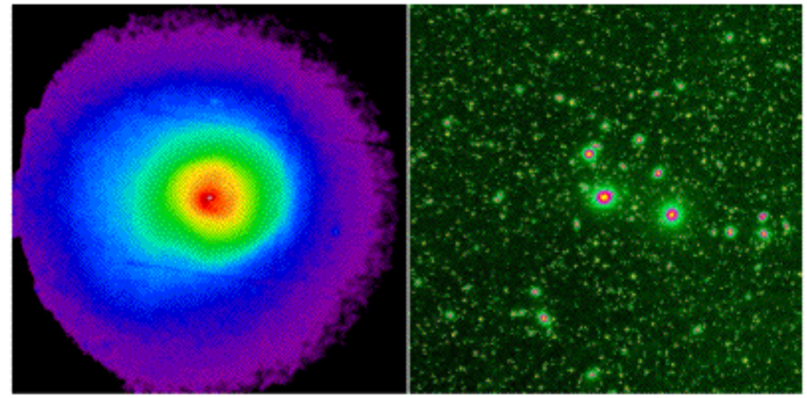
# Clusters of Galaxies

- Clusters of galaxies are the largest gravitationally bound systems in the Universe.
- At optical wavelengths they appear over-densities of galaxies with respe the field average density: hundreds t thousands of galaxies moving in a common gravitational potential well smaller assembly is defined a galaxy group).
- The typical masses of clusters of galaxies are ~ $10^{13}$- $10^{15}M_{sun}$ ($10^{46}$ - gm) and their sizes are of the order 4 Mpc ( $10^{24}$-$10^{25}$ cm).
- The combination of size and mass le to velocity dispersions/temperatures 300-1200km/sec; 0.5-12 keV
- $M \sim (kT)R$; $\sigma^2 \sim kT$



X-ray optical

Perseus cluster d~73Mpc

Dark matter simulation

V.Springel

# WHY ARE CLUSTERS INTERESTING?

- Largest, most massive systems in the universe

- Probes of the history of structure and galaxy formation
  - Dynamical timescale are not much shorter than the age of the universe
  - -clusters retain an imprint of how they were formed

- Provide a history of nucleosynthesis in the universe
  - - as opposed to galaxies, clusters probably retain all the enriched material
- Fair samples of the universe- laboratory to measure dark matter
- The gravitational potential is dominated by dark matter

on all scales

- Most of the baryons are in the hot gas (80%)

# Clusters of Galaxies X-ray Overview

## Probes of the history of structure formation

Dynamical timescales are not much shorter than the age of the universe

- Studies of their evolution, temperature and luminosity function can place strong constraints on all theories of large scale structure
- and determine precise values for many of the cosmological parameters

**Provide a record of nucleosynthesis in the universe-** as opposed to galaxies, clusters probably retain all the enriched material created in them

- Measurement of the elemental abundances and their evolution provide fundamental data for the origin of the elements
- The distribution of the elements in the clusters reveals how the metals were removed from stellar systems into the IGM

## Clusters should be "fair" samples of the universe"

- Studies of their mass and their baryon fraction reveal the "gross" properties of the universe as a whole
- Much of the entropy of the gas in low mass systems is produced by processes other than shocks-
  - a major source of energy in the universe ?
  - a indication of the importance of non-gravitational processes in structure formation ?

# Why Are Clusters Interesting for High Energy Astrophysics?

- Most of their baryons are in very hot ($T>3x10^6k$) gas
- They are very luminous
  - log L>42 ergs/sec
- Very large (R~1Mpc)
- And are thus visible with modern instrumentation as extended objects to z>1.4
- Their masses (both dark matter and gas mass) can be determined by x-ray imaging spectrometry
- The hot gas shows spectral features from the abundant elements (O,Ne,Si,S,Fe) which allows measurement of the abundance of the elements 'easily'

at z=1.4

scale is 8.502 kpc/" so massive cluster has a size of ~2').

Luminosity distance is 10,101.2 Mpc so flux is from log L=42 object is $8x10^{-17}$ ergs/cm$^2$/sec

