

EXTRA DIMENSIONS:

FLOUTING CONVENTIONAL
WISDOM in Particle Physics
and Cosmology

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Everything you never wanted to know about extra dimensions

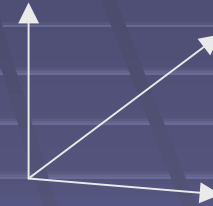
But don't be afraid to ask TM

Lisa Randall

Harvard University, Radcliffe

Introduction:

- Standard Lore is that there are three dimensions of space
- Strong Evidence



- Detailed tests of gravity
- Force laws, more on this later
- It's obvious!

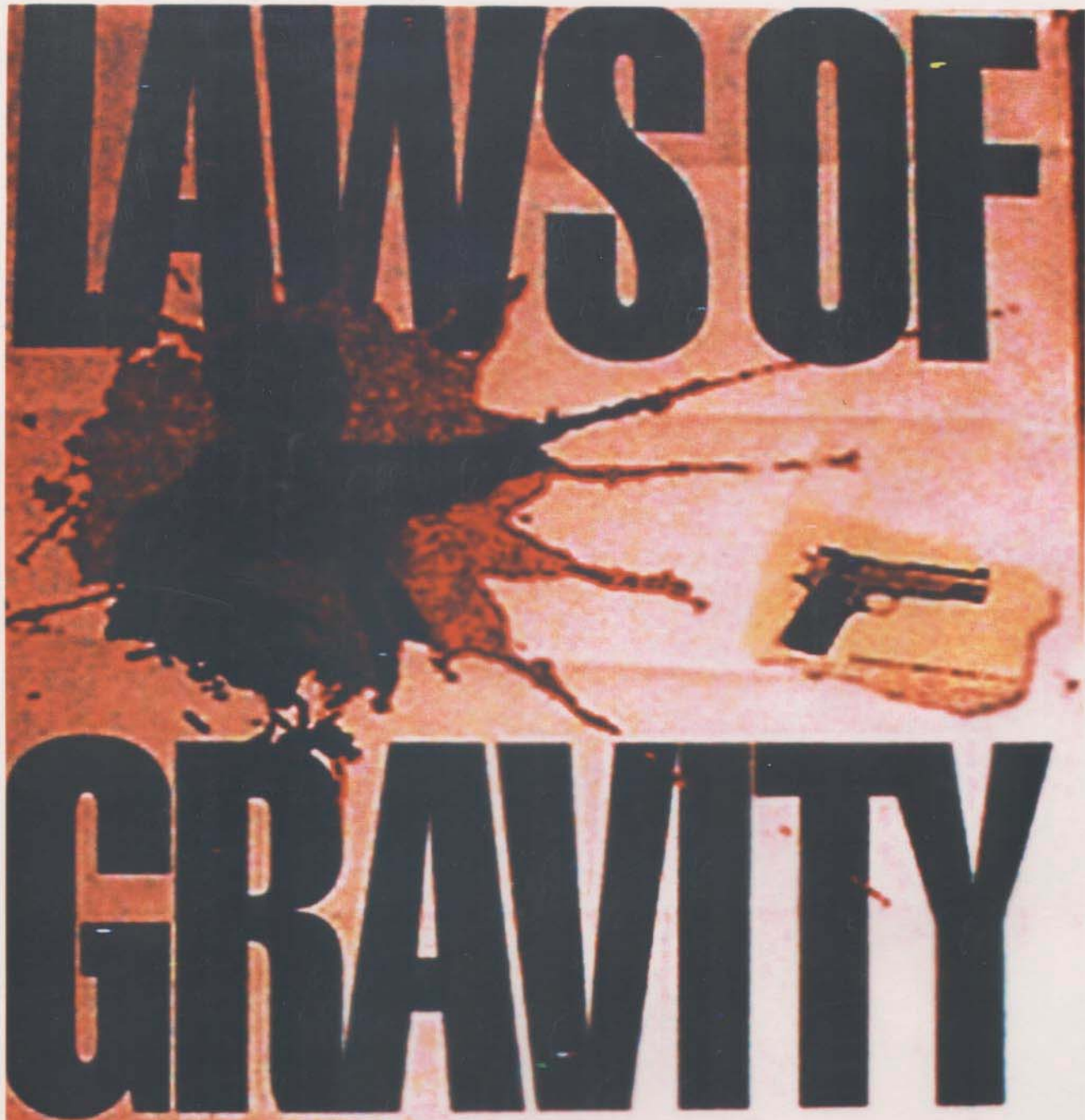
Not necessarily true!

- There can be more than 3 dimensions
- We actually don't (yet) know
- Need to distinguish what we take for granted and what has been verified
- Extra dimensions are not only permissible, but they can resolve puzzles of 3+1 dimensions

Outline

- Review gravity, notion of extra D
- Demonstrate viability of extra dimensions
- Curled up
- Even infinite ones (in warped space)!
- Why Particle Theorists Care
- Why Cosmologists Care

LAWS OF GRAVITY



Sooner or later, everything goes down.

Gravity



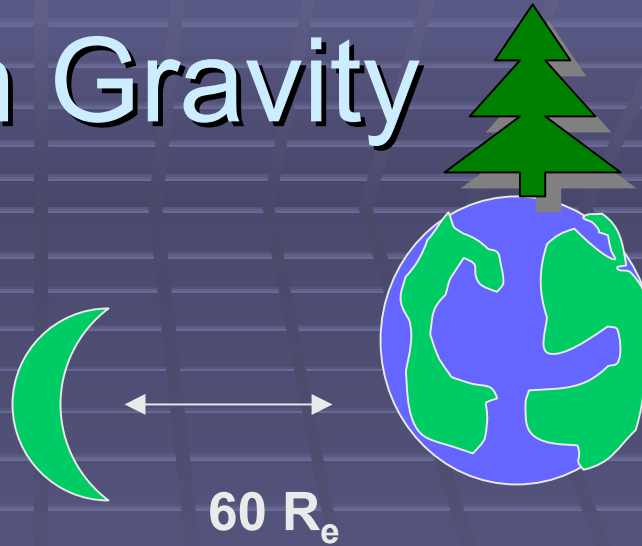
Physical Experience



- Other forces compete with gravitational force of *entire* Earth!
- Gravitational force on Earth: $a=9.8 \text{ m/sec}^2$
- For later: paradoxically, gravity extremely weak

Newtonian Gravity

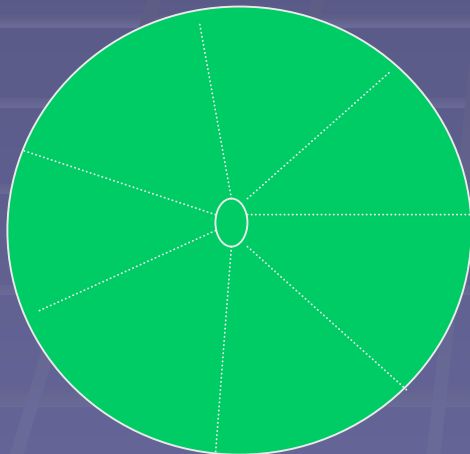
$$F \sim 1/r^2$$



- Many confirmations:
- Solar system
- Detailed gravity experiments

Inverse square law: $1/r^2$

- Easy to understand
- Force is isotropic
- Force lines uniformly distributed over the surface of a sphere

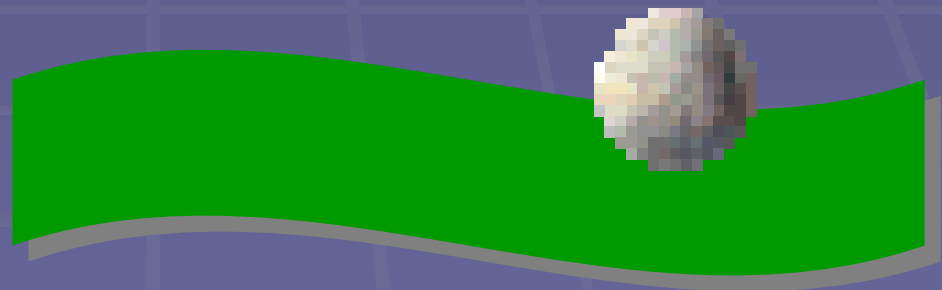


$$F \sim 1/r^2$$

Notice connection to 3 spatial dimensions!

