Observational Probes of Dark Energy

Lecture available on: http://www.astro.caltech.edu/~rse/ay211_de.ppt
General Reviews of Dark Energy

Recent:

Strategies for Funding Agencies:
Figure of Merit Working Group report, Albrecht et al, astro-ph/0901.0721

A skeptic’s view:
Is DE secure?, Sarkar, astro-ph/0710.2186

Historic:
Cosmological Constant: Carroll et al, ARAA 30, 499 (1992)
Cosmic Expansion History: Traditional View

Prior to 1980 cosmologists attempted to measure two quantities:

- Hubble’s constant: $H_0 = \frac{dR/dt}{R(t)}$; $\tau \sim 1/H_0 \rightarrow$ scale & age
- Deceleration parameter $q_0 = -\frac{d^2R/dt^2}{(dR/dt)^2} \rightarrow$ fate of expansion

In the simplest Friedmann cosmologies containing gravitating matter:

$$\Omega_M = \frac{\rho_M}{\rho_{crit}} = 2q_0$$

Two ways to determine the fate of expansion:

- Census of gravitating matter $\rho_M$ (redshift surveys): $\Omega_M < 0.3$
- Distance-redshift relation over significant look-back times

$$d_L(z,q_0) = \frac{cz}{H_0q_0^2} \left[ zq_0 + (q_0-1)(2q_0z+1)^{1/2} - 1 \right]$$

Inflation (horizon and flatness) suggested $\Omega_M = 2q_0 = 1$
Cosmic Dynamics & the Cosmological Constant

Friedmann Equations relate expansion to energy density (gravity and cosmological constant)

\[ H^2 \equiv \left( \frac{\dot{R}}{R} \right)^2 = \frac{8\pi G}{3} \rho_M + \frac{\Lambda}{3} - \frac{k}{R^2}. \]

\[ q_0 = \frac{1}{2} \Omega_M - \Omega_{\Lambda}. \]

Energy densities from mass and \( \Lambda \) govern curvature parameter \( k \):

\[ \Omega_M \equiv \frac{8\pi G}{3H_0^2} \rho_{M0}, \quad \Omega_{\Lambda} \equiv \frac{\Lambda}{3H_0^2}, \quad \Omega_k \equiv -\frac{k}{R_0^2 H_0^2}, \]

\[ \Omega_{\text{tot}} \equiv \Omega_M + \Omega_{\Lambda} = 1 - \Omega_k. \]

During 1990’s, observations revealed \( \Omega_M \sim 0.2 \) and \( \Omega_{\text{tot}} = 1 \).
2dFGRS Galaxy Redshift Survey
Kaiser (1987 MNRAS 227, 1) showed that peculiar velocities distort the distribution of galaxies in redshift space; this can provide a measure of the mass density of dark matter associated with galaxies on larger scales.
Dark matter via redshift-space clustering

- Distortions due to peculiar velocities arising from mass probed by $\xi(\sigma,\pi)$.
- Two effects:
  - Small separations on sky: ‘Finger-of God’
  - Large separations on sky: flattening along line of sight

$$\sigma_p = 385 \pm 50 \text{ km/s}$$
$$\Omega^{0.6}/b = 0.43 \pm 0.07$$

where $b$ is the bias between galaxy & DM distribution

Open geometries shift detail to smaller angles but we need $H_0$ and mass density $\Omega_m$ to measure curvature from this feature.

$\theta_H \propto (\Omega_m h^{3.4})^{0.14} \Omega_{\text{tot}}^{1.4}$

de Bernadis et al (2000)
In 1998 two teams had measured ~100 SNe Ia at 0.01 < z < 1.0. Surprise! The Universe is accelerating, propelled by dark energy.
Two (independent) teams agree

- Supernova Cosmology Project
- High Z SN Search Team

the supernovae are too faint at a given redshift for a decelerating model
"Precision Cosmology?"

- $\Omega_{DM} \approx 0.32 \pm 0.02$ (dark matter)
- $\Omega_B \approx 0.044 \pm 0.002$ (baryons)
- $\Omega_\Lambda \approx 0.74 \pm 0.04$ (dark energy)

(Dunkley et al 2009)

All 3 ingredients comparable in magnitude but only one component physically understood!

Dark Energy equation of state:

$$\frac{p}{\rho} = w = -0.97 \pm 0.08$$

$w = -1$ corresponds to Einstein $\Lambda$

$w < -1/3$ required for acceleration
So What Could “Dark Energy” Be?

