Present and Future
Dark Energy Probes (I)

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August 20-21, 2020
SLAC Summer Institute
Discovery of Accelerated Expansion

Type Ia SNe

Figure 4

Discovery data: Hubble diagram of type Ia supernovae (SNe Ia) measured by the Supernova Cosmology Project and the High-z Supernova Team.

Bottom: Residuals in distance modulus relative to an open universe with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$.

Figure adapted from Perlmutter & Schmidt (2003) and Riess (2000), based on Riess et al. (1998) and Perlmutter et al. (1999).

Two teams working independently in the mid- to late 1990s, the Supernova Cosmology Project and the High-z Supernova Search, took advantage of these breakthroughs to measure the supernova Hubble diagram to much larger distances than was previously possible. Both teams found that distant supernovae are $\sim 0.25$ mag dimmer than they would be in a decelerating universe, indicating that the expansion has been speeding up for the past 5 Gyr (Riess et al. 1998, Perlmutter et al. 1999) (see Figure 4). When analyzed assuming a universe with matter and cosmological constant, these researchers' results provided evidence for $\Omega_M > 0$ at greater than 99% confidence (see Figure 8 for the current constraints).

4. CURRENT STATUS

Since the supernova discoveries were announced in 1998, the evidence for an accelerating universe has become substantially stronger and more broadly based. Subsequent supernova observations have reinforced the original results, and new evidence has accrued from other observational probes. In this section, we review these developments and discuss the current status of the evidence for cosmic acceleration and what we know about dark energy. In Section 7, we address the probes of cosmic acceleration in more detail, and we discuss future experiments in Section 8.
What do we know about Dark Energy?

◆ **Dark Energy** is the term given for the cause of the Accelerated Expansion

◆ term Dark Energy is due to Turner (1999)

◆ previously called Vacuum Energy

◆ Einstein’s original Cosmological Constant

\[
G_{\mu\nu} = \frac{8\pi G_N}{c^4} T_{\mu\nu} - \Lambda g_{\mu\nu}
\]

◆ Value of \(\Lambda\), or \(\Omega_{\Lambda}\)

◆ \(\Omega_{\Lambda}=3.5\) proton mass equivalents per cubic meter

◆ Equation of State: \(w = P/\rho\)

◆ \(w \approx -1\)

◆ Vacuum Energies have Negative Pressure

◆ Homogeneous

◆ assumed

from Turner
Recent Measurements of $\Omega_M$, $\Omega_\Lambda$, and $w$

![Graph showing constraints on $\Omega_M$, $\Omega_\Lambda$, and $w$.](Image)

- $\Omega_M$: Matter density parameter
- $\Omega_\Lambda$: Vacuum energy density parameter
- $w$: Equation of state parameter

Recent Measurements of $\Omega_M$, $\Omega_\Lambda$, and $w$ show the constraints obtained from $\Lambda$CDM models, with $\Omega_M$ and $\Omega_\Lambda$ plotted against each other. The constraints are obtained from various cosmological probes, including supernova (SN) data, Baryon Acoustic Oscillations (BAO), and Planck satellite data. The figure illustrates the confidence contours at 68% and 95% levels, indicating the range of values consistent with the data.

The constraints from supernova data alone are shown in the left plot, while the combined constraints with additional probes are shown in the right plot. The combined analysis provides tighter constraints on the cosmological parameters, reflecting the synergy between different cosmic probes.
What Don’t we know about Dark Energy?

- Is \( w = -1 \) to high precision?
- Is \( w \) constant over cosmic time?
  - \( w(a) = w_0 + w_a(1 - a) \)
  - constraints on \( w_a \) are currently imprecise
- What \textit{is} Dark Energy?
  - Cosmological Constant
  - Quantum Field
  - Modification of General Relativity
- Why is the value of \( \Lambda \) so small?
  - \( 10^{120} \) times smaller than \( M_{\text{Planck}}^4 \)
- Will the Dark Energy component of the Universe persist into the indefinite future?
How can we Measure Dark Energy?

**Geometry**

\[ r(z) = \frac{1}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_M (1 + z')^3 + (1 - \Omega_M)(1 + z')^{3(1+w)} + \Omega_R(1 + z')^4}} \]

\[ \frac{\delta(z)}{\delta(z = 0)} \]

**Gravity**

\[ \ddot{\delta}_k + 2H \dot{\delta}_k - 4\pi G \rho_M \delta_k = 0, \]

Frieman, Turner, Huterer
Ann. Rev. 2008

CMB
Type1a SuperNovae
Baryon Acoustic Oscillation

Weak Lensing Power Spectra
Galaxy Cluster Mass & Abundance
Seeds of Structure & Matter Power Spectra

