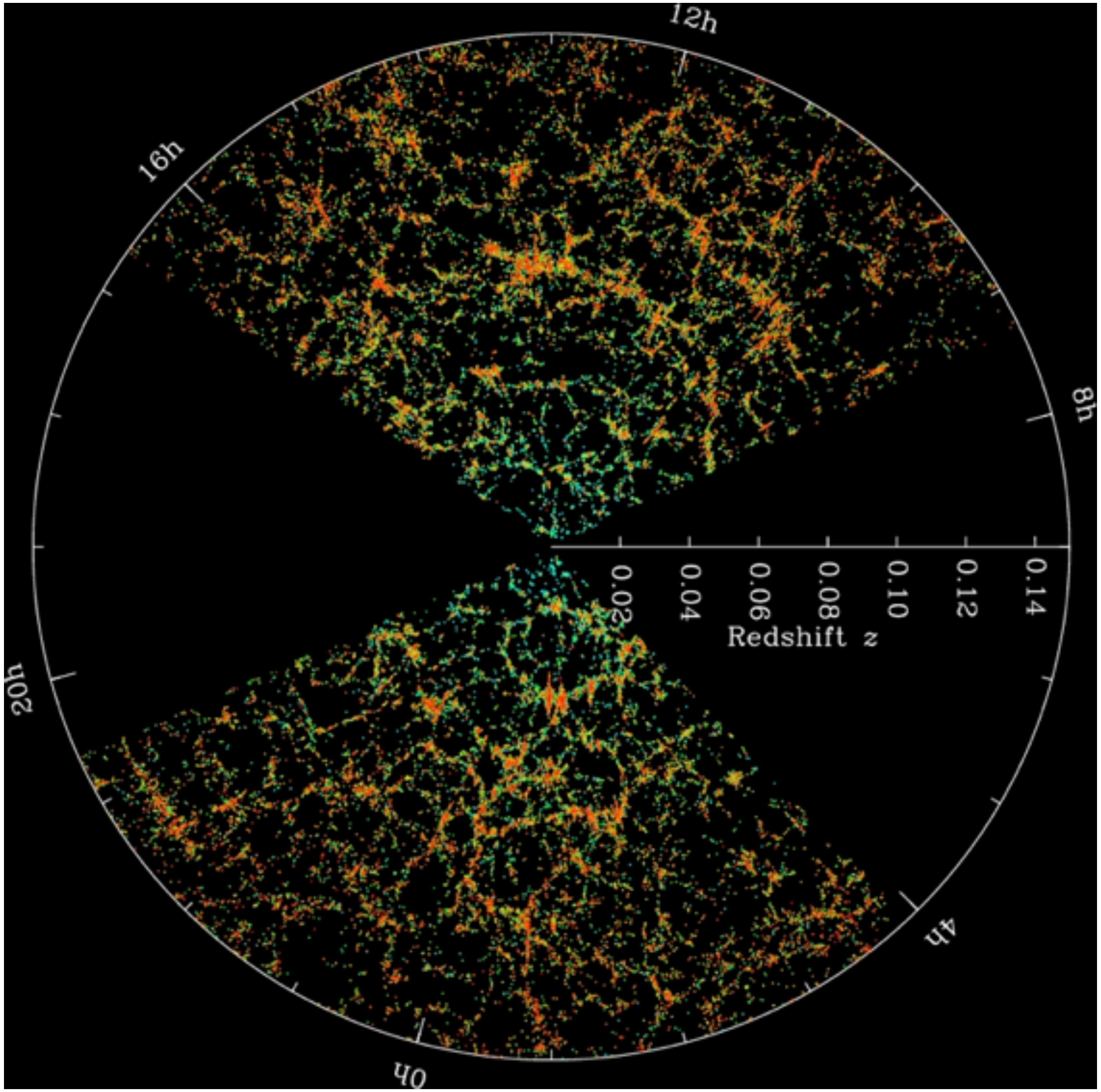
Galaxy clusters

Longair, Chapter 4

Large-scale distribution of galaxies in SDSS

"Voids" with sizes up to $\Delta z \sim 0.01\text{-}0.02$.
Physical scales $\Delta r = \Delta cz/H_0 \sim$ 40-80 Mpc



SDSS:
Sloan Digital Sky Survey.
600 simultaneous spectra,
redshifts of ~10^6 galaxies

Distribution of galaxies

- Galaxies are not distributed randomly in the Universe - most of them are found in *groups* or *clusters*.
- The groups and clusters are themselves clustered - the Universe is *hierarchically structured*
- The Milky Way belongs to a small group, the *Local Group* (first recognized by Hubble, 1936)

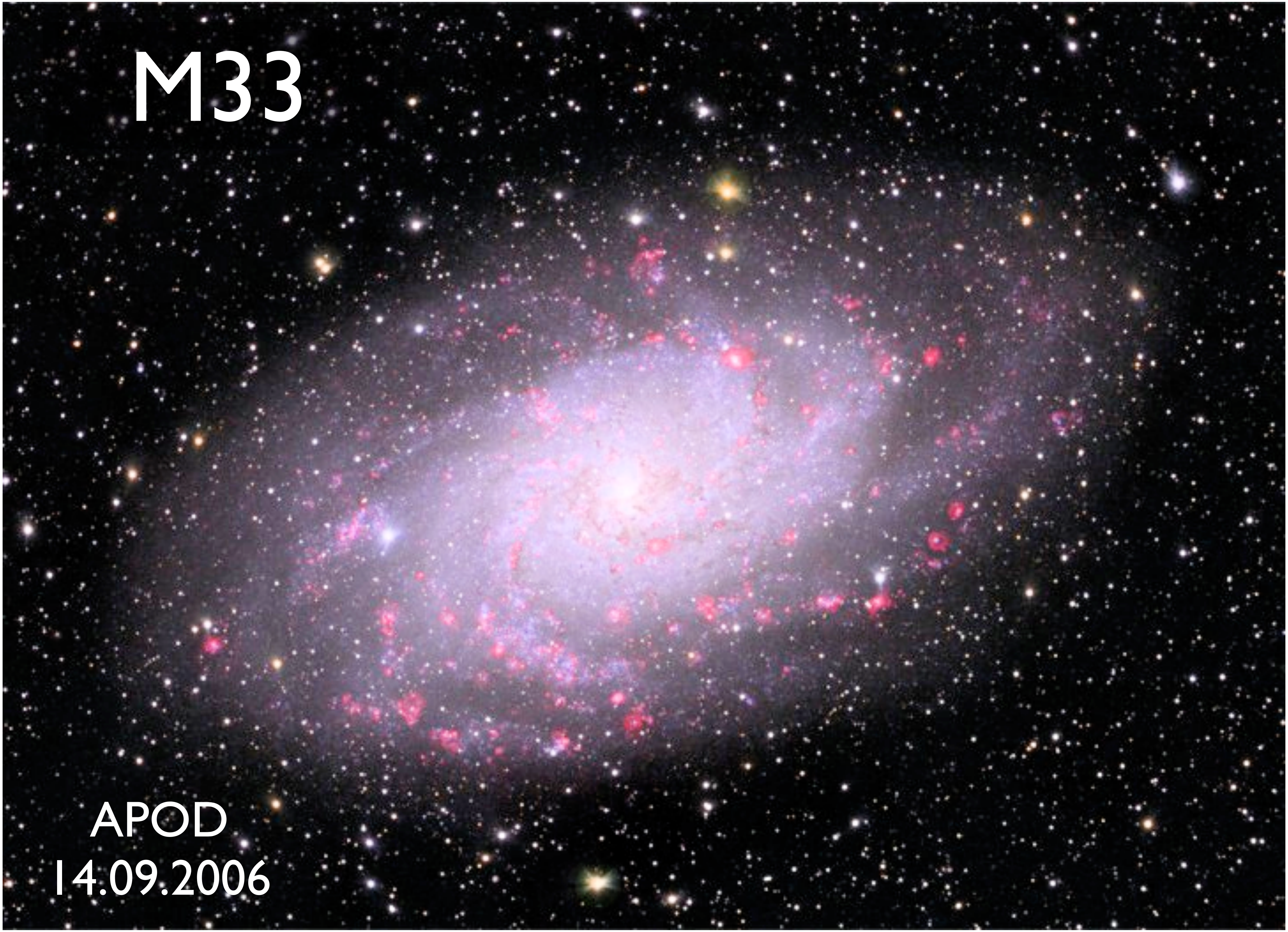
Brightest LG members

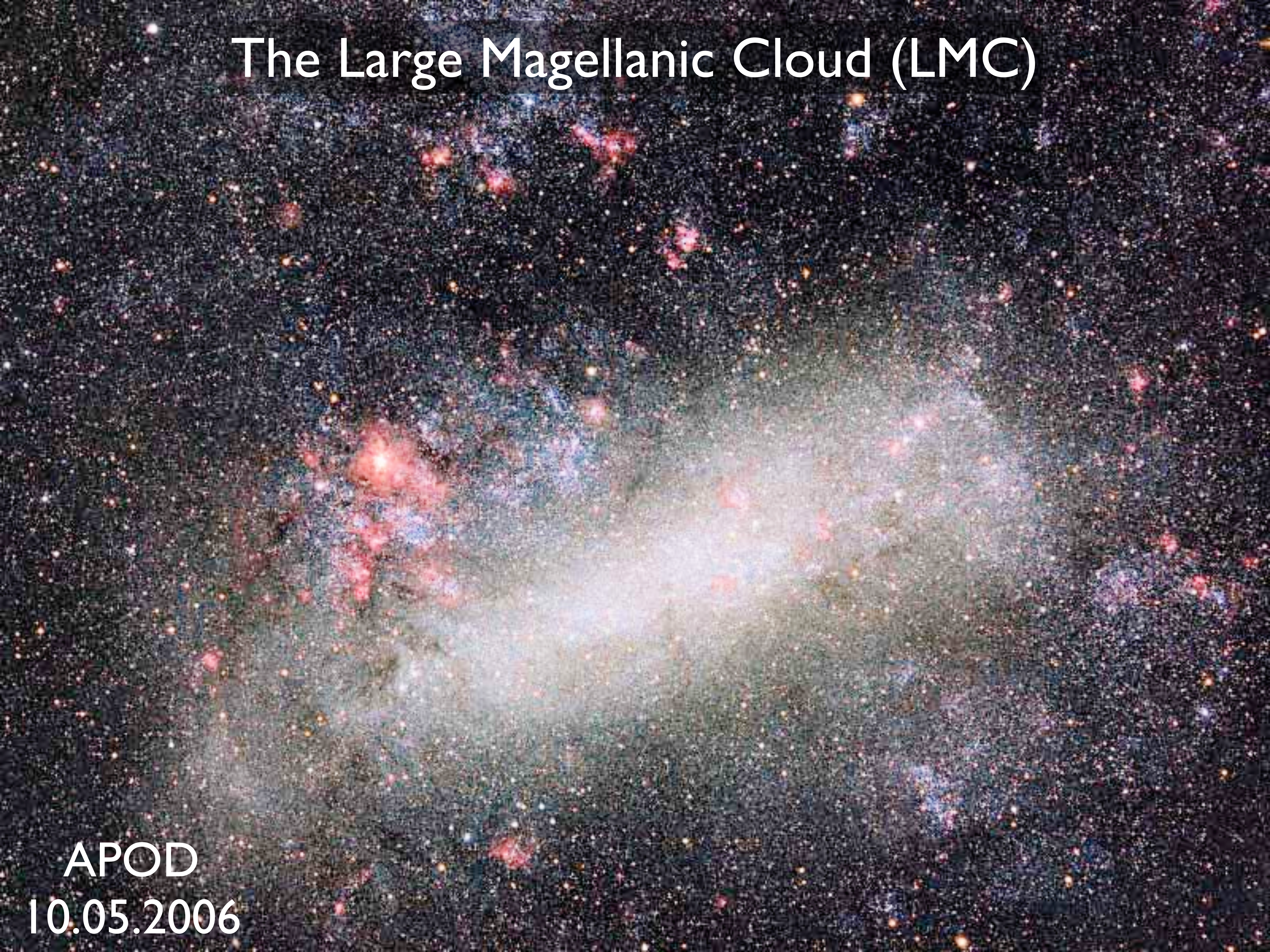
	M_V	% Lum.
M31	-21,2	49
Milky Way	-20,9	37
M33	-18,9	6
Large Magellanic Cloud	-18,5	4
Small Magellanic Cloud	-17,1	1
M32	-16,5	
NGC 205	-16,4	
IC 10	-16,3	
NGC 6822	-16	

The Milky Way and M31 together account for 86% of the total luminosity of the Local Group.

Today more than 50 members are known, but most are very small and faint.

