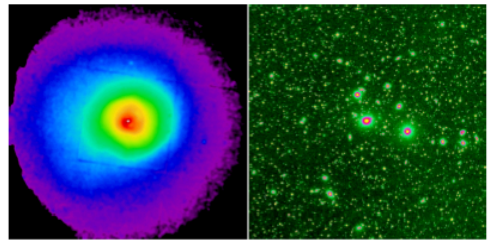
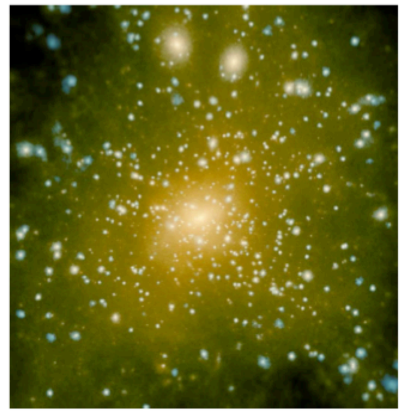
Clusters of Galaxies

Ch 4 Longair

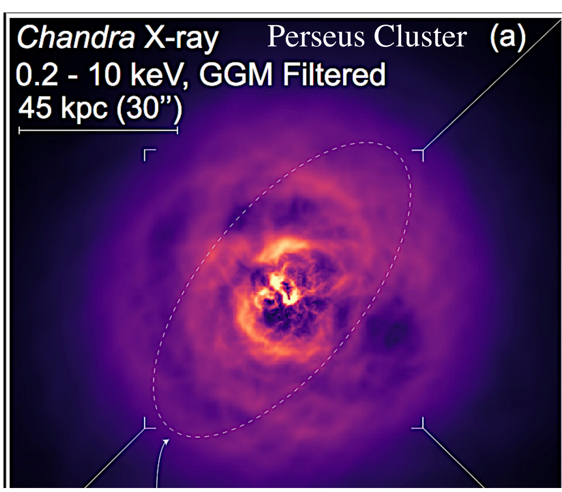
- Clusters of galaxies are the largest gravitationally bound systems in the Universe.
- At optical wavelengths they appear as over-densities of galaxies with respect to the field average density: hundreds to thousands of galaxies moving in a common gravitational potential well (a smaller assembly is defined a galaxy group).
- The typical masses of clusters of galaxies are ~ 10^{13}- $10^{15}M_\odot$ (10^{46} - 10^{51} gm) and "sizes" ~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
- see Rudnick arXiv:1901.09448 for nice intro

