

Dark Matter in an Evanescent Three-Brane Randall–Sundrum Scenario

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Based on arXiv: 2505.13601 and 2509.04580

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Motivation

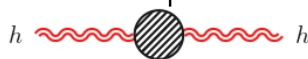
- Original motivation:

- SM **hierarchy problem**: fine tuning of the Higgs boson mass.
- Randall-Sundrum (RS) models $\Rightarrow$ geometric solution via one warped extra dimension. *Randall, Sundrum (1999)*

$$\mathcal{L}_h \sim \frac{1}{2} m_0^2 h^2 + \dots$$

+

M_{P}^2



$\Rightarrow$

$$m_h^2 \sim m_0^2 + M_{\text{P}}^2 + \dots$$
$$m_h \sim \mathcal{O}(100 \text{ GeV})$$
$$M_{\text{P}} \sim \mathcal{O}(10^{19} \text{ GeV})$$

- Our motivation:

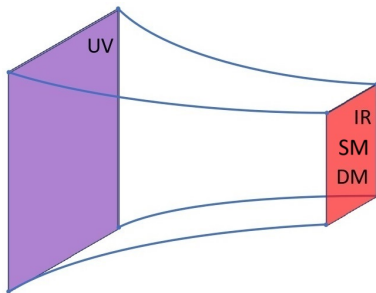
- Larger gravitational interaction with a smaller (warped) scale Λ .
- Two-brane RS setup $\Rightarrow$ **restricted** parameter space for DM candidates.

The Randall–Sundrum Setup

- Extra dimension $y \in [0, \pi r_c]$, compactified on S^1/Z_2 .
- Two 3-branes located at $y = 0$ (UV) and $y = \pi r_c$ (IR).
- 5D metric: $ds^2 = e^{-2ky} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2$.
- Masses on the IR brane are redshifted:

$$m_h^2 \sim (m_0^2 + M_{\text{P}}^2 + \dots) e^{-2\pi k r_c},$$

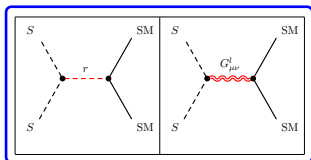
if $kr_c \approx 10 \Rightarrow M_{\text{P}} e^{-\pi k r_c} \sim \mathcal{O}(1 \text{ TeV})$. Excluded by LHC



DM Freeze Out

- Scalar singlet DM candidate in the IR brane (**WIMP DM Freeze Out**).
- KK graviton modes: $h_{\mu\nu}^{(n)}$, and a scalar: radion.
- KK mass spectrum m_n profile is **fixed**.
- **Universal coupling** with KK gravitons $\sim 1/\Lambda_{\text{IR}} \equiv 1/(M_{\text{P}} e^{-kr_c\pi})$.

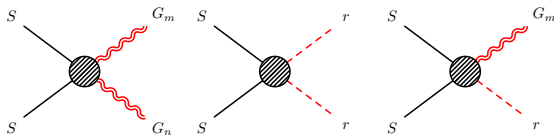
$$\mathcal{L} = -\frac{1}{\bar{M}_{\text{P}}} T^{\mu\nu}(x) h_{\mu\nu}^0(x) - \frac{1}{\Lambda_{\text{IR}}} \sum_{n=1} T^{\mu\nu}(x) h_{\mu\nu}^n(x) + \frac{1}{\sqrt{6}\Lambda_{\text{IR}}} r(x) T(x)$$



**Very constrained
parameter space**

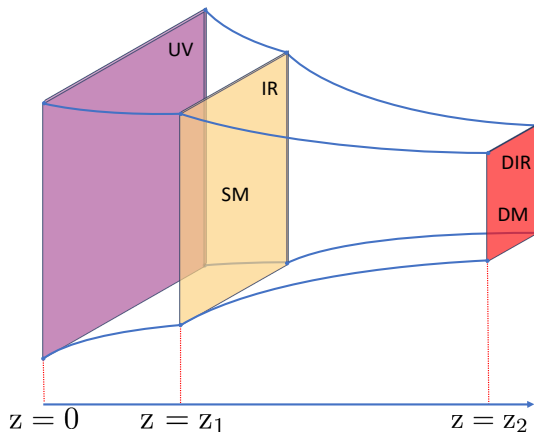


Lee et al. (2013.),
G. Folgado et al.
(2019,...),
Chivukula et al.
(2020,...),
de Giorgi and Vogl
(2021,...)...



