

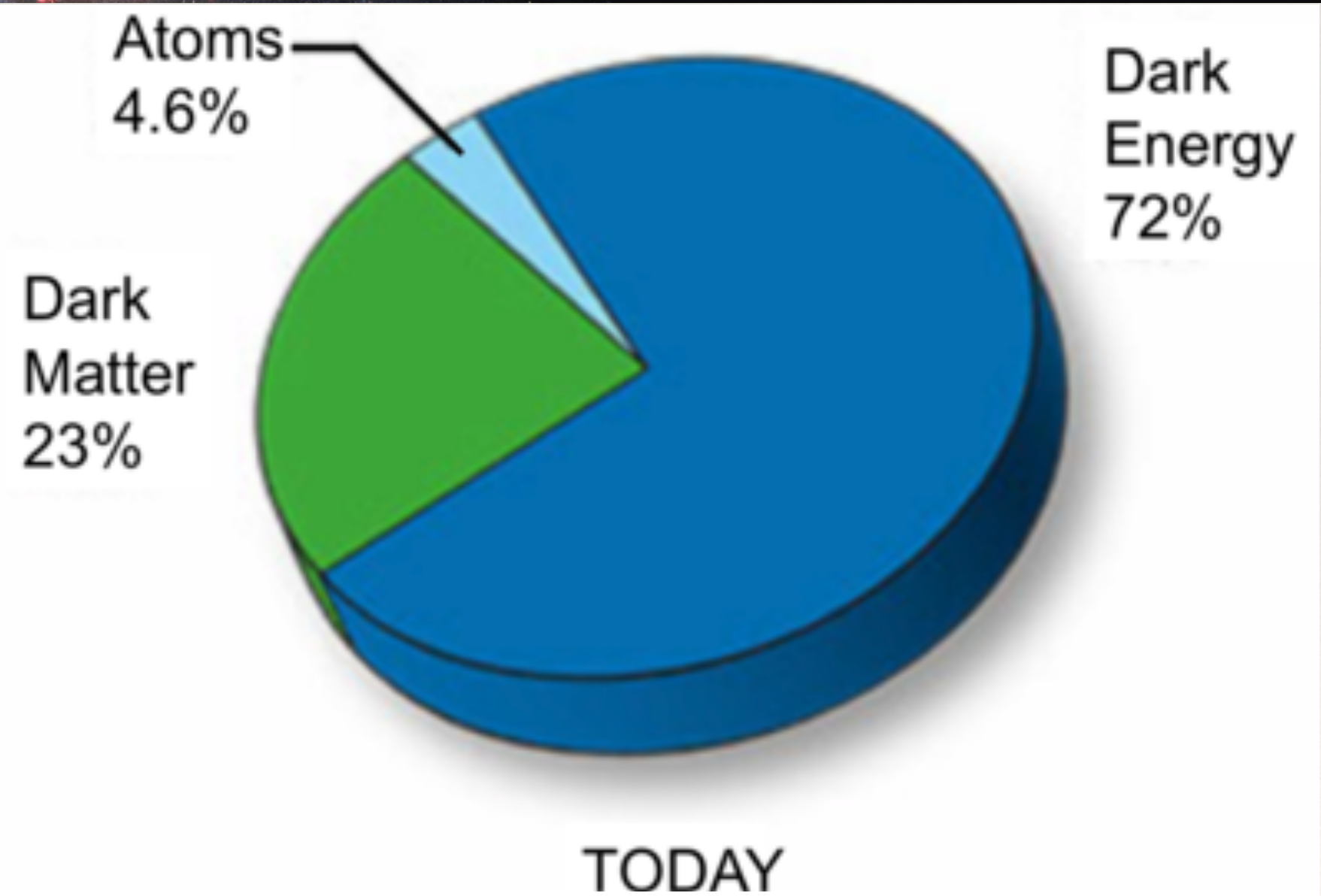
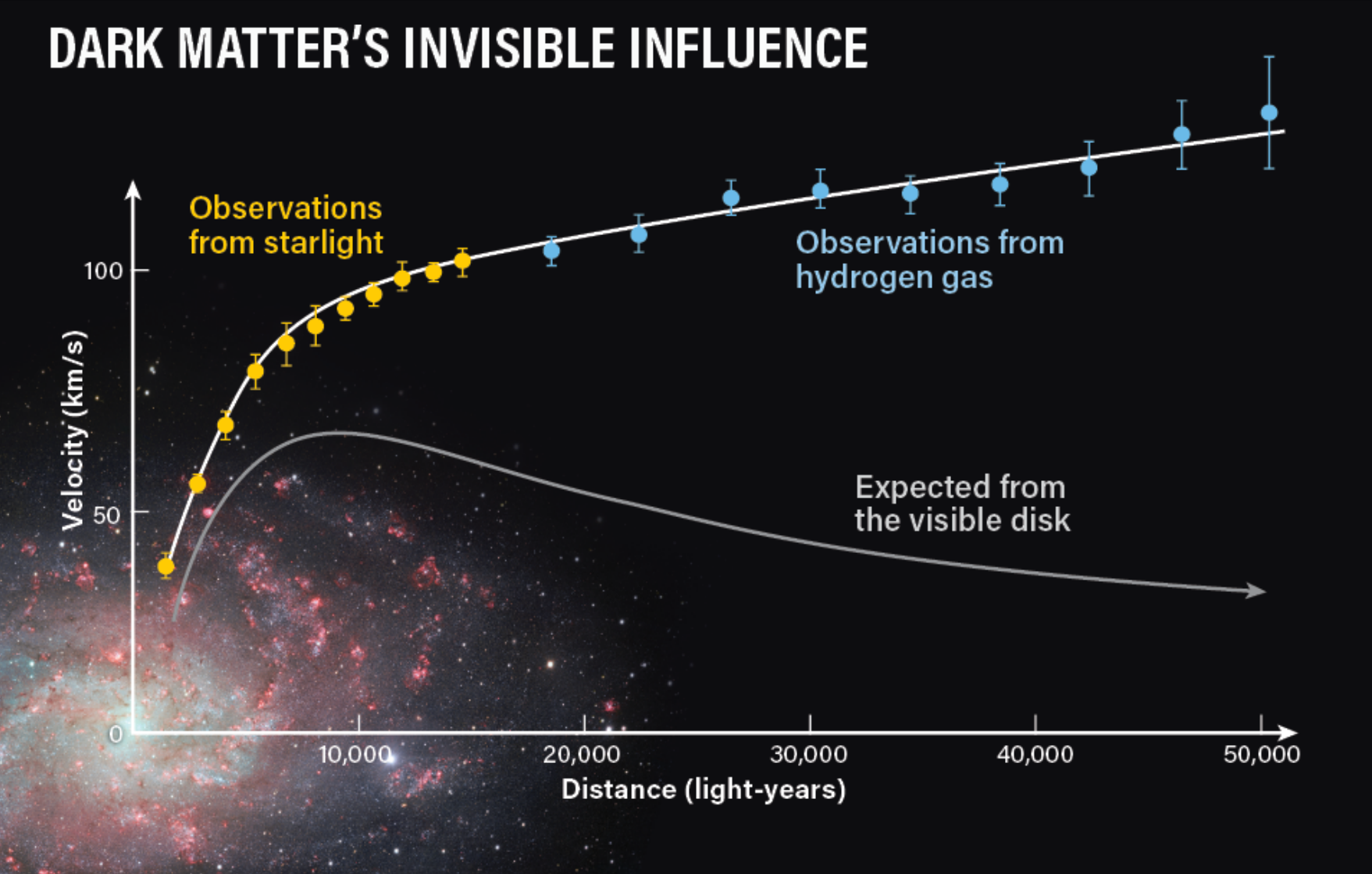
PPC 2026

Dark Matter in Randall-Sundrum Models

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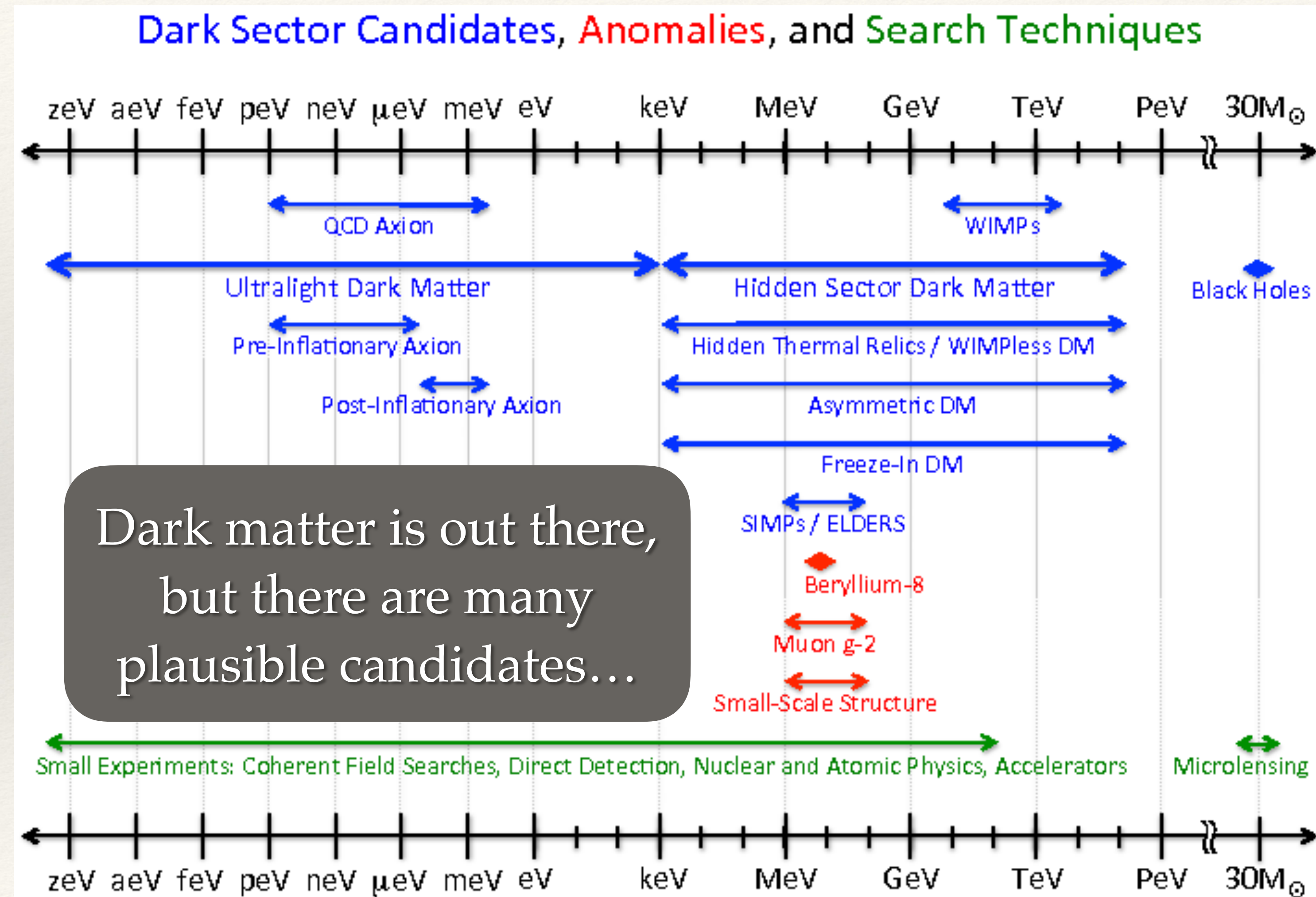


From astronomy.com / science / does-dark-matter-affect-our-solar-system



From: arXiv:1707.04591

Dark Matter



Dark matter is out there,
but there are many
plausible candidates...

