Dark Matter & the electroweak scale

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Dark matter candidates: two main possibilities

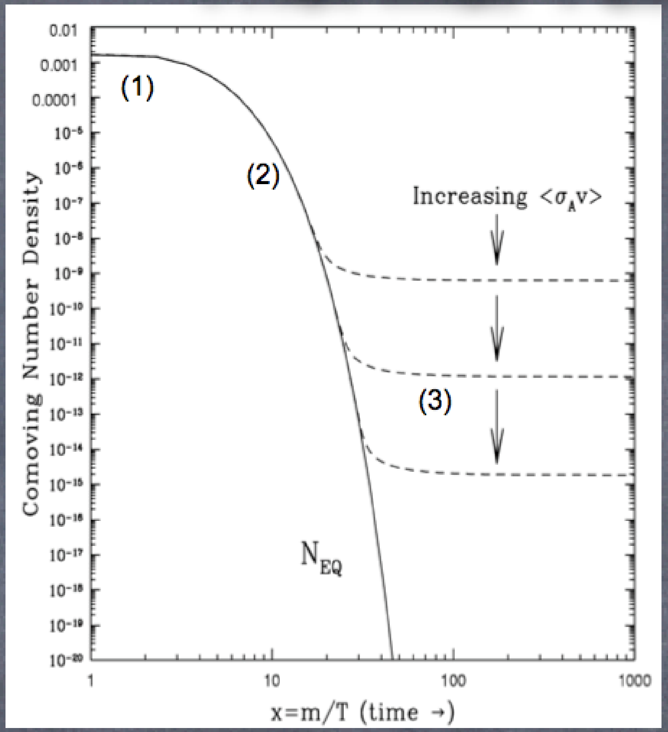
very light & only gravitationally coupled (or with equivalently suppressed couplings) -> stable on cosmological scales

Production mechanism is model-dependent, depends on early-universe cosmology

ex: meV scalar with $1/M_{Pl}$ couplings (radion)

sizable (but not strong) couplings to the SM -> symmetry needed to guarantee stability

Thermal relic: $\Omega h^2 \propto 1/\langle\sigma v\rangle$



$\Rightarrow \langle\sigma v\rangle = 0.1$ pb

The "WIMP miracle"

$\sigma \sim \alpha/m^2$

$\Rightarrow m \sim 100$ GeV

Very general, does not depend on early universe cosmology, only requires the reheat temperature to be $\geq m/25$ (= weak requirement)

an alternative: superWIMPs (where most often the above calculation is still relevant since SuperWIMPs are produced from the WIMP decay)

ex: gravitino, KK graviton

Dependence on reheat temperature

The most studied WIMP: The neutralino, as well as other LSPs: gravitino, axino.

Recently, some WIMP alternatives beyond the LSP have been explored. They reflect some evolution in the last years in our way of thinking beyond the Standard Model.

Until recently, physics beyond the Standard Model (SM) has been driven by naturalness motivations (=hierarchy pb, keep the Higgs light)

SUSY has long appeared to be the most realistic & best-motivated extension of the SM

However, LEP II has forced susy into fine-tuning territory
-> revival of interest for alternatives (Xdim, Little Higgs ...)

Plus, fine-tuning associated with Cosmological Constant much more severe

Plus, String Landscape

--> questioning of naturalness as a motivation for new physics @ the Weak scale

Aside from naturalness considerations, strongest motivations for new physics: dark matter and baryon asymmetry

Model building beyond the Standard Model: "historical" overview

Big hierarchy adressed

SUSY
[70 ies to now]

R-parity → LSP

ADD
[98-99]

RS
[99 to now]

the attitude:
Naturalness is what matters, dark matter is a secondary issue

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Little hierarchy adressed

UED
[2001 to now]

KK-parity → LKP
[2002]

Little Higgs
[2002-2004]

T-parity → LTP
[2003]

Lower your ambition (no attempt to explain the M_{EW}/M_{Pl} hierarchy); rather put a ~ TeV cutoff

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Big & little hierarchy pbs ignored

"Minimal" SM extensions
[2004 to now]

assume discrete symmetry, typically a Z_2

Give up naturalness, focus on dark matter and EW precision tests. Optional: also require unification

Dark Matter Candidates

	M_{EW}/M_{Pl} hierarchy adressed	little hierarchy adressed(∼TeV cutoff)	Hierarchy pb ignored
SPIN 0			
- axion }(not wimps)	×		×
- radion	?		
- branon	?		
- singlet scalar, scalar doublet			×
- adjoint scalar (=spinless photon)		×	
SPIN 1/2			
- Dirac neutrino	× (in RS)		
- SU(2) p-uplet			×
- neutralino	×		
- axino	×		
SPIN 1			
- Heavy photon (KK or B-partner in Little Higgs)		×	
SPIN 3/2			
- Gravitino	×		
SPIN 2			
- KK Graviton		× (in UED)	

←see T. Hambye's talk (//) and M. Lisanti's talk (//)

←see M. Cirelli's talk (//)

←see L. Bergstrom's talk and R. Trotta's talk (//)

←see M. Senami's talk (//) and I. Albuquerque (//)

←see L.Covi's talk and S. Matsumoto's talk (//)

Dark Matter from Extra Dimensions

ADD models

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

only gravity in bulk

- radion dark matter, m~meV
- KK graviton dark matter (both finely tuned)
- branon dark matter (not original ADD, hierarchy pbs remain)

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 graviton is unstable
- KK dark matter

WIMP! or SuperWIMP

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!

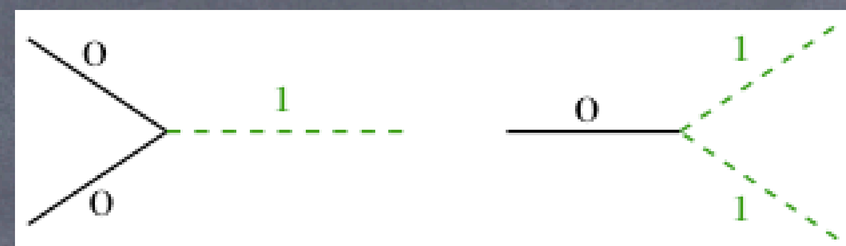
`Universal' Extra Dimensions

Appelquist, Cheng & Dobrescu '01

Assumption: All SM propagate in extra dimension(s).

Translation Invariance along the 5th dimension ⇛Conservation of the Kaluza-Klein number in interactions of the 4D effective theory.

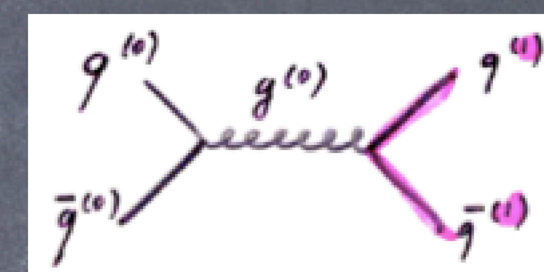
For instance:



forbidden allowed

Consequence: n=1 KK excitations can only be pair-produced and they do not contribute to EW precision observables at tree level: this helps the little hierarchy pb

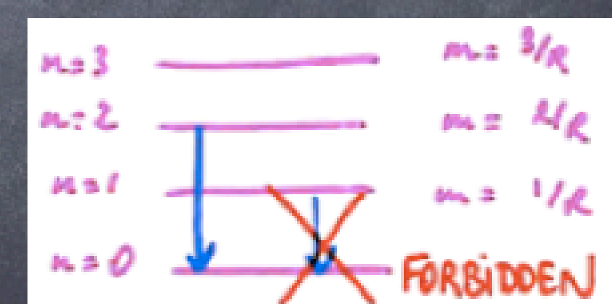
⇛Collider constraints are weak (~200 GeV)



