Warped Universal Extra Dimensions

Anibal D. Medina [1]

[1] Department of Physics
University of California Davis

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Outline

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Motivation

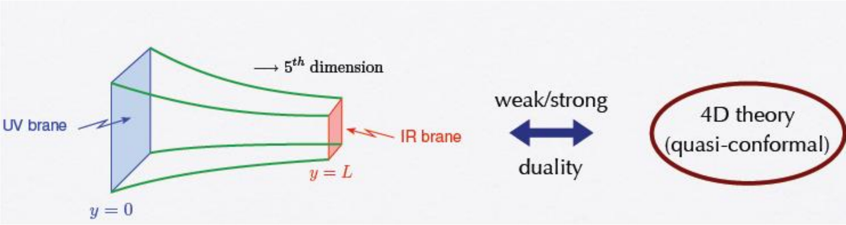
- THE LHC ERA HAS STARTED! Finally we are here and we have high expectations it will discover new phenomena which will revolutionize our understanding of physics.
- The possible link between dark matter (DM) and particle physics phenomena at the TeV scale has prompted many models with a suitable DM candidate 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 are Universal Extra Dimensions (UED).

General Features of Universal Extra Dimensions (UED)

- UED: 5D model with all particles propagating in a flat extra dimension (Appelquist, Cheng and Dobrescu, Phys. Rev. D **64**, 035002 (2001)).
- Standard Model (SM) fields are identified as the zero modes of 5D fields.
- Compactifying on $S^1/Z_2 \Rightarrow Z_2$ parity (KK parity and KK number, residual symmetries from 5D momentum conservation) is preserved $\Rightarrow$ KK particles are pair produced and there is a stable lightest KK particle (LKP).
- At tree level, UED has only two undetermined parameters, the Higgs mass m_h and the compactification scale R^{-1} .
- Does not address the hierarchy problem, Electroweak symmetry break (EWSB) or the fermion mass hierarchy.

Warped Extra Dimensions

- Very versatile model that has prompted many interesting ideas given its simplicity(Randall and Sundrum Phys. Rev. Lett. **83**, 3370 (1999)).
- Solves the hierarchy problem using the space-time geometry by means of localizing the Higgs field near the IR brane.
- When Standard Model fields in the bulk → generate fermion masses by localization in the extra dimension (explains fermion mass hierarchies).
- AdS/CFT correspondence relates the 5D setup to a 4D conformal theory.
- Unless new symmetries and extended gauge sectors are included (Agashe and Servant, Phys. Rev. Lett. **93**, 231805 (2004)), no natural symmetry is present to provide for a dark matter candidate.



- Another attempt consists of a 3-brane setup to generate a geometric Z_2 parity (Agasheet et al. JHEP **0804**, 027 (2008)).
- Stabilization of the extra dimension was not address in such setup and large IR brane localized terms are needed to separate the masses of KK even and odd gauge bosons.
- In the spirit of this last work, we study a Z_2 warped geometry, addressing the stabilization of the extra dimension.
- We seek to construct a minimal scenario that combines the "nice" features of UED and RS.
- Through the stabilization mechanism, we dynamically generate a mass for the lightest radion even state and the lightest odd excitation of the radion field becomes our DM candidate, with a mass parametrically smaller than the KK scale.

Outline

Backgrounds with Z_2 Symmetry

- Consider a 5D real scalar Φ minimally coupled to gravity,

$$S = \int_M d^5x \sqrt{g} \left[-\frac{1}{2} M_5^3 \mathcal{R}_5 + \frac{1}{2} \nabla_M \Phi \nabla^M \Phi - V(\phi) \right] + \int_{\partial M} d^4x \sqrt{g_{\text{ind}}} \, \mathcal{L}_4(\Phi) \,, \qquad (1)$$

- Interest in the stabilization of the extra dimension while 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,

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

- Weak energy condition $\to A''(y) \geq 0$. $\therefore$ 2 IR branes at $y = \pm L$.

