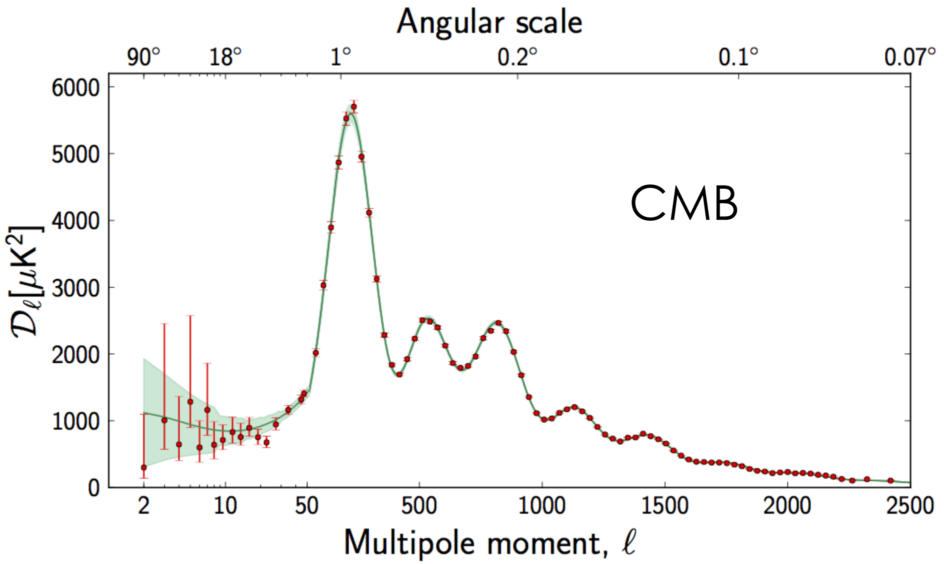

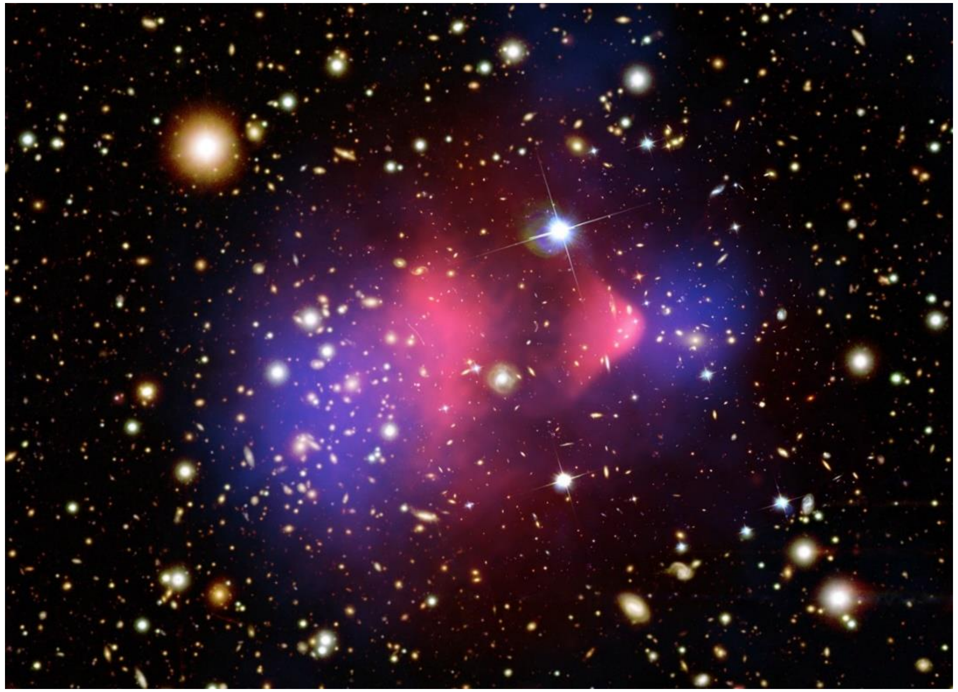

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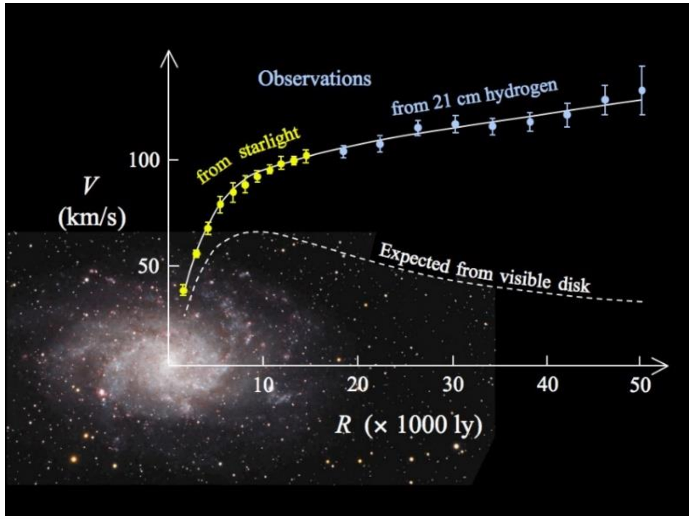


Rotation Curves

All of our current evidence for dark matter comes from its gravitational effects.

Can we build a model where dark matter only couples to the SM via gravity?

Gravity in the Randall-Sundrum Model

Randall and Sundrum proposed a model which solves the hierarchy problem with a warped extra dimension:

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - r_c^2 d\phi^2 \qquad \Lambda_\pi \equiv \overline{M}_{Pl} e^{-kr_c\pi} \sim \text{few TeV}$$

Gravity propagates in the fifth dimension, leading to a 5D gravitational action:

$$\begin{aligned} S_G = \quad & \frac{M_5^3}{4} \int d^4x \int r_c d\phi \sqrt{G} \left\{ R^{(5)} + [2\gamma_0/kr_c \;\; \delta(\phi) \right. \\ + \quad & \left. 2\gamma_\pi/kr_c \;\; \delta(\phi - \pi)]\, R^{(4)} + \ldots \right\} \end{aligned}$$