From: arXiv:1707.04591

So what is Dark Matter?

Bertone, G., Tait, T.M.P.
Nature **562**, 51–56 (2018)
DOI: 10.1038/s41586-018-0542-z

- ❖ There are many answers to the dark matter questions
- ❖ Many of these solve parts the Standard Model cannot
- ❖ Today I'll focus on ...



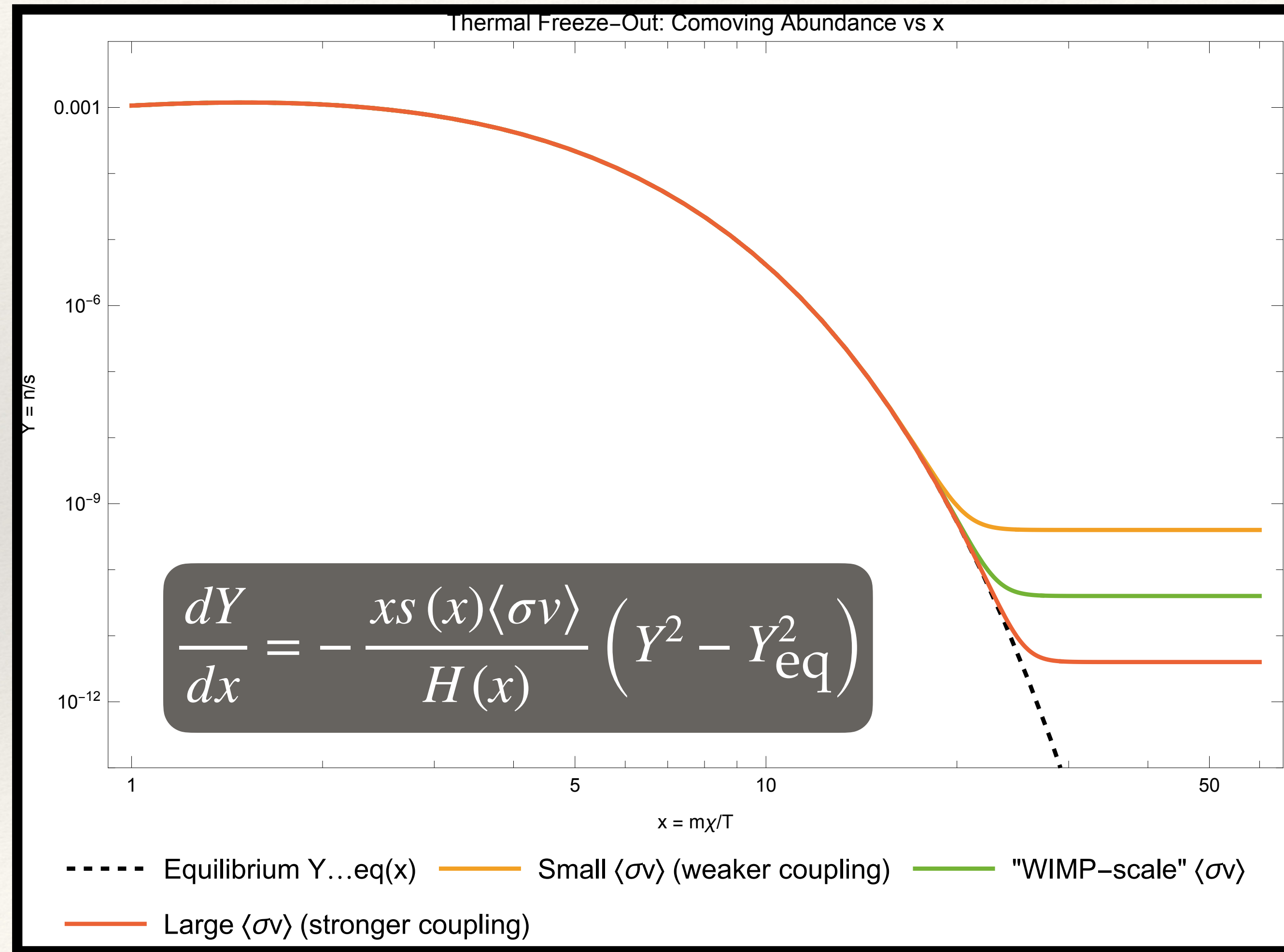
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- ❖ There are many answers to the dark matter questions
- ❖ Many of these solve parts the Standard Model cannot
- ❖ Today I'll focus on ...
 - ❖ **Extra-Dimensions with massive spin-2 portal**



Freeze Out Dark Matter



- ❖ Equilibrium (early times $T \gg m_\chi$)
- ❖ Annihilation / production
- ❖ Universe expands, cools $T \leq m_\chi$
- ❖ DM tracks equilibrium
- ❖ DM decouples with the plasma
- ❖ Decay rate $\leq$ Hubble expansion
- ❖ DM "Freezes out" to constant
- ❖ Observed relic $\Omega_\chi h^2 \sim 0.12$

What can we do with this?

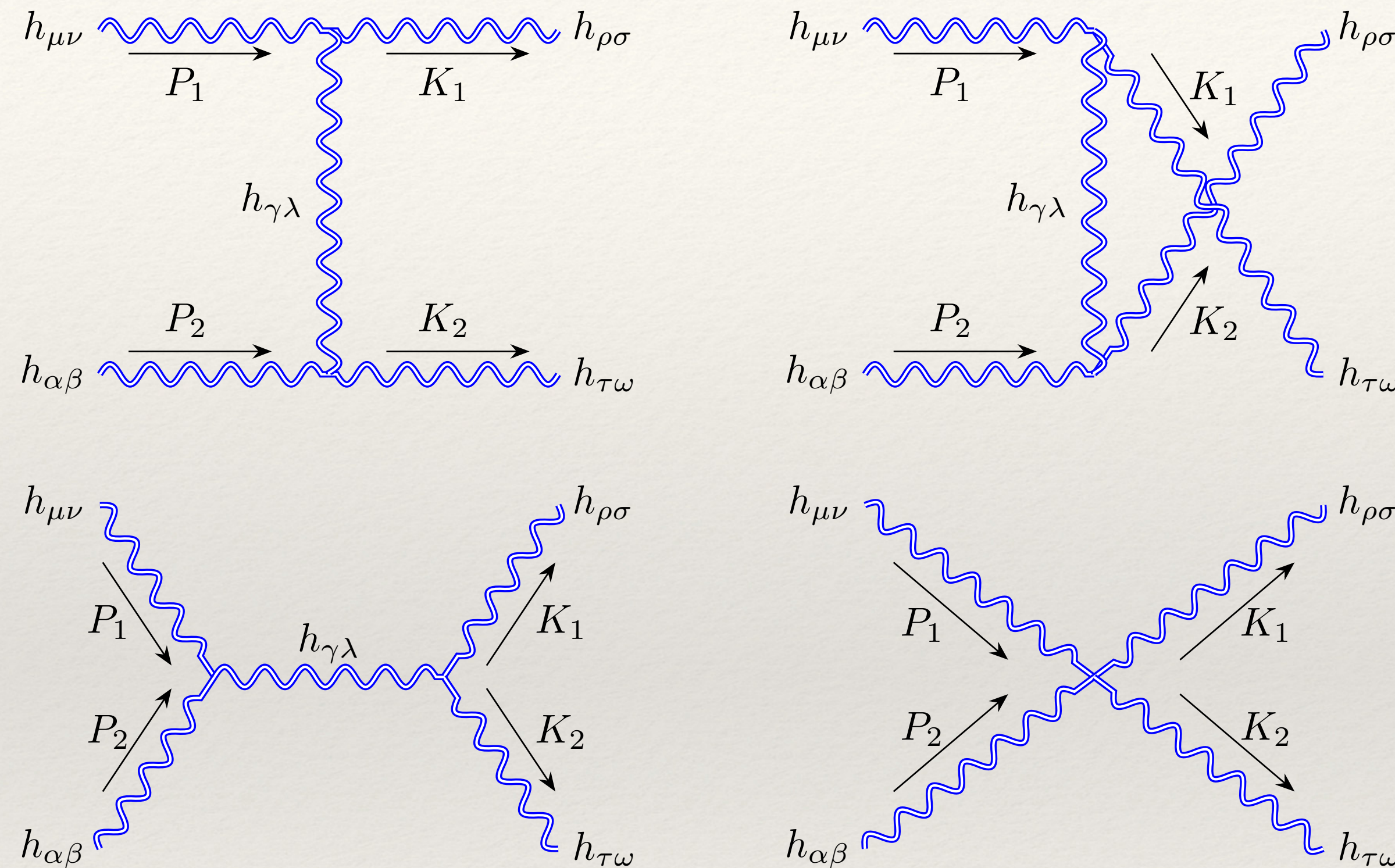
- ❖ Result controlled by $\langle \sigma v \rangle$ which is controlled by $|\mathcal{M}|^2$

$$\Omega_\chi h^2 \approx \frac{3 \times 10^{-27} \text{cm}^3 \text{s}^{-1}}{\langle \sigma v \rangle}$$

$$\langle \sigma v \rangle = \left[512 \pi^2 T m_\chi^4 \left[K_2 \left(\frac{m_\chi}{T} \right) \right]^2 \right]^{-1} \int_{4m_\chi^2}^{\infty} ds \left[\frac{1}{\sqrt{s}} \sqrt{(s - 4m_\chi^2)(s - 4m_\varphi^2)} K_1 \left(\frac{\sqrt{s}}{T} \right) \int d\Omega |\mathcal{M}_{\chi\chi \rightarrow \varphi\varphi}|^2 \right]$$

