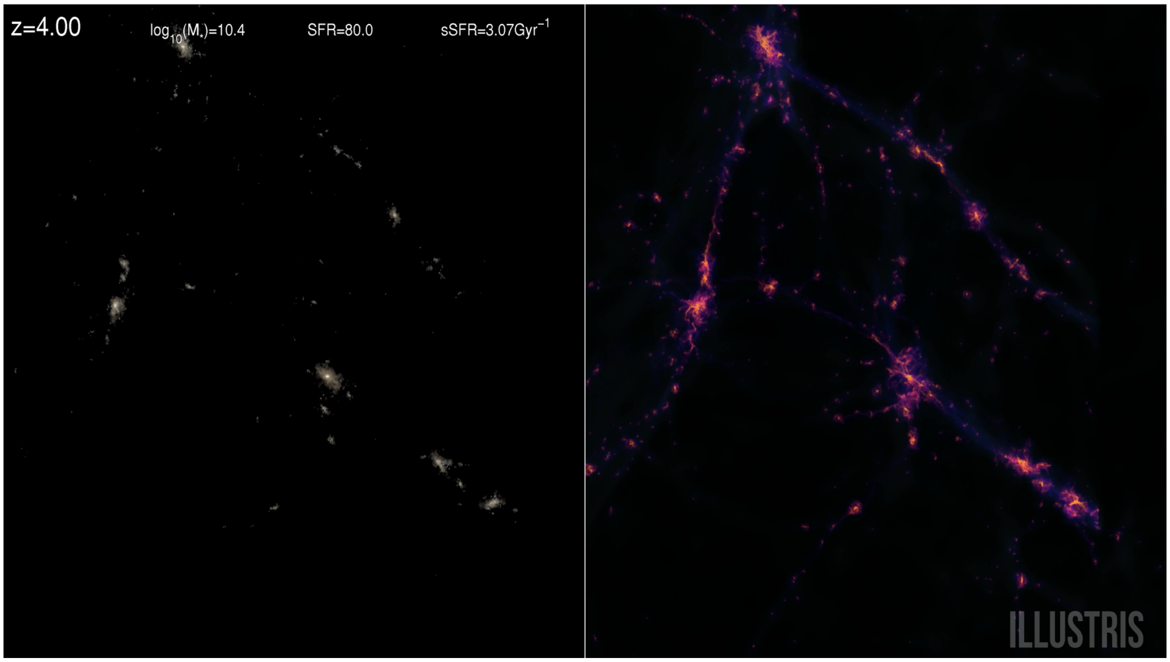
Formation of an Elliptical- Stellar Light on Left, Gas on Right

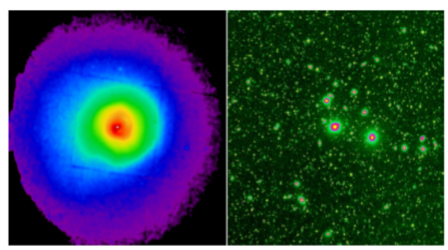


Clusters of Galaxies Ch 7 S&G

- Clusters of galaxies are the largest gravitationally bound systems in the Universe.

