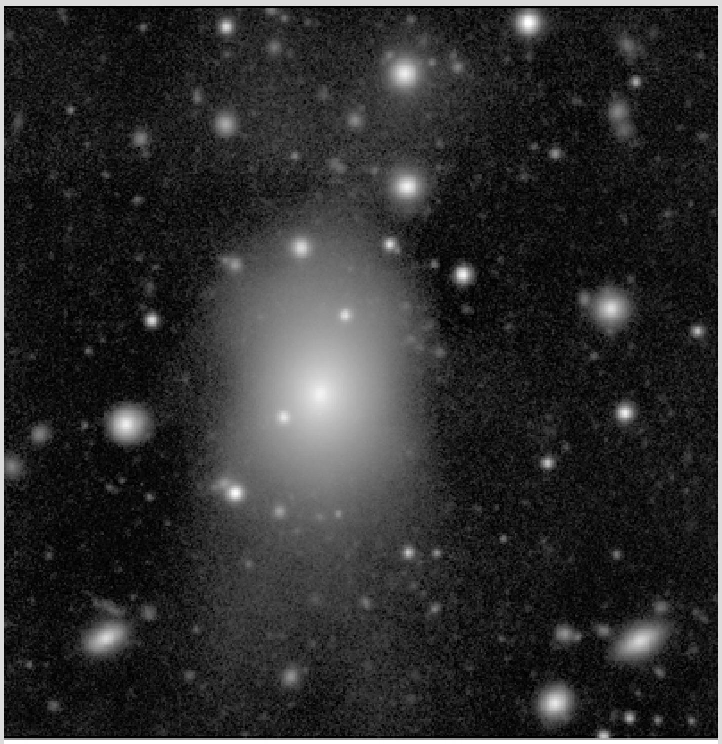
Properties of galaxies in galaxy clusters

Apart from the high density, two striking features of the galaxy population in clusters:

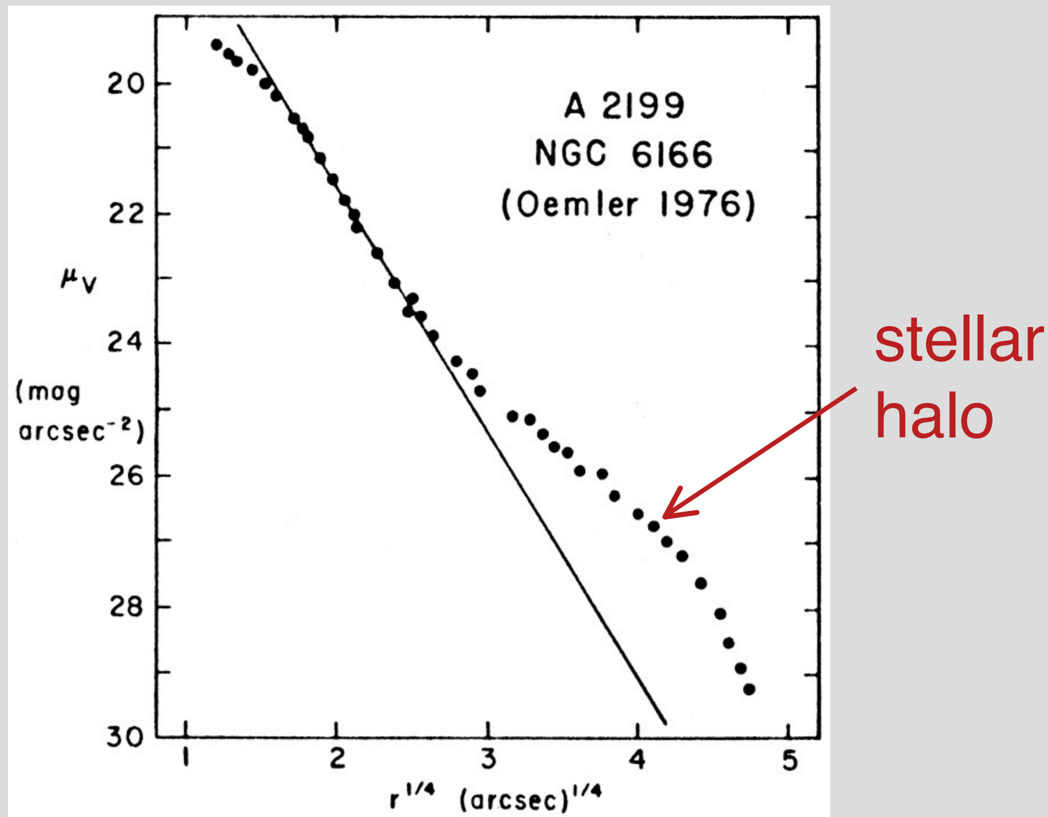
<u>cD galaxies</u>

Many clusters have a single, dominant central galaxy



cD Galaxy in Abell496 Field (MPG/ESO 2.2-m + WFI)

ESO PR Photo 46h/99 (21 December 1999) © European Southern Observatory



Morphology-density relation

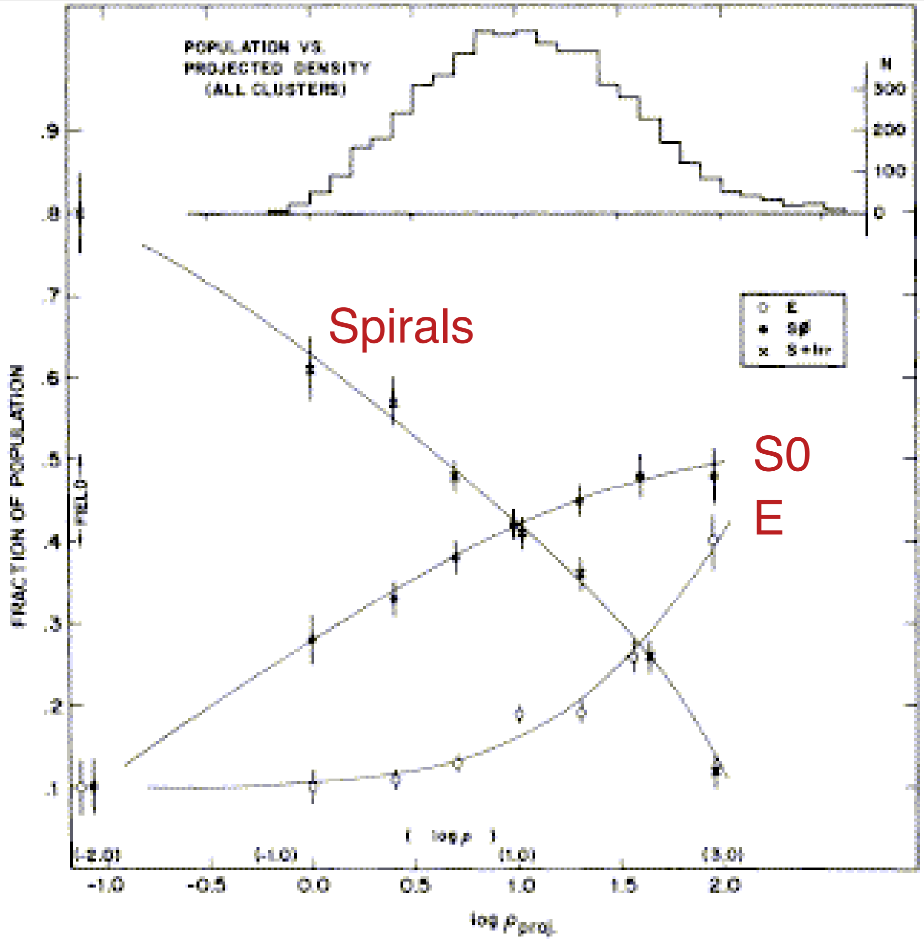


FIG. 4.—The fraction of E, S0, and S+I galaxies as a function of the log of the projected density, in galaxies Mpc^{-2}. The data shown are for all cluster galaxies in the sample and for the field. Also shown is an estimated scale of true space density in galaxies Mpc^{-3}. The upper histogram shows the number distribution of the galaxies over the bins of projected density.

