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Emission Lines in X-ray Spectra of Clusters of Galaxies

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INAF

X-ray band

0.1-10 keV ~ 100 -1 Angstrom ~ 1 -100 MK

Very Soft Band: 0.1 -0.5 keV

Soft Band: 0.5 -2 keV

Hard Band: 2 -10 keV

Very Hard Band: 10 -100 keV

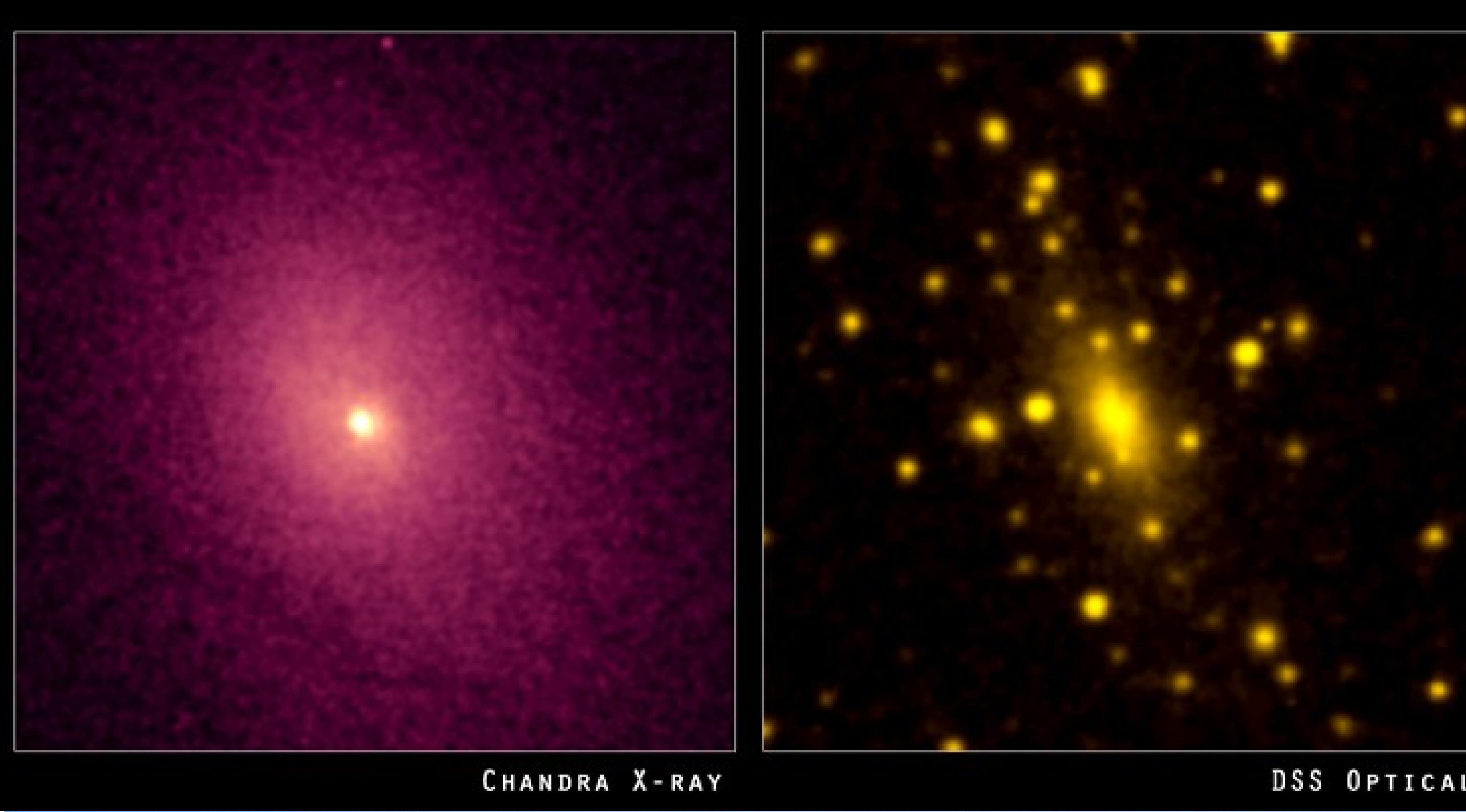
Clusters of Galaxies

Bound objects form via gravitational instability from the initial perturbation in the density field. Non collisional dark matter form potential wells together with the baryons (contributing ~15% of the total mass). The collapse leads to the violent relaxation: dark matter and baryons rapidly adjusts and reaches a pressure balance with the gravitational forces. The velocities of particles inside the structure become randomised, and the structure settles down into an equilibrium configuration, satisfying the average relation:

$$2T + U = 0$$

where

$$T = M_{tot} \frac{\langle V^2 \rangle}{2} \qquad U = -\frac{G M_{tot}^2}{R_c}$$



Beta profile $\beta \sim 2/3$

$\rho \propto r^{-2}$ **more or less spherical distribution**

$L \sim 10^{41}\ erg\, s^{-1} @ 1\, keV$

$$\rho = 1/(1+(r/r_c)^2)^{3\beta/2}$$

T ~ constant

$L \sim 5\, 10^{44}\, erg\, s^{-1} @ 10\, keV$

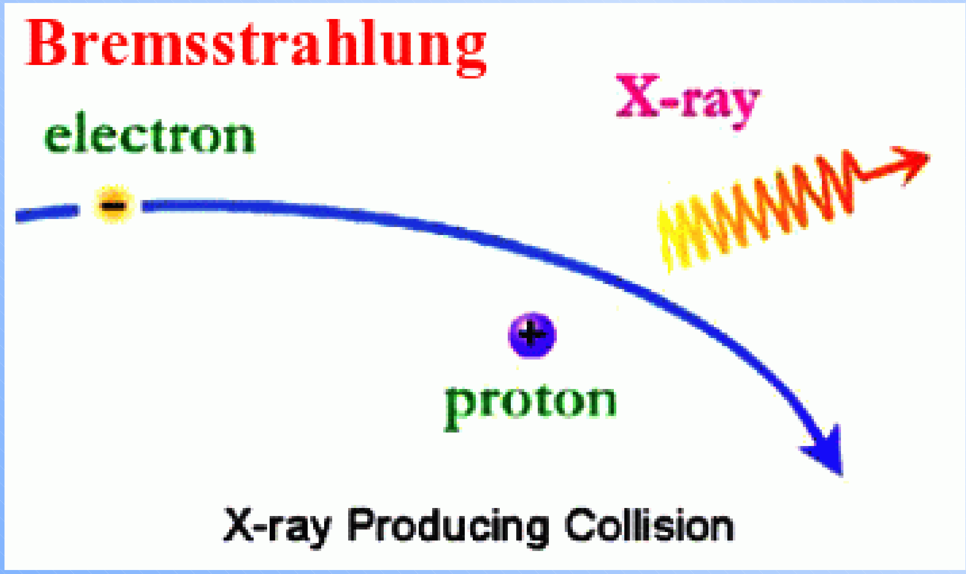
Bremsstrahlung

With a typical electron densities $n_e \sim 10^{-3}$ the Intra Cluster Medium is a hot, optically thin, thermal plasma in equilibrium.

Radiation due to the acceleration of a charge in the Coulomb field of another charge (also free-free emission). Classical treatment is ok, plus quantum corrections (Gaunt factor) and relativistic corrections (for kT > 10 keV).

Collision of like particles is 0 in the dipole approximation. In Electron-Ion bremsstrahlung the electrons are primary radiators.

Thermal Bremsstrahlung Emission is obtained averaging over a thermal distribution of speeds.



Bremsstrahlung Emission

Free electrons acceleration in the Coulomb field of an ion (most of them are protons or He nuclei)

$$\frac{d^2 P}{dV dE} = 10^{-11} n_e n_H T^{-1/2} e^{-\frac{E}{kT}} \; s^{-1} cm^{-3}$$

$$\int \epsilon_\nu d\nu = \frac{dL}{dV} = 1.4 \times 10^{-27} T^{1/2} n_e^2 Z^2 \bar{g}_B \; erg\, s^{-1} cm^{-3}$$

Plus bound-free and 2-photon emission

see Rybicki & Lightman
Radiative processes in Astrophysics

Line Emission in a Thin Thermal Plasma

Collisionally excited spectral lines from highly ionized atoms are signatures of the thermal nature of hot plasma

Coronal Model:

- **Optically Thin Collisionally Ionized Plasma**
- **Low density, negligible excited states population (all ions in ground state)**
- **Cooling time longer than relaxation time**
- **Heat input coupled to electrons and ions**
- **Maxwellian Energy distribution of energies (T determined by external processes)**
- **Ionization balance between the ions**

Nebular Model (opt thin/thick with photoionization/excitation from and external X-ray source)

Atmospheric Model (optically thick, collisional ionization)

Equilibrium: balance between competing processes.
The nature of the equilibrium determine the shape of the spectrum

Three main “actors”:

I) kinetic distribution of electrons and ions
II) atomic level populations
III) radiation field

Types of Equilibria:

Strict thermodynamic equilibrium: principle of detailed balance
(every atomic process is as frequent as its inverse process)

Local thermodynamical equilibrium (radiation field is not in equilibrium)

Collisional equilibrium (or coronal eq.)

