Galaxy Clusters

Giants of the Universe

Maciej
Soltynski

ASSA
Symposium
2012

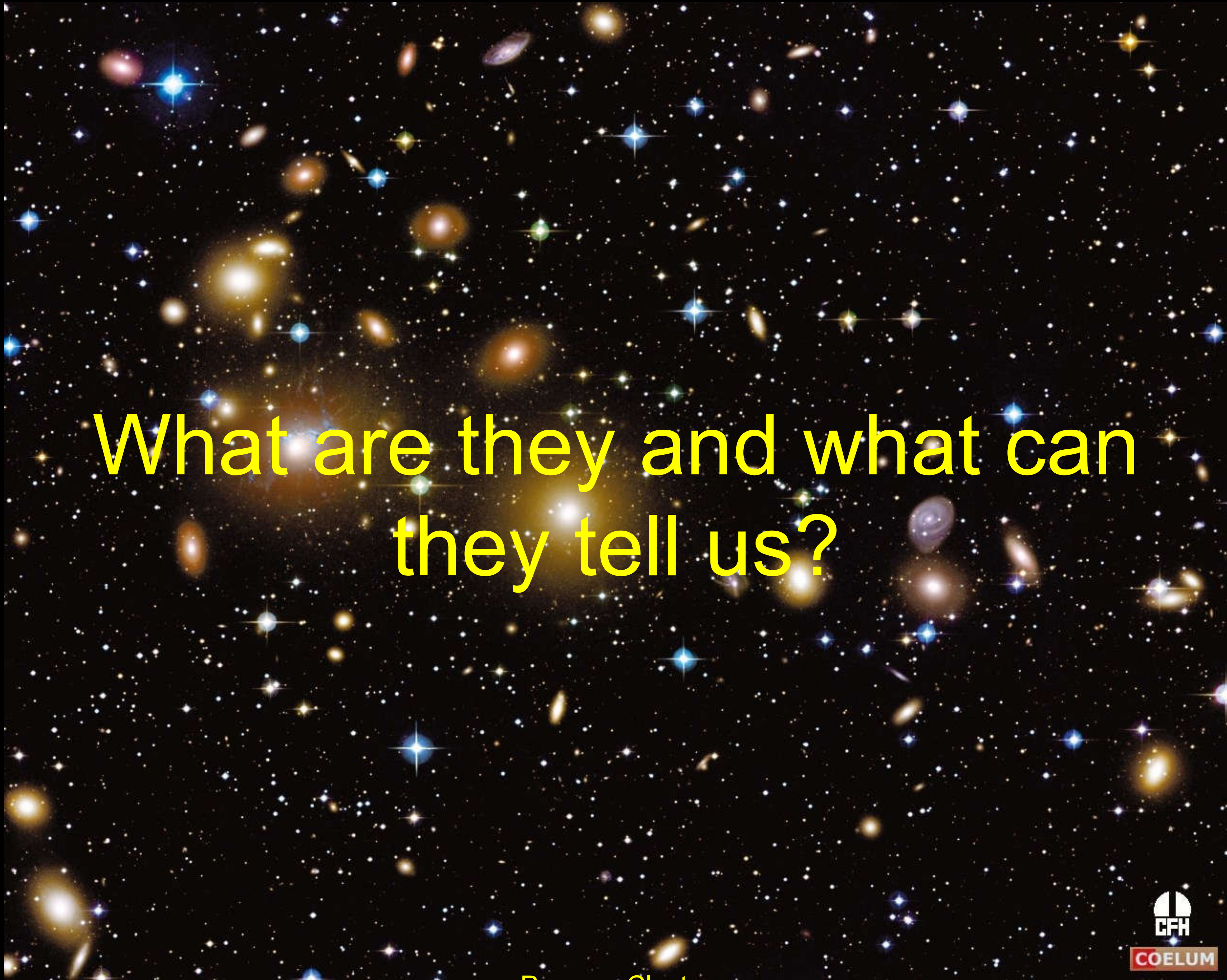
Virgo cluster around M86

Why am I talking about galaxy clusters?
(they are very faint objects)

- They are the biggest objects we know

- Because we live in a golden age of observational and physical astronomy, and galaxy clusters hold many of the keys to (unanswered) questions regarding the evolution of the Universe

- Because ‘observing’ them illustrates a new era of amateur astronomy (VO)
  - The Internet and the WWW are the new telescope
  - Unparalled access to astronomical information (free!)
    - Data bases (images, spectra, properties of objects, catalogues etc)
    - Programming languages and software applications
    - Explanations and science papers
    - Online and offline lectures
    - University courses e.g. Coursera (Galaxies and Cosmology Jan 2013 - George Djorgovski - Caltech)



Perseus Cluster

Palomar Sky Survey

- The National Geographic Society - Palomar Observatory Sky Survey (NGS-POSS) is a major photographic survey of the night sky completed at Palomar Observatory in 1958.
- 48-inch Samuel Oschin Schmidt Telescope
- Each plate 35.5 x 35.5 cm covers 6° x 6° (144 full Moons) in blue and red light
- 936 plates cover entire northern sky down to dec -34°

So George Abell picked up his trusty magnifying glass . . .

Virgo cluster

6º FOV

POSS II

George Abell

- Using a magnifying glass and a set of circular templates he examined 879 (x2) of the plates down to dec -27°
- He counted thousands of clusters and catalogued 2712 which met certain criteria
  - 50 or more galaxies in a circle of radius 1 Mpc
  - 3rd brightest must have magnitude brighter than 17.5
  - Luminosity of 10th brightest was used to find distance (z)

THE DISTRIBUTION OF RICH CLUSTERS OF GALAXIES*

GORGE O. ABELL†
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington, California Institute of Technology
Received September 30, 1957; revised November 13, 1957

ABSTRACT

A catalogue is prepared of 2712 rich clusters of galaxies found on the National Geographic Society–Palomar Observatory Sky Survey. From the catalogue, 1682 clusters are selected which meet specific criteria for inclusion in a homogeneous statistical sample. An investigation of the sample leads to the following conclusions: (1) the distribution function of clusters according to richness, $N(n)$, increases rapidly as n decreases; (2) the data allow no significant decision that the spatial density of cluster centers varies with distance; (3) galactic obscuration of the order of a few tenths of a magnitude (photored) exists at high northern galactic latitudes around galactic longitude 300°; (4) there is a highly significant non-random surface distribution of clusters, both when clusters at all distances and when clusters at various distances are considered. An analysis of the distribution yields evidence that suggests the existence of second-order clusters, that is, clusters of clusters of galaxies. A statistical test reveals no incompatibilities between the observed distribution and one of complete second-order clustering of galaxies.

The Abell catalogue is an almost complete list of 4 000 clusters containing at least thirty members up to a redshift of z = 0.2 The extended catalogue, including clusters in the southern hemisphere, was published posthumously in 1989 in collaboration with Harold G. Corwin and Ronald P. Olowin

Galaxy clusters

Faint because far

Gravitationally bound – not static

Largest physical objects in the Universe containing many galaxies packed into a volume of a few megaparsecs

- They contain 50 to 1000+ galaxies
- They have total masses of in the range 10^{14} to 10^{16} M
- Typical diameter from 2 to 10 Mpc
- (Milky Way about 10^{11} M with diameter 35 kpc)
- The spread of velocities for the individual galaxies is about 800-1000 km/s

Mostly elliptical (70%) and spiral (30%), few irregulars (a sign of age)

Clusters of galaxies are often dominated by a single giant elliptical galaxy, known as the brightest cluster galaxy BCG

