Introduction to Astrophysics

Michaelmas Term, 2020: Prof Craig Mackay

Module 8: Clusters of Galaxies.

- General properties, masses and mass-to-light ratios, galaxy interactions, dynamic stability, the inter-galactic medium, magnetic fields, x-ray emission,
- Virial temperature, gravitational lensing, dark matter content, mass derived from x-ray observations.
- Rich Clusters of Galaxies.
- Tidal stripping, the Sunyaev-Zel'dovich (S-Z) effect, cooling flows.

1

Rich Clusters of Galaxies: Summary of Properties

- Galaxy clusters are the largest gravitationally bound objects in the universe.
- They have four major components:
  1. hundreds or thousands of **galaxies** each containing stars, gas and dust
  2. vast amounts of **hot gas** (visible via x-rays) with a temperature of 3×10^7 - 10^8 K.
  3. intergalactic **magnetic fields** of poorly known strength and distribution
  4. **dark matter**, (non-luminous matter) which has been inferred to explain the dynamics of the galaxies within the cluster and their gravitational lensing properties.
- The hot gas threads through the galaxies and fills the spaces between galaxies.
- The hot gas contains more mass than all the galaxies in the cluster put together.
- However the mass visible in galaxies plus this hot gas still only accounts for ~ 3% - 10% of the mass needed to gravitationally bind the cluster.
- The general model we have of galaxy clusters is that they start as over-densities of dark matter and that the associated galaxies are then pulled together by their own gravity to form groups of dozens of galaxies which in turn merge to form clusters of hundreds or even thousands of galaxies.

Abell 2029 cluster, X-ray (left) and SDSS optical (right): from http://chandra.harvard.edu

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Rich Clusters of Galaxies: General Optical Properties

- A great deal of our knowledge of rich clusters of galaxies comes from photographic surveys with wide field optical telescopes.
- Clusters with > 50 galaxies within two magnitudes of the brightest, and within a circle of 3 Mpcs diameter are defined as rich clusters with a richness parameter in the range 0 - 5 dependent on the number of galaxies (5 is the richest class).
- The luminosity density in the universe is ~ 2×10^{8} $L_{\odot}$ Mpc^{-3} or ~ 0.01 - 0.02 galaxies per Mpc^{3}.
- The galaxy density in groups corresponds to an over-density, $\Delta\rho/\rho$ ~ 100 but this refers to a small number of galaxies in a very small volume.
- Rich clusters have $\Delta\rho/\rho > 100$ and they contain many galaxies. The overall scale is ~ 5 Mpc.
- This makes it clear that they exist in an extreme environment.
- The highest $\Delta\rho/\rho$ ~ 1000 in compact groups of galaxies.

- In this compact group we see that galaxy-galaxy separations are of the order of the sizes of the galaxies themselves.
- The vast majority of galaxies are in groups of ~ 5 – 50 galaxies over a few Mpc.

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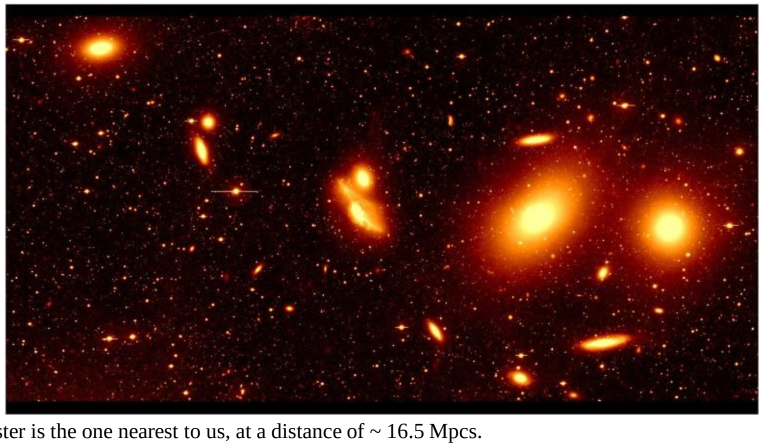
Rich Clusters of Galaxies: Cluster Statistics



- The Virgo cluster is the one nearest to us, at a distance of ~ 16.5 Mpcs.
- It only just qualifies as a rich cluster. It extends over 6° on the sky (12 times the diameter of the moon). Isolated galaxies do not really appear to exist.
- Approximately 5% of all galaxies are in rich clusters and only 1% of galaxies are present in the dense inner regions of rich clusters.
- In galaxy clusters the separation between galaxies is often of the order of the galaxy sizes themselves.
- The large and small Magellanic clouds are very close to our own Galaxy, for example.
- We can compare this with the situation for stars within a galaxy where the ratio of separation:size is ~ 10^{8}, and is >> 1 even in the core of globular clusters.
- Even for relatively sparse groups, where $\Delta\rho/\rho$ ~ 100, the separation:size ~ 10.
- This means that interactions - collisions etc., are important for galaxies.

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Rich Clusters of Galaxies: Masses of Galaxies and M/L Ratios

- We know from studies of spiral galaxies that their mass to light ratio, M/L ~ 4 in solar units.
- In the case of elliptical galaxies typical values of M/L ~ 30.
- Studying the velocity dispersion in a rich cluster of galaxies such as the Coma cluster (see figure) shows us that for the cluster as a whole, M/L ~ 600.
- It is this discrepancy that gives us the idea of ***missing mass*** in the cluster.
- The mass to light ratios in individual galaxies will include their gas content because they are derived dynamically.
- However there is also some of the "missing mass" that is contained in the gas that permeates the cluster.

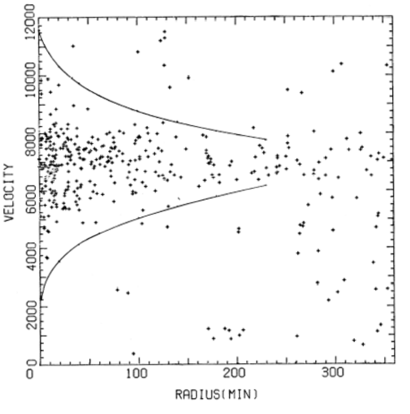

FIG. 1. Distribution of radial velocities in Coma as a function of distance from the cluster center.

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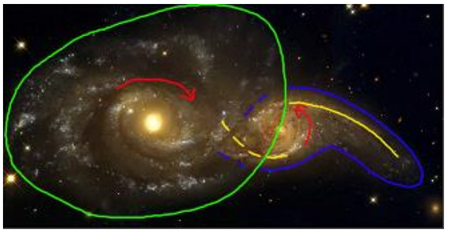
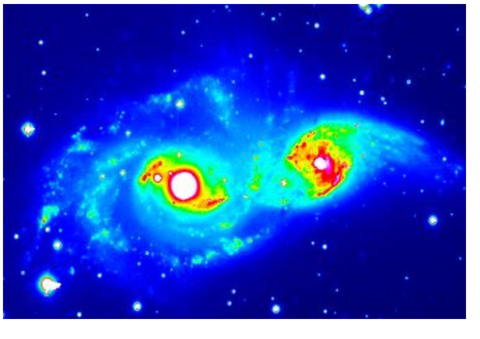
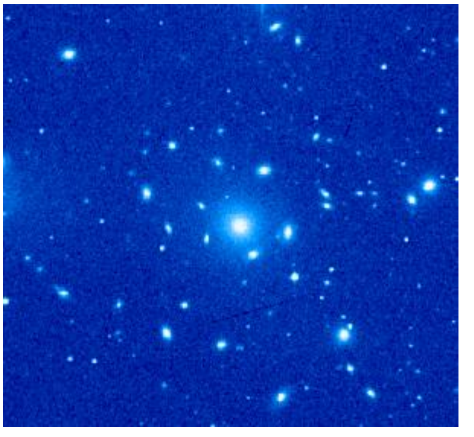
Rich Clusters of Galaxies: The Dynamics of Galaxy Interactions

- The dynamics of galaxies in groups and clusters are very complicated. For example here, the clockwise rotating NGC 2207, the bigger one, is in front of IC 2163. Both are marked with their motions and relative positions.
- The dashed lines indicate which parts are further away from the observer.
- This kind of complex interaction is very common in the centres of rich clusters of galaxies.
- These interactions will clearly mix the stars and galaxies very thoroughly and greatly affect the apparent structure of the final outcome.



