Probing Dark Energy: from SDSS to DES

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Fermilab and University of Chicago

Dark Energy and the Accelerating Universe

Brightness of distant Type Ia supernovae, along with CMB and galaxy clustering data, indicates the expansion of the Universe is accelerating, not decelerating.

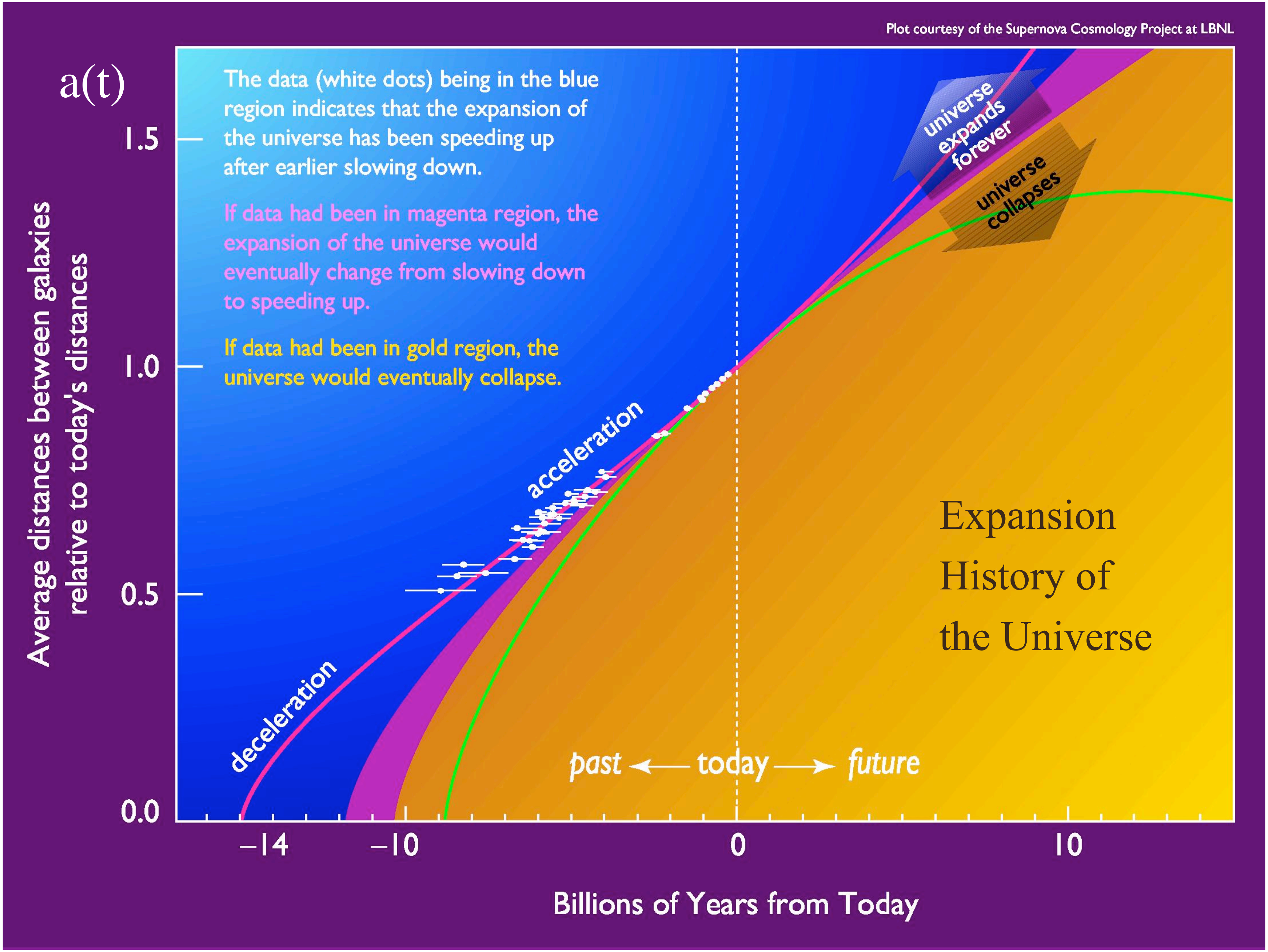
This requires *either* a new form of stress-energy with negative effective pressure *or* a breakdown of General Relativity at large distances:

DARK ENERGY

Characterize by its effective equation of state: $w = p/\rho$

and its relative contribution to the present density of the Universe: Ω_{DE}

Special case: cosmological constant: $w = -1$


Plot courtesy of the Supernova Cosmology Project at LBNL
a(t)
The data (white dots) being in the blue region indicates that the expansion of the universe has been speeding up after earlier slowing down.
If data had been in magenta region, the expansion of the universe would eventually change from slowing down to speeding up.
If data had been in gold region, the universe would eventually collapse.
universe expands forever
universe collapses
acceleration
deceleration
Expansion History of the Universe
past ← today → future
Average distances between galaxies relative to today's distances
1.5
1.0
0.5
0.0
−14
−10
0
10
Billions of Years from Today

Cosmic Problems

Why is the vacuum energy density so much smaller than we theoretically expect?

Why is the dark (perhaps vacuum) energy density non-zero, with its particular small value of $(0.001\ \mathrm{eV})^4$, coincidentally near the density of non-relativistic matter?

Naturalness: explain why $M_{vac} << M_{SUSY}$

Fine-tuning: explain why $M_{vac} \sim 10^{-3}$ eV

Dark Energy & Inflation

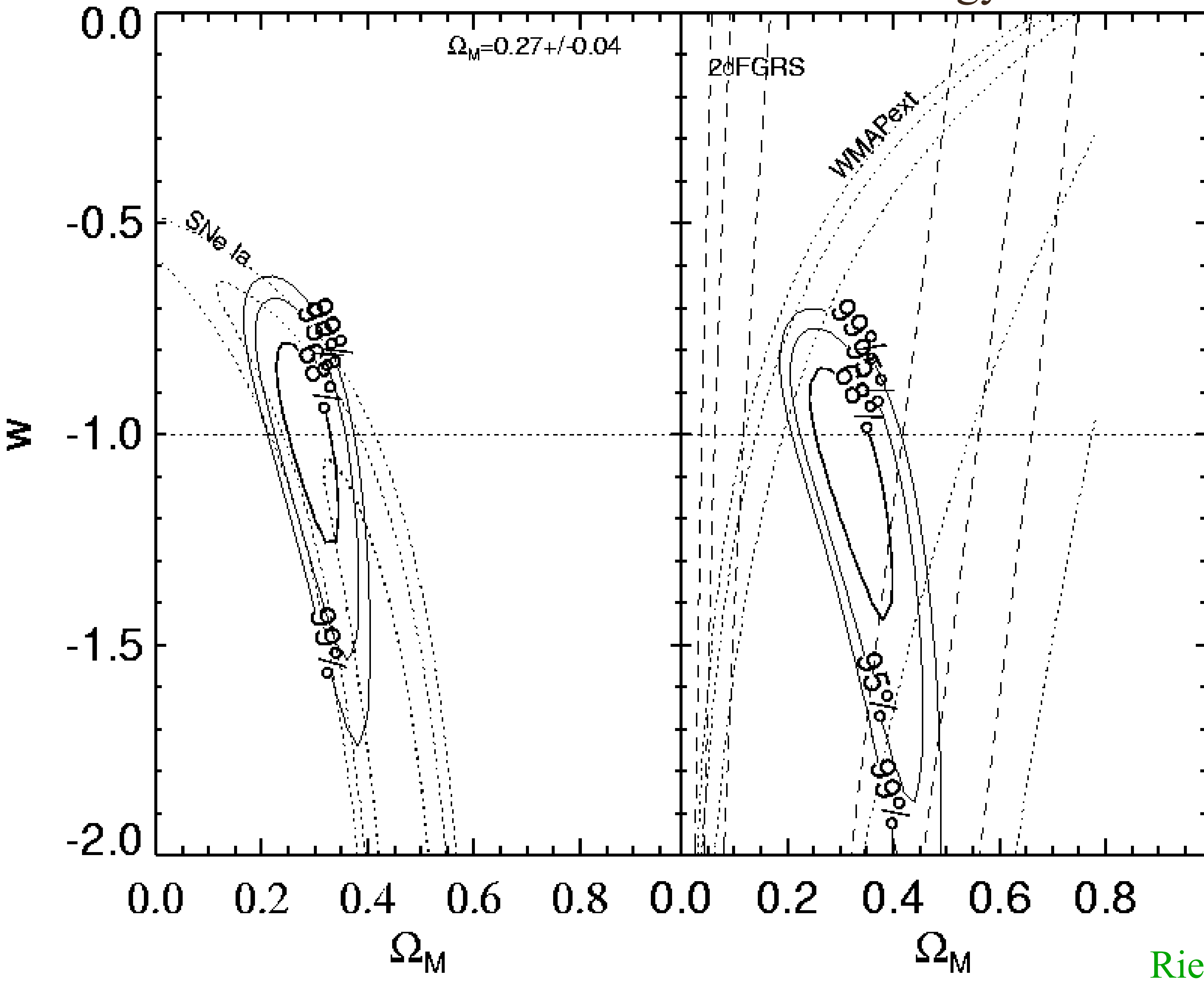
Imagine you were living ~ 1 Hubble time after the onset of primordial inflation, at t ~ 10^{-35} sec

(How) would you worry about these problems?

Inflation suggests existence of a new mass scale $M_{GUT} \sim 10^{15}$ GeV where we <u>expected</u> new physics. That addresses coincidence problem.

