Braneworld Gravity

José Santiago

Theory Group (FNAL)

hep-th/0511266 + in progress with R. Bao, M. Carena, J. Lykken and M. Park

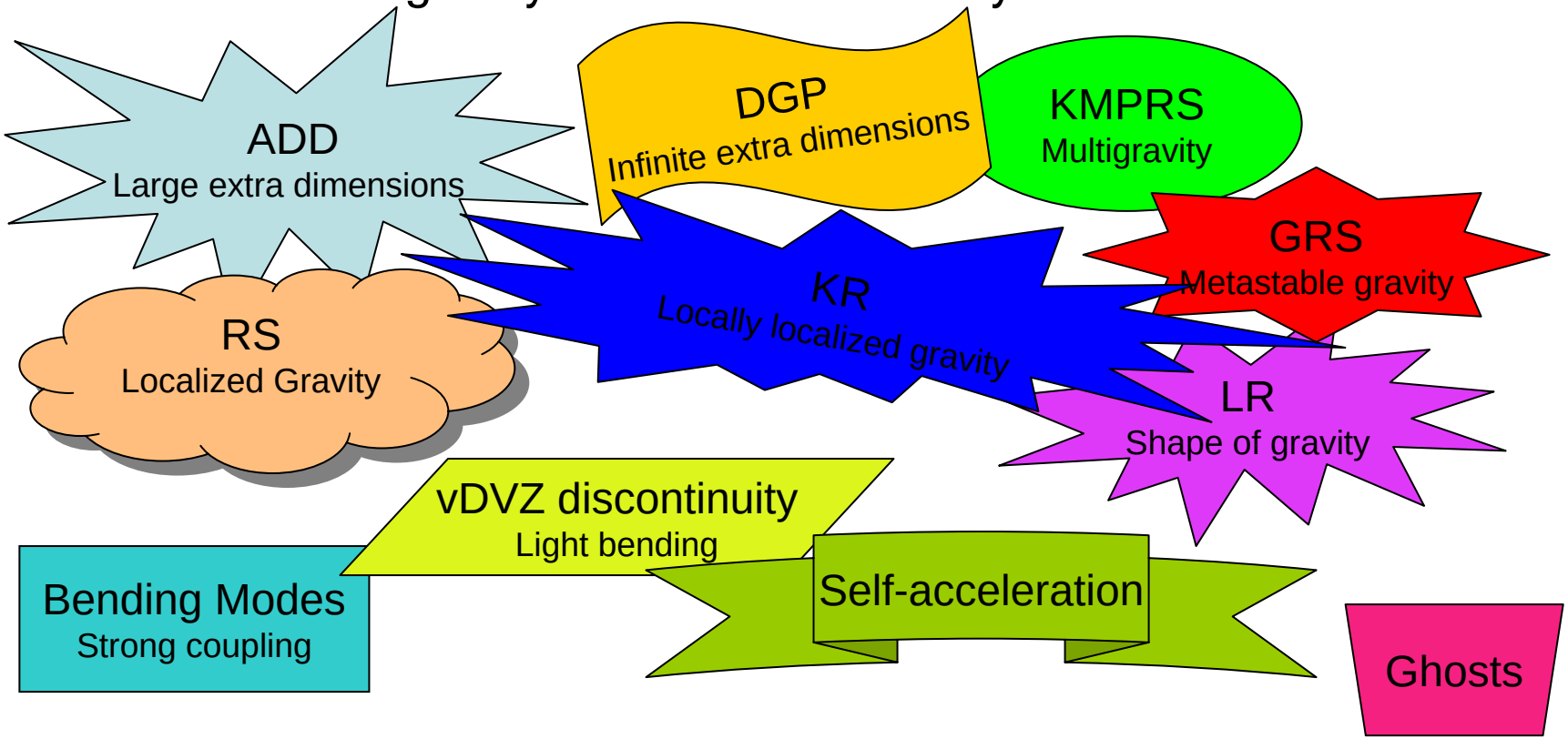
Why Braneworld Gravity?

