Dark Energy, Modified Gravity
and
The Accelerating Universe

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Makeup of universe today

- **Dark Energy**
  - (suspected since 1980s, established since 1998)
  - 74%

- **Dark Matter**
  - (suspected since 1930s, established since 1970s)
  - 22%

- **Baryonic Matter**
  - (stars 0.4%, gas 3.6%)
  - 4%

- Also:
  - radiation (0.01%)
Some of the early history of the Universe is actually understood better!

Physics quite well understood

95% of contents only phenomenologically described
DE status ~8 years after discovery

Measurements much better, LCDM still a good fit

Strong indirect (non-SNa Ia) evidence for DE from CMB+LSS

Physical mechanism responsible completely unknown

A lot of work on modified gravity proposals and observational signatures

Riess et al 1998; Perlmutter et al 1999
Current constraints

\[ \Omega_{\text{DE}} \approx 0.7 \]

Assuming constant \( w \)

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

\[ w = -1.05^{+0.15}_{-0.20} \text{ (statistical)} \]
\[ \pm 0.09 \text{ (systematic)} \]
What if gravity deviates from GR?

For example:

\[ H^2 - F(H) = \frac{8\pi G}{3} \rho, \quad \text{or} \quad H^2 = \frac{8\pi G}{3} \left( \rho + \frac{3F(H)}{8\pi G} \right) \]

Modified gravity

Dark energy
Modified gravity proposals

• Introduce modifications to GR (typically near horizon scale) to explain the observed acceleration of the universe

• Make sure Solar System tests are passed (can be hard)

• Constrain the MG theory using the cosmological data

• Try to distinguish MG vs. “standard” DE (can be hard!)
Example: f(R) gravity

\[ S = \frac{1}{16\pi G} \int d^4 x \sqrt{-g} \left[ R + f(R) \right] \]

- Einstein equations are now 4th order
- Two classes
  - \( f_{RR} < 0 \) (never Matter Dominated, long range forces)
  - \( f_{RR} > 0 \) (MD in the past, can evade Solar system tests)

Carroll, Duvvuri, Trodden, Turner 2005; Mena, Santiago & Weller 2006; Navarro & van Acoleyen 2006; Song, Hu & Sawicki 2006; many others...
Example: DGP braneworld theory

- 1 extra dimension ("bulk") in which only gravity propagates
- matter lives on the "brane"
- weakening of gravity at large distances = appearance of DE

Credit: Iggy Sawicki

Dvali, Gabadadze & Porrati 2000; Deffayet 2001
The structure of DGP

\[ H^2 - \frac{H}{r_c} = \frac{8\pi G}{3} \rho \]

\( r_c \) is a free parameter
(to be consistent with observation, \( r_c \sim 1/H_0 \))

New scale \( r_* = (r_gr_c^2)^{1/3} \)

Dvali, Gabadadze & Porrati 2000; Deffayet 2001
DGP linear growth

Growth relative to EdS

Scale factor

DE Mimicking
DGP expansion

DGP

LCDM

DGP→4D

Lue, Scoccimarro & Starkman; Koyama & Maartens; Sawicki, Song & Hu
ISW in DGP

Song, Sawicki, & Hu 2007
So DGP is (almost) ruled out

- Disfavored at a few sigma from distances (SNe etc)
- Disfavored at a few more sigma from CMB ISW
- Decisive rule-out will come from ISW cross-correlation at high $z$:

Song, Sawicki, & Hu 2007
Dark Energy or Modified Gravity?

• A given DE and modified gravity models may both fit the expansion history data very well

• But they will predict different structure formation history, i.e. deviation from

\[
\ddot{\delta} + 2H \dot{\delta} - 4\pi \rho_M \delta = 0
\]
• In standard GR, H(z) determines distances and growth of structure

\[ \ddot{\delta} + 2H \dot{\delta} - 4\pi \rho_M \delta = 0 \]

• So check if this is true by measuring separately

Distances (a.k.a. kinematic probes) (a.k.a. 0\textsuperscript{th} order cosmology)