<u>Does Dark Energy indicate a new mass scale in physics?</u>

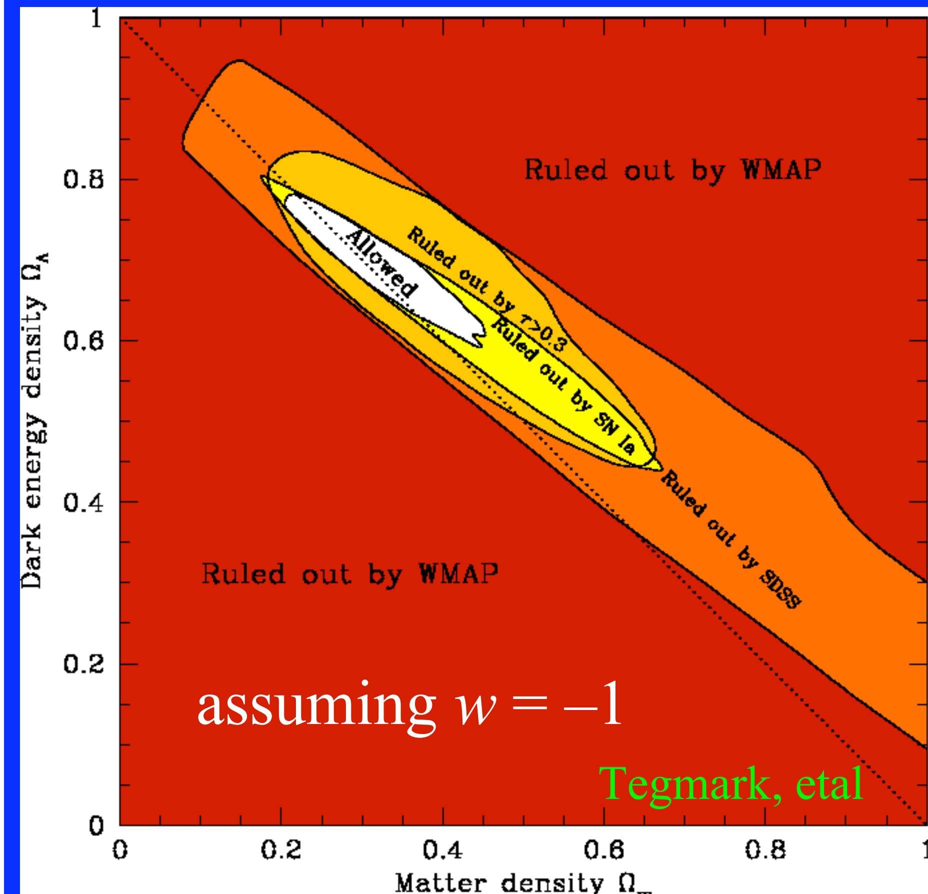
Current Constraints on Dark Energy

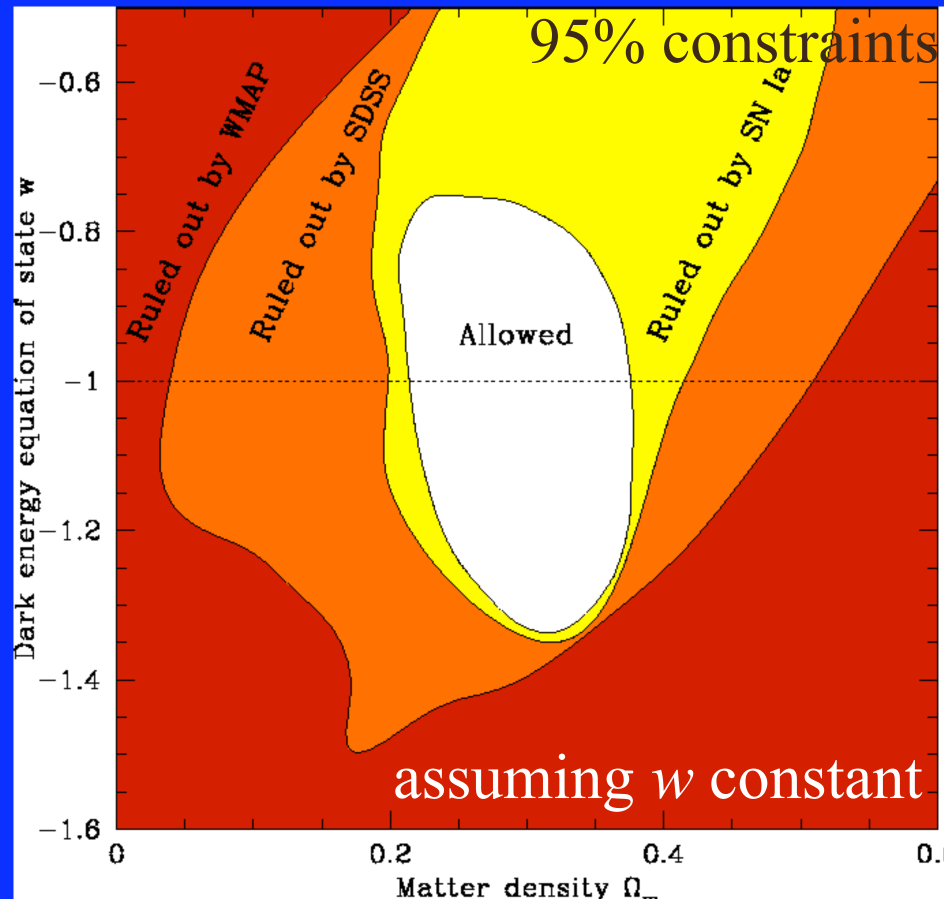


Riess, etal

Dark Energy: where we are now

$\sigma(w) \sim 0.15^*$, $w < -0.76$ (95%) with priors





Key priors: scale-free spectrum, no gravity waves, massless neutrinos, const. bias

Additional prior: flat Universe

*from CMB+LSS+SNe; no *single* dataset constrains w better than ~30%

DARK ENERGY SURVEY

Probing Dark Energy

- Probe dark energy through the history of the expansion rate:

$$H^2(z) = H^2_0 \; [\Omega_M (1+z)^3 + \Omega_{DE} (1+z)^{3(1+w)}] \qquad \text{(flat Universe)}$$

matter — dark energy — (constant w)

- Comoving distance $r(z) = \int dz/H(z)$
- Standard Candles $d_L(z) = (1+z)\, r(z)$
- Standard Rulers $d_A(z) = (1+z)^{-1}\, r(z)$
- Standard Population (volume) $dV/dzd\Omega = r^2(z)/H(z)$
- The rate of growth of structure also determined by H(z) and by any modifications of gravity on large scales

Classification of Supernovae

Type	Ia	Ib	Ic	II
Spectrum	No Hydrogen			Hydrogen
	Silicon	No Silicon		
		Helium	No Helium	
Physical mechanism	Nuclear explosion of low mass star	Core collapse of evolved massive star (may have lost its hydrogen or even helium envelope during red-giant evolution)		
Light curve	Reproducible	Large Variations		
Neutrinos	Insignificant	~ 100 × Visible energy		
Compact Remnant	None	Neutron star (typically appears as pulsar) Sometimes black hole ?		
Rate/h^2SNu	0.36 ± 0.11	0.14 ± 0.07		0.71 ± 0.34
Observed	Total ~ 2000 as of today (nowadays ~200/year)			

Georg Raffelt, Max-Planck-Institut für Physik (München)

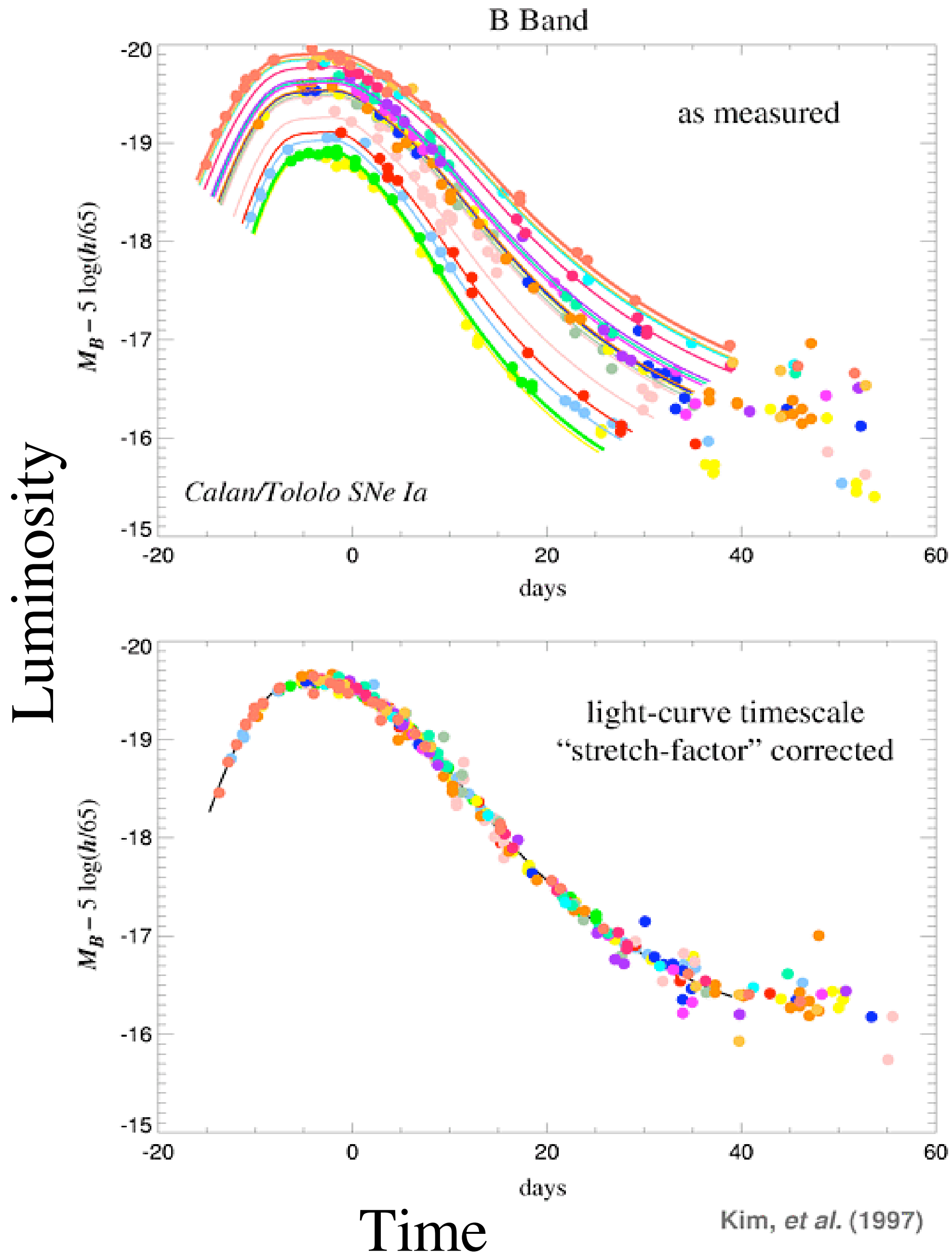
Type Ia SN
Peak Brightness
as a calibrated
`Standard' Candle

Peak brightness
correlates with
decline rate

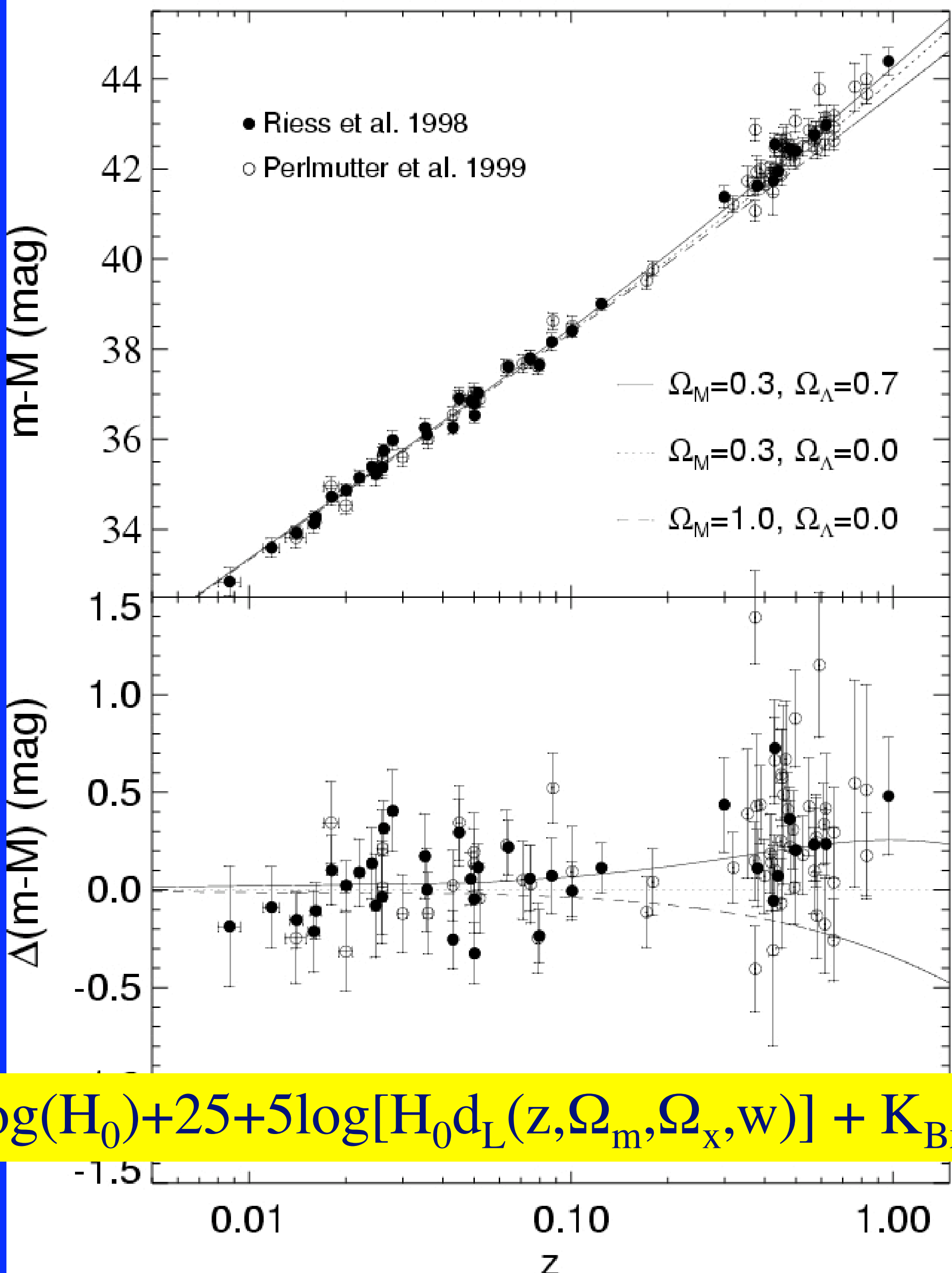
Phillips

After correction,
σ~ 0.12 mag

(~6% distance error)



Cosmology from High-z SN Samples



$$m(z) = M_B - 5\log(H_0) + 25 + 5\log[H_0 d_L(z,\Omega_m,\Omega_x,w)] + K_{Bx} + A$$

$\Omega_\Lambda = 0.7$
$\Omega_\Lambda = 0.$
$\Omega_m = 1.$

Type Ia Supernovae & Cosmology

Advantages:

- small dispersion in peak brightness (standard candles)
- single objects (simpler than galaxies)
- can be observed over wide redshift range (bright)

