Lecture 10
Groups and Clusters of Galaxies – II (ICM)

Intra-Cluster Plasma

X-Rays Emission

- thermal *bremsstrahlung*
- spectra
- luminosity & temperatures

Cooling Flows

Metallicity

Catalogs

Sunyaev-Zel´dovich Effect

- thermal S-Z
- kinetic S-Z

IC Ram Pressure

IC Magnetic Field

⇨ Intra-Cluster Medium (ICM)

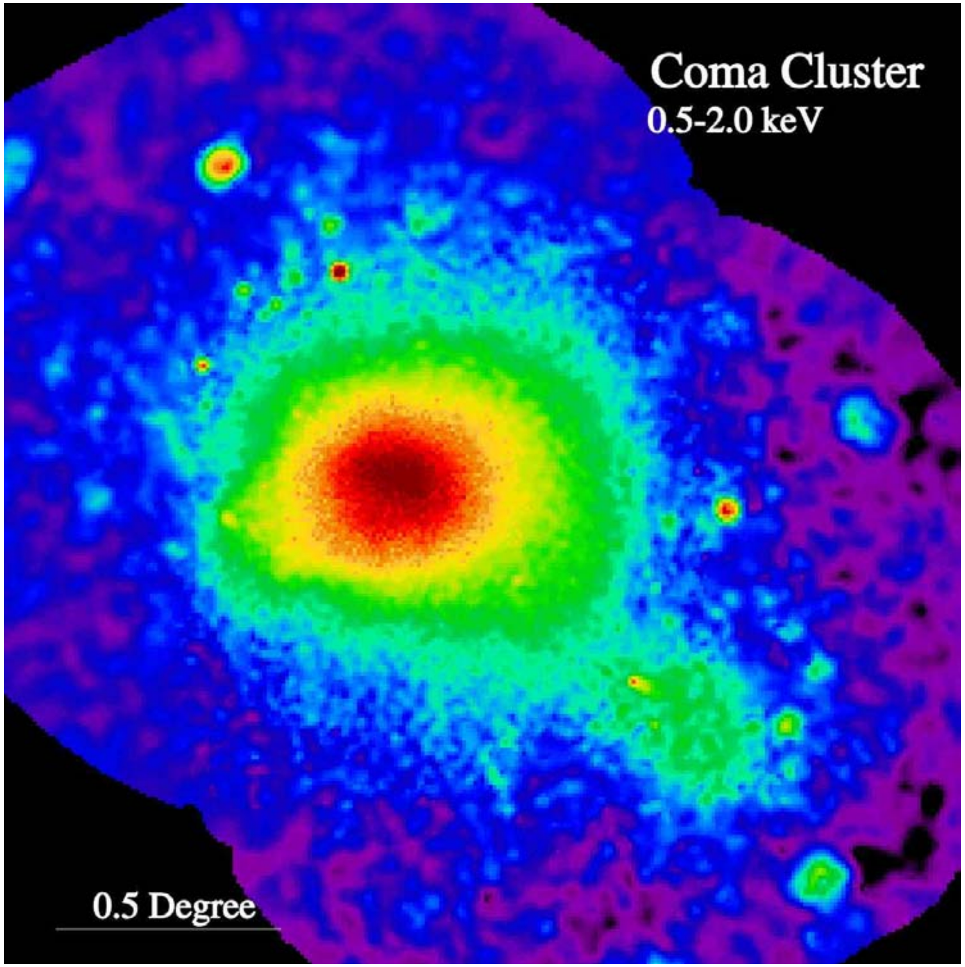
Hot Ionized Gas:

- ✓ **Galaxy formation** is **inefficient – most** of the **baryonic matter** (about 80%) is in the form of **gas** in the **ICM** (between the galaxies, concentrated toward the center)

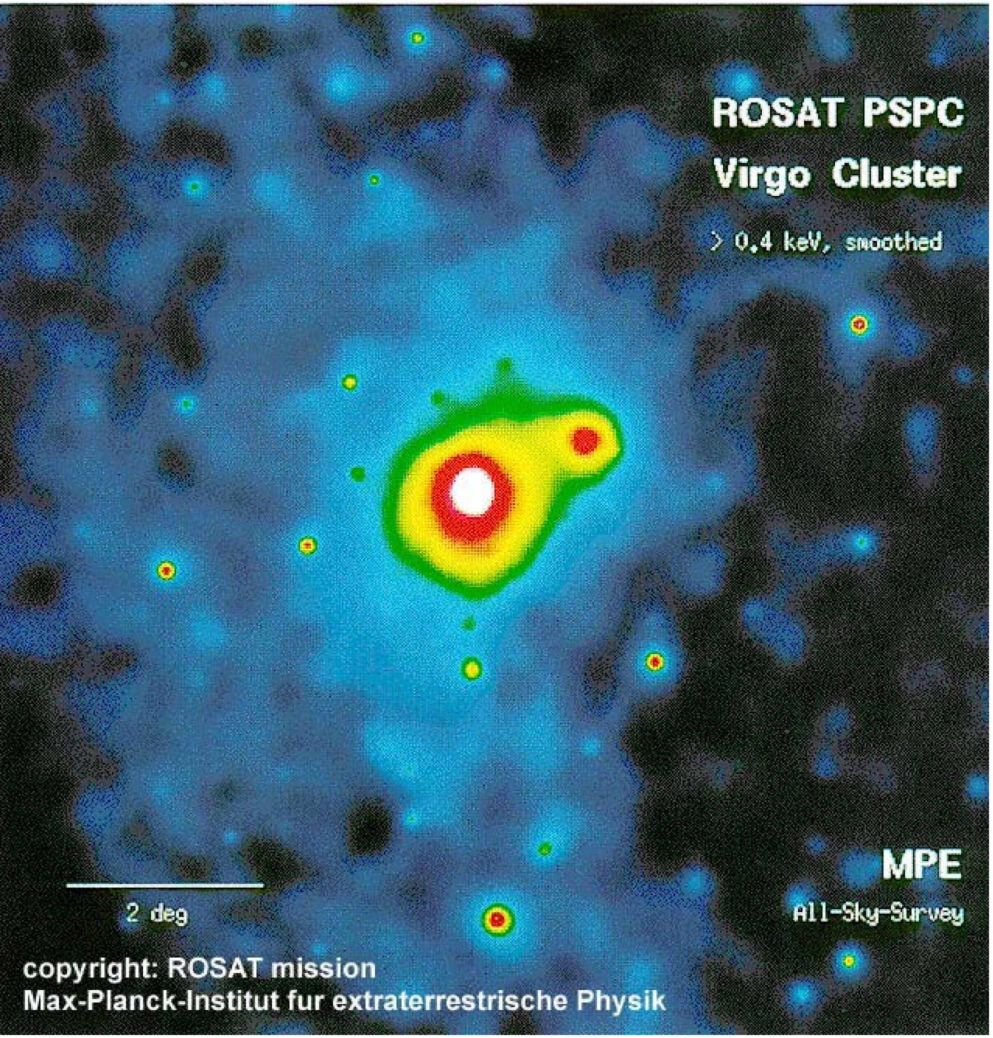
- ✓ this gas is heated by the **compression from the potential well** of the cluster, by the **motion of the galaxies**, and possibly by **AGN** and **SN feedback**

- ✓ the **temperature** it reaches is so **high** (**10^7—10^8 K**) that it **emits in X-rays** (as was first detected in Coma Cluster, in 1966, from balloon observations, and confirmed by *UHURU* satellite)

- ✓ this gas is composed predominantly of **H** and **He**, which are **fully ionized.** Also **highly ionized metals** are found (like FeXXVI, as was first detect by *Ariel-V* satellite)



⇨ Intra-Cluster Medium (ICM)



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Detection:

✓ the ICM can be observed in 4 ways:

- **X-ray emission**
- **Sunyaev-Zeldovich effect**
- **ram-pressure** of the ICM over the HI of spirals and jets/lobes of AGNs
- **radio emission** from IC magnetic field

✓ Clusters are among the **brightest X-ray sources** in the sky. Their emission is **extended** and **diffuse** and **do not vary** with time.

✓ **Projection effects** are much less a problem for their X-ray observations because there are far fewer X-ray sources that could be incorrectly attributed to the emission of a cluster.