- ❖ Need to understand scattering properties of the model

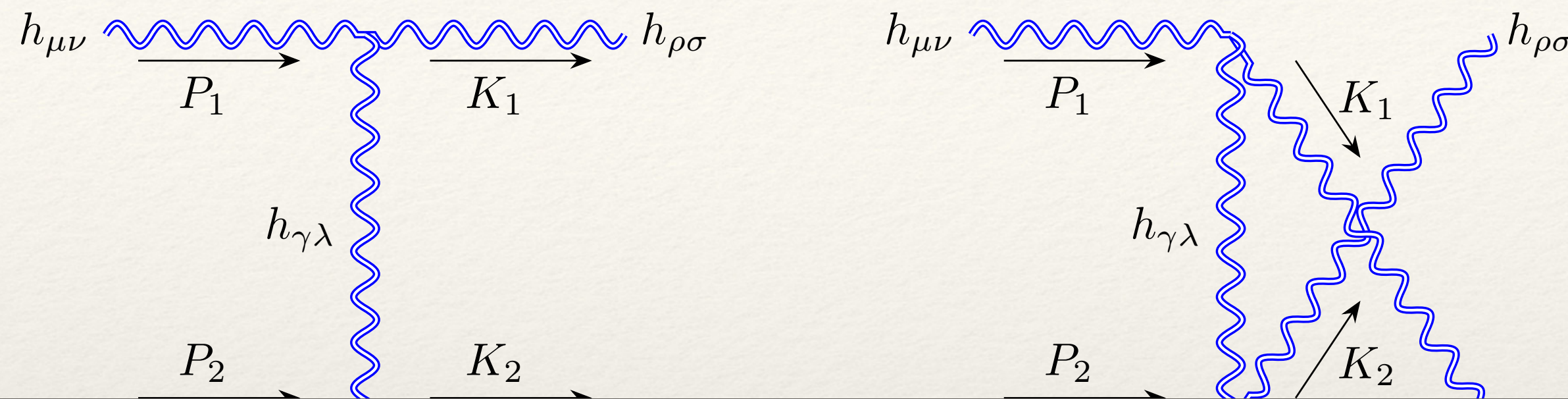
Massive Gravity (FP) - Self-Scattering



FP amplitude scales as $\mathcal{M} \sim \frac{s^5}{M_{\text{Pl}}^2 m^8}$

Effective Cutoff @ $\Lambda_5 = \left(M_{\text{Pl}}^2 m^8 \right)^{1/5}$

Massive Gravity (FP) – Self-Scattering



(Partial) Resolution: de Rham-Gabadadze-Tolley (dRGT) massive gravity model

Adding higher order potential terms and tuning coefficients

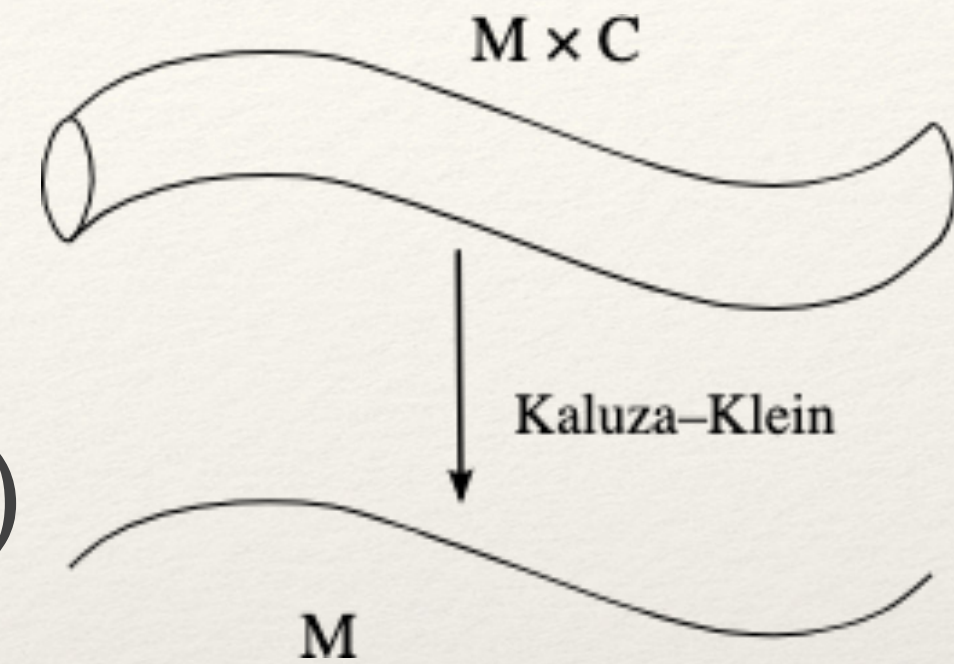
Brings effective scale down to Λ_3

dRGT scales as $\mathcal{M} \sim \frac{s^3}{M_{\text{Pl}}^2 m^4}$

Effective Cutoff @ $\Lambda_3 = \left(M_{\text{Pl}}^2 m^4 \right)^{1/3}$

Compactified Extra-Dimensions

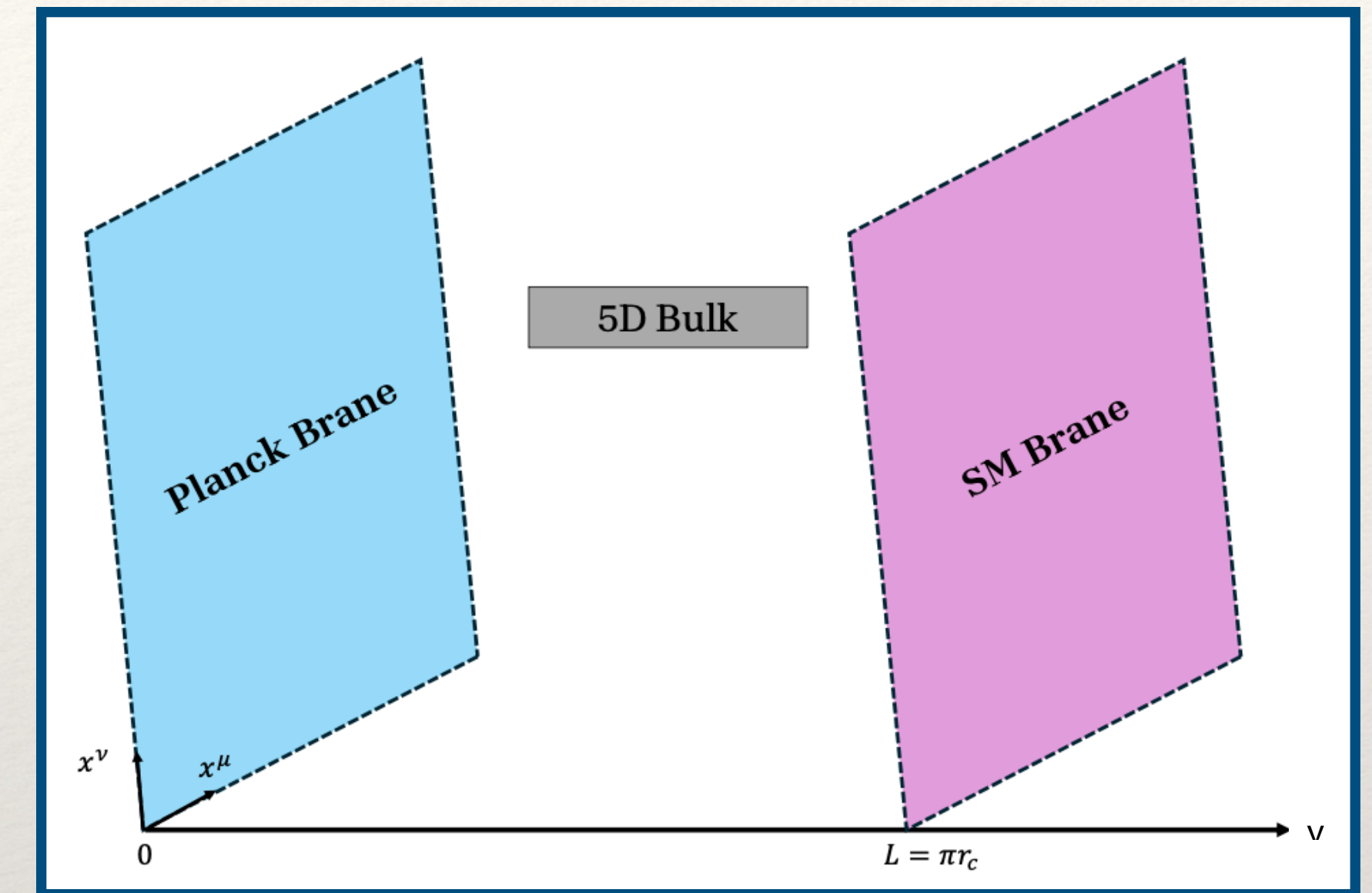
- ❖ **Kaluza-Klein** (1910s / 1920s) - unify gravity / electromagnetism
- ❖ Additional degree of freedom - radion field (inherently massless)
- ❖ Extra-dimension has **tiny** extent $L \sim 10^{-30}$ cm
- ❖ Exactly **ONE** massless spin-2 state (graviton - gravity!)
- ❖ **Infinite tower of massive spin-2 states**
- ❖ Byproduct: infinite tower of massive spin-1 / spin-0 states (can be gauged*)
- ❖ Independent of underlying geometry!



