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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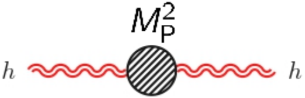
Motivation

- 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)*

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

$$+$$



$$\Longrightarrow$$

$$m_\mathrm{h}^2 \sim m_0^2 + M_\mathrm{P}^2 + \dots$$

$$m_\mathrm{h} \sim \mathcal{O}\left(100 \text{ GeV}\right)$$

$$M_\mathrm{P} \sim \mathcal{O}\left(10^{19} \text{ GeV}\right)$$

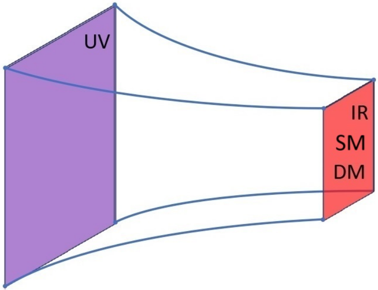
- Our motivation:
  - Larger gravitational interaction with a smaller (warped) scale Λ.
  - Two-brane RS setup $\Rightarrow$ restricted parameter space for DM candidates.

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:

$$m_{\mathrm{h}}^2 \sim (m_0^2 + M_{\mathrm{P}}^2 + \ldots)e^{-2\pi k r_c},$$

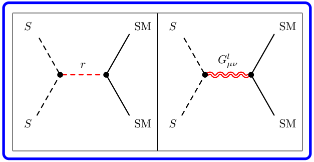
if $kr_c \approx 10 \Rightarrow M_{\mathrm{P}} e^{-\pi k r_c} \sim \mathcal{O}(1\ \mathrm{TeV})$. Excluded by LHC

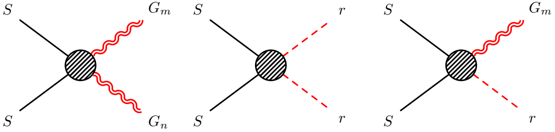


DM Freeze Out

- 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 $\sim 1/\Lambda_{\mathrm{IR}} \equiv 1/\left(M_{\mathrm{P}} e^{-kr_c\pi}\right)$.

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





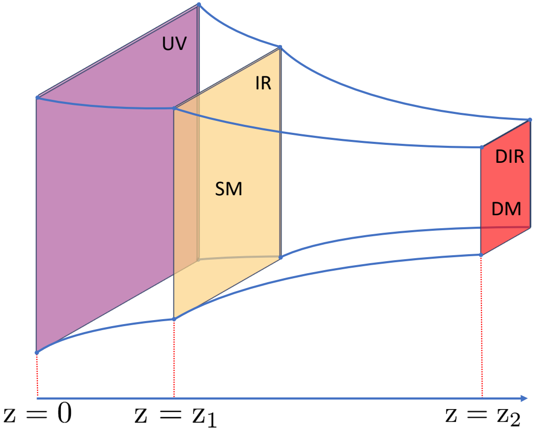
$\Rightarrow$

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

- Practical consequences for our three–brane scenario:
  - Only one light radion mode remains dynamically relevant[1].
  - 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: $\mathrm{DM}\,\mathrm{DM} \to G_m G_n,\ G_m r,\ rr$.
- We define the *evanescent* limit as $k_2 \to k_1$, where the tension of the intermediate brane vanishes:

$$\sigma_{\mathrm{IR}} \propto (k_2 - k_1) \quad \Rightarrow \quad \sigma_{\mathrm{IR}} \to 0.$$

- In this regime, the middle brane becomes "evanescent", simplifying the setup without introducing new hierarchies.
- This limit provides a well-controlled and physically transparent framework, used in our analysis (arXiv:2505.13601).

