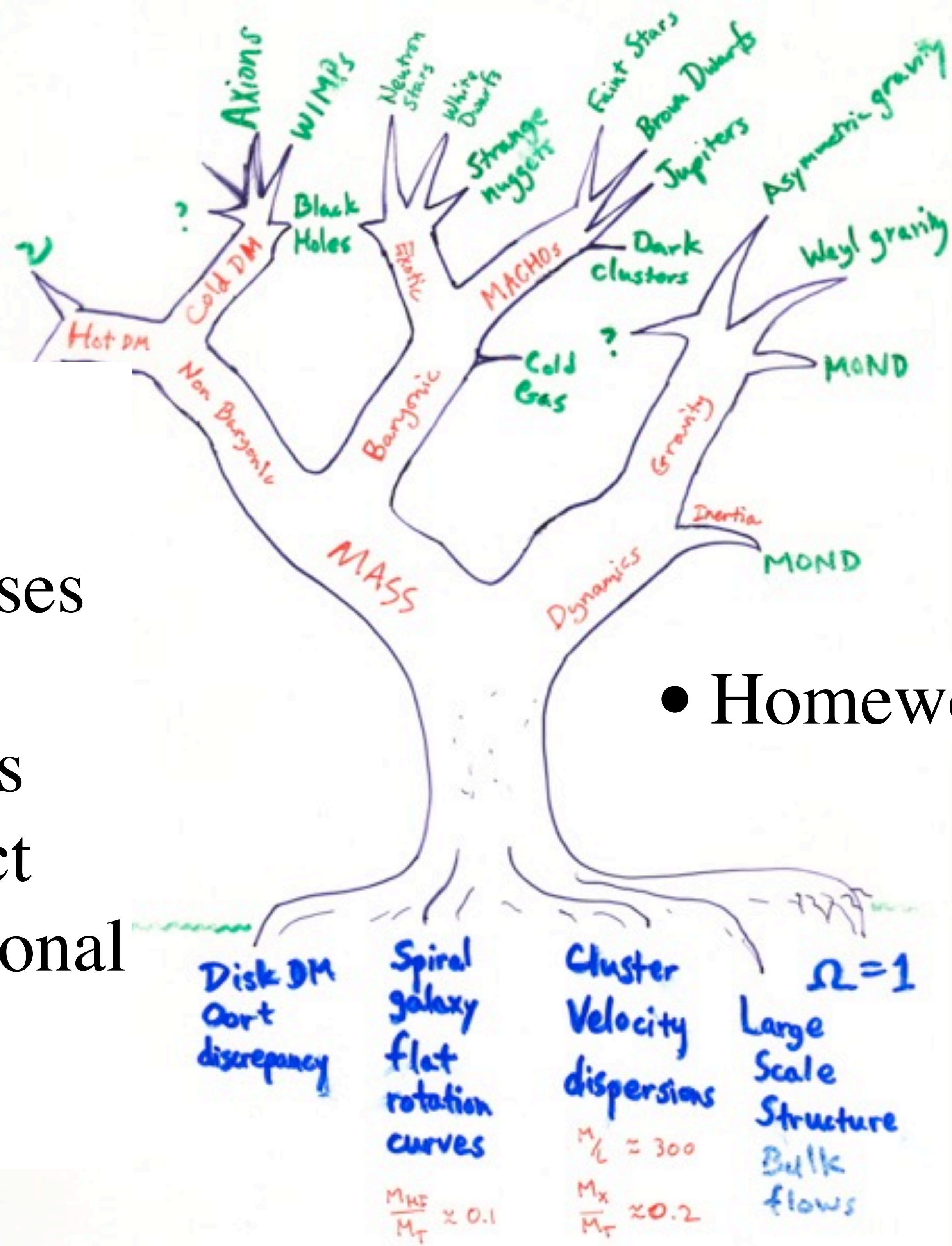
Today:
TDGs
cluster masses

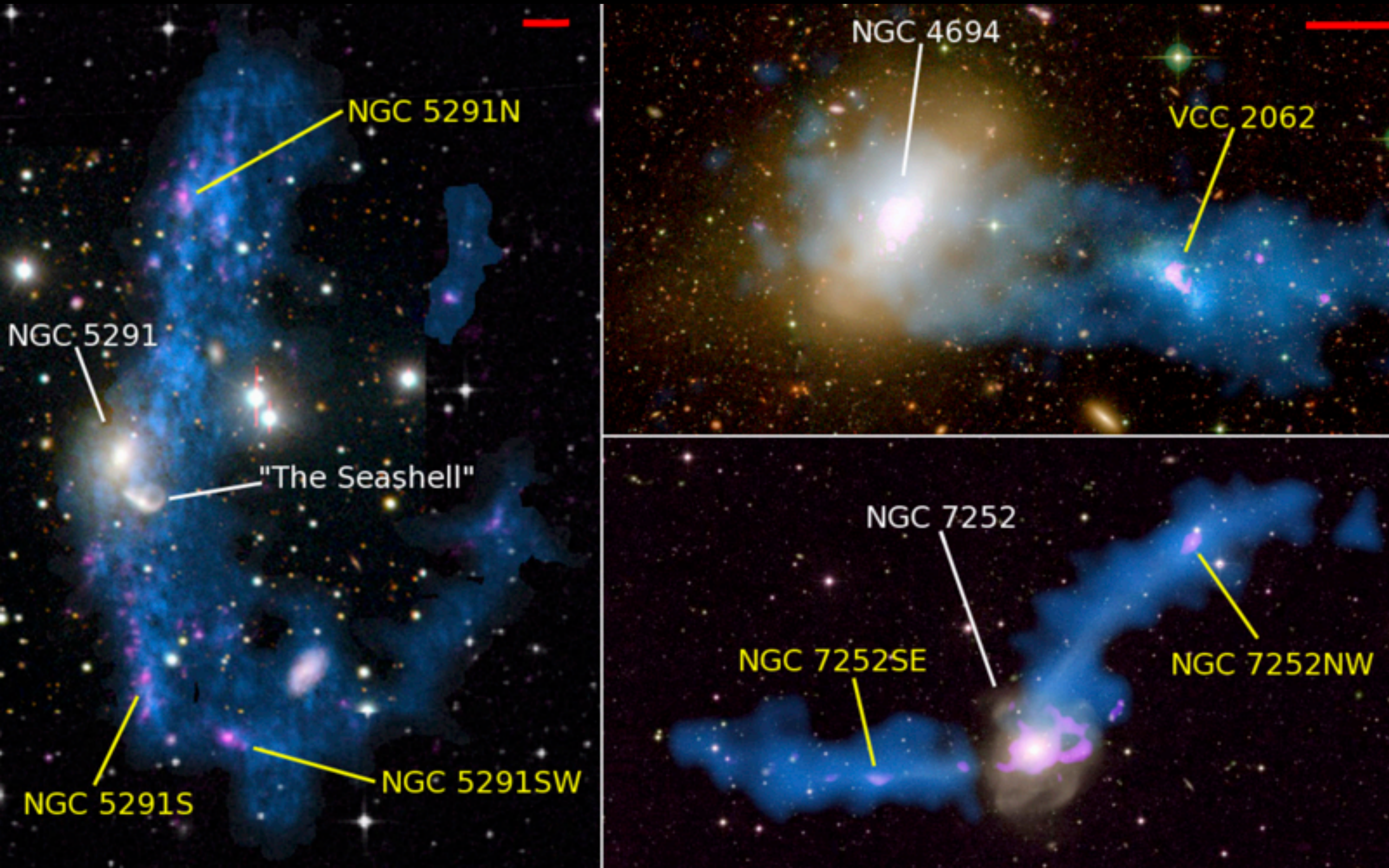


- Homework 3 due

- X-ray gas
- S-Z effect
- Gravitational lensing

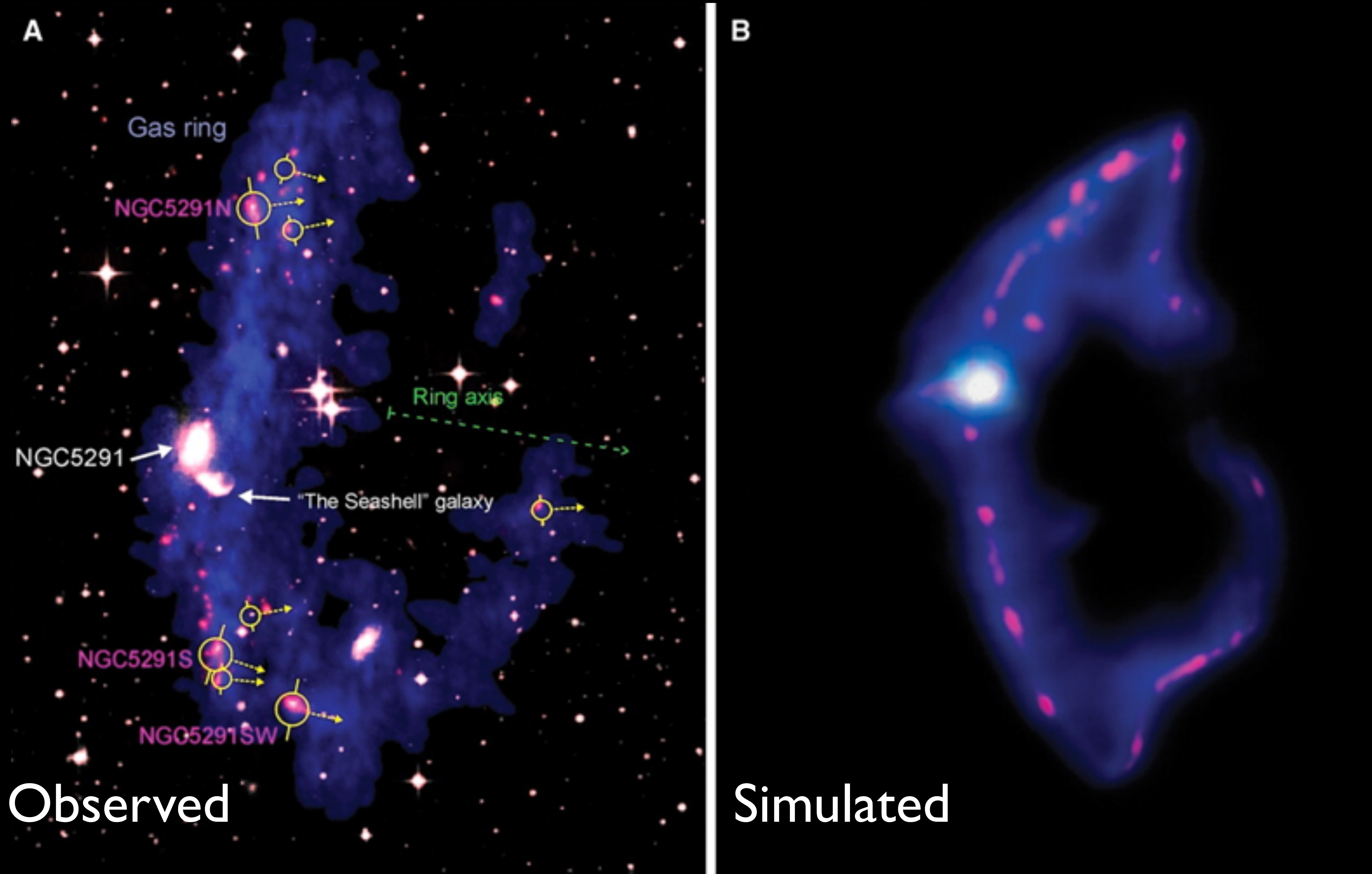
TDGs: Tidal Dwarf Galaxies

Lelli et al - see poster in hall!



Tidal interactions often produce long, narrow streams of material extracted from the dynamically cold stellar and gas disk of the progenitor spiral(s). This material moves on very different orbits than the quasi-spherical DM halos. Consequently, TDGs formed from this material should be devoid of dark matter (DM only a few % of baryonic mass according to simulations of Bernaud et al.)