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



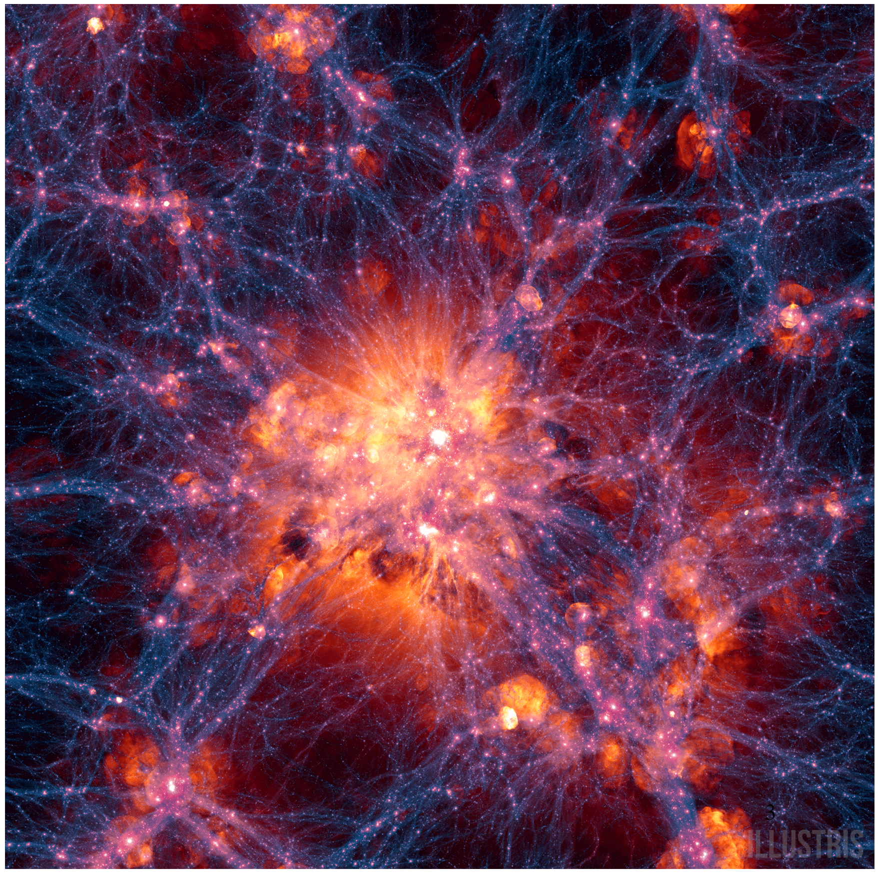
X-ray optical

Perseus cluster d~73Mpc

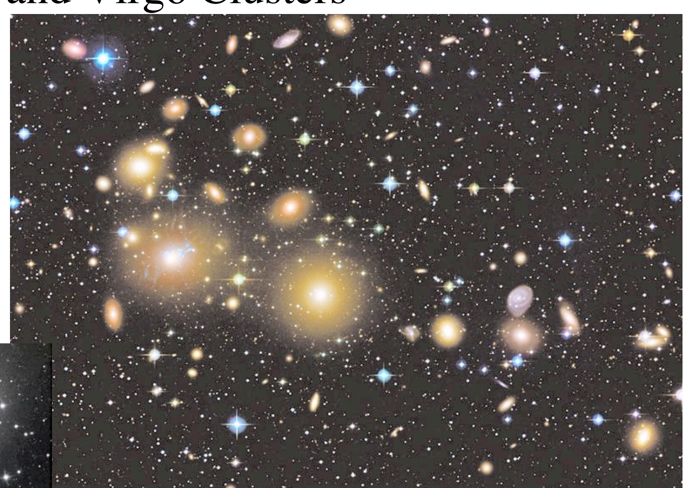
Dark matter simulation

V.Springel

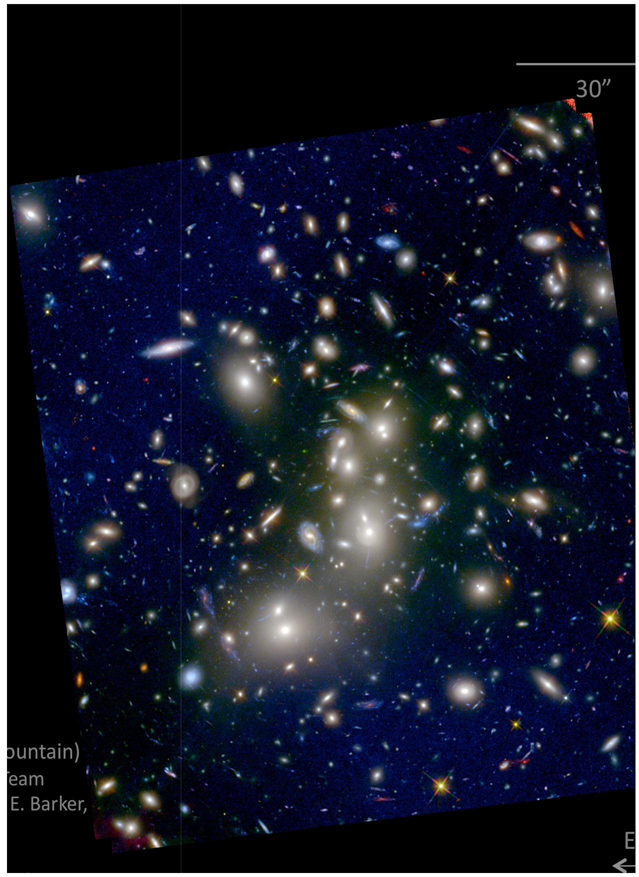
A Simulation of a Massive Cluster (Illustris)