[1] For a detailed justification, see: **Donini et al.**, arXiv: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:

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

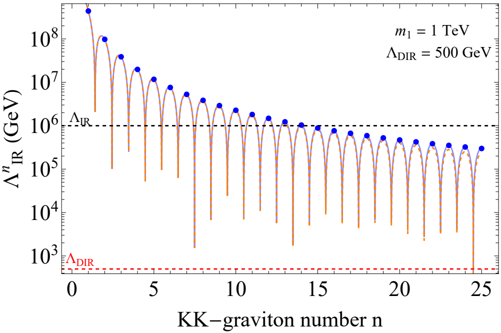
- For SM fields on the IR brane, KK-graviton couplings become more complicated.
- **Operational conclusion:** working in the evanescent limit is **conservative and reliable** for $\delta k \lesssim 1$.

Three-Branes RS Couplings

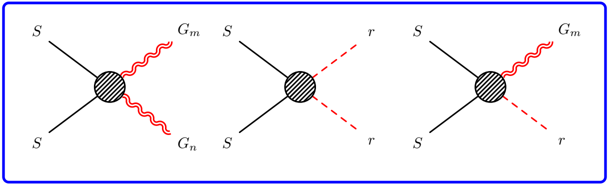
- Couplings to IR brane fields mode-dependent $\sim 1/\Lambda_{\rm IR}^n$.
- Universal coupling to DIR brane: $\sim 1/\Lambda_{\rm DIR}$.

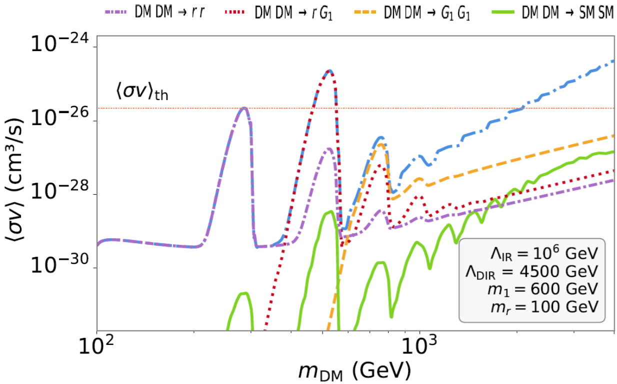
$$\mathcal{L}_{\rm eff} = \frac{1}{\bar{M}_{\rm P}}\, h^{(0)}_{\mu\nu}(x)\; T^{\mu\nu}_{\rm IR/DIR}(x) + \sum_{n=1}^{\infty} \frac{1}{\Lambda^n_{\rm IR}}\, h^{(n)}_{\mu\nu}(x)\; T^{\mu\nu}_{\rm IR}(x) + \sum_{n=1}^{\infty} \frac{1}{\Lambda_{\rm DIR}}\, h^{(n)}_{\mu\nu}(x)\; T^{\mu\nu}_{\rm DIR}(x) + \frac{1}{\sqrt{6}\Lambda_{\rm IR}} r(x)\, T_{\rm IR}(x) + \frac{1}{\sqrt{6}\Lambda_{\rm DIR}} r(x)\, T_{\rm DIR}(x)$$

