Is Cosmic Acceleration Telling Us Something About Gravity?

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Colloquium

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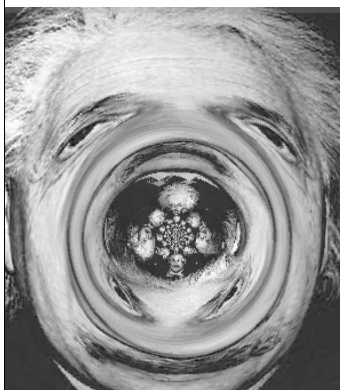
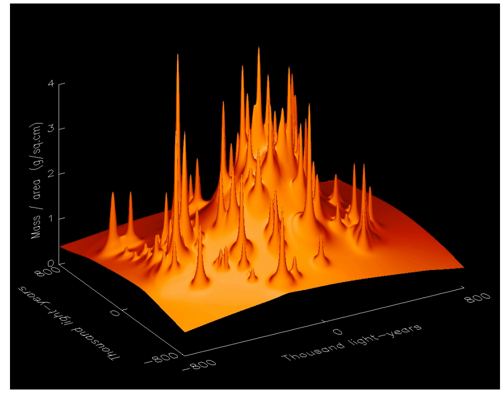
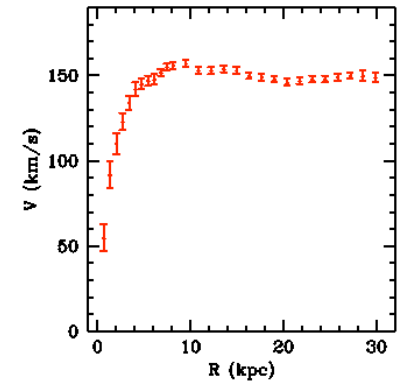
Outline

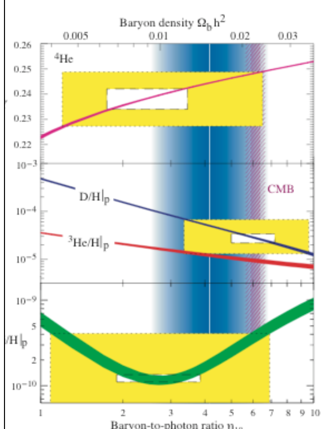
- Introduction.
- What Cosmologists don't know and how they know they don't know it
  - Dark Matter, Baryons, and Dark Energy
- Cosmic Acceleration and its challenges
- Are some of our observations revealing new secrets about fundamental physics?
  - the importance of gravity
  - some examples and constraints
- Summary

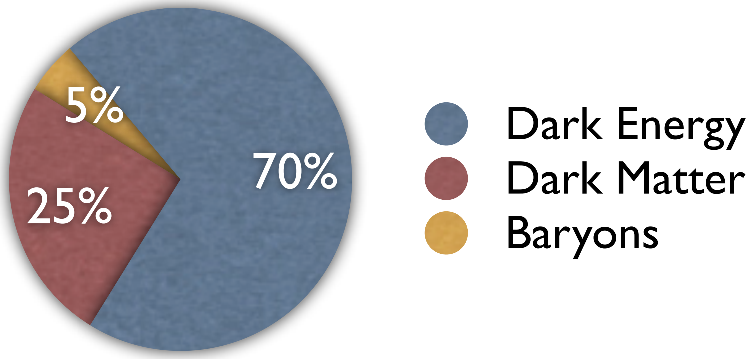
Establishing the New Cosmology

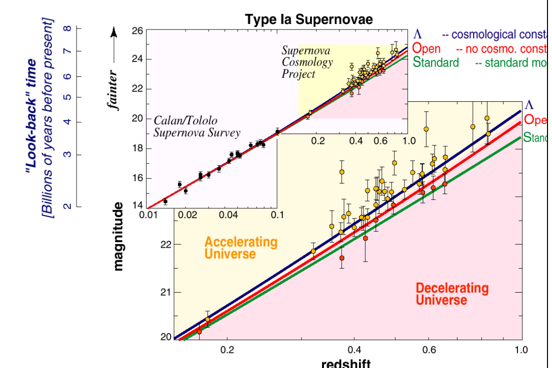


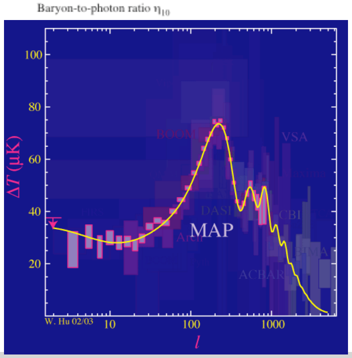


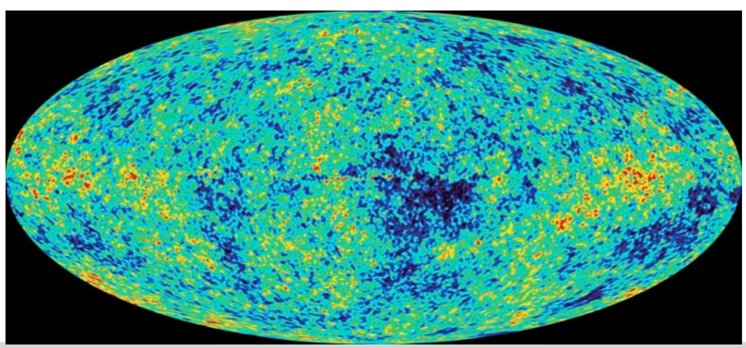


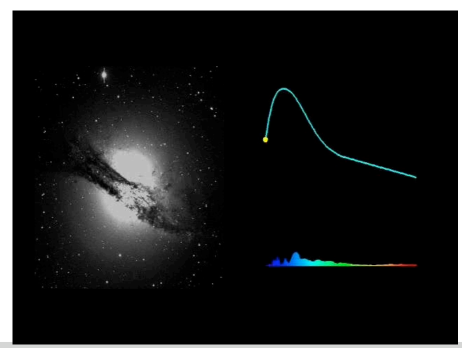








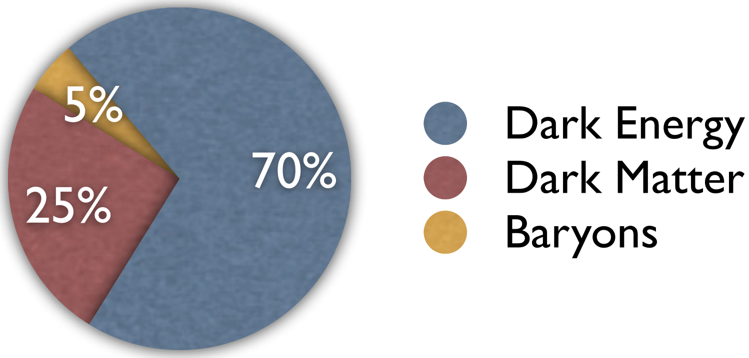




Understanding the New Cosmology

We don't know what these particles are but we have some well-motivated ideas

We know what these particles are but not why they haven't met their antiparticles

