Title: Dynamics in the Dark

Date: Mar 17, 2009 01:00 PM

URL: http://pirsa.org/09030035

Abstract: If Dark Energy is dynamical, it would indicate the existence of new physics beyond the standard model coupled to gravity. I will argue that the best motivated models of this new physics are all tied to whatever resolves the cosmological constant problem, and discuss the cosmological implications of several proposals that have been put forward in this vein.

Dynamics in the *Dark*

Andrew J. Tolley

Perimeter Institute for Theoretical Physics

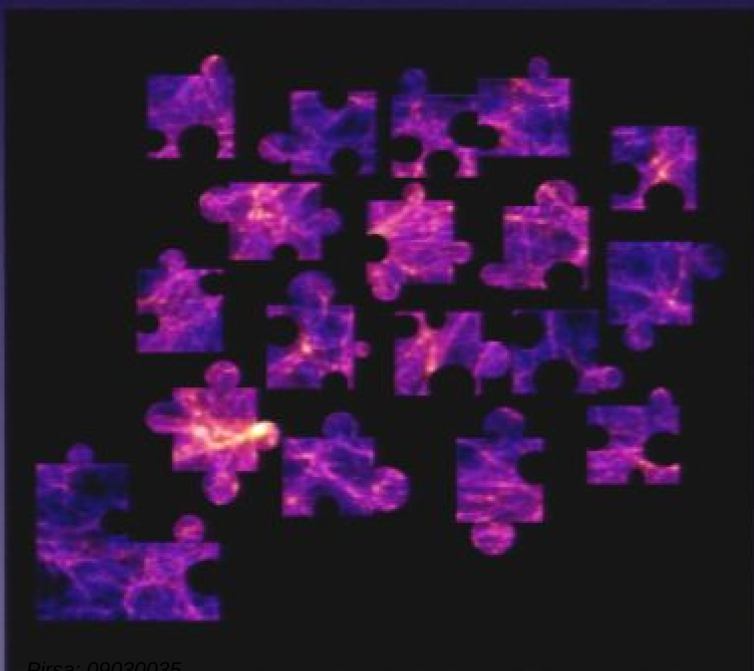
March 17th, 2009

Standard model of cosmology

The standard model of cosmology rests on two remarkable assumptions:

Standard model of cosmology

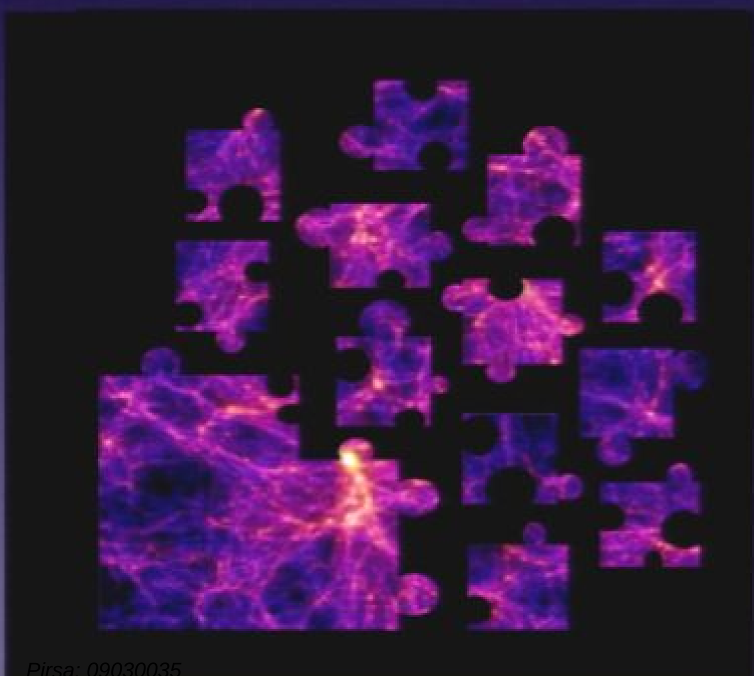
The standard model of cosmology rests on two remarkable assumptions:



~95 % of the universe is invisible to us

Standard model of cosmology

The standard model of cosmology rests on two remarkable assumptions:



~95 % of the universe is invisible to us

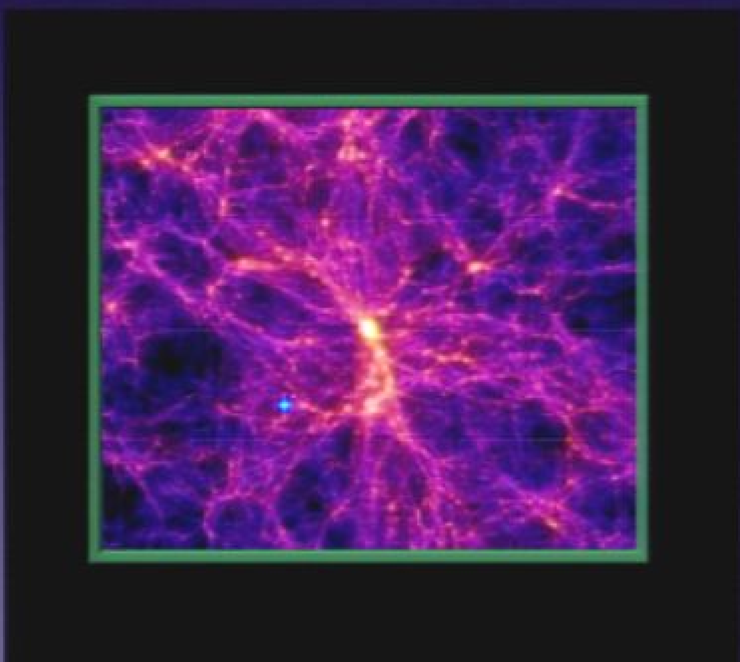
~75 % of the universe is filled with a fluid that has physical properties unlike anything we have ever measured

and yet it is a great success!

SNe: Type IA Supernovae: Standard Candles - measure expansion via luminosity distance

BAO: Acoustic oscillations - measure expansion via angular distance

CMB: Cosmic Microwave background - measure expansion via angular distance



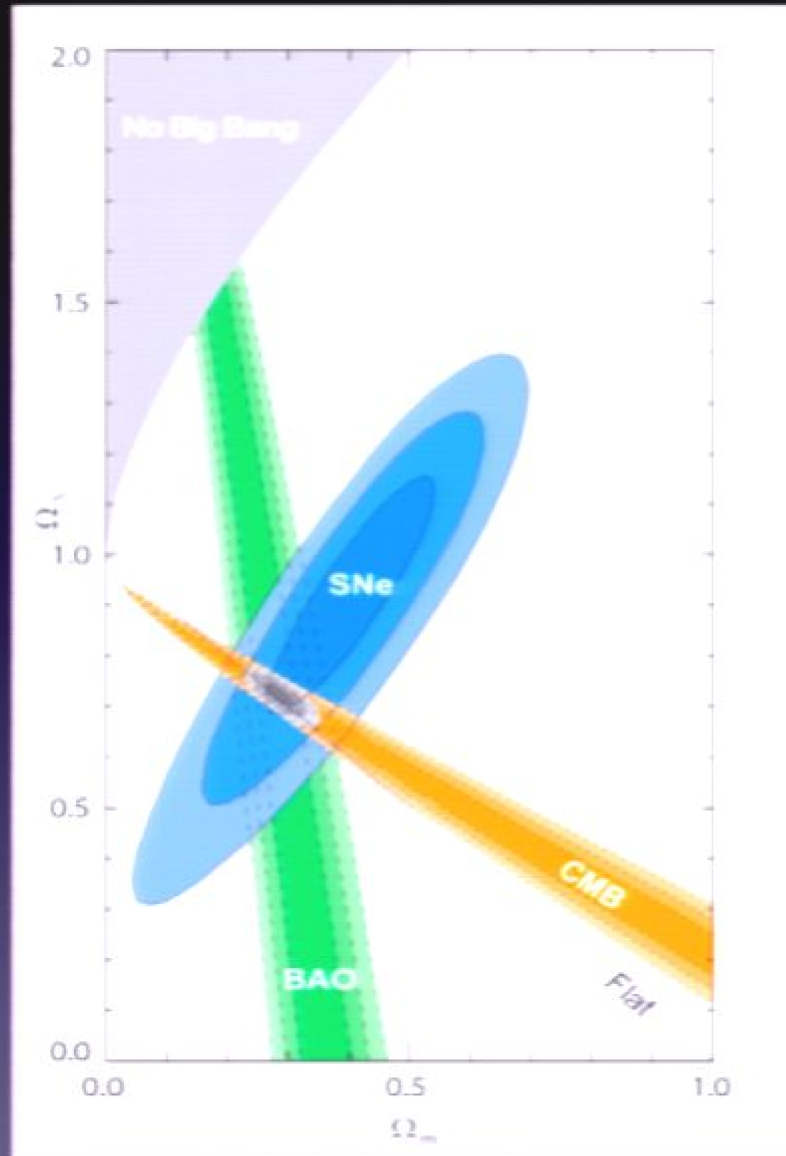
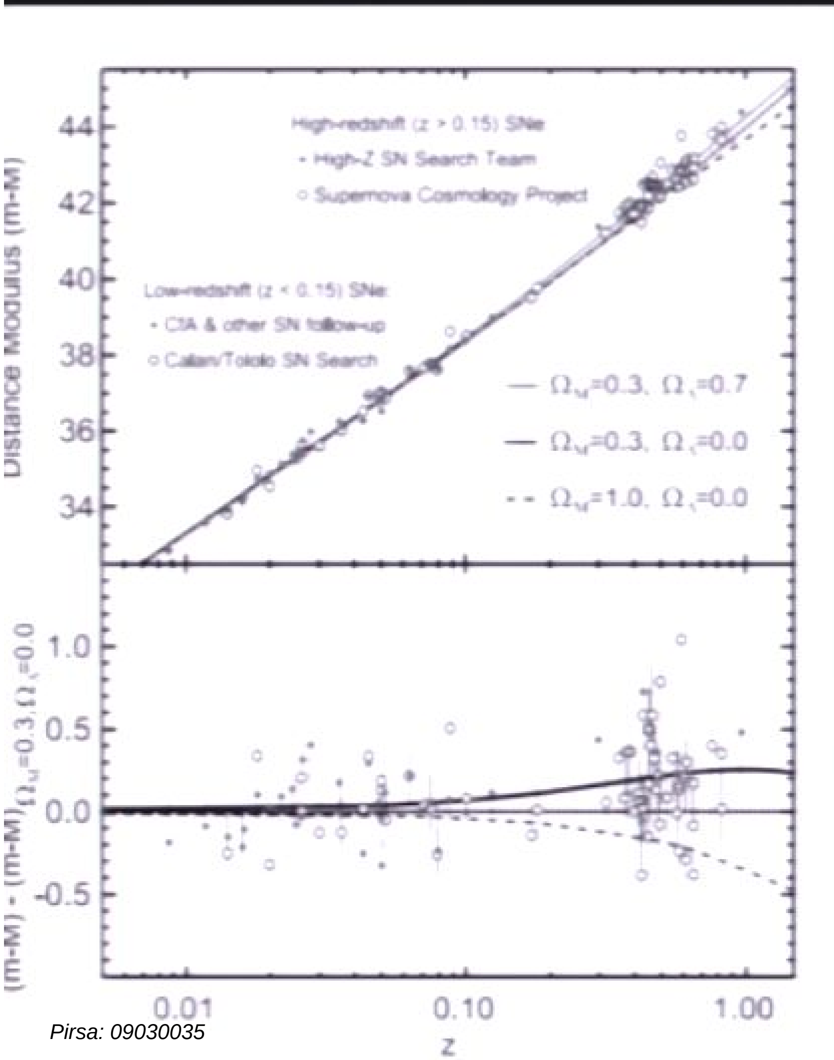


Figure taken from Frieman et al. (2008)

Matter Radiation Curvature Anisotropy

$$H^2(z) = \frac{8\pi G}{3}\left(\frac{\rho_M}{(1+z)^3} + \frac{\rho_R}{(1+z)^4} + \rho_{d.e.}\right) - \frac{k}{(1+z)^2} + \frac{B}{(1+z)^6}$$



Acceleration!!!

