Falsifying

Dark Energy Paradigms

Wayne Hu

Saclay, June 2012
Outline

• Falsifiable Predictions of
  • $\Lambda$CDM
  • Smooth Dark Energy

• Confrontation with
  • Clusters of Galaxies
  • Cosmic Shear

• Collaborators

  Tim Eifler
  Dragan Huterer
  Michael Mortonson
  Ali Vanderveld
Falsifying $\Lambda$CDM

- Geometric measures of distance redshift from SN, CMB, BAO

![Graph showing distance-redshift relationship between Supernovae and other cosmological measurements.](graph.png)

- Standard(izable) Candle Supernovae
- Luminosity vs Flux
- Sound Horizon vs CMB, BAO angular redshift separation

Source: Supernova Cosmology Project
Fixed Deceleration Epoch

- **CMB** gives **matter density** assuming standard radiation content

- **WMAP7**: $\Omega_m h^2 = 0.133 \pm 0.006 \rightarrow 4.5\%$

- **Distance** to recombination $D_*$ determined to $\frac{1}{4} 4.5\% \approx 1\%$

- **Expansion rate** during any redshift in the deceleration epoch determined to $\frac{1}{2} 4.5\%$

- **Distance** to any redshift in the deceleration epoch determined as

\[
D(z) = D_* - \int_z^{z_*} \frac{dz}{H(z)}
\]

- **Volumes** determined by a combination $dV = D_A^2 d\Omega dz / H(z)$

- **Structure** also determined by growth of fluctuations from $z_*$

- $\Omega_m h^2$ can be determined to $\sim 1\%$ from Planck.
Flat $\Lambda$CDM

- CMB predicts expansion history and distance redshift relation at all redshifts to few percent precision
- Any **violation** falsifies flat $\Lambda$CDM
  (violation of flatness falsifies standard inflation)

Mortonson, Hu, Huterer (2009)
$H_0 = \text{Dark Energy}$

- Flat constant $w$ dark energy model
- Determination of Hubble constant gives $w$ to comparable precision

For evolving $w$, equal precision on average or pivot $w$, equally useful for testing a cosmological constant

If $w \geq -1$, then Hubble constant can only decrease
Forecasts for CMB+\(H_0\)

- To complement CMB observations with \(\Omega_m h^2\) to 1%, an \(H_0\) of \(\sim1\%\) enables constant \(w\) measurement to \(\sim2\%\) in a flat universe

Planck: \(\sigma(\ln \Omega_m h^2) = 0.009\)
Falsifying ΛCDM

- Λ slows growth of structure in highly predictive way
Beyond $\Lambda$CDM
Smooth Dark Energy

- **Scalar field** dark energy has $\delta p = \delta \rho$ (in constant field gauge) – relativistic sound speed, no anisotropic stress

- **Jeans stability** implies that its energy density is spatially smooth compared with the matter below the sound horizon

$$ds^2 = -(1 + 2\Psi)dt^2 + a^2(1 + 2\Phi)dx^2$$

$$\nabla^2 \Phi \propto \text{matter density fluctuation}$$

- **Anisotropic stress** changes the amount of space curvature per unit dynamical mass: negligible for both matter and smooth dark energy

$$\nabla^2(\Phi + \Psi) \propto \text{anisotropic stress approx 0}$$

in contrast to modified gravity or force-law models
Falsifiability of Smooth Dark Energy

- With the smoothness assumption, dark energy only affects gravitational growth of structure through changing the expansion rate.
- Hence geometric measurements of the expansion rate predict the growth of structure.
  - Hubble Constant
  - Supernovae
  - Baryon Acoustic Oscillations
- Growth of structure measurements can therefore falsify the whole smooth dark energy paradigm.
  - Cluster Abundance
  - Weak Lensing
  - Velocity Field (Redshift Space Distortion)
Why PCs

- Principal components are the eigenbasis of the projected or actual covariance matrix for a discrete representation of $f(x_i)$

- Rank ordered in observability and decorrelated linear combination

Advantages:

- Define according to Fisher projected covariance matrix – no a posteriori bias in looking for features
- Efficient – can keep only observable modes and never requires MCMC over large correlated discrete space
- Complete – can include as many modes as required to make basis observationally complete
- Paradigm testing – rapidly explore all possible observational outcome of a given paradigm
- Falsifiable predictions for other observables not yet measured
10 PCs defined for StageIV (SNAP+Planck) define an observationally complete basis out to $z=1.7$
Falsifying Quintessence

• Dark energy slows growth of structure in highly predictive way

Cosmological Constant

• Deviation significantly $>2\%$ rules out $\Lambda$ with or without curvature

Quintessence

• Excess $>2\%$ rules out quintessence with or without curvature and early dark energy [as does $>2\%$ excess in $H_0$]
Dynamical Tests of Acceleration

- Dark energy slows growth of structure in highly predictive way

Mortonson, Hu, Huterer (2009)

Cosmological Constant

Quintessence
Elephantine Predictions

- Geometric constraints on the cosmological parameters of $\Lambda$CDM
- Convert to distributions for the predicted average number of clusters above a given mass and redshift
ΛCDM Falsified?

- 95% of ΛCDM parameter space predicts less than 1 cluster in 95% of samples of the survey area above the $M(z)$ curve.
- No currently known high mass, high redshift cluster violates this bound.

Mortonson, Hu, Huterer (2010)

Eddington Bias Correction
Lima & Hu (2005)
• 95% of $\Lambda$CDM parameter space predicts less than 1 cluster in 95% of samples of the survey area above the $M(z)$ curve

• Convenient fitting formulae for future elephants:

http://background.uchicago.edu/abundance
Number Bias

- For $M_{\text{obs}}$, scatter and steep mass function gives excess over $M$
- Equate the number $M_{\text{obs}}$ to $M_{\text{eff}}$
- Not the same as best estimate of true mass given model!

Lima & Hu (2005)
Number Bias

- For $M_{\text{obs}}$, scatter and steep mass function gives excess over $M$
- Equate the number $M_{\text{obs}}$ to $M_{\text{eff}}$
- Not the same as best estimate of true mass given model!

Lima & Hu (2005)
Pink Elephant Parade

- SPT catalogue on 2500 sq degrees

Williamson et al (2011)
Cosmic Shear Tests

- **Convergence power spectrum** of CFHTL-like survey; currently consistent with $\Lambda$CDM

Cosmic Shear Tests

- Systematics from baryonic feedback (e.g. AGN, cooling, star formation in clusters) comparable to statistical errors
- Calibration must be improved
- Residual uncertainties characterized by variations in Halofit parameters

van Daalen et al. (2011)
$c_n \rightarrow 1.15c_n$

Vanderveld et al. (2012)
Summary

- Flat $\Lambda$CDM is highly predictive and falsifiable
- Distance-redshift relation at all redshifts, including $z = 0$ and $H_0$ fixed at the few percent level largely from CMB
- Smooth dark energy predicts growth given distance-redshift
- Even including arbitrary $w(z)$ and uncertainties of current distance constraints, smooth dark energy make sharp predictions
- $\Lambda$CDM places firm upper bound on growth of structure for all quintessence models (smooth dark energy with $w \geq -1$)
- Observations of excess clusters or cosmic shear that falsify $\Lambda$CDM also falsifies quintessence