Is Cosmic Acceleration Telling Us Something About Gravity?

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[See many other talks at this meeting; particularly talks by Carroll, Dvali, Deffayet, ...]
Establishing the New Cosmology

- Dark Energy: 70%
- Dark Matter: 25%
- Baryons: 5%

Mark Trodden, Syracuse University

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NASA Meeting: From Quantum to Cosmos, Fundamental Physics Research in Space

Airlie Center, Washington D.C., 5/19/2006
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Cosmic Acceleration

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

(like throwing up a ball and having it accelerate away!)
Logical Possibilities for Acceleration

**Modifications of Gravity**

- Inverse Curvature Gravity
- DGP Braneworlds
- Cardassian Models
- ... [Carroll, Duvvuri, Trodden, Turner; Dvali, Gabadadze, Porrati; Freese, Lewis; De Felice, Easson; ...]

\[ G_{\mu \nu} = 8\pi G T_{\mu \nu} \]

**New Mass/Energy Sources**

- Quintessence
- K-essence
- Oscillating DE
- ...

**Other**

- Cosmological Constant
- Extra Dimensions
- Backreaction
- Environmental Selection
- ...

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

- [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 - Theory

Evolution of the universe governed by Einstein eqns

\[ H^2 \equiv \left( \frac{\dot{a}}{a} \right)^2 \propto \rho \quad \text{The Friedmann equation} \]

\[ \frac{\ddot{a}}{a} \propto -(p + 3\rho) \quad \text{The “acceleration” equation} \]

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

When evolution dominated by type i, obtain

\[ a(t) \propto t^{2/3(1+w_i)} \quad \rho(a) \propto a^{-3(1+w_i)} \quad (w_i \neq -1) \]
Cosmic Acceleration

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

Three Broad Possibilities

<table>
<thead>
<tr>
<th></th>
<th>$-1 &lt; w &lt; -1/3$</th>
<th>$w = -1$</th>
<th>$w &lt; -1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evolution of Energy Density</td>
<td>Dilutes slower than any matter</td>
<td>Stays absolutely constant ($\Lambda$)</td>
<td>Increases with the expansion!!</td>
</tr>
<tr>
<td>Evolution of Scale Factor</td>
<td>Power-law quintessence</td>
<td>Exponential expansion</td>
<td>Infinite value in a finite time!!</td>
</tr>
</tbody>
</table>
Data on $w$

**Supernova Cosmology Project**

Knop *et al.* (2003)

*Assuming constant $w$*

With limits from:
- 2dFGRS (Hawkins *et al.* 2002)
- CMB (Bennet *et al.* 2003, Spergel *et al.* 2003)

$$w = -1.05 \pm 0.15 \text{ (statistical)}$$

$$-0.20 \text{ (systematic)}$$
Are we Being Fooled by Gravity?

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

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

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.
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:

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

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


[See talk by Sean Carroll for a way in which one might avoid these new degrees of freedom]
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 \((n=1)\):**

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

With, for cosmology

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

$$\tau \sim \mu^{-1} \quad \text{(Easy to see soon)}$$

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 which is 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!

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

Like having instantaneous equation of state parameter

$a(t) \propto t^2$
Facing the (Solar System) Data

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

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

(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 \( \omega > 40000 \)
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 (For me, one useful distinction is in the motivations).

• In a subset of models (Modified Source Gravity), we have some conclusions to be reported within the next few weeks [See talk by Sean Carroll for more details]

• It remains to be seen whether there are definitive differences in general
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?

-Thank You-