⇨ X-Ray Emission (continuum)

Thermal *bremsstrahlung*:

✓ Since the first spurious detection of cluster X-ray emission, it was correctly attributed to **thermal *bremsstrahlung*** (or free-free emission) [Felten et al. 1966, ApJ 146, 955]

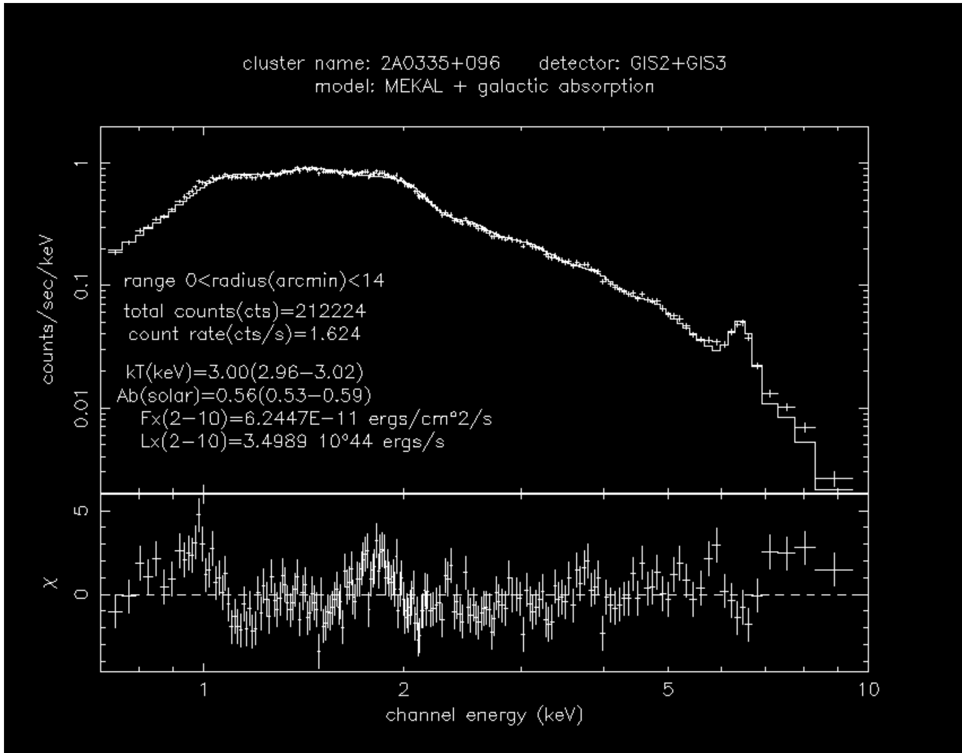
✓ **free e⁻** are **scattered** by the **ions** and **radiate** the energy they lose

✓ the **gas cools very slowly** by this radiation

✓ Emissivity (for a Maxwellian distribution of e⁻ velocities):

$$\kappa_\nu = \frac{dL}{dV\,d\nu} = n_e\, n_{HII}\, \Lambda_{cool}(T) \qquad \Lambda_{cool} = \frac{1}{3\pi^2}\,\frac{Z^2 e^6}{\varepsilon_0^3 c^3 m_e^{3/2}}\,(k_B T)^{-1/2}\, e^{-(h\nu/kT)}\, g(\nu,T)$$

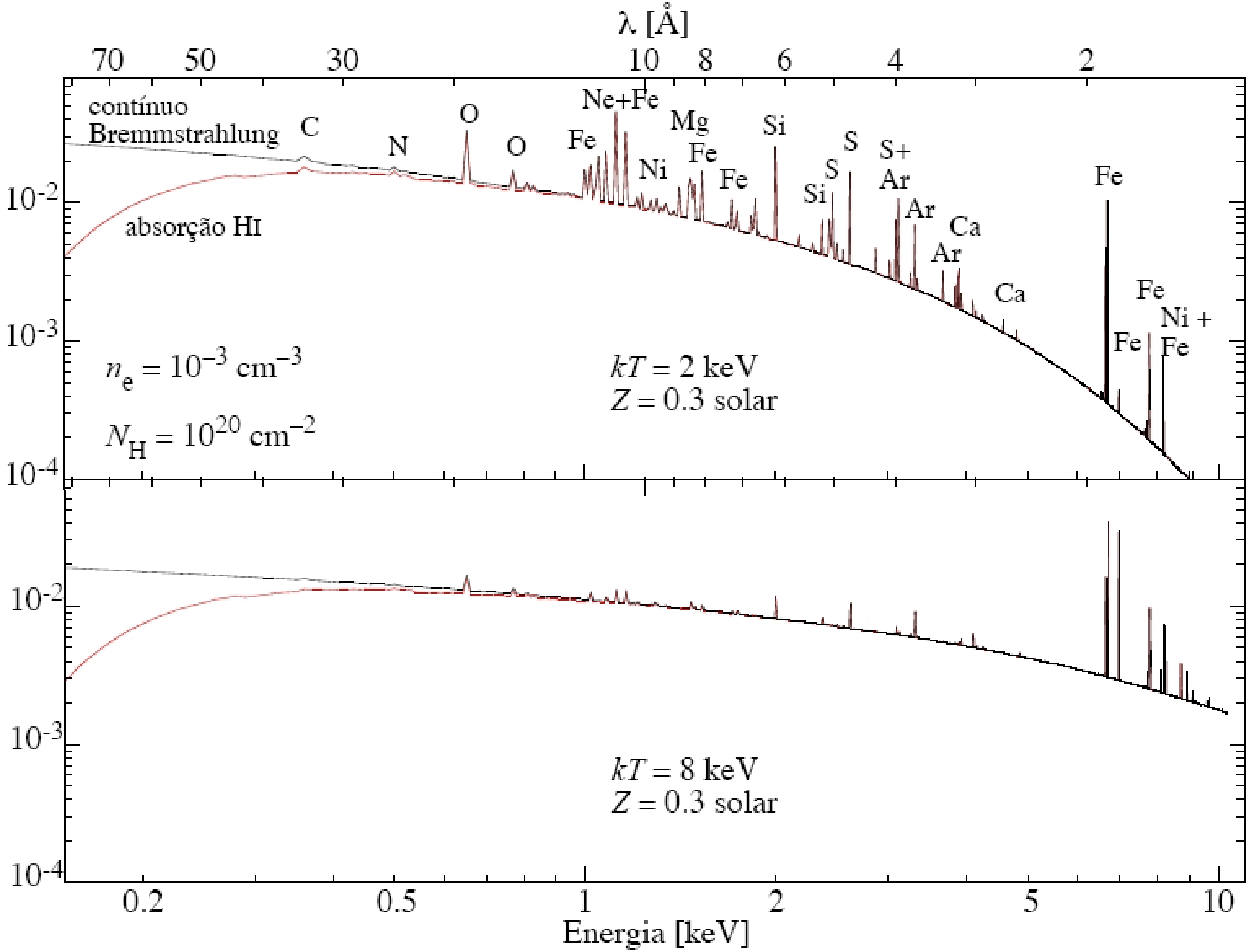
$g \approx \sqrt{3}/\pi \;\ln(k_B T/h\nu)$
(Gaunt factor: quantum and relativistic effects)



✓ Spectra:

- is roughly **flat up to** energies hν ~ ***k*$_B$T**, above which it **cuts off exponentially**
- for *k*$_B$T **below** or about **2 keV emission-lines** dominate; for *k*$_B$T **larger** than that (typical) emissivity of **thermal *bremsstrahlung* dominates**