- Einstein's equations and scalar equation of motion (EOM) can be solved by a class of potentials (DeWolfe et al., Phys. Rev. D **62**, 046008 (2000)),

$$V(\Phi) = \frac{1}{8}\left(\frac{\partial W(\Phi)}{\partial \Phi}\right)^2 - \frac{1}{6M_5^3} W(\Phi)^2 \ , \tag{3}$$

where $W(\Phi)$ is an arbitrary "superpotential".
- Scalar background $\phi(y) \equiv \langle \Phi(y) \rangle$ and $A(y)$ satisfy the simple equations,

$$\phi'(y) = \frac{1}{2}\frac{\partial W(\phi)}{\partial \phi} \ , \qquad A'(y) = \frac{1}{6M_5^3} W(\phi(y)) \tag{4}$$

- Simplest ansatz: linear superpotential,

$$W_1(\Phi) = 2m\phi_0\Phi \ , \tag{5}$$

where m is a mass scale and ϕ_0 a scalar "VEV". Then,

$$\phi(y) = m\phi_0 y \ , \tag{6}$$

$$A(y) = \frac{m^2\phi_0^2}{6M_5^3} y^2 \ , \tag{7}$$

Captures the correct physics of a large class of superpotentials once radion is stabilized.

- We will consider the following superpotential,

$$W(\Phi) = \sqrt{2} m \phi_0^2 \sin\left(\sqrt{2}\frac{\Phi}{\phi_0}\right) . \tag{8}$$

which leads to,

$$\phi(y) = \sqrt{2}\phi_0 \tan^{-1}\left[\tanh\left(\frac{my}{\sqrt{2}}\right)\right] \qquad A(y) = \frac{k}{\sqrt{2}m}\log\left[\cosh\left(\sqrt{2}my\right)\right] \tag{9}$$

where ϕ_0 and k are related by $\phi_0^2 = 6kM_5^3/(\sqrt{2}m)$.

- The geometry is asymptotically AdS with curvature k.
- The 3-brane model IR-UV-IR arises for $m \gg k$.
- Only a few of the infinite tower of operators in Eq.8 is relevant: the quadratic and quartic terms in the "UV brane" limit and the quadratic terms in the "central region" limit, $y < 1/m$.
- Allows us to interpolate between narrow and wide domain walls (we use this setup for numerical studies).

Radion Stabilization

- The 4D (reduced) Planck mass is given by,

$$M_P^2 = M_5^3 \int_{-L}^{L} e^{-2A(y)} dy = \frac{2M_5^3}{m} \int_0^{mL} dx \left[\cosh\left(\sqrt{2}x\right)\right]^{-\sqrt{2}k/m} , \quad (10)$$

item In the case $m \ll k$ (thick domain wall): $M_P^2 \approx 1.49 M_5^3/\sqrt{km}$.

- One can enforce that the scalar field attains a given value $\bar{\phi}_0$ at the boundaries,

$$\Delta\mathcal{L}_4(\Phi) = -\gamma\left(\Phi^2 - \bar{\phi}_0^2\right)^2 , \quad (11)$$

which doesn't contribute to the boundary conditions (b.c.) when $\gamma \to +\infty$.

- We can therefore use,

$$\mathcal{L}_4(\Phi) = -W(\bar{\phi}_0) - W'(\bar{\phi}_0)(\Phi - \bar{\phi}_0) + \Delta\mathcal{L}_4(\Phi) , \quad (12)$$

which leads to the correct b.c's. In the limit of a fixed VEV,

$$\bar{\phi}_0 = \phi(L) = \sqrt{2}\phi_0 \tan^{-1}\left[\tanh\left(\frac{mL}{\sqrt{2}}\right)\right] , \quad (13)$$

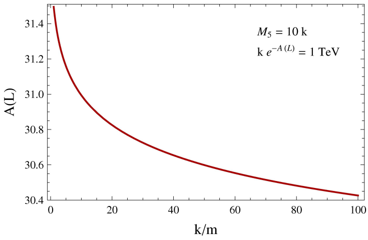
- This condition fixes the size of the extra dimension,