Particle physicists believe a vacuum can still be full of particles and anti-particles in constant creation/annihilation. These exert a *negative pressure* and a repulsion over large distances.

A piston expanding with positive pressure loses energy; *negative pressure* means gaining energy in expansion by an amount which means the *vacuum energy density* is constant.
Why not $\Lambda$? two puzzles:

- Expect $\Lambda = 8\pi G m_p^4$
  
  \((10^{120} \text{ larger})\)

- Why acceleration now?
  
  $\rho_M \propto R^{-3}$ (matter)

  $\rho_{\text{vac}} = \text{const}$ (vacuum)

Alternative: new physics - “dark energy”:

- Quintessence: equation of state $p = w \rho$ ; $\rho \propto R^{-3(1+w)}$
- Dynamical scalar field $w = w(t)$
In General Relativity, force $\propto (\rho + 3p)$
Equation of state has index $w = \frac{p}{\rho}$

If $w < -\frac{1}{3}$ the Universe accelerates
What’s the observational target?

- Dark energy has no agreed physical basis
  
  constant $\Lambda \rightarrow$ static $w \rightarrow$ dynamic
  
  $w = w_0 + w_a (1-a)$
  
  $w(t)$ has no naturally-predicted form

- Wrong parameterization can lead to incorrect deductions: models are degenerate!

- Incremental approaches:
  
  - reject null hypothesis of $\Lambda$ ($w \neq -1$)
  
  - prove via more than one method $w \neq$ const
  
  - derive empirical evolution $a(t), G(t), d_A(z)$

Linder (astro-ph/0511197)
Proposals for Tracking Dark Energy

DoE/NASA initiated studies of Joint Dark Energy Mission) following Turner report (also DETF, ESA/ESO reports)

Original contenders: SNAP, Destiny, ADEPT merged into JDEM

ESA merged DUNE/SPACE to Euclid

Shorter term initiatives on the ground (DoD/DoE/NSF/ESO..):

Should We Devote Significant Observational Resources to DE Studies?

Positive opinions: (e.g Kolb astro-ph/07081199)

• Dark Energy is the most pressing problem in the physical sciences; whatever the outcome, the impact on our view of the Universe will be profound

• We cannot ignore what we don’t understand; this is the ultimate scientific adventure

Negative opinions: (e.g White astro-ph/07042291)

• DE studies, if supported, would dominate our observing facilities for next 20 years & might offer improved precision without any further understanding. If \( w = -1.0000 \) in 2020 what will we have learned?

• DE will distract resources & young people from more tractable and fruitful astrophysical questions.

• Becoming particle physicists: `a community chasing one goal’
Contrasting Distance & Growth-based Methods:  I

Friedmann equation gives us epoch-dependent Hubble parameter which defines expansion history:

\[ H^2(a) = H_0^2 \left[ \Omega_v e^{-3(w(a)+1)} \frac{d \ln a}{a} + \Omega_m a^{-3} + \Omega_r a^{-4} - (\Omega - 1)a^{-2} \right] \]

This can be observed in two ways:

(i) geometry via comoving distance-redshift relation

\[ \frac{dD}{dz} = c/H(z). \]

(ii) effect on growth of density inhomogeneities

\[ \ddot{\delta} + 2\frac{\dot{a}}{a} \dot{\delta} = \delta \left( 4\pi G \rho_0 - c_s^2 k^2 / a^2 \right) \]
Contrasting Distance & Growth-based Methods: II

D(z): not very sensitive to \( w \): 1\% precision requires \( D \) to 0.2\%
also \( w \) degenerate with changes in \( \Omega_M \)

\( g(z) \): \( w \) has opposite effect to \( \Omega_M \)
but relevant methods less well-developed
Evolution of Dark Energy: Pivot Redshift

In the absence of a unique model, simplest parameterization for dynamic DE at scale factor $a$ is:

$$w(a) = w_0 + w_a(1 - a)$$

But this leads to strong correlation between $w_o$ & $w_a$ since bulk of sensitivity comes from data at $z>0$; $w_o$ represents an unobserved extrapolation.

Better to assume we are measuring $w$ at some intermediate \textit{pivot redshift}

$$w(a) = w_{\text{pivot}} + w_a(a_{\text{pivot}} - a)$$

Terms are now defined to be independent so a particular experiment best measures $w$ at $z_{\text{pivot}}$. 
More on Pivot Redshift

- The ability to exclude $\Lambda$ is better than it appears in $w_0 + w_\alpha (1 - a)$ formalism as terms are correlated & $w_0$ unobserved.