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

⇛Odd-n KK modes can only couple by pairs

⇛The lightest KK mode (LKP) is stable



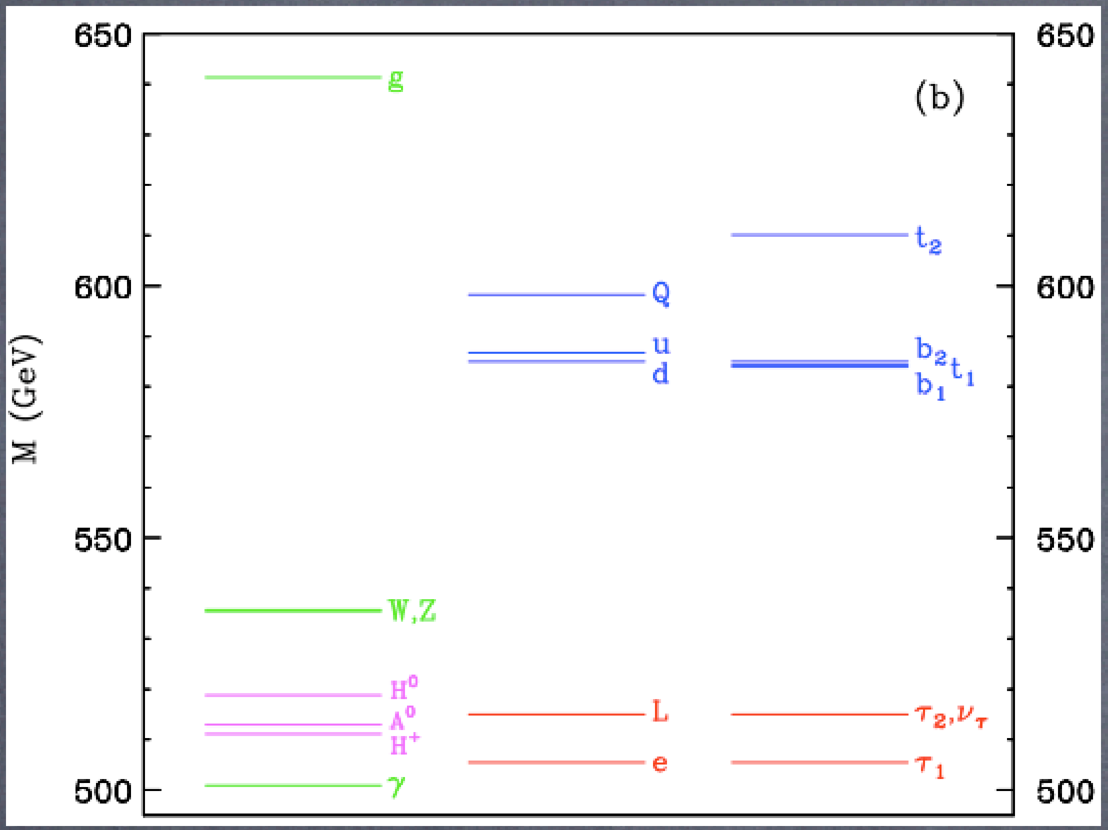
The Kaluza-Klein photon:
an excellent candidate for dark matter

Phenomenology very similar to supersymmetry with conserved R-parity

Every KK particle eventually decays into the LKP

1-loop spectrum of 1rst KK modes

Cheng, Matchev & Schmaltz'02



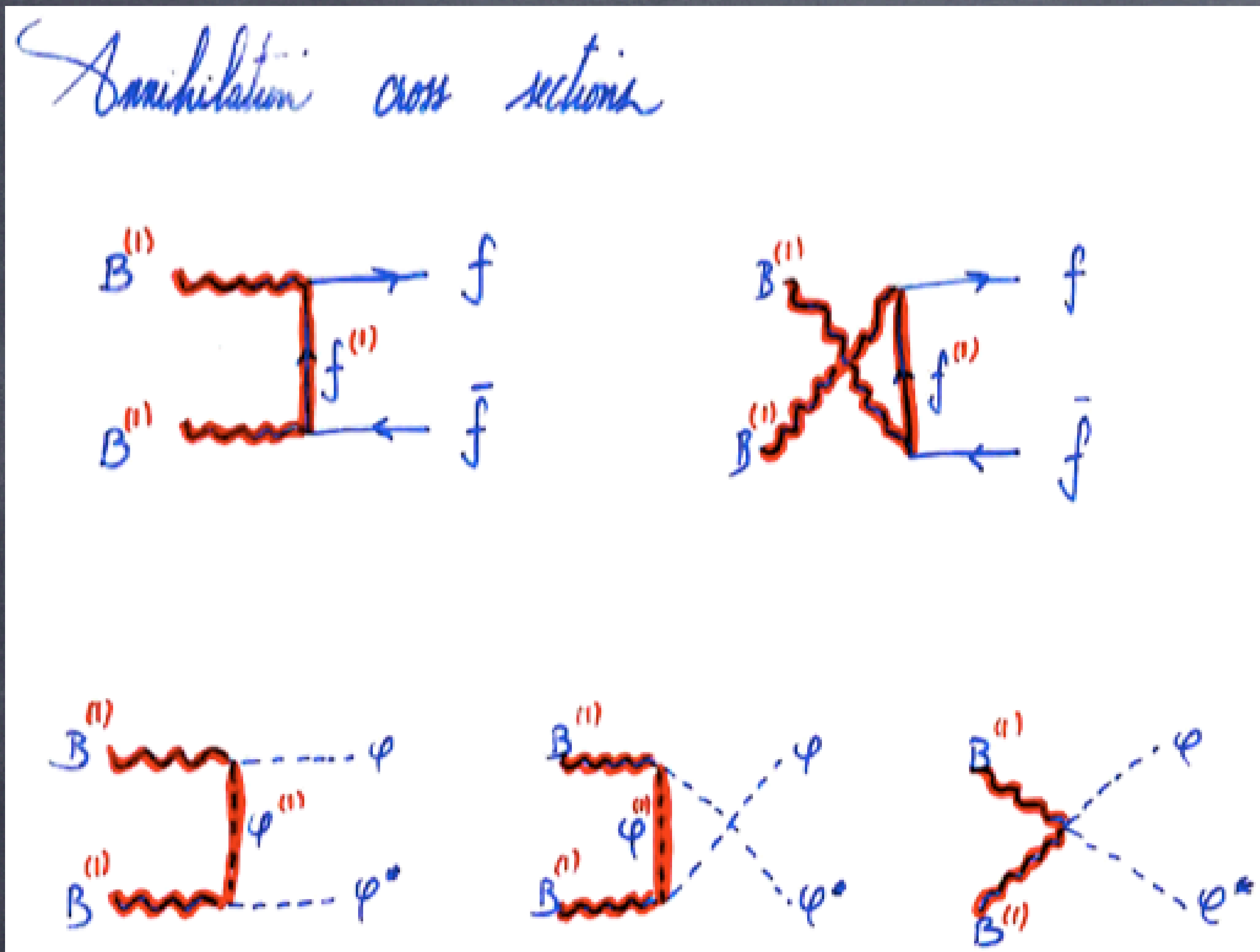
assuming:1/R=500 GeV, $\Lambda R = 20, m_h = 120$ GeV
and vanishing boundary terms at the cutoff Λ

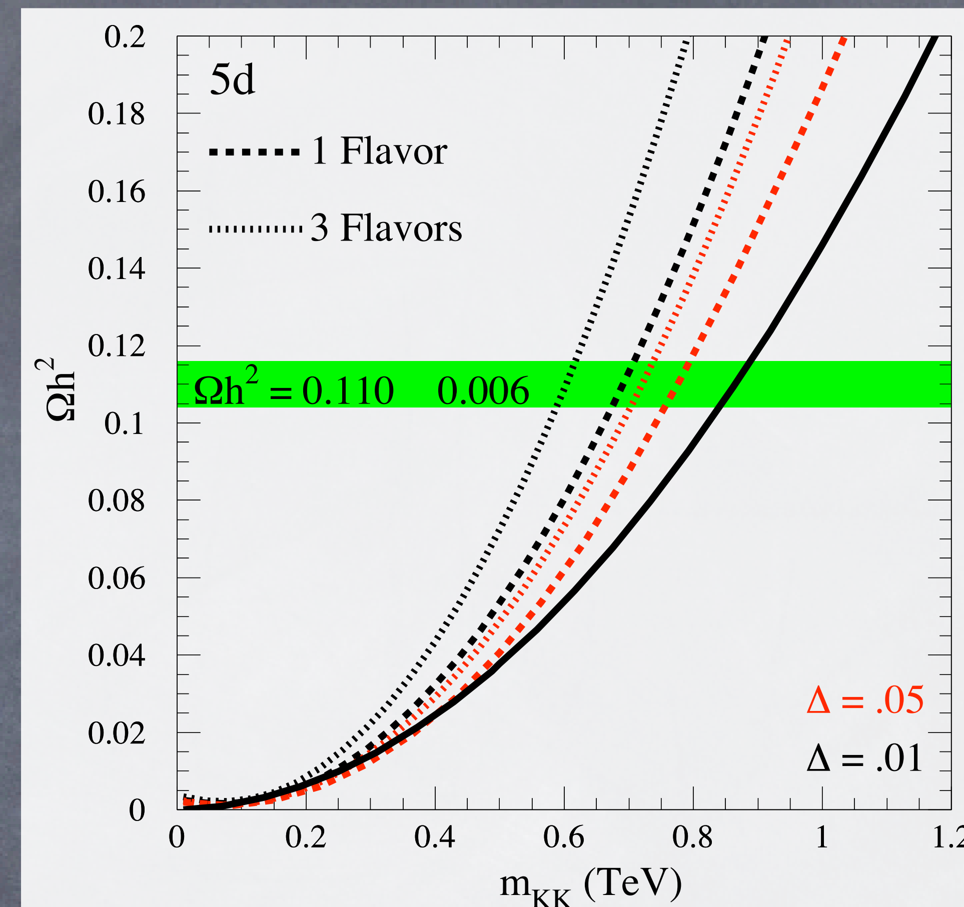
→ LKP: most likely a γ^1 (actually a B^1)

