Observational Cosmology

(C. Porciani / K. Basu)

Lectures on the topic:

Cosmology with galaxy clusters

Course website:

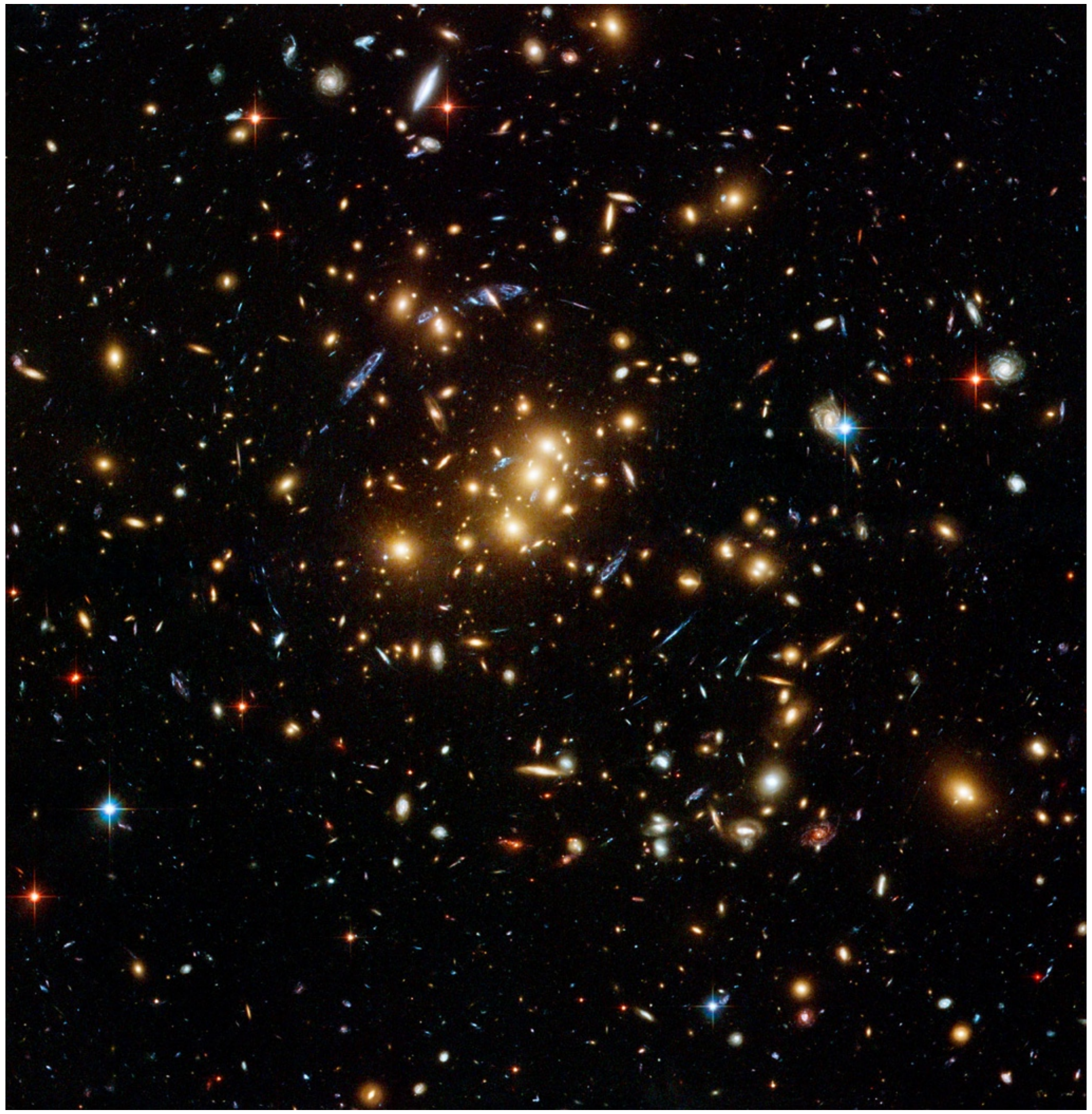
http://www.astro.uni-bonn.de/~kbasu/ObsCosmo

Outline of the lectures

- **Galaxy clusters as tools for cosmology**
- **The crossroad of** *cosmology* **and** *astrophysics*
- **Observation and mass modeling of clusters**
- **The X-ray and Sunyaev-Zel'dovich observables**
- **Optical and radio observation of galaxy clusters**
- **Current and future cluster surveys**

KITP, Santa Barbara, 2011

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-Zel'dovich Effect
- Light from galaxies
- Gravitational lensing

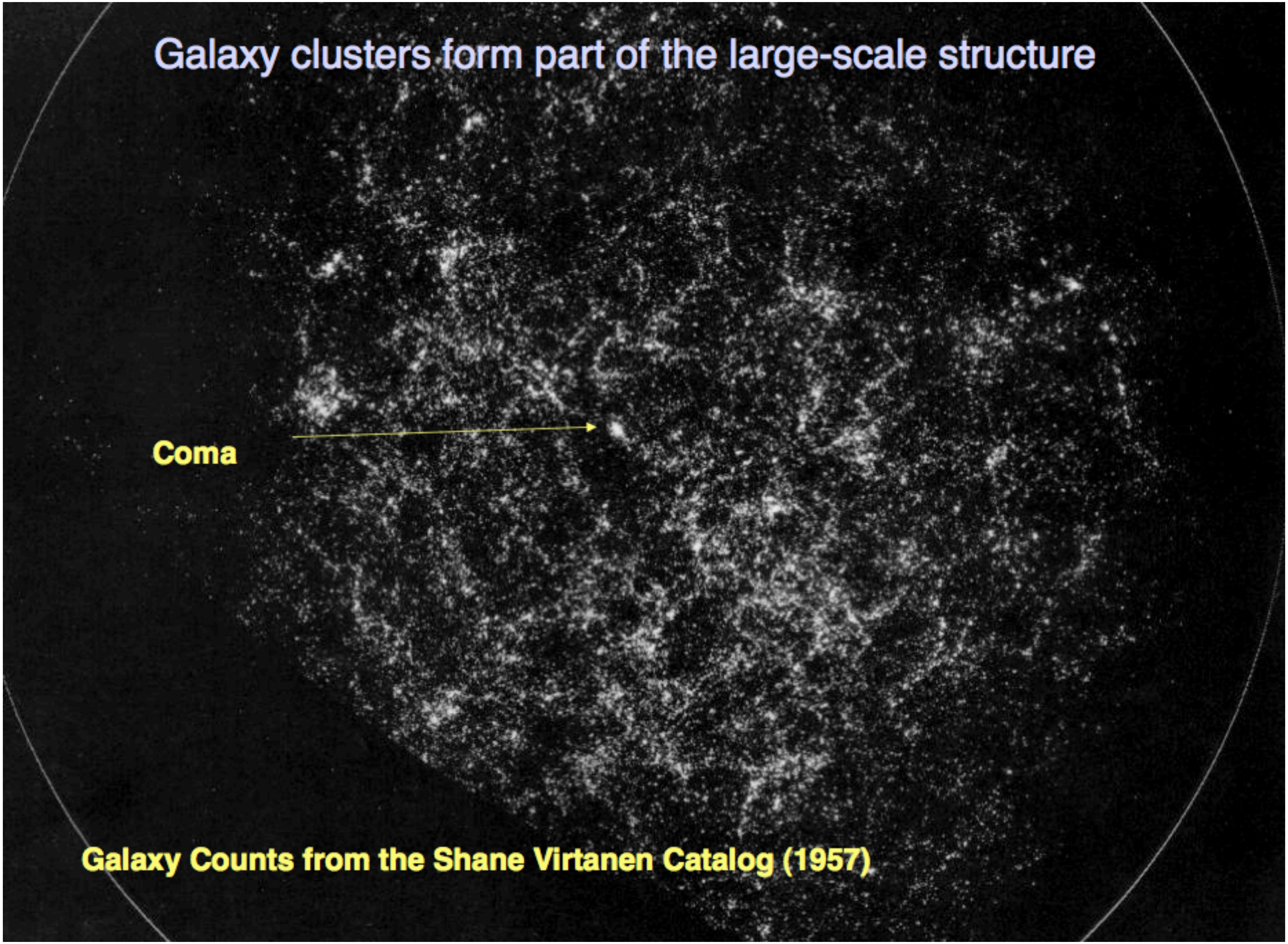
Galaxy cluster Superlatives
(apart from the “largest virialized object..”)

- Galaxy Clusters mergers are the most energetic processes in the Universe (since the Big Bang)

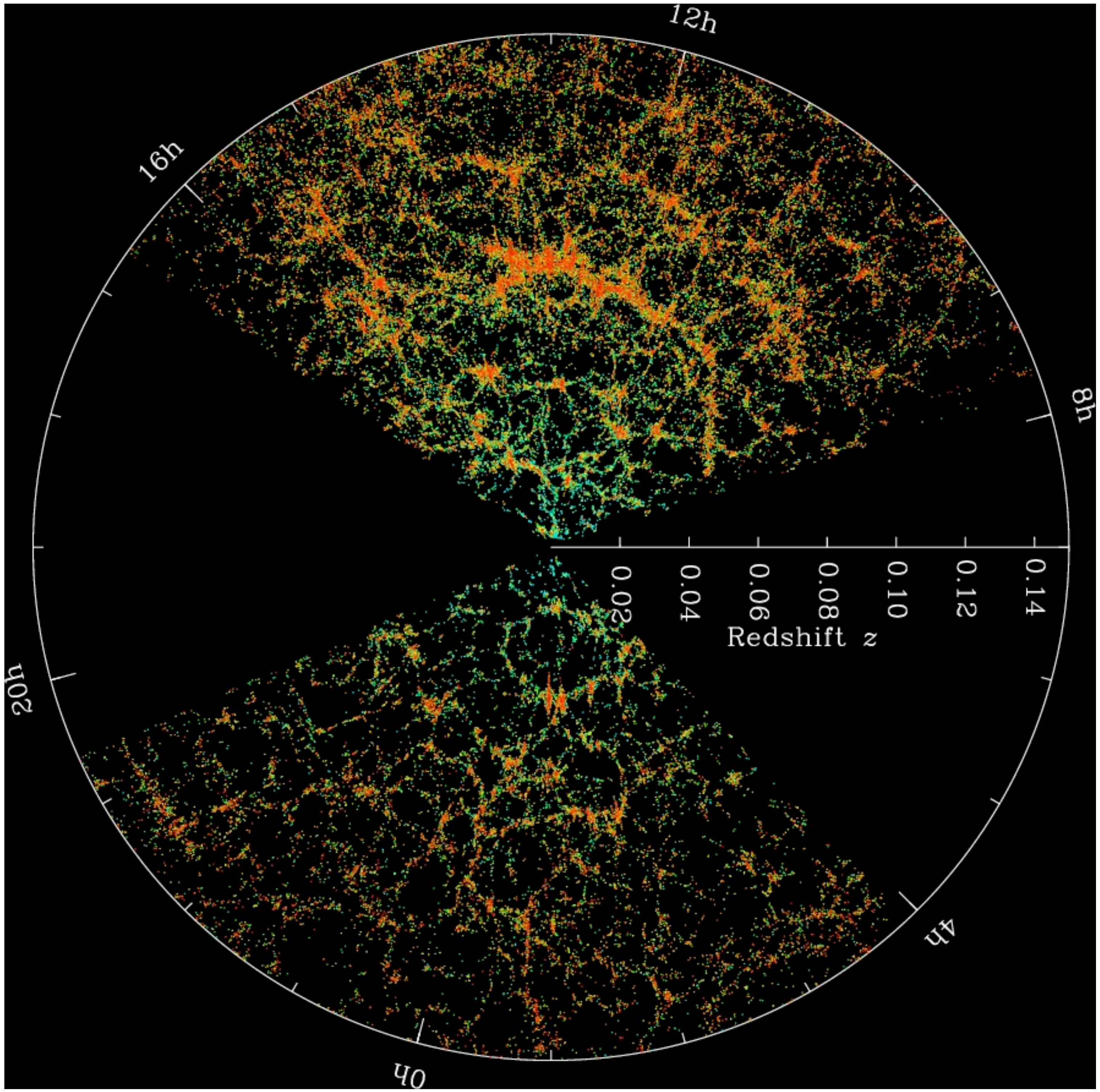
- The temperatures of the intra-cluster plasma in cluster of galaxies is up to 100 times higher than the fusion temperature of hydrogen in the interior of stars - it is most probably the hottest thermal plasma in the Universe today

- 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-Zel’dovich Effect)

