Dark Energy: Pedagogical Overview and Future Prospects

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Supernova Hubble diagram (binned)

sensitive to \( D_V(z) \equiv \left[ cz (1 + z)^2 \frac{D^2_A(z)}{H(z)} \right]^{1/3} \)

But, with separation of radial and angular modes, can measure \( D_A(z) \) and \( H(z) \) separately
Weak Gravitational Lensing

Key advantage: measures distribution of matter, not light

Credit: NASA, ESA and R. Massey (Caltech)
Weak Gravitational Lensing

current constraints on DE are weak

... but WL still has a lot of promise! (no bias)
Since the discovery of acceleration, constraints have converged to $w \approx -1$

SN + BAO + CMB(WMAP) data:

Ruiz, Shafer, Huterer & Conley, 1207.4781
In principal, constraints are good...

(components)

\[ w(z_j) = -1 + \sum_{i=1}^{N} \alpha_i e_i(z_j) \]

\[ \alpha_i = \text{PC amplitude} \]

\[ e_i(z) = \text{PC shape} \]

Red = with SN systematics
Systematic errors

- Already limiting factor in measurements
- Will definitely be limiting factor with future data
- Quantity of interest: \((\text{true sys.} - \text{estimated sys.})\) difference

- **Self-calibration**: measuring systematics internally from the survey -
  - e.g., parametrize systematics, solve internally for those parameters
Systematics summary for the “big four”

Table 2: Comparison of dark energy probes.

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<th>Weaknesses</th>
<th>Systematics</th>
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<td>BAO</td>
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<td>CL</td>
<td>growth+geometric, X-ray+SZ+optical</td>
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<td>determining mass, selection function</td>
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Theory Systematics: calibrating the matter (and, later, gal) $P(k)$ at large $k$
Poster child of systematics: photometric redshift errors

- Measure $z_{\text{phot}}$ from colors
- Calibrate $P(z_{\text{phot}} | z_{\text{spec}})$ relation from spectroscopic follow-up
- Need accurate characterization of “islands”, not just sigma_error of the “core” of distribution

**C. Cunha**

- Major challenge: spectroscopic surveys typically much shallower than photometric
Photometric calibration errors

SFD Galactic dust extinction map

Correction to the extinction map

Photometric calibration also can be due to:

• “seeing” and weather
• thickness of atmosphere
• instrumental effects
• need to avoid bright stars
• ....

Very generic!
How do calibration errors affect the measured galaxy angular power spectrum?

\[ \langle t_{\ell m} t_{\ell' m'}^* \rangle = \frac{1}{(1 + \epsilon)^2} \left\{ \delta_{m'm'} \delta_{\ell \ell'} C_{\ell} + \left[ U_{mm'}^{\ell \ell'} C_{\ell'} + (U_{mm'}^{\ell \ell'})^* C_{\ell} \right] + \sum_{\ell_2 m_2} U_{m_2 m_2}^{\ell_2 \ell_2} (U_{m_2 m_2}^{\ell_2 \ell_2})^* C_{\ell_2} + c_{\ell m} c_{\ell' m'}^* \right\} \]

where

\[ U_{m_2 m}^{\ell_2 \ell} \equiv \sum_{\ell_1 m_1} c_{\ell_1 m_1} R_{m_1 m_2 m}^{\ell_1 \ell_2 \ell} \]

\[ R_{m_1 m_2 m}^{\ell_1 \ell_2 \ell} \equiv (-1)^m \sqrt{(2\ell_1 + 1)(2\ell_2 + 1)(2\ell + 1)} \frac{1}{4\pi} \begin{pmatrix} \ell_1 & \ell_2 & \ell \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \ell_1 & \ell_2 & \ell \\ m_1 & m_2 & -m \end{pmatrix} \]

Final result for the observed power spectrum is:

- **True power**
- **Calibration (biases)**

Cancels effects of calibration monopole

- isotropic
- breaks statistical isotropy

\[ t_{\ell m} \] – observed galaxy field
\[ c_{\ell m} \] – calibration (systematics) field
\[ C_{\ell} \] – true galaxy clustering power

Calibration bias: Worked Example 1

SFD dust map

PG10 corrections to map

Angular power of corrections

Bias/error in cosmology

Calibration bias: Worked Example 2

DES magnitude limit (J. Annis)

![Image](attachment:DES_magnitude_limit.png)

For error = 10% of mag-limit-variation map

- $f_{NL}$
- $\text{FoM}_{w0wa}^{1/2}$

### Multipole $l$

- $C_l$

### Faint-end slope of luminosity func, $s(z)$

- $\text{bias} / \text{error}$

- $0.1$ to $3$
Summary of findings:

1. Calibration *breaks statistical isotropy* of LSS signal (obvious in retrospect)

2. *Large-angle* errors beyond the monopole - dipole, quadrupole, etc - are most damaging

3. Control at level $< 0.1\%$ might be required for DES-type survey and beyond
Recommendations of the “Rocky III” DOE/HEP report
(Albrecht et al, 2012)

1. Advanced wide-field spectroscopic survey in time frame roughly between DES and LSST (& Euclid/WFIRST)
   - Stage IV BAO/RSD information
   - Provide calibration data for systematic error mitigation to improve dark-energy constraints from photometric surveys like DES & LSST (in particular, helps WL & CL)

2. Advance SN technique to Stage IV
   - Clearest path: DOE participation in SNe at high-redshift from space (example: DOE-led modest upgrade to WFIRST)
   - Explore vigorously ground-based alternatives (R&D effort for near-IR technology and sky-line suppression)

3. Pilot studies to generate new ideas for the future
   - Deep spectroscopic calibration data needed for LSST. Pilot study to determine exact needs and how to meet them.
   - Pilot studies combining theory and targeted observations to chart an effective modified gravity program to study transition to modified gravity.
In the next 10-15 years, can expect measurements of:

- $w$ (or $w_{\text{pivot}}$) to 0.01 (incl systematics)
- $d(z)$, growth($z$) in bins out to $z=2-3$
- parametric DE vs MG consistency tests

**e.g. WFIRST**

Spergel et al. (2013) arXiv:1305.5422
Can we distinguish between DE and MG?

(Usual answer:) Yes; here is how:

• 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

\begin{align*}
\text{Distances} & \quad \text{(as known as kinematic probes)} \\
& \text{(a.k.a. 0\textsuperscript{th} order cosmology)} \\
\text{Probed by SN Ia, BAO, CMB, weak lensing, cluster abundance}
\end{align*}

\begin{align*}
\text{Growth} & \quad \text{(a.k.a. dynamical probes)} \\
& \text{(a.k.a. 1\textsuperscript{st} order cosmology)} \\
\text{Probed by galaxy clustering, weak lensing, cluster abundance}
\end{align*}

(Actually...) Not without assuming that DE has no e.g. anisotropic stress

\[
G_{\mu\nu} + X_{\mu\nu} = 8\pi GT_{\mu\nu} \quad \text{vs.} \quad G_{\mu\nu} = 8\pi GT_{\mu\nu} - X_{\mu\nu}
\]
What if gravity deviates from GR?

For example:

\[ H^2 - F(H) = \frac{8\pi G}{3} \rho, \]

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

Modified gravity

Dark energy

Notice: there is no way to distinguish these two possibilities just by measuring expansion rate \( H(z) \)!
$D_A(z)$ with $\Omega_M h^2$ fixed is basically the “CMB shift parameter” $R$

$$R = \sqrt{\Omega_M h^2} \int_0^{z_*} \frac{dz'}{H_0 \sqrt{\Omega_M (1 + z')^3 + (1 - \Omega_M)(1 + z')^3(1+w)}}$$

Redshift increases ⇔ more vertical

$\Omega_M h^2$ fixed ⇒ different orientation

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Frieman, Huterer, Linder & Turner 2003
CMB Lensing gives $D_A(z \sim \text{few})$

[Recall, CMB lensing additionally carries info about power spectrum $P(k)$]
Lensing potential:

$$\phi(\hat{n}) = -2 \int_0^{z_{\text{rec}}} \frac{dz}{H(z)} \Psi(z, D(z)\hat{n}) \left( \frac{D(z_{\text{rec}}) - D(z)}{D(z_{\text{rec}})D(z)} \right)$$

Angular power of potential:

$$C_{\ell}^{\phi\phi} = \frac{8\pi^2}{\ell^3} \int_0^{z_{\text{rec}}} \frac{dz}{H(z)} D(z) \left( \frac{D(z_{\text{rec}}) - D(z)}{D(z_{\text{rec}})D(z)} \right)^2 P_\Psi(z, k = \ell/D(z))$$
Current data LCDM predictions - flat or curved

Growth to z=1000

Distance

Ω_K ≠ 0
Ω_K = 0

Hubble parameter

ΔH/H

ΔD/D

ΔG/G

Δ(fG)/fG

Δγ/γ

Growth index

f×G

Growth to z=0
Current data Quintessence predictions (flat, no Early DE)
Future data

**LCDM predictions (flat or curved)**

Grey: flat  
Blue: curved

D, G to <1% everywhere  
H(z=1) to 0.1% for flat LCDM