Branes Worlds

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Exploring Extra Dimensions

- Example 1: Holography, cosmology and braneworld black holes.
- Example 2: black holes and how far can we push ads/cft?
- Example 3: Signatures of extra dimensions in cosmology
- challenges

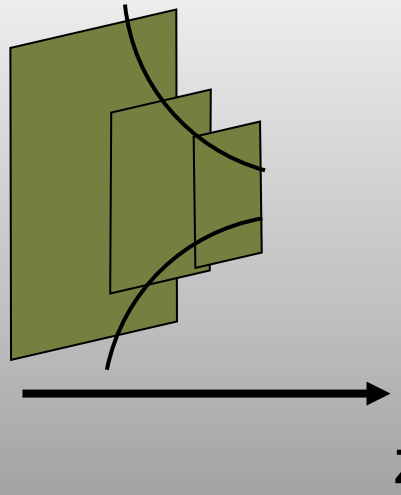
WHY?

Gravity and Extra Dimensions

- Einstein's GR is a successful theory, relating a fundamental observable (distance) to matter content of the Universe.
- But we could have modifications – extra dimensions – extra terms changing gravity in the UV and/or IR
- and the fact remains that over 95% of our universe is unknown!

Randall-Sundrum

The most compelling braneworld is a very simple model, based on branes in anti-de-Sitter space. Geometry away from the braneworld is strongly *warped.* Hierarchy between central (Planck) brane and brane at z_0.



$$ds^2 = e^{-2k|z|} [\ \eta_{\mu\nu}\, dx^\mu\, dx^\nu\ ] - dz^2$$

Warp factor *Flat spacetime* *Extra dimension*

Example 1:
Cosmology to black holes

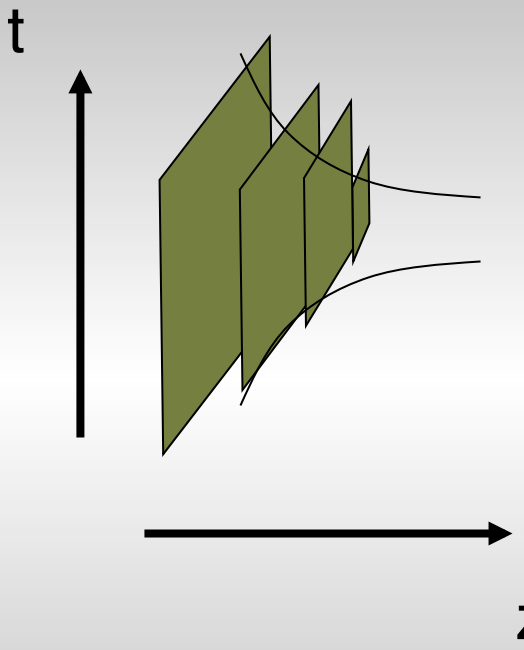
Although many problems as a real model, a useful tool and testing ground for more grandiose ideas.

Even though we can calculate a great deal analytically, we also rapidly hit the need for numerics.

Perfect for this conference!

Example 1:

Cosmology to black holes



RS cosmology turns out to be analytically tractable – the braneworld evolves in time, and the geometry warps into the extra dimension.

$$ds^2 = A^2(t,z)[dt^2 - dz^2] - B^2(t,z)\, d\mathbf{x}^2$$

$$E = E_0 + \rho$$
$$T = E_0 - p$$

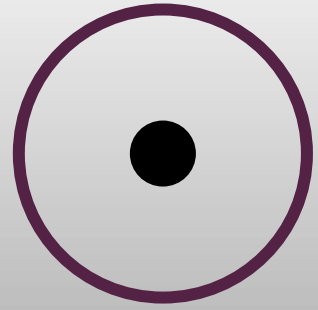
Because we want a brane-FRW universe, we now no longer have the energy equal to tension on the brane.

Cosmology as Geometry

There is sufficient symmetry that spacetime away from the brane is totally known (a black hole) and the cosmological brane is simply a slice equidistant from the horizon! The trajectory *defines* the scale factor.
From the point of view of the braneworld observer the cosmological equations are

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{\kappa}{a^2} = \frac{8\pi G\rho}{3} + \left(\frac{G\rho}{\lambda}\right)^2 + \frac{\mu}{a^4}$$

Modified Friedman Equation



R = a(t)

Braneworlds and Holography

Notice the effect of the bulk black hole on the brane: μ/a^4 is the same as a radiation dominated Universe, although our brane is empty! However, black holes radiate, and a QFT will be in a thermal state in a black hole background.

