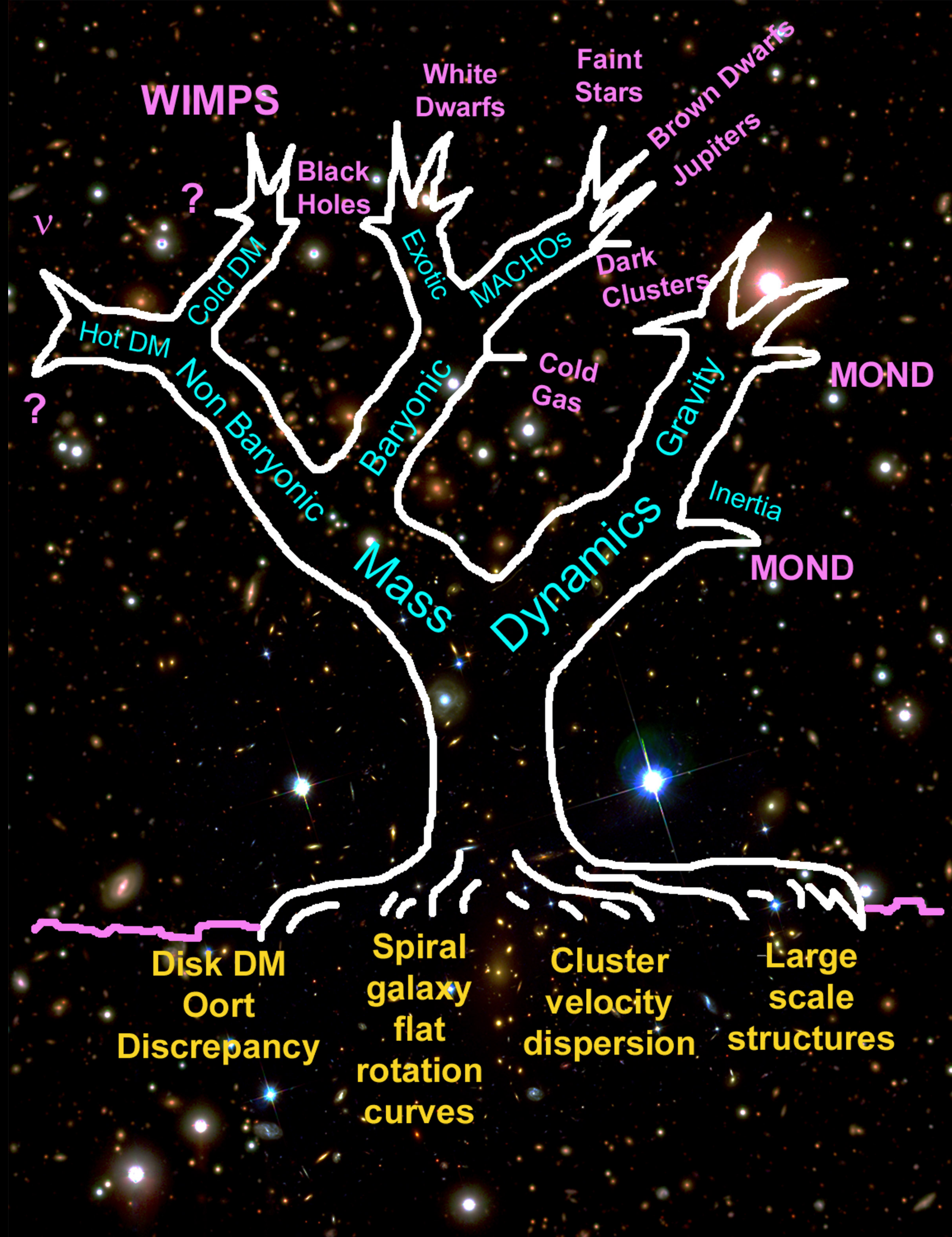
Dark Matter

ASTR 333/433

TODAY

Clusters of Galaxies

Hydrostatic Equilibrium
Sunyaev-Zel'dovich Effect
Gravitational Lensing



Mass estimators for Clusters of Galaxies

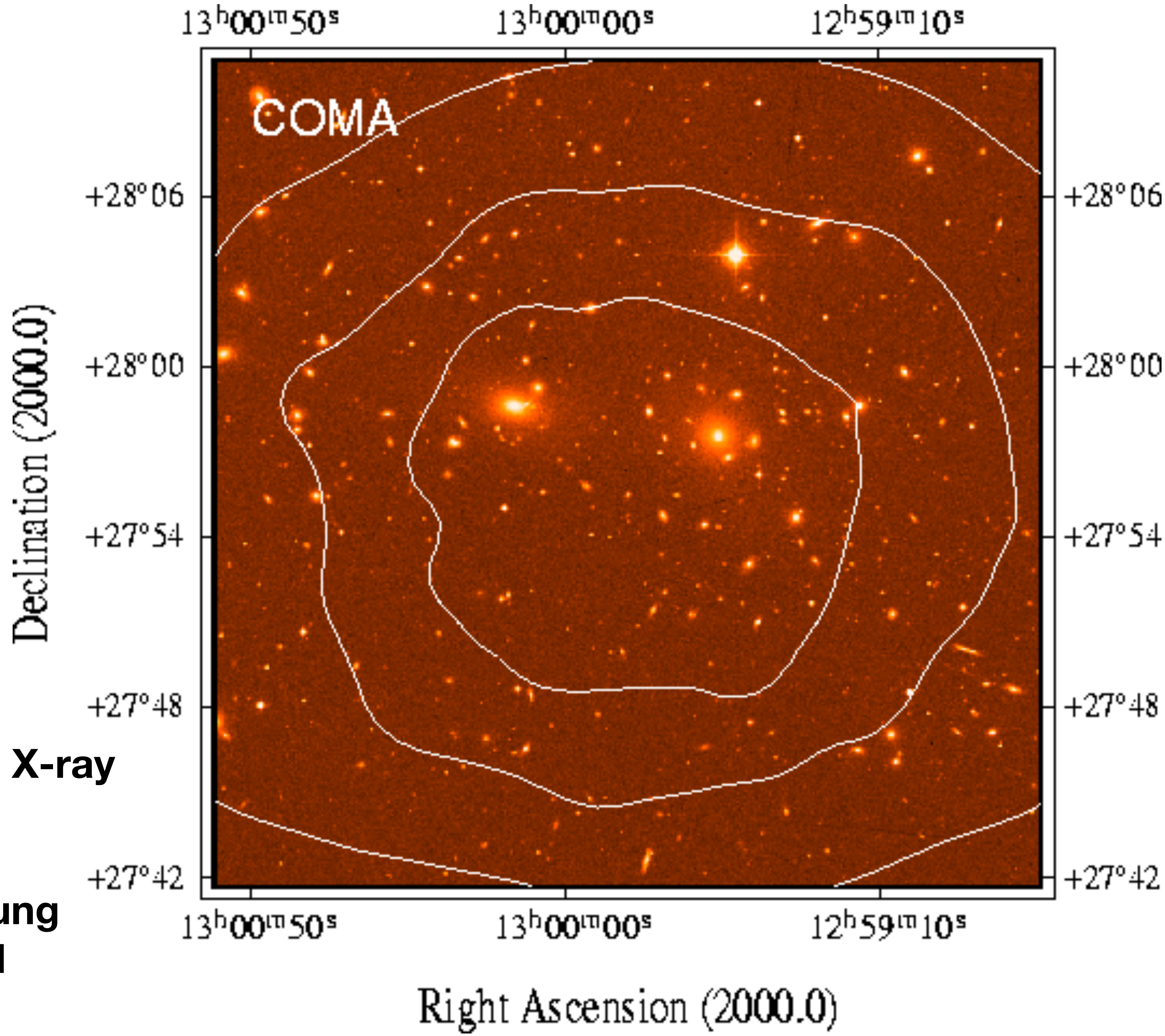
- Virial $$M = \frac{2.5}{G}\sigma^2 R_e$$

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

- 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

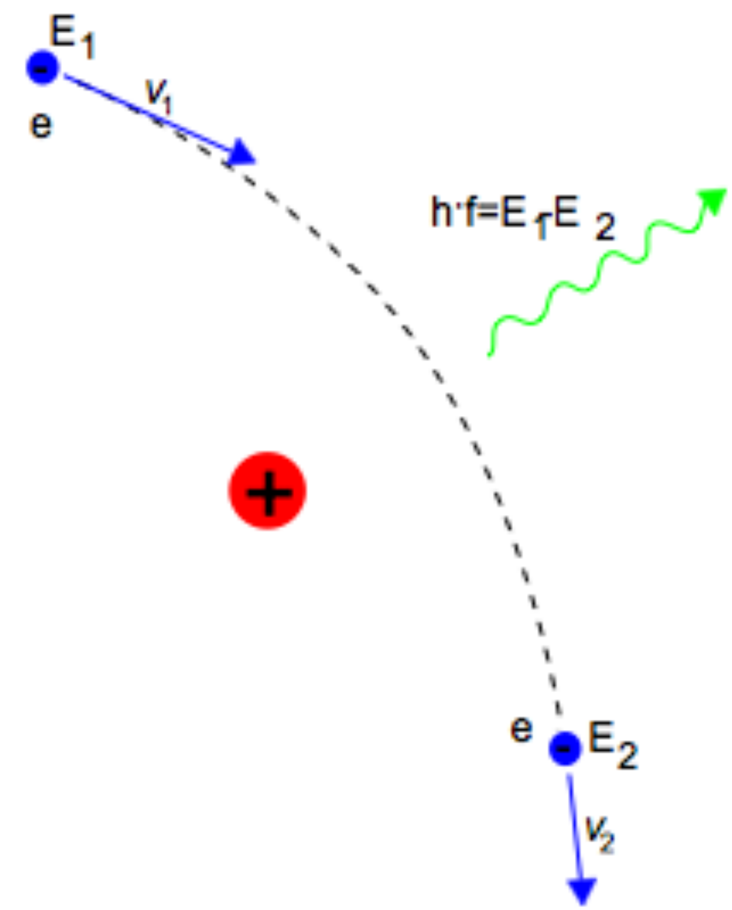
Reiprich ApJ, 567, 716-740 (2002)

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

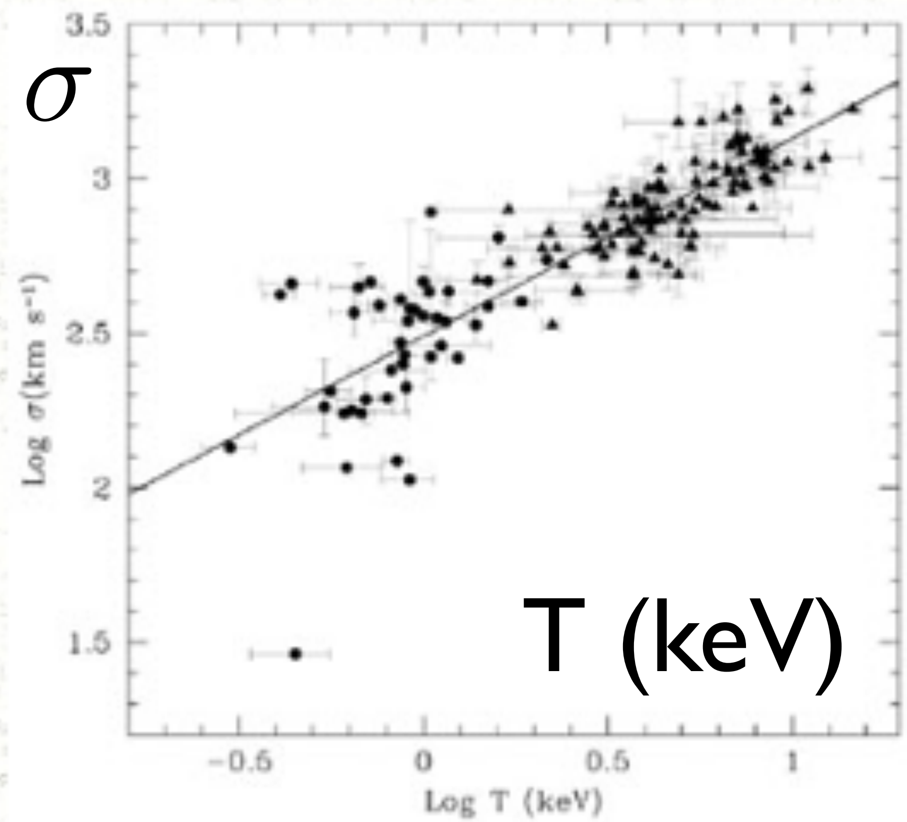


Figure 4. Logarithm of the X-ray temperature versus logarithm of optical velocity dispersion for a sample of groups (circles) and clusters (triangles). The group data are taken from the literature compilation of Xue & Wu (2000), with the addition of the groups in Helsdon & Ponman (2000). The cluster 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

