Observational Cosmology

Lectures on the topic:

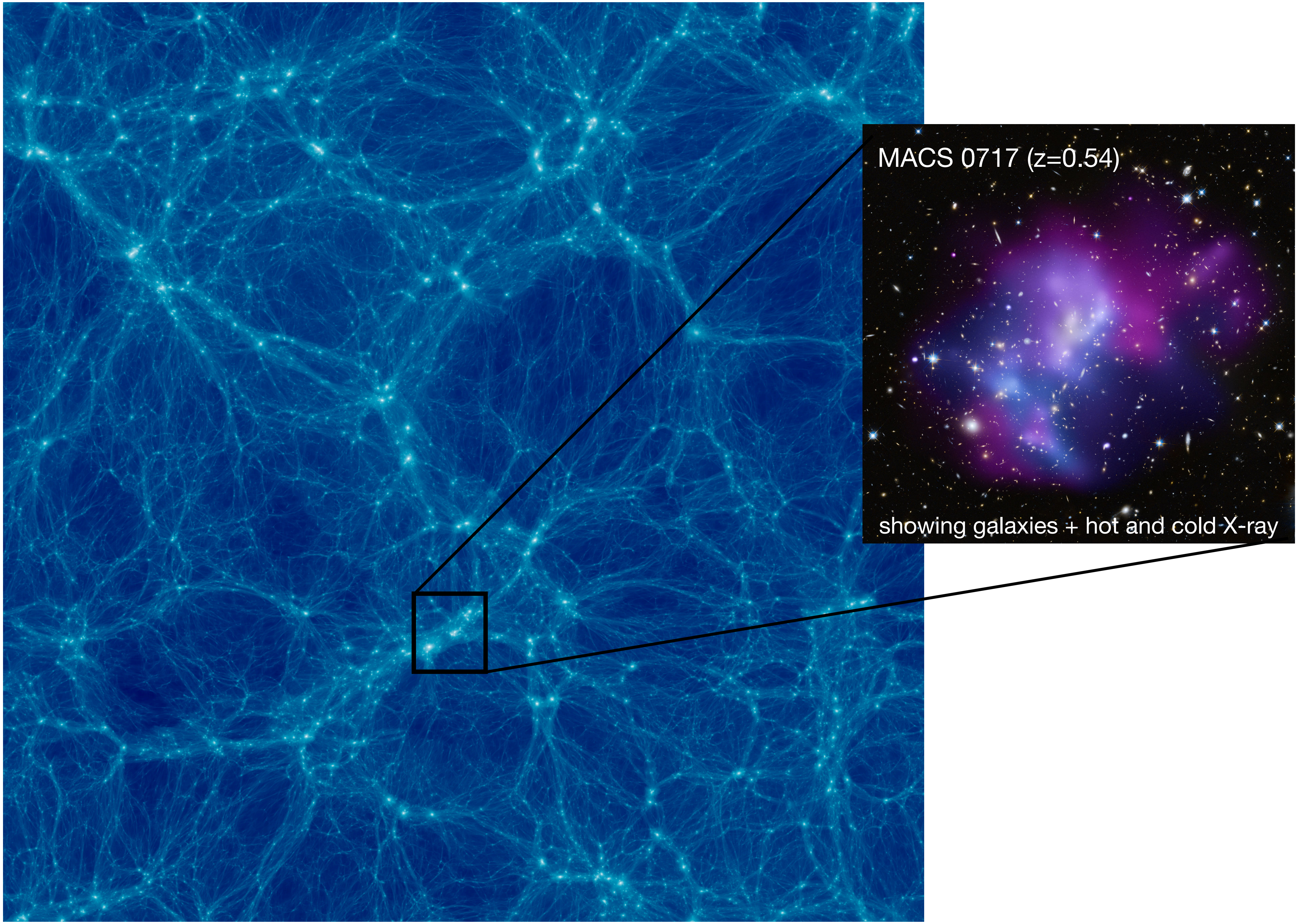
Cosmology with galaxy clusters

Kaustuv Basu

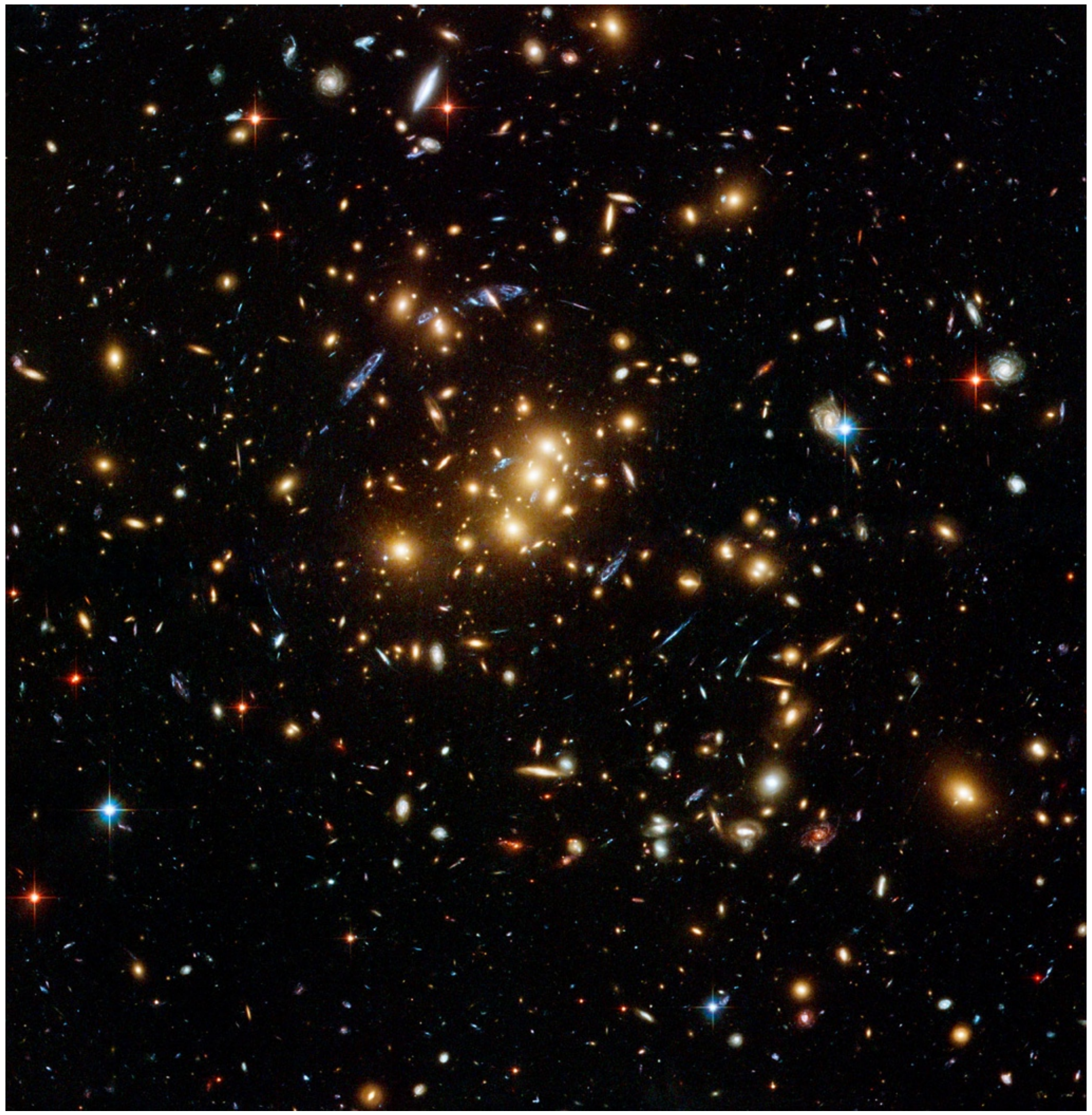
Course website:

https://www.astro.uni-bonn.de/~kbasu/ObsCosmo

What are galaxy clusters?



What are galaxy clusters?



Galaxy clusters are the most massive, collapsed structures in the universe. They contain 100s to 1000s of bright galaxies ($L > L_*$), a diffuse, ionized intra-cluster medium (10^{7-8} K) and dark matter.

Clusters are good cosmological probes, because they are massive – and "easy" to detect through multiple methods:

- X-ray emission
- Sunyaev-Zeldovich Effect
- Light from galaxies
- Gravitational lensing