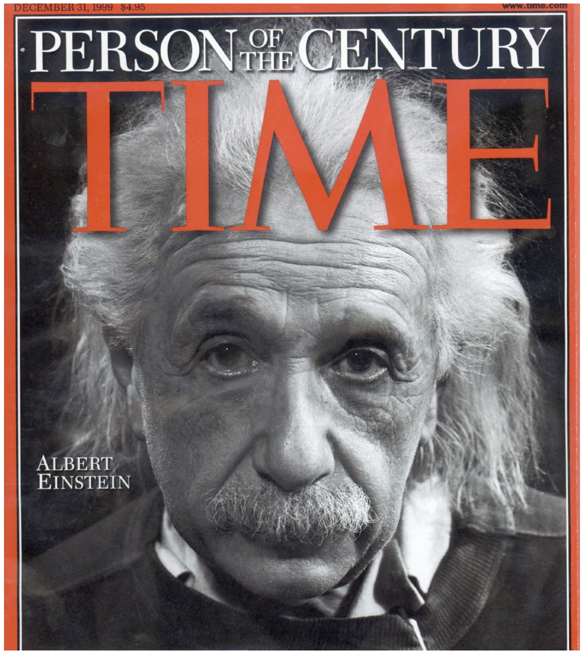


We have absolutely no idea what this stuff is and we have no ideas that are well-motivated and well-developed!

Our Three Problems

- Three problems posed by observational cosmology.
- A great achievement, but raises many issues.
- Need fundamental physics to understand what the universe is made of and why these observations look the way they do.

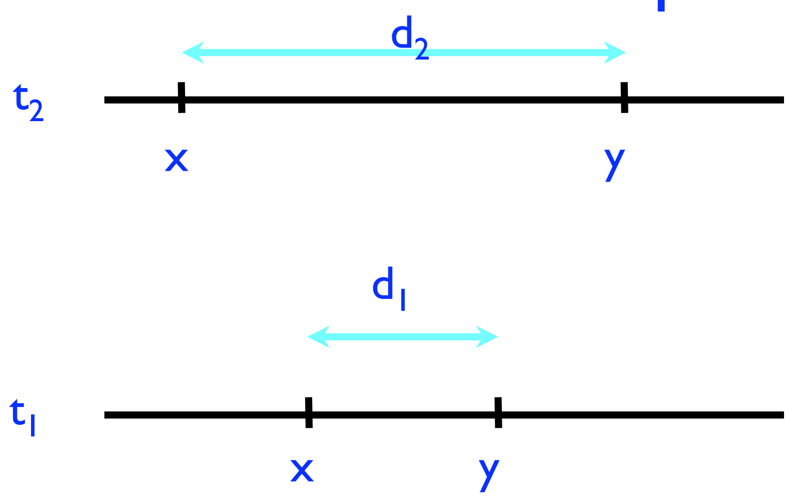
Theoretical Background



General Relativity: Gravity = Matter warping space and time.

Evolution of universe dependent on matter in it and vice versa.

GR tells us how the scale factor a(t) evolves. Related to Hubble parameter.



Relative distances at different times given by the metric.

Cosmology - one function, a(t)

$$H = \frac{\dot{a}(t)}{a(t)}$$

Logical Possibilities for Acceleration

Modifications of Gravity

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

New Mass/Energy Sources

Inverse Curvature Gravity
DGP Braneworlds
Cardassian Models
...

[Carroll, Duvvuri, Trodden, Turner; Dvali, Gabadadze, Porrati; Freese, Lewis; De Felice, Easson; ...]

Other

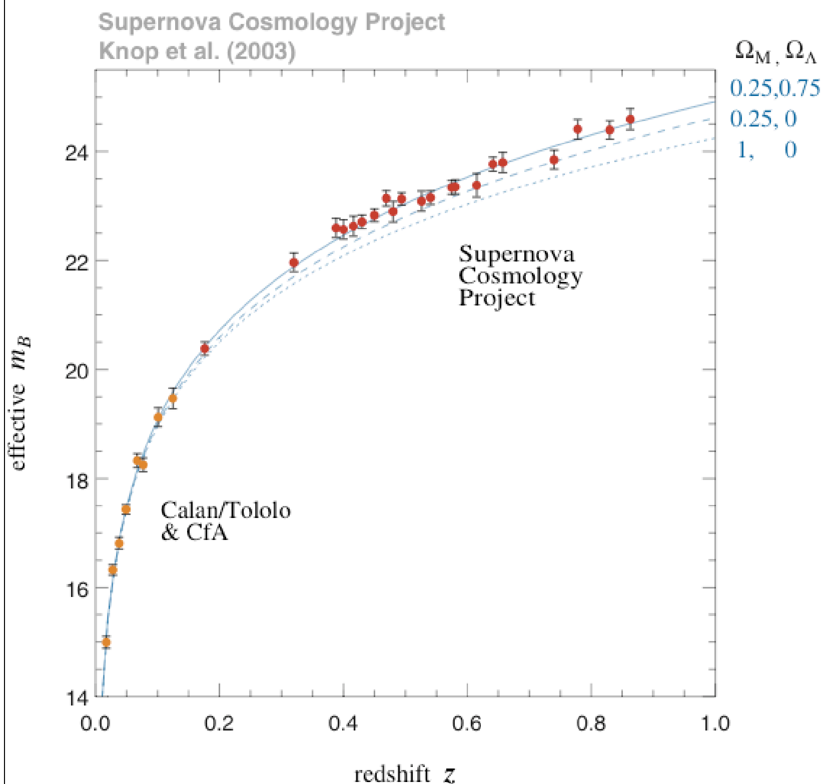
Cosmological Constant
Extra Dimensions
Backreaction
Environmental Selection
...