Four key electron-ion collisional processes and its inverse:

Collisional excitation	**Collisional deexcitation**
Collisional ionization	**Three body recombination**
Radiative recombination	**Photoionization**
Dielectronic Capture	**Autoionization**

Only few of these processes are relevant in the coronal model (or collisional ionization equilibrium CIE)

Collisional ionization equilibrium (CIE):

1) Excitation and ionization are dominated by electron-ion collisions.
2) Deexcitation is dominated by spontaneous radiative decay
3) Ion will recombine by radiative or dielectronic recombination
4) Density are low and atoms are always in their ground states
5) The plasma is optically thin, so that photoabsorption and scattering can be ignored

Equilibrium is given by the balance between impact ionization (and excitation autoionization) and radiative and dielectronic recombination.

The interpretation of such a spectrum will require a detailed knowledge of the ionization, recombination and excitation rates of:

K-shell transition of C, N, O, Ne, Mg, Si and Fe, and

L-shell transition of Si, S, Ar, Ca, Ni and Fe.

Ionization balance

In a steady state the energy balance is given by a balance between ionization and recombination. Ionization is controlled by electron impact and by radiative plus dielectronic recombination. The rate of change of the population density is given by (neglecting ejection with more than one electron):

$$0 = \frac{dn_j}{dt} = S_{j-1} n_{j-1} - S_j n_j - \alpha_j n_J + \alpha_{j+1} n_{j+1}$$

gains from reionization of less charged ions

losses towards higher charged ions

recombination losses

recombination gain

S_j=ionization rate for ion j with ejection of 1 electron (direct and autoionization)
α_j=recombination rate of ion j (radiative and dielectronic)

The ionization structure is derived by solving for each element Z a set of Z+1 coupled rate equations.

In the steady state the equation reduces to:

$$\frac{N_{Z,z+1}}{N_{Z,z}} = \frac{S_{Z,z}(T)}{\alpha_{Z,z+1}(T)},$$

This depends only on T and not on n_e (to first order) as long as stepwise ionization (more than one collision) in S_j and collisional coupling to the continuum (3 body recombination) in a_{j+1} can be neglected.

The fraction of ions at the stage z of an atom with atomic number Z is:

$$\eta_{Z,z} \equiv \frac{N_{Z,z}}{N_Z} = (1+\Sigma_{i=1}^{i=z}\Pi_{k=i}^{k=z}\frac{N_{Z,k-1}}{N_{Z,k}}+\Sigma_{i=1}^{i=Z-z}\Pi_{k=z+1}^{k=z+i}\frac{N_{Z,k}}{N_{Z,k-1}})^{-1}$$

The emissivity of a given emission line (the quantity which is proportional to the Equivalent Width of a line which is actually measured with X-ray spectroscopy) is given by:

$$\epsilon_{21} = n_e \, n_i \, \gamma_{21}(T) \, E_{12}$$

where γ is the collisional excitation rate for transition 1-2 and

$$n_i = A_Z \, \eta_Z(T) \, n_H$$

is the density of the ion in the ground state.

Metal Abundances

Equivalent Width

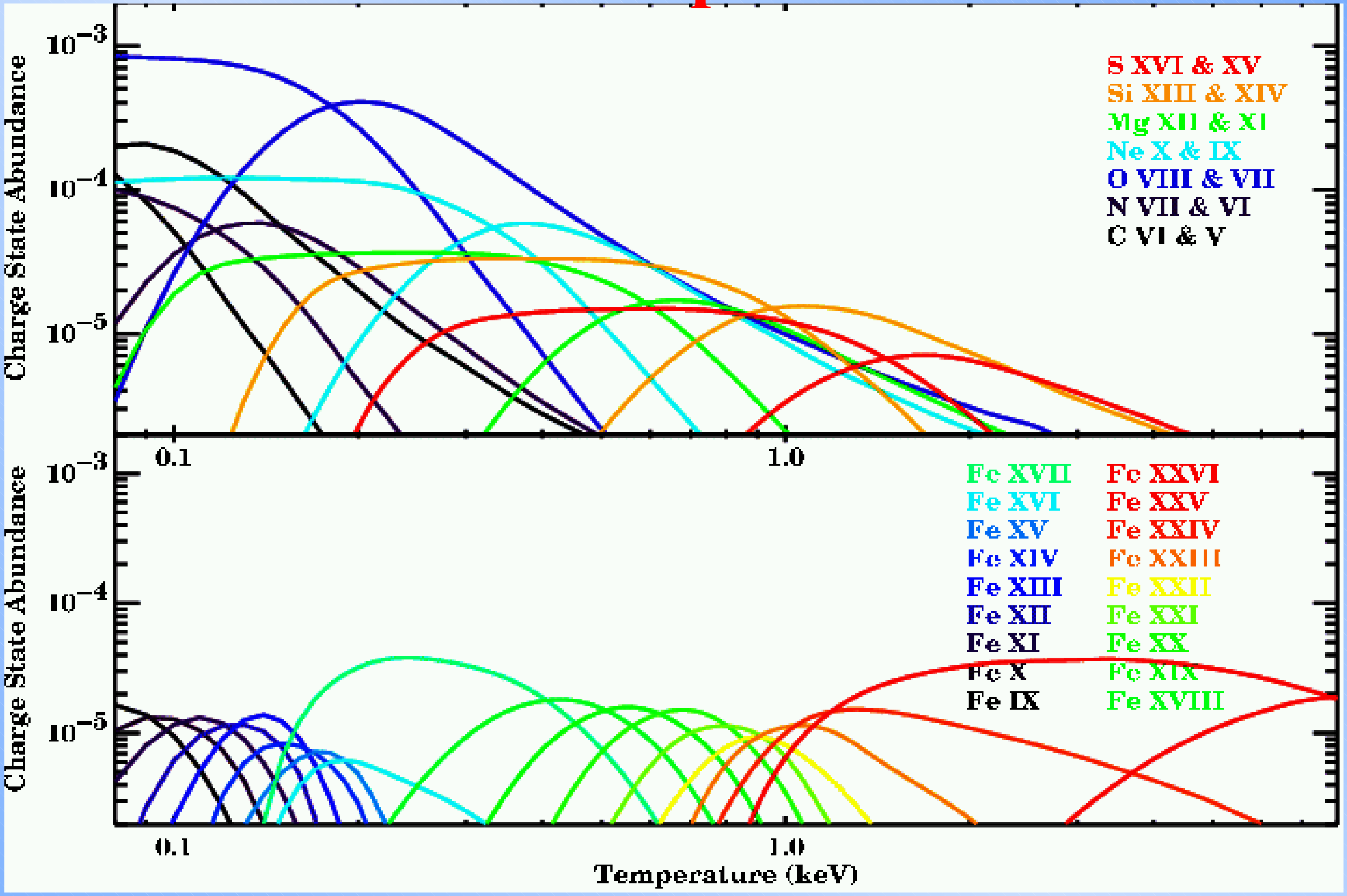
$$EW \equiv \int \left(\frac{I_\nu - I_\nu^0}{I_\nu^0}\right) d\,h\nu \propto \frac{n_i}{n_H}$$

In Cluster, this ratio is not dependent on the density, only on temperature and abundance. Over a wide range of T, the EW of the Fe -K line (Fe + 24, Fe +2 5) is several orders of magnitudes larger than any other spectral feature. At lower energies O, Si, S, and L shell transition in less Fe ions.

Once f_i is known from the collisional equilibrium. The temperature is measured at the same time from line ratios and the continuum shape.
Note that in general cases, when photo-ionization and optical depth are important, there is no such one-to-one relation between equivalent width and abundance!
The very low density plasma present in clusters is the best example of collisional equilibrium given the extremely low density.

Abundances are computed with the use of fitting packages which implement the atomic physics and the collisional equilibrium equation. Metals, mostly Fe, are always found in Clusters. Their abundance is consistent with being produced by the elliptical clusters galaxies (Matteucci Vettolani 1988).

Fe Ions concentration as a function of the ICM temperature



Example of a collisionally dominated optically thin coronal plasma as a function of T.

Over a wide range of T, the EW of the Fe -K line (Fe + 24, Fe+2 5) is several orders of magnitudes larger than any other spectral feature. At lower energies O, Si, S, and L shell transition in less ionized Fe.

Sources of uncertainties:

Accuracy of atomic physics for the ionization balance

Both ionization and recombination rate can be uncertain by a factor 2-4. Fortunately, ionization and recombination rates for H-like and He-like ions, which emits lines that are among the strongest in astrophysical plasmas, are known more accurately (largest uncertainties in dielectronic recombination rates).

