'New' Physics- See Longair 4.5

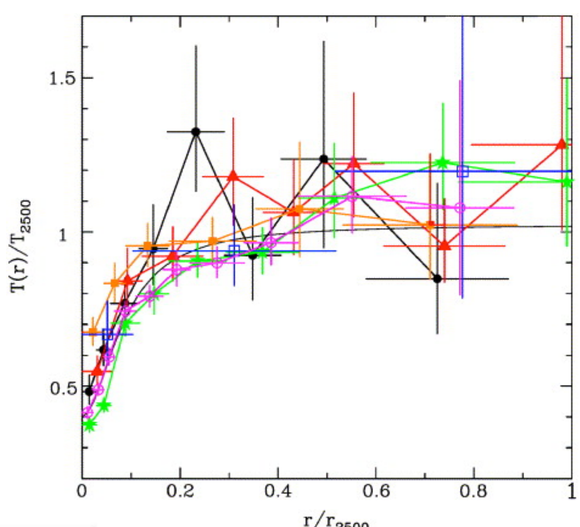
- The Cooling time $t_{\mathrm{cool}} = 3NkT/|dE/dt|$ ~8.5×10^{10}yrs$(n/10^{-3})^{-1}T_8^{1/2}$ For bremmstrahlung (Longair eq 4.24,4.25)
  - but for line emission dominated plasmas it scales as $T_8^{-1/2}$
- That is as the gas gets cooler it cools faster

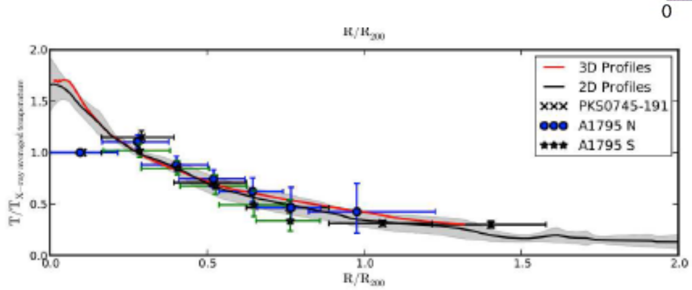
Λ=cooling function

- $T_{\mathrm{cool}}=5/2nkT/n^2\Lambda \sim t_{\mathrm{Hubble}} T_8 \Lambda^{-1}_{-23}\, n_{-2}^{-1}$
- In central regions of many clusters the density (n) is large, so the gas can cool in t<10^9 yrs
  - 5/2 (the enthalpy) is used instead of 3/2 to take into account the compression as it cools (and remains in pressure equilibrium)

Observed Temperature Profiles

- If the gas is in equlibrium with the potential (of the NFW form) it should be hotter in the center
- But in many clusters it is cooler- evidence for gas cooling





Left panel (from Burns et al 2010) shows the theoretical temperature profile if a NFW potential (in grey) compared to an set of actual cluster temperature profiles

Cooling Cores

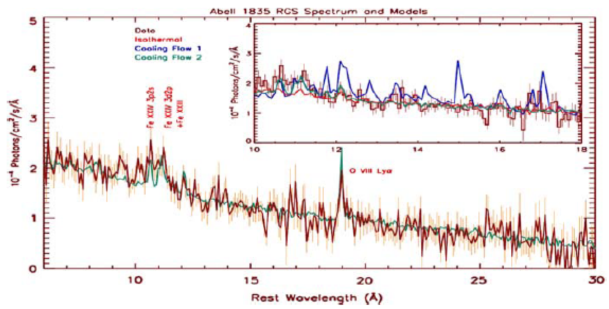
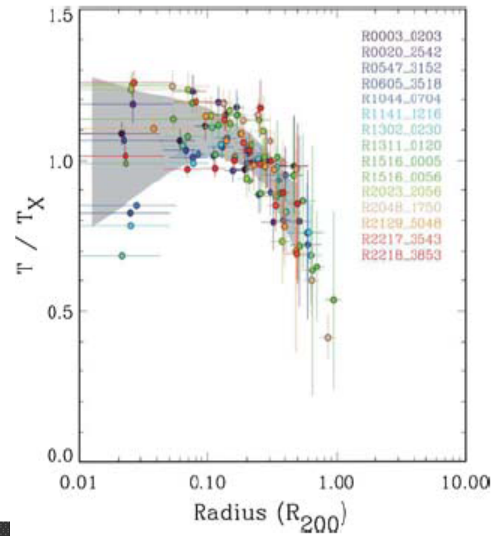
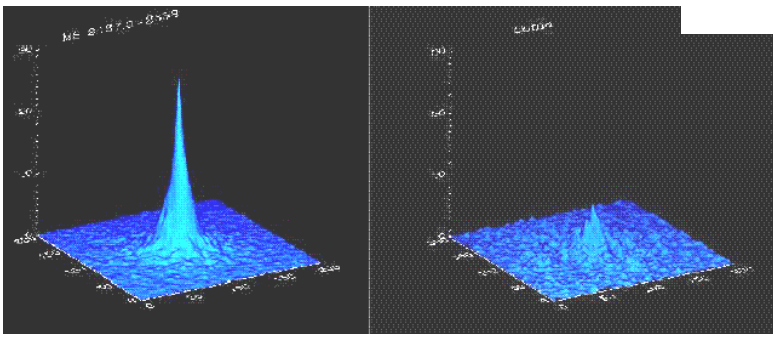


