# EXTRA DIMENSIONS, THE HIERARCHY PROBLEM, AND COLLIDER PHYSICS.

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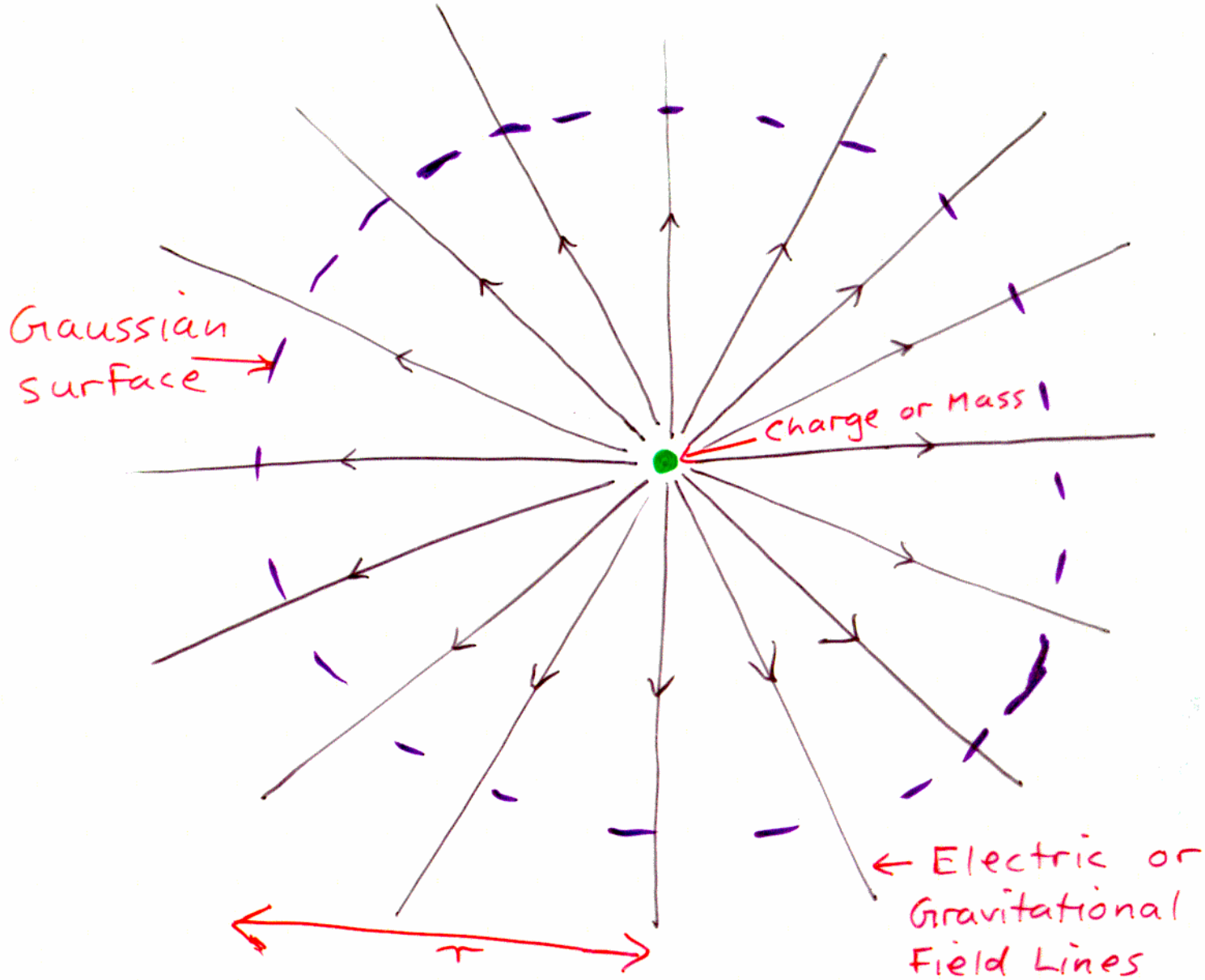
# OUTLINE

- Hiding & Seeking Extra Dimensions
- New Paradigm — A 3-Brane Universe
- Central Problem of Particle Physics —
  — The Hierarchy Problem
- Extra-Dimensions to the Rescue 1
  — The Arkani-Hamed, Dimopoulos, Dvali Proposal.
- Extra-Dimensions to the Rescue 2
  — The Randall, Sundrum proposal.
- Conclusions

[Units : $\hbar = c = 1$]

# DIMENSIONS & FORCES

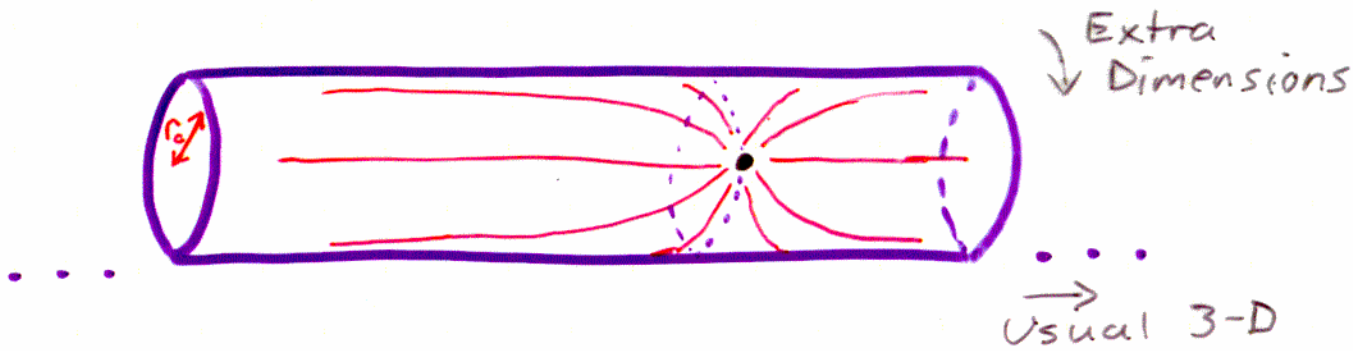



Gauss' Law: 3+1-Dim. $F \times 4\pi r^2 = \text{const.}$

d-Dim. $F \times r^{d-2} = \text{const.}$

# HIDING EXTRA DIMENSIONS — THE KALUZA-KLEIN IDEA

"Compact" Extra Dimensions



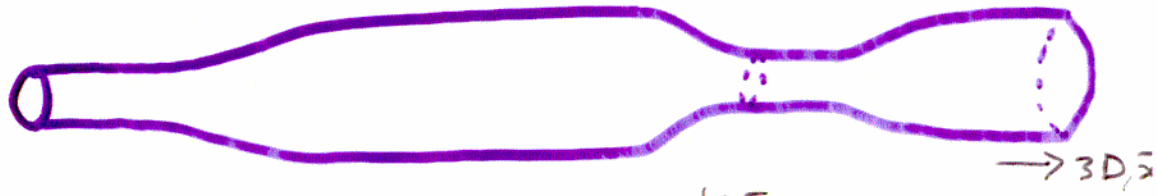

$$\therefore \quad F \approx \frac{G_d}{r^2 \cdot \mathrm{Min}\left( r^{d-4}, r_c^{d-4} \right)}$$

## WHY DO IT?

A powerful mechanism for unification.

Recall in General Relativity spacetime is dynamical.

