Introduction to clusters of galaxies

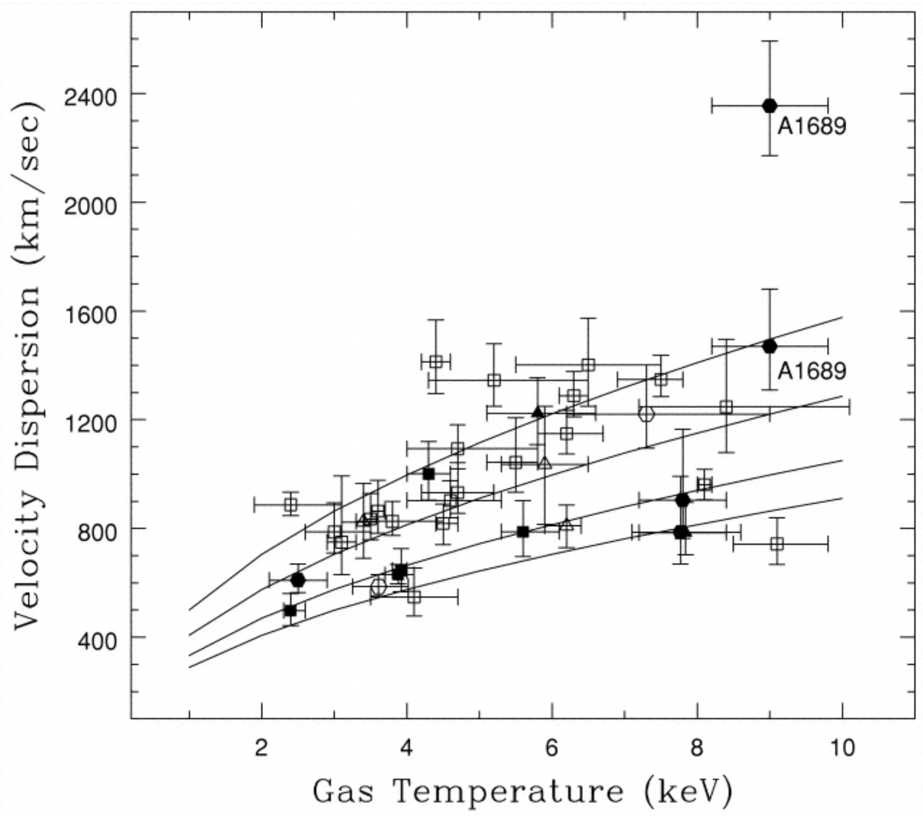
- Optical (galaxies)
- X-rays (intergalactic gas)
- Masses (baryonic and dark matter)

Optical (galaxies)

- 100-1000 galaxies
- size ~1 Mpc
- mass ~10^{13} $M_\odot$
- ~100 times a galaxy scale of 10kpc, 10^{11} stars

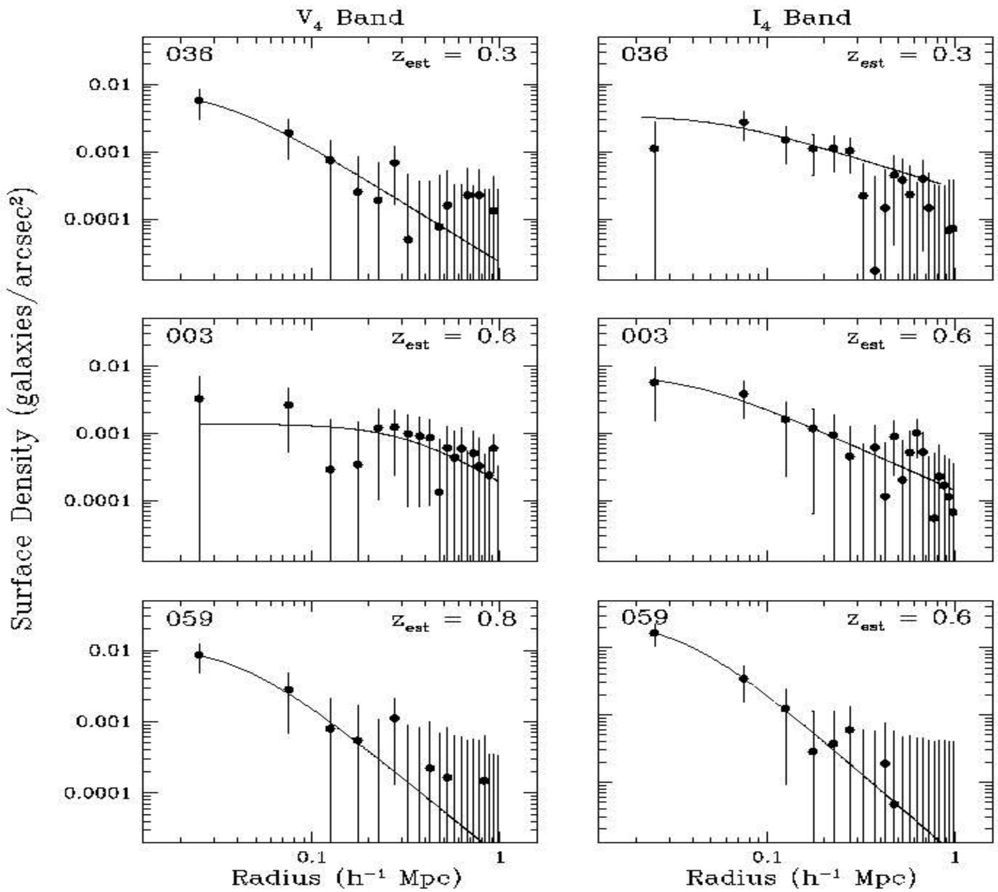
VIRGO

Velocity dispersion



- velocity dispersion σ ~ 1000 km / s
- Jones and Forman, 1999, ApJ, 511, 65

Galaxy distribution



- Lubin et al., 1996, AJ, 111, 1795

Galaxy distribution

- (modified) King profile:

$$S(r) = S_0\left[1+\left(\frac{r}{r_c}\right)^2\right]^{-\alpha/2}$$

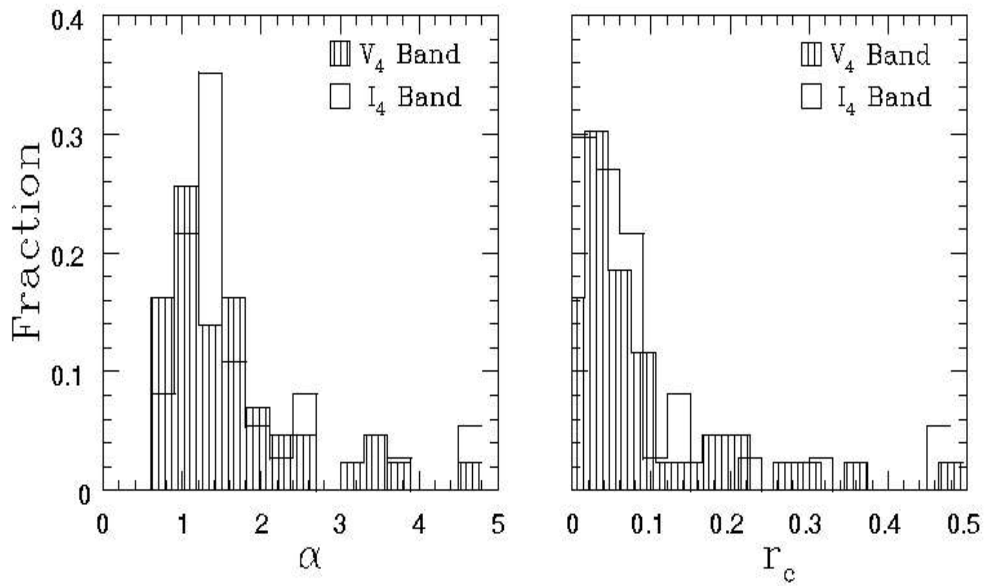
S = galaxy number density

r_c = core radius

α = index (King: $\alpha \equiv 1$)

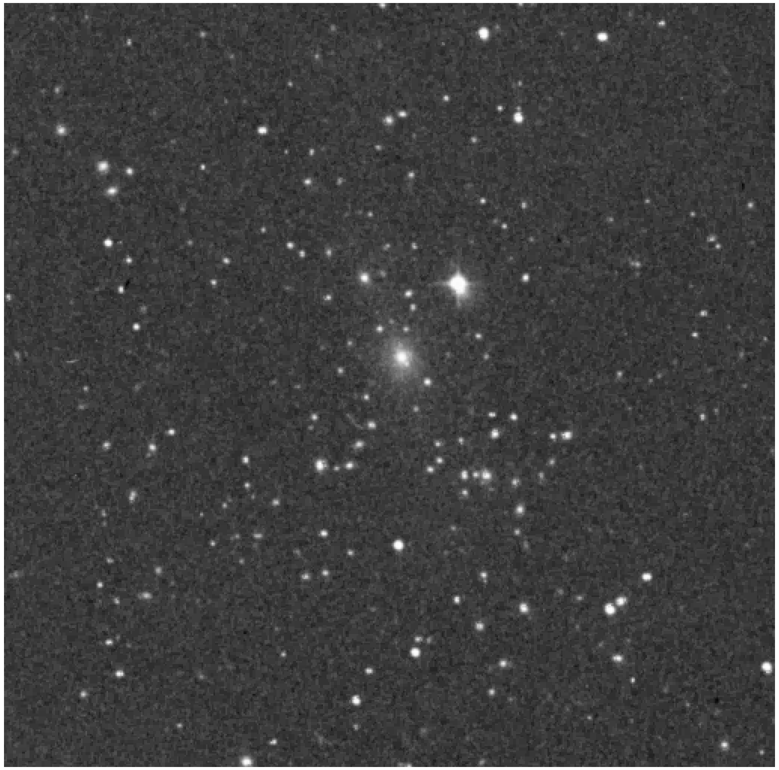
when $r \to \infty$, $S \to r^{-\alpha}$

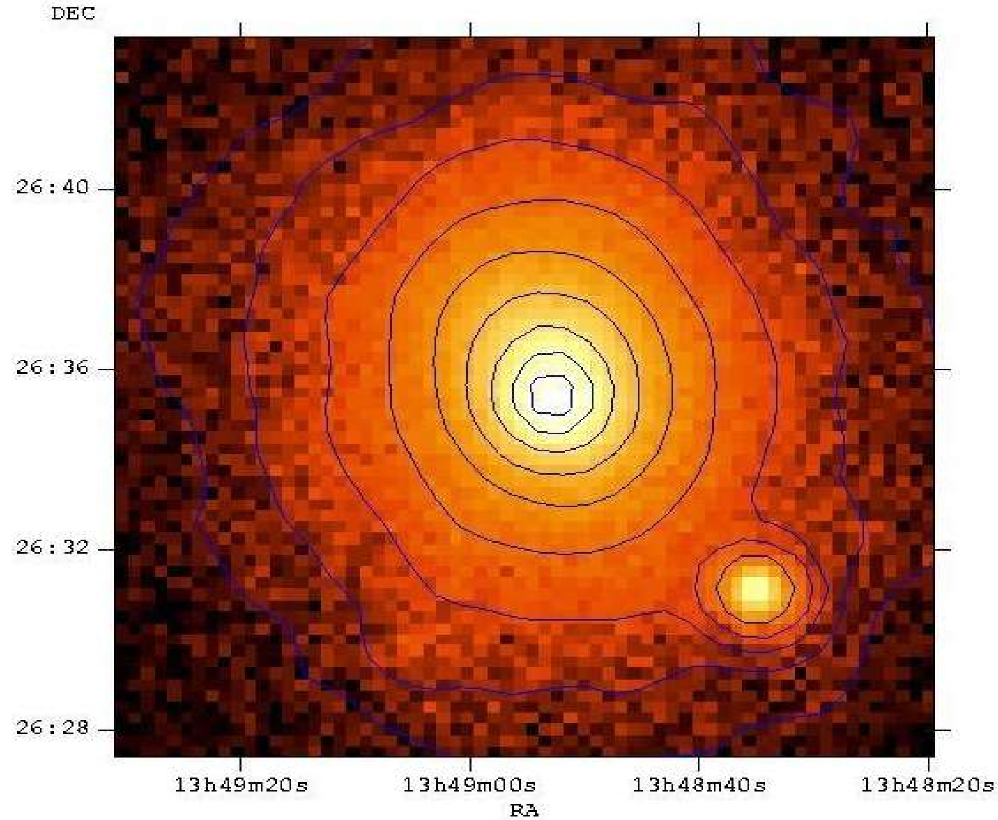
typically: $r_c \sim 0.1\,Mpc$, $\alpha \sim 1.0$



Optical v.s. X-rays

- optical light — X-rays
- (100-1000) galaxies — hot (10-100 millions degrees) gas





