Dark Matter & Extra Dimensions

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TIFR

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Plan of the Talk

- **Extra dimensions as a paradigm for new physics**
  - ▸ Kaluza-Klein theory, string theory
  - ▸ large extra dimensions (ADD), warped extra dimensions (RS)
  - ▸ effective field theories (AdS-CFT), universal extra dimension (UED)
- **Dark matter in extra dimensional theories**
  - ▸ dark matter introduction
  - ▸ LKP dark matter, other exotic candidates
  - ▸ modifications of gravity
- **Detection of extra dimensional dark matter**
  - ▸ direct detection experiments
  - ▸ indirect detection experiments
  - ▸ collider experiments
- **Summary**

KALUZA-KLEIN THEORY

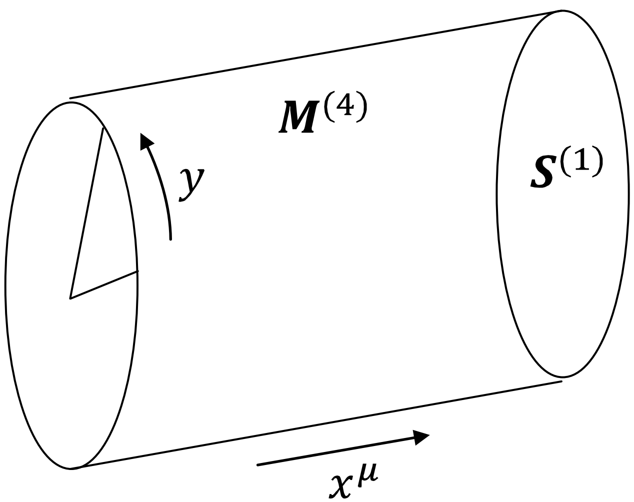
Originally intended as a model to unify electromagnetism with gravitation

▶ Introduce a fifth 'compact' dimension y : $X = (x^\mu, y)$

y has the topology of a circle, i.e. y and $y + 2\pi R_c$ are identified

↑ radius of compactification (small)

"cylinder world" $\boldsymbol{M}^{(4)} \times \boldsymbol{S}^{(1)}$



$$G_{MN}(X) = \begin{pmatrix} G_{\mu\nu}(X) & G_{4\nu}(X) \\ \hline G_{4\nu}(X) & G_{44}(X) \end{pmatrix}$$

metric is partitioned

compact dimension ≡ periodic boundary condition

► Any bulk ($\boldsymbol{M}^{(4)} \times \boldsymbol{S}^{(1)}$) field : $F(X) \equiv F(x,y) = F(x, y + 2\pi R_c)$

Expand as a Fourier series :

$$F(x,y) = \sum_n F^{(n)}(x)\, e^{iny/R_c}$$

↑

Kaluza-Klein modes (KK modes)

► Compactification limit : $R_c \to 0$ (⇒ physical probes have $\Delta x \gg R_c$)

only averaged value over y will be observed…

i.e. for any field $F(x,y)$, we must take

$$F(x) = \frac{1}{2\pi R_c}\int_0^{2\pi R_c} dy\ F(x,y) = \frac{1}{2\pi R_c}\int_0^{2\pi R_c} dy \sum_n F^{(n)}(x)\, e^{iny/R_c} = F^{(0)}(x)$$

⇒ only the zero mode survives the averaging process

⇒ to see higher KK modes, must use probes with $\Delta x \sim R_c$

► Metric fields can also be expanded:

$$G_{MN}(x,y) = \sum_n G_{MN}^{(n)}(x)\, e^{iny/R_c}$$

Parametrise the zero modes as:

$$G_{MN}^{(0)}(x) = \varphi^{-1/3} \left(\begin{array}{c|c} G_{\mu\nu}^{(0)} = g_{\mu\nu} + \lambda\varphi a_\mu a_\nu & G_{\mu 4}^{(0)} = \lambda\varphi a_\mu \\ \hline G_{4\nu}^{(0)} = \lambda\varphi a_\nu & G_{44}^{(0)} = -\varphi \end{array} \right)$$

Inverse:

$$G^{MN(0)}(x) = \varphi^{1/3} \left(\begin{array}{c|c} G^{\mu\nu(0)} = g^{\mu\nu} & G^{\mu 4(0)} = a^\mu \\ \hline G^{4\nu(0)} = a^\nu & G^{44(0)} = (\lambda\varphi)^{-1} + a^\mu a_\mu \end{array} \right)$$

► Translation along the compact dimension: $y \to y + \lambda\theta(x)$

$$a_\mu \to a_\mu + \partial_\mu\theta$$

looks like a gauge transformation

► Pure gravity in five dimensions:

$$S^{(5)} = \frac{1}{16\pi G_5} \int d^5X \, \sqrt{\det G} \;\; \mathcal{R}^{(5)}$$

in compactification limit $R_c \to 0$ reduces to

$$S^{(4)} = \frac{2\pi R_c}{16\pi G_5} \int d^4x \, \sqrt{-\det g} \left[\mathcal{R}^{(4)} - \tfrac{1}{4}\lambda^2 \varphi f_{\mu\nu} f^{\mu\nu} - \frac{1}{6\varphi^2} \partial_\mu \varphi \partial^\mu \varphi \right]$$

where $f_{\mu\nu} = \partial_\mu a_\nu - \partial_\nu a_\mu$

Put $\frac{2\pi R_c}{16\pi G_5} = \frac{1}{16\pi G_N} \Rightarrow G_N = \frac{G_5}{2\pi R_c}$ (Newton's constant)

$\frac{2\pi R_c}{16\pi G_5}\lambda^2 = 1 \Rightarrow \lambda = \sqrt{16\pi G_N}$ (unit length)

Scale $\varphi a_\mu = A_\mu$

$$S^{(4)} = \frac{1}{16\pi G_N} \int d^4x \, \sqrt{-\det g} \; \mathcal{R}^{(4)} - \int d^4x \sqrt{-\det g} \; \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

Kaluza-Klein miracle: 5D gravity $\xrightarrow{R_c \to 0}$ 4D gravity + electromagnetism

▶ Inclusion of matter: bulk scalar field $\Phi(x,y) = \frac{1}{\sqrt{2\pi R_c}} \sum_n \Phi^{(n)}(x)\, e^{iny/R_c}$

$$S_\Phi^{(5)} = \int d^5X \sqrt{\det G}\ \left[G^{MN}(\partial_M \Phi)^* \partial_N \Phi - M_0^2 \Phi^* \Phi\right]$$

in compactification limit $R_c \to 0$ reduces to

$$S_\Phi^{(4)} = \sum_n \int d^4x \sqrt{\det g}$$

$$\times \left[G^{\mu\nu} \left\{\left(\partial_\mu + \frac{in}{R_c}\lambda\varphi a_\mu\right)\Phi^{(n)}\right\}^* \left(\partial_\nu + \frac{in}{R_c}\lambda\varphi a_\nu\right)\Phi^{(n)} - \left(M_0^2 + \frac{n^2}{R_C^2}\right)\Phi^{(n)*}\Phi^{(n)}\right]$$

$$= \sum_n \int d^4x \sqrt{\det g}$$

$$\times \left[G^{\mu\nu}\left\{\left(\partial_\mu + iq_n A_\mu\right)\Phi^{(n)}\right\}^* \left(\partial_\nu + iq_n A_\nu\right)\Phi^{(n)} - M_n^2\ \Phi^{(n)*}\Phi^{(n)}\right]$$

where $q_n = n\frac{\lambda}{R_c} = n\frac{\sqrt{16\pi G_N}}{R_c}$ charge quantisation

$M_n^2 = M_0^2 + \frac{n^2}{R_C^2}$ KK tower of states

Similar quantisation conditions will hold for a bulk fermion $\Psi(x,y)$…

$$q_n = n \frac{\ell_P}{R_c} \qquad \text{where} \quad \ell_P = \sqrt{16\pi G_N} \sim 10^{-33}\ \text{cm}$$

► Two paradigms:

- $q_1 = e = \sqrt{4\pi\alpha} \approx 0.303 \quad \Rightarrow \quad R_c \sim 10^{-33}\ \text{cm}$

  $M_1 \sim \frac{1}{R_C} \quad \Rightarrow \quad M_1 \sim 10^{19}\ \text{GeV}$

tiny extra dimension: gauge interaction is electromagnetism
KK modes are very heavy

- $R_c \sim 10^{-17}\ \text{cm} \quad \Rightarrow \quad q_n \sim n\,.\frac{10^{-33}}{10^{-17}} \sim n\,.\,10^{-16}$

  $M_1 \sim \frac{1}{R_C} \quad \Rightarrow \quad M_1 \sim 10^3\ \text{GeV}$

large extra dimension: KK modes are accessible at collider energies
gauge interaction is effectively decoupled

either way Kaluza-Klein theory fails!

▶ **Higher dimensions**:

$\boldsymbol{M}^{(4)} \times \left[\boldsymbol{S}^{(1)}\right]^n$ *n*-torus ; $\boldsymbol{M}^{(4)} \times \boldsymbol{S}^{(n)}$ *n*-sphere ; $\boldsymbol{M}^{(4)} \times \boldsymbol{K}^{(n)}$ compact

- In general, $S^{(4+n)} = \frac{1}{16\pi G_{4+n}} \int d^{4+n}X \sqrt{\det G}\; \mathcal{R}^{(4+n)}$

  will reduce to $S^{(4)} = \frac{V_n}{16\pi G_{4+n}} \int d^4x \sqrt{-\det g}\; \left[\mathcal{R}^{(4)} - \cdots\right]$

  i.e. $G_N = \frac{G_{4+n}}{V_n}$ (Newton's constant)

- Gauge theory will be non-Abelian, e.g. with $S^{(2)}$ get SU(2) gauge theory
- KK masses will be

$$M_{\vec{n}}^2 = M_0^2 + \frac{\vec{n}^2}{R_C^2} \qquad \vec{n}^2 = n_1^2 + n_2^2 + \cdots + n_n^2$$

Problems are the same…

▶ **No-go theorem:** (Witten 1981)
Starting from $M^{(4)} \times K^{(7)}$, where $K^{(7)}$ is a compact manifold which contains the Standard Model symmetry SU(3)×SU(2)×U(1), one cannot have chiral fermions in the low-energy theory

STRING THEORY

► Elementary objects are not particles, but 1D strings which live in 1+25 D

► Superstrings live in 1+9 dimensions: $M^{(4)} \times K^{(6)}$
Revival of Kaluza-Klein ideas… $R_c \sim \ell_P$ paradigm (Scherk & Schwartz 1975)

► If $K^{(6)}$ is a Calabi-Yau manifold, compactification gives an $\mathrm{E}_8 \times \mathrm{E}_8$ gauge theory, which can spontaneously break to SU(3)×SU(2)×U(1) with three generations of chiral fermions
(Candelas, Horowitz, Strominger, Witten 1985)

► Duality proved equivalence of many different string theories: 'M theory'
(Witten & others 1990's)

► D-branes are solitonic excitations of Type-II string theories (equivalent to others by duality). Effectively, they are lower dimension hypersurfaces on which the ends of open strings are confined. (Polchinski 1995)

► AdS-CFT correspondence: gravity in bulk ⇔ gauge theory on brane
(Maldacena 1997)

Large Extra Dimensions

(Arkani-Hamed, Dimopoulos, Dvali, Antoniadis 1998)

Proposed as a solution to the 'hierarchy problem' in particle physics, i.e. why is the scale of gravity $\ell_P \sim 10^{-33}$ cm so much smaller than the electroweak scale $\ell_{EW} \sim 10^{-16}$ cm ?