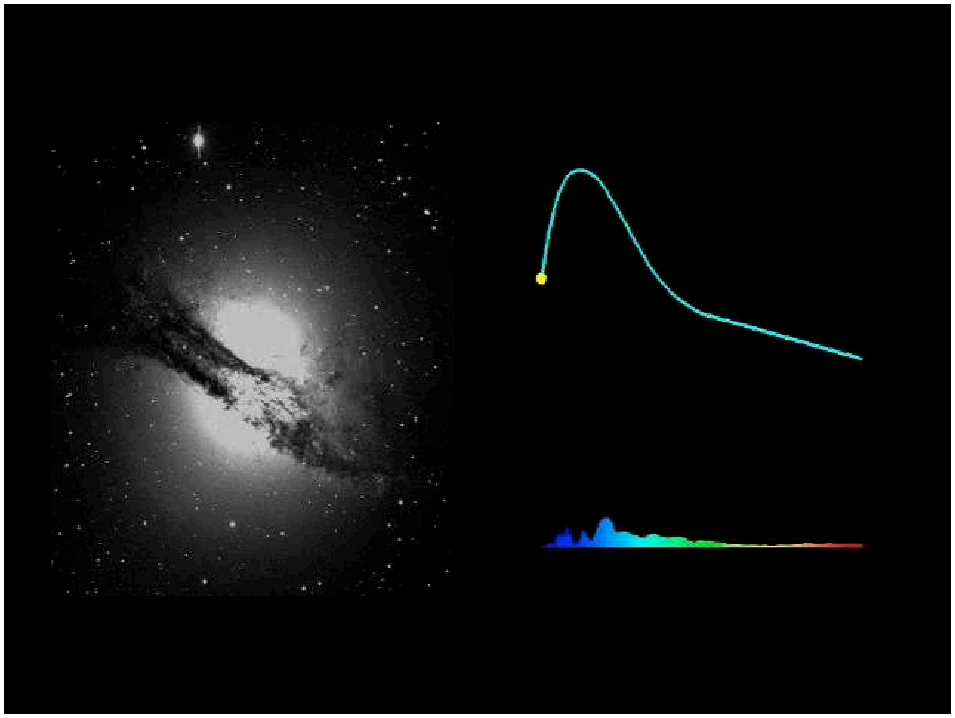
[Kolb, Matarrese, Notari, Riotto; Brandenberger; Abramo, Woodard; Weinberg; Vilenkin; Linde; Bousso, Polchinski; ...]

Quintessence
K-essence
Oscillating DE
...

[Ratra, Peebles; Wetterich; Caldwell, Dave, Steinhardt; Freiman, Hill, Stebbins, Waga; Armendariz-Picon, Mukhanov;
....
Basically every cosmologist you can think of ... and most particle theorists as well.]

Dark Energy





- Positive pressure matter slows the expansion
- Negative (enough) pressure matter speeds up the expansion

(like throwing up a ball and having it accelerate away!)

Dark Energy - Theory

Evolution of the universe governed by Einstein eqns

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 \propto \rho$$ The Friedmann equation

$$\frac{\ddot{a}}{a} \propto -(p+3\rho)$$ The "acceleration" equation

Parameterize different types of matter by equations of state: $p_i = w_i \rho_i$

When evolution dominated by type i, obtain

$$a(t) \propto t^{2/3(1+w_i)} \quad \rho(a) \propto a^{-3(1+w_i)}$$ $(w_i \neq -1)$

Cosmic Acceleration

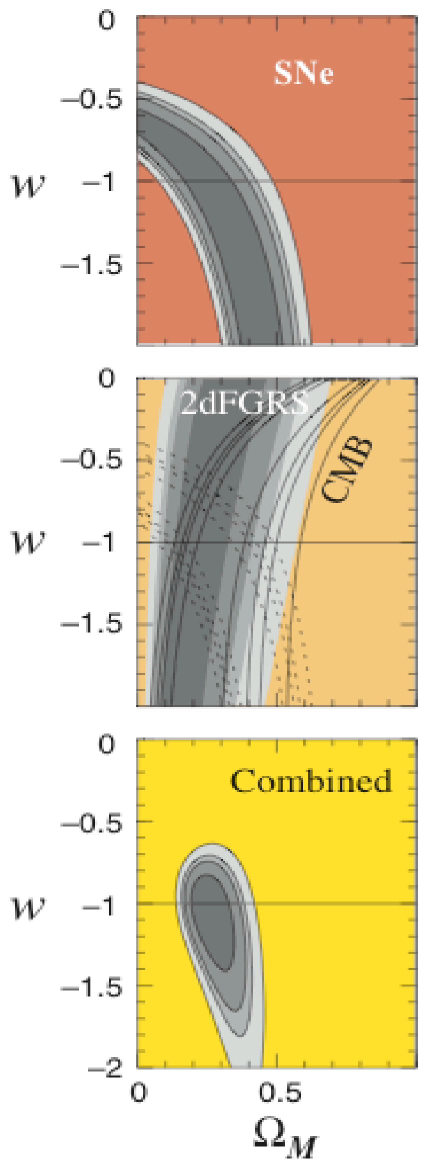
$$\frac{\ddot{a}}{a} \propto -(p+3\rho)$$

So, accelerating expansion means
$p<-\rho/3$ or **$w<-1/3$**

Three Broad Possibilities $a(t) \propto t^{2/3(1+w_i)}$ $\rho(a) \propto a^{-3(1+w_i)}$

	$-1<w<-1/3$	$w=-1$	$w<-1$
Evolution of Energy Density	Dilutes slower than any matter	Stays absolutely constant (Λ)	Increases with the expansion!!
Evolution of Scale Factor	Power-law quintessence	Exponential expansion	Infinite value in a finite time!!

Data on w



Supernova Cosmology Project
Knop *et al.* (2003)

Assuming constant w

With limits from;
2dFGRS (Hawkins et al. 2002)
and CMB (Bennet et al. 2003, Spergel et al. 2003)

$$w = -1.05 \; {}^{+0.15}_{-0.20} \text{ (statistical)} \pm 0.09 \text{ (systematic)}$$

We'll come back later to discuss what is really being measured here

The Cosmological Constant

- A long-standing problem for fundamental theory.
- Has a clear connection to particle physics
- Vacuum is full of virtual particles carrying energy.
- Should lead to a constant vacuum energy. How big? - ∞

BUT

- While calculating branching ratios - easy to forget SUSY is a space-time symmetry.
- SUSY state $|\psi\rangle$ s.t. $Q\,|\psi\rangle = 0$, has $H\,|\psi\rangle \propto \{Q,Q\}\,|\psi\rangle = 0$
- Only vacuum energy comes from SUSY breaking!

