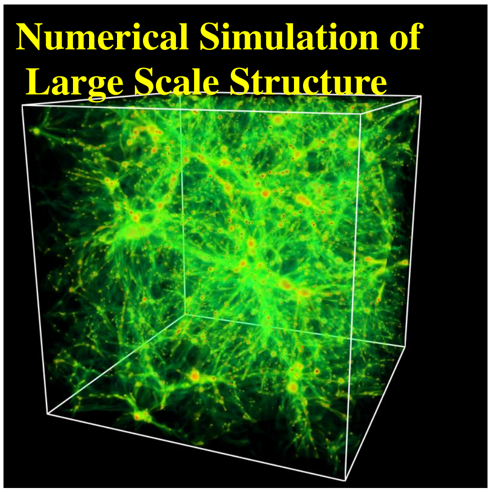
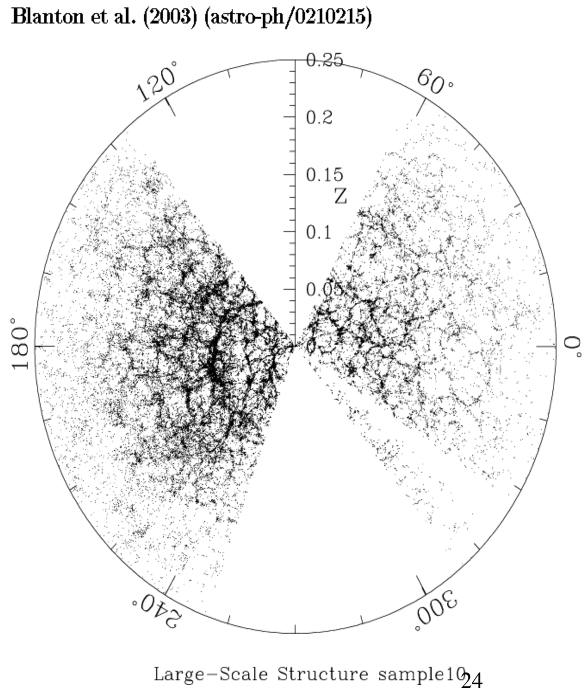
Cosmic Web (again)

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





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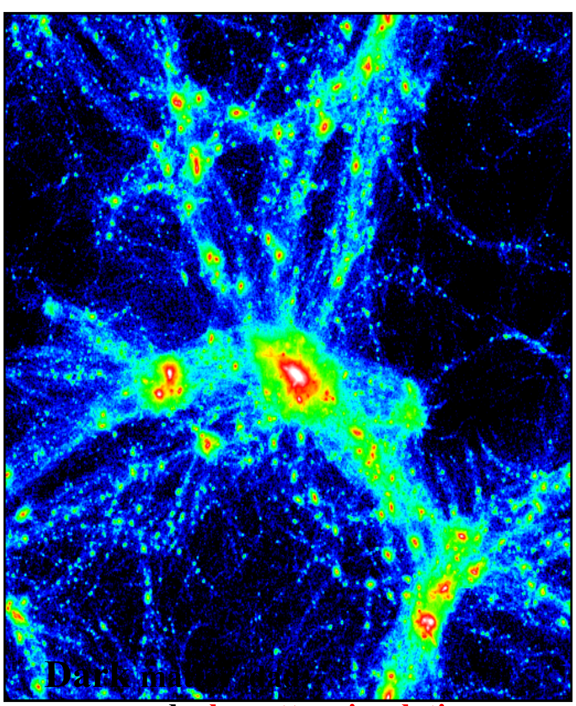
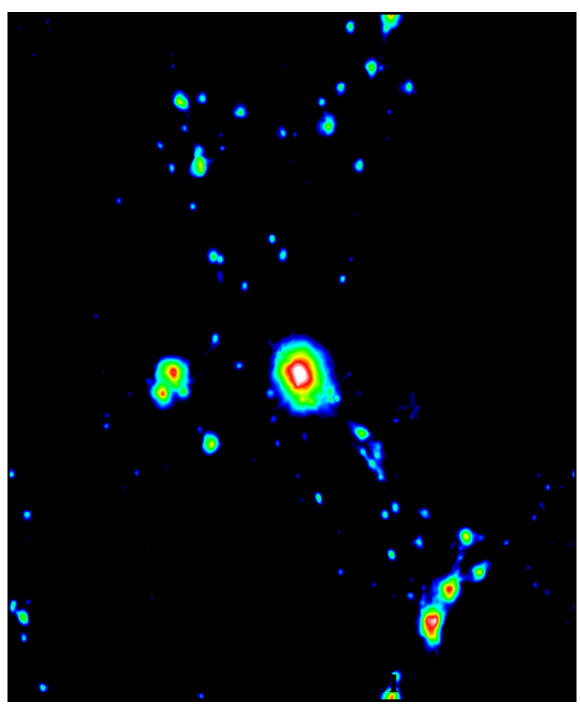
Comparison of dark matter and x-ray cluster and group distribution
every bound system visible in the numerical simulation is detected in the x-ray band -
bright regions are massive clusters, dimmer regions groups,



dark matter simulation



gas simulation

Dark Matter

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

1) high mass-to-light ratio.

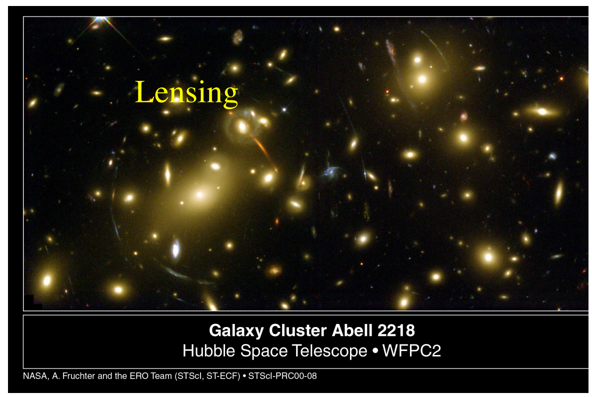
   estimate the cluster total mass by assuming that the member galaxies have become dynamically relaxed and that they are in an equilibrium configuration-the virial theorem) to obtain the virial mass

2) 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

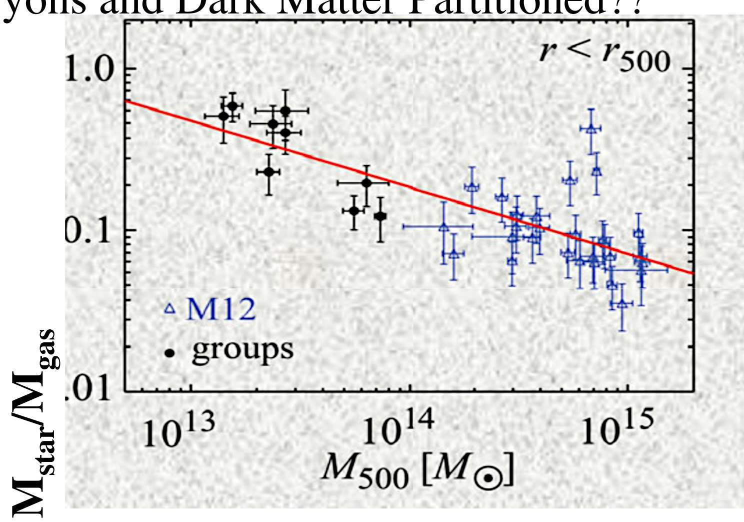
- **So a large quantity of matter not visible as stars**
  - X-ray emitting gas constitutes a portion- ~1/6th of this "missing mass".

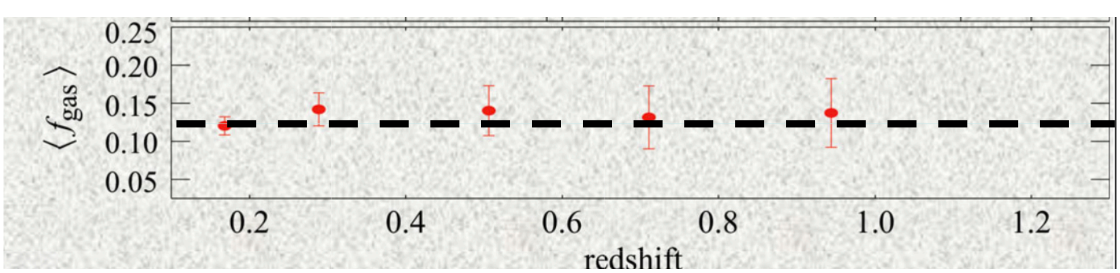
In clusters ratio ratio of DM to baryonic matter is ~6:1



How are the Baryons and Dark Matter Partitioned??

