The Dark Energy Survey

DARK ENERGY SURVEY

Outline

- Some Background
- Description of the Dark Energy Survey
- Dark Energy Survey Science
- Conclusions

Office of Science
U.S. Department of Energy

Argonne NATIONAL LABORATORY

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2 Dec. 2011

Some Background

- In the early 1900s, it was believed the universe was static.
  - Einstein modified his equations of General Relativity to account for a static universe by adding a “cosmological constant.”
- E. Hubble later found evidence for an expanding universe.
- The discovery of the 3° K cosmic microwave background (CMB) radiation in the 1960s was consistent with a Big Bang formation of the universe.
  - Recent detailed measurements indicate an age of 13.7 B years.
- Papers published in 1998 showed the expansion of the universe was accelerating.
  - This was the subject of this year’s Nobel Prize in Physics!
  - One possible explanation uses Einstein’s cosmological constant.
  - The cause of the accelerating expansion has been called **“dark energy”**.

Some Background (cont.)

Velocity

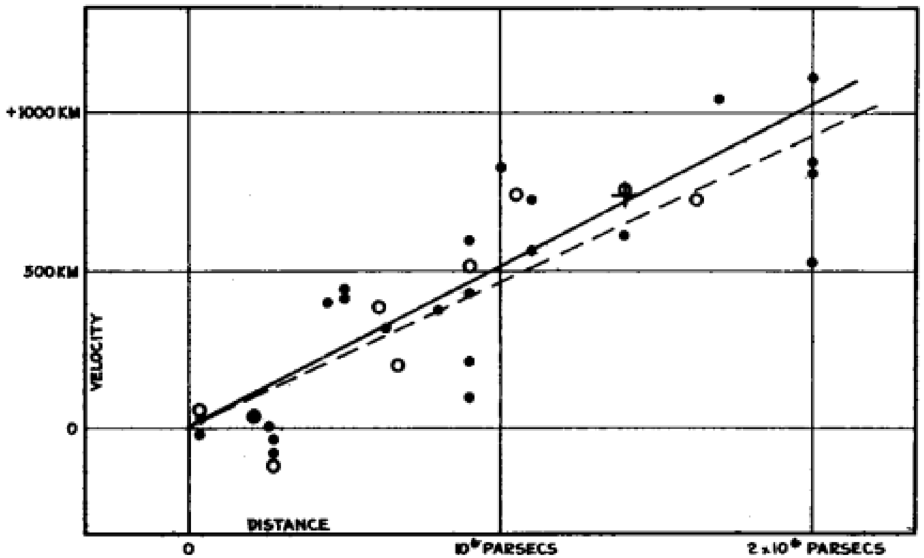


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

Radial velocities, corrected for solar motion, are plotted against distances estimated from involved stars and mean luminosities of nebulae in a cluster. The black discs and full line represent the solution for solar motion using the nebulae individually; the circles and broken line represent the solution combining the nebulae into groups; the cross represents the mean velocity corresponding to the mean distance of 22 nebulae whose distances could not be estimated individually.

The slope of the fitted line is termed the Hubble constant, H_0, today (subscript 0). In general, it is a function of redshift.

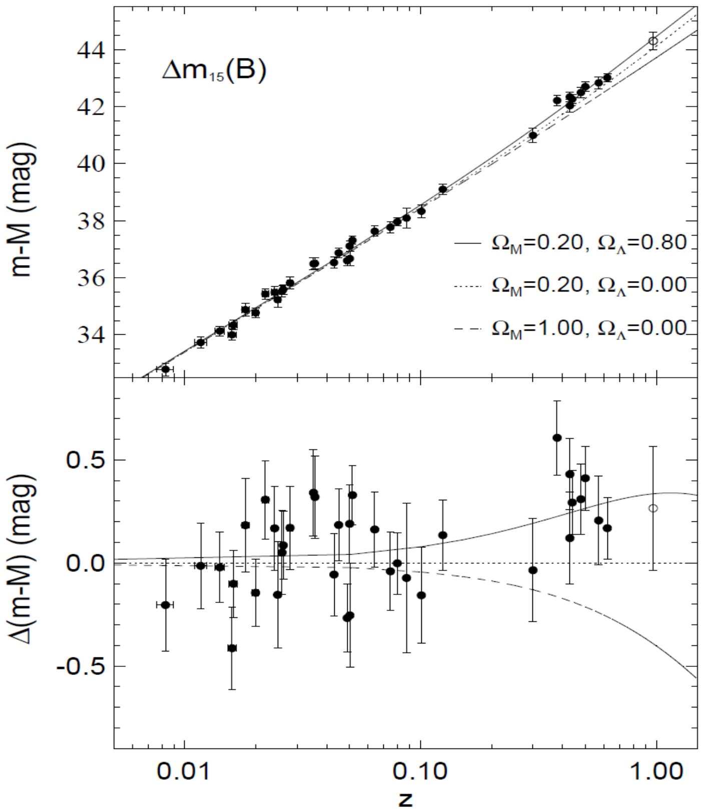
Distance

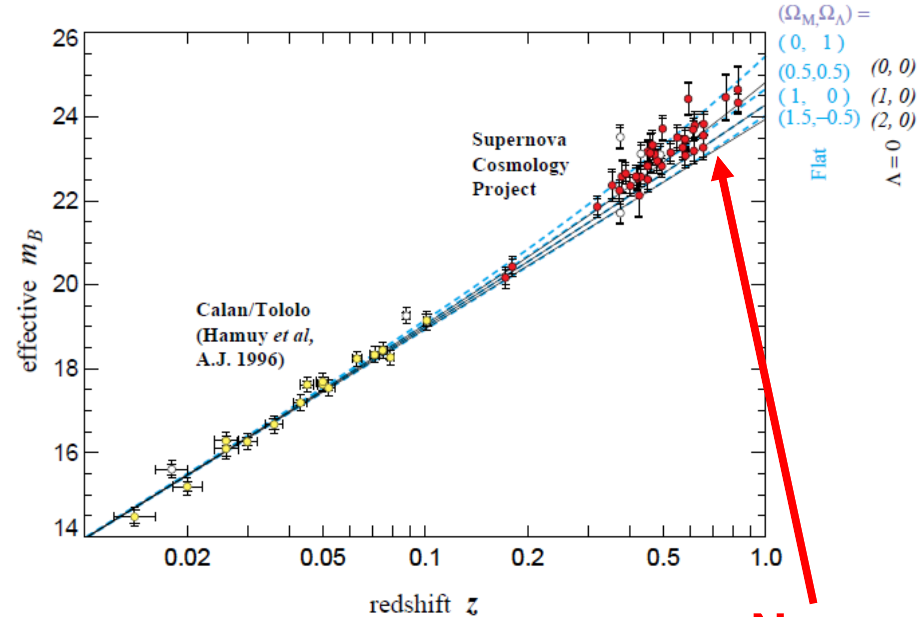
Edwin Hubble's 1929 Discovery of the Expanding Universe

from E. Hubble, PNAS 15, 168 (1929).

Some Background (cont.)

Dimmer Than Expected





No Dark Energy

No Dark Energy

- The figures are from A.G. Riess et al. Astr.J. 116, 1009 (1998) (left) and S. Perlmutter et al., Ap. J. 517, 565 (1999) (right), and provided the first evidence for accelerating expansion of the universe.

Some Background (cont.)

from

http://www.nobelprize.org/nobel_prizes/physics/laureates/2011/

$1+z \equiv \lambda_{obs}/\lambda_{emit}$

$z \equiv$ *redshift*

λ_{obs} = observed wavelength

λ_{emit} = emitted wavelength

NB. distance $\propto$ funct(z,Ω)

Distance modulus:

$\mu = 5 \log_{10}(d/10\ \mathrm{pc})$

d = distance

(1 pc = 3.09×10^{16} m)

- Some useful definitions are included above that will occur throughout the talk.

Some Background (cont.)

- The standard equation for the expansion of the universe is shown below.

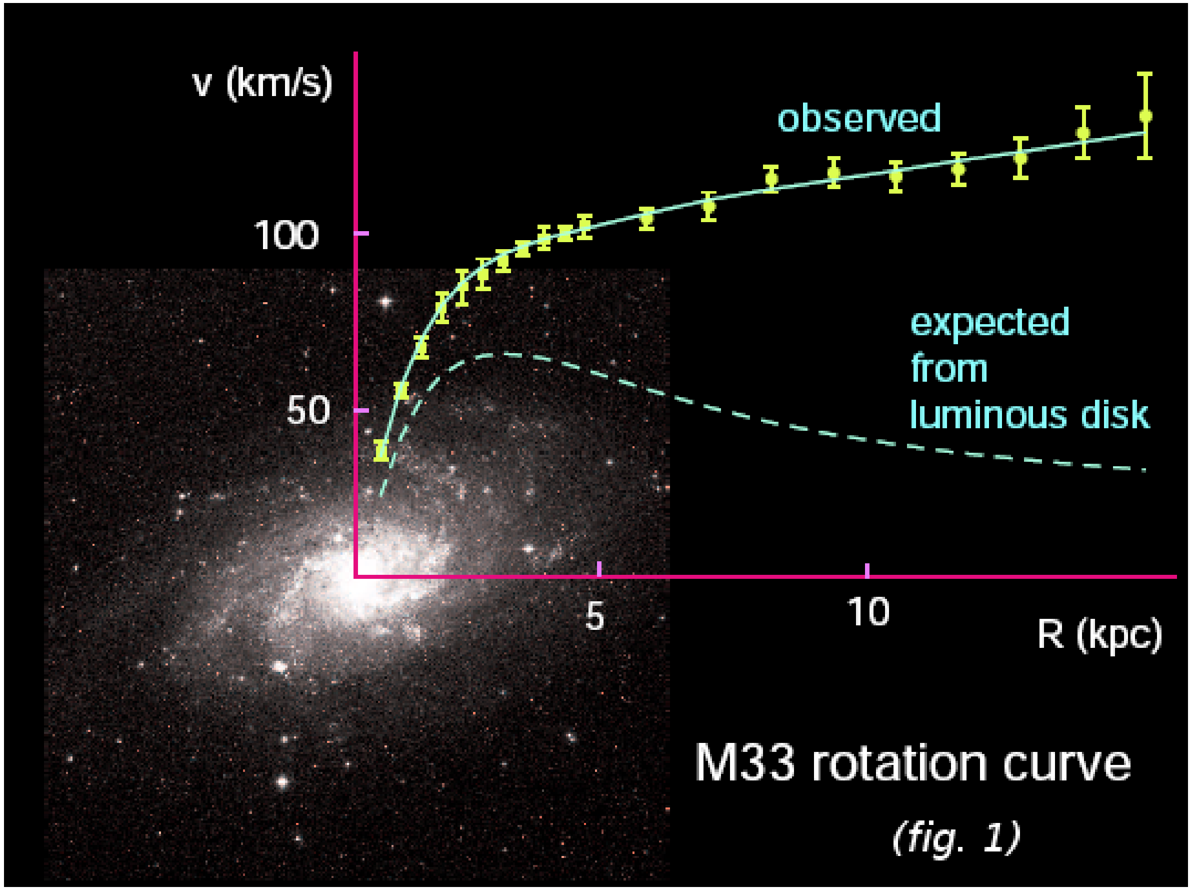
$$\left(\frac{\dot{a}}{a}\right)^2 = H_0^2\left[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_k a^{-2} + \Omega_{DE} a^{-3(1+w)}\right]$$

w = pressure / density = p_{DE} / ρ_{DE}

a(t) **is a scale factor (size) of universe relative to now (*a(now)=1*)**
H_0 is the Hubble constant, ~ 72 km s-1 Mpc-1
Ω_m is from non-relativistic matter (0.27)
Ω_r is from photons and relativistic neutrinos (10^{-5})
Ω_k is from curvature (0 if a flat universe)
Ω_{DE} (or Ω_Λ) is the cosmological constant if *w* = -1 (0.73)

