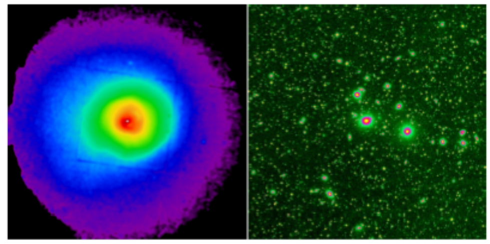
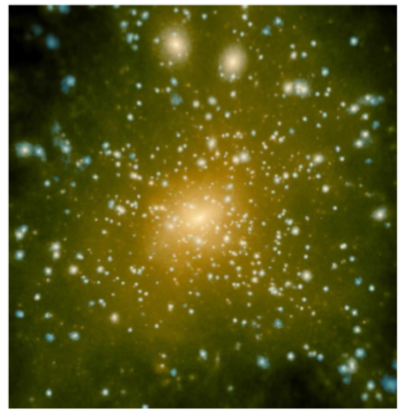
Clusters of Galaxies
Ch 4 Longair

- Clusters of galaxies are the largest gravitationally bound systems in the Universe.
- At optical wavelengths they appear as over-densities of galaxies with respect to the field average density: hundreds to thousands of galaxies moving in a common gravitational potential well (a smaller assembly is defined a galaxy group).
- The typical masses of clusters of galaxies are ~ 10^{13}-$10^{15} M_{\odot}$ (10^{46}-10^{51} gm) and their sizes are of the order of 1 - 4 Mpc (10^{24}-10^{25} cm).
- The combination of size and mass leads to velocity dispersions(σ)/temperatures of 300-1200km/sec; 0.5-12 keV
- M~(kT)R; σ^2~kT



