DARK MATTER

ASTR 333/433

TODAY

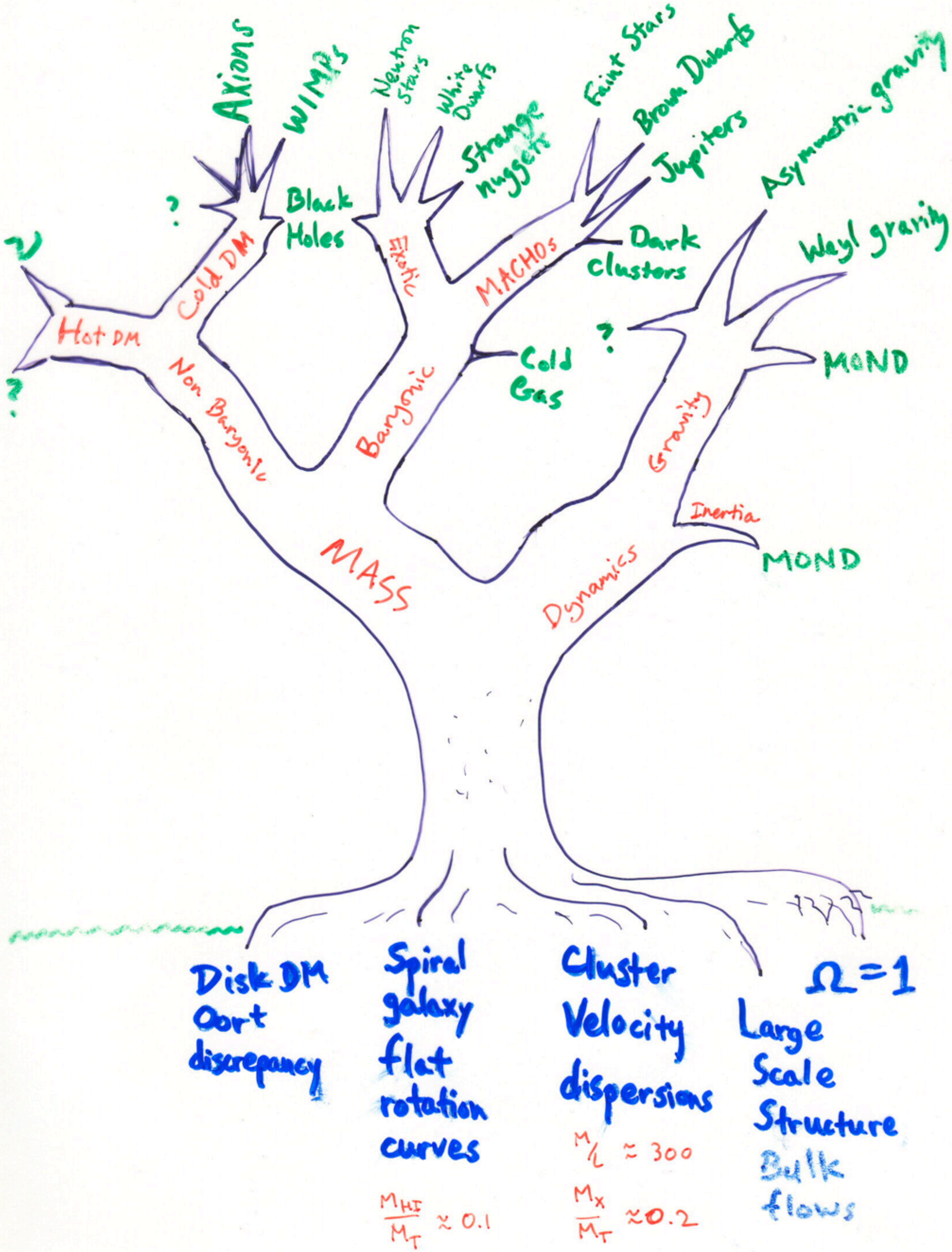
LOCAL GROUP TIMING

CLUSTERS OF GALAXIES

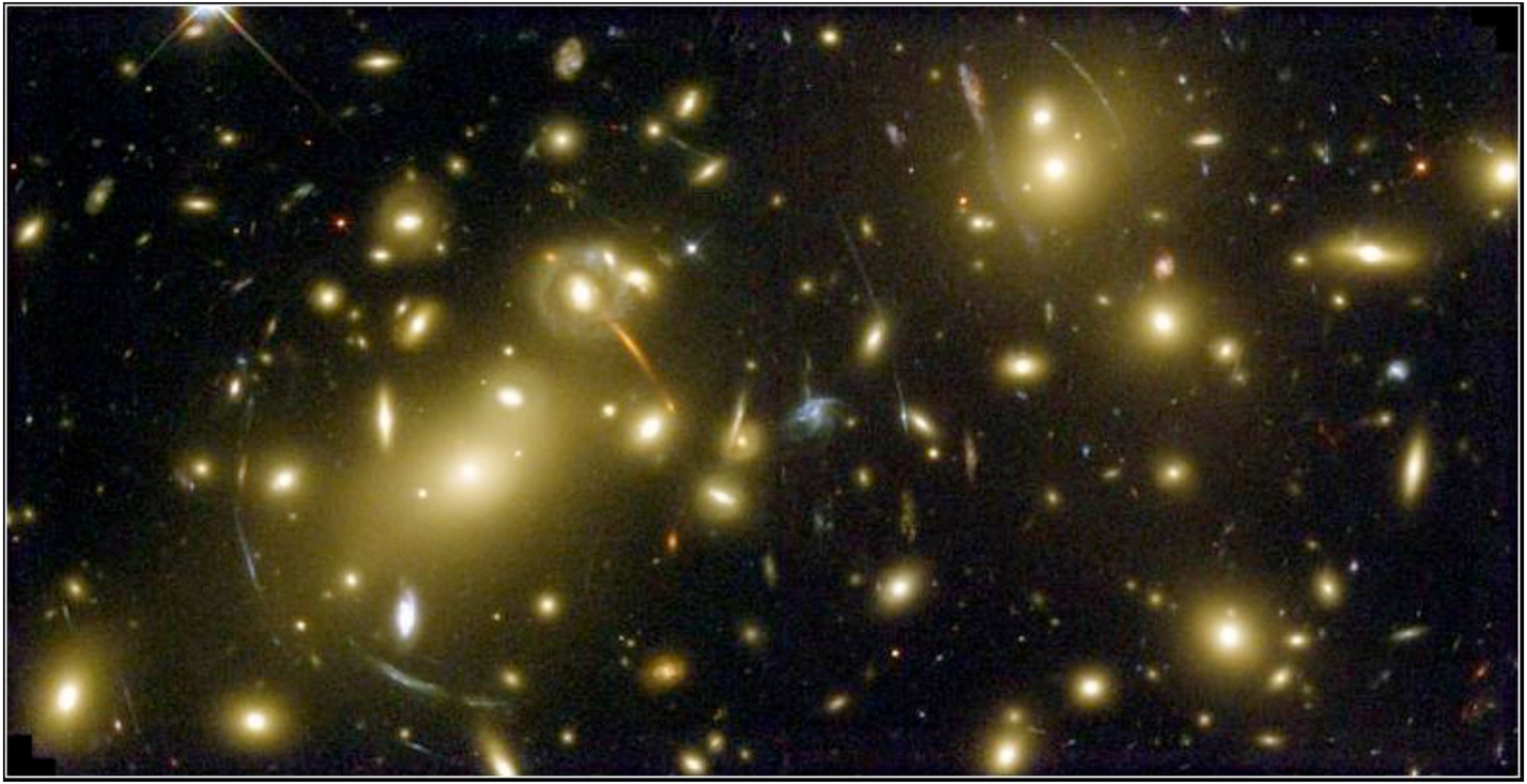
HYDROSTATIC EQUILIBRIUM

SUNYAEV-ZEL'DOVICH EFFECT

GRAVITATIONAL LENSING



Galaxy Clusters



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

Mass estimators for Clusters of Galaxies

- Virial

