DARK MATTER

ASTR 333/433
SPRING 2024
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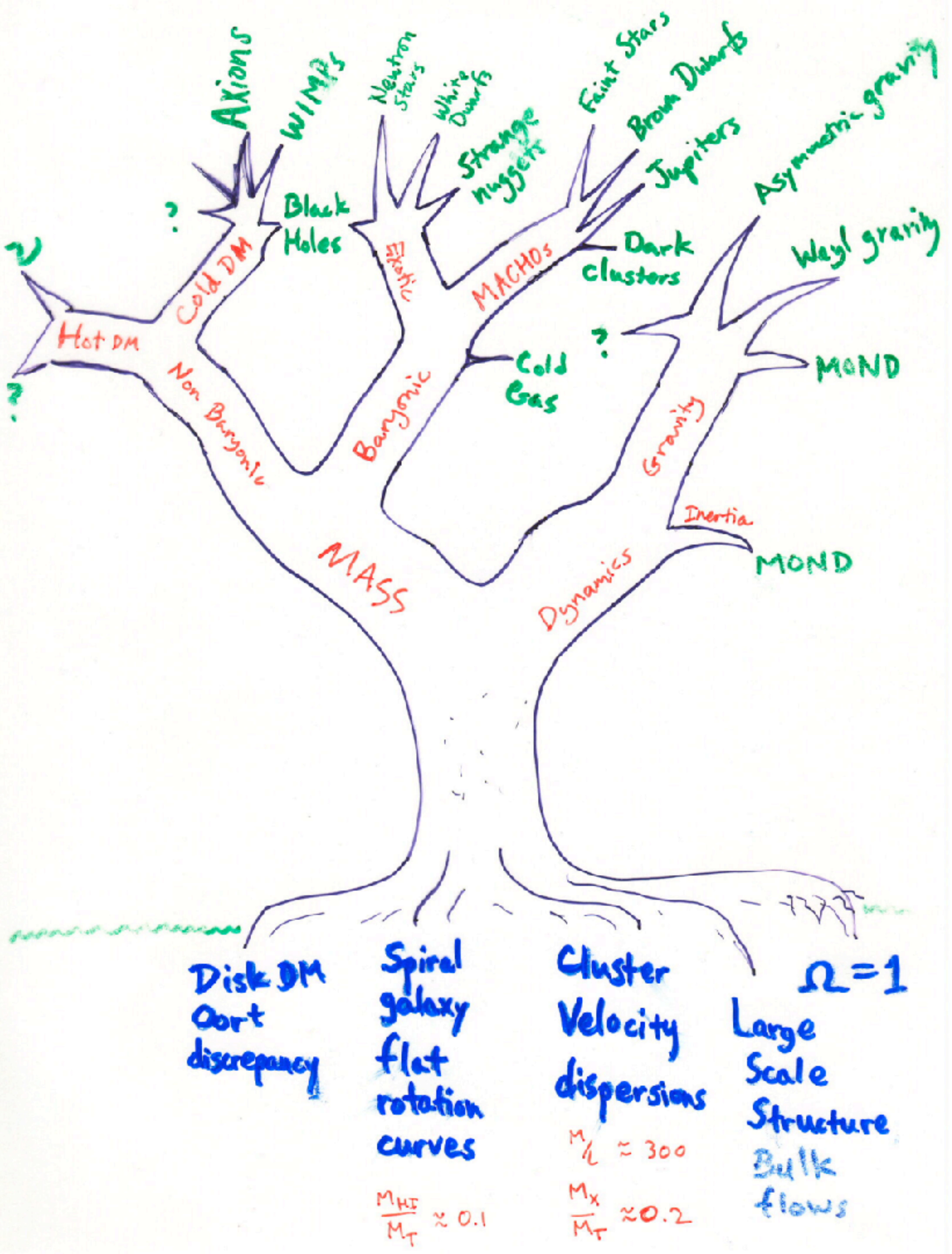


JWST First Release image

Gravitational lensing in Cluster SMACS 0723

Four distinct measures:

velocity dispersion, hydrostatic equilibrium of X-ray gas, the Sunyaev-Zel’dovich effect, and gravitational lensing

Mass estimators for Clusters of Galaxies

Four distinct measures:

velocity dispersion, hydrostatic equilibrium of X-ray gas, the Sunyaev-Zel'dovich effect, and gravitational lensing

- Virial mass estimator $M = \frac{2.5}{G}\sigma^2 R_e$

- Hydrostatic equilibrium (X-ray)

$$\frac{GM}{r} = -\frac{kT}{\mu m_p}\left(\frac{\partial \ln \rho}{\partial \ln r} + \frac{\partial \ln T}{\partial \ln r}\right)$$

- S-Z effect $M \propto D_A^2 \frac{\int \Delta T d\Omega}{\langle T \rangle}$

- gravitational lensing

$$\alpha_d = \frac{4GM}{c^2 b} \longrightarrow M(<\theta_I) = (1.1 \times 10^{14}\ \mathrm{M}_\odot)\left(\frac{\theta_I}{30''}\right)^2 \left(\frac{D_L}{D_S}\right)\left(\frac{D_{LS}}{1\ \mathrm{Gpc}}\right)$$

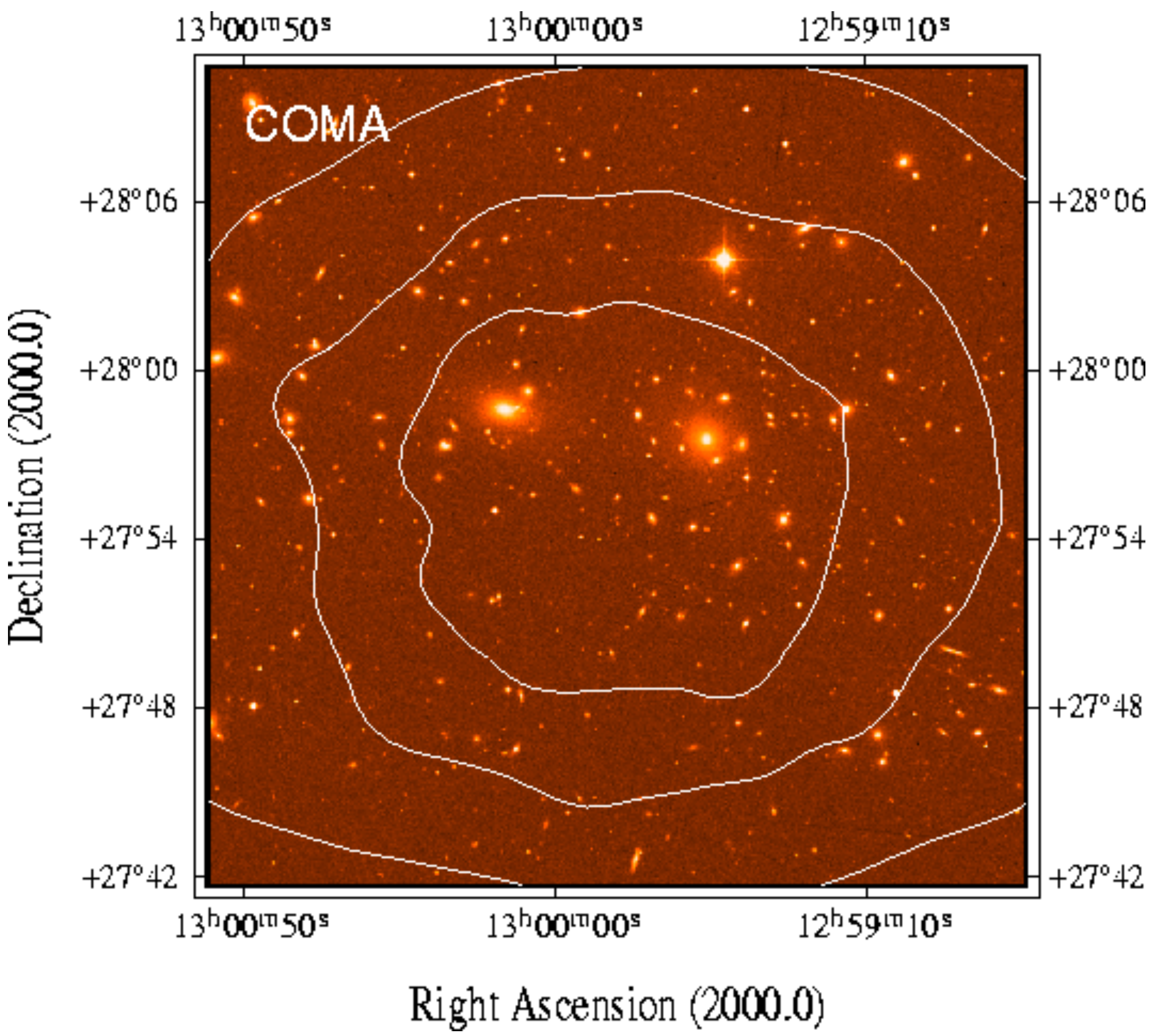
Clusters in optical and X-ray (contours)