$$\rho_\Lambda \sim M_{SUSY}^4$$

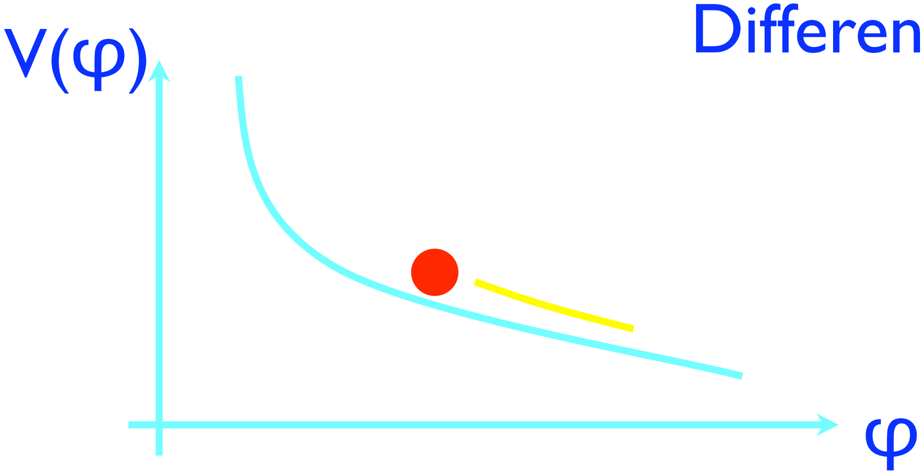
Still 10^{60} too big!

At this stage, fair to say we are stuck! Help needed!

Quintessence - Dark Energy

Maybe there's some principle that sets vacuum energy to zero. Then dark energy might be like low-scale inflation today.

Use scalar fields to source Einstein's equation.



Difference: no minimum or reheating

$$L = \frac{1}{2}(\partial_\mu\phi)\partial^\mu\phi - V(\phi)$$

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}(\nabla\phi)^2 + V(\phi)$$

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$

Homogeneity gives

Small slope $\rho_\phi \approx V(\phi) \approx constant$

$$w = -\left[\frac{2V(\phi) - \dot{\phi}^2}{2V(\phi) + \dot{\phi}^2}\right]$$

Can a Small Mass be Natural?

- Possibly, if field respects an approximate global symmetry (e.g. a pseudo-Goldstone boson) [Frieman, Hill, Stebbins, Waga]
- But then there are other fascinating constraints
- Such a field can have derivative couplings to the SM

$$\beta_{F\tilde{F}} \frac{\phi}{M} F_{\mu\nu}\tilde{F}^{\mu\nu}$$ (electromagnetism) [Carroll]

- Slowly varying field leads to rotation of polarized radio light from distant galaxies
- Non-observation of this constrains the coupling

$$|\beta_{F\tilde{F}}| \leq 3 \times 10^{-2} \left(\frac{M}{|\Delta\phi|} \right)$$

(there are some loopholes here though)

Beyond Minimal fields

- Can address coincidence problem w/ scalar field w/ dynamics sensitive to difference between matter and radiation domination
- K-essence models [Armendariz-Picon, Mukhanov, Steinhardt]

$$L = K + V \qquad K = f(\phi)g(\dot{\phi}^2)$$

Usually $K = \frac{1}{2}(\dot{\phi})^2$

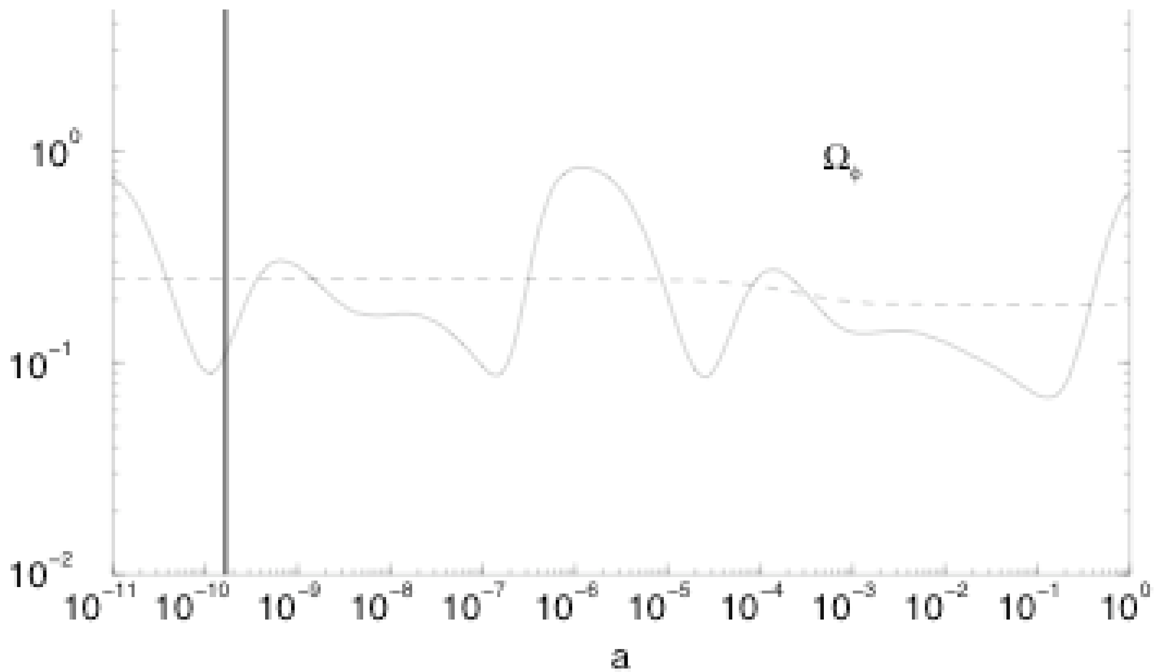
- For certain choices of f,g, field naturally tracks evolution of total radiation energy density during radiation domination, then becomes almost constant when matter begins to dominate.
- Requires some fine-tuning of kinetic term to get this behavior

Oscillating Dark Energy

- Maybe acceleration is a recurring phenomenon - happens from time-to-time [Dodelson, Kaplinghat, Stewart]

$$V(\phi) = e^{-\phi}[1 + \alpha \cos(\phi)]$$

- On average, tracks dominant matter/radiation component
- But have oscillations from negligible to dominant density and back, on Hubble timescales
- Fair to say no particle-physics motivation yet
- Behavior depends sensitively on parameters.



Are we Being Fooled by Gravity?

(Carroll, De Felice and MT)

We don't *really* measure w - we infer it from the Hubble plot via

$$w_{eff} = -\frac{1}{1-\Omega_m}\left(1+\frac{2}{3}\frac{\dot{H}}{H^2}\right)$$

Maybe, if gravity is modified, can infer value not directly related to energy sources (or perhaps without them!)