M31 - The Andromeda Galaxy


M33
APOD
14.09.2006

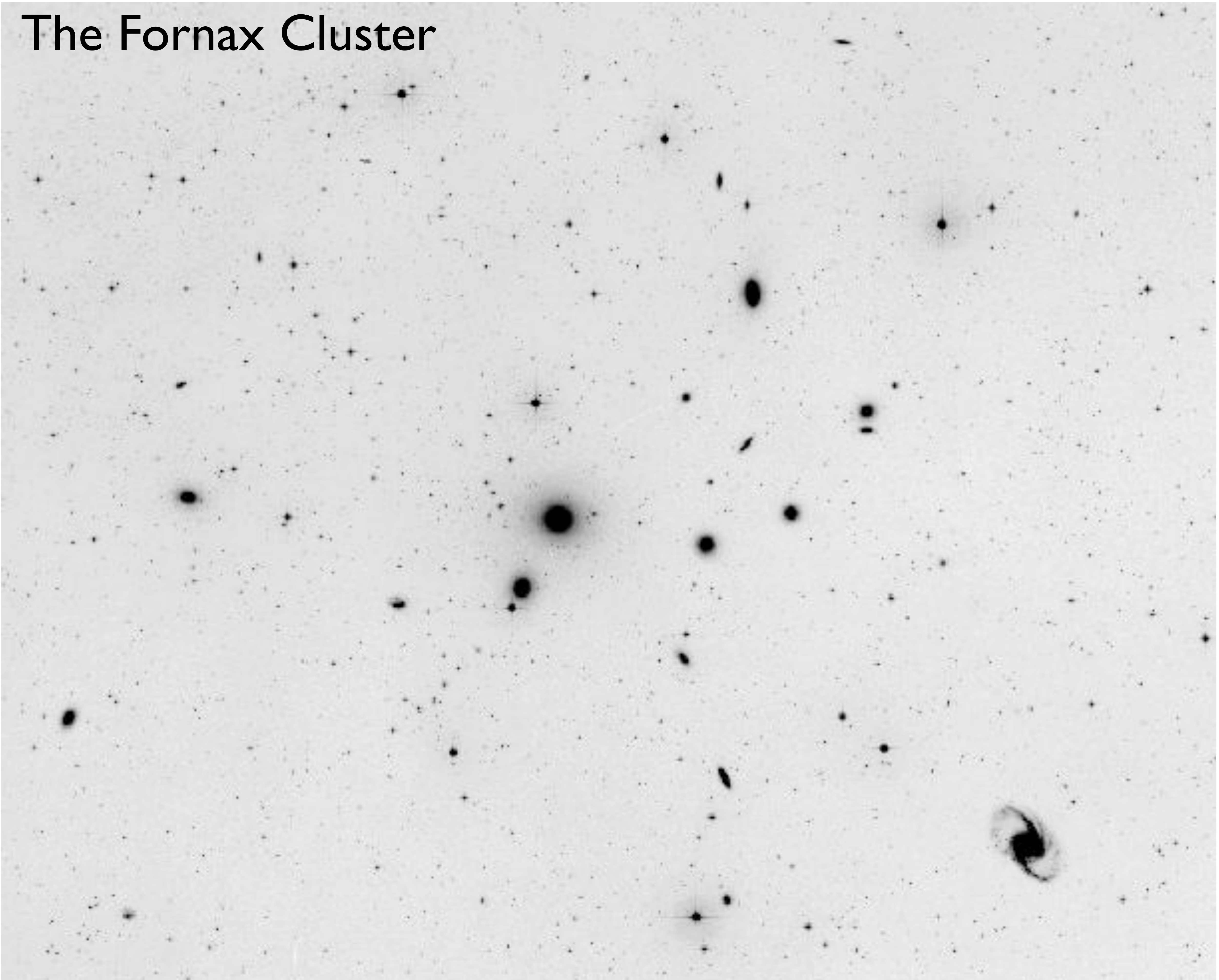

The Large Magellanic Cloud (LMC)
APOD
10.05.2006


The Small Magellanic Cloud
Globular cluster:
47 Tuc (foreground)
APOD
16.06.2005

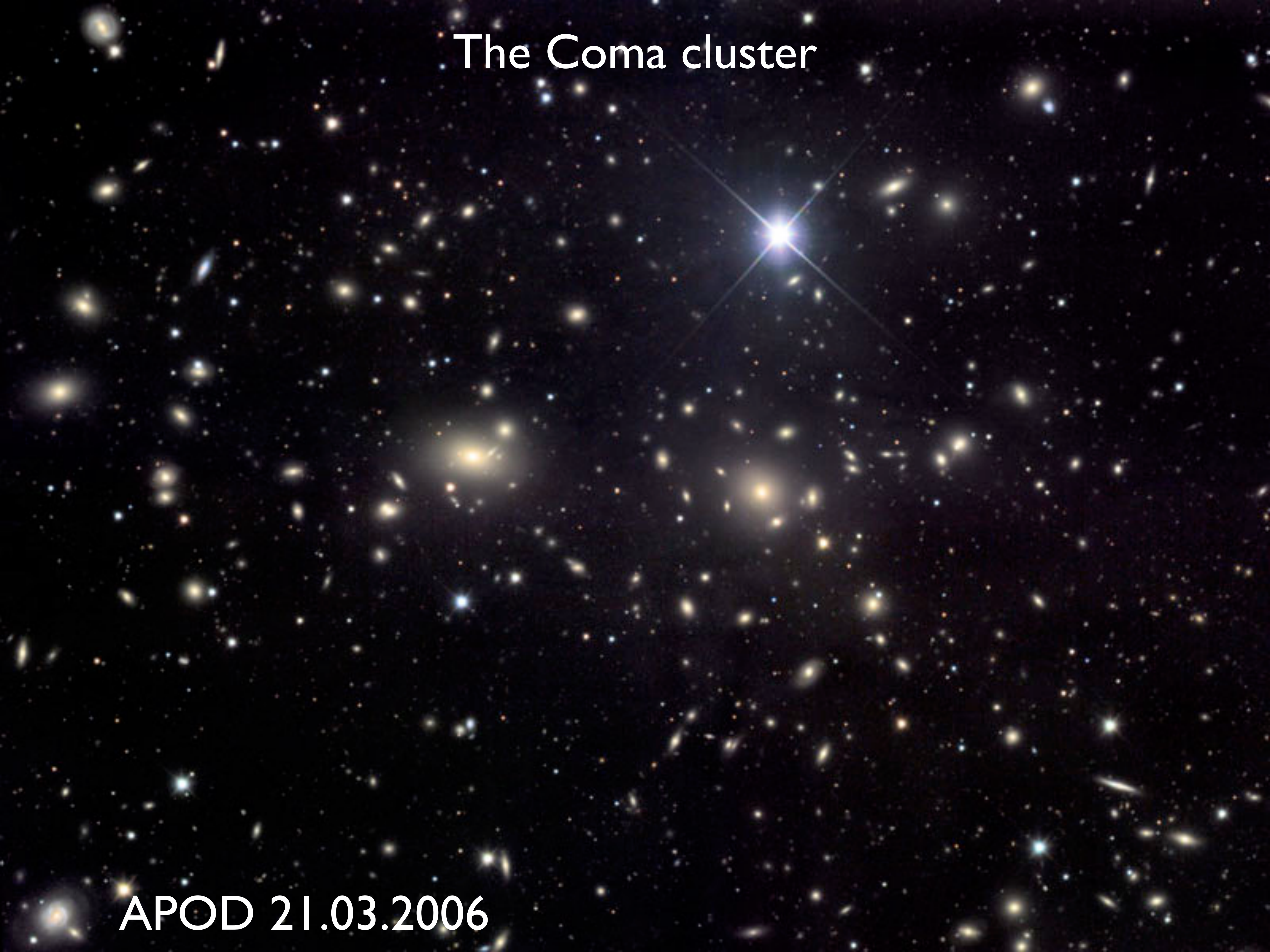

SMC
LMC
APOD 06.08.2006


M81 group
SABINFOTA ASTROPHOTOGRAPHY.2012

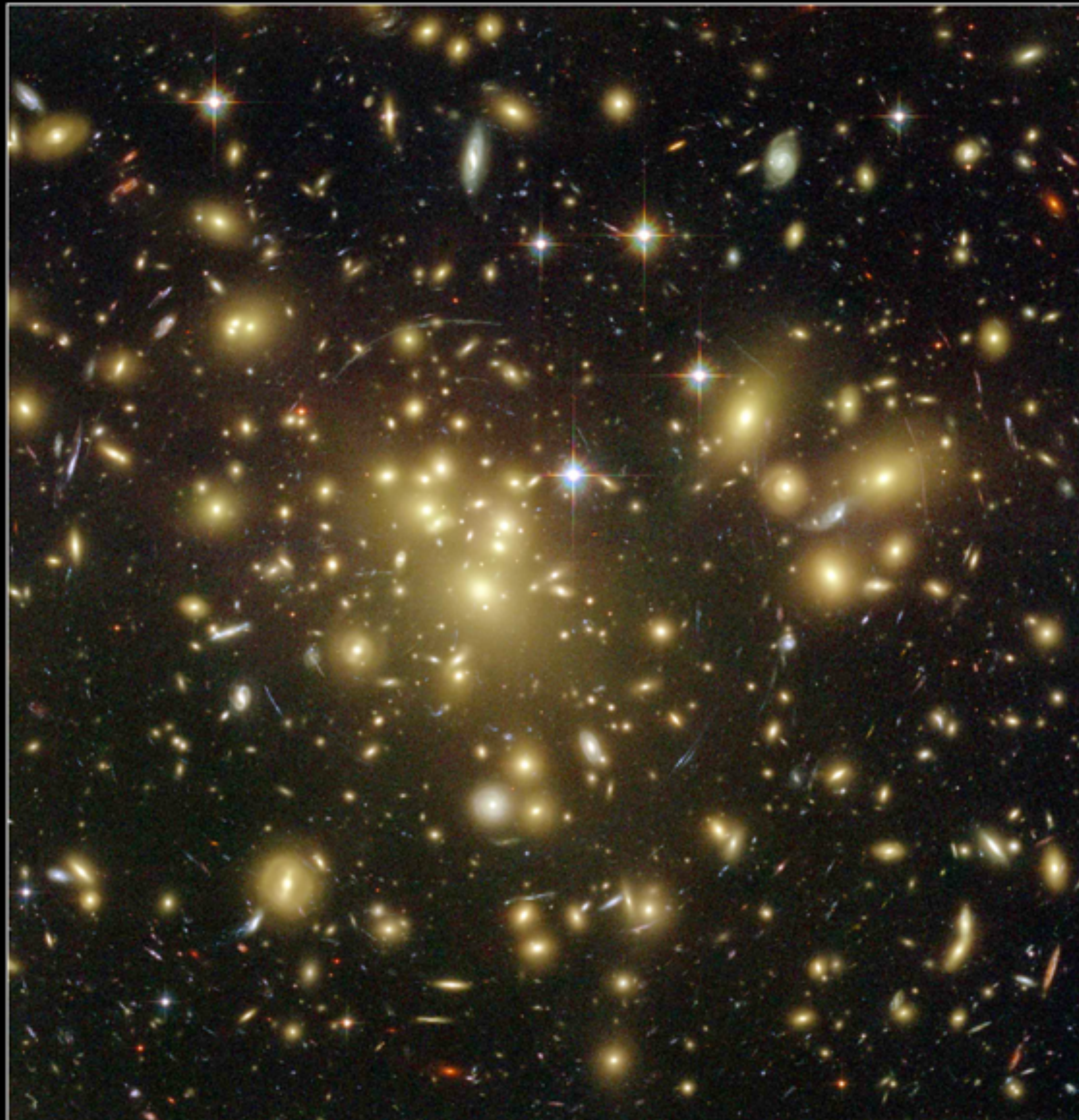
The Fornax Cluster



The Coma cluster



APOD 21.03.2006



Galaxy Cluster Abell 1689

Hubble Space Telescope • Advanced Camera for Surveys

NASA, N. Benitez (JHU), T. Broadhurst (The Hebrew University), H. Ford (JHU), M. Clampin(STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA
STScI-PRC03-01a

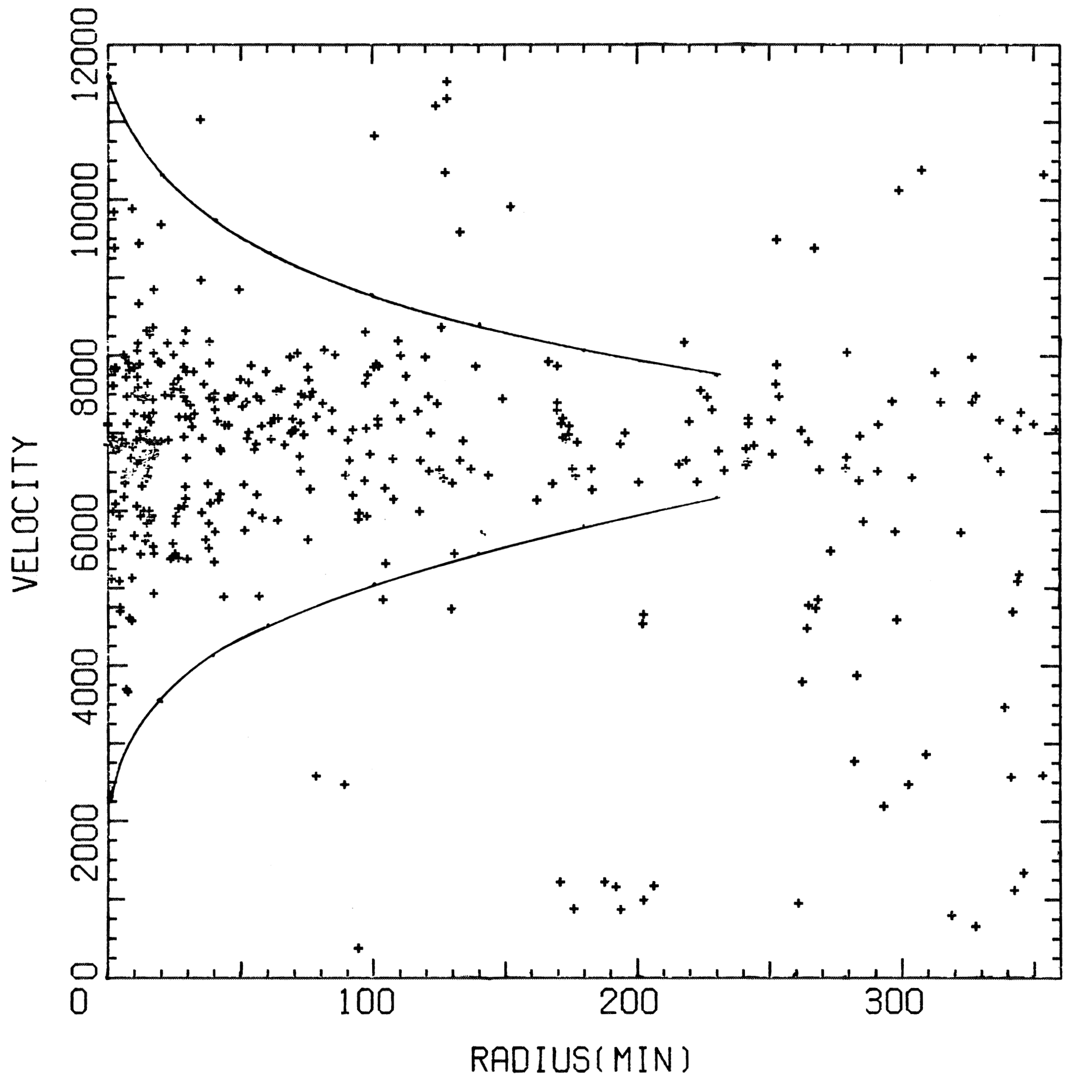
The Abell catalogue

- Northern survey (Abell 1958) - Palomar 48-inch Schmidt telescope, 2712 galaxy clusters
- Southern survey (Abell et al. 1989) - UK 48-inch Schmidt at Siding Spring - 1361 clusters
- Clusters classified by *Richness*, *Compactness* and *Distance*.

Case study: The Coma Cluster

- Mean radial velocity: $\langle v \rangle = 6900$ km s^{-1}, distance = 96 Mpc (for $H_0 = 72$ km s^{-1} Mpc^{-1})
- Located near Galactic north pole: little extinction, well suited for detailed study

Case study: The Coma Cluster



Kent & Gunn 1982

Line-of-sight velocity dispersion:

$$\sigma^2_{v,\mathrm{los}} = \frac{1}{N-1}\sum_{i=1}^{N}(v_i - \langle v \rangle)^2$$

$$\langle v \rangle \approx 6900 \text{ km s}^{-1}$$
$$\sigma_{v,\mathrm{los}} \approx 1100 \text{ km s}^{-1}$$
$$\approx 1.1 \text{ Mpc Gyr}^{-1}$$

Half-light radius:

r_h ~ 41 arcmin

~ 1.1 Mpc for distance ~ 96 Mpc

Crossing time at r_h is much less than the age of Universe - cluster is a bound entity.

Masses of clusters

Virial theorem for a system in dynamical equilibrium:

$$T = -\frac{1}{2}U$$

(*T* and *U*: total kinetic and potential energy)

$$T = \frac{1}{2}\sum_{i=1}^{N} m_i \left|\mathbf{v_i} - \langle\mathbf{v}\rangle\right|^2$$

For $m_1 = m_2 = .. m_N$:

$$T = \frac{1}{2}\frac{M}{N}\sum_{i=1}^{N} \left|\mathbf{v}_i - \langle\mathbf{v}\rangle\right|^2 \; = \; \frac{1}{2}M\sigma_{\rm 3D}^2$$

(also holds for unequal-mass systems if particles of all masses share the same velocity dispersion).

