Clusters of Galaxies

Clusters

Clusters of Galaxies: defined as an excess of galaxies with respect to their surroundings.

Review of X-ray properties: Arnaud (2005)

quantitative definition:

Abell: "Cluster" = more than 50 galaxies in brightness range $m_3 < m < m_3 + 2$ within 1.5 Mpc of cluster center (m_3: magnitude of 3rd brightest galaxy).

Catalogue: $\sim$ 4000 Clusters (including southern extension of catalogue, "Abell-Clusters", e.g., A1656=Coma)

Zwicky: "Cluster"= density of 50 galaxies weaker than $m_1 + 3$ is more than twice of local galaxy density outside of cluster.

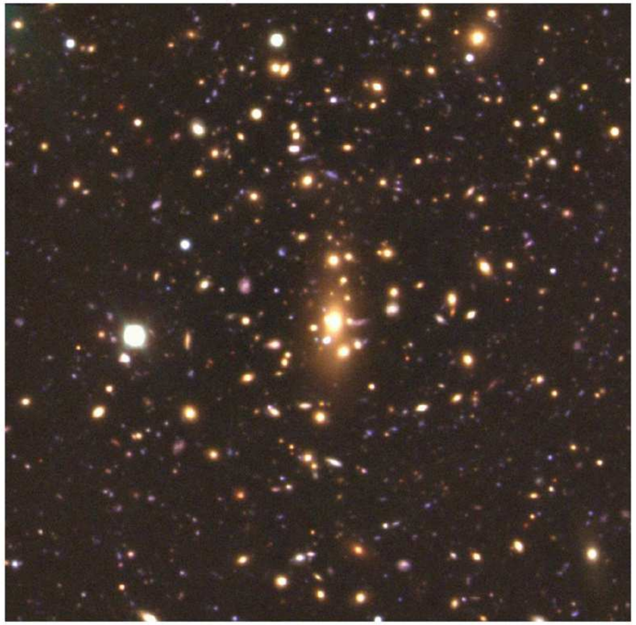
Catalogue: 9730 Clusters

Clusters

General properties of clusters:

- largest gravitationally bound objects in the universe
- clusters with up to 10000 galaxies known
- linear diameter 305. . . 12000 kpc
- total masses $10^{13}\,M_\odot$ for small groups, up to $10^{15}\,M_\odot$ for richest clusters
- small space density, since cluster formation started only at $z \sim 2$ in standard CDM scenario
- for "well defined" clusters, galaxy density $\propto r^{-\alpha}$, where $\alpha \sim 0.9 \ldots 1.6$.
- main baryonic cluster component: X-ray emitting gas (only few percent of cluster mass in optical galaxies)

Coma cluster: prototype for rich clusters; courtesy Jim Misti



Galaxy Cluster MS1008.1-1224 (Center)

Mass Luminosity Relation

Easiest method for mass determination: mass-luminosity relation.

Assumption: $M/L \sim$ const.

For elliptical galaxies: $M/L \sim 30$,

for spirals $M/L \sim 4$ (i.e., always > 1).

$\Longrightarrow$ Measure L for each galaxy, determine M, and add all galaxies.

Problems:

- Is M/L really constant?
- faint galaxies are ignored.

Virial Theorem

For mass of galaxy clusters, make use of the virial theorem:

$$E_{\text{kin}} = -E_{\text{pot}}/2 \tag{11.1}$$

in statistical equilibrium.

Measurement: assume isotropy, such that

$$\left\langle v^2 \right\rangle = \left\langle v_x^2 \right\rangle + \left\langle v_y^2 \right\rangle + \left\langle v_z^2 \right\rangle = 3 \left\langle v_\parallel^2 \right\rangle \tag{11.2}$$

assuming that velocity dispersion independent of m_i gives:

$$E_{\text{kin}} = \frac{1}{2} \sum_i m_i \boldsymbol{v}_i^2 = \frac{3}{2} M \left\langle v_\parallel^2 \right\rangle \tag{11.3}$$

where M total mass.

If cluster is spherically symmetric $\Longrightarrow$ Define weighted mean separation R_{cl}, such that

$$E_{\text{pot}} = \frac{GM^2}{R_{\text{cl}}} \tag{11.4}$$

From Eqs. (11.3) and (11.4):

$$M = \frac{3}{G} \left\langle v_\parallel^2 \right\rangle R_{\text{cl}} \tag{11.5}$$

Typical values: $v_\parallel \sim 1000\,\text{km}\,\text{s}^{-1}$, $R \sim 1$ Mpc.

