Selected topics in extra-dimensional cosmology

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Plan

Overview of the different models.

- Motivations
- ADD
- Randall-Sundrum models
- Flat TeV X-dim
- Dark Matter from X-dim: the different candidates
- cosmology of flat TeV X-dim: SuperWIMPS, Radion cosmology

properties, signatures and main exp. constraints for each of these models

→ 1st lecture (laptop)

- WIMP KK dark matter in UED
- RS1 cosmology
- radion stabilisation in RS. Goldberger-Wise mechanism
- EW phase transition from radion stabilisation

→ 2nd lecture (blackboard)

Many other subjects I am not covering

Inflation not discussed but covered by J. Cline's lectures and maybe by Lev Kofman

Brane cosmology (solutions to Einstein eqs, cosmological perturbations ... in D>4) — see for instance, hep-th/9905012 (Binetruy, Deffayet, Langlois), or Kofman al: hep-ph/0404141

Self-tuning approach to the Cosm. Constant pb.

Asymmetric warped space-time (spatial and time scales have different warp factors --> violation of Lorentz invariance) — see for instance Csaki et al: gr-qc/0105114

DGP model (Dvali-Gabadadze-Porrati) hep-th/0005016 — presented in Gabadadze lectures hep-ph/0308112; for a critical analysis see for instance: hep-th/0404159

Other attempts on modified gravity at large distances — Gregory-Rubakov-Sibiryakov th/0002072; Dvali-Gabadadze-Shifman th/0202174

Transplanckian effects

String gas cosmology

Deconstruction

...

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**

II- On cosmology

On dark matter from extra dimensions:

section 25 of Les Houches physics at TeV colliders 2005 beyond the standard model working group:

Summary report. hep-ph/0602198 (section 23 is on UED)

On RS1 cosmology:

Cosmology of brane models with radion stabilization.
Csaba Csaki, Michael Graesser , Lisa Randall , John Terning . **hep-ph/9911406**

Holography and the electroweak phase transition.
Paolo Creminelli, Alberto Nicolis , Riccardo Rattazzi **hep-th/0107141**

Order rho^2 corrections to Randall-Sundrum I cosmology.
James M. Cline, Jeremie Vinet **hep-th/0201041**

also relevant:

Exact identification of the radion and its coupling to the observable sector.
Lev Kofman, Johannes Martin, Marco Peloso **hep-ph/0401189**

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...

A few puzzles in Beyond the Standard Model Physics

electroweak sector

- Hierarchy problem $\frac{M_{\rm EW}}{M_{\rm Pl}} \sim 10^{-16}$
- Symetry breaking (electroweak symmetry, supersymmetry)

pbs related to fermions

- Neutrino masses and hierarchy in fermion masses $\frac{m_\nu}{m_{\rm top}} \sim 10^{-14}$
- Proton stability
- Flavour problem (FCNCs)

Grand Unification?

- Unification of couplings

cosmological pbs

- Cosmological constant
- Inflation
- Dark energy, quintessence $\rho_\Lambda \simeq ({\rm meV})^4$
- Dark matter $\Omega_{\rm mat\ noire} \simeq 25\%$
- Baryogenesis $\frac{n_b}{n_\gamma} \sim 10^{-10}$

Physics beyond theStandard Model implies new degrees of freedom.

Why not extra dimensions ?

Which size for extra dimensions?

Experimental constraints:

Roughly:

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

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

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

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

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

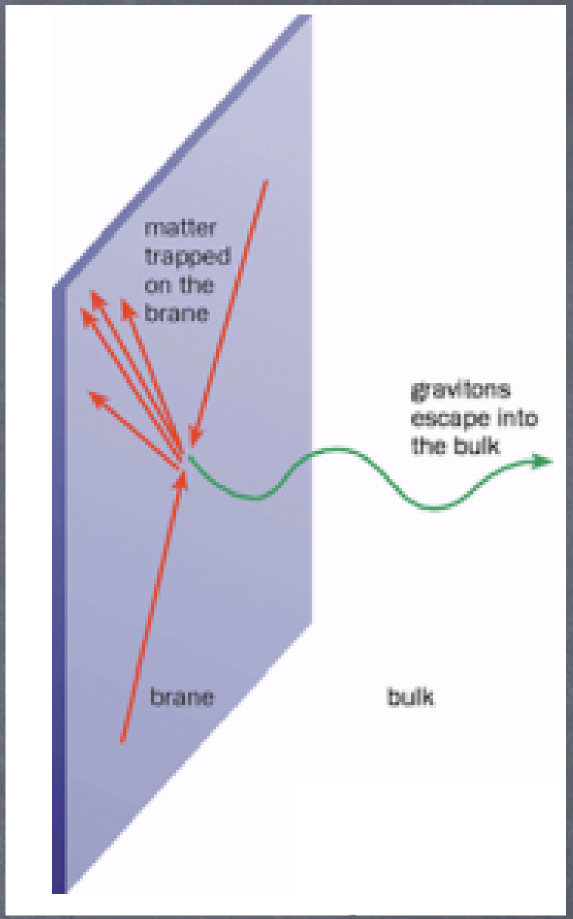
ADD models

- "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.

