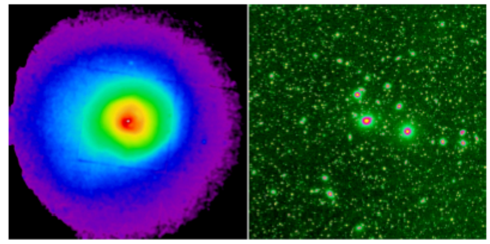
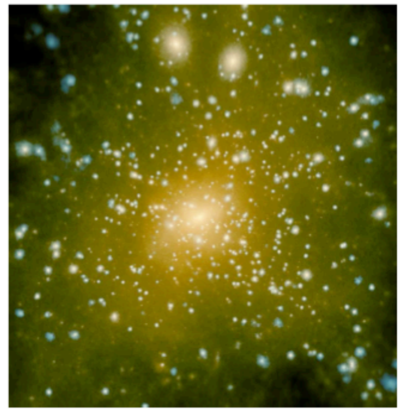
Clusters of Galaxies

- 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/temperatures of 300-1200km/sec; 0.5-12 keV
- M~(kT)R; σ^2~kT

Read Ch 4 of Longair



X-ray optical
Perseus cluster d~73Mpc



Dark matter simulation
V.Springel

Clusters of Galaxies

- High Energy Objects - most of (80%) the baryons are in a hot (kT~10^7-10^8k) gas.
- The x-ray luminosity is 10^{42}-10^{46} ergs/sec
- the hot gas is enriched in heavy elements (oxygen...iron) to ~1/3 solar
- Only objects in Universe which are both

  Small enough to be in equilibrium

  Big enough to be fair sample of materials in Universe (e.g., baryonic vs. nonbaryonic matter)

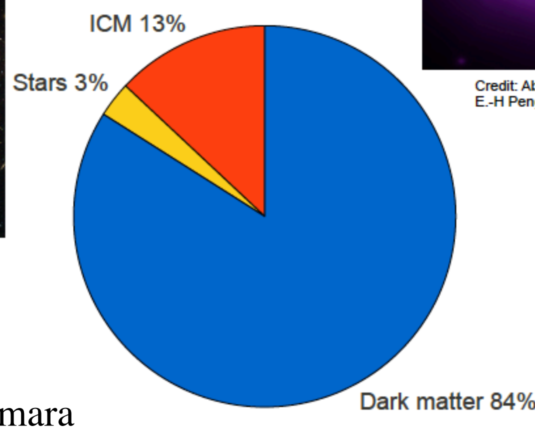
MASSIVE GALAXY CLUSTERS: GLOBAL PROPERTIES

Rudnick 2019

MASS BUDGET. Total 10^{15} Msun; "Virial" Radius ~2 Mpc			
Dark Matter: 85%	Hot plasma (ICM) 13%	Stars & cold gas 2%	Cosmic Rays* 10^{-6} %
ICM ENERGY DENSITY BUDGET. Total 10^3 J/m^3			
Thermal 88%	Kinetic 10%	Cosmic Rays* 1%	Magnetic Fields 1%

Galaxy cluster mass partitioning

Credit: Abell 1689, X-ray: NASA/CXC/MIT/
E.-H Peng et al.; Optical: NASA/STScI



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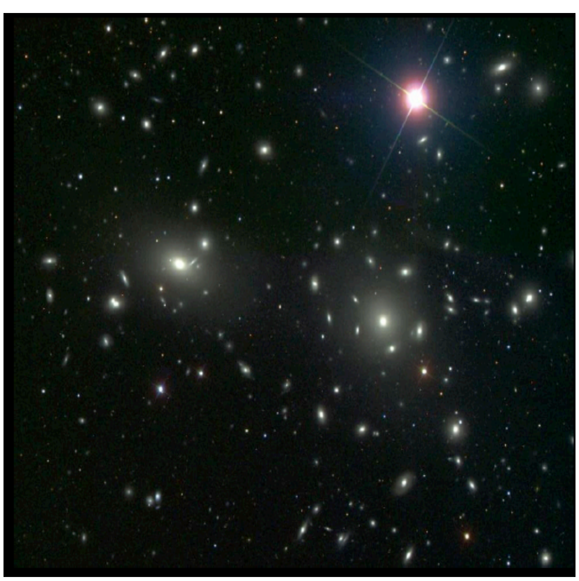
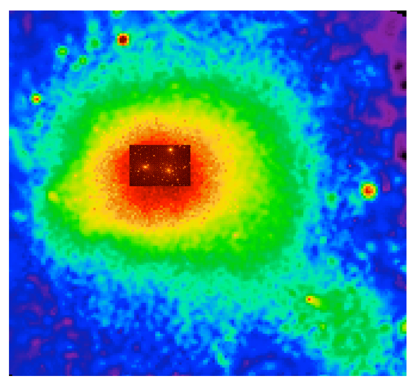
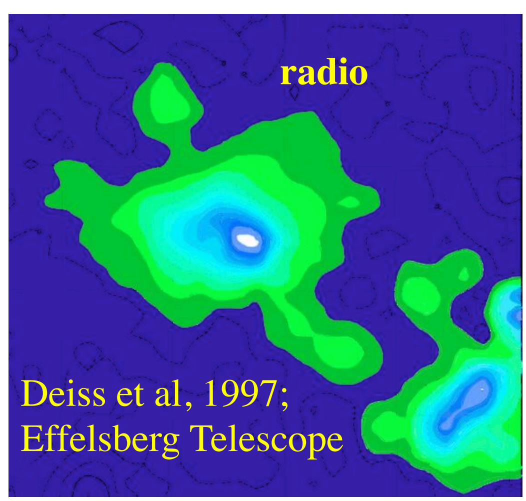
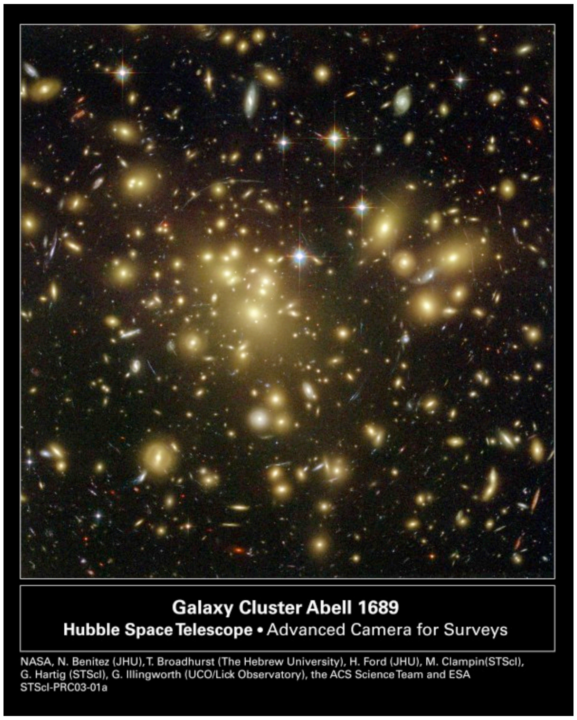
Coma Cluster