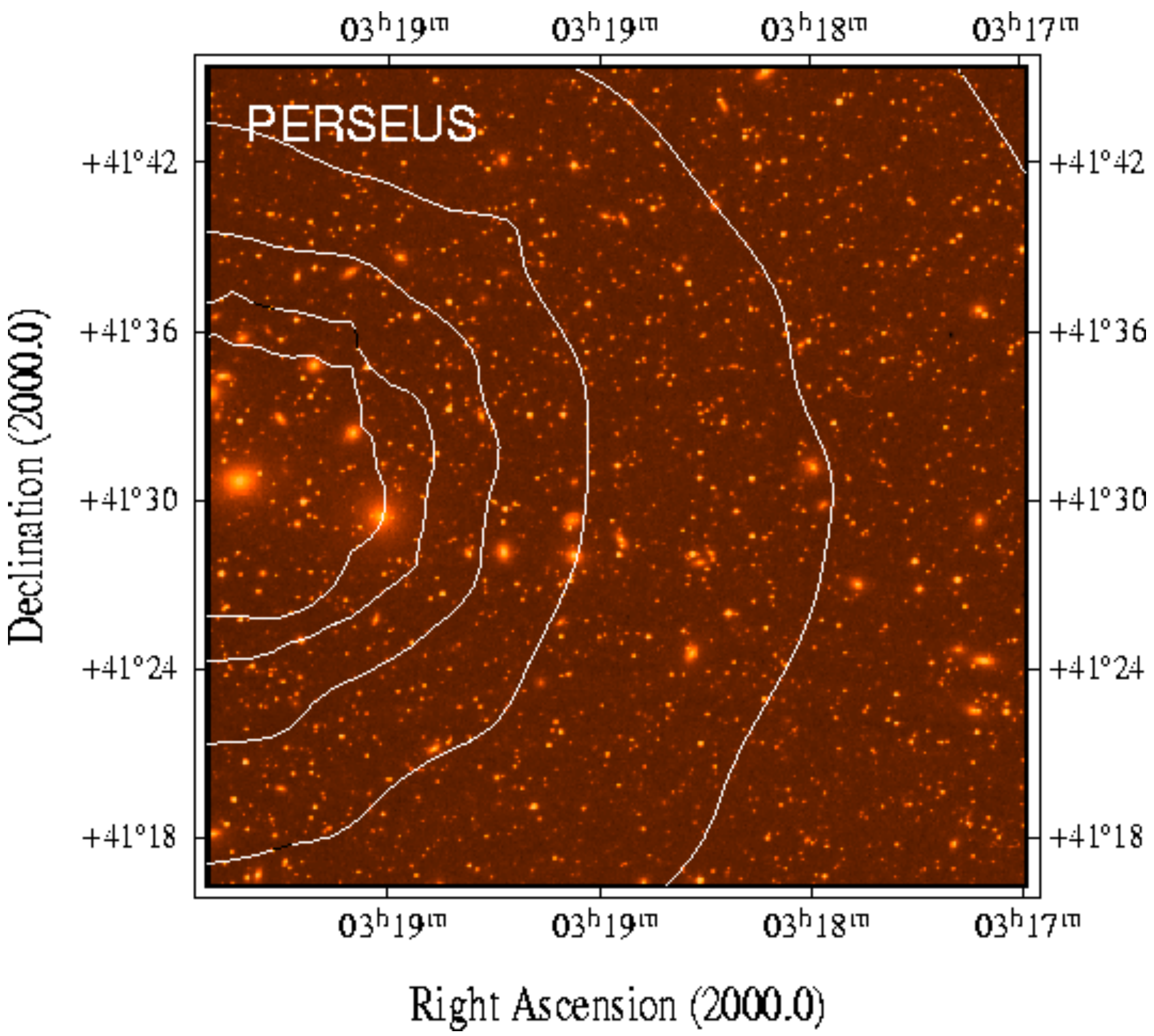
Typically two types of X-ray sources

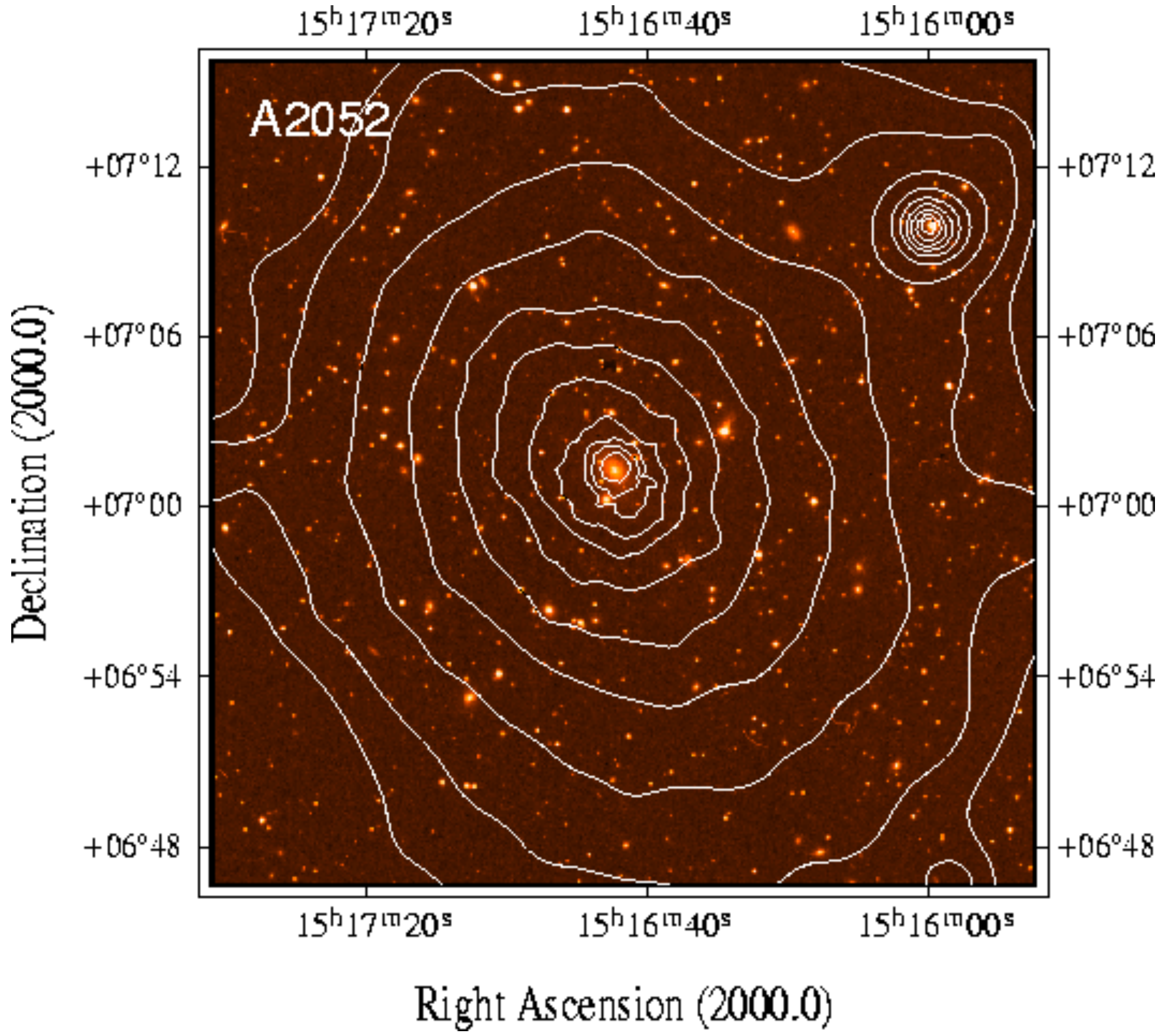
Bremsstrahlung from hot ICM
(large scale, diffuse emission)

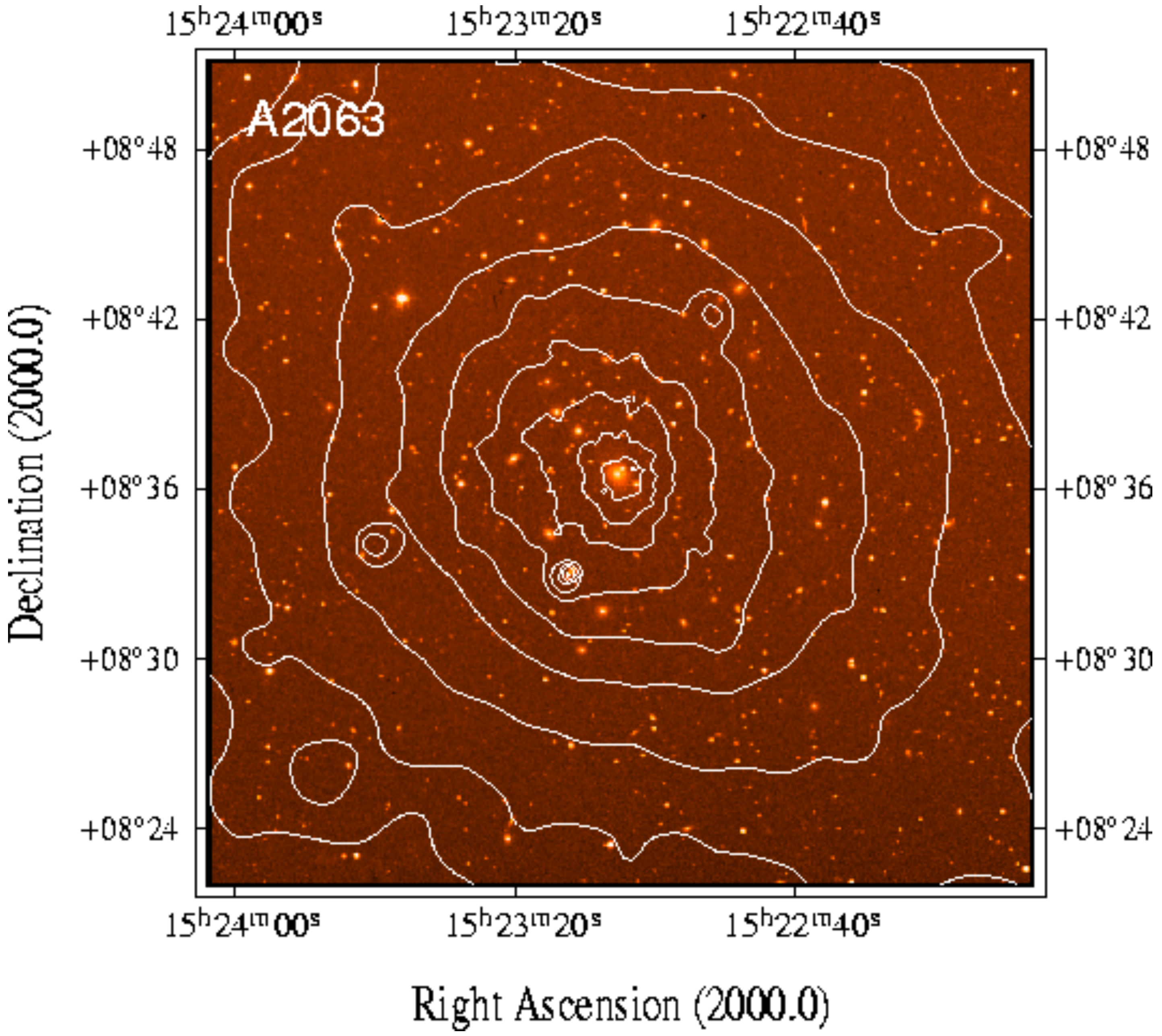
AGN and other point sources
(point sources)

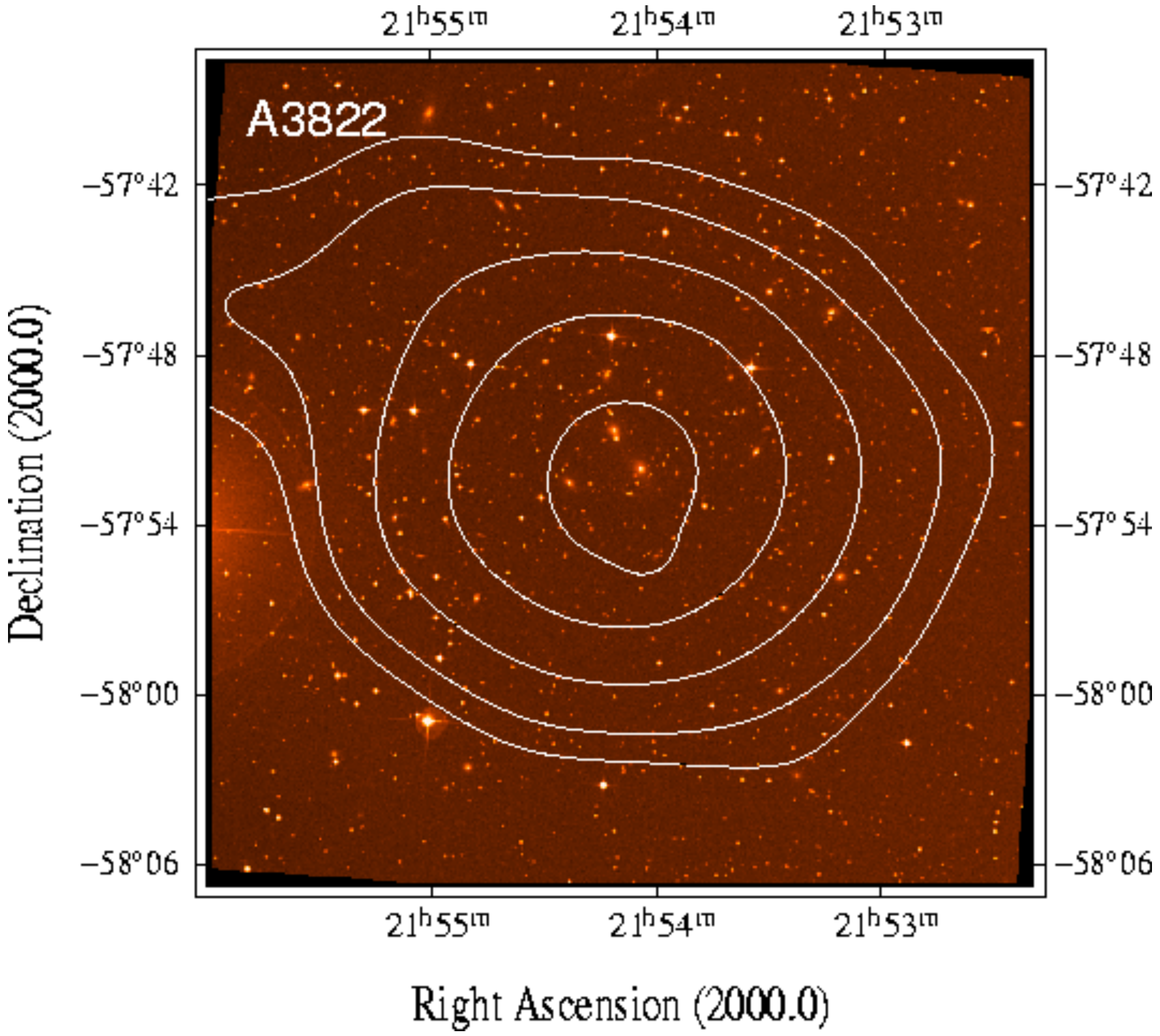
Reiprich ApJ, 567, 716-740 (2002)









