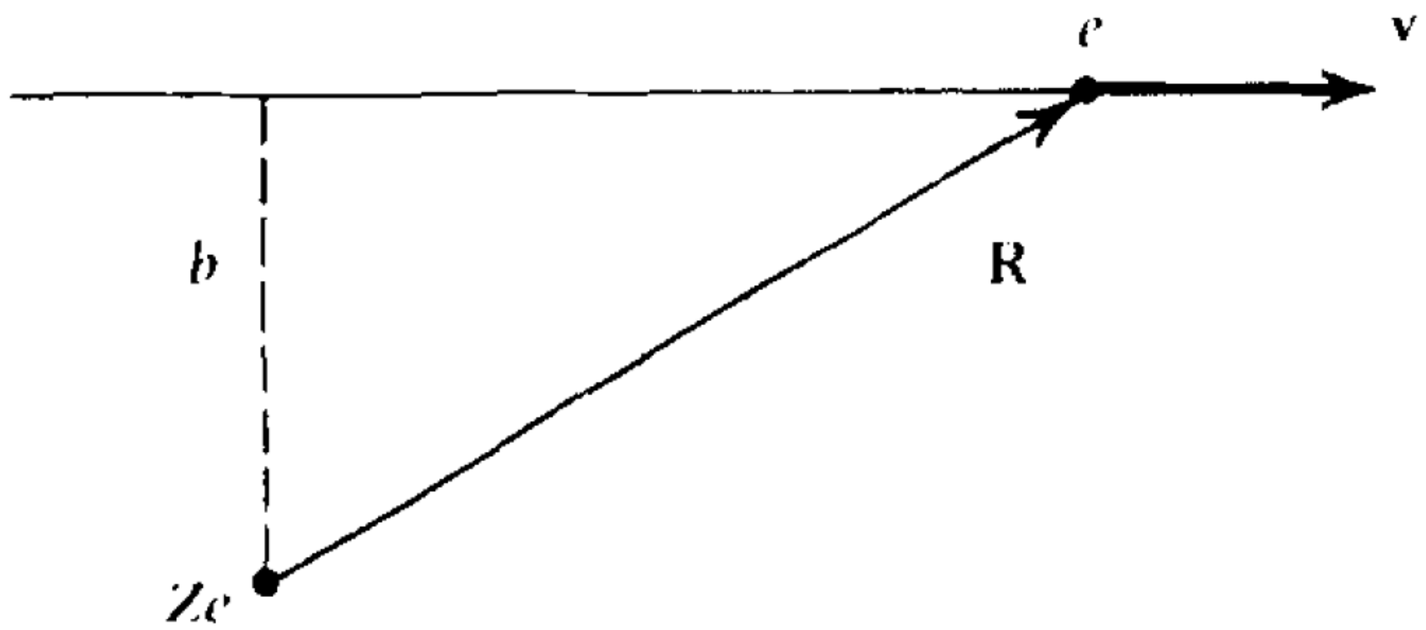


Figure 5.1   An electron of charge e moving past an ion of charge Ze.

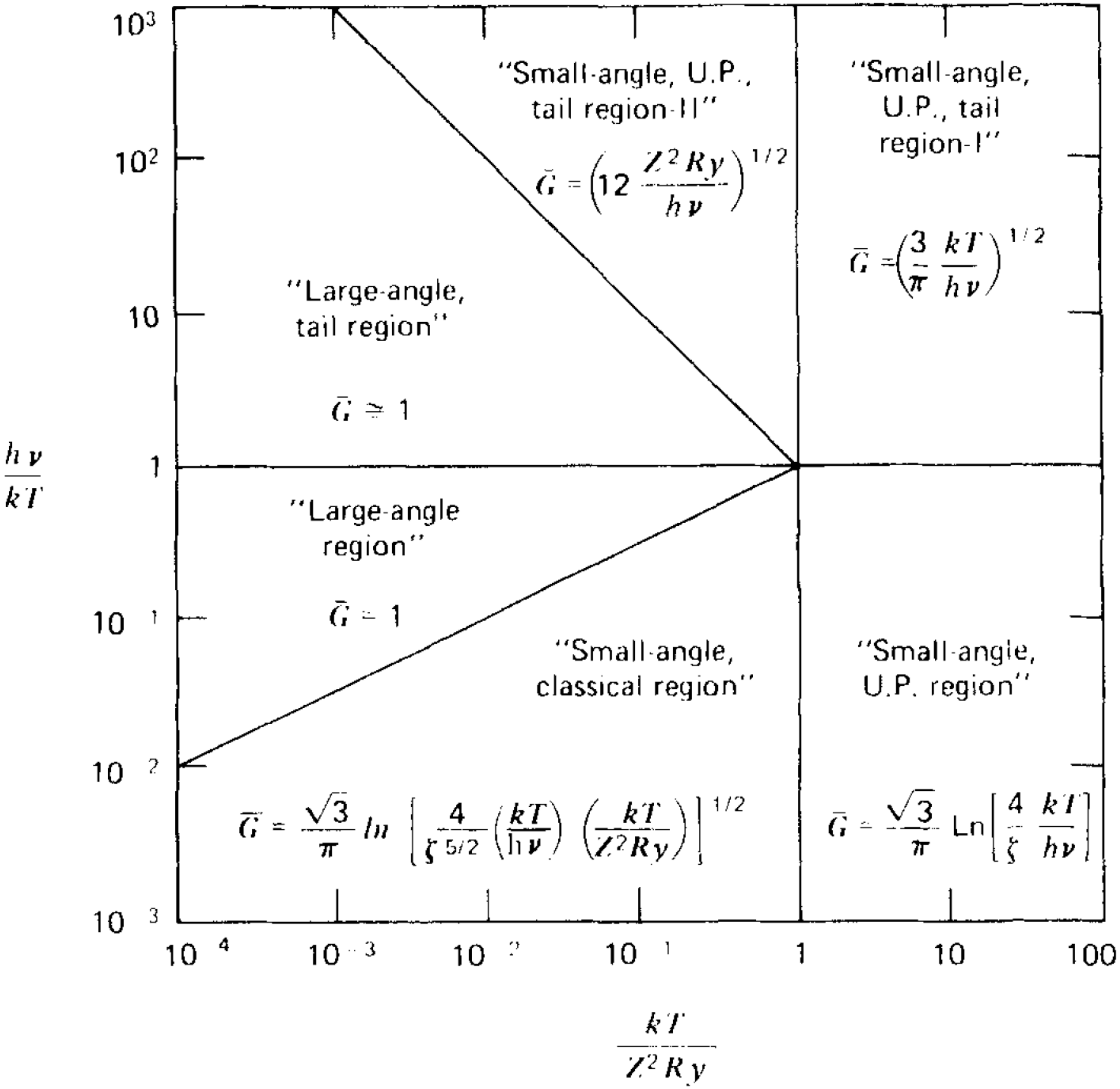


***Figure 5.2** Approximate analytic formulae for the gaunt factor $\bar{g}_{ff}(\nu, T)$ for thermal bremsstrahlung. Here $\bar{g}_{ff}$ is denoted by $\bar{G}$ and the energy unit $Ry = 13.6$ eV. (Taken from Novikov, I. D. and Thorne, K. S. 1973 in Black Holes, Les Houches, Eds. C. DeWitt and B. DeWitt, Gordon and Breach, New York.)*