Derivation of the Virial Theorem

Assume system of particles, each with mass m_i. Acceleration on particle i:

$$\ddot{\mathbf{r}} = \sum_{j \neq i} \frac{Gm_j (\mathbf{r}_j - \mathbf{r}_i)}{|\mathbf{r}_j - \mathbf{r}_i|^3} \tag{11.6}$$

…scalar product with $m_i \mathbf{r}_i$

$$m_i \mathbf{r}_i \cdot \ddot{\mathbf{r}}_i = \sum_{j \neq i} \frac{Gm_i m_j \mathbf{r}_i \cdot (\mathbf{r}_j - \mathbf{r}_i)}{|\mathbf{r}_j - \mathbf{r}_i|^3} \tag{11.7}$$

…since

$$\frac{1}{2} \frac{\mathrm{d}^2 \mathbf{r}_i^2}{\mathrm{d}t^2} = \frac{\mathrm{d}}{\mathrm{d}t} (\dot{\mathbf{r}}_i \cdot \mathbf{r}_i) = \ddot{\mathbf{r}}_i \cdot \mathbf{r}_i + \dot{\mathbf{r}}_i \cdot \mathbf{r}_i \tag{11.8}$$

…therefore Eq. (11.7)

$$\frac{1}{2} \frac{\mathrm{d}^2}{\mathrm{d}t^2} (m_i \mathbf{r}_i^2) - m_i \dot{\mathbf{r}}_i{}^2 = \sum_{j \neq i} \frac{Gm_i m_j \mathbf{r}_i \cdot (\mathbf{r}_j - \mathbf{r}_i)}{|\mathbf{r}_j - \mathbf{r}_i|^3} \tag{11.9}$$

Summing over all particles in the system gives

$$\frac{1}{2} \sum_i \frac{\mathrm{d}^2}{\mathrm{d}t^2} (m_i \mathbf{r}_i^2) - \sum_i m_i \dot{\mathbf{r}}_i{}^2 = \sum_i \sum_{j \neq i} \frac{Gm_i m_j \mathbf{r}_i \cdot (\mathbf{r}_j - \mathbf{r}_i)}{|\mathbf{r}_j - \mathbf{r}_i|^3} \tag{11.10}$$

$$= \frac{1}{2} \left(\sum_i \sum_{j \neq i} Gm_i m_j \frac{\mathbf{r}_i \cdot (\mathbf{r}_j - \mathbf{r}_i)}{|\mathbf{r}_i - \mathbf{r}_j|^3} + \sum_j \sum_{i \neq j} Gm_j m_i \frac{\mathbf{r}_j \cdot (\mathbf{r}_i - \mathbf{r}_j)}{|\mathbf{r}_j - \mathbf{r}_i|^3} \right) \tag{11.11}$$

$$= \frac{1}{2} \left(\sum_i \sum_{j \neq i} Gm_i m_j \frac{\mathbf{r}_i \cdot \mathbf{r}_j - \mathbf{r}_i^2}{|\mathbf{r}_i - \mathbf{r}_j|^3} + \sum_j \sum_{i \neq j} Gm_j m_i \frac{\mathbf{r}_j \cdot \mathbf{r}_i - \mathbf{r}_j^2}{|\mathbf{r}_j - \mathbf{r}_i|^3} \right) \tag{11.12}$$

$$= -\frac{1}{2} \sum_{\substack{i,j \\ i \neq j}} \frac{Gm_i m_j}{|\mathbf{r}_i - \mathbf{r}_j|} \tag{11.13}$$

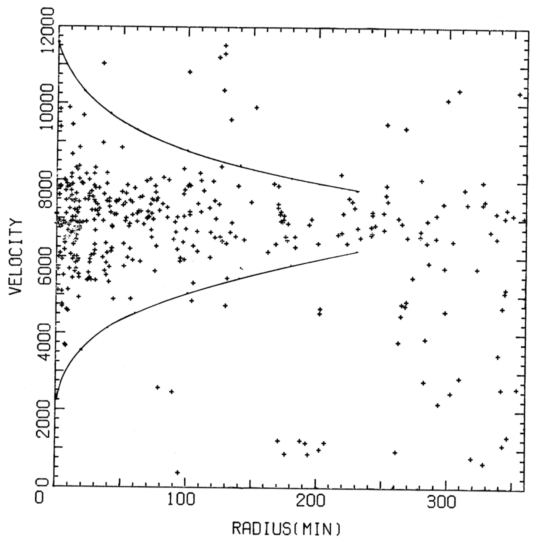
Thus, identifying the total kinetic energy, T, and the gravitational potential energy, U, gives

$$2T - U = \frac{1}{2}\frac{\mathrm{d}^2}{\mathrm{d}t^2}\sum_i m_i \mathbf{r}_i^2 = 0 \qquad (11.14)$$

in statistical equilibrium.