X-ray optical
Perseus cluster d~73Mpc



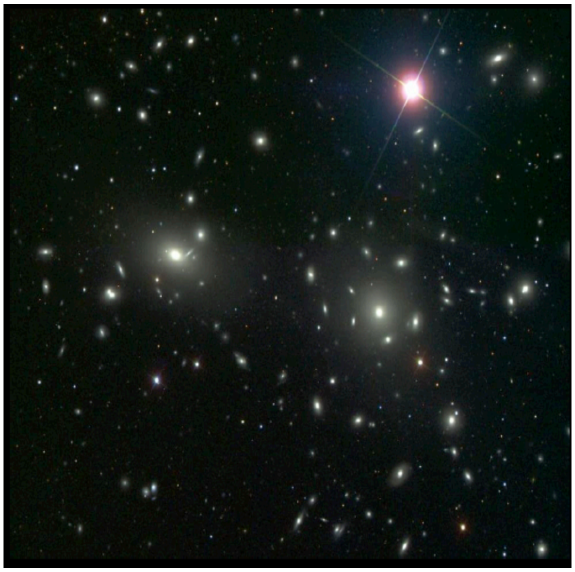
Dark matter simulation
V.Springel

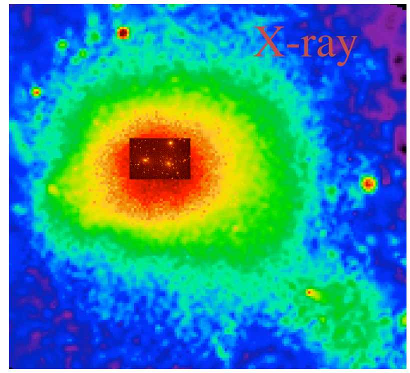
Clusters of Galaxies

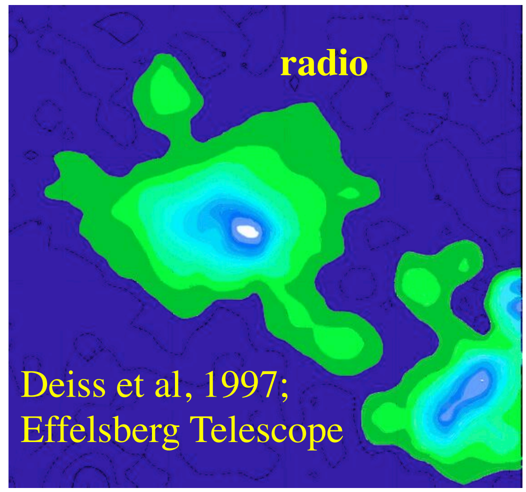
- High Energy Objects - most of the baryons are in a hot (kT~10^7-10^8k) gas.
- The x-ray luminosity is 10^{42}-10^{46} ergs/sec
  - with modern instrumentation x-ray emission can be detected at z>1.7 and the S-Z effect (later) at even higher redshifts.
- the hot gas is enriched in heavy elements (oxygen...iron) to ~1/3 solar
  - This combination indicates that most of the metals created in the stars that live in galaxies have been 'removed' and ended up in the ICM.

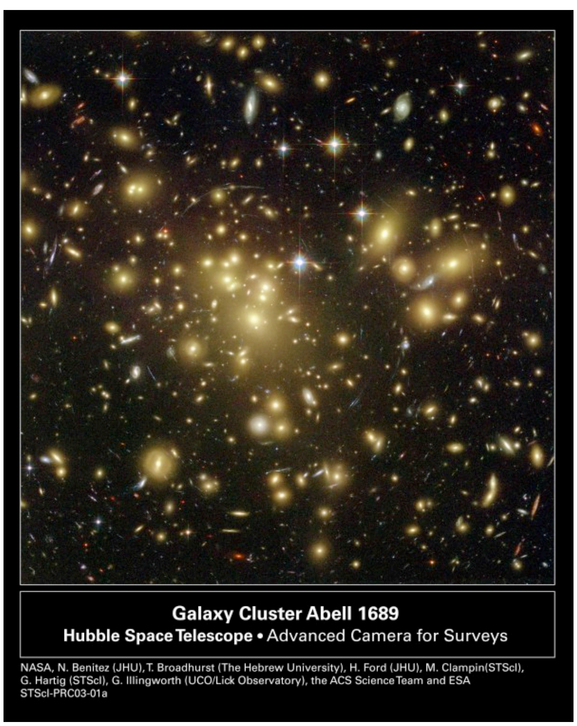
Coma Cluster-A Nearby Massive Cluster

- The apparent nature of clusters depends on the wavelength one looks at

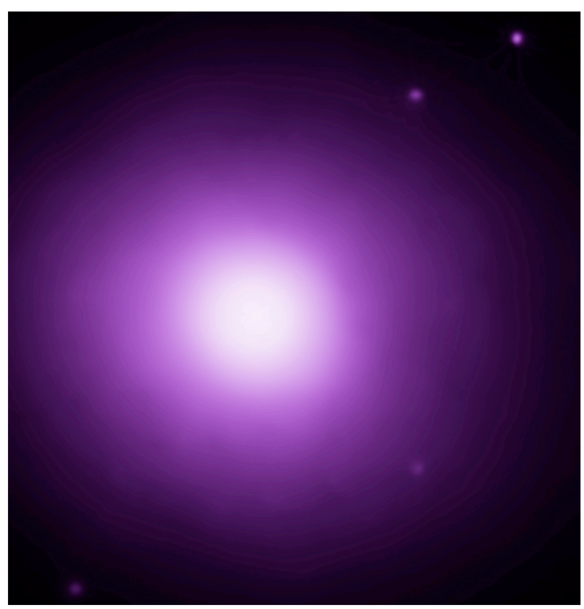








Chandra Image of Abell 1689



A Bit of History

- They were discovered early in the history of modern astronomy (Herschel as noted by Lundmark 1927)
- 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 matte**r 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

strict criteria for the Abell catalog proved to be a good guide to the physical reality of the objects

40 years later we are still using the Abell catalog.

- not until the early 1970s (Rood 1974) that the first large samples of estimated cluster masses, using the velocity distribution of the galaxies via the use of the viral theorem, were obtained.
- By the early 1970's it became clear (cf. Rood et al 1972,Kent and Gunn 1982) that clusters are dominated by dark matter with galaxies representing less than 5% of the total mass and that there were definitive patterns in their galaxy content (Dressler 1980).
- Thus the issue of the "missing mass" or "dark matter" became the central one of cluster research.

