Observational Cosmology

(C. Porciani / K. Basu)

Lecture 7
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 galaxies, hot, ionized gas (10^{7-8} K) and dark matter.

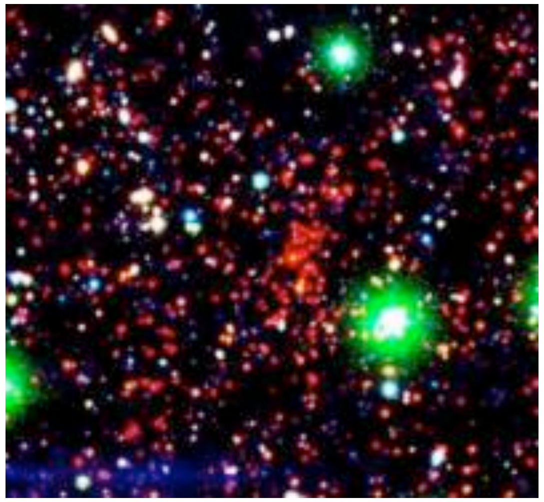
Better definition: Galaxy clusters are the massive end of halo mass function.

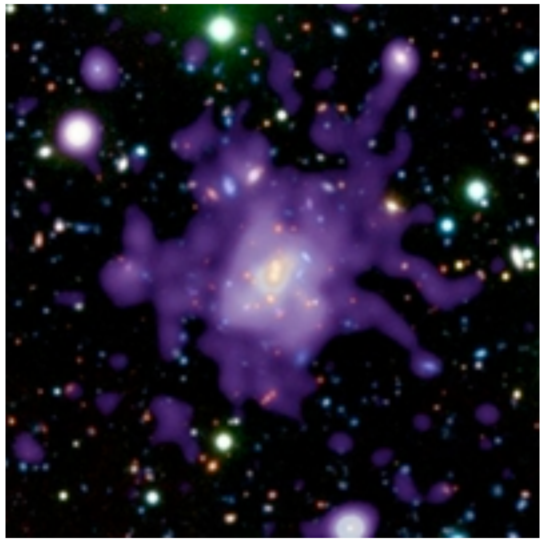
Clusters are good probes, because they are massive – and "easy" to detect through their:

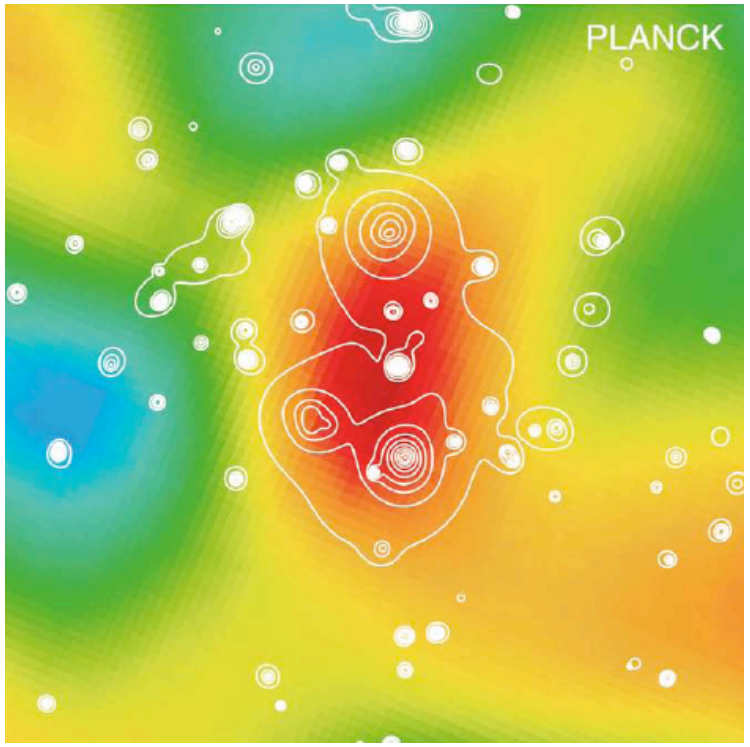
- X-ray emission
- Sunyaev-Zel'dovich Effect
- Light from galaxies
- Gravitational lensing