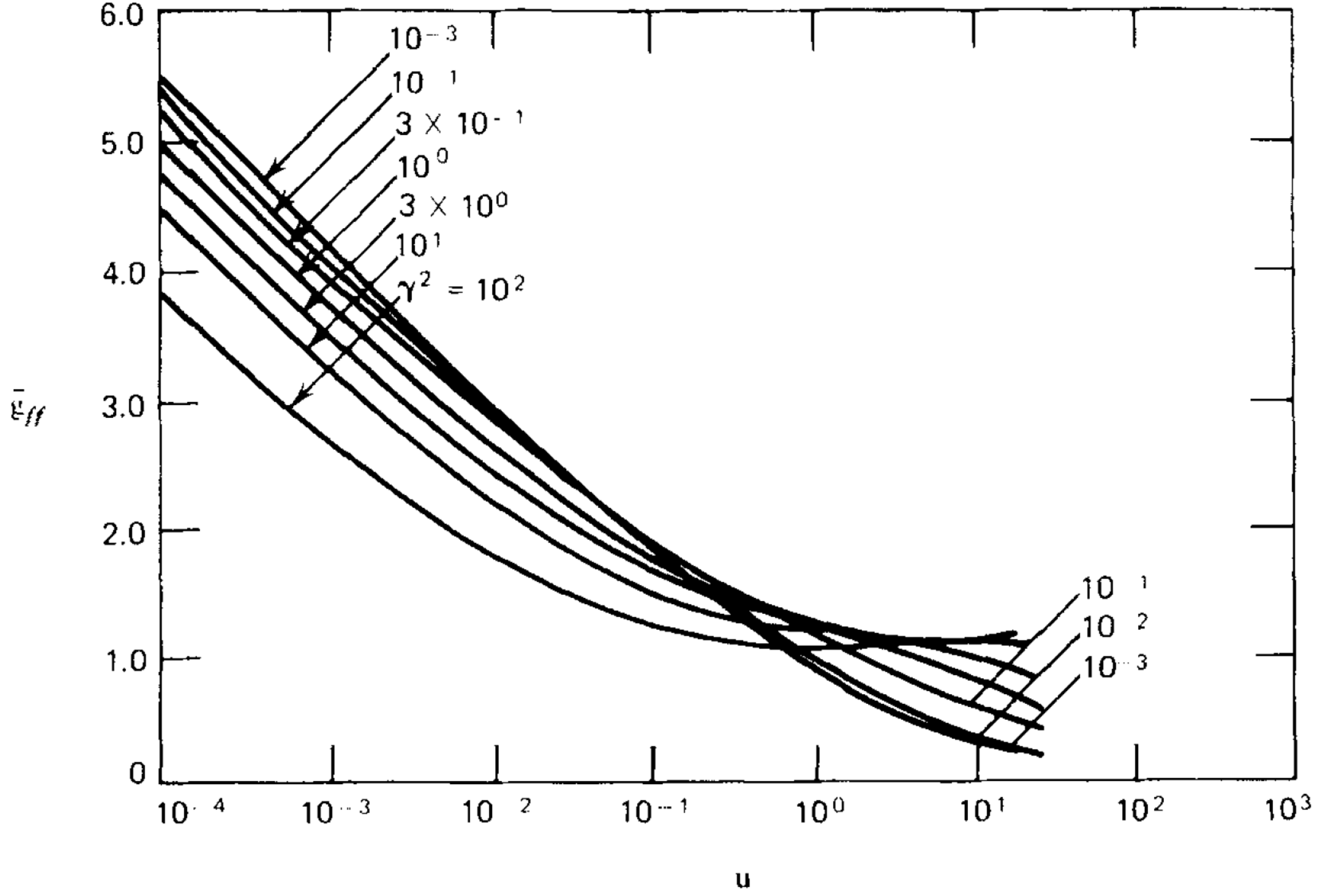
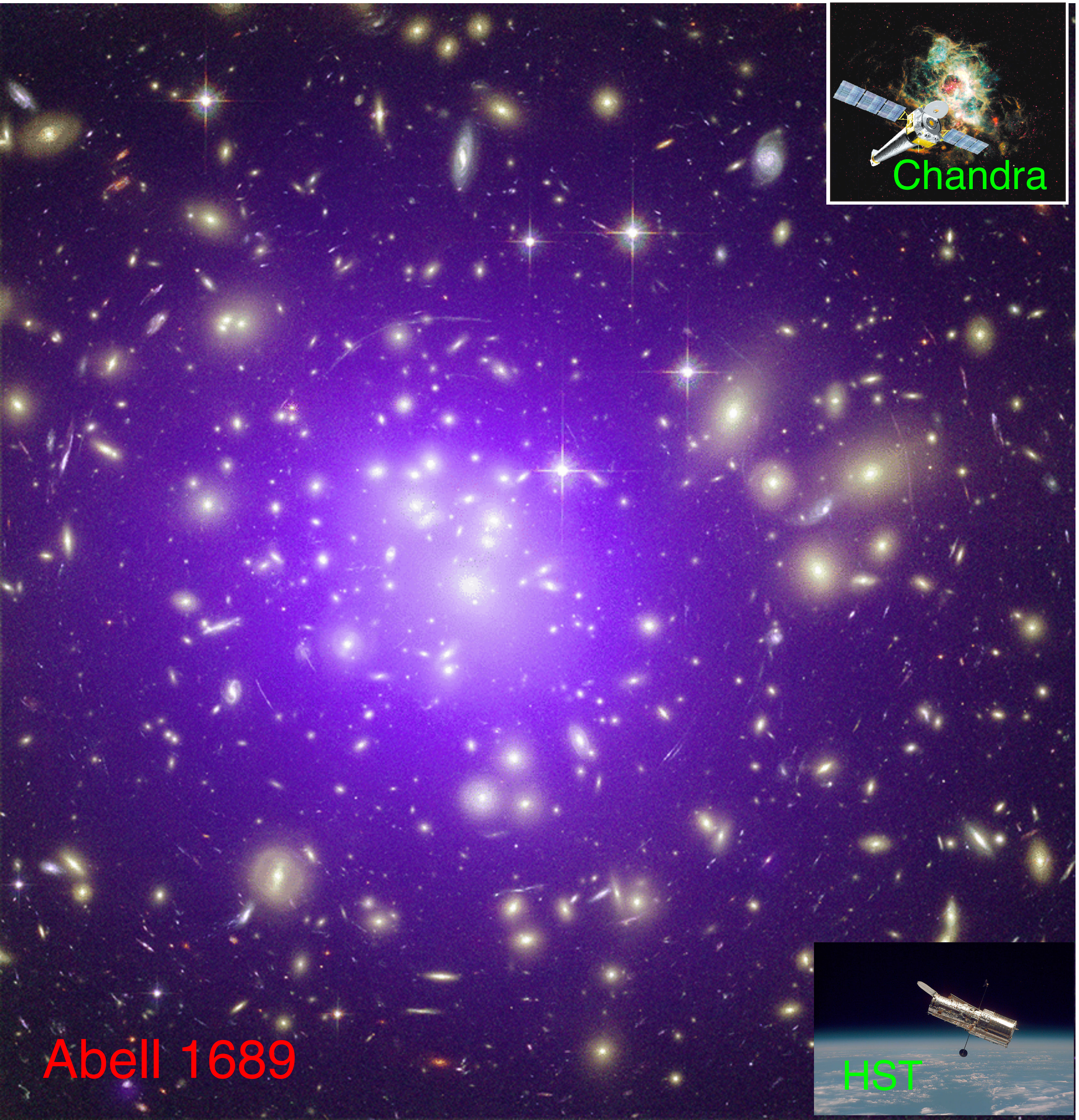