Revival of Kaluza-Klein ideas… $q_n \sim 10^{-16}$ paradigm

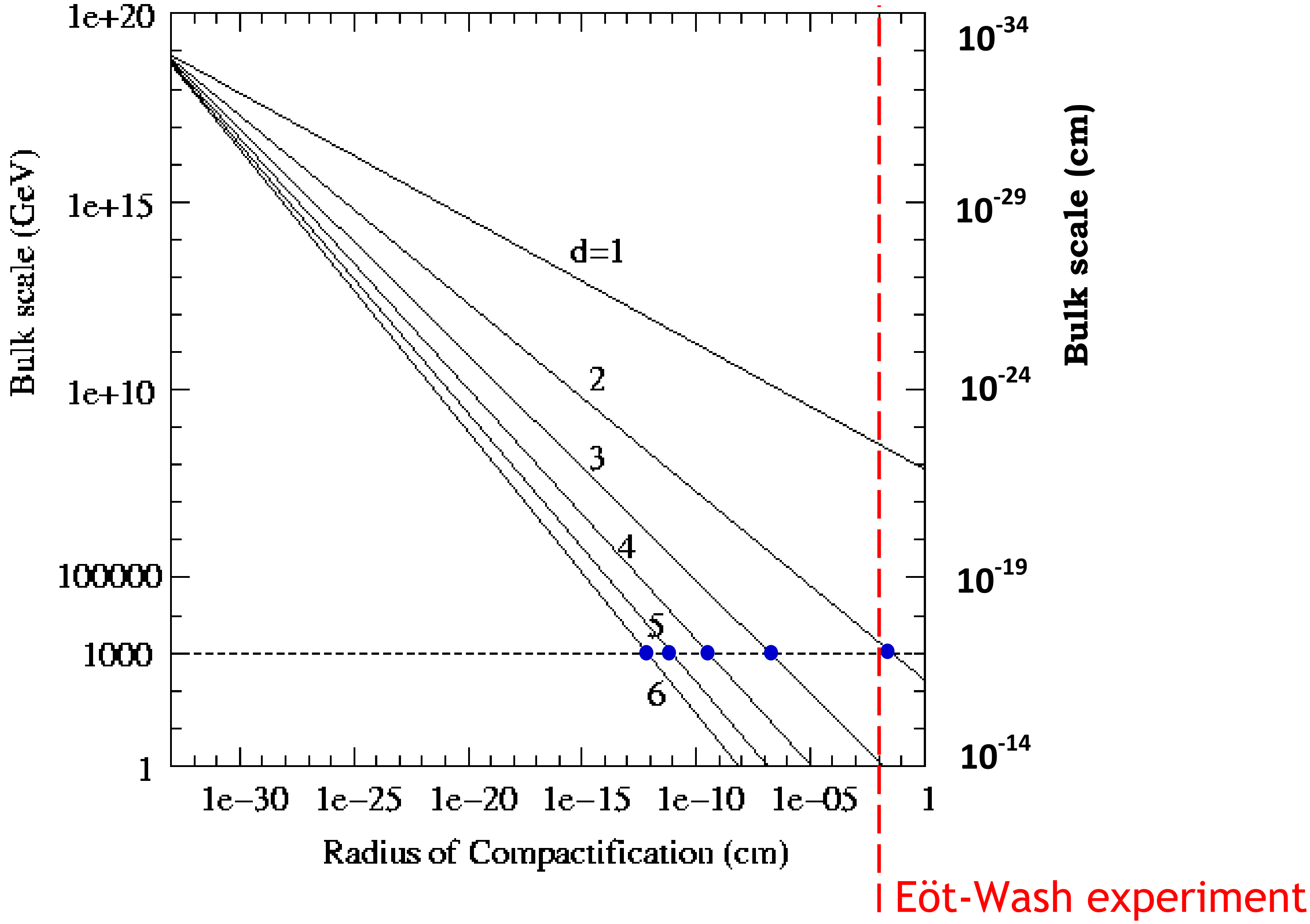
- Spacetime is $M^{(4)} \times K^{(n)}$ (bulk);
  Standard Model fields are confined to $M^{(4)}$domain wall (brane);
  Only gravity accesses the bulk…

Gravity is as strong as the electroweak interaction, but appears weak on the brane because only a small part of the graviton wavefunction is intercepted

If $K^{(n)} = \left[\boldsymbol{S}^{(1)}\right]^n$ (*n*-torus), then $G_N = \frac{G_{4+n}}{(2\pi R_c)^n}$ (Newton's constant)

Rewrite in terms of Planck length

$$\ell_P = \sqrt{16\pi G_N} = \frac{\sqrt{16\pi G_{4+n}}}{(2\pi R_c)^{n/2}} = \frac{\ell_{EW}^{1+n/2}}{(2\pi R_c)^{n/2}}$$



Hierarchy is due to the large size of some of the extra dimensions

Cute idea, but creates new hierarchy of large and small dimensions…

► Graviton field in $4+n$ dimensions: $g_{\mu\nu}(X) = \eta_{\mu\nu} + h_{\mu\nu}(X)$

$$\left(\nabla^2 + \partial_y^2 - \partial_t^2\right) h_{\mu\nu}(x,y) = 0$$

$$h_{\mu\nu}(X) = \sum_n h_{\mu\nu}^{(n)}(x)\, e^{iny/R_c}$$

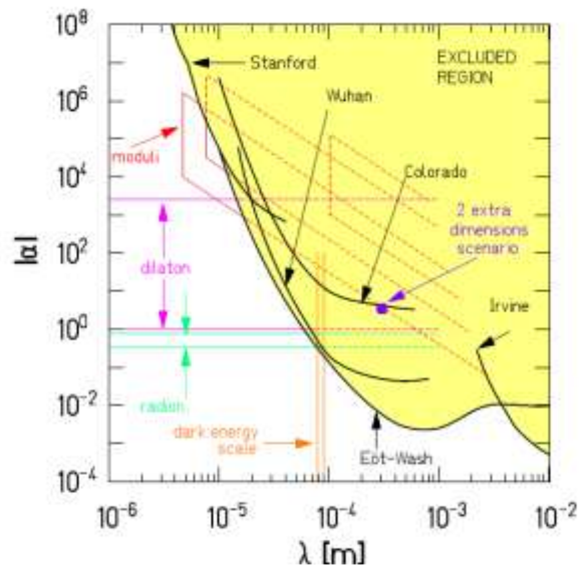
$$\left(\nabla^2 - \partial_t^2 + \frac{\vec{n}^2}{R_C^2}\right) h_{\mu\nu}^{(n)}(x) = 0$$

Static limit: $\left(\nabla^2 + \frac{\vec{n}^2}{R_C^2}\right) h_{\mu\nu}^{(n)}(\vec{x}) = 0$

Solves to give a wavefunction $h_{\mu\nu}^{(n)} \sim \frac{e^{-|\vec{n}|r/R_C}}{r}$

$h_{\mu\nu}^{(1)}$ creates modifications to Newton's Law:

$$F_{12} = G_N\left(\frac{1}{r} + \alpha\,\frac{e^{-r/R_c}}{r}\right)$$

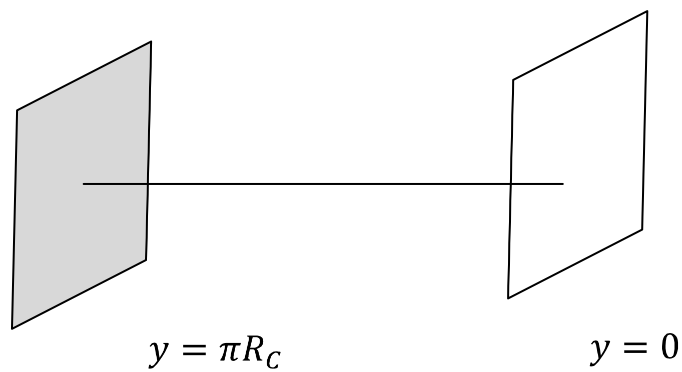


Warped Extra Dimensions

(Randall, Sundrum 1999)

Solution to the hierarchy problem which uses no unnaturally large/small numbers, but develops an 'exponential hierarchy'.

► Spacetime is $M^{(4)} \times S^{(1)}/Z_2$ (orbifold compactification);
Standard Model fields are confined to one $M^{(4)}$domain wall;
Gravity is strong on another $M^{(4)}$domain wall;
Only gravity accesses the bulk, but is exponentially damped across it…



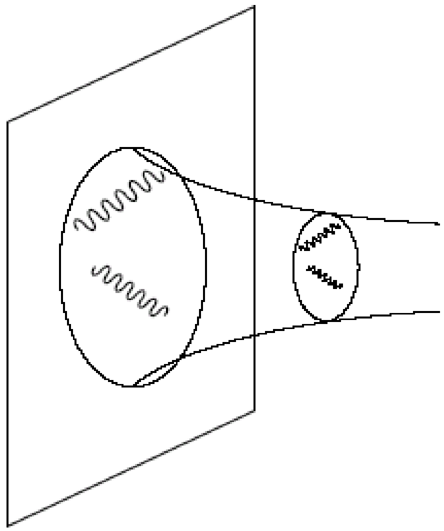
$$y \to y + 2\pi R_C$$

$$y \to -y$$

some fine tuning of vev's

$$K = \sqrt{-24M^3\Lambda} = V_0 = -V_\pi$$

RS metric : $ds^2 = e^{-2Ky}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$



Metric contracts exponentially along the 'AdS$_5$ throat'

$\Rightarrow$ measuring sticks contract exponentially

$\Rightarrow$ wavelengths increase exponentially

$\Rightarrow$ energies drop exponentially

At $y = 0 :\ e^{-Ky} = 1$ $\Rightarrow$ gravity is strong

At $y = 2\pi R_C :\ e^{-\pi R_C K} \sim 10^{-16}$ if $R_C K \approx 11.6$ $\Rightarrow$ gravity is weak

Hierarchy is due to the exponential damping of the graviton wavefunction

More ingenious than ADD, but requires fine tuning and a negative cosmological constant

Effective Field Theories

(AdS-CFT models)

▶ Bulk in RS is of AdS_5 type ⇔ Dual with a gauge theory on the brane

(Maldacena AdS-CFT correspondence)

Since gravity is weak in the bulk, dual gauge theory on the brane is a strongly interacting one

Arkani-Hamed, Porrati and Randall (2000)

Rattazzi and Zaffaroni (2001)

For every bulk field there is a CFT operator on the brane

$$\Phi(X) \Leftrightarrow \mathcal{O}$$

i.e.

strongly coupled gauge theory → $\langle \mathcal{O}\mathcal{O} \ldots \mathcal{O} \rangle = \frac{\delta^n S_{\text{eff}}}{\delta\Phi\delta\Phi \ldots \delta\Phi}$ ← tower of KK states

Holographic Standard Model with Higgs boson as a Nambu-Goldstone boson

Gherghetta Tasi lectures 2010

reminiscent of technicolor…

Universal Extra Dimensions

(Appelquist, Cheng, Dobrescu 2001)

Small twist to original Kaluza-Klein idea… $q_n \sim 10^{-16}$ paradigm

▶ Spacetime is $M^{(4)} \times S^{(1)}/Z_2$ (orbifold compactification)

All Standard Model fields can access the bulk; each has a tower of states

$\gamma, \gamma^{(1)}, \gamma^{(2)}, \ldots \quad g, g^{(1)}, g^{(2)}, \ldots \quad W, W^{(1)}, W^{(2)}, \ldots \quad Z, Z^{(1)}, Z^{(2)}, \ldots$

$\ell, \ell^{(1)}, \ell^{(2)}, \ldots \quad q, q^{(1)}, q^{(2)}, \ldots$

In $M^{(4)} \times S^{(1)}$ (KK) once cannot have chiral fermions:

since $\Gamma^4 = \gamma_5$ i.e. Lorentz symmetry would be violated

In $M^{(4)} \times S^{(1)}/Z_2$ just that much `violation' is permitted…

(orbifold compactification)

