Dark Matter

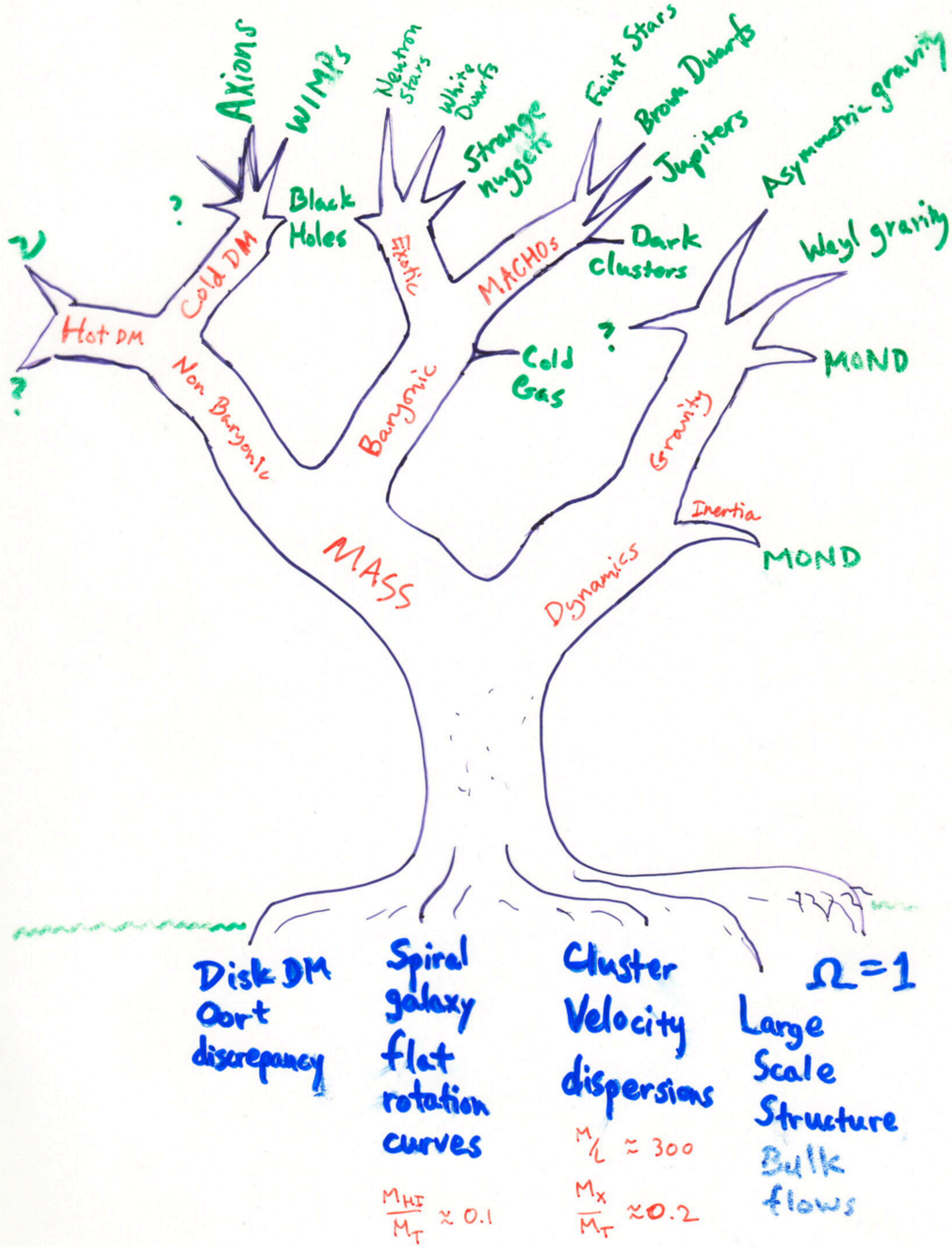
ASTR 333/433

TODAY

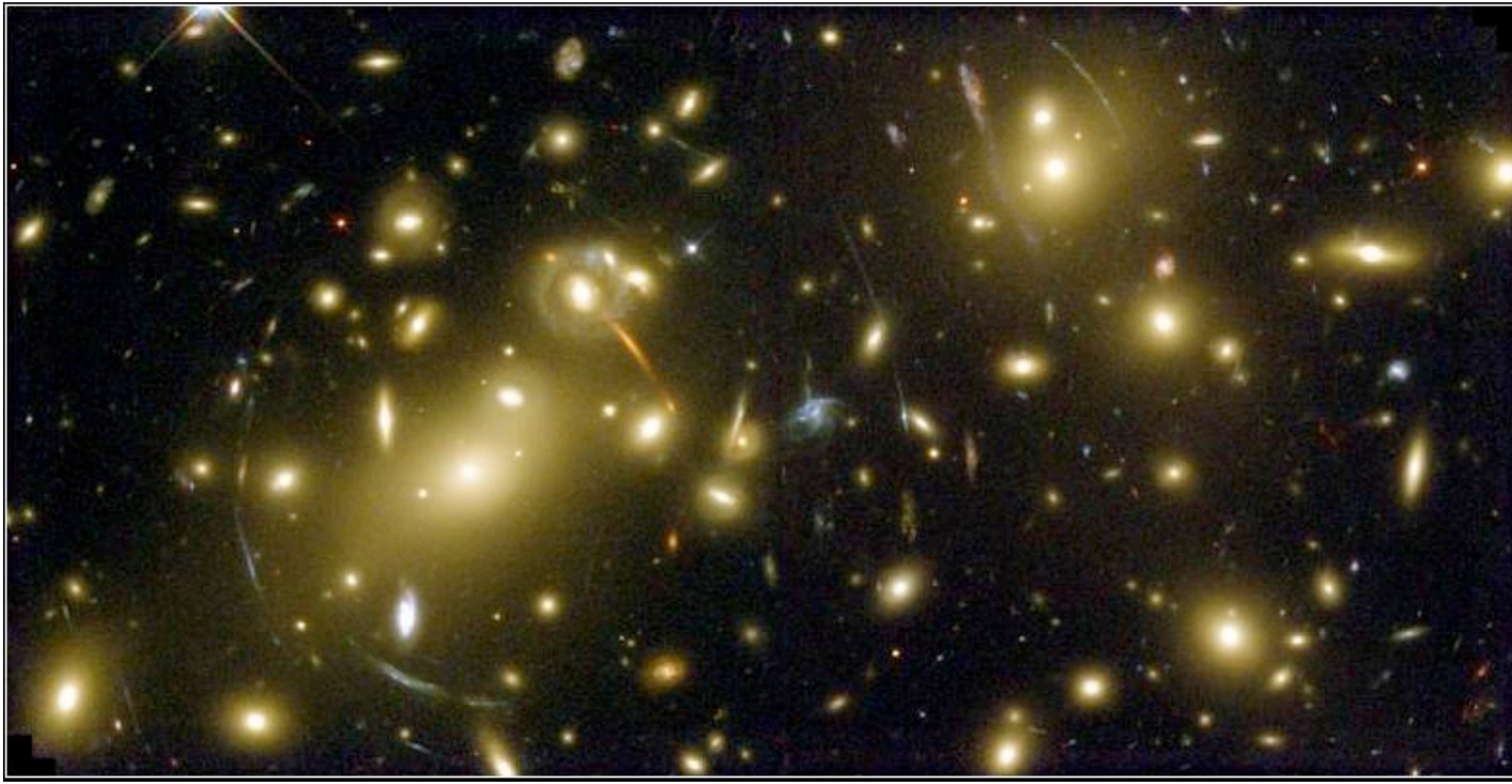
Clusters of Galaxies
Sunyaev-Zel'dovich Effect
Gravitational Lensing

Upcoming

10/25: Review (Monday)
10/27: Exam (One week from today)
11/08: HW 3 (ASTR 323 HW due 11/12)
11/24: U.Santiago seminar

