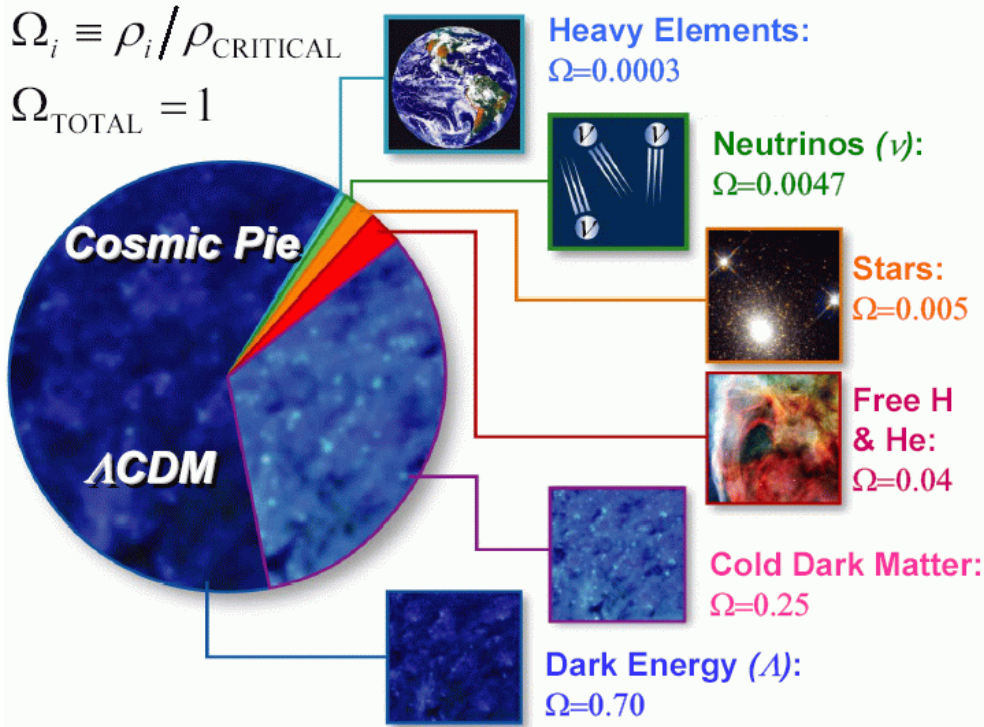




# Dark Energy and Dark Matter

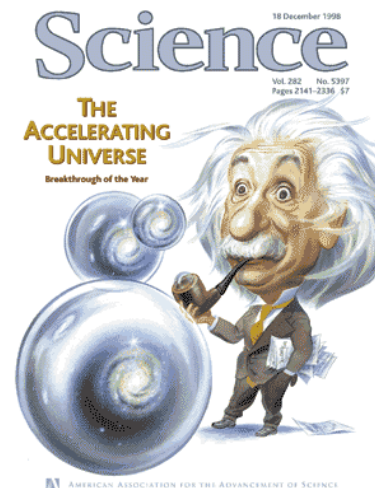
DARK ENERGY  
SURVEY



1998 and 2003 Science  
breakthroughs of the year

Dark Energy is the dominant  
constituent of the Universe  
Dark Matter is next

95% of the Universe is in Dark  
Energy and Dark matter for which  
we have no understanding





