# Kaluza-Klein Dark Matter: a review

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*Based on work with*

-Tim Tait: hep-ph/0206071 (NPB)
hep-ph/0209262 (New J.Phys.)

-Bertone & Sigl: hep-ph/0211342 (PRD)

-Kaustubh Agashe: hep-ph/0403143 (PRL)
hep-ph/0411254 (JCAP)

-Dan Hooper: hep-ph/0502247

**ADD** models

$R \sim meV^{-1}$ (flat)

only gravity in bulk

- radion dark matter, m~meV
- branon dark matter
- KK graviton dark matter

(all fine-tuned)

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**$TeV^{-1}$** X-dims

$R \sim TeV^{-1}$ (flat)

→ gauge bosons in bulk

→ all SM fields in bulk
"Universal" X-dims

- radion dark matter m~meV; (fine-tuned)
- KK dark matter

WIMP!

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*Hierarchy pb solved*

**Warped** geometries (Randall-Sundrum)

(AdS)

$R \sim M_{Pl}^{-1}$ but $M_{KK} \sim TeV$

- radion unstable

if GUT in bulk → - KK dark matter

WIMP!

# *WIMP KK dark matter*

So far, two working models :

## ✔ Universal Extra Dimensions (UED)

WIMP = Lightest KK particle (LKP)
stability symmetry = KK parity

## ✔ Warped GUTs

WIMP = Lightest $Z_3$ charged particle (LZP)
stability symmetry = $Z_3$ symmetry

+ a potential link between the LZP and baryogenesis...

# Literature on KK dark matter: the complete list

Kolb & Slansky '84 — Thought about it, but in 1984 $R^{-1}$~TeV was inconceivable...

Dienes, Dudas & Gherghetta '99
Mohapatra& Perez-Lorenzana '02 — mentionned the idea in passing

**KK dark matter in UED:**

- Servant & Tait '02 — Detailed relic density calculation
- Cheng, Feng & Matchev '02 — Direct and indirect detection
- Servant & Tait '02 — Direct detection
- Majumdar '02 — Direct detection
- Hooper & Kribs '02 — Prospects for neutrino telescopes
- Bertone, Servant & Sigl '02 — Indirect detection
- Hooper & Kribs '04 — Positron excess
- Bergstrom, Bringmann, Eriksson & Gustafsson '04
- Baltz & Hooper '04
- Bergstrom, Bringmann, Eriksson & Gustafsson II '04 — Indirect detection
- Kakizaki, Matsumoto, Sato & Senami '05 — A 2nd look at the relic density calculation

+ superWimp KK graviton papers

**Warped KK dark matter:**

- Agashe & Servant '04
- Agashe & Servant II '04 — Model building, relic density, direct detection, collider signatures ...
- Hooper & Servant '05 — Indirect detection

# LKP dark matter in Universal Extra Dimensions

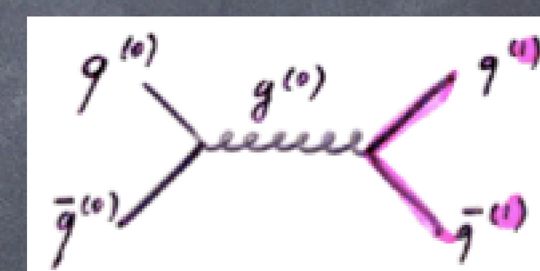
UED : ALL SM particles propagate into flat dimensions Appelquist, Cheng & Dobrescu '01

Translational invariance along the 5th dimension ⇛ Conservation of Kaluza-Klein number in the interactions of the effective 4D theory

For instance:


forbidden allowed

Consequence: n=1 KK excitations can only be produced by pairs



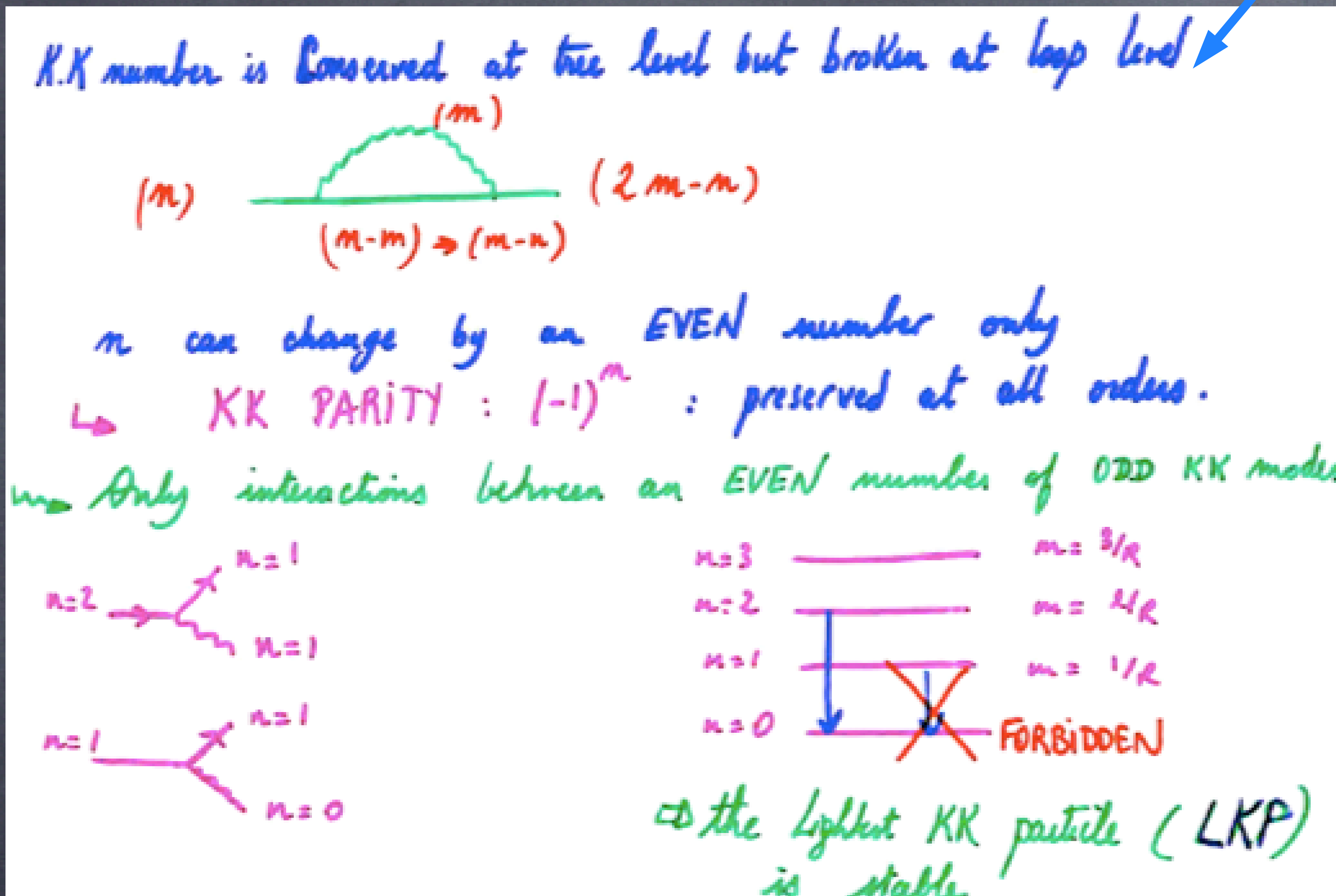

⇛ Collider constraints on 1/R are weak

$R^{-1} \gtrsim 300$ GeV for $\delta = 1$

$R^{-1} \gtrsim 500$ GeV for $\delta = 2$

Symmetry is broken by the orbifold but there remains a discrete symmetry called **Kaluza-Klein Parity: $(-1)^n$**

*by the orbifold we impose to recover a chiral theory*




⇛Odd KK modes can only couple by pairs

⇛The Lightest KK mode (LKP) is stable

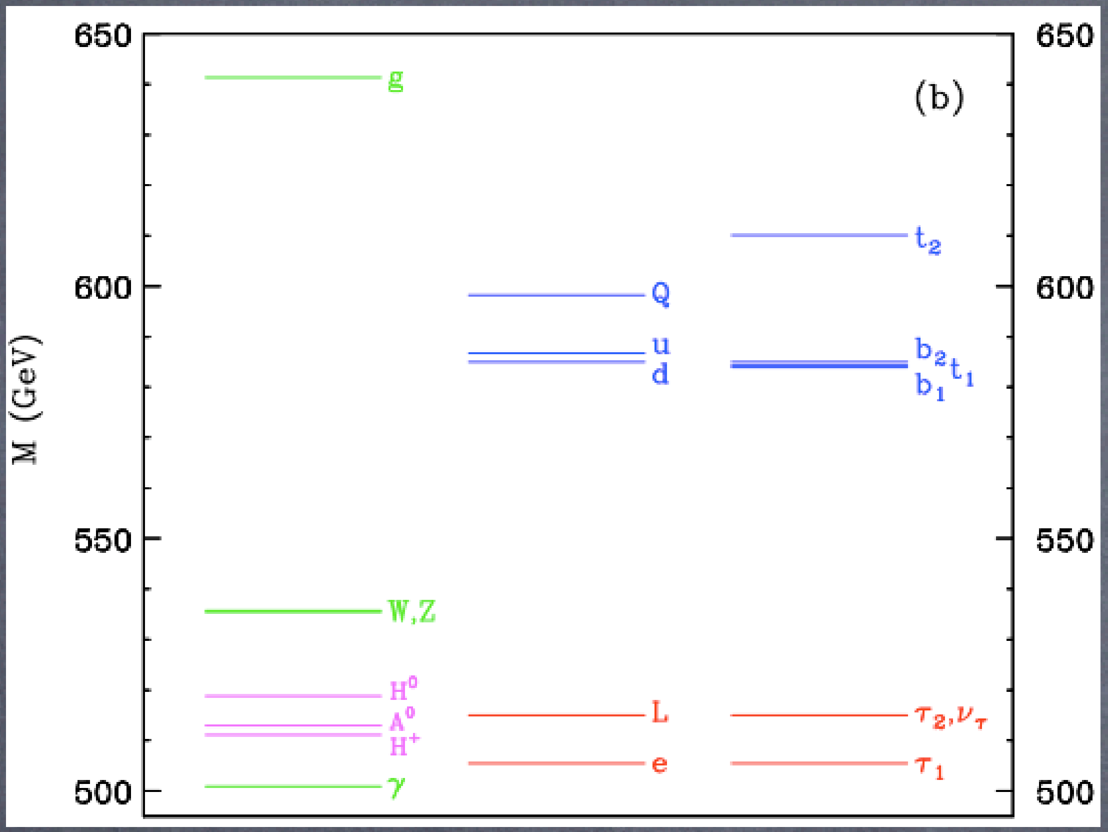
The Kaluza-Klein photon is an excellent dark matter candidate

Phenomenology is very similar to supersymmetry with conserved R-parity

All KK particles decay into the LKP

# 1-loop spectrum of 1rst KK modes

Cheng, Matchev & Schmaltz'02




assuming:1/R=500 GeV, $\Lambda R = 20, m_h = 120$ GeV
and vanishing boundary terms at the cutoff $\Lambda$

→ LKP: most likely a $\gamma^1$ (actually a $B^1$)

Another intriguing possibility: LKP=KK graviton (see Feng & al.)