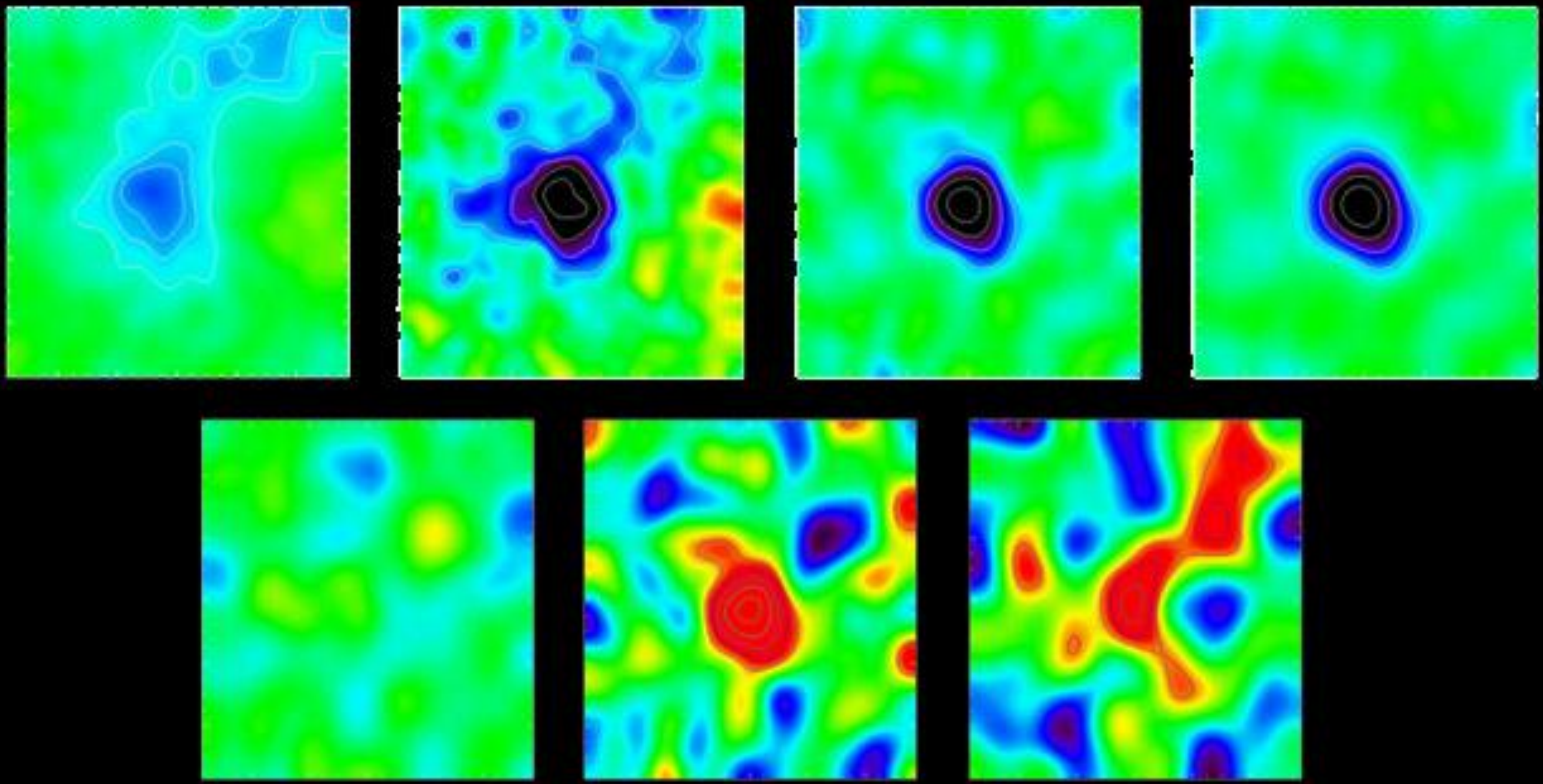


Galaxy Clusters

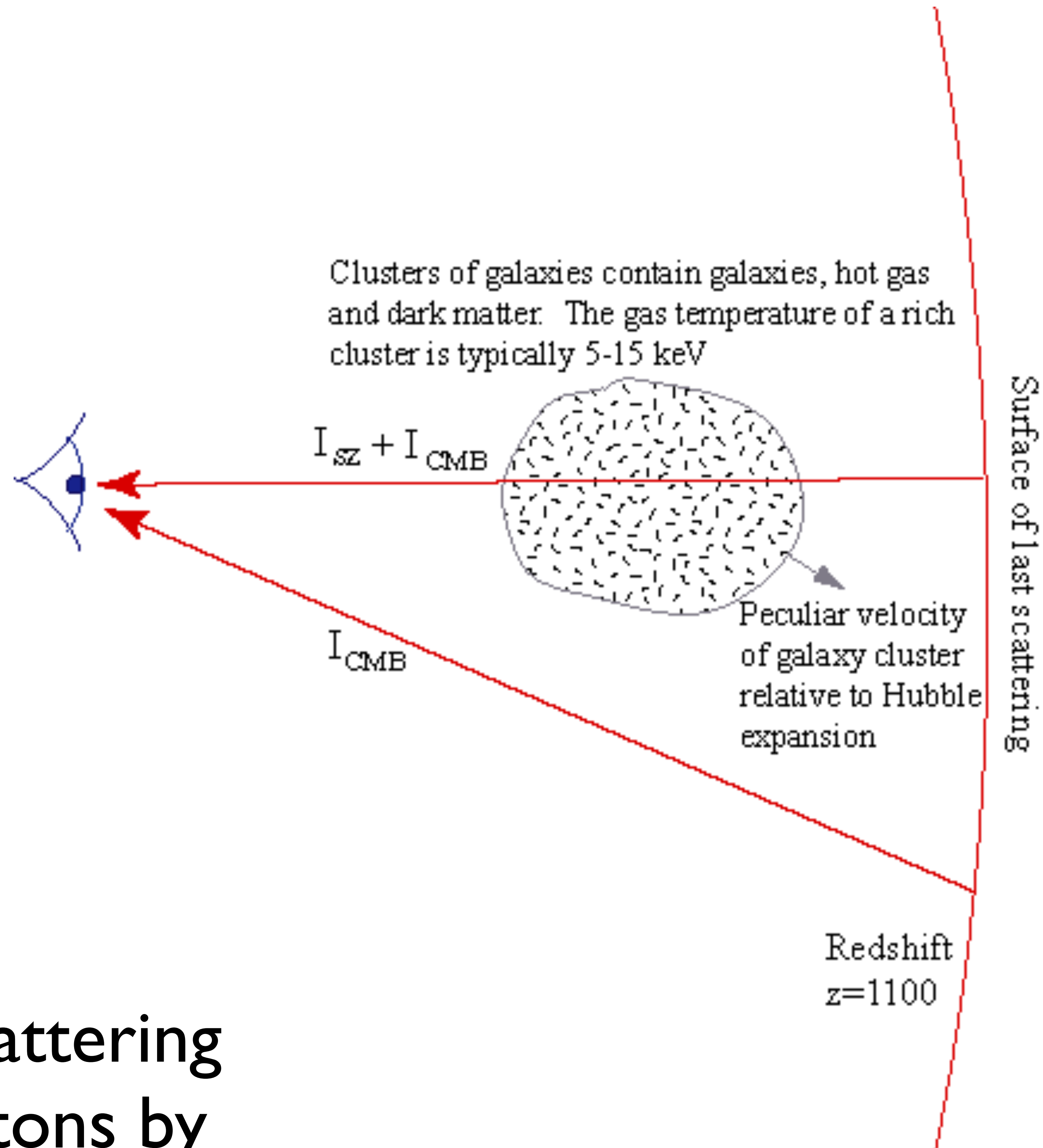


4 distinct measures: velocity dispersion, gravitational lensing, hydrostatic equilibrium of X-ray gas, and the Sunyaev-Zel'dovich effect

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

T_{rad}: CMB

σ_T: Thomson scattering cross-section

n_e: electron density

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

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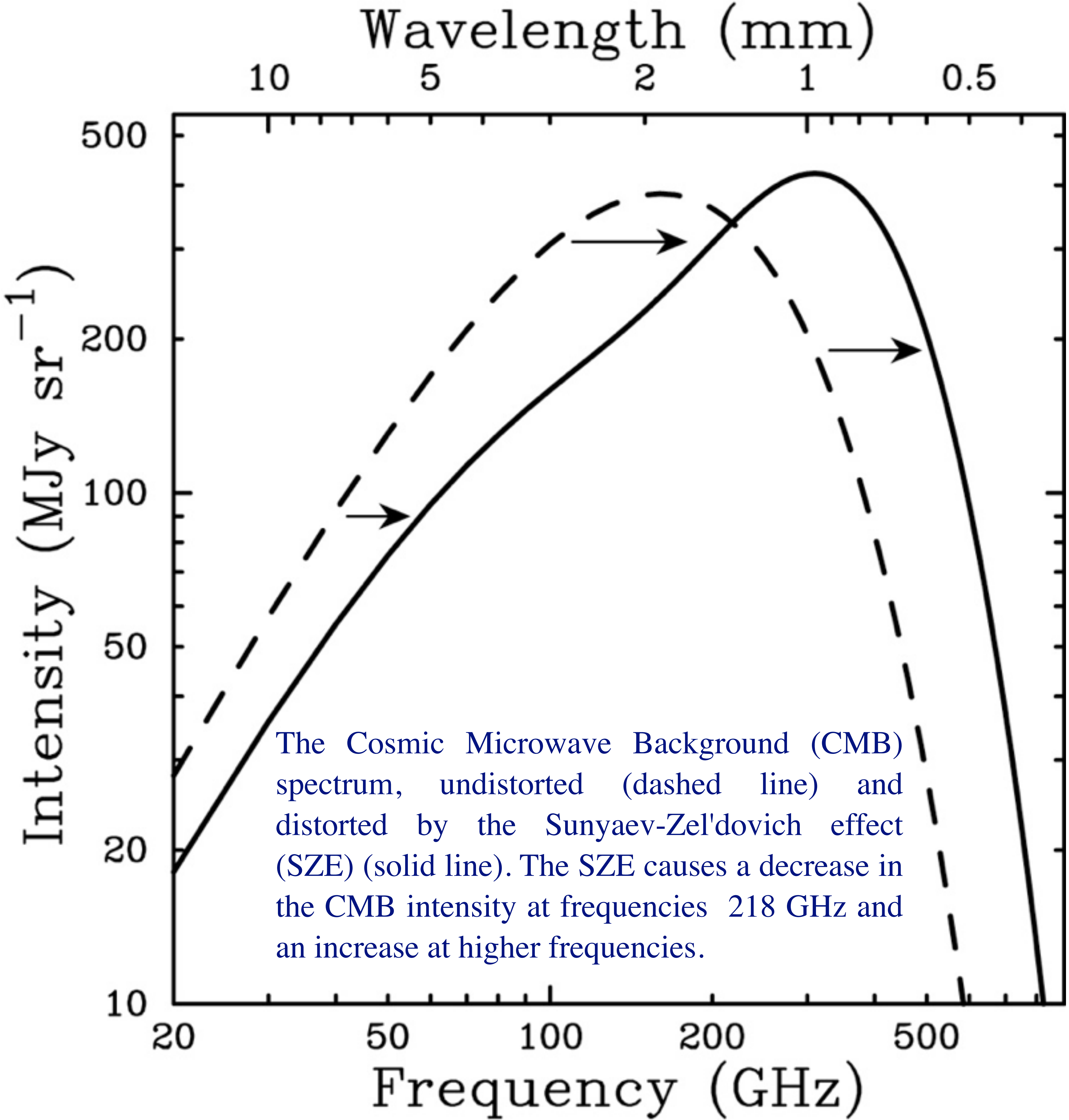
at low frequency in the Rayleigh-Jeans tail,