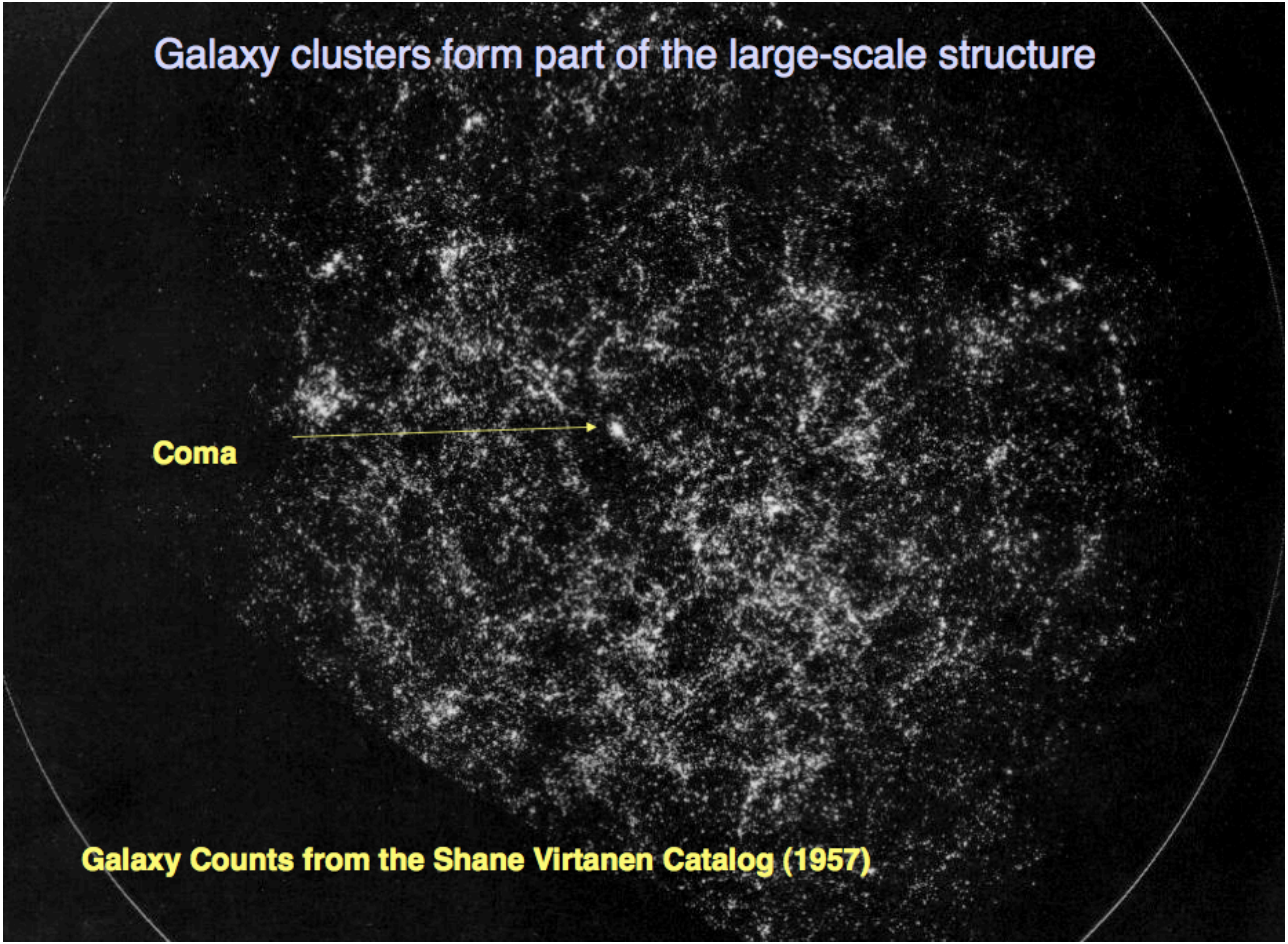
Galaxy cluster Superlatives
(apart from "largest virialized objects..")

• Galaxy Clusters mergers are the most energetic processes in the Universe since the Big Bang ($E \sim 10^{64}$ ergs)

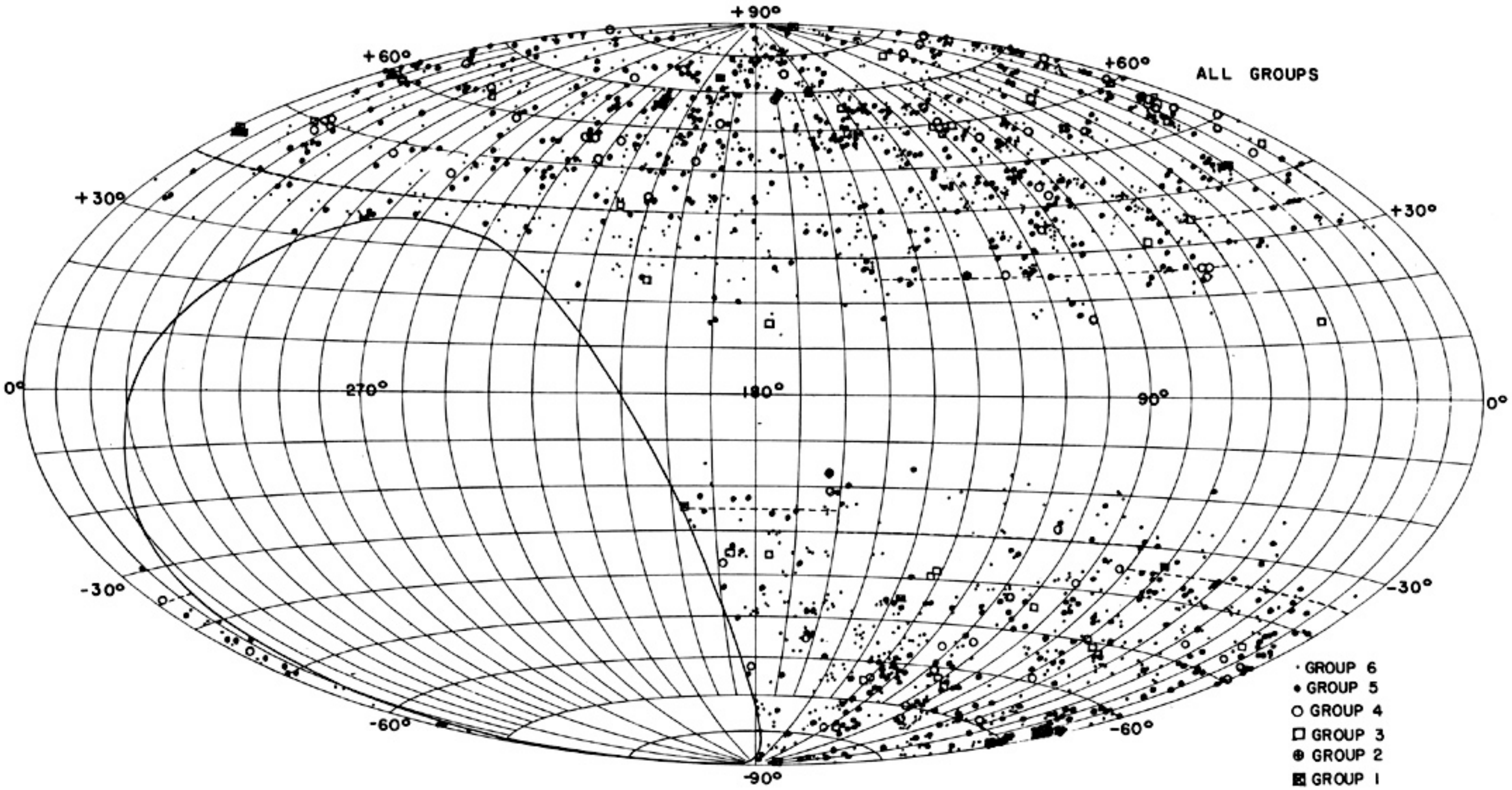
• The temperatures of the intra-cluster plasma in cluster of galaxies is up to 100 times higher than the fusion temperature of hydrogen in the interior of stars – it is most probably the hottest thermal plasma in the Universe today

• The large, compact mass aggregations cause the largest known gravitational angular light deflections (gravitational lensing effect)

• The large, hot mass of intra-cluster plasma causes the largest modification of the microwave background (in the line-of-sight to the cluster) by the so-called (Sunyaev-Zeldovich Effect)

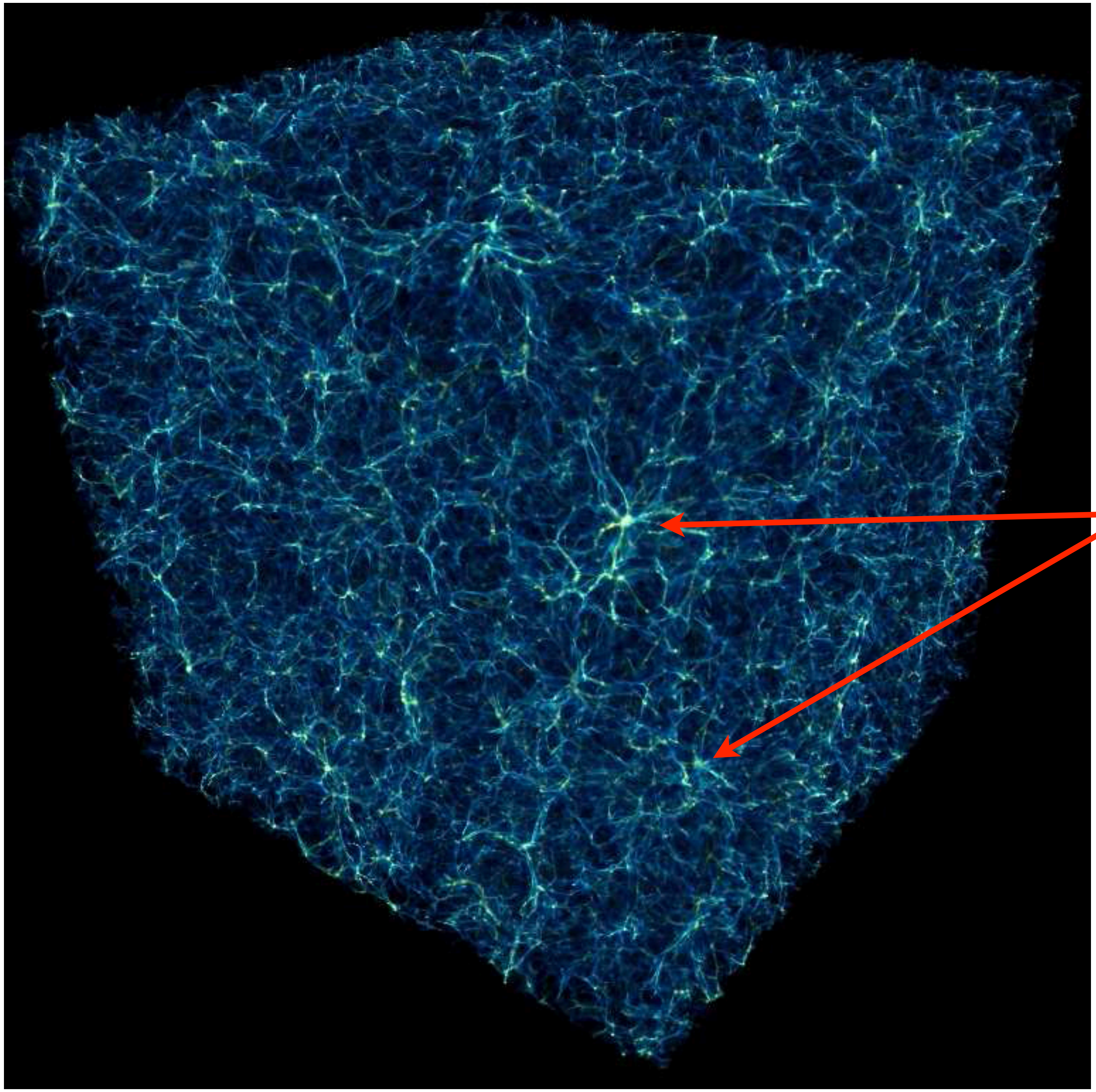

Galaxy clusters form part of the large-scale structure
Coma
Galaxy Counts from the Shane Virtanen Catalog (1957)