Spectral resolution

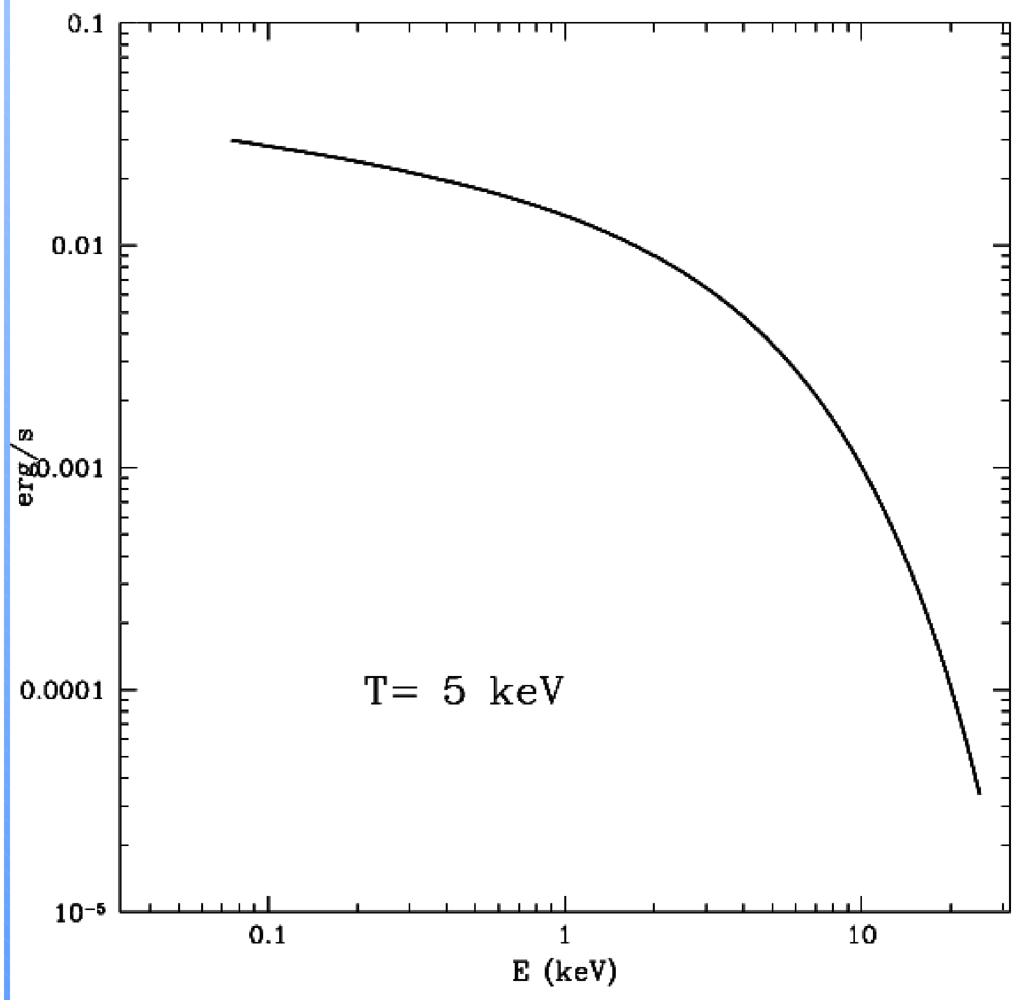
X-ray spectra may be obtained directly with CCD imagers or with gratings. In general lines blend with transitions of other elements, so that a low resolution may hamper the measure of a given element.

Non isothermality (temperature structure) in the ICM

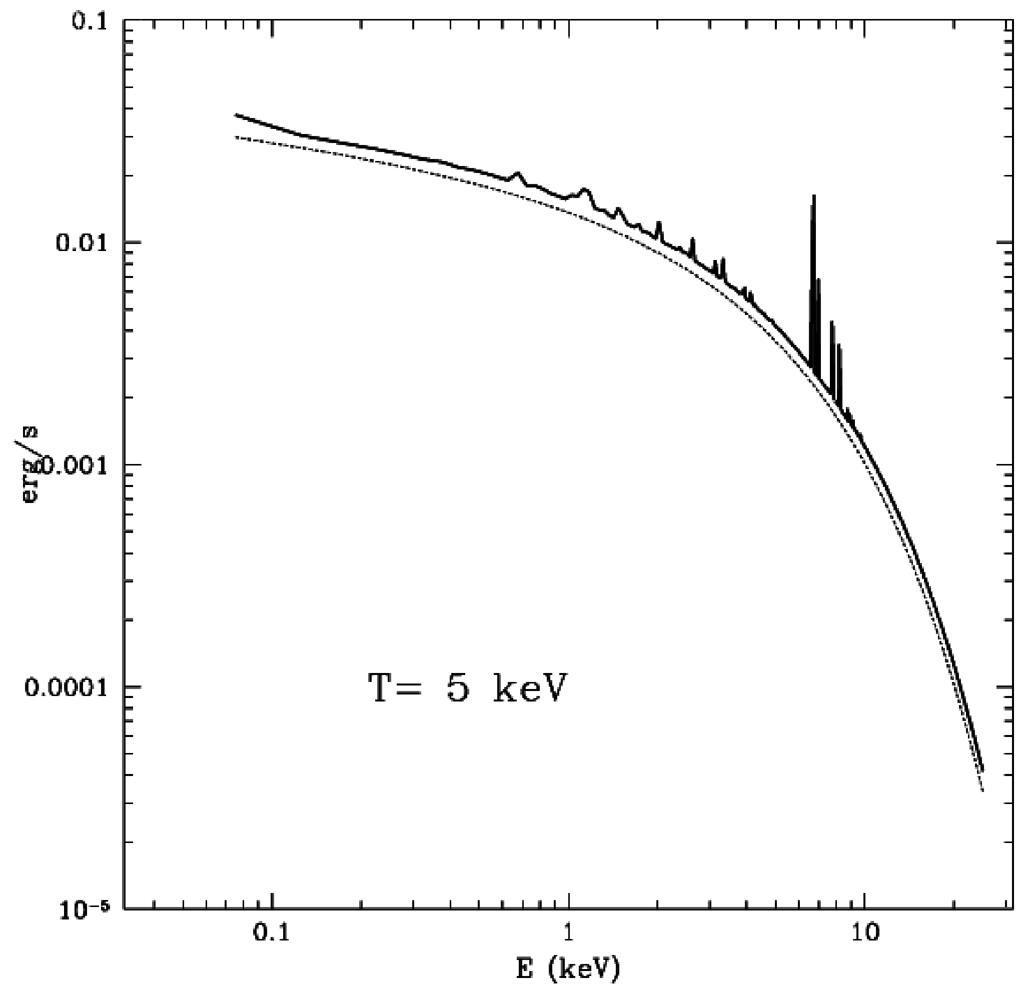
ICM may have different temperatures at different radii, with significant gradients in the central regions.