Thus we find the virial theorem: $T = \frac{1}{2}|U|$

Masses: Results

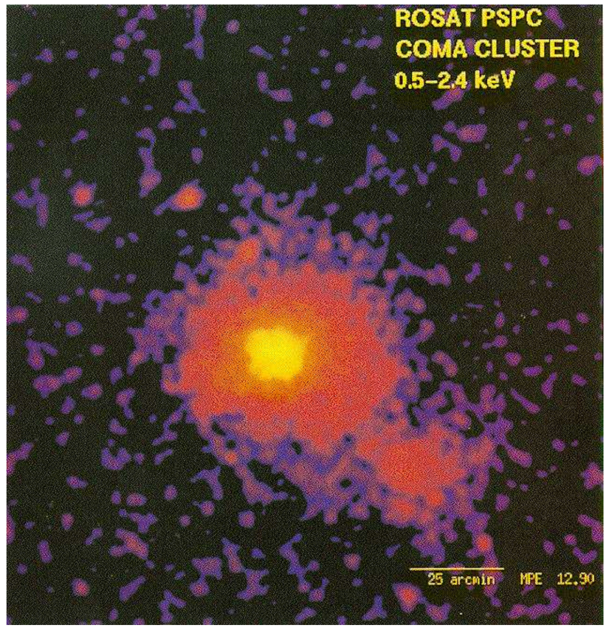


Dynamical cluster mass indicates $M/L \sim 300$
$\Longrightarrow$ Where is the missing mass?

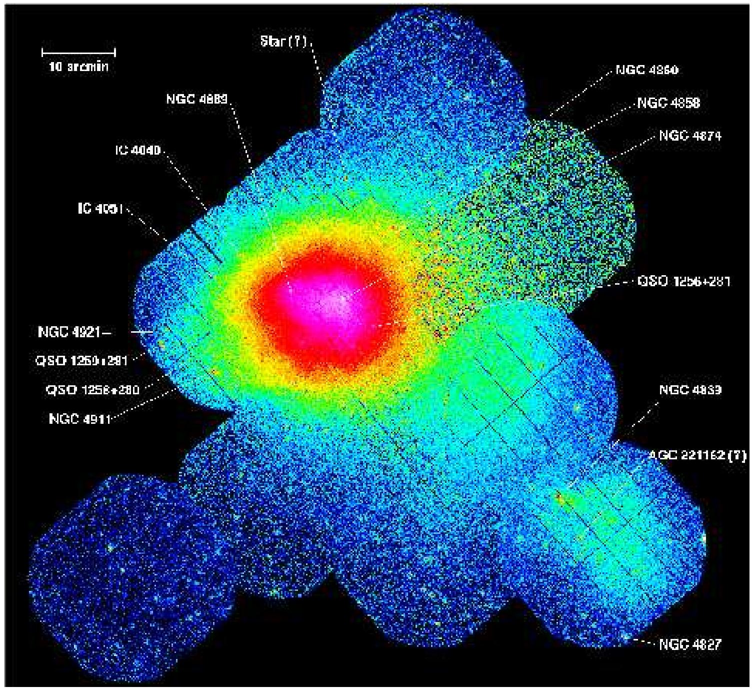
Coma Cluster   Kent and Gunn, 1982, AJ, 87, 945

History

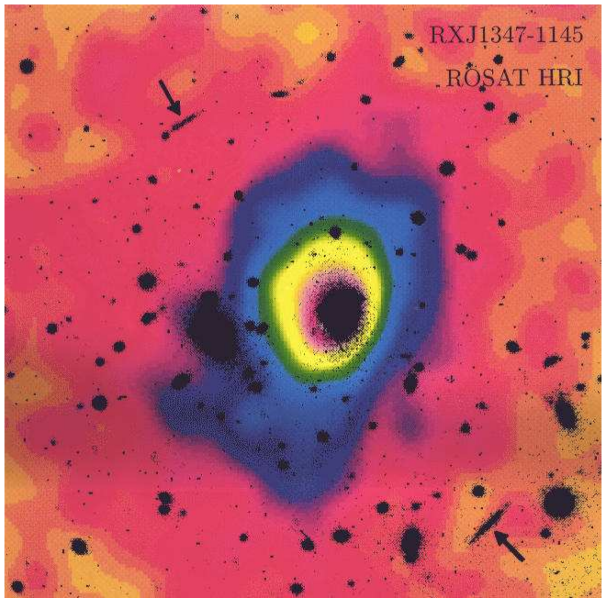
- 1965: M87 is first extragalactic source detected in X-rays
- 1969: Perseus clusters detected
- 1973–1975: *UHURU* detects emission from many clusters
- 1979: *HEAO-1*: Spectra: optically thin radiation
- 1984: Einstein: imaging and high resolution spectra
- 1990: *ROSAT*: Emission from essentially *all* clusters
- 1990: *ASCA*: high resolution spectra
- 2000: *XMM-Newton*/Chandra: high resolution spectra, imaging,. . .