One example - Brans-Dicke theories

$$S_{BD} = \int d^4x\sqrt{-g}\left[\phi R - \frac{\omega}{\phi}(\partial_\mu \phi)\partial^\mu \phi - 2V(\phi)\right] + \int d^4x\sqrt{-g}L_m(\psi_i, g)$$

$\omega > 40000$ (Signal timing measurements from Cassini)

We showed that (with difficulty) can measure w<-1, even though no energy conditions are violated.

Modifying Gravity

Since we're on the subject of abandoning sacred principles (energy condition, GR,...)

Quintessence requires incredible fine-tuning, so much so that one really is considering incredibly unnatural matter to put on the RHS of Einstein's equations

Maybe we should look at the LHS - or more properly, the gravitational action.

I'll focus mostly on a couple of examples that I've been involved with

Avoids Fundamental Scalars!

Cosmologists love scalar fields - sometimes its healthy to reduce our dependence on them

The Dubya Approach

Use as many scalar fields as you need to get the job done and don't give a second thought to where they're going to come from.

The Sierra Club Approach

Try to reuse your scalar fields or do without altogether, because there may not be that many of them (maybe none).

(Apologies to those of you who've heard me use this joke before!)

How Might We Modify Gravity?

Write an Lagrangian - a scalar involving the object $g_{\mu\nu}$ and its derivatives. What might this look like? One idea:

$$S = \frac{M_p^2}{2}\int d^4x\sqrt{-g}\,[R + f(R,P,Q)] + \int d^4x\sqrt{-g}L_{matter}$$

$$P \equiv R_{\mu\nu}R^{\mu\nu}$$

$$Q \equiv R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}$$

What are the propagating degrees of freedom? A first step is to identify the degrees of freedom in $g_{\mu\nu}$

Answer: turns out there are scalar and vectors as well as $h_{\mu\nu}$

How come we don't see all these in GR? - Depends on the action!

The equations of motion arising from the Einstein-Hilbert action yield constraints, which make everything except $h_{\mu\nu}$ non-dynamical!

Almost any other action will free up some of the other degrees of freedom. These can yield new problems.

Issues with new d.o.f.

A couple of different problems can arise with these new degrees of freedom.

First: Geodesics within the solar system can be appreciably altered

Best tests are from timing delays of signals from distant spacecraft.
Particularly the Cassini mission.

Second: They can lead to instabilities because they are ghost-like (have the wrong sign kinetic terms.

These would lead, among other things, to the decay of the vacuum on a microscopic timescale

(Carroll, Hoffman & M.T., *Phys.Rev.* **D68:** 023509 (2003) [astro-ph/0301273])

One Simple Example

(Carroll, Duvvuri, M.T. & Turner, *Phys.Rev.* **D70:** 043528 (2004) [astro-ph/0306438])

Consider modifying the Einstein-Hilbert action

$$S = \frac{M_P^2}{2}\int d^4x\,\sqrt{-g}\left(R - \frac{\mu^{2(n+1)}}{R^n}\right) + \int d^4x\,\sqrt{-g}L_m$$

(I'll focus on n=1 for most of this)

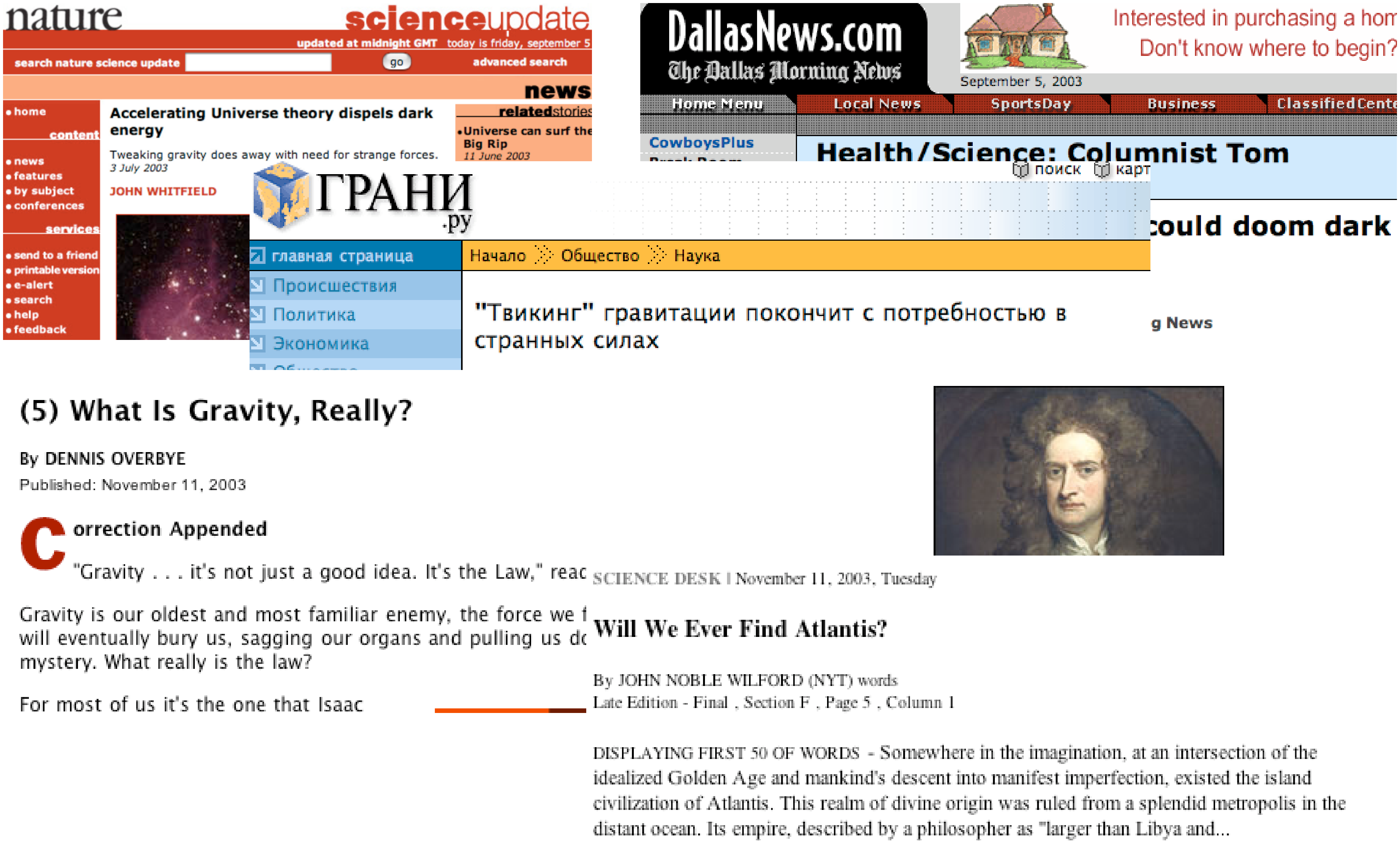
Field equation (n=1):

$$\left(1+\frac{\mu^4}{R^2}\right)R_{\mu\nu} - \frac{1}{2}\left(1-\frac{\mu^4}{R^2}\right)Rg_{\mu\nu} + \mu^4\left[g_{\mu\nu}\nabla_\alpha\nabla^\alpha - \nabla_{(\mu}\nabla_{\nu)}\right]R^{-2} = \frac{T^M_{\mu\nu}}{M_P^2}$$

With, for cosmology

$$T^M_{\mu\nu} = (\rho_M + P_M)U_\mu U_\nu + P_M g_{\mu\nu}$$

People Love Crazy Ideas!