Conservation of KK number/parity:

Particles have five-momentum $p = (E, \vec{p}, p_5)$ with $E^2 = M_0^2 + \vec{p}^2 + p_5^2$

Because of compactification/periodic boundary condition: $p_5 = \frac{n}{R_C}$

Hence, $E^2 = M_0^2 + \vec{p}^2 + \frac{n^2}{R_C^2} = M_n^2 + \vec{p}^2$ where $M_n^2 = M_0^2 + \frac{n^2}{R_C^2}$ (as in KK)

n is the KK number

Process: A + B → C + D + …

$$p_5(\mathrm{A}) + p_5(\mathrm{B}) = p_5(\mathrm{C}) + p_5(\mathrm{D}) + \cdots$$

$$\frac{n_A}{R_C} + \frac{n_B}{R_C} = \frac{n_C}{R_C} + \frac{n_D}{R_C} + \cdots$$

$$n_A + n_B = n_C + n_D + \cdots$$

conservation of KK number…

Some modes wind around compact dimension, crossing orbifold fixed points

at these points $y \to -y$ i.e. $p_5 \to -p_5 \Rightarrow n \to -n$: KK number flips sign

What is conserved is not KK number n ; but KK parity $(-)^n$

Process: A + B → C + D + …

$$(-)^{n_A}(-)^{n_B} = (-)^{n_C}(-)^{n_D} \ldots$$

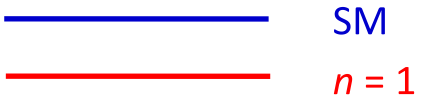
All SM fields have $n = 0$, i.e. KK parity $(-)^0 = +1$

All $n = 1$ KK modes have KK parity $(-)^1 = -1$

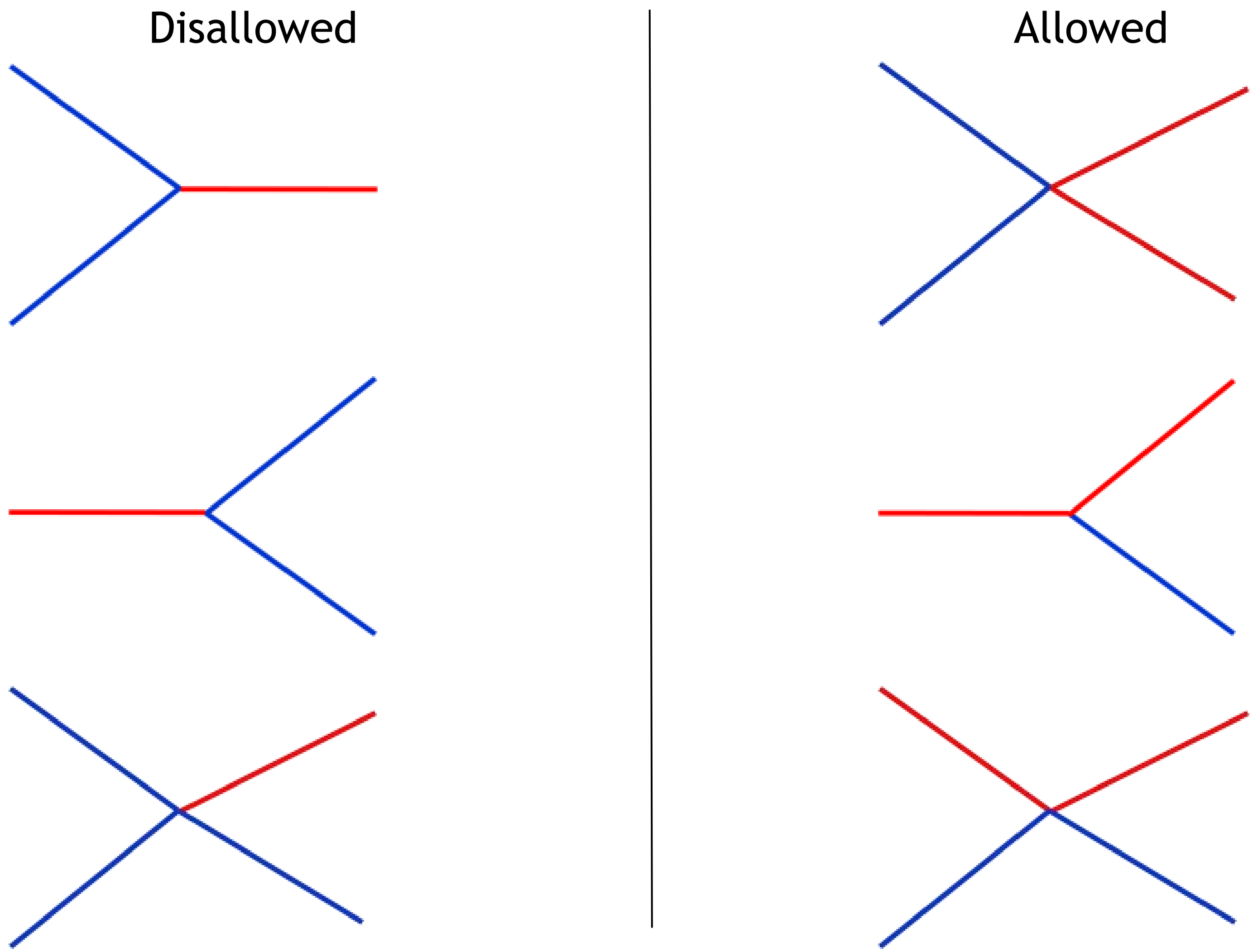
All $n = 2$ KK modes have KK parity $(-)^2 = +1$

$n = 1$ KK modes are similar to superparticles,

with KK parity instead of R parity



Universal Extra Dimensions (contd.)



▶ Lightest KK Particle (LKP) i.e. lightest n = 1 KK mode cannot decay

⇒ dark matter candidate!

Since all n = 1 modes have approximately the same mass $1/R_C$ radiative corrections determine their mass splitting…

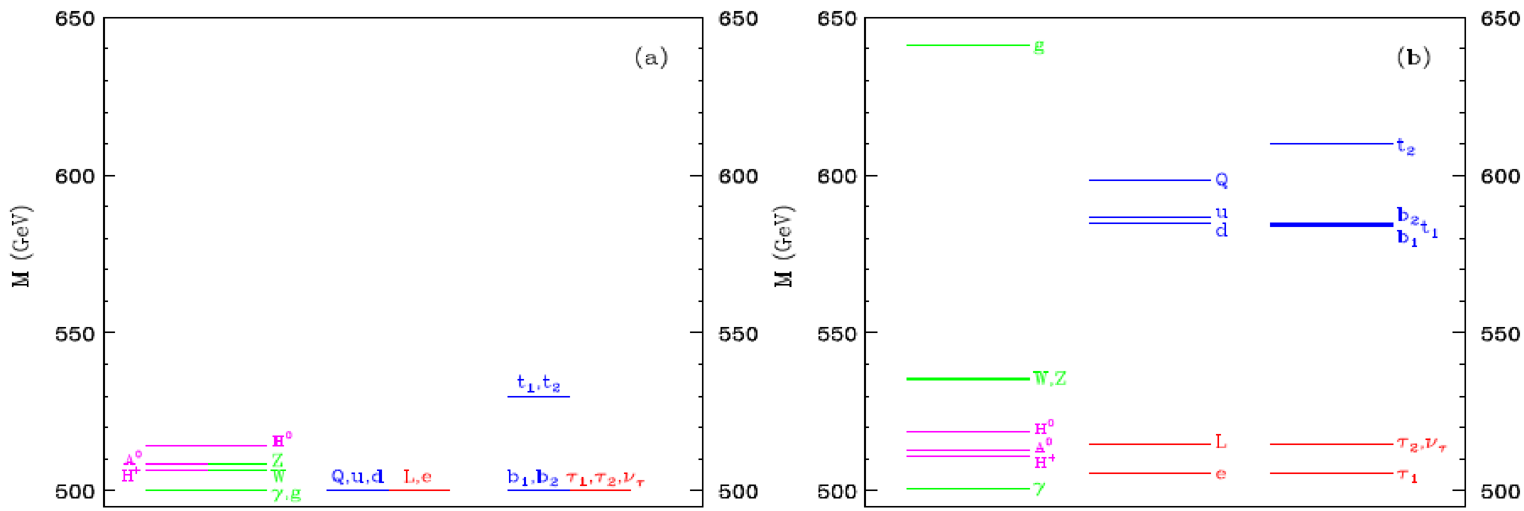
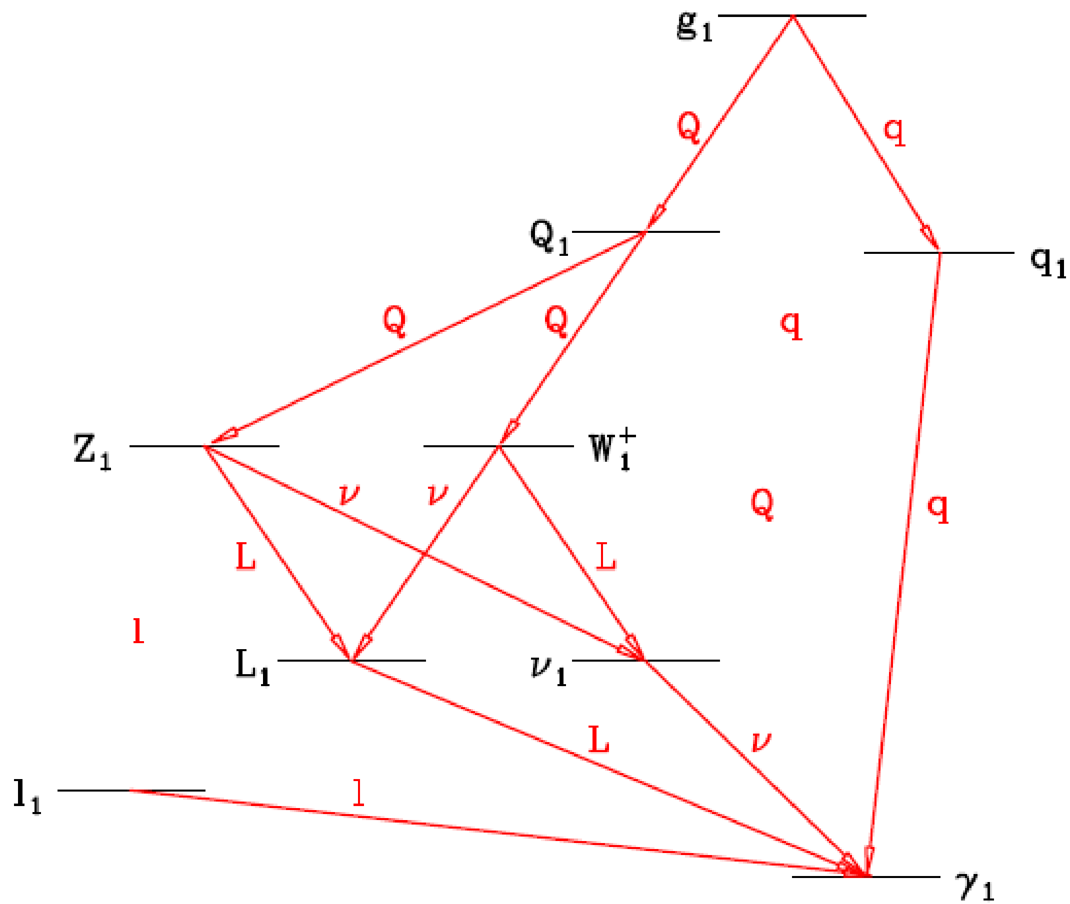


