Dark Energy: Observations

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Outline

• How dark energy affects cosmological observables
  • $a(t) \Rightarrow \text{distances}(z), \text{growth of structure}(z)$

• Dark energy probes
  • cosmic microwave background
  • supernovae (type Ia)
  • galaxy clustering
  • weak gravitational lensing
  • galaxy cluster number counts

Warning: not a comprehensive list of experiments!
Fig. 4: Confidence contours in the cosmological parameters $\Omega_m$ and $w$ assuming a flat universe produced using the CosmoMC program. The SNLS3 contours are in blue, the SDSS DR7 LRG contours in green, and the $H_0$ prior in red. WMAP7 constraints are included in all contours. The contours enclose 68.3% and 95.4% of the probability and include all SN systematic uncertainties. The dashed line indicates $w = -1$. Numerical results are in Table 4.

$w = -1.06 \pm 0.07$
Energy Densities in Cosmology

\[ H = H_o \sqrt{\Omega_m (1 + z)^3 + \Omega_x (1 + z)^{3(1+w)}} \]

- \( d(\ln a)/dt \)
- matter
- dark energy

\[ a = 1/(1+z) \]

- scale factor
- redshift
The expanding universe

- spatially flat FRW: $dt^2 = a^2(t) \, dr^2$
- mapping between comoving distance between points and time depends on expansion history
Dark Energy from Distances

- distance sensitive to expansion rate

\[ H = H_0 \sqrt{\Omega_m (1 + z)^3 + \Omega_x (1 + z)^{3(1+w)}} \]

\[ d_L = c(1 + z) \int_0^z dz' H^{-1}(z') \]
Gravity at work

Simulated density contrast at different times

$t=400,000$ yrs

$t=20$ million yrs

$t=500$ million yrs

$t=13.7$ billion yrs

Simulations carried out by the Virgo Supercomputing Consortium using computers based at Computing Centre of the Max-Planck Society in Garching and at the Edinburgh Parallel Computing Centre. The data are publicly available at [www.mpa-garching.mpg.de/NumCos](http://www.mpa-garching.mpg.de/NumCos)

\[ \ddot{\delta} + 2H(z)\dot{\delta} = 4\pi G\rho_0 \delta \]
Dark Energy Studies with Growth Tests

- Growth of structure sensitive to expansion rate

\[ H(z) = H_0 \sqrt{\Omega_m (1 + z)^3 + \Omega_x (1 + z)^{3(1 + w)}} \]

Amplitude of density fluctuations in linear theory:

\[ \ddot{\delta} + 2H(z)\dot{\delta} = 4\pi G\rho_0 \delta \]
Characterizing Dark Energy

from Dark Energy Task Force report
Cosmic Microwave Background

- acoustic scale (in cm) set by physics unrelated to dark energy
  - angular scale depends on expansion history

- provides normalization of fluctuation amplitude at $z \sim 1100$
CMB Power Spectrum

characteristic spacing set by angular size of sound horizon at $z=1089$

$SPT$ power spectra: Ryan Keisler; Christian Reichardt; Erik Shirokoff
Characterizing Dark Energy

Figure VI-2: The primary observables for dark-energy – the distance-redshift relation $D(z)$ and the growth-redshift relation $g(z)$ – are plotted vs. redshift for three cosmological models. The green curve is an open-Universe model with no dark energy at all. The black curve is the “concordance” CDM model, which is flat and has a cosmological constant, i.e., $w = -1$. This model is consistent with all reliable present-day data. The red curve is a dark-energy model with $w$, for which other parameters have been adjusted to match WMAP data. At left one sees that dark-energy models are easily distinguished from non-dark-energy models. At right, we plot the ratios of each model to the CDM model, and it is apparent that distinguishing the $w$ model from CDM requires percent-level precision on the diagnostic quantities.
Exploding stars: Supernovae

It appears that some supernovae (IA) all have the same intrinsic brightness.
Supernova!