$$M = \frac{2.5}{G}\sigma^2 R_e$$

- Hydrostatic equilibrium (X-ray)

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

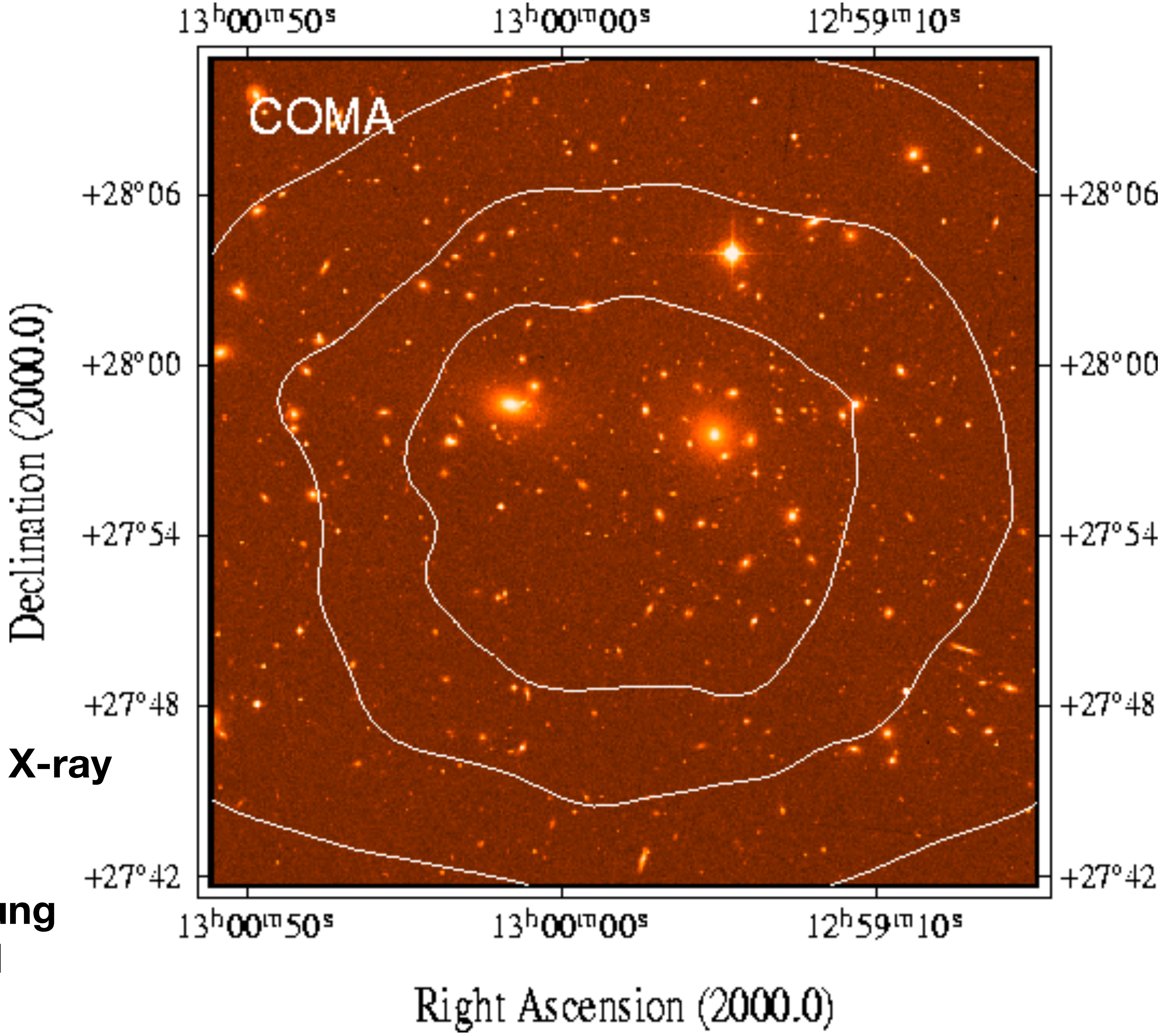
- gravitational lensing

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

- S-Z effect

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

Clusters in optical and X-ray (contours)