Cluster 5 keV metallicity Z= 0.3

Pure Bremsstrahlung Z= 0

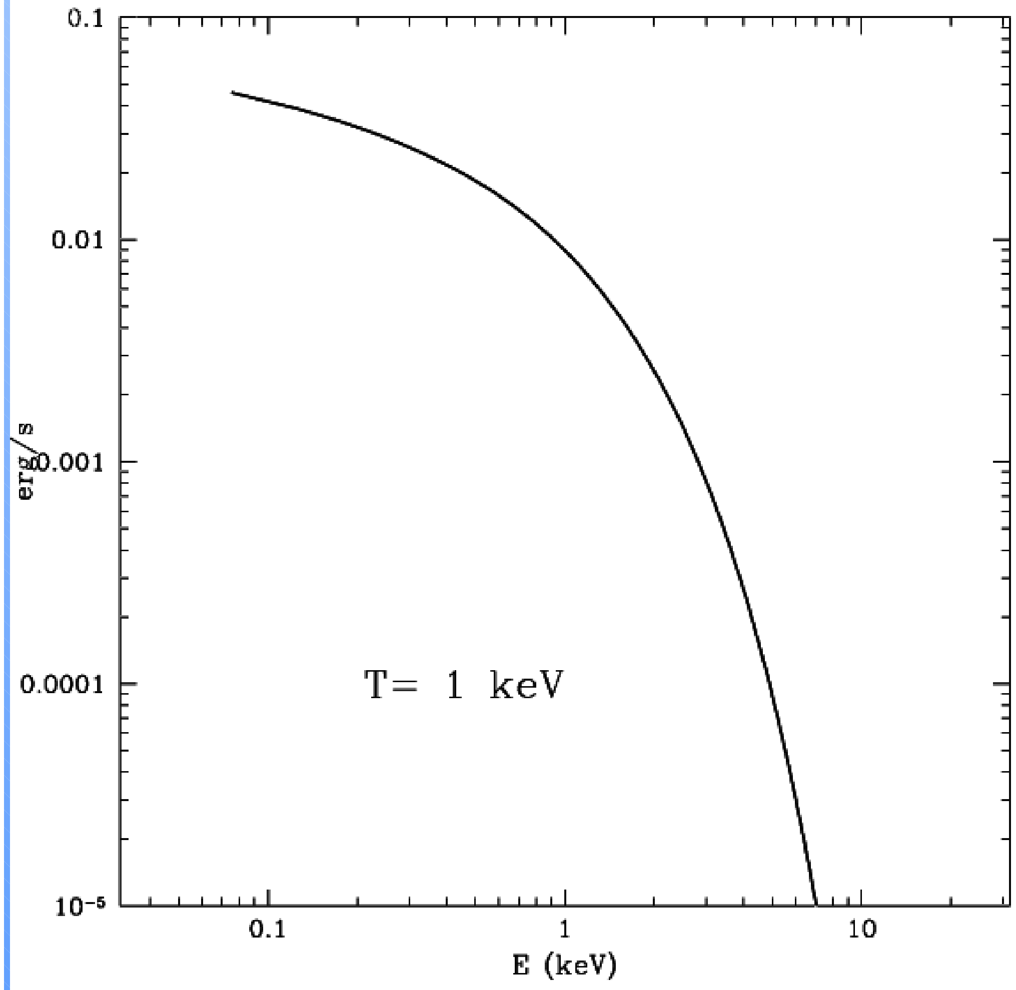


Raymond Smith $Z=0.3\ Z_\odot$

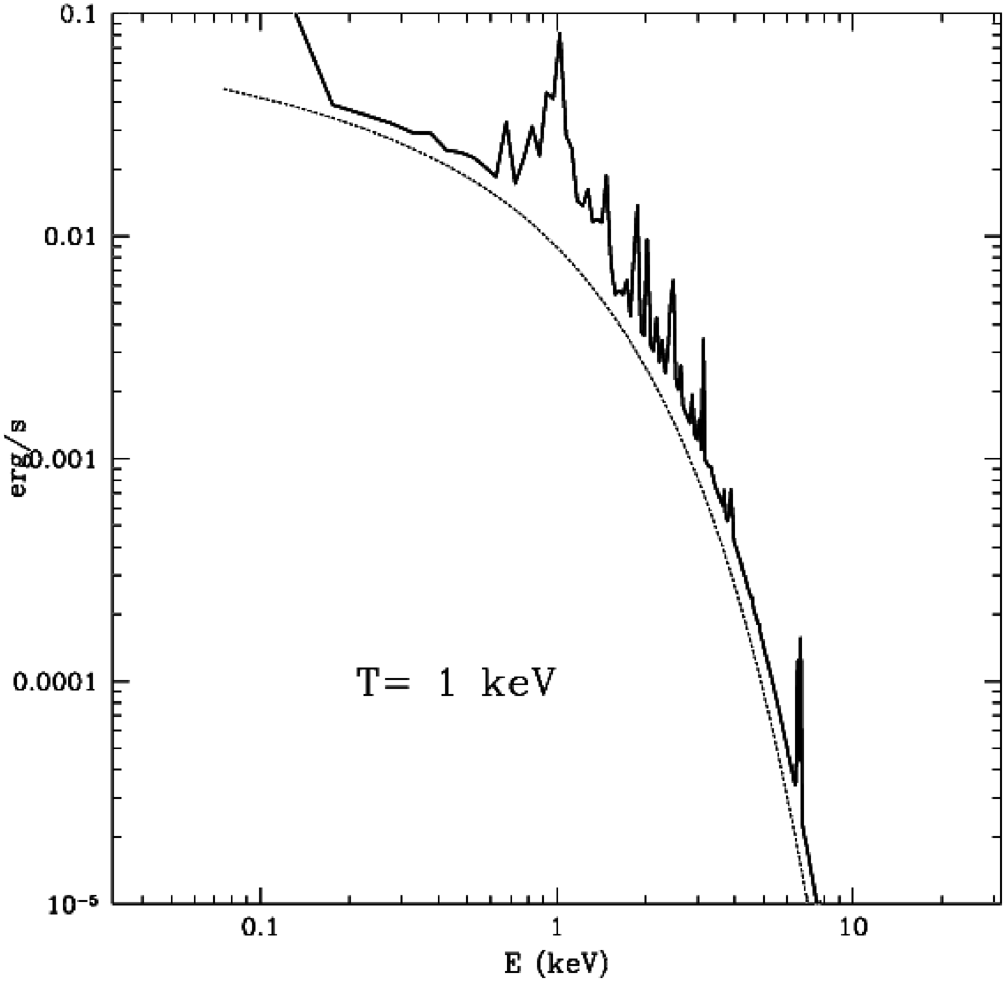


Cluster 1 keV metallicity Z= 0.3

Pure Bremsstrahlung
Z= 0



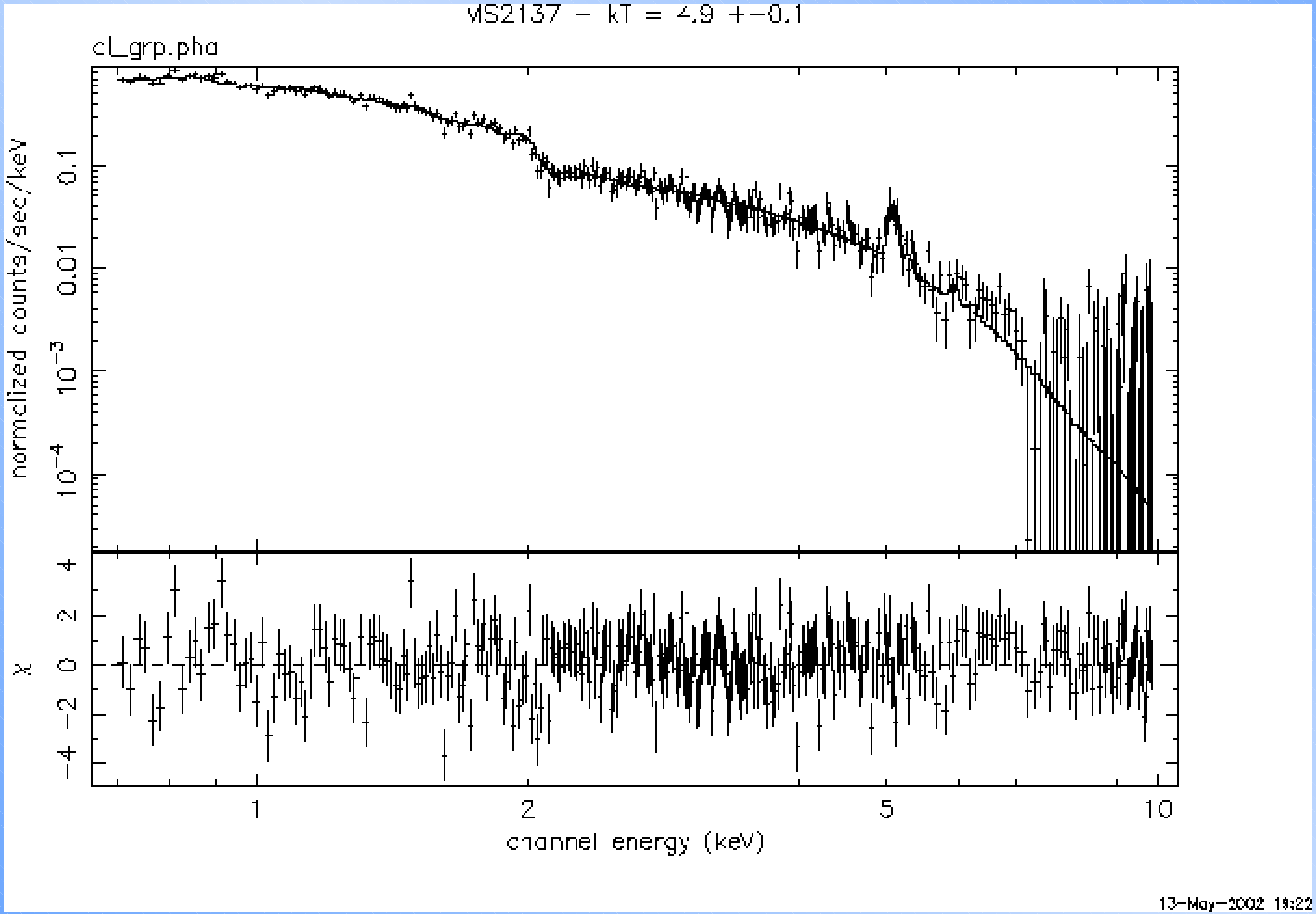
Raymond Smith
Z=0.3 $Z_\odot$