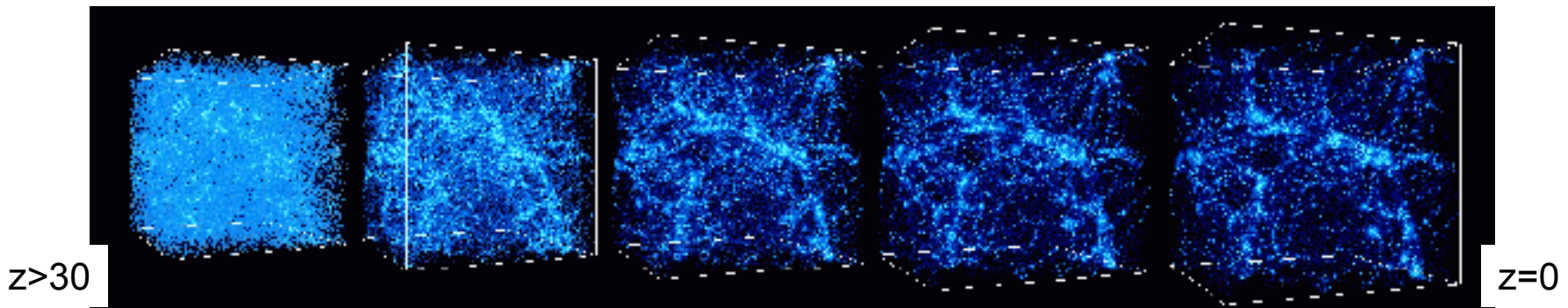
# Probing Dark Energy

DARK ENERGY  
SURVEY

- Expansion rate of the universe:

$$H^2(z) = H_0^2 \left[ \underbrace{\Omega_M (1+z)^3}_{\text{dark matter}} + \underbrace{\Omega_{DE} (1+z)^{3(1+w)}}_{\text{dark energy}} \right] \quad (\text{flat Universe, const. } w, \quad w = -1: \text{ cosm. const.})$$

- rate of growth of structure
  - mass, number and spatial distribution of galaxies as a function of  $z$



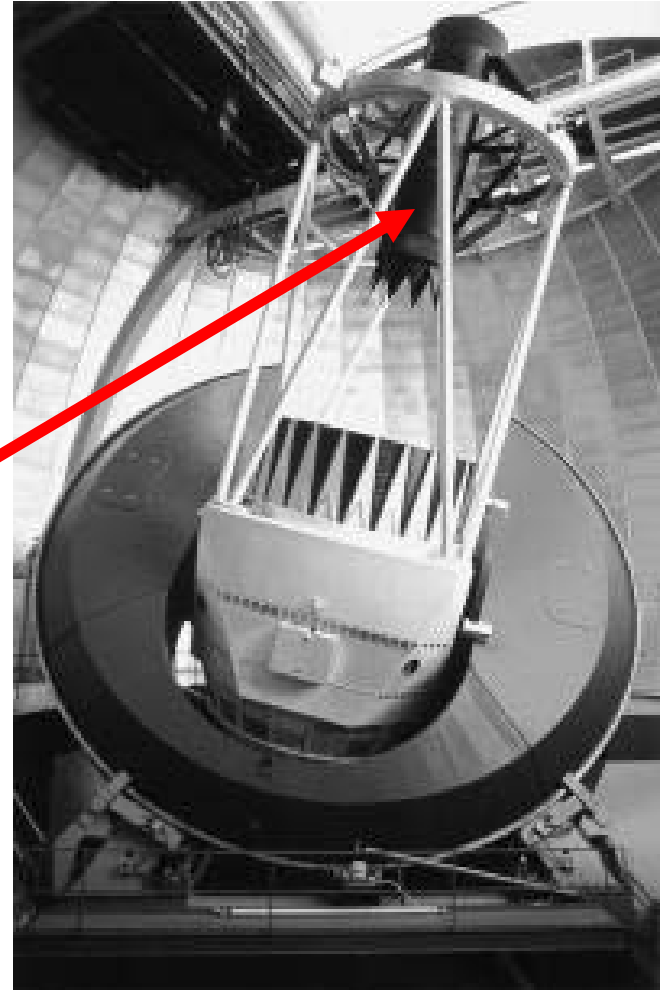
- The parameter,  $w = p/\rho$ , describes the evolution of the density of dark energy with redshift. \* CMB+LSS+SNe; no single dataset constrains  $w$  better than ~30%
- Current Status:  $\sigma(w) \sim 0.15^*$ ,  $w < -0.76$  (95%)



# The Dark Energy Survey (DES)

DARK ENERGY  
SURVEY

- **Proposal:**
  - Perform a 5000 sq. deg. survey of the southern galactic cap
  - constrain the Dark Energy parameter  $w$  to  $\sim 5\%$  with 4 complementary techniques
  - begin to constrain  $dw/dz$
- **New Equipment:**
  - Replace the PF cage on the CTIO Blanco 4m telescope with a new 2.2 deg. FOV optical CCD camera
- **Time scale:**
  - Instrument Construction 2005-2009
- **Survey:**
  - 30% of the telescope time from 2009-2013