Typically two X-ray sources

Bremsstrahlung from hot ICM

AGN and other point sources

Reiprich ApJ, 567, 716-740 (2002)

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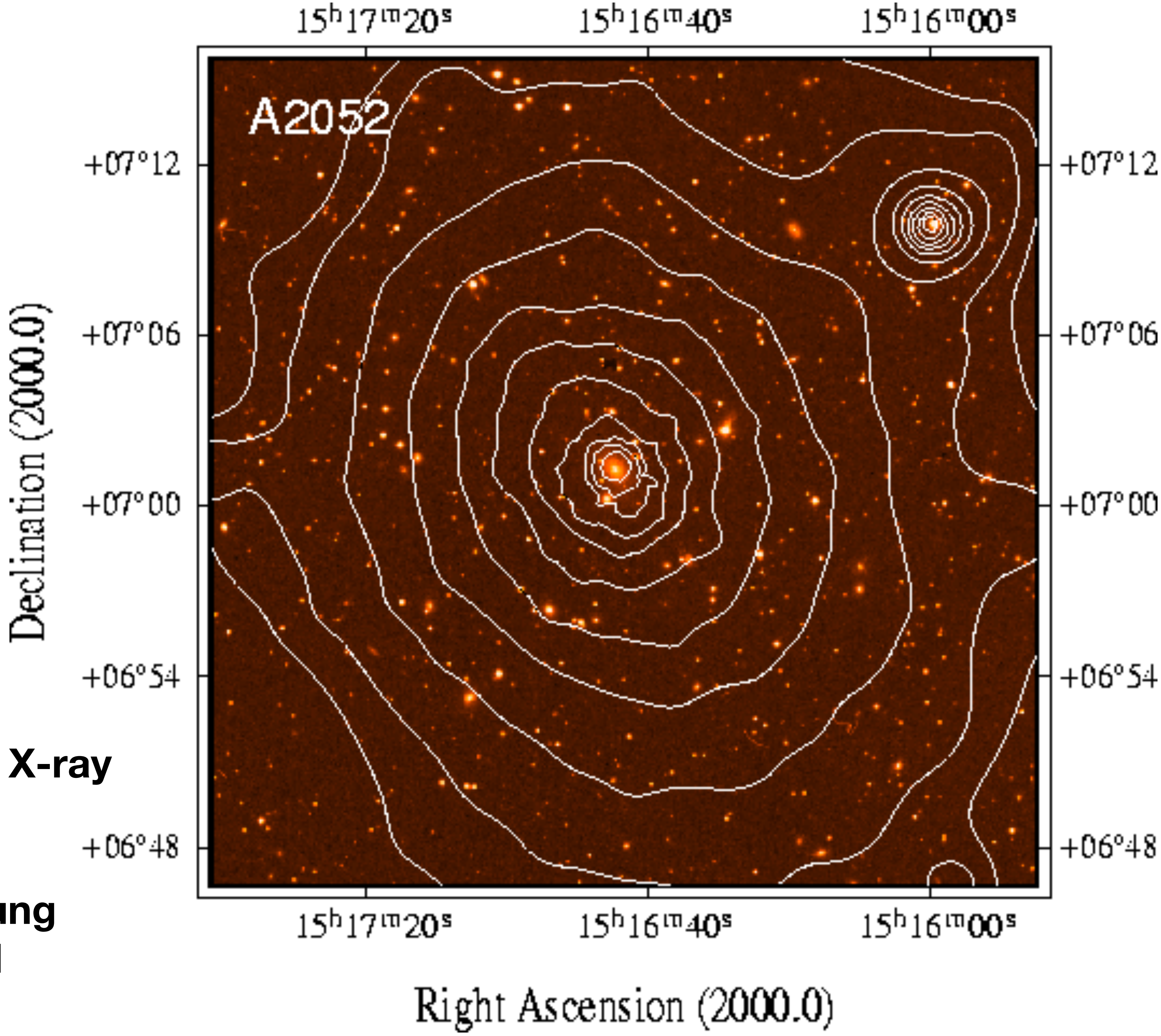

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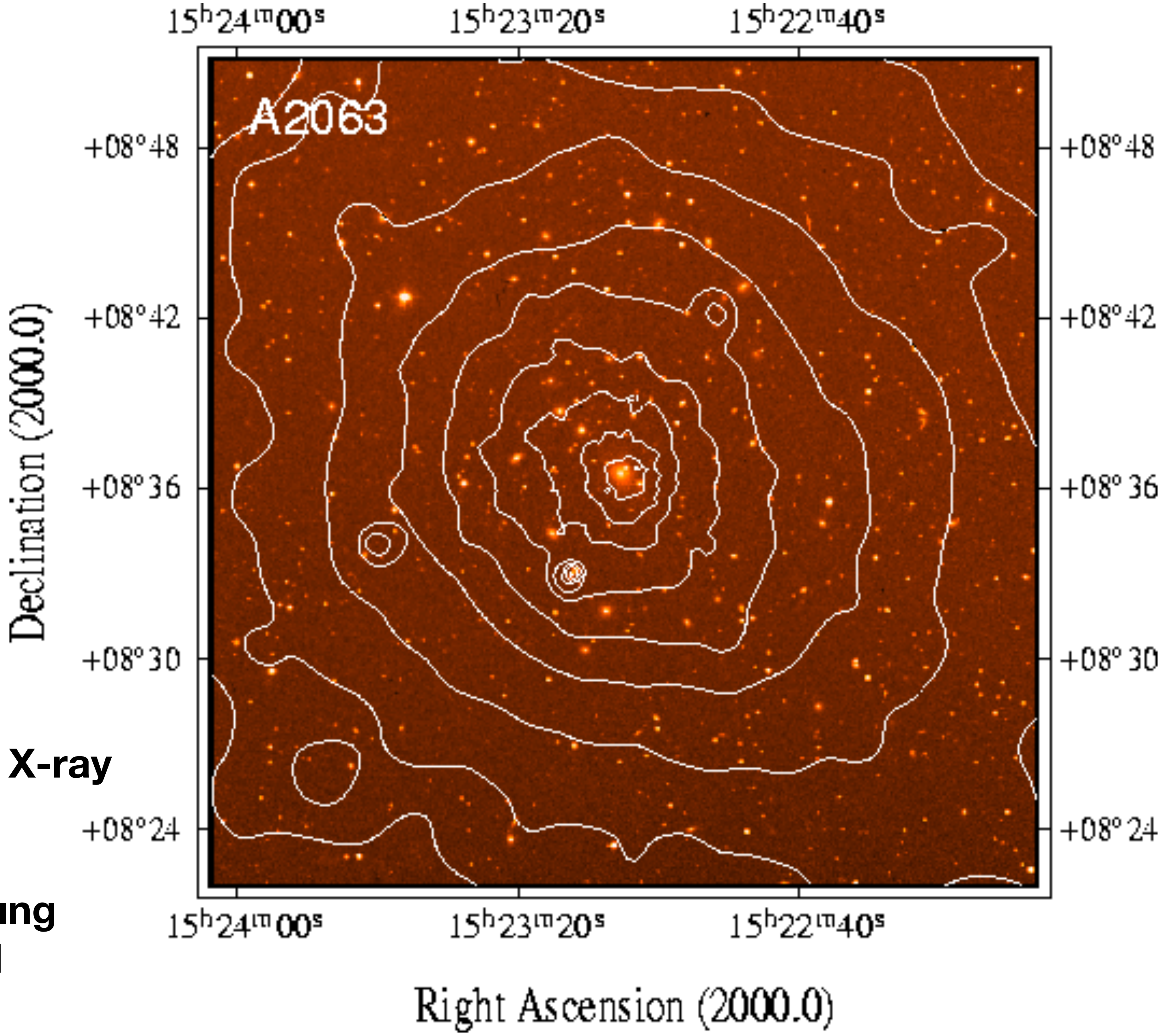