Figure 5.3 *Numerical values of the gaunt factor $\bar{g}_{ff}(\nu, T)$. Here the frequency variable is $u = 4.8 \times 10^{11} \nu / T$ and the temperature variable is $\gamma^2 = 1.58 \times 10^5 Z^2 / T$. (Taken from Karzas, W. and Latter, R. 1961, Astrophys. J. Suppl., 6, 167.)*

It’s a cluster of galaxies……



Concentrations of ~10^3 galaxies

σ_v~500-1000 km s^{-1}

Size: ~1-2 Mpc

Mass: ~10^{14}-10^{15} $M_\odot$

→ $\lambda_i \approx 10$ Mpc

Baryon content:

→ cosmic share in hydrostatic equilibrium

ICM temperature:

→ T ~ 2-10 keV

→ fully ionized plasma;

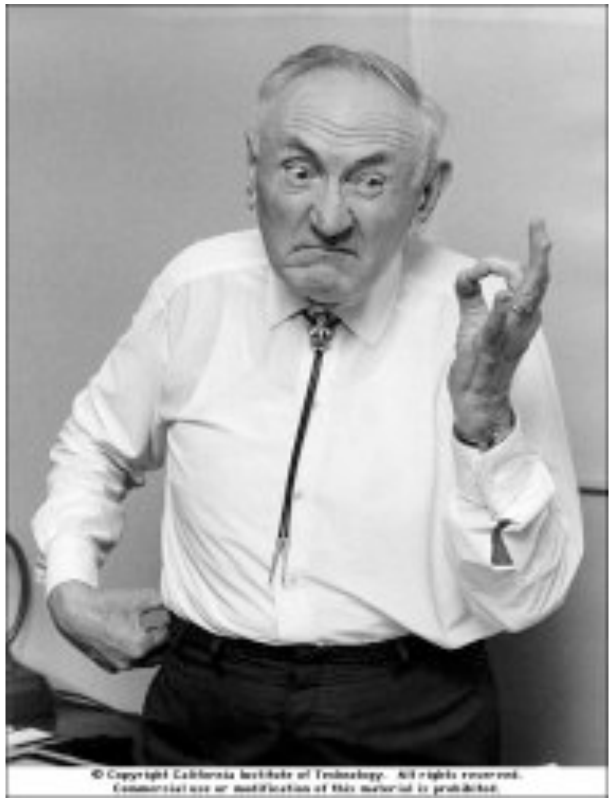
Thermal bremsstrahlung

→ n_e~10^{-2}-10^{-4} cm^{-3}

→ L_X~10^{45} erg s^{-1}

Cluster cosmology “ante litteram” (Zwicky 1933)

The Coma Cluster

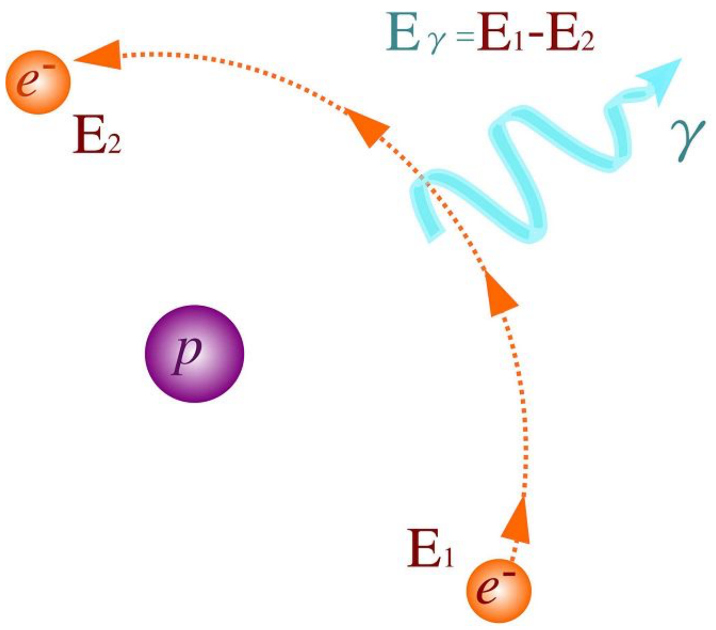


➔ Galaxies moving with a l.o.s. velocity of ~10^3 km/s

➔ Virial theorem: ~100 times more mass than in galaxies’ stars required to keep the system gravitationally bound

➔ Need to have “*dunkle Materie*”

X-ray emission by free-free



Total emission per unit time, unit frequncy range and unit volume, for electrons with single velocity:

$$\epsilon_\omega^{ff} = \frac{n_e\, n_i\, Z^2\, e^6}{12\sqrt{3}\,\pi^3 \varepsilon_0^3\, c^3 m^2\, \dot{r}} \boxed{g_{ff}(\dot{r}, \omega)} \longrightarrow \text{Gaunt factor}$$

Integrate over a thermal population of electrons with:

$$p(\dot{r}) \propto \exp(-m\dot{r}^2/(2kT))$$

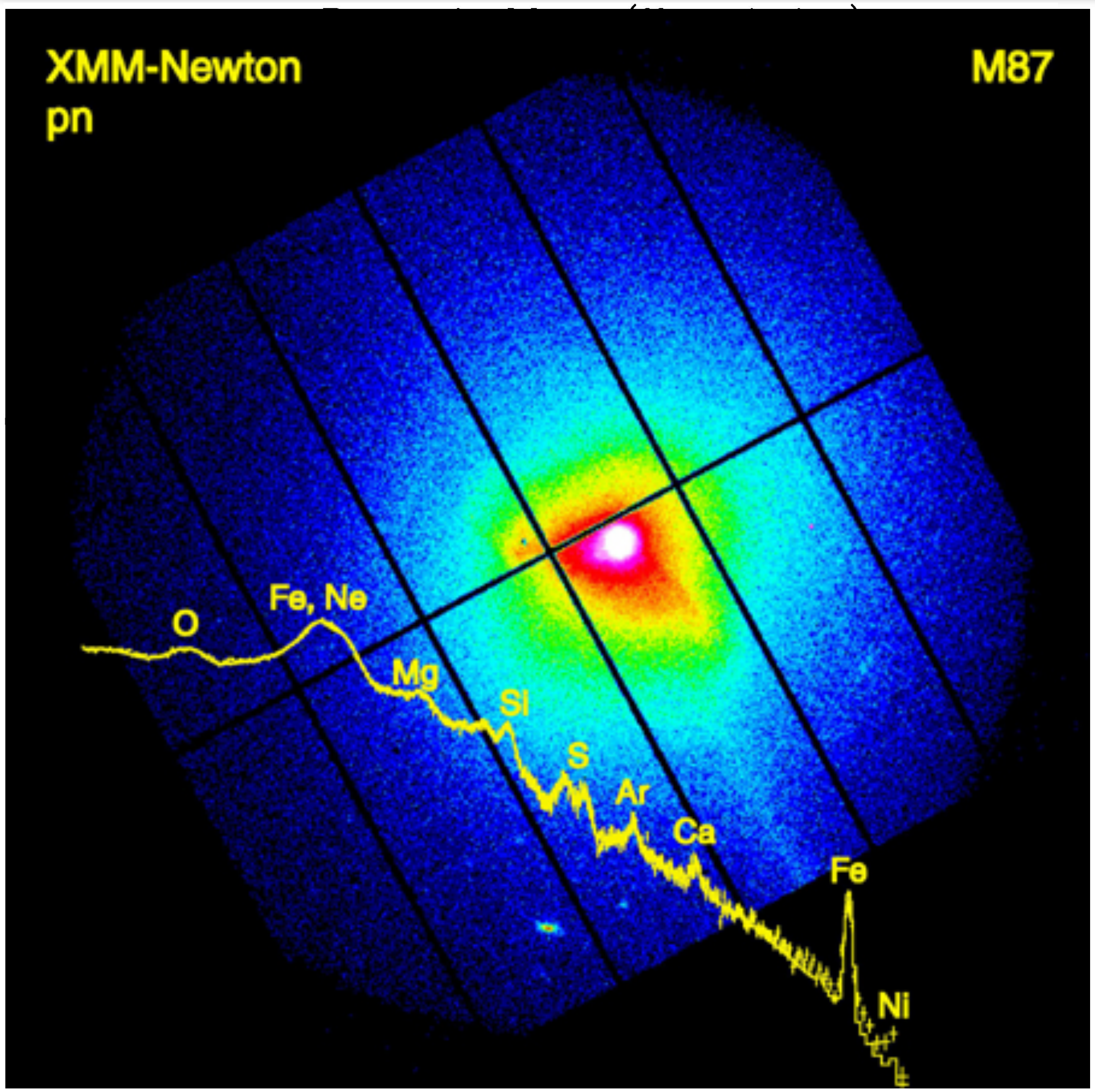
→

$$\boxed{\epsilon_\nu^{ff} = A\, T^{-1/2}\, Z^2\, n_e\, n_i\, \exp[-h\nu/(kT)]\, \bar{g}_{ff}(\nu)}$$

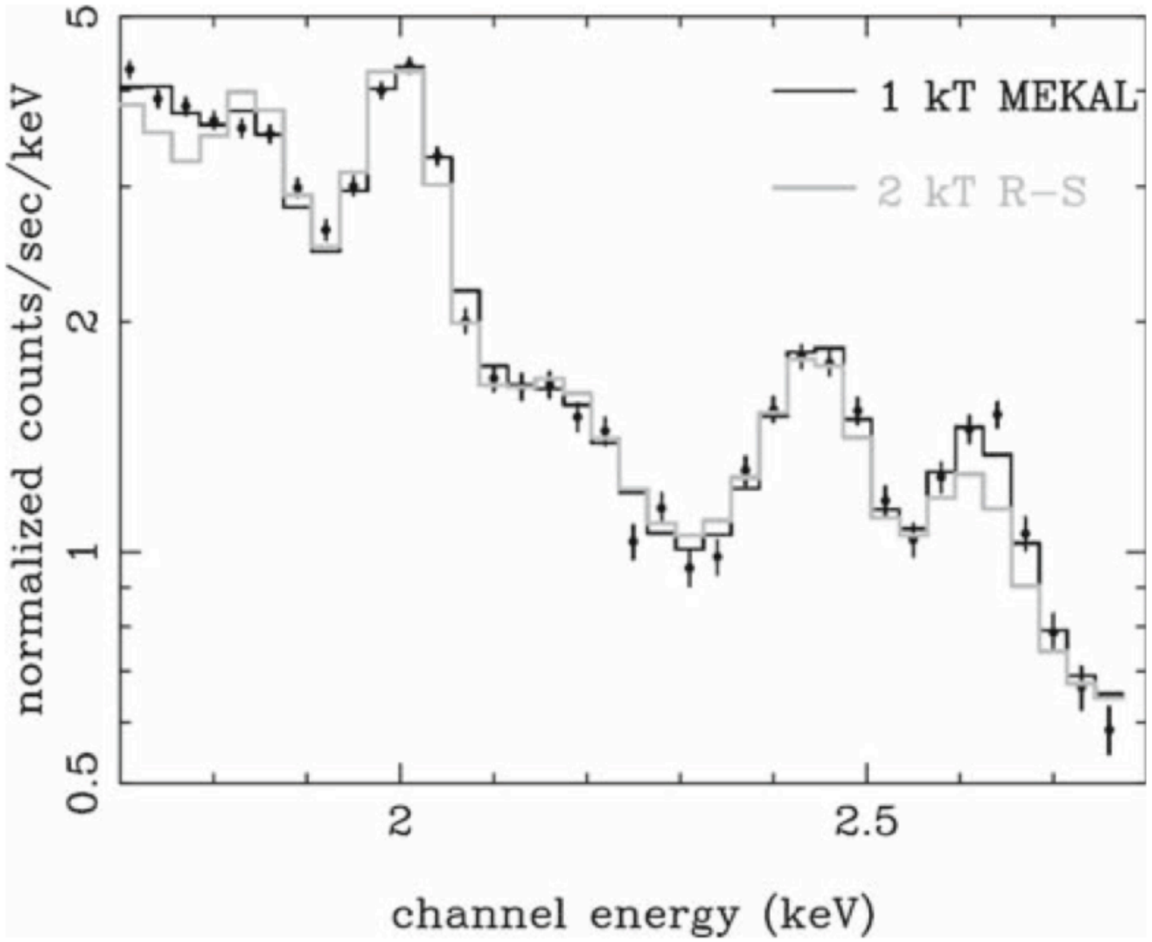
Integrate over frequency to obtain the total emissivity:

$$\epsilon^{ff} = 1.4 \times 10^{-28} T^{1/2}\, Z^2\, n_e\, n_i\, \bar{g}_B \quad W\, m^{-3}$$

X-ray emission by free-free



- ➔ Spectrum amplitude: sensitive to gas density squared
- ➔ Position of the cut-off: measure of the plasma temperature



- ➔ Crucial to understand the response of the instruments
- ➔ Calibration is fundamental!

Hydrostatic mass estimator

- Hydrostatic equilibrium: balance between gravitational and pressure forces

$$\nabla P_{gas} = -\rho_{gas} \nabla \Phi \qquad \Phi(r) = -\frac{GM}{r}$$: gravitational potential

- For a spherically symmetric system:

$$\frac{dP}{dr} = -\rho_{gas} \frac{d\Phi}{dr} = -\rho_{gas} \frac{GM(r)}{r^2} \rightarrow \boxed{M(r) = -\frac{r k_B T}{\mu m_p G}\left(\frac{d\ln \rho_{gas}}{d\ln r} + \frac{d\ln T}{d\ln r}\right)}$$