This leads to Kaluza Klein modes of the graviton, with masses determined by roots of the equation:

$$J_1(x_n^G) - \gamma_\pi x_n^G J_2(x_n^G) = 0 \qquad m_n^G = kx_n^G e^{-kr_c\pi}$$

KK Graviton Couplings to Matter

The KK modes of the graviton couple to matter through the stress energy tensor. For fields residing on the IR brane, the Lagrangian becomes:

$$\mathcal{L} = \frac{1}{\overline{M}_{Pl}} h^{(0)}_{\mu\nu}(x) T^{\mu\nu}(x) + \frac{1}{\Lambda_\pi} T^{\mu\nu}(x) \sum_{n=1}^{\infty} \lambda_n h^{(n)}_{\mu\nu}(x)$$

$$\lambda_n \equiv \left[\frac{1 + 2\gamma_0}{1 + (x_n^G \gamma_\pi)^2 - 2\gamma_\pi} \right]^{1/2}$$

Brane Localized Kinetic Terms make graviton couplings level dependent.

Gauge fields which propagate in the bulk have their 5D Yang Mills kinetic coupling modified by a factor:

$$\lambda_n \to \lambda_n \delta_n \qquad \delta_n = \frac{2(1 - J_0(x_n^G)) + (\delta_\pi - \gamma_\pi)(x_n^G)^2 J_2(x_n^G)}{(\pi k r_c + \delta_\pi + \delta_0)(x_n^G)^2 |J_2(x_n^G))|}$$

