Radion Portal Dark Matter in Stabilized Warped Extra-Dimensions

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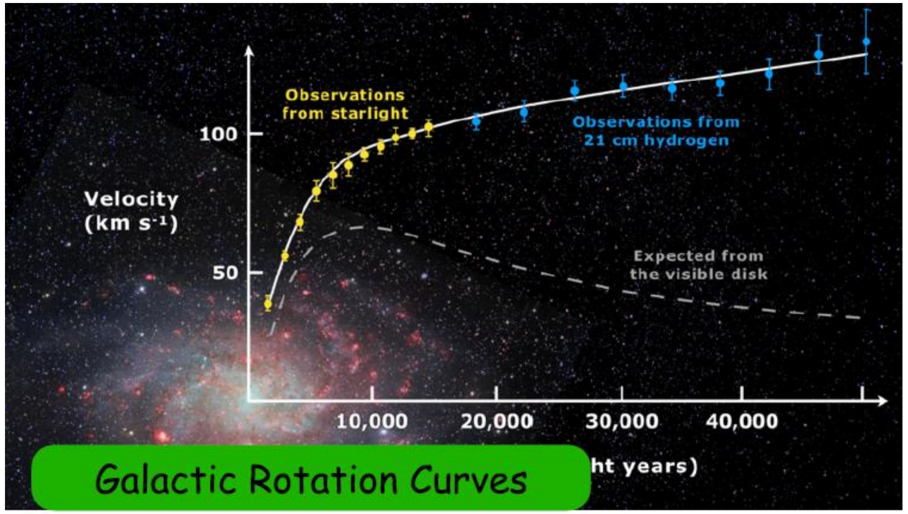
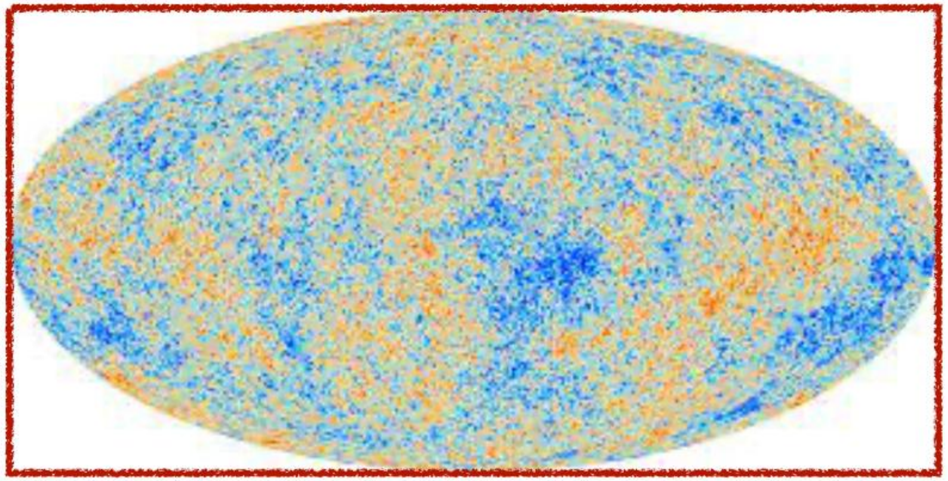
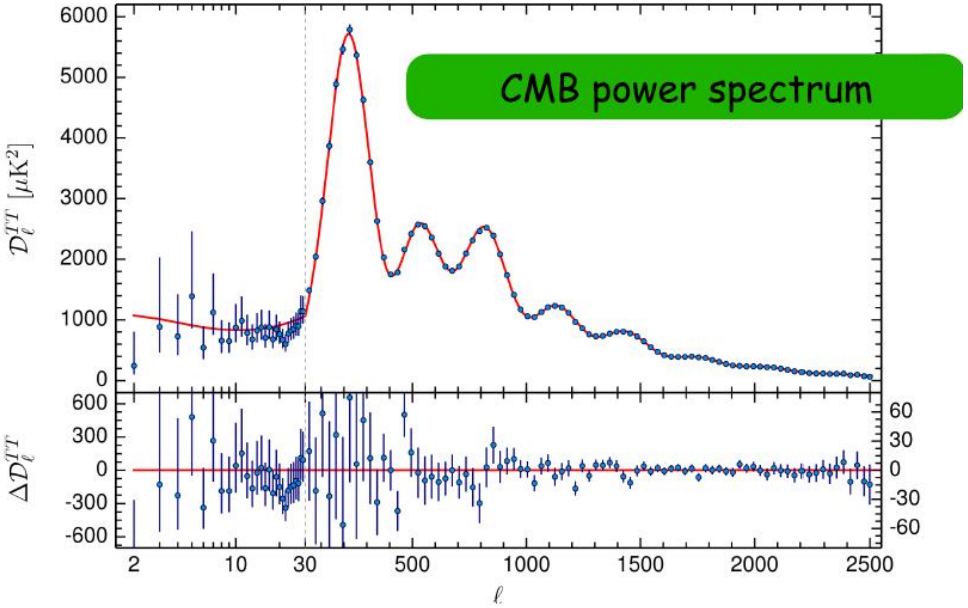
Dark Matter