→ Analogous to Jeans' equation BUT with β=0

→ Obtain gas density and temperature profiles from X-ray spectra

OR

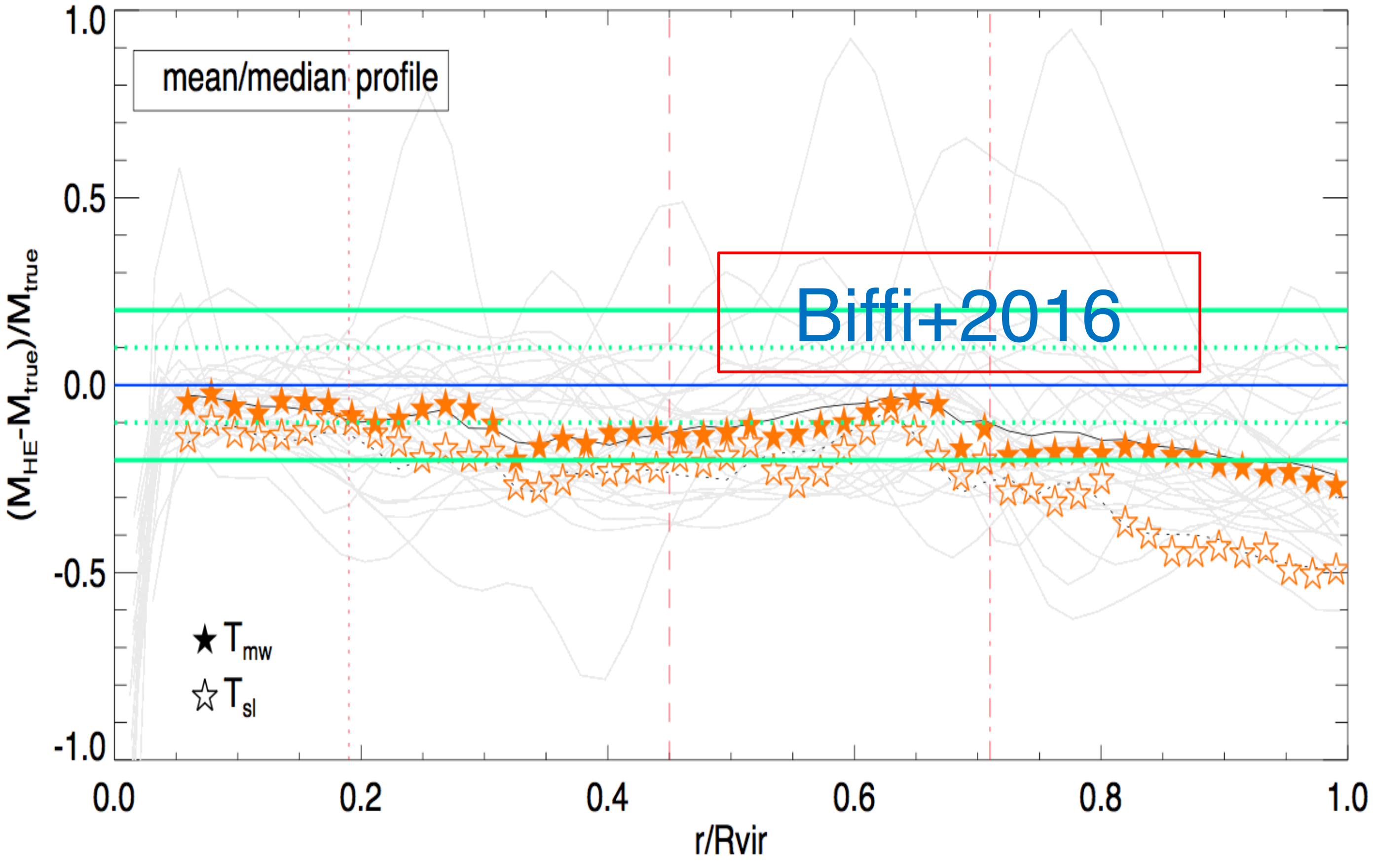
→ Pressure profiles from high-res thermal SZ observations

Masses from hydrostatic equilibrium

➔ Cosmological simulations to test the accuracy of hydrostatic equilibrium in clusters

(e.g. Rasia+06,12, Nagai+07, Morandi+07, Piffaretti & Valdarnini 08, Meneghetti+09, Lau+09,13, Kay+11, Suto+13, Biffi+16, …)

$$\boxed{\nabla P_{gas} = -\rho_{gas} \nabla \Phi}$$



General consensus: 10-20% underestimate of true masses from HE, depending on the cluster dynamical status

Origins of the bias:

1. Non-thermal motions generating a non-thermal pressure support
2. Acceleration term in the Euler equation

z=19.00

Masses from hydrostatic equilibrium

$$M(r) = -\frac{r k_B T}{\mu m_p G}\left(\frac{d\ln \rho_{gas}}{d\ln r} + \frac{d\ln T}{d\ln r}\right)$$

➔ Correct hydrostatic estimator by including terms due to gas motions as in the Jeans equation:

$$M_{\rm tot}(<r) = M_{\rm th} + M_{\rm rand} + M_{\rm rot}$$

➔ Thermal pressure support:

$$M_{\rm th}(<r) = \frac{-r^2}{G\rho_{\rm gas}}\frac{dP_{\rm th}}{dr}$$

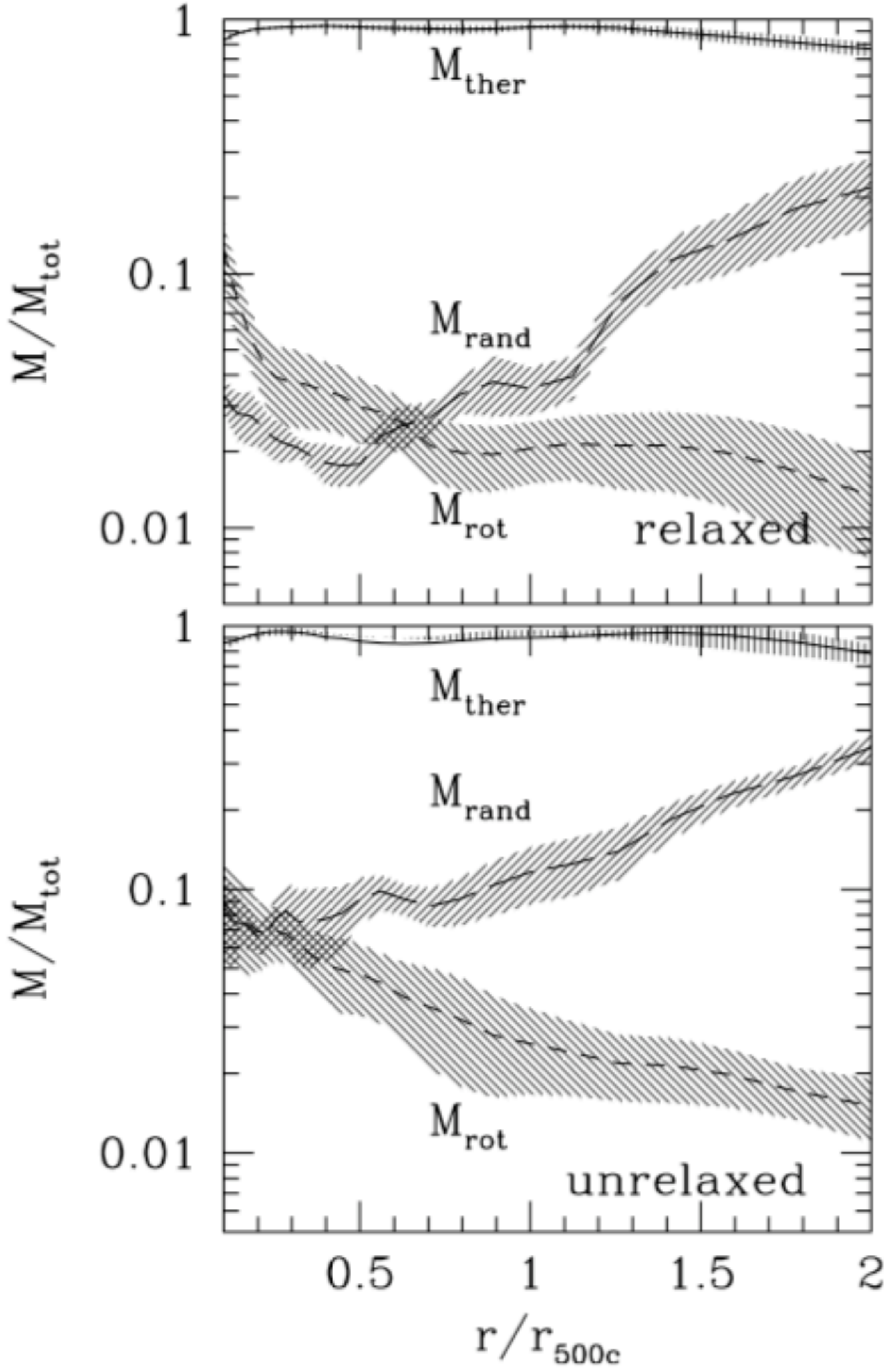
➔ Random gas motions:

$$M_{\rm rand}(<r) = \frac{-r^2}{G\rho_{\rm gas}}\left(\frac{\partial\left(\rho_{\rm gas}\sigma_r^2\right)}{\partial r}\right) - \frac{r}{G}\left(2\sigma_r^2 - \sigma_t^2\right)$$

