Dark Matter

ASTR 333/433

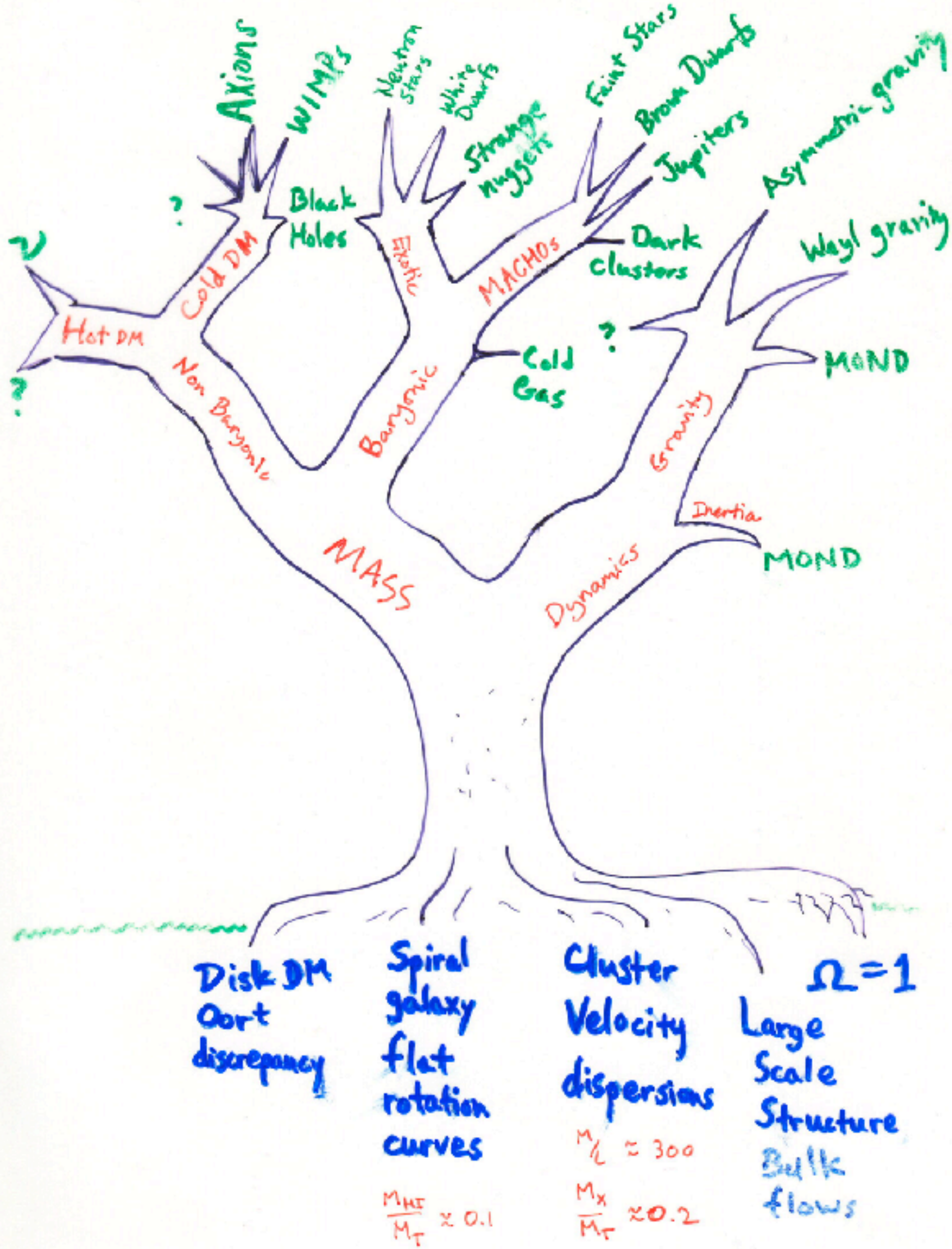
Today

Clusters of Galaxies

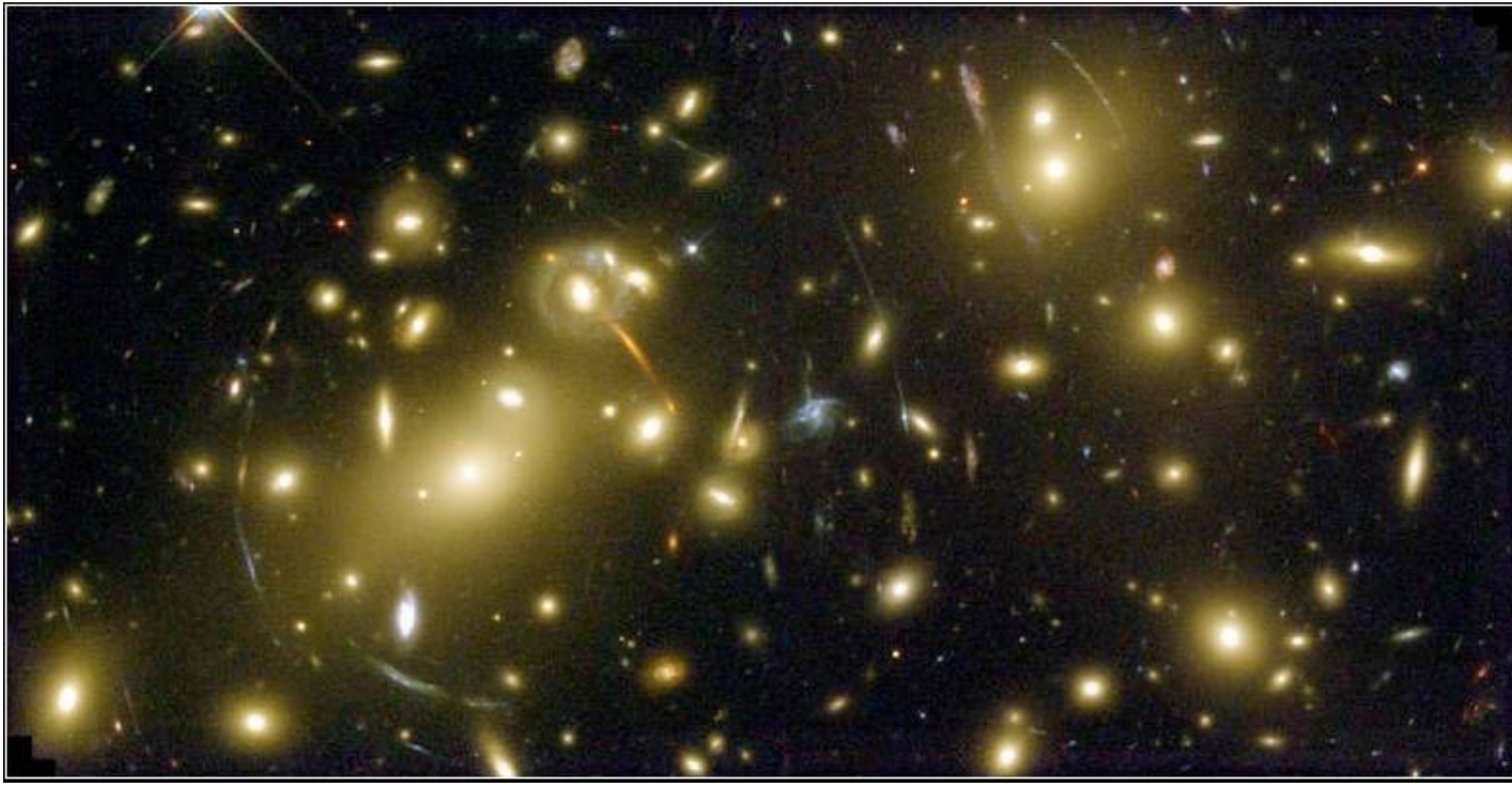
Homework 3 due

ASTR 433 Projects
4/17: distribute abstracts
4/19: 20 minute talks

4/24: Homework 4 due
4/26: Exam

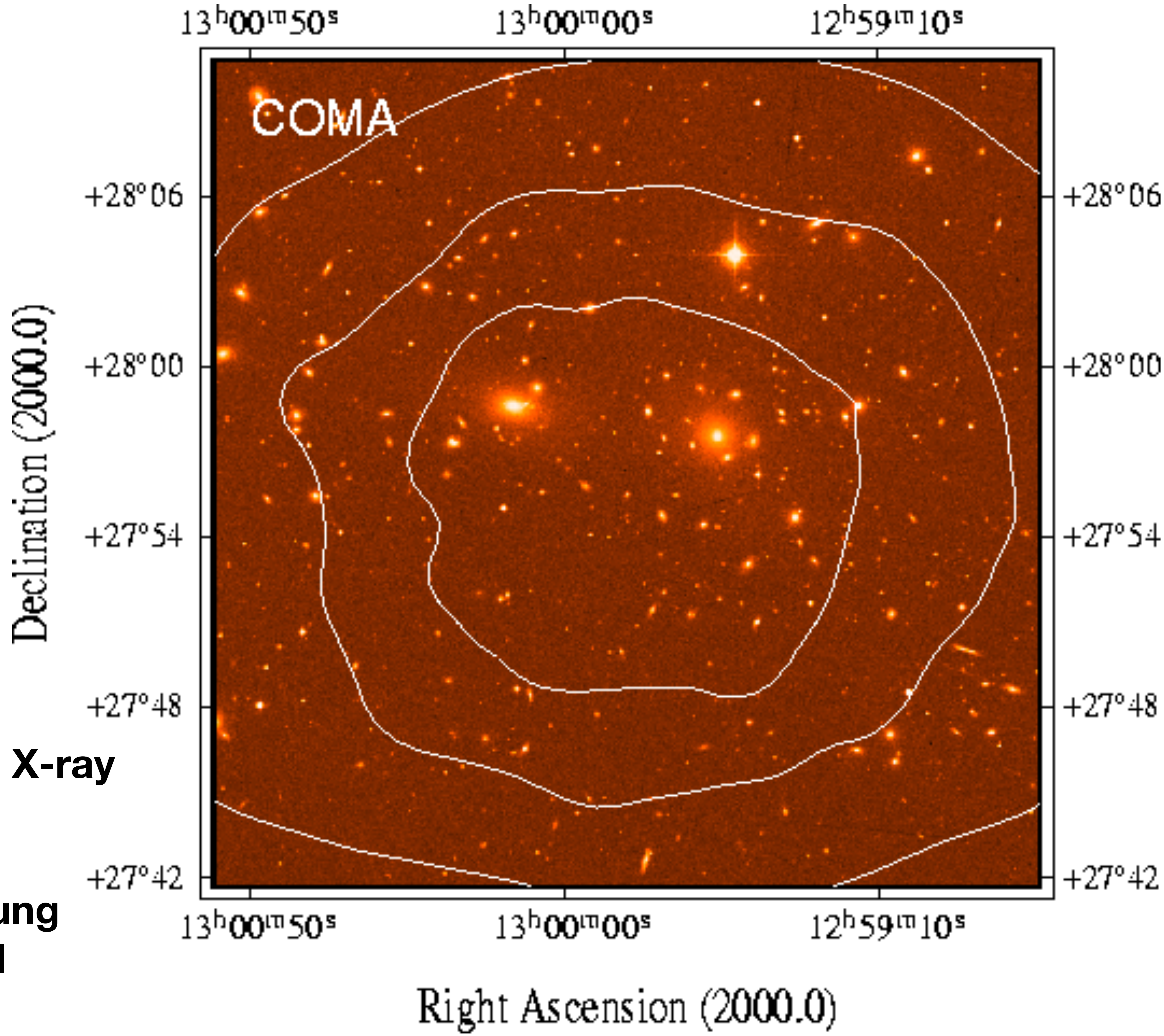


Galaxy Clusters



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)



Typically two X-ray sources

Bremsstrahlung from hot ICM

AGN and other point sources

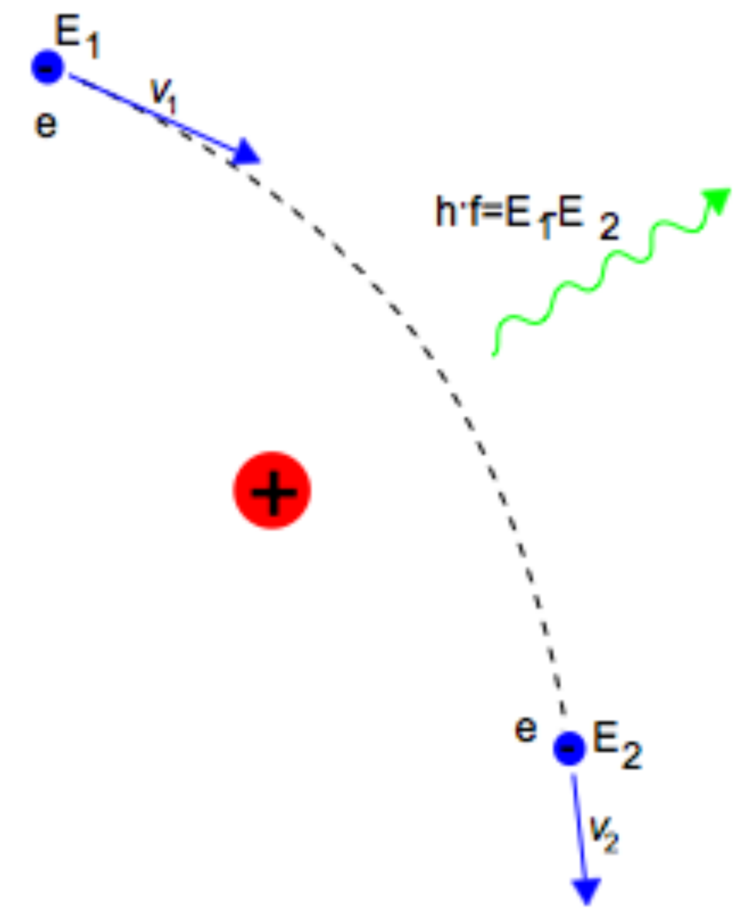
Reiprich ApJ, 567, 716-740 (2002)

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

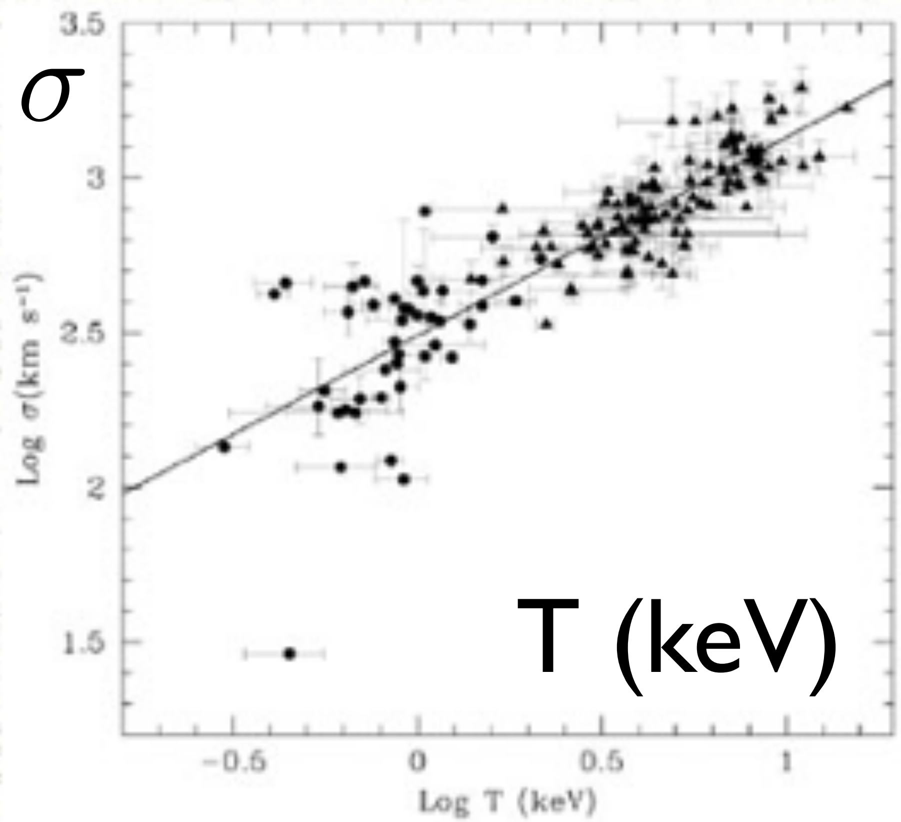


Figure 4. Logarithm of the X-ray temperature versus logarithm of optical velocity dispersion for a sample of groups (circles) and clusters (triangles). The group data are taken from the literature compilation of Xue & Wu (2000), with the addition of the groups in Helsdon & Ponman (2000). The cluster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