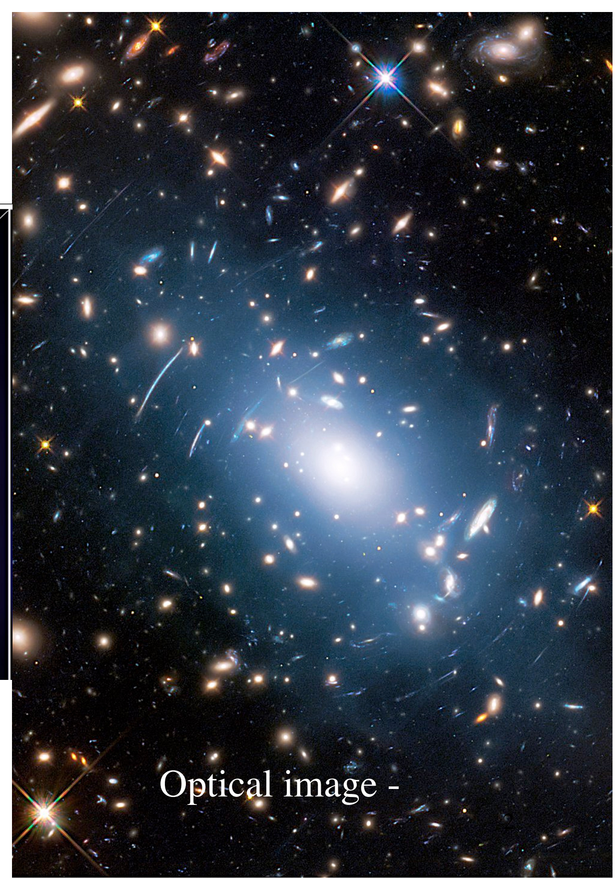


X-ray optical
Perseus cluster d~73Mpc



Dark matter simulation
V.Springel





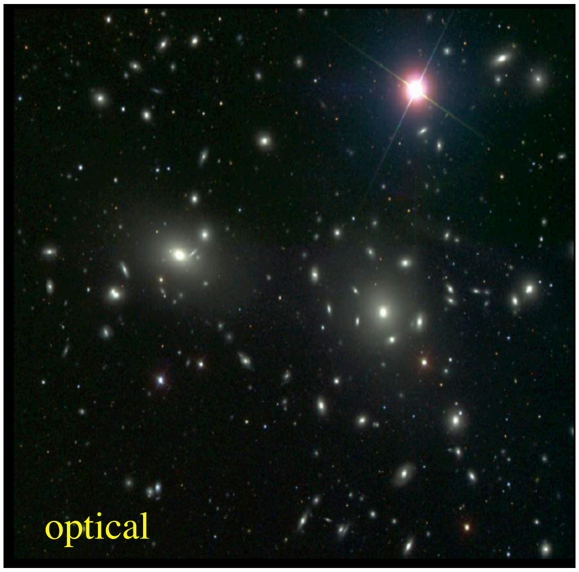
X-ray and Optical Combined

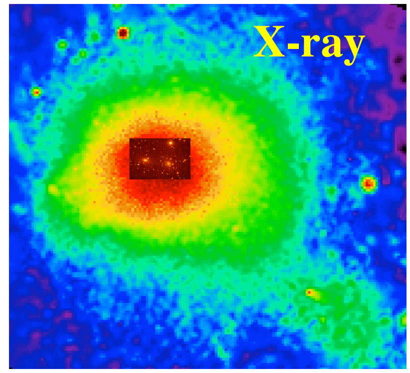
Clusters of Galaxies

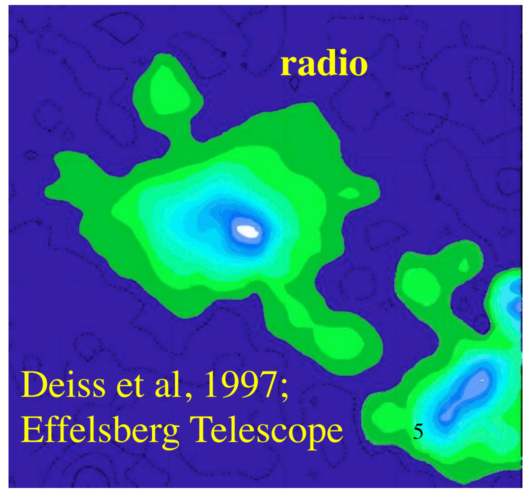
- High Energy Objects - most of the *baryons* are in the hot ($kT \sim 10^7$-10^8k) gas.
- The x-ray luminosity is 10^{42}-10^{46} ergs/sec
  - with modern instrumentation x-ray emission can be detected at z>1.7 and the S-Z effect (later) at even higher redshifts.
- the hot gas is enriched in heavy elements (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
    - (see Space Science Reviews: arXiv:1811.01967 Enrichment of the hot intracluster medium: observations F. Mernier, et al and arXiv:1811.01955 Enrichment of the hot intracluster medium: numerical simulations V. Biffi, F. Mernier, P. Medvedev)
- Sample will change radically with eRosita - expected todetect about 100,000 galaxy clusters (Pillepich et al. 2012,2018; Clerc et al. 2018). For a small subsample (~2 000 clus-ters) precise gas temperatures will be measured

Coma Cluster

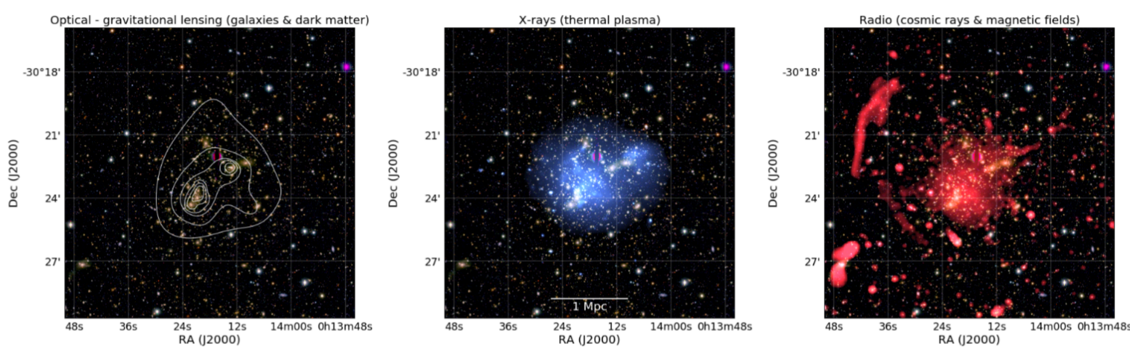
- The apparent nature of clusters depends on the wavelength one looks at