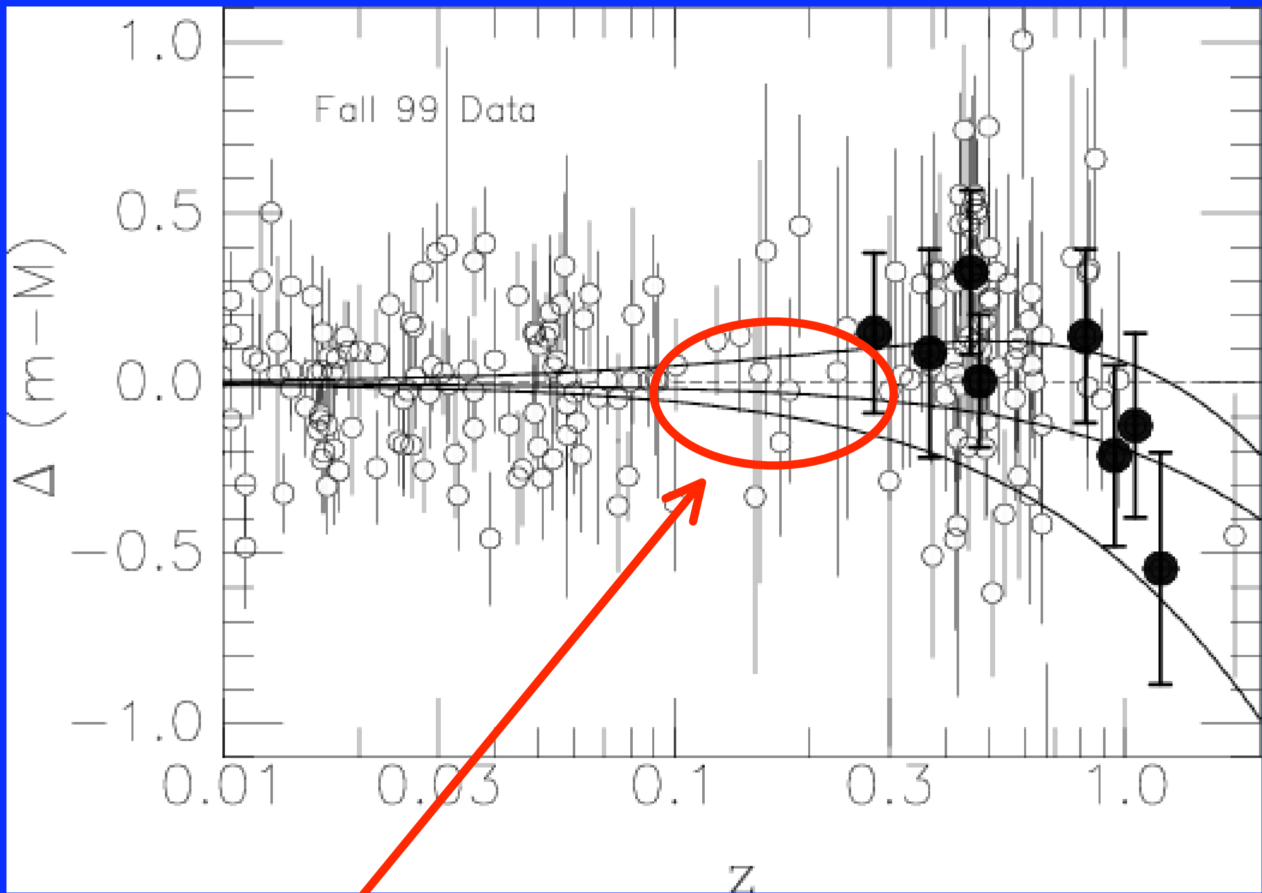
Challenges/Systematic concerns:

- dust extinction in host galaxy
- chemical composition variations/evolution
- evolution of progenitor population
- photometric calibration
- Malmquist bias
- environmental differences
- K correction uncertainties

Need new SN surveys for statistics and systematics

Compiled Supernovae Ia Sample

Brightness relative to empty Universe: ($\Omega_m = \Omega_\Lambda = 0$)



Ω_m Ω_Λ

0.3, 0.7

0.3, 0.0

1.0, 0.0

`Gold' sample of 157 SNe included only 6 between z = 0.1-0.3; SDSS naturally fills this gap

Tonry etal '03
Riess etal '04

SDSS and SDSS II

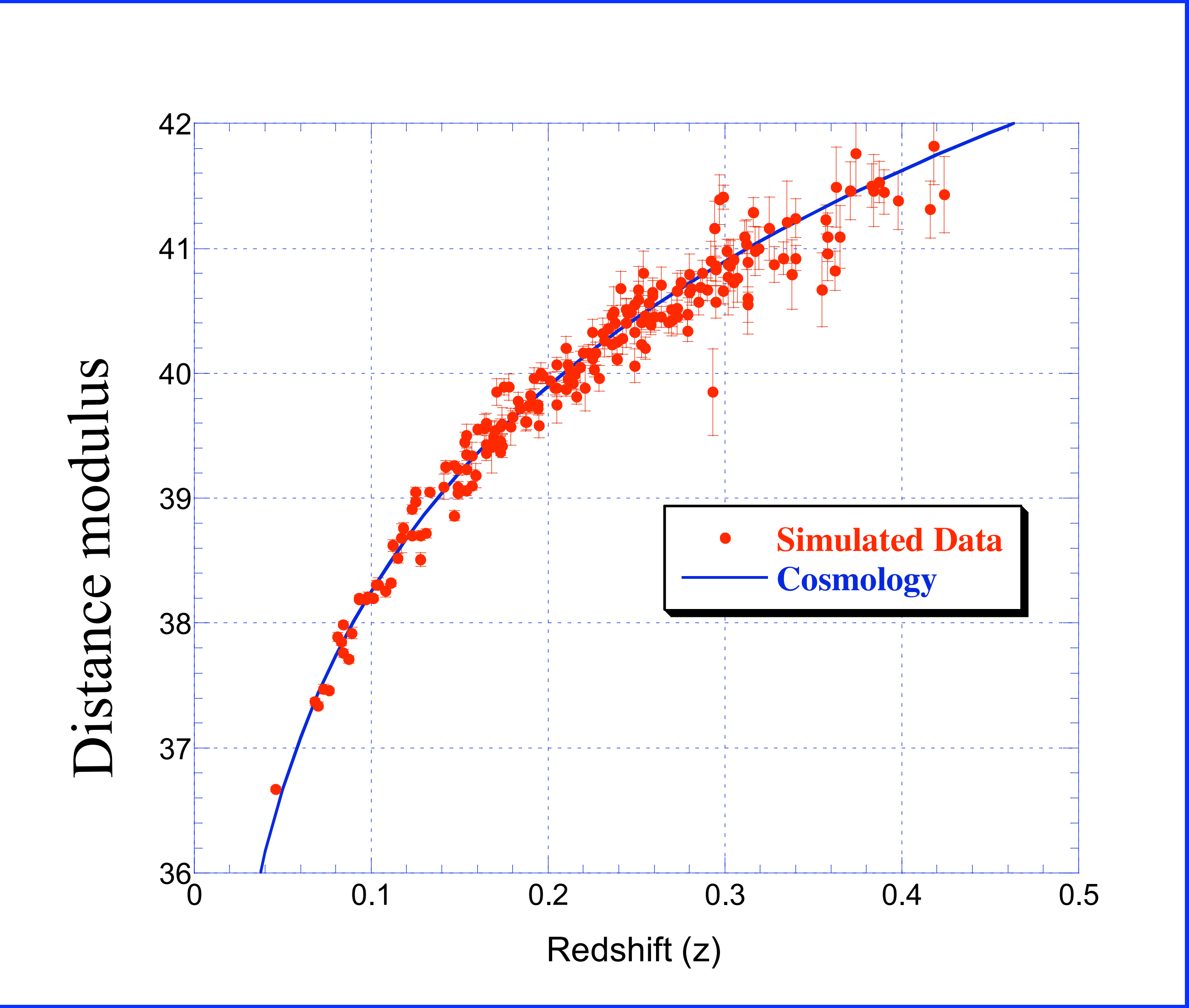
- SDSS I: April 2000-June 2005
- SDSS II: July 2005-2008 (contingent on funding):
  - Legacy Survey (complete northern survey) ~10^6 redshifts
  - SEGUE (low-latitude survey of Milky Way)
  - Supernova Survey

SDSS SN Science Goals

- Obtain ~200 *high-quality* SNe in the redshift desert:
  repeat multi-band data over ~250 square degrees
- Probe Dark Energy in *z* regime less sensitive to evolution than deeper surveys
- Study SN Ia systematics (critical for SN cosmology) with high photometric accuracy
- Search for additional parameters to reduce Ia dispersion
- Determine SN/SF rates/properties vs. *z*, environment
- Rest-frame *u*-band templates for z >1 surveys
- Study feasibility of cosmology with SN colors
- Database of Type II and rare SN light-curves

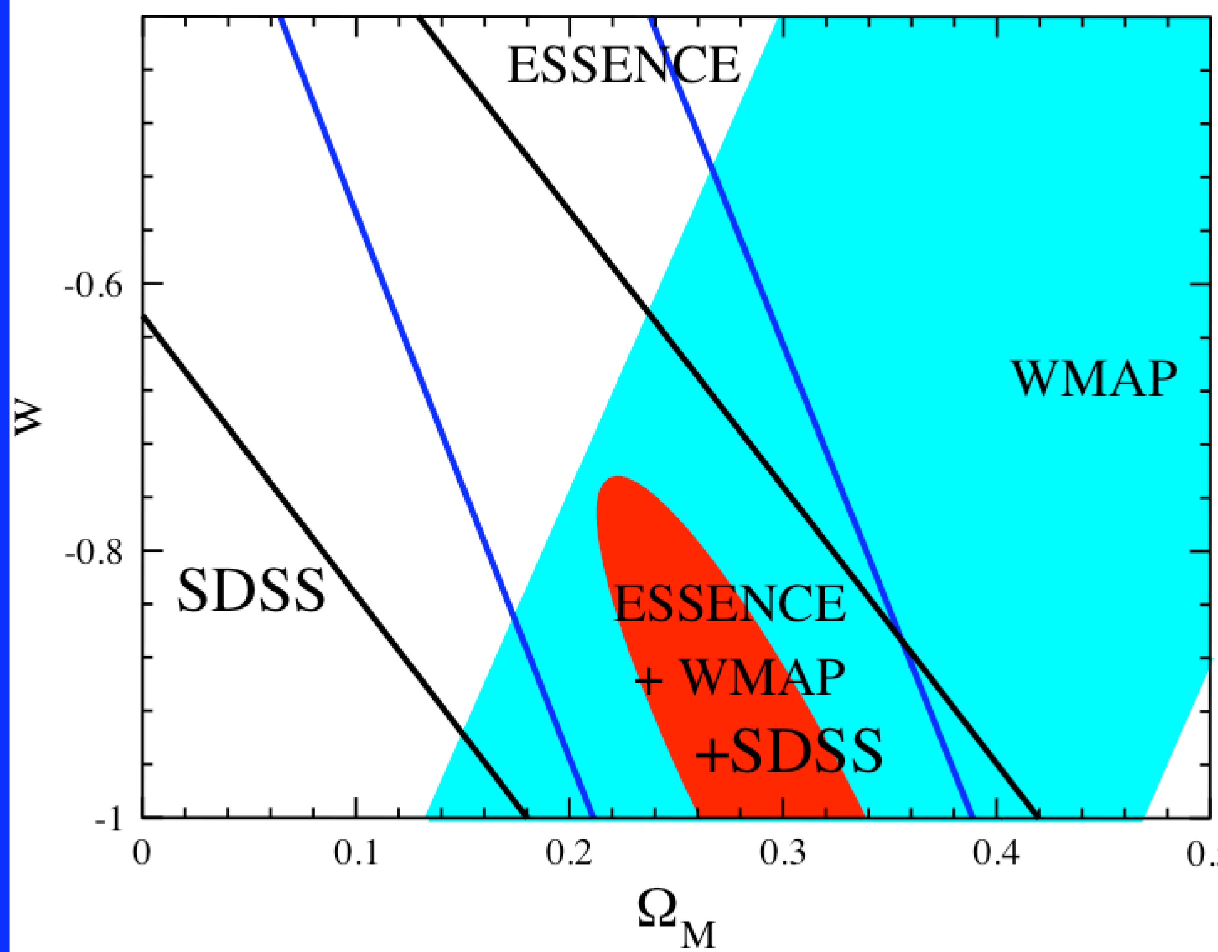
Monte Carlo Data

Simulated redshift distribution and photometric errors for completed SDSS SN sample (here assumed $\Omega_\Lambda=0.7=1-\Omega_m$ $H_0=72$)



Forecast Cosmological Constraints

Combining SDSS with deeper survey leads to improved constraints, due to broader redshift leverage.