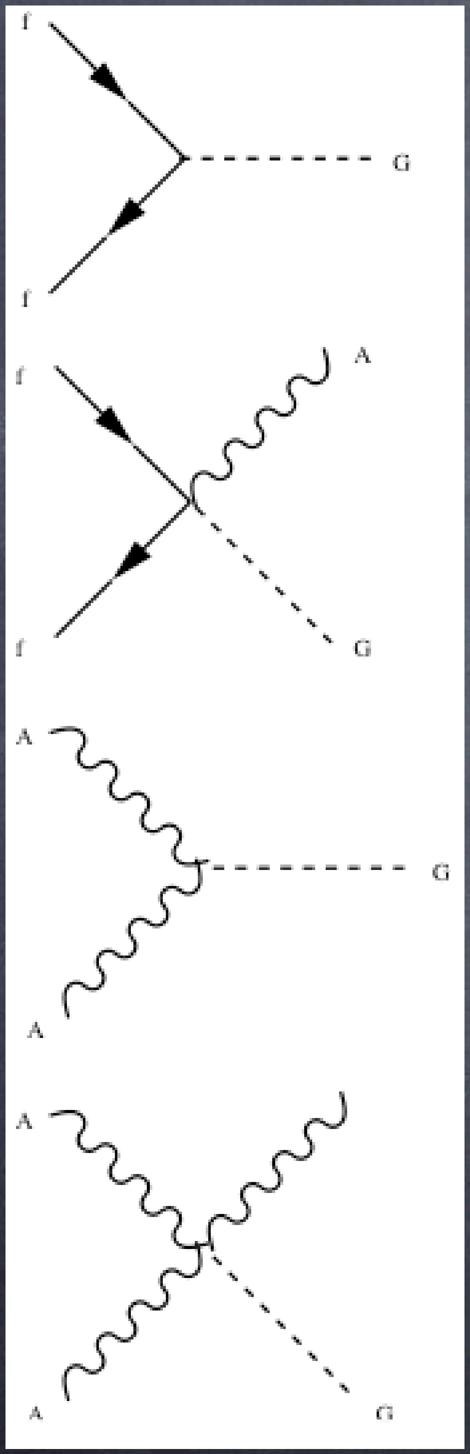


Gravity appears weak because it is 'diluted' in extra dimensions

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 est totally negligible.

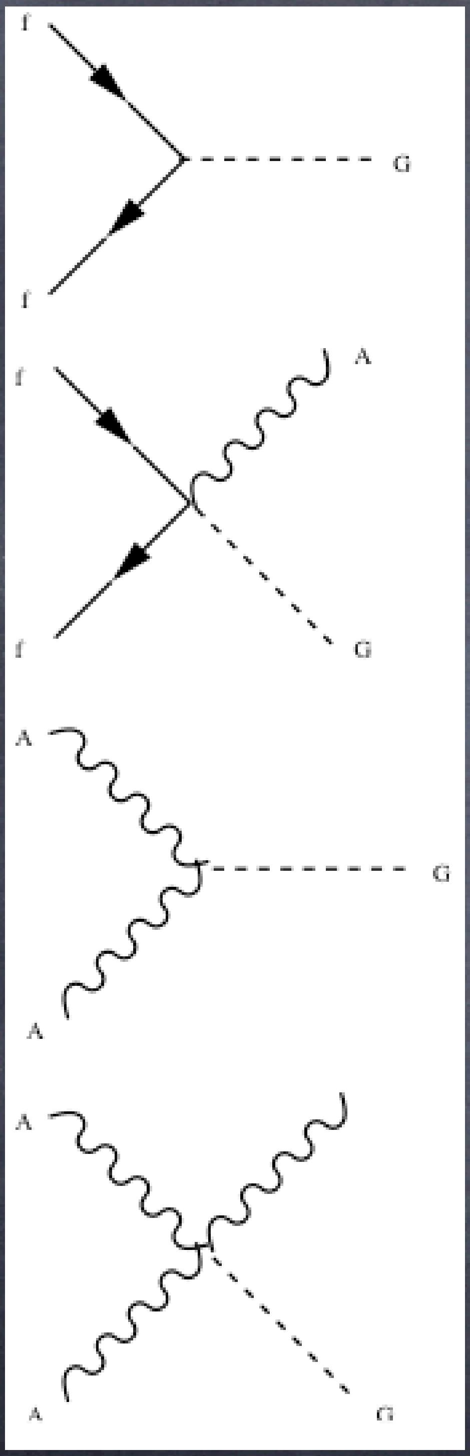
However, the cross section to produce a collection of massive gravitons is amplified due to the vary large number of gravitons.

