Atomic Emission Lines

Studying Ionized Gas and Hot Plasma

Application to clusters of galaxies

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Outline

- Physical Processes
- Principles of X-ray detection
- Clusters of galaxies
- Applications of x-ray observations

Physical conditions in clusters

low density $\rho \approx 10^{-3} cm^{-3}$

high temperature $T \approx 100\,M\,K$

enriched wit elements

ionization equilibrium

Principal atomic processes

Coronal equilibrium:

In plasma with low density → 3 body processes unlikely

Excitation   Spontaneous emission

$$A^{+Z} + h\nu \Leftrightarrow (A^{+Z})^{*}$$

Photoionization   Radiative recombination

$$A^{+Z} + h\nu \Leftrightarrow A^{+Z+1} + e$$

Bremsstrahlung   Photoabsorption

$$A^{+Z} + e \Leftrightarrow A^{+Z} + e' + h\nu$$

Ionization equilibrium

- elastic collision time << age /cooling time of the plasma
  → Maxwell-Boltzmann distribution
- collisional (de)excitation slower than radiative decays
  → ionization/excitation always from the ground state
- radiation field too weak for stimulated radiative transitions
- gas is optically thin due to low density

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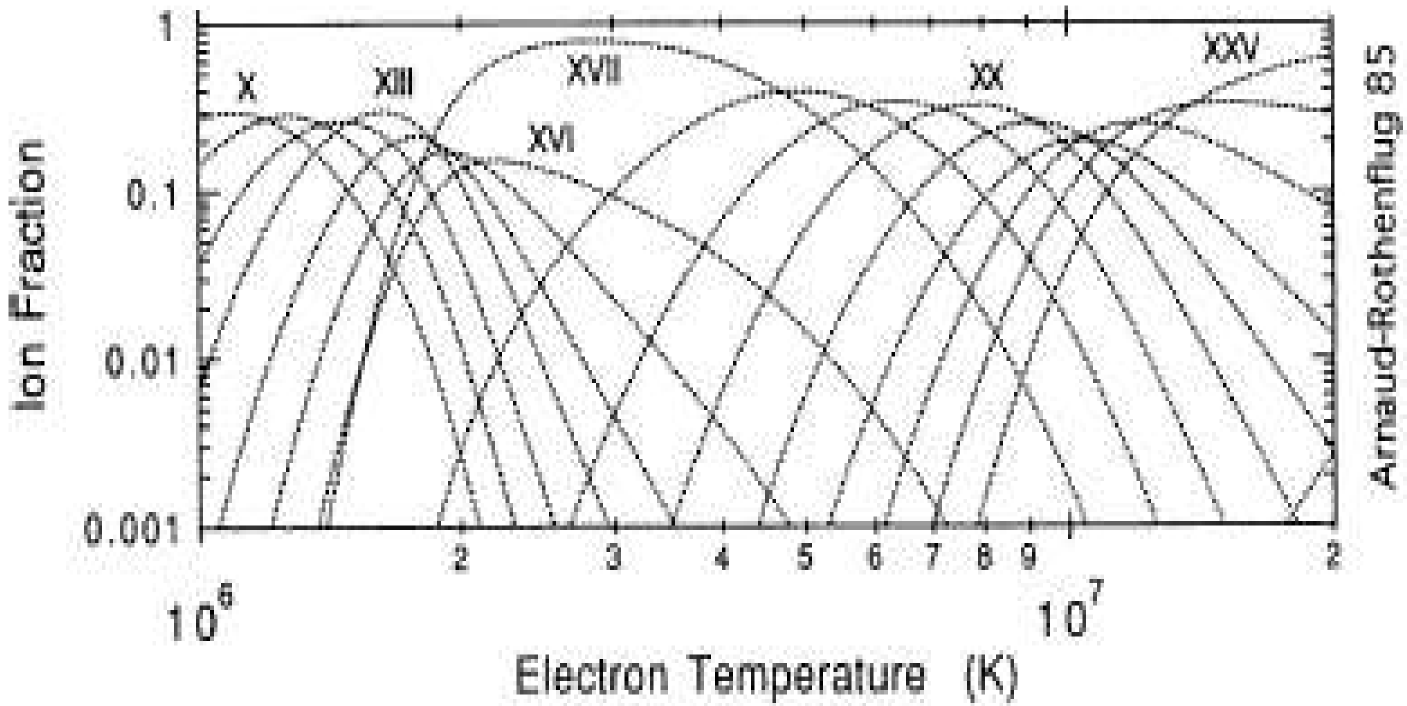
Thermal plasma

Ionization equilibrium



Iron ion fraction as function of electron temperature

Radiative processes

X-ray emission of hot plasma:

Continuum

- thermal bremsstrahlung (free-free emission)
- recombination (free-bound)

Line radiation

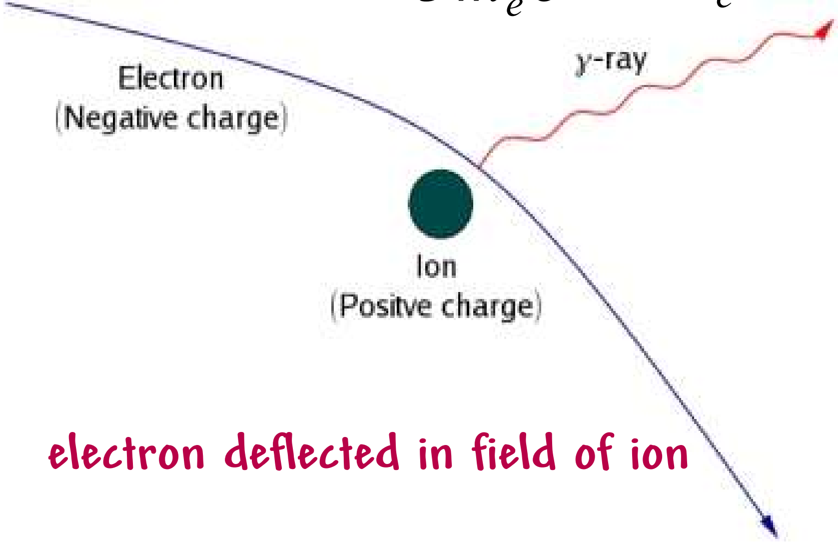
Thermal bremsstrahlung

Assume H gas at temperature $T \sim 10^8 K$ and density $\rho \sim 10^{-3} cm^{-3}$

→ (free free) bremsstrahlung dominant emission

Emissivity: $\epsilon := \frac{dL}{dV\, d\nu}$

$$\epsilon_\nu^{ff} = \frac{2^5 \pi e^6}{3 m_e c^3} \left(\frac{2\pi}{3 m_e k}\right)^{1/2} Z^2 n_e n_i g_{ff}(T,\nu) T^{-1/2} \cdot \exp(-h\nu/kT)$$



electron deflected in field of ion

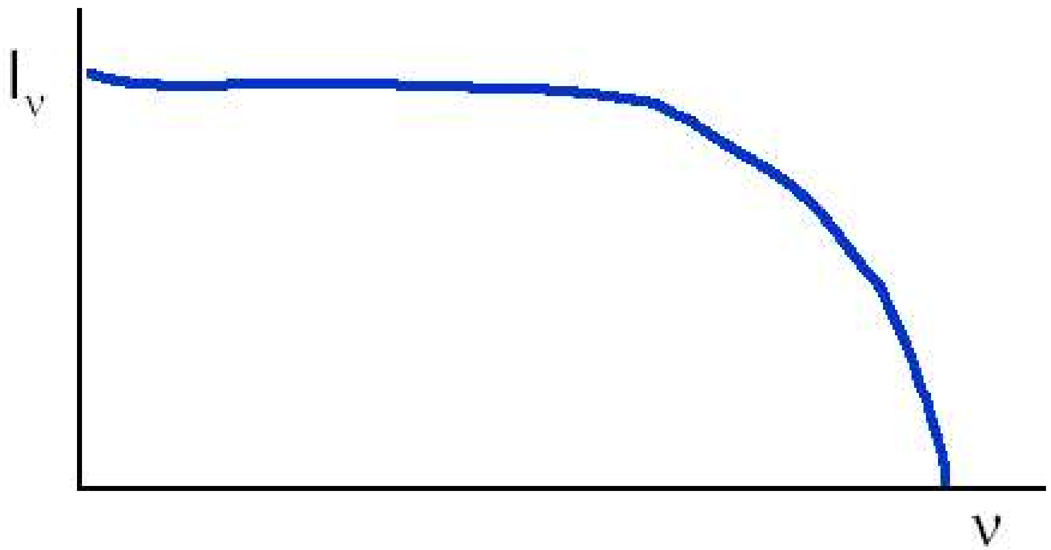
Gaunt factor (for X-ray)