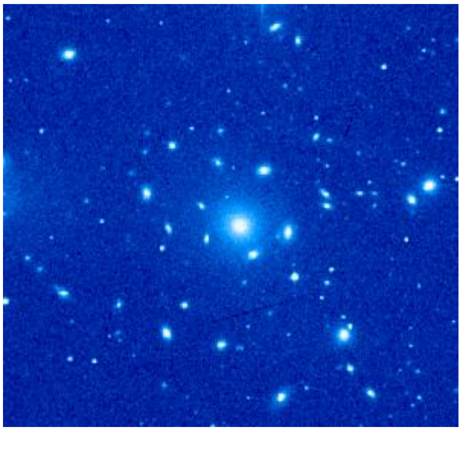


Rich Clusters of Galaxies: Dynamical Stability



- Rich clusters of galaxies are likely to be in equilibrium because they appear to be stable and long-lived.
- We can use the virial theorem which says that $2KE + PE = 0$.
- We can estimate the kinetic energy ($\frac{1}{2}mv^2$) from motions of the galaxies.
- We only detect the line of sight radial velocity, v_r relative to the cluster centre of mass. However if we assume that the velocities are random then we can show that $\langle v_r^2 \rangle \sim 1/3 \langle v^2 \rangle$. The exact relation depends on the detailed orbits of the galaxies.
- The total $KE = (3/2)\, Nm \langle v_r^2 \rangle$, where N is the number of galaxies and m is the mass of a galaxy.
- $PE \sim -GM^2/R$, where $M = mN$. The exact value of PE depends on the shape of the cluster. If the cluster is spherical then $PE = -(3/5)GM^2/R$

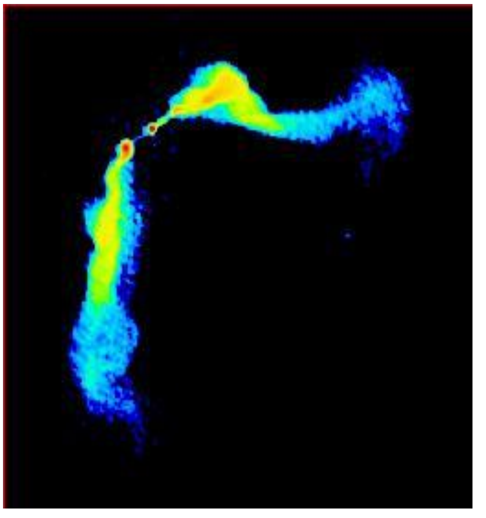
Rich Clusters of Galaxies: Dynamical Stability



- The Coma cluster is the nearest properly rich cluster, with a richness class = 3.
- It is at a distance of ~ 100 Mpc and contains ~ 1000 bright galaxies. The cluster diameter is ~ 7 Mpc.
- By using a histogram of the galaxy radial velocity measures we can determine the velocity dispersion of the cluster, σ_r. This gives us $(\langle v_r^2 \rangle)^{1/2} = \sigma_r \sim 1040$ kms^{-1}
- Within a radius of ~ 3 Mpc we find using the virial theorem that the virial mass M is given by $M = 5\, \sigma_r^2 R/G = 3.3\times10^{15}\, M_\odot$.
- The measured luminosity is ~ $5\times10^{12}\, L_\odot$, so M/L ~ 660 in solar units.
- The mass in stars is ~ $3\times10^{13}\, M_\odot$ so $(M/L)_{stars} \sim 6(M_\odot/L_\odot)$.

Rich Clusters of Galaxies: Intergalactic Matter and Magnetic Fields

- 3C465 is a radio galaxy that appears bent in a wide C-shape.
- It is located in the central region of the rich cluster of galaxies Abell 2634.
- The radio image here shows that two very narrow, well collimated jets emanate from the core of the galaxy.
- Suddenly, at the same distance from the core, each becomes wider and bent. This particular shape may be the result of the interactions of the jets with their environment.
- We will remember that the bright radio galaxies occur preferentially in rich clusters of galaxies. There are many examples of morphologies like this for AGNs in clusters of galaxies.
- The origin of this morphology is probably the motion of the AGN (and its linear jets) through the cluster medium threaded by an intergalactic magnetic field.
- What is the nature of this intra-cluster medium and does it contribute significantly to the mass of clusters?



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Rich Clusters of Galaxies

- Here are some examples of the complex structure that we see near bright radio sources, embedded in rich clusters of galaxies.
- The top picture is of the Virgo cluster with a central radio source, M87.
- The lower picture is of the radio source in the Seyfert galaxy NGC1265 in the Perseus cluster of galaxies.
- These structures are likely to be due to the presence of an intracluster medium.
- The strong synchrotron radio emission from these objects also makes it clear there has to be an intergalactic magnetic field.

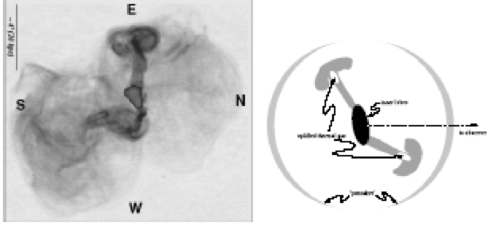

Figure 4: Left: 14′.6 × 16′.0 radio map of M87 (North to the right, East is up) (from Owen et al. [34]). Right: Suggested source geometry. The central black region denotes the inner radio lobes, the gray "mushrooms" correspond to buoyant bubbles already transformed into tori, and the gray lens-shaped structures are "pancakes" (seen edge-on) possibly formed by older bubbles [7].

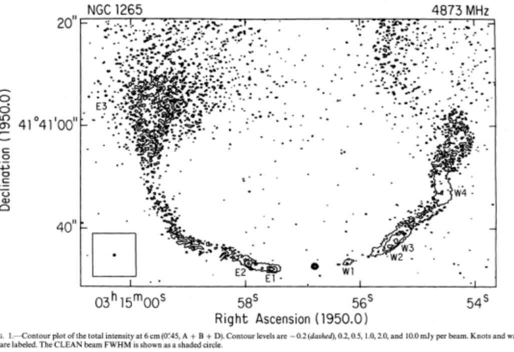

FIG. 1.—Contour plot of the total intensity at 6 cm (0".45, A + B + D). Contour levels are −0.2 (*dashed*), 0.2, 0.5, 1.0, 2.0, and 10.0 mJy per beam. Knots and warm spots are labeled. The CLEAN beam FWHM is shown as a shaded circle.

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Rich Clusters of Galaxies: Extended X-ray Emission

- We also see in many rich galaxy clusters extended x-ray emission often centred on the dominant cluster galaxy (a so-called cD galaxy).
- If the gas particles in the middle of the rich cluster have the same velocity dispersion as the galaxies (which is $\sim 1{,}000$ kms^{-1}) then we would expect from $kT \sim v^2$, a gas temperature of $T \sim 10^8$K. A temperature determined in this way is called a ***virial temperature***.
- This would certainly account for the x-ray radiation we see.
- Even relatively poor clusters of galaxies can show significant x-ray emission.
- The next two slides shows the extended x-ray emission from the gas in the Coma cluster.