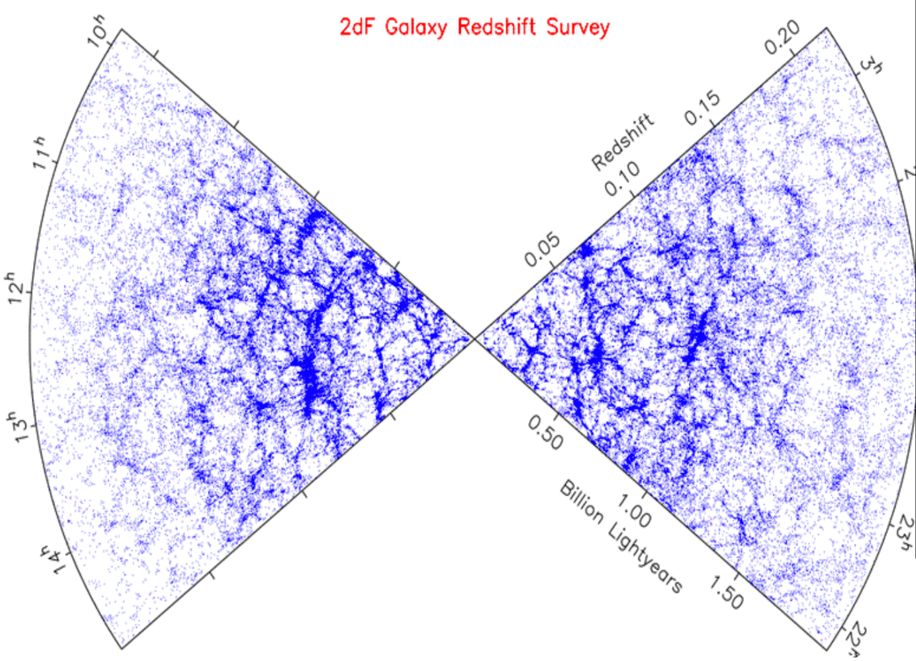
---------------------------------------

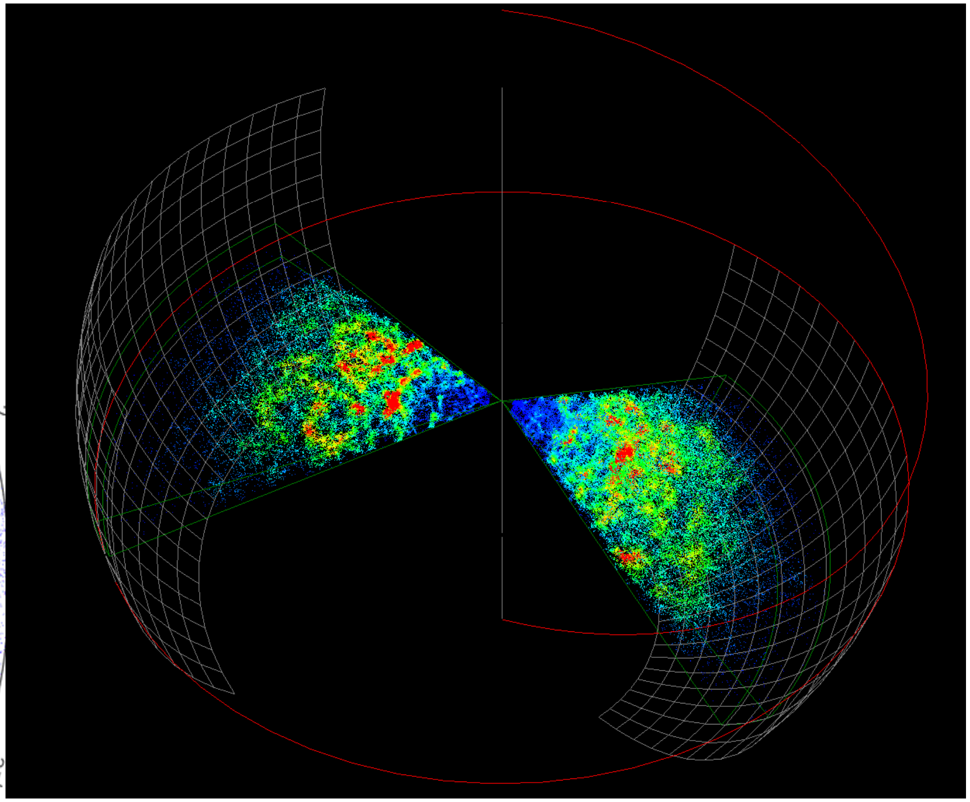
See [http://nedwww.ipac.caltech.edu/level5/Sept09/Bohringer/frames.html](http://nedwww.ipac.caltech.edu/level5/Sept09/Bohringer/frames.html) and

X-ray Emission from Clusters of Galaxies: C.Sarazin http://nedwww.ipac.caltech.edu/level5/March02/Sarazin/frames.html