Supernovae Cosmology Project
High-z Supernovae Team

Perlmutter et al. (1999) Astrophys J.
Riess at al. (1998) Astron J.

$$H(z) = \frac{\dot{a}}{a} \qquad a = 1 + z$$

Figure taken from Frieman et al. (2008)

Observational Evidence

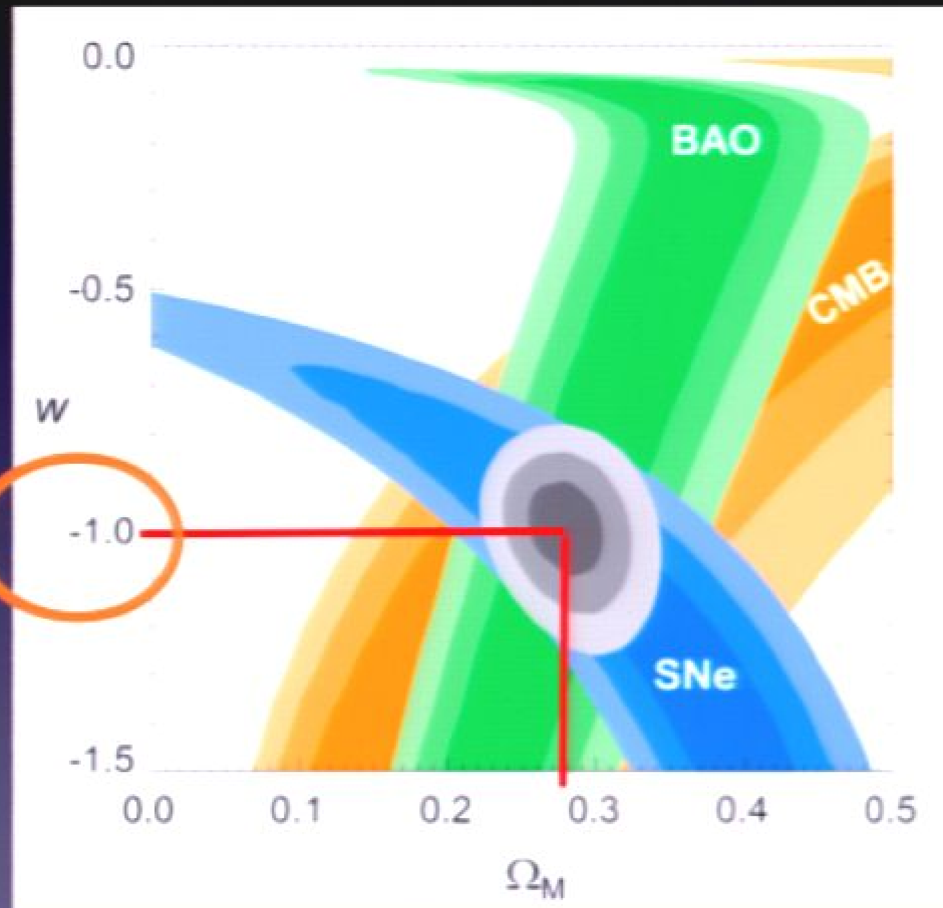
$$w = \frac{p_{d.e.}}{\rho_{d.e.}}$$

Data points tantalizingly close to

$$w = -1$$

to be precise...

$$w = -0.94 \pm 0.1$$



Frieman *et al.* (2008) Ann.Rev.Astron.Astrophys

What is dark energy?

Understanding nature of dark energy is probably one of the most important problems in cosmology today

'Good' theoretical ideas have been lacking! ...

... enter PI!

Cosmological Constant *versus* Dynamical Dark Energy

$$w = -1$$

↓

Cosmological constant

$$T_{\mu\nu} = -\frac{1}{8\pi G}\Lambda g_{\mu\nu}$$

$$w \neq -1$$

↓

Dynamical Dark Energy

existence of new d.o.f.
i.e. new particles
beyond gravity + SM (+DM)

Cosmological constant *problem*

Why is Λ so un(technically) naturally small?

C.C. is leading `relevant operator' in action for gravity

$$S = \int d^4x \sqrt{-g} \left(-\frac{1}{16\pi G}\Lambda + \frac{1}{16\pi G} R + \mathcal{L}_M \right)$$

Despite being most relevant operator, it is also most UV sensitive!

$$\Delta\rho_\Lambda = \frac{8\pi G}{3}\Delta\Lambda \sim \sum m_i^4 \ln(m_i/\mu)$$

$m_e^4/\rho \sim 10^{36}$ $m_W^4/\rho \sim 10^{56}$

Cosmological constant *problem*

Why is Λ so un(technically) naturally small?

Usually credited to Zeldovich

Y.B.Zel'dovich (1967); (1968)

Pauli (1930s) calculated vacuum energy using Bohr radius as cutoff ....

... size of universe (de Sitter curvature scale) = 31 km !!

Straumann (2002)

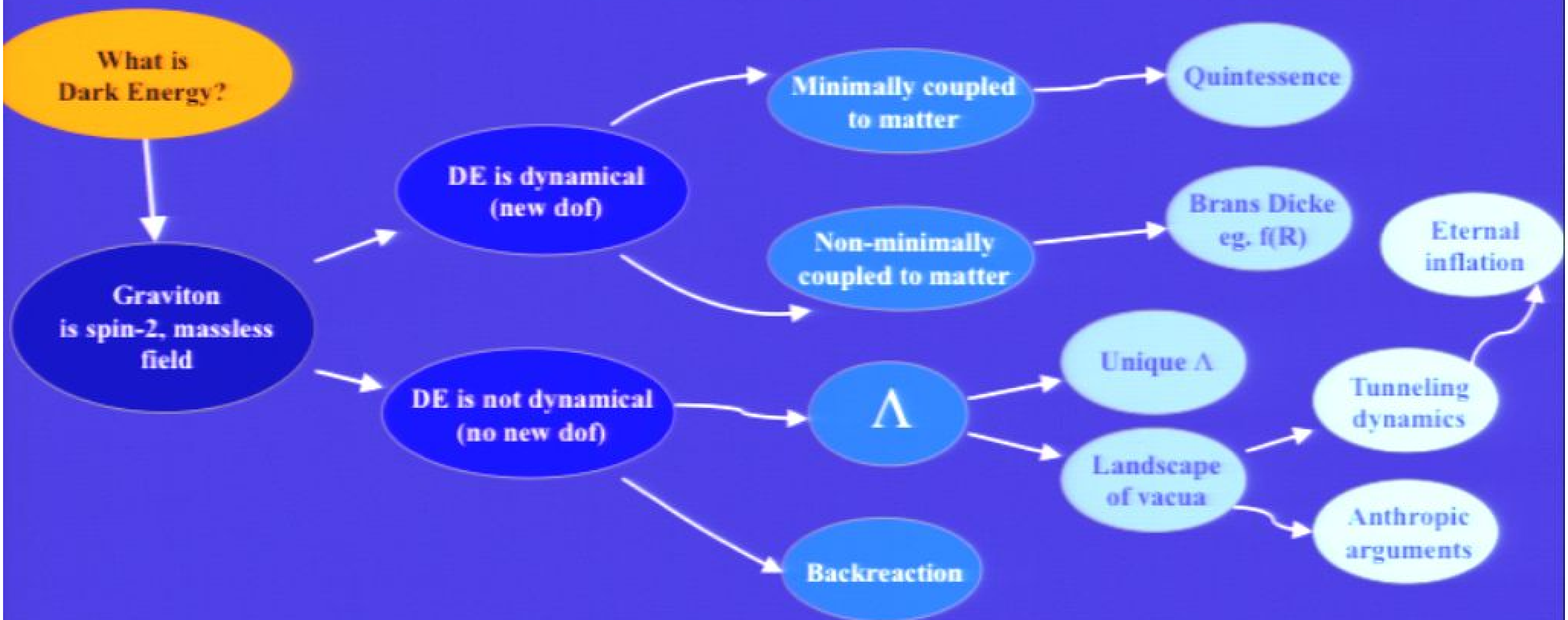
Gauge hierarchy *versus* c.c. hierarchy

- Higgs mass Quadratically sensitive to cutoff
- Problem only arise if assume existence of *unknown* physics beyond standard model
- Supersymmetry at TeV scale can protect

- C.C. is Quartically sensitive to cutoff
- Problem arises already from existence of *known* physics within the standard model
- Supersymmetry at meV scale can protect: but already ruled out!