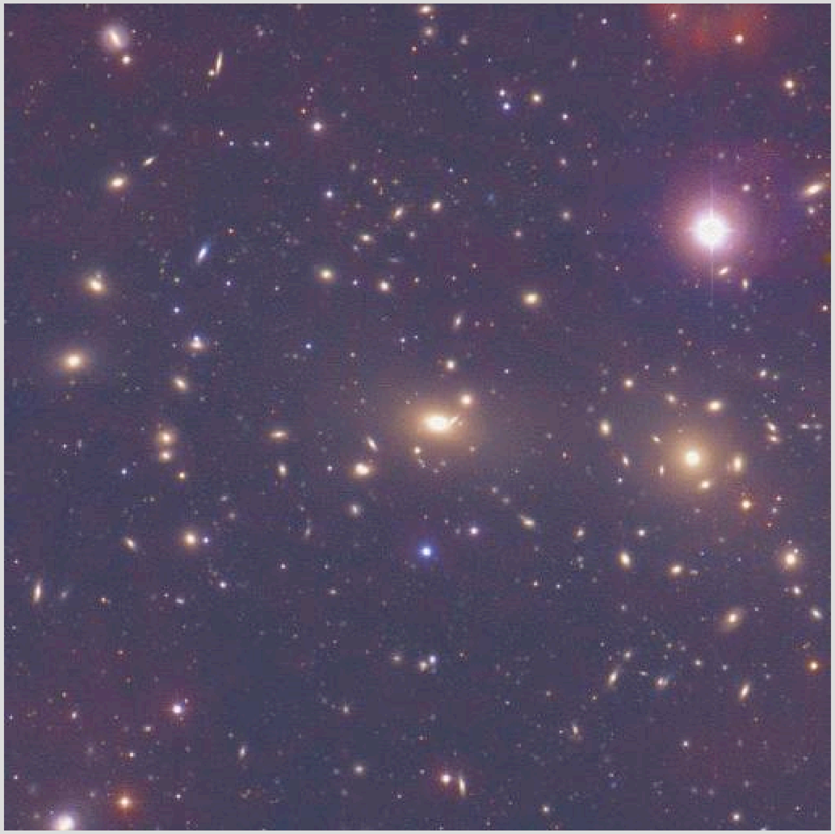
Galaxy population is correlated with the galaxy density:

Low density environments
Favor *spirals*

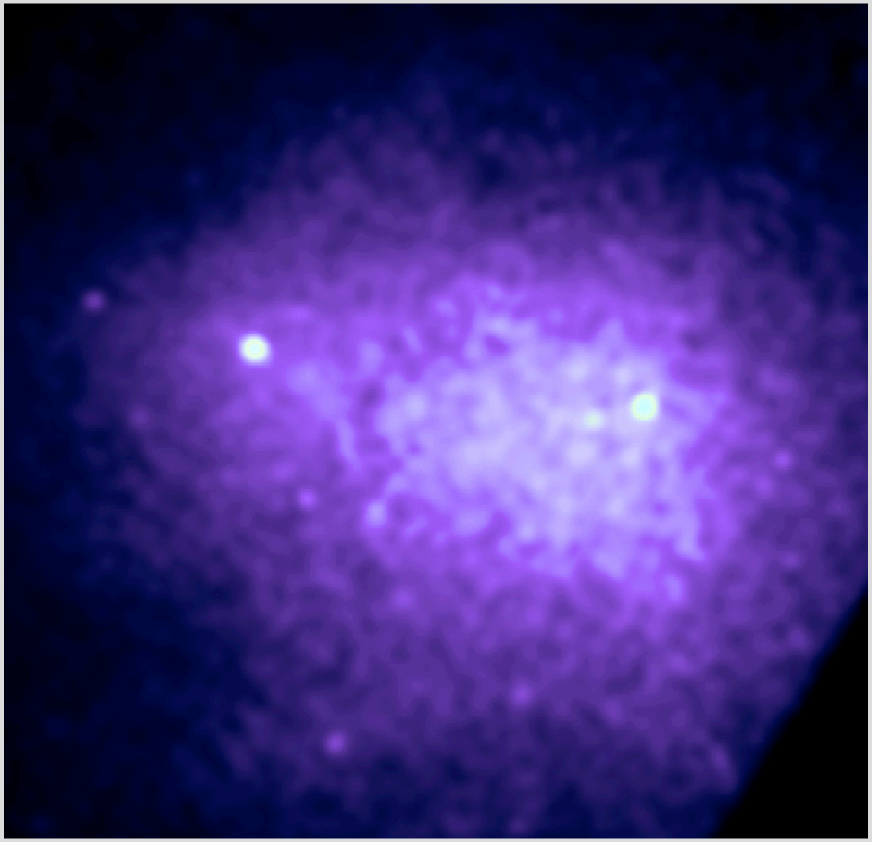
Cluster environments
Favor *ellipticals*

