Beyond the Standard Model

Lecture #4: Exotica

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2009 European School of High Energy Physics, Bautzen 14-27 June 2009

Outline of Lecture 4

- Warped extra dimensions.
- The AdS/CFT correspondence relating 5d warped models to 4d Technicolor-like models.
- Higgsless models.
- Unparticles.
- Quirks.
- The Black Hole that will (not) swallow the Earth.

Not all BSM models are created equal

- Theorists need to write papers.
- So they tend to Bose-condense on the latest fad.
- Indeed the definition of a good new BSM idea is that it suggests 100 new calculations leading to 100 new papers.
- As a result older ideas tend to be under-valued.
- However SOME newer ideas are also usually under-valued, because their real significance is not yet understood.

BSM super-ideas ⟷ **music super-stars**

string theory

Glenn Gould

Undeniably brilliant, the best,
a loner, a little creepy

BSM super-ideas ⟷ music super-stars

supersymmetry

Bono

Around for 30 years, but still wildly popular

BSM super-ideas ⟷ music super-stars

technicolor

Rolling Stones

Not looking good, but won't go away

BSM super-ideas ⟷ **music super-stars**

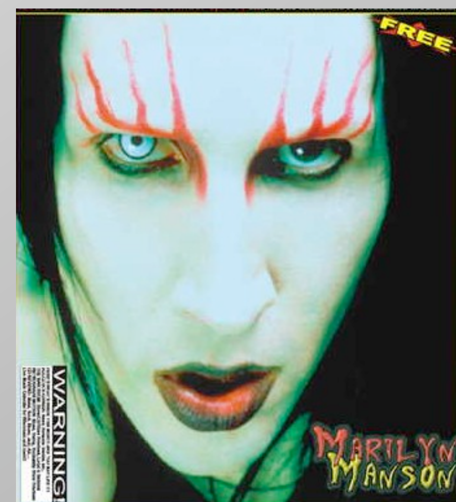
large extra dimensions,
warped extra dimensions
RSI, RSII, UED

Britney Spears,
Christina Aguilera

Sexy, insanely popular, hard to tell apart

BSM super-ideas ⟷ **music super-stars**

“unparticles”



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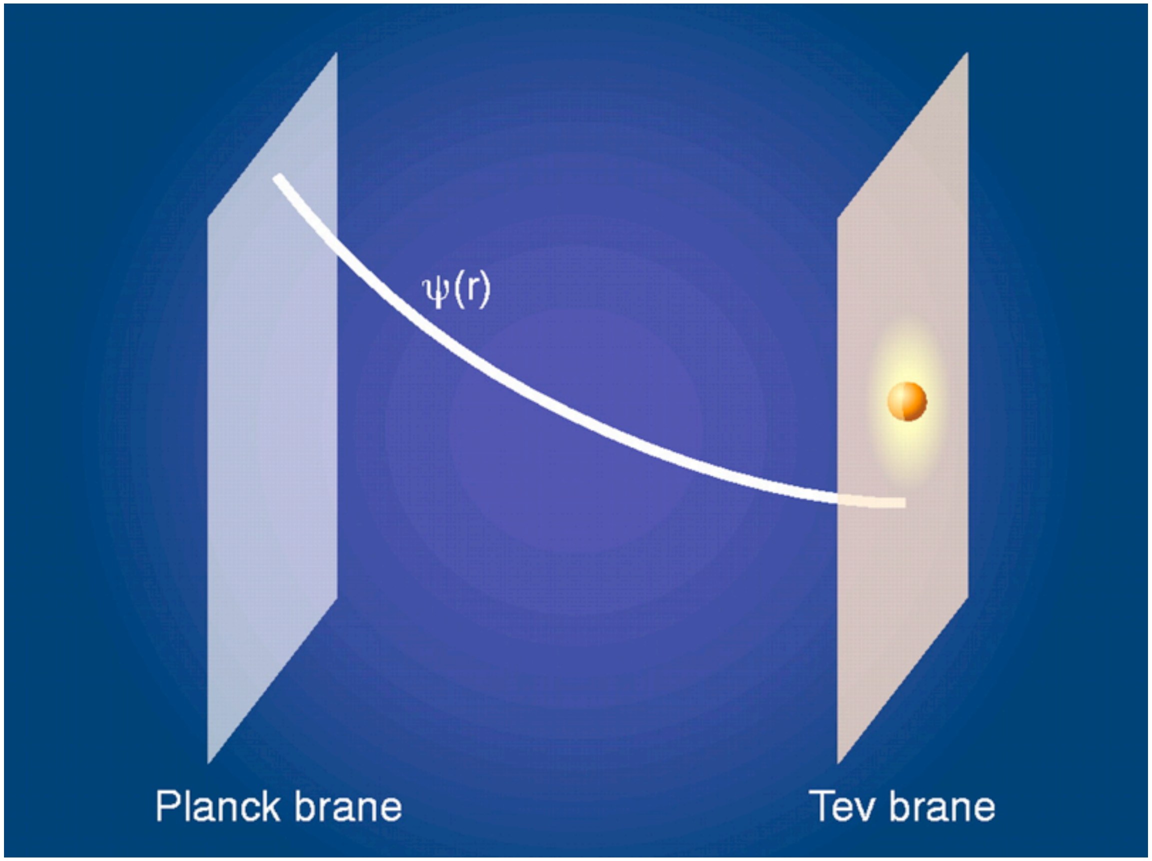
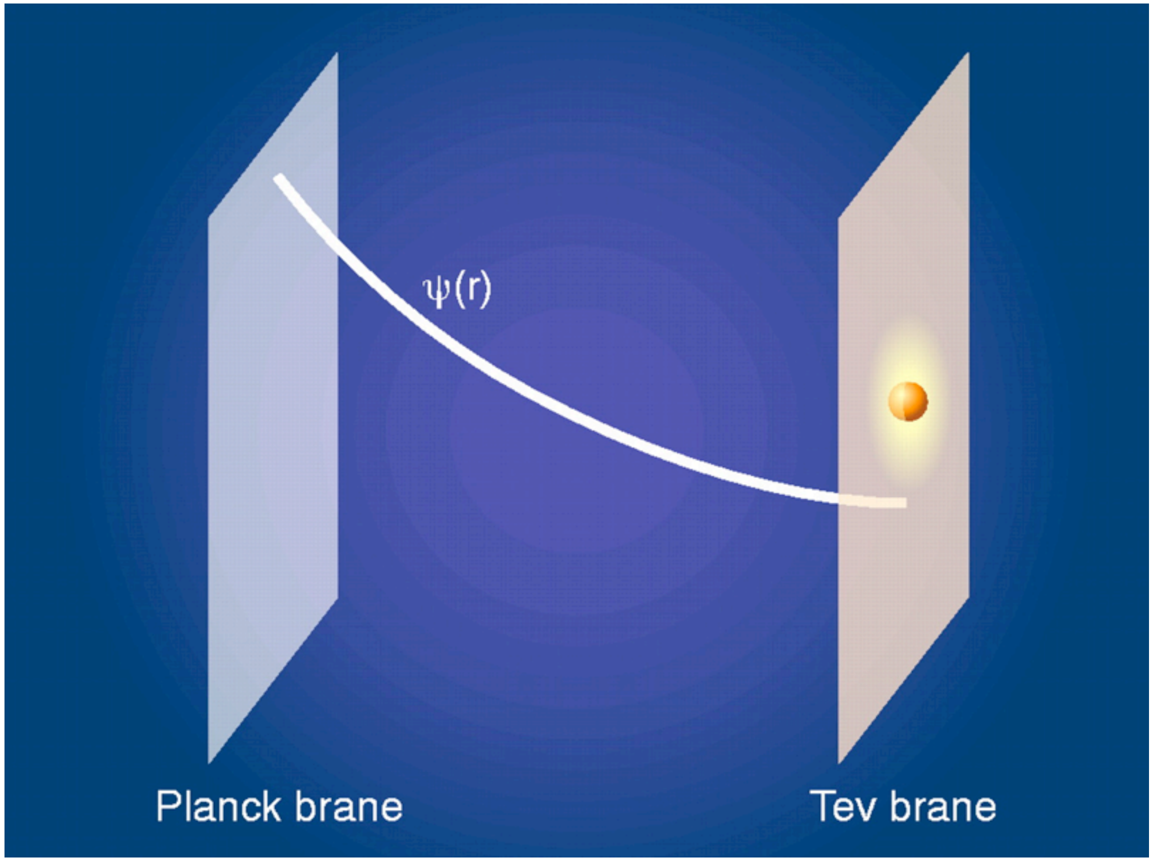
Only the kids can appreciate it