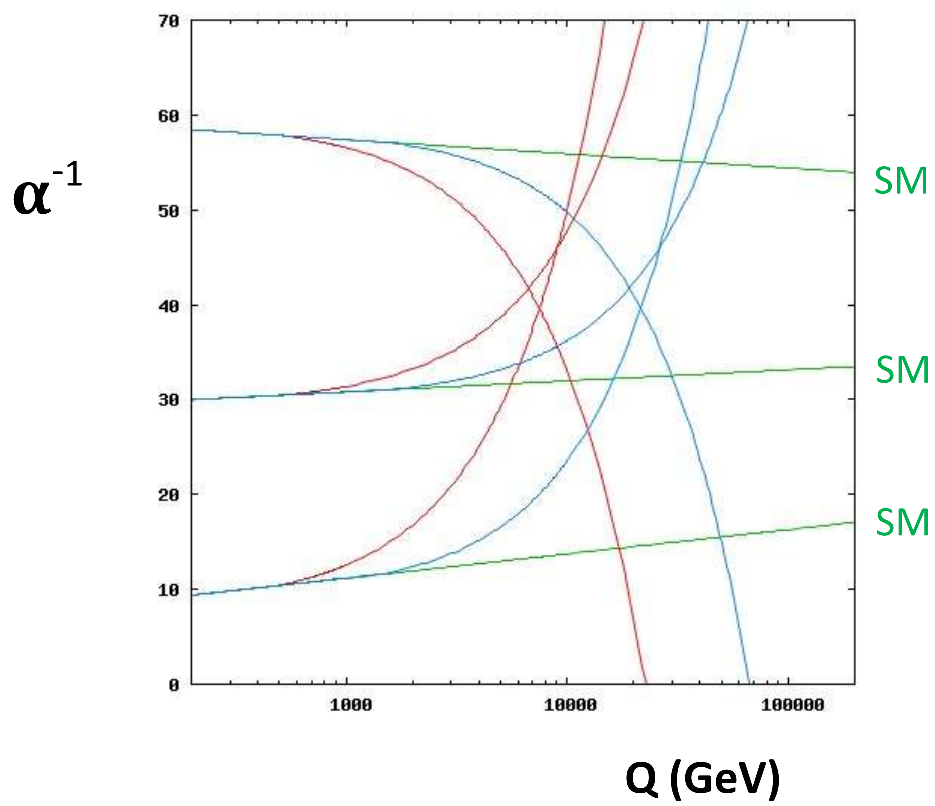
FIG. 6: The spectrum of the first KK level at (a) tree level and (b) one-loop, for $R^{-1} = 500$ GeV, $\Lambda R = 20$, $m_h = 120$ GeV, $\overline{m}_H^2 = 0$, and assuming vanishing boundary terms at the cut-off scale Λ.

Cheng, Matchev, Schmaltz 2002

- All KK decay chains end in the LKP $\gamma^{(1)}$



► Gauge coupling constants run very fast in UED models ;
beta functions receive contributions from all KK modes…

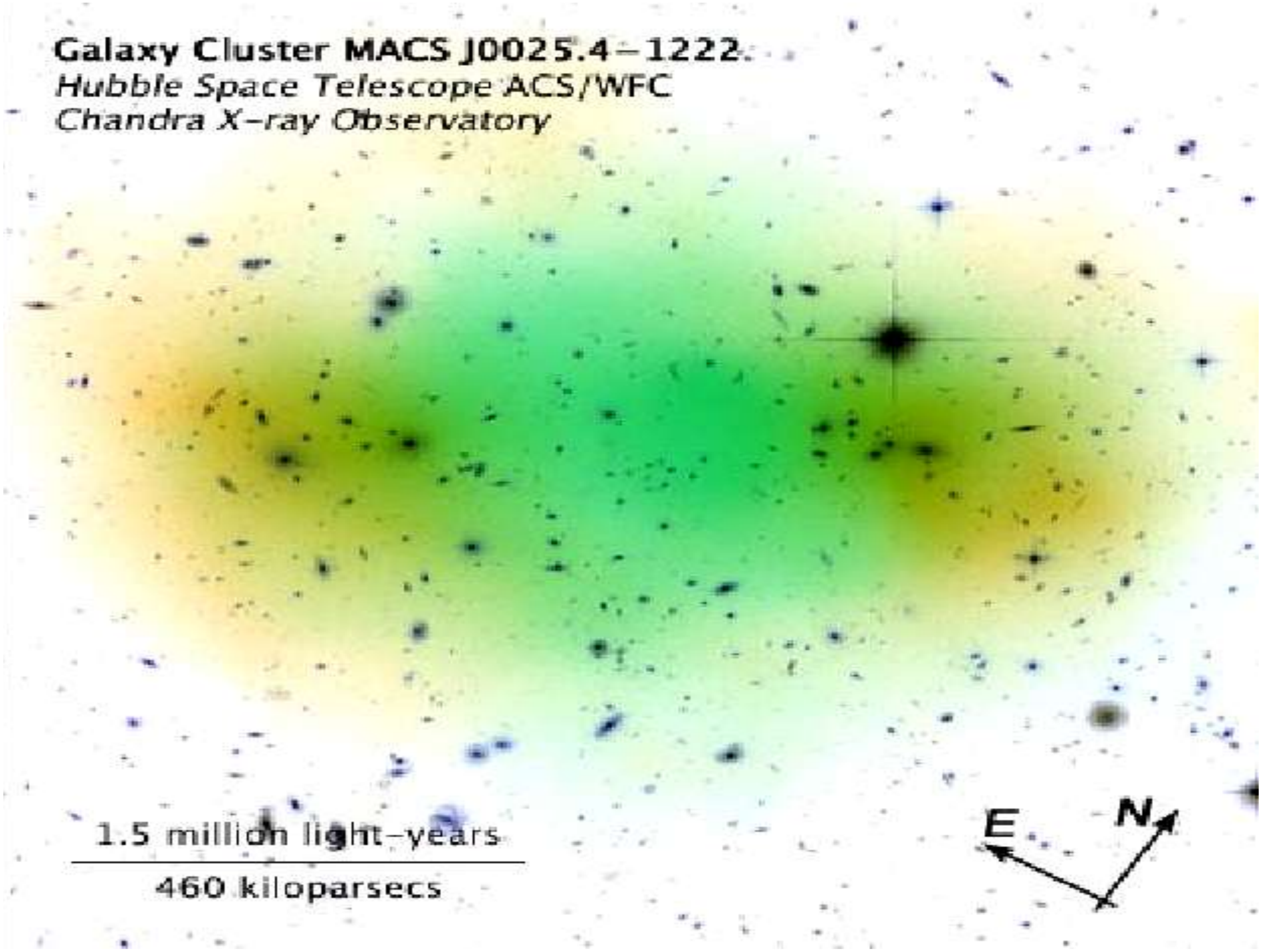


… approximate unification at: $Q = 20/R_C \Rightarrow$ choose cutoff $\Lambda = 20/R_C$

DARK MATTER INTRODUCTION

► Existence proofs:

- Oort (1932) : Milky Way has more mass than is observed
- Zwicky (1937): Luminous matter in the Coma cluster is only 10%
- Rubin et al (1983): Rotation curves of spiral galaxies indicate dark halo
- Walsh et al (1979) & others: Gravitational lensing indicates dark halo
- COBE (1994) and WMAP (2006) data indicate non-baryonic dark matter
  CMBR studies (2000 –): Type-1a SN, BAO, Lyman-α forest, structure formation
- Chandra (2006) : Bullet cluster – haloes pass through undistorted
- MACS J0025.4-1222 (2008) : similar to Bullet cluster
- Penny et al (2009) : Stability of dwarf spheroidal galaxies


Galaxy Cluster MACS J0025.4−1222
Hubble Space Telescope ACS/WFC
Chandra X-ray Observatory
1.5 million light-years
460 kiloparsecs
E
N

- Dark matter content in the Universe is best determined from WMAP data based on ΛCDM model with 6 parameters

Six-Parameter ΛCDM Fit [a]

Parameter	7-year Fit	5-year Fit
Fit parameters		
$10^2\Omega_b h^2$	$2.258^{+0.057}_{-0.056}$	2.273 ± 0.062
$\Omega_c h^2$	0.1109 ± 0.0056	0.1099 ± 0.0062
Ω_Λ	0.734 ± 0.029	0.742 ± 0.030
$\Delta^2_{\mathcal{R}}$	$(2.43 \pm 0.11) \times 10^{-9}$	$(2.41 \pm 0.11) \times 10^{-9}$
n_s	0.963 ± 0.014	$0.963^{+0.014}_{-0.015}$
τ	0.088 ± 0.015	0.087 ± 0.017
Derived parameters		
t_0	13.75 ± 0.13 Gyr	13.69 ± 0.13 Gyr
H_0	71.0 ± 2.5 km/s/Mpc	$71.9^{+2.6}_{-2.7}$ km/s/Mpc
σ_8	0.801 ± 0.030	0.796 ± 0.036
Ω_b	0.0449 ± 0.0028	0.0441 ± 0.0030
Ω_c	0.222 ± 0.026	0.214 ± 0.027
$z_{\rm eq}$	3196^{+134}_{-133}	3176^{+151}_{-150}
$z_{\rm reion}$	10.5 ± 1.2	11.0 ± 1.4

WMAP Seven-year Results: **Astrophys.J.Suppl. 192, 16 (2011)**

- Constrain any particle physics model by calculating relic density in that model and comparing with Ω_C

Interaction rate per particle : $\Gamma = n \, \sigma \, v$

number density (n) · cross-section (σ) · velocity (v)

Freeze-out time t_F : $\Gamma = H(t_F) \equiv \dot{a}(t_F)/a(t_F)$

Universe expands too fast for interaction to catch up

Frozen density n_F : $n_F = n(t_F)$

Convert to Ω_F in terms of critical density Ω_0

Compare with Ω_C from WMAP 0.222 ± 0.026

- Calculate number density $n(t)$ by using Boltzmann equation:

$$\frac{dn_i}{dt} = -3Hn_i$$ expansion of Universe

$$-\sum_j \langle\sigma_{ij}v_{ij}\rangle\left(n_i n_j - n_i^0 n_j^0\right)$$ co-annihilation

$$-\sum_{j\neq i}\left[\Gamma_{i\to j}\left(n_i - n_i^0\right) - \Gamma_{j\to i}\left(n_j - n_j^0\right)\right]$$ decays

$$-\sum_{j\neq i}\langle\sigma'_{ji}v_{ji}\rangle\left(n_X n_j - n_X^0 n_j^0\right)$$ thermal background

If there is only one kind of relic, reduces to the simple form

$$\frac{dn}{dt} = -3Hn - \langle\sigma v\rangle[n^2 - n_0^2]$$

reparametrise in terms of $x = m/T$ and $Y = n/s$ as

$$\frac{dY}{dx} = -\sqrt{\frac{\pi g_*}{45G_N}}\,\frac{m}{x^2}\,\langle\sigma v\rangle[Y^2 - Y_0^2]$$

where $g_* = 10.75 + \sum_B g_i\left(\frac{T_i}{T}\right)^4 + \sum_F \frac{7}{8} g_i\left(\frac{T_i}{T}\right)^4$