Gas in galaxy clusters

Observe extended emission in X-ray observations of clusters of galaxies - indicates presence of hot gas distributed throughout the cluster volume:



Coma in the optical



Coma in X-rays

If the gas is in virial equilibrium within the cluster, expect:

$$kT \sim \frac{1}{2} m_p v^2$$

Guess thermal velocity $\sim \sigma = 1000$ km s^{-1}

$\Rightarrow$ T ~ 6 x 10^7 K - radiation via bremsstrahlung

Formula for the bremsstrahlung emission from a thermal plasma at temperature T is:

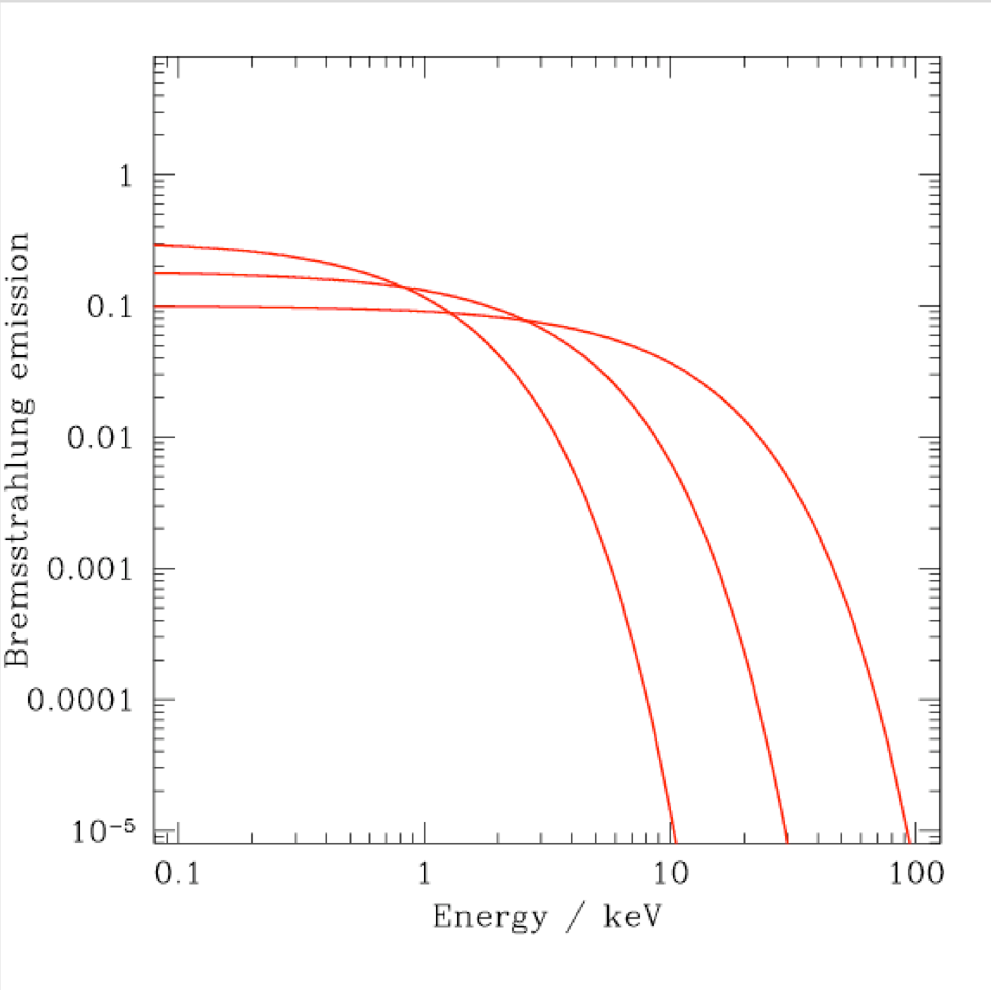
$$\epsilon_\nu^{ff} = 6.8 \times 10^{-38} Z^2 n_e n_i T^{-1/2} e^{-h\nu/kT} \text{ erg s}^{-1} \text{ cm}^{-3} \text{ Hz}^{-1}$$