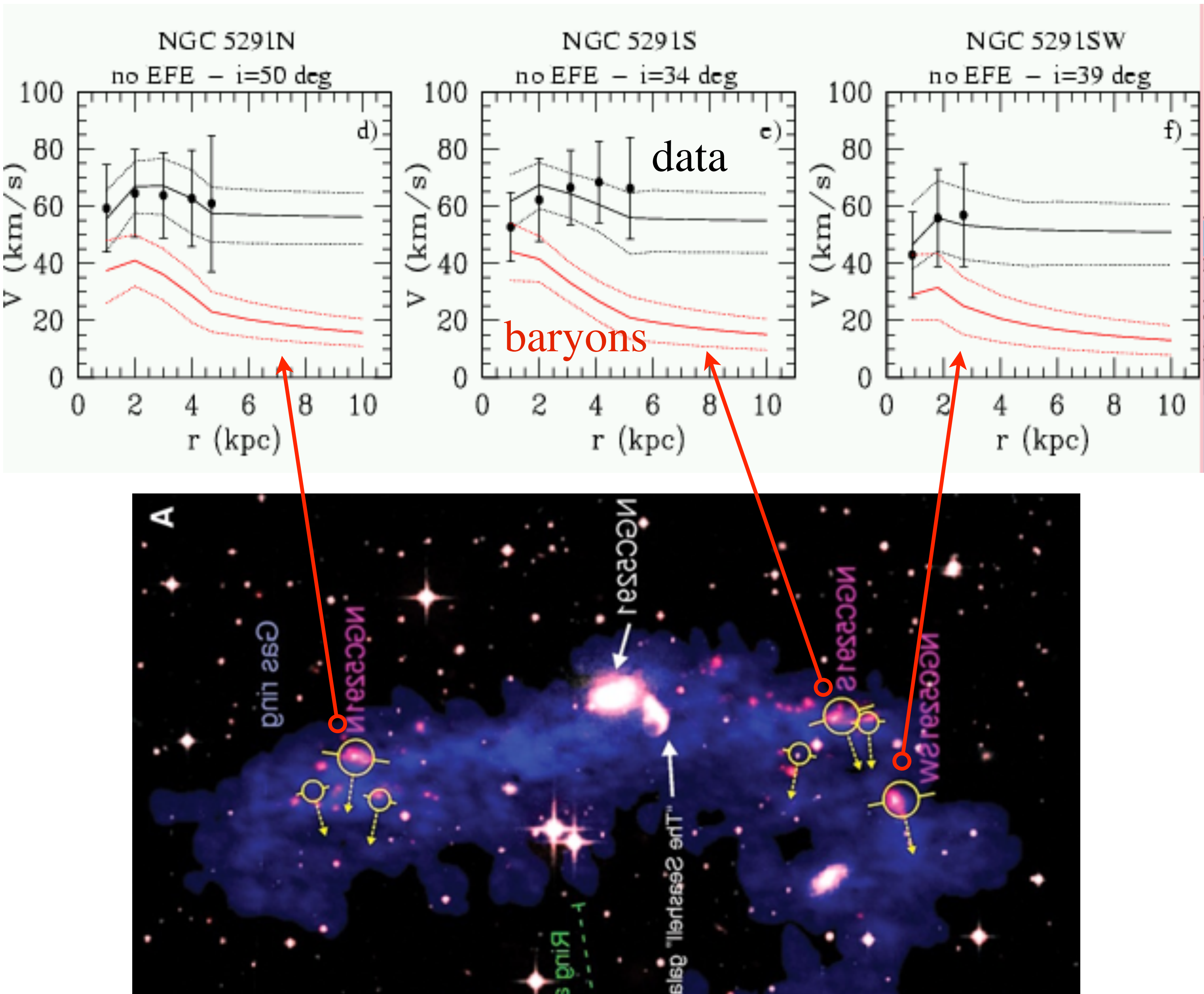
TDGs can form in the debris of tidal interactions. In this case, TDG candidates (pink) appear to have condensed from HI ring flung out by interaction



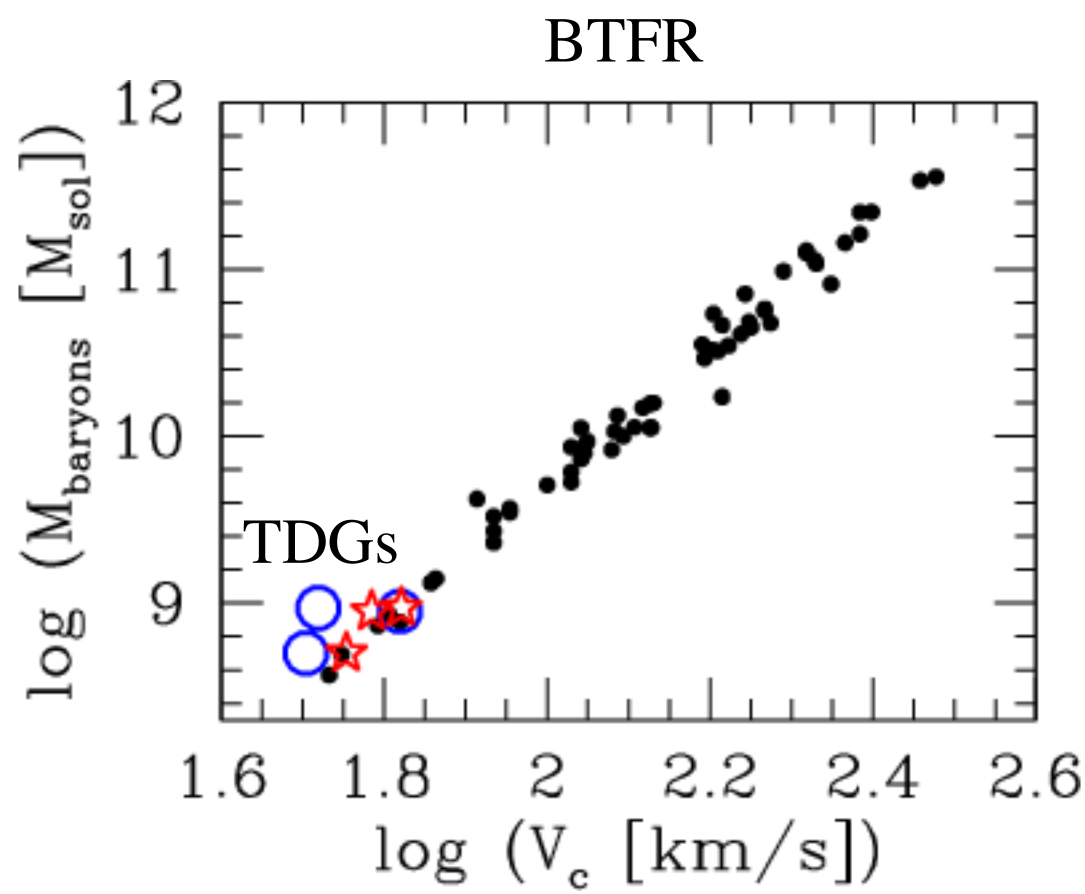
Observed

Simulated

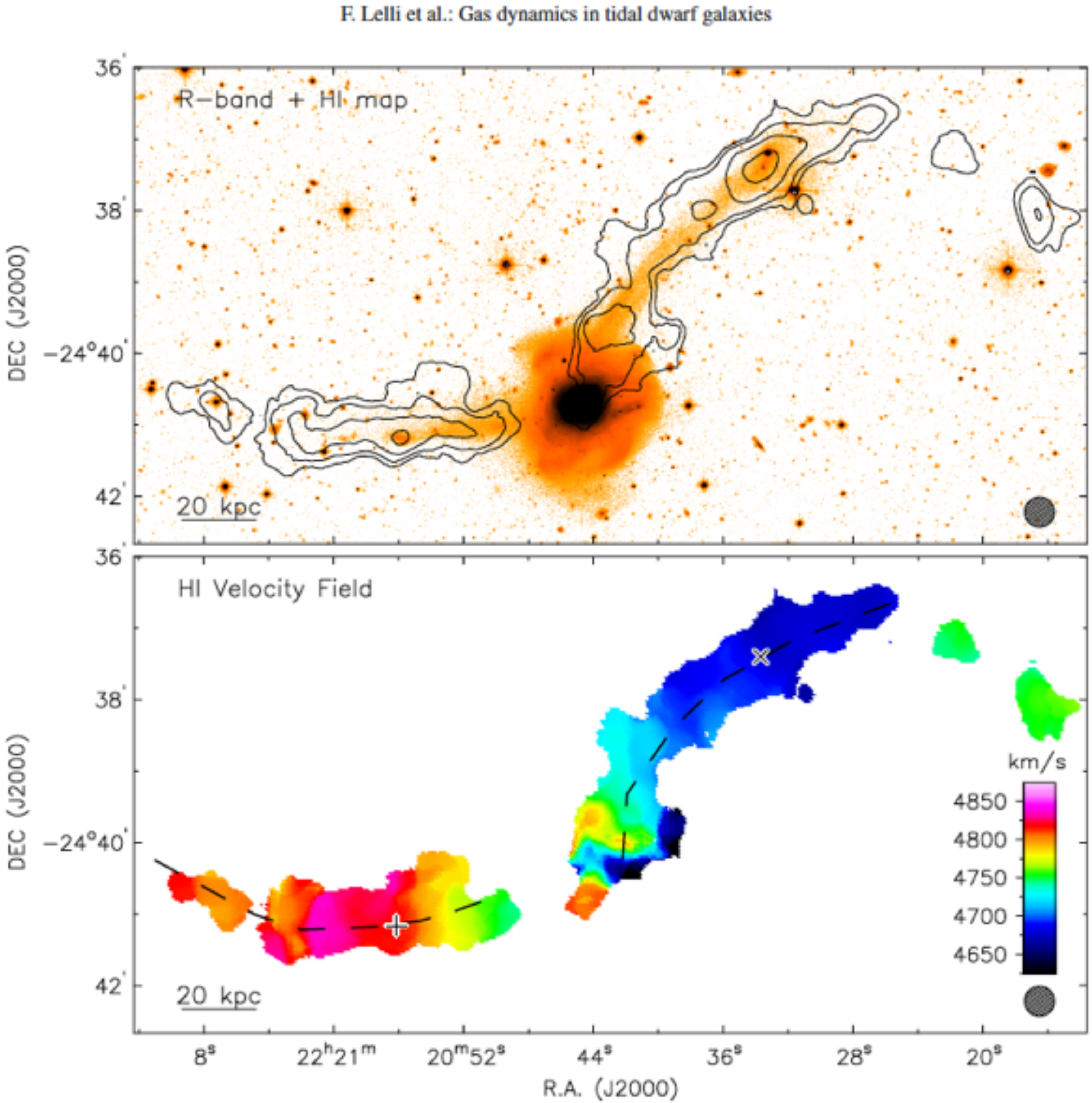
Prediction: rotation curves of TDGs should be as predicted by observed baryons.
Ironically, the absence of dark matter in TDGs would be evidence for dark matter.