Abell catalog of clusters



George Abell (1927–83) compiles a database of 2712 rich clusters based on the visual inspection of red plates from the Palomar Sky Survey (part of his PhD thesis). The clusters were characterized by their richness, compactness, and distance from the Galactic plane.

Galaxy clusters in simulations



Millennium simulation (Springel et al. 2005): 700 Mpc comoving cube

Galaxy clusters: rare peaks in the density field, capturing non-Gaussian information

Volume density of clusters

Clusters are rare objects. For standard ΛCDM cosmology (Ω_m=0.3, Ω_Λ=0.7, h=0.7, σ_8=0.9), the space density of $>10^{14}$ $M_\odot$ halos is 7×10^{-5} Mpc^{-3}.

In the sky, typically one finds one massive galaxy cluster per ~10 sq. deg.

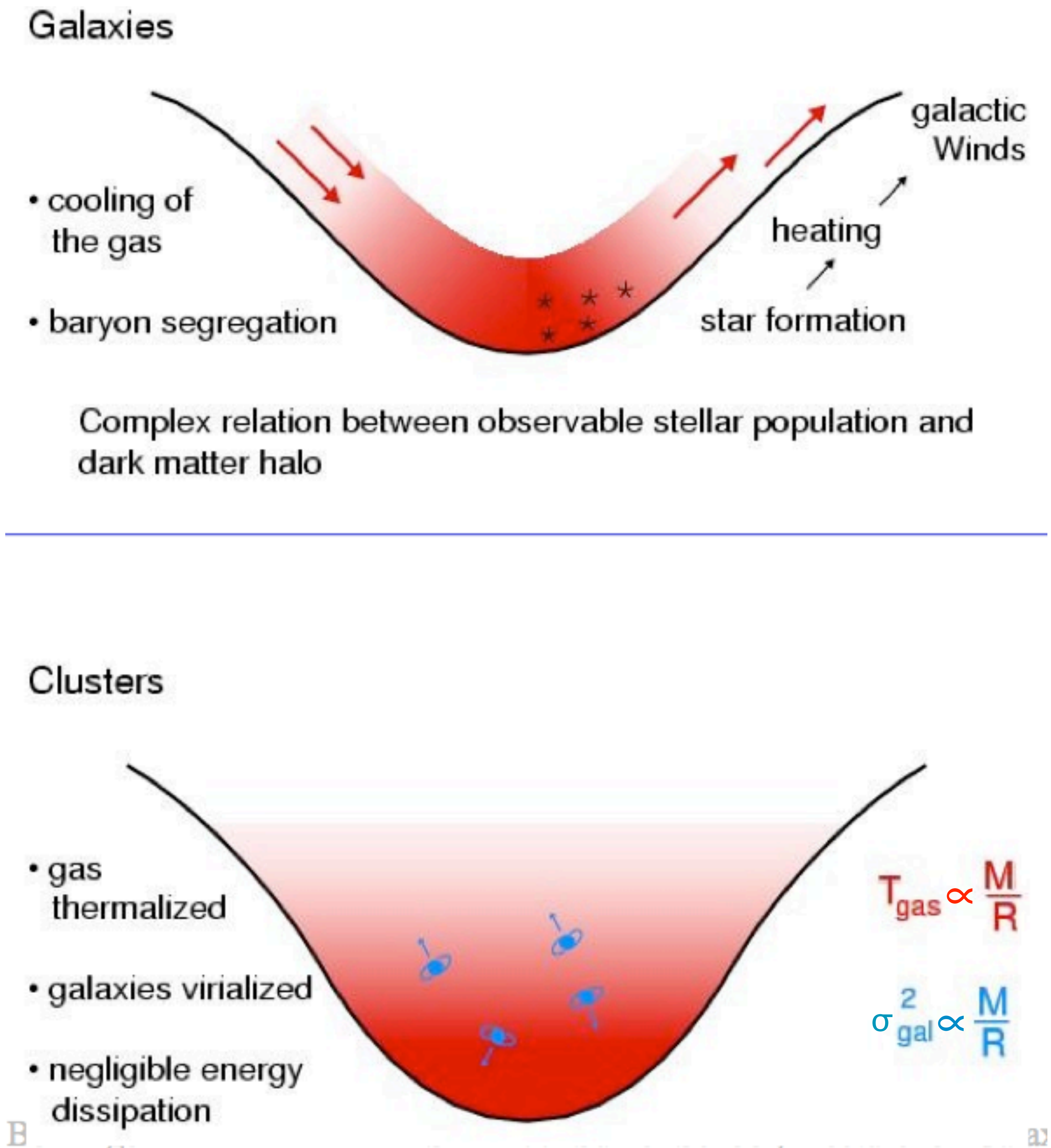
Galaxy clusters represent the end result of the density fluctuations involving comoving scales of ~10–20 Mpc.

This marks the transition between two distinct dynamical states:

On scales above ~10 Mpc, evolution of the universe is driven by gravity. This regime can be analyzed by analytical methods, or more accurately, with computer N-body simulations.

At scales below ~1 Mpc, the physics of baryons start to play an important role, and complicates the process.