Fig. 22 *XMM-Newton* RGS spectrum of the central region of the prominent cool core cluster, A1835 com-

$$t_{cool} = 69\left(\frac{n_e}{10^{-3}\,\mathrm{cm}^{-3}}\right)^{-1}\left(\frac{T}{10^{8}\,\mathrm{K}}\right)^{1/2}\ \mathrm{Gyr}$$

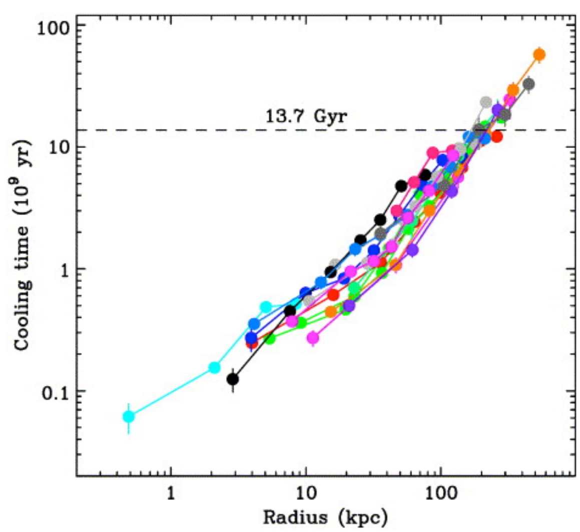




Notice that the central surface brightness of cool core clusters (left panel) is much higher than non-cooling core clusters

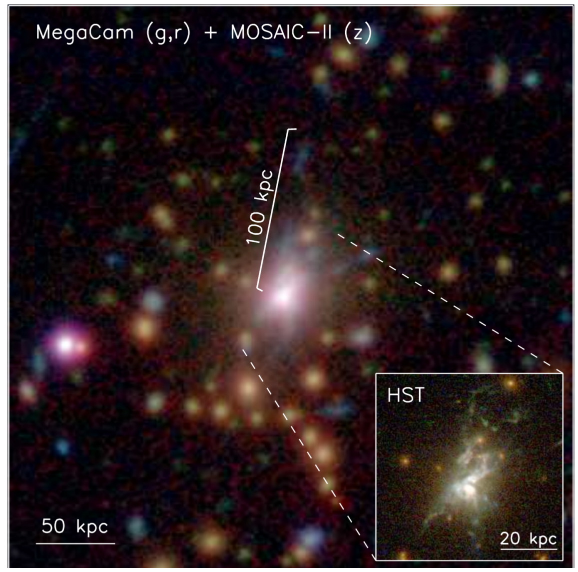
Cooling Time for a Sample of Clusters

- So what happens to the gas? ...



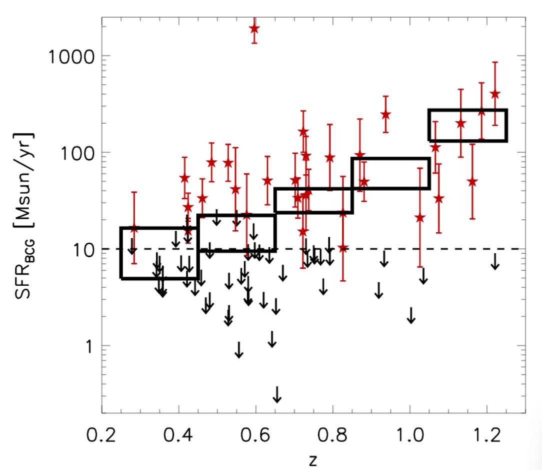
Star Formation

- Bursts of Star Formation in Cluster Centers
  - At z<1 elliptical galaxies show very little evidence for star formation
    - elliptical galaxies dominate the stellar population of clusters
  - However in the center of cool core clusters there can be lots of star formation! see Deep Chandra, HST-COS, and Megacam Observations Of The PhoeNix Cluster: Extreme Star Formation And AGNFeedback On Hundred Kiloparsecc Scales Michael McDonald et al



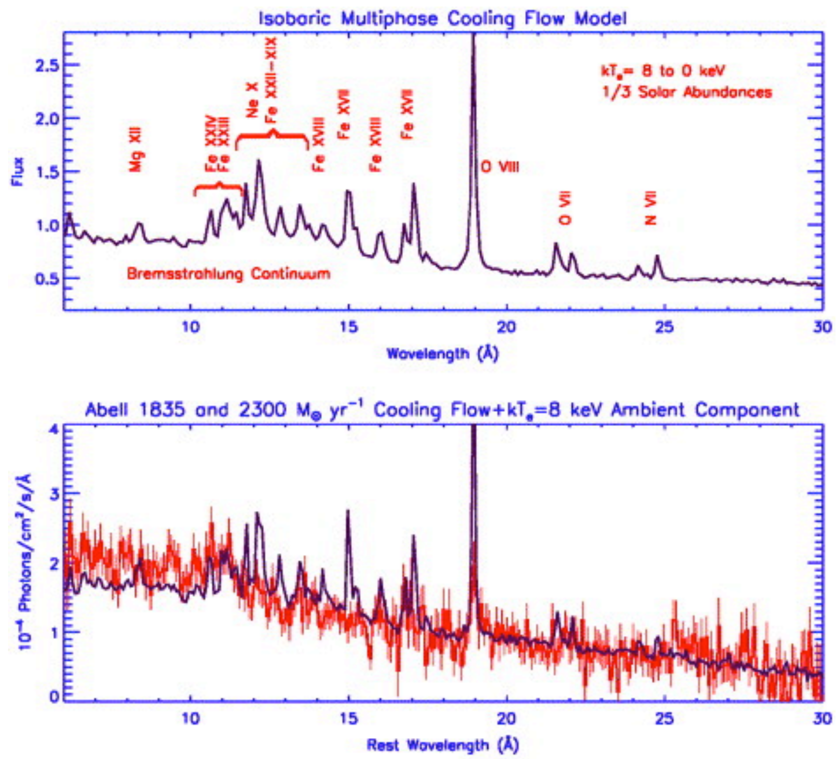
High Redshifts

- The 'cooling flow" clusters tend to show higher star formation rates at higher redshifts.
  - Up to $1000 M_{\odot}$/yr (!)
  - However the amount of material involved in star formation is much less than the amount of gas theoretically predicted to cool