If velocity distribution is isotropic, i.e. $\sigma_x = \sigma_y = \sigma_z$ then

$$\sigma_{\rm 3D}^2 = \sigma_x^2 + \sigma_y^2 + \sigma_z^2 = 3\,\sigma_{\rm 1D}^2$$

Estimating masses - cont'd

$$T = \frac{3}{2} M \sigma_{\rm 1D}^2$$

Potential energy:

$$U = -\alpha \frac{GM^2}{R}$$

α = constant of order unity

Then

$$T = -\frac{1}{2} U \qquad \Rightarrow 3M\sigma_{\rm 1D}^2 = \frac{\alpha G M^2}{R} \qquad \Rightarrow M = \frac{3}{\alpha} \frac{\sigma_{\rm 1D}^2 R}{G}$$

For realistic density profiles and R_h = half-mass radius, $\alpha \approx 0.4$, i.e.

$$M = 7.5 \, \frac{\sigma_{\rm 1D}^2 R_h}{G}$$

Finally, R_h(3D) ≈ 4/3 $R_{\rm eff}$ (2D), so

$$\boxed{M = 10 \, \frac{\sigma_{\rm 1D}^2 R_{\rm eff}}{G}}$$

Mass of the Coma cluster

σ_{1D} = 1000 km s^{-1}
R_{eff} = 1.1 Mpc $\rightarrow$ M = 2.6×10^{15} $M_\odot$

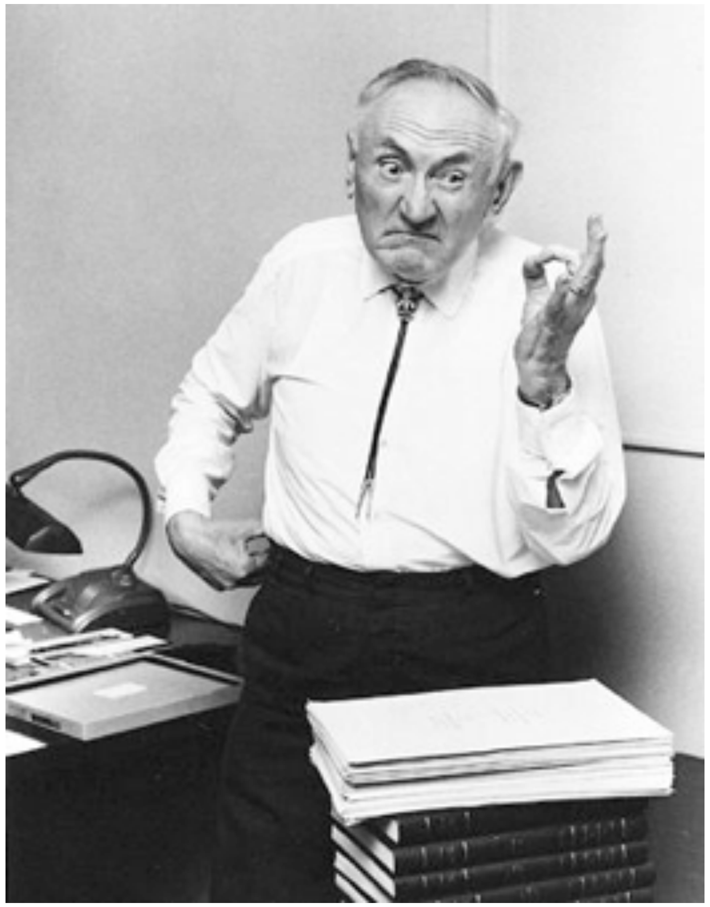
Compare this with the *luminosity* of the cluster:

$L_B \sim 7.7\times10^{12}\ L_{B,\odot}$

This gives a *mass-to-light (M/L) ratio* of

$$M/L_B \approx 340\, M_\odot/L_{B,\odot}$$

Dark matter in galaxy clusters



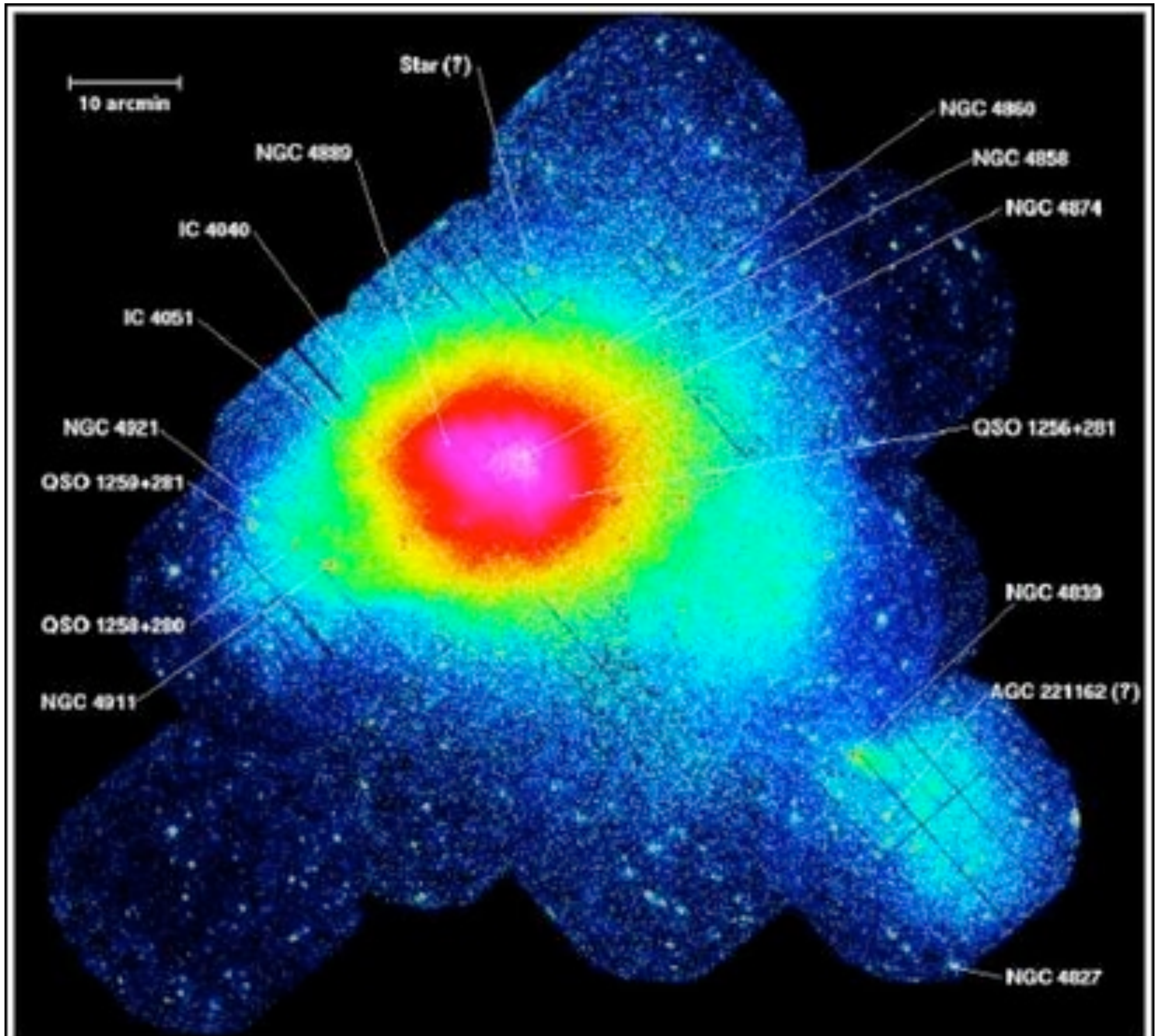
Stars alone can only produce M/L ratios on the order of ~a few.
(E.g. globular star clusters: $M/L_B \sim 1\text{-}2\ M_{\odot}/L_{B,\odot}$)

Most of the mass in galaxy clusters is in the form of invisible "*dark matter*"

Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

Fritz Zwicky (1933)

Masses from observations of hot gas



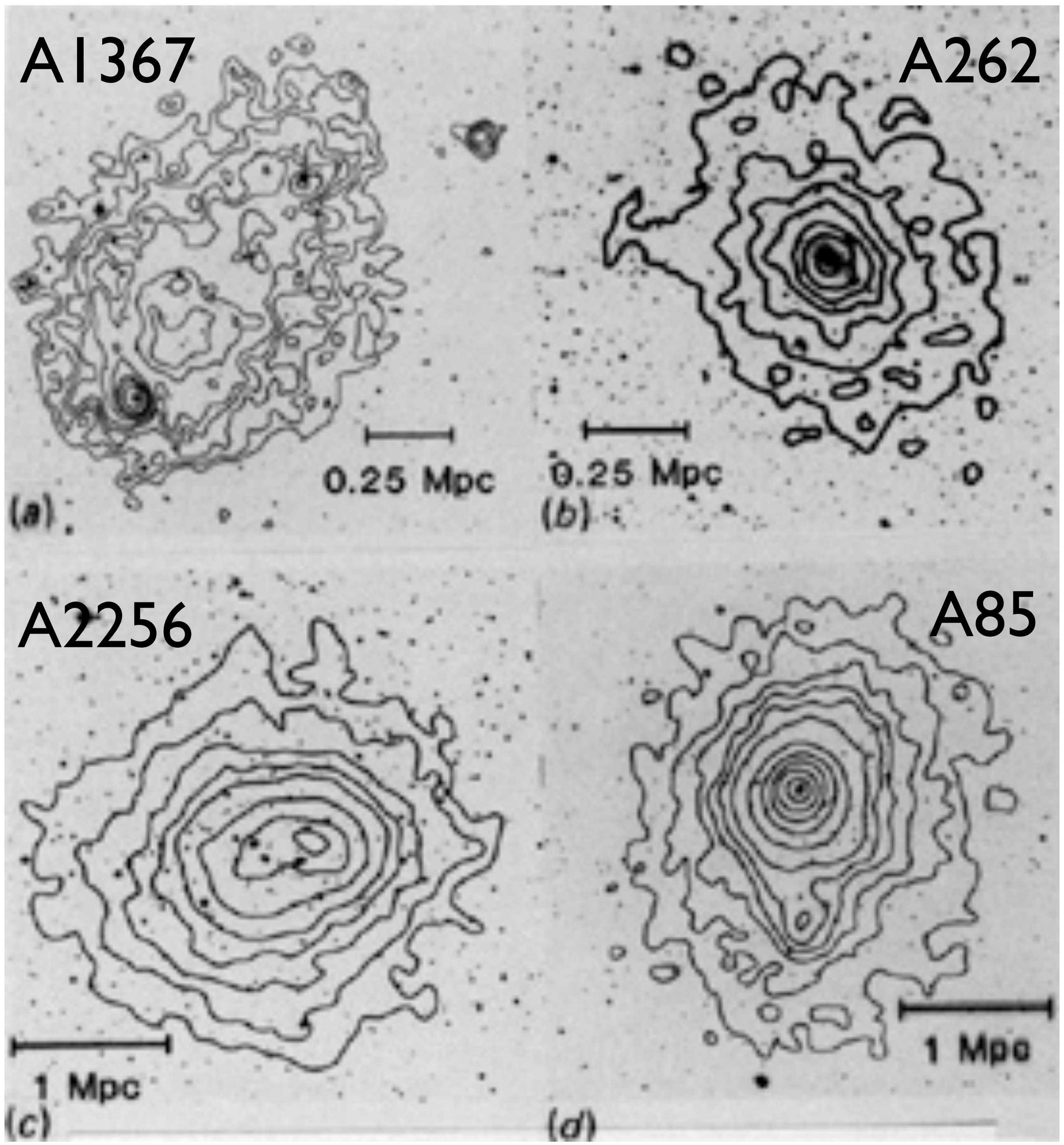
XMM-Newton X-ray image of the Coma cluster (© ESA)

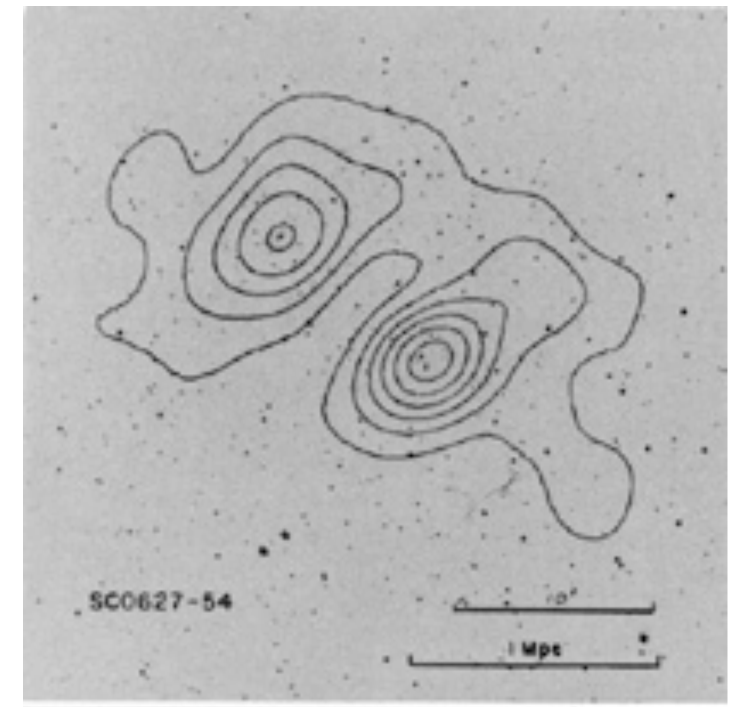
Rich galaxy clusters contain large amounts of hot X-Ray emitting gas.

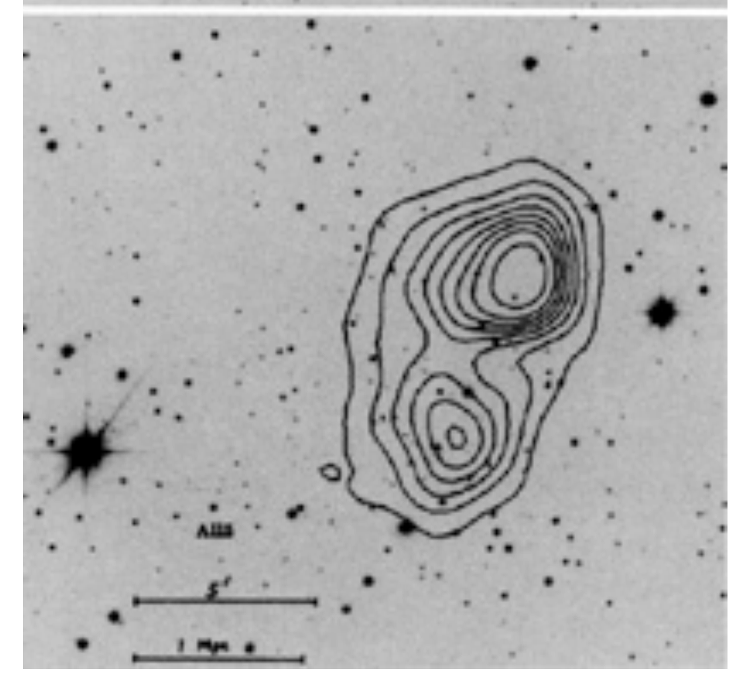
Mass in hot gas can exceed stellar mass by factors of several.

X-ray gas is also an important tracer of overall potential.