# Cosmic Web

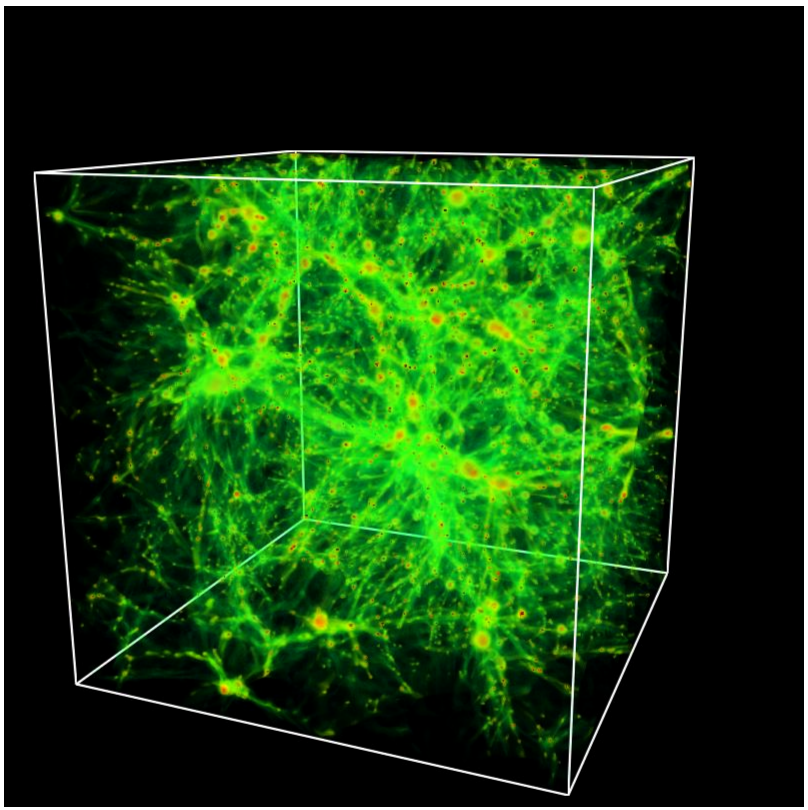
- large scale structure of the universe consists of sheets and filaments- clusters occur at the intersection of these structures



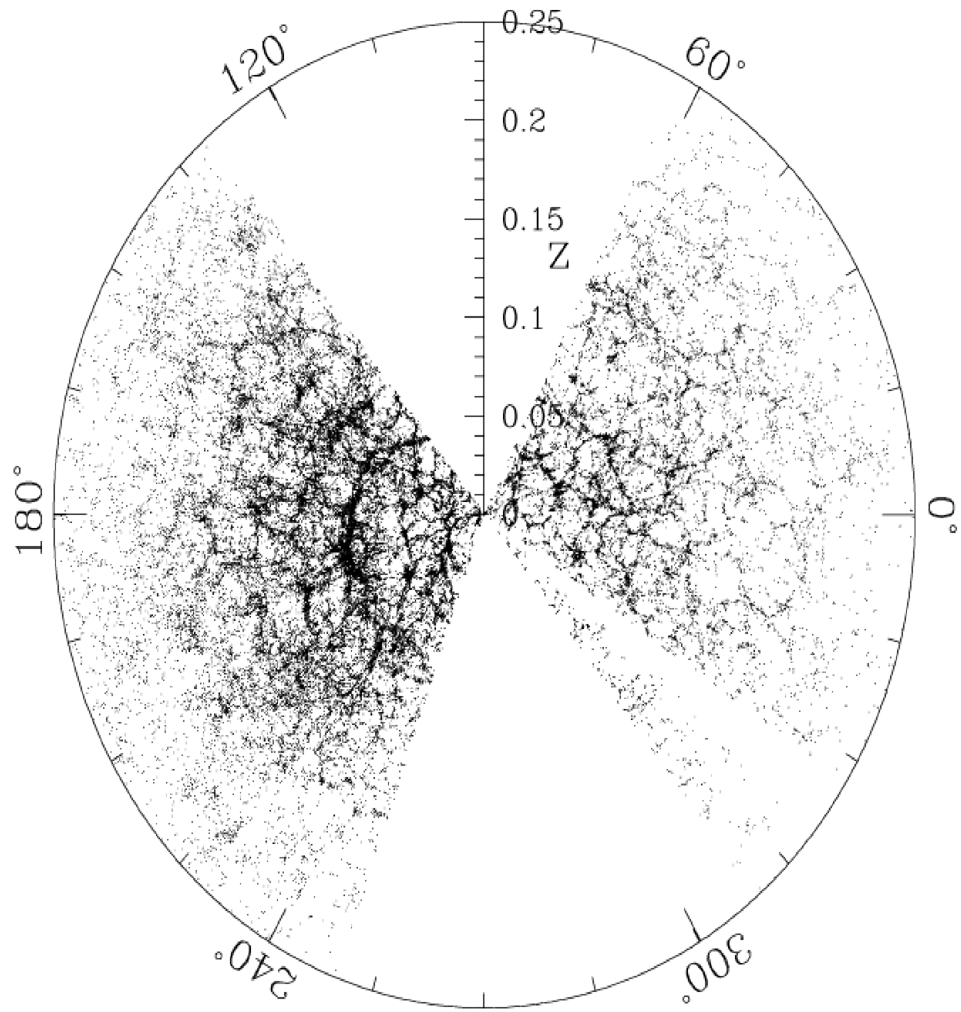



# Cosmic Web (again)

- The large scale structures are 'seen' in both the 2dF and SDSS surveys out to the largest redshifts

