Scattering Amplitudes of Massive Spin-2 Kaluza-Klein States with Matter

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Dark Matter Evidence

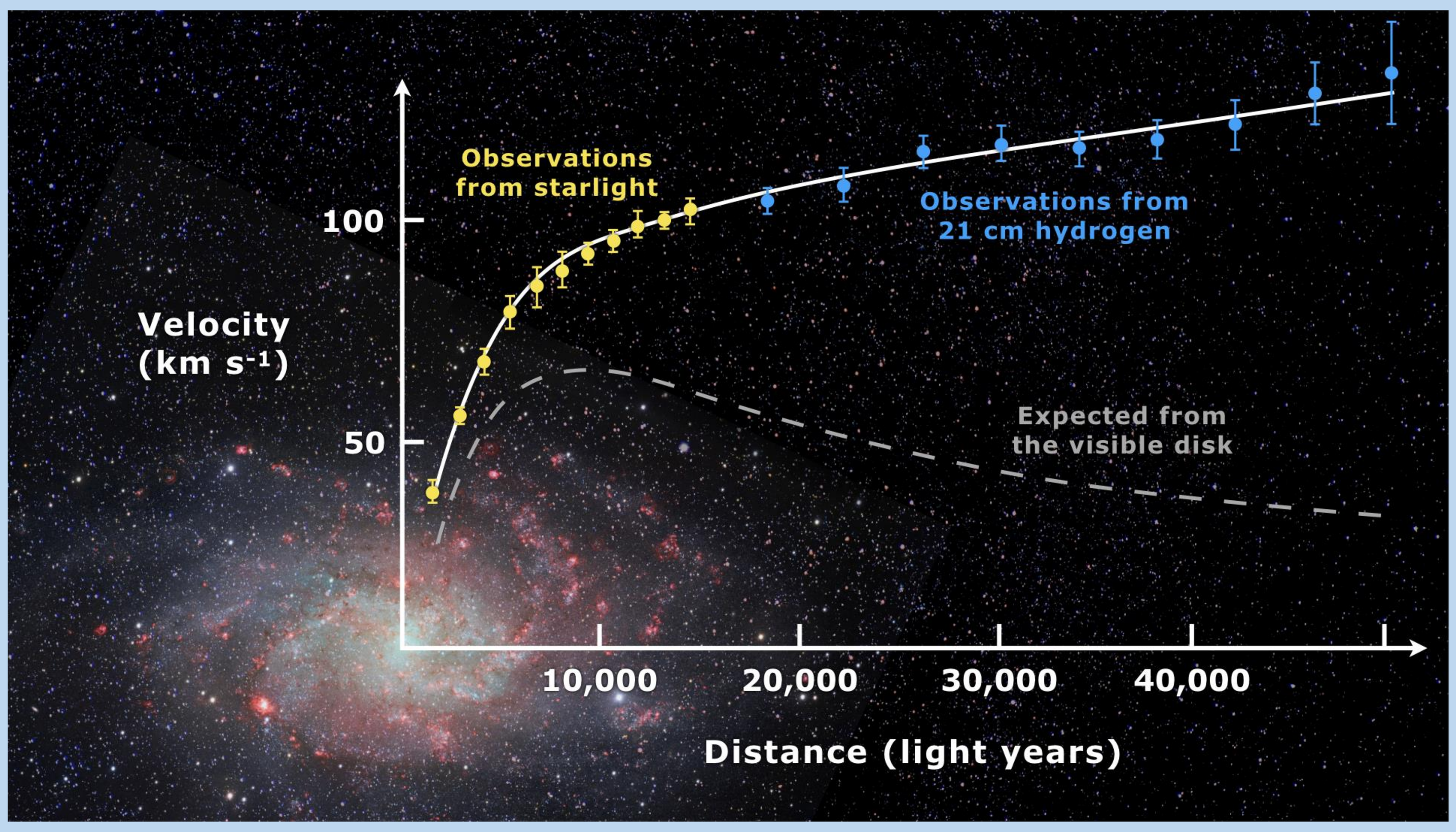


Image from De Leo [1], highlighting discrepancy in observed and expected galactic rotational curves.

