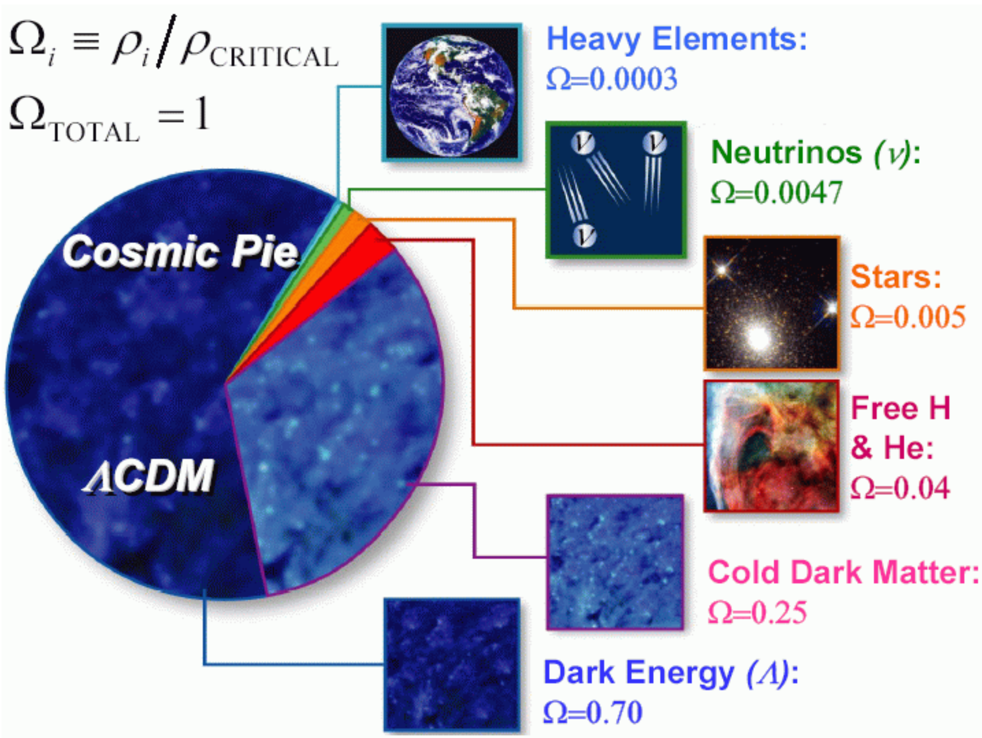
Dark Energy: The missing 70% of the Universe

Brenna Flaugher
Fermilab

Cosmic Pie



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

1998 and 2003 Science breakthroughs of the year

Outline

- A few definitions and concepts
- Cosmology today
- Evidence for Dark Matter
- Evidence for Dark Energy
- Targeted Dark Energy Project: The Dark Energy Survey
  - Science plans
  - Instrumentation

Revelations of the past decade: Dark Matter and Dark Energy

Most of the Mass in the Universe is **DARK – we can't see it**

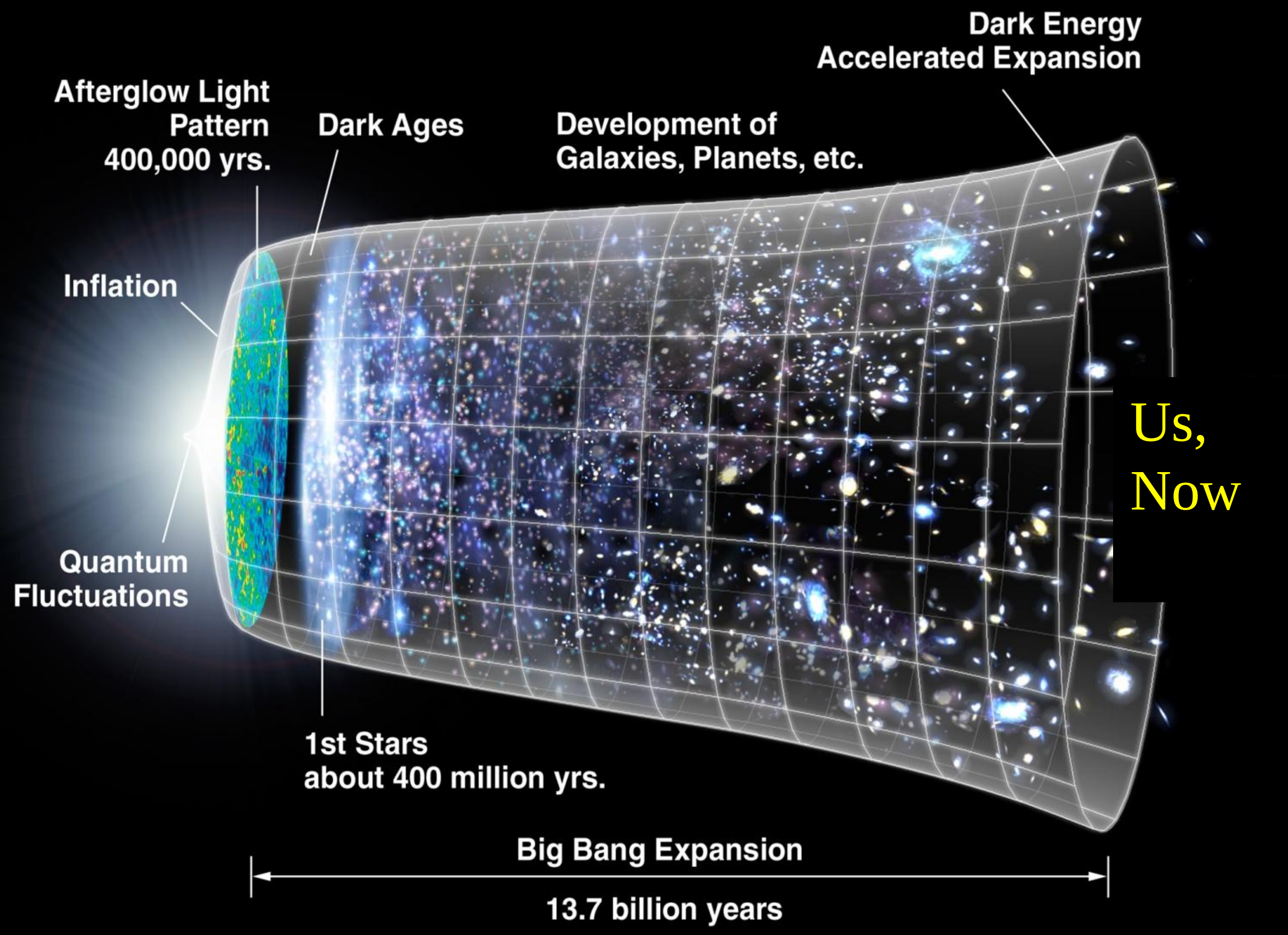
Dark Matter: any matter whose existence is inferred solely from its gravitational effects (i.e., does not emit light)

It also turns out that just summing up the matter (dark and luminous) does not agree with the observed expansion rate of the universe

Dark Energy: some sort of energy whose existence is inferred from expansion rate of the universe

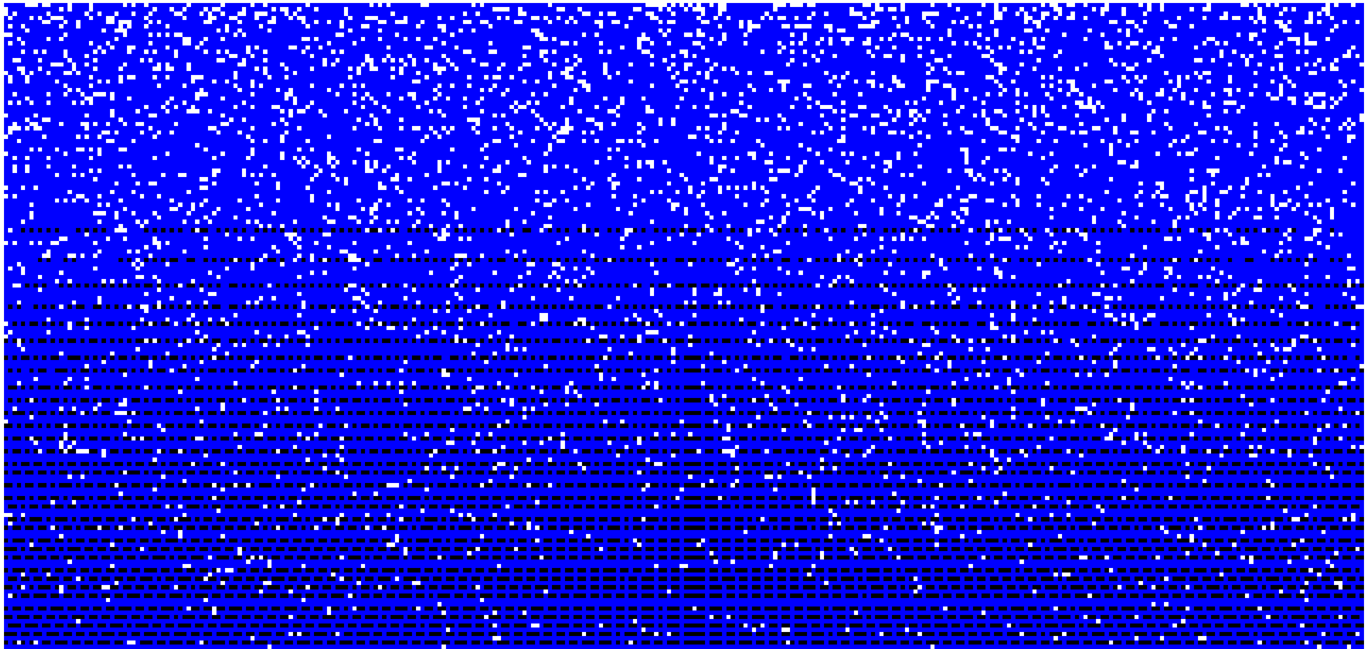
Two broadly defined approaches to constraining DM and DE:
Measure the expansion rate of the universe
Measure the rate of growth of structures in the universe (e.g galaxies and galaxy clusters)

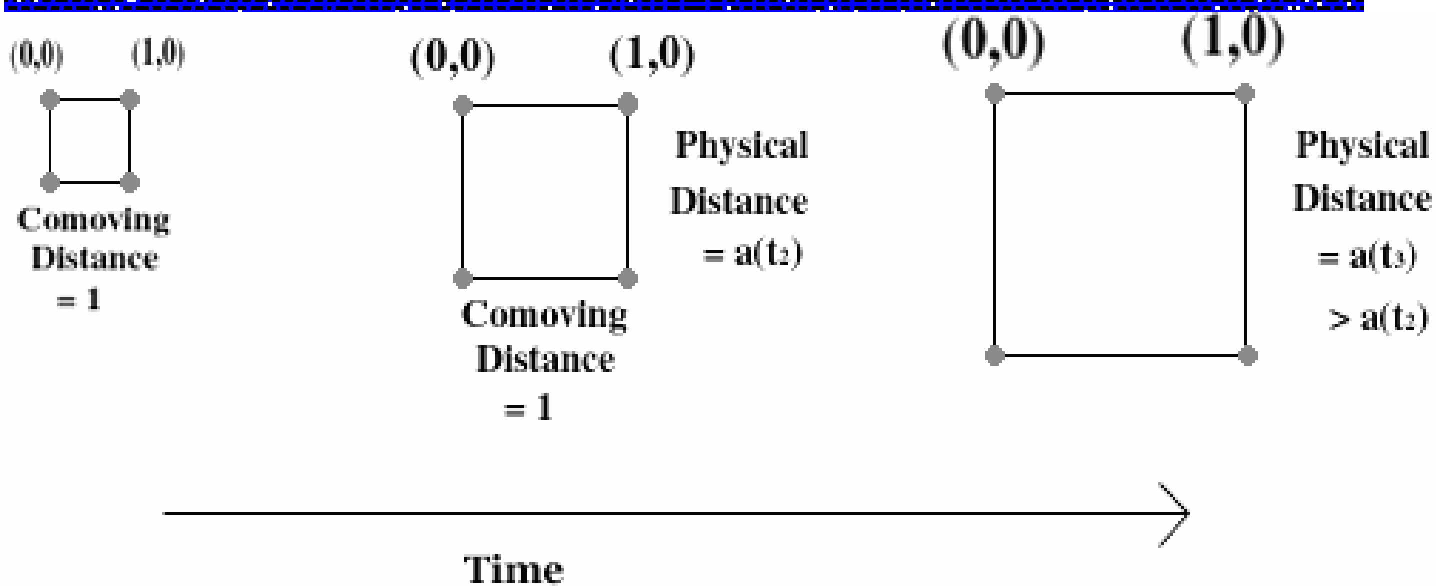
Cosmology as we understand it now



NASA/WMAP Science Team

The Universe is expanding





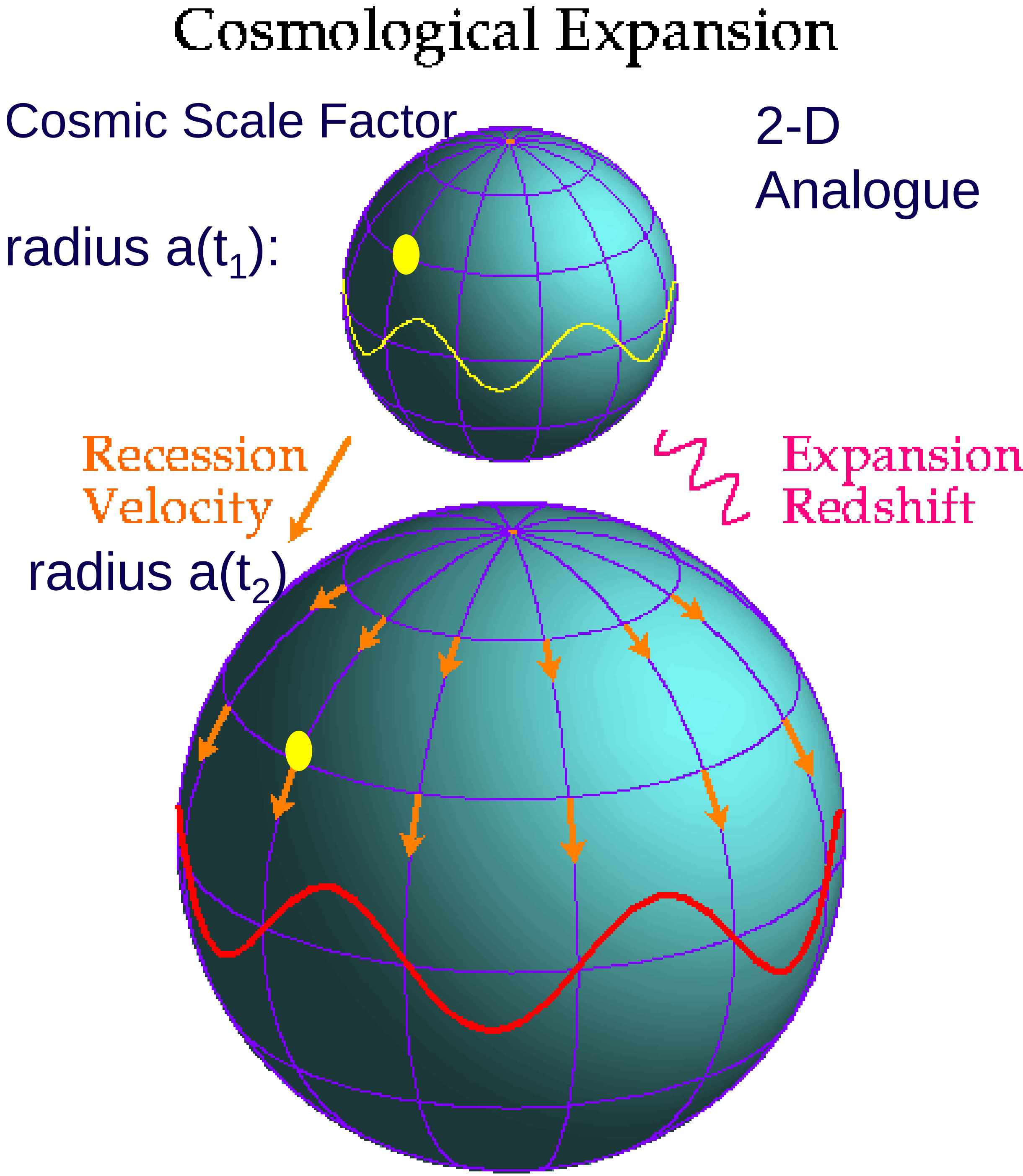
Redshift = z

$$1+z = a(t_0)/a(t_e)$$
$$= \lambda(t_0)/\ \lambda(t_e)$$

t_0 = age of U today

t_e = age when light was emitted

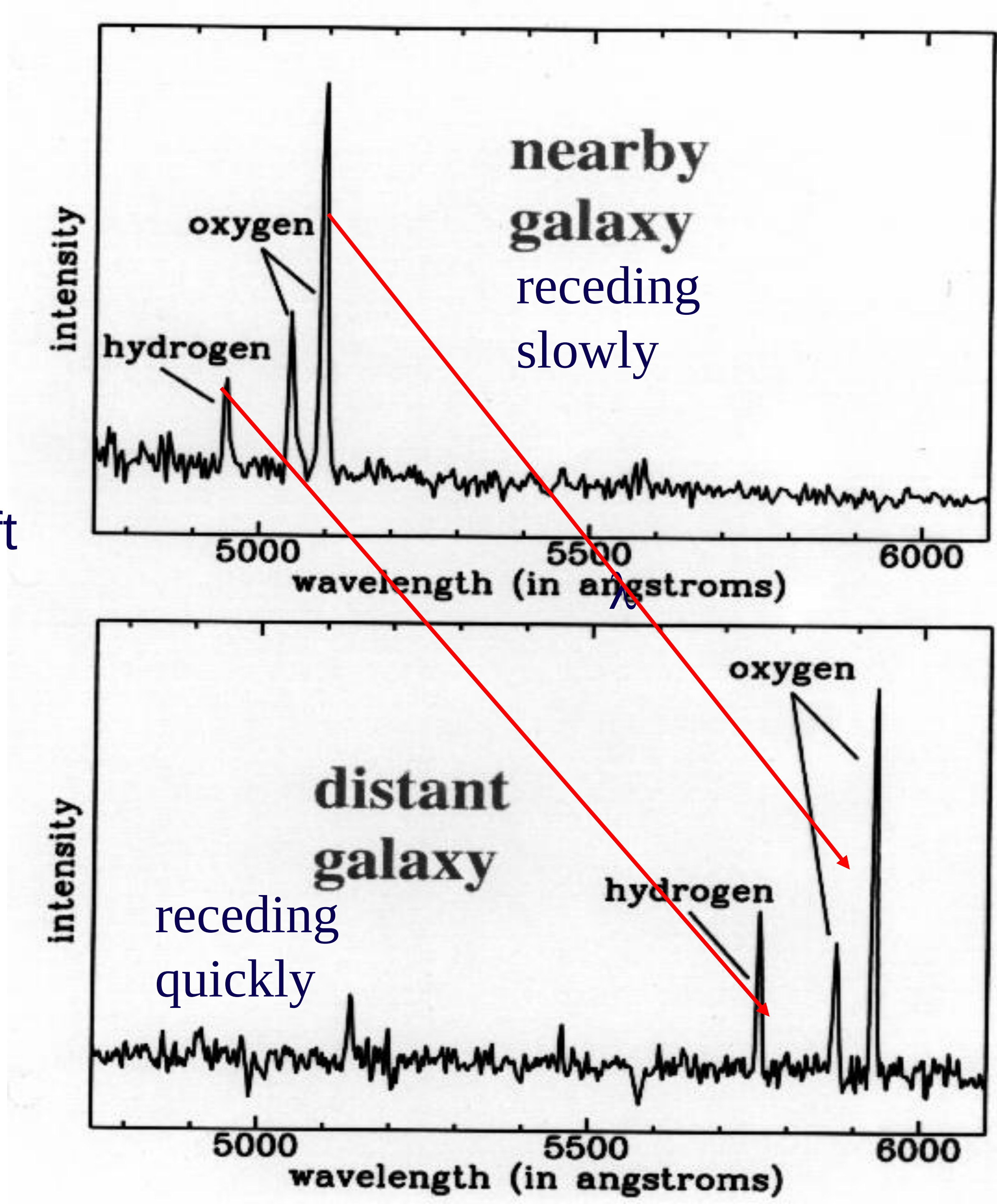
The redshift is an indication of age and distance:
z = 0 here and now
z = 1000 for the oldest photons, originating from the most distant place we can see (CMB)