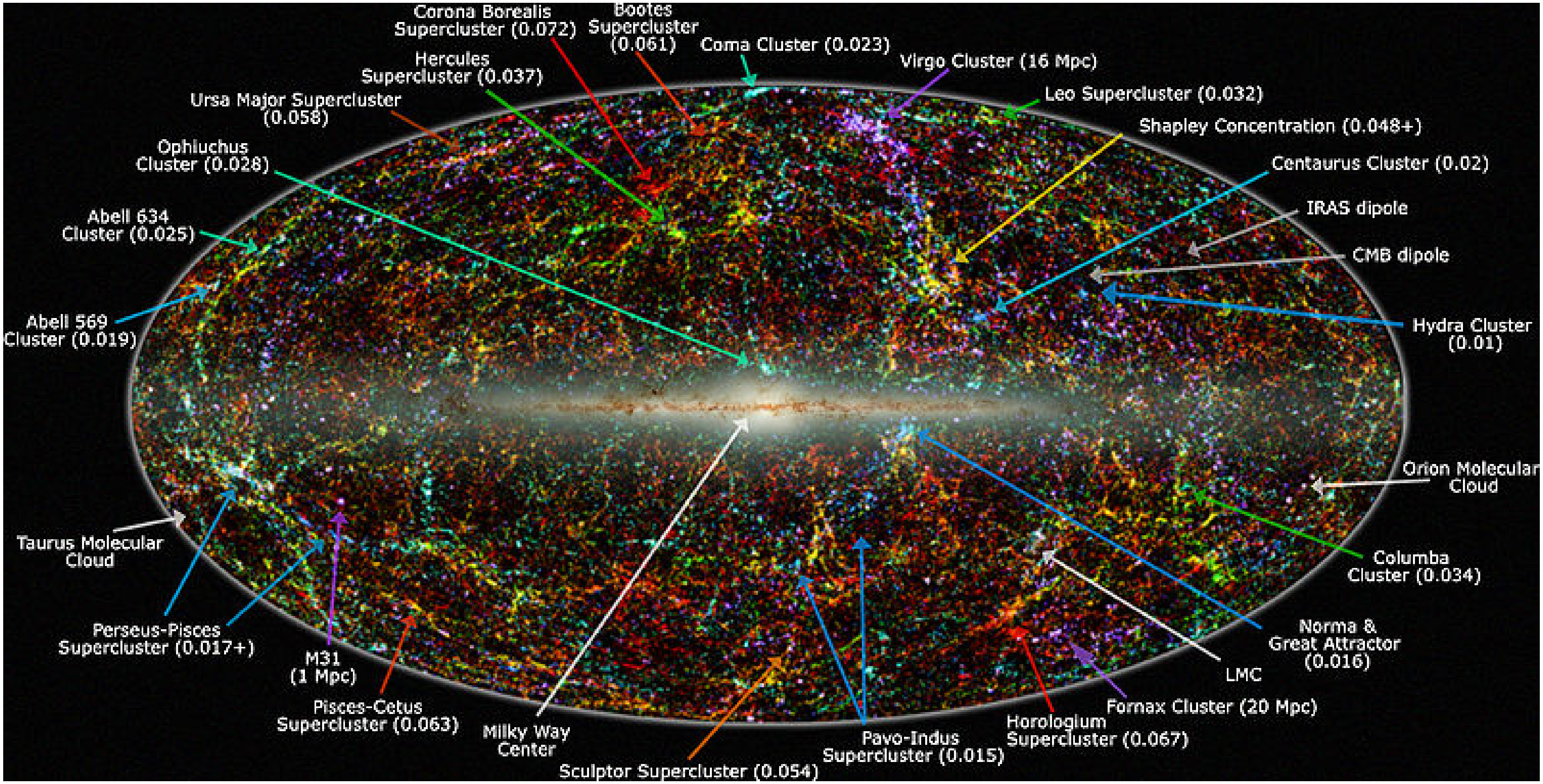


Blanton et al. (2003) (astro-ph/0210215)