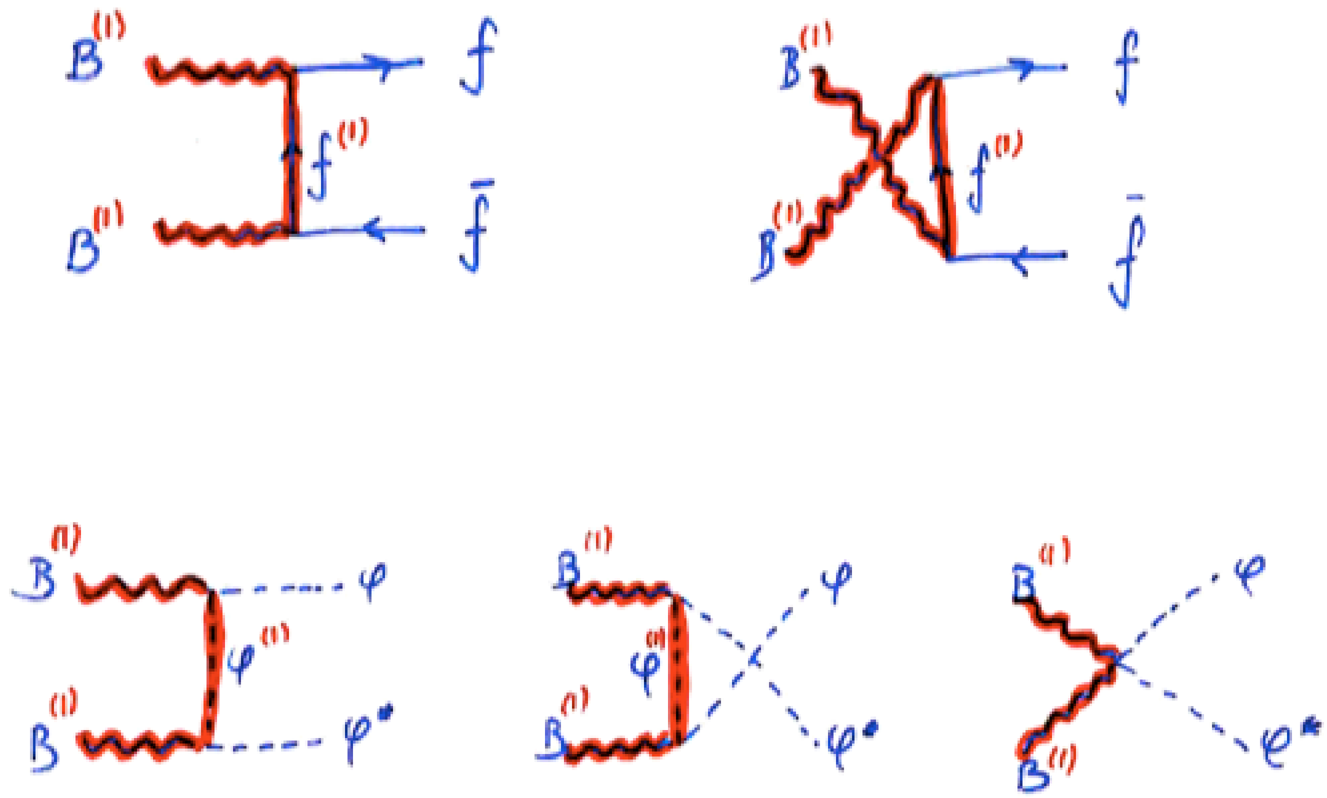
# Relic density predictions

REMINDER :

$$\Omega h^2 \simeq \frac{10^9}{m_{Pl}} \frac{x_F}{\sqrt{g_*}} \frac{\text{GeV}^{-1}}{\langle \sigma_{eff} v \rangle}$$

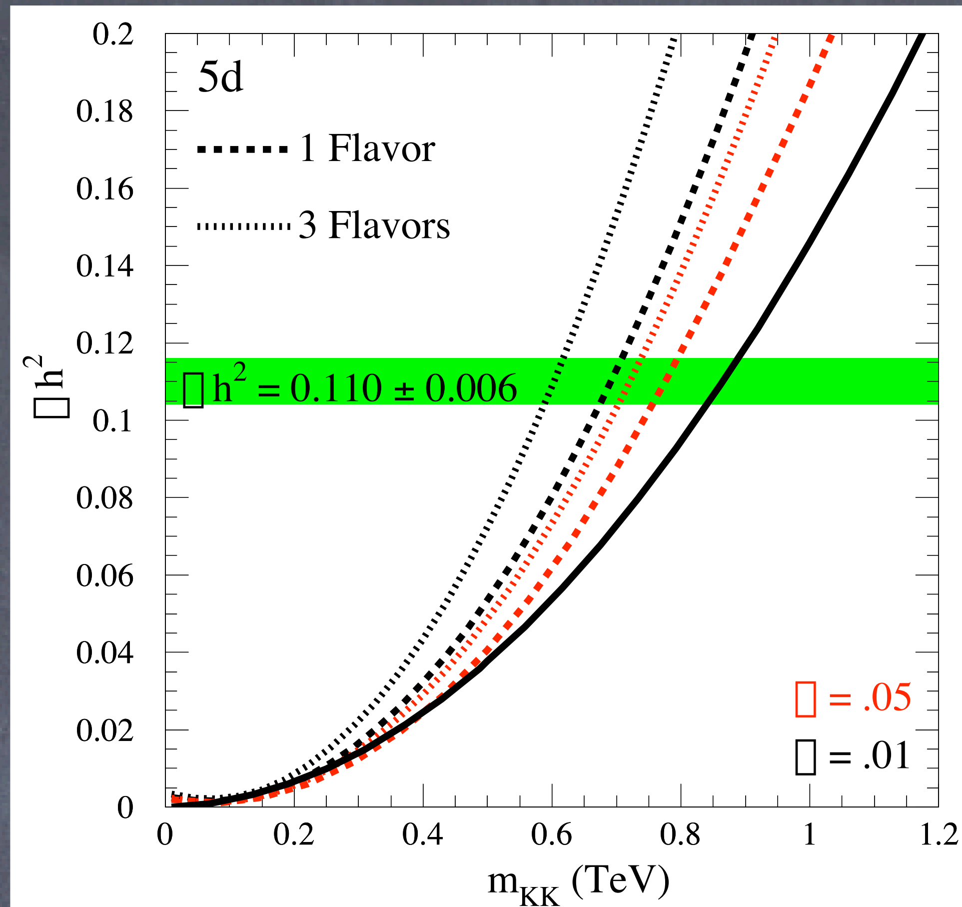
$\Omega h^2 \simeq 0.11 \rightsquigarrow \langle \sigma_{eff} v \rangle \sim 1\ \text{pb}$ $\quad$ ($x_F \simeq 25$-$35$)