Matter in galaxies & clusters

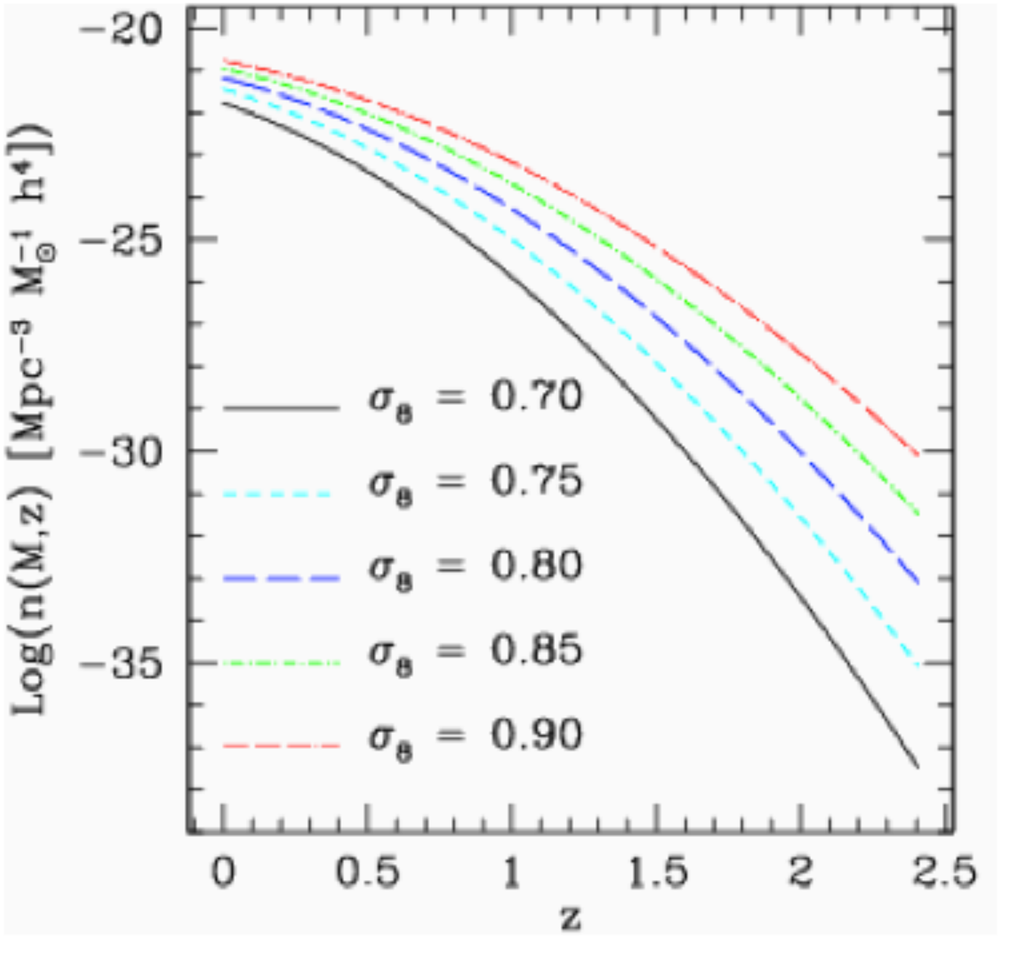


Counting clusters

Mass function describes number of clusters of mass M per unit comoving volume

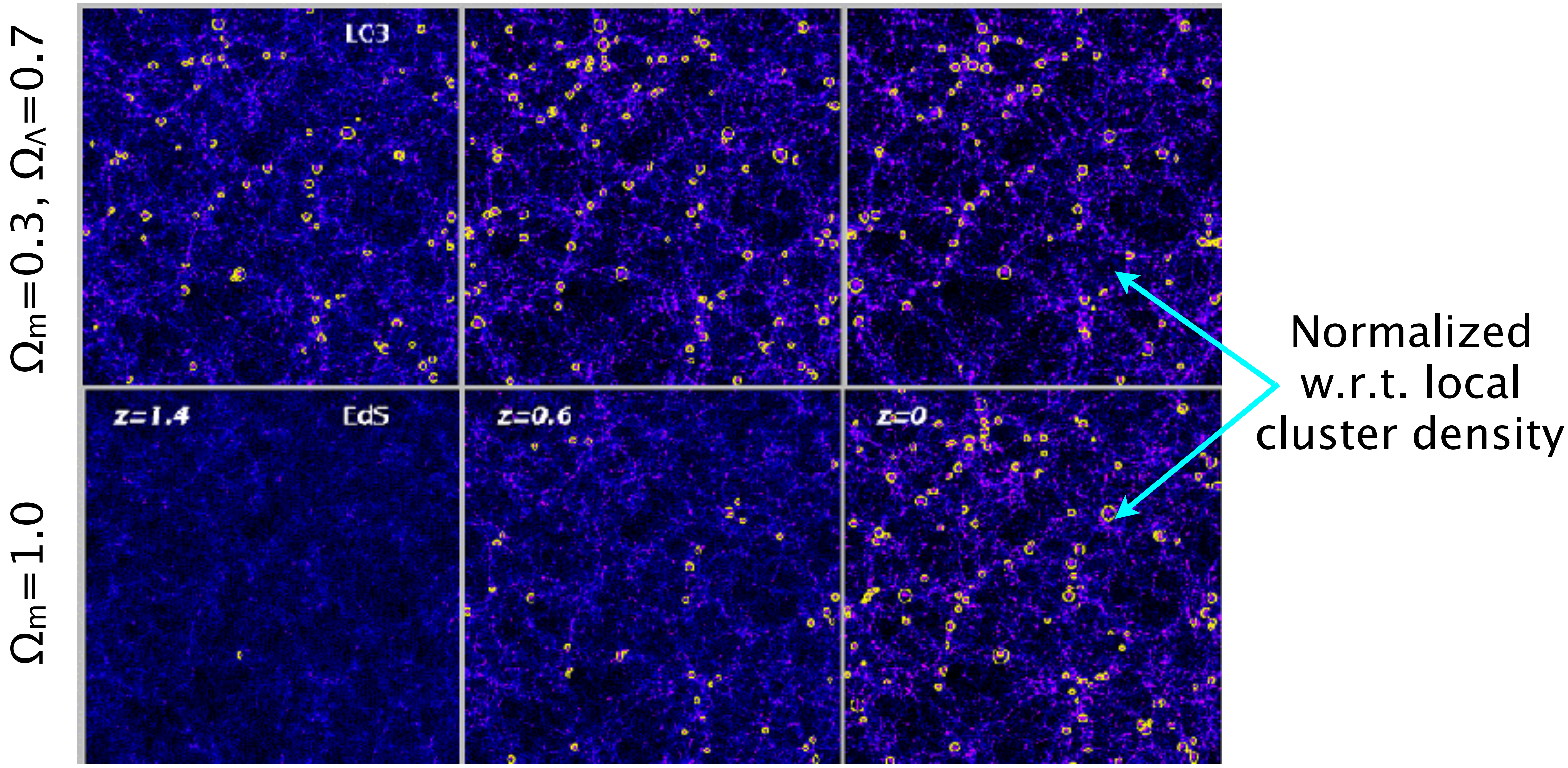
★ changing cosmological parameters affects:
  - shape of MF at z=0
  - evolution of MF with redshift

Obtain cosmological constraints by counting n(M) for clusters at different z



Fedeli et al, (2008, A&A, 486)

Structure growth & cluster count



Borgani & Guzzo, Nature, 2001

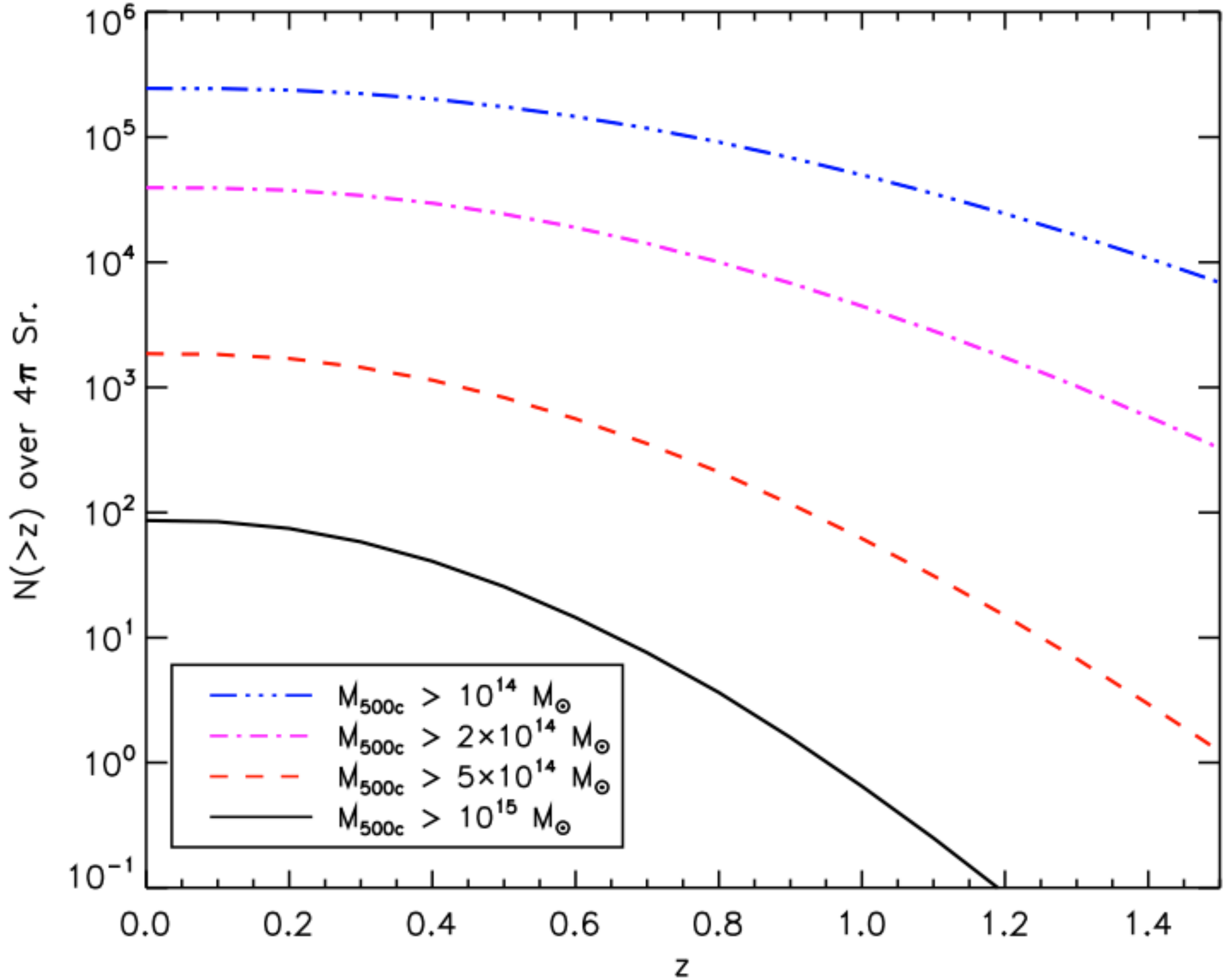
Example showing the role of galaxy clusters in tracing the cosmic evolution, in particular dark matter and dark energy contents.

Cosmology with galaxy clusters

- Growth of cosmic structure from cluster number counts (use of halo mass function)
- Measuring the large-scale angular clustering of clusters (clustering of clusters)
- Measuring distances using clusters as standard candles (joint X-ray/SZ effect fit)
- Using the gas mass fraction in clusters to measure the cosmic baryon density
- Measuring the large-scale velocity fields in the universe from kinematic SZE
- Constraints from SZ effect power spectrum
- and more..