What is *w?* Is it time dependent *(w(a))?*

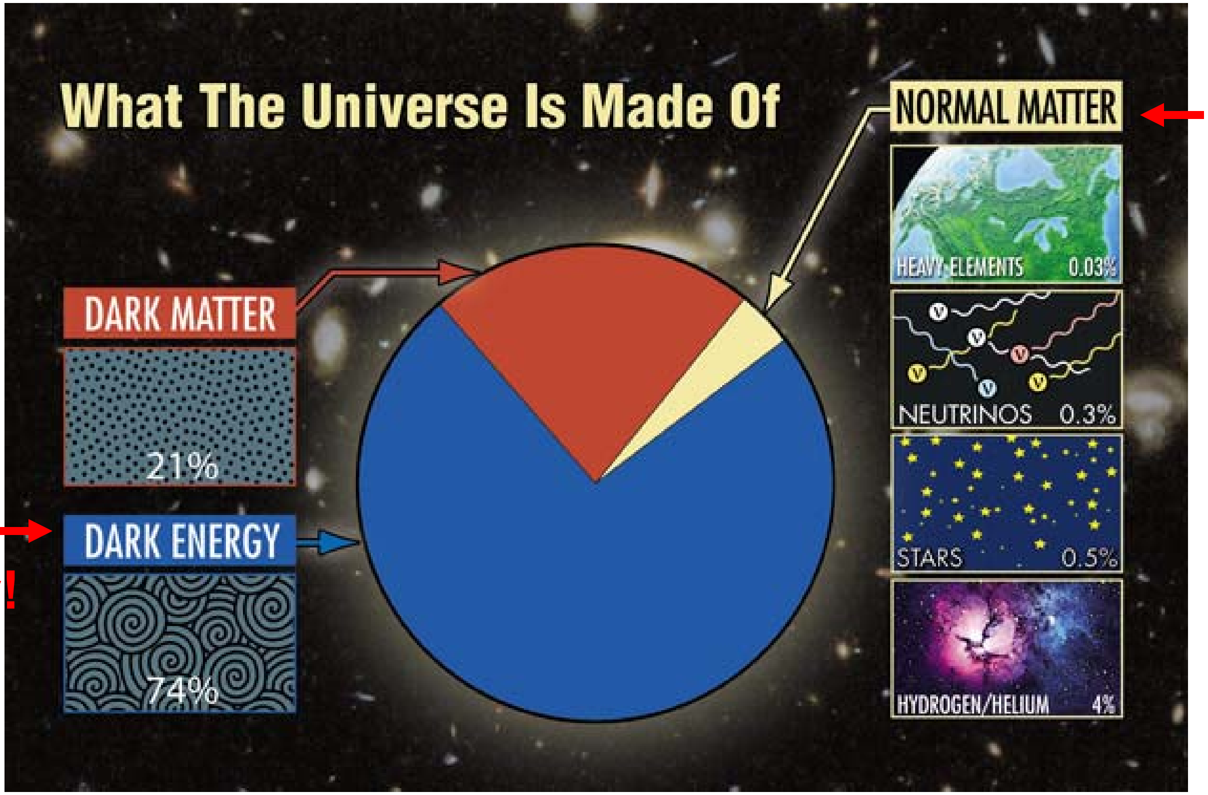
Some Background (cont.)



Evidence for **dark matter** was found from:
** the dispersion of galaxy velocities in galaxy clusters (~1933 – F. Zwicky).
** the orbital velocities of stars in spiral galaxies (~1970s) – see figure.
** gravitational lensing by galaxies (described later).

From http://w3.iihe.ac.be/icecube/

Some Background (cont.)



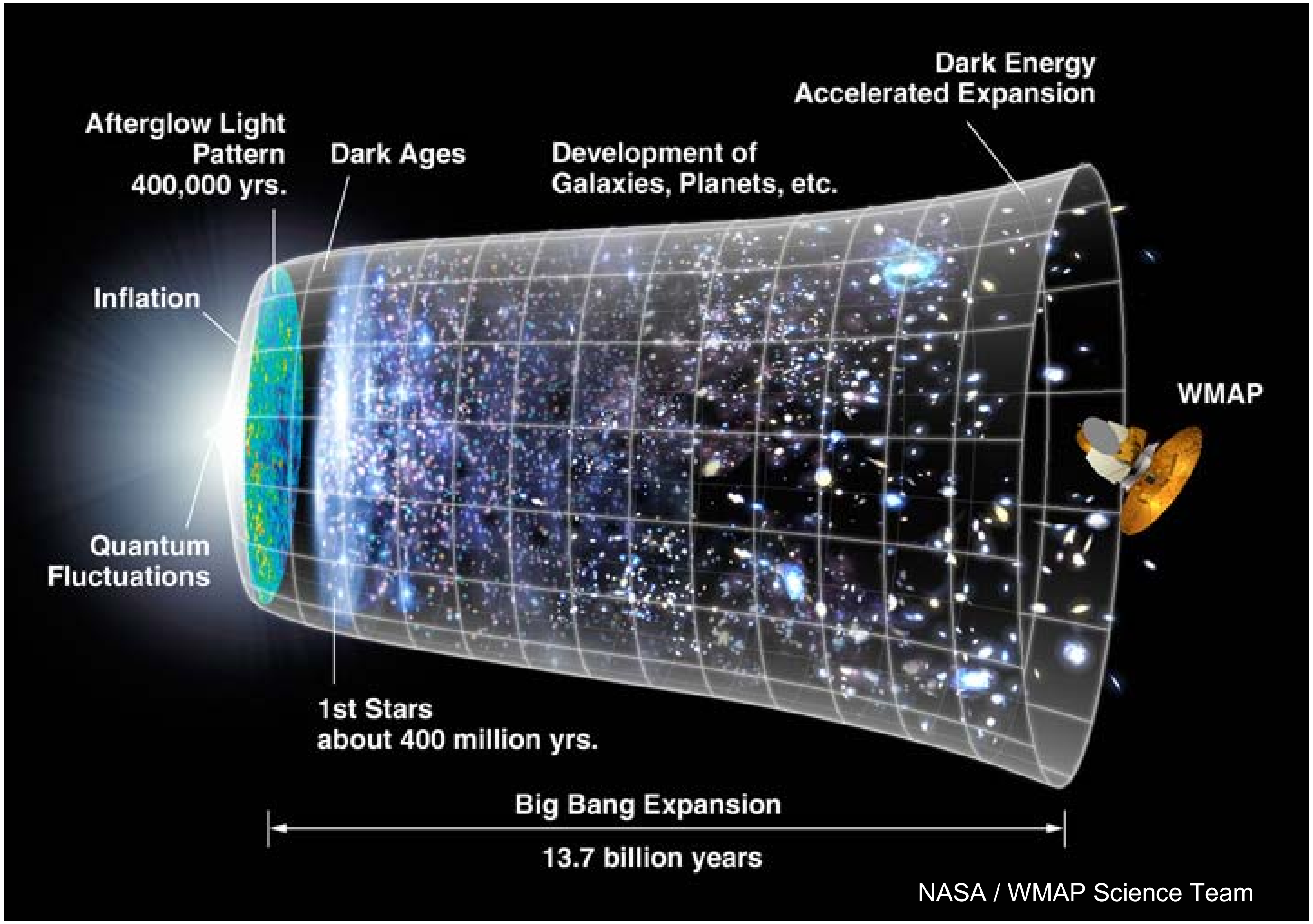
Only 4-5 % Normal Matter!

Over 70 % Dark Energy!

Courtesy: http://hetdex.org

- Evidence from the Wilkinson Microwave Anisotropy Probe (WMAP) spacecraft and other measurements have indicated the approximate fractions (above) today.

Some Background (cont.)



- The present understanding of the expansion of the universe is shown in the **simplified** drawing above.

Some Background (cont.)

- The present "standard model" of cosmology includes cold dark matter (CDM) and General Relativity with a cosmological constant.
  - CDM consists of unknown particles that are assumed traveling at non-relativistic speeds. They are affected by gravity, but do not interact with either the strong or electromagnetic interactions. They may annihilate with their anti-particles.
  - A variety of theories have possible candidates for the dark matter.
- There is a (not-so) minor problem!
  - Naïve calculations of quantum vacuum energy for General Relativity with a cosmological constant yield a value that is **at least 10^{55}** too large.
  - There are issues of how to connect Quantum Theory with gravity (or General Relativity).

The Dark Energy Survey

- The Dark Energy Survey **(DES)** is providing a new 520 Mpixel camera for an existing telescope in Chile.
  - The Blanco 4m telescope at Cerro Tololo Inter-American Observatory will be used. (Part of NOAO = National Optical Astronomy Observatory.) It was first constructed in 1974.
  - A large collaboration of astronomers and particle physicists are involved in the construction.
  - In exchange for the camera, there will be 525 nights of observing over ~5 years for the DES science program.
- Two multi-band surveys are planned:
  - g, r, i, z (and maybe y) filters or bands will be used over 5000 deg^2 in several observations over the 5 years.
  - g, r, i, z filters will be used over 30 deg^2 in many observations per year to search for supernovae and measure their light curves.

The Dark Energy Survey (cont.)

- The major goals are:
  - Place tighter constraints on whether dark energy is observationally distinguishable from a cosmological constant (w = -1).
  - Determine constraints on whether dark energy evolves ($w = w(z)$?).
  - Typically parameterize $w(z) = w_0 + w_a (1 – a)$ where "a" is a scale factor for the size of the universe, $a = (1 + z)^{-1}$.
  - Then, the goals are to measure w_0 and w_a .
  - Present values are w_0 = -0.93 ± 0.12, w_a = 0.38 ± 0.65 from E. Komatsu et al., Ap. J. Supp. 192, 18 (2011).

The Dark Energy Survey (cont.)

- Dark Energy investigation via 4 independent probes (different dependences on *w(z)*):
  – 1) Baryon acoustic oscillations
  – 2) Galaxy cluster counts
  – 3) Weak gravitational lensing
  – 4) SN Ia distances

Blanco 4m telescope

Cerro Tololo

The Dark Energy Survey (cont.)

- Collaborating Institutions:

United States

Fermilab
U. Chicago
NOAO/CTIO
UIUC
LBNL
U. Michigan
ANL

Ohio State U.
Texas A&M U.
U. Penn.
U.C. Santa Cruz
SLAC
Stanford U.

Spain

IEEC/CSIC
IFAE
CIEMAT

Brazil

Obs. Nacional
CBPF
UFRGS

United Kingdom

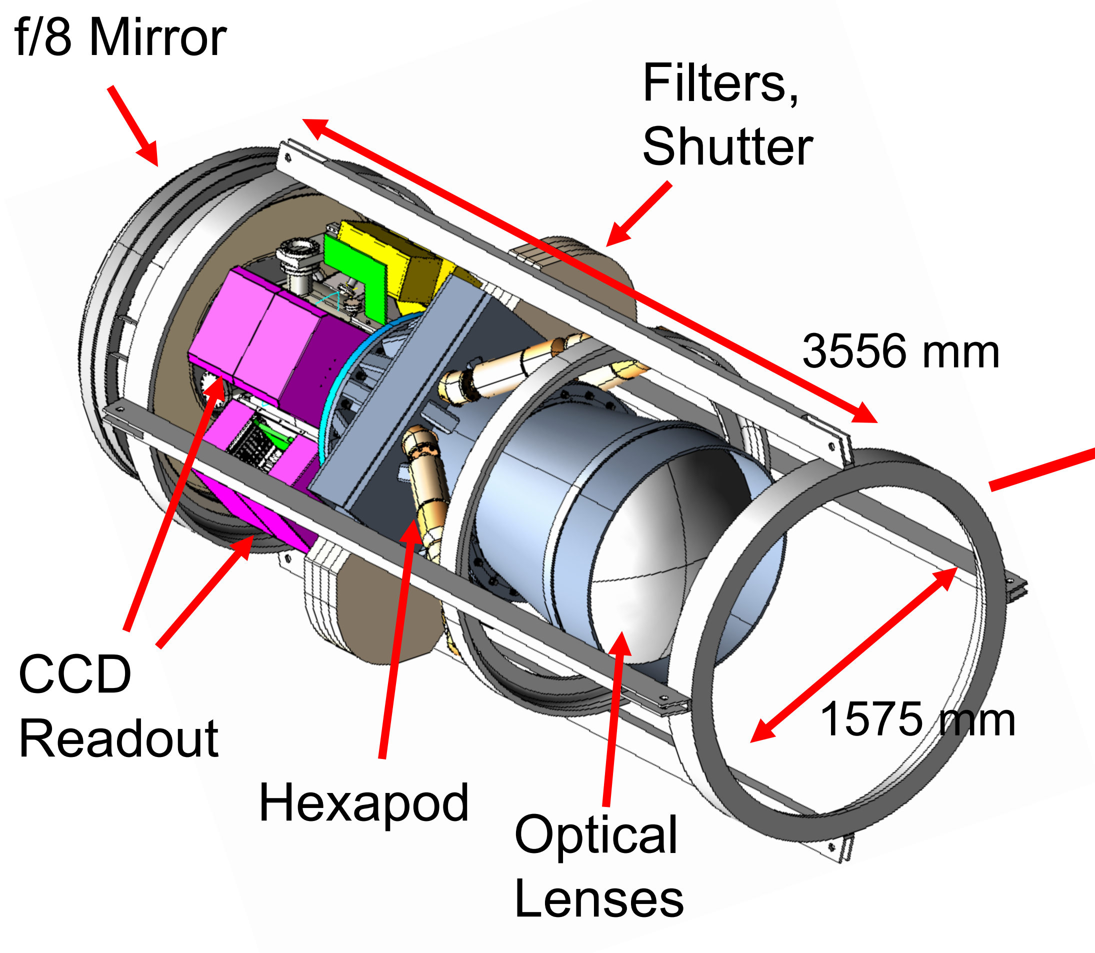
U. College London
U. Cambridge
U. Edinburgh
U. Portsmouth
U. Sussex
U. Nottingham

Germany

Ludwig-Maximilians U.
Excellence Cluster U.