Annihilation cross sections

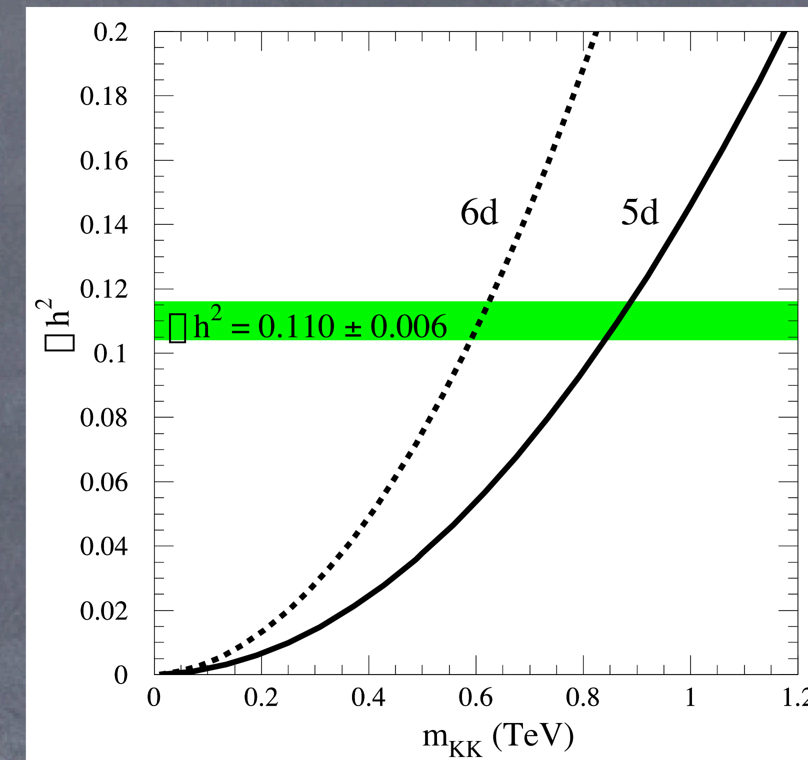


## ✔ Coannihilation effects

Servant-Tait




## ✔ Possible effect of additional dimension

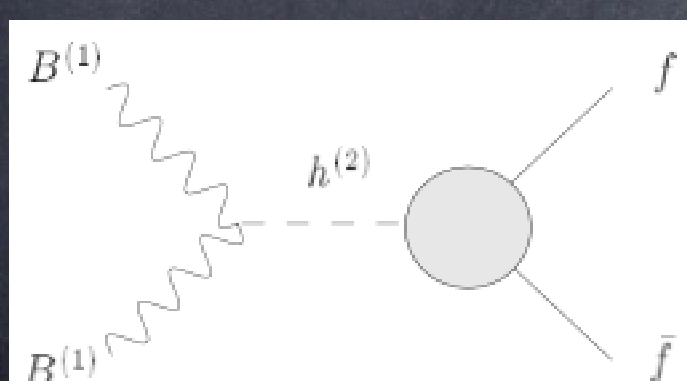


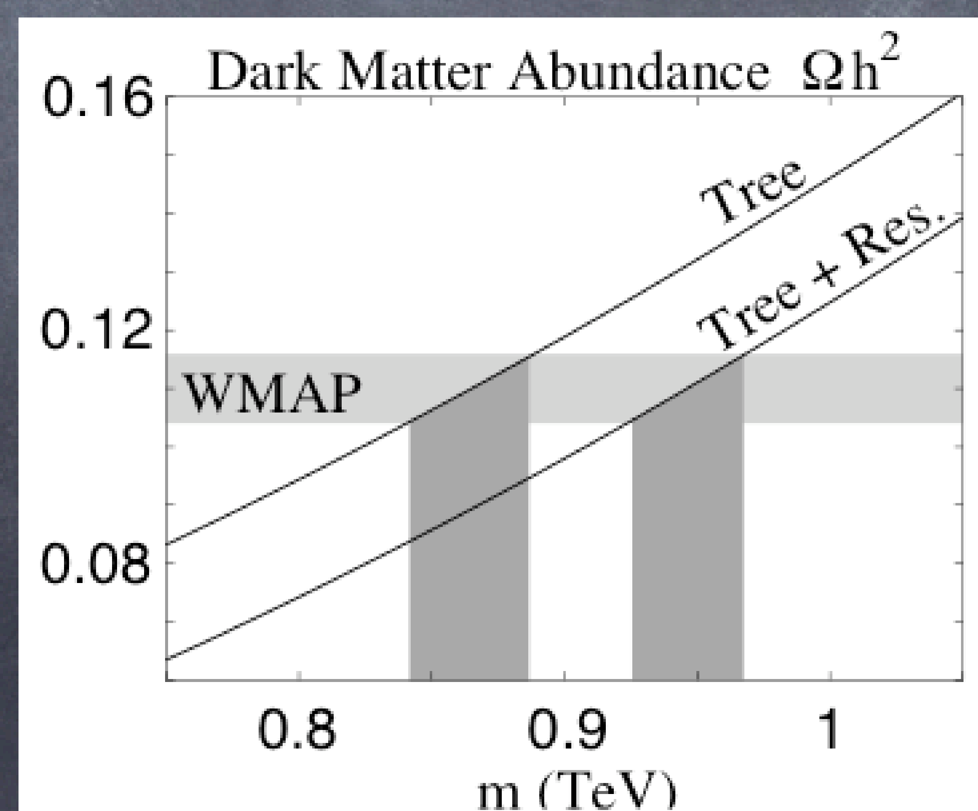

Servant-Tait

## ✔ Effect of 2nd KK modes

"natural KK resonance"

