Thick Branes in Extra Dimensions and Suppressed Dark Couplings

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Based on
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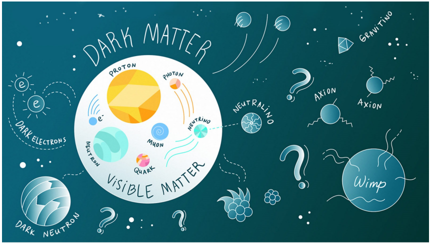
Dark matter: a puzzle of almost 100 years old



Symmetry Maganize

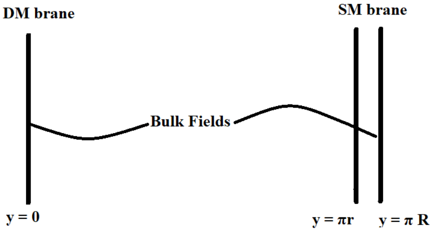
$$\text{kinetic mixing } \equiv \frac{\epsilon}{2} V^{\mu\nu} B_{\mu\nu} \qquad \text{Higgs portal} \equiv \lambda_S S^2 |H|^2 \tag{1}$$

Extra dimensions

Used to explain

- hierarchy problem
- origin of electroweak symmetry breaking
- proton stability
- breaking of grand unified gauge groups
- number of fermion generations
- cosmological constant

SM can be embedded in ED in the Universal Extra Dimension model [Appelquist, Cheng, Dobrescu 2001]



$L \equiv R - r$

BM	I	II	III	IV
R^{-1}	1 GeV	1 GeV	100 MeV	100 MeV
L^{-1}	2 TeV	10 TeV	2 TeV	10 TeV

Gauge field

$\sim g_{5D}(B-L+Q_D)$

$$S=\int d^4x\int_0^{\pi R}dy\left[-\frac{1}{4}V_{AB}V^{AB}-\frac{1}{4}V_{\mu\nu}V^{\mu\nu}\cdot\delta_A R\,\delta(y)-\frac{1}{4}V_{\mu\nu}V^{\mu\nu}\cdot\delta_B R\,\theta(y)\right], \quad (2)$$

$$\theta(y)=\alpha\quad\text{for } \pi r<y\leq\pi R\,,\qquad \theta(y)=0\quad\text{for } y<\pi r\,, \quad (3)$$

$$V^{\mu[5]}(x,y)=\sum_n v_n^{[5]}(y)V_n^{\mu[5]}(x)\,, \quad (4)$$

$$v_{1,n}(y)=N_n^V\left[\cos(m_n^V y)-\frac{\delta_A x_n^V}{2}\sin(m_n^V y)\right]\qquad 0\leq y\leq\pi r\,, \quad (5)$$

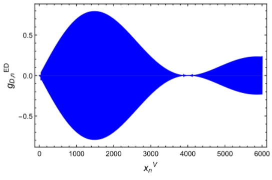
$$v_{2,n}(y)=v_{1,n}(\pi r)\cos[\bar{m}_n^V(y-\pi r)]+\frac{v'_{1,n}(\pi r)}{\bar{m}_n^V}\sin[\bar{m}_n^V(y-\pi r)]\qquad \pi r\leq y\leq\pi R\,. \quad (6)$$

$\bar{m}_n^V=\frac{x_n^V}{R}\sqrt{1+\delta_B\alpha R}$

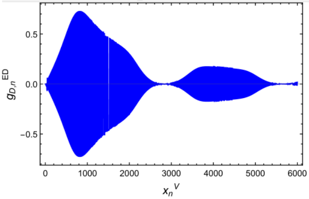
$$\tan(\bar{m}_n^V\pi L)=-\bar{m}_n^V\frac{v_{1,n}(\pi r)}{v'_{1,n}(\pi r)}\,, \quad (7)$$

Interactions

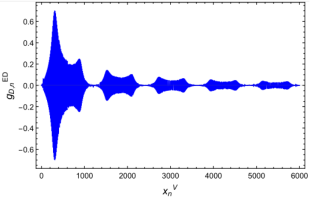
$$g_{D,n}^{ED} \equiv g_{5D} \int_{\pi r}^{\pi R} dy \, \frac{v_{2,n}(y)}{\pi L}$$
$$\approx g_{5D}\pi \frac{L}{R} x_n^V \frac{N_n^V}{2} \left[\sin(m_n^V \pi r) + \frac{\delta_A}{2} x_n^V \cos(m_n^V \pi r) \right] . \quad L \ll R \qquad (8)$$



$\delta_B\alpha = 10^{-2}$ MeV



$\delta_B\alpha = 1$ GeV



$\delta_B\alpha = 10$ GeV

- Direct constraints

$$\sigma_e = \frac{\mu^2}{4\pi}\left(\sum_n \frac{g_{D,n}g^{ED}_{D,n}}{(m_n^V)^2}\right)^2 , \tag{9}$$