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

Global correlations in galaxy clusters

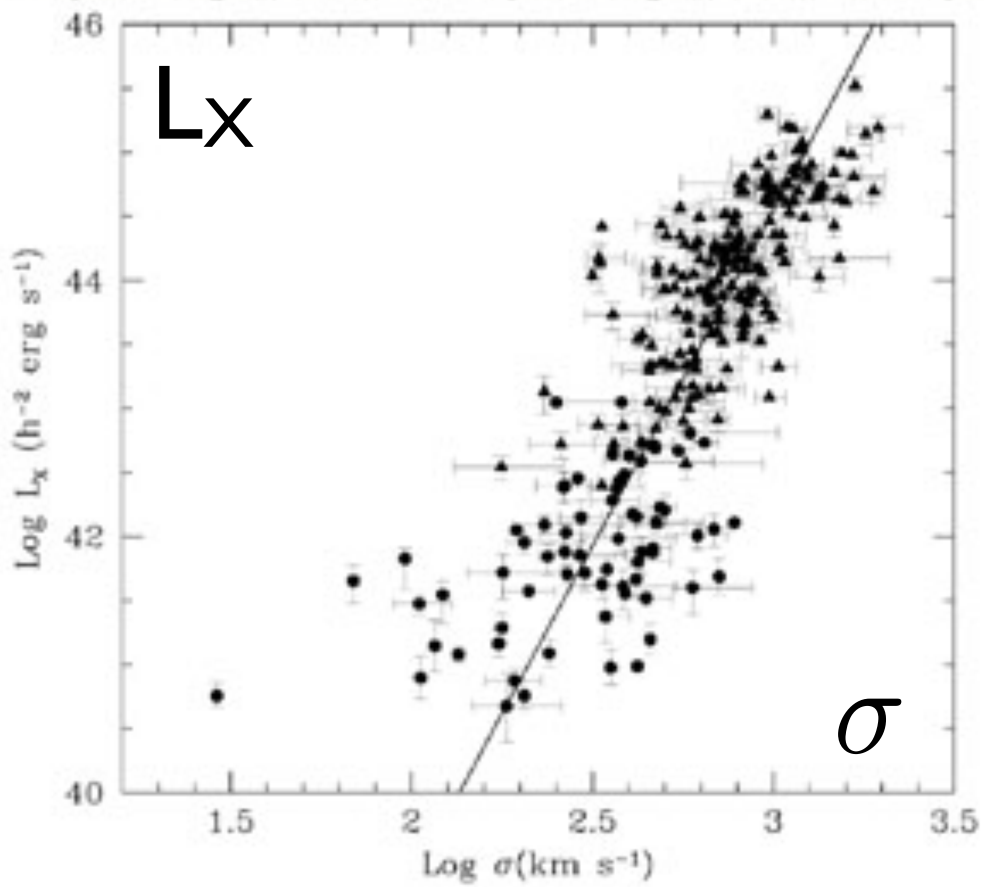

Figure 5. Logarithm of optical velocity dispersion versus logarithm of X-ray luminosity for a sample of groups (circles) and clusters (triangles). The data are taken from the same sources cited in Figure 4. The solid line represents the best-fit found by Wu et al (1999) for the clusters sample (using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

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Global correlations in galaxy clusters

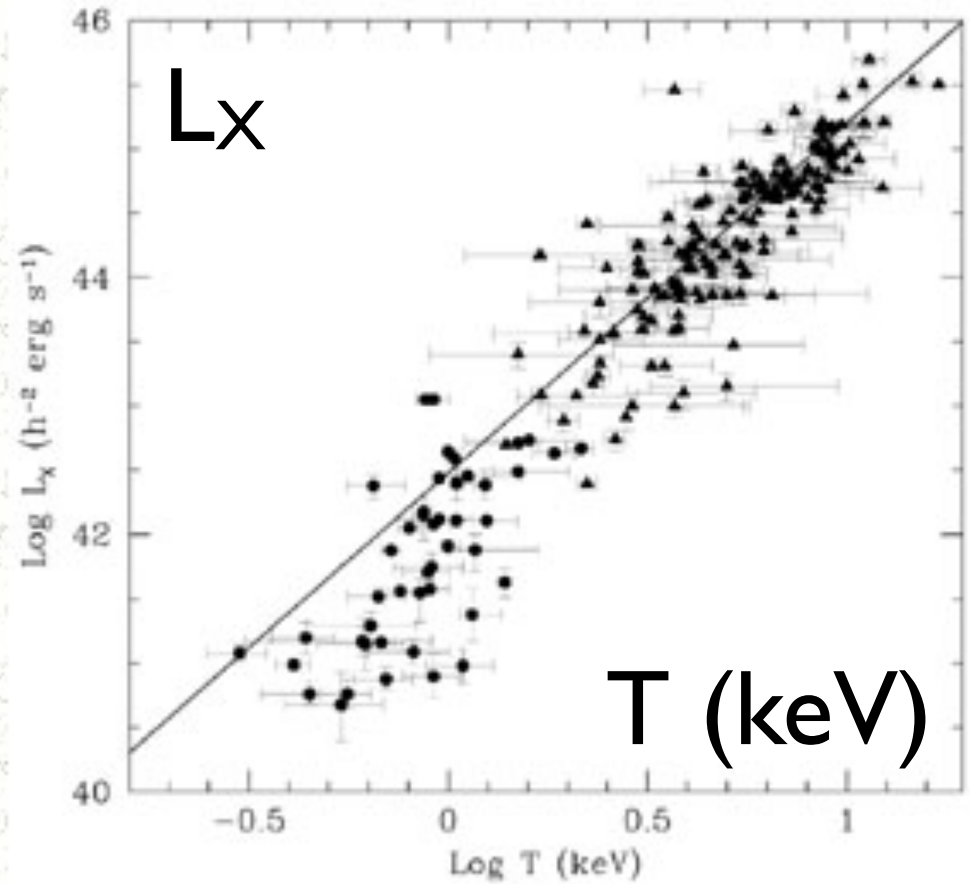


Figure 6. Logarithm of the X-ray temperature versus logarithm of X-ray luminosity for a sample of groups (circles) and clusters (triangles). The data are taken from the same sources cited in Figure 4. The solid line represents the best-fit found by Wu et al (1999) for the clusters sample (using an orthogonal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

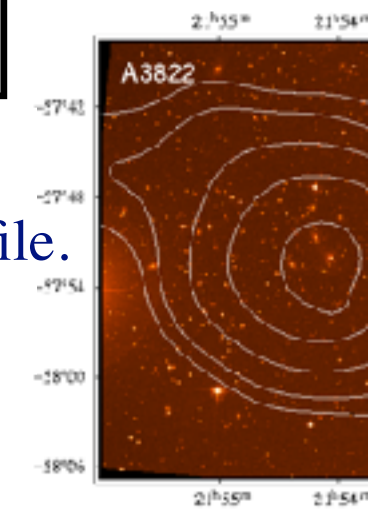
T_{g} is the temperature of the ICM

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

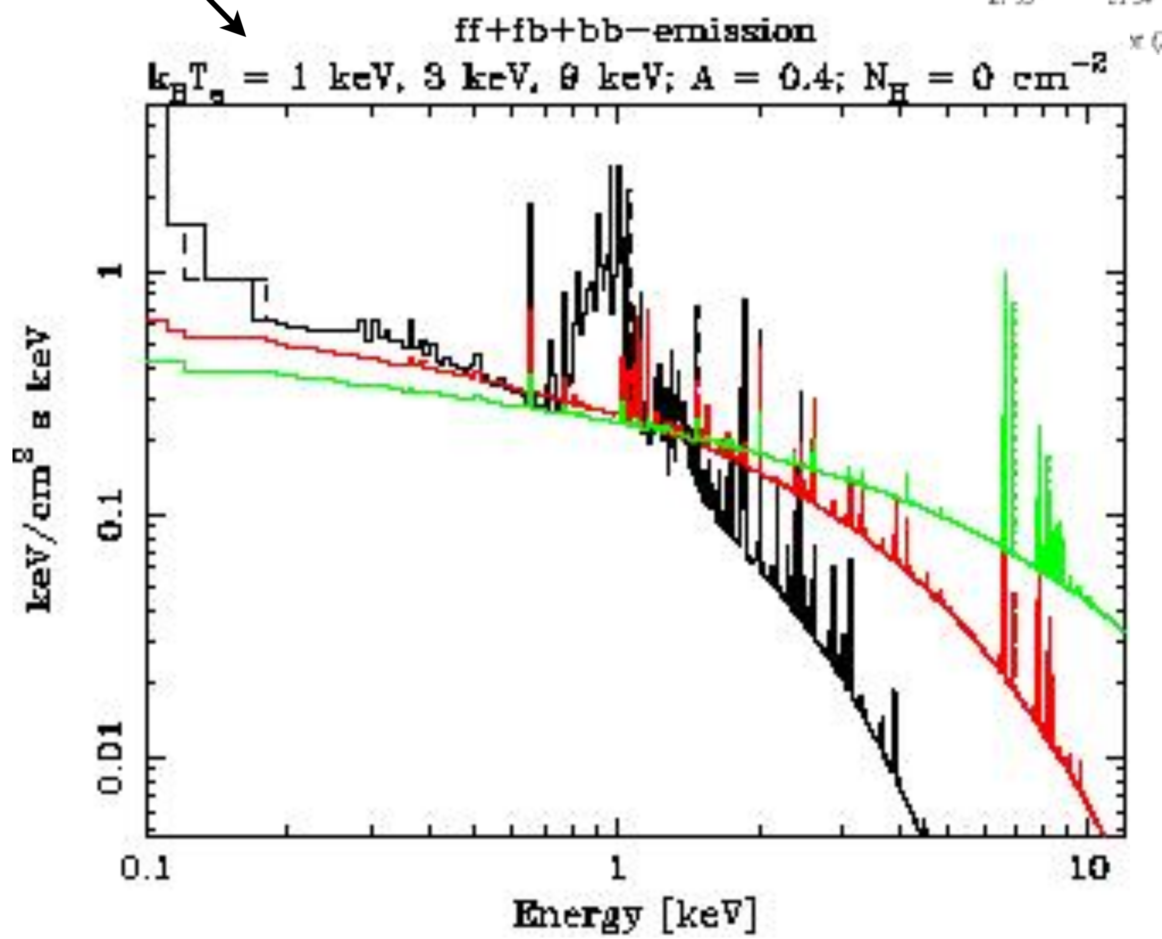
Mass Estimator

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



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

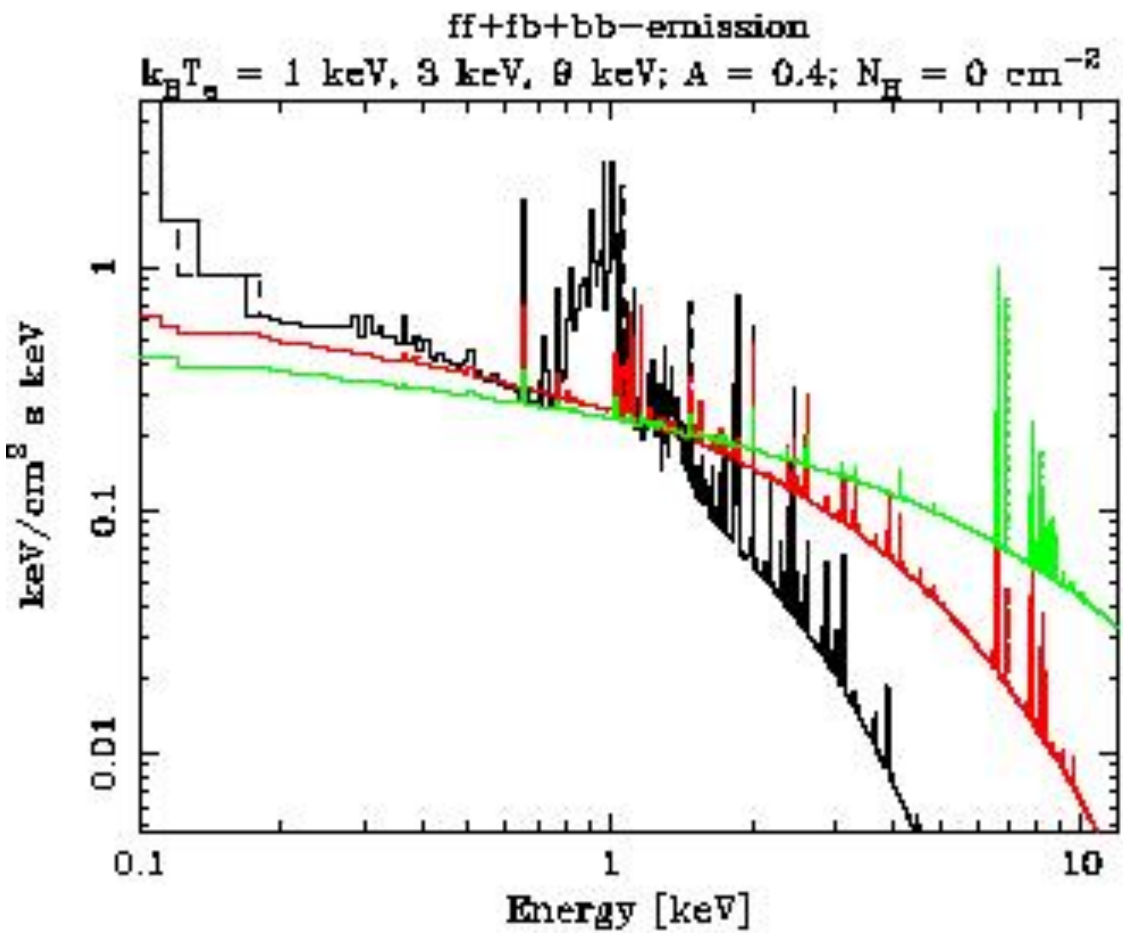
- isothermality $\longrightarrow \dfrac{\partial \log T}{\partial \log r} = 0$