Evidence

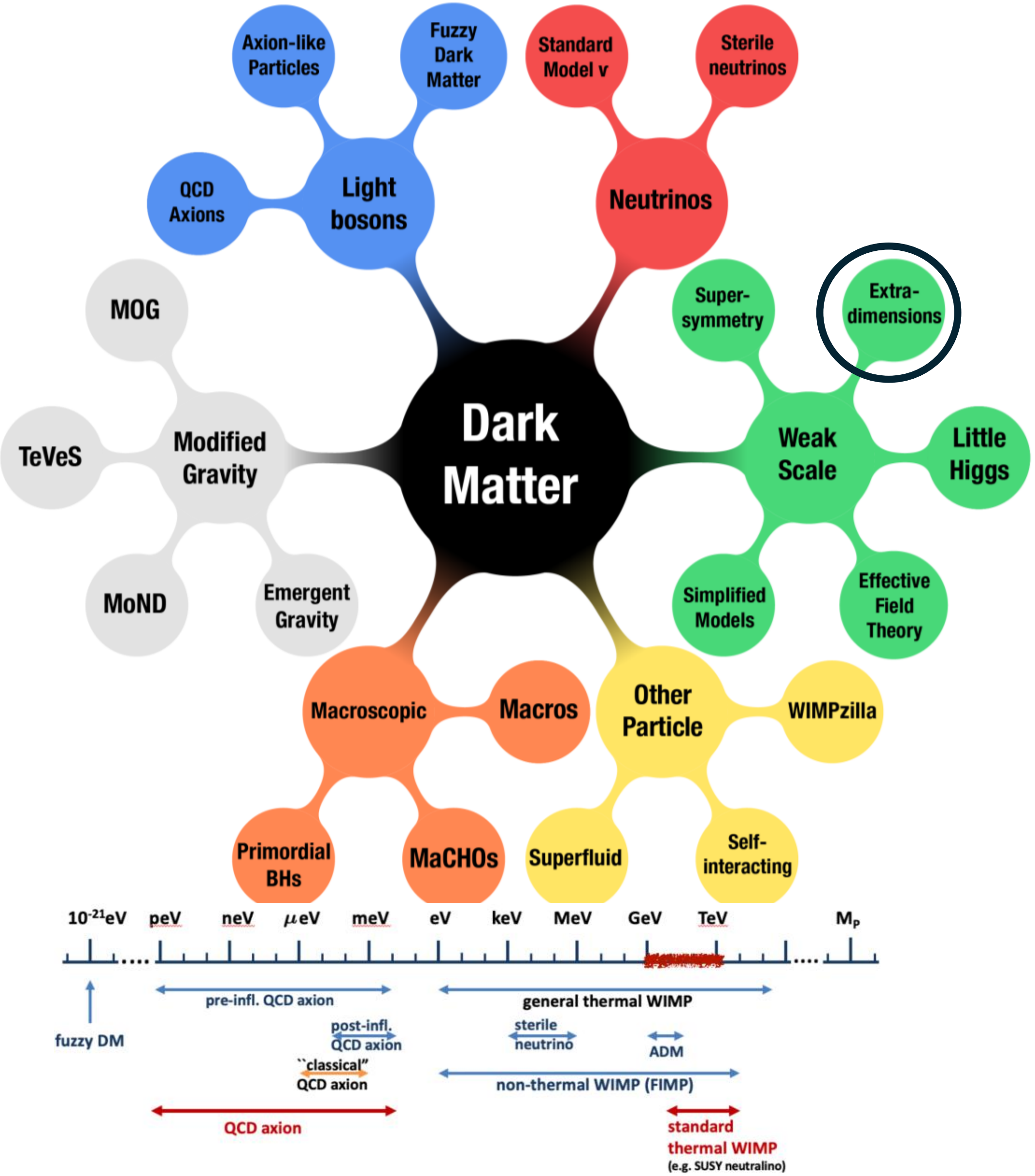




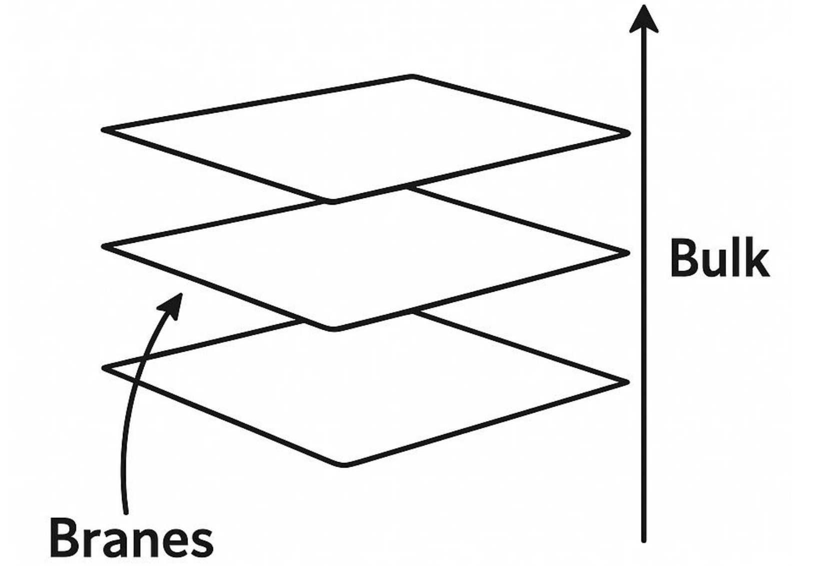


Dark Matter

Models



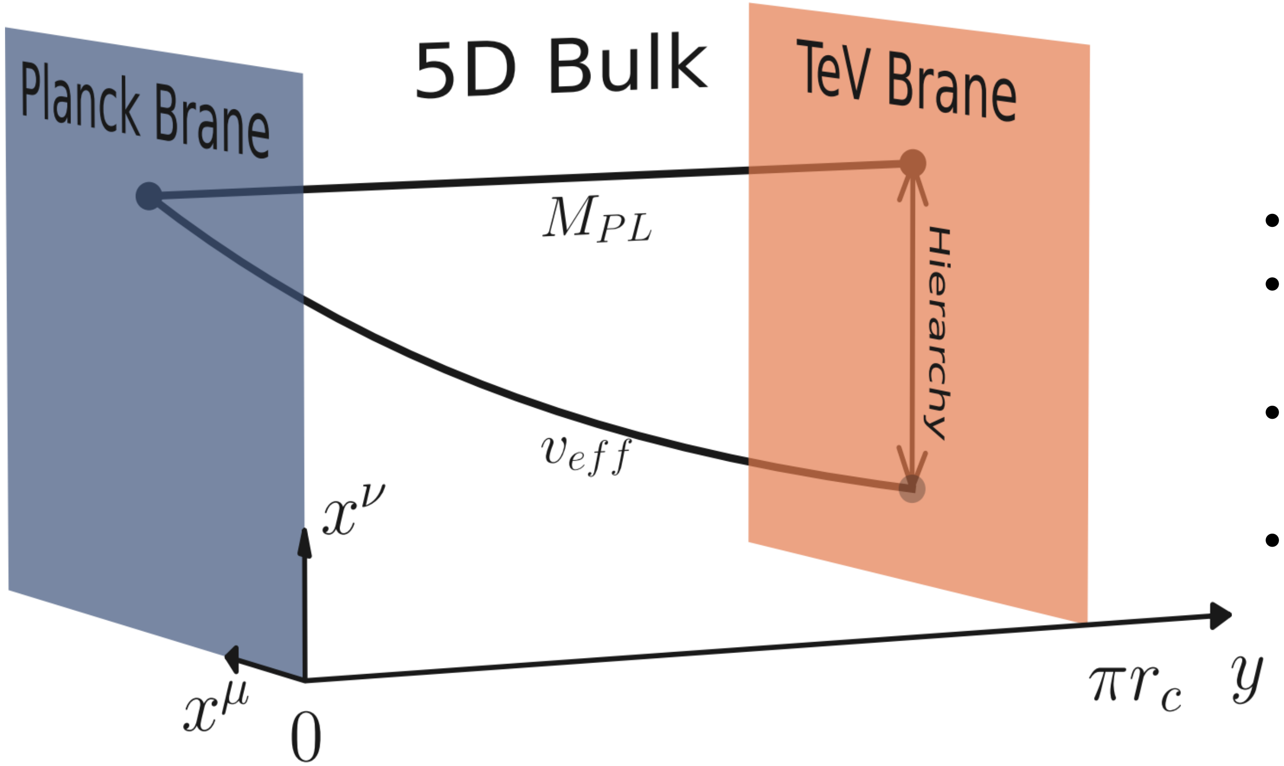
Extra dimensions (or Kaluza-Klein theory) in a nutshell:



- **Branes: $\mathbb{R}^{3,1}$ spacetime slices**
- **Bulk : The "extra" dimension**

Randall-Sundrum (RS-I) Model

Overview



$$ds^2 = \underbrace{e^{-2ky}}_{\text{warp factor}} g_{\mu\nu}dx^\mu dx^\nu - dy^2$$

- Two 4D-spacetime slices (branes) at $y = 0, \pi\, r_c$
- Higgs has exponentially suppressed VEV on the TeV brane (SM)
- Distance between branes, r_c corresponds to a scalar mode (radion)
- Bulk curvature is AdS ($R > 0$)