Warped extra dimensions



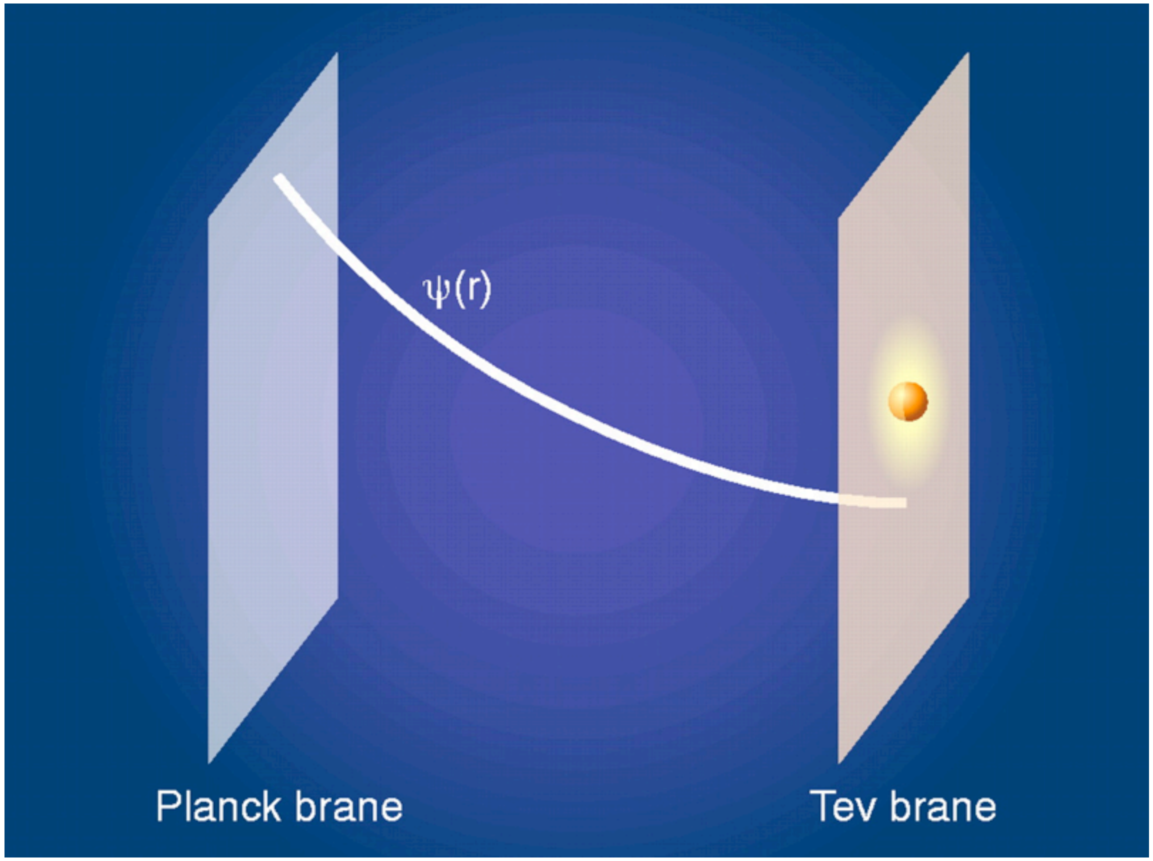
- **Basic idea:**
  - **There is a 5th dimension with a negatively curved geometry, like 5d Anti-de Sitter space (AdS5).**

Warped extra dimensions



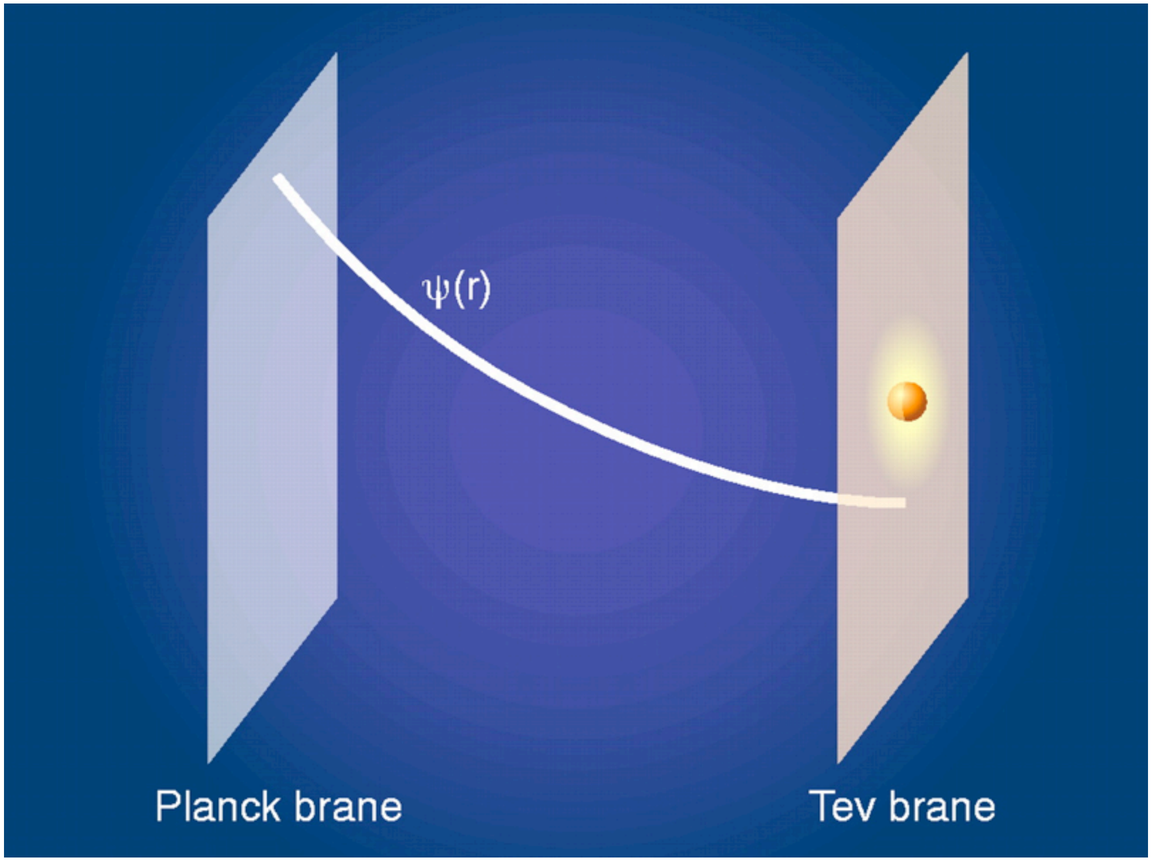
- **The 5th dimension has finite extent (usually), with branes on either end, called the Planck brane and the TeV brane.**

Warped extra dimensions



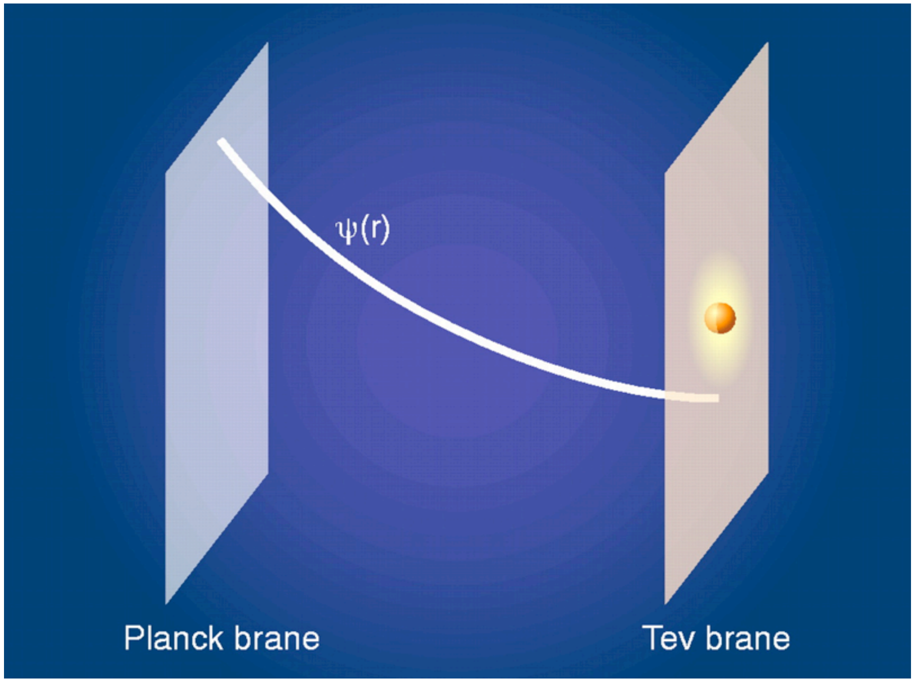
- Unlike in 4d, where we Fourier transform to momentum space and do quantum field theory in terms of plane waves, here every quantum field has its own nontrivial wavefunction shape in the 5th dimension.