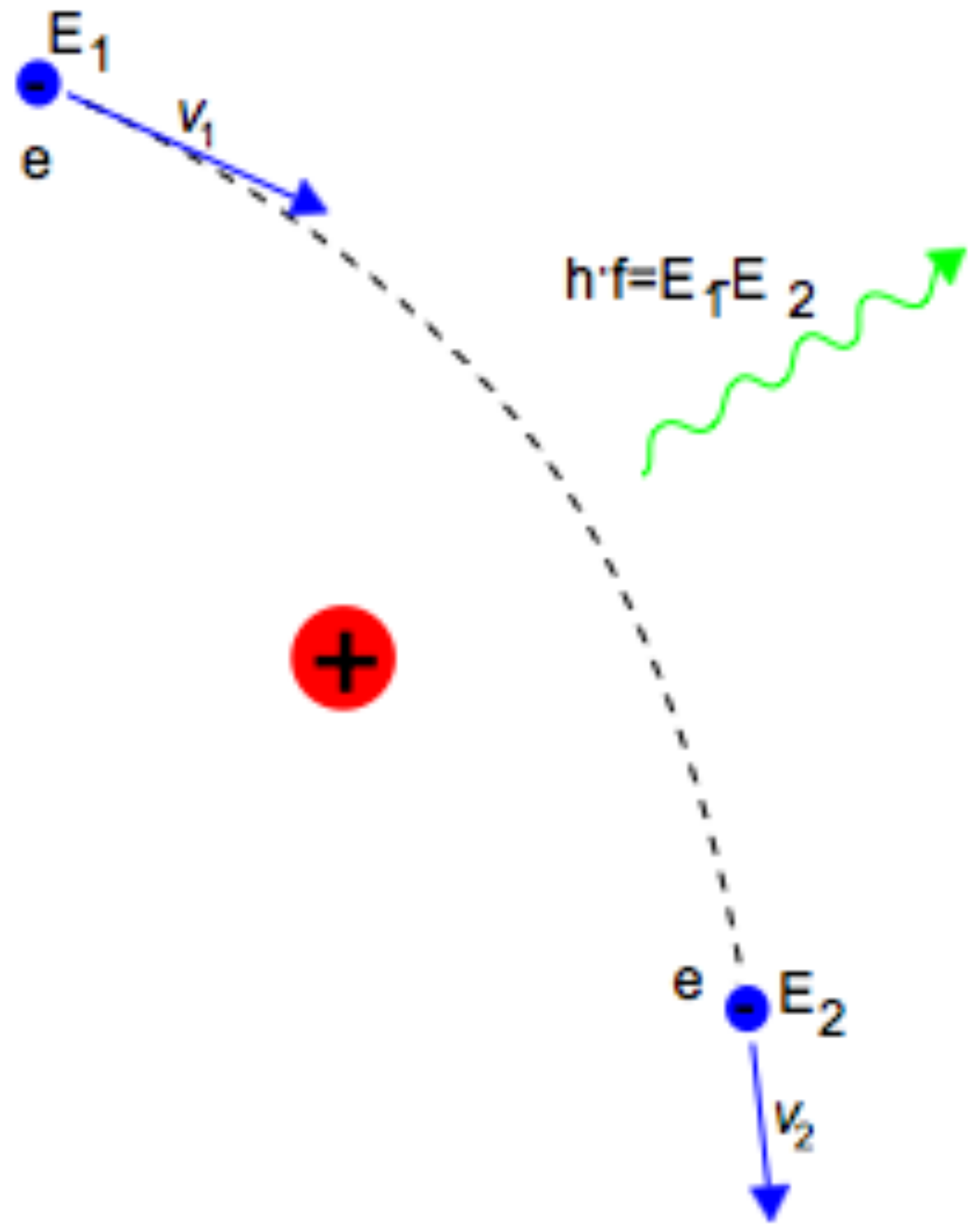


Bremsstrahlung

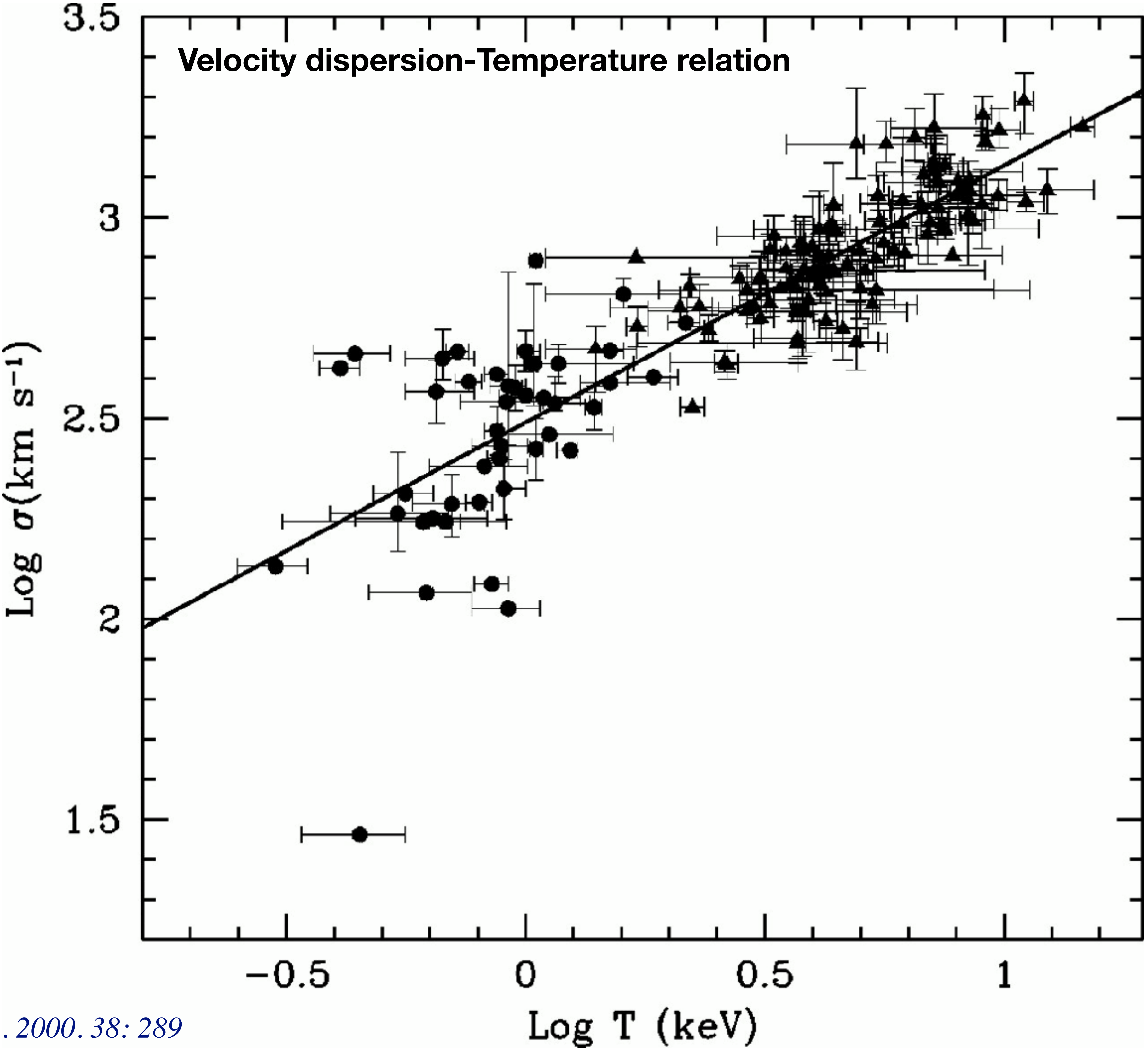
Gas falling into clusters shock heats to the virial temperature of the potential, $kT \sim mV^2$ resulting in an intracluster medium (ICM) composed of hot plasma. This plasma radiates in X-rays via Bremsstrahlung (braking radiation).

[Sometimes also called free-free radiation]

Just classical radiation from accelerated charges.



Global correlations in galaxy clusters

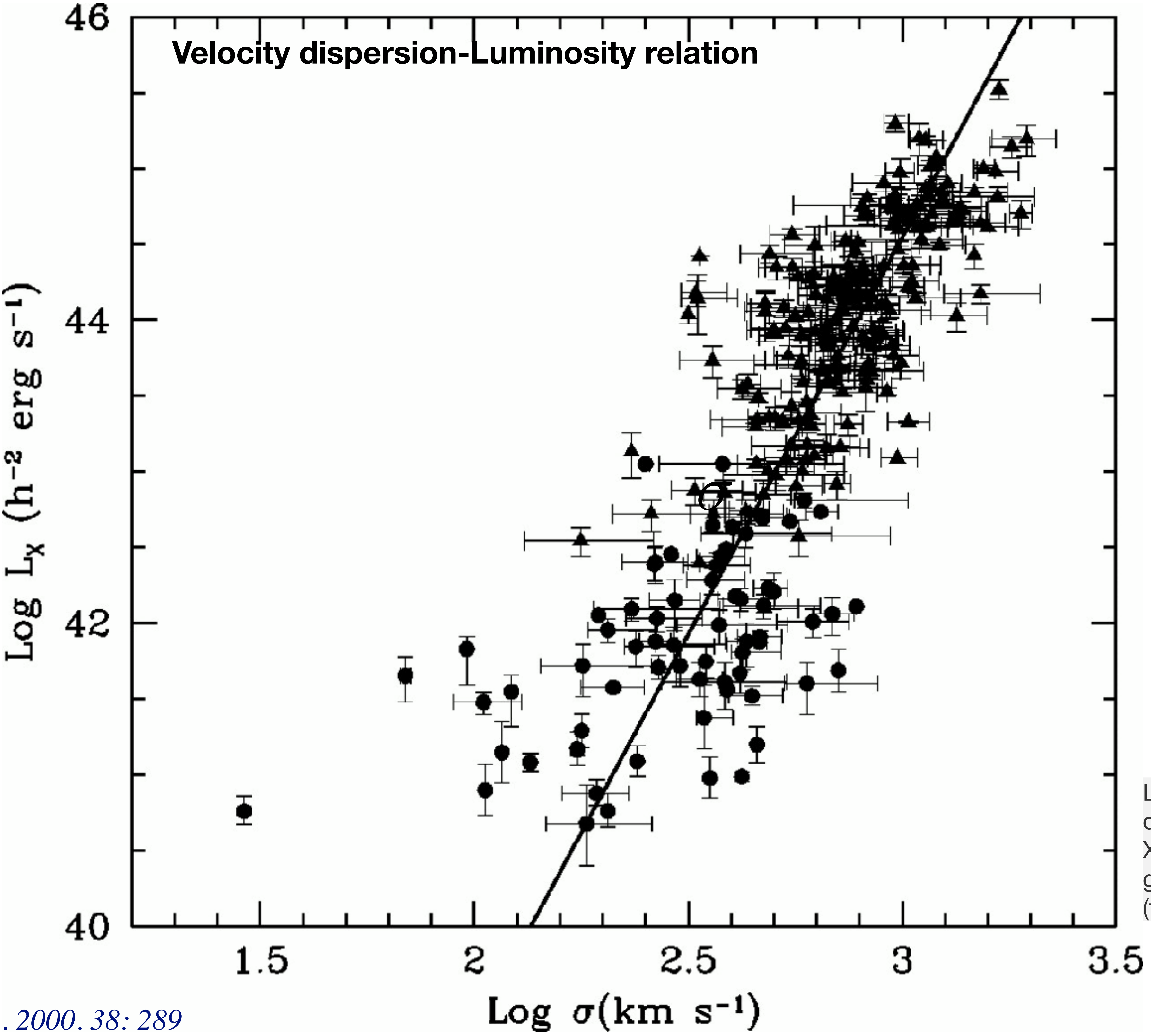


Logarithm of the X-ray temperature versus logarithm of optical velocity dispersion for a sample of groups (circles) and clusters (triangles).

Mulchaey

Annu. Rev. Astron. Astrophys. 2000. 38: 289

Global correlations in galaxy clusters



Logarithm of optical velocity dispersion versus logarithm of X-ray luminosity for a sample of groups (circles) and clusters (triangles).