Planck

Hahn, Abel, Koehler

Gruen, SSI 2020
Matter-Matter Power Spectra

Planck Collaboration: The cosmological legacy of Planck

Fig. 19. Linear-theory matter power spectrum (at $z = 0$) inferred from different cosmological probes (the dotted line shows the impact of non-linear clustering at $z = 0$). The broad agreement of the model (black line) with such a disparate compilation of data, spanning 14 Gyr in time and three decades in scale, is an impressive testament to the explanatory power of $\Lambda$CDM. Earlier versions of similar plots can be found in, for example, White et al. (1994), Scott et al. (1995), Tegmark & Zaldarriaga (2002), and Tegmark et al. (2004). A comparison with those papers shows that the evolution of the field in the last two decades has been dramatic, with $\Lambda$CDM continuing to provide a good fit on these scales.

One consistency check, which we can make internal to the Planck data set, is to check whether the large-scale structure that lenses the CMB anisotropies at $z' \approx 0.5–10$ has the right amplitude given the size of the anisotropies and the constituents inferred from the acoustic oscillations. Between the epoch of last scattering at $z' = 1100$ and the epoch corresponding to the peak of the lensing kernel ($z' = 2–3$), the fluctuations in the matter density are predicted to grow in amplitude by nearly three orders of magnitude. Since for much of this time the Universe is matter dominated and the fluctuations are in the linear regime, GR predicts the amount of growth at the percent level, allowing a precision test of the theory. In fact, the comparison can be done to such high accuracy that it is best phrased as a scaling, $A_L$, of the theoretical prediction – taking into account the distributed effects of lensing, etc. We find $A_L = 0.997 \pm 0.031$, which provides a stunning confirmation of the gravitational instability paradigm, and also allows us to constrain constituents of the Universe that do not cluster on small scales (such as massive neutrinos; see Sect. 5.3) and so reduce the small-scale power spectrum. Future, more precise, measurements of CMB lensing will provide strong constraints on neutrino masses, extra relativistic degrees of freedom, and early dark energy.

Also shown in Fig. 19 are measurements of the matter power spectrum inferred from galaxy clustering and the Ly-$\alpha$ forest.
Weak Gravitational Lensing

\( \kappa, \gamma \sim \frac{D_{ds} D_d}{D_s} \frac{\partial^2 \phi}{\partial_1 \partial_2} \)

\( \kappa \), convergence = change in size
\( \gamma \), shear = change in ellipticity

sensitive to all Matter
A Question...

How can we measure the weak gravitational effect on galaxy shape, when we don't know the unlensed shape of each galaxy?

Select only galaxies likely to be round
Assume galaxies are randomly oriented
Infer the unlensed shape of galaxies from their color
Infer the unlensed shape of galaxies from their rotational velocity

Results
Dark Energy Survey & DECam

Cerro Tololo, Chile

Corrector Lens

4-meter Primary Mirror

DECam & Blanco Telescope

530Mpixel Imager
Dark Energy Survey

- 5.5 year survey, 105 nights/yr
- completed in 2018
- 10 images/Filter (g,r,i,z,Y)
- 5000 sq. deg, overlapping SPT
- 10 SuperNovae fields
- imaged every few nights
- Cosmology results from Year1
- 1500 sq. deg., 4 images/Filter

Gruen, DES

DECam, Blanco, 2019
Weak Lensing Mass Map

- RM clusters ($\lambda > 30$)
- $\kappa_E$ peaks
- $\kappa_E$ voids

$\kappa_E$; $0.63 < z < 0.9$

Year1 WL Mass Map
Chang et.al. 2017
Weak Lensing changes the ellipticity of these galaxies by ~0.5%, and we must measure the ellipticity with multiplicative and additive bias to better than 0.1%

Also, we must measure the Point Spread Function from stars to better than 0.1%
Shear Calibration: *Metacalibration*

\[ \gamma_{measured} = m \gamma_{true} + a \]

Moments: measure moments of *Observed* Galaxy, correct for PSF to yield Shear of *True* Galaxy

Forward Models: parametrize Shear of *True* Galaxy, convolve with PSF and fit to *Observed* Galaxy

**Metacalibration:**
- Deconvolve *Observed* Galaxy with PSF
- Numerically apply Shear
- Re-convolve PSF
- Measure Shear, Determine multiplicative correction

Huff, Mandelbaum (2017)
Sheldon, Huff (2017)
Photometric Redshifts

Elliptical galaxy at redshift $z = 1.15$

Elliptical galaxy at redshift $z = 0.80$

Elliptical galaxy at redshift $z = 0.40$

$F_{\lambda}$

Wavelength [\AA]
Calibrate photometric redshifts by cross-correlating galaxies with known-redshift sample.

\[ w(r, z_{\text{ref}}) = \phi_u(z_{\text{ref}}) f(r, z_{\text{ref}}) w_{\text{mm}}(r) \]