**Geometric
Higgs
Mechanism**

Randall-Sundrum (RS) Models

- ❖ Warped 4-dim, flat extra-dim
- ❖ Two 4D slices (branes) at $y = 0, \pi r_c$
- ❖ Fundamental 5D Planck mass M_5
- ❖ Bulk Λ , brane-localised λ_i cosmological constants
- ❖ Fixed Λ, λ_i by matching to $\Lambda_{4D} = 0$
- ❖ Massless 5D spin-2 decomposes into infinite tower of *massive* 4D spin-2



$$ds^2 = e^{-2A(y)} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2$$

$$S = -\frac{M_5^3}{4} \int d^4x \int_0^{\pi r_c} dy \sqrt{|\det G|} (\tilde{R} - 2\Lambda) + \int d^4x \sqrt{|\det G_i|} [\lambda_i]_{y=y_i}$$

$$h_{\mu\nu}(x, y) = \sum_{n=0}^{\infty} h_{\mu\nu}^{(n)}(x) \psi_n(y)$$

RS Behaviour

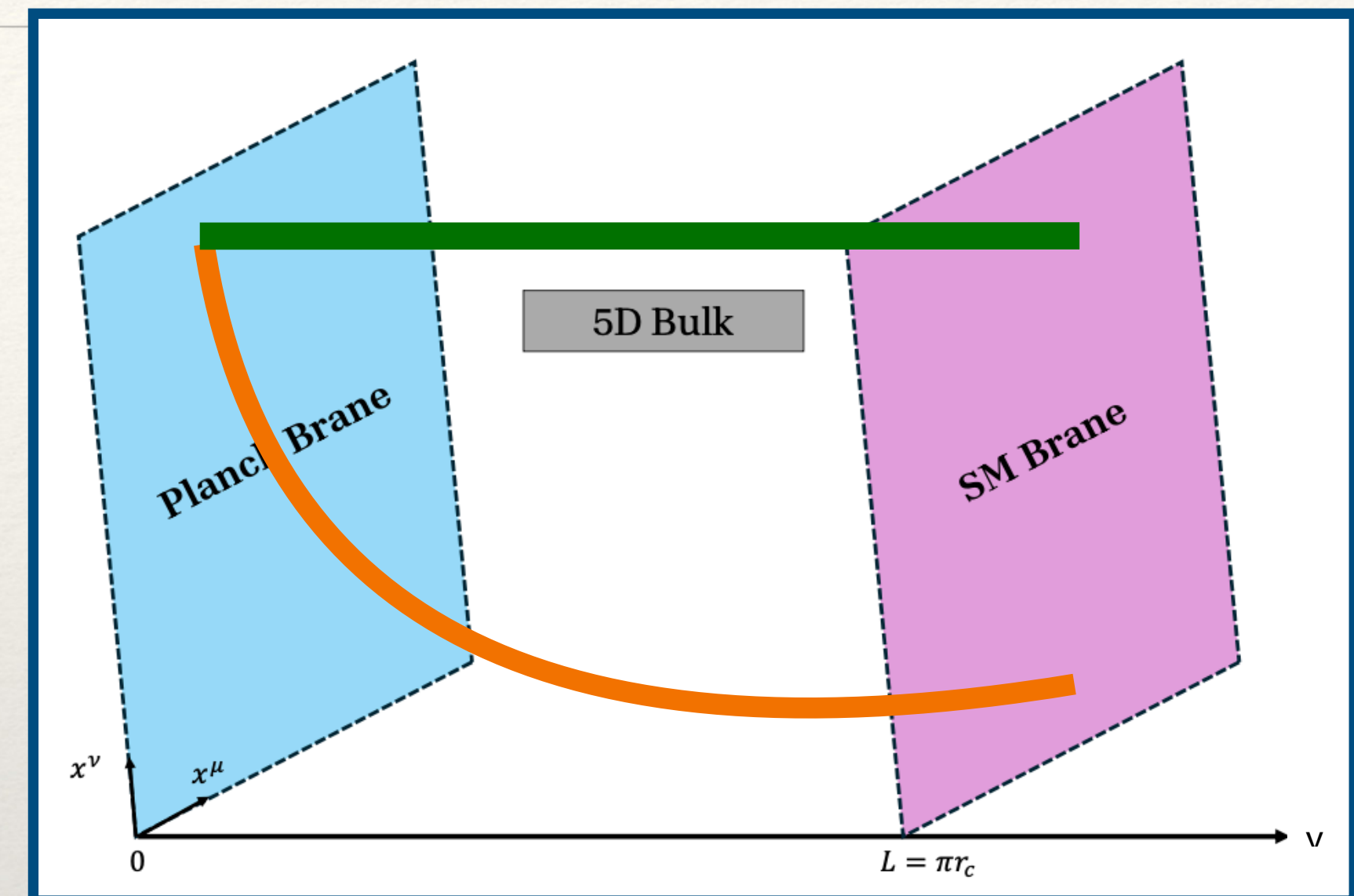
- ❖ Motivated by the Anti de-Sitter / Conformal Field Theory duality, choose AdS bulk with $\Lambda > 0$

- ❖ **Graviton** has universal coupling to matter

- ❖ **SM Higgs VEV** exp. suppressed $\frac{\langle \Phi \rangle_{\text{SM}}}{\langle \Phi \rangle_{\text{Pl}}} = e^{-k\pi r_c}$

- ❖ Matter coupling in general is KK mode dependant

$$\Lambda_{\text{SM}}^{(n)} = \frac{M_{\text{Pl}} |\psi_0|}{|\psi_n(y = \pi r_c)|} \sim M_{\text{Pl}} e^{-k\pi r_c}$$



$$ds^2 = e^{-2A(y)} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2$$

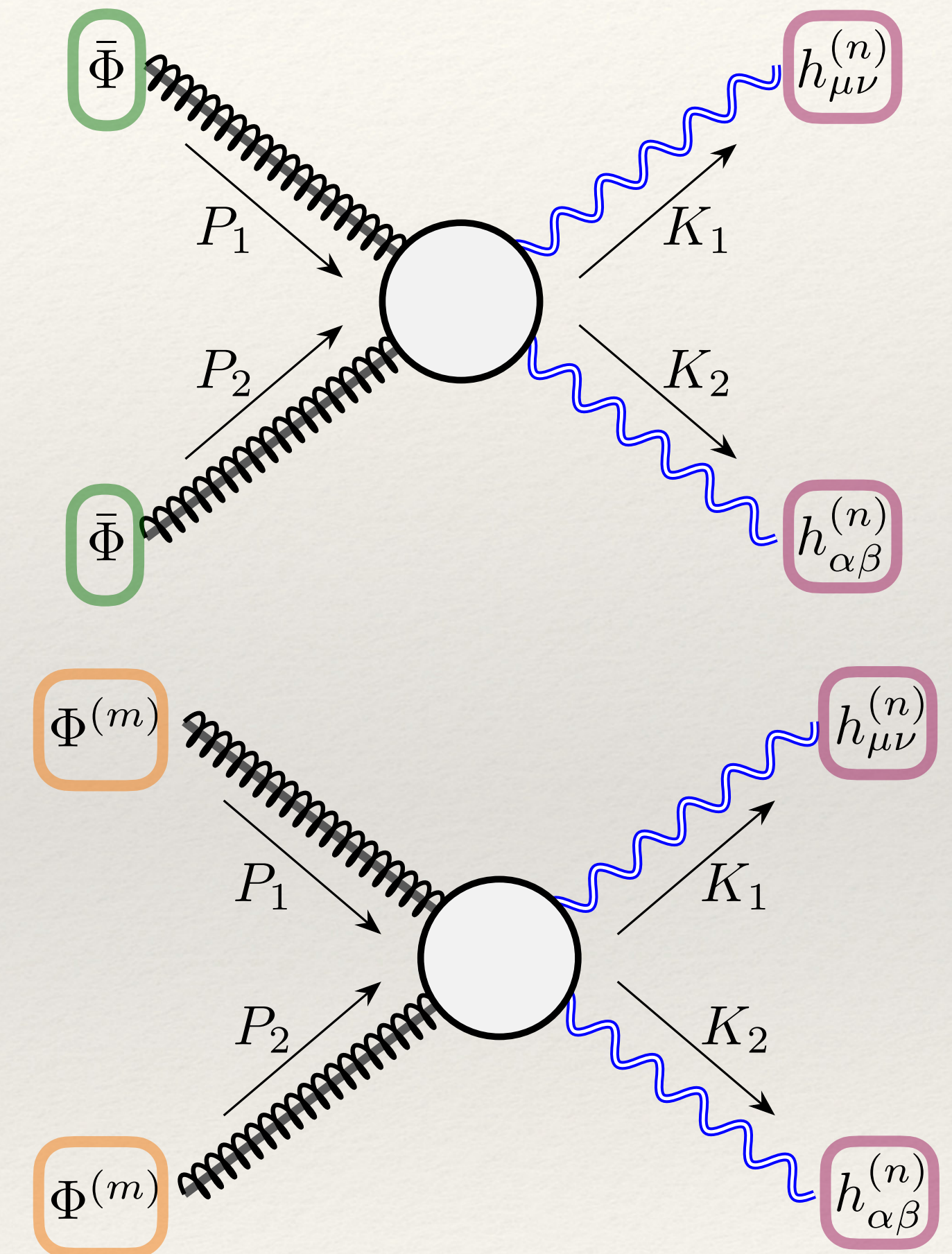
$$A(y) = ky, \quad k = \sqrt{\frac{\Lambda}{3}}$$

Amplitude Scaling

- ❖ Need to be extremely careful with calculations
- ❖ Different amplitude scaling gives various phenomenological probes
- ❖ Incorrect amplitude $\rightarrow$ not meaningful phenomenology
- ❖ Many cases of this, one example is $q\bar{q} \rightarrow \gamma G$ (massive spin-2 G):
 - ❖ Scaling like $\mathcal{M} \sim s m_q^4 / \Lambda m_G^4$
 - ❖ Phenomenology based on result (i.e. before / after EW breaking)
 - ❖ Correct scaling $\mathcal{M} \sim s / \Lambda$

Scattering Amplitudes With Matter

- ❖ Produce **spin-2 KK modes** from **brane-localised** or **bulk** matter
- ❖ Unitary gauge calculation
- ❖ Main results:
 - ❖ We define **sum-rules** that relate summation of propagating KK modes to external (on-shell) KK modes
 - ❖ For all (brane / bulk) matter species - sum-rules eliminate bad high-energy behaviour
 - ❖ The leading high-energy behaviour $\mathcal{M} \sim s/\Lambda$