- Argonne group members:
  - J. Bernstein, R. Biswas, V. Guarino, E. Kovacs, K. Kuehn, S. Kuhlmann, H. Spinka, R. Talaga, A. Zhao + students.
  - Includes 2 engineers, 3 postdoctoral fellows, 4 scientists.

The Dark Energy Survey (cont.)

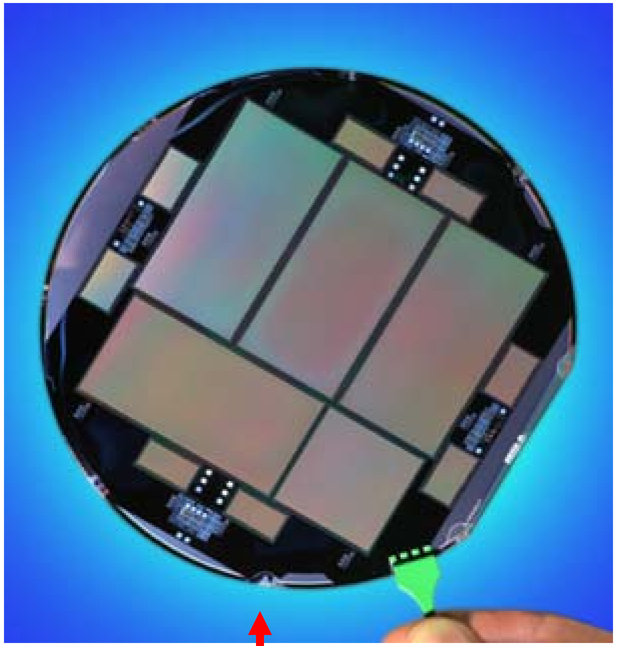


The new DES instrument, DECam, will replace the existing prime focus cage.

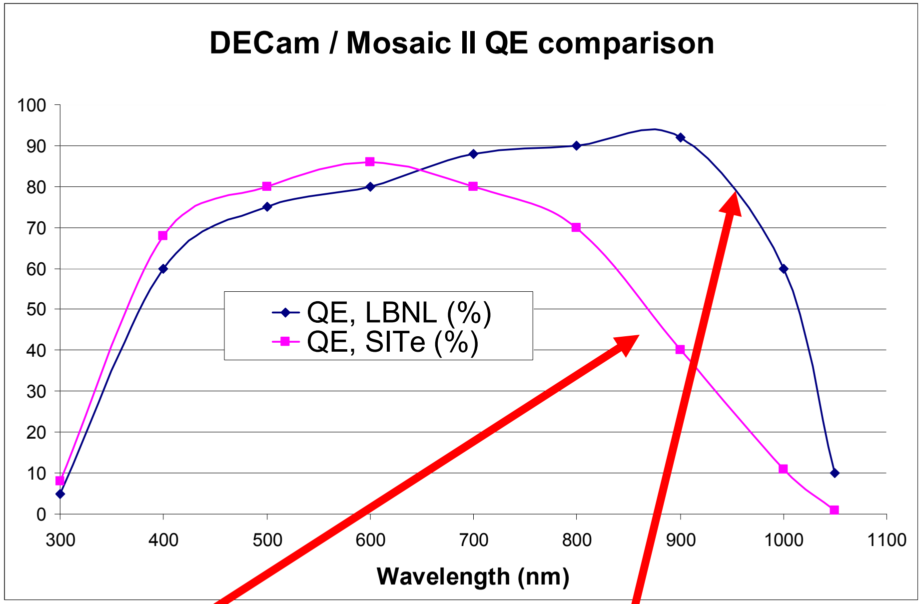
The Dark Energy Survey (cont.)

- DECam consists of:
  - A set of lenses to focus the light scattered from the 4m mirror onto the CCDs.
  - About 70 2K x 4K CCDs with associated electronics readout, cooling, vacuum, etc. One pixel ~ 15 x 15 μm^2.
  - An alignment mechanism (hexapod) to permit positioning to high accuracy.
  - A mechanical structure to permit 180° rotation of the camera to allow use of a f/8 mirror instead of the DECam. Then the telescope could use other instruments instead of DECam.
- Also included in the project are:
  - Various mounting assemblies for these multi-ton objects.
  - A data collection and data management system.
  - All data will become public after some time.

The Dark Energy Survey (cont.)



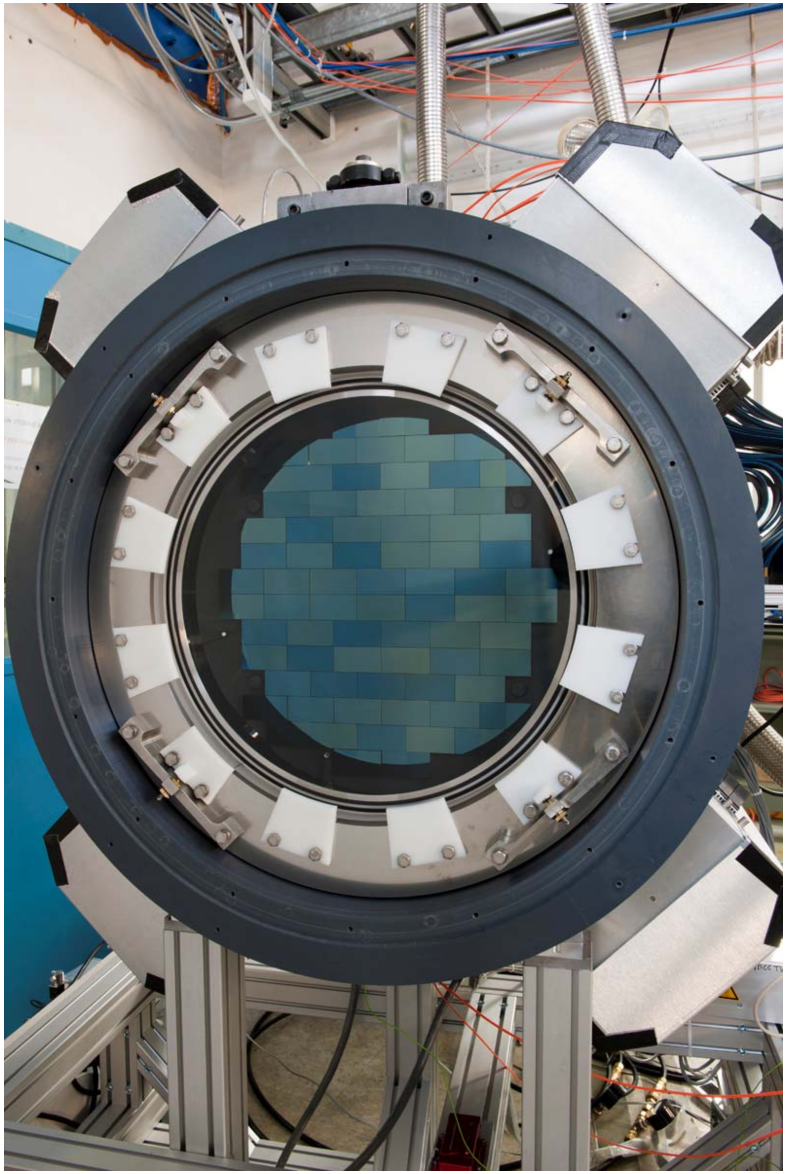
Four 2K x 4K and one 2K x 2K CCDs are made on a single Si wafer.



Old Blanco camera CCDs

- Red sensitive CCDs developed by LBNL:
  - Quantum Efficiency > 50% at 1000 nm
  - 250 microns thick
  - readout 250 k pixels / sec
  - 2 readout channels / CCD
  - readout time ~ 17sec

The Dark Energy Survey (cont.)

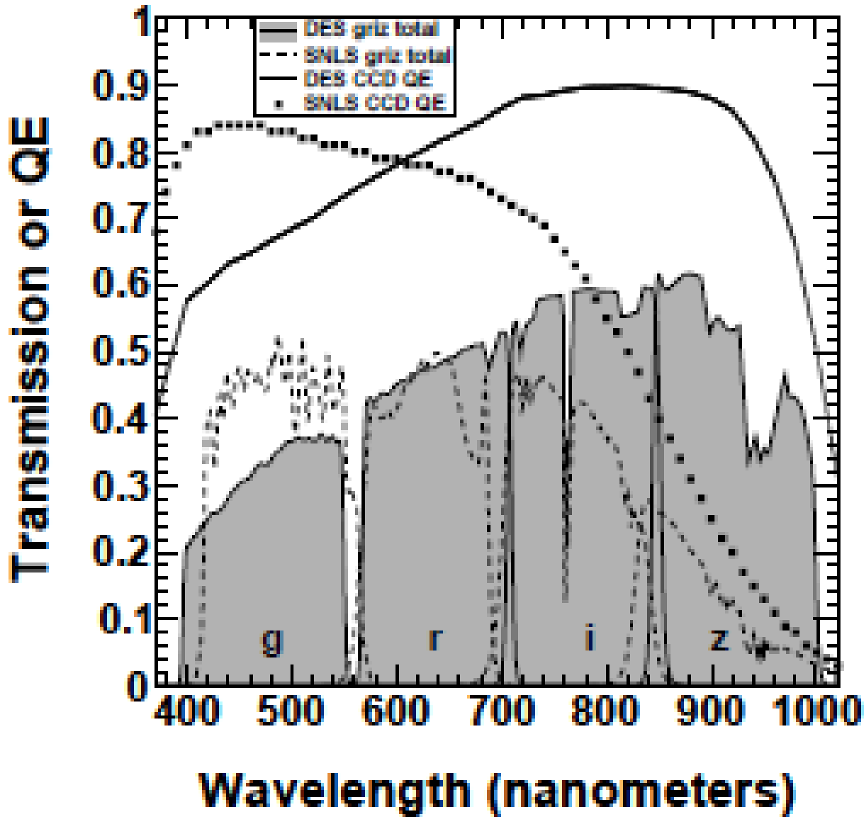


- The CCDs are shown in the “imager” just before their recent shipment to Chile.
  - Each CCD was quality tested before installation, with limits on the number of various types of defects allowed.
  - This process took over two years to complete! Most of the work was done at LBNL and FNAL.
  - Our group assisted with studies of a certain type of defect and “edge effects”.

The Dark Energy Survey (cont.)

DES Transmission Compared to Supernova Legacy Survey

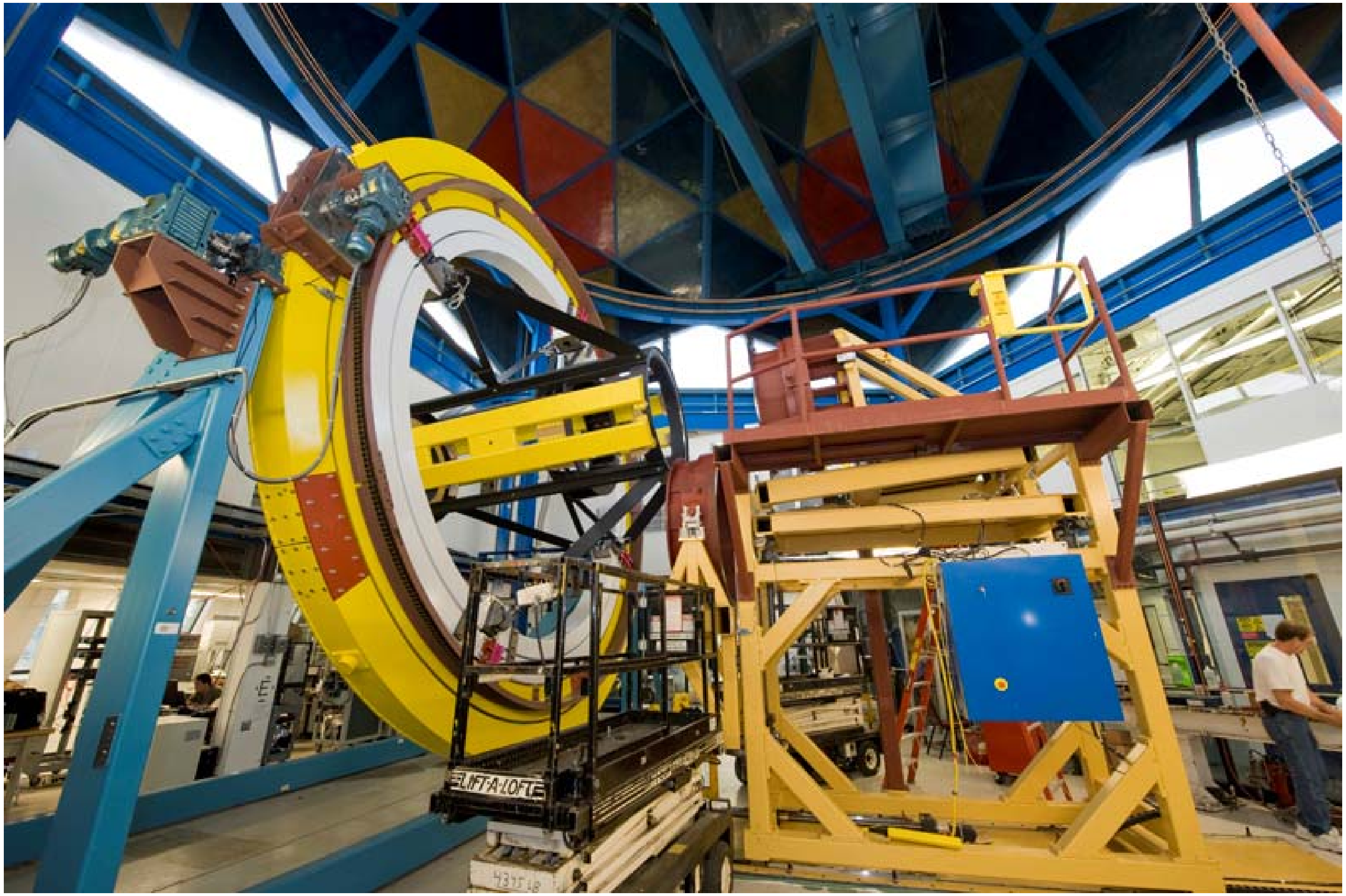
The improved response in the red allows measurements to larger redshifts.