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

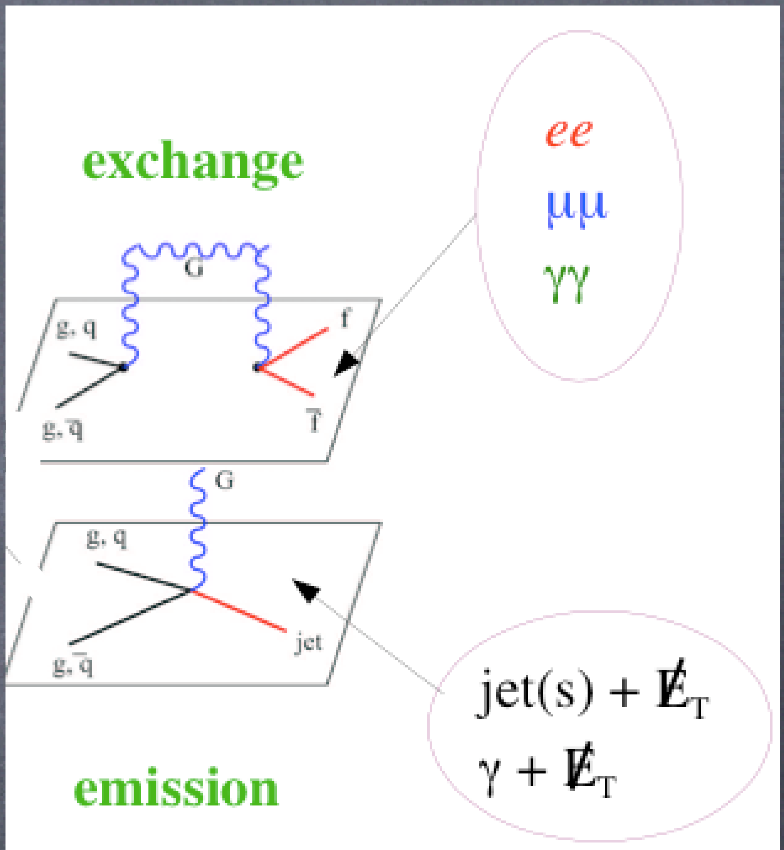


⇛ Direct production of gravitons

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.

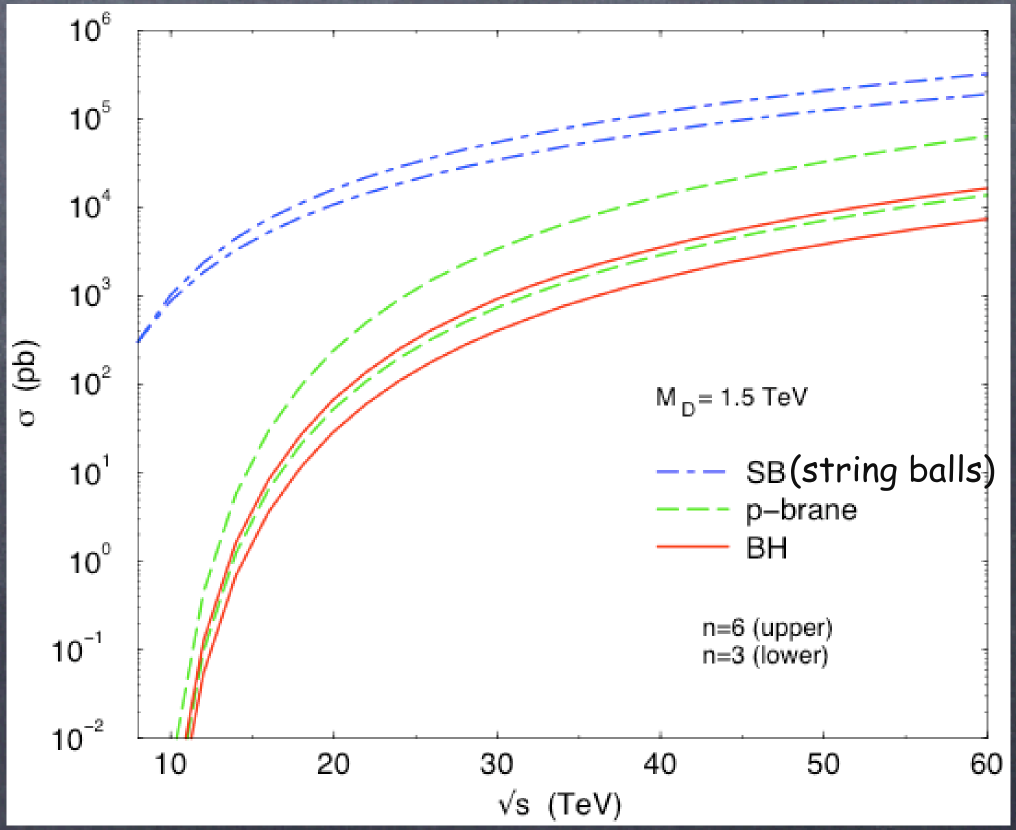
i.e geometrical approximation $\sigma \sim \pi r_H^2$
(transplanckian energies)

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

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

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



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: $\rho_G(T = MeV) \sim \rho_G(T) \left(\frac{MeV}{T}\right)^3$