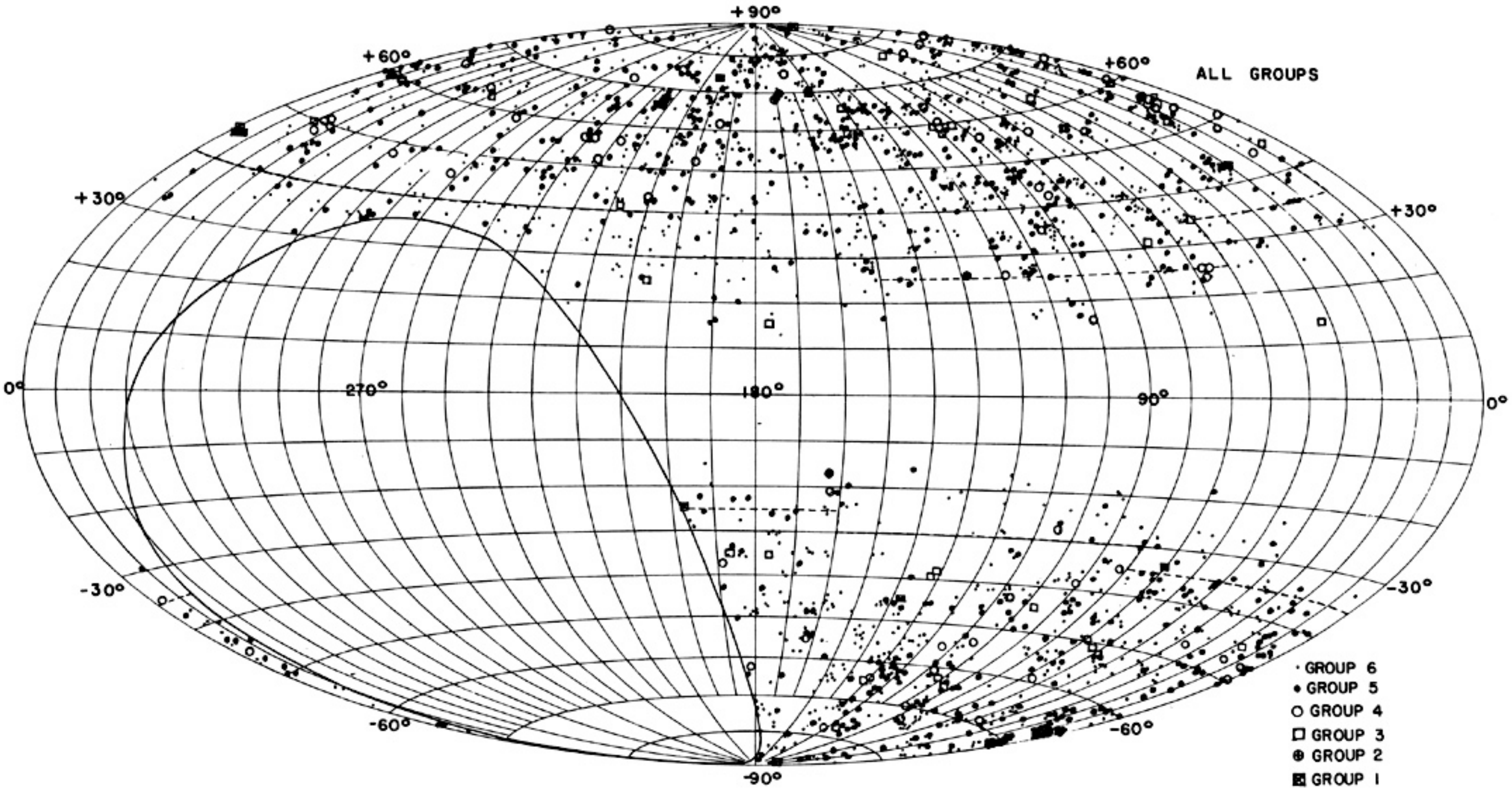

Galaxy clusters form part of the large-scale structure
Coma
Galaxy Counts from the Shane Virtanen Catalog (1957)

Galaxy clusters from optical surveys



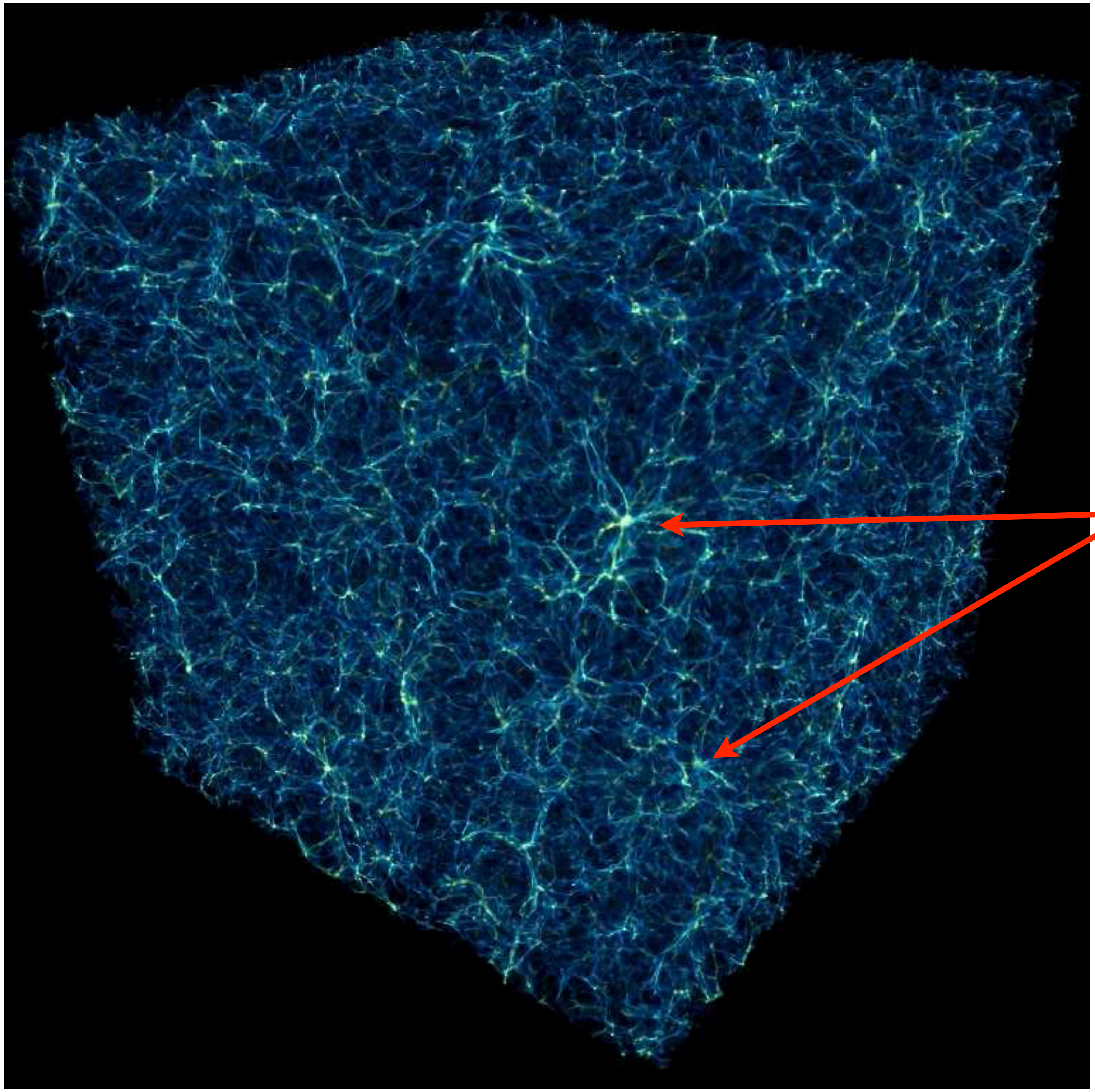
(c) SDSS collaboration

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



700 Mpc comoving cube

Galaxy clusters: rare peaks in the density field

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}.

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.

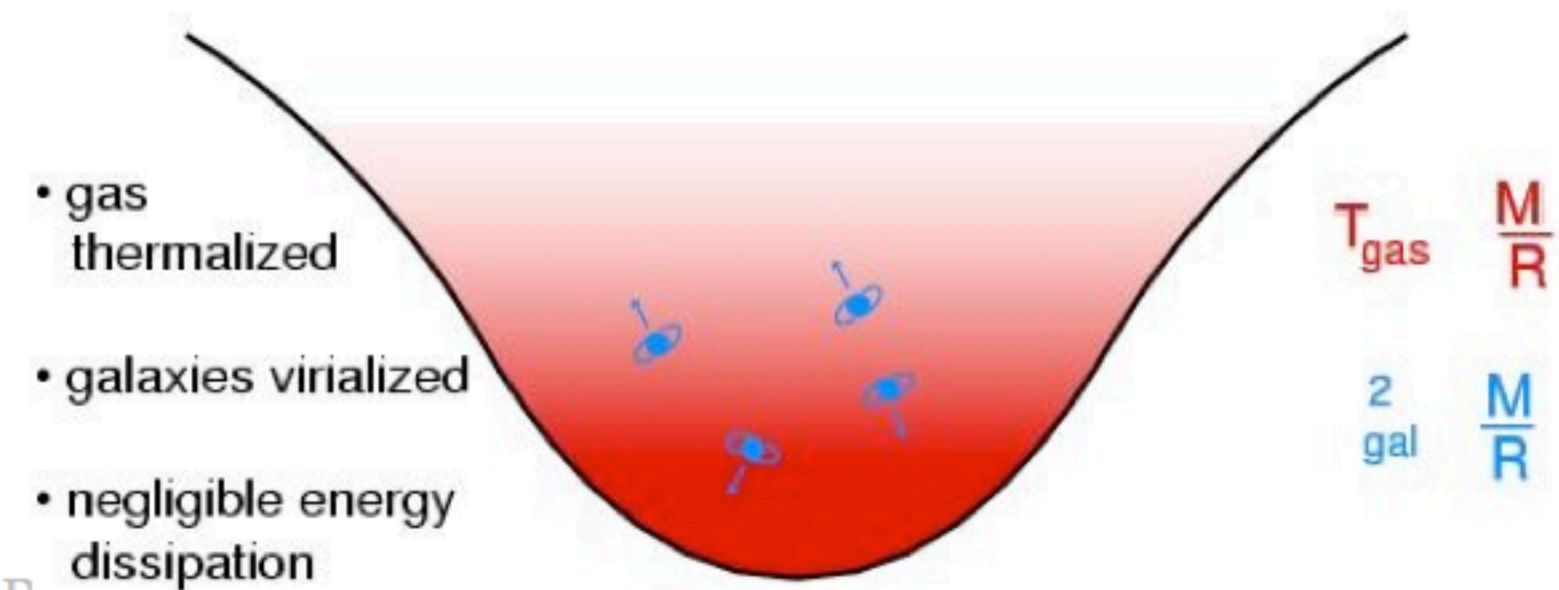
At scales below ~1 Mpc, the physics of baryons start to play an important role, and complicates the process.