- Indirect constraints

$$\sigma v \approx a + bv^2 \tag{10}$$

$$b_f = \frac{m_{DM}^2}{6\pi}\sqrt{1-\frac{m_f^2}{m_{DM}^2}}\left(1-\frac{m_f^2}{2m_{DM}^2}\right)\left(\sum_n \frac{g_{D,n}g^{ED}_{D,n}}{(m_n^V)^2-4m_{DM}^2}\right)^2 , \tag{11}$$

$$\Omega h^2 \simeq \frac{x_f\, 1.07\times 10^9\ \mathrm{GeV}^{-1}}{g_*^{1/2} m_{Pl}(a+3b/x_f)} = 0.12\,,\ \text{[Planck 2018]} \tag{12}$$

BM	I	II	III	IV
$\delta_A = 1$				
m_1^V [MeV]	430	430	43	43
m_{DM} [MeV]	400	400	40	40
g_D	0.89	1.98	0.96	2.15
σ_e [cm^2]	1.1×10^{-40}	1.1×10^{-40}	1.6×10^{-38}	1.6×10^{-38}
$\delta_A = 1/2$				
m_1^V [MeV]	460	460	46	46
m_{DM} [MeV]	430	430	43	43
g_D	0.88	2.00	0.95	2.12
σ_e [cm^2]	8.8×10^{-41}	9.6×10^{-41}	1.2×10^{-38}	1.2×10^{-38}
$\delta_A = 10$				
m_1^V [MeV]	230	230	23	23
m_{DM} [MeV]	200	200	20	20
g_D	0.88	1.95	0.93	2.08
σ_e [cm^2]	1.1×10^{-39}	1.1×10^{-39}	1.4×10^{-37}	1.4×10^{-37}
$\delta_B\alpha = 1/2\,\text{GeV}$				
m_1^V [MeV]	430	430	43	43
m_{DM} [MeV]	400	400	40	40
g_D	0.81	1.98	0.96	2.14
σ_e [cm^2]	7.7×10^{-41}	1.1×10^{-40}	1.5×10^{-38}	1.5×10^{-38}
$\delta_B\alpha = 10\,\text{GeV}$				
m_1^V [MeV]	430	430	43	43
m_{DM} [MeV]	400	400	40	40
g_D	0.81	1.98	0.96	2.14
σ_e [cm^2]	7.8×10^{-41}	1.1×10^{-40}	1.5×10^{-38}	1.5×10^{-38}
$\delta_B\alpha = 10\,\text{TeV}$				
m_1^V [MeV]	430	430	43	43
m_{DM} [MeV]	400	400	40	40
g_D	0.72	1.98	0.94	2.14
σ_e [cm^2]	3.0×10^{-41}	1.1×10^{-40}	1.3×10^{-38}	1.5×10^{-38}

$g_D = g_{5D}/N_1^V$ – BM III and IV are excluded by current constraints.

Neutrino in the bulk

$$S = \int d^4x\,dy \left[i\bar{\Psi}\Gamma^A\partial_A\Psi - m_D\bar{\Psi}\Psi - m_M\bar{\Psi}\Psi^c + \bar{\Psi}\partial\!\!\!/\Psi \cdot \delta_A\theta(y)R \right], \tag{13}$$

$\Gamma^4 = i\gamma^5$, $\Psi^c = C^5\bar{\Psi}^T$ and $C^5 = \gamma^0\gamma^2\gamma^5$
$\Psi = \Psi_1 + \Psi_2$

$$\Psi_{1,2}(x^\mu, y) = \sum_{n=0}^{\infty} f_{1,2}^{(n)}(y)\psi_{1,2}^{(n)}(x^\mu)\,. \tag{14}$$

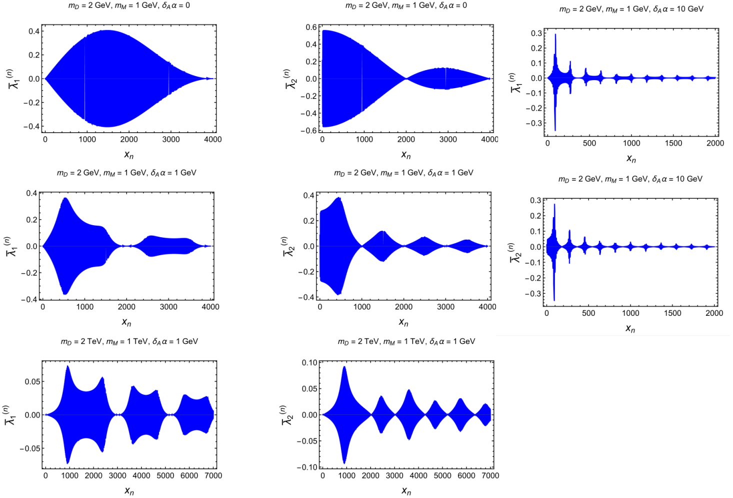
$$f_{1,\mathrm{I}}^{(n)}(y) = \frac{\Lambda_n}{m_n - m_M}\left[m_D \sin\left(\frac{x_n y}{R}\right) + \frac{x_n}{R}\cos\left(\frac{x_n y}{R}\right)\right], \tag{15}$$