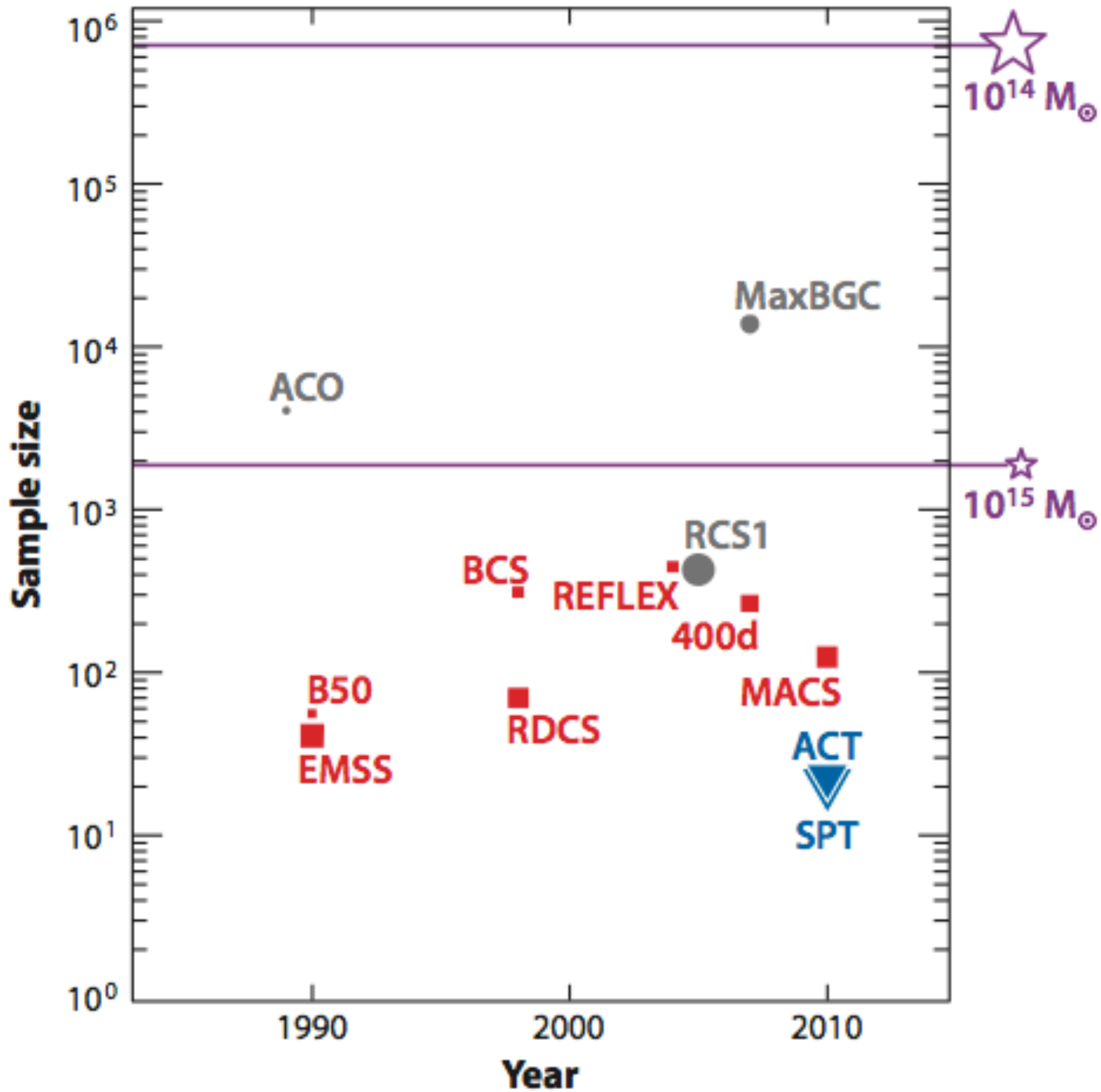
How many clusters?

Computed from the Tinker et al. (2008) mass function, standard ΛCDM cosmology

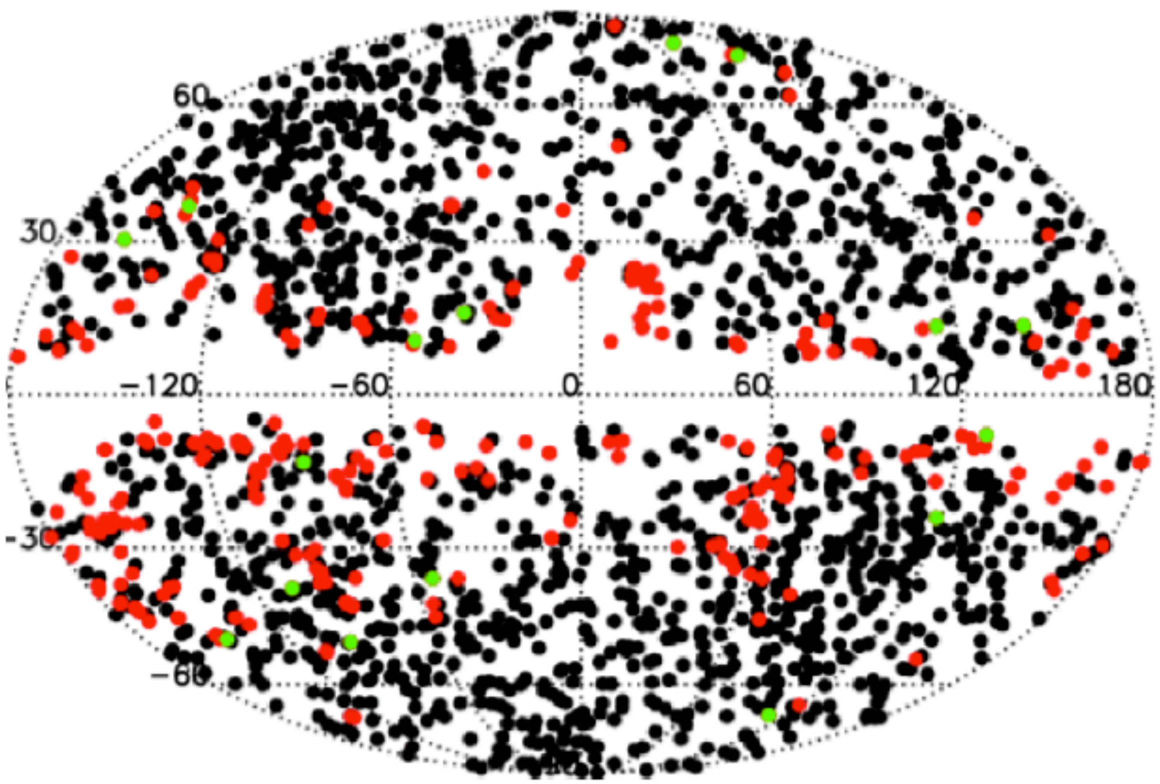


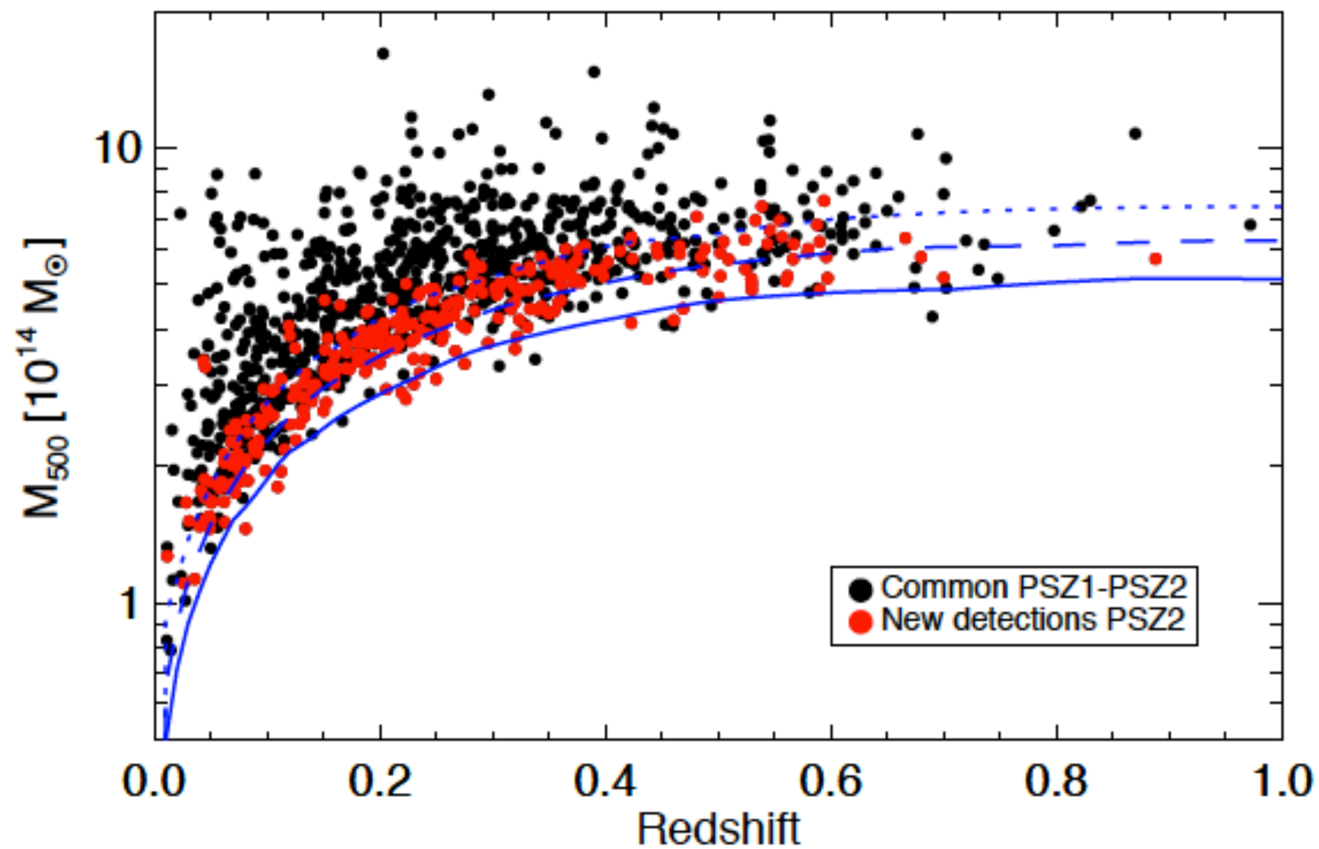
How many clusters?