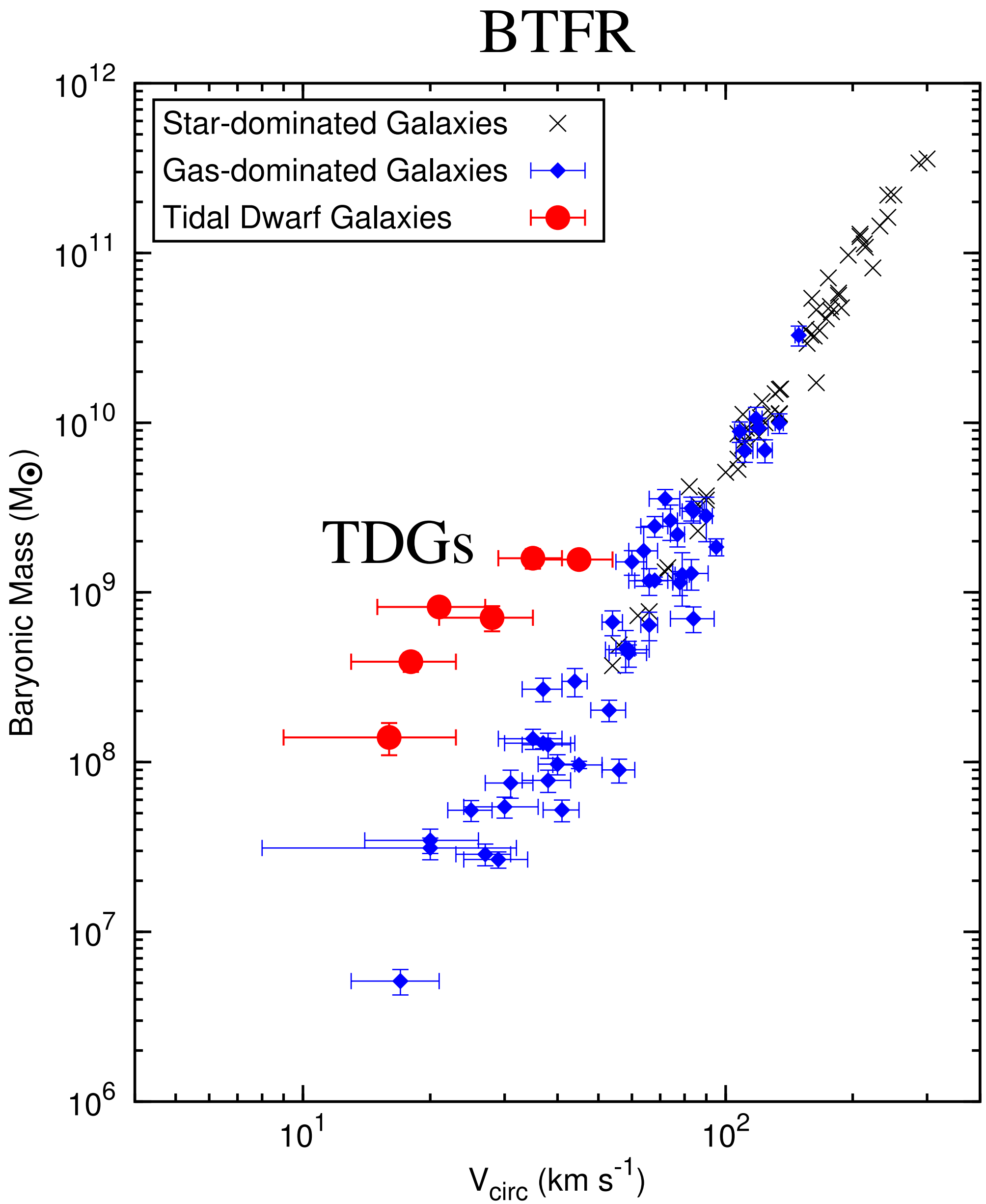


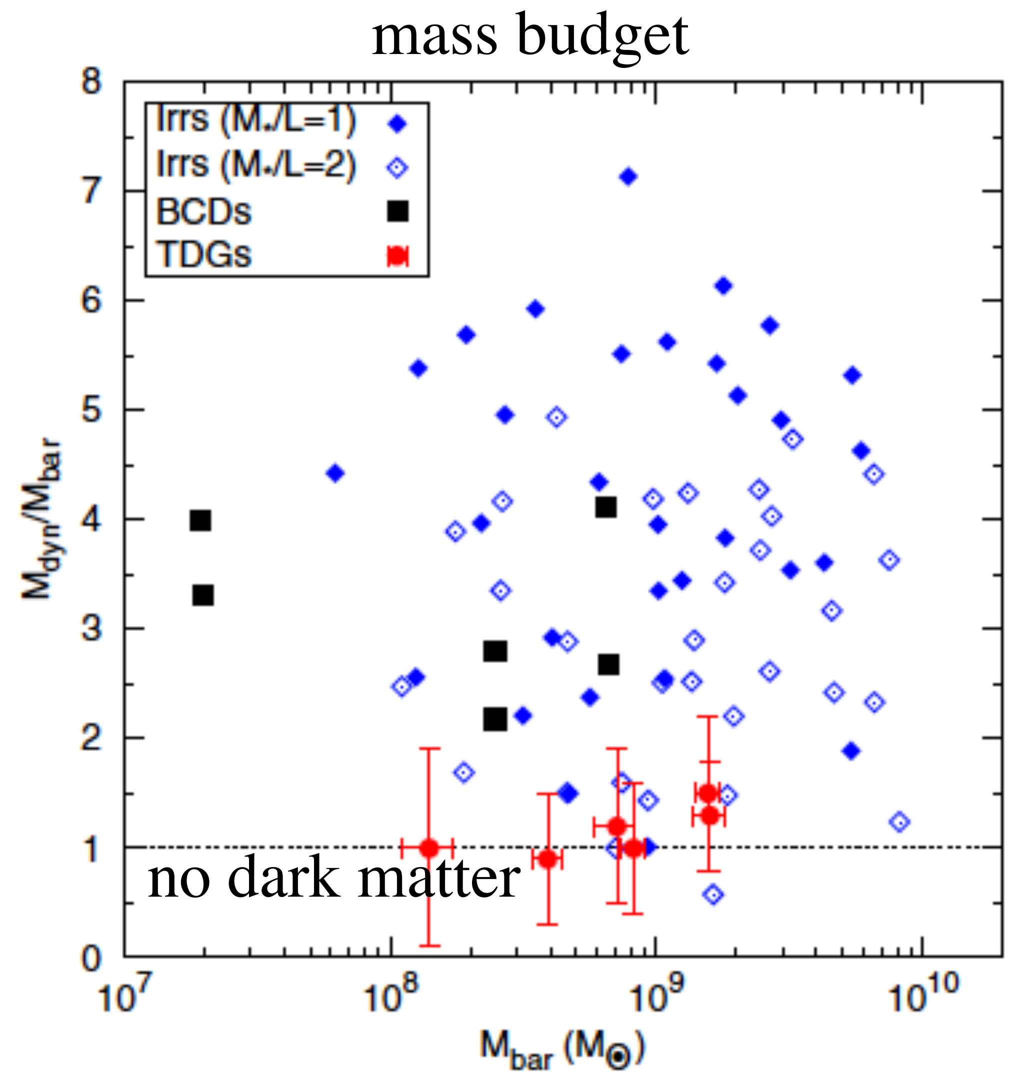
Gentile et al. (2007) found TDGs to be consistent with the baryonic Tully-Fisher - as expected for isolated galaxies, NOT for TDGs. Weird.



Lelli et al. (2015) examined more TDGs. Found the opposite - TDGs deviate from BTFR in the expected sense (slower rotators with mass consistent with just baryons)



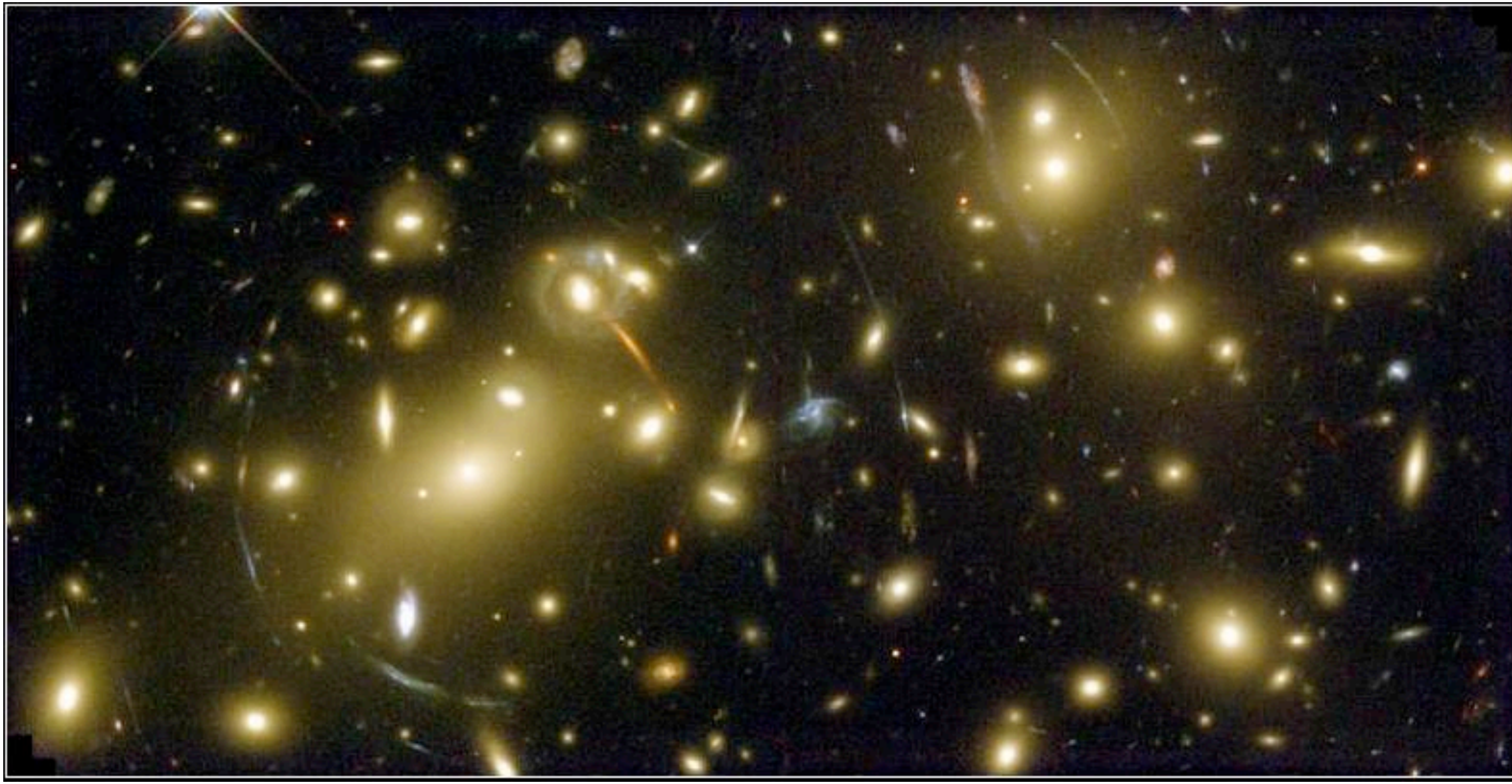




BUT - Orbital timescale for TDGs longer than the age of the merger that created them, so assumption of dynamical equilibrium is dubious. Weird.

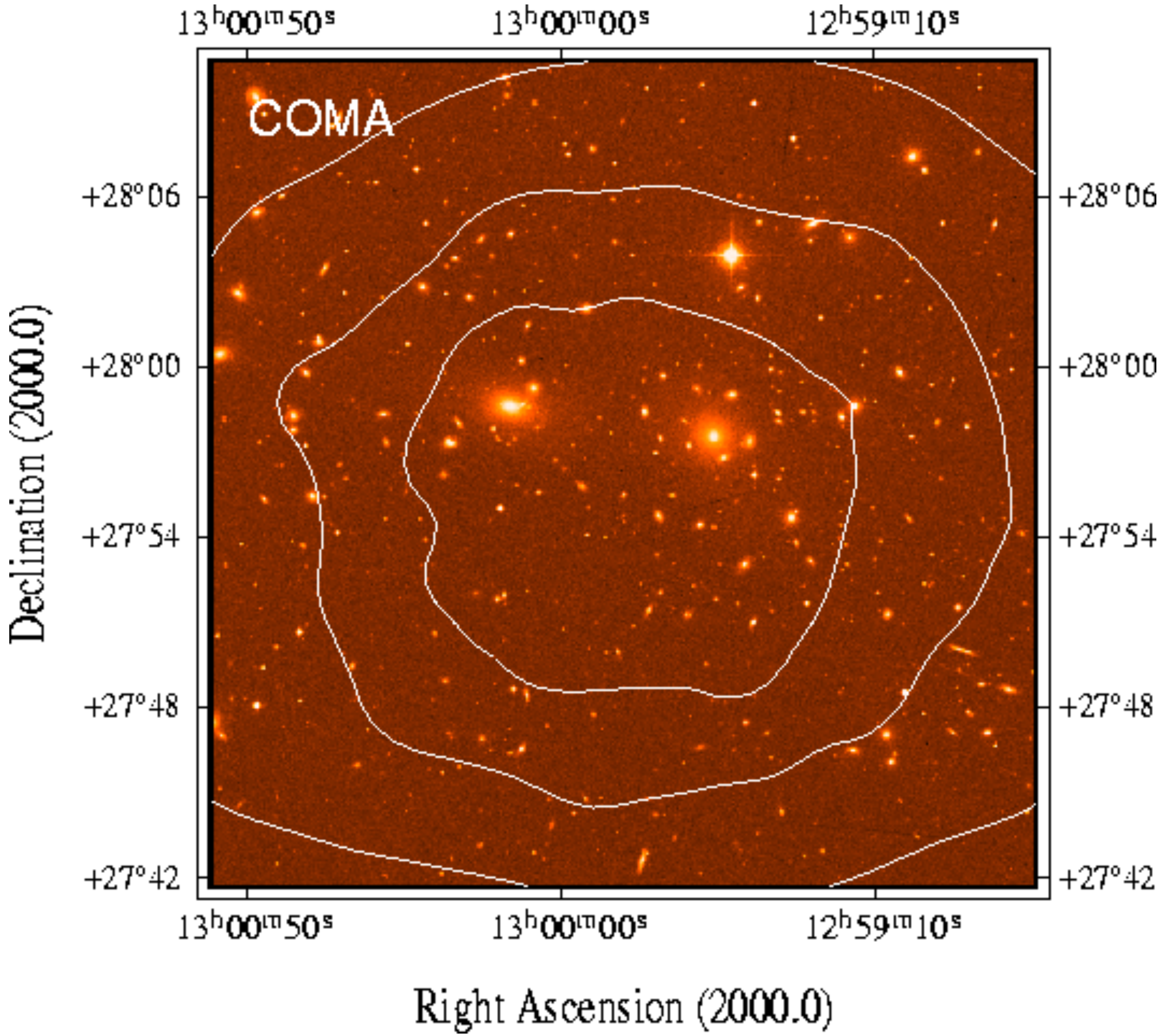
TDGs are an important test, but the jury is still out.

Galaxy Clusters



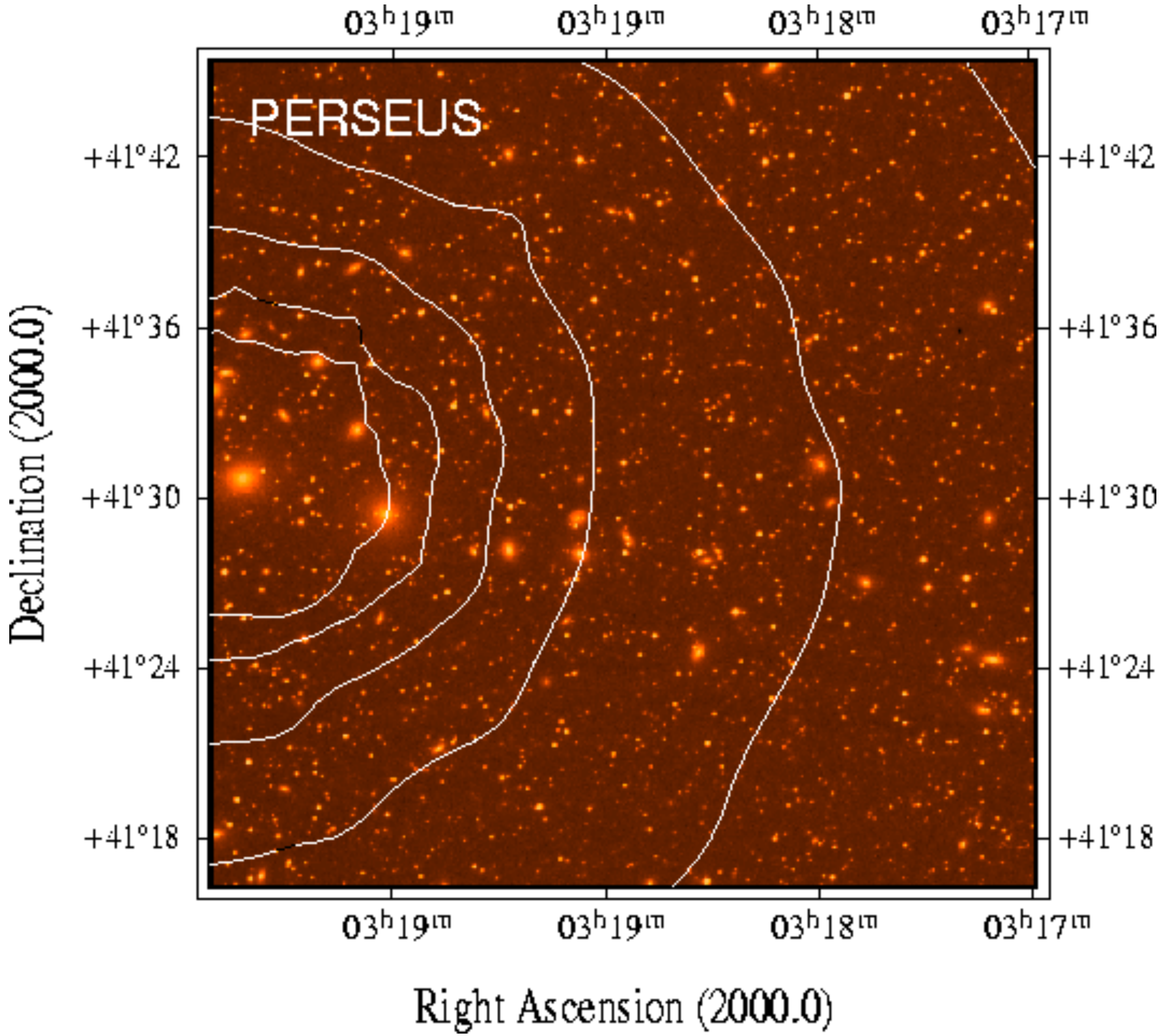
4 distinct measures: velocity dispersion, gravitational lensing, hydrostatic equilibrium of X-ray gas, and the Sunyaev-Zel'dovich effect