Matter in galaxies & clusters

Galaxies

Complex relation between observable stellar population and dark matter halo

Clusters

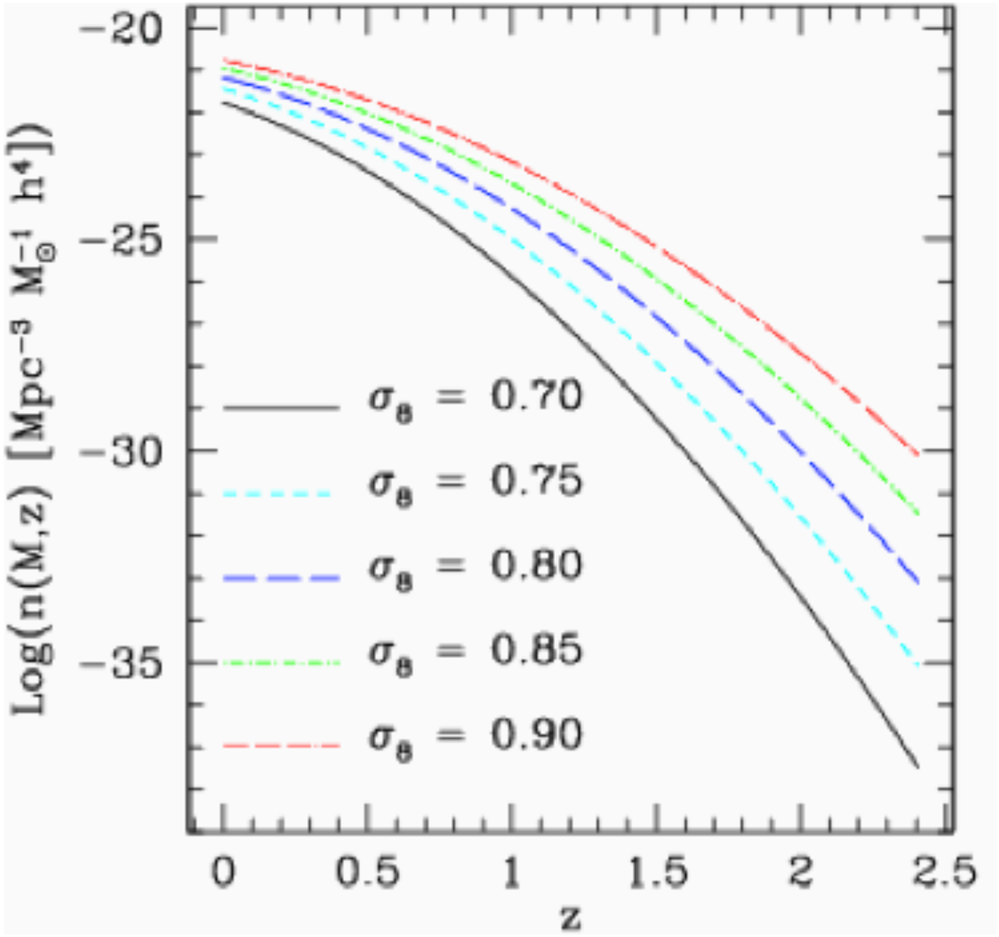


Cluster number counts

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

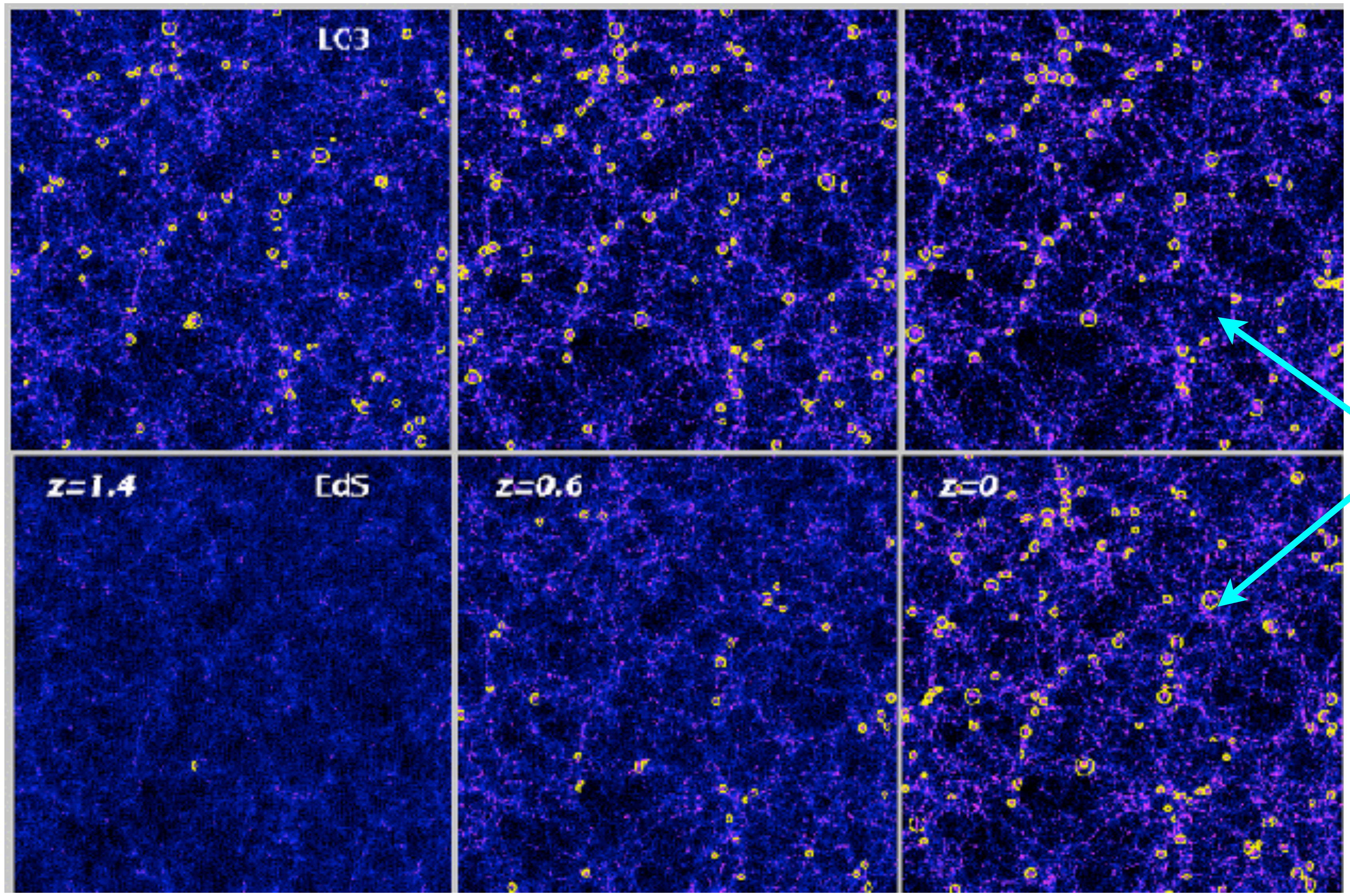
★ changing cosmological parameters affects:
  - shape of MF at z=0
  - evolution of MF with redshift

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



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

Structure growth & cluster count



$\Omega_m=0.3,\ \Omega_\Lambda=0.7$

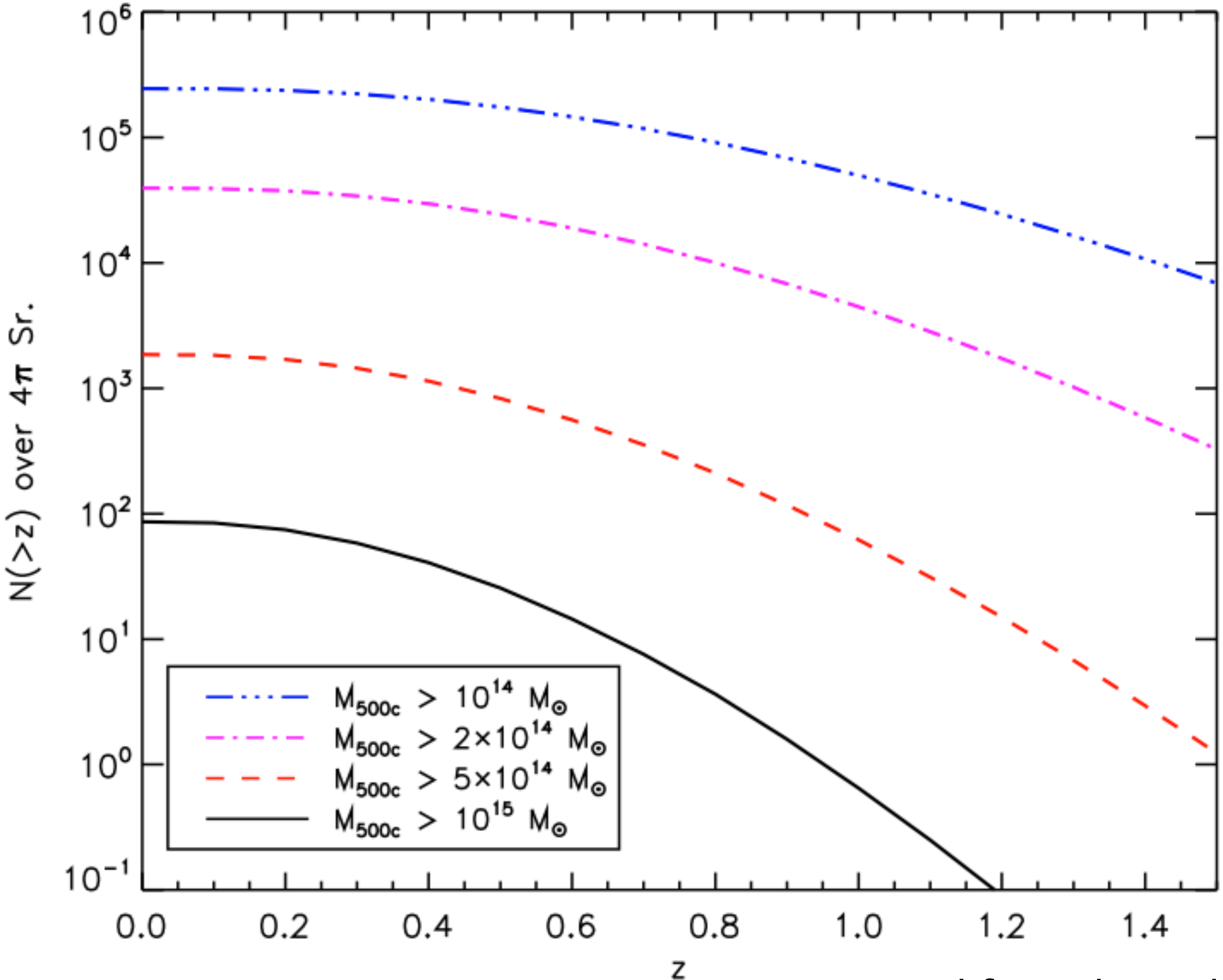
$\Omega_m=1.0$

Normalized w.r.t. local cluster density

Borgani & Guzzo, Nature, 2001

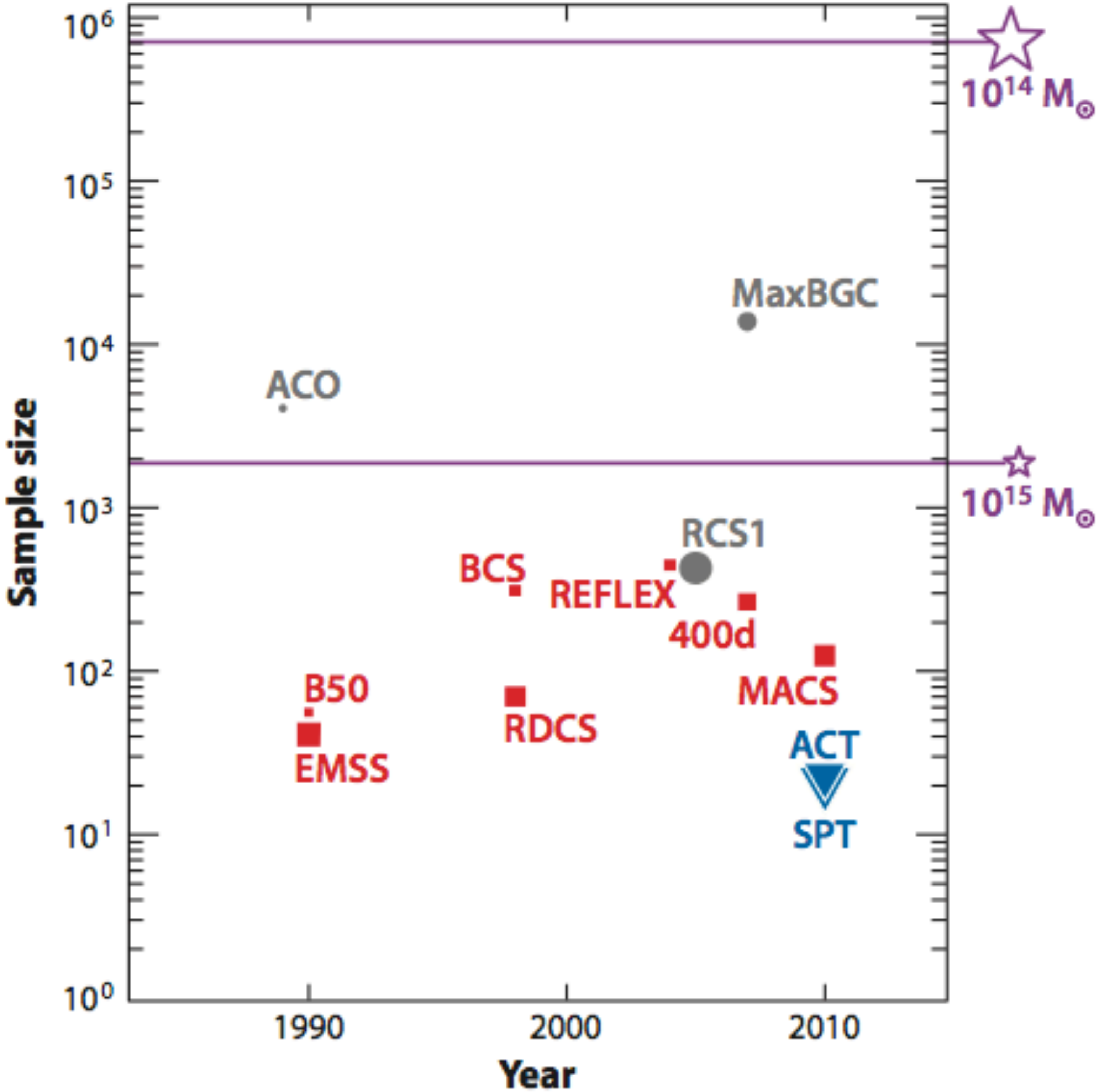
Example showing the role of galaxy clusters in tracing the cosmic evolution, in particular dark matter and dark energy contents.

How many clusters?



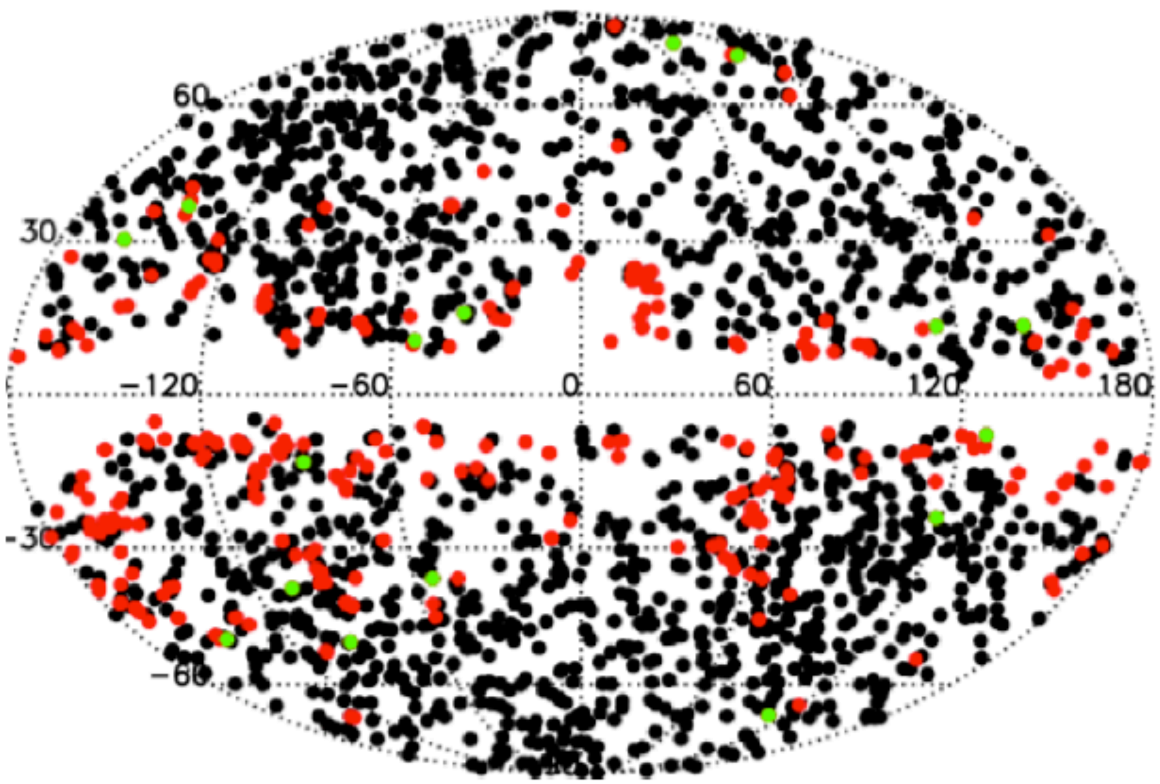
Computed from the Tinker et al. (2008) mass function