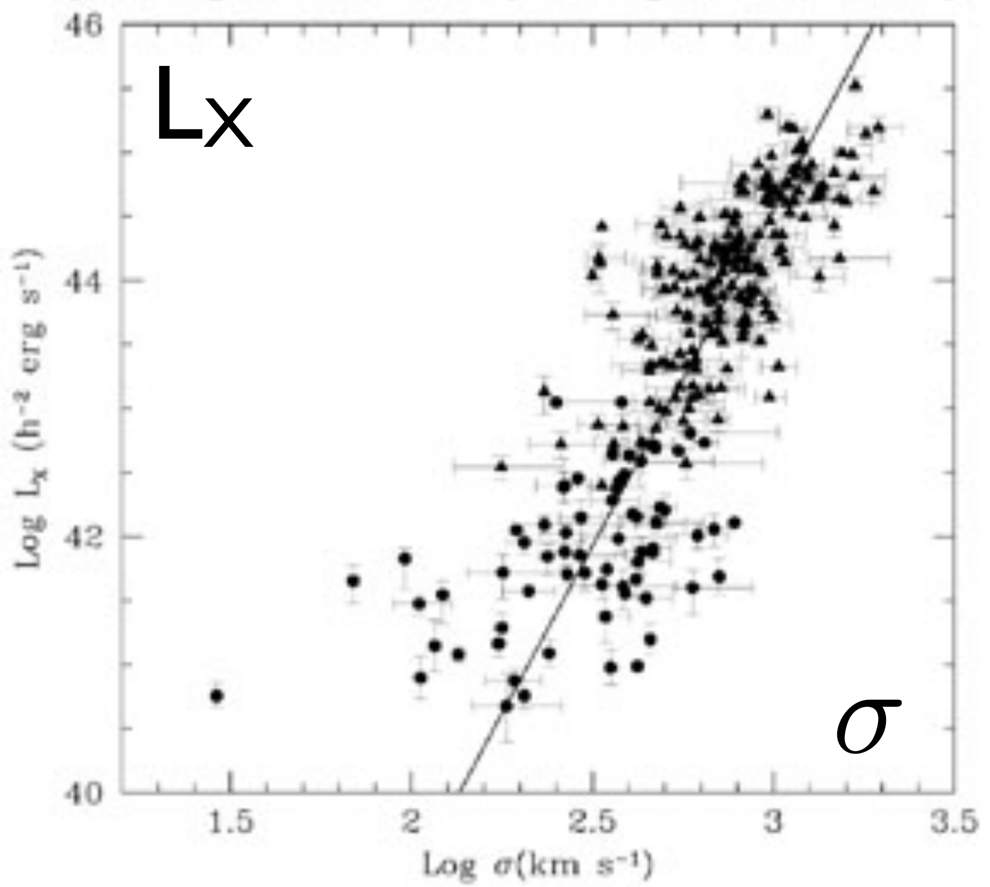


Figure 5. Logarithm of optical velocity dispersion versus logarithm of X-ray luminosity for a sample of groups (circles) and clusters (triangles). The data are taken from the same sources cited in Figure 4. The solid line represents the best-fit found by Wu et al (1999) for the clusters sample (using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

Velocity dispersion-Luminosity relation

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

Global correlations in galaxy clusters

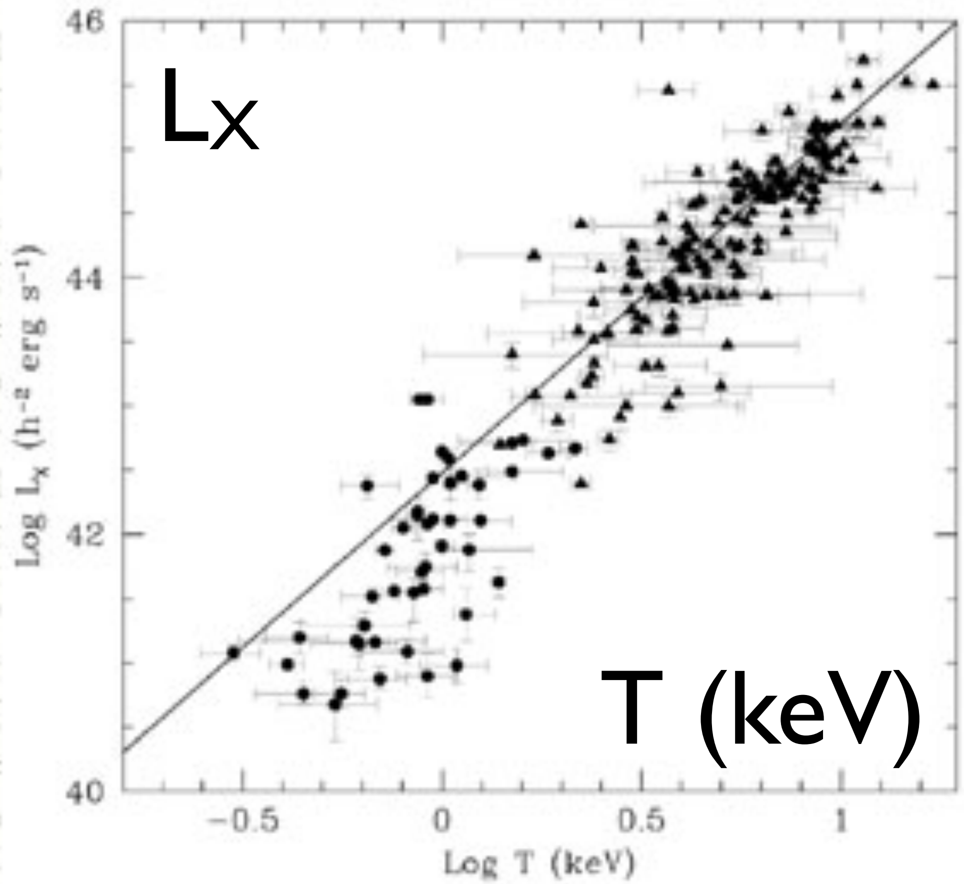


Figure 6. Logarithm of the X-ray temperature versus logarithm of X-ray luminosity for a sample of groups (circles) and clusters (triangles). The data are taken from the same sources cited in Figure 4. The solid line represents the best-fit found by Wu et al (1999) for the clusters sample (using an orthogonal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

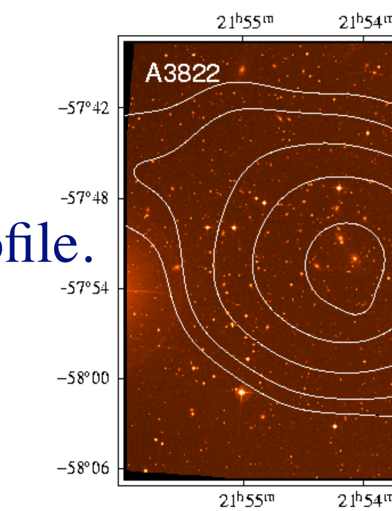
Typically the gas is assumed to be isothermal