Clusters in optical and X-ray (contours)



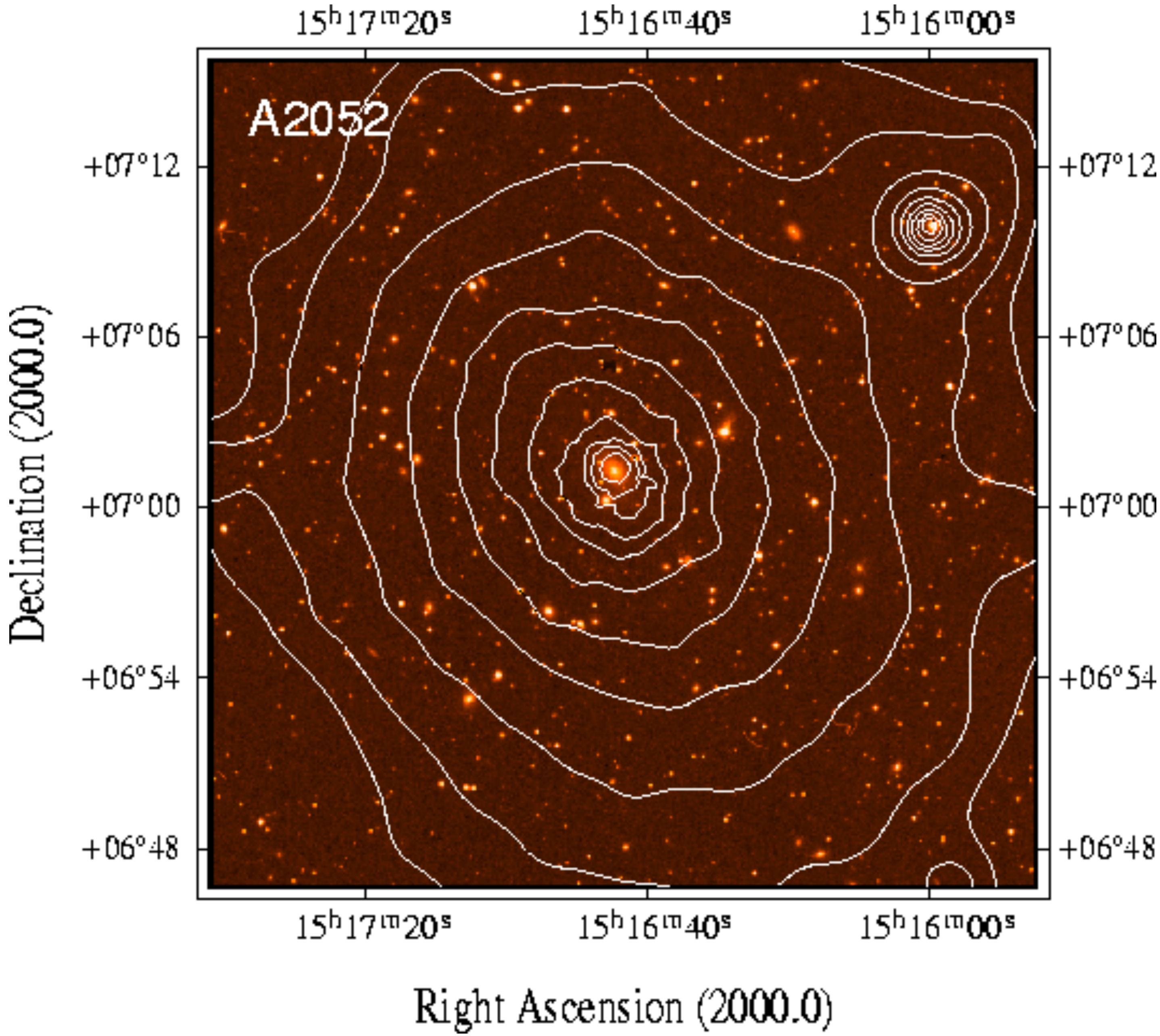
Reiprich ApJ, 567, 716-740 (2002)

Clusters in optical and X-ray (contours)



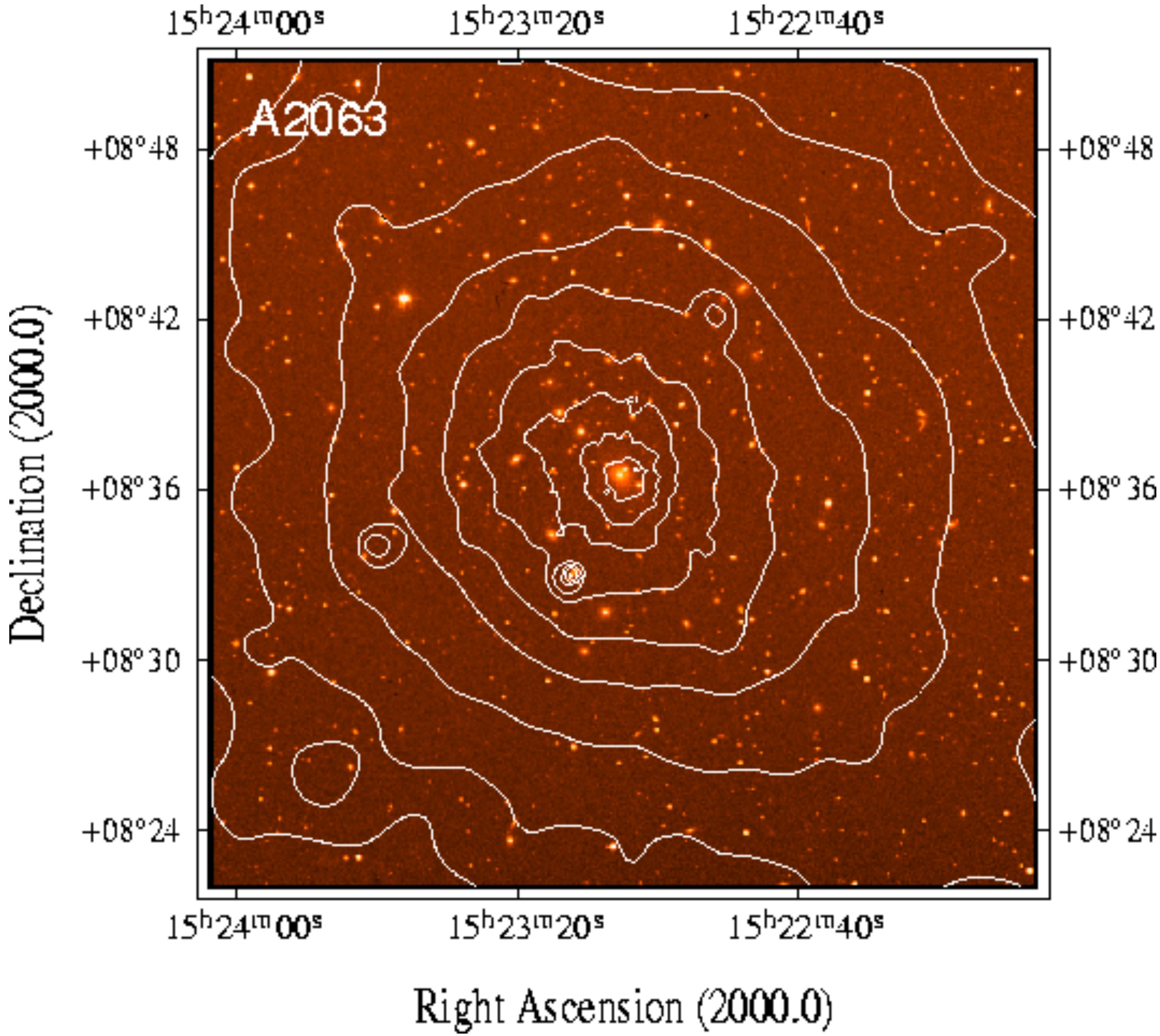
Reiprich ApJ, 567, 716-740 (2002)

Clusters in optical and X-ray (contours)



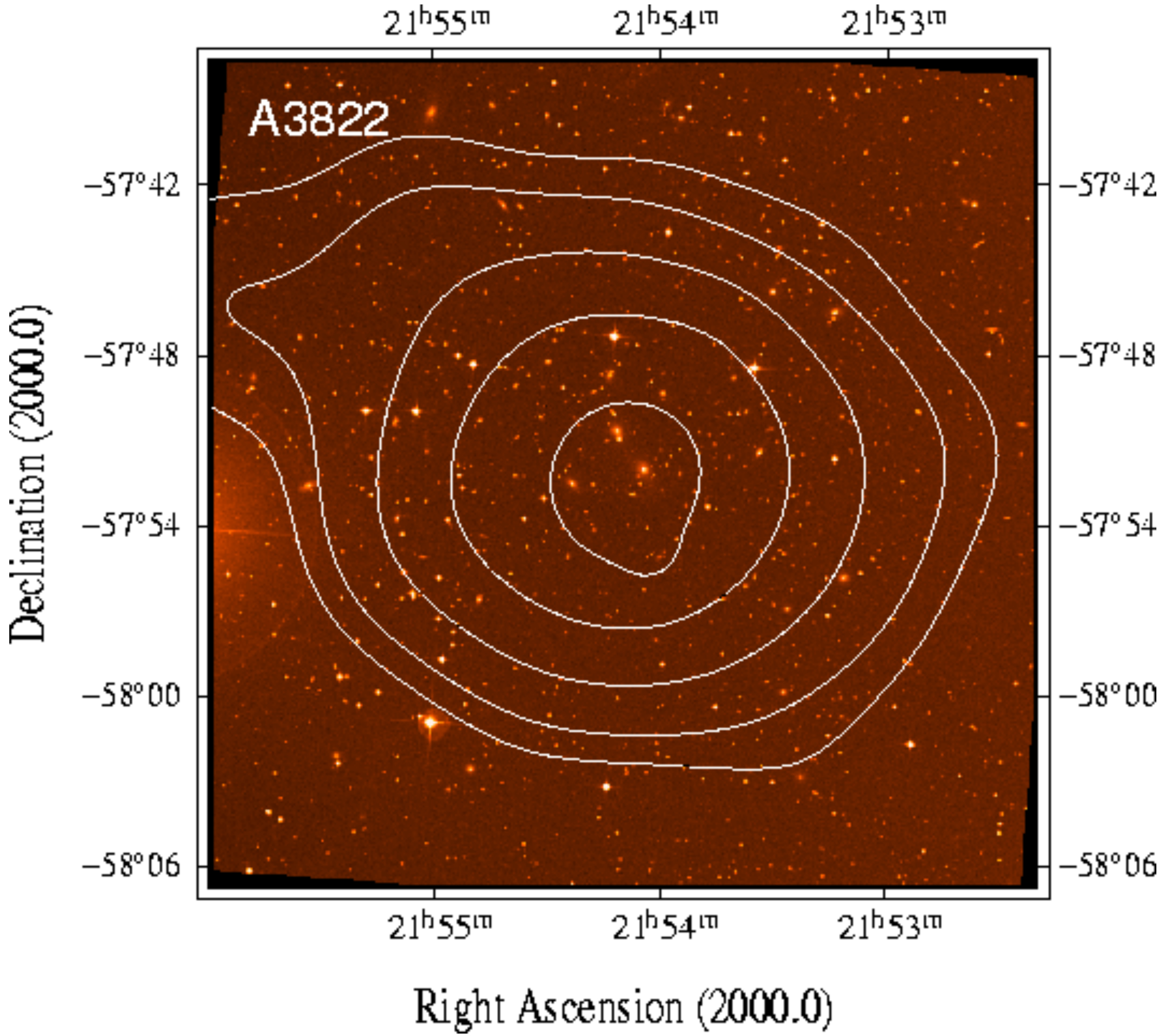
Reiprich ApJ, 567, 716-740 (2002)

Clusters in optical and X-ray (contours)



Reiprich ApJ, 567, 716-740 (2002)