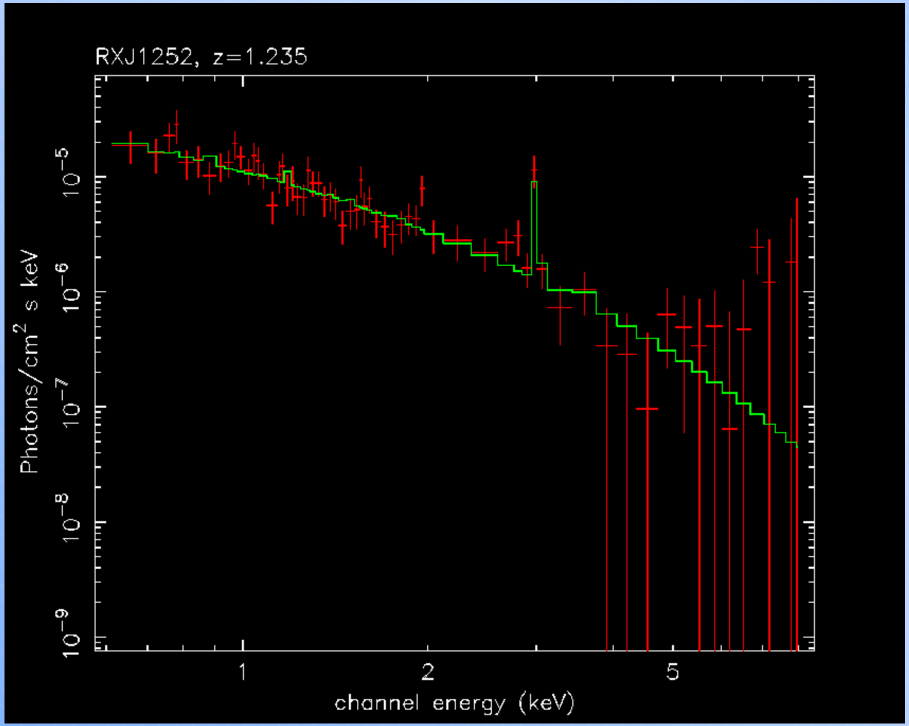
Looking for Metals at high z

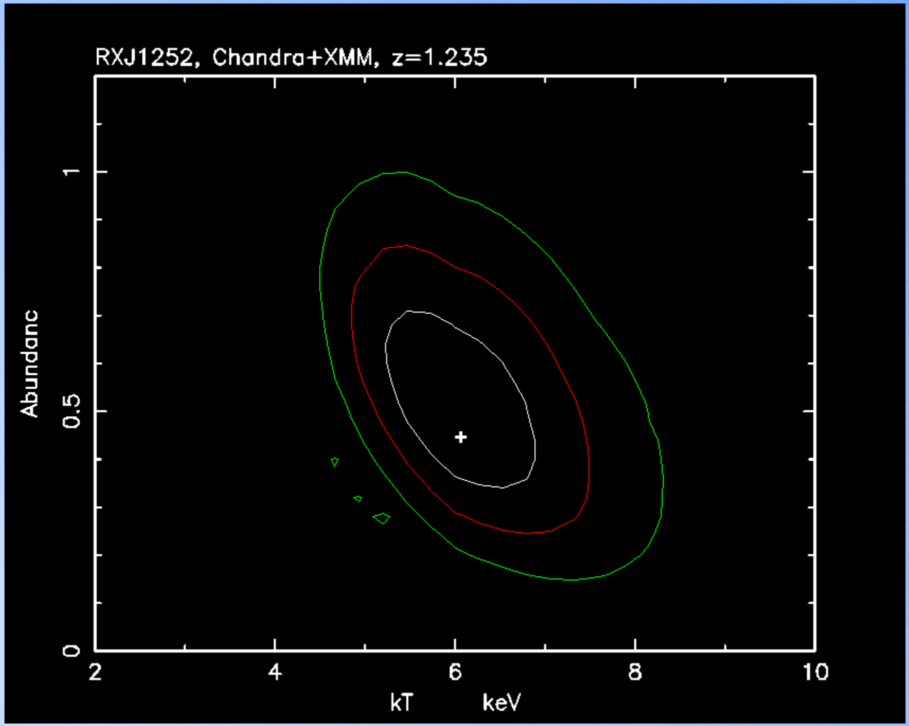
Simple approach: fix the relative abundance to solar, fitting for the average metallicity in terms of Z_o. Software: XSPEC.

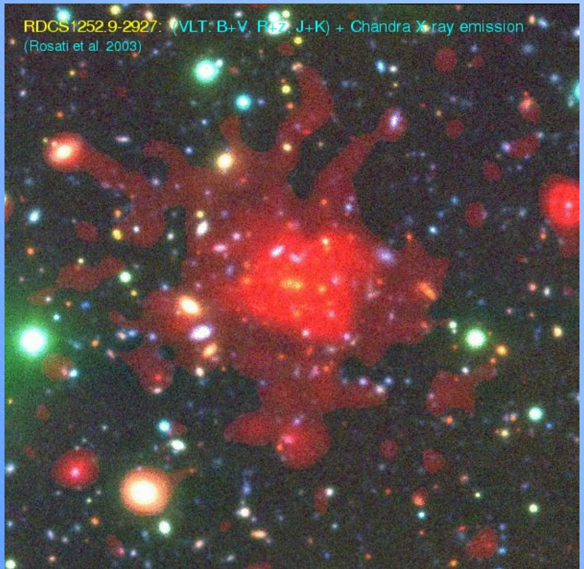
z= 0.31, exp= 37 ksec



Iron abundance at highredshift (z~1)