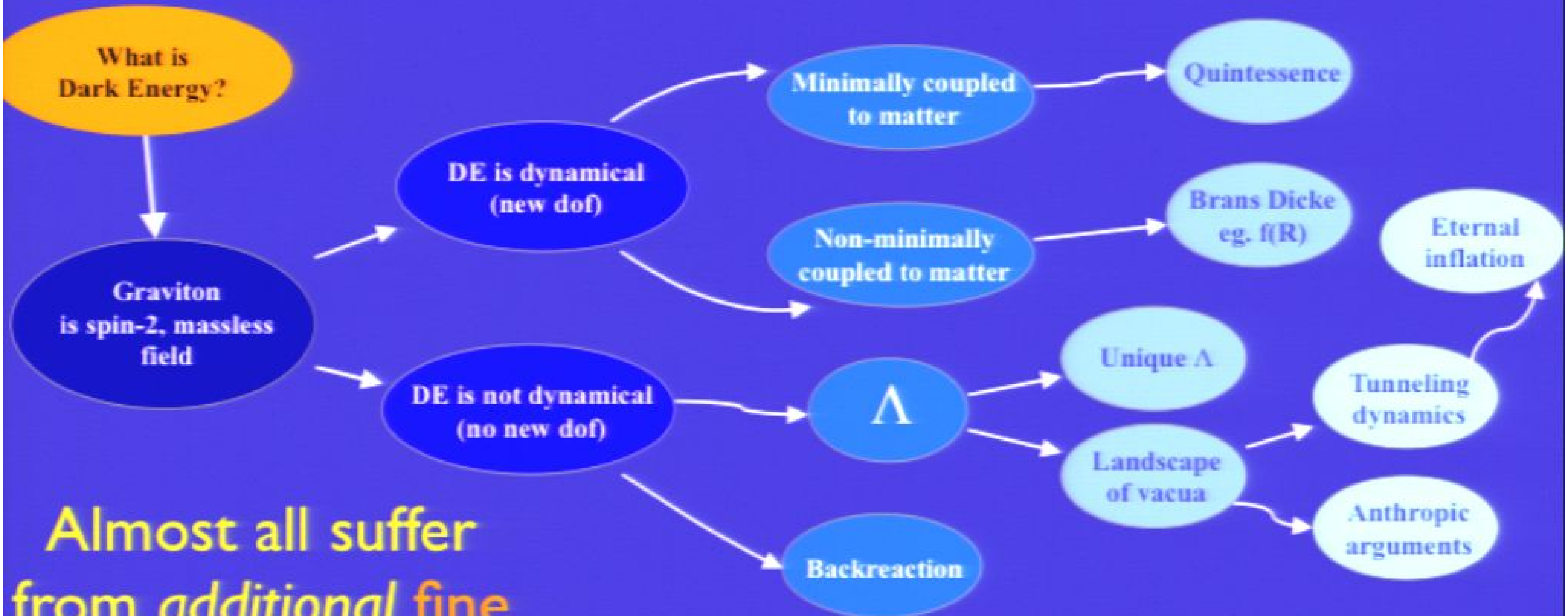
only other useful symmetry: scale invariance

There are many possible models of dark energy



de Rham & AJT,
Lectures on Dark Energy and the Cosmological Constant Challenge,
Nordita 2008

There are many possible models of dark energy



Almost all suffer from *additional* fine tuning problems

$$m_\phi \sim H_0 \sim 10^{-33}\ \mathrm{eV}$$

de Rham & AJT,
Lectures on Dark Energy and the Cosmological Constant Challenge,
Nordita 2008

Strategy

Before understanding nature of dark energy ...

... we must understand what resolves the cosmological constant problem

How can we attack the C.C. problem?

Look to the energy/length scales as a guide ......

Scales

There are two natural scales associated with Λ

$$H^2 = \frac{8\pi G}{3}\rho$$

Scales

There are two natural scales associated with Λ

$$\boxed{H^2} = \frac{8\pi G}{3}\rho$$

Curvature scale

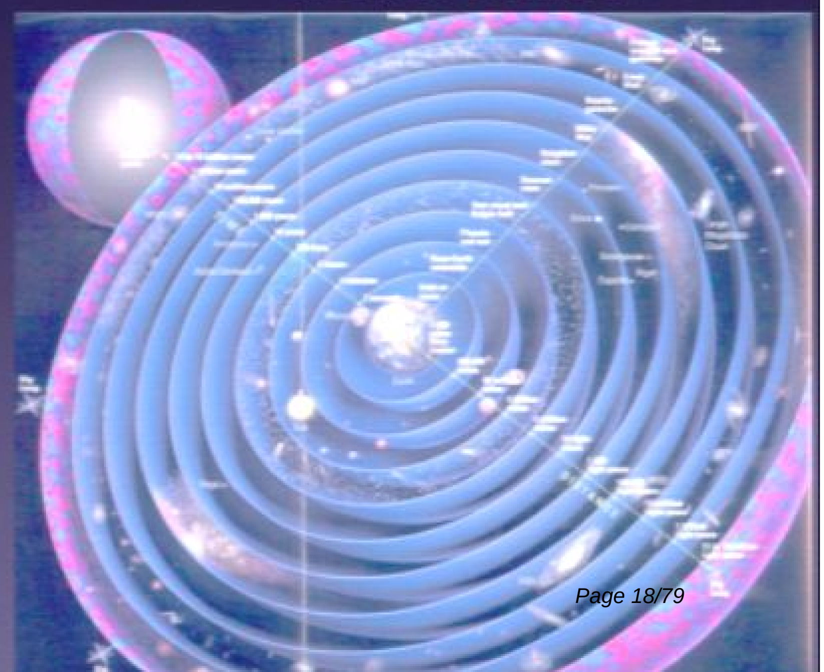
$$\Lambda \sim m^2 \sim \frac{1}{R^2}$$

$$m = 10^{-33}\mathrm{eV}$$

$$R \sim 3800\,\mathrm{Mpc}$$

→ Cosmological scale

Only cosmology probes these scales



Scales

There are two natural scales associated with Λ

$$H^2 = \frac{8\pi G}{3}\rho$$

Curvature scale

$$\Lambda \sim m^2 \sim \frac{1}{R^2}$$

$$m = 10^{-33}\mathrm{eV}$$

$$R \sim 3800\,\mathrm{Mpc}$$

Energy scale

$$\rho_\Lambda = \frac{1}{8\pi G}\Lambda \sim m^4$$

$$L = 0.1\mathrm{mm}$$

$$m = 0.1\mathrm{eV}$$

→ Submillimeter scale

Different scales = Different resolutions

New physics at mm scale ⟶

Loop calculation no longer valid

Tackle quantum problem directly

Different scales = Different resolutions

New physics at mm scale ⟶

Loop calculation no longer valid

Tackle quantum problem directly

New physics at Hubble scale ⟶

Dynamical Relaxation

Quantum intact, modify dynamics

Dynamical Relaxation

New physics at Hubble scale

↓

Dynamical Relaxation

→ 1st order phase transition

→ 2nd order phase transition

Dynamical Relaxation

New physics at Hubble scale

↓

Dynamical Relaxation → 1st order phase transition

↓

Abbott model (1985)

Recently revamped by Steinhardt + Turok (2006)

$$V(\phi) = \Lambda + \epsilon \frac{\phi}{2\pi M} - V_0 \cos\left(\frac{\phi}{M}\right)$$

Dynamical Relaxation

New physics at
Hubble scale

↓

Dynamical
Relaxation

→ 2nd order
phase transition

Idea:

$$\Lambda_{\text{eff}} = f(t)\Lambda = f(\phi)\Lambda$$

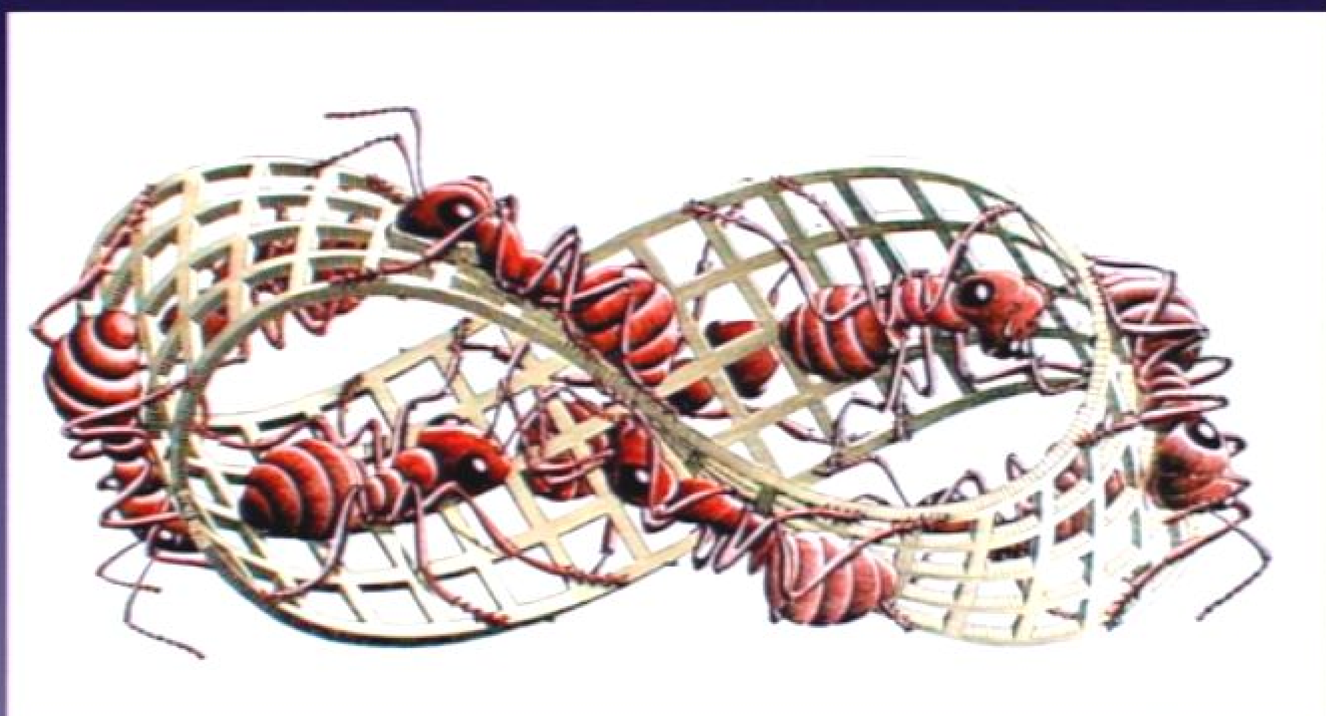
Dynamics of scalars drives

$$\Lambda_{\text{eff}} \to 0$$

e.g. Dolgov (1982)

Ruled out by S. Weinberg, but ..... more on this later!

New physics at submillmeter scales:
Attacking the quantum



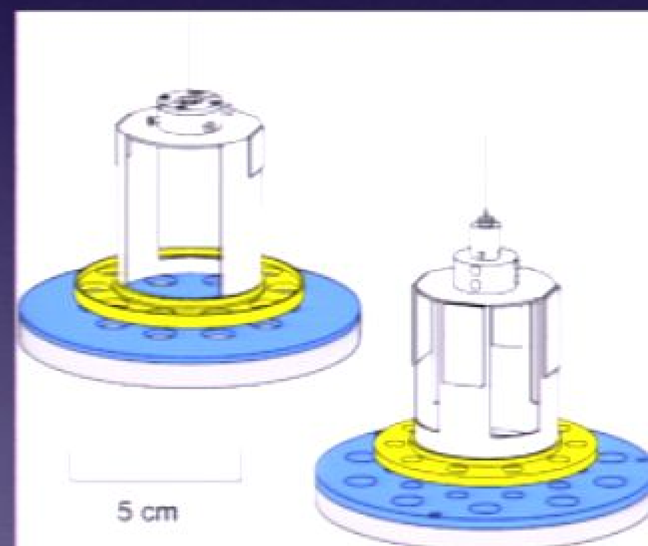
What could lead to new physics at submillimeter scale ?

$$H^2 = \frac{8\pi G}{3}\rho$$ → Submillimeter scale

SM physics well understood at this scale

But NOT Gravity !