A y-band filter may be used as well. It would (mostly) be a part of the z-band range.

- The transmission of the four DES filters includes also the effects of the atmosphere and the lenses, plus the CCD Quantum Efficiency.
  - SNLS results from N. Regnault et al., Astr. & Astr. 506, 999 (2009).

The Dark Energy Survey (cont.)

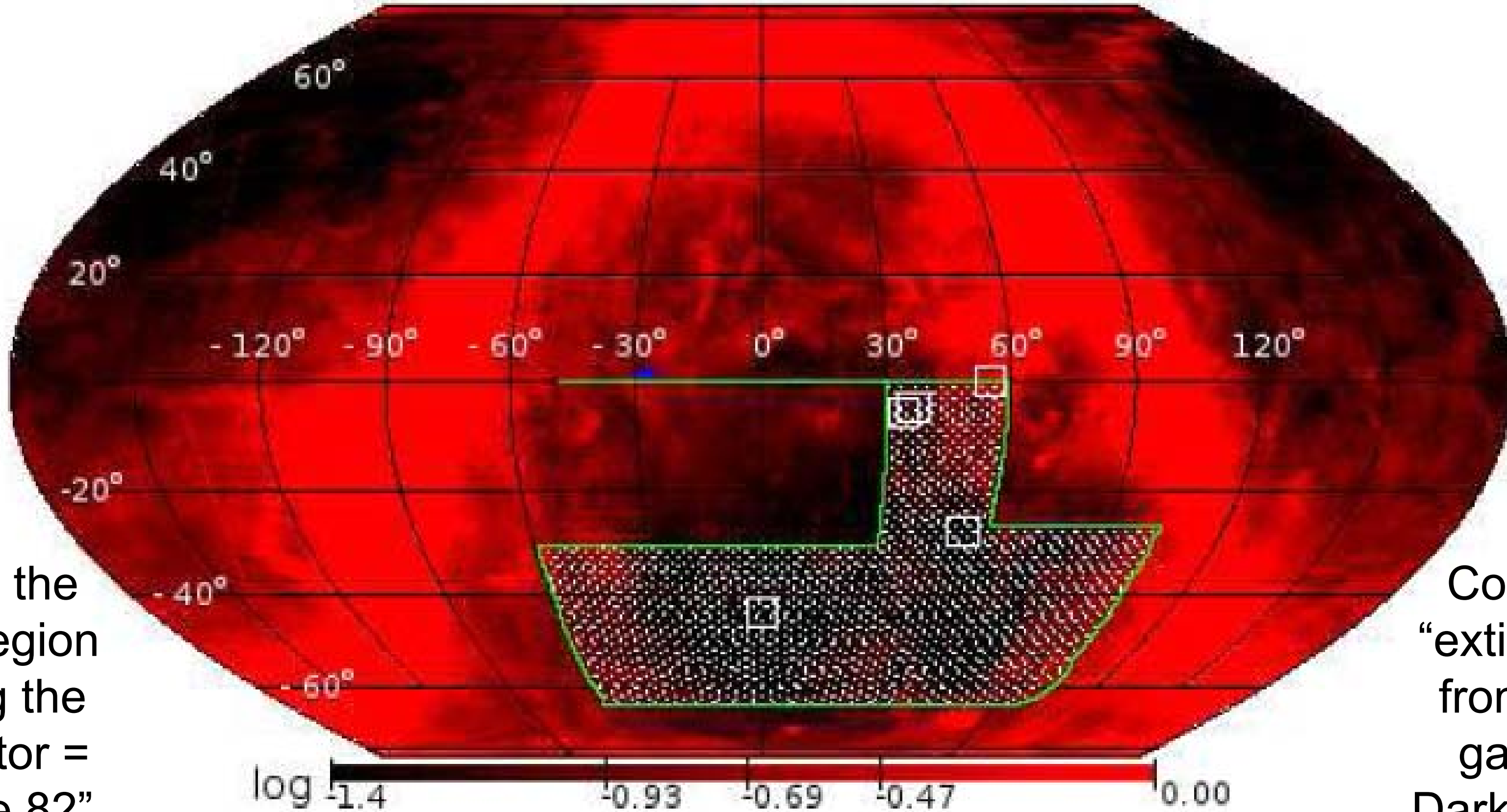


- The DECam “cage” before shipment to Chile from FNAL.

The Dark Energy Survey (cont.)

- The f/8 mirror handling system was constructed at Argonne.
  - It will be used to install and remove the large f/8 mirror on the one end of the DECam.
  - It has very tight tolerances on alignment and must withstand earthquakes and not drop the multi-ton mirror!

The Dark Energy Survey (cont.)



Note the thin region along the equator = "Stripe 82".

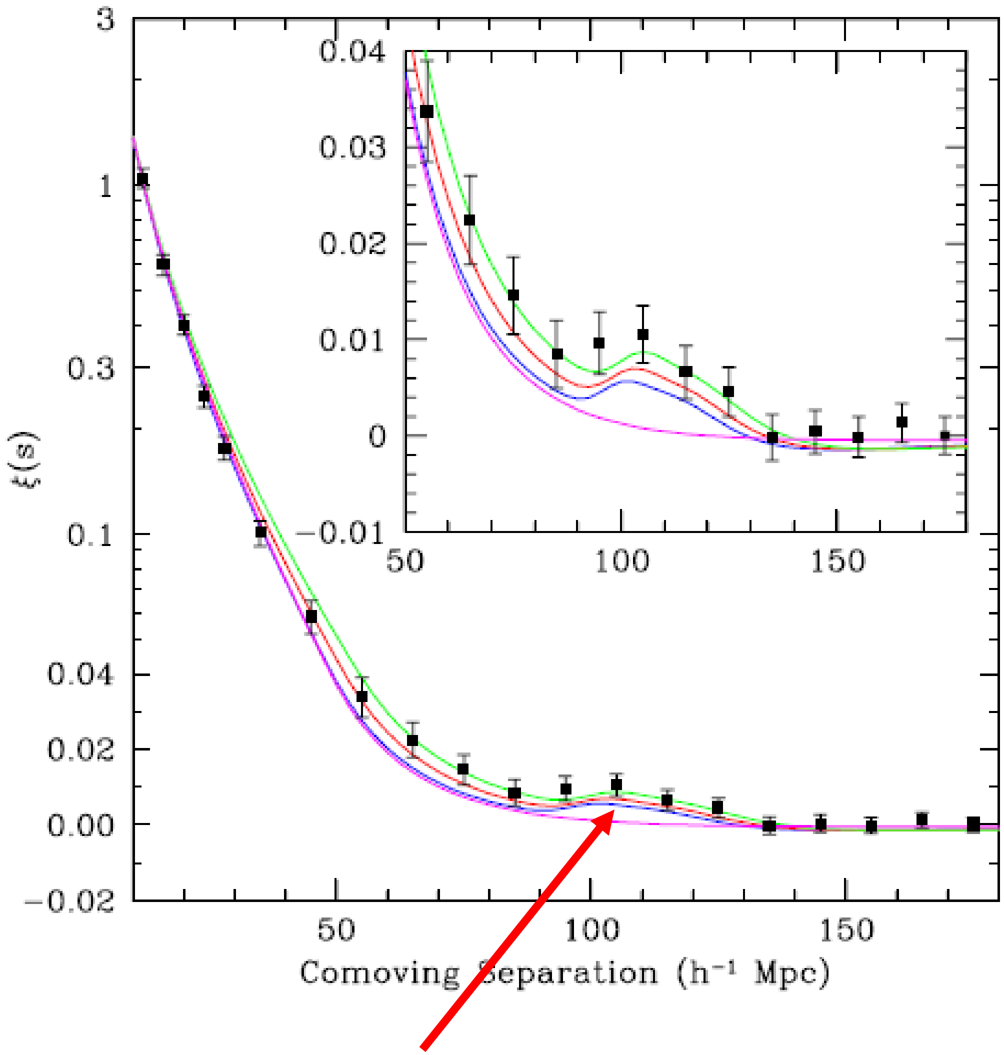
Color is "extinction" from our galaxy. Dark is less extinction.

- The presently planned survey area is shown.
  - There is significant overlap with the South Pole Telescope and VISTA surveys in different wavelength bands.
  - The small squares are for the supernovae survey (not to scale).

DES Science - I

- In the early universe, sound waves propagated in a relativistic plasma of protons, electrons, photons, etc.
  - When the electrons and protons recombined, and the photons no longer immediately re-ionized them, the sound speed dropped and wave propagation ended.
  - The time from the origin of perturbations giving the sound waves until the recombination, multiplied by the predicted sound velocity, gives a characteristic distance scale of ~ 150 Mpc ~ 450 M ly.
    - In these perturbations, the dark matter density grew in place, while the increased pressure pushed the baryons away / outward.
  - Looking for correlations of distances between galaxies should show evidence for a bump at this scale due to these sound waves (this is termed **Baryon Acoustic Oscillations**).
  - The Sloan Digital Sky Survey group performed such an analysis on ~ 47K luminous red galaxies with $0.16 < z < 0.47$.
    - D.J. Eisenstein et al., Ap. J. 633, 520 (2005)

DES Science - I (cont.)



Curves with different amounts of matter and dark matter

- The two-point correlation function is plotted vs. separation distance between galaxy pairs.
  - This correlation function describes the probability that another galaxy lies within the separation distance from an arbitrary galaxy.
- A smooth curve (no bump) would suggest no Baryon Acoustic Oscillations.
- Note in this plot, $h = H_0 / 100 \text{ km sec}^{-1} \text{ Mpc}^{-1} \sim 0.7$, so the peak is ~ 150 Mpc!