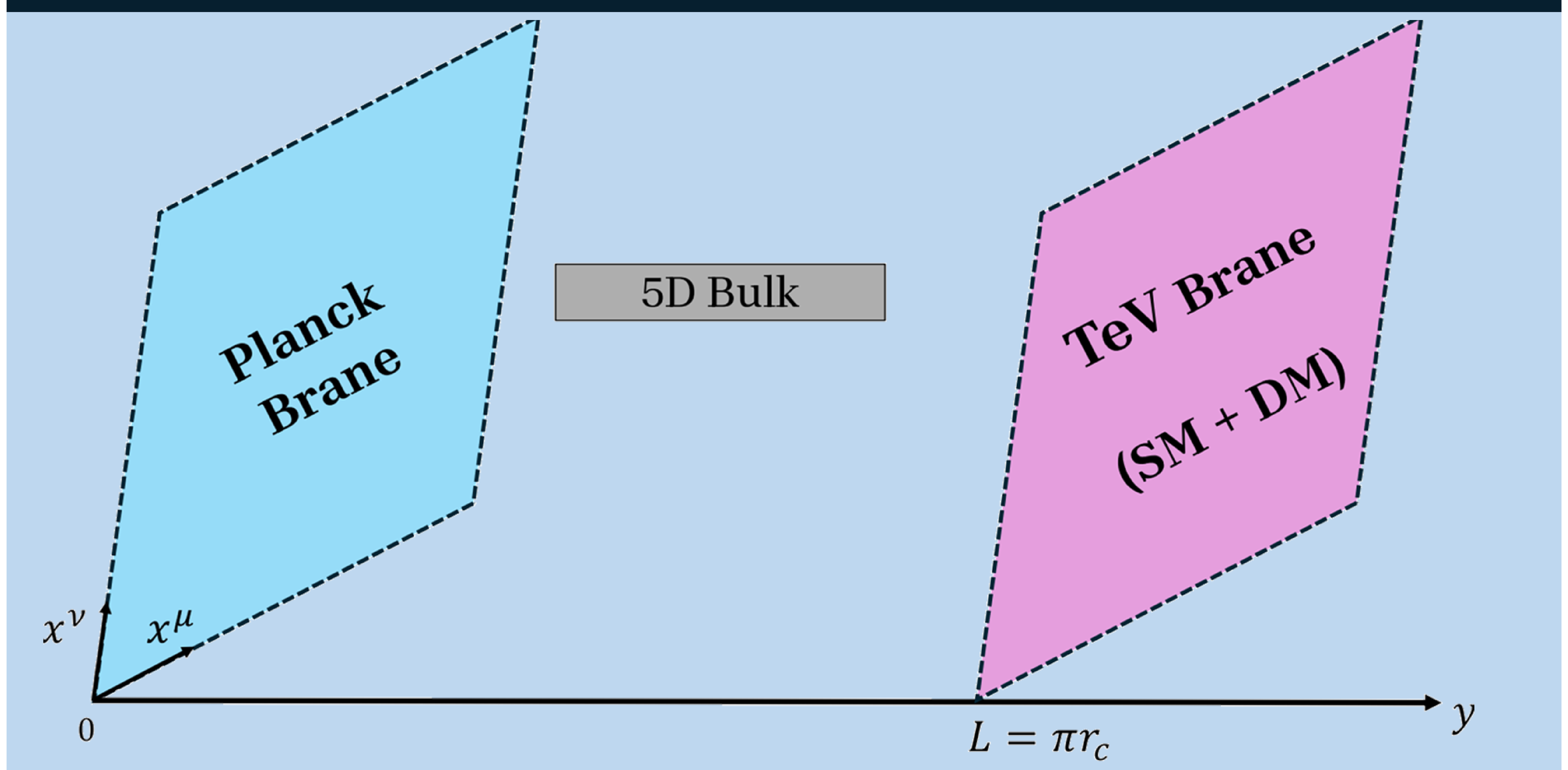
Compact Extra-Dimensions

- No Higgs mechanism for spin-2 fields - look to extra-dimensions for equivalent mechanism and hierarchy solution.
- 4D coordinate x, additional coordinate y, expansion parameter κ_5.
- Weak field expansion $G_{AB} = \eta_{AB} + \kappa_5 \hat{h}_{AB}$.
- Assume KK decomposition of wavefunctions - ψ_n is extra-dim profile of mode:

$$\hat{\phi}(x,y) \sim \sum_n \phi_n(x)\psi_n(y).$$

- The ψ_n satisfy Sturm-Liouville equation - generates **discrete mass spectrum without breaking coordinate invariance!**
- Particle coupling ∝ overlap integral of profiles ψ_n.
- Need appropriate boundary conditions - Randall-Sundrum 1 (RS1) Model [2,3].

Randall-Sundrum 1 Model



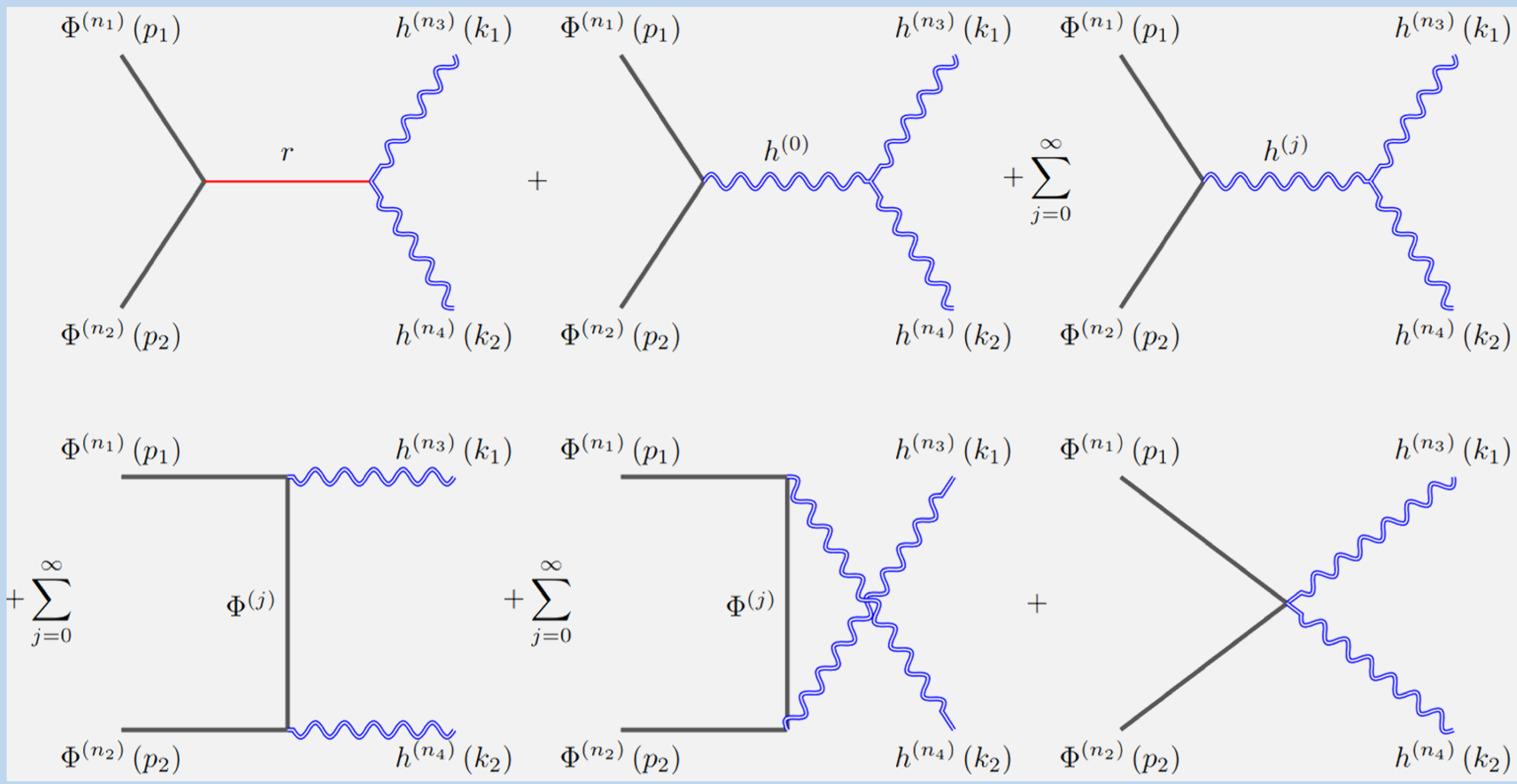
- Two 4D spacetime slices (branes) at $y = 0$ (Planck) and $y = L = \pi r_c$ (TeV).
- Warped geometries described by below metric, with warping k and fluctuations $\hat{h}_{\mu\nu}$ (Spin-2) and $\hat{r}$ (Spin-0 / Radion):