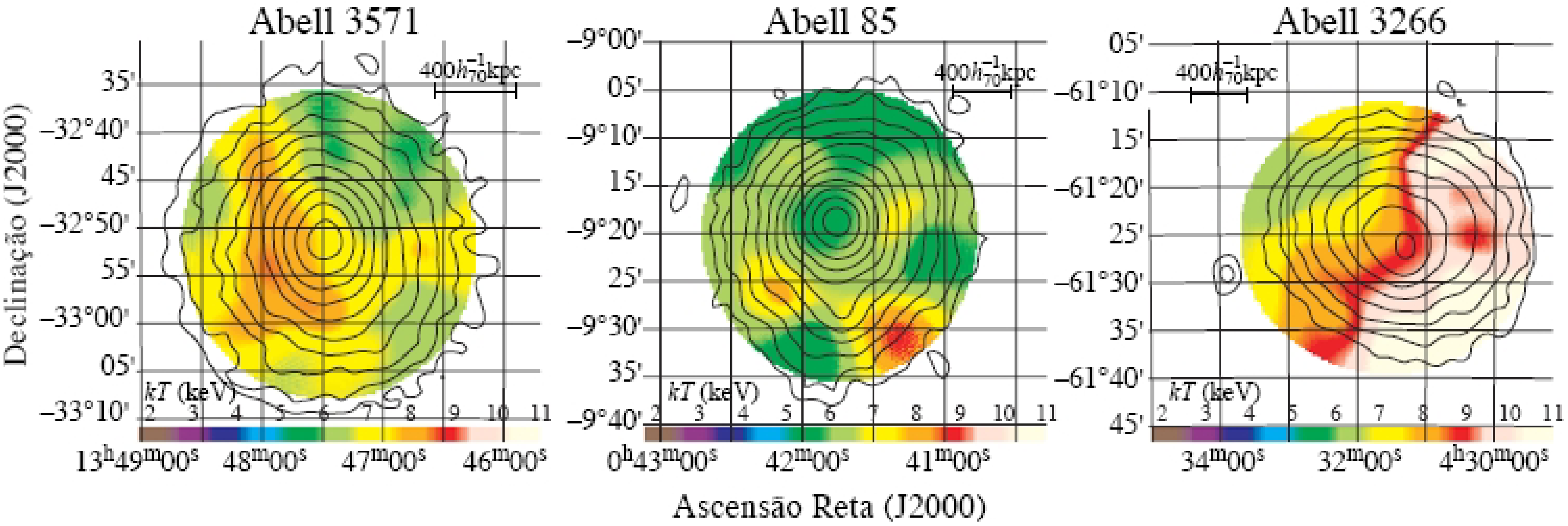
⇨ X-Ray Spectra



⇨ X-Ray Emission (luminosity & temperatures)

- ✓ L_X:
  - plasma **density** (ρ_{gas})
- ✓ T_X
  - **mass** ($\mathcal{M}_{total}$)
  - **cooling flows**
  - **shocks**

[Forman & Jones 1982, AARA 20, 547]



[Donnelly et al. 2004, astro-ph/0310145]

⇨ X-Ray Emission (surface brightness radial profile)

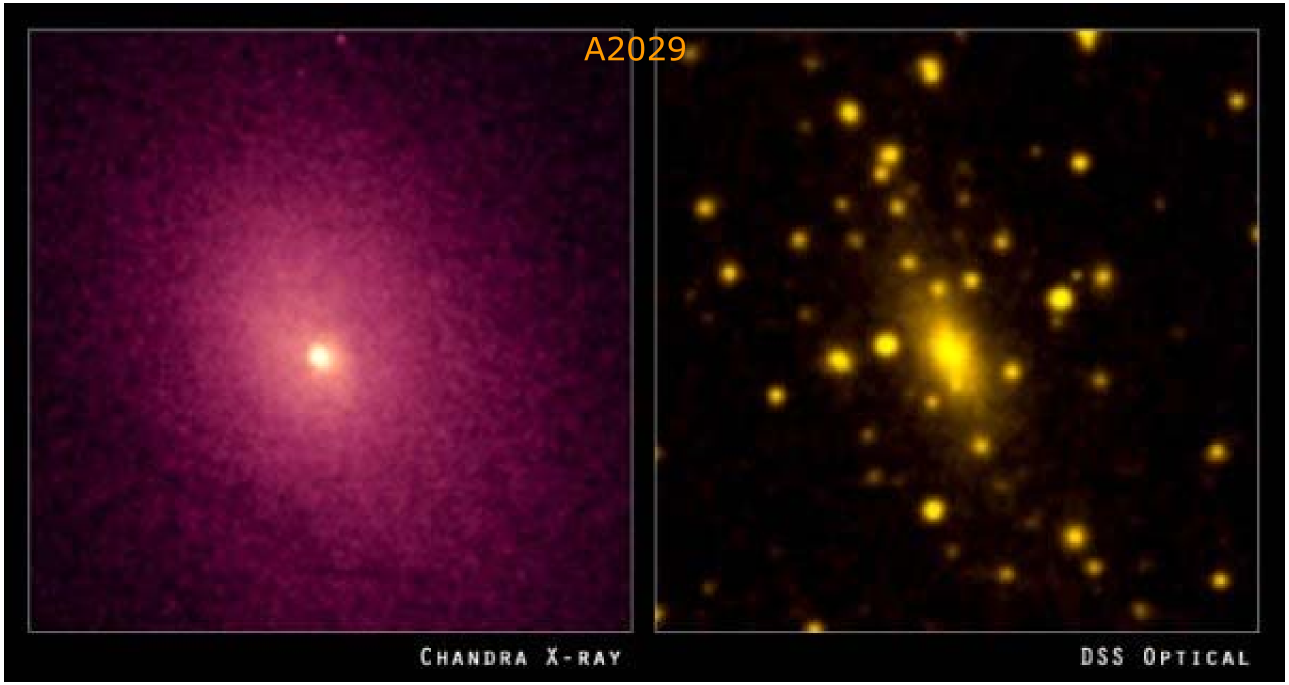
Isothermal sphere:

1976 – Cavaliere & Fusco-Femiano [A&A 49, 137]: proposed a model, called β model, for the surface brightness radial profile of cluster X-ray emission, based on the King's profile:

$$\Sigma_X(r) = \Sigma_0 \, [1 + (r/R_c)^2]^{-3\beta+1/2} \qquad \text{(in 2D)}$$

where Σ_0 is the **central surface brightness** and R_c is the **core radius**. If the gas is isothermal, this corresponds to a gas density:

$$\rho_{gas}(r) = \rho_0 \, [1 + (r/R_c)^2]^{-3\beta/2} \qquad \text{(in 3D)}$$



⇨ Cooling Flows

- ✓ the **ICM loses energy** (cools) by different ways, but **mainly** by the *bremsstrahlung* **radiation**

  $t_{cool} \approx E / L_X$

  $E = (3/2)\, n\, k_B\, T$ (“ideal” gas)

  $t_{cool} \sim 5{,}1 \times 10^8 - 1.7 \times 10^{10}$ years ($10^{-2} > n\,[\mathrm{cm}^{-3}] > 10^{-3}$, $10^7 < T\,[\mathrm{K}] < 10^8$)

- ✓ so, the **ICM** has a **very long cooling time** ($\sim t_H$), except in denser areas (like the center)

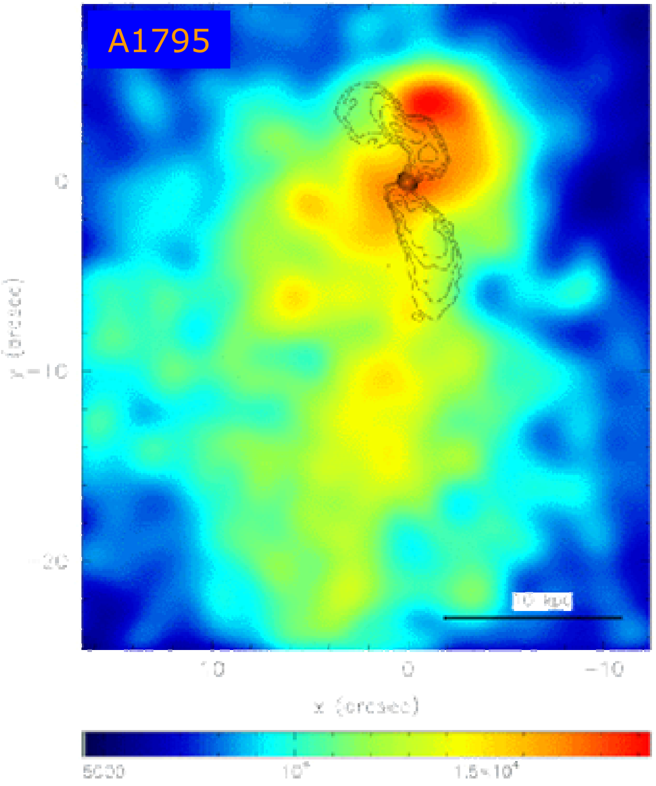
- ✓ if the center cools significantly, its **pressure becomes smaller** than that on the region around (where the gas is still hot), producing a **cooling flow** towards the center of the potential well (as proposed originally by Cowie & Binney [1977, ApJ 215, 723] and Fabian & Nulsen [1977, MNRAS 180, 479])