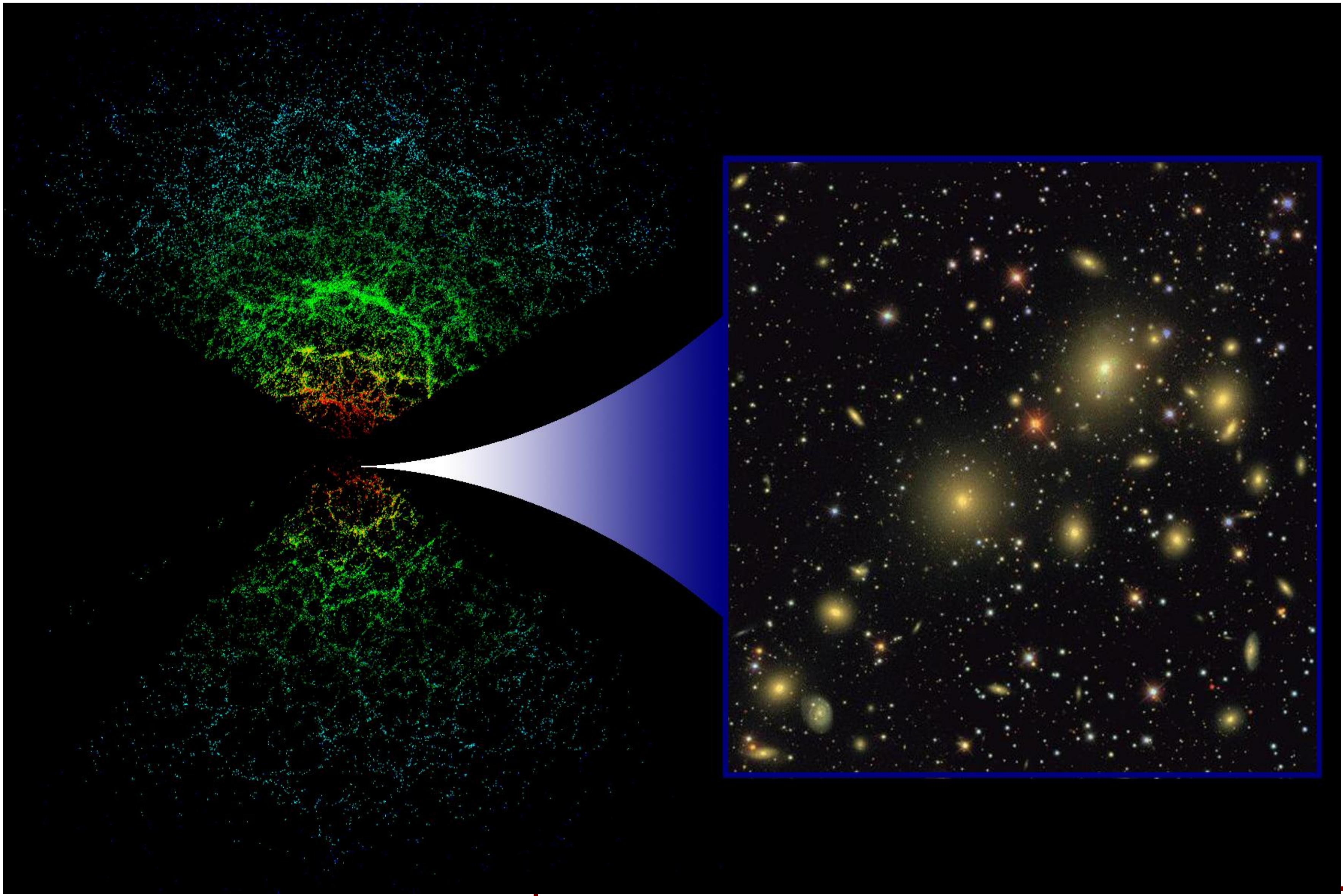



Large−Scale Structure sample10

# Map of the Local Universe




2MASS map of the local universe- < 1 billion light years



- SDSS map of the universe < 6 billion light years

dark matter appears in all 'big' things in the universe including, on average, the universe itself

# A Bit of History

- Clusters were discovered early in the history of modern astronomy (Herschel as noted by Lundmark 1927)
- Their nature was not really recognized until the 1930's (Zwicky 1937, Smith 1936) as very large conglomerations of galaxies at great distances.

- The first dynamical analysis of clusters(Zwicky) showed that there must exist much more gravitational material than indicated by the stellar content of the galaxies in the cluster.

  **This was the first discovery of the preponderance of dark matter in the universe.**

- The development of large catalogs of clusters (Abell 1958, Zwicky and Herzog 1963) based on eye estimates of the number of galaxies per unit solid angle Abell catalog was used for over 40 years
- In the early 1970s (Rood 1974) the first detailed of estimate of cluster masses using the velocity distribution of the galaxies via the use of the viral theorem were obtained.

These analysis showed that clusters of galaxies were dominated by dark matter with galaxies representing less than 5% of the total mass and that there were definitive patterns in their galaxy content

- **Thus the issue of the "missing mass" or "dark matter" became the central one of cluster research.**

# More History

- X-ray emission from clusters of galaxies was not predicted and its discovery was essentially serendipitous.

- Rocket flights in the 1960s discovered x-ray emission from the direction of the Virgo cluster, the closest cluster of galaxies.