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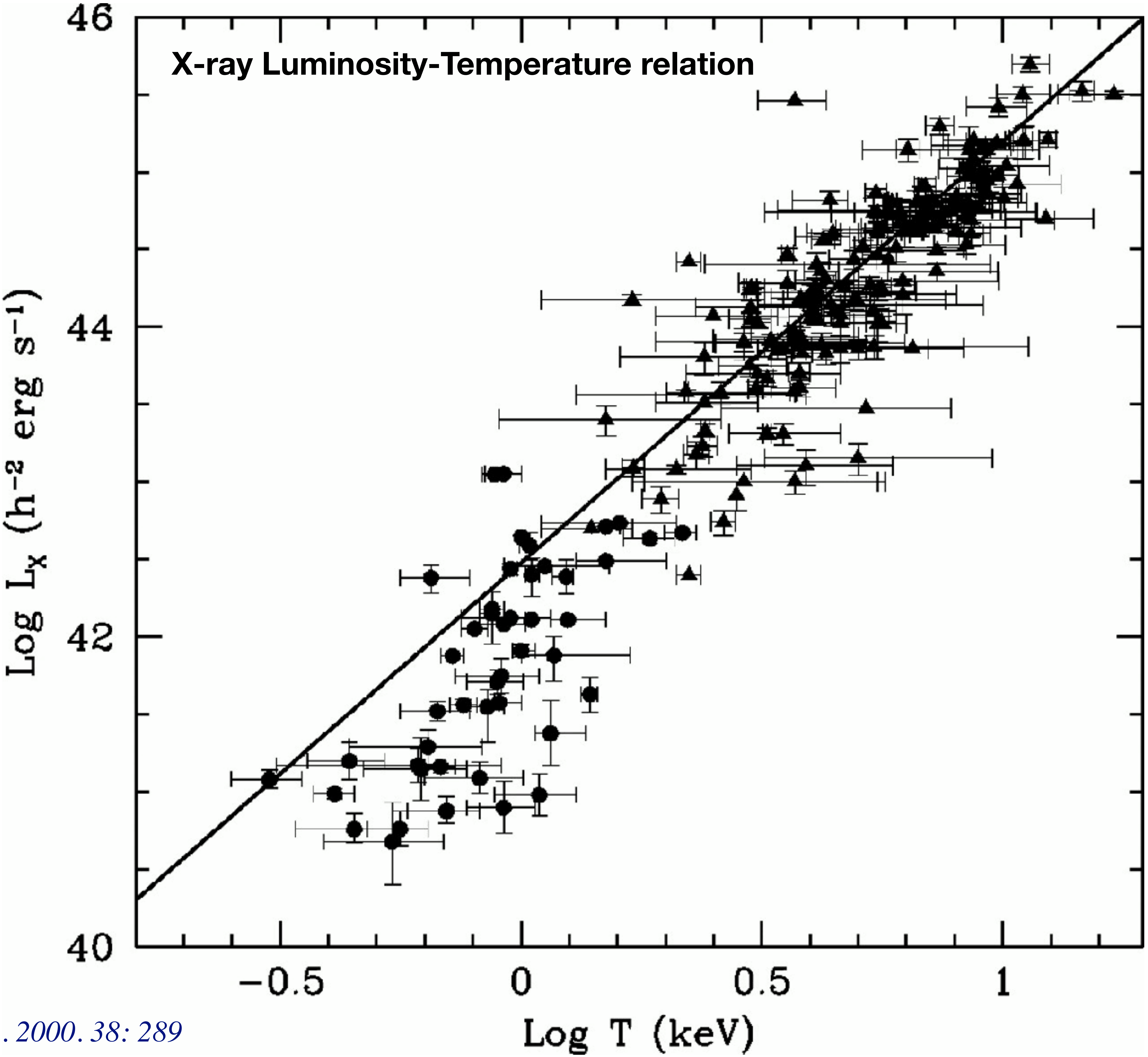

Logarithm of the X-ray temperature versus logarithm of X-ray luminosity for a sample of groups (circles) and clusters (triangles).

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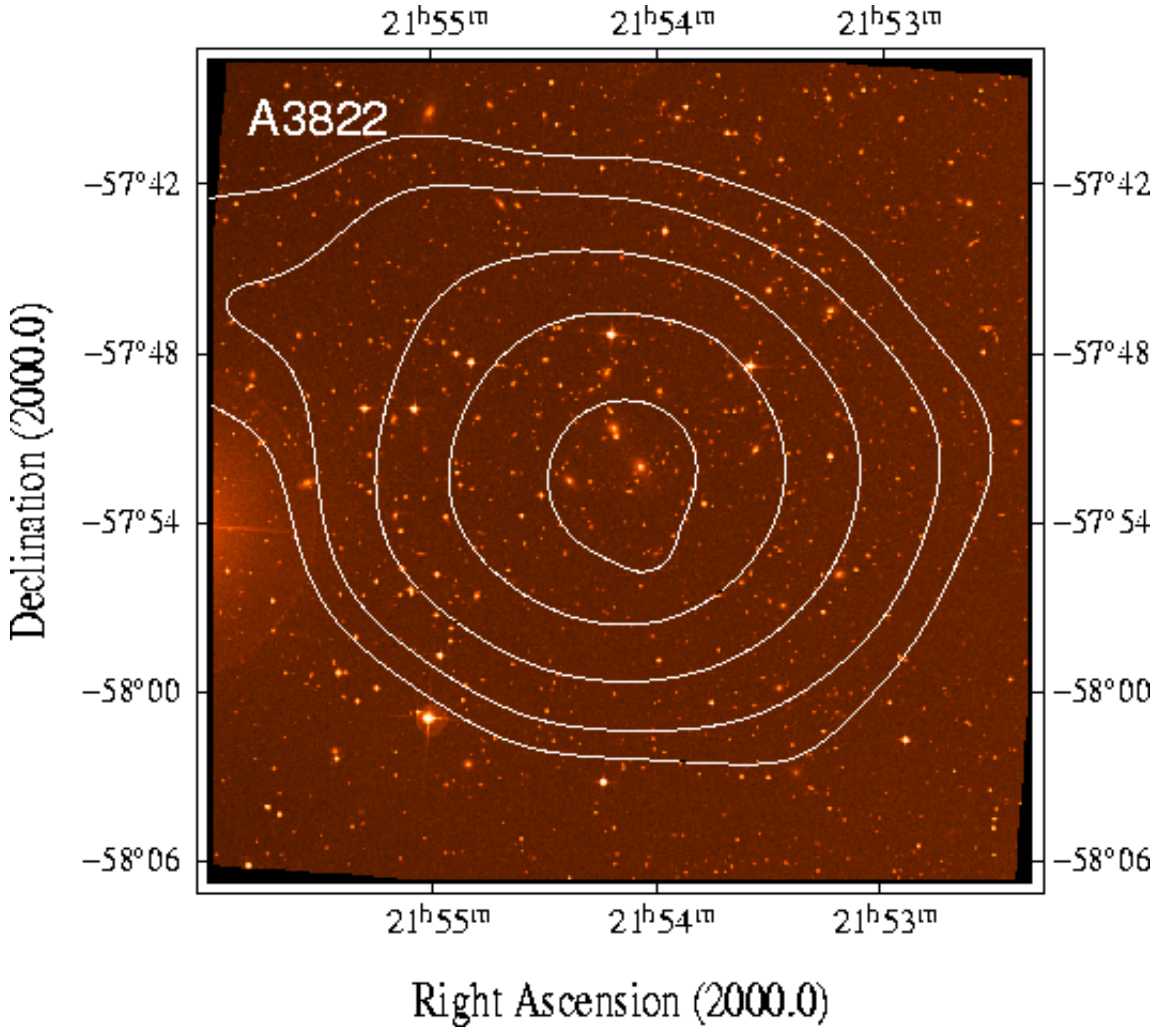
Beta models



The X-ray surface brightness at a projected radius R

for an isothermal sphere is given by:

$$S(R) = S_0[1 + (R/r_c)^2]^{-3\beta+1/2}$$

S_0	central surface brightness
r_c	core radius of gas distribution

$$\beta \equiv \frac{\mu m_p \sigma^2}{kT_g} = \frac{\text{specific energy in galaxies}}{\text{specific energy in the hot gas}}$$

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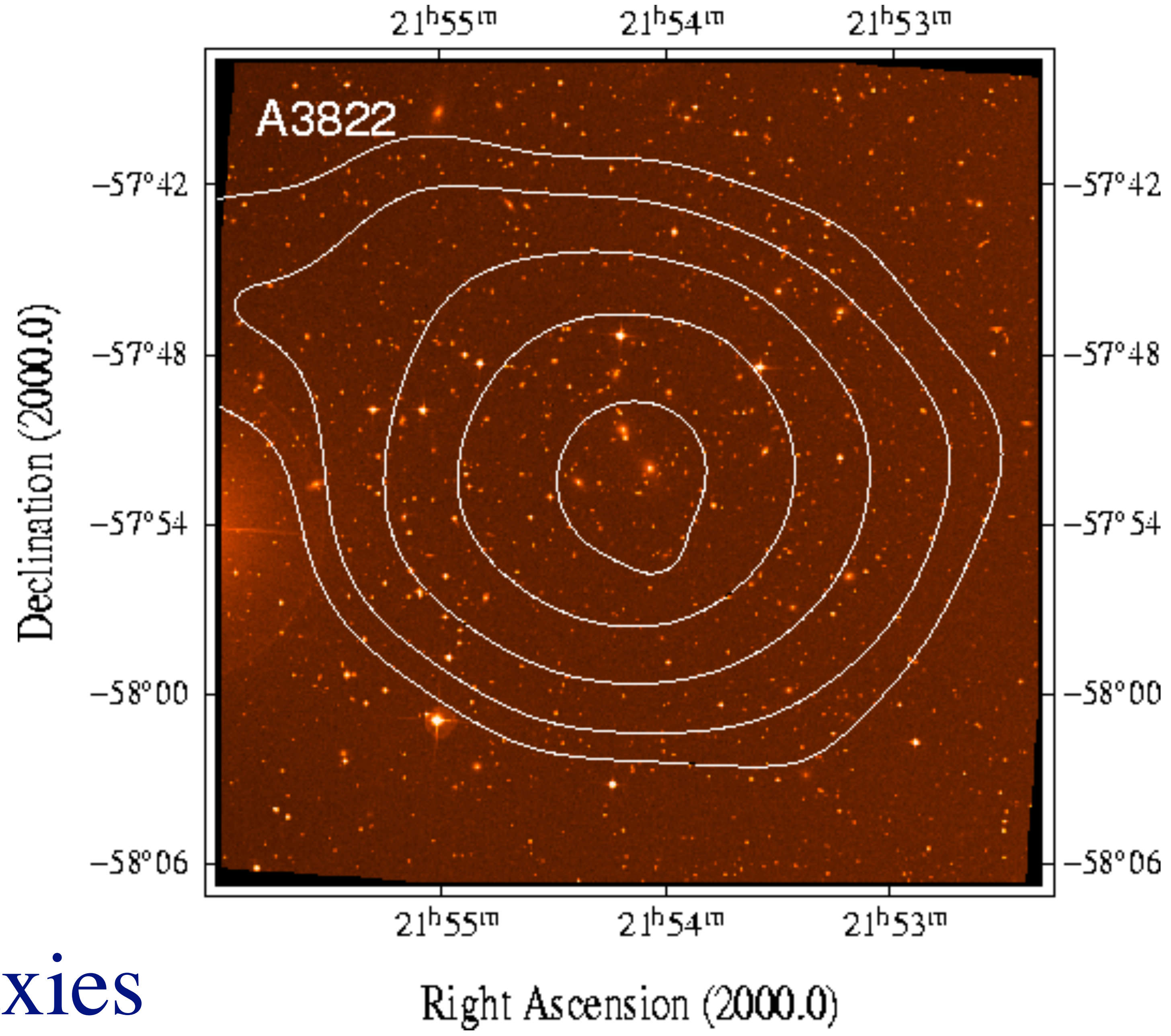