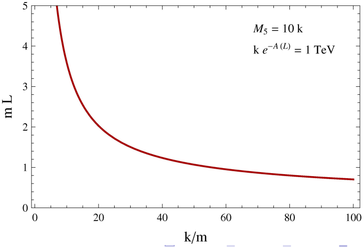
$$mL = \sqrt{2}\tanh^{-1}\left[\tan\left(\frac{\bar{\phi}_0}{\sqrt{2}\phi_0}\right)\right] . \quad (14)$$

- We can write,

$$A(L) \quad = \quad \frac{k}{\sqrt{2}m} \log\left[\cosh\left(\sqrt{2}mL\right)\right] \;, \tag{15}$$

which is parametrically large for $m \ll k$, when $mL \sim \mathcal{O}(1)$.
- Model depends on two dimensionless ratios: k/m and $\bar{\phi}_0/\phi_0$.
- Neglect higher order terms, we take $M_5 = 10k$. Get the correct 4D Planck mass and solve the hierarchy problem $\tilde{k} \equiv k\, e^{-A(L)} \sim \,\mathrm{TeV}$





- Unless $\bar{\phi}_0/(\sqrt{2}\phi_0) \approx \pi/2$, we have $mL \sim \mathcal{O}(1)$, and therefore we need $k/m \gg 1$ to generate the hierarchy $\rightarrow$ physical space restricted to "central region" of domain wall.
- For $k/m \gg 1$, $\phi(y)$ and $A(y)$ are well approximated by,

$$\phi(y)/\phi_0 \approx s_\phi y/L\,, \qquad A(y) \approx s_A k y^2/(2L)\,, \tag{16}$$

where $s_\phi = \sqrt{2}\tan^{-1}\left[\tanh\left(\frac{mL}{\sqrt{2}}\right)\right]$ and $s_A = \tanh\left(\sqrt{2}mL\right)$.

- The present radion stabilization mechanism naturally gives rise to a "fat UV brane".
- Benchmark scenario based on the "sine" superpotential: $k/m = 50$ and $A(L) \approx 30.6$. For reference, the other parameters are $mL \approx 1.07$, $kL \approx 53$, $\bar{\phi}_0/\phi_0 \approx 0.8$ and $M_5/k \approx 10$ with $k \approx 1.9 \times 10^{16}$ GeV.

Outline

Normalization and Radion Decay Constant

- Parameterize 4D physical scalar fluctuations in the 5D metric/scalar system by

$$ds^2 = e^{-2A(y)-2F(x,y)}\eta_{\mu\nu}dx^\mu dx^\nu - [1+2F(x,y)]^2\, dy^2\ , \qquad (17)$$

$$\Phi(x,y) = \phi(y) + \varphi(x,y)\ , \qquad (18)$$

where $\varphi(x,y) = (3M_5^3/\phi'(y))\, e^{2A(y)}\partial_y\left[e^{-2A(y)}F(x,y)\right]$.

- In terms of the KK decomposition $F(x,y) = \sum_{n=0}^{\infty}\tilde{r}_n(x)F_n(y)$, the $F_n(y)$ obey the "KK radion-scalar" equation of motion (Csaki et al., Phys. Rev. D **63**, 065002 (2001)),

$$F_n'' - 2A'F_n' - 4A''F_n - 2\frac{\phi''}{\phi'}F_n' + 4A'\frac{\phi''}{\phi'}F_n + e^{2A}m_n^2F_n = 0\ , \qquad (19)$$

with b.c. $(F_n' - 2A'F_n)|_{\pm L} = 0$.