- There is some $z_p$ where limits on $\Delta w$ are better than limits on $\Delta w_0$.
Consumer’s Guide to Observing Dark Energy

• Type Ia Supernovae: $d_L(z)$ to $z \sim 2$
  • Most well-developed and ongoing with rich datasets
  • Key issue is physics/evolution: *do we understand SNe Ia?*

• Weak lensing: $g(t)$ to $z \sim 1.5$
  • Less well-developed; ground vs space, needs photo-z’s
  • Key issues are *fidelity, calibration*

• Baryon “wiggles”: $d_A(z)$, $H(z)$ to $z \sim 3$
  • Late developer: cleanest *requiring huge surveys*

Although investing in DE facilities seems controversial (e.g. White 2007), most opportunities will generate unique datasets for other purposes

*See US DETF (Kolb et al) & ESA-ESO reports (Peacock et al).*
Supernova Surveys

First generation surveys:
- Supernova Cosmology Project (Perlmutter et al 99)
- Hi Z Supernova Project (Riess et al 98)
- Extensions using HST (Knop et al 03, Riess et al 04)

Second generation surveys:
- CFHT SN Legacy Survey (Astier et al 06, Sullivan et al 07, 09)
- ESSENCE project (Sollerman et al 05, Woods-Vasey et al 07)
- Carnegie IR survey
- New HST projects (z > 1 clusters and deep fields, Riess et al 06)
- Intermediate redshift surveys (SDSS2)

Fundamental Issues:
- Progenitor physics: evolution, host galaxy dependencies etc
- Dust extinction, photometric calibration

Might there be a systematic floor in the use of SNe in precision studies?
Early SN search strategies

• SN search using wide field cameras with modest telescopes in one lunation

• Redshift from large telescope spectra using scheduled time next lunation

• Light curve of supernova gives its peak brightness & hence relative distance

• Velocity-distance relations tracks expansion rate at various times
SNe Ia are not *perfect* standard candles

Peak luminosity correlates with `stretch' s of light curve. If the shape of the light curve can be measured, empirically a corrected peak luminosity is a more precise measure of distance & can be used to trace cosmic expansion.

Kim, et al. (1997)
Improved Photometry from HST: $z < 1$

Improved resolution of HST allows better discrimination of point-like SN in distant host galaxy - hence more reliable photometry.

Deep HST Survey: SNe with $z > 1$

23 HST SNe Ia with $z > 1$; glimpse of early deceleration?

CFHT Legacy Survey (2003-2008)

Deep Synoptic Survey
`Rolling search’
Four 1 × 1 deg fields in ugriz
5 nights/lunation
5 months per accessible field
2000 SNe 0.3 < z < 1

Caltech role: verify utility of SNe for cosmology
Sullivan+Nugent+Gal-Yam+RSE

Detailed spectral followup of 0.4<z<0.7 SNe Ia
Tests on 0.2<z<0.4 SNe IIP
First Year Results from CFHT SNLS


71 homogenously studied SNe Ia

\[ w = -1.023 \pm 0.090 \]

When combined with SDSS BAO

...third year results imminent
Host Dependence of SNe Ia: z-dependent bias

SN Ia rate correlates with specific SFR
Light curve `stretch’ likewise correlates
SN properties depend on mix of stellar population and hence redshift

Redshift bias predicted & observed by Howell et al (astro-ph/0701912)
Do SNe Ia Evolve? UV Probes Metallicity

UV dependence expected from deflagration models when metallicity is varied in outermost C+O layers (Lenz et al Ap J 530, 966, 2000)

Some models (not all) predict metals increase UV blanketing & produce shift in UV features

UV dependence expected from deflagration models when metallicity is varied in outermost C+O layers (Lenz et al Ap J 530, 966, 2000)
Comparison of Mean Max Light Spectra 0<z<1.3

Reddening corrected using various prescriptions based on optical SN color; dispersion remains and strongly increases in UV: is this due to progenitor metallicity?

