

**Warped
Geometry:
Its Consequences
and
Signatures**

Lisa Randall, Harvard University

A New View of Weak Scale Physics

- Many new results in theoretical physics
- Some of the most exciting involve extra dimensions of space
- Intriguing possibilities for our universe: both theoretical and experimental
- Warped geometry has particularly interesting signatures: resonances!
- Extra dimensions of space could be the next big discovery at CERN

Sampling of what we now know is possible—in physics!

- Braneworlds and Multiverses
- Extra dimensions can be infinitely large, yet be invisible
- New place in the universe: three-dimensional sinkhole
- Extra dimensions can illuminate connections, resolving puzzles of a 3+1 dimensional world
- With testable experimental consequences

Why should such different results connect?

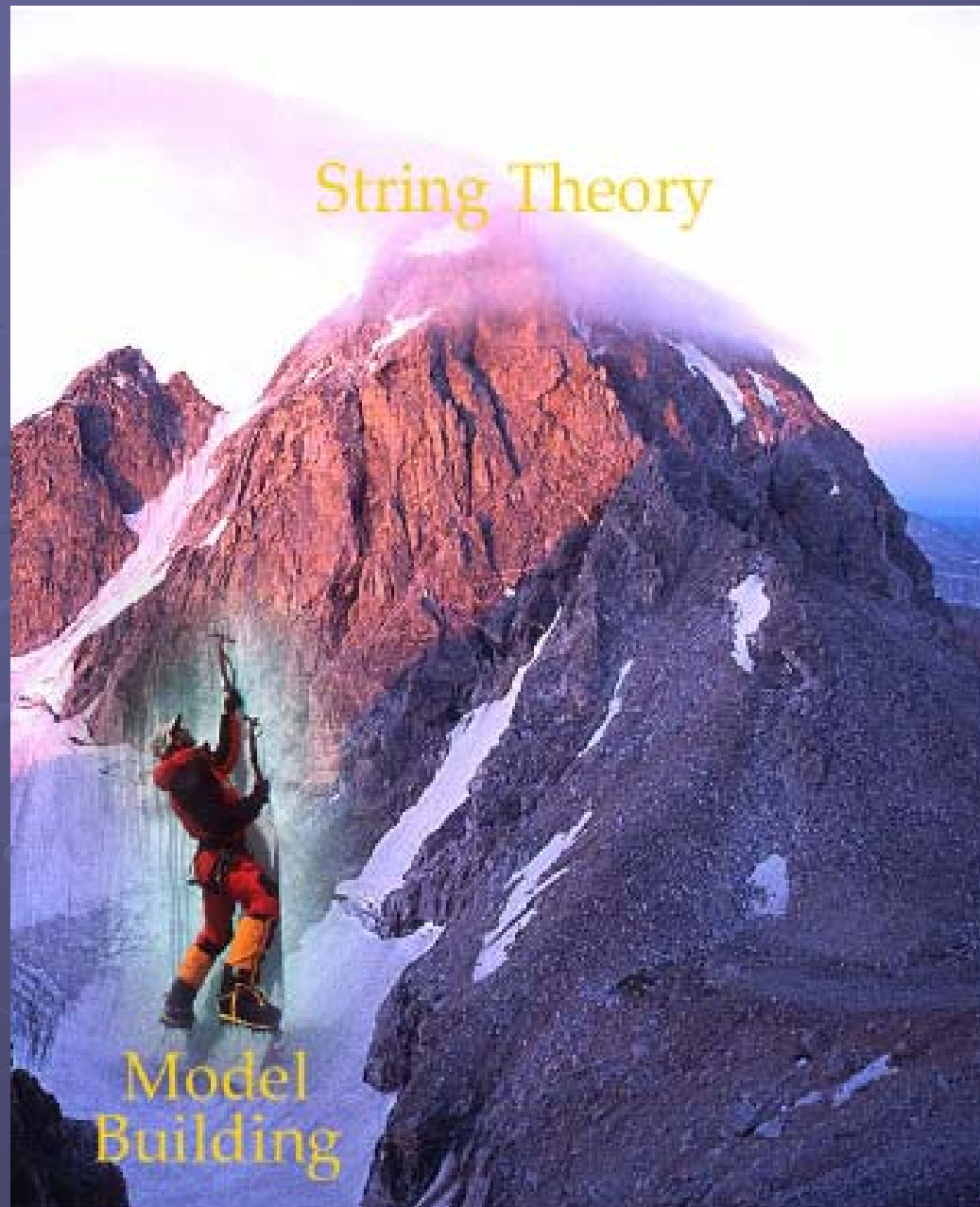
- High-energy physics covers an enormous range of energies
- At the highest energies, we need a theory of quantum gravity—a theory that includes quantum mechanics and general relativity
- String theory, in which the fundamental ingredients are oscillating, vibrating strings, is the leading candidate



Lower Energies?

- At lower energy scales, there are physical phenomena that we can study experimentally
- Understand basic elements of matter and their interactions
- New ideas might provide deeper connections among known physical quantities: masses, forces
- These are theories we can experimentally test

The best route?



Model Building:
adventure travel
through world of
ideas

Extra Dimensions One Route?

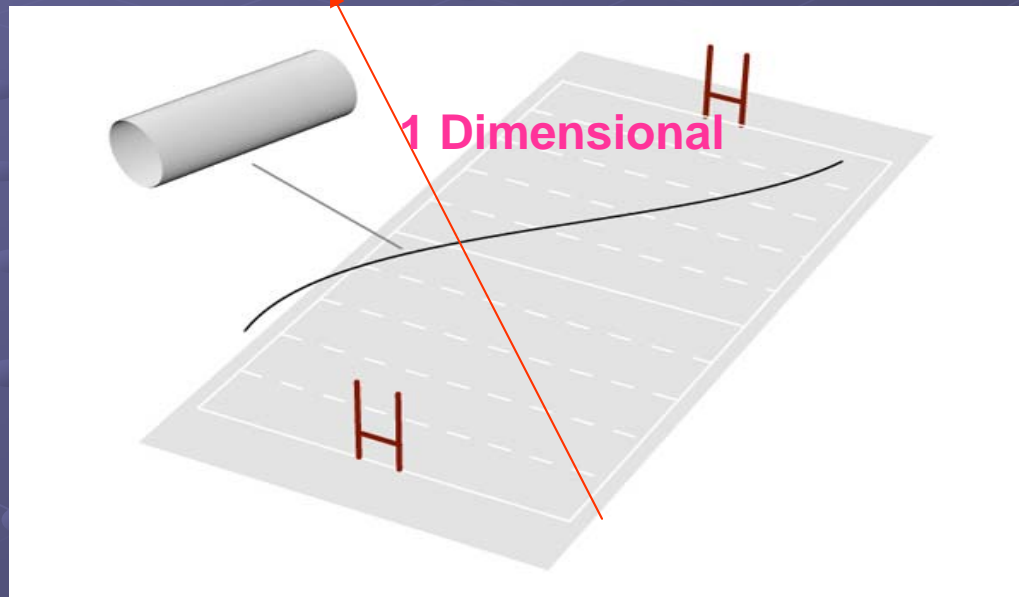
- String theory: extra dimensions essential
- Lower energies: Extra dimensions can illuminate connections among observable phenomena in new ways
- They are after all a possibility from perspective of general relativity
- Plus:
- Bonus: Even shed light on purely four-dimensional physics

Extra Dimensions in Physics

- Theodor Kaluza proposed extra dimensions in 1919
- Einstein (referee) delayed publication for two years
- Interesting idea, but what makes the other dimension different?
- Old answer: Extra dimensions can be rolled up to a tiny size
- ❖ But Also New Answers...

Hose Across Football Field

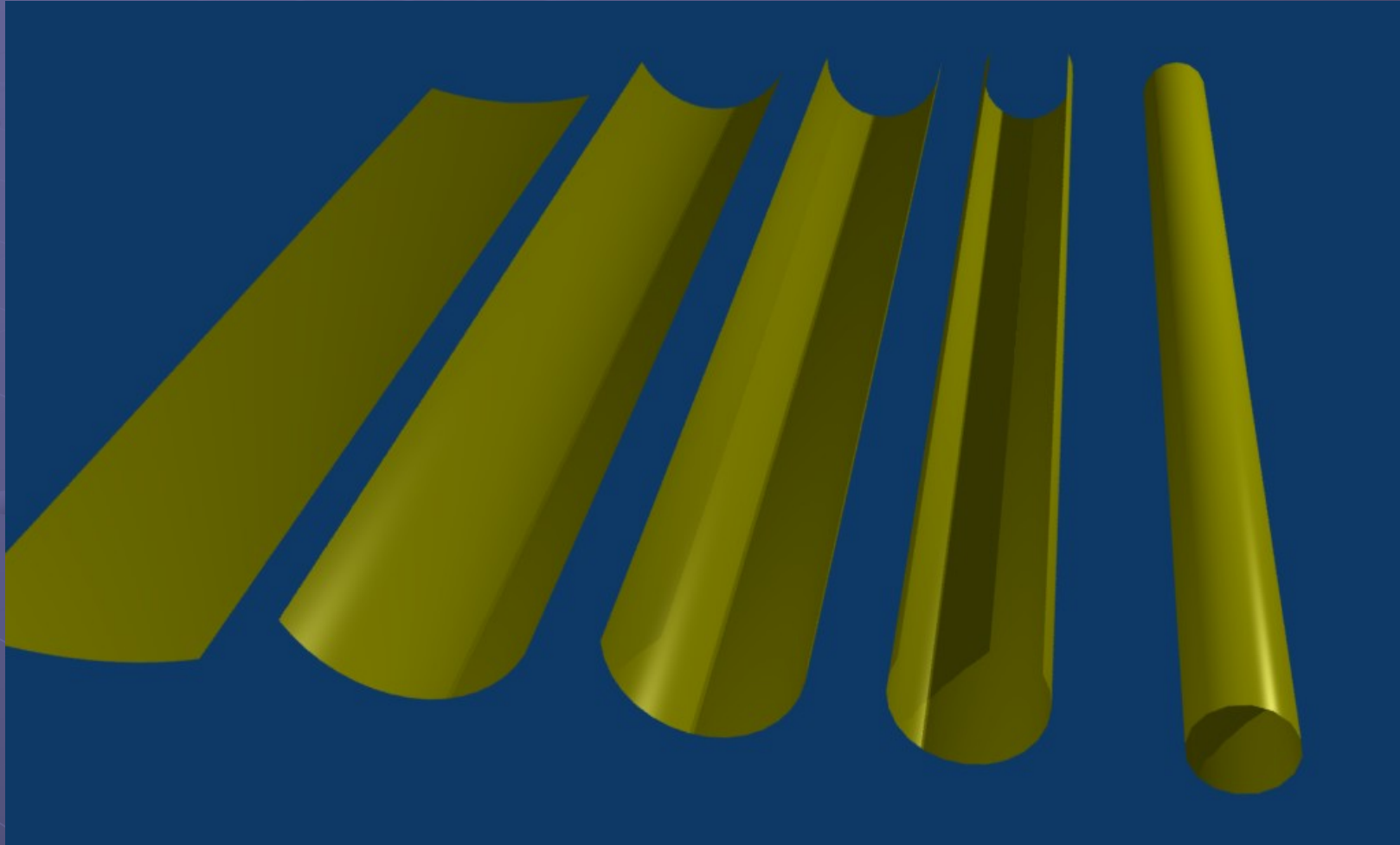
Oskar Klein proposed idea that dimension is rolled up in 1926
If a dimension is wound sufficiently tightly you won't see it