- Orthonormality relation for $F_n(y)$,

$$\int_{-L}^{L} dy\, \frac{F_m(y)F_n(y)}{A''(y)} = \frac{e^{-2A(L)}}{km_n^2}\delta_{mn}\ , \qquad (20)$$

- The action Eq. (1) reads at quadratic order in $\tilde{r}_n(x)$:

$$
\begin{aligned}
S &= \frac{3}{2} M_5^3 \sum_{m,n} \int d^4x \, m_n^2 \int_{-L}^{L} dy \, \frac{F_m(y) F_n(y)}{A''(y)} \, \partial_\mu \tilde{r}_m \partial^\mu \tilde{r}_n + \cdots \, , \\
&= \Lambda_r^2 \int d^4x \sum_n \frac{1}{2} \, \partial_\mu \tilde{r}_n(x) \partial^\mu \tilde{r}_n(x) + \cdots \, , \qquad (21)
\end{aligned}
$$

where we used the orthonormality relation (20), and defined the radion decay constant,

$$
\Lambda_r = \sqrt{\frac{3M_5^3}{k}} \, e^{-A(L)} \approx \sqrt{2} \left(\frac{m}{k} \right)^{1/4} M_P e^{-A(L)} \, . \qquad (22)
$$

Radion Mode

- When $A''(y) = 0 \rightarrow$ zero-mode solution $F_0 \propto e^{2A}$. General case $F_0(y) \propto e^{2A(y)+g(y)}$.
- Radion EOM and b.c's,

$$g'' + g'^2 + 2\left(A' - \frac{\phi''}{\phi'}\right) g' = 2A'' - e^{2A} m_0^2 \,, \qquad (23)$$

$$g'\big|_{\pm L} = 0 \,. \qquad (24)$$

- One can solve for $g'(y)$ (neglecting g'^2) and replacing in the b.c's to find,

$$m_0 = \sqrt{\frac{2\int_0^L dz \, \frac{A''(z)}{k^2 \phi'(z)^2} \, e^{2A(z)}}{\int_0^L \frac{dz}{\phi'(z)^2} e^{4A(z)-2A(L)}}} \, k \, e^{-A(L)} \approx \sqrt{\frac{2 s_A}{kL}} \, k \, e^{-A(L)} \,, \qquad (25)$$

  where we used Eqs. (16) for the approximation. For the benchmark scenario $m_0 = 0.155 \, k \, e^{-A(L)}$ and the approximation $m_0 \approx 0.147 \, k \, e^{-A(L)}$.
- The neglected g'^2 terms is comparable to the other terms only near the UV brane, but the wavefunction profile is exponentially localized near the boundaries at $y = \pm L$

Lightest Odd-Scalar (LKP)

- Radion profile exponentially localized near the boundaries $y = \pm L$. After normalization $\rightarrow$ value at $y = 0$ extremely small. $\therefore$ By adjusting m_0 by an exponentially small amount one can obtain a solution that vanishes at the origin (Odd mode), with a mass exponentially close to m_0.
- By writing $F_{\rm odd}(y) = F(y) + \epsilon(y)$, where $F(y)$ is the radion wavefunction and $m^2_{n=1} = m_0^2 + \delta m^2$, where m_0 is the radion mass, we find that,

$$\delta m^2 \approx \frac{1}{kL}\frac{F(0)}{F(L)}\, k^2\, e^{-2A(L)}\,, \tag{26}$$

- This expression shows that $\delta m^2/m_0^2$ is (exponentially) small due to the IR localization of the radion wavefunction, $F(y)$. Hence, the radion and the lightest odd-scalar are exponentially degenerate in this scenario.

Outline

Equations of Motion and KK Decomposition

- The fermions actions is,

$$S_{\text{fermion}} = \int d^5x\sqrt{g}\left\{\frac{i}{2}\overline{\Psi}e^M_A\Gamma^A D_M\Psi - \frac{i}{2}(D_M\Psi)^\dagger\Gamma^0 e^M_A\Gamma^A\Psi - y_\Psi\Phi\overline{\Psi}\Psi\right\} , \quad (27)$$

  where y_Ψ is a Yukawa coupling (with mass dimension $-1/2$).