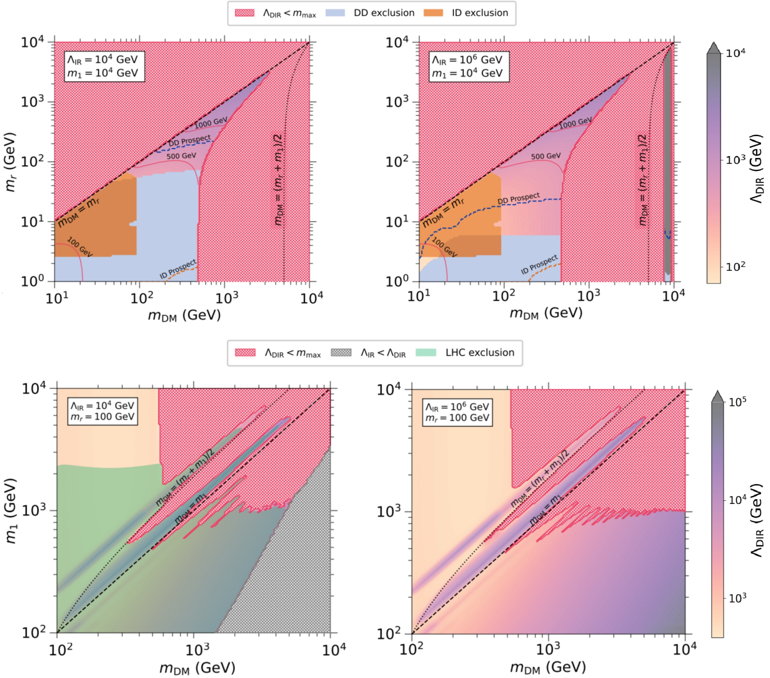
Brane	$h^0_{\mu\nu}$	$h^{n\geq 1}_{\mu\nu}$	r
IR (SM)	$\frac{1}{\bar{M}_{\rm P}}$	$\frac{1}{\Lambda^n_{\rm IR}}$	$\frac{1}{\sqrt{6}\,\Lambda_{\rm IR}}$
DIR (DM)	$\frac{1}{\bar{M}_{\rm P}}$	$\frac{1}{\Lambda_{\rm DIR}}$	$\frac{1}{\sqrt{6}\,\Lambda_{\rm DIR}}$



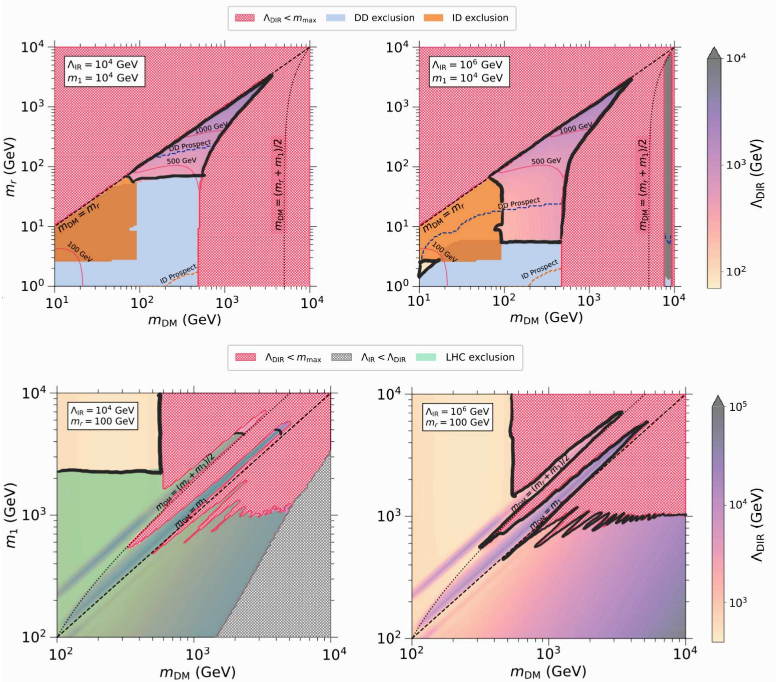
Relevant DM Annihilation Channels







$\Lambda_{\rm DIR} < m_{\rm max}$
DD exclusion
ID exclusion
$\Lambda_{\rm IR} = 10^4$ GeV
$m_1 = 10^4$ GeV
$\Lambda_{\rm IR} = 10^6$ GeV
$m_1 = 10^4$ GeV
1000 GeV
DD Prospect
500 GeV
100 GeV
ID Prospect
$m_{\rm DM} = m_r$
$m_{\rm DM} = (m_r + m_1)/2$
m_r (GeV)
$m_{\rm DM}$ (GeV)
$\Lambda_{\rm DIR}$ (GeV)
$\Lambda_{\rm DIR} < m_{\rm max}$
$\Lambda_{\rm IR} < \Lambda_{\rm DIR}$
LHC exclusion
$\Lambda_{\rm IR} = 10^4$ GeV
$m_r = 100$ GeV
$\Lambda_{\rm IR} = 10^6$ GeV
$m_r = 100$ GeV
$m_{\rm DM} = m_1$
m_1 (GeV)