Outstanding Issues with SNe Ia

• A single parameter (stretch/luminosity) is clearly inadequate as a description of the Ia population

• Host galaxy-stretch dependencies are profound. They could signify more than one progenitor mechanism whose mix will change with z. The current light curve shape correction may not correct such biases to the 0.02 mag level at z > 1

• UV evolution and dispersion results represent additional complications (as stretch correlation is weak). Until understood, these may represent further biases, especially at z > 1

• We should be prepared for a systematic floor in precision of using SNe for dark energy studies: probably doesn’t affect current usage (δw ~ ±0.05) but suggests more work before investing in precision SNe work with future missions
Weak Gravitational Lensing

Intervening dark matter distorts the pattern: various probes: shear-shear, g-shear etc

Unlensed

Lensed
Wide Field Imaging from CFHT/Subaru

CFHT: 100deg² (Mellier et al)
Subaru: 30 deg² (Miyazaki et al)
Basics of Gravitational Lensing: - I

Thin lens approximation:

$\theta_I, \theta_S$ represent positions on image & source plane, $\alpha$ is deflection

Geometric lens equation relevant in weak regime where 1-to-1 mapping is ok
Basics of Gravitational Lensing: - II

GR relates deflection angle $\alpha$ to the gravitational potential $\Phi$

$$\alpha = \frac{2}{c^2} \int \nabla_2 \Phi \, dl = \nabla_2 \frac{2}{c^2} \int \Phi \, dl,$$

$\nabla_2$ is 2-D gradient operator in lens plane ( $\perp r$ to photon path)

So deflection $\alpha \propto$ gradient of dimensionless 2-D function $\psi$

irrespective of 3-D density distribution:

$$\theta_I - \theta_S = \frac{D_{LS}}{D_S} \alpha \equiv \nabla_\theta \psi(\theta_I)$$

With Poisson’s eqn, and defining surface density $\Sigma = \int \rho \, dl$

$$\nabla^2_\theta \psi = \frac{D_L D_{LS}}{D_S} \frac{8\pi G}{c^2} \Sigma \equiv 2 \frac{\Sigma}{\Sigma_c}.$$
Basics of Gravitational Lensing: - III

Differentiate lens equation \( \theta_I - \theta_S = \nabla_{\theta \psi} \)

\[
\left( \frac{\partial (\theta_I)}{\partial (\theta_S)} \right)_{ij} = \delta_{ij} + \frac{\partial^2 \psi}{\partial \theta_i \partial \theta_j}.
\]

Defines an isotropic magnification/convergence) \( \kappa \) & shear \( \gamma \)

\[
\left( \frac{\partial (\theta_I)}{\partial (\theta_S)} \right)_{ij} = \begin{pmatrix} 1 + \gamma - \kappa & 0 \\ 0 & 1 - \gamma - \kappa \end{pmatrix}.
\]

Convergence \( \kappa \) is ratio of projected \( \Sigma \) to a critical value which just refocuses for zero shear (corresponding to multiple imaging)

\[
\kappa = \frac{4\pi G}{c^2} \int \frac{D_L D_{LS}}{D_S} \rho \, d\ell \equiv \frac{\Sigma}{\Sigma_C}.
\]

Strong lensing: \( \Sigma > \Sigma_C \)  
Weak lensing: \( \Sigma < \Sigma_C \)
Shear and Mass Density

Measure `shear’ from mean ellipticity of background galaxies in a given direction. This is used to give The convergence $\kappa$ is the mass density along the line of sight.
Deriving Shear $\gamma$ from Measured Galaxy Shapes


Model galaxies as ellipses, from their quadrupole moments

$$Q_{ij} = \int d^2x \; x_i x_j w(x) I(x)$$

$$\epsilon_1 = \frac{Q_{11} - Q_{22}}{Q_{11} + Q_{22}}, \quad \epsilon_2 = \frac{2Q_{12}}{Q_{11} + Q_{22}}$$

Relation to ellipticity: $\epsilon_i = P^\gamma \gamma_i$
Detecting DM from Shear Correlation Functions

- 8.4σ detection of shear
- Ruled out at 5.4σ
- X-correlation is zero
Fidelity via separation of E- and B- modes

![Diagram showing E- and B-modes separation with plots for VIRMOS and RCS data.]
Shear Recovery in Simulated Data

\[ \gamma_{out} = (0.8 \pm 0.1) \gamma_{in} \]

The recovery algorithms are not perfect!
The angular DM power spectrum is analogous to that of CMB provides direct probe of projected DM distribution free from “bias” and astrophysical assumptions probes complexities of non-linear regime constrains cosmology (modulo degeneracies between $\sigma_8$, $\Omega_M$ and $w$)
CFHT Wide Field Survey

22 deg$^2$ (from planned 170 deg$^2$)

Yields $\sigma_8=0.85\pm0.06$ ($\Omega=0.3$)

