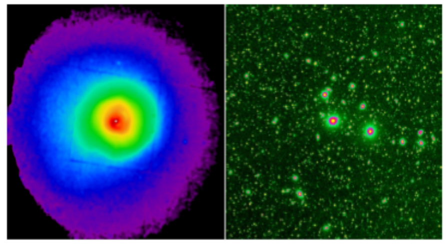
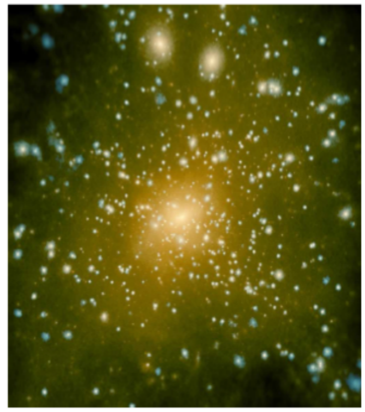
Clusters of Galaxies Ch 7 S&

- 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 virial radii are of the order of 1 - 4 Mpc (10^{24}-10^{25} cm).
- The combination of size and mass leads t velocity dispersions/temperatures of 300-1200km/sec; 0.5-12 keV
- M~kTR; σ^2~kT



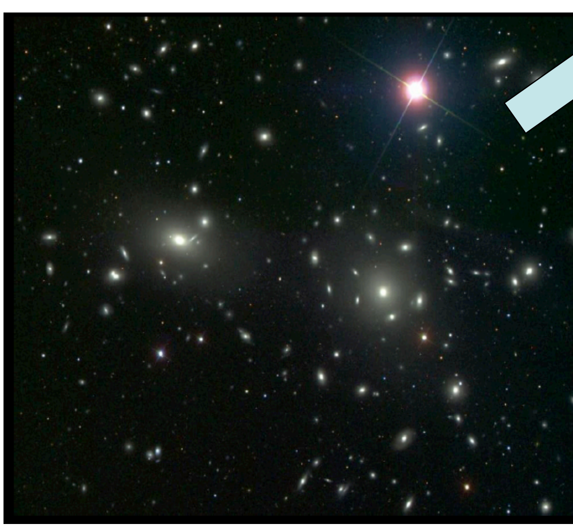
X-ray optical
Perseus cluster d~73Mpc

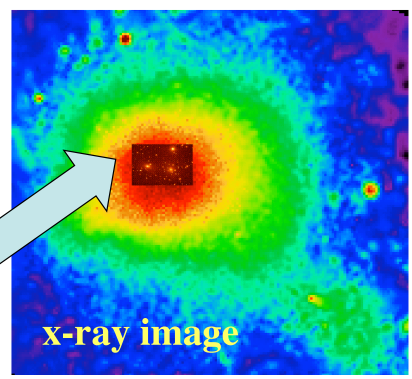


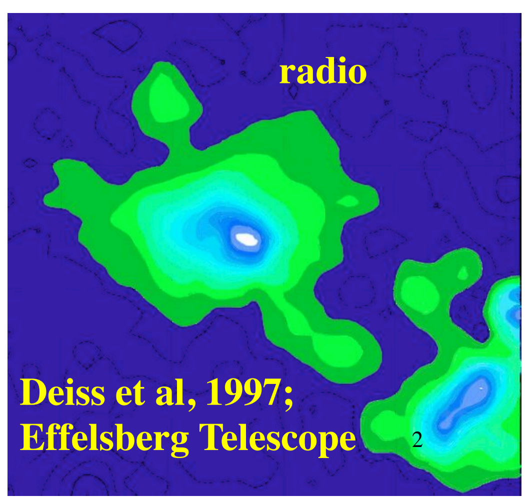
Dark matter simulation
V.Springel

Coma Cluster-the nearest massive cluster

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







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 probably 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

  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 mass using the velocity distribution of the galaxies via the use of the viral theorem were obtained.
- By the early 1970's it became clear 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 (Dressler 1980).
- Thus the issue of the "missing mass" or "dark matter" became the central one of cluster research.