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

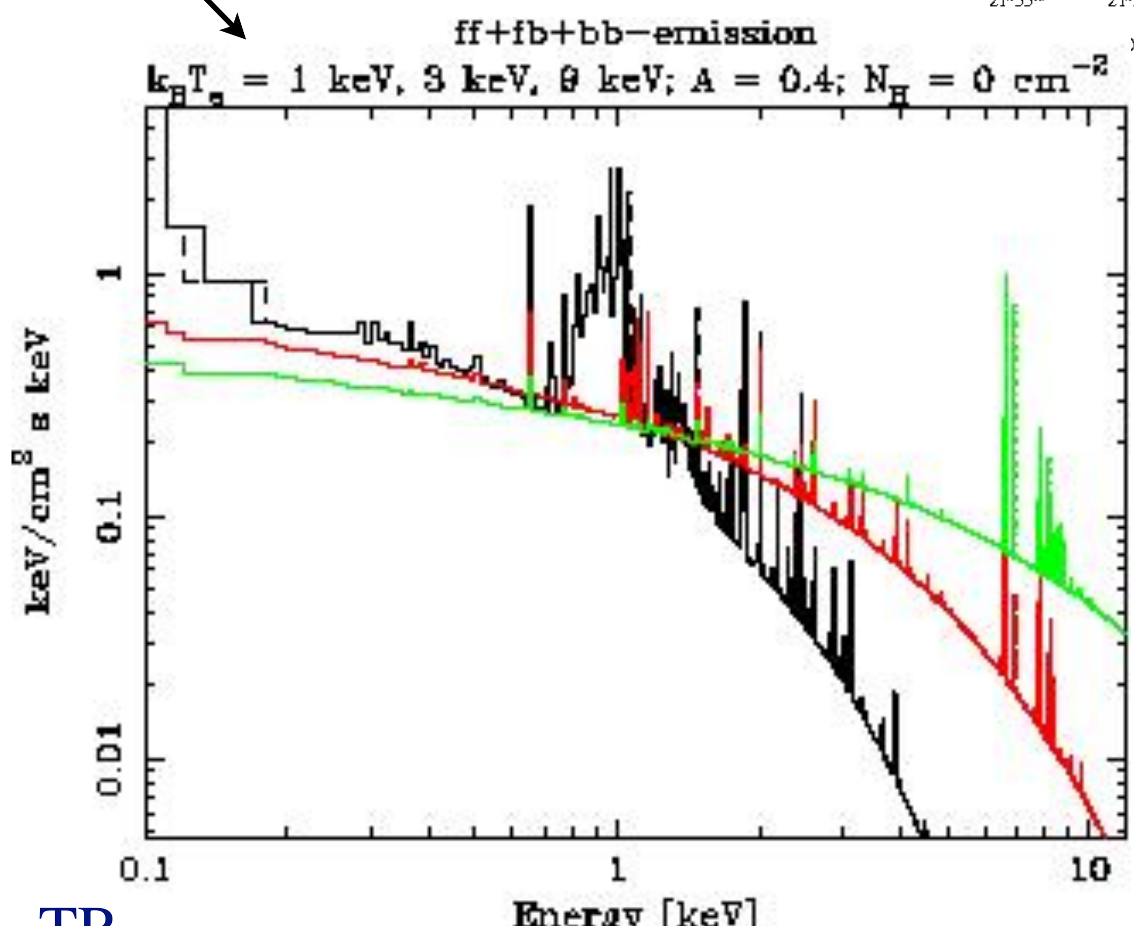
Mass Estimator

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

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

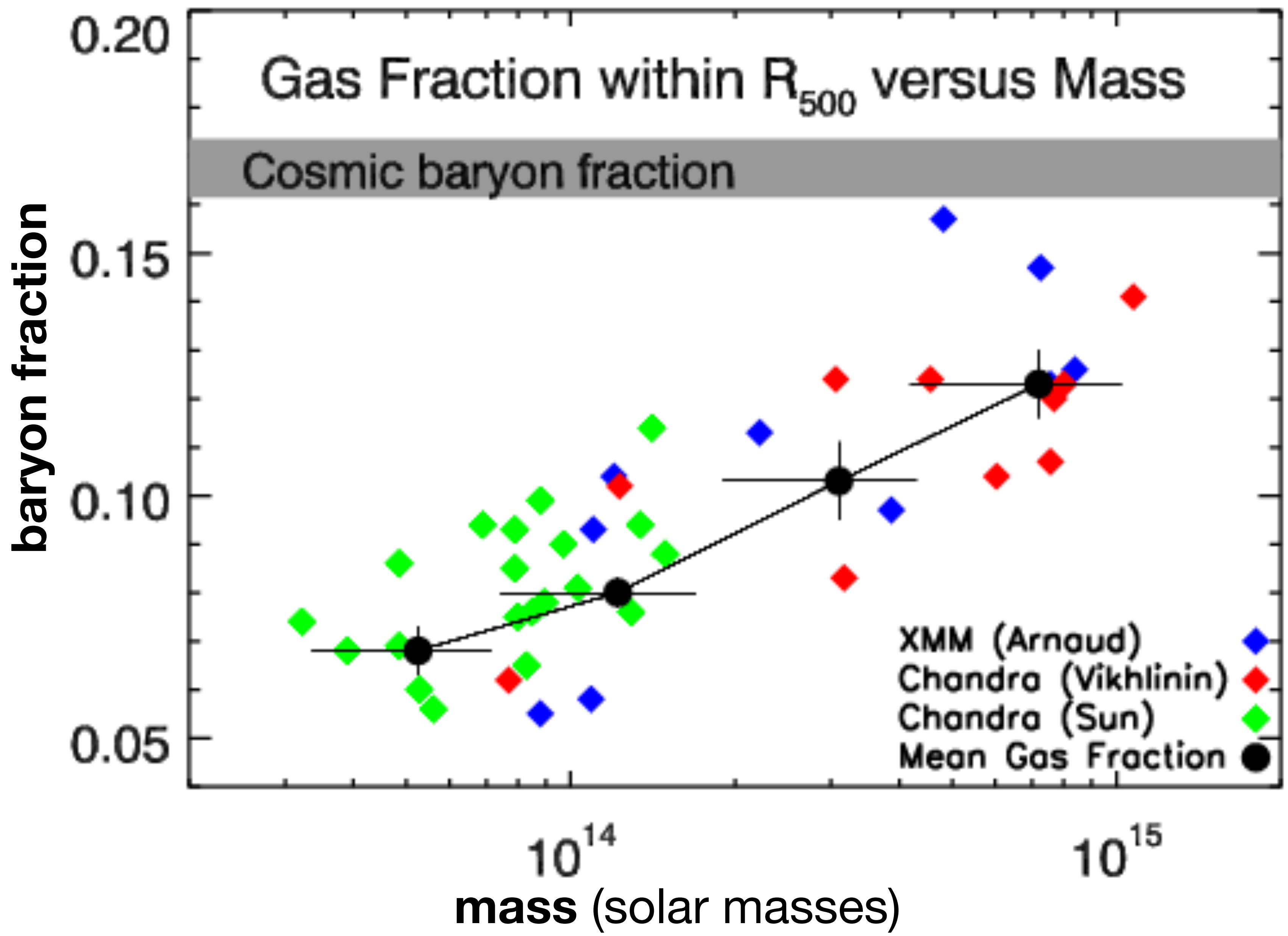
often assumes

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

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

recall the detected baryon-mass relation from last time

variation with cluster mass



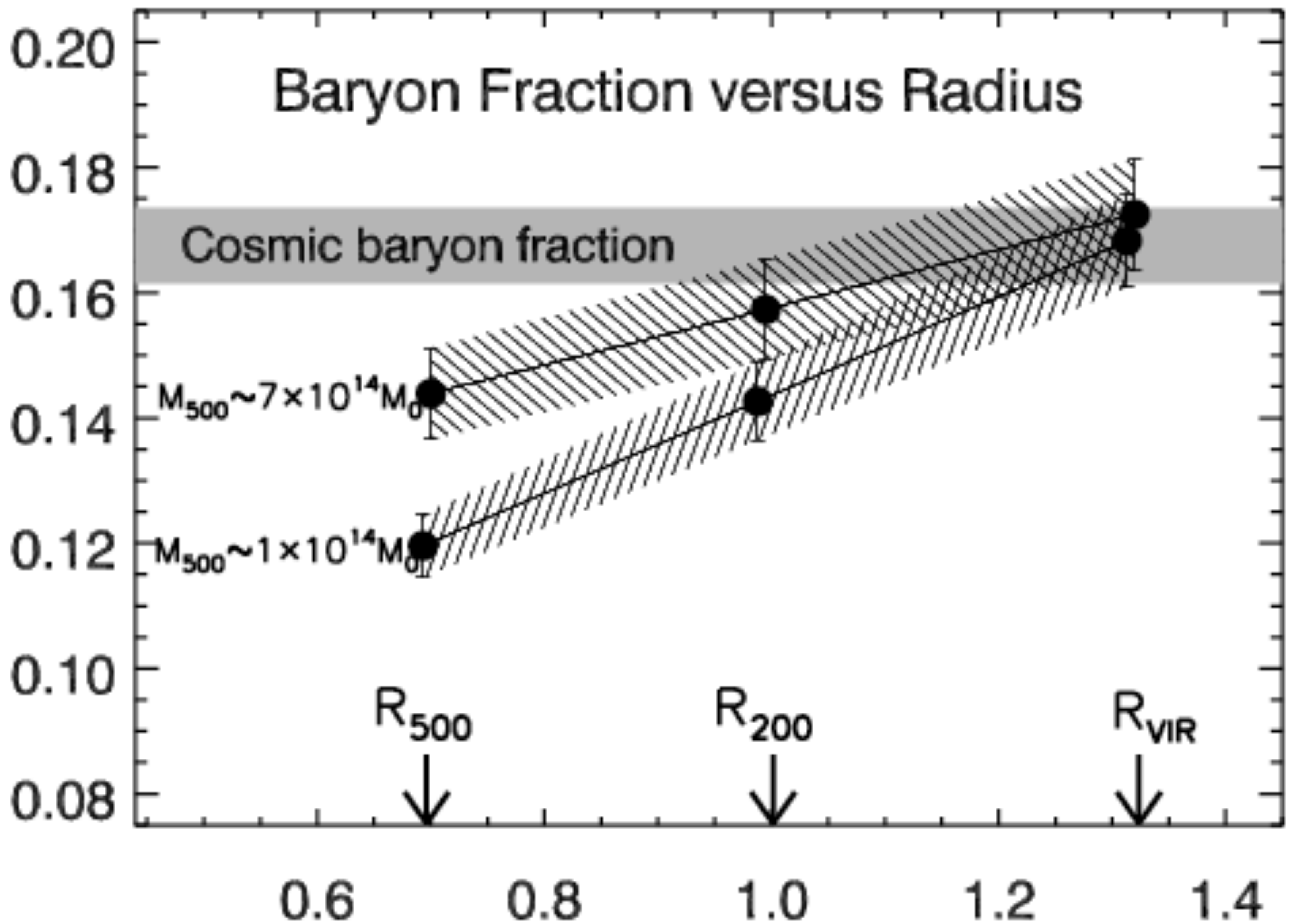
Rasheed (2010)

Typical result:

The most massive clusters have close to, but not quite, the expected baryon fraction

Rasheed (2010)

variation with radius within individual clusters



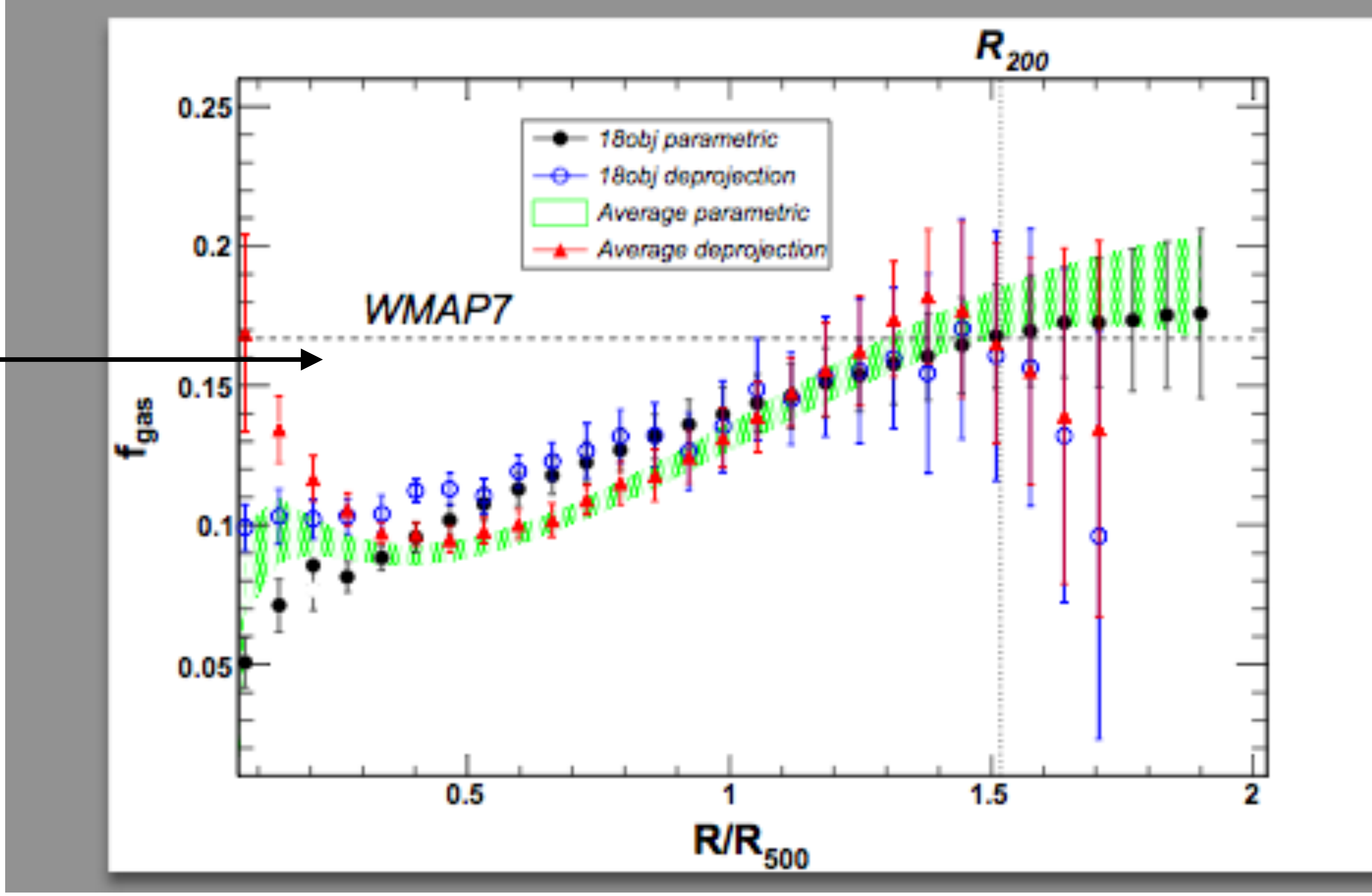
Rasheed (2010)

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



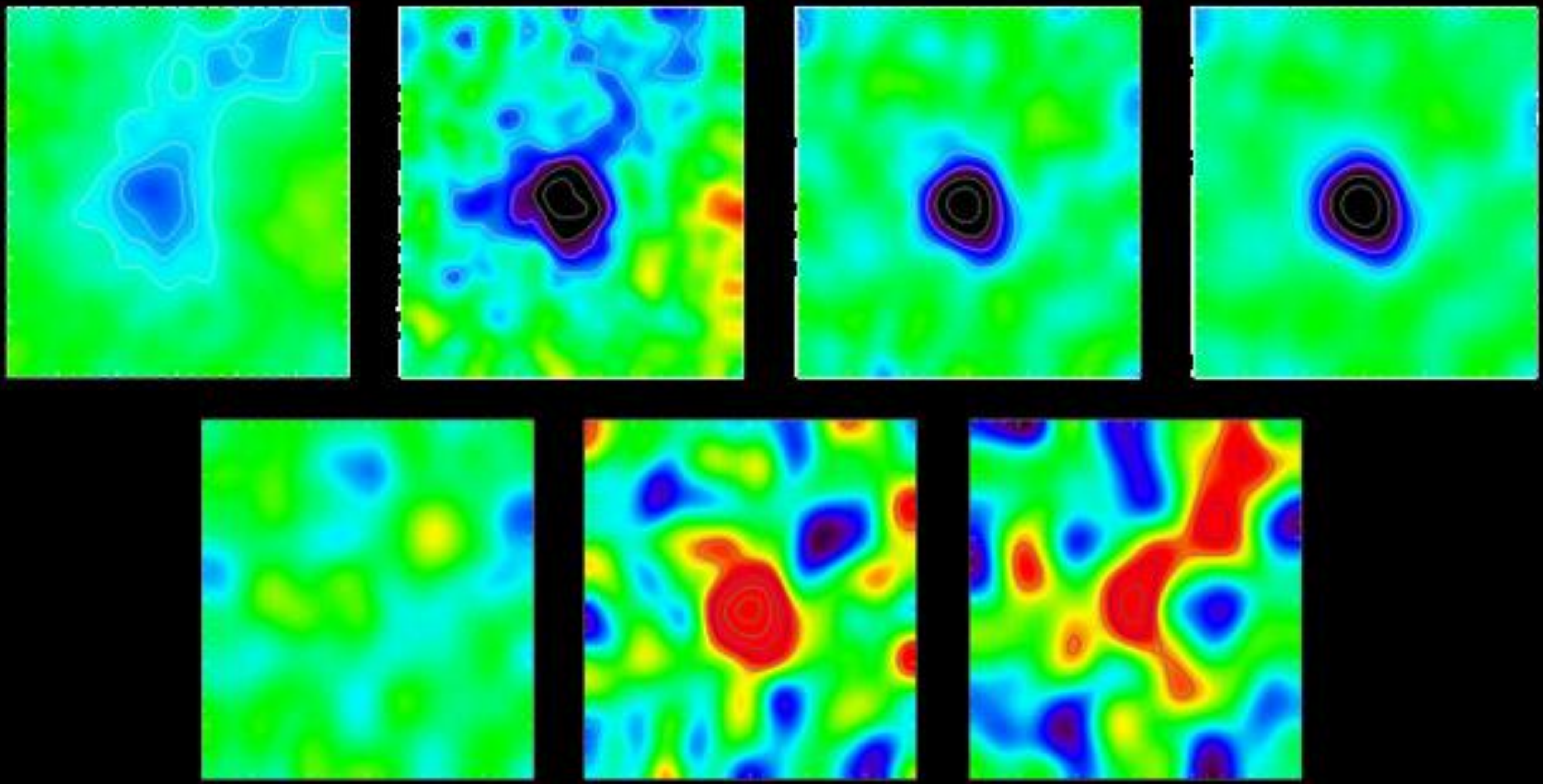
Typical result:

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

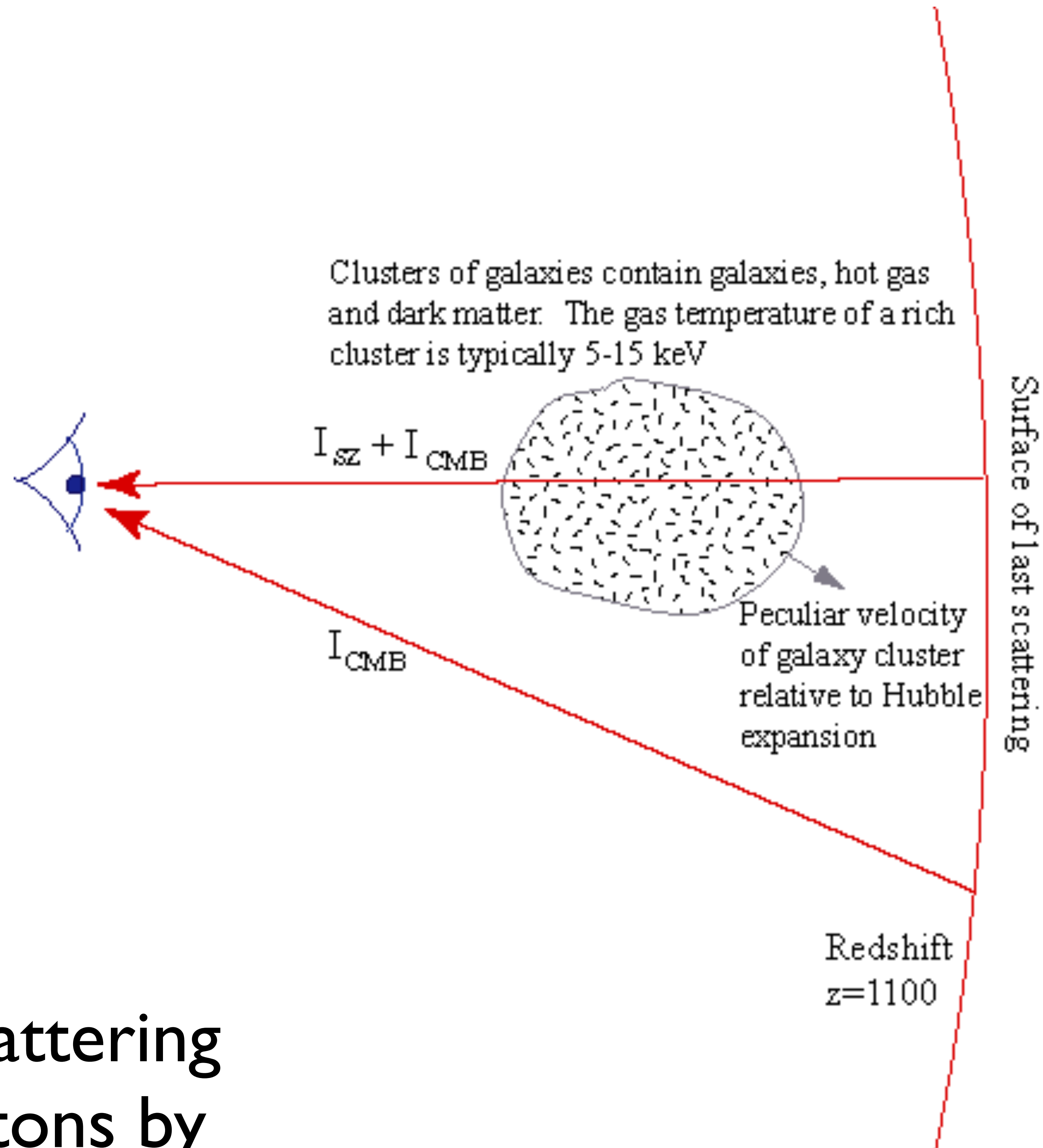
$$M_{tot} \approx 6M_{ICM} \approx 6^2 M_*$$

(crudely speaking — in detail, varies with mass)

SUNYAEV–ZEL'DOVICH EFFECT



SUNYAEV–ZEL'DOVICH 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 $y = \int \sigma_T n_e \frac{kT_g}{m_e c^2} d\ell$

T_{rad}: CMB

n_e: electron density

σ_T: Thomson scattering cross-section

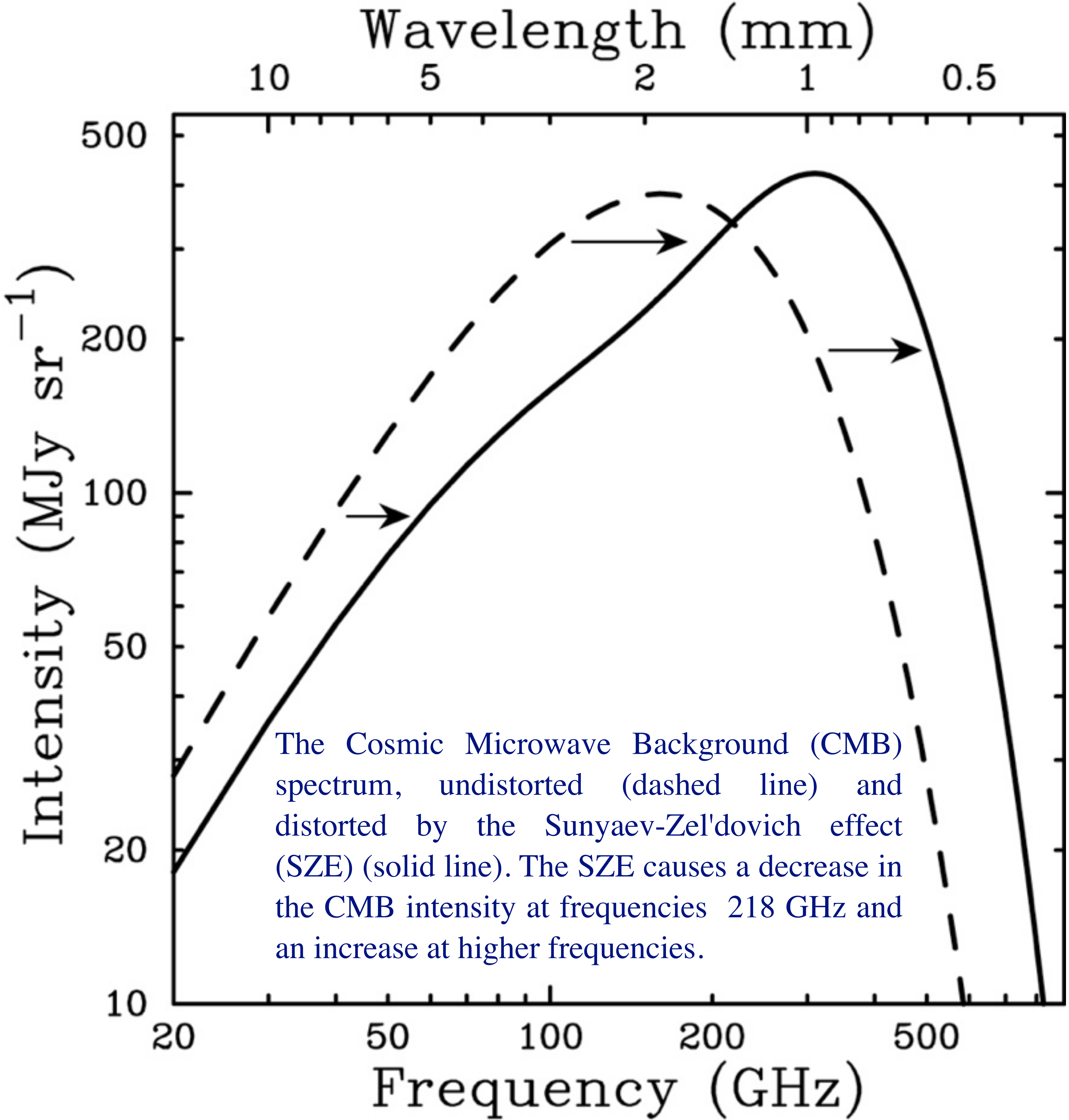
y is the Compton y-parameter which quantifies how much effect the plasma has frequency dependent change in intensity

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

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,

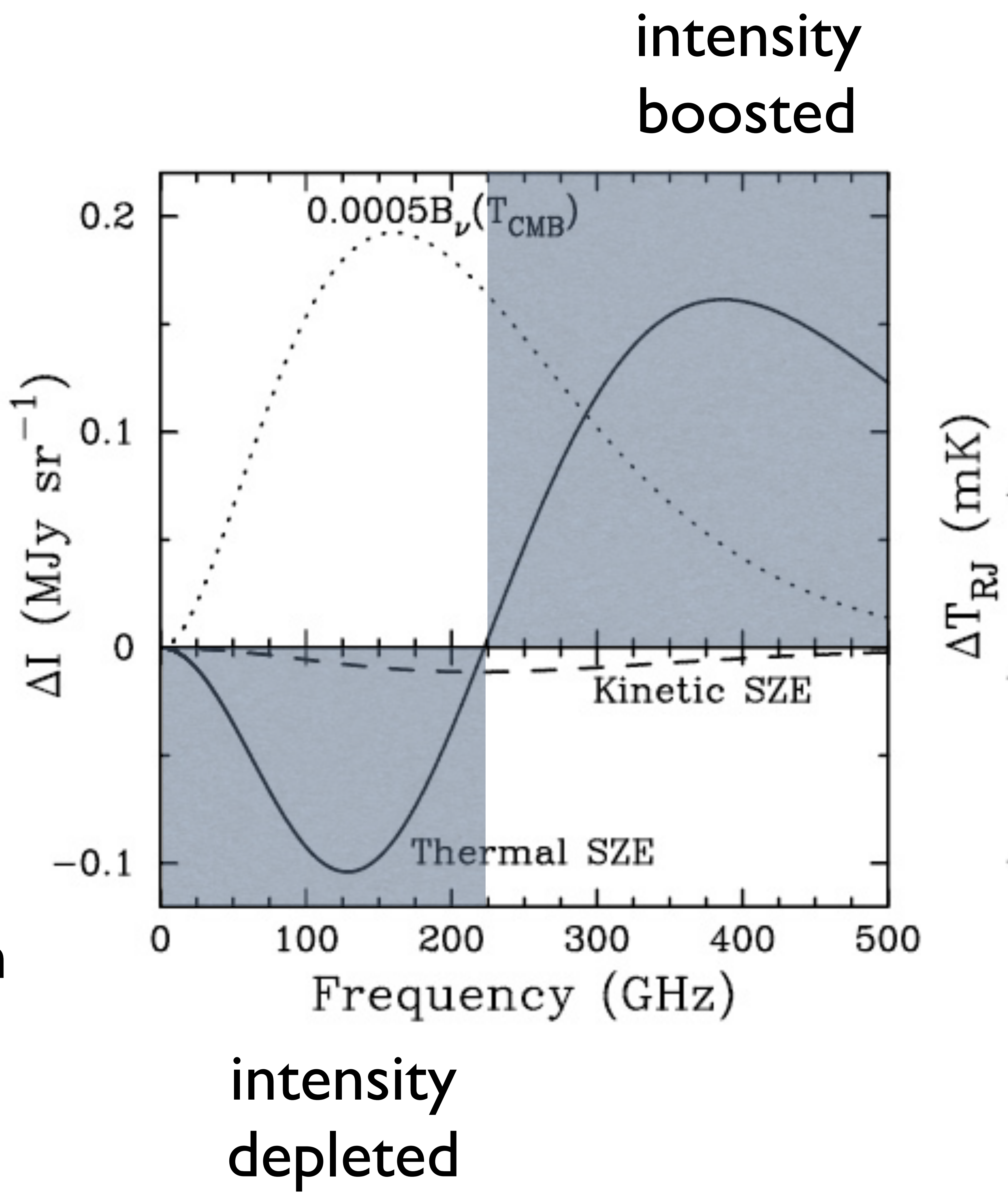
$$\frac{\delta I}{I} = \frac{\delta T}{T} = -2y$$