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

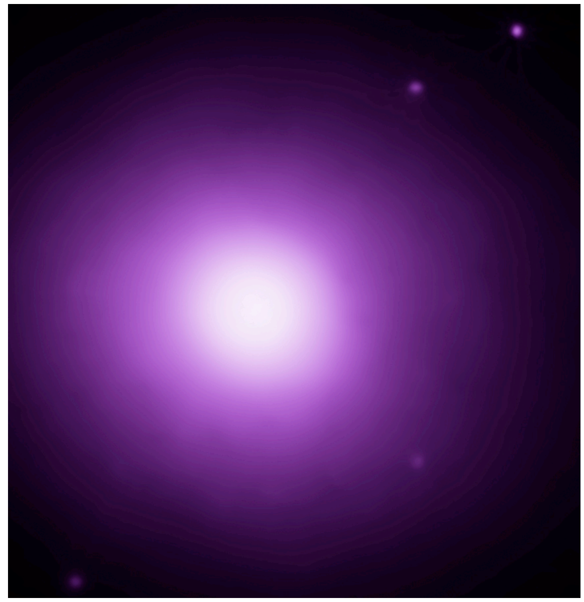


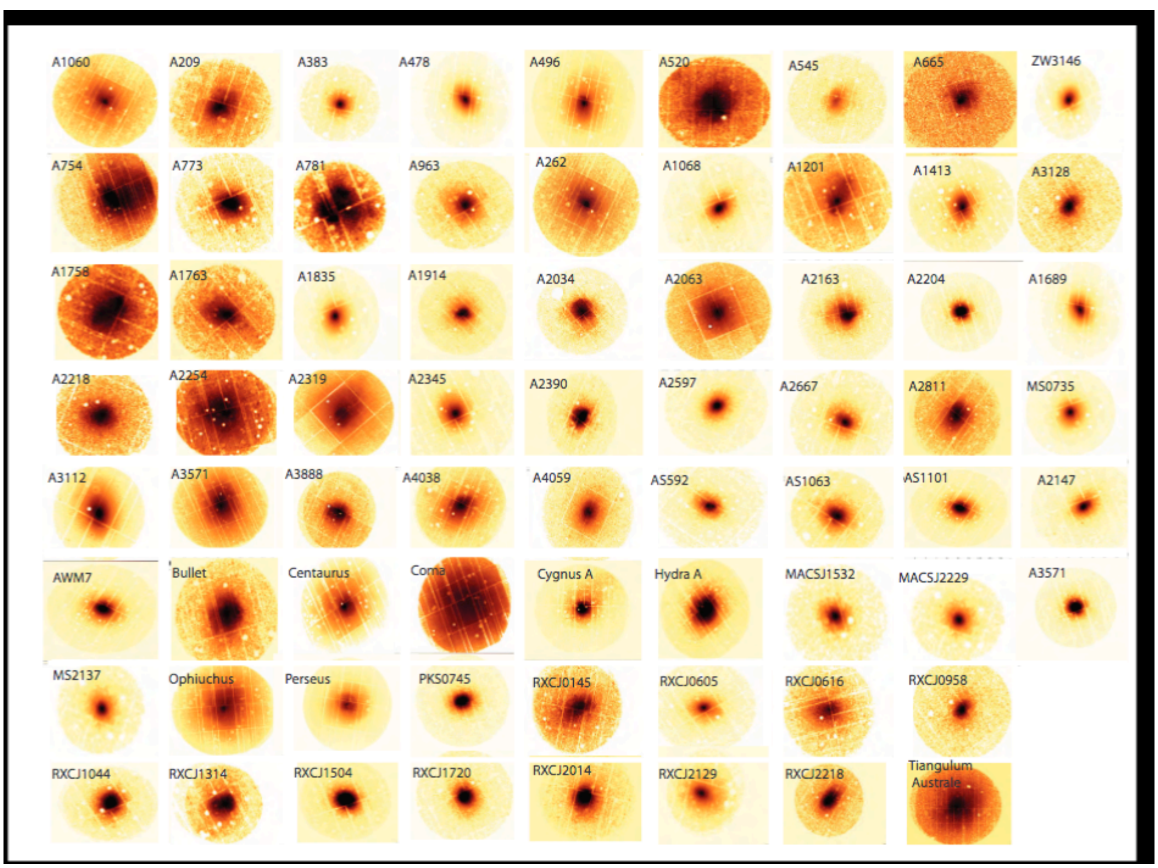






Chandra Image of Abell 1689

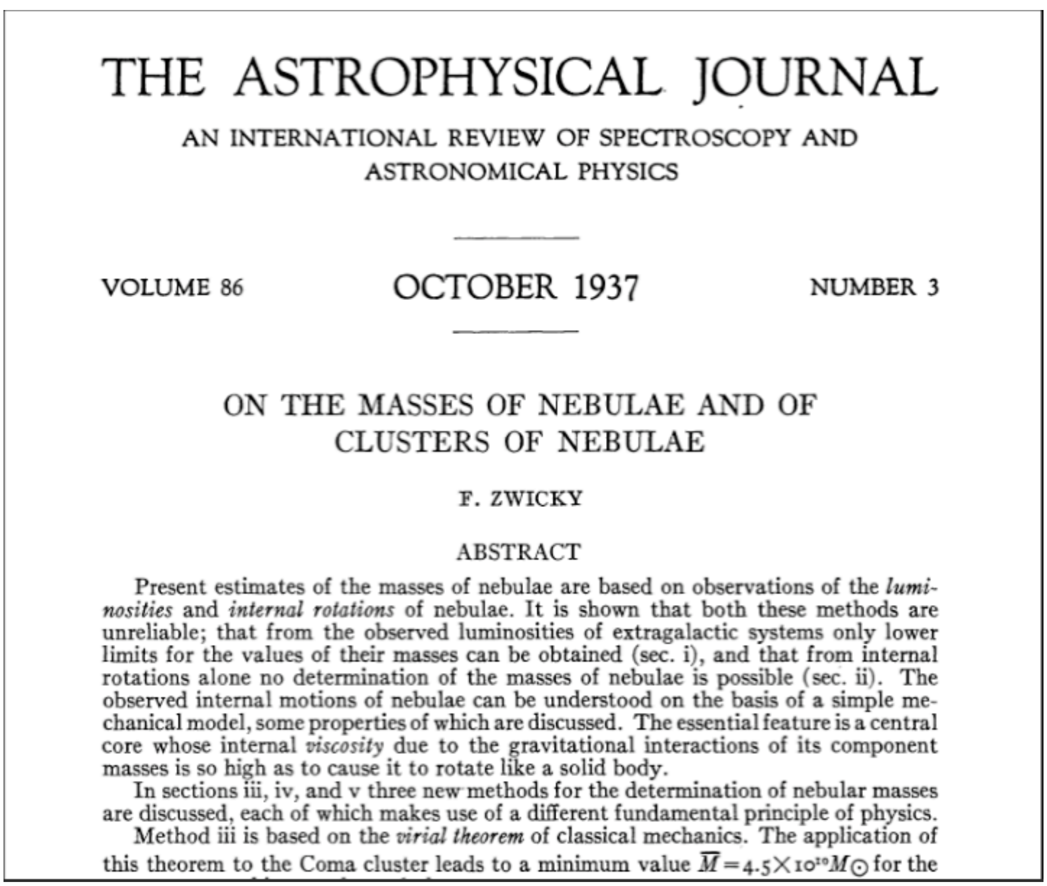




A Bit of History

- 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 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 (cf. Rood et al 1972, and the detailed study of the Coma cluster (Kent and Gunn 1982) 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.


THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 86 OCTOBER 1937 NUMBER 3

ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

ABSTRACT

Present estimates of the masses of nebulae are based on observations of the *luminosities* and *internal rotations* of nebulae. It is shown that both these methods are unreliable; that from the observed luminosities of extragalactic systems only lower limits for the values of their masses can be obtained (sec. i), and that from internal rotations alone no determination of the masses of nebulae is possible (sec. ii). The observed internal motions of nebulae can be understood on the basis of a simple mechanical model, some properties of which are discussed. The essential feature is a central core whose internal *viscosity* due to the gravitational interactions of its component masses is so high as to cause it to rotate like a solid body.

In sections iii, iv, and v three new methods for the determination of nebular masses are discussed, each of which makes use of a different fundamental principle of physics.

Method iii is based on the *virial theorem* of classical mechanics. The application of this theorem to the Coma cluster leads to a minimum value $\overline{M}=4.5\times10^{10}M_{\odot}$ for the

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 of 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.

Yet Still More History

the first all sky x-ray survey, (Uhuru 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.

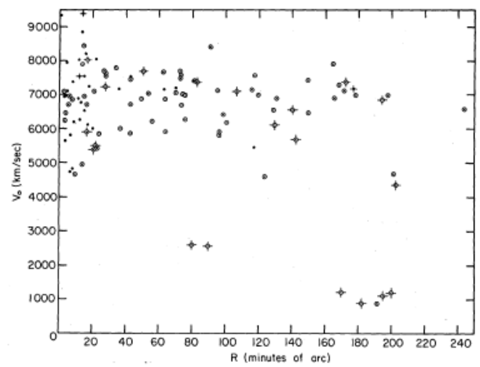
The rarity of optically selected clusters, ~1 per 10 sq deg, and the similarly low areal density of the high galactic latitude Uhuru x-ray sources of ~1 per 100 sqe deg indicated that the presence of an Abell cluster inside an x-ray error box < 1 square degree was statistically unlikely (Bahcall and Bahcall 1975) and allowed a high certainty of identification

Optical Cluster Surveys

- Abell (1958)
  - All-sky, 4073 clusters z < ~0.25 (*part* of his PhD thesis!), POSS
  - Zwicky (1961-68)
- Red-sequence Cluster Survey (RCS; Gladders & Yee 2005)
  - 72 deg^2, 956 clusters, z < 1 (CFHT, CTIO)
- SDSS surveys(2007+)
  - Max BCG: 7400 deg^2 ~10,000 clusters, z < 0.3
  - Others (using photo-z): z < 0.6
- Future
  - Dark Energy Survey (DES) 5000 deg^2 10^5 clusters
  - スミレ (SuMIRe) (Subaru

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



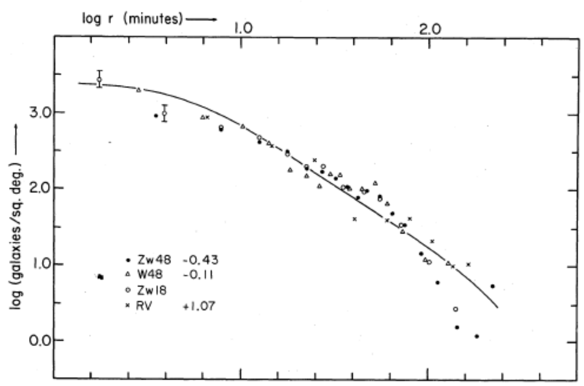


FIG. 5.—Surface densities, corrected for backgrounds given in table 2. For this fitting, logarithms of

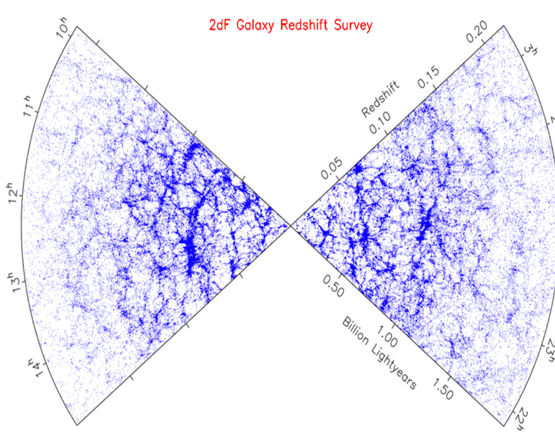
Rood 1972- velocity vs position of galaxies in Coma

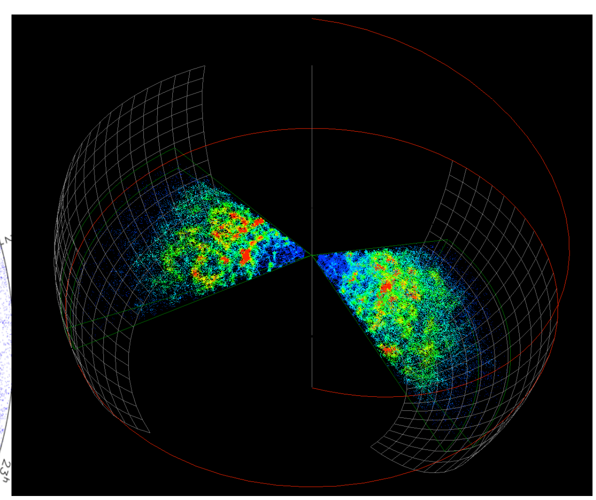
Surface density of galaxies

Paper is worth reading ApJ 175,627

Cosmic Web

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

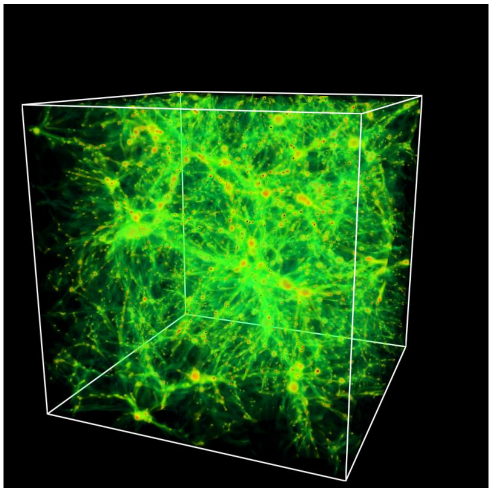


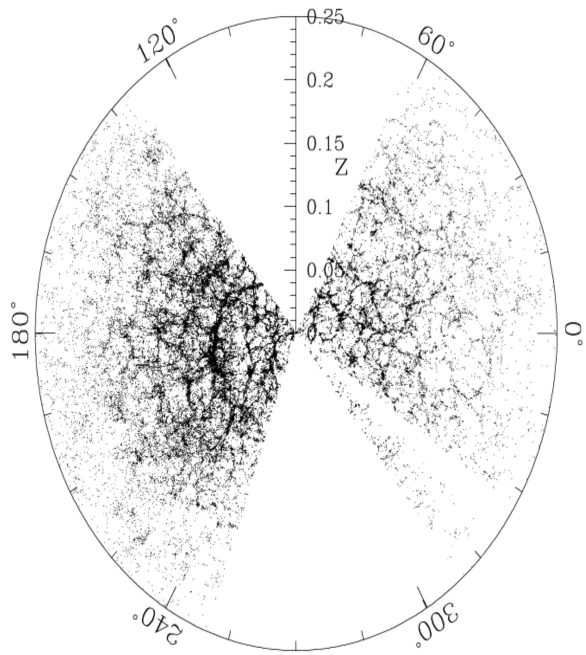


Cosmic Web (again)