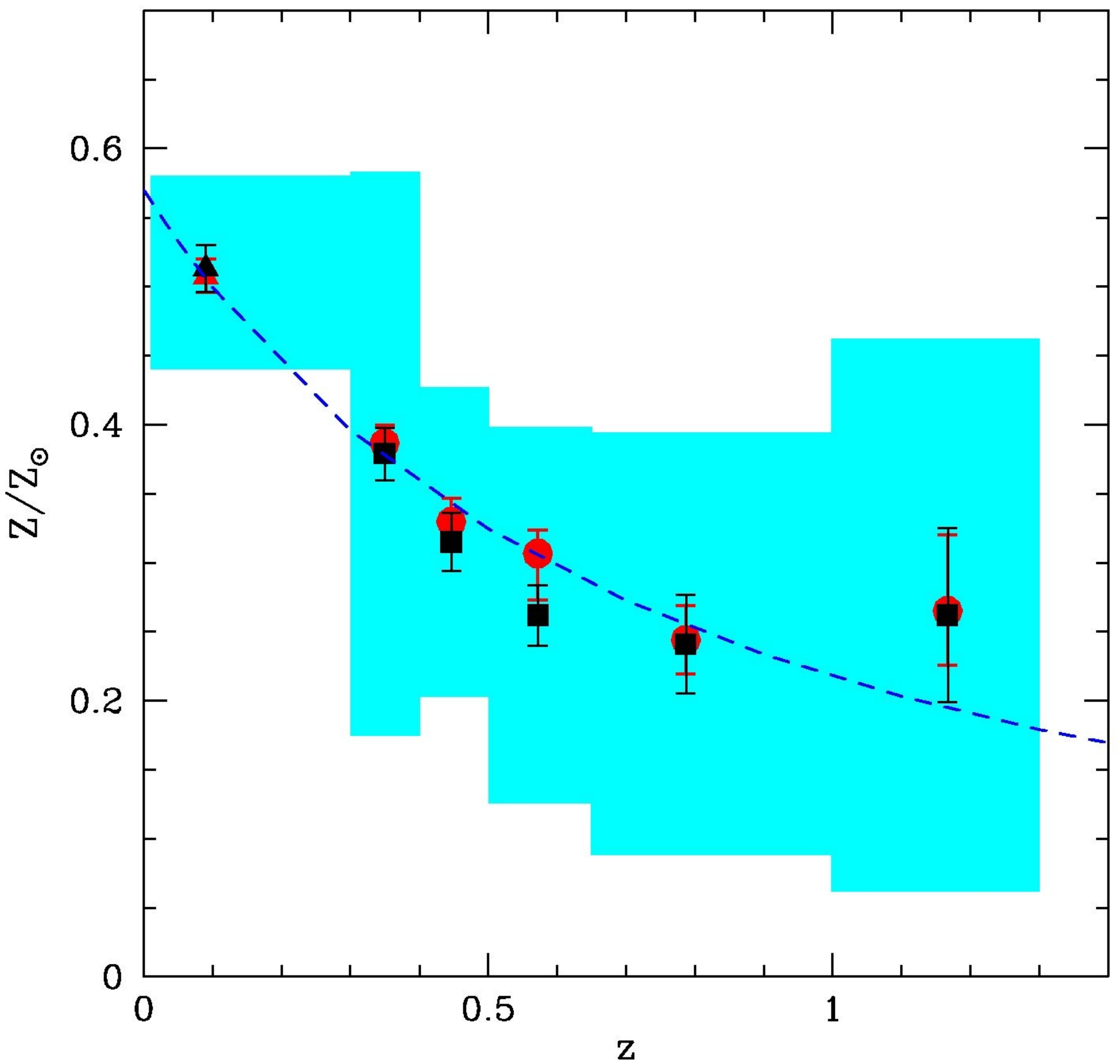






Z=0.3 $Z_\odot$ is a canonical value in local and distant clusters

Iron abundance vs redshift



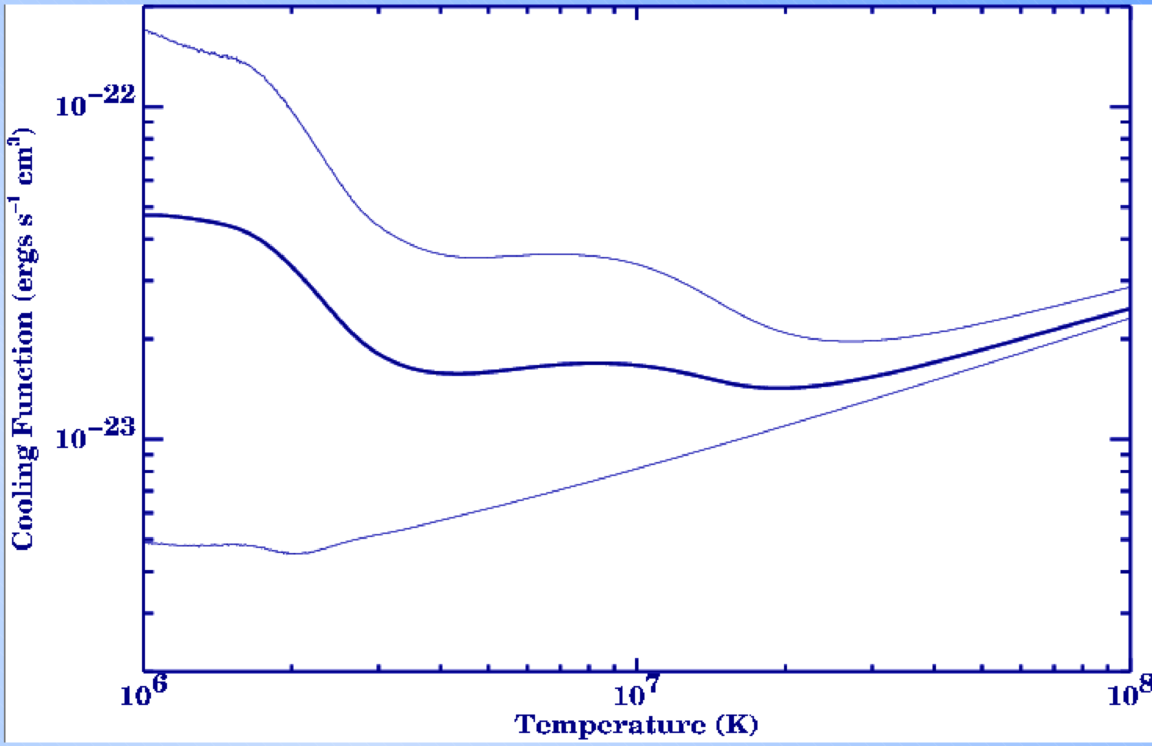
Balestra et al. 2007

Cooling Time

Cooling Function:

$L \propto n^2 \Lambda(T)$

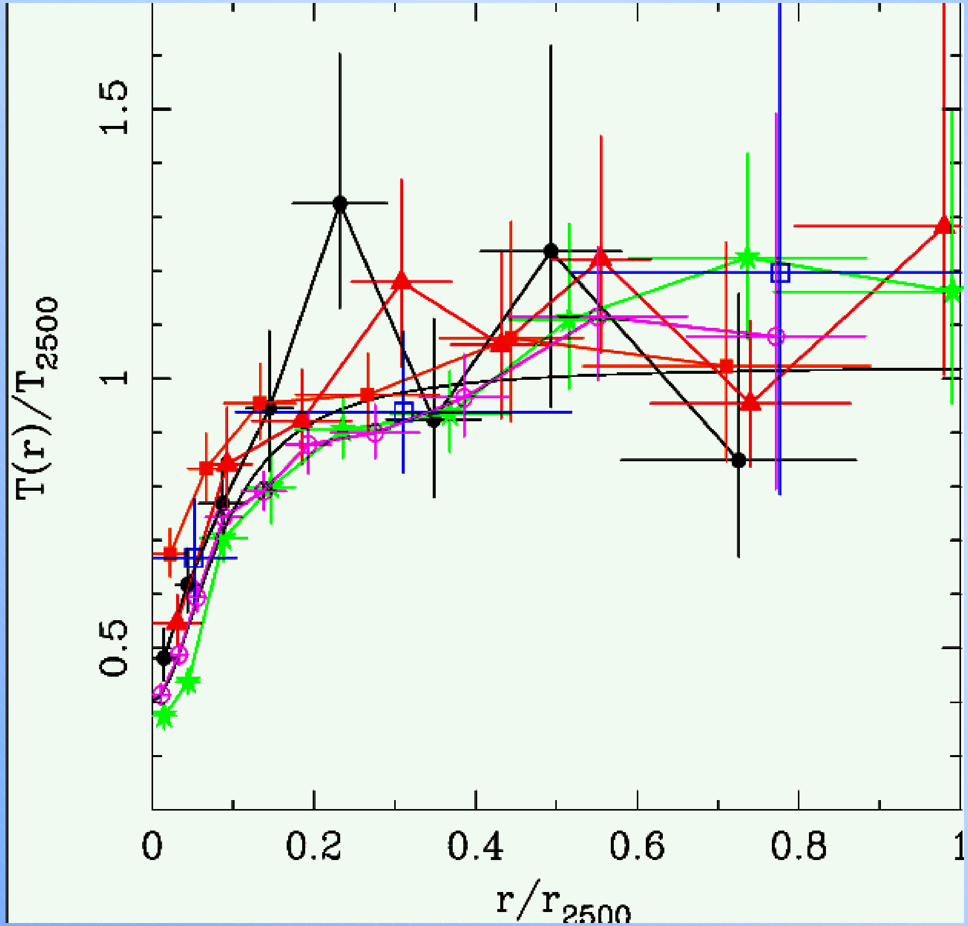
including continuum and line emission processes

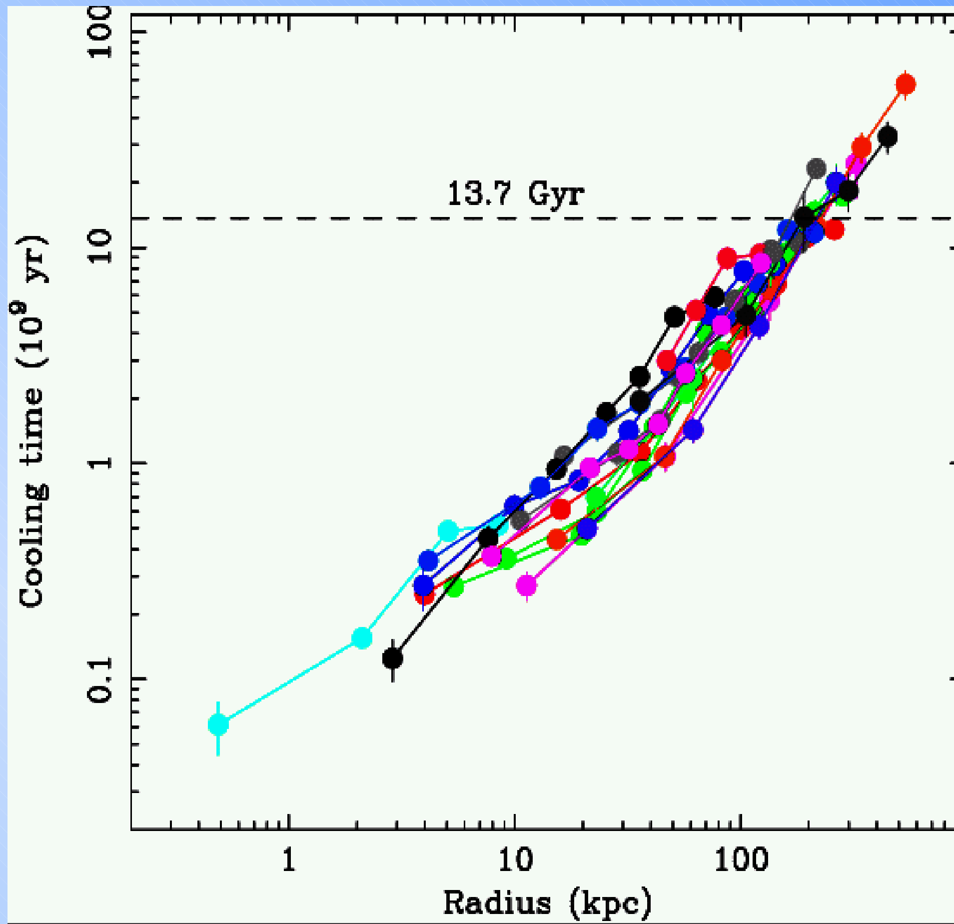


$$t_{cool} \equiv \frac{\frac{5}{2}kT}{n^2\lambda} \sim t_H T_8 \left(\frac{\lambda}{10^{-23}}\right)^{-1} \left(\frac{n}{10^{-2}}\right)^{-1}$$

If $t_{cool} < t_H$ the baryons are expected to cool

Cold cores/Cooling Flows in Clusters?





