A Quasilocalization Theory

w/ Andreas Karch

Time permitting:

Phenomenological Holography

w/ Nima Arkani-Hamed
Massimo Porrati

Spectrum of KK

fluctuations includes

<u>graviton bound state</u>

$\psi \sim e^{-k|y|}$ $\quad M_{4D}^2 \sim \frac{M^3}{k}$

Strongly peaked on "Planck" brane

massless graviton bound state

mediates conventional 4D gravity

What about mode analysis?

Again, analog Schrodinger Eqn in Volcano Potential

$$V = -\tfrac{9}{4}\sqrt{\Lambda} + \frac{15}{4}\frac{1}{\cos^2(k|z|+z_0)} - 3\tan z_0\,\delta(z)$$

$$z_0 = \mathrm{ArcSin}\left(\frac{L\sqrt{\Lambda}}{\sqrt{\Lambda}}\right) \qquad \left(\begin{matrix} z_0 \to L \\ \sqrt{\Lambda} \to 0 \end{matrix}\right)$$

$$-\left(\frac{\pi}{\sqrt{\Lambda}} - z_0\right) \le z \le \left(\frac{\pi}{\sqrt{\Lambda}} - z_0\right)$$

Physics in "box"

Discretization of Massive energy levels $\sim\sqrt{\Lambda}$

I. Propagator Analysis

Same equation (up to $e^{-\partial c}$ suppressed)
at $E \ll C$

AdS bran

Expect Newtonian force
laws at
Intermediate energy scales

Q: whats is force law?

What is spectrum?

Clearly, 0-mode not normalizable

but Expect at $r \gg \frac{1}{\lambda_{\to 0}}$

you should reproduce Newton's Law

Imagine $\Lambda \to 0$

Physics at 'short' distance

should be roughly Λ-ind

How does this work?

1. propagator argument
2. Expansion in KK model

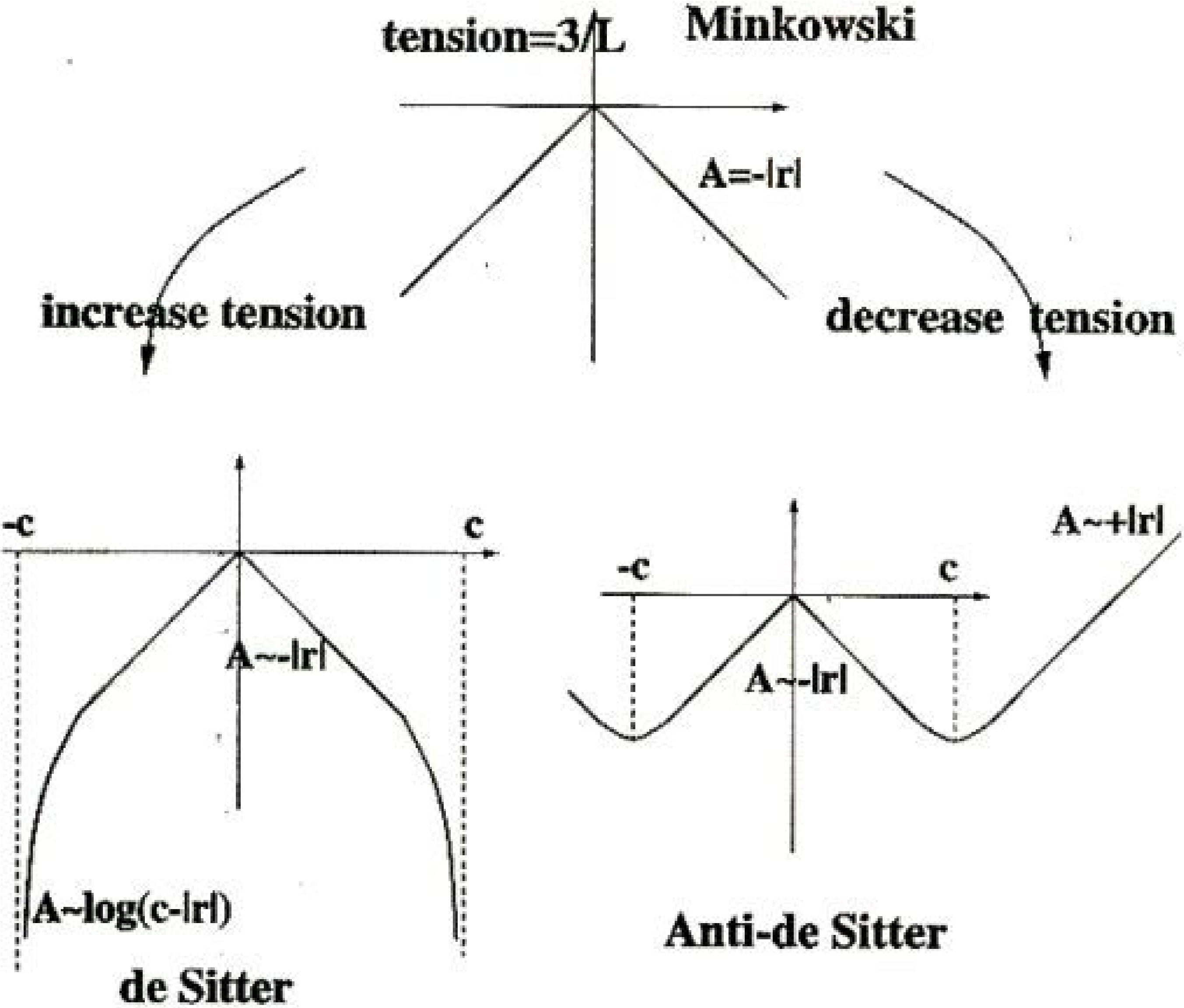


Figure 1: The behaviour of the warp-factor for $\Lambda = -1$, 0 and 1.