Classical Bulk Gravity  Quantum Corrected Brane gravity

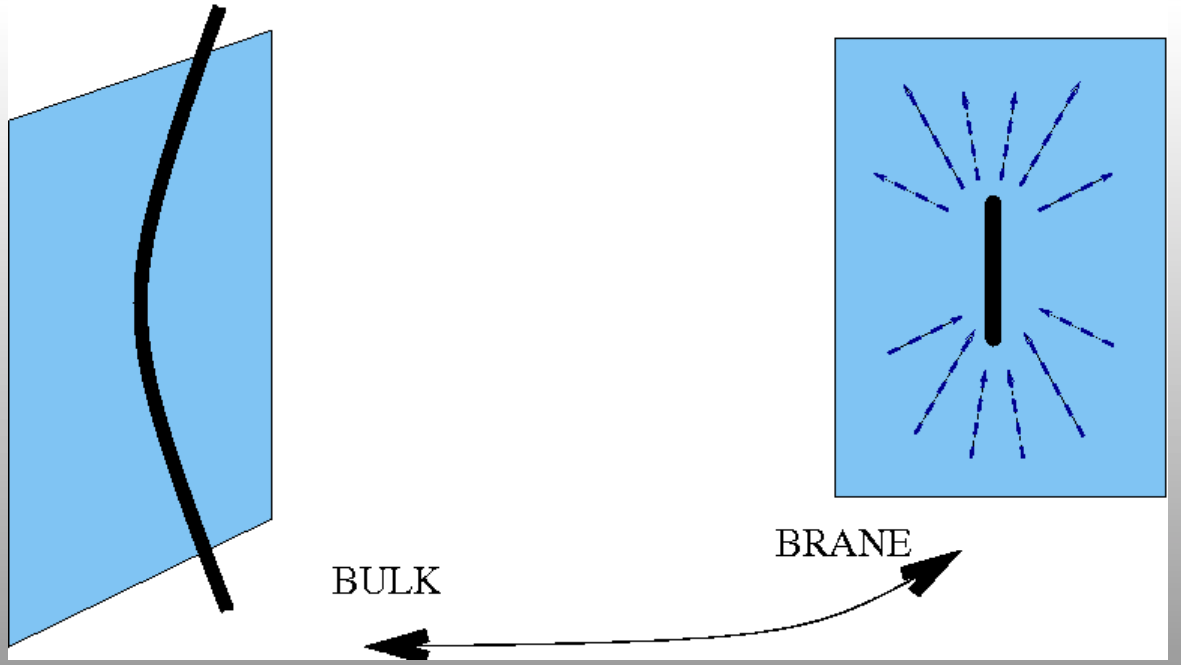
Gubser, Verlinde, Duff….

Brane Black Hole?

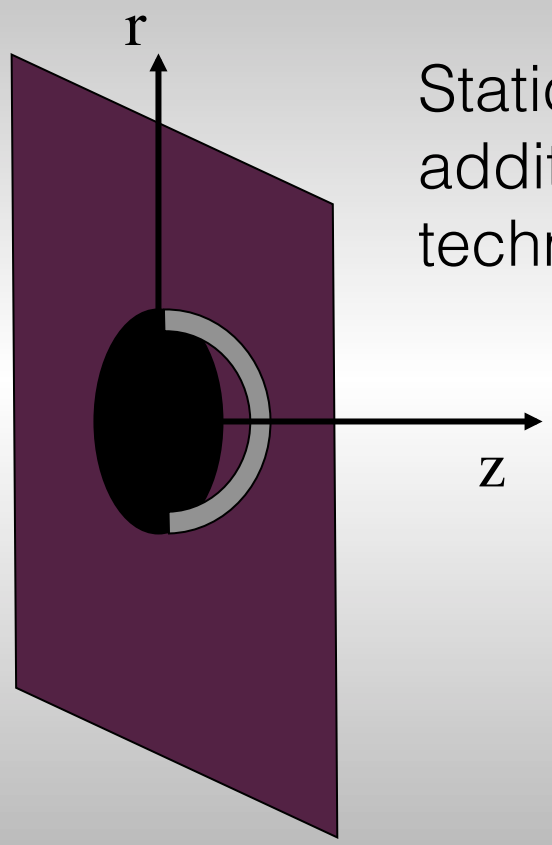
If we displace the bulk black hole a little, and allow it to move towards the brane, then from the brane point of view this might correspond to collapsing radiation, formation of a black hole, and subsequent evaporation.

Hawking radiation might simply be the result of a bulk dynamical process.

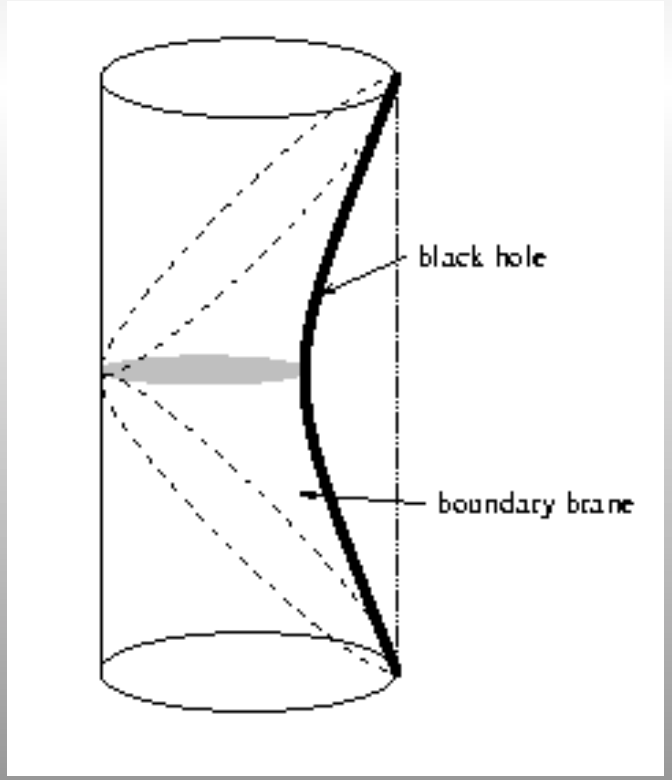
Tanaka: gr-qc/0203082



Brane black holes?



Static or Time dependent? Unlike cosmology, additional field prevents integrability. Analytic techniques limited.