- New framework to look at (and attempt to solve) long standing problems: Hierarchy problem, Cosmological Constant problem(s), ...

- Can have a wealth of phenomenological implications:
  - Graviton KK production in accelerators
  - Table-top (sub-millimeter) experiments
  - Solar System observations
  - Cosmology
  - Black hole physics

Braneworld Gravit*ies*

- Braneworld gravity has been extensively studied ...



IT'S GETTING TOO CROWDED!!

Outline

- Unified framework for braneworld gravity
- Static Case: AdS_5/AdS_4 with localized curvature
- Phenomenological issues:
  - Ghosts and tachyons
  - Strong Coupling
  - vDVZ discontinuity
  - Cross-over behavior of gravity
- Time-dependent backgrounds: implications for cosmology
  - Modified Friedmann equation
  - Acceleration in AdS!
- Conclusions and future work

Can we do all in one?

- Can we study all these interesting features in a unified framework?

- We have to choose a general enough model:

  AdS_5/AdS_4 with localized curvature terms

  Karch, Randall '01

  Dvali, Gabadadze, Porrati '00

- And then study all phenomenological implications:
  - Spectrum: masses and couplings
  - Instabilities due to ghosts, tachyons
  - Strong coupling effects
  - Cosmological implications

The Model

- The Action

$$\frac{S}{4M^3} = \int d^5x\sqrt{-G}\left[R + \underbrace{12k^2}_{-\Lambda}\right] + \int_{\partial\mathcal{M}} K + \frac{1}{2}\sum_i \int_{\Phi_i=0} d^4x^{(i)}\sqrt{-g^{(i)}}\left[\frac{v_i}{k}R^{(i)} - \frac{\mathcal{L}_i}{2M^3}\right]$$

- Equations of Motion

$$R_{MN} - \frac{G_{MN}}{2}(R + 12k^2) = 0$$

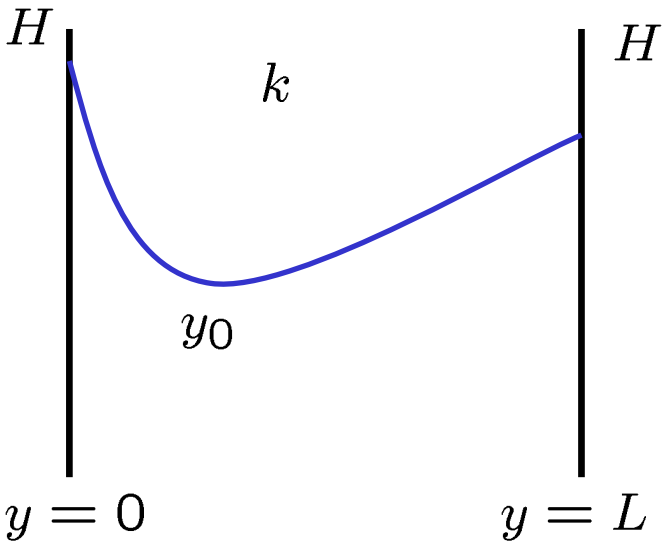
$$\frac{v_i}{k}\left(R^{(i)}_{\alpha\beta} - \frac{g^{(i)}_{\alpha\beta}}{2}R^{(i)}\right) + 2(K^{(i)}_{\alpha\beta} - g^{(i)}_{\alpha\beta}K^{(i)}) = \frac{T^{(i)}_{\alpha\beta}}{2M^3}$$

Static Case I: Background

- Brane EMT is pure tension $T^{(i)}_{\alpha\beta}/(2M^3) = \omega_i k g^{(i)}_{\alpha\beta}$ Karch, Randall '01

$$ds^2 = \frac{\cosh k(y-y_0)}{\cosh k y_0}\frac{\eta_{\mu\nu}dx^\mu dx^\nu}{1-H^2x^2/4} + dy^2$$