The Modified C-Theorem

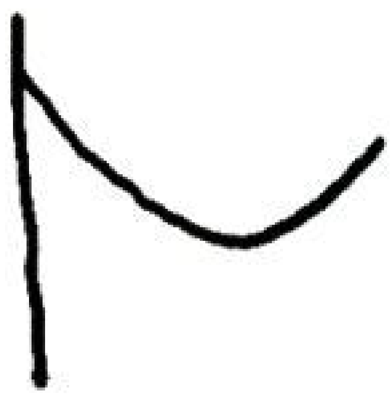
GRS proposal violates positive energy condition

$A'' \leq 0$ AdS

AdS_4 brane

$A'' \leq -\Lambda e^{-2A}$

supports quasi localization



AdS$_4$ brane in AdS$_5$

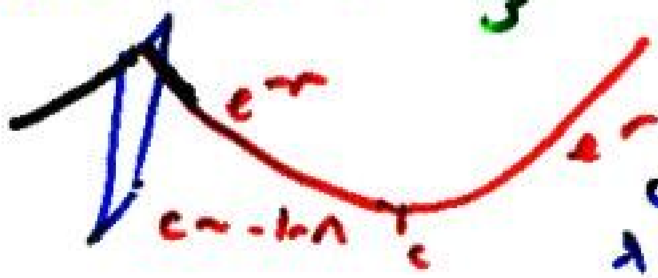
$$ds^2 = e^{2A(r)} \underbrace{g_{ij}}_{AdS_4} dx^i dx^j - dr^2$$

$$e^A = \sqrt{-\Lambda_0}\, L \cosh \frac{c-r}{L}$$

$$\sim e^{-r} + \underline{\underline{e^{-2c+r}}}$$

$$\Lambda_{4D} = \frac{1}{L^2 \cosh^2 c/L} = \frac{1 - \left(\frac{\lambda L}{3}\right)^2}{L^2}$$

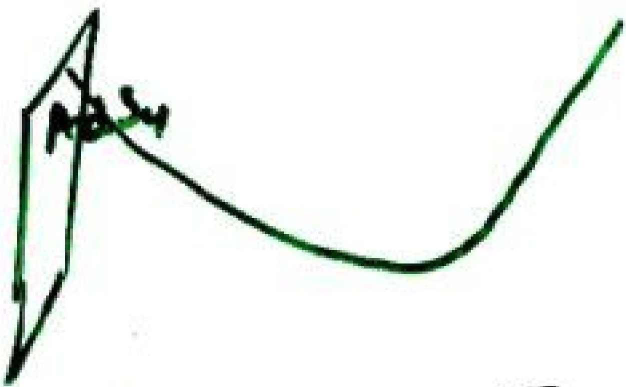
$$\tanh c/L = \frac{\lambda L}{3}$$



no brane
$\lambda = 0$
$c = 0$

critical brane
$\lambda = 3/L$
$c = \infty$

Quasi Localization on AdS_4 brane



$$ds^2 = \int d^5x \sqrt{g} \left[-\tfrac{1}{4} R - \Lambda^{5d} \right]$$

$$\Lambda_{5d} = -3/L^2 - \lambda \int d^4x \, dr \sqrt{\det g} \; \delta(r)$$

$\lambda_c = 3/L \Rightarrow$ flat (Mink) brane

$\lambda < 3/L \Rightarrow AdS_4$ brane

However, GRS proposal very controversial

I) Negative tension brane violates weak energy condition; unstable

II) Unacceptable classical potential, quantum effects?

- Massive graviton vs ghost
  Dvali Gabadadze Porrati
- Scalar antigravity! GRS
- Ghost resolution?
  Pilo Rattazzi Zaffaroni
- Also Csaki Erlich Hollowood Terning

Clearly good to address w/

Physical Stable example

* no violn weak energy condition

$ke^{-kr_c} < E < k$

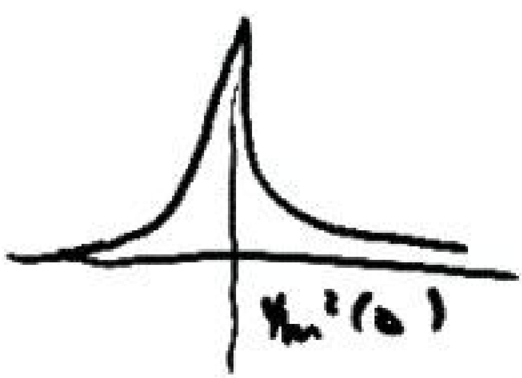
~ physics resembles localized gravity ⇒ "4-D" graviton potential

$E < ke^{-kr_c}$

Flat space (5D)