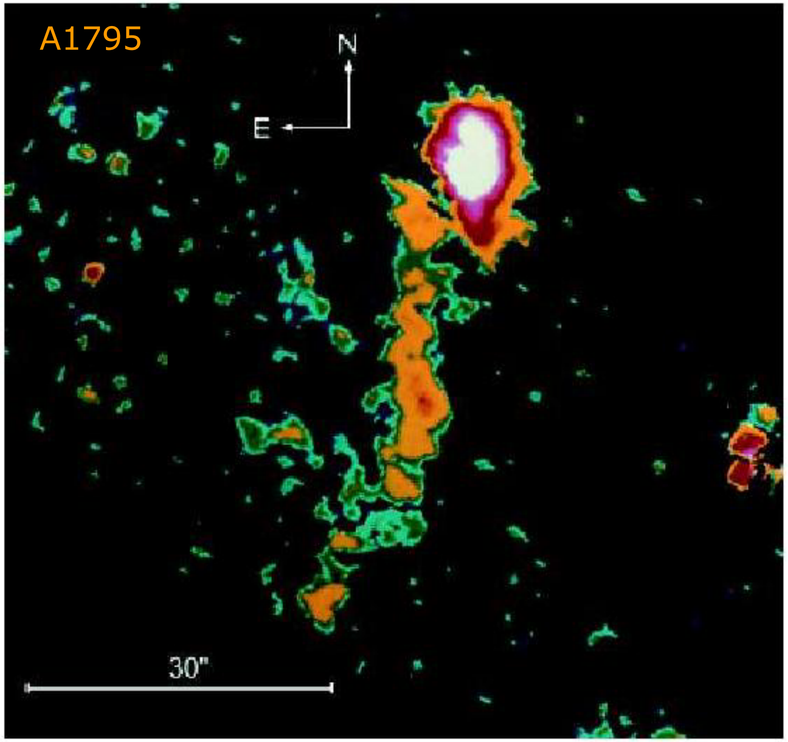
- ⅄ beyond the lower temperatures in the center, an **excess surface brightness** at the center (with respect to the β profile) should be observed

- ⅄ **cooling flows** have been suggested as a way to **build cD gals** over cosmic time, but (with a few notable exceptions such as A1795) there is **no trace of a massive SF** as expected if the gas is been dumped into the center

- ⅄ since **no large amount of cool gas** ($k_B T < 1$ keV) **has been observed** in the centers of the clusters, two things may be happening:
  - there could be a **heating mechanism** in the central regions (AGN or SN feedback, for ex.)
  - the external regions might be losing heat by **conduction**

Cooling Flows





⇨ Metallicity

- ✓ Once the T of the gas is determined, **abundances** of elements like **Fe**, **O**, **Si**, **Mg** and **Ni** can be measured from their **emission-line fluxes** (adjusting the abundances in the model to produce the best fit)

- ✓ on average, **overall abundances** of heavy elements with respect to H, in the ICM, are about **0.3** times the **solar** ratios (apparently with no substantial change from z ~ 1 to present)

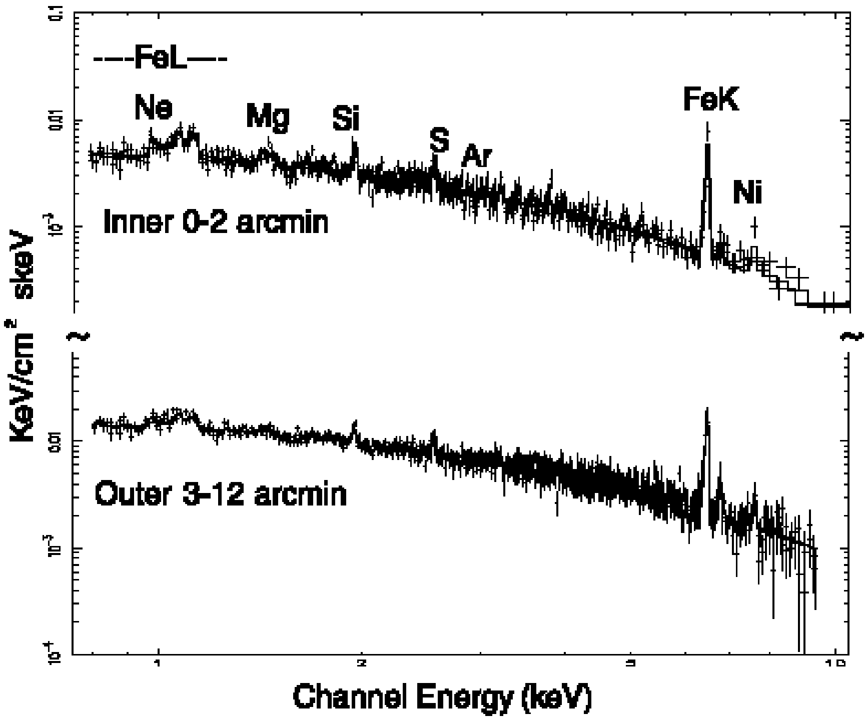
- ✓ so, the ICM gas is not primordial, it **has been enriched**!

- ✓ the two most popular mechanisms for enrichment of ICM are the **ram pressure stripping of late-type spirals falling into the cluster** [Gun & Gott 1972, ApJ 176, 1] and **SB winds produced by mergers** [Schindler et al. 2005, A&A 435, 25], but both need levels of these effects much higher that expected

- ✓ an alternative model is that the **hot gas arrives latter** at the clusters, after galaxy formation and some evolution in groups (like the formation of cDs and SB to produce metals), and then "**cleans**" the metals of the galaxies by (inverse) **ram pressure** – like the "run-off" rain water that cleans the pollutants of the atmosphere [Coziol et al. 2008, submitted to AJ]

⇨ Metallicity gradients

- ✓ For **Fe** and **Si**, spatially resolved observations can be used to measure **metallicity gradients** – at least **Fe abundances** seem to be **higher at** the cluster's **center** (particularly when there is a cD); farther out the Fe gradient appear to **flatten at ~ 0.3 $[\mathrm{Fe/H}]_\odot$** extending to about ~ 5 R_c
- ✓ the **total amount of Fe** is quite impressive, exceeding the total amount of Fe contained within all the stars in the cluster's galaxies! (according to some estimates, it requires a **disproportionately large number of massive stars** to have formed and exploded as SNe in the history of the cluster)



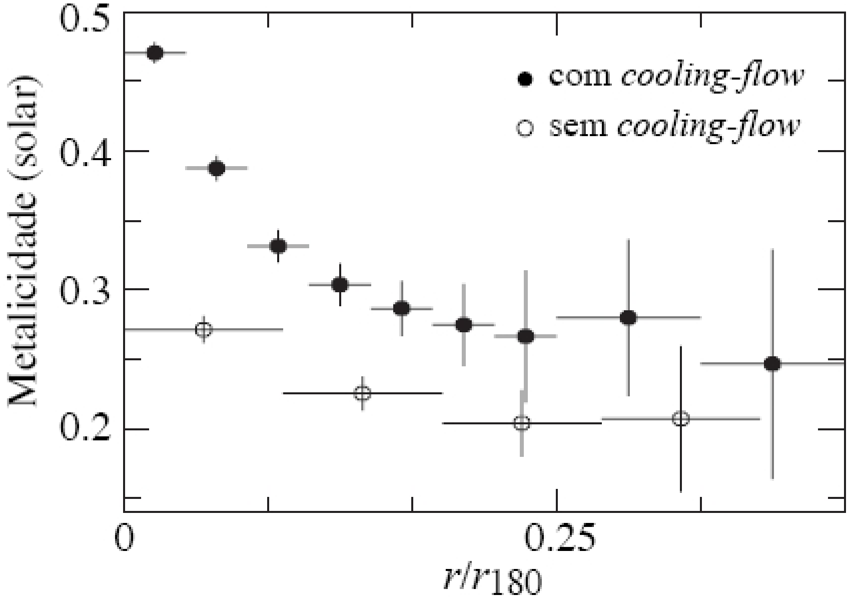


Figura 100: Gradiente de metalicidade em aglomerados ricos com e sem *cooling-flow* obtidos com satélite BeppoSAX. A distância radial é dada em termos de $r_{180} \approx R_{\mathrm{virial}}$ (cf. seção 7.1). Figura tirada de De Grandi & Molendi (2001)