Ion charge is Ze

Number density of electrons, ions

From X-ray observations, easiest quantities to measure are:

- **Luminosity** L_X - depends on density, temperature and volume of the cluster
- **X-ray surface brightness** as f(radius)
- **Mean temperature** from the spectrum



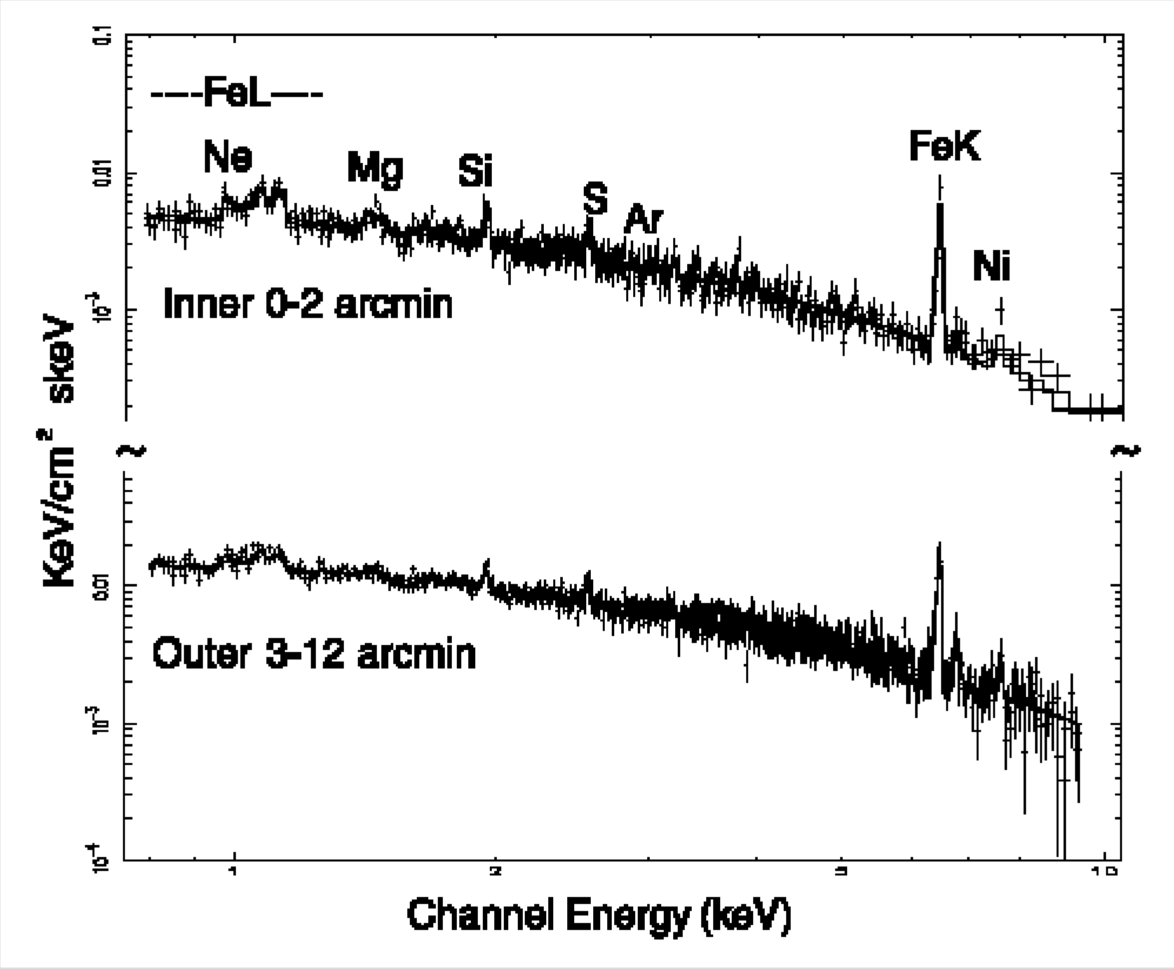
Bremsstrahlung has a flat spectrum up to $h\nu = kT$ followed by an exponential cutoff