Three-Brane Extension

- Extra brane in between UV and DIR: the *evanescent* brane (IR).
- SM in IR brane and DM in DIR brane. **Different Branes!!**
- **Different coupling** of KK gravitons with SM and DM.



Cai et al. (2022), Koustroulis et al. (2024)...

The Evanescent Limit: Definition and Motivation

- We define the *evanescent limit* as $k_2 \rightarrow k_1$, where **the tension of the intermediate brane vanishes**:

$$\sigma_{\text{IR}} \propto (k_2 - k_1) \Rightarrow \sigma_{\text{IR}} \rightarrow 0.$$

- In this regime, the middle brane becomes “evanescent”, simplifying the setup without introducing new hierarchies.
- Practical consequences for our three-brane scenario:
 - Only **one light radion** mode remains dynamically relevant¹.
 - **Couplings of DM** (on the DIR brane) **to bulk particles** (radion and KK gravitons) **are universal**.
 - The DM relic abundance is mostly determined by **annihilations into bulk states**: $\text{DM DM} \rightarrow G_m G_n, G_m r, rr$.
- This limit provides a well-controlled and physically transparent framework, used in our analysis ([arXiv:2505.13601](https://arxiv.org/abs/2505.13601)).

¹For a detailed justification, see: **Donini et al.**, [arXiv:2509.04580](https://arxiv.org/abs/2509.04580).

Why the Evanescent Limit is a Good Approximation

- We can parametrize deviations from the limit as $k_2 = k_1(1 + \delta k)$.
- **Key result:** Most relations obtained in the evanescent limit remain valid even for $\delta k = \mathcal{O}(1)$ — no new fine-tuning or hierarchy is introduced.
- The couplings of the radion and KK gravitons to bulk and DIR-brane fields can be obtained from the evanescent case by a **simple rescaling**:

$$\Lambda_{\text{DIR}}(\delta k \neq 0) = \left(\frac{k_2}{k_1} \right)^{\frac{1}{2}} \Lambda_{\text{DIR}}(\delta k = 0).$$

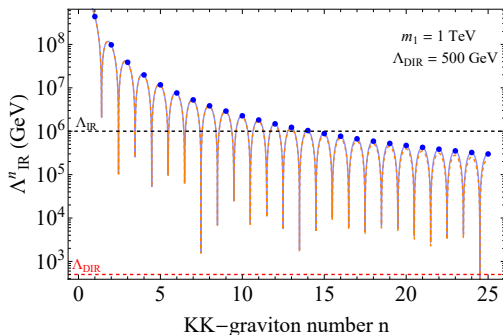
- For SM fields on the IR brane, KK-graviton couplings become more complicated.
- **Operational conclusion:** working in the evanescent limit is **conservative and reliable** for $\delta k \lesssim 1$.

Three-Branes RS Couplings

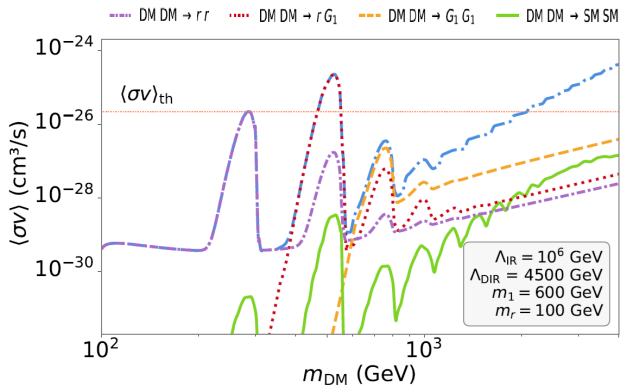
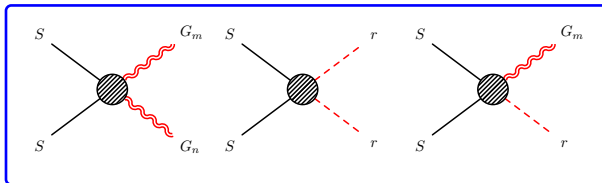
- Couplings to IR brane fields mode-dependent $\sim 1/\Lambda_{\text{IR}}^n$.
- Universal coupling to DIR brane: $\sim 1/\Lambda_{\text{DIR}}$.

