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NEW THEORETICAL IDEAS IN COSMOLOGY

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Bibliography

- D-branes in SM building , gravity and cosmology

Review on new realizations of gravity and new phenomena in cosmology

E. Kiritsis [arXiv:hep-th/0310001]

- Braneworld cosmology

Review of Randall Sundrum cosmology

P. Brax, C. Van der Bruck, A Davis [arXiv:hep-th/0404011]

- Lectures on String/Brane cosmology

Review of brane-antibrane inflation

F. Quevedo [arXiv:hep-th/0210292]

Plan of the talk

- Introduction:Branes and cosmology

- Mirage (brane) cosmology

- Brane/antibrane inflation.

- Brane Induced Gravity

- Cosmological Brane-Bulk energy exchange.

- Outlook

Introduction

• Quantum Field theory describes surprisingly well fundamental interactions up to energies of order 200 GeV. It fails with gravity

• String theory succeeds with gravity and seems to be able to accommodate the rest of the interactions.

• We have two, rather solid results emerging from recent research in cosmology:

♣There was an inflationary period, most probably at $T \sim 10^{14-15}$ GeV that flattened the universe.

♠We are accelerating today with a rough vacuum energy $\Lambda \sim (10^{-3}\ \text{eV})^4$.

Both involve cosmological acceleration, but with hierarchically different values.

Accommodating cosmological acceleration

- Do we have a theory of inflation?

No! We have a phenomenological theory (parametrization) of the effect, with some ideas on where it could come from.

Moreover, there is heavy fine tuning involved, and it is not known how its fits in the theory of particles and forces.

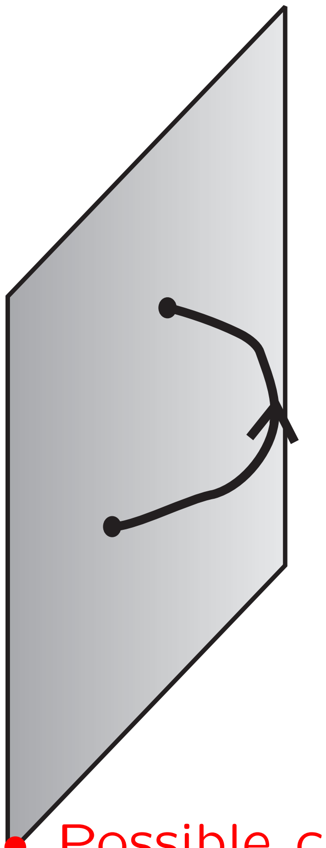
- Do we have a theory of today's acceleration?

Ditto!!!

♣Worse: For QFT and ST both effects are VERY UNNATURAL!

Branes and cosmology

A new idea that emerges from string theory is that of a brane:



The important property: There are particles (the brane particles) that cannot leave the brane. There are other particles (the bulk particles) that propagate everywhere. Gravitons are always of the second kind

Branes can fluctuate. The fluctuations are the brane particles. Branes can move in the transverse space

If the universe is a 3-brane embedded in a higher-dimensional (D=10?) space-time, then:

- Possible cosmological evolution in the bulk space, driven by bulk energy density.
- Possible cosmological evolution on the brane, driven by brane or bulk energy.

Mirage Cosmology

The motion of a brane inside a higher-dimensional bulk space, with non-trivial background fields induced a cosmological evolution on the brane.

Kehagias+Kiritsis *Kraus*

Kachru+McAllister

Example: a 3 brane with world-volume action

$$S_{brane} = T\int d^4x\sqrt{\hat{g}} = T\int d^4x\sqrt{det(G_{\mu\nu}\partial_\alpha X^\mu \partial_\beta X^\nu)}$$

moving in a non-trivial bulk metric of a collection of other 3 branes:

$$ds^2 = \frac{-dt^2 + dx^i dx^i}{f(r)} + f(r)(dr^2 + r^2 d\Omega_5^2) \quad , \quad f(r) = \frac{L^2}{r^2}$$

Look ar radial motion $r \to r(t)$:

$$S_{eff} = TV_3\int dr\sqrt{\frac{1 - f(r)^2\dot{r}^2}{f(r)^4}} \to \dot{r}^2 = \frac{1}{f(r)^2}\left(1 - \frac{1}{E^2 f(r)^4}\right)$$