Warped extra dimensions



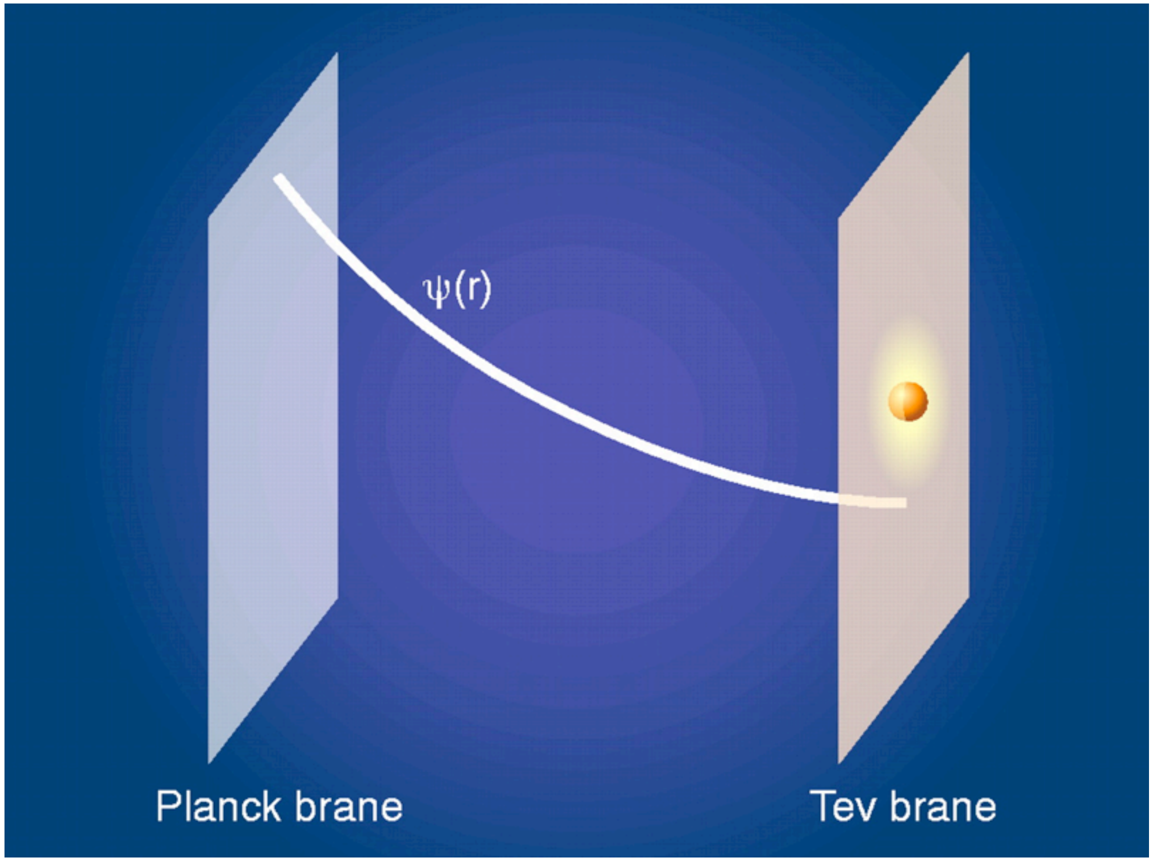
- You can compute these wavefunctions by solving the appropriate 5d equation of motion, taking into account the warped geometry and the boundary conditions on the branes.

Warped extra dimensions



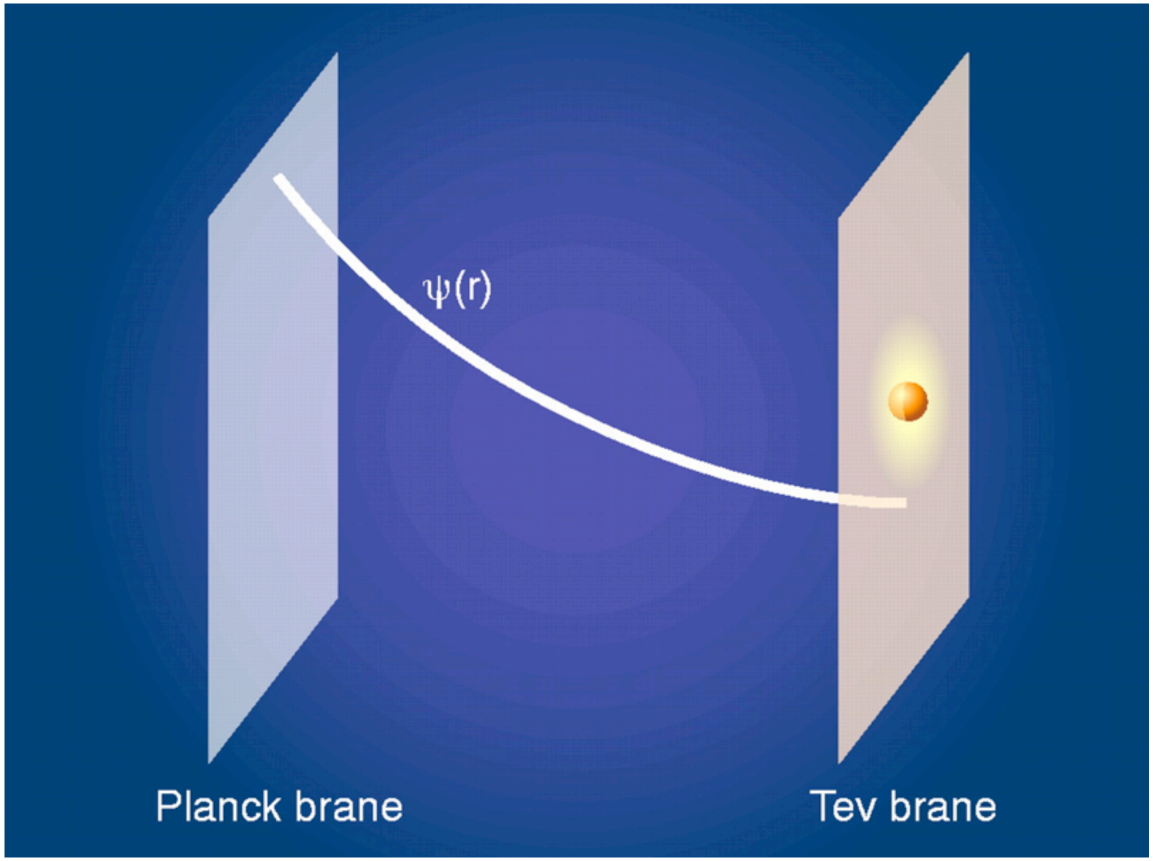
- For the 5d graviton, the solutions can be expanded in KK modes, but the KK modes are Bessel functions, not sines and cosines.
- The graviton zero mode (which will be our massless 4d graviton) has a wavefunction localized near the Planck brane, and exponentially suppressed (by ~ 15 orders of magnitude) near the TeV brane.