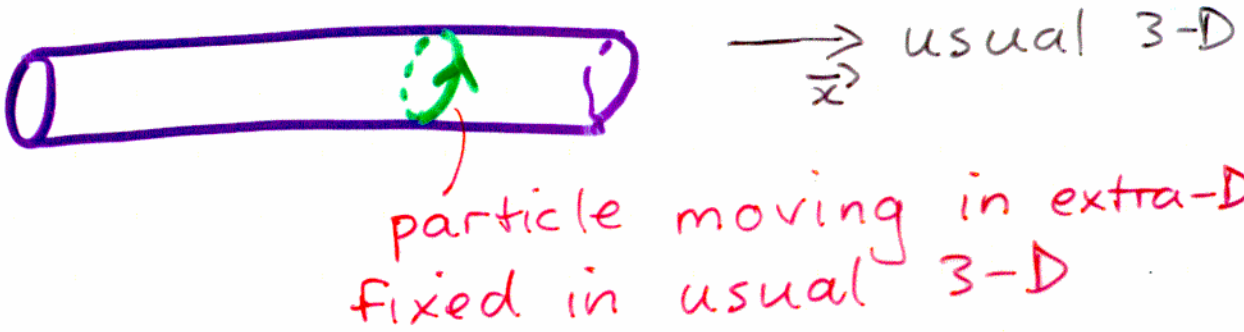
Eg.




5D Gen. Rel. $\Rightarrow$ 4D Gen. Rel. + New scalar field $r_c(\vec{x}, t)$

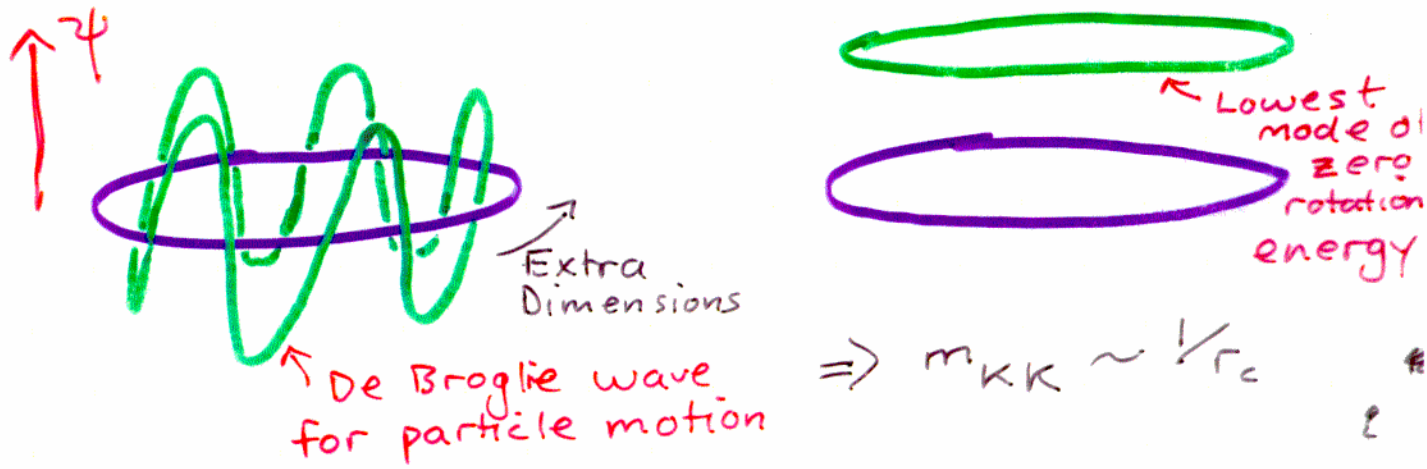
"Radion"

# SEEKING MICROSCOPIC EXTRA DIMENSIONS



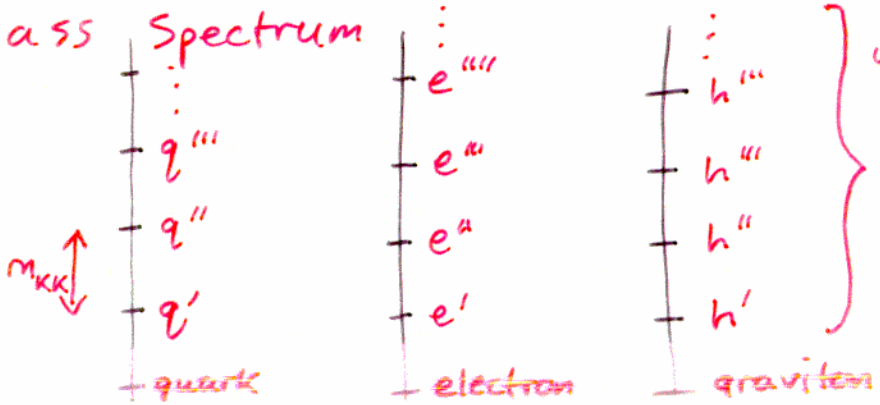

- Kinetic energy of extra-dimensional motion appears as 3-D "rest energy" $\equiv$ 3+1-D MASS.
- Rotational energy is quantized:

Fixed $\vec{x}, t$ (3+1) cross-section:




$\Rightarrow m_{KK} \sim 1/r_c$

Mass Spectrum




"KK states"

Experiment $\Rightarrow$ $m_{KK} > \text{TeV}$

$\Leftrightarrow$ $\boxed{r_c < 10^{-15}\ \text{mm}}$

# SUPERSTRINGS

- ONLY known consistent theory of GENERAL RELATIVITY and QUANTUM MECHANICS.

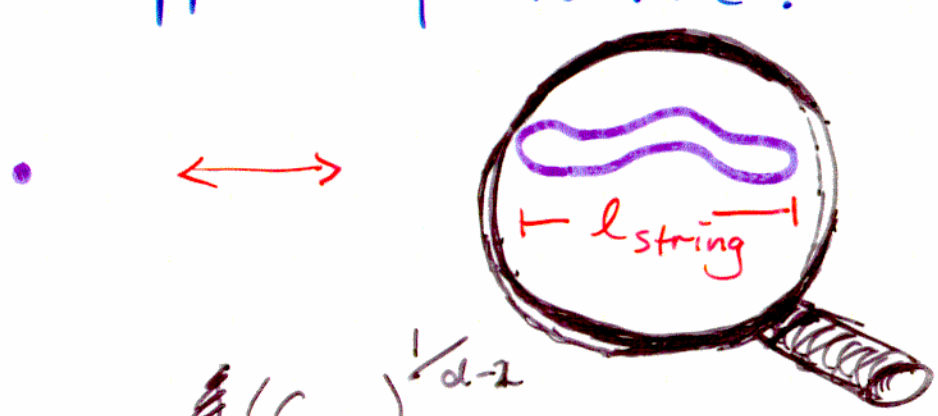
- Still incomplete, Fit to nature unclear. $\approx$ A LARGE CLASS of theorie

- Generically involve several EXTRA DIMENSIONS (usual total of 10, 11)

- For $E_{experiment} \ll m_{string}$,

  $r_{experiment} \gg l_{string} \equiv \frac{1}{m_{string}}$

  strings appear point-like.