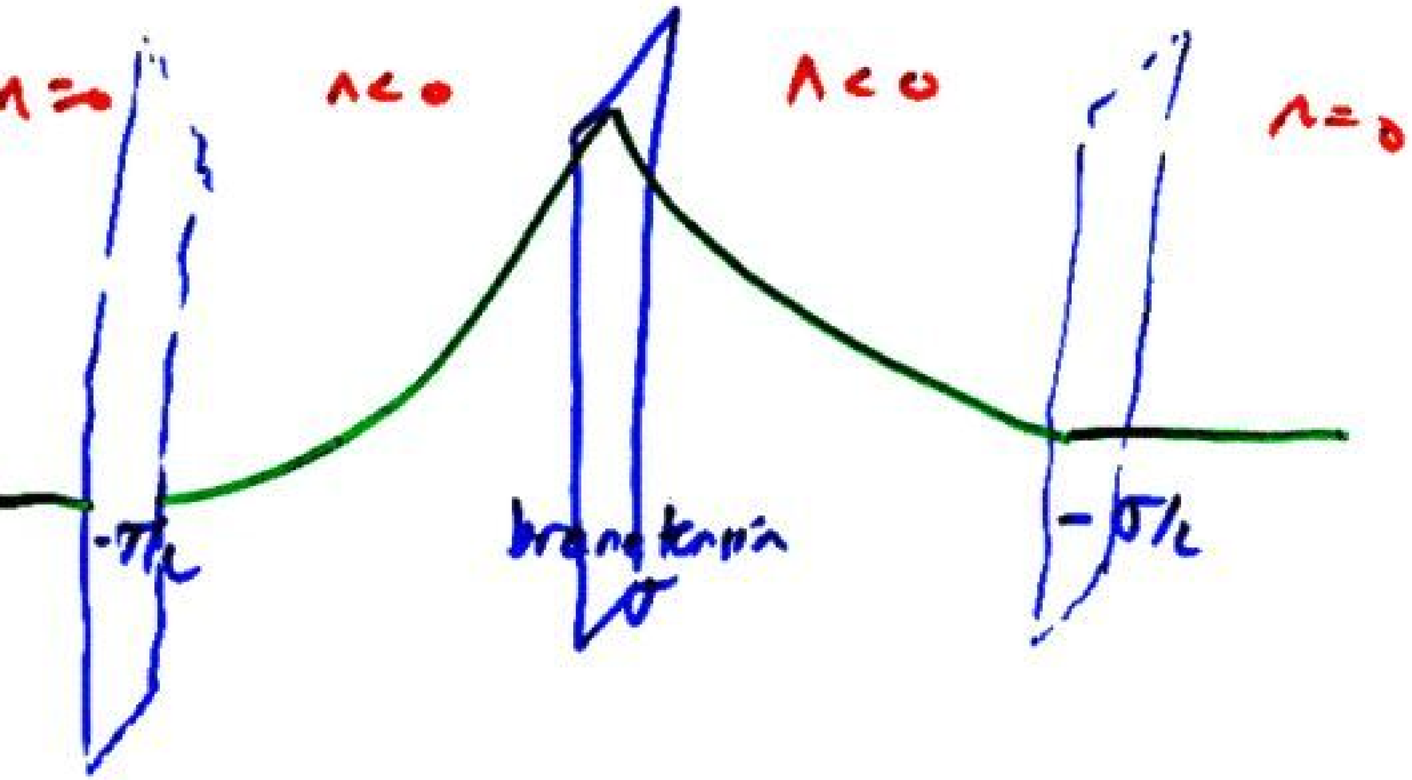
Clearly, no normalizable 0-mode.

<u>But</u> at intermediate energy, resonant mode mediates 4-D gravity



Csaki
Hollowood
Erlich

Gregory Rubakov Sibiryakov



$$ds^2 = a^2(z)\,\eta_{\mu\nu}\,dx^\mu dx^\nu - dz^2$$

$$a(z) = \begin{cases} e^{-kz} & 0 < z < z_c \\ c & z > z_c \end{cases}$$

Even more dramatic possibility

4-D Physics at Intermediate Scales

5-D at <u>Short</u> and <u>Long</u> Distance

QUASILOCALIZATION

Can also compute gravitational potential from the propagator

Giddings Katz LR

(scalar)

$$\Delta_{d+1}(x,z,x',z') = \int \frac{d^d p}{(2\pi)^d} e^{ip(x-x')} \Delta_p(z,z')$$

$$\frac{z^2}{L^2}\left(\partial_z^2 - \frac{d-1}{z}\partial_z - p^2\right)\Delta_p(z,z') = \left(\frac{z}{L}\right)^{d+1}\delta(z-z')$$

$$\Delta_{d+1}(x,L,x',L) = \int \frac{d^d p}{(2\pi)^d} e^{ip(x-x')} \left[\underbrace{\frac{d-2}{q^2 L}}_{\text{"4D"}} - \underbrace{\frac{1}{q}\, \frac{H^{(1)}_{\frac{d}{2}-1}(qL)}{H^{(1)\prime}_{\frac{d}{2}-1}(qL)}}_{\text{"KK corrections"}} \right]$$

Gravity: Need to include brane bending

Propagator $\longleftrightarrow$ modes

4D Gravity $\underline{LE}$ + corrections

4D EFT of Localized Gravity

$$V \sim G_N \frac{m_1 m_2}{r} \left(1 + \frac{1}{k^2 r^2} \right)$$

BS

continuum

$$\int dm \, \frac{e^{-mr}}{r} \left(\frac{m}{k}\right)$$

$\Rightarrow E < k$

Gravity $\simeq$ 4-D!