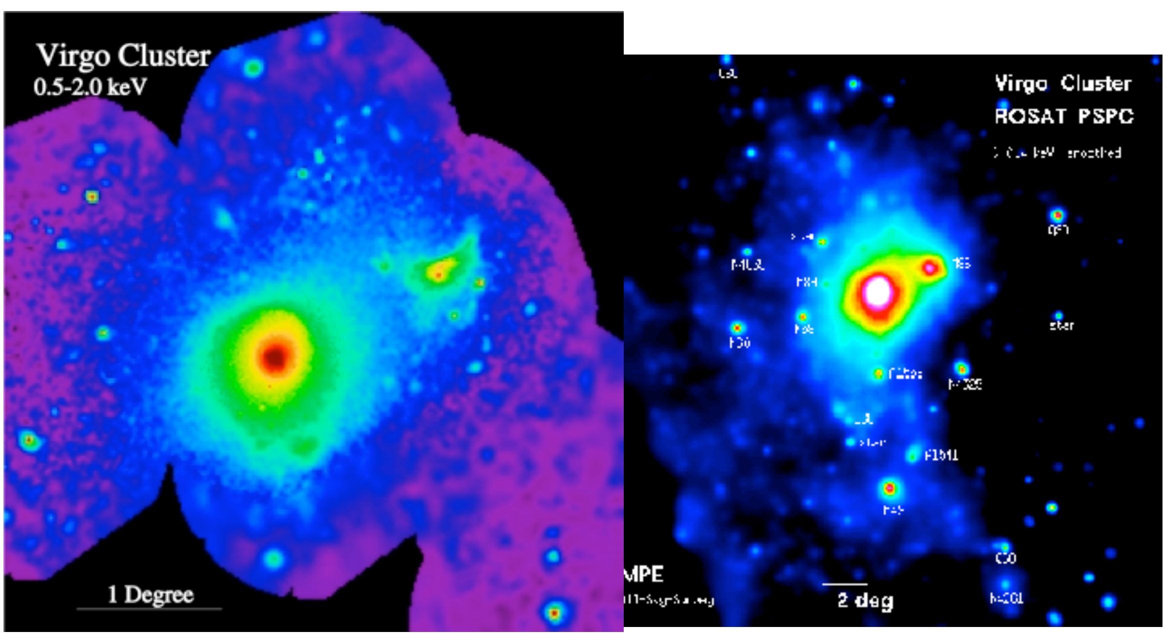
Perseus and Virgo Clusters



Very Deep HST image
of z~0.38(1200 Mpc)
Cluster

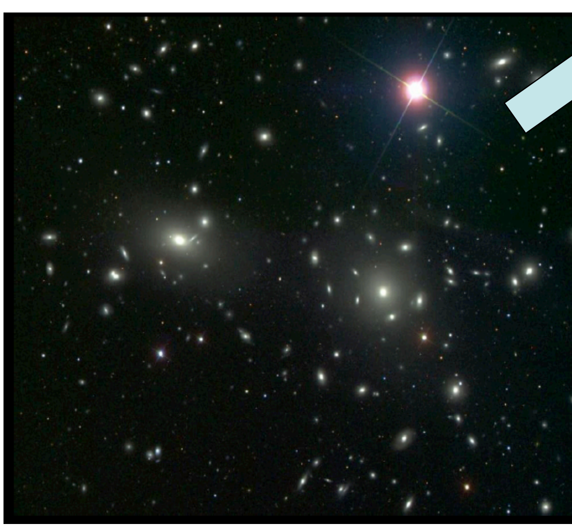


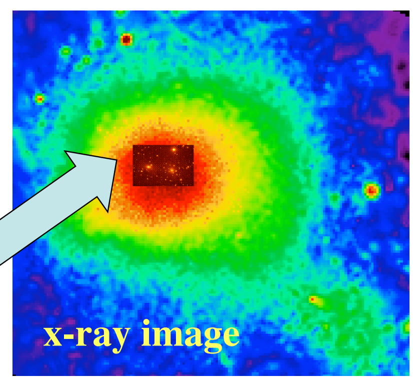
X-ray Images of Virgo Cluster

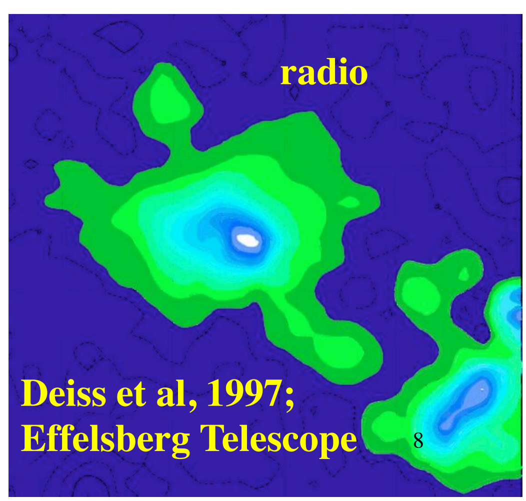


Coma Cluster-the nearest massive cluster

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

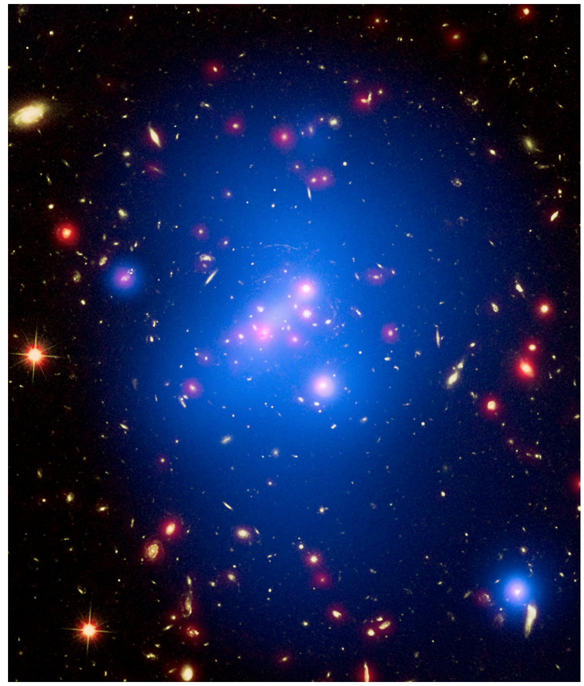






Composite Image

- X-rays are blue, optical in green, IR in red



A Bit of History

- Clusters 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 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 that clusters of galaxies were dominated by dark matter with galaxies representing less than 5% of the total mass
- Thus the issue of the "missing mass" or "dark matter" became the central one of cluster research.

More History

- "Rich" clusters[1] dominated by "early" type (elliptical and S0 galaxies); "poorer" clusters had a larger fraction of spiral galaxies (Dressler 1980).
- Many clusters had a rather unusual central galaxy, a cD , or centrally dominant galaxy (Morgan and Osterbrock 1969) rarely 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) .