Mass Estimator

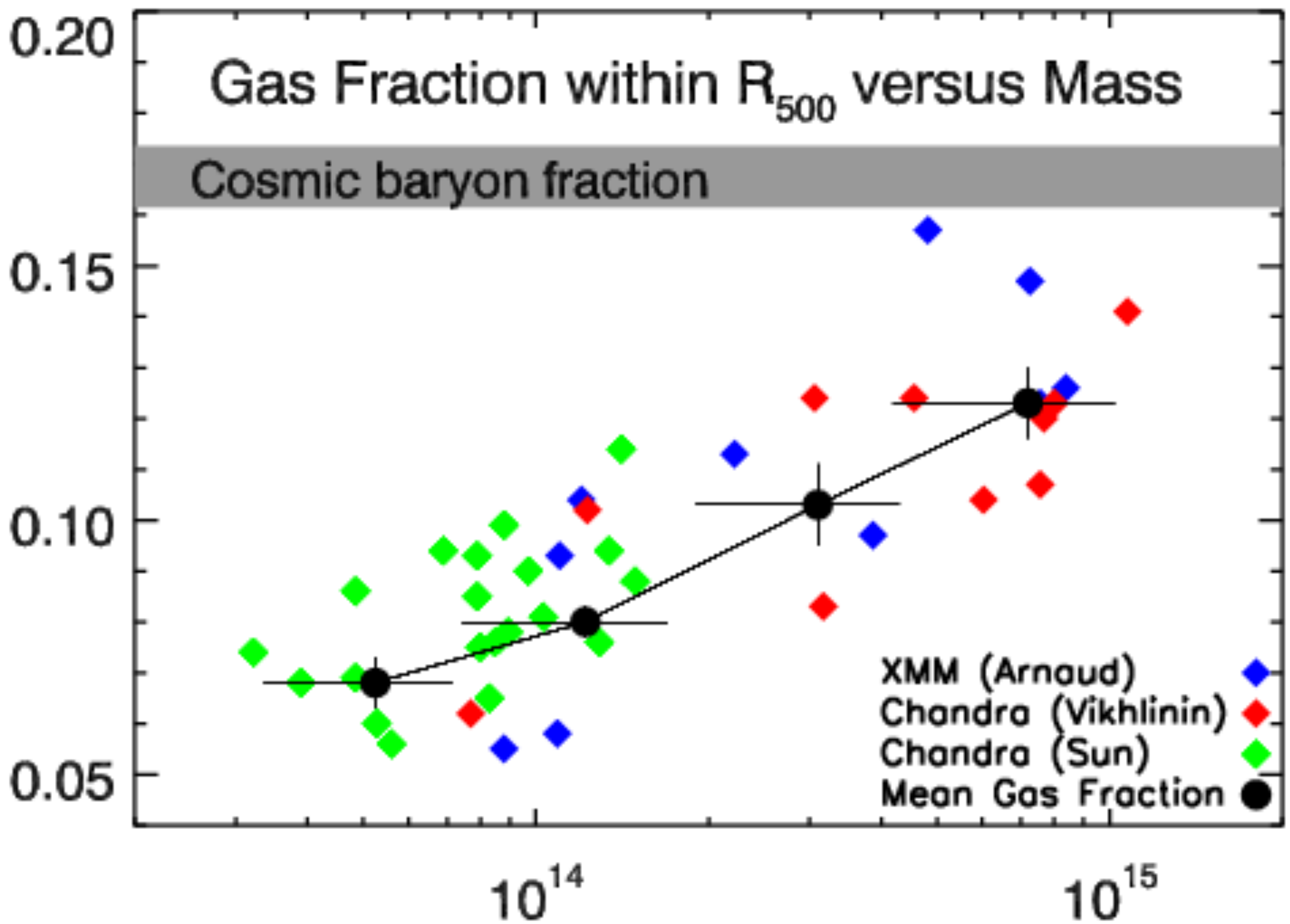
$$M_{tot}(< R) = \frac{kT_g(R)}{G\mu m_p}\left[\frac{\partial \log \rho}{\partial \log r} + \frac{\partial \log T}{\partial \log r}\right] R$$

basically,

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



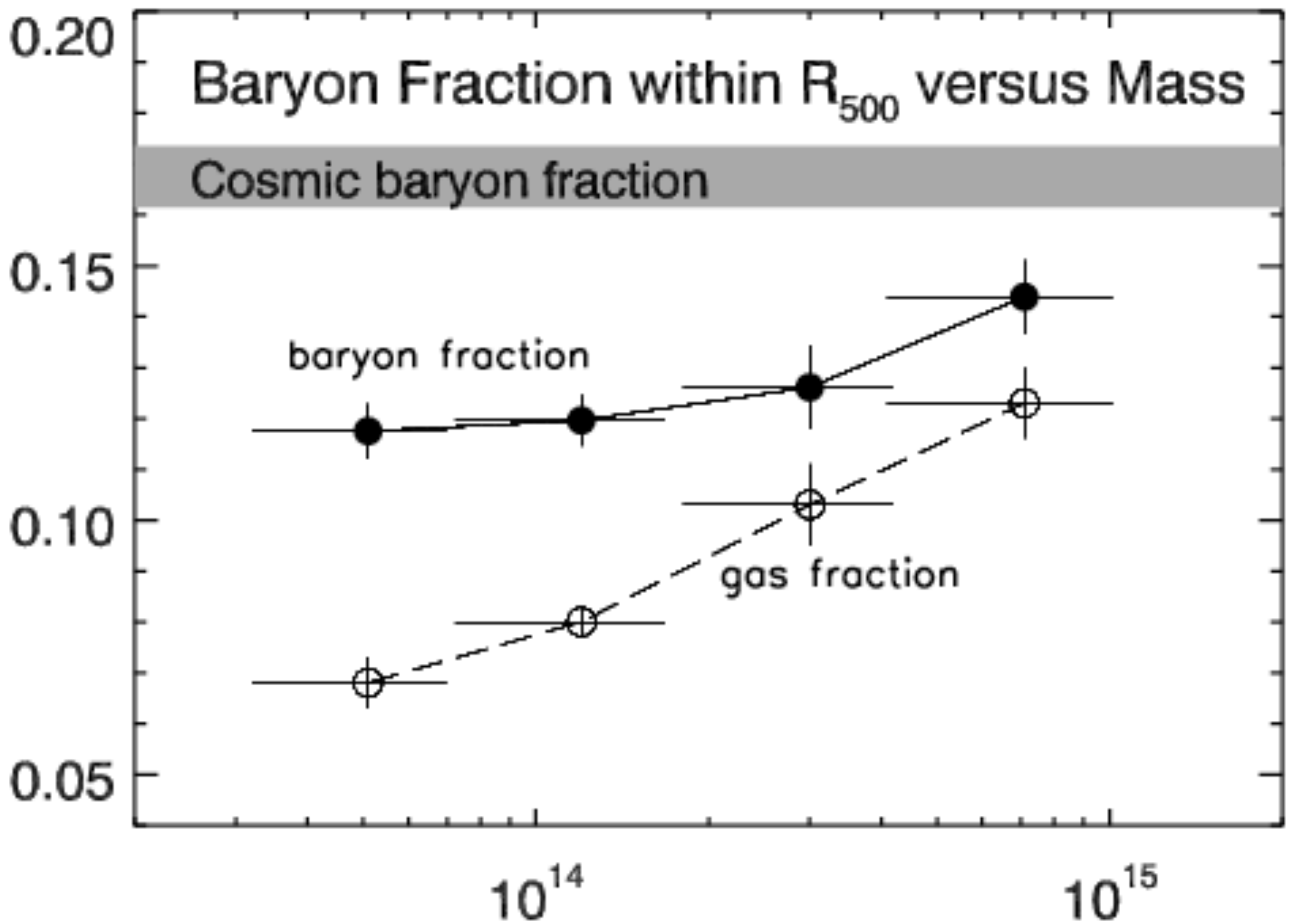
Rasheed (2010)



Typical result:

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

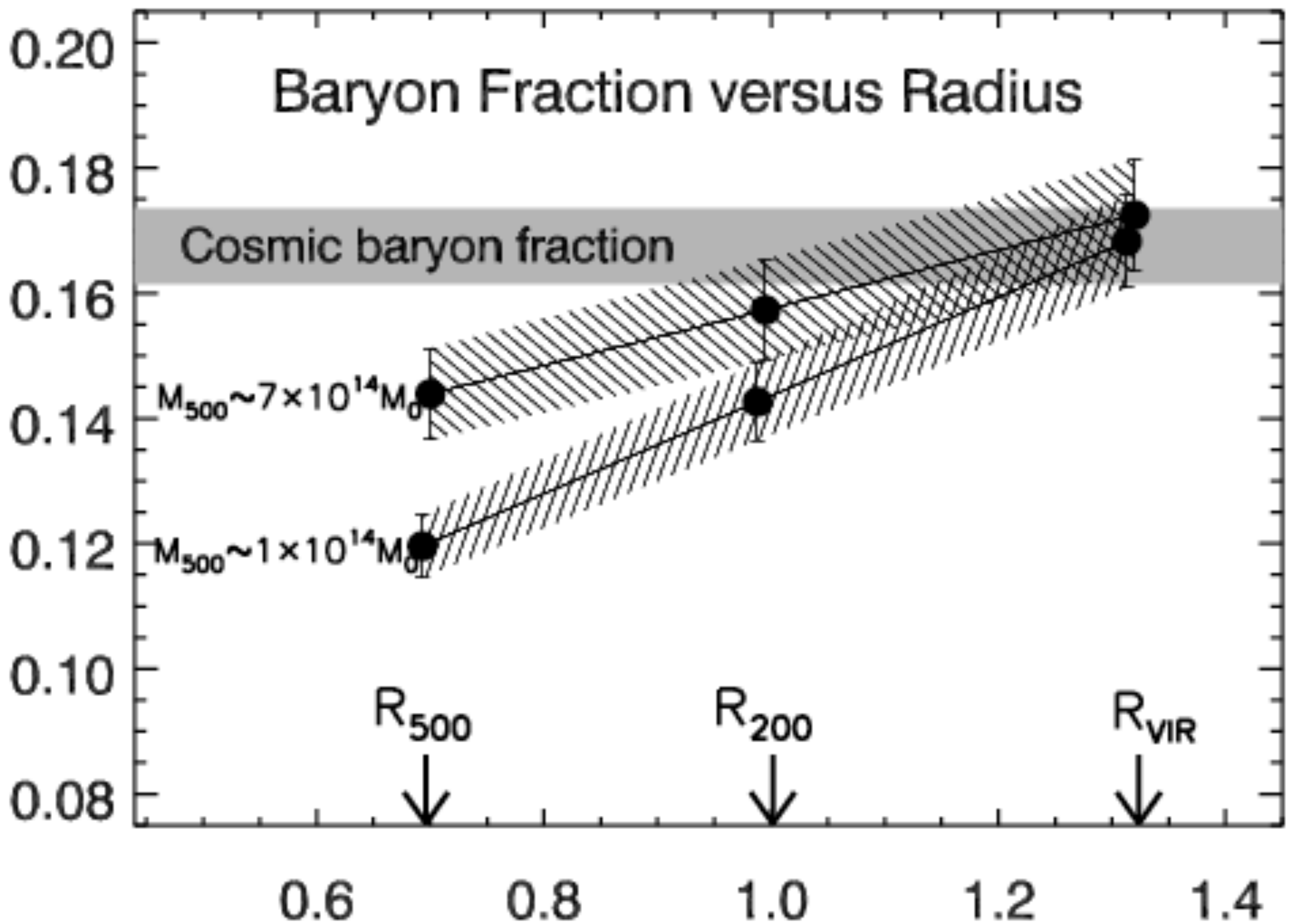
Rasheed (2010)



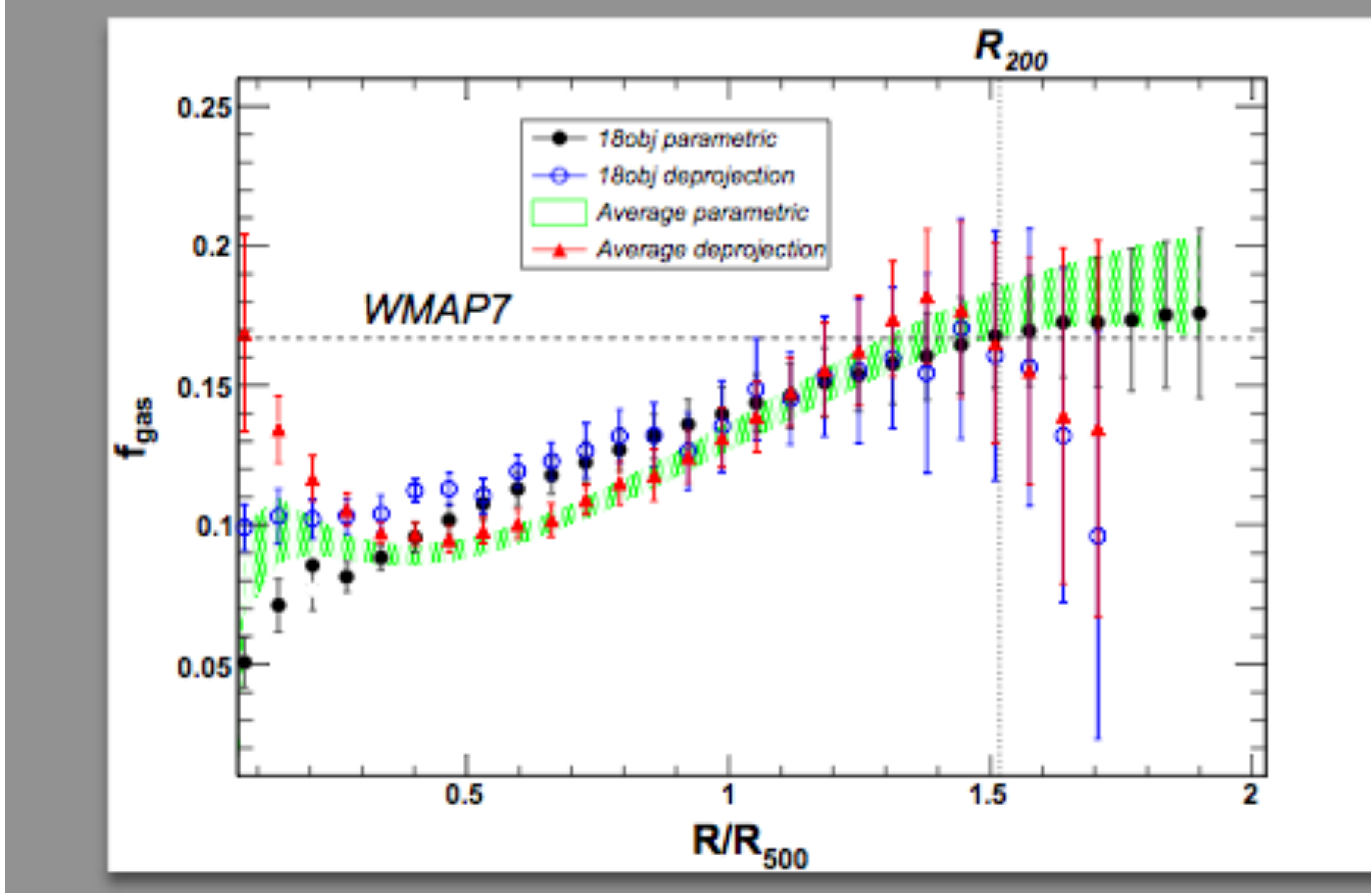
Typical result:

clusters have progressively more gas than stars at higher masses

Rasheed (2010)



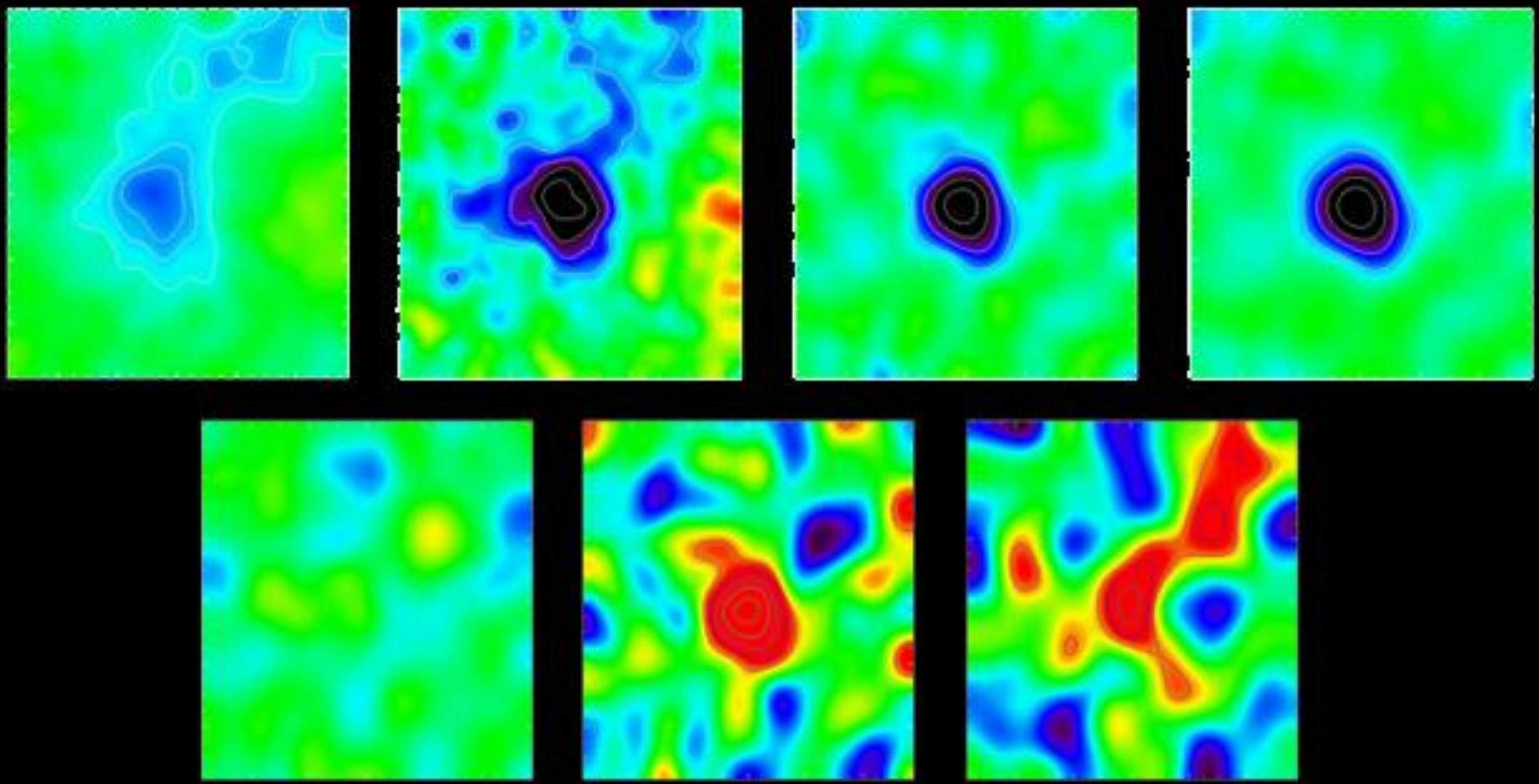
Typical result:
 the baryon fraction increases with radius