General Relativity

- Matter determines geometry
- Curved geometry introduces gravity
- Matter *warps* space-time
- Distorted space yields gravitational force



Not the end of the story

- Major physics revolutions of the last century

General Relativity

Quantum Mechanics

Large Scales

Incompatible!

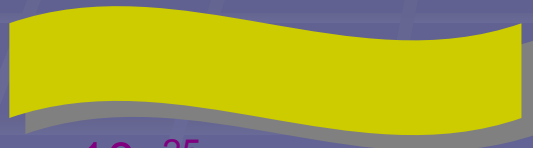
Small scales

Cosmological

Particles, electrons, quarks



- Classical stationary background vs. uncertainty and short distance
- String Theory** reconciles the two



10^{-25} cm

10^{-31} cm



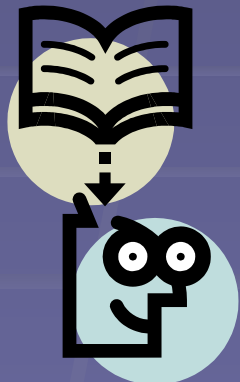
10^{-33} cm

String Theory

- Expected to reconcile **Quantum Mechanics** and **Gravity**
- Only consistent with
- more than 3 dimensions of space!**
- Generally need 9 (or more)!
- Very dramatic consequences
- But why don't we see them?

String theorist:
NOT do extra
dim exist

Where are
they?



Extra d?
Sounds
Interesting



Nonstring
theorist:

Logical
possibility

Einstein
doesn't pick
out 3D

Rapid Intro to Xtra D

- Thinking about more than 3 D is done every day
- Most don't think of it that way
- One dimensional:

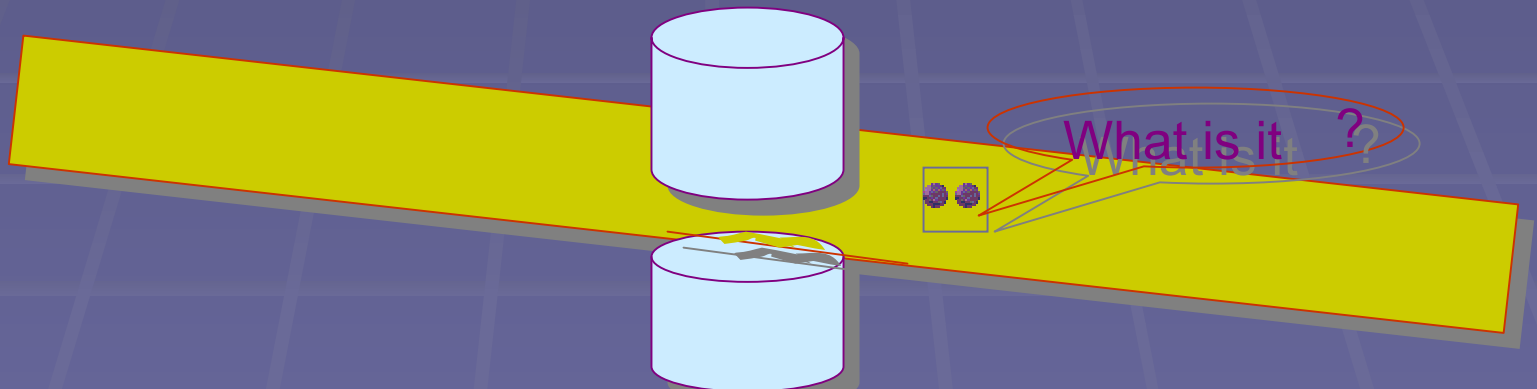


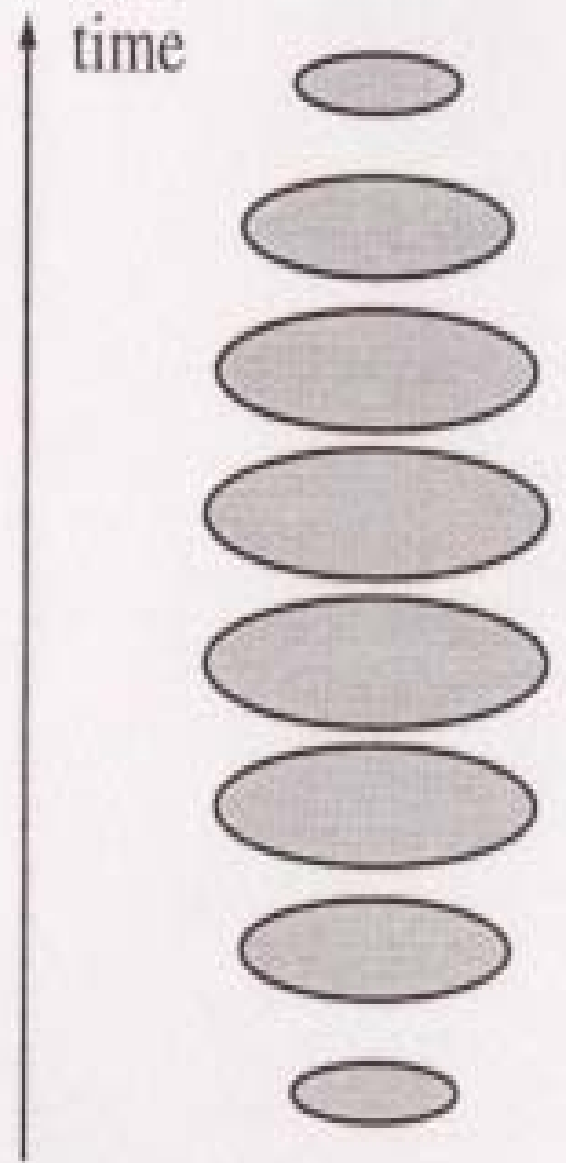
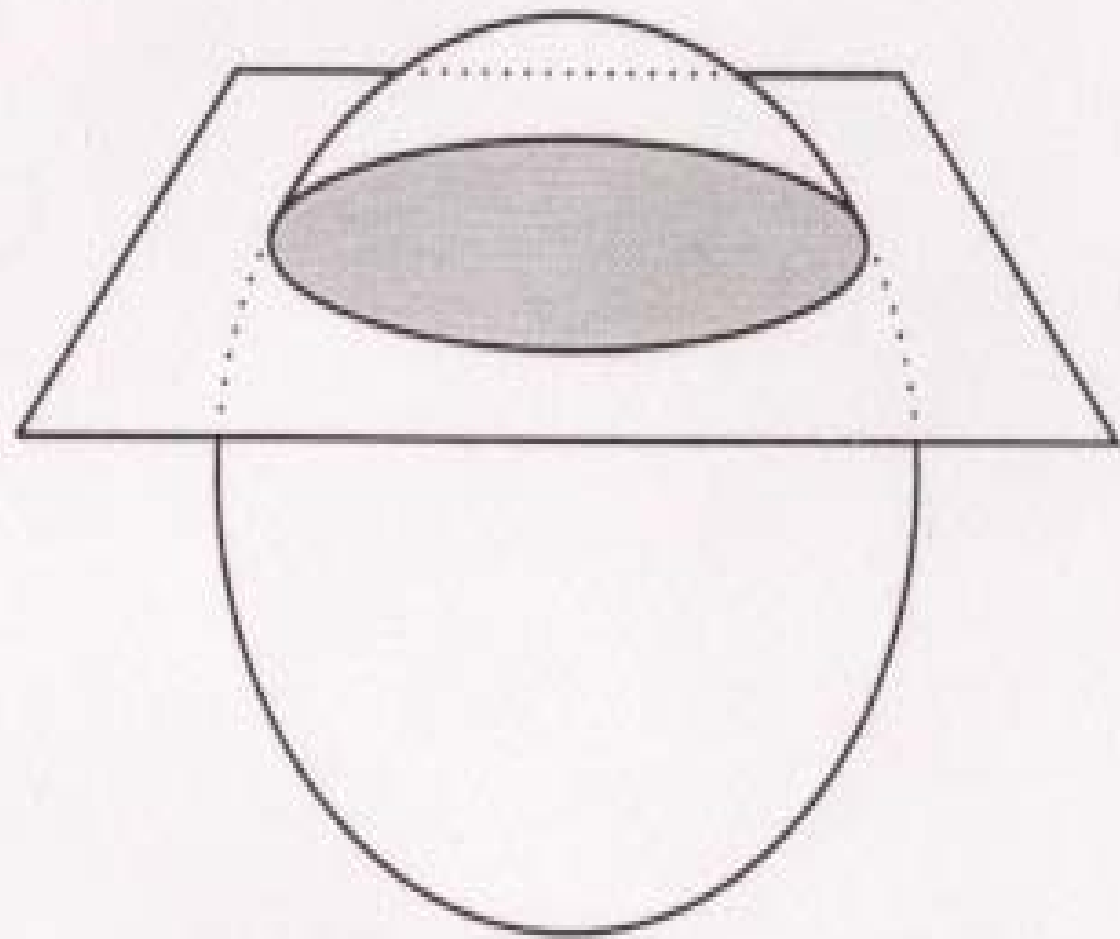
- Multidimensional person: works, plays, reads, does sports, engages in political activity
- (40, 10, 7, 6, 3) # hours on each activity
- 5 D: hard to plot
- Database has multidimensional information
- Dimension: number of points to specify the person/thing