More History

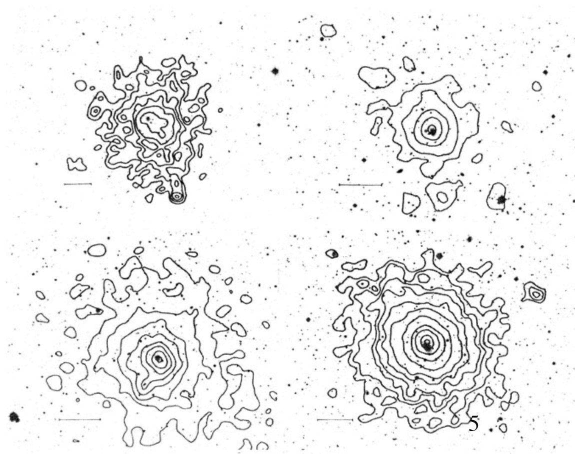
- "Rich" clusters (that is those with many galaxies inside a fixed metric (Abell) radius) had a preponderance of "early" type (elliptical and S0 galaxies) while "poorer" clusters had a larger fraction of spiral galaxies.
- It was clear that many clusters had a rather unusual central galaxy, a cD , or 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.

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.

Hot Gas In Clusters

- One of the major surprises in astrophysics was the discovery in the 1970's (Kellogg et al 1972- for a review see Mushotzky 2001 The Century of Space Science Bleeker and Huber eds)
- That clusters (as a class) were luminous x-ray sources
- Early estimates (Felten 1969, Lea et al 1973) under the assumption that the emission was due to thermal bremmstrahlung from hot gas required that the mass of the gas be a substantial fraction of the 'total' mass of the cluster
- However these early data had very little information on the size of the emission

With the launch of the Einstein Obseratory in 1979 with true x-ray imaging capabilities (Jones and Forman Annu. Rev. Astron. Astrophys. 1982. 20: 547-85) the first cluster x-ray images were obtained



Why are Clusters Interesting or Important

- Laboratory to study
  - Dark matter- Clusters are DM dominated
    - 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

How 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
  - 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- lots of detailed physics

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) to Gamma rays
- 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
  - Collosional 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

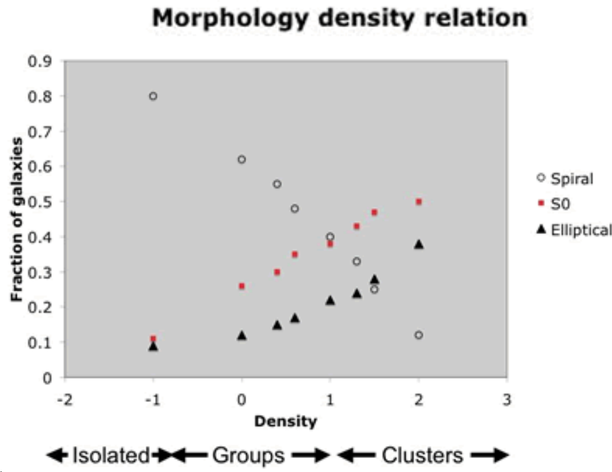
• Studies of their evolution, temperature and luminosity function can place strong constraints on all theories of large scale structure and determine precise values for many of the cosmological parameters

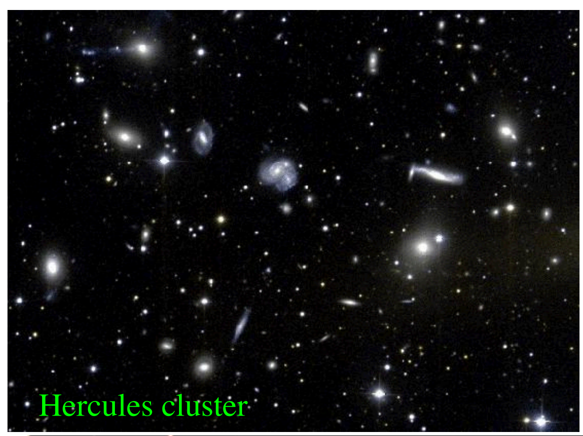
- Provide a record of nucleosynthesis in the universe- as opposed to galaxies, clusters retain all the enriched material created in them
  - •Measurement of the elemental abundances and their evolution provide fundamental data for the origin of the elements
  - •The distribution of the elements in the clusters reveals how the metals were removed from stellar systems into the IGM

Clusters are so big and massive that they 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