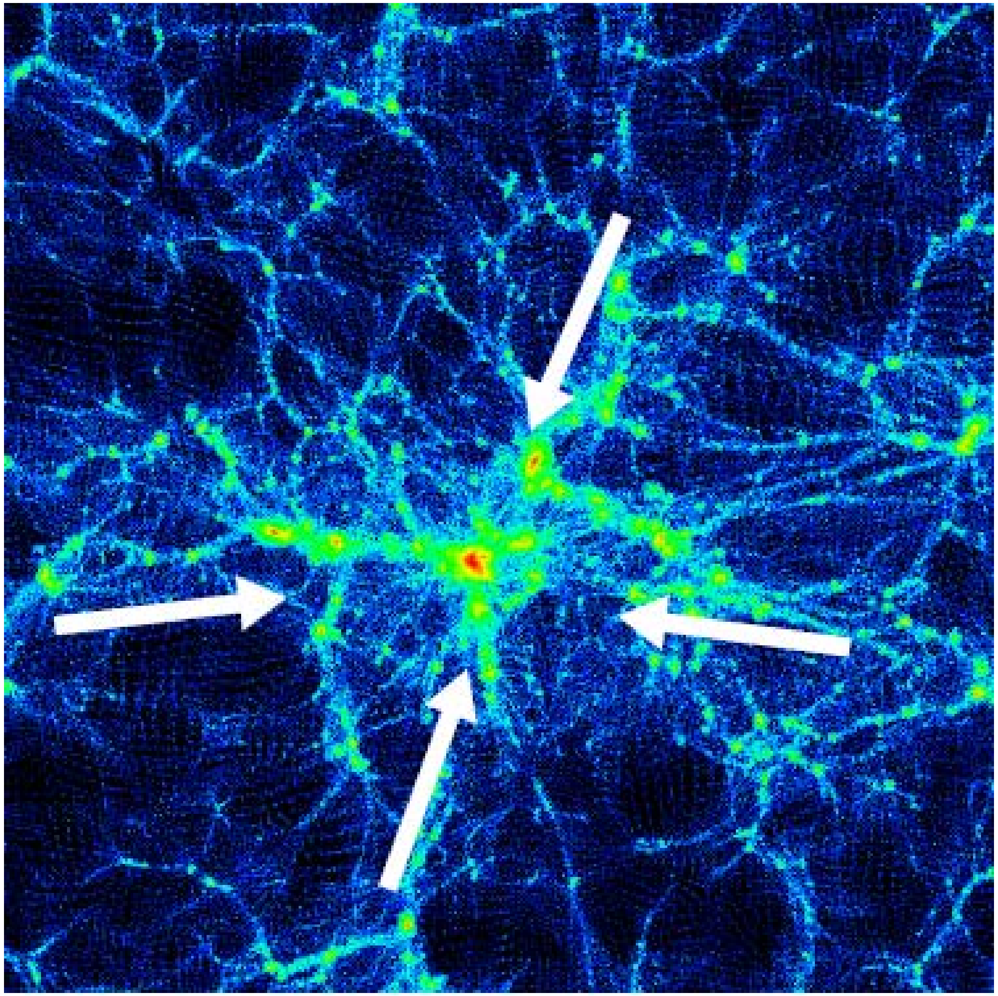
DES Science - I (cont.)

- The position of the peak in the two-point correlation function is predicted to move depending on *w(z)*.
- DES will measure ~ 300 M galaxies over a broader redshift range and will thus provide constraints on both w_0 and w_a.
  - How large is the characteristic distance scale as a function of redshift? Changes to *w(z)* provide differences in the scale.
- These results are somewhat complementary to the cosmic microwave background (CMB) data which show peaks in the multipole decomposition of the temperature of the CMB.
  - The CMB originated at the time of recombination of electrons with protons or other nuclei.

DES Science - II

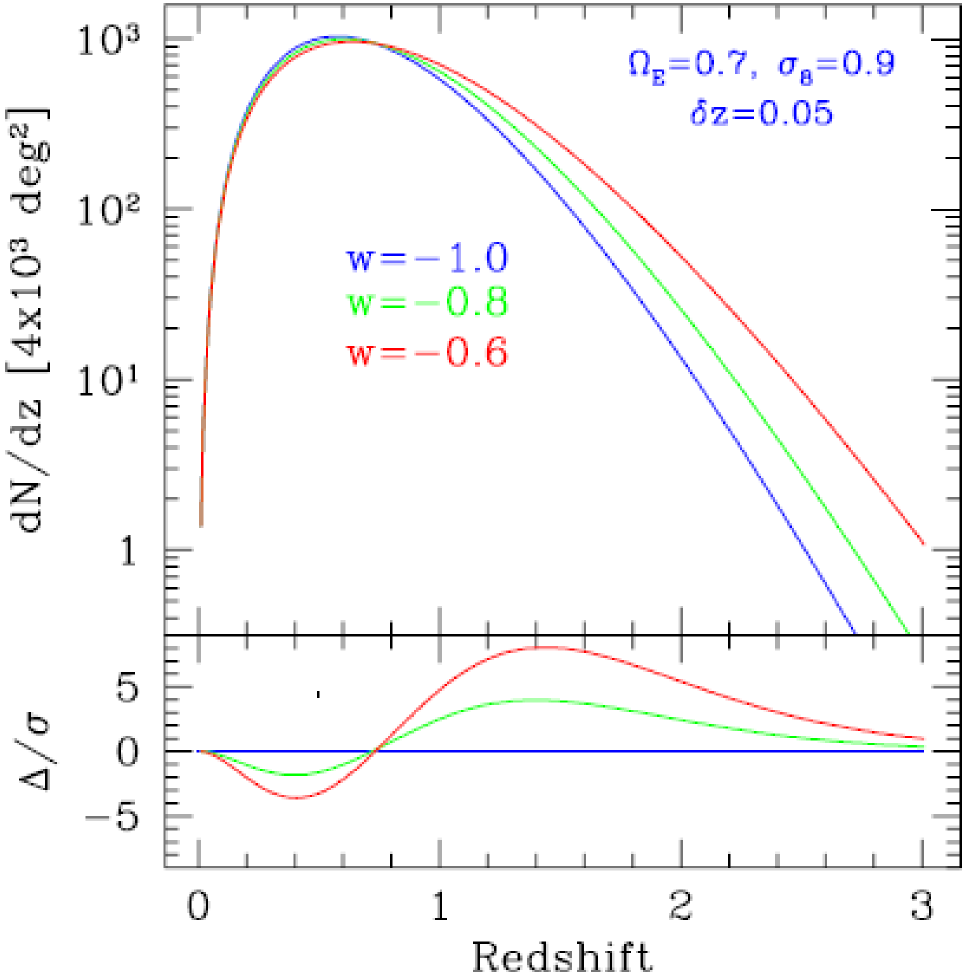
- Among the huge number of galaxies detected, there will also be lots of (~100,000) galaxy clusters observed.
- Another method to set limits on dark energy parameters is to **count the number of galaxy clusters of a particular mass range in bins of redshift**.
  - Dark energy influences how the universe expands and hence the volume.
  - The formation of galaxy clusters is affected by a combination of gravity (attractive) and dark energy (repulsive).
  - Measuring as a function of redshift allows distinguishing differences in w_0 and w_a.
- There are problems calibrating the galaxy cluster masses.
  - Some other properties seem correlated with mass.
  - Cross check with South Pole Telescope results on ~ thousands of galaxy clusters using gravitational lensing from the clusters. The SPT observes in the microwave range.

DES Science - II (cont.)



- Clusters form through merging and accretion of smaller objects.
  - Based on simulations, matter collects in filaments, then flows towards intersections.
  - Rich clusters lie at these intersections.
- Expected cluster composition
  - ~ 1% galaxies
  - ~ 10% intracluster gas
  - ~ 90% dark matter

DES Science - II (cont.)



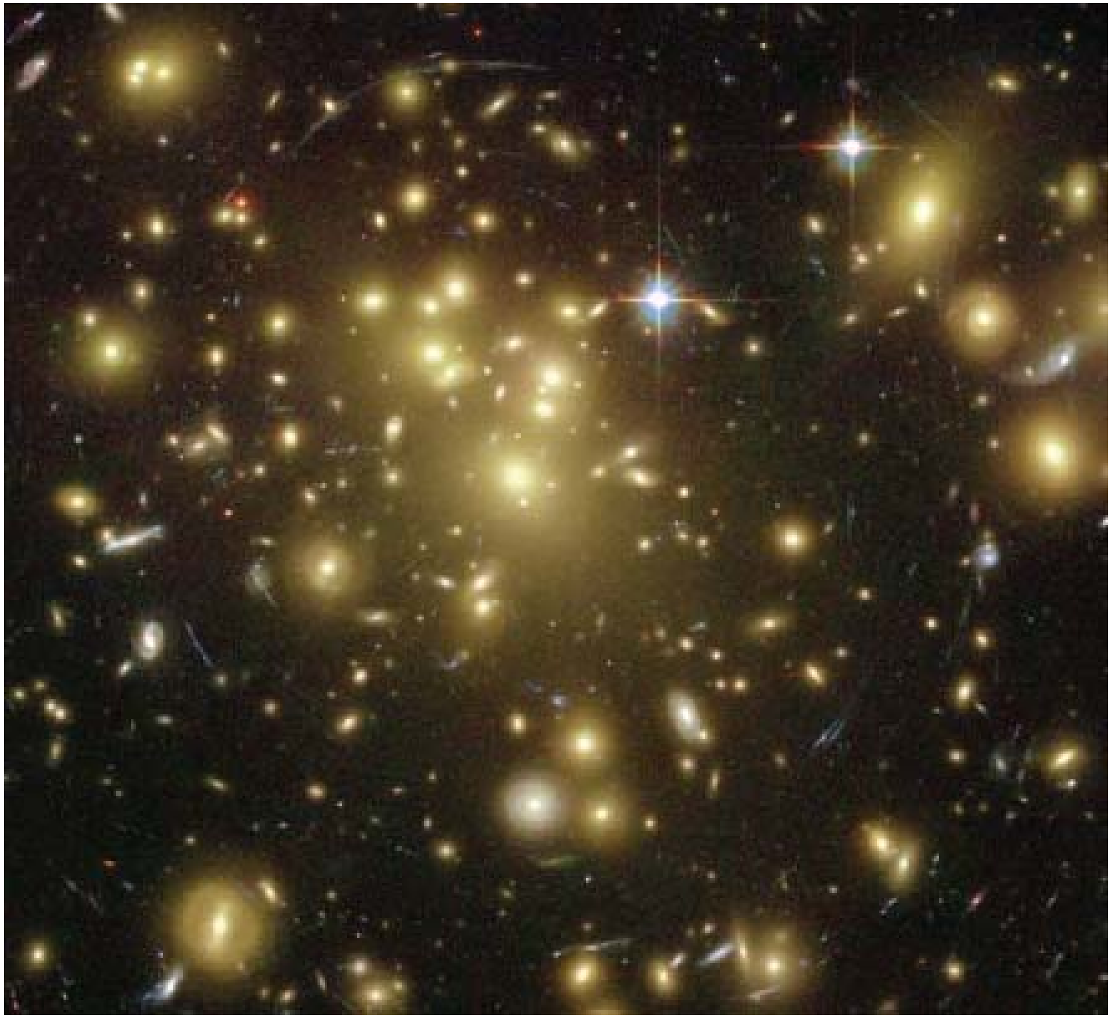
From J.J. Mohr, Proceedings of the 2004 NOAO "Observing Dark Energy" Meeting

- Estimates of the variation in galaxy cluster counts vs. redshift for several values of w_0.
- Galaxy clusters are the largest gravitationally bound objects in the universe (~10^{13} – 10^{15} solar masses).
- Note, σ_8 is related to the density fluctuations in a sphere of radius 8 h^{-1} Mpc. And Ω_E is the fraction of dark energy.

DES Science - III

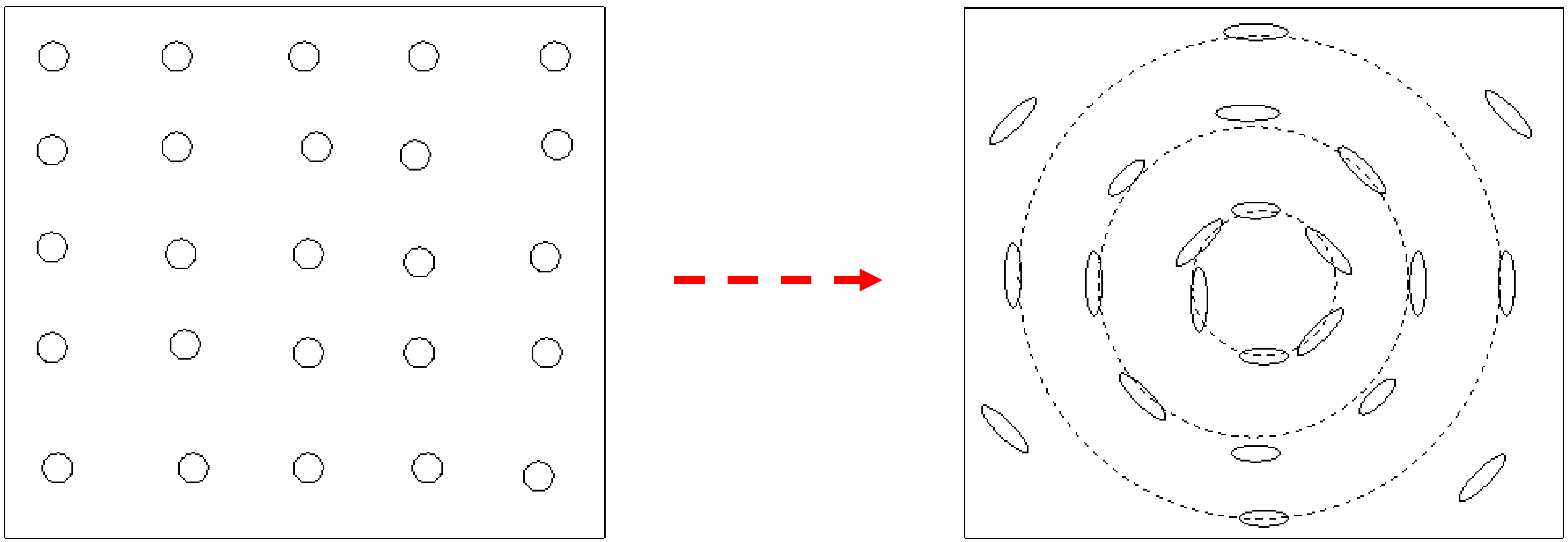
- The shapes of many of the ~ 300 M galaxies observed by DES will be distorted by **weak gravitational lensing**.
  - This can also be used on a statistical basis to study dark energy.
  - Bin the observed galaxies in redshift, and study the amount of lensing vs. redshift.
  - The distances to the galaxies are related to the geometry of the universe.
  - The foreground mass distribution causing the lensing is dependent on the growth of structure, such as galaxy clusters, which is a balance between gravitational attraction and dark energy repulsion.
- This requires that optical images have no distortions due to the telescope or camera.
  - Problems found near CCD edges.
  - Desire best seeing conditions for the measurements.