Measuring redshifts with spectra

Galaxy Emission Lines are stretched to higher wavelengths as redshift increases

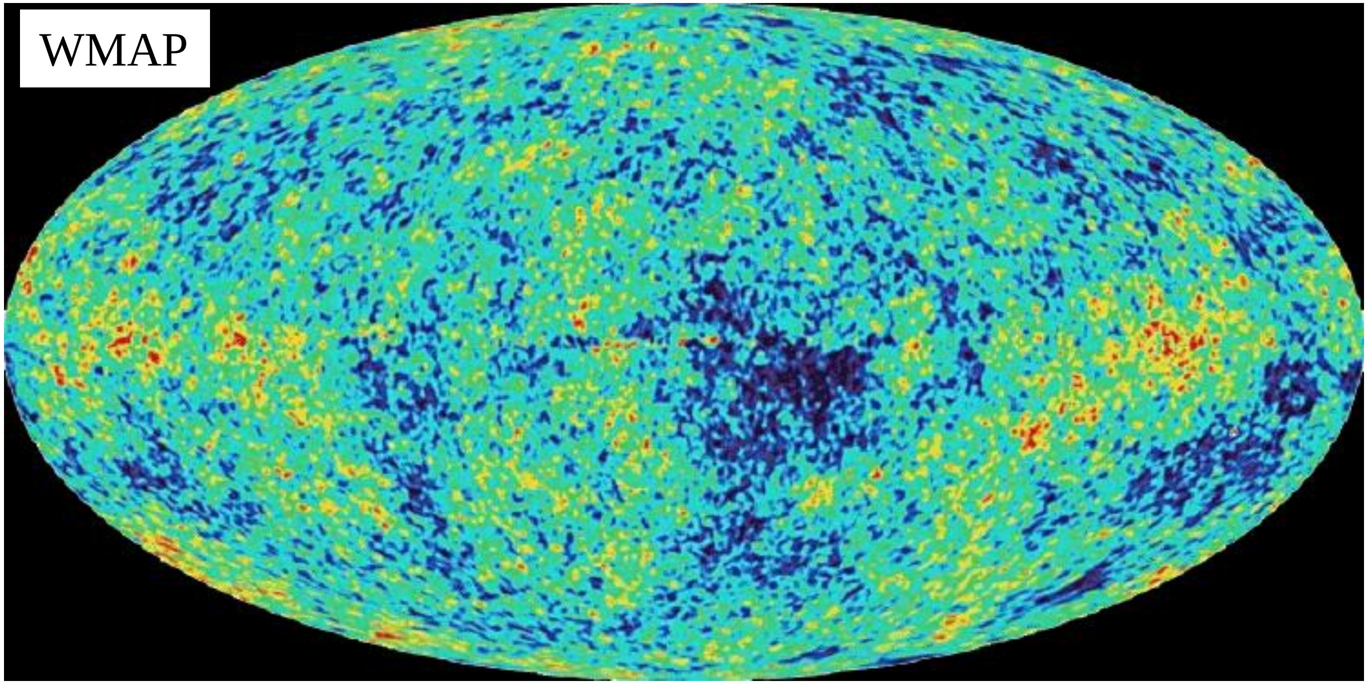
$z \sim \Delta\lambda/\lambda_e$



New (2003) picture of the **young** universe

Right after the Big Bang the photons, p, and e were in thermal eq.- a big cloud
Once things cooled off a bit, H formed and the photon interactions slowed way down – meaning the photons got away – these are the CMB photons

CMB radiation density field at z ~ 1000 when the Universe was ~400,000 years old

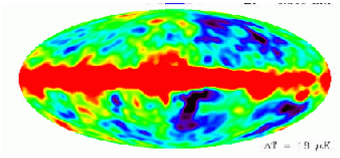


Red:
2.7+0.00001 deg

Blue:
2.7-0.00001 deg

Scale of the Observable Universe:
Size ~ 10^{28} cm
Mass ~ 10^{23} M_{sun}

These small anisotropies in the CMB are temperature differences that could evolve into the structures (e.g. galaxies, and galaxy clusters) we see now. **2006 Nobel Prize in Physics was for the 1st measurement of this (1992, COBE)**



Measurement of the old universe (~ today)

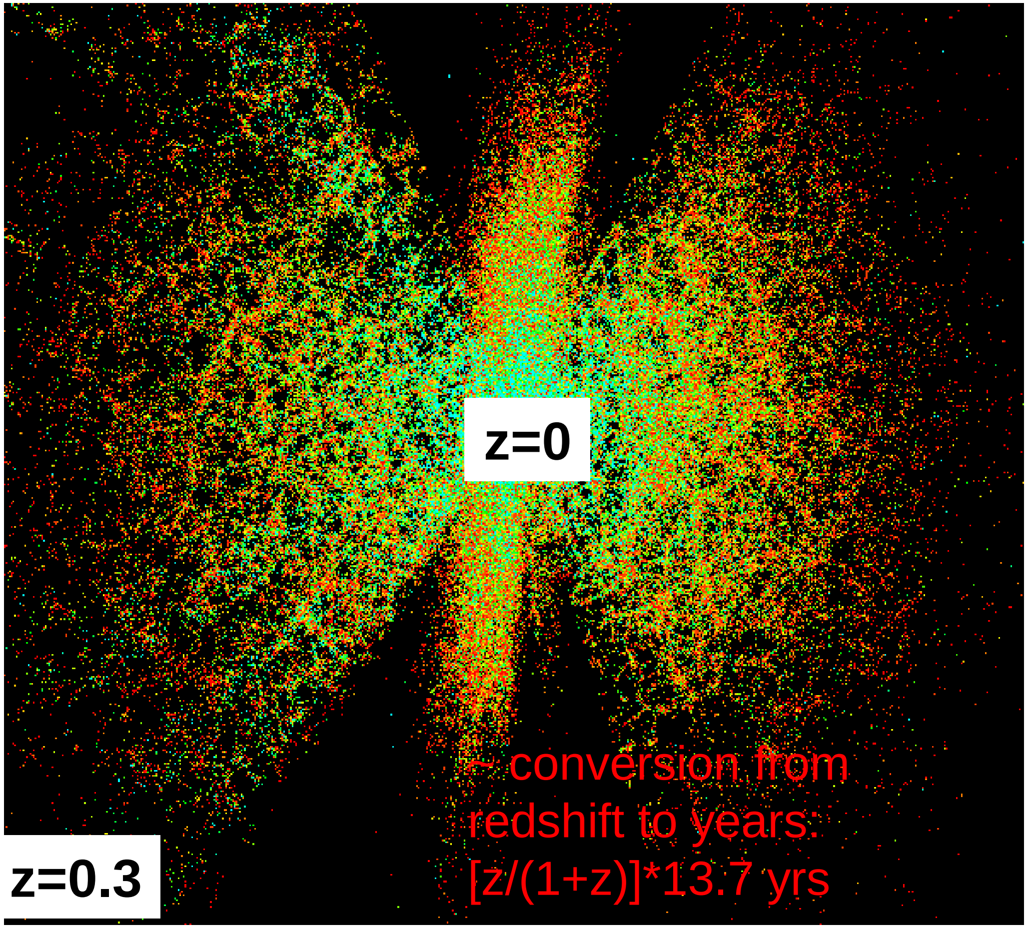
Sloan Digital Sky Survey (SDSS) measures the galaxy density field out to z ~ 0.3

Overdense regions are visible

These are clusters of galaxies

Voids and filamentary structure are also evident

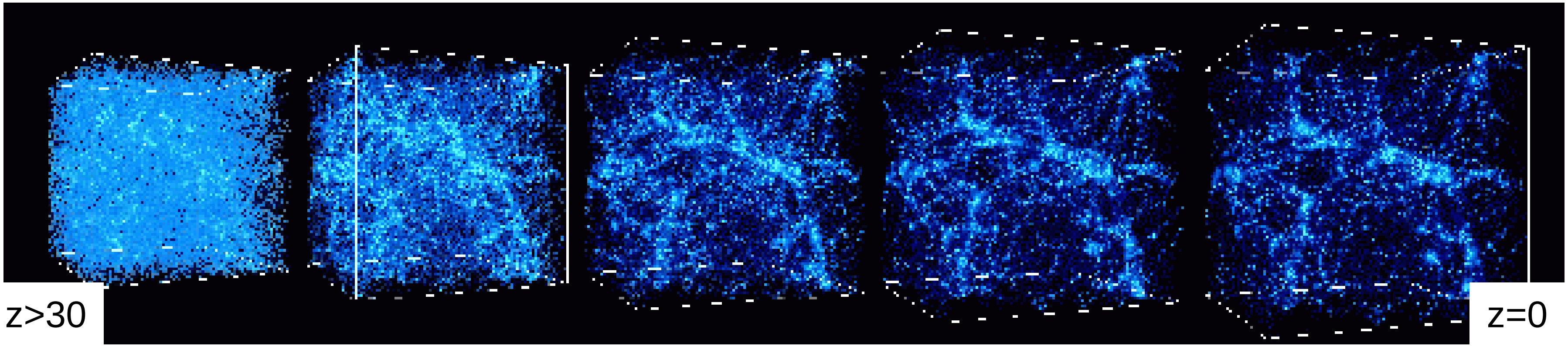
Note – the sample density drops off with z: fainter, harder to see



z = 0 is Now

z = 0.3 ~ 3 billion yrs ago

Simulation of the evolution of the Universe



~ conversion from redshift to years: [z/(1+z)]*13.7 Byrs

z = 30 is about 13.2 billion years ago (in the "dark ages")

z = 0 is now

The of growth of structure: is determined by the initial conditions (CMB), the amount and distribution of dark matter, dark energy and the expansion rate of the universe

The "discovery" of dark energy came from measuring the expansion rate of the universe with type 1A supernovae

Recent experimental and theoretical progress includes probes based to growth of structure too - different systematics, both theoretical and experimental, will provide new and tight constraints

Next few slides describe the evidence for DM and DE

Evidence for Dark Matter: Two different observations

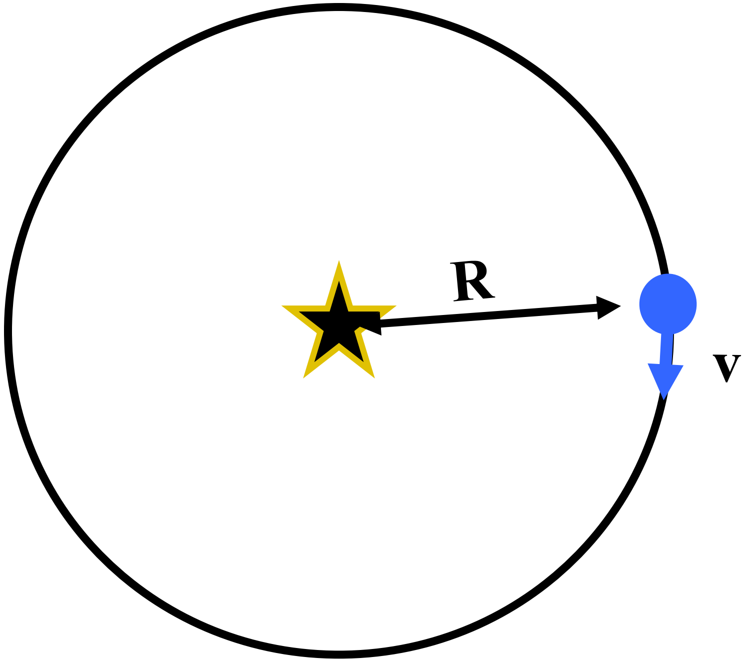
Dynamical evidence for Dark Matter:

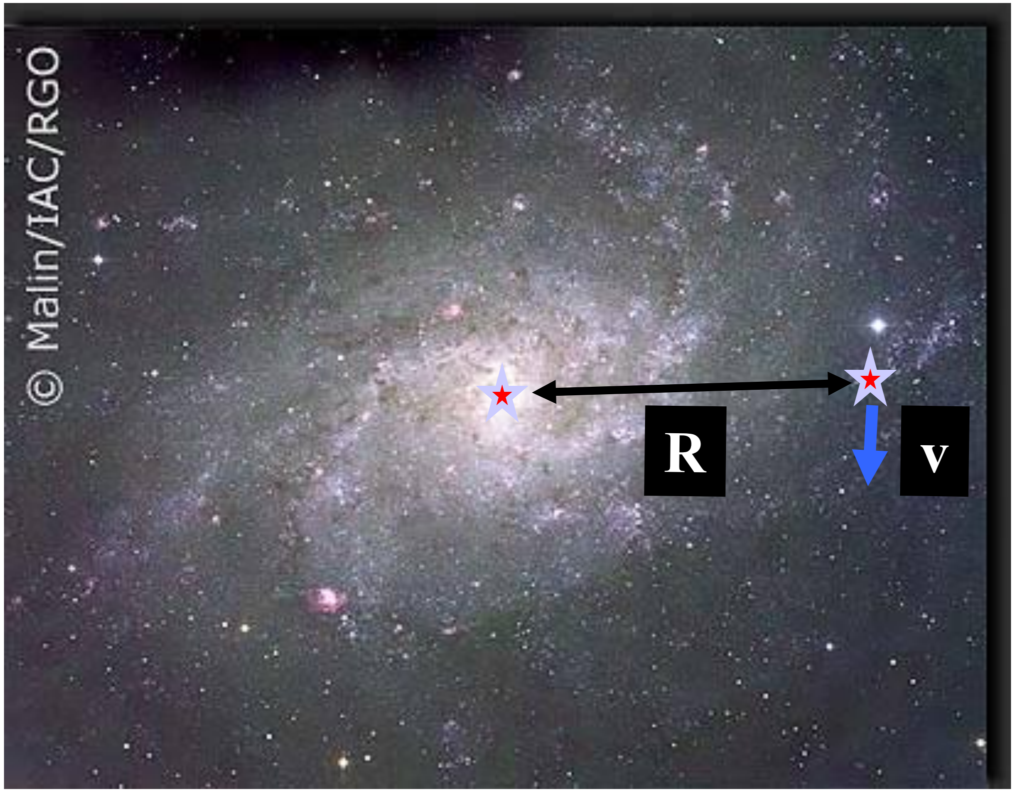
DM affects the motions of gas and stars (in galaxies) and galaxies themselves (in clusters)

Lensing evidence for Dark Matter:

DM curves spacetime and thus bends light rays coming from background sources

Galaxies: The Visible Part of our Universe

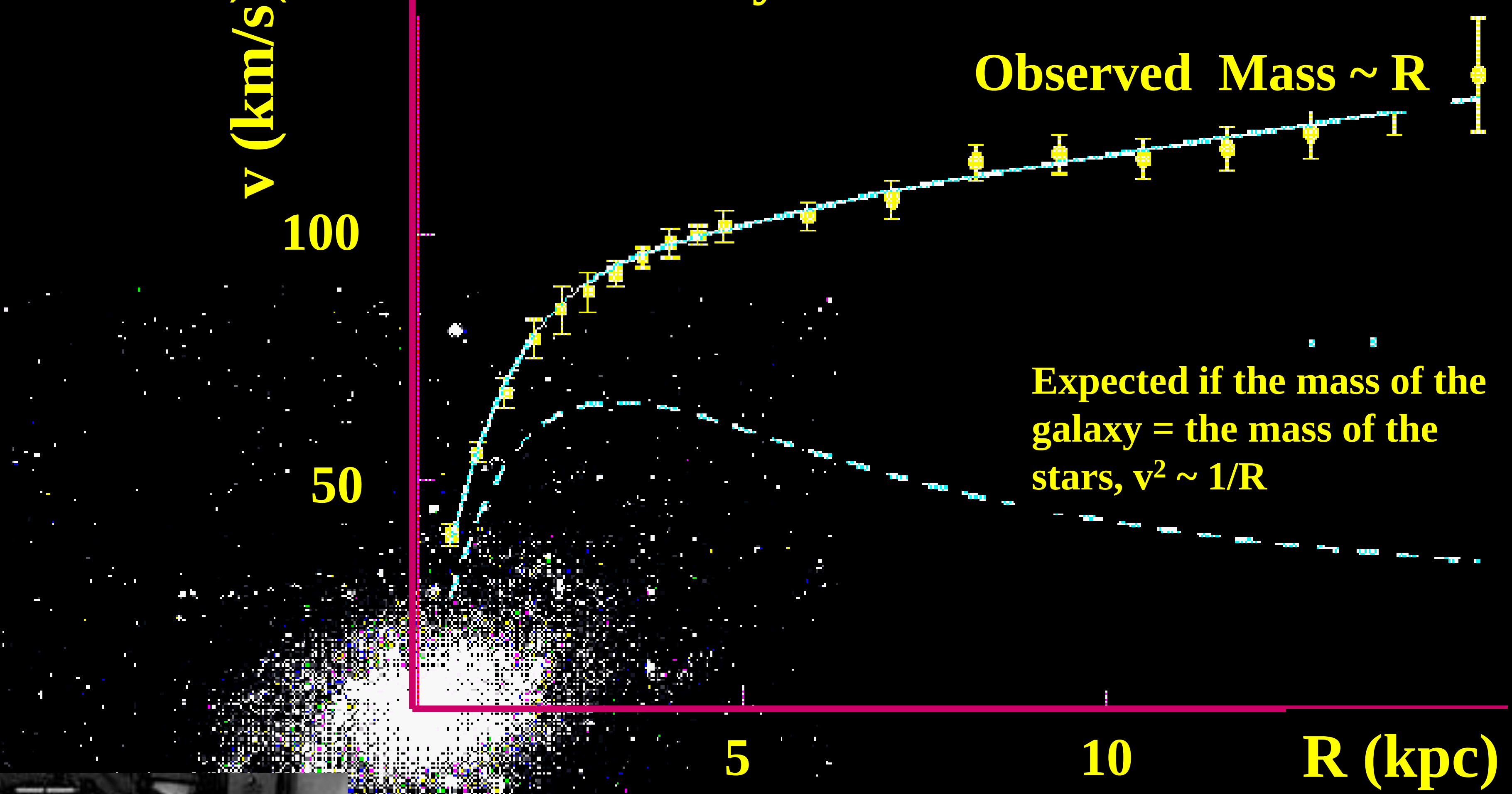




$$\frac{v^2}{R} = \frac{G\,M_{GALAXY}}{R^2}$$

measure v & R ➡ M_{Galaxy}

Galaxy rotation curves



Some sort of Mass must extend out ~10 times further than the stars!

Check out the Science Channel series “Through the Worm Hole” with Morgan Freeman!

The same is true for clusters of galaxies: if you measure the velocities of the visible galaxies in a cluster, you find that ~ 90% of the mass of the cluster is not visible

Identification of galaxy clusters is remarkably similar to jet clustering in collider physics but also have depth (red shift) info./confusion

The big questions: who is in, who is out, what is the mass (and redshift) ?

Cluster of Galaxies:
Largest gravitationally bound objects

Size ~ 10^{25} cm ~ Megaparsec (Mpc) ~ 3.2 Million light years

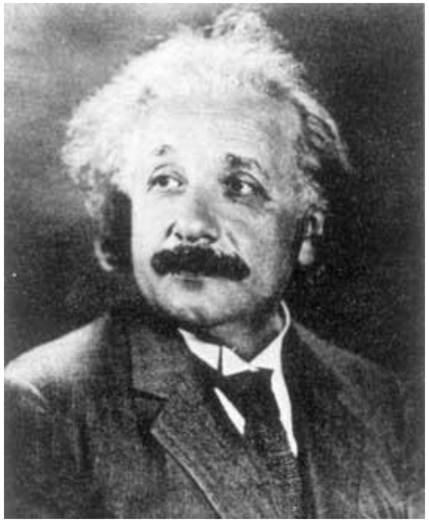
Mass ~ 10^{15} Msun

SDSS data

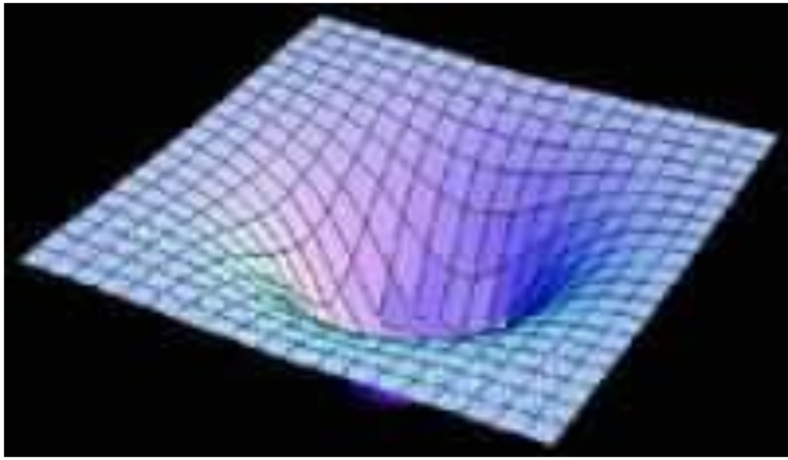
Einstein and General Relativity

Matter affects the structure of Space-Time

A massive object (star, galaxy, cluster of galaxies) attracts nearby objects by distorting spacetime