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

Relic density predictions

Servant-Tait'02

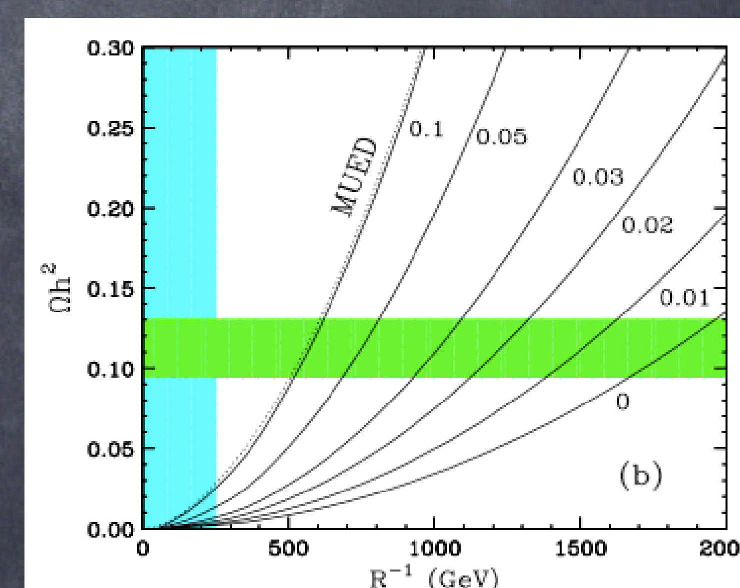




full effect of coannihilations Kong-Matchev, hep-ph/0509119

effect of 2nd level KK modes, "natural KK resonance"

Kakizaki & al , hep-ph/0502059



Summary of KK photon dark matter in 5D UED

✔ KK parity= a remnant of translational invariance along extra dimension

✔ highly degenerate spectrum of KK states ⇒ coannihilation effects are important

✔ No helicity-suppression of annihilation into fermions (in constrast to neutralino)

good for indirect detection (high energy neutrinos and positrons)

Note: Another "heavy photon" DM candidate arises in Little Higgs theories (where higgs is a goldstone boson arising from a global symmetry breaking)

Also: A heavy KK photon from a non-universal extra dimension
Regis-Serone-Ullio'06;

The spinless photon

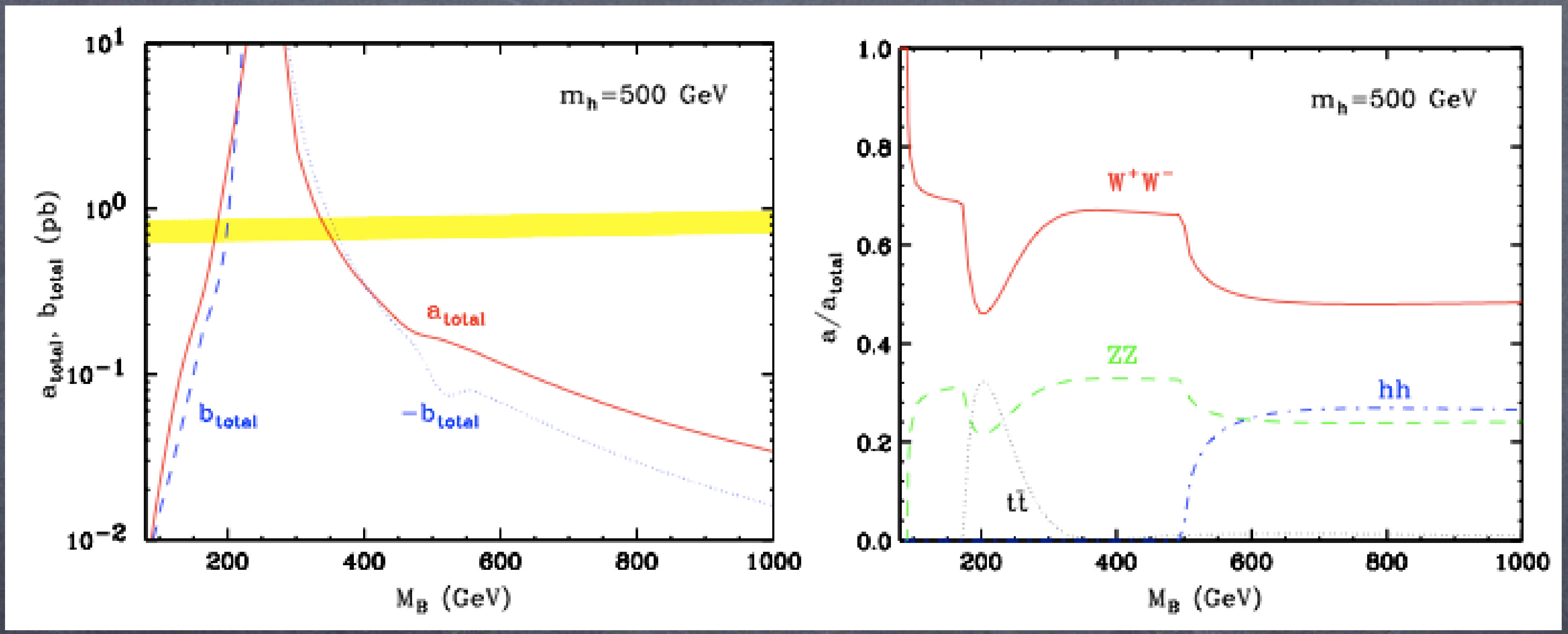
[Dobrescu, Hooper, Khong, Mahbubani '07]

Standard Model in 2 universal extra dimensions

2 towers of spin-0 fields, one is eaten by heavy spin-1 field, another one remains in the spectrum

[Burdman, Dobrescu, Ponton'05]

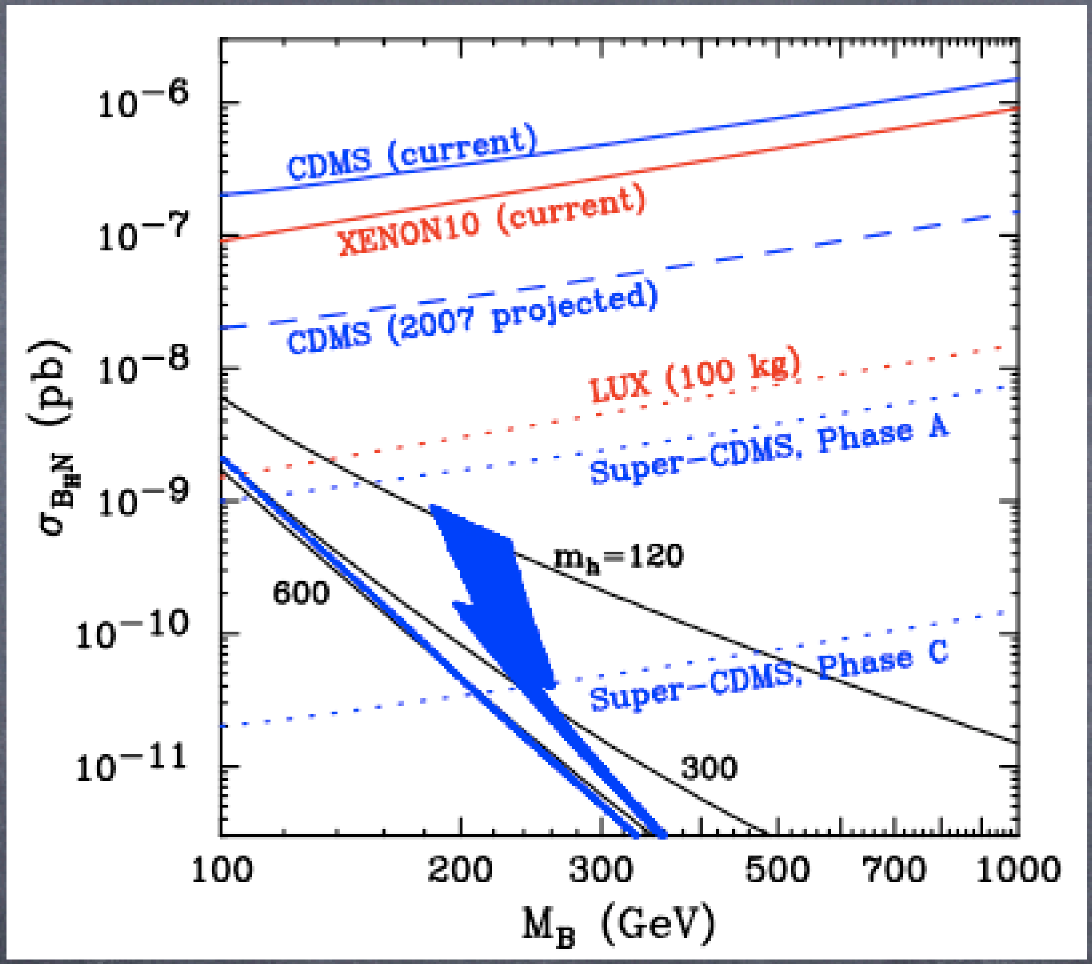
The Lightest spin-0 field is stable by KK parity and a good DM candidate