- In massive clusters the vast majority of the baryons are in he gas phase (Laganá et al. 2013)
- ~12% of the total mass is in gas- independant of redshift





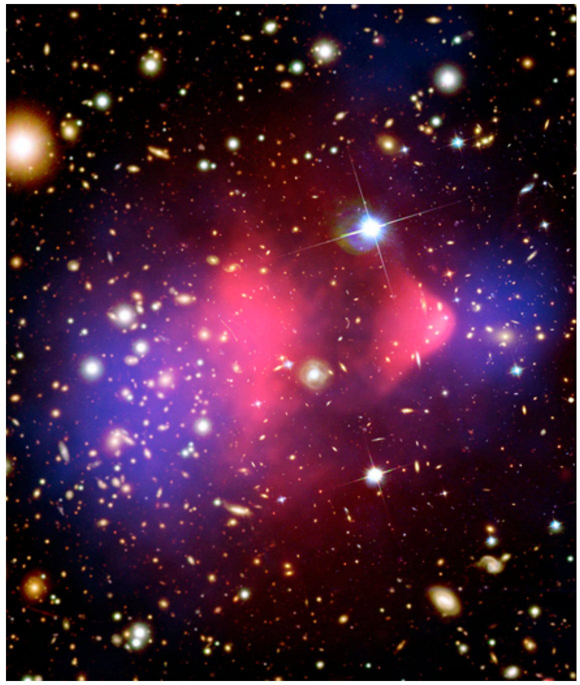
Bullet Cluster

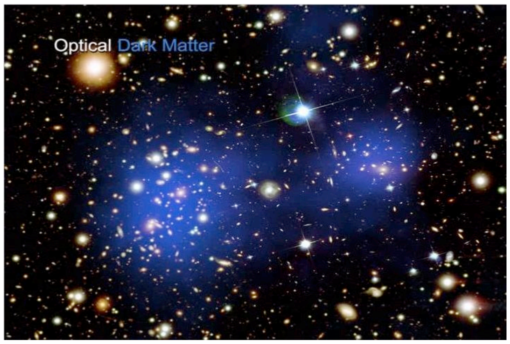
- Direct evidence (Bullet cluster) that dark matter and baryons can be in different places

    Gravitational mass from lensing (blue)

    Hot x-ray emitting gas (red)

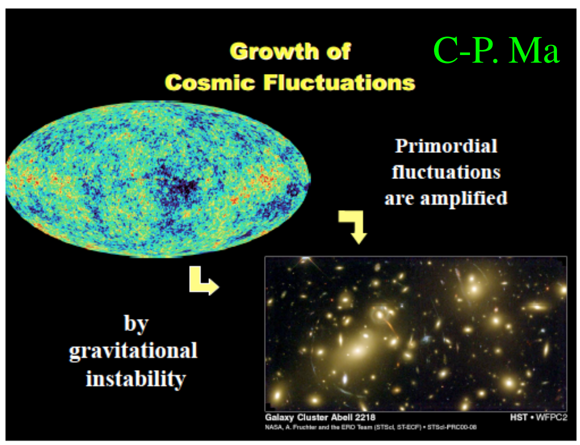
    Galaxies – white

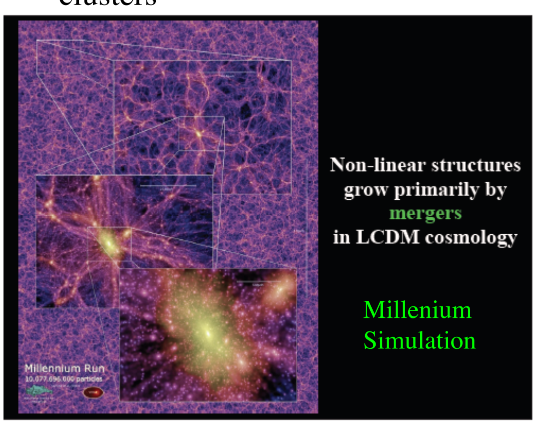




Formation

- 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



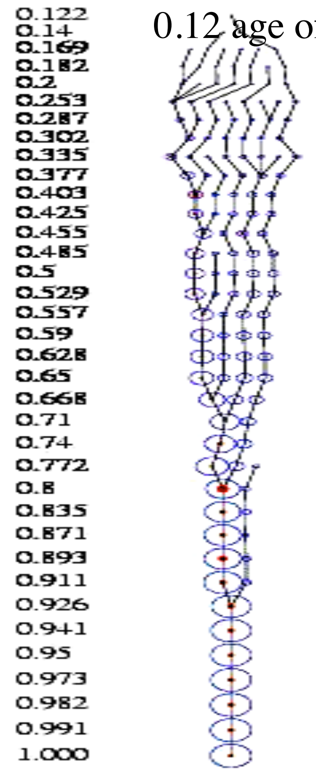


What is a Merger Tree

- In LCDM cosmology structure grows by the merging of bound systems + infall
- The fraction of contribution of each component depends on time and mass.

n

0.12 age of universe

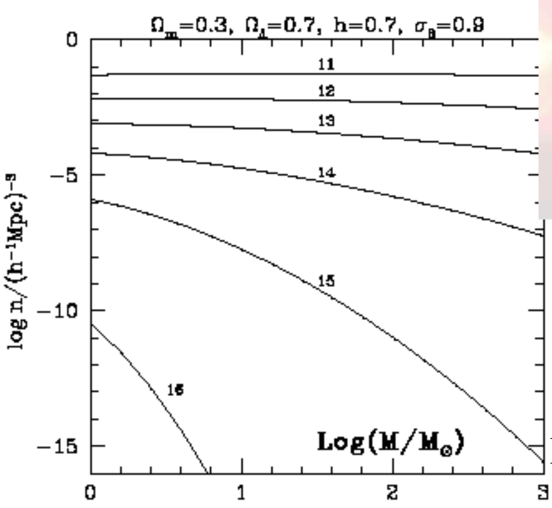


today

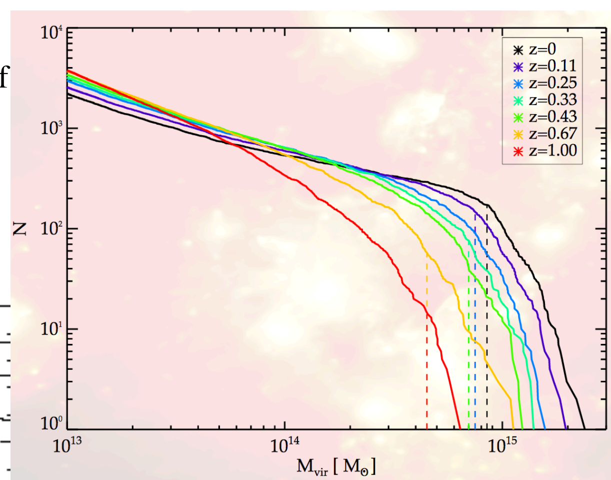
R. Wechsler

Massive Clusters Grow at Late Times

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



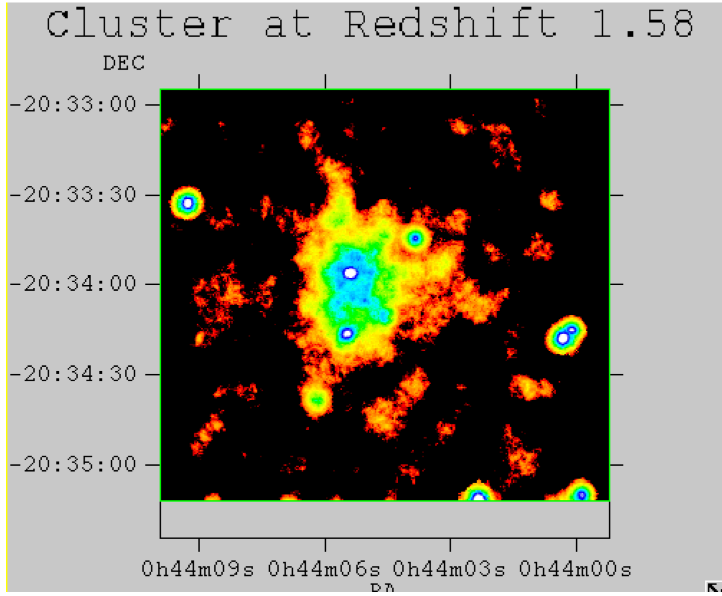
H. Mo



G. Yepes and the MUSIC Collaboration

X-ray Image of Cluster at z=1.58

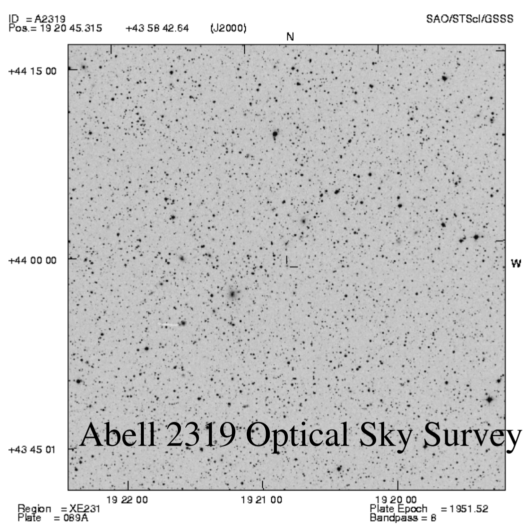
- $M_{500}=3.2\times10^{14}M_{\odot}$
- R_{500}=560kpc.