How Does this Work?

Can see immediately constant curvature vacuum solutions are de Sitter and anti-de Sitter $R = \sqrt{3}\mu^2$

Seems encouraging for dark energy, but dS is unstable, with decay time $\tau \sim \mu^{-1}$ (Easy to see soon)

Can transform to an Einstein frame - a neat trick

$$\tilde{g}_{\mu\nu} = p(\phi) g_{\mu\nu}$$

In the ``tilde'd'' frame, this becomes a theory of Einstein gravity, minimally coupled to a scalar field, with a potential and whichis nonminimally coupled to matter.

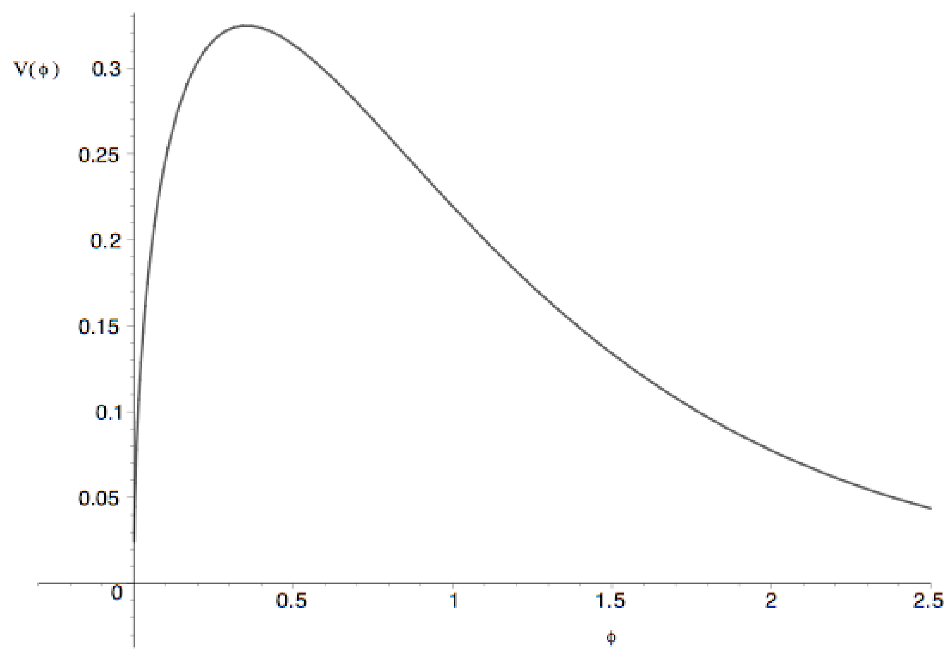
Einstein-Frame Dynamics

$$\tilde{H}^2 = \frac{1}{3M_P^2}\left[\rho_\phi + \tilde{\rho}_M\right]$$

$$\rho_\phi = \frac{1}{2}\phi'^2 + V(\phi)$$

$$\phi'' + 3\tilde{H}\phi' + \frac{dV}{d\phi}(\phi) - \frac{(1-3w)}{\sqrt{6}}\tilde{\rho}_M = 0$$

$$\tilde{\rho}_M = \frac{C}{\tilde{a}^{3(1+w)}} \exp\left[-\frac{(1-3w)}{\sqrt{6}}\frac{\phi}{M_P}\right]$$

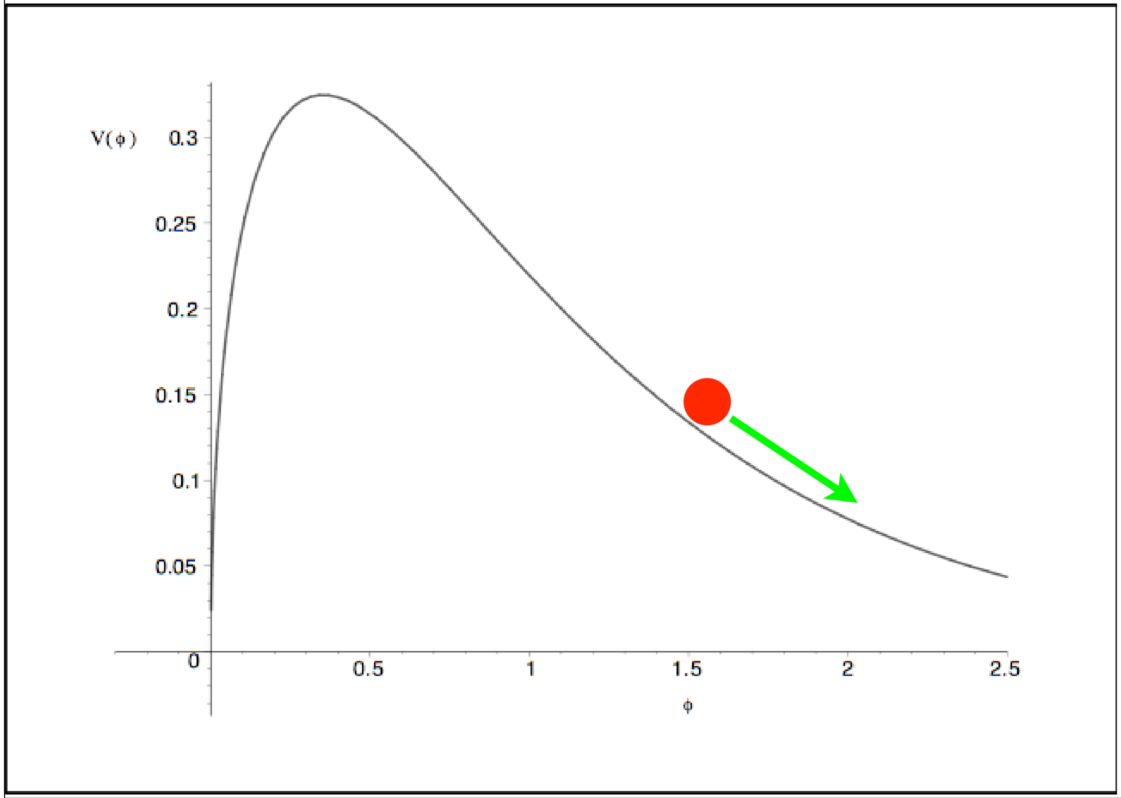


$$V(\phi) = \mu^2 M_P^2 e^{-2\beta\phi}\sqrt{e^{\beta\phi} - 1}$$

A Surprise Possibility

φ gets over the maximum

Then, φ rolls down potential and asymptotic solution is easy to find… Power-law acceleration! $a(t) \propto t^2$