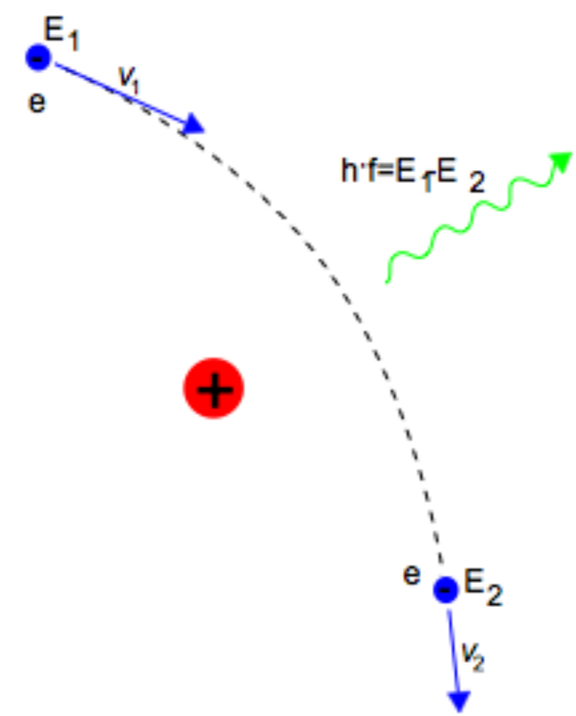
Clusters in optical and X-ray (contours)



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

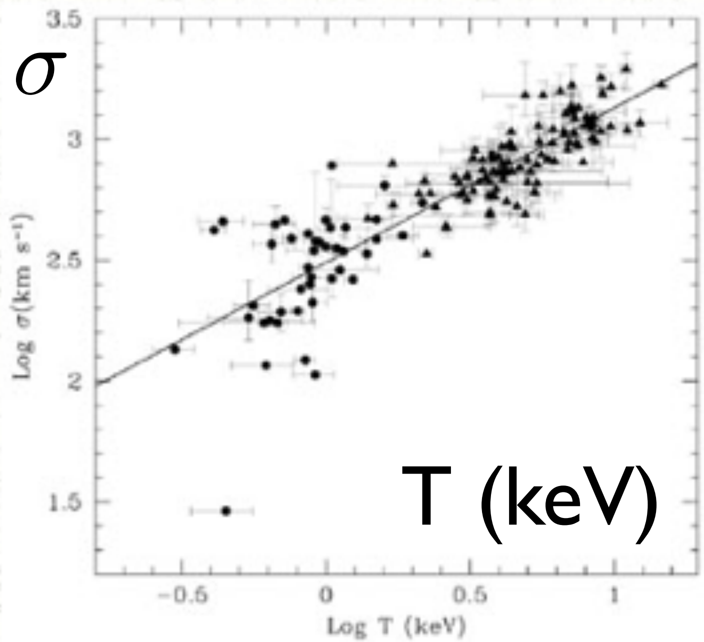


Figure 4. Logarithm of the X-ray temperature versus logarithm of optical velocity dispersion for a sample of groups (circles) and clusters (triangles). The group data are taken from the literature compilation of Xue & Wu (2000), with the addition of the groups in Helsdon & Ponman (2000). The cluster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

ext Contents Previous

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

Global correlations in galaxy clusters

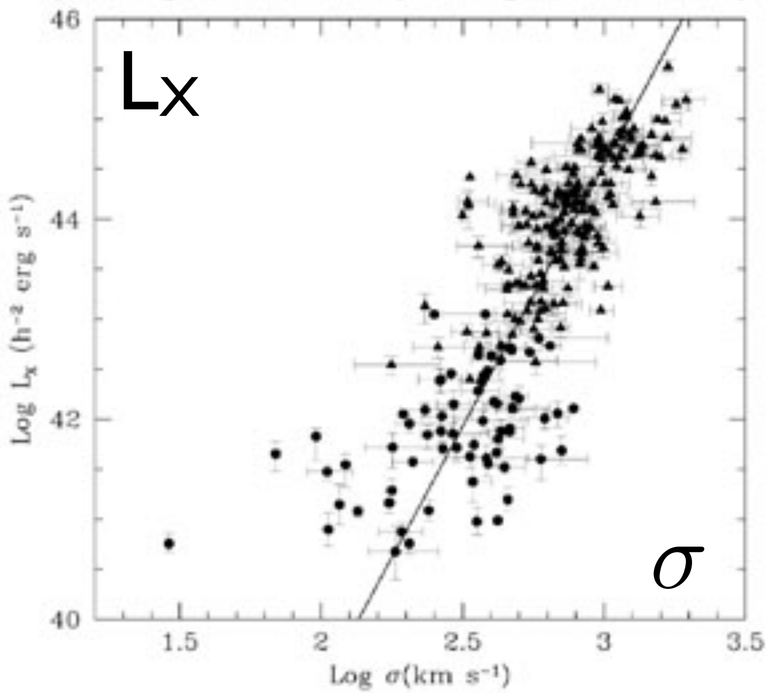


Figure 5. Logarithm of optical velocity dispersion versus logarithm of X-ray luminosity for a sample of groups (circles) and clusters (triangles). The data are taken from the same sources cited in Figure 4. The solid line represents the best-fit found by Wu et al (1999) for the clusters sample (using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

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

Global correlations in galaxy clusters

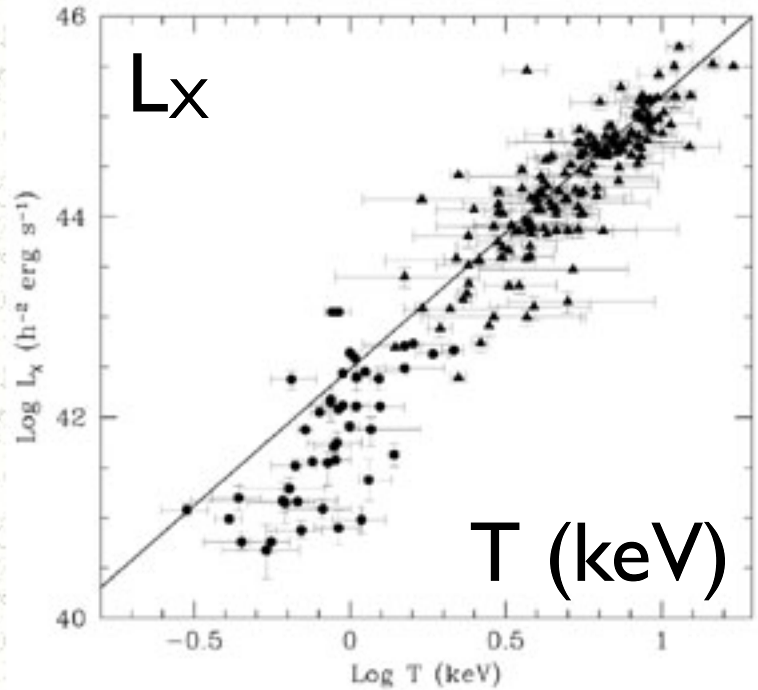


Figure 6. Logarithm of the X-ray temperature versus logarithm of X-ray luminosity for a sample of groups (circles) and clusters (triangles). The data are taken from the same sources cited in Figure 4. The solid line represents the best-fit found by Wu et al (1999) for the clusters sample (using an orthogonal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

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

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

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

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

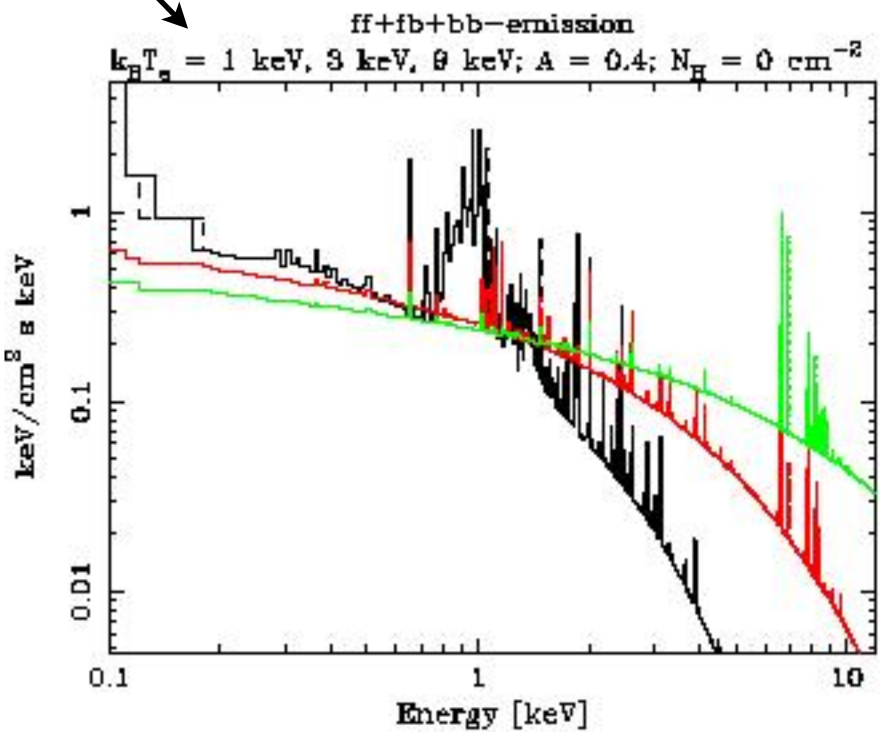
β treated as fit parameter; typically ~ 2/3
BUT often higher when sigma well measured
and often lower in groups

Mass Estimator

$$M_{tot}(< R) = \frac{kT_g(R)}{G\mu m_p}\left[\frac{\partial \log \rho}{\partial \log r} + \frac{\partial \log T}{\partial \log r}\right] R$$

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

the gas temperature is measured directly from the X-ray spectrum



Assumes
- hydrostatic equilibrium
- sphericity

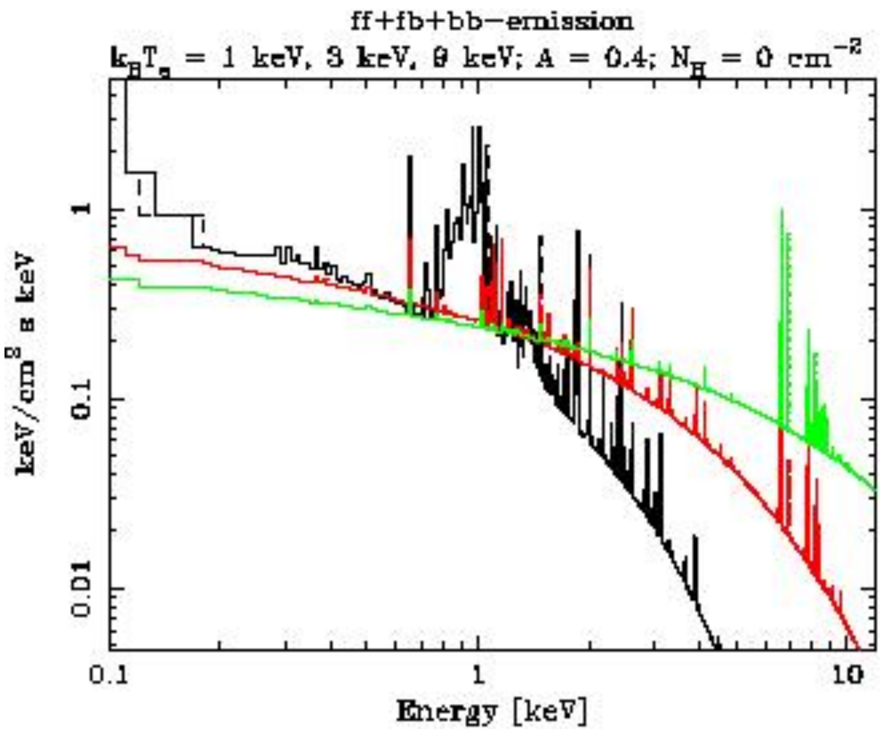
often assumes
- isothermality → $\frac{\partial \log T}{\partial \log r} = 0$