Tozzi et al 2015

Finding Clusters- A Difficult Job

- Despite the high degree of difficulty Abell did a fantastic job- but catalog suffers from incompleteness and projection effects



X-ray image

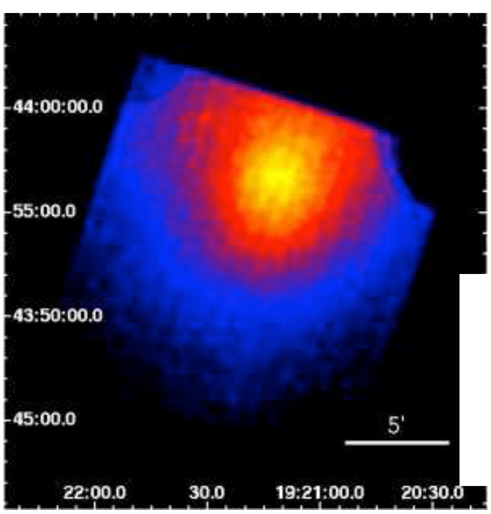
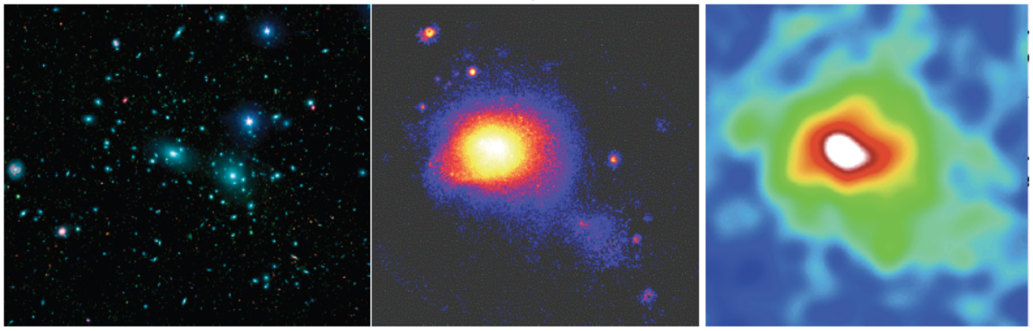


Table 1. Table 1: Abell Richness Class

	Abell 0	Abell 1	Abell 2	Abell 3
N_{Abell}	35–45	45–75	75–125	125–200
Number	$\sim$ 1000	1224	383	6
σ (km s^{-1})	600	750	950	1250
Mass (10^{14}M$_{\odot}$)	2	4	9	15

How are they found

Optical | X-ray | Radio - Infrared



Current Surveys:
SDSS
PanSTARRS

Future Surveys:
LSST
DES
Euclid

Current Surveys:
ROSAT
XMM

Future Surveys:
EROSITA

Current Surveys:
Planck
SPT
ACT

Future Surveys:
CCAT
SPTpol

Pierpaoli 2013

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What is the "right" survey

- There are many ways to find clusters- we need a uniform approach from which mass can be estimated

So far there are 4 promising techniques

- Large scale x-ray imaging surveys
- Sunyaev-Zeldovich surveys (more later)
- Multi-color deep optical images (Gladders and Yee 2002)
- Lensing surveys

X-ray surveys are a proven technique, luminosity and mass strongly correlated. Works over large mass range to z~1.3. Non-gravitational effects may be important at low mass

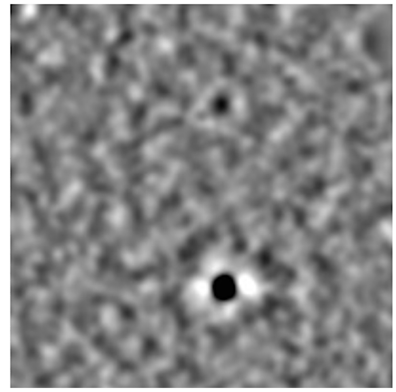
S-Z surveys working well, PLANCK all sky catalog.Very little redshift bias

Red galaxy survey is surprisingly successful, redshift estimates easy - not clear how complete it can be as a function of mass. Extension to large solid angles takes lots of telescope time

Just starting- so far small number statistics, yield based on detailed studies of x-ray selected clusters not yet clear- direct detection of mass

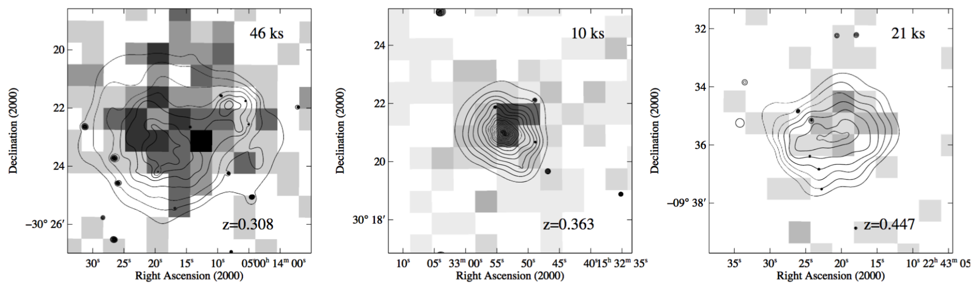
Finding Clusters

- Clusters are found by
  - optical surveys finding overdensities of galaxies
  - x-ray surveys finding extended x-ray sources
  - S-Z- radio sources



S-Z clusters Bleem et al 2015

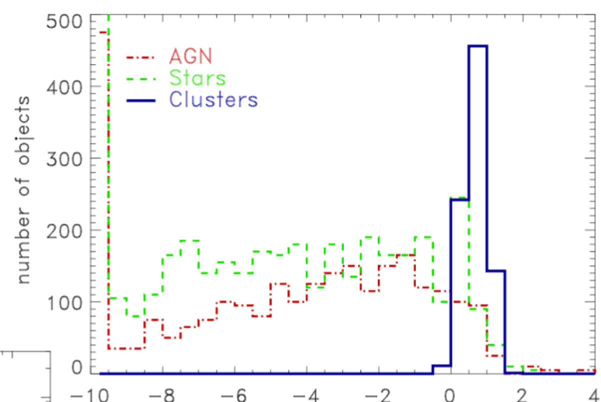
4 *H. Ebeling et al.*



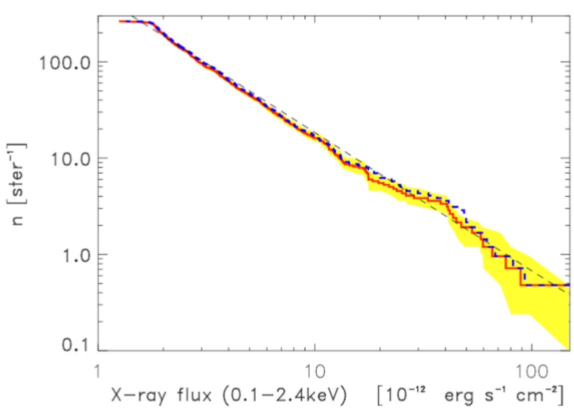
X-ray selected clusters, boxes Rosat image, contours Chandra

X-ray Spectra

- Clusters have a narrow range of x-ray spectra compared to AGN and Stars (Bohringer et al 2017)



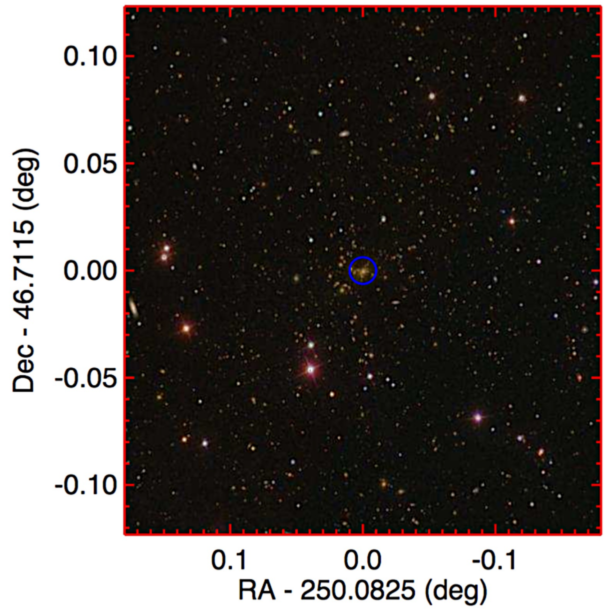
x-ray spectral slope



number of sources as a function of flux
-1722 clusters in a sky area of ~8.25 ster.