# Dark Energy Survey

DARK ENERGY  
SURVEY

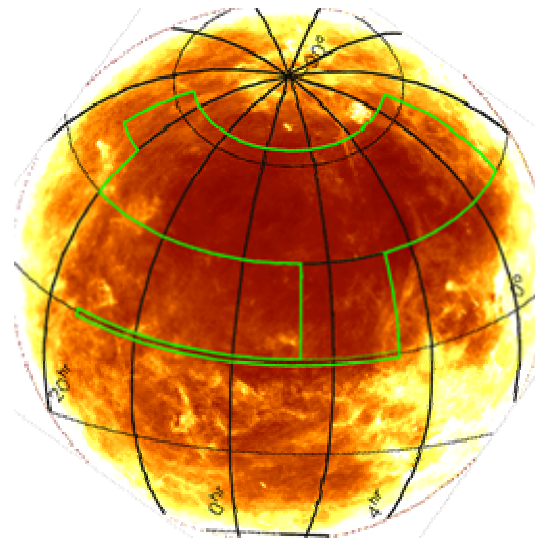
## Science Program

## Instrument Description

- Four Probes of Dark Energy

- Galaxy Cluster counting
  - 20,000 clusters to  $z=1$  with  $M > 2 \times 10^{14} M_{\odot}$
- Weak lensing
  - 300 million galaxies with shape measurements over 5000 sq deg.
- Spatial clustering of galaxies
  - 300 million galaxies to  $z = 1$  and beyond
- Standard Candles
  - 2000 SN Ia,  $z = 0.3-0.8$

- 3 sq-degree camera with  $\geq 2.2$  deg FOV
- 62 CCDs, 2kx4k – 0.5G pixel focal plane
- SDSS g,r,i,z filters covering 400 to 1100nm
- $10\sigma$  Limiting mag: 24.6, 24.1, 24.3, 23.9
- Pixel size 15 microns, 0.27" /pixel
- Readout time  $\sim 17$  sec.

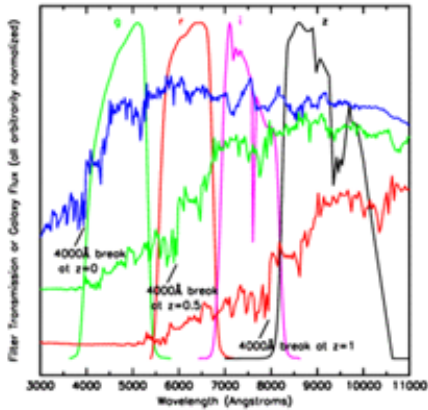


Survey Area  
5000 sq. deg.  
in Southern  
Galactic Cap  
with connection to  
SDSS stripe 82 for  
calibration



