Dark Energy

- J. Frieman: Overview 30
- A. Kim: Supernovae 30
- B. Jain: Weak Lensing 30
- M. White: Baryon Acoustic Oscillations 30

P5, SLAC, Feb. 22, 2008
Progress since last P5 Report

- BEPAC recommends JDEM as highest-priority for NASA’s Beyond Einstein program: joint AO expected 2008
- DES recommended for CD2/3a approval
- LSST successful Conceptual Design Review
- ESA Cosmic Visions Program: DUNE, SPACE Concept Advisory Team studying possible merger
What is causing cosmic acceleration?

Dark Energy: \[ G_{\mu\nu} = 8\pi G[T_{\mu\nu} \text{ (matter)} + T_{\mu\nu} \text{ (dark energy)}] \]

DE equation of state: \[ w = \frac{T_i}{T_0} > -1/3 \]

Gravity: \[ G_{\mu\nu} + f(g_{\mu\nu}) = 8\pi G T_{\mu\nu} \text{ (matter)} \]

Key Experimental Questions:

1. Is DE observationally distinguishable from a cosmological constant, for which \( w = -1 \)?
2. Can we distinguish between gravity and dark energy?
   Combine distance with structure-growth probes
3. Does dark energy evolve: \( w = w(z) \)?
What is the nature of Dark Energy?

- Probe dark energy through the history of the expansion rate:

\[
\frac{H^2(z)}{H_0^2} = \Omega_m (1 + z)^3 + \Omega_{DE} \exp \left[ 3 \int (1 + w(z)) d\ln(1 + z) \right] + (1 - \Omega_m - \Omega_{DE})(1 + z)^2
\]

- and the growth of large-scale structure:

\[
\frac{\delta \rho(a)}{\rho} = r(z) = F \left[ \int \frac{dz}{H(z)} \right]
\]

Four Primary Probes (DETF):

- Weak Lensing cosmic shear
  Distance \( r(z) + \) growth
- Supernovae
  Distance
- Baryon Acoustic Oscillations
  Distance + \( H(z) \)
- Cluster counting
  Distance + growth
What is the nature of Dark Energy?

- Probe dark energy through the history of the expansion rate:

\[
\frac{H^2(z)}{H_0^2} = \Omega_m (1 + z)^3 + \Omega_{DE} \exp\left[3 \int (1 + w(z)) d \ln(1 + z)\right] + (1 - \Omega_m - \Omega_{DE})(1 + z)^2
\]

- and the growth of large-scale structure:

\[
\frac{\delta \rho(a)}{\rho} = \frac{\dot{r}(z)}{r(z)} = F \left[ \int \frac{dz}{H(z)} \right]
\]

Four Primary Probes (DETF):

- Weak Lensing cosmic shear
- Supernovae
- Baryon Acoustic Oscillations
- Cluster counting

Distance \( r(z) \)+growth
Distance
Distance+\( H(z) \)
Distance+growth
Model Assumptions

• Most current data analyses assume a simplified, two-parameter class of models:

\[ \Omega_m, \Omega_{DE}, w(z) \Rightarrow \text{either: } \Omega_m, \Omega_{DE} (w = -1) \]

or: \[ \Omega_m, w \text{ (constant), flat: } \Omega_m + \Omega_{DE} = 1 \]

• Future experiments aim to constrain (at least) 4-parameter models:

\[ \Omega_m, \Omega_{DE}, w(a) = w_0 + w_a (1 - a) \]

• Higher-dimensional EOS parametrizations possible

• Other descriptions possible (e.g., kinematic)
Current Constraints on Constant Dark Energy Equation of State

2-parameter model: 
\[ w, \Omega_m \]

Data consistent with 
\[ w = -1 \pm 0.1 \]

Allen et al 07
Current Constraints on Constant Dark Energy Equation of State

2-parameter model: $w, \Omega_m$

Data consistent with $w = -1 \pm 0.1$

Allen et al 07
Kowalski et al 08
Curvature and Dark Energy

WMAP3+
SDSS+2dF+
SN

w(z) = constant
3-parameter model:

w, \Omega_m, \Omega_k

Spergel et al. 07
Much weaker current constraints on Time-varying Dark Energy

3-parameter model

\[ w(z) = w_0 + w_a (1 - a) + \ldots \]

marginalized over \( \Omega_m \)

Kowalski et al 08

Assumes flat Universe

• Defined Figure of Merit to compare expts and methods:

\[ FoM \propto \frac{1}{\sigma(w_0)\sigma(w_a)} \]

• Highlighted 4 probes: SN, WL, BAO, CL

• Envisioned staged program of experiments:
  
  Stage II: on-going or funded as of 2006
  Stage III: intermediate in scale + time
  Stage IV: longer-term, larger scale
  LSST, JDEM
Much weaker current constraints on Time-varying Dark Energy

3-parameter model

\[ w(z) = w_0 + w_a (1 - a) \]

marginalized over \( \Omega_m \)

Kowalski et al 08
Growth of Large-scale Structure

Robustness of the paradigm recommends its use as a Dark Energy probe

**Price:** additional cosmological and structure formation parameters

**Bonus:** additional structure formation parameters
Expansion History vs. Perturbation Growth

Growth of Perturbations probes $H(z)$ and gravity modifications

Linder

\[ g'' + \left[ 5 + \frac{1}{2} \frac{d \ln H^2}{d \ln a} \right] g' a^{-1} + \left[ 3 + \frac{1}{2} \frac{d \ln H^2}{d \ln a} - \frac{3}{2} G \Omega_m(a) \right] g a^{-2} = S(a) \]
Expansion History vs. Perturbation Growth

Growth of Perturbations probes $H(z)$ and gravity modifications

$$g'' + \left[ 5 + \frac{1}{2} \frac{d \ln H^2}{d \ln a} \right] g' a^{-1} + \left[ 3 + \frac{1}{2} \frac{d \ln H^2}{d \ln a} - \frac{3}{2} G \Omega_m (a) \right] g a^{-2} = S(a)$$
Probing Dark Energy

Primary Techniques identified by the Dark Energy Task Force report:

- Supernovae
- Galaxy Clusters
- Weak Lensing
- Baryon Acoustic Oscillations

Multiple Techniques needed: complementary in systematics and in science reach
Table 3: Dark energy projects proposed or under construction. Stage refers to the DETF time-scale classification.