Optical Surveys

- These are difficult due to foreground/background projections
  - Use colors to help
  - works to z~1 , then need IR data



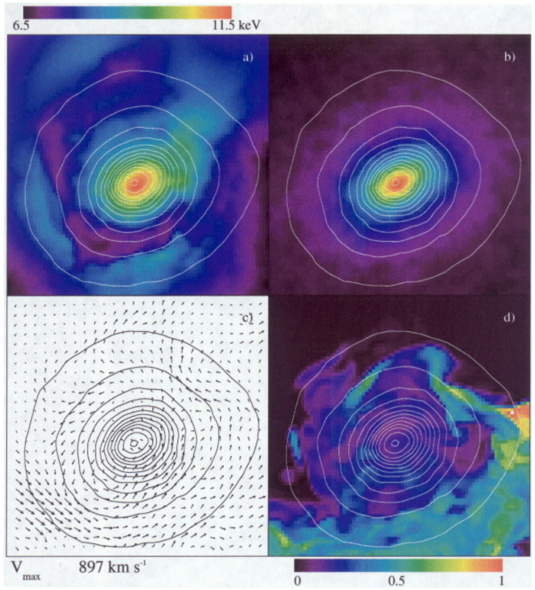
Sloan digital sky survey image of Abell 2219

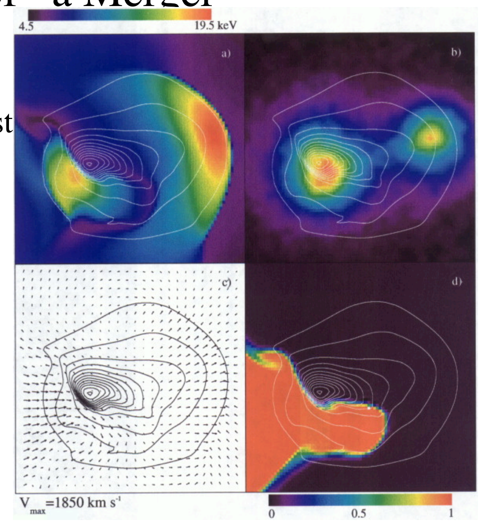
Cluster Formation

- 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

Numerical Simulation of a Merger

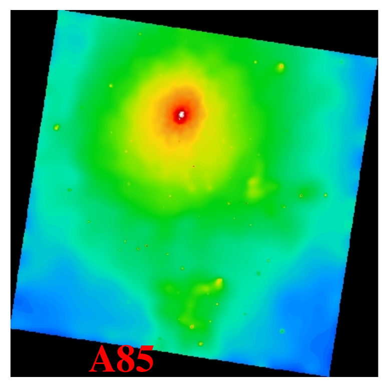
- X-ray contours with kT in color, dark matter distribution, velocity vectors and how the two gas components mix (0.3 and 3.5Gyr after closest approach)

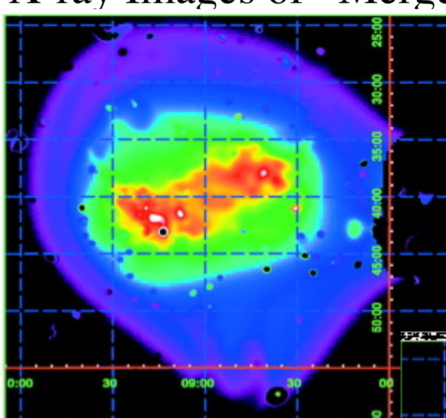


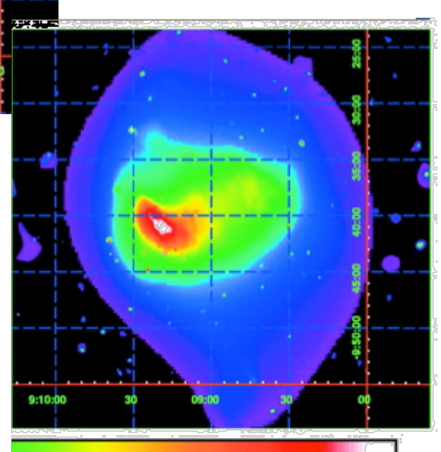


Roettiger, Stone and Mushotzky 1998 simulation of a merger- trying to match A754

X-ray Images of Mergers







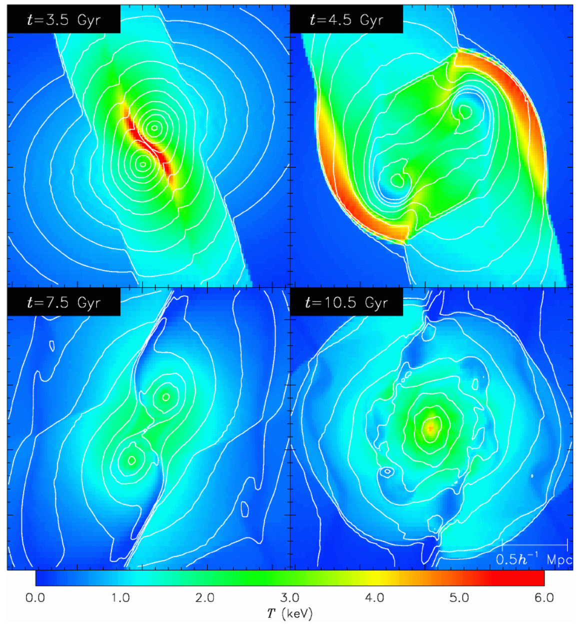
- A754 (Henry et al 2004) gas pressure and x-ray intensity images

Merger Shocks

Main heating mechanism of intracluster gas

- Most of energy in large clusters due to gravity, conversion of potential energy into heat via merger shocks

ICM/IGM records thermal history of Universe



Galaxy Cluster Merger

Rubens Machado, Gastão Lima Neto
IAG-USP
2012

The Center for Astrophysical Thermonuclear Flashes

Binary Galaxy Cluster Merger Simulated using the Flash Code Mass Ratio 1:1, with an Offset Impact

This work was supported in part by the DOE NNSA ASC ASAP and by the NSF. This work also used computational resources at the ALCF at ANL awarded under the INCITE program, which is supported by the DOE Office of Science.

An Advanced Simulation and Computation (ASC) Academic Strategic Alliances Program (ASAP) Center at The University of Chicago

Brightest Cluster Galaxies

- most luminous and most massive galaxies in the Universe at the present epoch.
- At low redshift, these objects exhibit a small dispersion in their luminosities
- lie close to the peaks of the X–ray emission
- Have small relative velocity to cluster average
- Different luminosity profiles than typical cluster elliptical galaxies- show a shallow very large 'envelope'
- Very large number of globular clusters

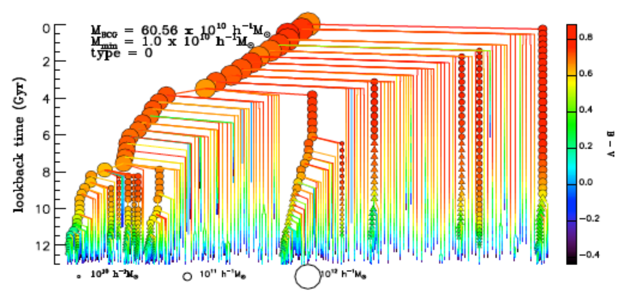
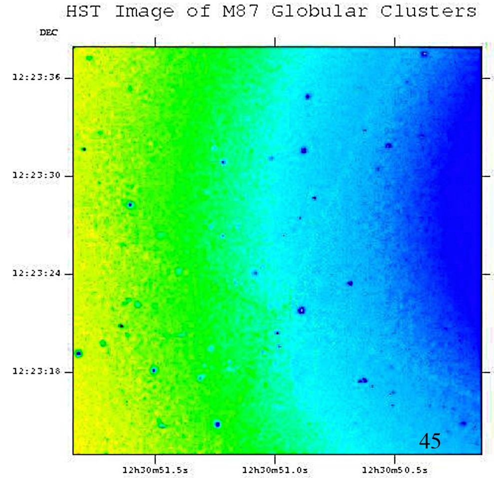


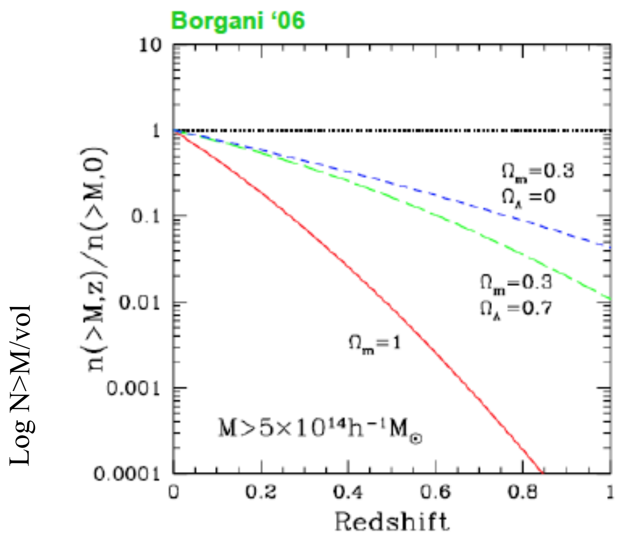
Figure 1. BCG merger tree. Symbols are colour-coded as a function of B - V colour and their area scales with the stellar mass. Only progenitors more massive than 10^{10} $M_{\odot}$ h^{-1} are shown with symbols. Circles are used for galaxies that reside in the FOF group inhabited by the main branch. Triangles show galaxies that have not yet joined this FOF group.