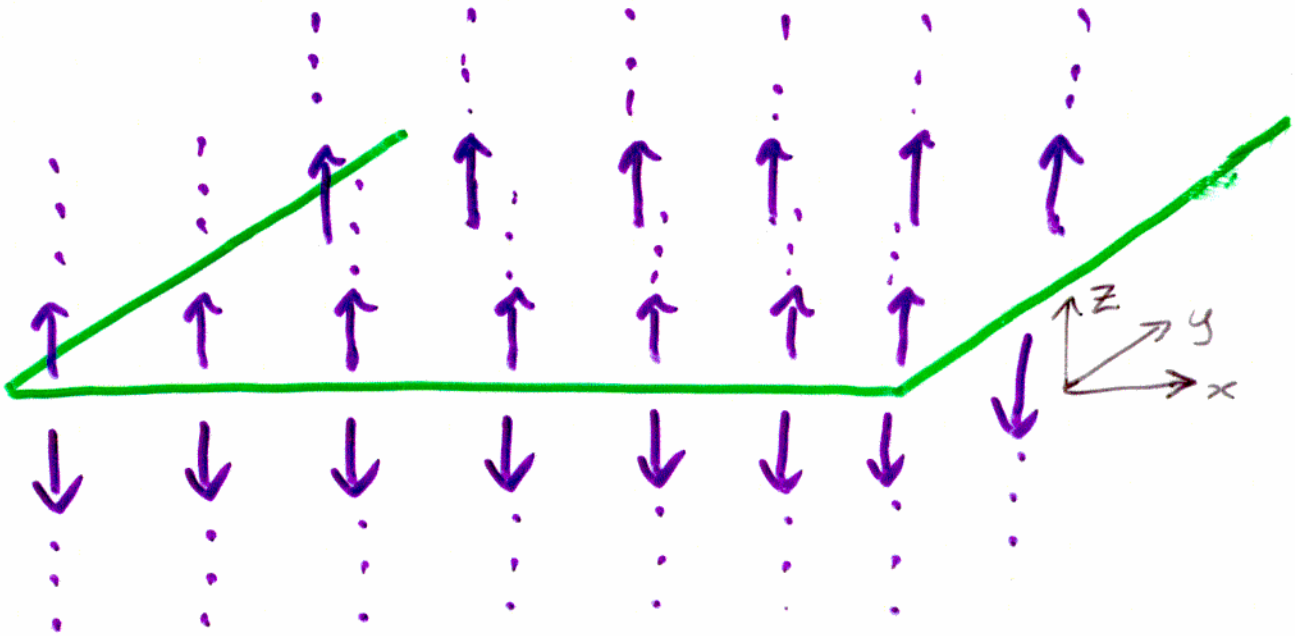

- $l_{string} \sim (G_d)^{1/d-2}$

# THE NEW INGREDIENT—BRANES

"p-brane" $\equiv$ p-D hypersurface in space

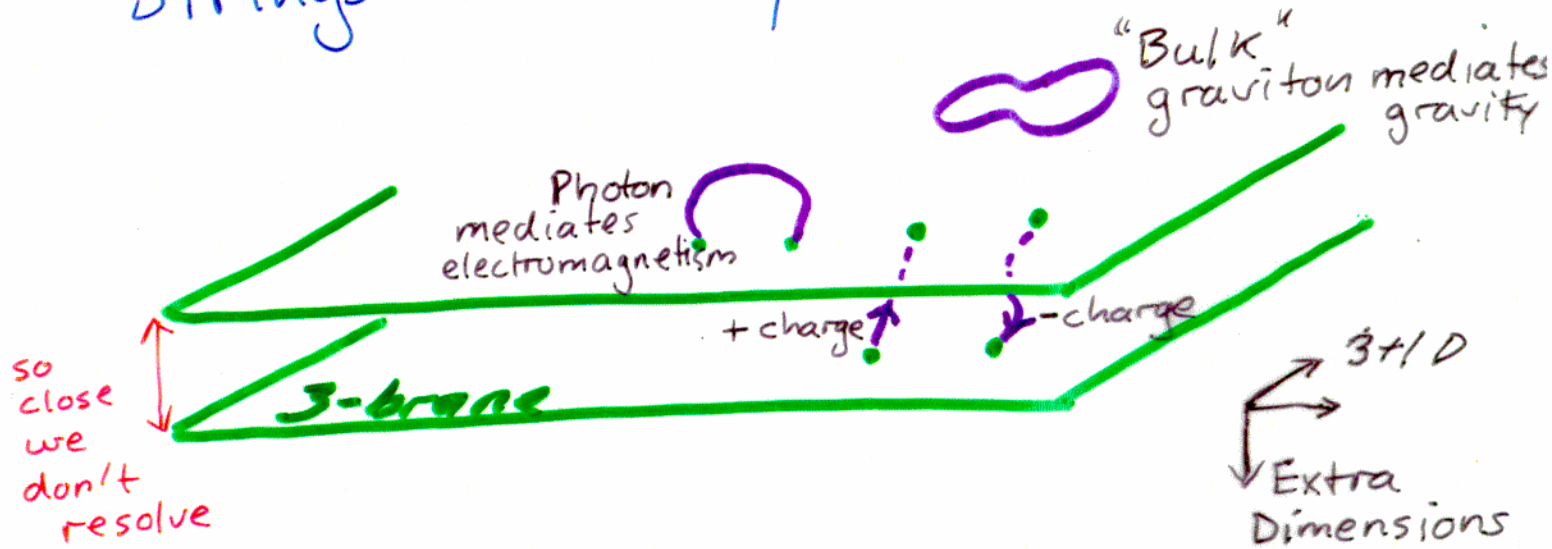
- Some particles/fields may be confined to propagate on p-brane.
- p-brane itself can act as a gravitational source.

Eg. Domain Wall $\equiv$ 2-brane



# 3-Brane Solitons of String Theory

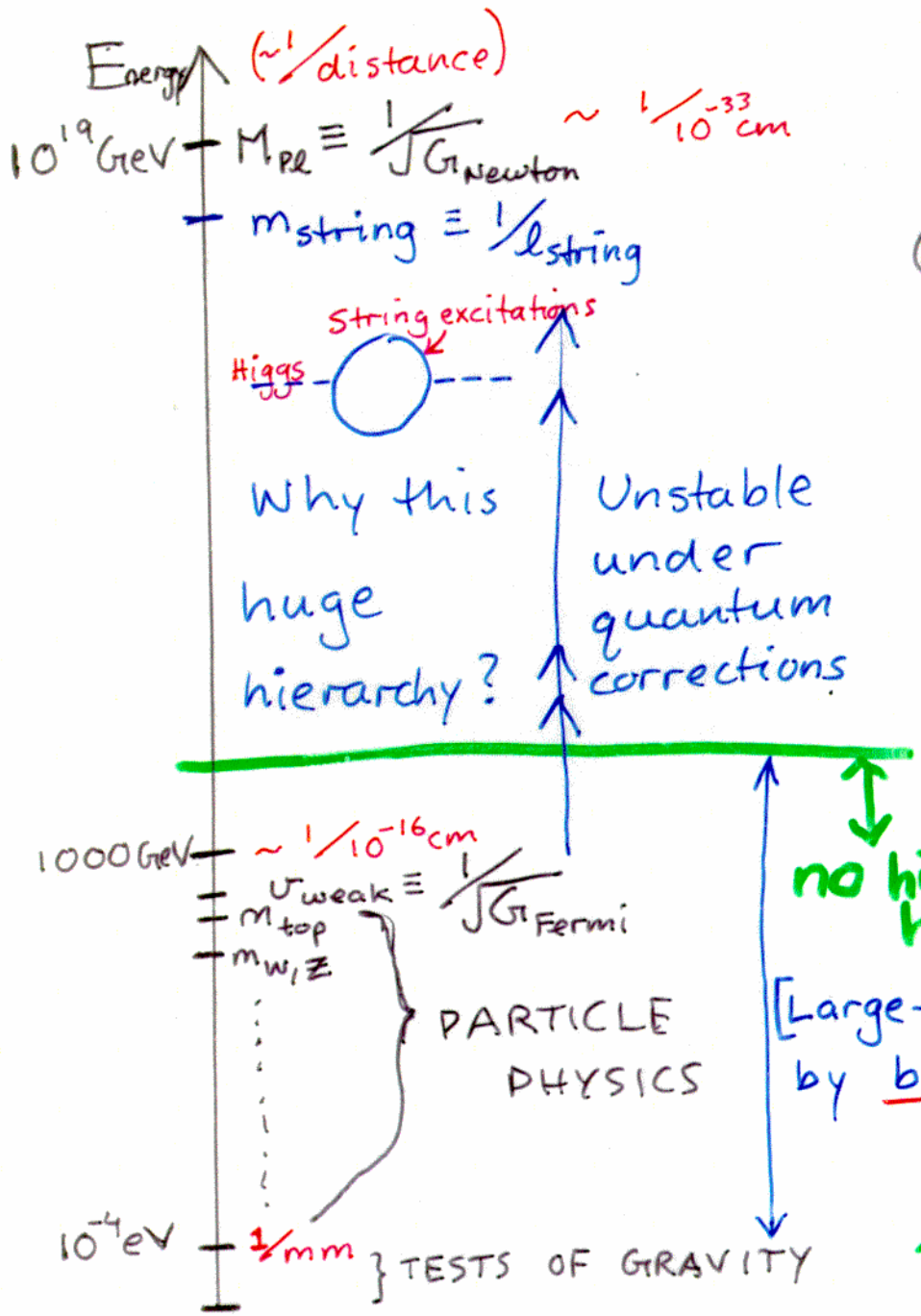
- Strings can only end on branes:




- Strings can move off branes but not with their charges. They become neutral bulk gravitons.

- Quite naturally, non-gravitational forces live on branes, while gravity lives in the higher-dimensional bulk spacetime.

# THE HIERARCHY PROBLEM




Standard Model

Gravitational Field

$$\doteqdot \frac{G_{5-D}}{r^2 \, \mathrm{Min}(r^2, r_c^2)}$$

$$\Rightarrow G_{Newton} = \frac{G_{5-D}}{r_c^2}$$

$1/G_5^{1/4} \sim m_{string}$

no hierarchy here

[Large-$r_c$ hierarchy protected by bulk supersymmetry]

$1/r_c$ = KK gravitons

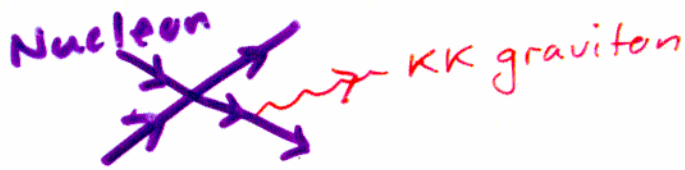
Arkani-Hamed, Dimopoulos, Dvali '98

# KK PHENOMENOLOGY

(Lots of light, gravitationally coupled new particles

Supernova SN1987a:

KK graviton processes like

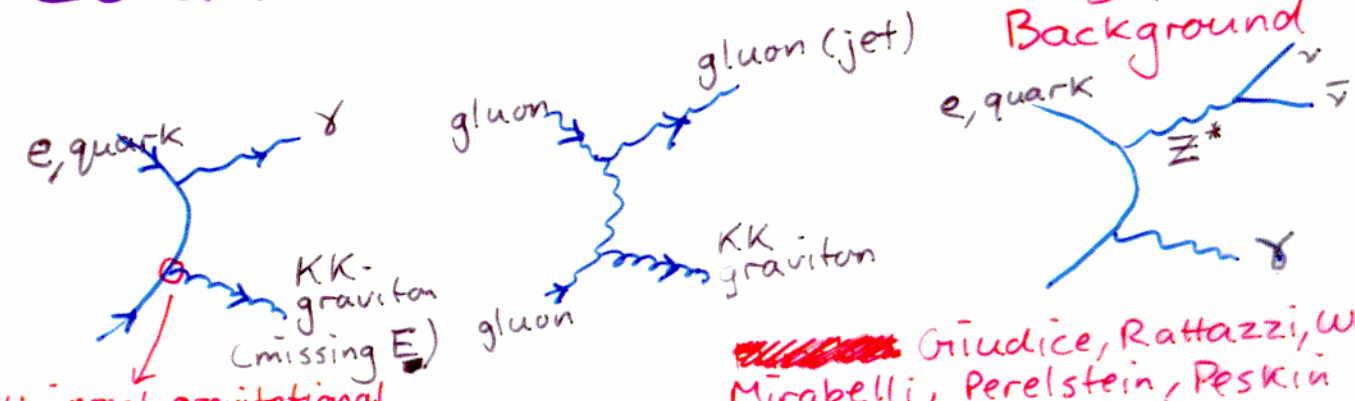



can compete in cooling supernova with standard neutrino radiation (agreeing with observation).

$\Rightarrow$ Bound for $d=6$, $M_6 \gtrsim 50$ TeV, $r_c \lesssim \mu m$

Arkani-Hamed, Dimopoulos Dvali '99
Cullen, Perelstein '99
Barger, Han, Kao, Zhang '99
Hanhart, Phillips, Reddy, Savage '00

# COLLIDERS:




Giudice, Rattazzi, Wells '9
Mirabelli, Perelstein, Peskin '98

Present Constraints $\Rightarrow$ $r_c < \frac{1}{2}$ mm

Better constraint than tests of Newton's Law.