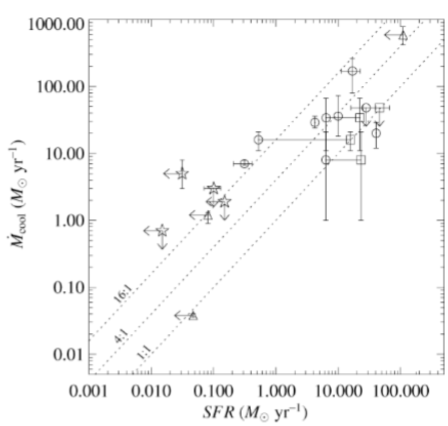
Theoretical and Observed Spectrum of 'Cooling' Regions

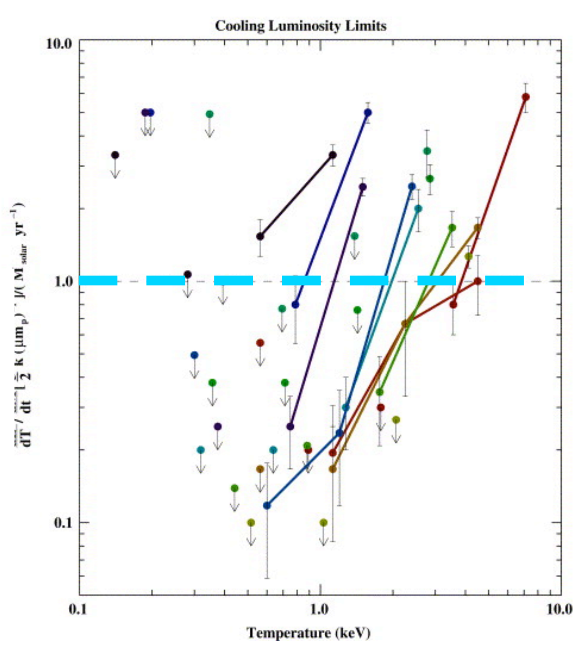
- The theoretical models of cluster cooling predict strong lines from gas at $kT<10^7$k- these are not seen
- So the gas does not cool isobarically- what else is going on??



- Theoretical cooling model predicts the flat line
- Data are in strong disagreement
- Something is wrong with the assumptions (gravity, cooling)
- Best idea is 'something else' is happening- input of energy from active galaxy in center
- Not all the gas theoretically predicted to cool forms stars

How much Gas is at Each Temperature

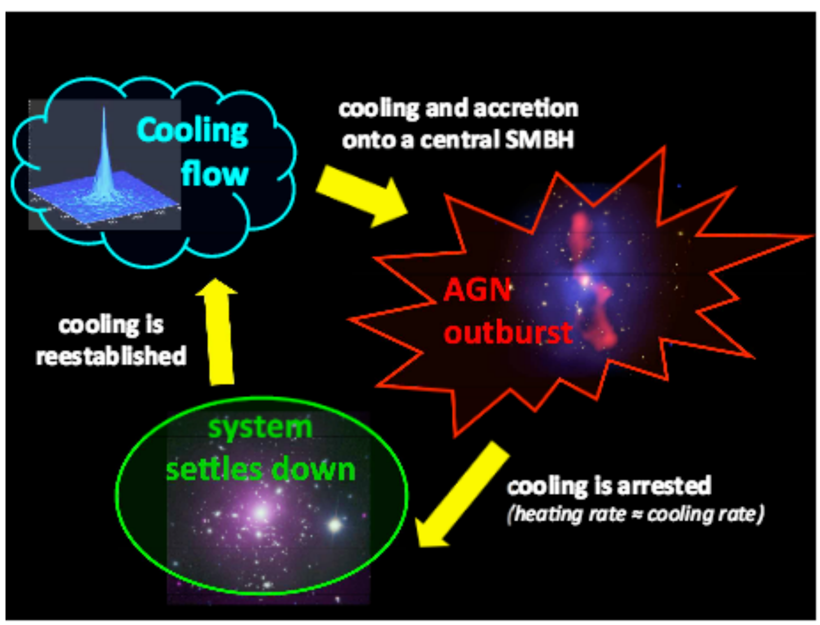




Feedback

- There is evidence from
  - cluster evolution,
  - relation of temperature and luminosity,
  - cutoff in galaxy star formation etc
- that additional physics beside gravity is needed to model structure formation- this is called 'feedback'
- The injection of energy (momentum, entropy) from the structures that have formed into the system
  - We do not know how this process occurs but the only two forms of structures that potentially have enough energy are
    - star formation- 7 Mev/proton (nuclear processes
    - AGN ~90-360 Mev/proton (star formation)