Randall-Sundrum (RS-I) Model

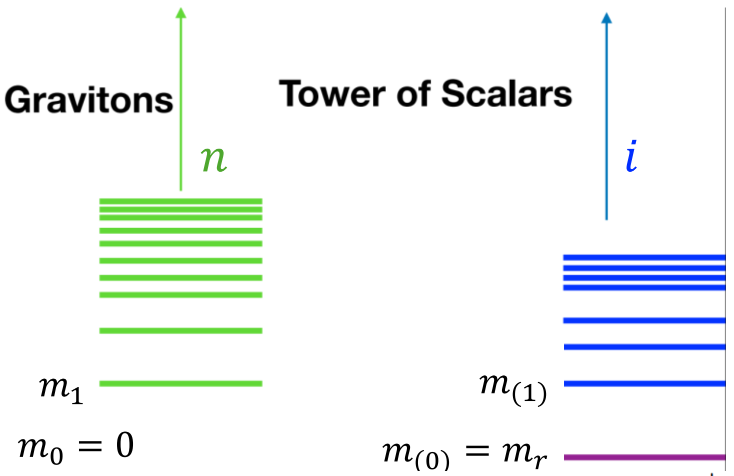
Some housekeeping

Stabilisation

- Introduce a scalar field $\hat{\phi}(x,y)$, brane potentials $V_i(\hat{\phi})\big|_{i=1,2}$ and general bulk potential $V(\hat{\phi})$:

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

- $\hat{\phi}$ and radion $\hat{r}$ mix, generating Kaluza-Klein tower of states



$$\hat{h}_{\mu\nu}(x,y) = \frac{1}{\sqrt{r_c}}\sum_{n=0}^{+\infty}\hat{h}^{(n)}_{\mu\nu}(x)\,\psi_n(y)\ , \qquad \hat{r}(x,y) = \frac{1}{\sqrt{r_c}}\sum_{i=0}^{+\infty}\hat{r}^{(i)}(x)\,\gamma_i(y)$$

Randall-Sundrum (RS-I) Model

Some housekeeping

DeWolfe-Freedman-Gubser-Karch model

- Parameterise metric as

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

where $\hat{u} := \frac{e^{2A(y)}}{\sqrt{6}M_5^{\frac{3}{2}}}\hat{r}$ and warp factor $A(y) = kr_c|y| + \frac{\phi_1}{48}\left(e^{-2ur_c|y|} - 1\right)$

- Parameterise fields as vacuums and fluctuations, e.g.

$$\hat{\phi}(x,y) = \phi_0(y) + \hat{f}(x,y)$$

where $\phi_0(y) = \phi_1 e^{-ur_c|y|}$.

- Model has four free parameters: (r_c, k, u, ϕ_1),

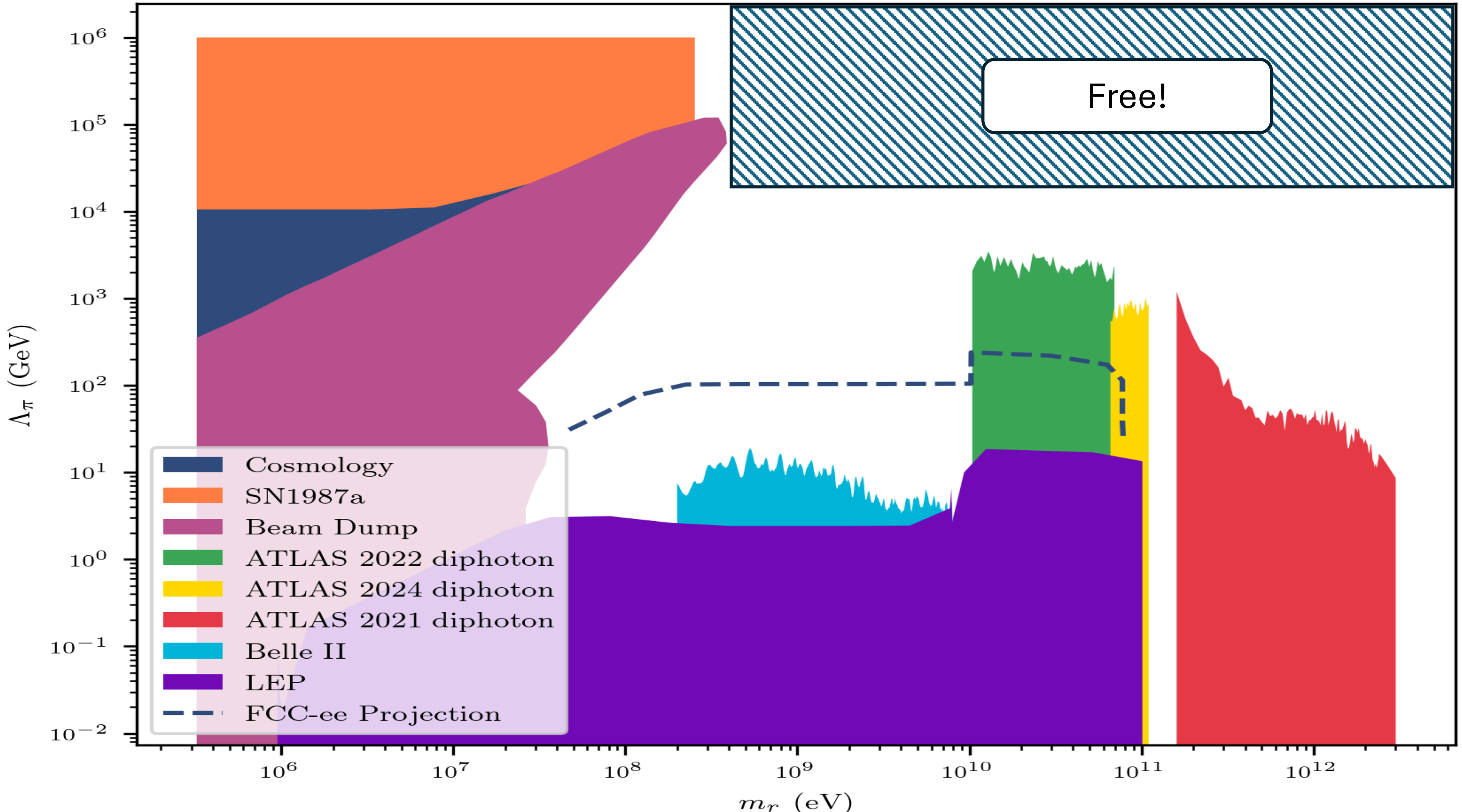
  which can be traded for physical parameters: $(\Lambda_\pi, m_1, m_r, m_{(1)})$
    - Cutoff scale Λ_π
    - Mass of first spin-2 KK mode m_1
    - Mass of zeroth spin-0 KK mode $m_{(0)} = m_r$
    - Mass of first spin-0 KK mode $m_{(1)}$