Host Galaxies of Distant Supernovae

HST04Sas  HST04Yow  HST04Zwi  HST05Lan  HST05Str

NASA, ESA, and A. Riess (STScI)

STScI-PRC06-52
SNe Multi-color Light Curves

Conley et al 2008
Standardized Candles

each panel is a different wavelength range

Conley et al 2008
Fig. 5.— Hubble diagram of the combined sample. The residuals from the best fit are shown in the bottom panel.

Conley et al 2011
Forecast & Wish List for SNe

• need more SNe both at low-z and at z＞1
  – population studies to ensure that there isn’t some evolution in either each SN or in the demographics of the SN population
• more colors would be nice (IR, UV?)
  – space-based? (WFIRST)
• a strong theoretical understanding of spectra & light curves would be reassuring
Characterizing Dark Energy

from Dark Energy Task Force report

Expansion History

Growth History

SNe

CMB
Baryon Acoustic Oscillations leave imprint in matter distribution

Eisenstein, Seo & White 2006
Galaxy Clustering

- galaxies are clustered
- amplitude a bit tricky to use because galaxies live at peaks of density field (``biased")
- BAO signature leads to boosted clustering on acoustic scale (∼100 h⁻¹Mpc)

slice through SDSS survey
Baryon Oscillations imprinted in Galaxy Clustering

- first detected in Eisenstein et al 2005 using SDSS LRG sample (extends to $z \sim 0.5$)
- actually detected in angular & radial clustering

- **standard ruler**
The BAO Hubble Diagram

- BAO measurements at different $z$ allow a test of the distance-redshift relation.
The BAO Hubble Diagram

- BAO measurements at different $z$ allow a test of the distance-redshift relation
Forecast & Wish List for BAO

• minimal (but not completely negligible) non-linear physics

• mainly need more volume
  • 100 Mpc/h scale + 1% precision requires at least a few Gpc on a side surveys ($cH_0^{-1} \sim 3$ Gpc/h)

• lots of ideas & new surveys
  • e.g., quasar absorption lines/optical galaxies (BigBoss); CHIME (21cm intensity mapping)

  just my personal favorites, no offense to the many others...
permitting a test of the underlying GR theory

Fig. VI-2: The primary observables for dark-energy – the distance-redshift relation \( D(z) \) and the growth-redshift relation \( g(z) \) – are plotted vs. redshift for three cosmological models. The green curve is an open-Universe model with no dark energy at all. The black curve is the "concordance" /CDM model, which is flat and has a cosmological constant, i.e., \( w = -1 \). This model is consistent with all reliable present-day data. The red curve is a dark-energy model with \( w \), for which other parameters have been adjusted to match WMAP data. At left one sees that dark-energy models are easily distinguished from non-dark-energy models. At right, we plot the ratios of each model to the /CDM model, and it is apparent that distinguishing the \( w \) model from /CDM requires percent-level precision on the diagnostic quantities.

Four Astrophysical Approaches to Dark Energy Measurements

1. Type Ia Supernovae

Characterizing Dark Energy from Dark Energy Task Force report
Gravitational Lensing

- Distortion, multiple imaging of distant sources

www.hubblesite.org

Gravitational Lensing

- Distortion, multiple imaging of distant sources
- Amount of lensing depends on source/lens/observer geometry (distances)

DEFLECTION OF LIGHT RAYS CROSSING THE UNIVERSE, EMITTED BY DISTANT GALAXIES

SIMULATION: COURTESY NIC GROUP, S. COLOMBI, IAP.
Weak Lensing

- gravitational potentials distort shapes by stretching, squeezing, shearing
- typical cosmic shear signal \( \sim 1\% \)
Galaxies are not round

- individual galaxies have complex morphologies
- solution: average over many galaxies
Cosmic Shear Measurements

- very strong detections are now being made
- e.g., CFHTLS has published results from 57 sq deg of single-band ground-based imaging

Fig. 4. Two-point statistics from the combined 57 pointings. Red filled points show the E-mode, only statistical uncertainty contributes to the error bars. The error bars of the E-mode include statistical noise and cosmic variance calibrated for non-Gaussianity, while the error for the B-modes only includes statistical noise and cosmic variance, but which is not always within 1σ of a zero detection. Notice that the errors on the B-mode are very strong detections made in the angular range 35′ to 120′. The enlargements in each panel show the signal in the angular range 35′ to 120′.