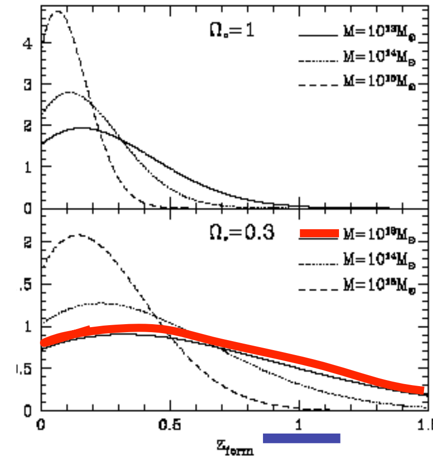
HST Image of M87 Globular Clusters

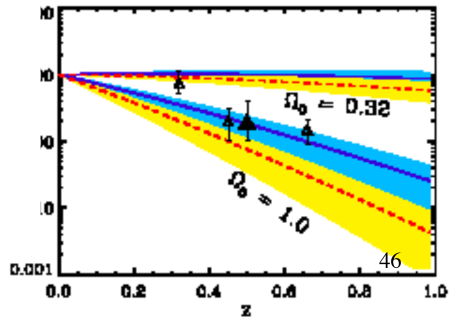


Cosmology

- The rate of cluster growth is a strong function of cosmological parameters







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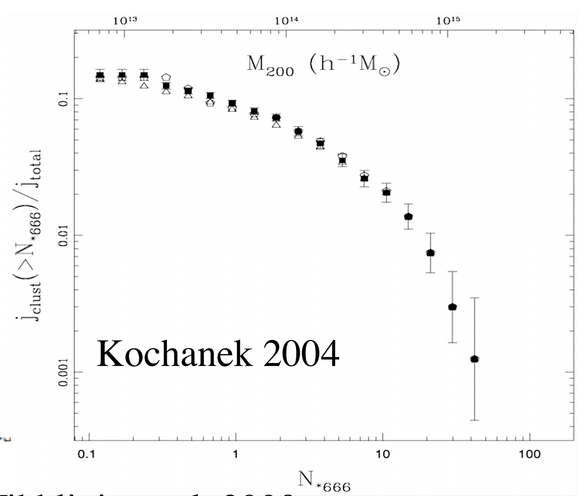
Mass Function

- 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.



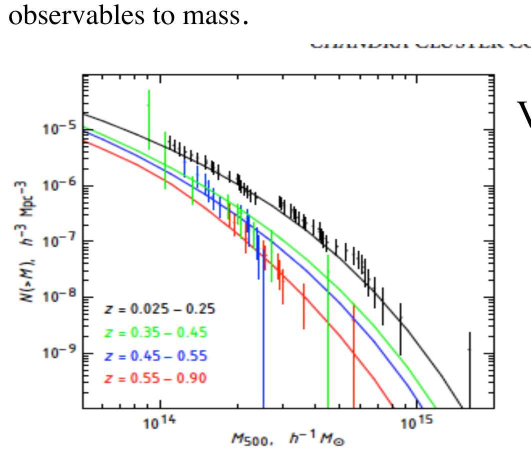
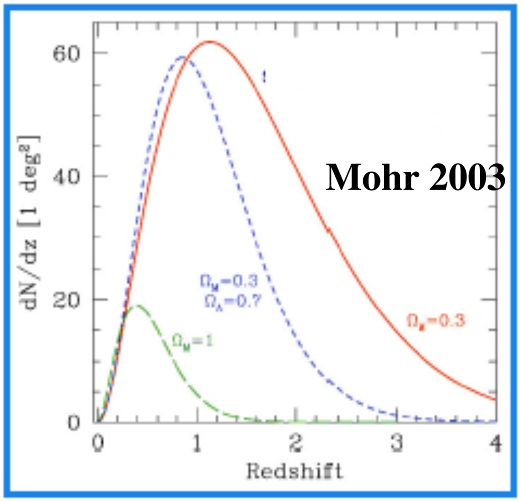


FIG. 18.— Same as Fig. 16 but the high-z sample is split into three redshift bins.

Vikhlinin et al 2009

The Galaxy Cluster Redshift Distribution



Redshift distribution of clusters for 3 sets of cosmological parameters

Notice for for a 'low' Ω universe with no cosmological constant there are many more clusters in the high z universe

Mass Estimation- Girardi et al 1998

In principle, one can estimate the cluster mass within a radius r, $M_J(<r)$, by using the Jeans equation, coupled with the equation which links the two observable quantities $\Sigma(R)$ and $\sigma_P(R)$, i.e. the projected galaxy number density and the projected velocity dispersion as a function of the projected radius R:

$$\frac{d(\rho\sigma_r(r)^2)}{dr} + \frac{2\rho(r)\beta\sigma_r^2}{r} = -\frac{G\rho(r)M_J(<r)}{r^2}, \quad (1)$$

$$\sigma_P^2(R)\Sigma(R) = 2\int_R^\infty \rho(r)\sigma_r^2(r)(1-\beta\frac{R^2}{r^2})\frac{r}{\sqrt{r^2-R^2}}dr \quad (2)$$

where r is the distance from the cluster center, $\rho(r)$ is the spatial number density of galaxies linked to $\Sigma(R)$ via the Abel integral, $\sigma_r(r)$ is the radial component of velocity dispersion $\sigma(r)$, and $\beta(r) = 1 - \sigma_\theta^2/\sigma_r^2$ is the velocity anisotropy parameter (e.g., Binney & Tremaine 1987).

Unfortunately, there are three unknowns ($M(<r)$,$\sigma(r)$, $\beta(r)$) and only two equations. In order to solve these equations it is therefore necessary to make some assumptions.

The virial theorem derives from the Jeans equation via an integration step. It relates the global kinetic energy with the potential one ($2T + U = 0$, e.g. Binney and Tremaine 1987) and is usually used to compute virial masses.

Mass Estimation- Girardi et al 1998

3.2 THE MASS DERIVED FROM THE VIRIAL THEOREM

The total virial mass of the cluster, M_V, depends on the global velocity dispersion, σ and the spatial distribution of the galaxy population (e.g., Merritt 1988):

$$M_V = \frac{< v^2 >}{G < r^{-1} F >}, \quad (3)$$

where the brackets indicate spatial averages over the observed sample of N galaxies, r are the galaxy distances from the cluster center, and v are the galaxy velocities referred to the cluster mean velocity. The function $F(r)$ is the mass fraction within r and depends on the (generally) unknown form of mass distribution.

If mass is distributed like the observed galaxies (i.e., $\rho_{mass} \propto \rho$), then the appropriate form of eq. 3 is (Limber & Mathews 1960):

$$M_V = \frac{< v^2 >}{G < r_{ij}^{-1} >} = \sigma^2 R_V / G \quad (4)$$

where R_V is the virial radius which depends on r_{ij}, i.e. the distance between any pair of galaxies.