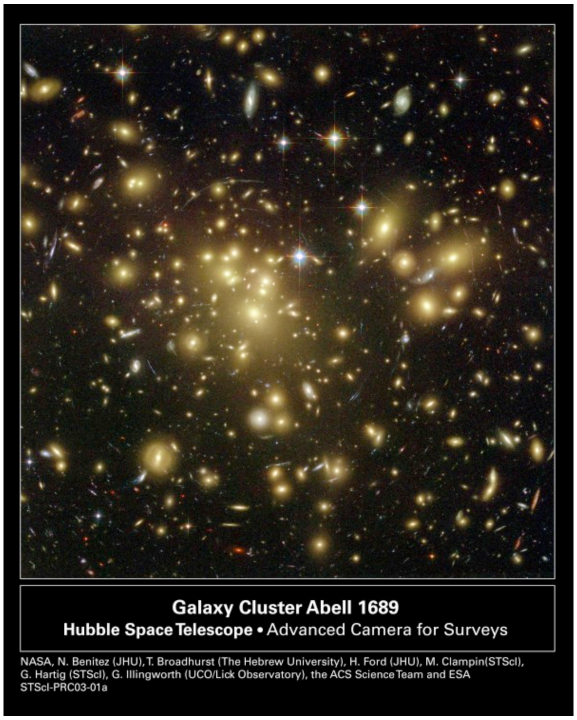


Optical, X-ray Radio Images

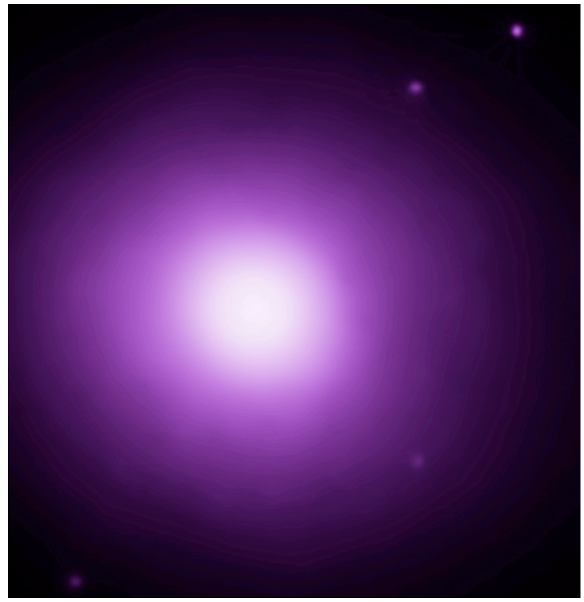


optical x-ray radio

- Abell 2744 (Pearce et al 2017)
  - left panel optical- stars, white contours surface mass density from grav lensing
  - middle x-ray emission –hot gas
  - right panel radio- tracing cosmic rays and magnetic field

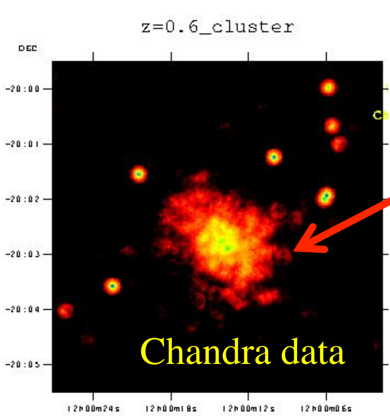


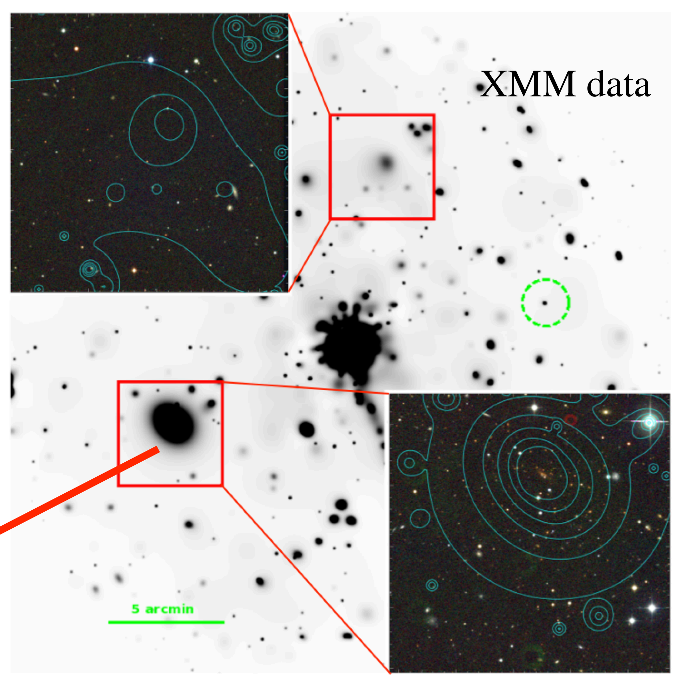
Chandra Image of Abell 1689



X-ray and Optical Images of High Z Clusters

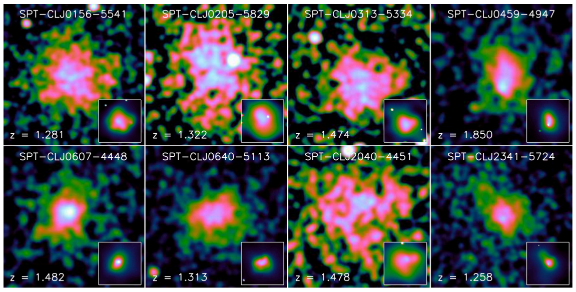
- Chandra has the spatial resolution and sensitivity to 'map' clusters at any redshift and XMM has the sensitivity and FOV to find them



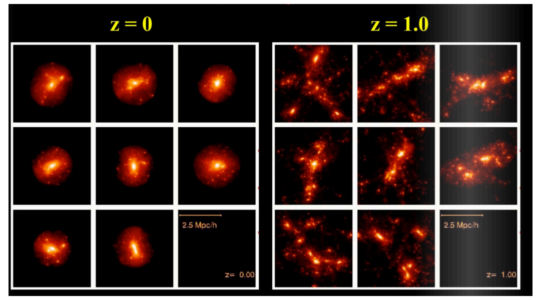


X-CLASS 2305 (z=0.62)

Clusters Are Evolving



Real High Z Clusters (McDonald et al 2018)



Theoretical models of cluster evolution

A Bit of History-

see https://ned.ipac.caltech.edu/level5/Biviano2/Biviano_contents.html

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

"W. Herschel's description of the Coma cluster of galaxies

``that remarkable collection of many hundreds if nebulæ which are to be seen in what I have called the nebulous stratum of Coma Berenices"

- 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.

