Non-supersymmetric WIMP candidates

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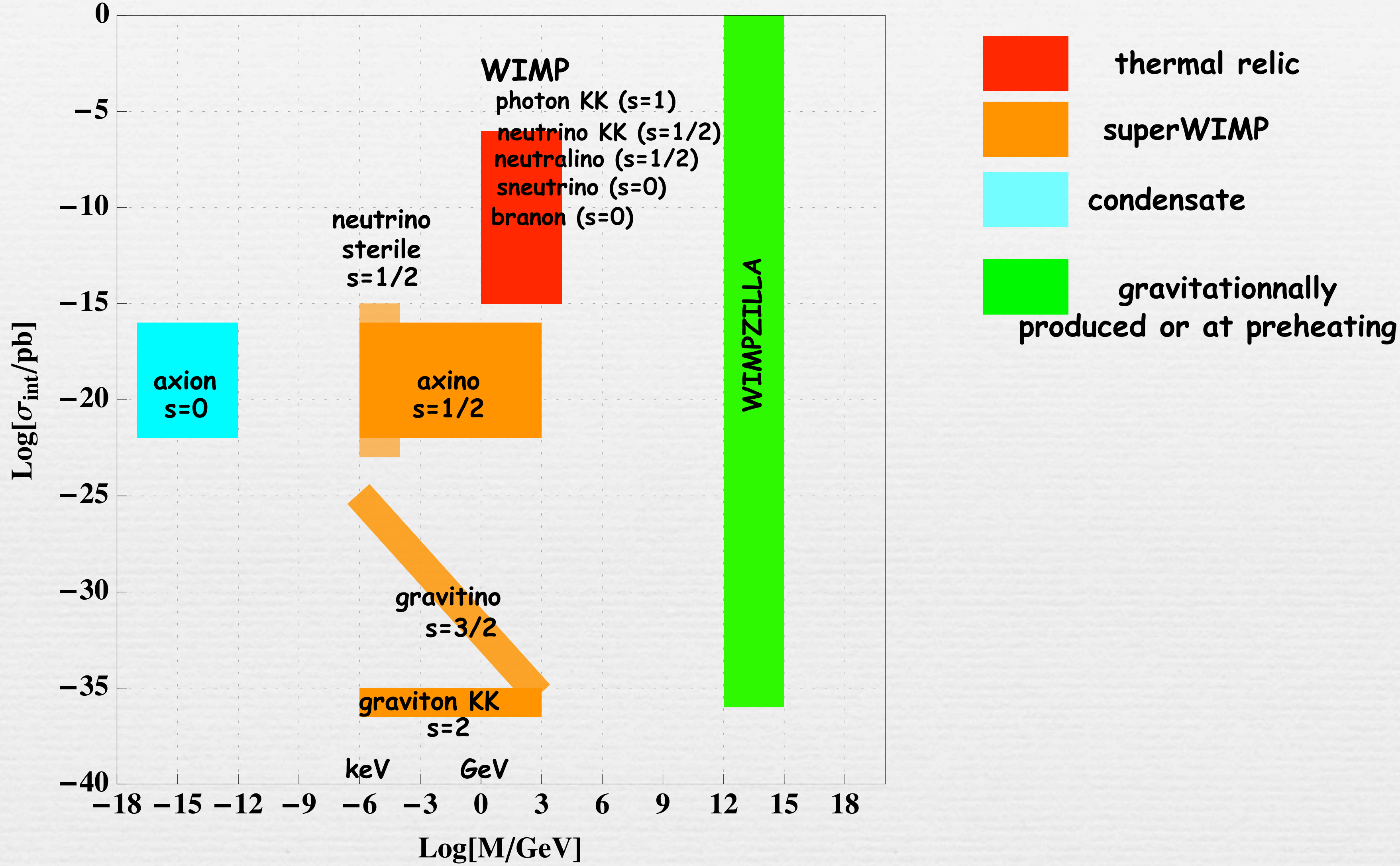
Dark Matter Candidates Ω~1



Not only a large range of candidates but also of production mechanisms

I will only highlight some of these points

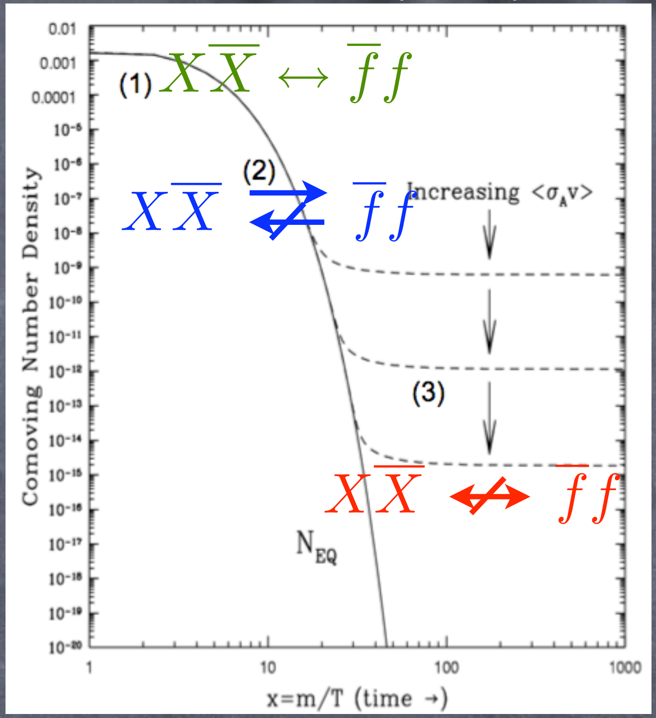
Dark matter candidates: two main possibilities

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

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

Thermal relic: $\Omega\ h^2 \propto 1/<\sigma_{anni}\ v>$

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



$\Rightarrow <\sigma_{anni}\ v>= 0.1$ pb

The "WIMP miracle"

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

$\Rightarrow m \sim 100$ GeV

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

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

What is the origin of the WIMP stability?

[see discussion by T. Hambye in 1012.4587 & his talk at PPC2011]

The lifetime of DM should be larger than the age of the universe $\tau_{universe} \sim 10^{18}$ s.

Actually even larger, $\tau_{DM} \geq 10^{26}$ s, not to overproduce e^+, p, γ fluxes

To get an idea, consider stable particles in the Standard Model:

- The photon is stable because it is the massless gauge boson of the exact electromagnetic $U(1)_{QED}$ gauge symmetry
- The electron is stable because it is the lightest particle charged under the $U(1)_{QED}$ gauge symmetry
- The lightest neutrino is stable because of Lorentz invariance since it is the lightest fermion
- The proton is stable because of the conservation of baryon number, which results accidentally from the SM gauge symmetries and the gauge charges assigned to the SM particles.

Can we use similar arguments for the dark matter particle?

The MSSM case

The lightest neutralino is stable due to R-parity, a symmetry distinguishing partners and super-partners, originally **assumed** to avoid proton decay

$$R_p = (-1)^{3B+L+2s}$$

Note that proton decay can be avoided by assuming either B or L conservation. This would allow R-parity breaking terms and thus the LSP unstability.

Anyhow, R-parity can be justified, as it is connected to the superfield R-symmetry, under which quark and lepton superfields are odd while the Higgs superfields are even.

$$R_s = (-1)^{3(B-L)}$$

$$R_p = R_s(-1)^{2s}$$

If $U(1)_{B-L}$ is only broken by scalar vacuum expectation values that carry even integer values of 3(B-L), i.e. are even under R_s, then R-parity arises naturally.

-> R_s is a discrete Z_2 remnant of $U(1)_{B-L}$, thus of SO(10)

-> constraints on SO(10) GUT model building

$U(1)_{B-L}$ justification of DM stability

This justification of DM stability goes beyond the supersymmetric context

See recent studies: [Kadastik et al' 2010; Frigerio- Hambye '2010]

$U(1)_{B-L}$, $SO(10)$ broken by even (B-L) field vev

If SM fermions are in the 16 of SO(10) which is B-L odd and the SM Higgs doublet is in the 10 of SO(10) which is B-L even, then:

-> The lightest component of an extra B-L odd scalar SO(10) representation is stable

-> The lightest component of an extra B-L even fermion SO(10) representation is stable

Dark Matter as the lightest charged particle under a hidden unbroken gauged U(1)

[Ackerman et al' 2008; Feng et al '2008,2009]

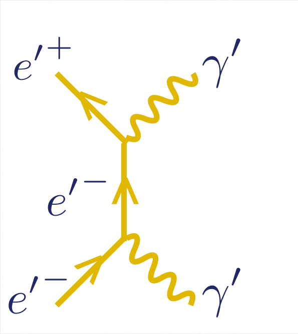
-> DM is stable for the same reason the electron is stable

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{QED'}$$

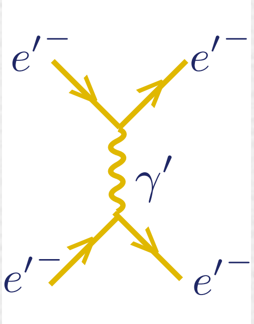
$$\mathcal{L}_{QED'} = \overline{\psi}_{e'}(i\not\partial - e\not{A}_{\gamma'} - m_{e'})\psi_{e'}$$

stable

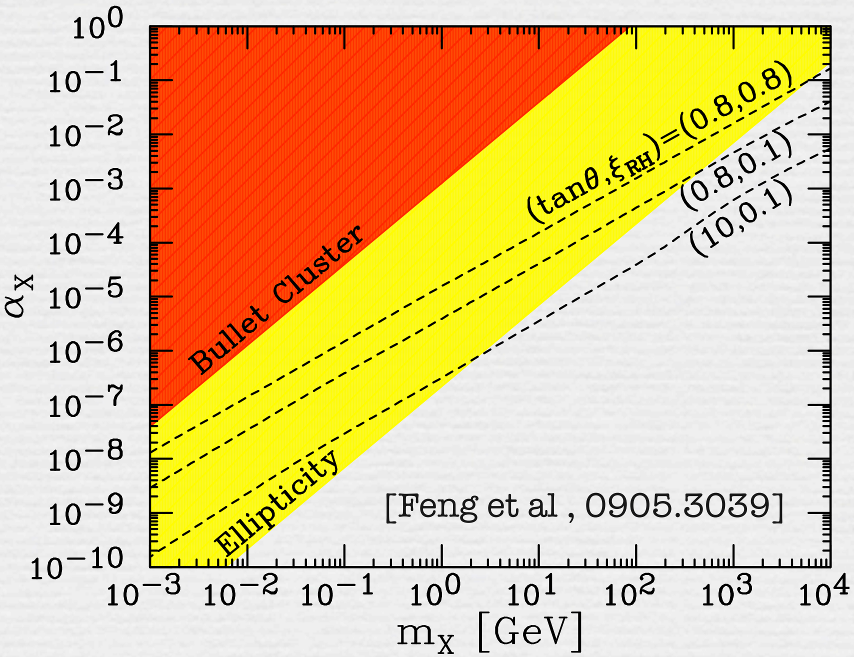
relic density controlled by annihilations :



long range force between DM particles



modifies galactic halo morphology + collisions in bullet cluster + damping of small scale structures



Dark Matter as the lightest fermion of a secluded sector

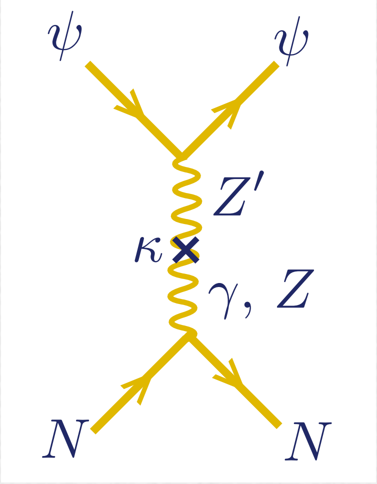
[Pospelov, Ritz, Voloshin'07]
[Gopalakrishna, Jung, Wells'08]
[Gopalakrishna, Lee, Wells'08] ....

Consider a new U(1)' spontaneously broken by Φ' and a fermion Ψ' charged under U(1)'.

$$\mathscr{L} = \mathscr{L}_{SM} + \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi}'(i\not{D} - m_{\psi'})\psi' + D_\mu \phi' D^\mu \phi'^\dagger$$
$$-\mu^2_{\phi'} \phi' \phi'^\dagger - \lambda_{\phi'}(\phi' \phi'^\dagger)^2 - \lambda_m \phi' \phi'^\dagger H H^\dagger + \kappa F^Y_{\mu\nu} F^{\mu\nu},$$

Ψ' is stable since all interactions involve it in pairs.

Z' phenomenology, communication with SM through kinetic mixing and Higgs portal.



DM stability from accidental symmetry: Minimal Dark Matter

[Cirelli, Fornengo, Strumia' 2006]

-> DM is stable for the same reason the proton is stable

No new gauge group in addition to the Standard Model.
Only add new large $SU(2)_L$ multiplet.
-> fermion quintuplet and septuplet are stable by $SU(2)_L$ invariance (no renormalizable interaction leading to their decay)

$SU(2)_L$	$U(1)_Y$	spin	M (TeV)	ΔM(MeV)	decay ch.
2	1/2	S		348	EL
		F	1.0	342	EH
3	0	S	2.5	166	HH^*
		F	2.7	166	LH
	1	S		540	HH, LH
		F		526	LH
4	1/2	S		353	HHH^*
		F		347	(LHH^*)
	3/2	S		729	HHH
		F		712	(LHH)
5	0	S	9.4	166	(HHH^*H^*)
		F	10	166	—
	1	S		537	$(HH^*H^*H^*)$
		F		534	—
	2	S		906	$(H^*H^*H^*H^*)$
		F		900	—
7	0	S	25	166	—

DM stability from accidental symmetry: Non-abelian Vector Dark Matter

Hambye'09
Hambye, Tytgat'10
Arina, Hambye, Ibarra, Weniger'10

hidden sector non-abelian group $SU(2)_{HS}$ broken by ϕ

$$\mathcal{L} = \mathcal{L}^{SM} - \frac{1}{4}F^{\mu\nu} \cdot F_{\mu\nu} + (\mathcal{D}_\mu\phi)^\dagger(\mathcal{D}^\mu\phi) - \lambda_m \phi^\dagger\phi H^\dagger H - \mu_\phi^2 \phi^\dagger\phi - \lambda_\phi(\phi^\dagger\phi)^2$$

A_i^μ : stable because of accidental custodial global SO(3)

stability broken by non-renormalizable operators:

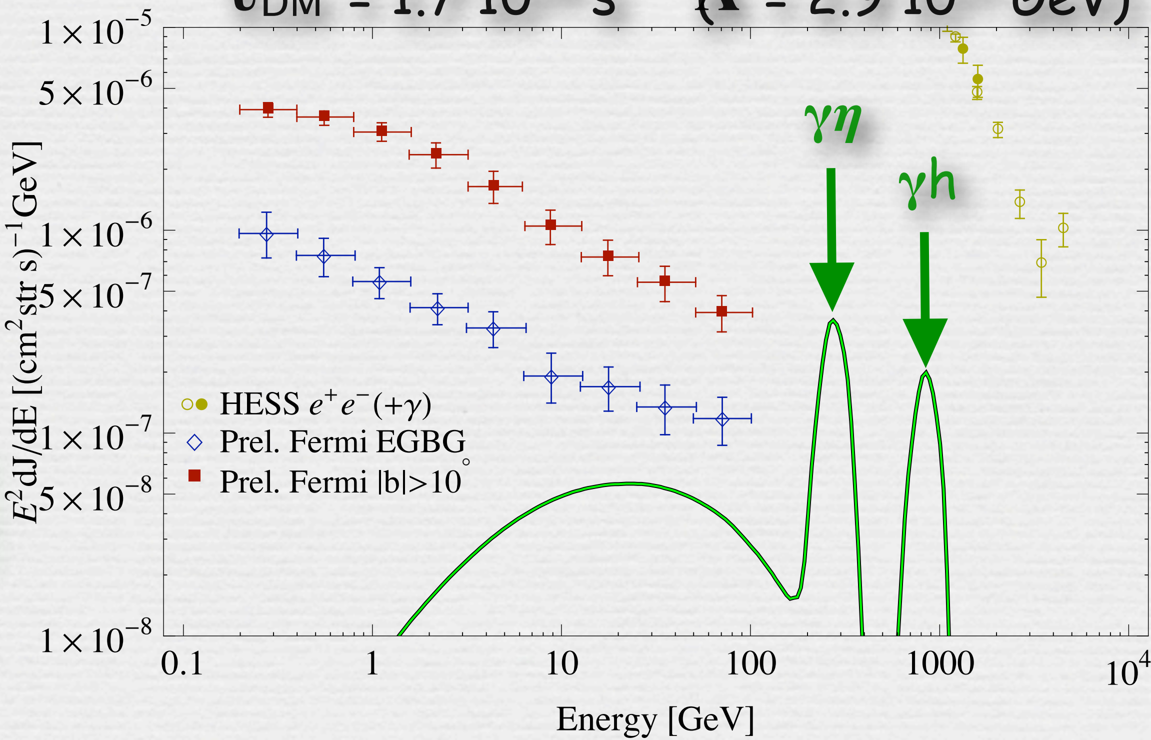
$$\frac{1}{\Lambda^2}\,\mathcal{D}_\mu\phi^\dagger\phi\;\mathcal{D}_\mu H^\dagger H \qquad \frac{1}{\Lambda^2}\,\mathcal{D}_\mu\phi^\dagger\mathcal{D}_\nu\phi\;F^{\mu\nu Y}$$

$$\frac{1}{\Lambda^2}\,\mathcal{D}_\mu\phi^\dagger\phi\;H^\dagger\mathcal{D}_\mu H \qquad \frac{1}{\Lambda^2}\,\phi^\dagger F^a_{\mu\nu}\frac{\tau^a}{2}\phi F^{\mu\nu Y}$$

late decay of DM → γh & $\gamma\eta$ lines :