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

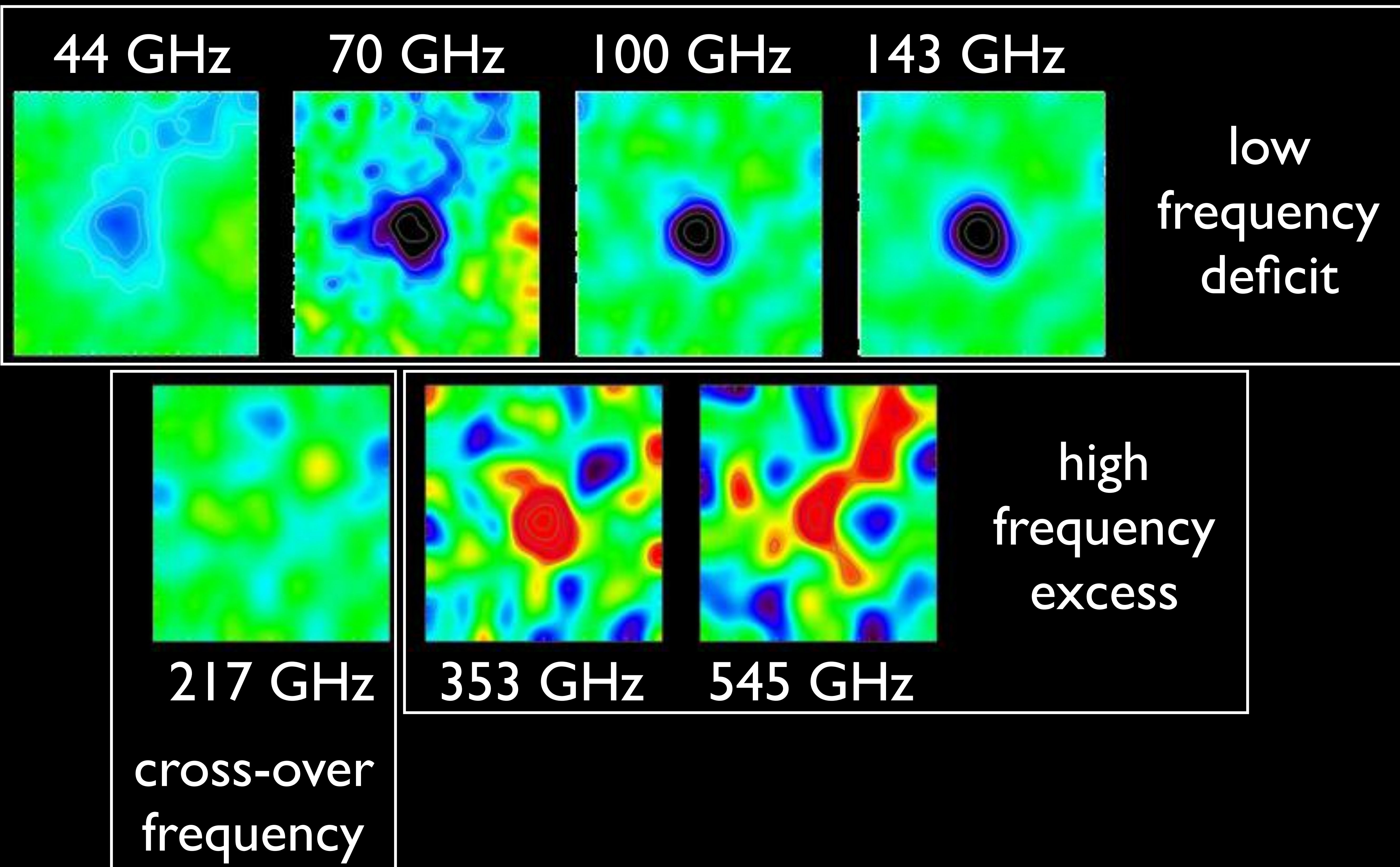
Thermal SZ effect from Compton scattering of CMB photons by cluster plasma

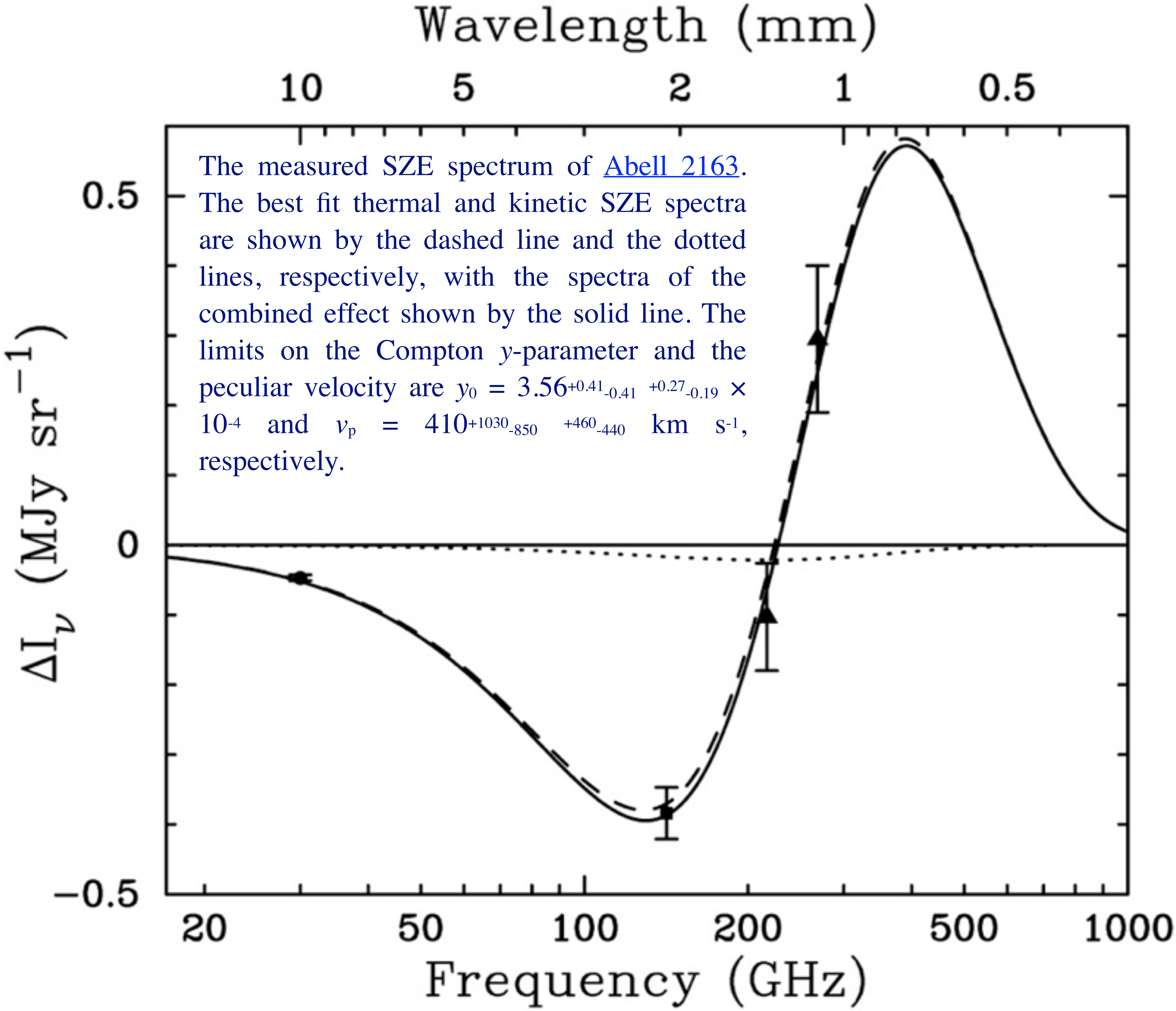


Kinematic SZ effect from peculiar velocity of cluster wrt CMB frame

SUNYAEV–ZEL'DOVICH EFFECT

detected by Planck





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!

Gravitational Lensing

Flavors of gravitational lensing:

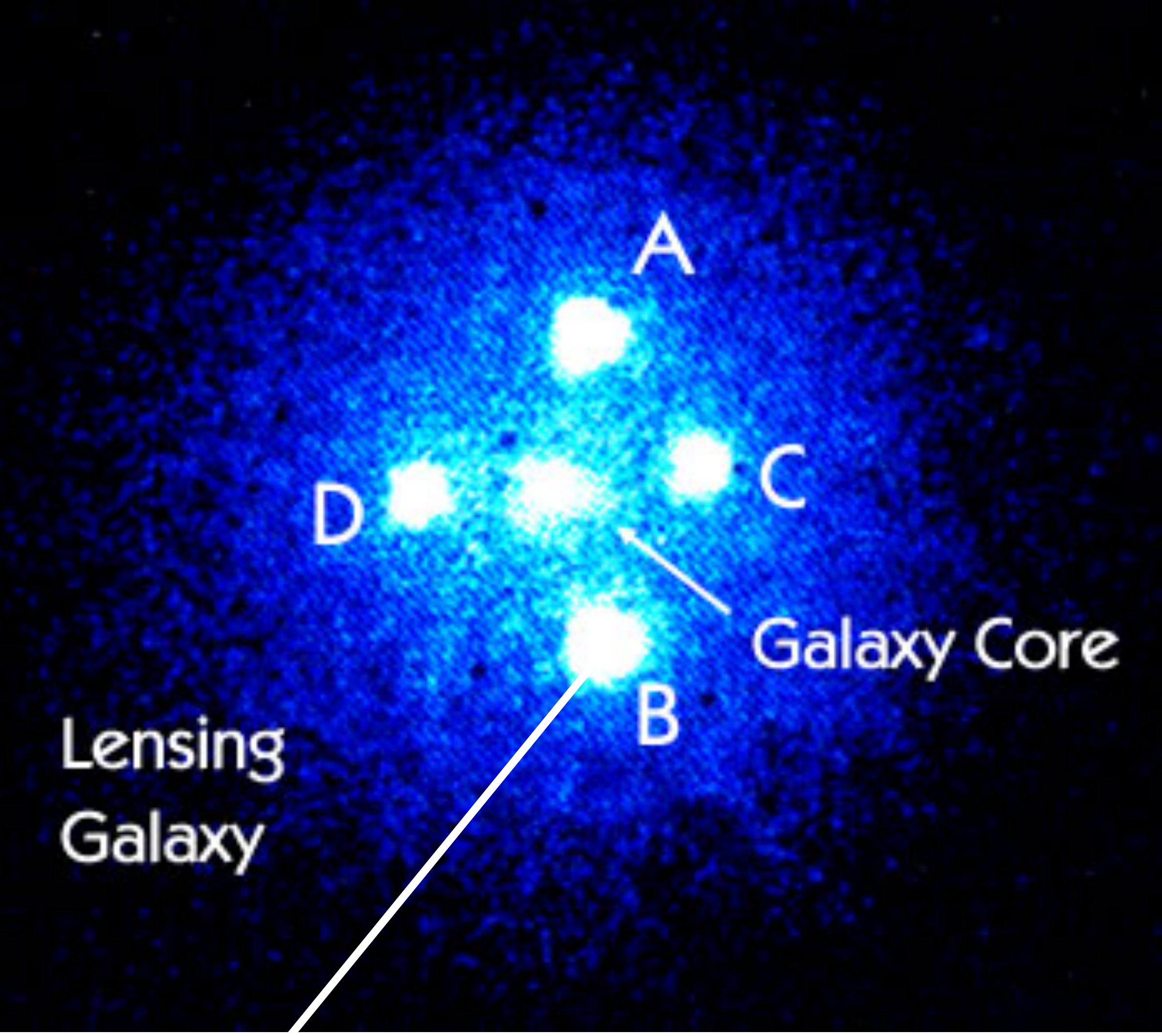
— weak lensing
mild distortion of lensed image