Newtonian gravity has only been tested down to scales of ~50 of microns



Eotwash group, U Washington

Test Newton with Torsion Pendulum

What could lead to a modification of gravity at submillimeter scale ?

Submillimeter extra dimensions !!!

2 large extra dimensions

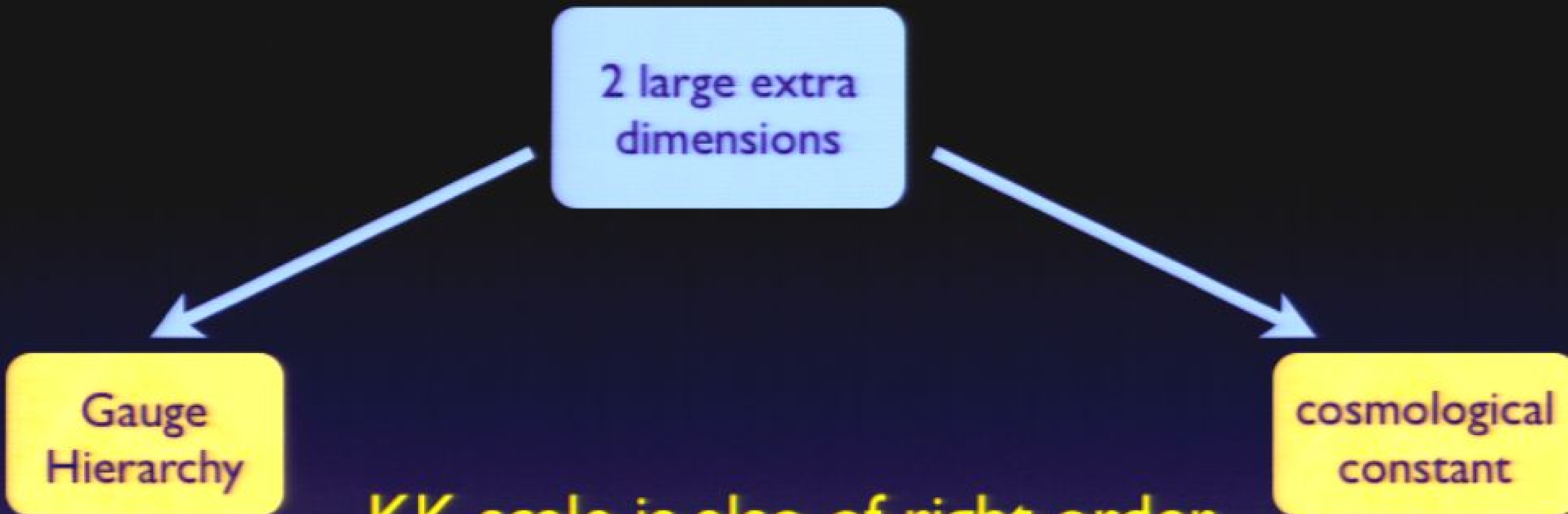
Gauge Hierarchy

Arkani-Hamed, Dimopolous, Dvali (1998)

$$M_4^2 = M_{4+n}^{2+n}\ \ell^n$$

for $n = 2$,

$$\ell \sim 0.1\,\mathrm{mm} \Rightarrow M_6 \sim \mathrm{TeV}$$

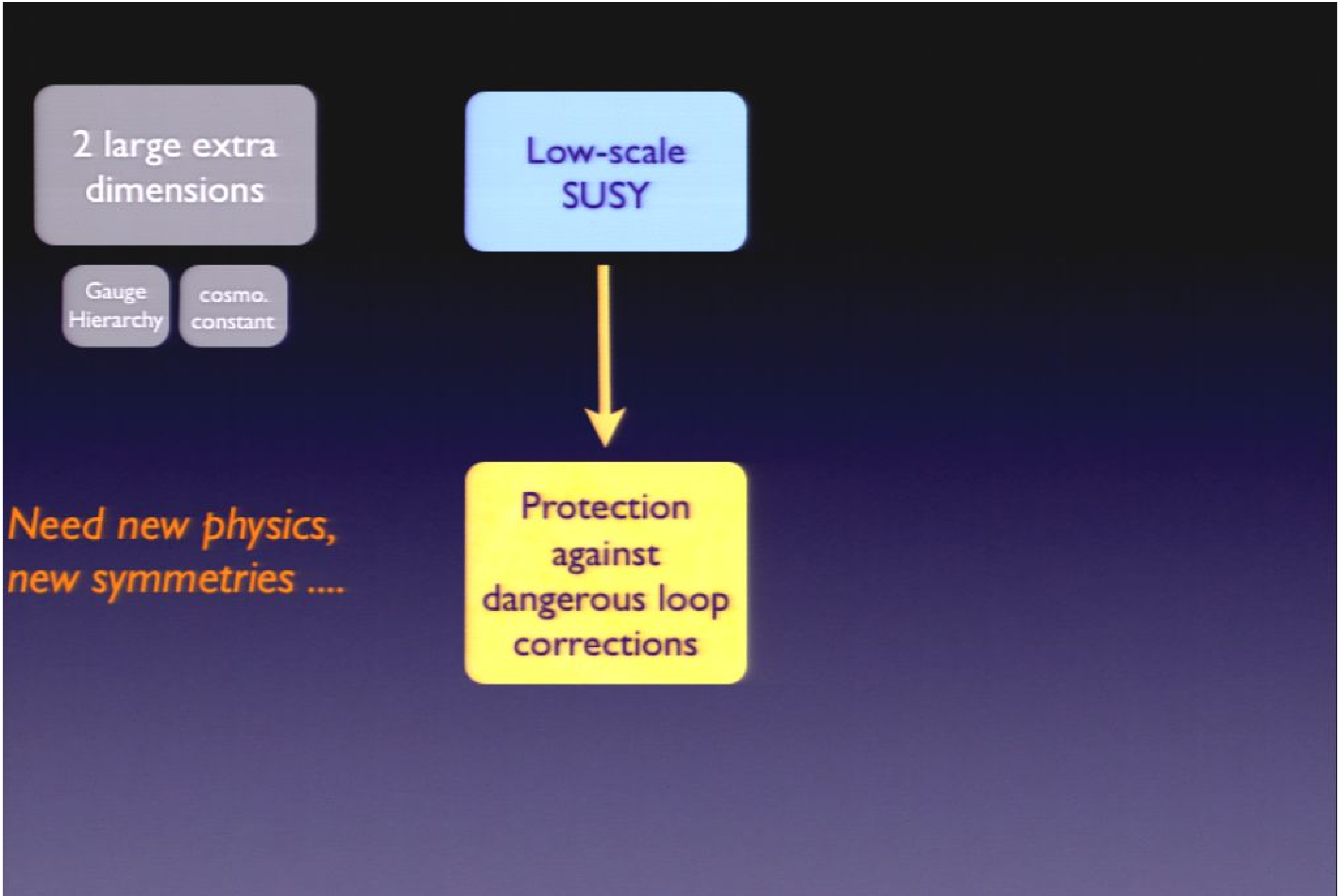


KK scale is also of right order

$$\rho_\Lambda = \frac{1}{8\pi G}\Lambda \sim m^4$$

$$L = 0.1\text{mm}$$

$$m = 0.1\text{eV}$$


2 large extra dimensions
Gauge Hierarchy
cosmo. constant
Low-scale SUSY
Protection against dangerous loop corrections
Need new physics, new symmetries ....

2 large extra dimensions

Gauge Hierarchy

cosmo. constant

Low-scale SUSY

Protection against loops

Scale Invariance

$$\Lambda_{\text{eff}} = 0$$

Need new physics, new symmetries ....

AJT et al. (2006)
'Bulk singularities and the effective cosmological constant for higher codimension branes'

AJT et al. (2006)
'Scaling solutions to 6D gauged chiral supergravity'

2 large extra dimensions

Gauge Hierarchy

cosmo. constant

Low-scale SUSY

Protection against loops

Scale Invariance

$\Lambda_{\rm eff} = 0$

Supersymmetric Large Extra Dimensions

Aghababaie et al. (2003)

Crucial questions:

1. How do loop corrections on brane, mediate via bulk, to give brane curvature?

Scale invariance gets broken: allow for de Sitter solutions

AJT et al. (2006)
'Bulk singularities and the effective cosmological constant for higher codimension branes'

Crucial questions:

2. Are the models dynamically stable?

Found classically one massless moduli ⟶ *Lifted by quantum corrections, gives viable model of quintessence!*

Burgess, de Rham, Hoover, Mason, AJT (2007)
'Kicking the Rugby Ball'

de Rham, AJT (2005)

Crucial questions:

3. What are the implications for cosmology? How do extra dimensions respond to phase transitions on the brane?

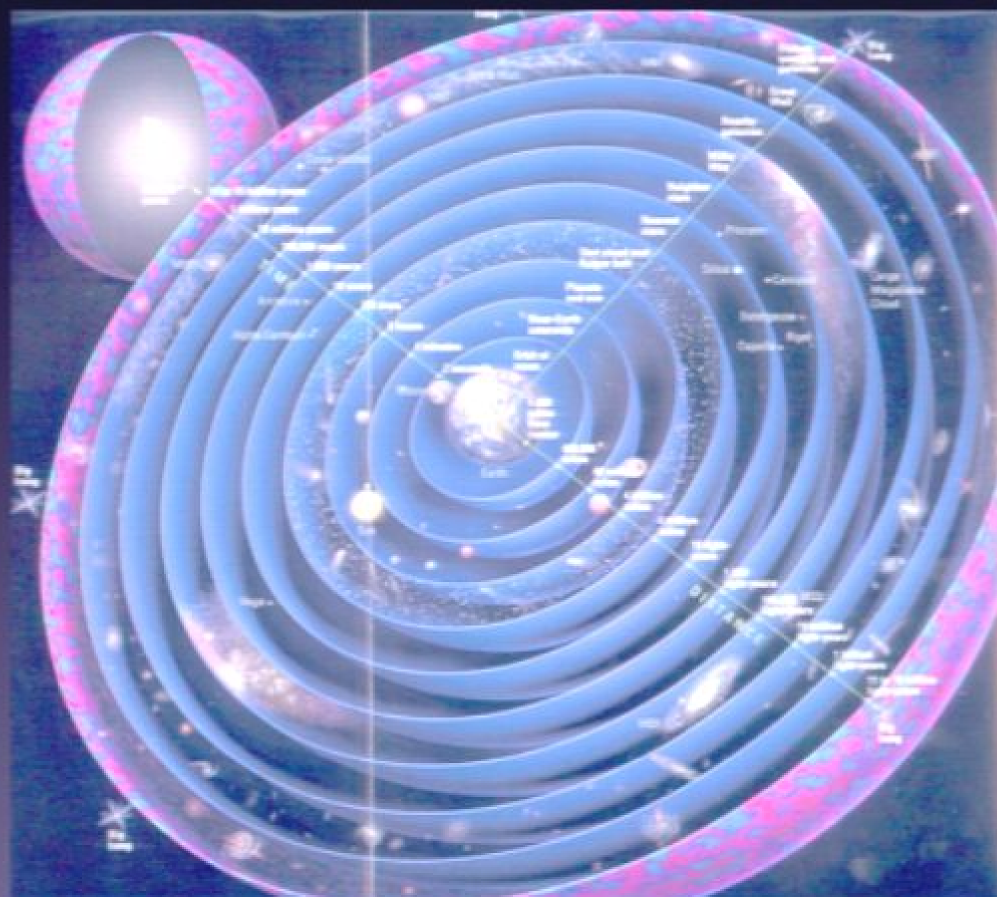
AJT et al. (2006)
'Scaling solutions to 6D gauged chiral supergravity'
AJT et al. (2006)
'Exact wave solutions 6D gauged chiral supergravity'
AJT and Bayntun (2009)
work in progress