Can see 2D or 3D with small probe

Very intuitive; if sufficiently tiny, it doesn't look like it's there

Curled-up Dimension

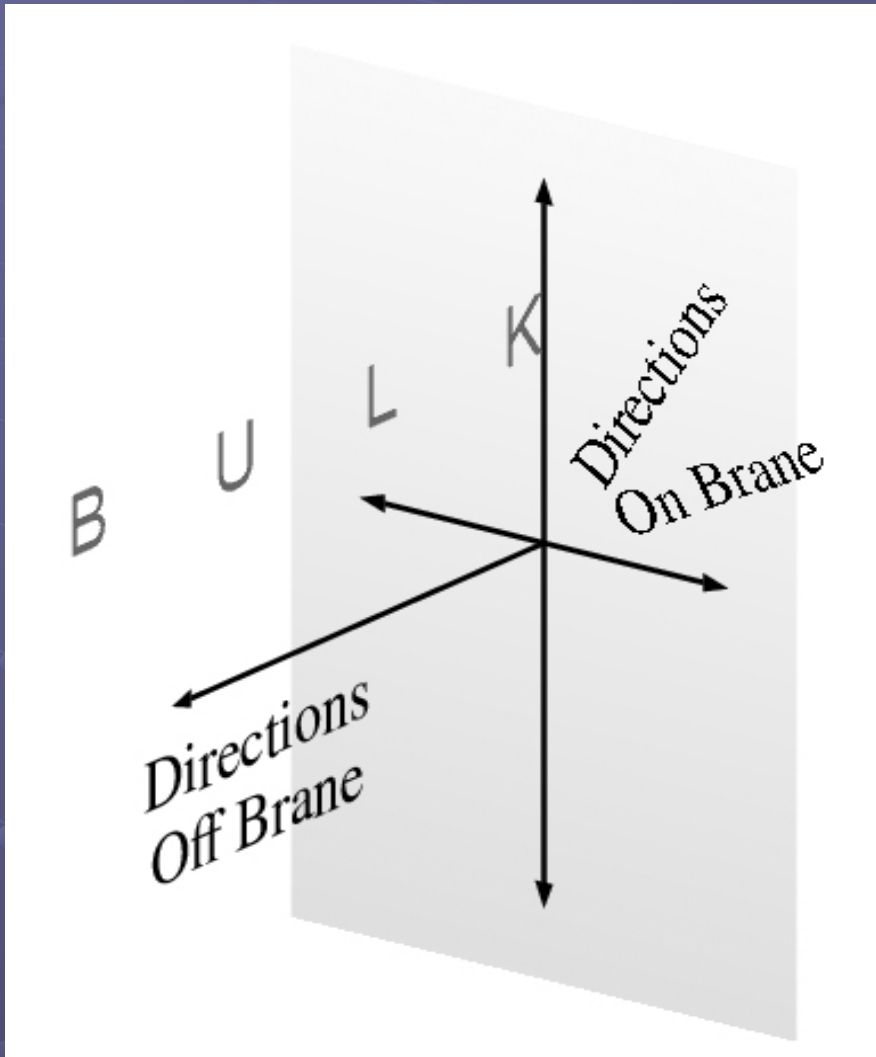


New (1999) Way to Hide Dimensions

Based on an important ingredient in “string” theory whose importance was only recently recognized

- **BRANES**
- Membrane-like objects in higher dimensional space
- Play an essential role in string theory

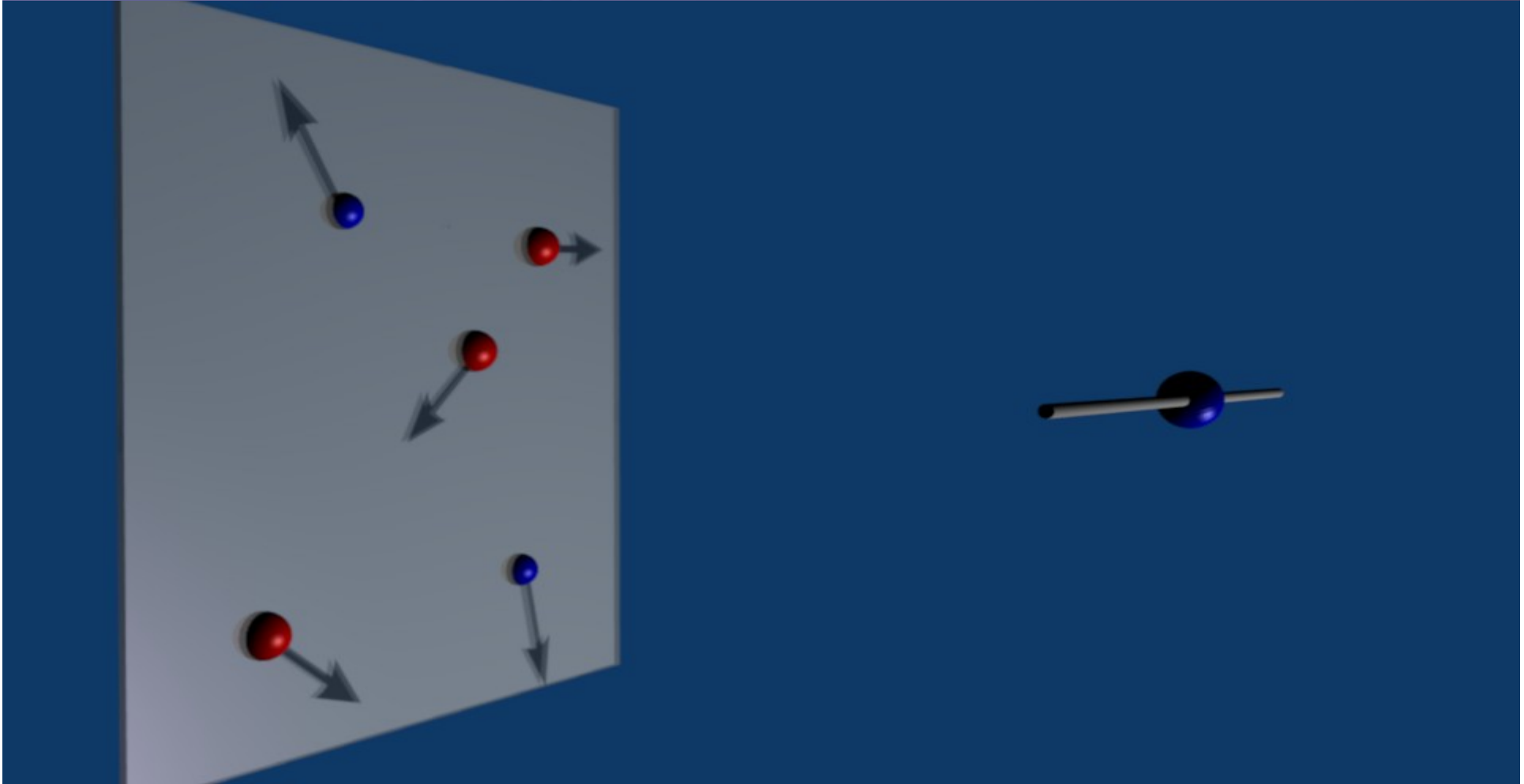
What's New? Branes



Branes:

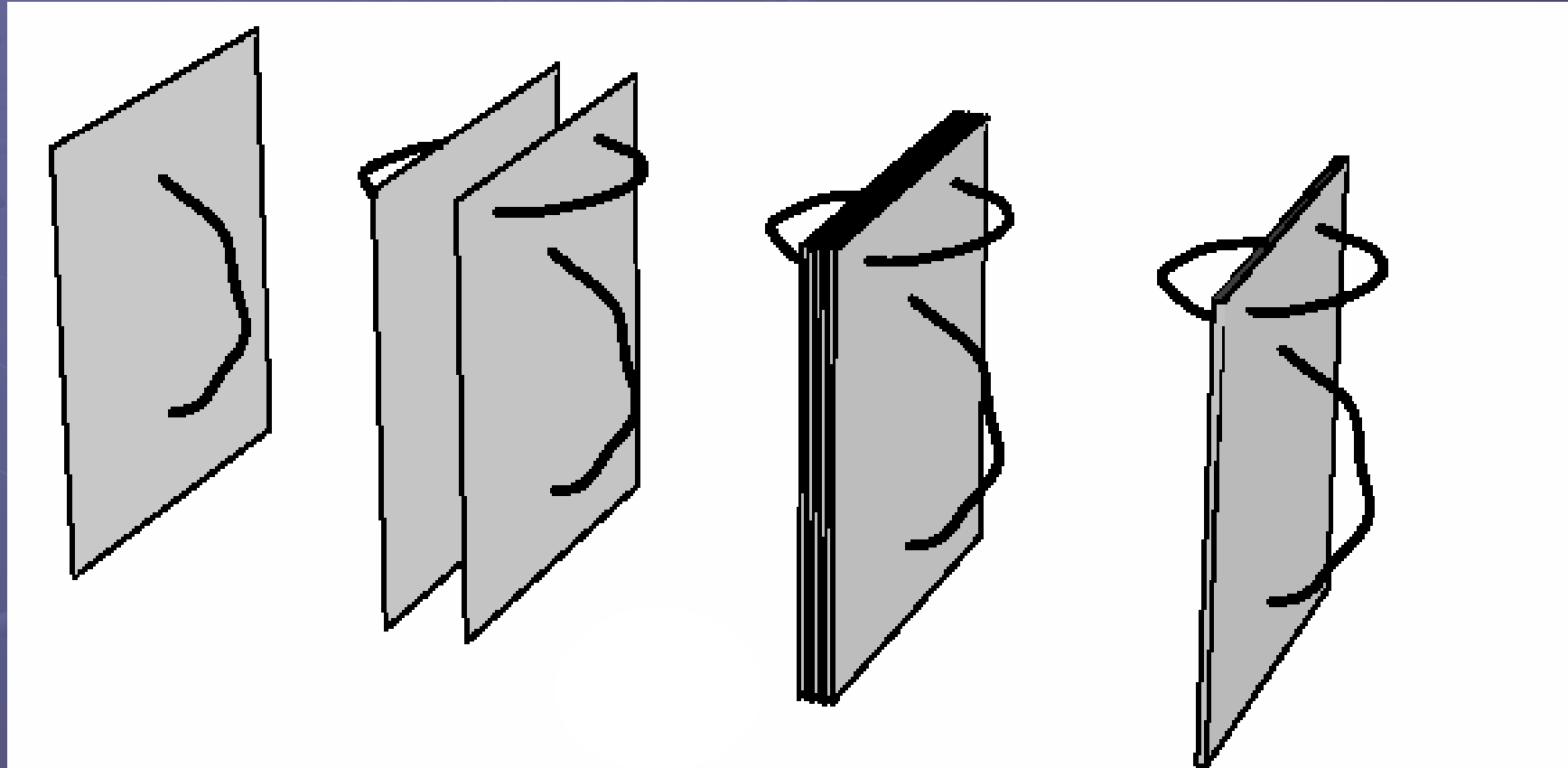
Distinguish
dimensions
along a brane
from those
perpendicular to
it

Branes can trap particles and forces



Particles stuck on a brane like beads on a wire

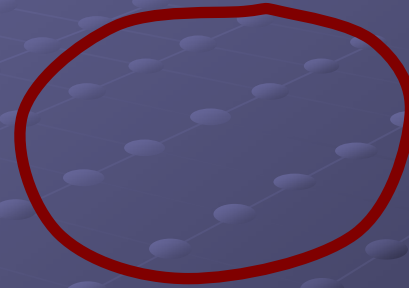
D-Branes: Where Open Strings End



Particles and forces stuck on branes—not gravity!