Kakizaki & al , hep-ph/0502059



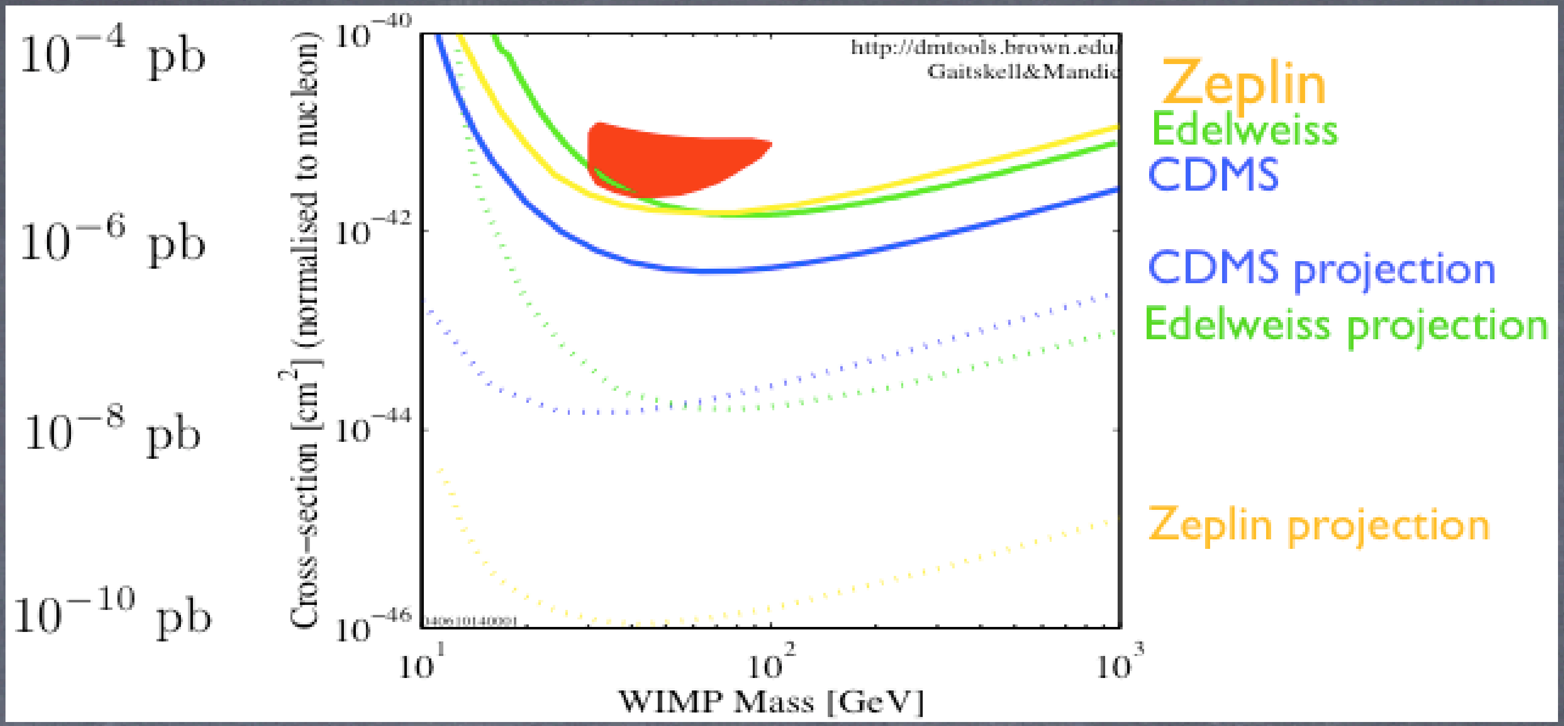




$\delta \equiv (m_{h^{(2)}} - 2m)/2m$

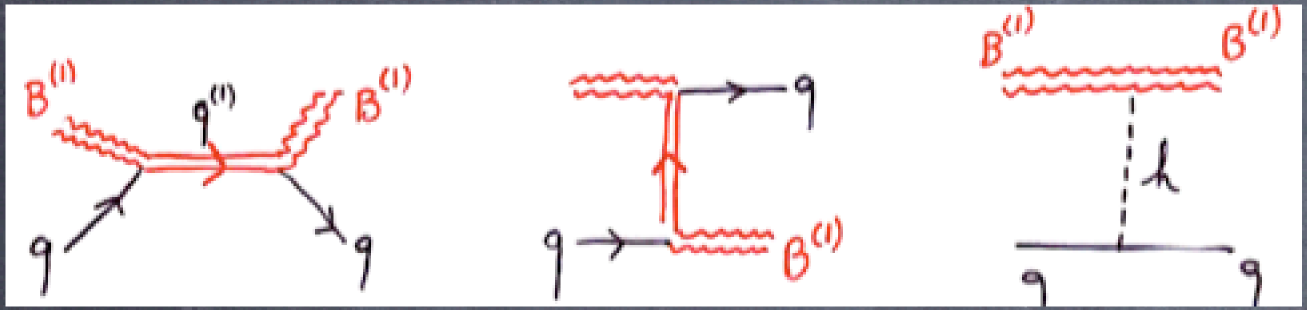
$\delta \sim 0.01$

# *Direct detection*

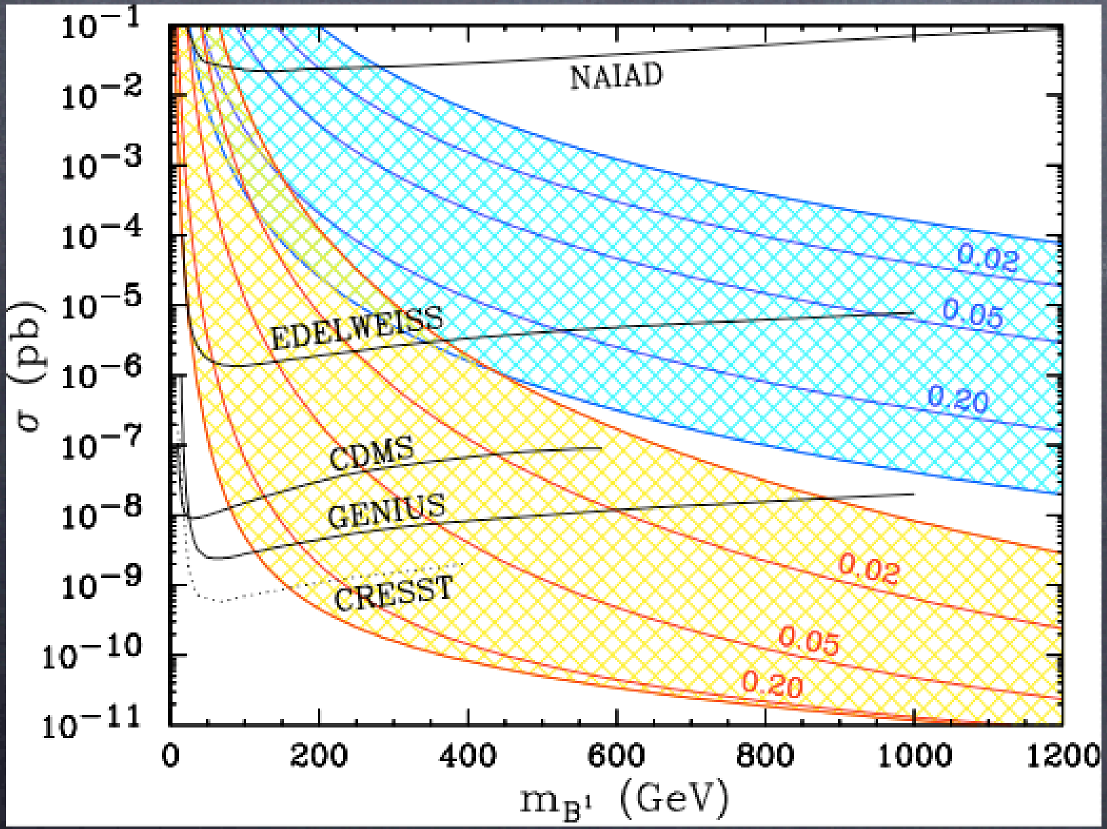
Experimental limits :

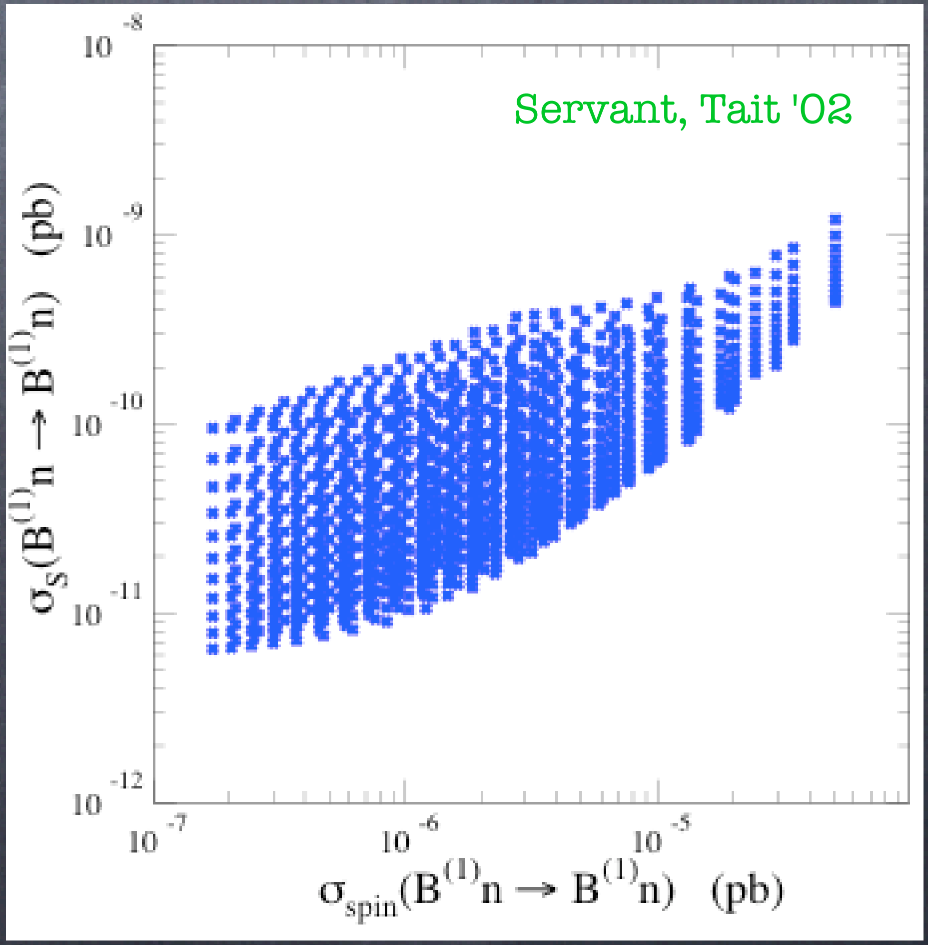



LKP signal :