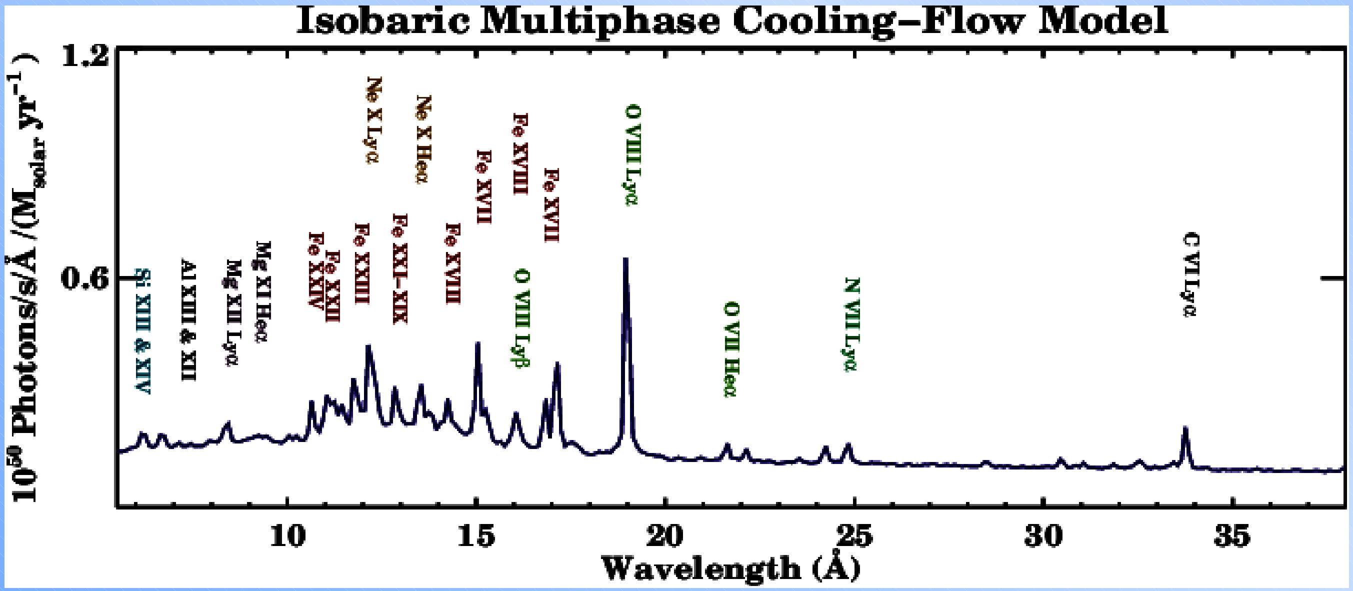
Peterson & Fabian 2005

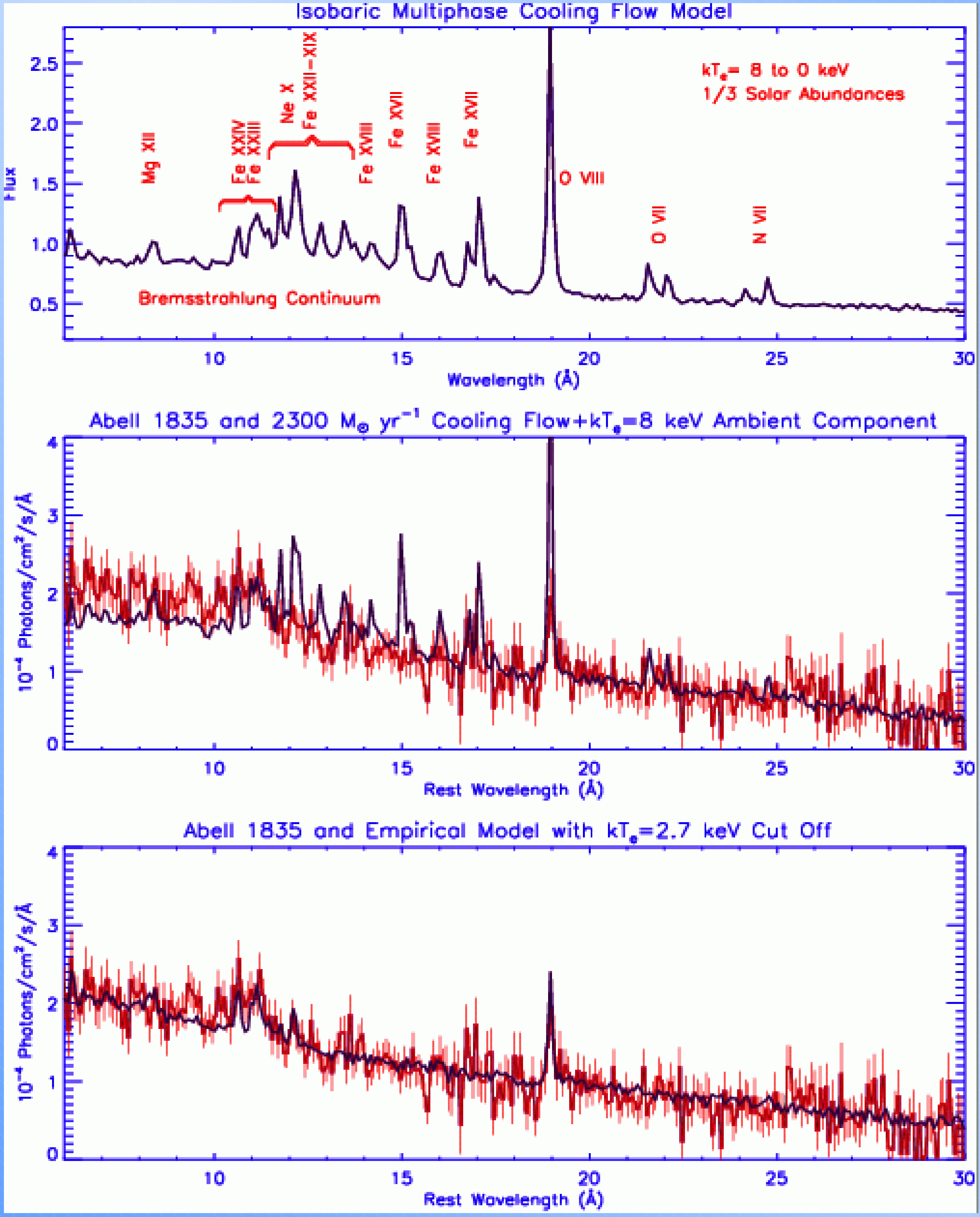
Cool cores are associated to higher Fe abundances (De Grandi et al. 2004)

Cooling Flow Model

$$\frac{dL}{dT} \propto \frac{5}{2} \frac{\dot{M}\, k}{\mu\, m_P}$$

X-ray observations of cool cores (low temperatures and peaked surface brightness) implied mass deposition rate of 100-1000 M /year in more than 50% of local clusters.
The isobaric cooling flow model predict a spectrum constituted by several temperatures, including very low temperatures which imply a lot of emission lines





Lack of emission line associated to low-T gas in cooling flow (Peterson et al. 2001)

Thumb rule: $T_{min}=T_{vir}/3$

The implications of this discovery are huge!

The cooling flow problem

Cluster plasma looses energy by emitting X-ray

The plasma appears to cool with high dM/dT

but

There is no gas below $T_{vir}/3$

The cooled gas resulting from the cooling is not seen

then

Who is heating constantly the ICM?

This is an open problem, relevant not only for ICM, but also for galaxy formation and evolution

Cooling catastrophe/Cooling crisis/Baryonic crisis

In the standard galactic formation scenarion, baryons in CDM halos cool via thermal bremsstrahlung and line emission. All the baryons are simply turned into stars when
$t_{cool} < H^{-1}$ (White & Rees 1978).

But the blind application of this criterion would result in the large majority of the baryons locked into stars, while it is observed to be less than 10%.

It is not clear yet which is the mechanism which hampers the baryons from cooling, despite many possible solutions.