Increasing at larger radii and for non-relaxed systems

➔ Gas rotation: $M_{\rm rot}(<r) = \frac{r\bar{v}_t^2}{G}$

Lau+2009



X-ray temperature bias

Q: What's the temperature measured from an X-ray spectrum for a plasma which is not single temperature? (Mazzotta+2004; Vikhlinin 2006)

➔ In realistic conditions, single-T model still a good fit to a multi-T model

What do we measure in simulations?

Mass-weighted temperature:

$$T_{\mathrm{mw}} \equiv \frac{\int mT\,\mathrm{d}V}{\int m\,\mathrm{d}V}$$

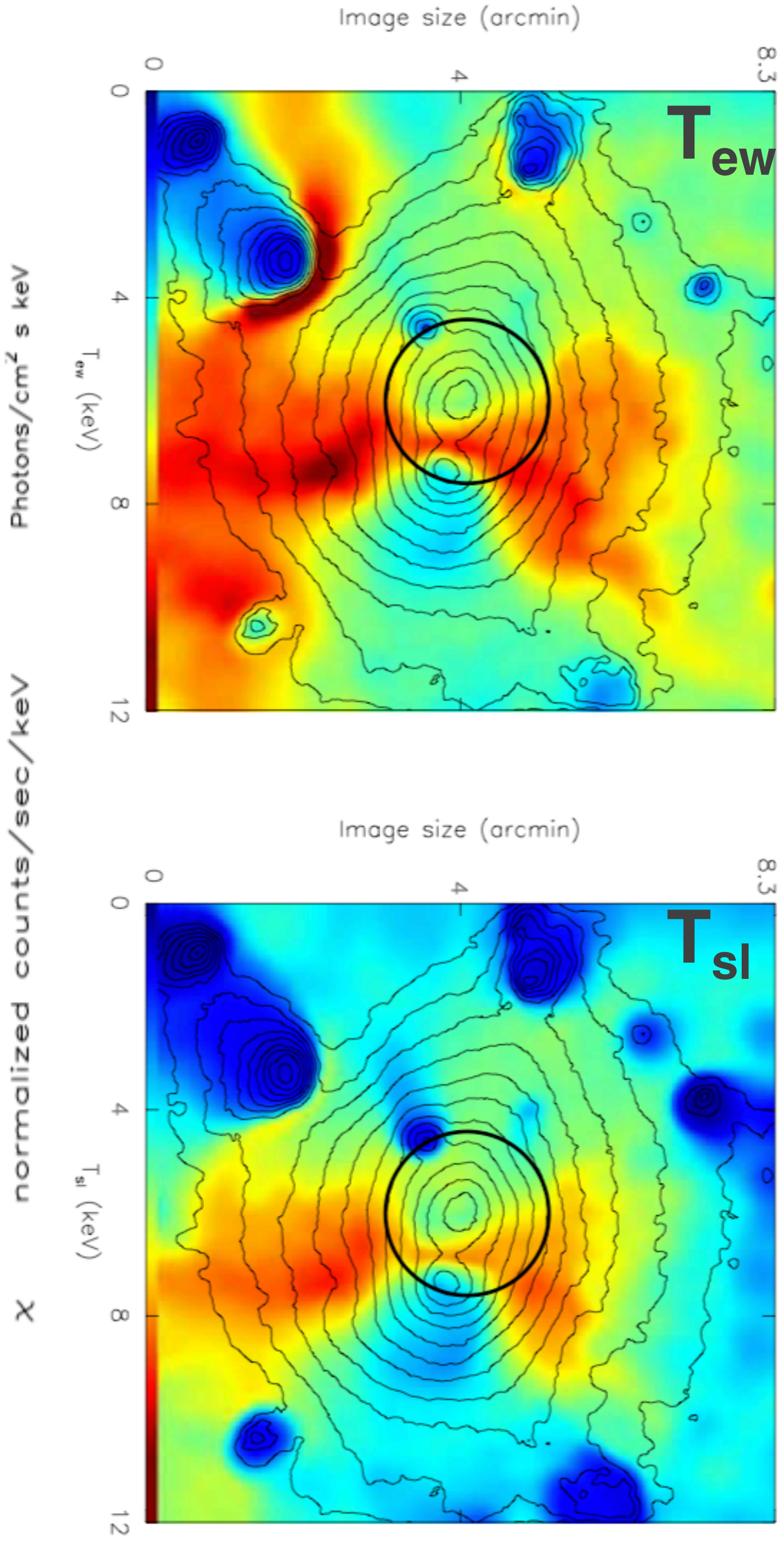
Emission-weighted temperature:

$$T_{\mathrm{ew}} \equiv \frac{\int \Lambda(T) n^2 T\,\mathrm{d}V}{\int \Lambda(T) n^2\,\mathrm{d}V}$$

Spectroscopic-like temperature:

$$T_{\mathrm{sl}} = \frac{\int W T\,\mathrm{d}V}{\int W\,\mathrm{d}V} \qquad W = \frac{n^2}{T^{3/4}}$$

➔ Proxy of the temperature from spectral fitting, accounting for thermal complexity of the ICM