Scattering Amplitudes With Matter

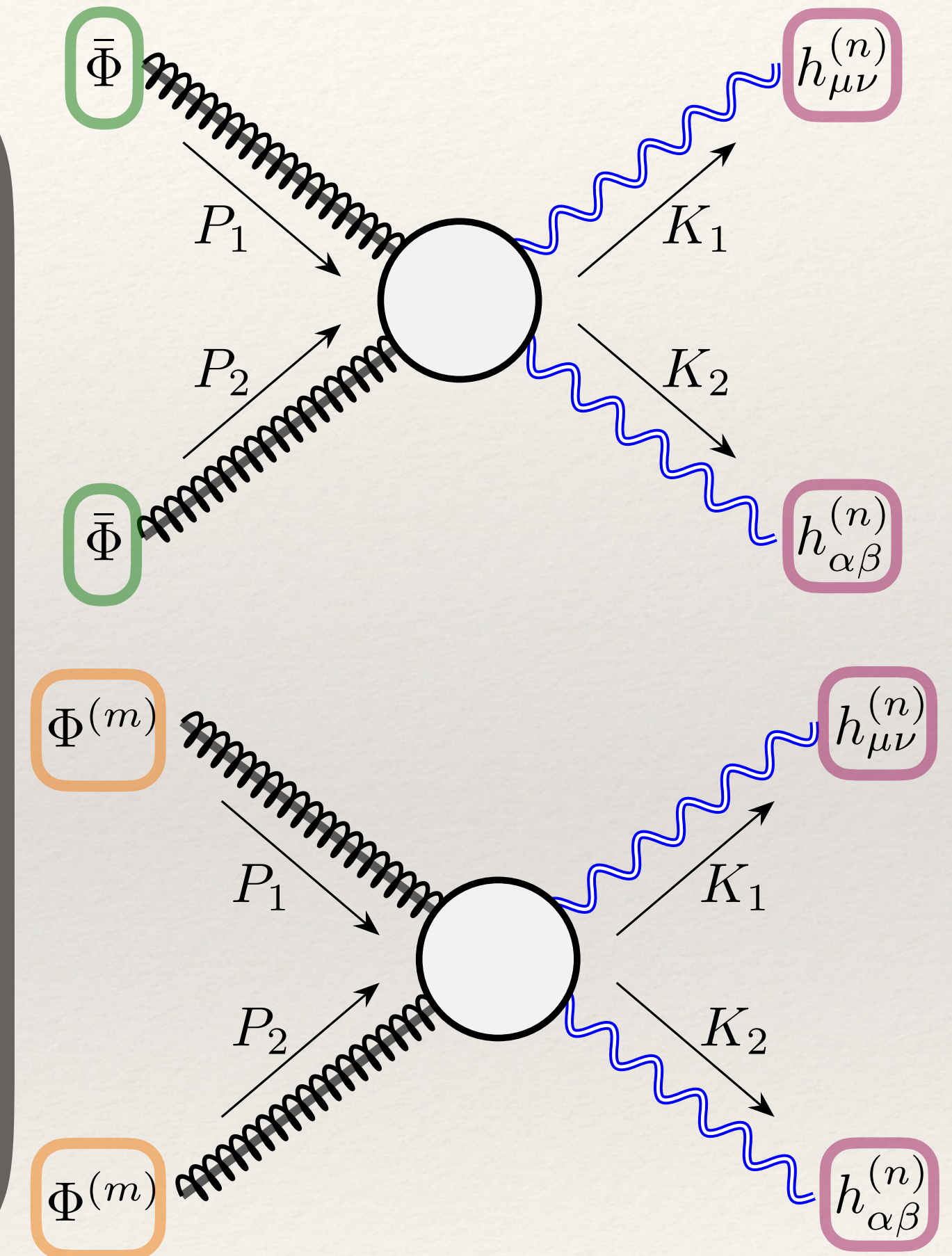
Perform the same calculation in a 't Hooft-Feynman-like gauge

We keep unphysical massive vector and scalar modes - changes:

1. Additional propagating vector / scalar channels
2. KK mode degeneracy between spin-2 / spin-1 / scalar states
3. Mass degeneracy $\rightarrow N = 2$ SUSY relationship

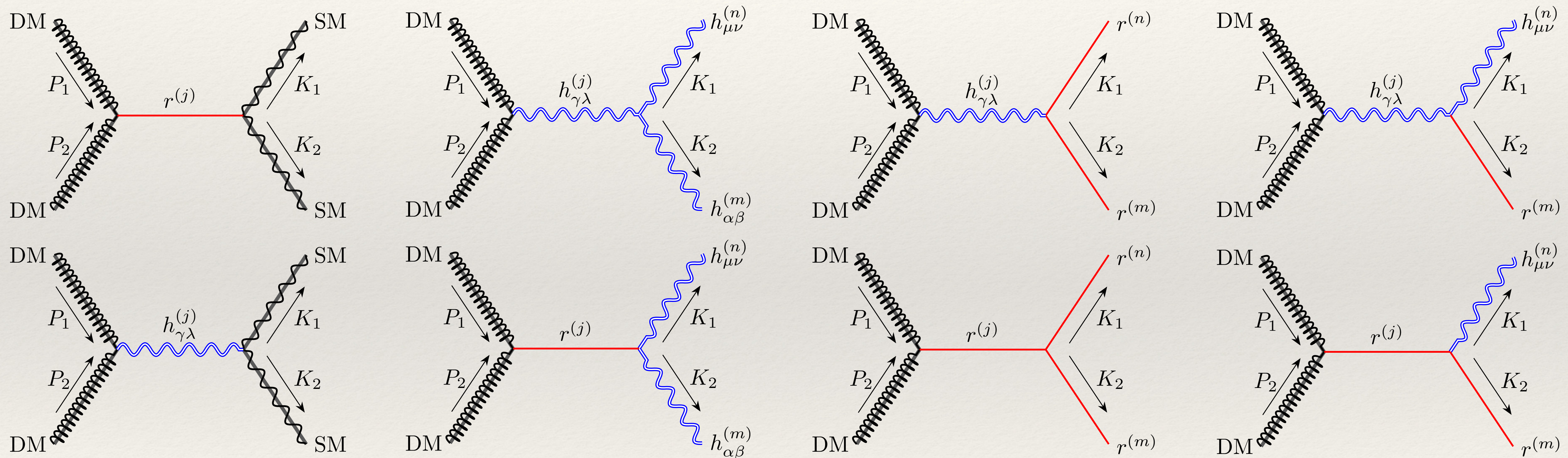
High energy limit **looks like** scattering of scalar KK modes

Precisely a Goldstone-Equivalence theorem...



Gravitational Portal Phenomenology

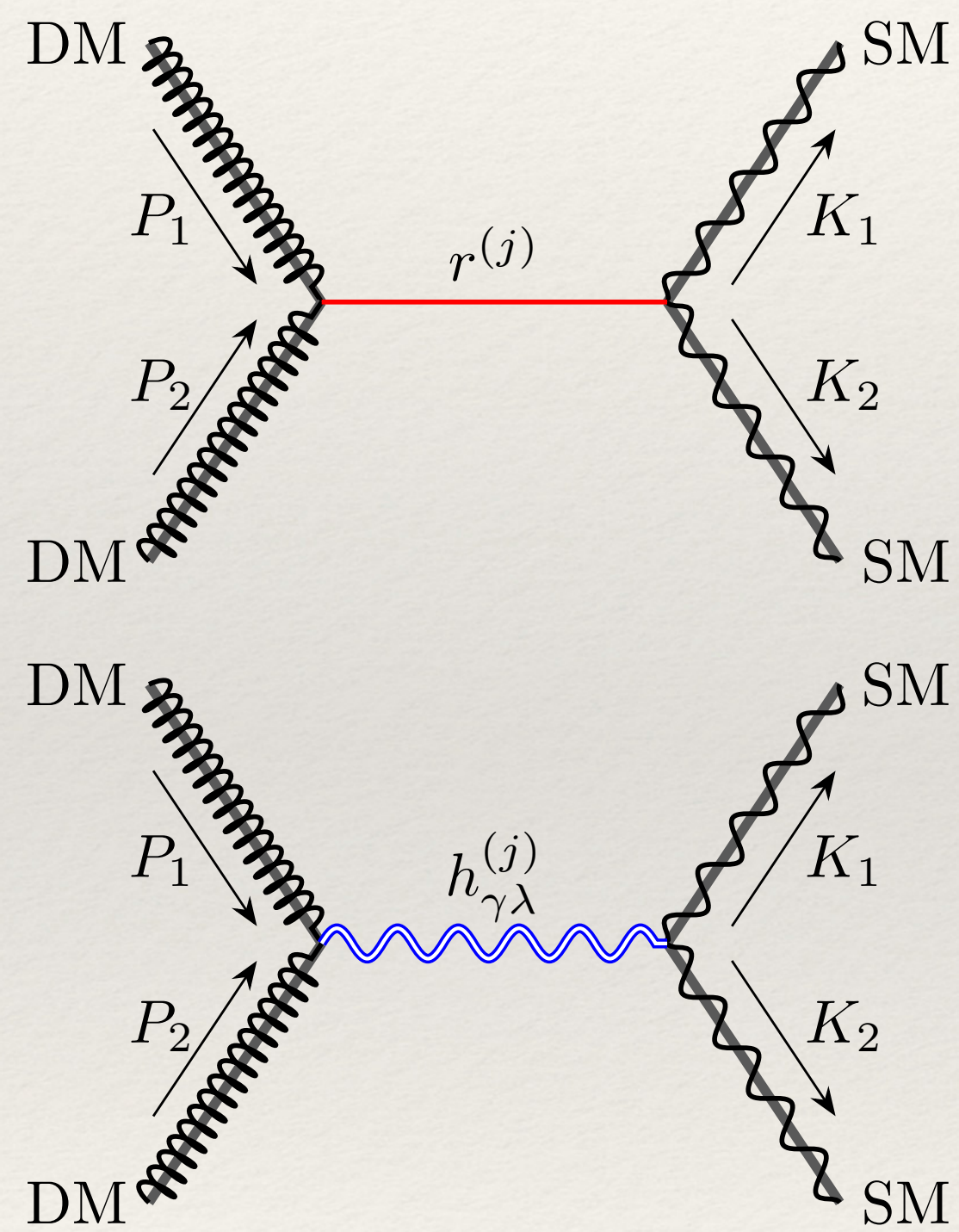
DM localised on TeV brane - interacts gravitationally



