Prospects for measuring the properties of Dark Energy

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Makeup of universe today

- **Dark Energy**
  - suspected since 1980s
  - established since 1998

- **Dark Matter**
  - suspected since 1930s
  - established since 1970s

- **Baryonic Matter**
  - stars 0.4%
  - gas 3.6%

- Also:
  - radiation (0.01%)
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
Dark Energy Parametrization

Equation of state ratio:

\[ w = \frac{\rho_{\text{DE}}}{\rho_{\text{DE}}} \]

Energy density today (relative to critical):

\[ \Omega_{\text{DE}} = \frac{\rho_{\text{DE}}}{\rho_{\text{crit}}} \]

For vacuum energy

\[ w = -1 \left( G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu} \right) \]
Wish List

Goals:

Measure $\Omega_{DE}, w$

Measure $\rho_{DE}(z)$ or $w(z)$

Measure any clustering of DE

\[
\begin{align*}
w &= \frac{p_{DE}}{\rho_{DE}} \\
\Omega_{DE} &= \frac{\rho_{DE}}{\rho_{crit}}
\end{align*}
\]
Wish List

Goals:

- Measure $\Omega_{DE}, w$
- Measure $\rho_{DE}(z)$ or $w(z)$
- Measure any clustering of DE

Difficulties:

$w(z)$ enters the observables via integral relations

$$w = \frac{\rho_{DE}}{\rho_{DE}}$$

$$\Omega_{DE} = \frac{\rho_{DE}}{\rho_{crit}}$$

$$r(z) = \int_0^z \frac{dz'}{H(z')}$$

$$H^2(z) = H_0^2 \left[ \Omega_M (1 + z)^3 + \Omega_{DE} \exp \left( 3 \int_0^z (1 + w(z')) d\ln(1 + z') \right) \right]$$

DE clustering affects cosmology negligibly on scales $\ll H_0^{-1}$
Two crucial questions:

Is dark energy the vacuum energy \( (w(z) = -1) \) ?
Is \( w(z) = \text{const} \) ?

Simplest ways to approach these questions:

\[
\begin{align*}
\frac{d}{dz}w(z) &= w_0 + w'a_z \\
&= w_0 + w_a \frac{z}{1+z}
\end{align*}
\]
Direct Reconstruction of $w(z)$

\[ 1 + w(z) = f \left( \frac{dr}{dz}, \frac{d^2 r}{dz^2} \right) \]

\[ V[\phi(z)] = g \left( \frac{dr}{dz}, \frac{d^2 r}{dz^2} \right) \]

- The **most general** possible approach to constrain dark energy, but
- Very hard in practice: needs **second derivative** of (noisy) data
- Nevertheless, studied, refined and used by many authors

Huterer & Turner 1999
Direct reconstruction of the equation of state leads to biases, or large errors, or both

Weller & Albrecht 2002
Principal Components of $w(z)$

These are best-to-worst measured linear combinations of $w(z)$

Uncorrelated by construction

- Shows where sensitivity of any given survey is greatest
- Used by various authors to study optimization of surveys
- Used to make model-(in)dependent statements about DE

Huterer & Starkman 2003
Principal Components of $w(z)$

Linder & Huterer 2005
Uncorrelated measurements of Dark Energy evolution

Using Riess et al 2004 data

Cosmological constant case

Huterer & Cooray 2005;
...and with more recent HST data

(SNe + BAO only)

Cosmological Constant case

(SNe + BAO + CMB)

Riess et al, astro-ph/0611572
Cosmological Probes of Dark Energy

- CMB (out to z=1000)
- Galaxy clustering
- Cluster Counts
- Weak Lensing
- Baryon Oscillations
- Supernovae

Redshift Coverage
Two kinds of tests

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)
Two kinds of tests

Distances
(a.k.a. kinematic probes)
(a.k.a. 0th order cosmology)

Growth
(a.k.a. dynamical probes)
(a.k.a. 1st order cosmology)

• In standard GR, $H(z)$ determines distances and growth of structure

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

So measuring growth and distance separately tests the GR
Kinematic probes: SNe Ia

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

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

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

Credit: WMAP team

Bennett et al 2003 (WMAP collaboration)
CMB and Dark Energy

One linear combination of DE parameters is measured by the CMB

Hu 2001; Frieman, Huterer, Linder & Turner 2003
Structure formation probes: Galaxy cluster counts