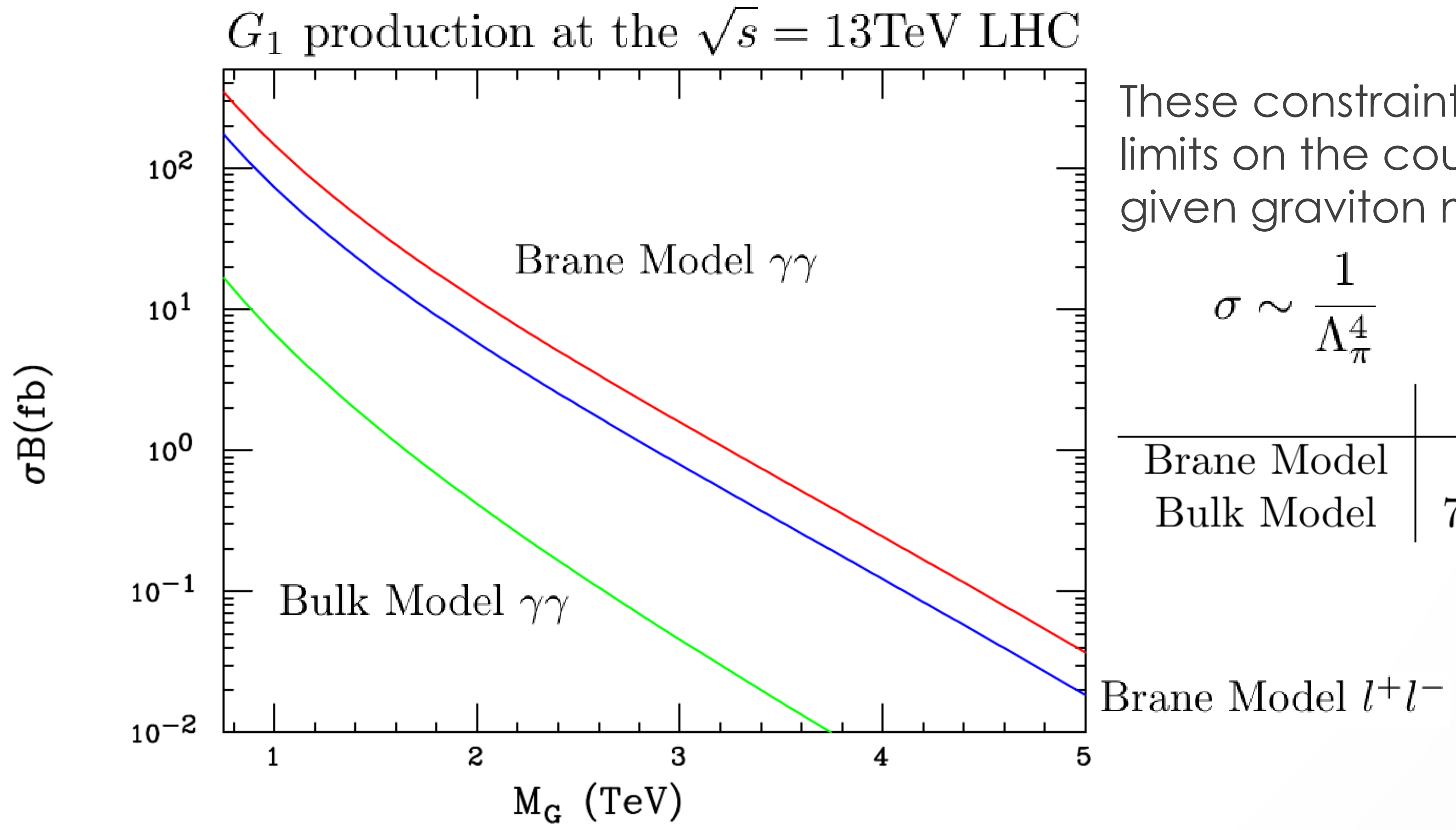
Field Localizations of the Models

We consider two benchmark models, with the following localizations for the various fields:

Field	Brane Model	Bulk Model
Higgs	IR brane	IR brane
SM Gauge bosons	IR brane	5D bulk
t,b	IR brane	IR brane
Light fermions	IR brane	near UV brane
Dark Matter	IR brane	IR brane

Constraints from the LHC

The Brane Model is most constrained by LHC searches for graviton production and decay into dilepton, and diphoton final states. The Bulk Model is constrained by the diphoton final state.