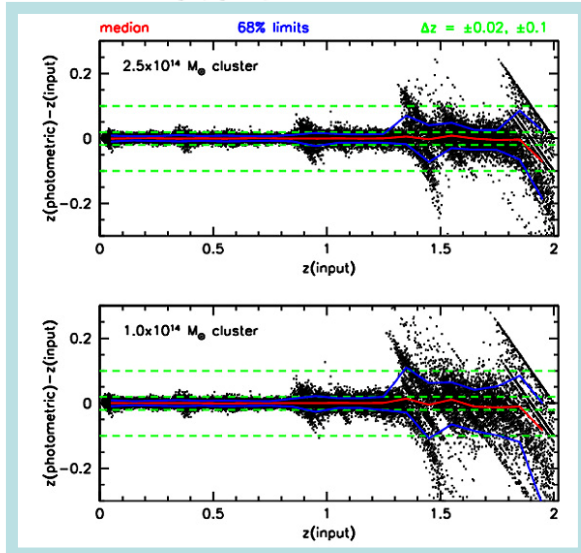
# Galaxy Cluster Redshifts

DARK ENERGY SURVEY

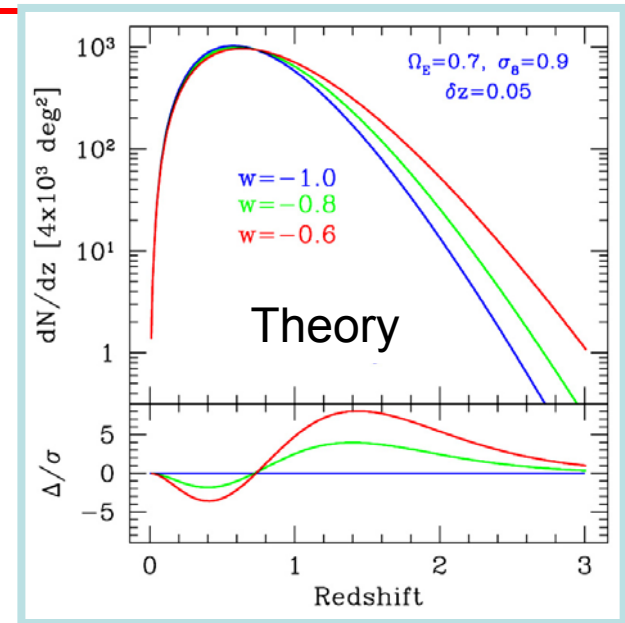


four filters (griz) track 4000 Å break.

Need z band filter to get out to redshift  $> \sim 1$



- DES data will enable cluster photometric redshifts with  $\Delta z \sim 0.02$  for clusters out to  $z \sim 1.3$



for  $M > 2 \times 10^{14} M_{\odot}$

- the distribution of the number of clusters as a function of redshift is sensitive to the dark energy equation of state parameter,  $w$ .

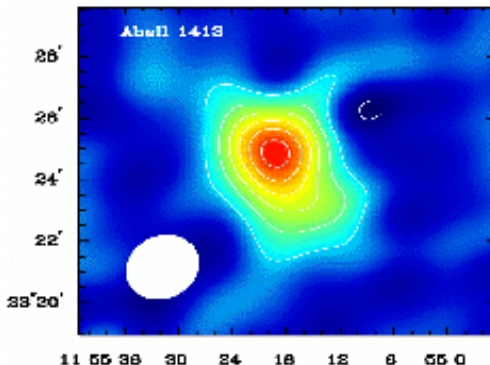
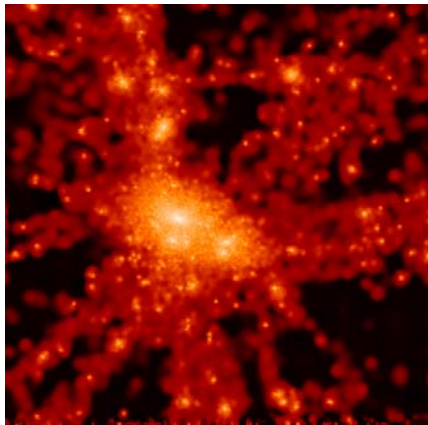


DARK ENERGY  
SURVEY

# Cluster Masses

The cluster redshift distribution depends on the cluster masses

- Mass estimators
  - Count Galaxies (or luminosity) in a cluster
  - Weak lensing
  - Sunyaev-Zeldovich (SZ)
    - hot electrons in clusters scatter CMB photons, distorting the frequency spectrum
    - scattering is proportional to cluster mass
    - insensitive to redshift
- The South Pole Telescope (SPT)
  - 4000 sq. deg. survey Southern Galactic cap
  - measures cluster masses using SZ effect
  - funded and in construction – expect first data in 2006