The induced metric on the brane is

$$ds^2_{induced} = \frac{-dt^2 + dx^i dx^i}{f(r)} + f(r)dr^2 = -\left(\frac{1}{f} - f\dot{r}^2\right)dt^2 + \frac{dx^i dx^i}{f(r)}$$

Substitute $\dot{r}$ to obtain

$$ds^2_{induced} = -\frac{1}{E^2 f^5}dt^2 + \frac{dx^i dx^i}{f(r)}$$

This is a RW metric on the brane: Define the cosmic time τ and scale factor $a(t)$

$$d\tau = \frac{1}{E f(r(t))^{5/2}}dt \quad , \quad a^2 = \frac{1}{f} \quad \Rightarrow \quad ds^2_{induced} = -d\tau^2 + a^2(\tau) dx^i dx^i$$

Effective Freedman equation

$$\frac{\dot{a}^2}{a^2} = \frac{E^2/L^2}{a^8} - \frac{1}{L^2}$$

Standard cosmological evolution like it was due to exotic energy density with

$$\frac{1}{a^8} \quad \sim \quad w = \frac{5}{3} \quad > \quad 1$$

with a negative cosmological constant.

It is possible to also obtain Phantom densities with $w < -1$.

Brane-Antibrane inflation

Alexander
Dvali+Shafi+Sogalnik
Burgess+Majumdar+Nolte+Quevedo+Rajesh+Zhang

Kachru+Kallosh+Linde+Maldacena+McAllister+Trivedi

Consider now a string theory background were there are non-trivial background fields, that generate and AdS_5-like throat (as we had before). This can be generated by many D_3 branes.

$$ds^2 = \frac{r^2}{L^2}(-dt^2 + dx^i dx^i) + L^2 \frac{dr^2}{r^2}$$

Consider now a D_3 and an antibrane $\bar{\mathrm{D}}_3$ in this background. The action for the antibrane is

$$S_{\bar{\mathrm{D}}_3} = T_3 \int d^4x \sqrt{\hat{g}} + \int d^4x \; C$$

The only difference now is: The brane is charged, and the D-$\bar{\mathrm{D}}$ is attractive.

$$S_{\mathrm{D}_3\bar{\mathrm{D}}_3} = T_3 \int d^4x \;\; \frac{1}{f(r)^2} \;\; \left[\sqrt{\det(1 - f^2 \partial_\mu r \partial_\nu r)} + 1\right] \quad , \quad f^2 \simeq \frac{L^4}{r_0^4} + \frac{1}{N}\frac{L^4}{r^4}$$

r=position of D-brane, r_0=position of $\bar{\text{D}}$ brane.
For slow motion, expand and define $\phi = \sqrt{T_3}\ r$

$$S_{\text{D}_3\bar{\text{D}}_3} = \int d^4x \left[\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - 2T_3\frac{r_0^4}{L^4}\left(1 - \frac{T_3}{N}\frac{r_0^4}{\phi^4}\right)\right]$$