Mass Estimator

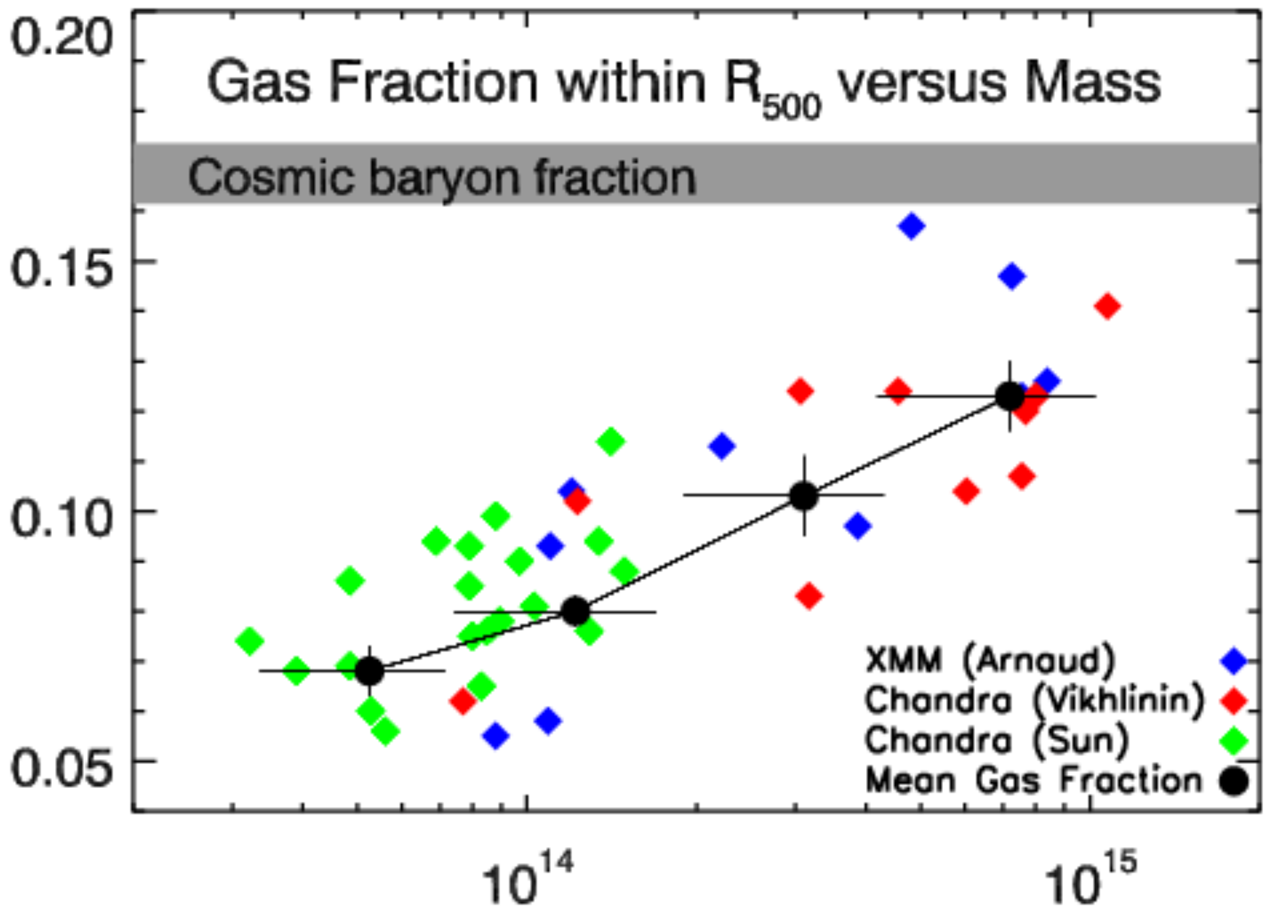
$$M_{tot}(< R) = \frac{kT_g(R)}{G\mu m_p}\left[\frac{\partial \log \rho}{\partial \log r} + \frac{\partial \log T}{\partial \log r}\right] R$$

basically,

$$M_{tot}(< R) \sim T_{gas}\, R$$

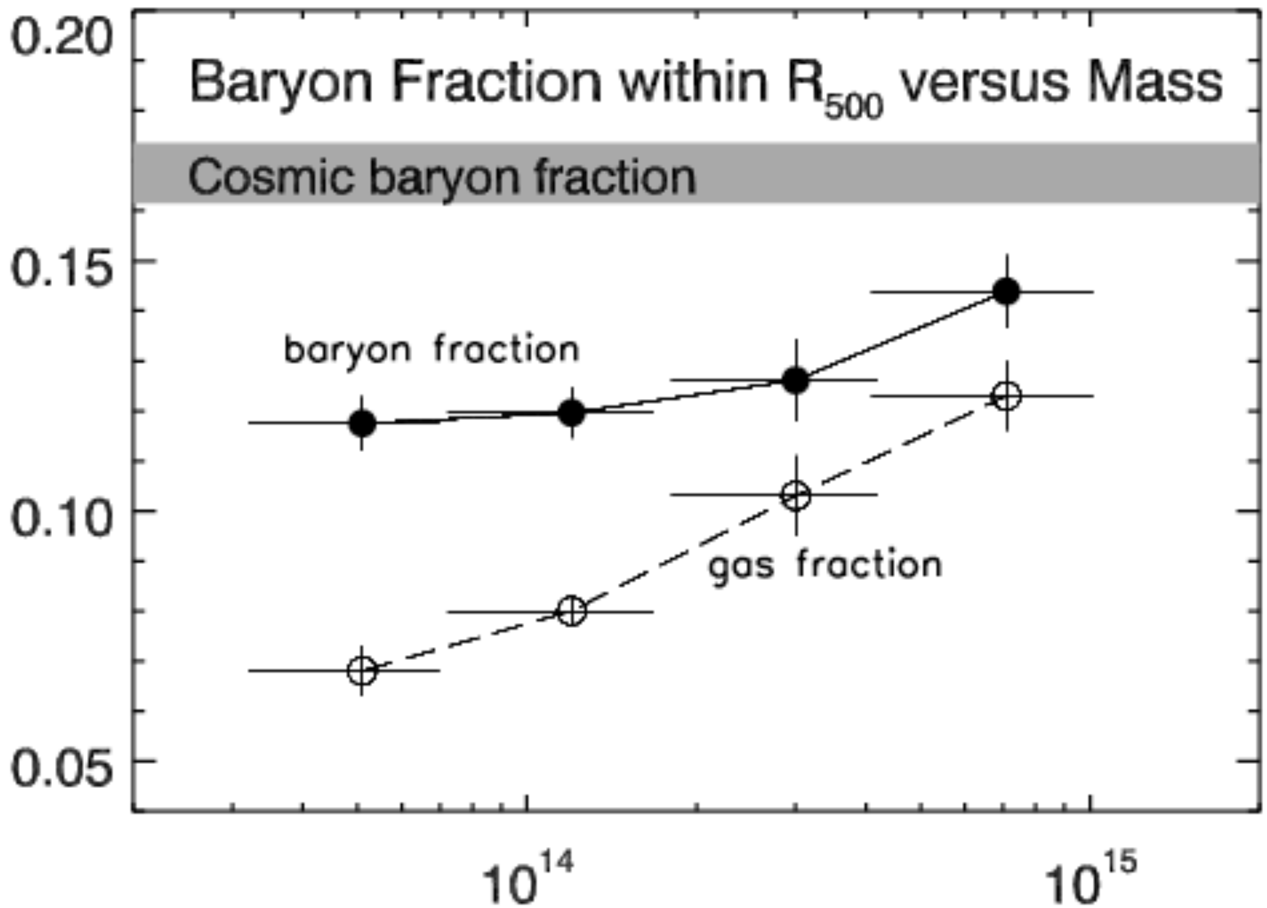


Rasheed (2010)



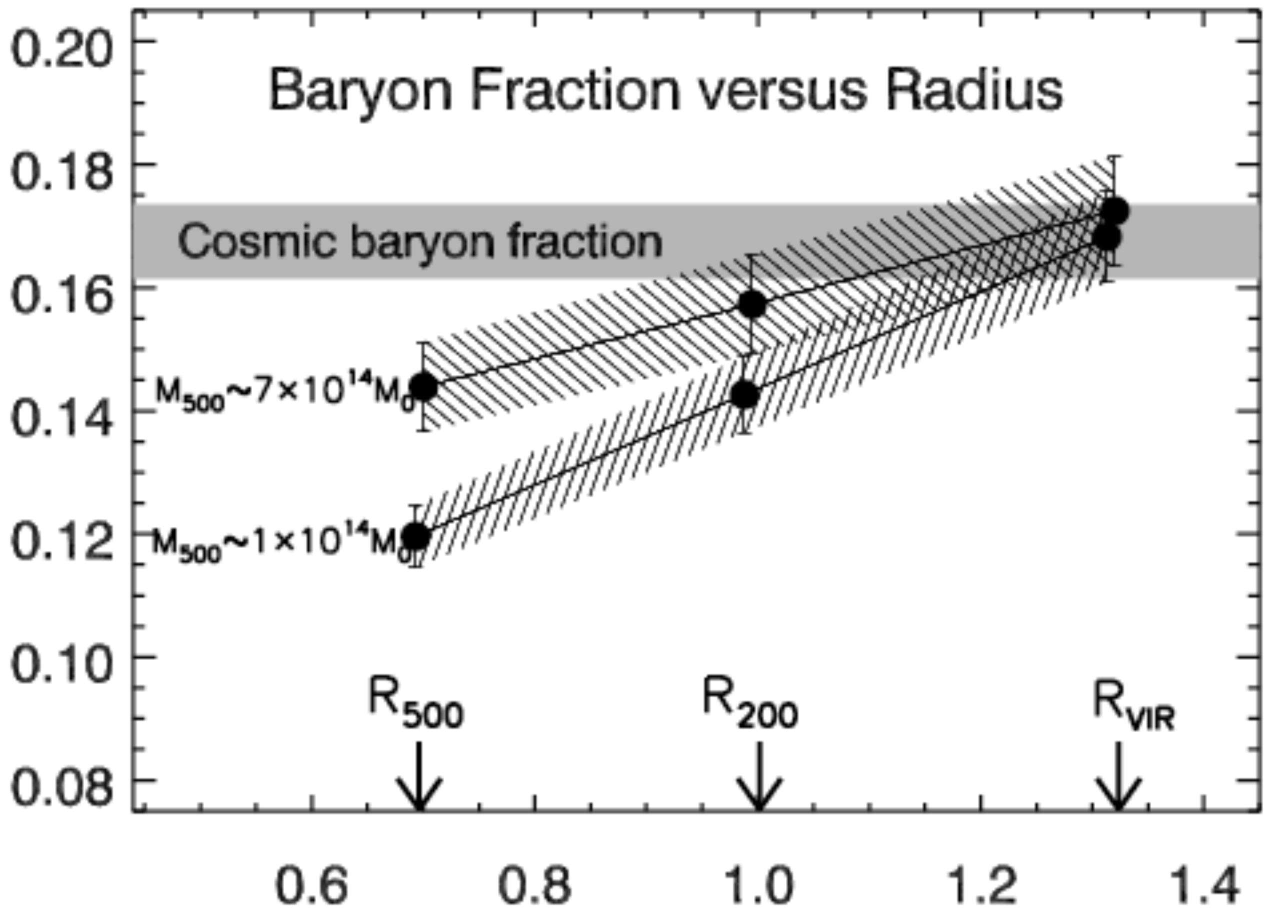
Typical result:
clusters have close to, but not quite, expected baryon fraction

Rasheed (2010)

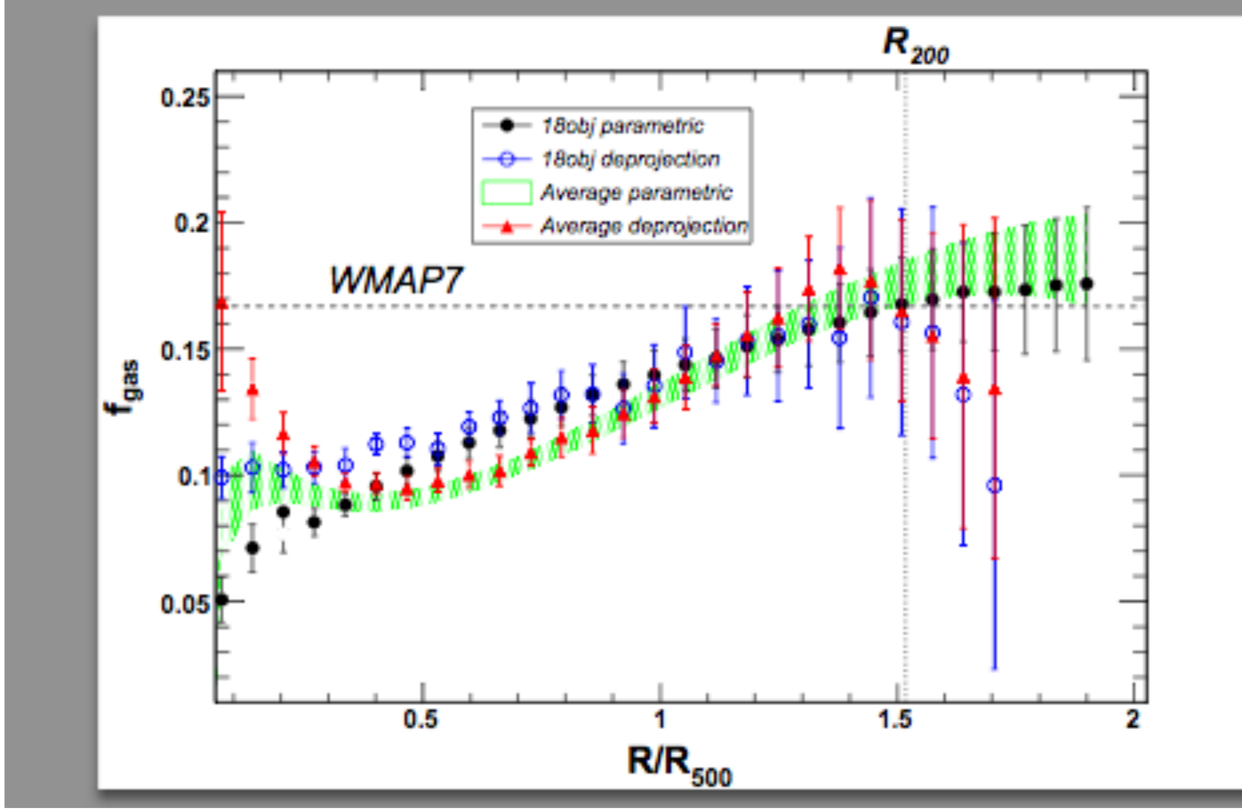


Typical result:
clusters have progressively more gas than stars at higher masses

Rasheed (2010)



