Warped Radion Dark Matter

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Motivation

- The possible link between dark matter (DM) and particle physics phenomena at the TeV scale has prompted many models with a suitable DM candidate in the TeV mass range such as Supersymmetry with R-parity, little Higgs with T-parity among others.
- In extra dimensional theories the best known example of a theory that naturally provides a DM candidate is Universal Extra Dimensions UED (Appelquist, Cheng and Dobrescu, 2001).
- We seek to construct a minimal scenario that combines the "nice" features of UED and Randall-Sundrum RS (Randall and Sundrum, 1999).
- We study a Z_2 warped geometry, addressing the stabilization of the extra dimension.
- We stabilize the extra dimension by dynamically generating a mass for the lightest radion even state (KK-radion tower) and we identify the lightest odd KK radion mode as our DM candidate, with a mass parametrically smaller than the KK scale.

Backgrounds with Z_2 Symmetry

- Consider a 5D real scalar Φ minimally coupled to gravity,
- Interest in the stabilization of the extra dimension leading to a symmetric background about $y = 0$, $y \in [-L, L]$.
- Solve the coupled gravity/scalar system taking into account the backreaction of the scalar VEV on the geometry (generate a mass for the zero mode radion).
- Restrict to backgrounds with 4D Lorentz symmetry,

$$ds^2 = e^{-2A(y)}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2 , \tag{1}$$

- An approximate solution is given by (IR-UV-IR)

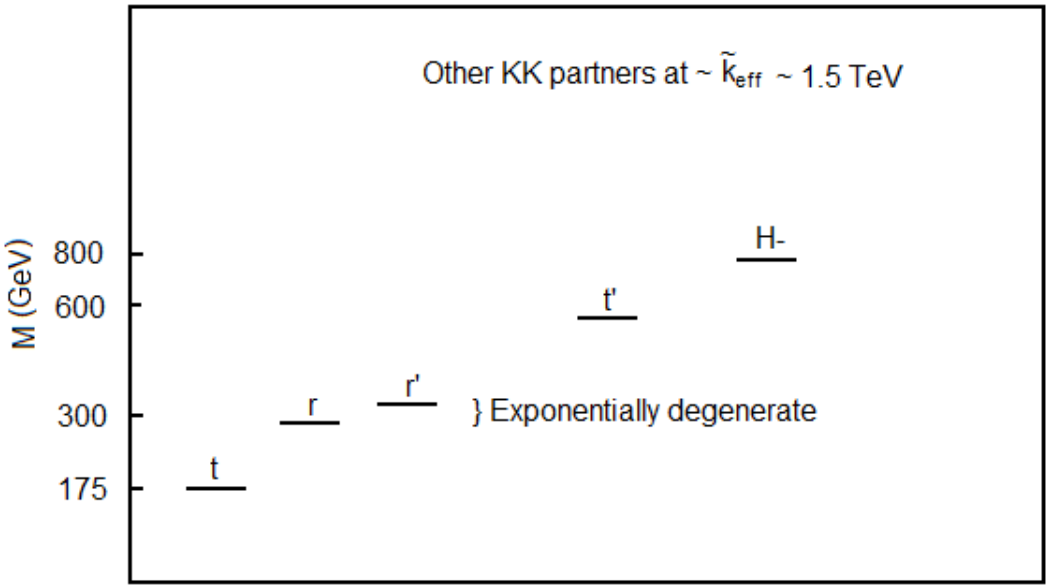
$$\phi(y)/\phi_0 \approx s_\phi y/L , \qquad A(y) \approx s_A k y^2/(2L) = k_{eff} y^2/(2L) , \tag{2}$$

- For the radion we find that its profile is given by $F_0 \approx e^{2(A(y)-A(L))}$, and that its mass scales as,

$$m_0 \approx \frac{2}{\sqrt{k_{eff} L}} k_{eff}\, e^{-A(L)} \approx 0.25\, \tilde{k}_{eff} , \tag{3}$$

- Profiles that are localized near the IR branes have exponentially degenerate mass for odd and even modes.

- Typical spectrum in this kind of scenario.