Philosophy

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.

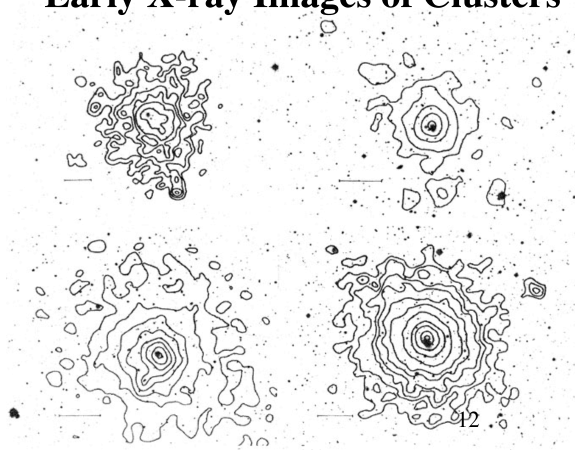
1 those with many galaxies inside a fixed metric (Abell radius)

Hot Gas In Clusters

- One of the major surprises in astrophysics- 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 are luminous extended x-ray sources
- Early estimates (Felten 1969, Lea et al 1973) that the mass of the gas is a substantial fraction of the 'total' mass of the cluster
  - However these early data had very little information on the size of the emission

Einstein Observatory in 1979 with true x-ray imaging capabilities (Jones and Forman Annu. Rev. Astron. Astrophys. 1982. 20: 547-85) - first x-ray images.

Early X-ray Images of Clusters



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?

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 radio 'bubbles', indicative of feedback, are best seen at long 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 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

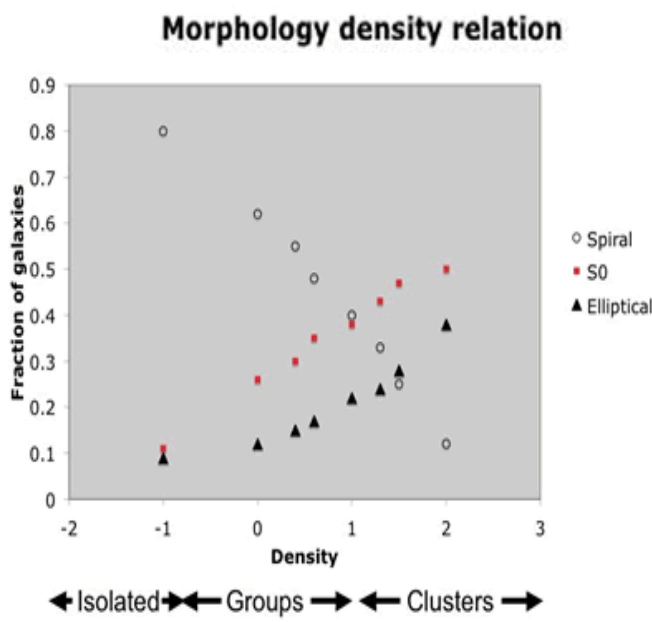
Clusters are so big and massive that they should be "fair" samples of the universe"