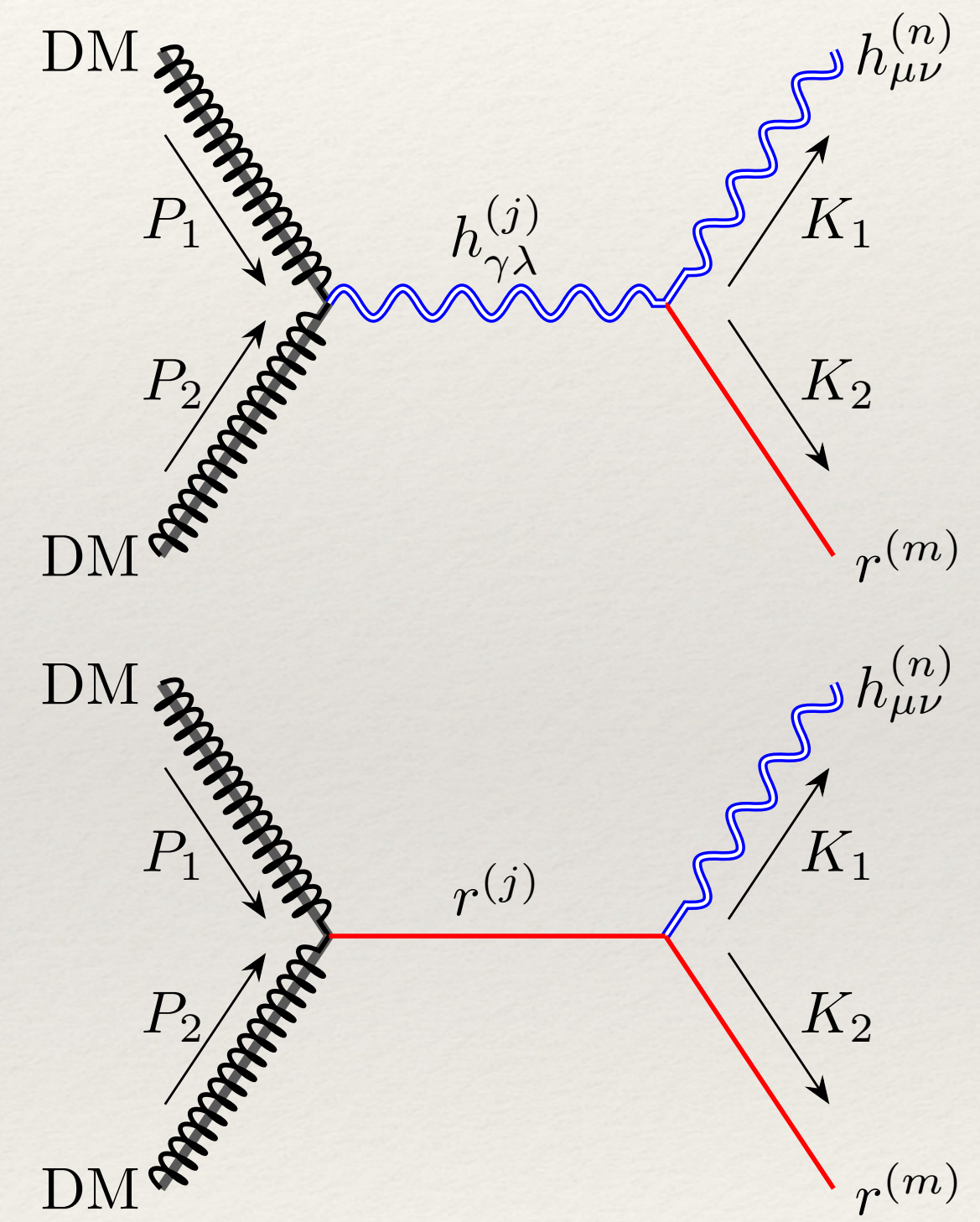
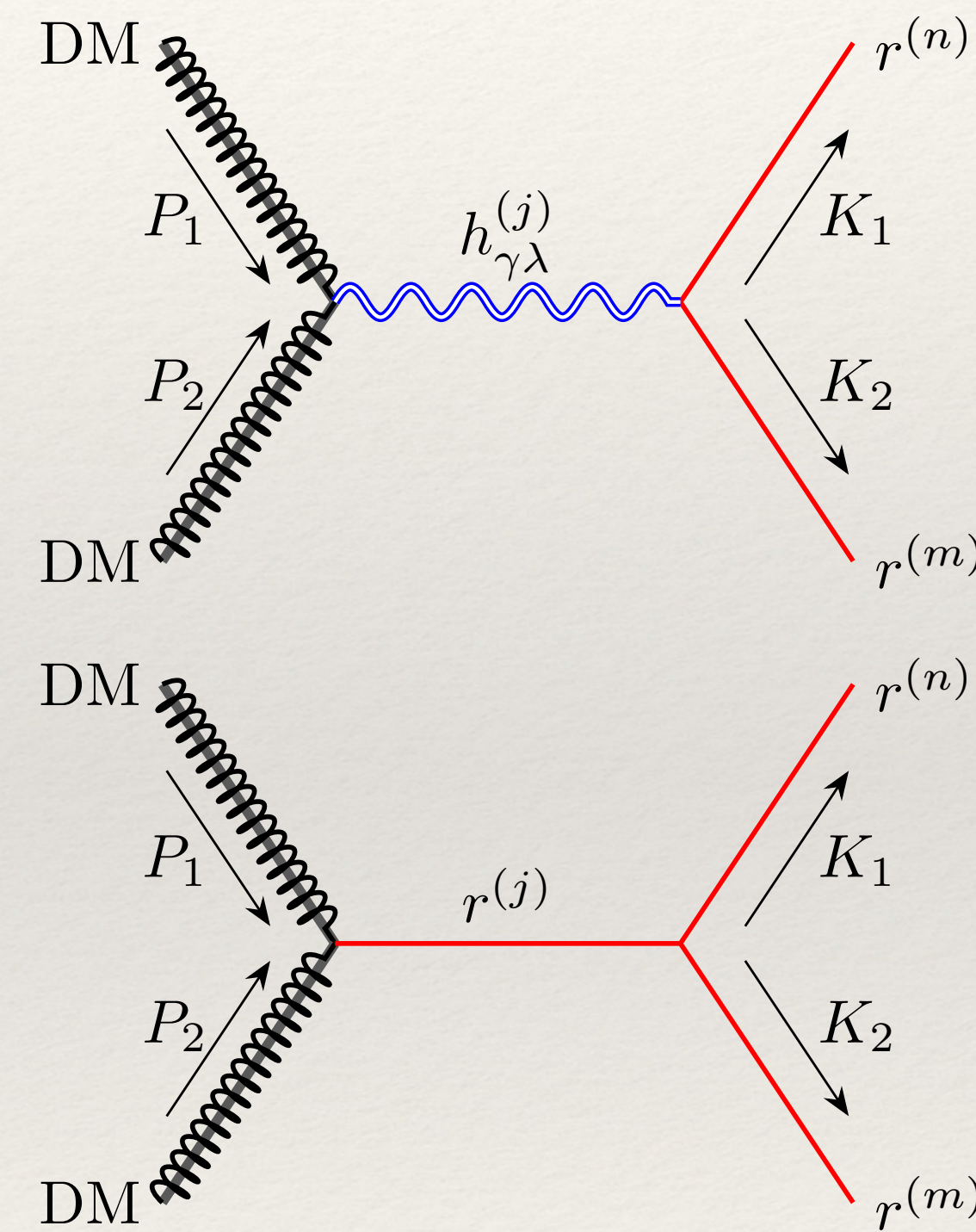
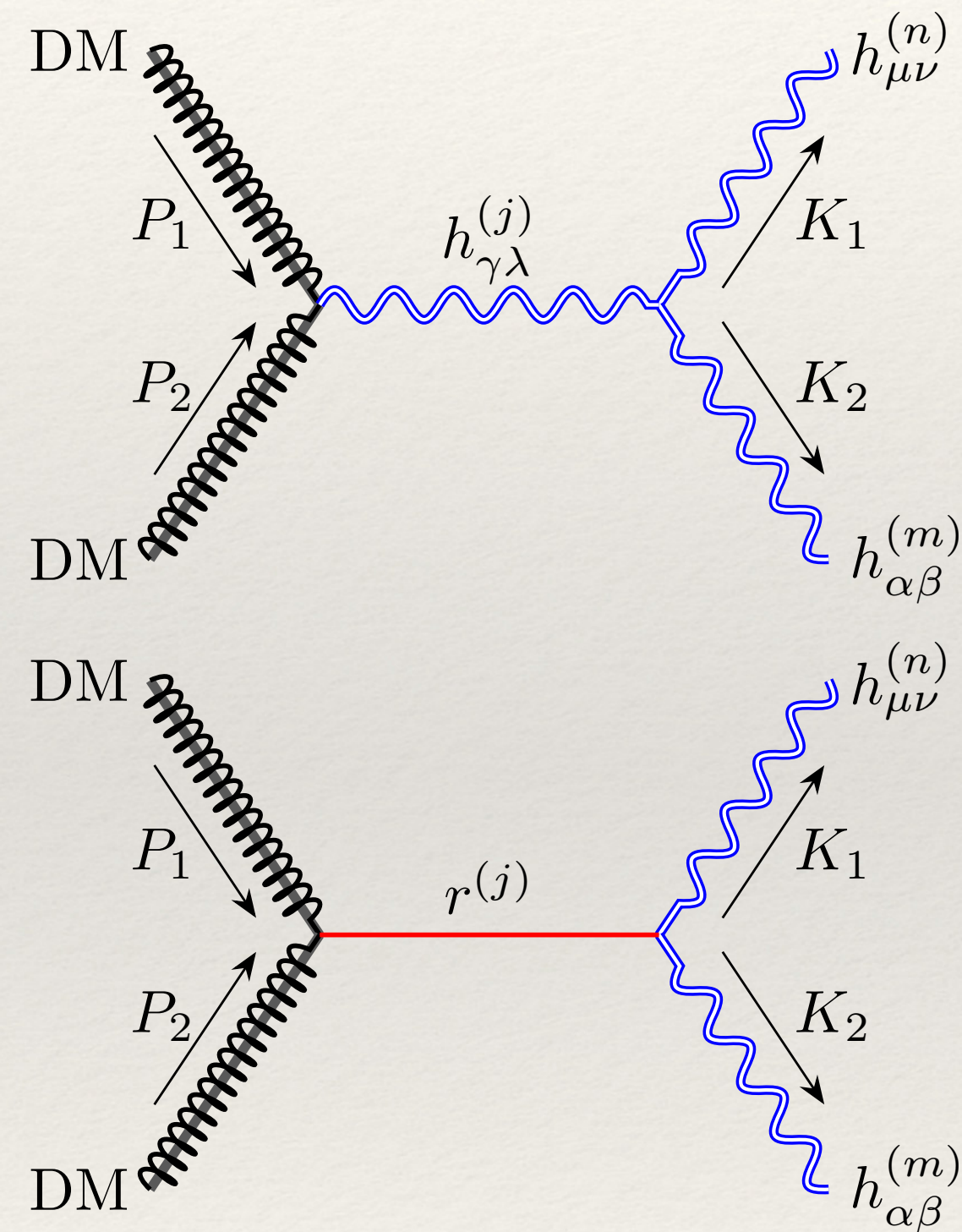
Corresponding t and u channels and subsequent decays to SM...