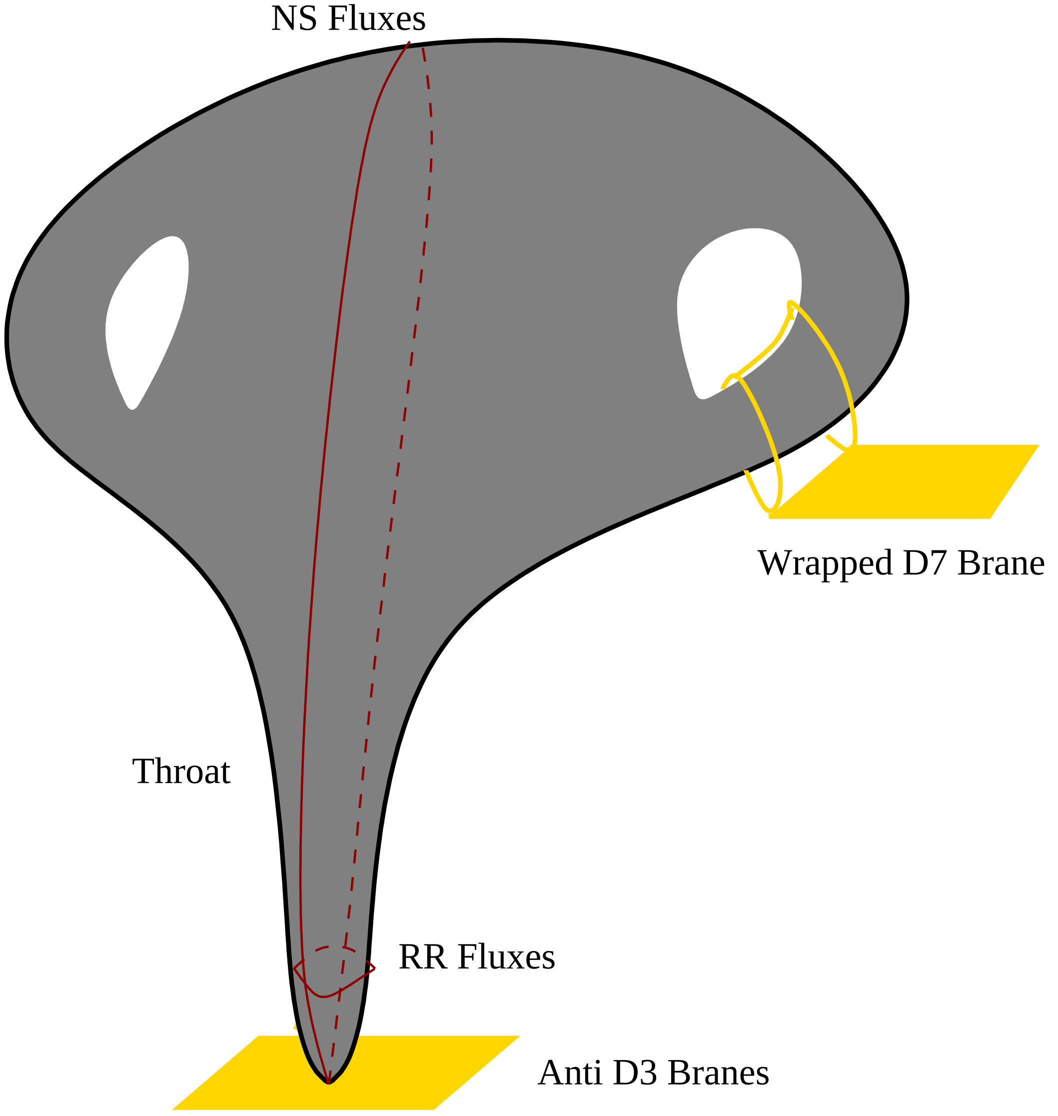
Parameters: T_3=tension, N (number of D_3 branes), L (size of throat, function of the other parameters) r_0=position of $\bar{\text{D}}_3$ brane.

$$\epsilon \sim M_P^2\ \frac{T_3^4\ r_0^8}{N^2\phi^{10}} << 1 \quad , \quad \eta \sim M_P^2\ \frac{T_3^2\ r_0^4}{N\phi^6} << 1$$

This is not possible if there is no warping!

Problems to solve:

- A fine tuning of order 100 for the mass of the inflaton due to D-terms.
- An incorporation into a realistic string ground-state.



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Brane Induced Gravity (alias DGP)

Dvali+Gabadadze+Porrati   *Dvali*

Brane induced gravity is an IR modification of gravity due to an Einstein term on a brane: Consider a 3-brane in a (4+1)-d bulk:

$$S = M^3 \int dy\ d^4x\ \sqrt{g}\ R_5 + \delta(y) M^3 r_c \int d^4\xi \sqrt{\hat{g}}\ \hat{R}_4$$

Gravitational interaction, by solving

$$M^3(\vec{p}^2 - \partial_y^2 + r_c\ \delta(y)\ \vec{p}^2) G(\vec{p}; y) = \delta(z) \Rightarrow G(\vec{p}; y=0) = \frac{1}{M^3(2|\vec{p}| + r_c\ \vec{p}^2)}$$

$$G(\vec{p}; y=0) \simeq \begin{cases} \dfrac{1}{2M^3|\vec{p}|} & |\vec{p}| << \frac{1}{r_c} \qquad V(r) \sim \frac{1}{M^3 r^2} \\[2ex] \dfrac{1}{2M^3 r_c\ |\vec{p}|^2} & |\vec{p}| >> \frac{1}{r_c} \qquad V(r) \sim \frac{1}{M^3 r_c\ r} \end{cases}$$