Why not gravity?

- Gravity ---closed string:
no ends!

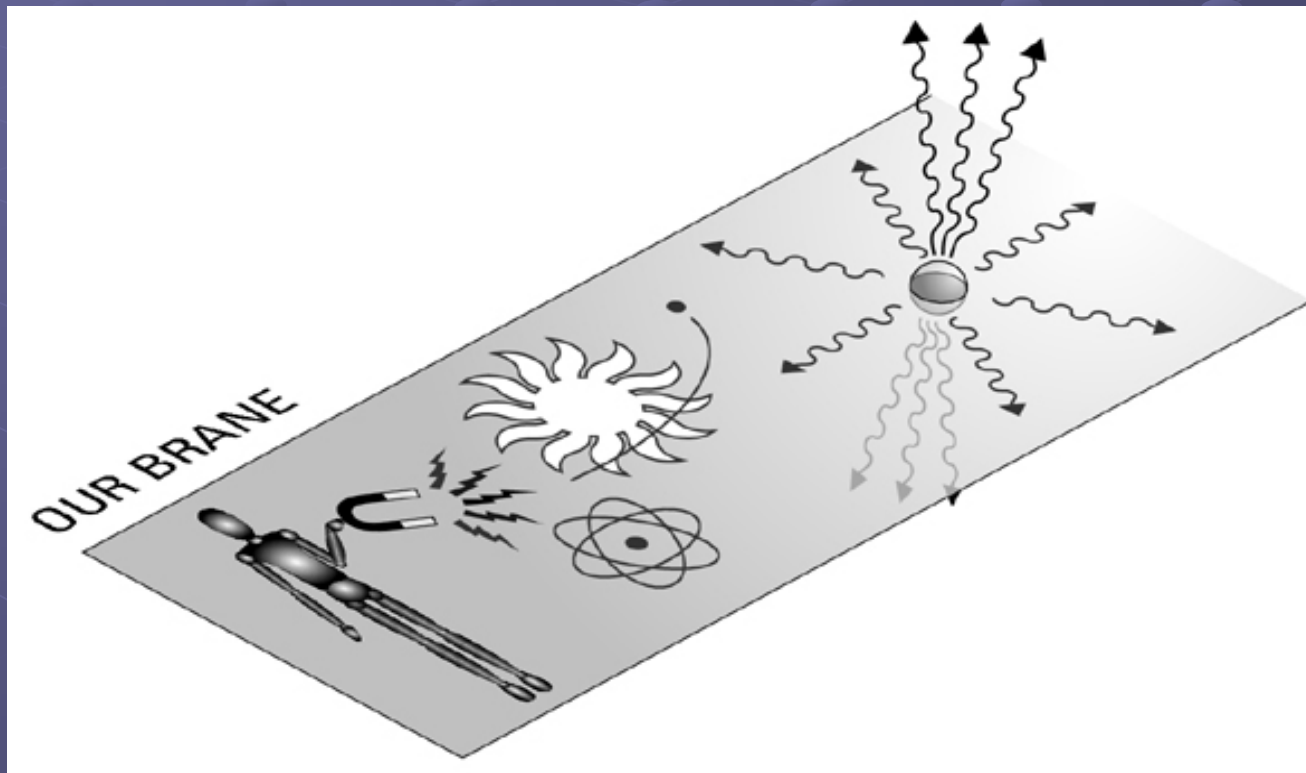


- Energy: all energy
interacts via gravity

- Geometry: gravity
connected to spacetime

Braneworld

Higher-dimensional world in which particles and matter are stuck on a brane



Drawn as
2D

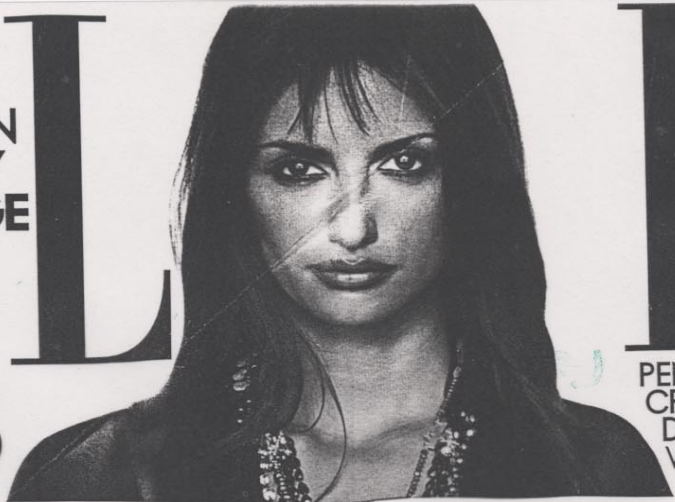
Really 3D

And really
infinite

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E L L E

HOW YOU CAN REALLY CHANGE YOUR BODY



PENÉLOPE CRUZ ON DAMON VS. DEPP

FALL'S NEW VINTAGE CLASH

FA... READ FOR ACTIVE SPORTS STARS SEXY STYLE

SCAND CITY: IN RAPE CO

MARK LEYNER OFFERS A PRIMER ON BUSH WHACKING

The other day, as I sat in my car in a Home Depot parking lot and waited for my friend Eugene to pick up joint filler and some lime putty, I began sketching out the kind of ad campaign I believe Al Gore needs to conduct in order to make people afraid of George W. Bush. The man evinces an aura of utter innocuousness, which could make him almost impossible to beat. Innocuous candidates are notoriously lethal. W.'s not intellectually intimidating or sexually predatory, there's no guile, no insidious agenda, et cetera. Even his occasional flashes of belligerence seem born more out of insecurity than anything else, an insecurity that many people find appealing.

Al Gore, on the other hand, does frighten some people. Imperturbably articulate, with rigidly precise gestures, there's an eerie, wind-up-key-in-the-neck quality. The male preying mantis, having been decapitated by its mate, continues to copulate with undiminished vigor. One can easily imagine the headless body of Al Gore still gesticulating at a podium or avidly shaking hands in some lavishly catered tent in pursuit of soft money.

The gist of my advice to Gore was that if he has any hope of winning in November, he must twist W.'s putative assets into, if not terrifying, at least anxiety-provoking liabilities. And he can't go after his actual weaknesses, e.g., his famous aphasia, which people find charming. Nor would it be wise to hammer W. on the whole intellectual-lightweight thing. It would be easy to simulate a scene in which, at a news conference, a reporter for, say, *Scientific American* asks W. if he agrees with superstring theorists who contend that the universe is one of many bubbles floating inside a ten-dimensional hyperspatial megaverse. W. would, of course, redden and aver indignantly that "people know what's in my heart." But this would invariably backfire and

only engender more sympathy for Bush as the Anti-Wonk. No, you need to take those of W.'s attributes that are most familiar and most appealing, extrapolate from the factual record, and go totally reductio ad absurdum. Computer-generated imagery, digitally manipulated documentary materials, portentous montage with voice-over, et cetera.

● **Re: W.'s filial devotion.** W. holds his dad in awe, viewing Bush père as a godlike figure. To dissonant twelve-tone music, run a montage of other tightly bonded father-son politicians: Saddam and Uday.

Make sure W. mistakenly refers to Osama bin Laden as Oksana Baiul.



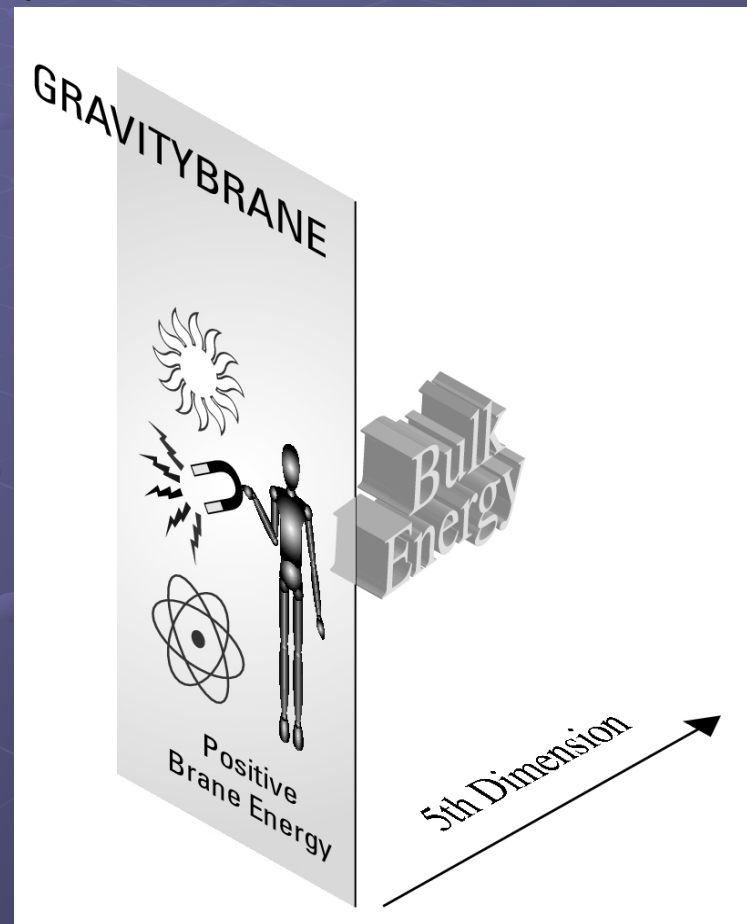
With branes, we've found warped geometry

Solutions that provide:

- New way to hide dimensions
- New way to explain weakness of gravity
- New concept of our place in the universe

RS2 Braneworld— New way to hide a dimension

(LR with Raman Sundrum)



Extra dimension can be infinite in size! Spacetime is warped and gravity stays near the brane.