Gravitational Portal Phenomenology

DM localised on TeV brane - interacts gravitationally



Dominating process

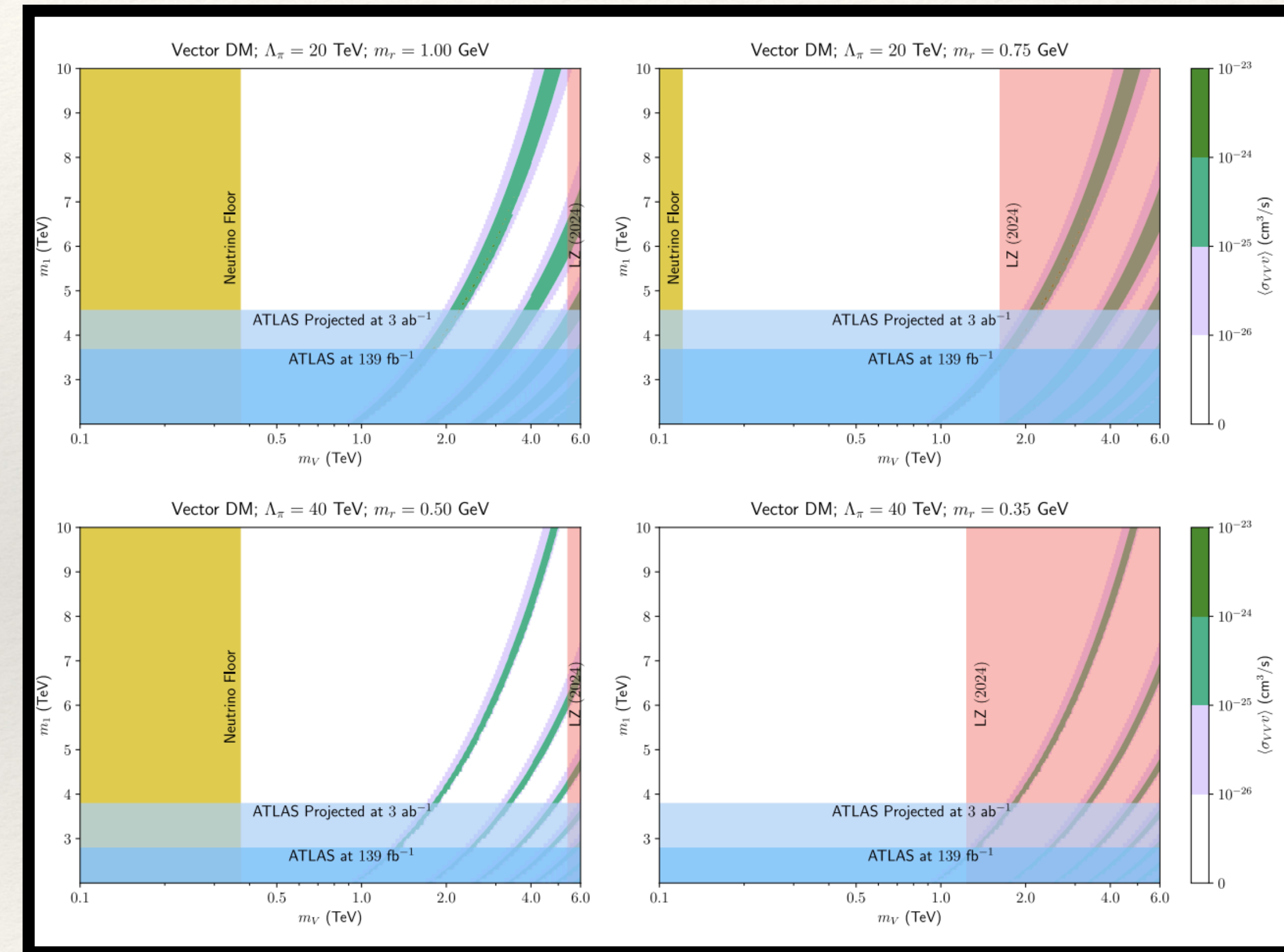


Corresponding t and u channels and subsequent decays to SM...

Light Radion Results

arXiv: 2411:02509

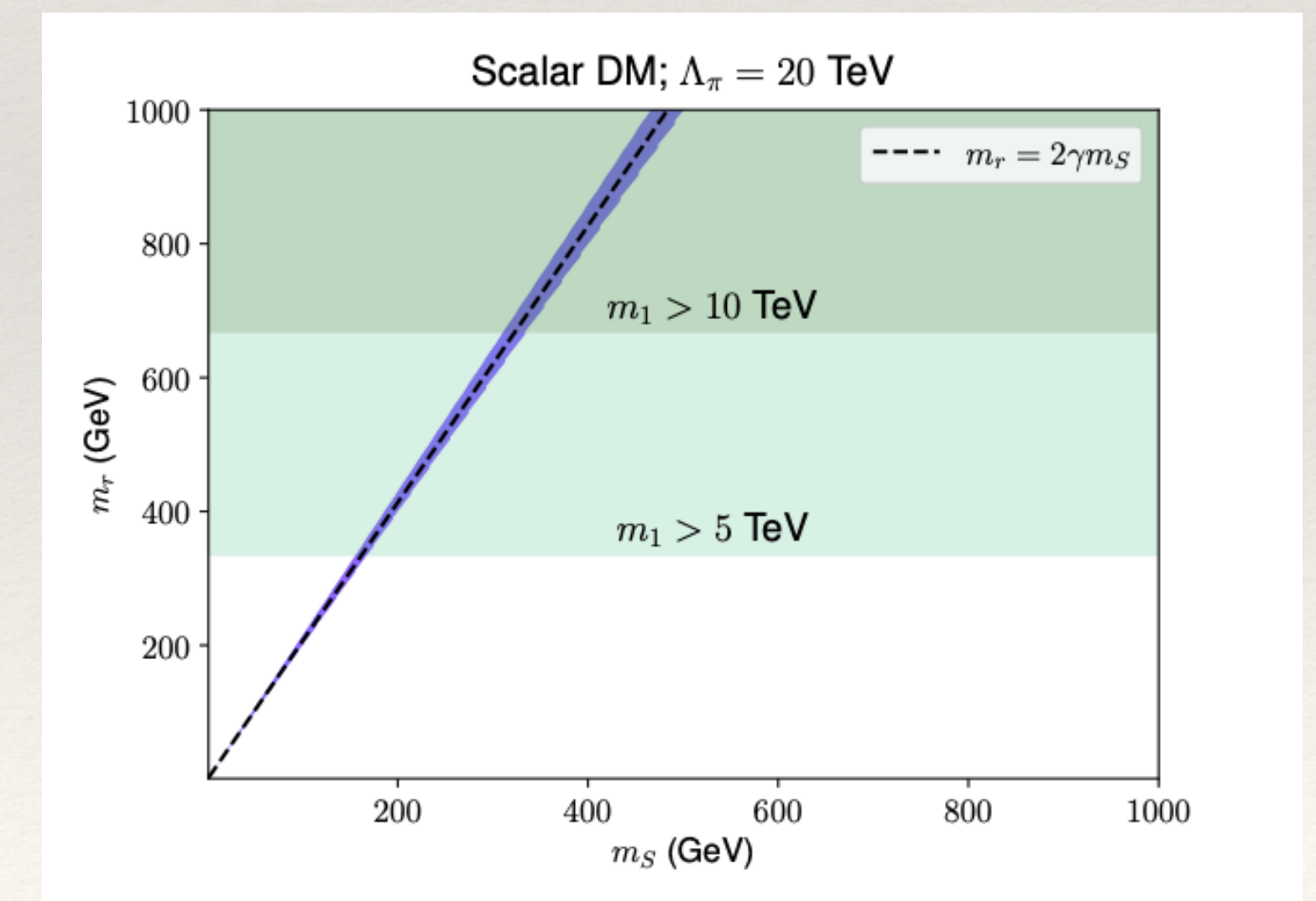
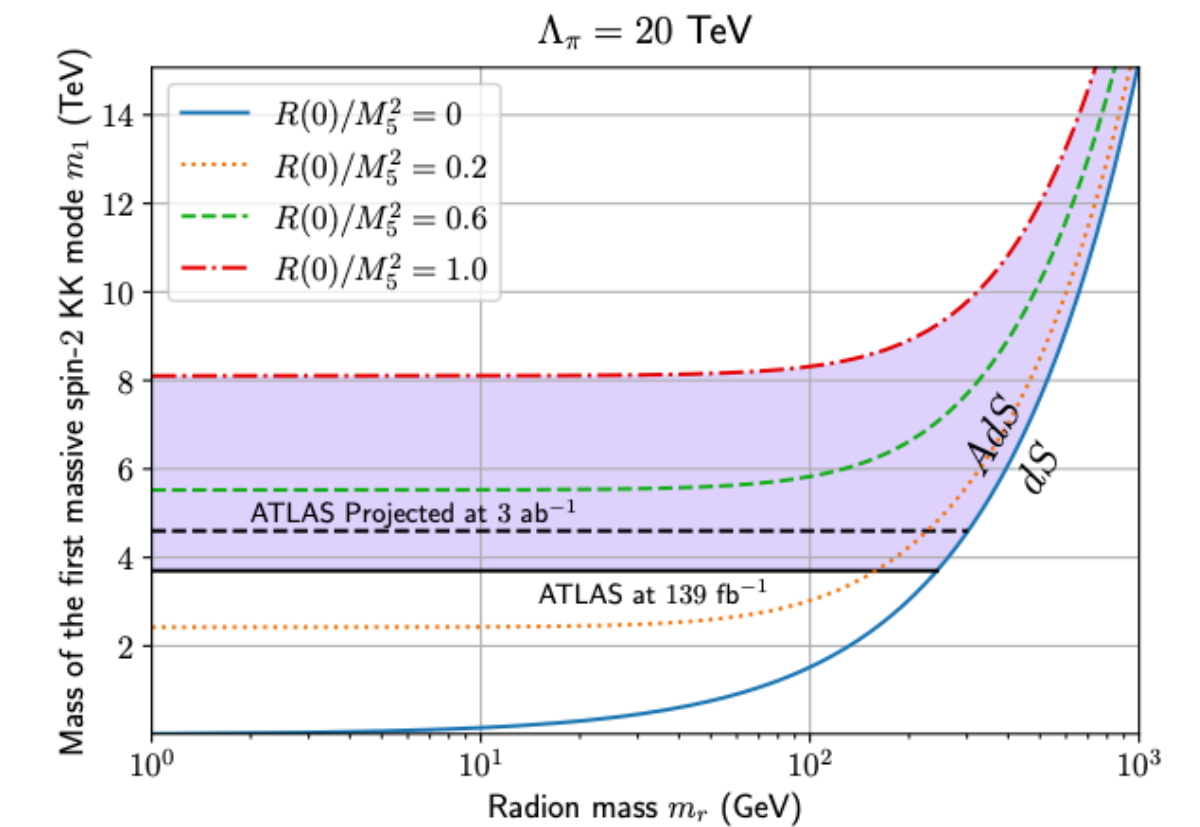
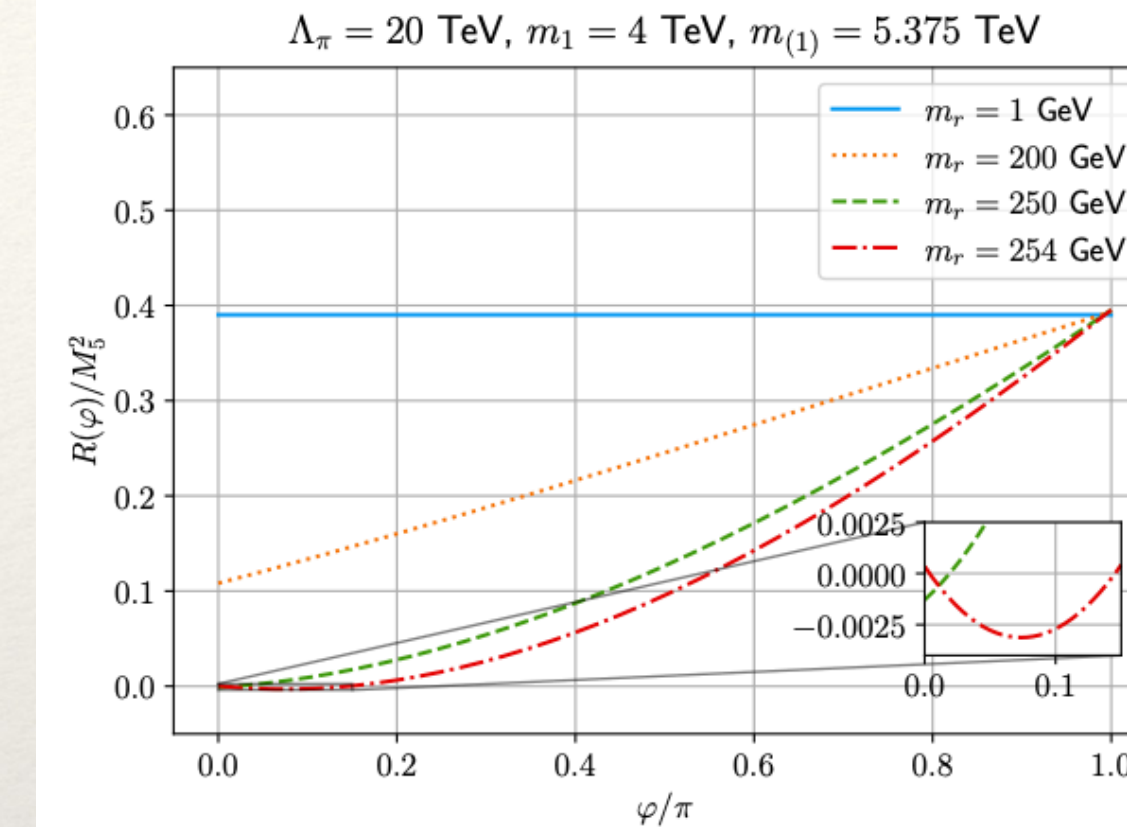
- ❖ Vector DM - viable gap in parameter space
- ❖ Lilac / green - equals / exceeds DM relic
- ❖ Stabilised geometry:
 - ❖ Bulk matter effects geometry
 - ❖ Small radion mass $m_r \sim \mathcal{O}(1 \text{ GeV})$
 - ❖ Low *backreaction*