Highly falsifiable model

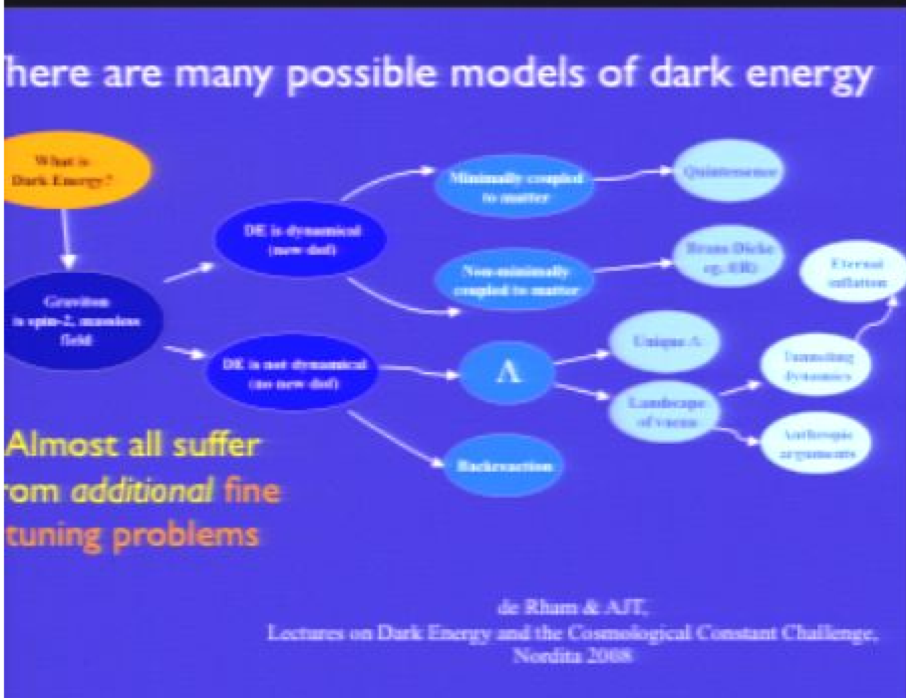
- Predicts dark energy dynamical: quintessence of Albrecht-Skordis form
- Deviations of Newton's law at ~ 1 micron
- Distinctive missing-energy signals at LHC due to emission into KK modes into extra dimensions.

Lesson: Tying solution of C.C. with dark energy makes for enormously predictive models!

New physics at Hubble scales:
Dynamical Relaxation



What new physics could arise at Hubble scales?



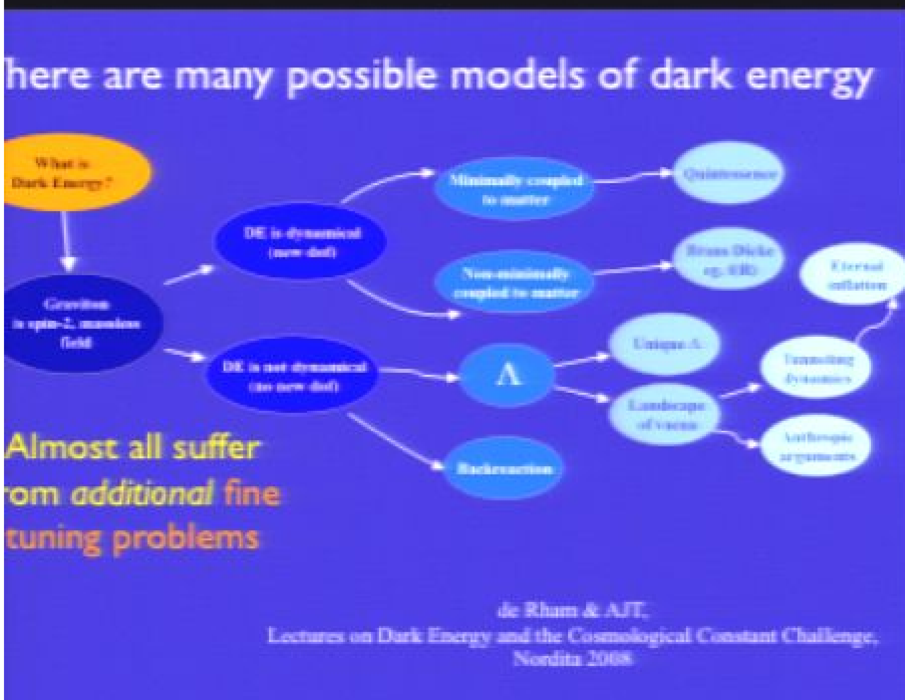
Lots of possibilities!

e.g. quintessence, k-essence, Brans-Dicke ....

However,

almost none of these ideas has made a dent in the C.C. problem

Why? because Weinberg no-go theorem!



The cosmological constant problem*

Steven Weinberg

Theory Group, Department of Physics, University of Texas, Austin, Texas 78712

Astronomical observations indicate that the cosmological constant is many orders of magnitude smaller than estimated in modern theories of elementary particles. After a brief review of the history of this problem, five different approaches to its solution are described.

VI. ADJUSTMENT MECHANISMS

I now turn to an idea that has been tried by virtually everyone who has worried about the cosmological constant [see, e.g., Dolgov (1982); Wilczek and Zee (1983); Wilczek (1984, 1985); Peccei, Sola, and Wetterich (1987); Barr and Hochberg (1988)]. Suppose there is some scalar ϕ whose source is proportional to the trace of the energy-momentum tensor

$$\Box^2\phi \propto T^\mu{}_\mu \propto R \qquad (6.1)$$

(Here $T^{\mu\nu}$ is the total energy-momentum tensor that includes a possible cosmological constant term $-\lambda g^{\mu\nu}/8\pi G$.) Suppose also that $T^\mu{}_\mu$ depends on ϕ and vanishes at some field value ϕ_0. Then ϕ will evolve until it reaches an equilibrium value ϕ_0, where $T^\mu{}_\mu = 0$, and the

Weinberg no-go theorem forbids dynamical relaxation via *2nd order* phase transition in models with graviton = massless spin two field

What new physics could arise at Hubble scales?

How do we evade Weinberg's no-go theorem?

The "no-go" theorem .. should not be regarded as closing off all hope in this direction. No-go theorems have a way of relying on apparently technical assumptions that later turn out to have exceptions of great physical interest.

S. Weinberg

What new physics could arise at Hubble scales?

How do we evade Weinberg's no-go theorem?

Assumption of no-go:

Graviton is 4D massless spin two field

How can you modify gravity at Hubble scales?

All (Lorentz perserving) modifications of gravity correspond to giving the graviton a mass, or a resonance of masses

Kallen-Lehmann spectral representation:

$$\vec{F} = m_1 m_2 \vec{\nabla} \left(\int_0^\infty dm \frac{\rho(m) e^{-mr}}{r} \right)$$

Massive graviton has 5 degrees of freedom

2 helicity-2 $\oplus$ 2 helicity-1 $\oplus$ 1 helicity-0

New particles mediating gravitational force $\longrightarrow$ New physics! ***Fifth forces***

$m \to 0$ limit *is* equivalent to $m = 0$

van Dam&Veltman, Nucl. Phys B 22 (1970), Zakharov JETP Lett 12 (1970) ✗

Vainshtein, PL 39 (1972) ✓

New particles mediating gravitational force $\longrightarrow$ New physics! ***Fifth forces***

$m \to 0$ limit *is* equivalent to $m = 0$

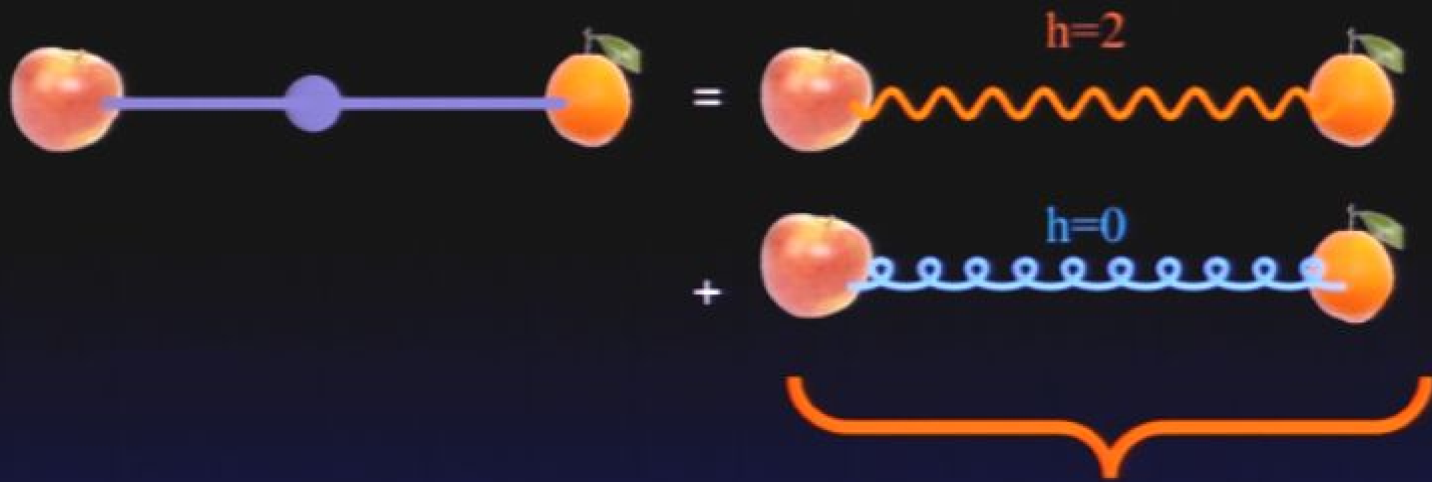
van Dam&Veltman, Nucl. Phys B 22 (1970), Zakharov JETP Lett 12 (1970) ✗

Vainshtein, PL 39 (1972) ✓

but ...