C-metric

Holographic Conjecture

Emparan, Fabbri, Kaloper: hep-th/0206155

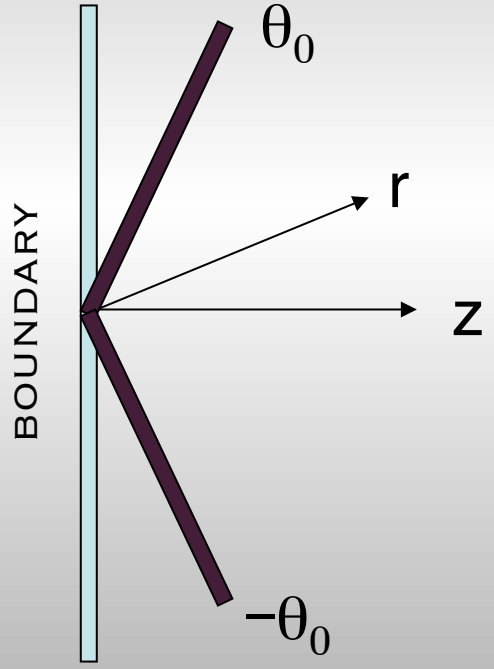
From both linearized and cosmological brane gravity, there is evidence to support a **Holographic Conjecture**: that a classical bulk solution corresponds to a quantum corrected braneworld solution.
However, this conjecture relies on the fact that N^2h is finite as $h \to 0$.

- ***All*** the N^2 states have to be accessible.

Fitzpatrick, Randall, Wiseman: hep-th/0608208

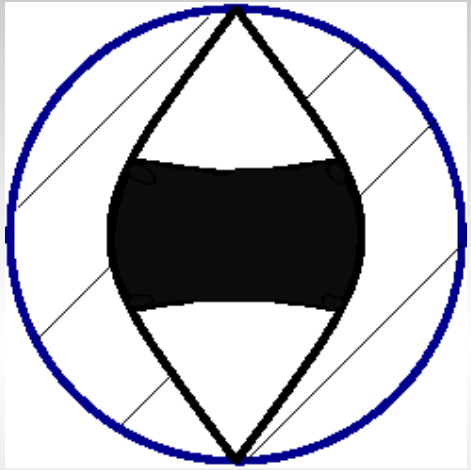
Testing Holography

It is difficult to get an exact RS solution (more from Toby) – but can explore holography with ads or Karch Randall branes.



Karch-Randall black string

A Karch Randall black string runs across the bulk between two positive tension branes and has no bulk horizon singularity. As for any black string, this has a classical instability at a characteristic wavelength, but since these strings have finite length, if the black string is massive enough - it is stable.



AdS black holes have two possible solutions at finite T, the large mass one being thermodynamically stable.

This appears consistent with the bulk classical instability.

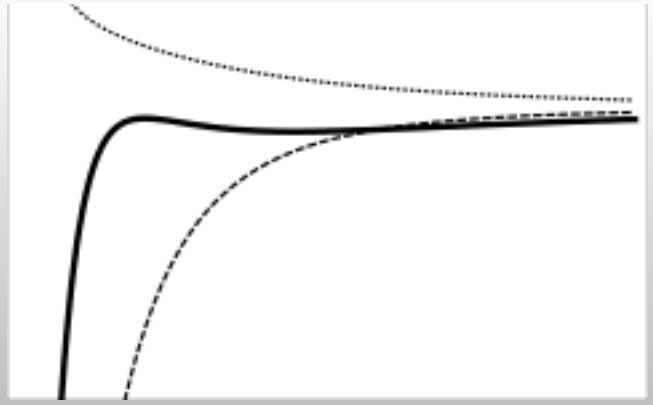
Quantum back-reaction (weak coupling)

RG, Simon Ross, Robin Zegers: 0802.2037 [hep-th]

At weak coupling, can use Page's heat kernel approximation, the energy momentum has three independent functions:

$$< T^{\mu}{}_{\nu} > \propto T_1(\delta^{\mu}{}_{\nu} - 4\,\delta^{\mu}{}_{0}\,\delta^{0}{}_{\nu}) + 3\,T_2\,\delta^{\mu}{}_{0}\,\delta^{0}{}_{\nu} + T_3\,\delta^{\mu}{}_{r}\,\delta^{r}{}_{\nu}$$

But the classical answer is proportional to the metric!



Appears holography not consistent with expected back reaction, access to the N^2 states disappears in the RS limit.

Example 2: ADS/CMP

- Black holes have a wide range of applications
- ADS/CFT is a fascinating tool to study strongly coupled QFT
- Can we go beyond conformal?
- ...and still be within string theory?

BACKGROUND

By its nature, the ADS/CFT correspondence concerns scale invariant systems, but often we want to study more general systems.
An interesting scaling is Lifshitz, in which there is a dynamical exponent:

$$t \to \lambda^z t \quad , \quad x \to \lambda x \quad , \quad r \to r/\lambda$$

Can we have such solns or asymptopia?
Can we build black holes?

Asymptopia

A simple way of getting Lifshitz scaling is to impose the obvious generalization of ads by hand

$$ds^2 = r^{2z} dt^2 - \frac{dr^2}{r^2} - r^2 dx^2$$

Computing the Ricci tensor implies background matter

$$R_t^t = z(z+2) \quad , \quad R_x^x = z+2 \quad , \quad R_r^r = z^2 + 2$$

Models

First achieved in 4D by having an empirical model with coupled 1 and 2-form gauge fields. *(Kachru, Liu, Mulligan)*
As always, empirical models useful, but would like to have a holographic correspondence with a field theory, hence embed in string theory.