relic density calculation predicts low mass (< 500 GeV)

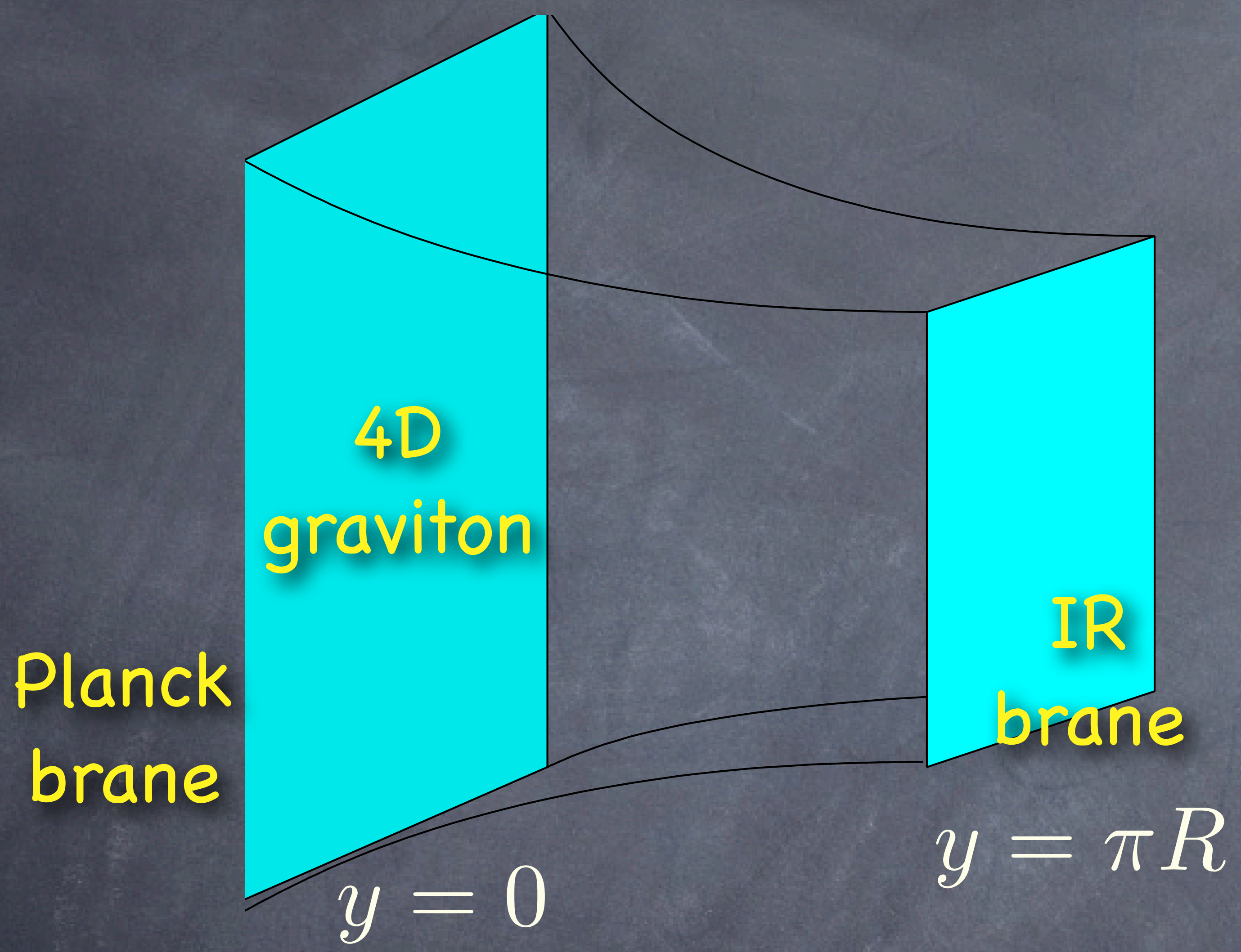
helicity suppression of annihilation and scattering cross section. Annihilates mainly into WW

Both direct and indirect detection of the spinless photon are very challenging



[Dobrescu, Hooper, Khong, Mahbubani ‘07]

Space-time is a slice of AdS5



$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$

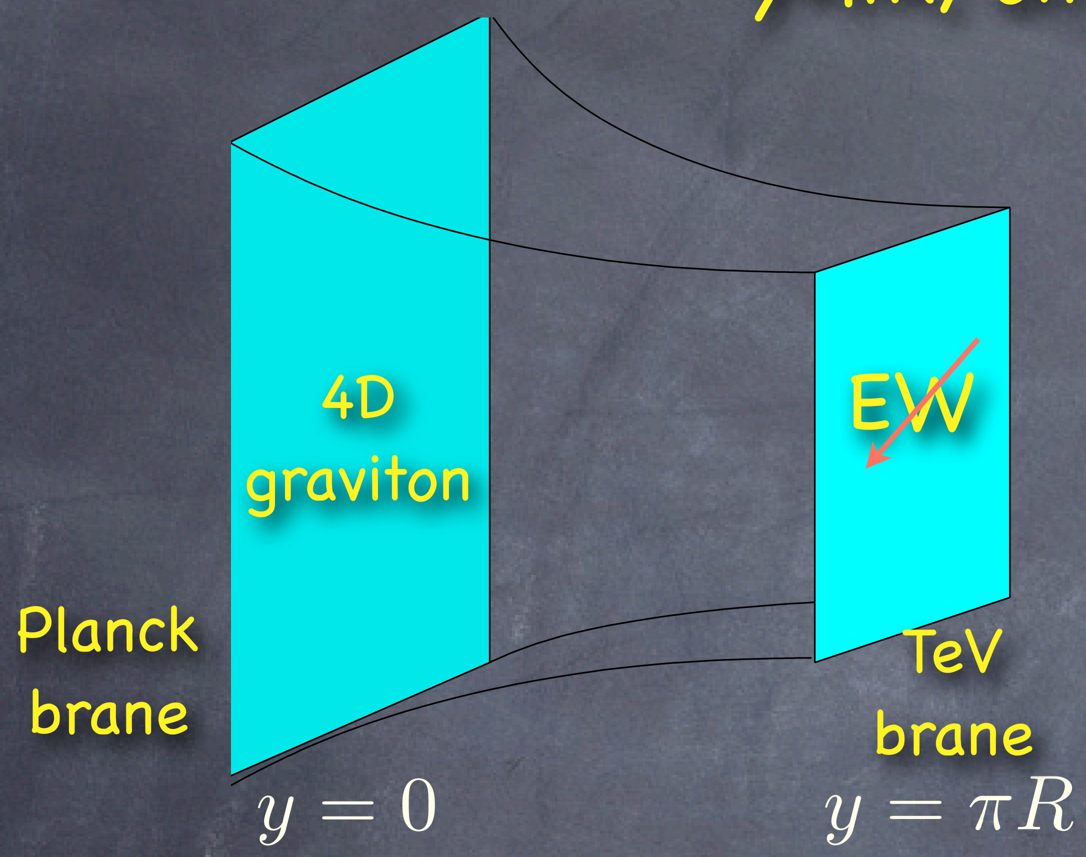
$$M_{Pl}^2 \sim \frac{M_5^3}{k}$$

The effective 4D energy scale varies with position along 5th dimension

RS1 (has two branes) versus RS2 (only Planck brane)