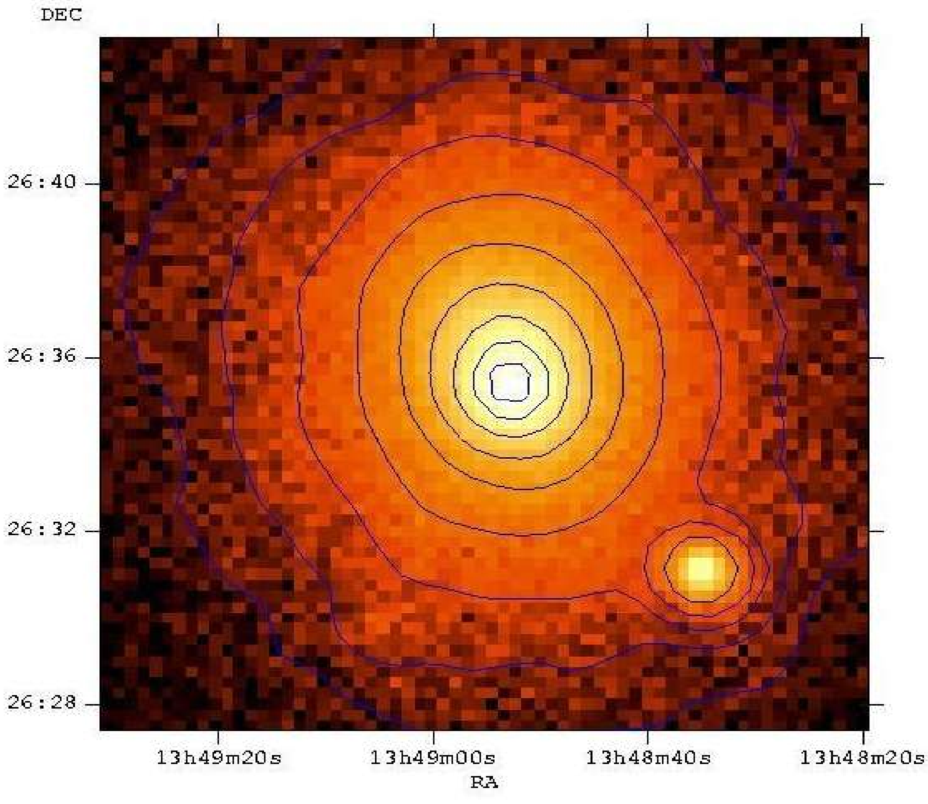
X-ray properties of clusters of galaxies

- Size : ~ Mpc
- Mass: Galaxies 10^{13} $M_\odot$; Gas 10^{14} $M_\odot$; Dark matter 10^{15} $M_\odot$
- Origin: gravitational collapse, subsequent merging →
- Heating and ionisation of the matter into 10–100 x 10^6 K temperatures
- gas density ~10^{-3} – 10^{-5} cm^{-3}
- bremsstrahlung → X-rays

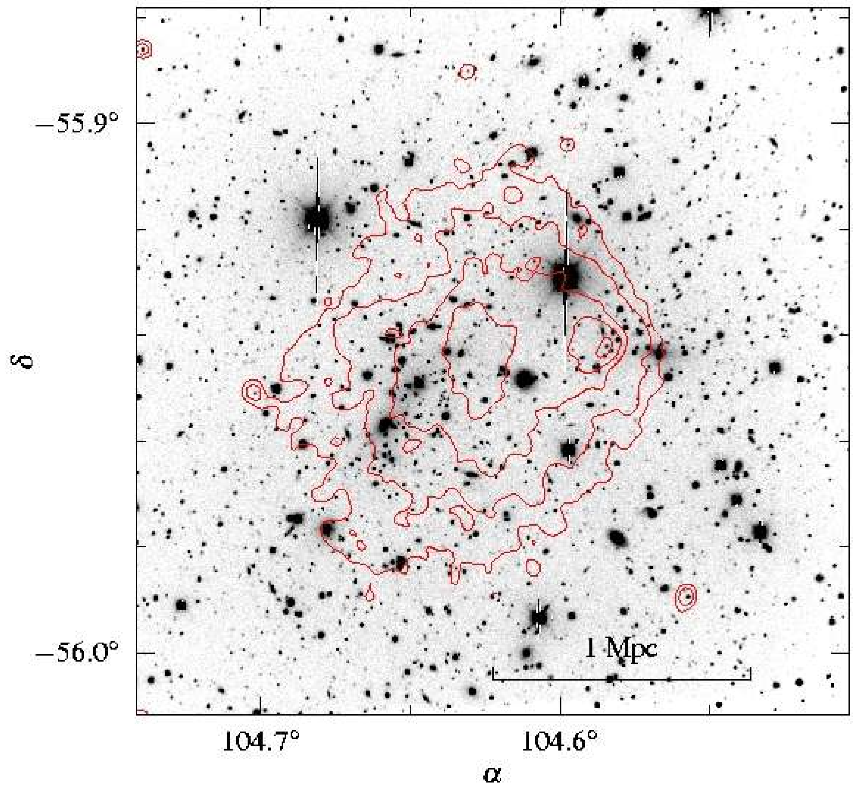
X-ray properties of clusters of galaxies

- Rough division into relaxed and merger clusters by the deviations from azimuthal symmetry in X-ray brightness and temperature

relaxed cluster Abell 1795



merger cluster 1E0657-56 (Bullet cluster)



X-ray morphology classification (Jones and Forman, 1999, ApJ, 511, 65)

- regular (~50% of clusters)
- irregular:

- Elliptical

- Offset center

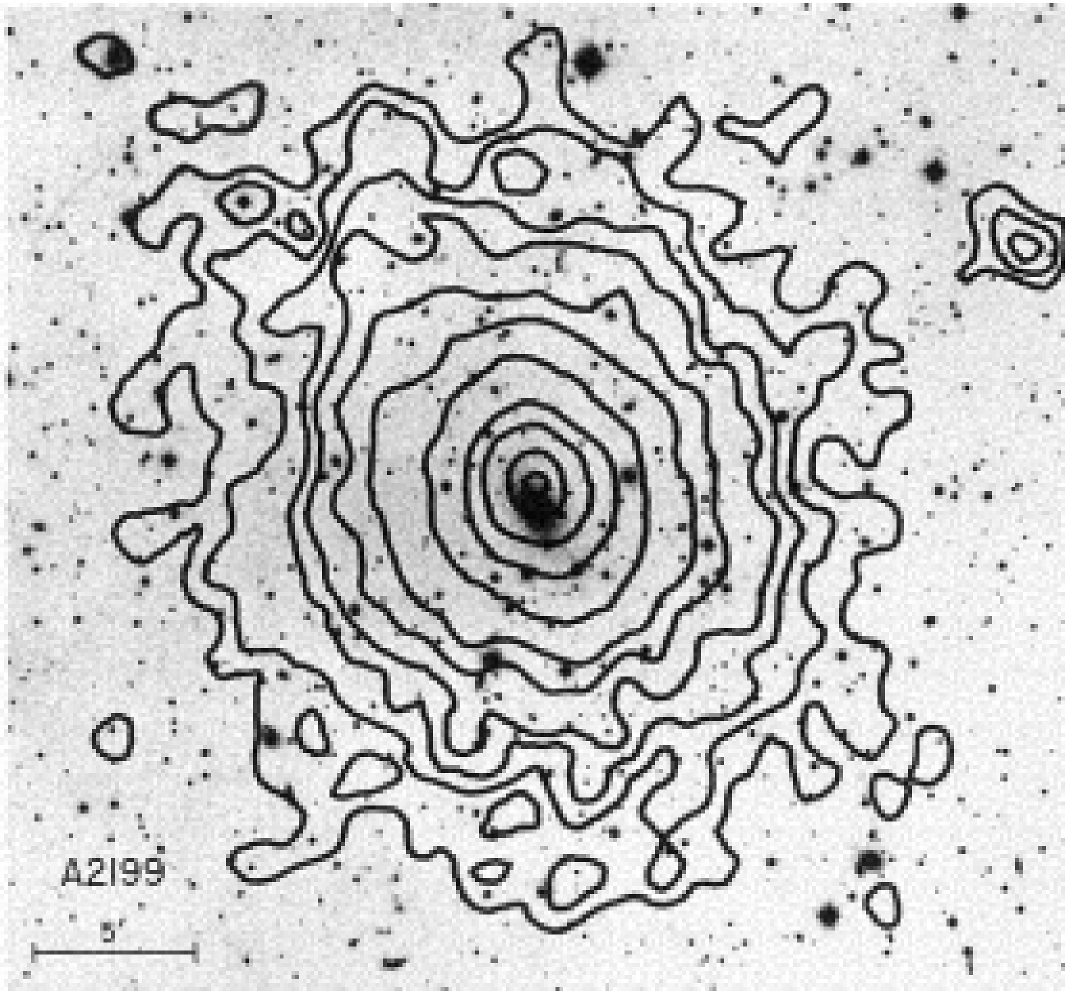
- Primary with a small secondary

- Double with equal components

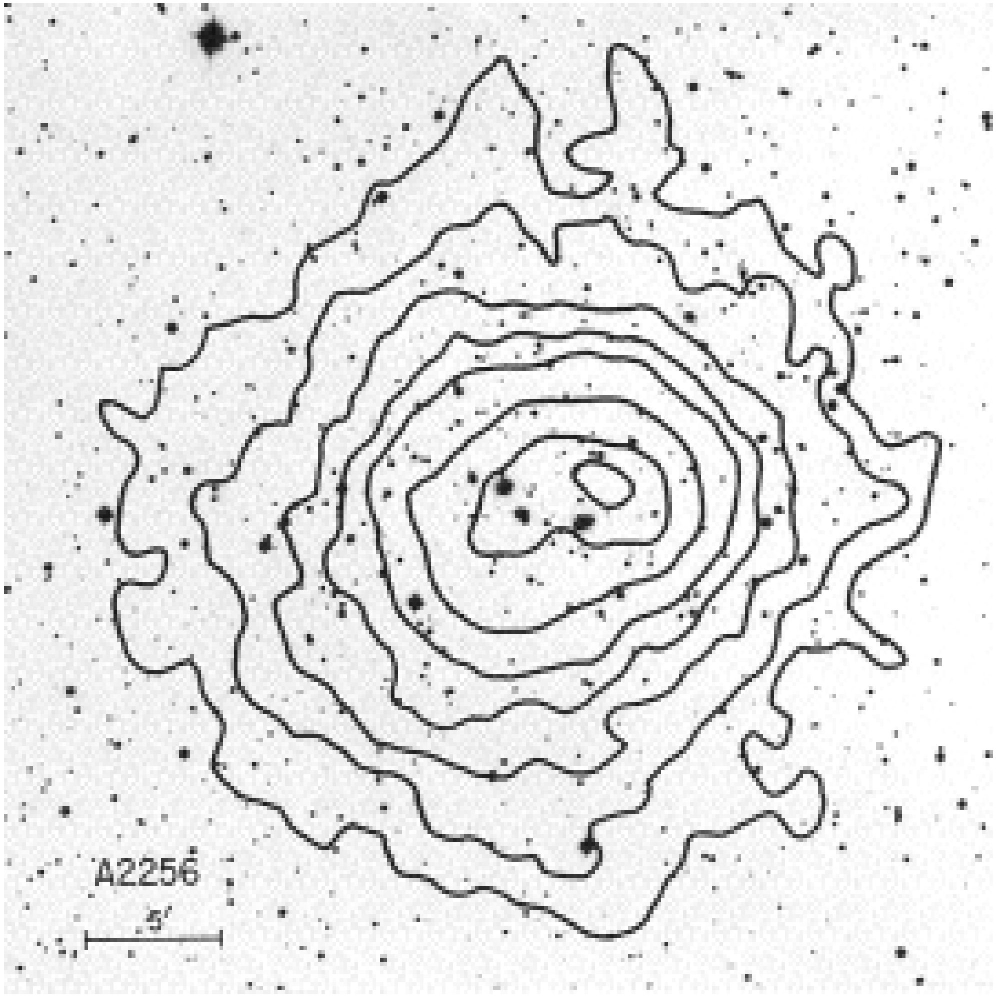
- Complex

- Primarily galaxy emission

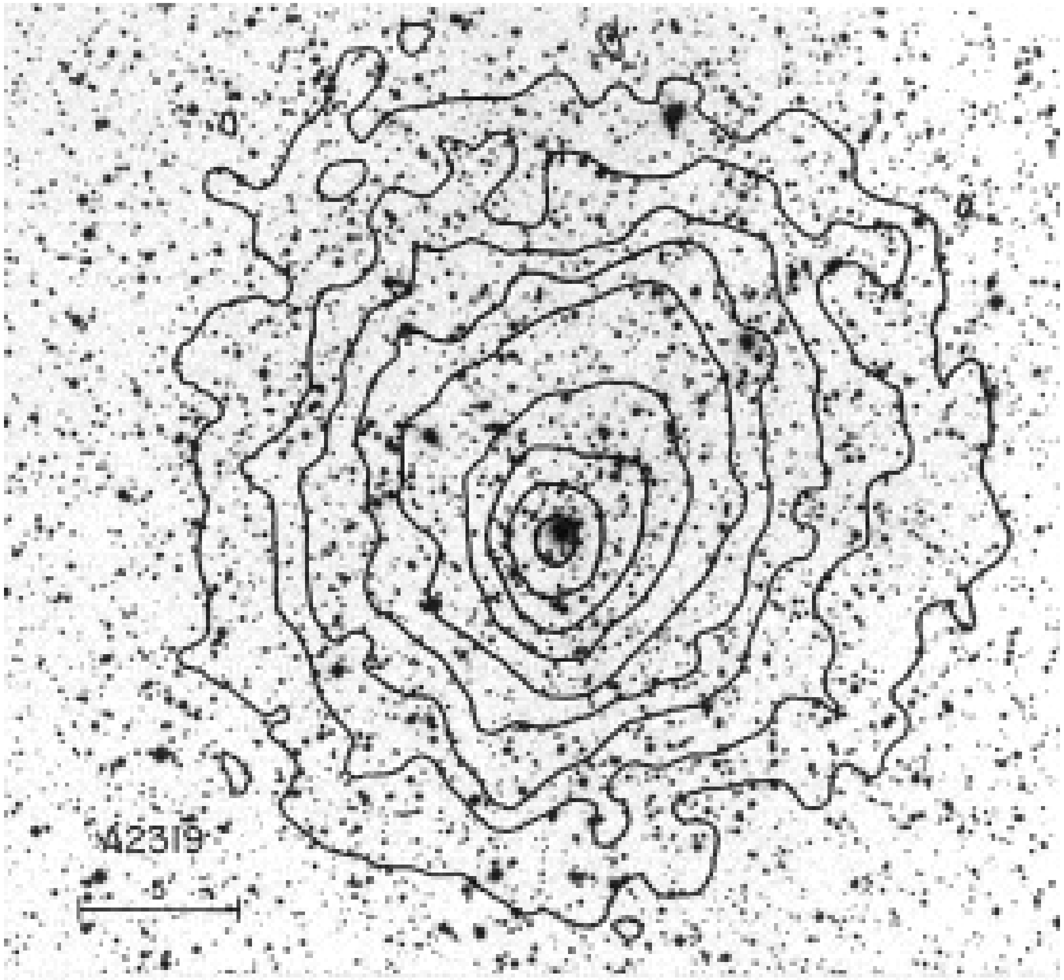
Regular: A2199



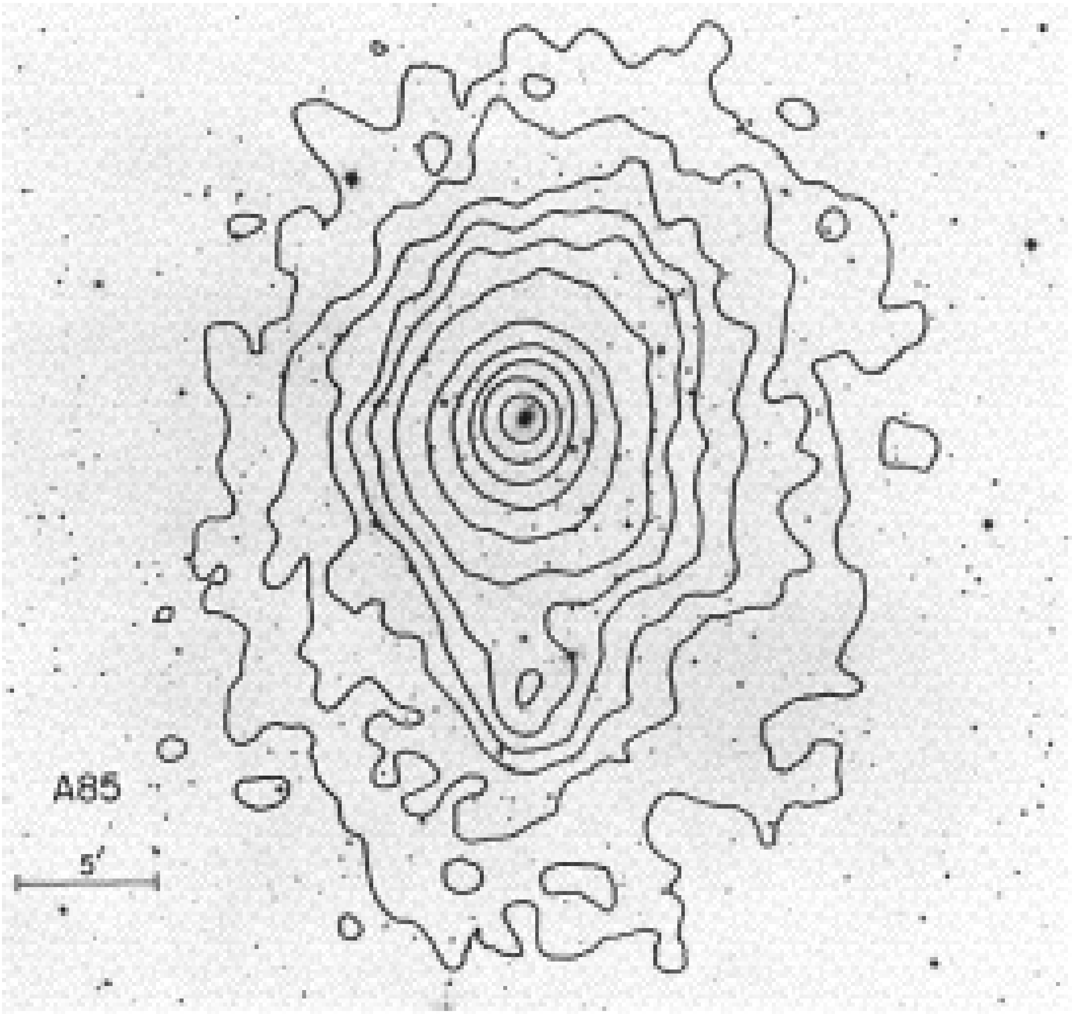
Elliptical: A2256



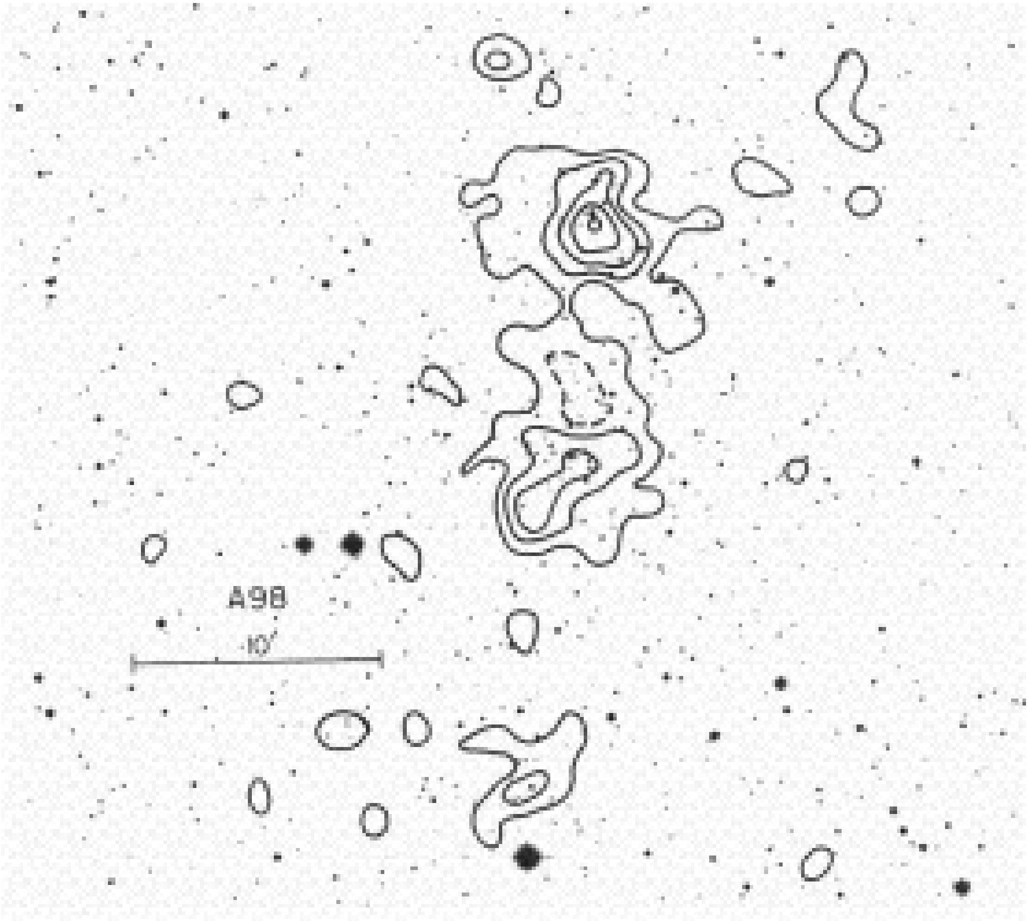
Offset center: A2319



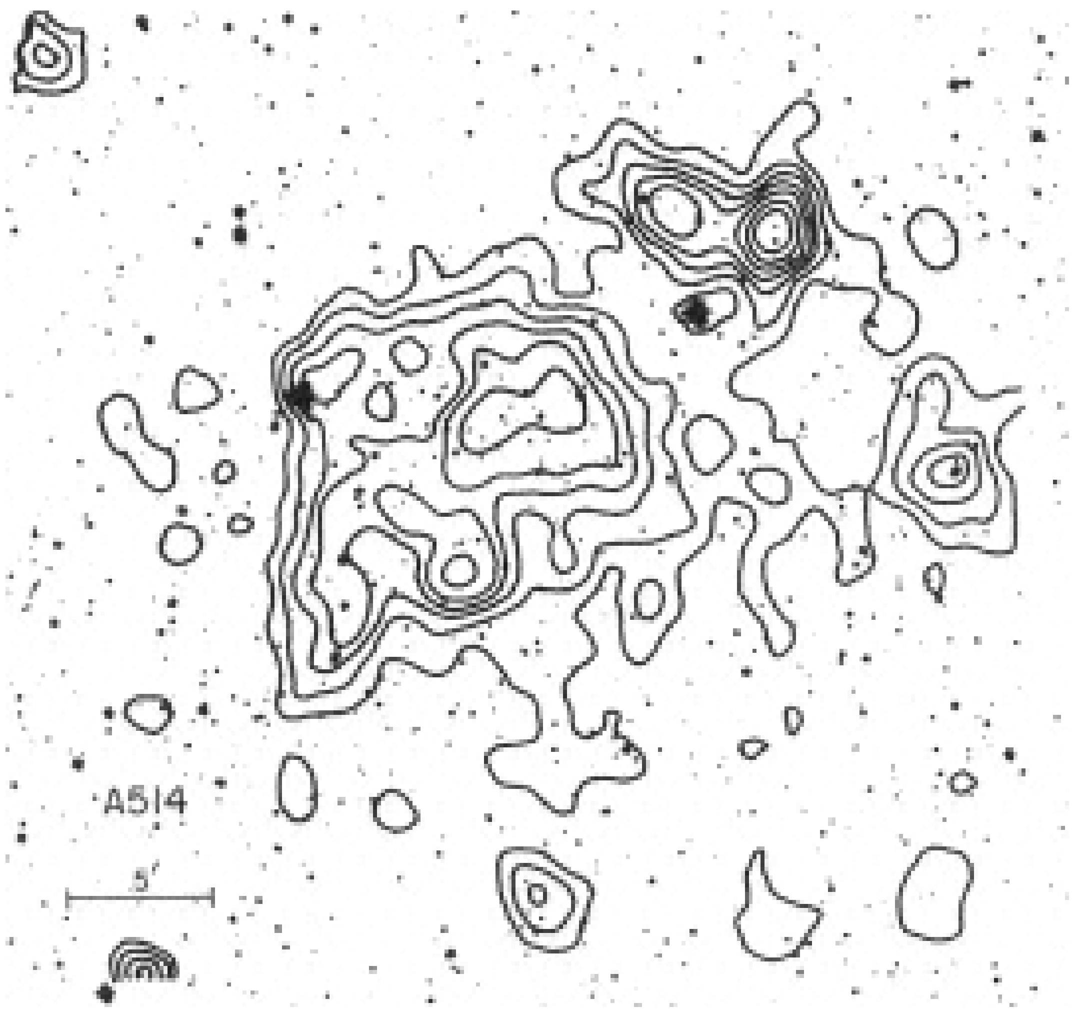
Primary with a small secondary: A85



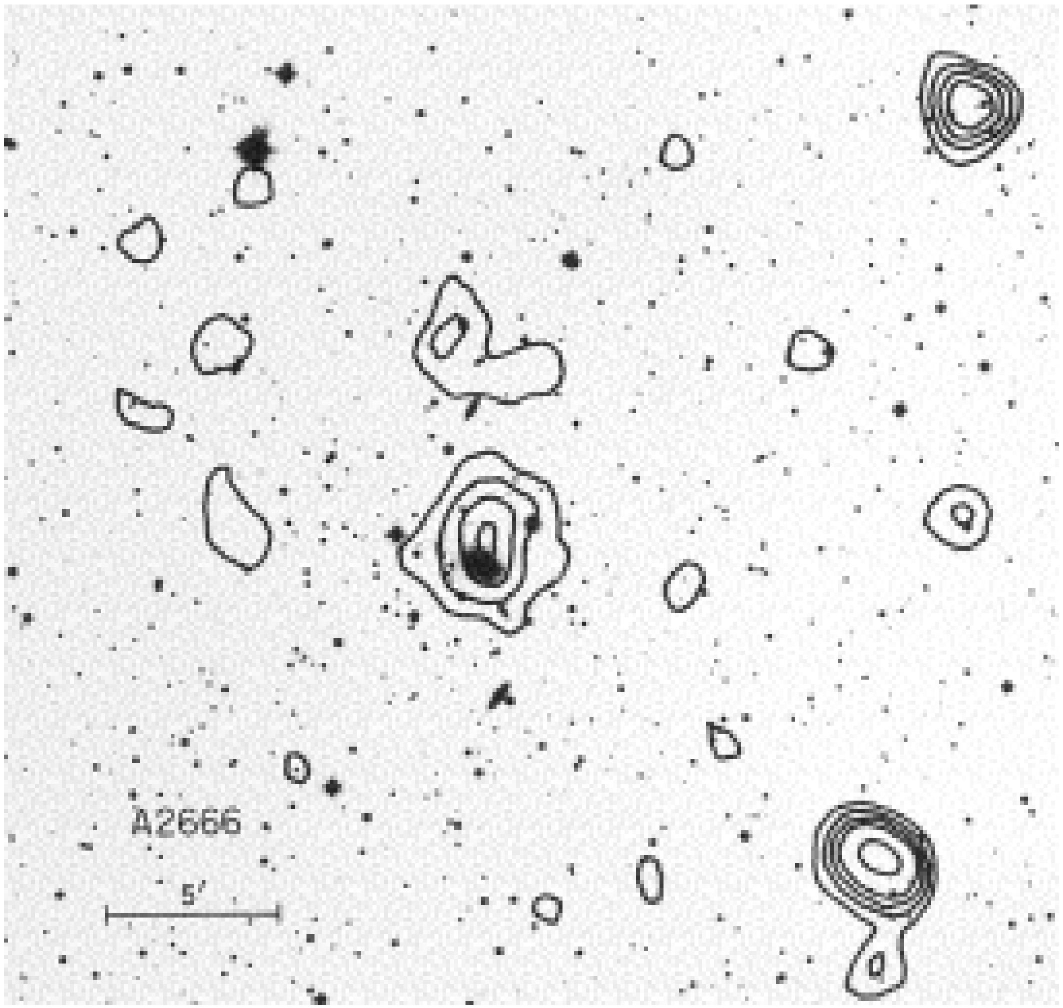
Double with equal components:
A98



Complex: A514



Primarily galaxy emission: A2666



keV units

keV as a unit of photon energy

- photon energy $E = h\nu = \dfrac{hc}{\lambda}$ where

h = 4.13608 x 10^{-18} keV s (Planck's constant)

e.g. for a photon with E = 1 keV:

$$E = 1\,\mathrm{keV} \rightarrow \nu = \frac{E}{h} = \frac{1\,\mathrm{keV}}{4.13608\times10^{-18}\,\mathrm{keV}\,s} \approx 10^{17}\ Hz$$