- Using a KK decomposition $\Psi_{L,R}(x,y) = \frac{e^{\frac{3}{2}A(y)}}{\sqrt{2L}}\sum_{n=0}^{\infty}\psi^n_{L,R}(x)f^n_{L,R}(y)$, with orthonormality conditions,

$$\frac{1}{2L}\int_{-L}^{L}dy\, f^n_{L,R}(y)f^m_{L,R}(y) \quad = \quad \delta_{nm}\,, \quad (28)$$

  the first order EOM take the form,

$$\left(\partial_y + m_D - \frac{1}{2}A'\right)f^n_L = m_n e^A f^n_R \qquad \left(\partial_y - m_D - \frac{1}{2}A'\right)f^n_R = -m_n e^A f^n_L \quad (29)$$

  with b.c's (in the case of a left-handed zero mode),

$$\left.f^{n\prime}_L + \left(m_D - \frac{1}{2}A'\right)f^n_L\right|_{y=\mp L} \quad = \quad 0\,, \qquad f^n_R(\mp L) \;=\; 0\,, \quad (30)$$

- Zero mode solutions,

$$f^0_{L,R}(y) = N \exp\left(\frac{1}{2}A(y) \mp \int_0^y dz\, m_D(z)\right) \; , \tag{31}$$

- These solutions are even. When Eq.(16) holds, we can write $m_D(y) \approx \pm cA'(y)$, where $c = \pm y_\Psi (s_\phi/s_A)(\phi_0/k)$. In that case the zero mode profile takes the simple form,

$$f^0(y) = N_0\, e^{-\left(c-\frac{1}{2}\right)A(y)} \; , \tag{32}$$

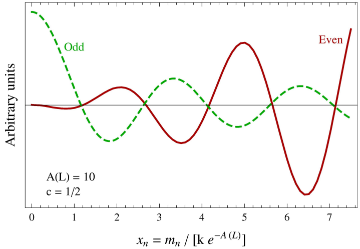
  like in RS models, independently of the chirality of the zero-mode sector.

- KK modes satisfy,

$$f^{n\prime\prime}_L - 2A' f^{n\prime}_L + \left[\frac{3}{4}A'^2 - \frac{1}{2}A'' - m_D A' + m'_D - m_D^2 + e^{2A} m_n^2\right] f^n_L \;=\; 0 \;, \tag{33}$$

$$f^{n\prime\prime}_R - 2A' f^{n\prime}_R + \left[\frac{3}{4}A'^2 - \frac{1}{2}A'' + m_D A' - m'_D - m_D^2 + e^{2A} m_n^2\right] f^n_R \;=\; 0 \;. \tag{34}$$

- In the absence of closed solutions, one can find the spectrum and wavefunctions numerically by the "shooting method".



- Note the high degree of degeneracy between the even and odd KK modes. This is due to the fact that KK-mode wavefunctions are highly peaked near the IR boundaries → small changes in m_n can change $f_L^{n\prime}(0) = 0$ to $f_L^n(0) = 0$.

Light Vector-like Odd Modes (NLKP)

- Focusing in the case of a left-handed zero mode that is exponentially localized near the IR branes, we expect to find an ultra-light odd-fermion solution (same reasons as previous slide).
- To find this small mass, we write on the interval $[0, L]$, $f_L^1(y) = f_L^0(y) + \epsilon(y)$, where f_L^0 is the (even) zero-mode profile. Then Eq. (33) becomes

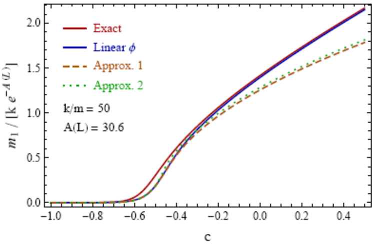
$$\epsilon'' - 2A'\epsilon' + \left[\frac{3}{4}A'^2 - \frac{1}{2}A'' - m_D A' + m_D' - m_D^2 + e^{2A}m_1^2\right]\epsilon + e^{2A}m_1^2 f_L^0 = 0\ , \quad (35)$$