A Bit of History

- The development of large catalogs of clusters (Abell 1958, Zwicky and Herzog 1963)

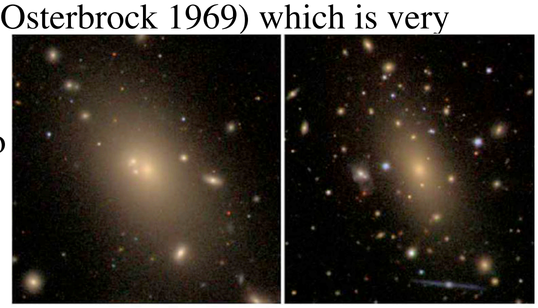
based on eye estimates of the number of galaxies per unit solid angle

strict criteria for the Abell catalog proved to be a good guide to the physical reality of the objects **-60** years later we are still using the Abell catalog.

- 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.

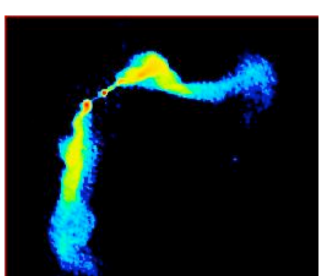
More History

- "Rich" clusters (that is those with many galaxies inside a fixed metric (Abell) radius) have 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) .



NGC 6166 cD A2199 IC 1101 cD A2029

radio image of a WAT sources



https://blog.galaxyzoo.org/2014/01/16/more-information-on-tailed-radio-galaxies-part-1/

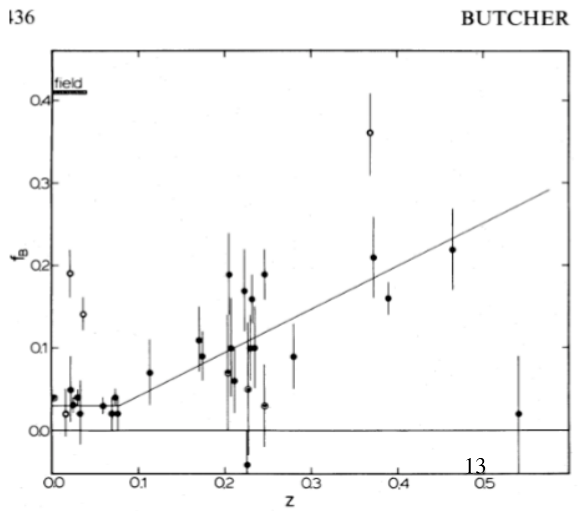
More History

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 reason for this was unknown (now known to be due

to due to vigorous episodes of star formation in a subset of the cluster members.)

fraction of galaxies that are blue vs redshift



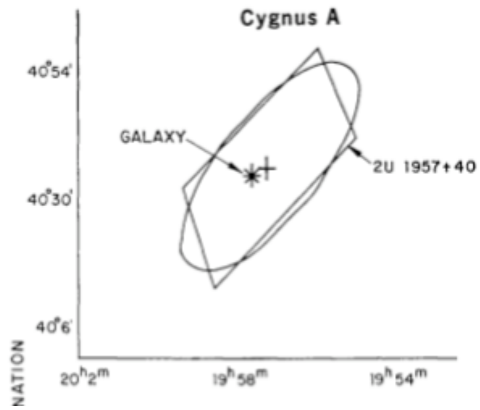
Even More History

- **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 and the Coma cluster the most massive low redshift cluster.

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.

- First all sky x-ray survey, (Uhuru satellite Kellogg et al 1971,Gursky et al 1972) established x-ray emission from clusters as a class-see ARA&A Gursky and Schwarz "**Extragalactic X-ray sources**" .
  - Even the relatively low angular resolution (~0.5x0.5 degree) 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.
- Uhuru's coarse angular resolution showed that the 4 nearest brightest cluster x-ray sources were extended (~1/2 degree in size).

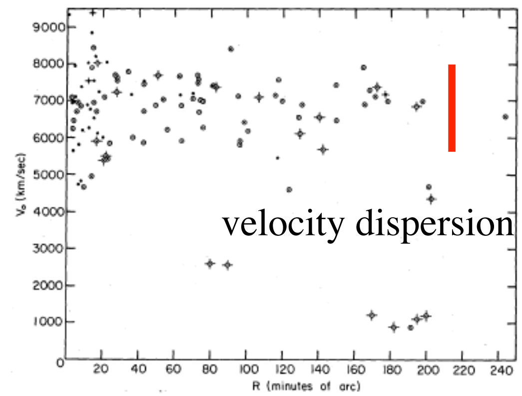
	SIZE angular	SIZE kpc	Lx (erg/sec)
ABELL 2256	35' ± 15'	2800	5×10^{44}
PERSEUS - NGC 1275	35' ± 3'	740	3×10^{44}
COMA	36' ± 4'	1050	2×10^{44}
CEN - NGC 4696	37' ± 8'	500	2×10^{43}
VIRGO - M87	50' ± 5'	200	7×10^{42}

- 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

- So far clusters are NOT γ-ray sources

The First Detailed Analysis of Mass

- 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 (M/L) of ~230. $M \sim \sigma^2 R/G$ *(math on board)*
- Since "no" stellar system had M/L>12 dark matter was necessary