(η:hidden sector scalar)

τ_{DM} = 1.7 10^{28} s (Λ = 2.9 10^{15} GeV)



Dark Matter from extra dimensions

Some “historical” overview

Some references. I- Set of lectures

TASI lectures **on extra dimensions and branes.**
Csaba Csaki : **hep-ph/0404096**

effectives theories, ADD, symmetry breaking in flat Xdim via orbifolds (EW,susy,GUTs), mediation of susy breaking, warped pheno

TASI lectures on electroweak symmetry breaking from extra dimensions. Csaba Csaki, Jay Hubisz, Patrick Meade **hep-ph/0510275**

more detailed look at gauge theories in Xdim, higgsless models, fermions in Xdim, EW precision observables

TASI 2004 lectures on the phenomenology of extra dimensions. Graham D. Kribs. **hep-ph/0605325**

more phenomenological + Universal Extra Dimensions (UED)

Les Houches lectures on warped models and holography.
Tony Gherghetta **hep-ph/0601213**

warped models, susy warped, warped GUTs, AdS/CFT, holography

Cargese Lectures **on Extra Dimensions.**
R. Rattazzi: **hep-ph/0607055**

effective actions, ADD,RS,Goldberger-Wise stabilization, AdS/CFT, holography

Large and infinite extra dimensions: An Introduction.
V.A. Rubakov : **hep-ph/0104152**

similar as above + localization of fermions and gauge fields + Cosm. Const. + modified gravity + lorentz violation

ICTP lectures **on large extra dimensions.**
Gregory Gabadadze : **hep-ph/0308112**

KK theories, ADD, warped models + DGP model

Tasi 2004 lectures**: To the fifth dimension and back.**
Raman Sundrum **hep-th/0508134**

effective theories, orbifolds and chirality, radion stabilisation, cosm. constant pb, warpeds models

An Introduction to extra dimensions.
Abdel Perez-Lorenzana **hep-ph/0503177**

effective actions ... + neutrino mass models, split fermions, 6D models

II- Some original references

Phenomenology, astrophysics and cosmology of theories with submillimeter dimensions and TeV scale quantum gravity.
Nima Arkani-Hamed, Savas Dimopoulos, G.R. Dvali **hep-ph/9807344**

An Alternative to compactification.
Lisa Randall , Raman Sundrum **hep-th/9906064**

A Large mass hierarchy from a small extra dimension.
Lisa Randall, Raman Sundrum
hep-ph/9905221

Holography and phenomenology.
Nima Arkani-Hamed, Massimo Porrati, Lisa Randall **hep-th/0012148**

Comments on the holographic picture of the Randall-Sundrum model.
R. Rattazzi , A. Zaffaroni **hep-th/0012248**

Why consider theories with extra dimensions?

- ✗ D=3+1 is not a prediction in Einstein's theory
- ✗ Only string theory predicts the number of dimensions i.e D=1+9(10).

We have to 'hide' extra dimensions
Indeed , $F \sim \frac{1}{r^2}$ *: only in 3 dimensions!*

- ✗ Easy to hide extra dimensions if they are compact and tiny:

$$F \sim \frac{1}{r^{2+n}} \text{ for } r < r_c$$
$$F \sim \frac{1}{r^2} \text{ for } r \geq r_c$$

- ✗ Not only are extra dimensions allowed but they could also be useful to help us resolve the big puzzles of 4D physics...

Which size for extra dimensions?

Experimental constraints:

Roughly:

- If Standard Model fields propagate in extra dimensions
$\Rightarrow R < (\mathrm{TeV})^{-1} \sim 10^{-19}\mathrm{m}$

-If only gravity propagates in extra dimensions $\Rightarrow R <$ sub mm

If we assume that ALL fields propagate in ALL extra dimensions (which moreover have ALL the same size) :

$$\left.\begin{array}{l} M_{\rm Pl}^2 \sim R^n M_*^{n+2} \\ \dfrac{1}{g_4^2} \sim R^n M_*^n \end{array}\right\} R \sim \frac{g_4^{\frac{n+2}{n}}}{M_{\rm Pl}} \qquad \text{i.e.} \qquad R \sim M_{\rm Pl}^{-1}$$

Things change if, in particular, fields are LOCALIZED in extra dimensions.

and this brings us to the ADD idea: (Arkhani-Hamed, Dimopoulos, Dvali '98)

The Planck scale is no longer a fondamental scale but an effective scale:

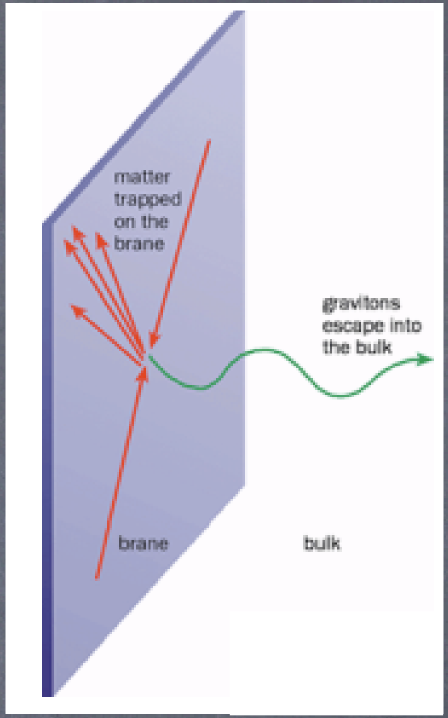
If M_* is the fundamental scale and $M_* \sim \mathrm{TeV}$

then $n = 2$ ⇛ $R^{-1} \sim \mathrm{meV} \sim \mathrm{mm}^{-1}$

ADD models

- "Large" flat extra dimensions(can be almost macroscopic in size) where only gravity propagates.

- The Standard Model is localized in 3 dimensions.



$R \sim meV^{-1} \sim mm$

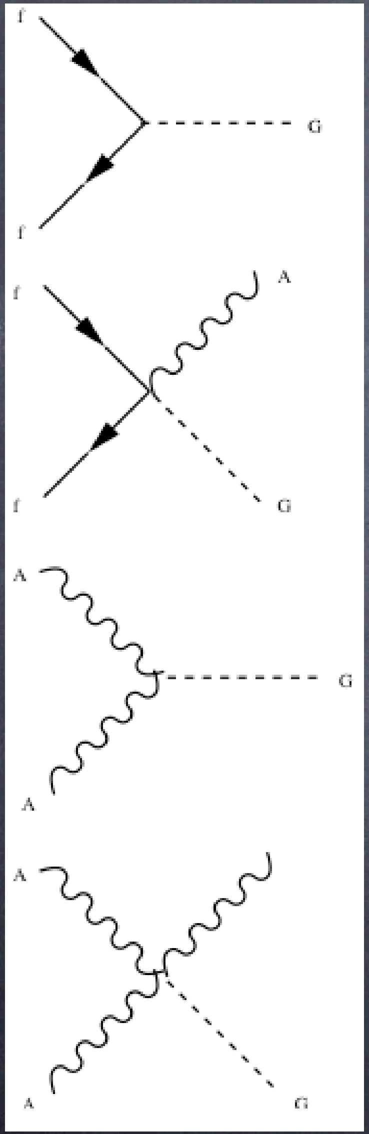
: no stark disagreement with experiments and observations.

Gravity appears weak because it is 'diluted' in extra dimensions

Extra-dimensional gravitons look to us as a "tower" of massive gravitons with masses regularly-spaced in n/R

Signatures at colliders

Observing quantum gravity at the LHC



Each graviton taken individually has a coupling suppressed in 1/Mpl and the production of a single graviton is totally negligible.

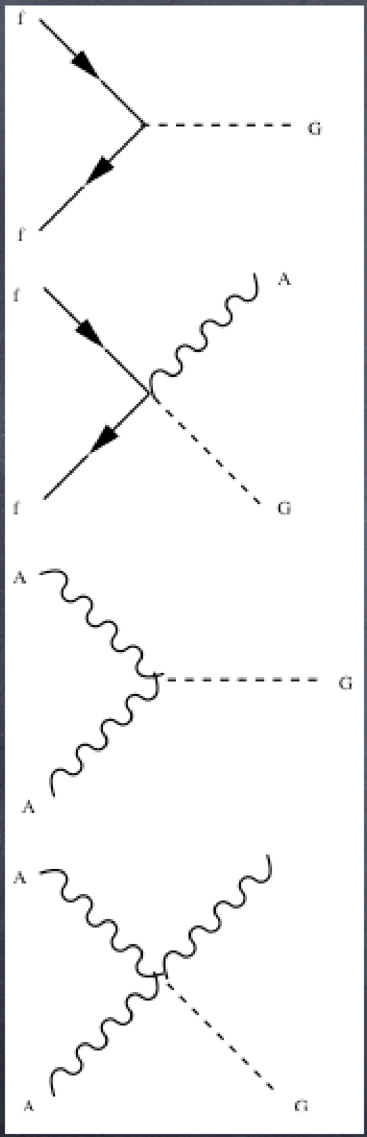
However, the cross section to produce a collection of massive gravitons is amplified due to the vary large number of gravitons.

Δm~meV -> continuum of states $$\sigma \sim \frac{(ER)^n}{M_{\rm Pl}^2} \sim \frac{E^n}{M_*^{n+2}}$$

The effective scale suppressing the coupling is in fact M_* and not $M_{\rm Pl}$

Signatures at colliders

Observing quantum gravity at the LHC

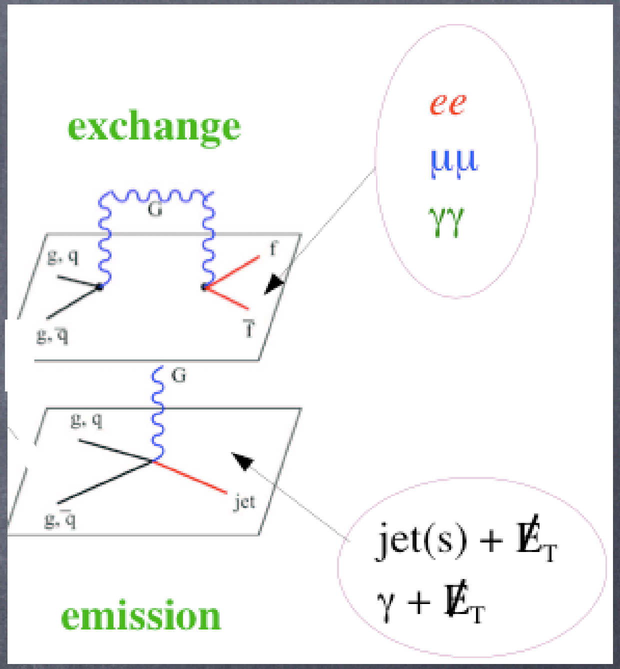


⇛ Direct production of gravitons

gravitons escape from the brane ->invisible KK graviton

signature is monojet + missing energy

continuum of states: mass distribution is a continuun



⇛virtual graviton exchange

new reaction $g\ g \rightarrow l^+ l^-$

+ deviations with respect to standard processes (interference with the amplitude in the SM)

⇛black hole production

For $\sqrt{s} >> M_*$ semi classical description becomes adequate as $r_s >> M_*^{-1}$

quantum-gravity effects are subleading with respect to classical gravitational effects

When the impact parameter $b < r_s$ we expect black hole formation

The LHC : a black hole factory

Black hole production of mass $M_{\rm BH} = \sqrt{s}$ if the impact parameter of the collision is smaller than the Schwarzschild radius.

i.e geometrical approximation $\sigma \sim \pi r_H^2$

(transplanckian energies)

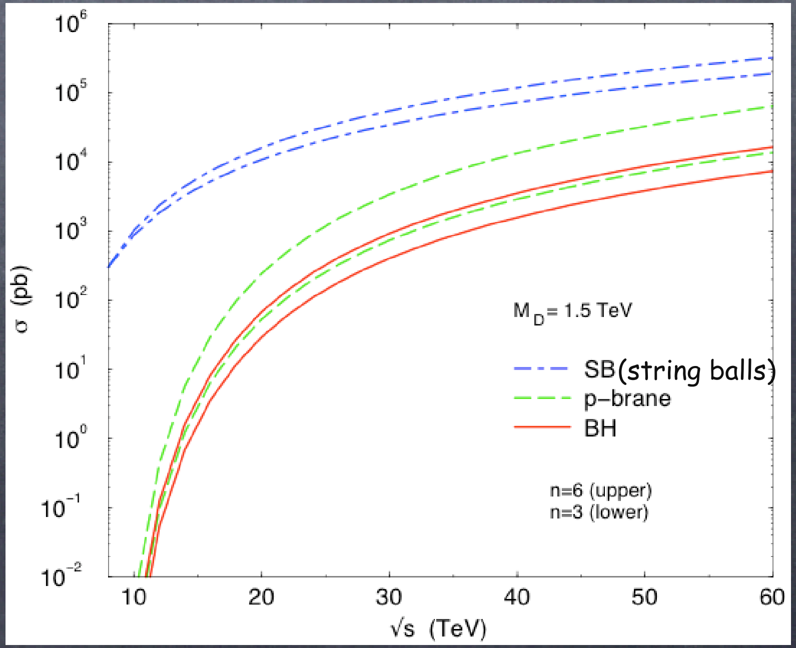
$$\sqrt{s} \geq M_*$$

Schwarzschild radius in 4+n dimensions:

$$r_H \sim \left(\frac{M_{\rm BH}}{M_*}\right)^{\frac{1}{n+1}} \frac{1}{M_*}$$

4+n generalization of $ds^2 = (1 - \frac{GM}{r})dt^2 - \frac{dr^2}{1 - GM/r} + r^2 d^2\Omega$

$$\boxed{\sigma \sim \pi r_H^2 \sim \frac{1}{M_*^2}\left(\frac{M_{BH}}{M_*}\right)^{\frac{2}{n+1}} \sim \mathrm{TeV}^{-2}}$$



Evaporation via Hawking radiation:

$$T_H = \frac{n+1}{4\pi r_H} \in$$ [80-600] GeV for n=1...7

$$\tau \sim \frac{1}{M_*}\left(\frac{M_{BH}}{M_*}\right)^{\frac{n+3}{n+1}} \sim 10^{-26}\mathrm{sec}$$

The mass gap is 1/R.

For n=2 and M_* =1 TeV, this is meV.

BBN energy is MeV and the number of KK gravitons which are kinematically accessible is more than 10^18!

problem: Too much energy is released into KK gravitons.

At $T \gtrsim 1/R$ the number of KK modes which are kinematically accessible is $(TR)^n$

The cross section for graviton production from brane thermal processes is

$$\sigma \sim \frac{(TR)^n}{M_{\rm Pl}^2} \sim \frac{T^n}{M_*^{n+2}} \qquad \Gamma_G = \langle n_\gamma \sigma_{\gamma\gamma\to G} v \rangle \sim \frac{T^{n+3}}{M_*^{n+2}}$$

no backward processes: $\frac{dn_G}{dt} \sim n_\gamma \Gamma_G \qquad \to n_G \sim n_\gamma \Gamma_G H^{-1} \sim \frac{T^{n+4} M_{Pl}}{M^{n+2}}$

$$\frac{n_G}{n_\gamma} < 1 \to \qquad T_* < \left(\frac{M^{n+2}}{M_{Pl}}\right)^{1/(n+1)}$$

cooling bound

which can also be derived by demanding that the cooling of the universe due to evaporation of KK gravitons in extra dimensions be smaller than the cooling due to expansion:

$$\frac{d\rho}{dt}|_{evap} \sim -\frac{T^{n+7}}{M_*^{n+2}} < \frac{d\rho}{dt}|_{exp} \sim -3H\rho \sim -3\frac{T^6}{M_{Pl}}$$

BBN bound

Once KK gravitons are produced, they behave as matter of mass T (the probability to interact with the thermal bath on the brane is very small) and their energy density $\rho_G \sim T \times n_G$ redshifts as 1/R^3: $\rho_G(T = MeV) \sim \rho_G(T) \left(\frac{MeV}{T}\right)^3$

$$\Rightarrow \frac{\rho_G}{\rho_\gamma}|_{BBN} \sim \frac{T}{1\ MeV} \frac{\rho_G}{\rho_\gamma}|_T \sim \frac{T}{1\ MeV} \frac{T_*^{n+1} M_{Pl}}{M^{n+2}} \quad \Rightarrow \quad T < \left(\frac{10^{-3} M^{n+2}}{M_{Pl}}\right)^{1/(n+2)}$$

slightly stronger than the overcooling bound

The two previous bounds apply to 4D particles with 1/TeV coupling. Moreover, the specificity of our gravitons is that the probability that they interact with the SM wall is very tiny: the energy stored in them can easily overclose the universe.