Typical result:
the baryon fraction increases with radius

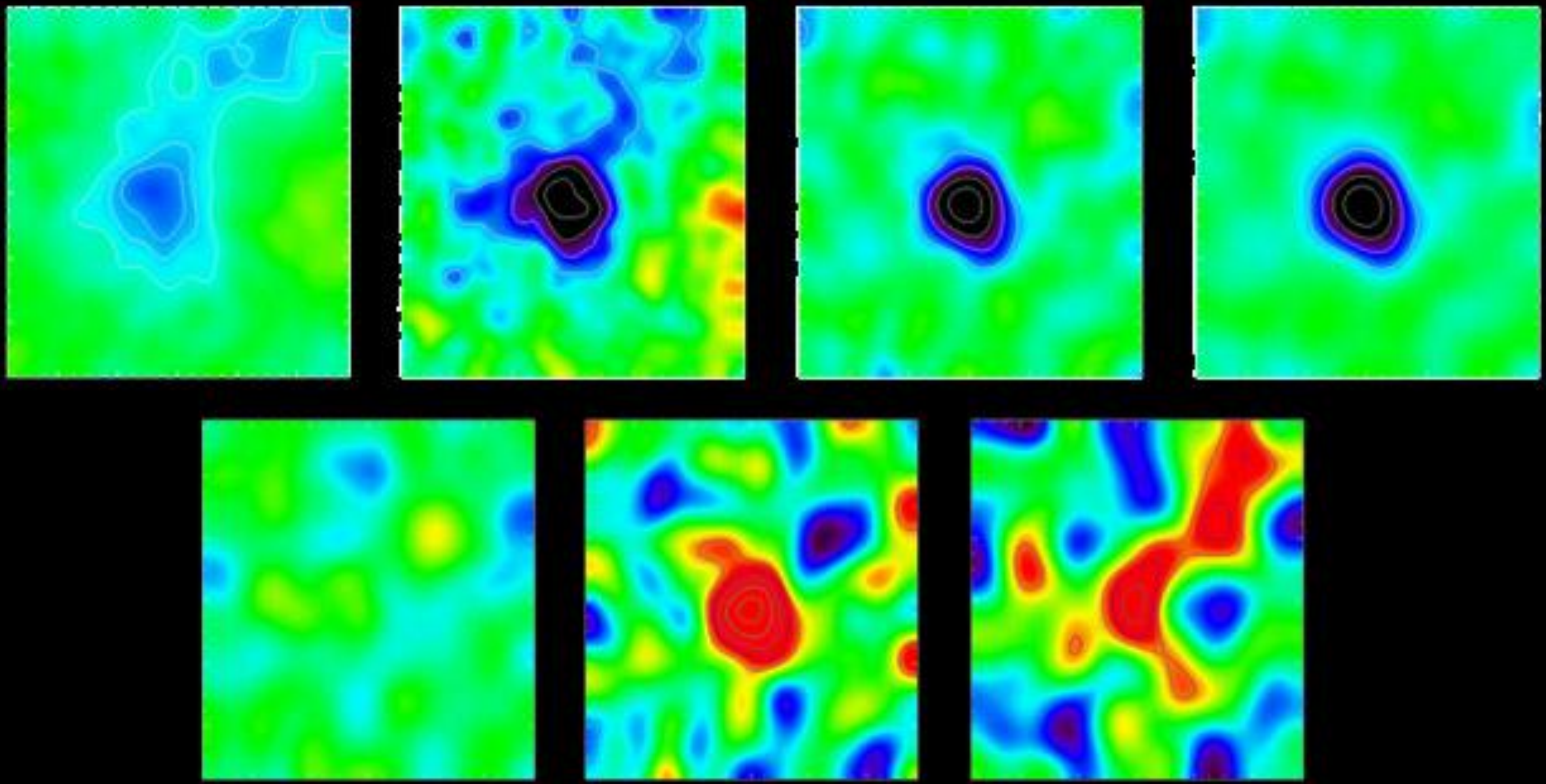


Typical result:

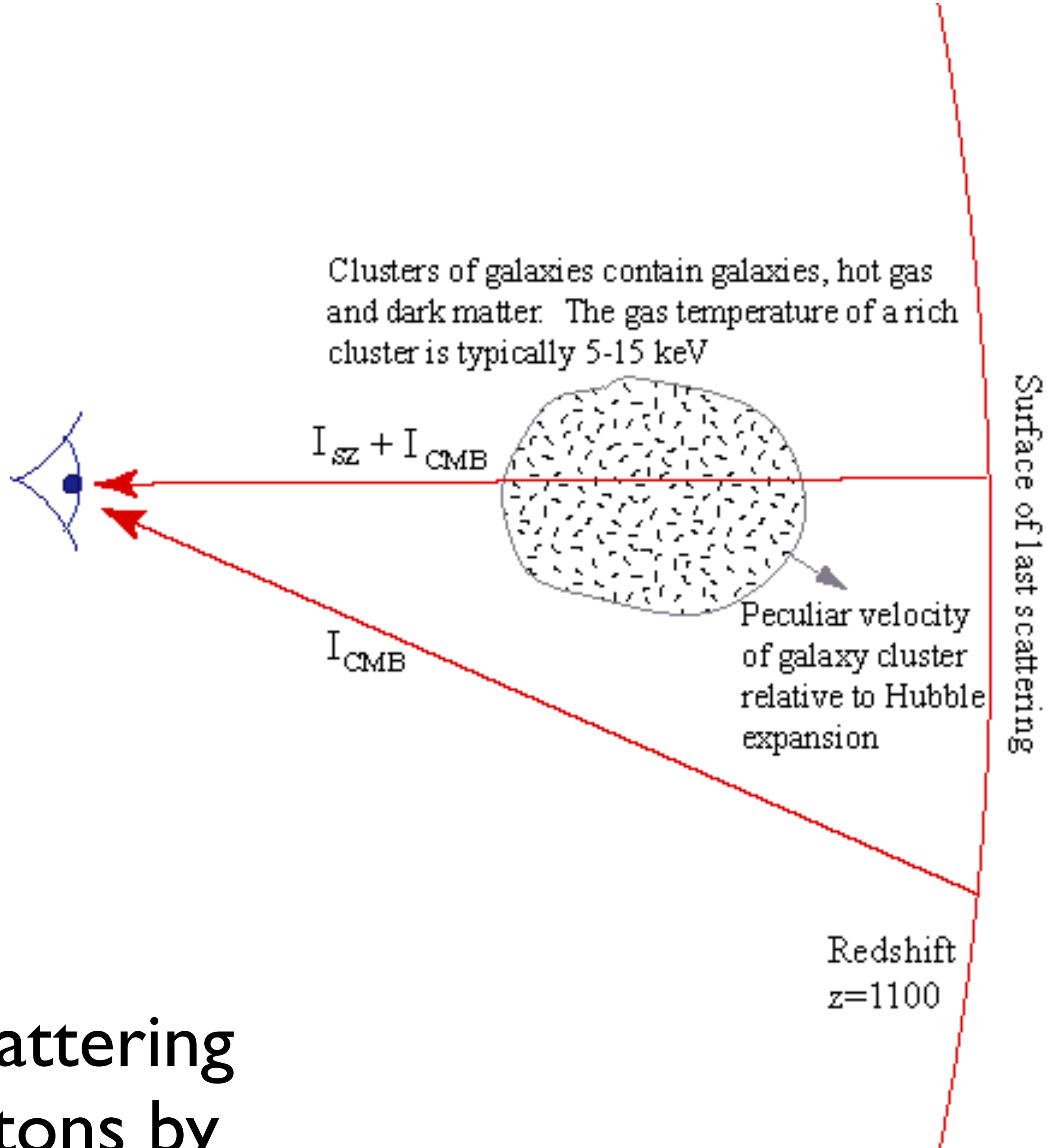
ICM gas outweighs the stars by factor of ~6;
outweighed by dark matter by the same factor

There seems to be more dark matter towards the centers of clusters

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

T_{rad}: CMB

n_e: electron density

σ_T: Thomson scattering cross-section

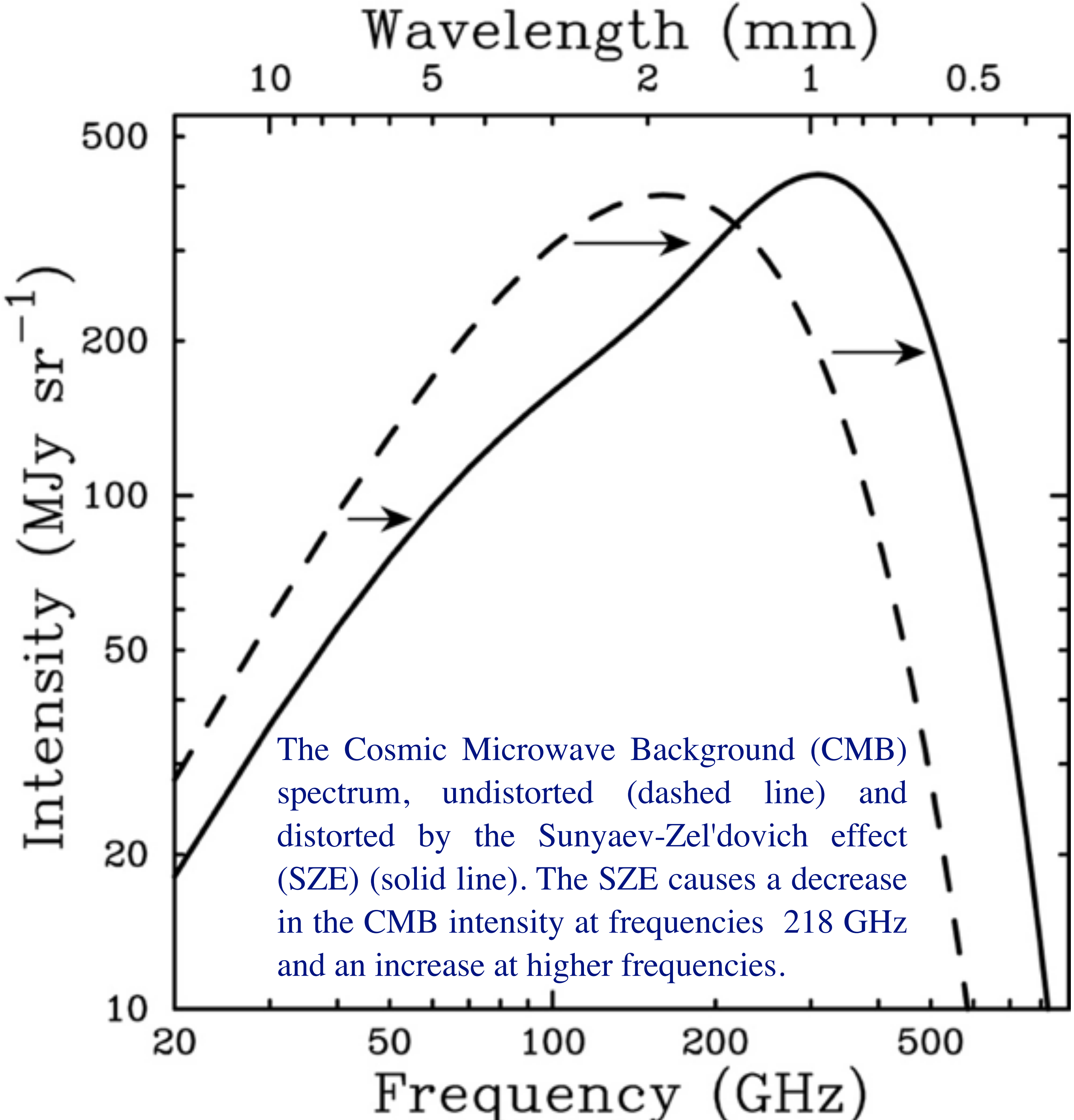
y is the Compton y-parameter which quantifies how much effect the plasma has frequency dependent change in intensity

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

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,

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

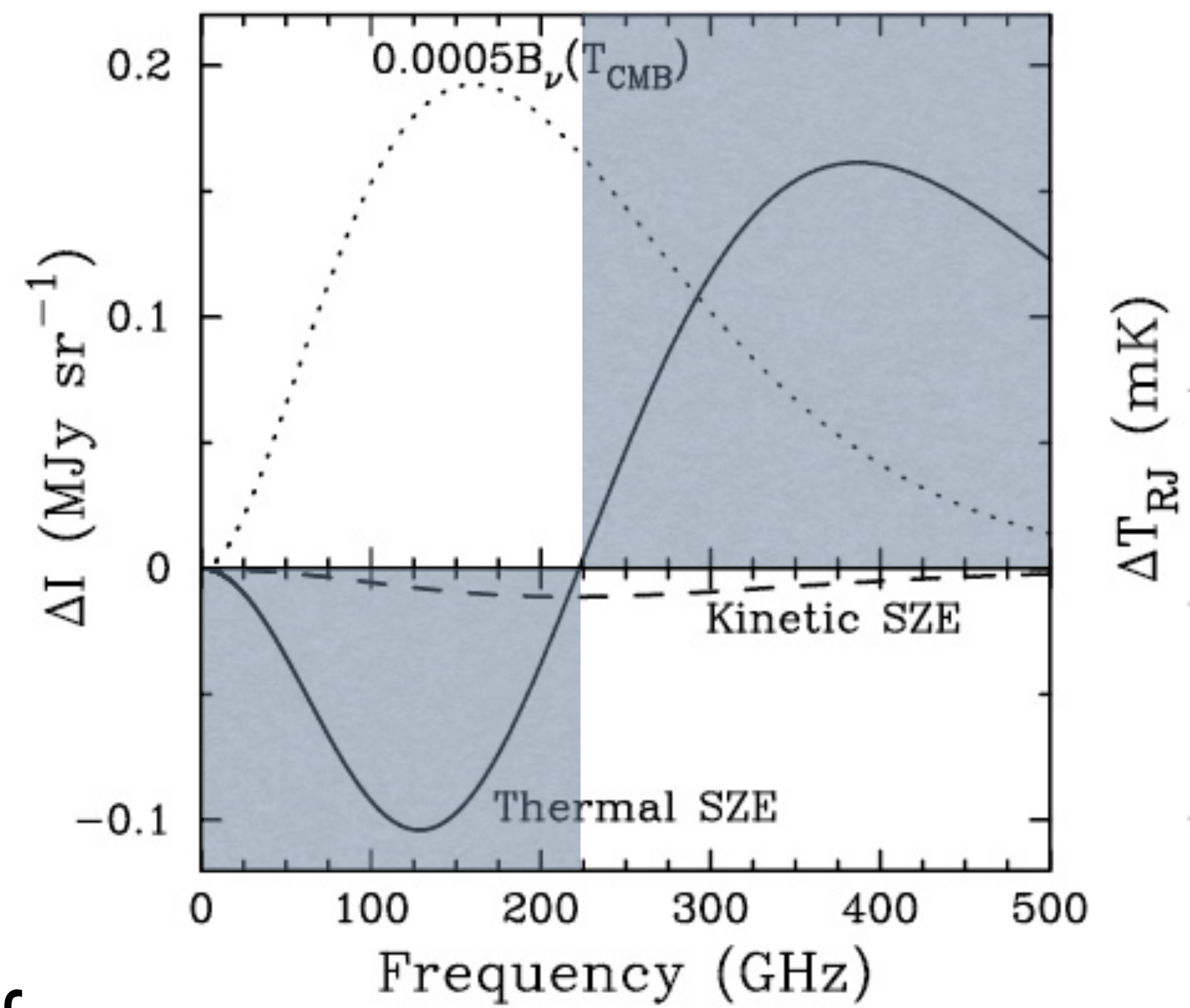


The Cosmic Microwave Background (CMB) spectrum, undistorted (dashed line) and distorted by the Sunyaev-Zel'dovich effect (SZE) (solid line). The SZE causes a decrease in the CMB intensity at frequencies 218 GHz and an increase at higher frequencies.