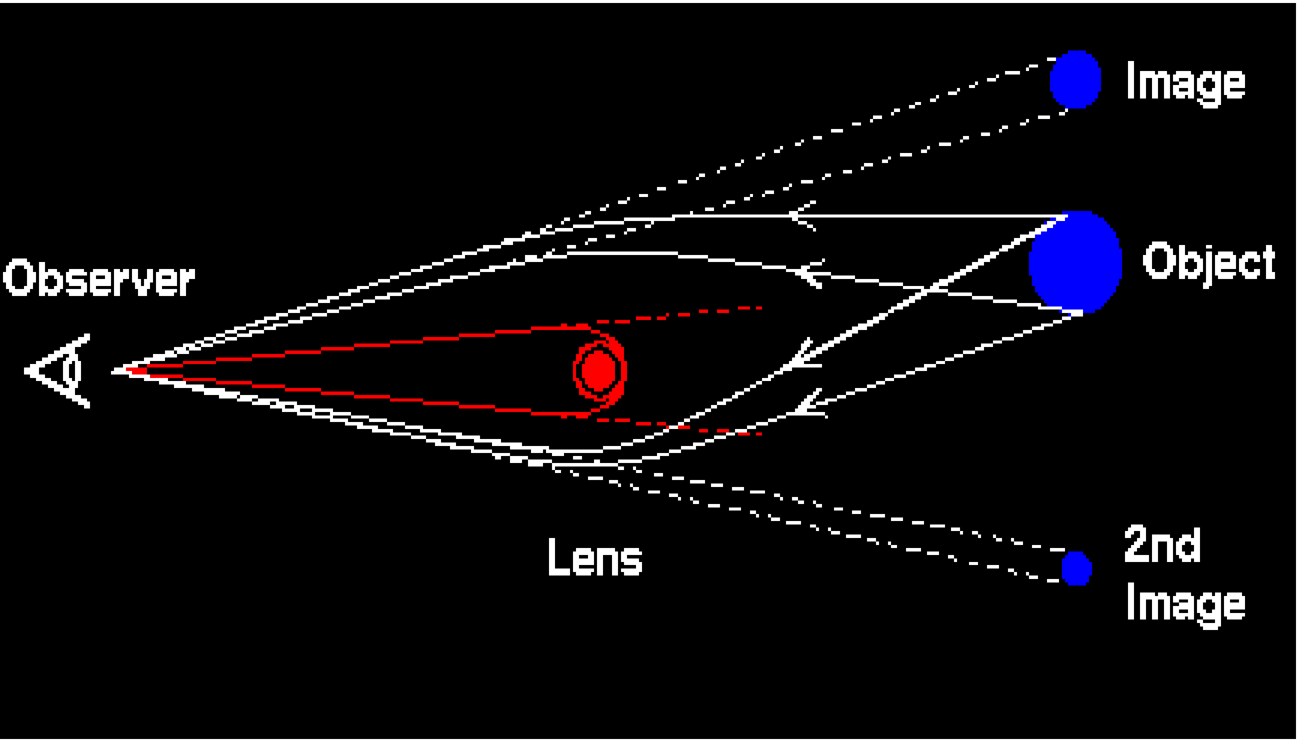


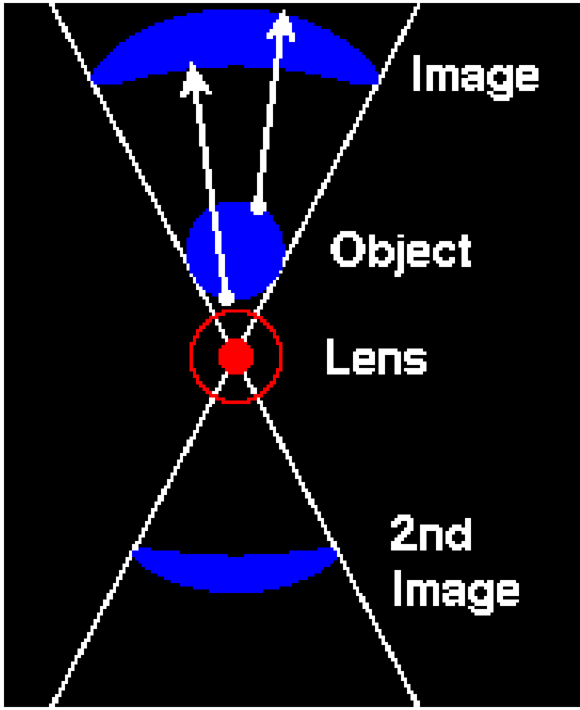
Light follows lines of spacetime: Large clumps of Mass (dark and visible) curve spacetime and thus bend light like a lens



Light rays coming from sources behind clumps of matter (such as a galaxy cluster) will be bent and distorted ("lensed")

Gravitational Lensing Geometry

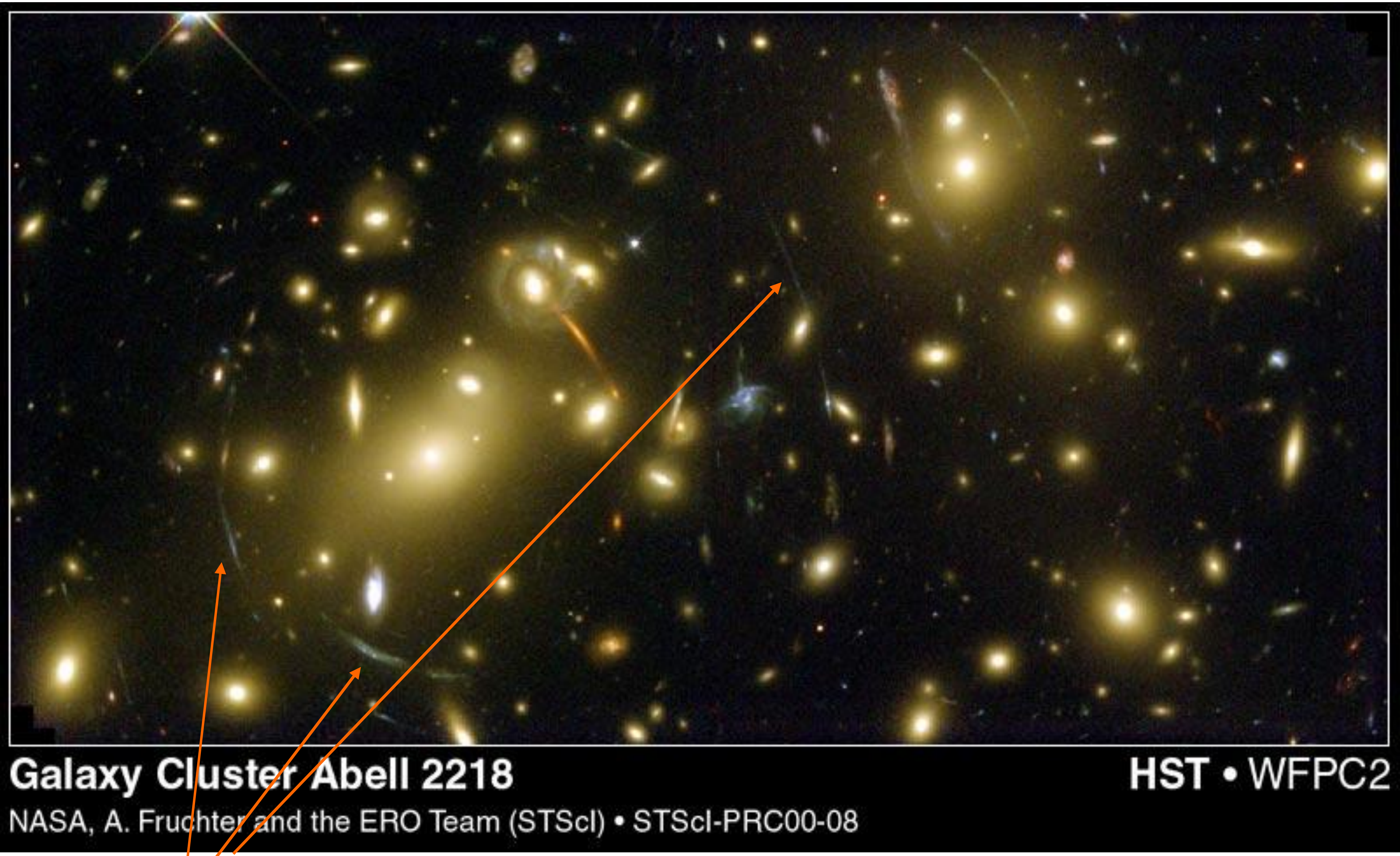




Gravitational Lensing: multiple images or pronounced distortion of images

Great book: *Einstein's Telescope: the hunt for Dark Matter and Dark Energy in the Universe* by Evalyn Gates (U. Chicago)

Zoom in on a galaxy cluster – Gravity is bending light. There must be a lot of gravity (dark matter) beyond the visible galaxies in the cluster



giant arcs are galaxies behind the cluster, gravitationally lensed

Dark Energy

I. Direct Evidence for Acceleration

Brightness of distant Type Ia supernovae:

Standard candles → measure magnitude and distance $d_L(z)$ sensitive to the expansion history $H(z)$

Found that distant supernovae are not as bright as they should be:

–> the universe is expanding faster than expected

II. Evidence for `Missing Energy'

CMB→ Flat Universe: $\Omega_0 = 1$

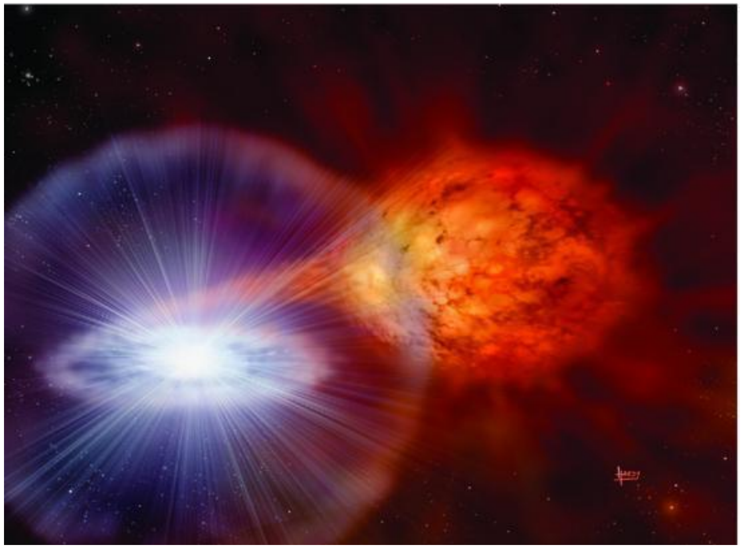
Add up all the visible and Dark Matter

→ matter density $\Omega_m \approx 0.3$

$\Omega_{missing} = 1 - 0.3 = 0.7 = \Omega_{DE}$

Can't see it and it is pushing the universe apart so call it "dark energy"

Type Ia Supernovae are a type of Standard Candle

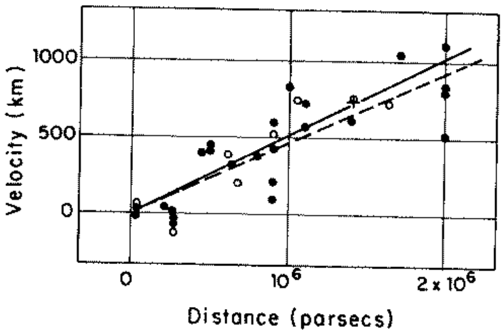


A white dwarf star, accreting mass from a companion star, exceeds a critical mass (Chandrasekhar) and explodes. These explosions are billions of times brighter than our sun.

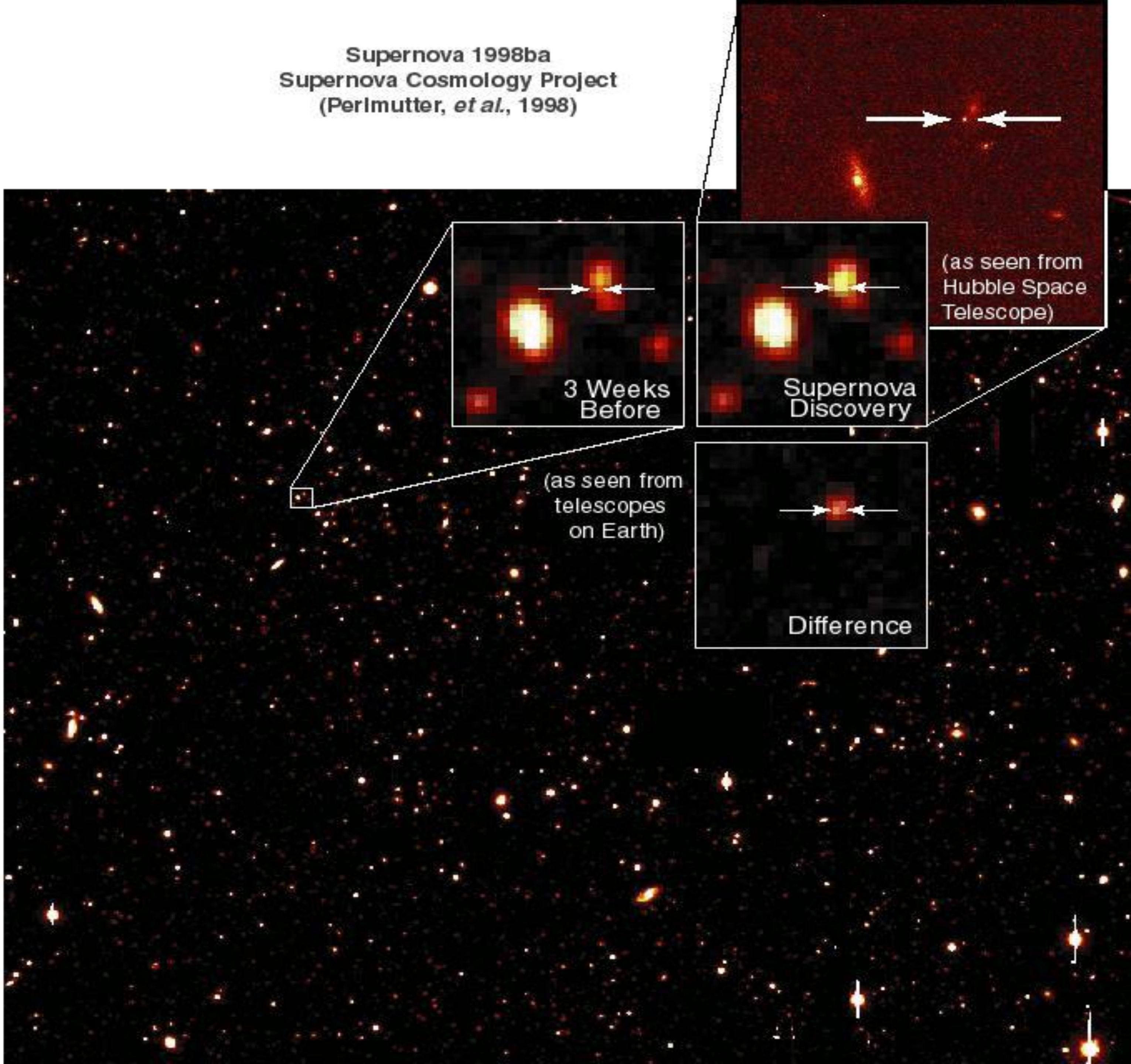
The peak brightness of these type of explosions is standardizable and thus can be related to its distance.

There is about 1 SN every 50 years in the Milky Way. Explosions are usually visible for about 40-60 days.

Cepheid Stars are another type of standard candle, their period T is proportional to luminosity, they are about 30,000 times brighter than our sun – Hubble used Cepheids to derive Hubble's law (v = Hd) in the 1920's:



Observation of Supernova requires repeated observations of the same area of sky and detailed measurement of the differences as a function of time (typically over ~ 60 days)



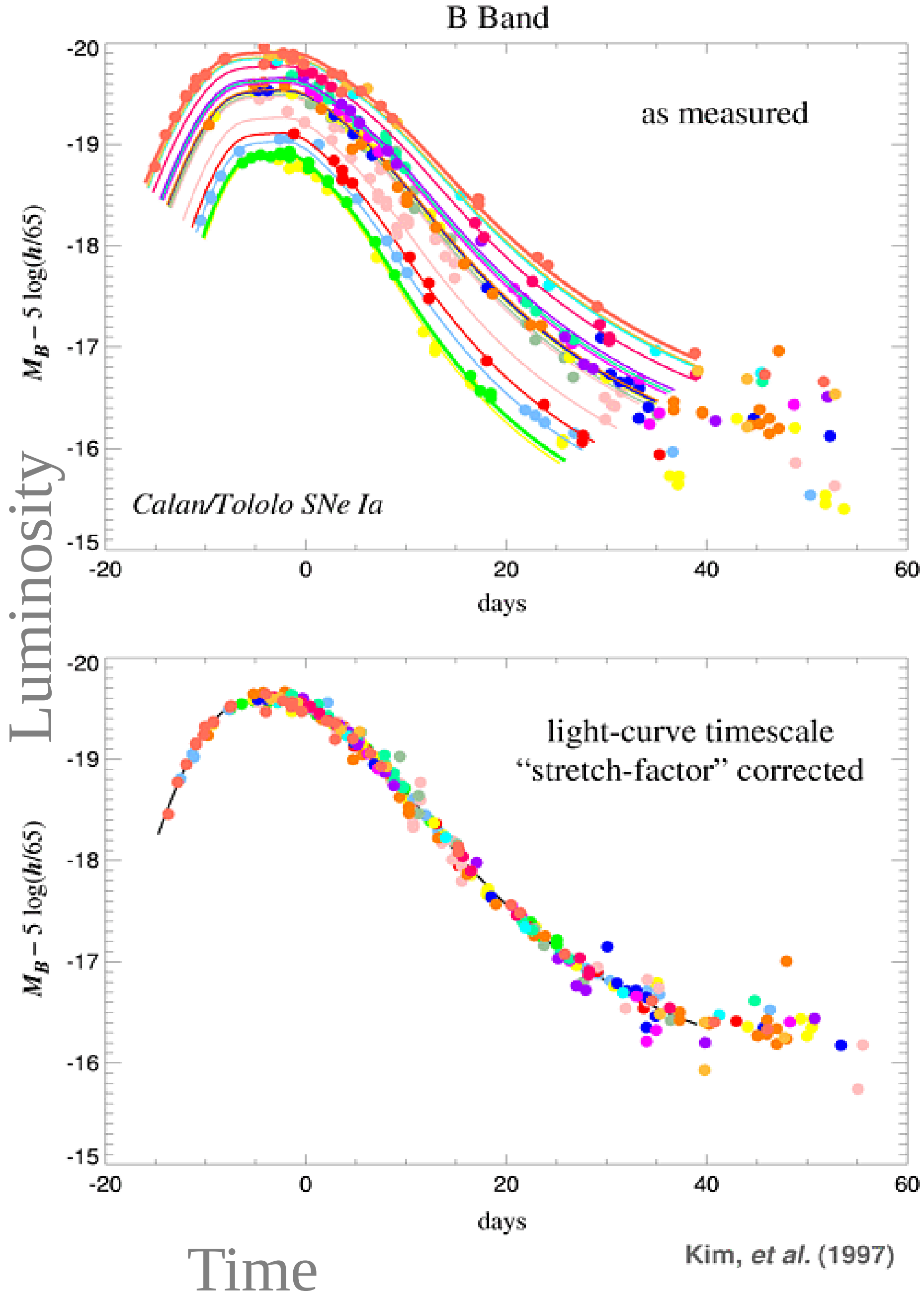
Type Ia Supernovae Peak Brightness Is `Standardizable' Candle

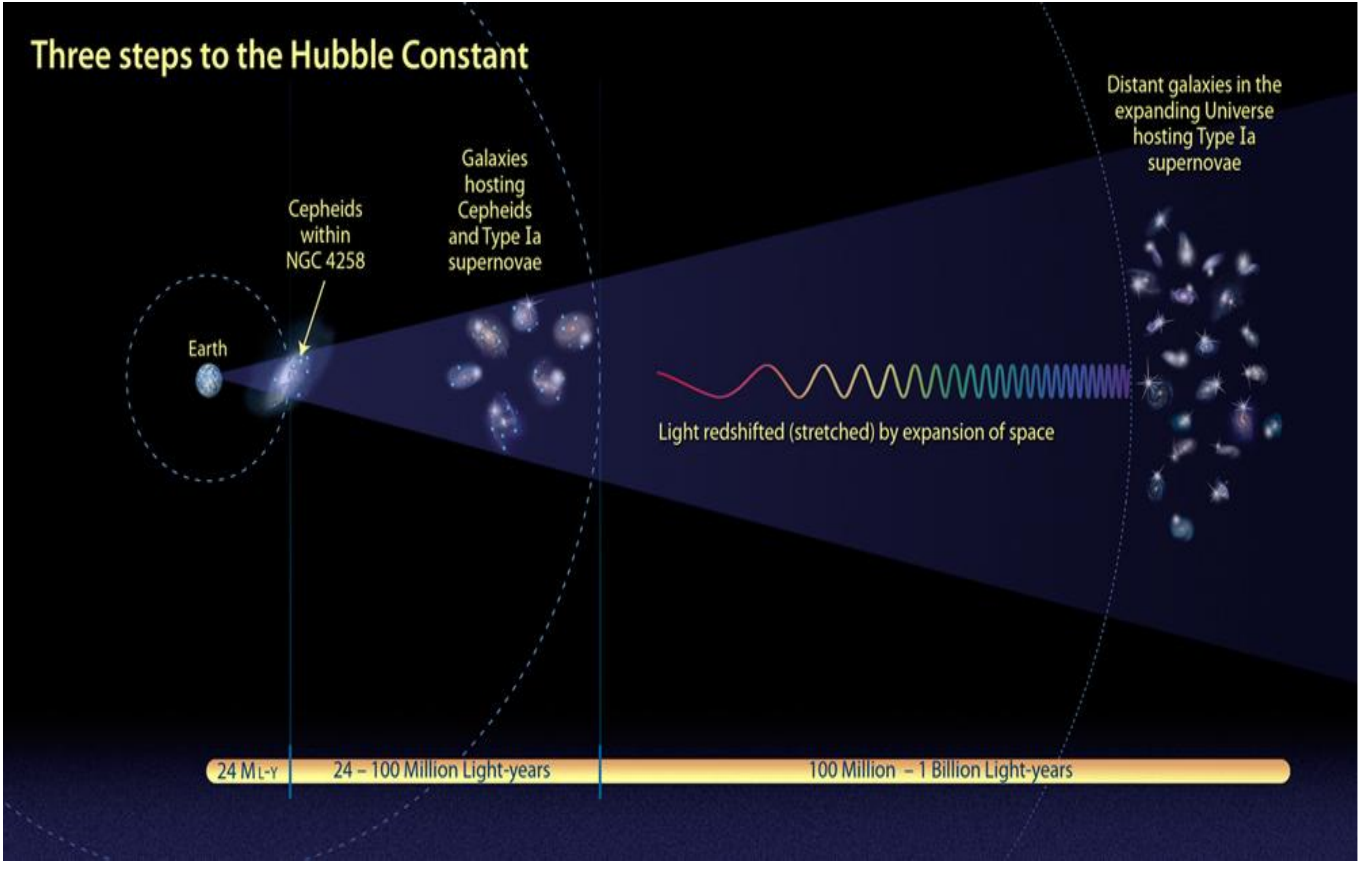
Type 1a Supernovae happen when a white dwarf star, accreting mass from a companion star, explodes when it exceeds a critical mass (Chandrasekhar)

Once corrected for known effects, the peak magnitudes of all Type Ia Supernova are the same.