Cosmology and Brane Induced Gravity

Deffayet *Dvali+Deffayet+Gabadadze*

The cosmological evolution on the brane is

$$H^2 + \frac{k}{a^2} = \left(\sqrt{\frac{\rho}{3M_P^2} + \frac{1}{4r_c^2}} + \frac{\epsilon}{2r_c} \right)^2 \quad , \quad \epsilon = \pm 1$$

$$\rho >> \frac{M_P^2}{r_c^2} \qquad \rightarrow \qquad H^2 + \frac{k}{a^2} \simeq \frac{\rho}{3M_P^2}$$

$$\rho << \frac{M_P^2}{r_c^2} \qquad \begin{cases} \epsilon = -1 & H^2 + \frac{k}{a^2} \simeq \frac{r_c^2}{9M_P^4}\rho^2 + \cdots \\ \\ \epsilon = 1 & H^2 + \frac{k}{a^2} \simeq \frac{1}{r_c^2} + \frac{4}{3M_P^2}\rho + \cdots \end{cases}$$

Choosing the scale $r_c =$ size of observable universe today gives the correct order of magnitude for the cosmological constant $M_P^2/r_c^2 \sim (10^{-3}\ \text{eV})^4$

This idea can be realized in string theory, on D-branes

Kiritsis+Tetradis+Tomaras

or on non-compact CY manifolds

Antoniadis+Minasian+Vanhove

It is however, extremely fine tuned: It depends crucially on UV details of the theory

Kiritsis+Tetradis+Tomaras

Moreover, it suffers from a strong coupling problem at macroscopic distances.

Luty+Porrati+Rattazzi *Rubakov*

At least this prohibits it being excluded from Brans-Dicke constraints.

Cosmological brane-bulk energy exchange

• In all brane-world contexts, the matter on the brane must interact with the bulk matter (including the graviton).

• If the bulk Planck scale is as high as the 4d one, this interaction is weak.

• It may be that this scale is quite low, ($M \sim$ a few TeV) as in large extra dimension contexts. Then above the KK scale (that can be as low as 10^{-4} eV) there is strong interaction between brane and bulk.

Kiritsis+Tetradis+Tomaras *Langlois+Sorbo*

♣Energy can flow out to the bulk.

♠Energy can flow in, on the brane. This can cause cosmological acceleration on the brane.

Kiritsis+Kofinas+Tetradis+Tomaras+Zarikas

Examples in Randall-Sundrum cosmology:

$$, \quad H^2 + \frac{k}{a^2} = \rho^2 + \rho + \chi$$

$$\dot{\rho} + 3(1+w)\frac{\dot{a}}{a}\rho = -T(\rho) \quad , \quad \dot{\chi} + 4\frac{\dot{a}}{a}\chi = (2\rho + 1)\, T(\rho)$$

The rough intuition: incoming energy, sustains a constant ρ despite the expansion $\rightarrow$ cosmological acceleration.