Cheng, Feng, Matchev '02



# Particle physics model building in warped space

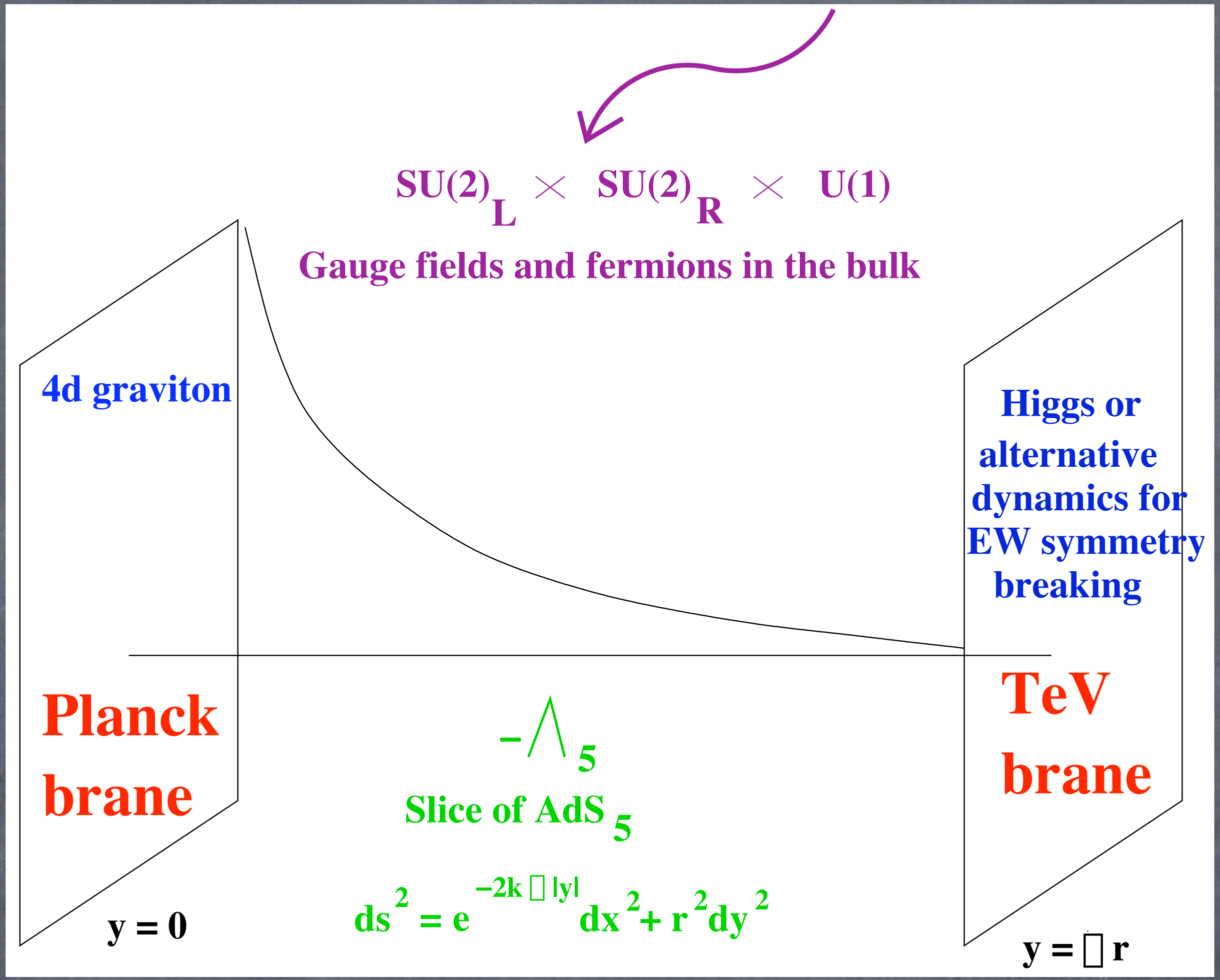
**2005 FAVOURITE SET-UP:**

✔ hierarchy pb

✔ fermion masses

✔ High scale unification

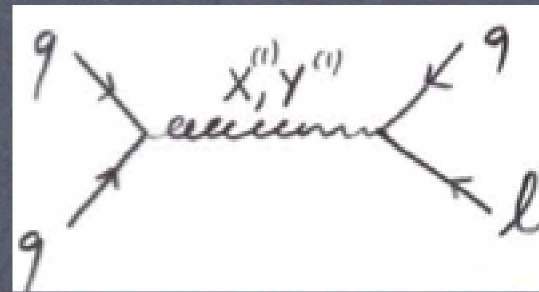
✔ FRW cosmology




Now embed this into a GUT + solve proton stability

⟶

✔ Dark matter

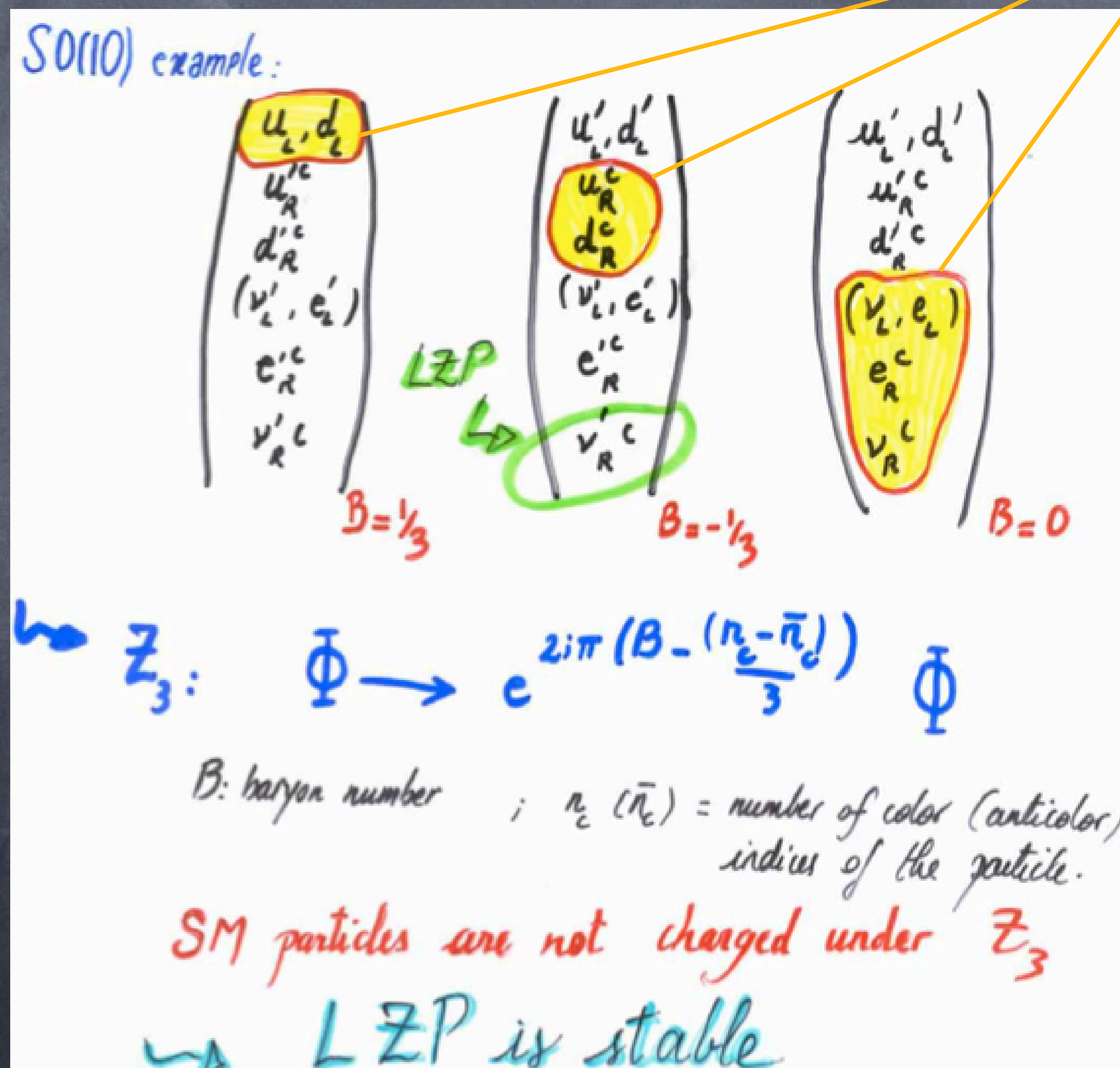
In GUTs ⇛ 


where $M_{X,Y} \sim$ few TeV

⇛ very fast proton decay

Solution: Break GUT by boundary conditions which split GUT multiplets

zero modes= SM fermions



# Mass spectrum of KK fermions

Depends on:

✔ type of boundary conditions on TeV and Planck branes

✔ c-parameter (=5D bulk mass)
(=localization of zero-mode wave function)

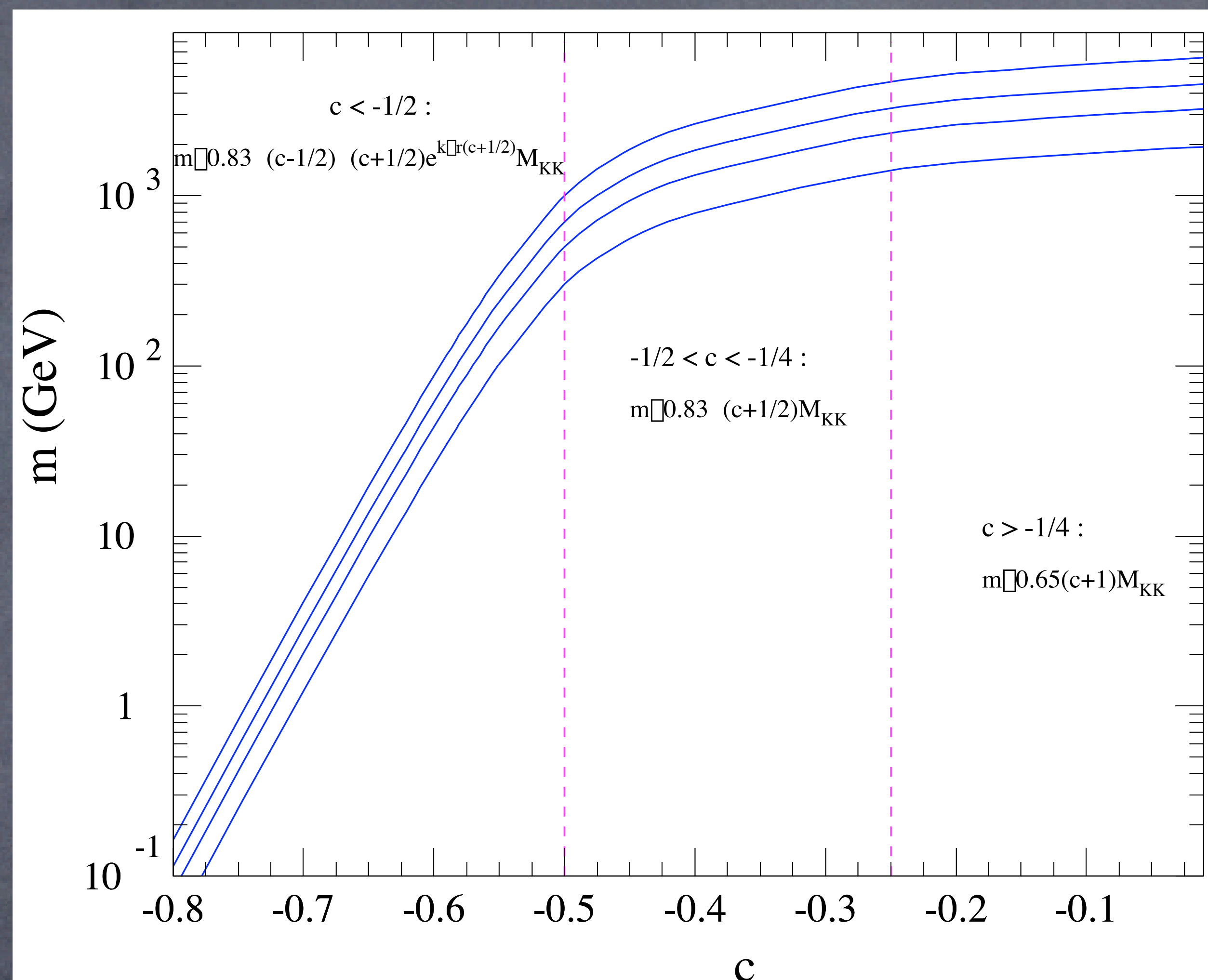
For certain type of boundary conditions on fermions, there can be a hierarchy between the mass of KK fermion and the mass of KK gauge bosons