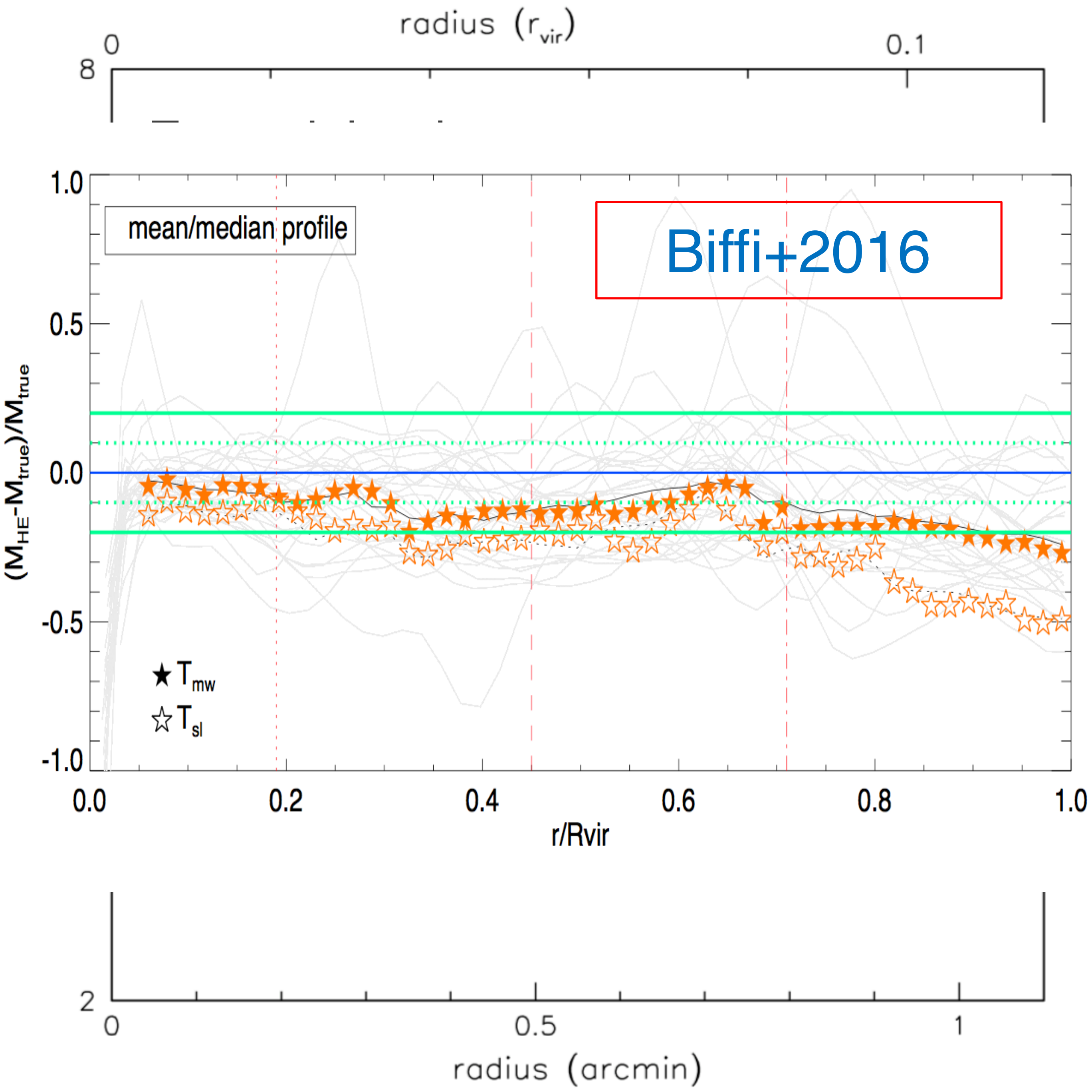


X-ray temperature bias

- T_{sl} is a close proxy to the temperature obtained from spectral fitting, *<u>in a Chandra- or XMM-like setup</u>*
- Sizeble difference between T_{ew} and T_{sl}
- T_{sl} lower due to larger weight of cooler regions

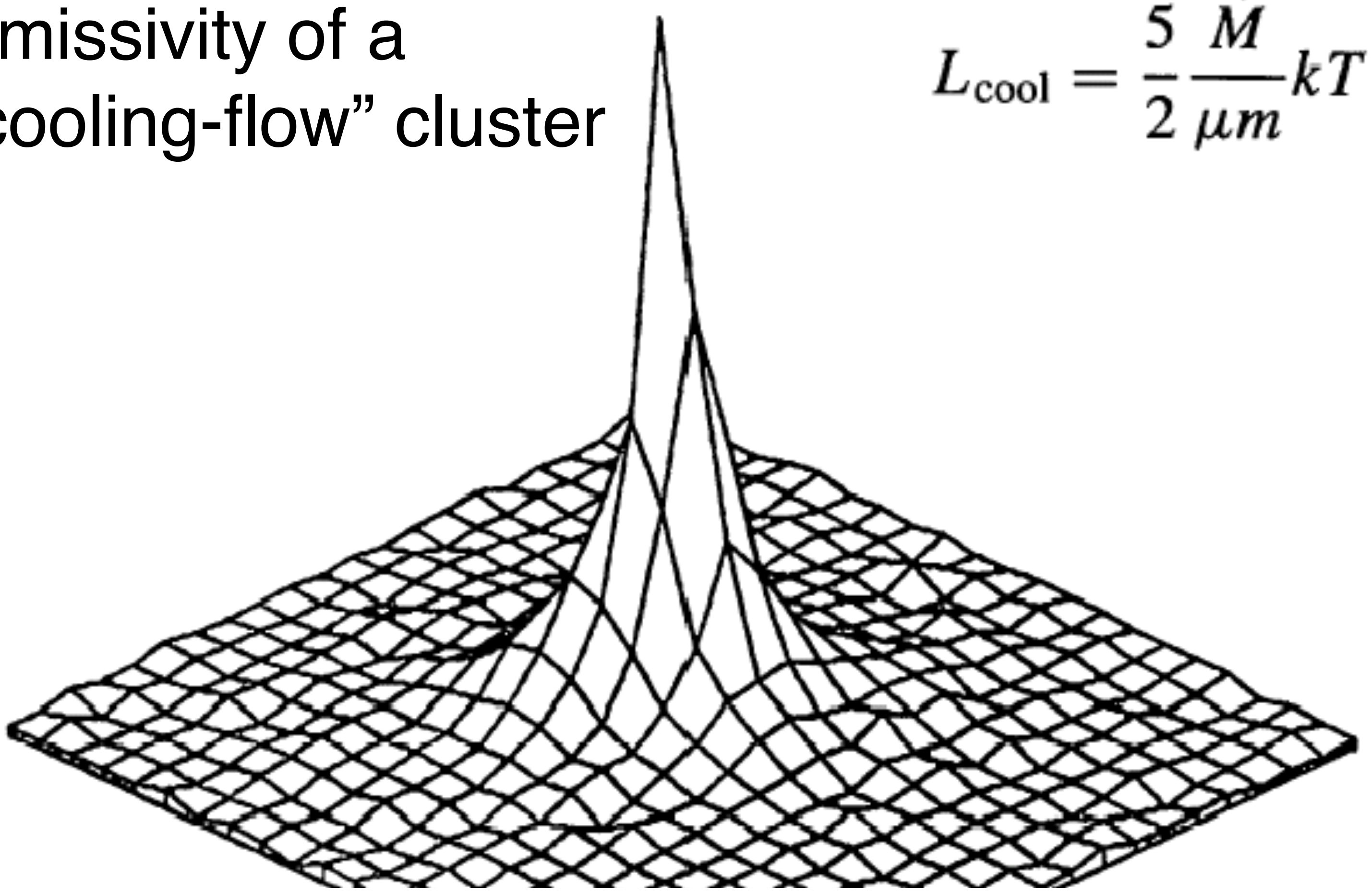
- Small but sizeable mass-bias that adds to the HE bias
- Effect dependent on the thermal complexity of the ICM