Warped extra dimensions

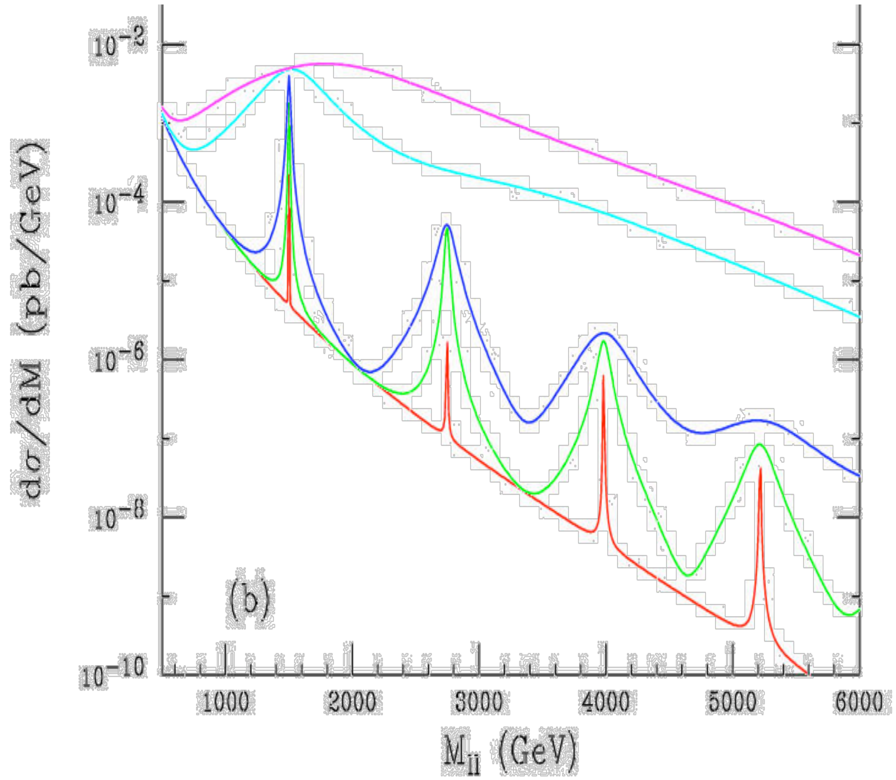


- To first approximation, you see the same gravitational force no matter where you live in the 5th dimension, but the interpretation varies.

Warped extra dimensions

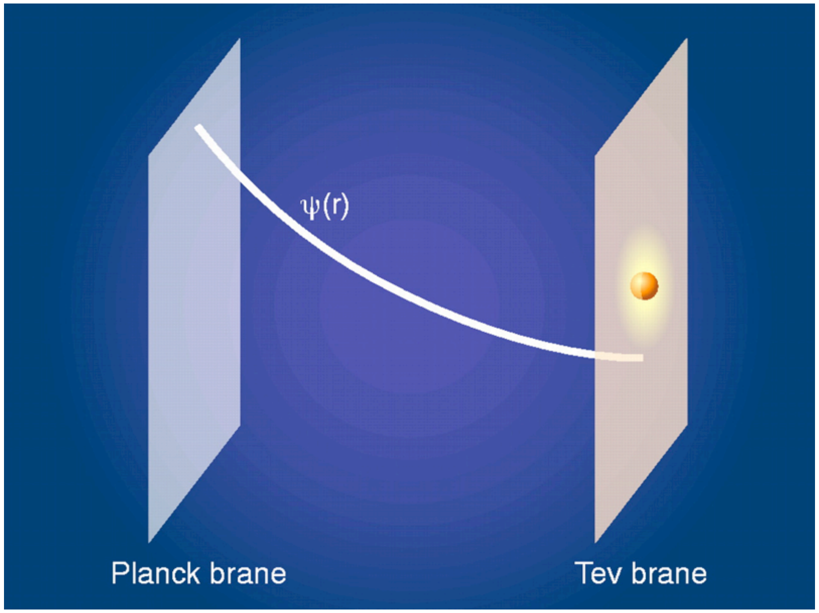


- At the Planck brane, the real Planck energy scale (where e.g. superstrings appear) is 10^{19}GeV, and the wavefunction factor =1.
- At the TeV brane, the real Planck energy scale is ~ 10 TeV, but in addition gravitational interactions have a 10^{15}wavefunction suppression (squared).



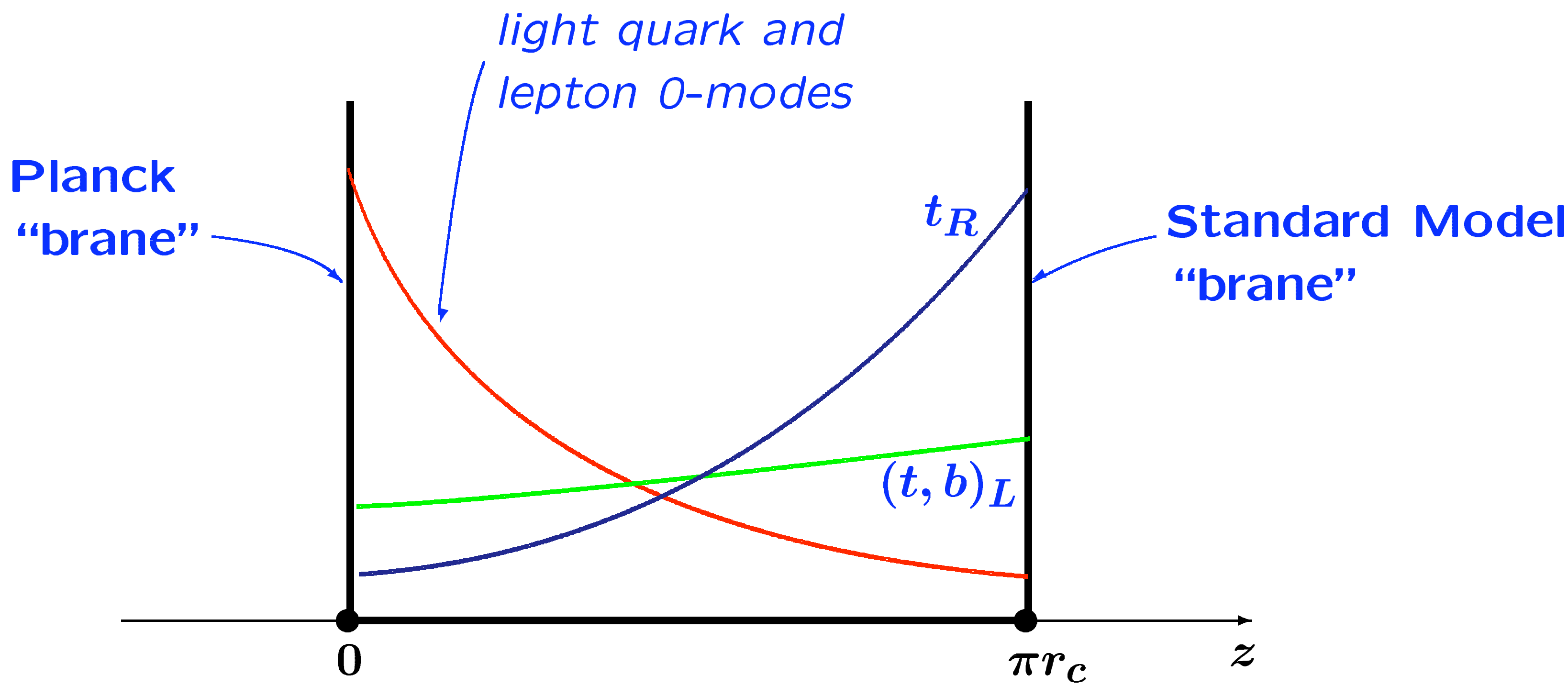
- This "Randall-Sundrum" RS1 idea is a very original solution to the hierarchy problem of the SM (though not to the Higgs naturalness problem).
- It predicts massive spin 2 partners of the graviton, with ~TeV masses given by the zeroes of Bessel functions.
- These massive spin 2 particles could have sizable cross sections at the LHC, because their wavefunctions, if SM matter has enough wavefunction overlap with these states.