$\Rrightarrow$ Not a single KK scale

# Mass spectrum of lightest KK fermion

$M_{KK}$ value

10 TeV
7 TeV
5 TeV
3 TeV

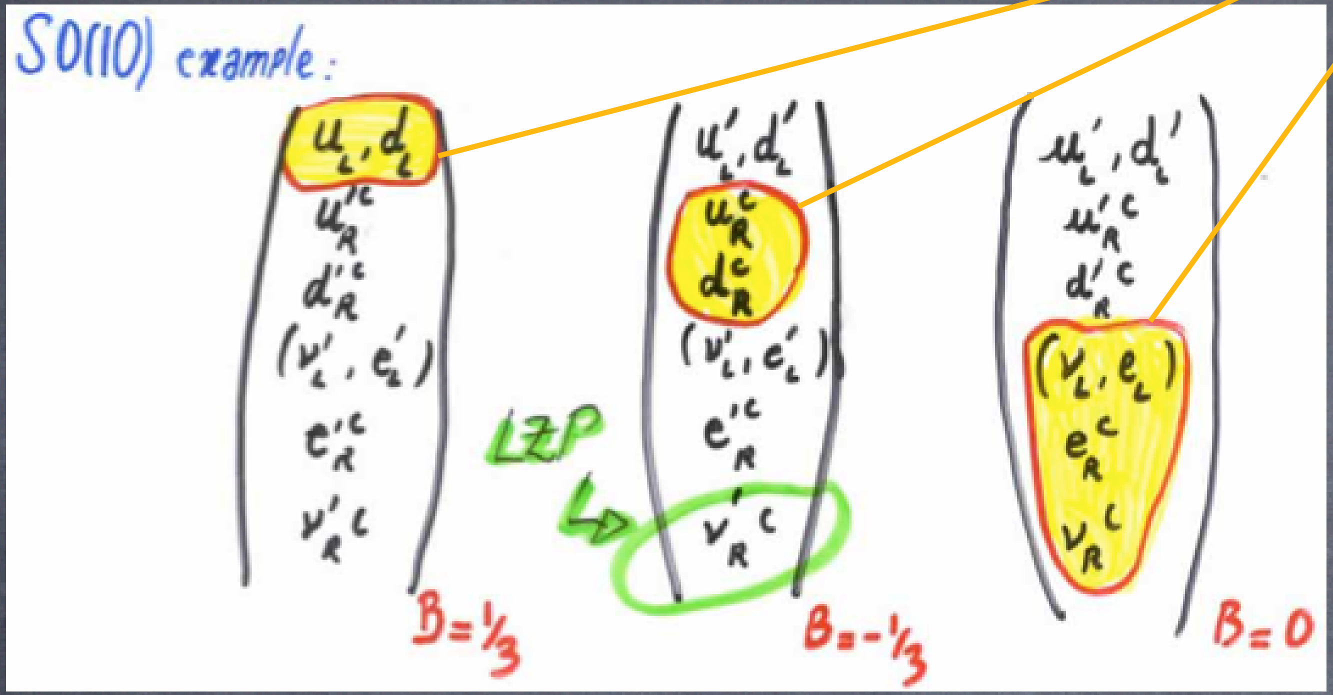



and smallest c: c of the top quark

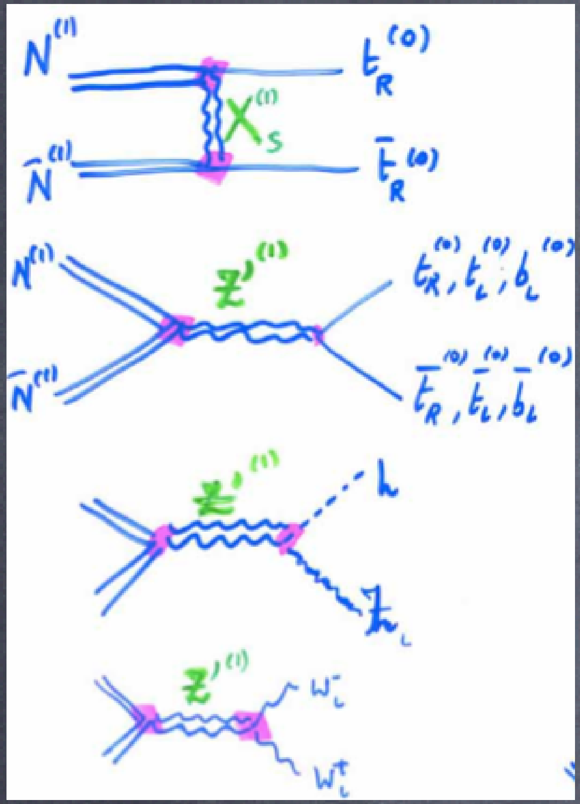
⇛ LZP belongs to the multiplet containing SM top quark

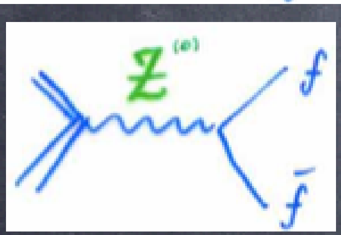
There exists a very light KK fermion as a consequence of the heaviness of the top quark

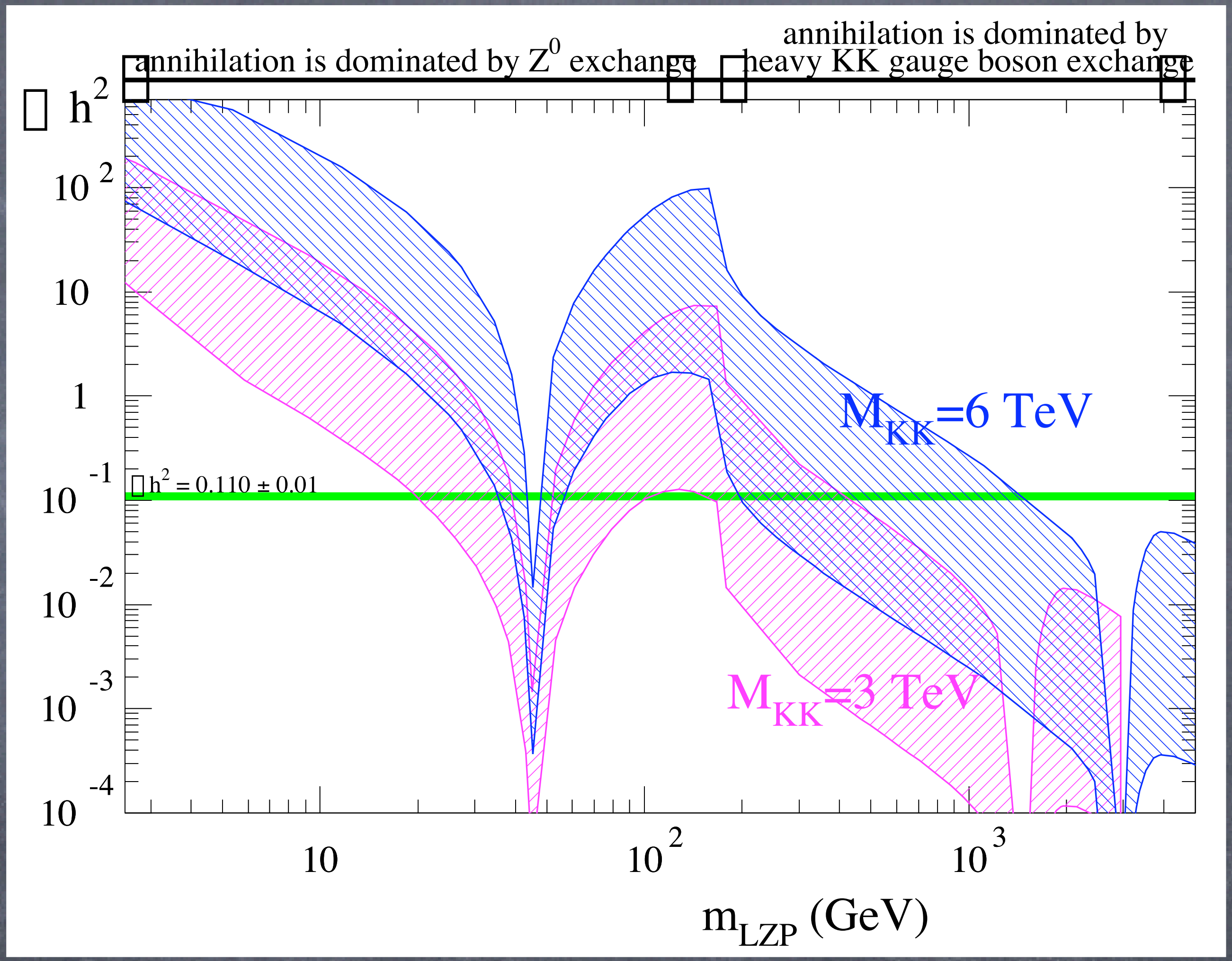
zero modes=
SM fermions



# Relic density predictions

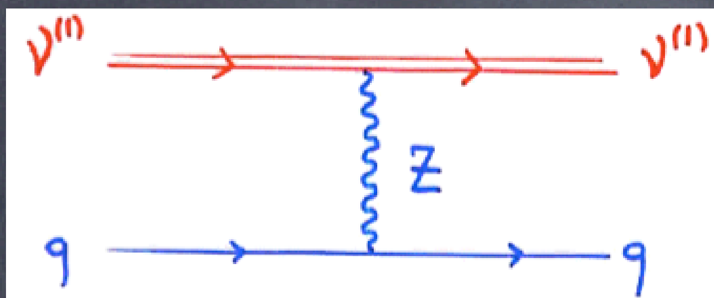






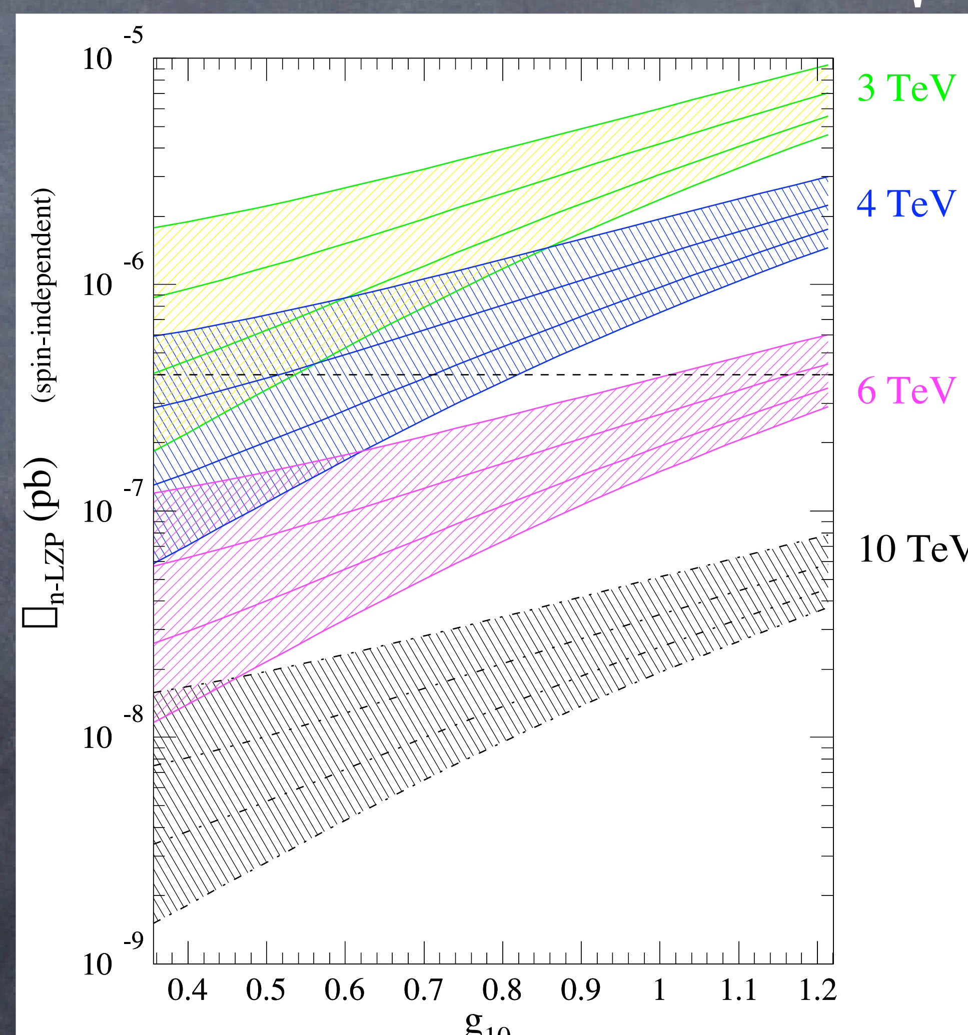

Agashe-Servant '04

# Direct detection




Wimp-nucleon elastic scattering cross section (spin-independent)