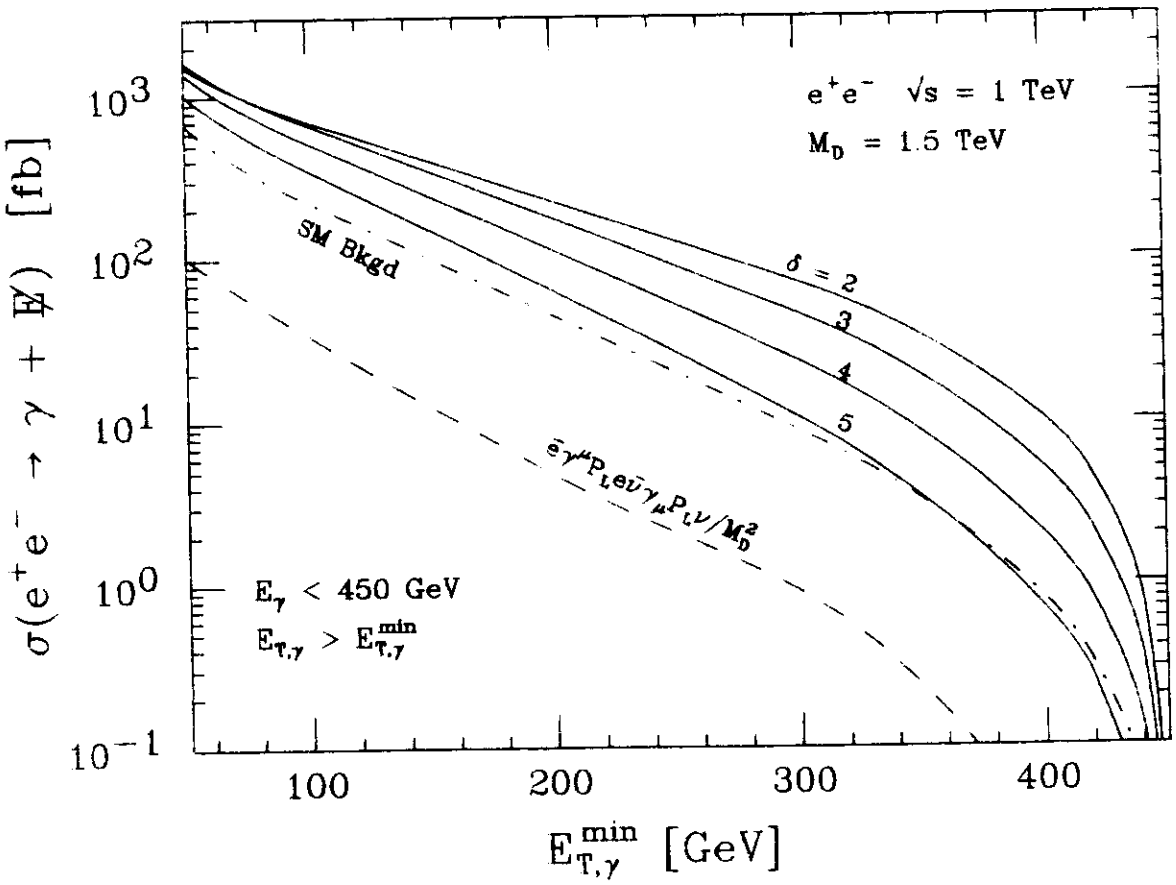



Figure 1: Total $\gamma$ + nothing cross section at an $e^+e^-$ collider for $\sqrt{s}$ = 1 TeV with $E_{T,\gamma} > E_{T,\gamma}^{min}$. The dash dotted line represents the background, and the solid lines represent the signal for various numbers of extra dimensions and $M_D$ = 1.5 TeV. To eliminate the background contribution from $\gamma Z \to \gamma\nu\nu$ we have required $E_\gamma$ < 450 GeV for both the signal and the background. The dashed line is the Standard Model background subtracted signal from a representative dimension-6 operator.

From Giudice, Rattazzi, Wells '98

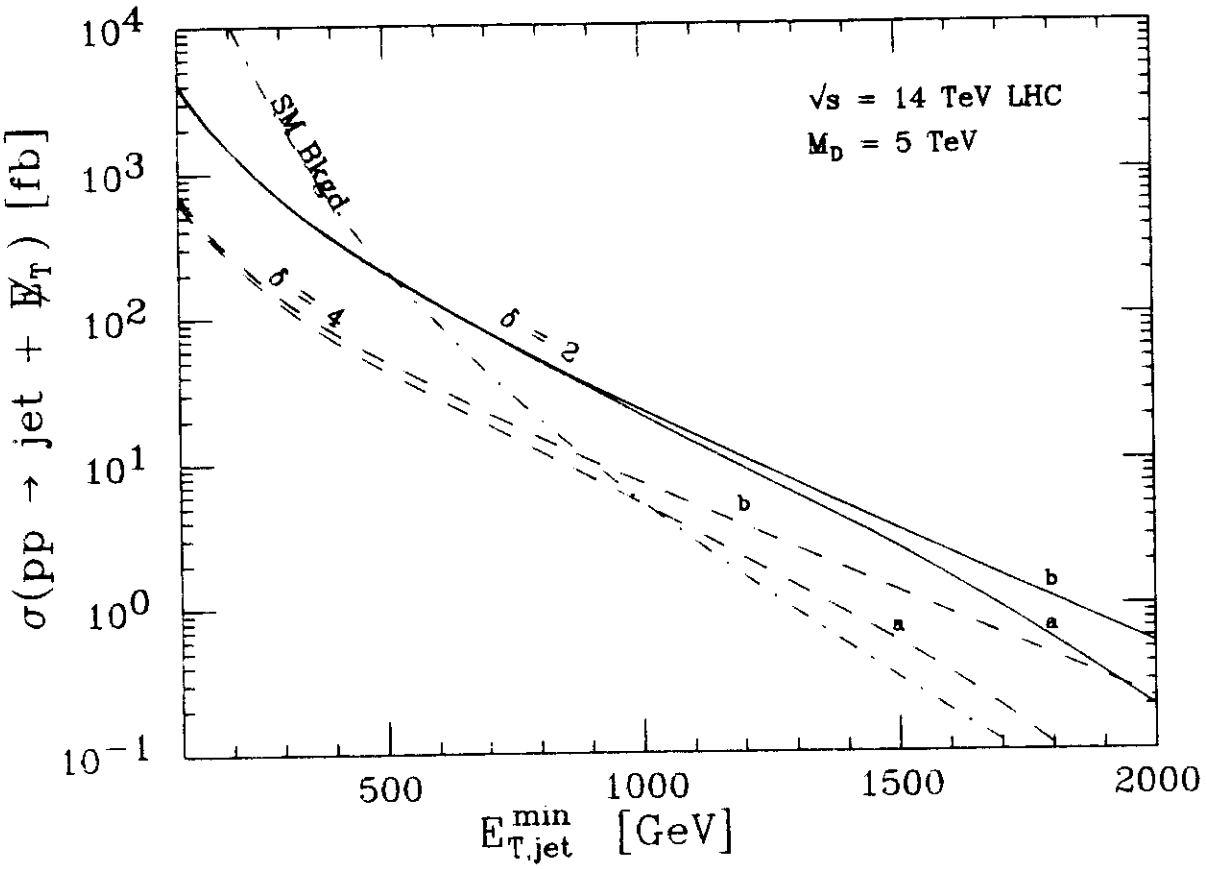



Figure 3: The total jet + nothing cross-section at the LHC integrated for all $E_{T,jet} > E_{T,jet}^{min}$ with the requirement that $|\eta_{jet}| < 3.0$. The Standard Model background is the dash dotted line, and the signal is plotted as solid and dashed lines for fixed $M_D = 5$ TeV with $\delta = 2$ and 4 extra dimensions. The a (b) lines are constructed by integrating the cross section over $\hat{s} < M_D^2$ (all $\hat{s}$).