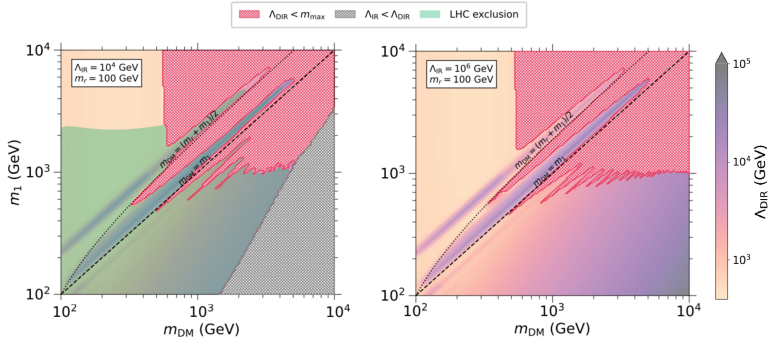
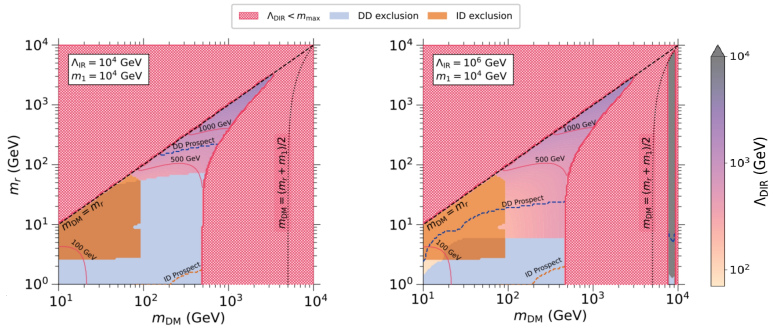
$$\mathcal{L}_{\text{eff}} = \frac{1}{\bar{M}_{\text{P}}} h_{\mu\nu}^{(0)}(x) T_{\text{IR/DIR}}^{\mu\nu}(x) + \sum_{n=1}^{\infty} \frac{1}{\Lambda_{\text{IR}}^n} h_{\mu\nu}^{(n)}(x) T_{\text{IR}}^{\mu\nu}(x) + \sum_{n=1}^{\infty} \frac{1}{\Lambda_{\text{DIR}}} h_{\mu\nu}^{(n)}(x) T_{\text{DIR}}^{\mu\nu}(x) + \frac{1}{\sqrt{6}\Lambda_{\text{IR}}} r(x) T_{\text{IR}}(x) + \frac{1}{\sqrt{6}\Lambda_{\text{DIR}}} r(x) T_{\text{DIR}}(x)$$