General Idea of Feedback

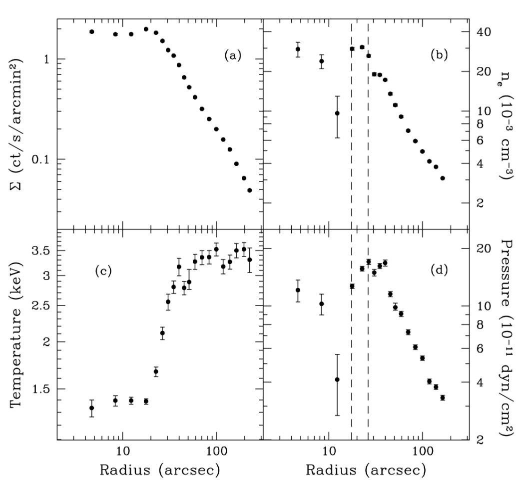


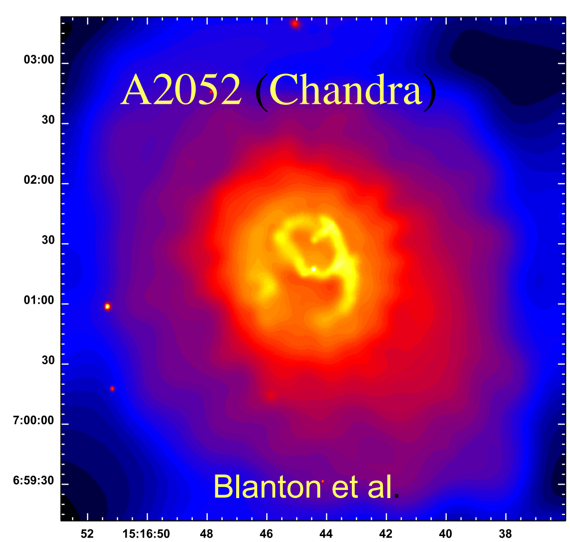
M. Gitti 2016

Feedback- How AGN Influence the Cluster Gas

Direct evidence from cluster x-ray images combined with radio data that central AGN has strongly influenced the gas

Effects of Feedback in Image and Temperature





AGN Feedback

- 'Color' Image of the Perseus Cluster

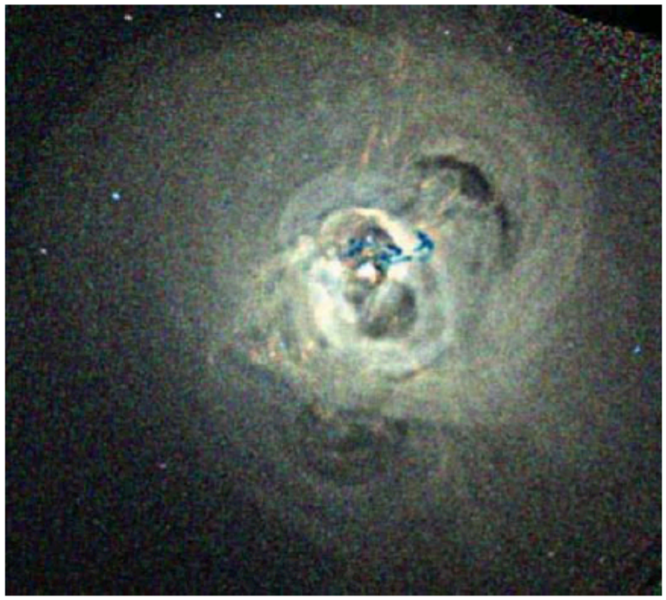
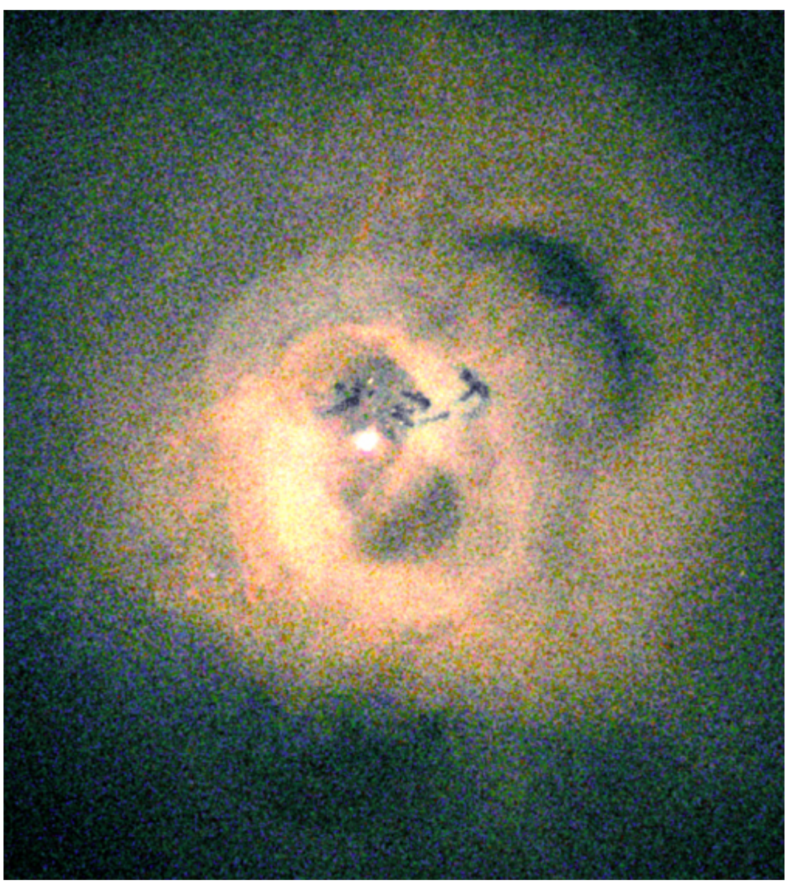