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*Caveat:* Representative list, not guaranteed to be complete or accurate.
Type Ia SN Peak Brightness as calibrated Standard Candle

Peak brightness correlates with decline rate

Variety of algorithms for modeling these correlations

After correction, $\sigma \sim 0.15$ mag ($\sim 7\%$ distance error)
Global SNIa
Hubble
Diagram 2007

Hamuy 1996a,b
Riess 1998
Perlmutter 1999
Riess 1999
Riess 2001
Tonry 2003
Knop 2003
Barris 2004
Riess 2004
Clochiatti 2005
Astier 2006
Jha 2006
Wood-Vasey et al. 07
Large-scale Correlations of SDSS Luminous Red Galaxies

Redshift-space Correlation Function

\[ \xi(r) = \langle \delta(\mathbf{x})\delta(\mathbf{x} + \mathbf{r}) \rangle \]

Baryon Acoustic Oscillations seen in Large-scale Structure

Eisenstein, et al. 05
Cold Dark Matter Models

Power Spectrum of the Mass Density

\[ \delta(k) = \int d^3x \cdot e^{i\vec{k} \cdot \vec{x}} \frac{\delta \rho(x)}{\rho} \]

\[ \langle \delta(k_1)\delta(k_2) \rangle = (2\pi)^3 P(k_1) \delta^3(\vec{k}_1 + \vec{k}_2) \]

- Baryon Oscillations
- Matter-radiation equality

Primordial

\[ P(k) \]
Power spectrum $P(k)$ [(h^{-1}Mpc)^3] as a function of $k$ [h Mpc^{-1}].

- LRG
- Main

SDSS

Tegmark et al. 06
Weak lensing: shear and mass
Cosmic Shear Correlations

VIRMOS-Descart Survey

Shear Amplitude

\[ \xi_{E,B}(\theta) \]

- 55 sq deg
- \( z = 0.8 \)

Van Waerbeke et al. 05
Clusters and Dark Energy

Number of clusters above observable mass threshold

- **Requirements**
  1. Understand formation of dark matter halos
  2. Cleanly select massive dark matter halos (galaxy clusters) over a range of redshifts
  3. Redshift estimates for each cluster
  4. Observable proxy $O$ that can be used as cluster mass estimate:
     $$p(O|M,z)$$

Primary systematic:
Uncertainty in bias & scatter of mass-observable relation

$$\frac{dN(z)}{dzd\Omega} = \frac{dV}{dzd\Omega} n(z)$$

Dark Energy equation of state
- $w = -1.0$
- $w = -0.8$
- $w = -0.6$
Clusters form hierarchically

Kravtsov

dark matter
time

5 Mpc
Theoretical Abundance of Dark Matter Halos

\[ n(z) = \int_{M_{\text{min}}}^{\infty} (dn / d\ln M) d\ln M \]

Warren et al
Cluster Selection

- 4 Techniques for Cluster Selection:
  - Optical galaxy concentration
  - Weak Lensing
  - Sunyaev-Zel’dovich effect (SZE)
  - X-ray

- Cross-compare selection to control systematic errors
Photometric Redshifts

- Measure relative flux in multiple filters: track the 4000 Å break
- Precision is sufficient for Dark Energy probes, provided error distributions well measured.
- Need deep spectroscopic galaxy samples to calibrate
Photometric Redshifts

• Measure relative flux in multiple filters: track the 4000 Å break

• Precision is sufficient for Dark Energy probes, provided error distributions well measured.

• Need deep spectroscopic galaxy samples to calibrate
Cluster Mass Estimates

4 Techniques for Cluster Mass Estimation:

- Optical galaxy concentration
- Weak Lensing
- Sunyaev-Zel’дович effect (SZE)
- X-ray

- Cross-compare these techniques to reduce systematic errors
- Additional cross-checks: shape of mass function; cluster correlations
Calibrating the Cluster Mass-Observable Relation

- Weak Lensing by stacked SDSS Clusters
- insensitive to projection effects
- Calibrate mass-richness

Johnston, Sheldon, et al. 07
Current Constraints: X-ray clusters

Mantz, et al 2007
Systematic Errors

- **Supernovae**: uncertainties in dust and SN colors; selection biases; “hidden” luminosity evolution; limited low-z sample for training & anchoring
- **BAO**: redshift distortions; galaxy bias; non-linearities; selection biases
- **Weak Lensing**: additive and multiplicative shear errors; photo-z systematics; small-scale non-linearity & baryonic effects
- **Clusters**: scatter & bias in mass-observable relation; uncertainty in observable selection function; small-scale non-linearity & baryonic effects
Conclusions

• Excellent prospects for increasing the precision on Dark Energy parameters from a sequence of increasingly complex and ambitious experiments over the next 5-15 years

• Exploiting complementarity of multiple probes will be key: we don’t know what the ultimate systematic error floors for each method will be. Combine geometric with structure-growth probes to help distinguish modified gravity from dark energy.

• What parameter precision is needed to stimulate theoretical progress? It depends in large part on what the answer is.