$$E = 1\,\mathrm{keV} \rightarrow \lambda = \frac{hc}{E} = \frac{4.13608\times10^{-18}\,\mathrm{keV}\,s \times 2.9979\times10^{8}\,m\,s^{-1}}{1\,\mathrm{keV}} \approx 1\,nm$$

keV units

keV as "unit" of electron temperature

- Real temperature unit is Kelvin
- In X-ray astronomy, it is customary to use k T as temperature unit, even though this actually has a dimension of energy
- k = 8.617 x 10^{-8} keV K^{-1} (Boltzmann's constant)
- This is because the average energy E of a photon from a black-body emission from a source with temperature T is E = k T
- Cluster with temperature T = "1 keV" (really E = 1 keV) has a real temperature

$$\mathrm{T} = \frac{\mathrm{E}}{\mathrm{k}} = \frac{1\,\mathrm{keV}}{8.617 \times 10^{-8}\,\mathrm{keV\,K^{-1}}} \approx 10^{7}\,K$$

Bremsstrahlung

Sarazin chapters 4.3., 4.3.1, 5.1.3, 5.2, 5.2.1, 5.2.2, 5.2.3, 5.3, 5.3.1, 5.3.2, 5.4, 5.4.1

- Diffuse baryonic matter in galaxy clusters is very hot, T ~$10^{7\text{-}8}$ K ➔
- highly ionised, most electrons stripped from atoms