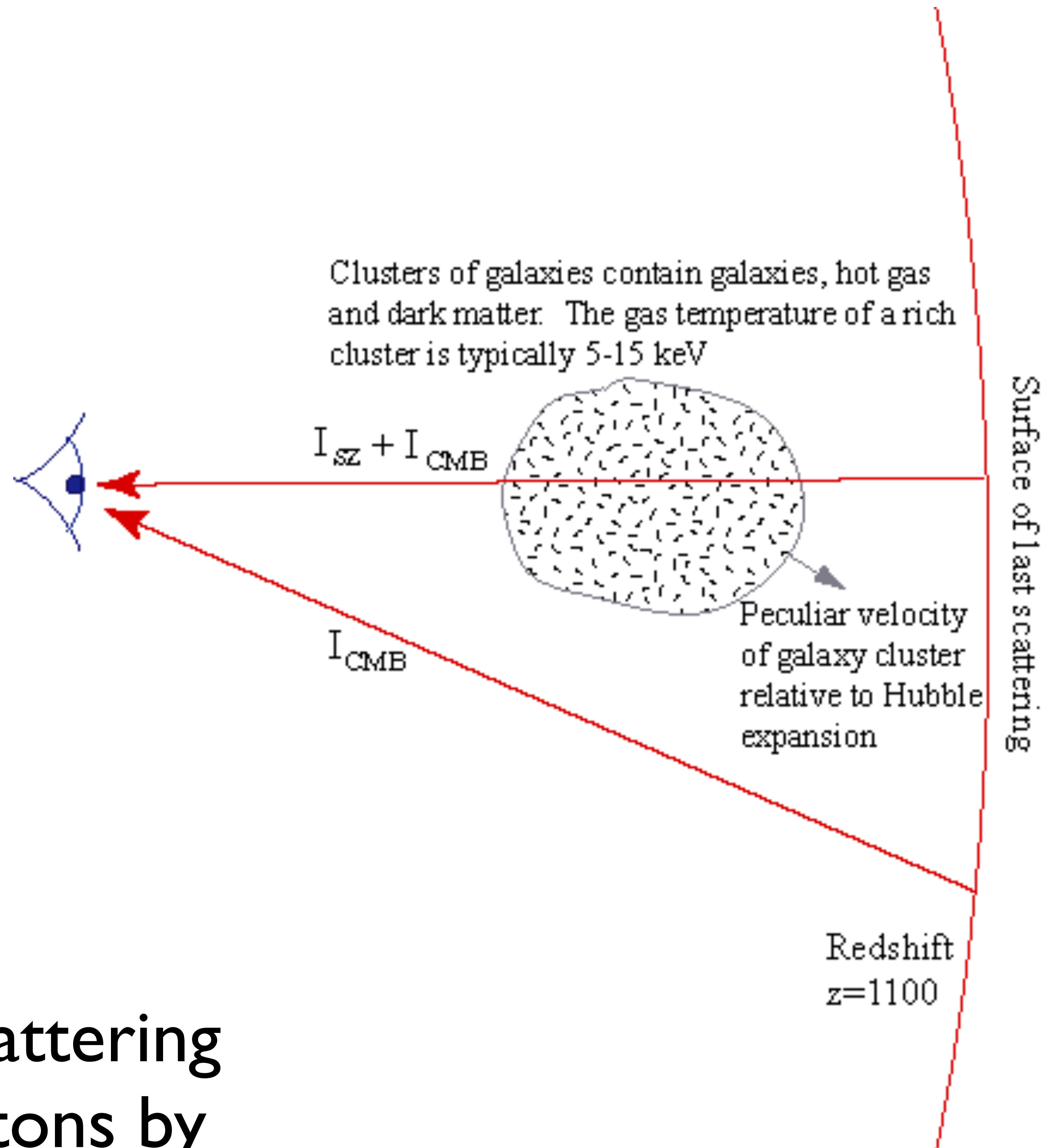
Typical result:
ICM gas outweighs the stars by factor of ~6;
outweighed by dark matter by the same factor

There seems to be a missing baryon problem 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

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

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

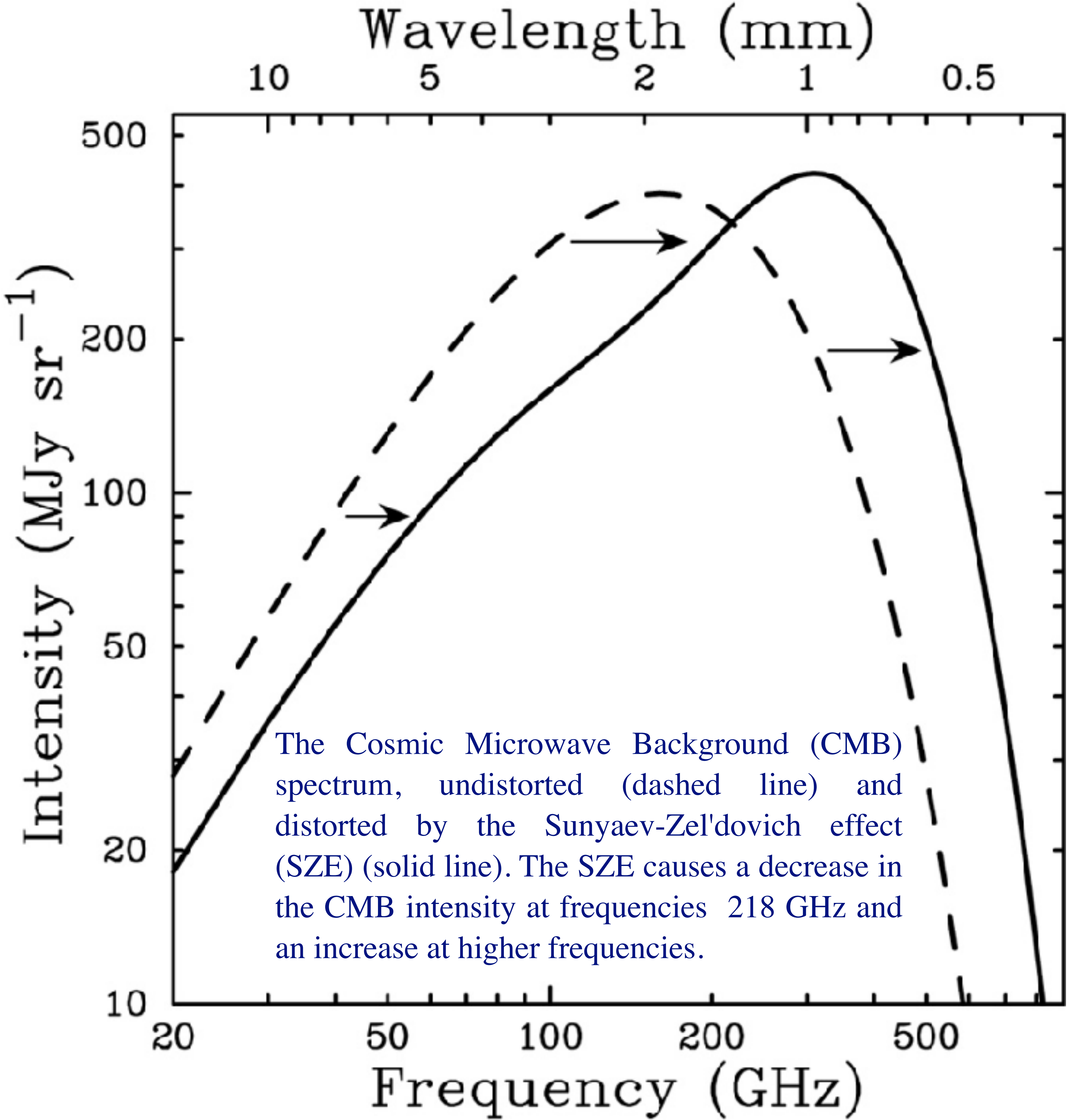
y is the Compton y-parameter which quantifies how much effect the plasma has frequency dependent change in intensity

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

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,

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

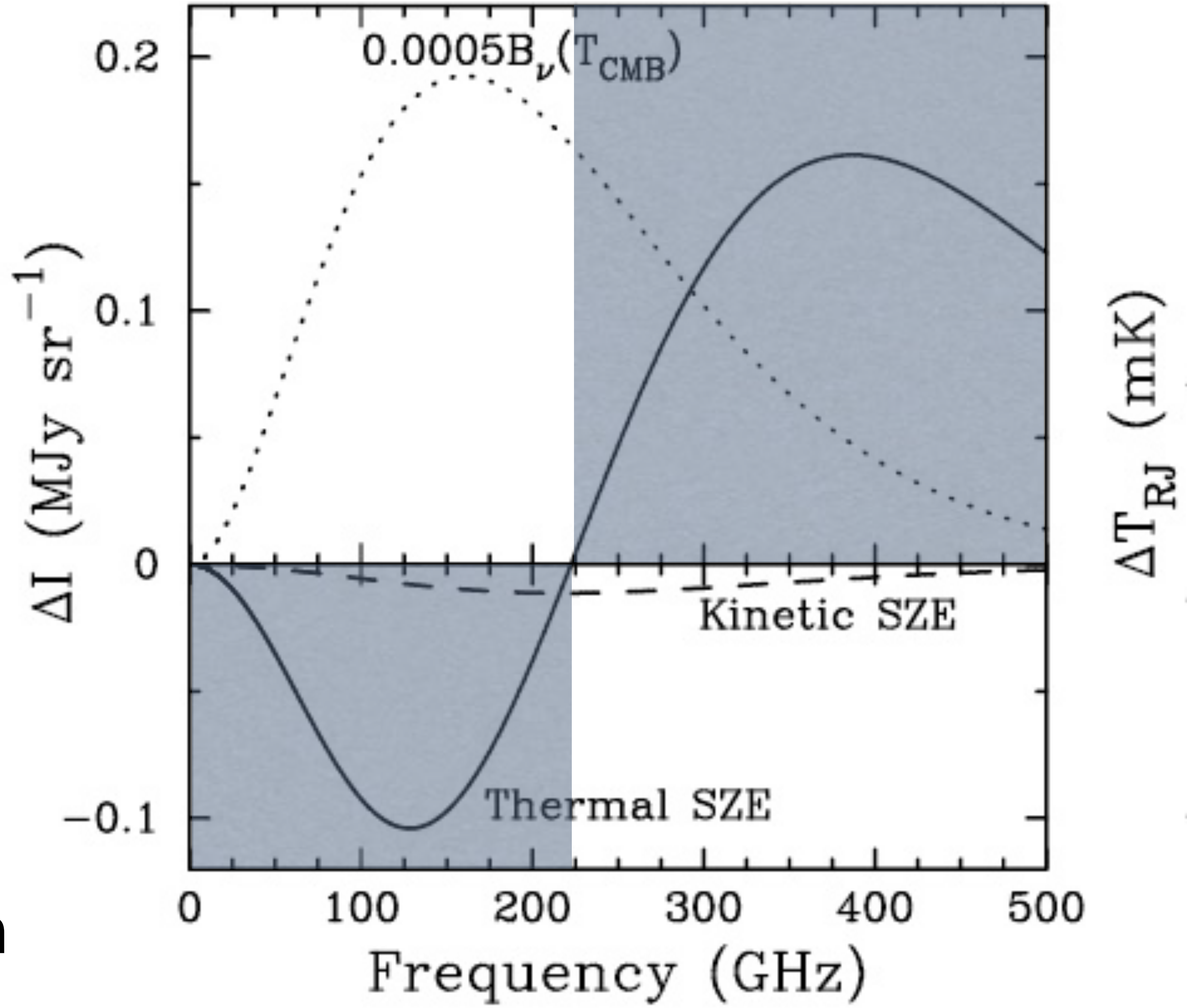


The Cosmic Microwave Background (CMB) spectrum, undistorted (dashed line) and distorted by the Sunyaev-Zel'dovich effect (SZE) (solid line). The SZE causes a decrease in the CMB intensity at frequencies 218 GHz and an increase at higher frequencies.