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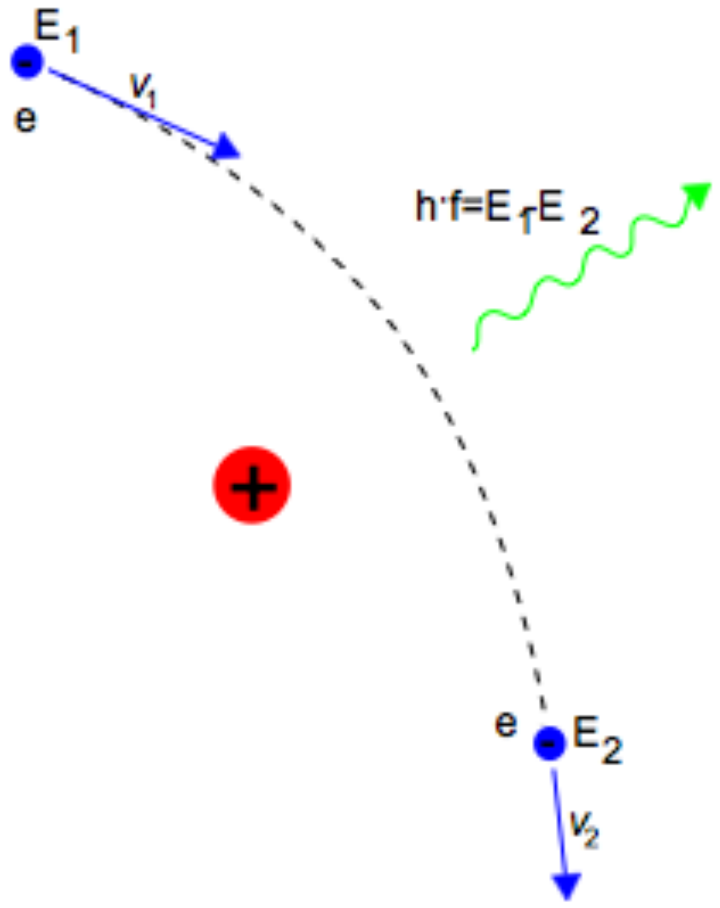
Bremsstrahlung

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

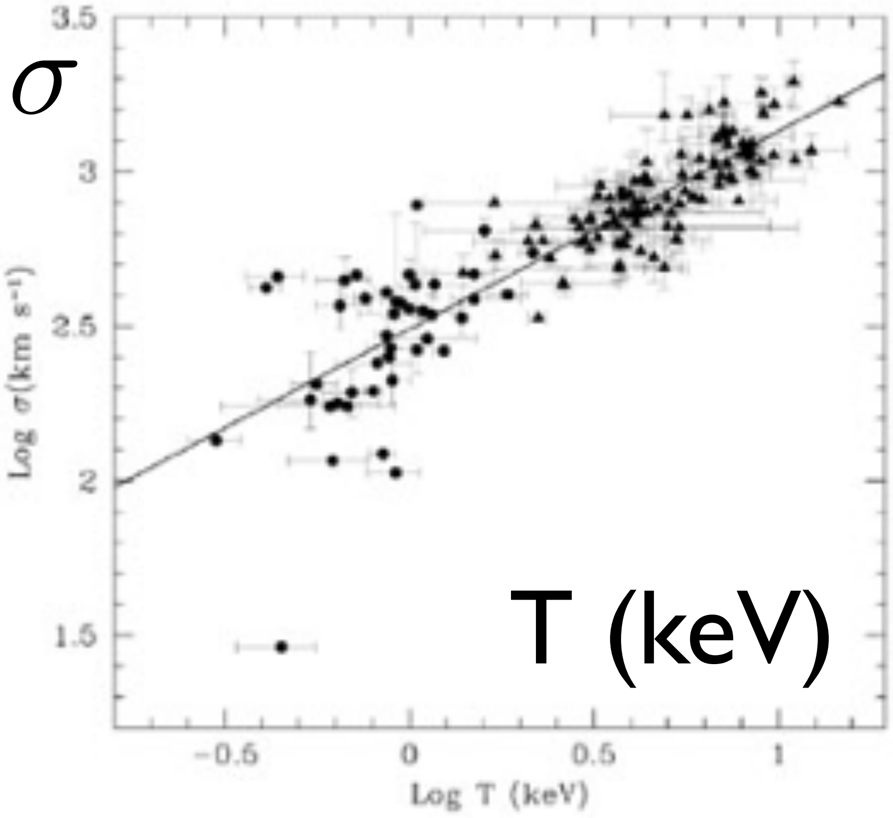


Figure 4. Logarithm of the X-ray temperature versus logarithm of optical velocity dispersion for a sample of groups (circles) and clusters (triangles). The group data are taken from the literature compilation of Xue & Wu (2000), with the addition of the groups in Helsdon & Ponman (2000). The cluster data are taken from Wu et al (1999). The solid line represents the best-fit found by Wu et al (1999) for the clusters sample (using an orthogonal distance regression method). Within the large scatter, the groups are consistent with the cluster relationship.