— strong lensing
multiple images, strong distortion

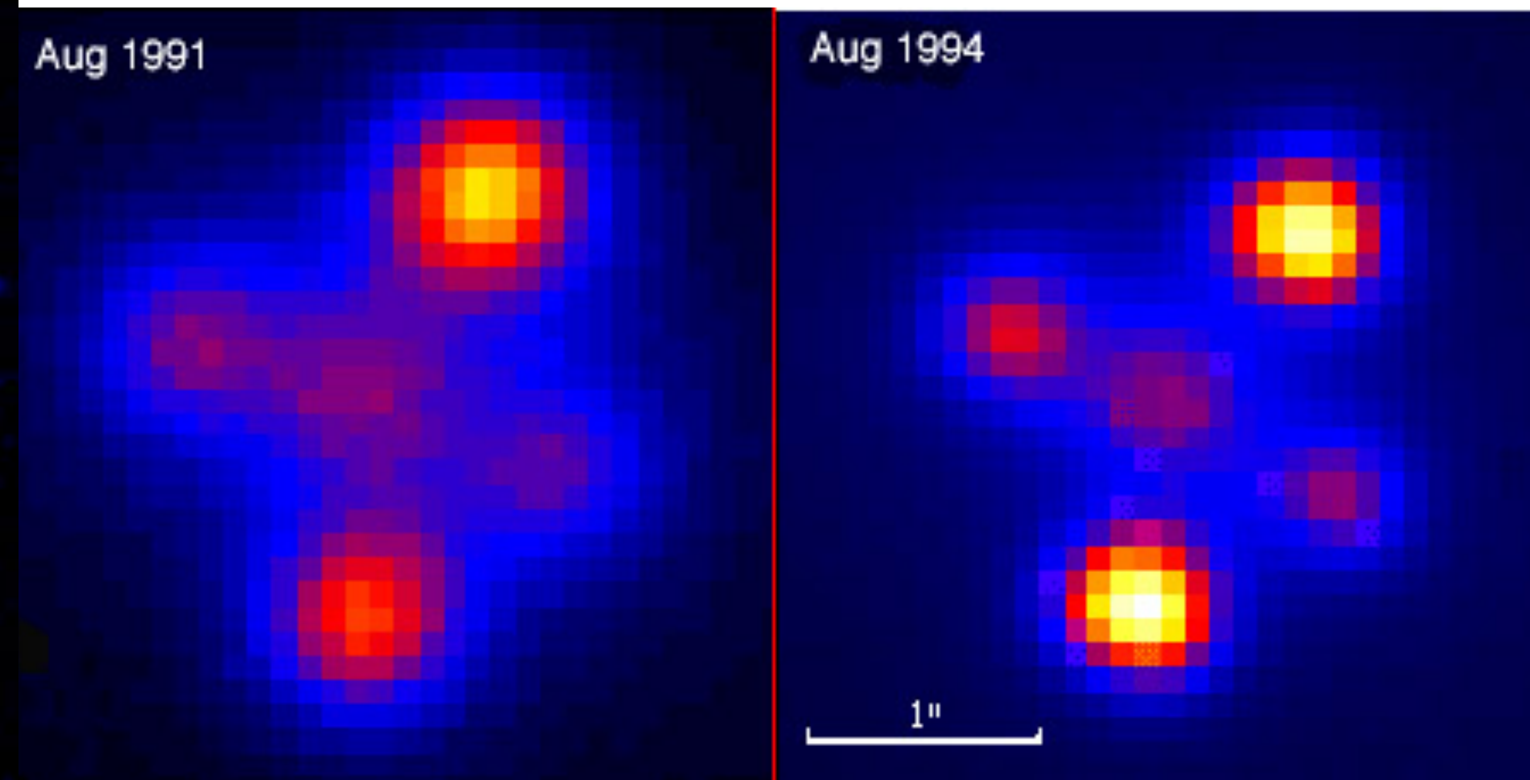
— microlensing
temporary brightening due to unresolved lensing

Fake illustration of weak lensing

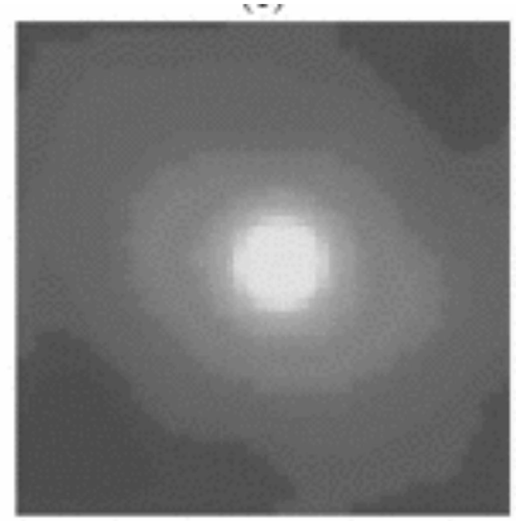
Strong lensing: Einstein Cross



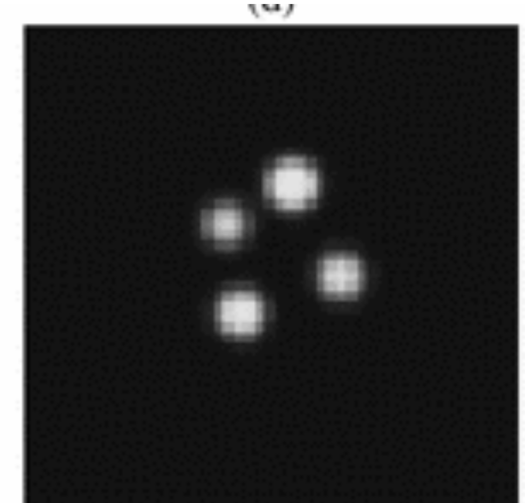
ABCD: same QSO seen 4 times



time variable multiple QSO image



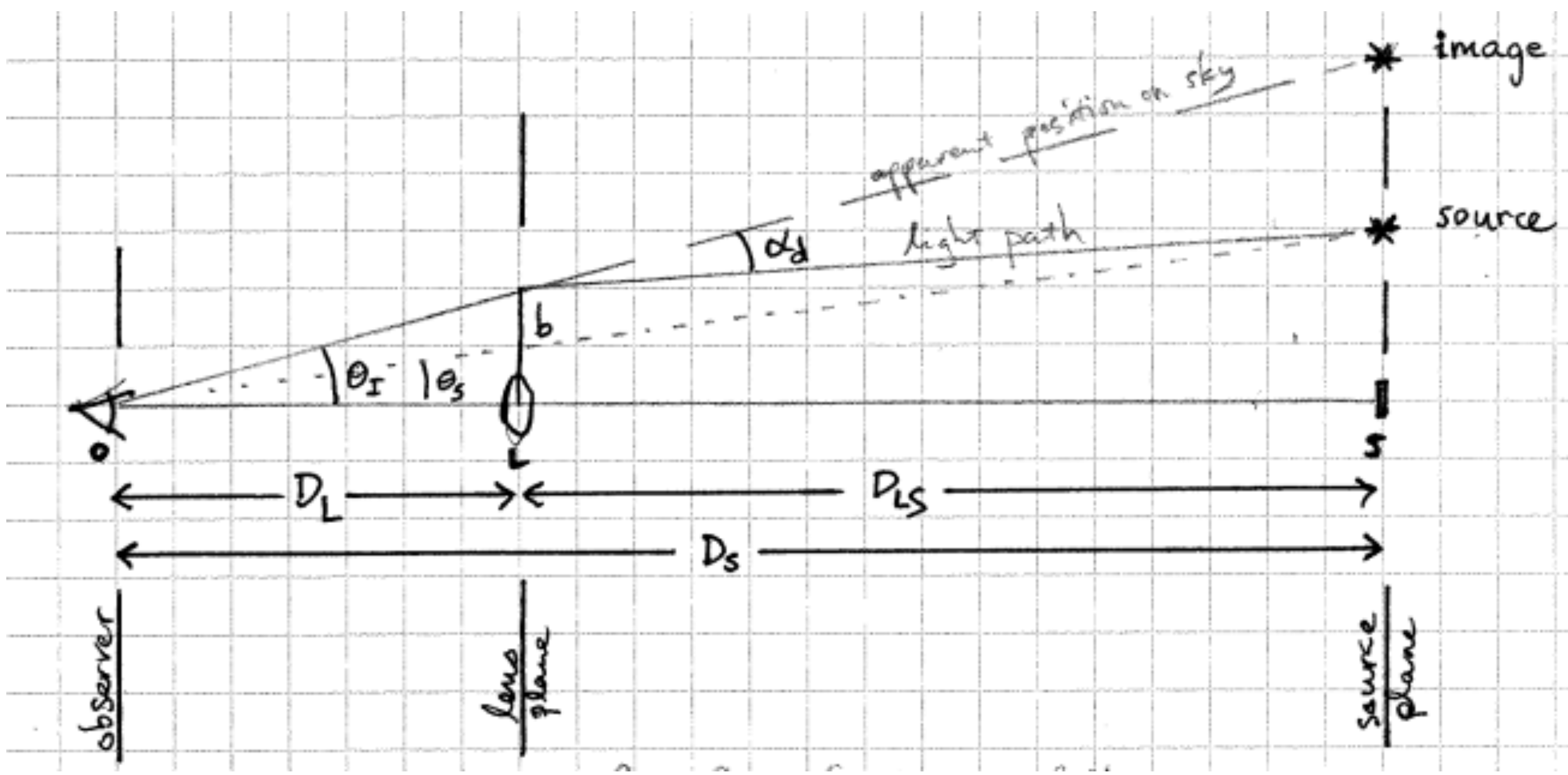
lensing galaxy



lensed QSO

Gravitational Lensing

θ_I	observed angle between image and lens	D_L	lens distance
θ_S	true separation angle between image and lens	D_S	source distance
α_d	bend angle	D_{LS}	lens-source separation
b	impact parameter		