Fig. 25 False color image of the central region of the Perseus cluster produced from images in three energy bands 0.3–1.2, 1.2–2, and 2–7 keV. An image smoothed on a scale of 10 arcsec (with 80% normalization) has been subtracted from the image to highlight regions of strong density contrast. The image shows a series of nearly concentric "ripples" which are interpreted as sound waves or weak shock waves set off by the activity of the central AGN (Fabian et al. 2006)

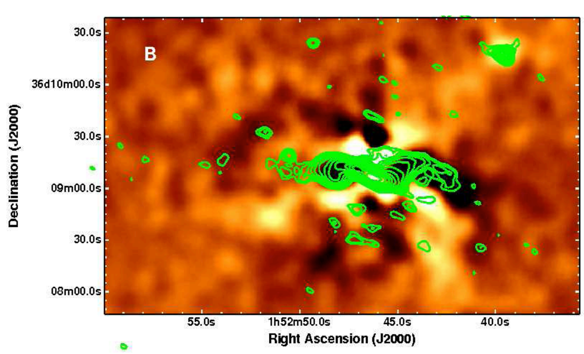


X-ray and Radio Image

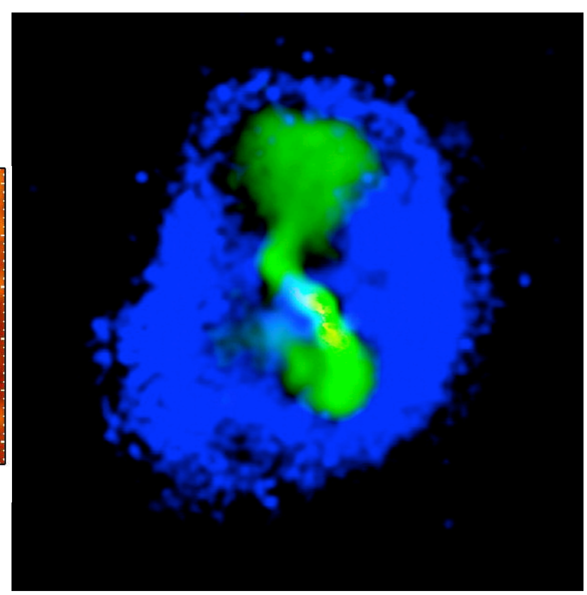
- Abell 2052 (Blanton et al 2015) the radio plasma (red) 'fills' the 'holes' in the x-ray image (blue)

Cavaties and Low Freq Radio Emisson

- The giant cavities seen in many cooling flow clusters are often 'filled' by low frequency radio emitting plasma



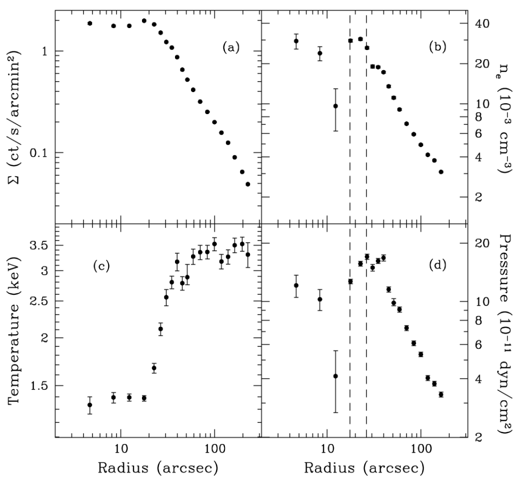
A262 Clarke et al 2009

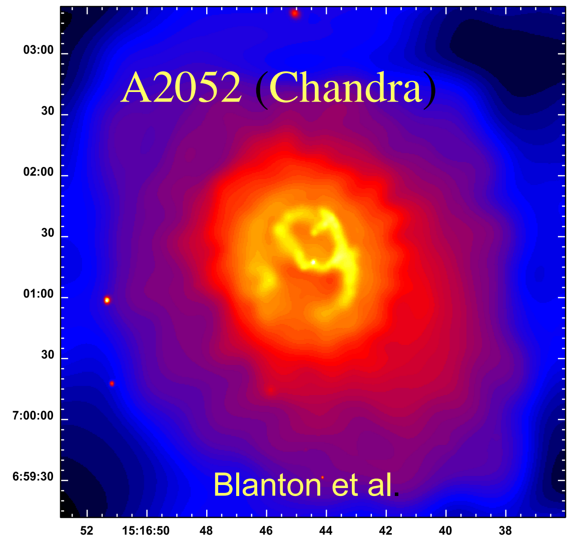


Hydra A Wise et al 2007

Effects of Feedback in Image and Temperature

the hot gas can apparently be strongly affected by AGN activity- direct evidence of the ability of SMBHs to influence environment on large scales