Fitting $P(k)$ gives $w < -0.80$ (68%)
Tomography in the HST COSMOS Survey

COSMOS:
PI: N. Scoville (Caltech)
Largest HST survey
587 ACS fields
2 deg$^2$ in F814W
F814W$<26.6$ (5$\sigma$)
2. $10^6$ galaxies
~80 resolved arcmin$^{-2}$

http://irsa.ipac.caltech.edu/Missions/cosmos.html
Weak lensing mass map
Redshift tomography

Years ago

X-ray sensitivity
Weak lensing sensitivity
Source galaxy distribution

z=0.3

z=0.5

z=0.7

3.5 billion years ago
5 billion years ago
6.5 billion years ago
Growth of structure

\[ C_1(\theta) = \langle \gamma_1^r(\mathbf{r}) \gamma_1^r(\mathbf{r} + \theta) \rangle \]
\[ C_2(\theta) = \langle \gamma_2^r(\mathbf{r}) \gamma_2^r(\mathbf{r} + \theta) \rangle \]


\[ \sigma_8 = 0.866 (+0.085/-0.068) \]

for \( \Omega = 0.3 \)

• 3D analysis reduces 2D statistical errors \( \times 3 \)
Weak Lensing: The Big Issues

- **Calibration**: Need to measure shear to $10^{-3}$ & control systematics to $10^{-3.5}$; current methods 10 x worse. OK if we understand limitations - not clear we do, much work needed (STEP project: Heymans et al, Massey et al)
- **PSF correction**: Ground versus space: is space required? (Kasliwal et al)
- **Redshift distributions**: require accurate photometric N(z) for background populations (van Waerbeke et al)
- **Intrinsic Alignments**: e.g. due to tidal torques; ~few % effect mitigated by down-weighting very close pairs or using photo-z information (Heyman & Heavens)
- **Shear-Galaxy Correlations**: Subtle bias first noticed by Hirata & Seljak, due to possible correlation of foreground galaxy with density enhancement which could contaminate cosmic shear at 10% level for typical surveys (Heymans et al).

Technique at earlier stage than SNe but ultimately more promising
Δγ = m_1γ + c_1


Most algorithms don’t yet recover shear at the necessary precision (in terms of linearity m_1 or calibration c_1)
Baryonic Features in the Large Scale Structure

Residual of acoustic horizon at last scattering in galaxy distribution.

\[ D_{\text{LS}} \simeq 147 \left( \frac{\Omega_m h^2}{0.13} \right)^{-0.25} \left( \frac{\Omega_b h^2}{0.023} \right)^{-0.08} \text{ Mpc} \]

Confirmed at 3-4\(\sigma\) by 2dF (Cole et al) and SDSS (Eisenstein et al)

Peebles & Yu 1970;
Sunyaev & Zel’ dovich 1970
Physics of Baryon Oscillations

CMB features arise from acoustic waves in *photons* and baryons, whereas galaxy distribution depends on *dark matter* and baryons.

*Courtesy: Eisenstein/CMBfast*
Combining SDSS and 2dF

Combining with WMAP, SNLS in flat case:

\[ \Omega = 0.249 \pm 0.018; \quad w = -1.004 \pm 0.088 \]

Baryon Wiggles: how it works

\[ \frac{P(k)}{P_{nb}(k)} \]

\( k_A \) is the “standard rod”

Divided by smooth fit

Beyond SDSS/2dF: must measure wiggle wavelength as \( f(z) \)

Clean method but sensitive to assumed linear scale and redshift accuracy
Fundamental goal is to measure redshift evolution of acoustic peak which occurs at $k_{\text{max}} \approx 0.065 \text{ Mpc}^{-1}$ (150 Mpc) where $P(k) \approx 2500 \left( h^{-1} \text{Mpc} \right)^3$

Limitations are largely fractional error in galaxy power spectrum

$$\sigma_{\ln P} = \frac{2\pi}{(V k^2 \Delta k)^{1/2}} \left( \frac{1 + nP}{nP} \right)$$

Typically $nP > 1$, so cosmic variance defines survey volume $V$

$$\text{\% error in } D(z) = \left( \frac{V}{5 h^{-3} \text{Gpc}} \right)^{-1/2} \left( \frac{k_{\text{max}}}{0.2 h \text{Mpc}^{-1}} \right)^{-1/2}.$$  

- Given the need to survey huge volumes, is it worth doing BAO surveys in different $z$ slices?

- $P(k)$ is non-linear at $k \approx 0.07 \text{ Mpc}^{-1}$ which introduces shift in peak; interpretation may rely on numerical models (a source of frustration!)