→ Not trivial to calibrate with simulations

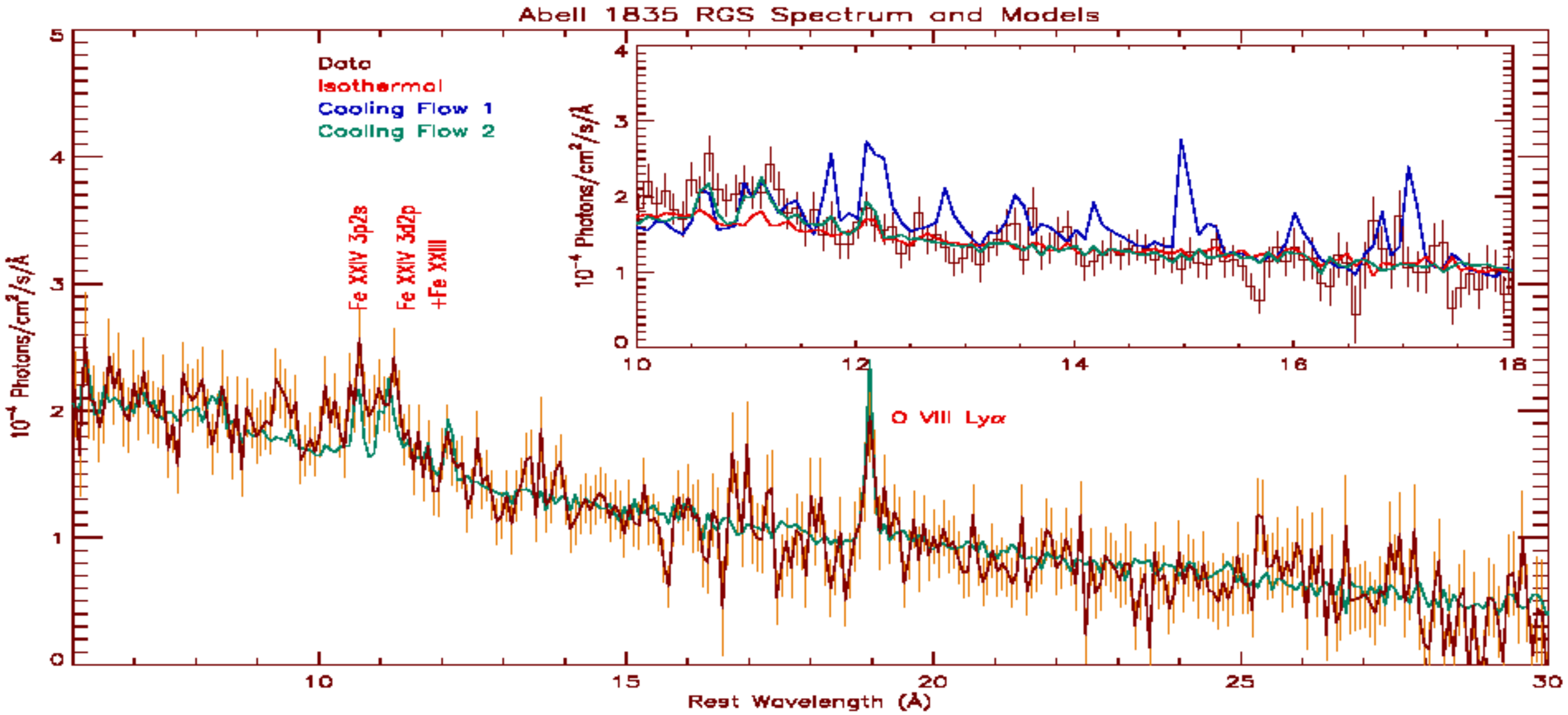


Cool cores in galaxy clusters

Emissivity of a
“cooling-flow” cluster



$$L_{\mathrm{cool}} = \frac{5}{2}\frac{\dot{M}}{\mu m}kT$$



Pre-XMM: High Mass-Deposition Rates: few 10^2 $M_\odot$ /yr

Spectroscopic MDR: few 10 $M_\odot$ /yr

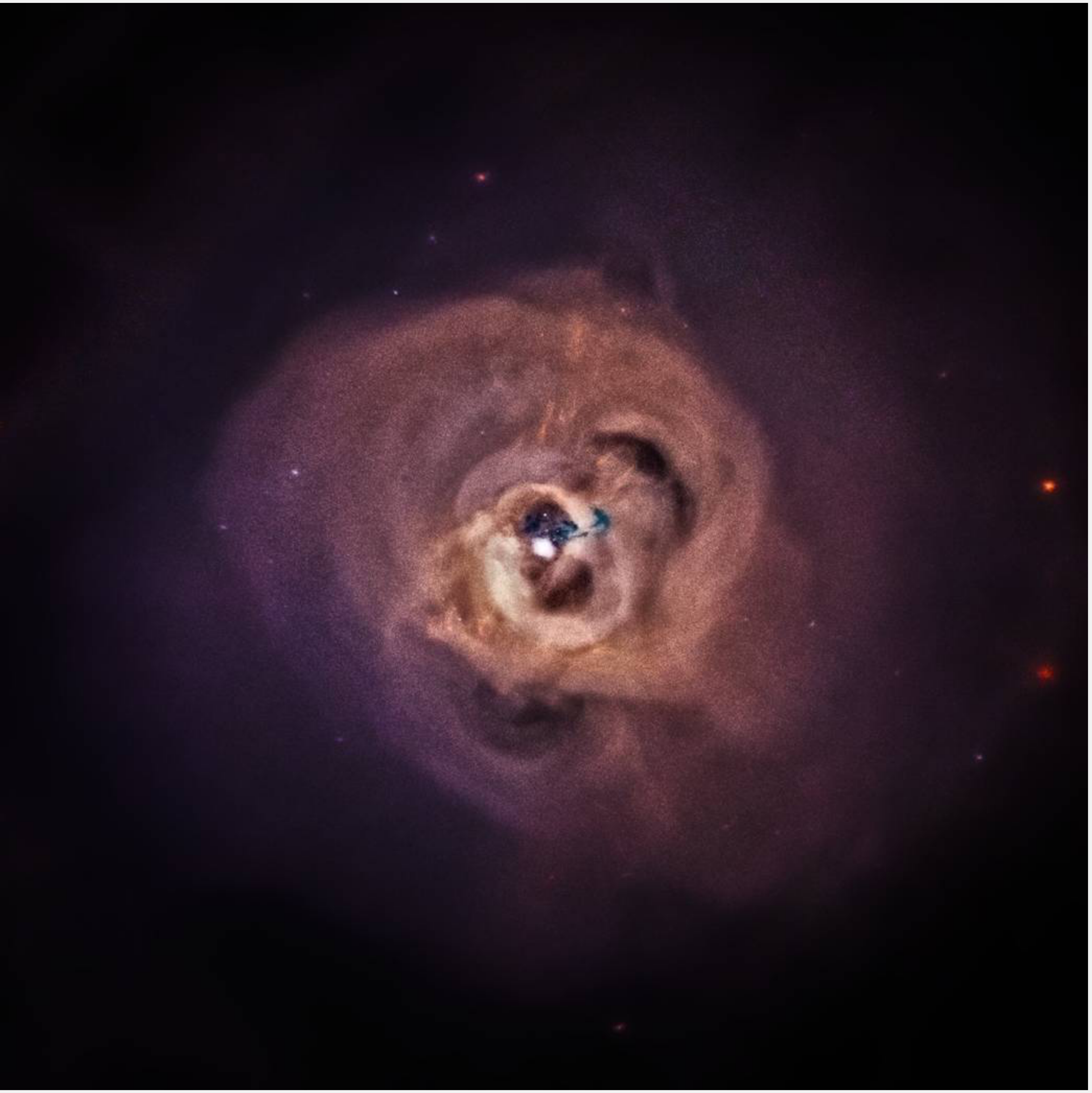
➔ No gas detected with $T < (0.3\text{-}0.5)\ T_{\mathrm{vir}}$

How to prevent this gas from cooling?

E.g.:

Peterson et al. ‘01
Boehringer et al. ‘02
XMM-Newton spectra

Interaction between galactic activity and ICM



Evidences for heated bubbles

Perseus cluster:

➔ 1.5 Msec Chandra ACIS-S3 exposure (Fabian+2011)

➔ Bubbles and ripples: signatures of AGN feedback