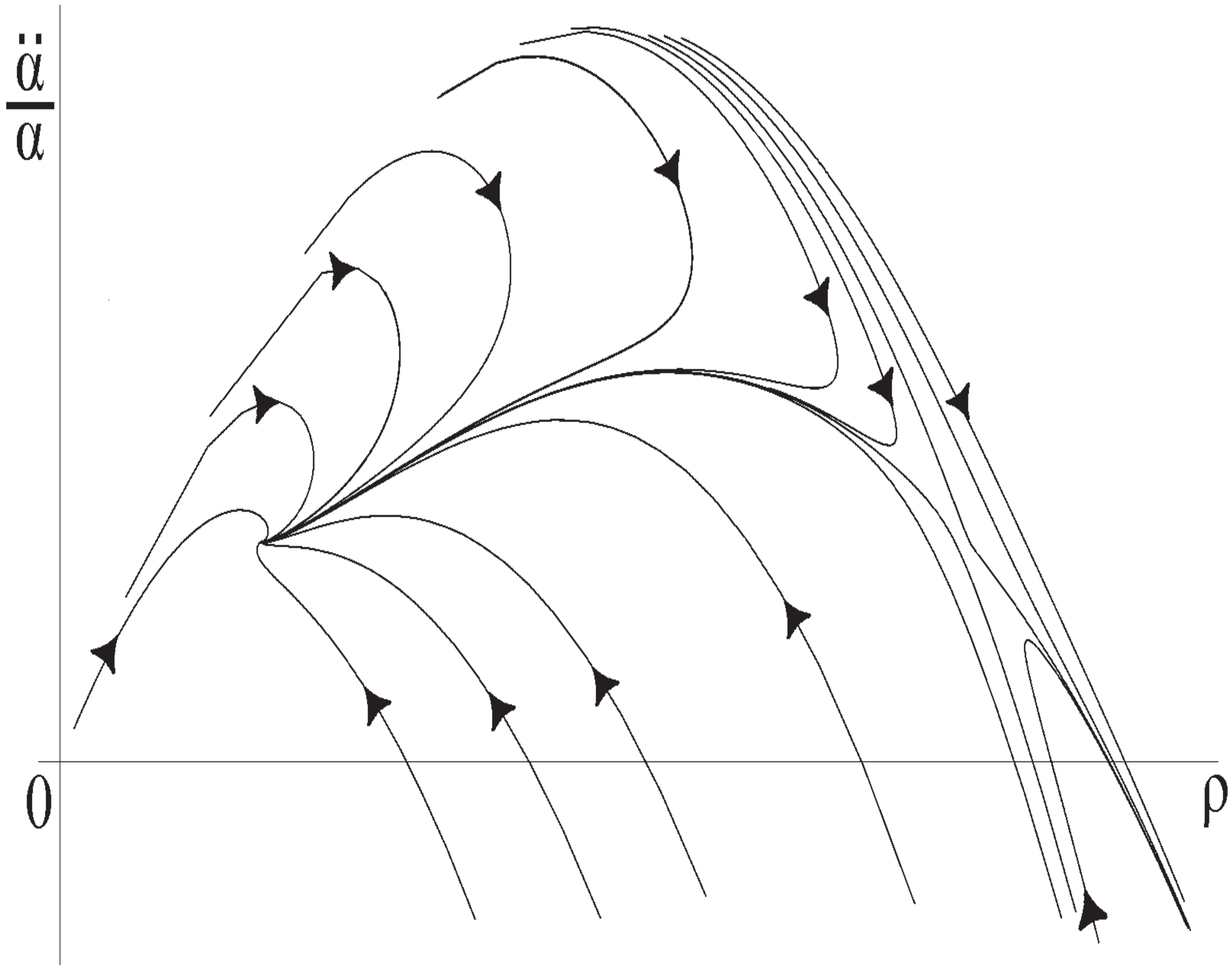
A $T(\rho) \sim \rho^{-0.06} H$ fits the acceleration data as well (if not better) than Λ.

Umezu et al.