BCG

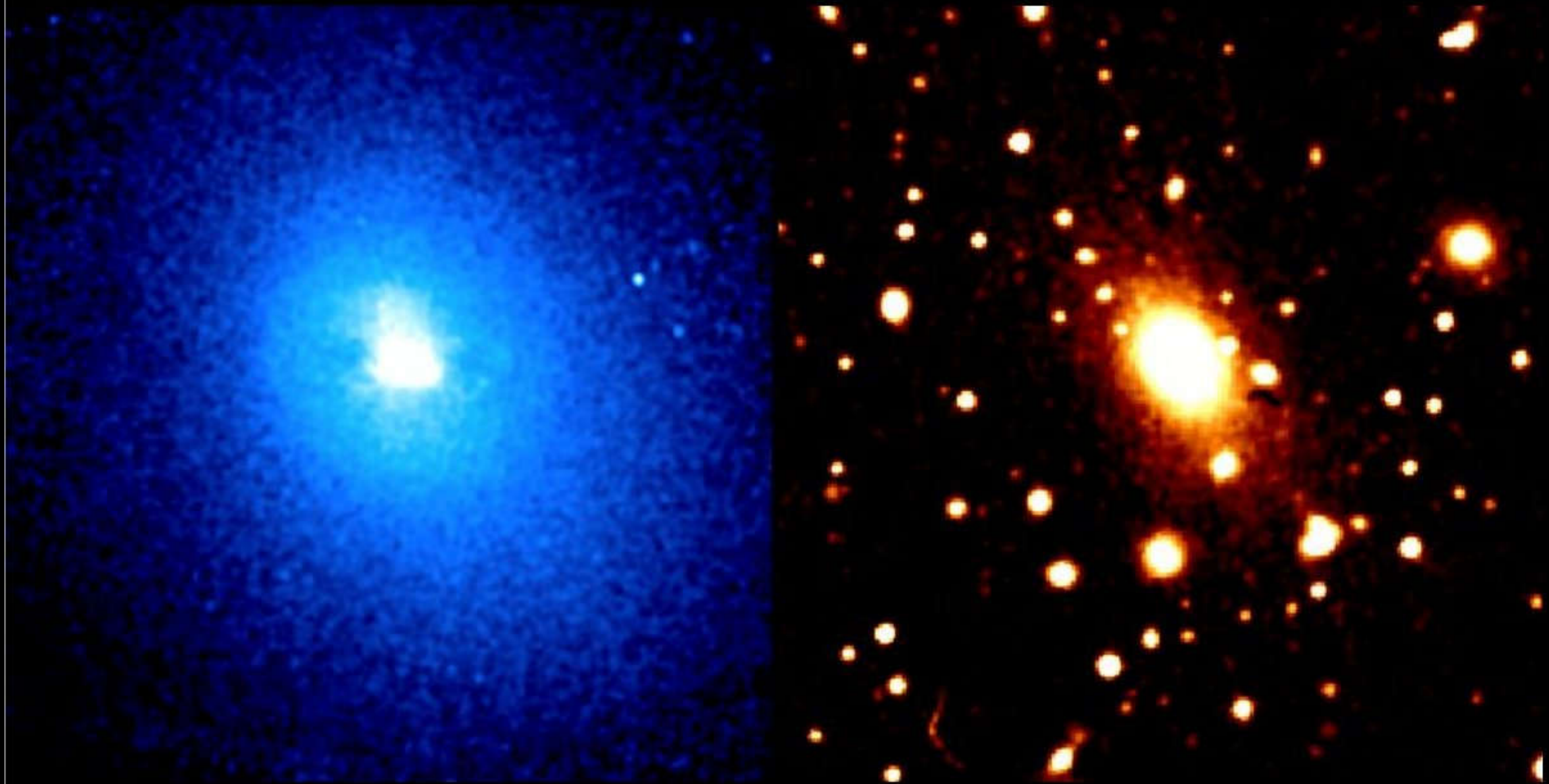
- Brightest cluster galaxy (BCG) is defined as the brightest galaxy in a cluster of galaxies.
- BCGs include the most massive galaxies in the universe.
- They are generally elliptical galaxies which lie close to the geometric and kinematical center of their host galaxy cluster, hence at the bottom of the cluster potential well.
- They are also generally coincident with the peak of the cluster X-ray emission and centre of radio lobes


Abell 85
Optical


Abell 85
X-ray

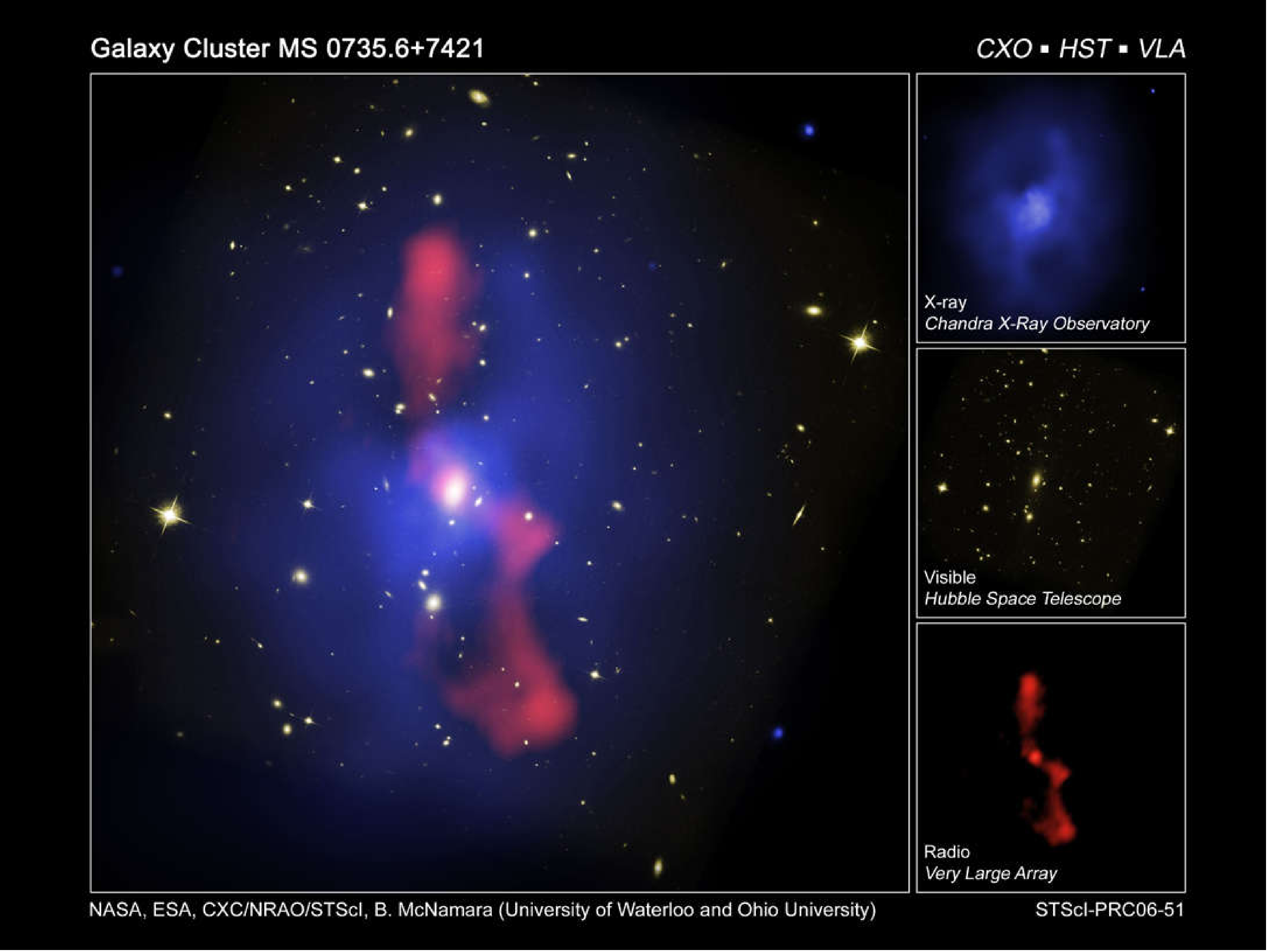
Abell 2199

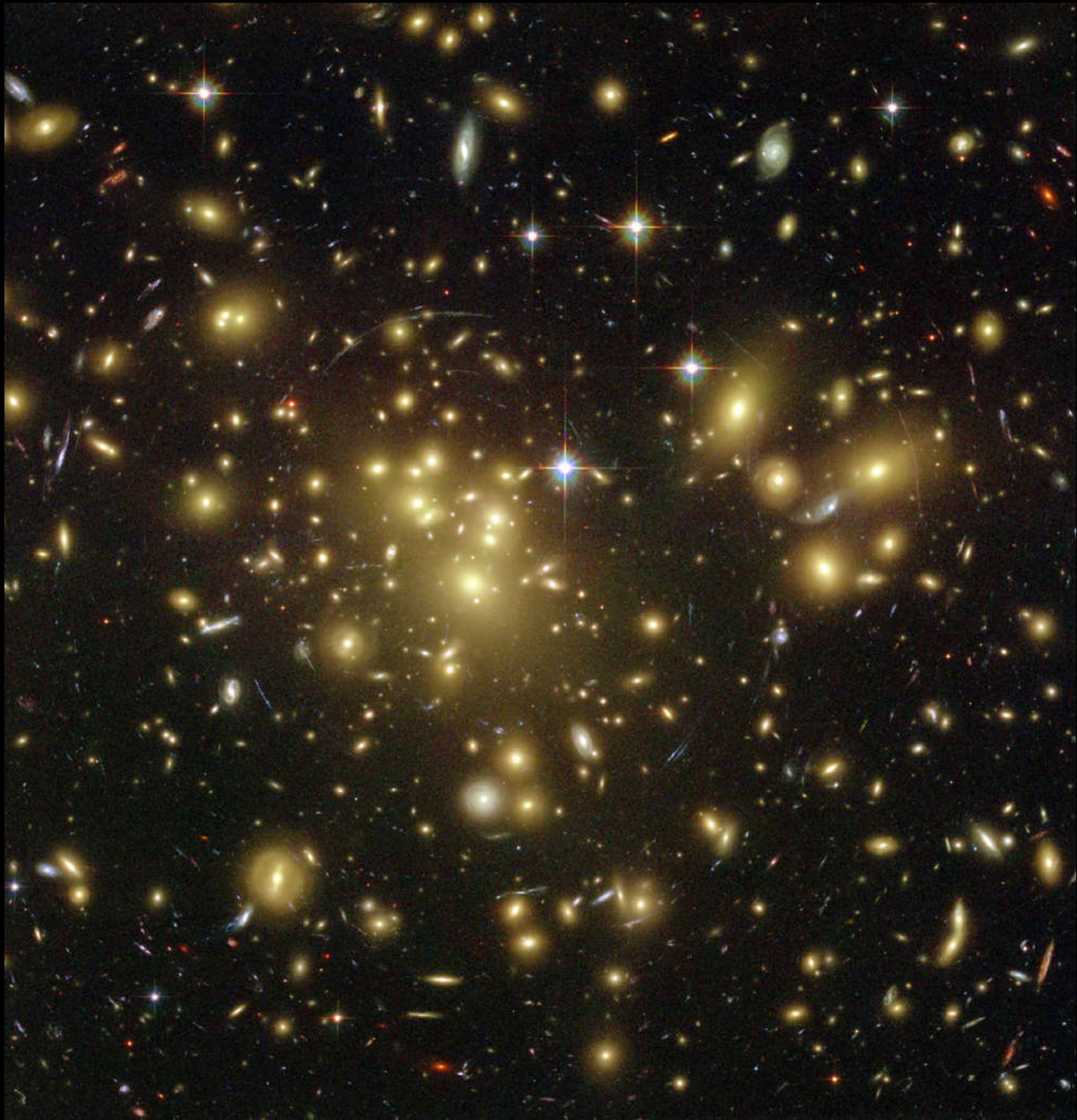
Chandra (X-ray) DSS (Optical)



redshift, z = 0.0309

50 thousand light years


Galaxy Cluster MS 0735.6+7421
CXO ▪ HST ▪ VLA
X-ray
Chandra X-Ray Observatory
Visible
Hubble Space Telescope
Radio
Very Large Array
NASA, ESA, CXC/NRAO/STScI, B. McNamara (University of Waterloo and Ohio University)
STScI-PRC06-51