From Cavalli, Rattazzi, Wells '98

# NEW SOLUTION TO THE HIERARCHY PROBLEM

Randall, Sundrum '99

- Started with Heterotic-M-theory

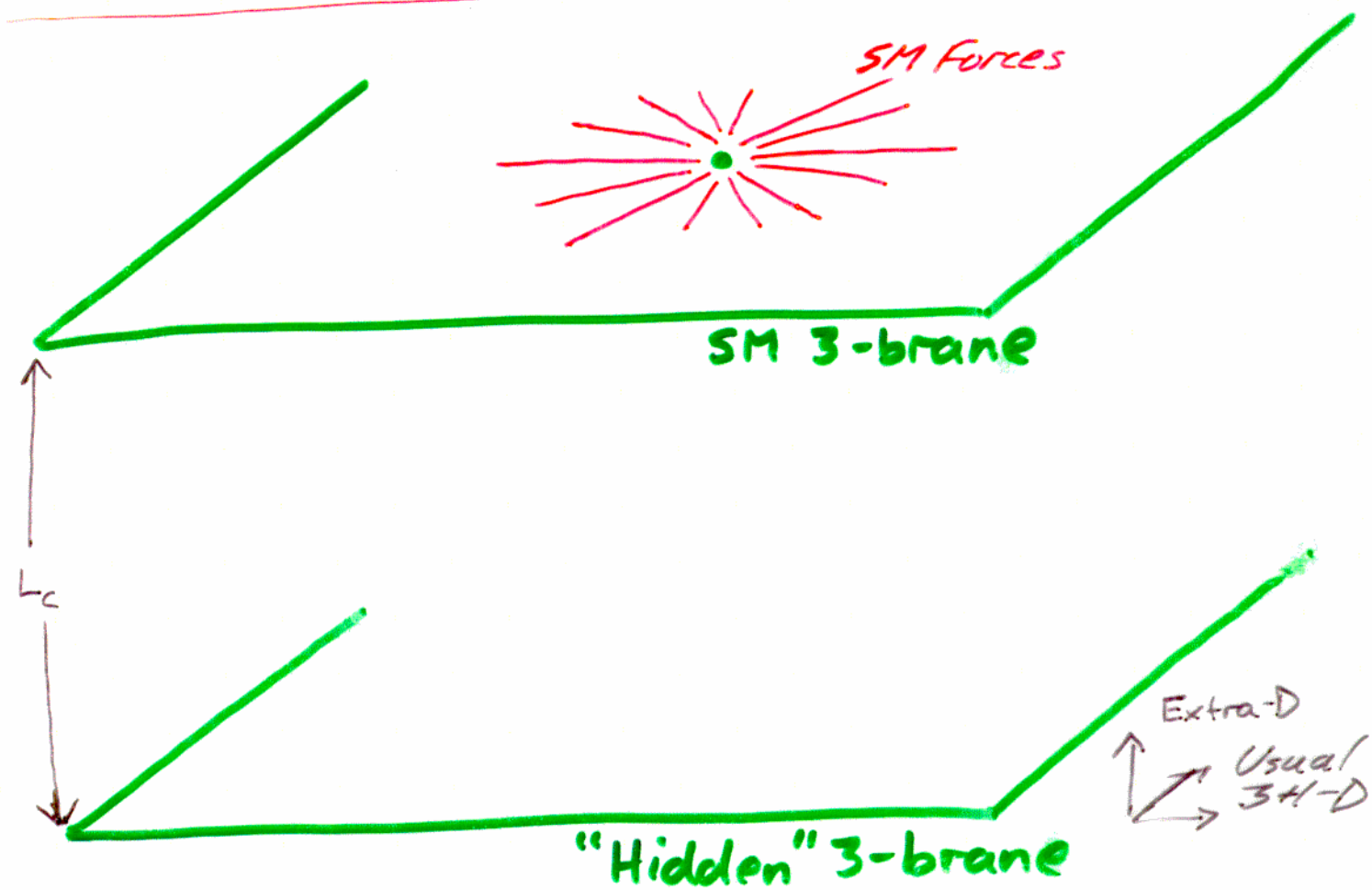
Horava, Witten '95

reduced to 4+1-D

Lukas, Ovrut, Stelle, Waldram '99

BUT without supersymmetry.

One Extra Dimension = An Interval




The 3-branes themselves carry (opposite) energy densities. ie. are gravitational sources.

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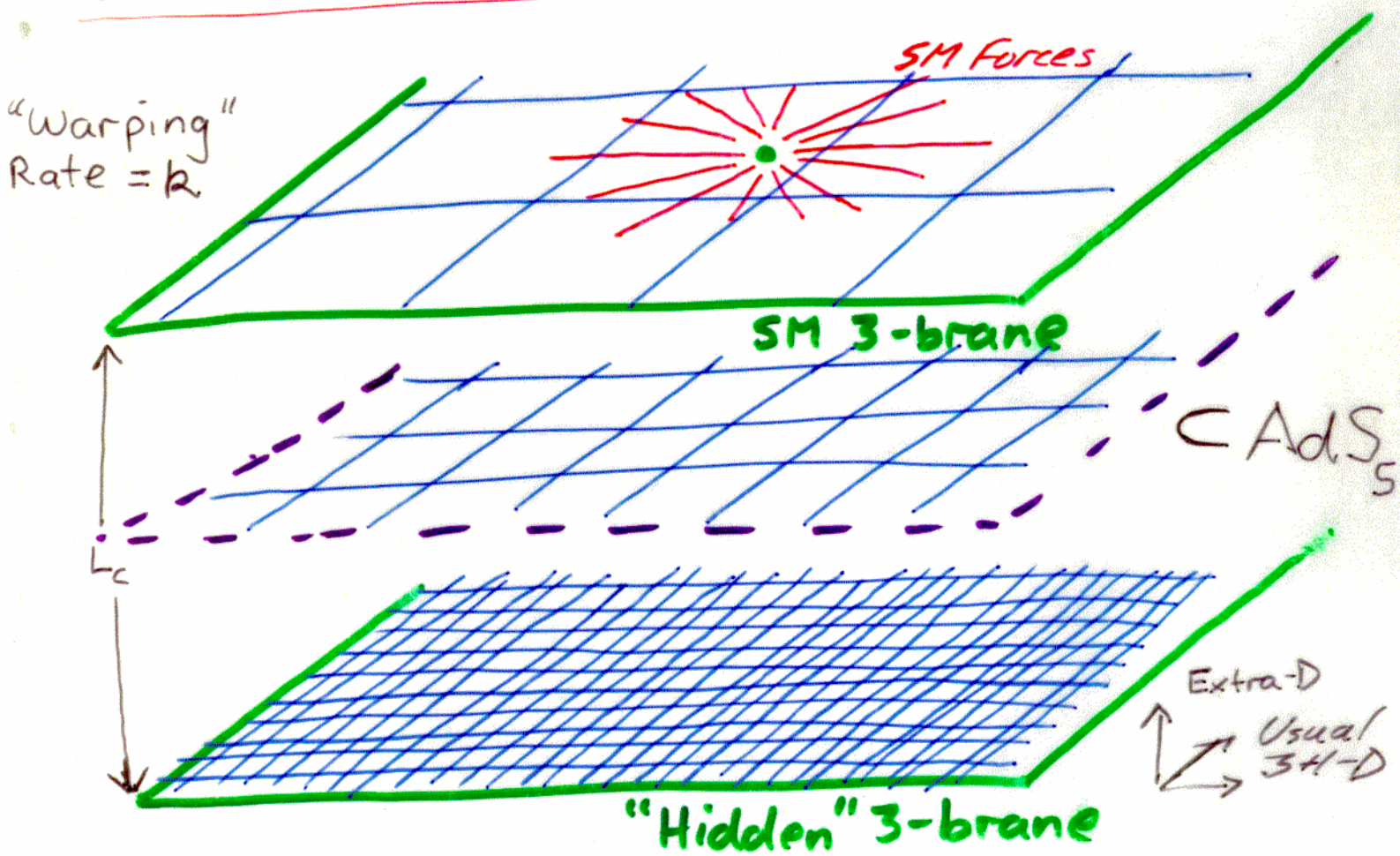