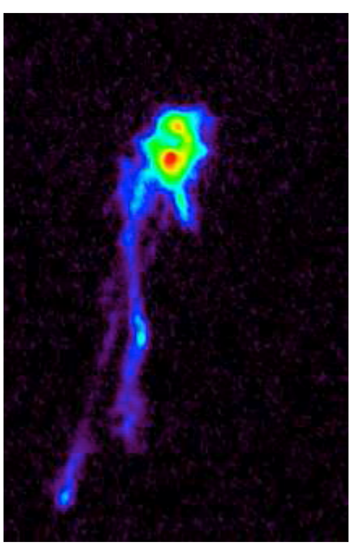


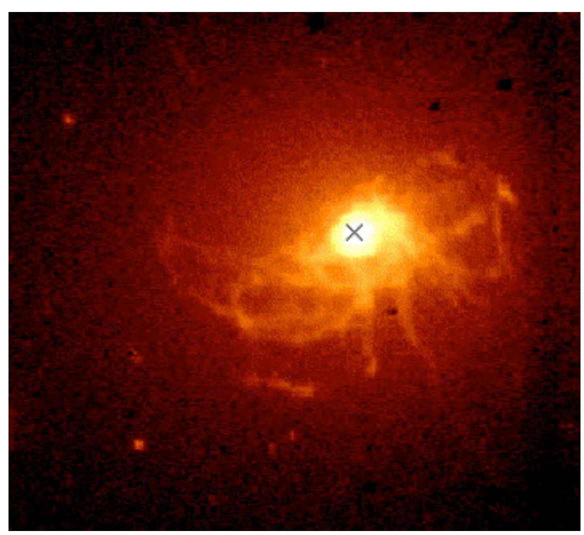


Other Signs of Unexpected Activity

- Strong emission from Hα (gas at T~10^4 k) in centers of many cool core clusters

Sanders et al 20098

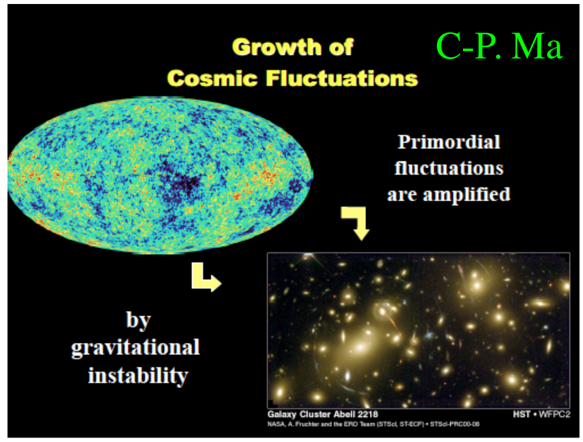


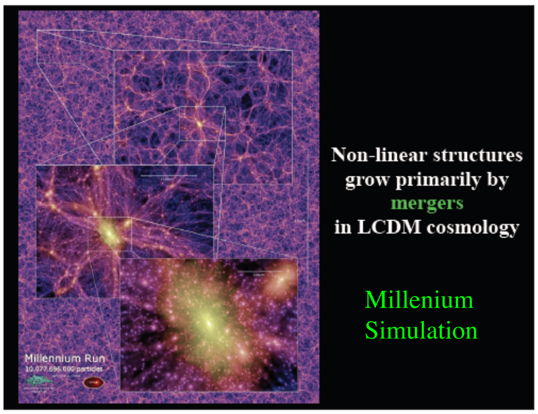


McDonald and Veilleux 2009

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





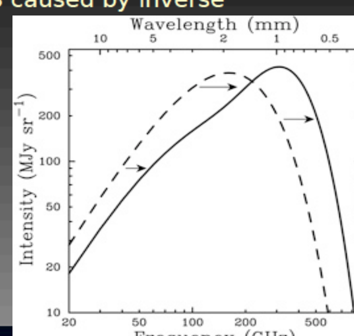
Sunayev-Zeldovich Effect

[redacted]

https://ned.ipac.caltech.edu/level5/Sept05/Carlstrom/Carlstrom2.html#2.1

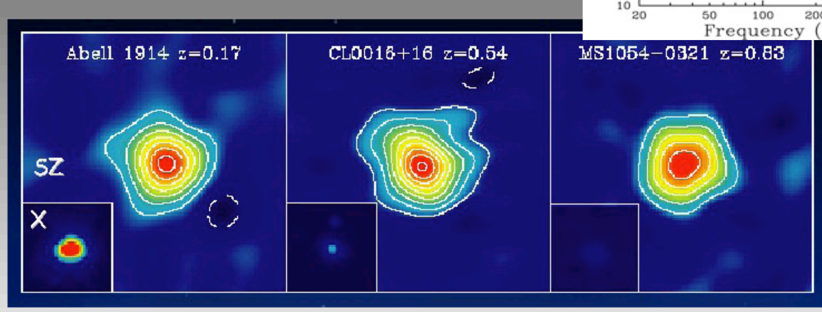
Thermal SZE is a small (<1 mK) distortion in the CMB caused by inverse Compton scattering of the CMB photons

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



Total cluster flux density is independent of redshift!