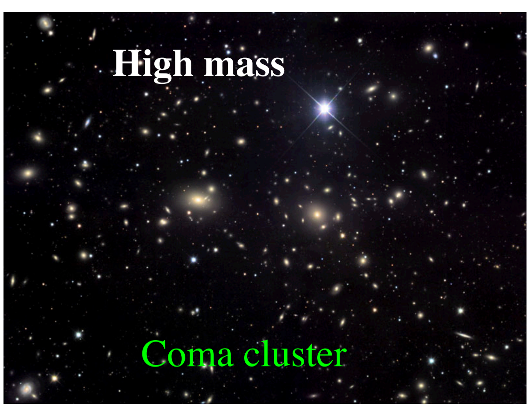
- Studies of their mass and their baryon fraction reveal the "gross" properties of the universe as a whole

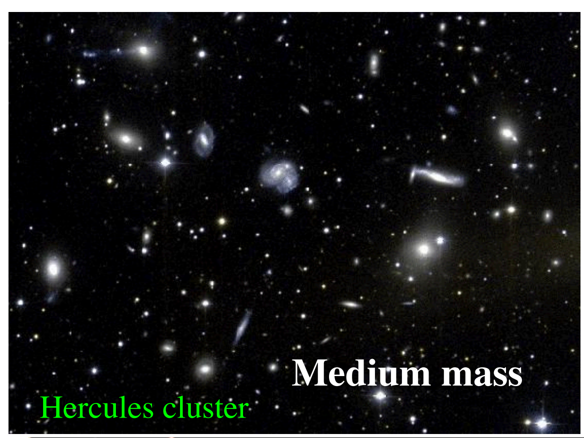
(in simple collapse calculation, a 10Mpc 'average' place in the universe collapses to a 1Mpc cluster, density goes up by 1000)

How 'Important' Are Clusters

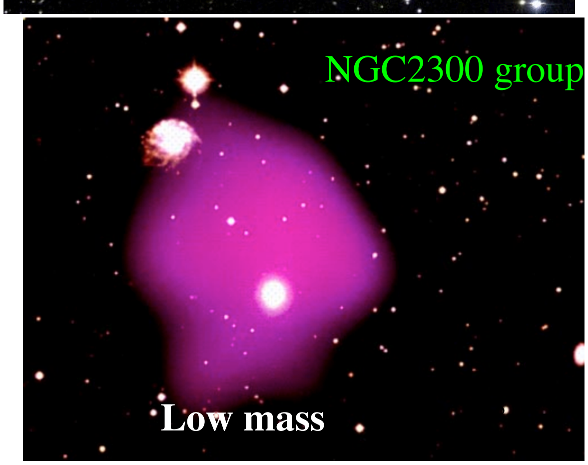
- Integrating over all clusters more massive than $M_{200}=10^{14}$ M_{solar} the virialized regions of the cluster contain ~7% of the local stellar luminosity (Kochanek et al 2004)
- "Most" of the galaxies in massive (rich) clusters are ellipticals (manifestation of the density morphology relation (Dressler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





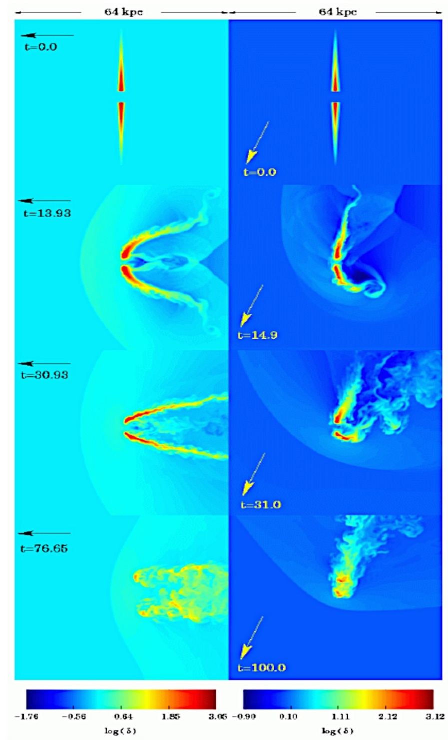


- As the mass of the cluster increases the fraction of 'early type' galaxies increases