$$g_{ff}(T,\nu) \sim \ln\left(\frac{kT}{h\nu}\right)$$

weakly dependant on T, E

Thermal bremsstrahlung

Typical bremsstrahlungs spectrum



Recombination radiation

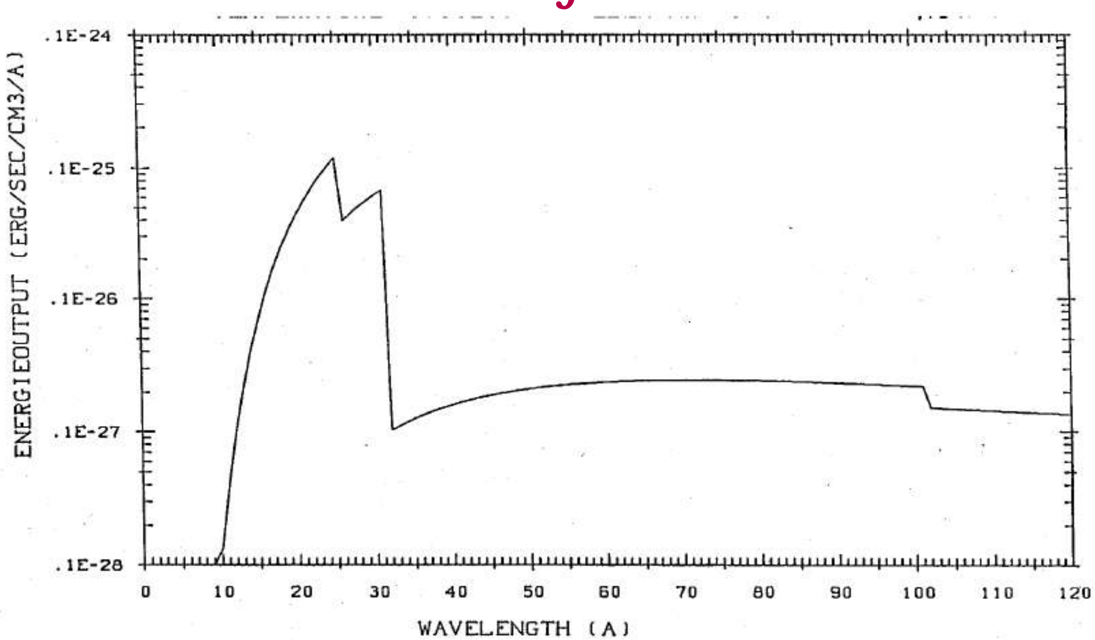
$$\epsilon_\nu^{bf}(X^i) \simeq \sum_l \frac{\omega_l(X^i)}{\omega_{gs}(X^{i+1})} a_\nu^l \left(\frac{\nu^2}{kT}\right)^{3/2} \exp\left[-\left(\frac{h\nu - \chi_l(X^i)}{kT}\right)\right]$$

ionization potential

sum over all energy levels

statistical weights

photoion. cross section



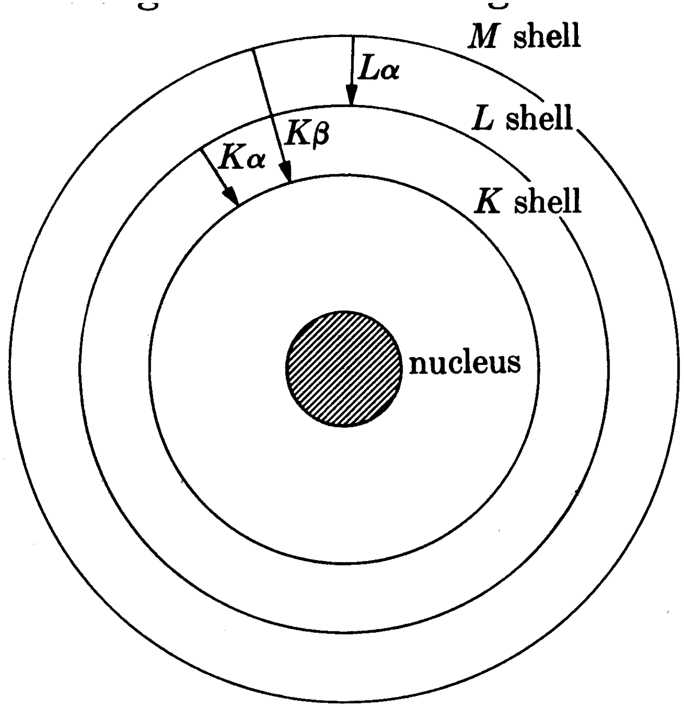
Recombination continuum of C at $10^6 K$

Emission lines

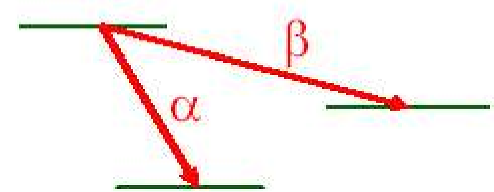
Process:

Collisional Inner-shell excitation/ionization → radiative decay (cascades)

→ collisional deexcitation neglected (due to low density)



Branching ratio of transition into different levels



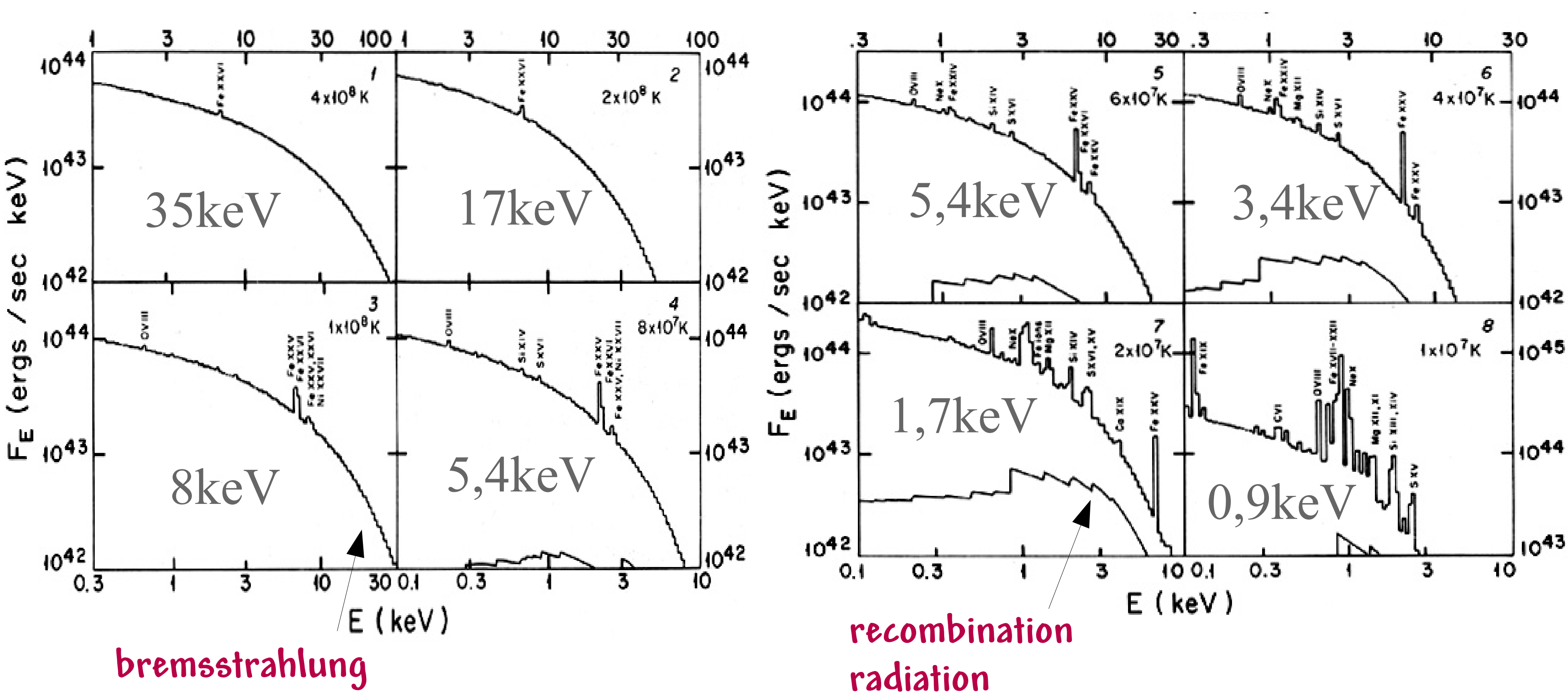
$$\int \epsilon_\nu^{\text{line}} d\nu \sim n(X^{\text{i}}) n_e B\, \Omega(T) (kT)^{-1/2} \exp(\Delta E / kT)$$

collisional strength slowly varying with T

Excitation energy above ground state

X-ray spectra

Predicted x-ray spectra of ICM at various temperatures
(gas isothermal, density 0,001 1/cm³, radius 0,5 Mpc)