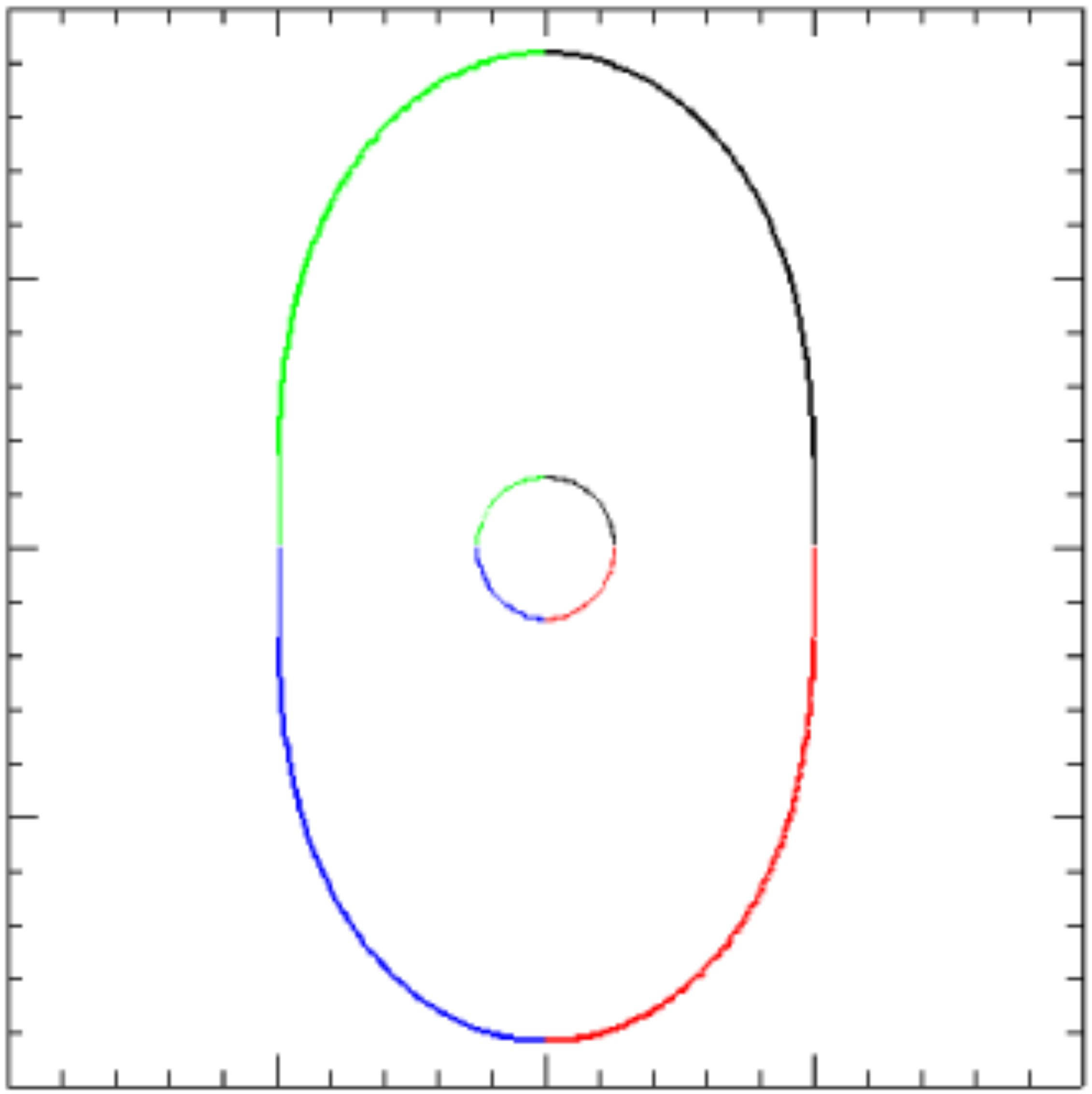


observer

lens plane

source plane

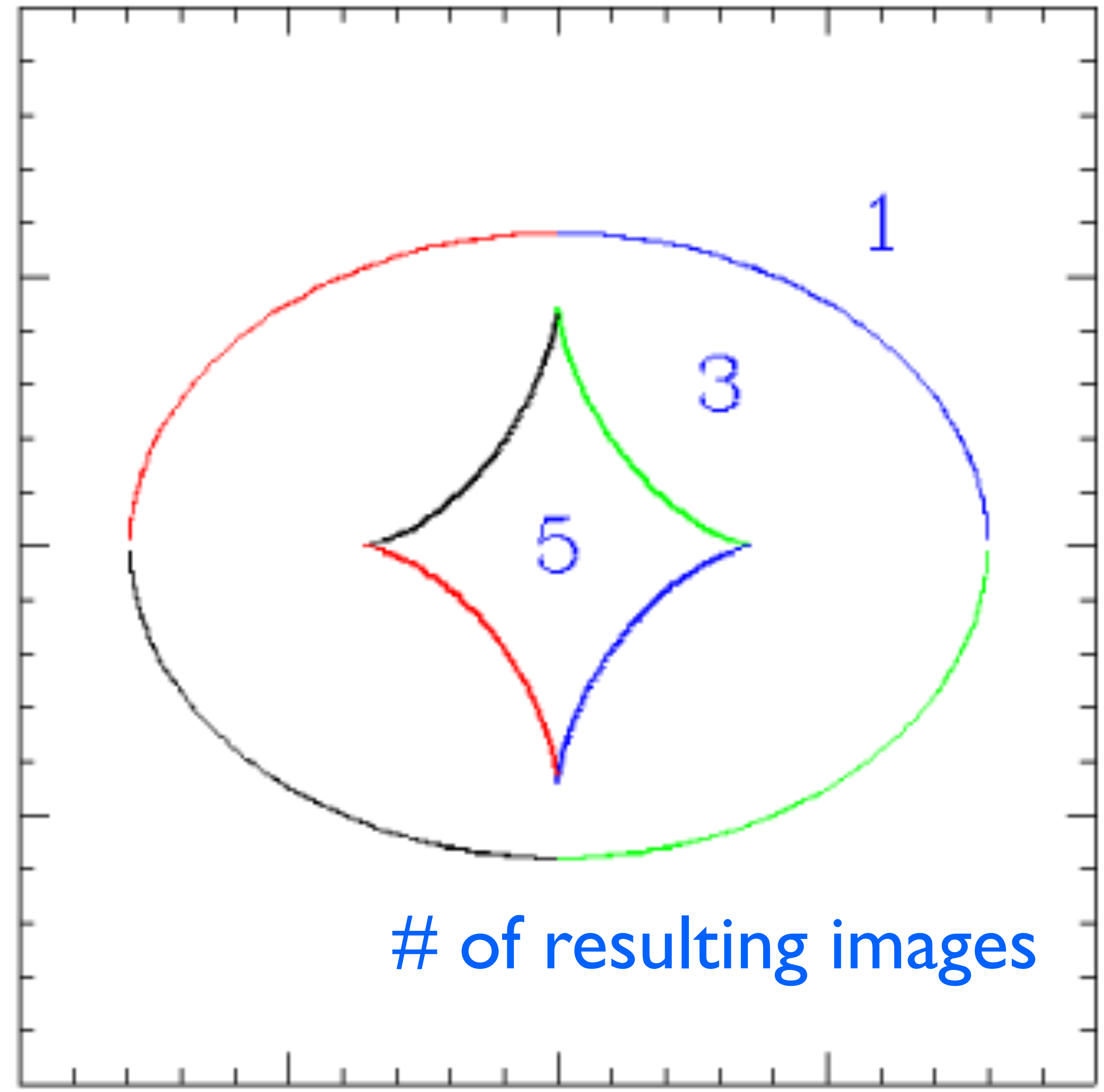
Lens plane



critical curves

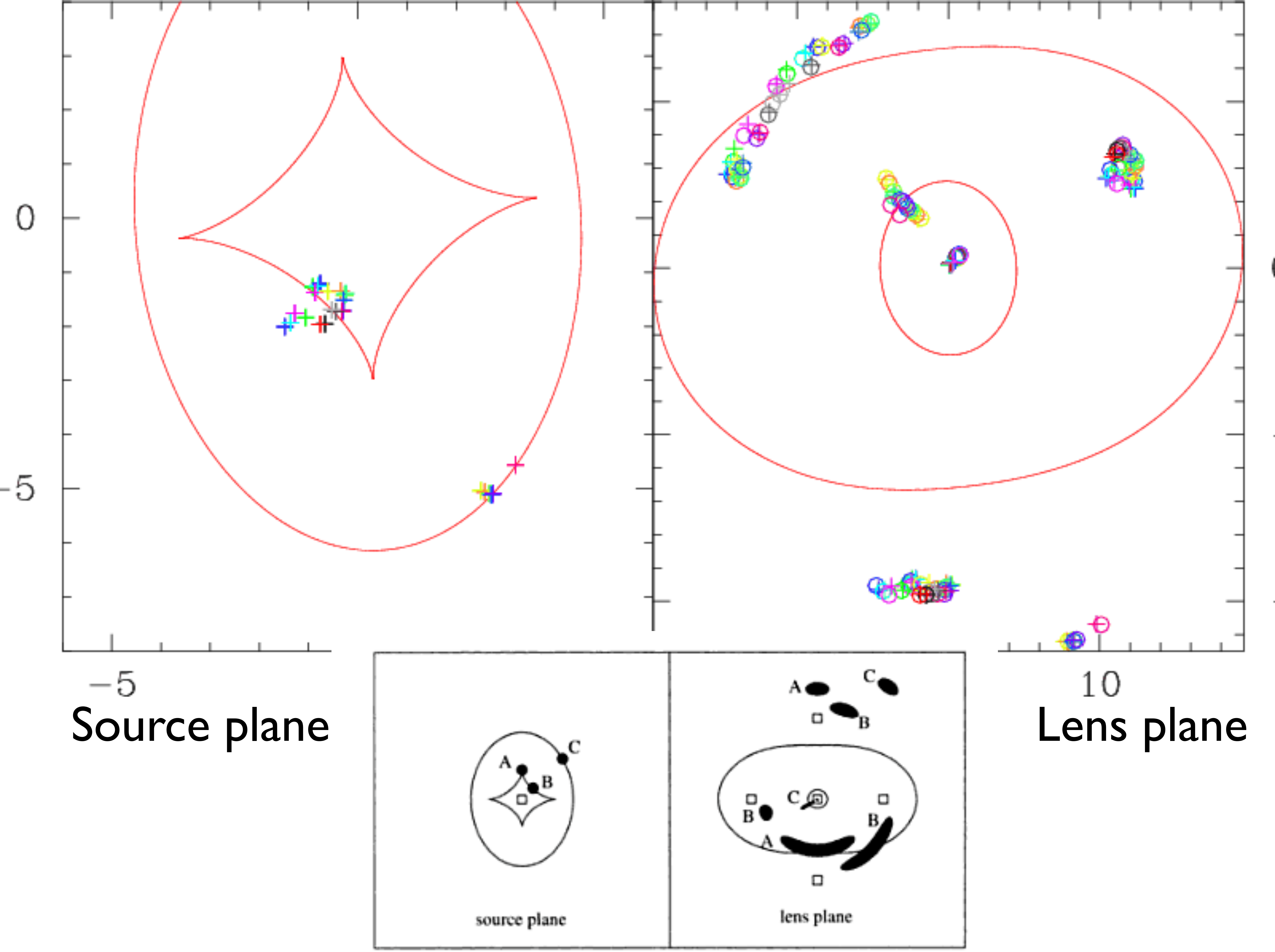
Critical curves are the lines in the lens plane where the magnification diverges towards infinity.