Origin of Morphological Differences in Galaxies- M. Postman

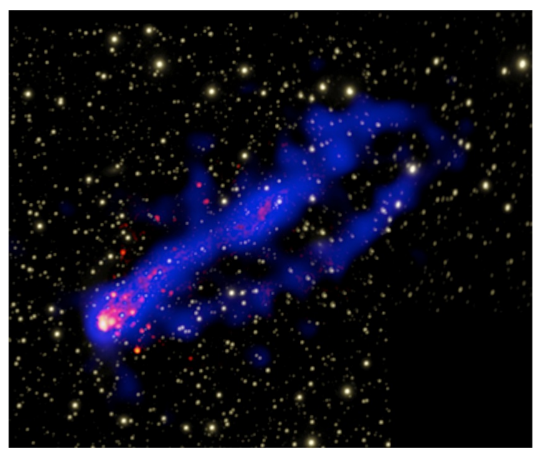
- The relative fraction of galaxy morphologies depends on density (Dressler 1980, Postman & Geller 1984) and/or on clustocentric radius (Whitmore & Gilmore 1993)
- galaxy morphology altered by: ram pressure, tidal disruption, mergers

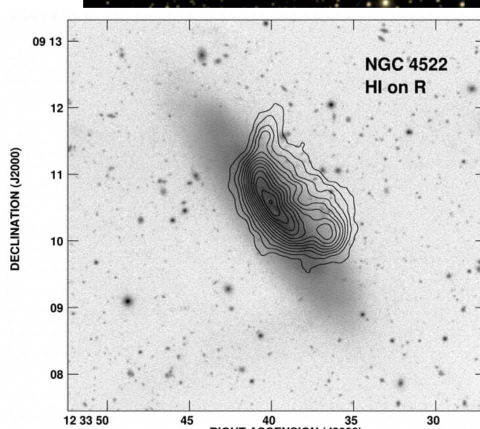


Quilis, Moore, & Bower 2000: Ram pressure induced gas stripping; Timescale ~100 Myr

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 , x-ray in blue
- HI contours 'pushed back' in NGC4522