⇨ Metallicity

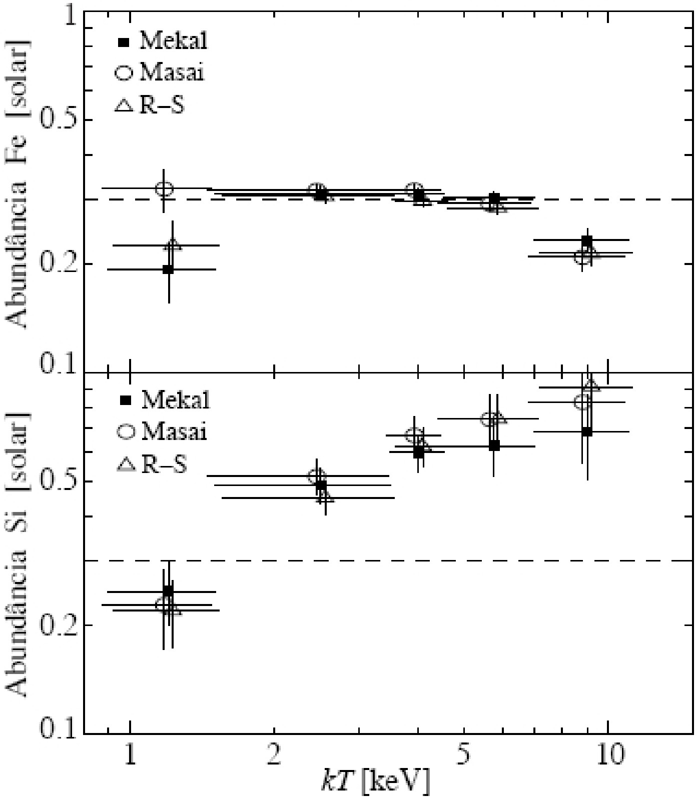


Figura 101: Abundância de ferro e silício em função da temperatura do aglomerado (excluindo a região central) obtidas com satélite ASCA. Enquanto que o Fe é praticamente independente, o Si apresenta uma forte correlação, sendo mais abundante em aglomerados mais quentes (logo, mais maciços). Cada símbolo representa um modelo de plasma diferente. Figura adaptada de Fukazawa et al. (1998).

- ✓ in principle, one can probe the origins of elements in the ICM by comparing the **abundances of different metals**, since different processes and products come from **massive** (SNe II) or **white dwarf** (SNe Ia) stars
- ✓ the observations suggest that the abundance of **α-metals** (O, Si, etc) is **higher than** the abundance of **Fe** and **Ni**, indicating a predominant enrichment by SNe II ejection. If so, it **happened in the early history** of the cluster, since the galaxy population is dominated by **ellipticals** (that exhausted their SNe II in the initial burst)
- ✓ there is also a abundance difference between more and less massive clusters: **cooler clusters** (shallower potentials) have **abundance ratios** characteristic of **SNe Ia** (less α-elements, like Si, in the above figure) while **hotter** (massive) clusters have ratios close to that of **SNe II**

⇨ X-Ray Catalogs of Galaxy Clusters

✓ X-ray emission from clusters is **less subjected to projection effects**

✓ it seems that the **properties of ICM** have **not changed much** since z ~ 0.7 [e.g. WARPS survey], and so X-ray emission is suitable for **searching clusters up to z ~ 1**

Catalog	N_{gr}	z_{lim}	F_{min} (erg s^{-1} cm^2)	Area	Ref.
XBACS	283	0.2	5.0×10^{-12}	~8.2 sr	Ebeling et al. 1996
BCS	206	0.3	4.4×10^{-12}	3.96 sr	Ebeling et al. 1998
eBCS	107	0.3	2.8×10^{-12}	3.96 sr	Ebeling et al. 2000
REFLEX	447	0.3	3.0×10^{-12}	4.24 sr	Bohringer et al. 2004
CIZA	151	0.3	3.0×10^{-12}	~4.3 sr	Ebeling et al. 2002
Abell/ACO	4 073	0.20	$m_{ph} \le 20.0$	~8.2 sr	Abell 1958, ACO 1989
EDCC	737	0.19	$b_J \le 20.5$	0.5 sr	Lumsden et al. 1992
APMCC	937	0.13	$b_J \le 20.5$	1.31 sr	Dalton et al. 1997
NoSOCs	16 546	0.25	$r_F \le 19.5$	3.35 sr	Gal et al. 2006

⇨ X-Ray Catalogs of Galaxy Clusters

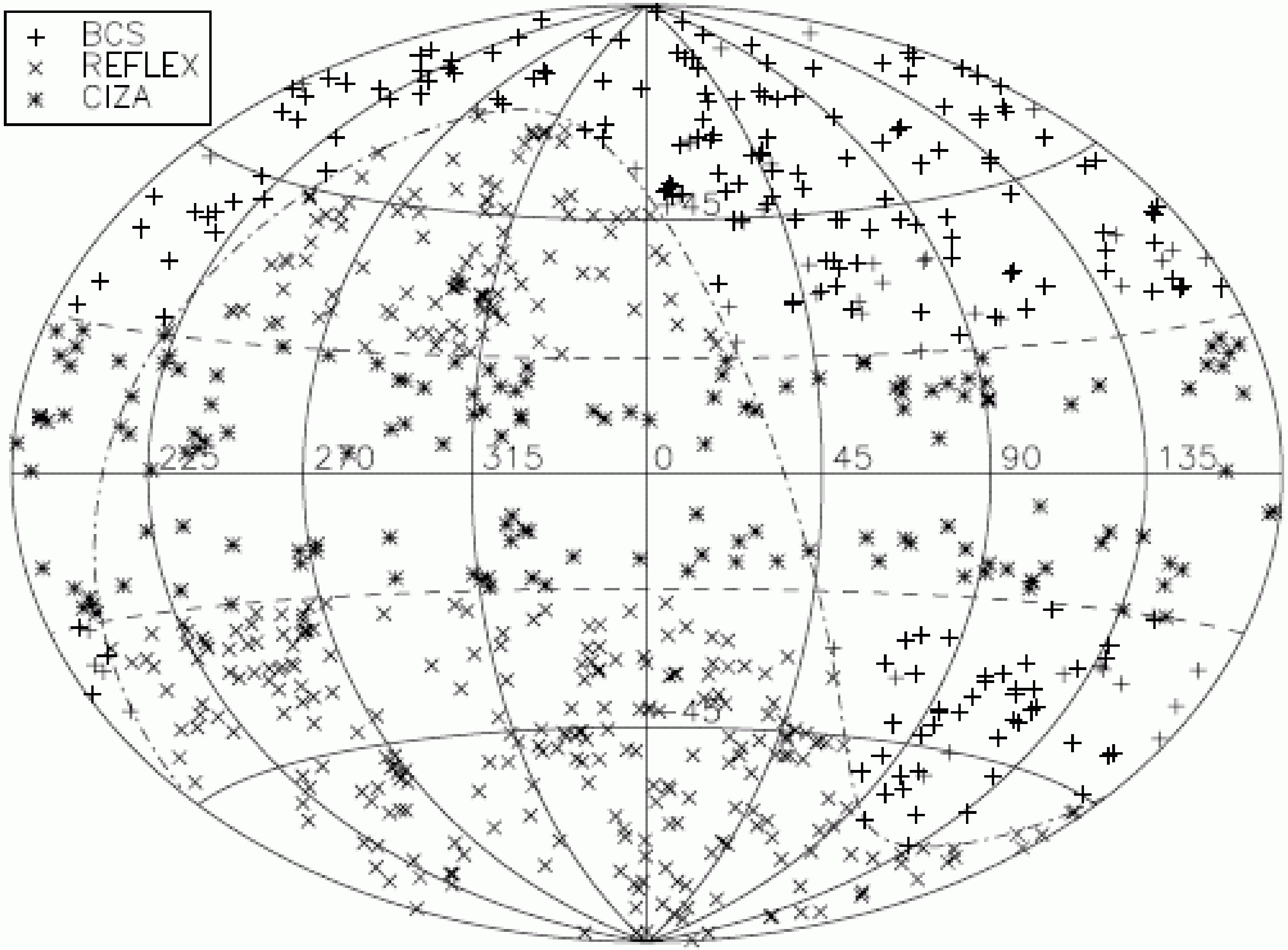
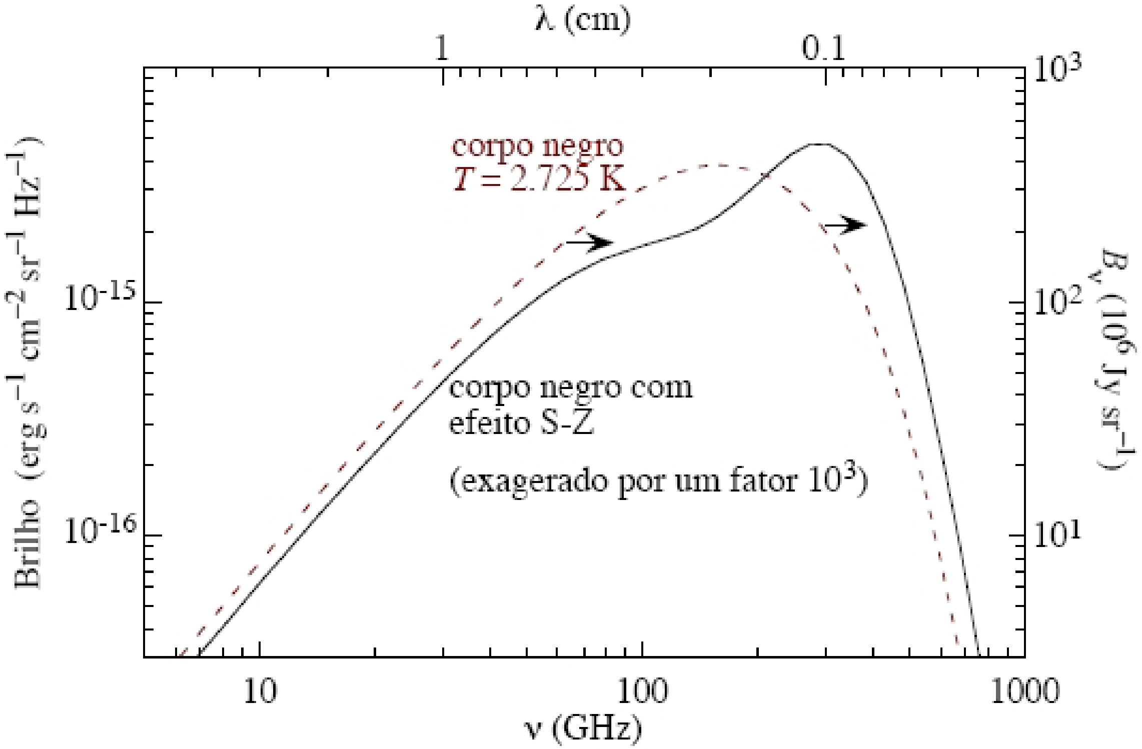