Velocity dispersion-Temperature relation

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

Global correlations in galaxy clusters

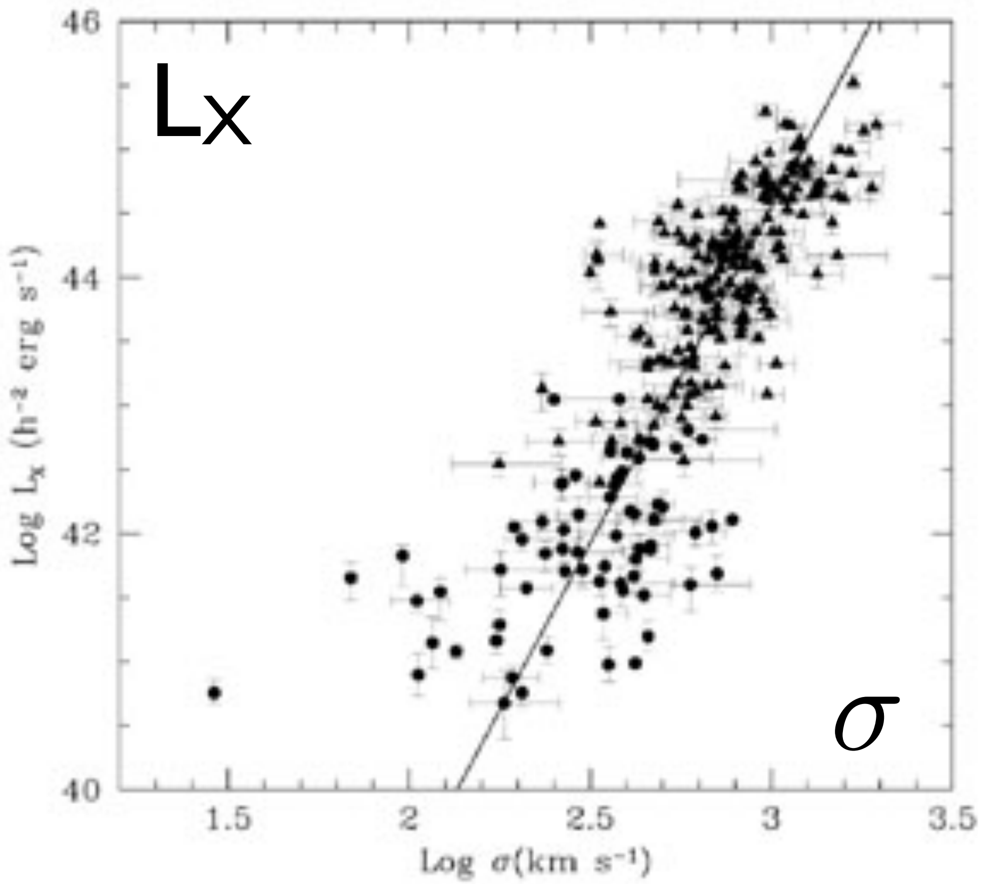


Figure 5. Logarithm of optical velocity dispersion versus logarithm of X-ray luminosity for a sample of groups (circles) and clusters (triangles). The data are taken from the same sources cited in Figure 4. The solid line represents the best-fit found by Wu et al (1999) for the clusters sample (using an orthogonal distance regression method).