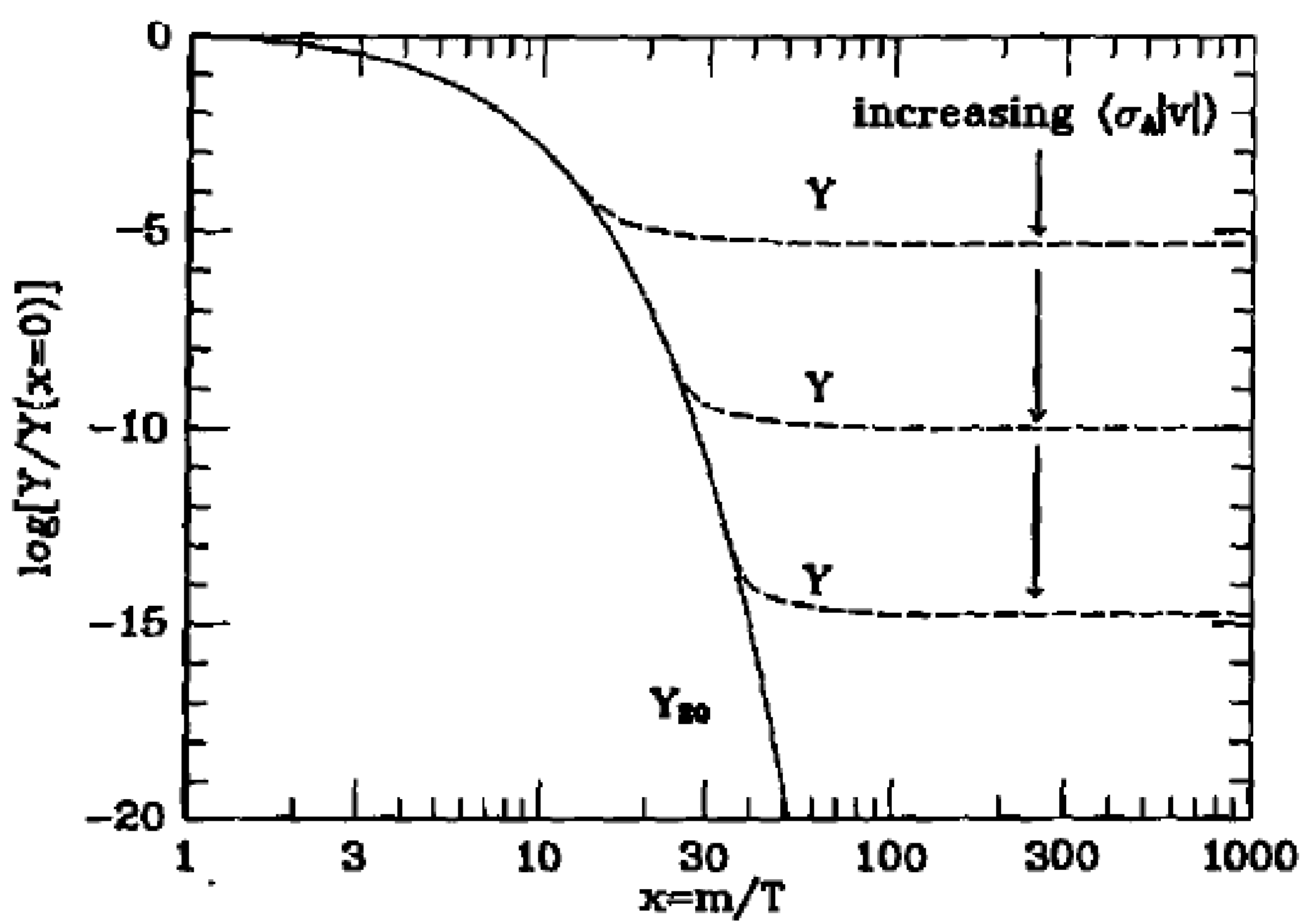


Fig. 5.1: The freeze out of a massive particle species. The dashed line is the actual abundance, and the solid line is the equilibrium abundance.

Kolb and Turner (1994)

LKP Dark matter

- In UED models, the Lightest KK Particle (LKP) is stable and hence will have a relic density… dark matter candidate!

  only real candidate is the $\gamma^{(1)} \approx B^{(1)}$ ($\theta_W^{(1)}$ is very small)

  Boltzmann equation:

$$\frac{dn_{LKP}}{dt} = -3Hn_{LKP} - \langle\sigma v\rangle\left[n_{LKP}^2 - n_{LKP,0}^2\right]$$

$$n_{LKP,0} = g_{LKP}\left(\frac{M_{LKP}T}{2\pi}\right)^{3/2} e^{-\frac{M_{LKP}}{T}} \qquad (g_{LKP} = 3 \text{ for massive boson})$$

$$\sigma v = A + Bv^2 + \cdots$$

$$\Omega_{LKP}h^2 \approx \frac{1.04 \times 10^9\, \ell_P x_F}{\sqrt{g_*}\left(A + \frac{3B}{x_F}\right)}$$

$$x_F = \frac{M_{LKP}}{T} = \log c(c+2)\sqrt{\frac{45}{8}}\frac{g_{LKP}M_{LKP}\left(A + \frac{6B}{x_F}\right)}{2\pi^3 \ell_P \sqrt{g_* x_F}}$$

$$g_* \approx 92$$

Require only to calculate A and B …

$$\langle \sigma v \rangle \approx \frac{95 g_1^4}{324 \pi m_{B^{(1)}}^2}$$

Many ingredients:

$$\sigma\left(B^{(1)}B^{(1)} \to f\bar{f}\right) = \frac{N_c (g t_w)^4 \left(Y_{f_L}^4 + Y_{f_R}^4\right)}{72 \pi s^2 \beta^2} \left(-5s(2m^2+s)L - 7s\beta\right)$$

$$\sigma\left(B^{(1)}B^{(1)} \to \phi\phi^*\right) = \frac{(g t_w Y_\phi)^4}{12 \pi s \beta}$$

$$\sigma\left(B^{(1)}B^{(1)} \to H^{(2)} \to t\bar{t}\right) = \frac{g^2 t_w^4 m_w^2}{36 \beta m} \frac{\Gamma_{t\bar{t}}^{H^{(2)}}}{(s - m_{H^{(2)}}^2)^2 + 4 - m_{H^{(2)}}^2 \Gamma_{H^{(2)}}^2} \left(3 + \frac{s(s-4m^2)}{4m^4}\right)$$

$$\Gamma_{H^{(2)}} = \Gamma_{t\bar{t}}^{H^{(2)}} + \Gamma_{HH}^{H^{(2)}} + \Gamma_{AA}^{H^{(2)}}$$

$$\Gamma_{t\bar{t}}^{H^{(2)}} = \frac{y_t \alpha_s^2 m}{12 \pi^3} \log^2(\Lambda^2 R^2)$$

- Compare with Ω_C from WMAP at 1σ :

$$850 \text{ GeV} < M_{LKP} < 900 \text{ GeV}$$

Servant and Tait 2003

Kong and Matchev 2006

Burnell and Kribs 2006

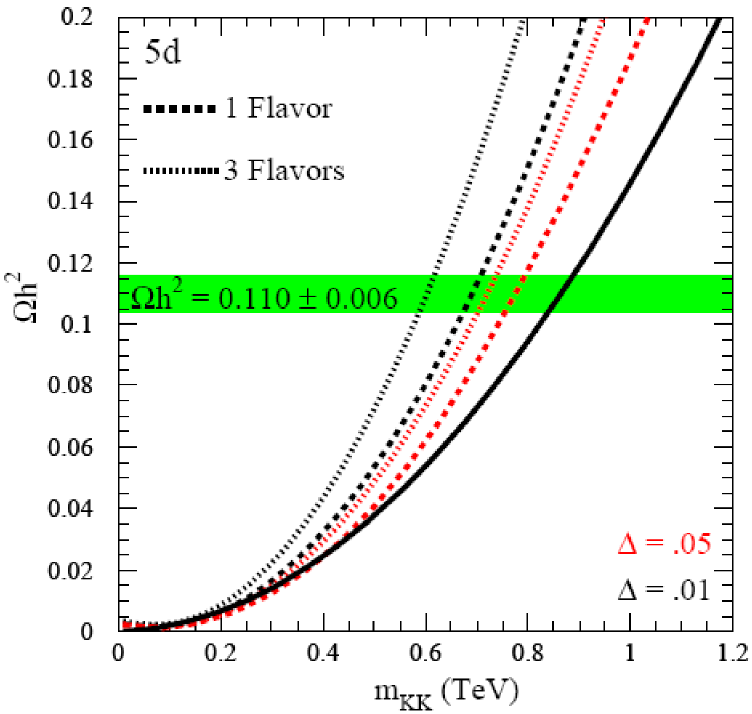
Kakizaki, Matsumoto, Senami 2005, 2006

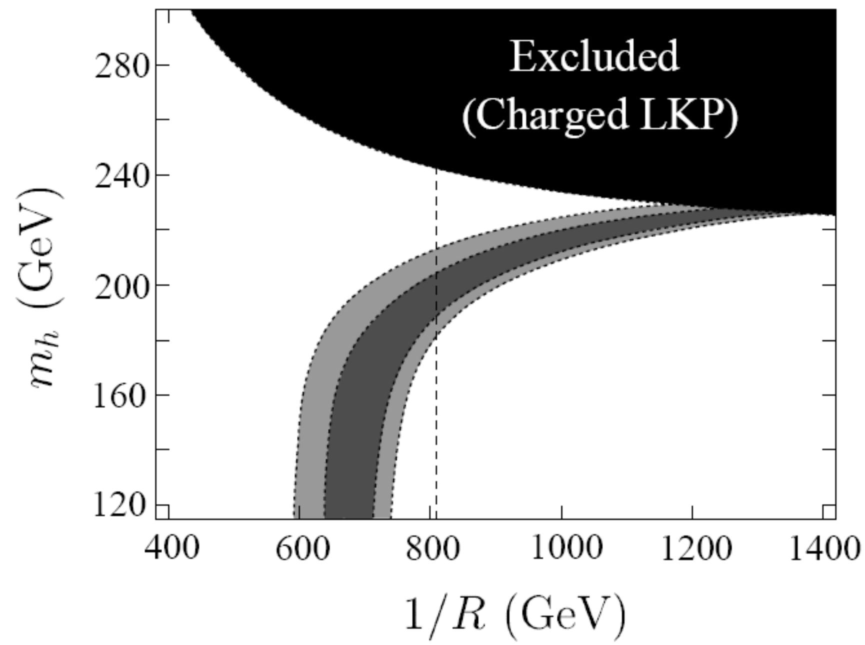
One-component coannihilation is too simplistic

KK modes are nearly degenerate ⇒ many coannihilation modes

inclusion of n = 2 modes

Hooper and Profumo 2007





$$600 \text{ GeV} < R_C^{-1} < 1400 \text{ GeV}$$

for $\Lambda R_C = 20$

Branon Dark matter

- Consider the brane to have its own dynamics

its fluctuations are quantised as ‘branons’

Branon mass acts as a cutoff scale, providing good UV behaviour of KK tower calculations…

Sundrum 1999, Bando et al 1999, Dobado & Maroto 2001, Kugo and Yoshioka 2001, Cembranos et al 2003

Branons are WIMPs :
interact very weakly with SM fields, typical missing energy signatures at colliders and very large branon lifetime ⇒ relic density