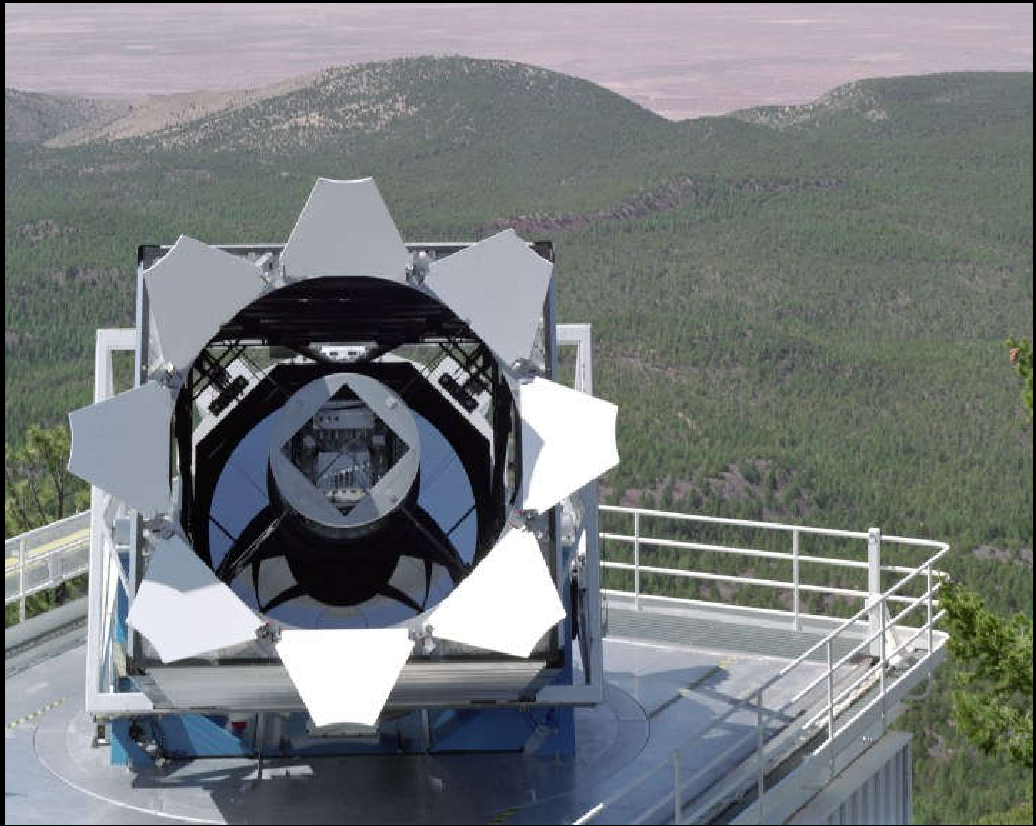
Abell 1689

(HST)

Arp 272 - HST

Sloan Dark Sky Survey (SDSS)

New Mexico

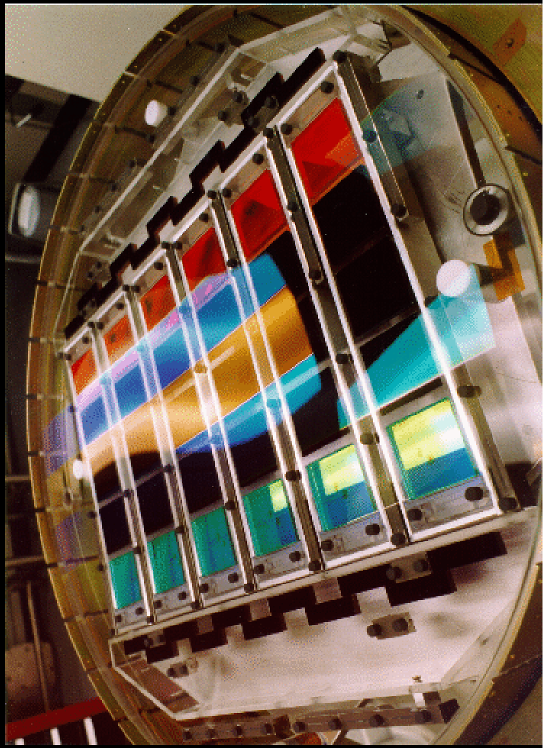


2.5 metre telescope, semi-automatic

In addition to the camera, a pair of spectrographs fed by optical fibers measure spectra of (and hence distances to) more than 600 galaxies and quasars in a single observation.

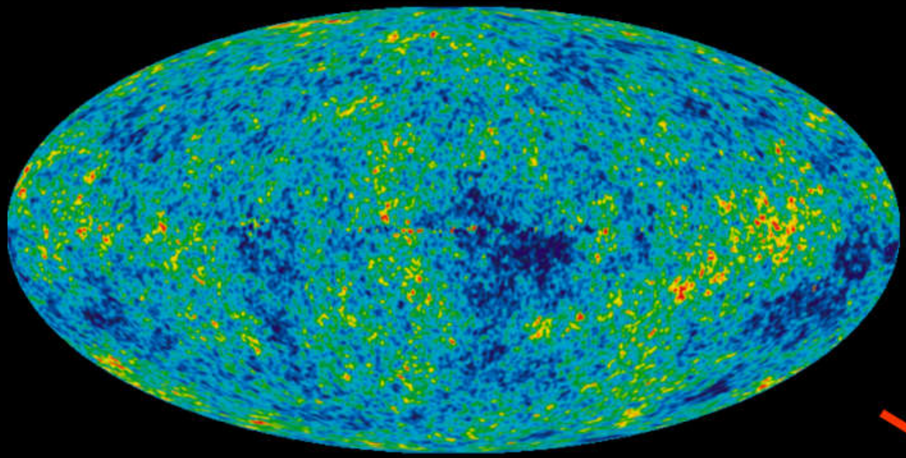
Data Release 9 (DR9)

Sky Coverage	14555 square degrees
Catalog objects	932 891 133
Galaxy spectra	1 457 002
Quasar spectra	228 468
Star spectra	668 054



All the images, measurements, and spectra are available free online

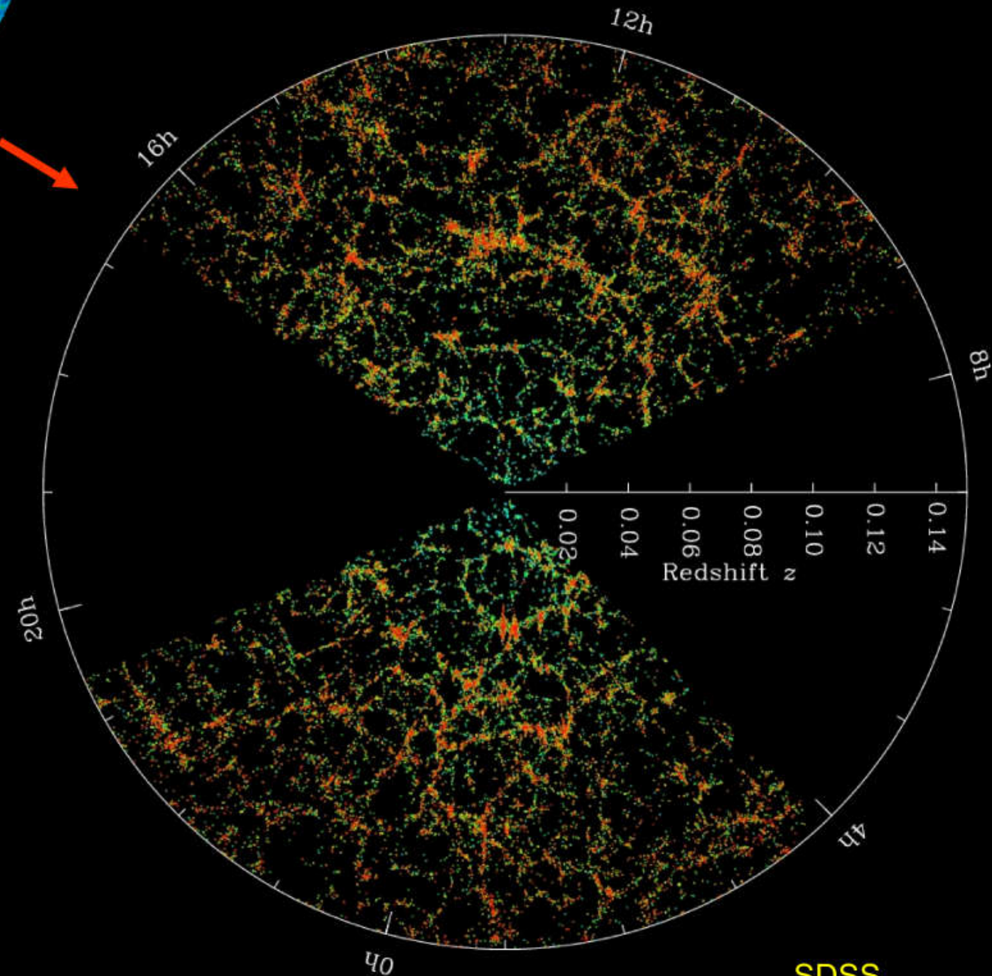
How did the Universe get from this?