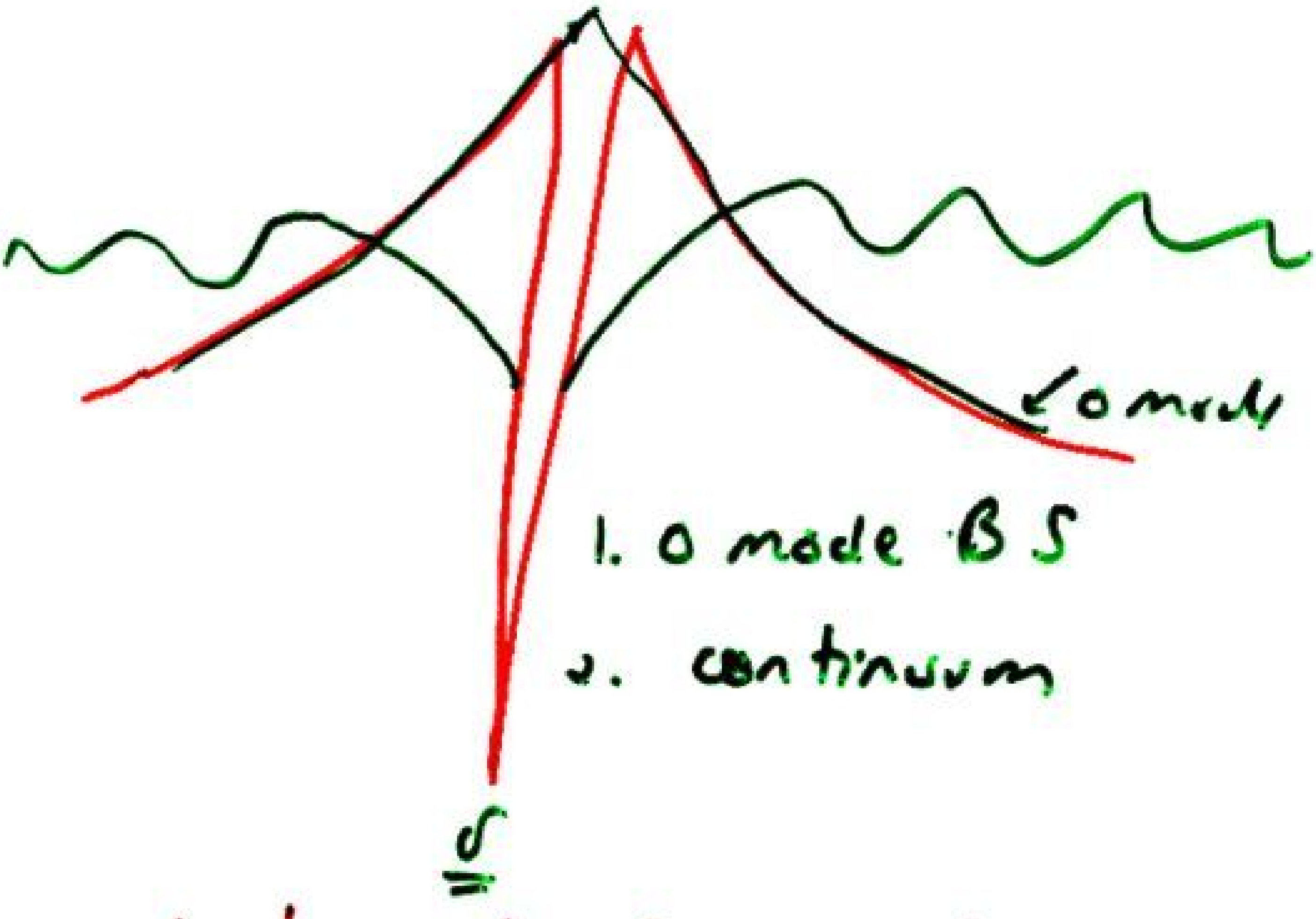
Low Energy 4-D EFT

High Energy $E > k$ (short distance)

5-D Theory

Can define 4D theory

KK modes, mass m



≡

soln to analog QM problem

"volcano potential"

Gravitational forces can be found by

I) Finding spectrum of linearized gravity fluctuations

II) Directly computing the propagator

I. $ds^2 = e^{2A(r)}(g_{ij} + h_{ij})\,dx^i dx^j - dr^2$

$$\left(-\partial_z^2 + V(z)\right) H_{ij}(z) = m^2 H_{ij}(z) \qquad \to e^{3A/2} h$$

$$V(z) = \frac{9}{4} A'(z)^2 + \frac{3}{2} A''(z)$$

$$= \frac{15 k^2}{\underset{\text{RS}}{\ } (\tfrac{3}{2} k|z| + 1)^2} - \frac{3k}{2}\delta(z)$$

$k = 1/L$

Detailed setup:

$$S = \int d^5x \sqrt{g}\left[-\frac{1}{4}R - \Lambda^{5d}\right]$$

$$-\lambda \int d^4x\, dr \sqrt{\det g_{ij}}\, \delta(r)$$

Metric:

$$ds^2 = e^{-2A\frac{|r|}{L}}\, \eta^{\mu\nu} dx_\mu dx_\nu - dr^2$$

$$\Lambda^{5d} = -3/L^2$$

$$\lambda = 3/L \longleftarrow \text{critical value for flat (mink) brane}$$

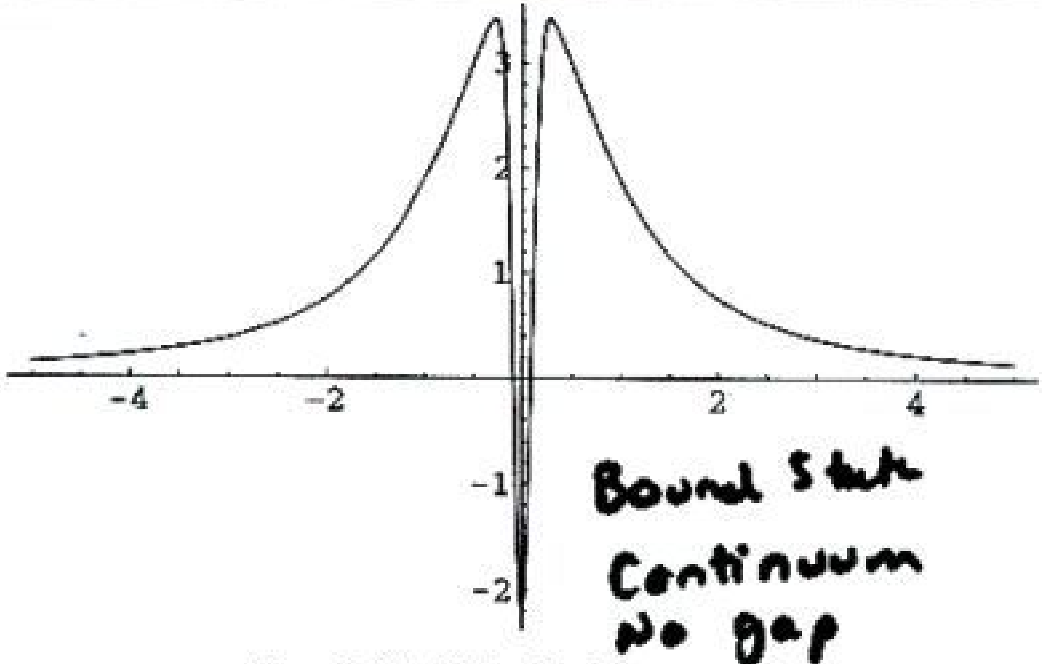


Figure 2: The Minkowski volcano potential.