Solution to the Planck/Weak scale hierarchy

The Higgs (or any alternative EW breaking) is localized at $y=\pi R$, on the TeV (IR) brane



After canonical normalization of the Higgs:

$$v_{\mathrm{eff}} = v_0 e^{-k\pi R}$$

parameter in the 5D lagrangian

$$k\pi R \sim \log\left(\frac{M_{Pl}}{\mathrm{TeV}}\right)$$

Exponential hierarchy from O(10) hierarchy in the 5D theory

One Fondamental scale : $M_5 \sim M_{Pl} \sim k \sim \Lambda_5/k \sim r^{-1}$

Radius stabilisation using bulk scalar (Goldberger-Wise mechanism)

$$kr = \frac{4}{\pi}\frac{k^2}{m^2}\ln\left[\frac{v_h}{v_v}\right] \sim 10$$

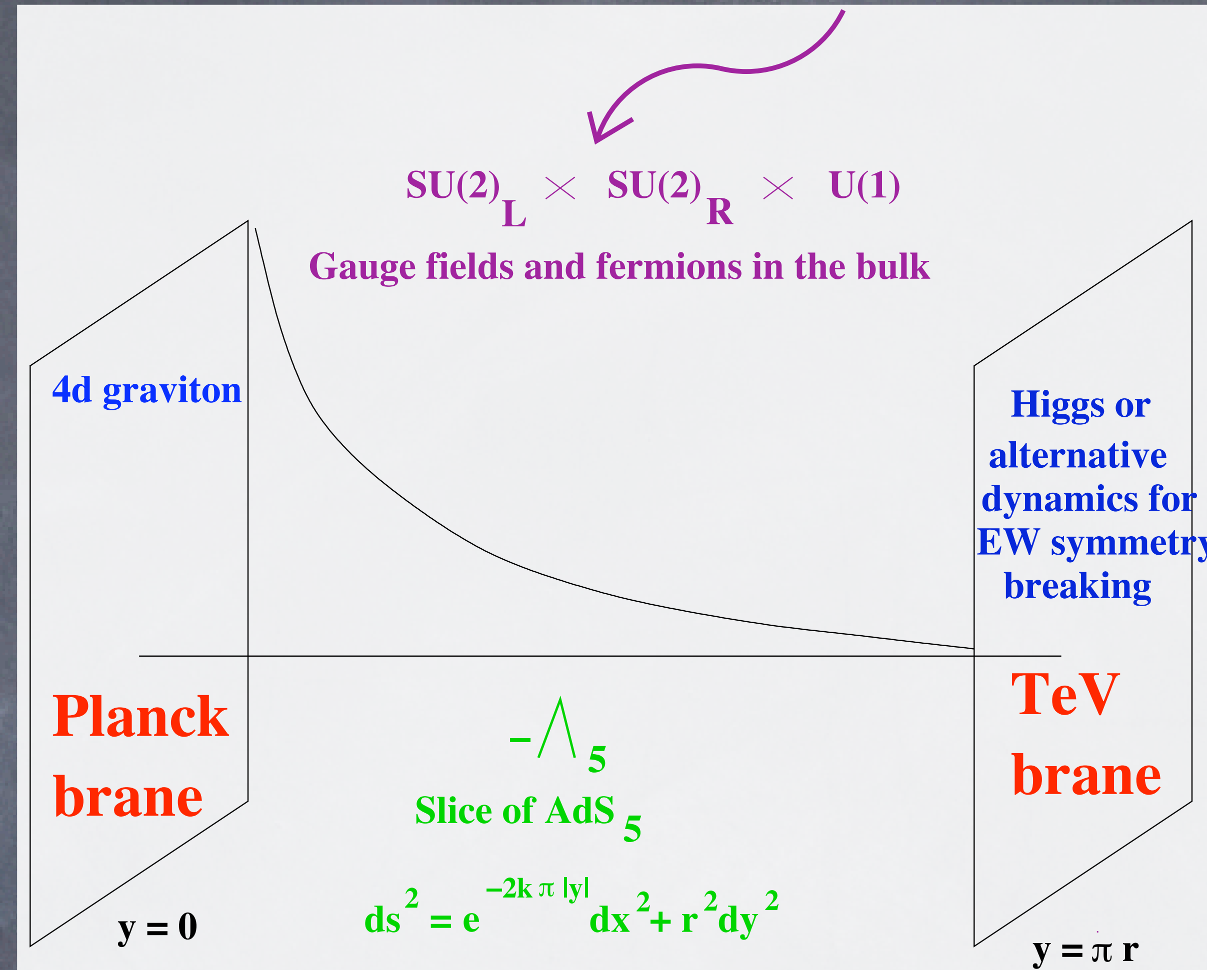
Warped hierarchies are radiatively stable as cutoff scales get warped down near the IR brane

Particle physics model building in warped space

2007 favourite set-up:

✔ hierarchy pb
✔ fermion masses
✔ High scale unification
✔ FRW cosmology

✔ Still active research on consistency with EW precision tests & little hierarchy pb



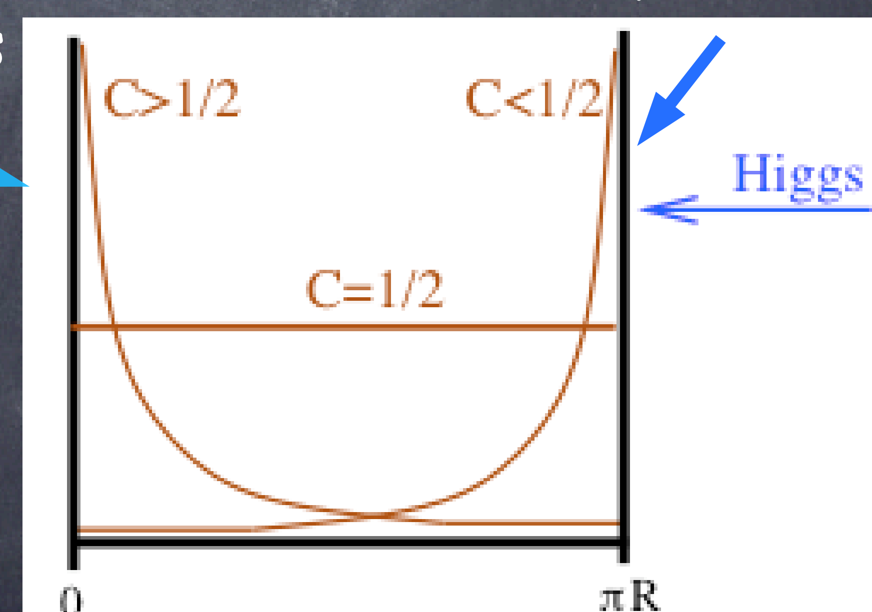
Note: No susy here

and many different realizations

M_{KK}~few TeV

light fermions

heavy fermions



[Grossman, Neubert ‘99]
[Gherghetta, Pomarol ‘00]

Mass spectrum of KK fermions

Depends on:

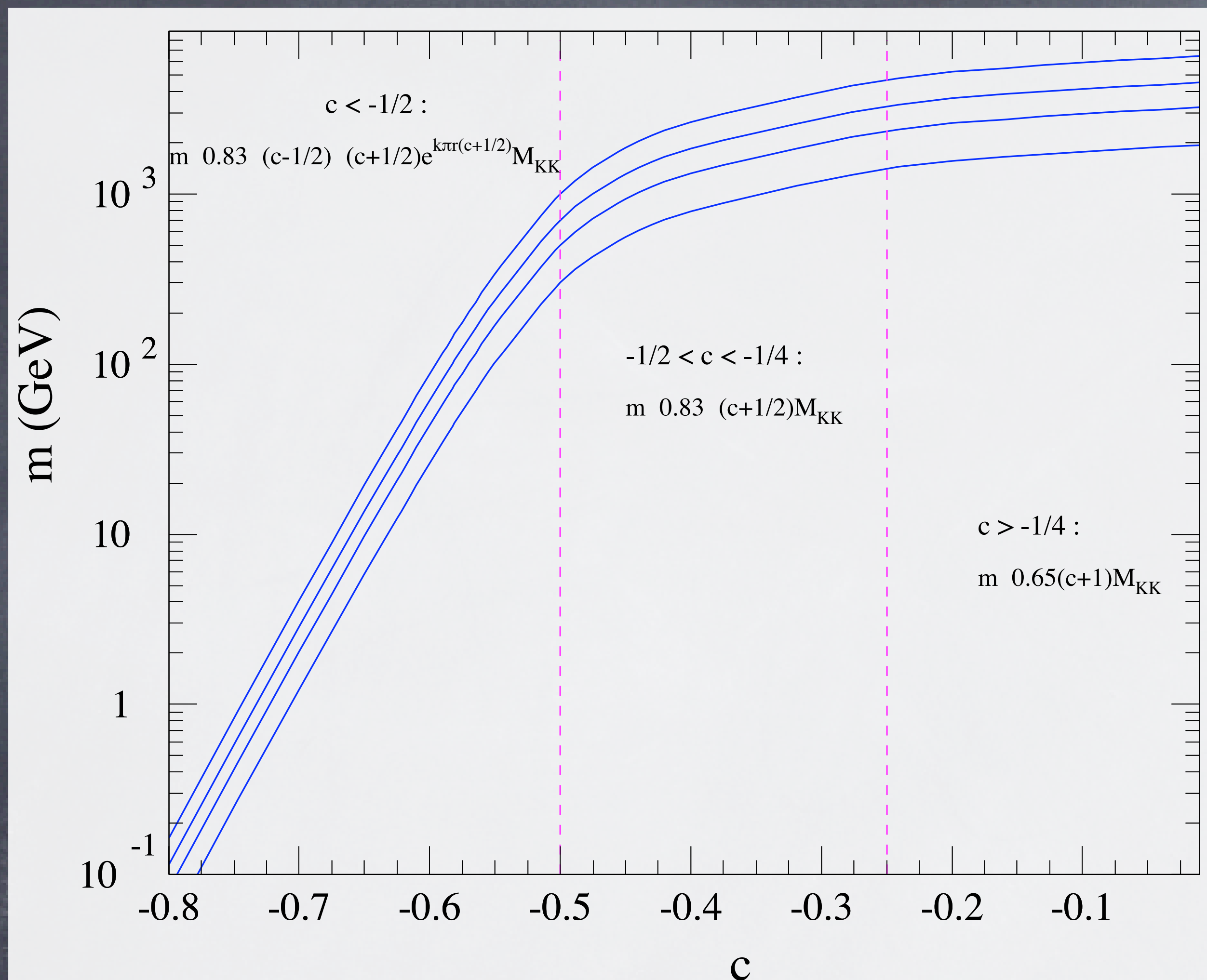
✔ type of boundary conditions on TeV and Planck branes

✔ 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



10 TeV
7 TeV ← M_{KK} value
5 TeV
3 TeV

c= 5D fermion mass in Planck units

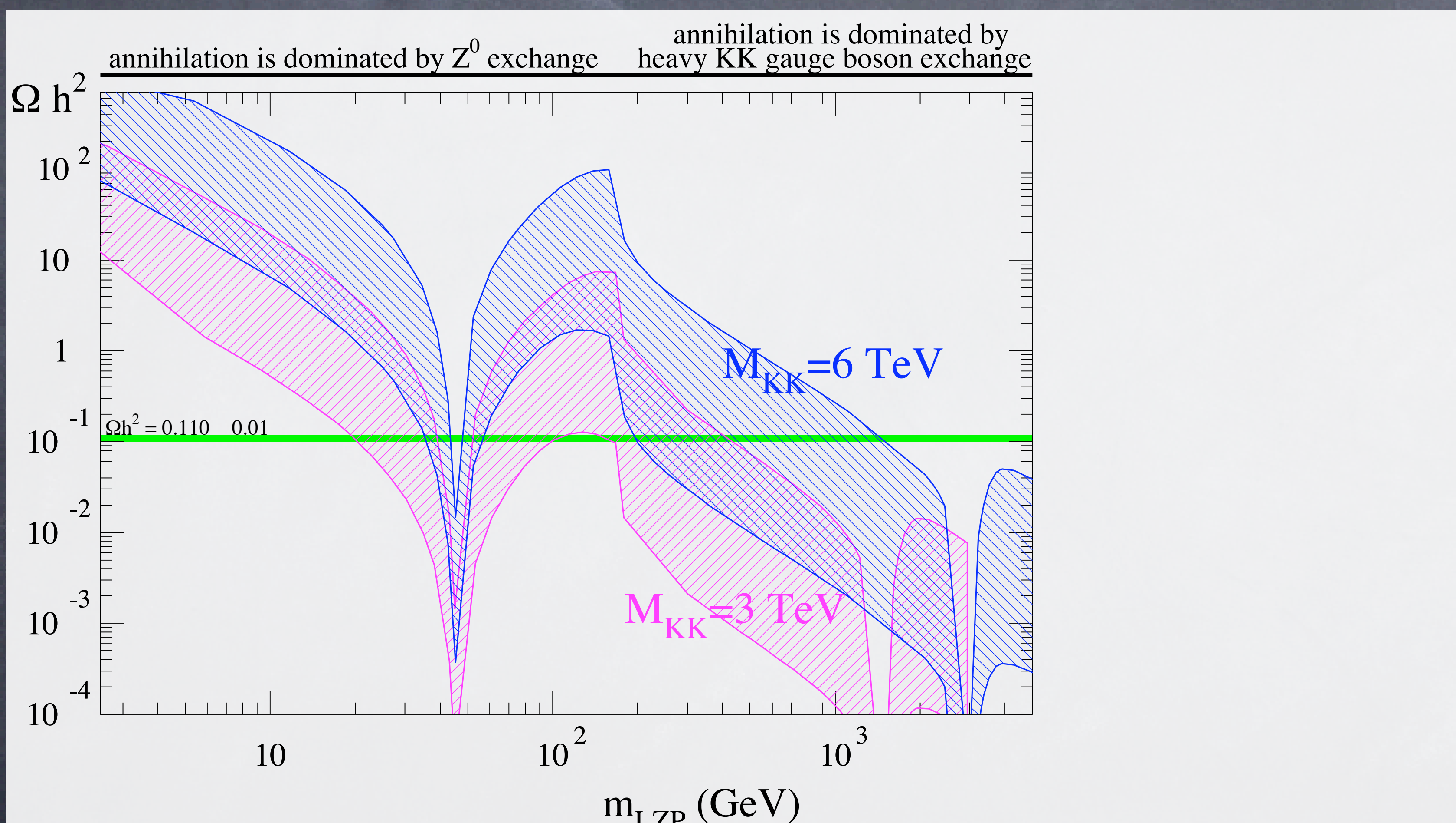
Agashe-Servant hep-ph/0403143, hep-ph/0411254

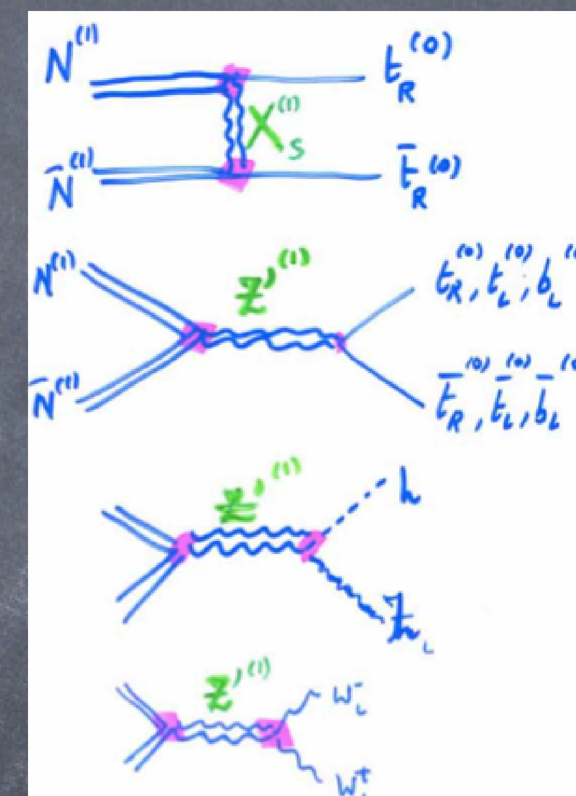
Right-handed top quark has $c \approx -1/2 \Rightarrow$ (-+) KK modes in its multiplet have mass of a few hundreds of GeV: Accessible at LHC!

Light KK fermions are expected as a consequence of the heaviness of the top quark

e.g. KK RH neutrino, GUT partner of the top is light.