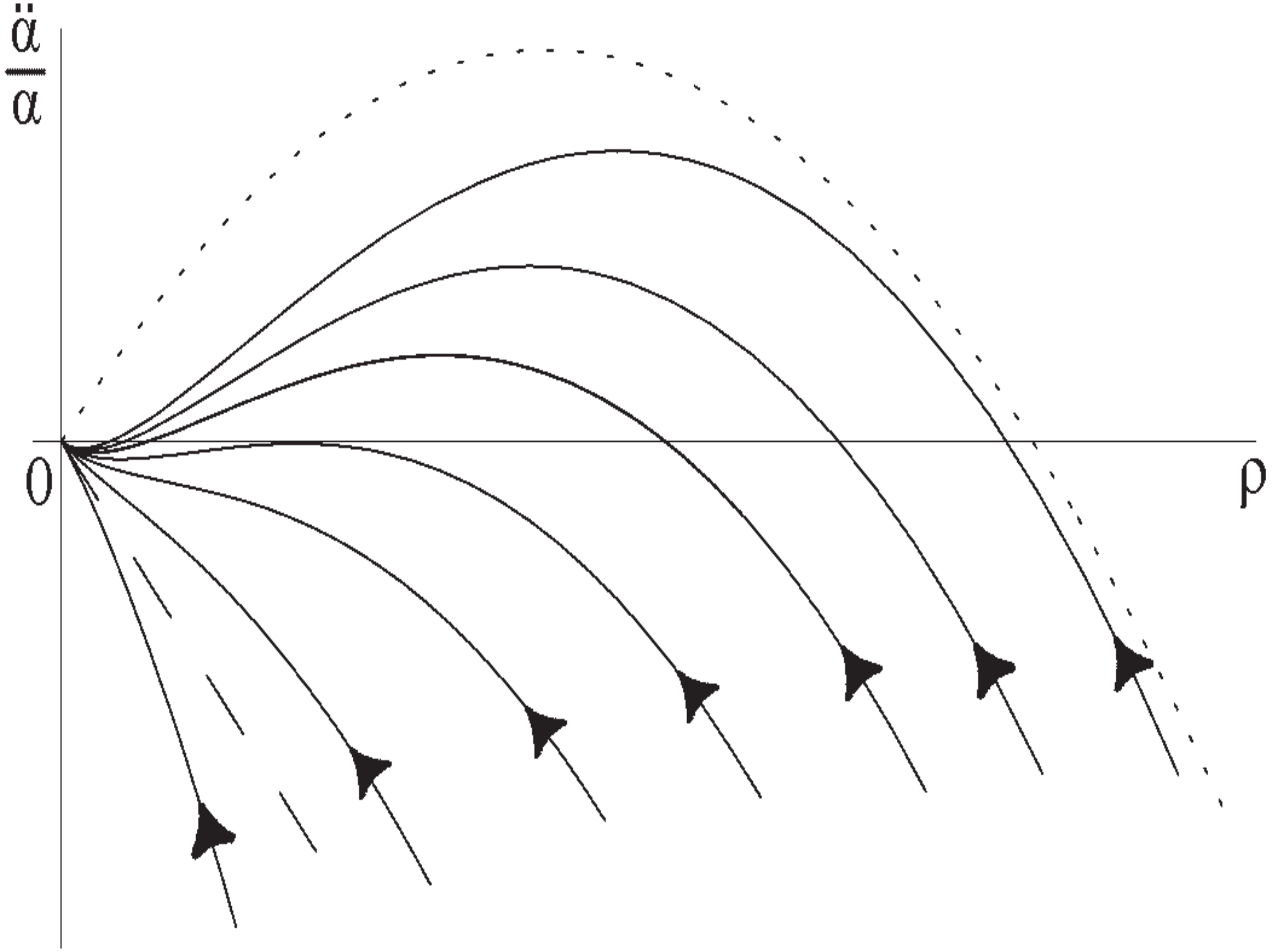
There is dual, four dimensional formulation of this type of cosmology using ideas of the AdS/CFT correspondence.

Kiritsis

Open problems: Implement this scenario in a full-fledged fundamental theory.



$T(\rho) = -\rho$, Inflow , $k = 0$, $w = 0$



$T(\rho) = \rho \quad , \quad \text{Outflow} \quad , \quad k = 0 \quad , \quad w = 0$

Conclusions

• There are many ideas on how to accomodate the comsological data in a fundamental theory like string theory.

• They all need severe FINE TUNING!

♣Either, nature is very fine tuned, or

♠There is something important we are missing.

Warped versus flat space in Brane-Antibrane inflation

The harmonic function between a D_3 and $\bar{D}_3$ is

$$f^2 = 1 + \frac{L^4}{r^4} \qquad \Rightarrow \qquad f_w^2 = L^4 \left(\frac{N}{r_0^4} + \frac{1}{r^4} \right)$$

That gives rise to a potential

$$V = \frac{2T_3}{f^2} \simeq 2T_3 \left(1 - \frac{L^4}{r^4} \right) \qquad \Rightarrow \qquad V_w = \frac{2T_3}{f_w^2} \simeq \frac{2T_3 r_0^4}{N L^4} \left(1 - \frac{r_0^4}{N r^4} \right)$$