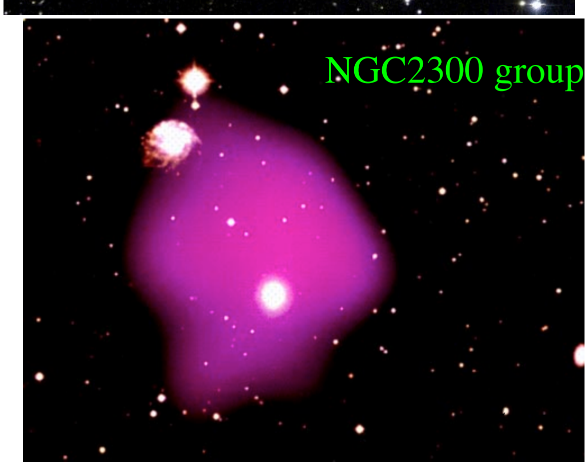
How 'Important' Are Clusters

- Integrating over all clusters more massive than $M_{200}=10^{14}$ h^{-1} M_{solar} the virialized regions of the cluster contain ~7% of the local stellar luminosity (Kochanek et al 2004)
- "Most" of the galaxies in massive (rich) clusters are ellipticals (manifestation of the density morphology relation (Dressler 1980))
- Most of the light is in objects with M<-19





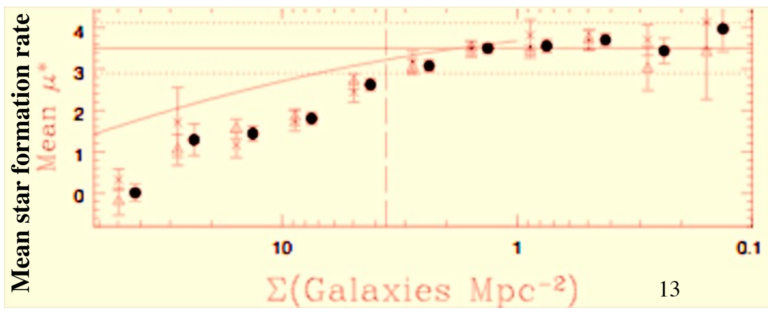
- As the mass of the cluster increases the fraction of 'early type' galaxies increases



High Galaxy Density Supresses Spiral Galaxies and Star Formation

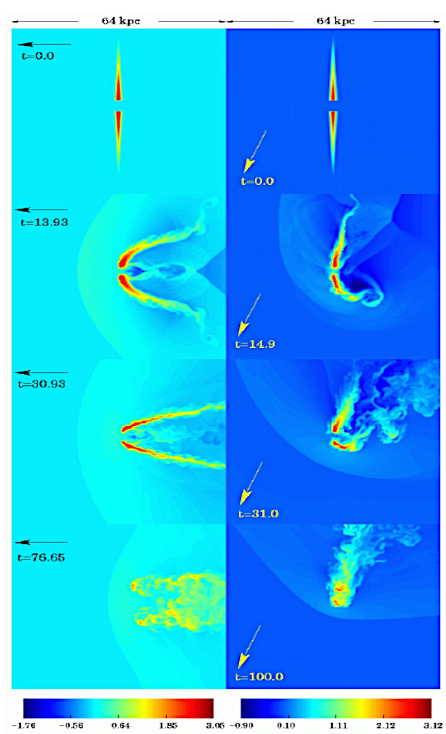
- So why where and when does this occur?
- ram pressure or viscous stripping and/or , galaxy harassment, or strangulation
  - Ram pressure stripping- cold gas removed
  - 'Strangulation' - 'the stripping of a galaxy' s hot gas halo as it falls into a cluster leading to a cessation in star formation in lower mass galaxies thus providing a mechanism for the build up of passive red galaxies in the cluster (Larson et al. 1980).
  - Harrasment- galaxies influencing each other, rather than a cluster wide process- clusters are a bad place for mergers since the relative velocity of the galaxies is too high

Whether the relationship between local density and the properties of galaxies is intrinsic, or is a result of physical processes that occur in dense regions after initial galaxy formation is still an unresolved issue.
Conselice 2006



Understanding the Origin of Morphological Differences in Galaxies- M. Postman

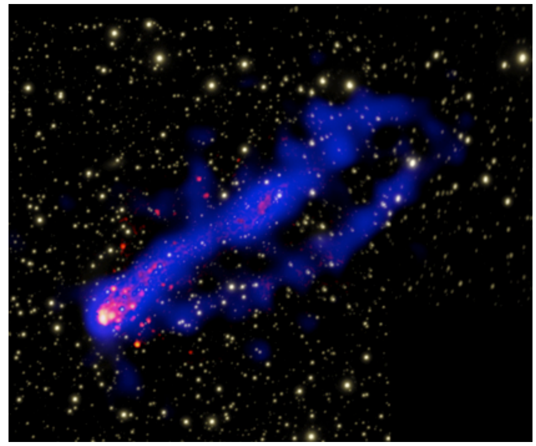
- The relative fraction of galaxy morphologies depends on density (Dressler 1980, Postman & Geller 1984) and/or on clustocentric radius (Whitmore & Gilmore 1993)
- Physical processes exist that can alter galaxy morphology on timescales much less than the current age of the universe: ram pressure, tidal disruption, mergers
- Possible evolution in the morphological composition of clusters over the past ~5 Gyrs: z~0.5 to the present epoch (Dressler et al 1997; Fasano et al. 2000; Treu et al. 2003).