- When the approximations for $A(y)$ and $\phi(y)$ hold, we can use Eq. (32) to get,

$$m_1^2 \quad \approx \quad \left\{\int_0^L dz_2\, k\, e^{(2c+1)A(z_2)-A(L)} \int_{z_2}^L dz_1\, k\, e^{-(2c-1)A(z_1)-A(L)}\right\}^{-1} k^2 e^{-2A(L)}\ .$$

- This expression can be analyzed in different regions of c,
  - For $-1/2 < c < 1/2$ we find $m_1 \approx \sqrt{2(1+2c)}\, s_A k\, e^{-A(L)}$.
  - For $c \leq -1/2$, we find $m_1 \approx \sqrt{\frac{2s_A(1-2c)}{kL}\frac{1}{1+e^{-(2c+1)A(L)}}}\, k\, e^{-A(L)}$.

- Lightest odd-fermion mass as a function of c,



- Simple expressions match reasonably the exact solution when $m_1/(k\, e^{-A(L)}) \lesssim 1$.

Yukawa Couplings to the Higgs

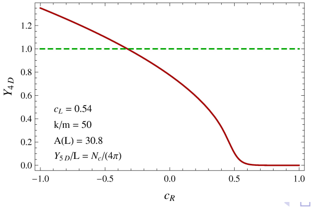
- For simplicity, we assume the Higgs field symmetrically localized on the IR boundaries. Consider the top Yukawa interaction,

$$\delta S = \int d^5x \sqrt{g}\; Y_{5D} H(x) \left[\bar{Q}_L(x,y) t_R(x,y) + h.c.\right] \left[\delta(y-L) + \delta(y+L)\right] \;, \quad (36)$$

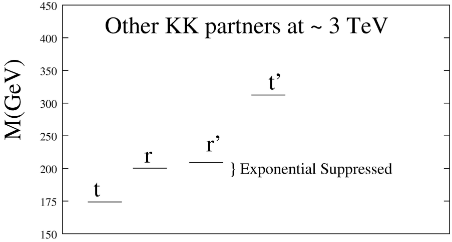
- Concentrating on the zero-mode fermions, the 4D Yukawa coupling reads,

$$Y_{4D} = \frac{Y_{5D}}{L} f_L^0(L) f_R^0(L) \;, \quad (37)$$

- Estimate Y_{5D} from NDA (Chacko et al. JHEP **0007**, 036 (2000)), $Y_{5D}^{\mathrm{NDA}} \sim (N_c L)/\sqrt{l_4} = (3/4\pi)L$.



- Typical spectrum in this kind of scenario.



Outline

- To study the DM implications of this scenario we consider the couplings of the LKP to the zero mode t_R and the NLKP, as well as quartic couplings involving the LKP, the NLKP, t_R and the Higgs or a SM gauge boson.
- The interactions induced by the bulk action take the form,

$$\mathcal{L}^{\rm bulk}_{r\psi\psi} = -\sum_{ijk=0}^{\infty} \frac{r_i}{\Lambda_r} \left[g^{LL}_{ijk} \, \bar{\psi}^j_L \, i \overleftrightarrow{\partial\!\!\!/} \, \psi^k_L + g^{RR}_{ijk} \, \bar{\psi}^j_R \, i \overleftrightarrow{\partial\!\!\!/} \, \psi^k_R \right] + \sum_{ijk=0}^{\infty} \frac{r_i}{\Lambda_r} \, m_{ijk} \left[\bar{\psi}^j_R \psi^k_L + \text{h.c.} \right] , \tag{38}$$

where $\bar{\psi} \overleftrightarrow{\partial\!\!\!/} \chi \equiv \frac{1}{2} \left[\bar{\psi}\gamma^\mu \partial_\mu \chi - (\partial_\mu \bar{\psi})\gamma^\mu \chi \right]$, and

$$g^{LL}_{ijk} = \frac{1}{2L} \int_{-L}^{L} dy \, F_i f^j_L f^k_L \, , \qquad g^{RR}_{ijk} = \frac{1}{2L} \int_{-L}^{L} dy \, F_i f^j_R f^k_R \, , \tag{39}$$

$$m_{ijk} = 2g^{LL}_{ijk} \, m_j + 2g^{RR}_{ijk} \, m_k - \frac{1}{2L} \int_{-L}^{L} dy \, e^{-A} \left[2F_i m_D + \frac{m'_D}{A''} e^{2A} (e^{-2A} F_i)' \right] f^j_R f^k_L \, .$$

- We have neglected EWSB boundary masses.