Growth (a.k.a. dynamical probes) (a.k.a. 1\textsuperscript{st} order cosmology)
Price of ignorance of MG

allows for modified gravity

neglects modified gravity having $\Delta \gamma = 0.1$

Huterer & Linder, astro-ph/0608681
Cosmological Probe

Redshift Coverage

CMB (out to z=1000)
- Galaxy clustering
- Cluster Counts
- Weak Lensing
- Baryon Oscillations
- Supernovae
Cosmological Probes of Dark Energy (and Modified Gravity)

- CMB (out to z=1000)
- Galaxy clustering
- Cluster Counts
- Weak Lensing
- Baryon Oscillations
- Supernovae
Kinematic probes: SNe Ia

- Get pure (luminosity) distances
Kinematic probes: CMB and BAO

\[ T = 2.726 \text{ K} \]

\[ \frac{\delta T}{T} \approx 10^{-5} \]

Bennett et al. 2003 (WMAP collaboration)
Structure formation probes: Galaxy cluster counts

\[
\frac{d^2 N}{d\Omega \, dz} = n(z) \frac{r(z)^2}{H(z)}
\]

Credit: Quinn, Barnes, Babul, Gibson

• Essentially fully in the nonlinear regime (scales ~1 Mpc)
Structure formation probes: Weak Gravitational Lensing

\[ P_{\text{shear}} \approx \int_0^\infty W(r)P_{\text{matter}}(r)dr \]

- Mostly in the nonlinear regime (scales \(\sim 10 \text{ arcmin, or } \sim 1 \text{ Mpc}\))

Credit: Colombi & Mellier
More general approach

Measure the DE parameters from **distances** and **growth** separately

Ishak, Upadhye and Spergel 2006; others...
Still more general approach: measure functions $r(z)$ and $g(z)$ see if they are consistent

Knox, Song & Tyson 2005
Minimalist Modified Gravity vs. DE

Describe deviations from GR via a **single** new parameter

\[
g(a) \equiv \frac{\delta}{a} = \exp \left[ \int_0^a d \ln a \left[ \Omega_M(a)^\gamma - 1 \right] \right]
\]

Excellent **fit** to standard DE growth function with

\[
\gamma = 0.55 + 0.05 [1 + w(z = 1)]
\]

Also fits the DGP braneworld theory with \( \Delta \gamma = 0.13 \)

Huterer & Linder, astro-ph/0608681
see also Linder & Cahn, astro-ph/0701317
Cluster counts

Weak lensing tomography
## Constraints on the growth index

<table>
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<tr>
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<th>$\text{sig}(w_0)$</th>
<th>$\text{sig}(w_a)$</th>
<th>$\text{sig}(\gamma)$</th>
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<tr>
<td>WL</td>
<td>0.33</td>
<td>1.16</td>
<td>0.23</td>
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<tr>
<td>+SNE</td>
<td>0.06</td>
<td>0.28</td>
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<tr>
<td>+Planck</td>
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<td>+Clusters</td>
<td>0.05</td>
<td>0.16</td>
<td>0.037</td>
</tr>
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</table>

Recall, for DGP $\Delta \gamma = 0.13$
Discarding the small-scale info in weak lensing

Using the Nulling Tomography of weak lensing (Huterer & White 2005)
Conclusions

• distinguishing dark energy from modified gravity is becoming one of the key goals of cosmology in years to come

• assuming nonlinear clustering that follows the usual prescription even with MG, we find that future probes can achieve very interesting constraints on this parameter

• restriction to linear scales severely degrades the errors, but well worth pursuing

• ambitious, general approach: measure functions $r(z)$ and $g(z)$, check if they are consistent

• minimalistic approach: measure a single parameter that describes departures between DE and MG

• bright future with upcoming powerful surveys
Physically motivated MG parametrization

$$ds^2 = a^2(\tau) \left[ -(1 + 2\psi) d\tau^2 + (1 - 2\phi) d\vec{x}^2 \right]$$

$$\psi = (1 + \varpi)\phi \quad \text{and assume} \quad \varpi = \varpi_0 \frac{\rho_{DE}}{\rho_M}$$

Caldwell, Cooray & Melchiorri, astro-ph/0703375
Physically motivated MG parametrization

CMB-galaxy cross-correlation

Weak lensing power spectrum

Caldwell, Cooray & Melchiorri, astro-ph/0703375