More History

- "Rich" clusters (that is those with many galaxies inside a fixed metric (Abell) radius) had a preponderance of "early" type (elliptical and S0 galaxies) while "poorer" clusters had a larger fraction of spiral galaxies.
- It was clear that many clusters had a rather unusual central galaxy, a cD , or centrally dominant galaxy (Morgan and Osterbrock 1969) which is very seldom, if ever found outside of clusters.
- There were also an unusual type of radio source found primarily in clusters, a so-called WAT, or wide angle tailed source (Owen and Rudnick 1976) .
- first indications of cluster evolution (Butcher and Oemler1978) in which distant clusters at z~0.2 tend to have more "bluer" galaxies than low redshift clusters (to an optical astronomer elliptical galaxies have rather "red" colors while spirals tend to be bluer) but the morphology of these galaxies was unknown.

Even More History

- X-ray emission from clusters of galaxies was not predicted and its discovery was essentially serendipitous.
- The first detections of what we now know as cluster x-ray emission was from rocket flights in the 1960s (Friedman and Byram 1967, Bradt et al 1967) which discovered x-ray emission from the direction of the Virgo cluster, the closest cluster of galaxies.

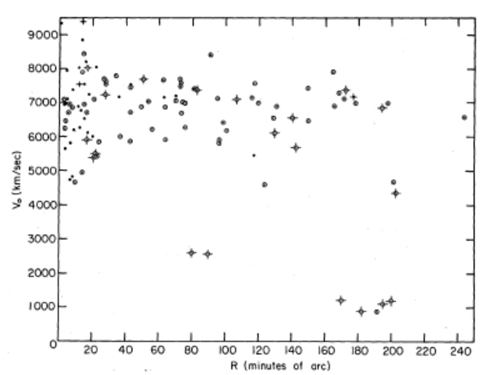
In a paper of remarkable prescience, Felten et al 1966, attributed the detection o**f x-ray emission from the Coma cluster to thermal bremsstrahlung.**

These early rocket 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 (Kellogg et al 1971,Gursky et al 1972) established x-ray emission from clusters as a class.
  - Even the relatively low angular resolution (~0.5x0.5 degree at best) of the Uhuru data were able to derive relatively small positional uncertainties (error boxes) of ~0.05 sq degrees for the brightest sources and ~5 sq degrees for the weakest "real" objects. The dynamic range of Uhuru, ~1000 between the brightest galactic sources and the much dimmer extragalactic objects was vital to the discovery of cluster emission. The relative rarity of optically selected clusters, ~1 per 10 square degrees, and the similarly low areal density of the high galactic latitude Uhuru 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 (Bahcall and Bahcall 1975) and allowed a relatively high certainty of identification

The First Detailed Analysis

- Rood et al used the King (1969) analytic models of potentials (developed for globular clusters) and the velocity data and surface density to infer a very high mass to light ratio of ~230.
- Since "no" stellar system had M/L>12 dark matter was necessary



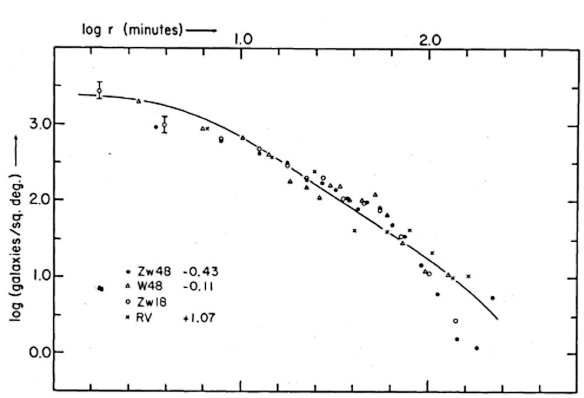


FIG. 5.—Surface densities, corrected for backgrounds given in table 2. For this fitting, logarithms of