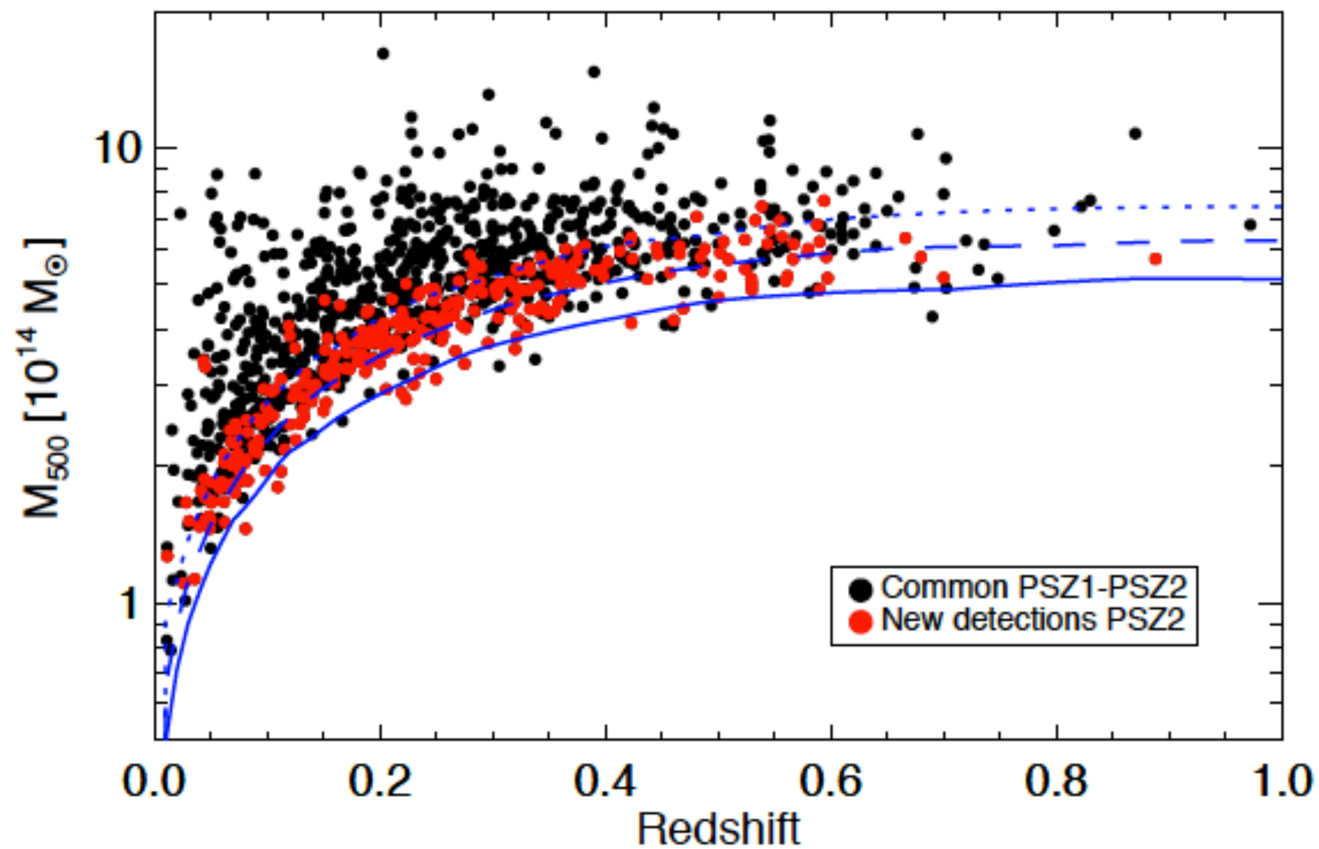
How many clusters?



From Allen, Evrard, Mantz (2011)

The Planck clusters





The ~500 clusters from the Planck cosmology sample. These might very well represent *all* the massive clusters in the universe.

The halo mass function and cluster number counts

The Halo Mass Function

• The mass function (MF) at redshift z, *n(z,M)*, is defined as the number density of virialized halos found at that redshift within mass range of [*M*, *M*+Δ*M*]

• Originally devised by Press and Schechter (1974, "PS theory") based on simple analytical formulation. Not very accurate at low- and high-mass ends.

• Nowadays we use fitting results from N-body simulations, whose accuracy have been confirmed to better than 5%

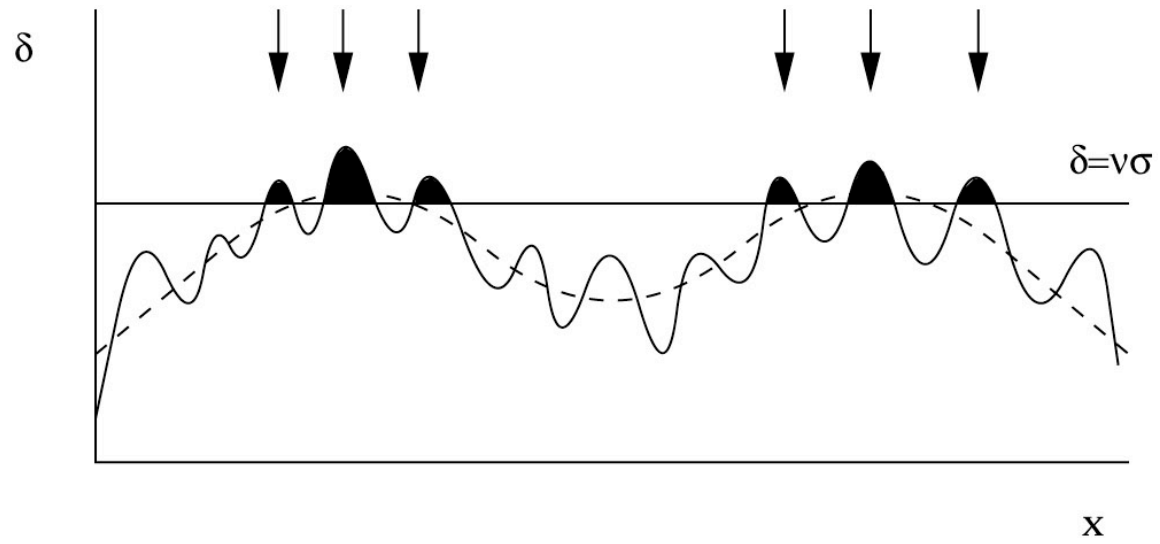
$$\frac{dN}{d\Omega dz} = \frac{dV}{d\Omega dz} \times \int_{M_{min}}^{\infty} dM \frac{dn}{dM}$$

Observable

Theory

# of clusters per unit area and z

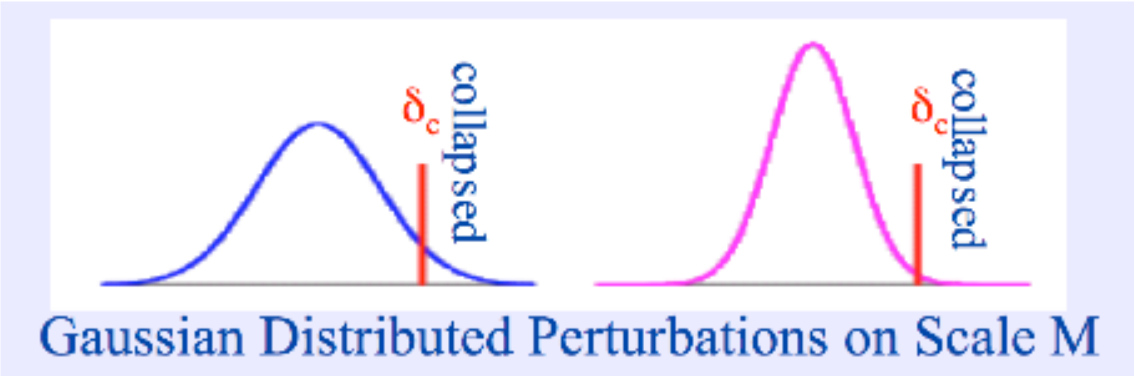
The Halo Mass Function



- Consider the cosmic density field filtered on mass scale M

- Assume that density perturbations have collapsed by the time their linearly evolved overdensity exceeds some critical value δ_c

- Number density (abundance) of collapsed objects with mass M is then proportional to the integral of the tail of a Gaussian distribution above δ_c



Press–Schechter formalism

• The PS derivation of the MF is based on the assumption that the fraction of matter ending up in objects of a given mass M can be found by looking at the portion of the initial density field, smoothed on the mass-scale M, that produce an overdensity exceeding a given critical threshold value, δ_c.

• Under the assumption of Gaussian perturbations, the probability for a given point to lie in a region with $\delta > \delta_c$ will be

$$p_{>\delta_c}(M,z) = \frac{1}{\sqrt{2\pi}\sigma_M(z)} \int_{\delta_c}^{\infty} \exp\left(-\frac{\delta_M^2}{2\sigma_M(z)^2}\right) d\delta_M = \frac{1}{2}\mathrm{erfc}\left(\frac{\delta_c}{\sqrt{2}\sigma_M(z)}\right)$$

• $\delta_c \approx 1.69$ corresponds to the density contrast predicted from linear theory, which the initial density field must have, in order to be able to end up in a collapsed, virialized structure.

• **PROBLEM:** Integrating the above equation in the whole mass range gives $\int_0^\infty dp_{>\delta_c}(M,z) = 1/2$. This means only half the mass of the whole universe is accounted for in collapsed objects!

Press–Schechter formalism

- The reason is that we assigned zero probability for all the density peaks with $\delta < \delta_c$. These under-dense regions correspond to half the mass. These low density peaks end up inside collapsed halos of larger mass (halos in halos)

- Press–Schechter solved it by waving their hands, simply multiplying their formula by 2. Modern approach based on excursion-set theory (e.g. *extended Press-Schechter*) naturally accounts for this missing factor 2.

- The previous equation gives the *volume* of objects in a given mass range. The *number density* of object will be obtained if we divide by the volume, $V_M = M/\bar{\rho}$, , of each object. Thus the final for for PS mass function is

$$\frac{dn(M,z)}{dM} = \frac{2}{V_M}\frac{\partial p_{>\delta_c}(M,z)}{\partial M}$$
$$= \sqrt{\frac{2}{\pi}}\frac{\bar{\rho}}{M^2}\frac{\delta_c}{\sigma_M(z)}\left|\frac{d\log\sigma_M(z)}{d\log M}\right|\exp\left(-\frac{\delta_c^2}{2\sigma_M(z)^2}\right).$$

The Halo Mass Function

$$\frac{dn(M,z)}{dM} = \sqrt{\frac{2}{\pi}}\frac{\bar{\rho}_m}{M^2}\frac{\delta_c}{\sigma(M,z)}\left|\frac{d\log(\sigma(M,z))}{d\log(M)}\right|\exp\left(-\frac{\delta_c^2}{2\sigma^2(M,z)}\right)$$

$$\sigma(M,z) = \sigma(M,z_{init})\frac{G(z)}{G(z_{init})}\frac{(1+z_{init})}{(1+z)}.$$

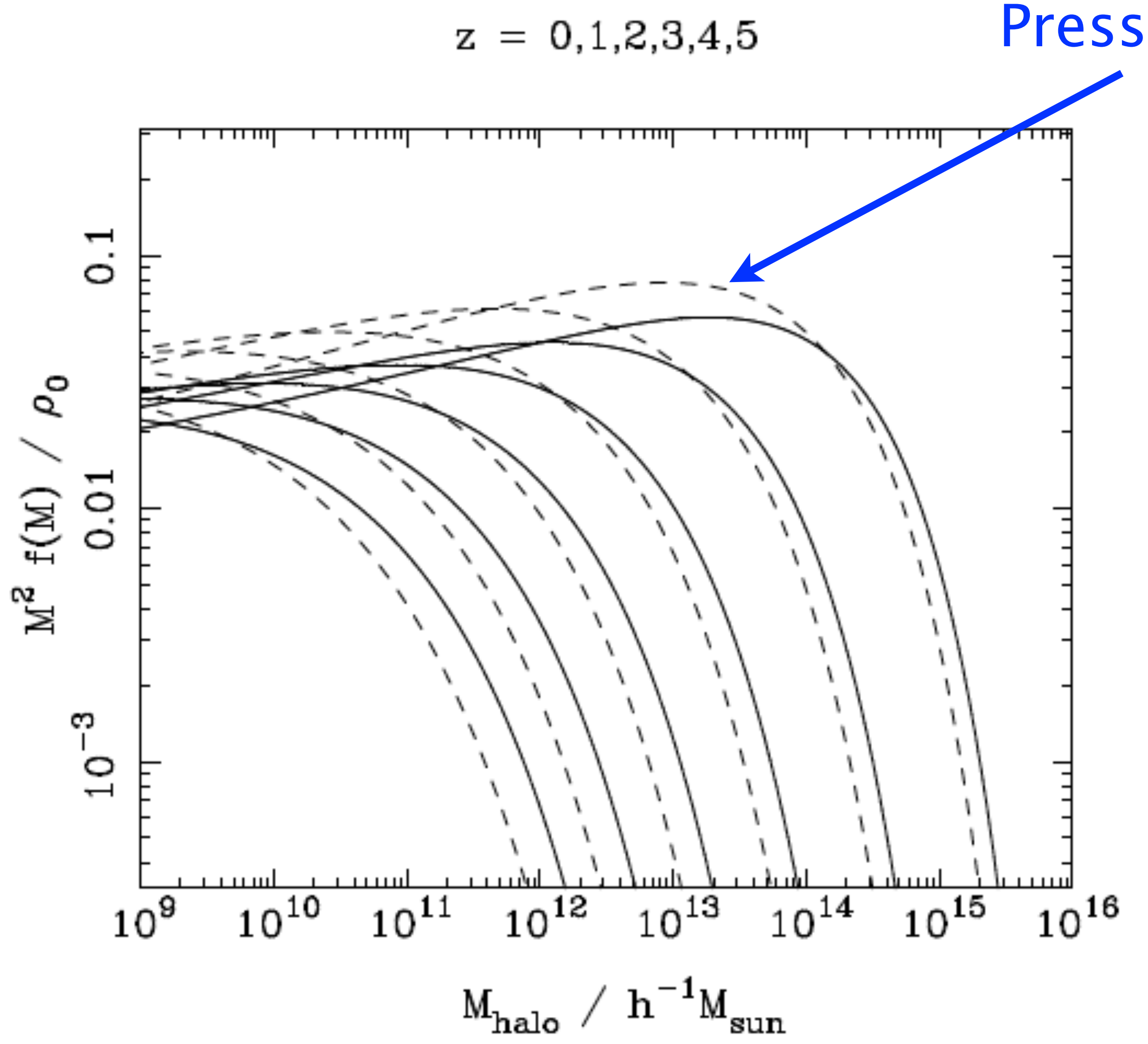
Cosmological parameters enter through the mass variance σ_M , which depends on the power spectrum and on the cosmological density parameters, through the linear perturbation growth factor, and, to a lesser degree, through the critical density contrast δ_c.