FIG. 1.— Aitoff projection of the combined REFLEX+eBCS+CIZA cluster sample in Galactic Coordinates. The dashed lines represent the traditional ZOA ($|b| < 20^\circ$), while the dashed-dotted line is the celestial equator ($\delta = 0^\circ$).

[Kocevski & Ebeling 2006, ApJ 645, 1043]

⇨ The Thermal Sunyaev-Zel´dovich Effect

- ✓ Since the ICM is a hot plasma full of **free e⁻**, when the CMBR **photons** (γ) cross it they suffer **inverse Compton scattering** by the free e⁻
- ✓ although, to first order, γ are just as like to gain as lose energy in these Compton scatterings, to second order **there is a net statistical gain of energy**
- ✓ thus, the **CMBR spectrum is shifted** to slightly **higher energies** and so, in the **Rayleigh-Jeans** region there is expected to be a **decrement** in the spectrum **intensity** (while in the **Wien** region there should be a slightly **excess**)
- ✓ this effect was predicted by Zel´dovich & Sunyaev [1969, Ap&SS 4, 301; 1970, Ap&SS 7, 3] and became known as the ***Sunyaev-Zel´dovich (S-Z) effect***



⇨ The Thermal Sunyaev-Zel´dovich Effect

✓ The **amplitude of the S-Z effect** is characterized by the Compton **y** parameter (the integral of the plasma pressure along the LOS):

$$y = \frac{\sigma_T k_B}{m_e c^2} \int T(\ell)\, n_e(\ell)\, d\ell$$

where $\boldsymbol{\sigma_T}$ is the Thomson cross-section and $\boldsymbol{\ell}$ is the cluster dimension along the LOS

✓ since: $\tau = \sigma_T \int n_e(\ell)\, d\ell$, is the **optical depth**, and if the plasma is **isothermal**:

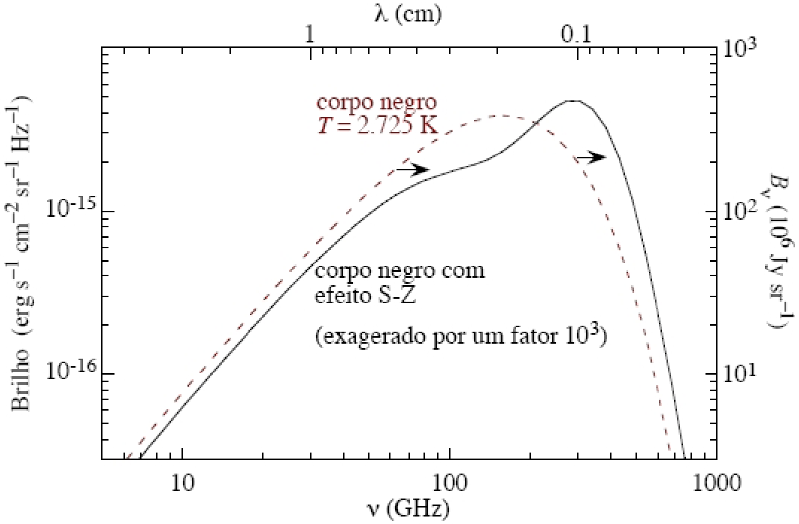
$$y = (\tau k_B T) / (m_e c^2)$$

✓ the **decrement** in the **Rayleigh-Jeans** region can, thus, be measured by:

$$\Delta T_{CMBR} / T_{CMBR} = -2y$$

✓ typically $\Delta T_{CMBR} / T_{CMBR} \sim -10^{-4}$

[see Sunyaev & Zel'dovich 1980, ARAA 18, 537]



⇨ The Sunyaev-Zel´dovich Effect

✓ Cosmological applications of the **thermal S-Z effect** benefit greatly from the fact that it is **independent of the distance** (unlike optical and X-ray surface brightness)