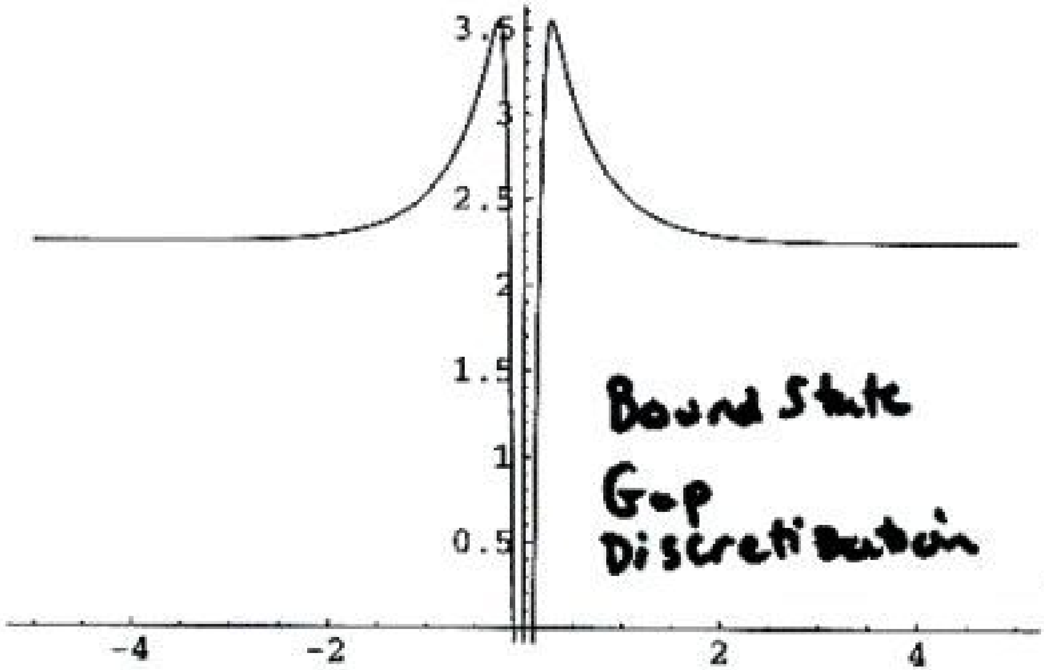


Figure 3: The deSitter volcano potential.

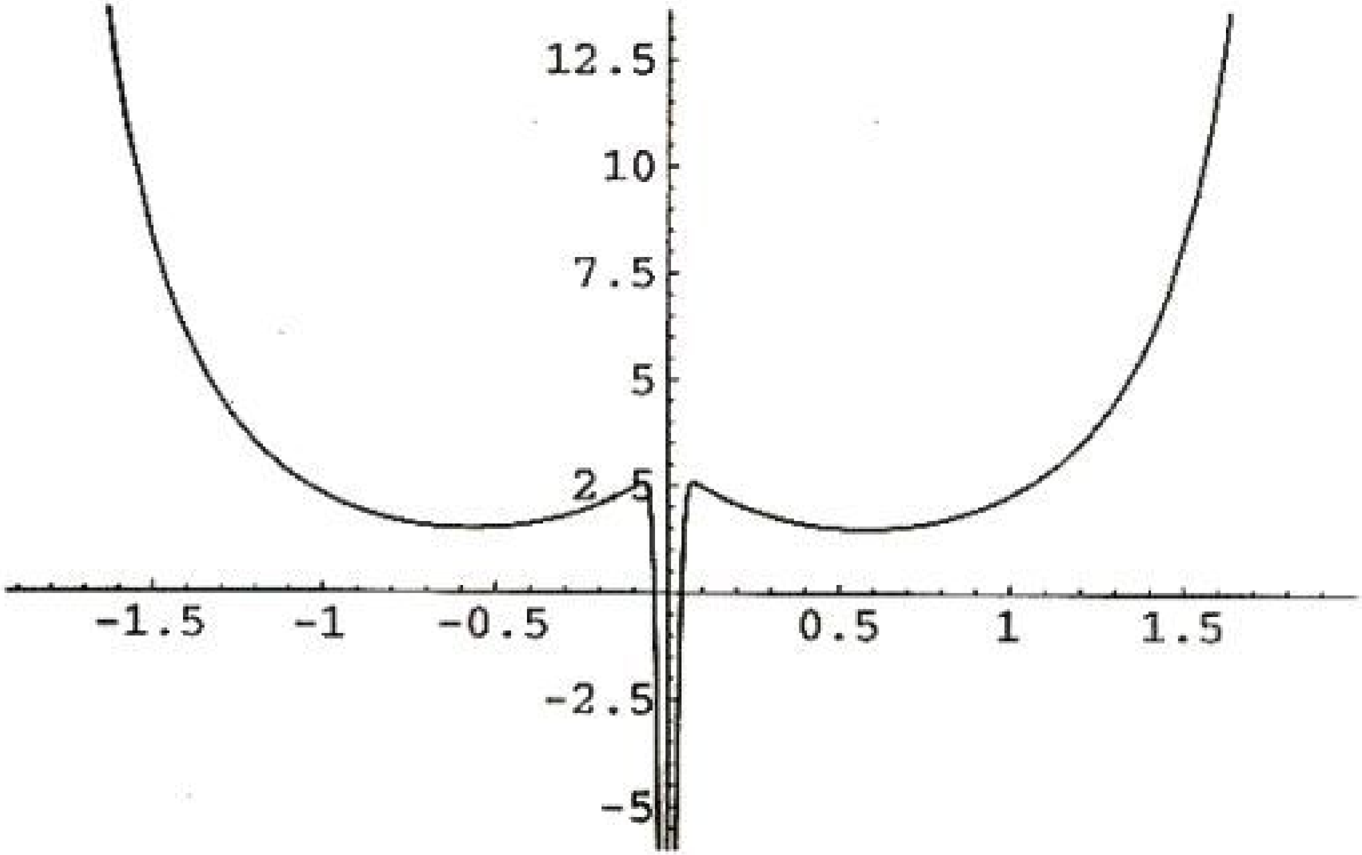


Figure 4: The Anti-deSitter volcano potential.