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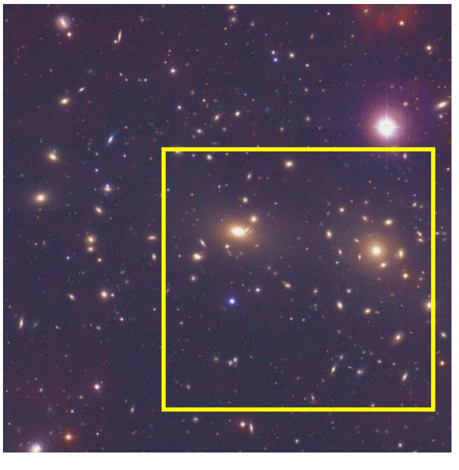
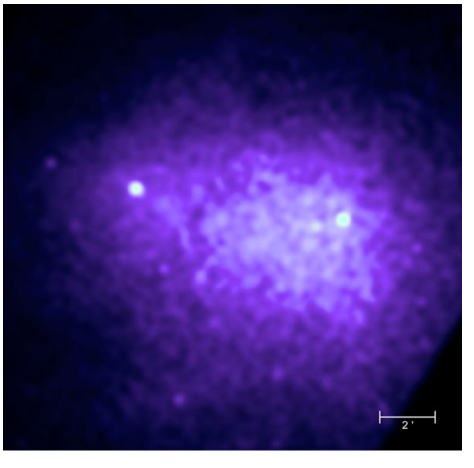
The Coma cluster





Optical

X-ray (Chandra)

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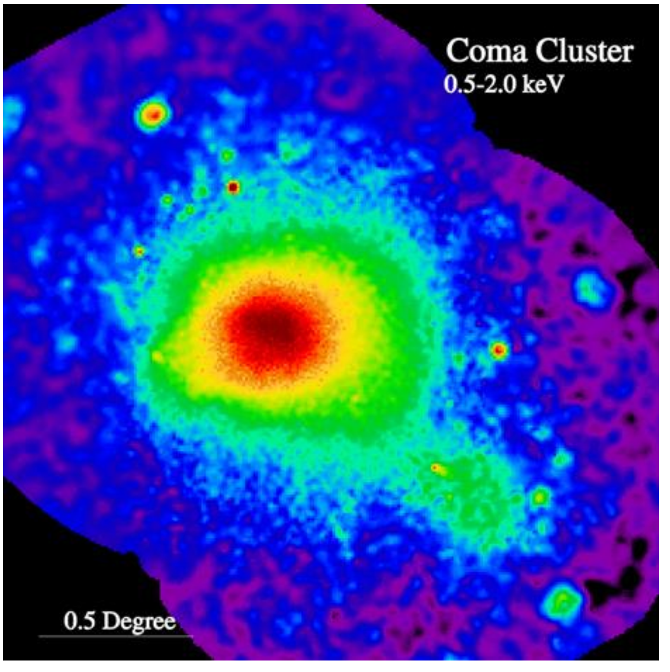
Mass of gas is $\sim 3 \times 10^{14}$ solar masses



ROSAT image of the Coma cluster

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Free-free X-rays from the Coma cluster of galaxies

Temperature obtained by fitting a model to the observed spectrum.

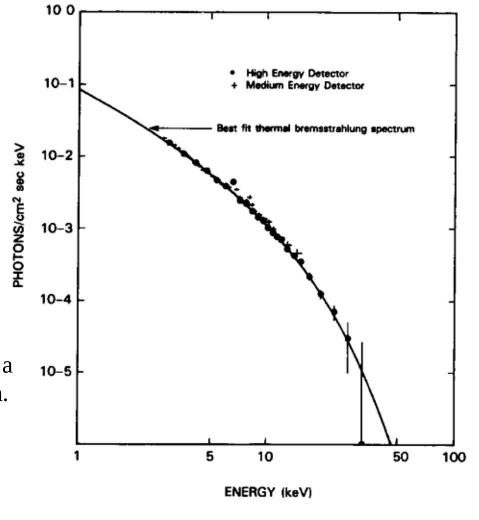

Figure 25.18 Thermal bremsstrahlung spectrum (line) for 88 million K. The points are observations of x-rays from the Coma cluster's intracluster gas. Photon energy is plotted on the horizontal axis. (Figure from Henriksen and Mushotzky, *Ap. J.*, *302*, 287, 1986.)

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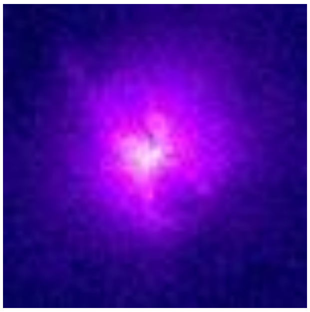
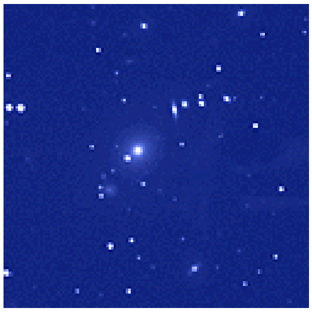
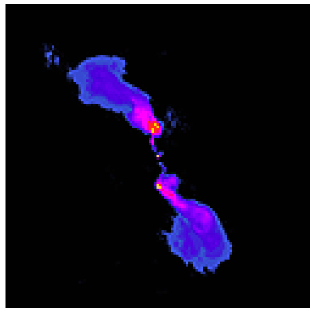
Rich Clusters of Galaxies: Multi-wavelength imaging







- These images show the very distant (z=0.54) Hydra cluster in: x-rays from Chandra (on the left); in the optical (centre); and a radio wavelengths (on the right).
- The size of this field is approximately one Mpc square.
- They make it clear just how extended the x-ray emission is from this rich regular cluster.
- Optical observations show a few hundred galaxies in the cluster.
- The Chandra X-ray observations reveal a large cloud of hot gas that extends throughout the cluster.
- The gas cloud is several million light years across and has a temperature of about 40 million degrees in the outer parts decreasing to about 15 million degrees in the inner region.
- In the very central regions the gas temperature is significantly cooler with the ***virial temperature*** closer to the velocity dispersion of the material within the central galaxy.

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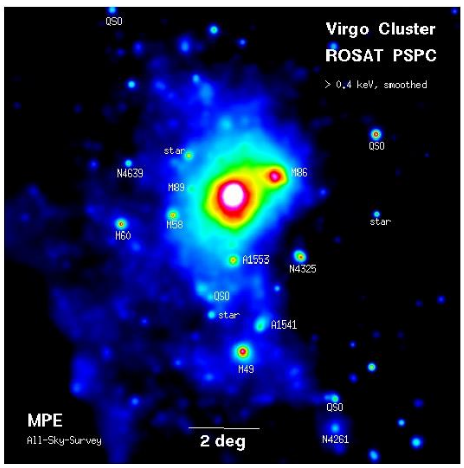
Rich Clusters of Galaxies: X-ray Tracing of the Gas Properties



- This image is of the whole of the Virgo cluster imaged by ROSAT in x-rays.
- Many of the individual galaxies can be identified easily but the image is dominated by extended diffuse luminous emission.
- Assume the gas is in hydrostatic equilibrium. (M_r is mass interior to r) $$\frac{dP}{dr} = \frac{-GM_r\rho}{r^2}$$
- Assume an ideal gas. $$P = nkT = \frac{\rho}{\mu m_H}.kT$$
- substituting for ρ to eliminate P we get:

$$M_r = \frac{-kT_r}{\mu m_H G}\left(\frac{\partial \ln\rho}{\partial \ln r} + \frac{\partial \ln T}{\partial \ln r}\right)$$

- The x-ray emission depends on the temperature and density of the gas so we can determine the RHS of this equation from observations and hence derive a mass.
- The x-ray observations confirm the gas properties as follows: In Hydra, the virial temperature is ~ $2\text{x}10^7 – 10^8$ K, the density is ~ $10^2 – 10^4$ m^{-3} (x100 lower than best lab vacuum of 10^{-17} torr), radius is ~ 1 – 2 Mpc, luminosity ~ $10^{36} – 3\text{x}10^{38}$ Js^{-1}, mass is $5\text{x}10^{13} – 5\text{x}10^{14}$ $M_\odot$ and the metallicity ~ Solar.

