ICTP Lectures on Extra Dimensions 2008

Lecture 3

Phenomenology of ADD models

some Refs

General reviews

- PDG (Giudice and Wells) W.M. Yao et al J Phys G33 : 1-1232, 2006
- Kribs, TASI 2004 Lectures, hep-ph/0605325
- Hewett, Les Houches 2005 Lectures SLAC-pub-12188
- ADD hep-ph/9807344

Papers

- Adelberger et al hep-ph/0307284
- Kapner et al hep-ph/0611223
- Cullen Perelstein ph/9903422
- Hanhart et al ph/0102063
- Hall, Smith ph/9904267
- Hannestad, Raffelt ph/0103201
- " ph/0110067
- Arkani-Hamed et al ph/9807344
- Giudice, Rattazzi, Wells ph/9811291

Today: Experimental constraints on ADD models from:

- Modification of the Gravitational force Law
- Astrophysics
- Cosmology
- Particle colliders

II Modifications of the gravitational force law

[⇒ Adelberger et al hep-ph/0307284]

Last time we saw for an ADD model with $D = d + 4$ dims (d compact dims with radius R)

for distances $r \ll R$: $V(r) \sim -\frac{m_1 m_2}{M_D^{D-2}} \frac{1}{r^{D-3}}$

for distances $r \gg R$: $V(r) \sim -\frac{m_1 m_2}{M_D^{D-2}} \frac{1}{(2\pi R)^{D-4}} \frac{1}{r} = -\frac{m_1 m_2}{M_{PL}^2} \frac{1}{r} = -G \frac{m_1 m_2}{r}$

and hence $M_{PL}^2 = M_D^{D-2} (2\pi R)^{D-4}$

Conventionally, modifications of the force law are parameterized as

(1) $$V(r) = -G \frac{m_1 m_2}{r} \left[1 + \alpha e^{-r/\lambda} \right]$$

[To get a feeling for α, λ: The exchange of a scalar particle with mass $1/\lambda$ and interaction strength $G\alpha$ induces the above correction to the gravitational potential]

from (1) modifications due to the heavier KK modes are exponentially suppressed → consider only the lightest KK excitations.
They have mass $1/R \Rightarrow \lambda = R$

α is determined by the coupling strength of the lightest KK mode, which is G, then coupling of a massive spin 2 field contributes a factor of 4/3, and an additional factor arises from the degeneracy of the first KK mode.

→ $\alpha = 4/3 \cdot \text{deg}$ for an d-dim torus, $\text{deg} = 2d$
(d-dim sphere, $\text{deg} = d+1$)

Note: This is not including the radion (would contribute another +2) which needs to be heavy for stability of the ED.

The currently best bounds:
Eöt Wash experiment [Low frequency torsion oscillator]

see · Kapner et al hep-ph/0611223

· URL www.npl.washington.edu/eotwash/experiments/shortRange/sr.html

for $d=2$ (Torus) : $R < 37\ \mu m$ @ 95% cl

$\longleftrightarrow M_D > 3.6$ TeV

II Astrophysics bounds on ADD models

The coupling of individual graviton kk modes is small, but for large R, the kk spectrum is very dense.

Bounds from production of kk-modes

Reminder from last lecture:

For a production process at energy E, the couplings of the individual kk modes are $\sim \frac{1}{M_{Pl}}$.

the number of states with mass $< E$ (which can be produced on shell) scales like $\rho(E) \sim (ER)^{D-4}$

$\Rightarrow$ the production amplitude scales like $A \sim \frac{1}{M_{Pl}} (ER)^{D-4}$

the production rate scales like $\Gamma \sim \frac{1}{M_{Pl}^2} (ER)^{D-4} \sim \frac{1}{M_D^2} \left(\frac{E}{M_D}\right)^{D-4}$

so the production rate is enhanced by the multiplicity of kk modes.

once the kk modes are produced, their individual coupling is $\sim \frac{1}{M_{Pl}}$
$\rightarrow$ very weak $\rightarrow$ long free path in a plasma.

Consider energy loss processes in stars or supernovae

Graviton kk modes, when produced, can carry away energy freely and contribute to cooling of stars or energy deposition of supernovae

but stars still burn, and for SN1987, the neutrino flux has been measured and it matches the energy deposition.

$\rightarrow$ Bound on the energy carried away by graviton kk modes.