$\Lambda_{\rm DIR} < m_{\rm max}$
DD exclusion
ID exclusion
$\Lambda_{\rm IR} = 10^4$ GeV
$m_1 = 10^4$ GeV
$\Lambda_{\rm IR} = 10^6$ GeV
$m_1 = 10^4$ GeV
1000 GeV
DD Prospect
500 GeV
100 GeV
ID Prospect
$m_{\rm DM} = m_r$
$m_{\rm DM} = (m_r + m_1)/2$
m_r (GeV)
$m_{\rm DM}$ (GeV)
$\Lambda_{\rm DIR}$ (GeV)
$\Lambda_{\rm DIR} < m_{\rm max}$
$\Lambda_{\rm IR} < \Lambda_{\rm DIR}$
LHC exclusion
$\Lambda_{\rm IR} = 10^4$ GeV
$m_r = 100$ GeV
$\Lambda_{\rm IR} = 10^6$ GeV
$m_r = 100$ GeV
$m_{\rm DM} = (m_r + m_1)/2$
$m_{\rm DM} = m_1$
m_1 (GeV)
$m_{\rm DM}$ (GeV)
$\Lambda_{\rm DIR}$ (GeV)

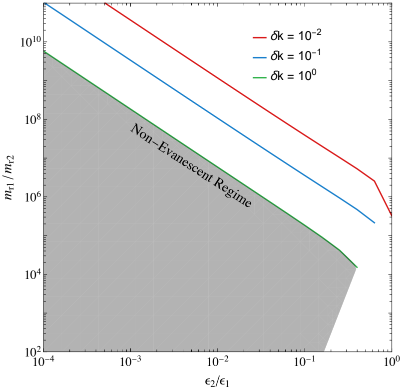
Conclusions

- The *evanescent* three–brane Randall–Sundrum setup broadens the viable parameter space for scalar DM 2505.13601.
- The evanescent limit $(k_2 \to k_1)$ provides **results than can be used for the non-evanescent scenarios** 2509.04580.
- Bulk–dominated annihilations are the new 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.

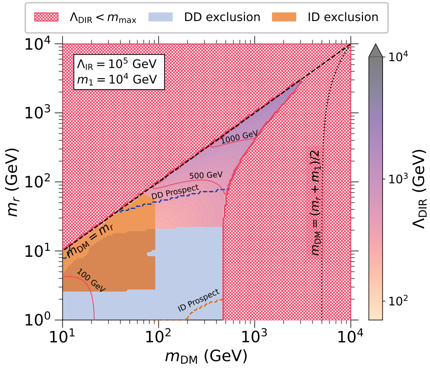
Thank you!

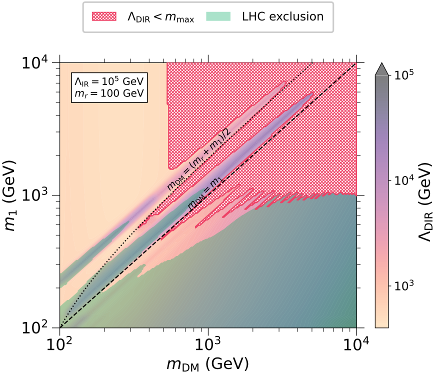
Why is there only one radion even with N branes?

- $N-1$ "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.
- $m_{\rm heavy} \propto \frac{1}{k_2-k_1} \Rightarrow$ *evanescen limit* makes it heavier!!!



Plots with different parameters





Pruducing a percentage of DM relic abundance