These early results were entirely serendipitous, as no one had any idea that clusters of galaxies should be luminous x-ray sources. Thus the study of clusters, as so much in the field of x-ray astronomy, was entirely an unexpected discovery.

- The first all sky x-ray survey, with the Uhuru satellite (1971) established x-ray emission from clusters as a class. Uhuru had poor angular resolution (~0.5x0.5 degree) - but one could centroid the data to obtain relatively small positional uncertainties of ~0.05 sq degrees.
- The relative rarity of bright optically selected clusters, ~1 per 10 square degrees, and the similarly low areal density of the bright high galactic latitude x-ray sources of ~1 per 100 square degrees indicated that the presence of an Abell cluster inside an x-ray error box of size less than 1 square degree was statistically rather unlikely allowing a relatively high certainty of identification

# History of Science Comment

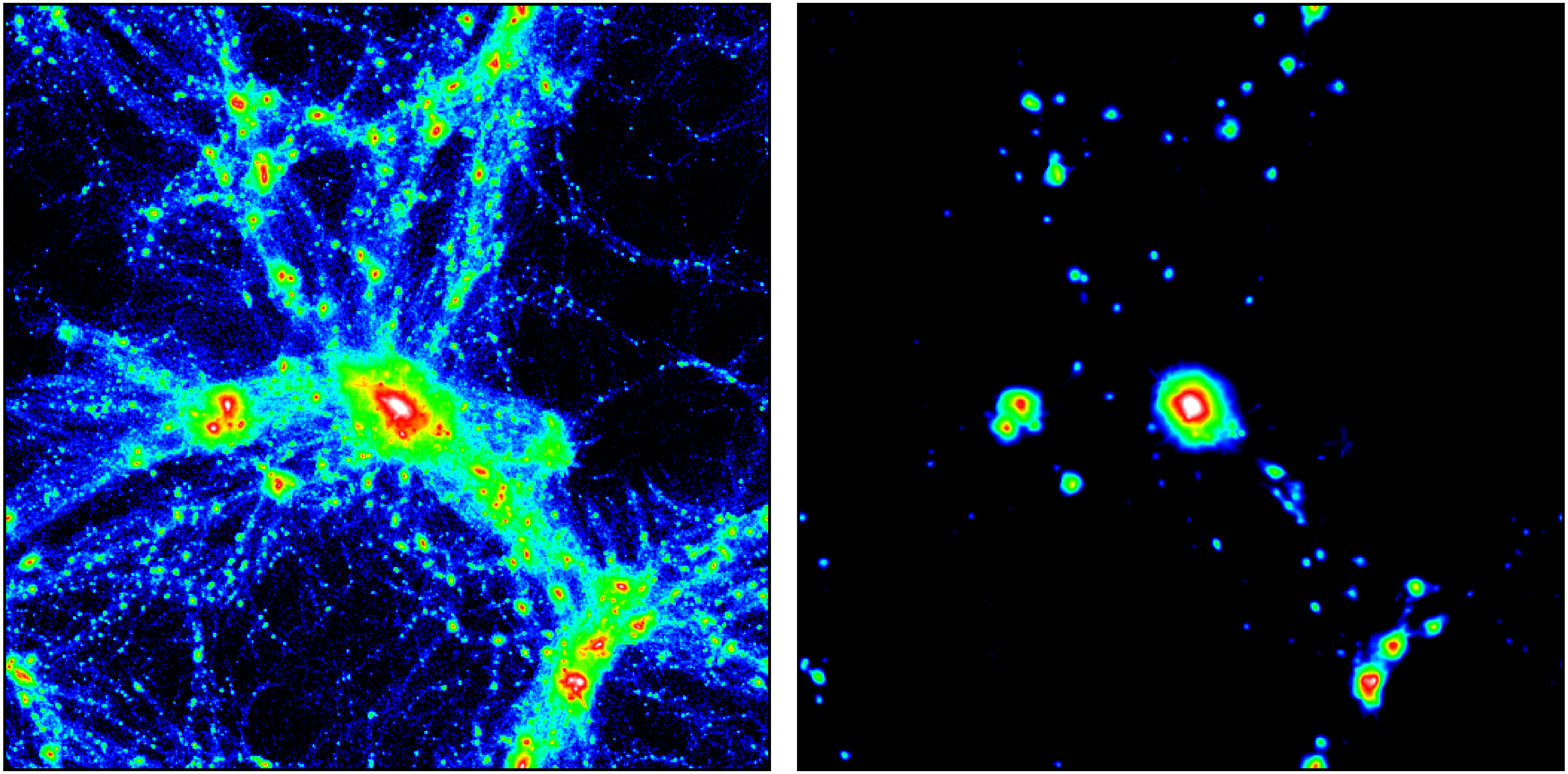
- It is rather surprising to realize not only is most of the material in the universe dark and non-baryonic, but that most of the baryons in the universe do not shine in optical light.
- The anthropomorphic picture that the universe can be best studied

with the light visible to our own eyes is not only seriously in error, it drives science in the wrong directions.