Spectra are limited, so use well-measured galaxies (red-sequence).
\[ \xi_{\pm}(\theta) = \left\langle \gamma_t(\phi) \gamma_t(\phi + \phi) \right\rangle \pm \left\langle \gamma_x(\phi) \gamma_x(\phi + \phi) \right\rangle \]

\[ q_i(x) = \frac{3H_0^2 \Omega_m}{2c^2} \frac{\chi}{a(x)} \chi^h \int_\chi^{\chi_h} d\chi' \frac{n_k^i(z(\chi'))d\chi'}{n_k^i} \frac{\chi' - \chi}{\chi'} \]

\[ \xi^{ij}_{+/-}(\theta) = (1 + m^i)(1 + m^j) \int \frac{dl}{2\pi} J_{0/4}(l\theta) \int d\chi \frac{q_k^i(x)q_k^j(x)}{\chi^2} P_{NL} \left( \frac{l + 1/2}{\chi}, z(\chi) \right) \]
DES Year 1, Galaxy-Galaxy Lensing

\[ \gamma_t(\theta) = \left\langle g(\phi) \gamma_t(\phi + \theta) \right\rangle \]

\[ q_\delta^i(k, \chi) = b^i(k, z(\chi)) \frac{n_g^i(z(\chi))}{\bar{n}_g^i} \frac{dz}{d\chi} \]

\[ \gamma_t^{ij}(\theta) = (1 + m^j) \int \frac{dl}{2\pi} J_2(l\theta) \int d\chi \frac{q_\delta^i(l+1/2, \chi)}{\chi^2} \frac{q_\kappa^j(\chi)}{\chi} \times P_{NL}\left(\frac{l + 1/2}{\chi}, z(\chi)\right) \]

Prat & Sanchez et al., 2018
\[ w(\theta) = \left\langle g(\bar{\phi})g(\bar{\phi} + \bar{\theta}) \right\rangle \]

\[ q_{\delta g}^i(k, \chi) = b^i(k, z(\chi)) \frac{n_g^i(z(\chi))}{\bar{n}_g^i} \frac{dz}{d\chi} \]

\[ w^i(\theta) = \int \frac{dl}{2\pi} J_0(l\theta) \int d\chi \frac{q_{\delta g}^i \left( \frac{l+1/2}{\chi}, \chi \right)}{\chi^2} \frac{q_{\delta g}^j \left( \frac{l+1/2}{\chi}, \chi \right)}{\chi^2} \times P_{NL} \left( \frac{l + 1/2}{\chi}, z(\chi) \right) \]
To combine the 3x2pt measurements, we need to know their individual errors & correlations: Covariance Matrix
In the context of DES data sets, we anticipate constraining more extended cosmological parameters. We focus on the lensing signal that is independent of galaxy bias, and we do so throughout the paper. The cosmic shear signal is independent of galaxy bias, and that is required to obtain cosmic shear only (green), galaxy-galaxy lensing (red), and their combination are shown in these two-dimensional constraints. Independent results from each 2pt correlation function are comparable to those from the CMB obtained by Planck. Finally, if one ignores any intuition or prejudice about logical alternatives, models in which the dark energy content is allowed to vary in a consistent way must be rejected. In the next section, we revisit the question of inconsistency. We find a Bayes factor of 583, an independent result from each 2pt correlation function.
DES Y1 Cosmology Results

Early Universe (Planck) & Late Universe (DES) consistent, although $\sigma_8$ from DES is lower than Planck

Abbott et al., 2018

Planck No Lensing
DES Y1
DES Y1+Planck No Lensing
DES Y1+Planck+BAO+JLA

$S_8$

$\Omega_m$

$\Omega_m$

$h$

$w$

$S_8$
DES Year 3 Results (soon)

300M Galaxies in DR1
KiDS-1000

$\Omega_m$ vs. $\sigma_8$

9 Filters (u,g,r,i,Z,Y,J,H,K)

Heymans 2020

- BOSS+KV450 (Tröster et al. 2020)
- DES Y1 3 $\times$ 2pt (DES Collaboration 2018)
- KiDS-1000 3 $\times$ 2pt
- Planck 2018 TTTEEE+lowE
Tension in Matter-Matter Power Spectrum Amplitude

\[ S_8 \equiv \sigma_8 \sqrt{\Omega_m/0.3} \]

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Prospects

Way forward: more precise tests of more general dark energy model

- These are precise tests of $\Lambda$CDM, and they show any potential discrepancies are < their uncertainty.
- They do not 'confirm' or 'explain' $\Lambda$CDM.
- They are not very sensitive to models with time-varying Dark Energy equation of state (among others).
- Future joint analyses will be!

Credit: T. Eifler, E. Krause, J. Frieman

Current geometrical probes + DES Y5 (all probes)

Eifler, Krause, Frieman