From the observational point of view, the large advantage of the virial theorem is that the global projected velocity dispersion σ_P and, consequently, the total mass are independent of possible anisotropy of galaxy velocities, always being $\sigma^2 = 3\sigma_P^2$ for spherical systems (e.g., The & White 1986; Merritt 1988). Therefore, in the case of spherical systems, for the respective projected quantities σ_P and R_{PV}, eq. 4 becomes:

$$M_V = 3\pi/2 \cdot \frac{< V^2 >}{G < R_{ij}^{-1} >} = 3\pi/2 \cdot \sigma_P^2 R_{PV} / G. \quad (5)$$

X-ray Mass Estimates

- use the equation of hydrostatic equilibirum
-

$$\frac{dP_{\rm gas}}{dr} = \frac{-G\mathfrak{M}_*(r)\rho_{\rm gas}}{r^2} \quad (3)$$

where $P_{\rm gas}$ is the gas pressure, $\rho_{\rm gas}$ is the density, G is the gravitational constant, and $\mathfrak{M}_*(r)$ is the mass of M87 interior to the radius r.

$$P_{\rm gas} = \frac{\rho_{\rm gas} K T_{\rm gas}}{\mu \mathfrak{M}_{\rm H}} \quad (4)$$

where μ is the mean molecular weight (taken to be 0.6), and $\mathfrak{M}_{\rm H}$ is the mass of hydrogen atom.

$$\frac{KT_{\rm gas}}{\mu\mathfrak{M}_{\rm H}}\left(\frac{d\rho_{\rm gas}}{\rho_{\rm gas}} + \frac{dT_{\rm gas}}{T_{\rm gas}}\right) = \frac{-G\mathfrak{M}_*(r)}{r^2}dr, \quad (5)$$

which may be rewritten as:

$$-\frac{KT_{\rm gas}}{G\mu\mathfrak{M}_{\rm H}}\left(\frac{d\log\rho_{\rm gas}}{d\log r} + \frac{d\log T_{\rm gas}}{d\log r}\right) r = \mathfrak{M}_*(r) \quad (6)$$

Putting numbers in gives

$$M(r) = -3.71 \times 10^{13} M_\odot T(r)\, r \left(\frac{d \log \rho_g}{d \log r} + \frac{d \log T}{d \log r}\right),$$

ere T is in units of keV and r is in units of Mpc (

3 VIKHLININ ET AL.

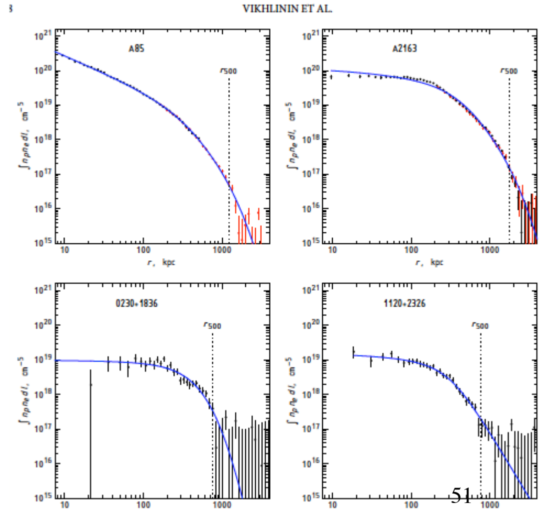


FIG. 5.— Examples of the surface brightness profile modeling for clusters shown in Fig. 3 and 4. The observed X-ray count rates are converted to the projected emission measure integral (see § 3.4 and V06). The black and red data points show the *Chandra* and *ROSAT* measurements, respectively. The best fit models (the projected emission measure integral for the three-dimensional distribution given by eq. 2) are shown by solid lines. The dashed lines indicate the estimated r_{500}

Intracluster Gas

- Majority (75%) of observable cluster mass (majority of baryons) is hot gas
- Temperature $T \sim 10^{7\text{-}8}$ K ~ 1-10 keV
- Electron number density $n_e \sim 10^{-3}$ cm^{-3}
- Mainly H, He, but with heavy elements (O, Fe, ..)
- Mainly emits X-rays
- $L_X \sim 10^{45}$ erg/s, most luminous extended X-ray sources in Universe
- Age ~ 2-10 Gyr

Sarazin

The Intracluster Medium as a Fluid

$$\lambda_p \approx \lambda_e = \frac{3^{3/2}(kT)^2}{8\sqrt{\pi}\, n_e e^4 \ln\Lambda}$$

mean free path of a **particle**

$$\approx 23\left(\frac{T}{10^8\,\mathrm{K}}\right)^2\left(\frac{n_e}{10^{-3}\,\mathrm{cm}^{-3}}\right)^{-1}\mathrm{kpc}$$

⇨ **Mean-free-path λ_e ~ 20 kpc < 1% of diameter → fluid (except possibly in outer regions, near galaxies, or at shocks and cold fronts)**

Sarazin

Physical State of Intracluster Gas: Local Thermal State

- Mainly ionized, but not completely
- Coulomb collision time scales

  $\tau(e,e) \sim 10^5$ yr

  $\tau(p,p) \sim 4 \times 10^6$ yr

  $\tau(p,e) \sim 2 \times 10^8$ yr

  all < age ($>10^9$ yr)

  Kinetic equilibrium, Maxwellian at T

  Equipartition $T_e = T_p$

  (except possibly at shocks)

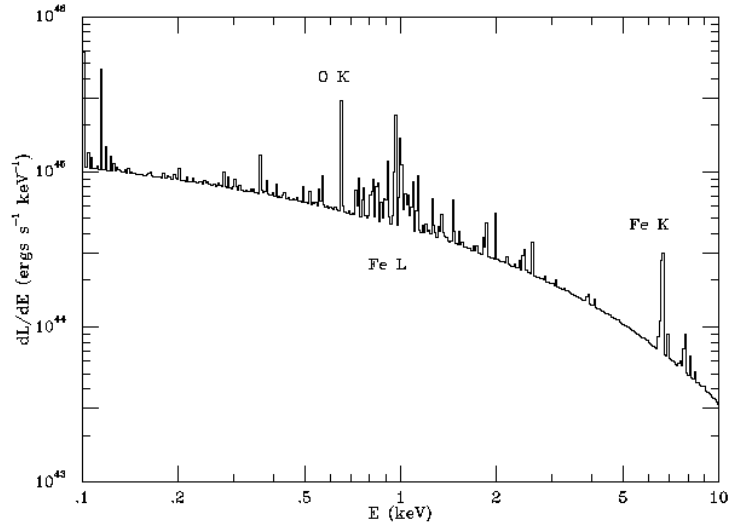
X-ray Emission Processes

- Continuum emission
  - Thermal bremsstrahlung, $\sim \exp(-h\nu/kT)$
  - Bound-free (recombination)
  - Two Photon
- Line Emission

  (line emission)

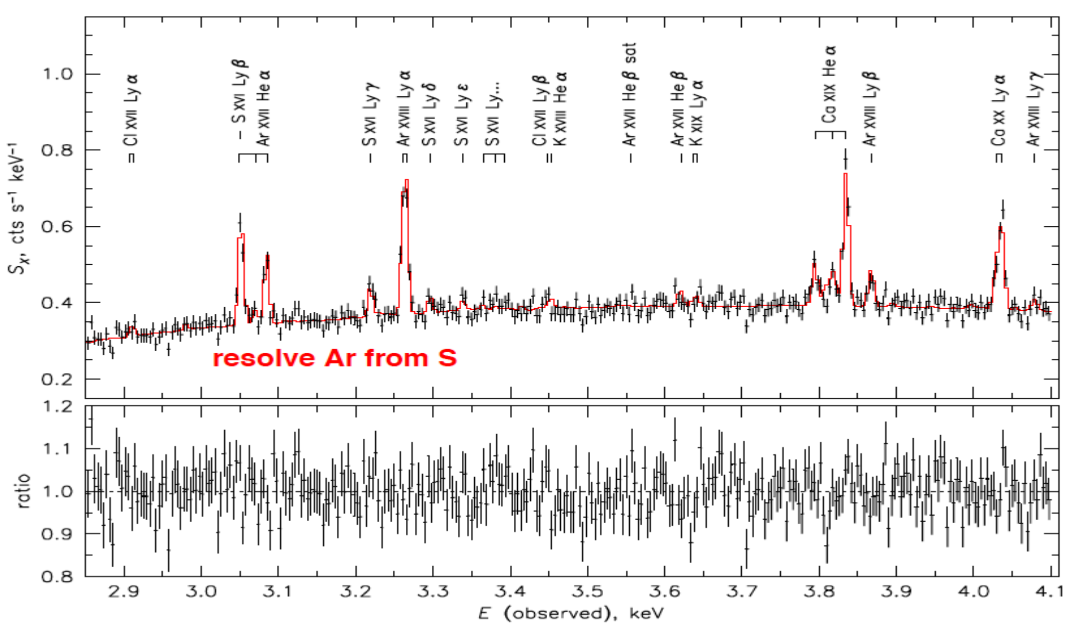
$L_\nu \propto \varepsilon_\nu\,(T, \text{abund})\,(n_e^2\, V)$