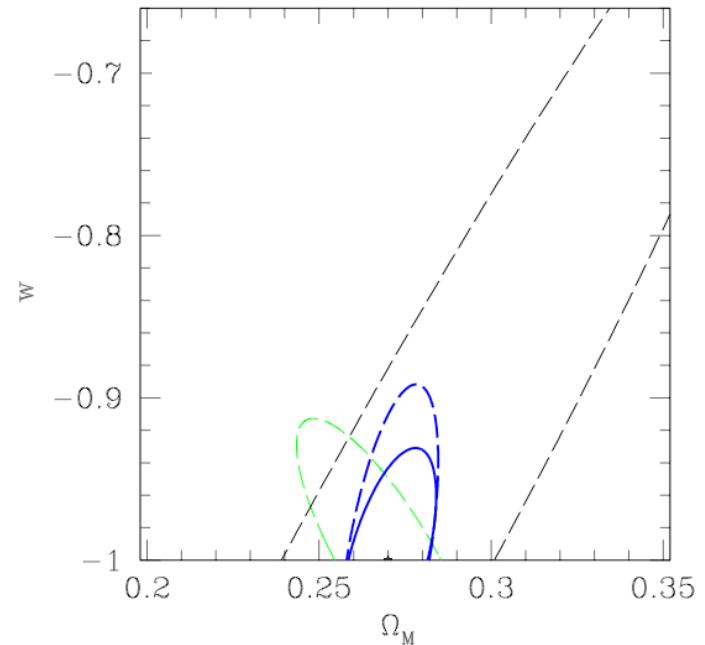




# Cluster Surveys: Complementary systematics

DARK ENERGY  
SURVEY

- Combination of SPT mass measurements and DES redshifts place joint constraints on  $w$  and  $\Omega_m$  :
  - Fiducial cosmology parameters from WMAP:  $\sigma_8=0.84$ ,  $\Omega_m=0.27$ ,  $w = -1$
  - 29000 clusters in the 4000 deg<sup>2</sup> DES+SPT survey area
  - Curvature free to vary (dashed); one sigma uncertainty on  $w$  is 0.071
  - Curvature fixed @ 0 (solid); one sigma uncertainty on  $w$  is 0.046
- Parameter degeneracies complementary



DES + SPT: Majumdar & Mohr 2003

SNAP: Perlmutter & Schmidt 2003

WMAP: Spergel et al 2003



# Galaxy Angular Power Spectrum

## DARK ENERGY SURVEY

- DES main survey will yield photo-z's on approximately 300 million galaxies extending beyond a redshift  $z \sim 1$
- We can study the angular clustering within redshift bins to  $z \sim 1$
- Theory predicts how the shape of the angular power depends on redshift
- Peak of the angular power spectrum represents a standard rod
- Location of the peak is a measure of the angular diameter distance to each redshift shell (i.e. Cooray et al 2001).