It has gauge interactions with TeV mass KK gauge bosons of $SU(2)_R$
--> behaves as a WIMP, and is stable under a combination of baryon number and SU(3) color.



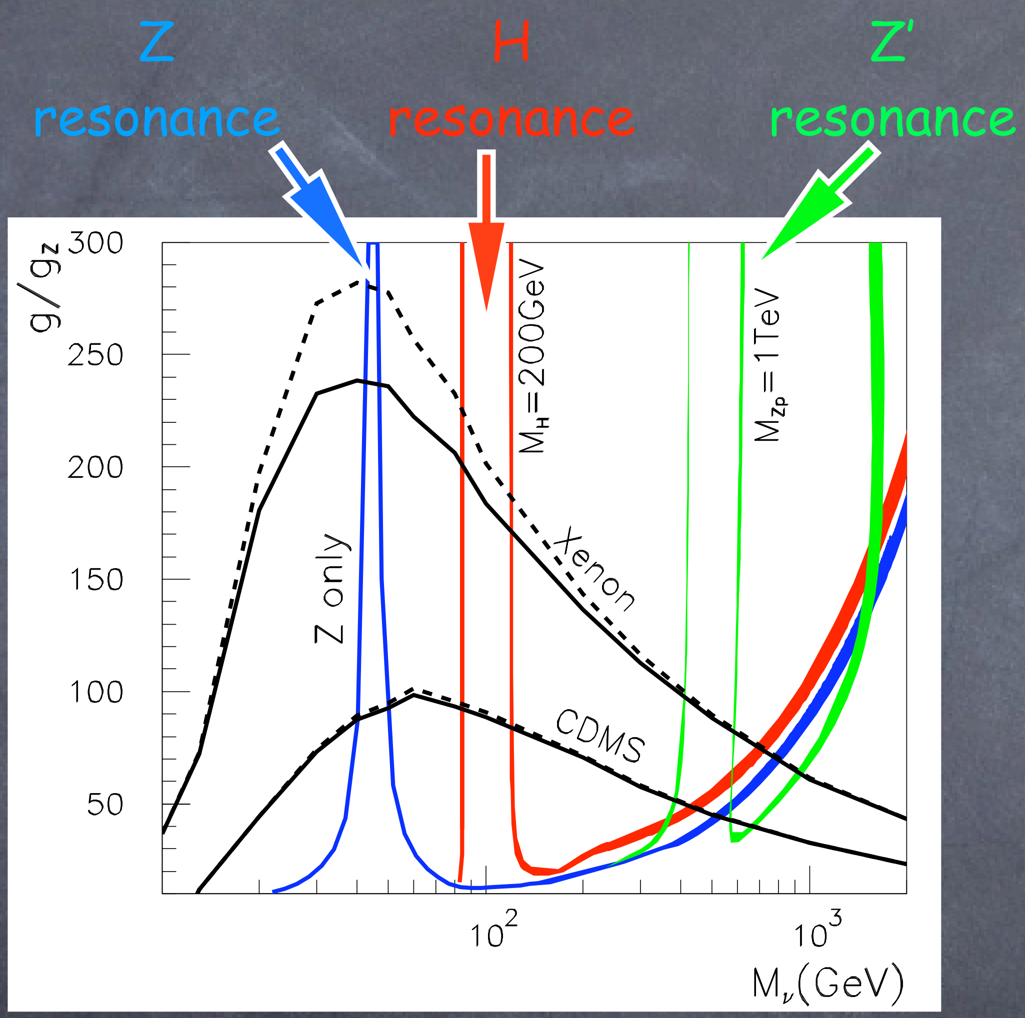


[Agashe, Servant '04]

Dirac Neutrino dark matter

[Belanger, Pukhov, Servant '07]

general model-independent analysis as a function of the heavy neutrino mass M_ν and its coupling to Z, g_Z



Allowed region is above the black lines and below the colored lines

Coupling to Z has to be suppressed by at least a factor 100 compared to the SM neutrino coupling

"Minimal" approaches

= focus on dark matter only and do not rely on models that solve the hierarchy problem

The Inert Doublet

Deshpande-Ma'78;
Barbieri-Hall-Rychkov 06
Lopez Honorez-Nezri-Oliver-Tytgat 06; Gerard-Herquet'07
Hambye, Tytgat 07; Pierce-Thaler 07;

light (< M_W)

SU(2) p-uplet

Cirelli, Fornengo, Strumia 06;

best: quintuplet, heavy (multi TeV)

lepton doublet + neutral Majorana state

Mahbunani-Senatore'05; D'Eramo, 07;
Enberg-Fox-Hall-Papaioannou'07;

The Inert Doublet Model (IDM)

studied by ≠ groups
with ≠perspectives

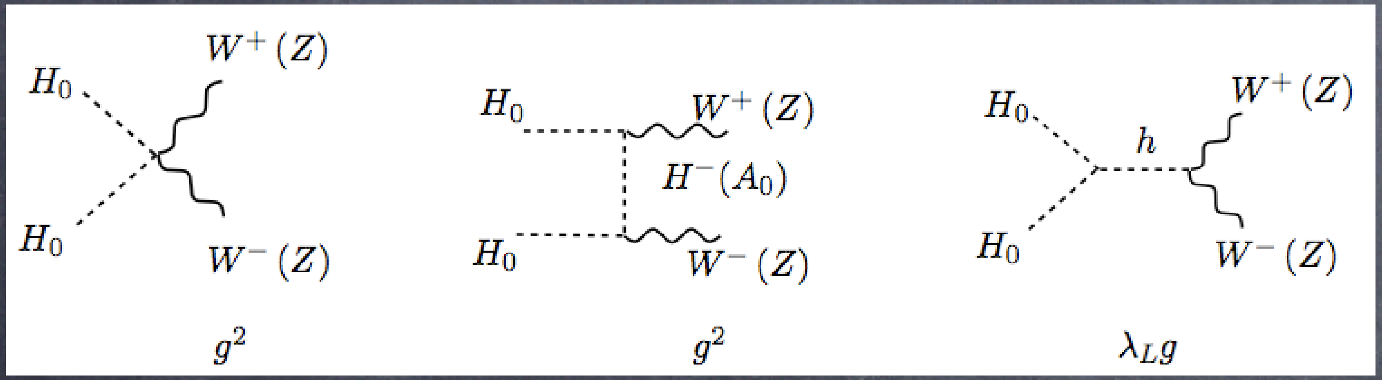
Deshpande-Ma'78;
Barbieri-Hall-Rychkov 06
Lopez Honorez-Nezri-Oliver-Tytgat 06; Gerard-Herquet'07
Hambye, Tytgat 07;

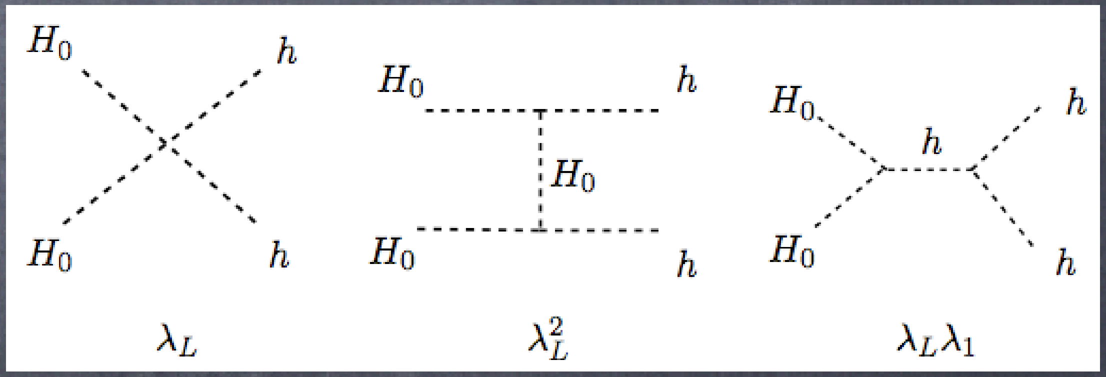
A two-Higgs extension of the SM with an unbroken Z_2 symmetry