- Cluster baryonic matter density very low (10^{-3} – 10^{-5} cm^{-3})
- Mean free path due to Coulomb collisions:

$$\lambda_e = \lambda_i \approx 23 \text{ kpc} \left(\frac{T_g}{10^8 K} \right)^2 \left(\frac{n_e}{10^{-3} \text{cm}^{-3}} \right)^{-1}$$

- For a typical cluster $T \approx 10^8 K, n_e \approx 10^{-3} \rightarrow \lambda_e \approx 10 \, \text{kpc}$
- Size of a cluster ~ Mpc, much bigger than the mean free path of an electron ➔
- lots of interactions between protons and electrons ➔ electron decelerates in the Coulomb field of a proton, and emits a photon ➔ bremsstrahlung

Bremsstrahlung

- Elastic collisions will render the plasma electron distribution to relax to a Maxwell distribution in a time scale

$$t_{eq} \approx 3\times10^{5}\ \mathrm{yr}\left(\frac{T_e}{10^8 K}\right)^{3/2}\left(\frac{n_e}{10^{-3}\,\mathrm{cm}^{-3}}\right)^{-1}$$

- For a typical cluster $T \approx 10^8 K\,,\, n_e \approx 10^{-3} \rightarrow t_{eq} \approx 10^5\,\mathrm{yr}$

the equilibration time scale is much shorter than cluster age ($\sim 10^{8\text{-}9}$ yr) ➔

- electron velocity distribution Maxwellian to the first order (mergers for example will modify this)
- energy of emitted bremsstrahlung photon is proportional to the electron velocity
- Continuous electron velocity distribution ➔ continuum spectrum

Bremsstrahlung

- Bremsstrahlung emissivity (emitted energy per volume, frequency and time):

$$\varepsilon_\nu = \frac{dL}{dV d\nu} = \frac{2^5 \pi e^6}{3 m_e c^3} \left(\frac{2\pi}{3 m_e k} \right)^{1/2} Z^2 n_e n_i g_{ff}(Z, T_g, \nu)\, T_g^{-1/2} \exp(-h\nu / kT_g)$$

- dL = dE/dt = luminosity = emitted energy per time
- T_g = average electron temperature (= gas temperature)
- $n_{e,i}$ = number density of electrons and ions
- Z = atomic number ~ charge
- g_{ff} = Gaunt factor (quantum mechanical corrections)

Bremsstrahlung

- Luminosity from a given frequency range and volume:

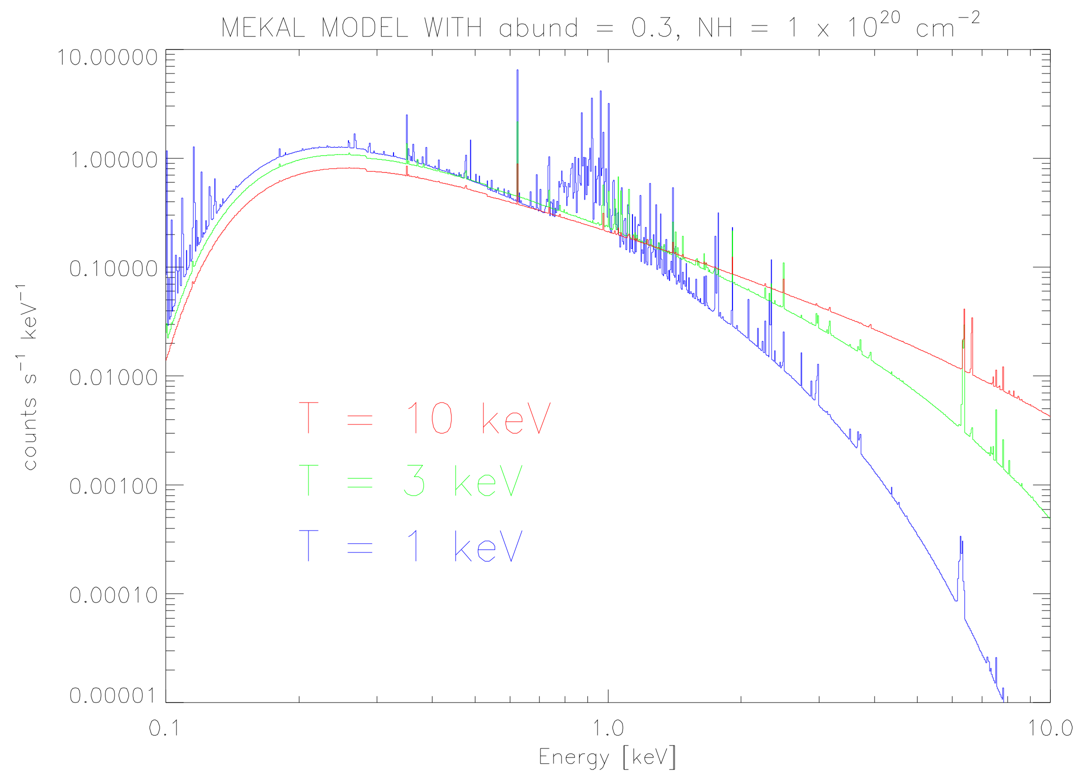
$$L_{\nu 1-\nu 2}\,[\mathrm{erg}\ s^{-1}]=\int_{\nu_1}^{\nu_2}\int_V \varepsilon_\nu\,\mathrm{dV}\,\mathrm{d}\nu=\int_{\nu_1}^{\nu_2} f(\mathrm{T},\nu)\,\mathrm{d}\nu\int_V n_e^{\,2}\,\mathrm{dV}$$

- Emission measure:

$$\mathrm{EM}\equiv\int_V n_e^{\,2}\,\mathrm{dV}\rightarrow$$

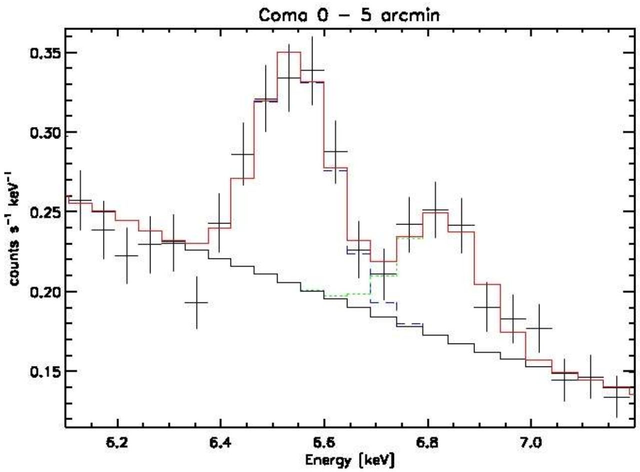
$$L_{\nu 1-\nu 2}=\mathrm{EM}\times\int_{\nu_1}^{\nu_2} f(\mathrm{T},\nu)\,\mathrm{d}\nu$$

- $\mathrm{n_e}$: normalisation
- T: shape $\quad L\propto\exp(-h\nu/kT_g)$



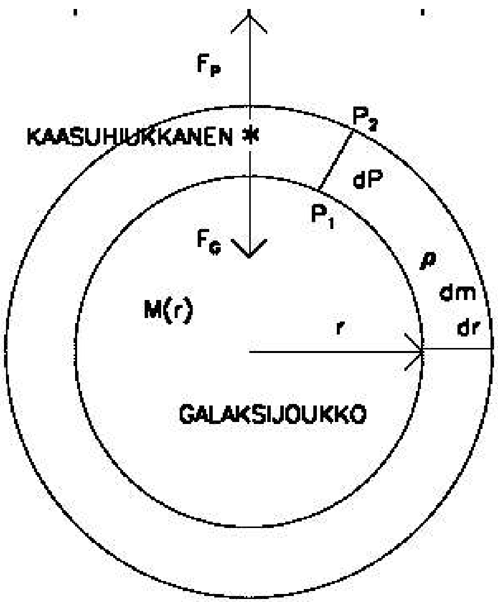
Line emission Sarazin 4.3.2, 4.3.3

- electron energies quantized
- e first excited to higher energy level E_2 due to e.g. a collision with another e
- the e decays to a lower energy level E_1 and emits a photon with energy $E_2 - E_1$
- Ionisation degree depends on the temperature : higher T → line emission at heavier elements and shorter wavelengths
- At cluster temperatures (T=1-10 keV) the most important emission lines are FeXXV (He-like) and FeXXVI (H-like), at photon energies E = 6-7 keV



Coma cluster T= 9 keV

Hydrostatic equilibrium Sarazin 5.5, 5.5.5



Force due to the pressure difference: $F_p = A \times dP = 4\pi r^2 dP$

Gravity: $F_G = \frac{-GM(r)}{r^2} dm = \frac{-GM(r)}{r^2} \rho(r) 4\pi r^2 dr$

Balance: $F_p = -F_G \rightarrow 4\pi r^2 dP = \frac{-GM(r)}{r^2} \rho(r) 4\pi r^2 dr \Leftrightarrow$

$$\frac{dP}{dr}\frac{1}{\rho} = \frac{-GM(r)}{r^2}$$

Hydrostatic equilibrium

$$\text{Ideal gas}: P = knT = \frac{\rho}{\mu m_p} kT \rightarrow$$

$$\frac{k}{\mu m_p} \frac{1}{\rho} \frac{d(\rho T)}{dr} = \frac{-GM(r)}{r^2} \Leftrightarrow$$

$$M(r) = -\frac{k}{\mu m_p G} \frac{r^2}{\rho} \frac{d(\rho T)}{dr} \Leftrightarrow$$

$$M(r) = -\frac{k}{\mu m_p G} Tr \frac{r}{dr} \frac{d(\rho T)}{\rho T} \Leftrightarrow \quad \left(\frac{d \ln x}{dx} = \frac{1}{x} \rightarrow \frac{dx}{x} = d \ln x \right)$$

$$M(r) = -\frac{k}{\mu m_p G} Tr \frac{d \ln(\rho T)}{d \ln r} \Leftrightarrow$$

$$M_{tot}(<r) = -\frac{k}{\mu m_p G} T_g(r) r \left(\frac{d \ln \rho_g(r)}{d \ln r} + \frac{d \ln T_g(r)}{d \ln r} \right)$$

- only for relaxed clusters
- ρ_g from imaging
- T from spectroscopy