Redshifts can be determined from measurement of the spectra

SN Ia are very bright (~14 magnitudes brighter than cepheids) and thus can be seen much farther away (higher redshift)

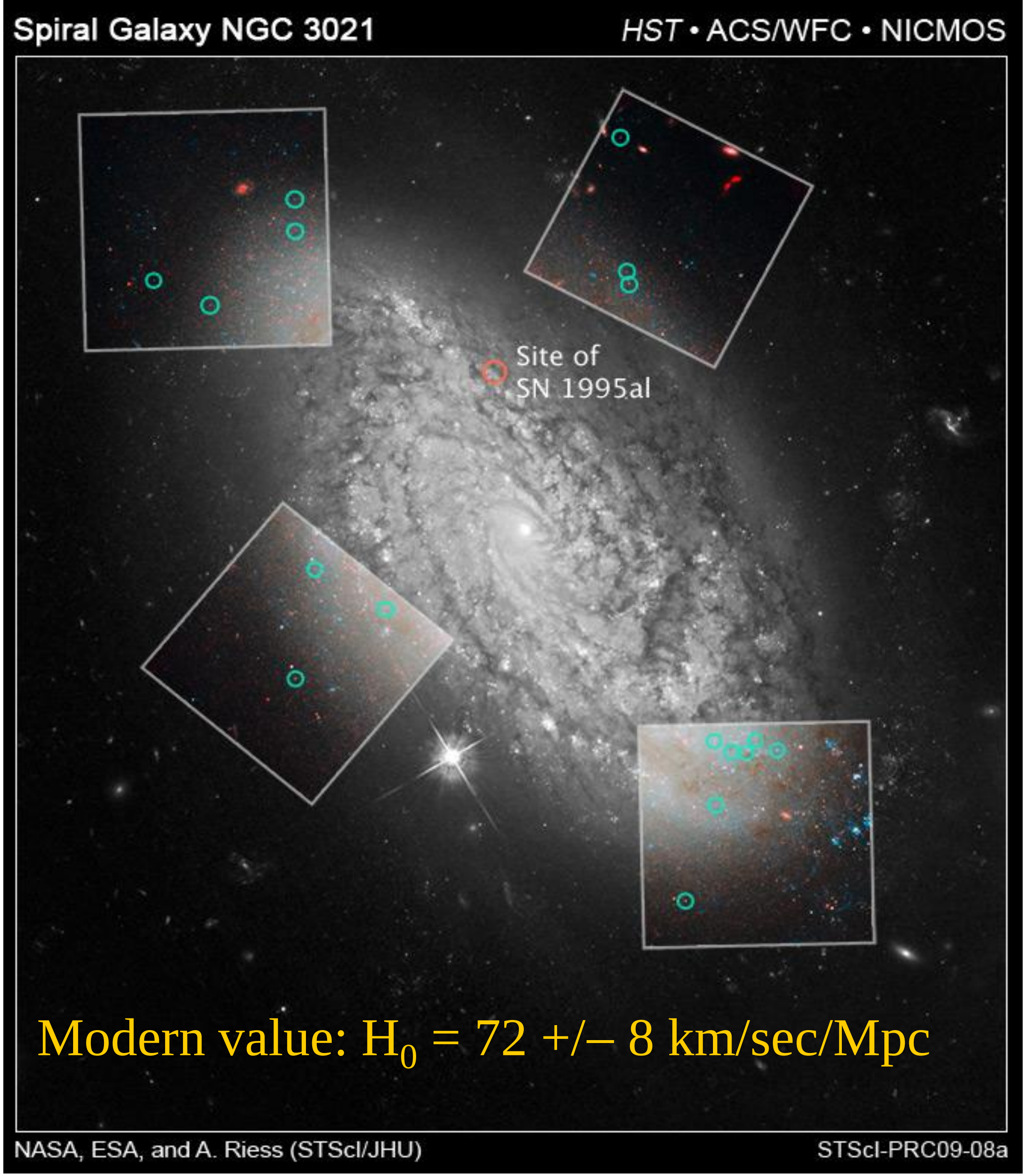



Three steps to the Hubble Constant
Distant galaxies in the expanding Universe hosting Type Ia supernovae
Galaxies hosting Cepheids and Type Ia supernovae
Cepheids within NGC 4258
Earth
Light redshifted (stretched) by expansion of space
24 M L-Y
24 – 100 Million Light-years
100 Million – 1 Billion Light-years

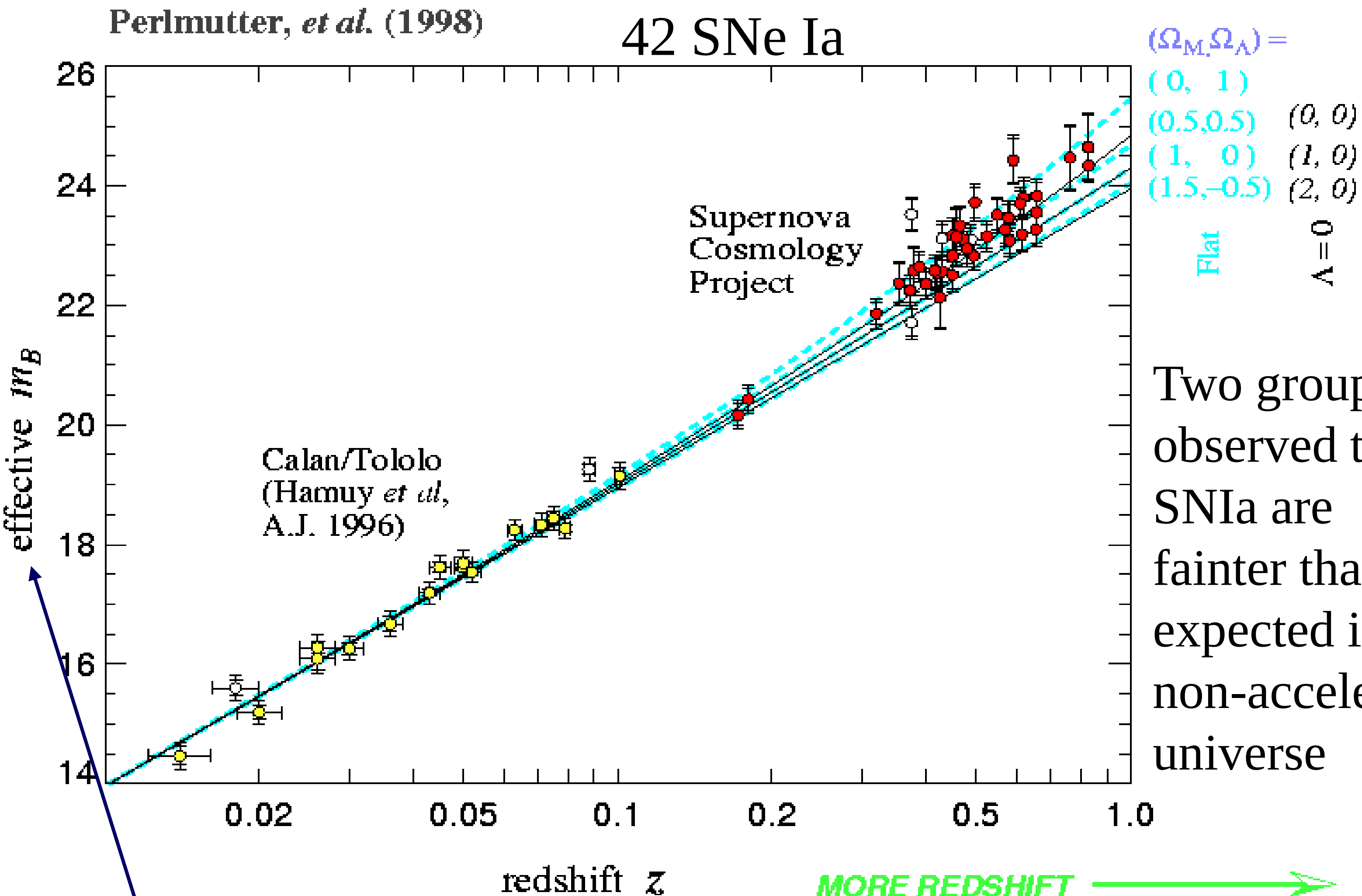
Hubble Space Telescope:

Measured 240 Cepheids over 7 galaxies

6 of the galaxies also had type Ia supernovae



42 SNe Ia



Fainter

Apparent Brightness

Two groups observed that SNIa are fainter than expected in a non-accelerating universe

MORE REDSHIFT
(More total expansion of universe since the supernova explosion)

distance

$$m(z) = M+5\log(H_0 d_L)=(1+z) \int dz'/H(z')$$

In flat universe: $\Omega_M = 0.28$ [± 0.085 statistical] [± 0.05 systematic]

Prob. of fit to $\Lambda = 0$ universe: 1%

Dark Energy

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

Expansion rate of the universe:

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

(dark matter: Ω_M; dark energy: Ω_{DE}) (flat Universe, const. *w*, w = -1: cosm. const.)

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 energy density of the Universe: Ω_{DE}

Current Status: $\sigma(w) \sim 0.15$*, $w < -0.76$ (95%) from CMB+LSS+SNe; no *single* dataset constrains *w* better than ~30%, and this is for constant w!

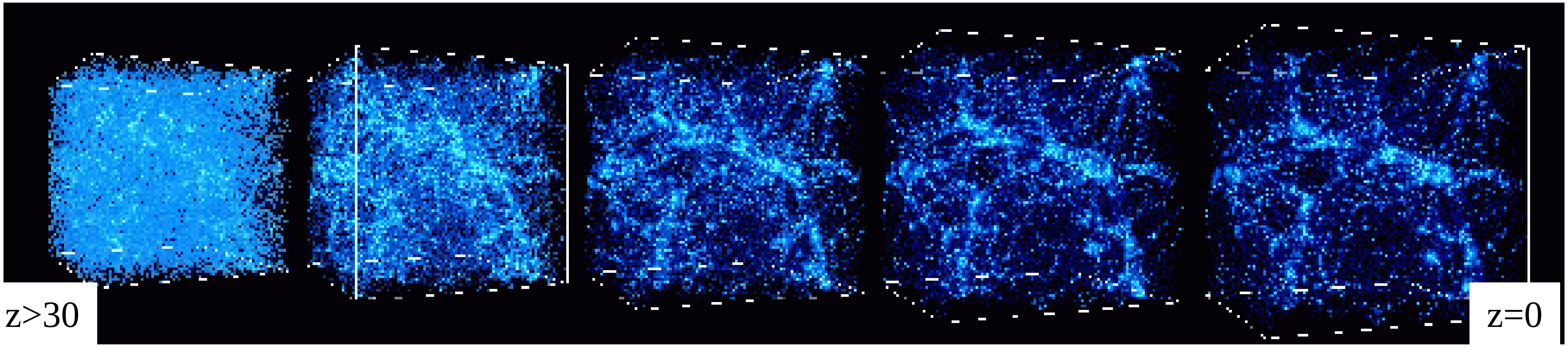
Key Experimental Questions

1. Is DE observationally distinguishable from a cosmological constant (w =-1)? A cosmological constant means the energy density is constant although universe is expanding.

2. Can we distinguish between gravity and stress-energy? Compare measurements that are sensitive to expansion rate to measurements that are sensitive to growth of structure

3. Does dark energy evolve: w=w(z)? parameterize DE evolution as $w(z) = w_o + w_a(1-a)$

Simulation of the evolution of the Universe



The of growth of structure is determined by the initial conditions (CMB) and amount and distribution of dark matter, dark energy and by the expansion rate of the universe.

The project I am working on is the Dark Energy Survey. We will measure the effects of Dark Energy and Dark Matter 4 different ways and by combining the results we hope to get a better understanding of what they are

Sensitive to gravity and expansion rate

1) Count the Galaxy Clusters as a function of red shift and cluster mass

2) Measure the distortion in the apparent shape of galaxies due to intervening galaxy clusters and associated clumps of dark matter (Lensing)

Sensitive to expansion rate not gravity

3) Measure the spatial clustering of galaxies as a function of red shift; this is a standard ruler (Baryon Acoustic Oscillations)

4) Use Supernovae as standard candles to measure the expansion rate

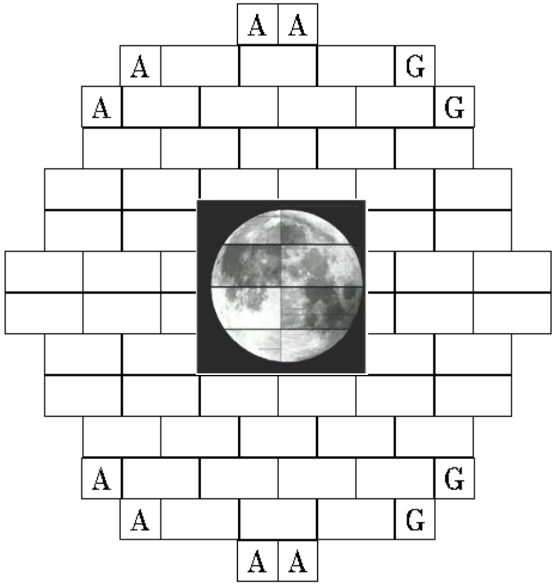
The Dark Energy Survey (DES)

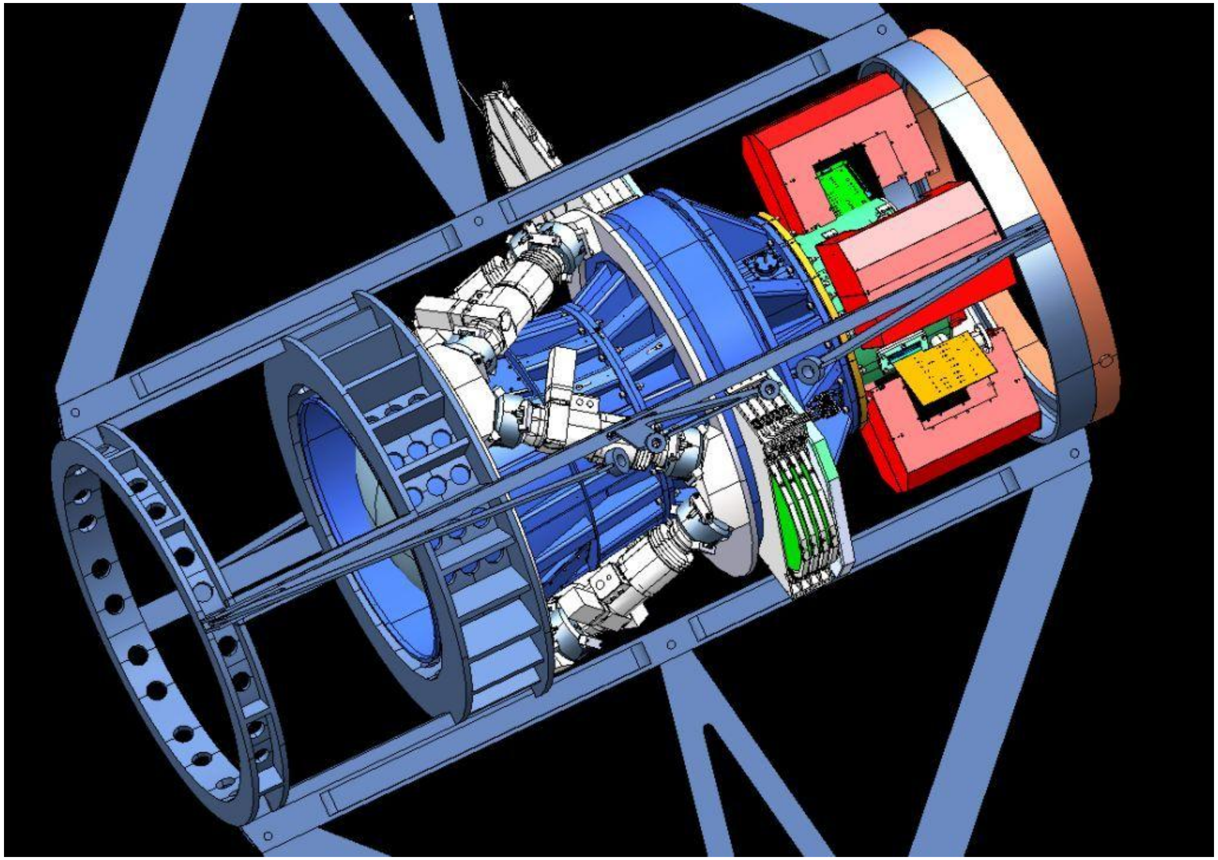
- The Deal:
  - DES Collaboration provides a state-of-the-art instrument and data system for community use
  - NOAO (NSF) allocates 525 nights of 4m telescope time during Oct.–Feb. 2011-2016
  - DES Collaboration performs a 5000 sq deg. survey and makes the data public after a year!
- New Instrument (DECam):
  - Replace the PF cage with a new 2.2 FOV, 520 Mega pixel CCD camera + optics
- Collaboration Funding:
  - DOE, NSF, STFC (UK), Ministry of Education and Science (Spain), FINEP (Brazil), and the Collaborating Institutions

Use the Blanco 4m Telescope at the Cerro-Tololo Inter-American Observatory (CTIO)

The DES Instrument: DECam

DECam Focal Plane





3 sq. deg. field of view (~ 0.5 meter diameter focal plane)

62 2kx4k Image CCDs: 520 MPix

8 2kx2k Alignment/focus CCDs

4 2kx2k Guide CCDs

Prime Focus Cage and the Blanco Telescope

Built in the 1970’s
A big solid telescope,
~ 15 tons at the top end

People used to ride in the Prime Focus cage and aim/drive the telescope

Pictures were taken on glass negatives

In Mid-late 80’s digital camera technology (CCDs) started to be used on telescopes

By mid 90’s these were the standard, but very expensive.

The Blanco currently has a 64MPixel Camera (8 2k x 4k CCDs)

The Dark Energy Survey Science

- Study Dark Energy using 4 complementary* techniques:

I. Cluster Counts: N(M,z):

Measure red shifts and masses of 30,000 clusters to z=1 with M > 2×10^{14} $M_\odot$

II. Weak Lensing: 300 million galaxies with shape measurements over 5000 sq deg.

III. Baryon Acoustic Oscillations : angular correlation function of 300 million galaxies to z = 1

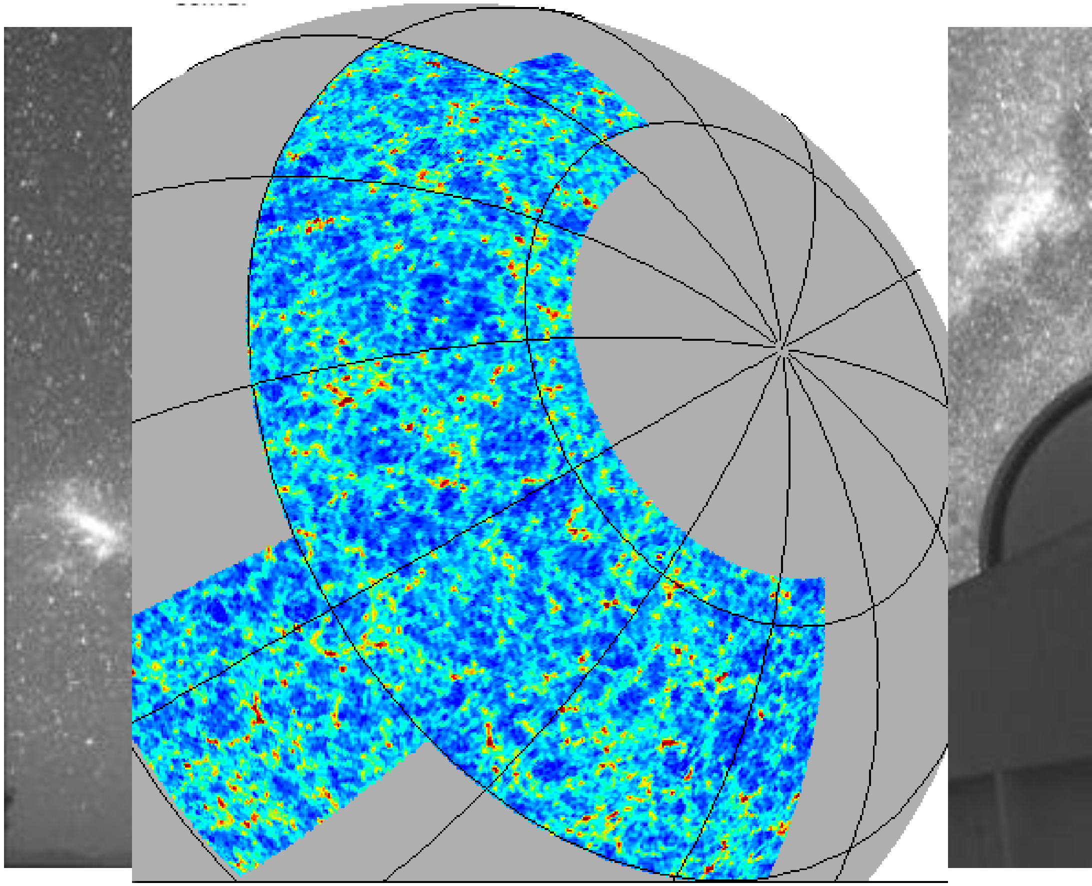
IV. Supernovae:

~2000 SN Ia, z = 0.3-0.8

- Two multiband surveys:

5000 deg^2 *g, r, i, z*

15 deg^2 repeat (SNe)

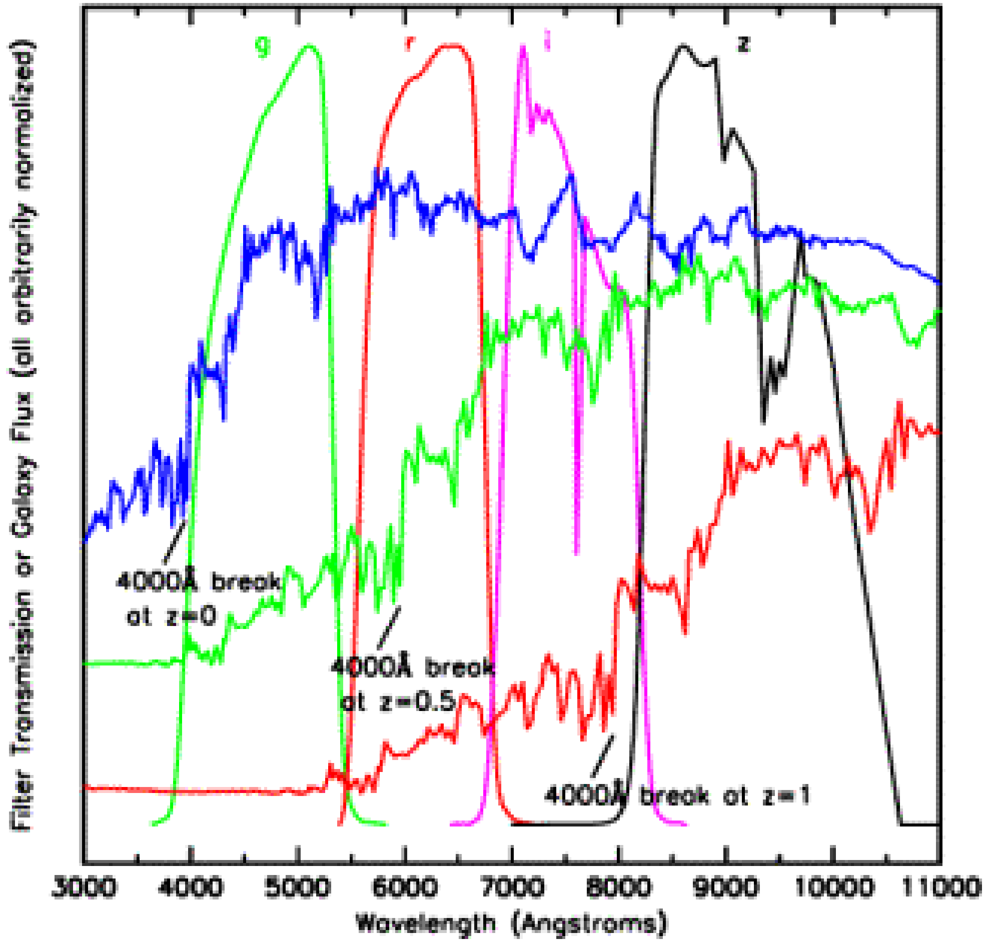


*in systematics & in cosmological parameter degeneracies
*geometric+structure growth: test Dark Energy vs. Gravity

Photometric Redshifts (Photo-z's)

- Measure relative flux in multiple filters: track the 4000 A break
- Estimate individual galaxy redshifts with accuracy $\sigma(z) < 0.1$ (~0.02 for clusters)
- Precision is sufficient for Dark Energy probes, provided error distributions well measured.
- Good detector response in *z* band filter needed to reach z>1

Elliptical galaxy spectrum



Galaxy Photo-z Simulations

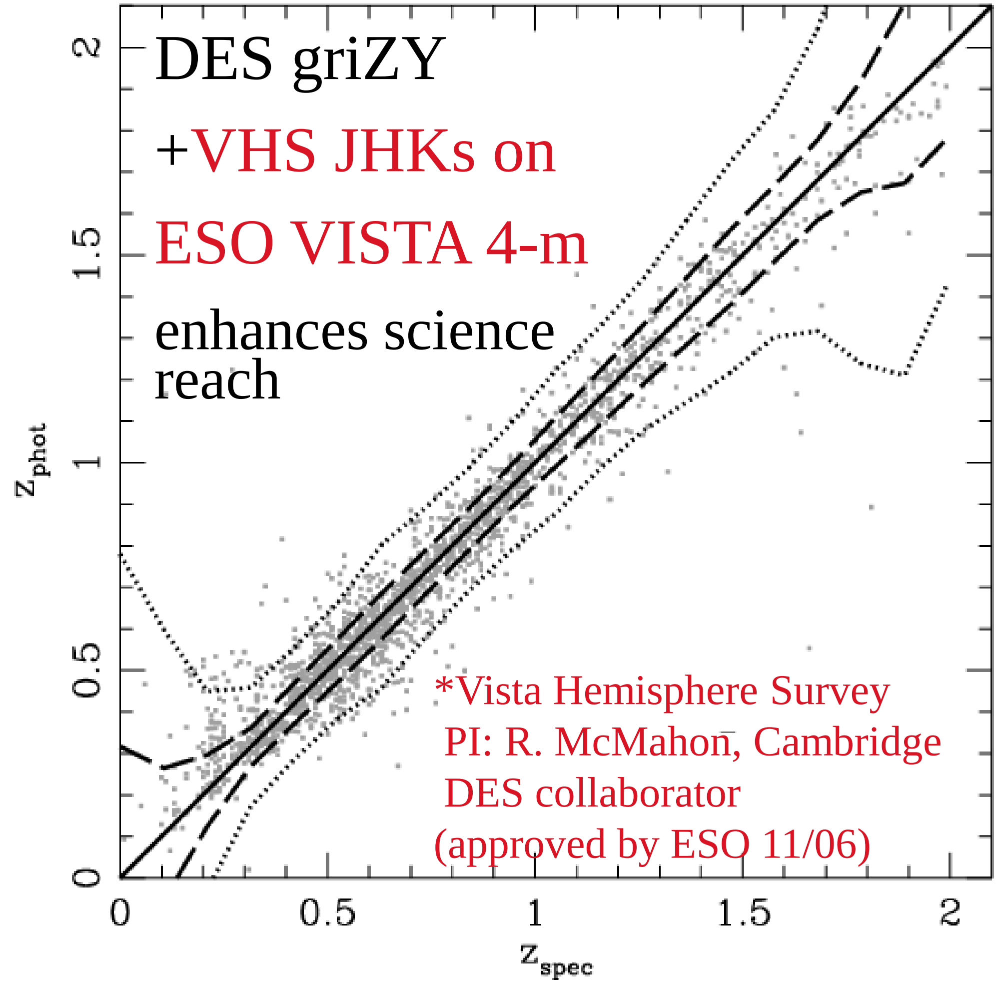
DES +VHS*

10σ Limiting Magnitudes

g	24.6	J	20.3
r	24.1	H	19.4
i	24.0	Ks	18.3
Z	23.8		
Y	21.6		

+2% photometric calibration error added in quadrature

Key: Photo-z systematic errors under control using *existing* spectroscopic training sets to DES photometric depth: low-risk



+Developed improved Photo-z & Error Estimates and robust methods of outlier rejection

I. Clusters and Dark Energy

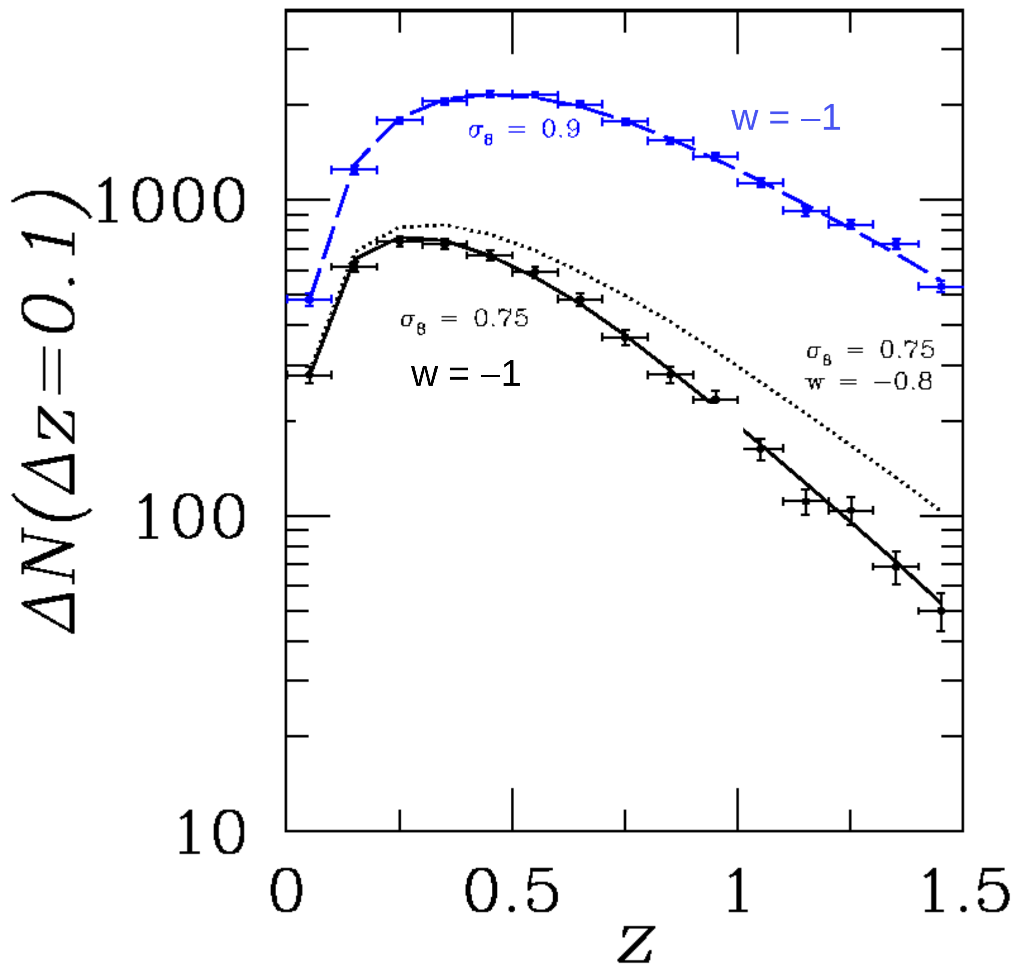
- Analysis
  1. Understand formation of dark matter halos
  2. Cleanly select massive dark matter halos (galaxy clusters) over a range of redshifts
  3. Redshift estimates for each cluster
  4. Observable proxy that can be used as cluster mass estimate:

     O =g(M)

Primary systematic:

Uncertainty in bias & scatter of mass-observable relation

Number of clusters above observable mass threshold



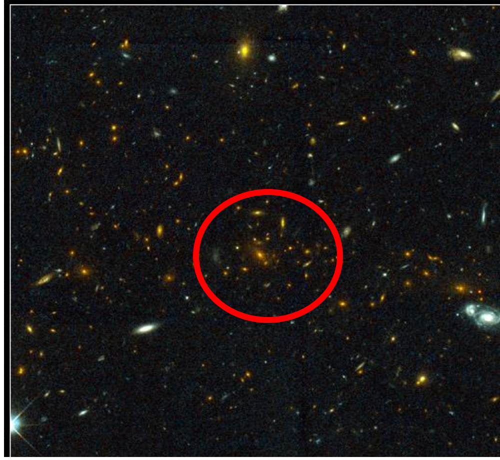
Cluster Cosmology with DES

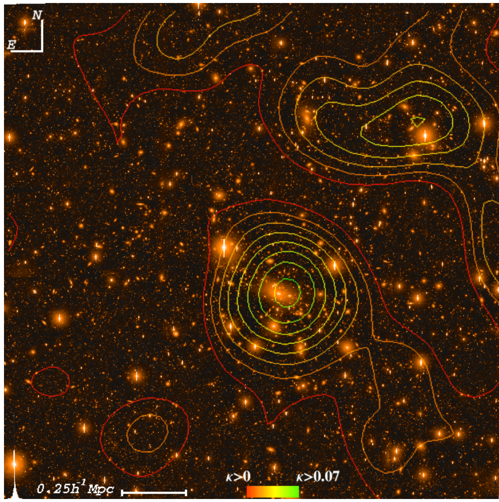
3 Techniques for Cluster Selection and Mass Estimation:

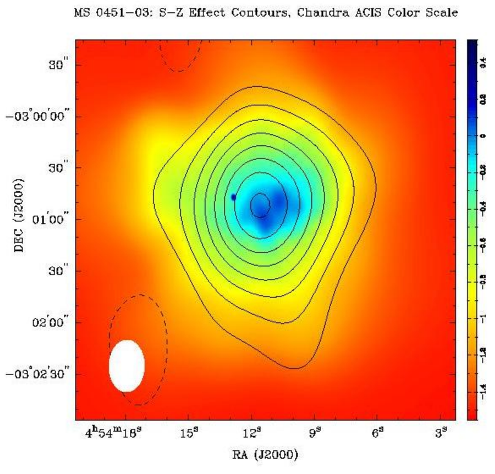
- Optical galaxy concentration
- Weak Lensing
- Sunyaev-Zel'dovich effect (SZE)
    - Compton upscattering of CMB photon by hot gas in clusters gives measure of Mass, nearly independent of redshift
    - South Pole Telescope is measuring cluster masses now in the DES survey area

Compare these techniques to reduce systematic errors

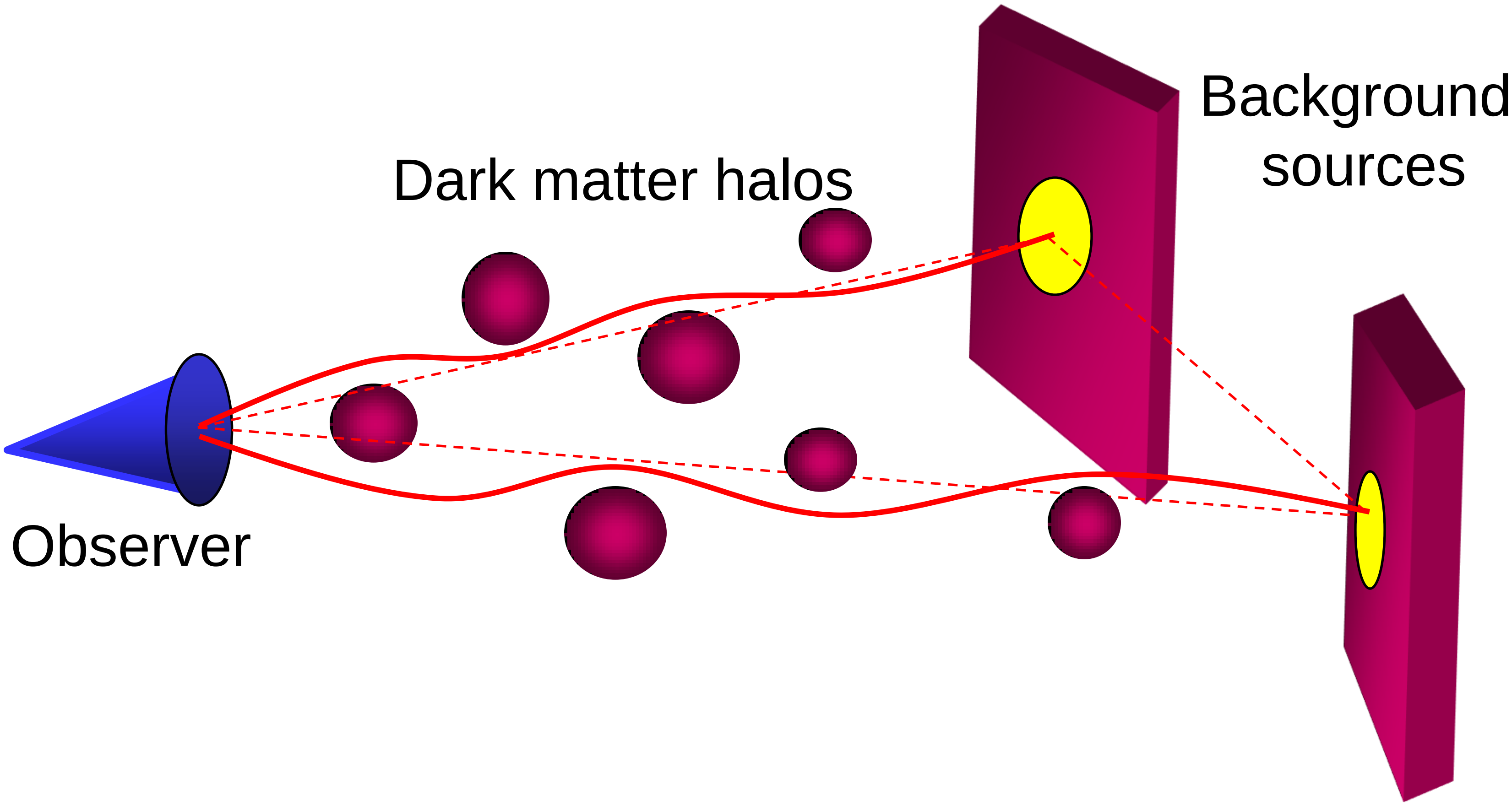
Additional cross-checks: shape of mass function; cluster correlations







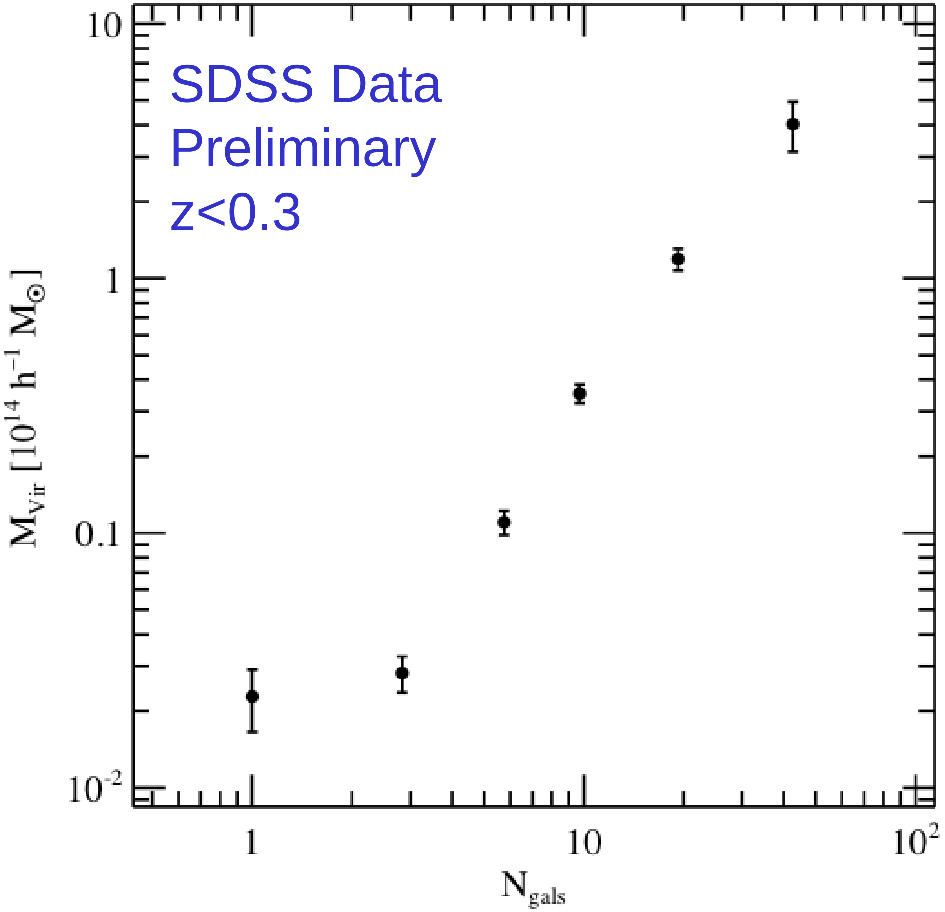
II. Weak Lensing



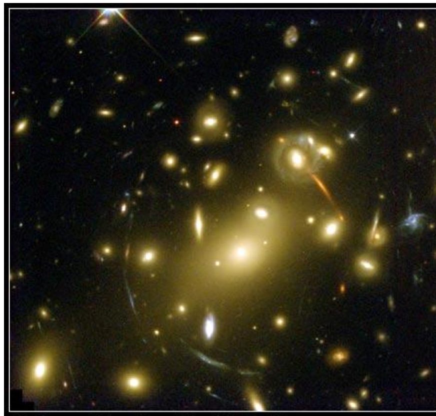
Statistical Weak Lensing Calibrates Cluster Mass vs. Observable Relation