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

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

intensity boosted

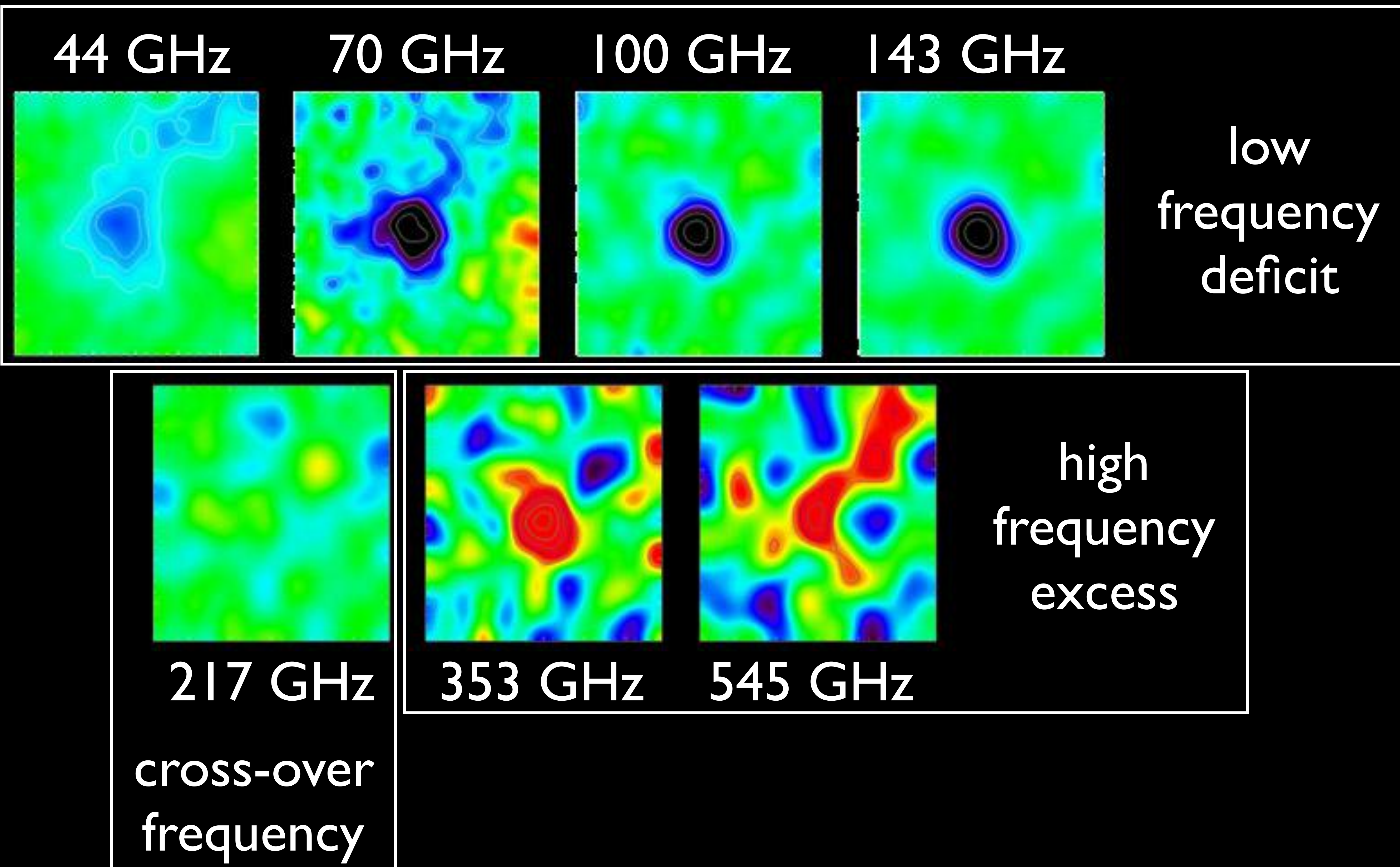


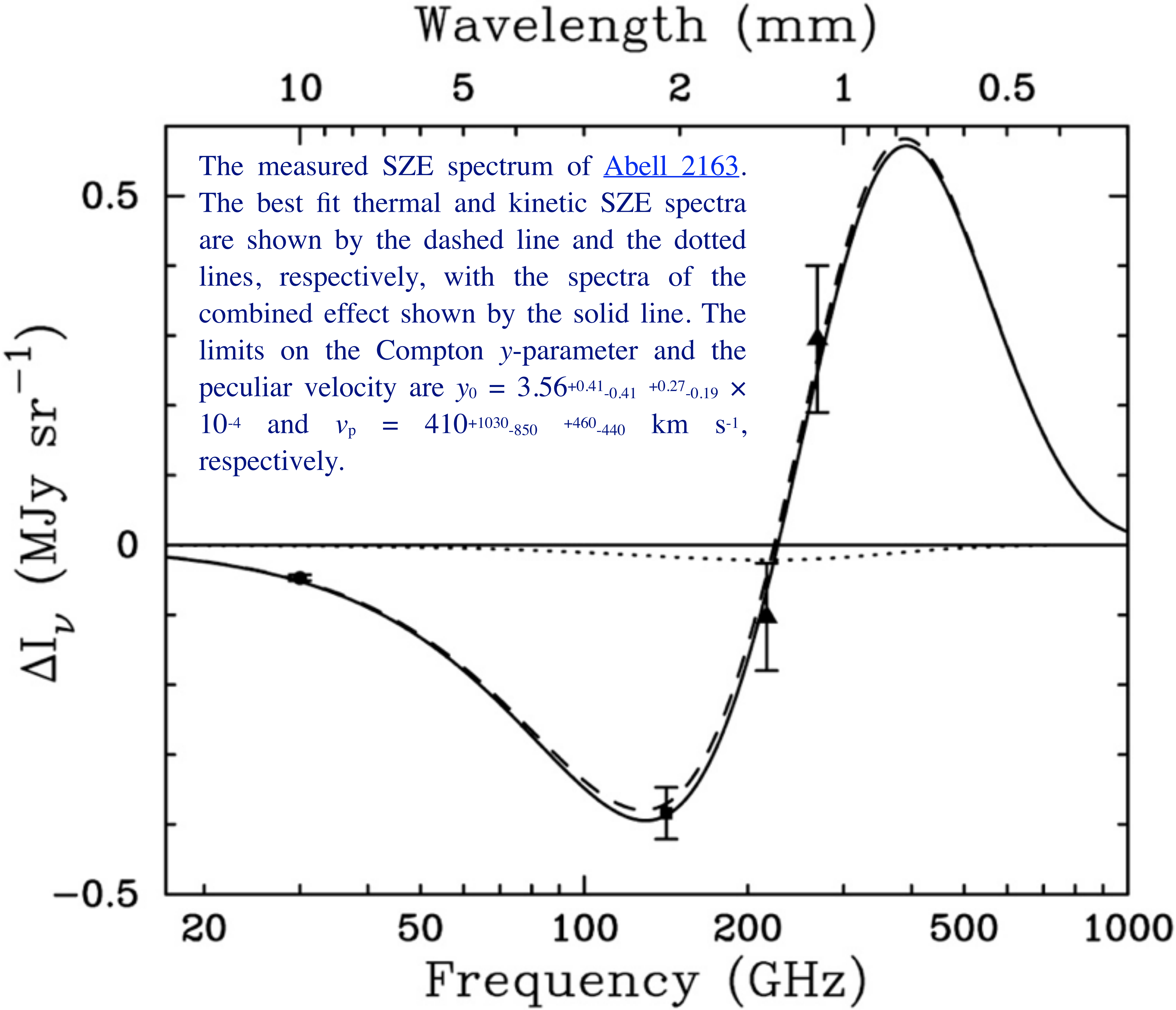
Kinematic SZ effect from peculiar velocity of cluster wrt CMB frame

intensity depleted

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.

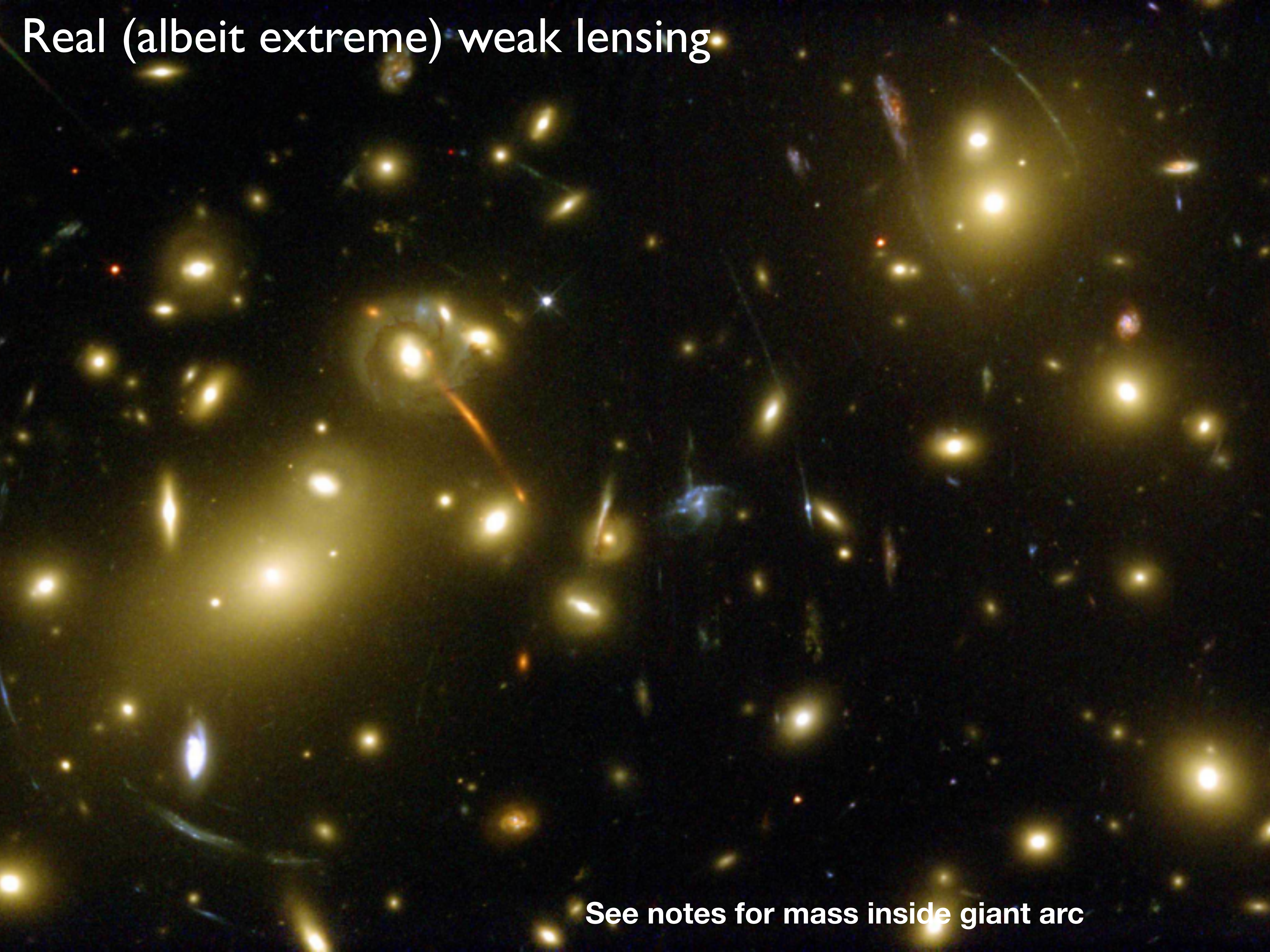
D_A is the angular diameter distance.
At high z, it varies slowly, while the density increases as $(1+z)^3$