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

- Essentially **fully in the nonlinear regime** (scales \(\sim 1\) Mpc)
Structure formation probes:
Weak Gravitational Lensing

\[ P_{\text{shear}} \simeq \int_{0}^{\infty} W(r) P_{\text{matter}}(r) dr \]

- Mostly in the nonlinear regime (scales \( \sim 10 \) arcmin, or \( \sim 1 \) Mpc)
Upcoming Experiments

Planck  South Pole Telescope  LSST

Lots and lots of data coming our way
Dark Energy Survey

Blanco 4m telescope in Chile

Four techniques to probe Dark Energy:
1. Number Counts of clusters
2. Weak Lensing
3. SNe Ia
4. Angular clustering of galaxies
SuperNova/Acceleration Probe

~2500 SNe at 0.1<z<1.7
~2500 SNe Ia

**Diagram:**

- **x-axis:** redshift
- **y-axis:** magnitude

The graph illustrates the relationship between redshift and magnitude for approximately 2500 SNe Ia. This data is crucial for understanding dark energy properties, dark matter properties, and cosmological parameters.
1. Unprecedented SNa Ia dataset
2. Weak Lensing (2pt, 3pt function; cosmography)
3. Huge amount of other science
   (cluster counts, galaxy clustering, galaxy evolution,
   strong lensing, type II supernovae, GRBs, .......)
The future

Once we have access to data from surveys...
What else do we need to have at hand?

- Systematic error control
- Alternative, complementary probes of DE
- Sophisticated statistical methods for data mining
- Understanding how to separate DE from modified gravity
- Reliable predictions for classes of models and how to distinguish them
The future

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Cosmological implications of a dark energy model scan

Idea: test cosmological implications by considering all DE models within a given (large) class

• What constraints are obtained on $w(z)$, $\rho(z)$ within this class? On $w_0$ and $w_a$?

• Does the class of models itself significantly limit the range of DE histories?

• Is it worth spending $$$ for future experiments, or have “all reasonable non-Lambda models already been ruled out”?
Scan through quintessence models

Adopting to DE the flow-equation formalism from inflation:
Scan all (sample millions) of models, and ICs, within a general paradigm - e.g. quintessence with polynomial potentials

\[ w(z) = \frac{\dot{\phi}^2/2 - V(\phi)}{\dot{\phi}^2/2 + V(\phi)} \]

sample DE models in prior

sample DE models in posterior
DE Monte Carlo algorithm

- Set the class of models you are considering
- Generate models using a wide range of ICs
- For each model, compute the dark energy history $w(z)$ and any other observables
- Compute the likelihood of the model from data
- Repeat

Initial conditions prior:

- $\Omega_{DE}^{\text{start}} \in [0, 1]$
- $w^{\text{start}} \in [-1, 1]$
- $\epsilon^{\text{start}} \in [0, \infty]$
- $\eta^{\text{start}} \in [-\infty, \infty]$

+ other cosmo parameters
+ higher slow roll parameters
Scan through quintessence models

Also allows straightforward computation and constraints on the principal components, phase-space flows, figures of merit....

Huterer & Peiris, astro-ph/0610427
Generic behavior of scalar fields (??)

- Do scalar field models follow the freezing/thawing behavior?
- The claim was based on specific scalar field models
Generic behavior of scalar fields (??)

More general models do NOT cleanly fall into freezing/thawing

Caldwell & Linder 2005
Huterer & Peiris, astro-ph/0610427
DE vs. modified gravity

Measure the DE parameters from distances and growth separately

Ishak, Upadhye and Spergel 2006; others...
The most general DE vs. MG: 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

\[ g(a) = \exp \left[ \frac{\delta}{a} \int_{a_0}^{a} d\ln a (\Omega_M(a)\gamma - 1) \right] \]

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
Constraints on the growth index

<table>
<thead>
<tr>
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<th>sig($w_0$)</th>
<th>sig($w_a$)</th>
<th>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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<td>+Planck</td>
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<td>0.21</td>
<td>0.044</td>
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<td>+Clusters</td>
<td>0.05</td>
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<td>0.037</td>
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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

• Recent accelerated expansion of the universe is a great mystery of modern physics and cosmology

• Constraints on the expansion history are becoming tight; however, fundamental understanding is lacking

• Incredible amount of new data is starting to come in, sophisticated analytical, statistical and numerical methods are required

• We need a combination of experiments that are
  • ground and space probes,
  • expansion and growth probes,
  • linear and nonlinear theory
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