μ is the mean molecular weight

m_p is the mass of the proton

σ is the one-dimensional velocity dispersion of the galaxies

T_g is the temperature of the ICM

Typically the gas is assumed to be isothermal

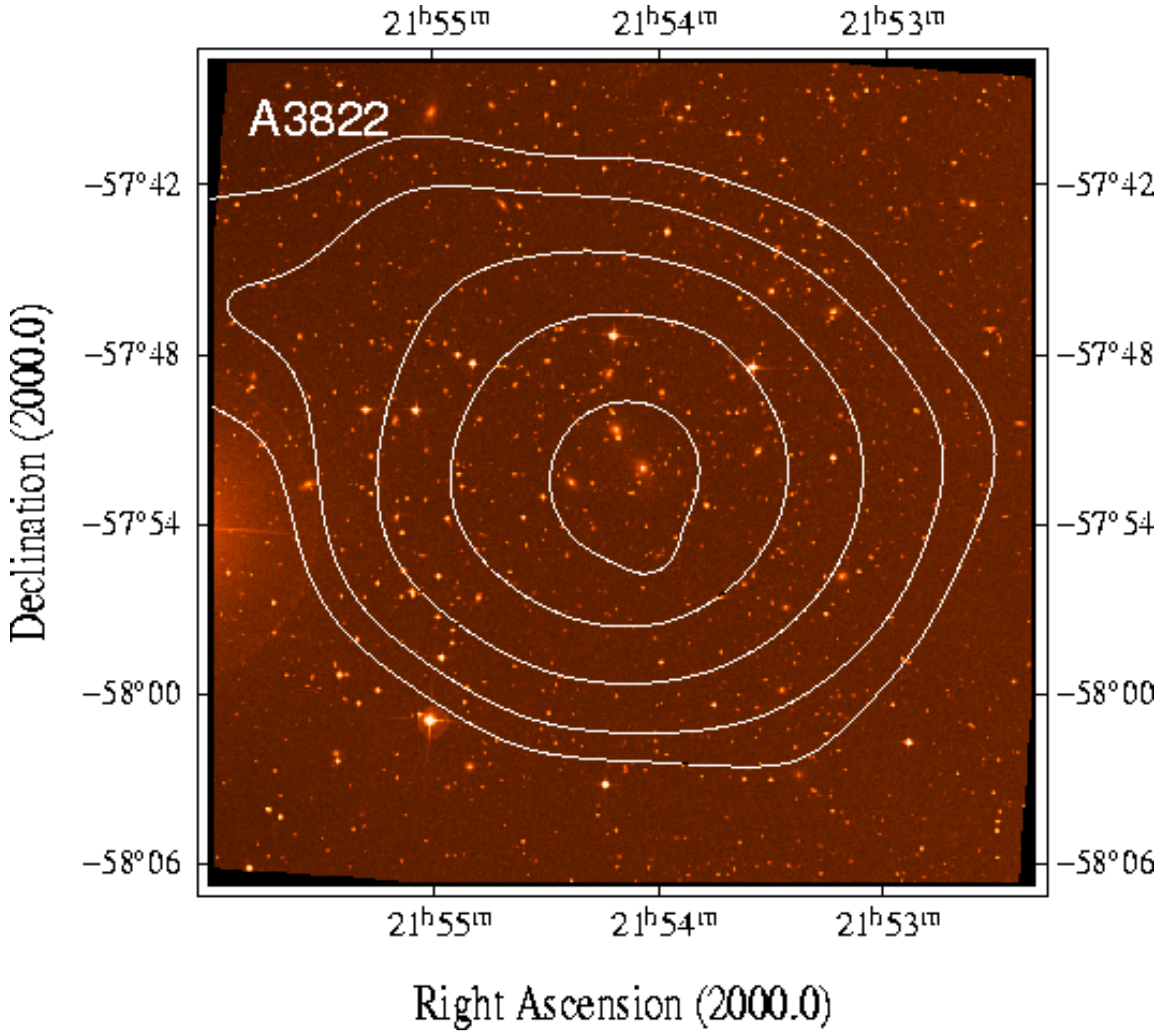
β treated as fit parameter; typically ~ 2/3
BUT often higher when sigma well measured;
and often lower in groups

Mass Estimator

$$M(<r) = -\frac{r}{G}\frac{kT}{\mu m_p}\left(\frac{\partial \ln \rho}{\partial \ln r} + \frac{\partial \ln T}{\partial \ln r}\right)$$

the 3D gas density profile $\rho(r)$ is obtained by fitting the standard beta model to the surface brightness profile.