Plot shows temperatures of 10^7, 3×10^7 K, 10^8 K

Most clusters have T between 2×10^7 K and 10^8 K

Harder to measure…

- **Temperature gradient**
- **Metallicity** of the cluster gas



Example of an ASCA spectrum of a cluster showing line emission

Cooling cores

Is the gas in galaxy clusters radiating enough to cool significantly? Integrated over frequency, bremsstrahlung emission is:

$$\varepsilon^{ff} = 1.4 \times 10^{-27} T^{1/2} n_e n_i Z^2 \text{ erg s}^{-1} \text{ cm}^{-3}$$

Roughly, estimate:

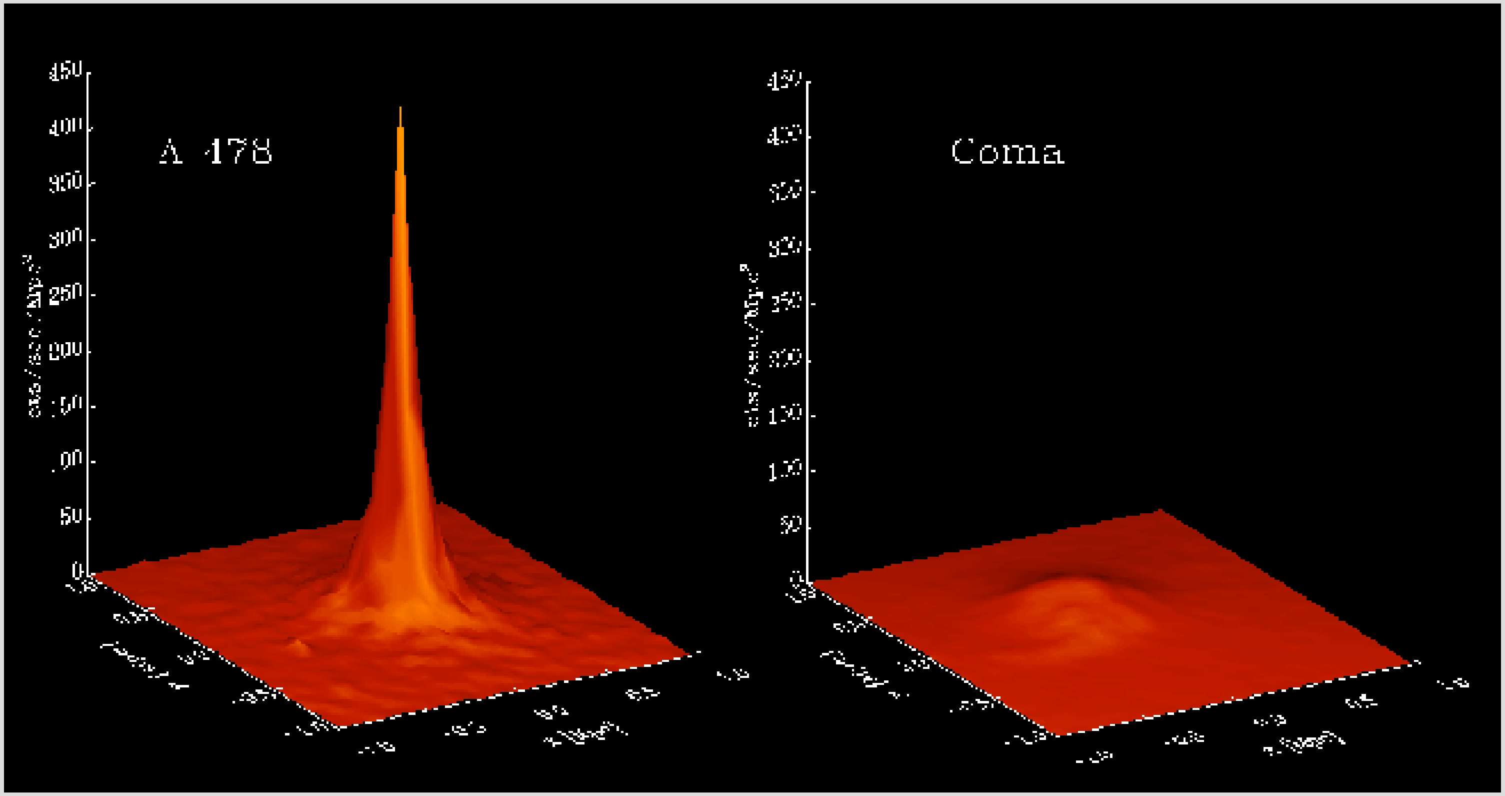
$$t_{cool} \sim \frac{n_e kT}{1.4 \times 10^{-27} T^{1/2} n_e^2}$$