The KK-Radion as a WIMP

- Radion interactions are non-renormalizable and controlled by the decay constant $\Lambda_r = \sqrt{\frac{3M_5^3}{k_{\rm eff}^3}} \times \tilde{k}_{\rm eff}$.
- $\therefore$ Allows to interpolate between RS-like "strong warping" scenarios (when $k_{\rm eff} \sim M_5$) and "UED-like" scenarios (when $k_{\rm eff} \ll M_5$).
- In the strong warping scenario, KK-radions can annihilate into SM fermion (mainly top) pairs and Higgses (annihilation into massless gauge bosons is suppressed),

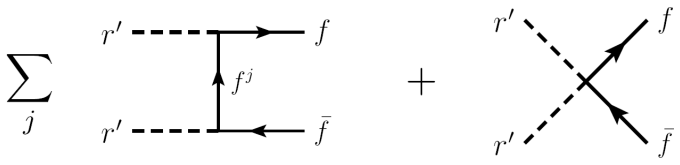
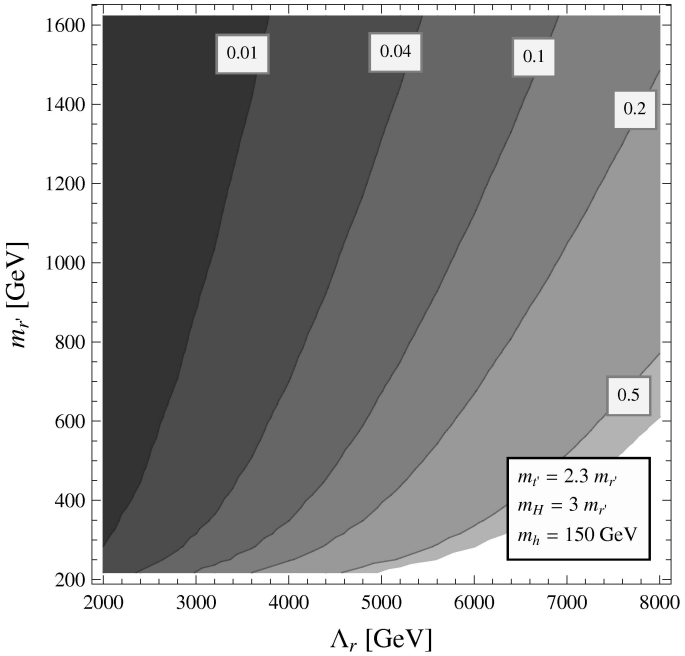


Figure: Annihilation into fermions

Figure: Annihilation into Higgs and longitudinal gauge bosons

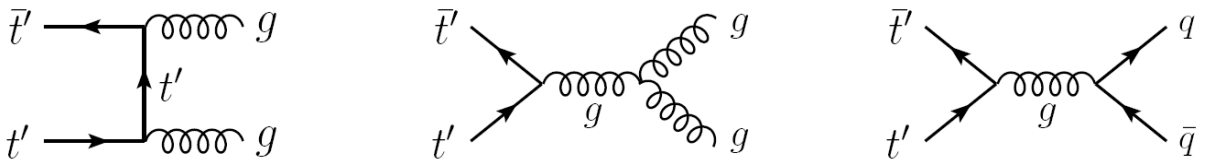
- Contours of constant $\Omega_{r'} h^2$ in the $m_{r'}$-Λ_r plane