Rood 1972- velocity vs position of galaxies in Coma

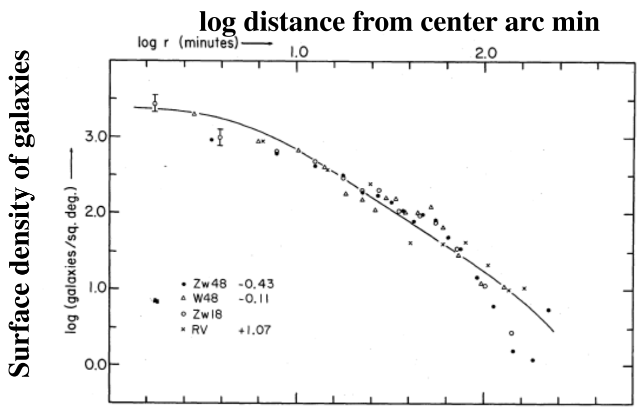


FIG. 5.—Surface densities, corrected for backgrounds given in table 2. For this fitting, logarithms of

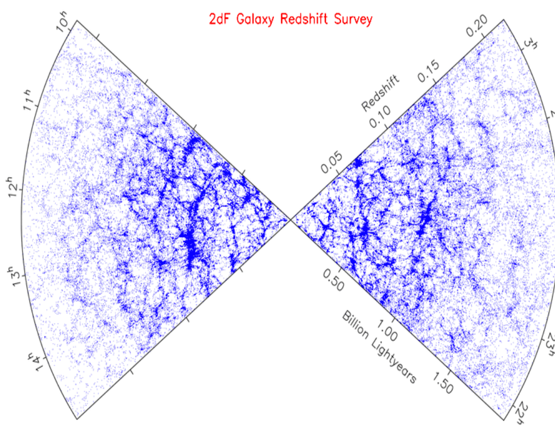
Paper is worth reading ApJ 175,627 17

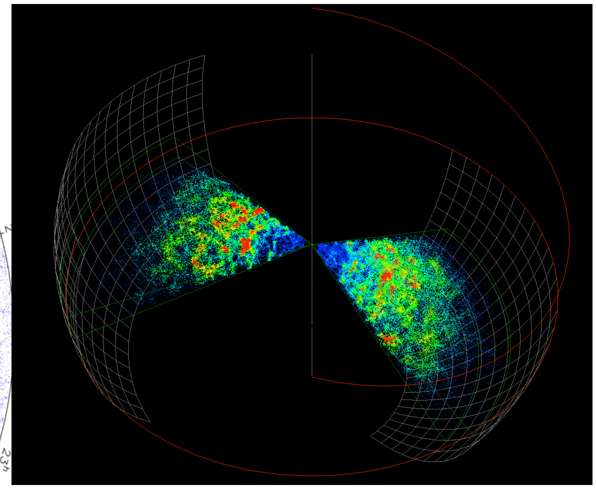
It is rather surprising to realize not only that most of the material in the universe is dark and non-baryonic, but that most of the baryons in the universe do not shine in optical light.

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

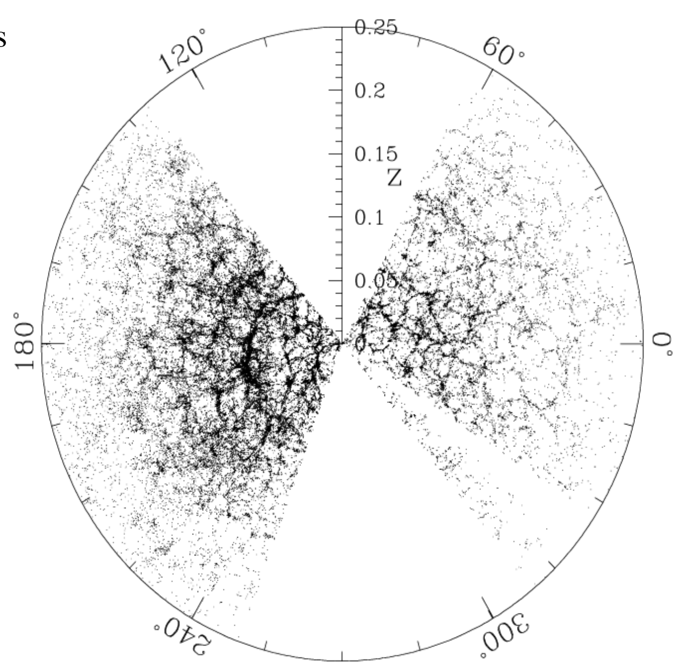


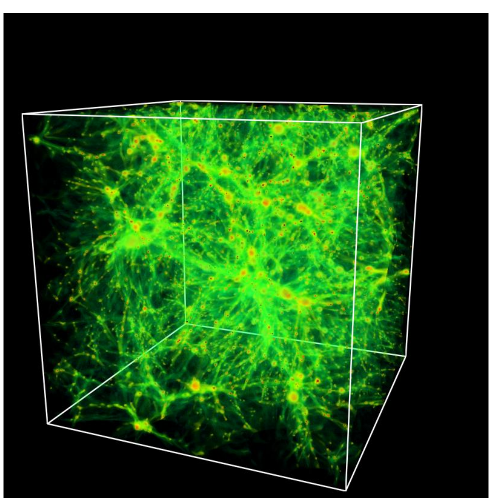


Cosmic Web (again)