Branon coupling to SM is parametrised by f_0 , mass by M_0

Tevatron has pushed M_0 up to around 1 TeV

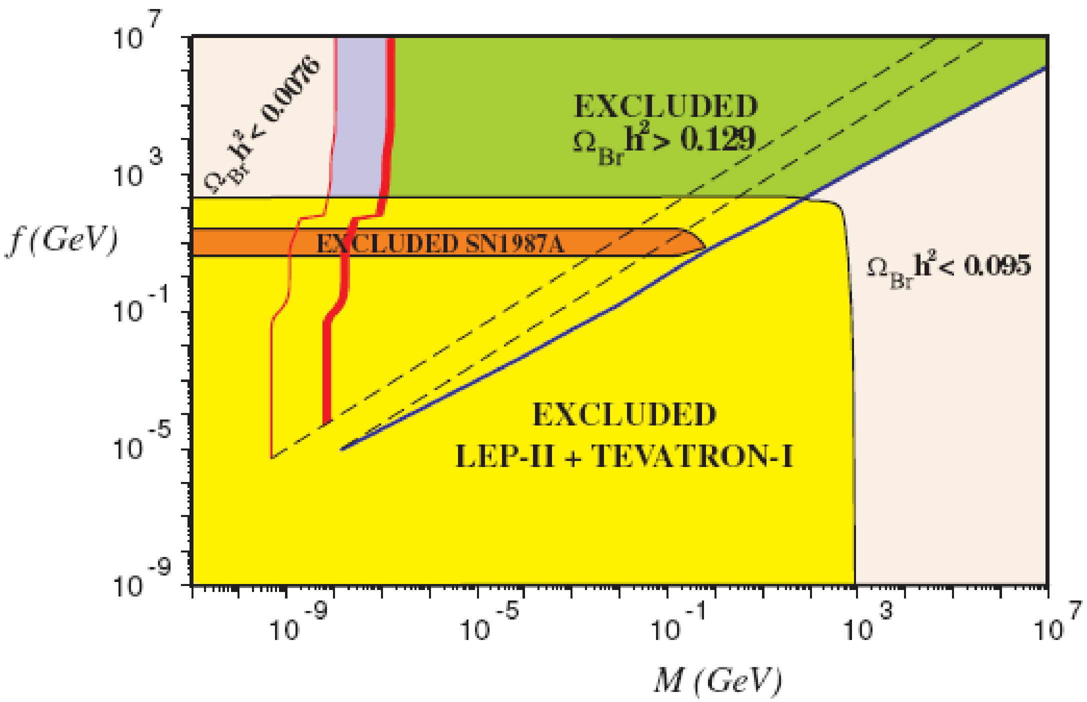


FIG. 3: Relic abundance in the $f - M$ plane for a model with one branon of mass M. The two lines on the left correspond to the $\Omega_{Br}h^2 = 0.0076$ and $\Omega_{Br}h^2 = 0.129 - 0.095$ curves for hot-warm relics, whereas the right line corresponds to the latter limits for cold relics (see [8] for details). The lower area is excluded by single-photon processes at LEP-II [7, 11] together with monojet signal at Tevatron-I [7]. The astrophysical constraints are less restrictive and they mainly come from supernova cooling by branon emission [8].

Cembranos et al 2005

BULK NEUTRINOS

- Revival of an old idea: put a sterile neutrino in the bulk

Arkani-Hamed et al 1999
Kadota 2008

Now mostly relevant in the RS context

These neutrinos have no gauge interactions,
but are produced by interactions with radion (dilaton) field in the early Universe; remain as relics ⇒ dark matter candidates

Require its mixing with active neutrino species to be negligible

Calculate relic density in the usual way :
constrains the radion-bulk neutrino coupling λ

$$\lambda^2 \sim 0.3 \times 10^{-20} \left(\frac{1MeV}{m_N}\right) \left(\frac{m_r}{100GeV}\right)$$

NEW TWIST TO MOND

- MOdified Newtonian Dynamics as a solution to problem of rotation curves etc, was proposed long ago (1983); doesn't work for CMBR, colliding galaxy clusters etc.

- Collisonless CDM model also faces problems in explaining density profiles of DM haloes

  Simulations indicate sharp cusp towards centre of halo; observation indicates much smoother behaviour

  Consistent with a self-interaction of DM particles

  Spergel and Steinhardt 2000

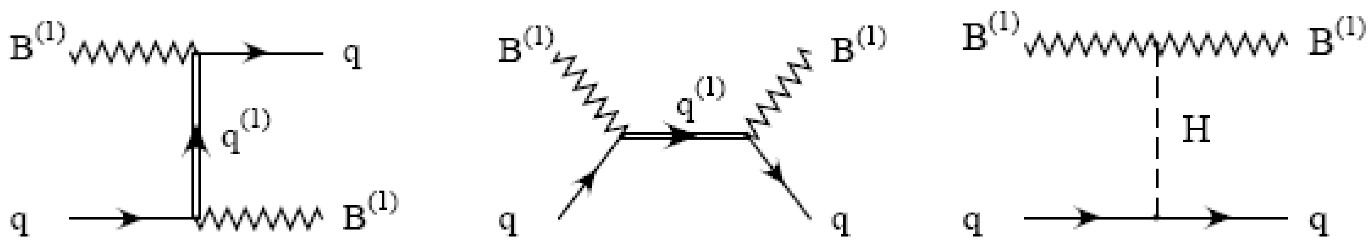
- Suggestion that this DM self-interaction could be a short-range modification of gravity as in ADD model

Works only for $n = 3$ Requires $R_C \sim 10^{-7}$cm $M_X \sim 10^{-16}$ GeV

Qin, Pen, Silk 2005

Direct Detection Experiments

▸ Interaction of LKP with matter: Servant and Tait 2002



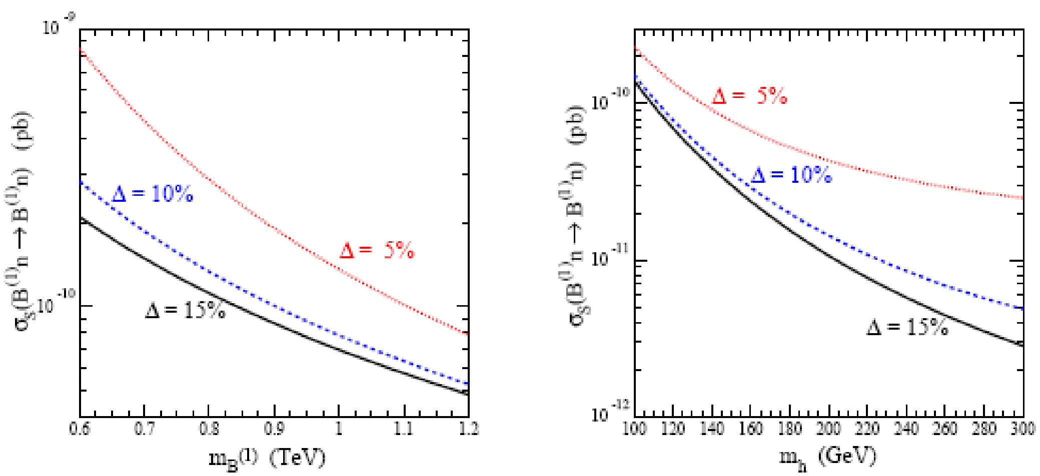


Figure 13: The spin-independent $B^{(1)}$-nucleon elastic scattering cross section. In the left frame, m_h has been fixed to 120 GeV. In the right frame, $m_{B^{(1)}}$ has been fixed to 1 TeV. The quantity Δ is defined as $\Delta \equiv (m_{q^{(1)}} - m_{B^{(1)}})/m_{B^{(1)}}$. From Ref. [32].

In general : $\sigma \sim 10^{-10}$ pb i.e. too small for current experiments to see

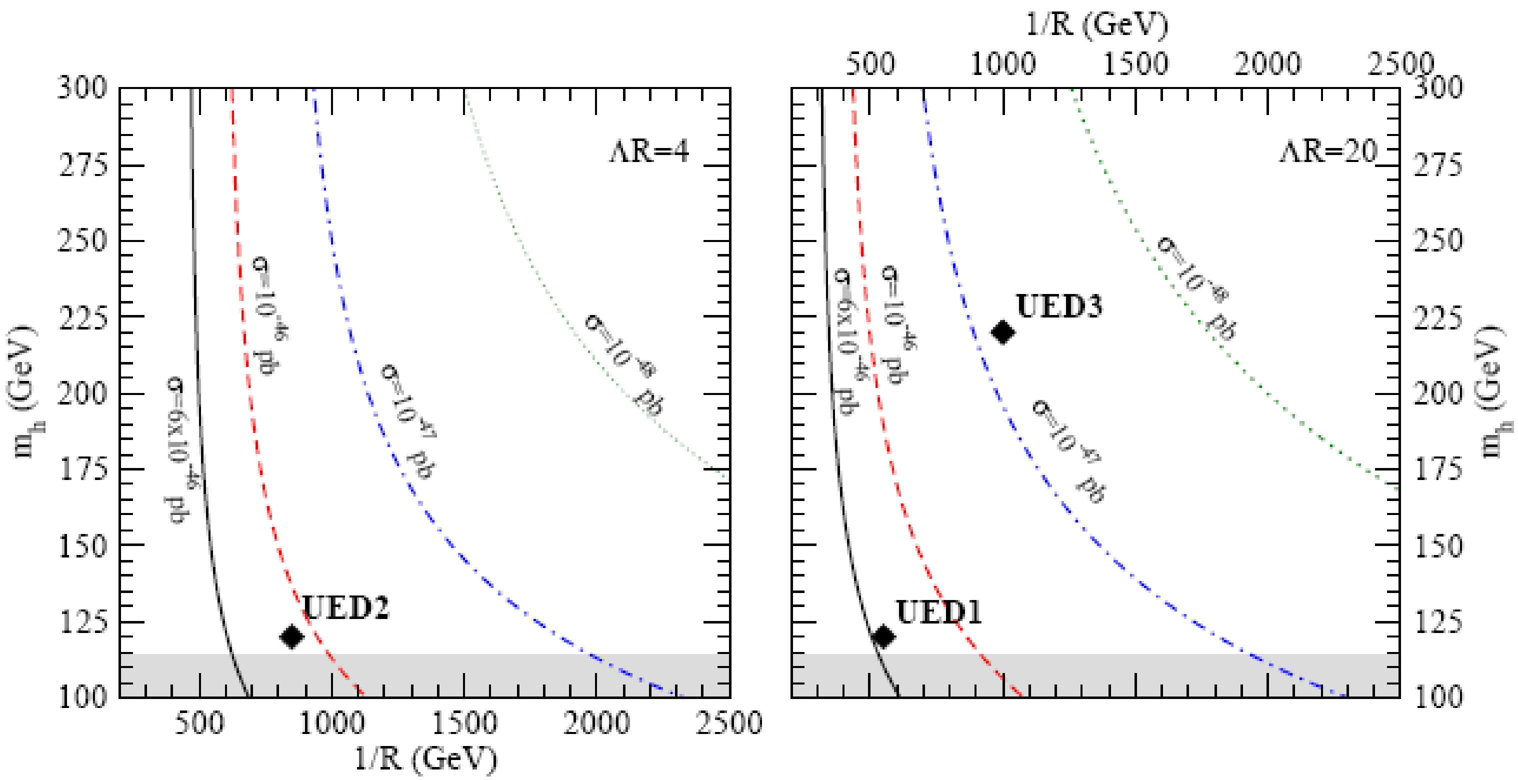
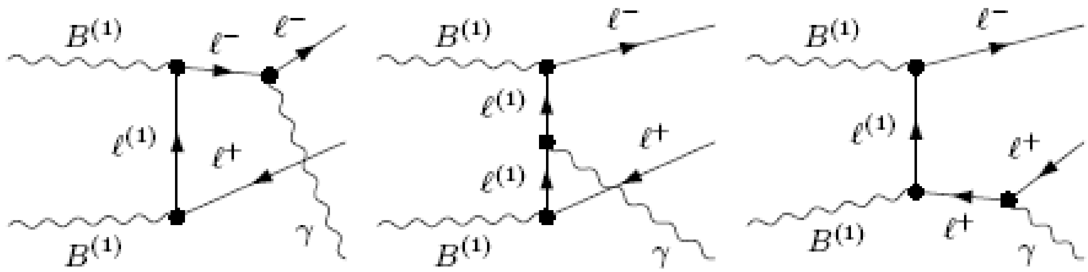


Figure 14: Contours of constant spin-independent $B^{(1)}$-proton scattering cross sections in the $(1/R, m_h)$ plane, for two choices of $\Lambda R = 4$ and 20. The reach of the future direct detection experiments "Xenon-1 ton" and "Super-CDMS C" approximately correspond to the black solid line and to the red dashed line. We also indicate the location of three of the benchmark models of Appendix A.