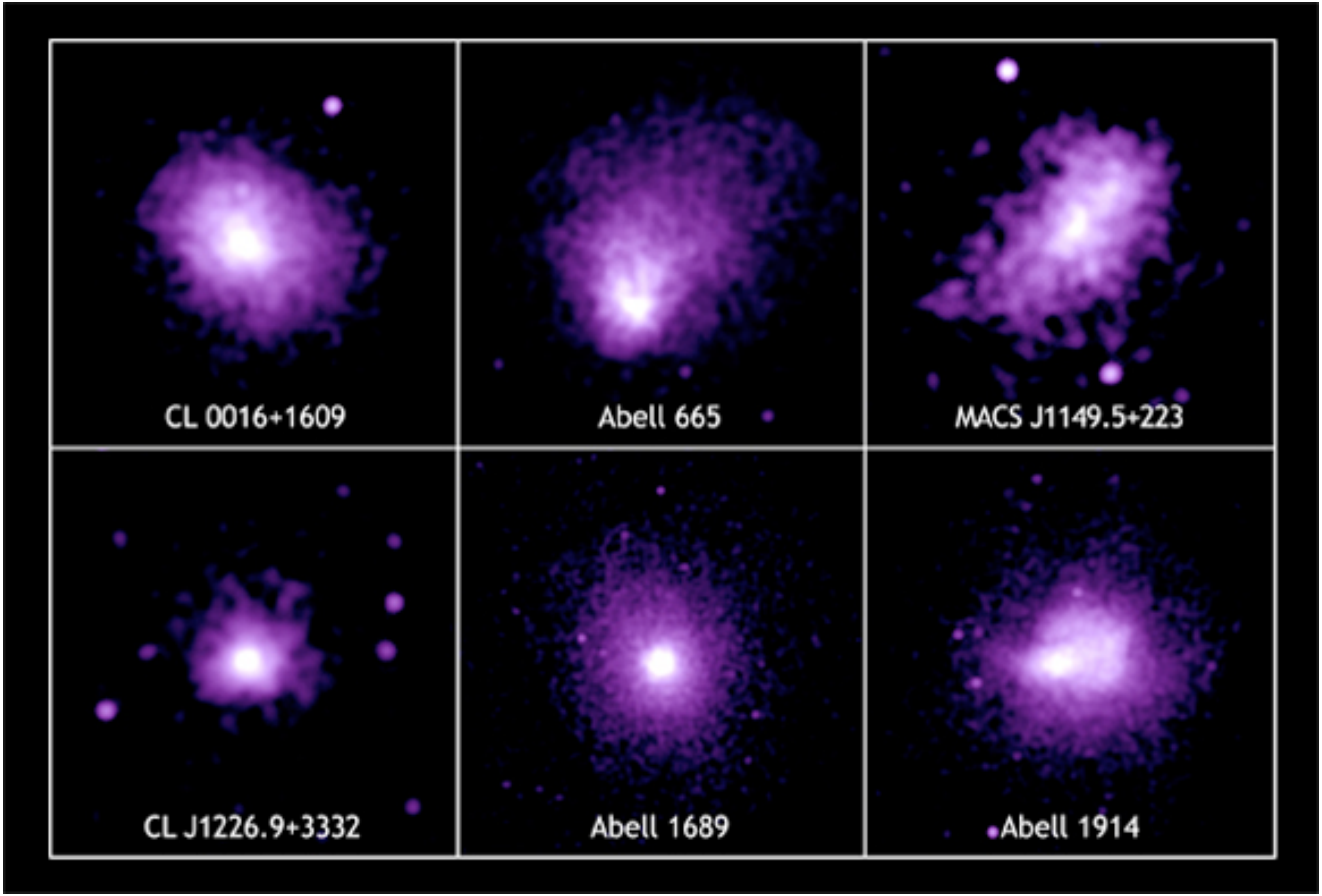
Hot gas in galaxy clusters







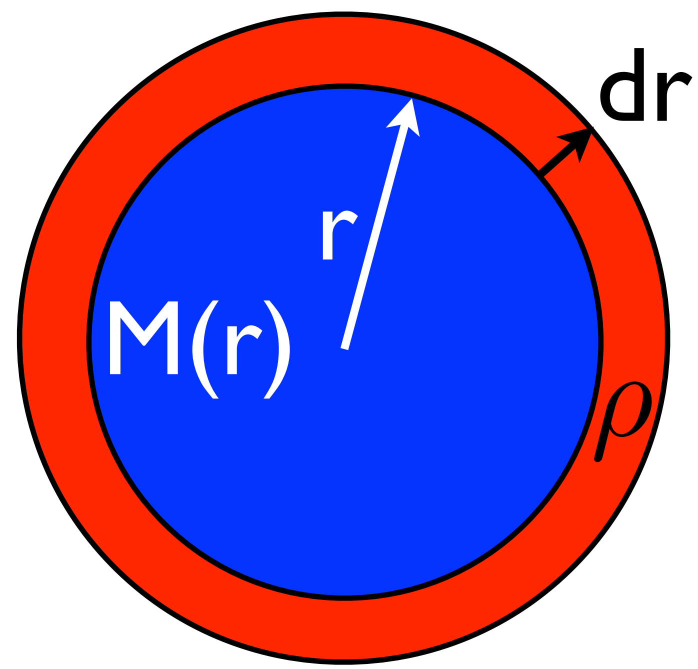
Credit: C. L. Sarazin
http://ned.ipac.caltech.edu/level5/March02/Sarazin/frames.html



Chandra images of galaxy clusters
(Credit: NASA, CXC, MSFC, M. Bonamente et al.
http://www.learner.org/courses/physics)

Hydrostatic equilibrium

Assume spherical geometry



Gravitational pull on a thin shell:

$$F_g = -\frac{G(4\pi r^2 \rho_{\rm gas} {\rm d}r) M_{\rm tot}(r)}{r^2}$$

"Lift" due to pressure gradient:

$$F_p = 4\pi r^2 \left(\frac{{\rm d}p}{{\rm d}r}\right) {\rm d}r$$

Equilibrium:

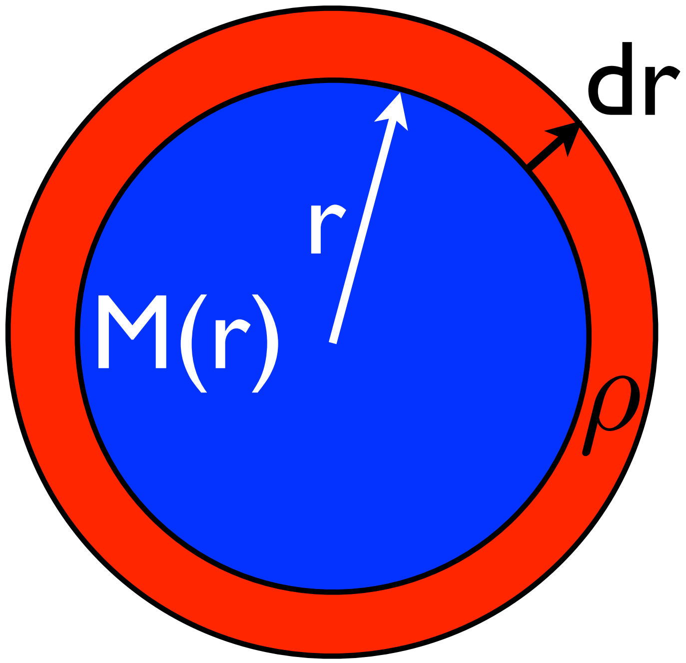
$$\boxed{\frac{{\rm d}p}{{\rm d}r} = -\frac{G\rho_{\rm gas} M_{\rm tot}(r)}{r^2}}$$

Cluster masses from X-ray observations

From hydrostatic equilibrium:

Total mass within r

$$\frac{\mathrm{d}p}{\mathrm{d}r} = -\frac{G\rho_{\mathrm{gas}} M_{\mathrm{tot}}(r)}{r^2}$$



and ideal gas law:

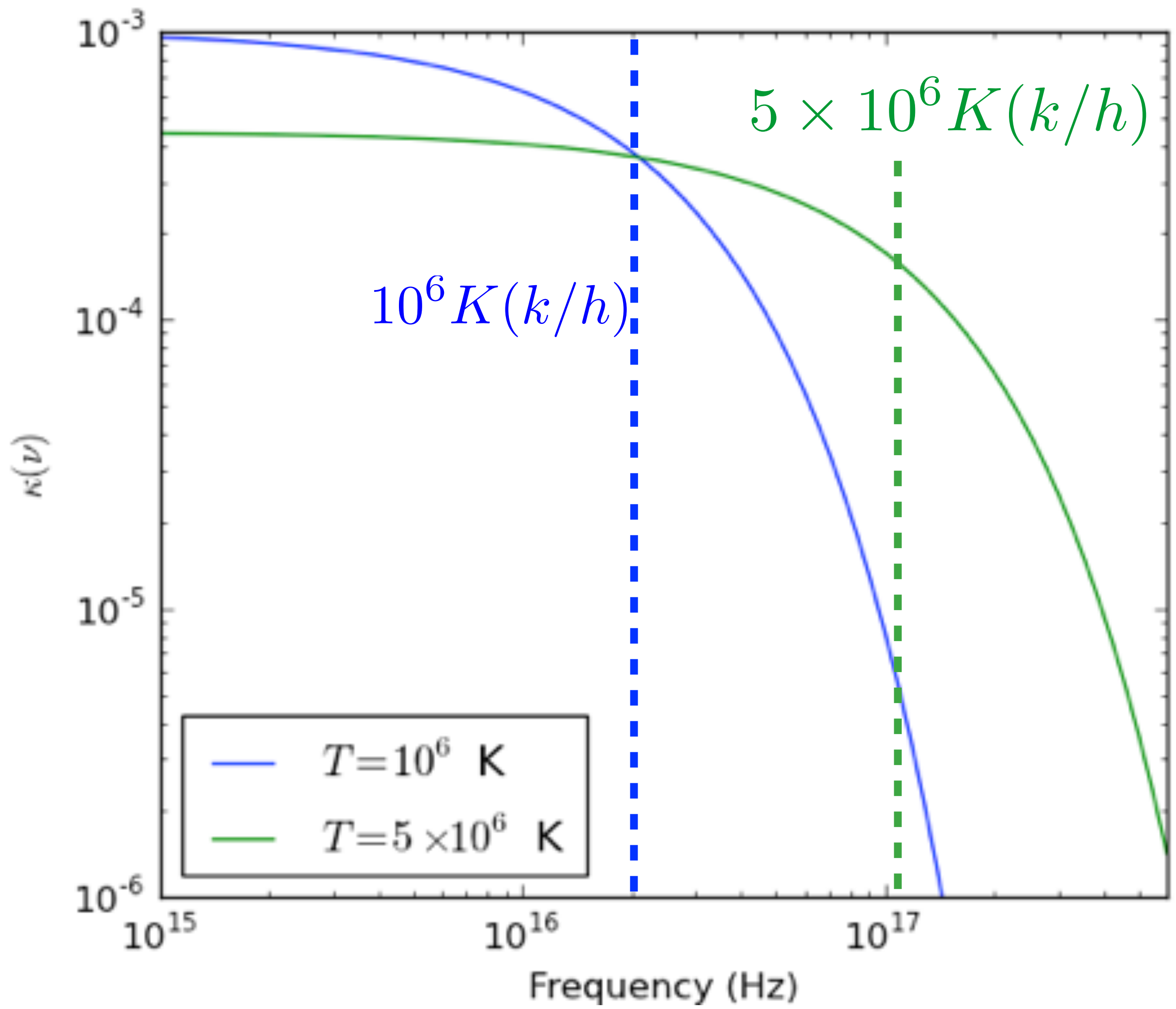
$$p = \frac{\rho k T}{\mu m_H}$$

If we can determine *T(r)* and *gas* density ρ*(r)*, then we can solve for $M_{tot}(r)$

X-ray masses cont'd

Intra-cluster gas is hot, optically thin - main radiation mechanism is free-free emission ("bremsstrahlung").
Emissivity (energy per time per unit volume) is given by

$$\kappa(\nu) = (\text{const}) \times \; g(\nu, T) N N_e T^{-1/2} e^{-h\nu/kT}$$



T follows directly from shape of spectrum - corresponds to "break" where spectrum changes from flat to steep.

Density ρ then follows from overall scaling.

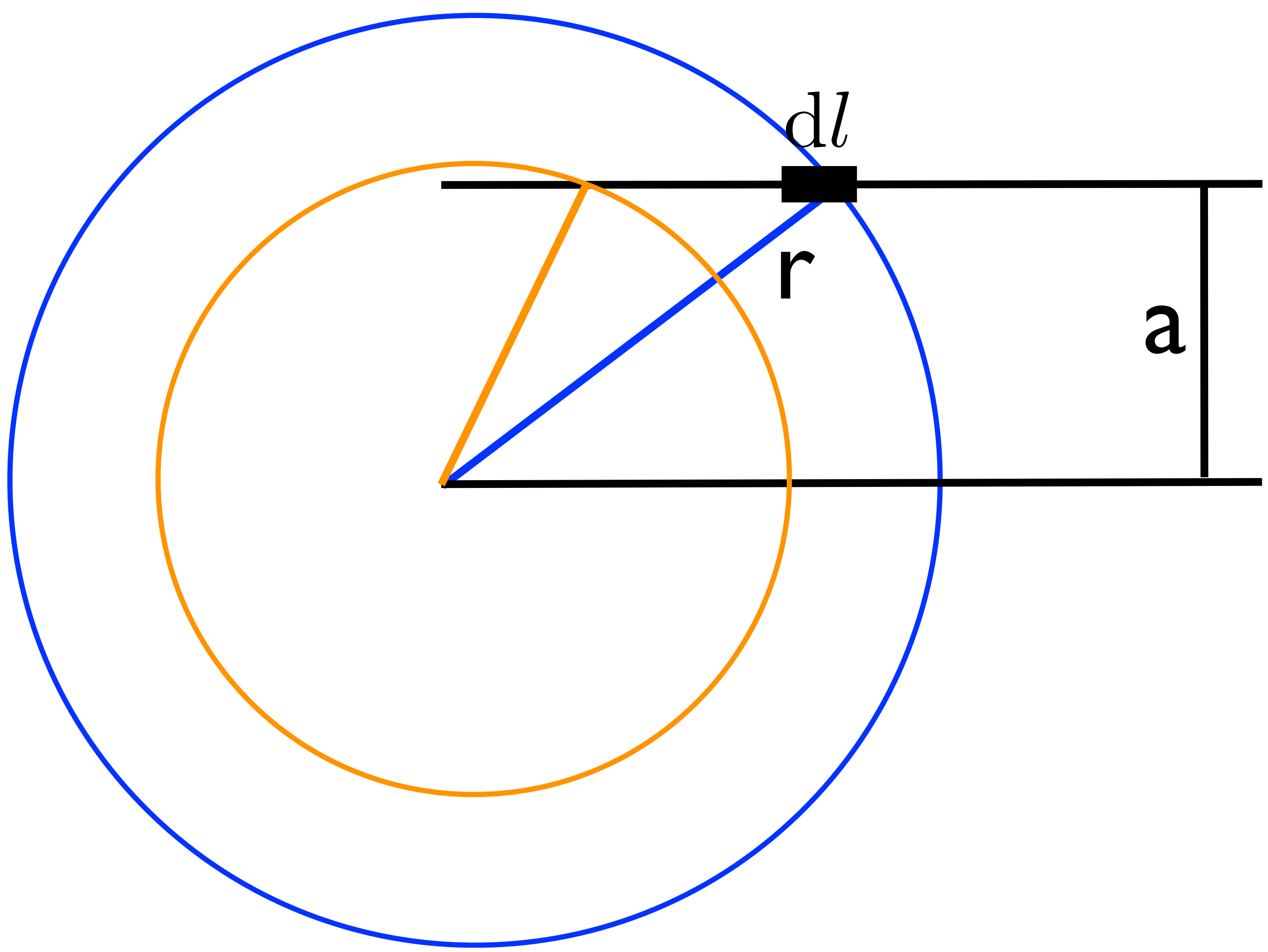
X-ray masses cont'd

$$\kappa(\nu) = (\mathrm{const}) \times \; g(\nu, T) N N_e T^{-1/2} e^{-h\nu/kT}$$

- We do not measure $\kappa(\nu)$ directly.
- We measure its line-of-sight integral, i.e. the intensity $I(\nu)$
- This needs to be *deprojected*