From Allen, Evrard, Mantz (2011)



The Planck clusters

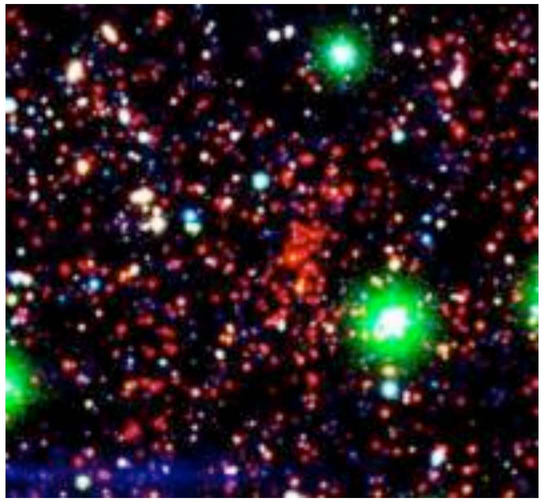
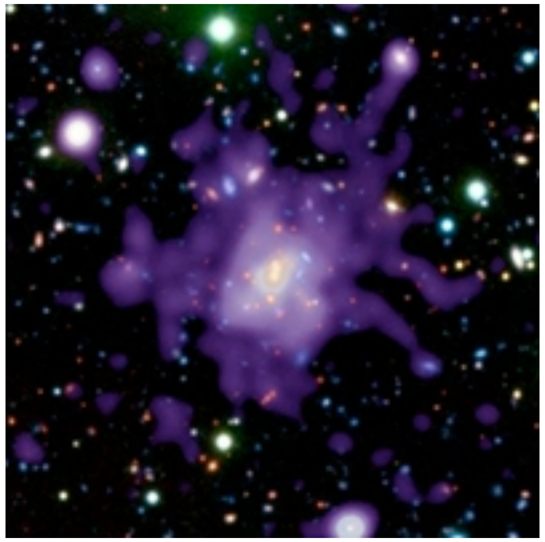
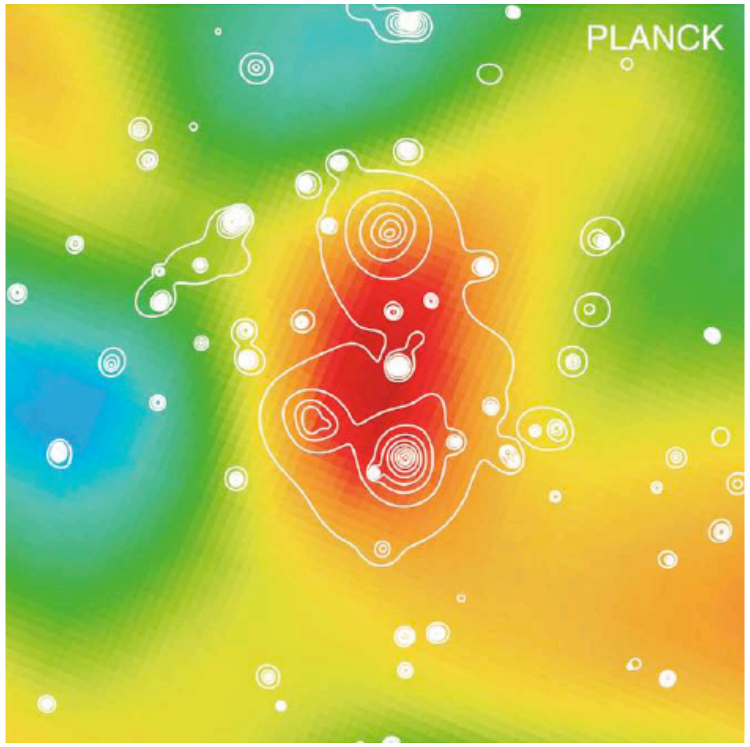


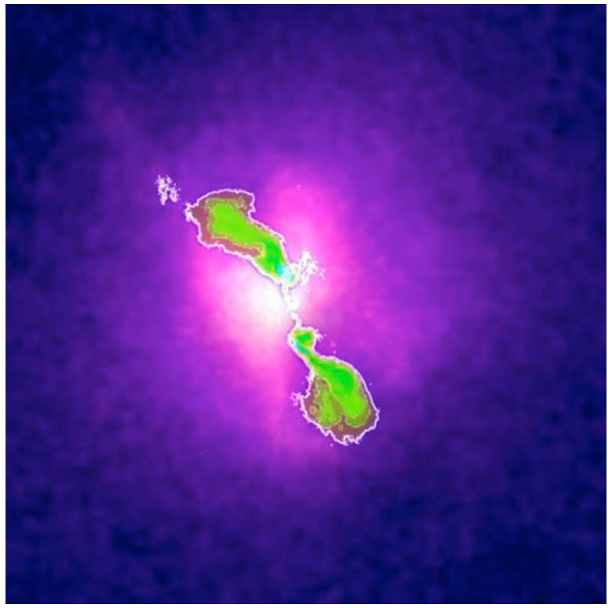


The ~1200 clusters from the Planck catalog in 2015 (PSZ-2). These might very well represent *all* the massive clusters in the universe (barring those behind our Galaxy).

Windows to galaxy clusters

- Optical: σ_v , N_{gal}
- X-ray: L_X, T_X
- Millimeter/ Submillimeter: Y_{SZ}
- Optical: Red sequence, lensing shear
- Radio: halo, relic, etc.