Hooper and Profumo 2007

Indirect Detection Experiments

- Gamma rays



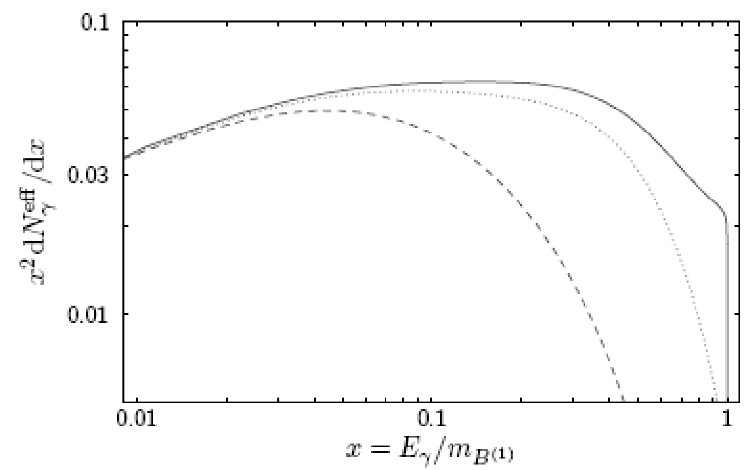
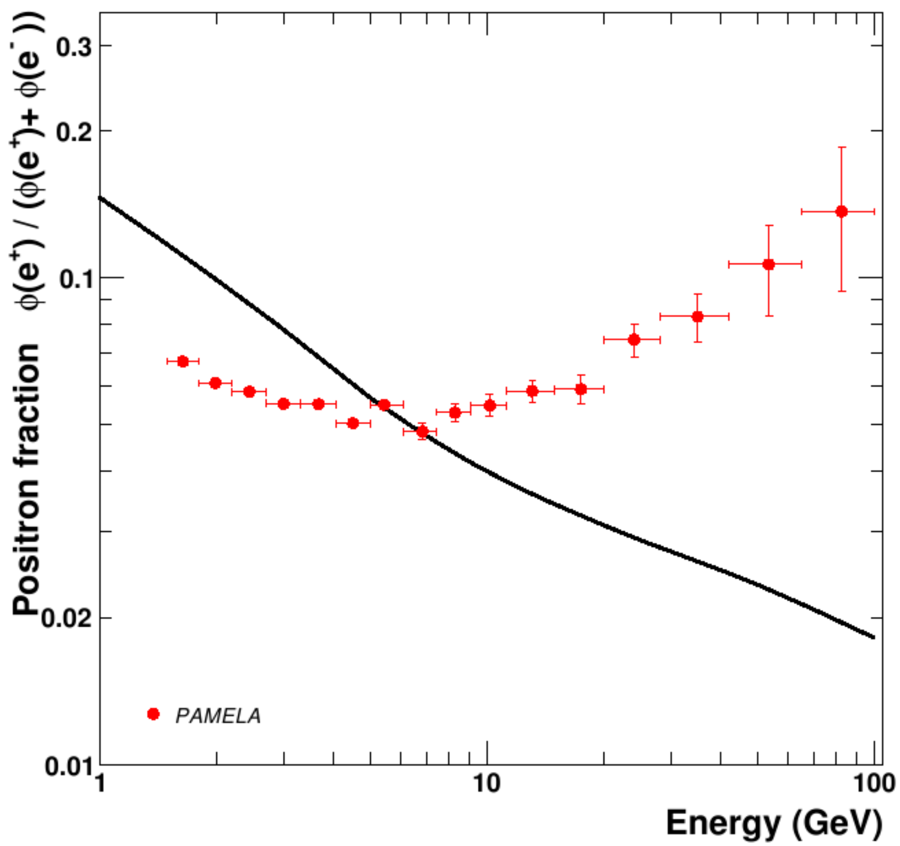


Figure 17: The spectrum of photons per $B^{(1)}B^{(1)}$ annihilation (solid line). Shown as a dashed line is the contribution from quark fragmentation alone. The dotted line is the quark fragmentation contribution plus the contribution from τ leptons. From Ref. [127].

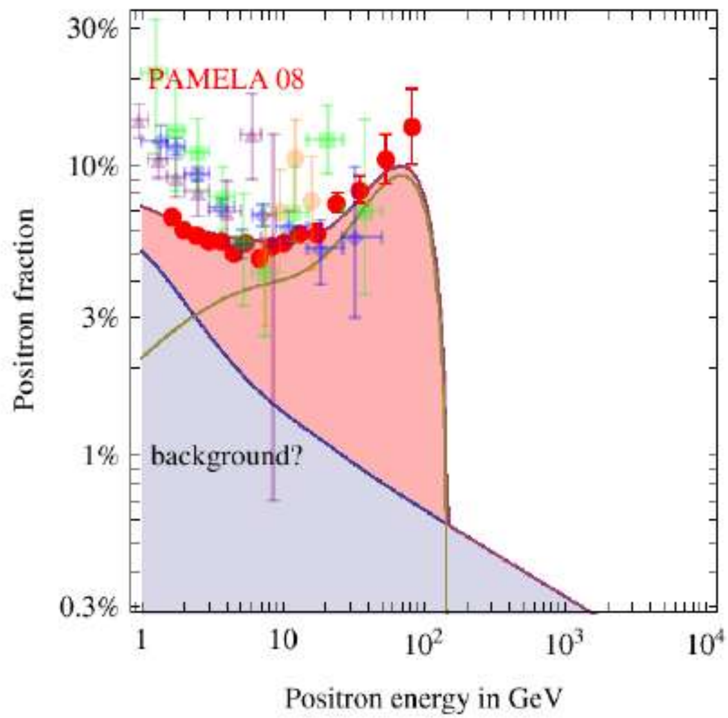
Bergstrom et al 2006

- Antimatter:

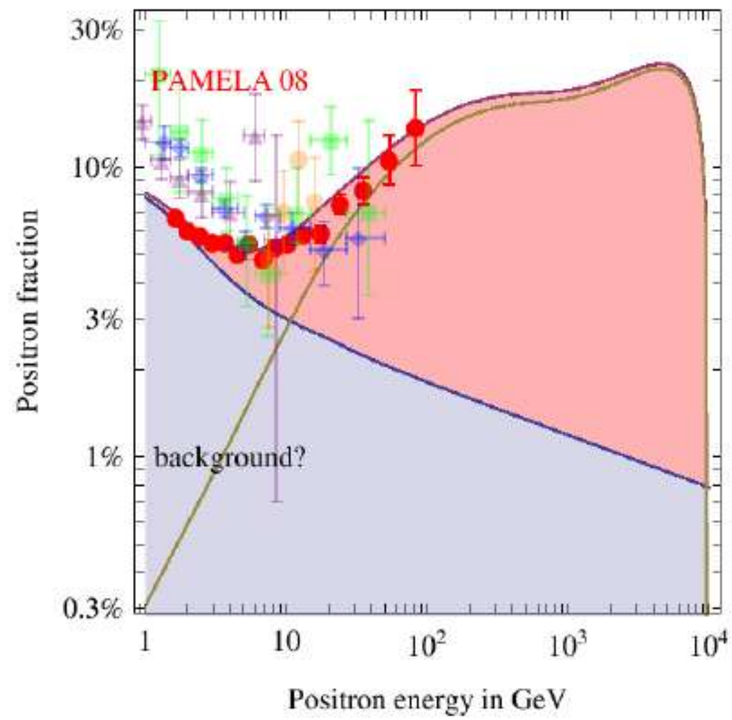
PAMELA sees a positron excess



Consistent with DM coannihilation



M_{DM} = 150 GeV into W^+W^-

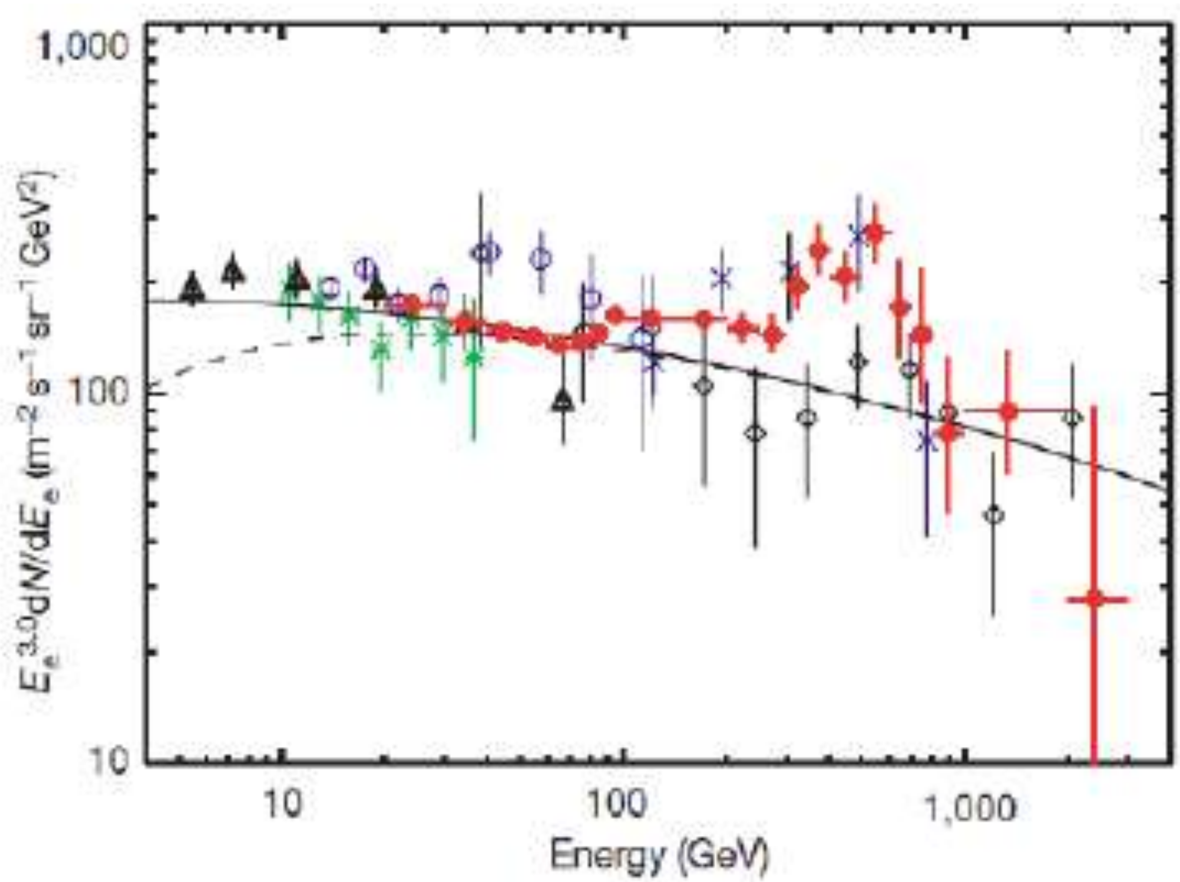


M_{DM} = 10 TeV into W^+W^-

Can LKP DM fit the bill?