Observing clusters in X-ray

Emission: (coronal plasma at ionization equilibrium)

- mainly bemstrahlung
- Emission lines

Number of photons emitted:

$$dN = n_e^2 \epsilon(E, T, [Z/H])\, dE\, dV$$

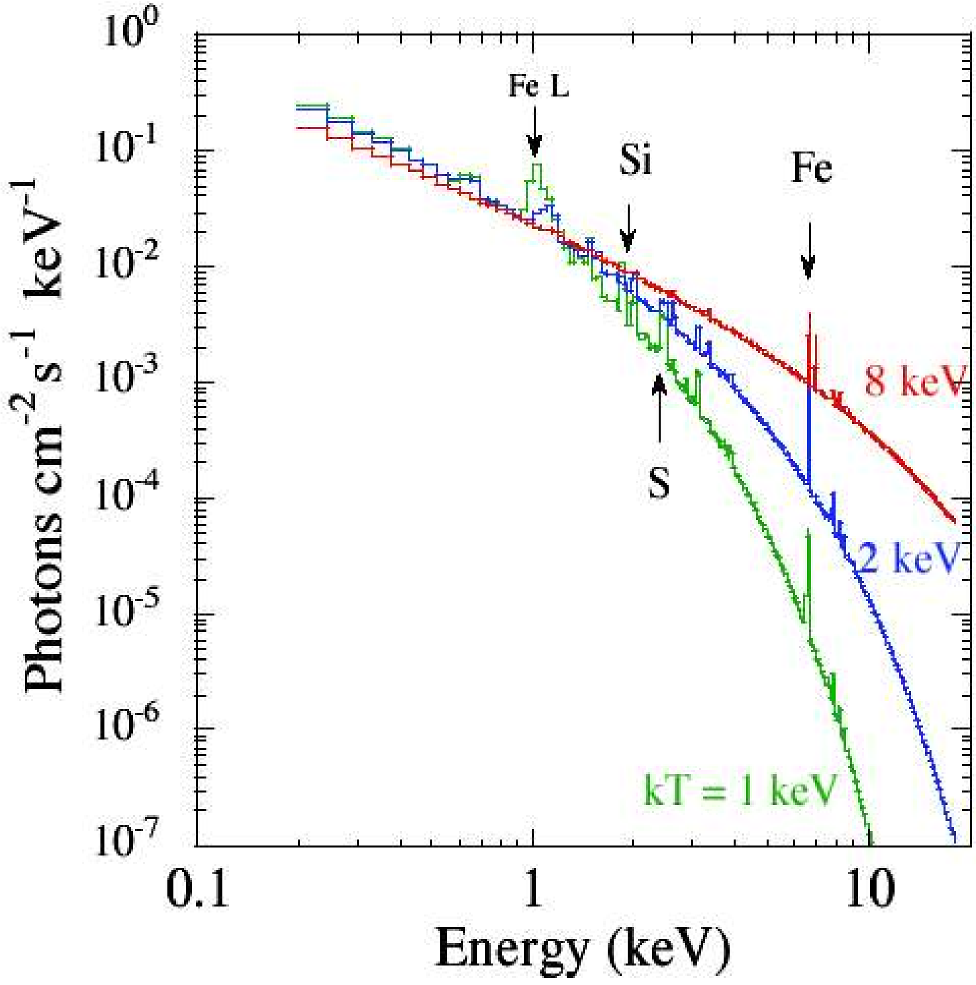
process: collision electron - ion

ε: photon emissivity at energy E

Continuum emission dominated by thermal bremstrahlung

$$\rightarrow \frac{dN(E)}{dE} \sim n_e^2 dV\, g(E, T)\, T^{-1/2} \exp(-E/kT) + \text{lines}$$

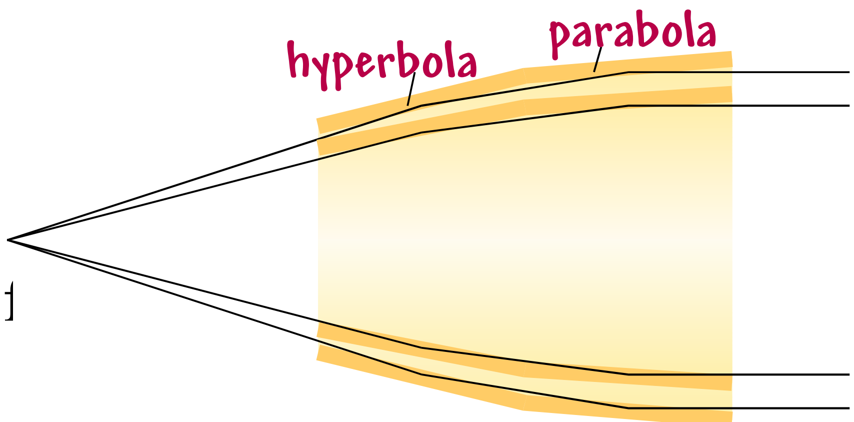
Observing clusters in X-ray



Predicted X-ray emission of optically thin plasma at different temperatures (0.35 solar abundances)

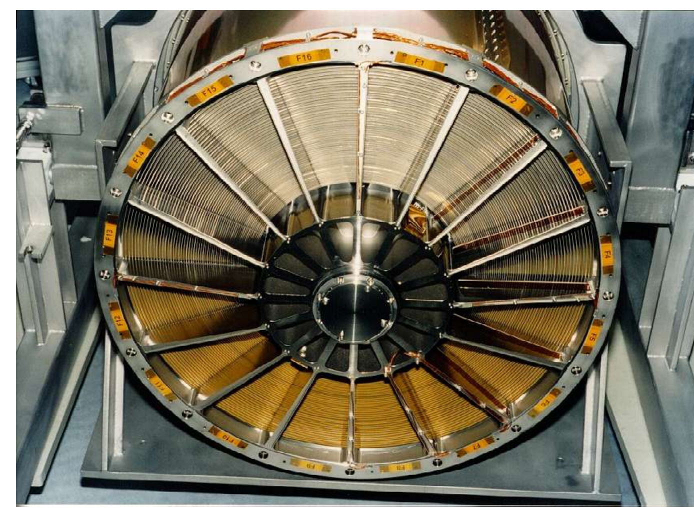
several K-Lines of elements
with increasing temperature more and more elements are completely ionized → lines vanish

X-ray telescopes



increase effective area
nested mirrors

XMM-Newton



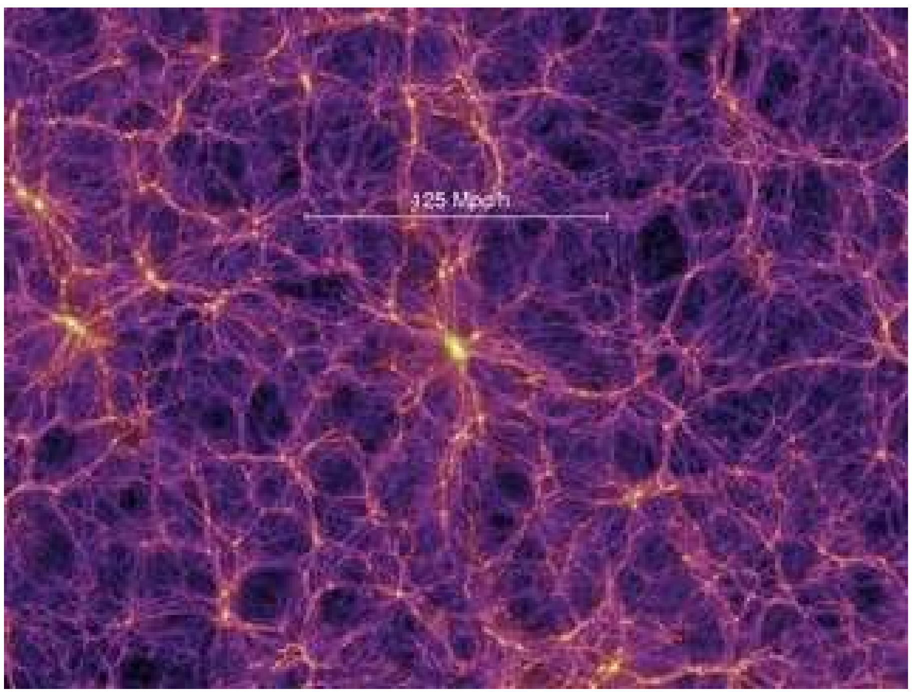
focussing with small angles
grazing incidence optics

