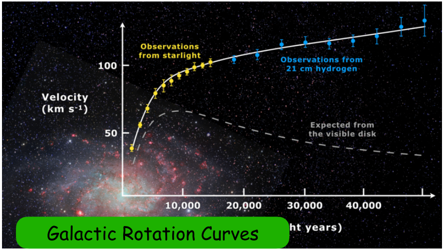
# Dark Matter in Stabilised Warped Extra-dimensional Model with Heavy Radion

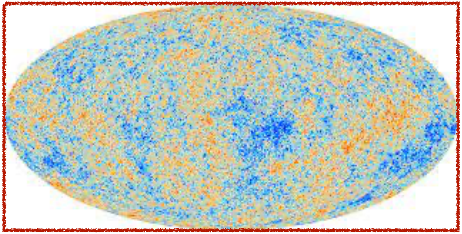
G. Sanamyan

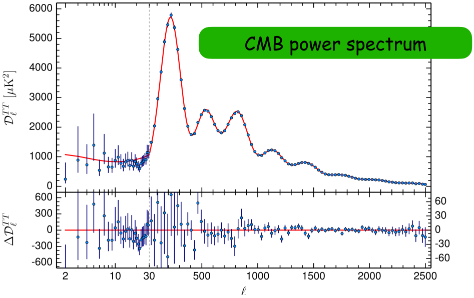
ARC Centre of Excellence for Dark Matter Particle Physics, Department of Physics, University of Adelaide, South Australia 5005, Australia

# Dark Matter

## Evidence

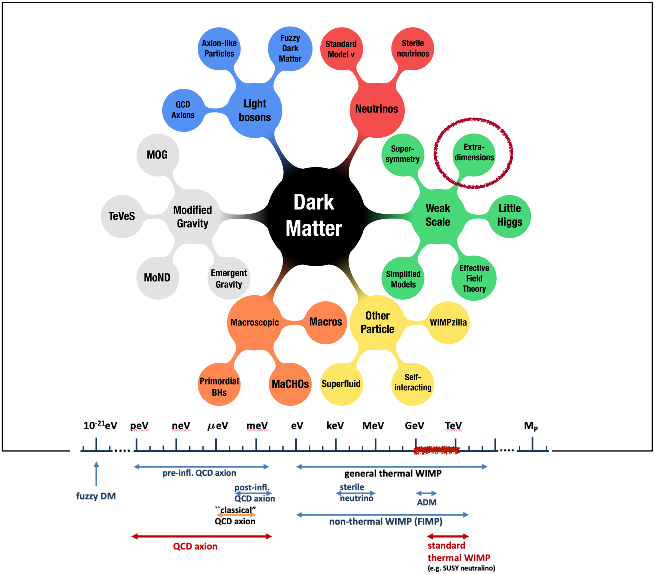


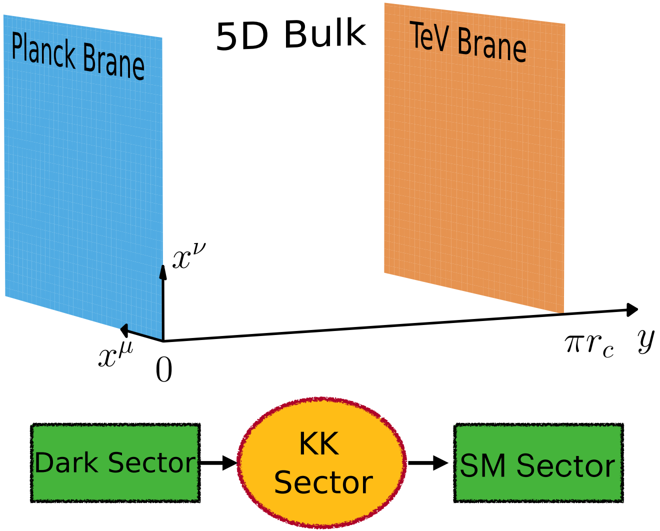
# Dark Matter

## Models



# Dark Matter

## Models



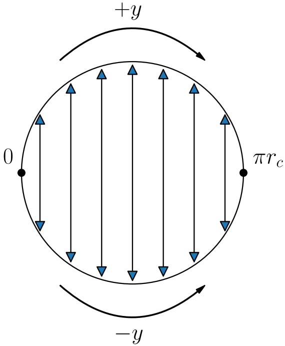
# Compact Extra Dimensions

## Brief Overview

- A $5D$ field appears as a tower of KK modes from the $4D$ point of view.
- A profile of these modes in the extra dimension and their masses are obtained from solving an eigenvalue problem.
- The couplings between the KK modes are proportional to the overlap of their profiles.