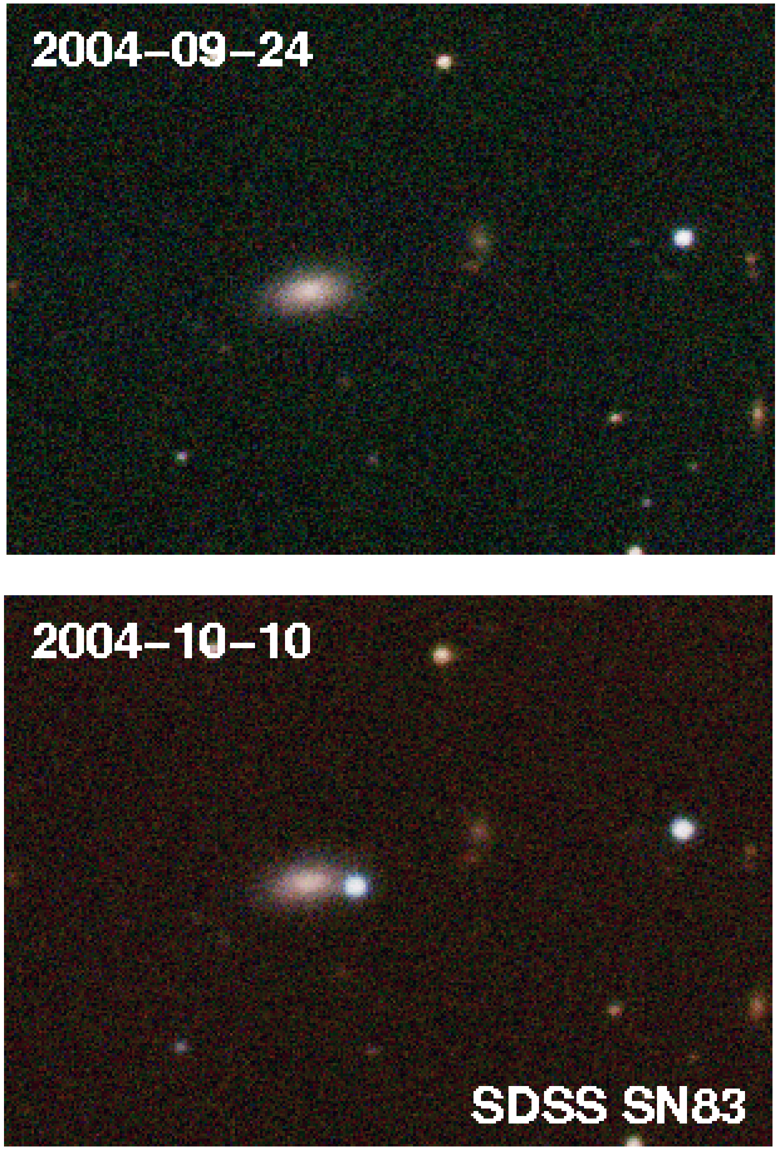
$\sigma(w) = 0.10$ from SDSS+ESSENCE+WMAP+LSS

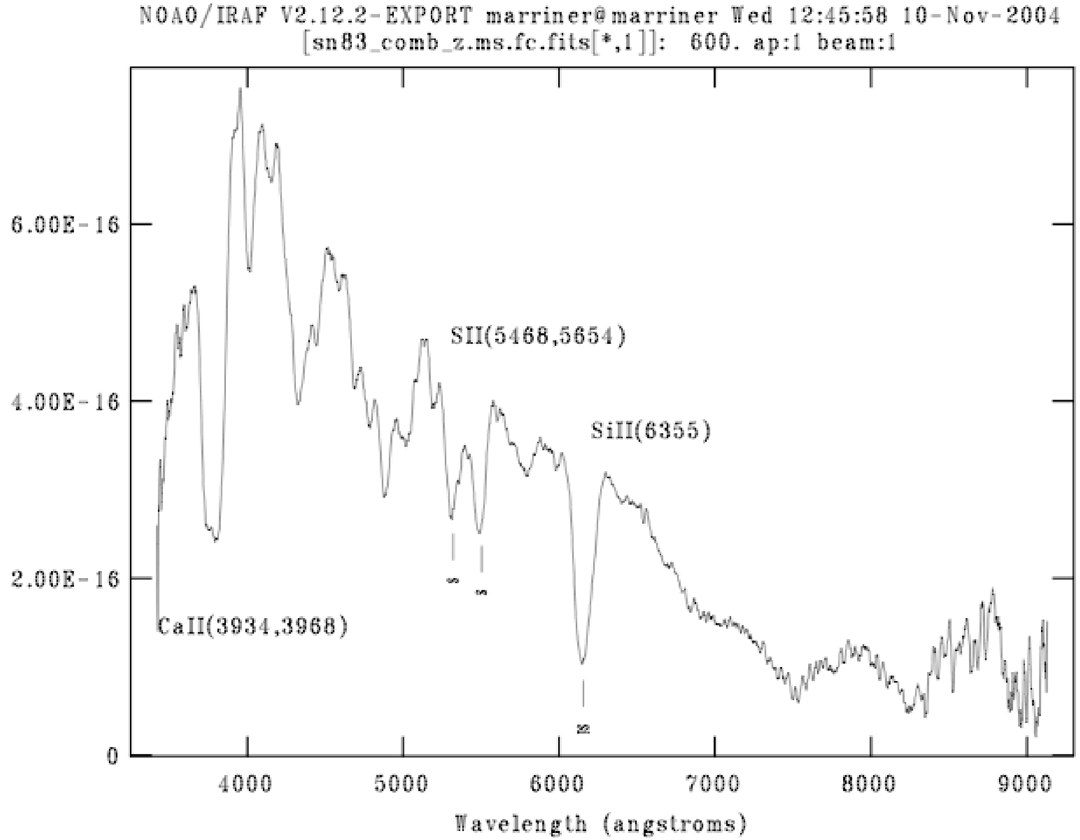
(statistical errors only, constant *w*, flat Universe)

Fall 2004: Early Science & Test Run

- Imaging: 20 nights of SDSS 2.5m scheduled every other night late Sept.-mid Nov., covered half the survey area: ~1/2 the nights were useable.
- Follow-up spectroscopy: ARC 3.5m, HET 9.2m
- Follow-up imaging (during/after run): NMSU 1m, ARC 3.5m
- Science Goal: ~10 well-measured SN Ia light-curves with confirmed spectroscopic types and redshifts.
- Yield: 16 confirmed Ia's: $0.05<z<0.32$ with $\langle z \rangle = 0.15$,

  5 Type II, 1 luminous Type Ic
- Engineering goals met:
- Rapid processing and selection of candidates in *g,r* (48 hours)
- Coordinated follow-up observations
- Study detection efficiency and photometric accuracy under varying conditions



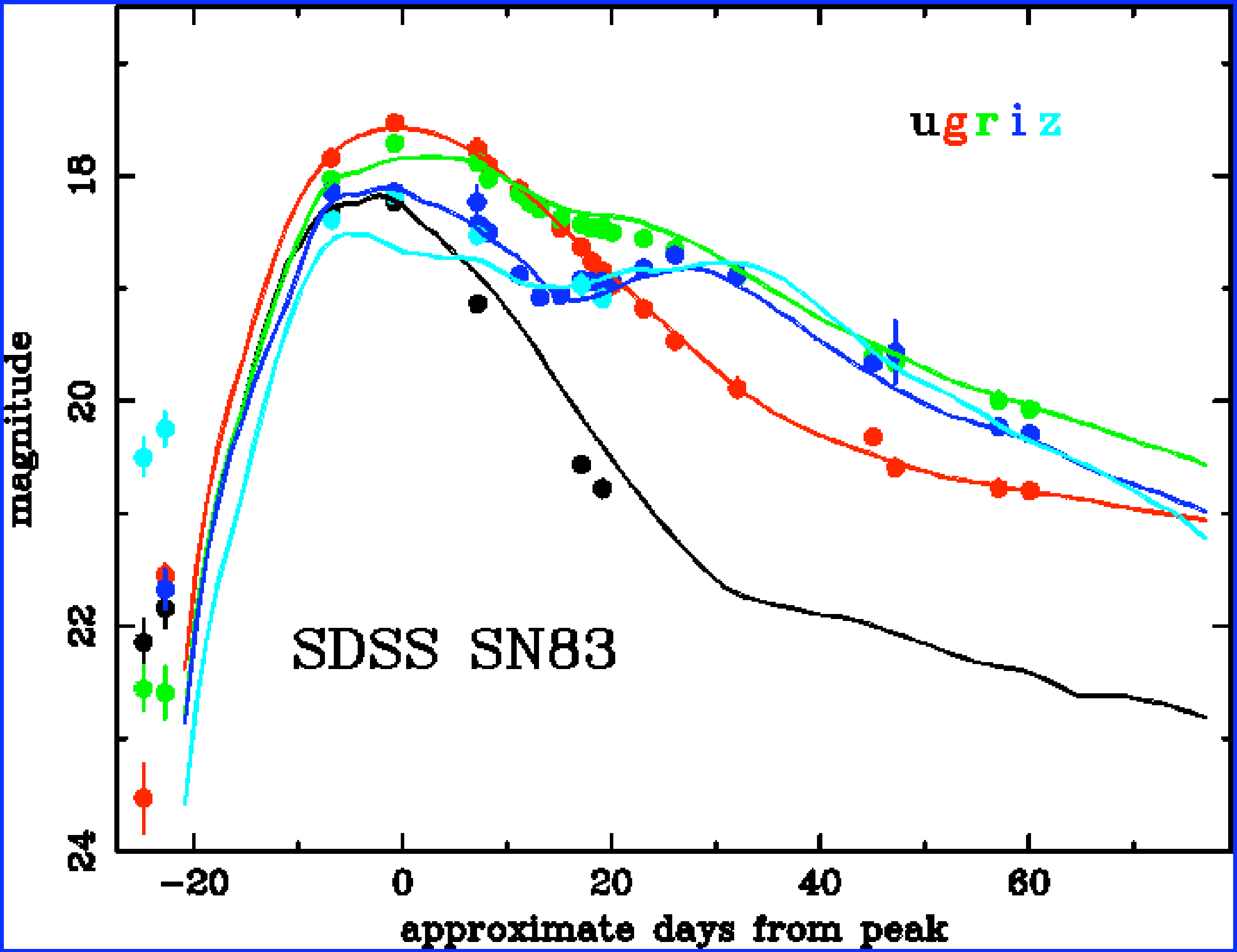


SN Ia z=0.0513

ARC 3.5m

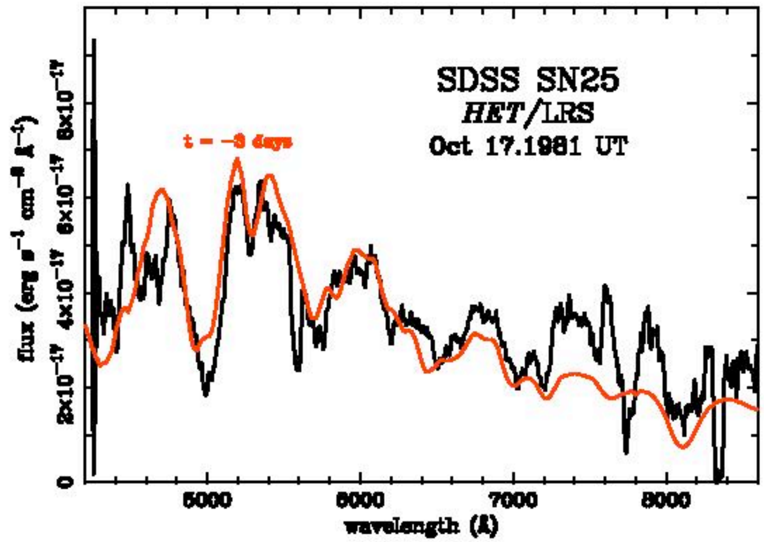
spectroscopy

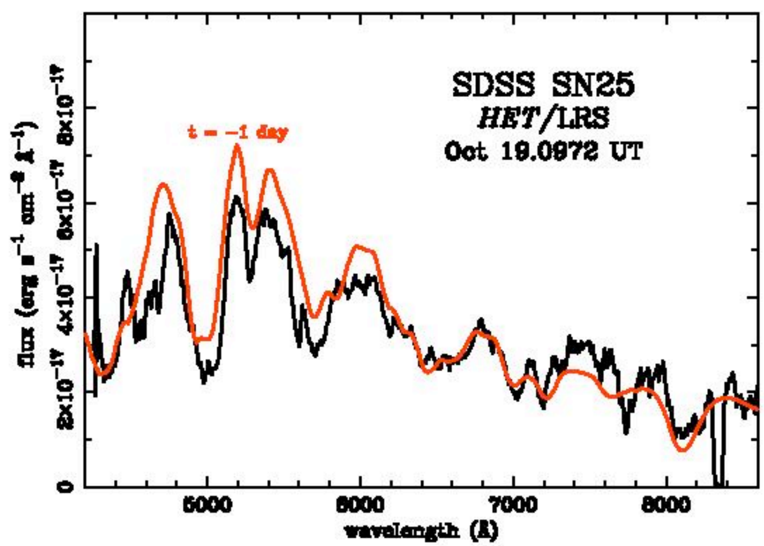
SN 83: Observed vs. Synthetic Light-curves (preliminary)