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

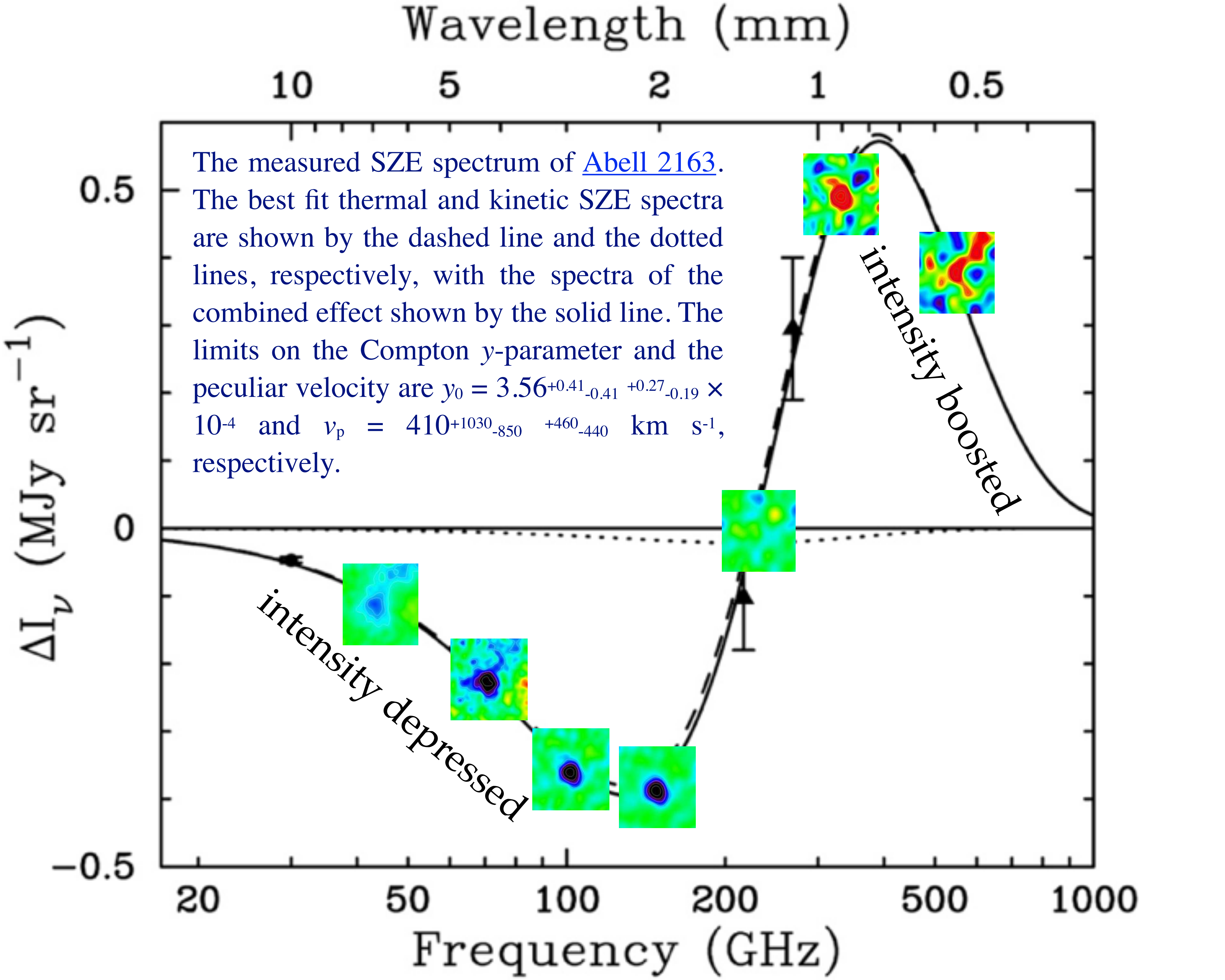
Thermal SZ effect from Compton scattering of CMB photons by cluster plasma

intensity boosted



Kinematic SZ effect from peculiar velocity of cluster wrt CMB frame

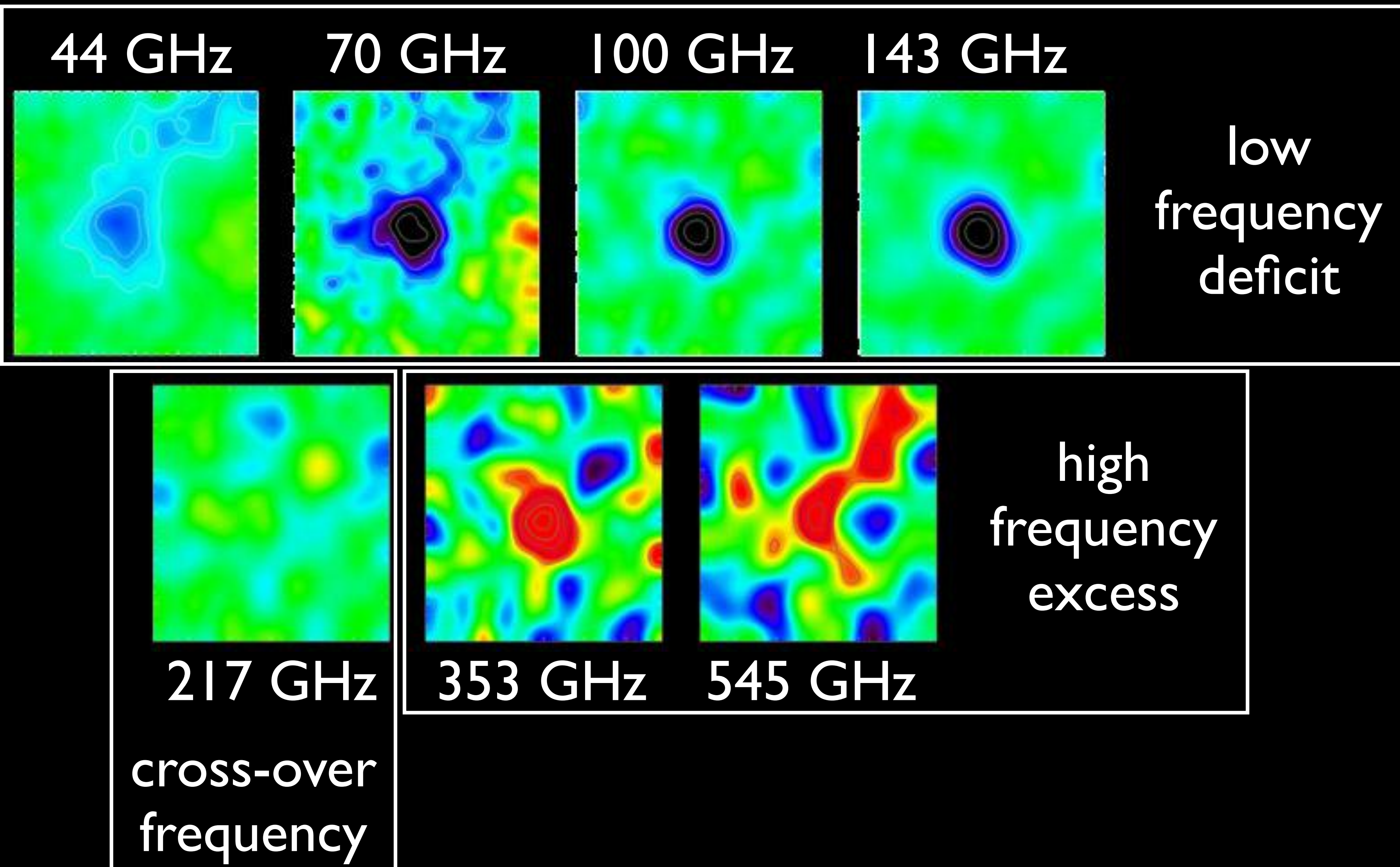
intensity depleted

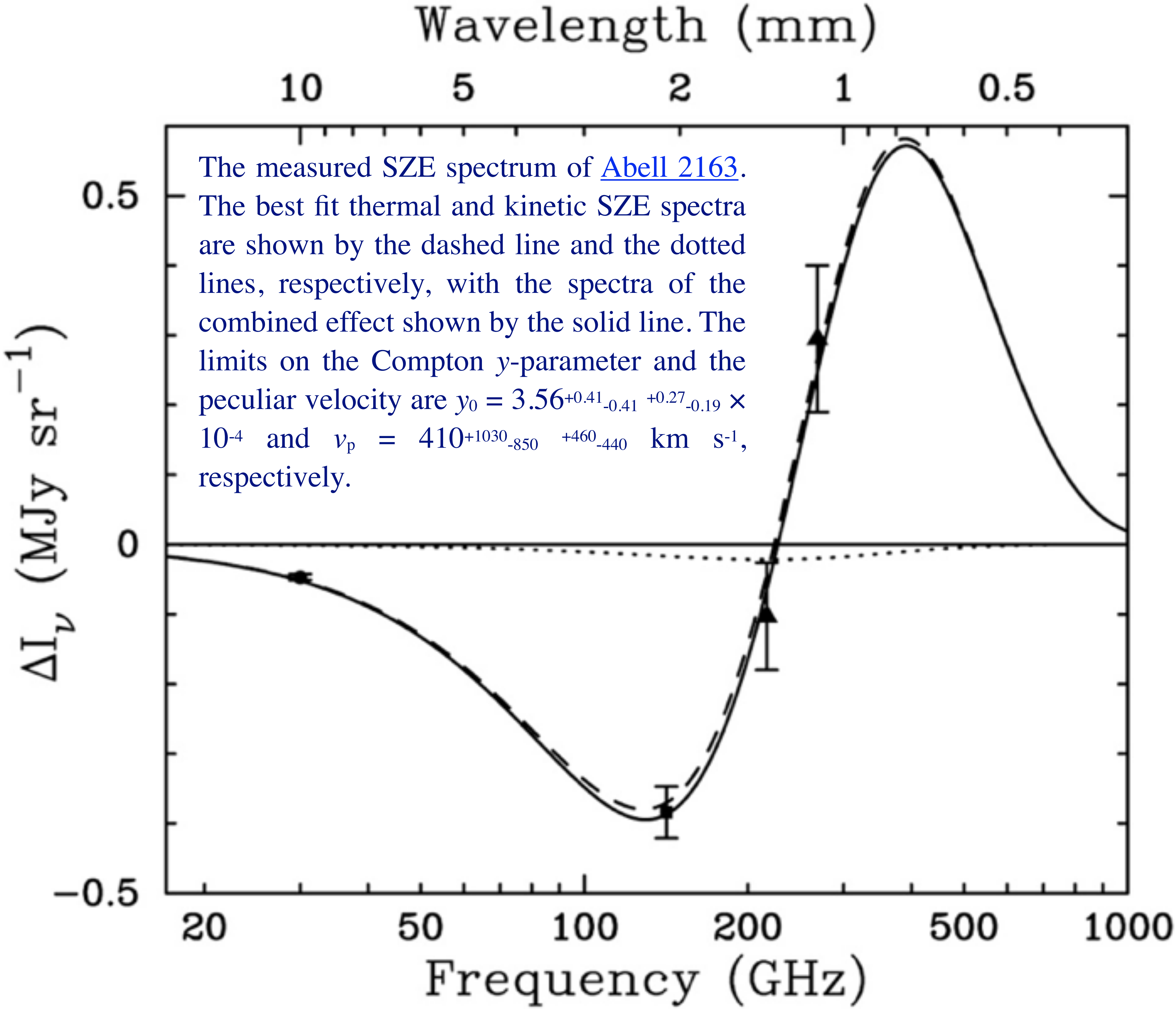


Wavelength (mm)
10
5
2
1
0.5
The measured SZE spectrum of Abell 2163. The best fit thermal and kinetic SZE spectra are shown by the dashed line and the dotted lines, respectively, with the spectra of the combined effect shown by the solid line. The limits on the Compton y-parameter and the peculiar velocity 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.
intensity boosted
intensity depressed
ΔI_ν (MJy sr^{-1})
0.5
0
−0.5
20
50
100
200
500
1000
Frequency (GHz)

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!