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

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

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

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

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

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

bound from diffuse photon background

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

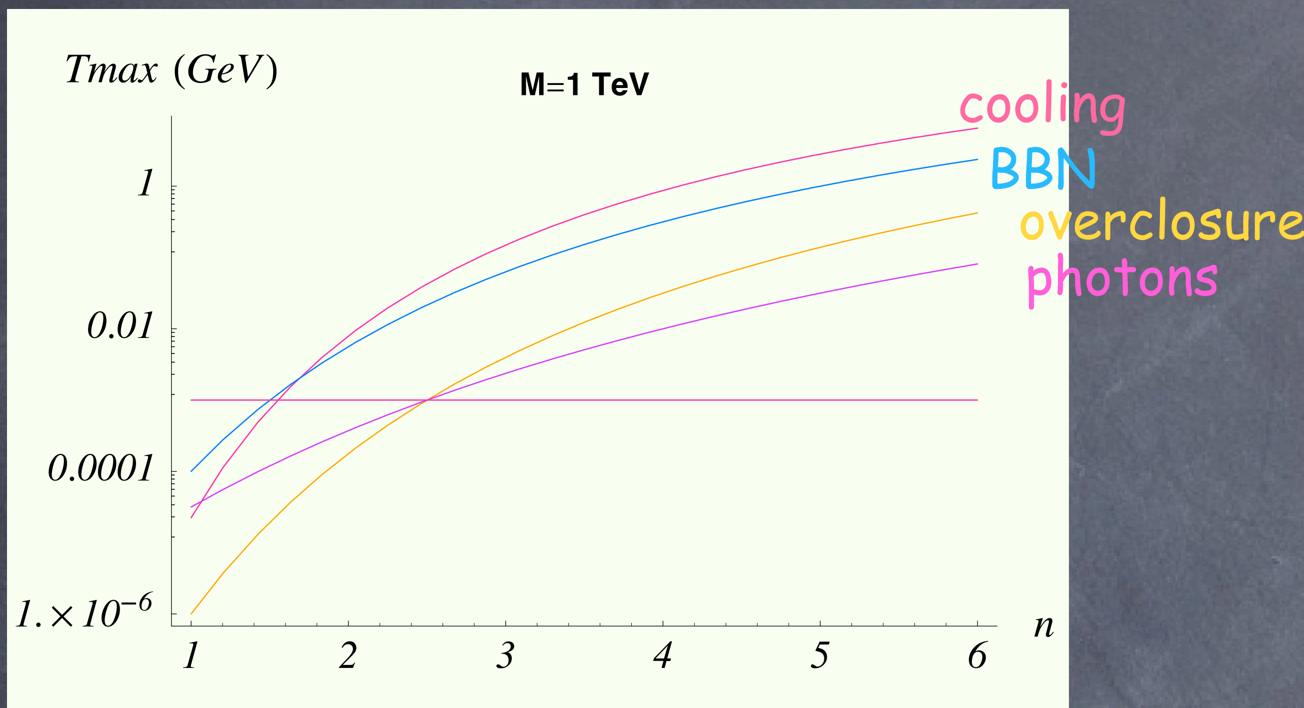
$\tau(T) \sim 10^{10}\mathrm{yr} \times \left(\frac{100\mathrm{MeV}}{T}\right)^3$ which have already decayed is $\left(\frac{100\mathrm{MeV}}{T}\right)^3$

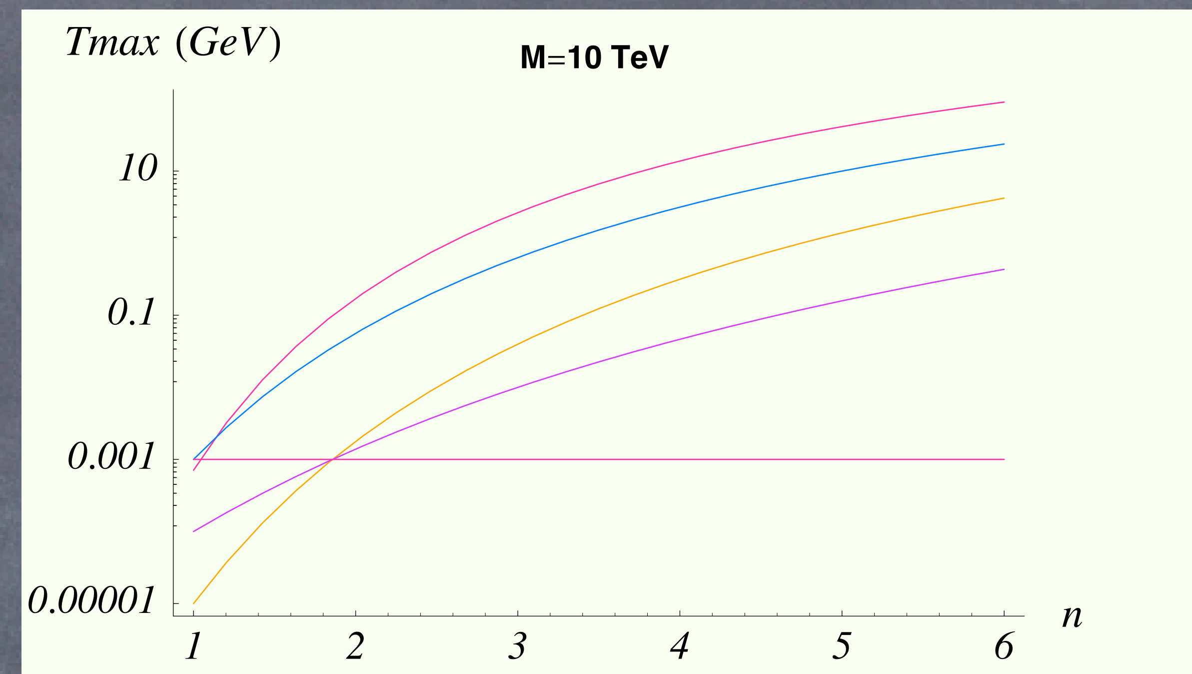
The resulting number density of photons is $n_{\gamma \text{ from KK decays}} \sim n_{0,G} \times \left(\frac{T_*}{100\mathrm{MeV}}\right)^3$