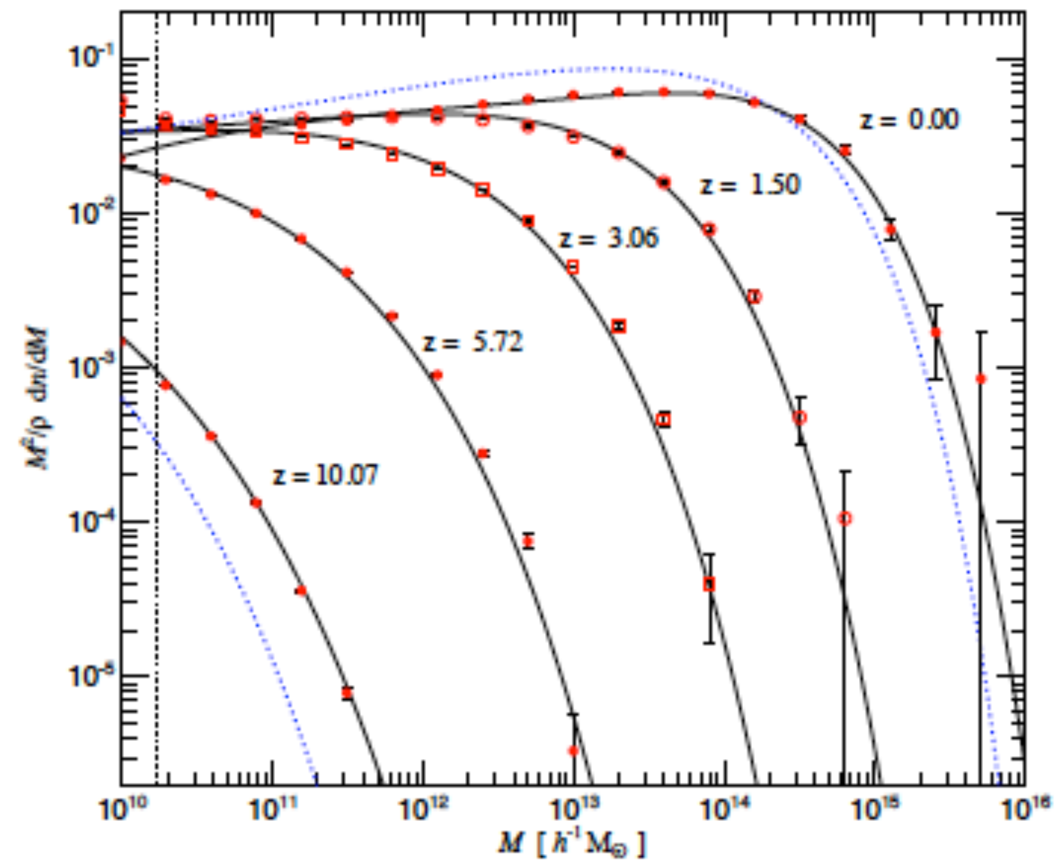
Taking this expression in the limit of massive objects (i.e., rich galaxy clusters), the MF shape is dominated by the exponential tail. This implies that the MF becomes exponentially sensitive to the choice of the cosmological parameters. In other words, a reliable observational determination of the MF of rich clusters would allow us to place tight constraints on cosmological parameters.

The Halo Mass Function

Despite its very simple theory, Press-Schechter formula has served remarkably well as a guide to constrain cosmological parameters from the mass distribution of galaxy clusters. Only with the advent of large N-body simulations, significant deviations of the PS description from the exact numerical description is noticed.

Press-Schechter (dashed curves)





Jenkins et al. (2001) mass function

The Halo Mass Function

Press-Schechter (1974)

$$\frac{dn_M}{d\ln\sigma^{-1}} = \sqrt{\frac{2}{\pi}}\frac{\Omega_M\rho_{cr0}}{M}\frac{\delta_c}{\sigma}\exp\left[-\frac{\delta_c^2}{2\sigma^2}\right].$$

Jenkins et al. (2001)

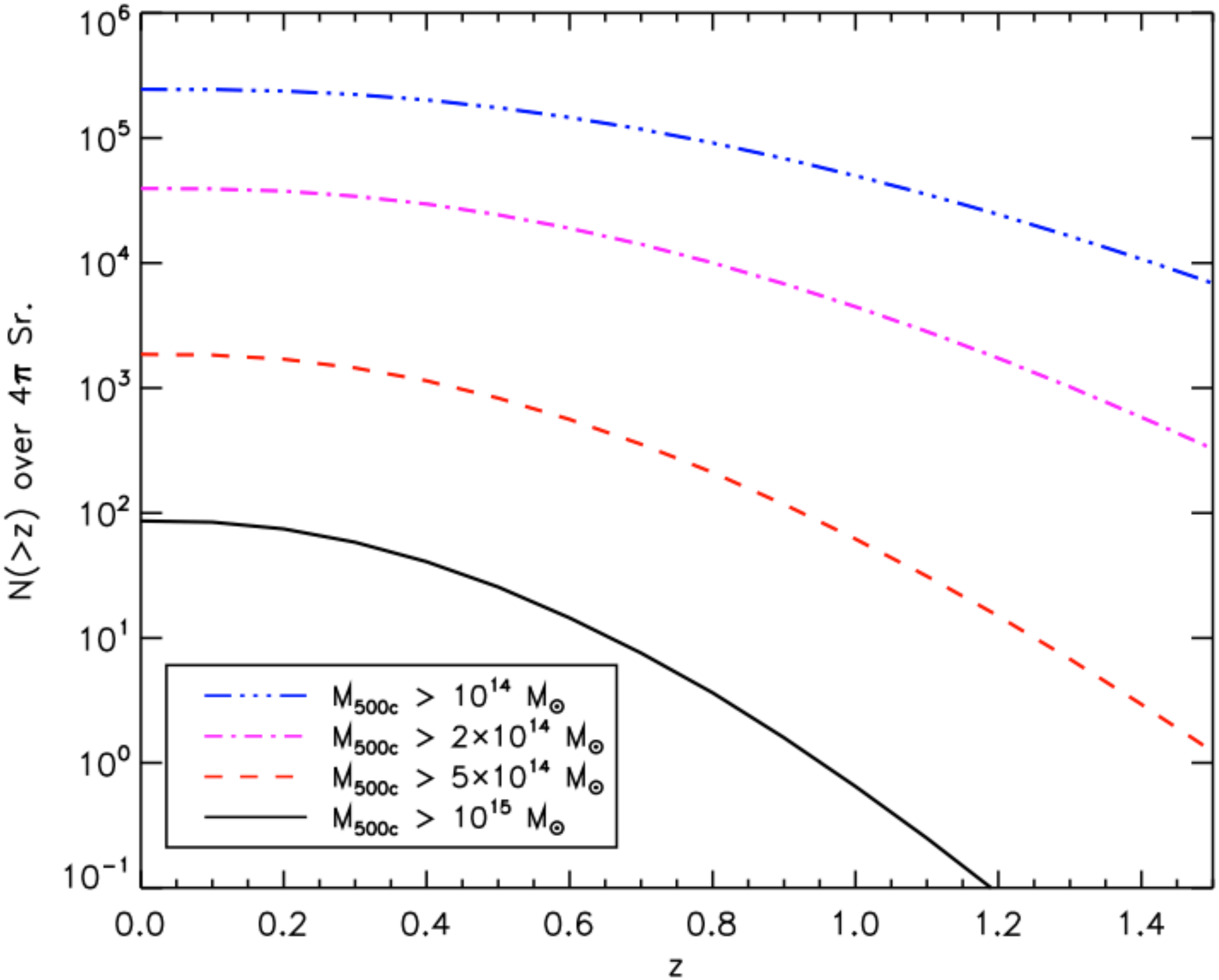
$$\frac{dn_M}{d\ln\sigma^{-1}} = A_J\frac{\Omega_M\rho_{cr0}}{M}\exp[-|\ln\sigma^{-1} + B_J|^{\epsilon_J}]$$

Tinker et al. (2008)

$$\frac{dn}{dM} = f(\sigma)\frac{\bar{\rho}_m}{M}\frac{d\ln\sigma^{-1}}{dM}.$$

$$f(\sigma) = A\left[\left(\frac{\sigma}{b}\right)^{-a} + 1\right]e^{-c/\sigma^2}$$

Cluster number count

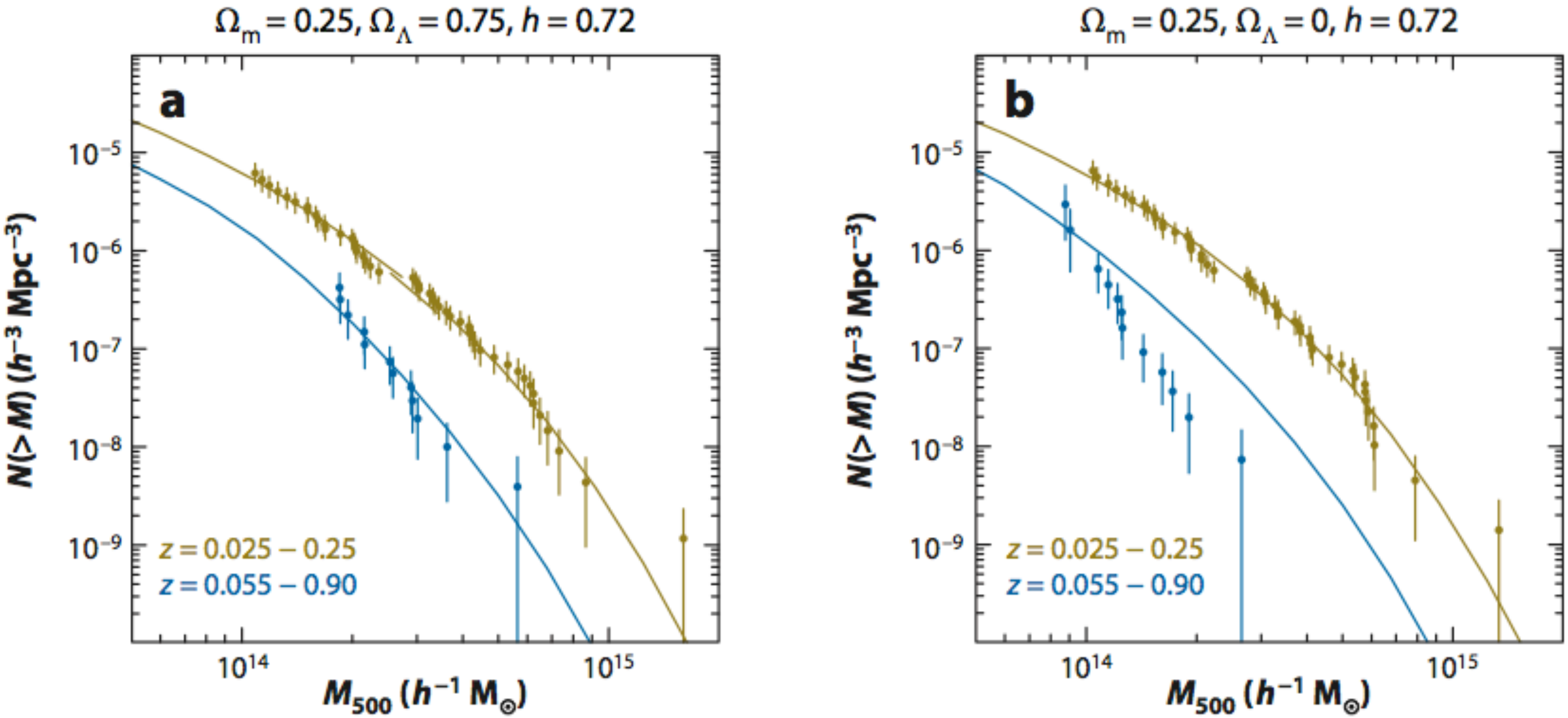


Computed from Tinker et al. (2008) mass function

$$\frac{dn}{dM} = f(\sigma)\,\frac{\bar{\rho}_m}{M}\,\frac{d\ln\sigma^{-1}}{dM}.$$

