Clusters of Galaxies

Clusters

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

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.

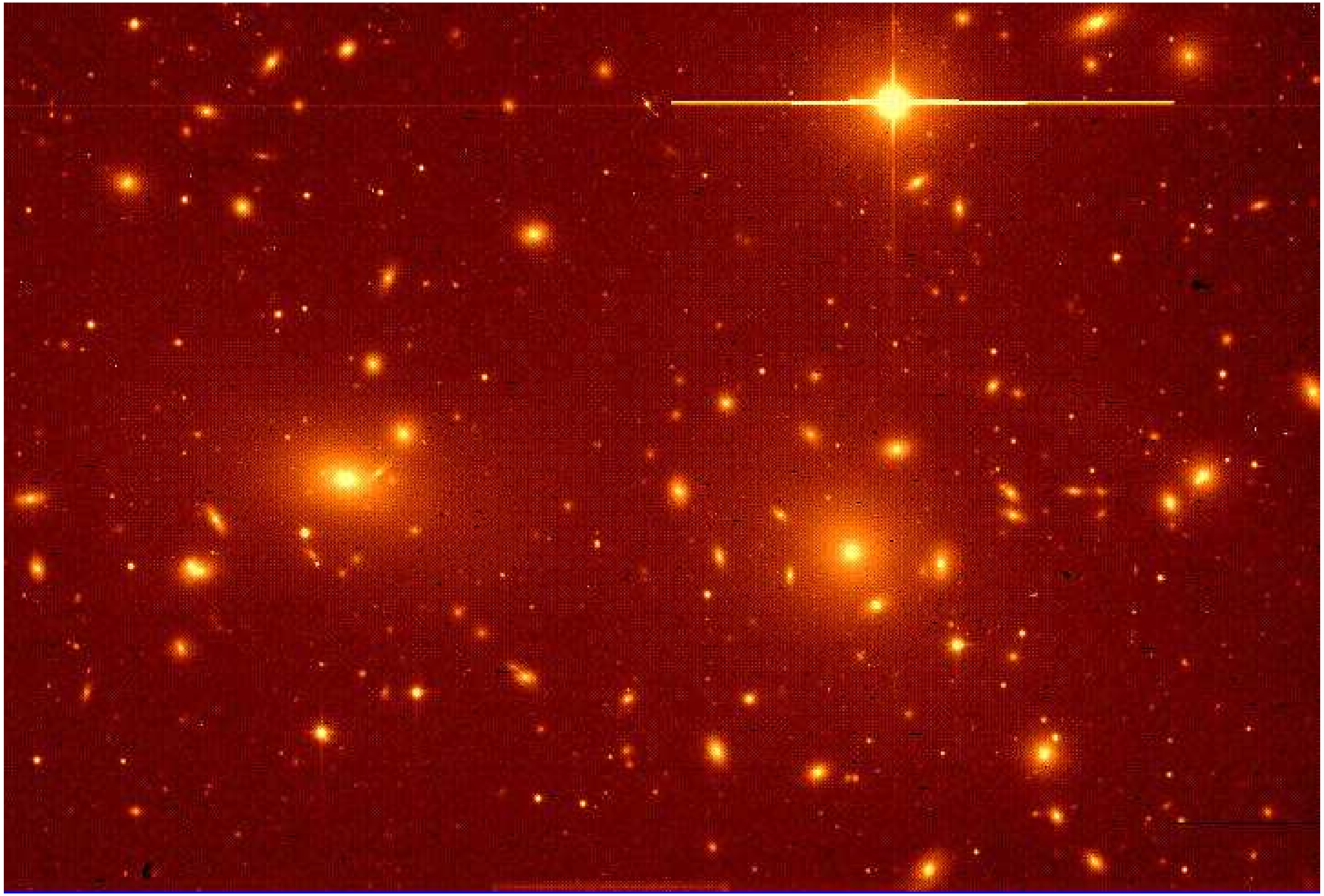
Catalogue: 9730 Clusters

Clusters

General properties of clusters:

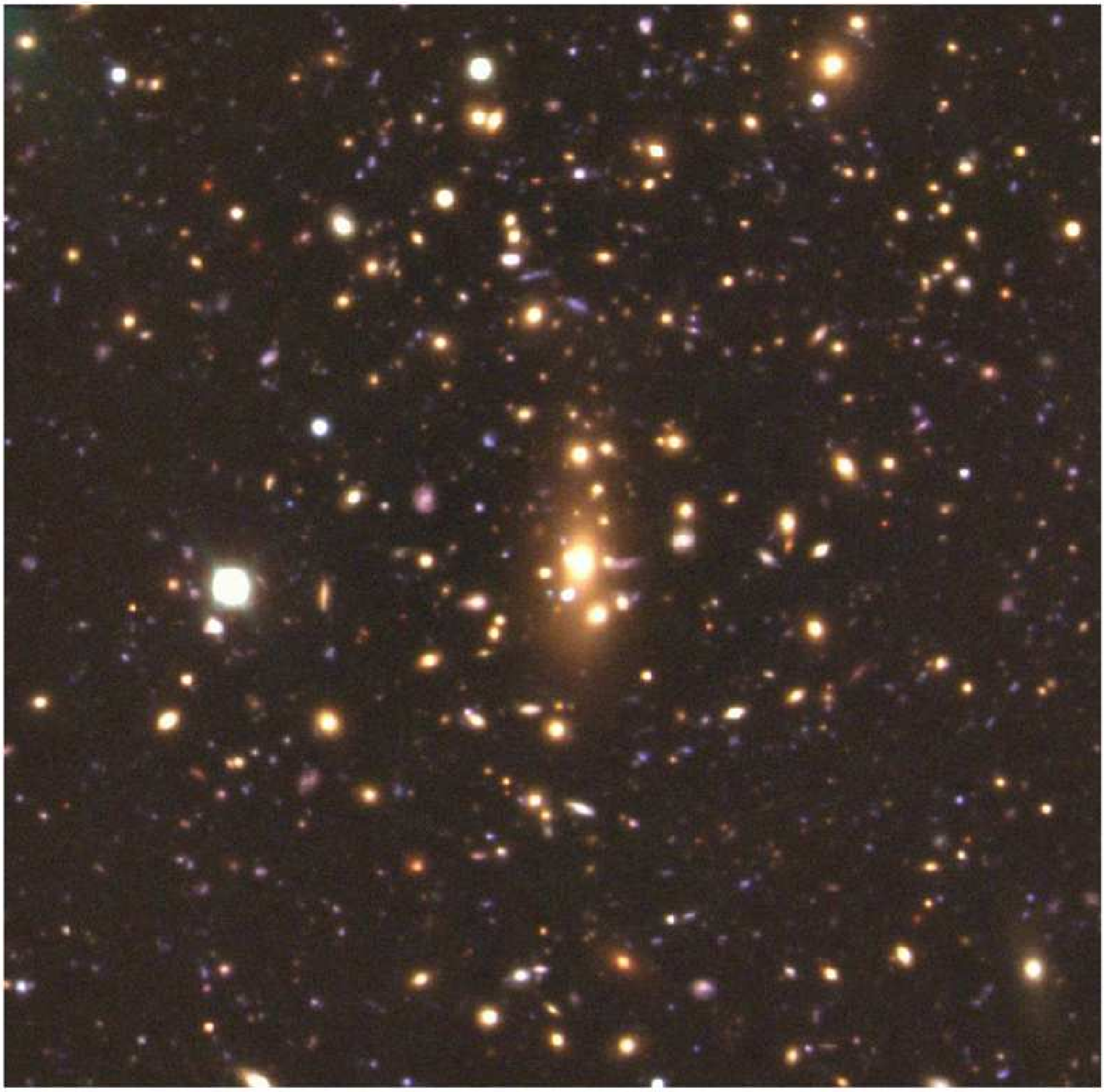
- largest gravitationally bound objects in the universe
- clusters with up to 10000 galaxies known
- total masses up to $10^{15}\,M_\odot$
- linear diameter 305...12000 kpc
- small space density
- for "well defined" clusters, galaxy density $\propto r^{-\alpha}$, where $\alpha \sim 0.9\ldots1.6$.

Clusters



Coma cluster: prototype for rich clusters; courtesy Gregory Bothun

Clusters



Galaxy Cluster MS1008.1-1224 (Center)

ESO PR Photo 09b/99 (27 February 1999)

MS1008.1−1224, courtesy ESO (VLT UT1, FORS)

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

Preferred way: *Virial theorem*

In equilibrium: $V + 2T = 0$

where

$$V = -\frac{\alpha G M^2}{R}$$

where M total mass, and α depends on density distribution ($\alpha = 3/5$ for uniform density).