Overclosure bound

$$\Gamma \sim \left(\Gamma_{\text{near wall}} \sim \frac{T^{n+3}}{M_*^{n+2}}\right) \times \begin{array}{c}\text{proba to be}\\ \text{near wall}\end{array} \sim \frac{T^3}{m_{Pl}}$$

$$\sim \left(\frac{T^{-1}}{R}\right)^n$$

Compton wavelength ~1/T

: Decay of a single graviton is indeed suppressed by 1/Mpl

$$\tau(T) \sim 10^{10}\text{yr} \times \left(\frac{100\text{MeV}}{T}\right)^3$$

The energy density stored in KK gravitons produced at temperature T, $\rho_G \sim \frac{T^{n+5} M_{Pl}}{M^{n+2}}$

redshifts as 1/R^3 so $\frac{\rho_G}{T^3} \sim \frac{T^{n+2} M_{Pl}}{M^{n+2}} = \text{constant}$ and we require that

$$\frac{\rho_G}{T^3} < \frac{\rho_c}{T_0^3}$$

where $\frac{\rho_c}{T_0^3} \sim 3 \times 10^{-9}\text{GeV}$

$$\Rightarrow \qquad T < \left(\frac{10^{-21} M^{n+2}}{M_{Pl}}\right)^{1/(n+2)}$$

bound from diffuse photon background

The fraction of KK gravitons produced at temperature T, with lifetime

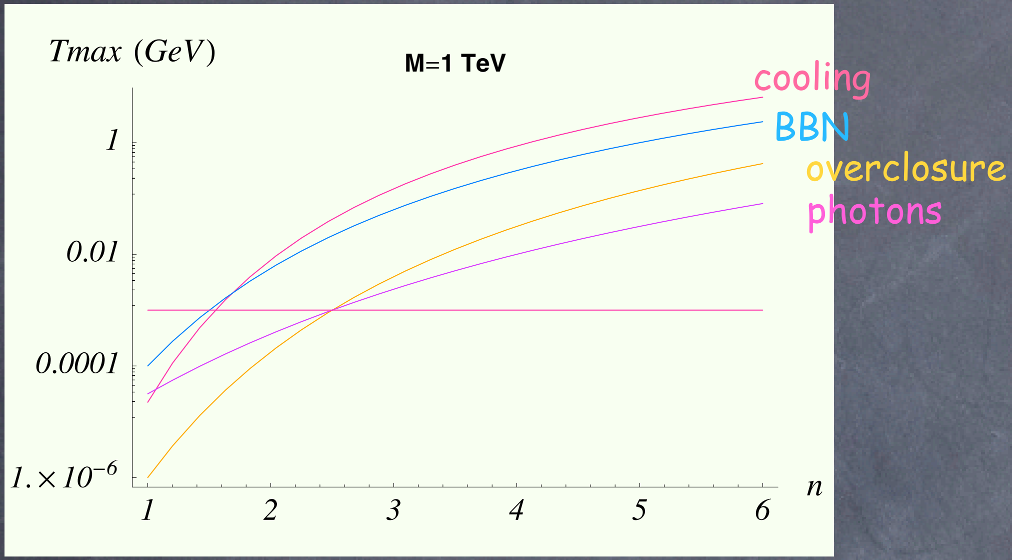
$\tau(T) \sim 10^{10}\mathrm{yr} \times \left(\frac{100\mathrm{MeV}}{T}\right)^3$ which have already decayed is $\left(\frac{100\mathrm{MeV}}{T}\right)^3$

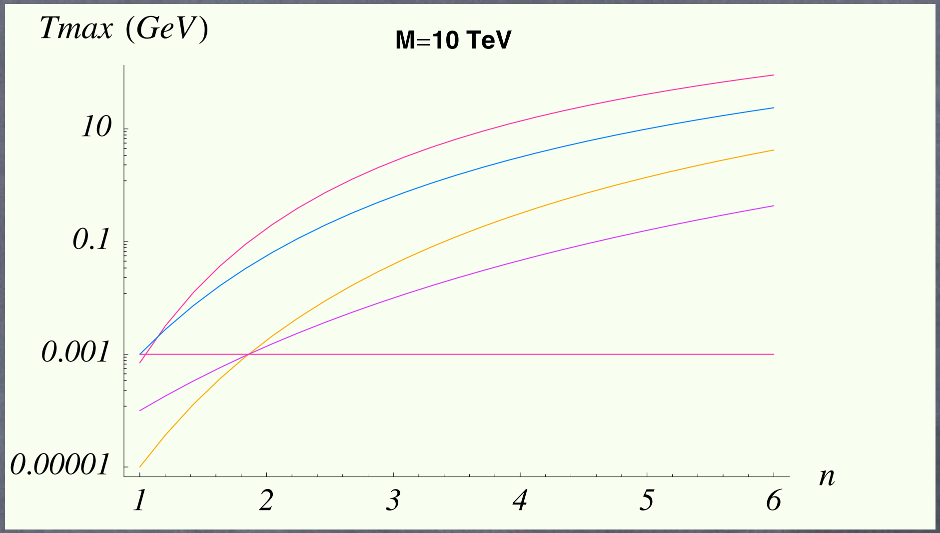
The resulting number density of photons is $n_{\gamma \text{ from KK decays}} \sim n_{0,G} \times \left(\frac{T_*}{100\mathrm{MeV}}\right)^3$

Constraint from COMPTEL data leads to $T < (10^{-40} GeV^3 M^{n+2})^{1/(n+5)}$

(Gamma ray observations
in the MeV range)

Summary of constraints





Conclusion: Difficulty to implement leptogenesis/baryogenesis in this context.
Cut off is TeV:
How to make inflation natural?

Very strong constraints from astrophysics & cosmology

✗ Cooling of supernovae and red giants due to graviton emission. $(M_* \geq 30 \text{ TeV (n=2)})$

✗ Distorsion in CMB due to graviton decay (primary or secondary) $(M_* \geq 110 \text{ TeV (n=2)})$

✗ heating of neutron stars due to KK graviton decay $(M_* \geq 1700 \text{ TeV (n=2)})$

✗ Overclosure of the universe by gravitons $M_* \geq 8 \text{ TeV}$

✗ Reheating temperature of the universe has to be very low otherwise gravitons evaporate into the bulk

$$T_{RH} \leq T_* \qquad T_* \sim \left(\frac{M_*^{n+2}}{M_{\rm Pl}}\right)^{\frac{1}{n+1}}$$

$M_* = 1 \text{ TeV} \Rrightarrow$ n=2 ->T~0.7GeV, n=6 ->T~317 GeV

$M_* = 30 \text{ TeV} \Rrightarrow$ n=2 -> T~10 MeV, n=4 ->T~1 GeV, n=6 ->T~7 GeV

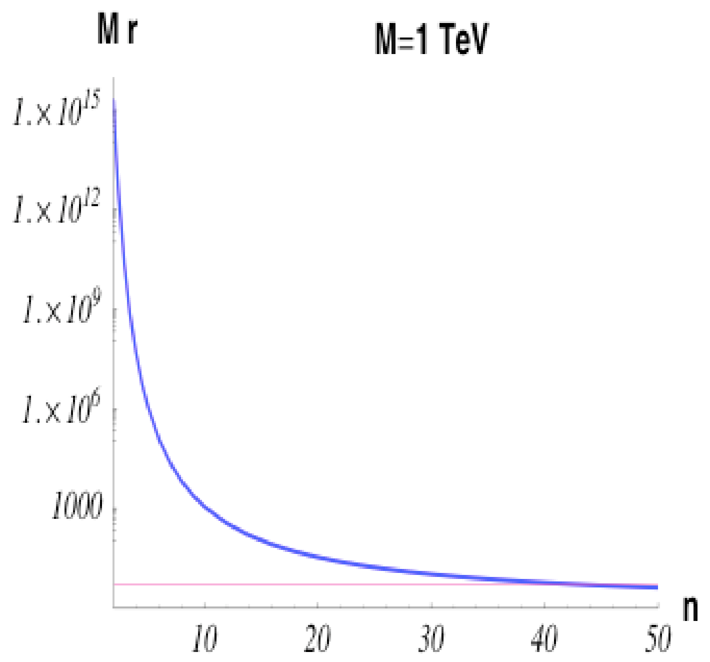
Note: These constraints are relaxed if compact extra dimensions are hyperbolic rather than toroidal

Kaloper et al **hep-ph/0002001**

problems related to the radion

∗Stabilisation:

Explain $r \sim \frac{10^{-12}}{M_*}$?



M×r~O(1) for n≥40 ...

unless we compactify on a manifold with non trivial topology

∗Cosmology:

Radion dark matter?

The energy stored in radion oscillations overclose the universe (similar to axions)...

The Randall-Sundrum model

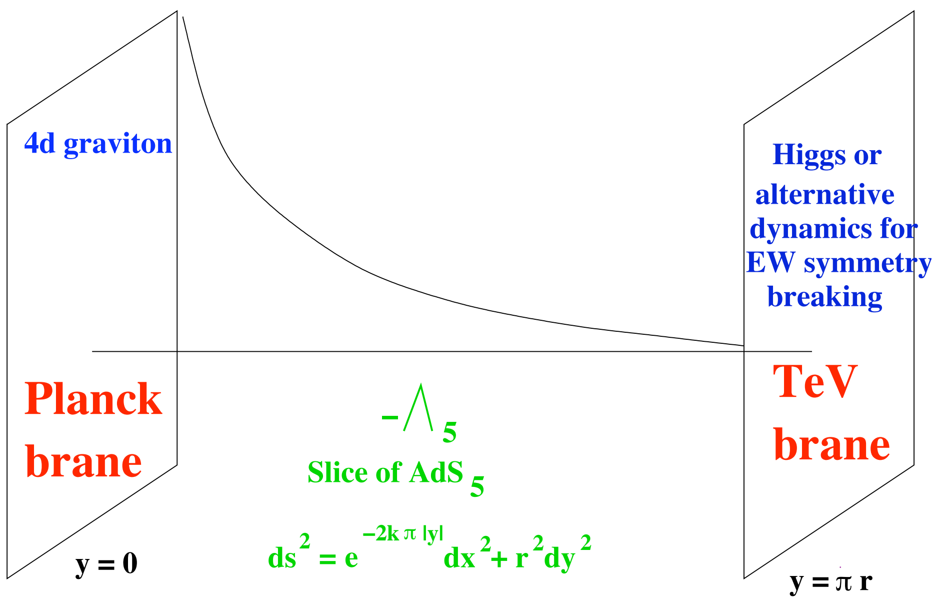
A complete solution to the hierarchy problem

Non flat geometry but Anti de Sitter (non factorisable geometry: "warping")

Fondamental scale : $M_{\rm Pl}$ $\quad (k \sim r^{-1} \sim \Lambda_5 \sim M_{\rm Pl})$

(appearing in the 5D effective action)

AdS space: the energy scale varies with position along 5th dimension



$$\Rightarrow \quad M_{\rm EW} \sim M_{\rm Pl} e^{-k\pi r}$$

Natural stabilisation of radius (à la Goldberger-Wise) :

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

Randall-Sundrum KK gravitons are very different from ADD

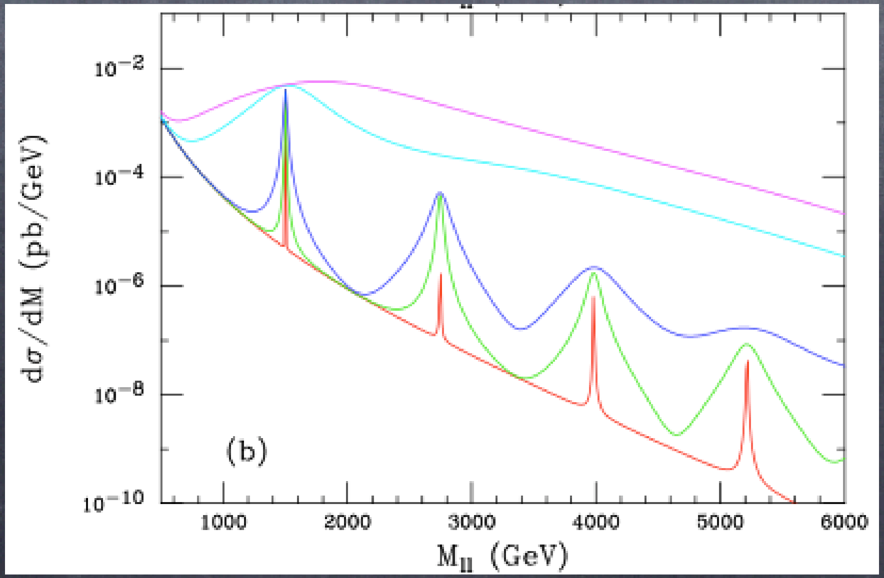
✗ Discrete spectrum with KK states non regularly spaced (proportional to the zeros of Bessel functions)

✗ Δm~O(TeV) compared to Δm~O(meV) in ADD

Remark: $r^{-1} \sim M_{\rm Pl}$ but $M_{KK} \sim \rm TeV$

✗ Each KK graviton couples as 1/TeV and not 1/ $M_{\rm Pl}$

$$q\bar{q}, gg \to G^{(n)} \to l^+ l^-$$



The radion of Randall-Sundrum is also very different from that of ADD

- ✗ m ~ O(100) GeV
- ✗ strongly coupled radion (in 1/TeV and not 1/$M_{\rm Pl}$)

} *no cosmological pb associated with the radion*

the coupling of the radion to matter is similar to the coupling of Higgs to matter ⇛ radion phenomenology = Higgs phenomenology

… and possibility of Higgs-Radion mixing modifying Higgs phenomenology at LHC

Induced operator on the TeV brane: $\int d^4x \sqrt{g}\, \mathcal{R}\, \xi\, H^\dagger H$ ⇛ $\mathcal{L} \supset 6\xi\gamma h \Box r$

radion-higgs kinetic mixing

After diagonalisation, modification of the Higgs standard couplings

3rd class of models:
(Flat) extra dimensions at the TeV

Solution to the hierarchy problem?

Same status as in SUSY : The higgs mass is stabilized against radiative corrections $(m_h \sim R^{-1})$ but it remains to explain why R^{-1}~TeV

same as in supersymmetry where we have to explain why M_{SUSY} ~TeV

2 sub-classes of models → only bosons in bulk

2 sub-classes of models → All SM fields in bulk "Universal" Extra Dimensions (UED)

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

An important feature of the SM: Its fermions are chiral, i.e. the left and right-handed components of any Dirac fermion have different gauge quantum numbers.

While 5D fermions are 4 component- spinors.

This imposes constraints on the compactification of extra dimensions

The simplest compactification on a circle or a torus leads to non-chiral “vector-like” fermions.

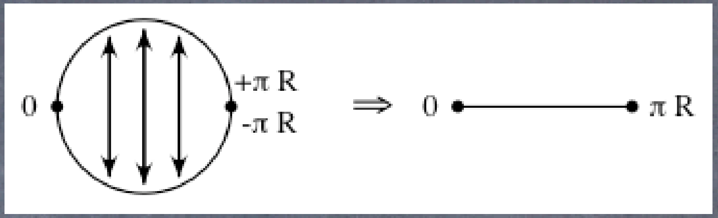
The chirality of the 4D fermions has to be introduced by the boundary conditions at the end points of the interval.

A little detour : orbifold projections

-If D=5, the gauge field contains a quadri-vector V_μ and a scalar V_5

-5D fermions are 4 component- spinors and lead to mirror fermions at low energy.

In order to eliminate unwanted degrees of freedom and get a chiral theory in 4D, we apply an orbifold projection



We fold the circle (= identify y and -y) ⇛ we get a segment (0 and πR are the 2 fixed points)

The orbifold projection consists in imposing the following conditions

$$y \to -y \qquad A_\mu \to A_\mu \qquad \Psi_L \to \Psi_L$$
$$A_5 \to -A_5 \qquad \Psi_R \to -\Psi_R$$

At y= 0, πR : Even fields have Neumann boundary conditions $\partial_y \Phi = 0$

Odd fields have Dirichlet boundary conditions $\Phi = 0$

The zero mode of the odd field is projected out by the Z_2

Kaluza-Klein decomposition

$$\Phi(x^\mu, y) = \sum_n f^n(y)\Phi^n(x^\mu)$$

Fields which are even (A_μ, Ψ_L) have a zero mode

Fourier expansion for compactification on a circle

$$\Phi(x^\mu, y) = \sqrt{\frac{1}{\pi R}}\Phi^0(x^\mu) + \sum_{n\geq 1}\sqrt{\frac{2}{\pi R}}\cos\left(\frac{ny}{R}\right)\Phi^n(x^\mu)$$

Standard Model particle

Fields which are odd (A_5, Ψ_R) do not have a zero mode

$$\Phi(x^\mu, y) = \sum_{n\geq 1}\sqrt{\frac{2}{\pi R}}\sin\left(\frac{ny}{R}\right)\Phi^n(x^\mu)$$

The "zero" mode fermions are chiral (and identified with the SM fermions). However, the other KK fermions are vector-like.

(a bit similar to supersymmetry where each SM particle is accompanied by partners)

Each left-handed (right-handed) SM fermion possesses a distinct Kaluza-Klein tower

Orbifold projections are intensively used to break symmetries:

One imposes different boundary conditions for the different components of a given multiplet

- ✗ *Electroweak symetry*
- ✗ *Grand unification symmetry*
- ✗ *Supersymmetry*

ADD models

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)

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

TeV^{-1} X-dims

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

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

Hierarchy pb solved

Warped geometries
(Randall-Sundrum)

(AdS)

- radion unstable

if GUT in bulk $\longrightarrow$ - KK dark matter

WIMP!

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

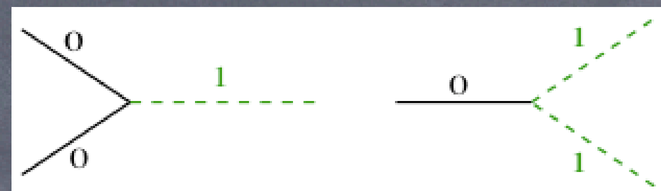
`Universal' Extra Dimensions

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.