Can do this via consistent truncations of IIA and IIB supergravity. *(RG, Parameswaran, Tasinato, Zavala)*

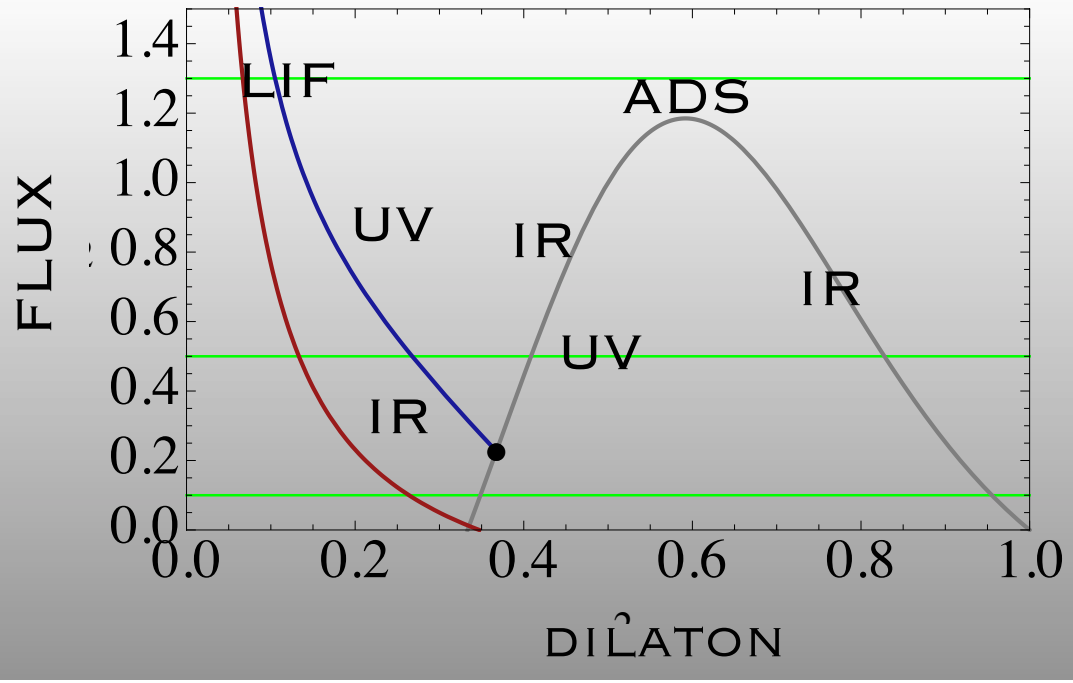
6D Romans

This has dilaton, massive 2-form and nonabelian gauge field. Lifshitz solution has compact H^2 carrying flux. 1-parameter family of analytic solutions determined by z for ANY z.

$$F^3_{tr} = L^2 Q r^{z-1}$$

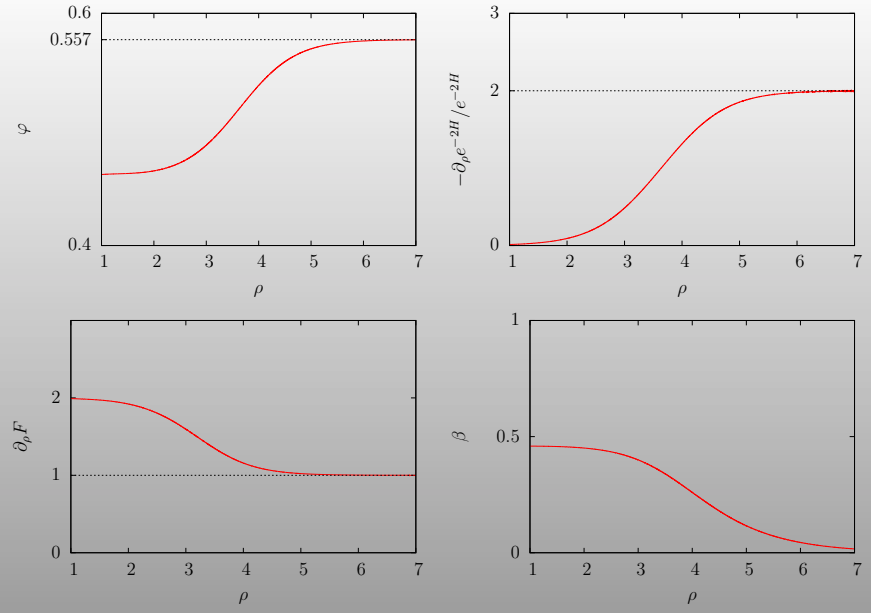
$$F^3_{y_1 y_2} = q\varepsilon_{12}$$

$$B_{x_1 x_2} = L^2 P r^2 / 2$$



Flows

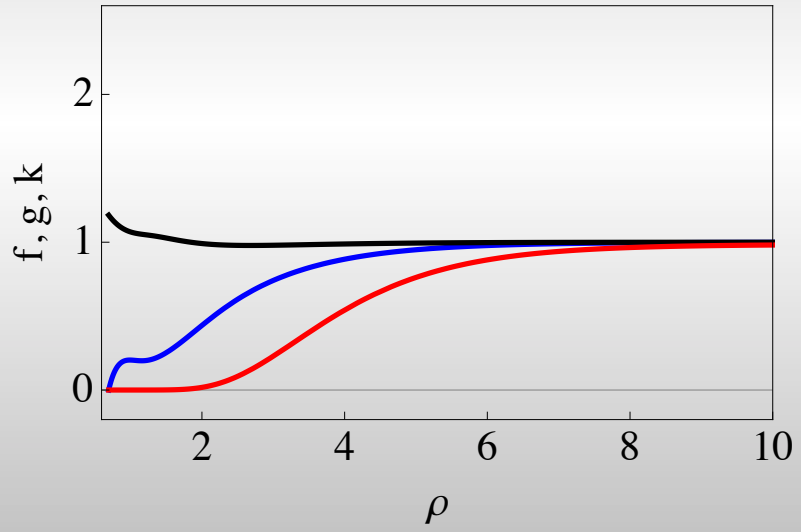
Some simple numerical techniques can be used to find flows between Lifshitz and AdS solutions. These will correspond to a field theory with different dynamical scaling at different scales