the gas temperature is measured from the X-ray spectrum



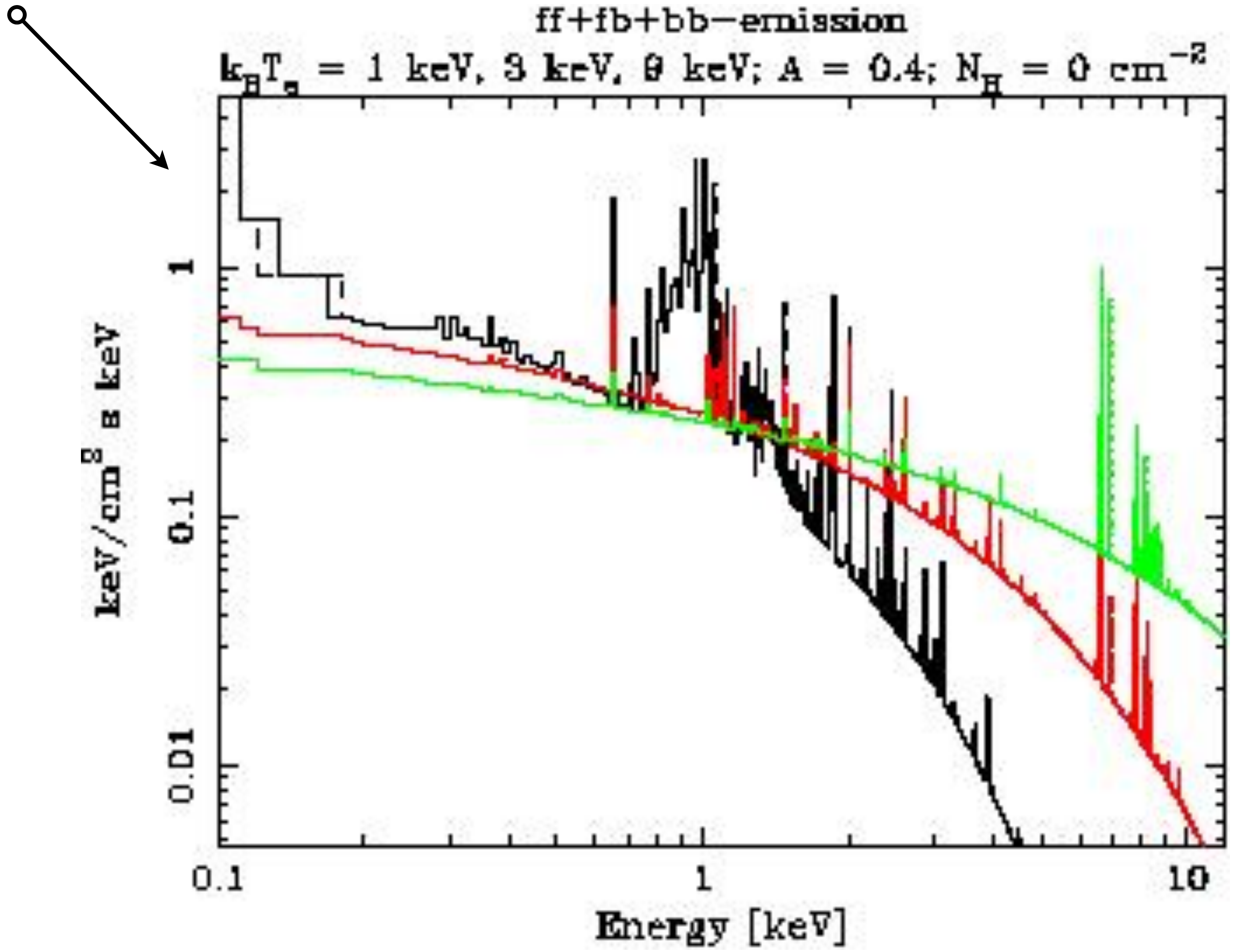
Assumes

- hydrostatic equilibrium
- sphericity

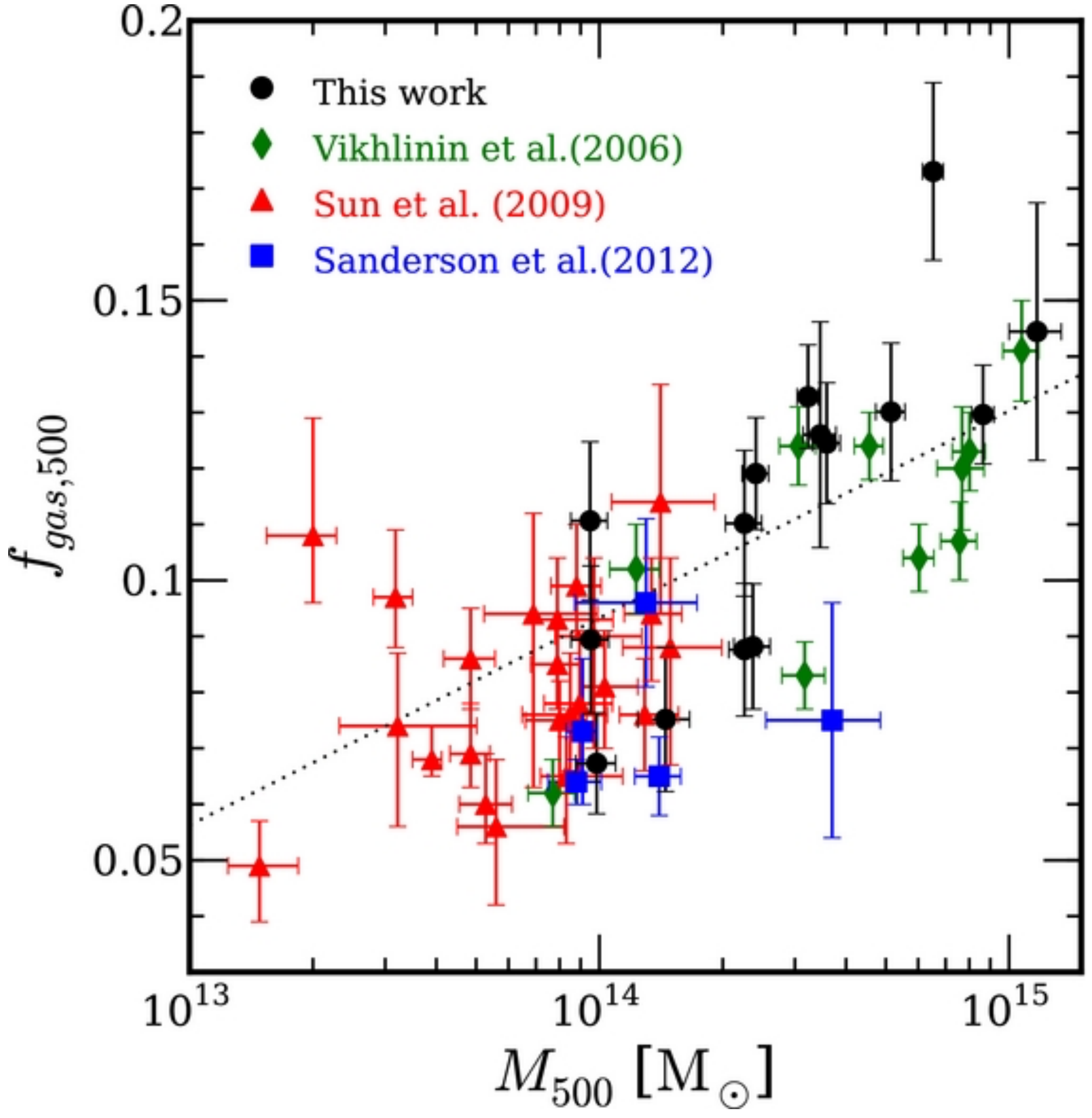
often assumes

- isothermality ⟶ $\frac{\partial \ln T}{\partial \ln r} = 0$

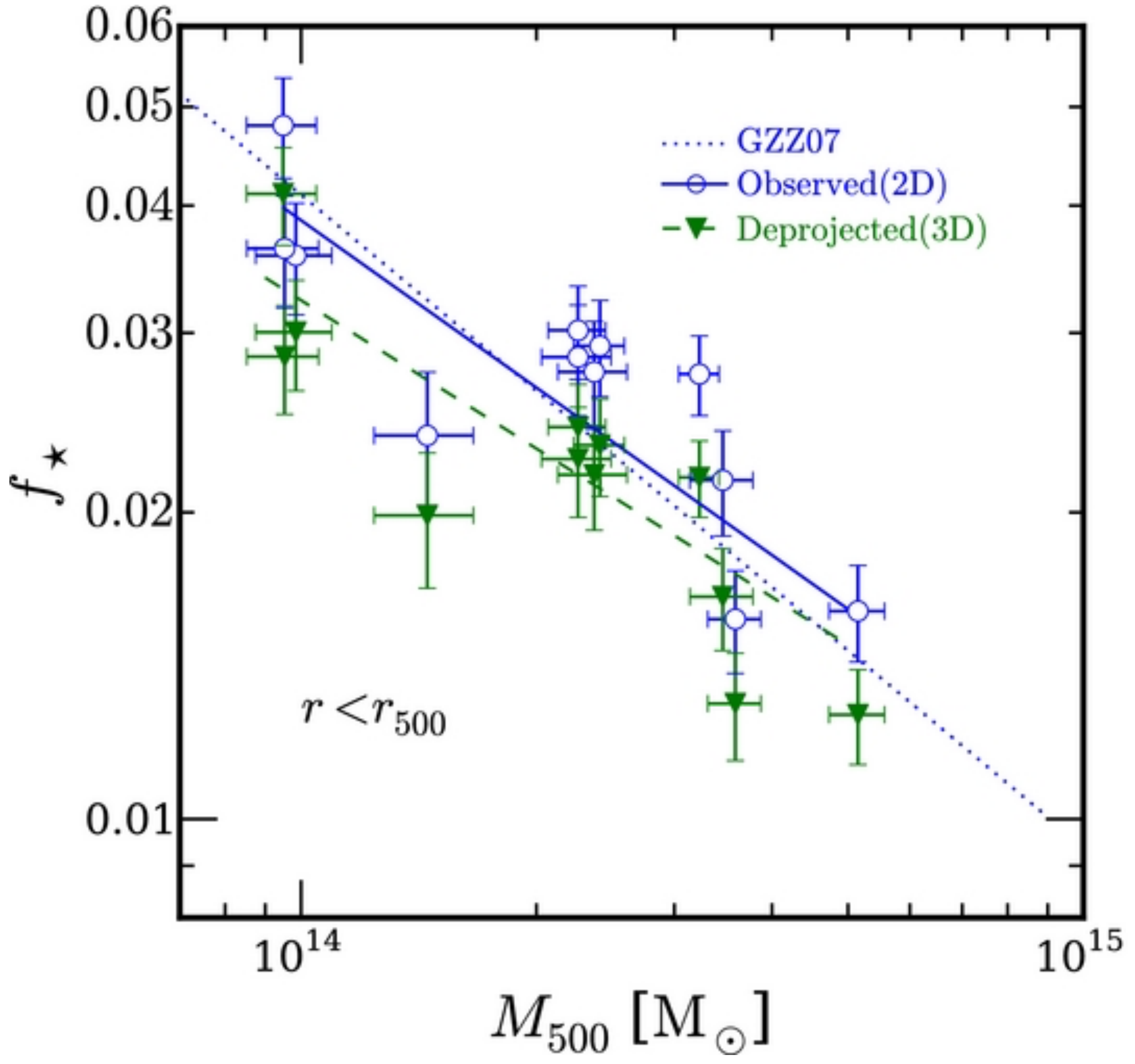
basically, temperature traces the kinetic energy: $T \sim V^2$ so $M \sim TR$



gas fraction



star fraction

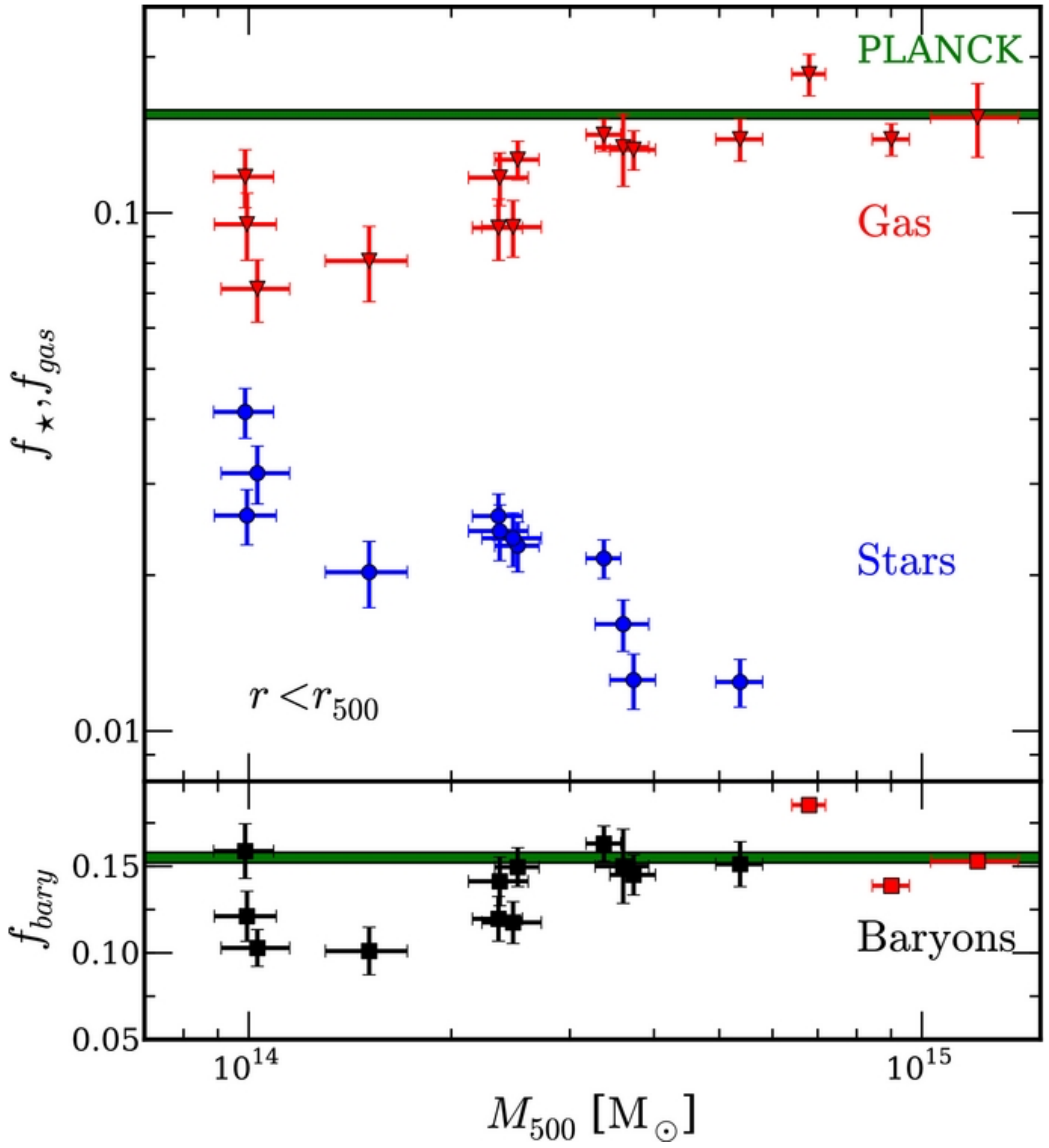


Typical result:

ICM gas outweighs the stars by factor of ~6;
outweighed by dark matter by the same factor

Gonzalez *et al* 2013 *ApJ* **778** 14

gas, star, and baryon fraction



cluster baryon fraction
comparable to the
cosmic baryon fraction,
but only for high mass clusters

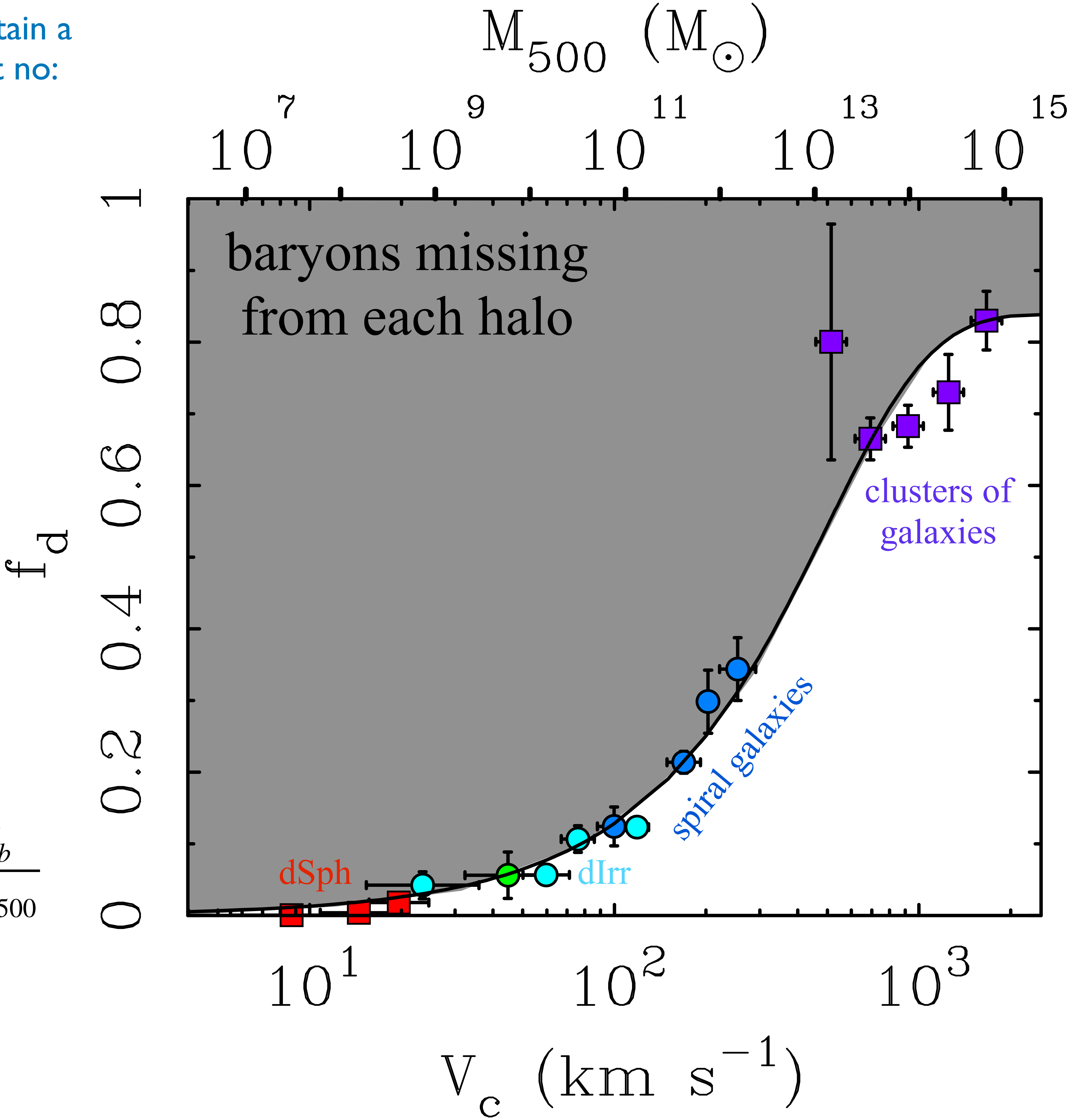
Typical result:
ICM gas outweighs the stars by factor of ~6;
outweighed by dark matter by the same factor