Velocity dispersion-Luminosity relation

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

Global correlations in galaxy clusters

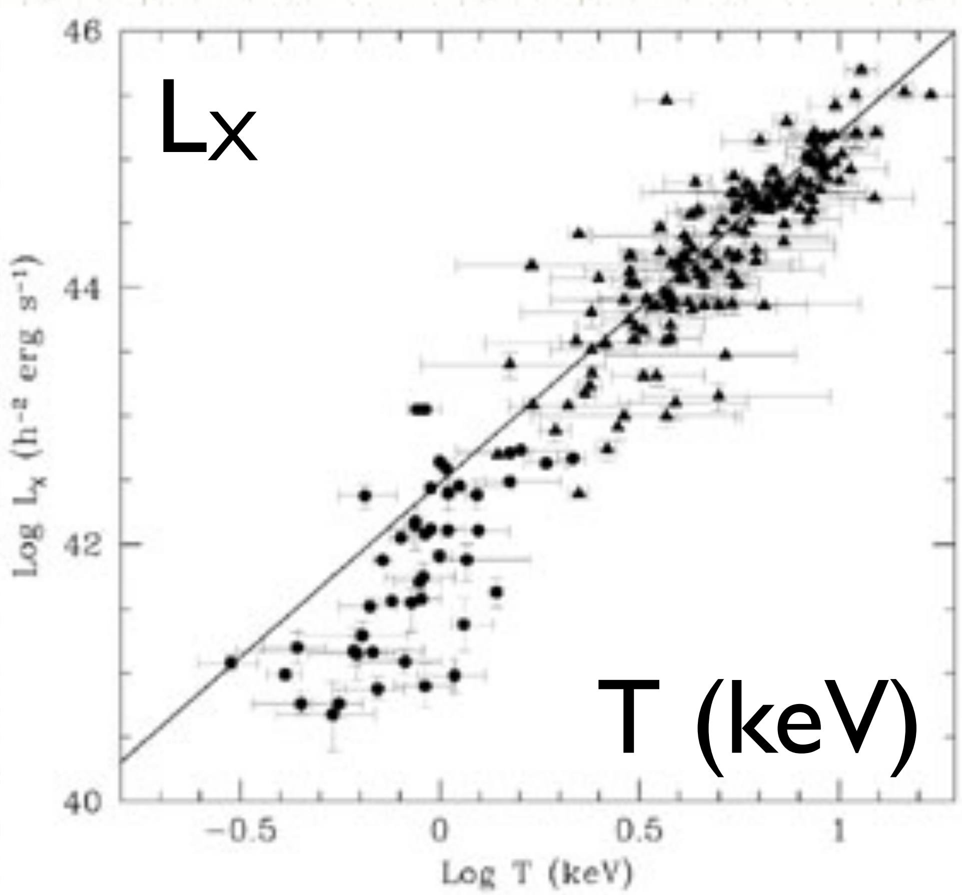


Figure 6. Logarithm of the X-ray temperature versus logarithm of X-ray luminosity for a sample of groups (circles) and clusters (triangles). The data are taken from the same sources cited in Figure 4. The solid line represents the best-fit found by Wu et al (1999) for the clusters sample (using an orthogonal distance regression method). The observed relationship for groups is somewhat steeper than the best-fit cluster relationship.

Luminosity-Temperature relation

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

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

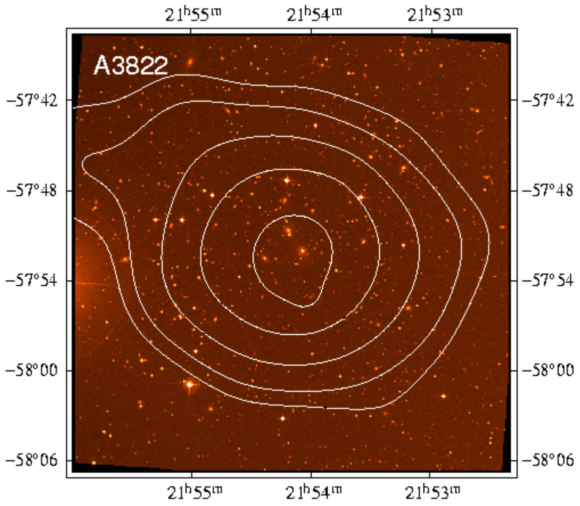
Typically the gas is assumed to be isothermal

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

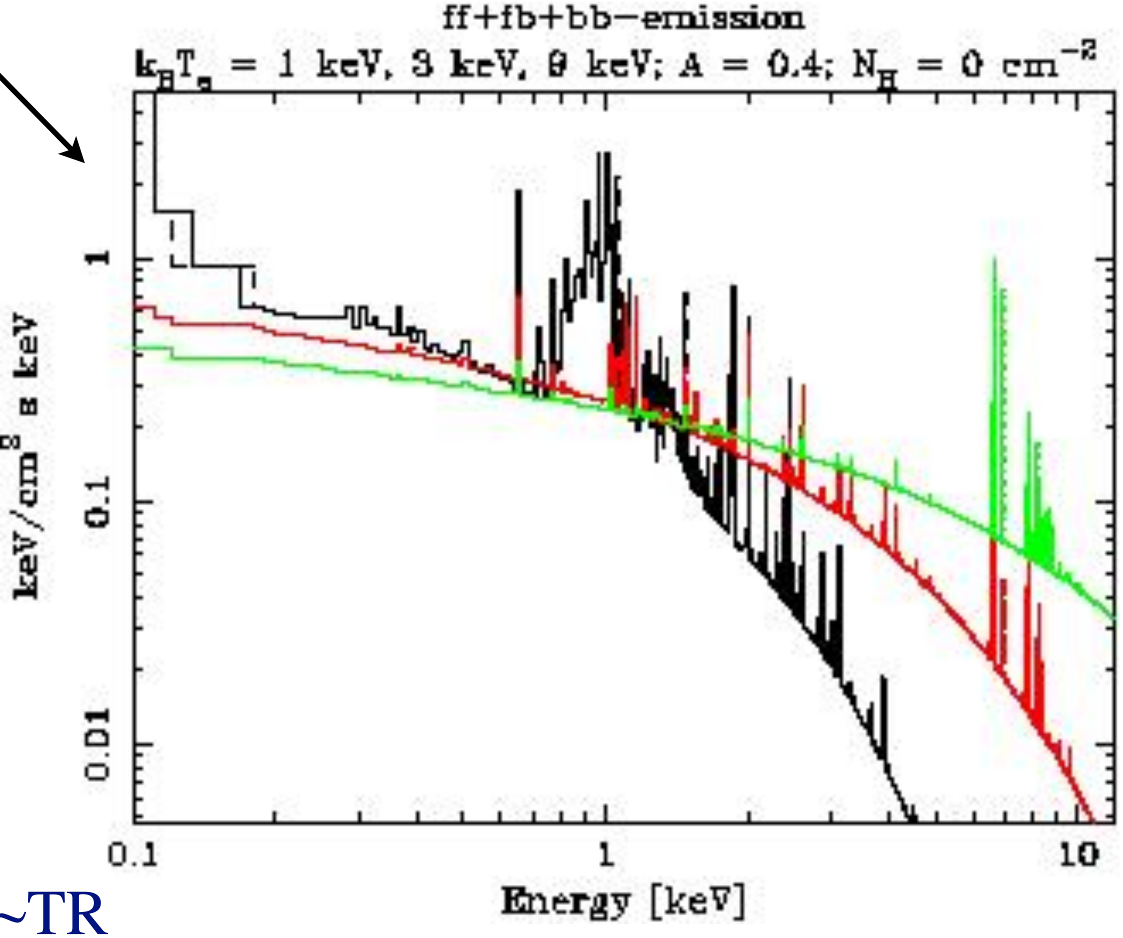
Mass Estimator

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

the gas density profile is determined by fitting the standard beta model to the surface brightness profile.