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

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

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

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

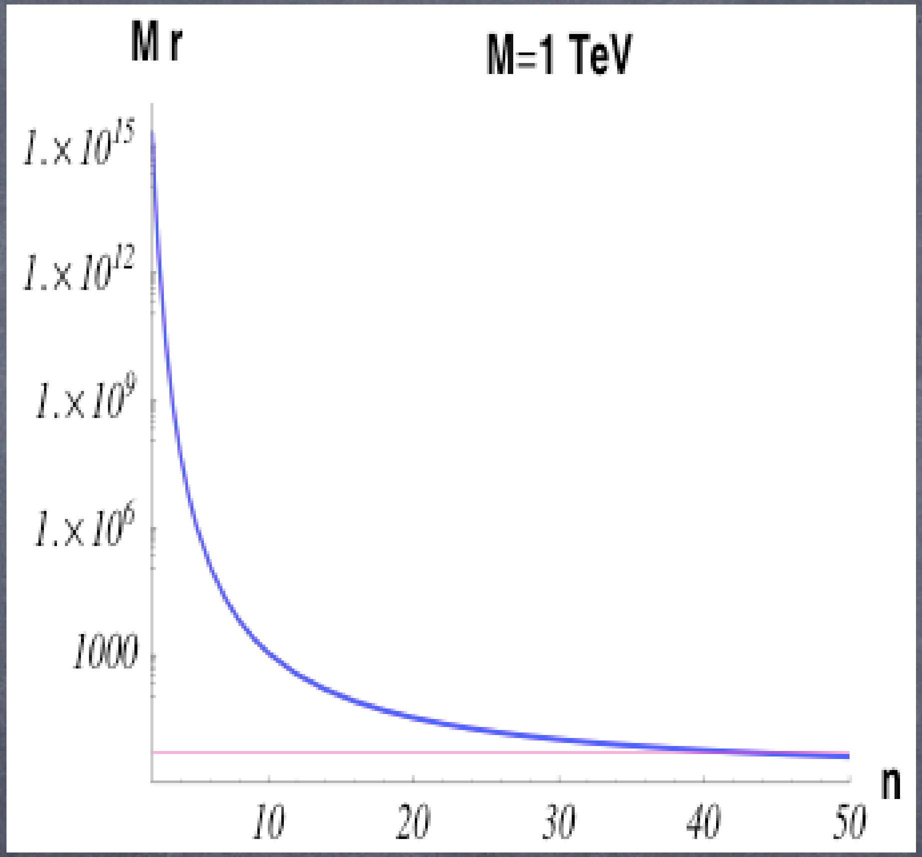
Note: These constraints are relaxed if compact extra dimensions are hyperbolic rather than toroidal

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:

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

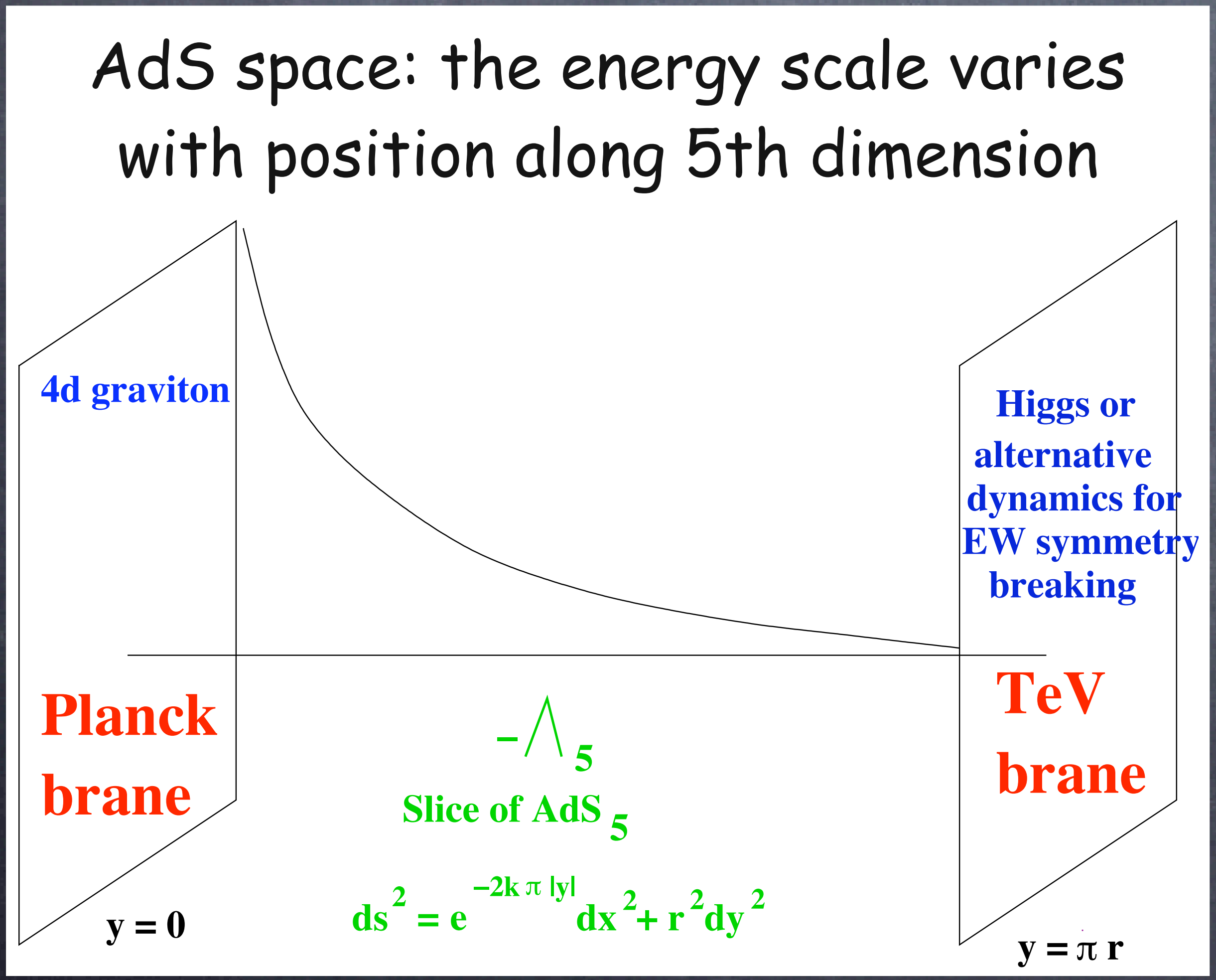
The Randall-Sundrum model

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)



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

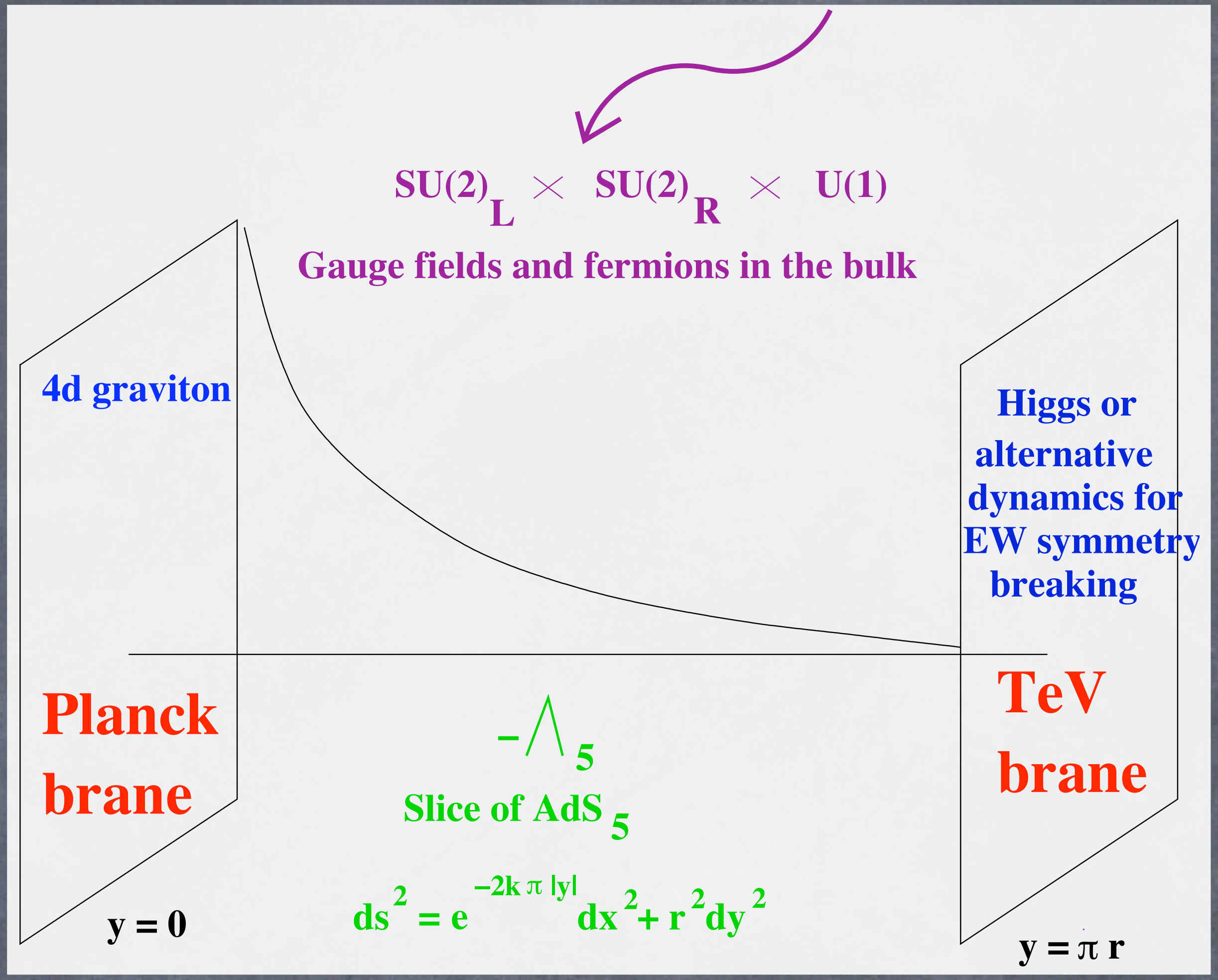
Natural stabilisation of radius (à la Goldberger-Wise) :