Gonzalez *et al* 2013 *ApJ* **778** 14

The halo missing baryon problem

Expect each halo to contain a fair share of baryons, but no:

$$M_b < f_b M_{200}$$

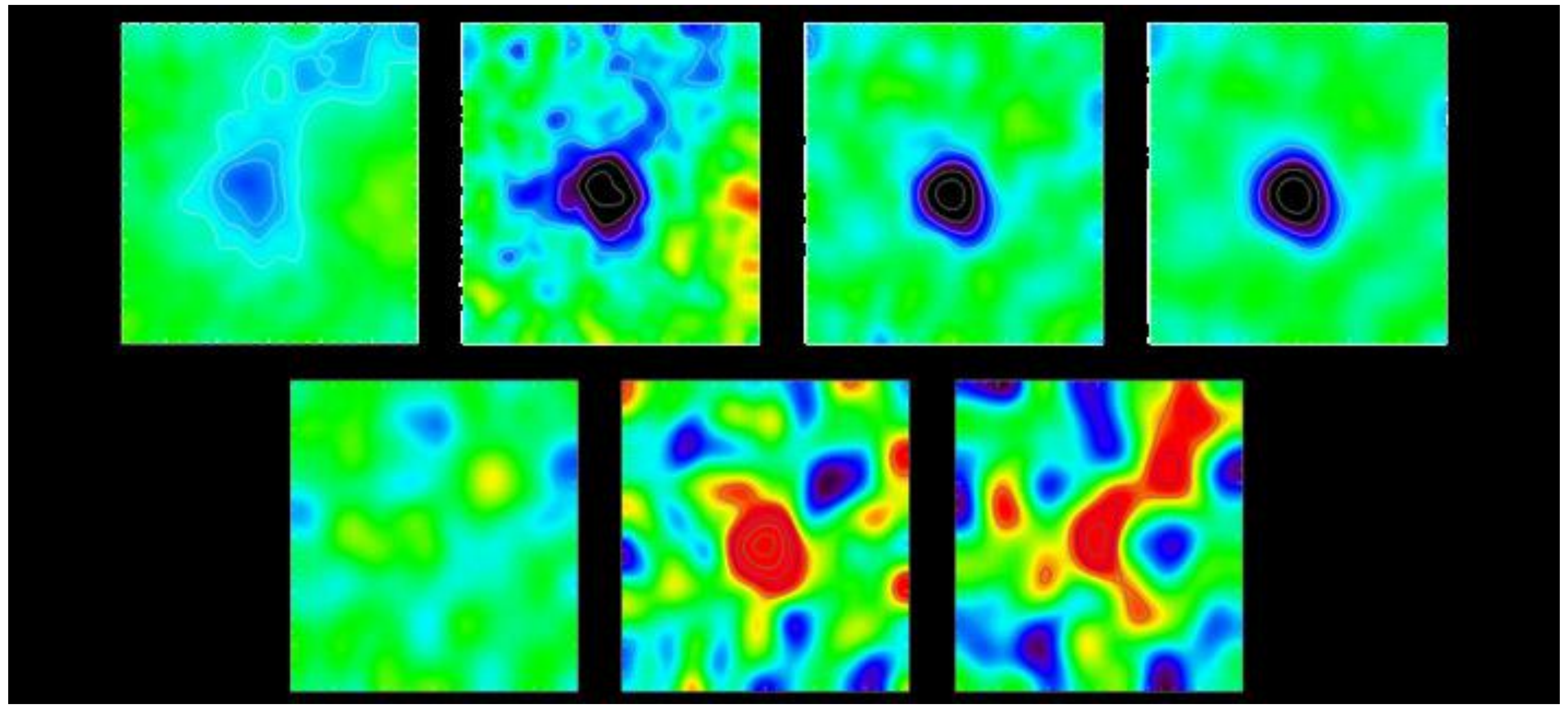


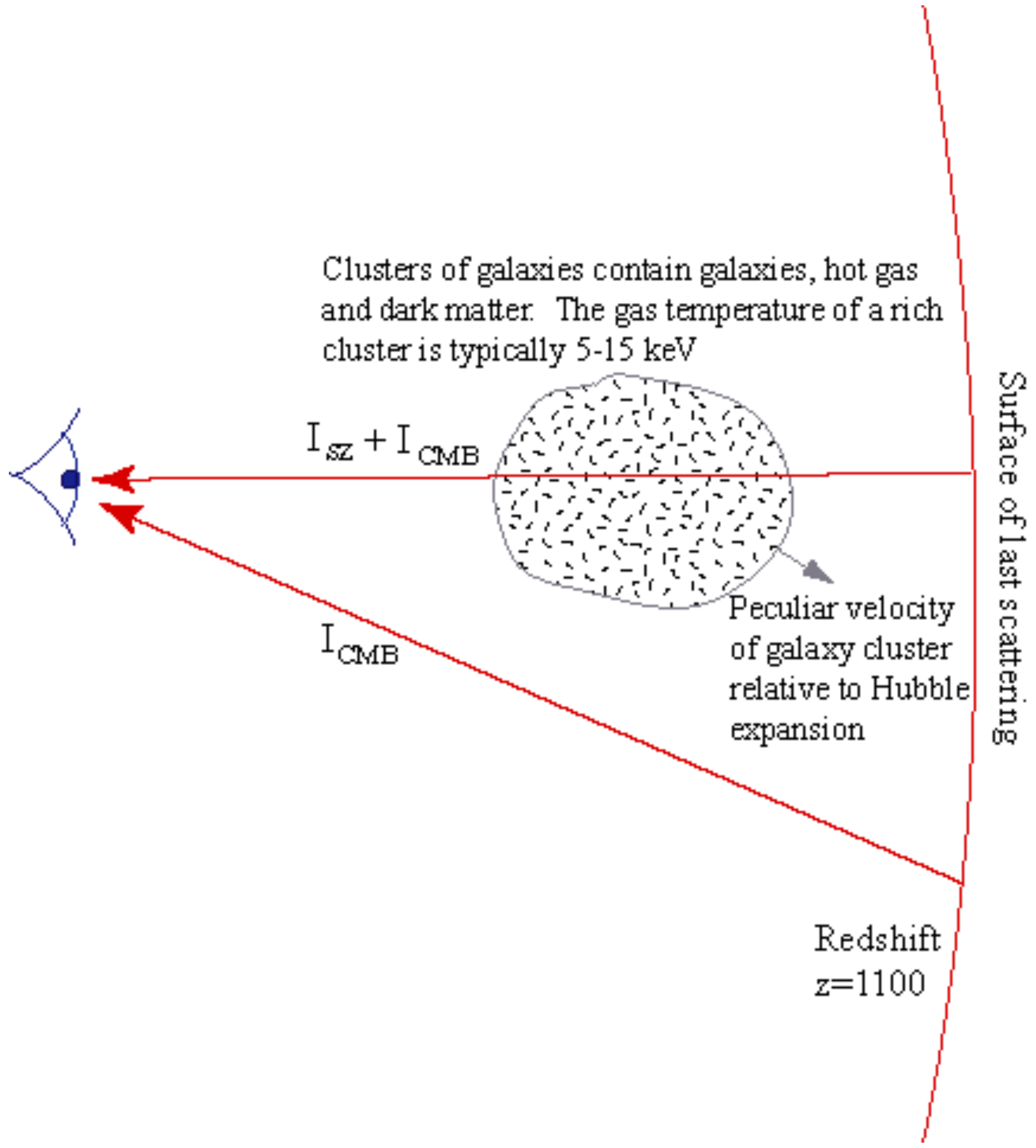
detected baryon fraction

$$f_d = \frac{M_b}{f_b M_{500}}$$

cosmic baryon fraction
$f_b = 0.17$

SUNYAEV–ZEL'DOVICH (SZ) EFFECT





Compton scattering of CMB photons by hot ICM plasma

Frequency dependent change in intensity

$$\frac{\delta I_\nu}{I_\nu} = -y \frac{x e^x}{e^x - 1} \left[4 - x \coth\left(\frac{x}{2}\right) \right]$$

where $x = \frac{h\nu}{kT_{rad}}$ and $y = \int \sigma_T n_e \frac{kT_g}{m_e c^2} d\ell$

CMB

electron density

Thomson scattering cross-section

y is the Compton y-parameter
which quantifies how much
effect the plasma has

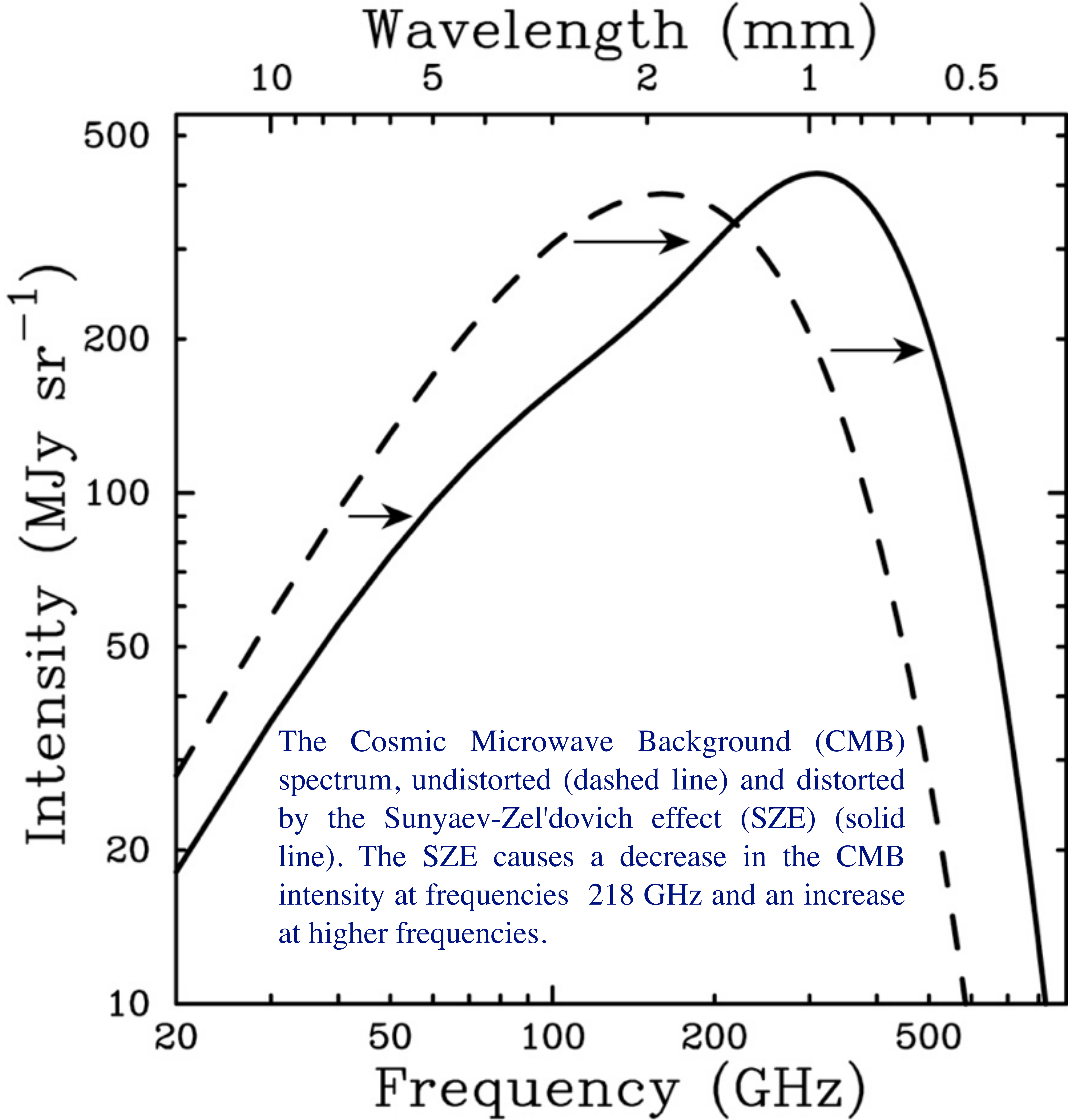
Frequency dependent change in intensity

$$\frac{\delta I_\nu}{I_\nu} = -y\frac{xe^x}{e^x - 1}\left[4 - x\coth\left(\frac{x}{2}\right)\right]$$

where $x = \dfrac{h\nu}{kT_{rad}}$ and $y = \displaystyle\int \sigma_T n_e \frac{kT_g}{m_e c^2} d\ell$