Charmousis Gregory Kaloper

Padilla Rattazzi Zaffaroni

Radion in Quasilocalization Scenario

- Solve for MOST General $h_{\mu\nu}$

$$h_{\mu\nu} = h_{\mu\nu}^{T} + f(\text{radion})$$

- Do most general gauge xform

$$h_{ab} \to h_{ab} + D_a \chi_b + D_b \chi_a$$

h_{55}, $h_{\mu 5}$ unchanged

- Can you gauge away radion?
- What is its effect?

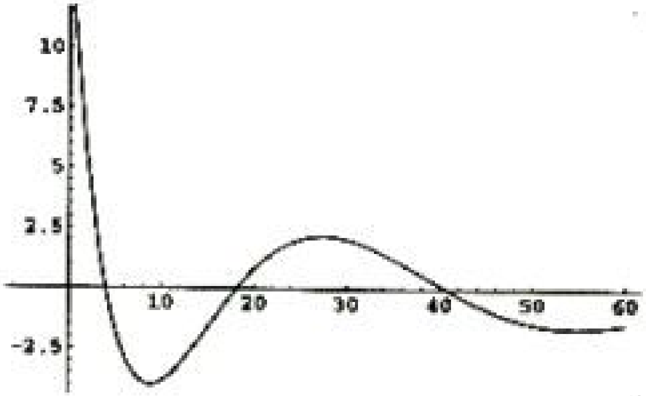


Figure 7: Spectrum at zero tension.

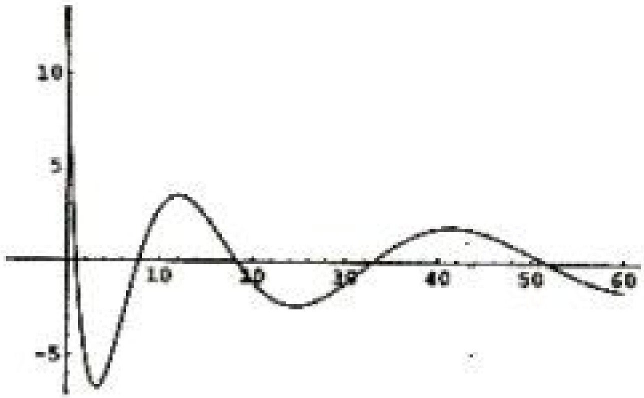


Figure 8: Spectrum at z0=0.7.

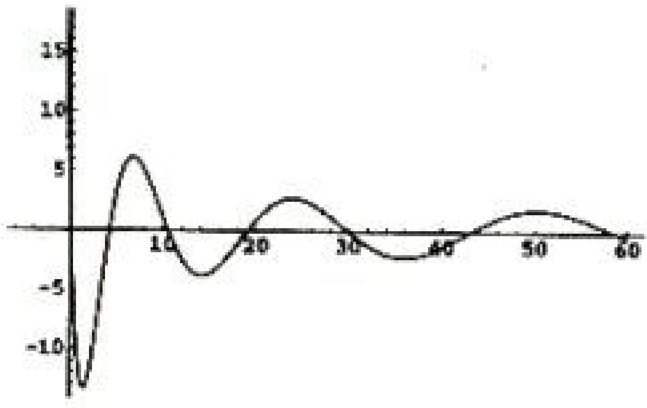


Figure 9: Spectrum at z0=1.4.

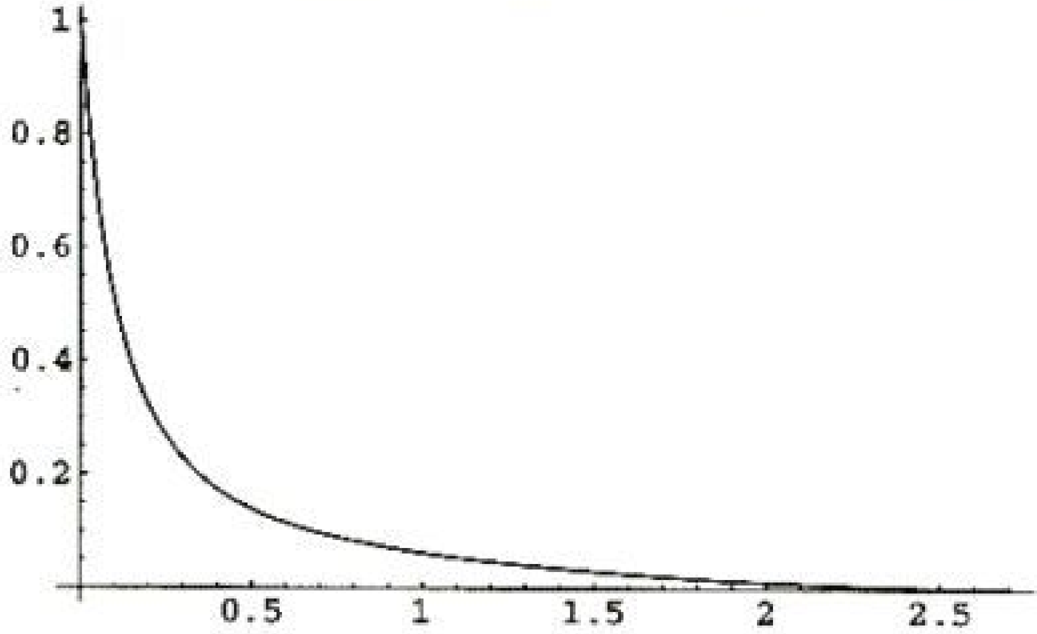


Figure 10: Wavefunction of the almost massless mode, E=0.0419 at z0=1.4.