These constraints lead to limits on the coupling for a given graviton mass.

$$\sigma \sim \frac{1}{\Lambda_\pi^4}$$

	m_{G_1}	Λ_π
Brane Model	3 TeV	30 TeV
Bulk Model	750 GeV	6 TeV

Dark Matter Annihilation

We consider thermally produced spin-0, spin-1/2, or spin-1 whose only SM interactions are mediated by the KK graviton modes. The spin of the DM determines the velocity suppression of the annihilation cross section:

Spin-0: $$\frac{d\sigma_{SS\to hh}}{dz} = \frac{s^3\beta_S^3\beta_h^5(1-3z^2)^2}{9216\pi\Lambda_\pi^4}\sum_{i,j}\lambda_i^2\lambda_j^2 P_{ij}$$

Spin-1/2: $$\frac{d\sigma_{F\bar{F}\to hh}}{dz} = \frac{\lambda^4 s^3\beta_F\beta_h^5}{18432\pi\Lambda_\pi^4}(1-\beta_F^2+3z^2(1+2\beta_F^2)-9z^4\beta_F^2)\sum_{i,j}\lambda_i^2\lambda_j^2 P_{ij}$$

Spin-1: $$\frac{d\sigma_{XX\to hh}}{dz} = \frac{s^3\beta_h^5(24-8\beta_X^2(1+3z^2)+3\beta_X^4(1-3z^2)^2)}{82944\pi\beta_X\Lambda_\pi^4}\sum_{i,j}\lambda_i^2\lambda_j^2 P_{ij}$$

$$P_{ij} = \frac{(s-m_i^2)(s-m_j^2)+m_i\Gamma_i m_j\Gamma_j}{[(s-m_i^2)^2+m_i^2\Gamma_i^2][(s-m_j^2)^2+m_j^2\Gamma_j^2]}$$

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d-wave

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p-wave

Spin-1:

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$$P_{ij} = \frac{(s-m_i^2)(s-m_j^2) + m_i\Gamma_i m_j\Gamma_j}{[(s-m_i^2)^2 + m_i^2\Gamma_i^2][(s-m_j^2)^2 + m_j^2\Gamma_j^2]}$$

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Spin-0:

$$\frac{d\sigma_{SS\to hh}}{dz} = \frac{s^3 \underbrace{\boxed{\beta_S^3}}_{\text{d-wave}} \beta_h^5 (1-3z^2)^2}{9216\pi\Lambda_\pi^4} \sum_{i,j} \lambda_i^2 \lambda_j^2 P_{ij}$$

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Spin-1:

$$\frac{d\sigma_{XX\to hh}}{dz} = \underbrace{\boxed{}}_{\text{s-wave}} \frac{s^3 \beta_h^5 \left(24-8\beta_X^2(1+3z^2)+3\beta_X^4(1-3z^2)^2\right)}{82944\pi\beta_X\Lambda_\pi^4} \sum_{i,j} \lambda_i^2 \lambda_j^2 P_{ij}$$