the gas temperature is measured from the X-ray spectrum

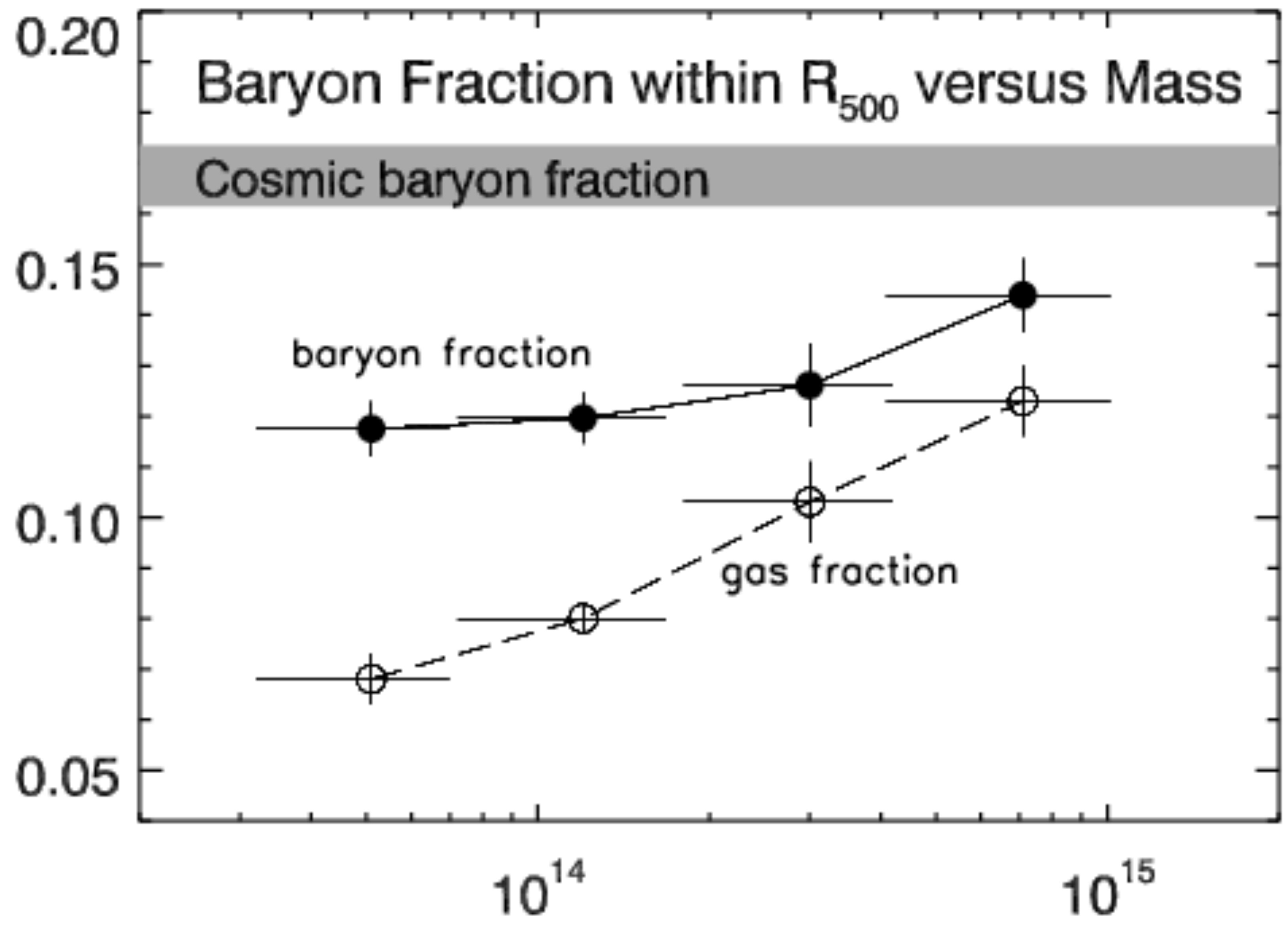


Assumes
- hydrostatic equilibrium
- sphericity

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

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

Rasheed (2010)