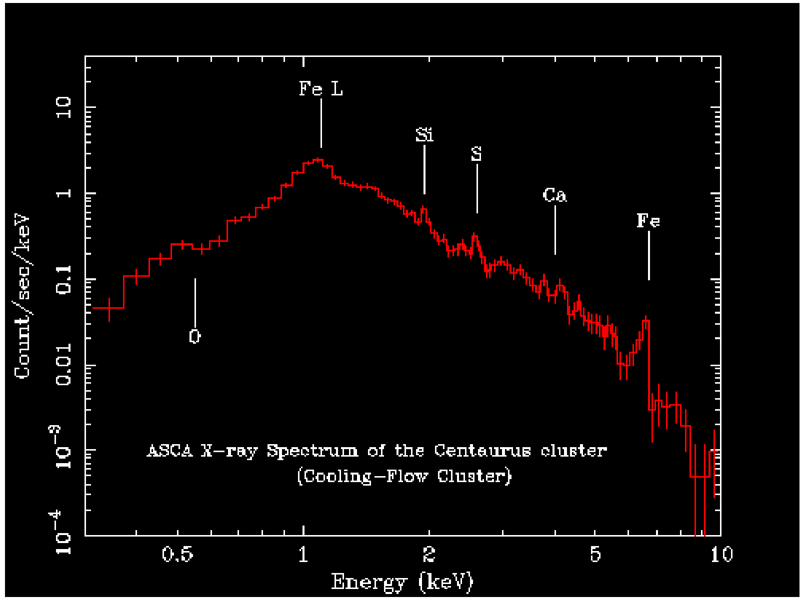
ROSAT All Sky Survey image of the Coma cluster



XMM-Newton mosaic of the Coma cluster

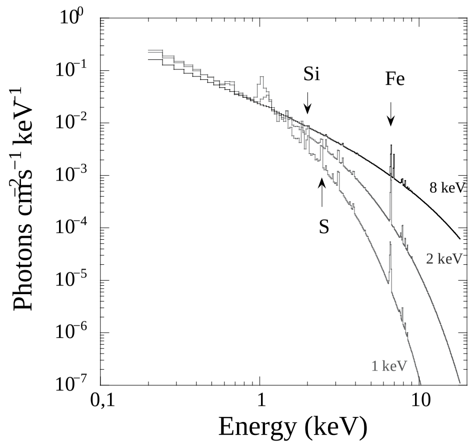


RXJ1347−1145: Note decrease of the X-ray emissivity with distance from center of cluster.



First seen with Einstein: Cluster gas emits Kα lines from highly ionized Mg, Si, S, Fe, etc.
X-ray emission seen from same area as optical cluster.

X-ray Emission



Arnaud (2005), assuming $Z = 30\%$ solar

- X-ray Luminosity $\sim 10^{42} \dots 10^{45}\,\mathrm{erg\,s^{-1}}$
- Thermal bremsstrahlung dominant for continuum,

  $$\epsilon \propto n_e n_p T^{-1/2} \exp\left(-E/kT\right) \quad (11.15)$$

  $\Longrightarrow$ emissivity is density tracer
- Temperature of the gas $\sim 10^7 \dots 10^8\,\mathrm{K}$ (0.5–15 keV)

  consistent with $kT \sim GM/r$
- enriched in metals, Fe $\sim$ 30% solar (other elements difficult, since often fully ionized)

- density $n_e \lesssim 10^{-3}\,\mathrm{cm^{-3}}$ in outer regions, $\sim 10^{-2}\,\mathrm{cm^{-3}}$ in center.

Deprojection

X-ray emission from galaxy clusters gives mass:

Assume gas in potential of galaxy cluster. Hydrostatic equilibrium:

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{GM_r\rho}{r^2} \tag{11.16}$$

Pressure from equation of state:

$$P = nkT = \frac{\rho kT}{\mu m_{\mathrm{H}}} \tag{11.17}$$

where m_{H}: mass of H-atom, μ mean molecular weight of gas ($\mu = 0.61$ for fully ionized). Eq. (11.17) gives

$$\frac{\mathrm{d}P}{\mathrm{d}r} = \frac{k}{\mu m_{\mathrm{H}}}\left(T\frac{\mathrm{d}\rho}{\mathrm{d}r} + \rho\frac{\mathrm{d}T}{\mathrm{d}r}\right) = \frac{\rho kT}{\mu m_{\mathrm{H}}}\left(\frac{\mathrm{d}\log\rho}{\mathrm{d}r} + \frac{\mathrm{d}\log T}{\mathrm{d}r}\right) \tag{11.18}$$