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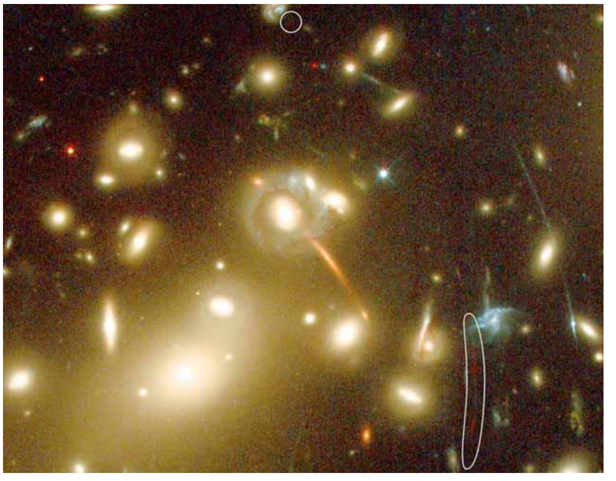
Rich Clusters of Galaxies: Cosmological Telescopes



- Rich clusters of galaxies are the largest and most massive bound structures in the Universe.
- They provide a powerful test of cosmological models as well as of the theory of the structure and formation of galaxies.
- The rich clusters provide an extreme environment for galaxies and allow us to investigate the influence of the environment on galaxy evolution. We can compare galaxy evolution in rich clusters with that in low-density environments.
- They provide constraints on the distribution and the amount of dark matter which is needed to bind the clusters.
- They also are important as gravitational telescopes because of their lensing effect on much more distant objects.
- This cluster, Abell 2218 , has a gravitationally lensed image of possibly one of the most distant objects ever detected, a galaxy with z ~ 7.

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Rich Clusters of Galaxies: Dark Matter

- We can undertake a mass census within a cluster. For example, for the Coma cluster:

  virial (total) mass ~ $3.3 \times 10^{15}\, M_\odot$

  mass in stars ~ $3 \times 10^{13}\, M_\odot$

  mass in the x-ray emitting gas ~ $1 \times 10^{14}\, M_\odot$

- So the hot gas mass exceeds the mass in stars.
- It also tells us that $(M_{total}/M_{gas+stars})$ ~ 20-30, so there is clearly a lot of dark matter.
- However the primordial nucleosynthesis constraint tells us that $\Omega_{baryons}/\Omega_{critical}$ ~ 0.01 - 0.02
- So if the only baryons are in the form of gas and stars and the clusters are a fair sample of the ratio of baryons to dark matter then we deduce that $\Omega \sim 0.3\, \Omega_{critical}$.
- This was one of the first arguments in favour of $\Omega < \Omega_{critical}$.

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Rich Clusters of Galaxies: Origin of X-ray Emission

- The x-rays that we see from the gas in the cluster are due to free-free radiation: electrons which are accelerated by nuclei or ions. It is also sometimes called thermal bremsstrahlung.
- The energy loss for an electron is $\propto Z^2 N_i v$, where Z is the ionic charge, N_i is the density of ions and v is the relative velocity which is $v \propto T^{½}$.
- For each ion there is approximately one electron so $N_i \sim N_e$.
- This tells us that the emission per unit volume of gas is $\propto Z^2(kT)^{½} N_i N_e \propto T^{½} N_e^2$. –(*)
- The spectrum of radiation has a cut-off at high frequencies where $h\upsilon_c \sim m_e v^2$.
- The low frequency cut-off occurs when the gas becomes optically thick and electrons absorb photons.

- The intra-cluster medium interacts with the gas in galaxies and the gas in the extended structures of the active galactic nucleus.
- For a galaxy moving through the cluster, momentum is transferred to the gas within the galaxy.
- If the density of the intracluster medium is ρ_o, and the galaxy is moving with a velocity of v and has a surface area A then the momentum transferred (force) is $\rho_o v^2 A$.
- If the surface density of the gas within the galaxy is μ and the mass surface density in the galaxy is μ_T, we know that $\mu_T >> \mu$.
- Then the gravitational field due to the disk is $2\pi G\mu_T$, and the force holding the disk of the gas to the galaxy is $2\pi G\mu_T\mu A$.
- Comparing forces tells us that the gas will be stripped from a galaxy if the density $\rho_o > (2\pi G\mu_T\mu/v^2)$.
- Exercise: put in typical numbers for a galaxy in a rich regular cluster such as v ~ 1000 kms^{-1}, and use r_{gal} ~ 10 kpc, $M_{disc} \sim 5\mathrm{x}10^{10}\, M_\odot$ and $M_{gas} \sim 5\mathrm{x}10^{8}\, M_\odot$ to work out μ and μ_T.

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Rich Clusters of Galaxies: Masses from X-ray Observations

- We can measure the x-ray mass of a cluster by fitting a theoretical model. For example, use a singular isothermal sphere (SIS)

$$\rho(r) = \frac{K}{2\pi G r^2} \qquad \rho = \rho_c \exp\left(-\frac{\Phi}{K}\right)$$

- to predict the cluster's observed radial surface brightness distribution as follows……

- The observed surface brightness is normalized to its central value and is given as a function of the angular distance from the cluster centre (see examples on the next slide).
- Chose the cluster mass and gas distributions $\rho(r)$ (our parametric model).
- Let us use a simple isothermal sphere model with T(r) = constant.
- And let the mass density be given by [1]:

$$\rho = \rho(0)\left(1+\left(\frac{r}{r_c}\right)^2\right)^{\frac{-3}{2}} \qquad [1]$$

- and the gas density by [2]: more realistic than SIS because $\rho(0)$ is the density at r = 0 which is finite.

where r_c = core radius.

$$\rho_g = \rho_g(0)\left(1+\left(\frac{r}{r_c}\right)^2\right)^{\frac{-3\beta}{2}} \qquad [2]$$

- This model then predicts the observed surface brightness from [3] (integrate (*) from the previous slide) at a projected distance (or angle) from the cluster centre.

$$\int n_e^2 dl \qquad [3]$$

- We get the temperature T from the observed x-ray spectrum.
- We then adjust r_c and β to achieve the best fit, and normalise the density from the x-ray luminosity information.
- The mass and the gas distribution satisfy hydrostatic equilibrium if [4] applies (where σ^2=K):

$$\frac{T_{mass}}{T_{gas}} = \beta = \frac{\mu m_H \sigma^2}{kT}\left(\beta = 1\right) \qquad [4]$$

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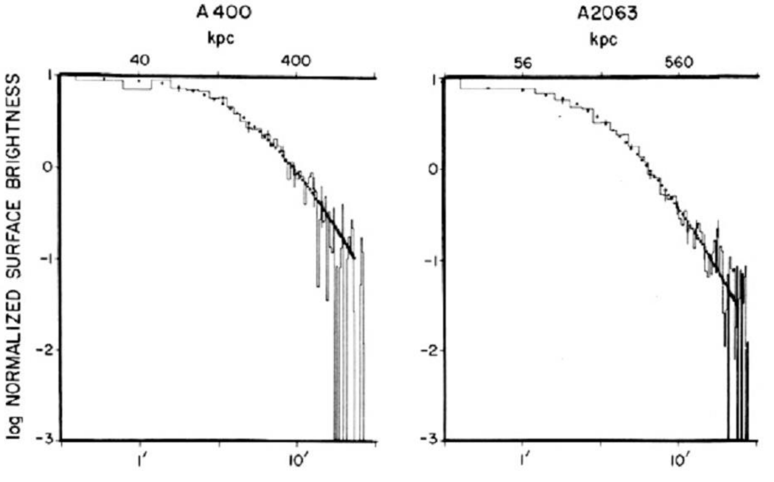
Rich Clusters of Galaxies: Masses from X-ray Observations



- The solid curves give the observed surface brightness, and the dots are the best fit using the above model, projected on to the sky.
- The mass is obtained by integrating the best fitting density profile.