Rood 1972- velocity vs position of galaxies in Coma
Surface density of galaxies

Paper is worth reading ApJ 175,627

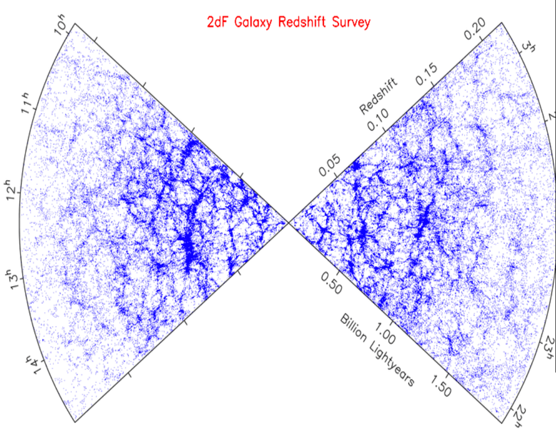
A Strange Universe

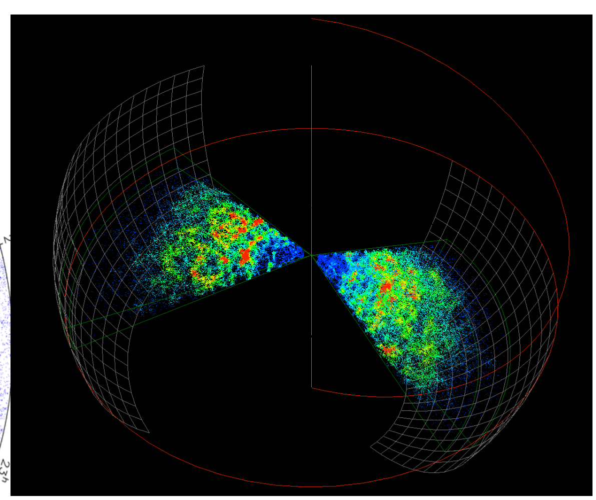
It is rather surprising to realize not only that most of the material in the universe is dark and non-baryonic, but that most of the baryons in the universe do not shine in optical light.

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.

Cosmic Web

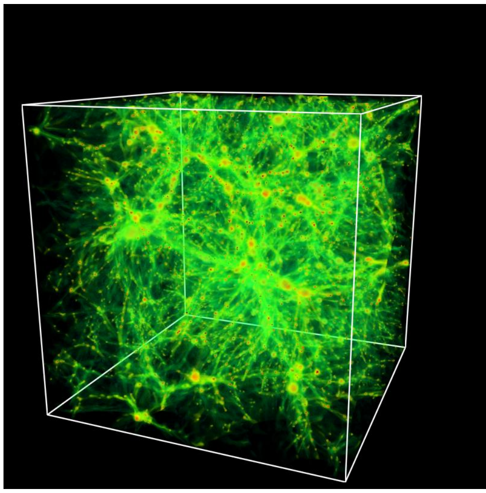
- large scale structure of the universe consists of sheets and filaments- **clusters occur at the intersection of these structures**