Dimensions of space

- Number of points needed to specify **location** of an object
- We are familiar with 3 (or less)
- We can only see *projections* of higher dimensions

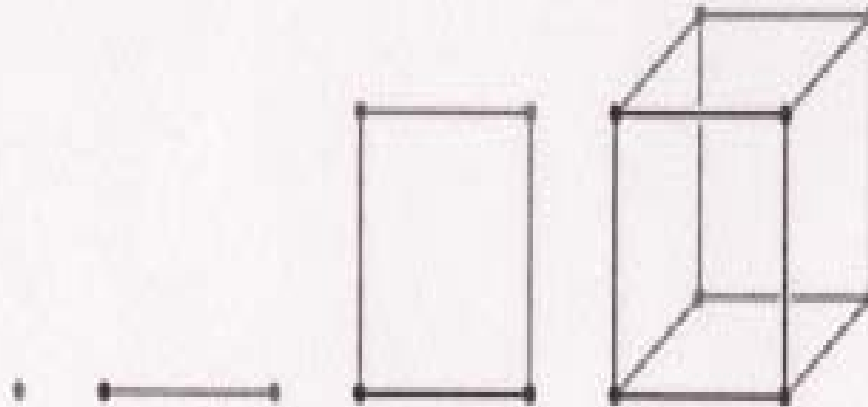
FLATLAND: EDWIN A ABBOTT, A², Narrated by A Square



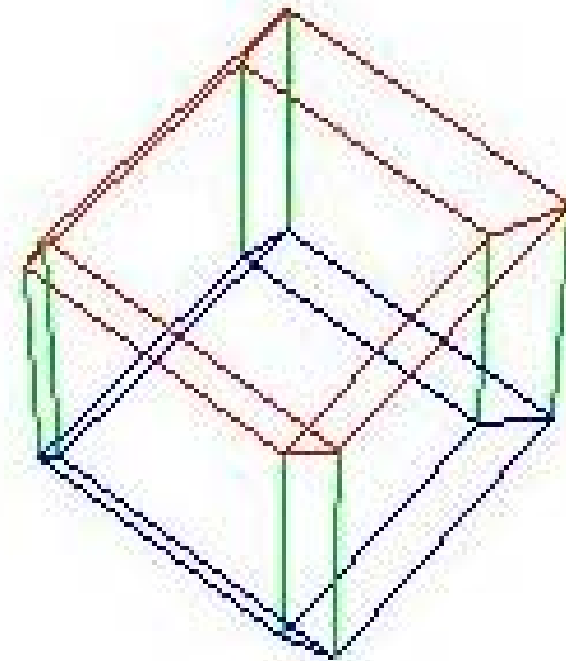
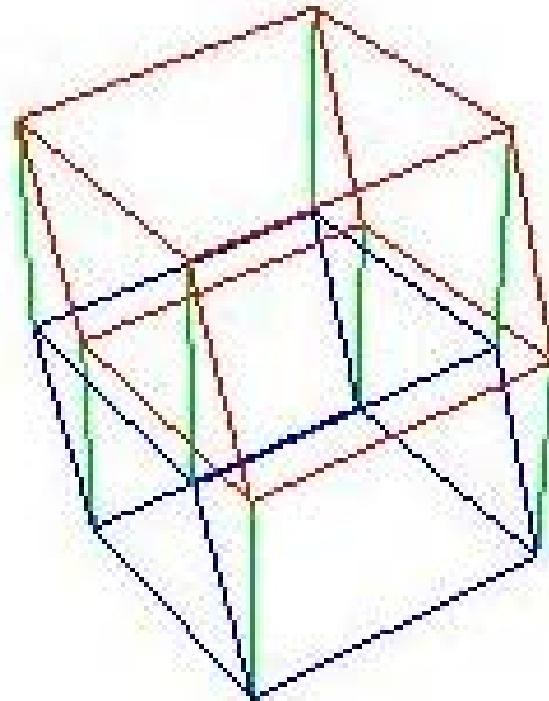
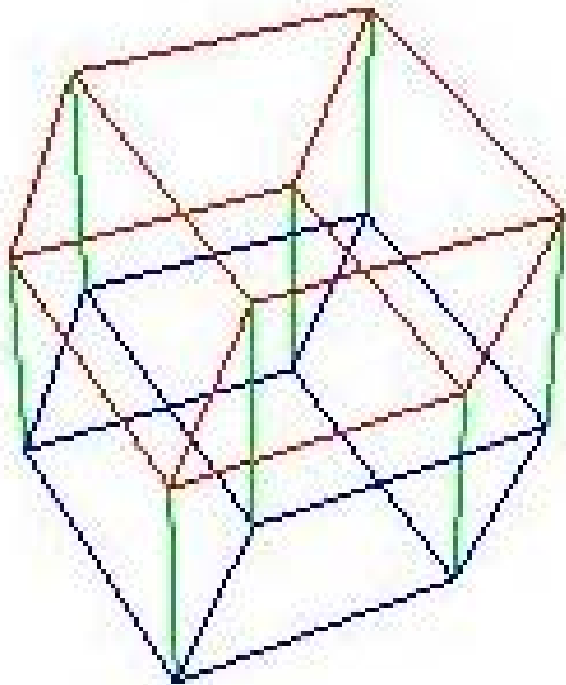