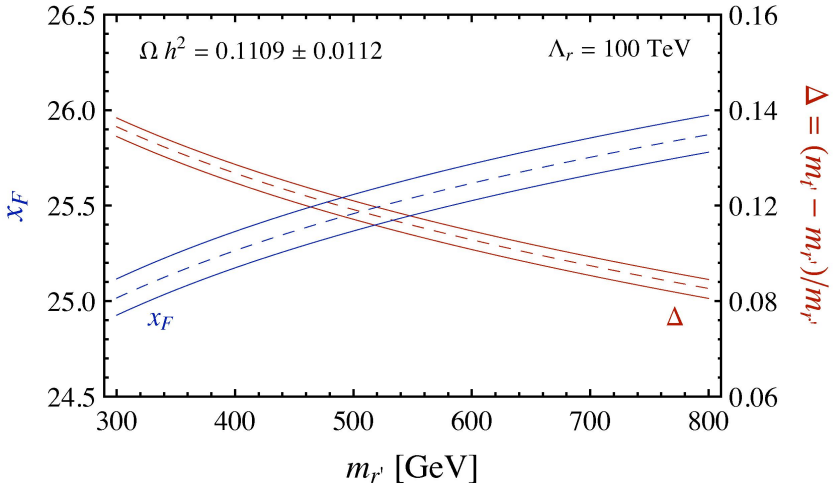
- Correct relic density of $\Omega_{r'} h^2 \approx 0.1$ can be obtained for natural values of the parameters ($\Lambda_r \approx 3.5$ TeV, $m_{r'} \approx 300$ GeV).

Coannihilations with t'

- If $\Lambda_r \sim 100$ TeV and $m_{t'} \gtrsim m_{r'}$, coannihilations with the strongly interacting t' can become dominant and the $\Omega_r h^2$ can be completely controlled by QCD.



- WMAP constraint on the degree of degeneracy, $\Delta = (m_{t'} - m_{r'})/m_{r'}$ as a function of $m_{r'}$



KK-Radion as a Non-Thermal Relic

- Situation arises when $\Lambda_r \gg k_{eff}$ (superweak radion coupling).
- Assume that $T_R \lesssim T_c \approx 1$ TeV, with T_c the critical temperature for the deconfinement/confinement phase transition. Otherwise, the universe trapped eternally in the false vacuum.
- Production channels from scattering and decays: $gq^j \to r' q^k$, $f^j \to r' f^k$, $V_\mu^{j,a} \to r' V_\nu^{k,b}$

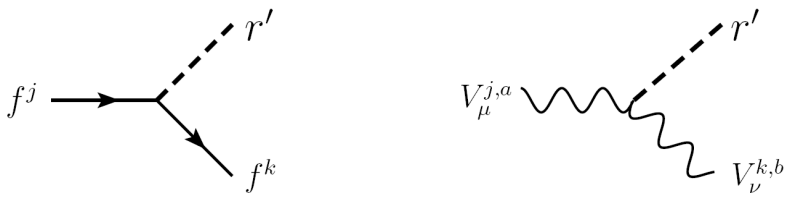


Figure: Production through decays

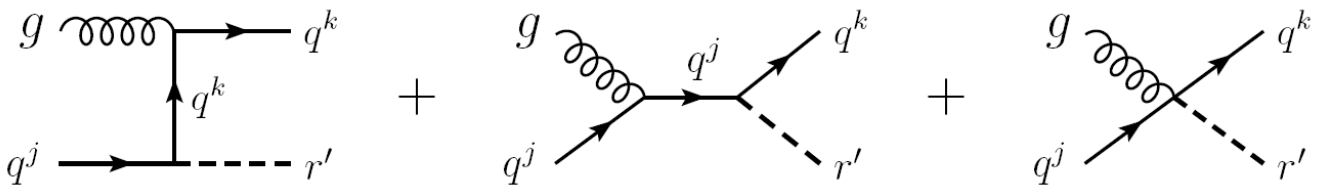
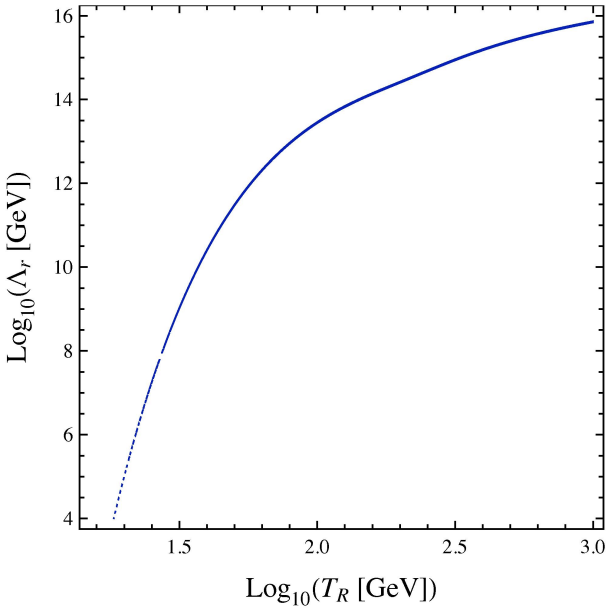


Figure: Production through scattering

- Decays are the dominant production mechanism. We study formally up to $T_R \sim 10 k_{eff}$ (4D cut-off of KK-theory).