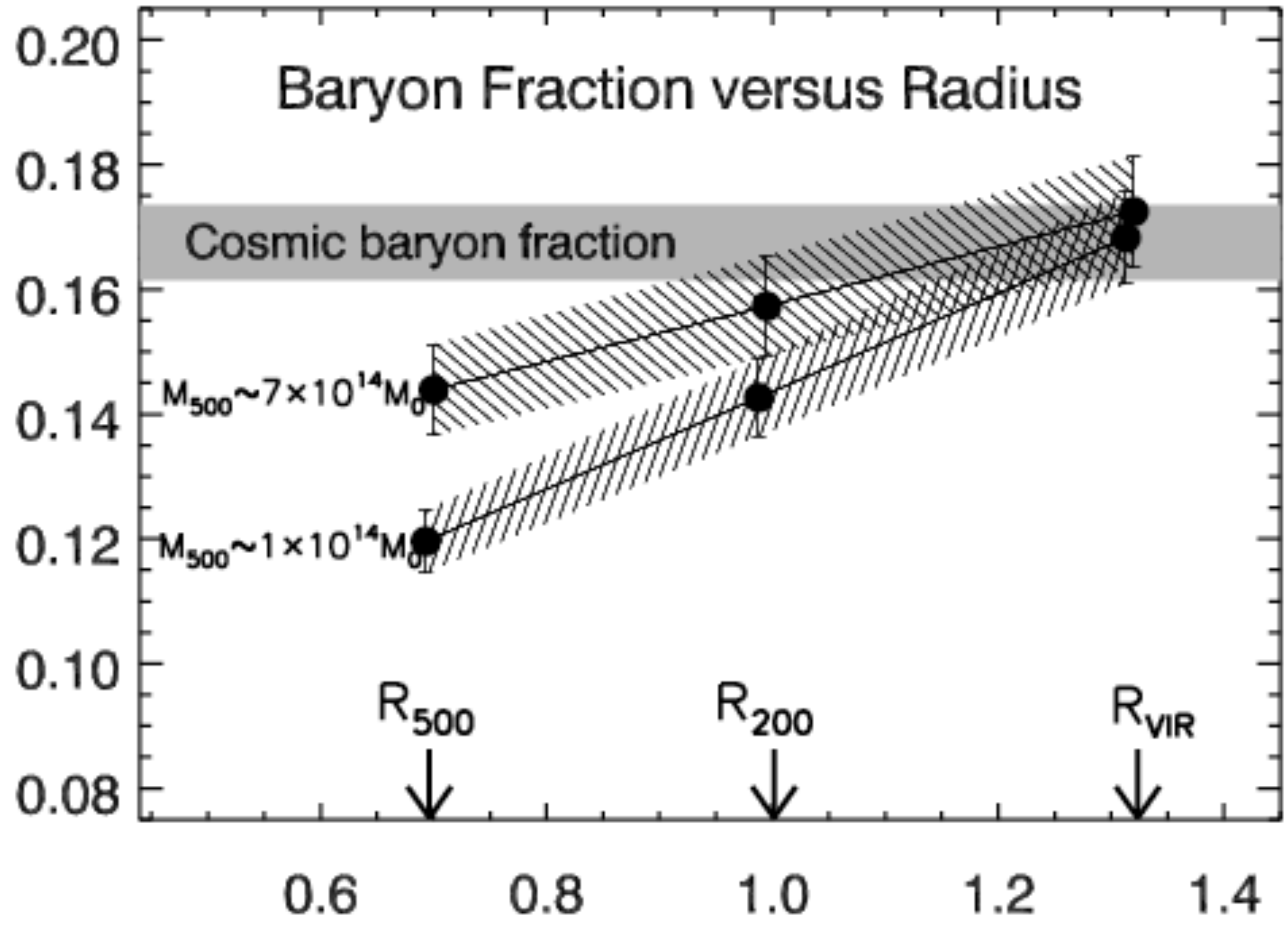


Typical result:

clusters have progressively more gas than stars at higher masses

Rasheed (2010)

variation with radius within individual clusters

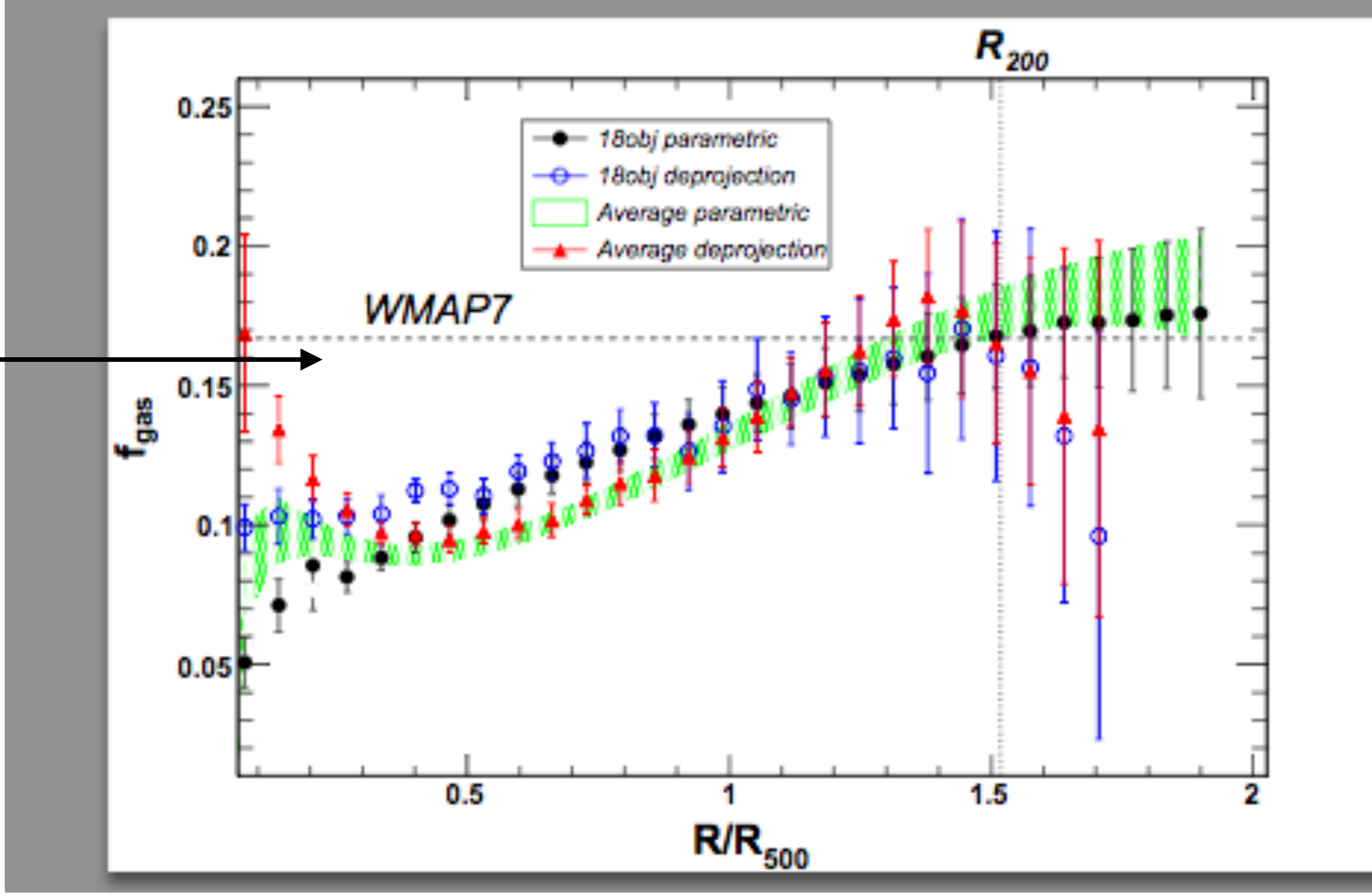


Rasheed (2010)

Typical result:

the baryon fraction increases with radius

(not often measured beyond R_{500})



There seems to be a missing baryon problem towards the centers of clusters

Typical result:

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

$$M_{tot} \approx 6M_{ICM} \approx 6^2 M_*$$

(crudely speaking — in detail, varies with mass)