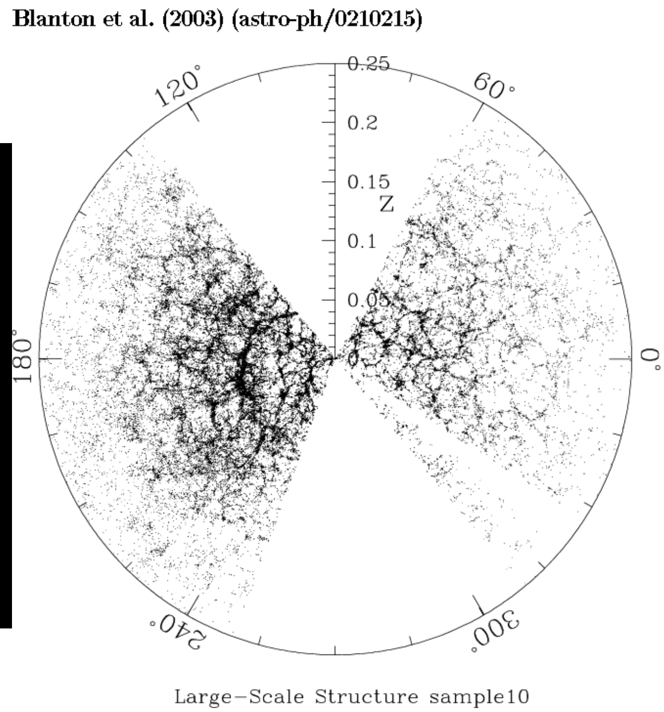




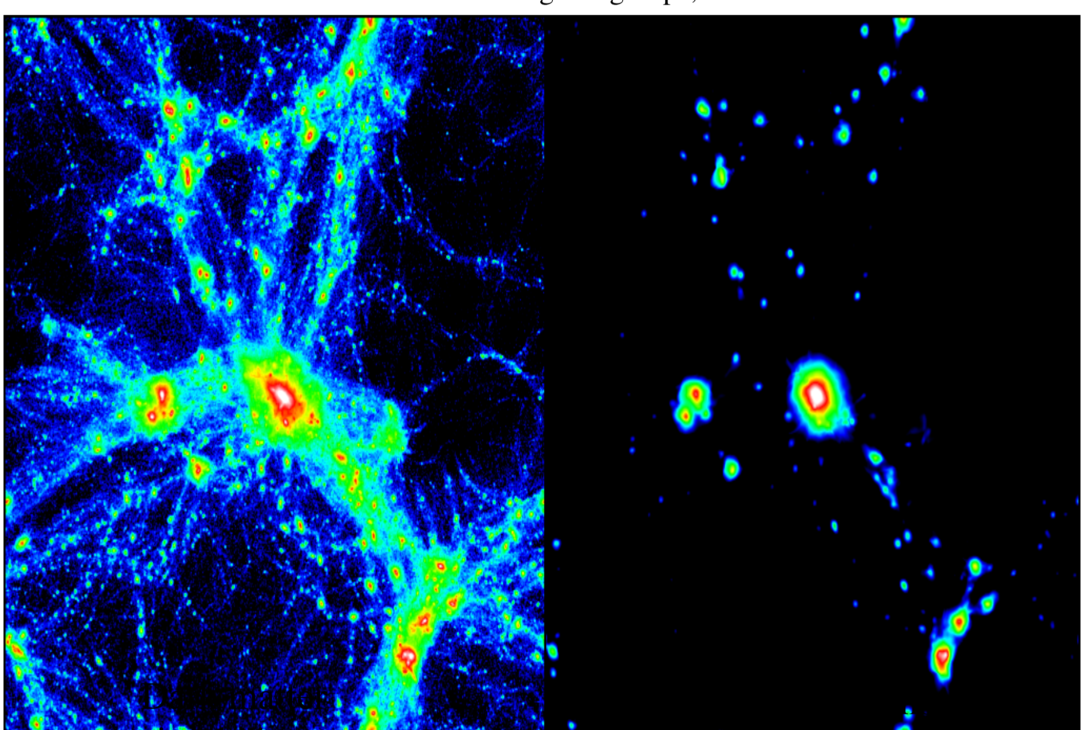
Cosmic Web (again)

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





Comparison of dark matter and x-ray cluster and group distribution numerical simulation every bound system visible is detected in the x-ray band - bright regions are massive clusters, dimmer regions groups,

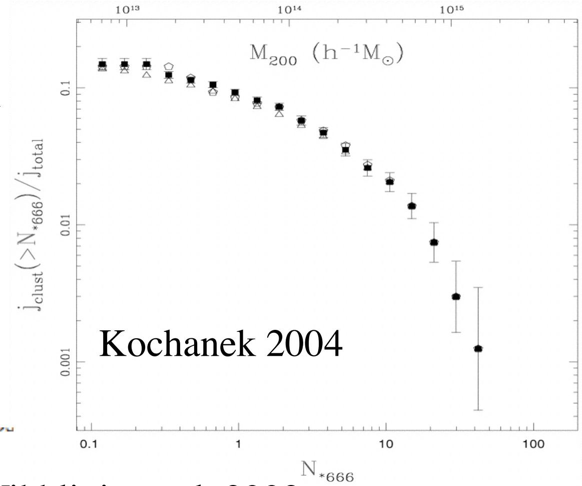


simulation

simulation

Mass Function

- The number of clusters per unit mass (optical luminosity, x-ray luminosity, velocity dispersion, x-ray temperature)
- Is a strong function of cosmology
- One of the main areas of research is to determine this function over a wide range in redshift.
- One of the main problems is relating observables to mass.