The kinetic energy is

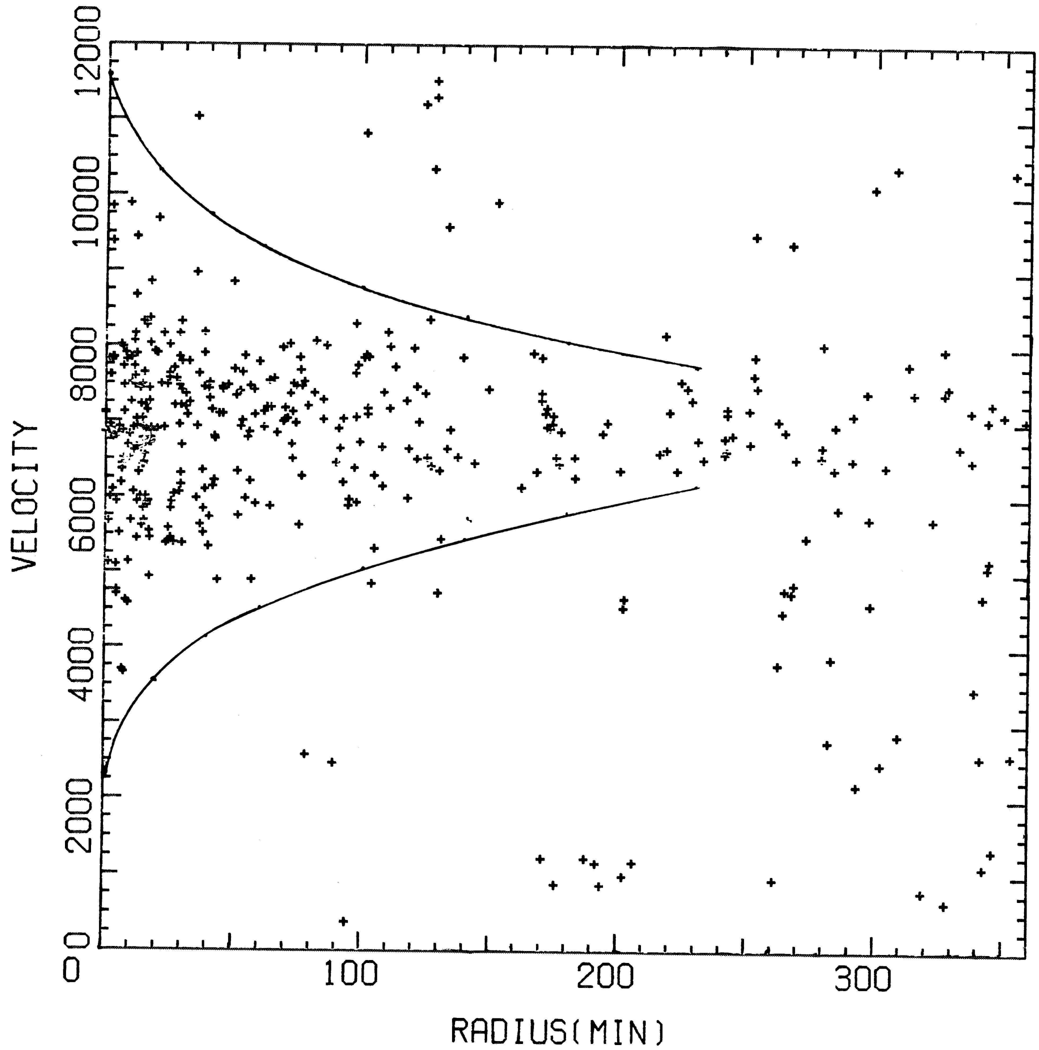
$$T = \frac{1}{2} \sum M_i \mathrm{v}_i^2$$

Gives equation that can be solved for M.

Problems:

- Measurement of velocities and radii (we only see projected components)
- Virial theorem assumes equilibrium

Masses: Results



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

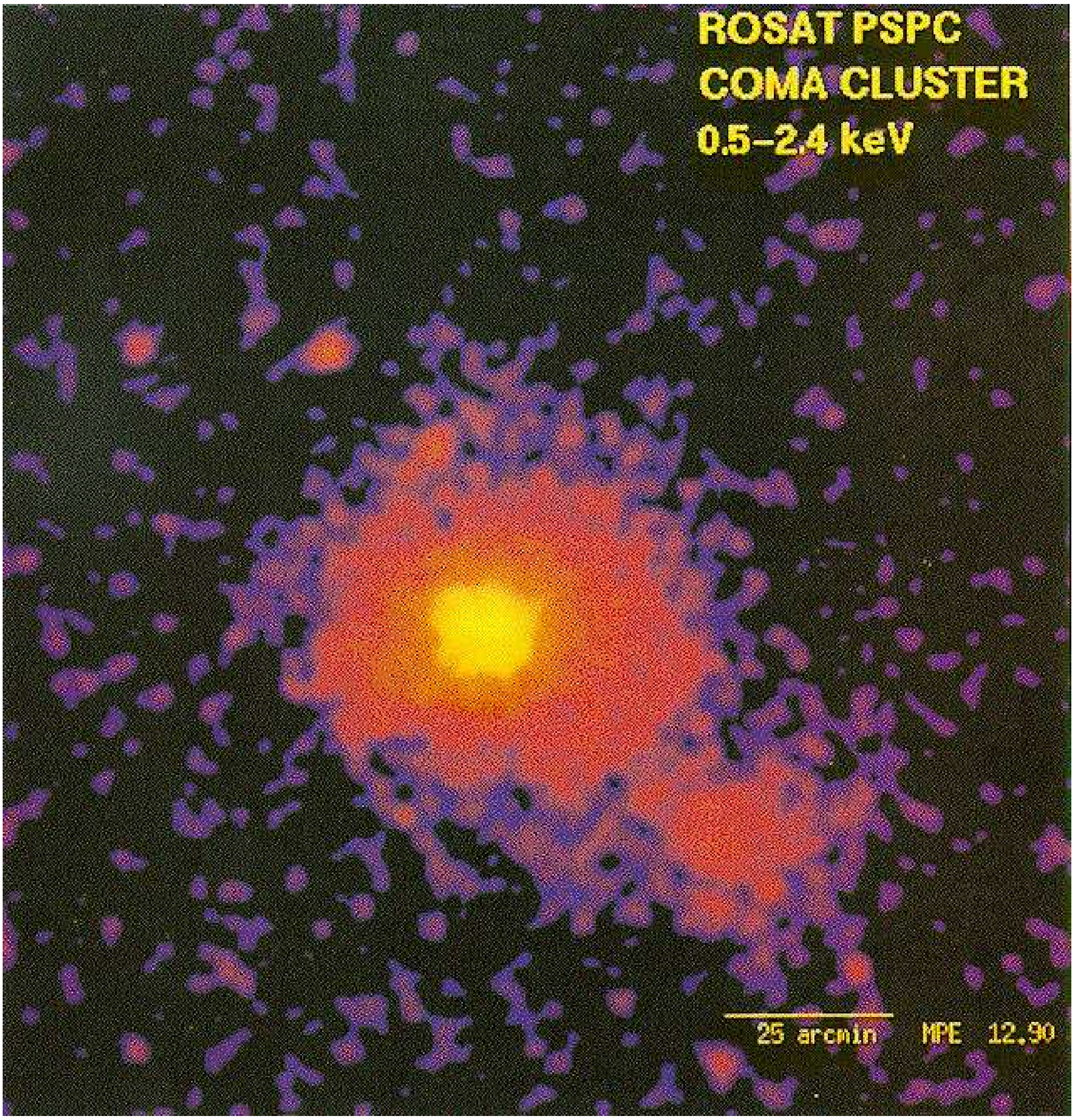
Dynamical cluster mass indicates $M/L \sim 300$