at low frequency in the Rayleigh-Jeans tail,

$$\frac{\delta I}{I} = \frac{\delta T}{T} = -2y$$

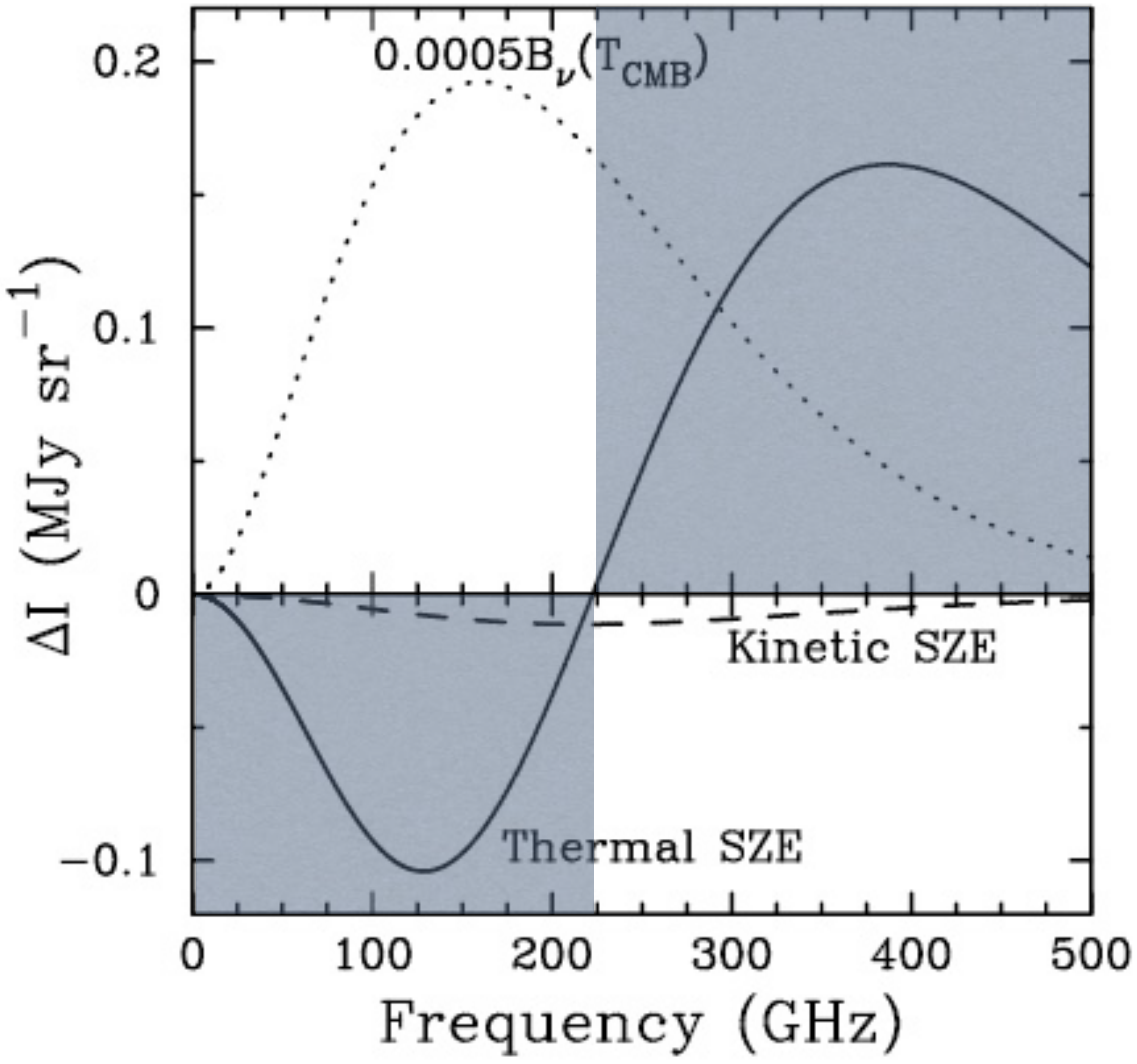


The Cosmic Microwave Background (CMB) spectrum, undistorted (dashed line) and distorted by the Sunyaev-Zel'dovich effect (SZE) (solid line). The SZE causes a decrease in the CMB intensity at frequencies 218 GHz and an increase at higher frequencies.

Carlstrom et al. Annu. Rev. Astron. Astrophys. 2002. 40: 643

Thermal SZ effect from Compton scattering of CMB photons by cluster plasma

intensity boosted

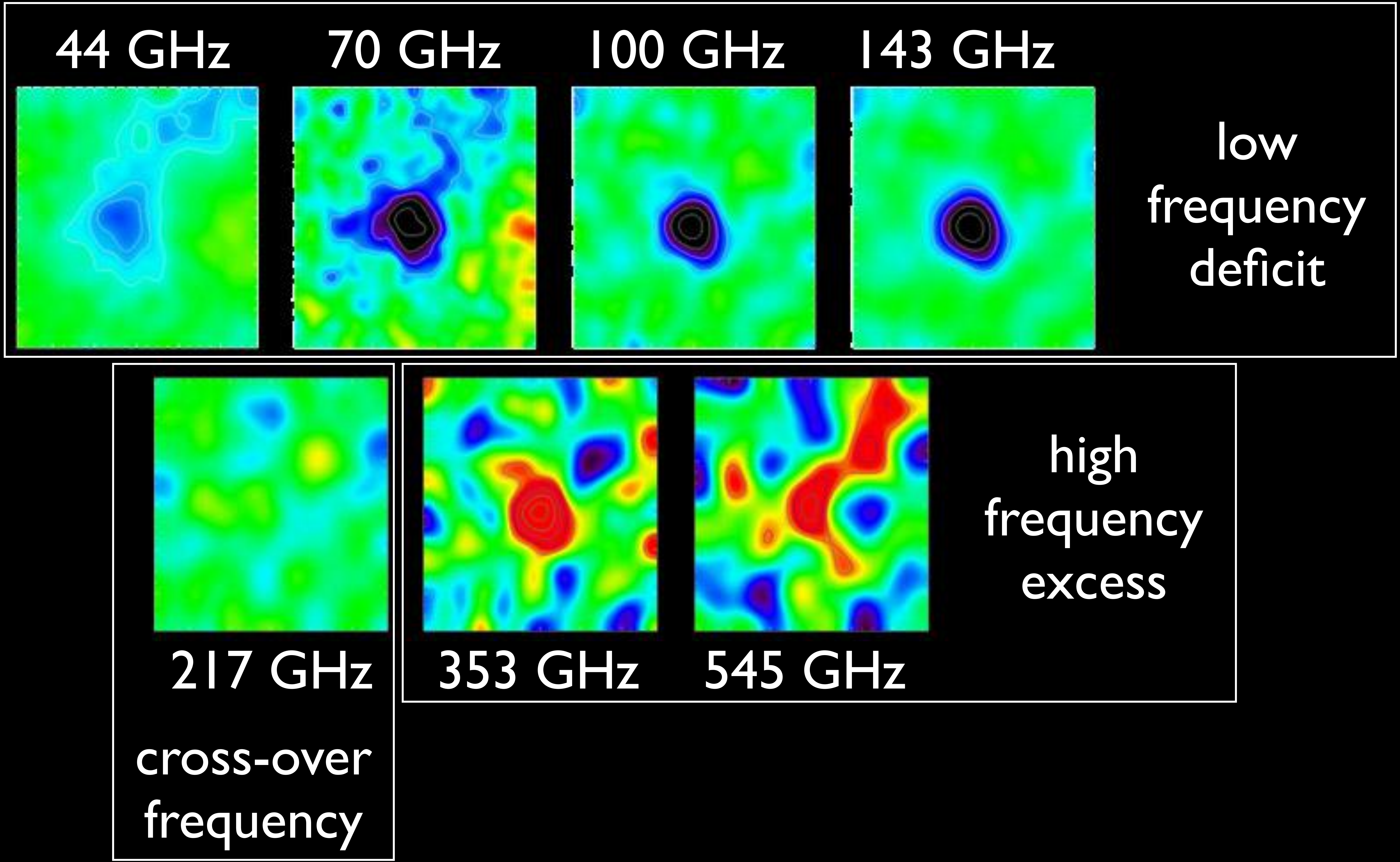


Kinematic SZ effect from peculiar velocity of cluster wrt CMB frame

intensity depleted

SUNYAEV–ZEL'DOVICH EFFECT

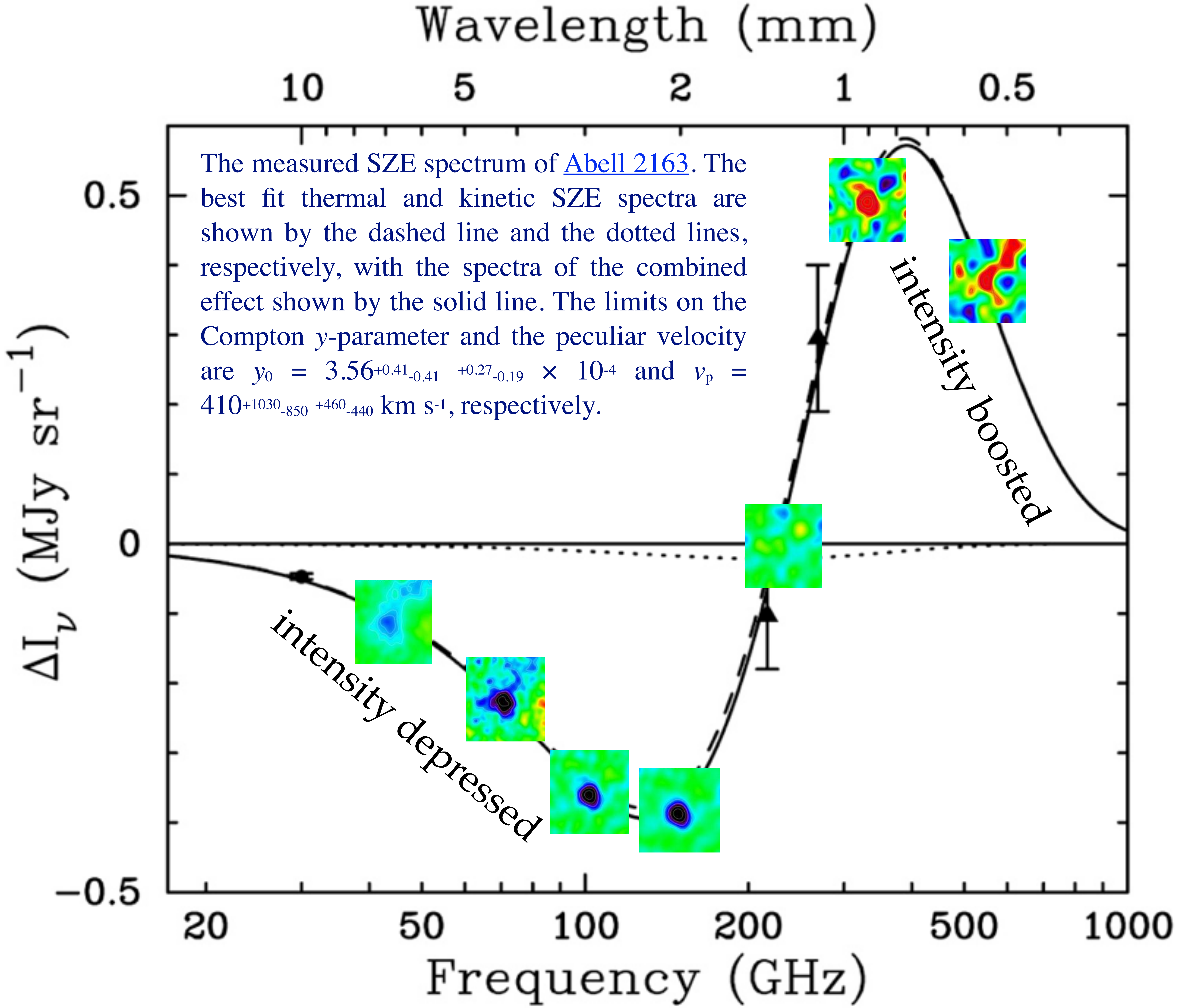
detected by Planck



low frequency deficit

cross-over frequency

high frequency excess



The measured SZE spectrum of Abell 2163. The best fit thermal and kinetic SZE spectra are shown by the dashed line and the dotted lines, respectively, with the spectra of the combined effect shown by the solid line. The limits on the Compton y-parameter and the peculiar velocity are $y_0 = 3.56^{+0.41}_{-0.41}\,{}^{+0.27}_{-0.19} \times 10^{-4}$ and $v_p = 410^{+1030}_{-850}\,{}^{+460}_{-440}$ km s^{-1}, respectively.

integrated change in CMB temperature

$$\int \Delta T d\Omega \propto \frac{N_e \langle T_e \rangle}{D_A^2} \propto \frac{M \langle T_e \rangle}{D_A^2}$$

depends on the total number of electrons, their temperature, and the area they subtend on the sky.
In effect measures Pressure, or Mass if T known.

D_A is the angular diameter distance.
At high z, it varies slowly, while the density increases as $(1+z)^3$

... SZ effect weak, but nearly independent of redshift!