Stabilised RS Model

Experimental constraints

*Previous work with spin-2 portal

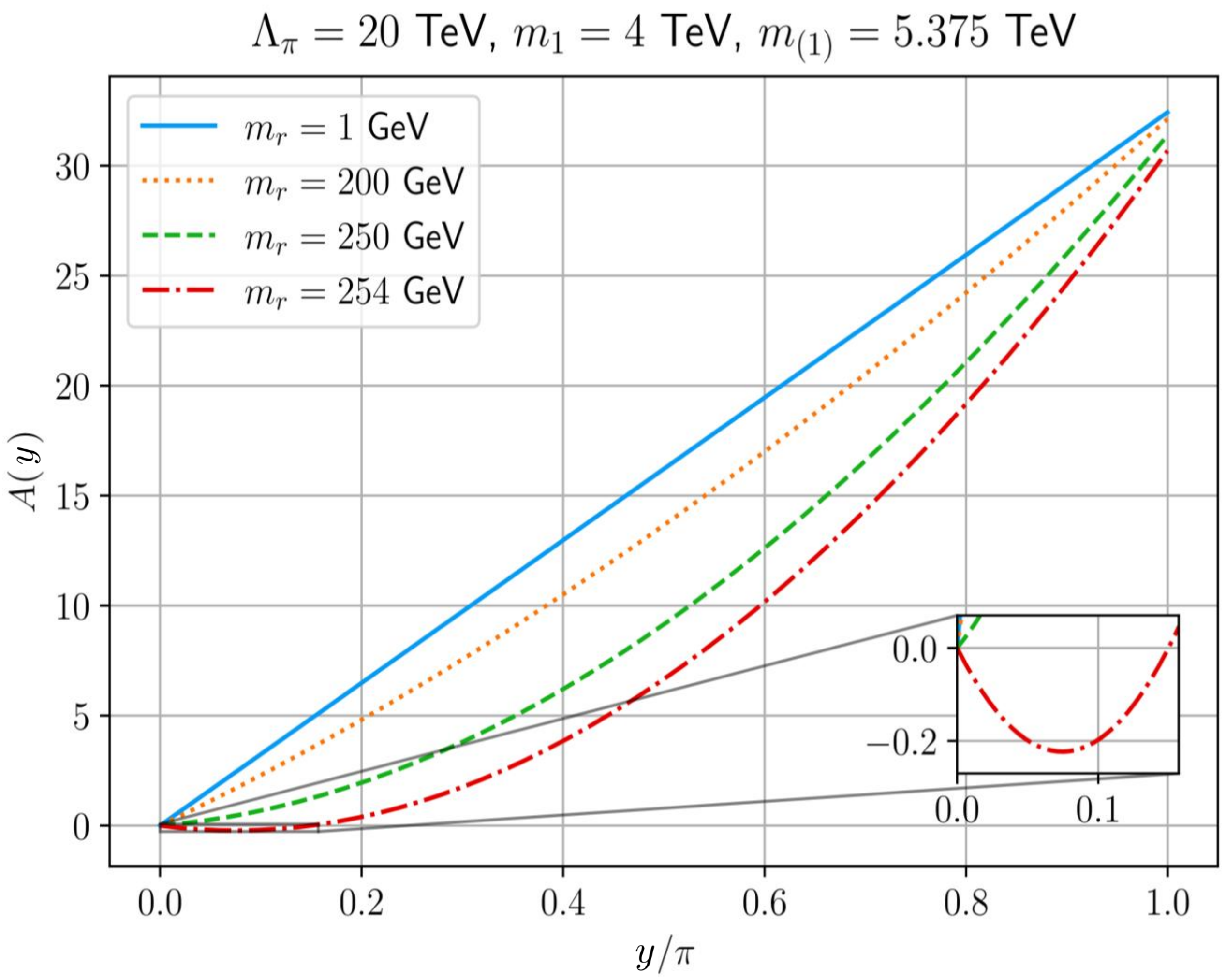
- Lower bound of $\Lambda_\pi = 20\ \mathrm{TeV}, \mathrm{m}_1 = 4\ \mathrm{TeV}$ set by ATLAS Run II diphoton searches. [Phys.Lett.B 822 (2021) 136651] [Phys.Rev.D 111 (2025) 7, 075030]*
- But for the radion at $\Lambda_\pi = 20\ \mathrm{TeV}$ ...



Stabilised RS Model

Backreaction

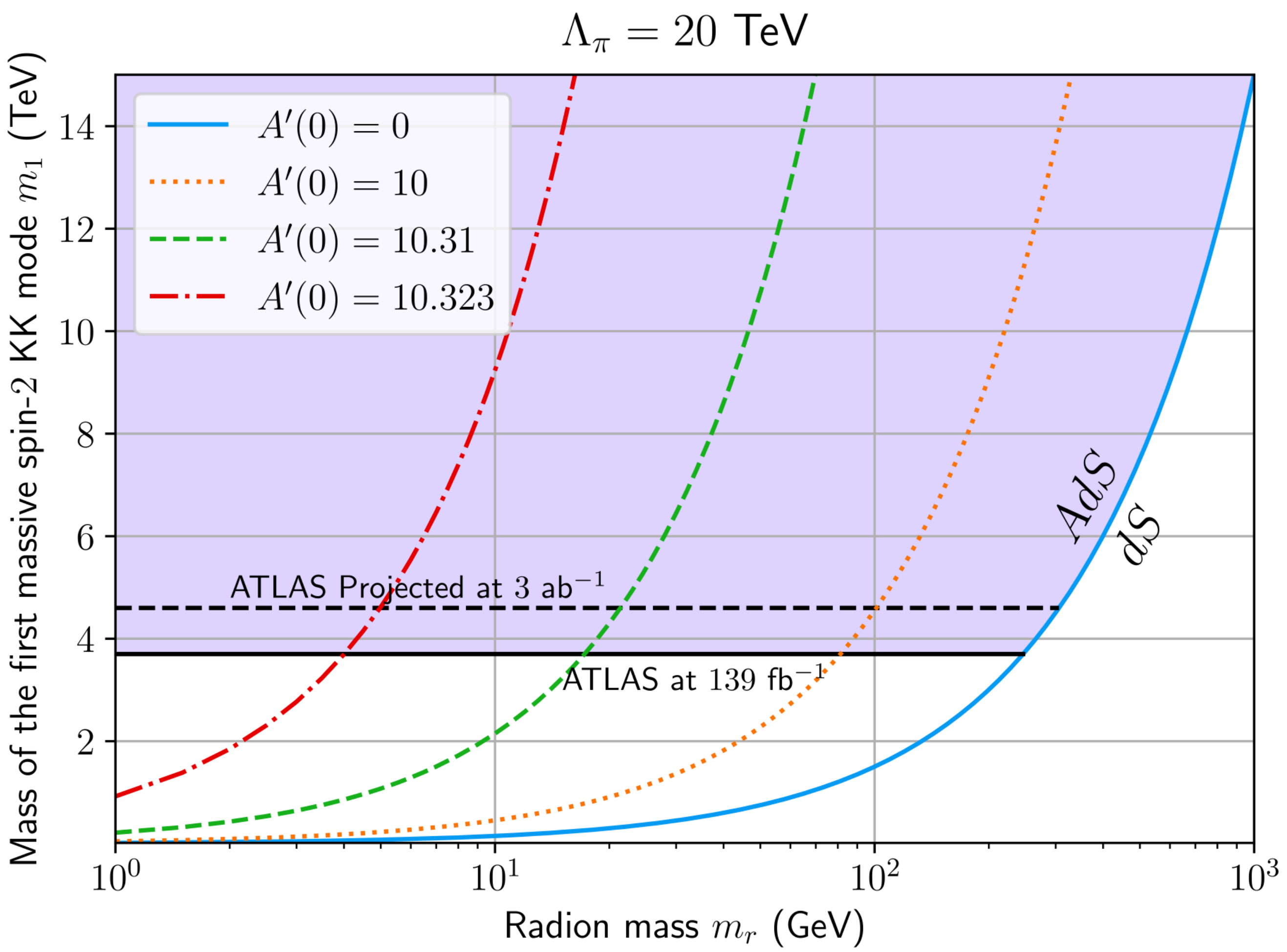
- We can increase m_r by increasing ϕ_1, ur_c , but $A(y) = kr_c|y| + \frac{\phi_1}{48}\left(e^{-2ur_c|y|} - 1\right)$
- For large enough ϕ_1, ur_c near $y = 0$, $A(y)$ flips sign and space is locally deSitter.