with inflation parameters

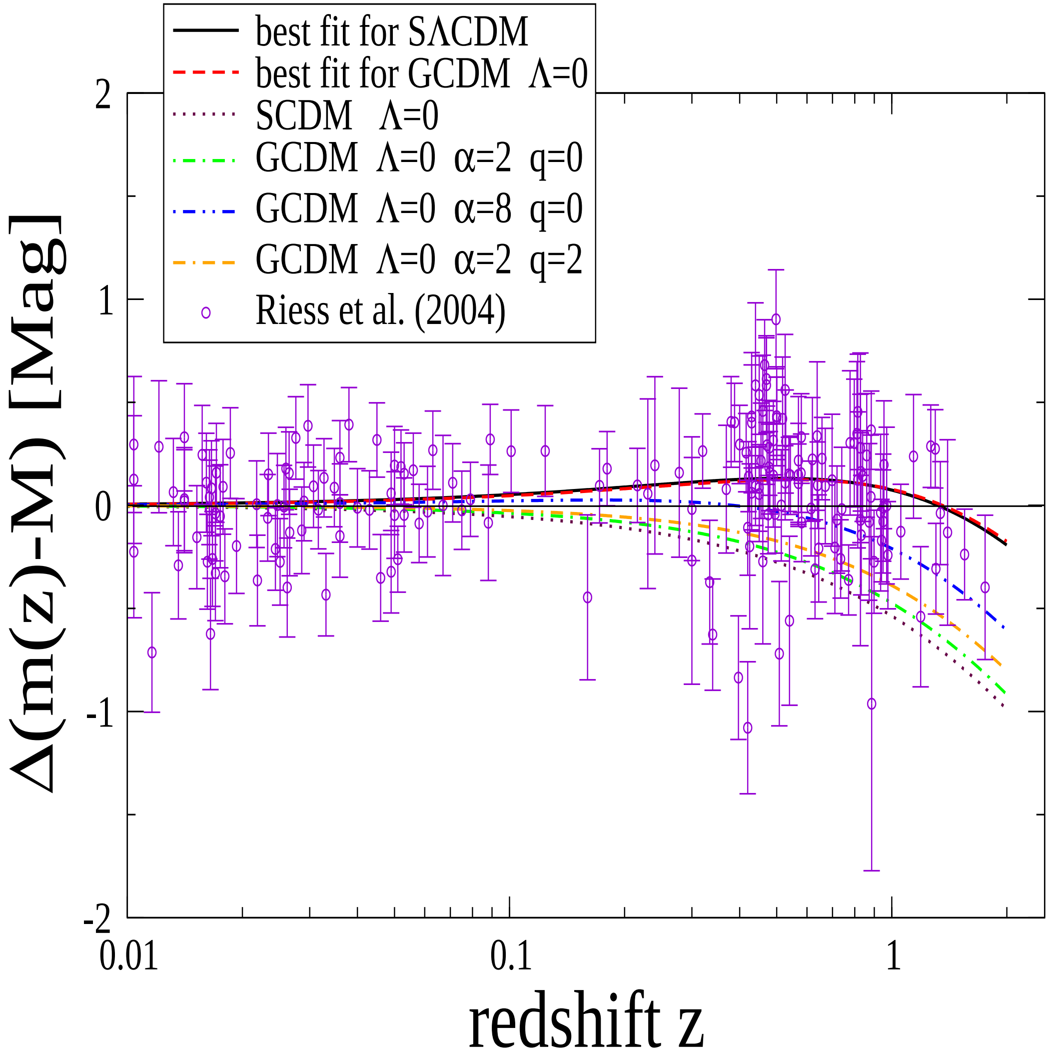
$$\epsilon \simeq M_P^2 \frac{L^8 T_3^4}{\phi^{10}} \qquad \Rightarrow \qquad \epsilon_w \sim M_P^2 \, \frac{T_3^4 \; r_0^8}{N^2 \phi^{10}} \quad , \quad \frac{\epsilon_w}{\epsilon} \sim \frac{1}{N^2} \frac{r_0^8}{L^8}$$

$$\eta \simeq M_P^2 \frac{L^4 \; T_3^2}{\phi^6} \qquad \Rightarrow \qquad \eta_w \sim M_P^2 \, \frac{T_3^2 \; r_0^4}{N \phi^6} \frac{\eta_w}{\eta} \sim \frac{1}{N} \frac{r_0^4}{L^4}$$