Inserting into Eq. (11.16) and solving for M_r gives

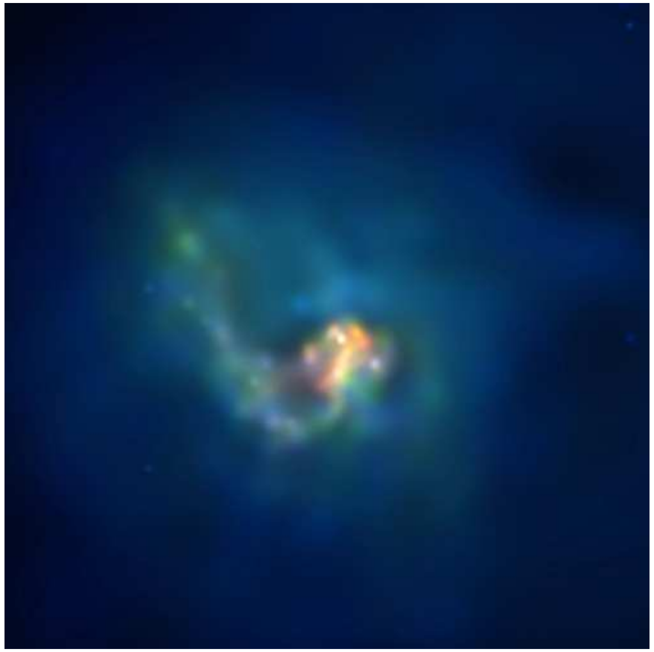
$$M_r = -\frac{kTr^2}{G\mu m_{\mathrm{H}}}\left(\frac{\mathrm{d}\log\rho}{\mathrm{d}r} + \frac{\mathrm{d}\log T}{\mathrm{d}r}\right) \tag{11.19}$$

Cluster gas mainly radiates by bremsstrahlung emission, with spectral shape

$$\epsilon(E) \propto \left(\frac{m_{\mathrm{e}}}{kT}\right)^{1/2} g(E,T)\, N\, N_{\mathrm{e}} \exp\left(-\frac{E}{kT}\right) \tag{11.20}$$

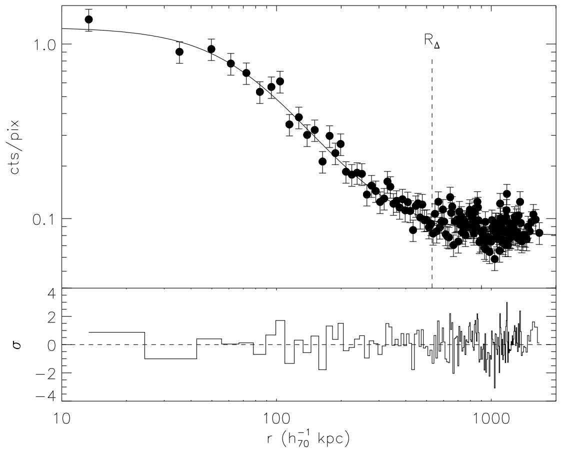
where N: number density of nuclei, $g(E,T)$: Gaunt factor (roughly constant).

$\Longrightarrow T$ from X-ray spectrum, N from measured flux $\Longrightarrow M_r$.



Temperature structure of Centaurus cluster as observed with *Chandra* (red: cold, blue: hot)

Cluster Properties



Radial intensity profile of RDCS 1252.9−2927 (Rosati et al., 2004)

Images are sum over 3D cluster, can determine the integrated emission measure:

$$\mathrm{EM}(r) = \int n_{\mathrm{e}}^2 \mathrm{d}l \tag{11.21}$$

from the angle averaged surface brightness distribution, $S(\theta)$

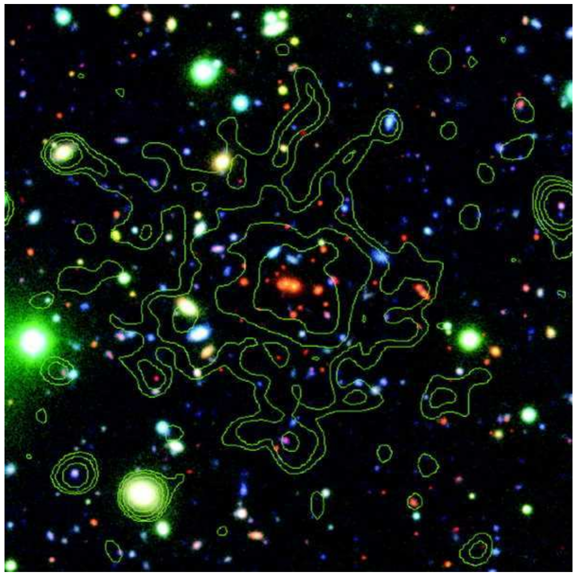
$$\mathrm{EM}(r) = \frac{4\pi(1+z)^4 S(\theta)}{\epsilon(T,z)} \tag{11.22}$$