AdS_5/AdS_4



H, y_0 and L are function of k, v_i and w_i

We can reproduce most of known models

Static Case II: Linearized analysis

- We want to study the spectrum of linearized perturbations
  - Expand around background metric

Carena, Lykken, Park '05

Bao, Carena, Lykken, Park, J.S. '05

$$G_{MN} = G^0_{MN} + h_{MN}$$

  - Perform a full gauge fixing

radion

Straight gauge, $h_{\mu 4} = 0,\ h_{44} = F(y)\psi(x)$

  - Compute the action at quadratic (+ leading cubic) level in h_{MN} and integrate out the extra dimension ⇒ 4D effective action

$$h_{\mu\nu}(x,y) = a^2(y) h^{(0)}_{\mu\nu}(x) + \sum_q \mathcal{Y}^{(q)}(y) h^{(q)}_{\mu\nu}(x) + \dots$$

Massless zero mode (2 dof)

massive modes (5 dof)

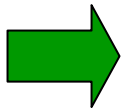
Static case II: Linearized analysis (cont'ed)

- Effective 4D Action:

$$\frac{S}{2M^3} = \int d^4x\sqrt{-g}\left\{C_\psi\psi[\nabla^2+4H^4]\psi + \frac{C_g^{(0)}}{4}h^{(0)\,\mu\nu}[\nabla^2+2H^2]h^{(0)}_{\mu\nu} + \sum_{q>0}\frac{C_g^{(q)}}{4}h^{(q)\,\mu\nu}[\nabla^2+2H^2-m_q^2]h^{(q)}_{\mu\nu}\right\}$$

- Kinetic coefficients and masses are functions of the parameters of the model:

$$k,\ v_i,\ w_i$$

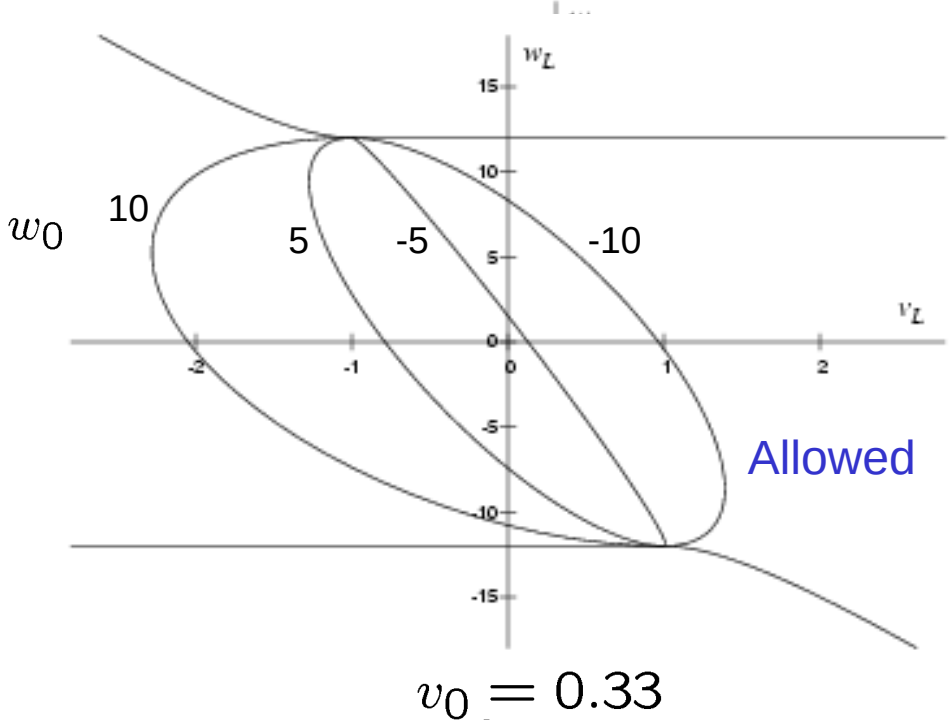


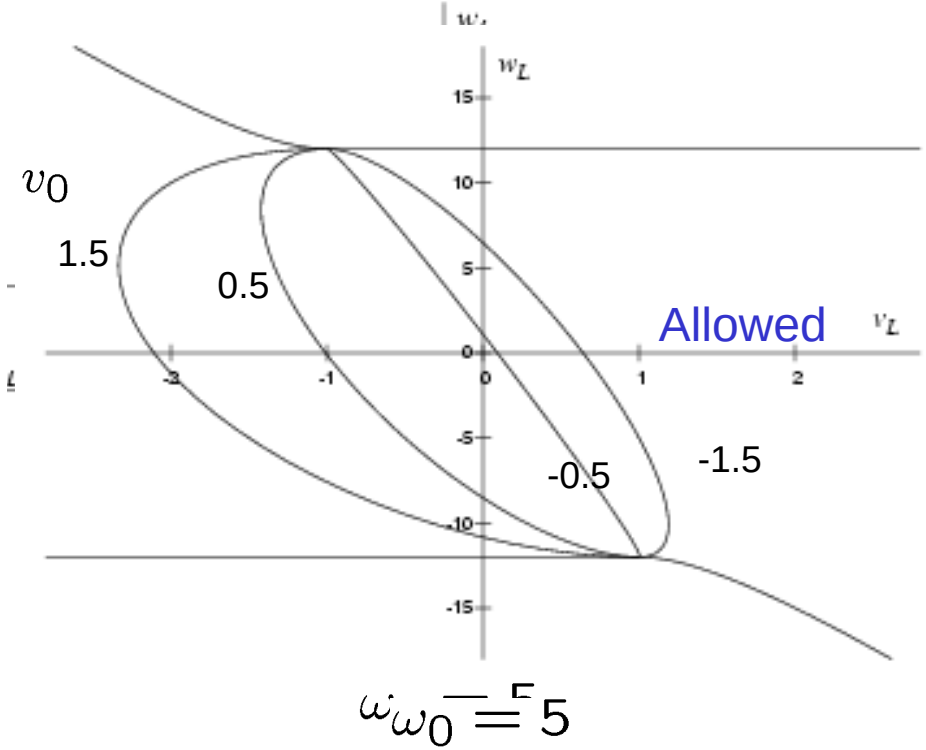
We can study the presence of ghosts, tachyons, strong coupling, or cross-over behavior of gravity as a function of them.