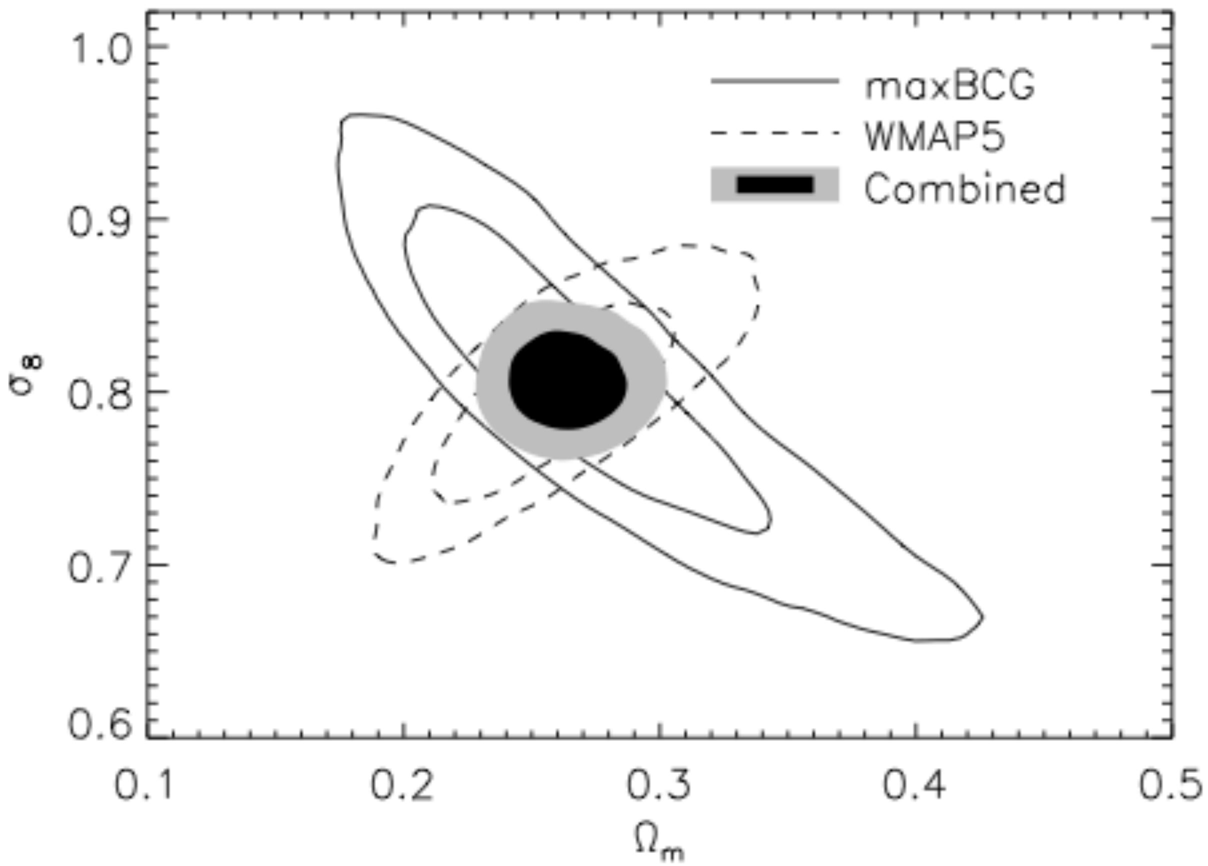
$$f(\sigma) = A\left[\left(\frac{\sigma}{b}\right)^{-a} + 1\right] e^{-c/\sigma^2}$$

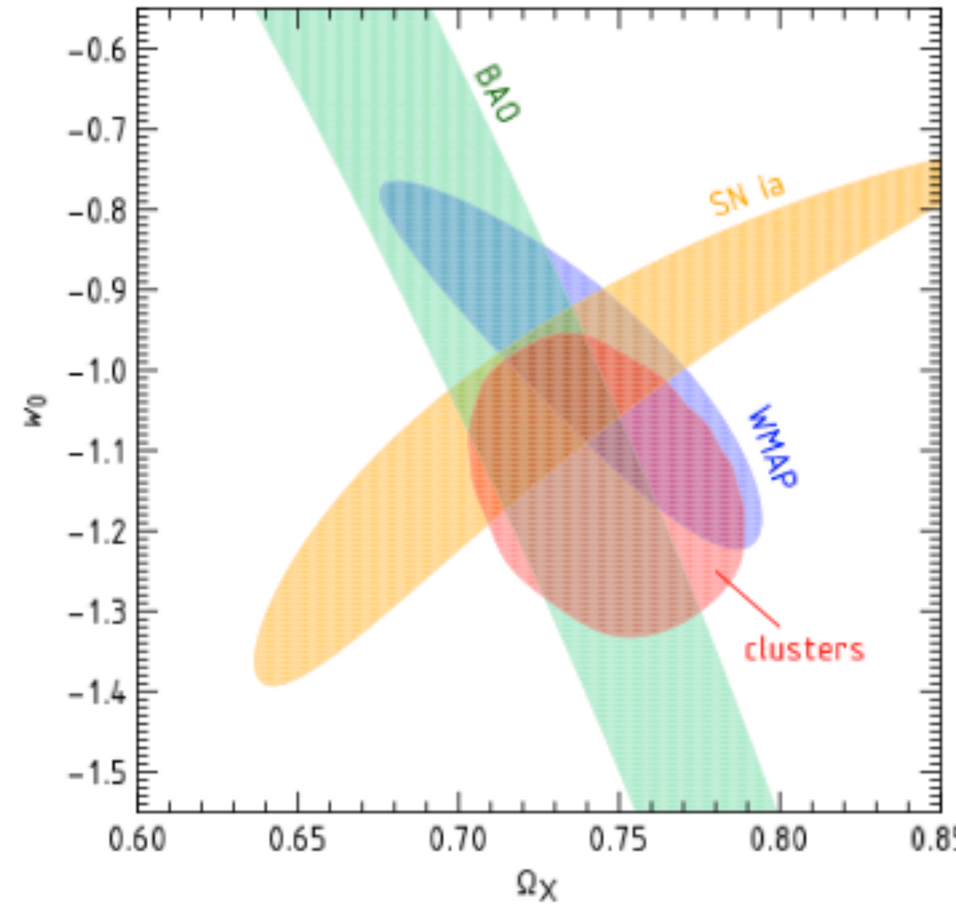
Example: X-ray cluster number count



From Vikhlinin et al. (2009)

Cosmology results from cluster count

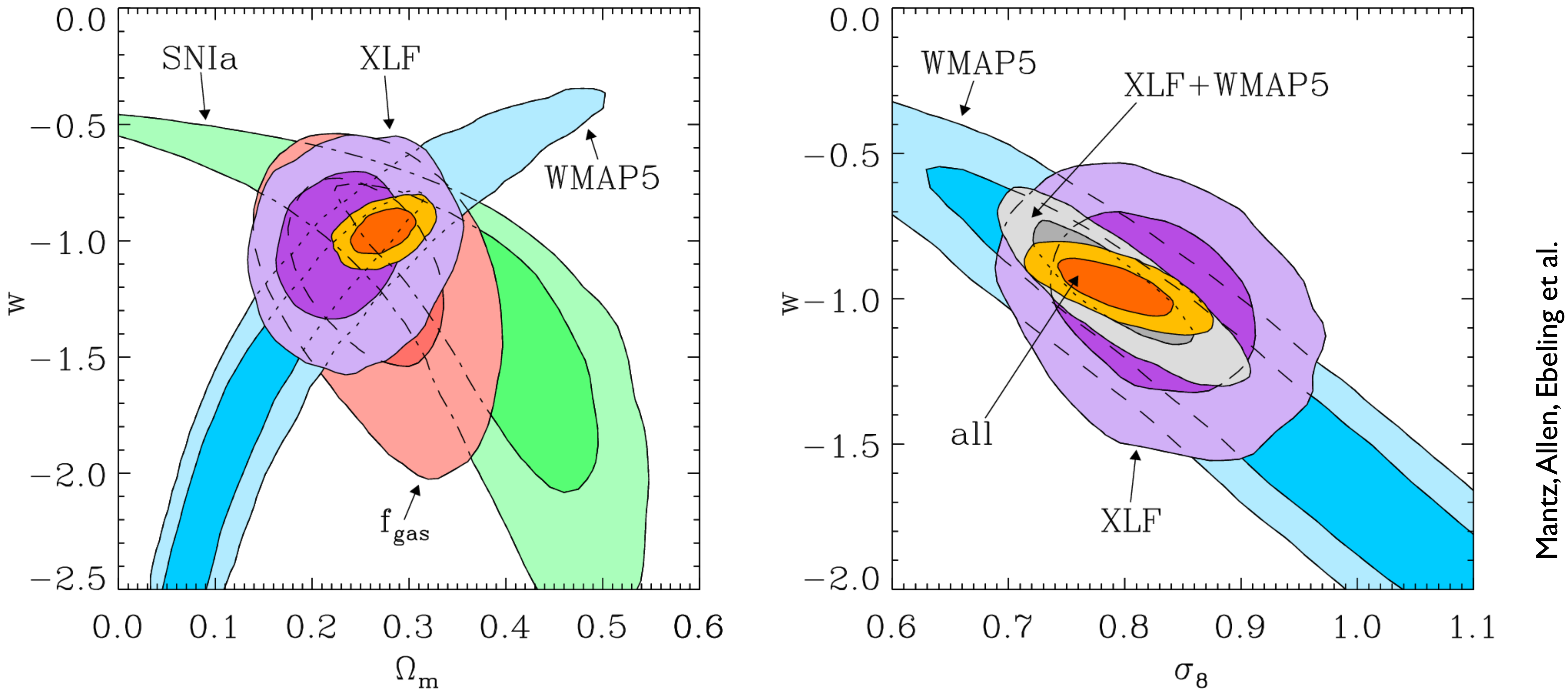




Left: Optical maxBCG sample with WMAP (Dunkley et al. 2009)
Right: 400 sq. deg. X-ray sample + others (Vikhlinin et al. 2009)

Note the almost orthogonal constraints from clusters as compared to the CMB.

Cosmology results from cluster count



238 clusters, $z < 0.5$ (XLF)
Including systematics

$$\Omega_m = 0.23 \pm 0.04$$
$$\sigma_8 = 0.82 \pm 0.05$$
$$w = -1.01 \pm 0.20$$

XLF+WMAP5+SNIa+f_{gas}+BAO

$$\Omega_m = 0.272 \pm 0.016$$
$$\sigma_8 = 0.79 \pm 0.03$$
$$w = -0.96 \pm 0.06$$

Many different ways to constrain cosmology

- Growth of cosmic structure from cluster number counts (use of halo mass function)

- Measuring the large-scale cluster correlation function ("clustering of clusters")

- Measuring distances using clusters as standard candles (joint X-ray/SZE)

- Using the gas mass fraction in clusters to measure the cosmic baryon density

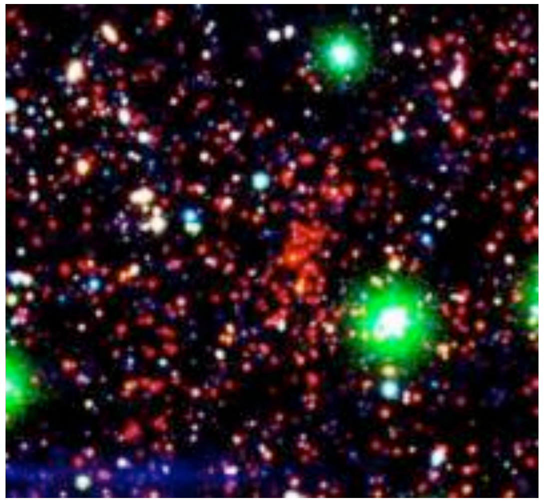
- Measuring the large-scale velocity fields in the universe from kinematic SZE

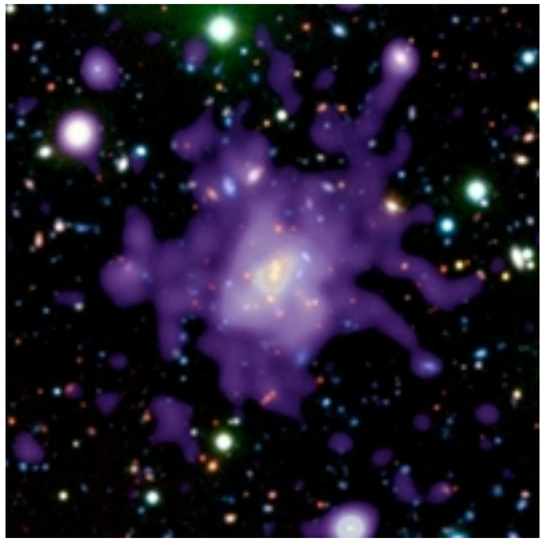
- Constraints from SZ effect power spectrum