NB: As $P(k)$ is measured in redshift space so we are sensitive to both $D(z)$ and $H(z)$ through geometric distortion (Alcock-Paczynski effect)
Does the galaxy distribution reliably trace the DM? N-body simulations suggest suppression of power & scale-dependent biases which will slightly shift the acoustic peaks

Situation better at z~3 than z~1

## Future BAO surveys

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Telescope</th>
<th>Redshift range</th>
<th>Area (deg²)</th>
<th>Survey start</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAOmega</td>
<td>AAT</td>
<td>0.5–1.0</td>
<td>1000</td>
<td>2006</td>
<td>Already exists</td>
</tr>
<tr>
<td>FMOS</td>
<td>Subaru</td>
<td>1.0–1.5</td>
<td>300</td>
<td>2009</td>
<td>Already exists</td>
</tr>
<tr>
<td>HETDEX</td>
<td>HET</td>
<td>1.8–3.8</td>
<td>200</td>
<td>2010?</td>
<td>$20M?</td>
</tr>
<tr>
<td>SDSS-III</td>
<td>2.5m SDSS</td>
<td>0.3–0.6</td>
<td>8000</td>
<td>2009</td>
<td>Funded</td>
</tr>
<tr>
<td>WFMOS</td>
<td>Subaru</td>
<td>0.5–1.5</td>
<td>3200</td>
<td>2014?</td>
<td>$60M?</td>
</tr>
<tr>
<td>JDEM/Euclid</td>
<td>1.3m space NIR slitless spectroscopy</td>
<td>1.3–2</td>
<td>20,000</td>
<td>2018?</td>
<td>$800M</td>
</tr>
</tbody>
</table>

Courtesy: Karl Glazebrook
AAOmega `WiggleZ’ Project (PI: Glazebrook)

- 400,000 spectra with AAΩ spectrograph
- Emission line galaxies \( z > 0.5 \) selected from GALEX+SDSS
- \( 10^3 \) deg\(^2\), 220 nights

Projected result: \( \Delta w \sim 8\% \)
• WFMOS – Wide Field Multi-Object Spectrograph

• Subaru is likely to fund a 1.3 deg$^2$ multi-fiber spectrograph for dark energy & Galactic studies

• Builds on 2dF experience

• Synergy with now-funded HyperSuprime-Cam - WL + BAO initiative

• Great opportunity…
Prime Focus Unit includes Wide Field Corrector (WFC) and Fiber Positioner

Fiber connector mounted on top end structure

Fiber Cable routed around elevation axis and brings light to the Spectrographs

Spectrograph room located above Naysmith platform
Positioner and Source Allocation

Subsection of Instrument Focal Plane

Edge of Field of View

- Patrol Region
  - Fiber Tip
  - Source

Overlapping Patrol Regions

- Fiber Tips that cannot reach a source
- Fiber Tips that can reach a source
- Unallocated sources
Positioner Element – “Cobra”

- Each Positioner element uses 2 “rotary squiggle” motors (2.4, 4.6mm) with 5µm resolution and almost instantaneous response.
- Each motor rotates to provide complete coverage of the patrol region.
- Optical fibers mounted in “fiber arm” which attaches to upper positioner axis.
- Fiber runs through the center of the positioner.
- Prototyped and tested in collaboration between JPL and New Scale Technologies.
Cosmology Road Map 2010-2020

1. Demonstrate $\Lambda$ ($w = -1$) to 5% by method other than SNe (WL/BAO)
2. Prove via more than one method $w \neq$ constant
3. *Empirically track* $d_L(z)$, $g(z)$

Linder (2005)
Conclusions

• Dark energy is here to stay: it represents the new cosmological frontier

• Its characterization is largely the province of the z<3 universe; CMB will help but is insufficient

• There is a sound incremental approach:
  \[ w \neq -1 \rightarrow w \neq \text{const} \rightarrow w(z) \]

• We are making promising progress on at least 3 probes: SNe, WL & BAO: need > 1 method spanning 0<z<1

• We should use present facilities to carefully investigate all systematics

• Observationally there are formidable challenges; it’s going to be hard, but the payoff will be great

• It is going to take a long time and a lot of $$$ but we will eventually get there
Discussion Topics

• Redshift-space distortions as a new measure of Dark Energy?
  
  

• What is the best `figure of merit’ for future DE surveys?
  
  
  - *Figure of Merit Working Group* (Albrecht et al astro-ph/0901.0721)

• How are numerical simulations used to interpret baryon wiggles
  
  