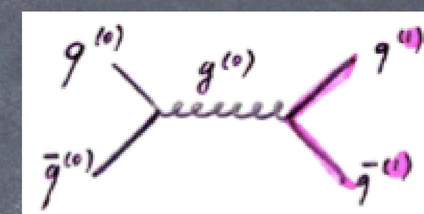
For instance:



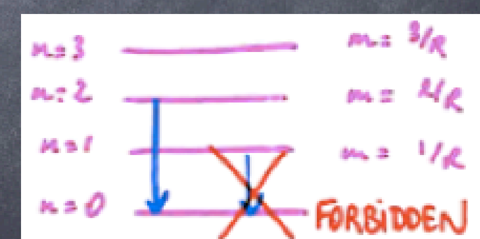
forbidden allowed

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

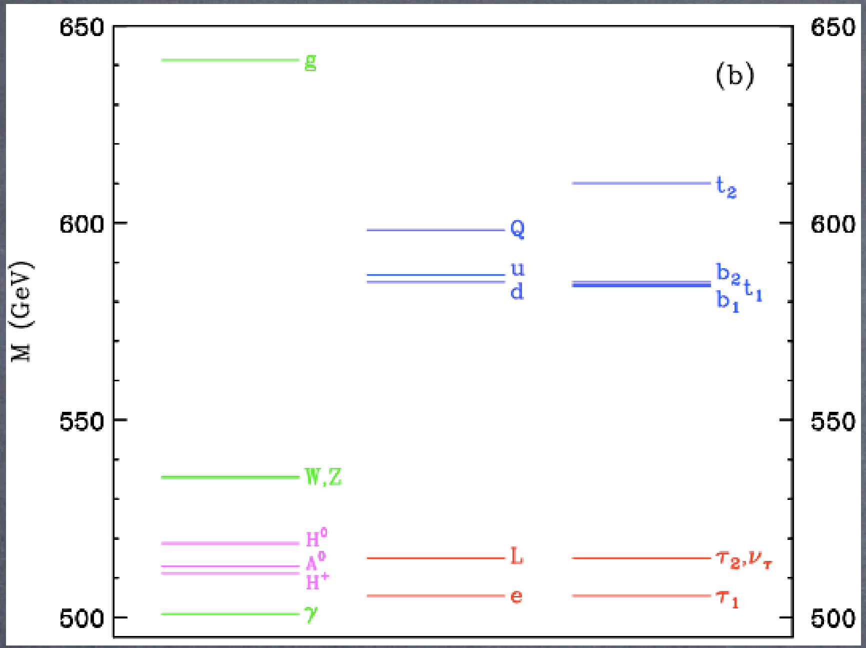
The Kaluza-Klein photon:
an excellent candidate for dark matter

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



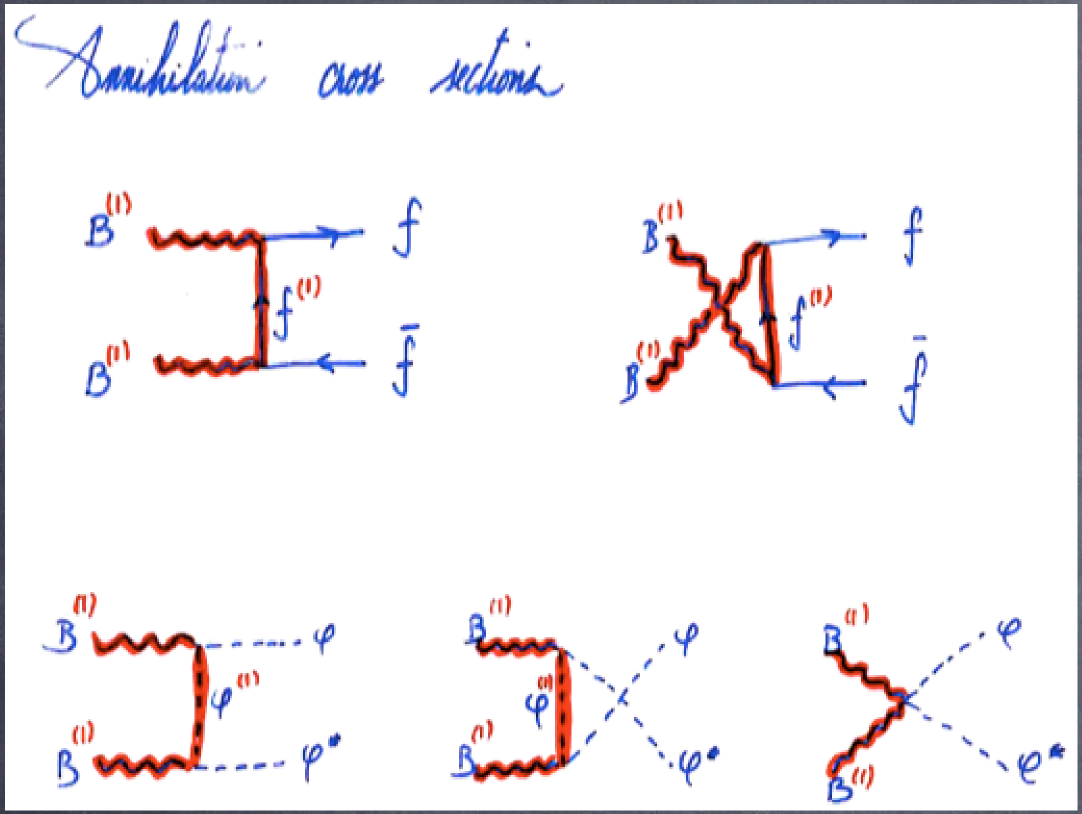
assuming:1/R=500 GeV, $\Lambda R = 20, m_h = 120$ GeV
and vanishing boundary terms at the cutoff Λ

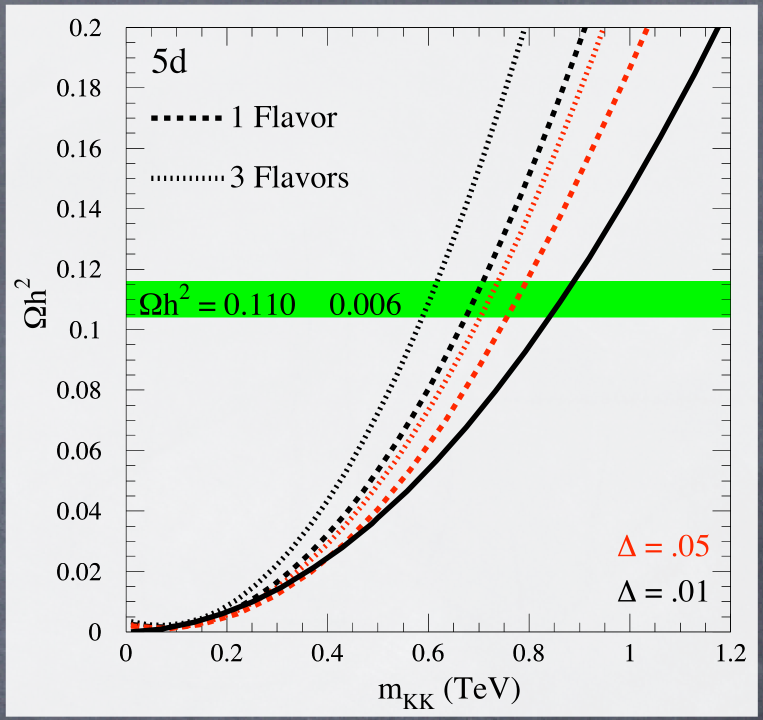
⇨ LKP: most likely a γ^1 (actually a B^1)

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

Relic density predictions

Servant-Tait'02

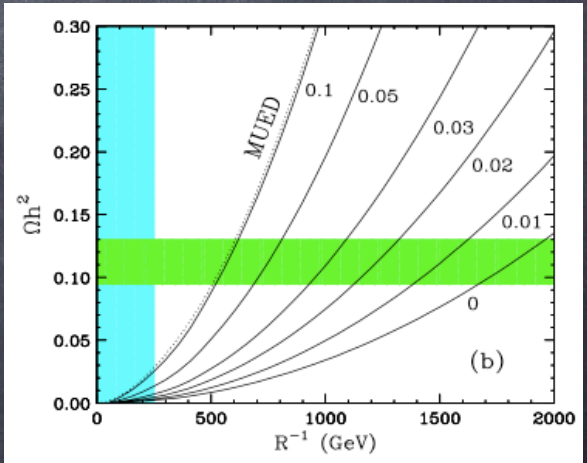




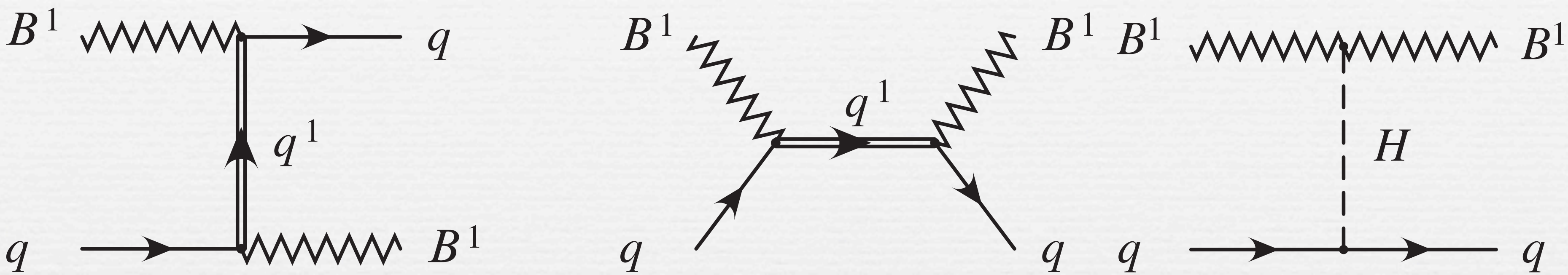
full effect of coannihilations Kong-Matchev, hep-ph/0509119

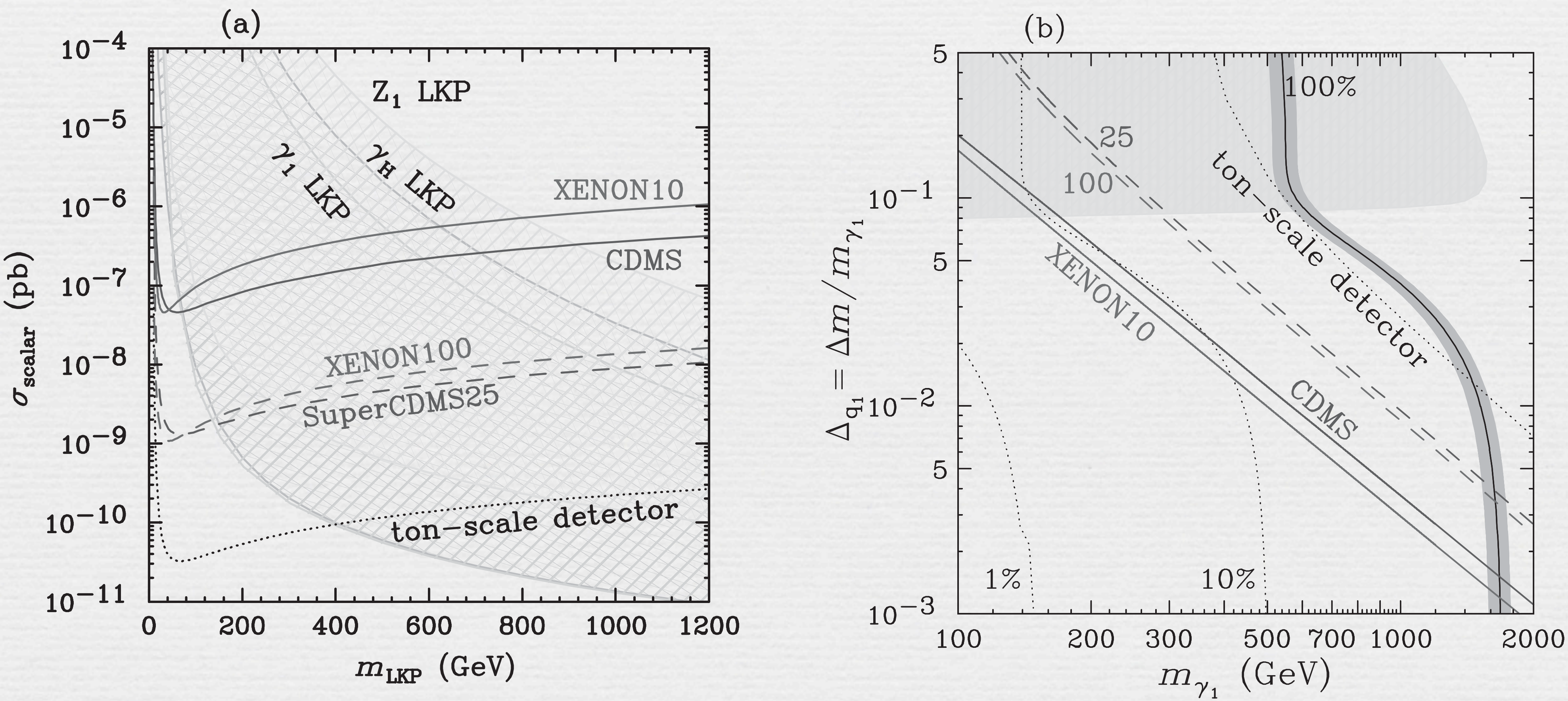
effect of 2nd level KK modes, "natural KK resonance"

Kakizaki & al , hep-ph/0502059



Direct detection





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

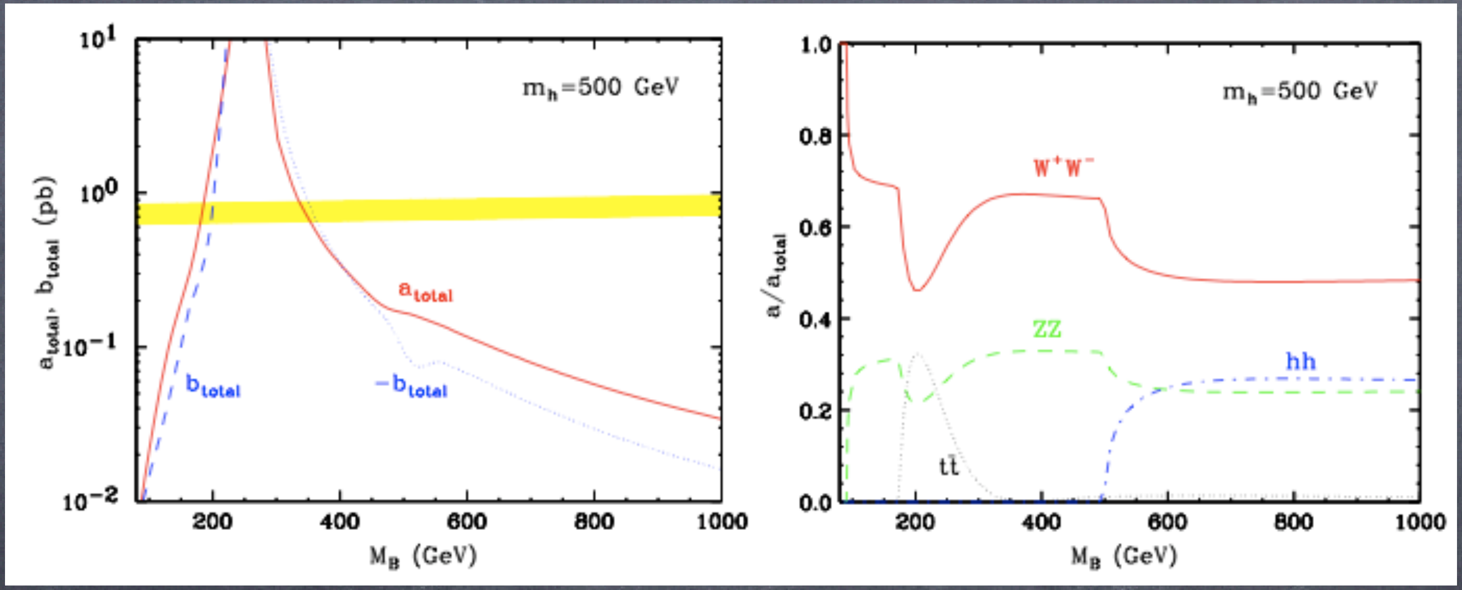
[Dobrescu, Hooper, Khong, Mahbubani '07]

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]