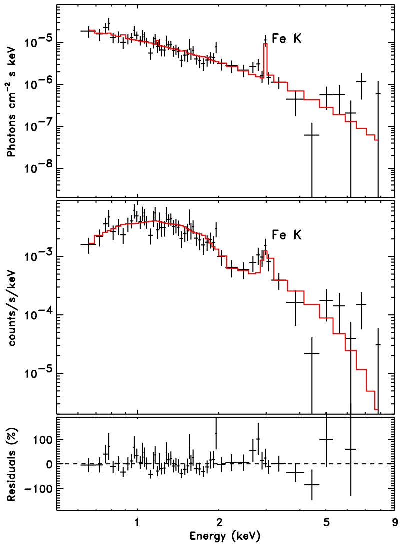
where

$$r = d_{\mathrm{A}}(z)\theta \tag{11.23}$$

and where d_{A}: angular distance at cluster redshift z, and $\epsilon(T,z)$ is the emissivity.

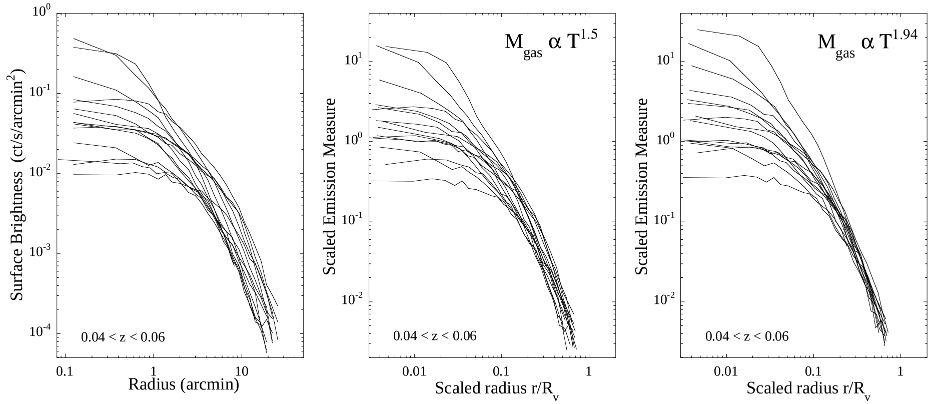
Note: $\epsilon(T,z)$ depends only weakly on T in soft X-rays $\Longrightarrow$ soft X-ray emissivity is rather insensitive to temperature variations!





VLT and X-ray image and X-ray spectrum of RDCS 1252.9−2927 at $z = 1.24$ (Rosati et al., 2004)

Cluster Properties

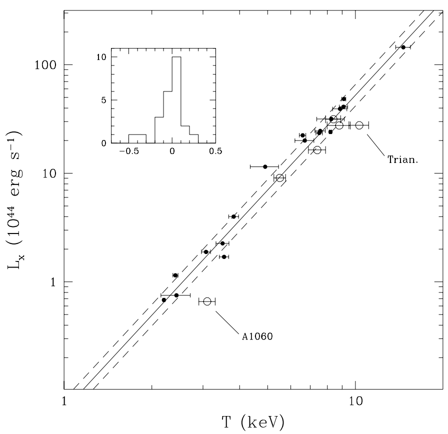


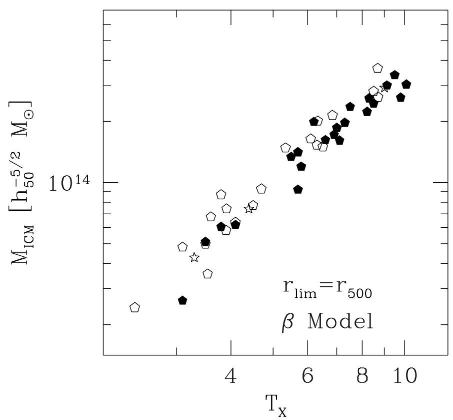
(Arnaud, 2005)

Surface brightness profiles and deduced emission measure, assuming classically EM $\propto$ $T^{1/2}$ ($M_{\text{gas}} \propto T^{3/2}$) and EM $\propto T^{1.38}$ ($M_{\text{gas}} \propto T^{1.38}$; empirically found best law)

Large dispersion in central region, outer regions similar (β-model).