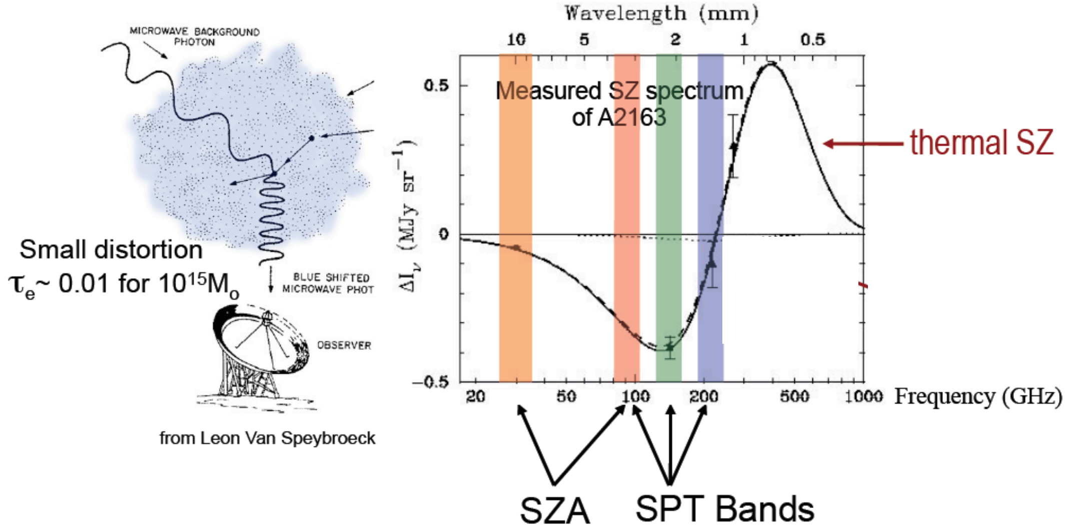
$$\Delta S_\nu = \int \Delta I_\nu\,d\Omega \propto \frac{\int n_e T_e\,dV}{D_A^2} \propto \frac{f_{\rm gas} M_{\rm tot} T_e}{D_A^2}$$



Carlstrom et al.

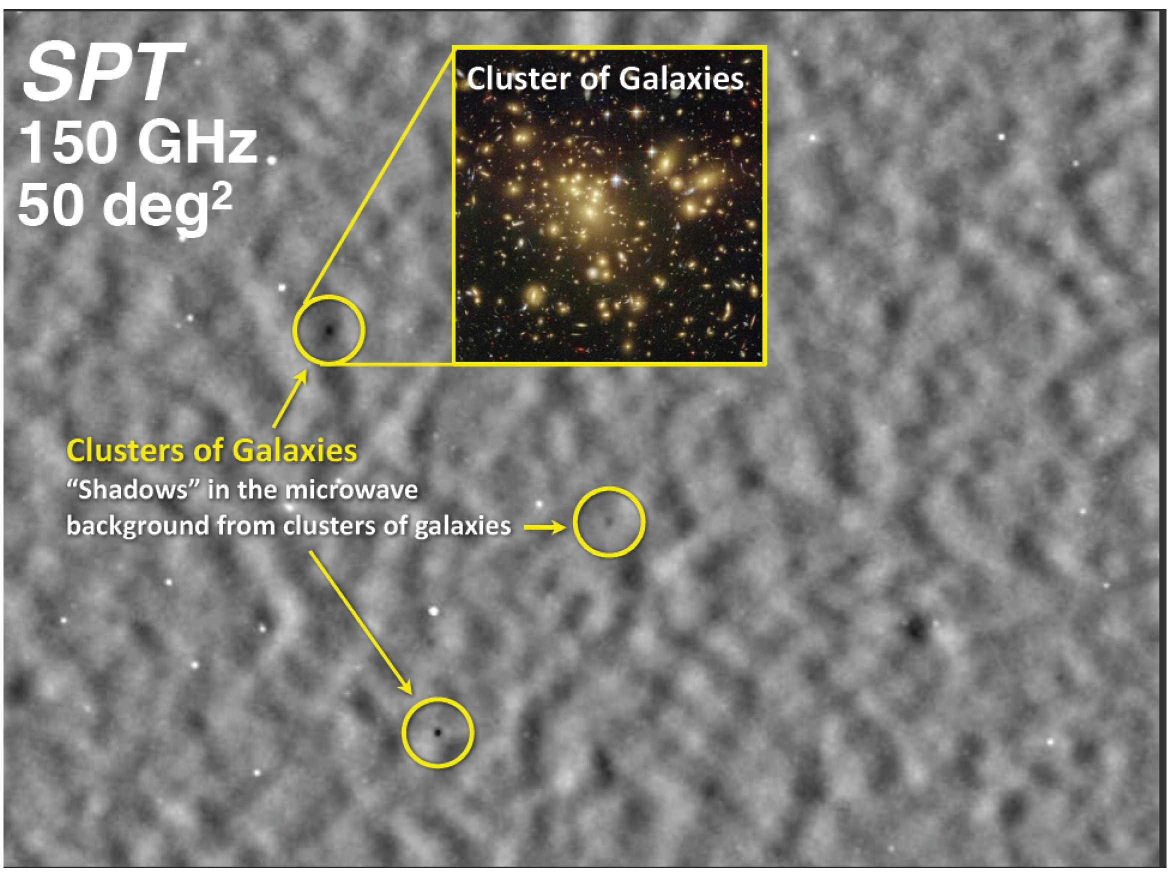
Sec 4.6 & 9.5 in Longair

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



Carlstrom

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



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

- *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

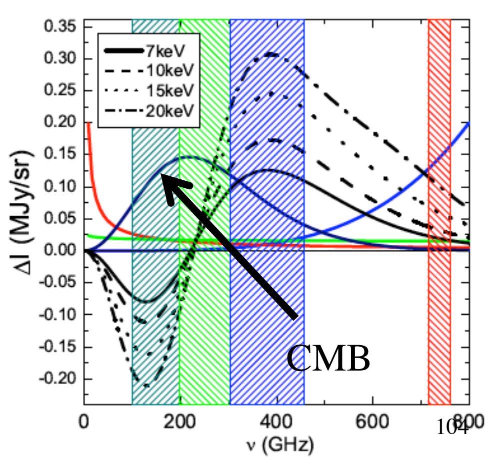
S-Z Simple Physics

- 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 $\delta\nu/\nu \sim kTe/m_e c^2 = 1\%$. 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