Like having instantaneous equation of state parameter

$$w_{eff} = -\frac{2}{3}$$

Facing the (Cosmology) Data

Recall that data yields -1.45< w_{eff} <-0.74 but I was using n=1 for illustrative purposes. In general have

$$S = \frac{M_P^2}{2}\int d^4x\,\sqrt{-g}\left(R - \frac{\mu^{2(n+1)}}{R^n}\right) + \int d^4x\,\sqrt{-g}L_m$$

Analysis is very similar for n>1, with similar potential in Einstein frame. Yields, in matter frame

$a(t) \propto t^q$ with $$q = \frac{(2n+1)(n+1)}{n+2}$$

Again, this is like having $$w_{eff} = -1 + \frac{2(n+2)}{3(2n+1)(n+1)}$$

Easily fits data for many n (approaches dS for n→∞)

Facing the (Solar System) Data

Easy to see model has problems agreeing with GR on scales smaller than cosmology. Can map theory to

$$S_{BD} = \int d^4x \sqrt{-g} \left[\phi R - \frac{\omega}{\phi} (\partial_\mu \phi) \partial^\mu \phi - 2V(\phi) \right] + \int d^4x \sqrt{-g} L_m(\psi_i, g)$$

(Remember this?)

i.e., a Brans-Dicke theory, with a potential that we may ignore, with $\omega=0$

But, as we said, solar system measurements constrain $\omega>40000$

More General Actions

(Carroll, De Felice, Duvvuri, Easson, M.T. & Turner, *Phys.Rev.* **D71:** 063513 (2005) [arXiv:astro-ph/0410031])

$$S=\frac{M_p^2}{2}\int d^4x\sqrt{-g}\,[R+f(R,P,Q)]+\int d^4x\sqrt{-g}L_{matter}$$

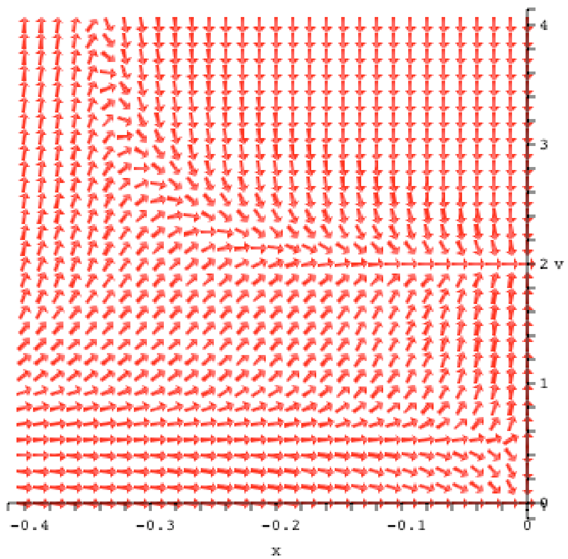
$$P\equiv R_{\mu\nu}R^{\mu\nu}$$

$$Q\equiv R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}$$

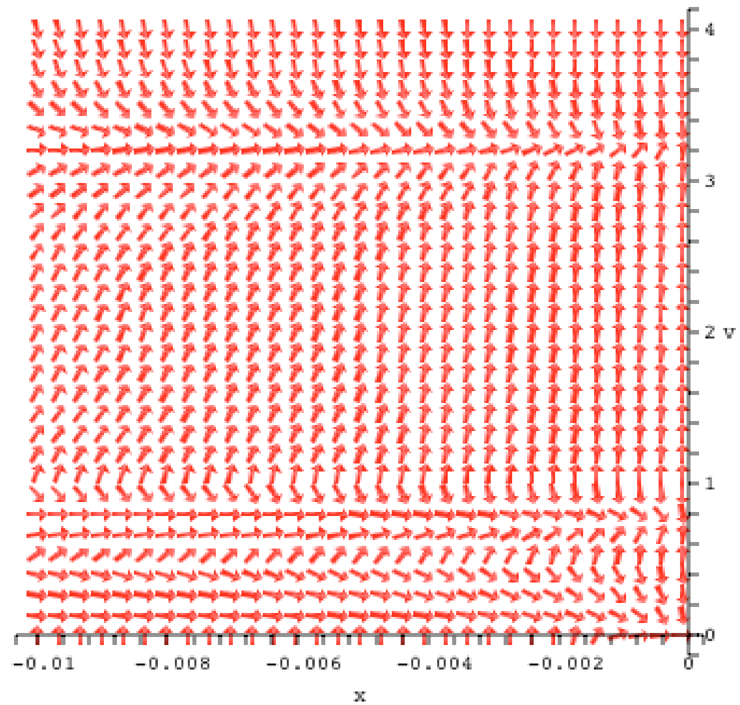
$$x=-H(t)$$

$$y=\dot{H}(t)$$

$$y=-\frac{x^2}{v(x)}$$



Original 1/R model



$$f=1/P$$

PPN Constraints & Ghosts

To get a theory which doesn't conflict with solar system measurements - need to have $c \neq 0$ (Navarro and van Acoleyen [gr-qc/0506096])

What about ghosts?