- Bulk action also leads to interactions of the radion, fermion pairs and gauge bosons V_μ of the form,

$$\mathcal{L}_{r\psi\psi V} = -\sum_{ijkl} \frac{r_i}{\Lambda_r} \left(g^{LL}_{ijkl}\, \bar{\psi}^j_L \not{V}^k \psi^l_L + g^{RR}_{ijkl}\, \bar{\psi}^j_R \not{V}^k \psi^l_R \right) , \quad (40)$$

where,

$$g^{LL}_{ijkl} = \frac{g_V}{2L} \int_{-L}^{L} dy\, F_i f^j_L f^k_V f^l_L \qquad g^{RR}_{ijkl} = \frac{g_V}{2L} \int_{-L}^{L} dy\, F_i f^j_R f^k_V f^l_R , \quad (41)$$

- Similarly brane localized Yukawa interactions induce cubic interactions of the form,

$$\mathcal{L}^{\text{brane}}_{\text{Hr}\psi\psi} = \sum_{ijk=0}^{\infty} X_{ijk}\, r_i \left(\bar{\psi}^j_{(L)L} \psi^k_{(R)R} + \text{h.c.} \right) \left(1 + \frac{h}{v} \right) , \quad (42)$$

where,

$$X_{ijk} = -\frac{m^0_f}{\Lambda_r} F_i \left[1 + (-1)^{i+j+k} \right] \left. \frac{f^j_{(L)L} f^k_{(R)R}}{f^0_{(L)L} f^0_{(R)R}} \right|_{y=L} . \quad (43)$$

Feynman Rules for DM annihilation

- For c_R close to -1/2, we find that $g^{LL}_{101} \ll g^{RR}_{101}$. $\therefore$ we neglect all the contributions that depend on $f^1_L(y)$.
- The couplings take the approximate form,

$$g^{RR}_{000} \approx g^{RR}_{011} \approx g^{RR}_{101} = g^{RR}_{110} \approx \left(\frac{1-2c}{3-2c}\right) s_A^{1/2}\,, \tag{44}$$

$$X_{000} \approx X_{101} \approx -2\, s_A^{1/2} \left(\frac{m_t}{\Lambda_r}\right)\,. \tag{45}$$

- The Feynman rules for annihilation take the form,

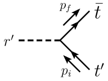


Figure: $-i\frac{g^{RR}_{101}}{\Lambda_r}\left[\frac{1}{2}\left(\not{p}_i + \not{p}_f\right) P_R - 2m_{t'} P_L\right] + iX_{101} P_R$.

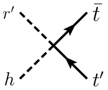


Figure: $i\frac{X_{101}}{v} P_R$.

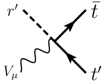


Figure: $-i\frac{g^{RR}_{101}}{\Lambda_r} g_V \gamma^\mu P_R$.

Outline

Annihilation Cross-Sections

- For LKP annihilating at rest, to leading order in m_t/m'_r, the cross-section times the relative velocity is,

$$v\sigma_{r'r'\to t\bar{t}} \approx \frac{N_c(g^{RR}_{101})^2}{64\pi}\left(\frac{m_t}{\Lambda_r^2}\right)^2 \frac{[3g^{RR}_{101} - 4(4z^2+1)X_{101}]^2}{(1+z^2)^2} \tag{46}$$

  where $z \equiv m'_t/m_r$. Cross-section suppressed by $(m_t/\Lambda_r)^4$ with respect to typical EW cross-sections $\longrightarrow$ overclosure of the Universe.
- However, we expect the NLKP parametrically lighter than the KK scale and it mass *could* be close to the LKP.
- The annihilation processes $t'\bar{t}' \longrightarrow gg, q\bar{q}$ are controlled by QCD interactions instead of being suppressed by Λ_r.
- The reactions $r'g \longrightarrow \bar{t}'t$ and $t'g \longrightarrow r't$ easily keep r's in thermal equilibrium until the time the t's decouple.