$$f_{2,\mathrm{I}}^{(n)}(y) = \Lambda_n \sin\left(\frac{x_n y}{R}\right), \tag{16}$$

$$f_{1,\mathrm{II}}^{(n)}(y) = f_{1,\mathrm{I}}^{(n)}(\pi r)\cos[\bar{m}_n(y-\pi r)] + \frac{f_{1,\mathrm{I}}^{'(n)}(\pi r)}{\bar{m}_n}\sin[\bar{m}_n(y-\pi r)], \tag{17}$$

$$f_{2,\mathrm{II}}^{(n)}(y) = \frac{m_n - m_M}{\sqrt{m_D^2 + \bar{m}_n^2}}\Lambda_n \sin\left(\frac{x_n \pi r}{R}\right)\cos[\bar{m}_n(y-\pi r)]$$
$$+ \frac{\bar{m}_n f_{1,\mathrm{I}}^{(n)}(\pi r) + f_{1,\mathrm{I}}^{'(n)}(\pi r) m_D/\bar{m}_n}{\sqrt{m_D^2 + \bar{m}_n^2}}\sin[\bar{m}_n(y-\pi r)], \tag{18}$$

$$\lambda_{5,1}\Psi_1 L_f H + \lambda_{5,2}\Psi_2 L_f H + \text{h.c.} \qquad \bar{\lambda}^{(n)}_{1(2)} \equiv \lambda_{5,1(2)} \int_{\pi r}^{\pi R} dy \frac{f^{(n)}_{1(2)\mathrm{II}}(y)}{\pi L} \tag{19}$$



- diagonalize masses $m^{(n)}_{1(2)} = \sqrt{x_n^2/R^2 + m_D^2} \pm m_M > 0 \begin{cases} N_1^{(n)} = (\psi_1^{(n)} + \psi_2^{(n)})/\sqrt{2} \\ N_2^{(n)} = i(\psi_1^{(n)} - \psi_2^{(n)})/\sqrt{2}, \end{cases}$
- $\lambda^{(n)}_{1(2)} N^{(n)}_{1(2)} L_f H + h.c. \begin{cases} \lambda_1^{(n)} = (\bar{\lambda}_1^{(n)} + \bar{\lambda}_2^{(n)})/\sqrt{2} \\ \lambda_2^{(n)} = -i(\bar{\lambda}_1^{(n)} - \bar{\lambda}_2^{(n)})/\sqrt{2} \end{cases}$
- $\frac{1}{2}\mathcal{N}^T \mathcal{M} \mathcal{N} +$ h.c., where

$$\mathcal{N}^T \equiv (\nu_L, N_1^{(0)}, N_2^{(0)}, N_1^{(1)}, N_2^{(1)}, \dots)\,, \tag{20}$$

and the mass matrix is

$$\mathcal{M} = \begin{pmatrix} 0 & \hat{m}_1^{(0)} & \hat{m}_2^{(0)} & \hat{m}_1^{(1)} & \hat{m}_2^{(1)} & \dots \\ \hat{m}_1^{(0)} & m_1^{(0)} & 0 & 0 & 0 & \dots \\ \hat{m}_2^{(0)} & 0 & m_2^{(0)} & 0 & 0 & \dots \\ \hat{m}_1^{(1)} & 0 & 0 & m_1^{(1)} & 0 & \dots \\ \hat{m}_2^{(1)} & 0 & 0 & 0 & m_2^{(1)} & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix} . \tag{21}$$

$$\prod_n (m_1^{(n)} - \lambda)(m_2^{(n)} - \lambda)\left[\lambda + \sum_n \left(\frac{\hat{m}_1^{(n)\,2}}{m_1^{(n)} - \lambda} + \frac{\hat{m}_2^{(n)\,2}}{m_2^{(n)} - \lambda}\right)\right] = 0\,. \tag{22}$$

$$\lambda_\nu \approx -\sum_n \left(\frac{\hat{m}_1^{(n)\,2}}{m_1^{(n)}} + \frac{\hat{m}_2^{(n)\,2}}{m_2^{(n)}}\right) \approx 10^{-2}\text{eV}\,. \tag{23}$$

R^{-1}	m_D	m_M	$\delta_A \alpha$	$\lambda_{4,1(2)}$
1 GeV	$\geq$ 30 TeV	$\leq$ 10 TeV	$\geq$ 30 TeV	1
100 MeV	$\geq$ 30 TeV	$\leq$ 10 TeV	$\geq$ 30 TeV	0.1
10 MeV	$\geq$ 30 TeV	$\leq$ 10 TeV	$\geq$ 30 TeV	0.01

$L^{-1} = 2$ TeV

$$R^{-1} = 1 \text{ GeV}, \lambda_{4,1(2)} = 0.01 \rightarrow m_{1,2}^{(0)} \sim 1 \text{ TeV}$$

Summary

- Suppressed coupling between vector (and scalar) mediator and SM particles, especially using BLKT
- Due to the suppressed couplings the seesaw mechanism can happen at TeV scale
- Works in 6D as well
- Leptogenesis can be realized in this scenario

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Thank you!