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

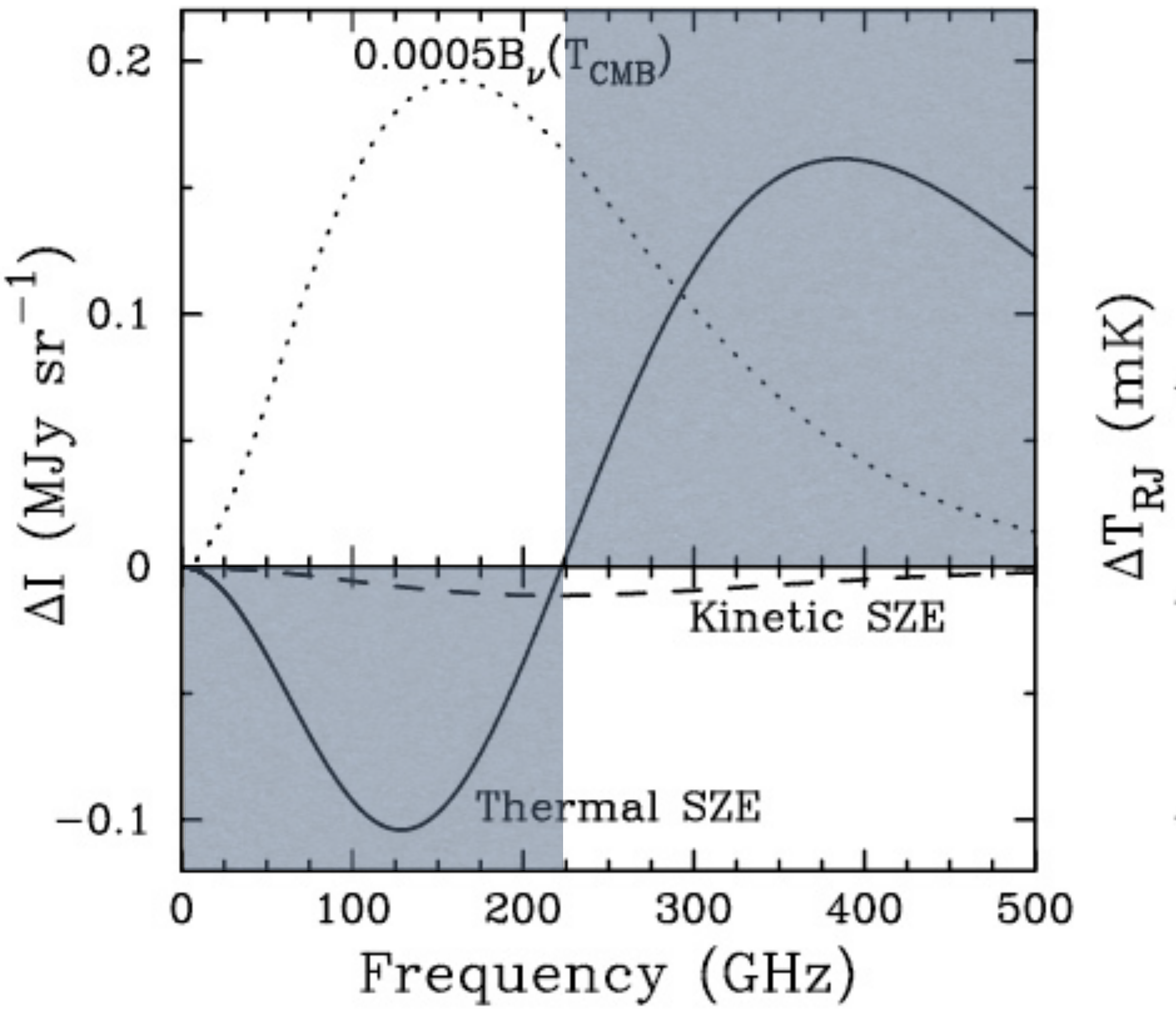


The Cosmic Microwave Background (CMB) spectrum, undistorted (dashed line) and distorted by the Sunyaev-Zel'dovich effect (SZE) (solid line). The SZE causes a decrease in the CMB intensity at frequencies 218 GHz and an increase at higher frequencies.