$$G_{MN} = \begin{pmatrix} G_{\mu\nu} & V_\mu \\ V_\mu & r \end{pmatrix},$$

where $G_{\mu\nu}$ is the tower of the spin-2 modes, vector modes $V_\mu$ vanish if we apply orbifold boundary conditions on the extra dimensions, $r$ corresponds to a scalar mode called the radion.



# Compact Extra Dimensions

## Calculations Going Wrong

Brane Localized Scalar Dark Matter annihilating via a KK/massive spin-2 portal

**Gravity-mediated Scalar Dark Matter in Warped Extra-Dimensions**

**Miguel G. Folgado,[a] Andrea Donini,[a] Nuria Rius[a]**

PRL **116**, 101302 (2016) PHYSICAL REVIEW LETTERS week ending 11 MARCH 2016

**Planckian Interacting Massive Particles as Dark Matter**

Mathias Garny,[1,*] McCullen Sandora,[2,†] and Martin S. Sloth[2,‡]
[1]*CERN Theory Division, CH-1211 Geneva 23, Switzerland*
[2]*$CP^3$-Origins, Center for Cosmology and Particle Physics Phenomenology, University of Southern Denmark, Campusvej 55, 5230 Odense M, Denmark*
(Received 20 November 2015; published 10 March 2016)

**Spin-2 portal dark matter**

Nicolás Bernal,[1,*] Maíra Dutra,[2,†] Yann Mambrini,[2,‡] Keith Olive,[3,4,§] Marco Peloso,[3,‖] and Mathias Pierre[2,¶]
[1]*Centro de Investigaciones, Universidad Antonio Nariño Carrera 3 Este # 47A-15, Bogotá, Colombia*
[2]*Laboratoire de Physique Théorique (UMR8627), CNRS, University of Paris-Sud, Université Paris-Saclay, 91405 Orsay, France*

Dark Matter Direct Detection from new interactions in models with spin-two mediators

A. Carrillo-Monteverde[1,‡], Yoo-Jin Kang[2,3,*], Hyun Min Lee[2,†], Myeonghun Park[4,♣], and Veronica Sanz[1,♠]

[1]*Department of Physics and Astronomy, University of Sussex, Brighton BN1 9QH, UK.*
[2]*Department of Physics, Chung-Ang University, Seoul 06974, Korea.*
[3]*Center for Theoretical Physics of the Universe, Institute for Basic Science, Daejeon, 34051, Korea.*
[4]*Institute of Convergence Fundamental Studies and School of Liberal Arts, Seoul National University of Science and Technology, Seoul 01811, Korea.*

PHYSICAL REVIEW LETTERS **128**, 081806 (2022)

**Massive Gravitons as Feebly Interacting Dark Matter Candidates**

Haiying Cai,[1,*] Giacomo Cacciapaglia,[2,3,†] and Seung J. Lee[1,‡]
[1]*Department of Physics, Korea University, Seoul 136-713, Korea*
[2]*University of Lyon, Université Claude Bernard Lyon 1, F-69001 Lyon, France*
[3]*Institut de Physique des 2 Infinis de Lyon (IP2I), UMR5822, CNRS/IN2P3, F-69622 Villeurbanne Cedex, France*

Wrong Scaling

$$\boxed{|\mathcal{M}|^2 \sim E^{12}/(m^8 \mathsf{M}_{\mathsf{PL}}^4)}$$

This issue is resolved in the full KK theory leading to $|\mathcal{M}|^2 \simeq E^2/M_{\mathrm{PL}}^2$