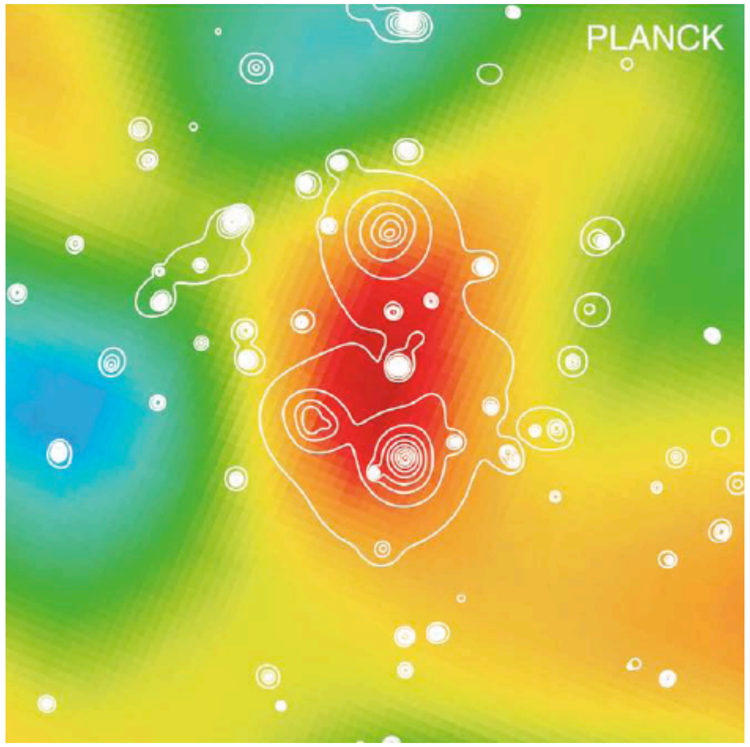
Cluster mass and observables

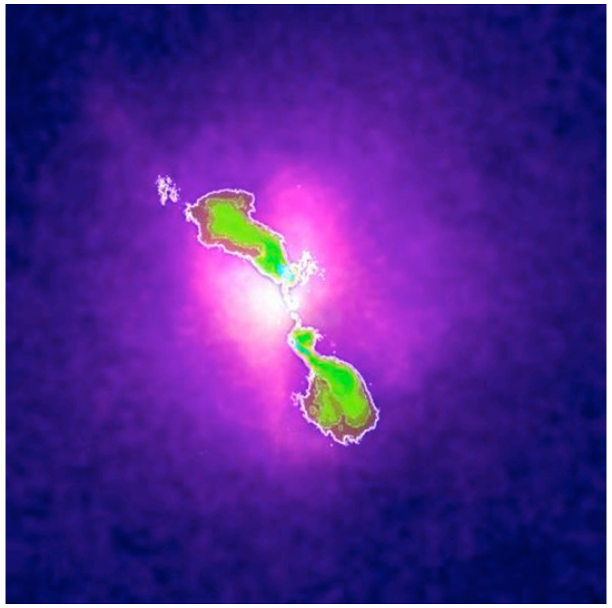
Windows to galaxy clusters

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







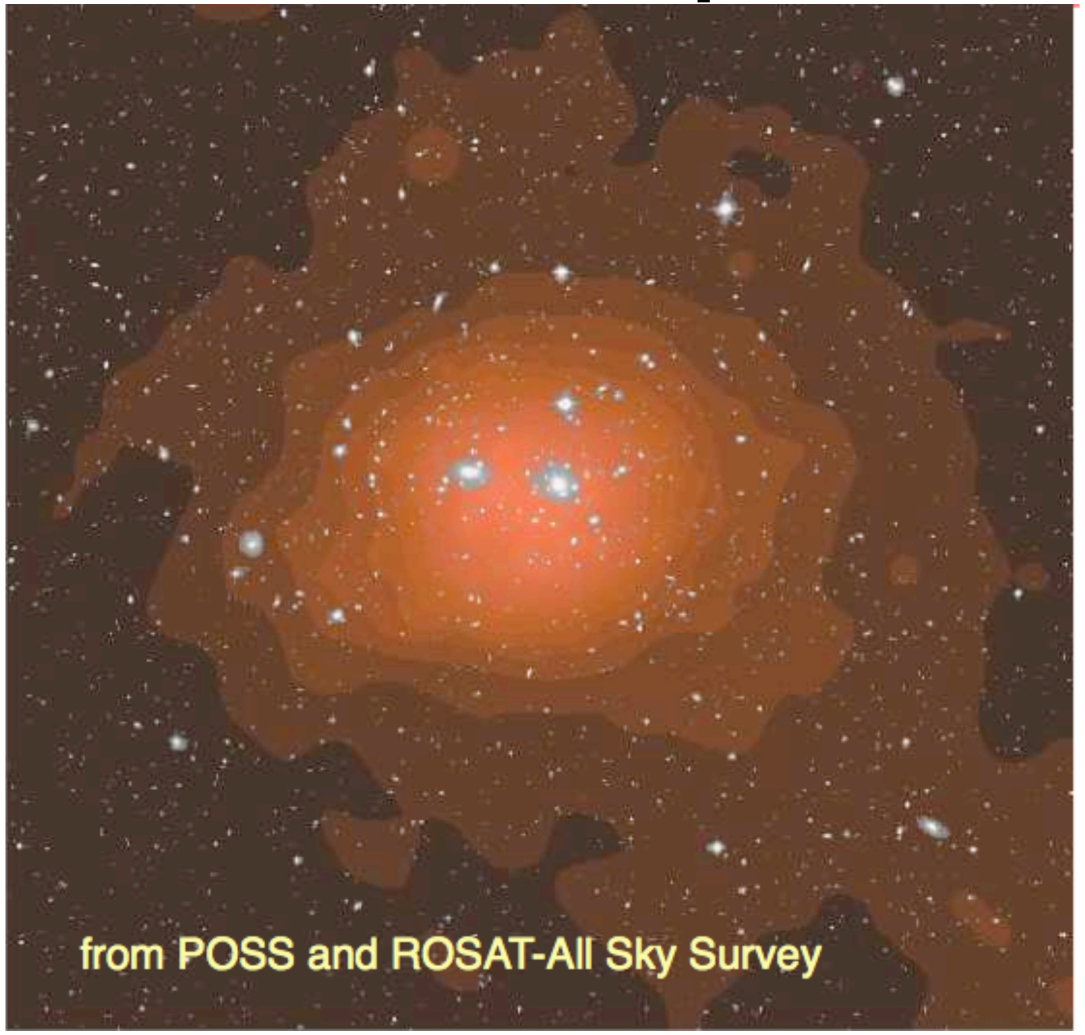


Mass budget in galaxy clusters

(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 $H_0 = 70$

Table 1.1. *Mass Hierarchy in the Coma Cluster*

Component	$M(< 1.5\,h^{-1}$ Mpc) $(M_\odot)$	$M/M_{\rm vis}$
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.

White et al. (1993)

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: $\boxed{2\,\langle T \rangle = -\,\langle V \rangle}$

$$\frac{1}{2}m(3\sigma^2)$$

$$G\frac{M_{tot}(r)m}{r}$$

$$\mathrm{KE_{avg}} = -\frac{1}{2}\ \mathrm{GPE_{avg}}$$

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

Virial theorem

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 $M_{tot} = N \cdot m$ 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) = $1/2\ m\ N\ v^2 = 1/2\ M_{tot}\ v^2$

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

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

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

Discovery of Dark Matter

Fritz Zwicky (1898 - 1974)

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

$$\mathcal{M} > 9 \times 10^{46}\,\mathrm{gr}\,. \tag{35}$$

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

$$\overline{M} > 9 \times 10^{43}\,\mathrm{gr} = 4.5 \times 10^{10}\,M_\odot\,. \tag{36}$$

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:

$$M = R\,v^2 / G$$

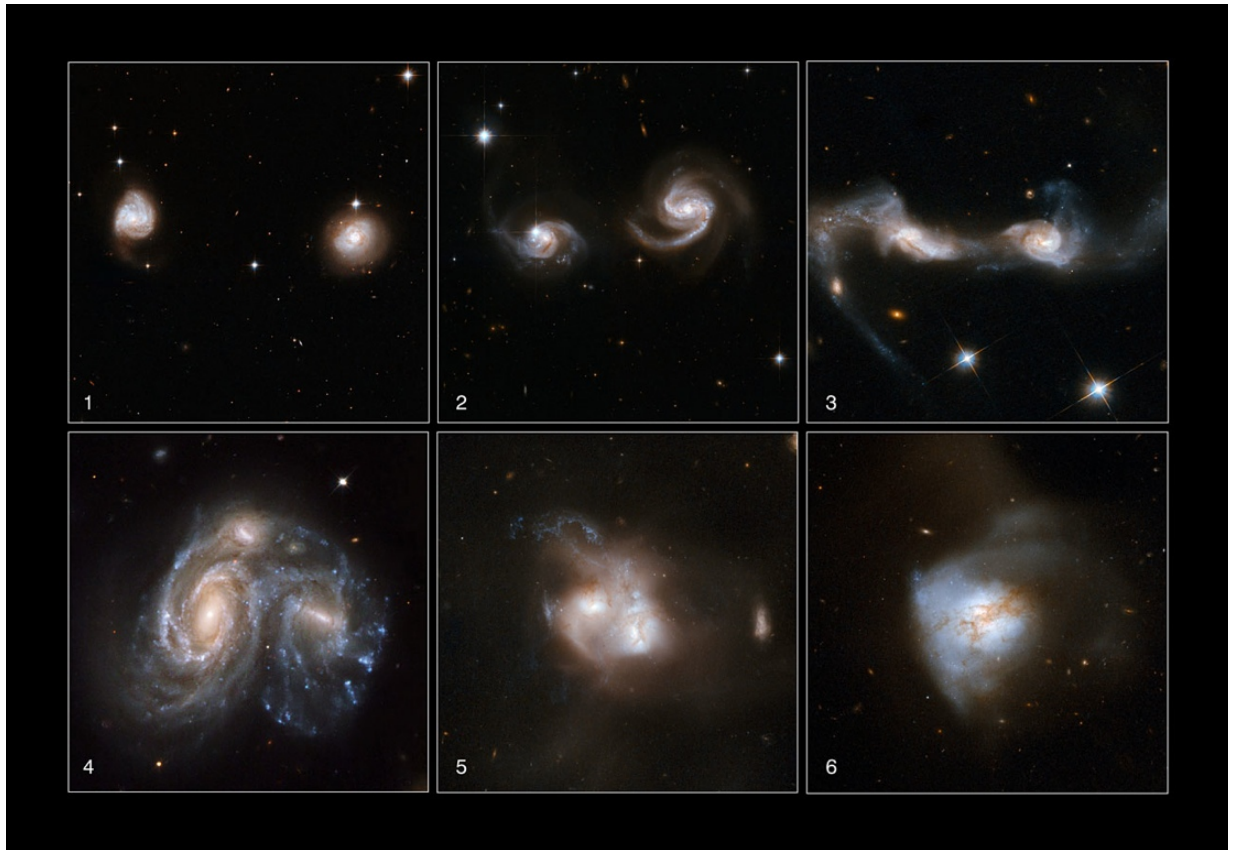
This assumes velocities in equilibrium. But two-body relaxation process with galaxies is extremely slow. How do galaxy clusters (and so to speak, also galaxies containing stars) attain equilibrium?

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 ? How is an approximately Maxwellian velocity distribution achieved, if two-body relaxation is so slow?

Answer: „Violent Relaxation“ – mixing of phase space in the strong fluctuating gravitational potential when the cluster forms (theory by Lynden-Bell) – the fine grained phase space density is preserved but the coarse grained phase space density is mixed.



arXiv: astro-ph/9602021

Violent relaxation

Difference of two-body and violent relaxation:

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

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

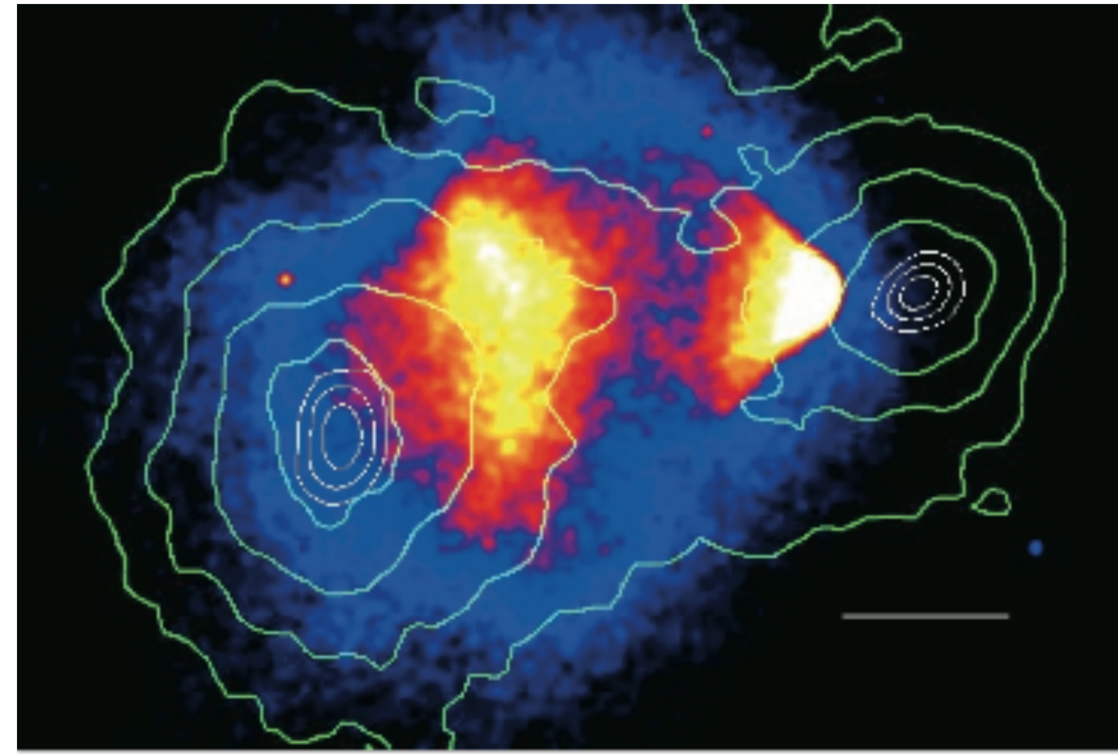
Toward the late stages of the merger the shape of the gravitational potential begins changing so quickly that galaxy orbits are greatly affected, and lose any memory of their previous orbit.