Stabilised RS Model

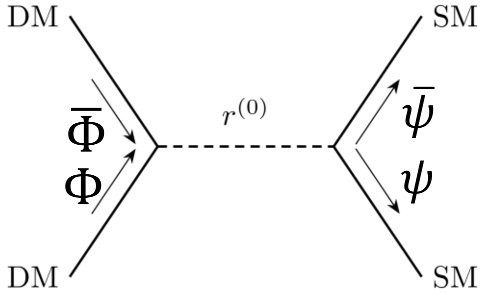
Backreaction

- Then for $\Lambda_\pi = 20$ TeV and $m_1 \approx 4$ TeV, $m_r \lesssim 250$ GeV
- Can increase m_1, but must choose appropriate Λ_π



Stabilised RS Model

Dark sector



- For a standard thermal WIMP freeze-out,
  - DM-SM annihilation cross section: $\sigma_{\Phi\Phi\to\bar{\psi}\psi} = \frac{1}{n!}\int \frac{d\Omega}{64\pi^2}\frac{1}{s}\sqrt{\frac{s-4m_\phi^2}{s-4m_\Phi^2}}\left|\mathcal{M}_{\Phi\Phi\to\bar{\psi}\psi}(s,\theta)\right|^2$
  - Freeze-out temperature $T = m_\Phi/20$
  - Average relative velocity $v = \sqrt{\frac{16T}{\pi m_\Phi}}$
  - $\langle\sigma v\rangle \approx 3\times 10^{-26} cm^3/s$
- KK modes couple to TeV brane's energy-momentum tensor (SM and DM):

$$\mathcal{L}_{gravity-couplings} \supset \left(\frac{\hat{h}_{\mu\nu}^{(0)}(x)}{M_{Pl}} + \frac{\hat{h}_{\mu\nu}^{(1)}(x)}{\Lambda_\pi}\right)T^{\mu\nu} + \frac{1}{\Lambda_\pi}\frac{\gamma_0(\pi)}{\psi_{1(\pi)}}e^{2A(\pi)}\hat{r}^{(0)}(x)T_\mu^\mu$$

- Calculate velocity-averaged cross section

$$\langle\sigma_{\Phi\Phi}v\rangle = \frac{\pi\sqrt{m_r^2-4m_\Phi^2}K_1\left(\frac{m_r}{T}\right)\upsilon_\Phi(m_r,m_\Phi)}{48\Lambda_\pi^2 m_\Phi^4 T K_2\left(\frac{m_\Phi}{T}\right)^2}$$

  - $K_{1,2}$: 1st and 2nd modified Bessel functions of the second kind
  - T : Temperature of thermal bath

Results

Dark matter species

$$\langle \sigma_{SS} v \rangle \approx (1.7163 \times 10^{-22}\ \mathrm{cm^3/s}) \left(\frac{1\ \mathrm{TeV}}{\Lambda_\pi}\right)^2$$

$$\langle \sigma_{VV} v \rangle \approx (6.3807 \times 10^{-24}\ \mathrm{cm^3/s}) \left(\frac{1\ \mathrm{TeV}}{\Lambda_\pi}\right)^2$$

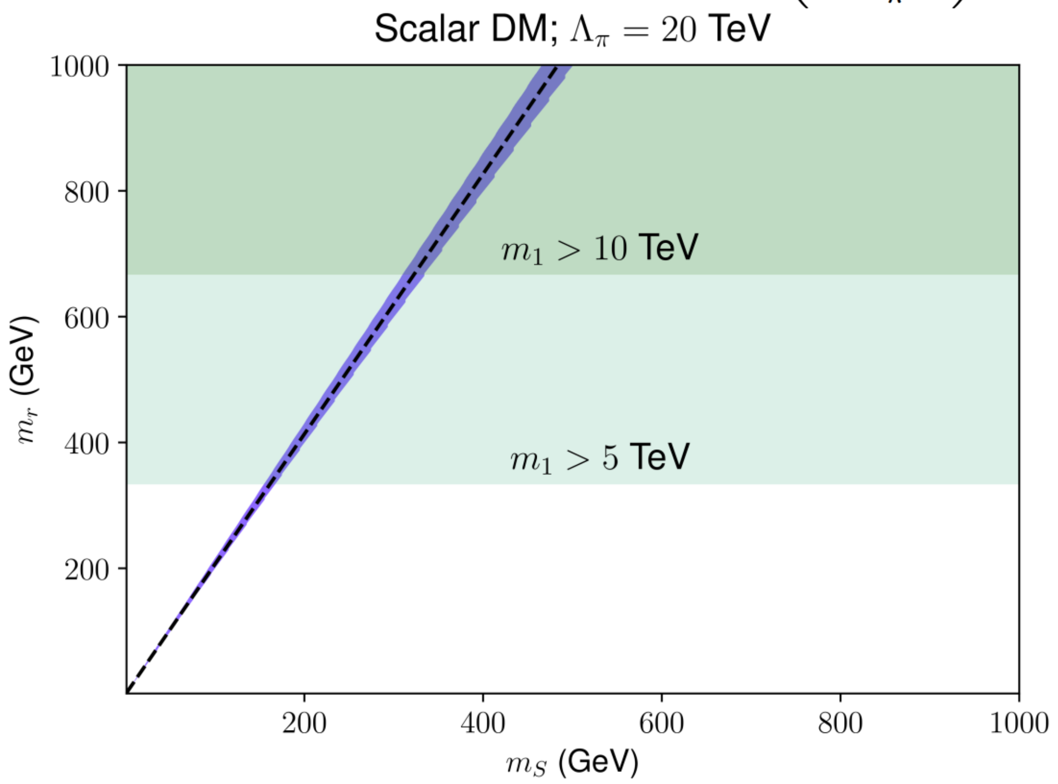
$$\langle \sigma_{\chi\chi} v \rangle \approx (5.9330 \times 10^{-25}\ \mathrm{cm^3/s}) \left(\frac{1\ \mathrm{TeV}}{\Lambda_\pi}\right)^2$$