Warped extra dimensions



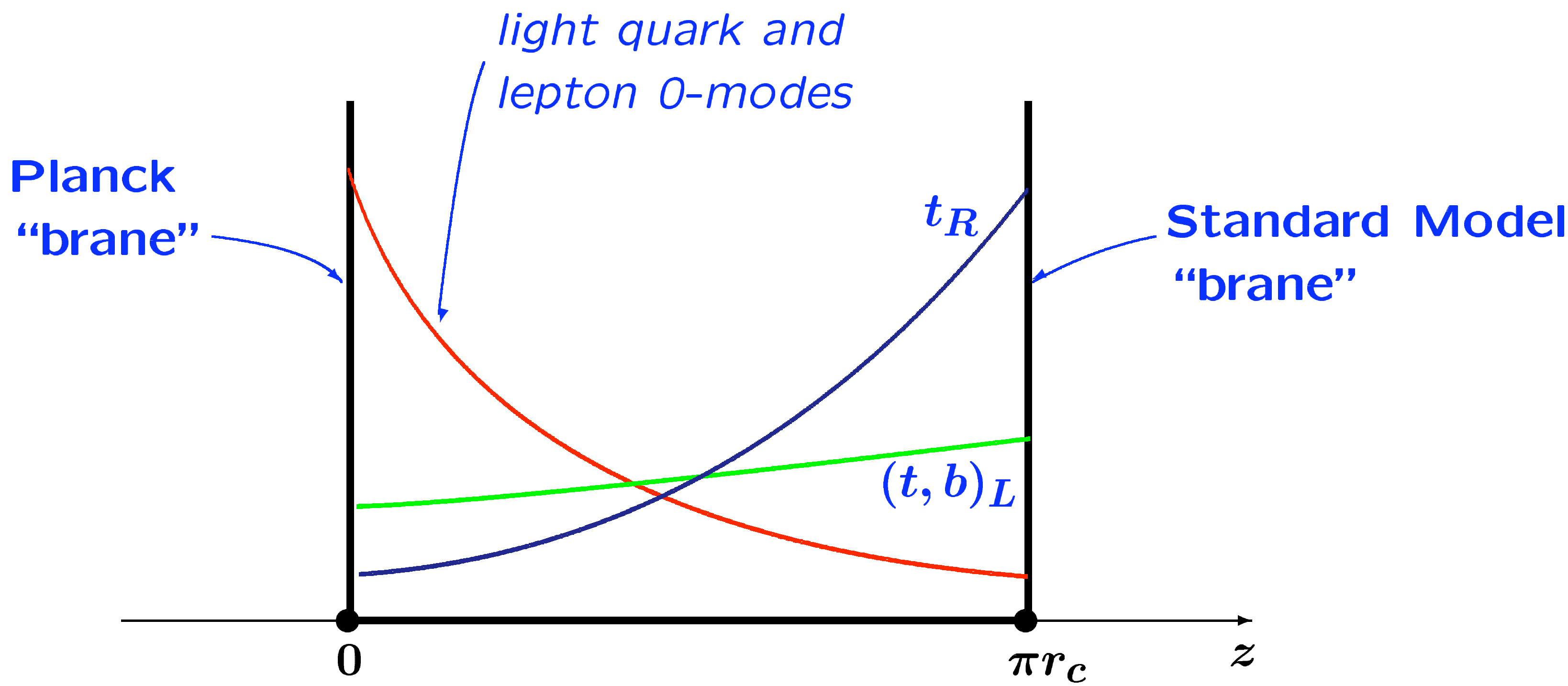
- For 5d gauge bosons, the zero mode wavefunctions are flat in the warped direction.
- The massive KK gauge boson partners have wavefunctions concentrated near the TeV brane.
- For 5d fermions, the zero modes can be localized at either the Planck or the TeV brane or neither, depending on the 5d bulk mass parameters.

A warped theory of flavor



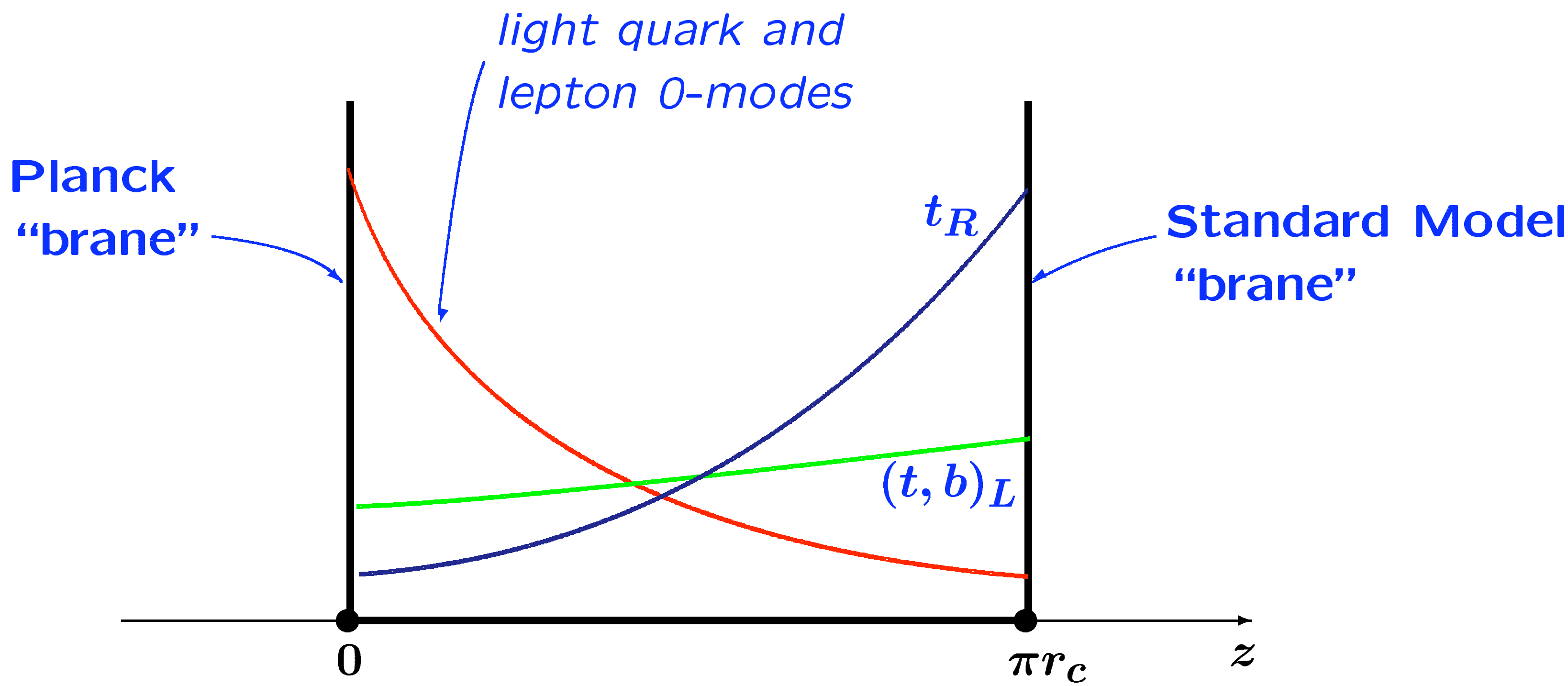
- These features suggest that warped models could also explain the mysterious *flavor* hierarchies of the SM.
- The basic idea is that the Higgs lives on the TeV brane, or is localized near it.
- Then fermion zero modes with wavefunctions localized nearer the Planck brane will be light (because of wavefunction suppression), while those localized near the TeV brane will have ~weak scale masses.