T = 2.725 K

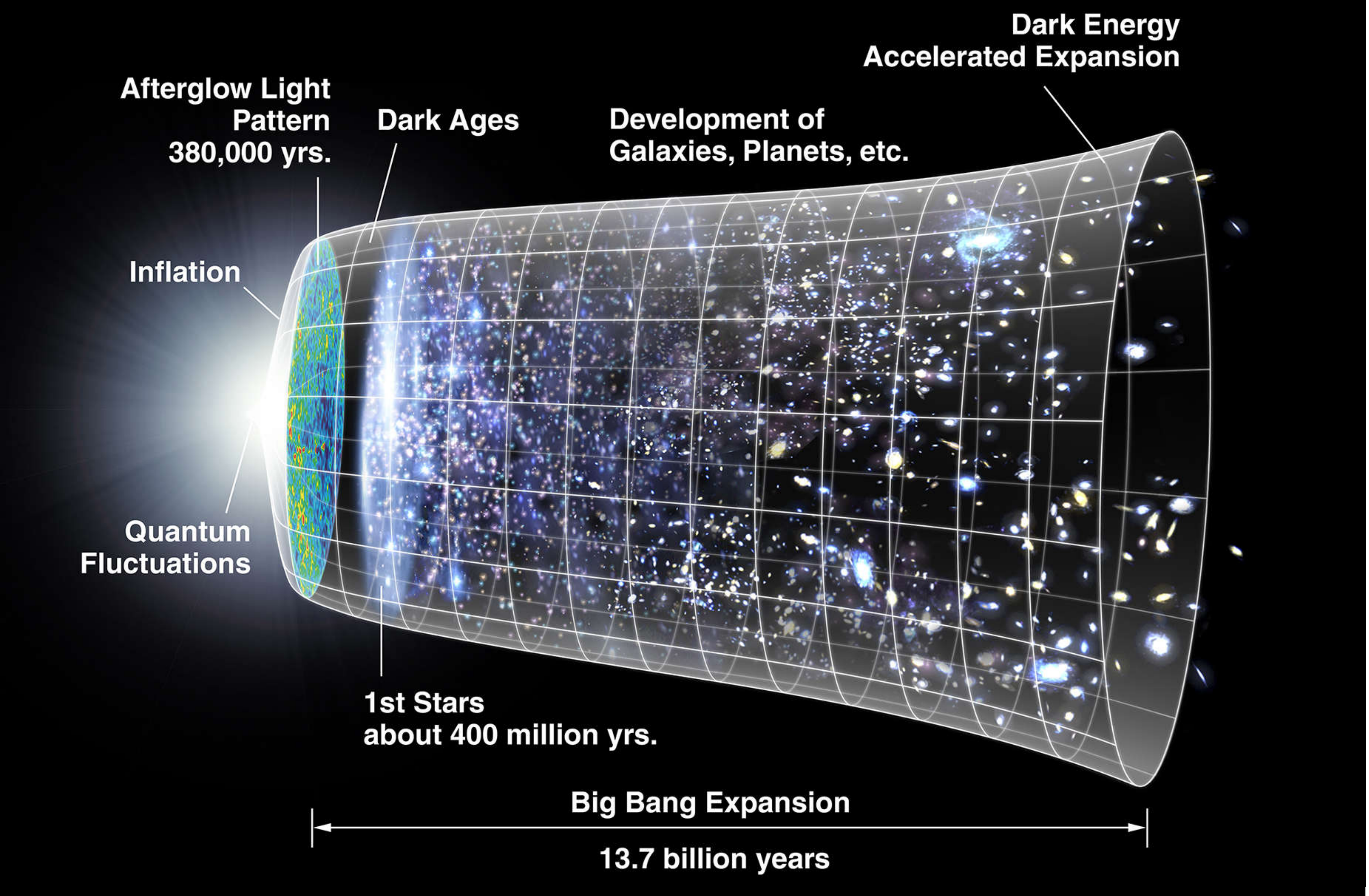
red warmer, blue colder by about 0.0002 degrees

NASA/WMAP Science Team



to this ?

SDSS



ΛCDM

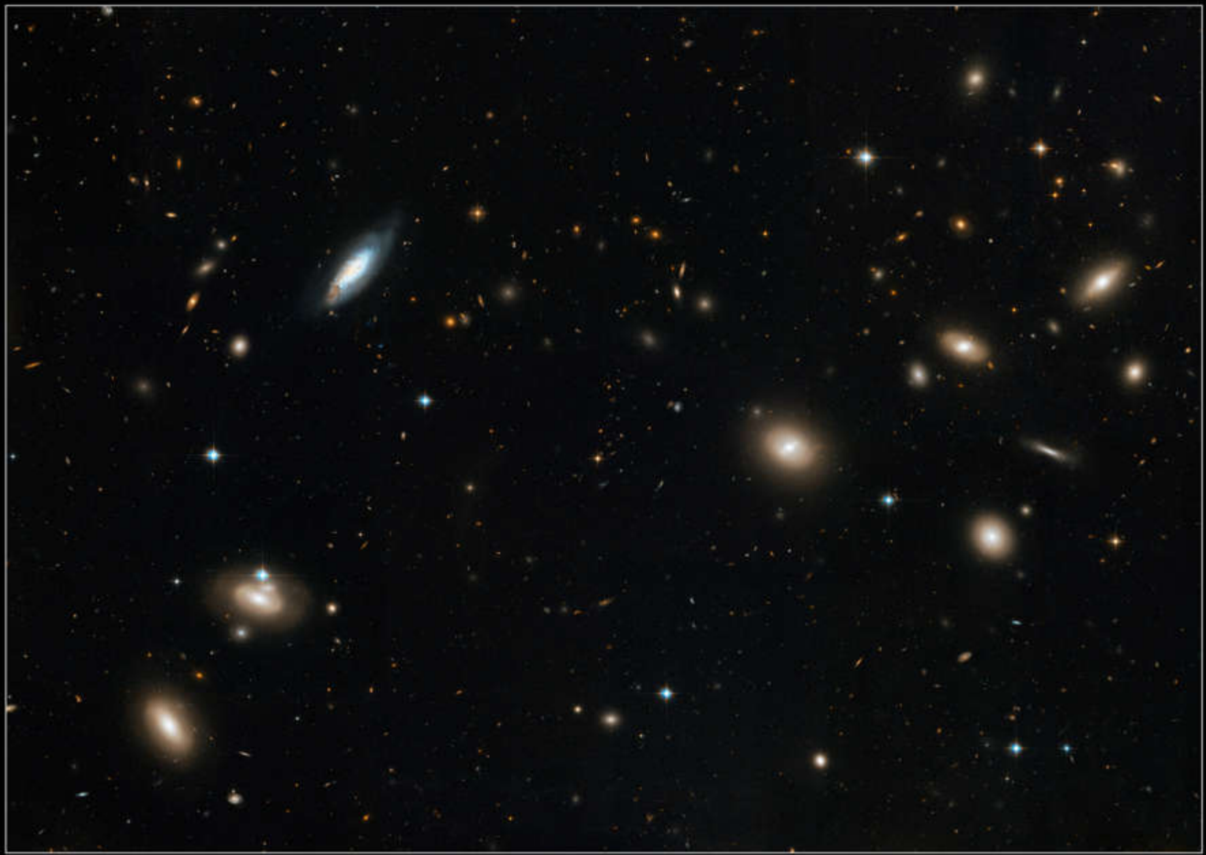
NASA/WMAP Science Team

A computing challenge

Given the DR9 database (1 400 000 galaxies) find those that occur in clusters

Friends of Friends (FoF) methods

Coma Cluster of Galaxies



Hubble Heritage

NASA, ESA, and The Hubble Heritage Team (STScI/AURA) • *Hubble Space Telescope* ACS • STScI-PRC08-24