$\Longrightarrow$ Where is the missing mass?

History

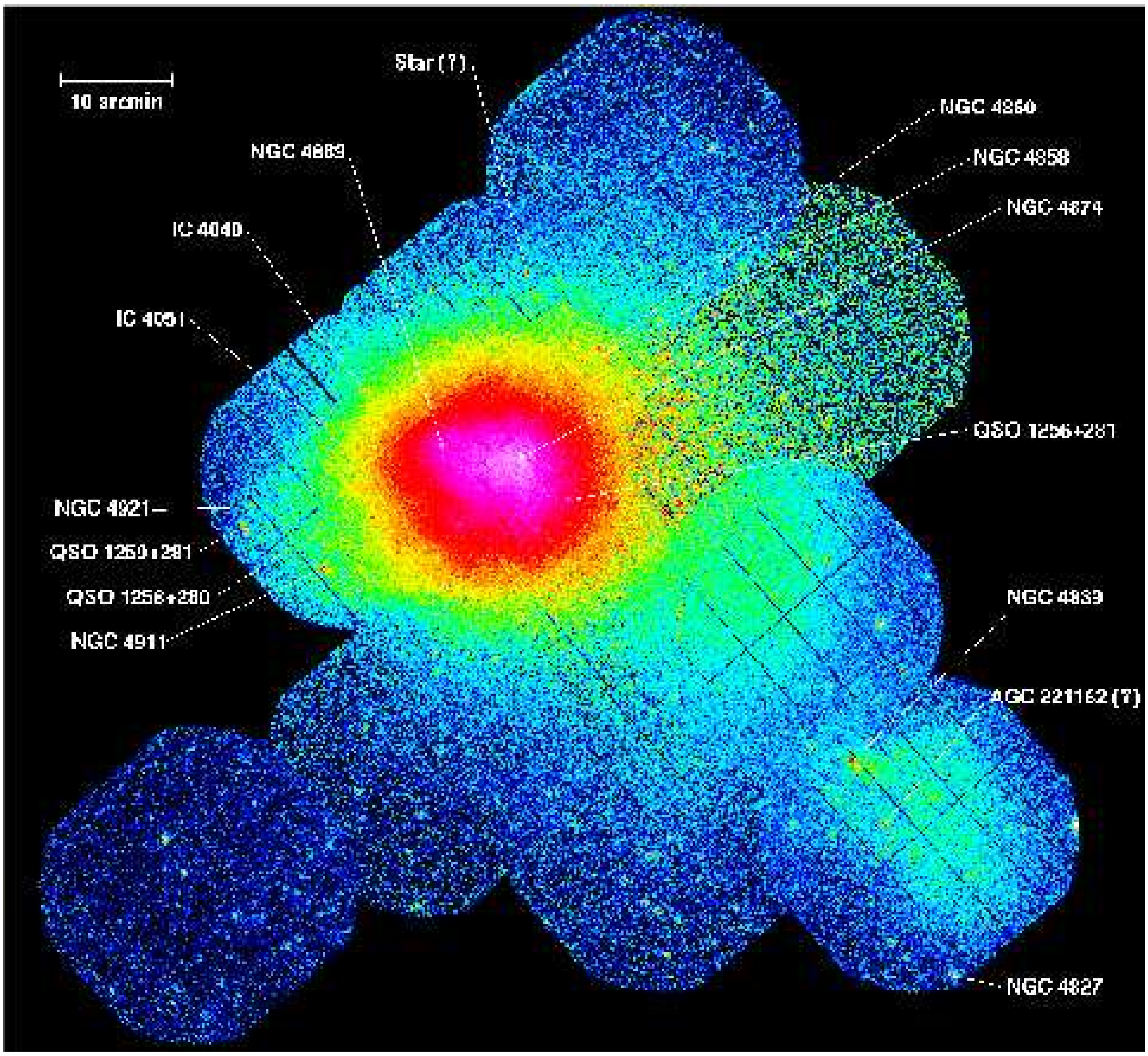
- 1965: M87 is first extragalactic source detected in X-rays
- 1969: Perseus clusters detected
- 1973–1975: UHURU detects emission from lots of clusters
- 1979: HEAO-1: Spectra: optically thin radiation
- 1984: Einstein: imaging and high resolution spectra
- 1990: ROSAT: Emission from essentially *all*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