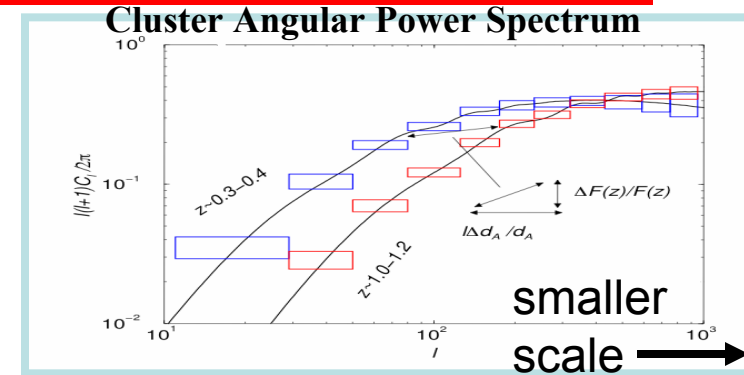


Figure from Cooray et al ApJ 2001

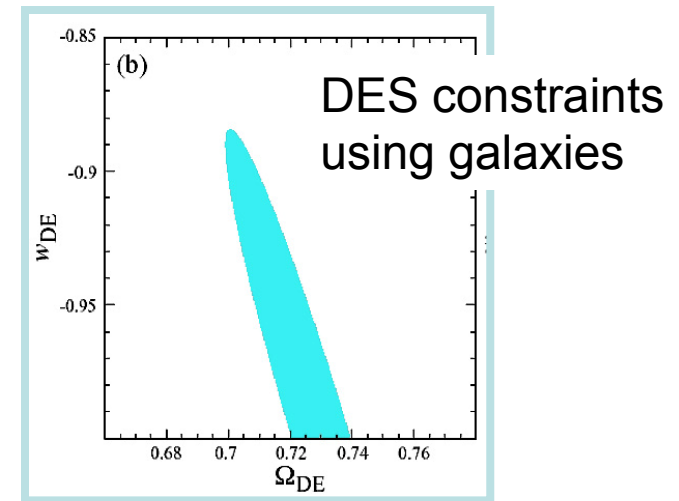
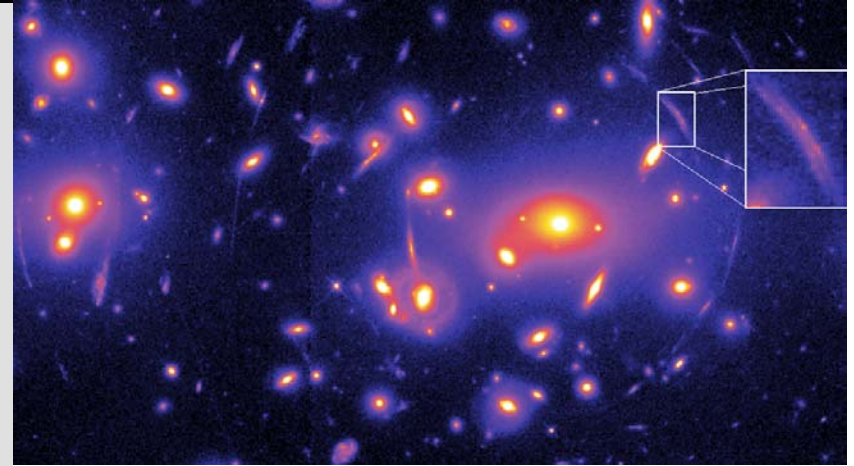
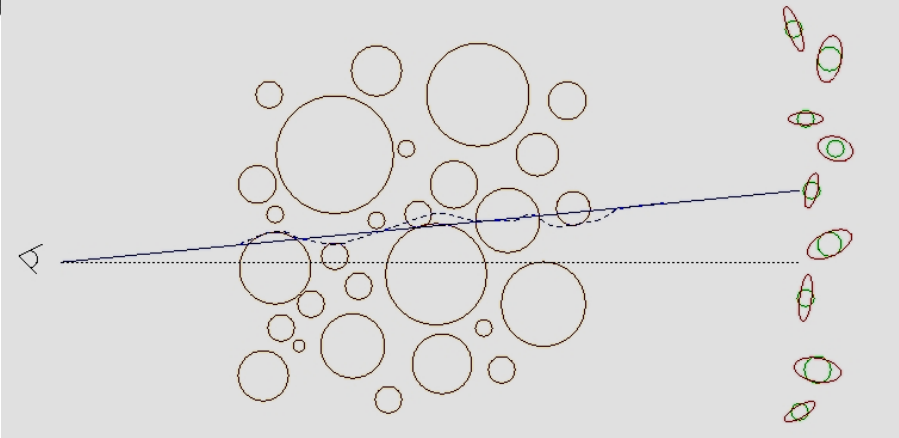


Figure from Wayne Hu 2004



# Weak Lensing

DARK ENERGY  
SUI

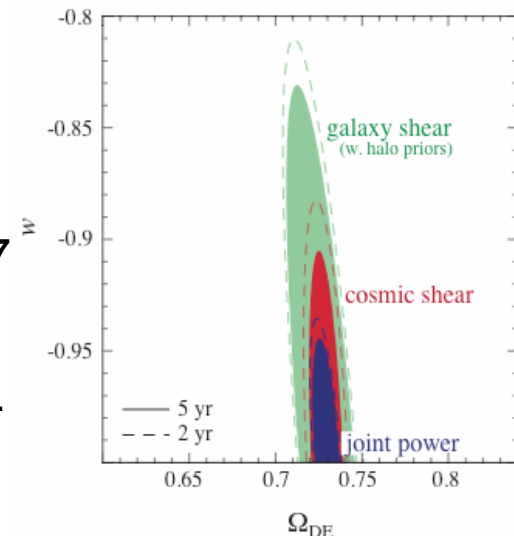


$$\Psi_{ij} = \frac{\partial \delta \theta_i}{\partial \theta_j} = \int dz g(z) \frac{\partial^2 \Phi}{\partial \theta_i \partial \theta_j}$$

Distortion  
Matrix

Measure shapes for ~300 million source galaxies with  $\langle z \rangle = 0.7$   
 Direct measure of the distribution of **mass** in the universe,  
 as opposed to the distribution of **light**, as in other methods (eg.  
 Galaxy surveys)