- 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)

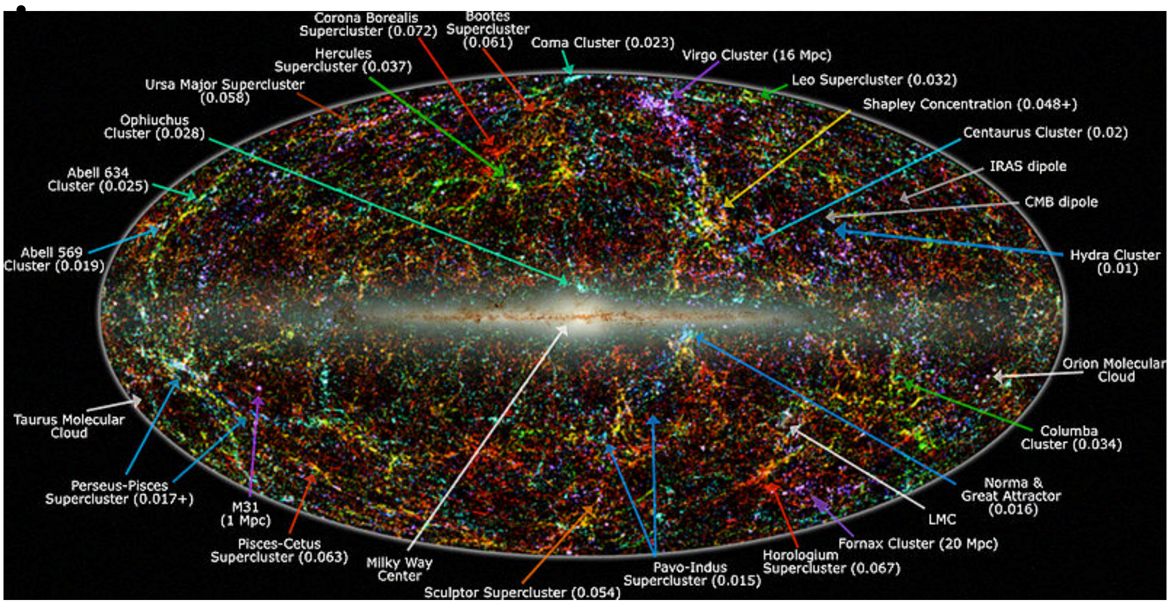




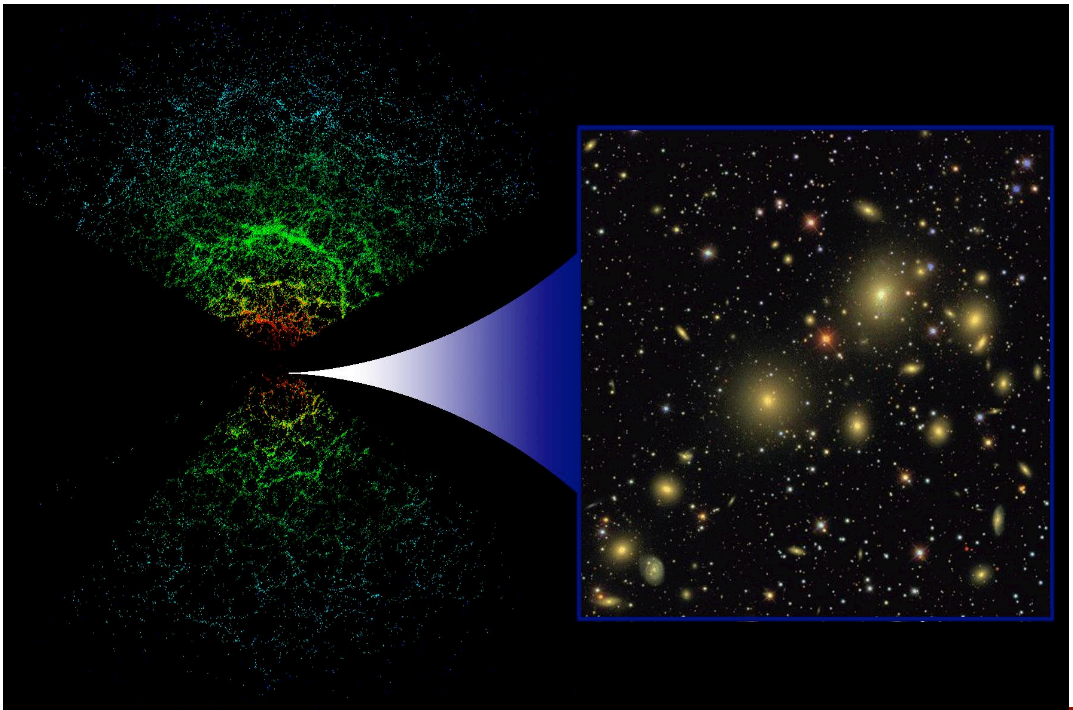
Large−Scale Structure sample10

Map of the Local Universe

•

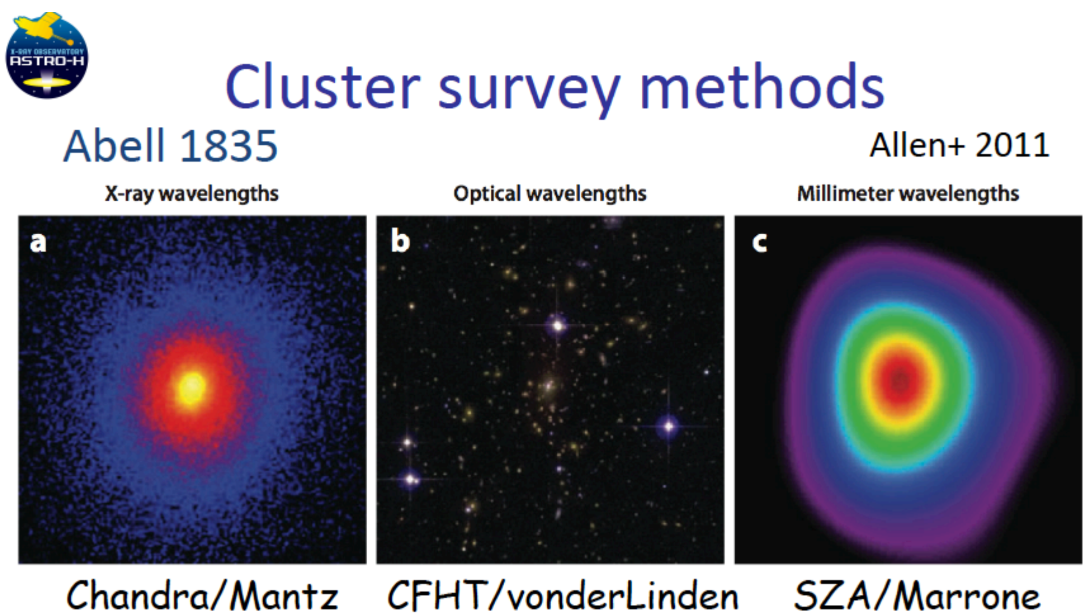


2MASS map of the local universe- < 1 billion light years



- SDSS map of the universe < 6 billion light years

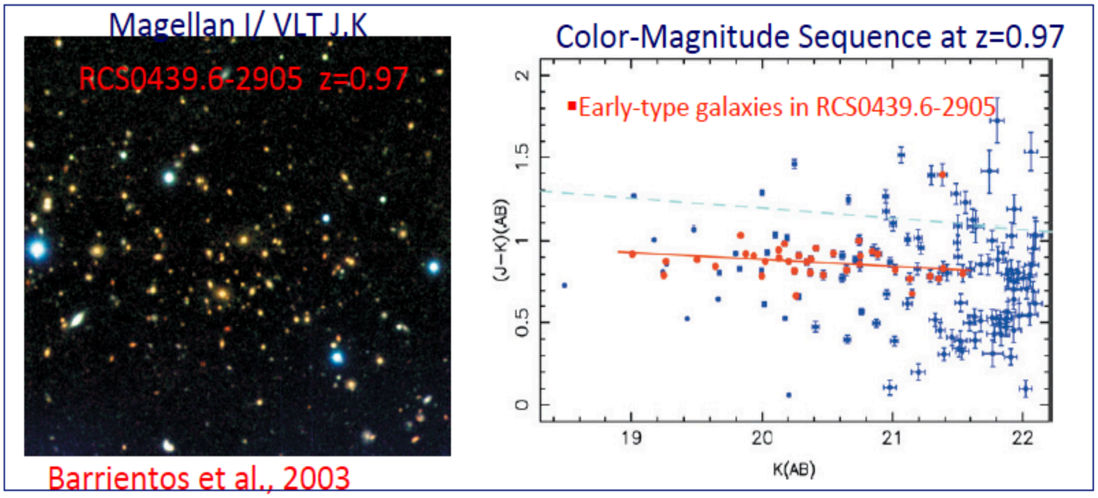
dark matter appears in all 'big' things in the universe including, on average, the universe itself



In x-ray and mm clusters show up as extended (at all z) 'blobs' almost unique signature-
Because of intrinsic large size and L cosmology clusters are 'bigger' than 2' at all redshifts
Bautz 2011

Bautz 2011

Optical Surveys



Method: Use the cluster red sequence

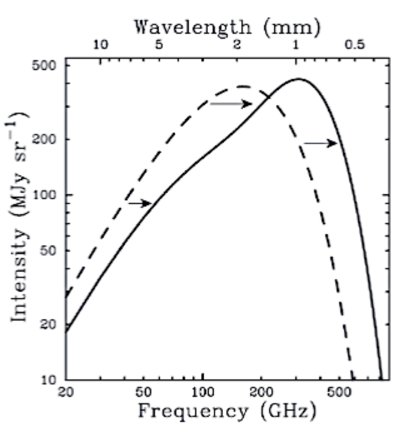
- Early-type cluster galaxies are redder than foreground objects
- Survey sky in 2+ bands; make images in several color 'bins'
- Search for galaxy over-densities within each color bin
- Color of red-sequence also provides estimate of z