Observational Probes of Cosmic Acceleration

Four most well established methods for making such measurements

- Type Ia supernovae

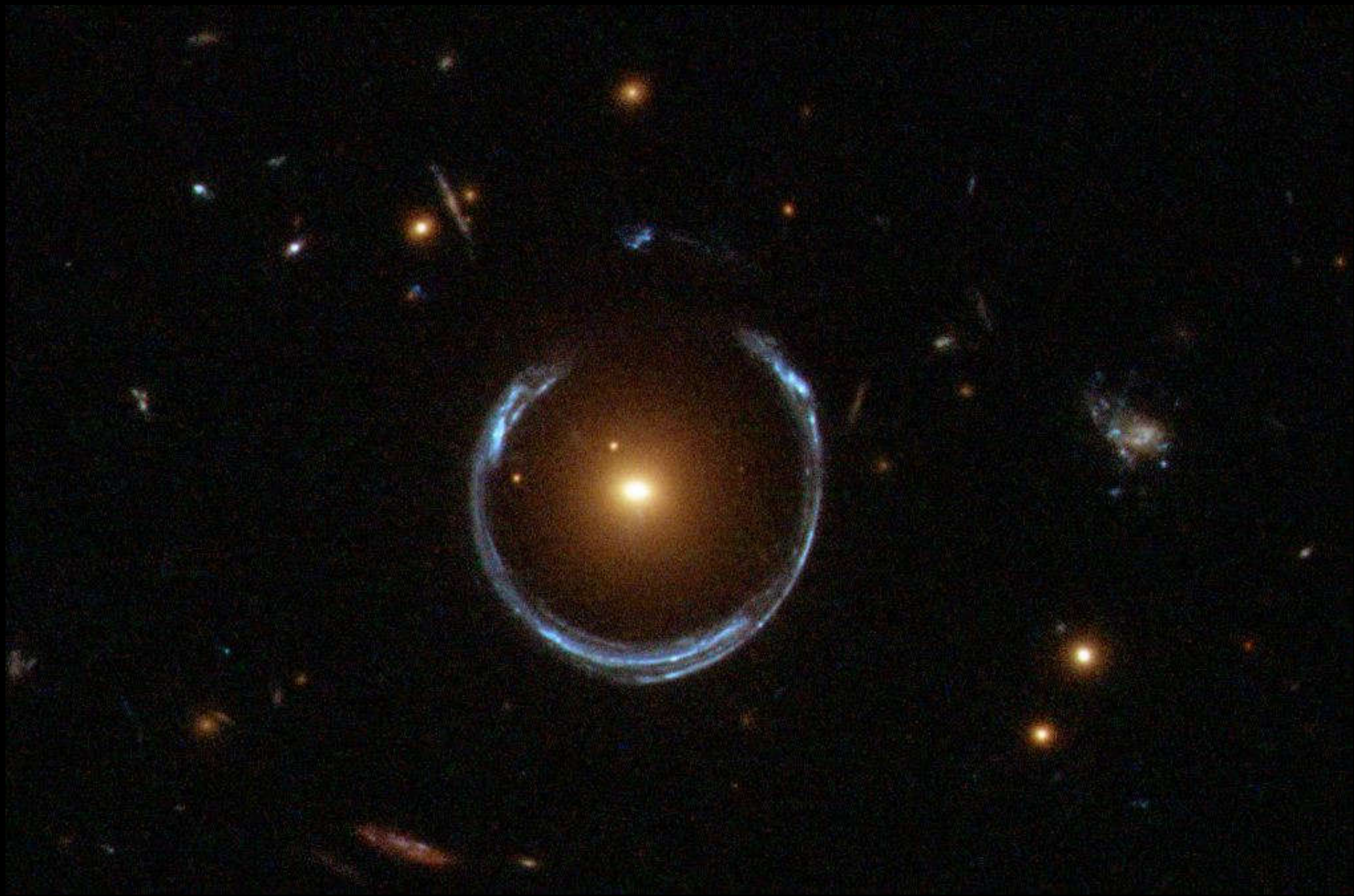
- Weak gravitational lensing

- Baryon acoustic oscillations (BAO)

- Abundance of galaxy clusters

- Integrated Sachs-Wolfe effect (ISW) Anisotropies in CMB photons can be produced gravitationally if the photons pass through time varying potential wells (e.g. galaxy clusters at low Z where DE is effective)

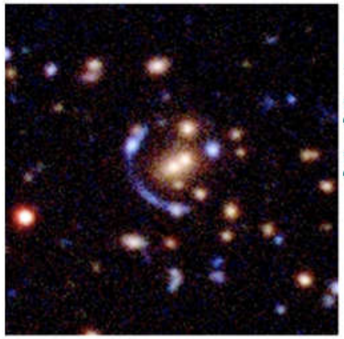
Good review by Weinberg et al 2012



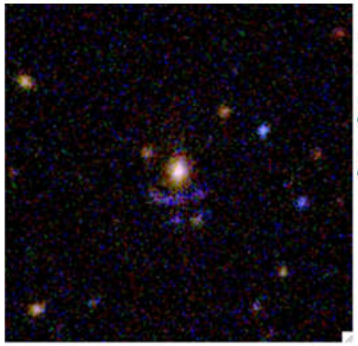
9 Spectroscopically Confirmed Lensing Systems

lrg-3-817
$z_l = 0.35$
$z_s = 2.26$

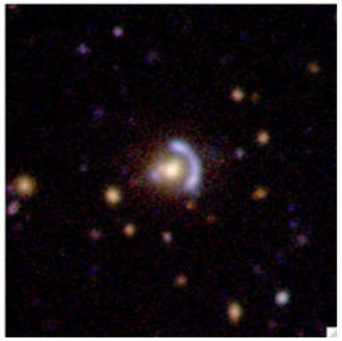
SSA_1113
$z_l = 0.35$
$z_s = 0.77$



lrg-4-606
$z_l = 0.49$
$z_s = 2.03$

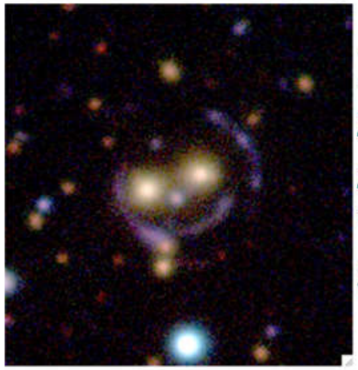


lrg-3-227
$z_l = 0.45$
$z_s = 0.98$

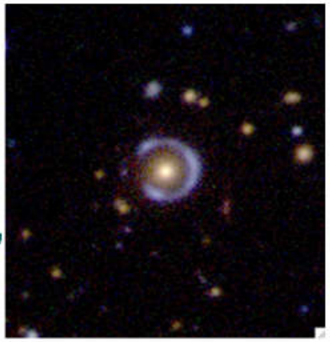


lrg-2-2811
$z_l = 0.42$
$z_s = 2.0$
"The Clone"

8 o'clock arc
$z_l = 0.38$
$z_s = 2.73$



lrg-4-581
$z_l = 0.43$
$z_s = 0.97$
"Cosmic Snowman"

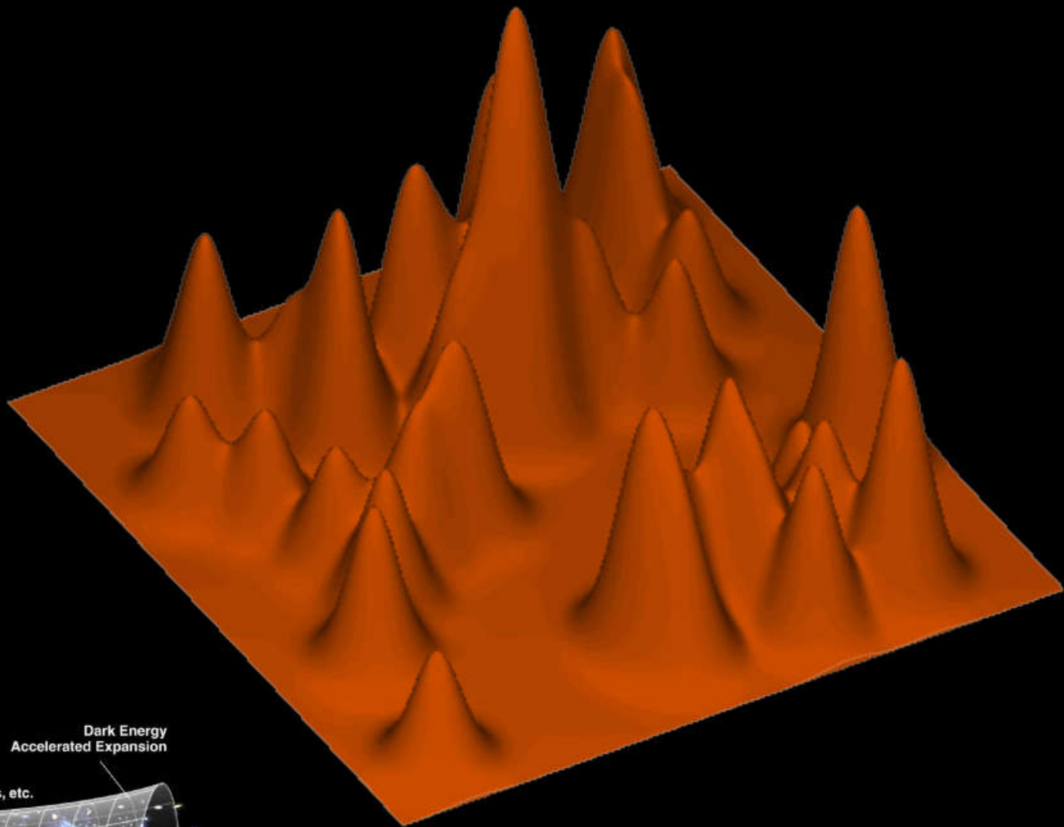


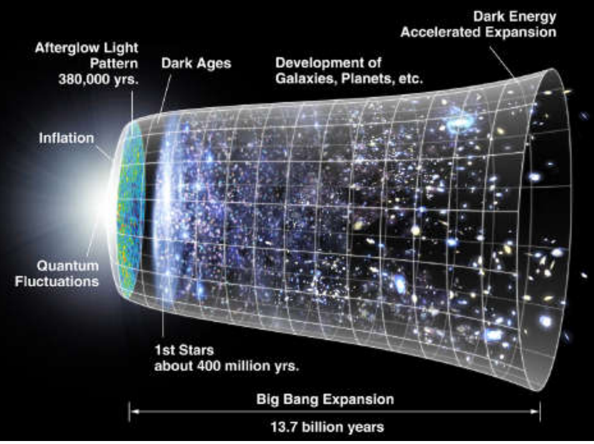
lrg-3-757
$z_l = 0.44$
$z_s = 2.38$
"Cosmic Horseshoe"