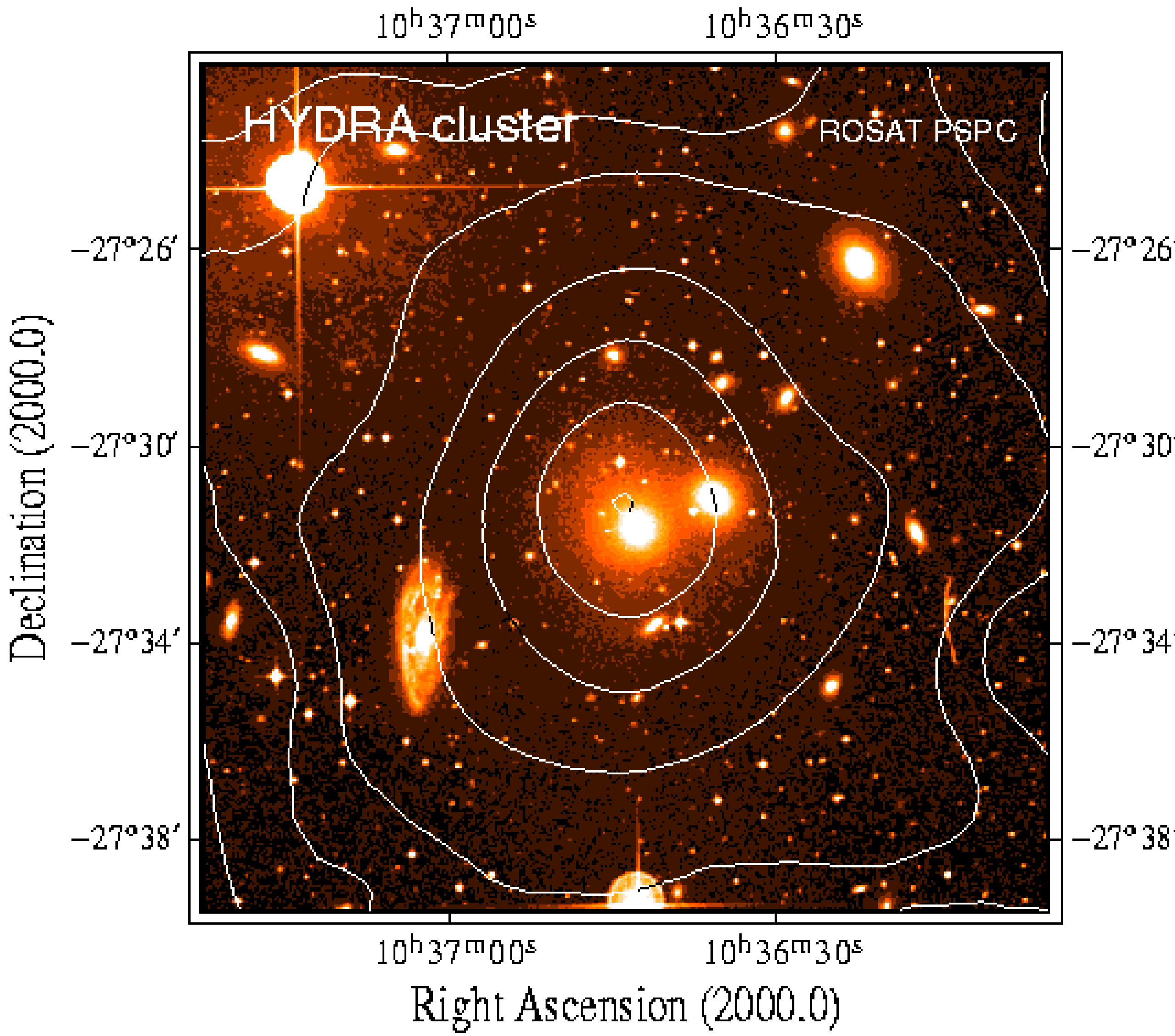
# Basic Ideas

- Fluctuations in density are created early in the Universe.
- These fluctuations grow in time. At recombination (when the Universe has cooled enough for atoms to form from electron-proton plasma) they leave their imprint on the microwave background. COBE, WMAP, Planck
- Fluctuations continue growing as overdense regions collapse under their own gravitational attraction.
- Baryons fall into the gravitational potential wells produced by the dark matter. Potential energy is converted to kinetic then thermalized -> hot plasma.