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

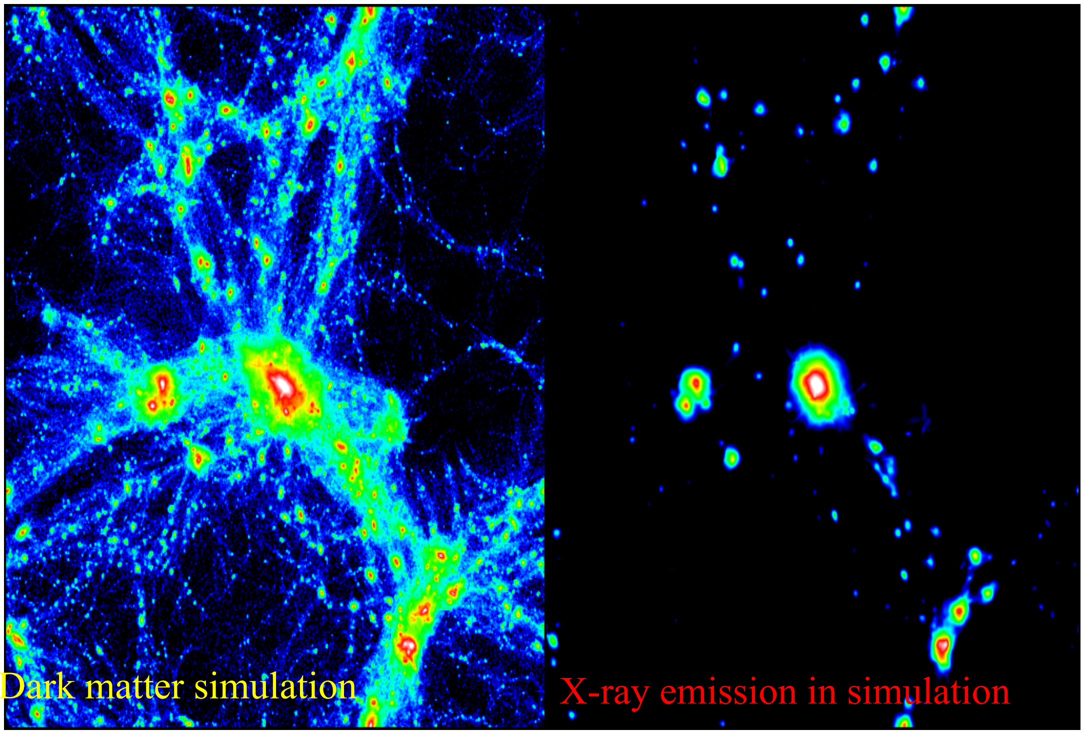
Blanton et al. (2003) (astro-ph/0210215)





theoretical simulation of
large scale structure- clusters are red

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,



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.**
  - lensing
  - hydrostatic equilibrium
  - velocity dispersion

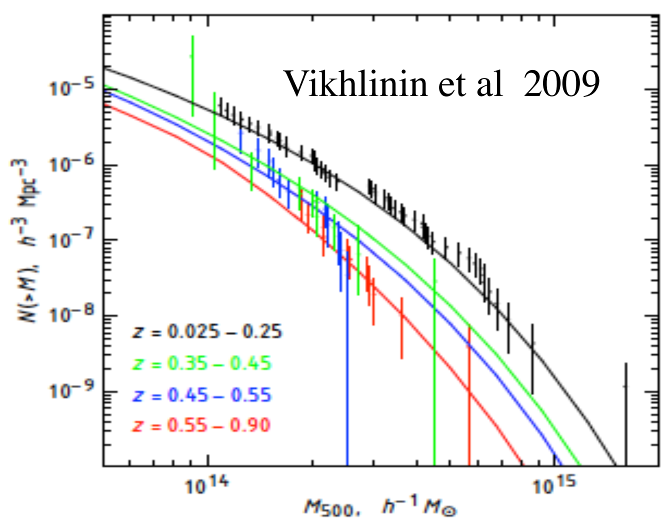
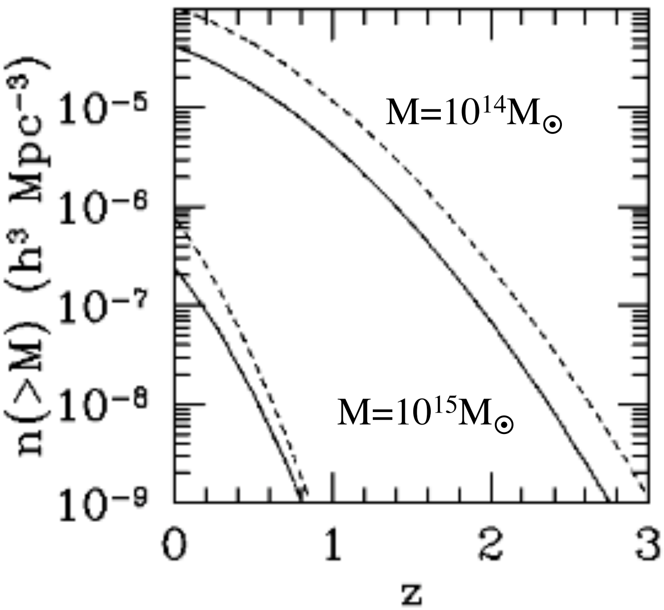


FIG. 18.— Same as Fig. 16 but the high-z sample is split into three redshift bins.