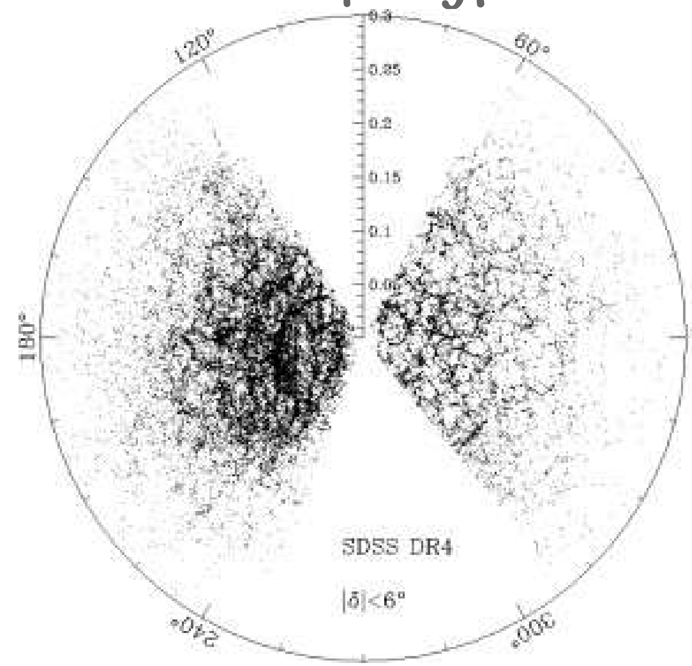
3 mirrors

- 58 gold covered mirror shells
- 60 cm diameter
- 750 cm focal length

Clusters of galaxies

At large scales → matter distribution shows web like topology
→ voids
→ filaments





Galaxy clusters are concentrations of matter (dark matter, gas, galaxies) located at crossing of filaments
nodes of cosmic structure

Clusters of galaxies

Cluster mass: $10^{13} - 10^{15} M_{Sun}$ massive!

- 80% Dark Matter (DM), 15% gas, 5% galaxies
- main baryonic component

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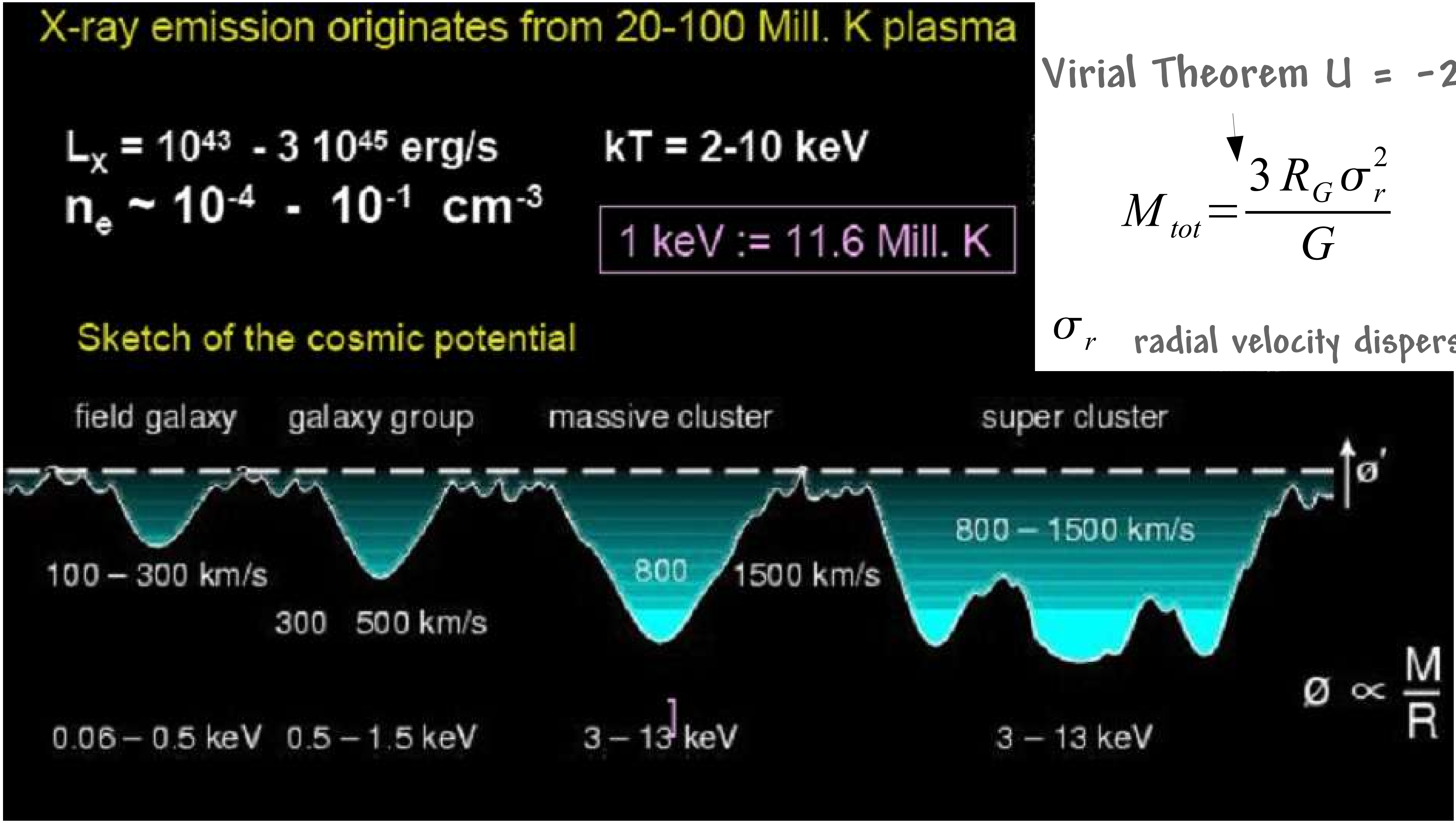
- **Intra-Cluster Medium (ICM):**

- hot, optically thin plasma (x-ray source)
- density: $10^{-4} cm^{-3}$ (outer region) - $10^{-2} cm^{-3}$ (center)
- temperature: $kT \approx 0{,}5 - 15\, keV$

virial theorem → depth of potential well ($kT \propto \frac{GM}{R}$)

Observing clusters in X-ray



Virial Theorem U = -2T

$$M_{tot} = \frac{3 R_G \sigma_r^2}{G}$$

σ_r radial velocity dispersion

Motivation

Why study clusters?

- structure formation
- missing mass
- abundance (enrichment of ICM)
- cosmological applications

Structure formation: nearby clusters

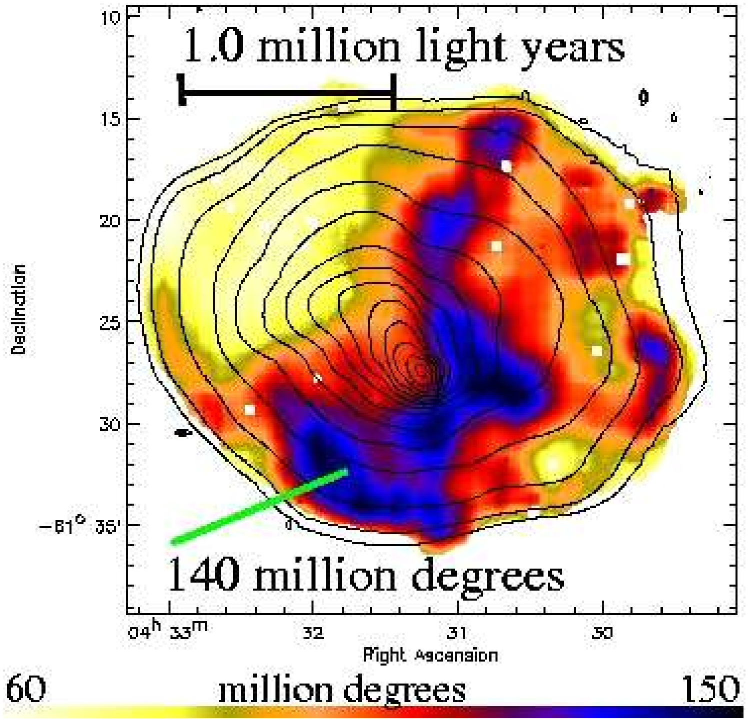
Clusters form through gravitational collapse