Cluster Mass vs. Number of galaxies they contain

For DES, we will use this to independently calibrate SZE vs. Mass



Johnston, Sheldon, et al

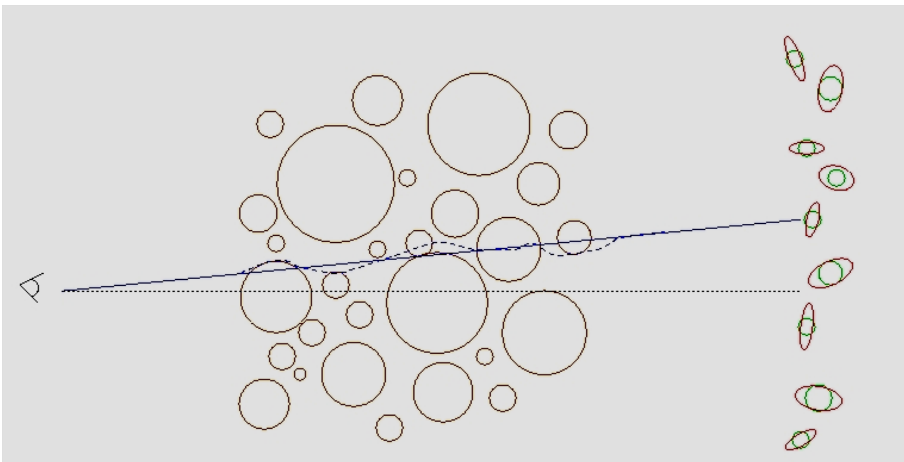


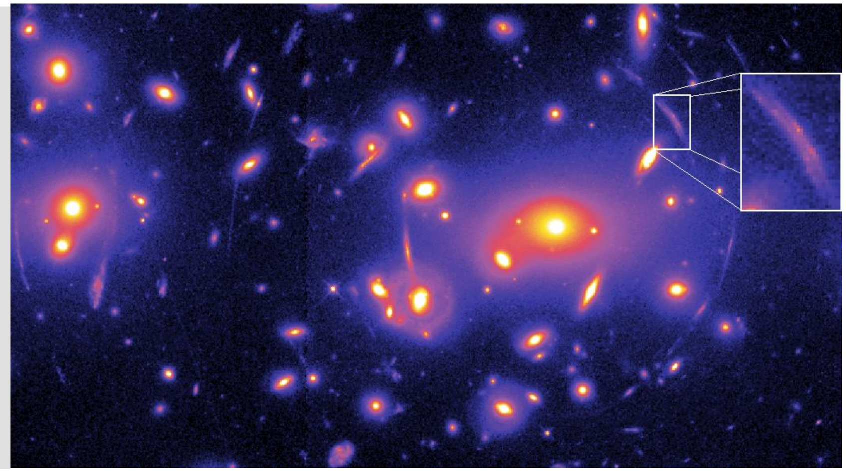
Galaxy Cluster Abell 2218
NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC

Statistical Lensing eliminates projection effects of individual cluster mass estimates

Johnston, etal astro-ph/0507467

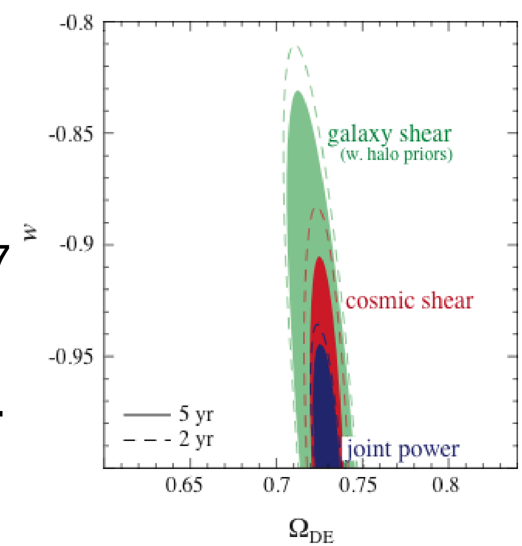
Weak Lensing: Cosmic Shear





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

Distortion Matrix



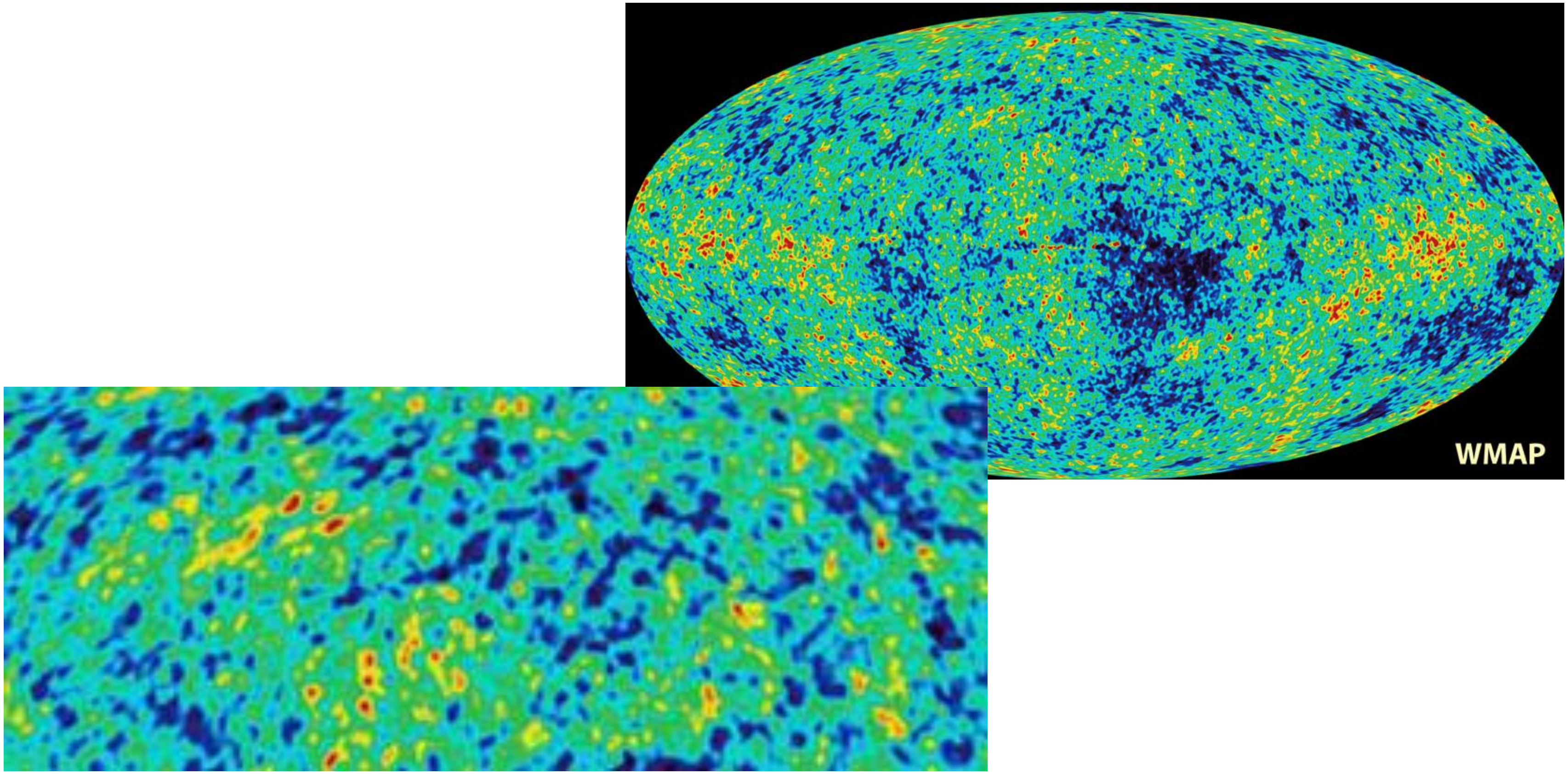
Measure shapes for ~300 million source galaxies with ⟨z⟩ = 0.7

Direct measure of the distribution of mass in the universe,

as opposed to the distribution of light, as in other methods (eg. Galaxy surveys)

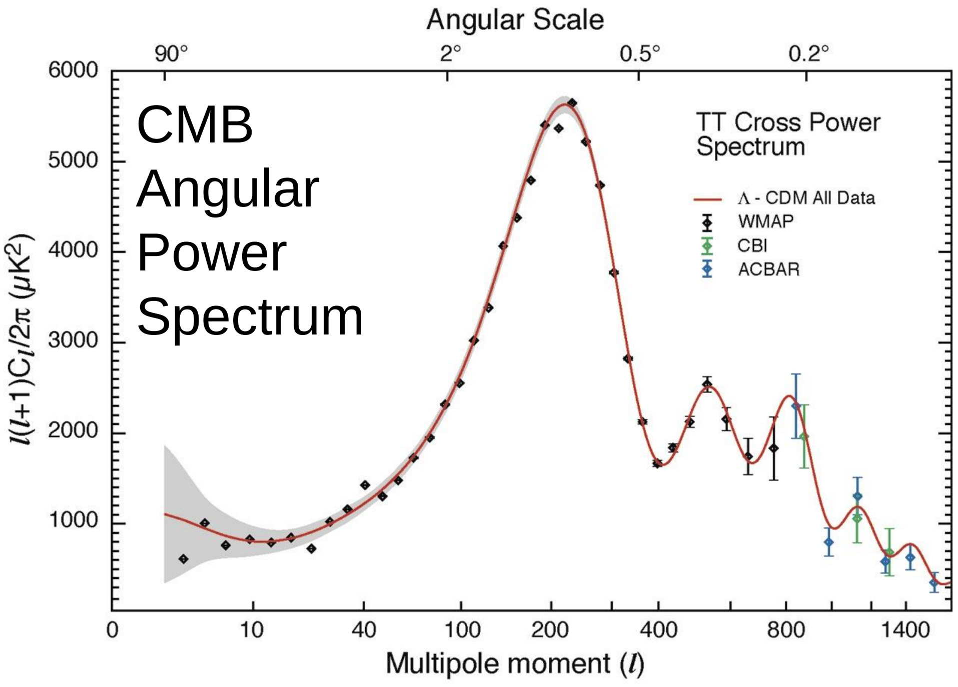
Sensitive to both the expansion rate of the universe and gravity (the number and distribution of dark matter halos)

III. Baryon Acoustic Oscillations (BAO) in the CMB

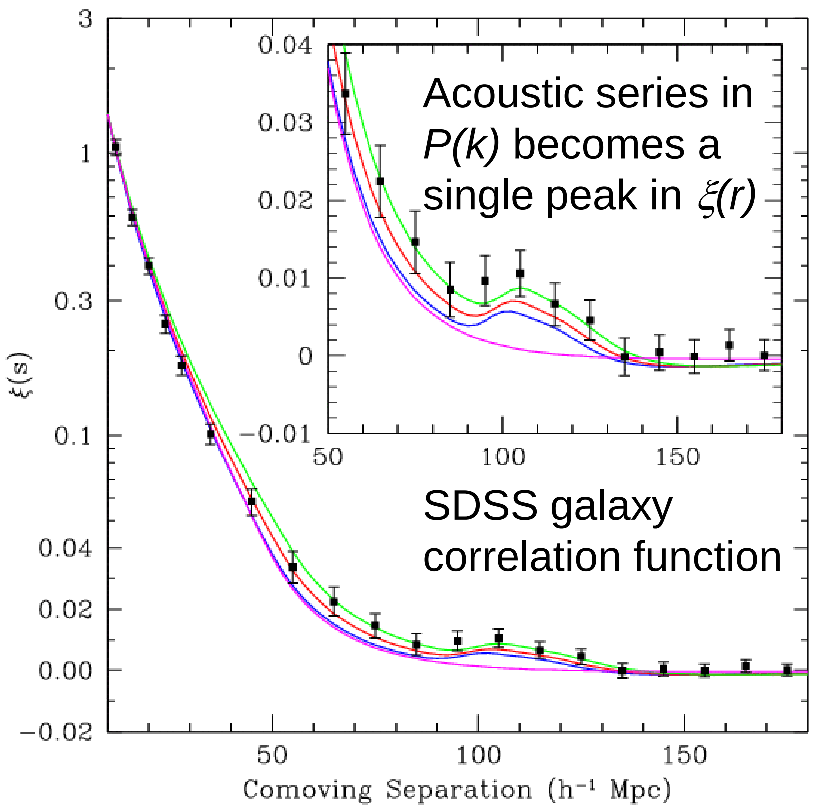


- Characteristic angular scale set by sound horizon at recombination: standard ruler (geometric probe).

Baryon Acoustic Oscillations: CMB & Galaxies



Bennett, etal



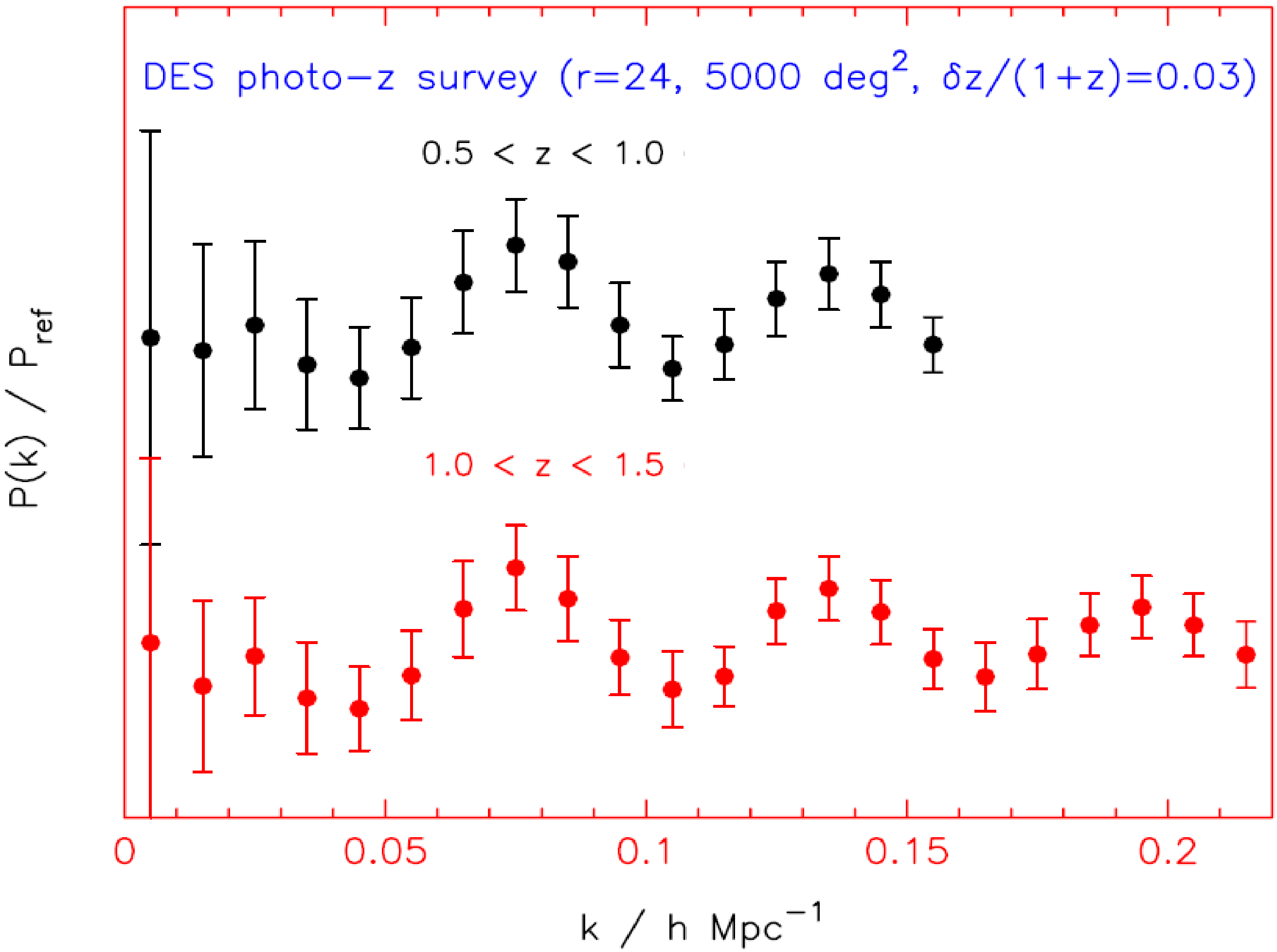
Eisenstein etal

BAO in DES: Galaxy Angular Power Spectrum

Wiggles due to BAO

Probe larger volume and redshift range than SDSS

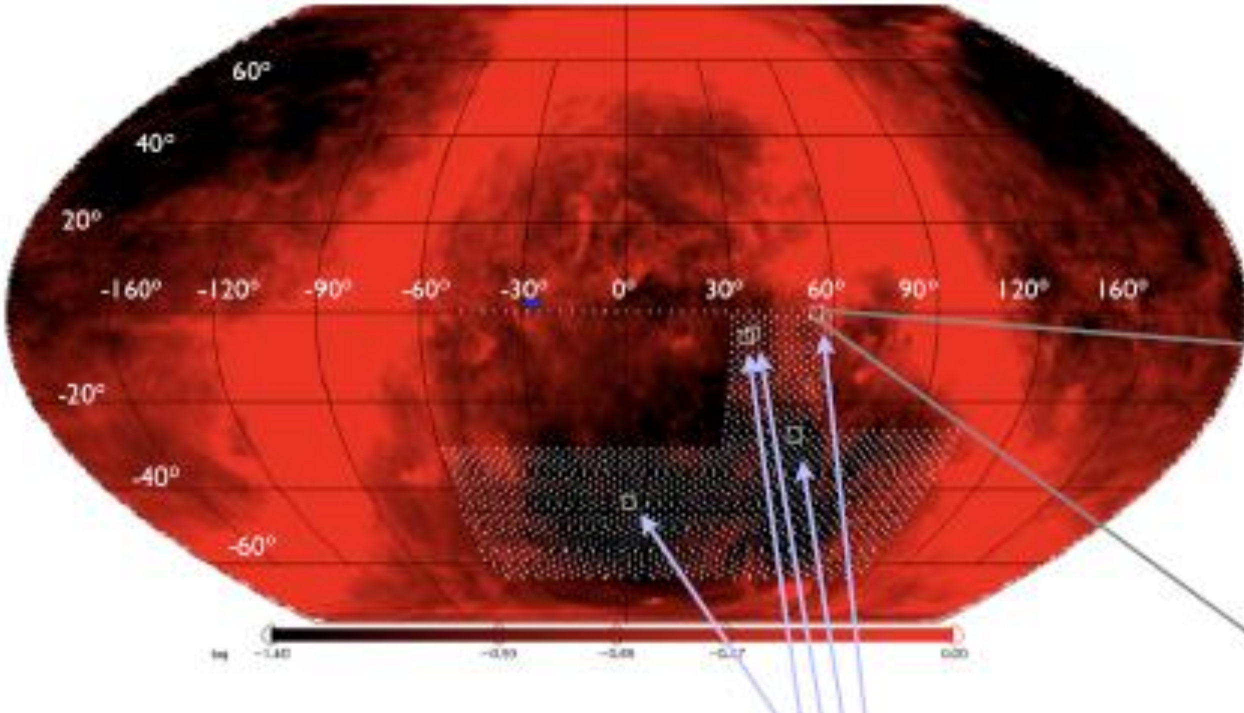
Systematics: photo-z's, photometric errors



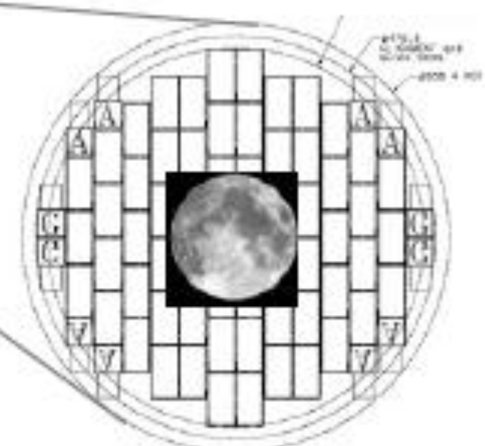
Fosalba & Gaztanaga

Blake & Bridle

DES SN survey



Fields were selected to overlap with existing and near-future deep imaging and spectroscopic surveys.



3 deg² each

<u>5 fields</u>

Visit once every ~4 days.

