Testing Generic Predictions of Dark Energy

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Outline

• Distance and growth probes of cosmology are connected by their dependence on the Hubble expansion rate.

• Depending on the degrees of freedom considered, the connection may be strong ($\Lambda$CDM, flat, GR) or weak ($w(z)$, curved, modified gravity).

• 3 steps to test cosmological models:
  1) Measure distances and redshifts
  2) Predict growth from $D(z)$
  3) Observe growth and compare with predictions

• Applications include tests of general dark energy models and tests of the flatness of the universe.
Distance measures

Type Ia supernovae
Distance measures

Baryon acoustic oscillations

Type Ia supernovae
Distance measures

Baryon acoustic oscillations

Type Ia supernovae

Cosmic microwave background

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Distance measures

\[ D(z) = \frac{1}{\sqrt{|\Omega_K| H_0}} S_K \left[ \sqrt{|\Omega_K| H_0} \int_0^z \frac{dz'}{H(z')} \right] \]

Baryon acoustic oscillations

Type Ia supernovae

Cosmic microwave background

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Growth

Galaxy cluster counts

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Growth

Galaxy cluster counts

Weak lensing/cosmic shear
Growth

Galaxy cluster counts

Weak lensing/cosmic shear

\[ G'' + \left( 4 + \frac{H'}{H} \right) G' + \left[ 3 + \frac{H'}{H} - \frac{3}{2} \Omega_m(z) \right] G = 0 \]
Distance + Growth

\[ D(\hat{z}) = \frac{1}{\sqrt{|\Omega_K|}H_0} S_K \left[ \sqrt{|\Omega_K|}H_0 \int_0^{\hat{z}} \frac{dz'}{H(z')} \right] \]

\[ G'' + \left(4 + \frac{H'}{H}\right)G' + \left[3 + \frac{H'}{H} - \frac{3}{2} \Omega_m(z) \right] G = 0 \]
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spatial curvature

dark energy evolution

\[ G'' + \left( 4 + \frac{H'}{H} \right) G' + \left[ 3 + \frac{H'}{H} - \frac{3}{2} \Omega_m(z) \right] G = 0 \]

(assume general relativity is correct at all scales)
Distance data

• Type Ia supernovae
  
  **current data:** Union SN compilation (Kowalski et al. 2008)
  
  307 SNe, $z \lesssim 1$

  **forecasts:** SNAP
  
  2000 SNe, $z < 1.7$ (+ 300 at $z < 0.1$)

• Cosmic microwave background $[D(z=1090), \Omega_m h^2]$
  
  **current data:** WMAP (5 yr) (Komatsu et al. 2009)
  
  temperature at $\ell < 530$, polarization at $\ell < 7$

  **forecasts:** Planck
  
  temp. at $\ell \lesssim 1000$, polarization at $\ell \lesssim 100$
Model parameters

Dark energy

- cosmological constant/vacuum energy ($\Lambda$CDM): $w = -1$
- scalar field (quintessence): $-1 < w < 1$
  redshift dependent equation of state $w(z)$
  - low $z$ (constrained by SNe, dark energy effects most important):
    complete set of basis functions for $w(z)$ (around $10^{-15}$)
  - high $z$ (early dark energy):
    constant effective equation of state, $w_\infty$

Curvature

- flat ($\Omega_K = 0$)
- curved ($\Omega_K \neq 0$)

Growth predictions

• Sample the dark energy/curvature parameter space (MCMC)
  distribution of parameter samples approximates the likelihood of the SN+CMB distance data

• Compute the linear growth function for each sample and plot the distribution of growth at each redshift

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*current data, flat $\Lambda$CDM*

Growth predictions: $\Lambda$CDM

- **Current data, flat vs. curved $\Lambda$CDM**

- **SNAP + Planck forecasts, flat vs. curved $\Lambda$CDM**

Growth predictions: quintessence (-1<w<1)

SNAP + Planck forecasts, quintessence with and without early DE (flat)

SNAP + Planck forecasts, flat vs. curved quintessence (no early DE)

Testing dark energy models

• Measure growth (clusters, weak lensing, etc.) and compare with the predicted ranges for each class of models

• Significant discrepancies between predicted and observed growth can falsify general explanations for cosmic acceleration (assuming systematics are under control)

Measuring curvature

- Combine distance and growth measurements to break the "geometrical degeneracy" and obtain model-independent estimates of spatial curvature
- SNAP+Planck distances and 1% growth measurements at $z < 2$ (IXO X-ray cluster survey, Vikhlinin et al., arXiv:0903.2297)

$\sigma(\Omega_K) = 0.002$

MM, arXiv:0908.0346

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Conclusions

• Current observations of distances already predict the growth of structure on large scales with an accuracy of a few percent for simple models like ΛCDM

• Future distance measurements can provide stronger growth predictions (1-2%) for ΛCDM and make testable predictions for models with general dark energy evolution and spatial curvature

• These growth predictions, combined with direct observation of the growth of large-scale structure, may allow us to falsify general classes of dark energy models and make precise, model-independent curvature measurements