Localized Gravity: Warped Geometry

We solved equations for gravity and according to Einstein's General Relativity

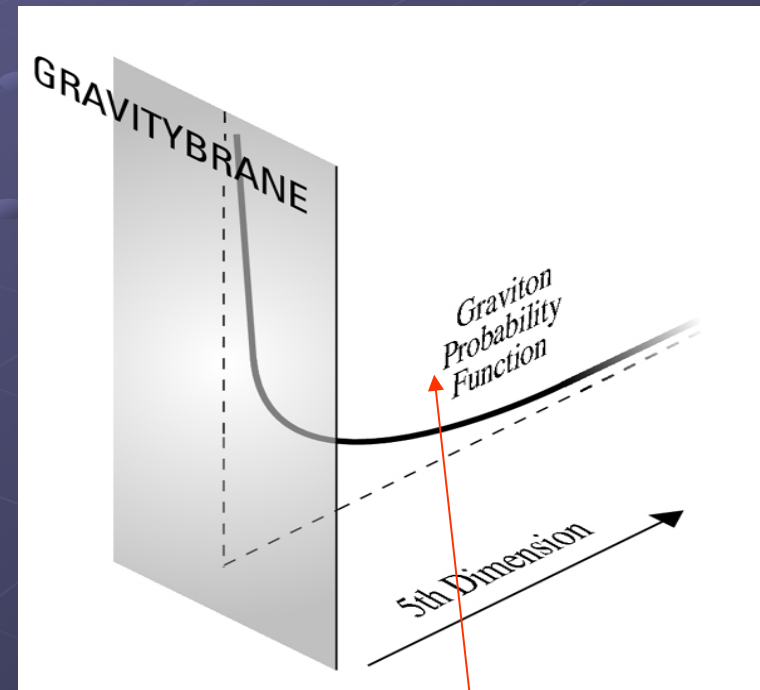
All of spacetime is warped

Gravity is concentrated near the brane

$$ds^2 = g_{MN} dx^M dx^N = e^{-2\sigma} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2,$$

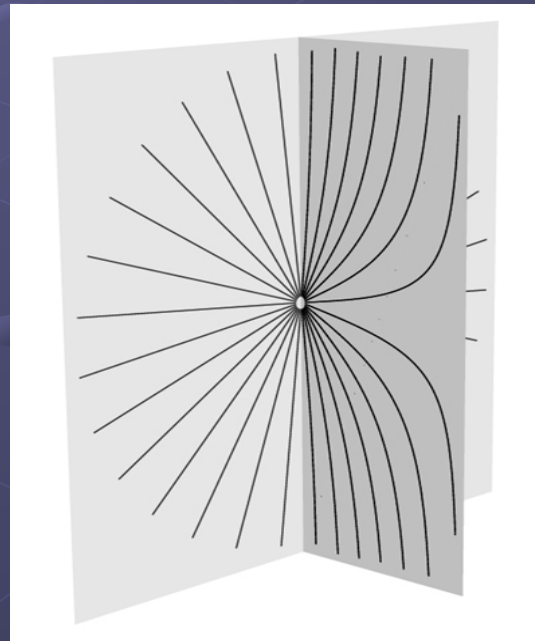
$$\sigma = k|y|$$

Tiny probability for gravity to leak away from brane



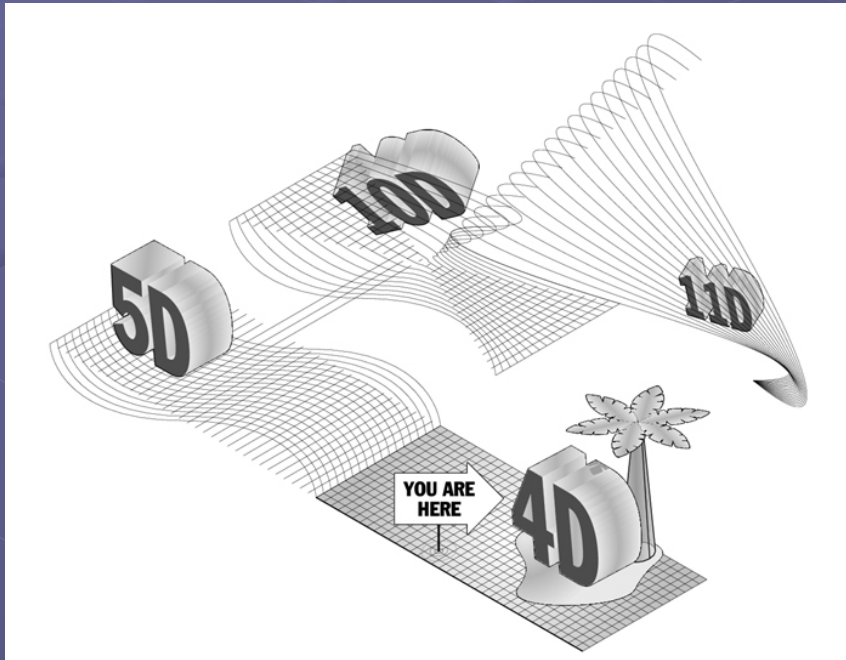
Gravitational Field Near Brane

- Force spreads very asymmetrically
- Lines of gravitational force almost parallel to brane
- Gravity doesn't leak into extra dimension as you would expect without warping
- Localized gravity: new way to hide dimensions



- Extra dimension can be infinite in size
- Without us knowing about it
- Because warped gravity spreads out in only three spatial dimensions
- ---Not four (really, tiny amount in fourth)
- **Alternative to rolled-up dimension!**

Even More Dramatic: Locality of Four Dimensions



- Why should you need to know about space far from the brane?
- With Andreas Karch, found four-dimensional gravity near the brane
- But higher-d everywhere else
- Four-dimensional sinkhole

Exciting but frustrating

- Could exist something as dramatic as an infinite extra dimension, pockets of lower-dimensional space, but we wouldn't know it!
- Can a warped extra dimension be tested?
- Yes, if connected to Particle Physics

Hierarchy Problem: One of the biggest puzzles in particle physics

- Why is gravity so weak compared to the other elementary forces?



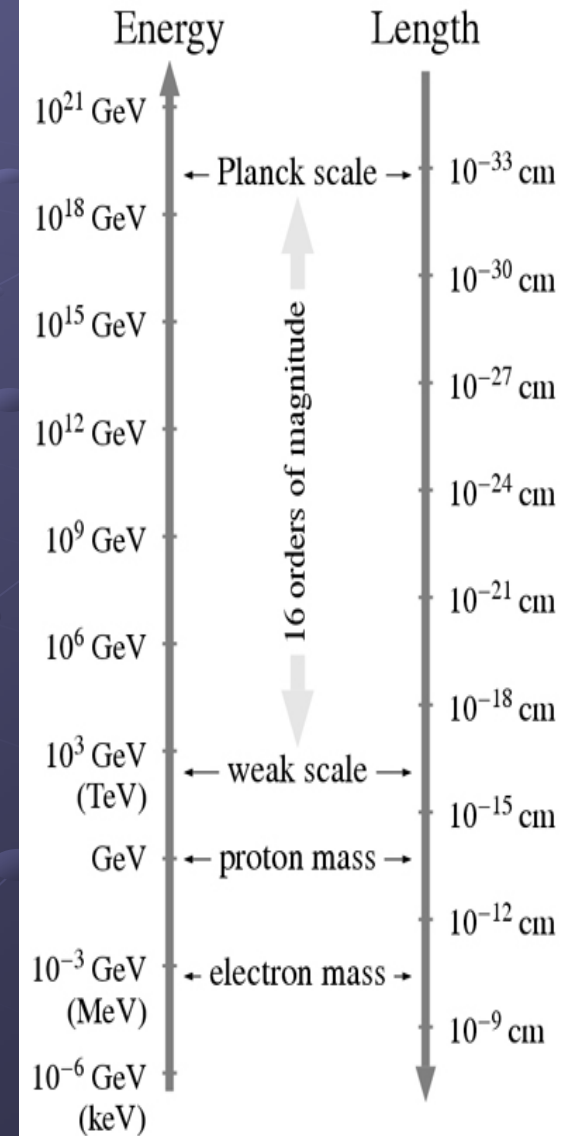
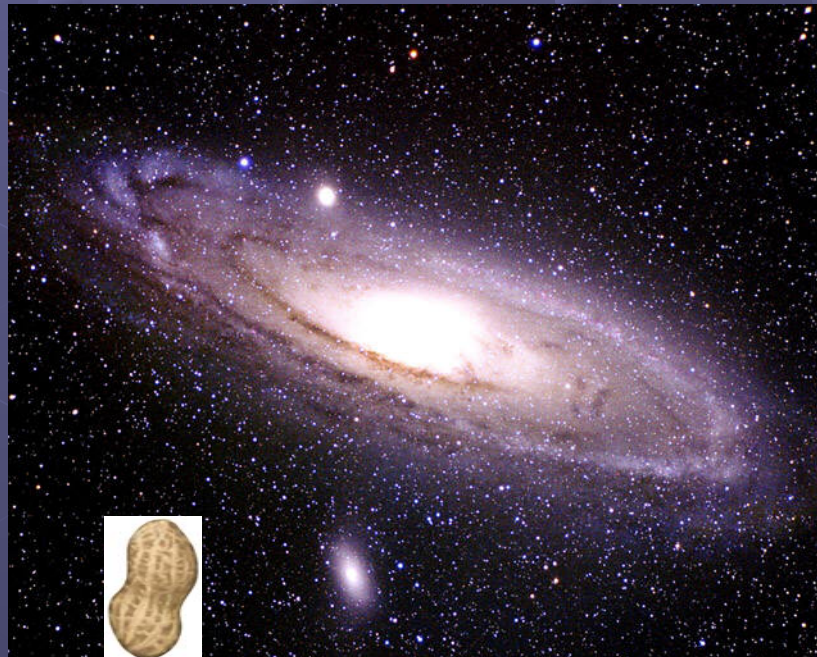
Might not seem weak but magnet can take on the entire Earth-