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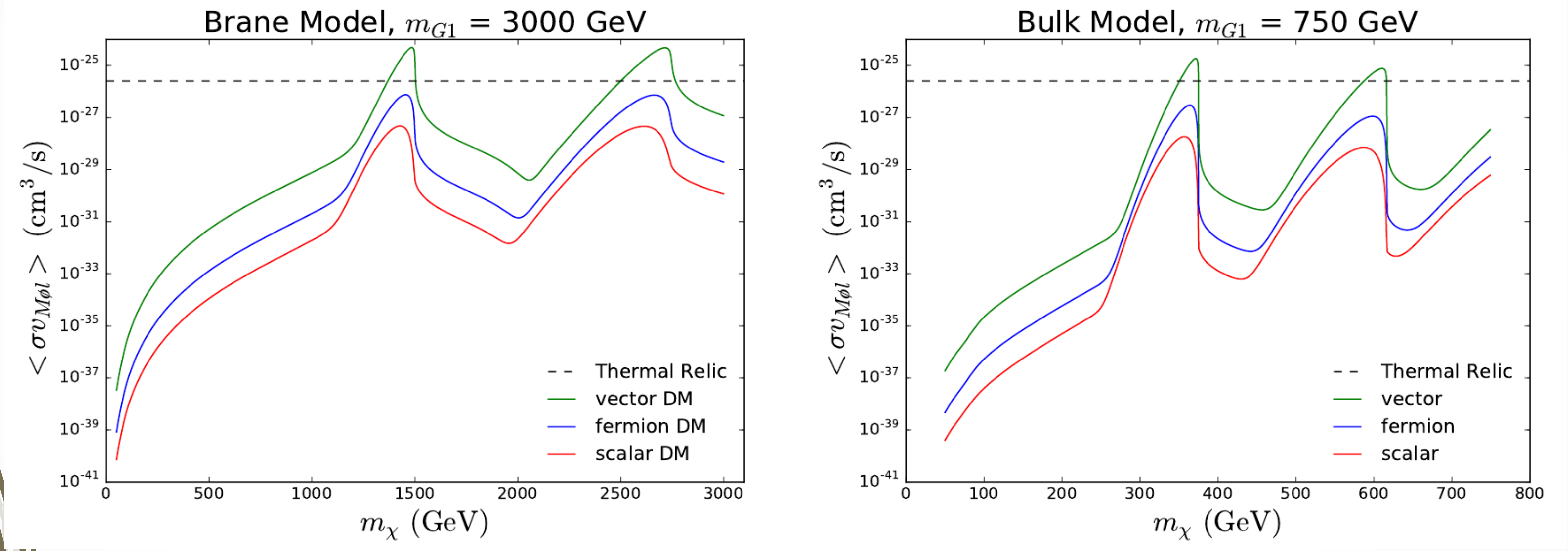
Thermal Production



Only spin-1 dark matter reaches the thermal production cross section near a KK graviton resonance.

Prospects for Direct Detection

We calculate the dark matter-nucleon spin-independent cross section, taking the non-relativistic limit of the dark matter stress-energy tensor:

$$\sigma_N = \frac{1}{9\pi} \left[\frac{\mu}{m_N}\right]^2 \left[\frac{m_N}{m_{GR}\Lambda_\pi}\right]^4 m_{DM}^2$$