Revenge of EWPT



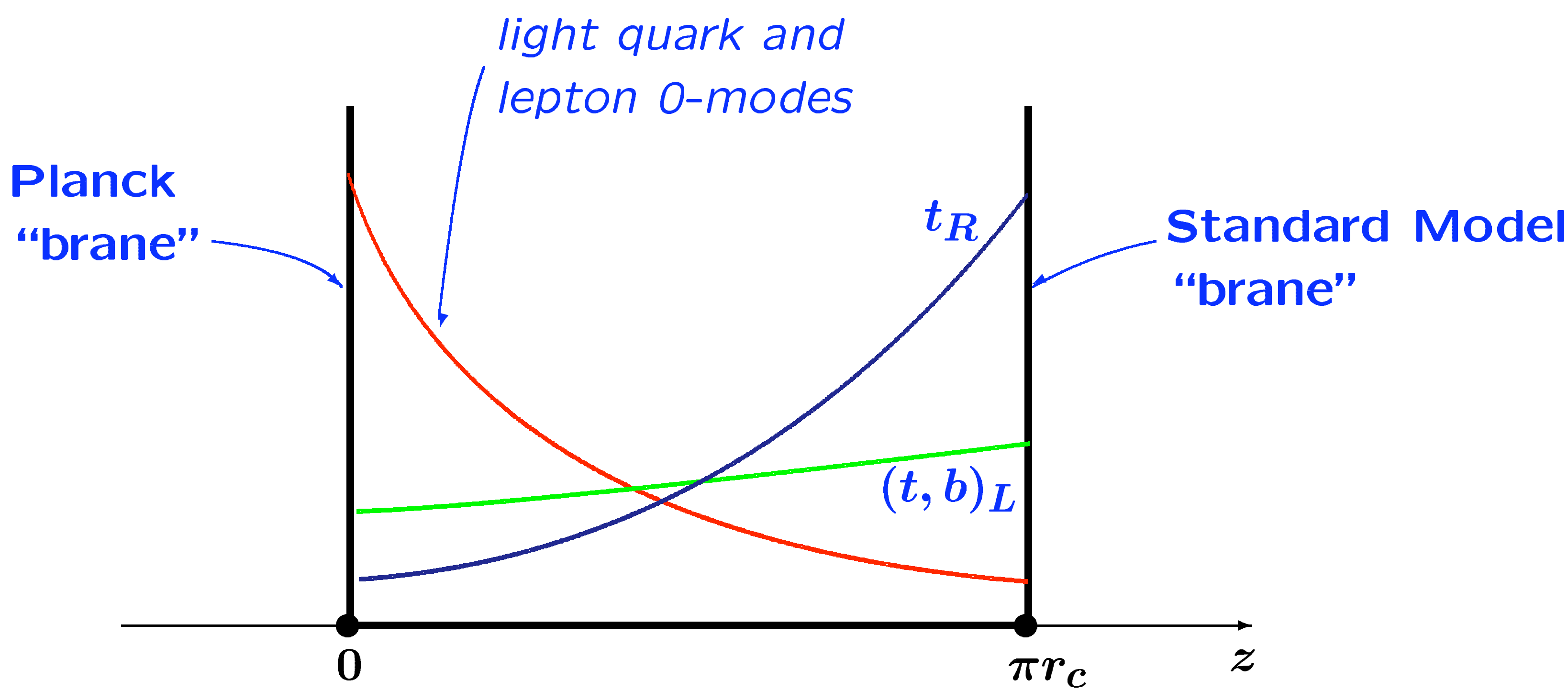
- Unfortunately such models get into trouble with EWPT (also proton decay).
- There is a tree level mixing of the KK gauge bosons with W,Z, leading to rather large contributions to S and T.
- There is also a tension between getting a large enough top quark mass and not messing up the well-measured Zbb coupling.

Revenge of EWPT



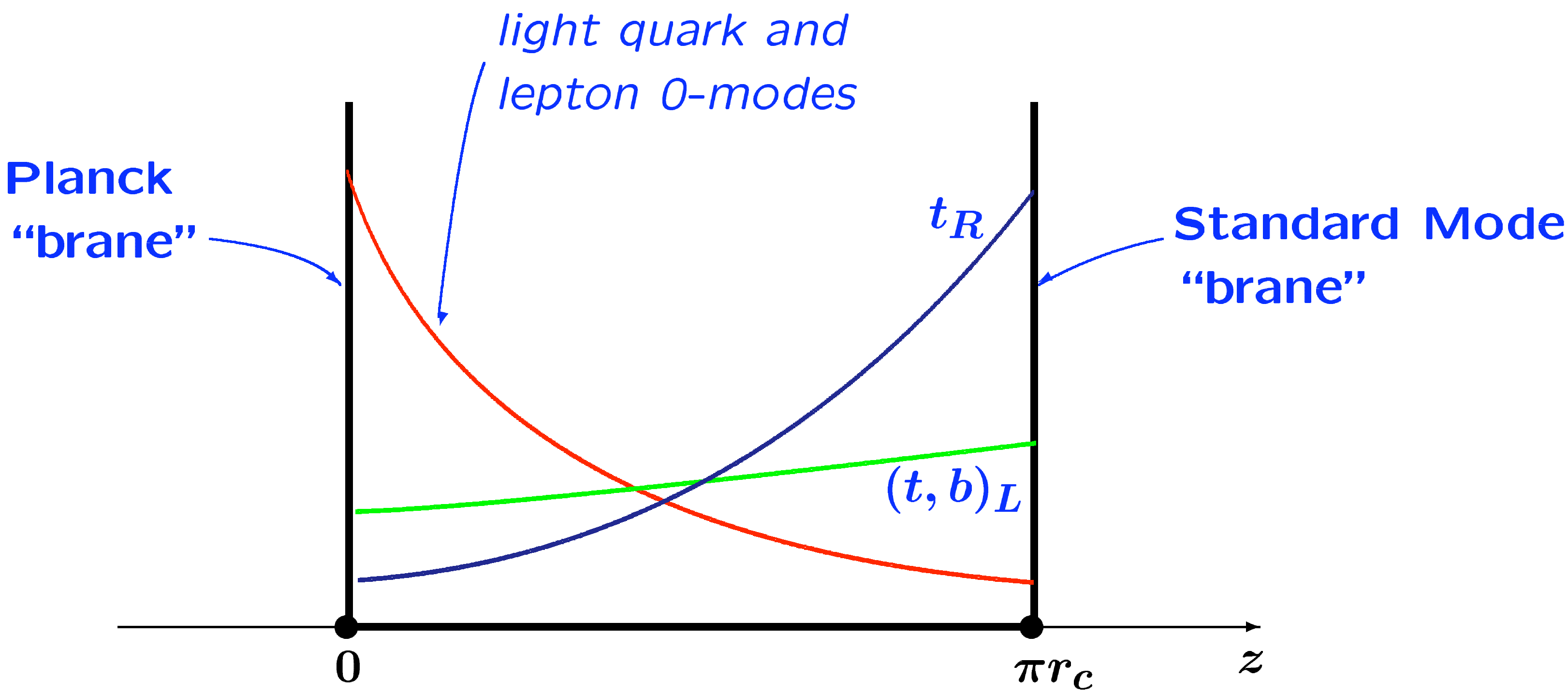
- Even with clever ideas, a complete warped theory of flavor not in conflict with EWPT requires pushing the lightest KK gauge boson mass up to 4-5 TeV.
- If you give up on complete theory of flavor, you can push this back down to 2.5 - 3 TeV.

Revenge of EWPT



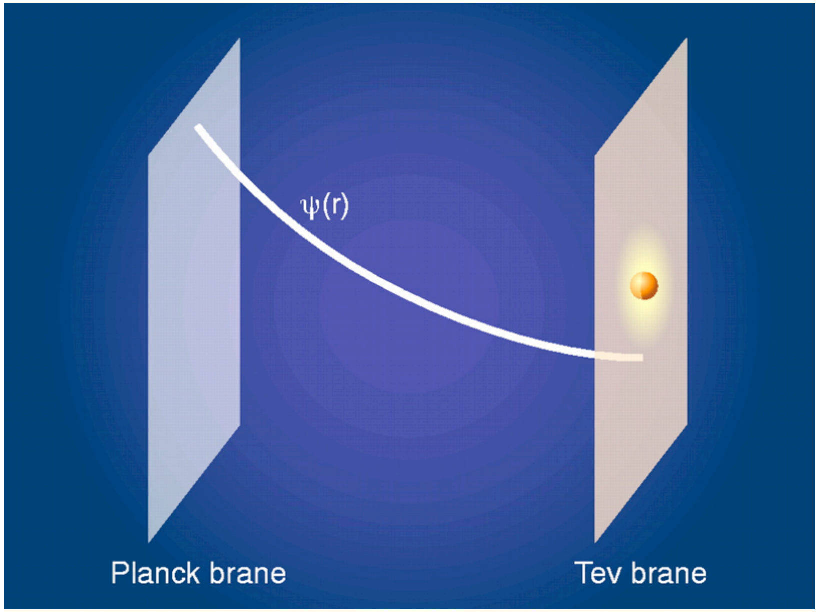
- **On the bright side, solving the Zbb problem and the Higgs naturalness problem in warped models leads to the introduction of interesting exotic fermions, e.g. a charge 5/3, mass=~500 GeV partner of the top quark.**

warped dark matter?