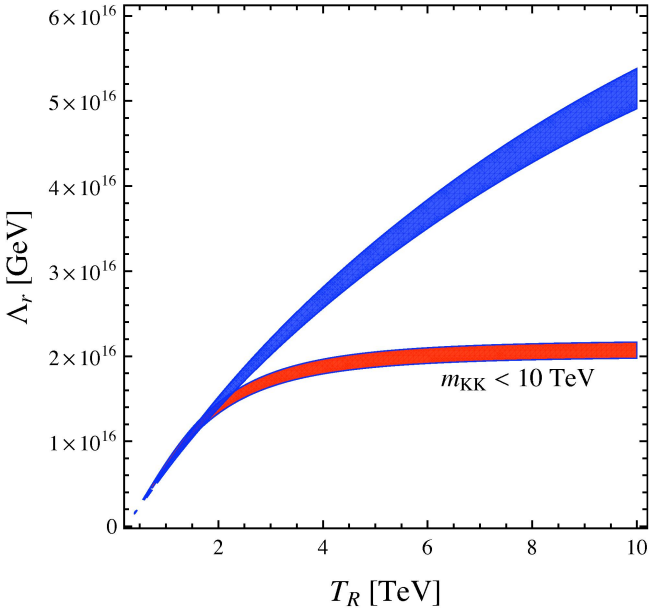


Figure: WMAP constraint in the Λ_R-T_R plane in Log scale. Figure: WMAP constraint in the Λ_R-T_R up to $T_R = 10$ TeV

- BBN constraints are satisfied as long as $T_R \lesssim$ few hundred GeV.

t' lifetime and yield

- Large value of $\Lambda_r \rightarrow$ t' is long-lived.
- If $m_{t'} > m_{r'} + m_t$, t' decays as $t' \rightarrow r' t$

$$\Gamma_{t'} = \frac{G^2 m_{t'}^3}{16\pi\Lambda_r^2}\sqrt{\left[1-\left(\frac{m_t}{m_{t'}}+\frac{m_{r'}}{m_{t'}}\right)^2\right]\left[1-\left(\frac{m_t}{m_{t'}}-\frac{m_{r'}}{m_{t'}}\right)^2\right]}, \quad (4)$$

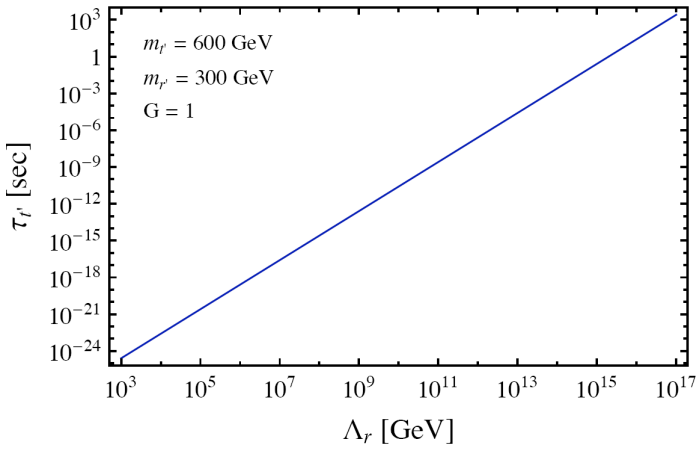


Figure: t'-lifetime vs Λ_r for $m_{t'} = 600$ GeV, $m_{r'} = 300$ GeV and $G = 1$.