No, require a more complicated model

ATIC sees an electron excess

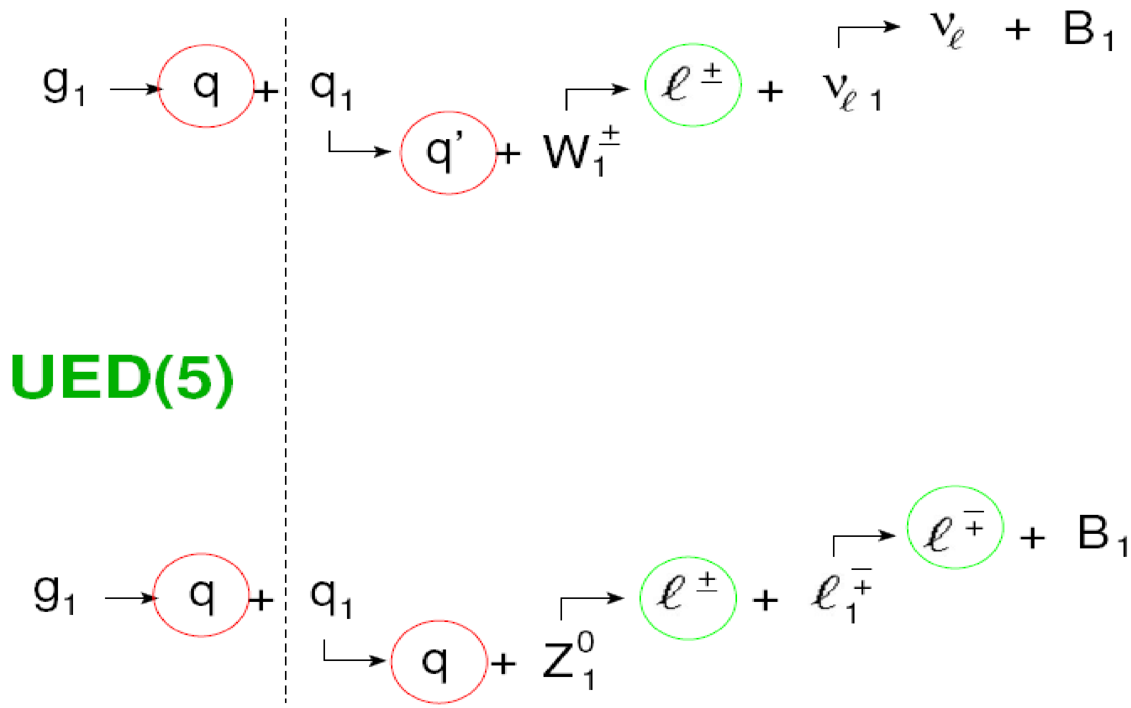


Consistent with DM particle of mass 620 GeV

More consistent with UED

Collider Experiments

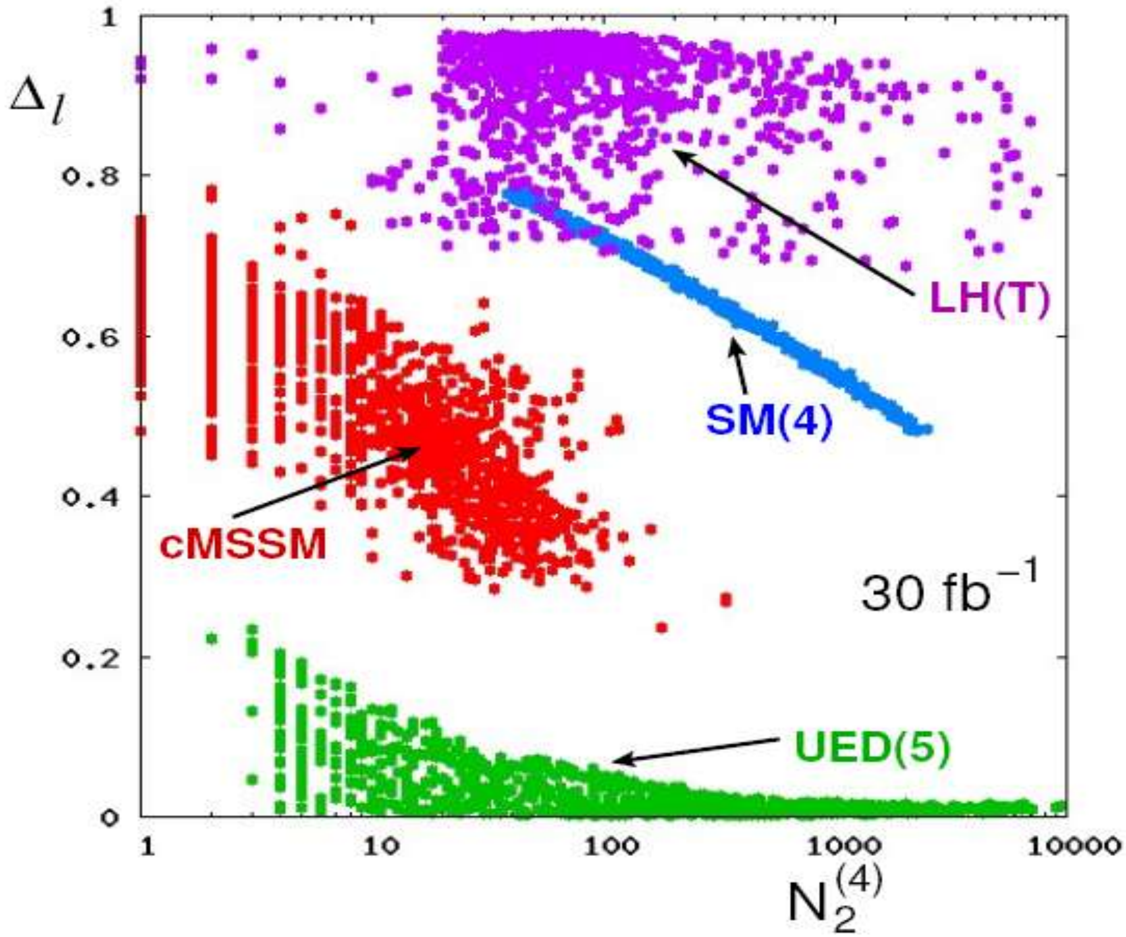
- UED Signals closely resemble SUSY signals, e.g. at the LHC



Cross sections are large and one should see these in a few years running

Critical issue is to distinguish from SUSY

Many suggestions: measure spin, detect n = 2 states, correlate jet multiplicity



Bhattacherjee, Kundu, Rai and SR 2009

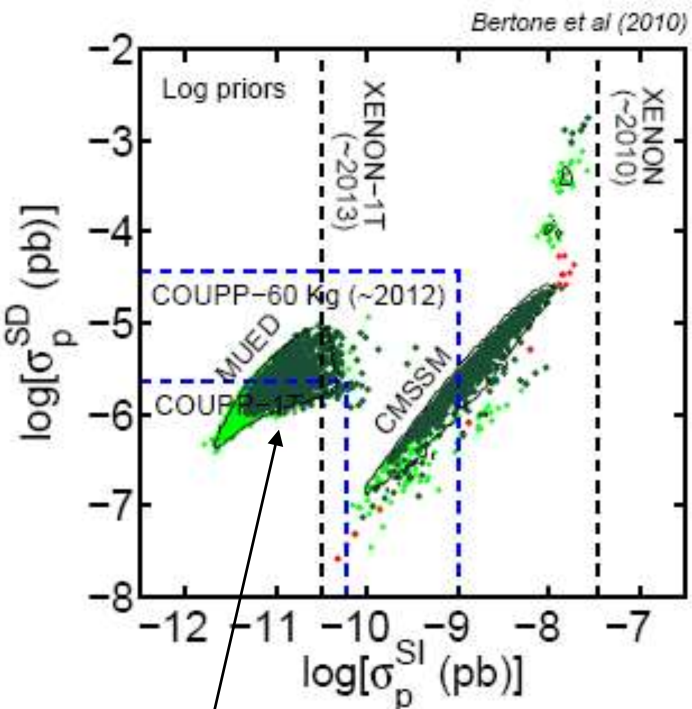
Global fits of the Minimal Universal Extra Dimensions scenario

Gianfranco Bertone[1,2], Kyoungchul Kong[3,4], Roberto Ruiz de Austri[5] and Roberto Trotta[6]

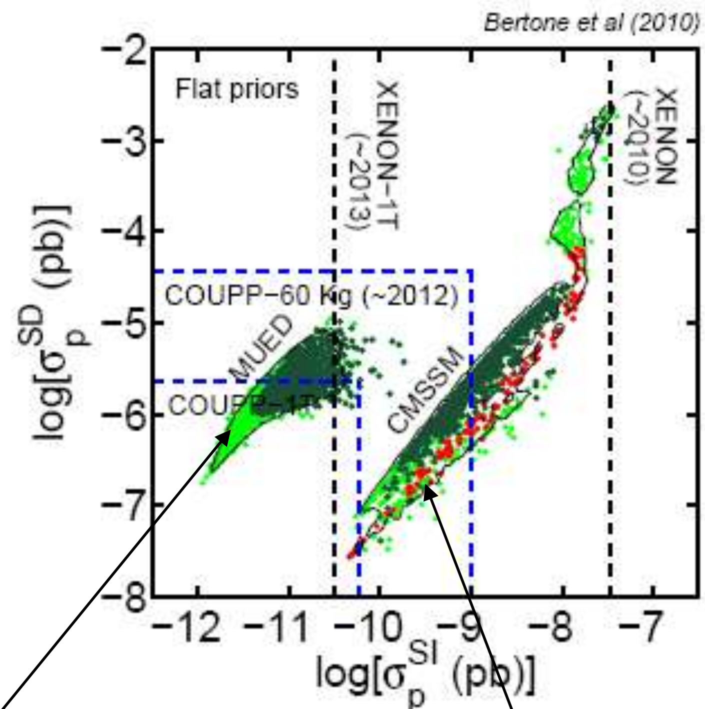
PRD 83, 036008 (2011)

Parameter	Mean	Best fit	68% range	95% range
LKP: the sole constituent of DM				
m_h (GeV)	198.4	215	[173 : 222.3]	[135.3 : 233.8]
R^{-1} (GeV)	640.9	641.6	[574.1 : 707.5]	[536.5 : 843.5]
ΛR	55	38	[23 : 86]	[12 : 98]
m_γ (GeV)	641	642	[574.7 : 707.8]	[537.3 : 843.4]
$\Omega_{\rm KK}h^2$	0.115	0.111	[0.1 : 0.128]	[0.091 : 0.145]
$\log(\sigma_{\rm p}^{\rm SI}$ (pb))	-11.1	-11.2	[-11.4 : -10.8]	[-11.7 : -10.5]
$\log(\sigma_{\rm p}^{\rm SD}$ (pb))	-5.7	-5.7	[-6 : -5.5]	[-6.3 : -5.2]
LKP: subdominant constituent of DM				
m_h (GeV)	224	226.7	[202.4 : 245.4]	[163.6 : 265.4]
R^{-1} (GeV)	602.9	607.4	[528.9 : 677.2]	[477.1 : 795.5]
ΛR	55	66	[25 : 86]	[12 : 98]
m_γ (GeV)	603.5	607.9	[529.7 : 677.5]	[478 : 795.4]
$\Omega_{\rm KK}h^2$	0.08	0.08	[0.057 : 0.108]	[0.035 : 0.127]
$\log(\sigma_{\rm p}^{\rm SI}\xi$ (pb))	-11.3	-11.4	[-11.6 : -11]	[-11.8 : -10.6]
$\log(\sigma_{\rm p}^{\rm SD}\xi$ (pb))	-5.8	-5.9	[-6.1 : -5.5]	[-6.3 : -5.2]

PURE LKP DM



SUBDOMINANT LKP DM



LHC : 7 TeV, 1 fb^{-1}

LHC : 14 TeV, 100 fb^{-1}

95% C.L.

• inaccessible to LHC

SUMMARY

- Extra dimensions are an exciting alternative to BSM physics models such as technicolor and supersymmetry
- New models are inspired by string theory, but not exactly derived from it
- Modern Kaluza-Klein theories focus on large/warped compact dimensions, off-diagonal terms in the metric are no longer considered important
- UED models offer an interesting dark matter candidate
- Other suggestions also exist: branons, neutrinos, …
- Modification of Newtonian gravity at small distances
- Weak prospects for direct detection, but better for indirect detection
- Collider detection may be the best bet… global fits… LHC/ILC…

Thank You