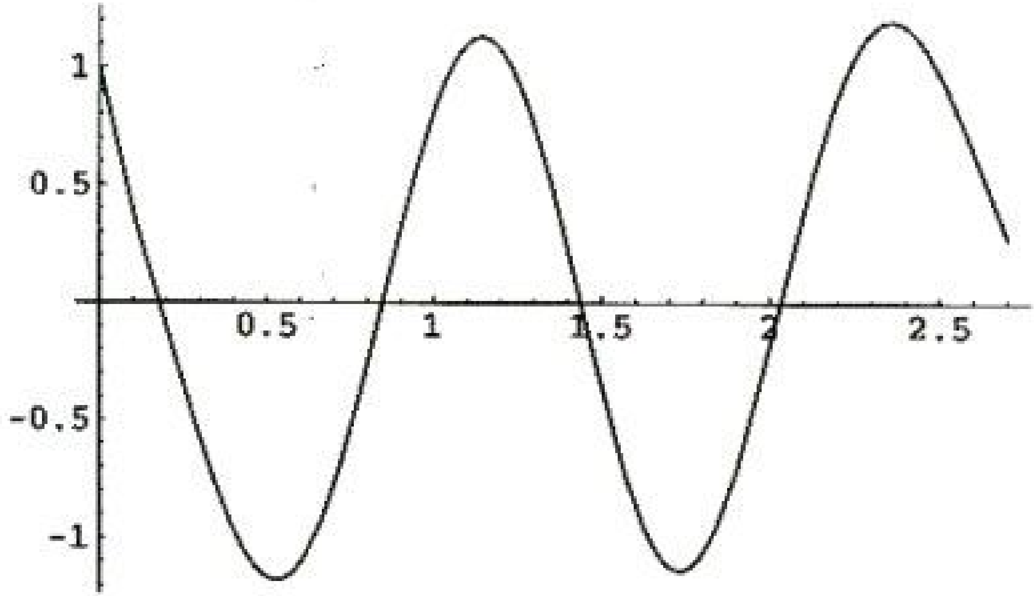


Figure 11: Excited mode at z0=1.4 and E=30.

Status :

- Almost zero mode bound state
- Discrete modes
- Conspire to give 4-D gravity at intermediate scales
- Quasi localization in *Physical* System!

In Progress

- understand extra polarization state, radion brane bending

Conclude:

- Quasi localization exciting possibility!
- Change physics short AND long distance scales
- Implications for CC?
- Implications for holography?

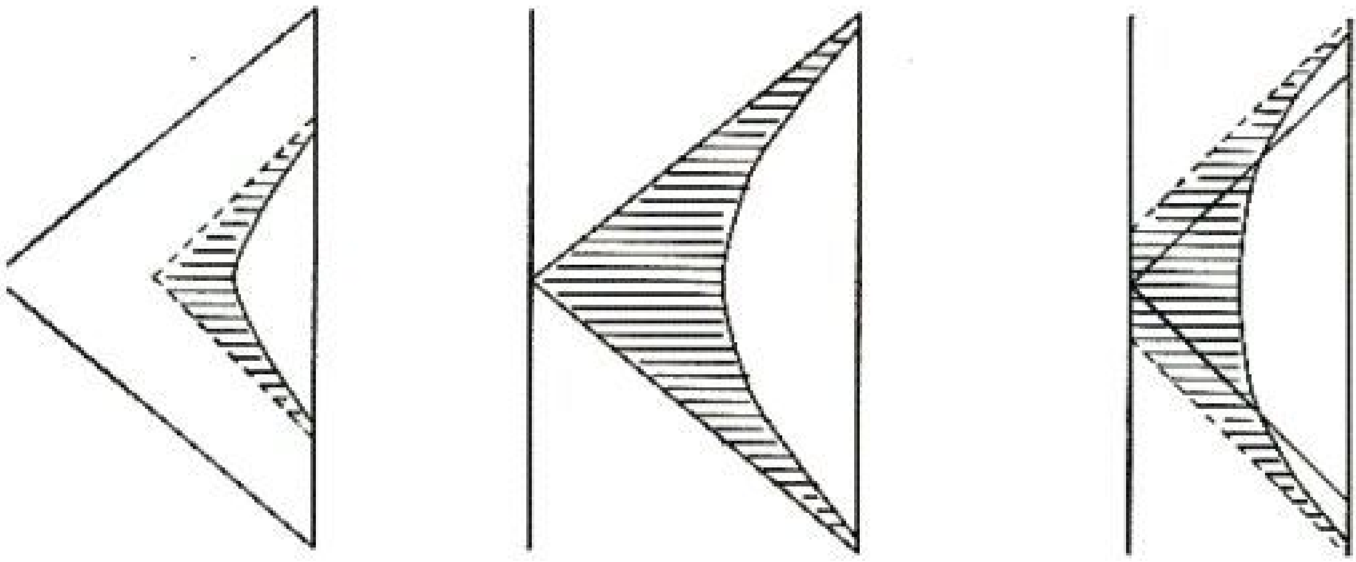


Figure 5: Schematics of the Penrose diagrams of the dS, Minkowski and AdS brane. The spacetime one is instructed to keep is shaded. Since the branes are accelerated, they have their own horizon, only for the Minkowski brane does this coincide with the Poincare patch. The spacetime one wants to keep is between the brane and the horizon. In the case of the AdS brane this obviously is a region that has a boundary that coincides with the AdS5 boundary.

Phenomenological Holography

w/ Nima Arkani-Hamed
Massimo Porrati

Apply AdS_5/CFT correspondence

to UV

UV + IR cutoff theories

AdS/CFT can be applied to cutoff versions

$M_{pl} \sim M \sim \frac{1}{L} \approx k$

I. only UV cutoff

$$M_{pl}^2 = M^3 \int_L^\infty dz \left(\frac{L}{z}\right)^3 \sim M^3 L$$

"Planck brane"

check: $\frac{1}{r^3}$ corrections to Newtonian force law

$\int dm \left(\frac{m}{k}\right) \frac{e^{-mr}}{r}$ vs. 