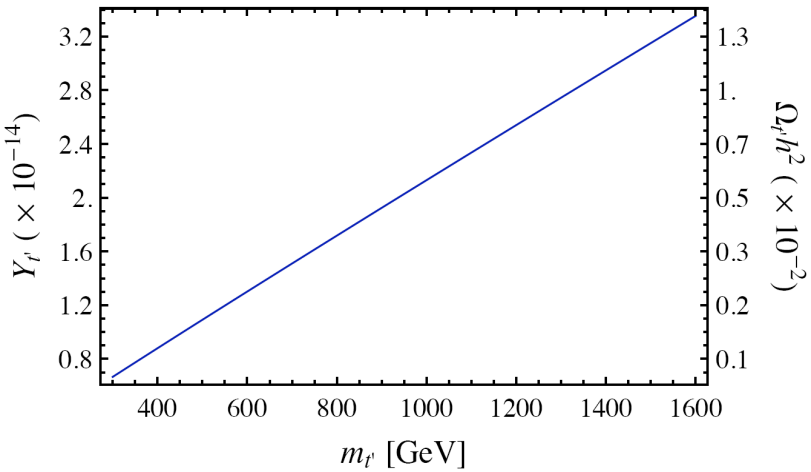


Figure: t' yield, $Y_{t'}(x_F)$, as a function of $m_{t'}$.

- If t'-decay time 10^{-2} s $< t < 10^4$ s, hadron scattering off background protons and neutrons $\rightarrow$ dangerous interconversion.
- Upper bound on Λ_r via the t' decay width,

$m_{t'}$ [GeV]	500	800	1000	1200
Λ_r [GeV] $\lesssim$	2×10^{16}	5×10^{16}	7×10^{16}	10^{17}

- Stronger constraint from late radion decays. $r \rightarrow W^+W^-, ZZ, h_+h_+$.
- Radion yield $Y_r \approx \Omega_{r'}\rho_c/(s_0 m_{r'})$ and radion lifetime

$$\tau_r \approx \left[\frac{m_r^3}{8\pi\Lambda_r^2}\right]^{-1} \approx 0.1 \times \left(\frac{\Lambda_r}{10^{15}\ \mathrm{GeV}}\right)^2 \left(\frac{500\ \mathrm{GeV}}{m_{r'}}\right)^3 \ \mathrm{sec}\ . \qquad (5)$$

- For $m_r \approx m_{r'} = 500$ GeV and $Y_r \approx 7 \times 10^{-13}$, $\tau_r \leq 0.5$ s, $\rightarrow T_R \lesssim$ few hundred GeV.

Direct Detection

- Consider brane Higgs-Radion mixing term, $\frac{1}{2}\left[\delta(y-L)+\delta(y+L)\right]\sqrt{g_{\rm ind}}\,\xi\mathcal{R}_4 H^\dagger H$.
- Interactions relevant for scattering of DM against nuclei are $r_-\,h_+h_-$ and $r_+\,h_-h_-$.

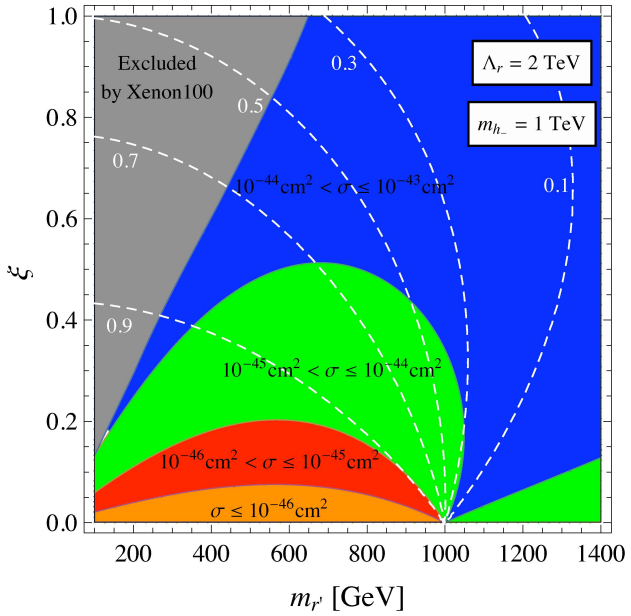


Figure: Contours of constant $\sigma_{\phi_{\rm DM}N\to\phi_{\rm DM}N}$ in the ξ–m_{r_-} plane for $\Lambda_r = 2$ TeV

- There is a region where the DM is mostly r_-, with a sizable nucleon cross section (below the dashed line of $|U_{r_-,L}|^2 = 0.9$).