Evolution of mass function of clusters over cosmic time
massive clusters are rare ~10^{-6} Mpc^3 and are rarer in the early universe

Cluster Evolution as a Function of Cosmology

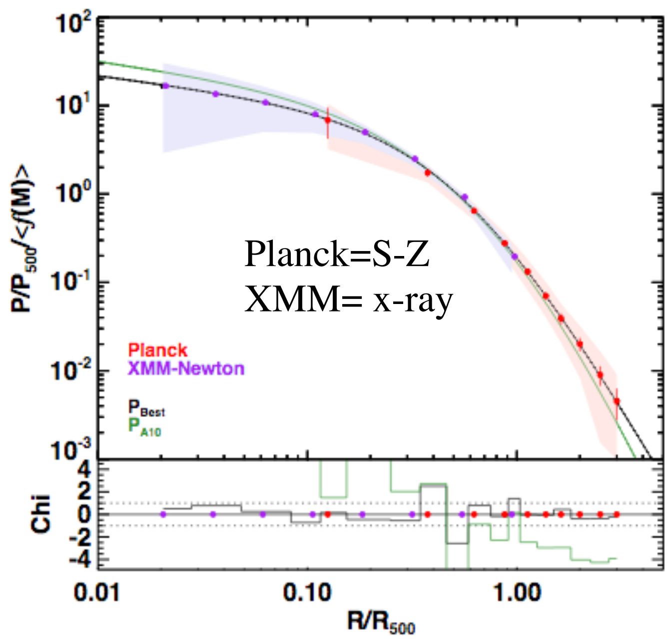
- The number of clusters as a function of mass and redshift is a strong function of cosmological parameters (e.g. Hubble constant H_0, matter density Ω_m, cosmological constant Ω_Λ, amplitude of fluctuations σ_8)
- Notice that there are predicted to be very few massive clusters in the high z universe.



(Ω_m, Ω_Λ,)=(0.3, 0.7) (solid) and (0.5, 0.5) (dashed) Carlstrom et al 2002 .

How is the Mass Partitioned

- If we use hydrostatic equilibrium we need to measure the density and temperature (pressure) profile
- Observations of the S-Z effect have extended this to very large radii where most of the mass lies



Chemical Abundances in Clusters- Not In Longair

Why are they interesting ?

What can we learn about how and when the elements were created, what processes injected the metals into the IGM

Which stars produce the metals, where and when

What is the chemical abundance

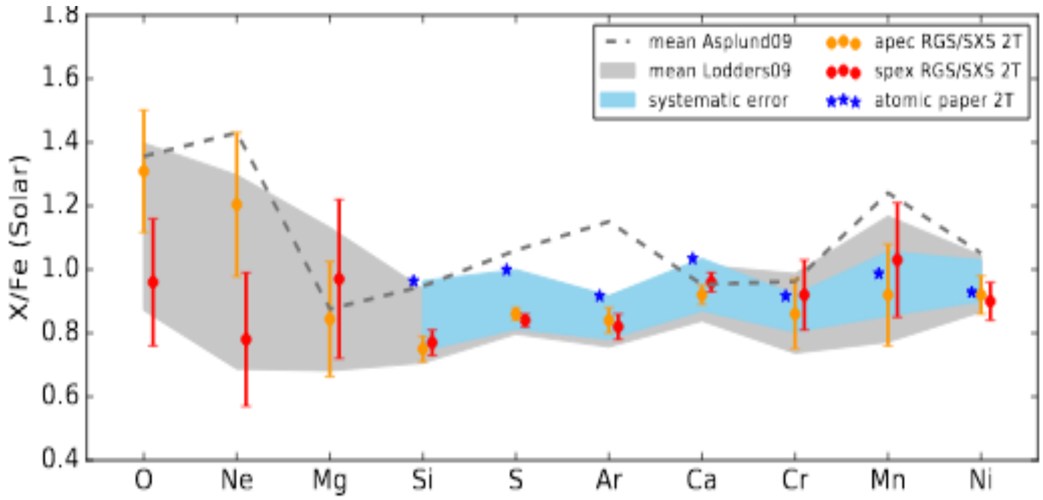
arXiv:1811.01967

Enrichment of the hot intracluster medium: observations

F. Mernier et al 2018

Chemical Abundances In Clusters

- Remember:
  - 80% of the baryons are in the gas
  - We detect line emission in the x-ray band from atomic transitions in H, He-like ions
  - Clusters are roughly big closed boxes
- Use these data to measure the chemical abundance of the gas
  - The strength of the lines depends on
    - Atomic physics
    - # of ions of a given species
    - Temperature
  - The number of protons (H atoms) depends on the strength of the bremmstrahlung continuum
  - The ratio of the number of ions to the number of protons is the abundance with respect to hydrogen
  - the gas is in 'coronal' equilibrium