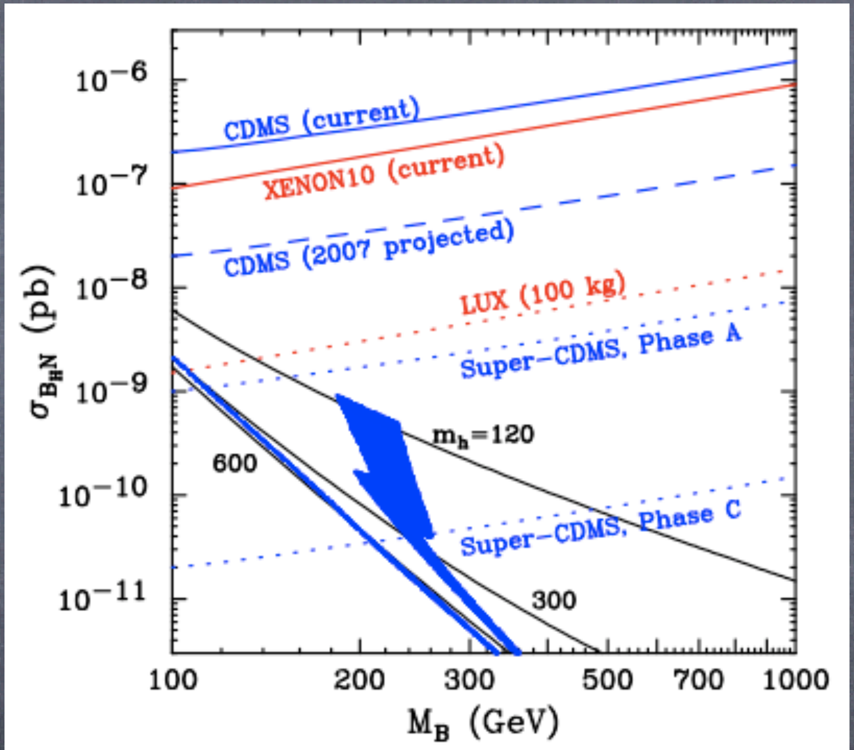
The Lightest spin-0 field is stable by KK parity and a good DM candidate



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]

6D UED (Real Projective Plane)

[Cacciapaglia, Deandrea, Llodra-Perez, 0907.4993]

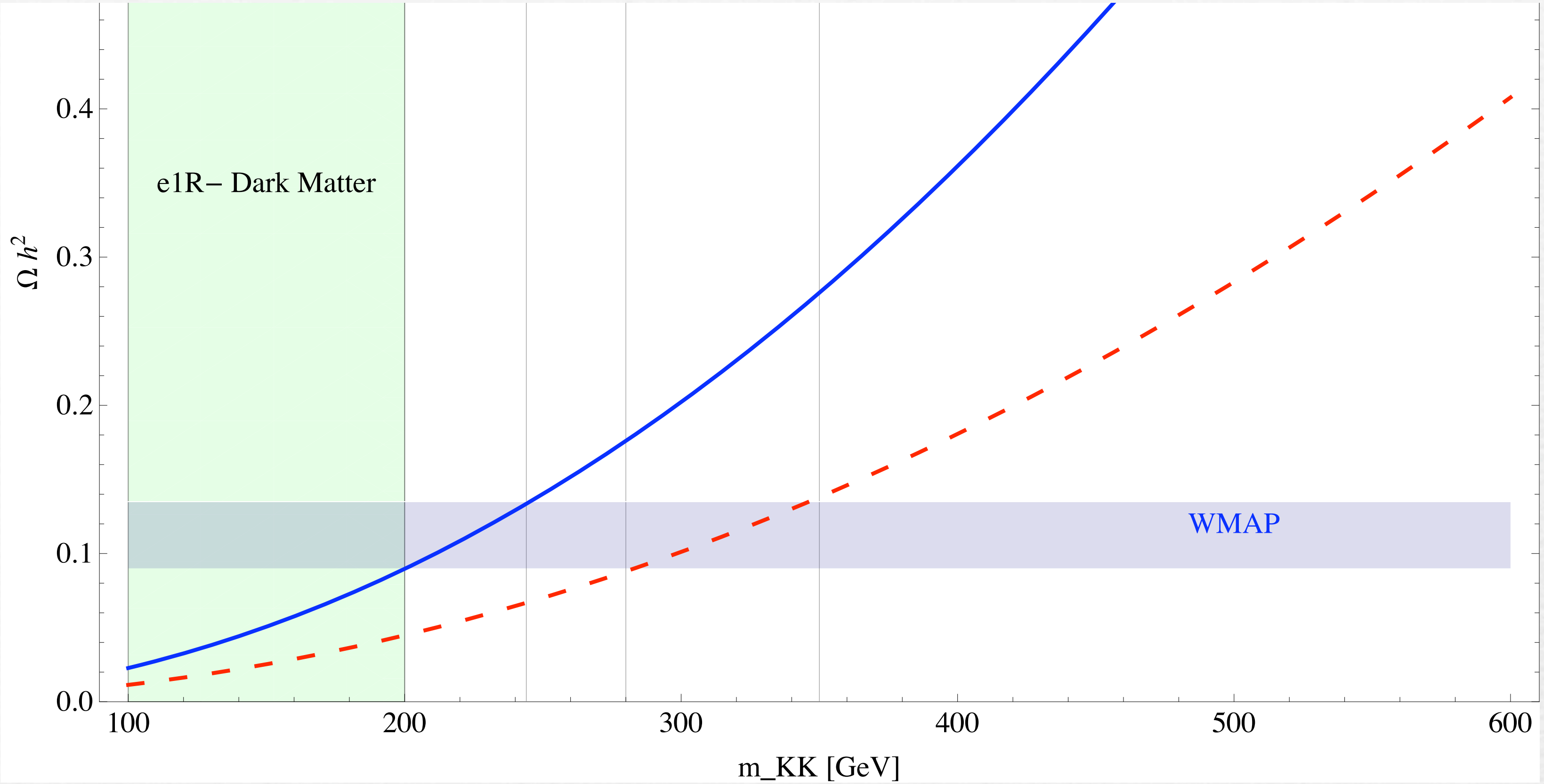
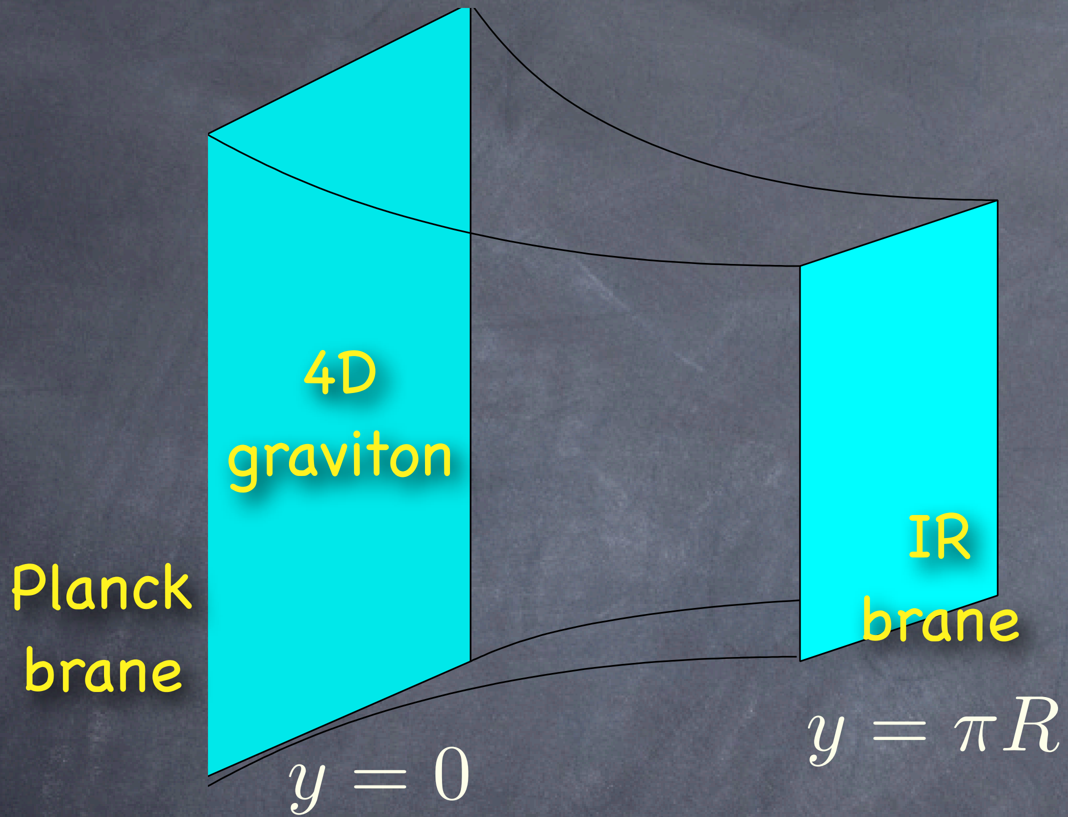


Figure 2.14: Relic density of LKP including $SU(2)\times U(1)$ gauge boson and lepton coannihilations as a function of m_{KK} in the RPP model. The solid blue line is for the degenerate case where $R_5 = R_6 = R$ and where (1,0) and (0,1) are both Dark Matter candidates. The red dashed line is for the asymmetric case where for instance $R_5 \gg R_6$ and where $(1,0)$ is the Dark Matter candidate. The light blue band denotes the WMAP preferred region for the relic density: $0.095 < \Omega_{dm}h^2 < 0.13$.

Warped extra dimensions

Space-time is a slice of AdS_5



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

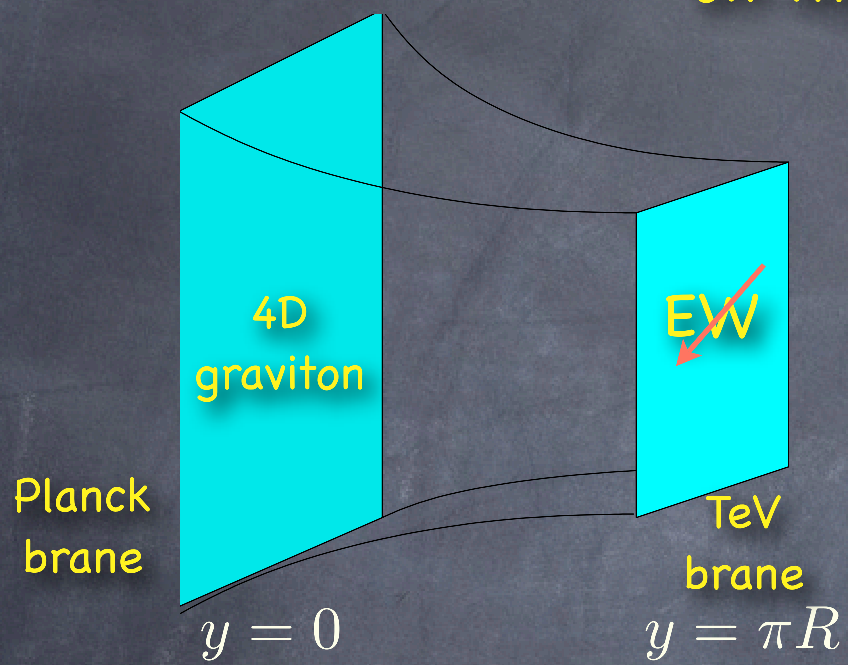
$$M_{Pl}^2 \sim \frac{M_5^3}{k}$$

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=πR, on the TeV (IR) brane



After canonical normalization of the Higgs:

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

parameter in the 5D lagrangian

$$k\pi R \sim \log(\frac{M_{Pl}}{\text{TeV}})$$

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)

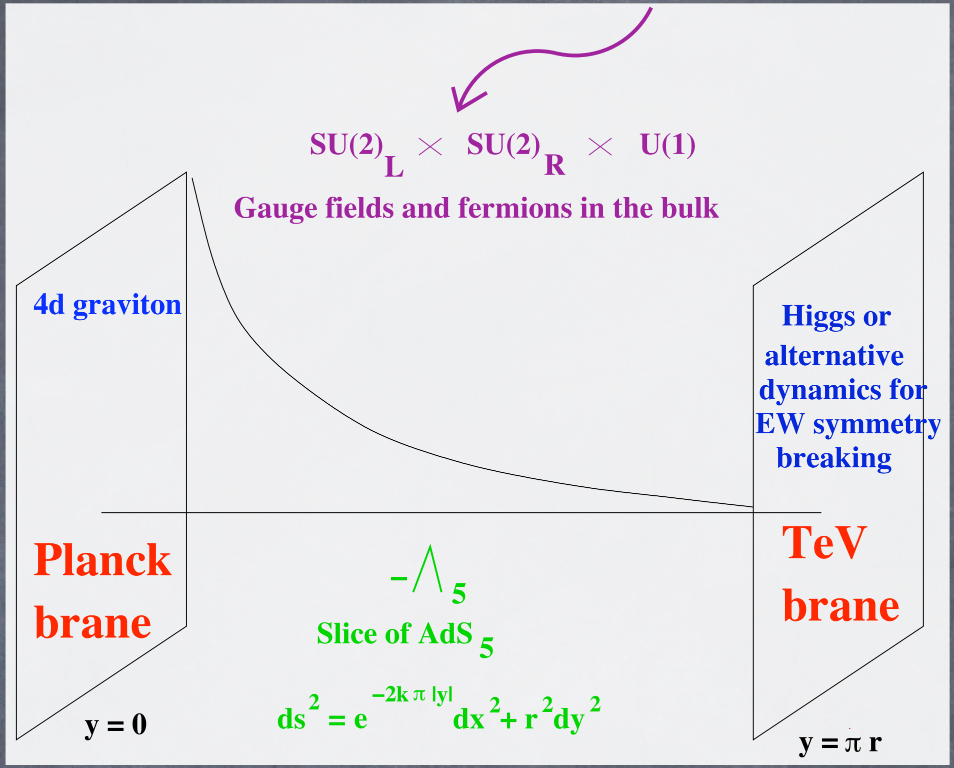
$$kr = \frac{4}{\pi}\frac{k^2}{m^2}\ln\left[\frac{v_h}{v_v}\right] \sim 10$$

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

Particle physics model building in warped space

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

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



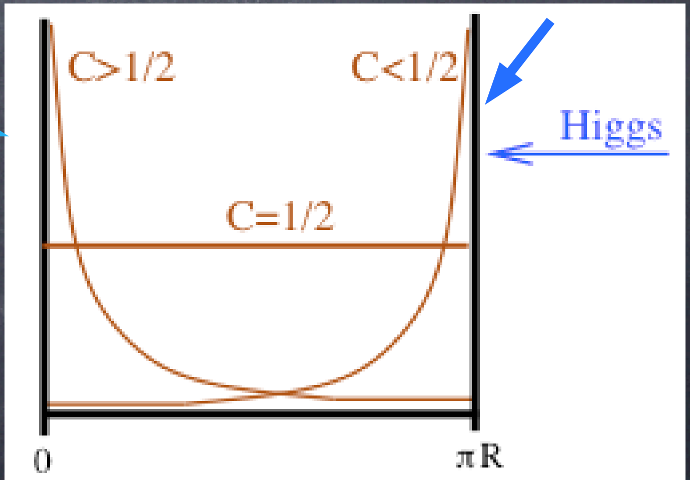
Note: No susy here

and many different realizations

M_{KK}~few TeV

light fermions

heavy fermions



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

Model building in Warped Spacetime
"historical" overview

Original RS1
[Randall, Sundrum '99]

SM on TeV brane

->Large FCNCs

No explanation for EW breaking

RS1 with SM in bulk & Higgs on TeV brane
[Agashe, Delgado, May, Sundrum '03]

Composite Higgs models
[Agashe, Contino, Pomarol '04]

$SU(2)_L \times SU(2)_R \times U(1)_X$
-> custodial symmetry

SM gauge fields & fermions in bulk

✔ EW breaking: Higgs as A_5

Higgsless models
[Csaki Grojean, Pilo, Terning '03]

✔ EW breaking: by boundary conditions on gauge fields

AdS/CFT dictionnary

[Maldacena '97]
[Arkani-Hamed, Porrati, Randall '01]
[Rattazzi, Zaffaroni '01]

RSI ⟷ An almost CFT that very slowly runs but suddenly becomes strongly interacting at the TeV scale, spontaneously breaks the conformal invariance and confines, thus producing the Higgs

Warped gravity with fermions and gauge field in the bulk and Higgs on the brane

The hierarchy problem is solved due to the compositeness of the Higgs

KK modes localized on TeV brane ⟷ bound state resonances

A gauge symmetry in the bulk ⟷ A global symmetry of the CFT

$SU(2)_R$ will protect the rho parameter

[Agashe, Delgado, May, Sundrum '03]
[Csaki, Grojean, Pilo, Terning '03]

UV matter ⟷ Fundamental particles coupled to the CFT

IR matter ⟷ Composite particles of the CFT

RSI: A calculable model of technicolor

For a slice of AdS_5, the warp factor is clearly not symmetric under reflection about the midpoint of the extra dimension.

To implement an analogue of KK parity of UED requires that 2 physically distinct slices of AdS_5 are glued and the symmetry interchanging the two AdS_5 slices is imposed.