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

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

intensity boosted

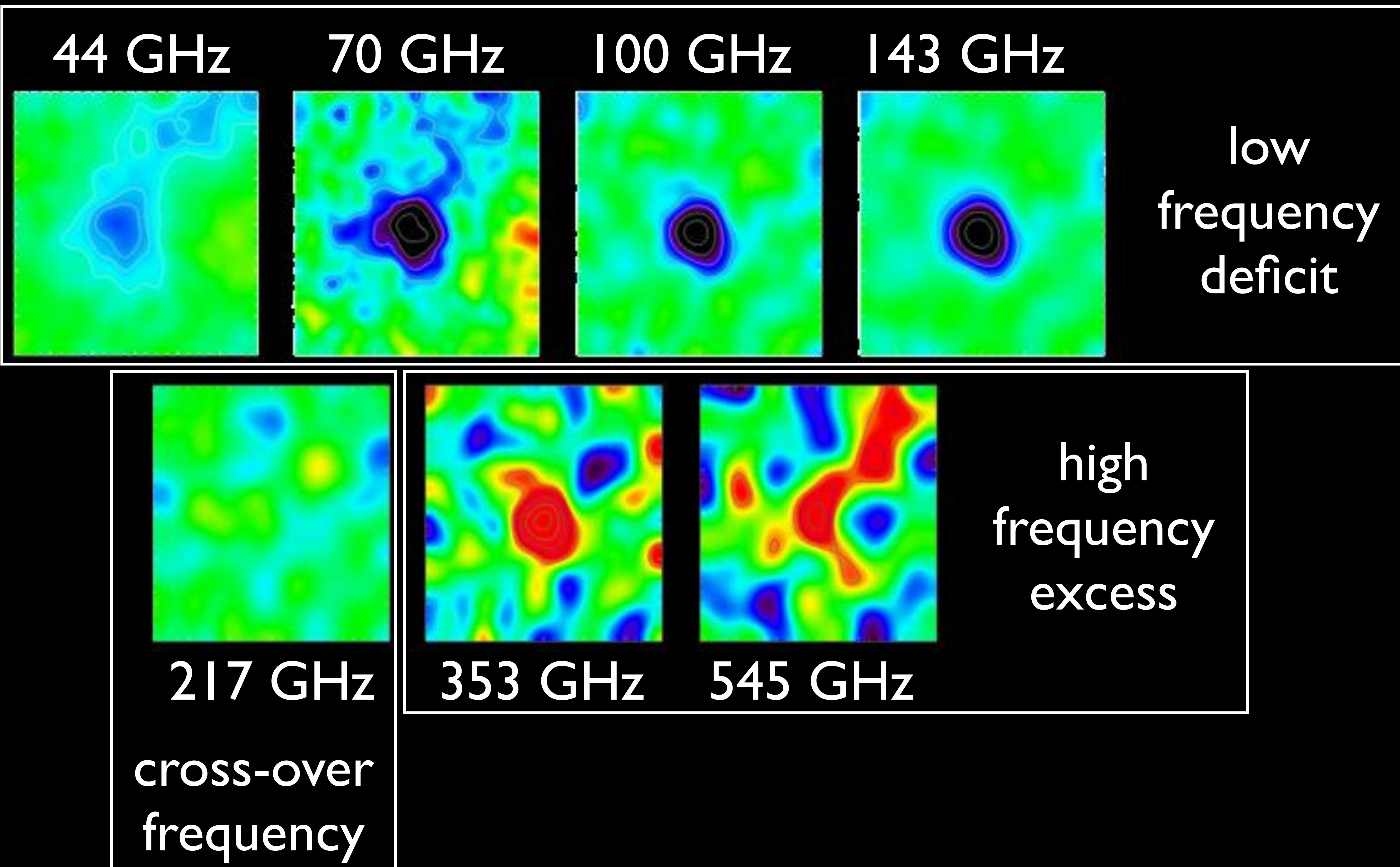


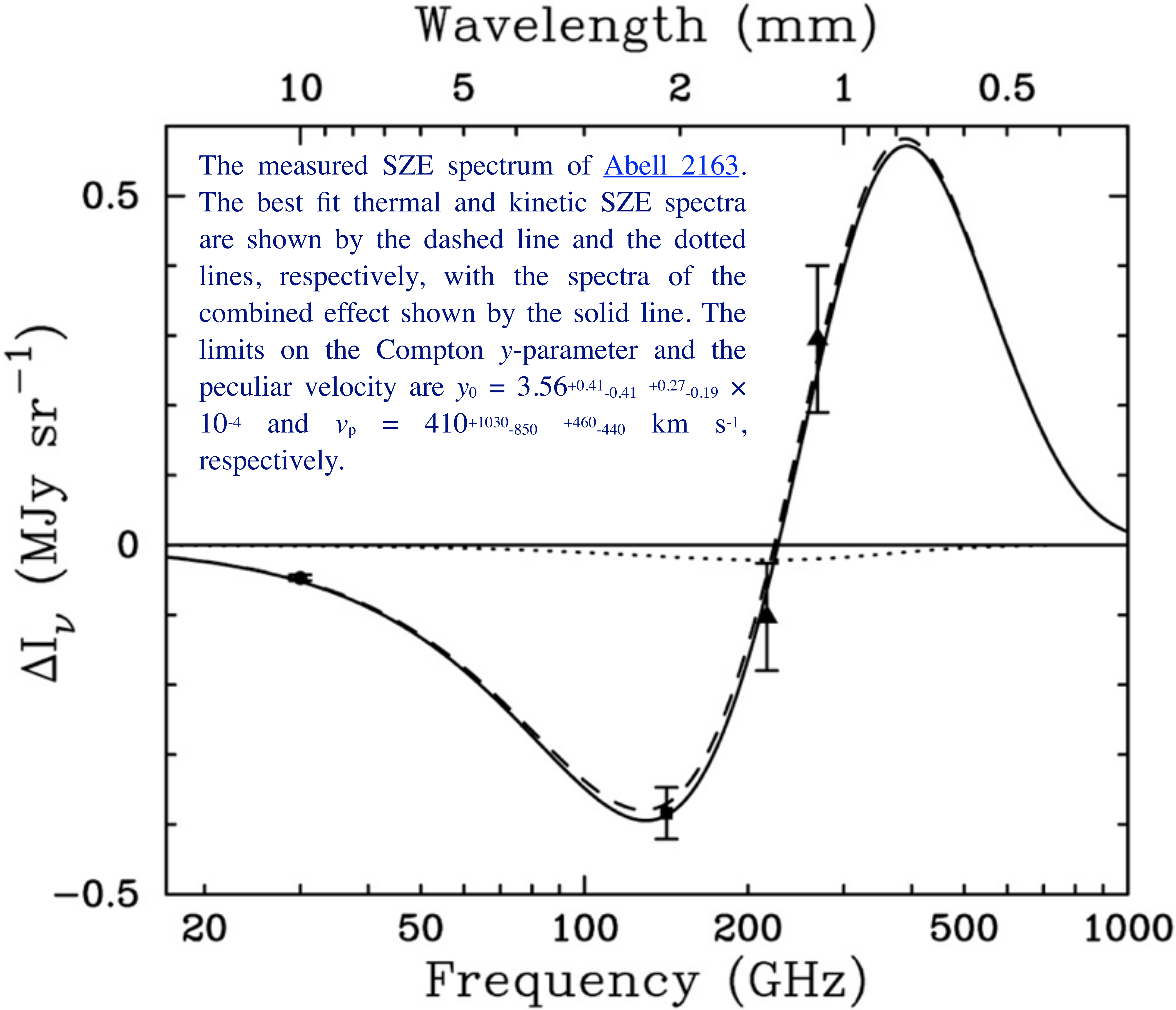
Kinematic SZ effect from peculiar velocity of cluster wrt CMB frame

intensity depleted

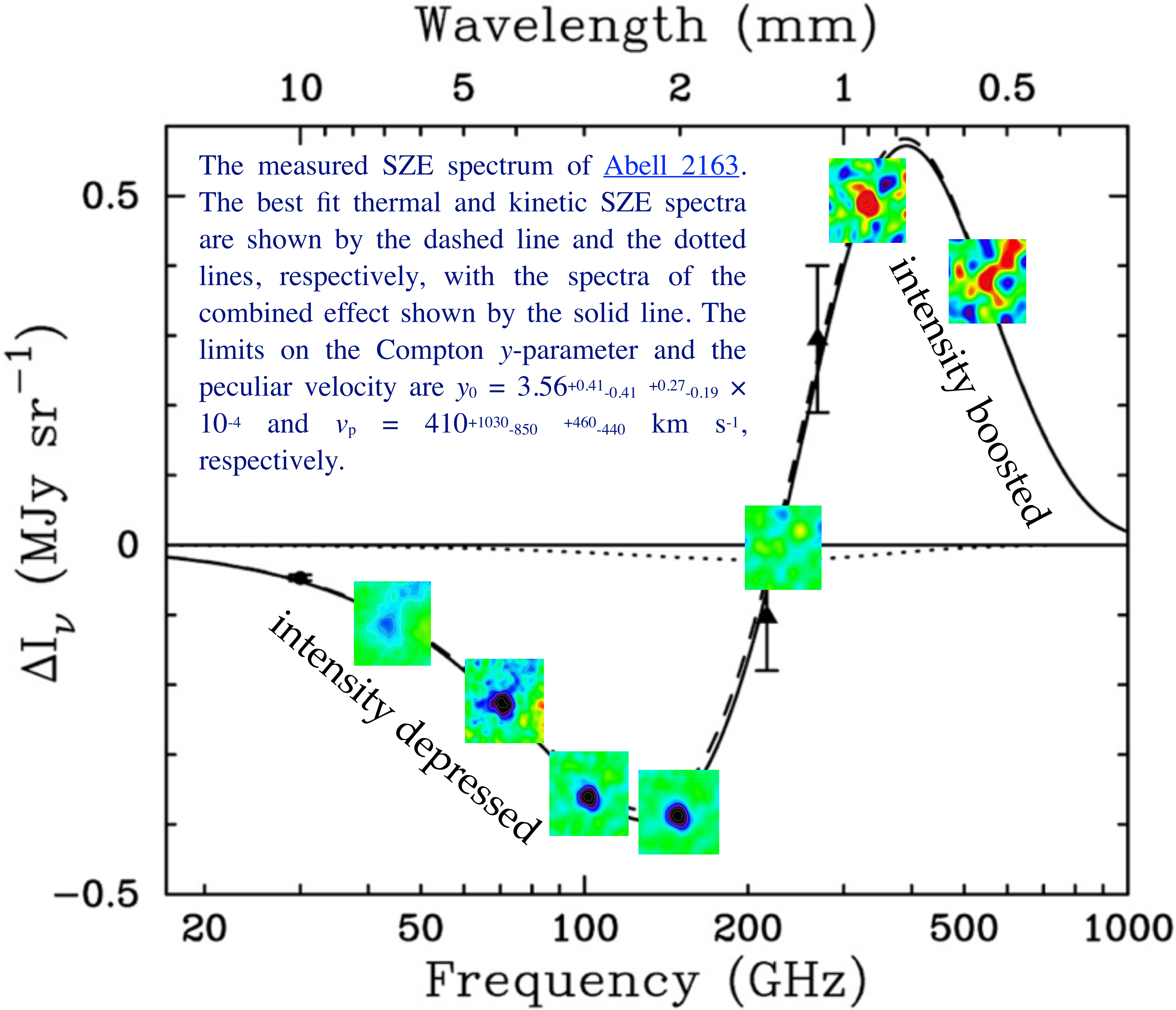
SUNYAEV–ZEL'DOVICH EFFECT

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.



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
0.5
0
−0.5
ΔI_ν (MJy sr^{-1})
20
50
100
200
500
1000
Frequency (GHz)

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

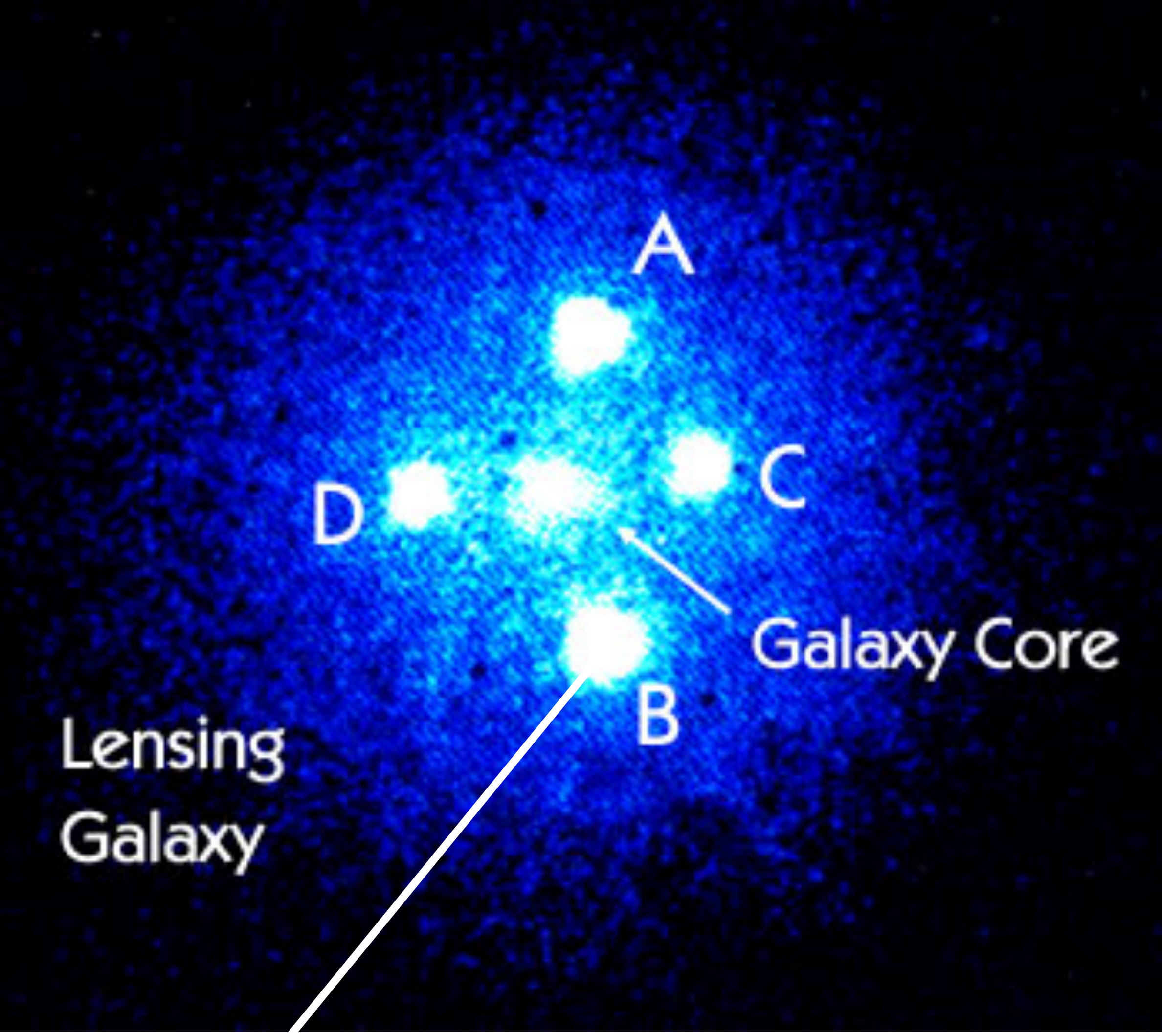
Flavors of gravitational lensing:

— weak lensing
  mild distortion of lensed image

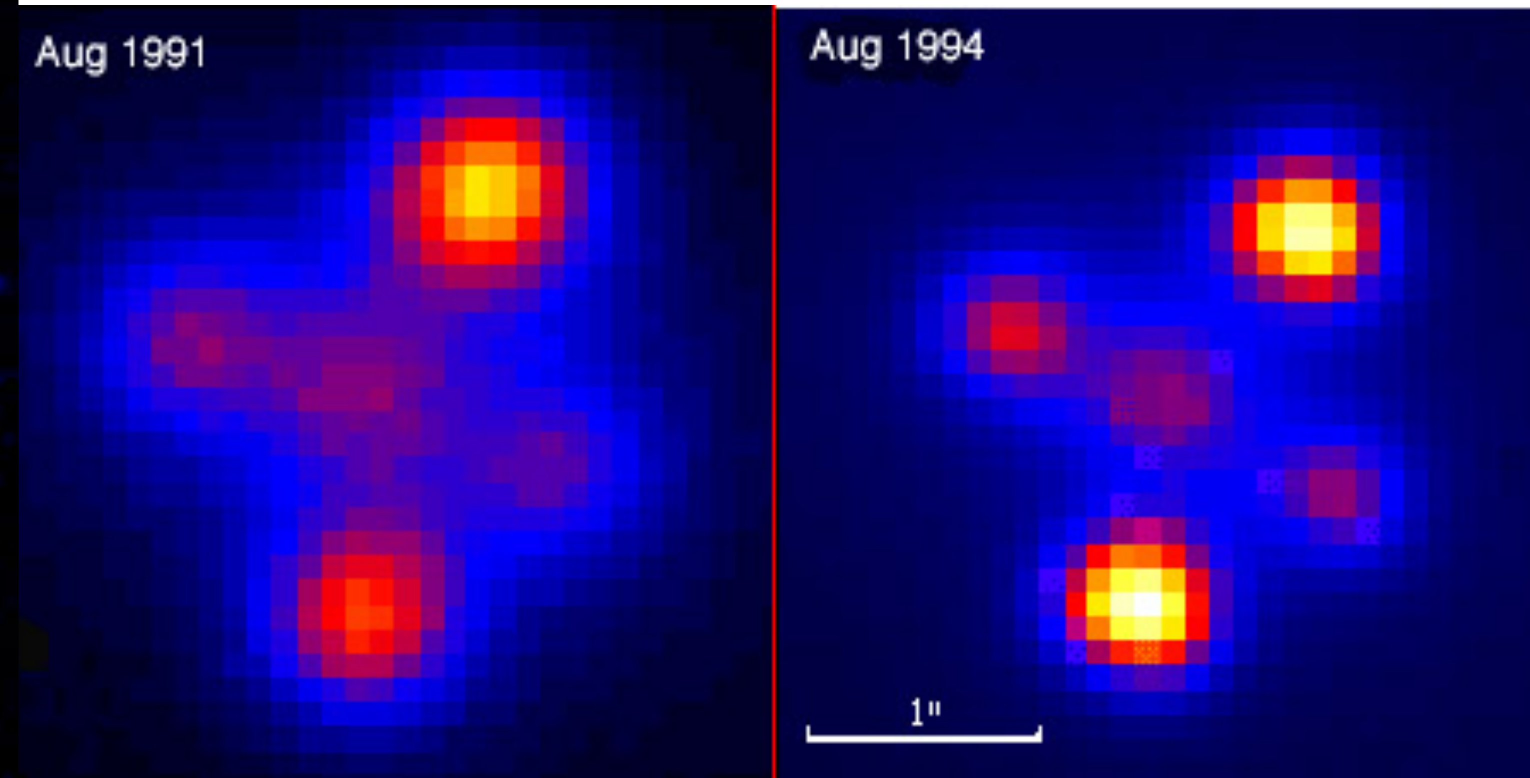
— strong lensing
  multiple images, strong distortion