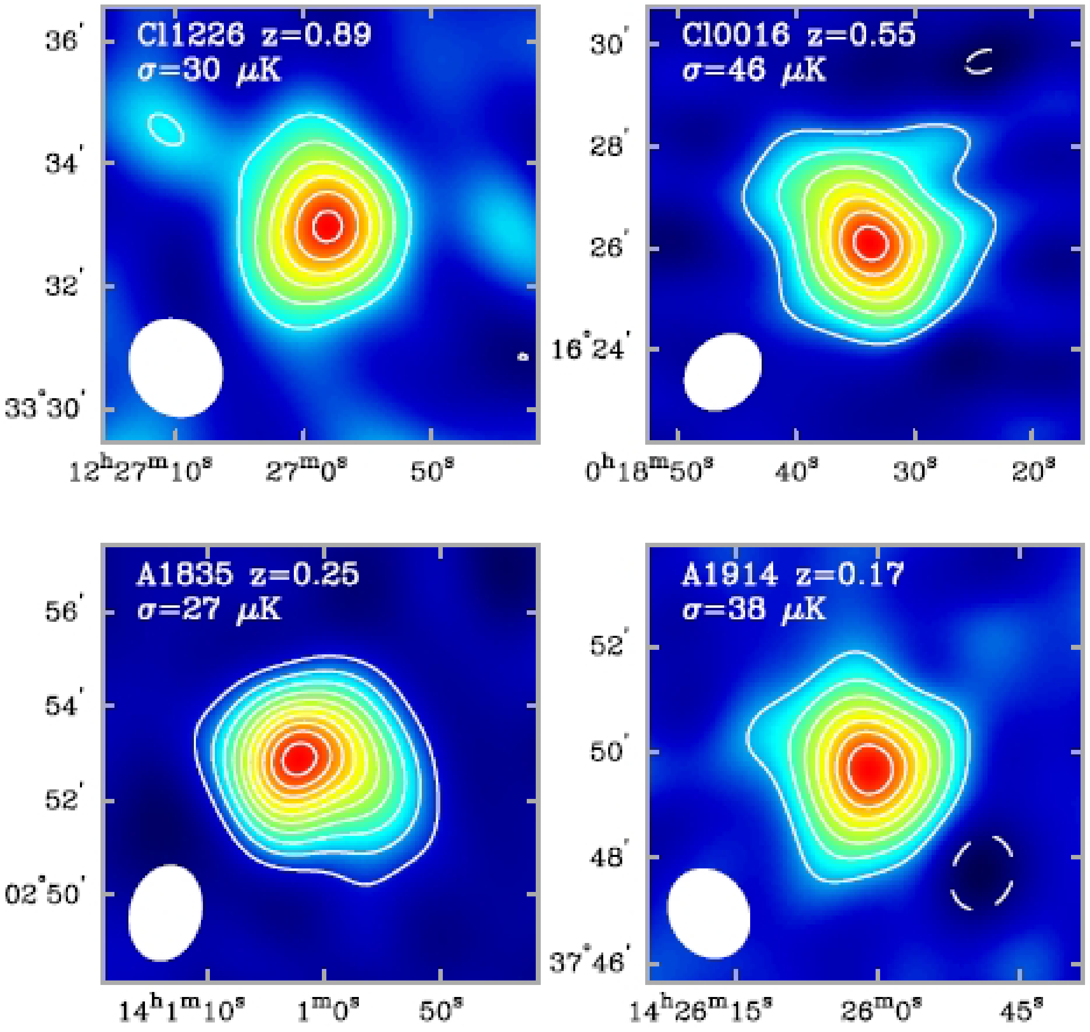


Figura 85: Efeito SZ observados em aglomerados a diferentes *redshifts*; para aglomerados com luminosidades em raios-X semelhantes, o sinal do efeito SZ é aproximadamente o mesmo. O níveis traçados em linhas contínuas correspondem a $\Delta T_{\rm CMB}/T_{\rm CMB} < 0$. A elipses nos cantos representam a largura da PSF (*point spread function*) a meia-altura (FWHM). Figura tirada de Reese (2003).

⇨ The Kinetic Sunyaev-Zel´dovich Effect

- A cluster’s **peculiar motion** with respect to CMBR produces **additional distortion**, due to the Doppler effect, known as the ***kinetic S-Z***
- it may be **positive** (if the cluster moves toward the us) or **negative** (if it runs away)
- for a isothermal plasma:

$$\Delta T_{CMBR} / T_{CMBR} = -\tau\, v_{pec} / c \qquad \text{(usually } \Delta T_K \sim 0.1\, \Delta T_T\text{)}$$

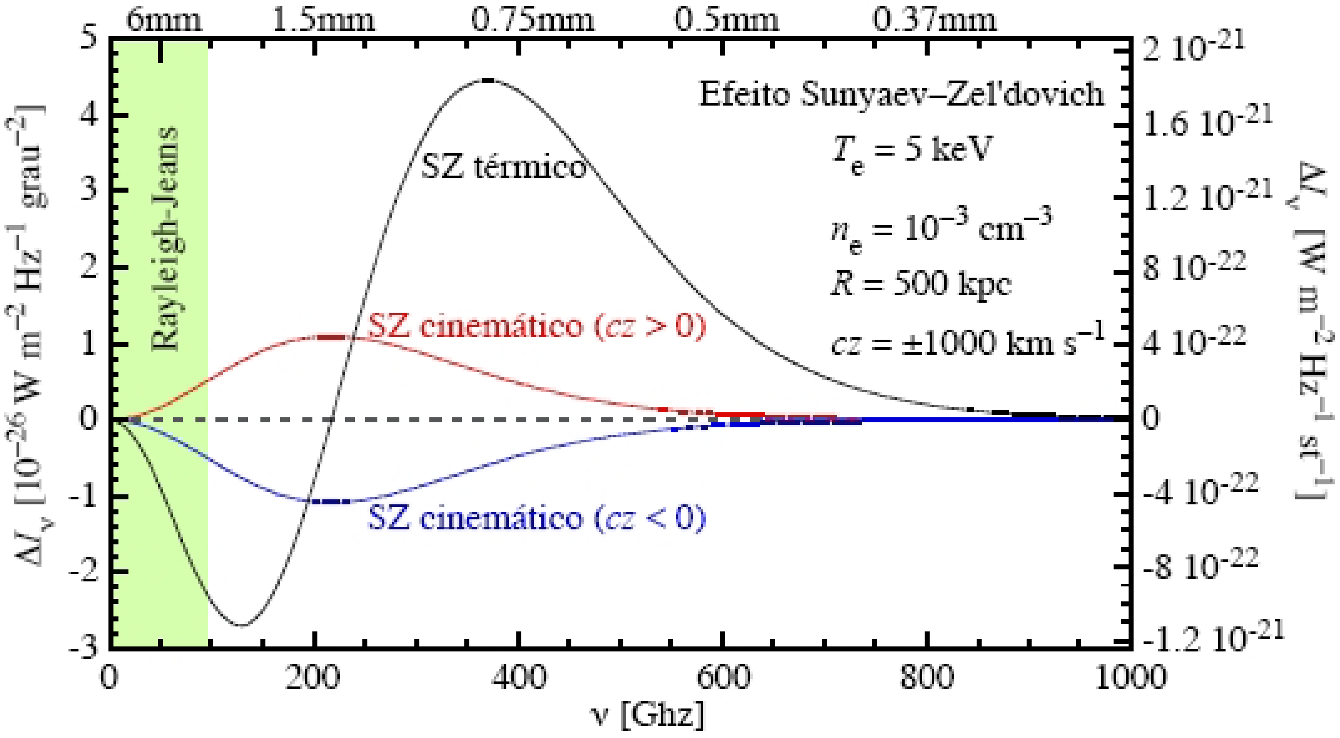
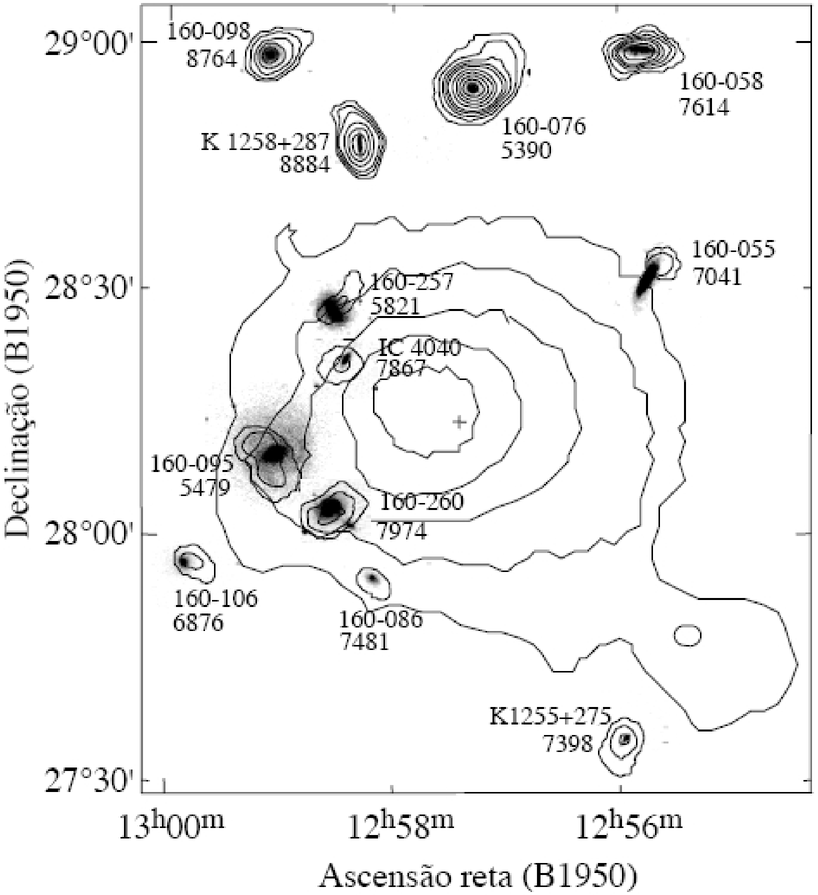


Figura 84: Variação da radiação cosmológica de fundo devido aos efeitos SZ térmico e cinético. Note que para $\nu = 215$ GHz o efeito SZ térmico é nulo enquanto que o efeito SZ cinético (em módulo) é máximo . Na parte Rayleigh-Jeans o efeito SZ térmico é sempre negativo.