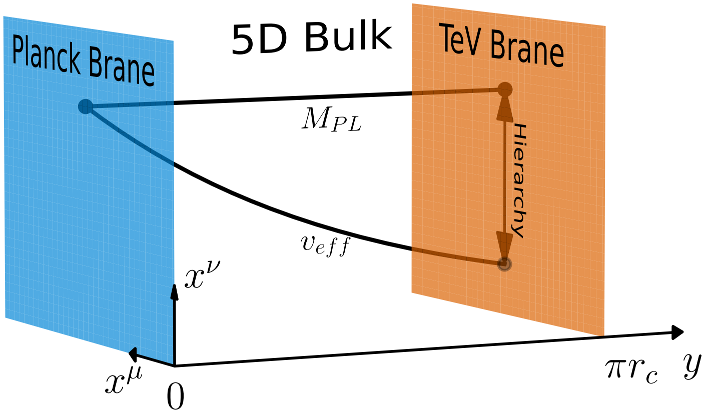
Phys.Rev.D 100 (2019) 11, 115033 Phys.Rev.D 101 (2020) 7, 075013 Phys.Rev.D 101 (2020) 5, 055013
**Phys. Rev. D 103 (2022), 095024 Phys. Rev. D 107,(2023) 03505, PRD Letters, ……**
**R. S. Chivukula, D. Foren, J.A.Gill, X. Wang, K. Mohan, E.H. Simmons, *DS***

arXiv:2411.02509 [hep-ph]

# Stabilised Randall–Sundrum model

## Geometry Set-up

- Two 4D spacetime slices (branes) at $y = 0$ (Planck) and $y = \pi r_c$ (TeV).
- TeV Higgs has exponentially suppressed VEV compared to Planck Higgs.
- The 4D-effective gravitational coupling is minimally affected between branes $\rightarrow$ resolves the hierarchy problem!



# Stabilised Randall–Sundrum model

## Brane Stabilisation

So far, there is nothing in our model to fix the locations of the branes.
Hence, the whole two-brane set-up is unstable!

We introduce a bulk scalar field $\hat{\Phi}$, bulk $V\left[\hat{\Phi}\right]$ and brane $V_i\left[\hat{\Phi}\right]$ potentials resulting in the bulk scalar sector

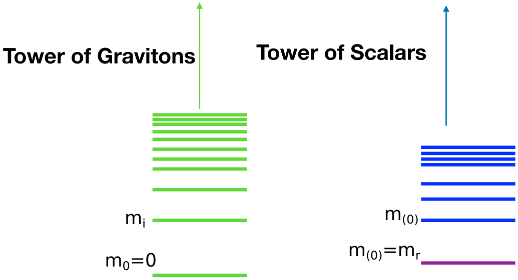
$$\mathcal{L}_\Phi = \frac{1}{2}\sqrt{G}G^{MN}\partial_M\hat{\Phi}\partial_N\hat{\Phi} - \left(\sqrt{G}V\left[\hat{\Phi}\right] + \sum_{i=1,2}\sqrt{-\bar{G}}V_i\left[\hat{\Phi}\right]\delta_i\left(y\right)\right)$$

- Bulk potential $\rightarrow$ non-trivial VEV for $\hat{\Phi}$,
- Brane potential fixes brane locations

The bulk scalar field $\hat{\Phi}$ and radion $\hat{r}$ mix, generating a Kaluza-Klein tower of states for the radion.

# Stabilised Randall–Sundrum model

## Brane Stabilisation




The lightest radion state has a VEV-dependent mass $m_r$. Masses of the KK modes are obtained by solving eigenvalue problems

$$\begin{cases} \partial_\varphi\left[e^{-4A}\partial_\varphi\psi_n\right] & = -r_c^2 m_n^2 e^{-2A}\psi_n, \\ \partial_\phi\left[\dfrac{e^{2A}}{\left(\phi_0'\right)^2}\partial_\phi\gamma_n\right] - \dfrac{e^{2A}}{6}\gamma_n & = -r_c^2 m_{(n)}^2 \dfrac{e^{4A}}{\left(\phi_0'\right)^2}\gamma_n, \end{cases} \to \begin{cases} \int_{-\pi}^{\pi} d\phi e^{-2A(\phi)}\psi_i(\phi)\psi_j(\phi) & = \delta_{ij}, \\ 6r_c^2 m_{(n)}^2 \int_{-\pi}^{\pi} d\phi \dfrac{e^{4A(\phi)}}{\left(\varphi_0'(\phi)\right)^2}\gamma_n(\phi)\gamma_m(\phi) & = \delta_{mn}, \end{cases}$$

for spin-2 and spin-0 sectors respectively $\to$ depends on the geometry through the warp-factor $A$.