X-ray Spectrum

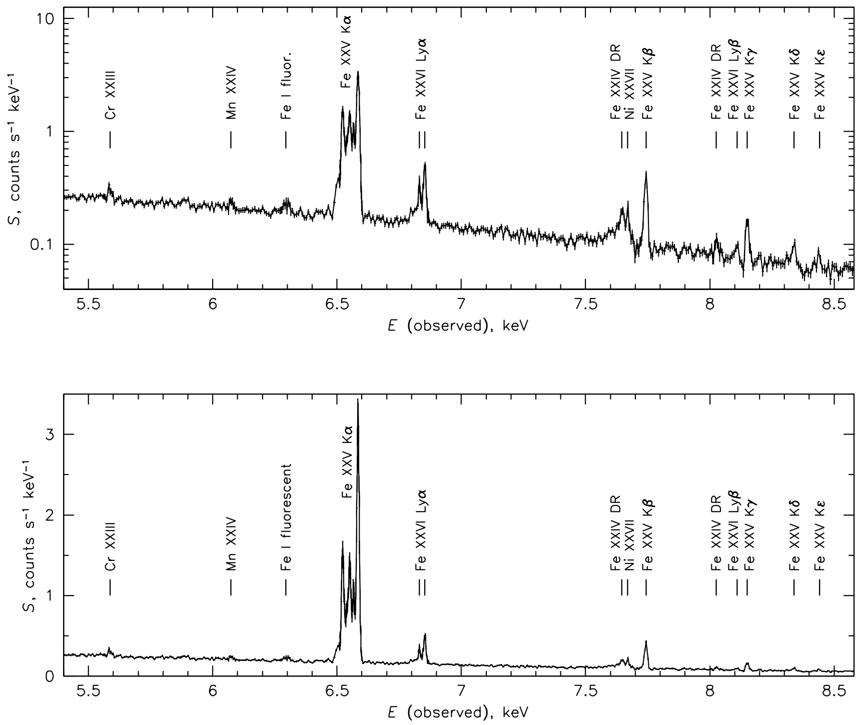


Chemical Abundances

Hitomi has the possibility to produce extremely precise chemical abundances which allow constraints on the ratio of double degenerat to single degenerate SNIa models



Hitomi SXS Data for Perseus Cluster



Full array

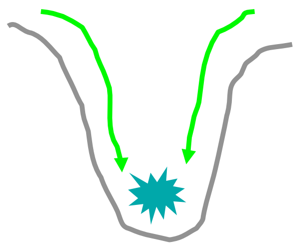
Heating and Cooling of ICM

- What determines temperature T?
- Why is ICM so hot?
- What are heating processes?
  - gravitational heating
  - nongravitational heating (SNe, AGNs)
- What are cooling processes?

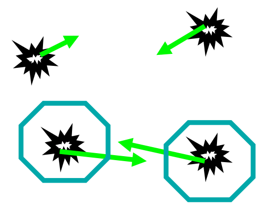
Why is gas so hot?

- Clusters have huge masses, very deep gravitational potential wells
- Any natural way of introducing gas causes it to move rapidly and undergo fast shocks

infall



galaxy ejection



Simple Scaling Laws for Gravitational Heating (Kaiser 1986)

- Gas hydrostatic in gravitational potential

  $kT \sim \mu m_p \, GM/R$
- Clusters formed by gravitational collapse

  $\langle \rho_{cluster} \rangle \sim 180 \; \rho_{crit} \, (z_{form})$
- Most clusters formed recently, $z_{form} \sim$ now
- Baryon fraction is cosmological value, most baryons in gas

  $R \propto (M / \rho_{crit0})^{1/3} \propto M^{1/3}$

  $T \propto M^{2/3}$

  $L_X \propto T^2$

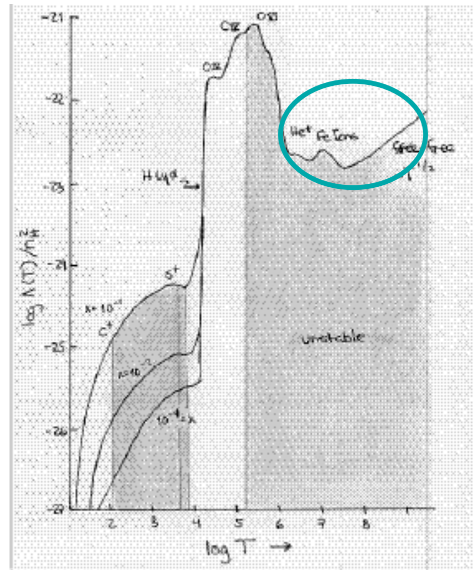
Radiative Cooling of ICM

- Main cooling mechanism is radiation, mainly X-rays

  L = Λ(T,abund) n_e^2
  ergs/cm^3/s

  T ≳ 2 kev, Λ ∝ $T^{1/2}$
  Thermal bremsstrahlung
  T ≲ 2 keV, Λ ∝ $T^{-0.4}$
  X-ray lines

Very important in high density regions- center of cluster, 'cooling flows'



Sound Crossing Time

- **Sound speed**

$$c_s^2 = \gamma \frac{P}{\rho} = \frac{5}{3}\frac{P}{\rho}$$

$$c_s \approx 1500 \left(\frac{T}{10^8\,\mathrm{K}}\right)^{1/2} \mathrm{km/s}$$

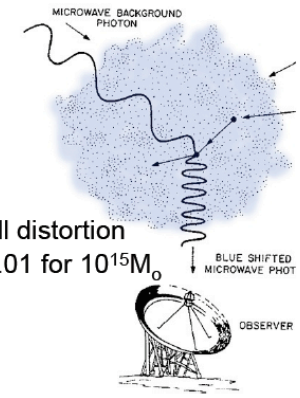
- **Sound crossing time**

$$t_s \approx 6.6 \times 10^8 \left(\frac{T}{10^8\,\mathrm{K}}\right)^{-1/2} \left(\frac{D}{\mathrm{Mpc}}\right) \mathrm{yr}$$

Less than age → unless something happens (merger, AGN, …) gas should be nearly hydrostatic

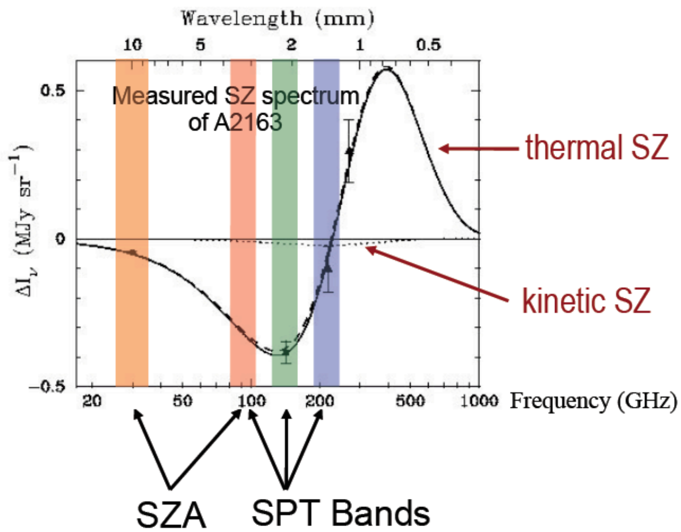
- **Sarazin**

The Sunyaev-Zel'dovich Effect: probe of Galaxy clusters



Small distortion
$\tau_e \sim 0.01$ for $10^{15} M_o$

from Leon Van Speybroeck



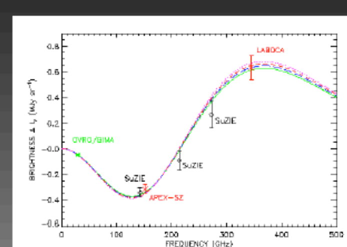
Carlstrom

Redshift independent: $\dfrac{\Delta T_{SZE}}{T_{CMB}} \propto \int n_e T_e dl$

The beauty of the SZ Effect

Thermal SZE is a small (<1 mK) distortion in the CMB caused by inverse Compton scattering of the CMB photons

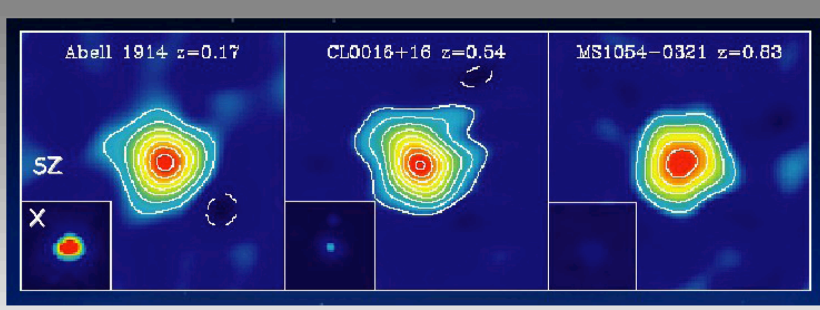
$$\frac{\Delta T}{T_{\rm CMB}} = g(x) \int n_e(l) \frac{k_{\rm B} T_e(l)}{m_e c^2}\, dl$$



Nord, Basu, Pacaud et al, 2009

Total cluster flux density is independent of redshift!

$$\Delta S_\nu = \int \Delta I_\nu \, d\Omega \propto \frac{\int n_e T_e \, dV}{D_{\rm A}^2} \propto \frac{f_{\rm gas} M_{\rm tot} T_e}{D_{\rm A}^2}$$



Carlstrom et al.