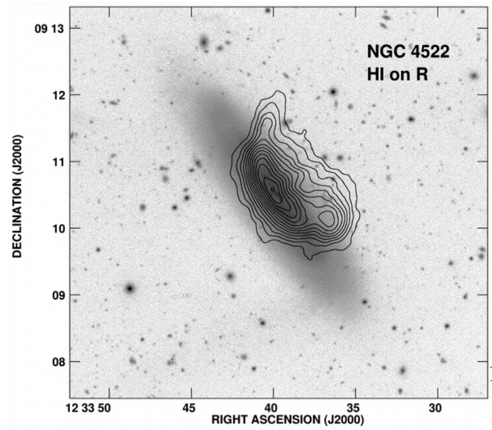


Quilis, Moore, & Bower 2000: Ram pressure induced gas stripping; Timescale ~100 Myr

Ram pressure gas stripping

- ESO 130-001: in Abell 3627
- In image below zoomed into galaxy
- Image to right, Hα in red, starlight in yellow
- Also see HI contours 'pushed back





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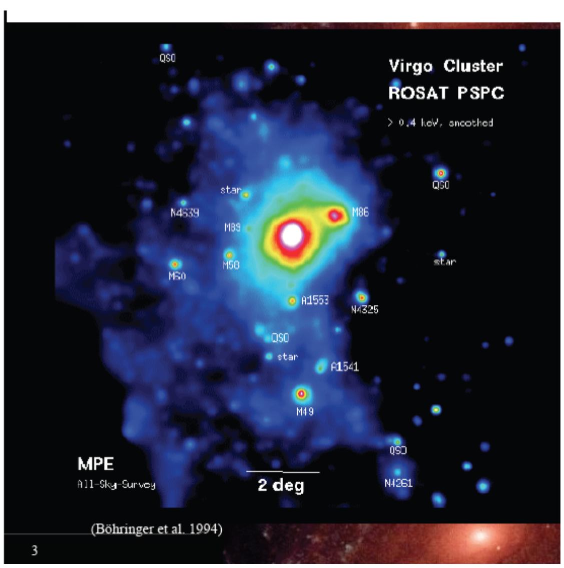
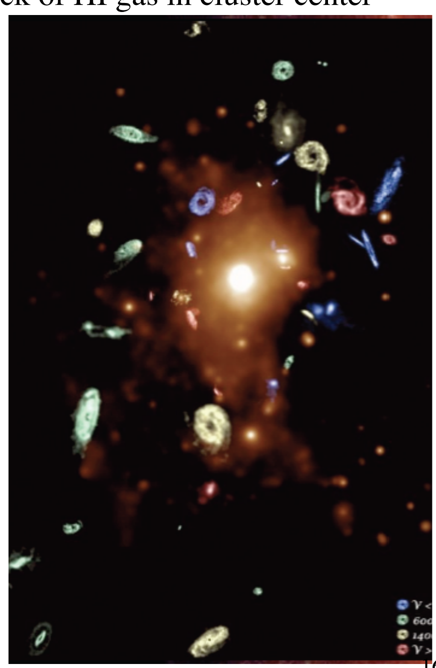
Hot Gas in Cluster Effects Cold Gas in Galaxies

- Atomic Gas in Virgo Galaxies- notice lack of HI gas in cluster center

X-ray Image of Virgo Cluster
Closest Massive Cluster





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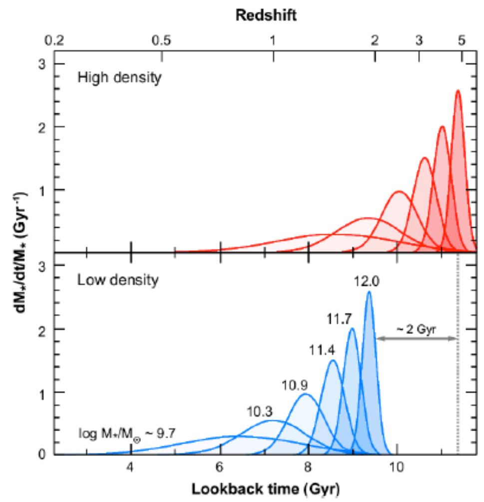
How Old are the Galaxies