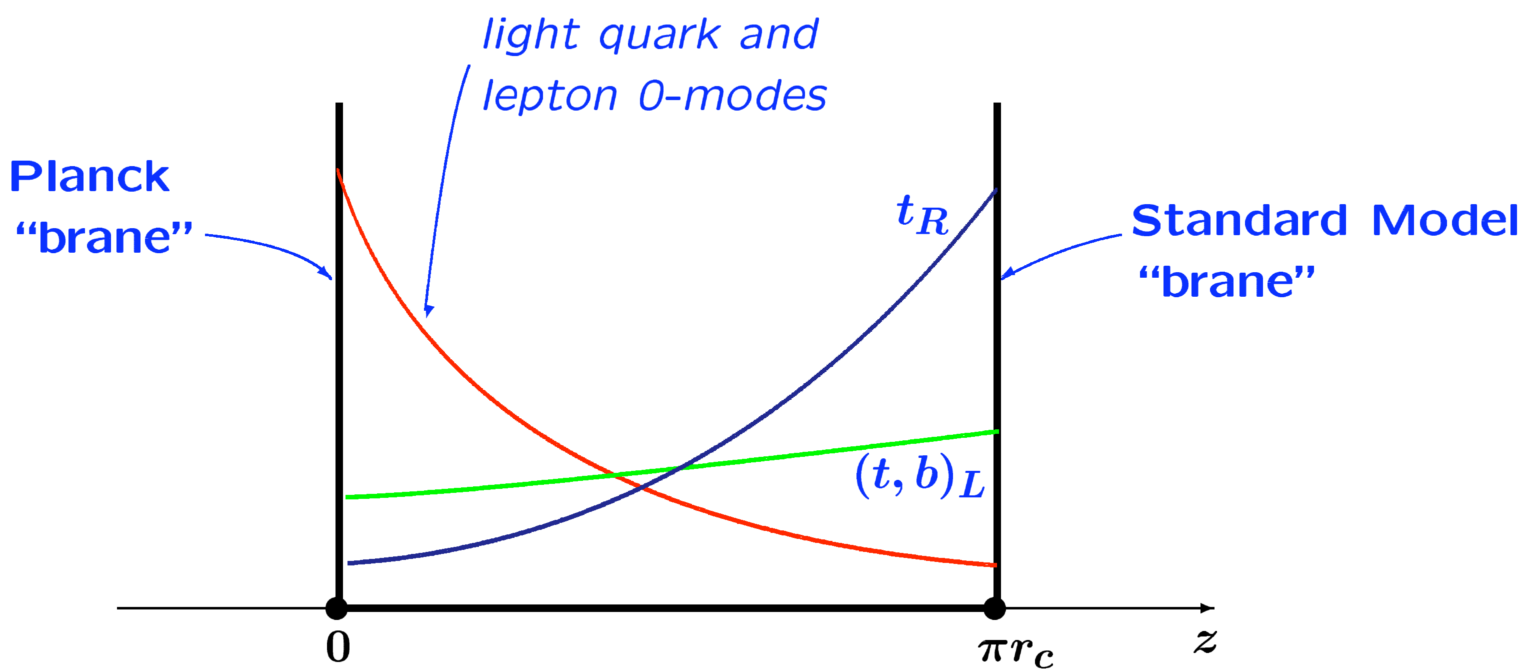
- Unlike SUSY, UED, Little Higgs, warped models have no obvious parity to simultaneously relax the EWPT constraints and provide a dark matter candidate.
- It is possible to get warped dark matter, but it is not generic.

AdS/CFT correspondence



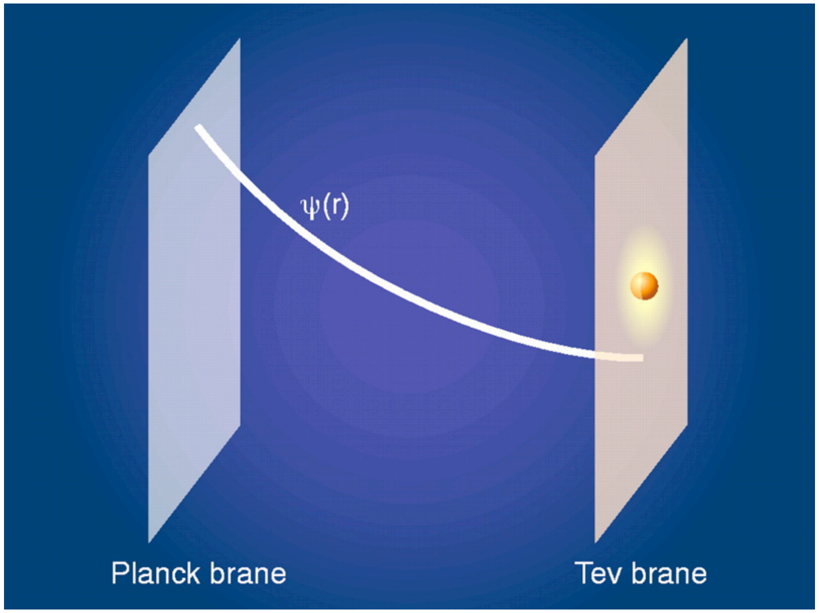
- There is now overwhelming evidence that weakly-coupled supergravity in 5d AdS is THE SAME PHYSICS as a strongly-coupled 4d superconformal gauge theory.
- For 5d warped models, this means that there is a DUAL 4d gauge theory that gives the same physics.
- In the 4d dual theory, what we were calling massive KK modes are instead composite bound states of some strong gauge interaction.

warped technicolor



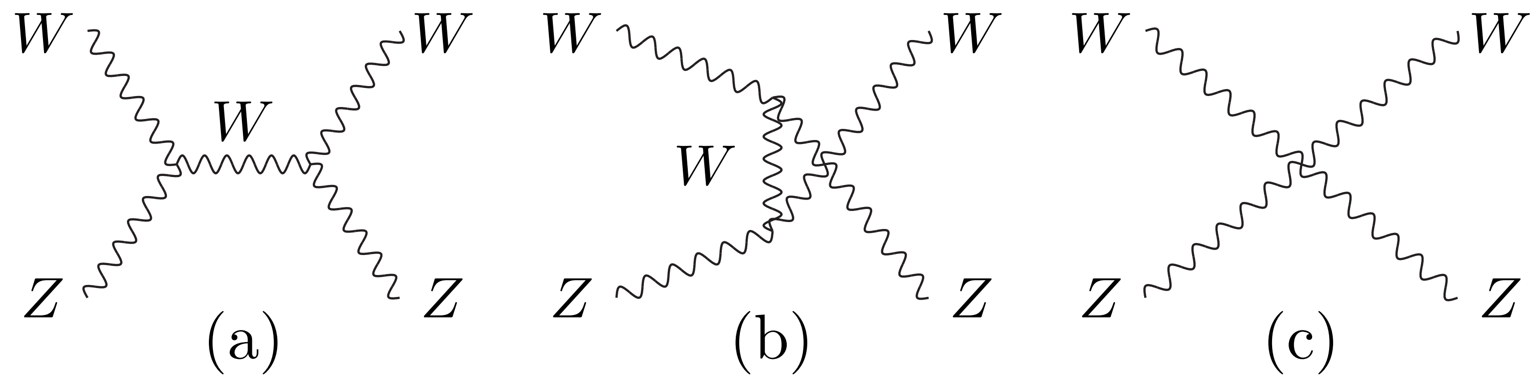
- So all of the fancy 5d warped models are secretly improved versions of Technicolor (more precisely, “walking” Technicolor).
- Thus the Higgs and the right-handed top quark are composites.
- The left-handed (t,b) doublet are mixtures of composites and fundamental fermions.
- Warped models and Technicolor have analogous problems with EWPT, but in principle could be complete theories of flavor.