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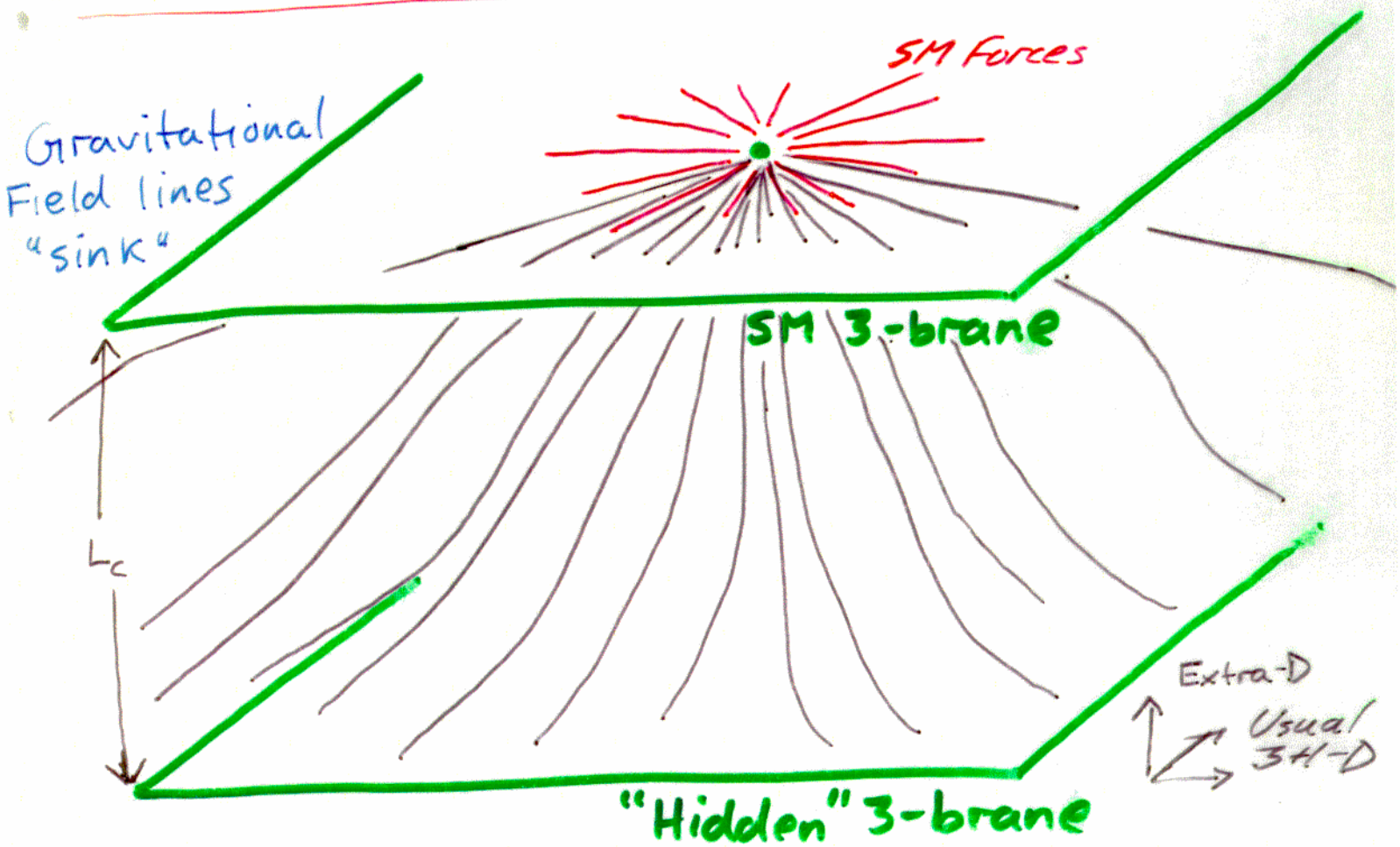


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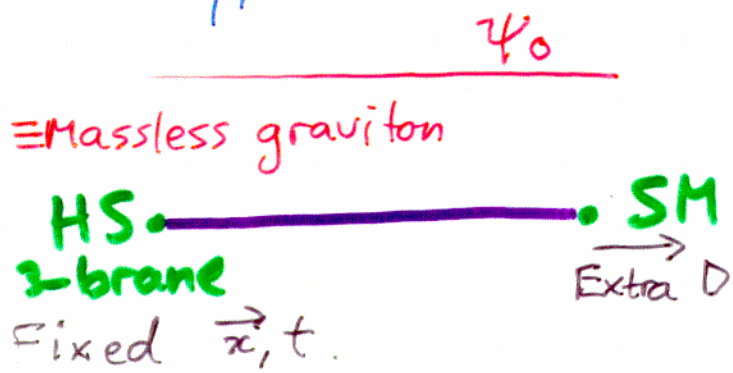
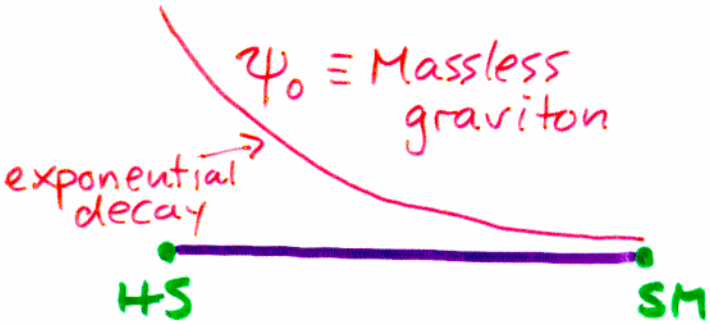
# KK GRAVITONS AND THE HIERARCHY PROBLEM

Naively,





But due to the high curvature,





∴ Long range gravitational Force

$$= \frac{G_5 |\psi_0(SM)|^2}{r^2} = \frac{\overbrace{G_5 k e^{-2kL_c}}^{G_{Newton}}}{r^2}$$

$G_{Newton} = 10^{-30} G_{Fermi}$ for $G_5^{1/3}, \frac{1}{k}, \sim G_{Fermi}^{1/2}$

if $kL_c \sim 30$ Mechanism: Goldberger, Wise '99

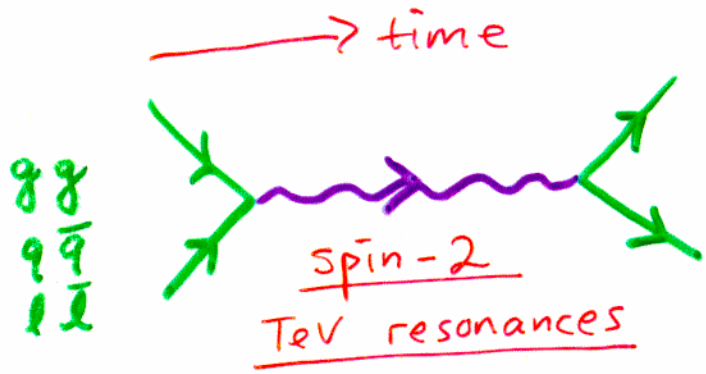
# PHENOMENOLOGY

- $\psi_{\text{massless graviton}}(SM) \sim \underline{\underline{10^{-15}}}\, \psi_{\text{KK gravitons}}(SM)$

$\Rightarrow$ TeV-mass KK gravitons couple to SM particles $\sim \dfrac{\text{Energy}}{\text{TeV}}$.

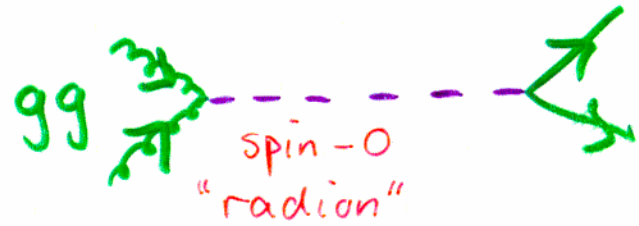
[rather than $\dfrac{E}{10^{15}\,\text{TeV}} = \dfrac{E}{M_{\text{Planck}}}$ for massless graviton].