$$\sim 3 \left(\frac{T}{10^8 \text{ K}} \right)^{1/2} \left(\frac{n_e}{0.01 \text{ cm}^{-3}} \right)^{-1} \text{ Gyr}$$

Gas in most of the cluster will not cool - $n_e < 10^{-2}$ cm^{-3}. But dense gas in the core is expected to cool significantly.

Cooling time scales as n^{-1}, hence might expect that:

- Cooling starts
- Pressure drops
- Gas flows in: increased density
- Increased cooling: runaway



Some clusters show very bright cores, suggesting that this process is going on…

But what happens to the cool gas? Do **not** observe:

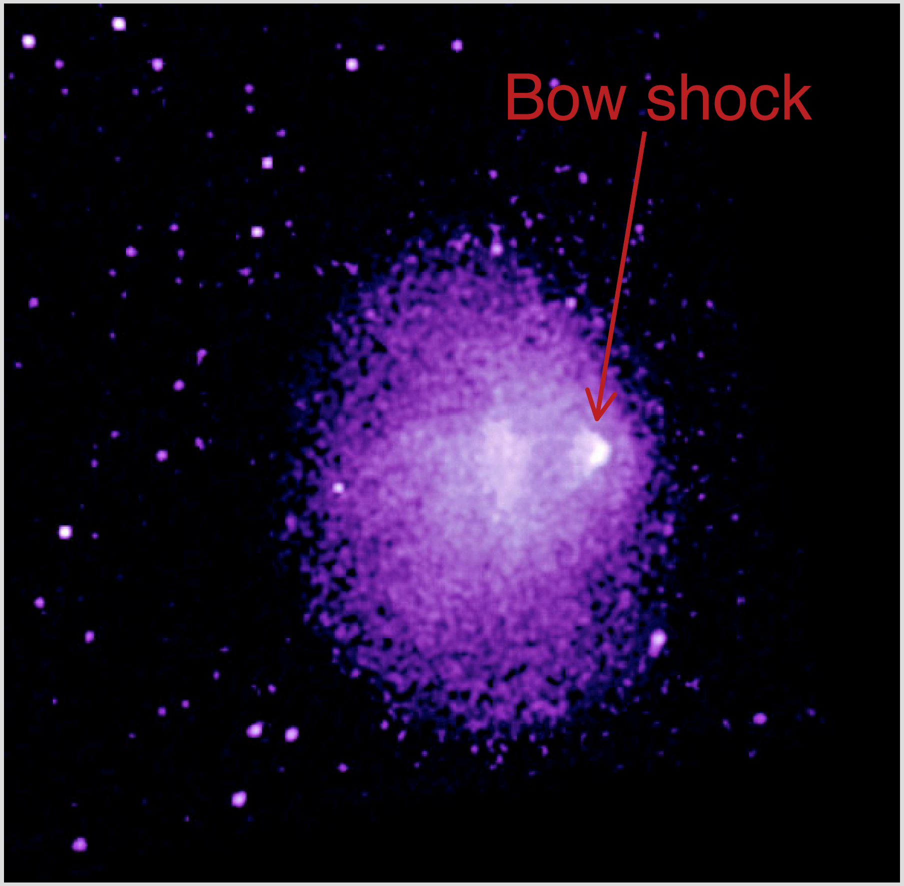
- Very high rates of star formation
- Lines in the soft X-ray spectrum from the cool material