DES Science - III (cont.)



- A Hubble Space Telescope image of Abell 1689
  - $z = 0.18$
  - Mass ~ 10^{15} solar masses
  - 34 multiply imaged weak-lensed galaxies shown.

DES Science - III (cont.)

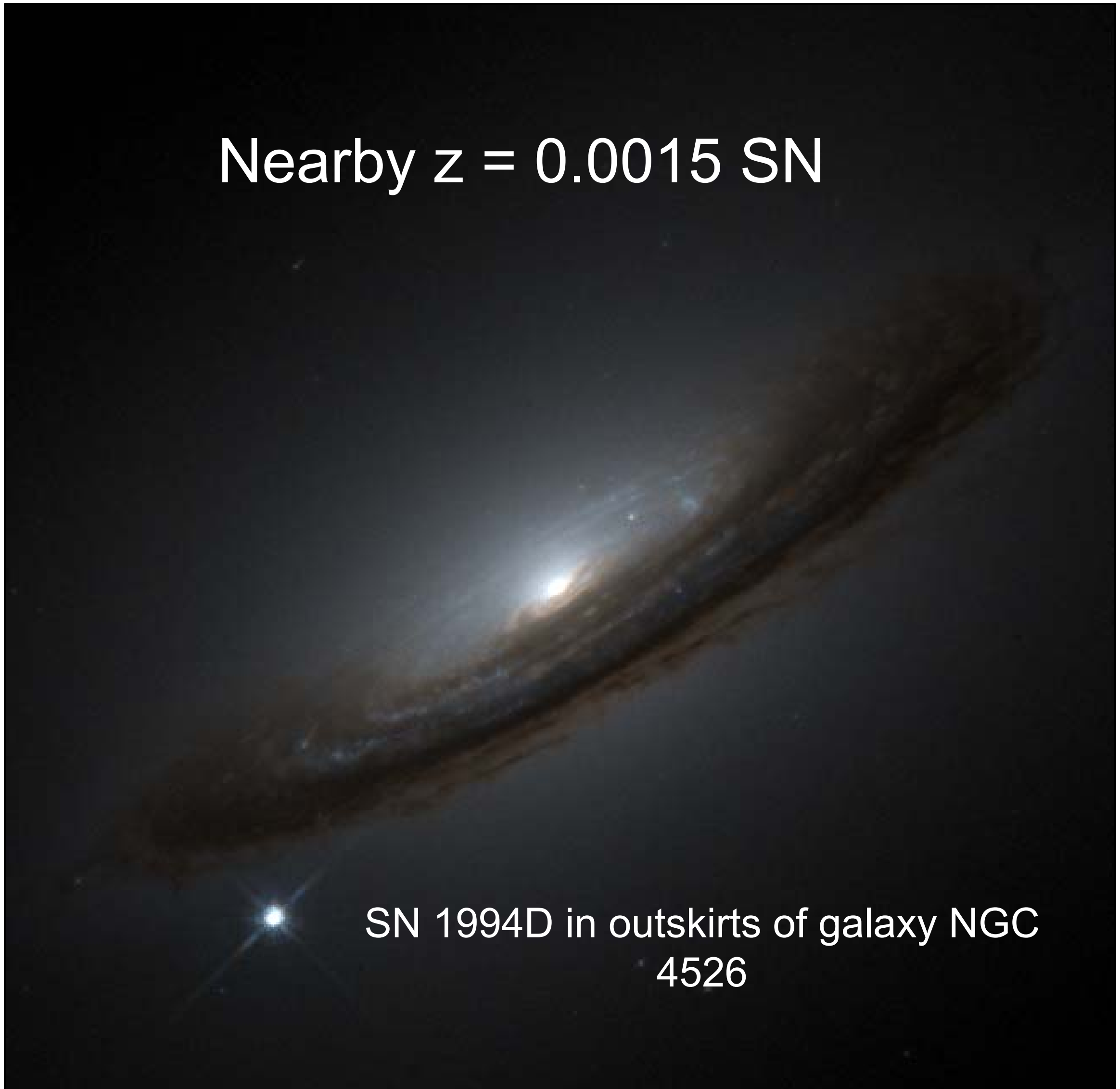


- A very simplified, non-accurate description of the effects of weak lensing is shown.
  - A field of evenly spaced circles is in the background.
  - A massive object is in the center between these objects and causes distortion of their shapes.
- Real galaxies are elliptically shaped as we view them, so things are more complicated.

DES Science - IV

- A special type of supernovae (SNe), type Ia, has been used as a standard candle and led to the discovery of dark energy. DES will also use these as a DE probe.
  - These are thought to be white dwarf stars in a binary star pair.
  - They begin with a large mass of carbon and oxygen.
  - They are believed to be accreting material from their partner until they reach the Chandrasekhar mass limit (~ 1.3 solar masses), when they explode as a supernova.
  - Until recently, simulations have been unsuccessful at reproducing these explosions. Gravity has overcome the initial outflow of mass in these calculations.
- There are other types of SNe, called core-collapse supernovae, that start out as massive stars.
  - There are various types, and astronomers have not figured out how to use them as standard candles (yet).

DES Science - IV (cont.)

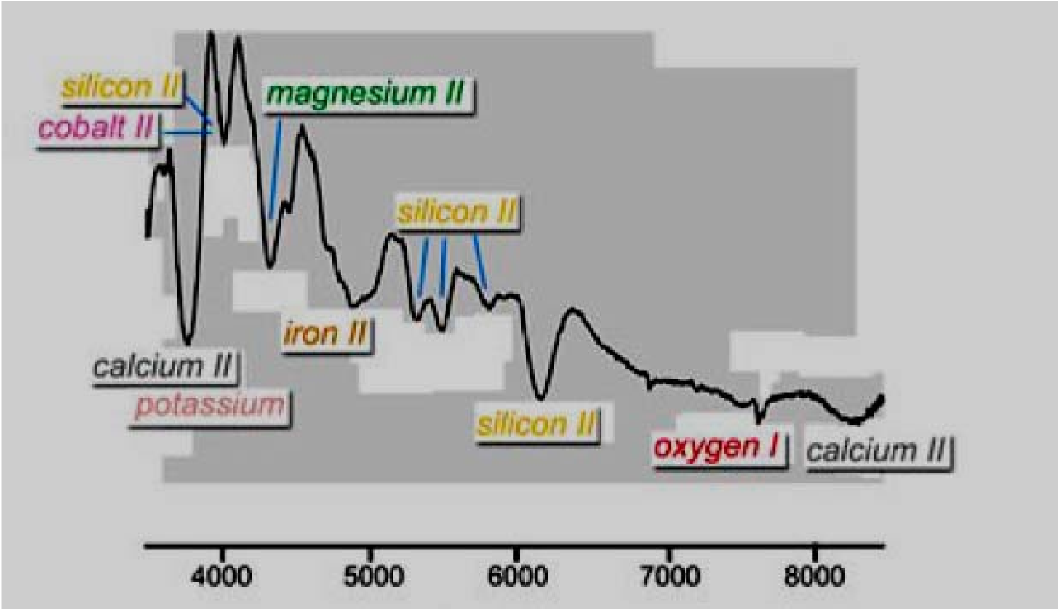


- For a few weeks, a supernova can be bright enough to rival its host galaxy's light.
  - From High-z Supernova Search Team, Hubble Space Telescope, NASA

DES Science - IV (cont.)

Filter	Wavelength Range (nm)	Exposure Time (s)
g	400-550	300
r	560-710	1200
i	700-850	1800
z	850-1000	4000

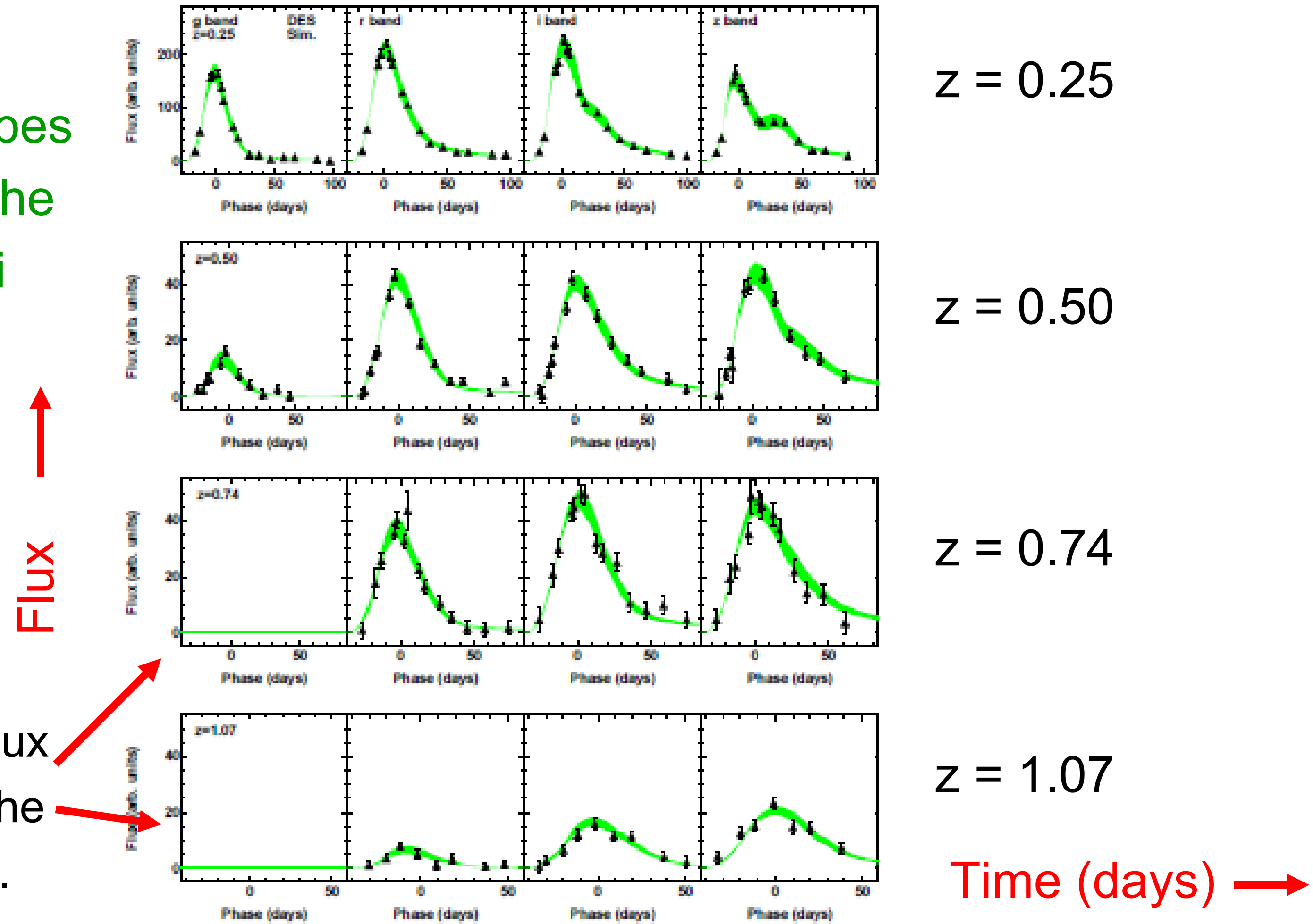
Exposure times for simulations



- A spectrum from a nearby SNe Ia near maximum intensity is shown with various absorption features indicated.
  - Note the wavelength scale is in Angstroms = 10 nm.

DES Science - IV (cont.)