- $\therefore$ at TeV colliders,




lepton, quark, W, Z, $\gamma$, g pair production with universal strength

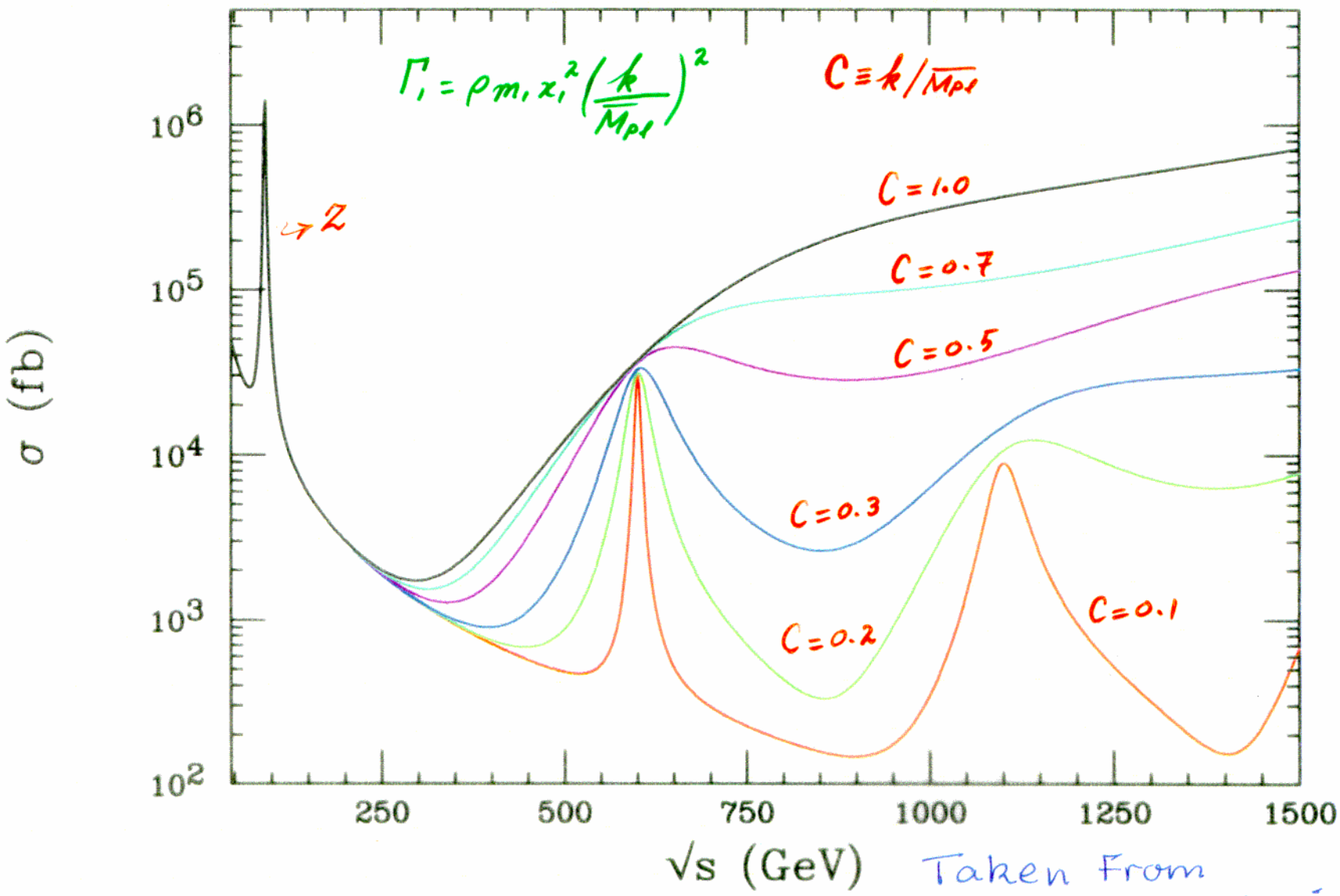
- The "radion" should also be visible:




W, Z, g, $\gamma$, top pair production

Goldberger, Wise '99
Giudice, Rattazzi, Wells. '00

$e^+e^- \to \mu^+\mu^-$




Taken From
Davoudiasl, Hewett, Rizzo '99

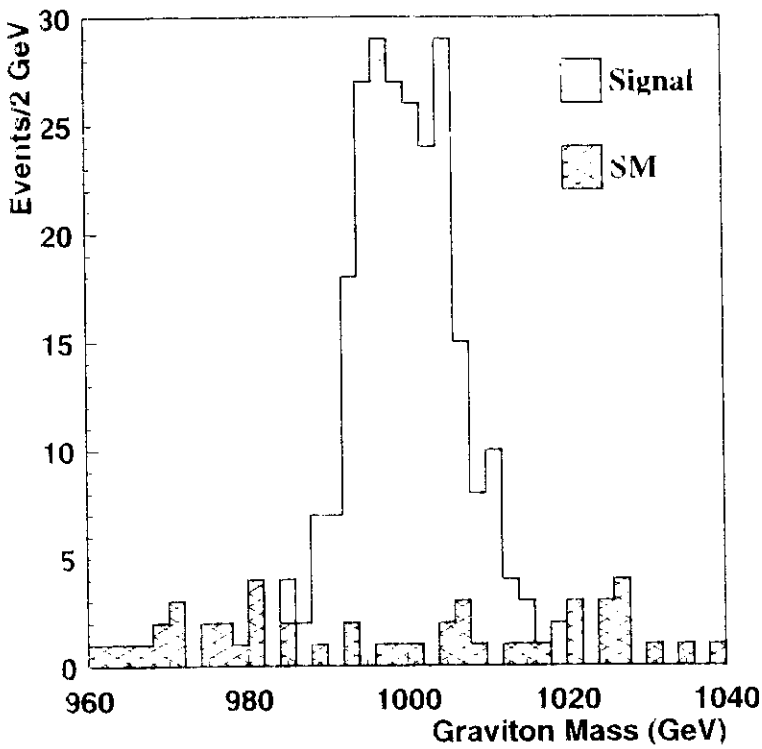



**Figure 2:** The number of events per 2 GeV mass bin from a graviton resonance, with $m_G = 1$ TeV (signal), superimposed on the expected Standard Model background (SM), for 100 fb$^{-1}$ of integrated luminosity.

From Allanach, Odagiri, Parker, Webber '00

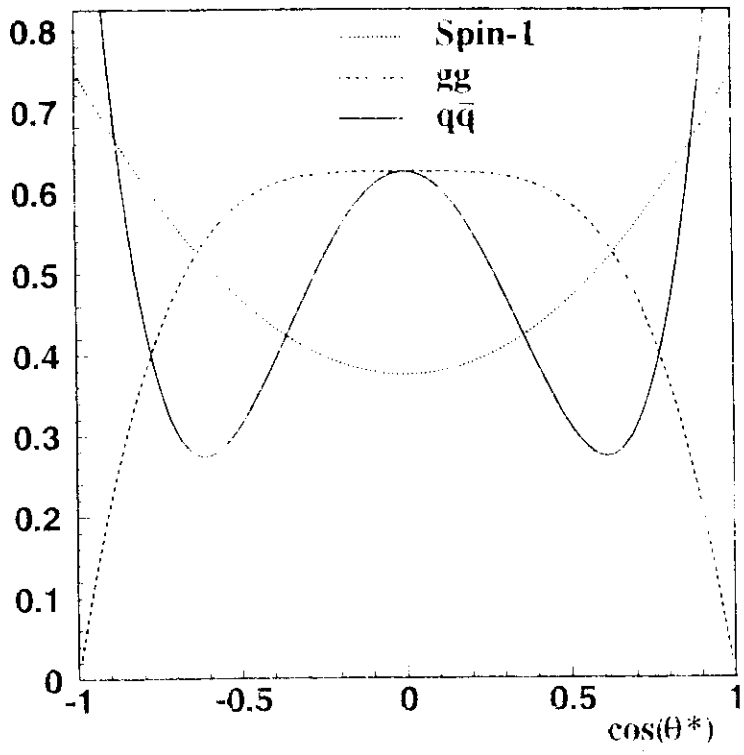



**Figure 1.** The normalised theoretical angular distributions for $gg \to G \to e^+e^-$ (dashed curve), $q\bar{q} \to G \to e^+e^-$ (solid curve) and $q\bar{q} \to \gamma/Z \to e^+e^-$ (dotted curve).

From Altarelli, Ordovini, Parisi, October '80

# CONCLUSIONS

- The Brane Universe Paradigm is a radical redrawing of the spacetime stage upon which fundamental physics plays out. It has surprising & useful properties.
- The paradigm is well-motivated by recent developments in Superstring Theory.
- Brane Universe solutions to the Hierarchy Problem involve lowering the fundamental Planck scale at which gravity becomes strong. The phenomenology of gravitational KK resonances would be dramatic & distinctive at upcoming colliders.
- The Early Universe would be very different in a Brane universe.