# Stabilised Randall–Sundrum model

## Backreaction

The background geometry is parametrised as

$$\eta_{MN}^{(RS)} = \begin{pmatrix} e^{-2A(y)}\eta_{\mu\nu} & 0 \\ 0 & -1 \end{pmatrix} \to \begin{cases} G_{\mu\nu}^{(RS)} & = e^{-2(A(y)+\hat{u})}\left(\eta_{\mu\nu} + \frac{2}{M_5^{\frac{3}{2}}}\hat{h}_{\mu\nu}\right), \\ G_{55}^{(RS)} & = -\left(1+2\hat{u}\right)^2, \end{cases}$$

with

$$\hat{u} = \frac{e^{2A(y)}}{\sqrt{6}M_5^{\frac{3}{2}}}\hat{r}.$$

The warp factor is given by

$$A(y) = k|y| + \frac{\phi_1}{48}\left(e^{-2u|y|} - 1\right),$$

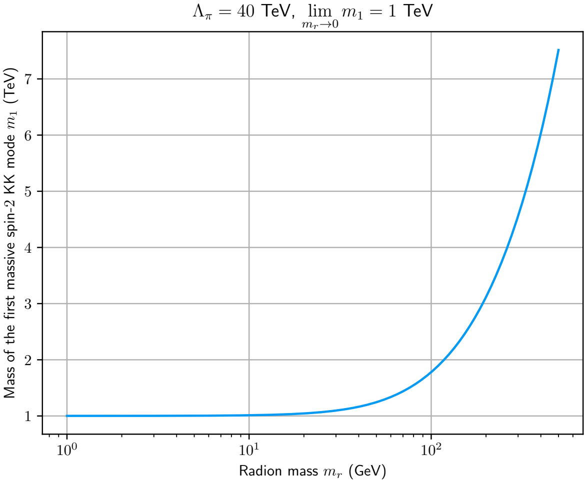
which contains two contributions, one from curvature of the extra dimension and the other one from the backreaction due to non-trivial VEV of the bulk scalar field (as per EFE: curvature = stress-energy tensor).

# Stabilised Randall–Sundrum model

## Backreaction

$\rightarrow$ Fix the extradimensional curvature by considering a zero VEV limit.

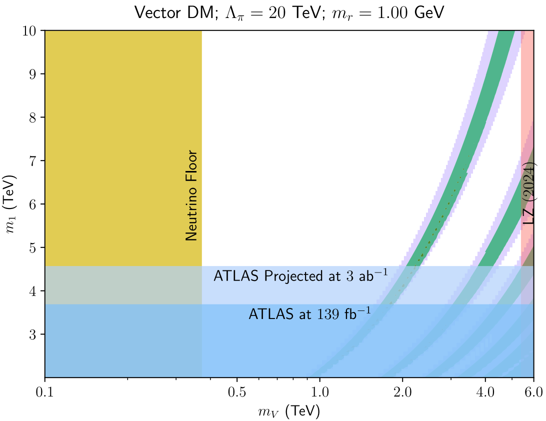
$\rightarrow$ Run the bulk scalar VEV to see the effects of the backreaction.



# Stabilised Randall–Sundrum model

## Backreaction

Light radion models $\rightarrow$ phenomenological viable region constrained by direct detection and collider searches:



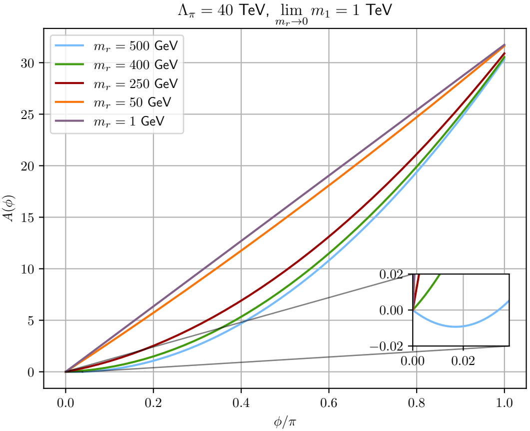

DM relic density is saturated through spin-2 resonances. More on Friday . . .