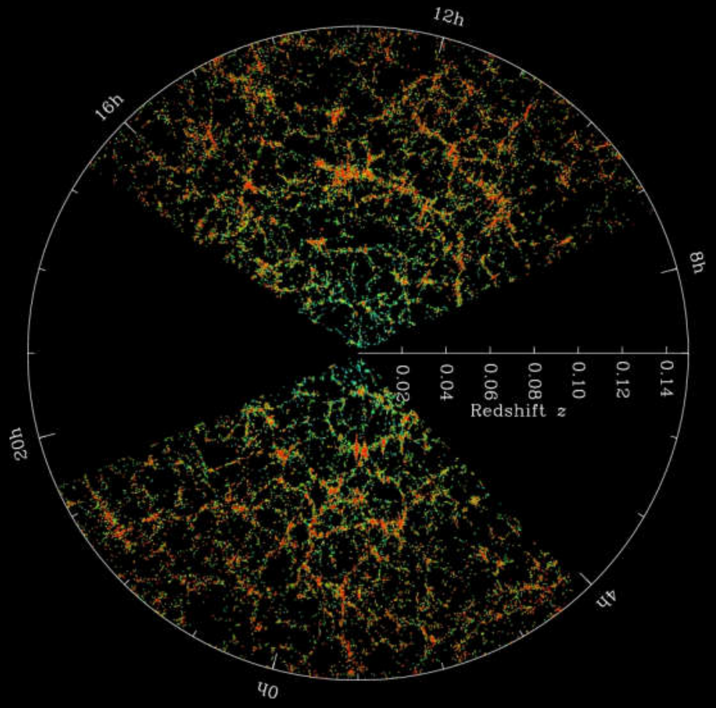
SSA_1343
$z_l = 0.34$
$z_s = 2.1$

MACS J1206
(HST)

BAO - Baryon Acoustic Oscillations





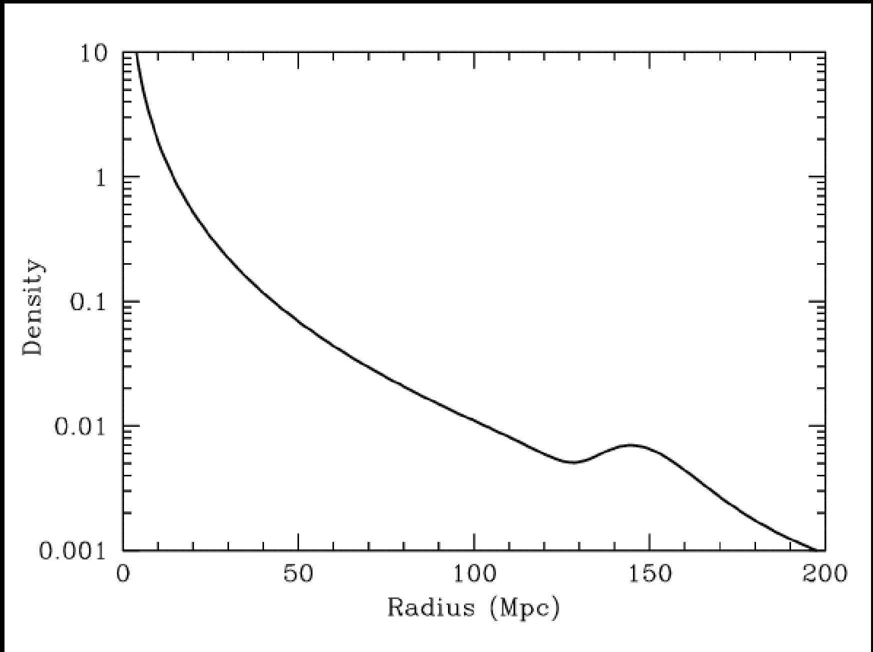


Correlation Function

In astronomy, a correlation function describes the distribution of galaxies in the universe. It describes the probability that two galaxies are separated by a particular distance.

It can be thought of as a lumpiness factor - the higher the value for some distance scale, the more lumpy the universe is at that distance scale.

Given a random galaxy in a location, the correlation function describes the probability that another galaxy will be found within a given distance (averaged over a large number of galaxies chosen as the first, random galaxy)

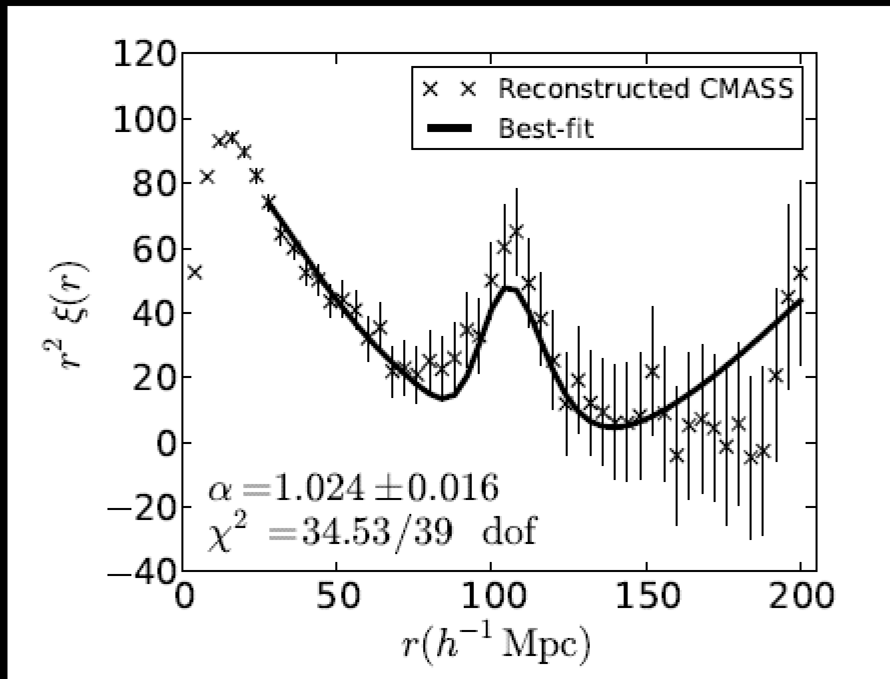


Eisenstein 2005

Galaxy clustering from the Baryon Oscillation Spectroscopic Survey (BOSS), part of SDSS-III

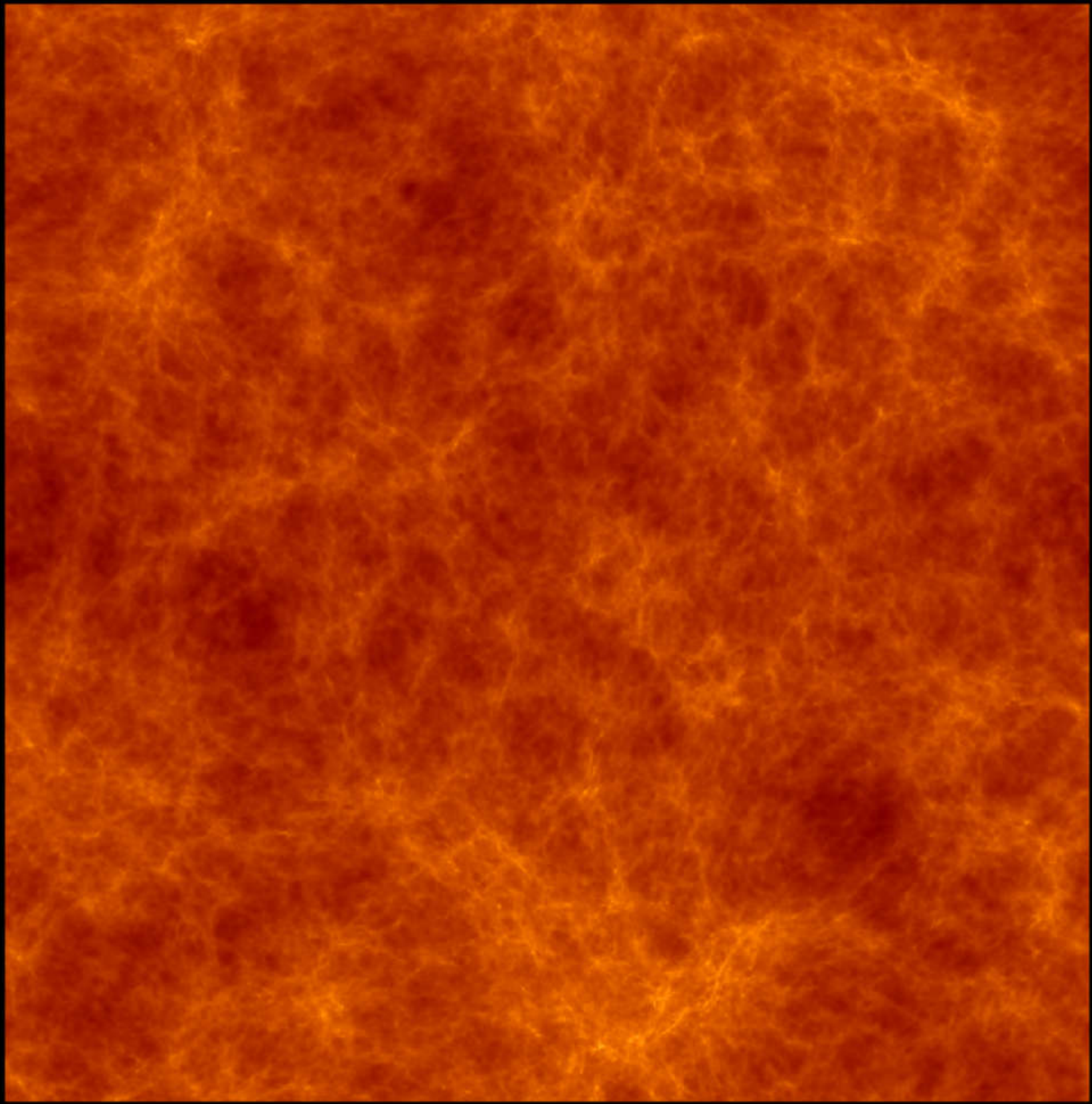
264 283 massive galaxies. the largest sample of the Universe ever surveyed at this density