-> warped KK parity

See Agashe et al, 0712.2455

However, warped extra dimensions without KK parity can exhibit dark matter candidates

Mass spectrum of KK fermions

Depends on:

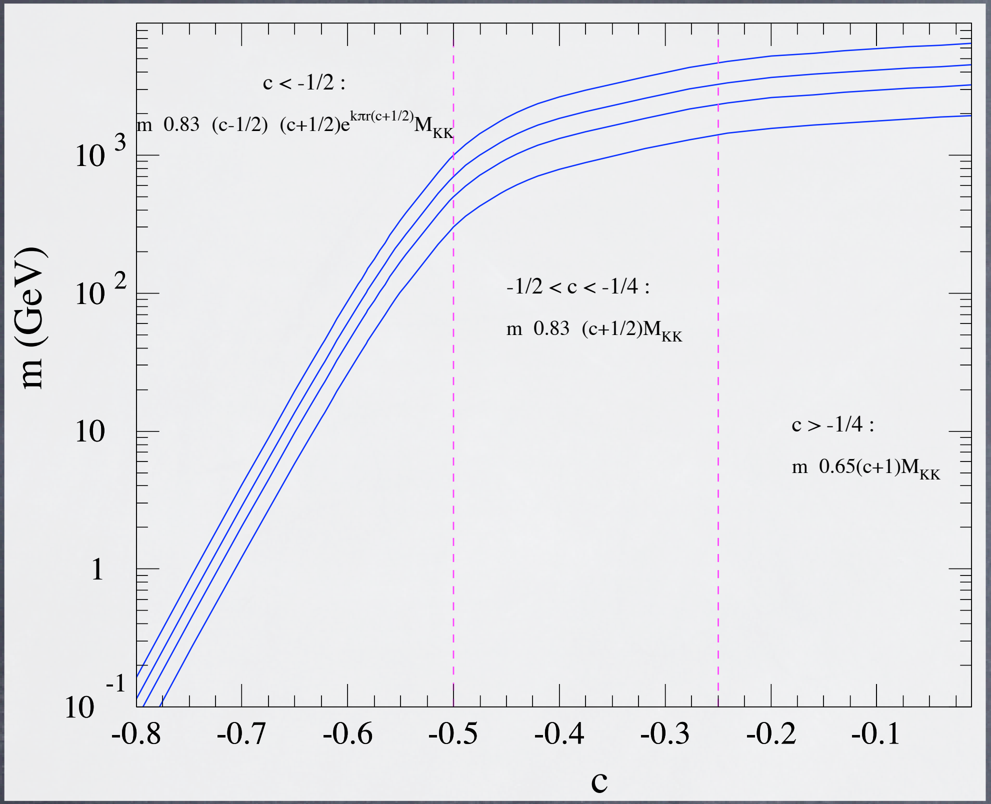
✔ type of boundary conditions on TeV and Planck branes

✔ 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
5 TeV
3 TeV

← M_{KK} value

c= 5D fermion mass in Planck units

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

Right-handed top quark has c ≈ -1/2 ⇛ (-+) 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

Proton stability & Stable GUT partner in Warped GUTs

Agashe-Servant'04

DM is RH neutrino from 16 of SO(10)

$$\begin{pmatrix} Q'_L \\ u^c_R \\ d^c_R \\ L'_L \\ e'^c_R \\ \nu'^c_R \end{pmatrix}$$

multiplet has B=1/3

bulk fermion with (-+) BC -> light!

number of color indices

stable under $$Z_3 : \Phi \longrightarrow \Phi\ e^{2\pi i\left[B - \frac{\alpha - \overline{\alpha}}{3}\right]}$$

Has enhanced couplings to TeV KK modes (such as Z') and top quark

UV | SO(10) | IR

light SM fermions | warping $\longrightarrow$ | t_R Higgs DM

A very simple effective theory

Jackson, Servant, Shaughnessy, Tait, Taoso,'09
Agashe-Servant '04; Belanger-Pukhov-Servant '07

There is a new spontaneously broken U(1)'.
The WIMP is a Dirac fermion, ν, singlet under the SM, charged under U(1)'

The only SM particle with a large coupling to the Z' is the top quark

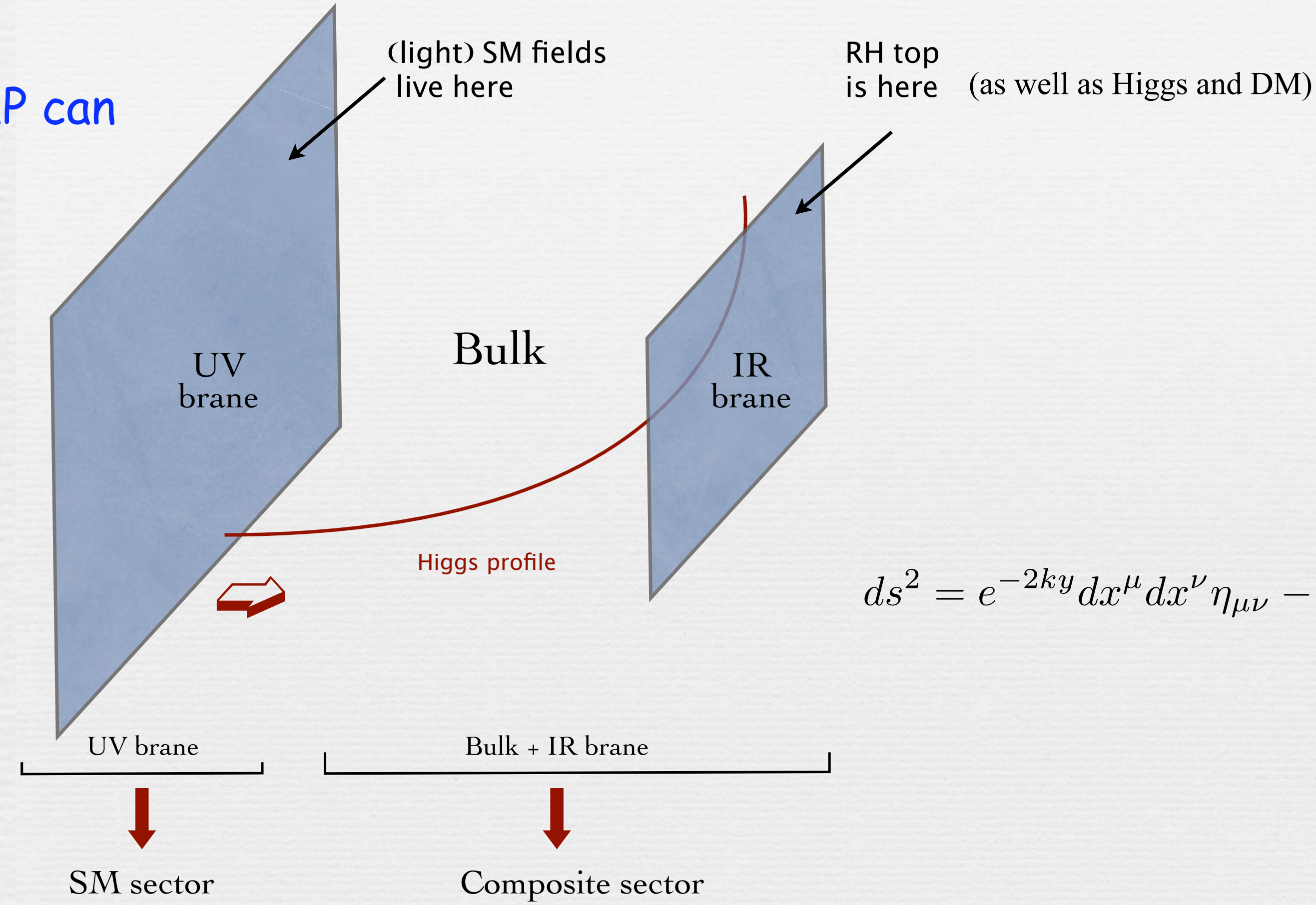
$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + M^2_{Z'} Z'_\mu Z'^\mu + \underbrace{i\bar{\nu}\gamma^\mu D_\mu \nu}_{\text{DM}} + g^t_R \bar{t}\gamma^\mu P_R Z'^\mu t + \frac{\chi}{2} F'_{\mu\nu} F^{\mu\nu}_Y$$

$$D^\mu \equiv \partial_\mu - i\left(g^\nu_R P_R + g^\nu_L P_L\right) Z'^\mu$$

There is no SM state the WIMP can decay into: ν is stable.

This model is inspired by the Randall-Sundrum setup (warped extra dimension):

TeV KK modes (such as Z') have enhanced couplings to RH top quark



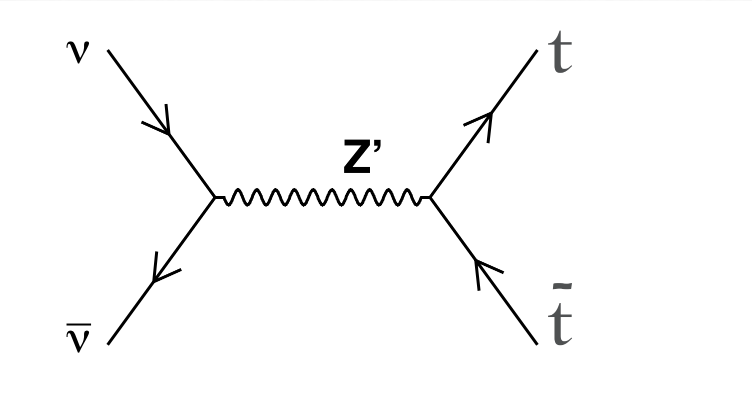
$$ds^2 = e^{-2ky} dx^\mu dx^\nu \eta_{\mu\nu} - dy^2$$

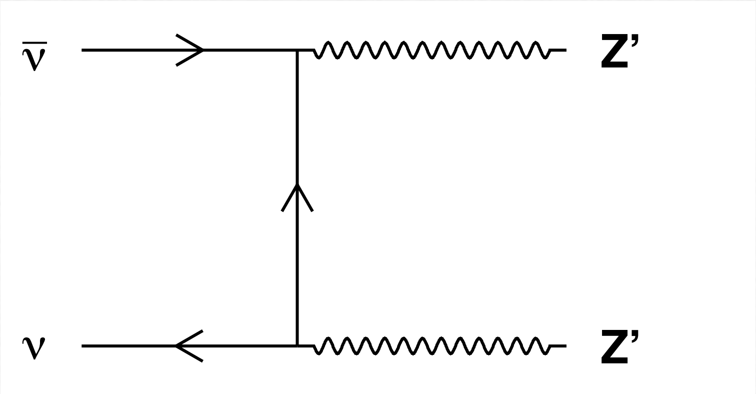
More generally, in models of partial fermion compositeness, natural to expect that only the top couples sizably to a new strongly interacting sector.

Relic density calculation

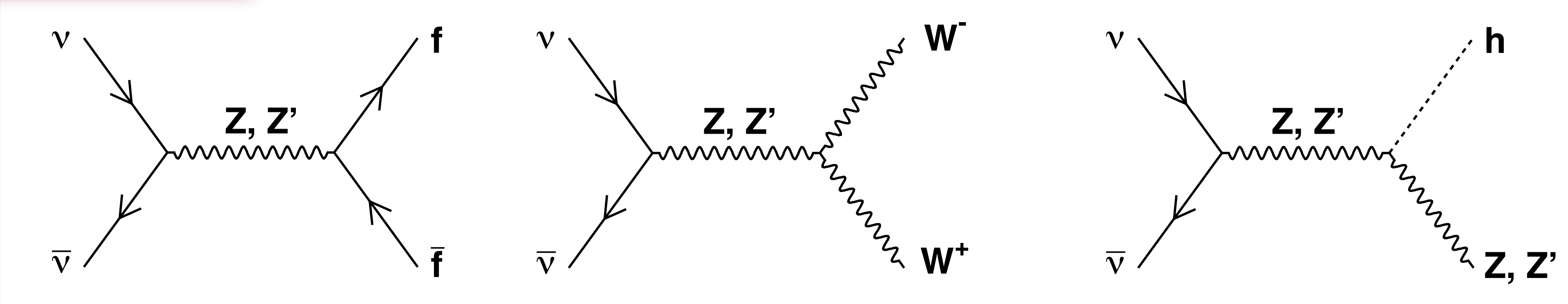
(assuming no $\nu\,\bar{\nu}$ asymmetry)