... decoupling of the extra states occurs in a very nonlinear way!

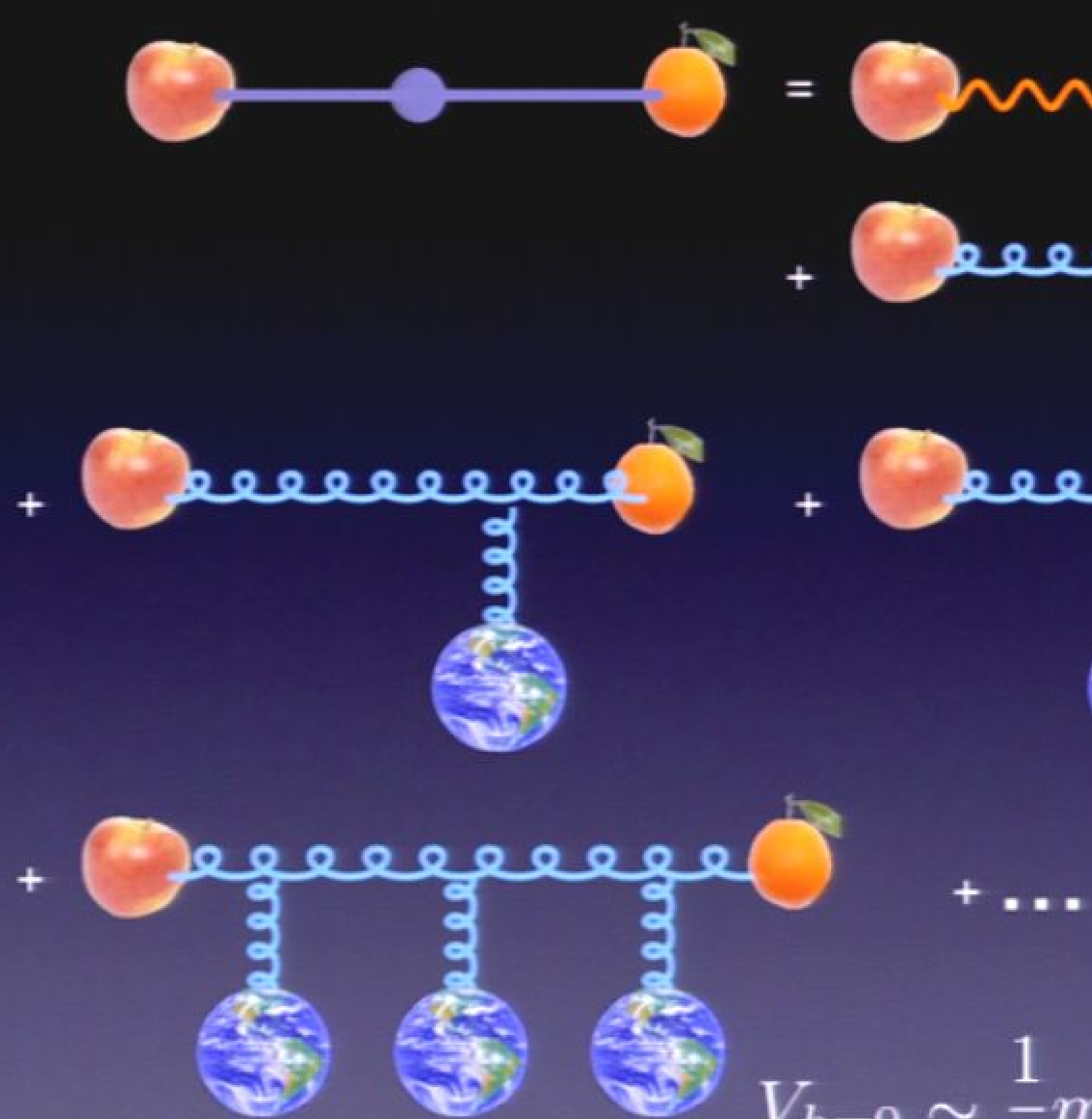
Decoupling absent at linear level, occurs after resumming tree diagrams from external interactions with nearby matter



Additional fifth force from scalar mode

$$V_{h=0} = \frac{1}{3} m_{\rm a} m_{\rm o} G \frac{e^{-mr}}{r}$$

at first sight such theories are ruled out!



Force now vanishes as

$$V_{h=0} \sim \frac{1}{3} m_{\rm a} m_{\rm o} G \frac{e^{-mr}}{r} \frac{1}{1 + \frac{\bar{\rho}_{\rm e}}{m^2 M_{\rm pl}^2}}$$

What has graviton mass to do with c.c.?

What has graviton mass to do with the cc? I

A massive theory of gravity can support C.C. without curvature!

$$G_{\mu\nu} + \frac{m^2}{2}(h_{\mu\nu} - h\eta_{\mu\nu}) = -\Lambda g_{\mu\nu} + \frac{8\pi G}{3} T_{\mu\nu}$$

new vacuum solution!

$$g_{\mu\nu} = \frac{1}{\left(1 - \frac{2\Lambda}{3m^2}\right)} \eta_{\mu\nu}$$

In specific case of fixed mass gravity this exhibits a ghost, but ...
... not necessarily true in all models of resonance massive gravity

AJT work in progress

What has graviton mass to do with the cc? I

But this is not enough!

Physics should be causal!

If such solutions exist,
we need to understand how
to dynamically relax to them

What has graviton mass to do with c.c.? II

The cosmological constant problem is a problem because of the *equivalence principle*

"*Everything couples to gravity with the same strength*"

PHYSICAL REVIEW VOLUME 135, NUMBER 4B 24 AUGUST 19

Photons and Gravitons in S-Matrix Theory: Derivation of Charge Conservation and Equality of Gravitational and Inertial Mass*

STEVEN WEINBERG†
Physics Department, University of California, Berkeley, California

(Received 13 April 1964)

If the graviton has a mass/resonance,
the equivalence principle would no longer hold !!!

$$G(k) \neq G(0)$$

What has graviton mass to do with c.c.? II

$$\delta G_{\mu\nu} + \frac{m^2}{2}(h_{\mu\nu} - \eta_{\mu\nu}h) = \frac{8\pi G}{3}T_{\mu\nu}$$

is, after some shenanigans, equivalent to

$$\delta G_{\mu\nu} = \frac{8\pi G_{\text{eff}}(\Box)}{3}T_{\mu\nu}$$

where

$$G_{\text{eff}}(\Box) = G\left(1 - \frac{m^2}{\Box}\right)$$

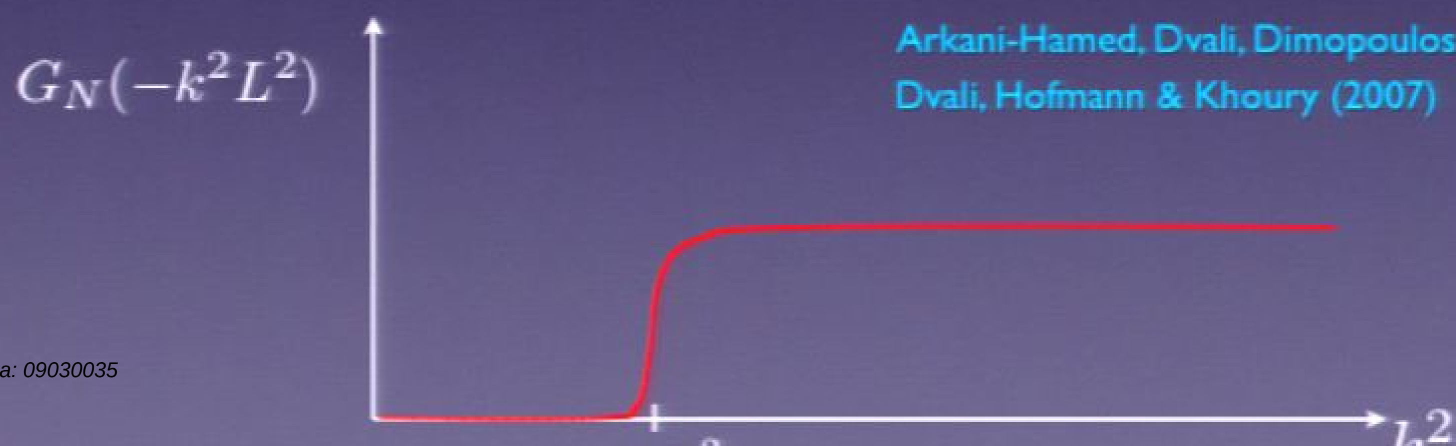
more generally ... $m^2 = m^2(\Box)$

What has graviton mass to do with the cc? II

This leads us to the idea of DEGRAVITATION

Vacuum energy is large, as dictated by particle physics, but gravitates very weakly because graviton has mass or is resonance state

Arkani-Hamed, Dvali, Dimopoulos & Gabadadze (2002)
Dvali, Hofmann & Khoury (2007)

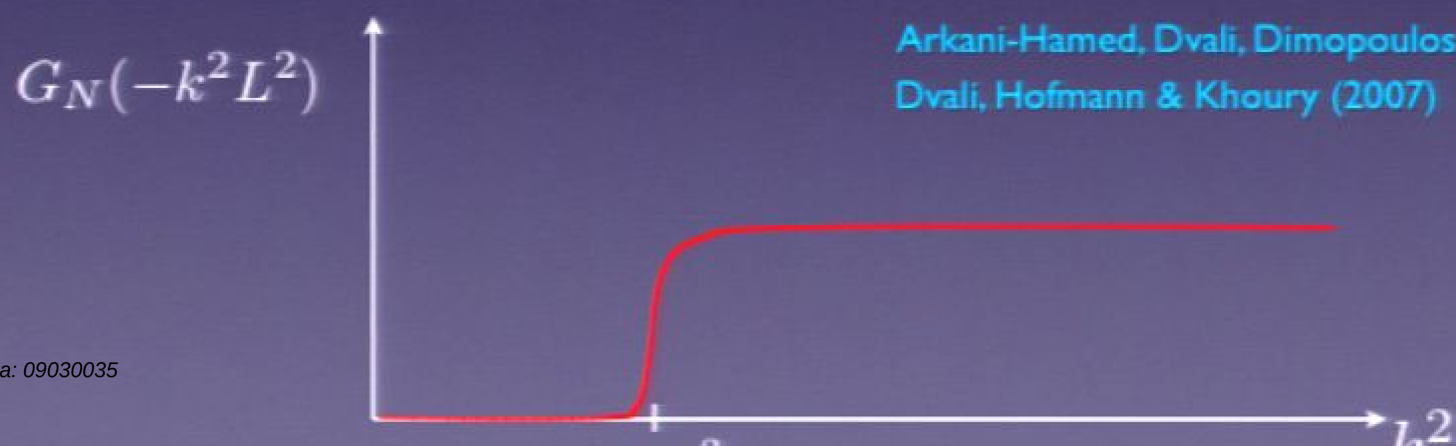


What has graviton mass to do with the cc? II

Mechanism must be causal:

Dynamical relaxation whose timescale is set by 'graviton mass'

Arkani-Hamed, Dvali, Dimopoulos & Gabadadze (2002)
Dvali, Hofmann & Khoury (2007)



Can we construct an explicit model of degravitation?

i.e. Can we construct a model of gravity in which effective C.C. dynamically relaxes (via a 2nd order phase transition) from its natural value to small value we see today?