There should be an small excess of galaxies 150 Mpc away from other galaxies, as opposed to 120 or 180 Mpc. We can see this as a single acoustic peak in the correlation function of galaxies



Anderson et al 2012

Evolution of galaxy clusters (simulation)

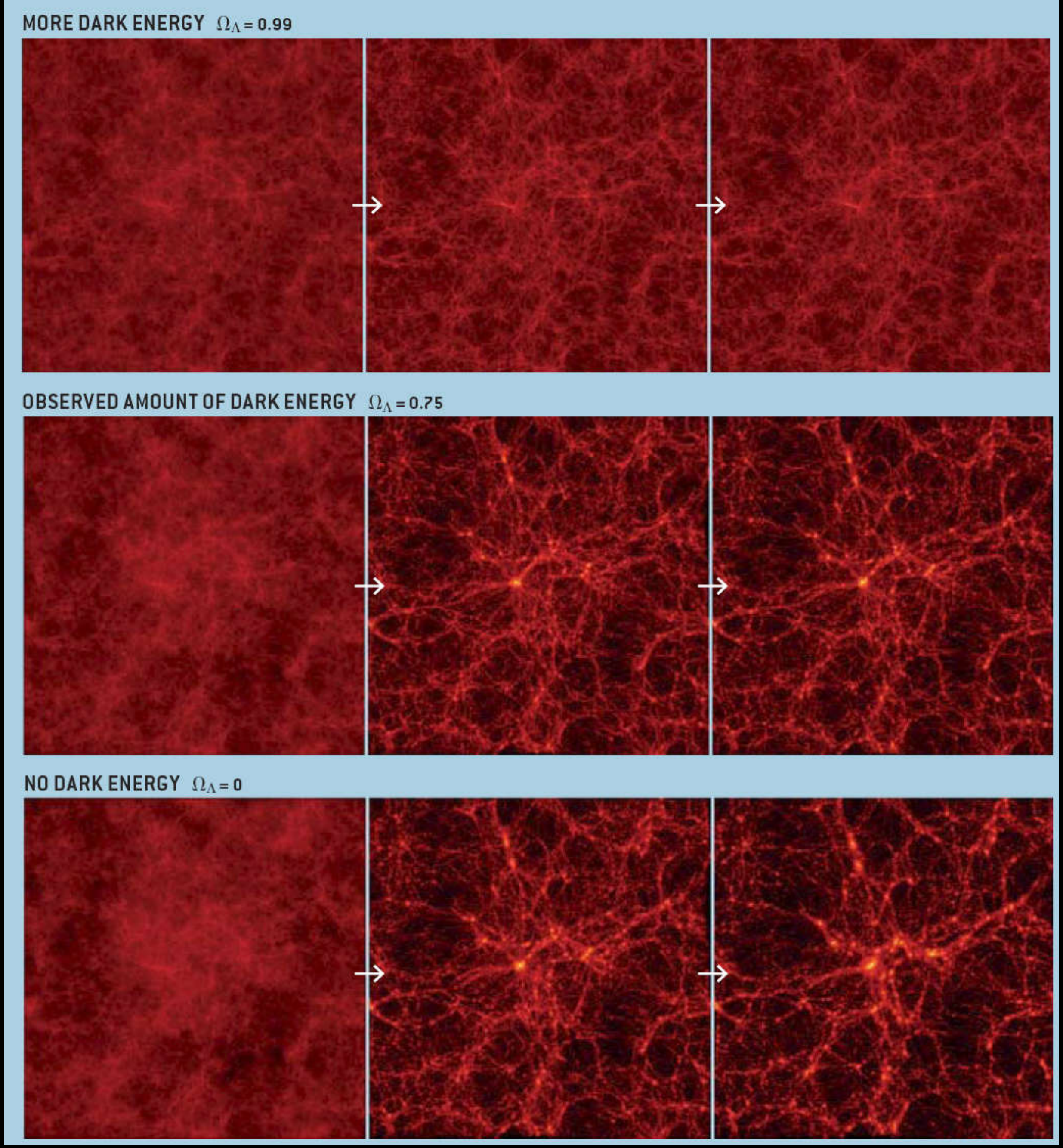


Modelling galaxy cluster formation

Dark energy 99% ▶

Dark energy 75% ▶

No dark energy ▶



early Universe now

Mass function of a galaxy cluster

- Based on semi-theoretical considerations by Press-Schechter 1974 (much extended since then)
- Gives a forecast of how many galaxy clusters of a given mass have formed as a function of time (i.e. redshift)
- Parameters include cosmological parameters of interest
- Output is a curve showing the distribution of cluster masses at a given z
- So all that is necessary is to weigh a whole lot of galaxy clusters and compare their mass distribution with the Press-Schechter based model!

‘Weighing’ the galaxy clusters

The X-ray temperature of a galaxy cluster is at present the most reliable estimator of its mass

This can then be used to relate the cluster mass function at different redshifts

Chandra and Rosat observations of 86 clusters were undertaken by a team of astronomers working for a number of years. The results were released in December 2008 in the last of three papers