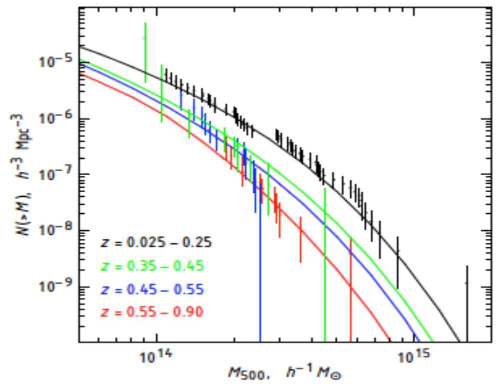


FIG. 18.— Same as Fig. 16 but the high-z sample is split into three redshift bins.

Vikhlinin et al 2009

The mass function shows that massive clusters are rare ~10^{-6} Mpc^3

Why are Clusters Interesting or Important

- Laboratory to study
  - Dark matter
    - Can study in detail the distribution and amount of dark matter and baryons
  - Chemical evolution
    - Most of the 'heavy' elements are in the hot x-ray emitting gas
  - Formation and evolution of cosmic structure
    - Feedback
    - Galaxy formation and evolution
    - Mergers
  - Cosmological constraints
    - Evolution of clusters is a strong function of cosmological parameters
  - Plasma physics on the largest scales
  - Numerical simulations
  - Particle acceleration

Each one of these issues Leads to a host of topics

Dark matter:
How to study it
lensing
Velocity and density distribution of galaxies
Temperature and density distribution of the hot gas

Chemical Evolution
Hot and when where the elements created
Why are most of the baryons in the hot gas
Does the chemical composition of the hot gas and stars differ?

Why are Clusters Interesting or Important

Formation and evolution of cosmic structure

- The Cooling flow problem
- Interaction of radio sources and the hot gas
- Star formation
  - At low and high z
  - Why are cluster galaxies different than those in the field
- AGN evolution

- Cosmological constraints
  - Evolution of clusters is a strong function of cosmological parameters
  - How to utilize this information
    - Evolution of mass function of clusters
  - Power spectrum of clusters (BAO)

Plasma physics on the largest scales

•What is the viscosity of the gas

•What is the nature of thermal conductivity

•How do we know?

•Measurements of properties of cluster radio sources

•Turbulence in the gas

Numerical Simulations

There is a vast literature on numerical simulations of the formation and evolution of structure

The properties of clusters of galaxies are one of the strongest tests of these techniques

Particle acceleration

Cluster shocks source of highest E cosmic rays?

Certain types of radio sources only appear in clusters

Observational and Theoretical Tools

- Clusters are the panchromatic objects 'par excellence' with important observations from the
  - Longest wavelengths (low frequency radio)
  - Gamma rays
- Here are some examples
  - The presence of radio 'bubbles' indicative of feedback is best seen at the longest radio wavelengths
  - The Sunyzaev Zeldovich effects requires measurements in the 100-500GHz band
  - Mid-far IR is sensitive to star formation and presence of dust and molecular gas (H_2)
- Near IR is one of the best place to find distant clusters and study the nature of their galaxies
- Optical imaging and spectroscopy is crucial for finding low z clusters and determining their velocity and spatial structure, determine merging properties and chemical abundances of stars
- UV is the best place to observe cluster related star formation
- Soft x-rays are critical to find clusters and to find and study 'cooling flows'
- Medium energy x-rays are necessary for cluster chemical abundances, mass measurements and finding AGN
- Hard x-rays and γ-rays to study particle acceleration and transfer

Theoretical Tools cont

- Physics of hot plasmas
  - Bremmstrahlung
  - Collisional equilibrium
  - Heat transport
  - Etc
- Formation of structure
- How to infer star formation rates from various observations
- How to determine amount of energy in feedback processes
- How to use lensing
- Study of magnetic fields
- Signature of dark matter (e.g. interacting dark matter signals)

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 ?