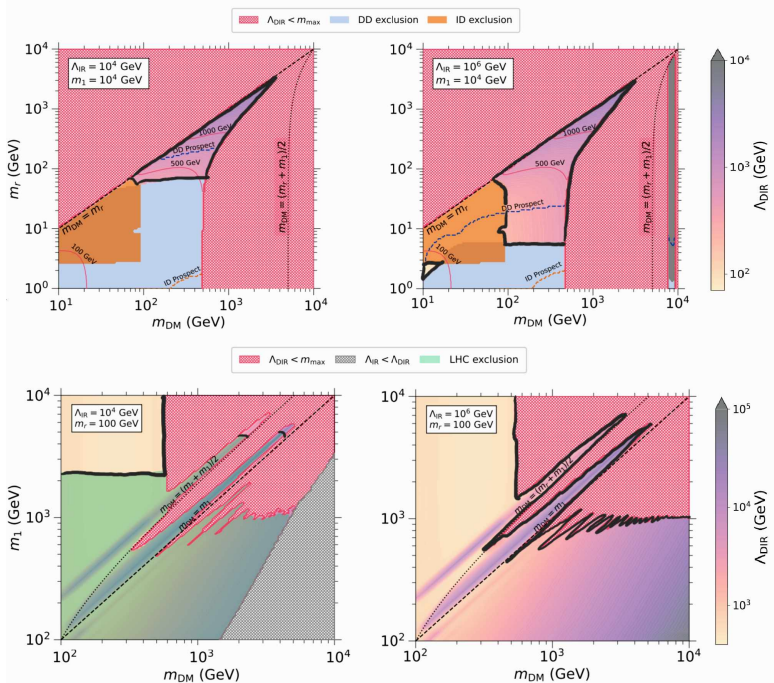
Brane	$h_{\mu\nu}^0$	$h_{\mu\nu}^{n \geq 1}$	r
IR (SM)	$\frac{1}{\bar{M}_{\text{P}}}$	$\frac{1}{\Lambda_{\text{IR}}^n}$	$\frac{1}{\sqrt{6}\Lambda_{\text{IR}}}$
DIR (DM)	$\frac{1}{\bar{M}_{\text{P}}}$	$\frac{1}{\Lambda_{\text{DIR}}}$	$\frac{1}{\sqrt{6}\Lambda_{\text{DIR}}}$



Relevant DM Annihilation Channels







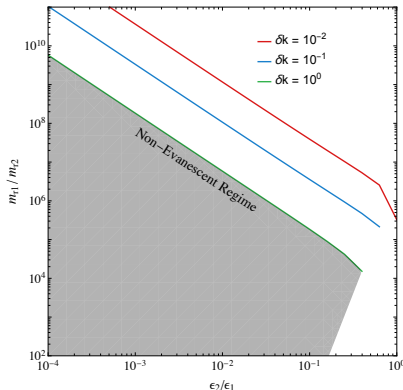
Conclusions

- The *evanescent* three-brane Randall–Sundrum setup **broadens the viable parameter space for scalar DM** 2505.13601.
- The **evanescent limit** ($k_2 \rightarrow k_1$) provides **results than can be used for the non-evanescent scenarios** 2509.04580.
- **Bulk-dominated annihilations** are the new the leading mechanism for DM freeze-out.
- Possible phenomenological handles to **probe the number of populated branes** through gravitational couplings.
- Warped geometry still **alleviates the hierarchy problem**.
- **Future work:** explore the parameter space beyond the evanescent limit and the impact of a light radion mediator on SIDM signals.

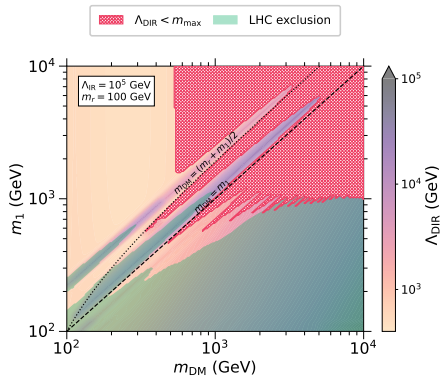
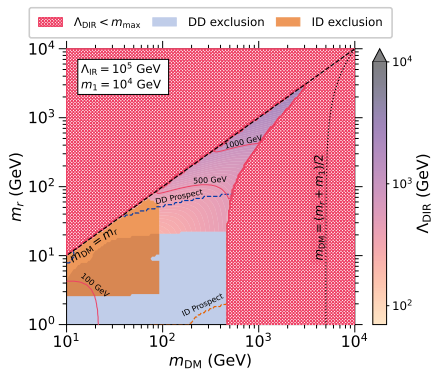
Thank you!

Why is there only one radion even with N branes?

- $N - 1$ “radion-like” modes can be built perturbatively.
- Boundary conditions and bulk dynamics make one of them heavy and it decouples.
- The remaining one corresponds to the **radion**. [arXiv:2509.04580](https://arxiv.org/abs/2509.04580).
- $m_{\text{heavy}} \propto \frac{1}{k_2 - k_1} \Rightarrow$ *evanescent limit* makes it heavier!!!



Plots with different parameters



Producing a percentage of DM relic abundance