$\langle \sigma v \rangle \geq 3 \times 10^{-26} cm^3/s$

Scalar : $\Lambda_\pi \sim 20 - 120$ TeV

Vector : $\Lambda_\pi \sim 20$ TeV

Fermion: ❌ (for reasonable values of Λ_π)



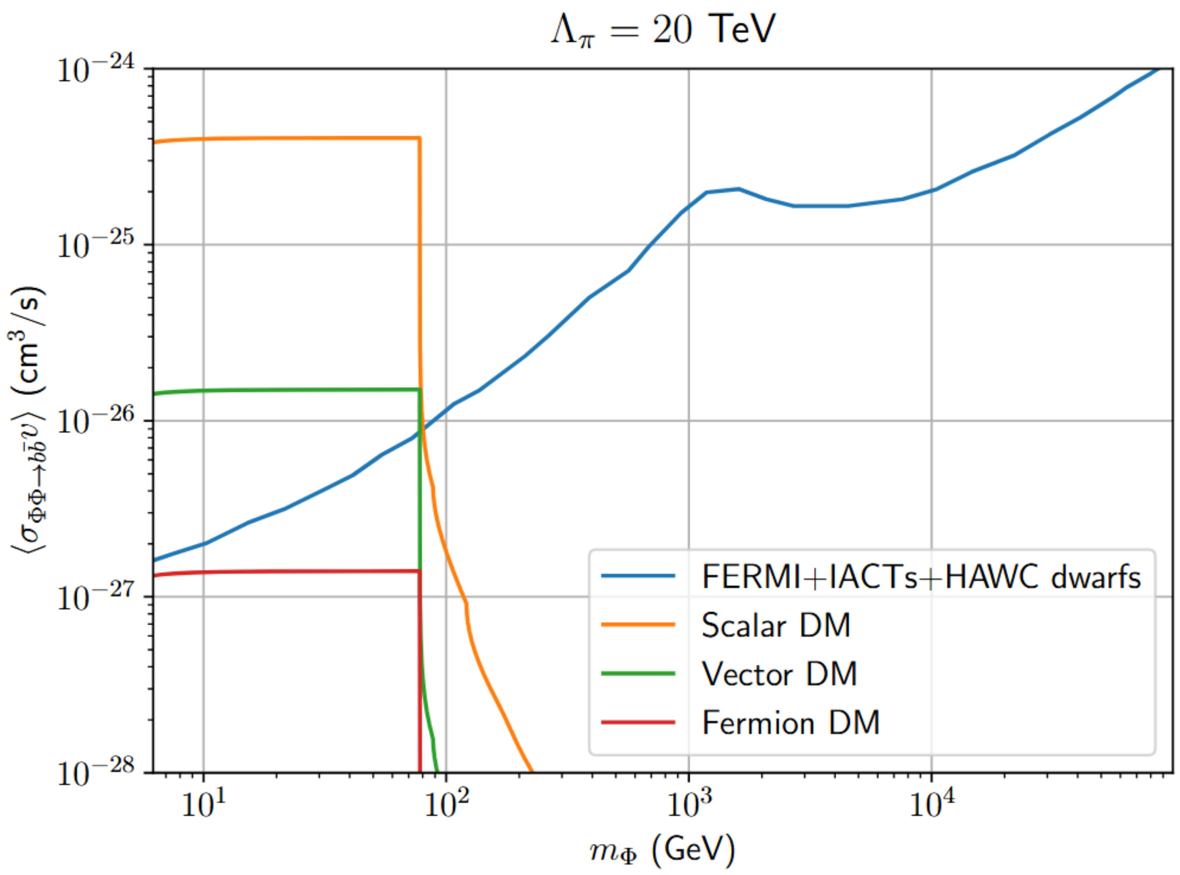
---- $m_r = 2\gamma m_S$
$\Omega_{DM} h^2 < 0.12$
$A'(0) > 0$ (AdS)

- Must be in narrow region near on-resonance production
- For vector DM, purple region is a lot more compact

Stabilised RS Model

More constraints?

- Because Λ_π is so large, also evades bounds from Lux-Zeplin DM direct detection.
- And for DM masses below W, Z mass:

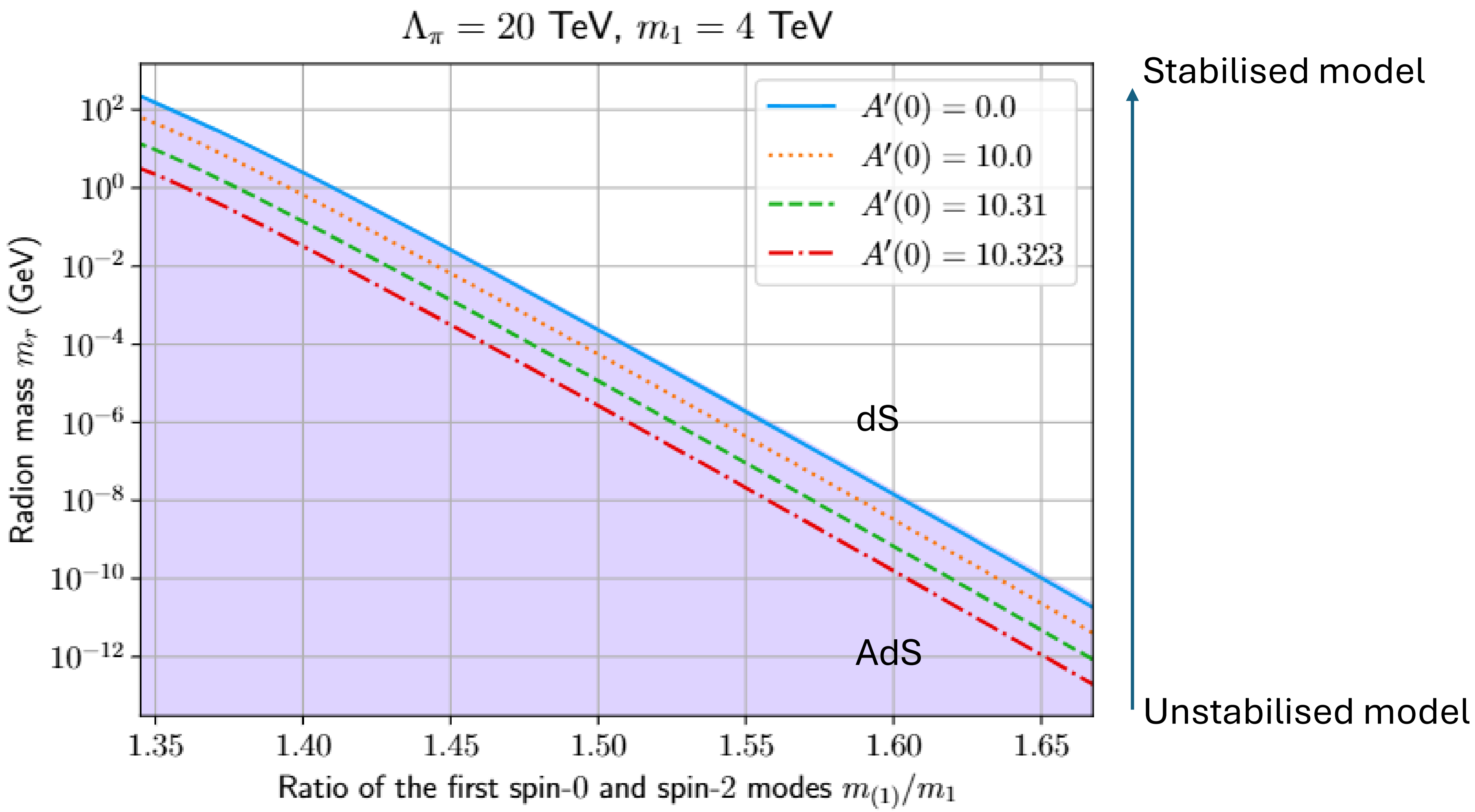


Conclusion

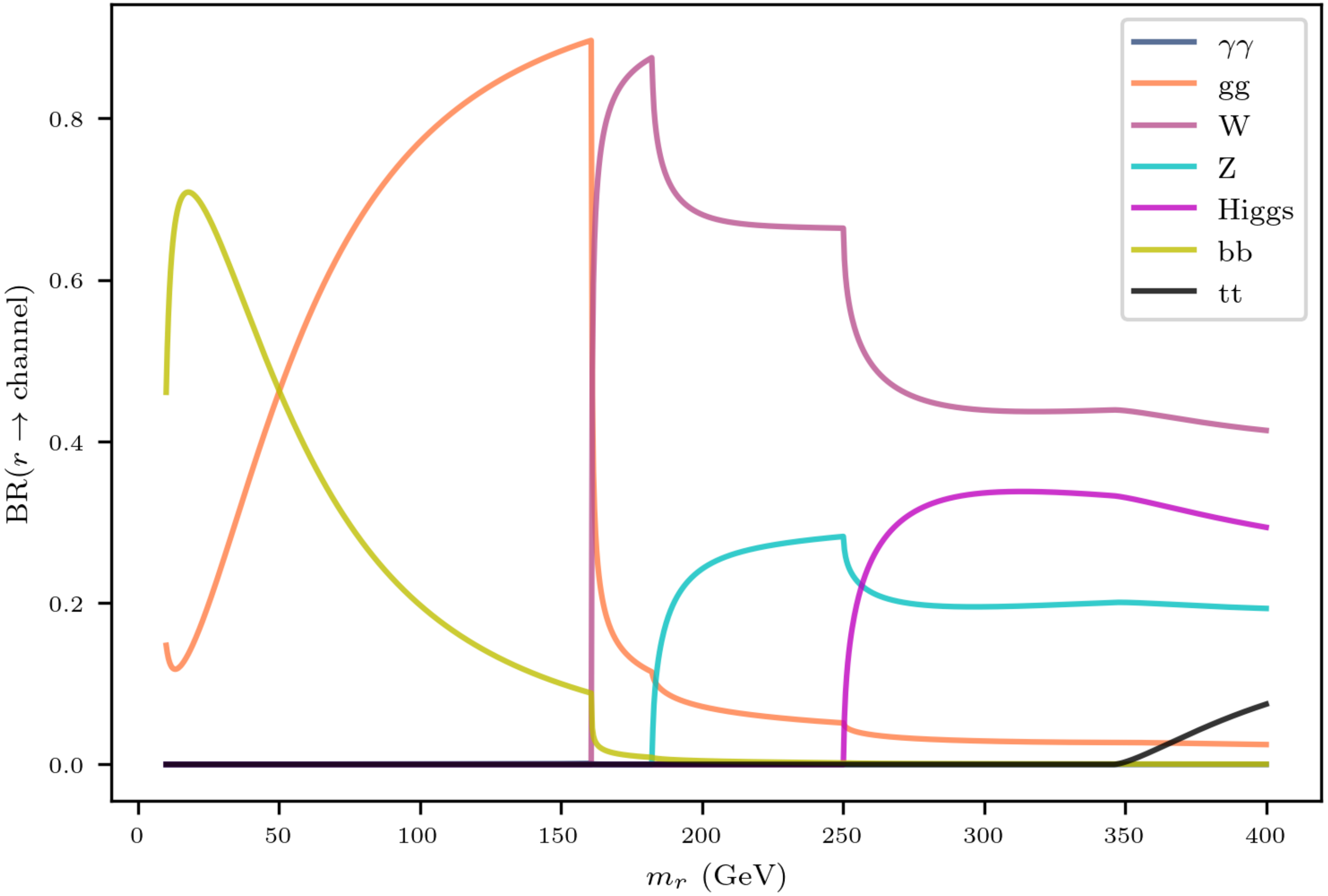
- Radion's parameter space at $m_r \sim \mathrm{GeV} - \mathrm{TeV}$ evades collider searches,
- but is indirectly constrained by $m_{(1)}$ by imposing curvature to be AdS.
- Calculated $\langle \sigma v \rangle$ for radion portal scalar, vector and fermion DM candidates.
- Radion-portal scalar and vector DM candidates are allowed, but would require near on-resonance production.

arxiv:2507.xxxx?