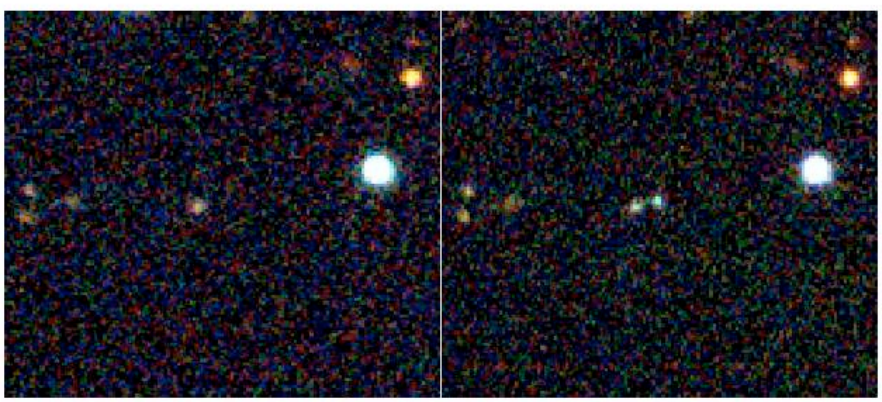


SN25

- Highest redshift Ia from this sample:
  z=0.32
- Luminous Ia: $M_r \sim -20$
- Cross-correlation analysis yields best-fit Ia spectral templates separated by 2 days, in excellent agreement with data

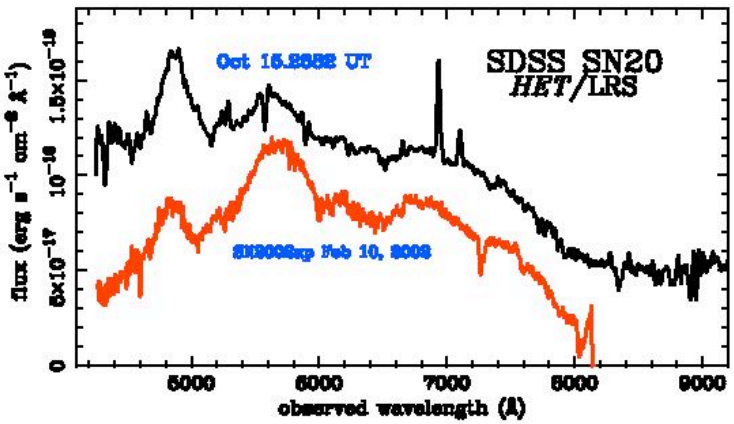


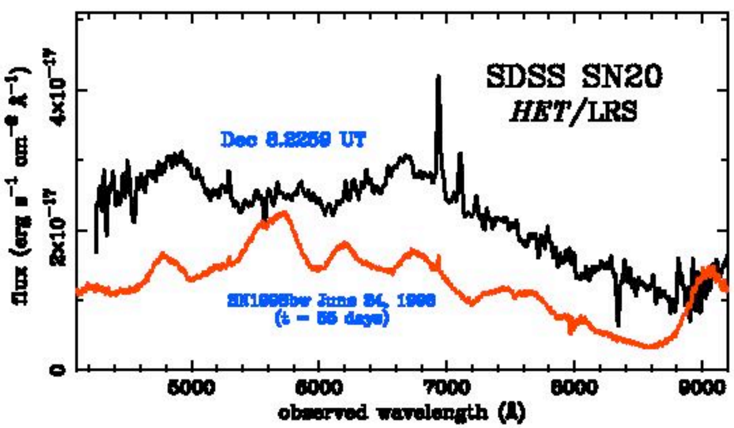




SN20

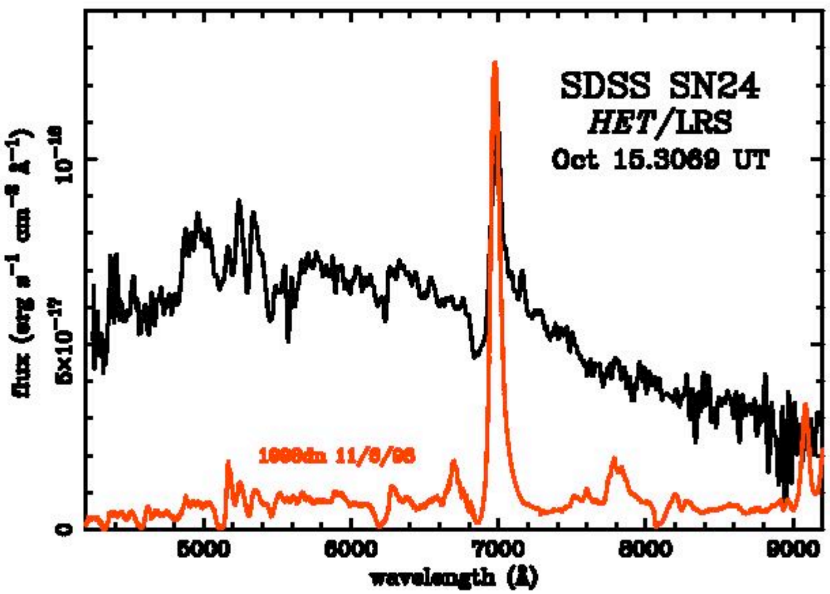
Type Ic





Additional visit on 1/2/05
(not yet analyzed)

SN24



Type II

SDSS II SN Follow-up

- Spectroscopy: SN typing, redshift, multi-epoch spectrophotometry to improve K-corrections
- NIR imaging: extinction/reddening and lightcurves

- Spectroscopy: ARC 3.5m, HET, MDM 2.4m (new high-throughput spectrograph), Subaru and VLT (proposed)
- NIR imaging: Carnegie Supernova Project (several telescopes)
- Optical imaging: NMSU 1m, ARC 3.5m, …

Dark Energy: Stress Energy vs. Modified Gravity

Stress-Energy: $G_{\mu\nu} = 8\pi G\, [T_{\mu\nu}(\text{matter}) + T_{\mu\nu}(\text{new})]$

Gravity: $G_{\mu\nu} + f(g_{\mu\nu}) = 8\pi G\, T_{\mu\nu}(\text{matter})$

To distinguish between these choices, we must have probes of both the geometry *and* the growth of large-scale structure.

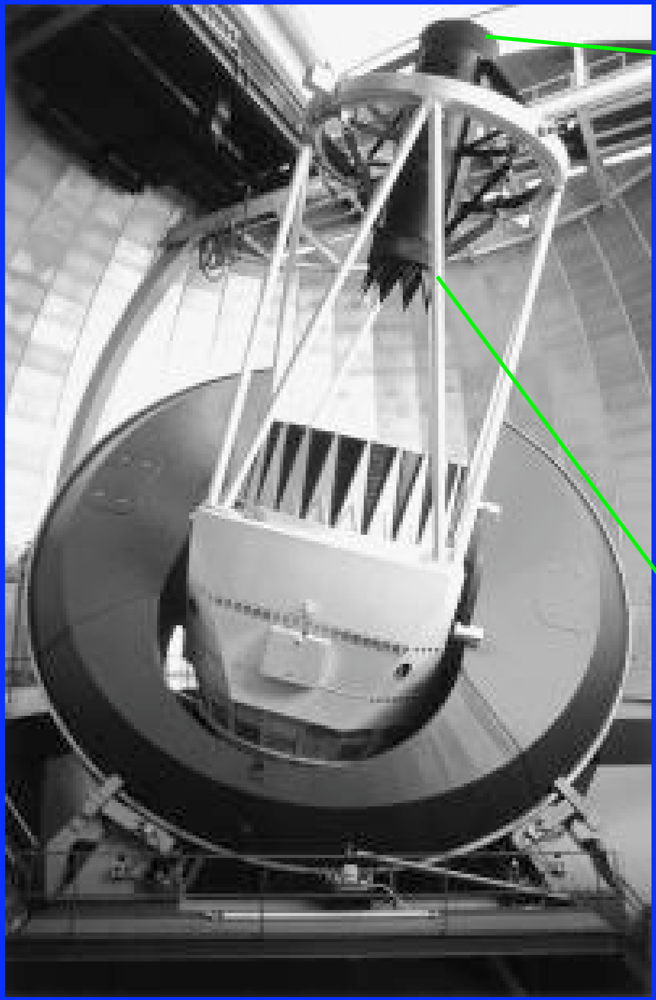
The Dark Energy Survey

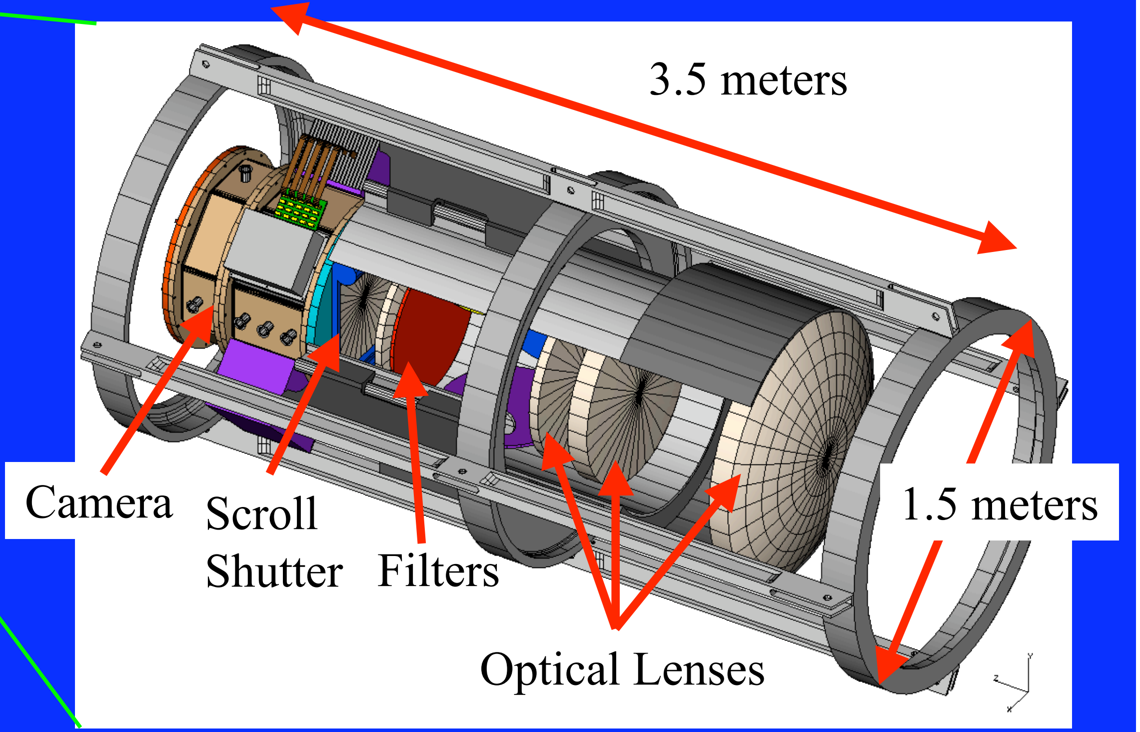
- Study Dark Energy using 4 complementary techniques:
  - Cluster counts & clustering
  - Weak lensing
  - Galaxy angular clustering
  - SNe Ia distances
- Two multiband surveys:
  - 5000 deg^2 *g, r, i, z*
  - 40 deg^2 repeat (SNe)
- Build new 3 deg^2 camera
  - Construction 2005-2009
  - Survey 2009-2014 (~525 nights)
  - Response to NOAO AO

Blanco 4-meter at CTIO

Science goal: *w* to ~5-10% on *each* technique

Dark Energy Survey Instrument





New Prime Focus Cage, Camera, and Corrector for the Blanco 4m Telescope

500 Megapixels, 0.27”/pixel

Project cost: ~20M$ (incl. labor)

Dark Energy Survey Collaboration

Fermilab- Camera, Survey Planning, and Simulations

Annis, Dodelson, Estrada, Flaugher, Frieman, Gladders*, Kent, Lin, Limon, Peoples, Scarpine, Stebbins, Stoughton, Tucker, Wester

*Carnegie Fellow, Carnegie Observatories

U Illinois- Data Management, Data Acquisition, SPT

Brunner, Karliner, Mohr, Ricker, Plante, Selen, Thaler

U Chicago- SPT, Simulations, Corrector

Carlstrom, Dodelson, Frieman, Hu, Kent, Sheldon, Wechsler

LBNL- CCD Detectors

Aldering, Bebek, Levi, Perlmutter, Roe

CTIO- Telescope & Camera Operations

Abbott, Smith, Suntzeff, Walker

Discussions starting/on-going with potential new partners

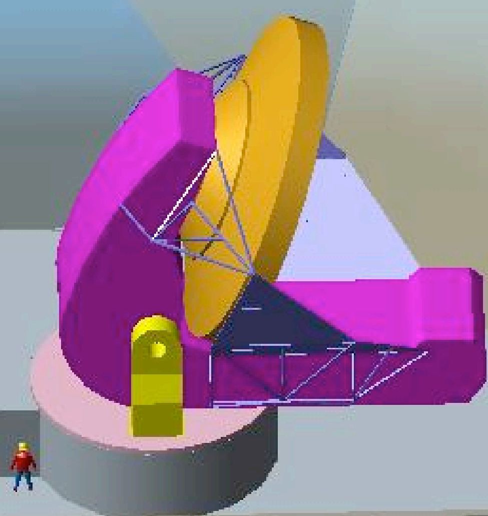
10m South Pole Telescope (SPT) and 1000 Element Bolometer Array