Coma in X-rays, I



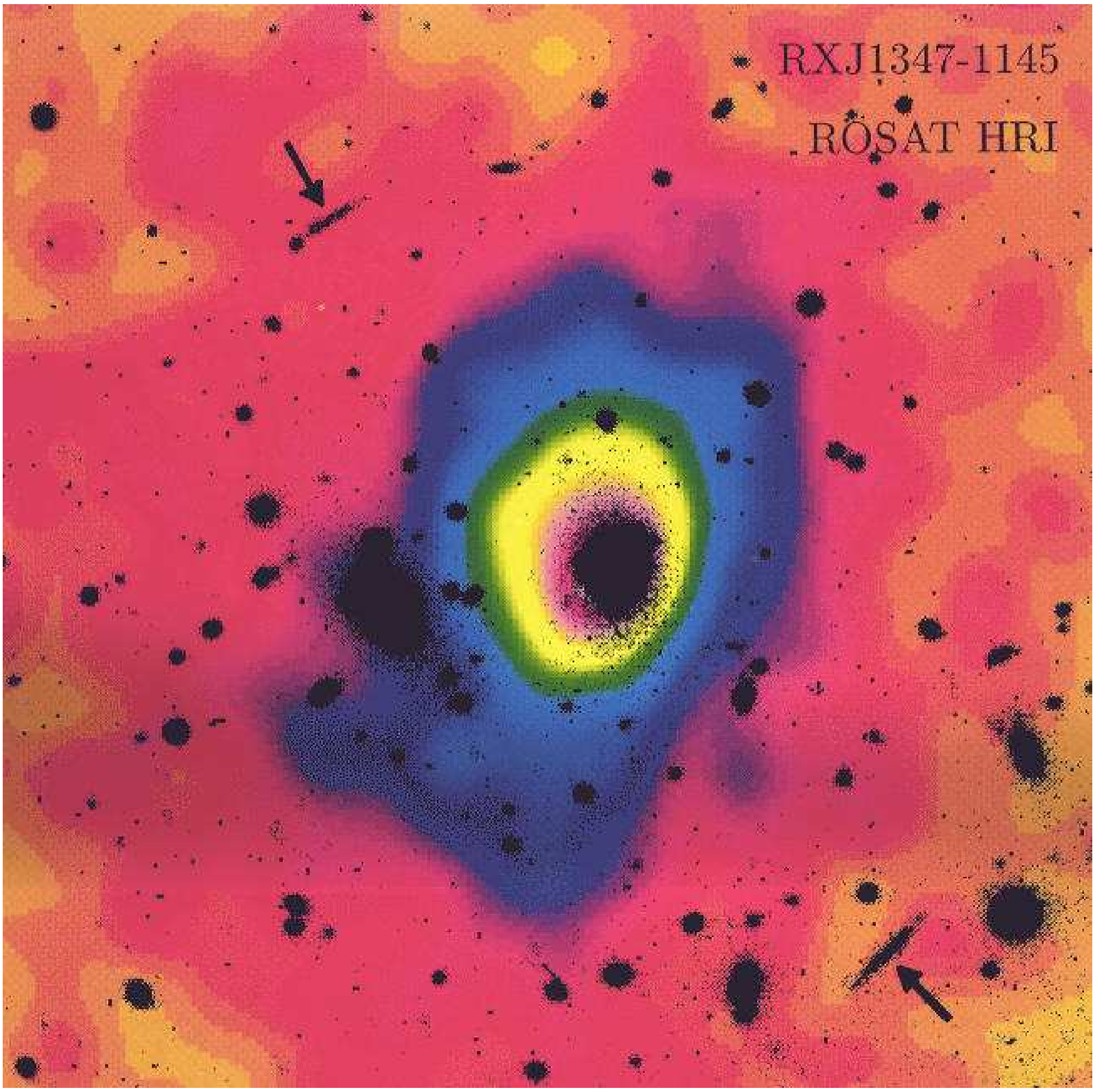
ROSAT All Sky Survey image of the Coma cluster