— microlensing
  temporary brightening due to unresolved lensing

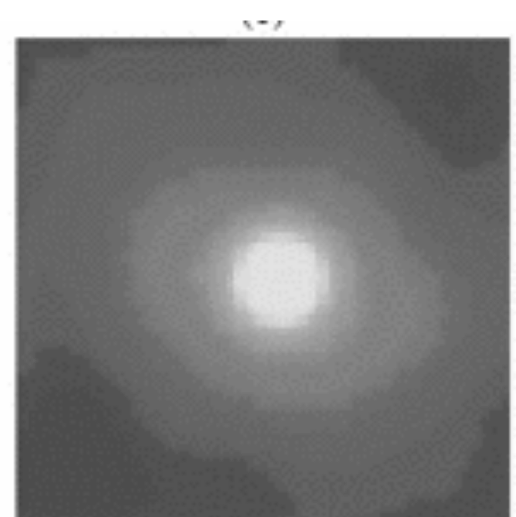
Strong lensing: Einstein Cross



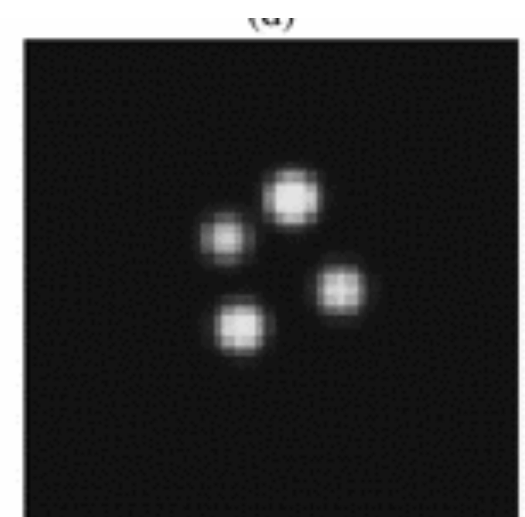
ABCD: same QSO seen 4 times



time variable multiple QSO image



lensing galaxy



lensed QSO

Gravitational Lensing

θ_I observed angle between image and lens

θ_S true separation angle between image and lens

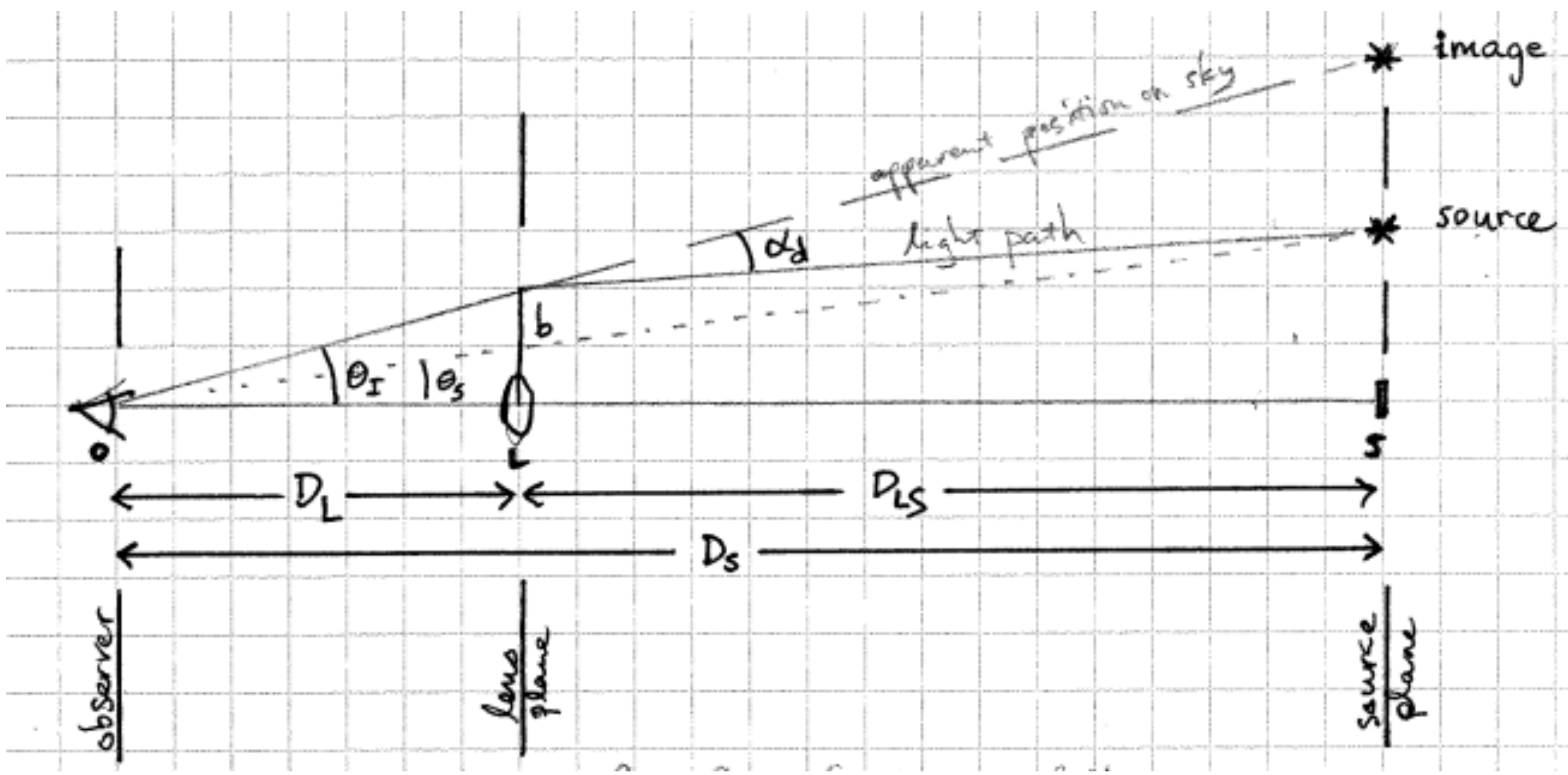
α_d bend angle

b impact parameter

D_L lens distance

D_S source distance

D_{LS} lens-source separation

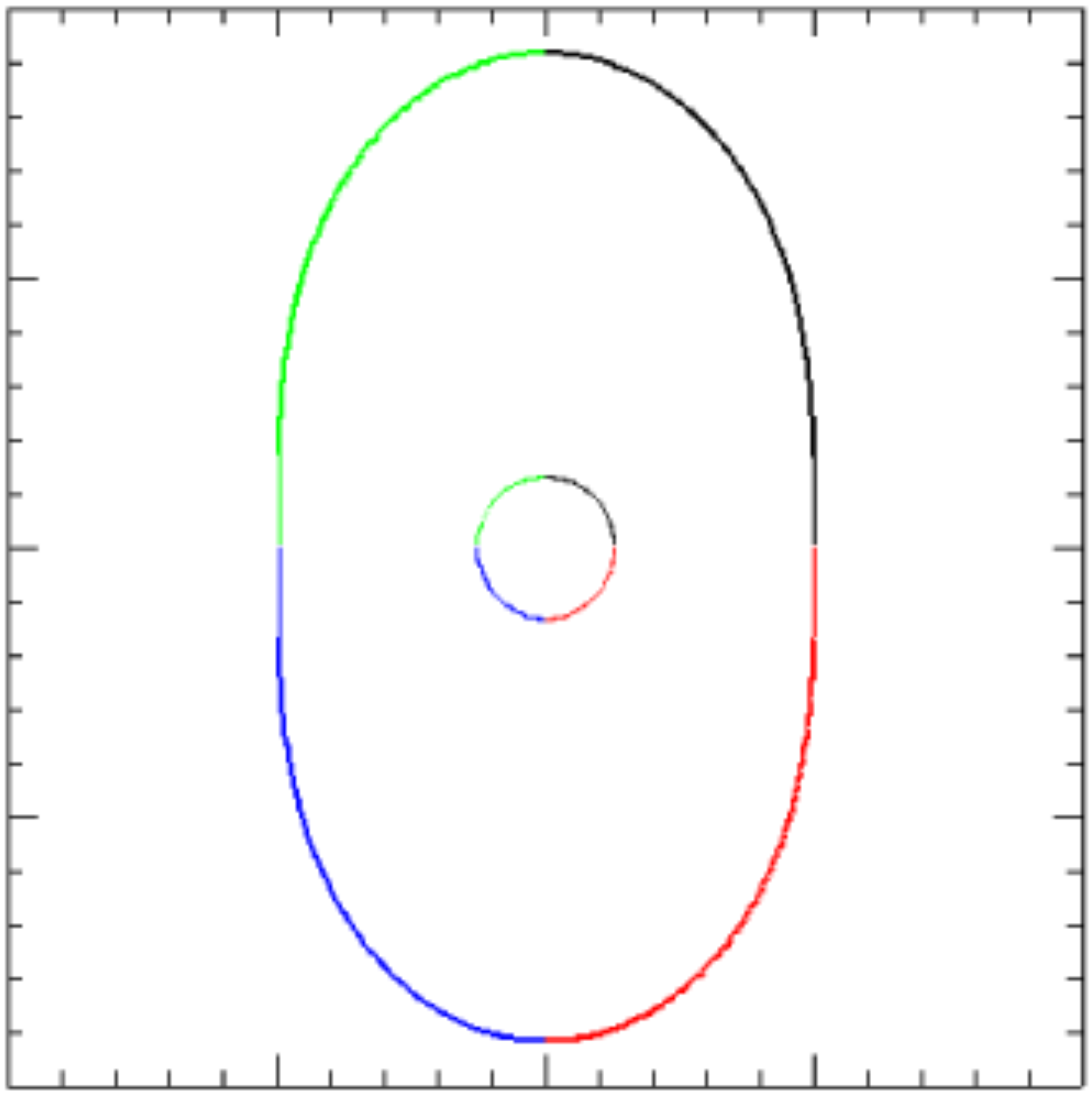