<u>3 deep</u> + <u>2 shallow</u>

deep: 6600 sec per visit

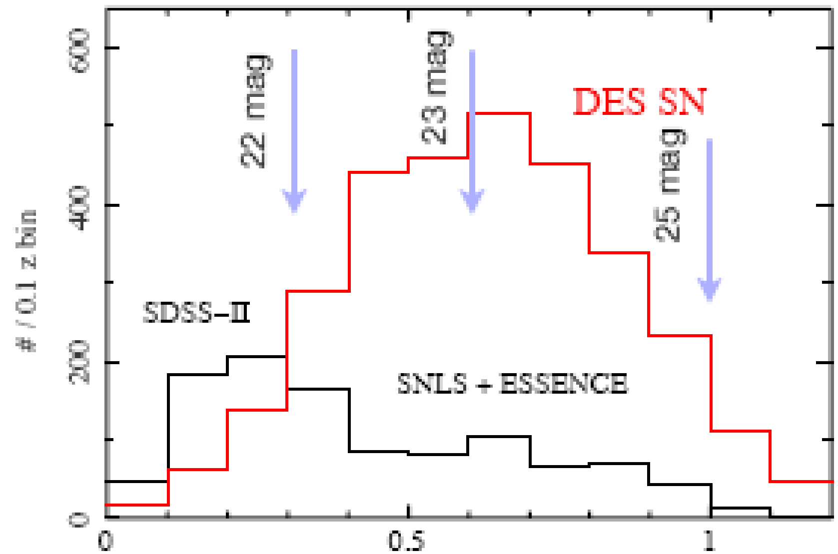
shallow: 3200 sec per visit

can monitor supernovae in over ~2 million galaxies in each field!

take advantage of much improved z-band efficiency and target high-z SN Ia

Current DES SN Strategy

- 6-month search seasons every year for 5 years (2011~2016).
- Use <u>1000+ hours</u> of total DES observing time (e.g., 10% of photometric + 50% of non-photometric time).
  - *robust point-source photometry in non-photometric conditions.*
- <u>5 DES fields</u> (15 deg^2) on a cadence of <u>~4 days</u> in *griz* filters.
- Will discover ~5000 SN Ia at 0.2 < *z* < 1.0.
  - **~3000 SN Ia** with "good" light curves



Hybrid Follow Strategy (goal)

- 1) DES/VIDEO sample - grizYJ(HK)
  - ~**60** SN Ia near peak at z < 0.4 with S/N > 10+
- 2) "Random" sample of all types of SN candidates
  - ~10 - 20% of all candidates (~**500 - 1000**) for studying sample purity (identify contaminating sources) and photometric SN typing
- 3) Spectroscopy of SN Ia in faint hosts (>25 mag)
  - ~5% of all SN Ia (~**150?**)
- 4) Post-search host spectroscopy of all SN Ia candidates (~**3000** galaxies or more)

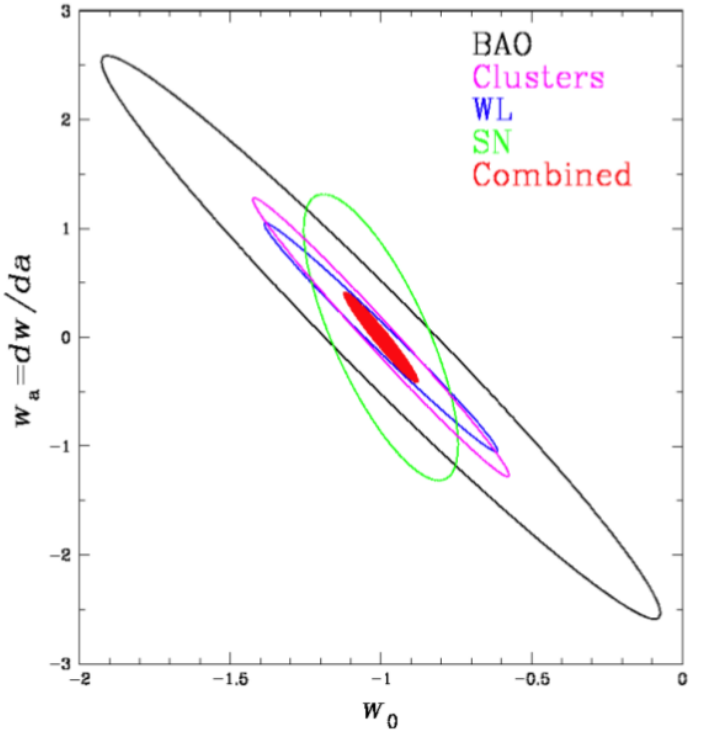
Dark Energy Survey Science

Four Probes of Dark Energy

- **Galaxy Clusters**
  - clusters to z>1
  - SZ measurements from SPT
  - Sensitive to growth of structure and geometry
- **Weak Lensing**
  - Shape measurements of 300 million galaxies
  - Sensitive to growth of structure and geometry
- **Large-scale Structure**
  - 300 million galaxies to z = 1 and beyond
  - Sensitive to geometry
- **Supernovae**
  - 15 sq deg time-domain survey
  - ~3000 well-sampled SNe Ia to z ~1
  - Sensitive to geometry

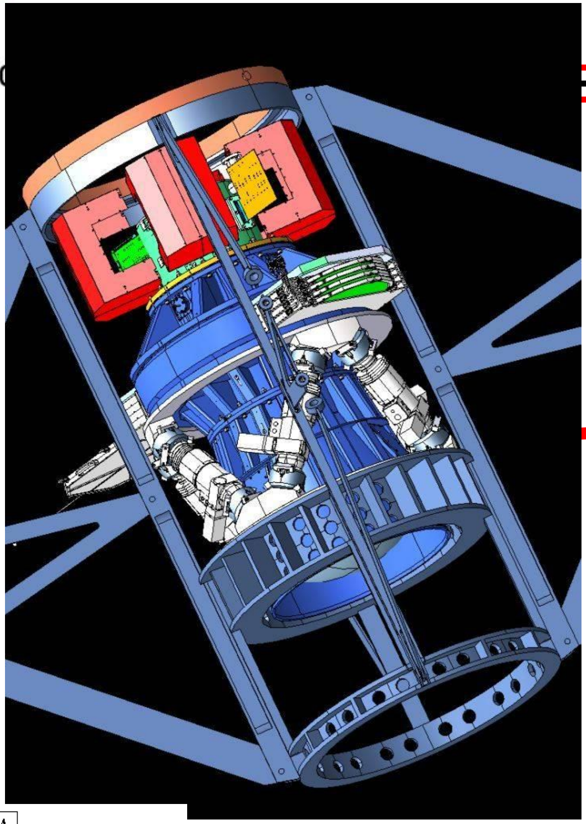
Plus QSOs, Strong Lensing, Milky Way, Galaxy Evolution

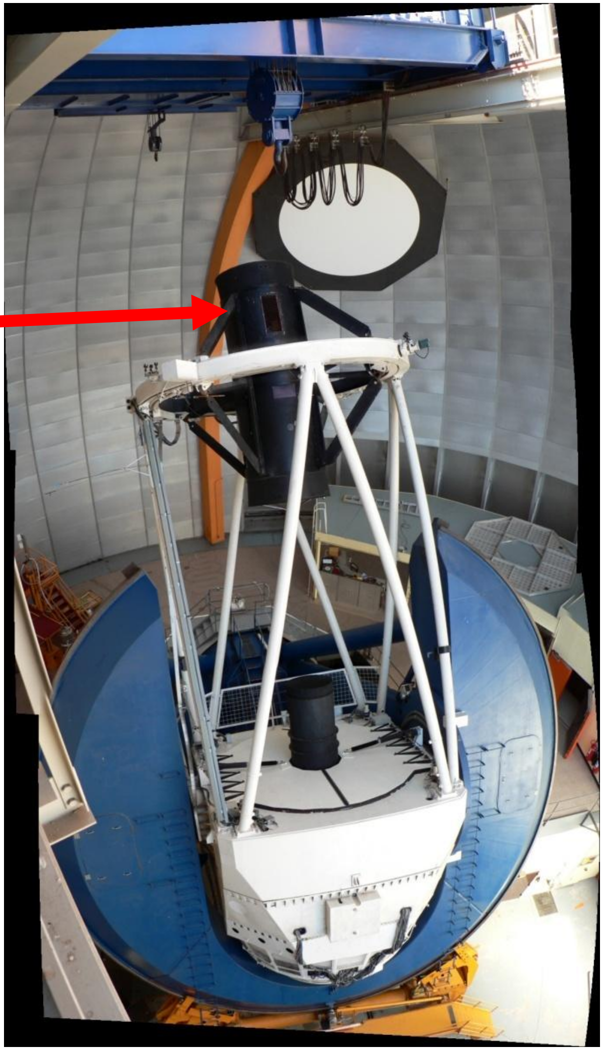
Forecast Constraints on DE Equation of State



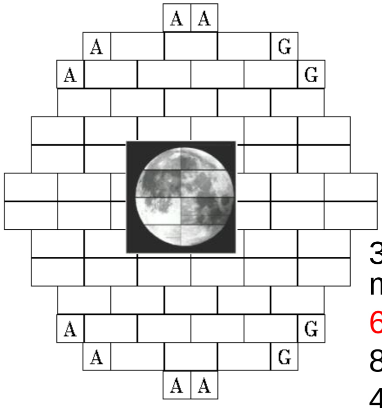
Stage III project (DETF)

The Dark Energy Survey Camera (DECam)





Use the Blanco 4M Telescope at the Cerro-Tololo Inter-American Observatory (CTIO)



3 sq. deg. field of view (~ 0.5 meter diameter focal plane)

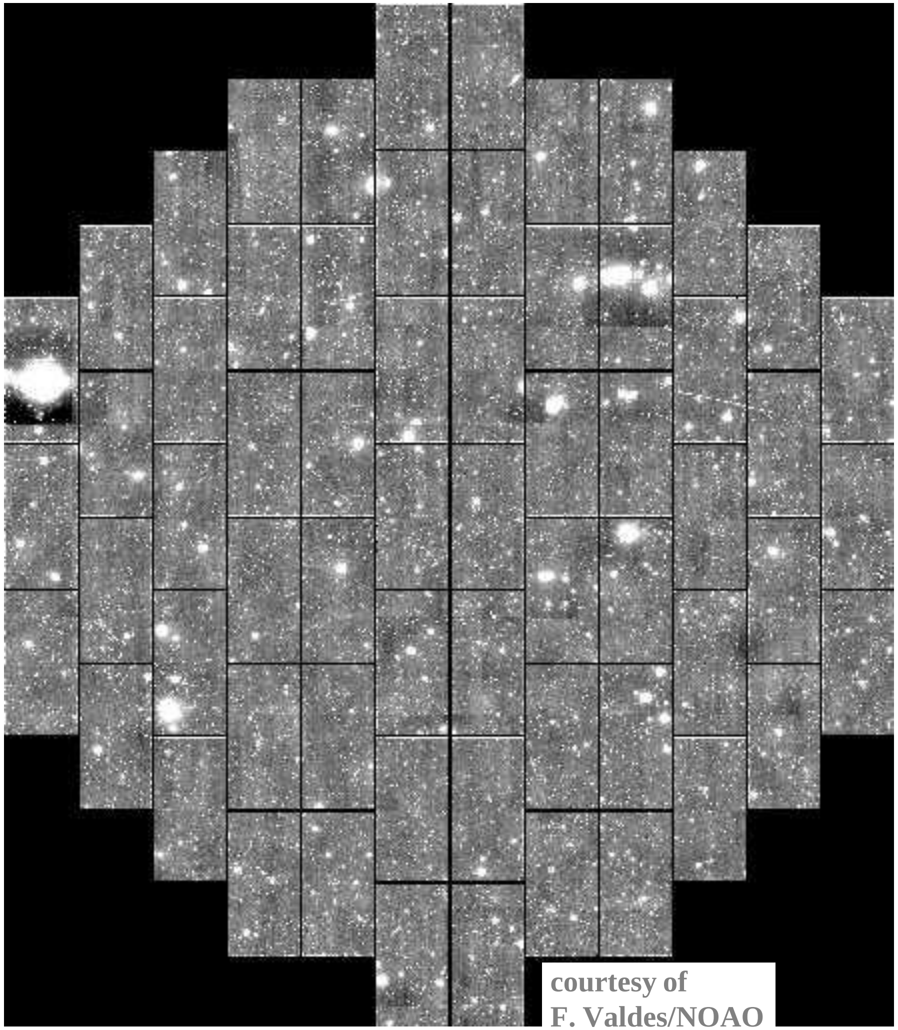
62 2kx4k Image CCDs: 520 MPix

8 2kx2k Alignment/focus CCDs

4 2kx2k Guide CCDs

DECam Image Simulation

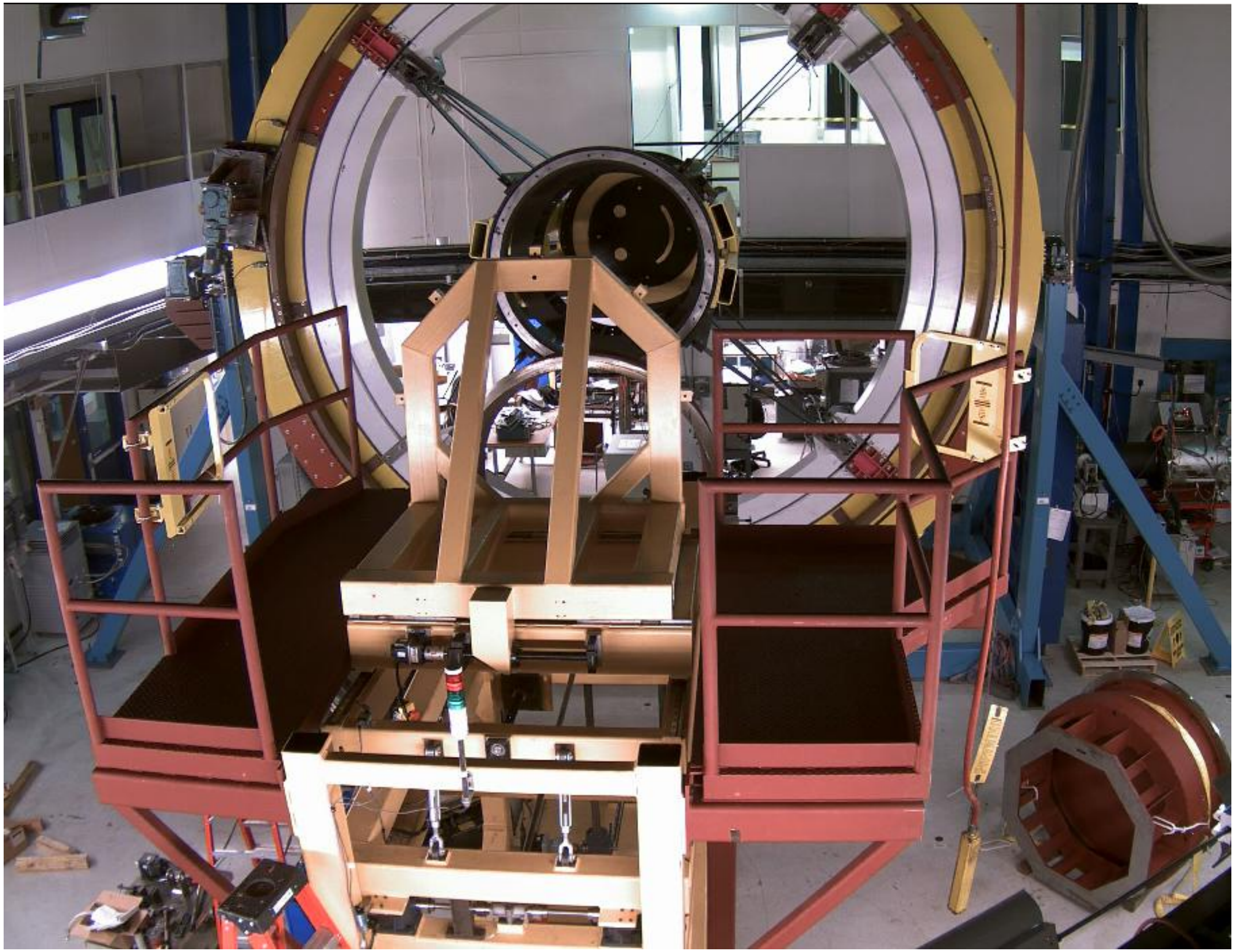
- DECam will be the largest CCD camera of its time.
- Each image
  - 3 sq. deg.
  - ~ 20 Galaxy clusters
  - ~ 200,000 Galaxies
  - 520 Mega pixels (62 CCDs)
  - ~ 1 GB (about the same as an ATLAS event)
  - Take one every ~ 2 min. for ~ 10 hours per “day”
- Each night ~ 300 GB of image data
- ~ 300 TB total raw data
- ~ 1PB total processed data



Telescope Simulator At Fermilab

- Provides platform for testing DECam operations and installation procedures prior to shipping to Chile

- Assembly and testing are in progress at Sidet (the silicon detector facility where the CDF, D0 and CMS silicon vertex detectors were made)



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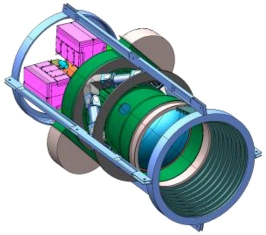
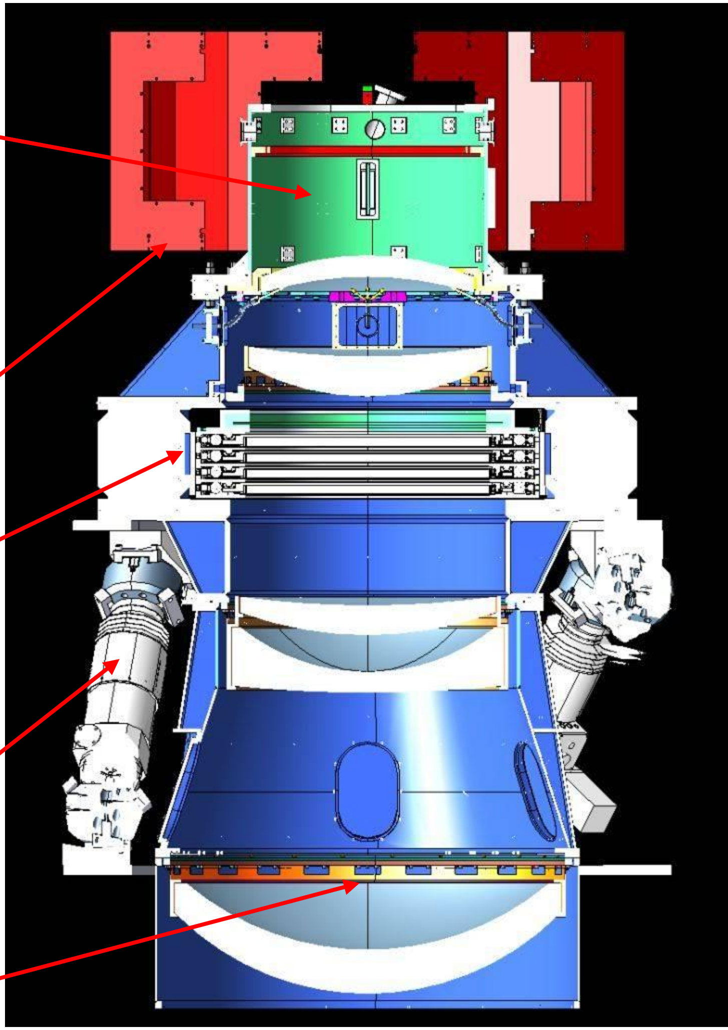
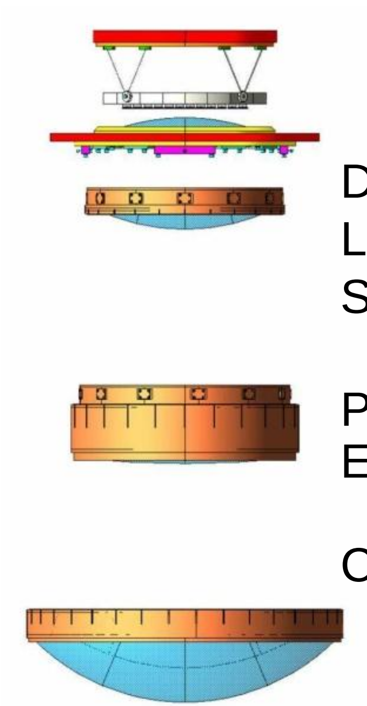
DECam Overview



- CCD focal plane is housed in a vacuum vessel (the imager) which is supported by the barrel
- LN2 is pumped from the telescope floor to a heat exchanger in the imager: cools the CCDs to -100 C
- CCD readout electronic crates are mounted to the outside of the Imager and are actively cooled to eliminate thermal plumes.
- Filter changer with 8 filter capacity (UMichigan) and Bonn shutter fit between 3rd and 4th lenses
- Hexapod provides focus and lateral alignment capability for the corrector-imager system
- Barrel supports the lenses and imager



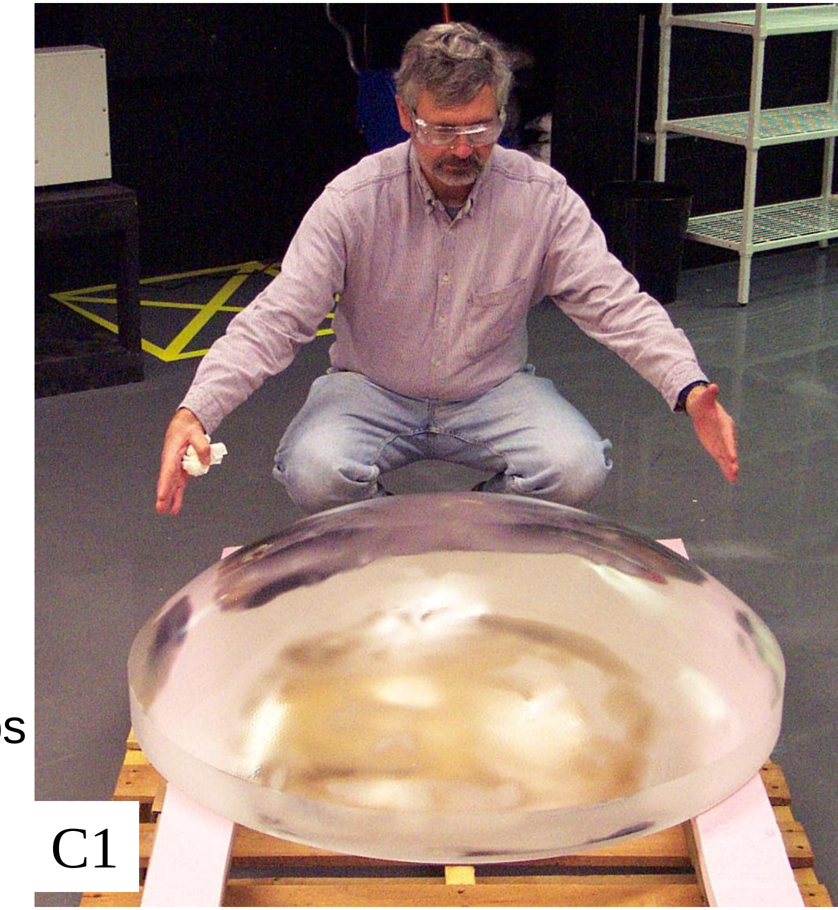
Optics Fabrication is in Progress in Europe