Fig. 5. The top-hat E-mode shear signals of W1 up to 230′ of W2 up to 120′ and of W3 up to 230′ are shown. On very large scales (120′ to 230′), Poissonian error, particularly on large scales where there are a significant number of galaxy pairs, may dominate the very small statistical uncertainty. We find a clear E-mode signal and detections are not biased by this level of residual systematics that are a significant number of galaxy pairs. In Sect. 6 we show that our cosmological results are not biased by this level of residual systematics that are a significant number of galaxy pairs.

σ \langle l_{ij}^2 \rangle

\theta [arcmin]

Fu et al 2008
DEFLECTION OF LIGHT RAYS CROSSING THE UNIVERSE, EMITTED BY DISTANT GALAXIES

SIMULATION: COURTESY NIC GROUP, S. COLOMBI, IAP.
Weak lensing tomography

- using source galaxies at different redshifts allows one to reconstruct the 3D mass distribution
- mass, not galaxy, density means you can measure the time evolution of the density fluctuations
- recent results using Hubble over ~1 sq deg

Massey et al
Weak lensing tomography

- using source galaxies at different redshifts allows one to reconstruct the 3D mass distribution
- mass, not galaxy, density means you can measure the time evolution of the density fluctuations

Schrabback et al. 2010
CMB Lensing

Photons get shifted

\[ T^L(\hat{n}) = T^U(\hat{n} + \nabla \phi(\hat{n})) \]

- CMB is a unique source for lensing
- Gaussian, with well-understood power spectrum (contains all info)
- At redshift which is (a) unique, (b) known, and (c) highest

**strong detections now exist**
Forecast & Wish List for lensing

• cosmic shear requires large areas, good redshift discrimination, good telescope understanding
  
  • space-based may be easier (high resolution, broad wavelength coverage, very dark sky)

• large surveys coming soon: 1000s of square degrees of deep imaging (DES, Pan-Starrs, ...,LSST)
Characterizing Dark Energy

from Dark Energy Task Force report
Number counts of rare objects

- simulated 2x2 degree map showing projected thermal pressure
- number of most massive objects highly sensitive to amplitude of density fluctuations
One of the heaviest objects in the universe $>10^{15}$ solar masses

CMB map made with South Pole Telescope
Cluster \(dN/dz\)

First SPT Cosmological result (Vanderlinde et al 2010), used SPT’s first 21 clusters to constrain cosmology

100 steps from WMAP7 \(wCDM\) MCMC chain with SPT \(dN/dz\) overplotted

*slide from Brad Benson*
Constraints on dark energy from X-ray selected galaxy clusters

- Vikhlinin et al 2009 (see also Mantz et al)
- ~60 clusters at z<0.7
Forecast & Wish List for galaxy clusters

• need larger samples: 1% requires 1000s of clusters just to beat Poisson noise: eROSITA (X-ray), DES (optical)

• need strong validation campaign to ensure the sample properties are well-understood (i.e., make sure that the number of objects is changing, not the type of object that is being found)
Characterizing Dark Energy

Four Astrophysical Approaches to Dark Energy Measurements

1. Type Ia Supernovae

2. Baryon Acoustic Oscillations (BAO)

3. Lensing

4. Clusters

from Dark Energy Task Force report
Summary

- dark energy is being observed in many different ways
  - first discovered through supernovae, but many independent cross-checks!
- distances & structure formation are two fundamentally different tests
- all methods have strengths and weaknesses but great promise for figuring out dark energy