Geometric objects of extra dimensions

- Build them up sequentially



Hypercube Projections

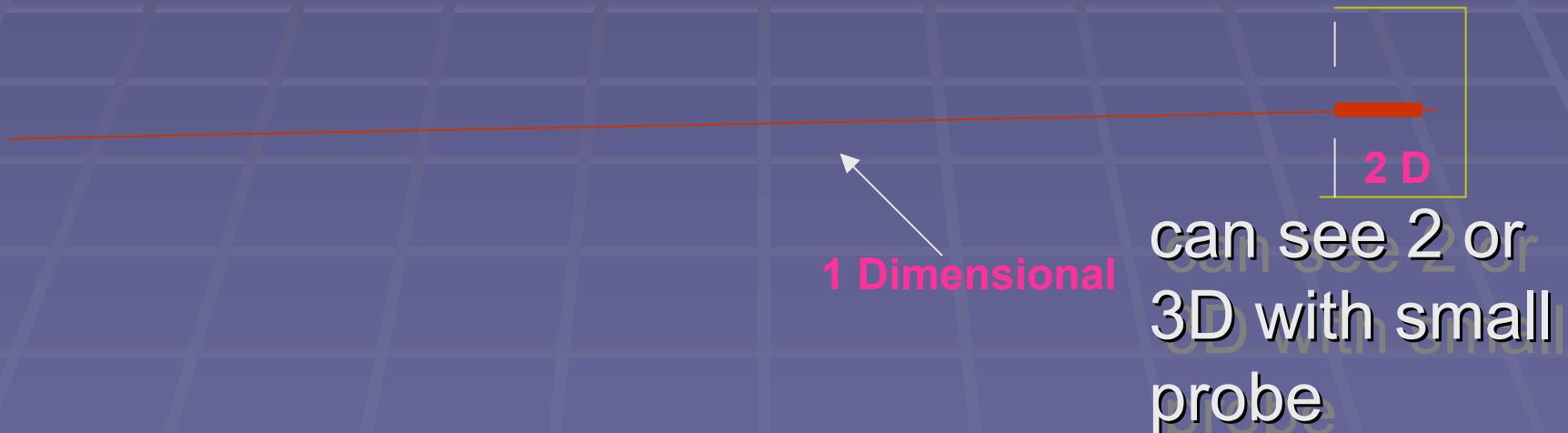


Dimensions

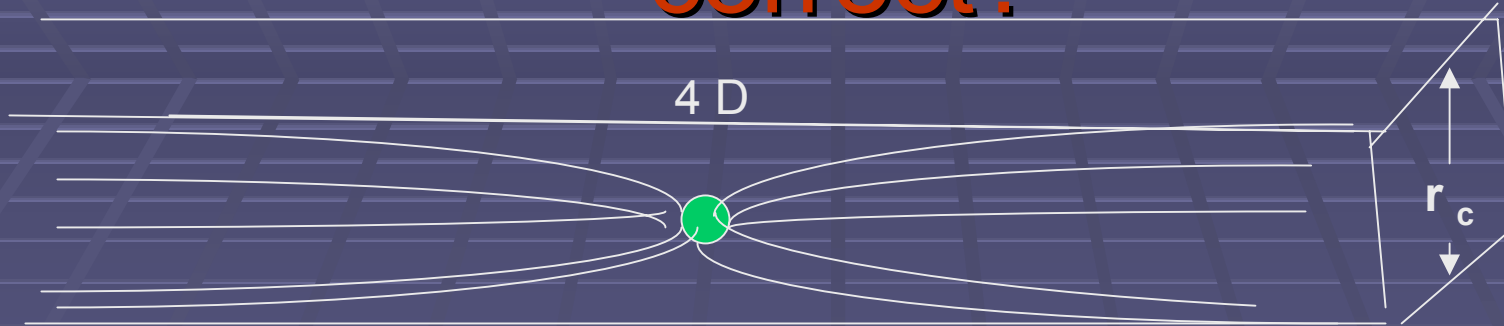
- D: Number of points to specify location
- With space, also need metric
- Tells how you measure distance
- Inches, meters, miles, parsecs?
- And angles: is space flat or curved?
- Sphere vs. flat space
- Necessary in 3D, necessary in more

Compactification: Curled up Dimensions

- If a dimension is wound sufficiently tightly you won't see it
- e. g. Curled up to a very small circle
- Very intuitive; if sufficiently small, it doesn't look like it's there



Why does force law appear correct?



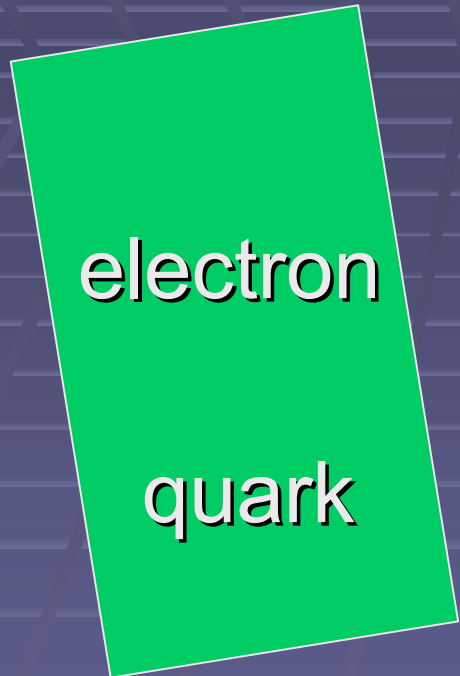
- For $r > r_c$, $F \sim 1/r^2$
- For $r < r_c$, $F \sim 1/r^{2+n}$
- Don't see extra dimension at low energy or long distance
- But how big would the extra dimensions be?

Novel Way to Hide Dimensions

LR, Sundrum

- An important ingredient in “string” theory was only recently recognized
- BRANES
- Like membranes in a higher dimensional space
- Play an essential role in string theory