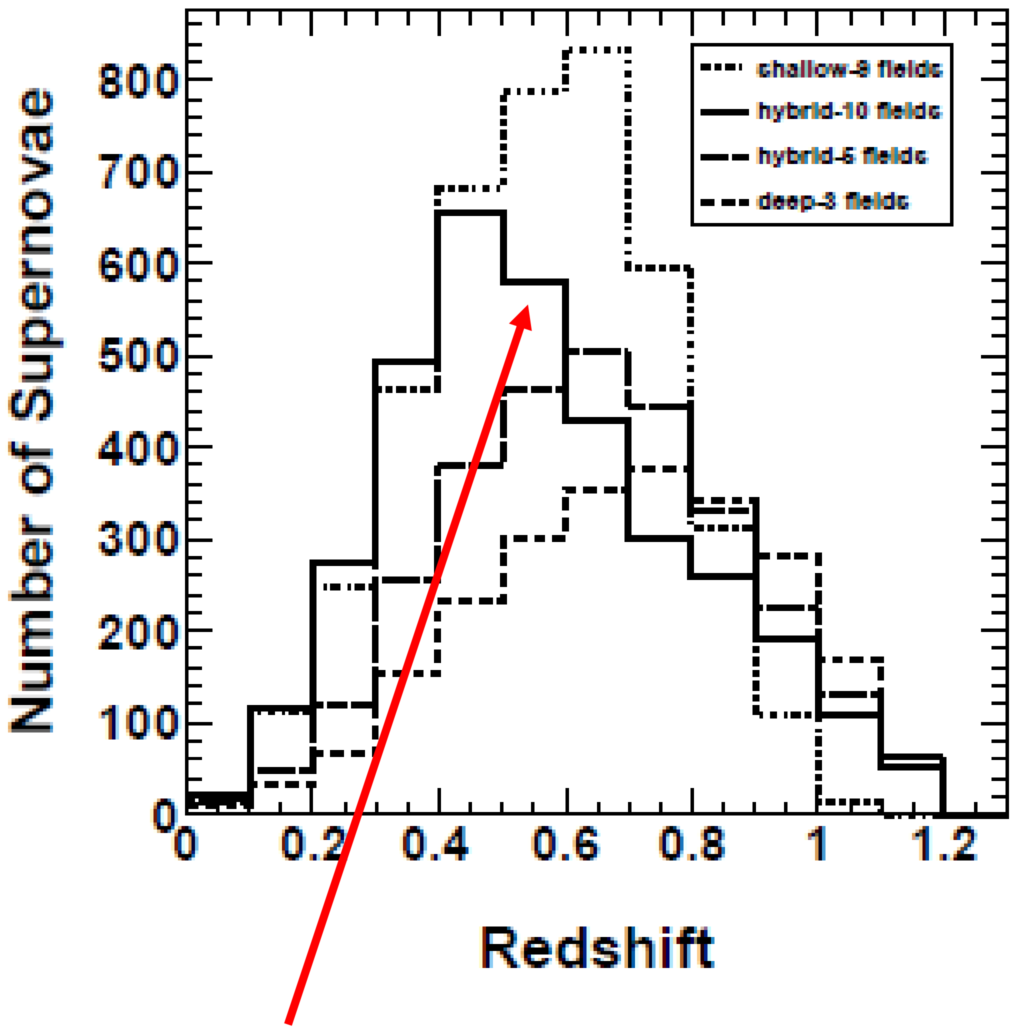
Light curve shapes dominated by the decay of ^{56}Ni



Note the lack of flux in the g-band at the higher redshifts.

- Predicted light curves for type Ia SNe at various redshifts in the four filters (g, r, I, z-bands).

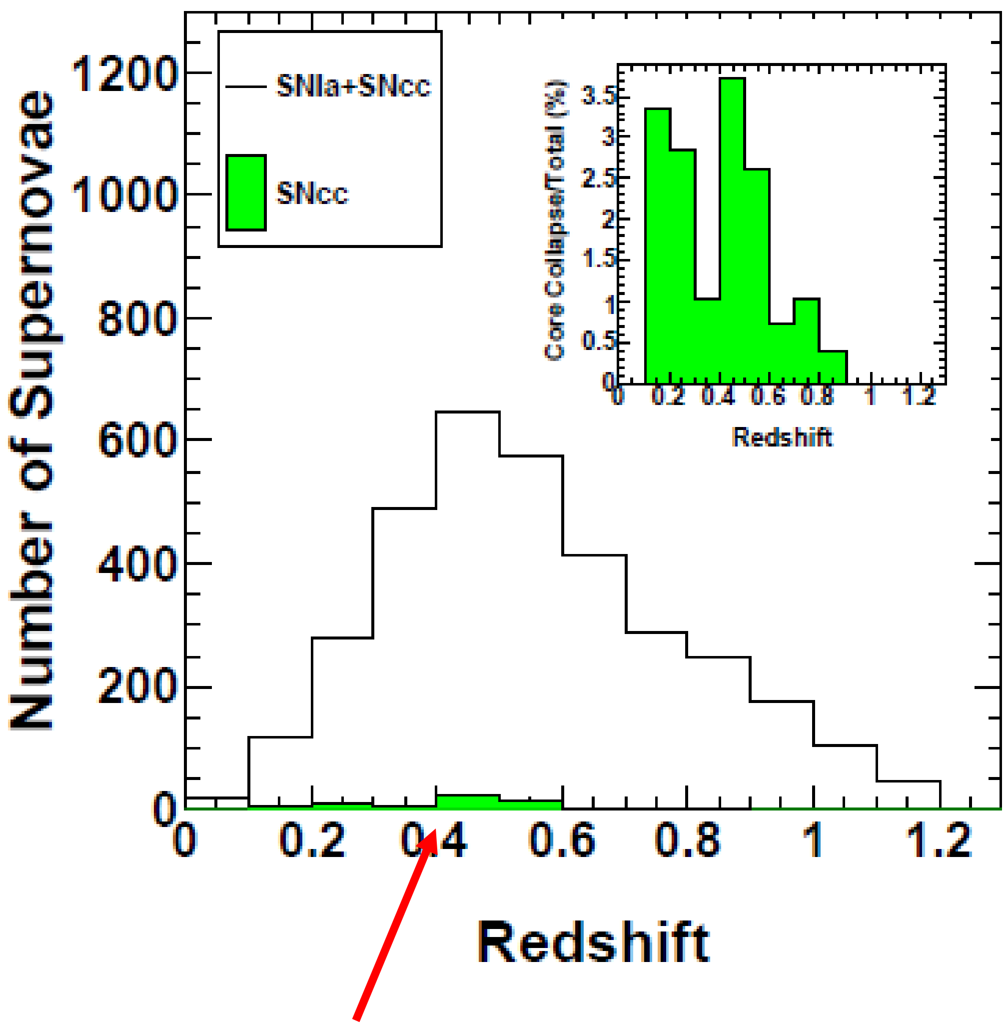
DES Science - IV (cont.)



Tentatively choose the hybrid 10-fields case.

- The time allocated for supernova measurements is ~ 10% of the total.
  - In addition there will be some amount of "non-photometric" time.
- Simulations were performed to optimize the use of the available time.
  - Includes weather, clouds, the moon, seeing, …

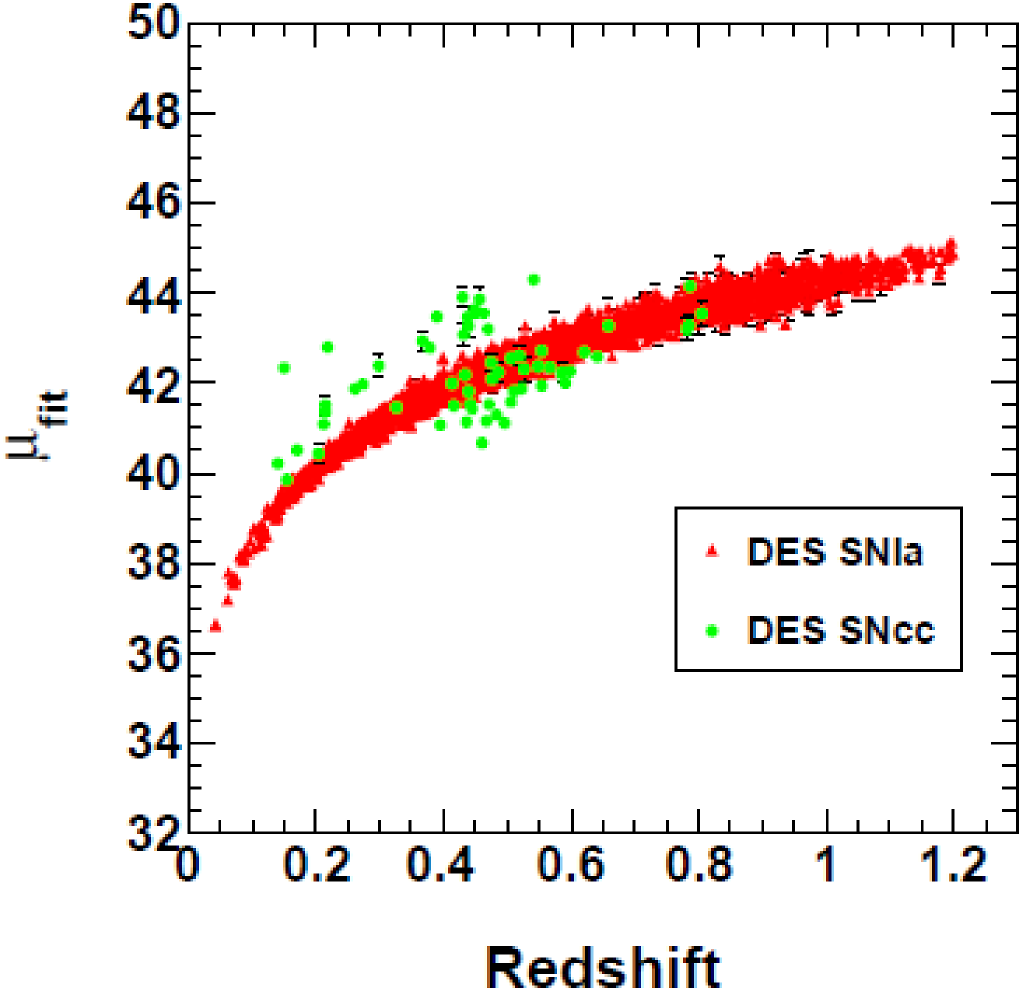
DES Science - IV (cont.)



Small backgrounds expected.

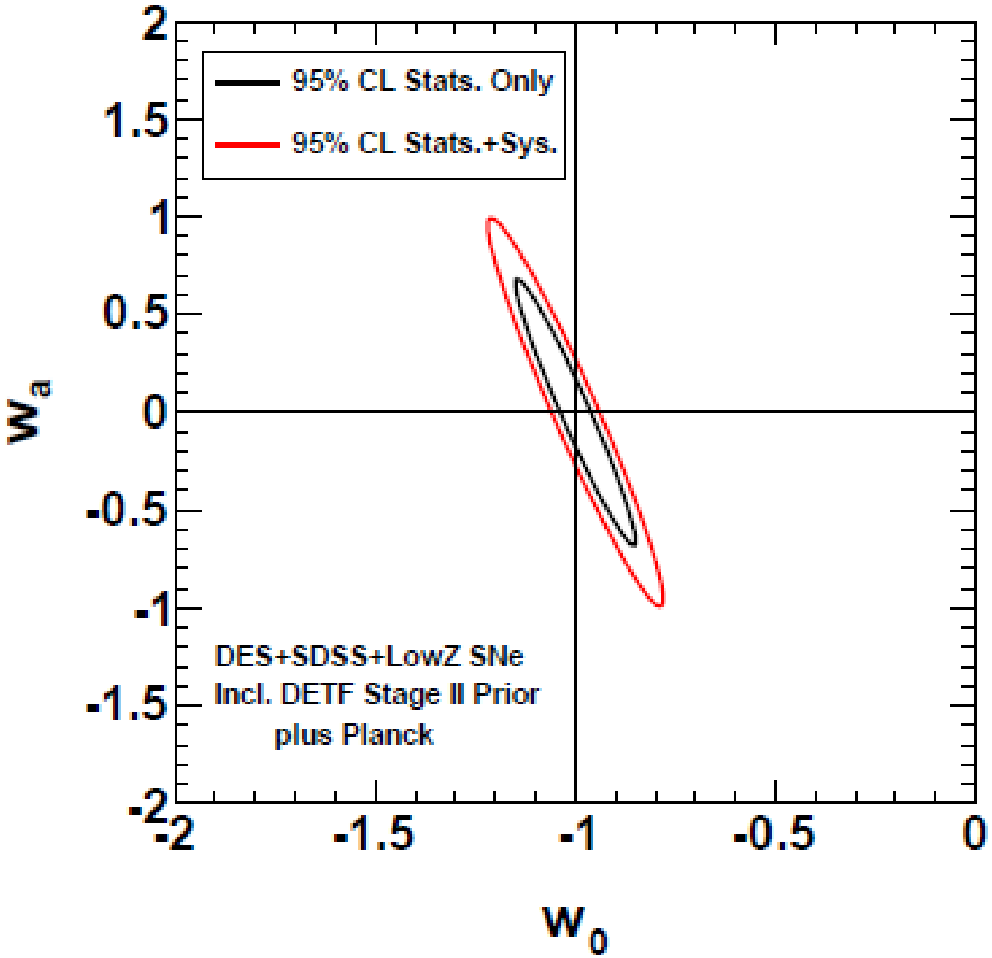
- Backgrounds from other types of SNe were simulated.
  - Unfortunately, there were few “templates” for light curves from these other types of (core collapse) SNe.
  - A special simulation package, SNANA, written mostly by Rick Kessler of U. Chicago, was used for these studies.
  - Lots of help from three ANL colleagues.