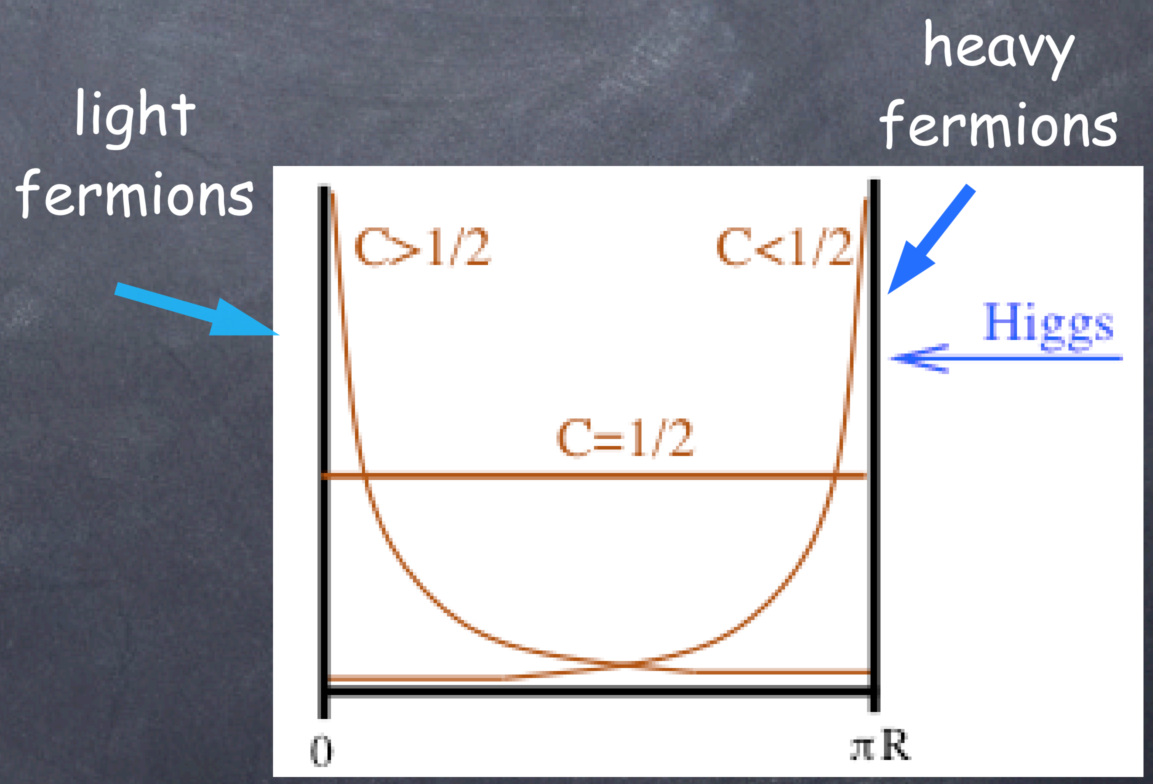
$$kr = \frac{4}{\pi}\frac{k^2}{m^2}\ln\left[\frac{v_h}{v_v}\right] \sim 10$$

Particle physics model building in warped space

2006 favourite set-up:

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





Note: No susy here
and many different realizations

Randall-Sundrum KK gravitons are very different from ADD

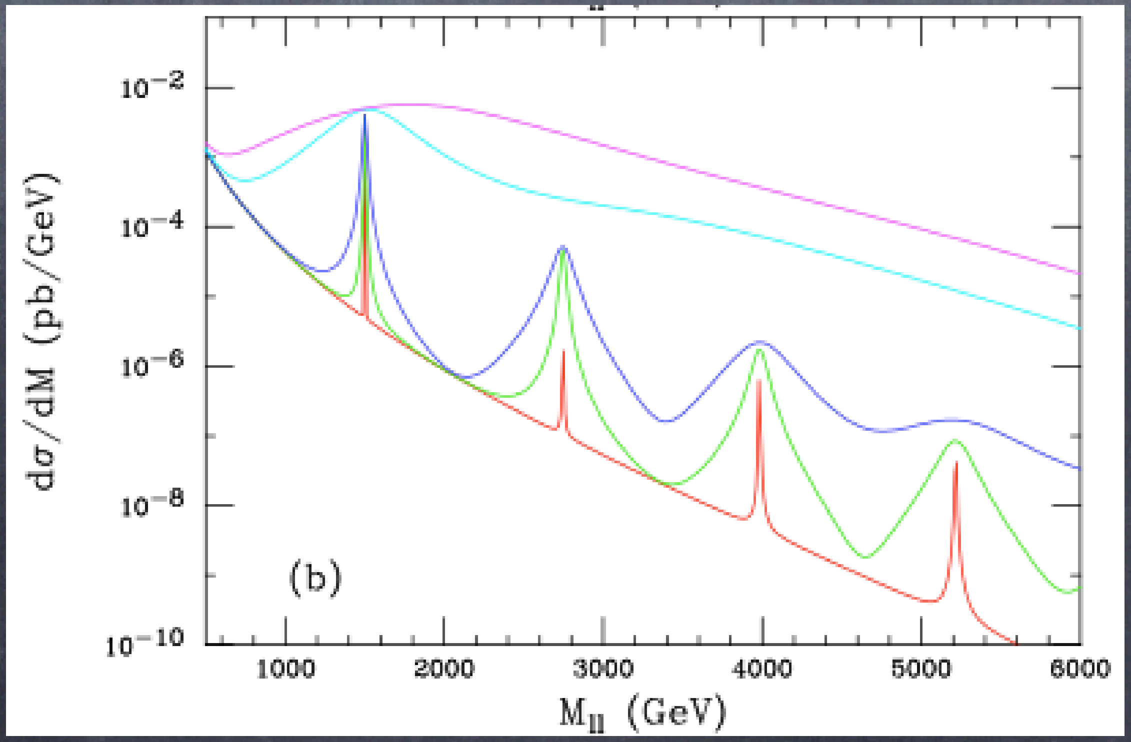
✗ Discrete spectrum with KK states non regularly spaced (proportional to the zeros of Bessel functions)

✗ 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:

$$\int d^4x\sqrt{g}\,\mathcal{R}\,\xi\,H^\dagger H \quad \Rrightarrow \quad \mathcal{L}\supset 6\xi\gamma h\Box r$$

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 $M_{\rm S\not{U}SY}$ ~TeV

2 sub-classes of models

- only bosons in bulk
- 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.