- One of the major issues is when did clusters form and what does that mean?
- CDM simulations indicate when the mass concentrations formed- but how were they populated with galaxies and gas?
- A separate issue is the age of the stellar population
  - The oldest average age for a stellar population is found in the most massive galaxies in clusters

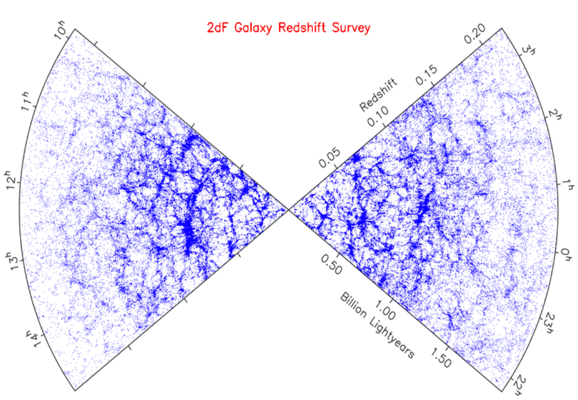
Galaxy Formation

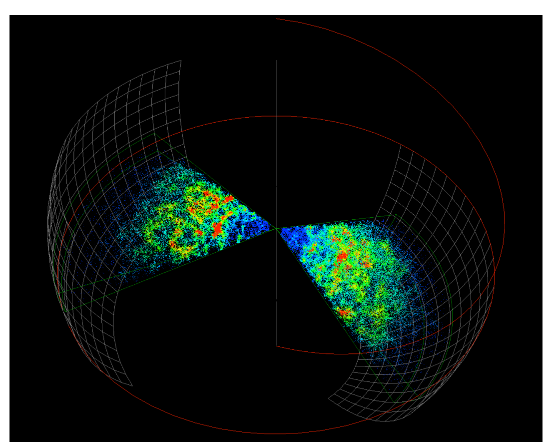


The scenario proposed by Thomas et al. (2005) for the average star formatio
laxies of different masses, from $5 \times 10^9 M_\odot$ up to $10^{12} M_\odot$, corresponding tc
n s^{-1}, for the highest and lowest environmental densities, respectively, in the

Cosmic Web

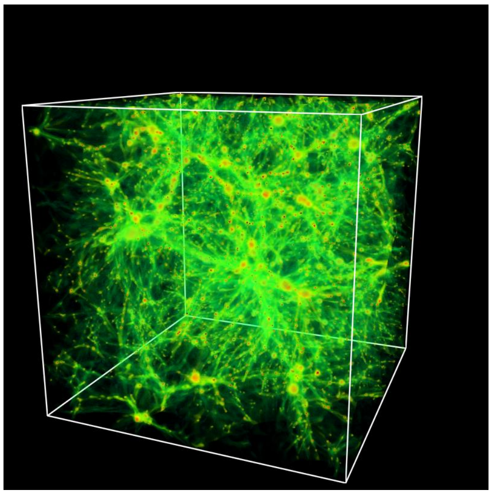
- large scale structure of the universe consists of sheets and filaments- clusters occur at the intersection of these structures

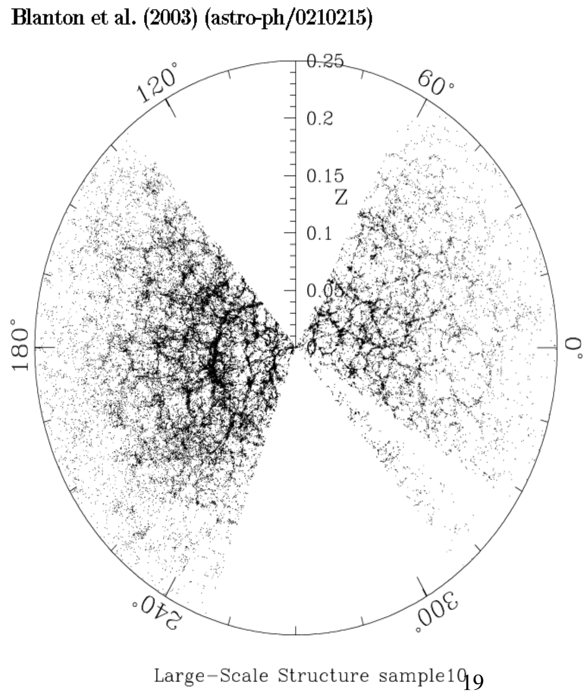




Cosmic Web (again)