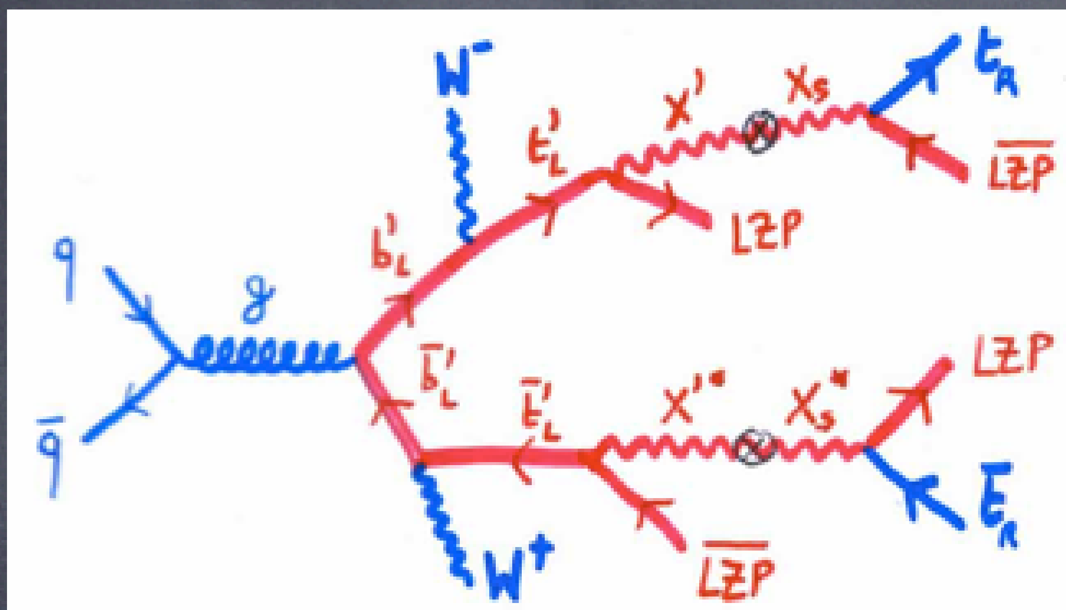
masses of KK gauge bosons



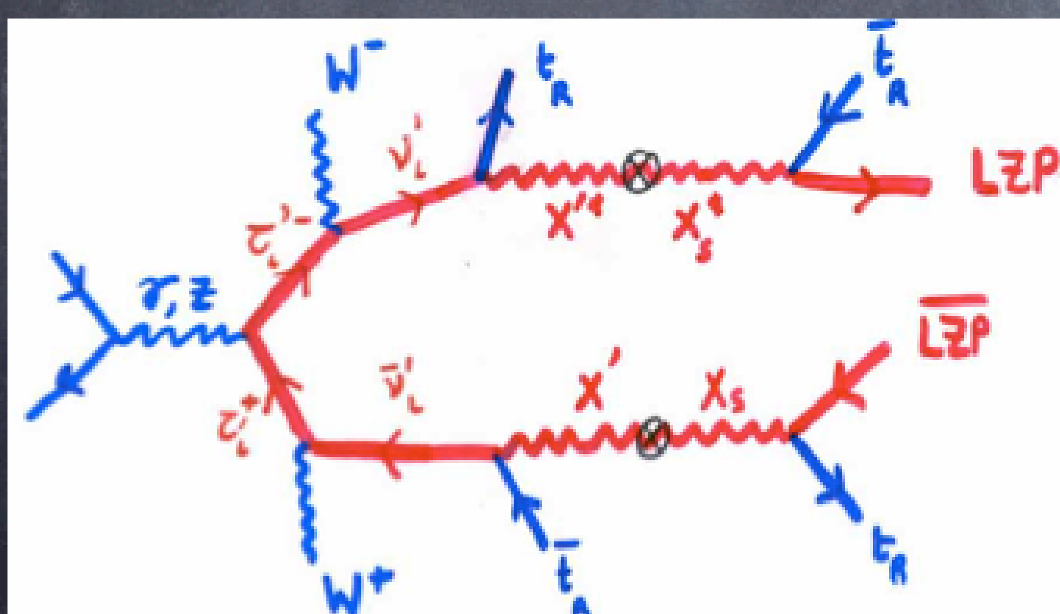

CDMS limit (only applies for some range of wimp masses)

Agashe-Servant '04

# *Collider Signatures: examples*



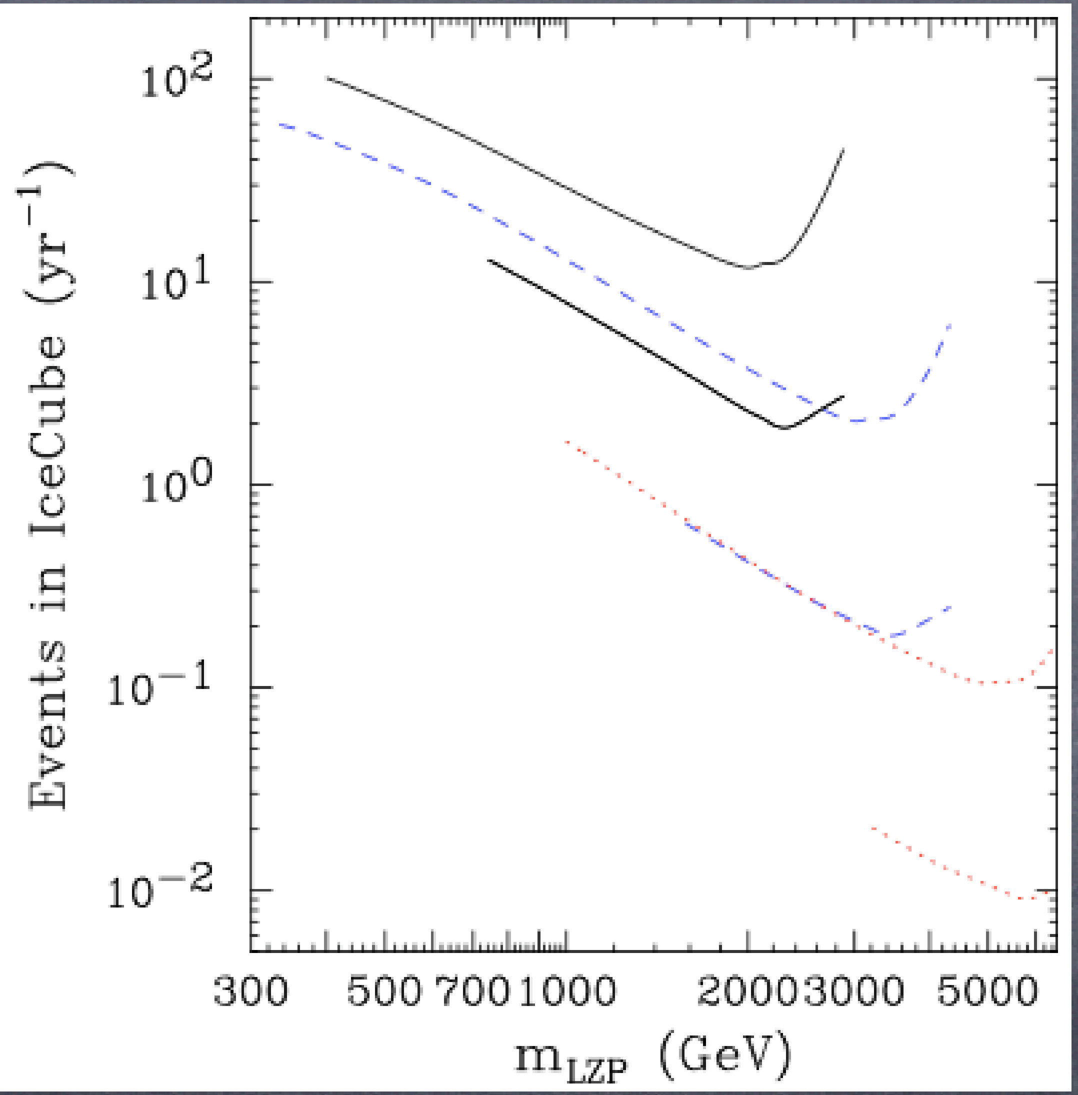

→ 4 W + 2 b+ $\not{E}_T$




→ 6 W + 4 b+ $\not{E}_T$

# Indirect detection in neutrino telescopes

Large elastic scattering cross section: large capture rate in the Sun
Efficient production of neutrinos in annihilations