DES Science - IV (cont.)



- The location of these background, core-collapse SNe is shown.

DES Science - IV (cont.)



- A figure of merit for the dark energy measurements can be defined in terms of the area of the uncertainty ellipse in w_0 - w_a space.
  - A paper with the simulations and the estimate of systematic uncertainties, etc. has been submitted to Ap. J.
  - This is not usually done for astronomical surveys.

Summary

- Observations show the universe is composed of only ~ 5% stars and interstellar/galactic gas.
  - Plus ~ 21% dark matter plus ~ 74% dark energy.
- It is unknown exactly what the dark energy is:
  - Various theories – and associated problems.
- The Dark Energy Survey will try to put much better constraints on the properties of dark energy
  - Using 4 different types of measurements.
  - Is DE a cosmological constant?
  - Does it vary with time / redshift?
- We are working towards "first light" in roughly a year. We hope to have some interesting science results to share soon afterwards.

The Blanco telescope dome at Cerro Tololo, Chile. Single, non-composite image taken using a 2Kx2K scientific CCD temporarily mated to a custom camera. 20 sec exposure, 40mm f/4 lens, starlight only.
Credit: Roger Smith/NOAO/AURA/NSF

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Photo: Ariel Zambelich, Copyright © Nobel Media AB

Saul Perlmutter

Photo: Belinda Pratten, Australian National University

Brian P. Schmidt

Photo: Homewood Photography

Adam G. Riess

The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"*.

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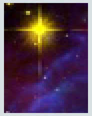

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Star Stories
The Nobel Prizes have rewarded many advances that revealed the secrets behind the life and death of stars.

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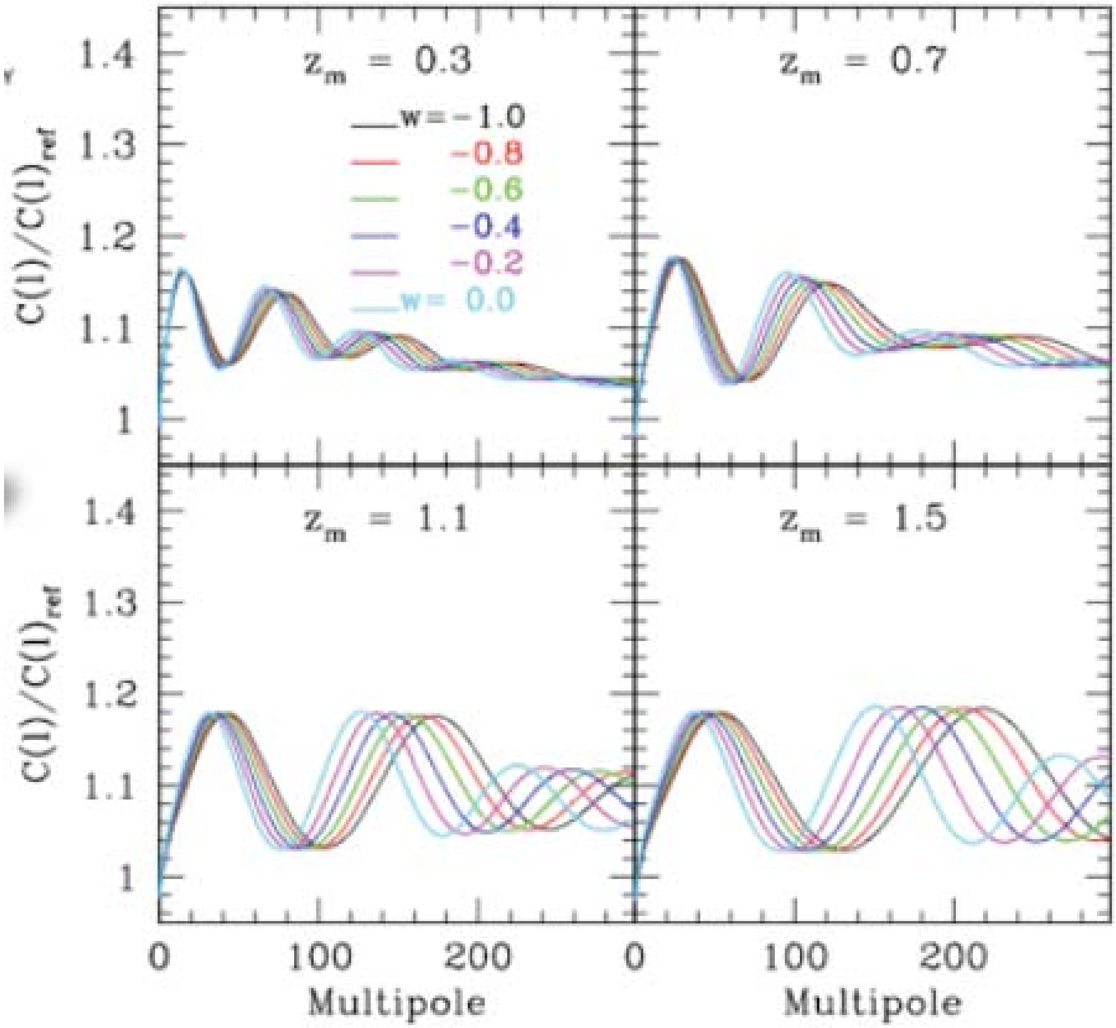
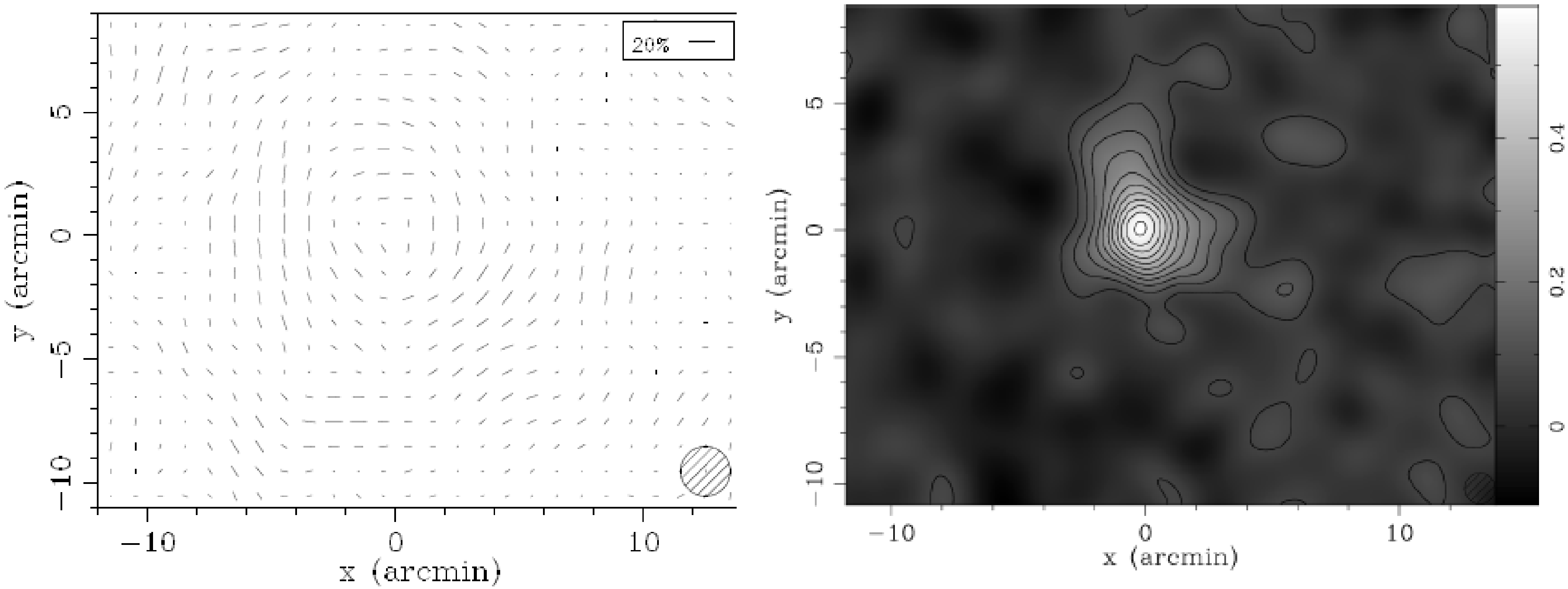
Internet 100%

DES Science - I (cont)



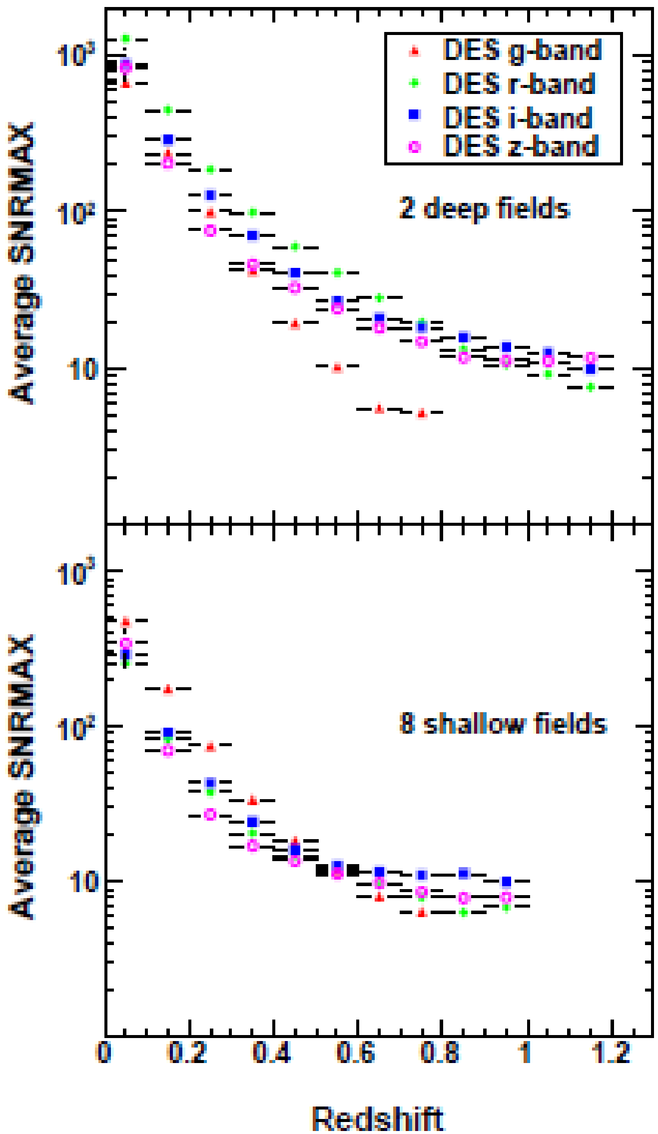
- Estimated differences in multipole decomposition for the Baryon Acoustic Oscillations at different redshifts.

DES Science - III (cont.)



- A weak lensing measurement example is shown.
  - 5700 background galaxies, with a galaxy cluster in the foreground causing shears, and the reconstructed mass distribution on the right.

DES Science - IV (cont.)



- The present nominal survey for supernovae includes two “deep fields” at 1/3 of the time each, and 8 shallow fields at 1/24 of the time each.
  - The predicted signal to noise ratio in each filter / band is shown for the two types of fields.
  - Typically a requirement of one observation with SNR > 5 or 10 is applied to SNe candidates.

PreCam

- A small, 2 2K x 4K pixel CCD camera was constructed and used on a small telescope at Cerro Tololo, Chile.

PreCam (cont.)

- The purposes of the observations with the small CCD camera were:
  - Create a network of DES calibrated g, r, i, z stars (note existing standard stars would saturate DECam in extremely short exposure).
  - Tie together the DES photometry over the whole 5000 deg^2 survey region.
  - Test hardware and software planned for DECam.
  - Used the U. of Michigan's Curtis-Schmidt telescope (shown).

PreCam (cont.)

- The camera, electronics, vacuum line, and electronics cables are shown mounted on the telescope.