$$G_{AB} = \begin{pmatrix} e^{-2(k|y|+\hat{u})}(\eta_{\mu\nu} + \kappa_5 \hat{h}_{\mu\nu}) & 0 \\ 0 & -(1+2\hat{u})^2 \end{pmatrix}, \qquad \hat{u} = \frac{\kappa_5 \hat{r}}{2\sqrt{6}} e^{k(2|y|-L)}.$$

- A **natural solution** to electroweak hierarchy problem.
  - Planck Higgs VEV **exponentially warped down** compared to TeV Higgs VEV.
  - Effective 4D gravitational coupling **minimally altered**:

$$\langle \Phi \rangle_{\text{TeV}} = e^{-kL} \langle \Phi \rangle_{\text{Pl}} \qquad \kappa_4^2 = \left(\frac{k}{1 - e^{-2kL}}\right)\kappa_5^2.$$

Matter Calculation



All annihilation processes of bulk and brane-localised DM candidates $\Phi = S, \psi, V$ (Scalar, Fermion and Vector) to external spin-2 modes (h).

- **Testing for unitarity – expect no additional scale dependence in amplitudes.**
- Unitarity requires high energy amplitudes grow ∝ $s\kappa_4^2 = E^2/\Lambda^2$, where Λ is the effective cutoff energy.
- In full extra-dimensional models, do **not** expect additional scales due to higher dimensional **diffeomorphism –** general coordinate invariance of General Relativity.
- Longitudinal modes of spin-2 fields naively generate the worst behaviour at E^2/m_n^2 per leg – we examine these modes in detail.

Results

Elastic Brane Localised (B-L) Matter Scattering ($n_3 = n_4 = n$)

B–L Scalar: $\mathcal{M} = -\dfrac{s\kappa_4^2(3\cos 2\theta + 1)}{96}\left[k^{(n)}(\bar{y})\right]^2 + \mathcal{O}(s^0).$

B–L Fermion: $\mathcal{M} = \dfrac{s\kappa_4^2 \sin 2\theta}{32}\left[k^{(n)}(\bar{y})\right]^2 + \mathcal{O}(s^0).$

B–L Vector: $\mathcal{M} = \dfrac{s\kappa_4^2(3\cos 2\theta + 1)}{96}\left[k^{(n)}(\bar{y})\right]^2.$

Elastic Bulk Matter Scattering ($\mathbf{n_1 = n_2 = m,\ \ n_3 = n_4 = n}$)

Bulk Scalar: $\mathcal{M} = \dfrac{s\kappa_4^2(1 - \cos 2\theta)}{32}\left\langle k^{(n)}k^{(n)}f_S^{(m)}f_S^{(m)}\right\rangle_S + \mathcal{O}(s^0).$