BRANES



Stuck
on a
brane
like a
bead
on a
wire

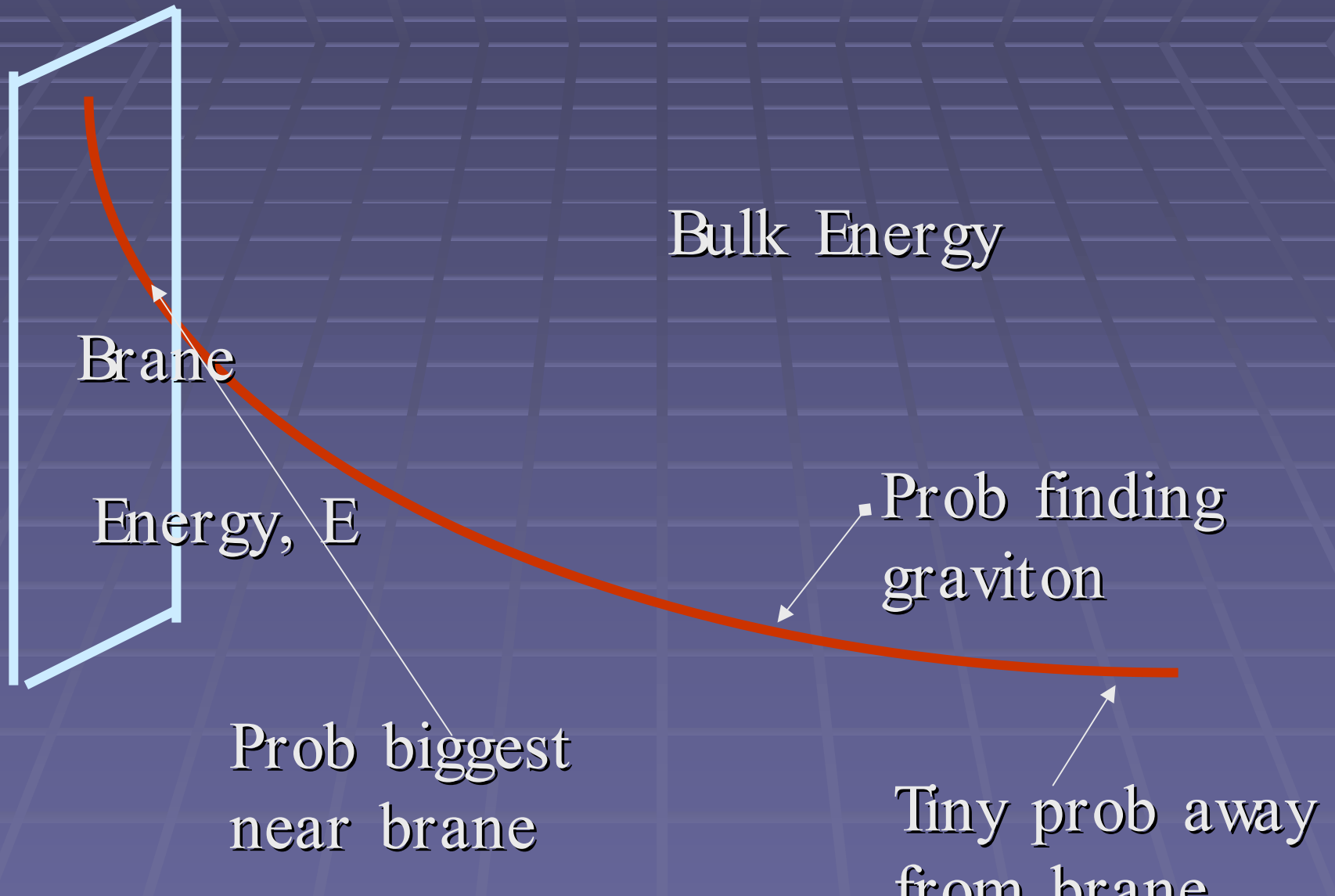


Weaker bounds on extra dimensions' size

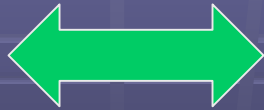
BRANES

- Branes carry energy and momentum
- According to Einstein's General Relativity, this means branes *bend* surrounding space
- Geometry is *warped*
- 3+1 D branes with fifth additional dimension
- Dramatic curvature of space

Brane → Localized Gravity

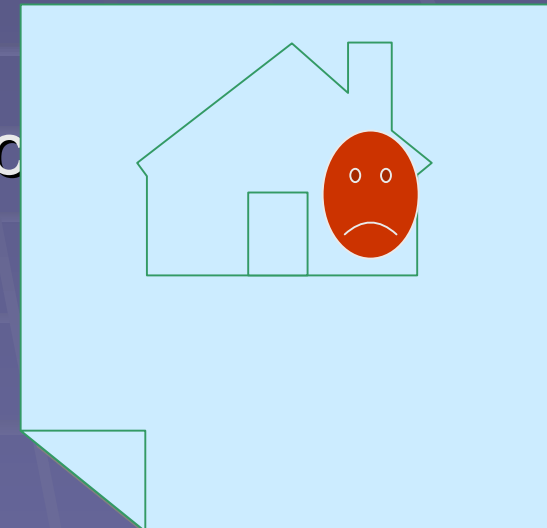


Localized Gravity ⊕ Infinite Dim



Compact Space ⊕ Finite Dims

- The graviton is so strongly peaked near the brane that gravity doesn't leak away
- Graviton essentially *bound* to the brane
- Difference between exhaustion and locked door
- You stay indoors either way!
- Force law is correct because
- Force lines spread very asymmetric
- Lines almost parallel to brane



Exciting but frustrating

- Exists something as dramatic as an infinite extra dimension but we don't know it!
- **Can this be tested?**
- Yes, if connected to Particle Physics
- (or Cosmology)

Hierarchy Problem

- Related to electroweak mass scale
- Where masses arise
- Must be much less than gravity mass scale

17 order of mag difference

Force	Mediating Particle	Interaction strength	Mass of particle
Strong	Gluon	4π	0
Electromag	Photon	$1/3$	0
Weak	W, Z	$1/2$	100 GeV
Gravity	Graviton	$E/10^{19} \text{ GeV}$ $\sim E/M_{\text{Pl}}$	0

Localized Gravity and the Hierarchy

- Suppose “multiverse”: two branes
- On one brane gravity is very strong
- On the other, gravity is very weak

Geometry naturally explains hierarchy !!



Gravity is exponentially suppressed!

$$e^{-35} \sim 10^{-17}$$

Natural for gravity to be weak!

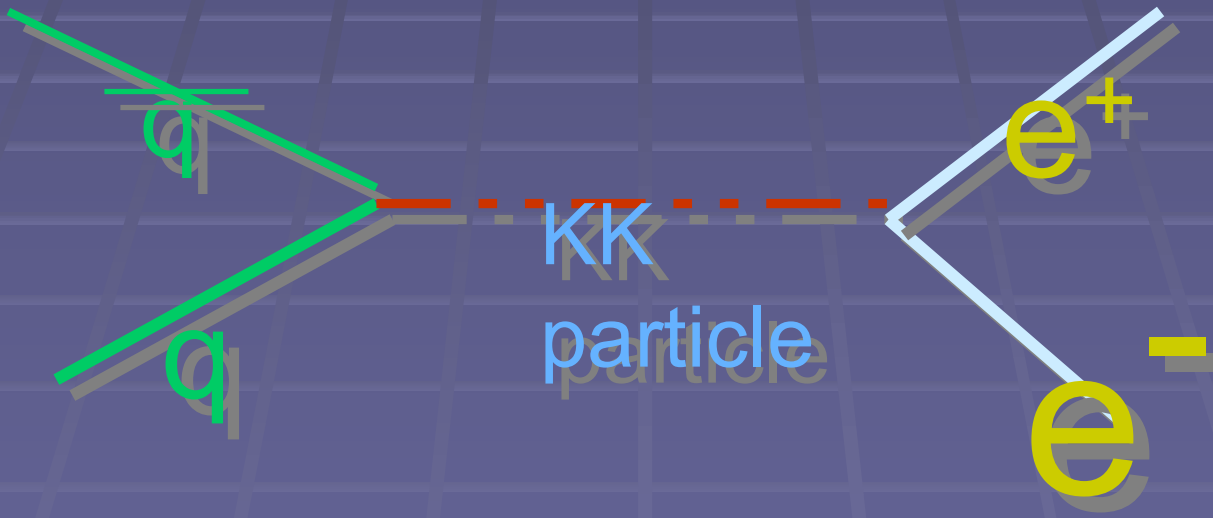
- If we live anywhere but the “gravity brane”, gravity will seem weak
- If we live on the “weak brane” gravity is so weak that the mass hierarchy is natural
- Gravity so weak because of small prob for graviton to be near the weak brane
- This scenario is testable at high energy colliders

Heralds of extra dimensions

- With extra dimensions, there are new (Kaluza-Klein) particles
- Carry momentum in extra dimensions
- Look to us like particles with mass characteristic of the extra-dimensional geometry
- Because of connection to hierarchy and weak mass physics, mass will be about 1000 GeV
- Precisely the energy that will be explored in upcoming collider experiments: LHC
- If we are very lucky, five-dimensional black holes and string states might also appear

Experimental Signal

- Kaluza-Klein particles
- Definite mass spectrum and “spin”-2



A Far-Out Theory Describing What's Out There

Physicists have long sought a unified theory to explain all the forces and matter in the universe. Superstring theory is an attempt at such a unification, and now "brane" theory expands on it, proposing that our universe is one of many membranes that "float" in a multidimensional megaverse.