Present-day build-up of structure

surface brigthness ⟶ morphology

temperature (only possible for nearby clusters)

z<0,2 ⟶ clusters are still forming today



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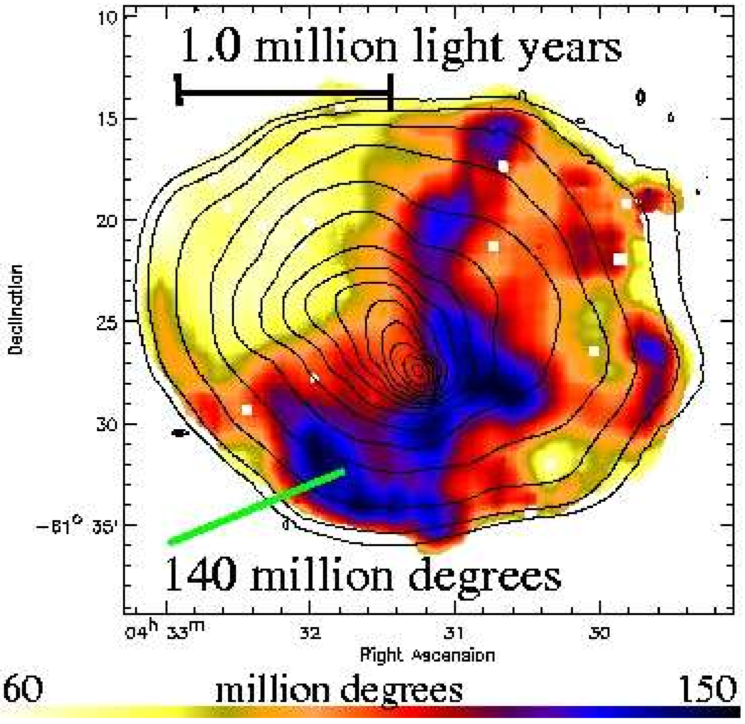
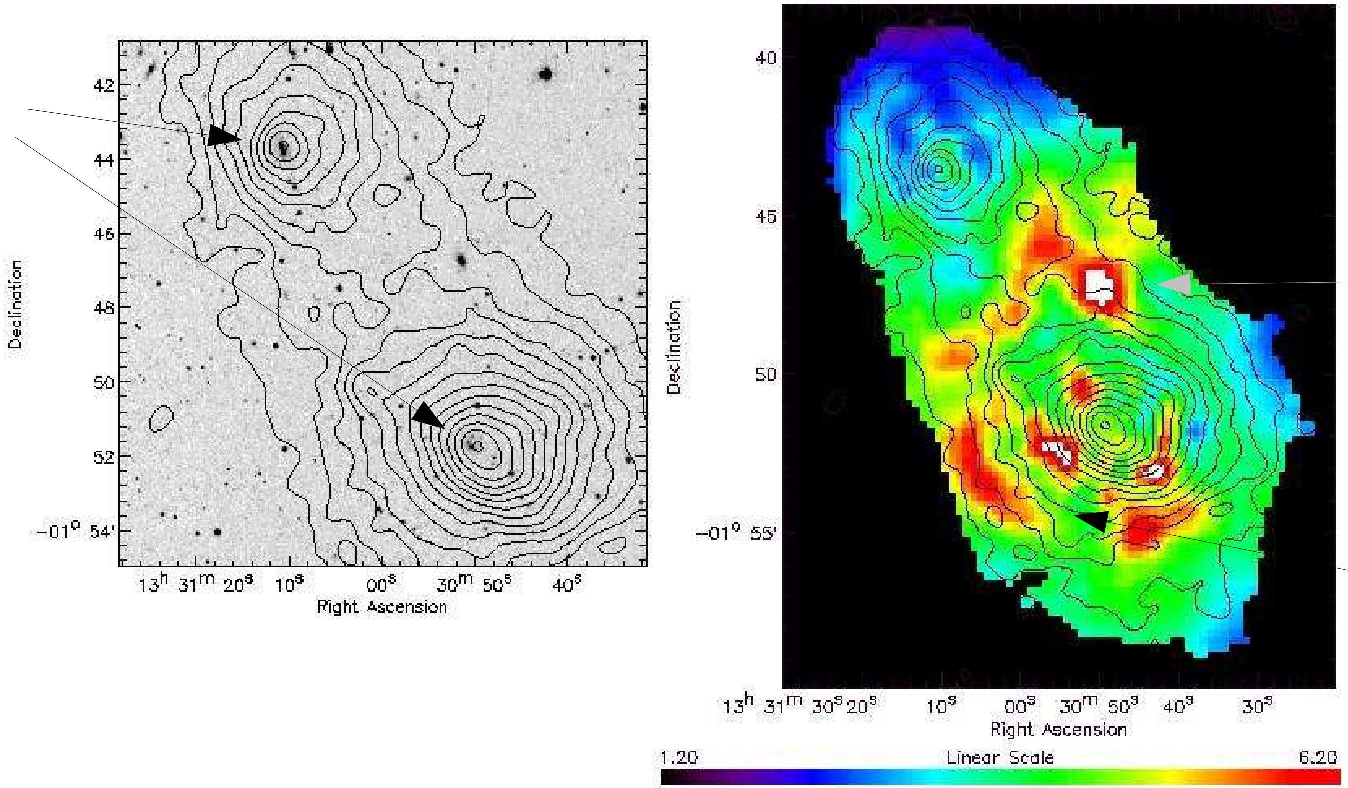


Structure formation: nearby clusters

giant cD galaxies
distance 2,9 Mio lyrs

Abell 1750



A dramatic galaxy cluster merger observed by XMM-Newton

Image courtesy of E. Belsole, CEA-Saclay (France)

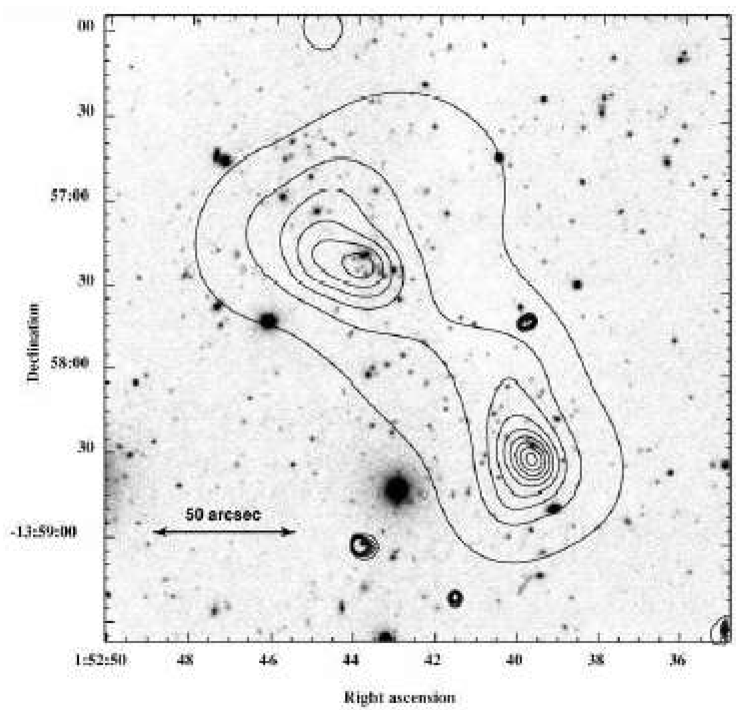
European Space Agency

shocked and compressed gas
→ merging
v ~ 1400 km/s

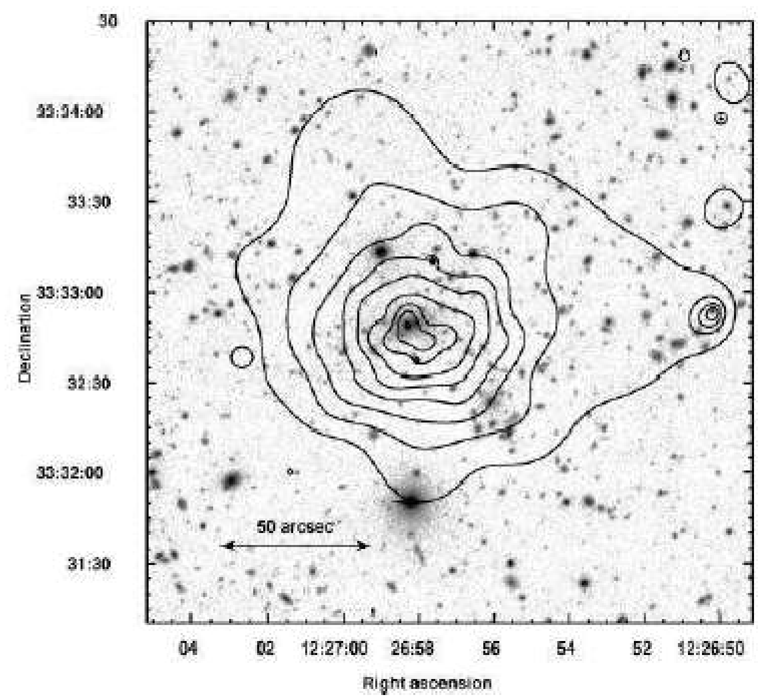
hot regions from older merger events (1 Gyr)

Structure formation: distant clusters

Only morphology



two merging clusters
RXJ0152.7-1357
at z = 0.83



massive cluster in relaxed state
RXJ1226.9+3332
at z= 0.89

Observing clusters in X-ray

Extracting physical information:

1. Temperature:

Exponential cut off ⟶ temperature

2. Density:

Emission integral (EI) $$EI = \int n_e n_p \, dV$$

$$L_X \propto EI \, T^{1/2}$$

⟶ radial density profile n(R)

Estimating total cluster masses with x-ray observations

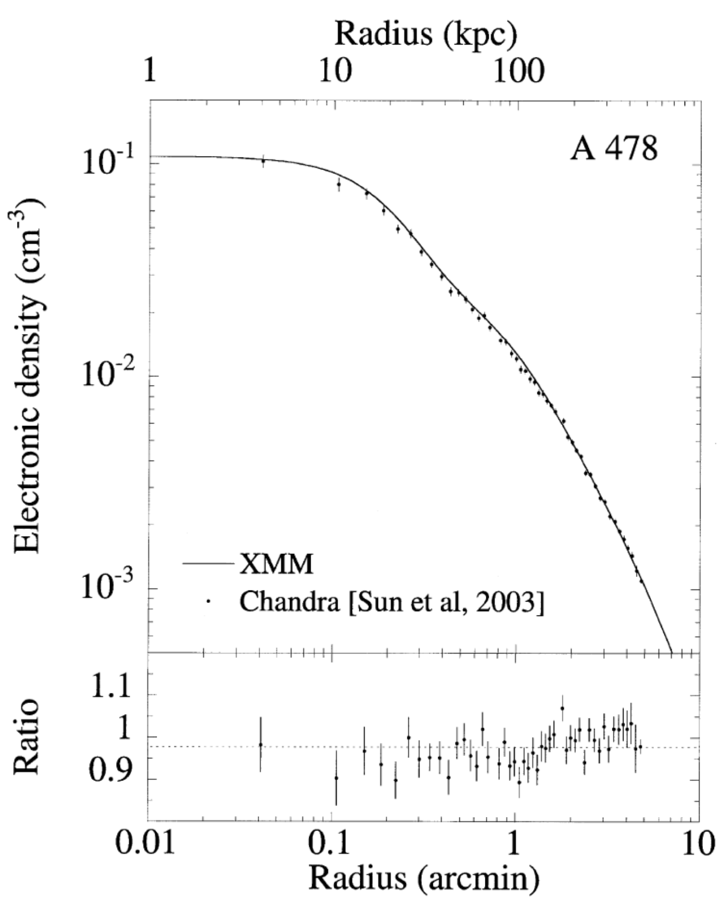
Assumptions

1. gas in hydrostatical equilibrium in potential well
2. spherical symmetry

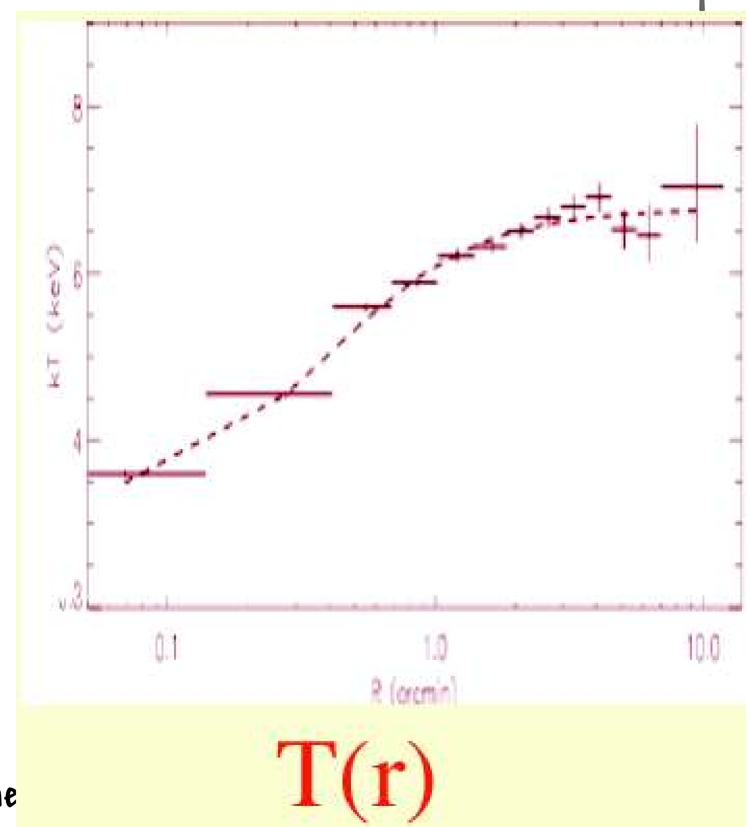
$$M(r) = -\frac{kT}{G\mu m_p}\left[\frac{d\ln n_e}{d\ln r} + \frac{d\ln T}{d\ln r}\right]$$