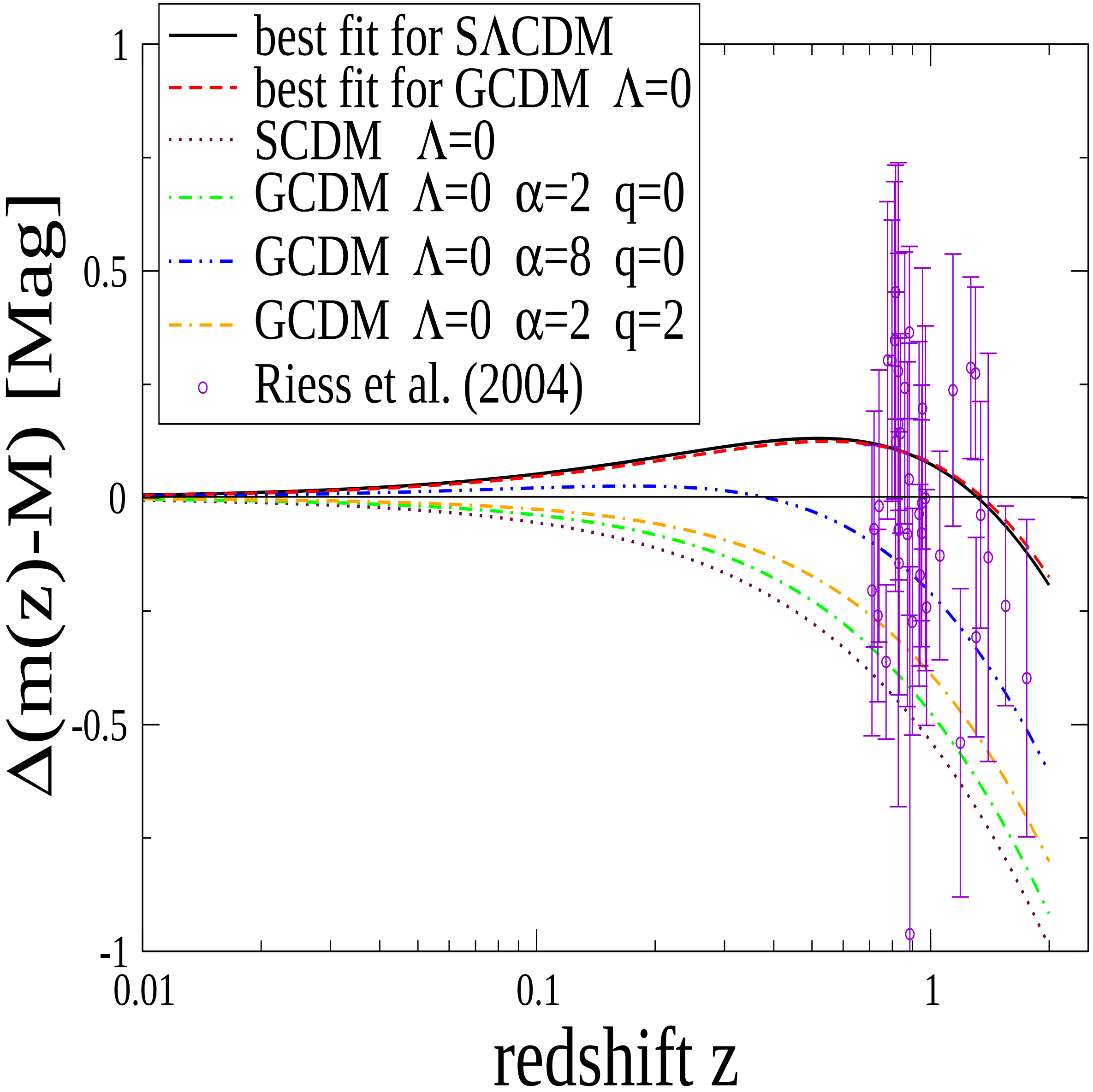
$$\eta \sim \frac{V_6}{r^6} \quad > \quad 1$$

for compactification.

Comparing BBEE to data



From Umezu et al.



From Umezu et al.

Plan of the presentation

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- Plan 3 minutes
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- Accommodating cosmological acceleration 5 minutes
- Branes and Cosmology 6 minutes
- Mirage cosmology 11 minutes
- Brane-Antibrane inflation 17 minutes
- Brane induced Gravity 22 minutes
- Cosmology and Brane Induced Gravity 26 minutes
- Cosmological brane-bulk energy exchange 32 minutes
- Conclusions 33 minutes

- Warped versus flat space in Brane-Antibrane inflation 34 minutes