Coma in X-rays, II



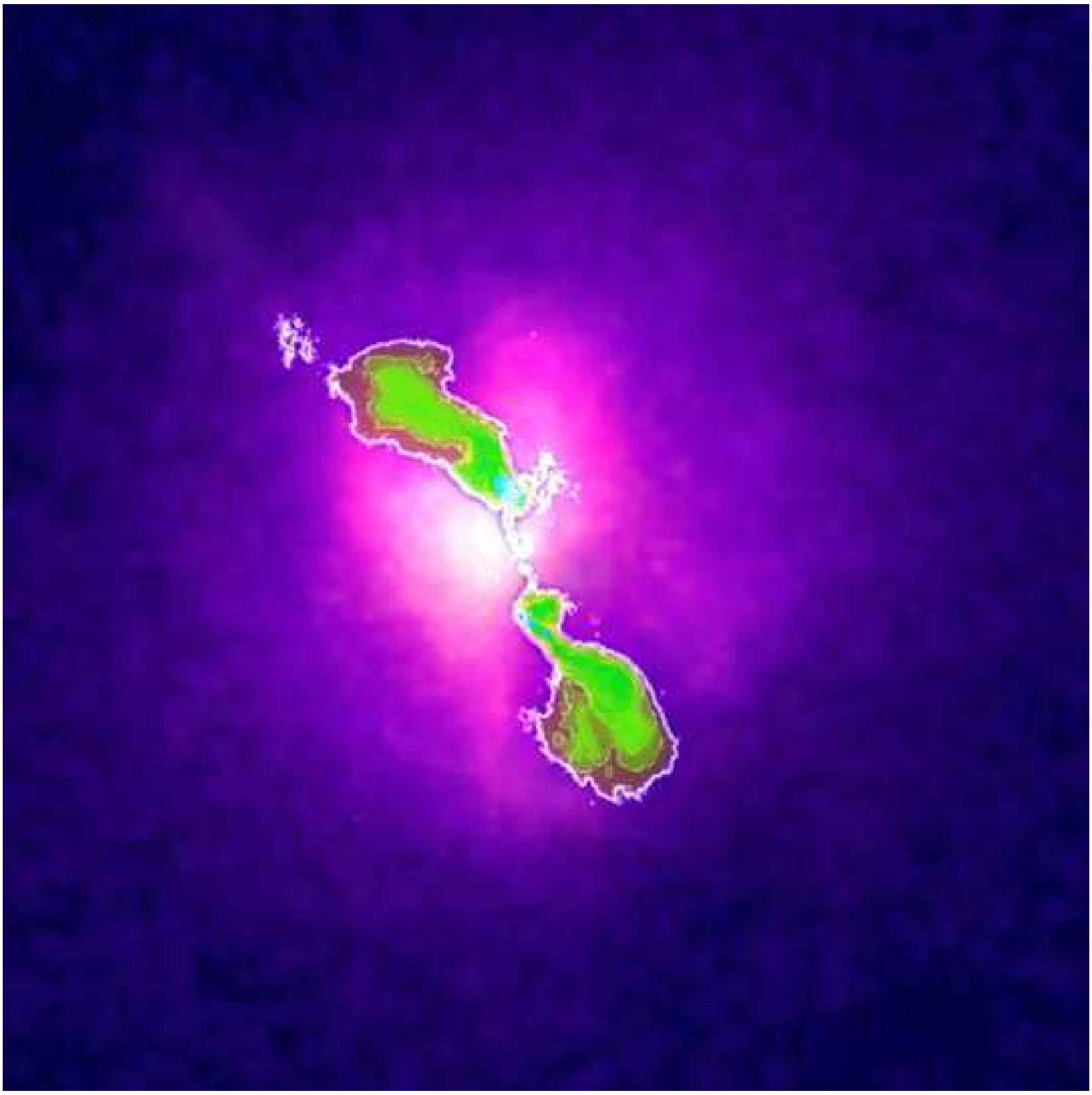
XMM-Newton mosaic of the Coma cluster

RXJ1347−1145: The Brightest Cluster



Note decrease of the X-ray emissivity with distance from center of cluster.