Low noise, precision telescope

- 20 um rms surface
- 1 arc second pointing
- 1.0 arcminute at 2 mm
- 'chop' entire telescope
- 3 levels of shielding
  - ~1 m radius on primary
  - inner moving shields
  - outer fixed shields

SZE and CMB Anisotropy

- 4000 sq deg SZE survey
- deep CMB anisotropy fields
- deep CMB Polarization fields



People

Carlstrom (UC)
Holzapfel (UCB)
Lee (UCB,LBNL)
Leitch (UC)
Meyer (UC)
Mohr (U Illinois)
Padin (UC)
Pryke (UC)
Ruhl (CWRU)
Spieler (LBNL)
Stark (CfA)

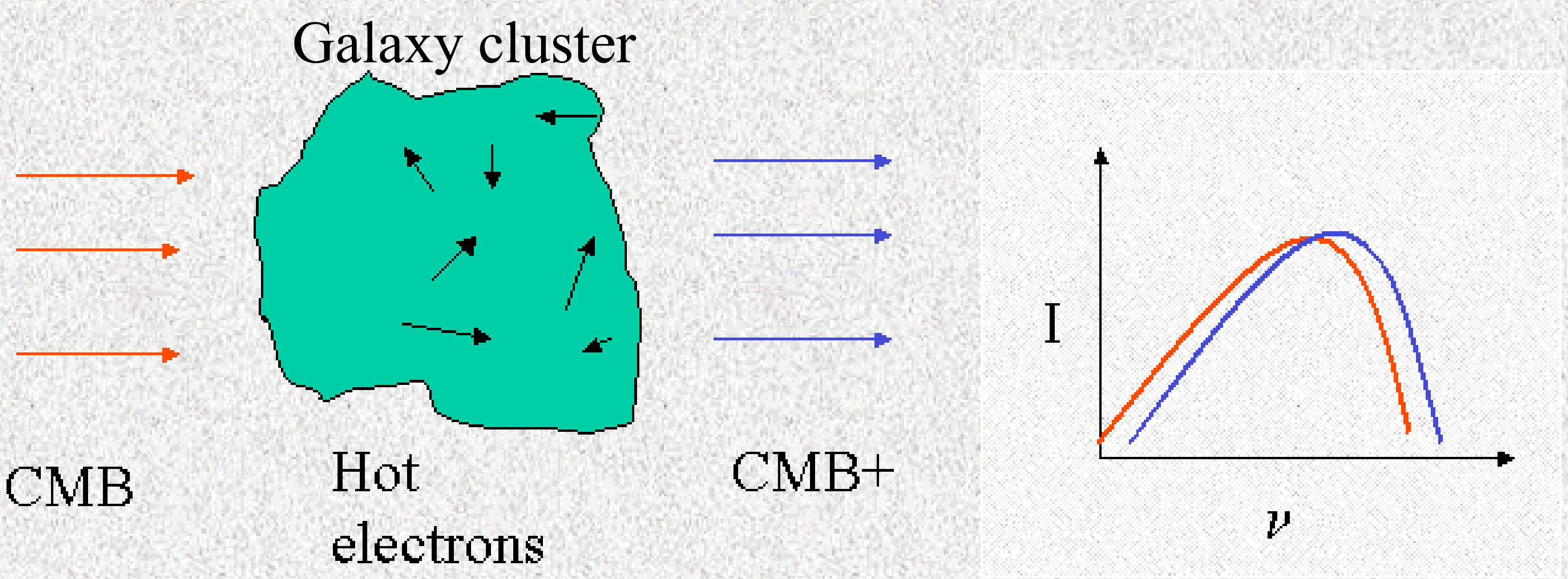
1000 Element Bolometer Array

- 3 to 4 interchangeable bands
  (90) 150, 250 & 270 GHz
- APEX-SZ style horn fed spider web absorbers

NSF-OPP funded & scheduled for Nov 2006 deployment

DoE (LBNL) funding of readout development

Sunyaev-Zel'dovich Effect



Optical depth: $\tau \sim 0.01$

Fractional energy gain per scatter: $\dfrac{kT}{m_e c^2} \sim 0.01$

Holder

Cluster Redshift Distribution and Dark Energy

Constraints:

Raising w at fixed Ω_{DE}:

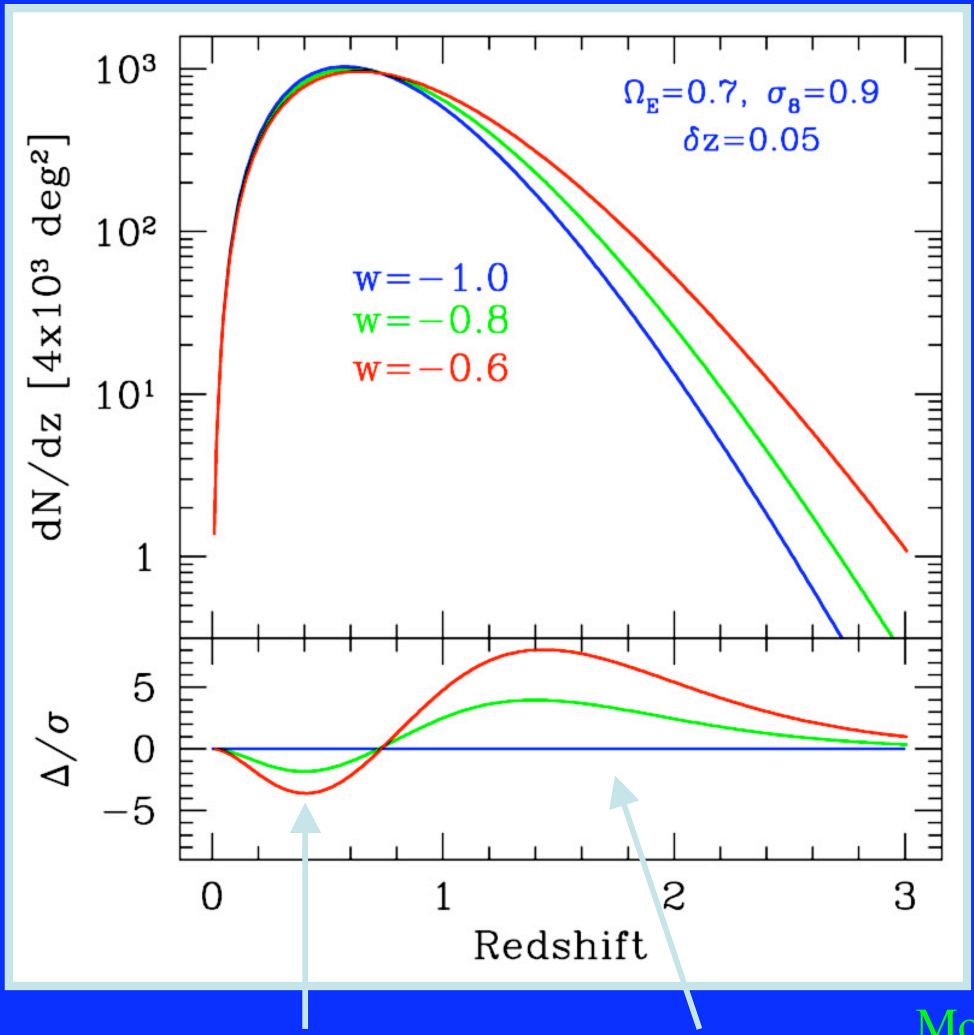
- decreases volume surveyed
- decreases growth rate of density perturbations

$$\frac{dN(z)}{dz\,d\Omega} = \frac{dV}{dz\,d\Omega} n(z)$$

$$\frac{dV}{dz\,d\Omega} = \frac{c}{H(z)} d_A^2 (1+z)^2 \qquad d_A \propto \int_0^z \frac{dz'}{E(z')}$$

$d_A(1+z)$ is proper distance

$H(z) = H_o E(z)$ is the Hubble parameter



Volume effect

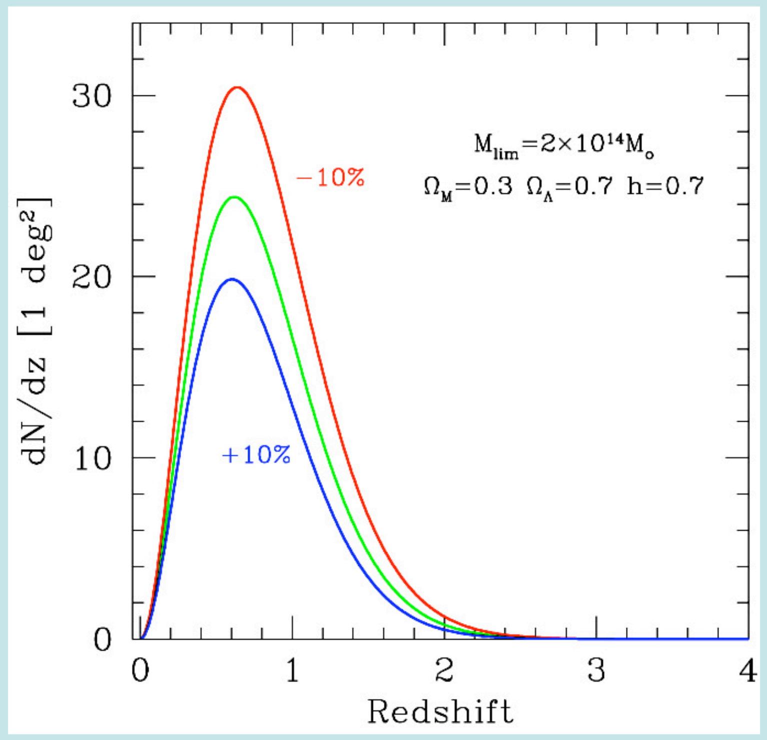
Growth effect

Mohr

Precision Cosmology with Clusters

- Requirements
  1. Quantitative understanding of the formation of dark matter halos in an expanding universe
  2. Clean way of selecting a large number of massive dark matter halos (galaxy clusters) over a range of redshifts
  3. Redshift estimates for each cluster (photo-z's adequate)
  4. Observables that can be used as mass estimates at all redshifts

Sensitivity to Mass



$$\frac{dN(z)}{dz\,d\Omega} = \frac{c}{H(z)} d_A^2 (1+z)^2 \int_0^\infty dM \frac{dn(M,z)}{dM} f(M)$$

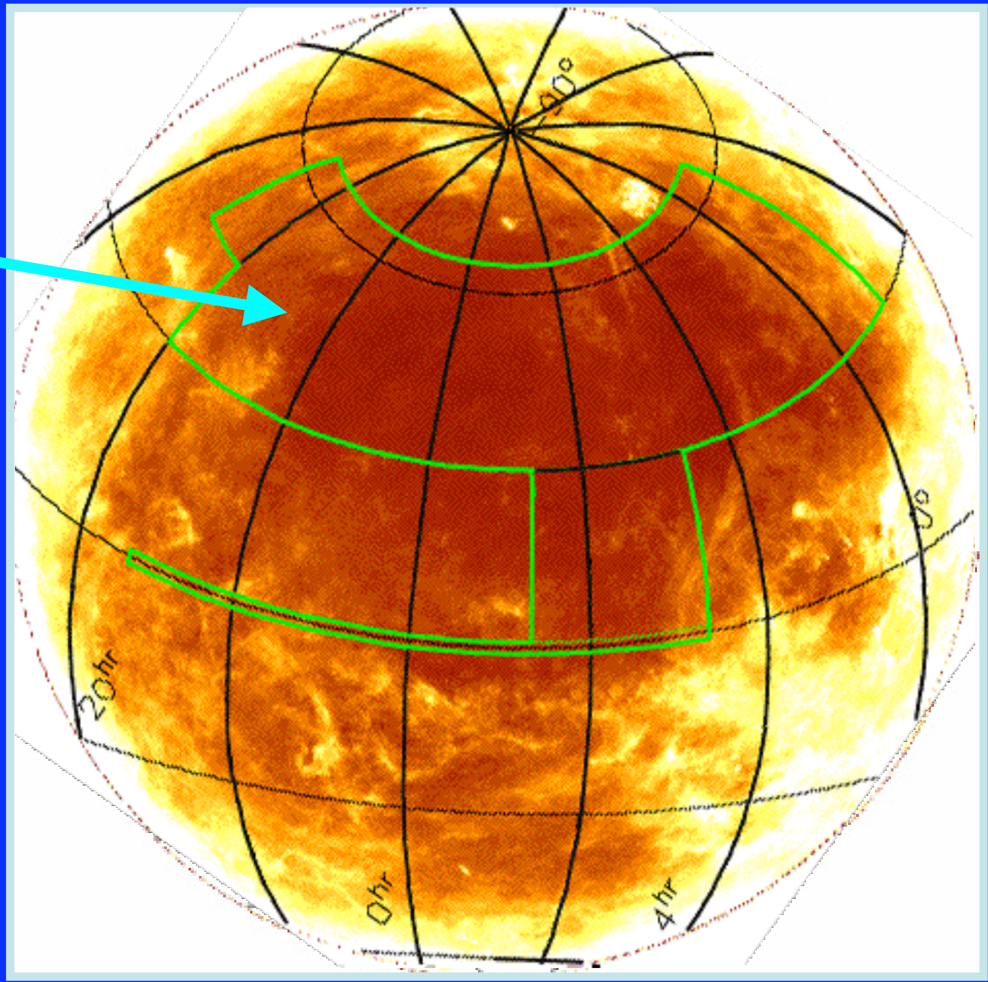
Jenkins, etal

$$\frac{dn}{dM}(z,M) = 0.315 \frac{\rho_0}{M} \frac{1}{\sigma_M} \frac{d\sigma_M}{dM} \exp\left[-\left|0.61 - \log(D_z \sigma_M)\right|^{3.8}\right]$$