- The amplitude of the S-Z effect is independent of D_A the angular distance

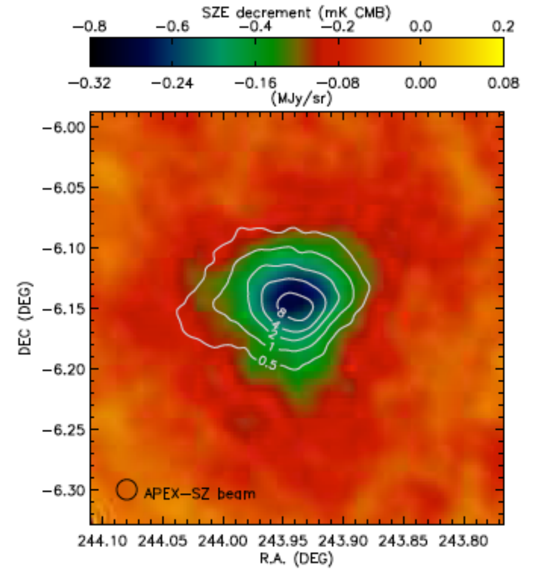


Fig. 1. Map of Abell 2163 at 150 GHz, overlaid with XMM-Newton X-ray contours (see Fig. 3) in units of 10^{-13} erg s^{-1}cm^{-2}arcmin^{-2}. Because the correlated-noise re-

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)

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

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

$$D_A \propto \frac{(\Delta T_0)^2 \Lambda_{eH0}}{S_{x0} T_{e0}^2} \frac{1}{\theta_c},$$

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

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

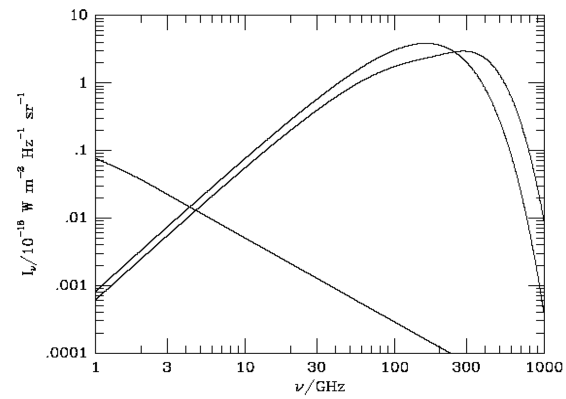
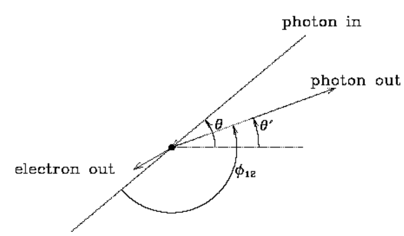


Fig. 1.— The spectrum of the microwave background radiation, and the microwave background radiation after passage through an (exaggerated) scattering atmosphere with $y = 0.1$ and $\tau\beta = 0.05$ (as defined in Sections 3 and 6), compared with the integrated

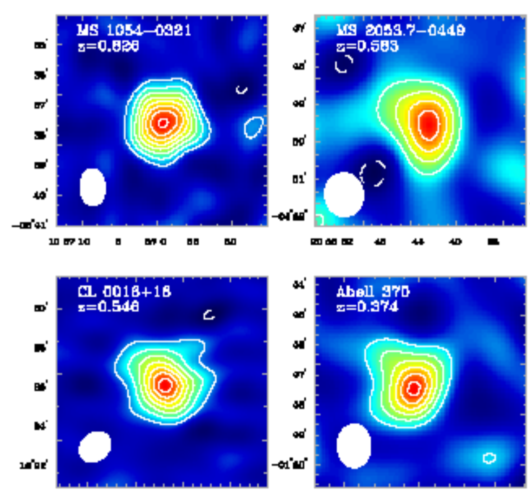


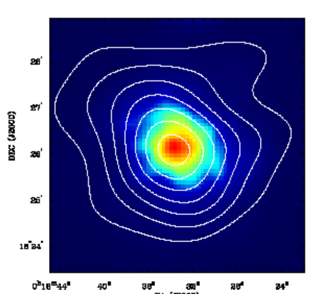
— The scattering geometry, in the frame of rest of the electron before the interaction. ming photon, at angle θ relative to the x_e axis, is deflected by angle ϕ_{12}, and emerges

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

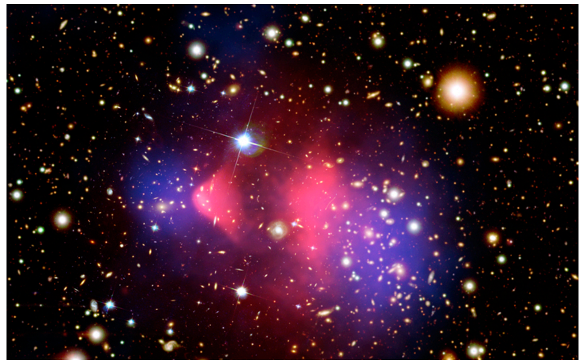




X-ray image with S-Z contours for z=0.54 cluster

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

Dark Matter-Summary



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

very high mass-to-light ratio.

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

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

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