Navarro and van Acoleyen have shown that, around the (unstable) de Sitter solution, there are no ghosts for

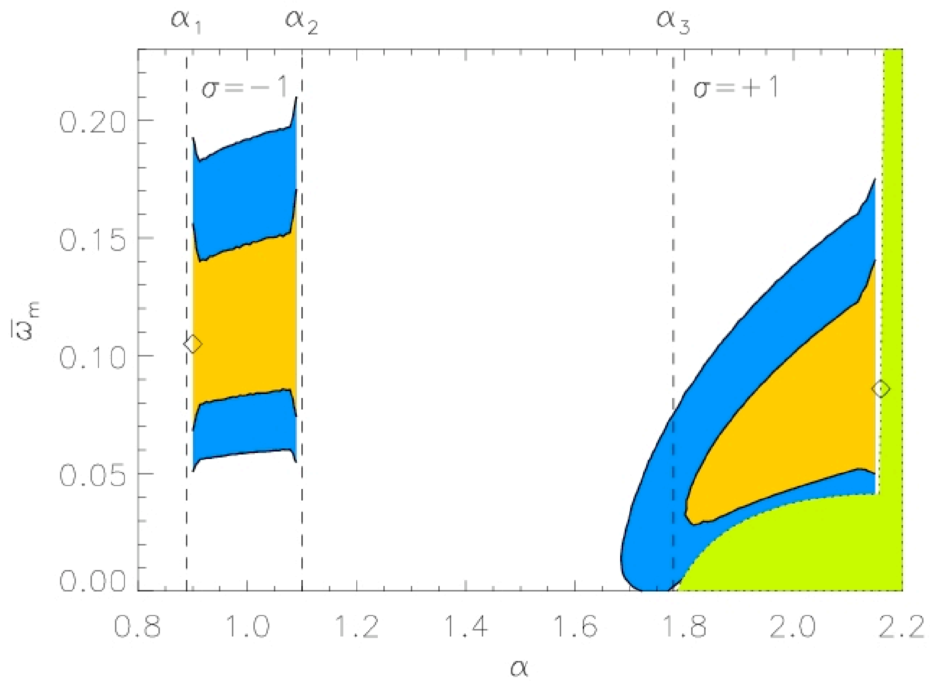
$$b = -4c$$

(Navarro and van Acoleyen [gr-qc/0511045])

It turns out that the situation is more subtle in general. I won't report on the details here, but see, very soon,

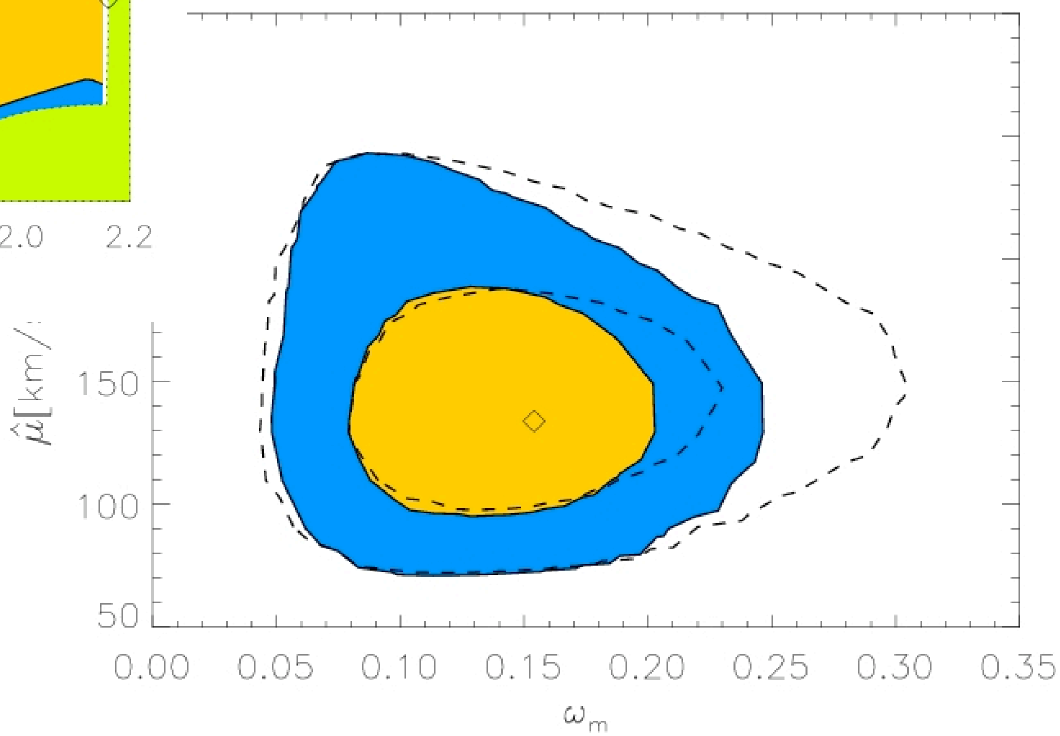
(De Felice, Hindmarsh and M.T. [astro-ph/0603???])

Cosmological Constraints



In these regions, the fit to all cosmological data is as good as Lambda-CDM

$$\alpha = \frac{12a + 4b + 4c}{12a + 3b + 2c}$$



Mena, Santiago and Weller, [astro-ph/0510453]

DGP Braneworlds

(Dvali, Gabadadze & Porrati; Deffayet)

$$S = \frac{M_P^2}{2r_c}\int d^5x\sqrt{-G}\,R^{(5)} + \frac{M_P^2}{2}\int d^4x\sqrt{-g}\,R$$

(crossover scale)

"Friedmann" equation

$$H^2 = \frac{8\pi G}{3}\rho_{matter} + \frac{1}{r_c}\sqrt{\frac{1}{r_c^2} + \frac{32\pi G}{3}\rho_{matter}} + \frac{1}{2r_c^2}$$

- Gravity "leaks into extra dimensions at large scales, leading to additional dimming of supernovae
- Lue and Starkman: close to being tested from anomalous precession of perihelion (Mars) and from future lunar ranging experiments.

[See very recent theoretical obstacles by Adams, Arkani-Hamed, Dubovsky, Nicolis and Rattazzi - arXiv:hep-th/0602178.]

A Comment on DE vs. MG

- There is a lot of great work going on showing how detailed comparisons between different datasets (CMB and LSS e.g.) may help distinguish between these two possibilities.
- However, as we've seen, in many cases one can write a modified gravity model as GR plus other stuff.
- It remains to be seen whether there are definitive differences
- For me, one useful distinction is in the motivations

Summary I

- Cosmic acceleration is certainly telling us something fundamental about physics.
- It may be that there are new energy sources out there to be identified (dark energy)
- It may be that we have not properly understood how matter and spacetime affect each other (cosmological constant; back-reaction)
- It may be that some features of our universe are environmentally selected.

Summary II

- Or...

it may be that, on cosmological scales, gravity is different from general relativity, and cosmic acceleration is our first hint of this!

Right now, we don't know, and there are many interesting ideas out there.
Only observations can tell, and here and in many other places, lots of us are working hard on the next steps

...how do we distinguish dark energy and modified gravity?

After All this Darkness...

-Thank You -