DES Area and Depth: Synergy with South Pole Telescope

- South Pole Telescope:
  - 4000 sq. deg. survey
  - Detect ~30,000 clusters through Sunyaev-Zel'dovich effect

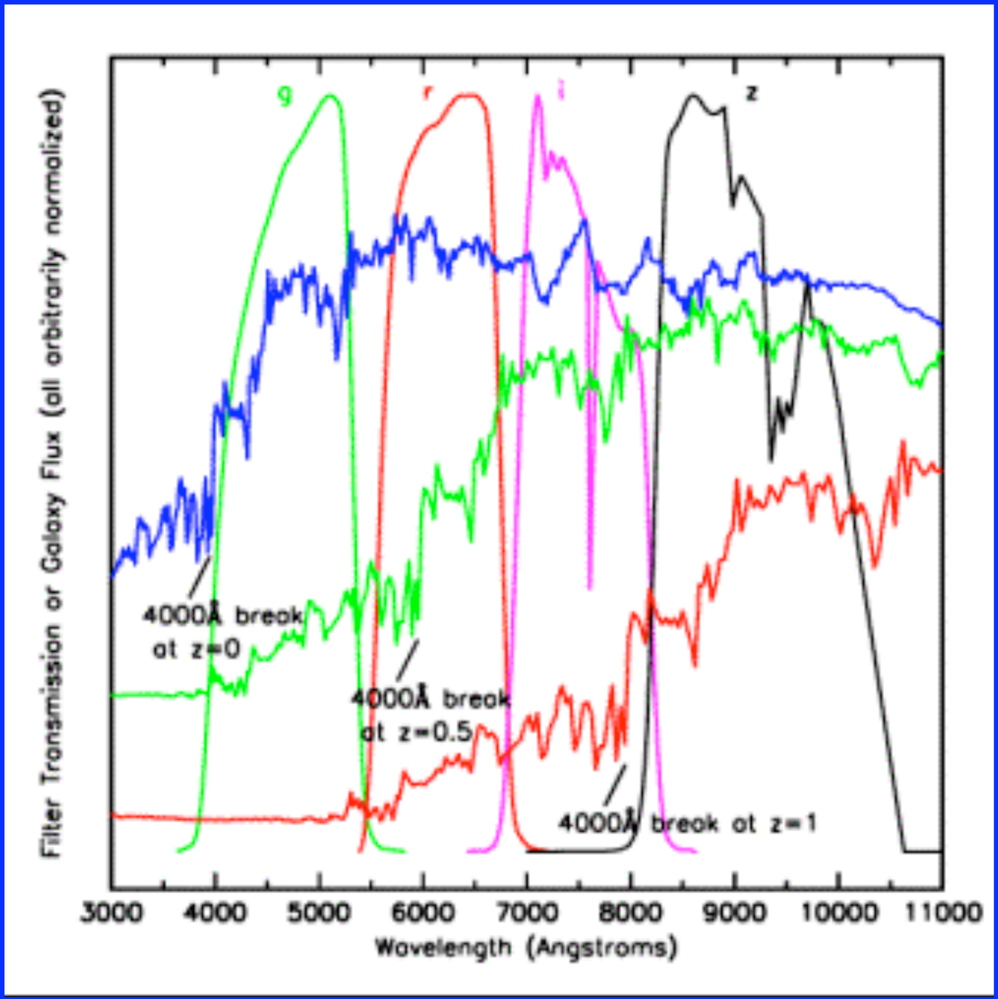
- Dark Energy Survey: measure *photometric* redshifts for these clusters to z ~ 1.3: *griz* ~ 24



Galactic Dust Map

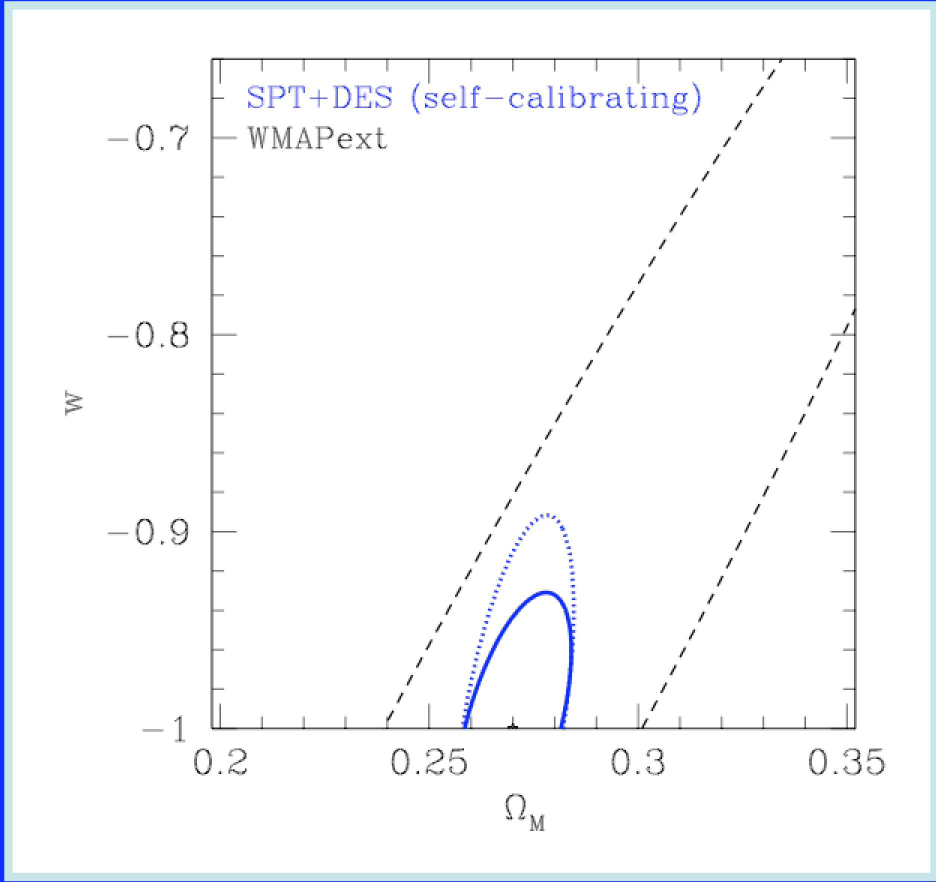
Photometric Redshifts

- Measure relative flux in the four filters *griz*: track the 4000 A break
- Estimate individual galaxy redshifts with accuracy $\delta z \sim 0.1$ (~0.02 for clusters)
- This is more than sufficient for Dark Energy probes, if biases can be controlled
- Note: good detector response in *z* band filter needed to reach z~1



DES+SPT Cluster Probes of Dark Energy

- Assumptions
  - The cluster redshift distribution, the cluster power spectrum, and 30% accurate mass measurements for 100 clusters between z of 0.3-1.2
  - Fiducial cosmology (WMAP: σ_8=0.84, Ω_m=0.27); 29000 clusters in the 4000 deg^2 SPT survey.
- Joint constraints on w and Ω_m:
  - Curvature free to vary (dashed); fixed (solid)
  - Marginalized constant w 68% uncertainty is 0.046 (flat) or 0.071 (curvature varying)
- Parameter degeneracies complementary to Supernovae



SPT: Majumdar & Mohr 2003
WMAP: Spergel et al 2003

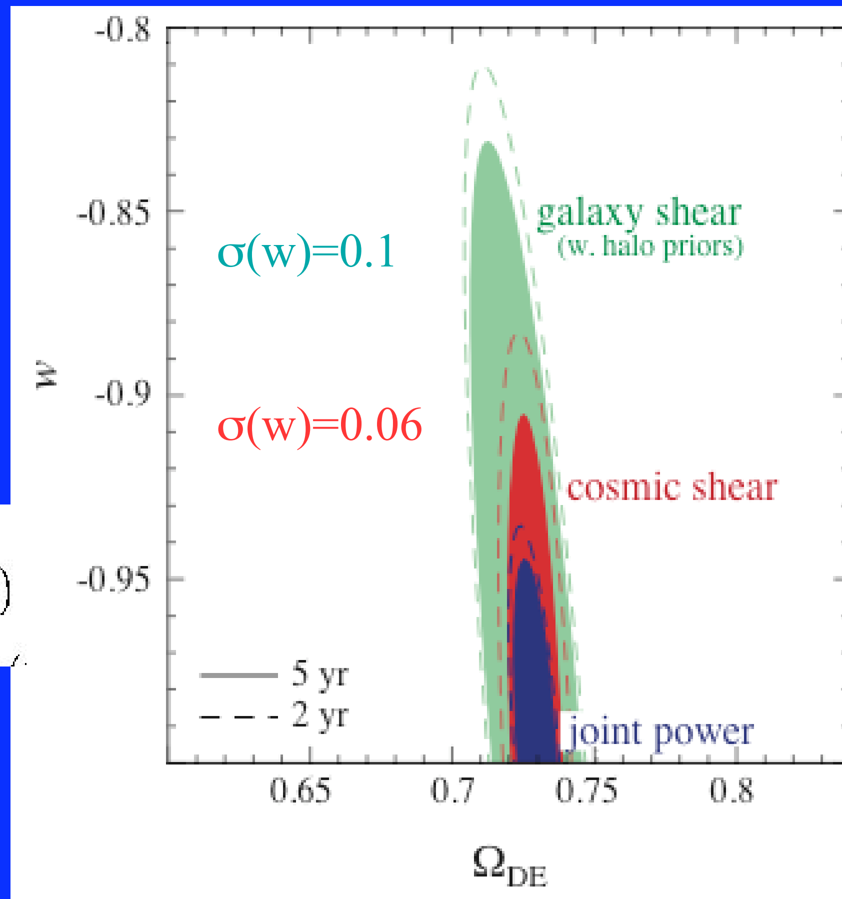
DES Weak Lensing

- Measure shapes for ~300 million source galaxies with $\langle z \rangle = 0.7$
- Shear-shear & galaxy-shear correlations probe distances & growth rate of perturbations

$$C_\ell^{x_a x_b} = \int dz \frac{H(z)}{D_A^2(z)} W_a(z) W_b(z) P^{s_a s_b}(k = \ell / D_A; z)$$

- Mass Power spectrum determined by CMB (WMAP accuracy)
- Galaxy-galaxy correlations determine halo model priors