- The large scale structures are 'seen' in both the all redshift surveys out to the largest redshifts





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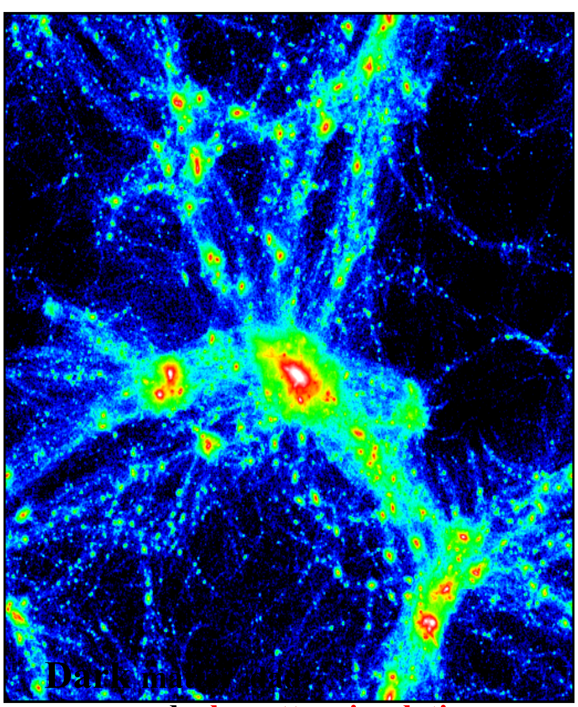
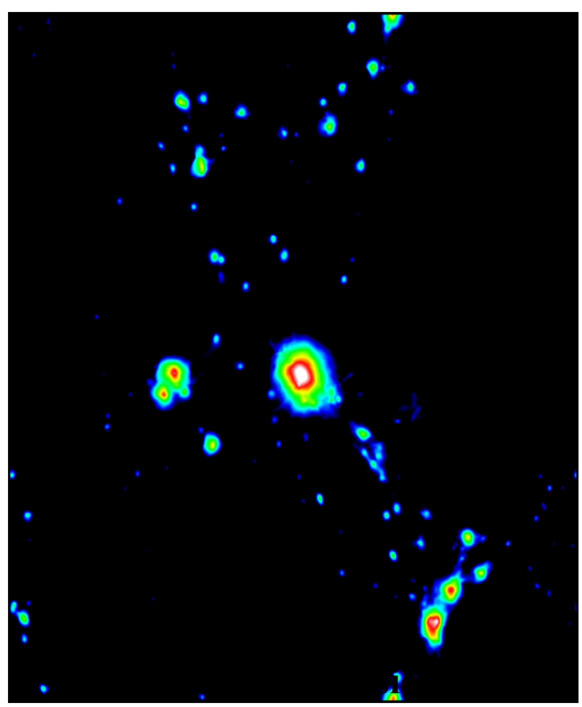
Comparison of dark matter and x-ray cluster and group distribution
every bound system visible in the numerical simulation is detected in the x-ray band -
bright regions are massive clusters, dimmer regions groups,