Suggests that some source of **heating** balances the cooling at a lower temperature, possibly:

- Conduction from the hotter regions at larger radius
- Heating due to AGN outflows

Chandra observations of clusters

High resolution observations with *Chandra* show that many clusters have substructure in the X-ray surface brightness



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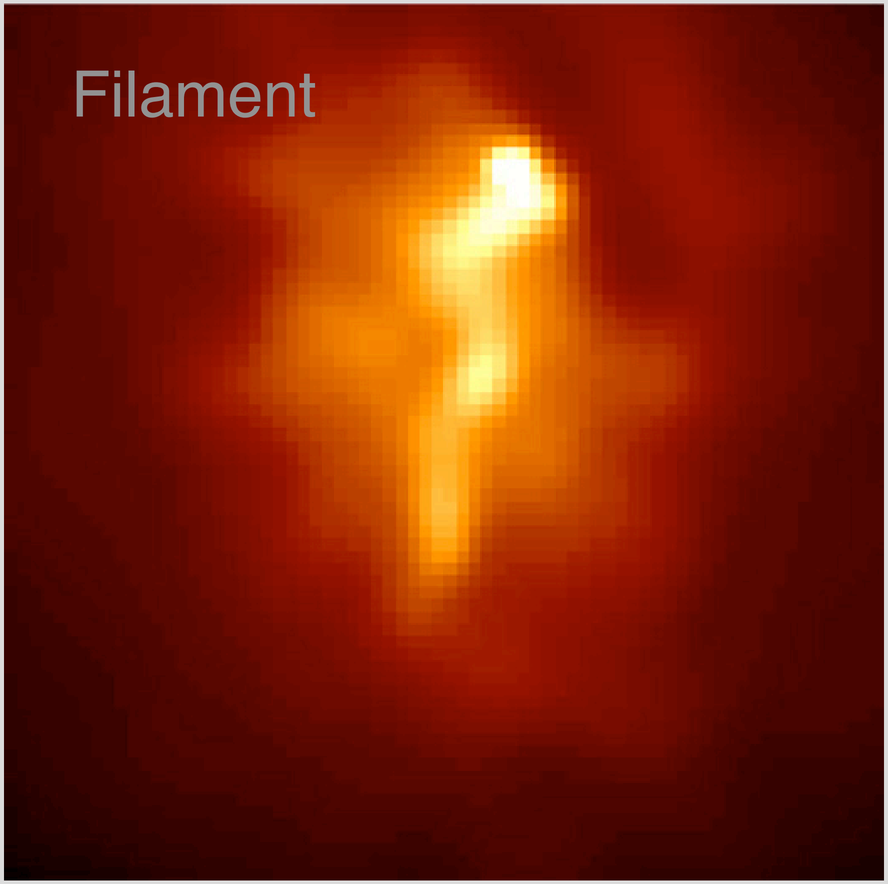

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