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

Fake illustration of weak lensing

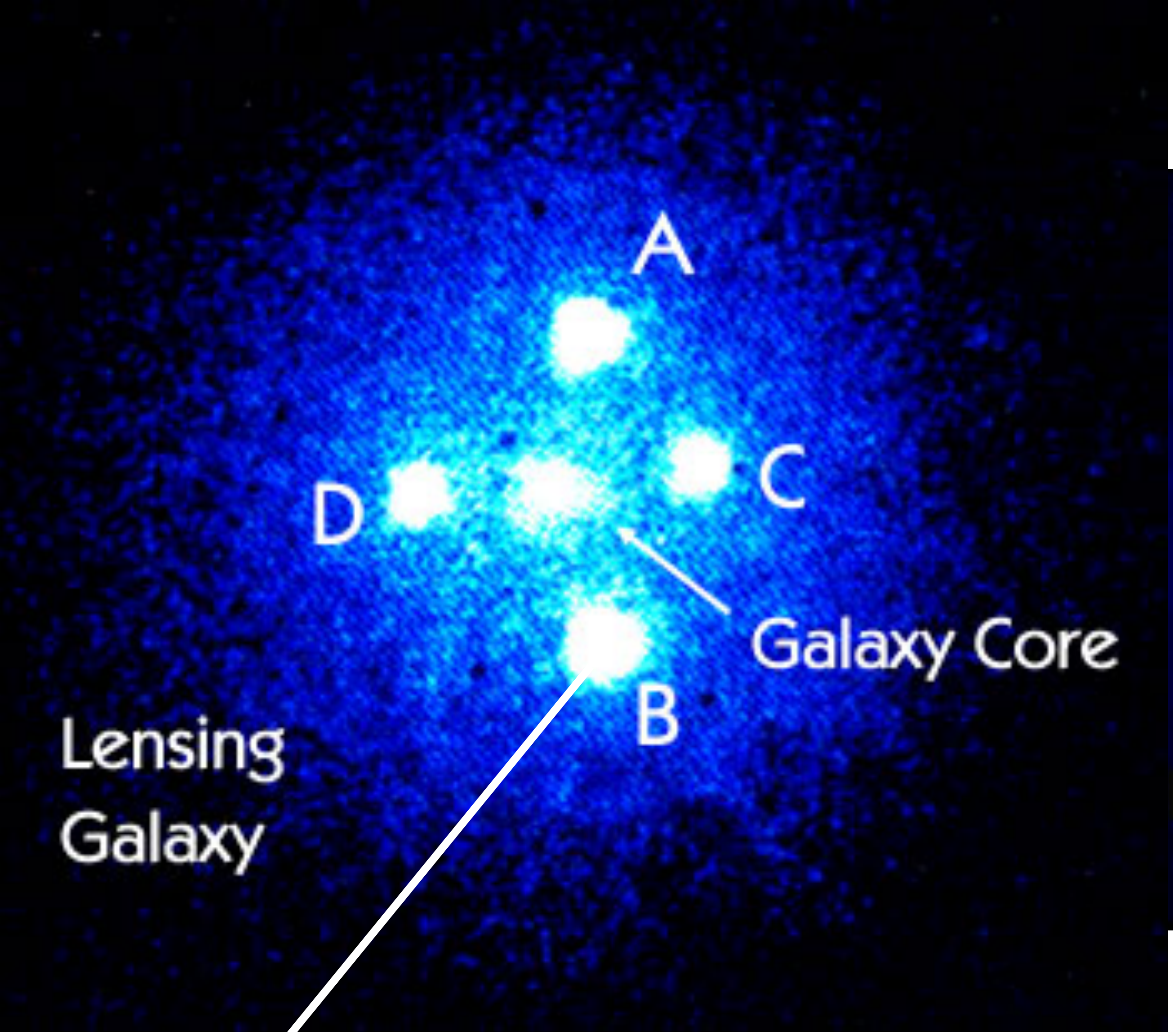
See notes for mass inside giant arc

Real (albeit extreme) weak lensing

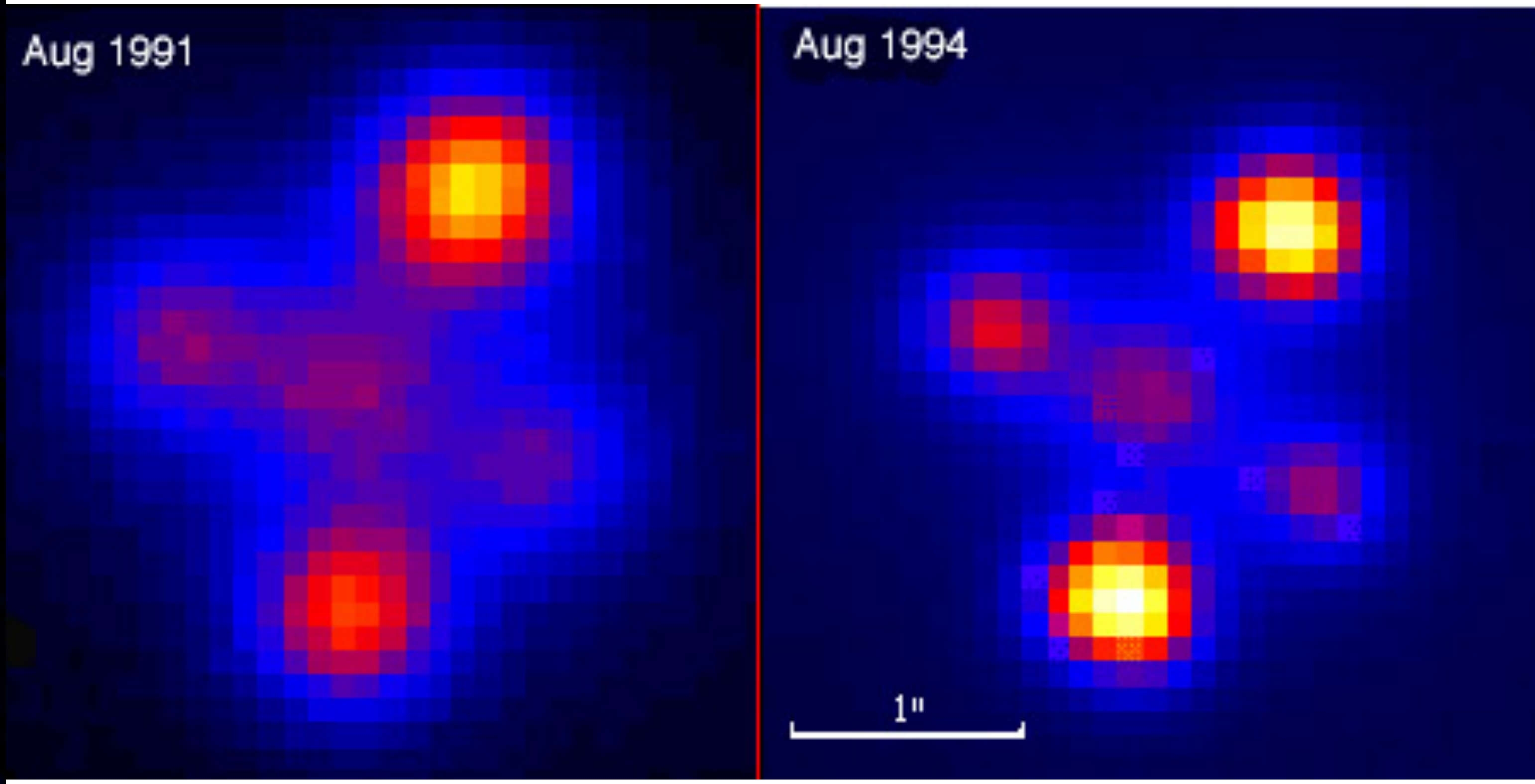


See notes for mass inside giant arc

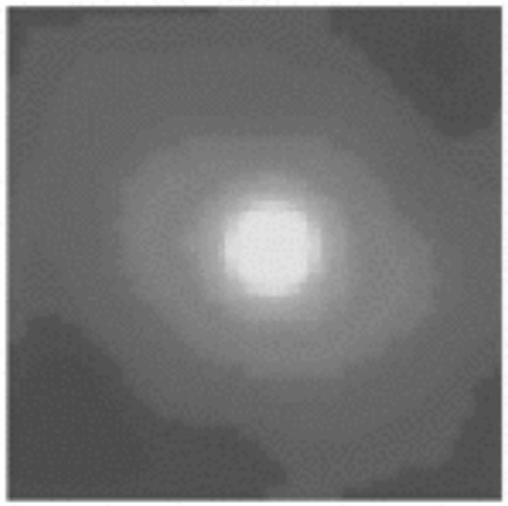
Strong lensing: Einstein Cross



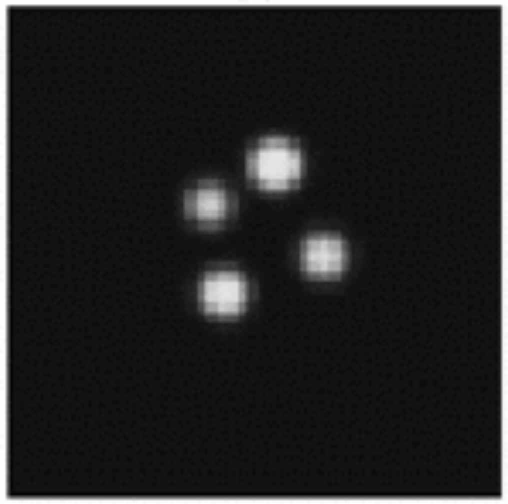
ABCD: same QSO seen 4 times



time variable multiple QSO image

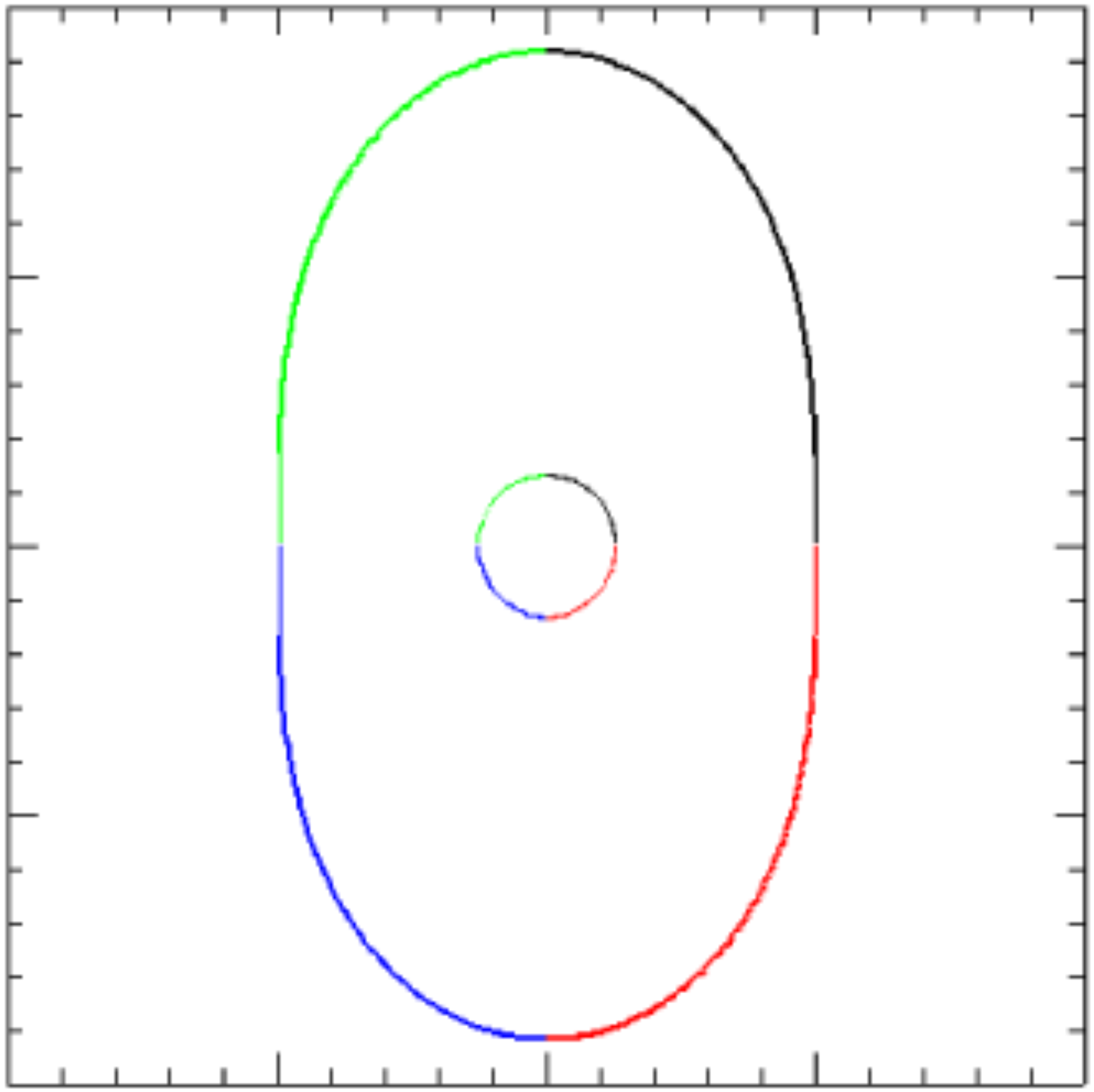


lensing galaxy