Proof: no velocity segregation in clusters

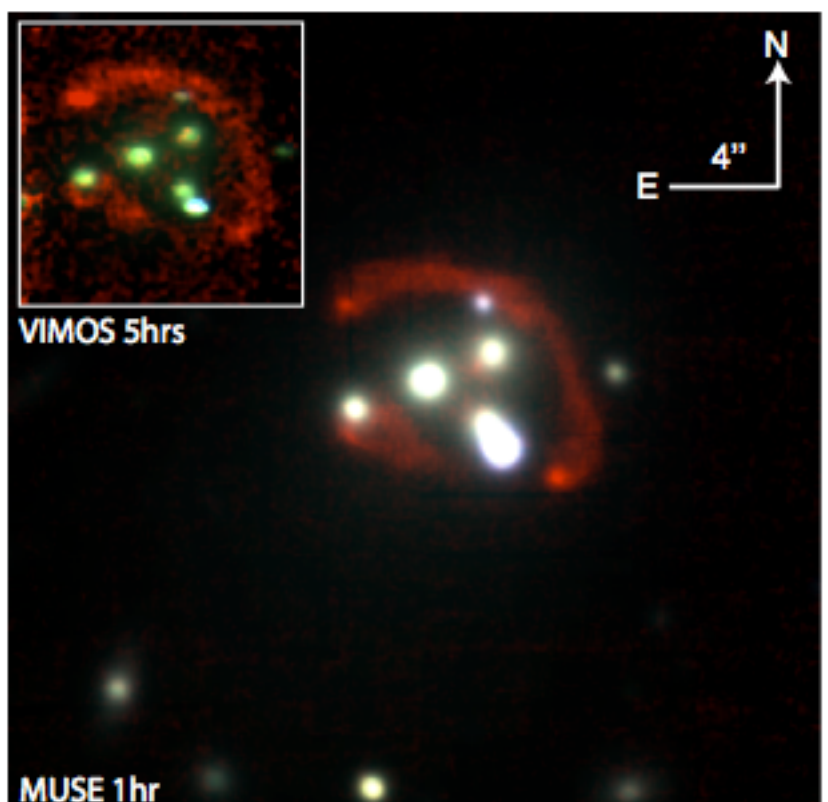
TABLE IV. Velocity dispersion vs magnitude.

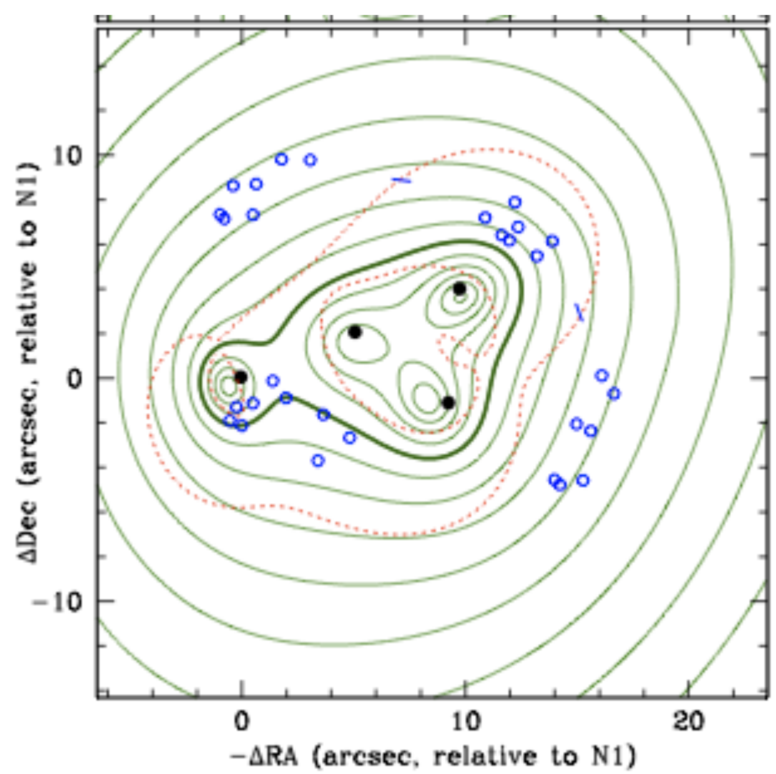
$(m_1 < m \leqslant m_2,\ r < 30')$			
m_1	m_2	n	σ
	$\leqslant 15.0$	21	1085
15.0	15.5	31	1081
15.5	16.0	37	984
16.0	16.5	24	1176
$16.5 \leqslant$		32	1250

Dark matter with galaxy clusters



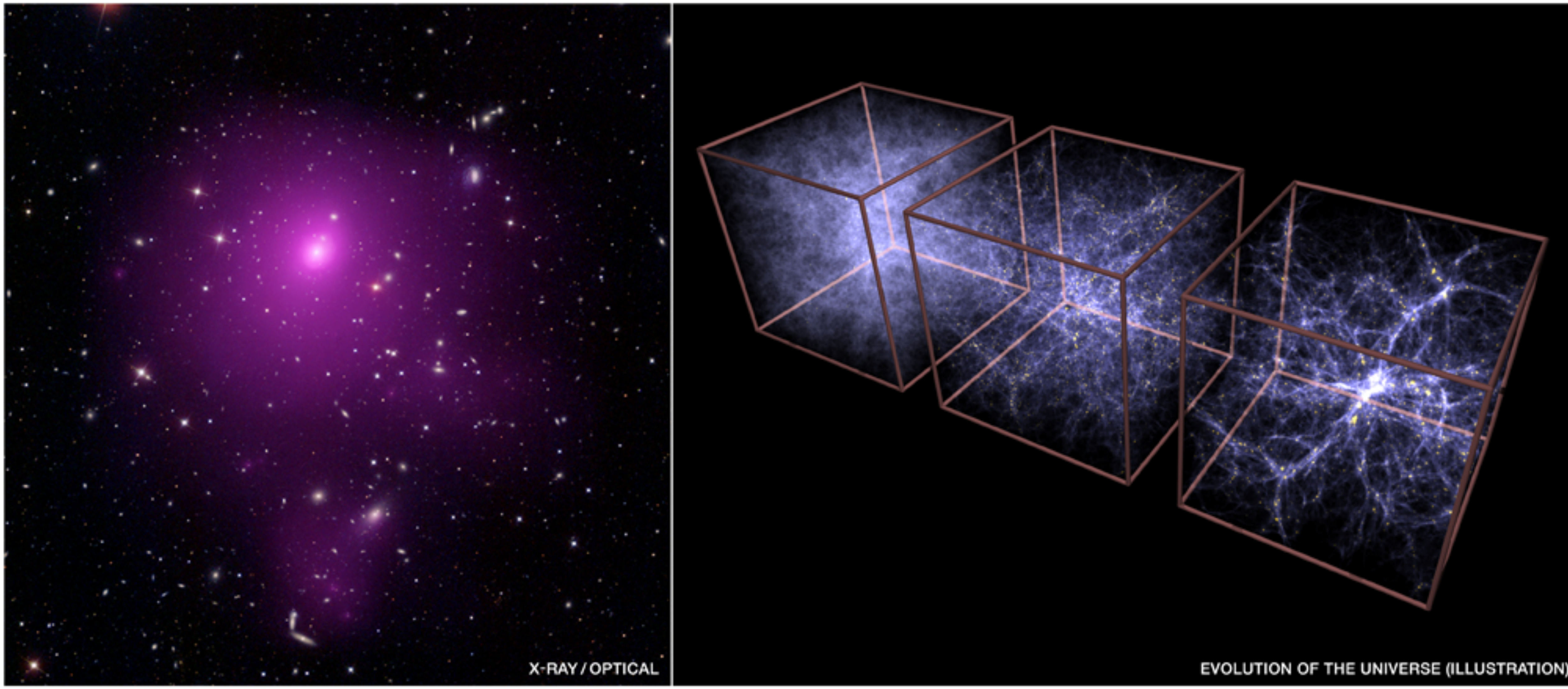
Clowe et al. 2006





Abell 3827
(Massey et al.
2015)

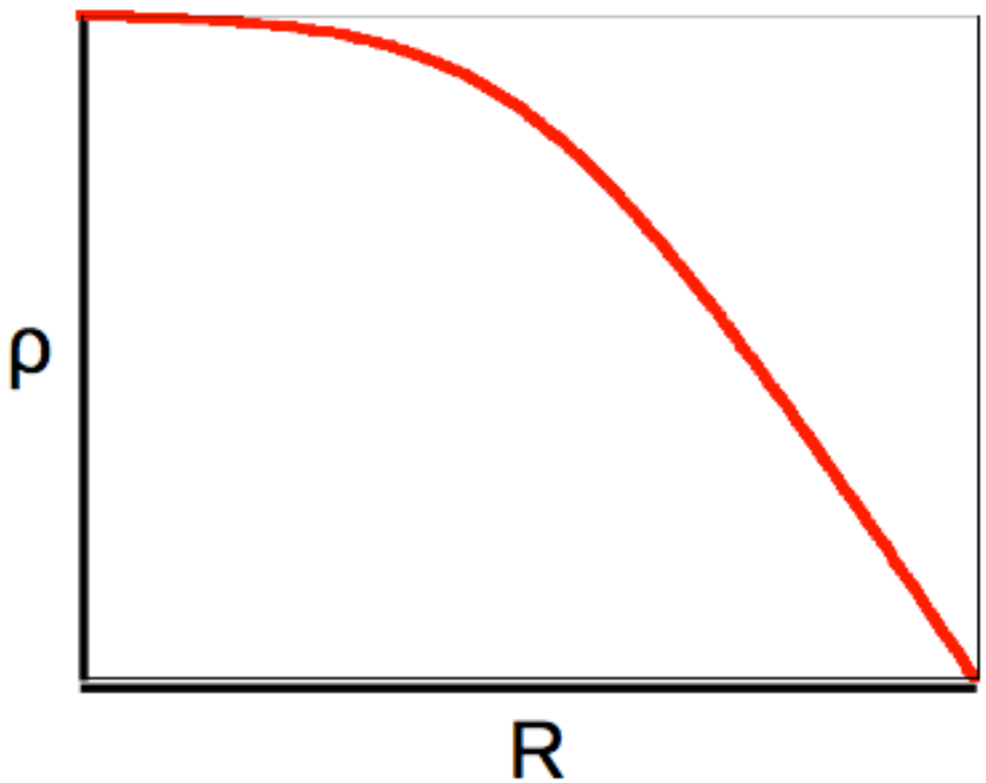
Cluster radii



Where are the boundaries of a cluster?

Overdensity radii

- ★ A radius within which the mean density is Δ times the critical density (ρ_c) at the cluster's redshift
- ★ Clusters are centrally concentrated so larger Δ correspond to smaller radii
- ★ Write radii as R_Δ
  - e.g. R_{200} means Δ=200



N.B. here ρ is the total mass density (not just gas)

Overdensity radii allow fair comparison of properties of clusters of different sizes, key part of self-similar model

Cluster virial radius

Beware: r_{200} is not the same thing as virial radius
but simulations show r_{200} to be a fair approximation

In a spherical collapse model, the behavior of a mass shell follows the equation:

$$\ddot{r}_{\rm sh} = -\frac{GM_{\rm sh}}{r_{\rm sh}^2} - \frac{1+3w}{2}\Omega_\Lambda H_0^2(1+z)^{3(1+w)} r_{\rm sh},$$

Under simplistic assumption ("top-hat model", which means cluster is assumed to be of constant density), the mean density of perturbations that lead to collapse is $18\pi^2 \approx 178$ for flat, EdS cosmology.

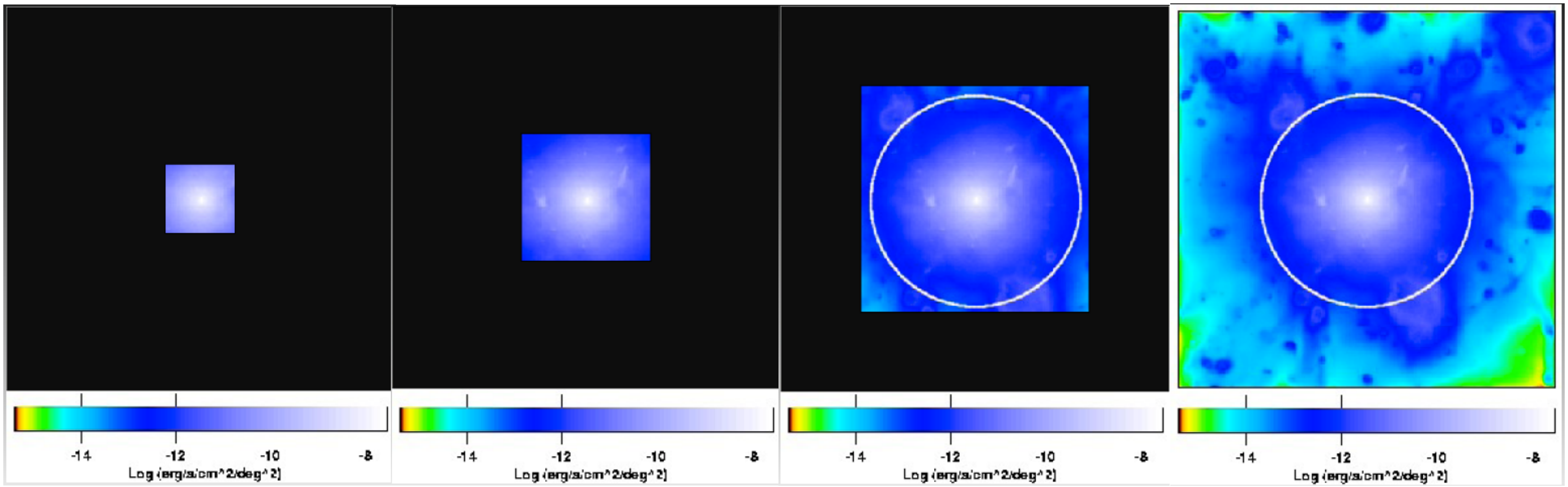
For ΛCDM the solution is:

$$\Delta_{\rm v} = 18\pi^2 + 82[\Omega_{\rm M}(z) - 1] - 39[\Omega_{\rm M}(z) - 1]^2$$

Thus for z=0, the "virial radius" should be ~ r_{100}

Radii comparison

X-ray strong lensing	X-ray SZE weak lensing	SZE weak lensing



Roncarelli, Ettori et al. 2006

R_{2500} $\sim 0.3\ R_{200}$ ~ 0.5 Mpc	R_{500} $\sim 0.7\ R_{200}$ ~ 1 Mpc	R_{200} ~ 1.5 Mpc

Questions?