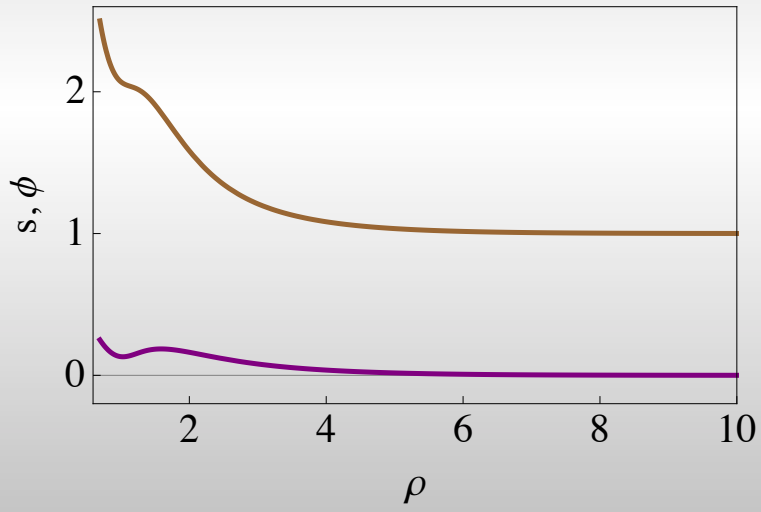


(Braviner, RG, Ross)

Black Holes

Black holes must also be found numerically.

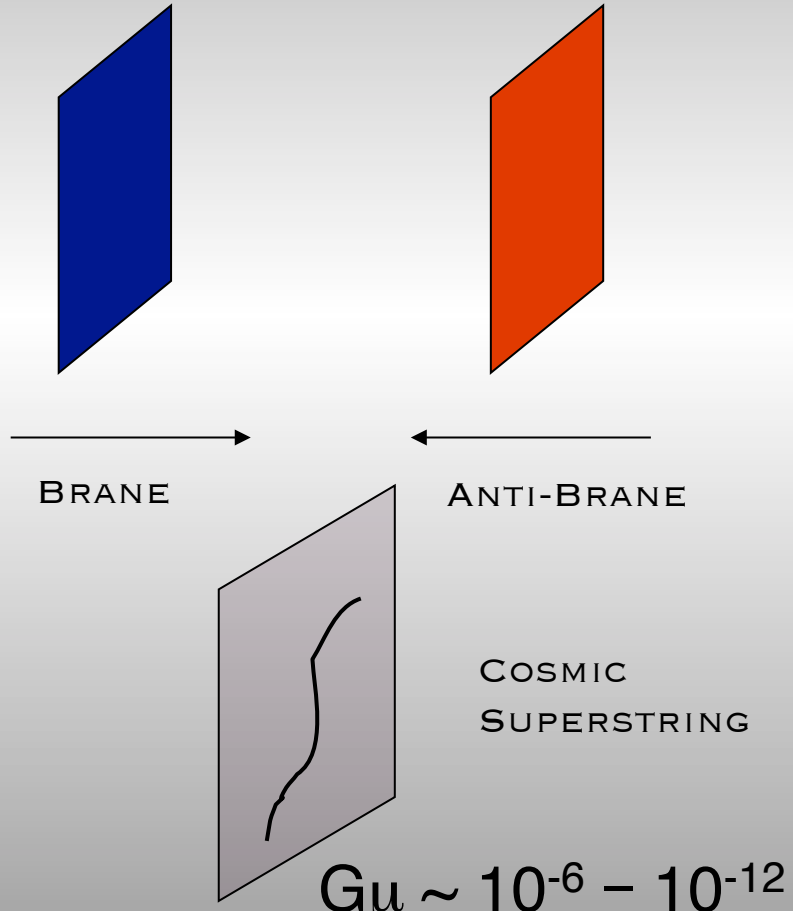




(Luke Barclay)

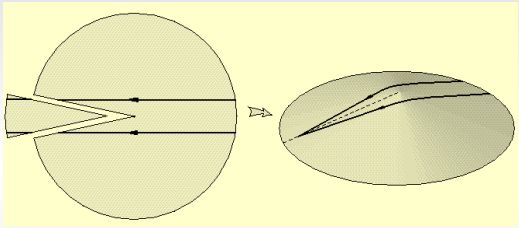
Example 3: Effects of Extra Dimensions

Models of *BRANE INFLATION* from string theory have the inflaton as a distance modulus in some internal large extra dimensions.



Detecting Strings?