radial surface brightness

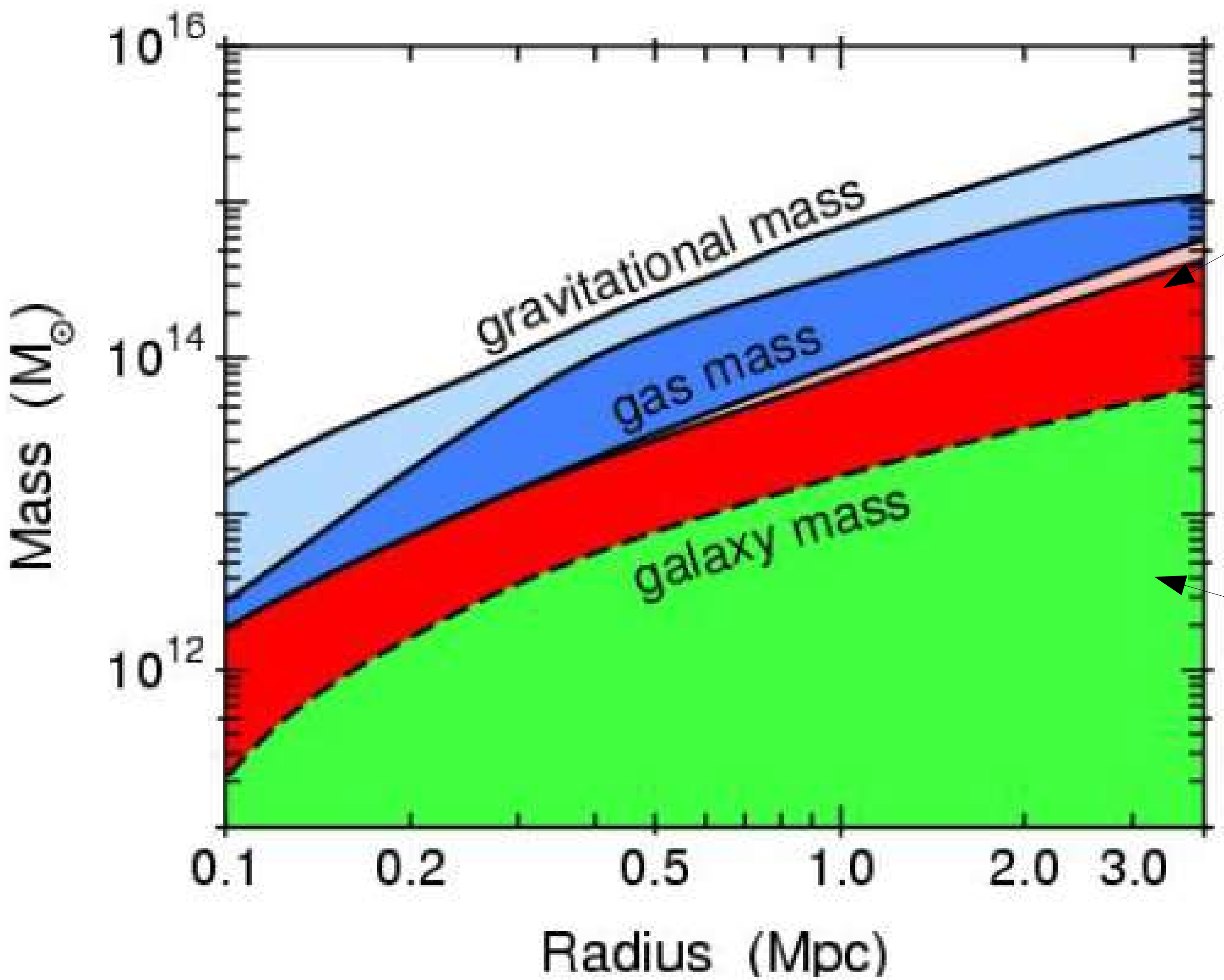
radial temperature profile



Atomic Emission Line



Mass of the nearby Perseus cluster



integration of radial density profile

~ 80% dark matter

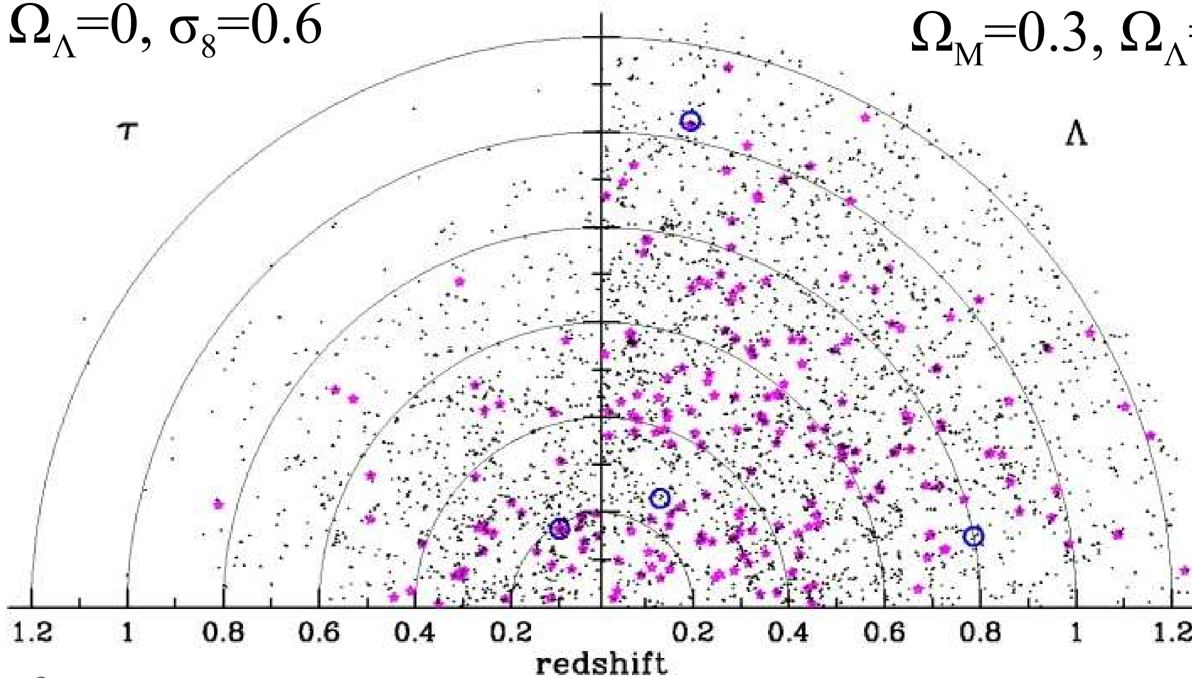
~ 15% intracluster gas

~ 5% galaxies

galactic mass luminosity relation

Cosmological application

$\Omega_M=1, \Omega_\Lambda=0, \sigma_8=0.6$ $\Omega_M=0.3, \Omega_\Lambda=0.7, \sigma_8=0.9$



formation of structure
Simulated distribution of clusters, depending on cosmological parameters

- ► clusters form earlier or later .....depending on cosmology
- ► evolution of mass - function N(M,z) gives constraints on cosmological parameters

Mass - temperature relation

Hydrostatical equilibrium, virial theorem

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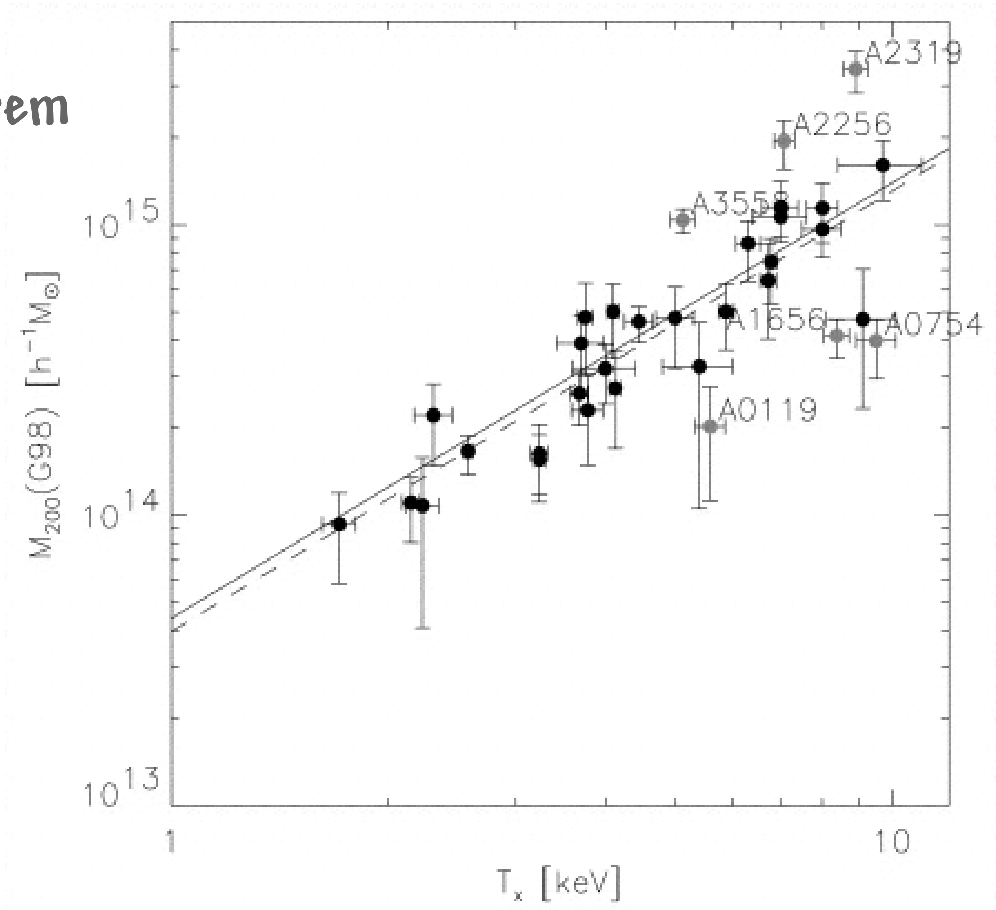
M-T relation (isothermal)

$$M \propto T^{1.5}$$

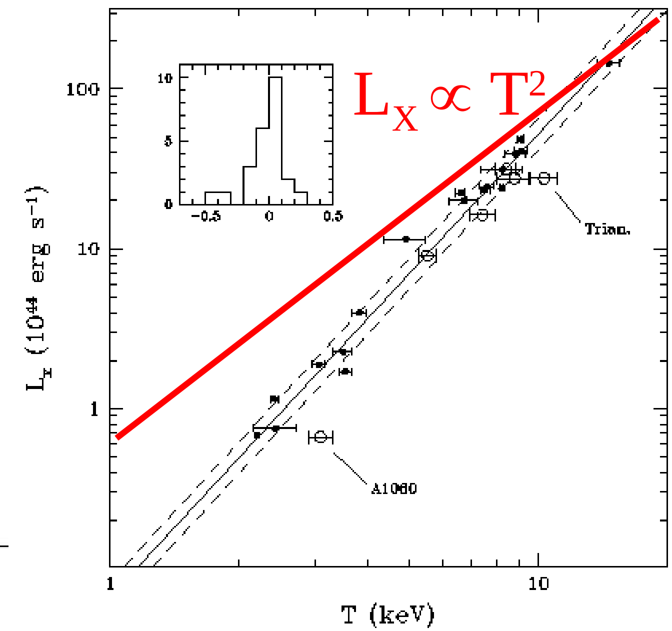


Mass - luminosity relation

Luminosity - temperature

$$L_X \propto T^2$$

assuming bremsstrahlung

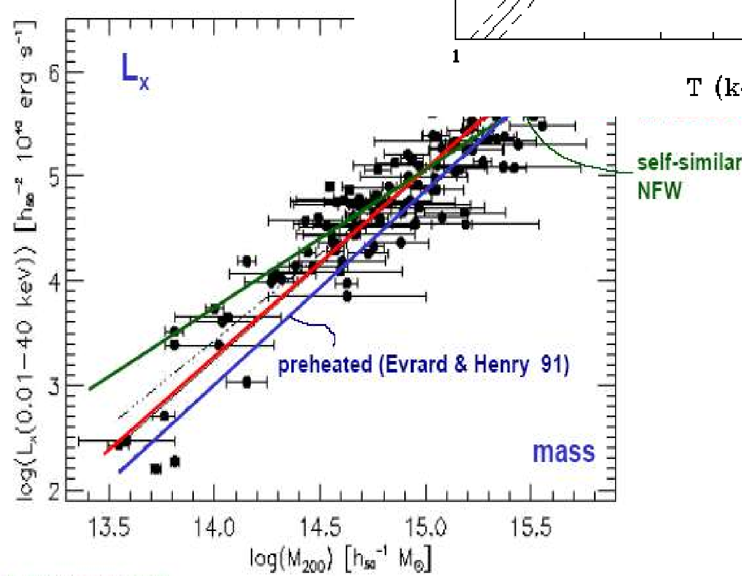


M-L relation (isothermal)

$$M \propto L_X^{3/4}$$

easily meausureable for
distant clusters

cosmological constraints



Reiprich & Böhringer 2002

Abundances

Extracting physical information:

3. Abundance:

line „strength“ → abundance

equivalent width (EW)

observed intensity

$$EW := \int \left(\frac{I_\nu - I_\nu^0}{I_\nu^0} \right) d(h\nu)$$

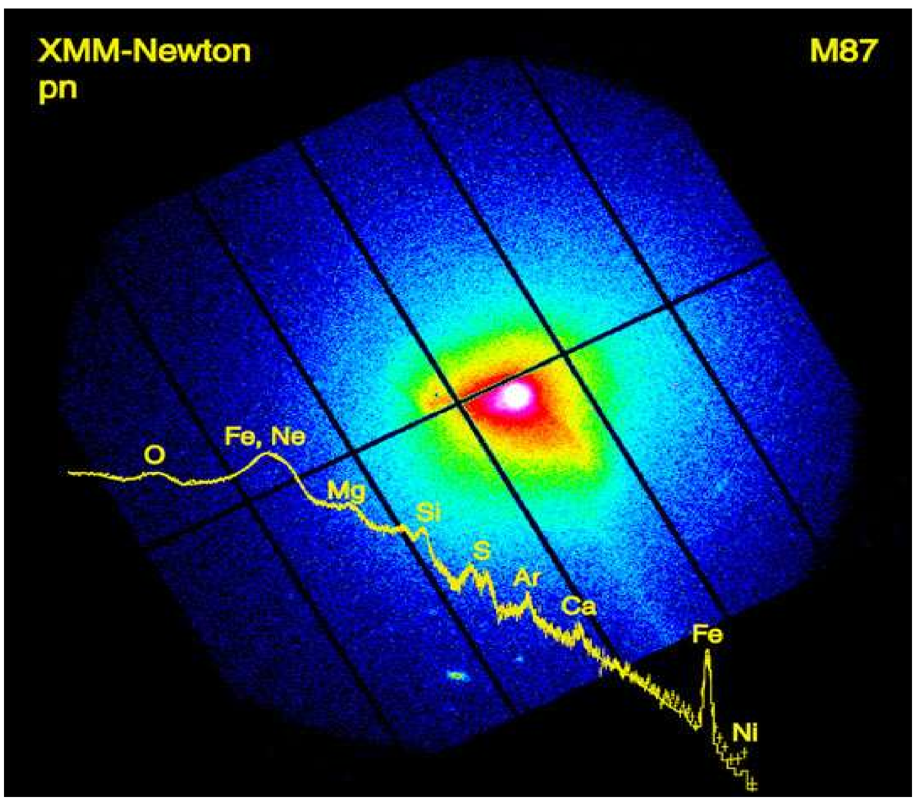
continuum intensity

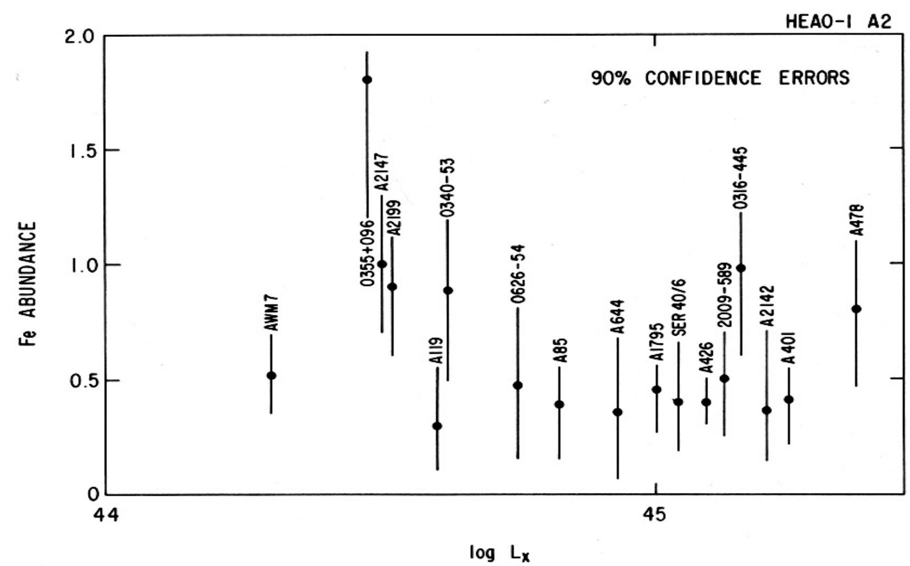
$$EW \propto \frac{X}{H}$$

abundance

Global abundances

Example:
„7-keV iron line"
(blend of mainly Fe^{24+} and Fe^{25+})



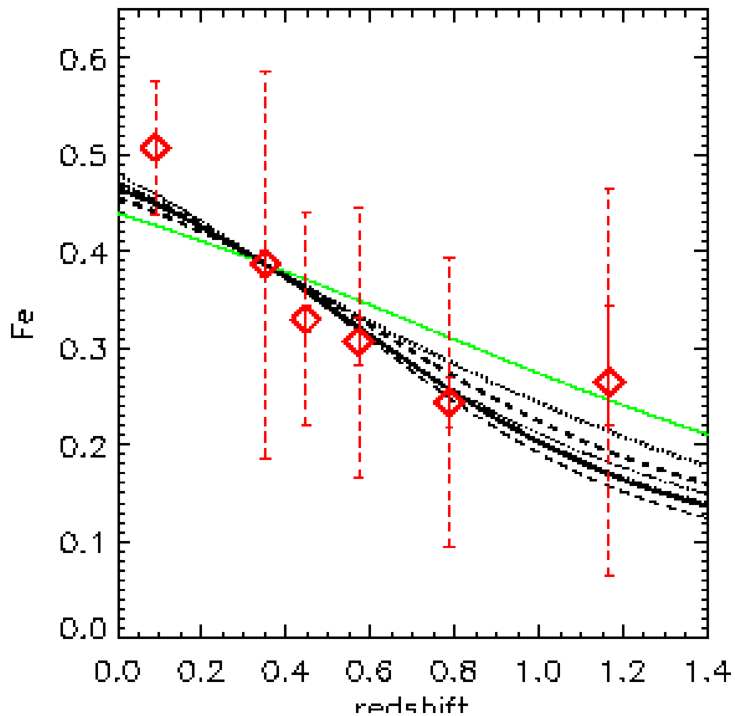


iron abundance relative to solar vs luminosity(mass)
constant with mass (at 0.3 solar)

M87 central galaxy of very nearby virgo cluster

Enrichment

When?

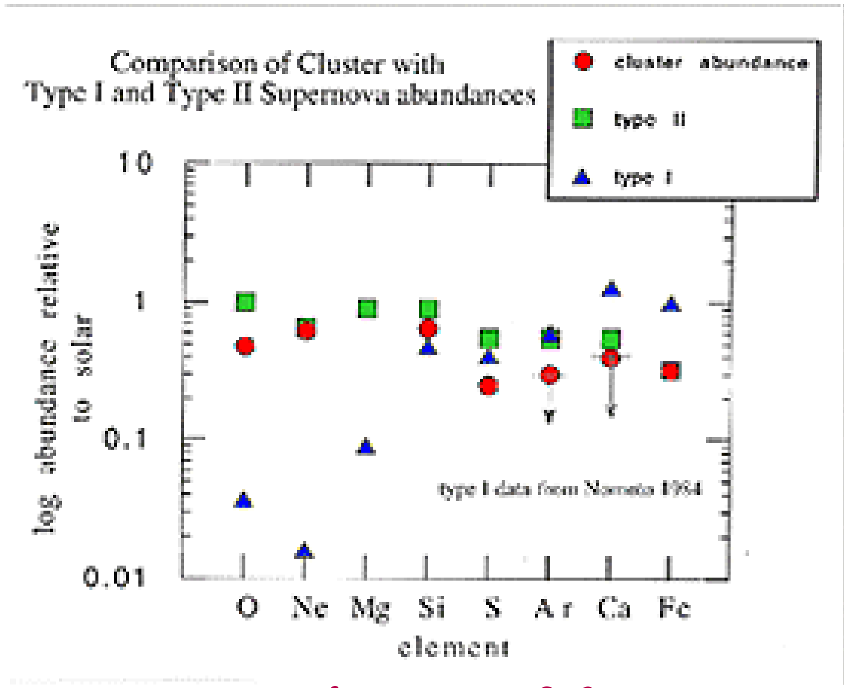


Observed distribution of the metal abundance (diamonds) and theoretical predictions (dashed,dotted lines)

distant clusters show similar abundance

→ early epoch of metal formation

How?



→ ratio and rates of SN

Thank you for your attention