X-ray masses cont'd

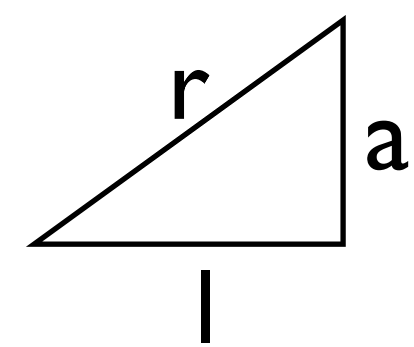
Observed intensity *I*(ν) is line-of-sight integral of κ(ν):



$$I(a) = \int_{-\infty}^{\infty} \frac{\kappa(r)}{4\pi} \mathrm{d}l$$

$$l = \sqrt{r^2 - a^2}$$

$$\mathrm{d}l = \frac{r}{\sqrt{r^2 - a^2}} \mathrm{d}r$$



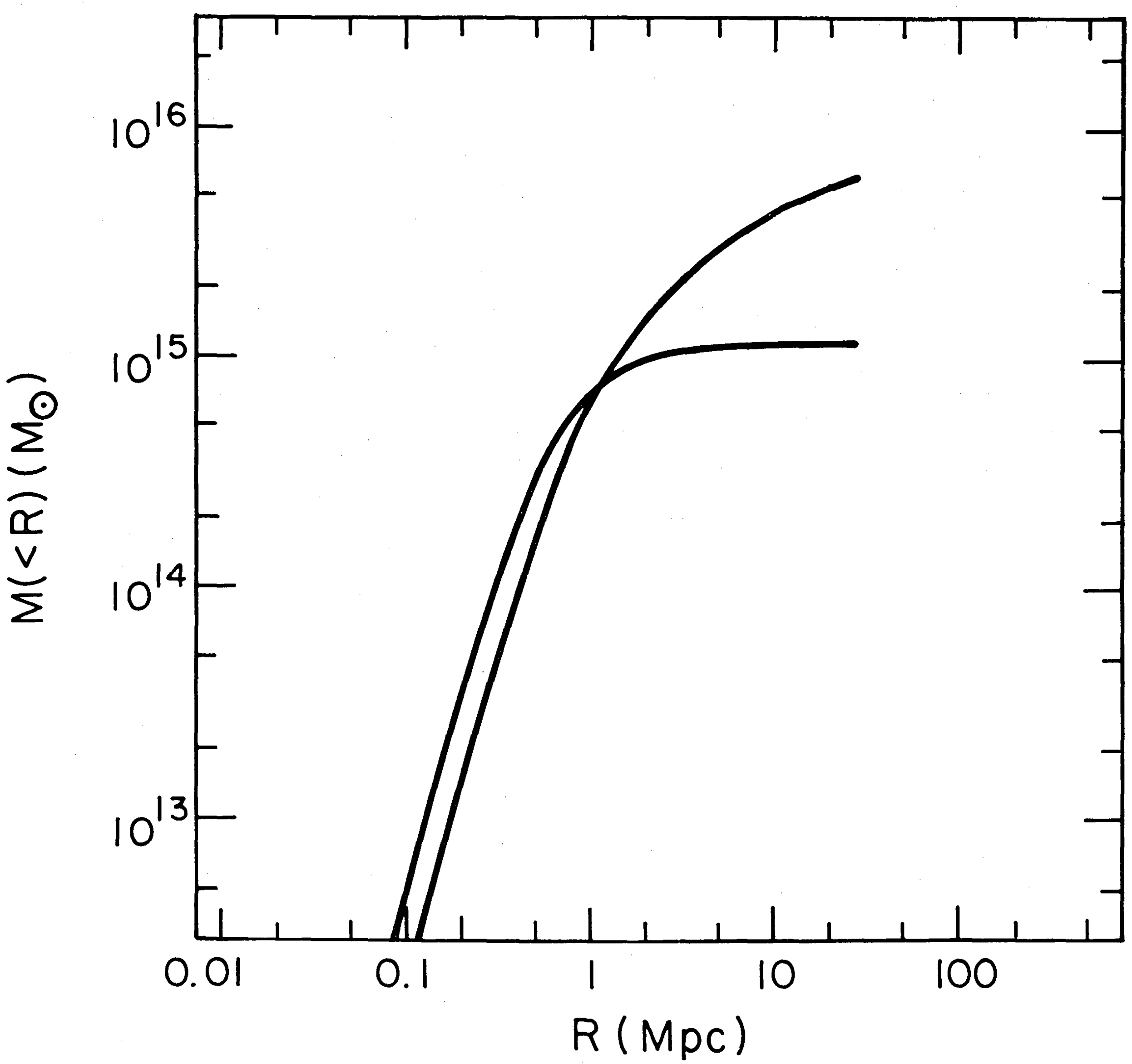
$$I(a) = \frac{1}{2\pi} \int_{a}^{\infty} \frac{\kappa(r) r}{\sqrt{r^2 - a^2}} \mathrm{d}r$$

Abel integral, can be inverted to find κ*(r)* for observed *I(a)*:

$$\kappa(r) = -4 \int_{r}^{\infty} \frac{\mathrm{d}I(a)}{\mathrm{d}a} \frac{\mathrm{d}a}{\sqrt{a^2 - r^2}}$$

(note: eq. 4.26 in Longair is incorrect)

Mass of Coma cluster from X-Ray data



Two curves show range of solutions allowed within uncertainties of data.

Total mass within 5 Mpc:

$$M_{\rm tot} \approx 2 \times 10^{15} M_\odot$$

$$(M_{\rm vir} \approx 2.6 \times 10^{15} M_\odot)$$

Gas mass:

$$M_{\rm gas} \approx 2 \times 10^{14} M_\odot$$

Hot gas accounts for about 10% of the total mass.

Significantly more mass in (hot) gas than in stars!
But not enough to explain D.M.

Hughes (1989)

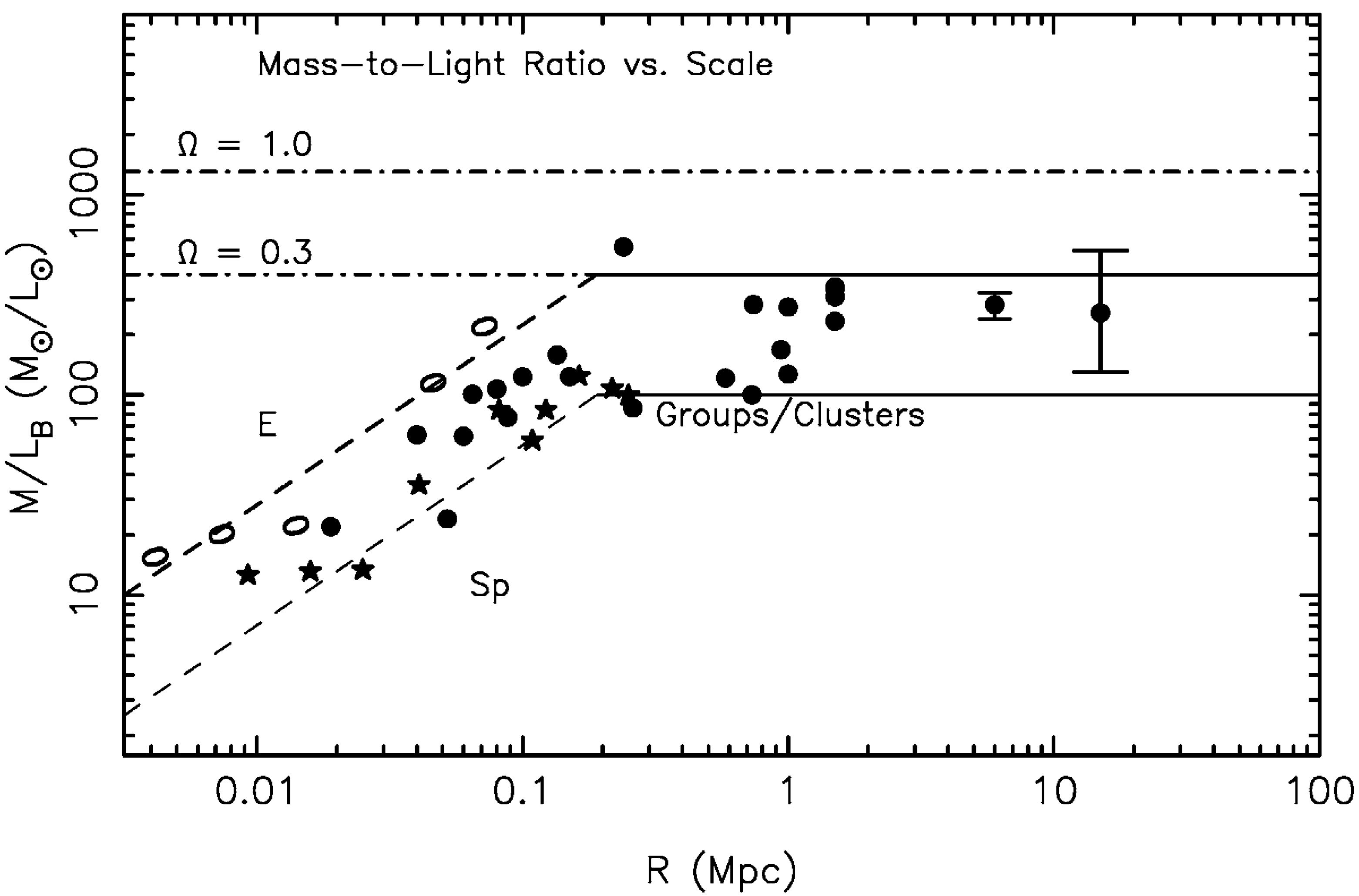
Evidence for DM

- Range of scales and phenomena:
  - Individual (spiral) galaxies: rotation curves
  - Local Group: relative motion of Milky Way and M31 (e.g. course on *sterrenstelsels*)
  - Elliptical galaxies: kinematics at large radii (globular clusters, planetary nebulae)
  - Masses of galaxy clusters (virial, X-ray gas, gravitational lensing)

The matter density appears to be *sub-critical*, $\Omega_0 \sim 0.2\text{-}0.3$

Agreement with SN Ia results (and CMB).

N.A. Bahcall / Physics Reports 333–334 (2000) 233–244



DM dominates on *large scales* - less “clumpy” than baryons

M/L ratio reaches a “plateau” of $(M/L)_B \sim 200\text{-}300$ h on large scales.

$(M/L)_B \sim 1350$ h needed to reach $\Omega_0 = 1.0$

Baryonic mass density

- For the Coma cluster: M(tot) ~ 10 M(gas) ~ 50 M(stars)
- These numbers are fairly typical: For rich clusters,

$$\langle M_{\rm gas}\rangle \approx 0.07\, M_{\rm vir}\, h^{-3/2} \quad \approx 0.11\, M_{\rm vir}$$

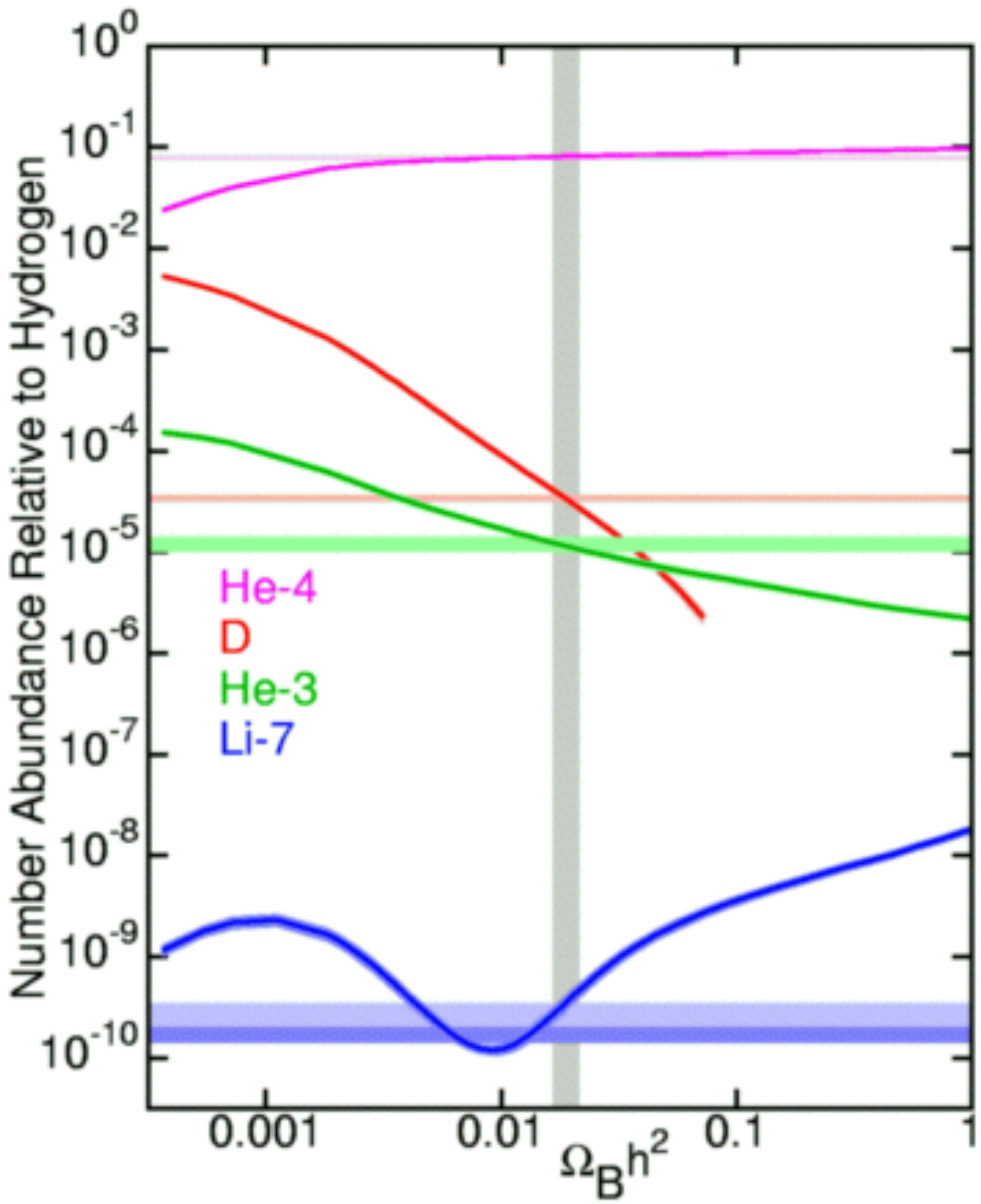
$$\langle M_{\rm stars}\rangle \approx 0.03\, M_{\rm vir}$$

$$\Omega_B \approx (0.11 + 0.03) \times \Omega_0 \approx 0.04$$

(Bahcall 2000)

- This baryon density agrees well with *independent* constraints from Big-Bang nucleosynthesis, $\Omega_B \sim 0.045$

Predicted abundances



Key results:

Observed He fraction (Y~25%) is *naturally explained* by BB nucleosynthesis.

Abundances of other light elements depend strongly on the baryon density, Ω_B.