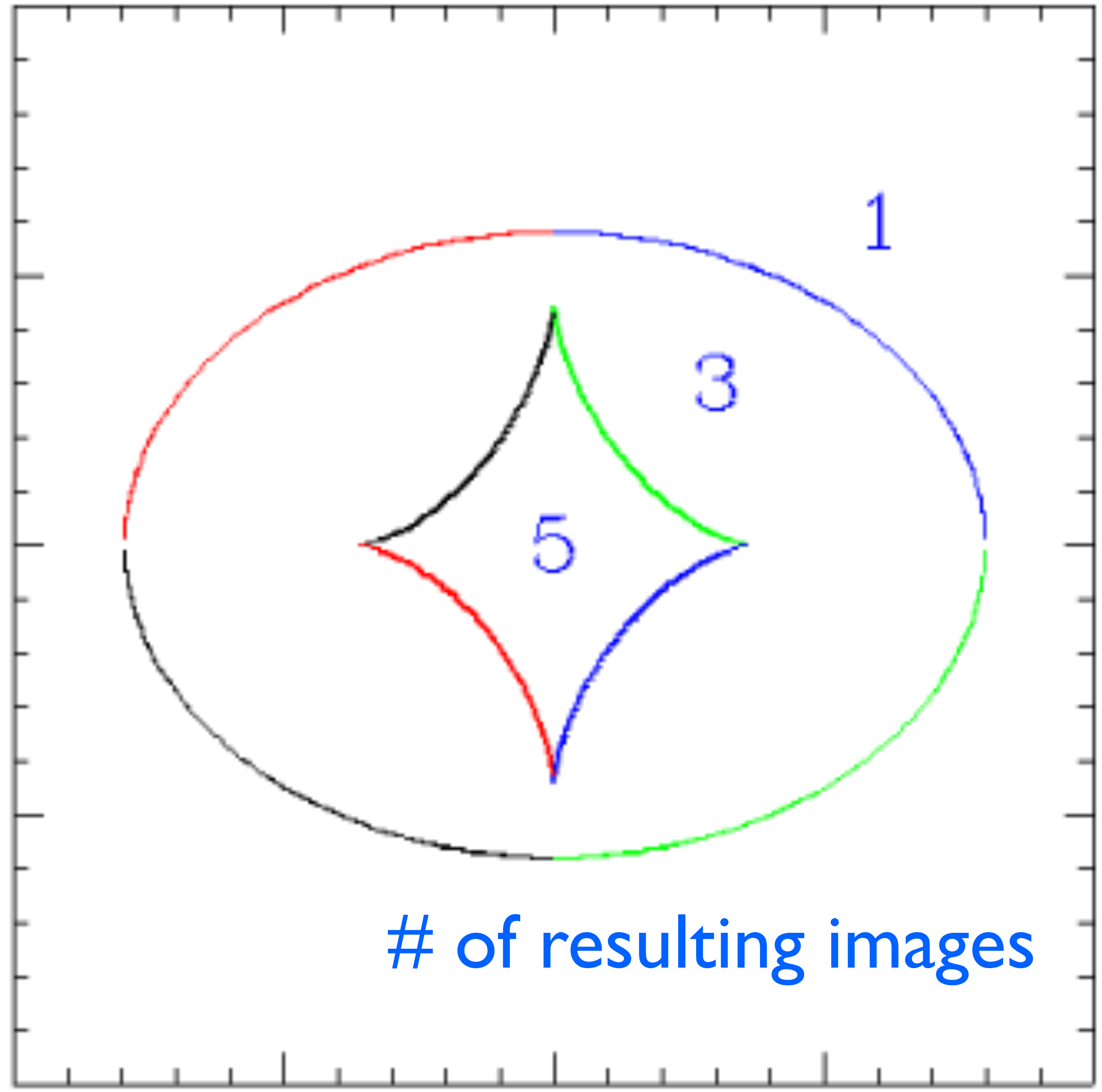
lensed QSO

Lens plane

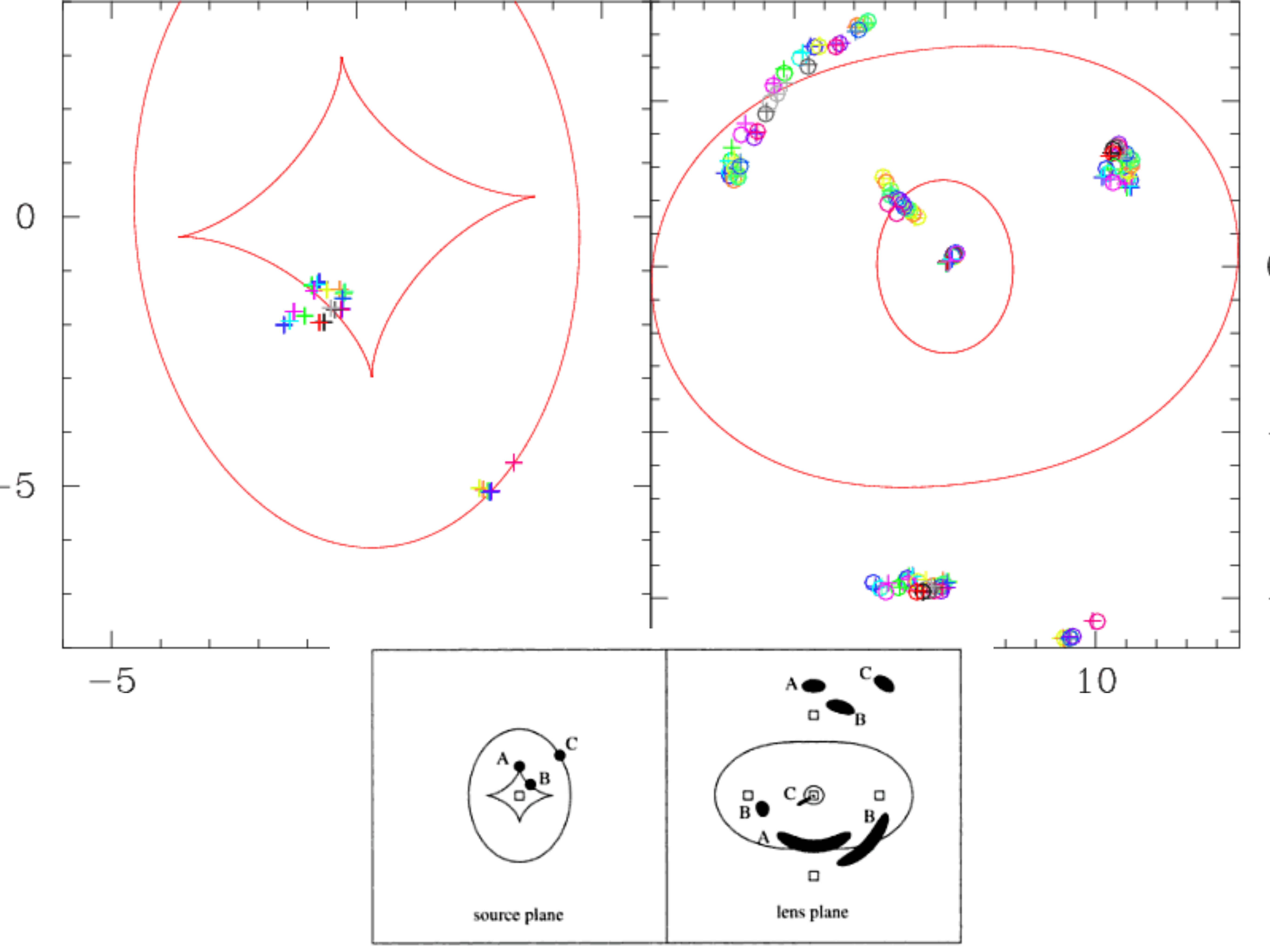


critical curves

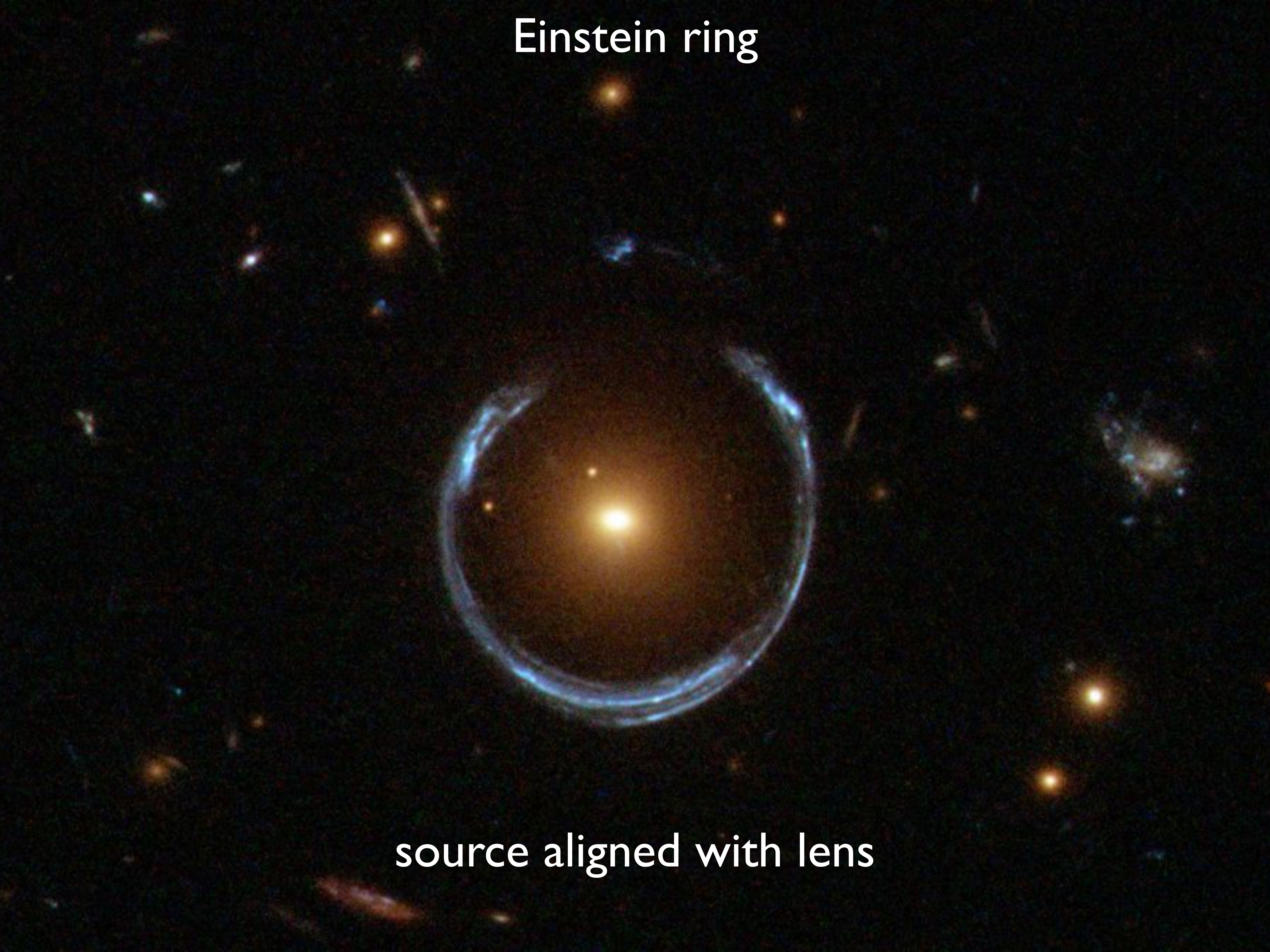
Source plane

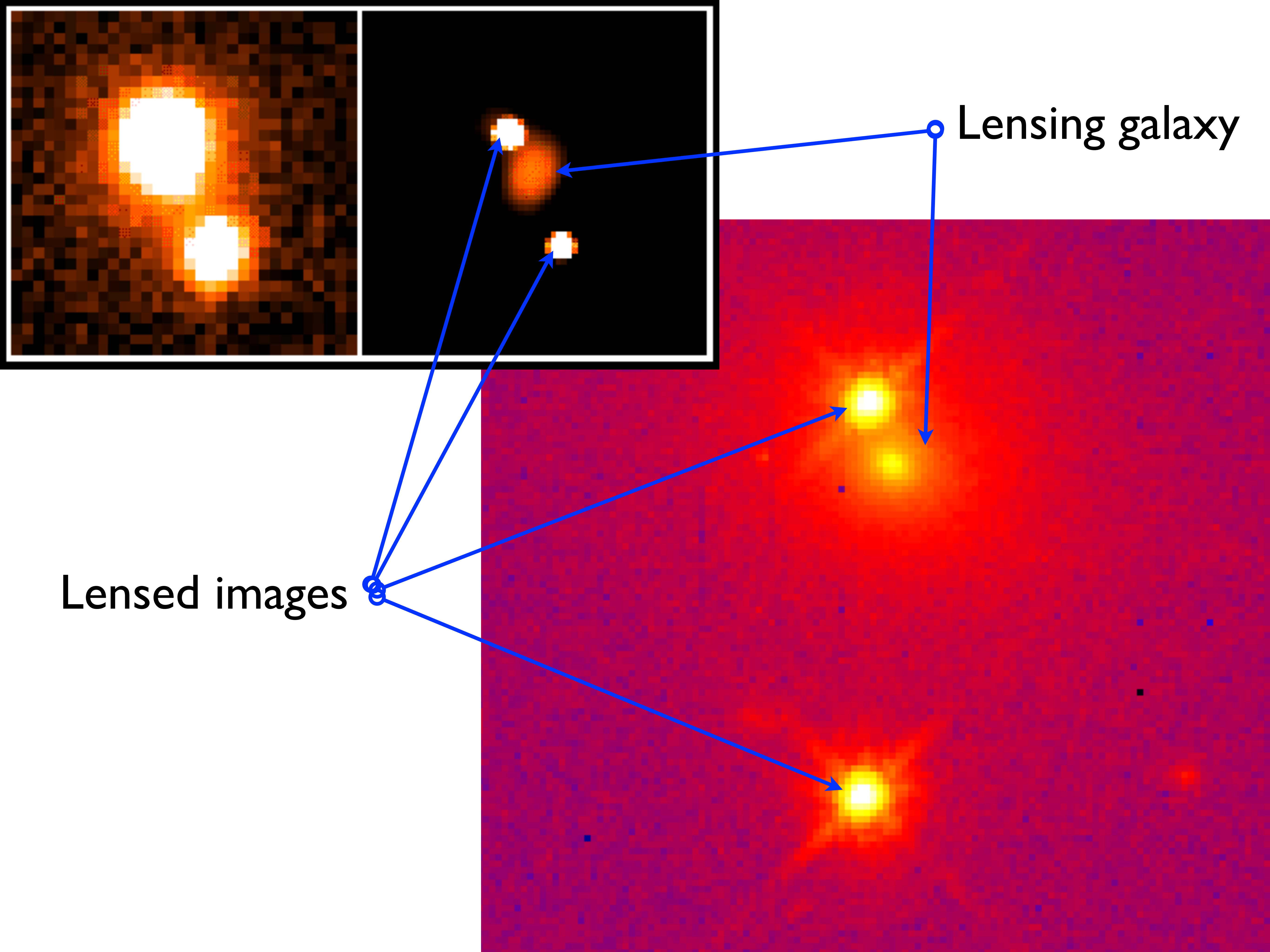


caustics

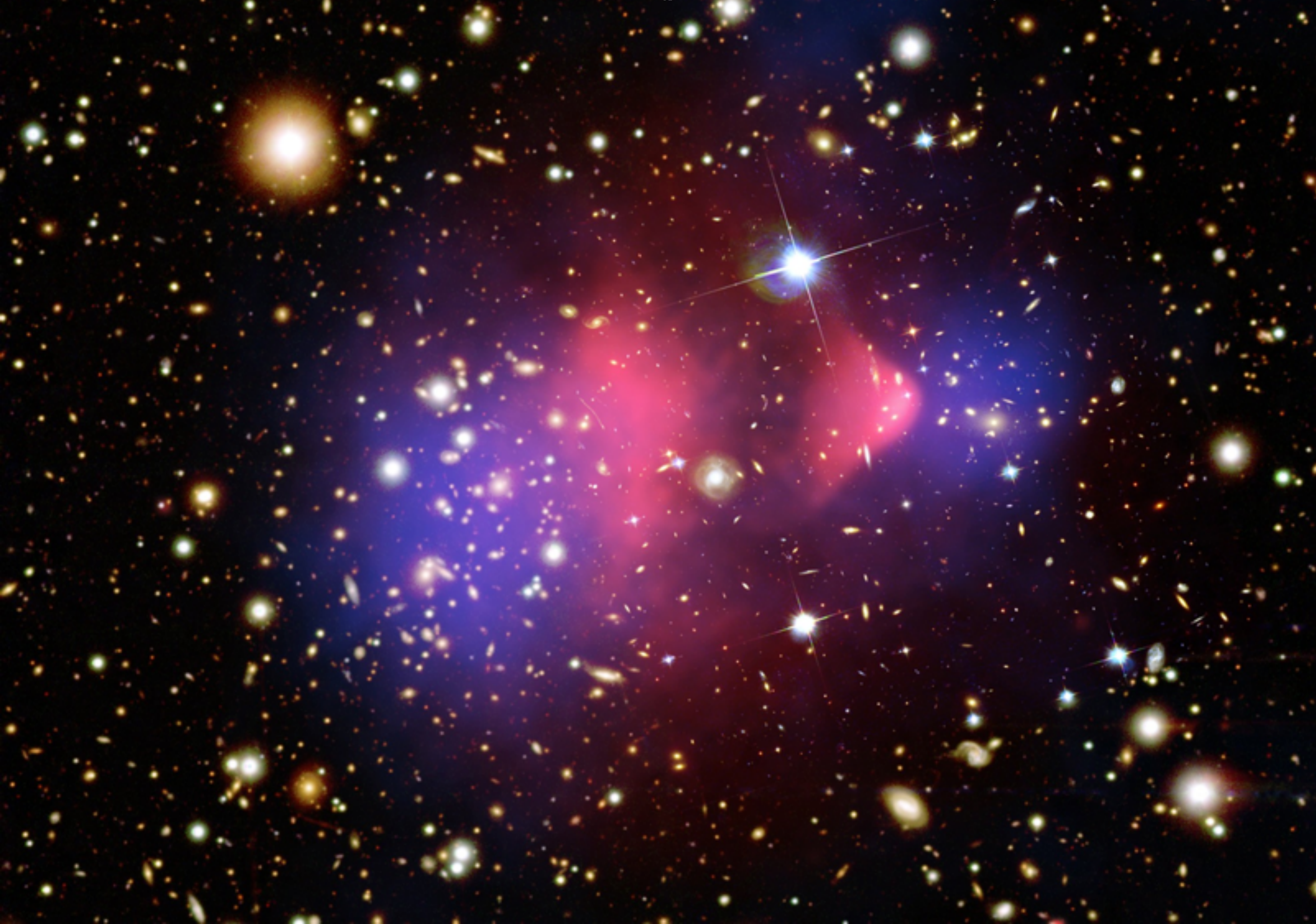


0
−5
−5
10
A
B
C
source plane
A
C
B
C
B
B
A
lens plane


Einstein ring
source aligned with lens

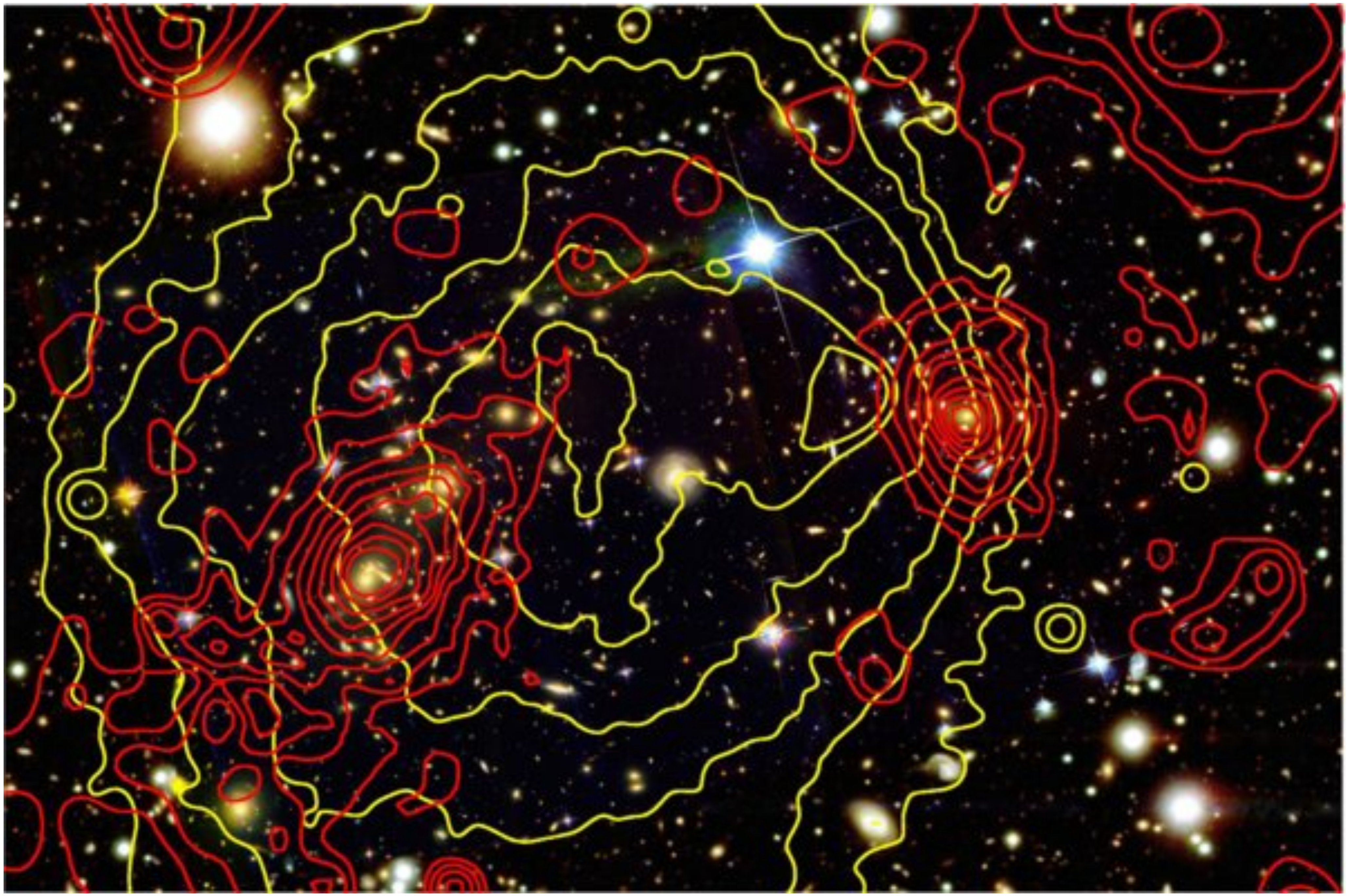

Lensing galaxy
Lensed images

Bullet cluster (press release version)



Bullet cluster (Bradac et al. 2009)