Hierarchy Problem

Need “fine-tuning” to get very different masses

Key issue in particle physics today

One that will be resolved at LHC



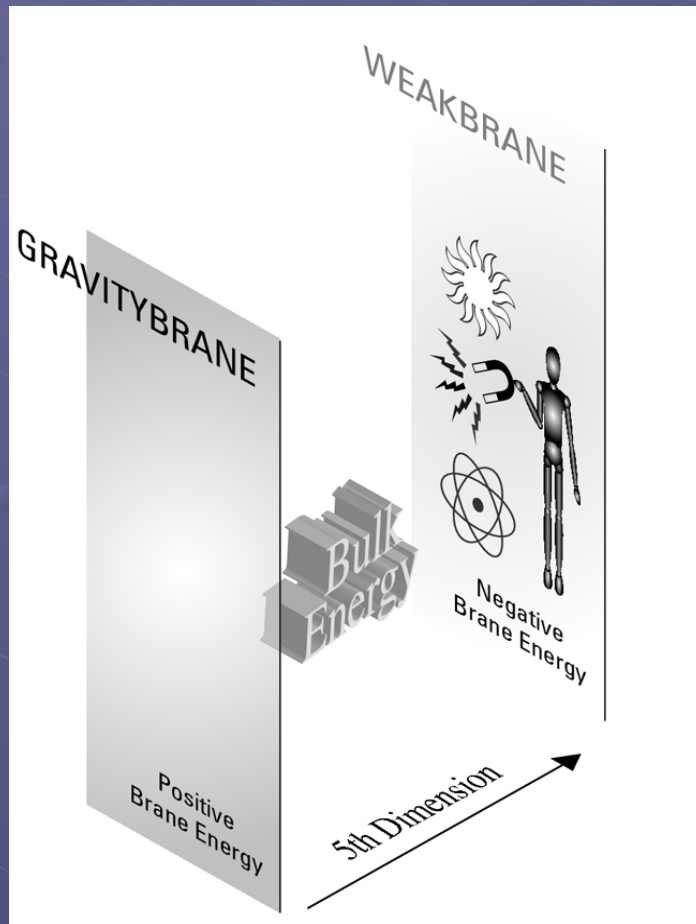
“Fine-tuning” is unlikely:
No artist so we need an
explanation



Barnett Newman: *Broken Obelisk*

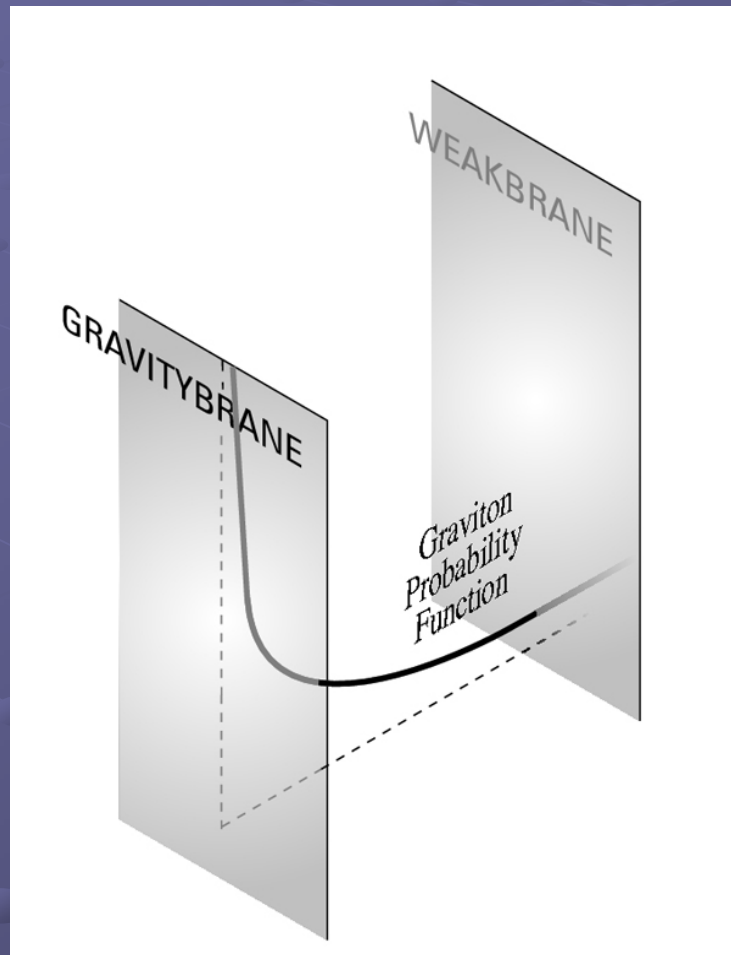
RS1 “Multiverse:”

Warped Spacetime Geometry Like Before



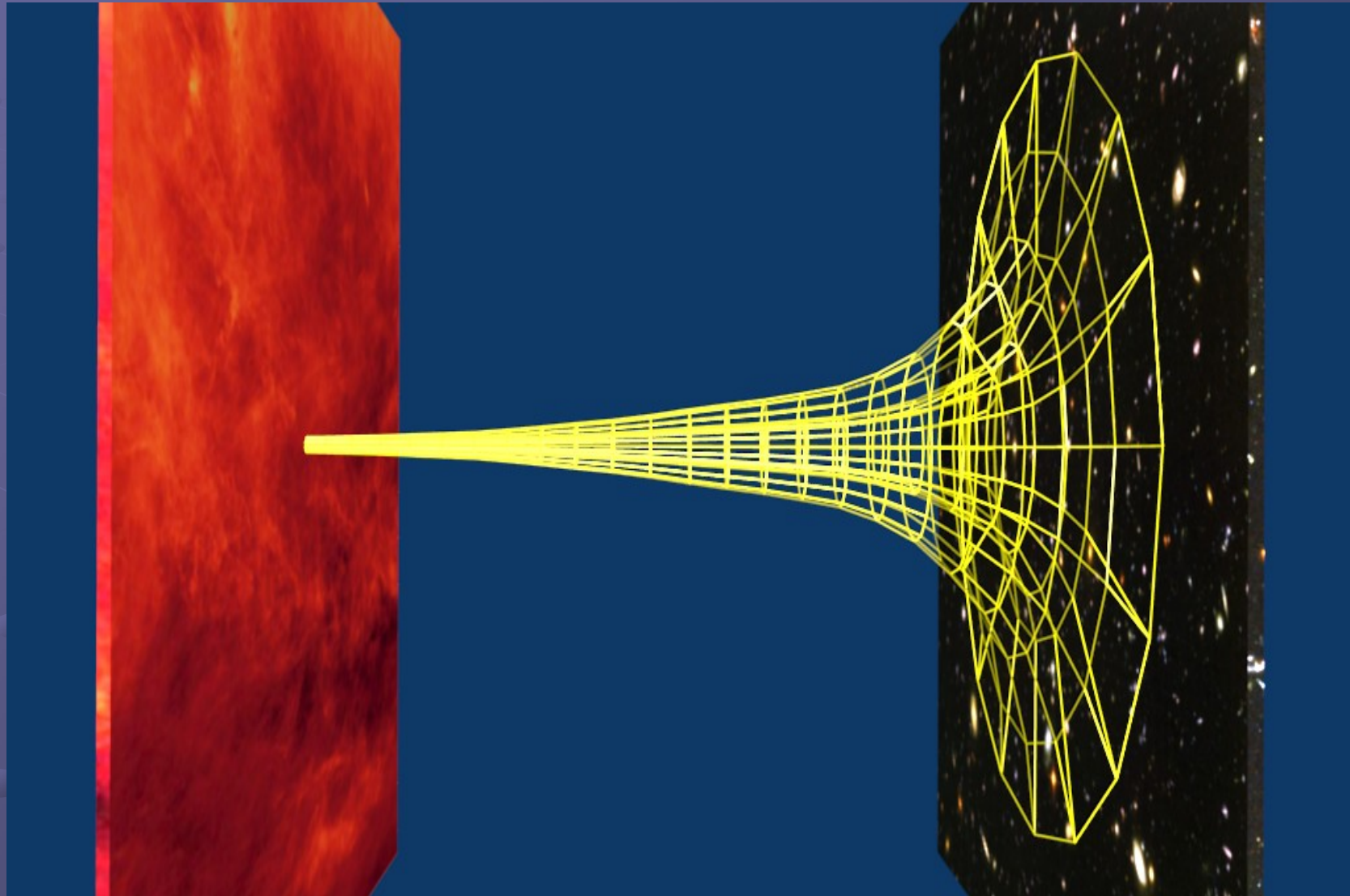
- Now two branes
- Gravity still concentrated on Gravitybrane
- But we live on a second brane:
- The Weakbrane

Natural for gravity to be weak!

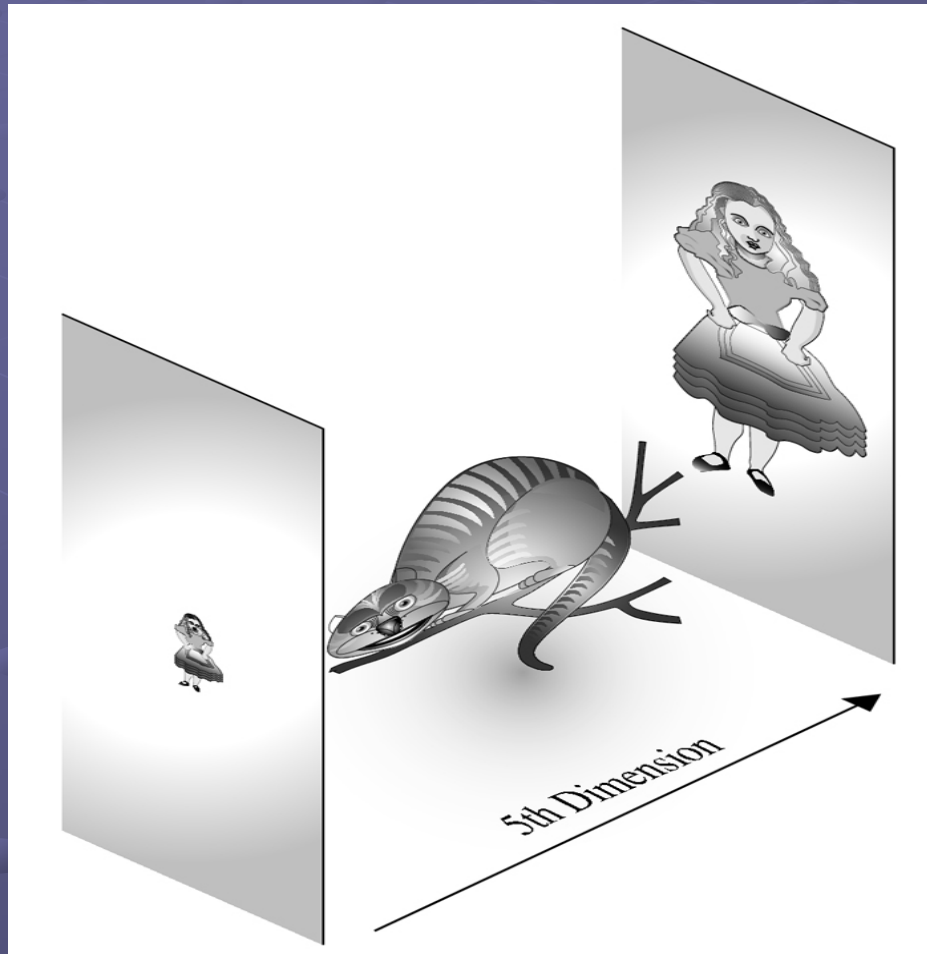


- If we live anywhere but the Gravitybrane, gravity will seem weak
- Small probability for graviton to be near the Weakbrane
- Natural consequence of warped geometry

Rescaling Across Fifth Dimension



Everything rescaled in warped geometry!