Indirect detection

- Focus on the photon flux from KK-radion annihilations (other signals are small).
- Consider the brane localized operator $[\delta(y+L)+\delta(y-L)]\sqrt{g_{\rm ind}}(\eta/8\Lambda_5^3)K^2F_{\mu\nu}F^{\mu\nu}$, where Λ_5 is the 5D cutoff and K is the trace of the extrinsic curvature.
- Reduction to 4D leads to $-\frac{e^2\kappa}{8\Lambda_r^2}\,r'^2F_{\mu\nu}F^{\mu\nu}$ with $e^2\kappa \approx 64\eta/(k_{\rm eff}L)\times(k_{\rm eff}/\Lambda_5)^3$, with η as large as $3/2\pi$.

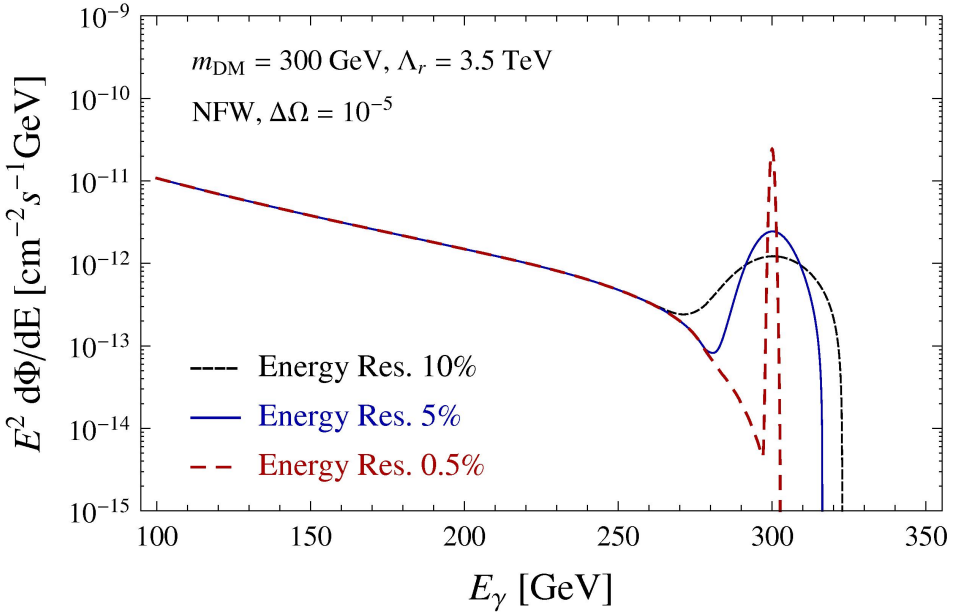


Figure: Continuum photon flux and 2γ-line signal from KK-radion annihilation at the center of the galaxy. For the line signal, we show three detector energy resolutions: 10% (black line),

Conclusions

- We discussed a novel scenario where the warped geometry provides the symmetry for a suitable dark matter candidate which we identify after stabilization of the extra dimension with lightest odd radion mode (the LKP).
- Depending on the value of the decay constant Λ_r, standard freeze out DM ($\Lambda_r \approx 2$ TeV), coannihilation ($\Lambda_r \approx 10 - 100$ TeV or non-thermal ($\Lambda_r \gg 100$ TeV) scenarios arise.
- In the presence of mixing with the Higgs sector $\rightarrow$ possible direct detection signals.
- In the Superweakly interacting particle scenario BBN constraints safely satisfied for low reheating temperatures, $T_R \lesssim 500$ GeV.
- Indirect detection signals that may be probed by FERMI-LAT.