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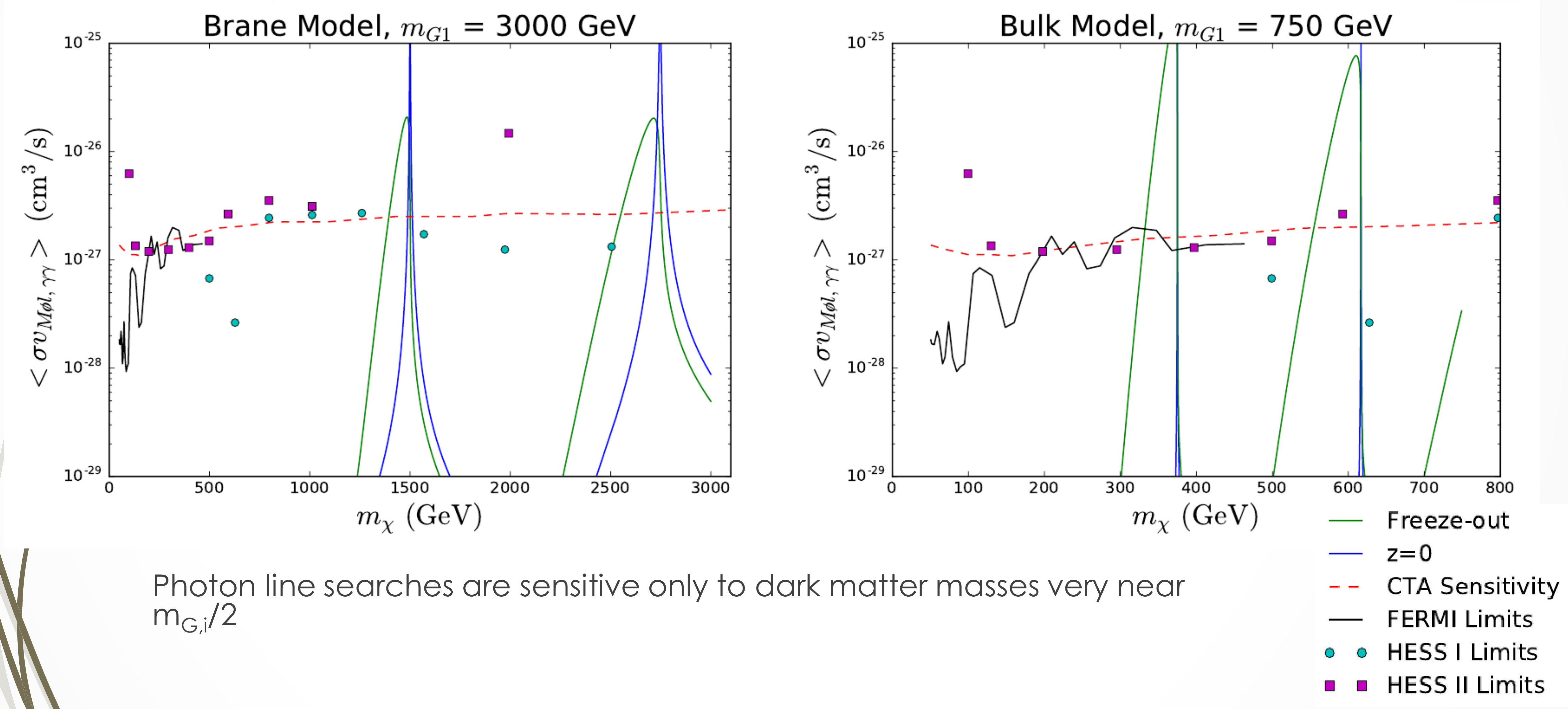
$$\simeq 3.3 \cdot 10^{-54}\mathrm{cm}^2 \left[\frac{m_{DM}}{500\mathrm{GeV}}\right]^2 \left[\frac{30\ \mathrm{TeV}^2}{m_{GR}\Lambda_\pi}\right]^4$$