dominant channels



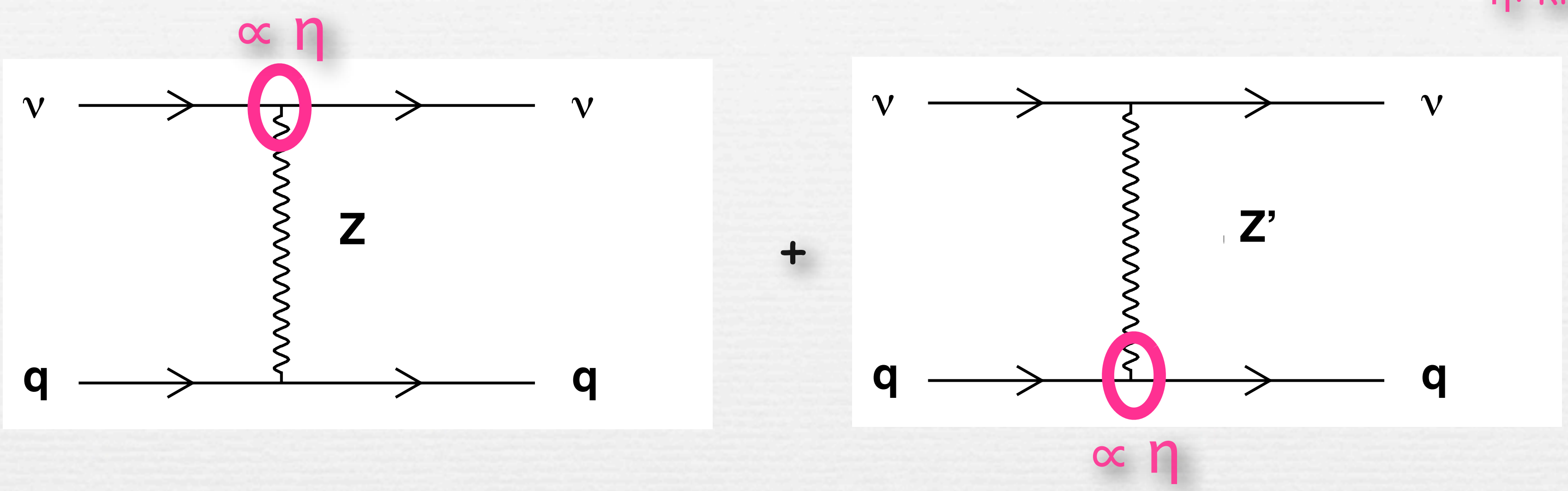


suppressed channels



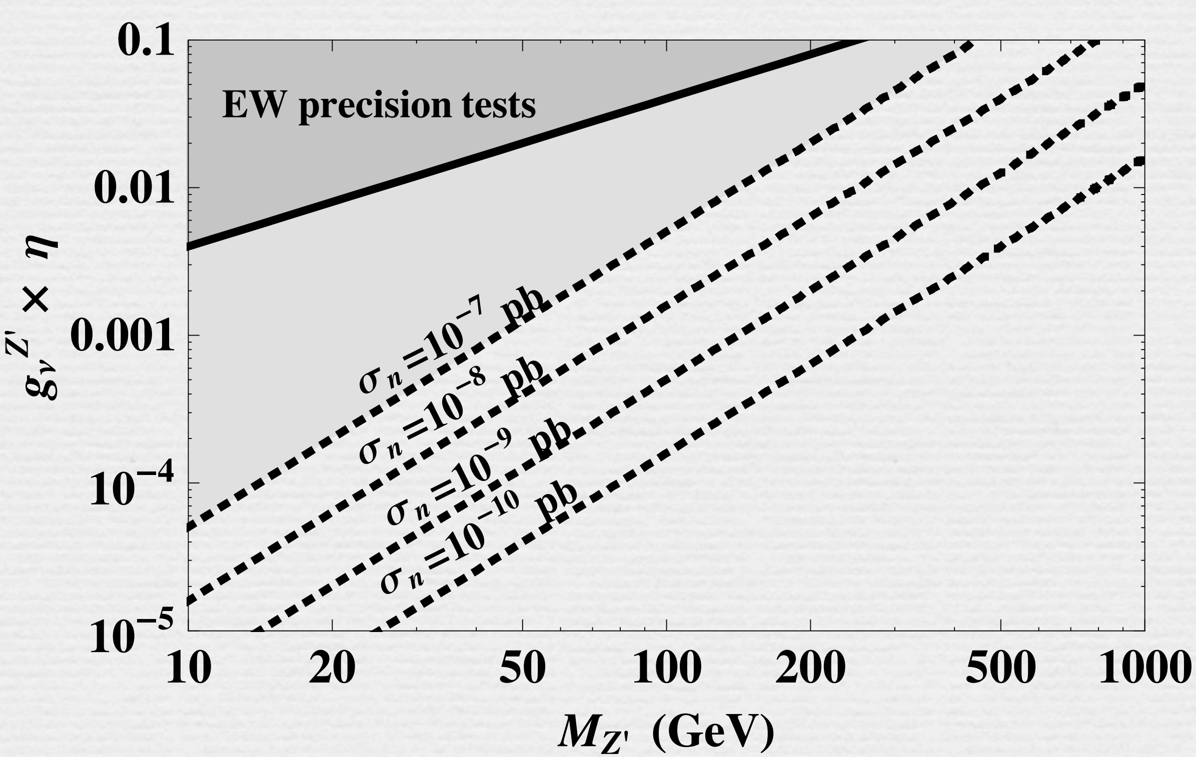
Direct detection constraints

η: kinetic mixing

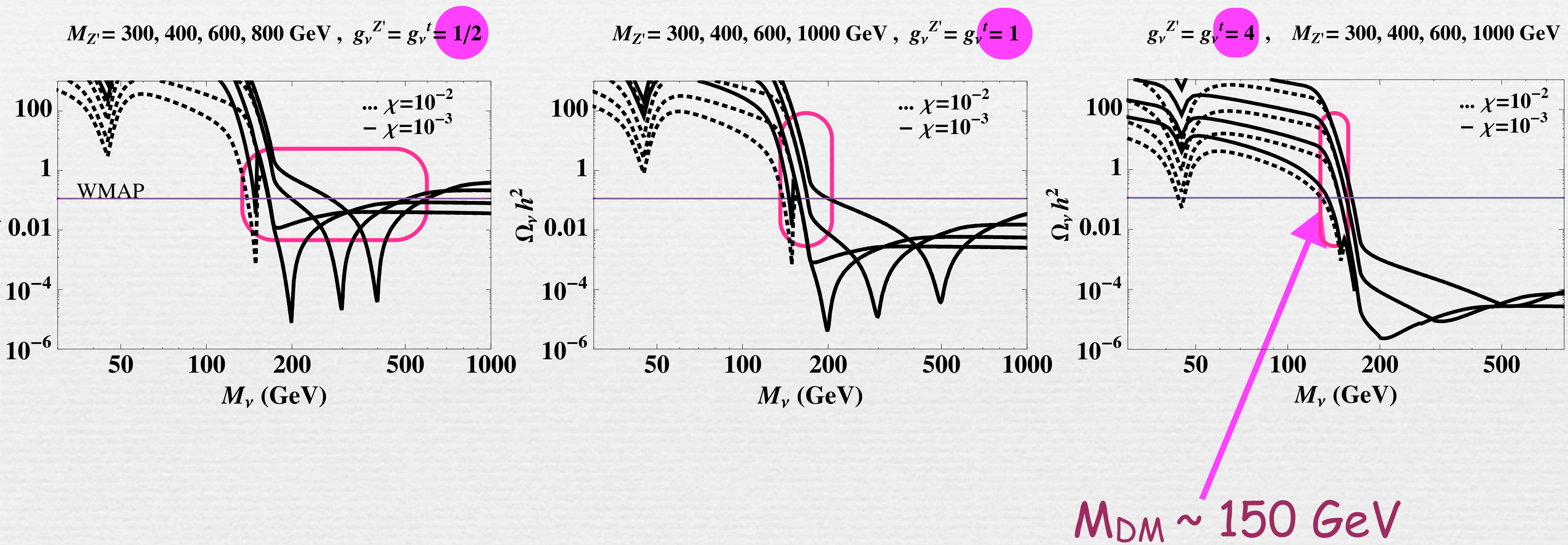


→ $\sigma \propto \eta^2$

ν-nucleon elastic scattering cross section contours



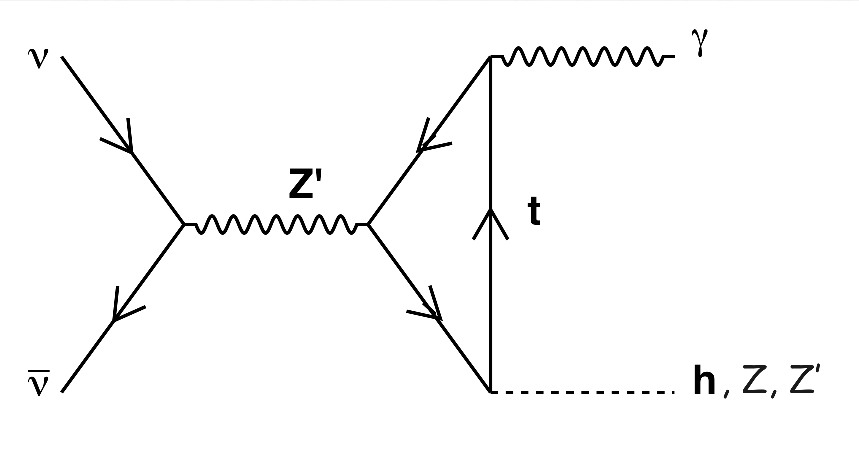
Dark matter mass from relic density calculation



as the Z′ coupling to top and ν increases, the prediction for MDM gets narrower -> MDM ~ 150 GeV

for $g_\nu^{Z'}, g_t^{Z'} \gtrsim 1$

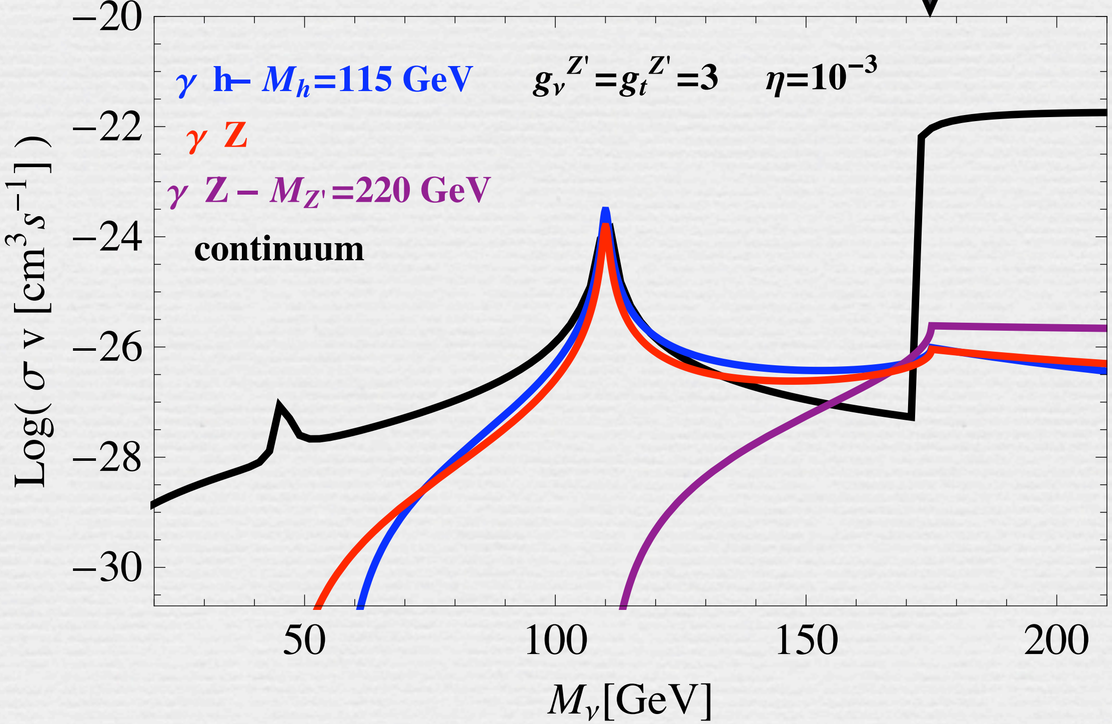
γ signal from ν annihilation



Note: no γγ line as dictated by Landau-Yang theorem (Z' being the sole portal from the wimp sector to the SM)

Lines not suppressed compared to continuum

continuum jumps due to opening of $t\bar{t}$ channel



To recap:

DM almost decouples from light fermions while still having large couplings to top

$M_{DM} < M_t$ since the strong coupling to top would otherwise give a too low relic density (for O(1) couplings).

DM mass is below kinematic threshold for top production in the zero velocity limit

Virtual top close to threshold can significantly enhance loop processes producing monochromatic photons.

A simple 4d UV completion

All SM fermions are uncharged under U(1)′

in addition to ν, add $\tilde{T}$ (vector-like) charged under U(1)′ with same gauge SM quantum numbers as t_R

to realize coupling of top quark to Z′ and h:

$$y H \overline{Q}_3 t_R + \mu \overline{\tilde{T}}_L \tilde{T}_R + Y \Phi \overline{\tilde{T}}_L t_R$$

higgs of U(1)′

the light mass eigen state identified with top quark is an admixture of t and $\tilde{T}$

Goldberger-Wise mechanism

Start with the bulk 5d theory $\mathcal{L} = \int dx^4 dz \sqrt{-g}[2M^3\mathcal{R} - \Lambda_5]$ $\Lambda_5 = -24M^3k^2$

The metric for RS1 is
$$ds^2 = (kz)^{-2}(\eta_{\mu\nu}dx^\mu dx^\nu + dz^2)$$
$$= e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$
where $k = L^{-1}$ is the AdS curvature
$$z = k^{-1}e^{ky}$$

and the orbifold extends from $z=z_0=L$ (Planck brane) to $z=z_1$ (TeV brane)

Which mechanism naturally selects $z_1 \gg z_0$? simply a bulk scalar field φ can do the job:

$$\int d^4xdz \left(\sqrt{g}[-(\partial\phi)^2 - m^2\phi^2] + \delta(z-z_0)\sqrt{g_0}L_0(\phi(z)) + \delta(z-z_1)\sqrt{g_1}L_1(\phi(z))\right)$$

φ has a bulk profile satisfying the 5d Klein-Gordon equation

$$\phi = Az^{4+\epsilon} + Bz^{-\epsilon}$$ where $$\epsilon = \sqrt{4+m^2L^2} - 2 \approx m^2L^2/4$$

Plug this solution into $$V_{eff} = \int_{z_0}^{z_1} dz\sqrt{g}[-(\partial\phi)^2 - m^2\phi^2]$$

$$V_{\mathrm{GW}} = z_1^{-4}\left[(4+2\epsilon)\left(v_1 - v_0\left(\frac{z_0}{z_1}\right)^\epsilon\right)^2 - \epsilon v_1^2\right] + \mathcal{O}(z_0^4/z_1^8) = z_1^{-4}P(z_1^{-\epsilon})$$

$\Rightarrow$ $$z_1 \approx z_0\left(\frac{v_0}{v_1}\right)^{1/\epsilon}$$

~ scale invariant fn modulated by a slow evolution through the $z^{-\epsilon}$ term

similar to Coleman-Weinberg mechanism

Cosmological phase transition associated with radion stabilisation (appearance of TeV brane)

↔

strongly 1st order confining phase transition of SU(N) gauge theory (N>3)

Cosmology of the Randall-Sundrum model

At high T: AdS-Schwarzchild BH solution with event horizon shielding the TeV brane

At low T: usual RS solution with stabilized radion and TeV brane

Start with a black brane, nucleate “gaps” in the horizon which then grow until they take over the entire horizon.

[Creminelli, Nicolis, Rattazzi’01]

Goldberger-Wise potential for the radion is of the form

$$V(\mu) = \mu^4 P((\mu/\mu_0)^\epsilon).$$

e.g. Rattazzi, Zaffaroni '00

[where $\mu = l^{-1} e^{-r/l}$, l being the AdS curvature $ds^2 = e^{-2r/l}\eta_{\rho\sigma}dx^\rho dx^\sigma + dr^2$]

a scale invariant function modulated by a slow evolution through the μ^ϵ term

for $|\epsilon| \ll 1$

similar to Coleman-Weinberg mechanism where a slow RG evolution of potential parameters can generate widely separated scales

# of bubbles per horizon volume

$$\beta/H = T \frac{d}{dT} \frac{S_3}{T}\bigg|_{T_n} \sim \epsilon \; \frac{S_3}{T}\bigg|_{T_n} \gtrsim 1.$$

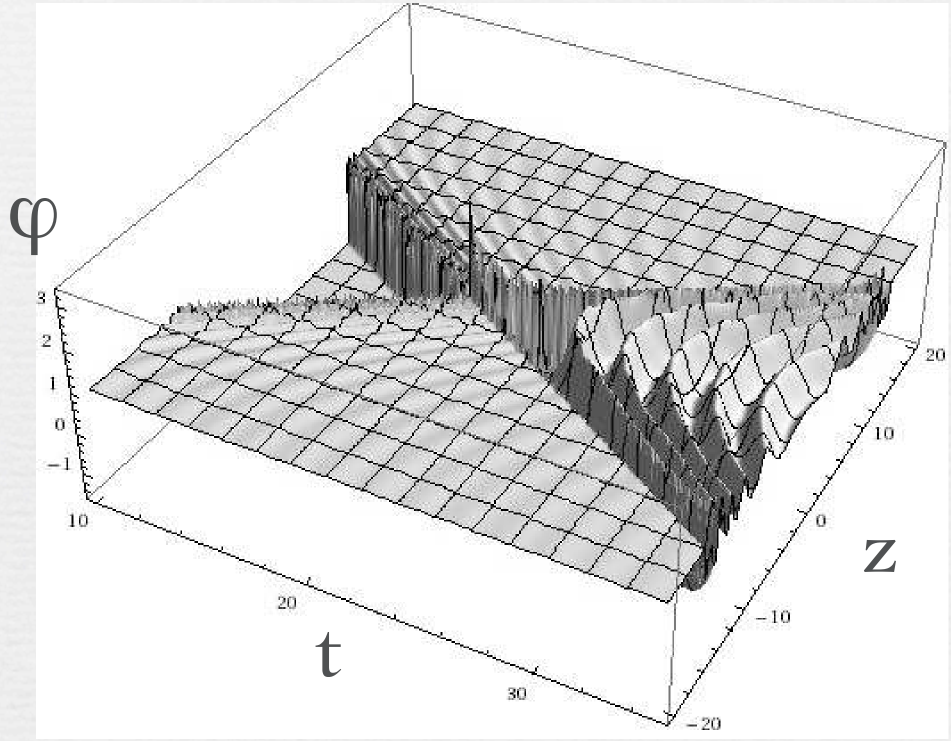
$S_3/T \approx \log \frac{T^4}{H^4}$ ~ 140

possible to achieve several efolds of inflation and still complete the phase transition if ϵ~O(1/10)

Servant-Konstandin '11

Efficient Out-of-equilibrium production of massive particles during bubble collisions

Watkins & Widrow '92



Konstandin-Servant'11

Some potentially interesting DM candidate in this context:
"Stable Skyrmions from Extra Dimensions", 0712.3276

Pomarol & Wulzer

Important to keep in mind non-standard production mechanisms as well as non-standard cosmologies.

Usual assumptions:
- Radiation domination before and during the epoch of DM production
- conservation of entropy since then

$$\begin{aligned} \frac{dn}{dt} &= -3Hn - \langle \sigma_{\rm ann} v \rangle \left(n^2 - n_{\rm eq}^2\right) \\ \frac{ds}{dt} &= -3Hs\,. \end{aligned}$$

$$H^2 = \frac{8\pi}{3M_P^2}\rho$$

$$\rho = \frac{\pi^2}{30} g_{\rm eff}(T) T^4\,, \quad s = \frac{2\pi^2}{45} h_{\rm eff}(T) T^3$$

$$\Longrightarrow \quad \frac{dY}{dx} = -\left(\frac{45}{\pi M_P^2}\right)^{-1/2} \frac{g_*^{1/2} m}{x^2} \langle \sigma v \rangle \left(Y^2 - Y_{eq}^2\right)$$

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

Alternative possibilities:
- A different expansion rate H
- Late entropy production due to a scalar field decay [e.g. see Watson et al]
- Low reheat temperature [e.g. Gelmini-Gondolo]

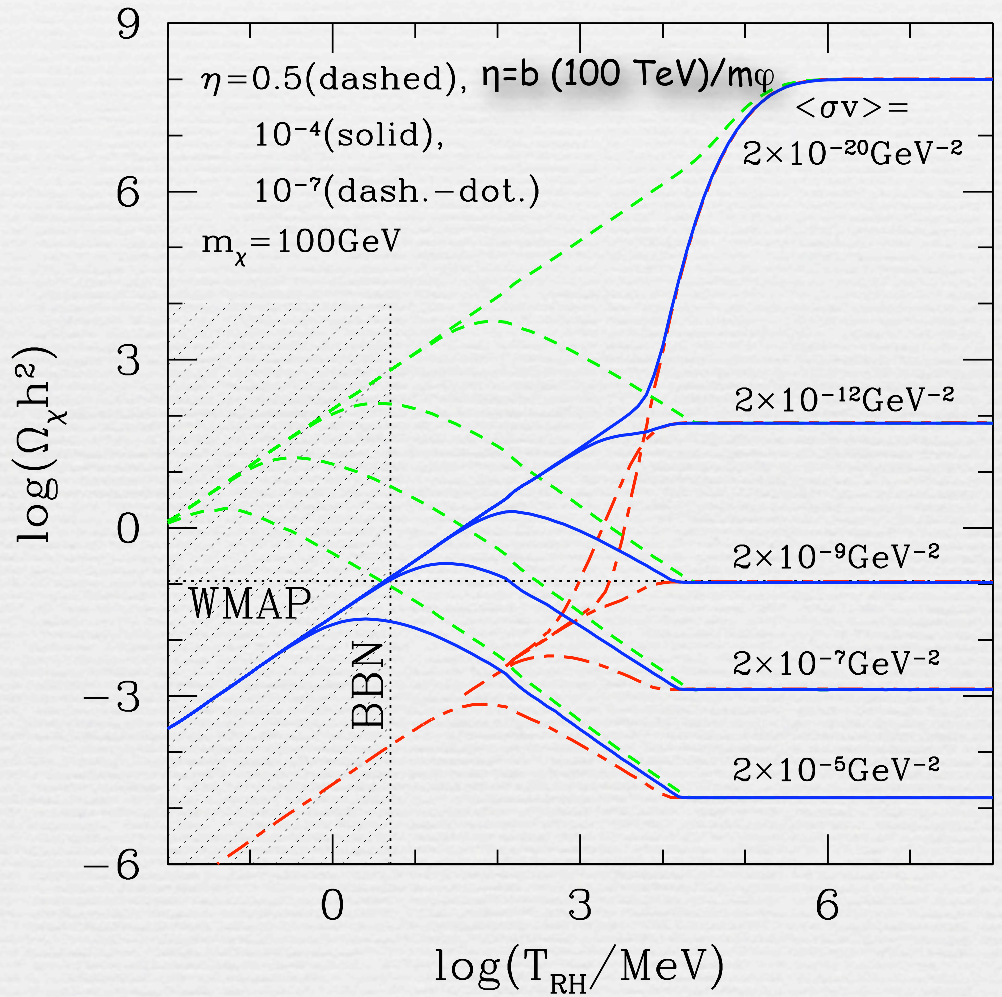
Low temperature reheating models

Consider late decaying scalar field which dominates the energy density of the universe while oscillating, and eventually decays with $\Gamma_\phi \simeq m_\phi^3/\Lambda_{\rm eff}^2$.

$$\Gamma_\phi = H_{\rm decay} = \sqrt{\left(\frac{8\pi}{3}\right)\rho_R} = \sqrt{\frac{8}{90}\pi^3 g_\star}\,\frac{T_{\rm RH}^2}{M_P} \longrightarrow T_{\rm RH} \simeq 10\ {\rm MeV}\left(\frac{m_\phi}{100\ {\rm TeV}}\right)^{3/2}\left(\frac{M_P}{\Lambda_{\rm eff}}\right)$$

$$\begin{aligned}
\dot\rho &= -3H(\rho+p) + \Gamma_\phi\rho_\phi \\
\dot n_\chi &= -3Hn_\chi - \langle\sigma v\rangle\left(n_\chi^2 - n_{\chi,\rm eq}^2\right) + \frac{b}{m_\phi}\Gamma_\phi\rho_\phi \\
\dot\rho_\phi &= -3H\rho_\phi - \Gamma_\phi\rho_\phi \\
H^2 &= \frac{8\pi}{3M_P^2}(\rho+\rho_\phi).
\end{aligned}$$

$$\dot s = -3Hs + \frac{\Gamma_\phi\rho_\phi}{T}.$$



[Gelmini-Gondolo, 1009.3690]

An alternative production mechanism in standard cosmology: -> DM from decays

If DM is non-interacting when the decays occur, it inherits the density of the parent particle:

$$\Omega_{\rm DM}\ h^2 \simeq \frac{m_{\rm DM}}{m_P}\Omega_P\ h^2$$

case of superWIMPs, produced in late decays of WIMPS

[Feng et al]

e.g axinos, gravitinos produced from the decay of neutralinos or sleptons

Asymmetric Dark Matter:

$$\frac{\Omega_{dm}}{\Omega_b} \sim 5$$

Does this indicate a common dynamics?