Marginalized 68% CL DES constraints



Statistical errors only, no bispectrum, $\ell < 3000$

based on Hu and Jain

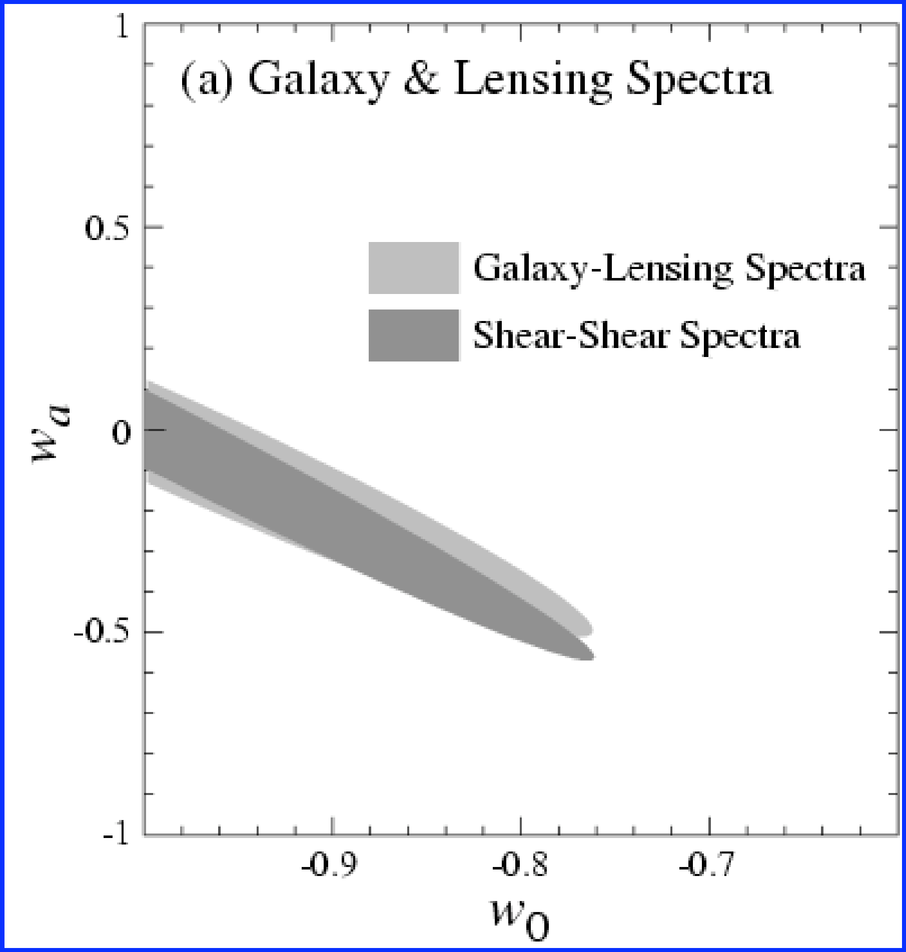
Lensing & Evolution of Dark Energy

- Time evolution of w is an important Dark Energy discriminator and currently weakly constrained:

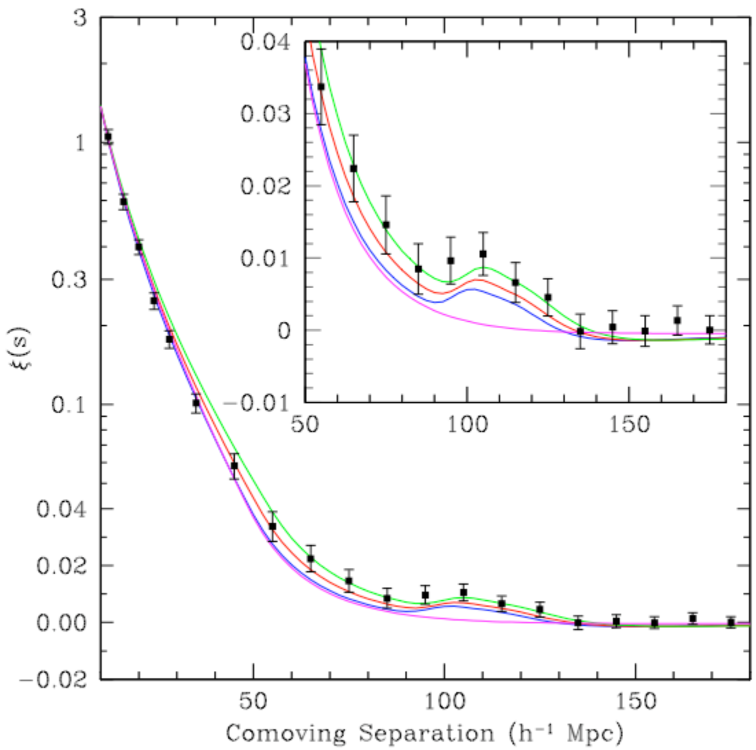
  $w_a = dw/da$

- Measure lensing correlations in redshift shells

Note: almost all other figures have assumed constant *w*

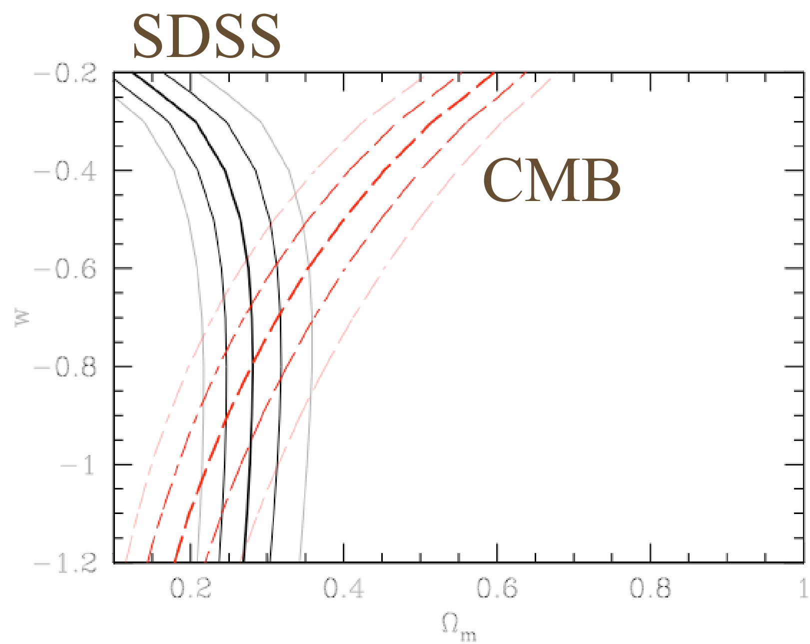


Standard Ruler: Baryon Oscillations



SDSS results

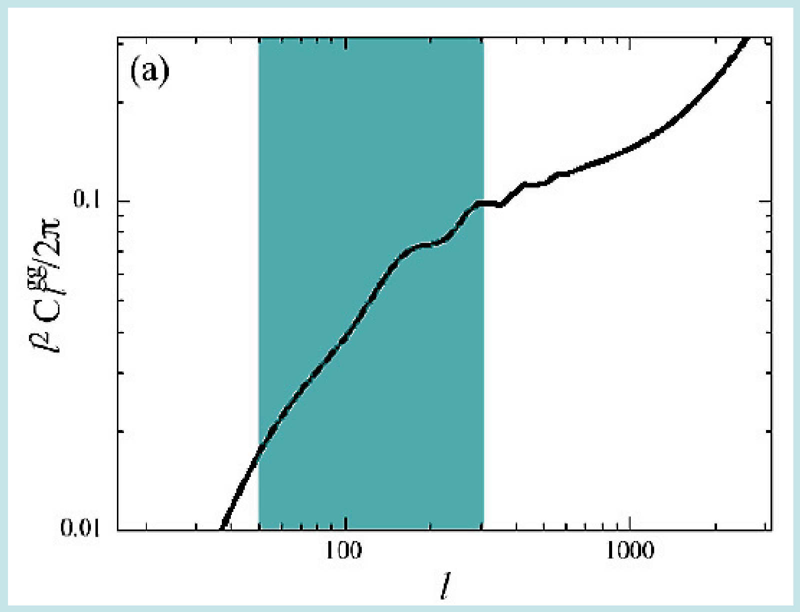
Eisenstein etal



Provides absolute distance measurement to ~mean galaxy redshift

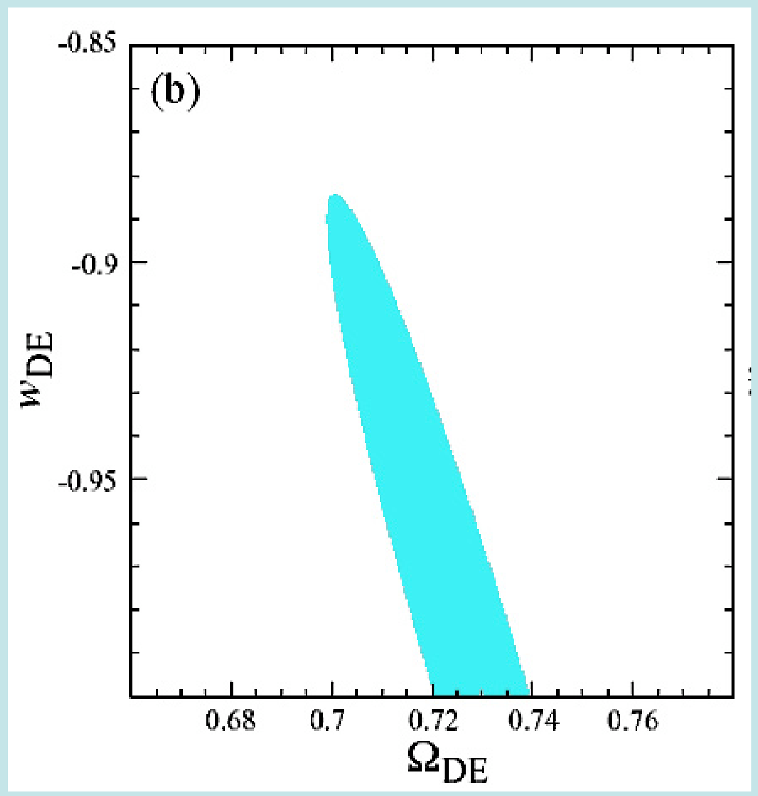
Galaxy Angular Power Spectrum

Angular Power Spectrum for 0.9 < z < 1



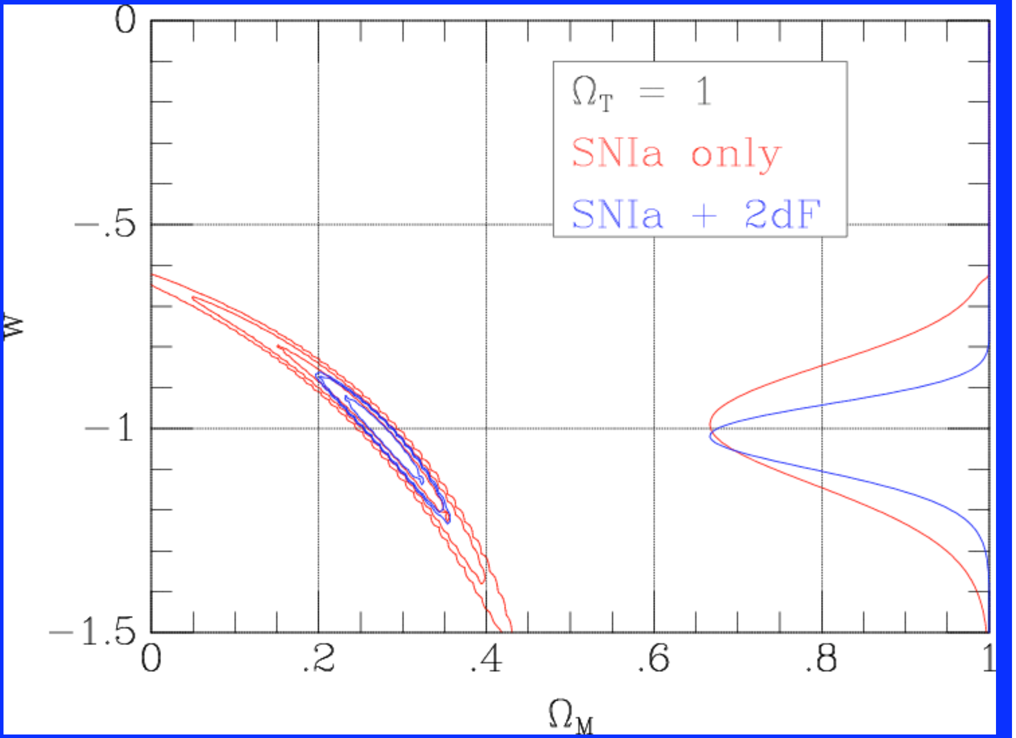
Use the galaxy angular power spectrum within redshift shells, concentrating only on the portion with $50 < \ell < 30$

With Planck CMB priors, constraints on *w* are better than ~0.1



DES Supernovae

- Repeat observations of 40 deg^2 , 10% of survey time
- ~1900 well-measured *riz* SN Ia lightcurves, $0.25 < z < 0.75$
- Larger sample, improved *z*-band response compared to ESSENCE, CFHTLS
- Combination of spectroscopic (~25%) and photometric redshifts
- Develop color typing and SN photo-z's (needed for LSST)



DES constraints
(assuming $\sigma = 0.2$ mag)

DARK ENERGY SURVEY

Dark Energy: 2009-2013

DES+SPT Logical next step in dark energy measurements:

- Will measure *w* to ~ 0.05–0.1 *statistical* accuracy* using multiple complementary probes, and begin to constrain *dw/dz*
- Scientific and technical precursor to the more ambitious Dark Energy projects to follow: LST and JDEM
- DES in unique position to synergize with SPT on this timescale
- *Cannot* be done with any existing facility: Blanco+DECAM ~5 times faster survey instrument than any existing facility, >10x faster than any current U.S. facility

*accuracy on each probe *separately*, with generally weak priors