What is measure of success?

- Consistent Low Energy Effective Field Theory
- No ghosts (Unitarity)

  (within regime of validity of EFT)

- Preserves notion of causality/locality

  (avoid closed timelike curves etc)

- No nonperturbative instability

  (unless lifetime longer than age of universe)

First question: how can we construct an explicit model of massive/resonance gravity?

Known problem ....

Interacting theories of massive gravitons pathological - extra ghostly non-pert. d.o.f., unbounded energy, causality violations

Boulware + Deser (1972)

Two known solutions ....

Nappi + L. Witten (1989)

Extra dimensions

Price: Infinite tower of massive KK modes

Argyres + Nappi (1989)

Strings

Price: Infinite tower of higher spins

Gravity in Higher Dimensions

In *4+n* dimensional spacetime, gravitational potential scales as

$$V(r) \sim \frac{1}{r^{1+n}}$$

weaker gravity

Gravity in Higher Dimensions

In *4+n* dimensional spacetime, gravitational potential scales as

$$V(r) \sim \frac{1}{r^{1+n}}$$ *weaker gravity*

we want to achieve this in the IR

$$V(r) \sim \frac{1}{r} \longrightarrow V(r) \sim \frac{1}{r^{1+n}}$$

UV, small r — IR, large r

Gravity in Higher Dimensions

Form of potential $$V(r) = \int_0^\infty ds^2 \rho(s^2) \frac{e^{-sr}}{r}$$

corresponds to propagator

$$G_F(k) = \int_0^\infty ds^2 \rho(s^2) \frac{1}{k^2 + s^2 - i\epsilon} = \frac{1}{k^2 + m^2(k) - i\epsilon}$$

Gravity in Higher Dimensions

Form of potential $$V(r) = \int_0^\infty ds^2 \rho(s^2) \frac{e^{-sr}}{r}$$

corresponds to Feynman propagator

$$G_F(k) = \int_0^\infty ds^2 \rho(s^2) \frac{1}{k^2 + s^2 - i\epsilon} = \frac{1}{k^2 + m^2(k) - i\epsilon}$$

de Rham, Hofmann, Khoury, AJT (2008)

$$m^2(k) \sim m_0^2(-k^2L^2)^\alpha$$

$\alpha = 1/2$	5d
$\alpha \sim 0$	6d
$\alpha = 0$	>6d

led to 6 or higher dim's to tackle C.C.

How can we achieve 4D to 6D transition?

More irrelevant ⟷ More relevant

$$S = \int d^4x\sqrt{-g_4}\left(\frac{M_4^2}{2}R_4 + \mathcal{L}_M\right) + \int d^6x\sqrt{-g_6}\left(\frac{M_6^4}{2}R_6\right)$$

Dominates in UV ⟷ Dominates in IR

How can we achieve 4D to 6D transition?

More irrelevant ⟷ More relevant

$$S = \int d^4x\sqrt{-g_4}\left(\frac{M_4^2}{2}R_4 + \mathcal{L}_M\right) + \int d^6x\sqrt{-g_6}\left(\frac{M_6^4}{2}R_6\right)$$

Dominates in UV ⟷ Dominates in IR

Two problems:

1. UV divergences associated with singular nature of codimension two branes

Geroch and Traschen (1987)

2. Scalar mode is a ghost

Dubovsky and Rubakov (2003)

How can we achieve 4D to 6D transition?

More irrelevant ⟵⟶ More relevant

$$S = \int d^4x\sqrt{-g_4}\left(\frac{M_4^2}{2}R_4 + \mathcal{L}_M\right) + \int d^5x\sqrt{-g_5}\left(\frac{M_3^4}{2}R_5\right) + \int d^6x\sqrt{-g_6}\left(\frac{M_6^4}{2}R_6\right)$$

Dominates in UV ⟵⟶ Dominates in IR

Newtonian potential transits from

4D to 5D to 6D

Solves UV divergence problem

de Rham, Dvali, Hofmann, Khoury, Pujolas, Redi, AJT (2007)

de Rham, Hofmann, Khoury, AJT (2008)

How can we achieve 4D to 6D transition?

More irrelevant — More relevant

$$S=\int d^4x\sqrt{-g_4}\left(\frac{M_4^2}{2}R_4+\mathcal{L}_M-\Lambda_4\right)+\int d^5x\sqrt{-g_5}\left(\frac{M_3^4}{2}R_5\right)+\int d^6x\sqrt{-g_6}\left(\frac{M_6^4}{2}R_6\right)$$

Dominates in UV — Dominates in IR

Minimum C.C. on our 3-brane

Solves ghost problem

$$\Lambda_4 \geq \frac{2}{3}\frac{M_4^2 M_6^8}{M_5^6}$$

de Rham, Dvali, Hofmann, Khoury, Pujolas, Redi, AJT (2007)
de Rham, Hofmann, Khoury, AJT (2008)
de Rham, Khoury, AJT, to appear

How can we achieve 4D to 6D transition?

More irrelevant ⟷ More relevant

$$S = \int d^4x\sqrt{-g_4}\left(\frac{M_4^2}{2}R_4 + \mathcal{L}_M\right) + \int d^5x\sqrt{-g_5}\left(\frac{M_3^4}{2}R_5\right) + \int d^6x\sqrt{-g_6}\left(\frac{M_6^4}{2}R_6\right)$$

Dominates in UV ⟷ Dominates in IR

Newtonian potential transits from

4D to 5D to 6D

Solves UV divergence problem

de Rham, Dvali, Hofmann, Khoury, Pujolas, Redi, AJT (2007)

de Rham, Hofmann, Khoury, AJT (2008)

How can we achieve 4D to 6D transition?

More irrelevant ⟷ More relevant

$$S = \int d^4x\sqrt{-g_4}\left(\frac{M_4^2}{2}R_4 + \mathcal{L}_M\right) + \int d^5x\sqrt{-g_5}\left(\frac{M_3^4}{2}R_5\right) + \int d^6x\sqrt{-g_6}\left(\frac{M_6^4}{2}R_6\right)$$

Dominates in UV ⟷ Dominates in IR

Newtonian potential transits from

4D to 5D to 6D

Solves UV divergence problem

de Rham, Dvali, Hofmann, Khoury, Pujolas, Redi, AJT (2007)

de Rham, Hofmann, Khoury, AJT (2008)

How can we achieve 4D to 6D transition?

More irrelevant ⟷ More relevant

$$S = \int d^4x\sqrt{-g_4}\left(\frac{M_4^2}{2}R_4 + \mathcal{L}_M - \Lambda_4\right) + \int d^5x\sqrt{-g_5}\left(\frac{M_3^4}{2}R_5\right) + \int d^6x\sqrt{-g_6}\left(\frac{M_6^4}{2}R_6\right)$$

Dominates in UV ⟷ Dominates in IR

Minimum C.C. on our 3-brane

Solves ghost problem $\Lambda_4 \geq \frac{2}{3}\frac{M_4^2 M_6^8}{M_5^6}$

de Rham, Dvali, Hofmann, Khoury, Pujolas, Redi, AJT (2007)

de Rham, Hofmann, Khoury, AJT (2008)

de Rham, Khoury, AJT, to appear

Does cascading model realize dynamical relaxation?

Criterion 1:

Existence of a Minkowski vacuum solution in the presence of a cosmological constant on the 3-brane

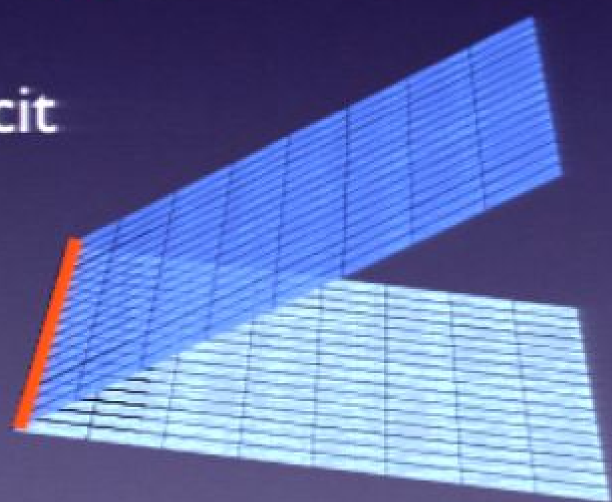
Does cascading model realize dynamical relaxation?

Criterion 1:

Existence of a Minkowski vacuum solution in the presence of a cosmological constant on the 3-brane

✓

Tension creates deficit angle in bulk



similar properties found in 7 dimensions

de Rham, Khoury, AJT, to appear

Does cascading model realize dynamical relaxation?

Criterion 2:

Dynamical and causal process by which we can relax to this solution

Does cascading model realize dynamical relaxation?

Criterion 2:

Dynamical and causal process by which we can relax to this solution

At linearized level ✓

Nonlinearly: much harder to check!