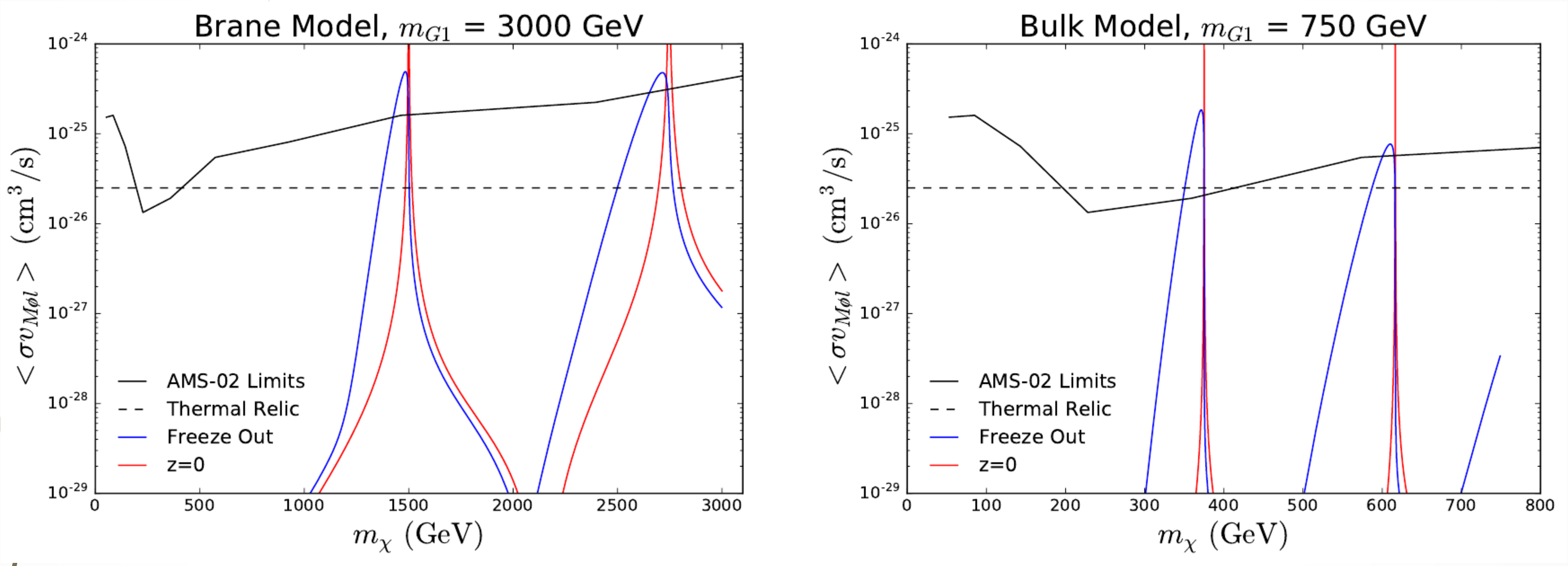
This is well below current direct detection bounds, and also below the neutrino floor!

Indirect Detection with Photons



Photon line searches are sensitive only to dark matter masses very near $m_{G,i}/2$

Indirect Detection with AMS-02



Using AMS-02 antiproton limits from Cuoco et al. [1610.03071] also offer constraints only near $m_{G,i}/2$.

Conclusions

- The KK gravitons of the Randall-Sundrum model provide a channel for dark matter annihilation which can account for thermal production if the dark matter is spin-1.
- Direct detection and astrophysical indirect detection prove very difficult due to the dark matter being cold today.
- The prospect for testing these models remains through KK graviton production at colliders.

Backup Slides

Direct Detection Calculation

For direct detection, we calculate the dark matter-nucleon cross section

$$\mathcal{M} \sim T^1_{\mu\nu} \; P^{\mu\nu\alpha\beta} \; T^2_{\alpha\beta} \to \mathcal{M} \sim 2 \, \tilde{T}^{1\mu\nu} \; \tilde{T}^2_{\mu\nu} - \frac{1}{6} \, T^1 T^2$$

$$\tilde{T}_{\mu\nu} = T_{\mu\nu} - \frac{1}{4}\eta_{\mu\nu} T \qquad T^i = \eta^{\mu\nu} T^i_{\mu\nu}$$

Summing over the quark and gluon contributions, we find the nucleon matrix elements:

$$< N|T_N|N >= 2m_N^2 \qquad < N|\tilde{T}^N_{\mu\nu}|N >= 2(k_\mu k_\nu - \frac{1}{4}\eta_{\mu\nu} m_N^2)$$

Taking the non-relativistic limit of the dark matter stress-energy tensor, we find the cross section in the lab frame to be well below current limits, and unlikely to be probed by future experiments

$$\sigma_N = \frac{1}{9\pi} \left[\frac{\mu}{m_N}\right]^2 \left[\frac{m_N}{m_{GR}\Lambda_\pi}\right]^4 m_{DM}^2 \simeq 3.3 \cdot 10^{-54} \mathrm{cm}^2 \left[\frac{m_{DM}}{500\mathrm{GeV}}\right]^2 \left[\frac{30 \ \mathrm{TeV}^2}{m_{GR}\Lambda_\pi}\right]^4$$