Heavy Radion Results

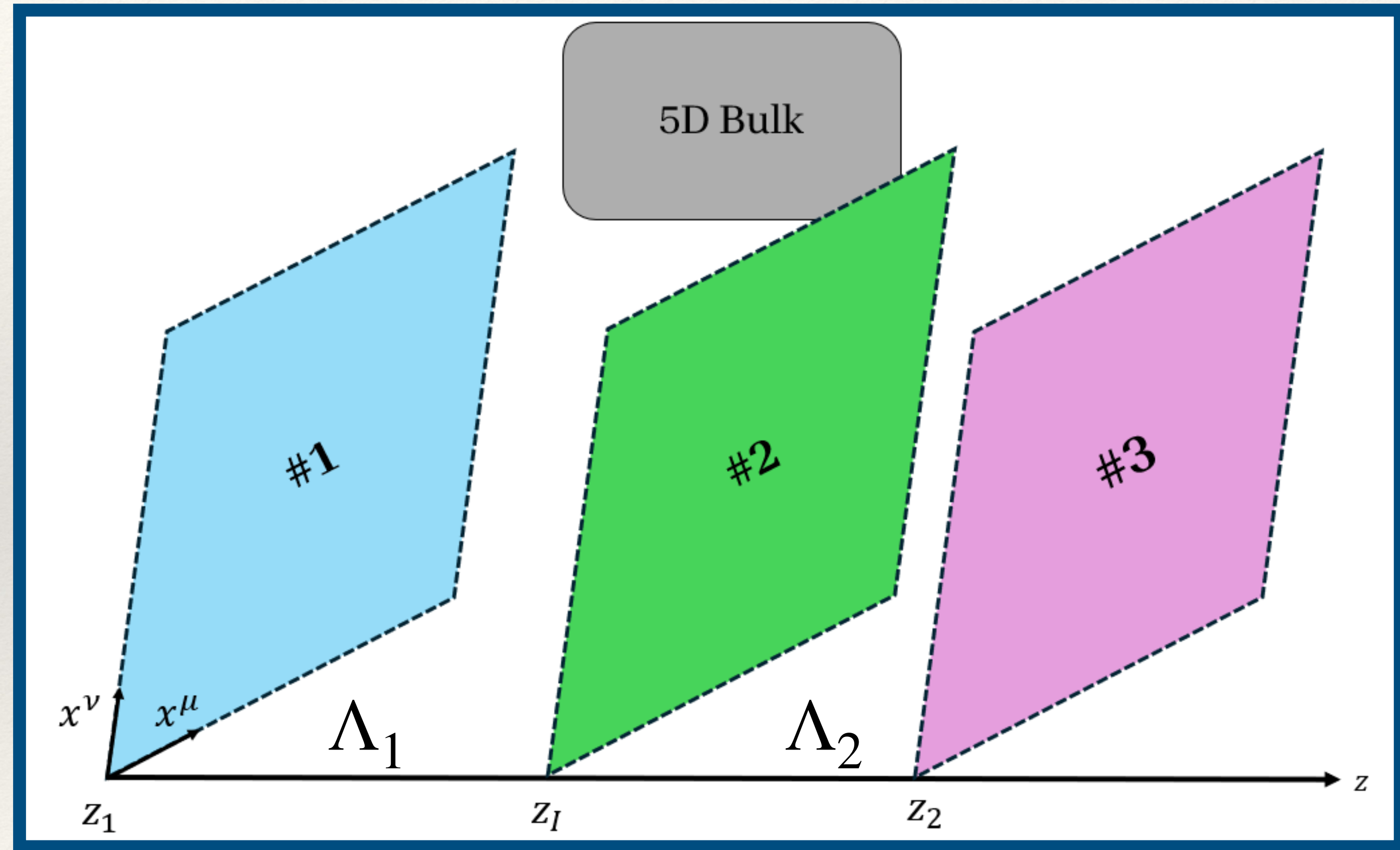
arXiv: 2507:21218

- ❖ Localise DM on TeV brane, but now large radion mass $m_r \sim \mathcal{O}(100 \text{ GeV})$
- ❖ Induces high *backreaction* to the geometry - injection of energy density
- ❖ Geometry AdS $\rightarrow$ dS: new constraint!
- ❖ Scalar / vector DM viable on resonance in a narrow band ($\Lambda = 20 \text{ TeV}$)
- ❖ DM annihilation to radion (decays to b -quarks) rules out $m_\chi \approx 5 - 80 \text{ GeV}$



Multibrane Extension - Preliminary**

- ❖ Introduce additional brane
- ❖ Two distinct $\Lambda_{1,2}$
- ❖ Positive definite wave functions require $\Lambda_2 > \Lambda_1$
- ❖ Mass spectrum is altered
- ❖ High-energy scaling $\mathcal{O}(s^2)$



Summary

- ❖ Dark matter exists - abundance of viable models
- ❖ Focusing on a Freeze Out mechanism (Freeze In - next talk by Amrita)
- ❖ Key issue is understanding leading order scattering behaviour
- ❖ Compactified and stabilised RS model
 - ❖ Introduces gravitational portal via KK radion mediators
- ❖ Small radion mass: resonant vector DM for may have eluded detection so far
- ❖ Large radion mass: introduces new constraint; resonant scalar / vector DM viable
- ❖ Preliminary: multibrane model could present so interesting phenomenology