SUPERSTRING THEORY

At its most basic level, the universe consists of tiny loops of string that vibrate at different frequencies.



Since matter can be described in terms of energy, each frequency (energy) corresponds to a type of particle (matter) just as different frequencies coming from a violin's strings produce different notes.

STRING SIZE

The strings are to an atom...



...as an atom is to the solar system.

Brane Theory

It expands superstring theory to include vibrating membranes, or branes, which may have many dimensions.

1

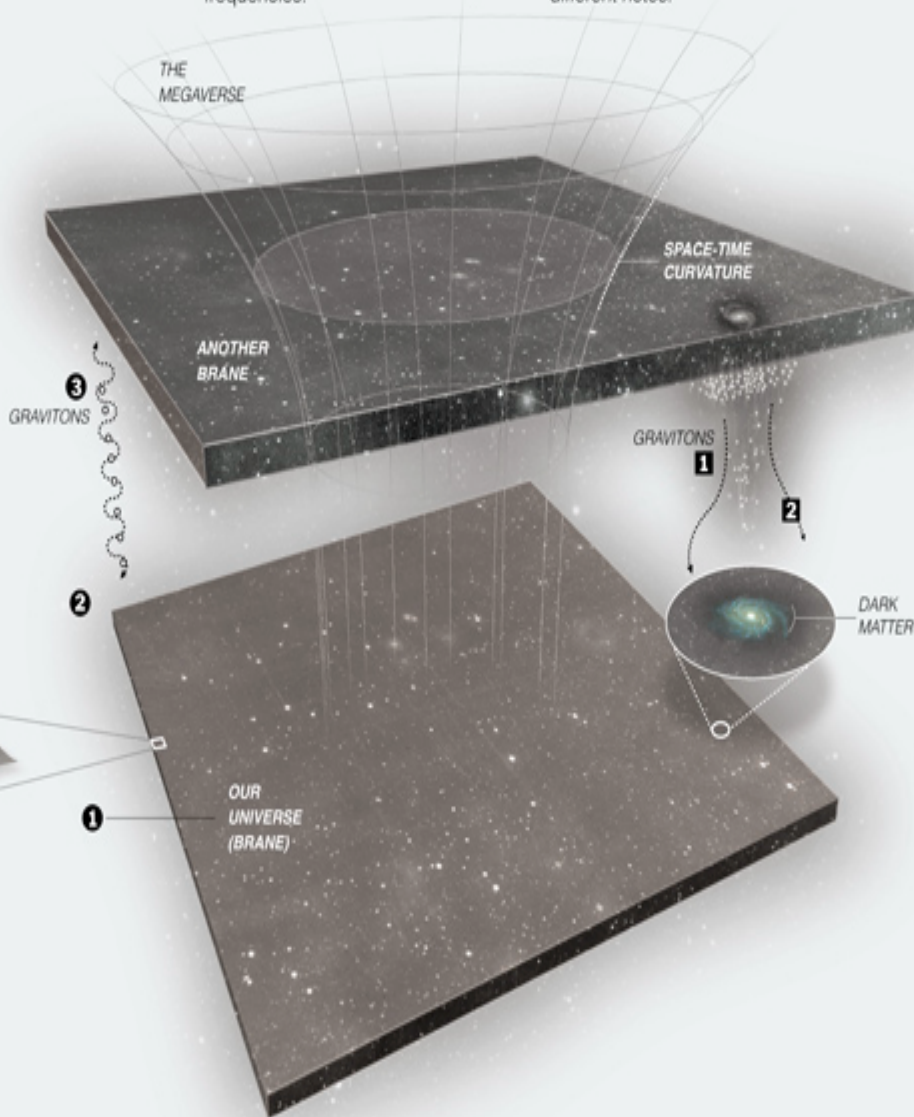
Our universe can be thought of as a three-dimensional brane floating inside a four-dimensional megaverse.

2

Most strings that compose our universe are attached to the brane's surface, and so most particles that exist on our brane are confined to its three-dimensional space.

3

However, the particles that convey gravity, gravitons, are not tightly confined to any particular brane, and some of them roam across to other branes in the megaverse.



BRANE THEORY AND GRAVITY

Gravity is described by relativity theory as curved space-time, and it is the weakest of the forces in our universe. Brane theory contains a possible explanation.

1

Gravitons, conveyors of gravity, may be concentrated on a different brane where the space-time of the megaverse is severely curved. Only a small number of gravitons make their way here, so gravity is felt as a weak force.

DARK MATTER

Cosmologists suggest that it makes up 90 percent of our universe. It neither emits or absorbs light, but it exerts gravity. According to brane theory, it may just be ordinary matter concentrated on other branes, and its light cannot shine through to this universe.

2

The light from dark matter, conveyed by particles called photons, would cling to the surface of the foreign brane, but gravitons might seep across the divide. Pulled by our galaxies' local gravitational force, the gravitons would cluster into halos around the galaxies.

Sources: "D is for Quantum," by John Gribbin; "The Ideas of Particle Physics," by J.E. Dodd

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ELLE

HOW YOU CAN REALLY CHANGE YOUR BODY



PENÉLOPE CRUZ ON DAMON VS. DEPP

FALL'S NEW VINTAGE CLASSICS

MARK LEYNER OFFERS A PRIMER ON BUSH WHACKING

FA... READ FOR ACTIVE SPORT STARS SEXY STYLE

SCAND CITY: IN RAPE CO

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.

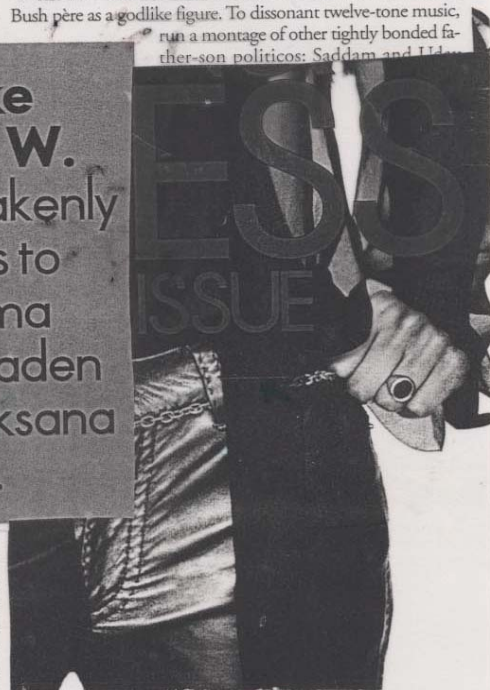
The gist of my advice to Gore was that if he has any hope of winning in November, he must twist W.'s putative assets into, if not terrifying, at least anxiety-provoking liabilities. And he can't go after his actual weaknesses, e.g., his famous aphasia, which people find charming. Nor would it be wise 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.