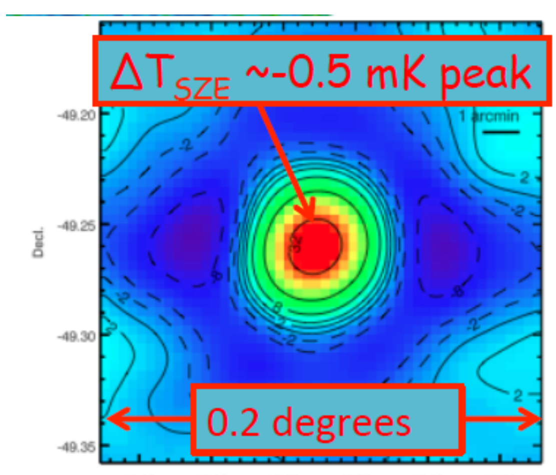
S-Z Cluster Selection

- Main problem is low amplitude

since CMB δT~0.2mK

At low frequencies shows up as a 'hole' in CMB- much more later

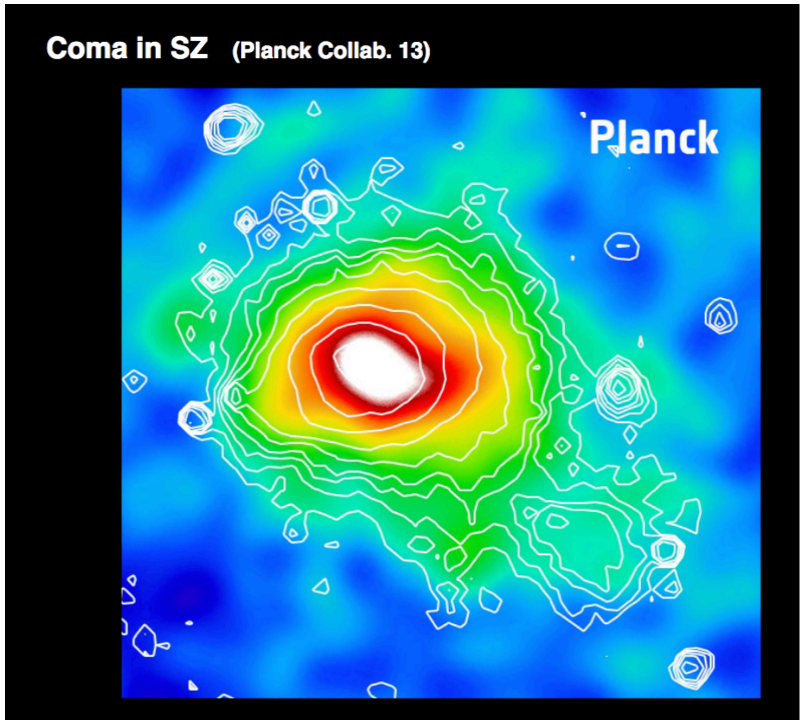




SPT: Williamson et al 2011

Bautz 2011

- S-Z image of Coma cluster in color, x-ray contours in white



History of Science Comment

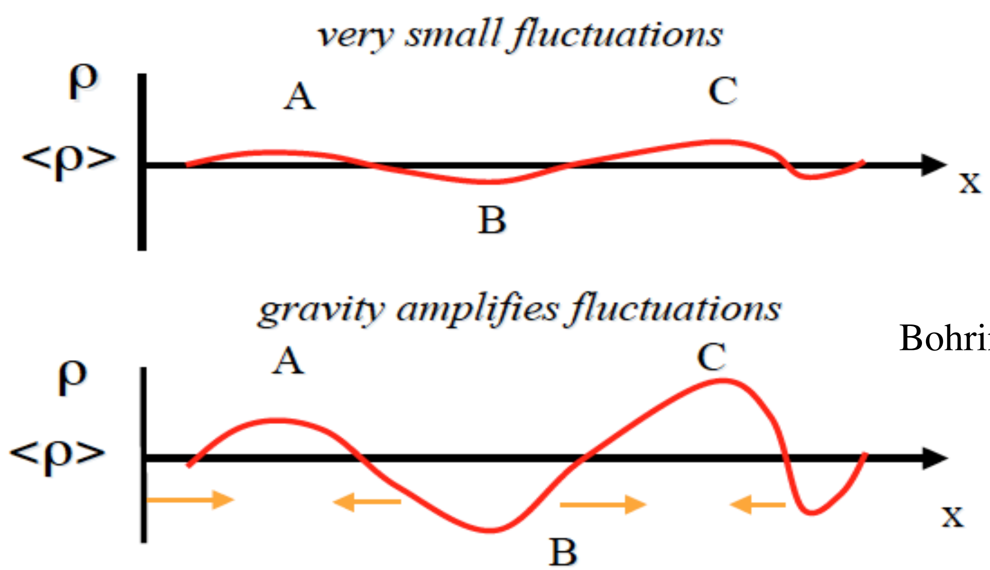
- It is rather surprising to realize not only is most of the material in the universe dark and non-baryonic, but that most of the baryons in the universe do not shine in optical light.

- 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.

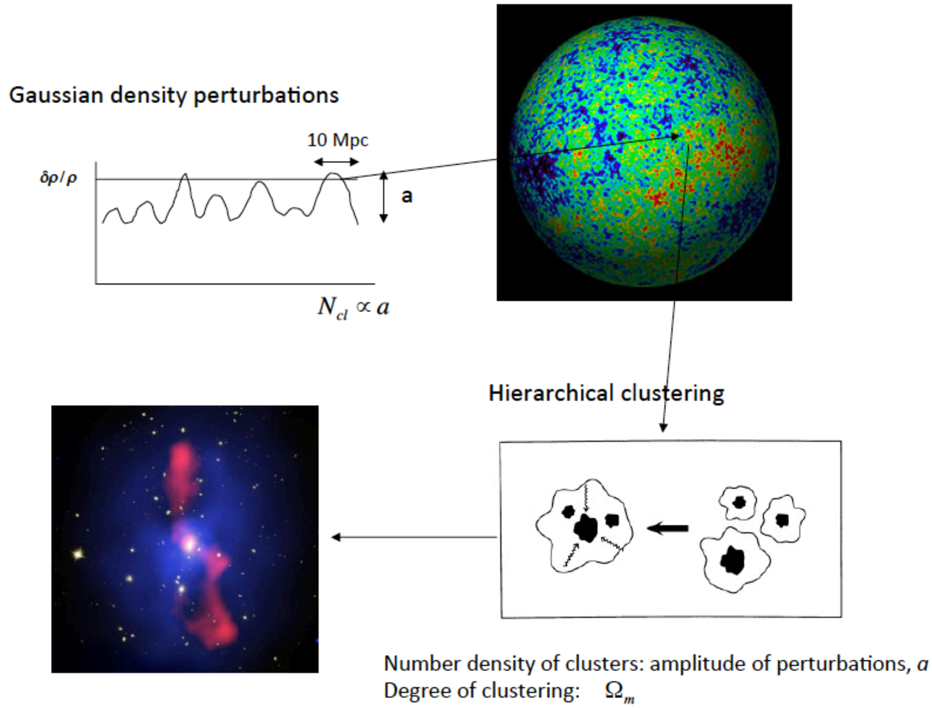
Basic Ideas

- 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.

Gravitational Instability: Origin of Cosmic Structure



Bohringer 2001



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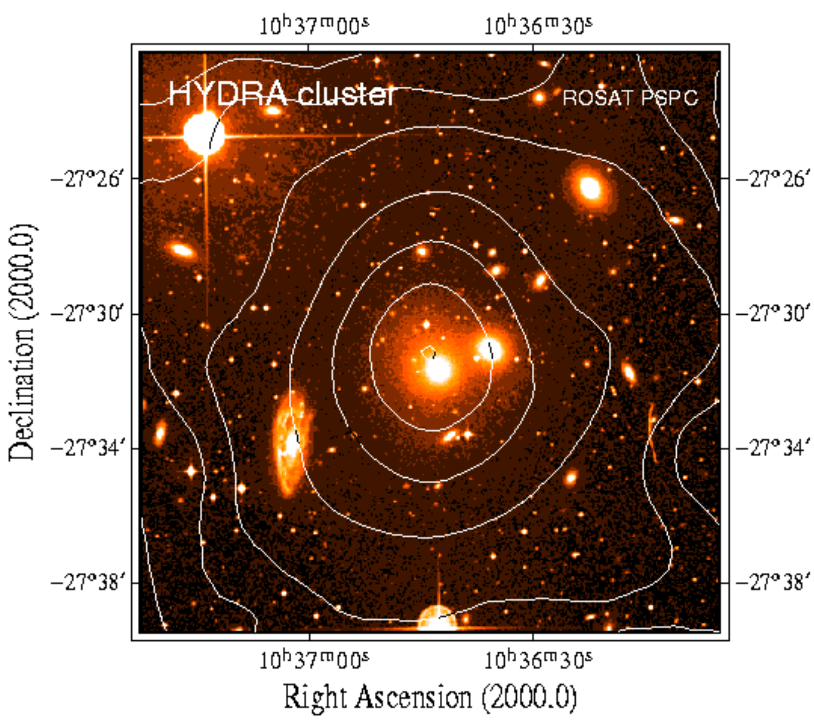
Optical image with X-ray isointensity contours



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)
- Fermi data have shown that clusters are NOT luminous γ-ray sources (ApJ 787, 18 (2014))

Box 3. ICM CHARACTERISTIC PARAMETERS				
Temperature $10^{7\text{-}8}$K	**Density** $10^{2\text{-}4}$ m^{-3}	**Sound speed** ~1000 km/s	**Particle mfp** ~ few kpc	**Plasma scattering length** >~ 10^8 m
Magnetic field <0.1-1 nT	**Plasma Beta** ~100	**Alfven speed** 20-100 km/s	**Magnetic field typical scale** ~10s kpc	**CR Diffusion time, ~Mpc** $10^{10.5}$ y @1GeV

Alfven speed:speed at which hydromagnetic waves can be propagated in a magnetically dominated plasma. $v_A = B / (\mu_o * \varrho)1/2$
Where, v_A = Alfven Speed, B = Magnetic Flux Density,
μo = Permeability Of Free Space, ϱ = Plasma Mass Density

Beta of a plasma, β, is the ratio of the plasma pressure ($p = n\, k_B\, T$) to the magnetic pressure ($p_{mag} = B^2/2\mu_0$).