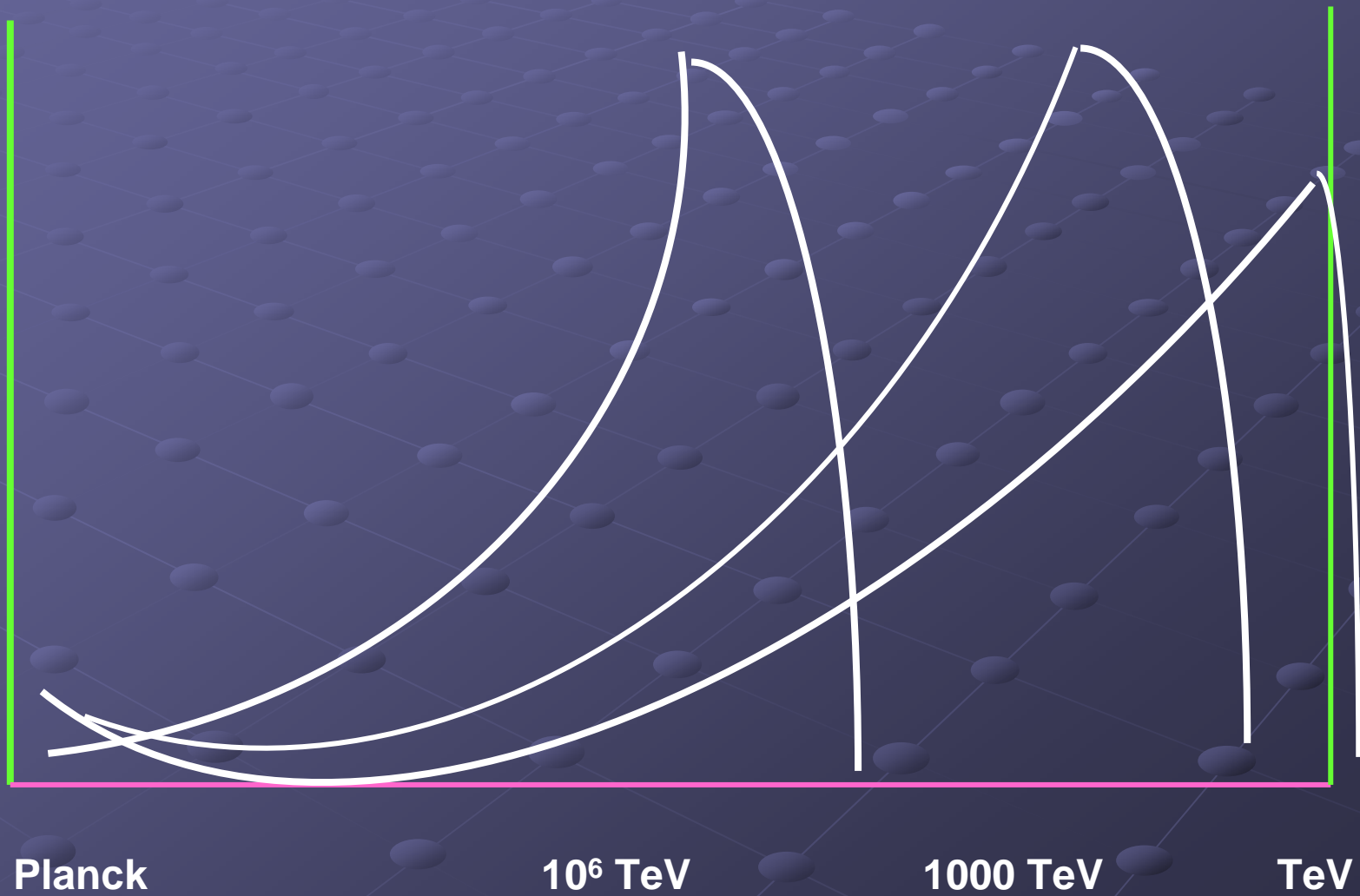


Can understand weakness of gravity as things being bigger and lighter on the Weakbrane

What rescaling means:

- Anything on or near the Weakbrane has
- Order TeV-scale mass
- Anything localized in the bulk has
- Correspondingly exponentially bigger mass
- On Gravitybrane-back to Planck-scale masses

Particles in bulk



Experimental Tests?

- Connection to mass and weakness of gravity relative to other known forces tells us
- LHC will have the right energy to search for consequences of this theory
- Anything on the Weakbrane should have roughly TeV energy/mass
- Many modes on the TeV/Weakbrane

KK Particles: Weak Scale Fingerprints of Extra Dimensions

- With extra dimensions, there are new **Kaluza-Klein (KK)** particles
- Travel and carry momentum in extra dimensions
- Look to us like particles with mass characteristic of the extra-dimensional geometry

KK modes of graviton

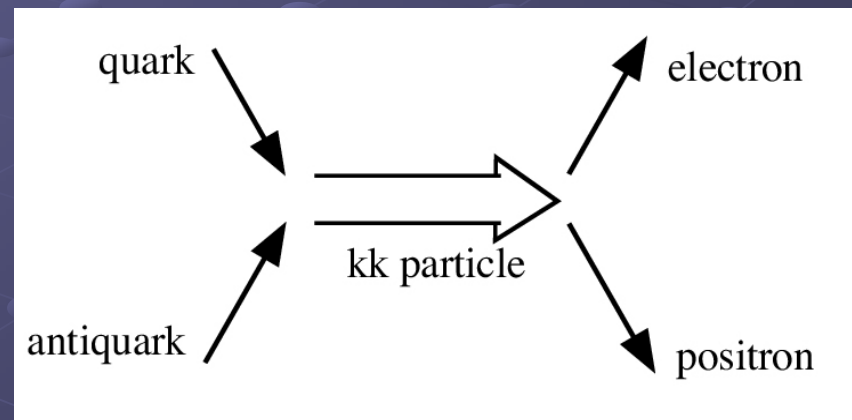
- In RS1, KK spectrum very distinctive
- TeV, 2 TeV, 3 TEV (rough) spectrum
- With much stronger than gravitational interaction strength!
- Interaction strength is warped too!
- Not $1/M_P$
- Instead, $1/\text{TeV}$

Implications

- If you produce a KK mode of the graviton
- Not just missing energy!
- Mode decays inside detector—just like most other heavy particles we hope to discover
- ✓ Means we can reconstruct mass, spin (we hope!)
- ✓ Would be first genuine signature of quantum gravity
- ✓ Graviton itself too weakly interacting to detect directly
- ✓ Not true for its KK modes!

Experimental Signal: Can search for extra dimensions!

- Kaluza-Klein particles
- Definite mass spectrum and “spin”-2
 - Truly different than other strongly interacting theories
 - Light spin-2 but gap
 - No other strongly interacting states as light



collider signals would be dramatically different

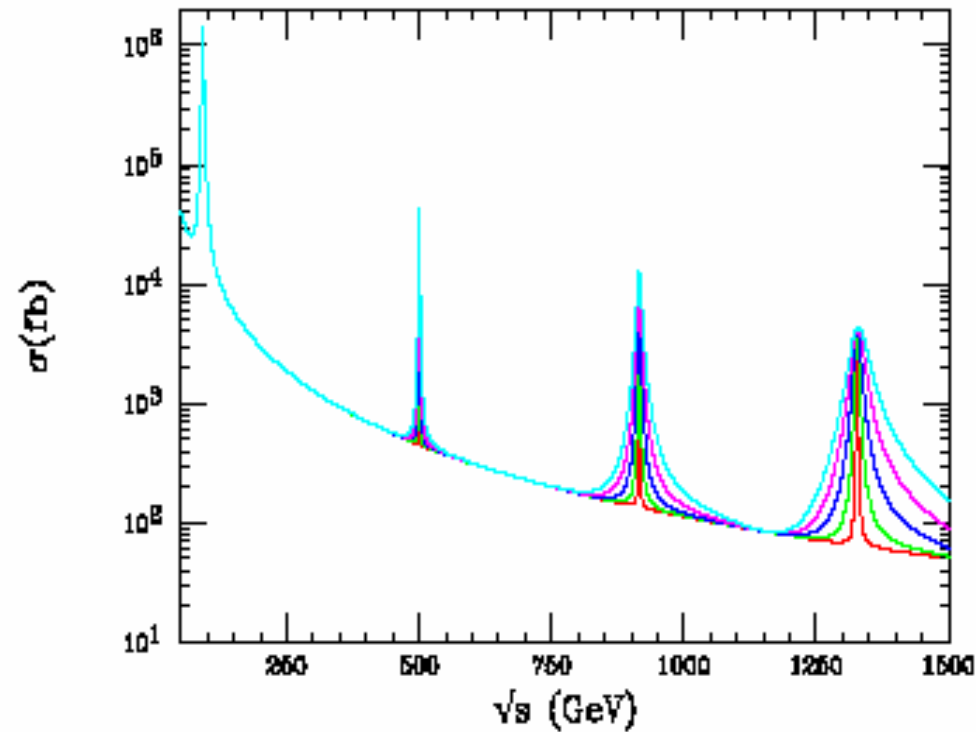


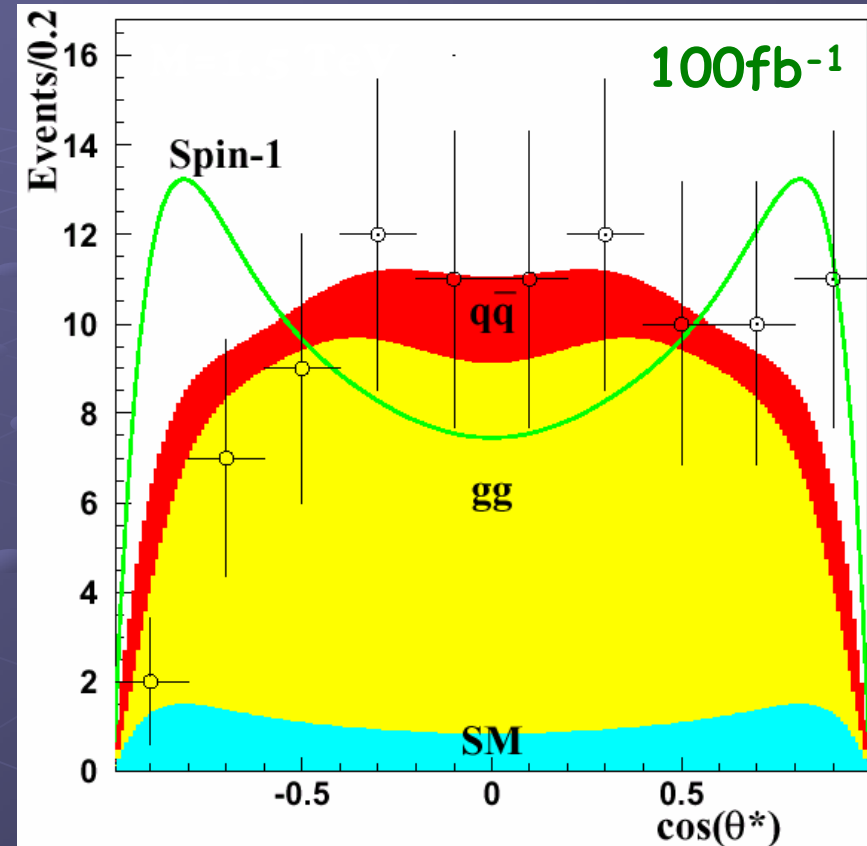
Figure 4: The cross section for $e^+e^- \rightarrow \mu^+\mu^-$ including the exchange of a KK tower of gravitons in the Randall-Sundrum model with $m_1 = 500$ GeV. The curves correspond to k/\overline{M}_{Pl} in the range 0.01 – 0.05.