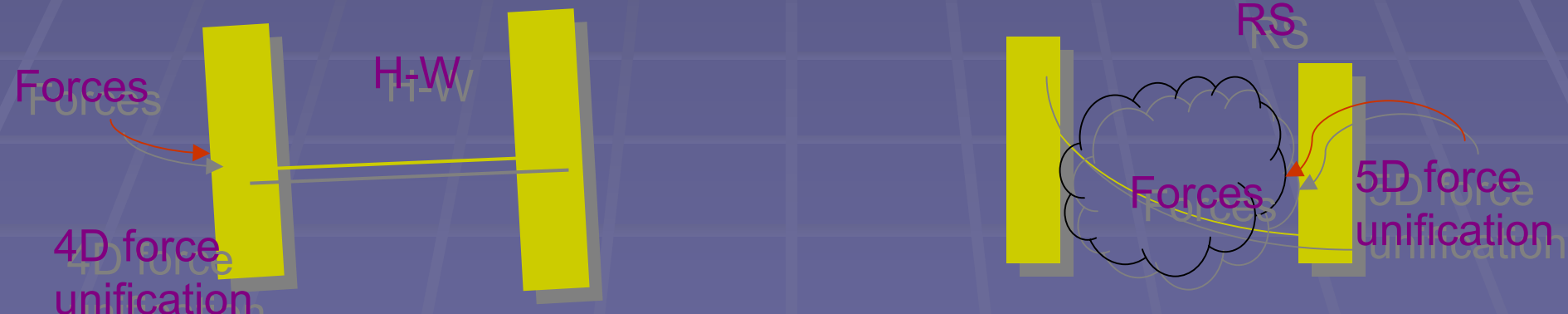
● **Re: W.'s filial devotion.** W. holds his dad in awe, viewing Bush père as a godlike figure. To dissonant twelve-tone music, run a montage of other tightly bonded father-son politicians: Saddam and Udd...

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



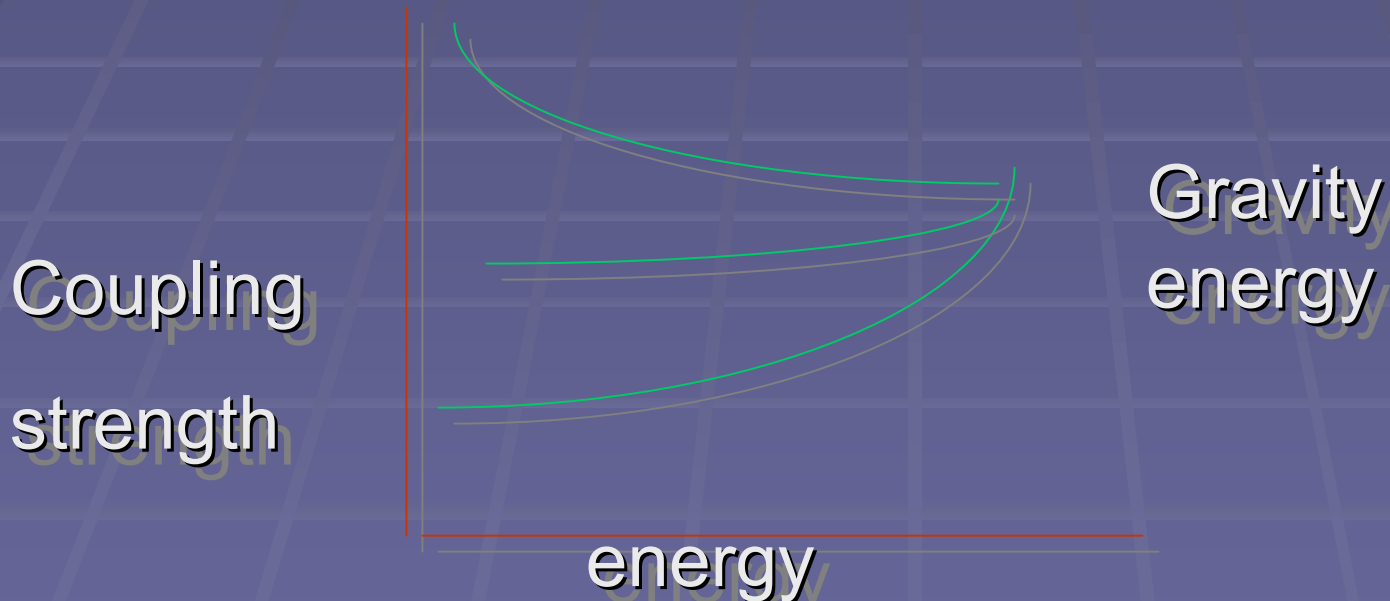
Extra Dimensions and Unification

- Strength of three nongravitational forces might be the same at high energy
- In that case, there could be a single unifying force at high energy (temperature)
- Never quite unifies with gravity however
- Except with larg(ish) extra dimension

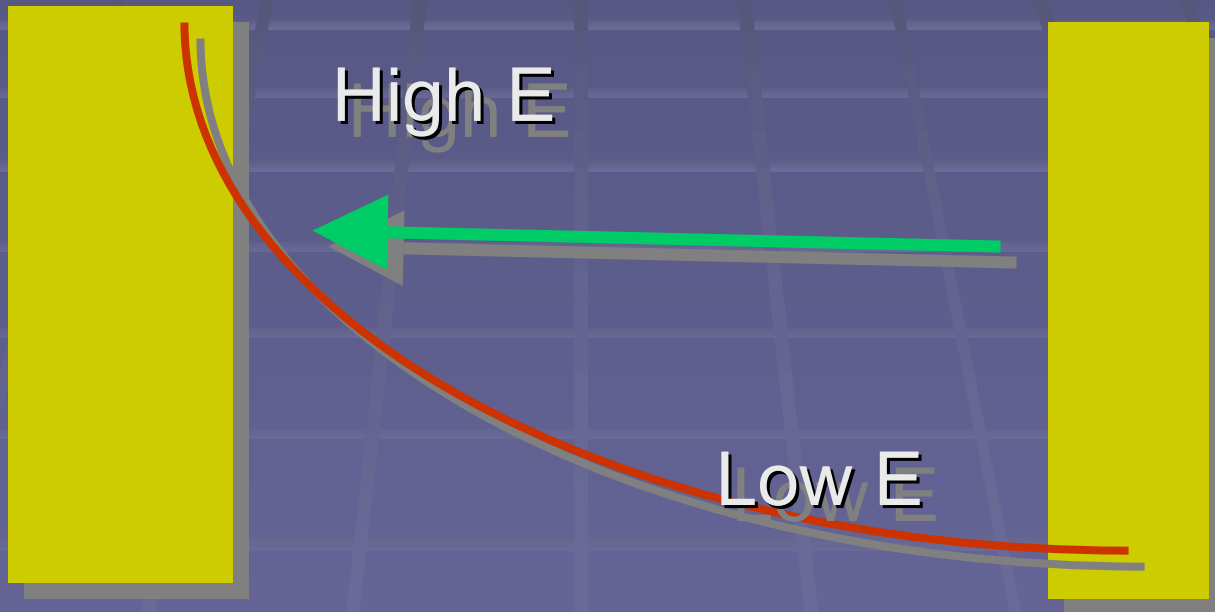


Bulk Unification

- Unification a feature of five-dimensional theory!
- Can calculate strength of coupling in bulk
- Find very natural to have unification



Bulk Calculation



Extra Dimensions and “Sequestering”

- Extra dimensions introduce new possibilities for Particle Physics
- New parameters: size, curvature
- Also new tool: locality
- Field theory: “Totalitarian Principle”
- Everything interacts
- Not true with extra dimensions

