

# Thick Branes in Extra Dimensions and Suppressed Dark Couplings

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Based on  
2005.10593,  
1911.00341 [EPJC 80 (2020) 124],  
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in collaboration with Tom Rizzo (SLAC) and Björn Garbrecht (TUM)

# Dark matter: a puzzle of almost 100 years old



Symmetry Maganize

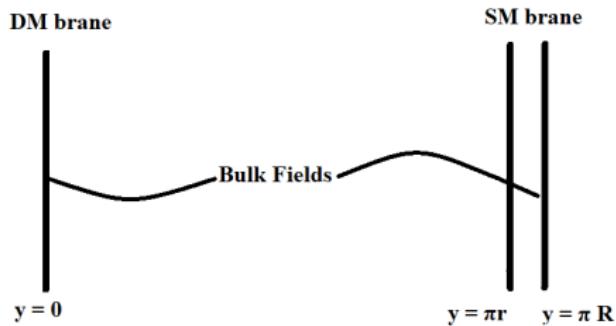
$$\text{kinetic mixing} \equiv \frac{\epsilon}{2} V^{\mu\nu} B_{\mu\nu} \quad \text{Higgs portal} \equiv \lambda_S S^2 |H|^2 \quad (1)$$

## 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

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

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

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

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

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

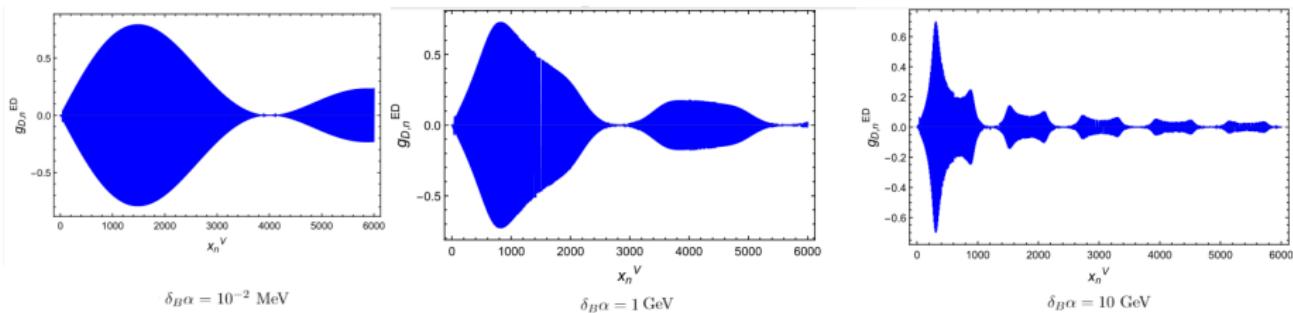
$$v_{2,n}(y) = v_{1,n}(\pi r) \cos[\bar{m}_n^V(y - \pi r)] + \frac{v'_{1,n}(\pi r)}{\bar{m}_n^V} \sin[\bar{m}_n^V(y - \pi r)] \quad \pi r \leq y \leq \pi R. \quad (6)$$

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

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

## Interactions

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



- Direct constraints

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

- Indirect constraints

$$\sigma v \approx a + bv^2 \quad (10)$$

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

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

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

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

## Neutrino in the bulk

$$S = \int d^4x dy \left[ i\bar{\Psi} \Gamma^A \partial_A \Psi - m_D \bar{\Psi} \Psi - m_M \bar{\Psi} \Psi^c + \bar{\Psi} \not{d} \Psi \cdot \delta_A \theta(y) R \right], \quad (13)$$

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

$$\Psi = \Psi_1 + \Psi_2$$

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

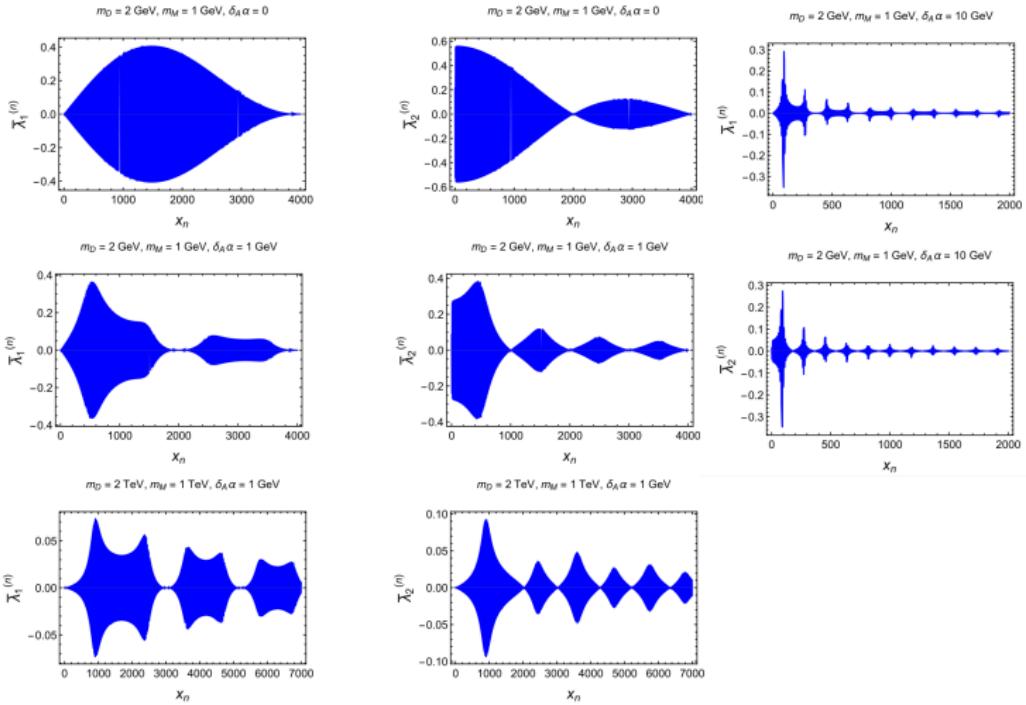
$$f_{1,\text{I}}^{(n)}(y) = \frac{\Lambda_n}{m_n - m_M} \left[ m_D \sin\left(\frac{x_n y}{R}\right) + \frac{x_n}{R} \cos\left(\frac{x_n y}{R}\right) \right], \quad (15)$$

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

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

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

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



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

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

and the mass matrix is

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

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

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

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

## 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!