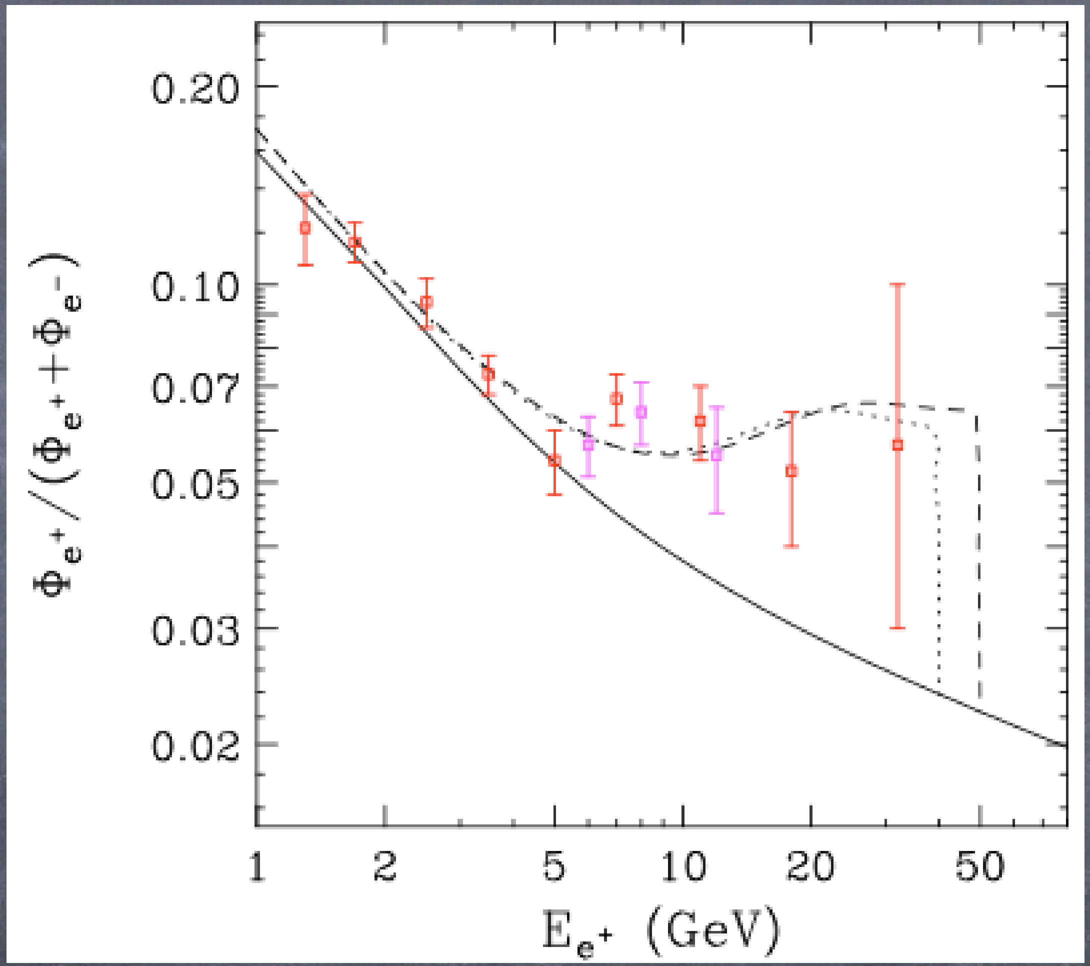

$M_{KK}$=4 TeV

$M_{KK}$=6 TeV

$M_{KK}$=10 TeV

Hooper & Servant '05

# Cosmic positrons from LZP annihilations

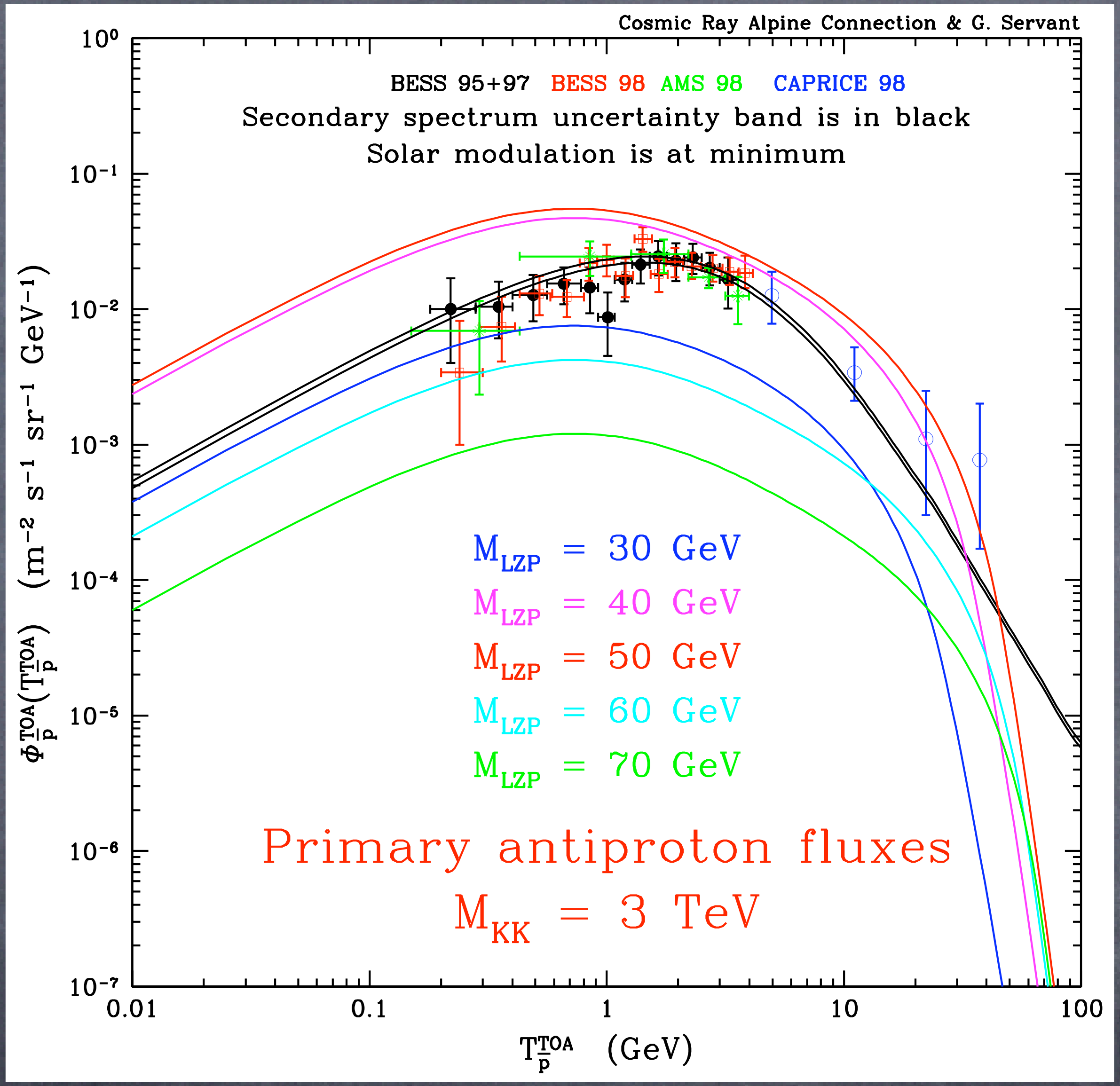



Hooper & Servant '05

Fit of the HEAT data from LZP annihilations

........... 40 GeV LZP
- - - - 50 GeV LZP

# Galactic antiprotons from LZP annihilation



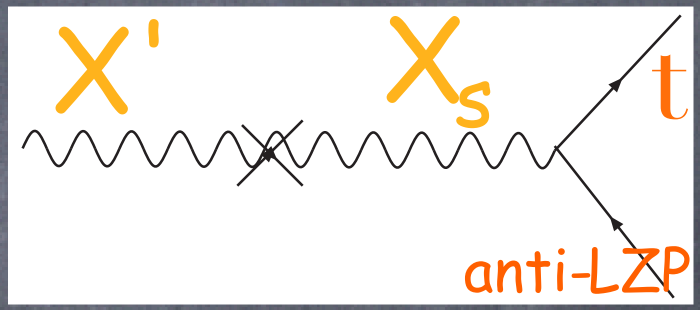

Barreau & al '05

# A natural framework to relate baryons and dark matter

Our dark matter candidate carries baryon number! (B=1/3)

$$B_{UNIVERSE} = 0 = \underbrace{B}_{\text{carried by baryons}} + (\underbrace{-B}_{\text{carried by anti-LZP}})$$

Assume an asymmetry between t and $\bar{t}$ is created via the out-of-equilibrium and CP-violating decay :




Baryon number conservation leads to:

$$1/3\,(n_{\overline{LZP}} - n_{LZP}) = n_b - n_{\bar{b}}$$

Assuming efficient annihilation between LZP and $\overline{LZP}$, and b and $\bar{b}$ :

$$\rho_{DM} = m_{LZP}\, n_{LZP} \approx 6\rho_b \longrightarrow m_{LZP} \approx 2\text{ GeV}$$

| | LKP | LZP | LSP |
| --- | --- | --- | --- |
| *nature* | gauge boson | Dirac fermion | Majorana fermion |
| *symmetry* | KK parity $(-1)^n$ | $Z_3$ $B - \frac{(n_c - \bar{n}_c)}{3}$ | R-parity $(-1)^{3(B-L)+2S}$ |
| | | related to proton stability | related to proton stability |
| *mass range* | ~600-1000 GeV | 20 GeV-few TeV | ~50 GeV-1 TeV |
| *annihilation cross section* | s-wave | s-wave | helicity suppressed (p-wave) |
| *favourite detection* | ✔ LHC<br>✔ Indirect detection | ✔ Direct detection!<br>✔ LHC!<br>✔ Indirect detection !<br>entire parameter space is testable | ✔ LHC |

# To conclude

Abundance of experimental activity related to dark matter detection:

- Colliders
- Direct detection: CDMS, Edelweiss, Dama, Cresst, Zeplin, Xenon, Naiad ...
- Indirect detection:
  - Gamma-ray telescopes: Hess, Veritas, Glast, Magic
  - Neutrino telescopes: Amanda, IceCube, Antares
  - Cosmic positron experiments: HEAT, Pamela, AMS-2

⇛It is timely to study the distinctive signatures expected in different dark matter scenarios.

LKPs, LZPs: viable alternatives to LSPs