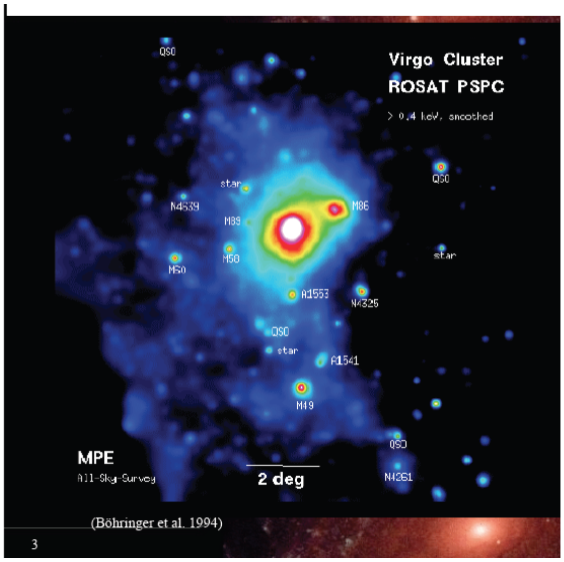


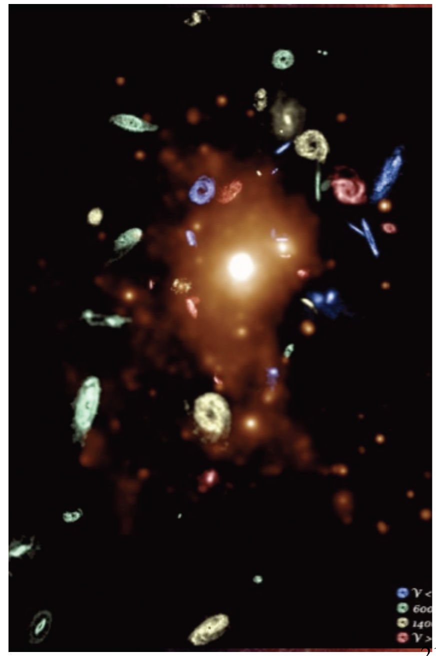


Hot Gas in Cluster Effects Cold Gas in Galaxies

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

X-ray Image of Virgo Cluster
Closest Massive Cluster

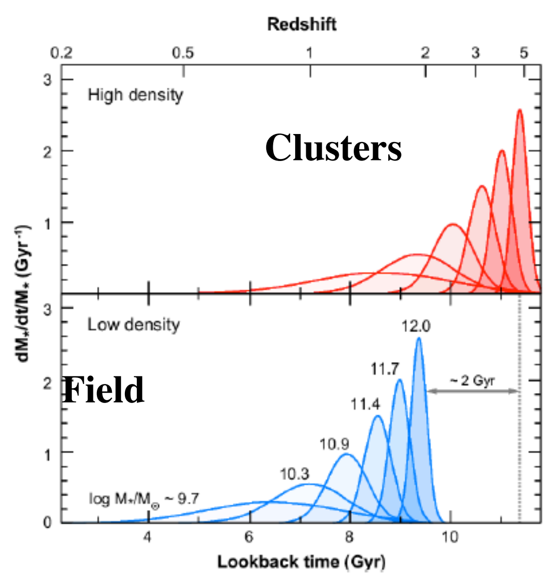




How Old are the Galaxies

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

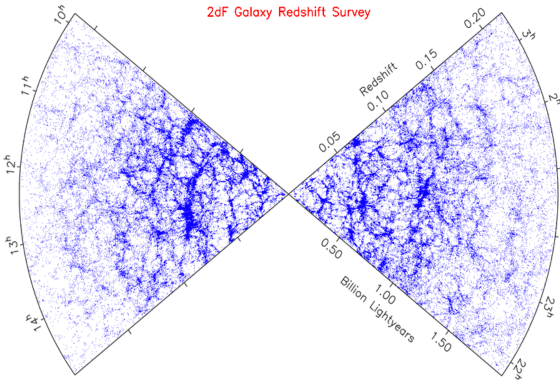
Galaxy Formation

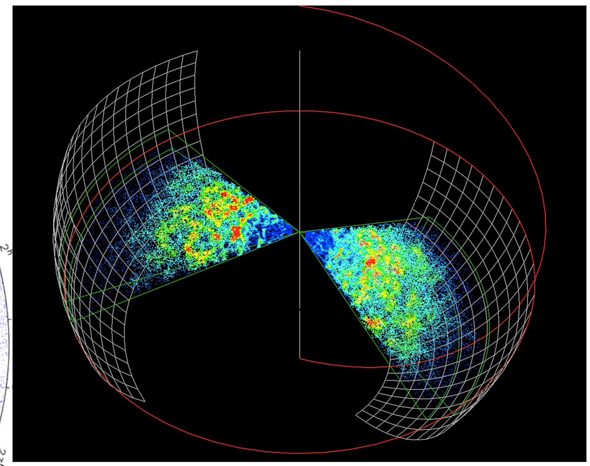


The scenario proposed by Thomas et al. (2005) for the average star formatio
laxies of different masses, from $5 \times 10^9 M_\odot$ up to $10^{12} M_\odot$, corresponding to
n s^{-1}, for the highest and lowest environmental densities, respectively, in the

Cosmic Web

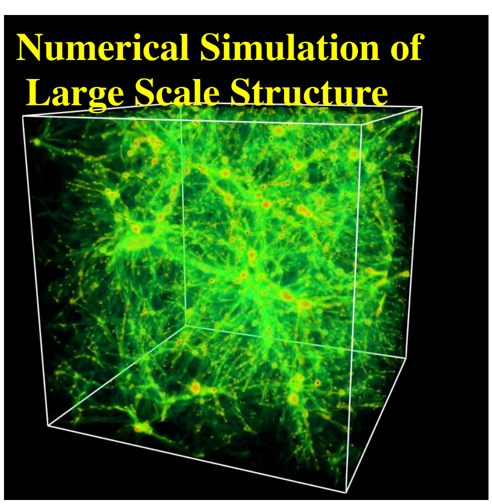
- large scale structure of the universe consists of sheets and filaments- clusters occur at the intersection of these structures