- Final relic density determined by an effective cross-section (Griest and Seckel, Phys. Rev. D **43**, 3191 (1991)):

$$\begin{aligned}\sigma_{eff} &= \frac{1}{g_{eff}^2}\Big[g_{t'}e^{-x\Delta}(1+\Delta)^{3/2}(\sigma_{r't'\to gt}+\sigma_{r'\bar{t}'\to g\bar{t}}+\sigma_{r't'\to ht}+\sigma_{r'\bar{t}'\to h\bar{t}}) \\ &+ \sigma_{r'r'\to t\bar{t}}+g_{t'}^2e^{-2x\Delta}(1+\Delta)^3\left(\sum_q \sigma_{t'\bar{t}'\to q\bar{q}}+\sigma_{t'\bar{t}'\to gg}\right)\Big], \qquad (47)\\ g_{eff} &= 1+g_{t'}e^{-x\Delta}(1+\Delta)^{3/2} \qquad (48)\end{aligned}$$

where $g_{t'} = 2\times N_c$, $x \equiv m_r'/T$ and $\Delta \equiv (m_{t'} - m_{r'})/m_{r'}$.

- The final relic density is largely determined by the QCD cross-sections,

$$v\sigma_{t'\bar{t}'\to q\bar{q}} \approx \frac{2\pi\alpha_s^2}{9m_{t'}^2} \qquad v\sigma_{t'\bar{t}'\to gg}\frac{7\pi\alpha_s^2}{27m_{t'}^2}, \qquad (49)$$

- The thermally averaged cross section (terms dependent on m_t make negligible contributions)is,

$$\langle v\sigma_{eff}\rangle \approx \frac{172\pi\alpha_s^2}{3m_{t'}^2}\frac{(1+\Delta)^3}{[e^{x\Delta}+6(1+\Delta)^3/2]^2}. \qquad (50)$$

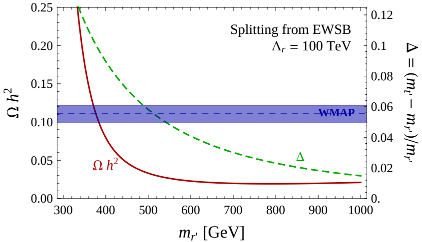
- The relic density is given by

$$\Omega h^2 \approx \frac{5.21 \times 10^9 \text{ GeV}^{-1}}{M_P} \frac{x_F}{\sqrt{g_*} I_a} \quad (51)$$

where $g_* = 86.25$ is the effective number of relativistic degrees of freedom at the time of t' decoupling,

$$x_F = \log\left[\zeta(\zeta+2)\sqrt{45\pi}\left(\frac{g_{eff}}{2\pi^3}\right)\frac{m_{r'} M_P \langle v\sigma_{eff}\rangle}{\sqrt{g_* x}}\right]|_{x=x_F} \quad (52)$$

one can take $\zeta \sim 0.5$ and $I_a \approx x_F \int_{x_F}^{\infty} dx \frac{\langle v\sigma_{eff}\rangle}{x^2}$.



Outline

Conclusions

- We discussed a novel minimal 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).
- As a consequence of the localization of KK modes, odd and even states are highly degenerate.
- The same scalar VEV that stabilizes the extra dimension generates the bulk Dirac masses for the 5D fermions.
- In order to generate a large top Yukawa coupling, the right handed top quark must be localized near the IR brane which leads to a light colored vector-like singlet state, the NLKP.
- Coannihilation of the LKP and the NLKP is necessary in order to get the right DM relic density.
- Superwimp scenario may be possible for a large hierarchy between M_5 and k, $M_5 \ggg k$.
- Outlook
    - Collider signals at the LHC.