Cluster Properties





(Arnaud, 2005)

More luminous clusters have higher temperatures and larger intra cluster gas masses.

Central Regions

Most clusters show central peak in density, reduced central temperature, and strong scatter overall in center.

Why? Gas density at center is high

$\Longrightarrow$ $\epsilon \propto n^2$, cooling timescale $t_{\text{cool}} \propto T^{1/2}/n_{\text{e}}$ smaller than cluster age
$\Longrightarrow$ gas has energy loss due to radiation
$\Longrightarrow$ gas cools faster
$\Longrightarrow$ Pressure drops
$\Longrightarrow$ Gas gets compressed by gravity well
$\Longrightarrow$ density and therefore ϵ increases
$\Longrightarrow$ Run away process

At the end gas is so cold that stars can form and it becomes invisible

Central Regions

Estimate for mass deposition rate from X-ray luminosity:

$$L_{\text{cool}} = \frac{5}{2}\frac{\dot{M}}{\mu m_{\text{p}}} kT \qquad (11.24)$$

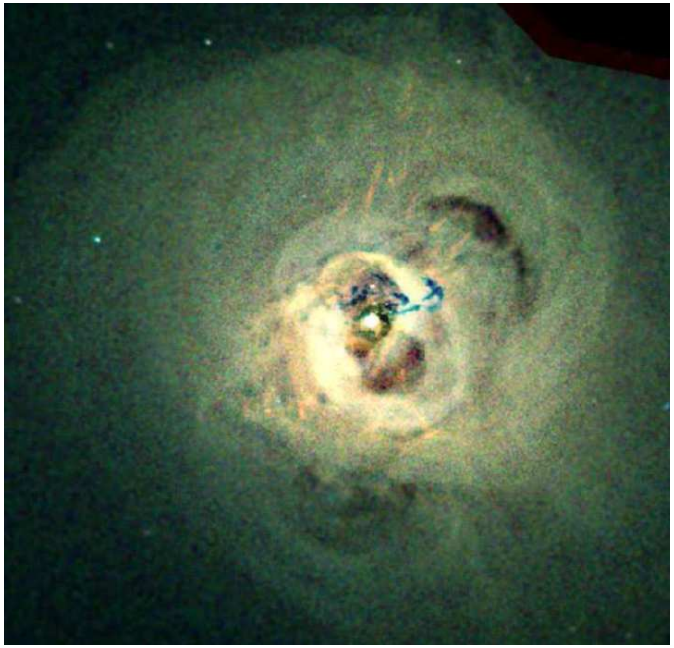
Typical accretion rates:

- 200–300 $M_\odot$ yr^{-1} for Perseus,
- 20–100 $M_\odot$ yr^{-1} for Centaurus,
- 5 $M_\odot$ yr^{-1} for the Virgo cluster.

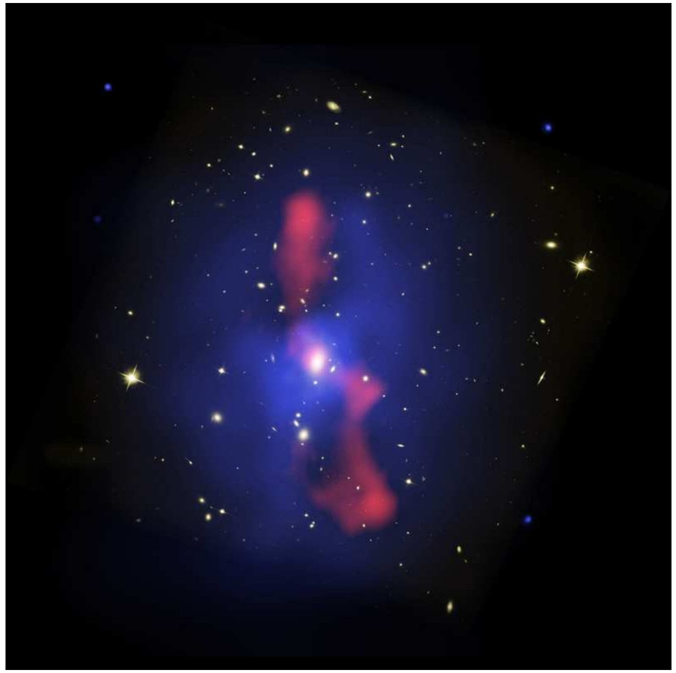
The accumulated mass over the time t is

$$M_{\text{total}} = 10^{12} \left(\frac{\dot{M}}{100\,M_\odot\,\text{yr}^{-1}}\right)\left(\frac{t}{10^{10}\,\text{yr}}\right) M_\odot$$