Independently calibrates SZ cluster masses





# SN Ia: "Standard" Candles

DARK ENERGY

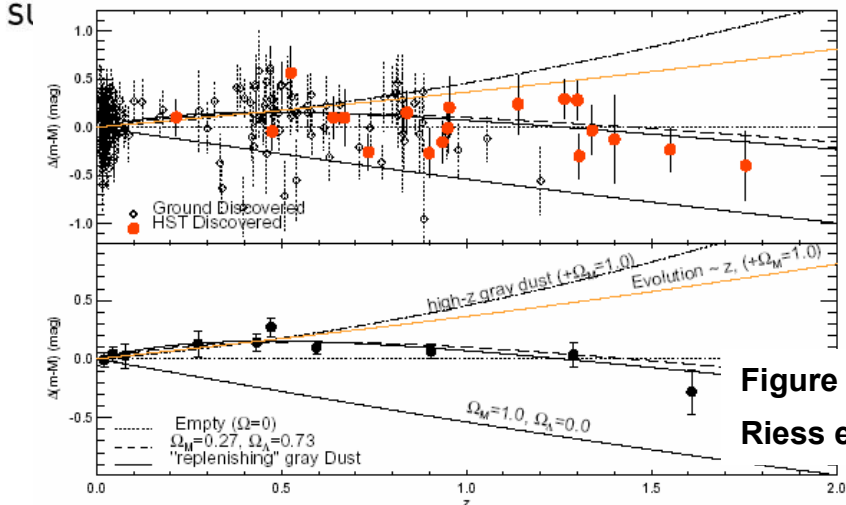
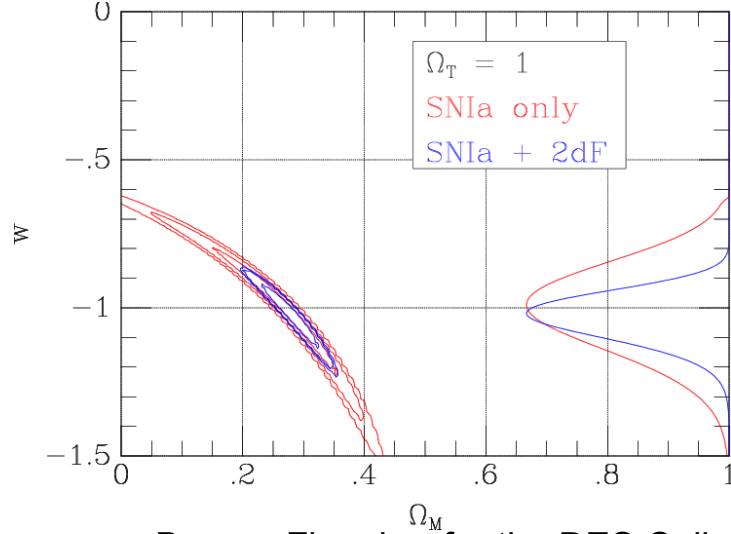


Figure from  
Riess et al 2004



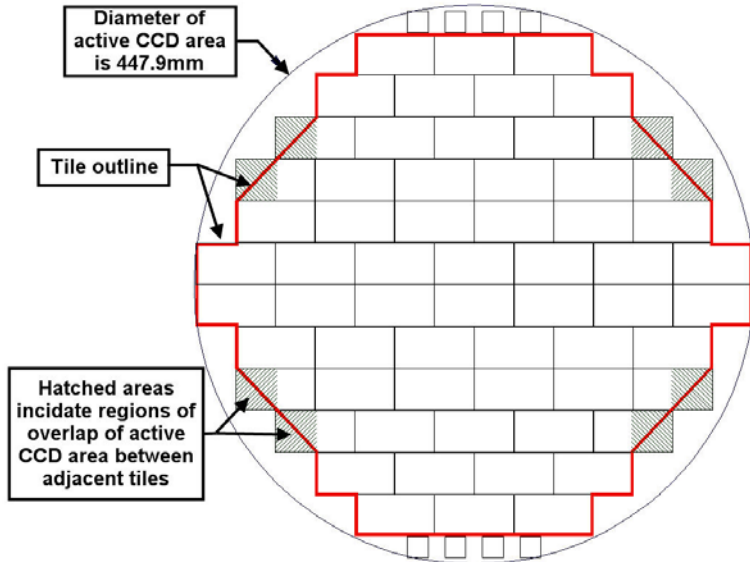
- Type Ia Supernovae magnitudes and redshifts provide a direct means to probe dark energy
  - Standardizable candles
  - Dark Matter dominates for  $z > \sim 0.75$
  - Dark Energy dominates at low  $z$
  