observer

lens plane

source plane

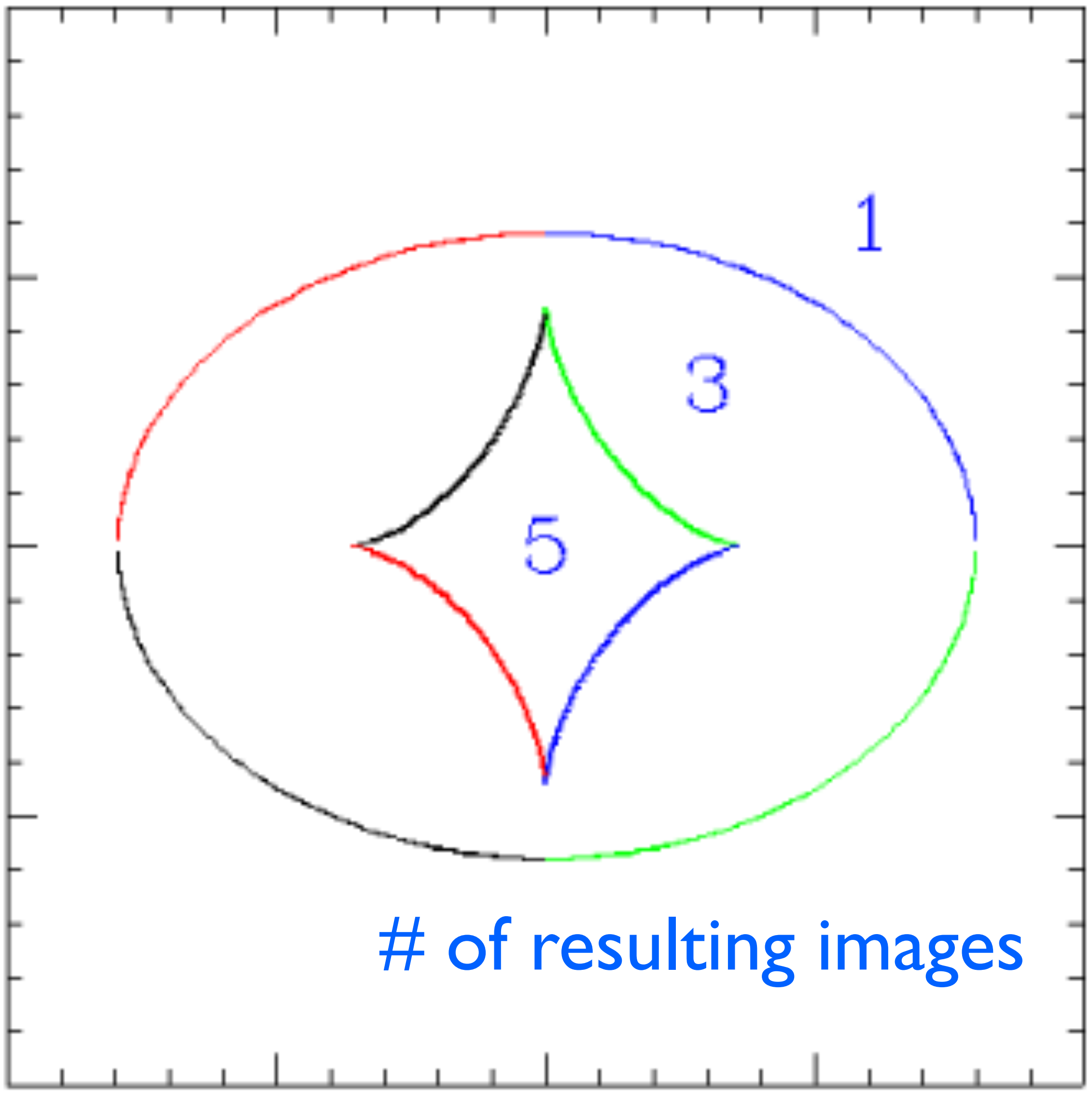
Lens plane



critical curves

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

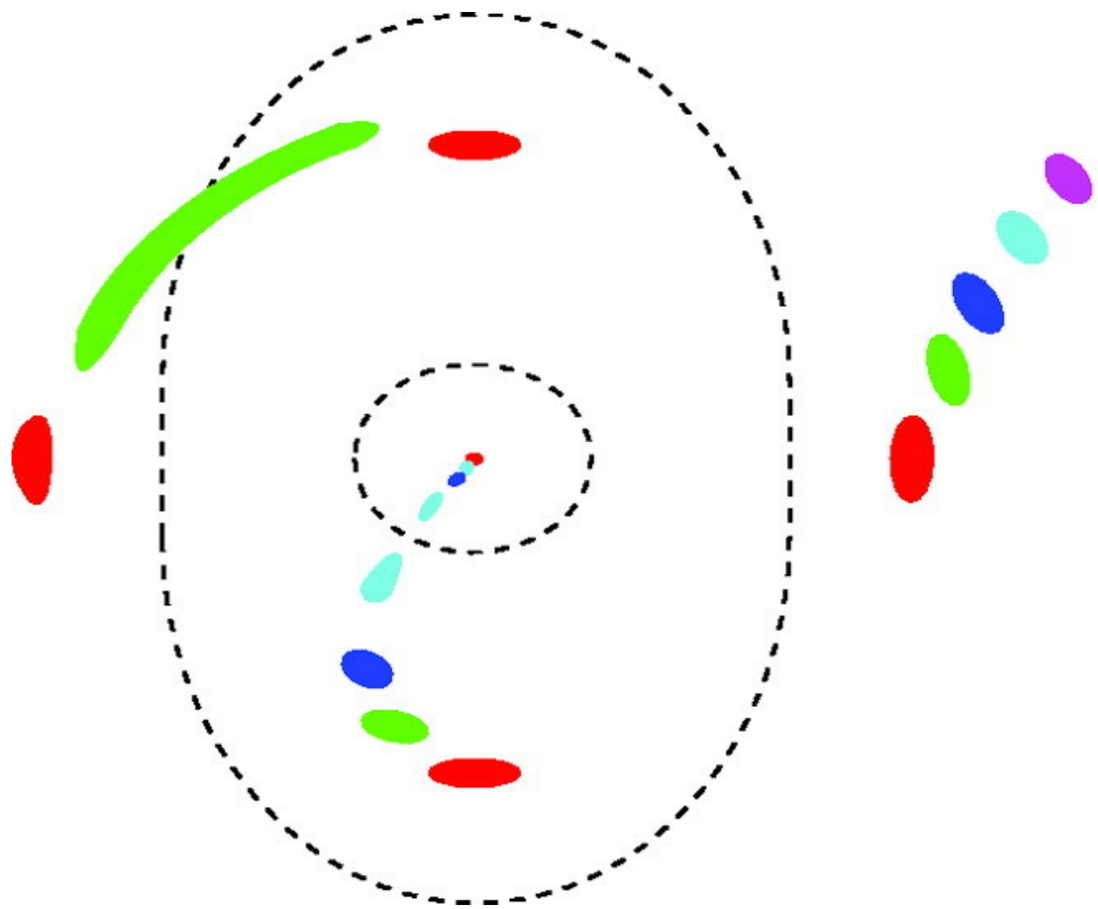
Source plane



caustics

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

Lens plane



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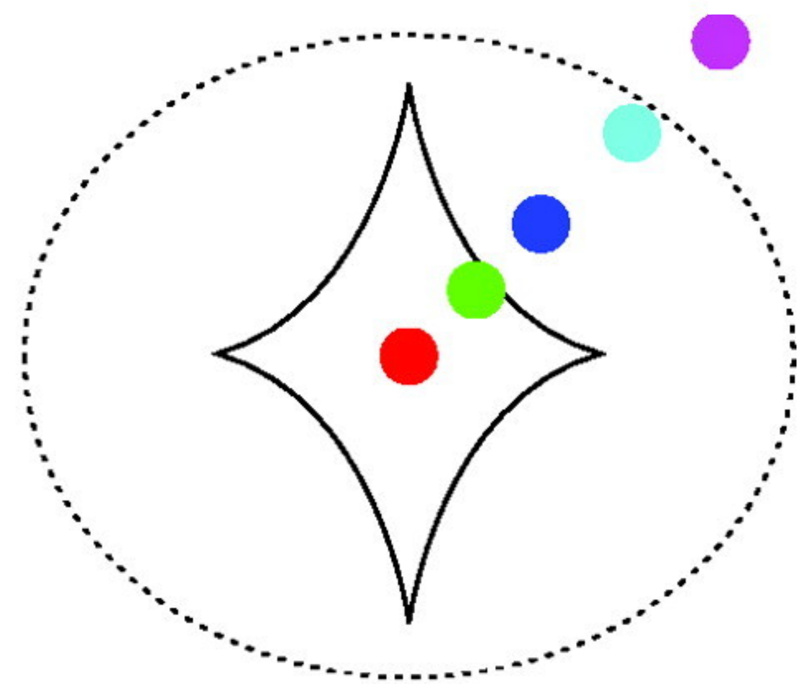

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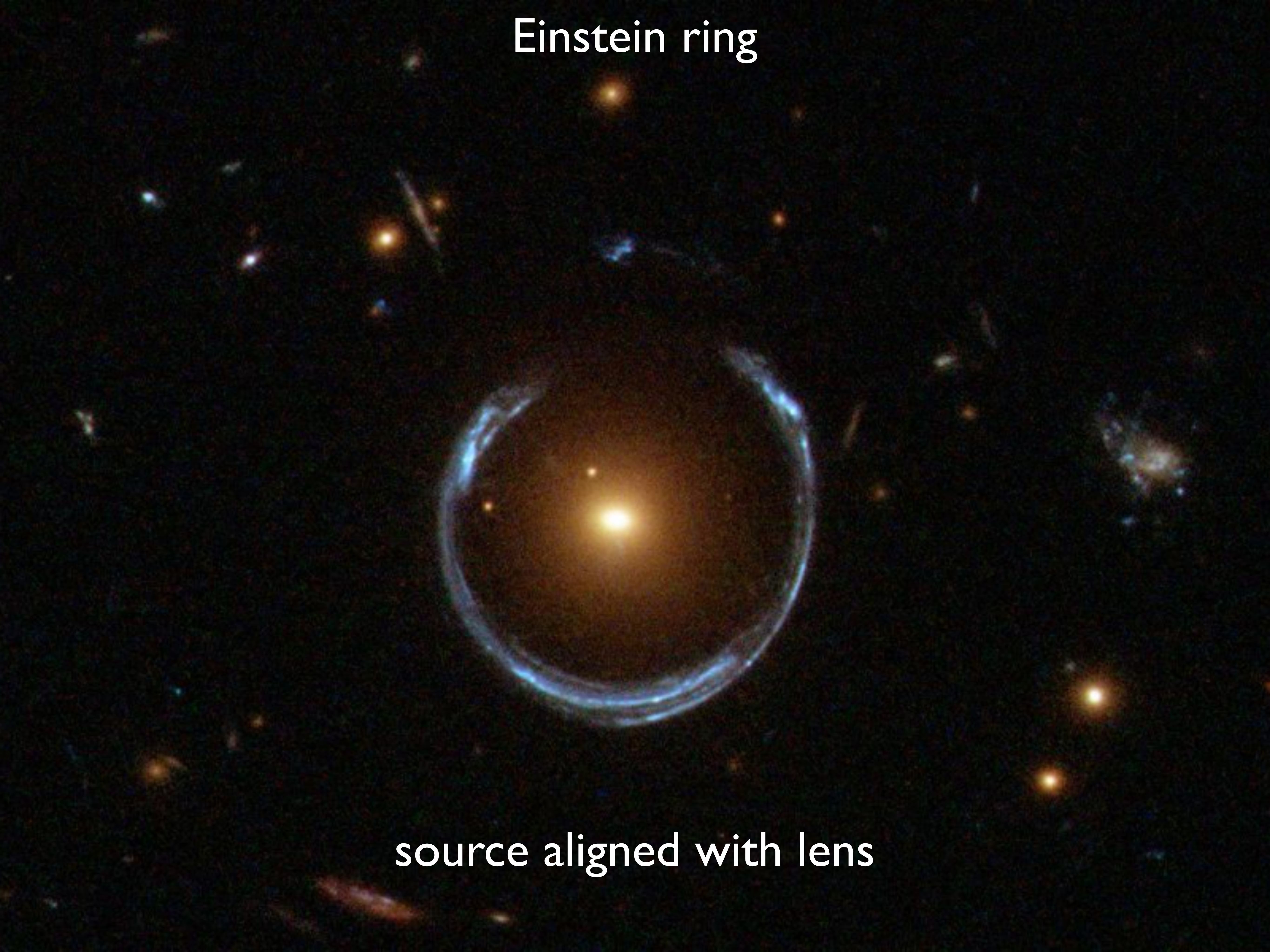
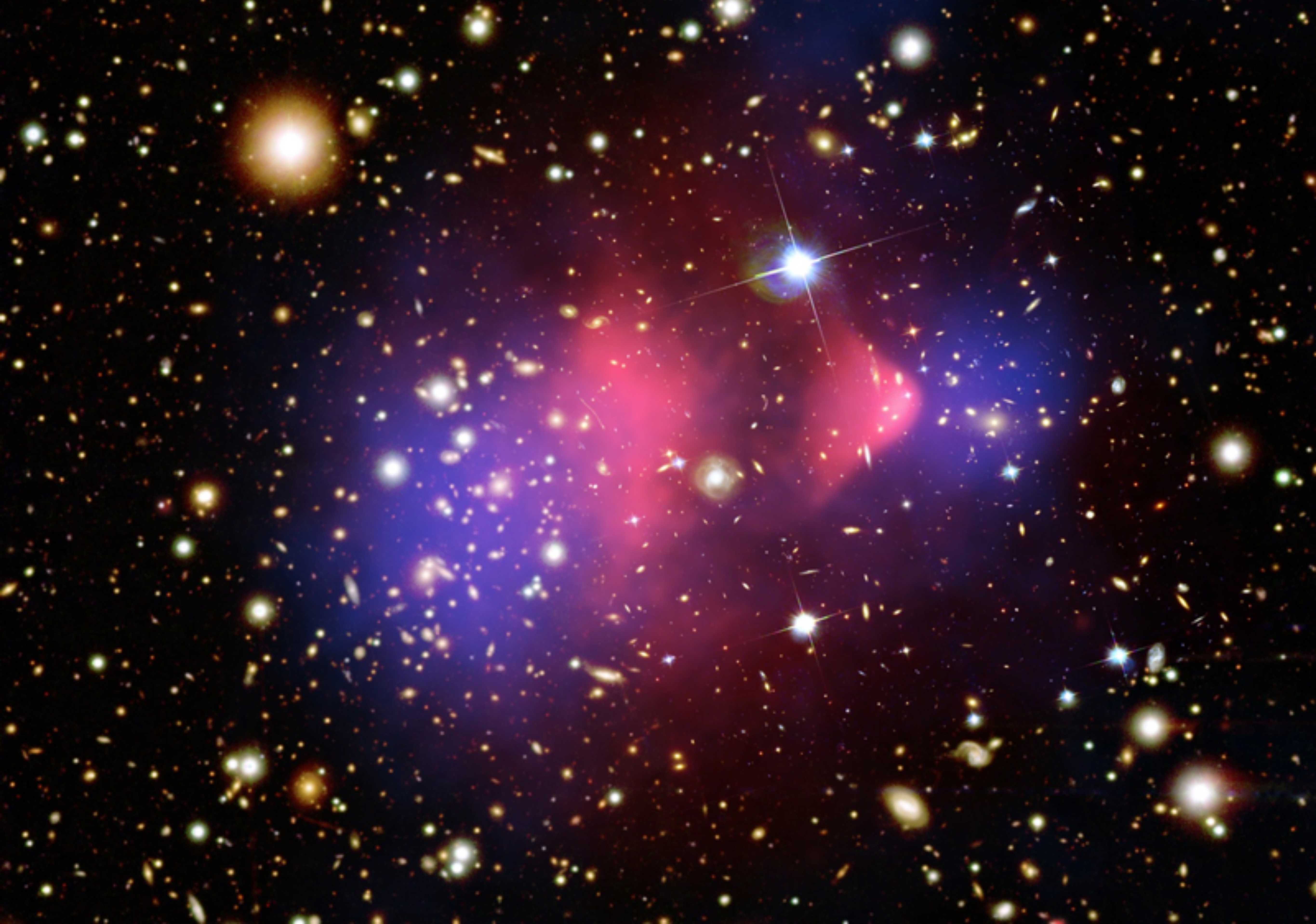
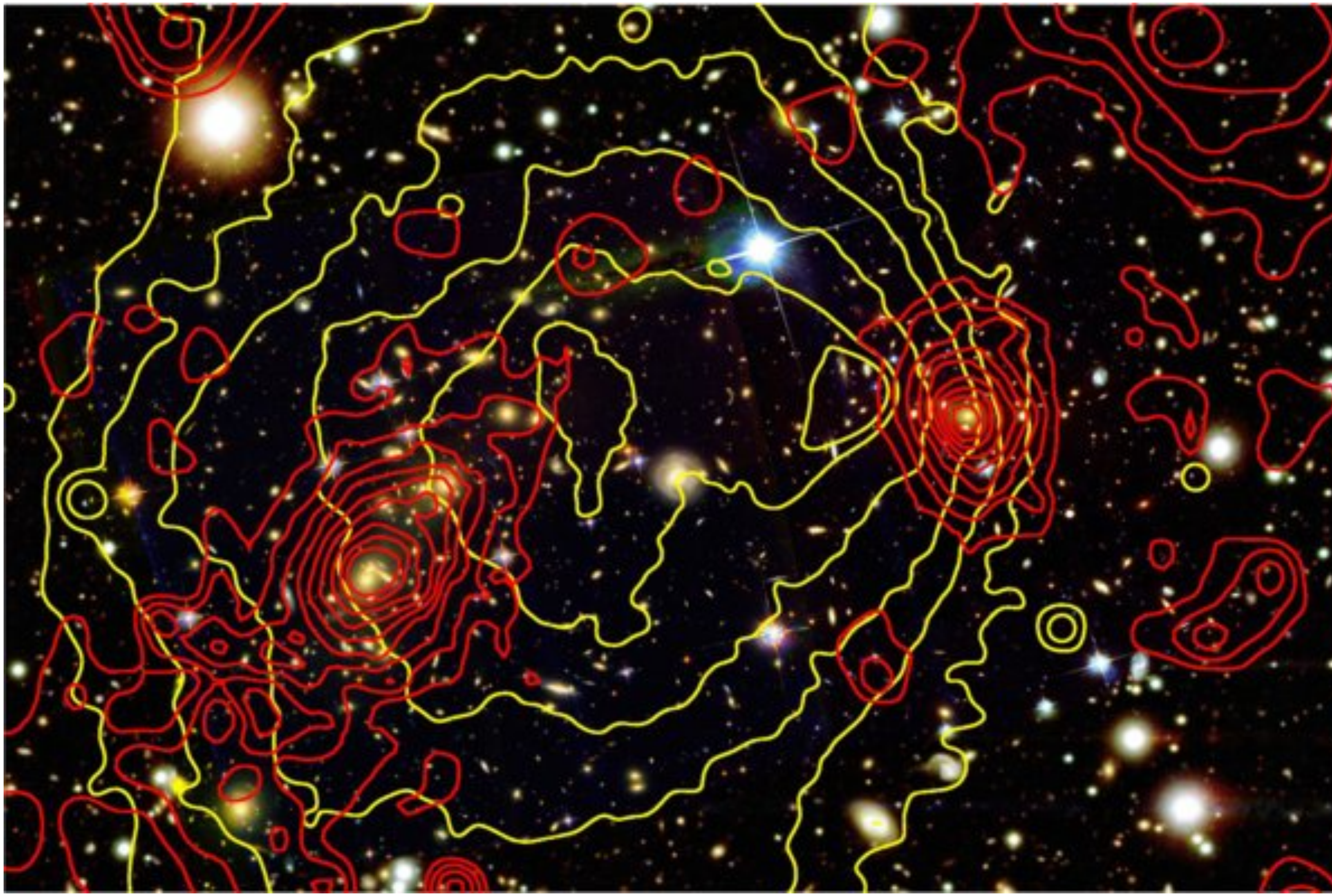