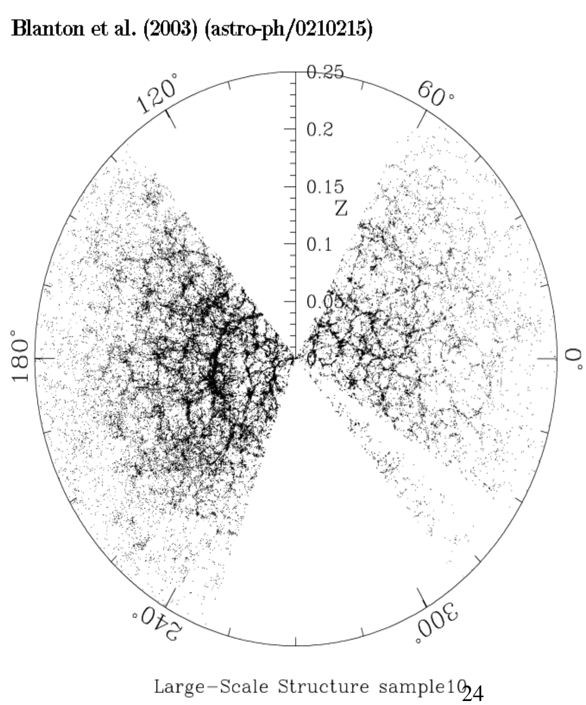




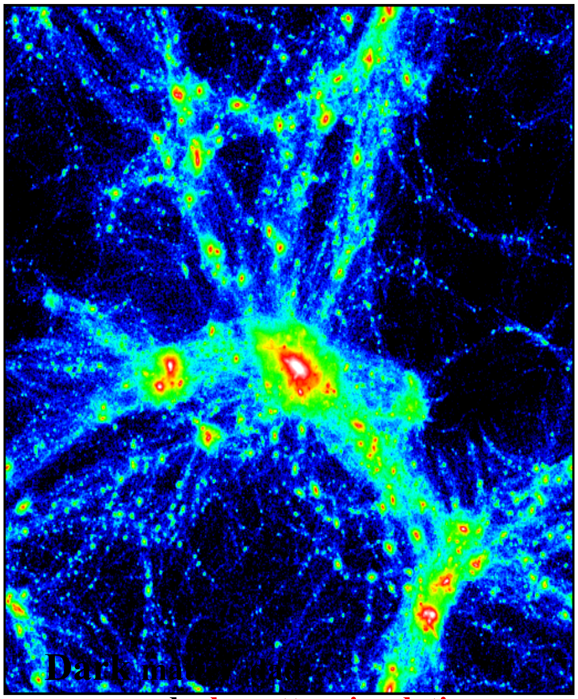
Cosmic Web (again)

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

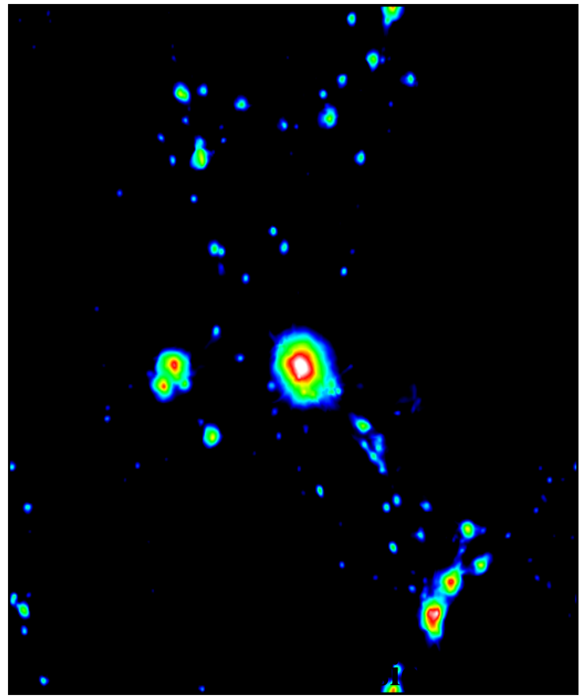




Comparison of dark matter and x-ray cluster and group distribution
every bound system visible in the numerical simulation is detected in the x-ray band -
bright regions are massive clusters, dimmer regions groups,



dark matter simulation



gas simulation

Dark Matter

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

1) high mass-to-light ratio.

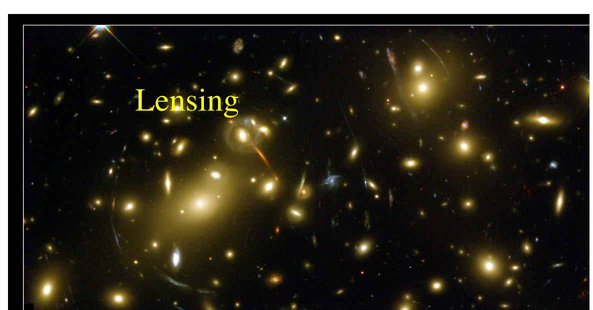
estimate the cluster total mass by assuming that the member galaxies have become dynamically relaxed and that they are in an equilibrium configuration☹ the virial theorem) to obtain the virial mass

Also lensing and x-ray measurements

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".

In clusters ratio ratio of DM to baryonic matter is ~6:1



Galaxy Cluster Abell 2218
Hubble Space Telescope • WFPC2

NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08