Source plane

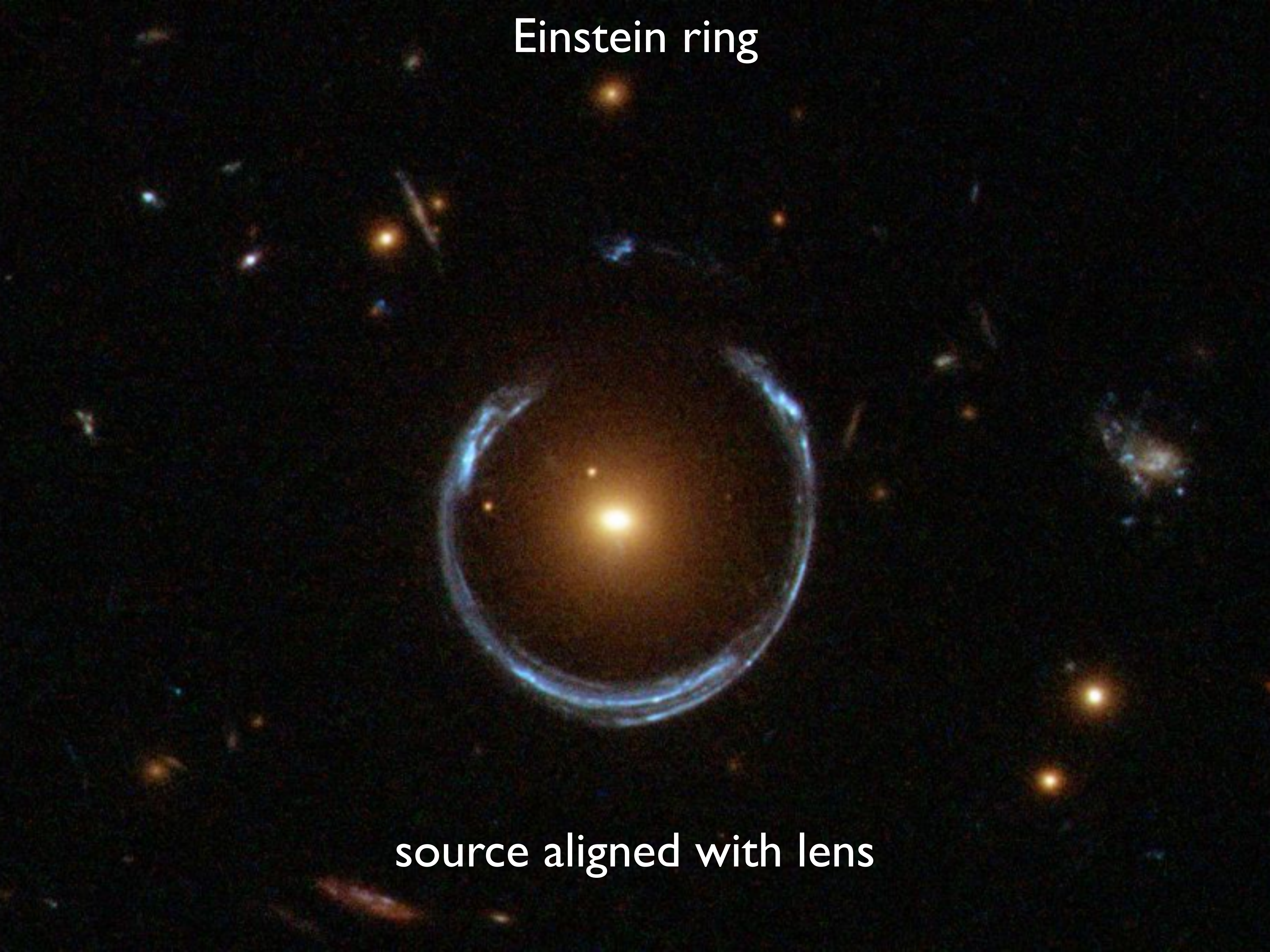


caustics

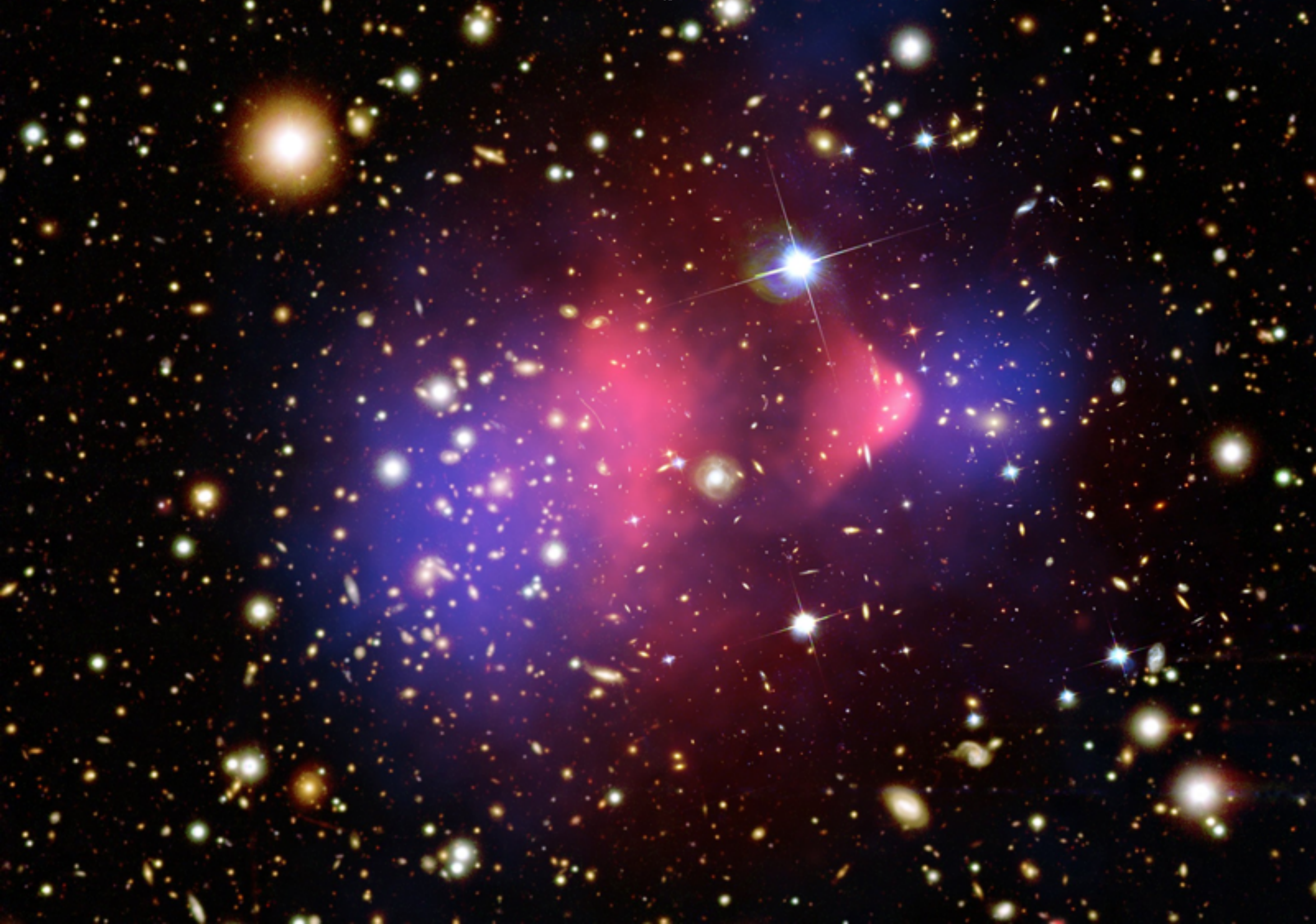
Caustics are the corresponding lines in the source plane. Traced back from the observer, multiple light rays bunch up, causing high magnification.



0
-5
−5
10
Source plane
Lens plane
A
B
C
source plane
lens plane

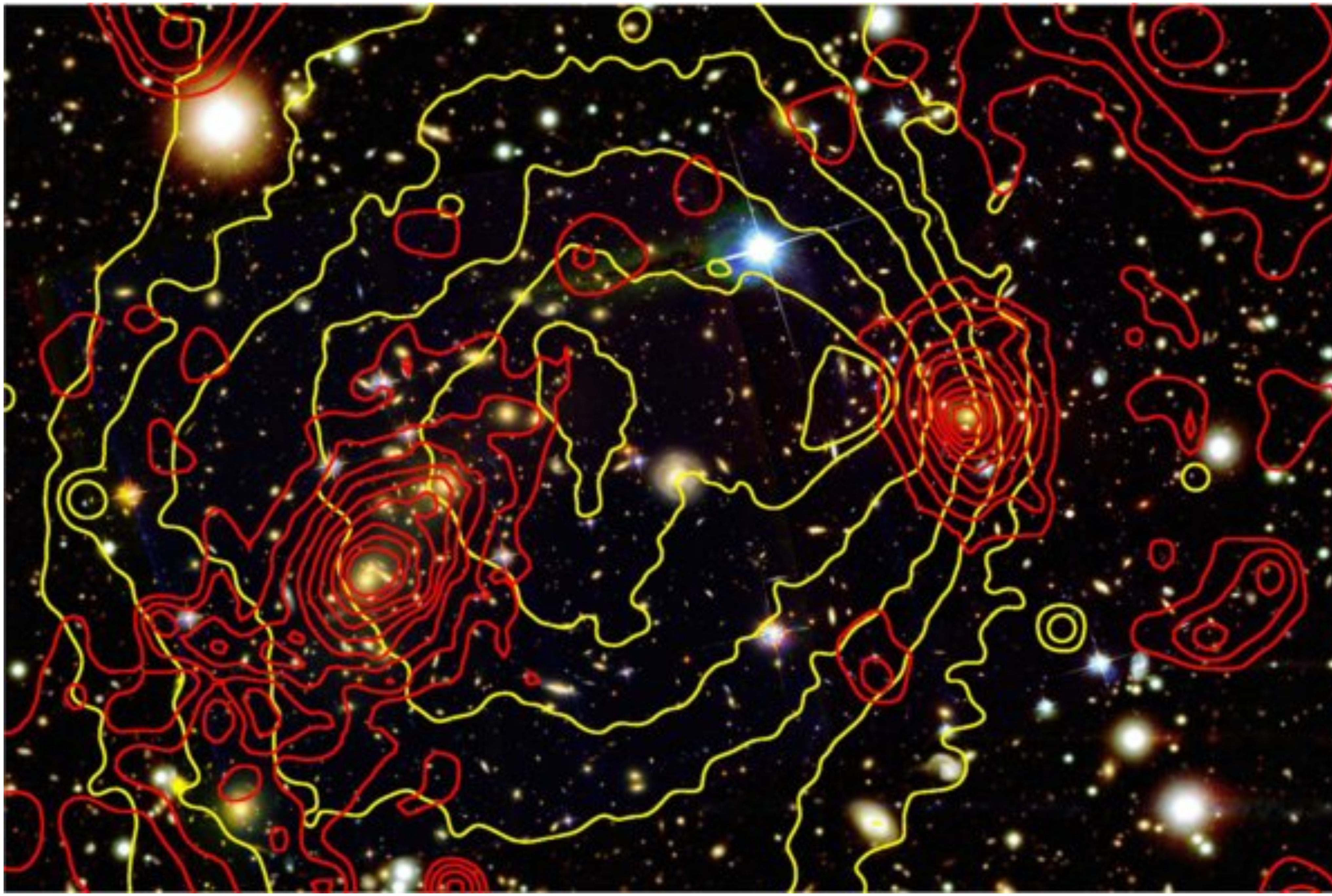

Einstein ring
source aligned with lens

Bullet cluster (press release version)



Bullet cluster (Bradac et al. 2009)

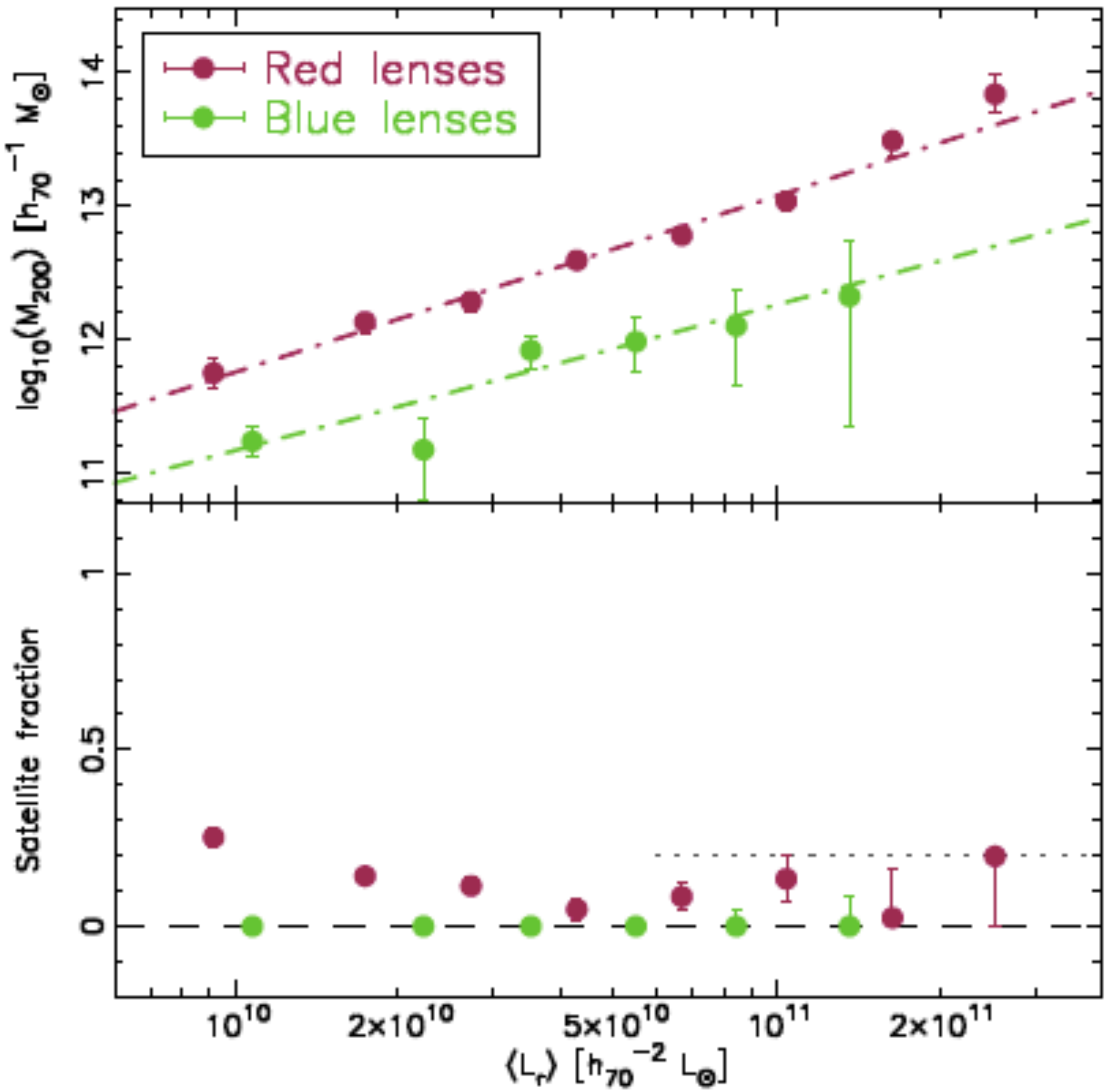
X-ray: yellow contours



gravitational (strong+weak) lensing: red contours

Velander et al (2013)
weak gravitational lensing

BIG SCALES
average shear across the universe



Weak lensing provides a statistical constraint on the total halo mass

$$M_{200} = 119 L_r^{1.32}$$

for red galaxies