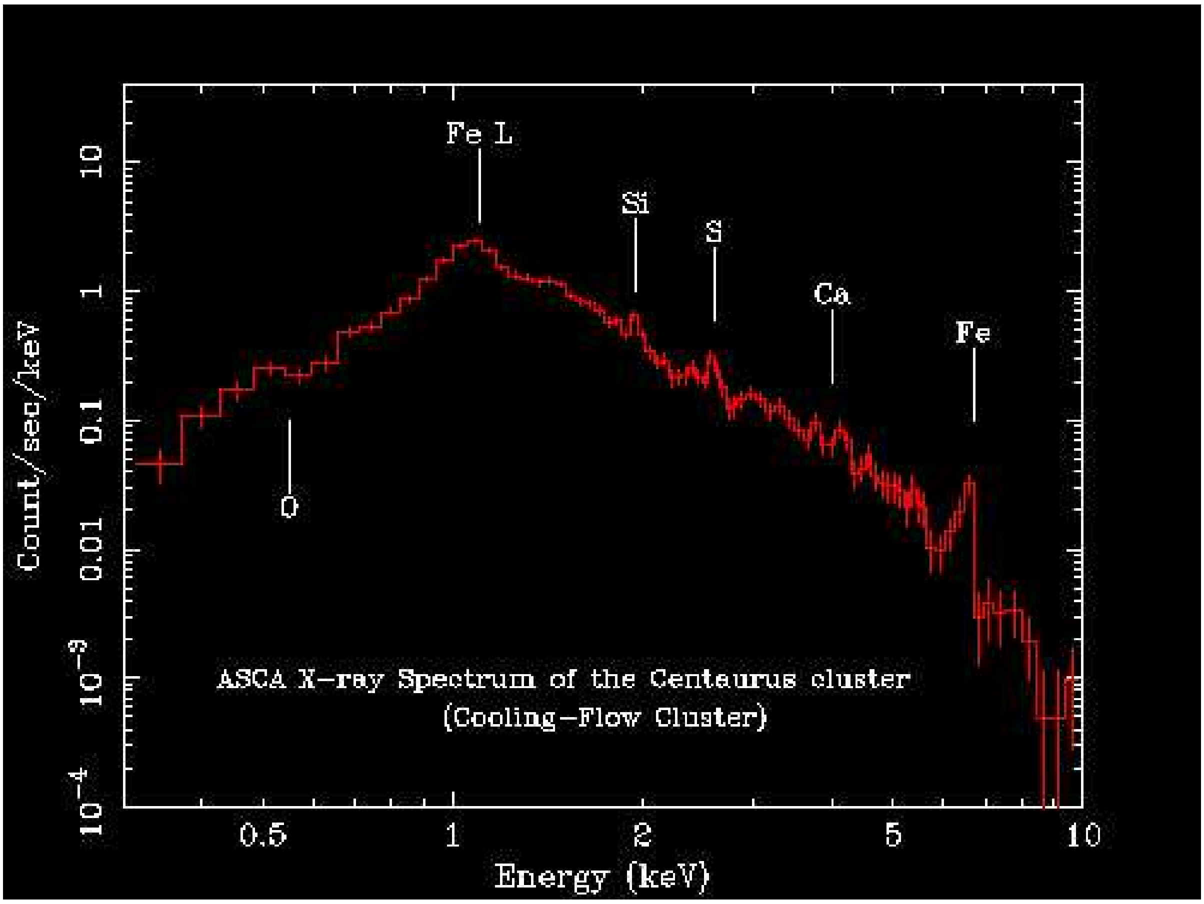
Hydra



Hydra cluster as seen in radio and X-rays

IAAT

X-ray Emission



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

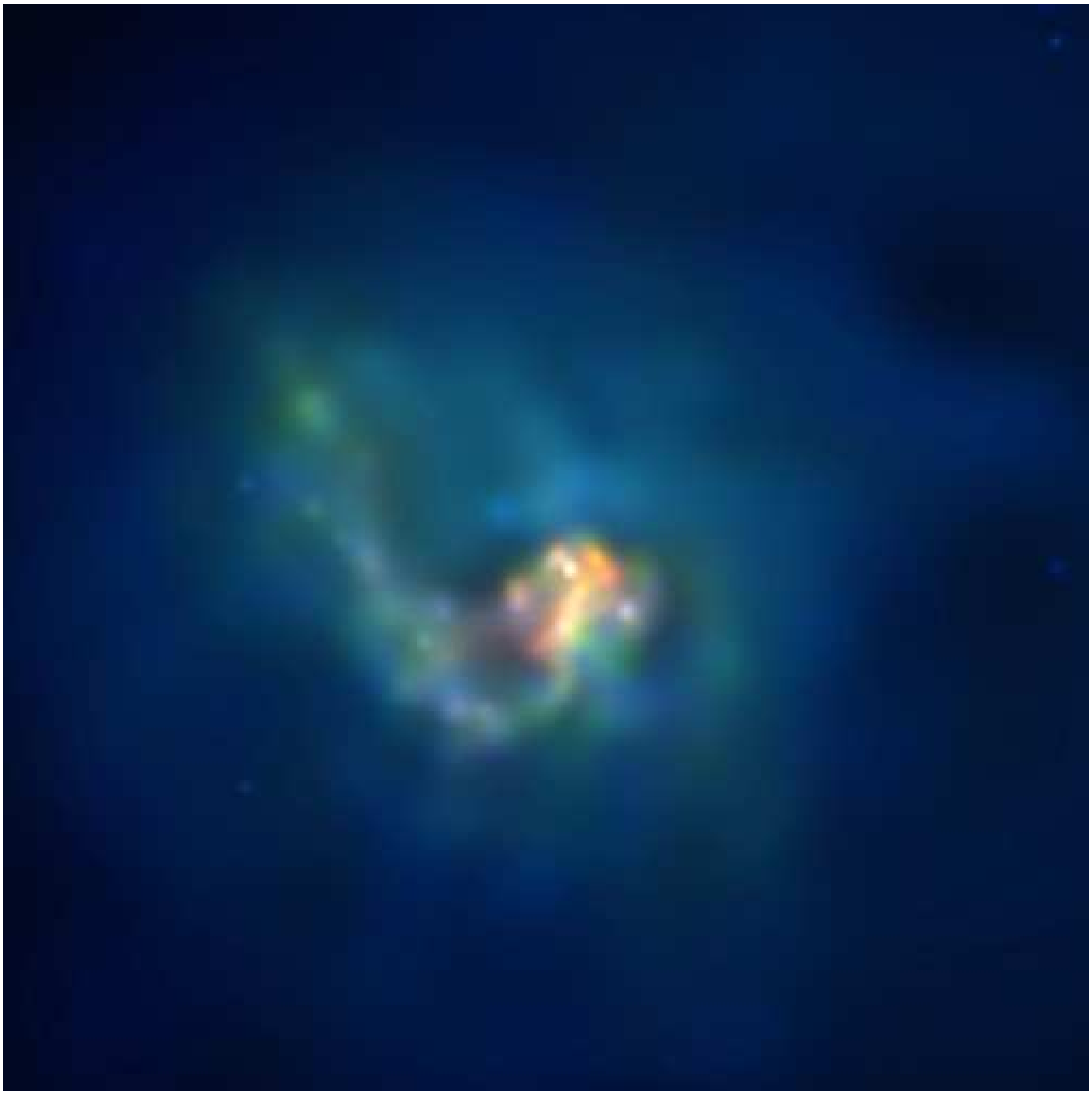
- X-ray Luminosity $\sim 10^{42} \ldots 10^{45}$ erg/s
- Thermal bremsstrahlung dominant for continuum,

$$\epsilon \propto n_\mathrm{e} n_\mathrm{p} T^{-1/2} \exp\left(-E/kT\right) \tag{7.1}$$

- $\Longrightarrow$ emissivity is density tracer
- Temperature of the gas $\sim 10^7 \ldots 10^8$ K
- density $n_\mathrm{e} \lesssim 10^{-3}\,\mathrm{cm}^{-3}$
- enriched in metals, e.g., Fe $\sim$ 30% solar

What powers the X-rays?

Deprojection, I



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

Deprojection, II

Let's first assume that the X-ray emitting gas is in hydrostatic equilibrium and obeys the equation of state of an ideal gas:

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\rho\frac{\mathrm{d}\Phi}{\mathrm{d}r} \qquad \text{and} \qquad P = \frac{\rho k T}{\mu m_{\mathrm{p}}} \tag{7.2}$$

in addition assume that the gravitational potential is of the form

$$\Phi = \frac{9\sigma^2}{4\pi G r_{\mathrm{c}}^2}(1 + r/r_{\mathrm{c}})^{-3/2} \tag{7.3}$$

(σ: galaxy velocity dispersion). ("King Profile")

Measure the temperature profile, $T(r)$, from the local X-ray emissivity assuming $\rho(r)$, and solve system of equations. Iterate until convergence reached.

Result: T, ρ, P, and Φ determined selfconsistently.

For clusters, Φ is decoupled from $\rho \Longrightarrow$ Missing mass determines gravitational potential.

Cooling Flows

Most clusters show central peak in density structure.

evidence for a cooling flow

Why? Gas density at center is high

$\Longrightarrow \epsilon \propto n^2$

$\Longrightarrow$ 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

$\Longrightarrow$ Inward motion of gas $\Longrightarrow$ Cooling flow

Cooling Flows

Estimate for mass deposition rate from X-ray luminosity:

$$L_{\text{cool}} = \frac{5}{2}\frac{\dot{M}}{\mu m_{\mathrm{p}}}kT \qquad (7.4)$$

Typical accretion rates: 200–300 $M_{\odot}$/yr for Perseus, 20–100 $M_{\odot}$/yr for Centaurus, 5 $M_{\odot}$/yr for the Virgo cluster.

The accumulated mass over the time t the cooling flow works is

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

$\Longrightarrow$ continued formation of a galaxy?