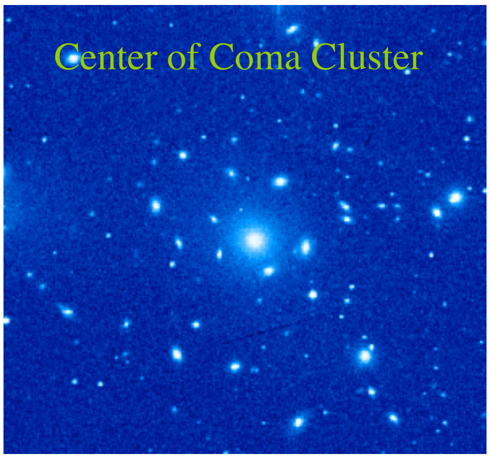


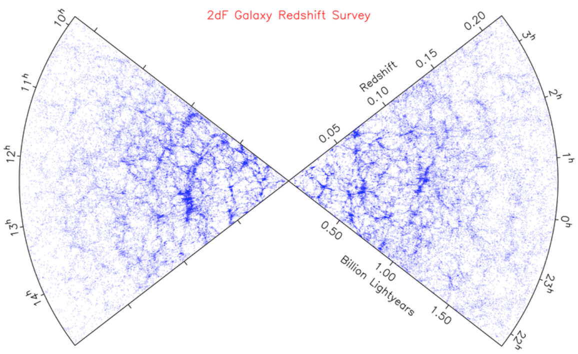
dark matter simulation



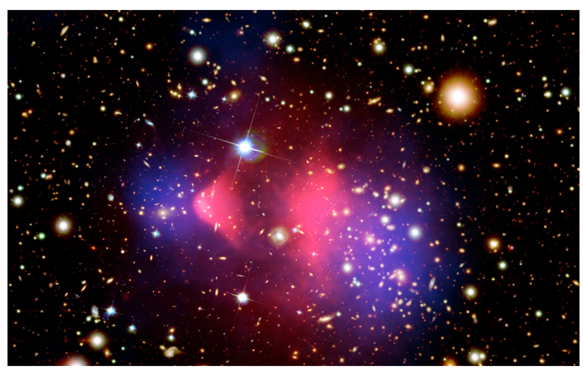
gas simulation

- http://nedwww.ipac.caltech.edu/level5/March02/Sarazin/frames.html
- X-ray emission from clusters of galaxies





Dark Matter



- The existence of dark matter in clusters and groups of galaxies is indicated by

1)high mass-to-light ratio.

estimate the cluster total mass by assuming that the member galaxies have become dynamically relaxed and

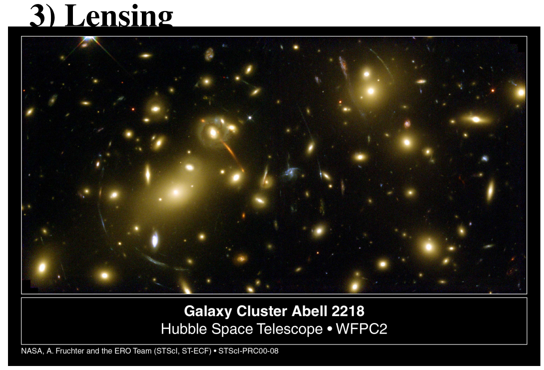
that they are in an equilibrium configuration: hence the virial theorem can be used (U = -2 K, where U and K are the potential and the kinetic energies respectively) to obtain the virial mass

The observed optical luminosity of the galaxies corresponds to a mass that is much lower than the total cluster mass

- So a large quantity of matter not visible as stars
- X-ray emitting gas constitutes a portion- ~1/6th of this "missing mass".

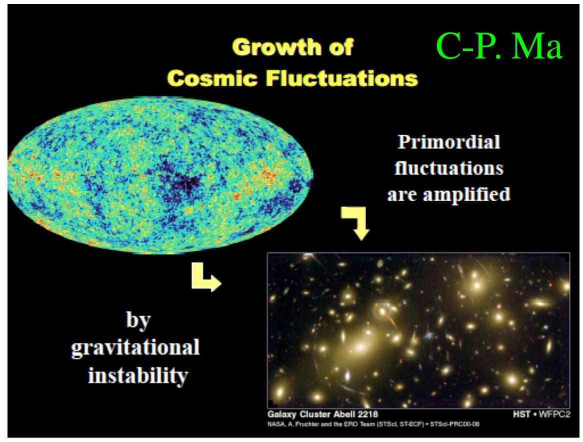
2) Direct evidence (Bullet cluster) That dark matter and baryons can be in different places