Einstein ring
source aligned with lens

Bullet cluster (press release version)



Bullet cluster (data: Bradac et al. 2009)

X-ray: yellow contours

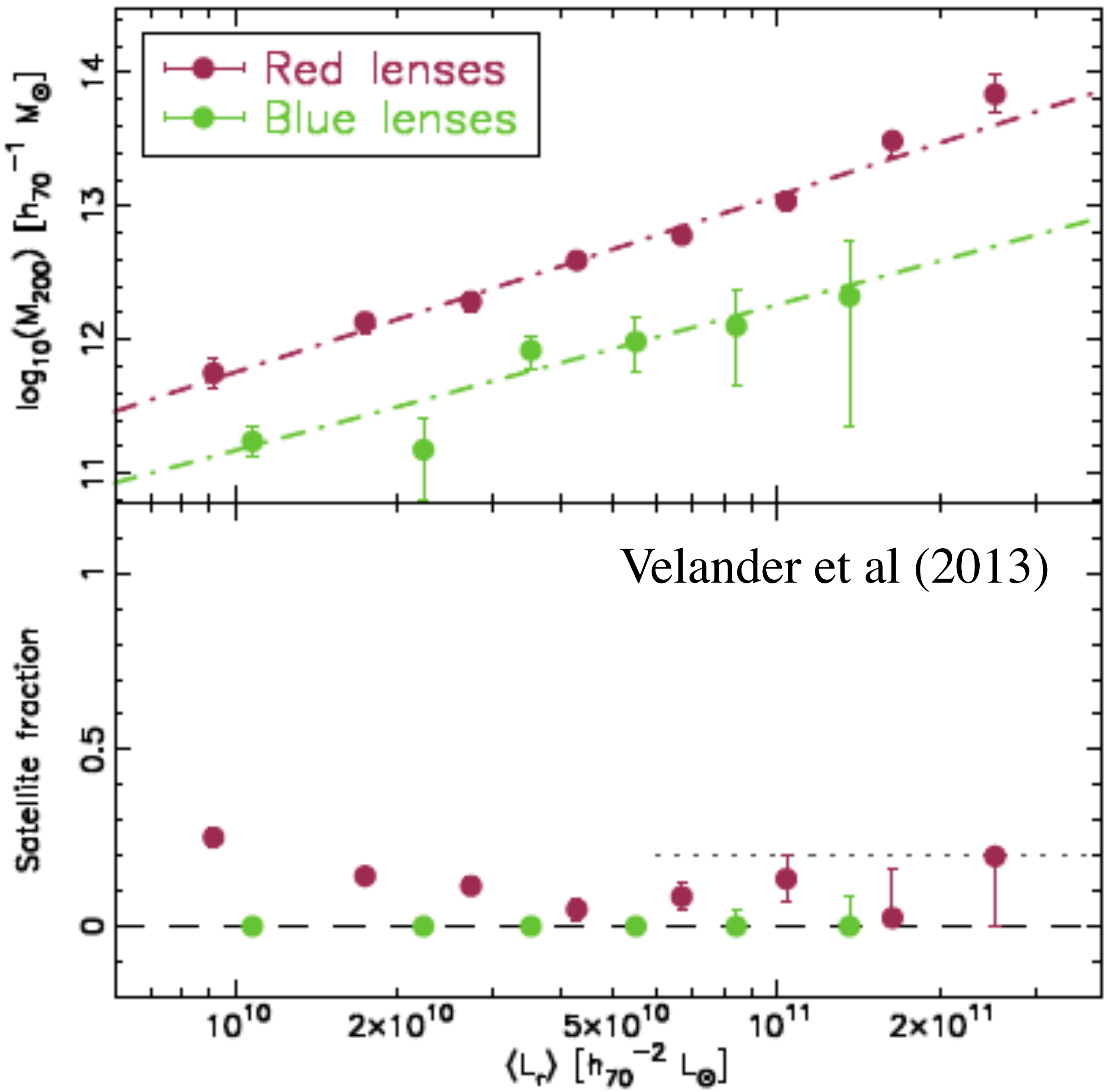


gravitational (strong+weak) lensing: red contours

weak gravitational lensing

BIG SCALES

average shear across the universe



Weak lensing provides a statistical constraint on the total halo mass

see also
Brimioulle et al (2013)

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