From the rate estimate we see that the rate grows with E^{D-4}
$\rightarrow$ expect the strongest bounds from the most energetic objects
[if measured with comparable precision]

$\rightarrow$ Bounds from SN1987
[Cullen, Perelstein, hep-ph/9903422]

process: $N+N \longrightarrow N+N+G$ "Gravi strahlung"
G: kk graviton

- calculate the matrix element $M^{\vec{j}}_{NN \rightarrow NNG}$ for production of the $\vec{j}^{th}$ kk mode
- energy loss is given by the phase space integral

$$\dot{\varepsilon} = \sum_{\vec{j}} \int d\pi_i \; S \left| M^{\vec{j}} \right|^2 \delta^4(p_1+p_2-p_3-p_4-p_g) E_g f_1 f_2 (1-f_3)(1-f_4)$$

where S symmetry factor
E_g energy of the produced graviton kk mode
$f_i(T)$ are the nucleon distribution functions.

		Cullen, Perelstein	Hanhart et al ph/0102063
Result: for	2 ED	$M_D \gtrsim 50$ TeV	$M_D > 38$ TeV
	3 ED	$M_D \gtrsim 4$ TeV	$M_D > 4.1$ TeV
	4 ED	$M_D \gtrsim 1$ TeV	

Bounds from kk-graviton decay

The kk gravitons are produced in stellar objects and they are very long lived. So they stay around and eventually decay.

- For decays into photons, find $\tau_{\gamma\gamma} \simeq 3 \cdot 10^{5} yr \left(\frac{100 \text{ MeV}}{m_{kk}} \right)^3$

the photon background spectrum for $E < 100$ MeV is very well measured by EGRET.

Hannestad, Raffelt [ph/0103201]

consider kk-gravitons produced by all supernovae and their decay into photons and compare this spectrum to the measured photon background spectrum.

find 2ED : $M_D > 84$ TeV
3ED : $M_D > 7$ TeV

- Another bound [Hannestad, Raffelt ph/0110067]

For the production of the heaviest kinematically excessible kk modes, no energy is left to go into kinetic energy
$\Rightarrow$ the heavy kk modes are trapped by the gravitational field of SN remnants
$\Rightarrow$ expect a photon excess [different spectrum as above because of the "kinetic selection"] from ~~the~~ direction of a neutron star.

Result 2ED : $M_D > 200$ TeV

3ED : $M_D > 16$ TeV

III Bounds on ADD models from Cosmology

[ADD hep-ph/9807344]
[Hall, Smith ph/9904267] | Kribs ph/0605325

The fundamental cut-off of ADD models is $M_D \ll M_{Pl}$

$\Rightarrow$ The early universe cosmology at scales $E > M_D$ drastically changes compared to standard 4D physics

$\rightarrow$ Challenges for inflation, baryogenesis, dark matter, ...

[see ADD ph/9807344

[Arkani-Hamed, Dimopoulos, March-Russell th/9809124, ph/9903224]

even below M_D, cosmology is affected by the presence of the graviton KK modes.

But we have a very good understanding of Big Bang Nucleosynthesis

$\rightarrow$ don't want modifications below $T \sim 1\,\text{MeV}$

In Standard cosmology the cooling of the universe is dominated by Hubble expansion

$$\frac{d\rho}{dt} \sim -3H\rho \sim -3\frac{T^2}{M_{Pl}^2}\rho$$

In ADD, cooling by KK graviton emission competes with a rate

$$\frac{d\rho}{dt} \sim \frac{T^{D-4}}{M_*^{D-2}}$$

these rates are equal for

$$T_* = 10^{\frac{6(D-4)-9}{D-3}} = \begin{cases} 10\ \text{MeV} & 2\,\text{ED} \\ \vdots & \\ 10\ \text{GeV} & 6\,\text{ED} \end{cases}$$

· **Overclosure from KK gravitons**

Due to the high multiplicity of KK gravitons, decays into them is quite probable, but they all couple very weakly → long life time

KK gravitons freeze out early and store energy density

estimate $\rho_{grav} \sim T_* \cdot n_{grav} \sim \frac{T_*^{D+1} M_{PL}}{M_D^{D-2}}$

if $\rho_{grav}/T^3 > 3 \cdot 10^{-9}$ GeV, gravitons overclose the universe

plugging in the $M_D \leftrightarrow M_{PL}$ rel^n

$\Rightarrow$ need $T_* \lesssim 10^{\frac{6(D-4)-15}{D-2}}$ MeV $\frac{M_D}{\text{TeV}}$ to prevent over closure.

We know from BBN constraints that we need $T_* > 1$ MeV

$\Rightarrow$ $M_D > 10$ TeV for 2 ED

[Calculation → Hall, Smith : $M_D > 6.5$ TeV for 2 ED]

· **Diffuse γ-ray background from KK gravitons** [Hall, Smith]

Assume that at T^*, no graviton KK modes are excited [conservative assumption].