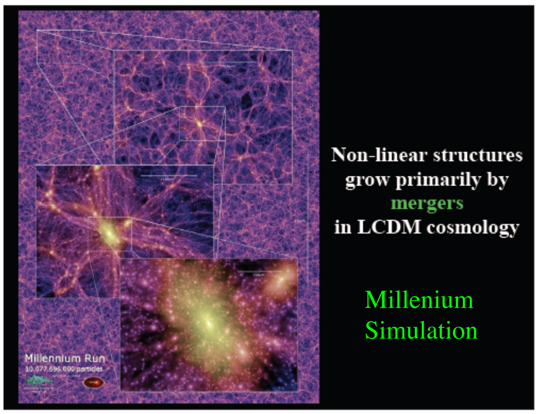
3) Lensing



Formation

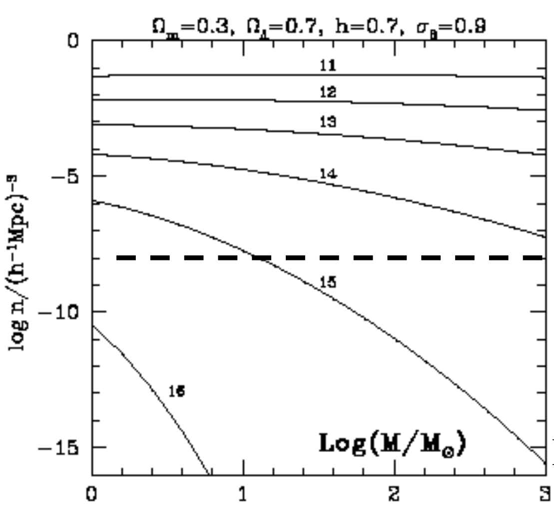
- Galaxy clusters form through gravitational collapse, driven by dark matter (~80% of their total mass)
- In the hierarchical scenario more massive objects form at later times: clusters of galaxies are produced by the gravitational merger of smaller systems, such as groups and sub-clusters





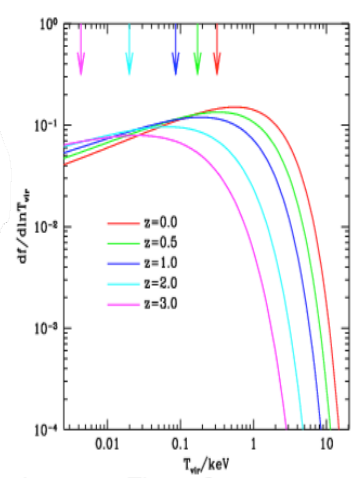
Clusters Grow at Late Times

- In standard cosmologies the number of massive clusters (log M~15) increases by ~ 30x from z~1 to the present



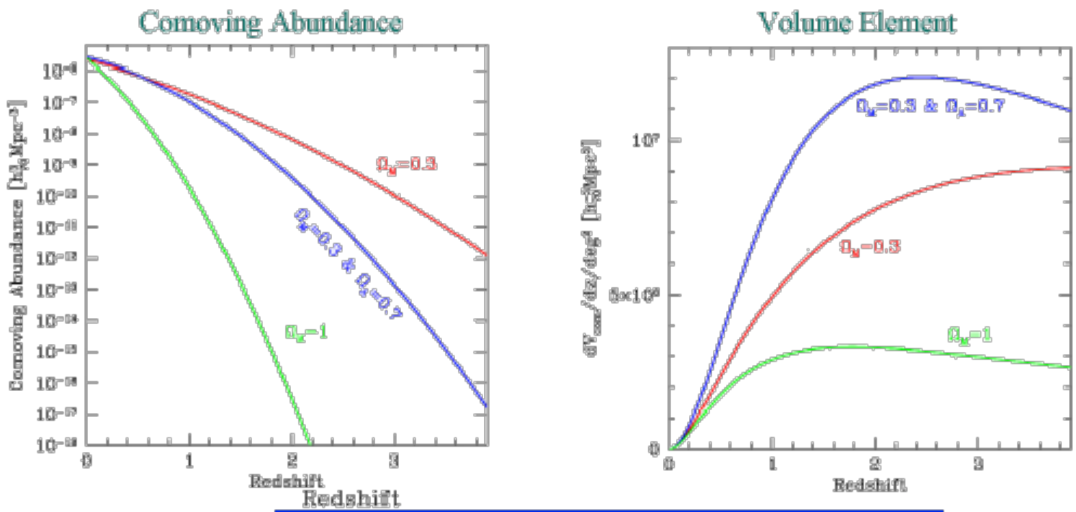
H. Mo

Fraction of Mass in Dark Matter Halos



A.Benson, C. Frenk and the Durham Group

Co-Moving Abundance and Volume elements are functions of cosmology



Mohr 2003

$$\frac{dV}{dz d\Omega} = \frac{c}{H(z)} d_A^2 (1+z)^2 \qquad d_A \propto \int_0^z \frac{dz'}{E(z')}$$

$d_A(1+z)$ is proper distance

$H(z) = H_o E(z)$ is the Hubble parameter

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Cluster Formation

- Cluster mergers are thought to be the prime mechanism of massive cluster formation in a hierarchical universe (White and Frenk 1991)
- the most energetic events in the universe since the big bang. These mergers with infall velocities of ~2000 km/s and total masses of 10^{15} $M_\odot$ have a kinetic energy of 10^{65} ergs.
- The shocks and structures generated in the merger have a important influence on cluster shape, luminosity and evolution and may generate large fluxes of relativistic particles