Strings are detected via gravity, rather than particle physics:



- Gravitational lensing

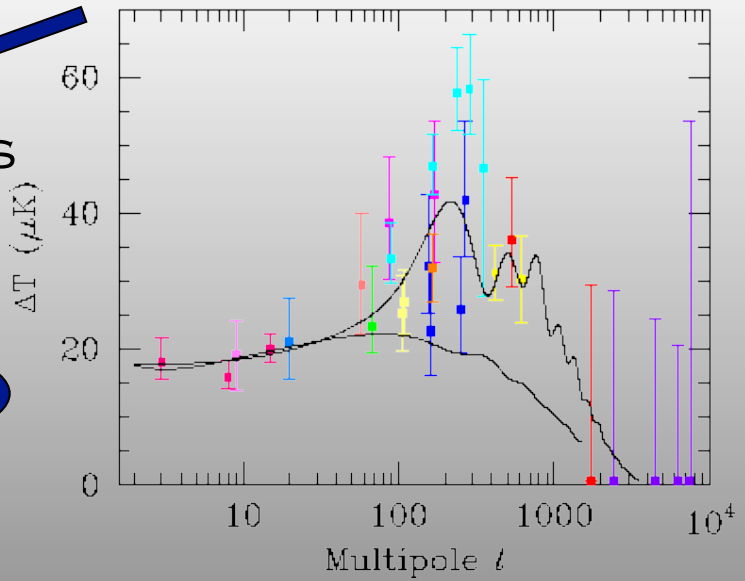
  Some candidates, no detection

- Gravitational perturbations

  CMB: $G\mu < 10^{-7}$, Pulsar: $G\mu < 10^{-6}$

- Gravity wave background

  No positive detection

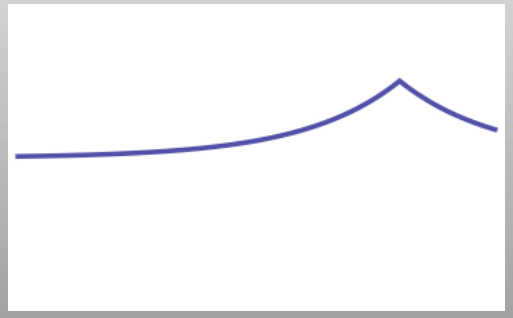


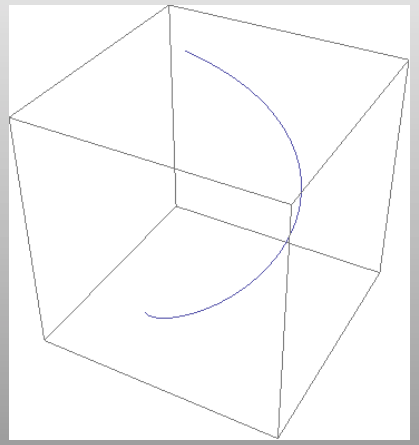
Cusps and Kinks

While the string is smooth, the gravitational radiation has low power, but the string can have a sharp profile for two reasons:

- KINKS: occur when a string self-intersects and cuts off; the loop or string has a kink in it. [One of $\mathbf{a}'$ or $\mathbf{b}'$ discontinuous]

- CUSPS: occur when the left and right moving waves constructively interfere to allow the string to (instantaneously) move at the speed of light. [$\mathbf{a}'$ and $\mathbf{b}'$ align]





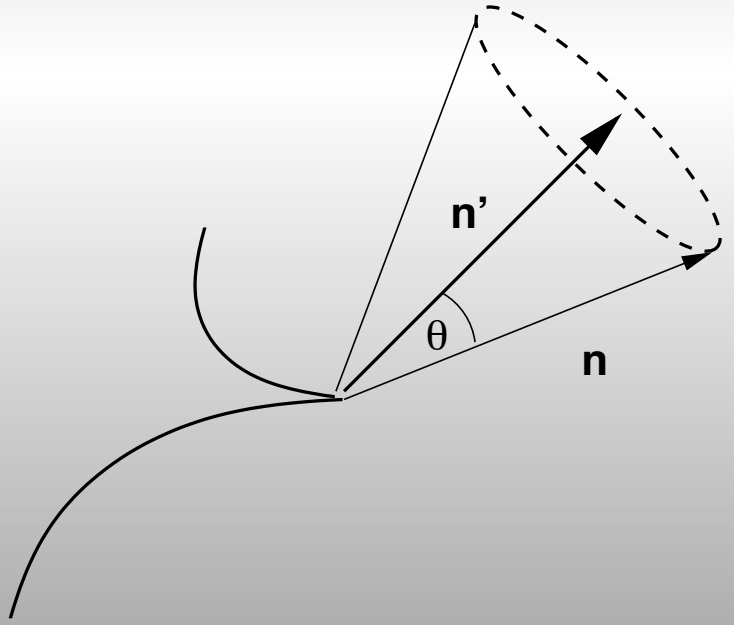
Cusp Signal

The left and right moving modes each contribute to $h_{\mu\nu}$ so when these align, a strong signal is produced – the CUSP

- Cusp beams out gravity waves in a tight cone around the cusp vector
- Opening angle defined by saddle point of $I_{\pm}$