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Rich Clusters of Galaxies: Tidal Stripping

- The gravitational field of the cluster of mass M(R) can rip galaxies apart.
- If we consider a galaxy with mass *m* and a radius r, then as it approaches the centre of the galaxy cluster at a distance R from the centre then the galaxy experiences an acceleration given by:

$$\frac{v^2}{R} = \frac{GM(R)}{R^2}$$

- The nearside and the far side of the galaxy experience different accelerations given by: $\frac{GM(R)}{(R-r)^2}$ and $\frac{GM(R)}{(R+r)^2}$
- for r << R the force difference is: $\approx \frac{2GM(R)r}{(R)^3} > \frac{Gm}{r^2}$
  since the galaxy itself is held together by a force of G*m*/r^2
- when we have the condition [tidal force] > [binding force]:
- Then the galaxy is tidally disrupted.
- This occurs when the galaxy approaches to a distance: $R \le \left(\frac{2M(R)}{m}\right)^{\frac{1}{3}}.r$

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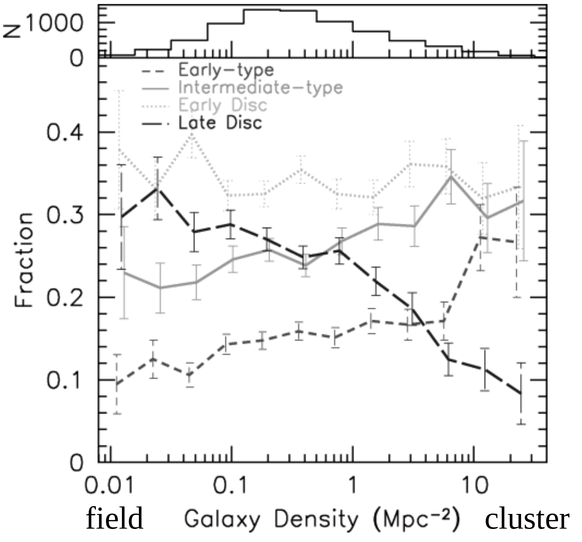
Rich Clusters of Galaxies: Tidal Stripping

- The figure here shows the morphology-density relation, the plot of the relative numbers of galaxies of different types as a function of the projected local galaxy density.
- The early type galaxies are ellipticals and the late disk type galaxies are spirals.
- There is a clear tendency for spirals to be depleted within clusters relative to ellipticals.
- This is one of the more impressive correlations in extragalactic astronomy.
- It fits in well with ideas that the evolution of galaxies are very much influenced by their environment.



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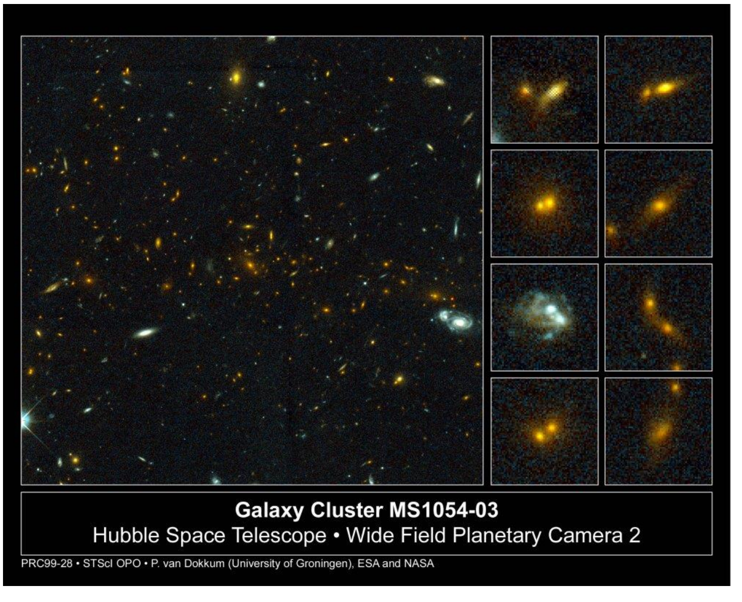
Rich Clusters of Galaxies: Tidal Stripping



24 This distant cluster (z = 0.82) possesses many examples of galaxy-galaxy interactions.

Rich Clusters of Galaxies: Sample Selection for Evolution Studies

- When studying galaxies there are so many apparent affects that are due to distance, redshift and age that we have to be very careful in choosing a well-defined sample.
- There are only a very few rich clusters: they are intrinsically very rare.
- If we select galaxies optically then we have problems with projection effects. We will generally assume that the mass is proportional to the number of galaxies.
- For example, what happens if we have two groups of galaxies each with N ~ 25 members that are projected together on the sky?
- With optical samples we have serious problems with the swamping of cluster galaxies by background (more distant) and foreground (closer) galaxies.
- If however we use x-rays then we will bias this in the sense that the mass we will find is proportional to the gas mass and the gas density. This is because $L_x \propto \rho_{gas}^2$, and so $L_x \propto M^2$.
- This selection method will be much less sensitive to projection effects.
- In addition the surface density of resolved x-ray sources is very low so that swamping by background and foreground sources is not a major problem.
- We should therefore find the most massive clusters by locating the most x-ray luminous clusters.

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Rich Clusters of Galaxies: Standard Rulers

- Because the radiation is free-free emission from an x-ray gas we find that the emission E is proportional to the integral of the electron density squared along the line of site, n_e^2.

$$E \propto \int n_e^2 dl$$

- However, if we imagine that we could look at a background source behind the cluster then the radiation from that source will experience an absorption A which will be proportional to the integral of the electron density along the line of sight, n_e.

$$A \propto \int n_e \, dl$$

- We can measure the emission and the absorption and deduce the density weighted measure of the path length through the cluster, $A^2/E = L$.
- We can also measure the angular size of the x-ray emitting gas in the cluster, Θ .
- Applying this to distant clusters gives the redshift z from Θ and L (at least in principle it does).
- So in principle we could have a measure of the angular diameter distance. We could determine the Hubble constant directly and constrain the geometry given a sample of clusters with a range of redshift.
- Under what circumstances might this work?

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Rich Clusters of Galaxies: The Sunyaev-Zel'dovich (S-Z) Effect

- Measuring the x-ray emission from a gas is possible but measuring the absorption is not yet viable.
- However photons from the Cosmic Microwave Background (CMB) are affected by passing through the gas in a cluster.
- The gas density is very low and so multiple electron-photon collisions can be neglected.
- The optical depth is related to the probability that a photon will interact with the gas. It is given by $\tau_e = n_e \sigma_T L$ where n_e is electron density, σ_T is the Thompson cross-section, and L is the path length.
- Electrons dominate the cross-section because the electron-photon cross-section is >> the nuclei-photon cross-section.
- Compton scattering photon-electron interactions are when the electrons gain energy because they start essentially at rest.
- However a cluster contains many fast moving electrons and their interaction is with lower energy photons. This leads to inverse-Compton scattering in which the photons gain energy.
- The calculations for Compton scattering and inverse Compton scattering are identical but in inverse Compton scattering we do the computation in the frame in which the electron starts at rest.
- For clusters, the electron velocities are sufficient to increase the energy of low energy photons from the Cosmic Microwave Background.
- At v << c, the scattering is almost elastic and so we have essentially classical Thompson scattering.
- The frequency shift for a CMB photon scattered by an electron is given by: $\frac{\Delta\upsilon}{\upsilon} = \frac{\Delta E}{E} = \frac{kT_e}{m_e c^2}$
- The photon energy increases and therefore the apparent temperature of the CMB also increases.