Basic parameters

- H_0 - Hubble constant ✔ (72 km s^{-1} Mpc^{-1})
- Ω_B - Baryonic matter density ✔ ($\Omega_0 \sim 0.04$)
- Ω_0 - Total matter density ✔ ($\Omega_0 \sim 0.25$)
- Ω_Λ - Dark energy density ✔ ($\Omega_\Lambda \sim 0.75$)
- T_0 - age of the Universe ✔ ($T_0 \sim 13.8$ Gyr)

The Sunyaev-Zeldovich effect

- Predicted by R. Sunyaev & Y. Zeldovich in 1969, first observed in 1983
- Basic idea:
  Photons from the Cosmic Microwave Background are scattered by free electrons in the hot intra-cluster gas (inverse Compton scattering)
- Distorts the CMB black-body curve in a characteristic way
- Small effect: typically only 1% of photons passing through a cluster are scattered
- S-Z effect *independent of redshift.*

The S-Z effect: basics

Photon from CMB is inversely Compton scattered by electron in host cluster gas with temperature T_e:

$$\Delta E_\nu / E_\nu \approx \frac{kT_e}{m_e c^2}$$

Compton optical depth of cluster gas:

$$y = \int \frac{kT_e}{m_e c^2} \sigma_T N_e dl$$

Depends only on *electron density*, *temperature* and *size* of the cluster.

Compton optical depth

Some typical numbers:

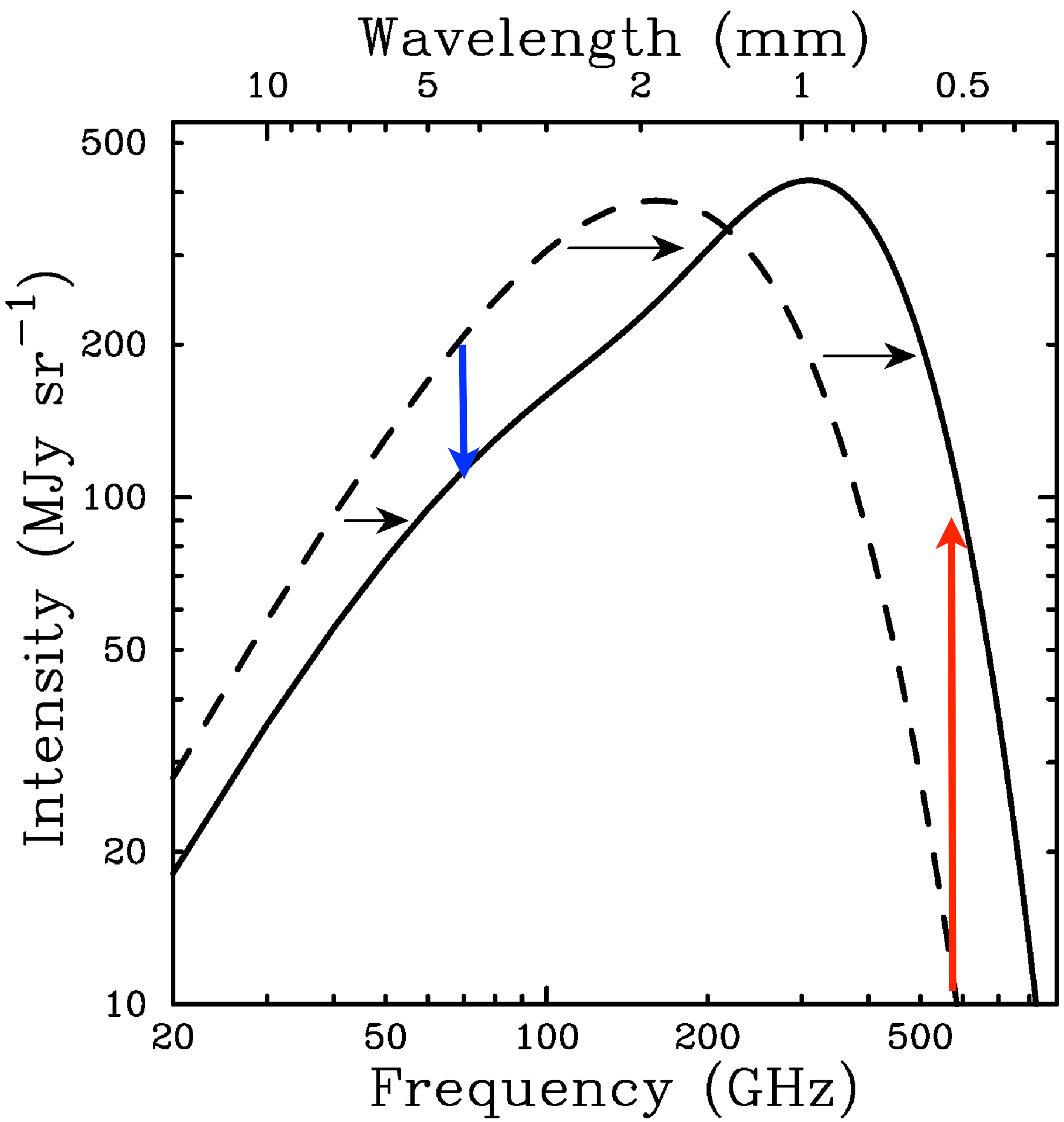
$M_{gas} \sim 10^{14}\ M_\odot$, $R \sim 1$ Mpc $\Rightarrow$ $\langle N_e \rangle \sim 1000\ m^{-3}$

Scattering probability $2\sigma_t N_e R \approx 0.004$

Compton optical depth for typical electron temperature $T_e \sim 10^8$ K:

$$y = \int \frac{kT_e}{m_e c^2} \sigma_T N_e \mathrm{d}l \quad \approx 2 \frac{kT_e}{m_e c^2} \sigma_T N_e R \ \approx \ 10^{-4}$$

The S-Z effect



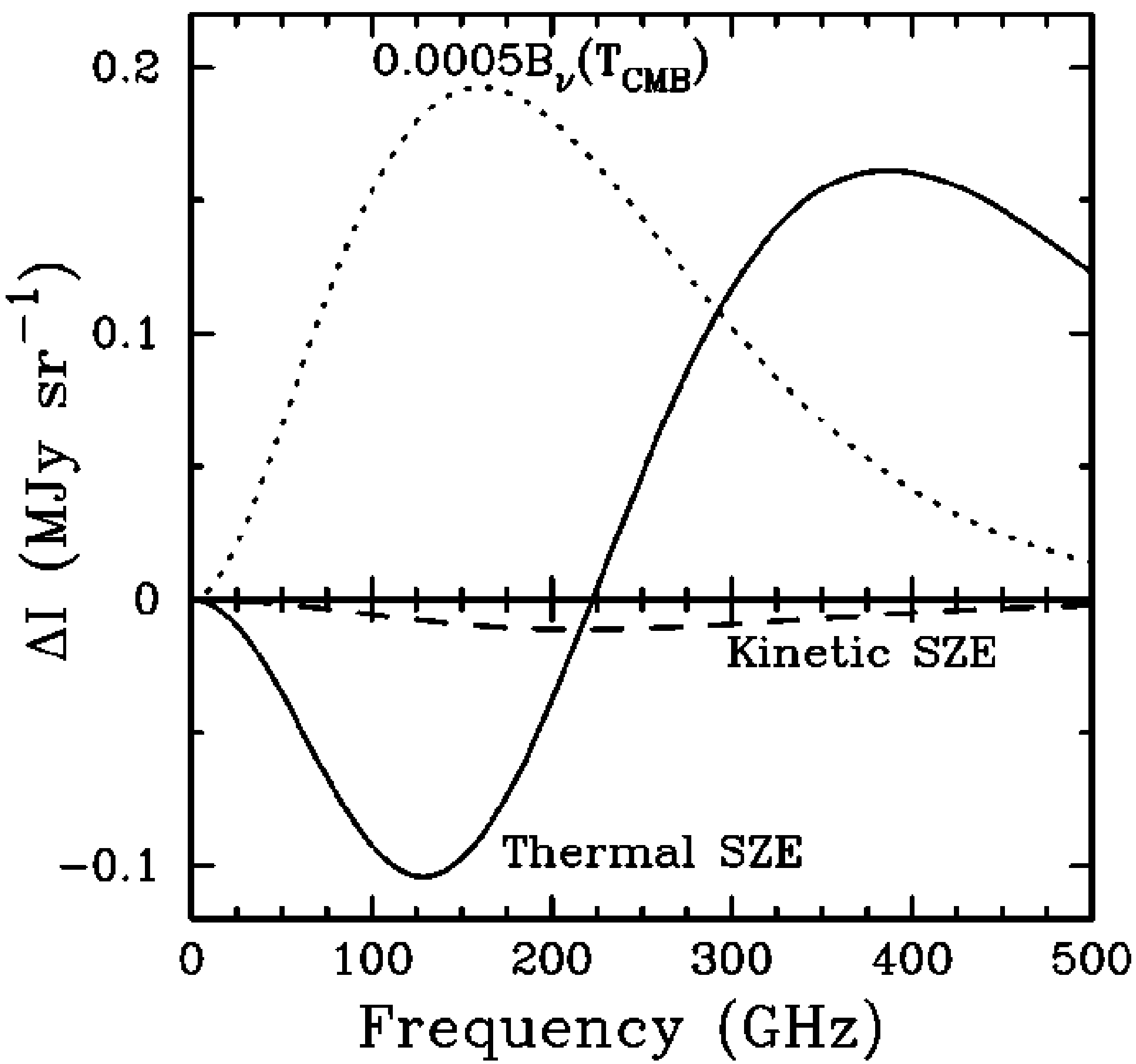
S-Z effect for a hypothetical cluster with a mass 1000x greater than a typical galaxy cluster (Carlstrom et al. 2002)

High frequencies:
Increased intensity of CMB

Low frequencies ($\lambda \gtrsim 1$ mm):
Reduced intensity, "Holes in the sky"

$$\Delta I_\nu / I_\nu = -2y$$

The S-Z effect

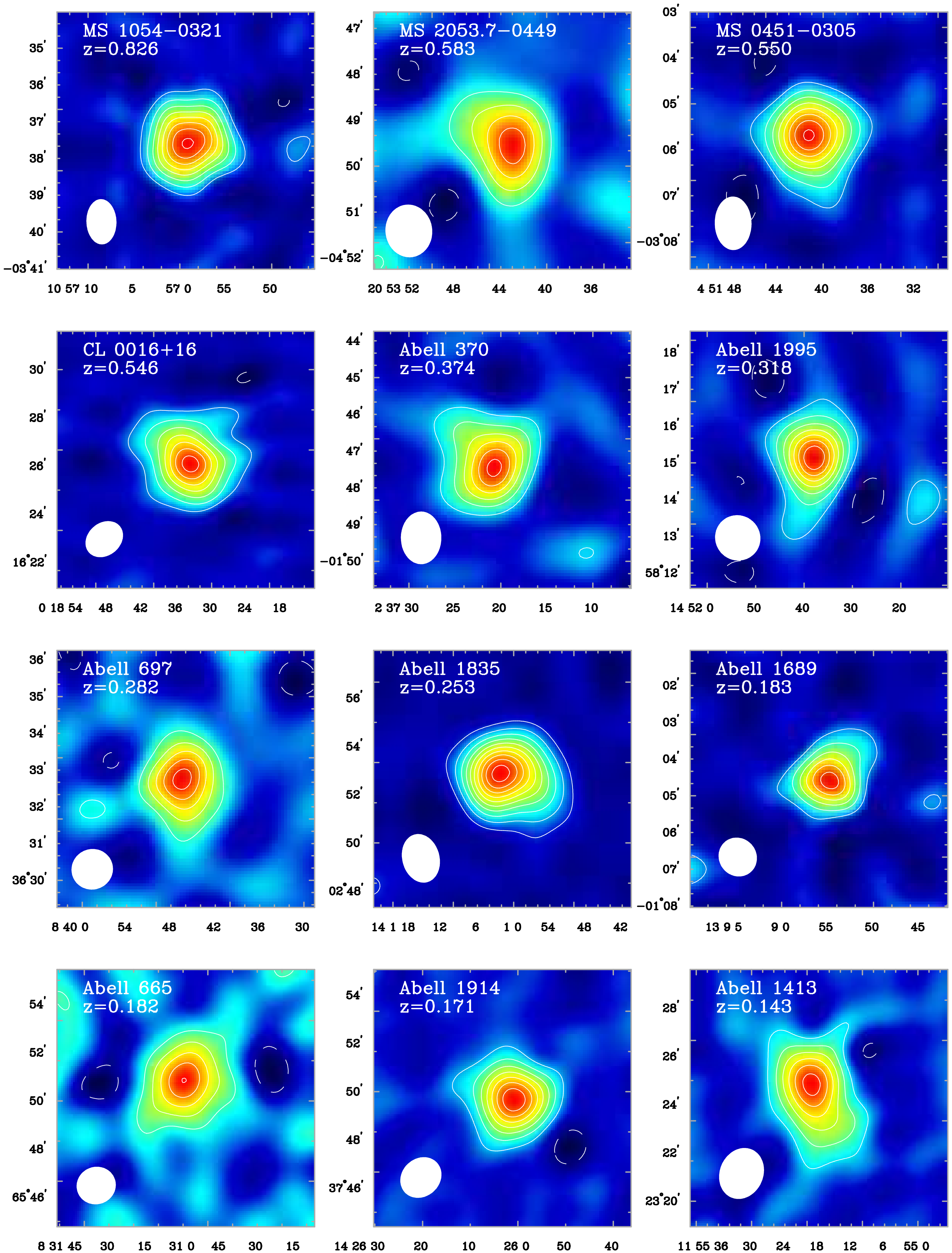


Carlstrom et al. (2002)

Distortion of CMB spectrum due to S-Z effect.

Main effect:
Thermal SZE (hot cluster gas)

Also relevant:
Kinetic SZE (bulk motion of cluster relative to CMB rest frame; here 500 km s^{-1})



Images of S-Z effect in high-redshift galaxy clusters (OVRO, BIMA. Wavelength ~ 1 cm)

Carlstrom et al. 2000

Observing the S-Z effect

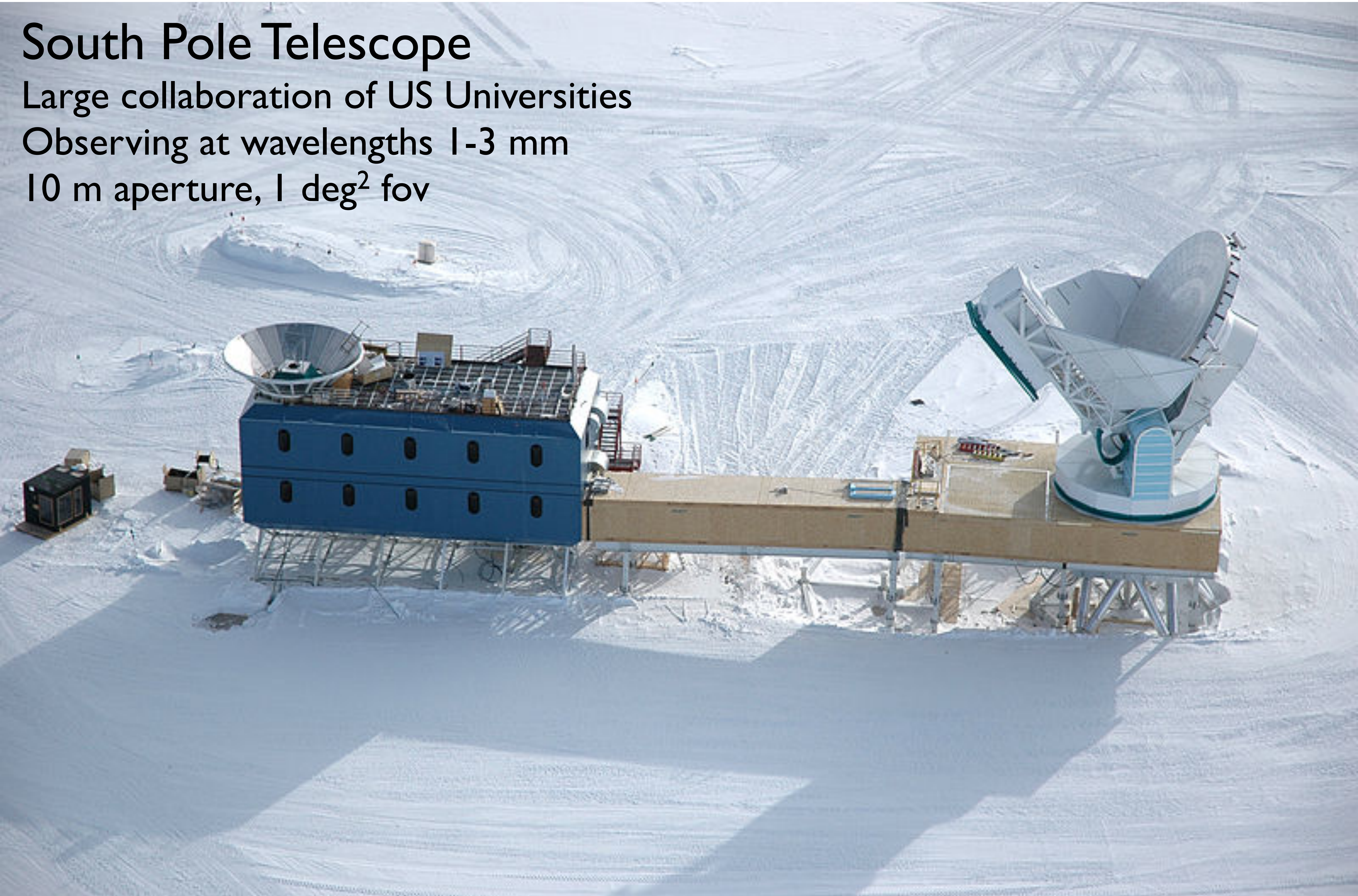
- Best seen at mm wavelengths
- Challenging from the ground - absorption due to water vapour in Earth's atmosphere
- Requires extremely dry conditions
- Or go to space