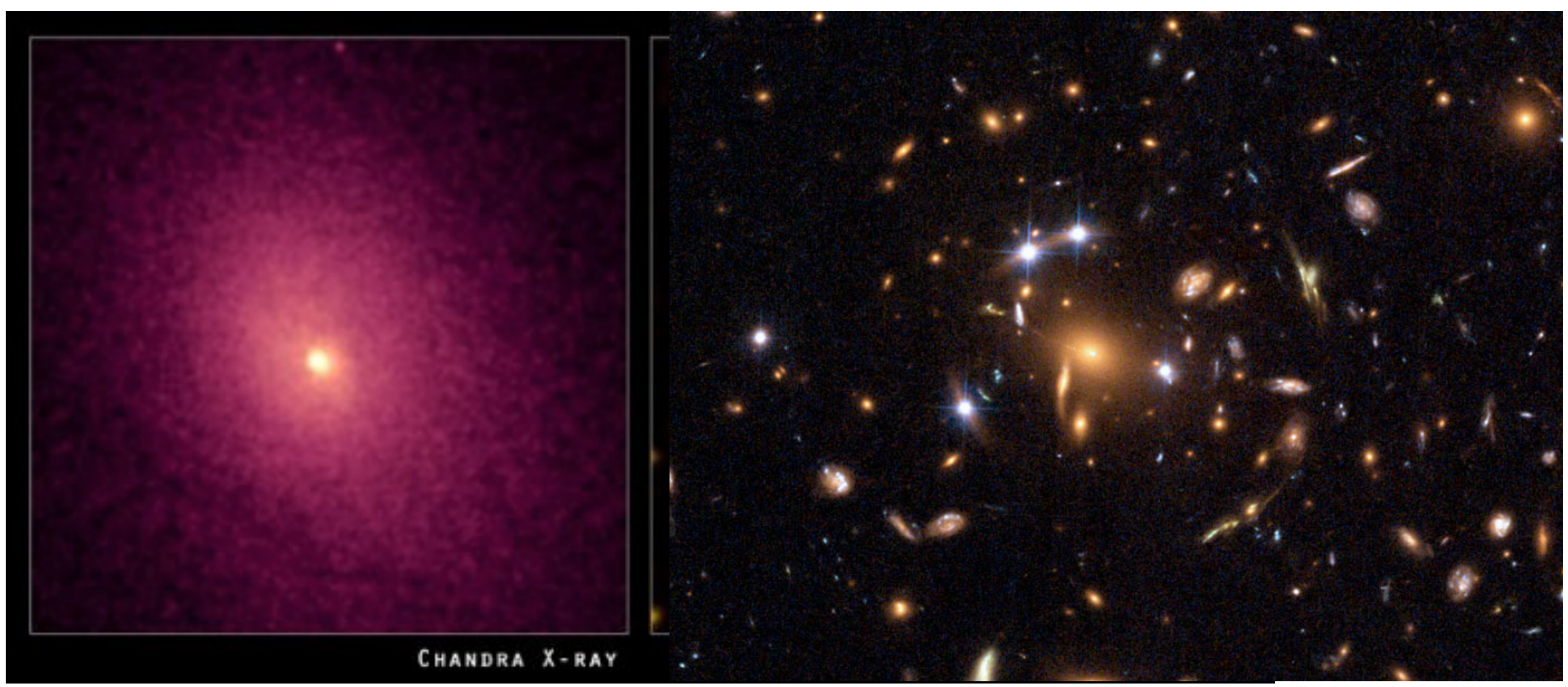






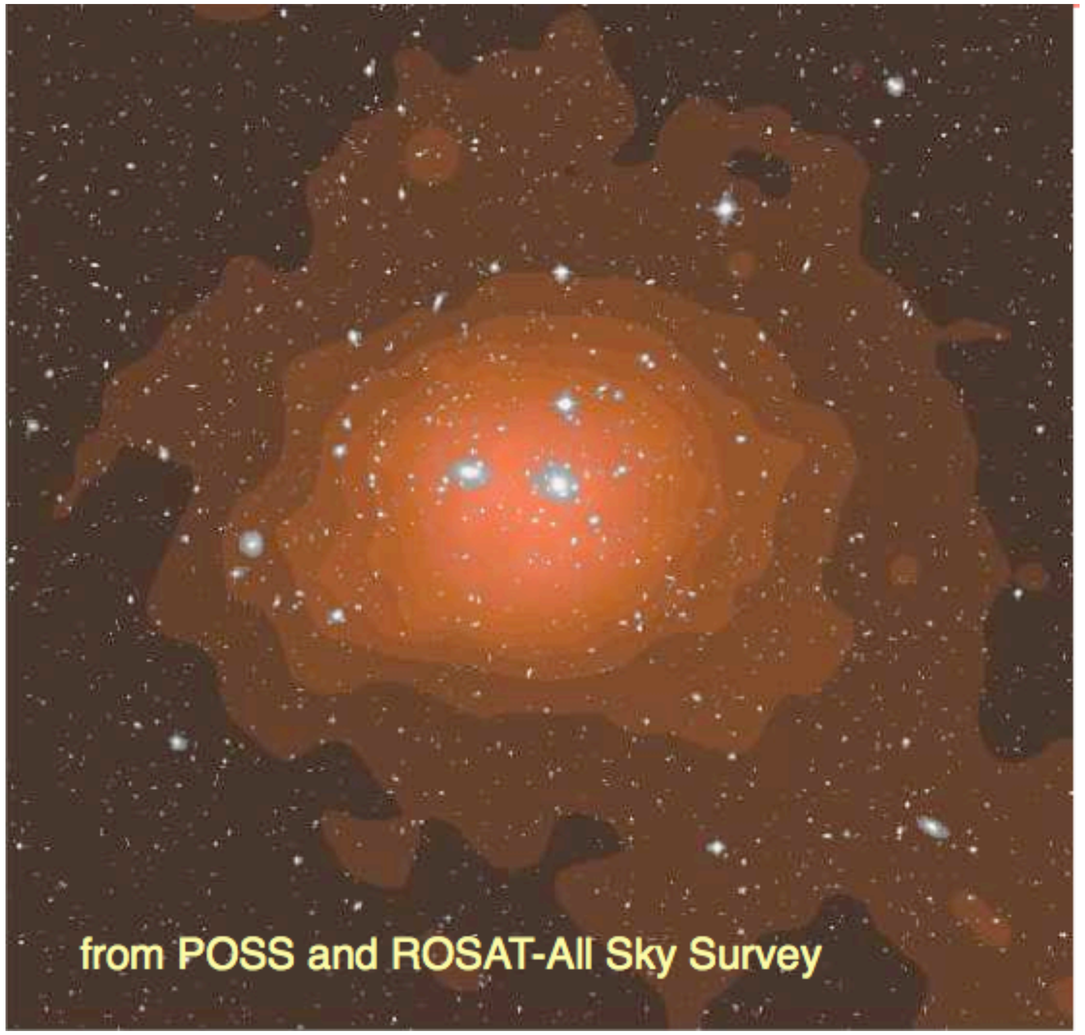
Mass budget in galaxy clusters

(The name “galaxy clusters” is a misnomer)

- ~2% mass in galaxies
- ~13% in the hot, ionized intra-cluster plasma (baryon that didn’t make it to the galaxies)
- ~85% dark matter



Example: Coma cluster



The composition of galaxy clusters:

- **78 – 87% = Dark Matter**
- **11 – 14% = hot gas**
- **2 - 6% = galaxies (in total)**

for $H_0 = 70$

White et al. (1993)

Table 1.1. *Mass Hierarchy in the Coma Cluster*

Component	$M(< 1.5\,h^{-1}$ Mpc) $(M_\odot)$	M/M_{vis}
Total[a]	$1.3 \pm 0.3 \times 10^{15}\ h_{70}^{-1}$	9.0 ± 2.5
Intracluster gas	$1.3 \pm 0.2 \times 10^{14}\ h_{70}^{-5/2}$	0.90 ± 0.02
Galaxies	$1.4 \pm 0.3 \times 10^{13}\ h_{70}^{-1}$	0.10 ± 0.03

[a]Estimated from gas dynamic simulations.

Virial theorem for mass

The virial theorem (for gravitational force) states that, for a stable, self-gravitating, spherical distribution of equal mass objects (stars, galaxies, etc), the total kinetic energy of the objects is equal to minus 1/2 times the total gravitational potential energy.

Suppose that we have a gravitationally bound system that consists of N individual objects (stars, galaxies, globular clusters, etc.) that have the same mass m and some average velocity v. The overall system has a mass $M_{tot} = Nm$ and a radius R_{tot}.

The kinetic energy of each object is K.E.(object) = $1/2\ m\ v^2$

while the kinetic energy of the total system is K.E.(system) = $1/2\ m\ N\ v^2 = 1/2\ M_{tot}\ v^2$

The virial theorem can then be used to find the total "virial mass" within any radius, if we can measure the individual K.E. of particles (stars, galaxies), i.e. their velocities.

$$P.E.(system) \simeq -\frac{1}{2}G\frac{N^2m^2}{R_{tot}} = -\frac{1}{2}G\frac{M_{tot}^2}{R_{tot}}$$

$$\frac{1}{2}M_{tot}v^2 = +\frac{1}{4}G\frac{M_{tot}^2}{R_{tot}}$$

$$M_{tot} \simeq 2\frac{R_{tot}v^2}{G}$$

This is the same formula as is used for galaxy rotation curves. Within any radius we get an estimate of the total enclosed mass by assuming virial equilibrium.

Side note: Virial theorem and hydrostatic equilibrium condition

The virial theorem is more restrictive than the hydrostatic equilibrium condition, because it assumes the self-gravitating system has reached equipartition between its kinetic energy and potential energy.

The application of hydrostatic equilibrium, on the other hand, only requires us to assume the net acceleration of the gas at any point (resulting from the sum of gravitational and hydrostatic forces) is zero.

$$\frac{dv}{dt} = -\frac{\nabla P}{\rho} + g + F$$

$$\frac{dv}{dt}; F \rightarrow 0 \quad (equilibrium)$$

$$-\frac{\nabla P}{\rho} \rightarrow -\frac{1}{\rho}\frac{\partial P}{\partial r} \quad (spherical\ symmetry)$$

$$\Rightarrow \frac{\partial P}{\partial r} = -\frac{Gm\rho}{r^2}$$

The virial theorem is then derived from the HE equation under suitable boundary conditions.

Discovery of Dark Matter

Fritz Zwicky (1898 - 1974)

Fritz Zwicky noted in 1933 that outlying galaxies in Coma cluster moving much faster than mass calculated for the visible galaxies would indicate

Virial Theorem: $2\,\langle T \rangle = -\,\langle V \rangle$

$$\mathrm{KE}_{\mathrm{avg}} = -\frac{1}{2}\ \mathrm{GPE}_{\mathrm{avg}}$$

$\frac{1}{2}m(3\sigma^2)$ → $\mathrm{KE}_{\mathrm{avg}}$; $G\frac{M_{tot}(r)m}{r}$ → $\mathrm{GPE}_{\mathrm{avg}}$

$$M \sim \frac{3R\sigma_v^2}{G} = 10^{15}\,h^{-1}\,\mathrm{Mpc}\left(\frac{R}{1.5\,h^{-1}\,\mathrm{Mpc}}\right)\left(\frac{\sigma_v}{1000\,\mathrm{km\,s^{-1}}}\right)^2$$

Discovery of Dark Matter

Fritz Zwicky (1898 - 1974)

F. Zwicky, Astrophysical Journal, vol. 86, p.217 (1937)

$$\mathscr{M} > 9 \times 10^{46}\text{gr} . \quad (35)$$

The Coma cluster contains about one thousand nebulae. The average mass of one of these nebulae is therefore

$$\overline{M} > 9 \times 10^{43}\ \text{gr} = 4.5 \times 10^{10}\ M_\odot . \quad (36)$$

Inasmuch as we have introduced at every step of our argument inequalities which tend to depress the final value of the mass $\mathscr{M}$, the foregoing value (36) should be considered as the lowest estimate for the average mass of nebulae in the Coma cluster. This result is somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about 8.5×10^7 suns. According

The mass of a self-gravitating system in equilibrium:

$$M(<R) = R\, v^2/G$$

This assumes velocities in equilibrium condition. But two-body relaxation process with galaxies is extremely slow. How do galaxy clusters (and also, galaxies containing stars which are also collisionless) attain equilibrium?