Design: 5 lenses
Largest is~ 1m diameter, ~ 300lbs
Smallest is ~ 0.5m, 60 lbs

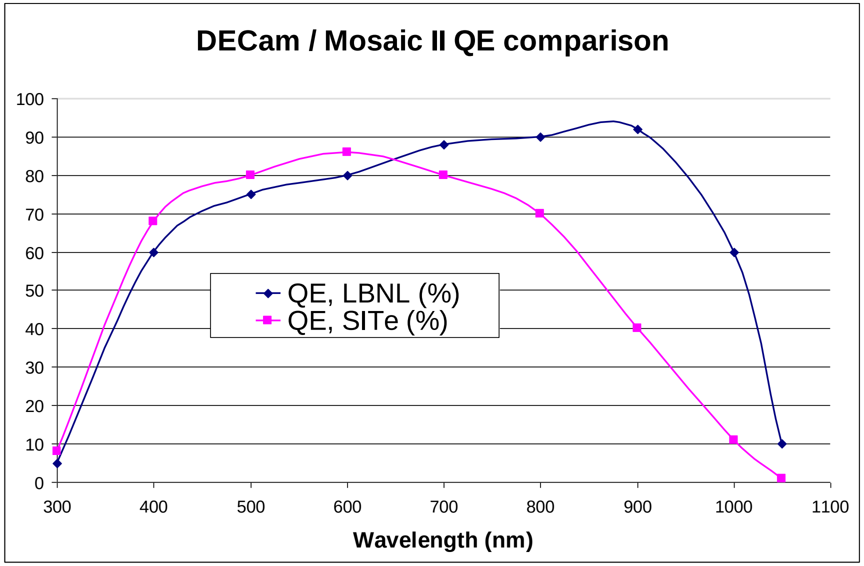
Polishing started in May 2008
Est. Delivery Oct. 2010

Cost of all 5 lenses ~ $3M

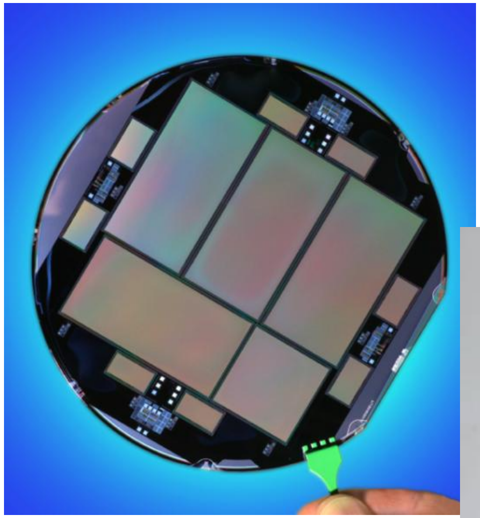


C1 blank inspection

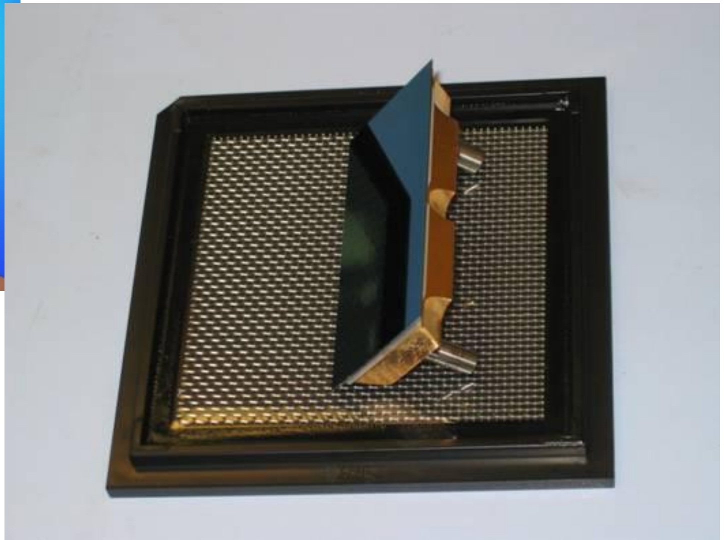
DECam CCDs



- Red Sensitive CCD wafers are processed at DALSA and LBNL:
  - QE> 50% at 1000 nm
  - 250 microns thick
  - readout 250 kpix/sec
  - 2 RO channels/device
  - readout time ~17sec



- Bare diced wafers are delivered to Fermilab
- At Fermilab we package and test the CCDs

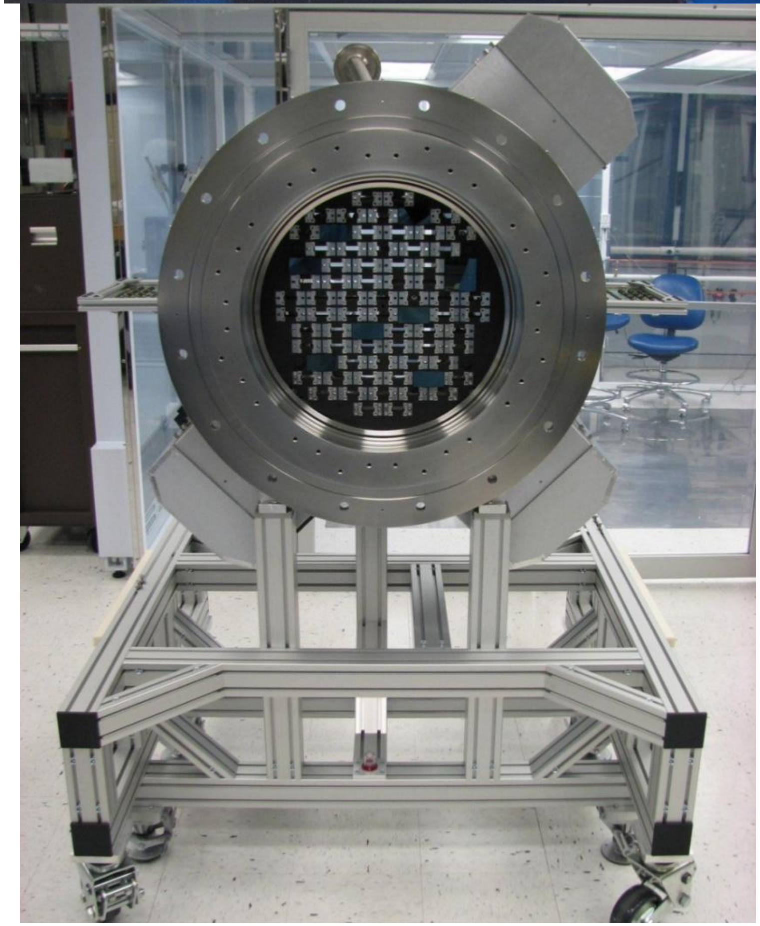


DECam parts: Shutter

- Bonn University in Germany made the DES Shutter
- Cost is about $200,000
- Opening is ~ 600mm diameter
- The DECam Shutter is the largest ever (so far)

DECam Imager

- Focal plane support plate is painted black to reduce scattered light between CCDs
- DECam imager with three readout crates on the handling cart
- June 26th First cool down with two engineering grade CCDs installed, production LN2 and crate cooling systems: read out with low noise!
- Now operating with 23 eng. grade CCDs



DES made it to the big time!

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START 18.01

Big Picture: 570-Megapixel, Intergalactic Camera

By Mark Anderson December 21, 2009 | 10:00 am | Wired Jan 2010

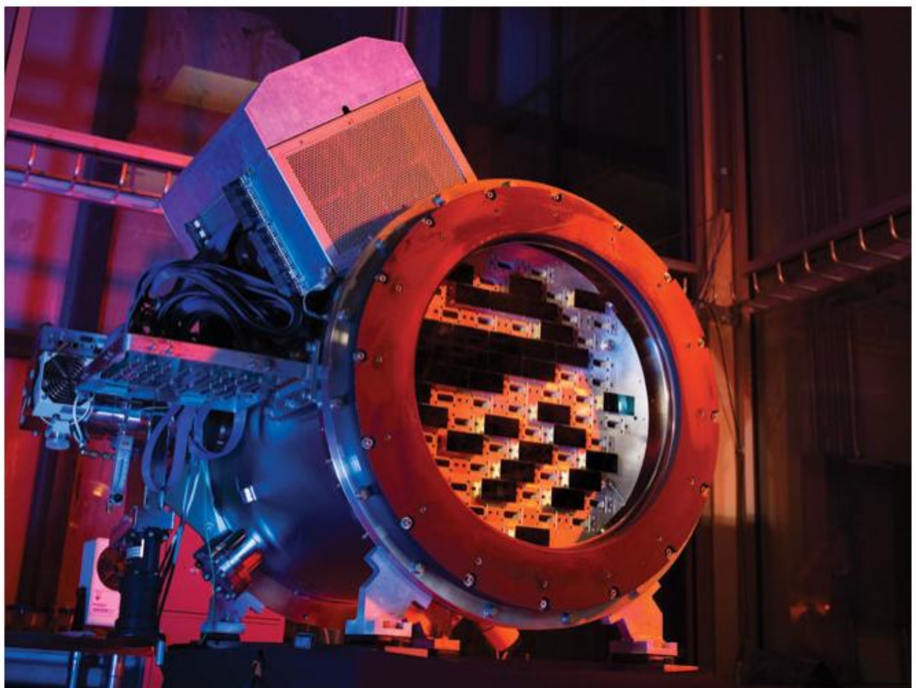

Photo: Fermilab

You're looking at the heart of one of the biggest digital cameras ever conceived — 74 CCD sensors that will go into an enclosure the size of a Mini Cooper. The 570-megapixel shooter is being built at Fermilab

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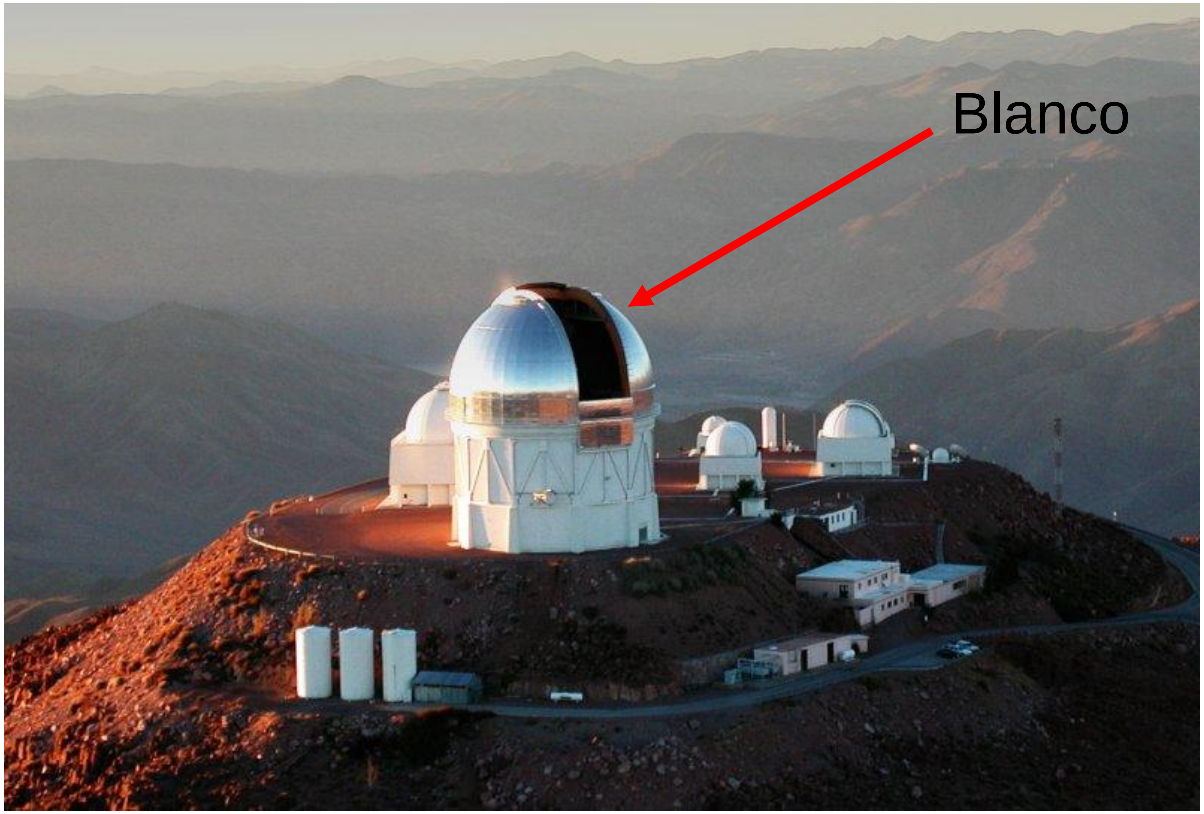
How long and how much does it cost to build a 520 Mpixel camera?

- We started talking about it and requesting funding in 2004
- Fully approved and funded in 2008
- First light expected in 2011
- $35M Total Project Cost to DOE; $29M spent so far (Nov.05-present)
- $10M contributed by NSF, Universities, foreign governments



Cerro Tololo Inter-American Observatory

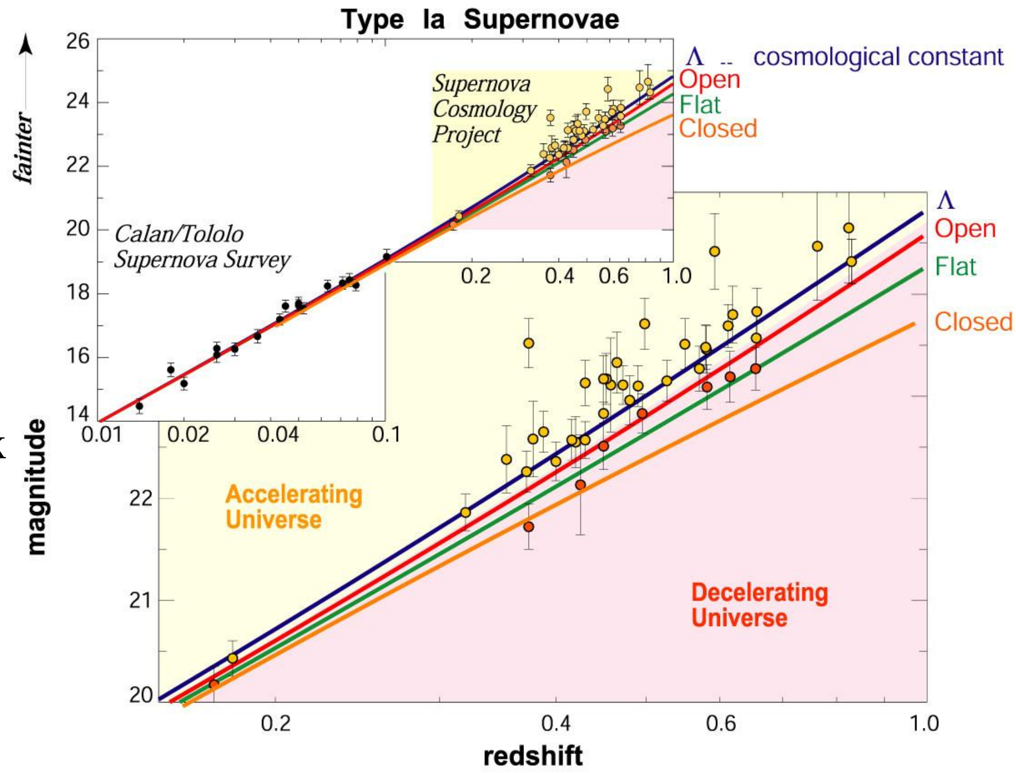
Conclusions

- Dark Energy and Dark Matter make up 95% of the energy density in the Universe and yet their properties are mysterious
- The theorists are stumped
- It is up to the observers to make new measurements
- Improved technology, bigger cameras, better CCDs, and new ways for measuring the effects of DE and DM hold great promise for beginning to reveal these secrets

QUESTIONS?

Type Ia Supernovae are standard candles

- SNIa can be used to measure the expansion rate of the universe
- Two groups, the Supernova Cosmology Project and the Hi-Z Team, find evidence that the expansion of the Universe is accelerating now: Dark Energy
- Up until 4 billion years ago (redshifts > ~ 0.75) the expansion rate was slowing, Dark Matter dominated.
- Measuring the expansion rate of the universe as a function of redshift tells us about the amount of Dark Matter and Dark Energy



from A. Kim

Fall 2005:

130 spectroscopically confirmed Type Ia's

14 spectroscopically likely/possible Ia

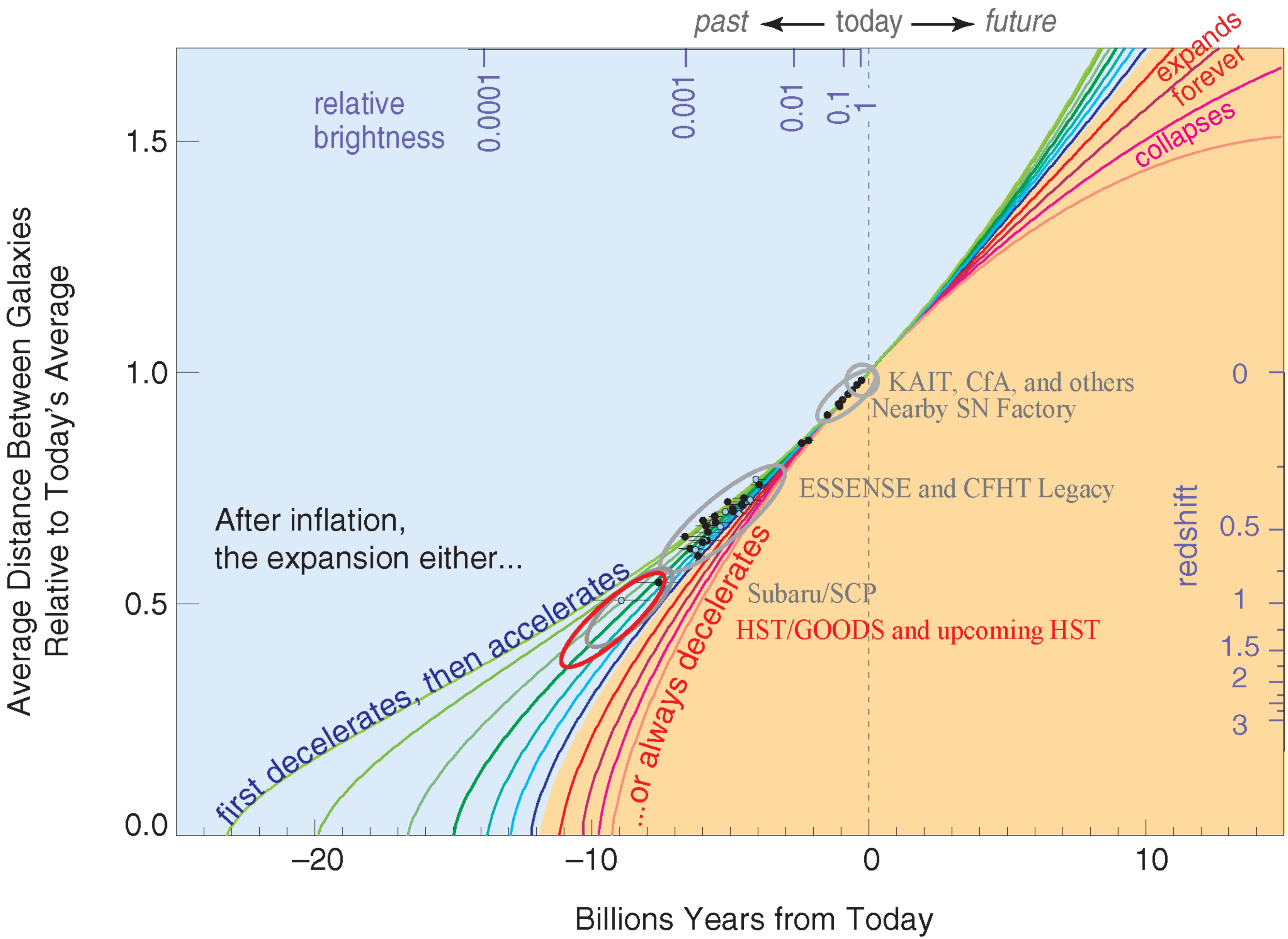
11 confirmed SN II

6 confirmed Ib/c

~100's of unconfirmed Ia's based on light curves

Full results coming this summer

Expansion History of the Universe



Forecast Constraints

DETF FoM

Method	$\sigma(\Omega_{DE})$	$\sigma(w_0)$	$\sigma(w_a)$	z_p	$\sigma(w_p)$	$[\sigma(w_a)\sigma(w_p)]^{-1}$
BAO	0.010	0.097	0.408	0.29	0.034	72.8
Clusters	0.006	0.083	0.287	0.38	0.023	152.4
Weak Lensing	0.007	0.077	0.252	0.40	0.025	155.8
Supernovae	0.008	0.094	0.401	0.29	0.023	107.5
Combined DES	0.004	0.061	0.217	0.37	0.018	263.7
DETF Stage II Combined	0.012	0.112	0.498	0.27	0.035	57.9

Table 1: 68% CL marginalized forecast errorbars for the 4 DES probes on the dark energy density and equation of state parameters, in each case including Planck priors *and* the DETF Stage II constraints. The last column is the DETF FoM; z_p is the pivot redshift. Stage II constraints used here agree with those in the DETF report to better than 10%.

- DES+Stage II combined = Factor 4.6 improvement over Stage II combined
- Consistent with DETF range for Stage III DES-like project
- Large uncertainties in systematics remain, but FoM is robust to uncertainties in any one probe, and we haven't made use of all the information