# Stabilised Randall–Sundrum model

## Backreaction

Large backreaction $\rightarrow$ region of space around the Planck brane where the background curvature changes sign ($AdS \rightarrow dS$). Avoid this issue by limiting ourselves to parameters where $m_r = 400$ GeV.

This is analogous to a massive body (such as the Sun) affecting the background curvature.

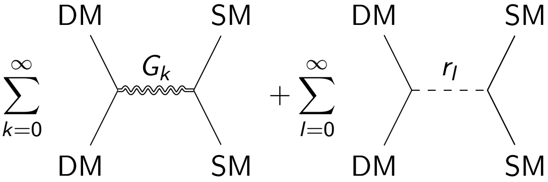


# Stabilised Randall–Sundrum model

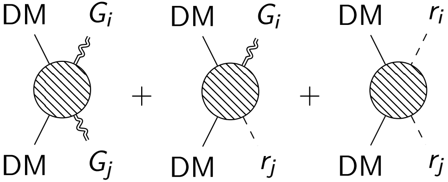
## Dark Sector

The dark Sector interacts with the visible sector exclusively via gravitational interactions from the KK sector:

- DM annihilation to SM through the KK portal



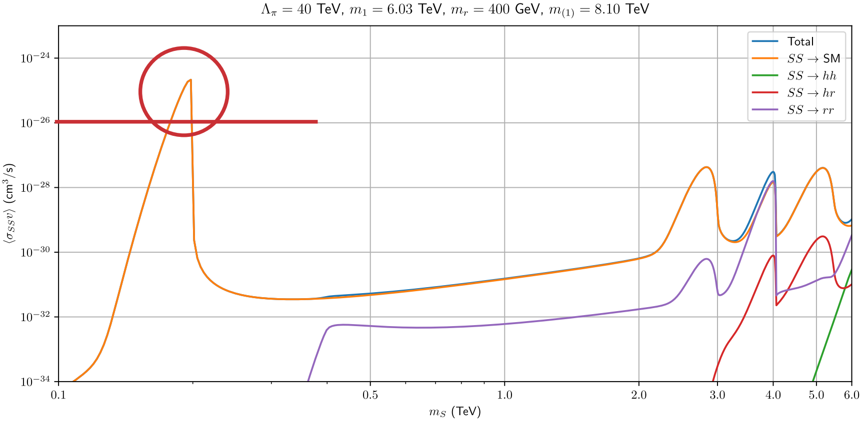

- DM annihilation to KK final state (graviton modes $G_n$ and radion modes $r_n$) $\rightarrow$ naive calculation yields a spurious divergence



# WIMP Freeze-out

## Velocity-averaged Cross-section

Unlike models with light radion, where the relic density cannot be satisfied with the scalar dark matter candidate, scalars can saturate relic density through the radion portal:



# WIMP Freeze-out

## Collider and Direct Detection Constraints

- Large backreaction pushes the mass of the first spin-2 KK mode all the way up to about 8 TeV $\rightarrow$ well beyond LHC limit of 2.8 TeV and projected HL-LHC limit of 3.8 TeV for the cut-off scale of 40 TeV.
- Direct detection cross-section scales as

$$\sigma \propto \frac{1}{\Lambda_\pi^4 m_r^4},$$

$\rightarrow$ for $\Lambda_\pi = 40$ TeV and $m_r = 400$ GeV falls well below the neutrino floor.

Therefore, in the stabilised RS model with heavy radion, freeze-out of the scalar dark matter candidate can saturate the relic density while evading both collider and direct detection constraints.

Our work on the models with light radion $\rightarrow$ arXiv:2411.02509 [hep-ph]

# Summary

## Conclusions and Future Work

- In the models with heavy radion, scalar DM candidates can saturate the relic density through the radion resonance. These models evade collider constraints due to large backreaction affecting the masses of the spin-2 sector and direct detection constants due to the direct detection cross-section scaling with $\simeq m_r^4$.
- Alternatively, we can have a freeze-in scenario through the radion resonance or a freeze-in of the radion itself.