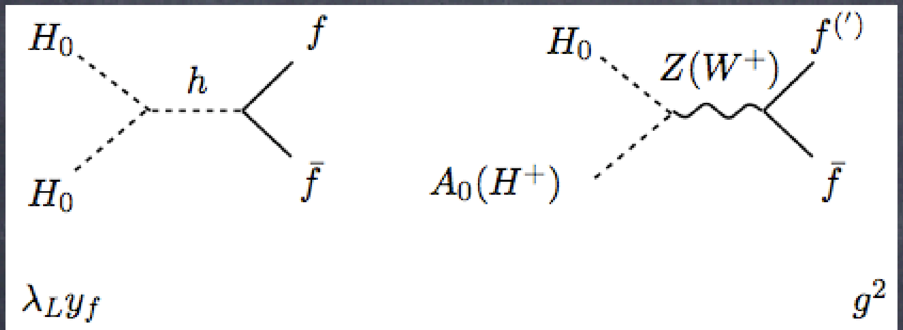
$H_1 \to H_1$ and $H_2 \to -H_2$ (and all SM fields are even)

$$V = \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + h.c.\right]$$

Annihilation:

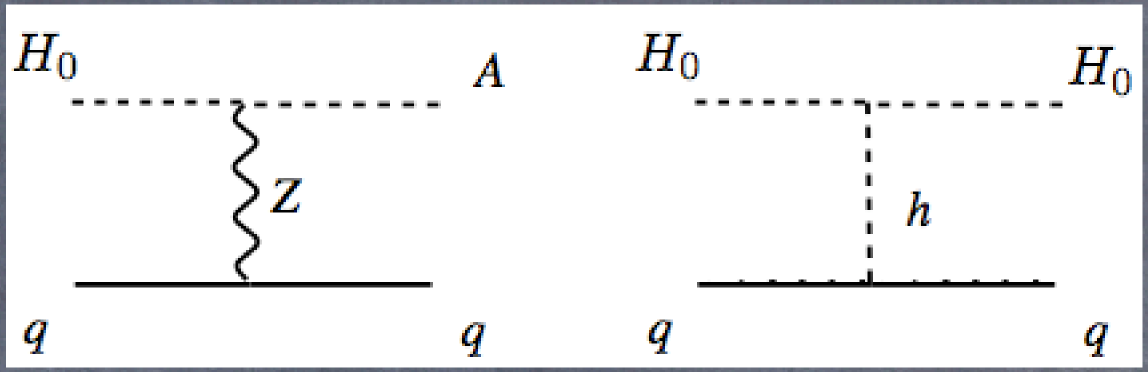






--> should be light (< M_W)

Elastic scattering



$\sigma \sim O(10^{-9})$ pb, within sensitivity of future experiments

Dark matter signals of improved naturalness

Another example

requiring that the higgs does not receive dominant loop corrections from the cutoff scale leads to an estimate of the cutoff $\Lambda_{max} \sim 3.7\ m_H$

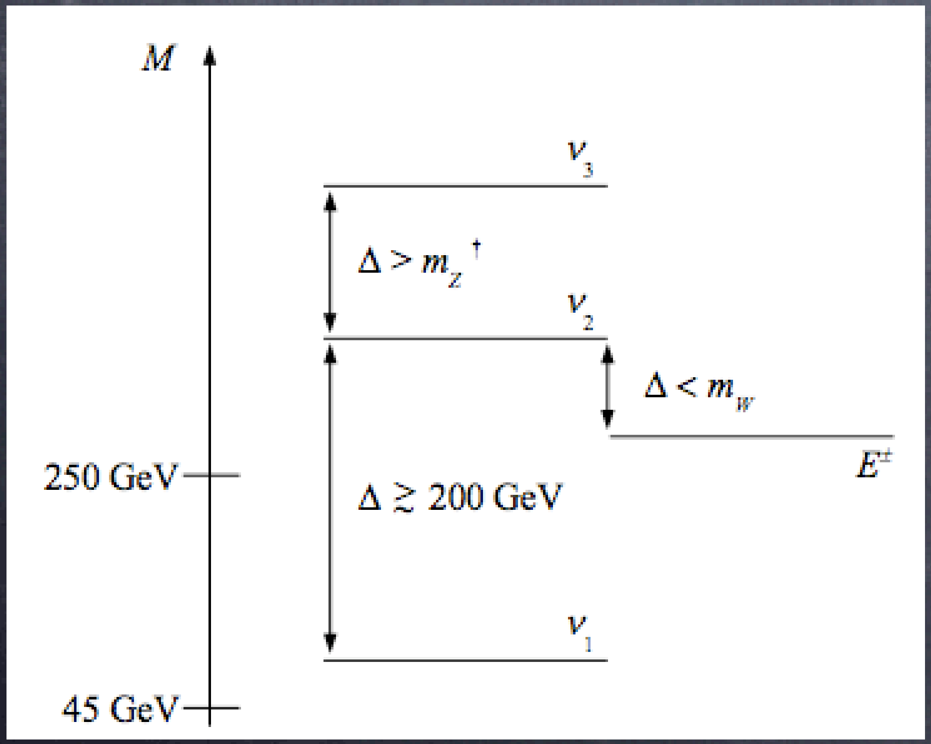
light higgs (from EW precision tests) --> new physics accessible at LHC

but also:

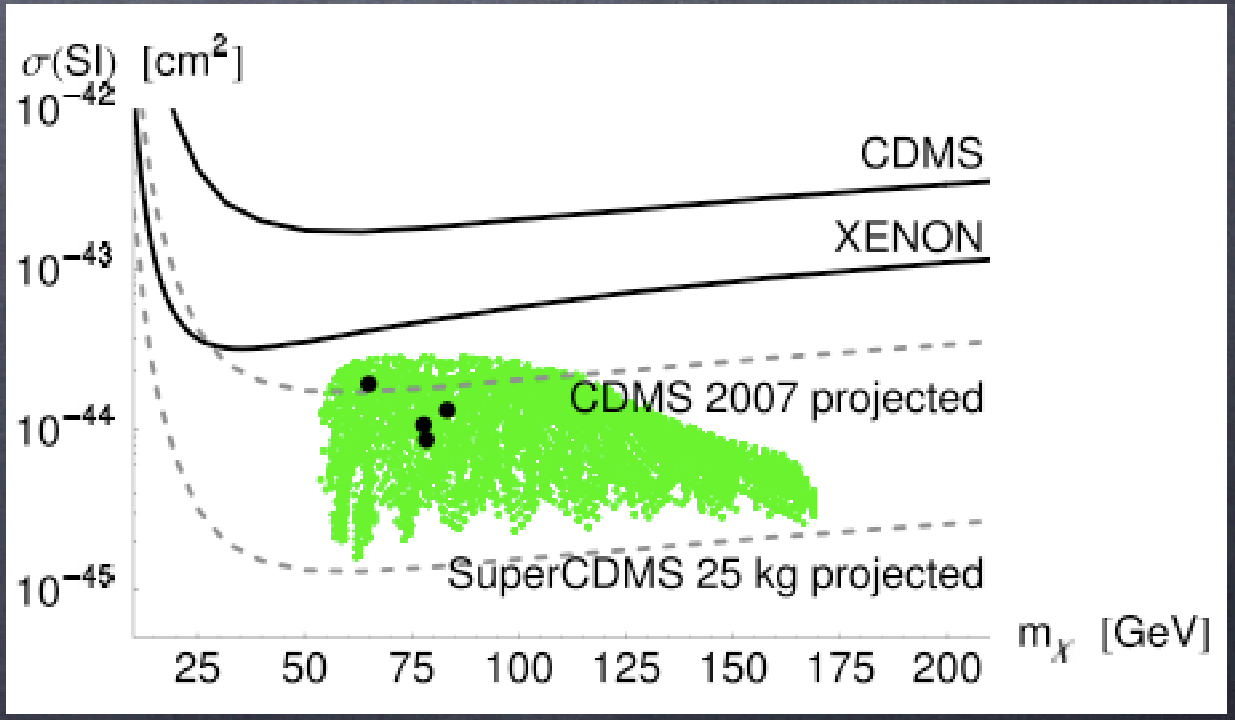
heavy higgs + heavy leptons --> EW precision tests are OK --> new physics may not be easily accessible at LHC

Enberg-Fox-Hall-Papaioannou'07;

odd under Z_2 :dark matter



m~ 50-170 GeV



Collider perspectives ?

see minireview talk by M. Fairbairn (//)

wide variety of signatures

(e.g in UED, long-lived NLKP tracks) Cembranos-Feng-Strigari '07

Not all models lead to observable signals at LHC (in particular the last two models where there are no new light colored states).

Direct and indirect signatures : important to study

To conclude

Abundance of experimental activity related to dark matter detection

and much activity as well in model building

LKPs, LZPs, LTPs, IDM ... : viable alternatives to LSPs

with a large variety of signatures