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Rich Clusters of Galaxies: The Sunyaev-Zel'dovich (S-Z) Effect

- This figure shows the distortions that one gets as a consequence of the S-Z effect both in terms of the change in flux that one sees and also in terms of the brightness temperature observed.
- The consequence is that the (remarkably uniform) cosmic microwave background radiation is distorted by the presence of a cluster of galaxies and this can be detected at radio wavelengths.
- At high frequencies the CMB intensity and temperature are increased by the cluster whereas at low frequencies they are decreased.

ν=30Ghz is λ=1cm, observe here

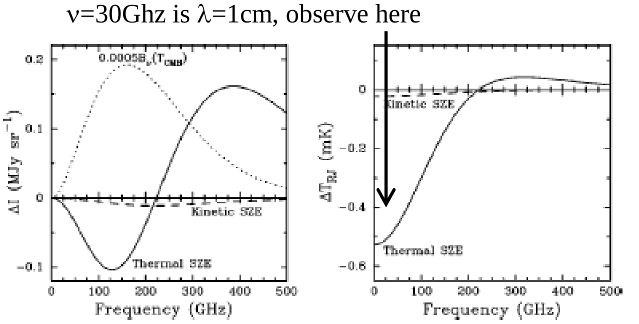

Figure 2 Spectral distortion of the cosmic microwave background (CMB) radiation due to the Sunyaev-Zel'dovich effect (SZE). The left panel shows the intensity and the right panel shows the Rayleigh Jeans brightness temperature. The thick solid line is the thermal SZE and the dashed line is the kinetic SZE. For reference the 2.7 K thermal spectrum for the CMB intensity scaled by 0.0005 is shown by the dotted line in the left panel. The cluster properties used to calculate the spectra are an electron temperature of 10 keV, a Compton *y* parameter of 10^{-4}, and a peculiar velocity of 500 km s^{-1}.

- Kinetic SZE is due to bulk motion of the whole cluster with respect to the CMB rest frame.
- The thermal SZE is due to the particle motion of cluster gas with respect to the CMB rest frame.

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Rich Clusters of Galaxies: The Sunyaev-Zel'dovich (S-Z) Effect

- Radio telescopes are used therefore to look for 'dips' in the background in order to identify clusters independently of any concerns of galaxy over-density.
- The background decrement is measured for known clusters of galaxies in the Rayleigh-Jeans portion of the CMB spectrum.

$$\frac{\Delta I_\upsilon}{I_\upsilon} \approx 2\tau_c \frac{\Delta E}{E}$$

- By combining these data with x-ray measurements of clusters we can measure the Hubble constant, H_o (at least in principle).
- However, quantifying the decrement is not easy since the effect is only of the order of ~ 10^{-4} even for the richest, most massive clusters.

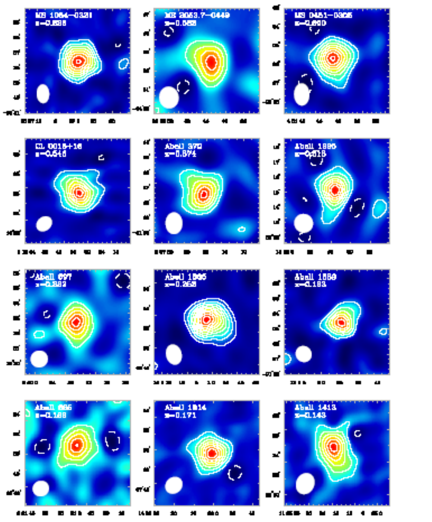

Figure 3: Images of the Sunyaev-Zel'dovich effect toward twelve distant clusters with redshifts spanning 0.83 (top left) to 0.14 (bottom right). The evenly spaced contours are multiples starting at ±1 of 1.5σ to 3σ depending on the cluster, where σ is the rms noise level in the images. The noise levels range from 15 to 40 μK. The data were taken with the OVRO and BIMA mm-arrays outfitted with low-noise cm-wave receivers. The filled ellipse shown in the bottom left corner of each panel represents the FWHM of the effective resolution used to make these images.

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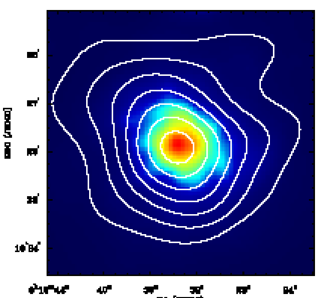
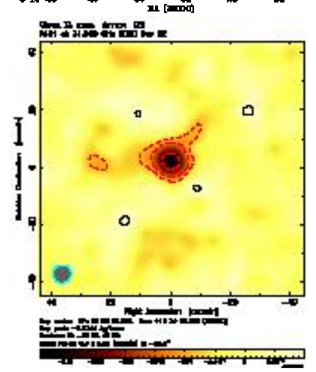
Rich Clusters of Galaxies: The Sunyaev-Zel'dovich (S-Z) Effect

- There is a good correlation between the S-Z effect and the distribution of x-ray emission over a cluster of galaxies. An example is shown in this figure.
- Here the S-Z effect data are shown as contours which overlay the image of x-ray emission in false colours for the Galaxy cluster CL0016+16.
- Generally however, it is very difficult to detect.
- The lower image shows the background fluctuations in another cluster, Abell 401.
- The full width half maximum resolution is just over six minutes of arc and the peak temperature difference that is detected is only 300 μK. The noise level is approximately 20μK.





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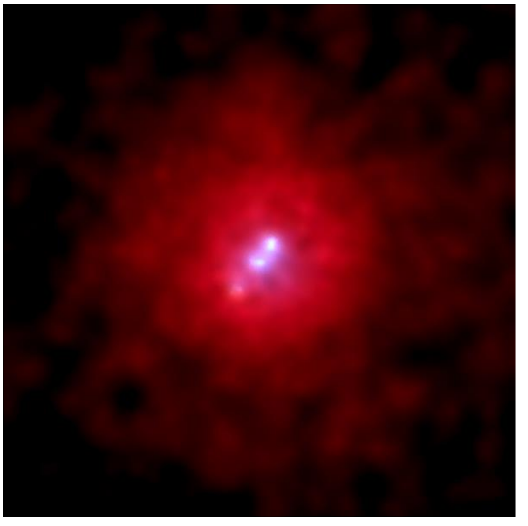
Cooling Flows

- The bright x-ray emission in the centre of this image indicates that the gas there is cooling rapidly (through radiative cooling).
- The central gas will therefore lose pressure and will be unable to support the outer parts.
- Gas therefore flows from the outer parts in to the centre.
- This is called a ***cooling flow***.
- They are seen in most clusters of galaxies, some small clusters and groups, and large isolated elliptical galaxies.



Chandra x-ray image of
the cluster containing 3C295

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Cooling Flows: cooling time suggests something is heating the gas

- For about two thirds of x-ray-bright rich clusters the gas in the core has a central radiative cooling time that is typically smaller than the Hubble time.
- The remaining one third of bright rich clusters are often merging or dynamically active, for example where there are two giant ellipticals near the centre and a lot of sub-clustering within the cluster. In these cases it is likely that the x-rays are coming from these interactions rather than the intergalactic medium.
- In those clusters which show very intense x-radiation from near the core there is a major issue because they ought to have cooled down a long time ago. This means that there has to be something else happening inside the cluster to keep the gas hot.
- The inward collapse of the gas as it cools may be restrained by 1) magnetic fields or 2) the energy generated in the presence of a super massive black hole at the core of the central galaxy in the cluster.

Chandra image of the galaxy
cluster Abell 2142 in X-rays.