H. Davoudiasl, J. Hewett, T. Rizzo

graviton has spin 2

Angular distributions

- $qq \rightarrow G \rightarrow ff: 1 - 3 \cos^2 \theta + 4 \cos^4 \theta$
- $gg \rightarrow G \rightarrow ff: 1 - \cos^4 \theta$
- $qq \rightarrow G \rightarrow VV: 1 - \cos^4 \theta$
- $gg \rightarrow G \rightarrow VV: 1 + 6 \cos^2 \theta + \cos^4 \theta$
- DY background: $1 + \cos^2 \theta$



- If RS1 solves the hierarchy problem, we should be able to tell

- And if we are very lucky, **five-dimensional black holes and string states** might also appear

- LESSON 1: RS1 gives clean TeV-KK-graviton

- Spin-2 and Gap in spectrum definite indication of warped extra-dimensional geometry

- Lots of strongly interacting TeV-scale physics to complement this measurement

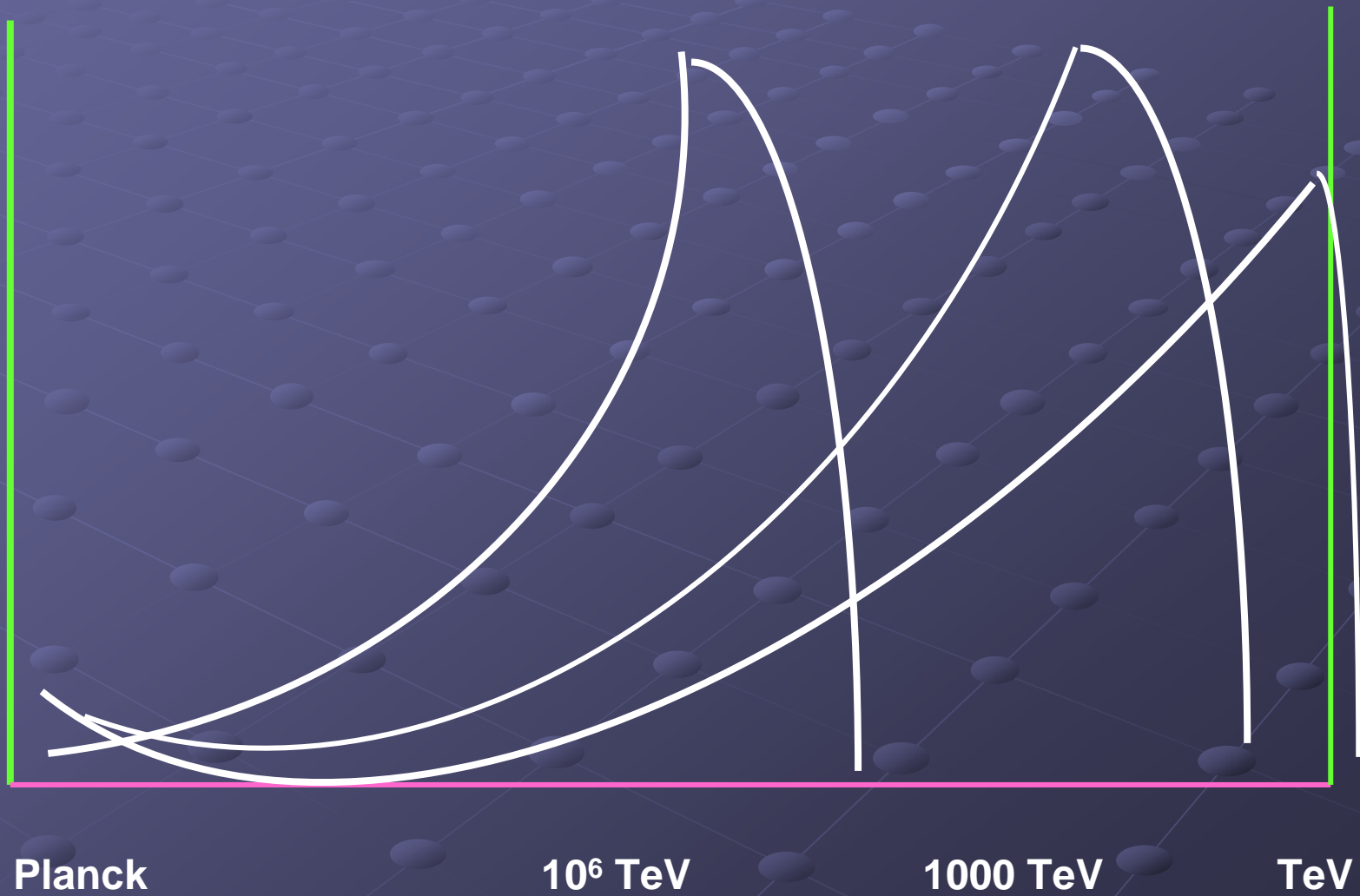
Other warped scenarios addressing the hierarchy?

- RS1 isn't the only scenario: variations interesting
- Depends on whether particles on brane or in bulk
- Two key features that make bulk matter possible
 - Size of fifth dimension extremely small (only about 30 times fundamental scale—exponential hierarchy)
 - ❖ Means you can have gauge bosons in the bulk
 - ❖ Coupling won't be too weak
 - You only need Higgs on the Weakbrane to address the hierarchy
 - ❖ Problem only for the Higgs scalar: gauge boson and fermion masses are protected

Suggests new scenarios

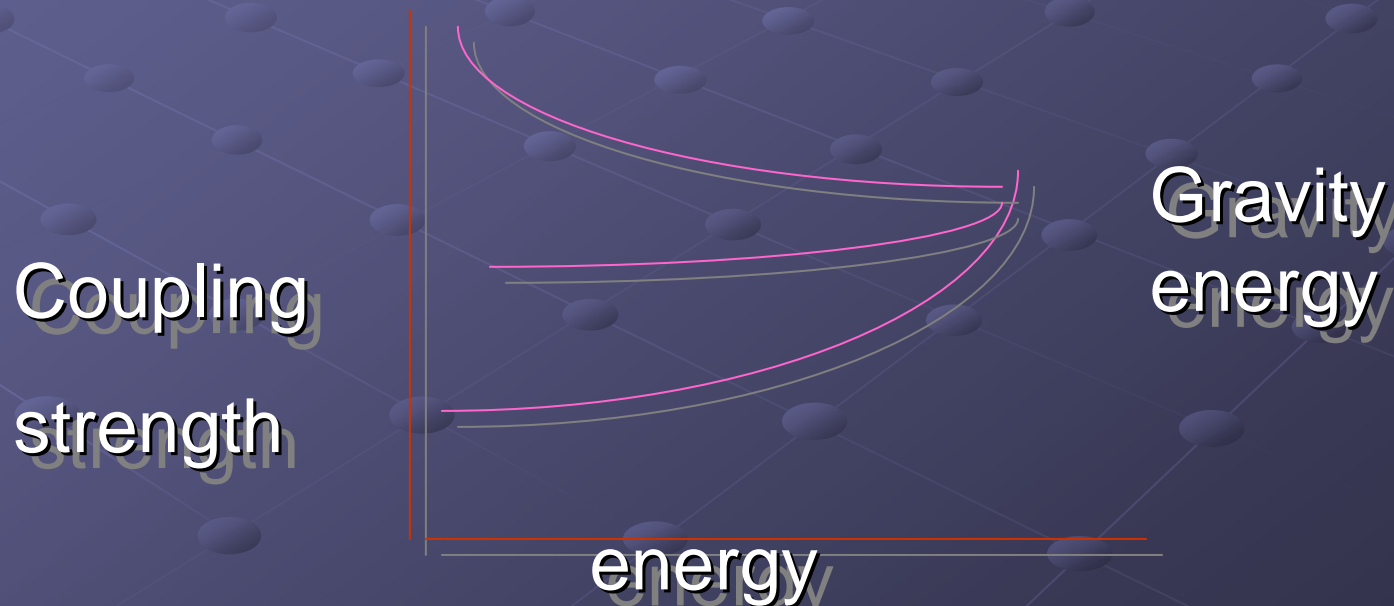
- Fermions and/or gauge bosons can be in the bulk
- Because **5D** cut-off is Planck scale
 - ✓ Allows for unification!
- Allows for interesting model-building:
 - ✓ Fermion masses from wavefunction overlap with Higgs field (on Weakbrane)
- **Bulk scenarios have distinctive signatures**

Particles in bulk



Bulk Unification

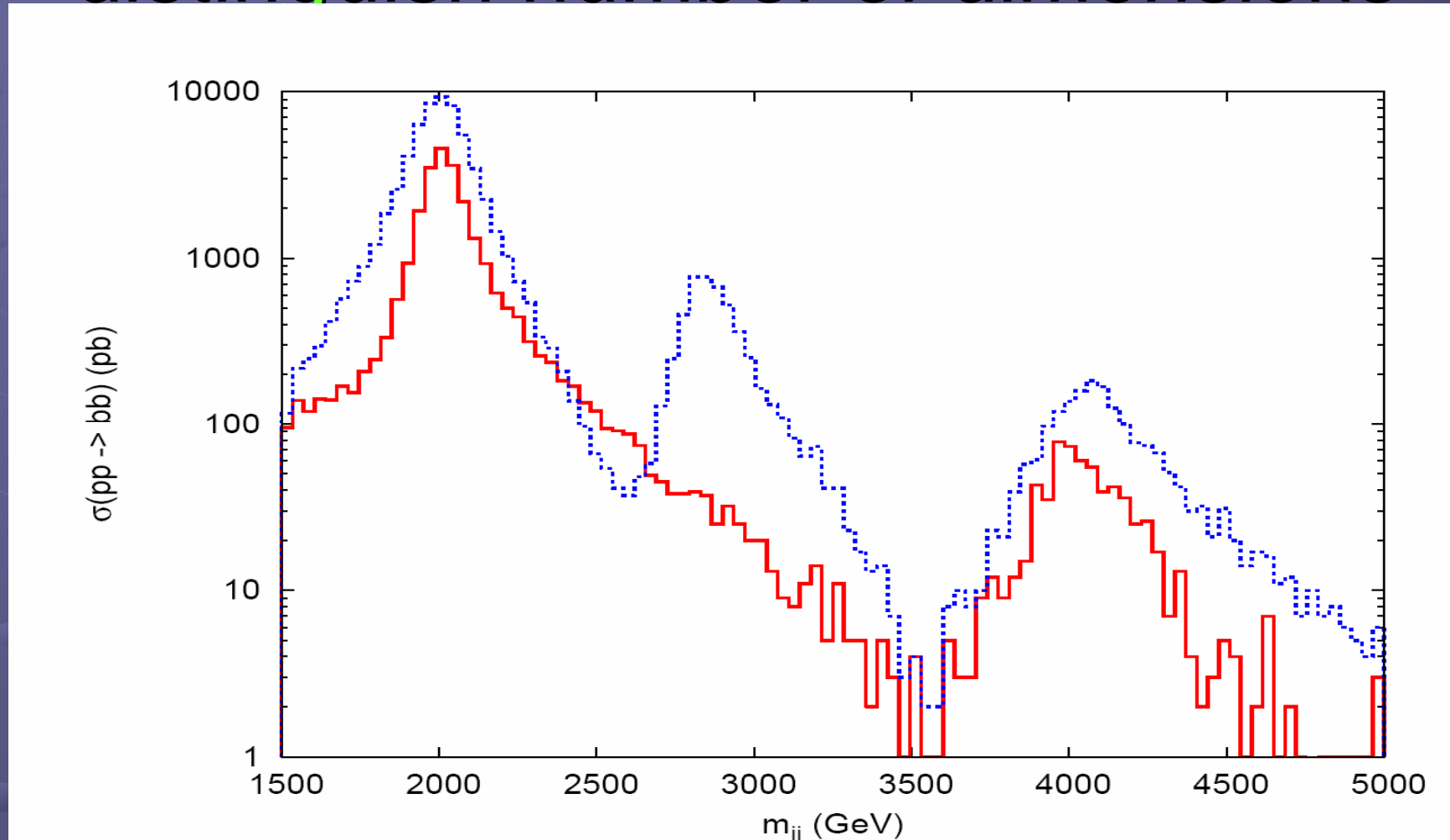
- Net contribution from all modes
- Gives *logarithmic* running
- From TeV scale to Planck scale
- LESSON 2: very natural to have unification