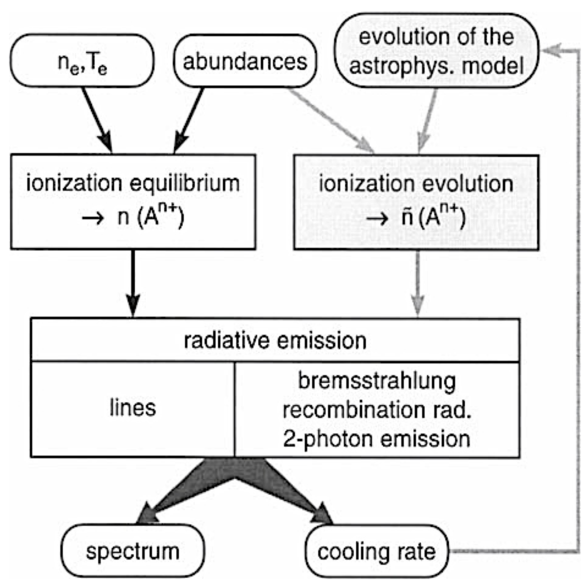
mfp=mean free path

Rudnick 2019

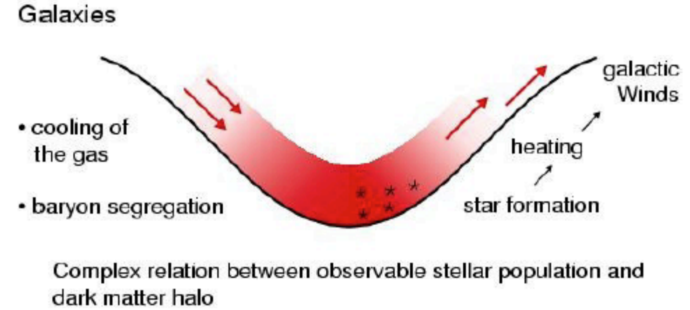
Why is Gas Hot

- 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 infall (e.g. rain)

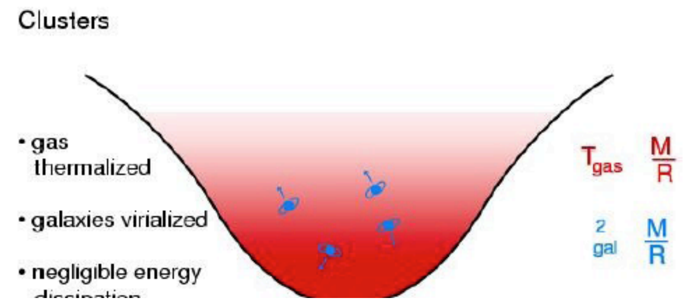
  BOTH



Comparison of galaxies and clusters as Dark Matter Halos

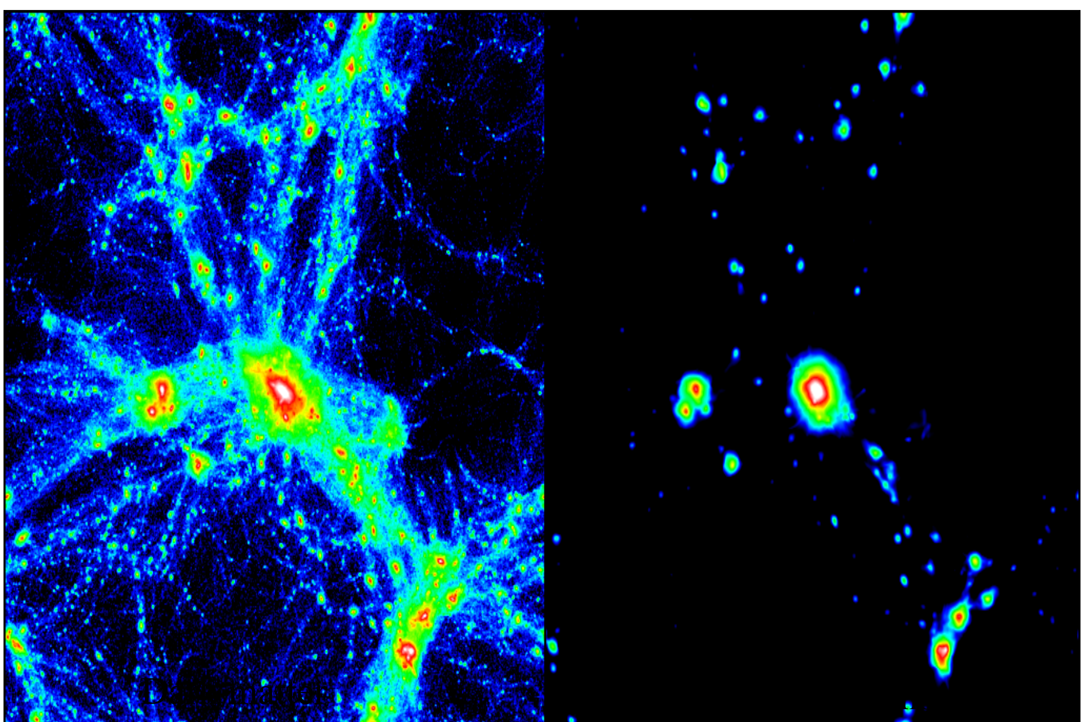


Bohringer



The intracluster gas is heated when the cluster forms and does not cool – it still reflects the potential depth.

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,

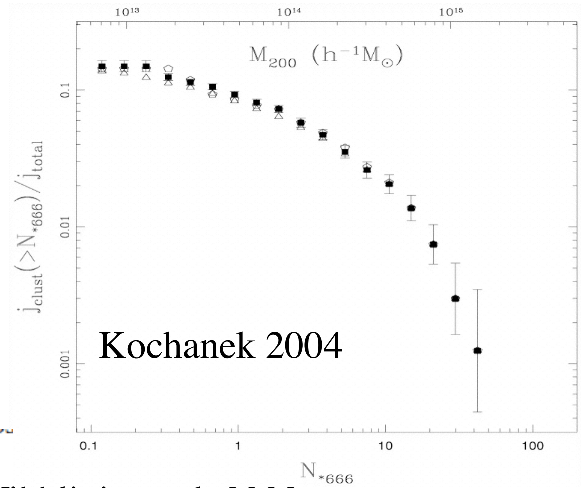


simulation

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.