Comparison with

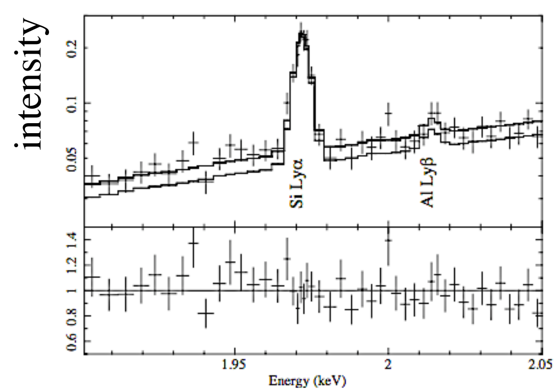
Stars in elliptical galaxies

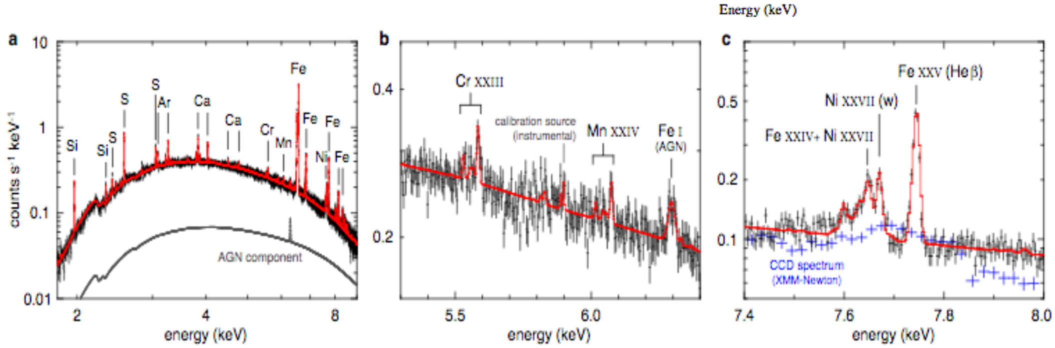
Milky Way stars

Consistent with the abundance ratios of
proto-solar nebula (Lodders et al. 2009), low-mass
early type
galaxies (Conroy et al. 2014),
typical Milky Way stars
with near solar absolute metallicity

Chemical Abundance

- Quality of data- With the coming launch of XRISM in 2022 high quality spectra will be obtained for many clusters.
- So far only results from Perseus cluster.





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
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?

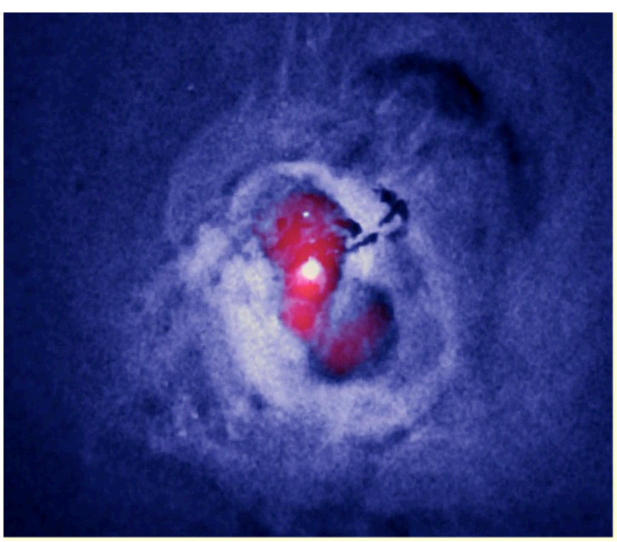
Why are Clusters Interesting or Important

Formation and evolution of cosmic structure

- The Cooling flow problem
- Interaction of radio sources and the hot gas

Center of Perseus Cluster
X-rays in blue
radio in red

Center of Virgo Cluster
Radio in red
X-rays in blue



Why are Clusters Interesting or Important

- 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

Plasma physics on the largest scales

•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

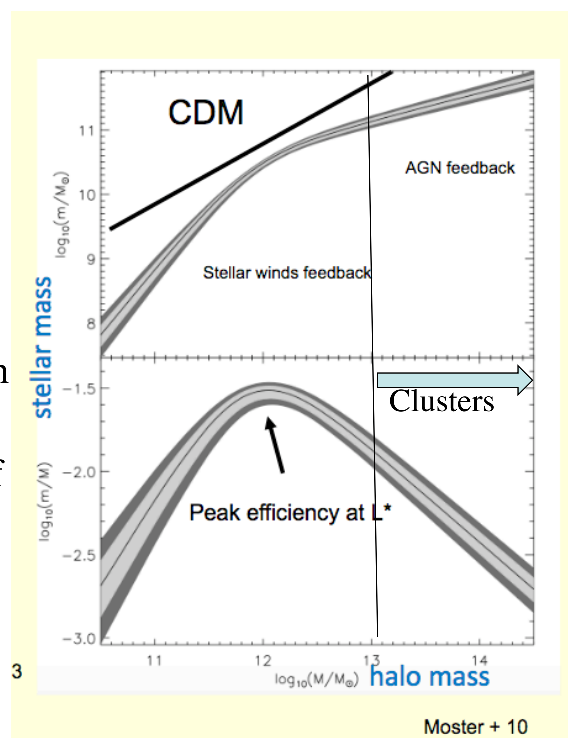
Particle acceleration

Cluster shocks source of highest E cosmic rays?

Certain types of radio sources only appear in clusters

Why are Clusters Interesting or Important

- Star formation
  - At low and high z
  - Why are cluster galaxies different than those in the field
  - Why is the fraction of mass in stars a strong function of the total mass??



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)