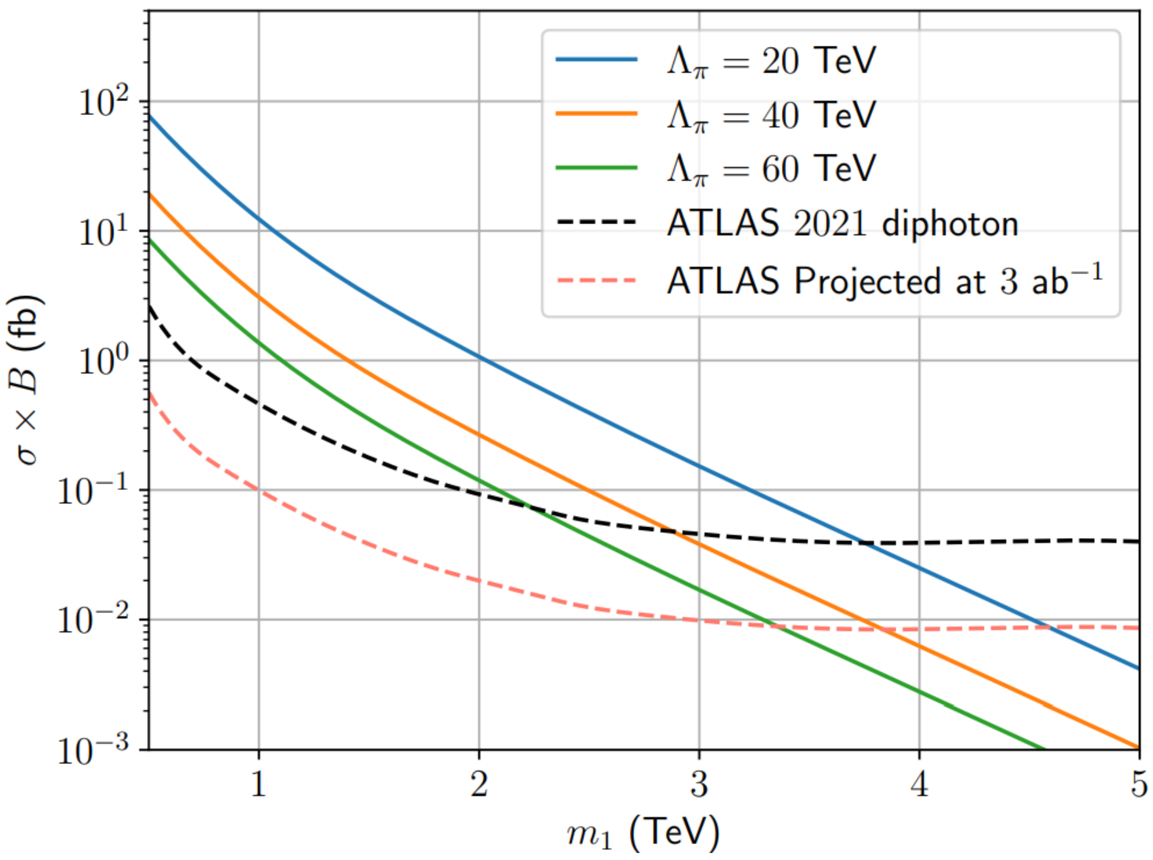
Backup slides



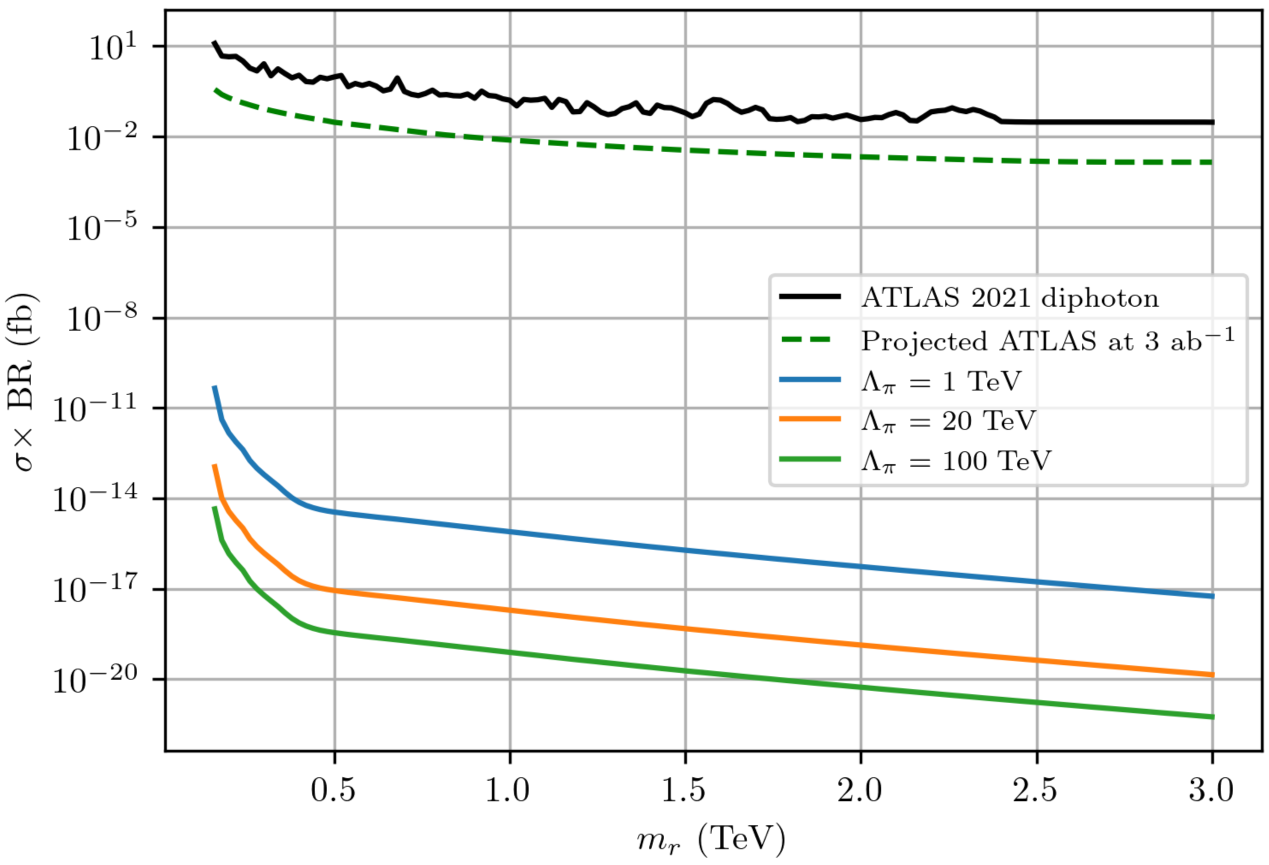
$\Lambda_\pi = 20$ TeV, $m_1 = 4$ TeV
$A'(0) = 0.0$
$A'(0) = 10.0$
$A'(0) = 10.31$
$A'(0) = 10.323$
dS
AdS
Radion mass m_r (GeV)
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
1.35
1.40
1.45
1.50
1.55
1.60
1.65
Ratio of the first spin-0 and spin-2 modes $m_{(1)}/m_1$
Stabilised model
Unstabilised model


$\gamma\gamma$
gg
W
Z
Higgs
bb
tt
0.0
0.2
0.4
0.6
0.8
$\mathrm{BR}(r \to \mathrm{channel})$
0
50
100
150
200
250
300
350
400
m_r (GeV)

10.1103/PhysRevD.111.075030



this work



Stabilisation

$$\phi(x, y) \equiv \phi_0(y) + \hat{f}(x, y)$$

$$\hat{f}(x, y) = \frac{2\sqrt{6}}{M_5^{3/2}} \frac{e^{2A}}{d_y \phi_0(y)} \partial_y \hat{r}(x, y)$$

DFGK model

$$V[\hat{\varphi}] = \frac{1}{8r_c^2}\left[\left(\frac{dW}{d\hat{\varphi}}\right)^2 - \frac{W^2}{3}\right]$$

$$W[\hat{\varphi}] = 12kr_c - \frac{1}{2}\hat{\varphi}(\phi)^2 ur_c$$

$\left|\mathcal{M}_{\Phi\Phi\to\bar{\psi}\psi}(s,\theta)\right|^2$ contains factors

$$\upsilon_S(m_r, m_S) = \left(m_r^2 + 2m_S^2\right)^2$$
$$\upsilon_V(m_r, m_V) = \frac{1}{9}\left(m_r^4 - 4m_r^2 m_V^2 + 12m_V^4\right)$$
$$\upsilon_\chi(m_r, m_\chi) = \frac{1}{2}m_\chi^2\left(m_r^2 - 4m_\chi^2\right)$$

$$\Lambda_\pi = \frac{\psi_0(\pi)}{\psi_1(\pi)} M_{PL},$$
$$m_1 = \frac{1}{r_c}\sqrt{\int_{-\pi}^{\pi} d\phi e^{-4A(\phi)}\left(\psi_1'(\phi)\right)^2},$$
$$m_r = \frac{1}{\sqrt{6}r_c}\sqrt{\int_{-\pi}^{\pi} d\phi \frac{e^{4A(\phi)}}{\left(\varphi_0'(\phi)\right)^2}\gamma_0(\phi)^2},$$