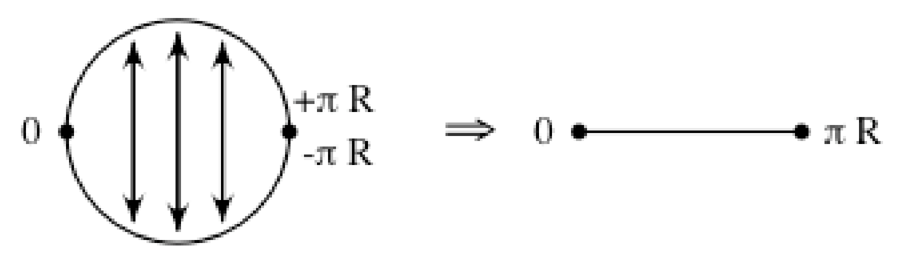
The chirality of the 4D fermions has to be introduced by the boundary conditions at the end points of the interval.

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

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

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*

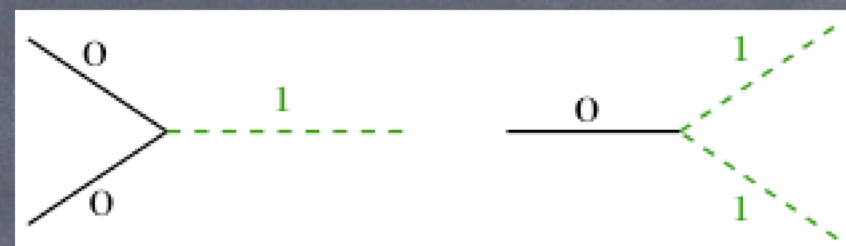
`Universal' Extra Dimensions

Appelquist, Cheng & Dobrescu '01

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

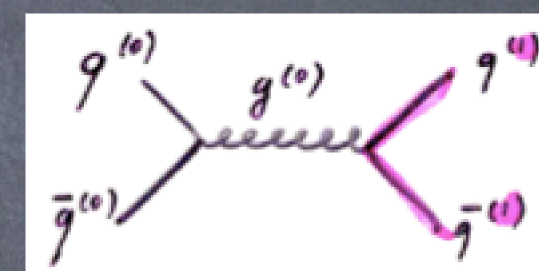
Translation Invariance along the 5th dimension ⇛Conservation of de Kaluza-Klein number in interactions of the 4D effective theory.

For instance:

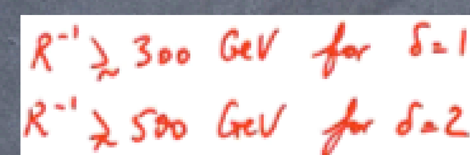


forbidden allowed

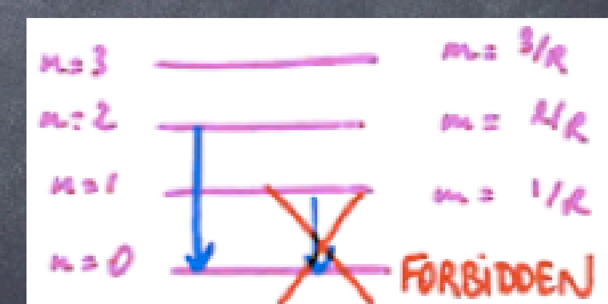
Consequence: n=1 KK excitations can only be pair-produced



⇛Collider constraints are weak



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

comparison between the ≠ models

	Fondamental scale of gravity	Size of dimensions	Kaluza-Klein Mass
ADD (flat)	$M_* \sim \text{TeV}$	$R^{-1} \sim \text{meV}$	$M_{KK} \sim R^{-1}$
RS (AdS)	$M_* \sim M_{\text{Pl}}$	$R^{-1} \sim M_{\text{Pl}}$	$M_{KK} \sim TeV$
TeV & UED (flat)	$n = 1 \rightarrow M_* \sim 10^{13}\ \text{GeV}$ $n = 2 \rightarrow M_* \sim 10^{10}\ \text{GeV}$	$R^{-1} \sim \text{TeV}$	$M_{KK} \sim R^{-1}$

Back to our to-do list ...

electroweak sector

✔ -Hierarchy problem $\frac{M_{\rm EW}}{M_{\rm Pl}} \sim 10^{-16}$

✔ -Symmetry breaking (electroweak symmetry, supersymmetry)

pbs related to fermions

✔ -Neutrino masses and hierarchy in fermion masses $\frac{m_\nu}{m_{\rm top}} \sim 10^{-14}$

✔ -Proton stability

✔ -Flavour problem (FCNCs)

Grand Unification?

✔ -Unification of couplings

-Cosmological constant

cosmological pbs

✔ -Inflation

-Dark energy, quintessence $\rho_\Lambda \simeq ({\rm meV})^4$

✔ -Dark matter $\Omega_{\rm mat\ noire} \simeq 25\%$

-Baryogenesis $\frac{n_b}{n_\gamma} \sim 10^{-10}$

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!