Sunyaev-Zel'dovich Effect

Single Clusters

- *Measure of integrated pressure (total thermal energy)*
- *Distances, H_o, $H(z)$*
- *Cluster gas mass fractions, cluster structure, evolution studies*
- *Peculiar velocities at high z*

$$\frac{\Delta T_{SZE}}{T_{CMB}} \propto \int n_e T_e dl$$

SZ Cluster Surveys

NEW

- *Exploit SZ redshift independence*
- *Measure growth of structure and large scale velocity fields to constrain Dark Energy*

$$S \propto \int \Delta T_{SZE}\, d\Omega$$
$$\propto \frac{1}{D_A(z)^2} \int n_e T_e dV$$

Carlstrom

S-Z Simple Physics

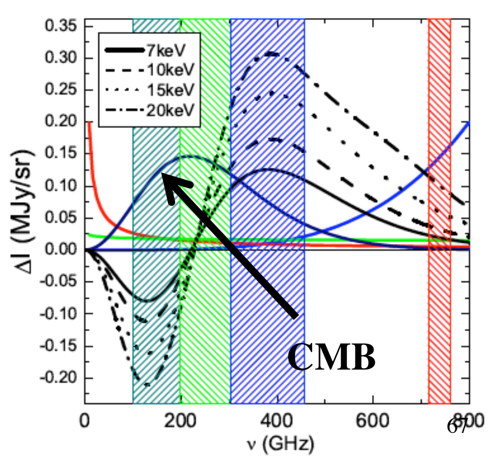
- The optical depth for the S-Z effect is small
- the density of electrons is of order $n_e \sim 10^{-3}$ cm^{-3}, the path length ` through a cluster medium ~ several Mpc. With a Thomson cross section $\sigma = 6.65 \times 10^{-25}$ cm^2,

optical depth $\tau = n_e \sigma l \sim 0.005$; ~ 1%

probability that a CMB photon crossing a rich cluster is scattered by an electron.

- Since the electron energy is much larger that the energy of the photon, to first order $\delta v/v \sim kTe/m_e c^2 = 1\%$. The resulting fractional temperature change of the CMB is of the order of 10^{-4},~300μk
- For a review see *Carnegie Observatories Astrophysics Series, Vol. 3: Clusters of Galaxies: Probes of Cosmological Structure and Galaxy Evolution, 2004* Using the Sunyaev-Zelídovich Effectto Probe the Gas in Clusters MARK BIRKINSHAW

The spectrum of the thermal SZE has a characteristic shape
all interacting CMB photons get approximately a 1% boost in energy, the result is a transfer of photons in the CMB spectrum from lower to higher frequencies, resulting in a decrease of brightness at low frequencies



A Strange Fact

- As clusters are observed at higher redshifts the solid angle which scatters the CMB gets smaller- however the CMB gets brighter in the past
- These two terms almost cancel IF the cluster hot gas were the same at higher redshifts.
- Since we expect the cluster hot gas to evolve with z it is not clear what the total effect will be .
- The amplitude of the S-Z effect is t independent of D_A the angular distance

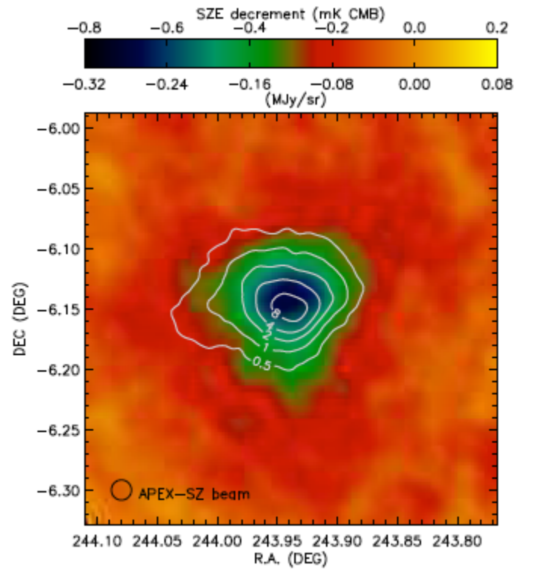


Fig. 1. Map of Abell 2163 at 150 GHz, overlaid with XMM-Newton X-ray contours (see Fig. 3) in units of 10^{-13} erg s^{-1}cm^{-2}arcmin^{-2}. Because the correlated-noise re-

Sunyaev-Zeldovich Distances

- The Sunyaev-Zeldovich effect is the Compton scattering of microwave background photons off the hot electrons in the IGM in the cluster
- At present ~400 clusters have measured S-Z effect "decrements" and x-ray temperatures (Primarily from Planck and the South Pole Telescope and the Atacama Cosmology telescope)

Angular distance D_A:ΔT_0 is the S-Z decrement, S_{X0} the x-ray surface brightness, T_{e0} the x-ray temperature,θ an angular size and Λ the cooling function

Line integral of pressure

$$\Delta T \propto g(\nu) \int dz\, n_e(\mathbf{r})\, T_e(\mathbf{r}),$$

$$S_X \propto \frac{1}{(1+z)^4} \int dz\, n_e(z)^2\, T_e(z)\, \Lambda(T_e, Z_{ab}),$$

Geometry uncertainty

$$H_0 \propto \left(\frac{T_e}{\Delta T_{SZ}}\right)^2 \theta S_X \frac{\ell_\perp}{\ell_\parallel},$$

$$D_A \propto \frac{(\Delta T_0)^2 \Lambda_{e\mathrm{H}0}}{S_{x0} T_{e0}^2} \frac{1}{\theta_c},$$

All quantities are directly measurable with an x-ray image, temperature map and S-Z image

Sunyaev-Zeldovich effect

- Compton scattering changes both the angular and energy distribution of the microwave background
- At low frequencies the result is a diminution (decrement) in the surface brightness of the MWB whose amplitude and shape depends on the Compton optical depth, the 3-D distribution of the hot electrons and their temperature

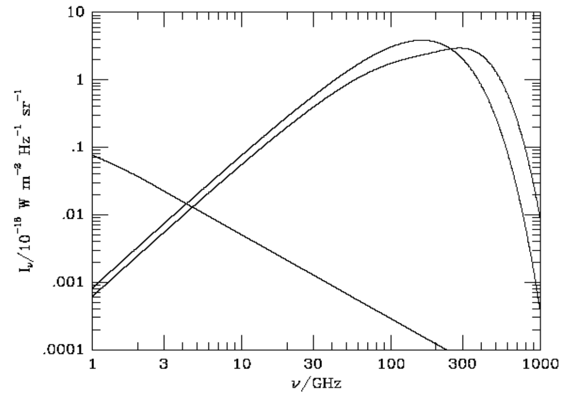
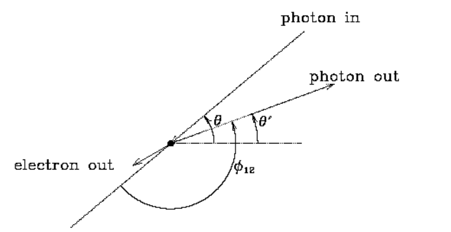


Fig. 1.— The spectrum of the microwave background radiation, and the microwave background radiation after passage through an (exaggerated) scattering atmosphere with $y = 0.1$ and $\tau\beta = 0.05$ (as defined in Sections 3 and 6), compared with the integrated

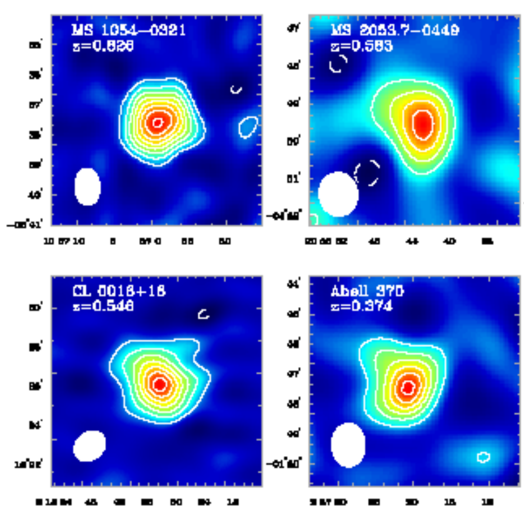


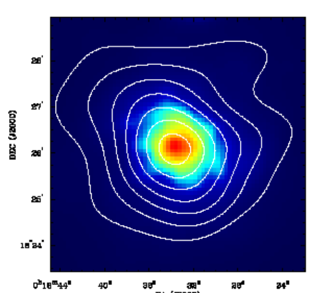
— The scattering geometry, in the frame of rest of the electron before the interaction. ...ming photon, at angle θ relative to the x_e axis, is deflected by angle ϕ_{12}, and emerges

Sunyaev-Zeldovich effect

- The main technical limits are the long exposures required in both the x-ray band and the milli-meter (~1 day each for the highest z clusters)
- The S-Z decrement is independent of redshift, while the x-ray surface brightness drops as $(1+z)^4$

  Setting a practical limit to z~1.3 for the x-ray measurements
- In a massive cluster the typical optical depth is τ ~0.1





X-ray image with S-Z contours for z=0.54 cluster

S-Z contours images for a sample of clusters from z~0.3-0.9

Clusters of Galaxies

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