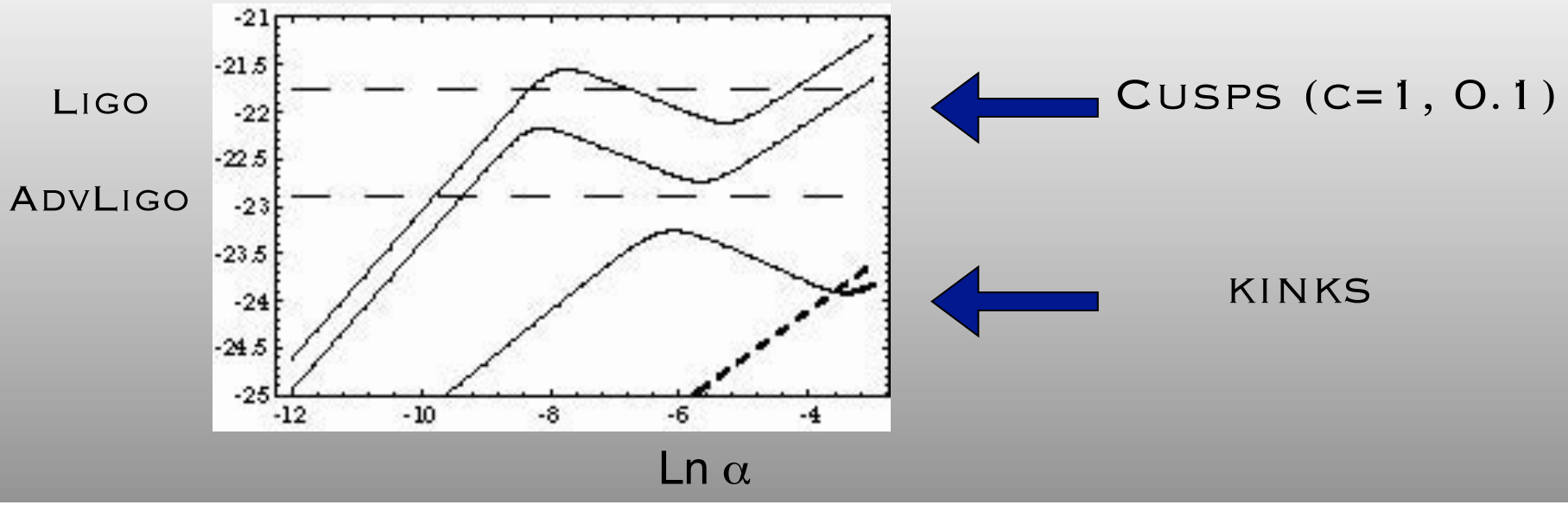
$$h^{cusp}(f,\theta) \approx \frac{G\mu L^{2/3}}{r|f|^{1/3}} H\left[\theta_m - \theta\right]$$

$$\theta_m = \left(\frac{2}{Lf}\right)^{1/3}$$



DV Ligo result

Damour and Vilenkin use analytic approximations, and take a desired event rate of 1 per year. Signal dominated by maximal redshift, use this to obtain amplitude at desired fiducial frequency.

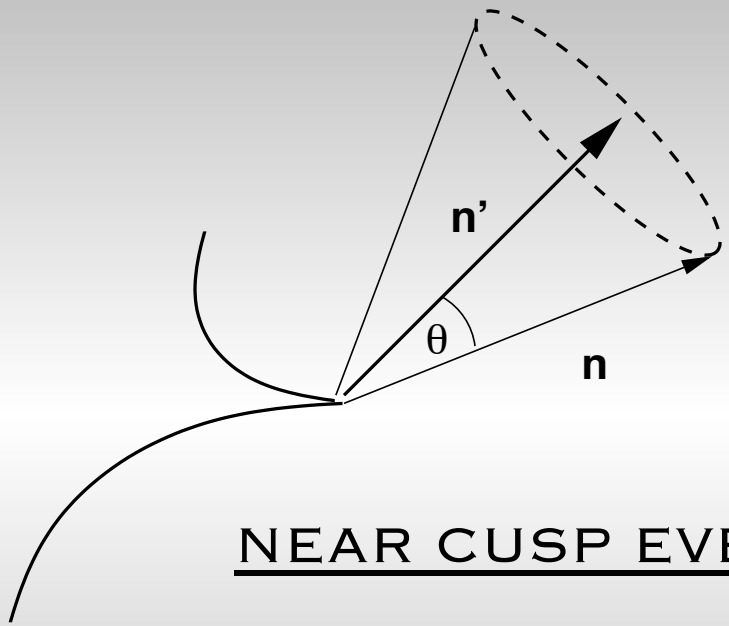


Cusp Rounding

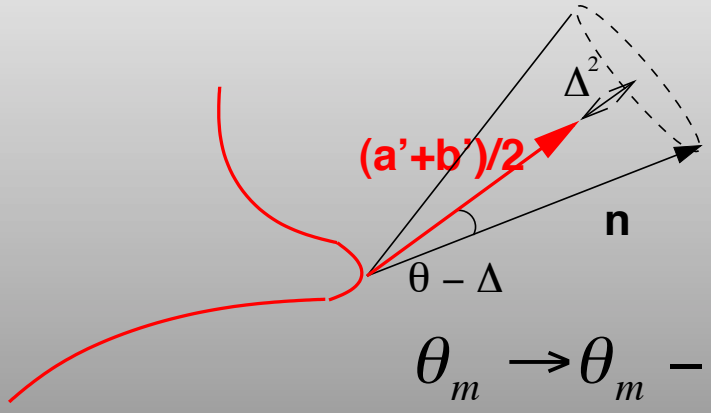
Extra dimensions cause the string to "slow down" and wave vectors of left & right movers no longer need be null.