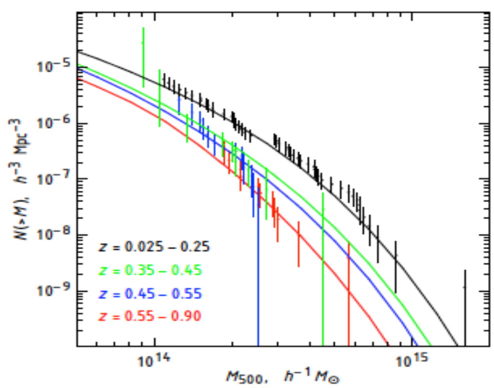
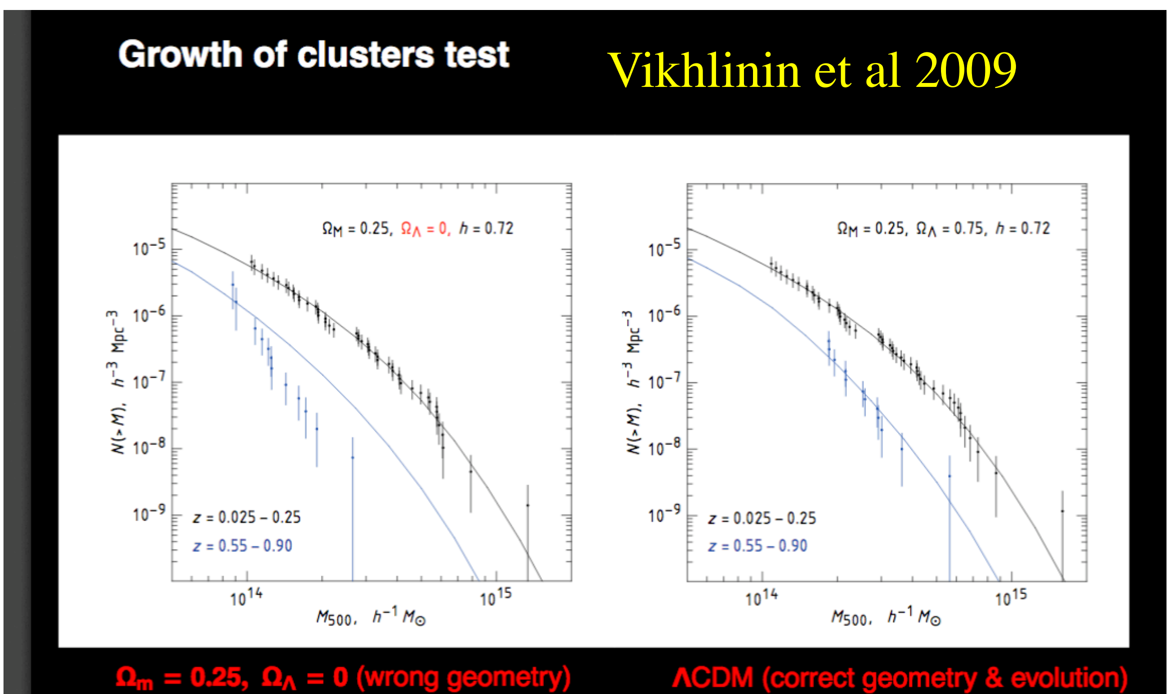


Fig. 18.— Same as Fig. 16 but the high-z sample is split into three redshift bins.

Vikhlinin et al 2009

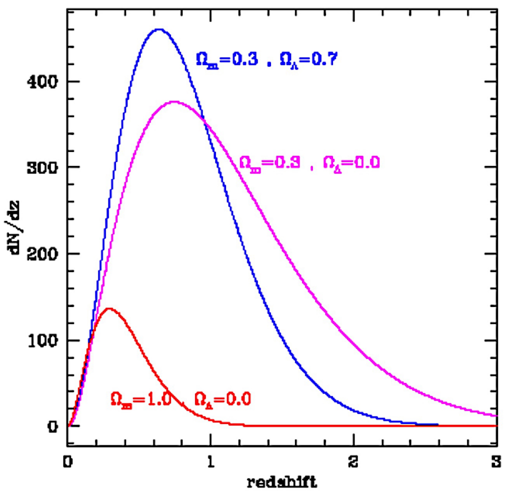
The mass function shows that massive clusters are rare ~10^{-6} Mpc3



Number of clusters per unit mass/volume as a function of z strong function of cosmological parameters

Theoretical Mass Function

- In a high density universe, clusters are just forming "now", expect few distant ones
- In a low density universe, clusters began forming long ago, and we expect to find many distant ones
- •Evolution of cluster abundances: – Structures grow more slowly in a low density universe, so see less evolution when we probe to large distances
- See Arnaud, M. [2017AN....338..342A]



Cluster Luminosity Function Evolution

- Solid line is the predicted relationship using a scaling between cluster mass and x-ray luminosity and ΛCDM

Klein et al 2018
1812.09956.pdf

New RASS Galaxy Clusters to z ~ 1 19

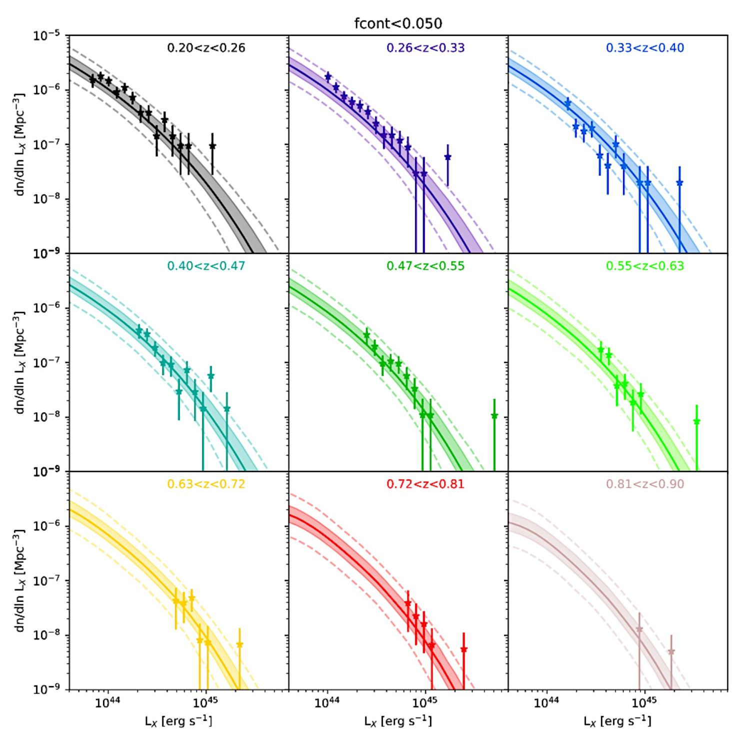


Figure 22. In each of nine redshift bins, we plot the completeness corrected luminosity function measurements (points with error bars)

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
  - 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)

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.

What we try to measure II

If we can measure the temperature and density at different positions in the cluster <u>then assuming the plasma is in hydrostatic equilibrium</u> 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.

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'.
Lowest mass clusters at z=2 flux ~$8x10^{-17}$ ergs/cm^2/sec above limit of Chandra deep surveys
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See 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

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 ?

Next Presentation

Please read Hitomi Collaboration 2017, Nature, 551, 478

Solar abundance ratios of the iron-peak elements in the Perseus cluster

Discuss the importance of sensitivity, resolution and bandpass, atomic physics and the physics of SN models.

Also see
arXiv:1806.00932
Constraints on the Chemical Enrichment History of the Perseus Cluster of Galaxies from High-Resolution X-ray Spectroscopy: A. Simionescu et al

this paper is very detailed and contains description of the instruments and analysis procedure and lots more of the SN physics and comparison to other astrophysical systems.