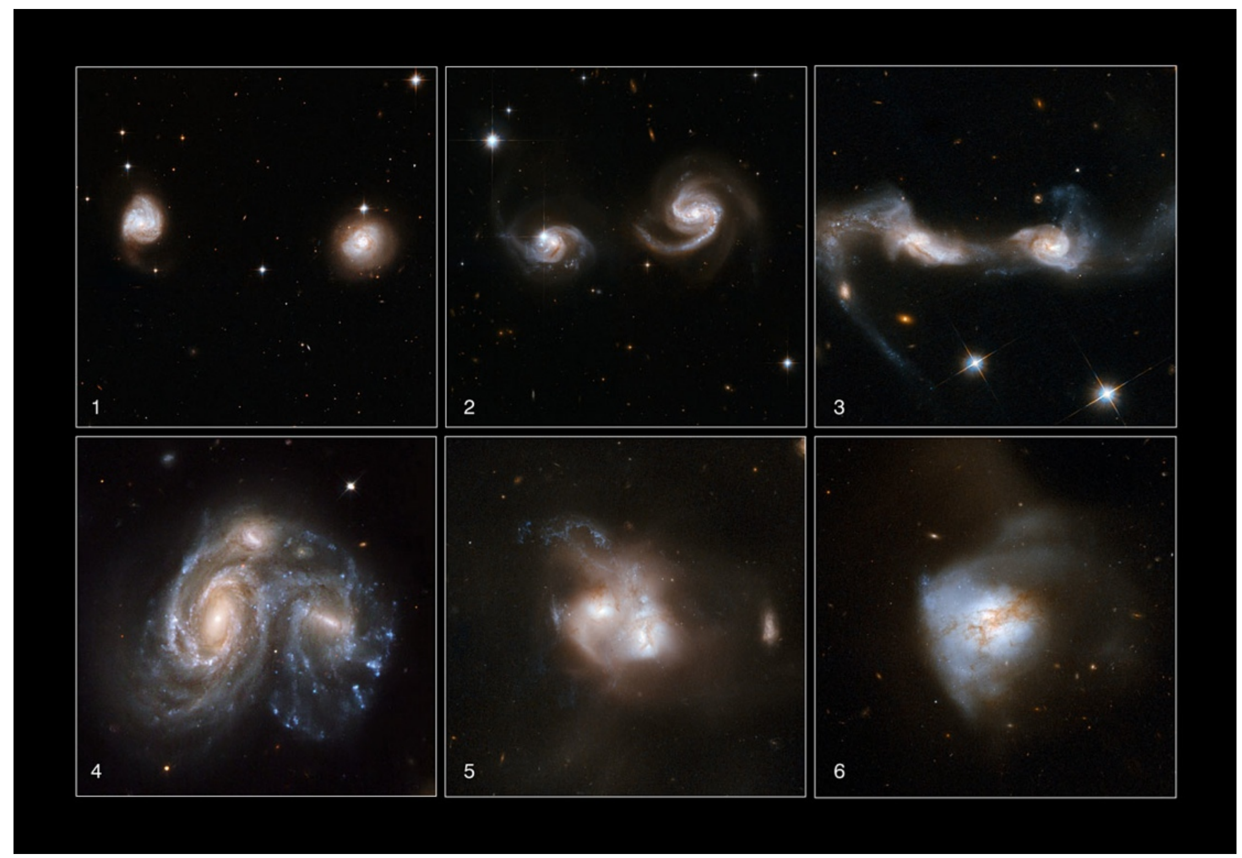
Violent relaxation

The thermalization of the molecules e.g. in this lecture room is achieved by two-body collisions moderated by short range forces. For stars in galaxies and galaxies, and Dark Matter particles in clusters of galaxies, we have to deal with long range forces. Here calculations show that two-body interactions are very ineffective. The thermalization of stars in galaxies would take many Hubble times.

How do equilibrium configurations form even when relaxation is so slow ?

Answer: "Violent Relaxation" - mixing of phase space in the strong fluctuating gravitational potential when the cluster forms (Lynden-Bell, 1967) - the fine grained phase space density is preserved but separated, so the coarse grained phase space density is uniform.

This is the main mechanism to re-distribute particles's energy in a collisionless system.



arXiv: astro-ph/9602021

Violent relaxation

Difference of two-body and violent relaxation:

Two-body : (collisional) $$v^2 \propto \frac{kT}{m} \Rightarrow v \propto \sqrt{m}$$

Violent relaxation : v independent of m (m mass of particle)

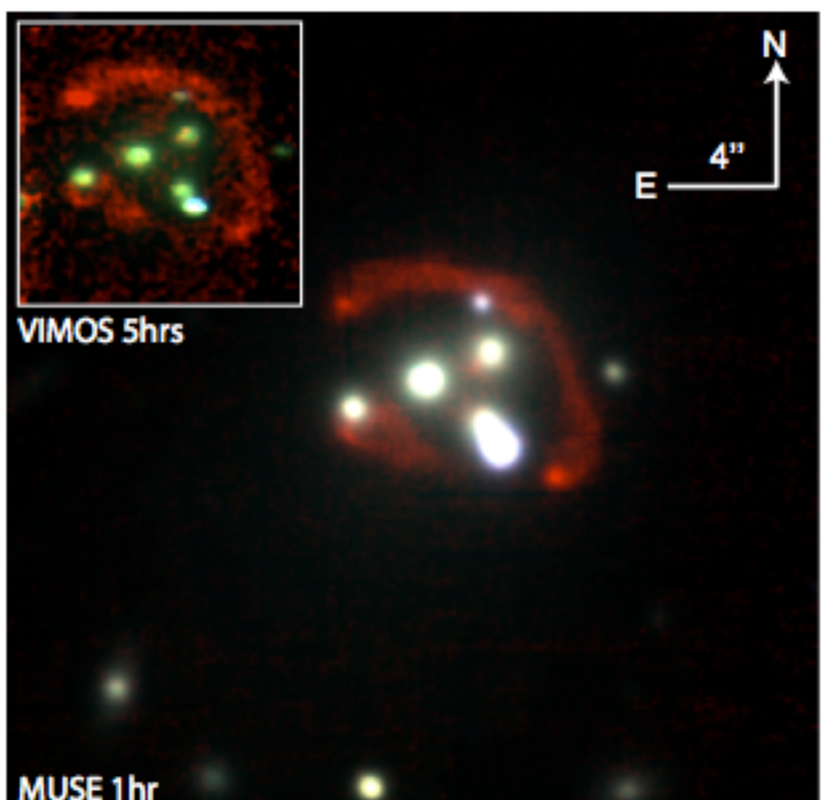
Toward the late stages of the merger the shape of the gravitational potential begins changing so quickly that galaxy orbits are greatly affected, and lose any memory of their previous orbit.

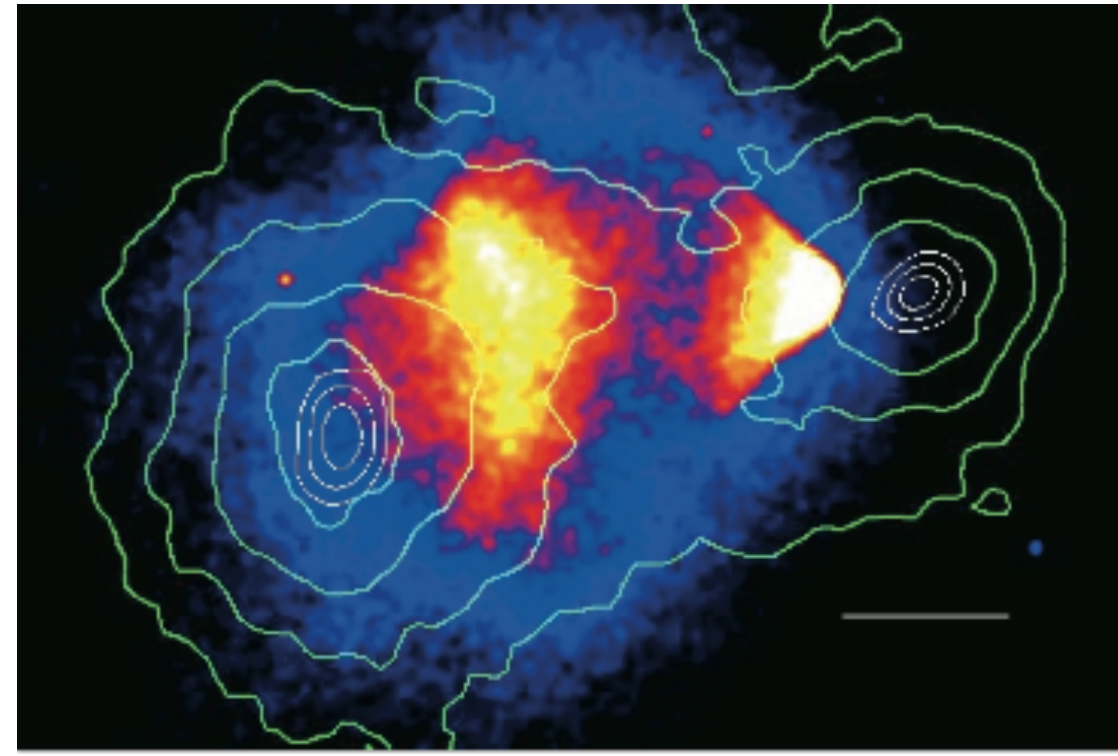
No velocity segregation in clusters

TABLE IV. Velocity dispersion vs magnitude.

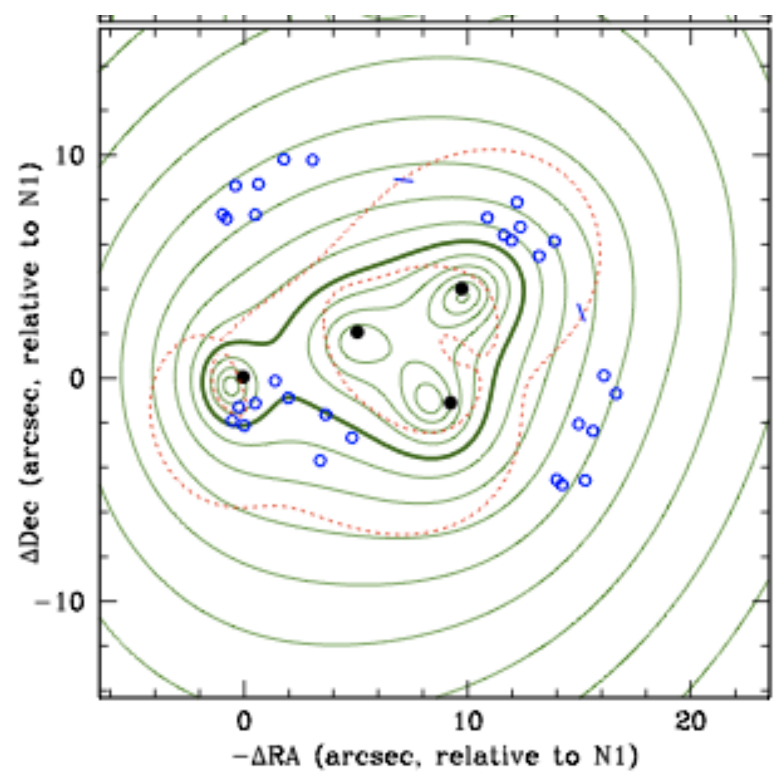
$(m_1 < m \leqslant m_2,\ r < 30')$			
m_1	m_2	n	σ
	$\leqslant 15.0$	21	1085
15.0	15.5	31	1081
15.5	16.0	37	984
16.0	16.5	24	1176
$16.5 \leqslant$		32	1250

Dark matter with galaxy clusters





Clowe et al. 2006



Abell 3827
(Massey et al. 2015)

Questions?