Higgsless models

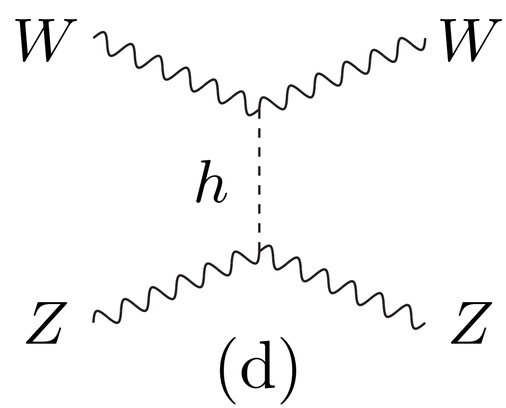


- In warped models you can use boundary conditions to break electroweak symmetry, and have no Higgs boson.
- These seems to conflict with the argument we used to fund a certain $10 billion collider…

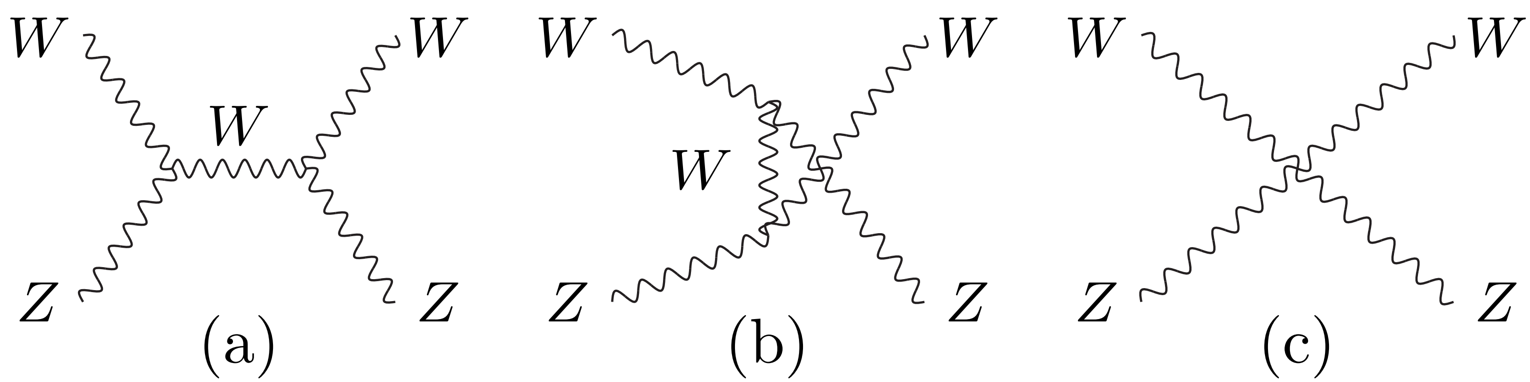
Unitarity requires a Higgs boson?



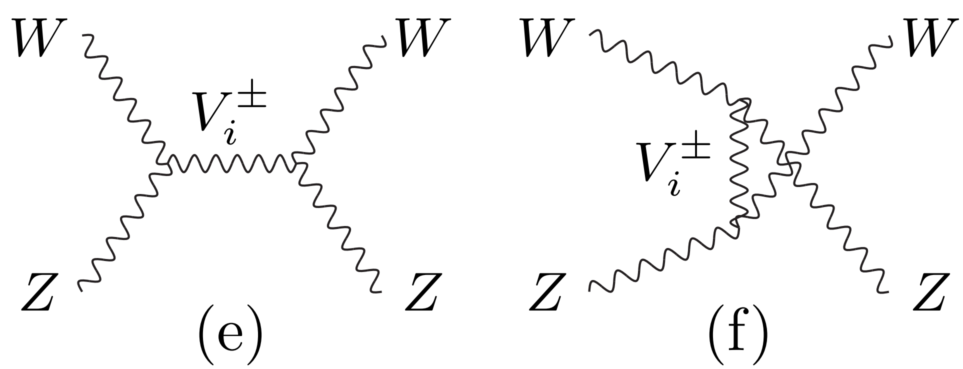
these diagrams give amplitudes that grow like $\mathbf{E^4}$ and $\mathbf{E^2}$, violating unitarity a little above a TeV



adding this Higgs diagram magically cancels the $\mathbf{E^4}$ and $\mathbf{E^2}$ behavior



But Higgsless models exist in which (weakly coupled) Kaluza-Klein gauge bosons do the same job (!)



Higgsless models have problems with EWPT, but can be made to work. They predict ~700 GeV KK gauge bosons.

Unparticles

- In Lecture 2 we said that conformal invariance requires either only massless particles or particles with a continuum mass spectrum. The latter has not been seen in Nature, but there might be a "conformal sector" weakly coupled to SM fields.

- In this conformal sector it doesn't really make sense to talk about particles, but there are well-defined operators with well-defined mass dimensions (which in general will not be integers).

- If there are couplings between these operators and operators made of SM fields, then energy+momentum can be transferred back and forth between these sectors.

Unparticles

$$\bar{\psi}(\mathbf{x})\gamma^{\mu}\psi(\mathbf{x})\,\frac{\mathcal{O}_{\mu}}{\mathbf{\Lambda^{d-1}}}$$

- Since these interactions with CFT operators mimic interactions with new particles, we call these CFT operators “unparticles”. But they have noncanonical mass dimensions, weird propagators, etc.
- They are (presumably) weakly interacting with SM particles.
- Since there would be lots of them, they would still be produced at the LHC with reasonable cross sections.
- But once produced they would probably not interact with the detectors.
- So this is another missing energy signature!

Quirks

- **QCD has a built-in scale $\Lambda_{\rm QCD} \sim 200$ MeV that comes from dimensional transmutation (i.e. the running of the gauge coupling such that, at a certain energy scale, the QCD interactions become strong).**

- **It just so happens that in QCD this scale is much larger than the masses of the light quarks ~ 10 MeV.**

- **When you try to pull a quark out of a hadron, a “string” or fluxtube of gluonic energy forms, with an energy per unit length of about $\Lambda_{\rm QCD}^2$.**

- **This immediately provides enough energy to create quark-antiquark pairs, and the string “fragments” into color singlet hadrons.**

Quirks

- **Now suppose that there is some new strong gauge force between some new massive particles ("quirks"). Suppose that the new particles also carry some SM charge, so we can pair produce them at the LHC if their mass M is <~TeV.**

- **Now suppose that, for these new particles, the analog of the QCD scale, $\Lambda_{\mathrm{QCD'}}$, satisfies $\Lambda_{\mathrm{QCD'}} << \mathrm{M}$.**

- **So if we make a pair of these particles, they will have a "gluonic" string between them that is hard to break.**

Quirks

- If the new scale is small enough, the string between the quirks will have macroscopic size.
- Thus at LHC it will look like you have produced oscillating strings.
- If the strings are somewhat smaller, ~microns, then the quirk-string-quirk system may reconstruct as a single particle, with a “mass” that varies event-by event.

Black holes

- All of the press and lawsuits about black production at the LHC are based on the serious idea that the energy scale where gravity becomes a strong force may be much less than our naive estimate of 10^{19} GeV.

- For example, if you have n extra spatial dimensions all compactified on circles of size R, then as soon as start to probe distances less than R, the suppression of gravity effects decreases from $1/\mathrm{M}_{\mathrm{Planck}}$ to $1/\mathrm{M}^*$, where

$$(\mathbf{M}^*)^{\mathbf{n+2}} = \frac{\mathbf{M}^{\mathbf{2}}_{\mathrm{Planck}}}{\mathbf{R}^{\mathbf{n}}}$$

Black holes

- Could gravity become strong a 1 TeV?
- Well if it did, gravity we have effects on electroweak precision observables. But we don't see such effects.
- But could gravity become strong at 4 or 5 TeV, still within the direct reach of the LHC?

Black holes

- When gravity becomes strong, hard collisions will mostly produce black holes. This argument is just based on black hole entropy, not on any theory of quantum gravity.

- However at somewhat lower energies we should see the physics of superstrings or whatever it is that makes quantum gravity work.

- Thus for example, I would expect to see excited superstrings at lower energies than I would be making black holes.

- So it is more likely that LHC experiments will see such exotics than that they will see black holes.

The Great Beyond

- What is the probability that LHC experiments will see something really weird?
- Applying Wagner's theorem, with the appropriate Bayesian prior, the best estimate is 50%.
- Alternatively, we an consult a leading theorist, Prof. Werner Heisenberg…

W. Heisenberg (read by H. Kramers)

" *The Limits of the Applicability of the Present System of Theoretical Physics* " **1939**

He identified 2 fundamental problems:

- The ultraviolet divergences of quantum field theory
- Multiparticle production in cosmic ray showers

Both imply a FUNDAMENTAL LENGTH

$$r_0 = \frac{e^2}{mc^2} \sim \frac{1}{m_p} \sim 3.10^{-13}\, cm.$$

" *below which the concept of length loses its significance* "

and quantum mechanics breaks down at $x < r_0$

slide by David Gross, Oskar Klein Symposium, 1998

Be ready for the unexpected