Grav   CFT

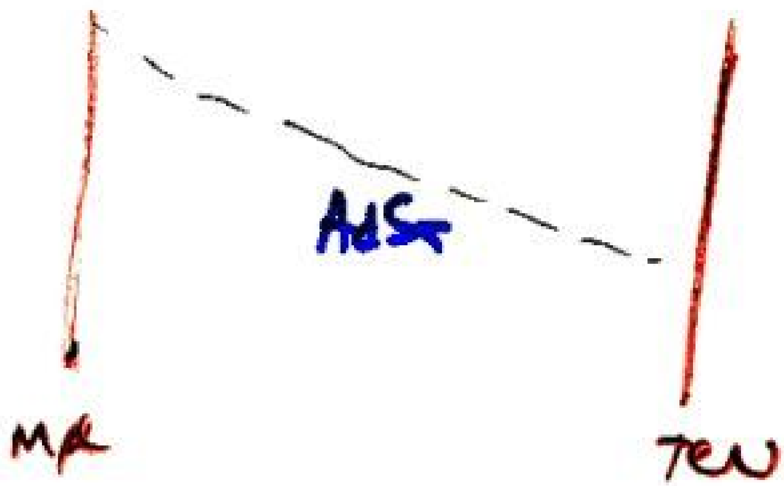
II. UV ⊕ IR cutoff

$$M_{pl}^2 = M^3 \int_L^{z^*} dz \left(\frac{L}{z}\right)^3 = M^3 L\left(1-\left(\frac{L}{z^*}\right)^2\right]$$

Planck brane   TeV brane / as in CFT w/ IR cutoff $\frac{1}{z^*}$

Recall

$$ds^2 = e^{-\frac{2r}{L}} \eta^{\mu\nu} dx_\mu dx_\nu + dr^2$$



- Nice laboratory
- w/ cutoffs, can compare same physical questions in Grav, CFT
- Many questions

gauge fields: MPL, bulk, TeV

matter: MPL, bulk, TeV

But Gravity description
weakly coupled.

When is holographic perspective
most useful?

→ Physics above TeV energy

Also physics on Planck brane
when UV/IR cutoffs

$E >> \mu \sim \frac{1}{\ell^2}$

CFT description should be valid

KK gravitons = CFT Bd states

Application I:

(unlike ADD - $\exists$ physics above TeV)

- solves hierarchy through warp factor
- strong coupling $\gtrsim$ TeV
- physics above TeV?
  cosmology
  particle collisions

. use AdS/CFT

- CFT + 4D gravity
  $\downarrow$
  broken at TeV

KK gravitons $\Leftrightarrow$ resonances of CFT
SM

$s < \text{TeV}^2$ KK production as AdS description

$\longrightarrow \; \longleftarrow$ $s > \text{TeV}^2$

CFT $\Rightarrow$ $\sigma \sim L_{AdS}^2$

Grav $\Rightarrow$ BH production only if $b < L_{AdS}$

$\Rightarrow \sigma \propto R^2 \sim E^2$

$\sigma_{max} \sim L_{AdS}^2$!

Answers:

- $M > \frac{1}{L}$

$\Rightarrow$ $\sigma \propto R^{3/2} T_{\_}$ $\quad L > R \frac{3}{M}$

weak gravity descrip

- See only TeV localized modes

Not full QG theory

5D QG well described by

cutoff CFT

ADD! Full QG at TeV

- intersecting branes ⟶ ADD

interpolate

App II: Gauge fields in Bulk

A) running coupling

B) KK production from Pl brane

C) unification?

A) CFT witten k33 grav

r dept cut//

$$e^2(p) = \frac{e^2 k}{1 - e^2 \frac{L}{g_s^2} \log pL}$$

$$g^2(p > m_{KK}) \sim g^2(p \sim m_{KK}) \frac{\log \frac{k}{m_{KK}}}{\log k/p}$$

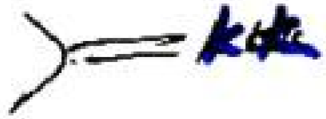
$e \to \infty$ UV

$\gamma = \frac{1}{L}$ Landau pole

$$e^2(p) \sim \frac{g_s^2}{L} \frac{1}{\log pL}$$

b) KK prod

CFT $\overset{NAH}{\text{??}}$ Grav (general)



$$A = \frac{g_5}{\sqrt{L}} \; \frac{1}{m_{KK} f(m_{KK} z_{IR})} \; \frac{1}{4_0(m_{KK})}$$

$$\sim \frac{e(m_{KK})}{10^3\, m_{KK} L}$$

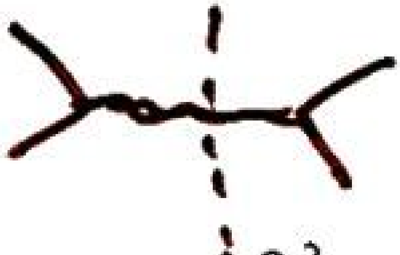
Big KK prod amp
from IR brane

But SE

$\langle J_\mu(p)\, J_\nu(q)\rangle \sim \frac{1}{g_5^2}$

CFT exact

but $p^2 = -m_{KK}^2$

 from 

$$eA' = \frac{\sqrt{L}}{g_5} \frac{1}{m_{KK} z^* J_1(m_{KK} z^*)} \frac{e^2}{1 + e^2 \frac{L}{g_5^2} Y_0(qL)}$$

$e \to \infty \Rightarrow$ Grav result!

Conclude

- AdS/CFT seems to give consistent results w/ UV, IR cutoffs
- Some cases ($E > \text{TeV}^{?}$) CFT gives clear picture ⇒ phenomenological consequences
- Other cases ($E \lesssim \text{TeV}$) weakly coupled gravity better description
- very nice to sort it all out!

cosmology
BUT
⋮