Then graviton KK-modes are produced from processes SM SM → G (eg $\nu\bar{\nu} \to G$)

and the graviton KK modes become populated.

Gravitons decay into photons with $\Gamma(G \to \gamma\gamma) = \frac{m^3}{80\pi M_{PL}^2}$

$\Rightarrow$ can calculate the γ-ray spectrum from such decays to get a bound $M_D > 110$ TeV for 2ED

IV Particle Colliders

· missing energy signals

In particle colliders, KK gravitons show up in processes like

$e^+e^- \to \gamma + \not{E}$,

Again, for the individual KK gravitons, the cross section is tiny, but for Large $R \to$ high multiplicity, the combined signal becomes relevant.

For an explicit and detailed calculation see Giudice, Rattazzi, Wells hep-ph/9811291

currently best bounds [LEP Exotica Working Group, LEP Exotica WG 2004-03]

$D-4$	2	3	4	5	6
M_D in TeV	1.60	1.20	0.94	0.77	0.66

· virtual exchange of KK gravitons

see Giudice, Rattazzi, Wells:

the coupling of the gravitons is dictated by $\mathcal{L} = \frac{1}{M_D^{\frac{D}{2}-1}} h^{AB} T_{AB}$

virtual graviton exchange at tree level induces operators

$$\mathcal{L} = \pm \frac{4\pi}{\Lambda_H^4} T_{\mu\nu} T^{\mu\nu}$$ where Λ_H is a cut-off parameter

$$\left[\text{GRW}: \frac{4\pi}{\Lambda_H^4} = \frac{\overset{\text{sum over KK gravitons}}{S_{D-3}}}{2} c_1 \frac{\Lambda^{D-6} \leftarrow \text{cutoff}}{M_D^{D-2} \leftarrow D\text{-dim Planck mass}} \right]$$

$\to$ new contributions to $e^+e^- \to G_n \to \gamma\gamma, VV, l^+l^-, f\bar{f}$

Current bounds on Λ_H

$\Lambda_H > 1.29\ (1.12)$ TeV from LEP for constructive (destructive) interference

$\Lambda_H > 1.43\ (1.27)$ TeV from Tevatron

For a comprehensive review of ADD phenomenology and further Refs

see Hewett, SLAC-Pub-12188

For an introduction → Kribs hep-ph/0605325
For a summary of the latest most relevant bounds: PDG (Giudice and Wells)

Some general remarks

From the experimental bounds it seems that the strongest bound arises from the photon excess from KK-gravitons captured by neutron stars, so why worry about the other bounds?

All these bounds have been calculated under very specific assumptions about a) the model
b) "initial conditions" at high energies

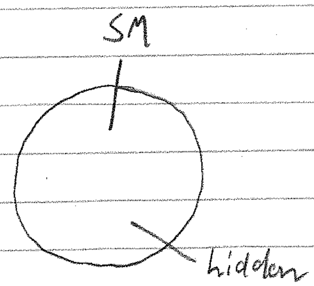
varying them can vary the bounds relative to each other.

Examples: i) For tests of Gravity we saw, that the result depends mainly on the Lightest KK mode and its degeneracy.
Results from Astrophysics and Particle Physics depend on all KK modes accessible

suppose we compactify on S^n instead of T^n

this changes the 1^{st} kk mode degeneracy by a factor of $\mathcal{O}(10)$, but leaves the kk-mode density merely unchanged.

b) Suppose we take a D dim model with one 4D SM brane and one 4D "hidden" brane.



Now kk graviton modes can also decay into "hidden" fields and the photon production from kk modes is reduced

→ weakens the bounds from photons from supernovae and neutron stars
→ also weakens the bounds from relic photons

• but the particle bounds are unchanged as SM - hidden interactions are suppressed by the spacial separation of the SM and the hidden brane in the extra dimension.

• bounds from overclosure should only be marginally be affected. kk gravitons contribute energy density, which now might get transferred to hidden particles, but it is still present in non-SM particles

c) dropping the assumption that at some temperature T^*, no kk-gravitons are excited [by building an early cosmology model from which the kk-gravity density $\rho(T)$ is calculable] strengthens bounds from overclosure and from relic photons but does not modify astro and particle constraints.

d) In the particle constraints, we assumed that the operators induced are of the form

$$\mathcal{L} = \pm \frac{4\pi}{\Lambda_H} T_{\mu\nu} T^{\mu\nu} \quad , \text{ i.e. dimension } 8,$$

and that they respect all symmetries of the SM.

But the cut off of the theory is low, and lepton- or baryon number violating operators could be induced at loop level
[only calculable if the embedding theory is known]
which gives additional (very strong) constraints from particle physics.