Ghostbusting

- $C_g^{(q)}, C_\psi < 0 \Longrightarrow$ physical spectrum contains ghosts

Bao, Carena, Lykken, Park, J.S. '05

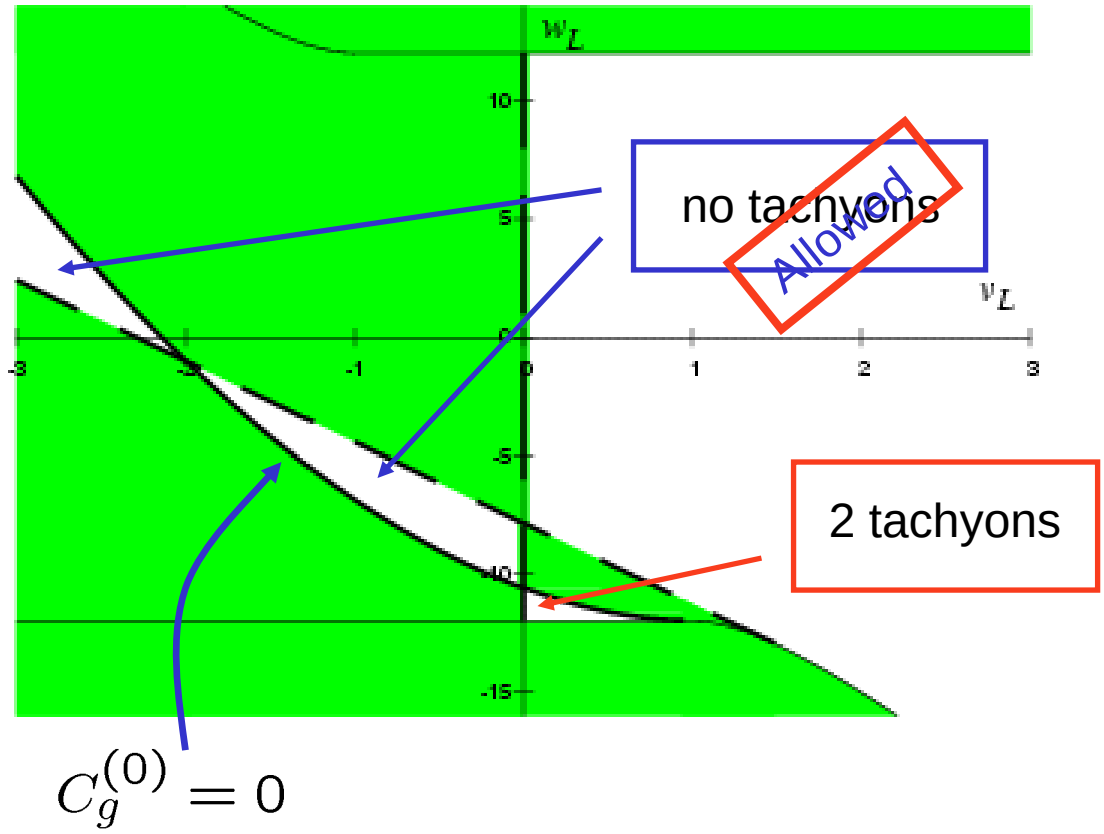




Tachyons

- It is also possible that $m_q^2 < 0$

Bao, Carena, Lykken, Park, J.S. '05



$$v_0 = 2$$

$$\omega_0 = 1$$

So what?

This AdS5/AdS4 model is very interesting but

what is it *really* useful for?

We don't live in Anti de Sitter space, do we?

Maybe yes!!

Carena, Lykken, Park, J.S. ***in progress***

Time-dependent case

- Let's consider a time dependent background (FRW-like)

$$ds^2 = -n^2(t,y)dt^2 + a^2(t,y)\gamma_{ij}dx^i dx^j + b^2(t,y)dy^2$$

- Brane energy-momentum tensor $T^{i\,\mu}_{\nu} = \mathrm{diag}(\rho, -p, -p, -p)$
- Equations of motion

Binetruy, Deffayet, Ellwanger, Langlois '00

Bulk

$$\frac{n'}{n}\frac{\dot{a}}{a} + \frac{a'}{a}\frac{\dot{b}}{b} - \frac{\dot{a}'}{a} = 0$$

$$\frac{\dot{a}^2}{a^2 n^2} + \frac{K}{a^2} + k^2 - \frac{\mathcal{C}}{a^4} = \frac{a'^2}{a^2 b^2}$$

Brane

$$3\frac{v_i}{k}\left(\frac{\dot{a}_i^2}{a_i^2 n_i^2} + \frac{K}{a_i^2}\right) \mp 6\frac{a_i'}{a_i b_i} = \frac{\rho_i}{2M^3}$$