In the spirit of the Occam razor, the same heating process may explain the cooling core problem and solve the cooling catastrophe.

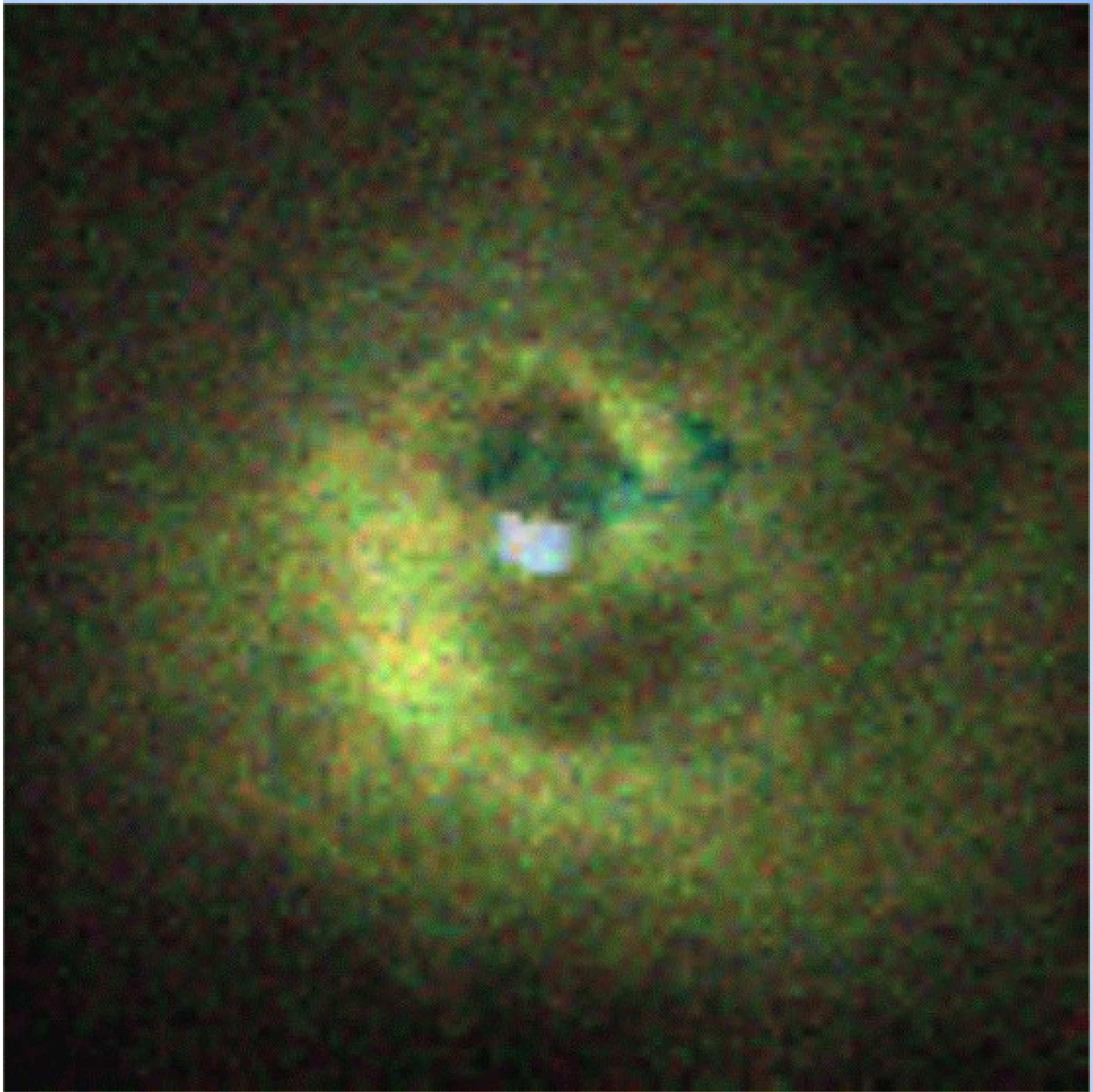
Feedback

These processes are known as "feedback", a key ingredient in the models of cosmic structure formation. It is basically the process of giving energy to the diffuse baryons and is usually associated to star forming processes and nuclear activity.

The main problem with feedback, is that any process we can think of scales with volume (and then with density), while cooling is a runaway process proportional to n^2

Understanding feedback is nowaday the most compelling goal for structure formation.

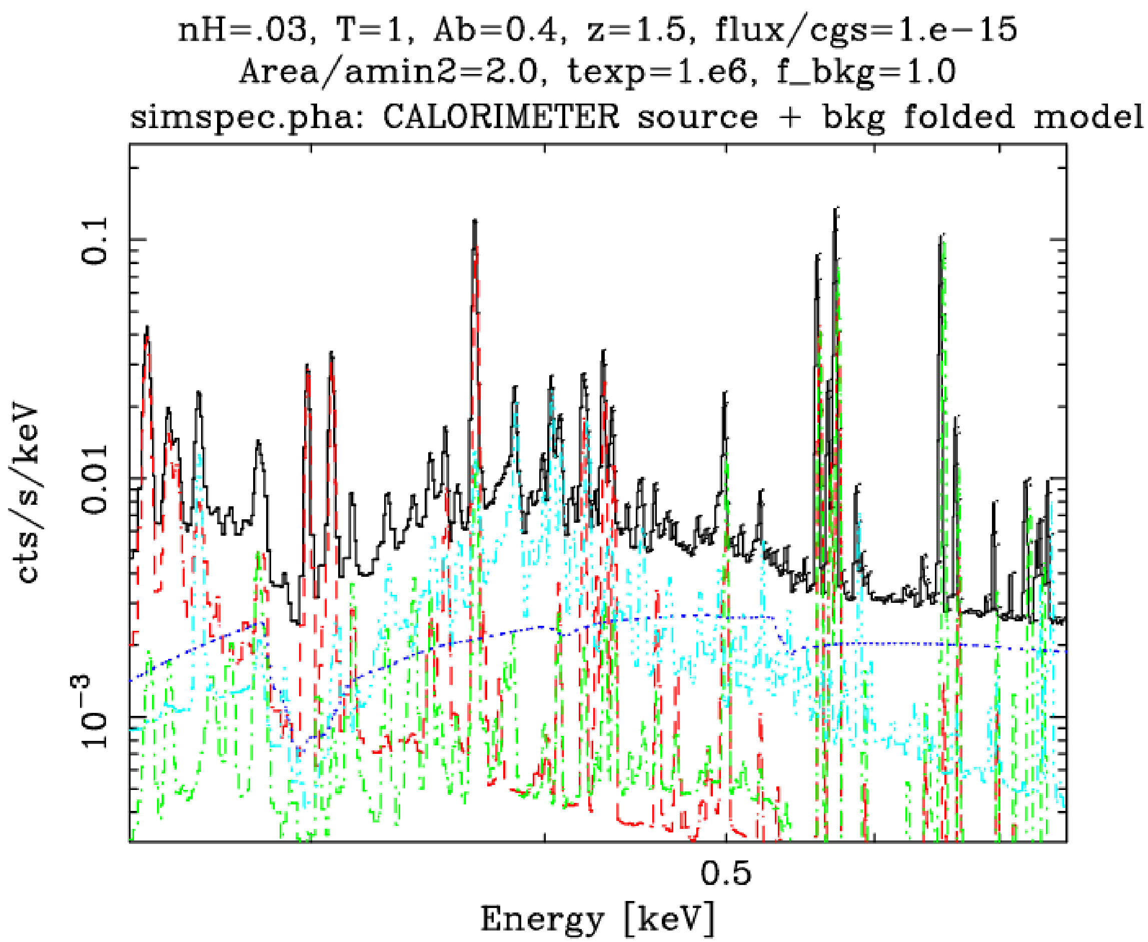
The Chandra view of local clusters: hot bubbles



Fabian et al. 2005

EDGE: a multi-purpose X-ray mission to study diffuse hot baryons

Making direct velocity measurements of the cluster cores is of great importance to address ICM physics issues:
Viscosity/turbulence
Cooling/heating problem
Subarcmin angular resolution very important.



Most of the baryon in the Universe is in the form of WHIM (Warm Hot Intergalactic Medium, Cen & Ostriker 1999)

WHIM:
outskirts of Clusters
Filaments
Line emission is the only way to detect the majority of the baryons in the universe (see Piro et al. 2007)

Conclusions

Line emission diagnostic in X-ray spectra of clusters of galaxies allows us to study the chemical and the thermodynamical state of the ICM.

Studies of the chemical enrichment of the ICM and of the temperature structure in cool core are relevant for the whole field of galaxy and structure formation.

So far X-ray spectroscopy is based on CCD or grating.
Future prospects with calorimeters will allow one to study in details dynamical/thermodynamical processes in the cores of Clusters, and to investigate the WHIM.