If $n_{dm} - \overline{n}_{dm} \propto n_b - \overline{n}_b$

then $$\frac{\Omega_{dm}}{\Omega_b} \sim \frac{(n_{dm} - \overline{n}_{dm})m_{dm}}{(n_b - \overline{n}_b)m_b} \sim C\frac{m_{dm}}{m_b}$$

conservation of global charge: $$Q_{\mathrm{DM}}(n_{\overline{\mathrm{DM}}} - n_{\mathrm{DM}}) = Q_b(n_b - n_{\bar{b}})$$

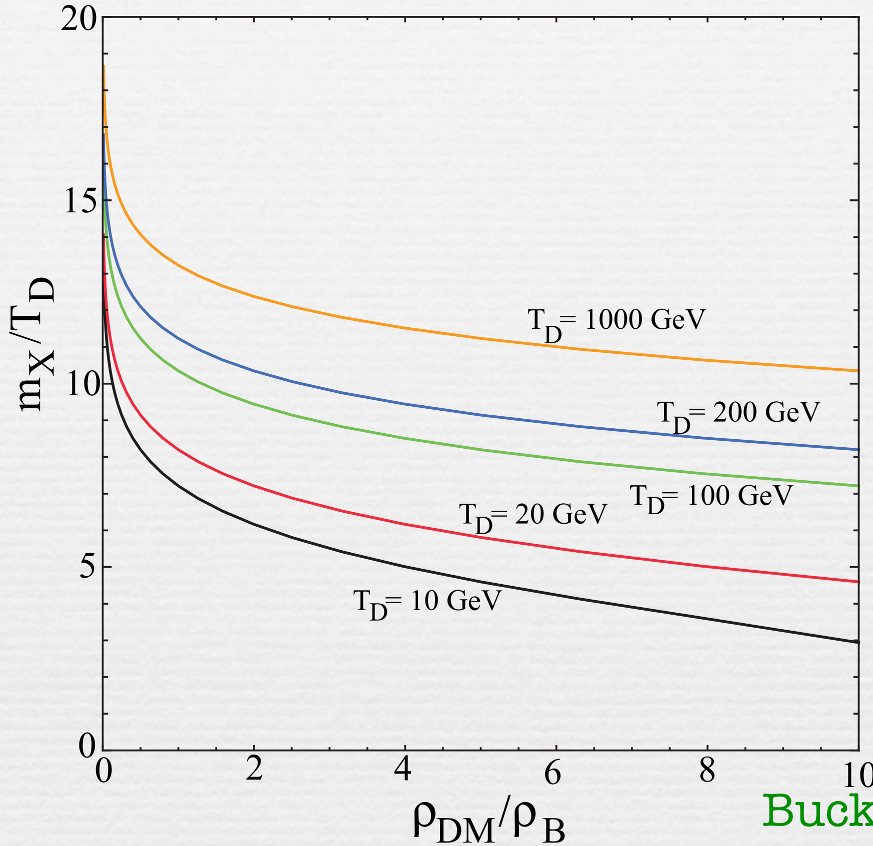
if efficient annihilations: $$\frac{\Omega_{dm}}{\Omega_b} \sim \frac{Q_b}{Q_{dm}}\frac{m_{dm}}{m_b} \longrightarrow$$ typical expected mass ~ GeV

two possibilities:

1) asymmetries in baryons and in DM generated simultaneously

2) a pre-existing asymmetry (either in DM or in baryons) is transferred between the two sectors

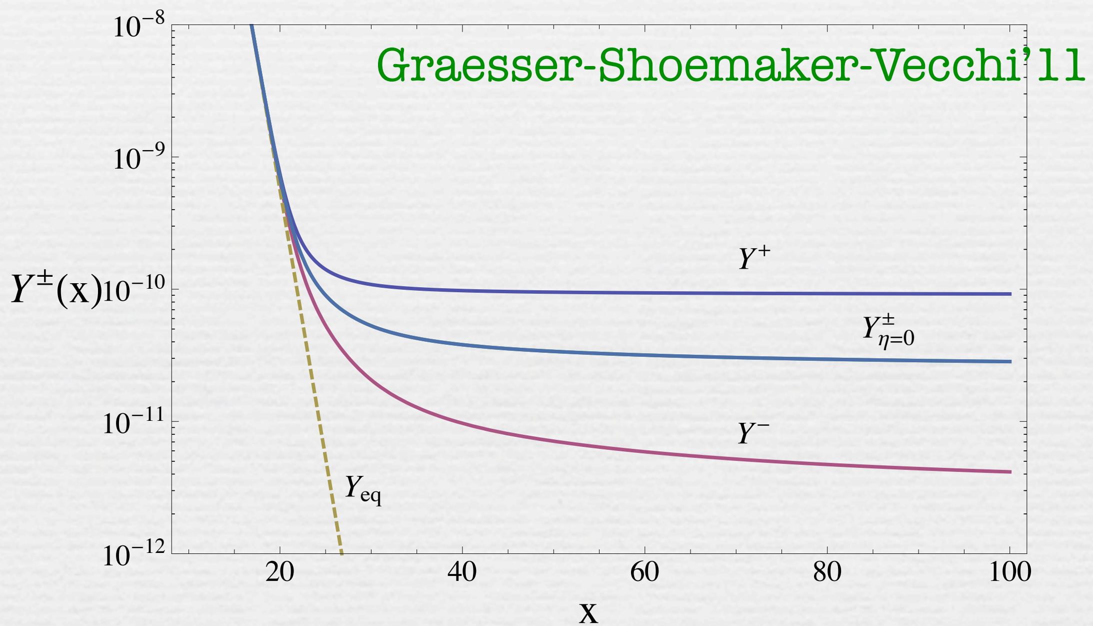
possible to have a much heavier mass (~ O(100 GeV)) if the decoupling temperature of the transfer operator is smaller than the DM mass



Buckley-Randall'10

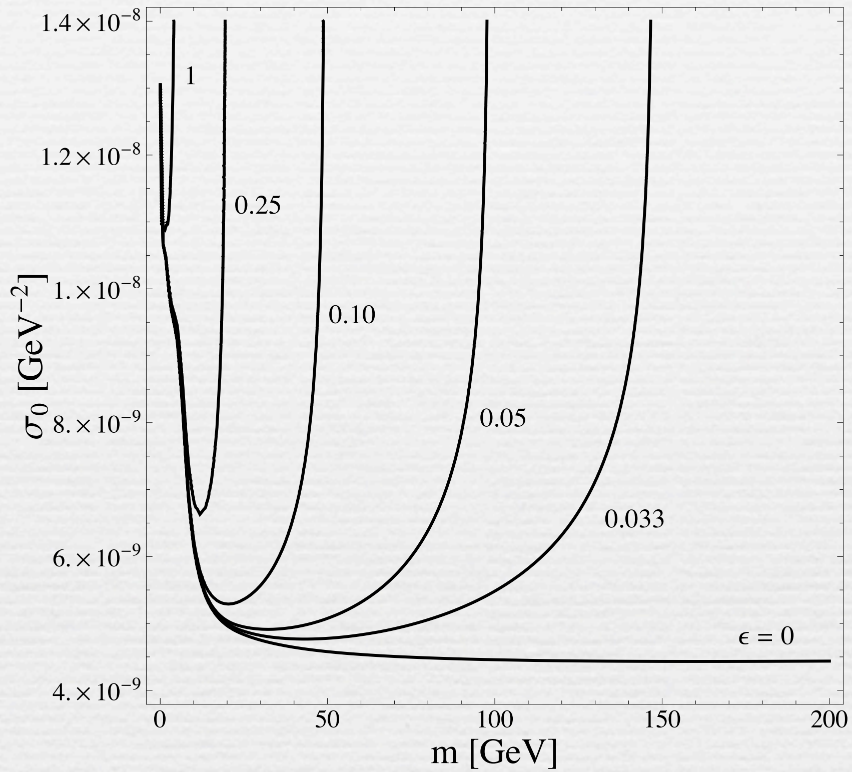
Asymmetric Freese-out

a large abundance of symmetric DM should be annihilated away



less depletion-> larger annihilation rate needed (by factor 2-3)

a typical difficulty in these models : no naturally large annihilations annihilation cross section required to reproduce the correct DM abundance (via s-wave process)



Graesser-Shoemaker-Vecchi'11

Sakharov's conditions for baryogenesis (1967)

1) Baryon number violation

(we need a process which can turn antimatter into matter)

2) C (charge conjugation) and CP (charge conjugation ×Parity) violation

(we need to prefer matter over antimatter)

3) Loss of thermal equilibrium

In thermal equilibrium, any reaction which destroys baryon number will be exactly counterbalanced by the inverse reaction which creates it. Thus no asymmetry may develop, even if CP is violated. And any preexisting asymmetry will be erased by interactions

(we need an irreversible process since in thermal equilibrium, the particle density depends only on the mass of the particle and on temperature --particles & antiparticles have the same mass , so no asymmetry can develop)

$$\Gamma(\Delta B > 0) > \Gamma(\Delta B < 0)$$

Baryogenesis without $\not{B}$ nor $\not{L}$ nor $CP\not{T}$

Possible if dark matter carries baryon number

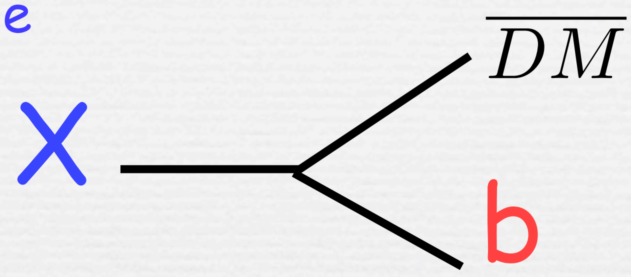
Farrar-Zaharijas hep-ph/0406281
Agashe-Servant hep-ph/0411254
Davoudiasl et al 1008.2399

In a universe where baryon number is a good symmetry, Dark matter would store the overall negative baryonic charge which is missing in the visible quark sector

Generalization: DM & baryon sectors share a quantum number (not necessarily B)

$$Q_{\text{universe}} = 0 = \underbrace{Q}_{\text{carried by baryons}} + \underbrace{(-Q)}_{\text{carried by antimatter}}$$

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



Charge conservation leads to

$$Q_{\rm DM}(n_{\overline{\rm DM}} - n_{\rm DM}) = Q_b(n_b - n_{\bar{b}})$$

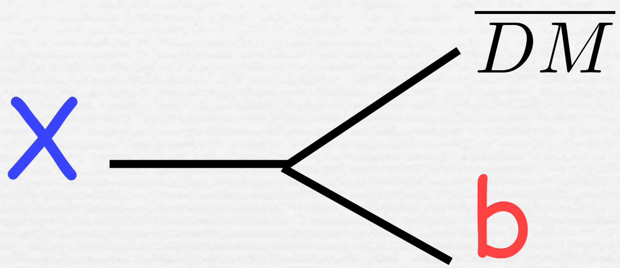
If efficient annihilation between DM and $\overline{DM}$, and b and $\bar{b}$:

$$\rho_{\rm DM} = m_{\rm DM} n_{\overline{\rm DM}} \approx 6\rho_b \to m_{\rm DM} \approx 6\frac{Q_{\rm DM}}{Q_b}\ \text{GeV}$$

Farrar-Zaharijas hep-ph/0406281
Agashe-Servant hep-ph/0411254
Davoudiasl et al 1008.2399
} (DM carries B number)

Kitano & Low, hep-ph/0411133
West, hep-ph/0610370
(X and DM carry Z2 charge)

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



$$Q_{\mathrm{DM}}(n_{\overline{\mathrm{DM}}} - n_{\mathrm{DM}}) = Q_b(n_b - n_{\bar{b}})$$

out-of equilibrium and CP violating decay of X sequesters the anti baryon number in the dark sector, thus leaving a baryon excess in the visible sector

If efficient annihilation between DM and $\overline{DM}$, and b and $\bar{b}$

$$\rho_{\mathrm{DM}} = m_{\mathrm{DM}} n_{\overline{\mathrm{DM}}} \approx 6\rho_b \to m_{\mathrm{DM}} \approx 6\frac{Q_{\mathrm{DM}}}{Q_b}\ \mathrm{GeV}$$

A unified explanation for DM and baryogenesis

$$\Omega_b \approx \frac{1}{6}\Omega_m$$

turns out to be quite natural in warped GUT models...

GUT baryogenesis at the TeV scale !

Agashe-Servant-Tulin in progress

Z_3 symmetry in the SM:

Agashe-Servant'04

number of color indices

$$\Phi \longrightarrow \Phi\ e^{2\pi i\left[B - \frac{(\alpha-\bar{\alpha})}{3}\right]}$$

conserved in any theory where baryon number is a good symmetry

any non-colored particle that carries
baryon number will be charged under Z_3

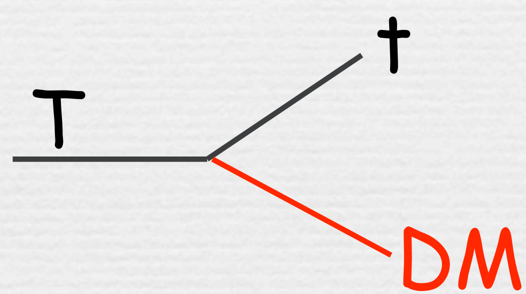
e.g warped GUTs

Z_2 versus Z_3 Dark Matter

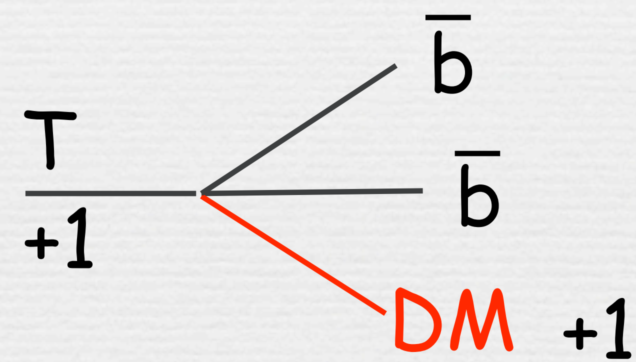
Agashe et al, 1003.0899

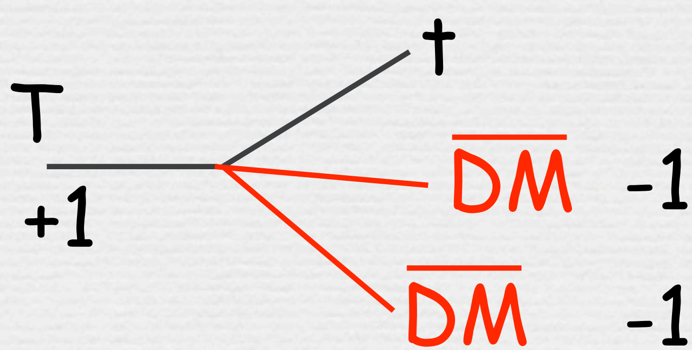
Many Dark Matter models rely on a Z_2 symmetry. However, other symmetries can stabilize dark matter. Can the nature of the underlying symmetry be tested?

Z_2



Z_3 (+1=-2)





To conclude

Plethora of DM candidates.
The LHC, direct & indirect detection experiments will enable us to reduce significantly the parameter space.

The determination of the WIMP relic density depends on the history of the Universe before Big Bang Nucleosynthesis, an epoch from which we have no data.

WIMPs have their number fixed at T ~ m/20 so with M> 100 =MeV, they freese out before BBN and thus would be the earliest remnants.

If discovered they would for the first time give information of the pre BBN phase of the universe.

Exploration beyond the standard WIMP paradigm has received a boost of interest lately.

For instance, the dark sector may turn out to be non-minimal and involve inter-WIMP dynamics i.e. be as complicated as the visible sector...
There is still a lot of theory to be worked out while experiments are running.