$$\dot{\rho}_i + 3\frac{\dot{a}_i}{a_i}(\rho_i + p_i) = 0$$

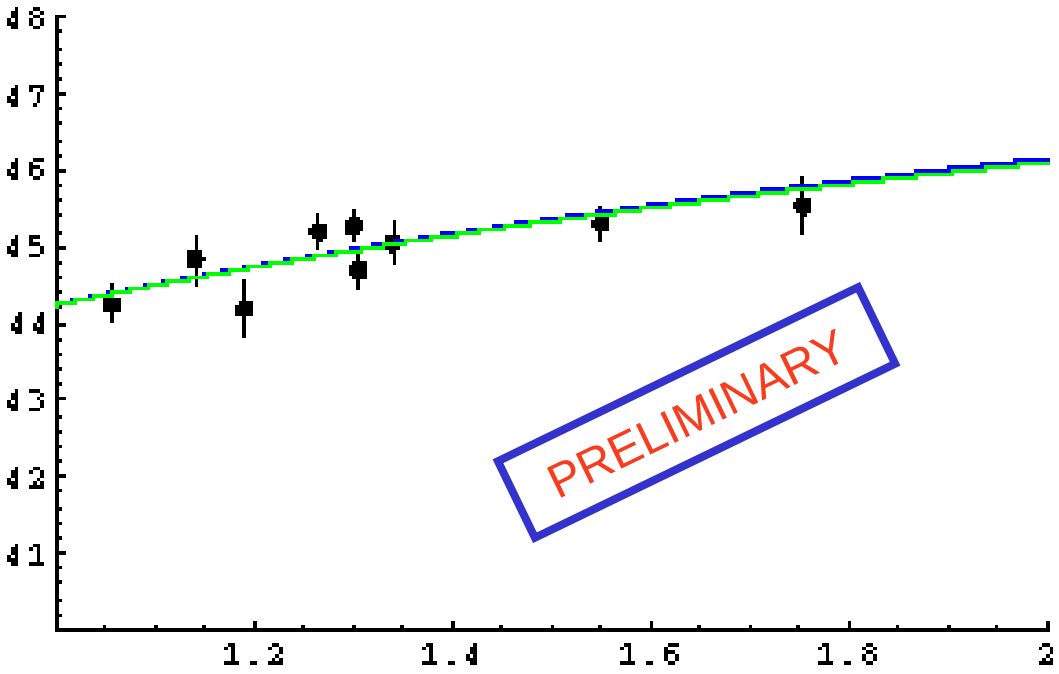
Time-dependent case (Cont'ed)

- The modified Friedmann equation has two branches

Deffayet '01; Deffayet, Dvali, Gabadadze '02; ...

$$H_i^2 = \frac{1}{6}\frac{k}{v_i M^3}\rho_i + 2\frac{k^2}{v_i^2} \pm 2\frac{k}{v_i}\sqrt{\frac{k^2}{v_i^2} + \frac{1}{6}\frac{k}{v_i M^3}\rho_i} + \dots$$

- Standard branch (-): Universe tends to AdS as in usual gravity
- Self-accelerating branch (+): Tends to a dS phase as matter dilutes
  - Very good fit to SNe data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PRELIMINARY

Time-dependent case (Cont'ed)

- The modified Friedmann equation has two branches

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- Standard branch (-): Universe tends to AdS as in usual gravity
- Self-accelerating branch (+): Tends to a dS phase as matter dilutes
  - Very good fit to SNe data
  - Possible issues with BAO Fairbairn, Goobar '05
  - Ghosts in self-accelerating branch?

(work in progress)

Luty, Porrati, Rattazzi '03; Nicolis, Rattazzi '04; Koyama '05

Acceleration in AdS!

- AdS_5/AdS_4 with localized curvature terms can thus explain the current acceleration of the Universe
- All necessary ingredients are present in string theory (that naturally prefers AdS vacua)
- Generic to models of infrared modifications of gravity to explain acceleration of the Universe
- Still many things to work out (but AdS curvature may help)
  - spectrum in time-dependent backgrounds (ghosts, tachyons, ...)
  - Strong coupling effects
  - Cosmological perturbations and non-geometrical tests

Conclusions and Outlook

- AdS_5/AdS_4 with localized curvature is a unified description that parametrizes a wide class of interesting braneworld gravity models
- It is possible to study once and for all phenomenological issues such as ghosts, tachyons, strong coupling, cross-over behavior, etc.
- Negative tensions allowed as long as positive and large localized curvature terms are included
- Very exciting cosmological implications: acceleration in AdS!!!
- Work in progress:
  - Study of spectrum in time-dependent backgrounds
  - Search of viable models that interpolate between DGP and RS
  - Check consistency with non-geometrical cosmological tests