Atacama Cosmology Telescope:

- In Chilean Atacama desert at 5170 m elevation.
- Run by Princeton University and collaborators
- Dedicated to measuring the CMB, including S-Z
- Wavelengths 1-2 mm
- Field size 1 deg

South Pole Telescope

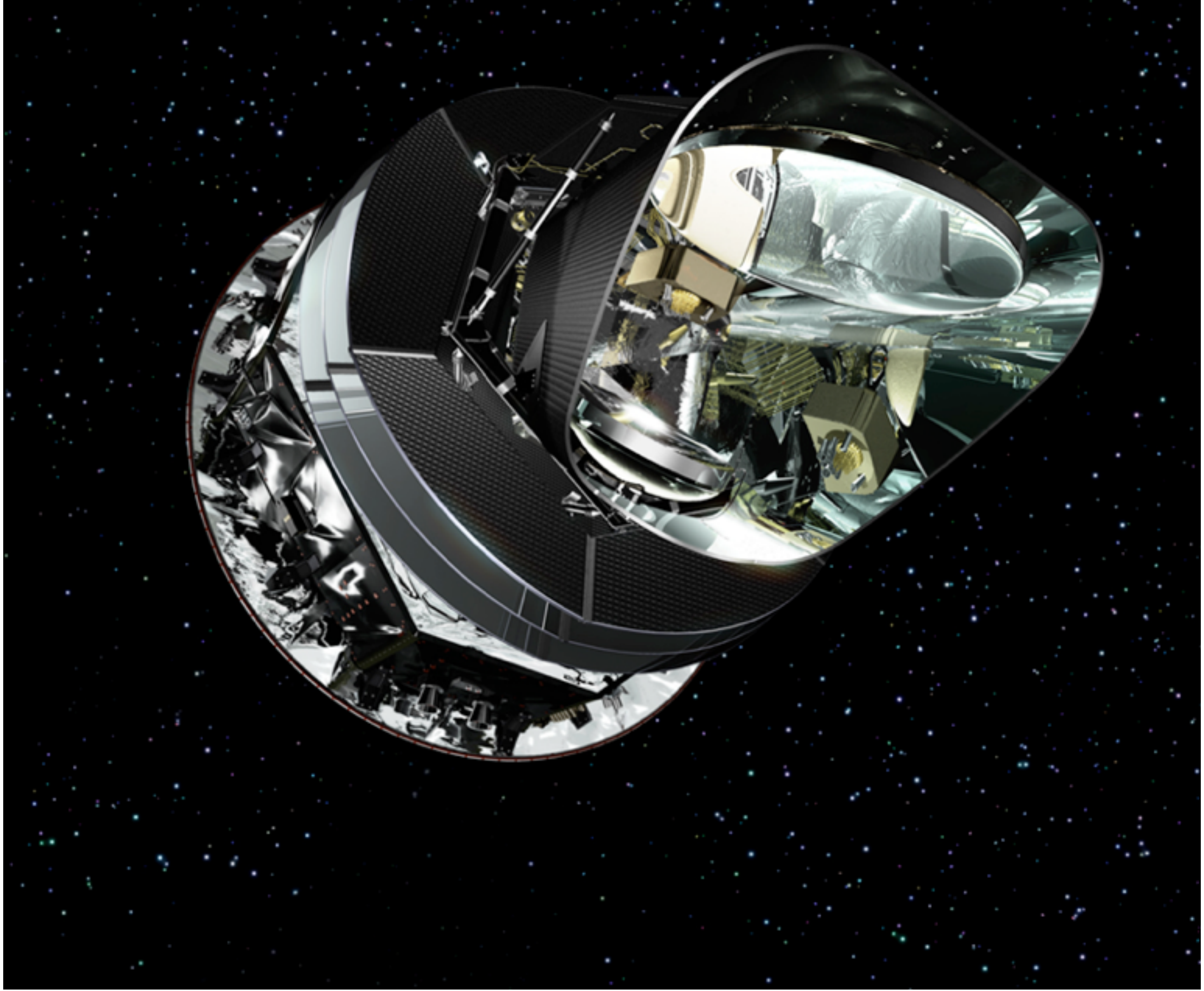
Large collaboration of US Universities
Observing at wavelengths 1-3 mm
10 m aperture, 1 deg^2 fov



ESA Planck satellite

Launched 2009

All-sky survey of CMB at 0.3-10 mm



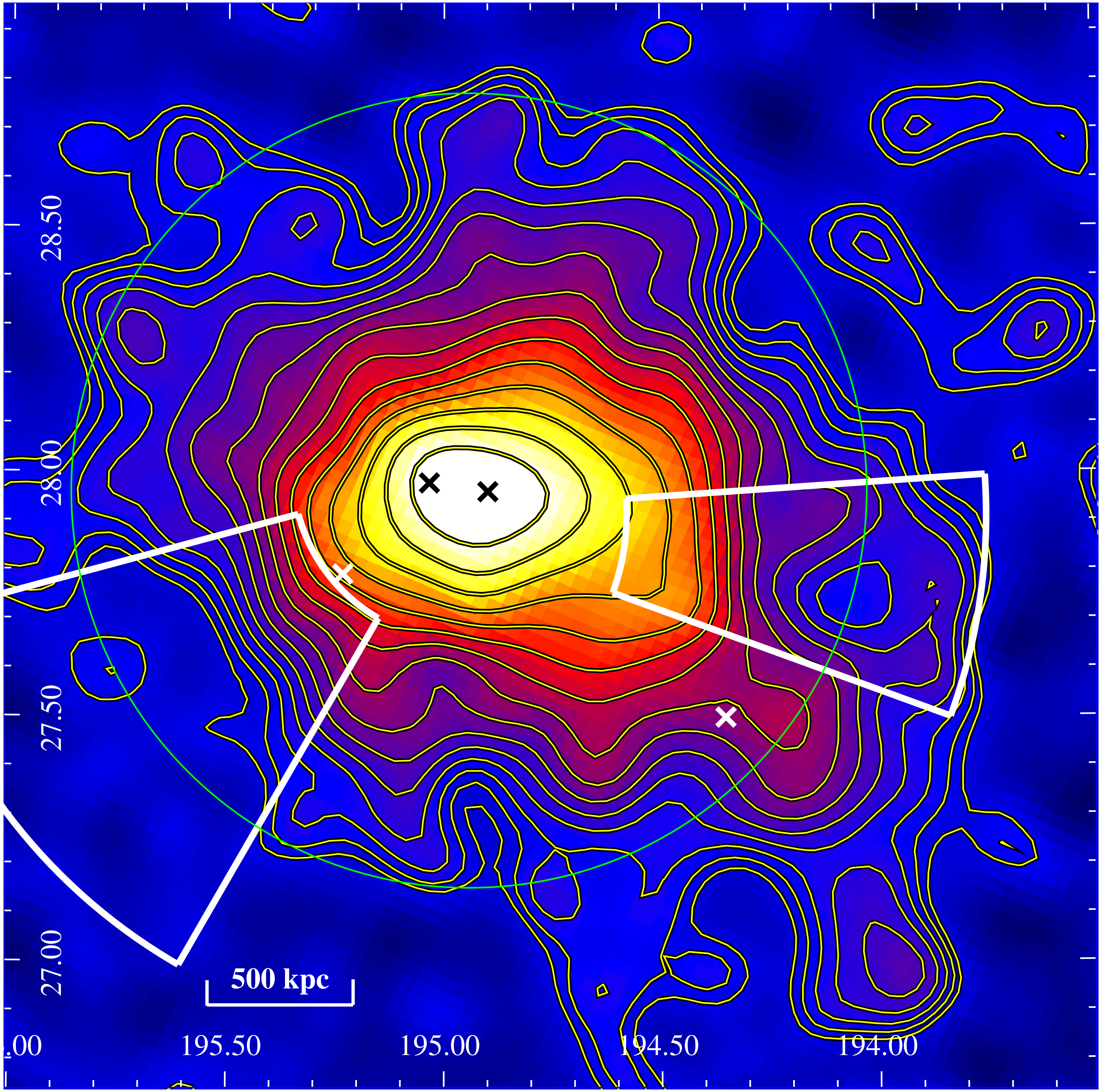


Fig. 2. The *Planck* y map of the Coma cluster obtained by combining the HFI channels from 100 GHz to 857 GHz. North is up and west is to the right. The map is corrected for the additive constant $y_{\rm off}$. The final map bin corresponds to $FWHM$ = 10′. The image is about 130 arcmin × 130 arcmin. The contour levels are logarithmically spaced by $2^{1/4}$ (every 4 lines, y increases by a factor 2). The outermost contour corresponds to $y = 2 \times \sigma_{\rm noise} = 4.6 \times 10^{-6}$. The green circle indicates R_{500}. White and black crosses indicate the position of the brightest galaxies in Coma. The white sectors indicate two regions where the y map shows a local steepening of the radial gradient (see Sect. 7 and Fig. 6).

Planck collaboration: Ade et al. 2013

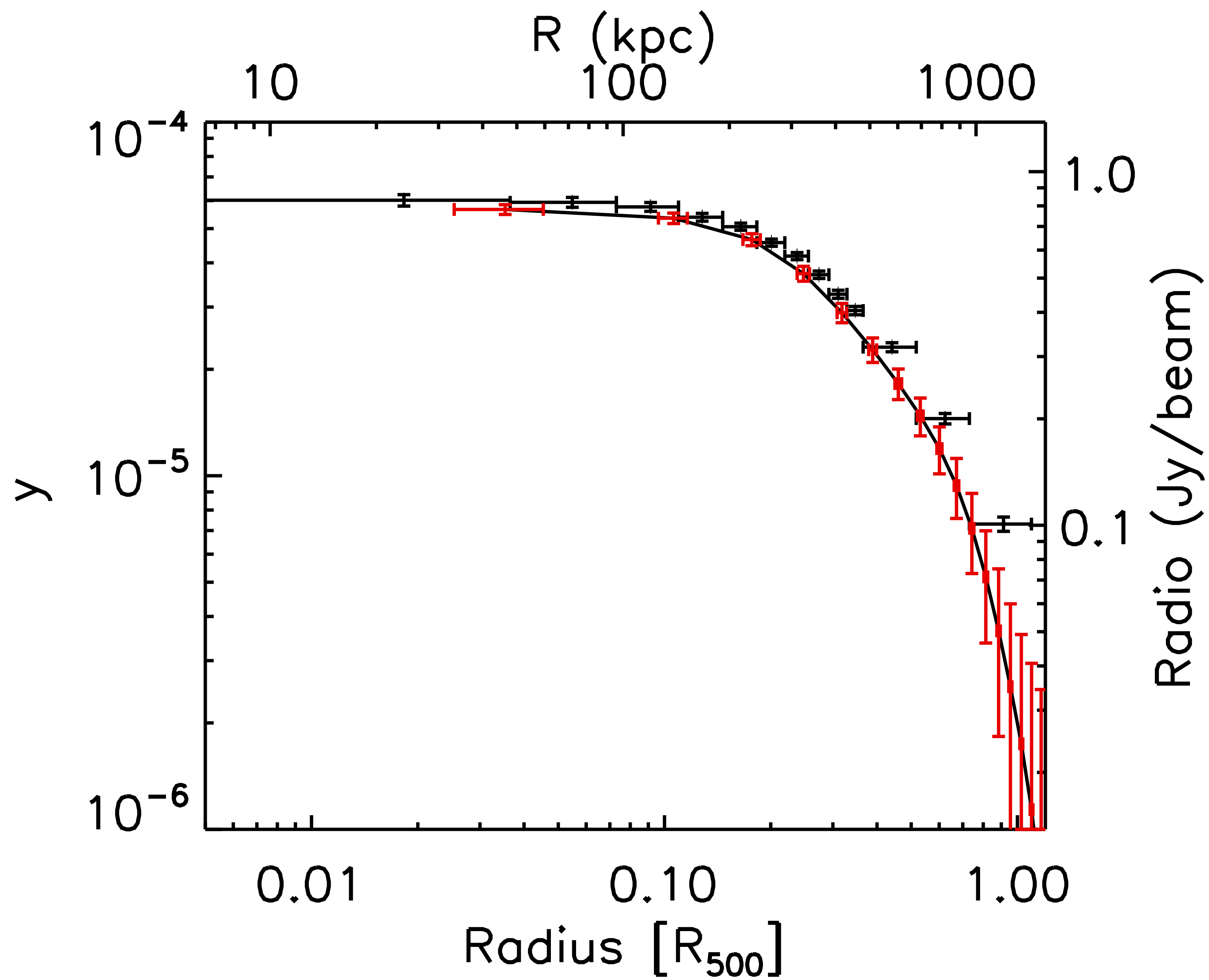


Fig. 10. Comparison of the y (black) and diffuse radio (red) global radio profiles in Coma. The radio profile has been convolved to 10 arcmin resolution to match the *Planck* FWHM and simply rescaled by the multiplication factor derived from the linear regression shown in Fig. 9.