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Cooling Flows

- The cooling time can be shown to be, for a simple gas model, $t_{cool} \propto T^a/\rho$.
  With -1/2 < a < 1/2.
- The cluster is much denser in the centre and therefore cools faster there.
- Because the gas throughout the cluster is essentially supported by pressure then the cooling of the central gas reduces the pressure and causes material to fall towards the centre, increasing the density and accelerating the process of cooling the gas.
- This means we expect the cores of clusters to be really quite cool and so we have to address the basic problem of how is it that cooling of the gas below a certain temperature (which is approximately one third of the virial temperature of the cluster) is suppressed?
- This is significant because within individual galaxies the gas must be cool enough to allow gas clouds to form which then in turn give rise to star formation.
- We should be able to observe cooling in clusters and groups of galaxies, and it may be that the suppression of cooling in the largest objects can explain the upper mass cut off of galaxies.

Chandra image of the galaxy cluster Abell 2142 in X-rays.

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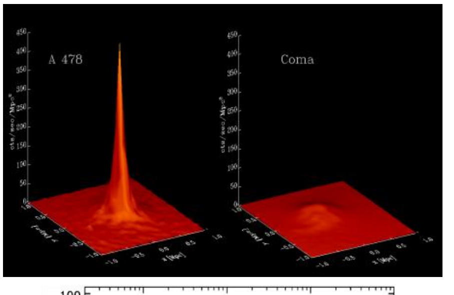
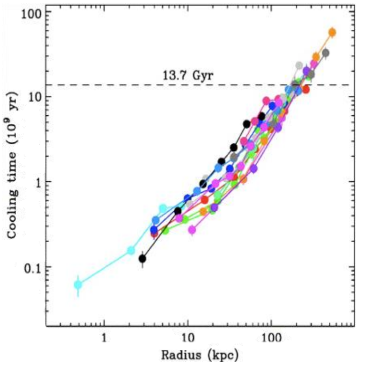
Cooling Flows: cooling timescales

- The profiles on the right show the difference between the very centrally condensed x-ray emission from the majority of rich clusters compared with the emission from the minority which are much more diffuse and are generally associated with clusters with interacting galaxies.
- By looking at the conditions within the cluster we can work out a cooling timescale as a function of distance from the cluster centre.
- This is what is shown in the lower figure opposite where it is clear that the cooling times towards the centre of these clusters can be very short.





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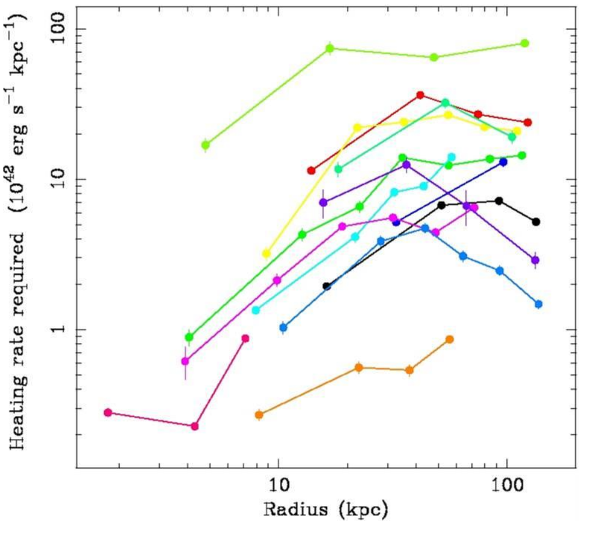
Cooling Flows: required heating rates

- We can also see that the energy demands are quite severe.
- We can translate the figure on the previous slide into the heating rate required in order to maintain the temperature profile that we see in these different clusters.



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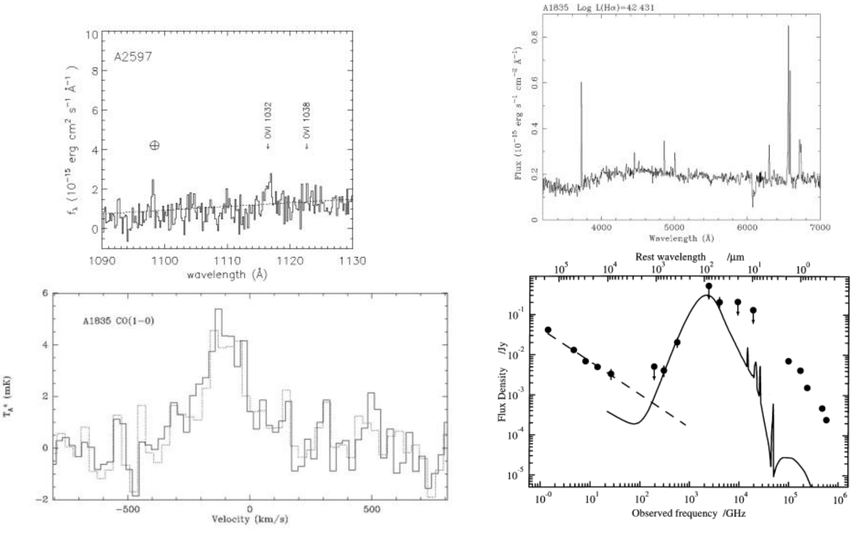
Cooling Flows: directly detecting cool gas



- Things are further complicated because clusters are generally non-uniform. There is no doubt that there is some cool gas and young star populations in these objects.
- These plots show detection in different galaxies of UV, H-alpha, CO and dust, all indicative of low temperatures.

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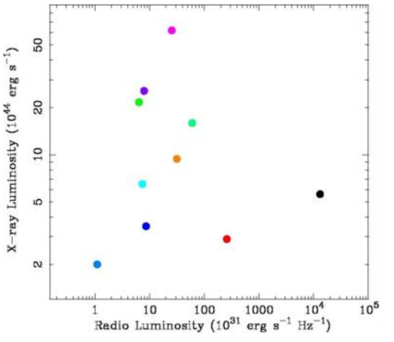
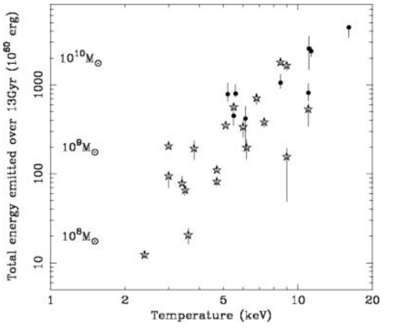
Cooling Flows: AGN

- What may be an important clue is that most clusters with an apparent cooling problem contain an active galactic nucleus/radio source. The most luminous clusters at x-ray wavelengths are also very luminous at radio wavelengths as well.
- These AGN may be the source of the extreme levels of energy required for luminous clusters to sustain the temperature in the centre of the clusters at a level consistent with what we observe.





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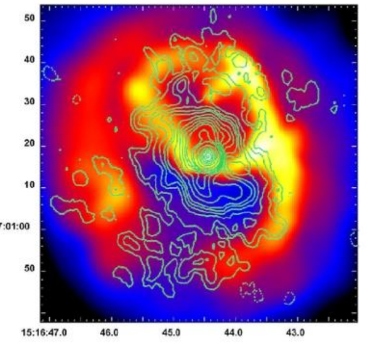
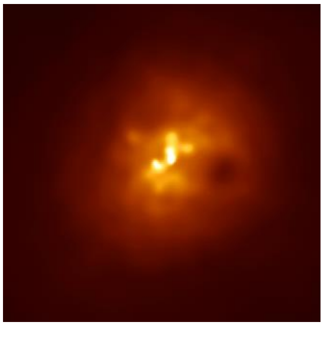
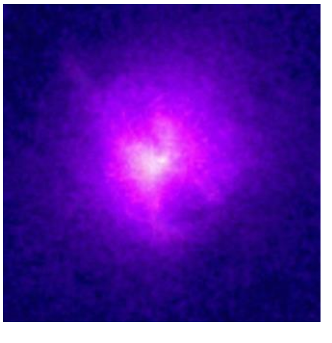
Cooling Flows: x-ray and radio images

- Looking at the radio images (top right) we see complex structures in the general background emission with cavities and bubbles clearly visible.
- High-resolution x-ray images of these clusters (lower pair) also show a relatively complex structure.
- This is true both of nearby and of much more distant clusters such as the one at the bottom right.