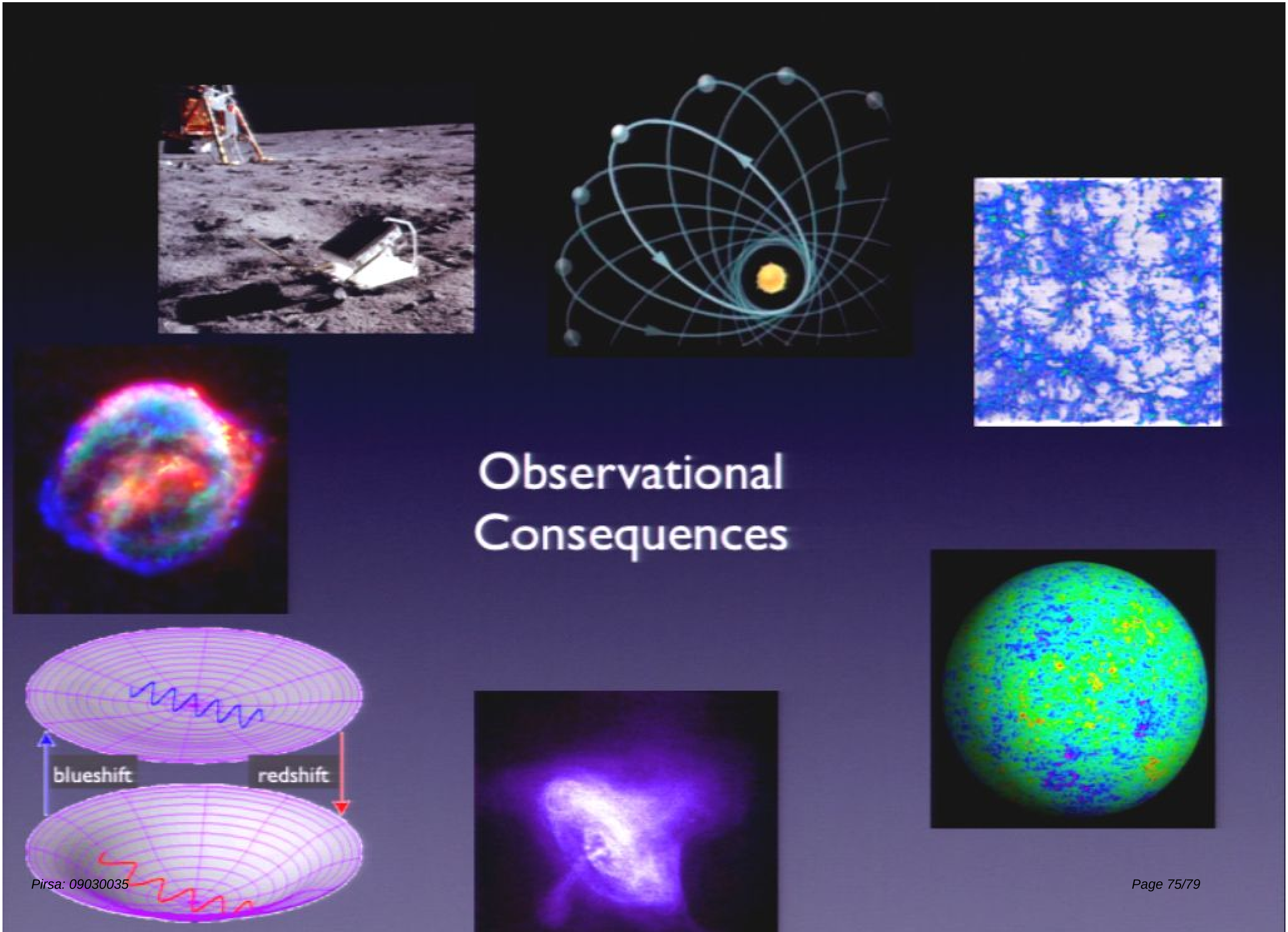
work in progress!

de Rham, Khoury, AJT, to appear

de Rham, AJT, to appear

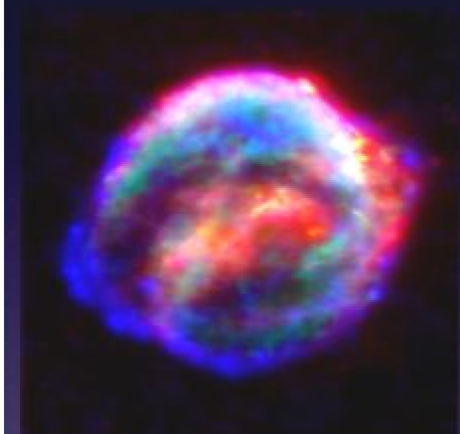
What is measure of success?

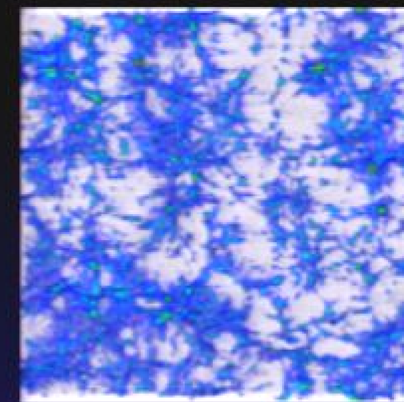
- Consistent Low Energy Effective Field Theory ✓
- No ghosts (Unitarity) ✓
- Preserves notion of causality/locality ✓
  (inherited from higher dimensions)
- No nonperturbative instability
  (unless lifetime longer than age of universe)


Observational
Consequences
blueshift
redshift

Modification of Friedmann equation

de Rham, AJT, work in progress



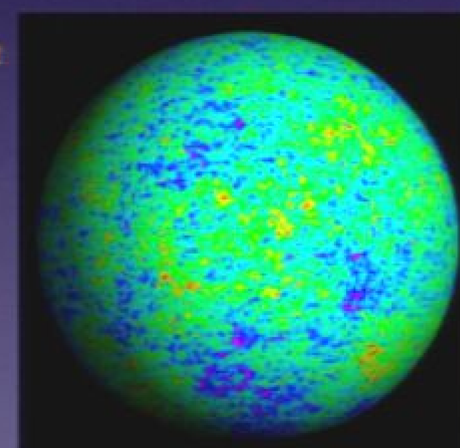


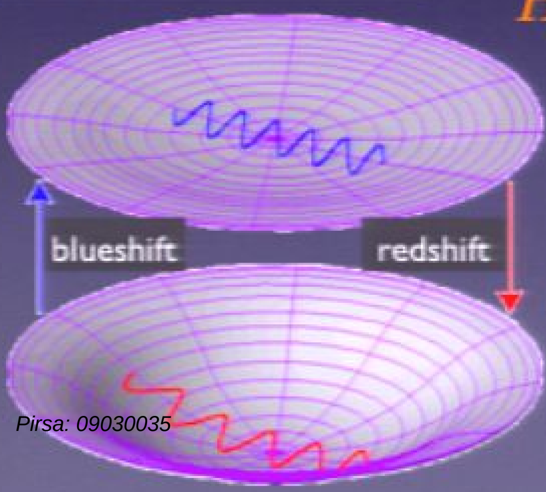
Khoury and Wyman (2009)

in certain regime...

$$H^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} - m^2 \left(\frac{H}{m}\right)^{2\alpha}$$

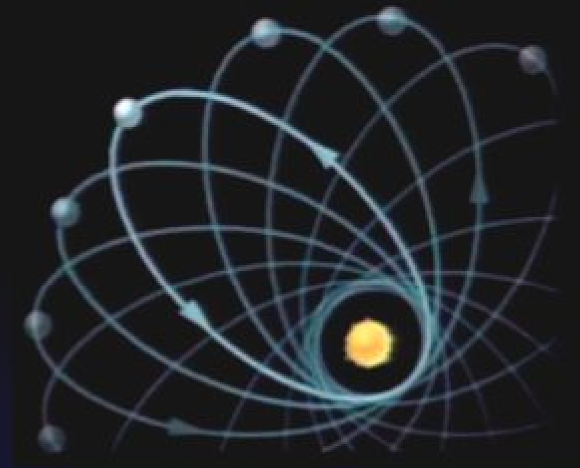
$$\alpha \sim 0 \longrightarrow H^{2\alpha} \sim \ln H$$



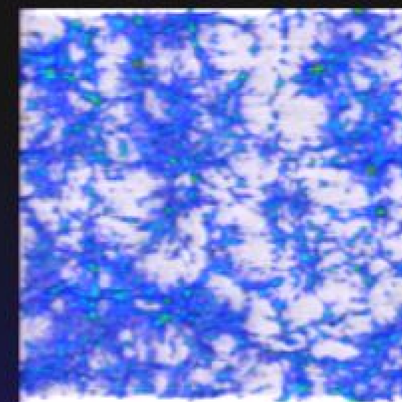


Afshordi, Geshniziani, Khoury (2008)

Dvali, Gruzinov, Zaldariagga (2002)



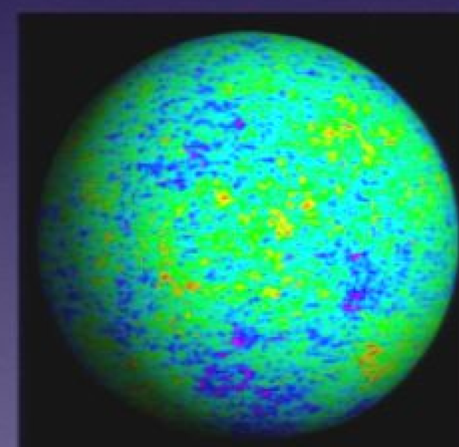
Lue and Starkman (2002)

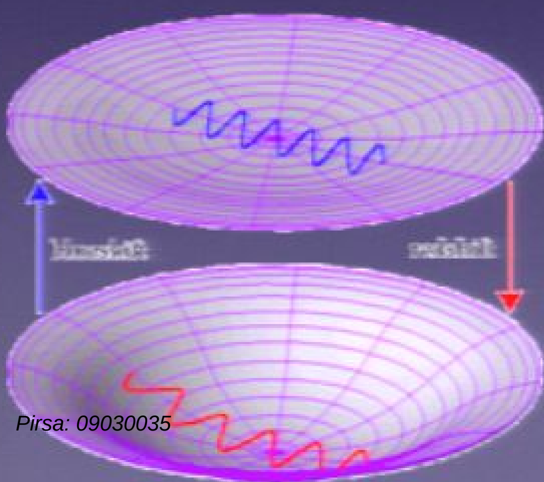


Khoury and Wyman (2009)

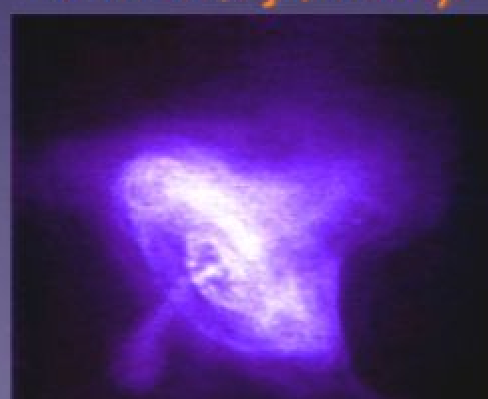
Modification of dynamics of dark energy from two additional scalar modes

de Rham, AJT, work in progress





de Rham, AJT, Wesley



Afshordi, Geshniziani, Khoury (2008)

Conclusions

- Tackling C.C. problem, requires giving up something cherished!
- Two natural scales for new physics (Hubble and mm)

  If mm - Attack quantum problem (SLED)

  If Hubble - Dynamical relaxation:

  Ist order: e.g. *Abbot model and extensions*

  2nd order: Degravitation, Cascading gravity

- Lead to extra dimensions, large or extra large!!
- Both classes of models are enormously predictive!

de Rham & AJT, Lectures on Dark Energy and the Cosmological Constant Challenge, Nordita 2008