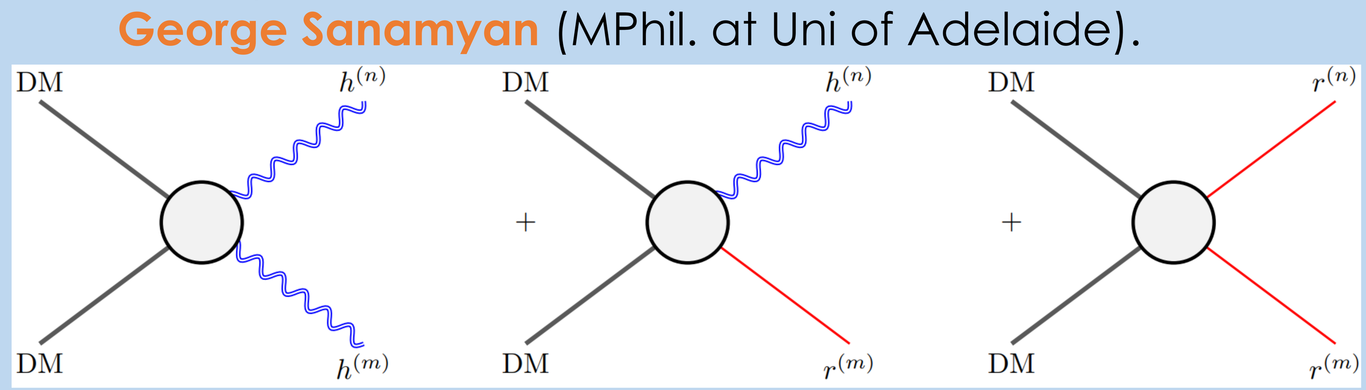
Bulk Fermion: $\mathcal{M} = \dfrac{s\kappa_4^2 \sin 2\theta}{32}\left\langle k^{(n)}k^{(n)}f_{\psi_{L/R}}^{(m)}f_{\psi_{L/R}}^{(m)}\right\rangle_\psi + \mathcal{O}(s^0).$

Bulk Vector: $\mathcal{M} = \dfrac{s\kappa_4(3\cos 2\theta + 1)}{96}\left\langle k^{(n)}k^{(n)}f_V^{(m)}f_V^{(m)}\right\rangle_V + \mathcal{O}(s^0).$

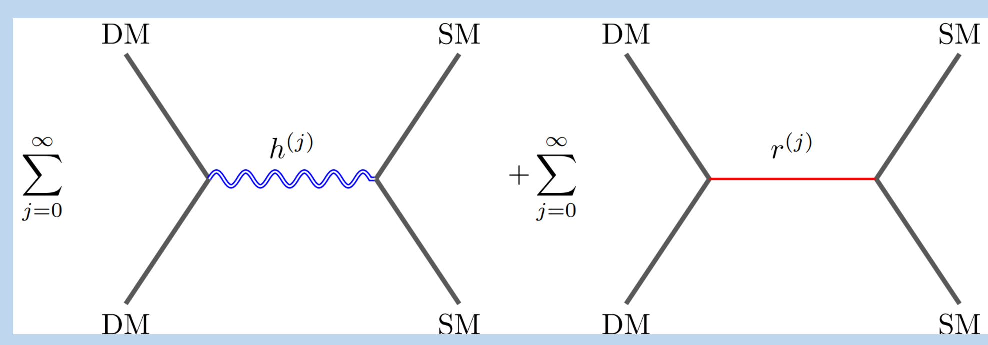
Amplitudes grow ∝ $s\kappa_4^2$ and external spin-2 modes behave as scalar fields $k^{(n)}$.
→ Goldstone Equivalence Theorem verification (see Phys. Rev. D 109, 075016)!

Future Work

- Radion field introduces **long-range force → branes can collapse.**
- Introduce **bulk scalar** field to stabilise geometry.
  - Mixes with radion → creates massive KK tower (**Goldberger-Wise GW** [3]).
- Test unitarity for external Goldberger-Wise states included.
  - Scanning parameter space to find DM family which saturates the relic density – **Results to be released shortly** in collaboration with **George Sanamyan** (MPhil. at Uni of Adelaide).



New GW states included – update unitarity results.



KK portal to produce SM in stabilised geometry.

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