Phenomenology?

- Bulk gauge bosons
- Means KK modes of weak bosons,
- gluons as well as gravitons
- Resonances with strong force interactions for example

Can find gluon KK modes and distinguish number of dimensions



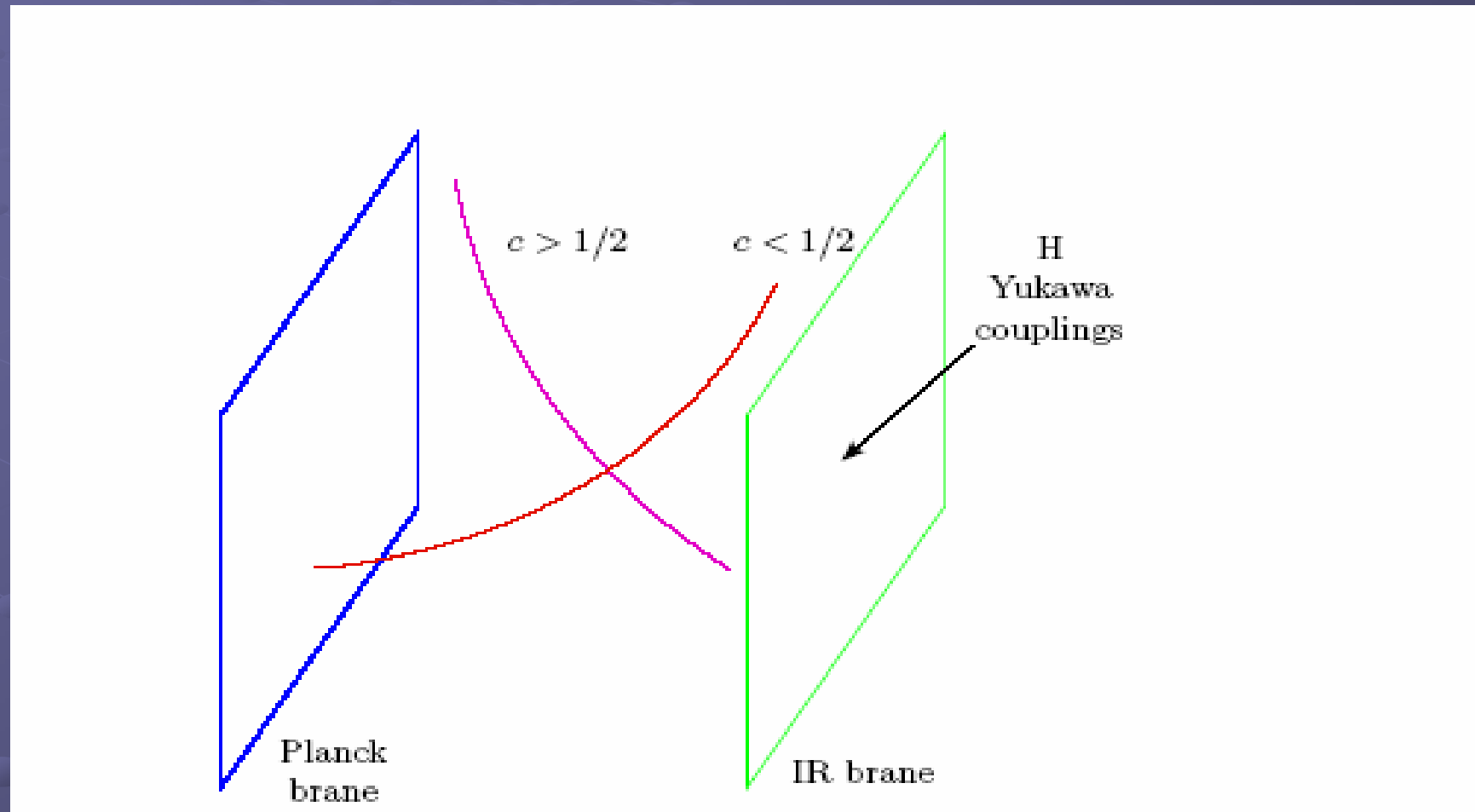
LESSON 2: Resonances have more
Info than we've explored yet

LR with Ben Lillie, Liantao Wangh

Precise signatures depend on fermion wavefunction profiles

- Might expect nontrivial profiles
- Masses depend on overlap with Higgs
- Expect light fermions localized near Planck/Gravity brane
- Top, bottom near Weakbrane

Fermion Profiles and Masses



Dual Interpretation of Warped Scenarios

- RS phenomenology has dual 4d strongly interacting conformal field theory interpretation
- Roughly, between Planck scale and TeV scale, CFT
- At TeV scale, CFT spontaneously broken
- Gives rise to composite states
- Which states are composite depends on details of wavefunction
- Those localized near TeV/Weak brane are more composite
- Those localized near Planck/Gravity brane are less composite

Signatures of Partial Compositeness

- Higgs (longitudinal modes) couplings to electroweak gauge bosons are enhanced

$$\begin{aligned}
 W_{long.}, Z_{long.}, \text{ and } W_{long.}, W_{long.} &\xrightarrow{g\sqrt{k\pi r_c}} W^{\pm(n)}, Z^{(n)}, \tilde{W}^{\pm(n)}, Z'^{(n)} \\
 &\xrightarrow{g\sqrt{k\pi r_c}} W_{long.}, Z_{long.}, \text{ and } W_{long.}, W_{long.}
 \end{aligned}$$

- Long W , $t_R \rightarrow b_L$ KK resonances
- Enhanced KK production through t_R loops (Agashe, Delgado, May, Sundrum)
- Also graviton KK resonance has interactions very similar to that of Higgs! (LR and RS)
- **LESSON 3: RICH PHENOMENOLOGY-NOT YET FULLY EXPLORED**

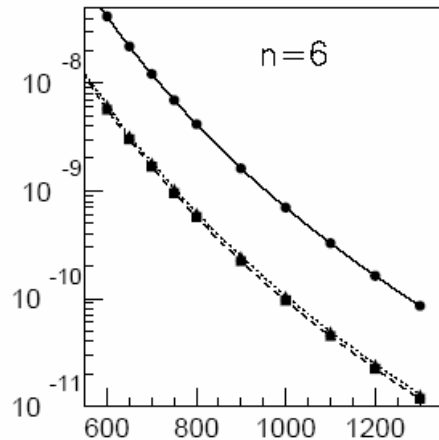
Signatures of Extra Dimensions Still?

- Still have distinctive spin-2 resonance
- What other distinguishing features in interactions?
- Is it extra dimensions or just some strong interactions?
- $\gamma\gamma$, gluon gluon interactions should be the same (LR with RS)
- After all, it's a gravitational interaction
- Worth investigating

One more variant: KR Model

- Can have RS without the 2nd brane bounding spacetime
- Then get a gapless continuum of KK modes
- Rather than resonance signatures,
- Reverts to missing energy

Cross Section and Missing Energy

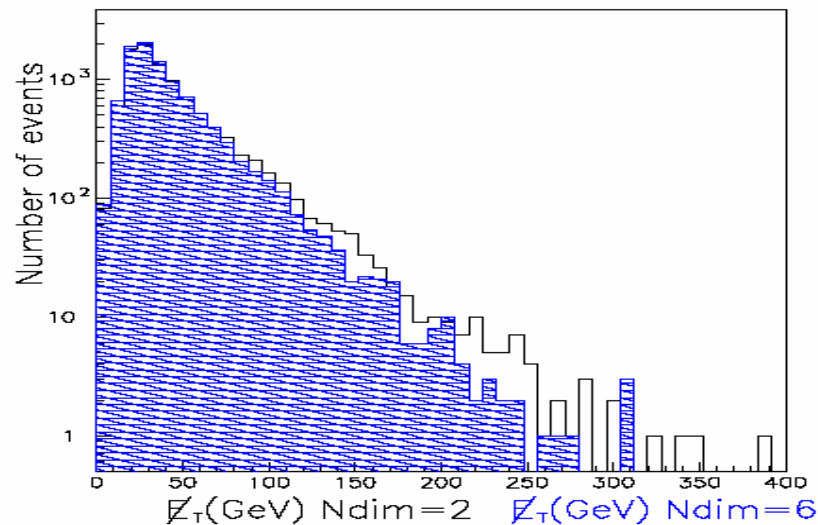


KR:
equivalent
to $n=6$

Spiropolu

Missing energy
searches might find
KR geometry

Only distinguished by
black holes and
strings!



LESSON 4: Even
missing energy
searches can find
warped scenario

Summary

- Best signature: spin-2 resonance and mass gap
- Good signatures: signals of partial compositeness
- Great signature if measurable: relative rate of $\gamma\gamma$ and gluon gluon: indicates warped extra dimension
- Plus possible missing energy signature if infinite extra dimension
- Lots of phenomenology
- Much still to be worked out
- But we really want to be able to pin this down

Entering a new era in physics

- Every time we've explored smaller or larger length scales, we've found new phenomena, new connections
- Many exciting new ideas for what we might discover
- More connections are there—we just have to find them
- Secrets of the universe are about to unravel

Hidden riches in the universe