# Dark matter and X-ray emission simulation



# Optical image with X-ray isointensity contours



# References

See X-RAY SPECTROSCOPY OF GALAXY CLUSTERS:
http://nedwww.ipac.caltech.edu/level5/Sept09/Bohringer/frames.html

and

X-ray Emission from Clusters of Galaxies: C.Sarazin
http://nedwww.ipac.caltech.edu/level5/March02/Sarazin/frames.html

And

HOT GAS IN CLUSTERS OF GALAXIES W. Forman and C. Jones

http://nedwww.ipac.caltech.edu/level5/Forman2/frames.html

# X-rays from Clusters of Galaxies

- The baryons thermalize to > $10^6$ K making clusters strong X-ray sources- the potential energy of infall is converted into kinetic energy of the gas.
- Most of the baryons in a cluster are in the X-ray emitting plasma - only 10-20% are in the galaxies.
- Clusters of galaxies are self-gravitating accumulations of dark matter which have trapped hot plasma (intracluster medium - ICM) and galaxies. (the galaxies are the least important constituent)

# What we try to measure

- From the x-ray spectrum of the gas we can measure a mean temperature, a redshift, and abundances of the most common elements (heavier than He).

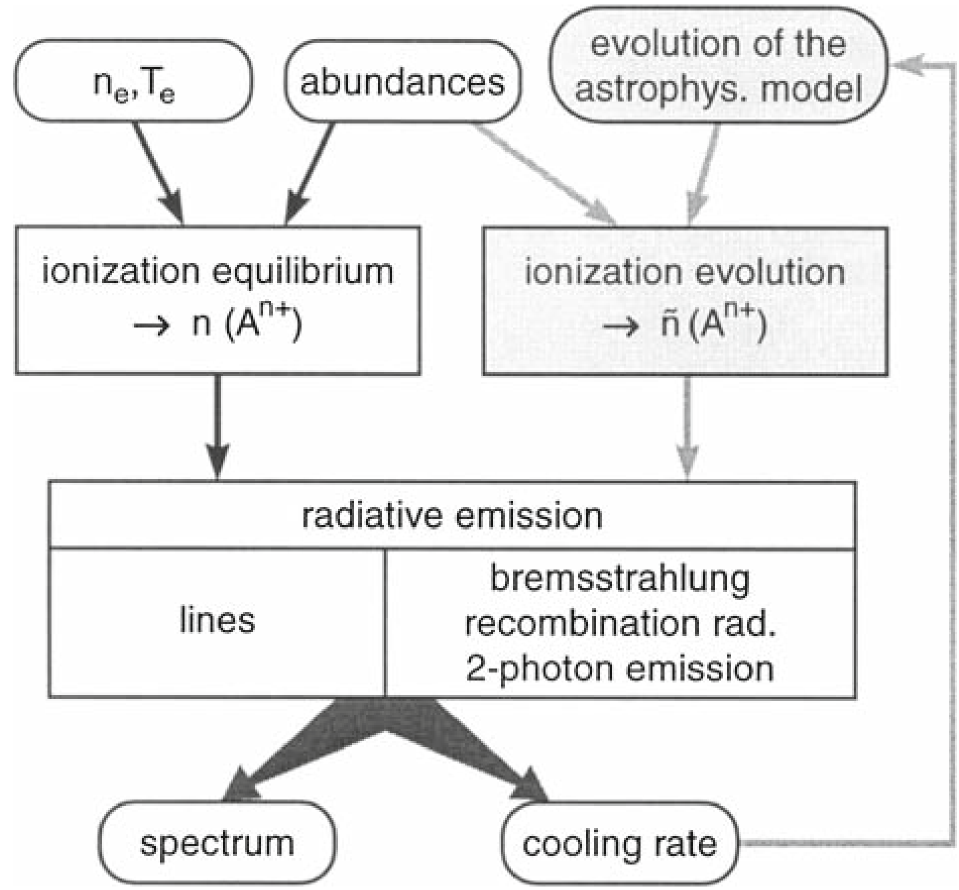
- With good S/N we can determine whether the spectrum is consistent with a single temperature or is a sum of emission from plasma at different temperatures.

- Using symmetry assumptions the X-ray surface brightness can be converted to a measure of the ICM density.

# Why is Gas Hot

- To first order if the gas were cooler it would fall to the center of the potential well and heat up
- If it were hotter it would be a wind and gas would leave cluster
- Idea is that gas shocks as it 'falls into' the cluster potential well from the IGM
  - Is it 'merger' shocks (e.g. collapsed objects merging)
  - Or in fall (e.g. rain)

  BOTH



# What we try to measure II

If we can measure the temperature and density at different positions in the cluster then assuming the plasma is in hydrostatic equilibrium we can derive the gravitational potential and hence the amount and distribution of the dark matter.

There are two other ways to get the gravitational potential :

- The galaxies act as test particles moving in the potential so their redshift distribution provides a measure of total mass.
- The gravitational potential acts as a lens on light from background galaxies.