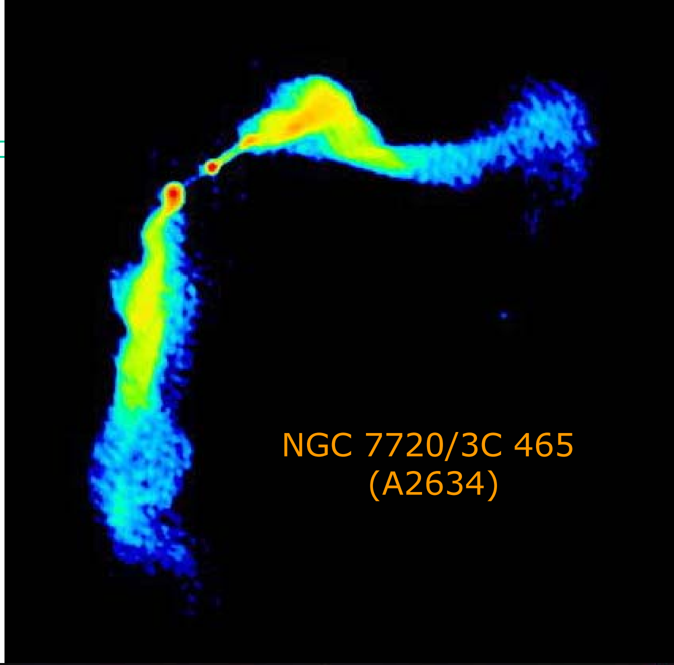
⇨ IC Ram Pressure

- ✓ The **motion of AGNs** with respect to the ICM produces **pressure over the relativistic particles** they emit
  – bending of jets and lobes (**head-tail radio galaxies**)

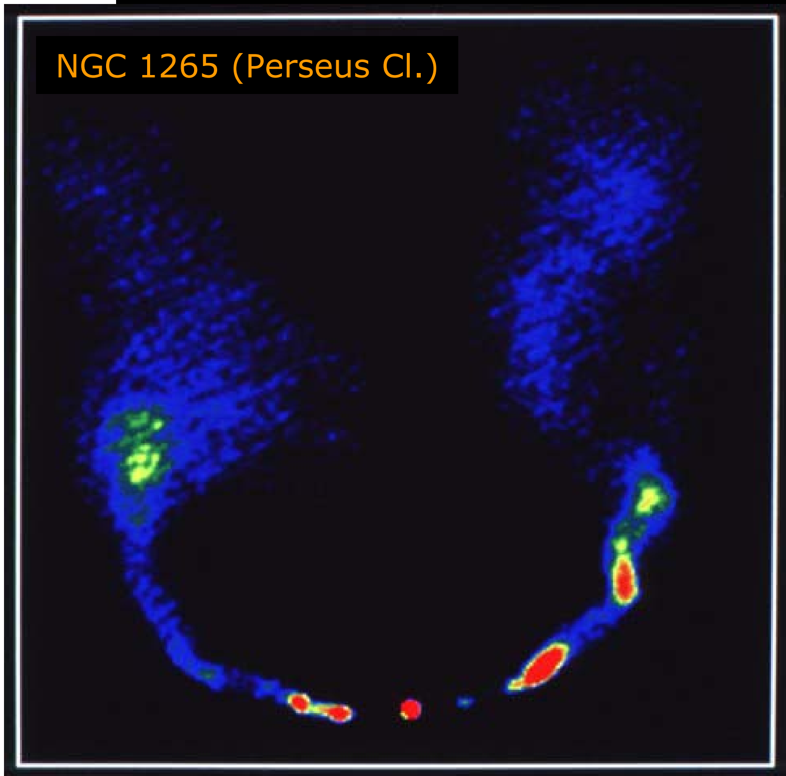
- ✓ **Pressure of the** hot **ICM over the** colder **HI** of spirals
  – loss of HI



[Bravo-Alfaro et al. 2000, AJ 119, 580]



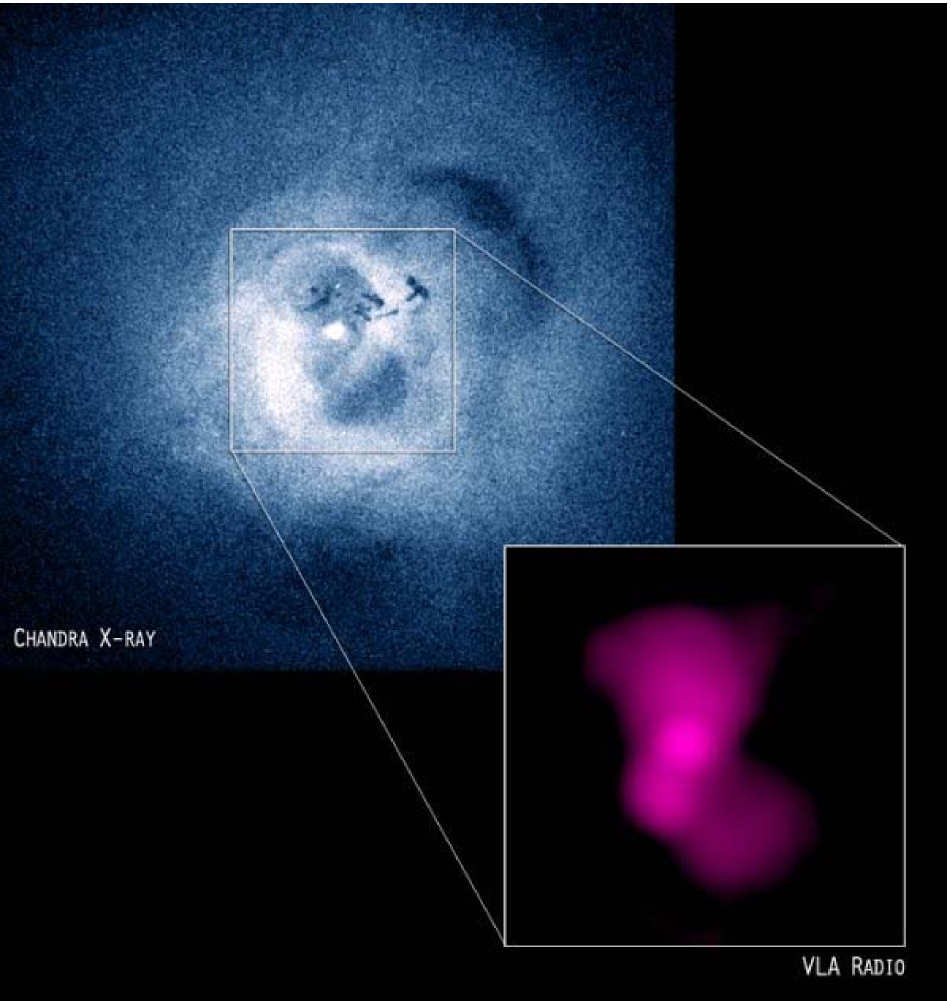
NGC 7720/3C 465
(A2634)



NGC 1265 (Perseus Cl.)

⇨ IC Magnetic Field

- ✓ A few clusters exhibit **diffuse radio emission**, probably associated to **synchrotron** radiation from relativistic e^-, emitted by an **AGN** or produced in merging **shocks**, and interacting with the **magnetic field** of the cluster



- ✓ one way to estimate the intensity of the magnetic field of a cluster is by observing the **polarization** in the radio emission due to the **Faraday rotation**

- ✓ the measurements indicate that the **ICM** have **magnetic fields** of about **1 μG**

⇨ Additional references

Papers:

- Sunyaev & Zeldovich 1980, ARAA 18, 537 (review on S-Z effect)
- Fabian 1994, ARAA 32, 277 (review of cooling flows)
- Birkinshaw 1999, Ph. Rep. 310, 97 (S-Z effect)
- Rosati et al. 2002, ARAA 40, 539 (review X-ray clusters)
- Voit, G.M. 2004, astro-ph/0410173 (Observable Properties of Clusters)
- Sehgal, Kosowsky & Holder 2005, ApJ 635, 22