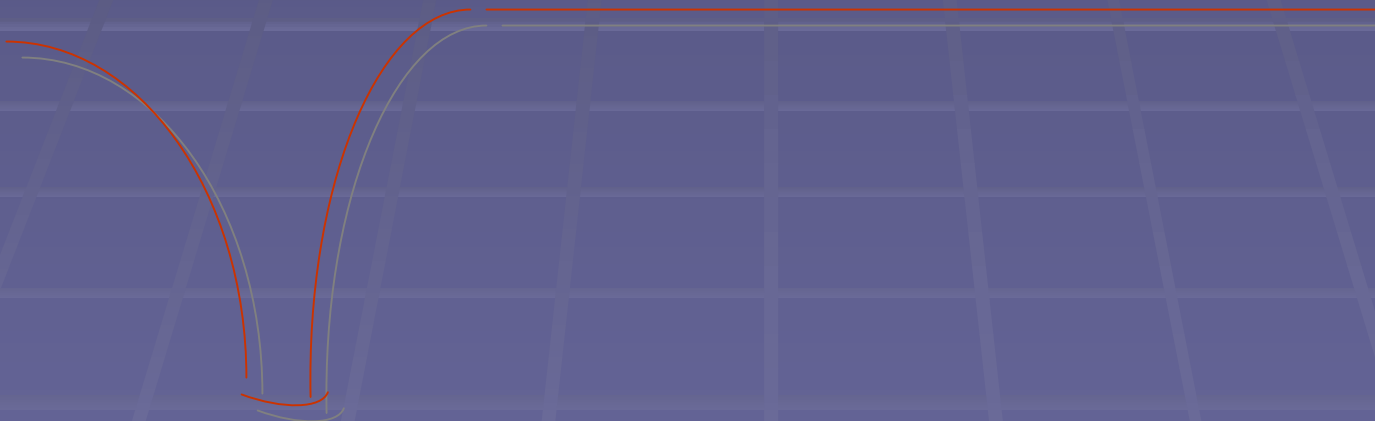


Extra Dimensions and Cosmology

- The problem of unexplained large numbers is even worse in cosmology
- The universe is extraordinarily big, smooth, homogeneous, isotropic
- **Inflation** is invoked to solve these problems
- With inflation, universe undergoes period of **exponential** expansion
- During this time, constant expansion rate

Requirements for Inflationary Potential

- Potential must be flat for a long time
- But inflation ends: phase where not flat
- And reheating: must interact with other fields



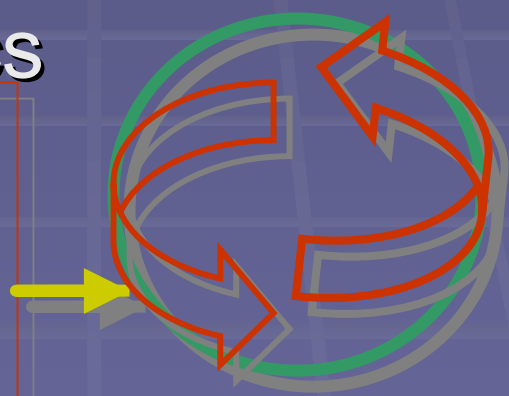
Alternative Idea:

- Don't have very flat potential
- Have large field value (greater than quantum gravity scale)
- Here no bizarre potentials required
- But need **large field values**
- Need **lower energy than M_{Pl}**
- Only sensible with additional dimensions
- A nice candidate is particle associated with extra dimensional forces
- Potential very constrained if it wraps an extra dimension by *locality*

Inflation and Extra Dimensions

- Problem is that 3+1-dimensional physics doesn't give any obvious candidates to trigger expansion
- Turns problem of large numbers into a different problem of small numbers
- With extra dimensions, very natural inflationary physics

Particle mediating force
Winds around curled up dimension
Potential for such a field very constrained



Predictions

- This model predicts significant
- (visible) deviation from flat spectrum
- Gravity waves that should be seen!
- Inflationary evidence for extra dimensions possible?!?

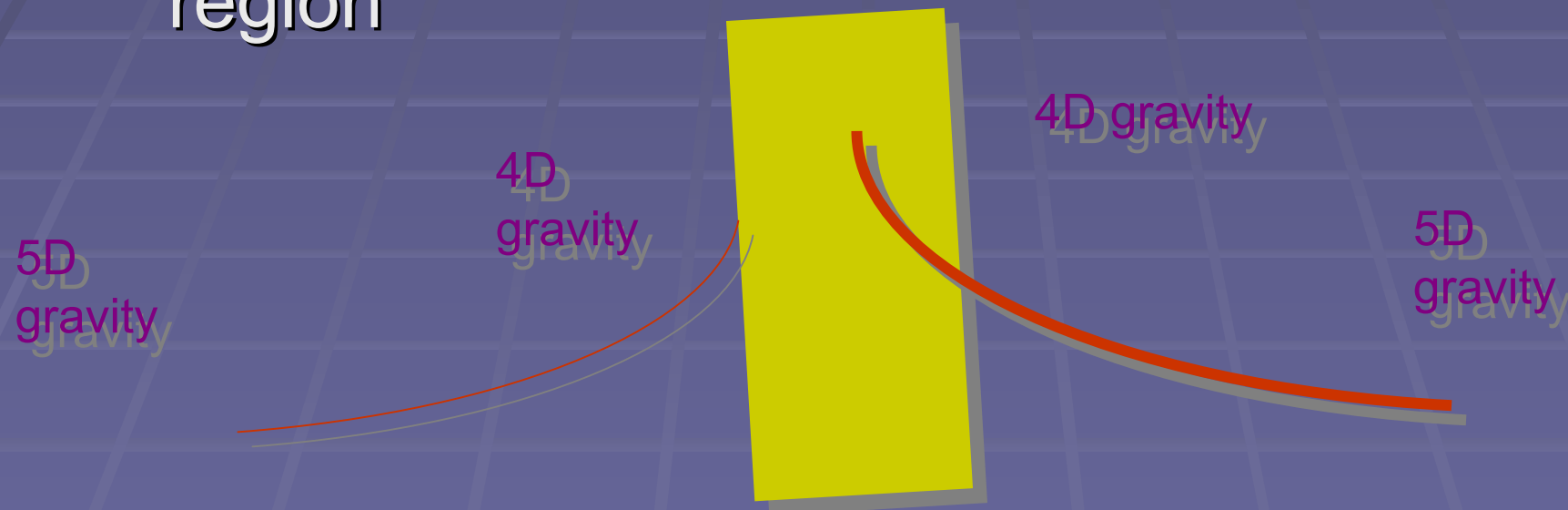
Infinite Extra Dimensions Give Radically Different Conception of Universe

- Black holes and gravity extend a bit into the fifth dimension
- Extremely small decay away from brane into the “bulk” higher dimensional space
- Natural scale for gravity depends on location!
- Evolution of universe involves more than 3 dimensions.

Even more dramatic possibility

- Dimensionality depends on location!
- Could see different dimensions in different places
- Determined by gravity bound state in that region

LR,
Karch



Conclusions

Implications for :

- Particle Physics Theory
- PP Experiment
- General Relativity
- String Theory
- Cosmology: explore time-dependence
- Rich blossoming field
- Yet to understand all connections

Physicists who call gravity Mother Nature's
weak force have been in the lab
way too long.

Photo: John Strickland

The penalty for breaking the laws of nature is severe. One false step and you're a bug on a windshield. You've got to stop when the wind says stop and stick when gravity demands it. Your shoes, and the rubber on them, matter.

Five.Ten makes many specialized shoes for the exact needs of your adventure. And only Five.Ten shoes have Stealth Rubber - the highest friction rubber known to man. These are the tools you need to play with the biggest force of all.

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