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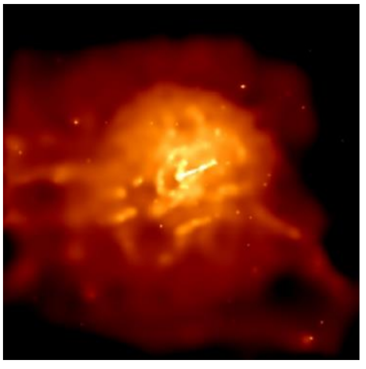
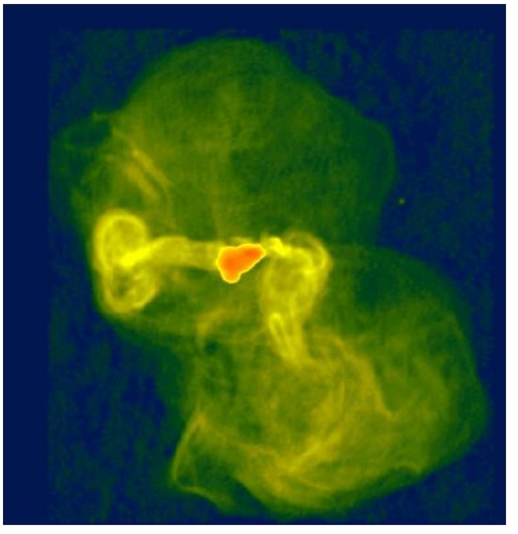
Cooling Flows: x-ray and radio images

- These are images of M87 taken at x-ray wavelengths (left hand side) and at radio wavelengths (on the right).





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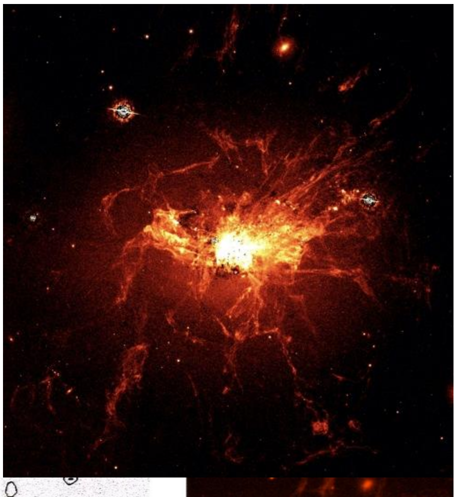
Cooling Flows: NGC1275



Young blue stars in the outer regions of NGC 1275 (Canning et al. 2010a)

- These are images of NGC1275, a nearby Seyfert I AGN galaxy, taken in H alpha (top right) and at CO radio wavelength (lower middle).

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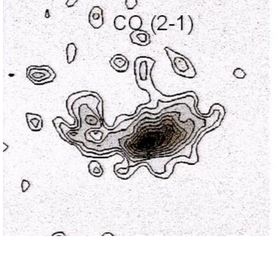
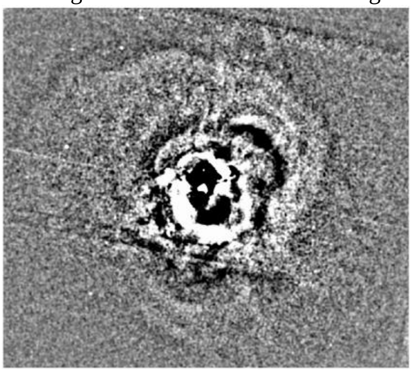
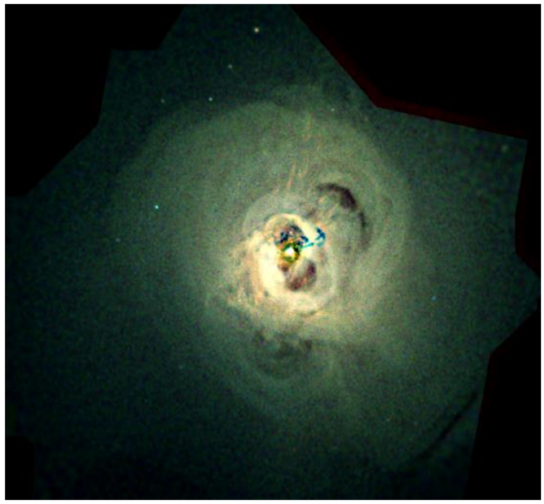


Cooling Flows: weak shocks

- Deep Chandra x-ray images of the galaxy at the centre of the Perseus cluster, NGC1275, were processed to remove the smooth background radiation so as to reveal the fine scale structure that is superimposed upon it.
- The radio bubbles from the supermassive black hole in the centre of the cluster displace the X-ray emitting gas, leading to the four cavities in the image.





- These pictures were obtained by Andy Fabian of the Institute of Astronomy

Cooling Flows: weak shocks

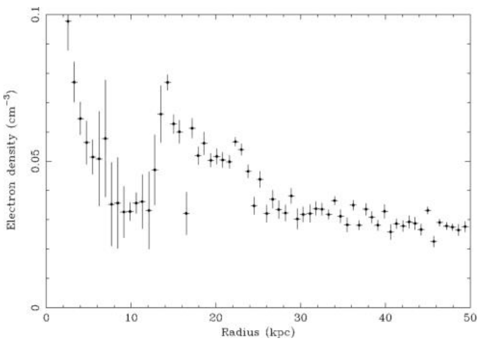
- There appear to be structures which may be bubbles propagating out from the centre.
- Bubbles make sound waves with a long period (~10^7 years). They will create weak shocks with some dissipation.
- Further out, dissipation depends on viscosity. The viscosity in this context is given by [1]:

  And the luminosity it generates will be of the form given by [2]:

- Within Perseus there is good evidence of a weak shock to the northeast of the core. We can plot the electron density as a function of radius within the cluster (see figure).
- This type of shock would produce enough viscous heating to balance the radiative cooling in the inner 50 kpc of the Perseus cluster.

$$\upsilon \sim 10^8 T^{5/2} \rho^{-1} \qquad \text{- [1]}$$

$$\frac{L}{\lambda} \sim \frac{3}{16\pi^2}\frac{c\lambda}{\nu} \qquad \text{- [2]}$$



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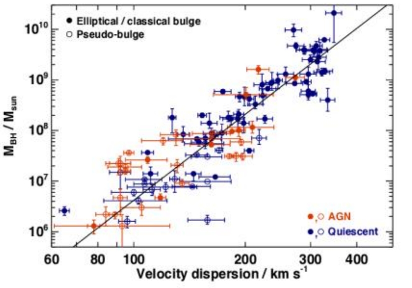
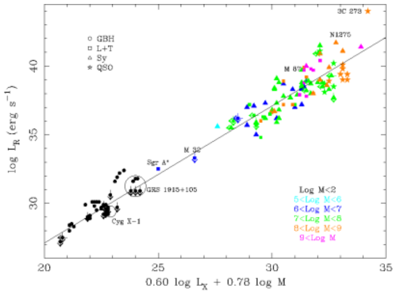
Galaxy Correlations

(Heckman & Best, 2014)

- There is such a wide variety of galaxy types that correlations between key physical parameters should be taken very seriously.
- One shows the correlation between the velocity dispersion of the stars in the bulge of the Galaxy and the blackhole mass.
- Another links the radio and X-ray luminosity combined with mass.
- These correlations are being used actively to better understand what parameters appear to be universal in Galaxy formation and evolution.
- Correlations this good must help us understand the fundamentals of galaxy formation and evolution.





(Andrea Merloni)