This rounds off the cusp, narrowing the beaming cone.

$$\left|\underline{a}' - \underline{b}'\right| = 2\Delta << 1$$



NEAR CUSP EVENT



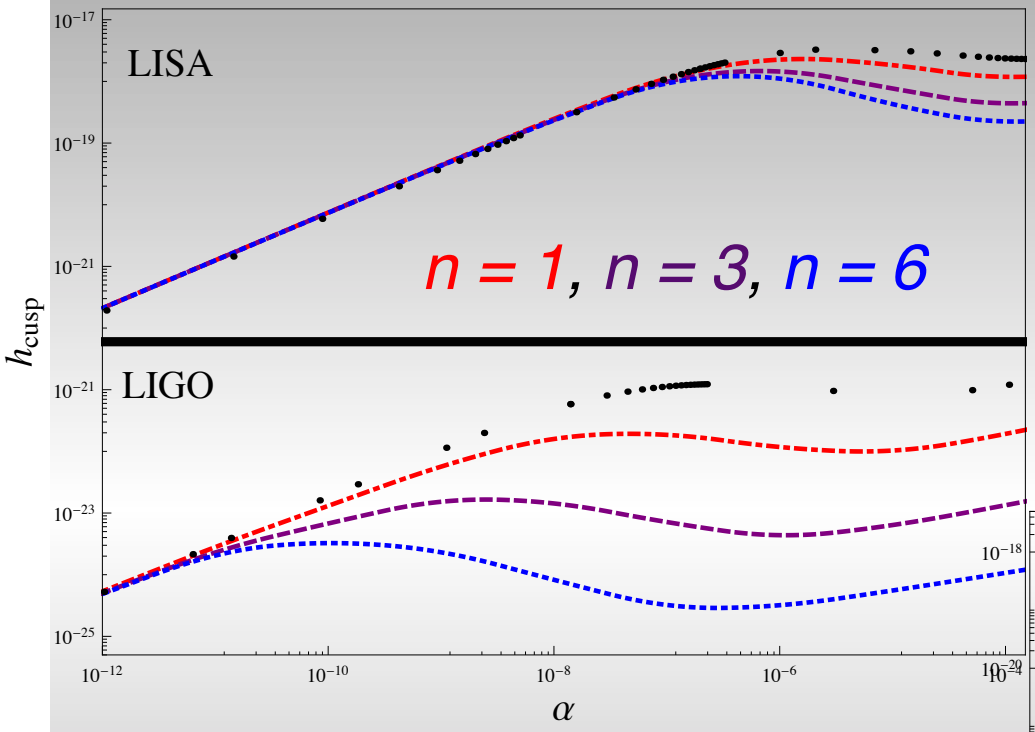
$$\theta_m \rightarrow \theta_m - \Delta$$

Measure Reduction

In 3d, cusps are generic, but in higher dimensions not so – have to estimate probability of near cusp event. Also model string width empirically by modifying zero width measure result:

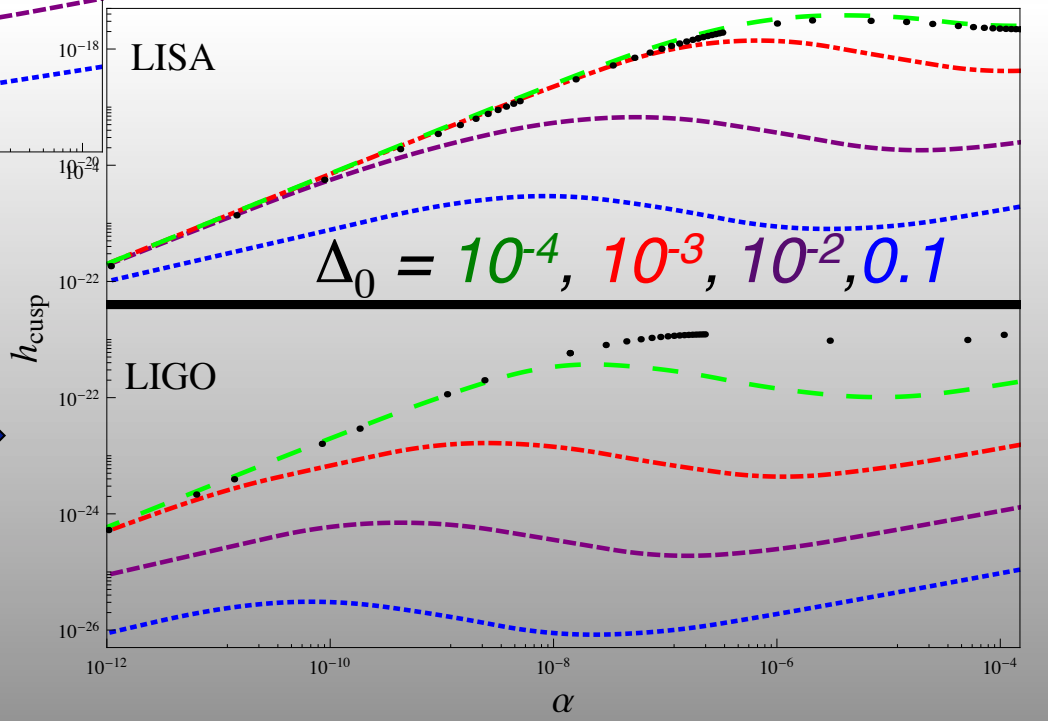
$$\Delta \in [0, \Delta_0] \quad \Rightarrow \quad C(\Delta) = \frac{n\Delta^{n-1}}{\Delta_0{}^{n}}$$

New Measure



FIX $\Delta_0=10^{-3}$

FIX $n = 3$



O'Callaghan, Chadburn, Geshnizjani, RG, Zavala, 1003.4335, 1005.3220

Numerical Opportunities

- Good understanding of brane black holes has implications for astrophysics, LHC physics and (perhaps) quantum gravity
- AdS/CMP – many systems with inhomogeneity – vortices, stripes…
- Holography and more general CMP systems a really open question!
- A great deal of opportunity in cosmology more generally.