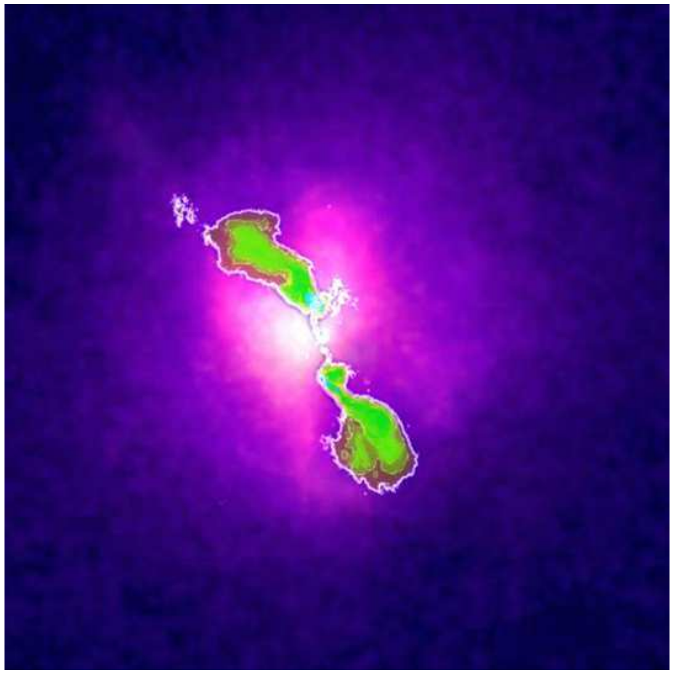
$\Longrightarrow$ continued formation of a galaxy?


A.C. Fabian / CXC / NASA

X-ray structure of the Perseus cluster. Note cavities, shocks, “ripples”

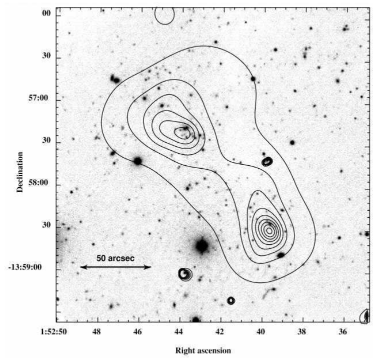


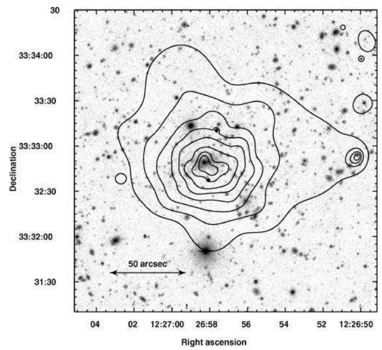
MS 0735 as seen in radio and X-rays



Hydra cluster as seen in radio and X-rays

Hierarchical Structure Formation



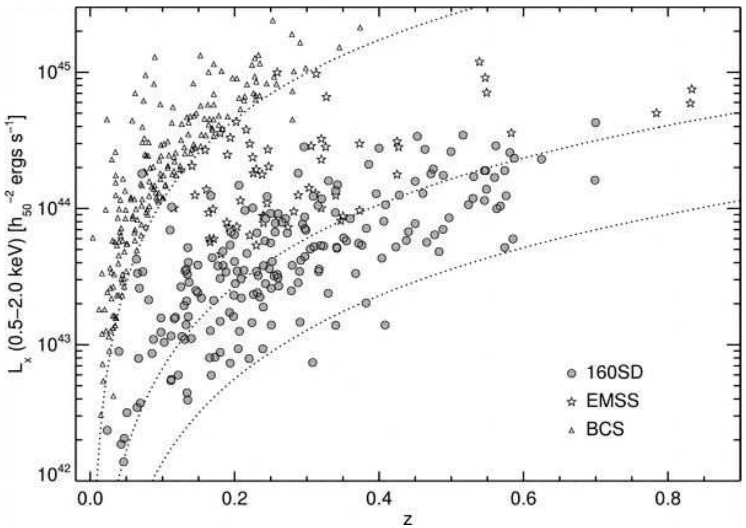


(Arnaud, 2005, *Chandra* overlaid on optical Keck and Subaru images)

RX J0152.7−1357 at $z = 0.83$: merging is ongoing:
X-ray analysis shows temperature increase between clusters.

RXJ1226.9+3332: a relaxed cluster at $z = 0.89$

Hierarchical Structure Formation



(Arnaud, 2005)

The End

Arnaud, M., 2005, in Background Microwave Radiation and Intracluster Cosmology, ed. F. Melchiorri, Y. Rephaeli, 77

Rosati, P., et al., 2004, AJ, 127, 230