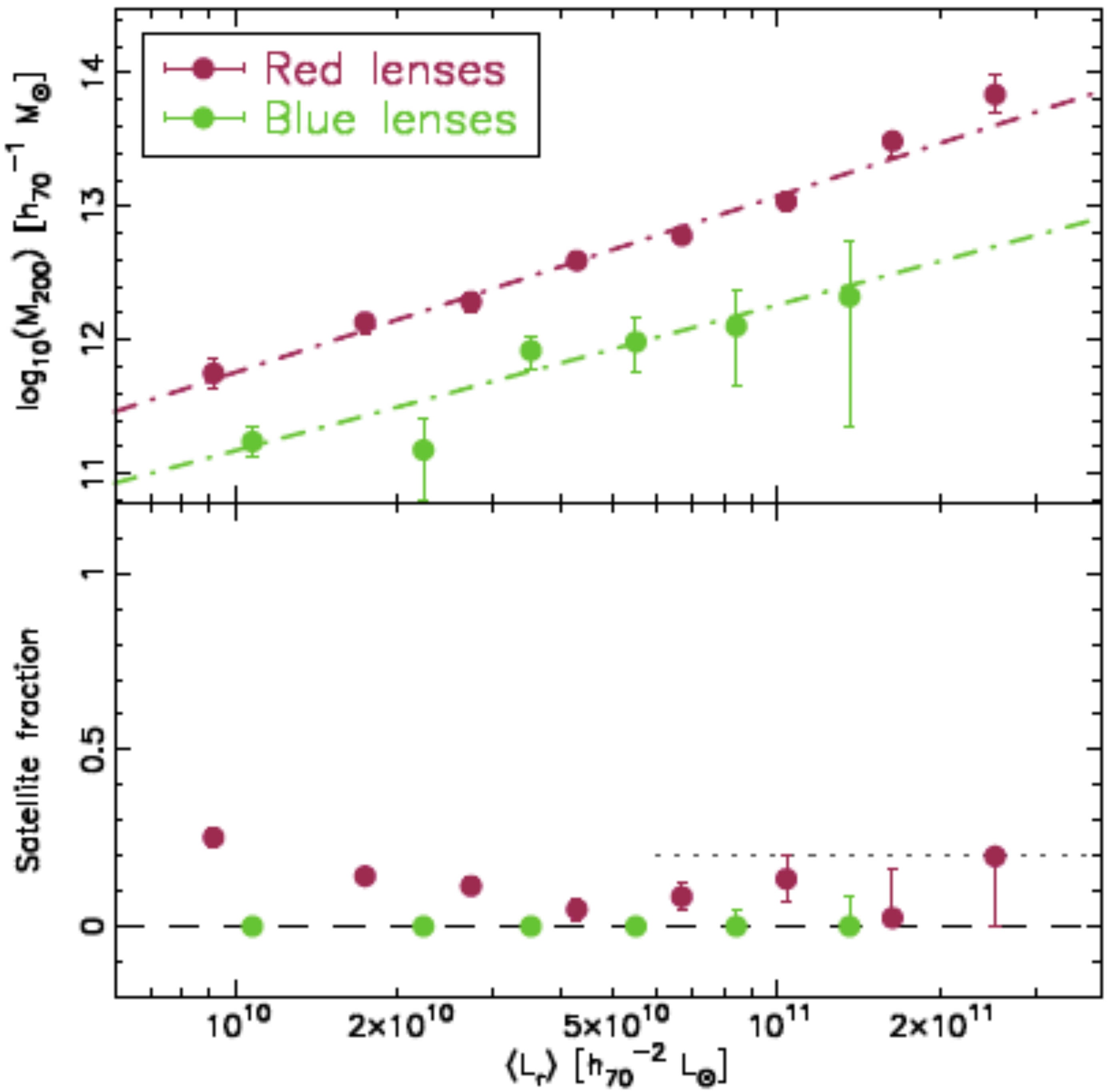
X-ray: yellow contours



gravitational (strong+weak) lensing: red contours

Velander et al (2013)
weak gravitational lensing

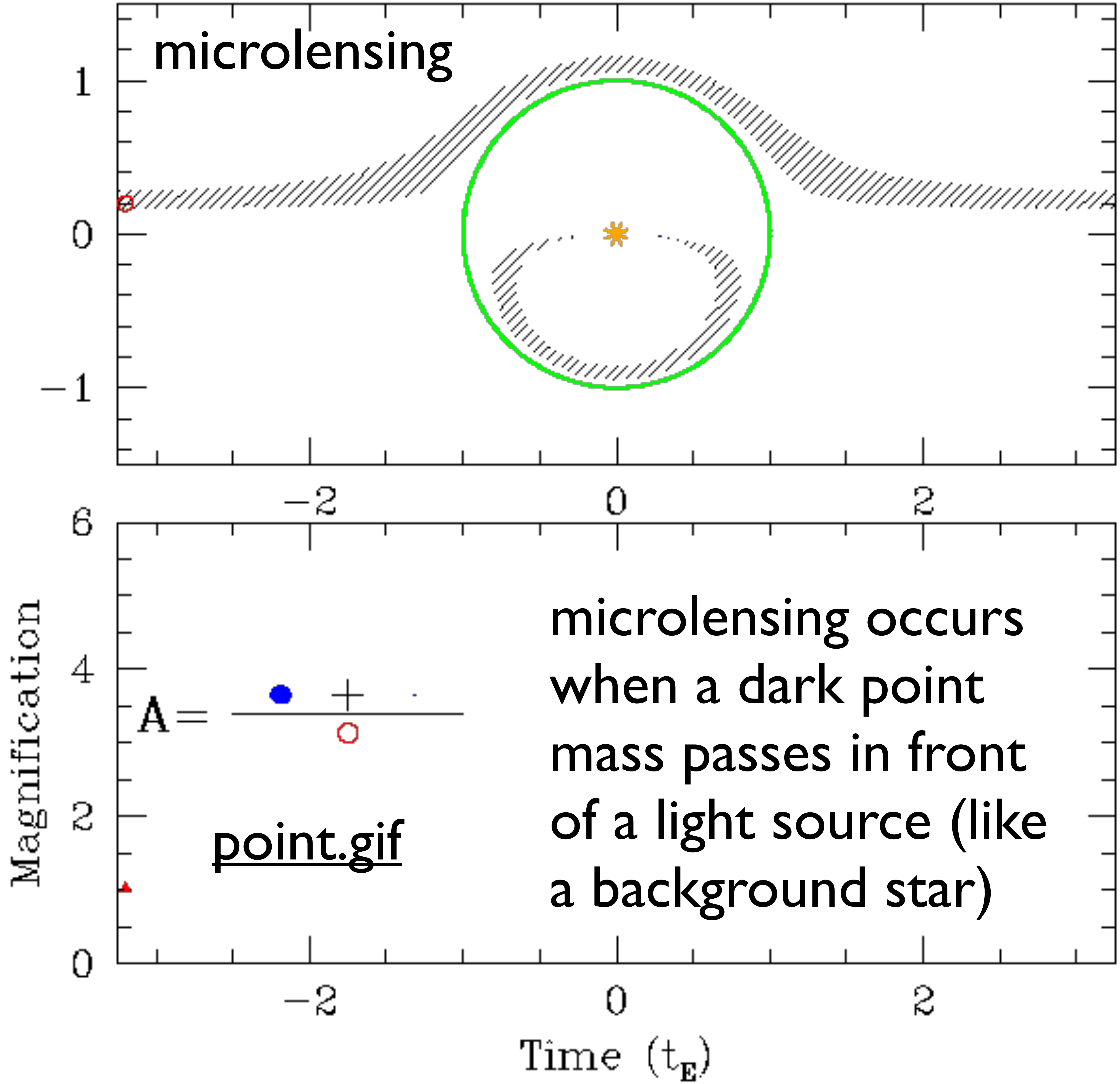
BIG SCALES



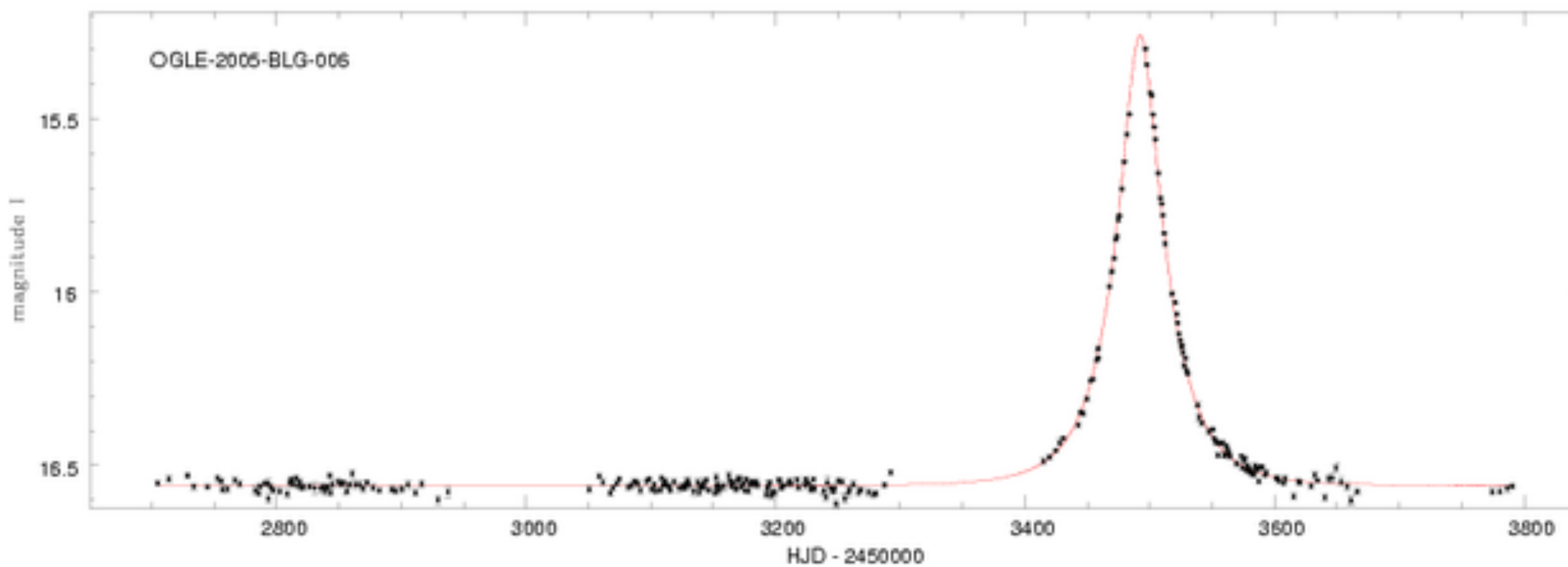
Weak lensing provides a statistical constraint on the total halo mass

$$M_{200} = 119 L_r^{1.32}$$ for red galaxies

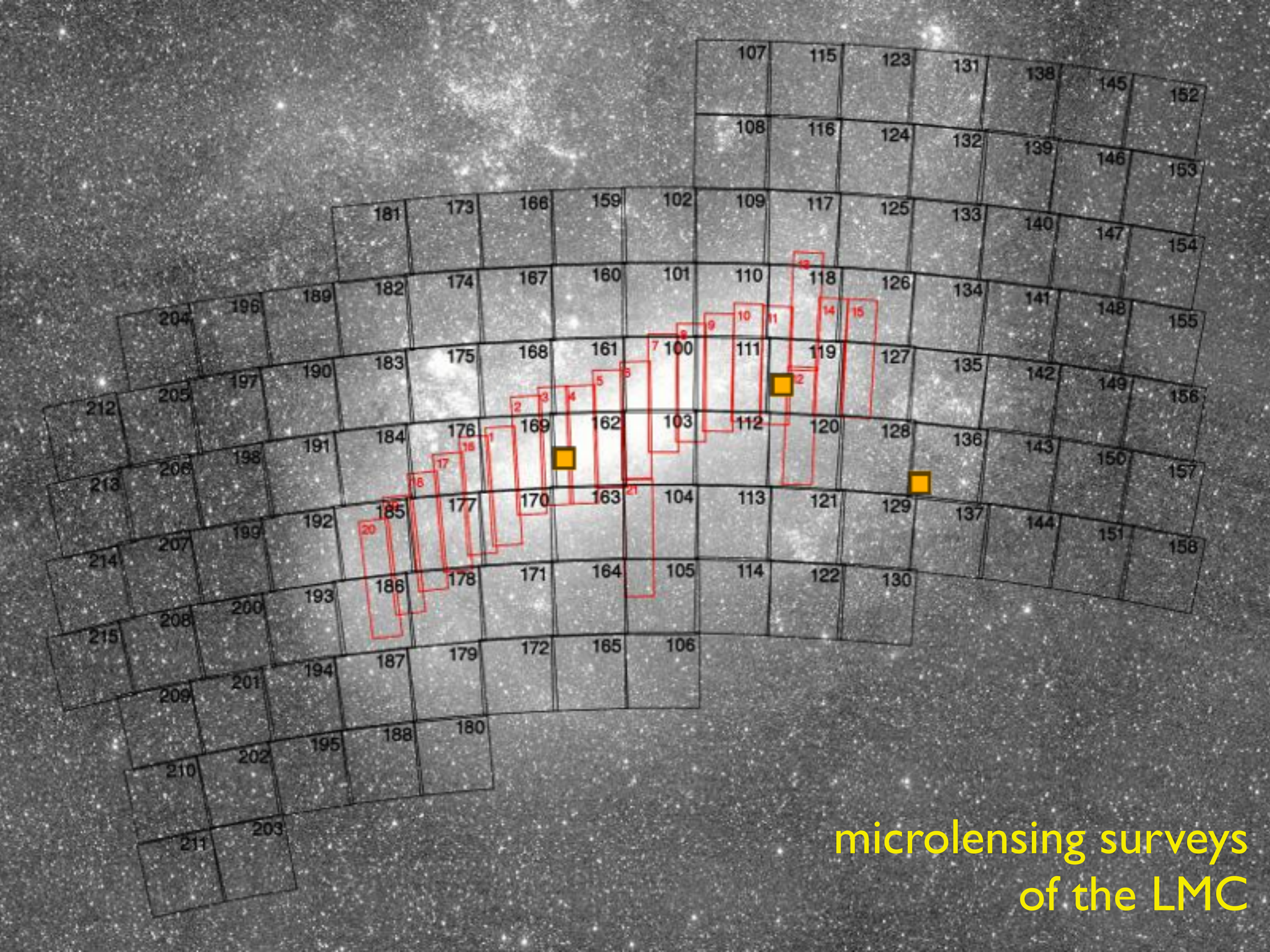
SMALL SCALES



microlensing occurs when a dark point mass passes in front of a light source (like a background star) microlensing even observed by OGLE



Microlensing surveys:
MACHO
EROS
OGLE
stare at LMC/SMC to look for micorlensing events due to intervening dark matter. Sensitive to brown dwarfs.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108 116 124 132 139 146 153
181 173 166 159 102 109 117 125 133 140 147 154
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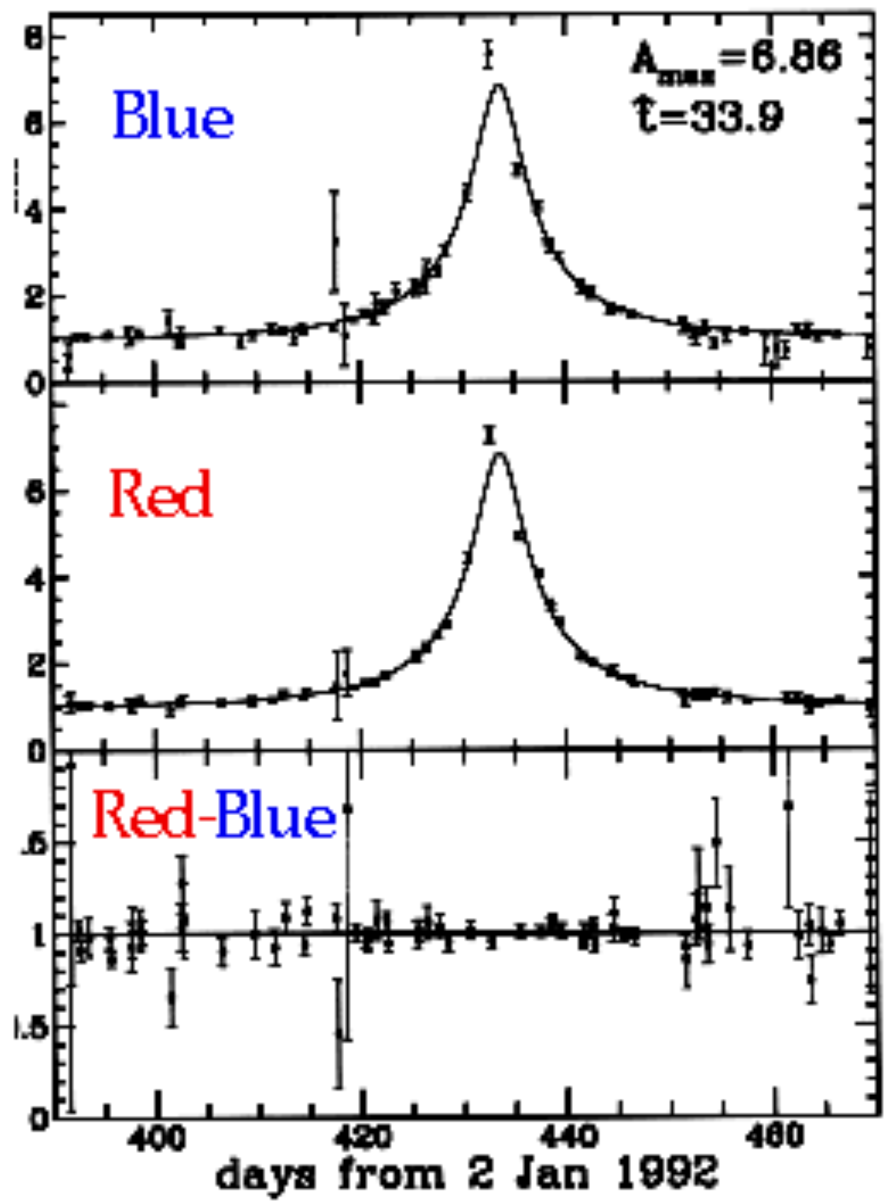
212 205 197 190 183 175 168 161 100 111 119 127 135 142 149 156
213 206 198 191 184 176 169 162 103 112 120 128 136 143 150 157
214 207 199 192 185 177 170 163 104 113 121 129 137 144 151 158
215 208 200 193 186 178 171 164 105 114 122 130
209 201 194 187 179 172 165 106
210 202 195 188 180
211 203
microlensing surveys
of the LMC

microlensing events achromatic



should also be symmetric in time
(unless there is a companion planet)

Planet detections by microlensing