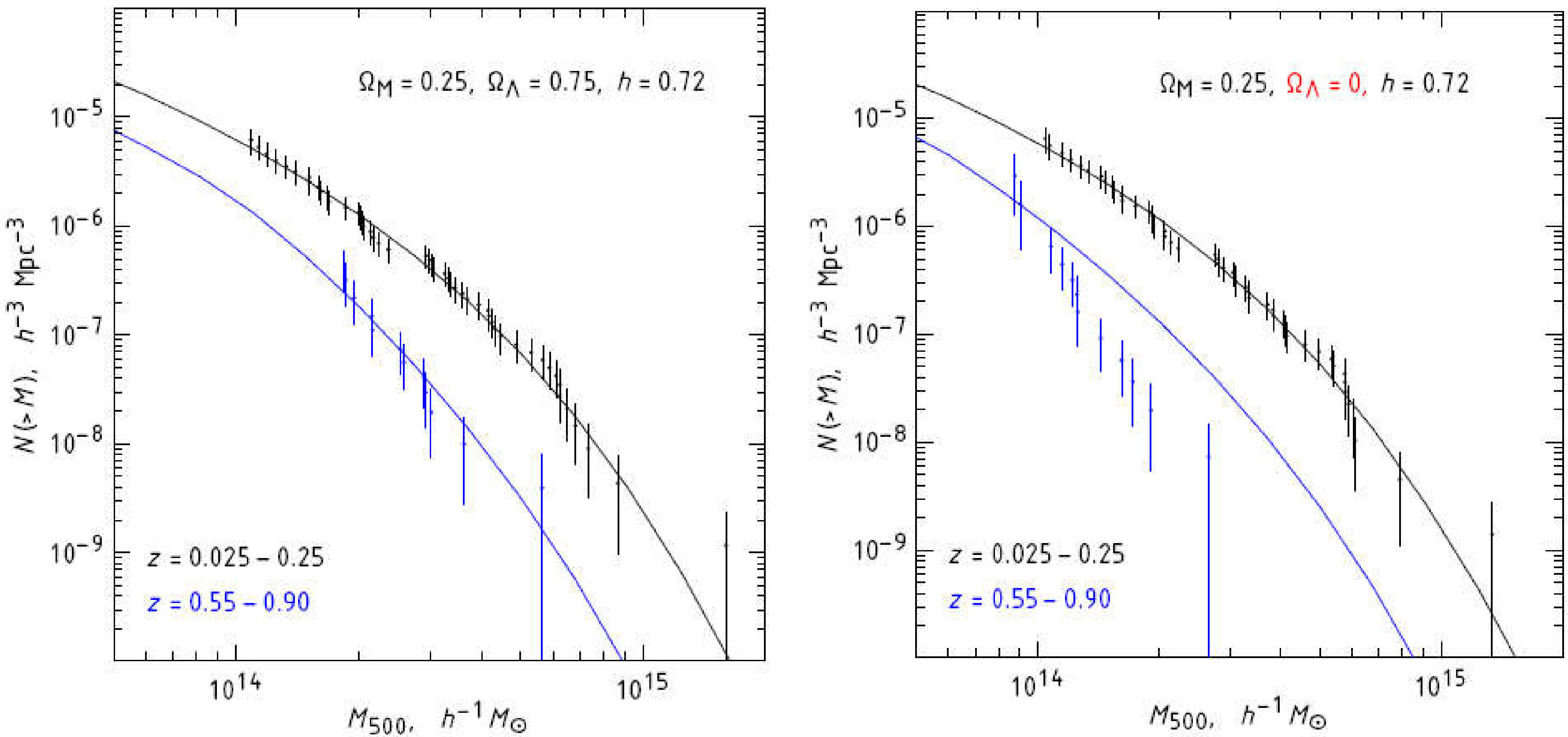
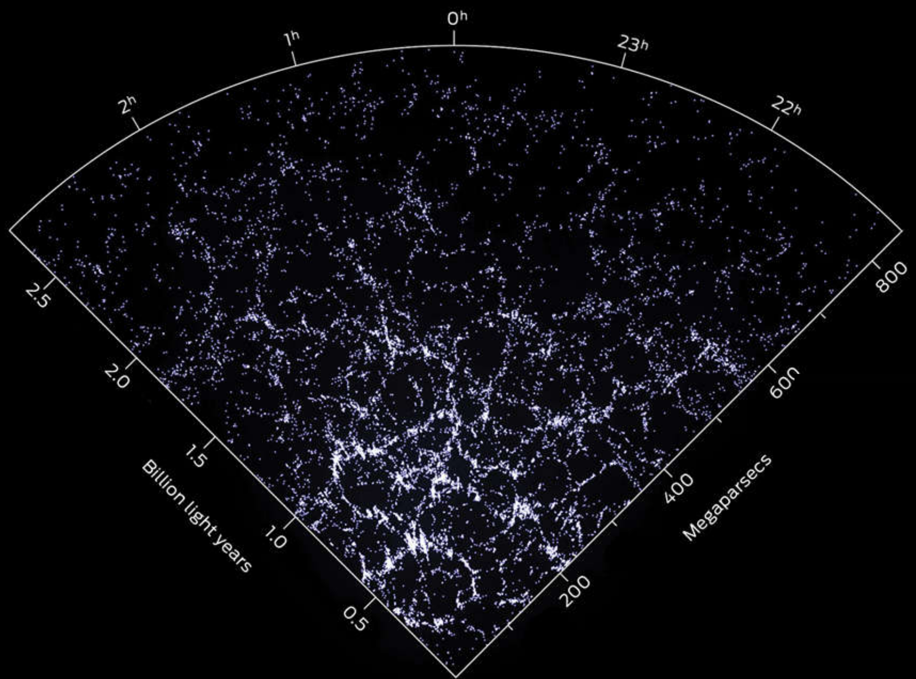
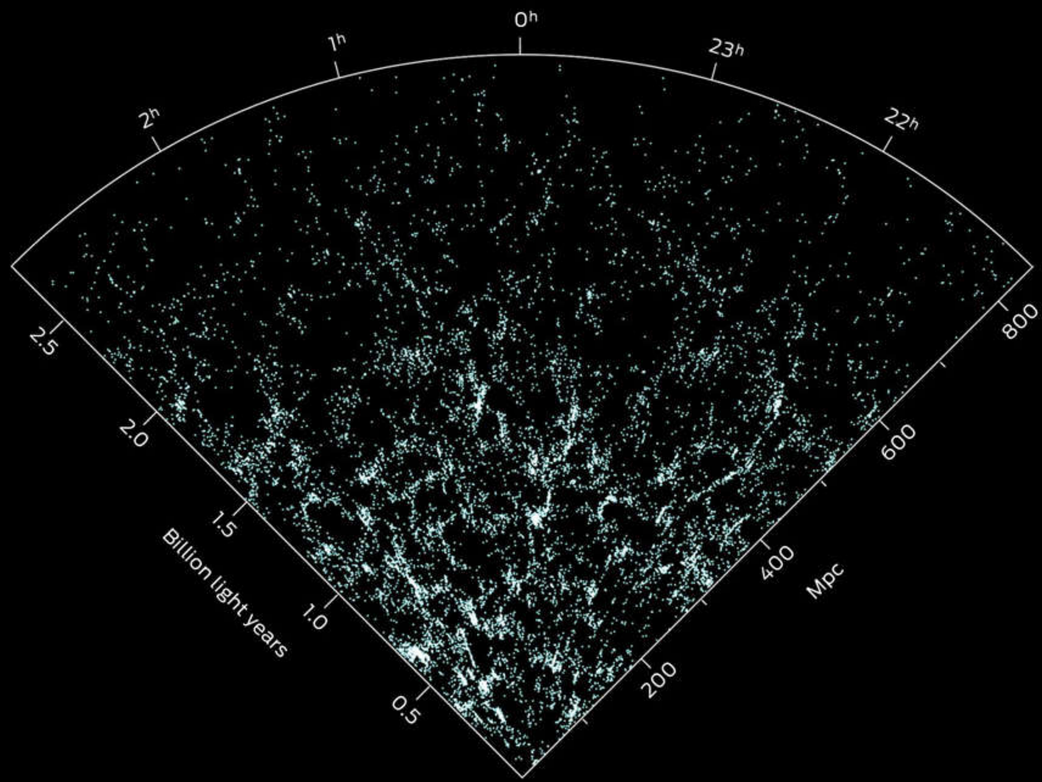


FIG. 2.— Illustration of sensitivity of the cluster mass function to the cosmological model. In the left panel, we show the measured mass function and predicted models (with only the overall normalization at $z = 0$ adjusted) computed for a cosmology which is close to our best-fit model. The low-z mass function is reproduced from Fig. 1, which for the high-z cluster we show only the most distant subsample ($z > 0.55$) to better illustrate the effects. In the right panel, both the data and the models are computed for a cosmology with $\Omega_\Lambda = 0$. Both the model and the data at high redshifts are changed relative to the $\Omega_\Lambda = 0.75$ case. The measured mass function is changed because it is derived for a different distance-redshift relation. The model is changed because the predicted growth of structure and overdensity thresholds corresponding to $\Delta_{\rm crit} = 500$ are different. When the overall model normalization is adjusted to the low-z mass function, the predicted number density of $z > 0.55$ clusters is in strong disagreement with the data, and therefore this combination of Ω_M and Ω_Λ can be rejected.

Sloan Digital Sky Survey



Bolshoi Simulation



Pleiades supercomputer (14 000 cores) 7th fastest of the world’s top 500 supercomputers at NASA Ames Research Center

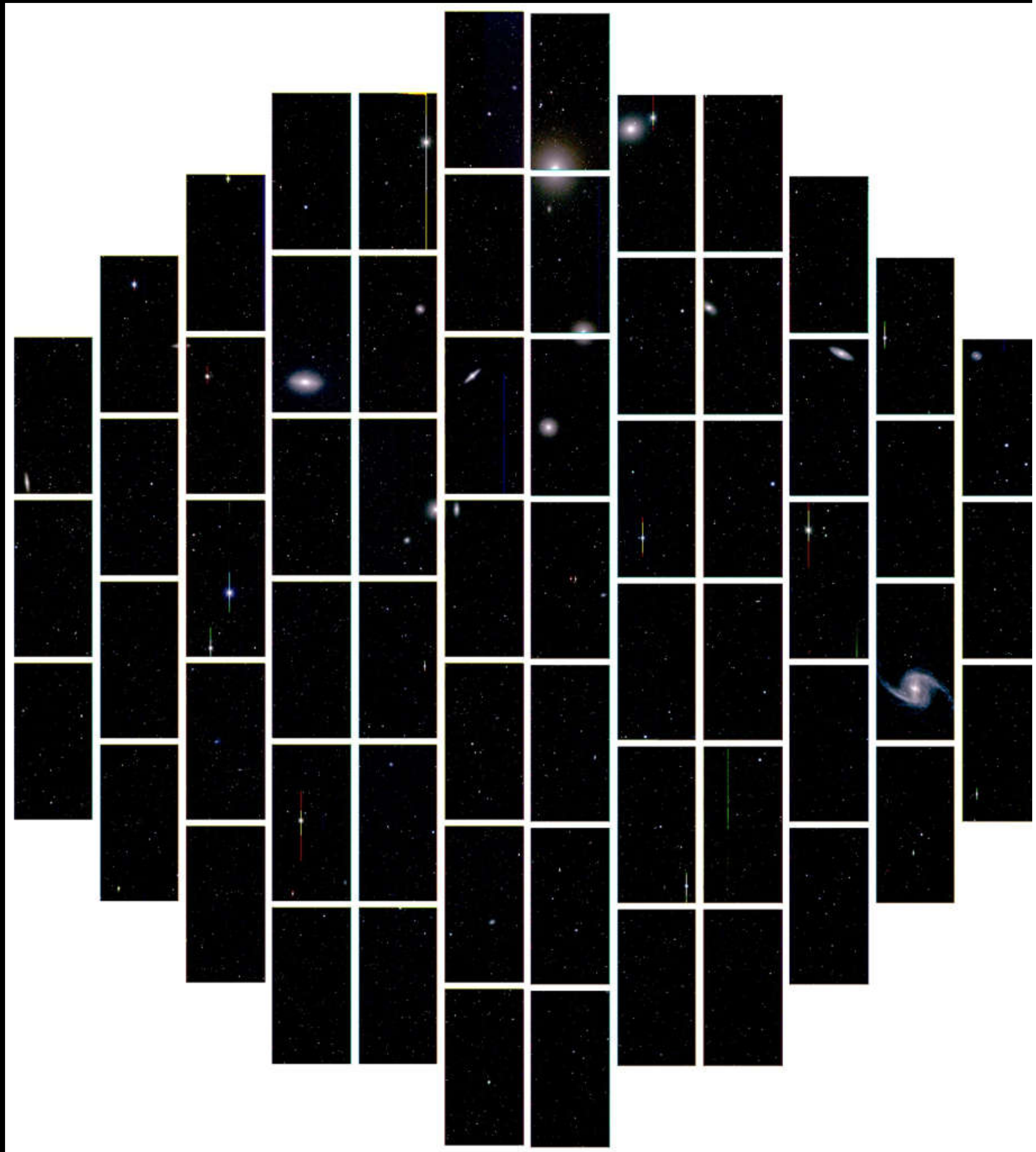
Coming next

The Dark Energy Survey

(DES)

570 Megapixel digital camera DECam

mounted on the Blanco 4m telescope(Chile)



Fornax cluster