- DES will make the next step:
  - Image 40 sq-degree repeatedly
  - 2000 supernovae at  $z = 0.3-0.8$
  - Well measured light curves
  - photo- $z$ 's for all, + some spectroscopic redshifts



# DES Instrument Design

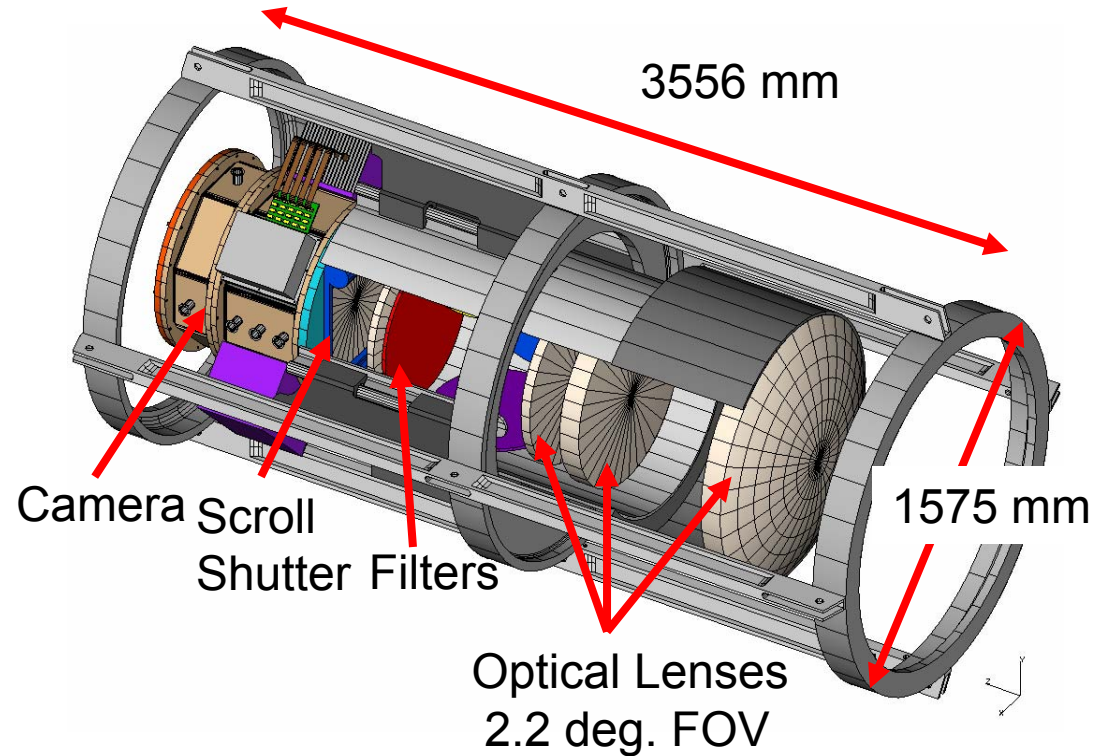
DARK ENERGY  
SURVEY

## Focal Plane



62 2k x 4k CCDs for main image,  
4-side buttable, 15 micron pixels

8 1k x 1k guide and focus CCDs



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



# DES time scale and Conclusions

DARK ENERGY  
SURVEY

Present to 2008:  $\sigma(w) \sim 0.1$  (SNE+WMAP combined ,  $\sim 0.3$  alone)

Dark Energy Survey: 2009-2013

**Will measure  $w$  using multiple complementary probes with statistical accuracy\*:**

Cluster counts:  $\sigma(w) \sim 0.05$

Weak lensing:  $\sigma(w) \sim 0.05$

Angular power spectrum:  $\sigma(w) \sim 0.1$

SN Ia :  $\sigma(w) \sim 0.15$

**\*statistical accuracy on each probe separately, with at most weak priors**

**DES will be in a unique position to provide constraints on the Dark Energy parameter  $w$  and start to constrain the time evolution  $dw/dz$**