Planck collaboration:
Ade et al. 2013

The S-Z effect and CMB fluctuations

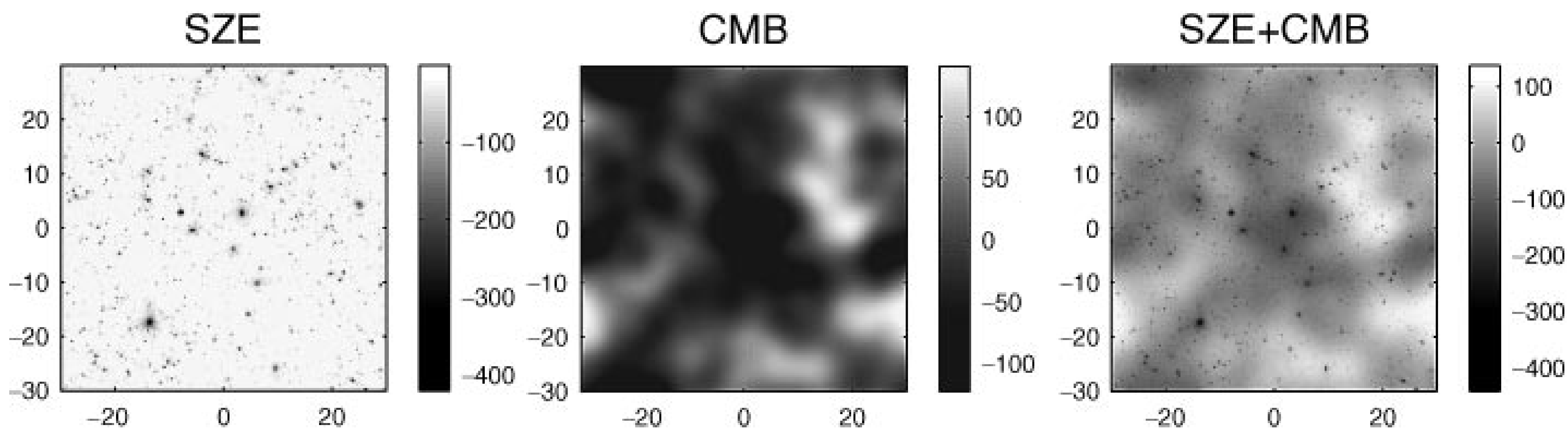
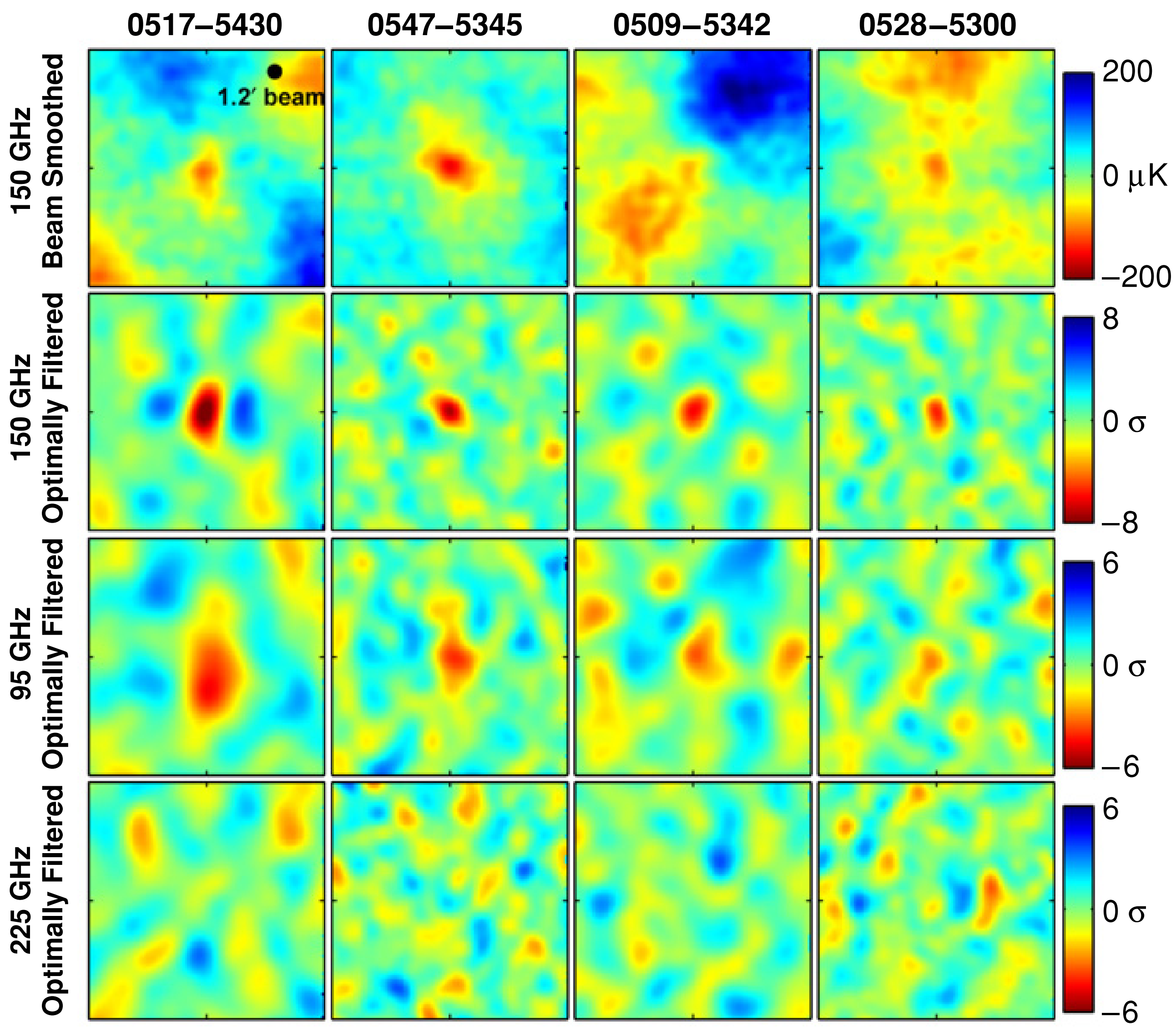
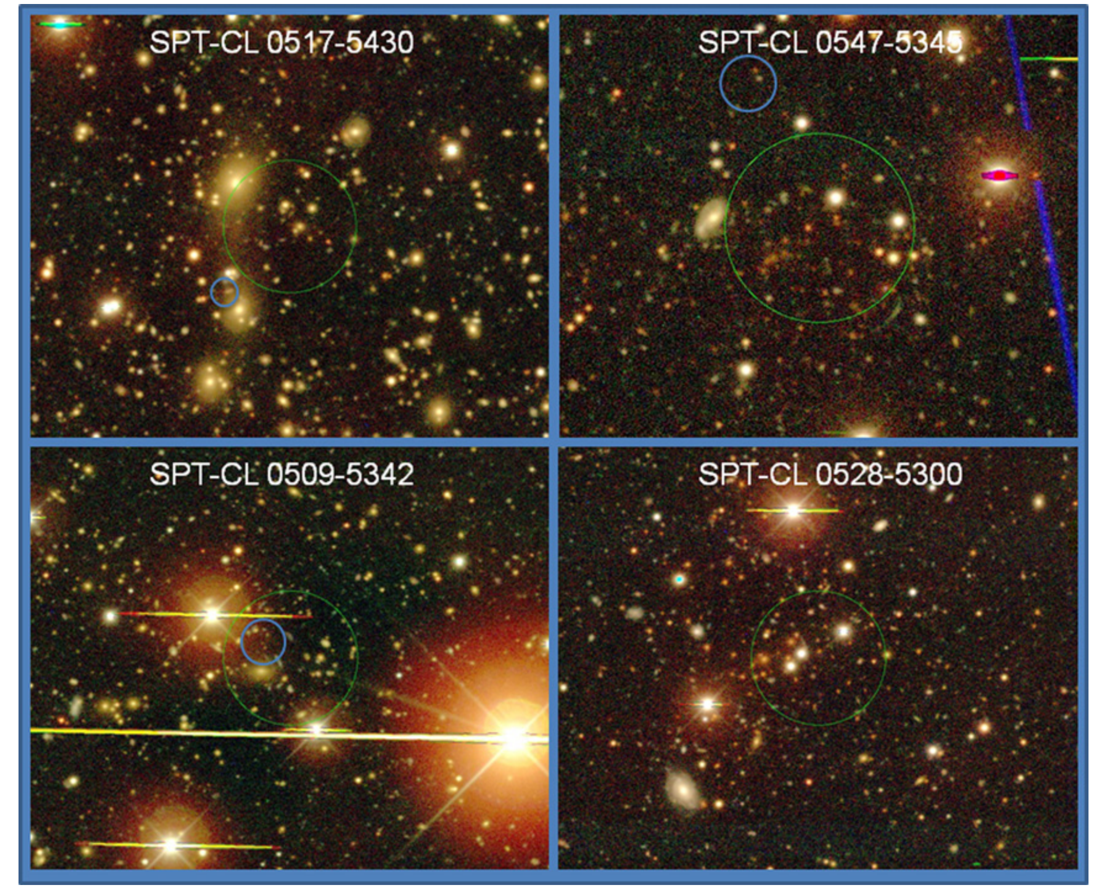


Figure 3 Illustration of the characteristic angular scales of primary CMB anisotropy and of the SZE. The images each cover one square degree and the gray scales are in μK. (*Left*) An image of the SZE from many galaxy clusters at 150 GHz (2 mm) from a state-of-the-art hydrodynamic simulation (Springel et al. 2001). The clusters appear point-like at this angular scale. (*Center*) A realization of CMB anisotropy for a ΛCDM cosmology. (*Right*) The combination of the CMB and SZE signals. Note, the SZE can be distinguished readily from primary CMB anisotropy, provided the observations have sufficient angular resolution.

Carlstrom et al. (2002)



Optical images

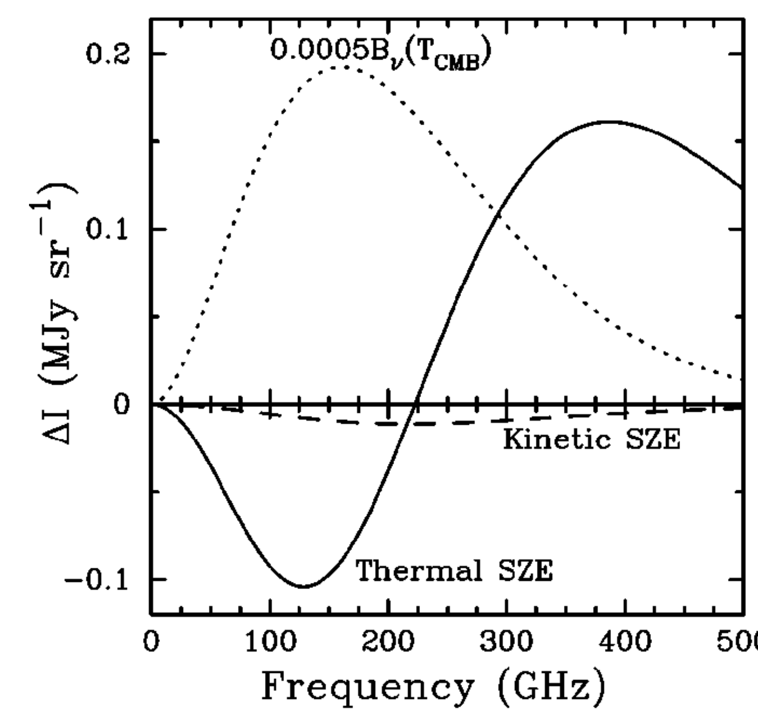


Redshifts z=0.35 - 0.9

Galaxy clusters discovered with SPT (Staniszewski et al. 2009)

Note:

- No signal is seen at 225 GHz
- Strongest signal at ~150 GHz



The S-Z effect as a distance indicator

S-Z effect + assume spherical geometry:

$$y \propto N_e R = N_e D_A \theta$$

for (diameter) distance D_A and angular size θ

X-Ray intensity:

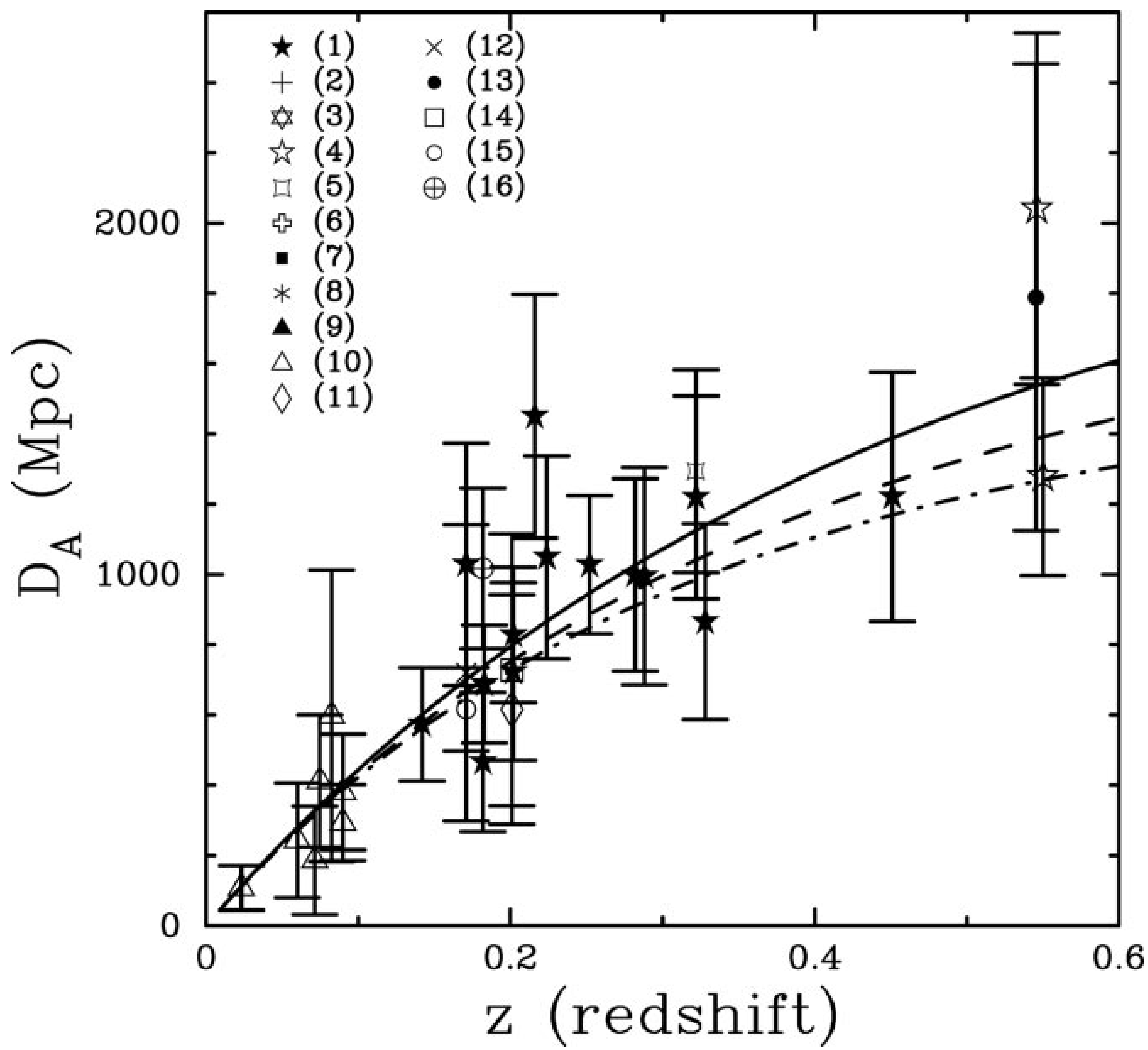
$$I_X \propto N_e^2 R = N_e^2 D_A \theta$$

Eliminate N_e:

$$\frac{I_X}{D_A \theta} \propto \frac{y^2}{D_A^2 \theta^2}$$

$$\boxed{D_A \propto \frac{y^2}{\theta I_X}}$$

S-Z distances vs redshift



Carlstrom et al. (2002)

S-Z distances independent of other techniques

Best fit:
$H_0 = 60 \pm 3$ km s^{-1} Mpc^{-1}
(but dominated by ~30% systematic uncertainties)