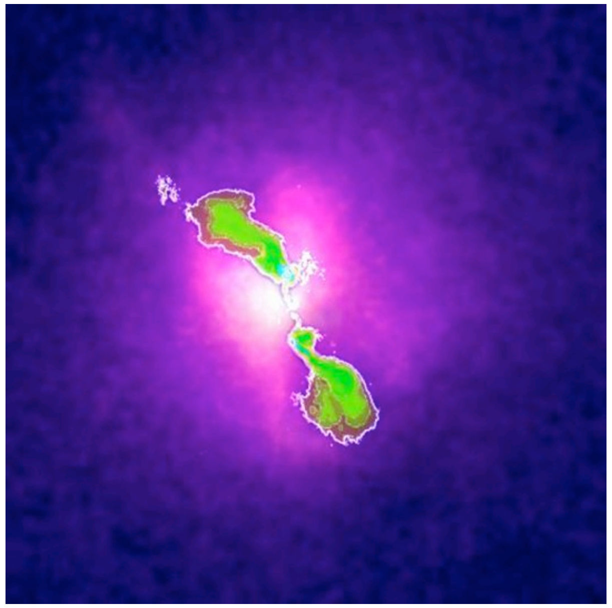
Windows to galaxy clusters

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









Mass budget in 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

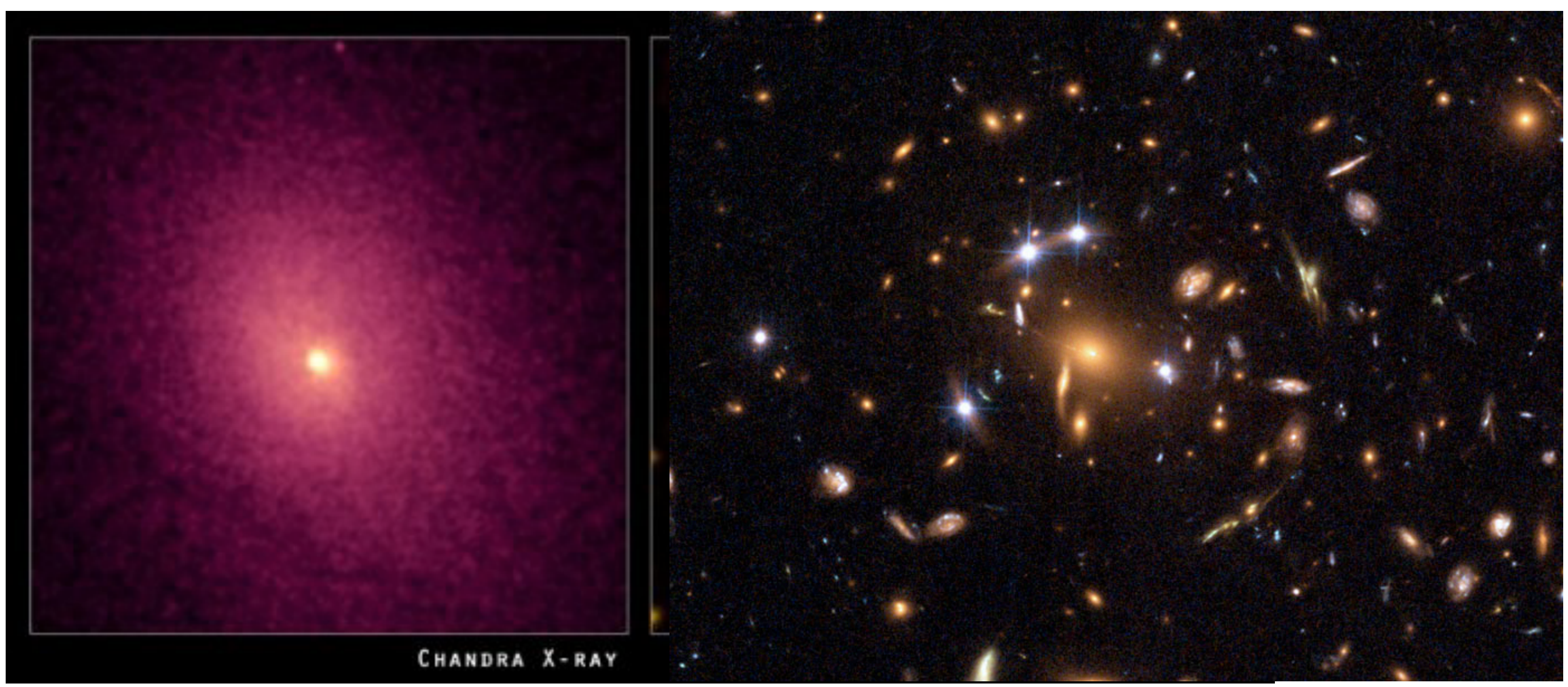
Mass budget in clusters

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:

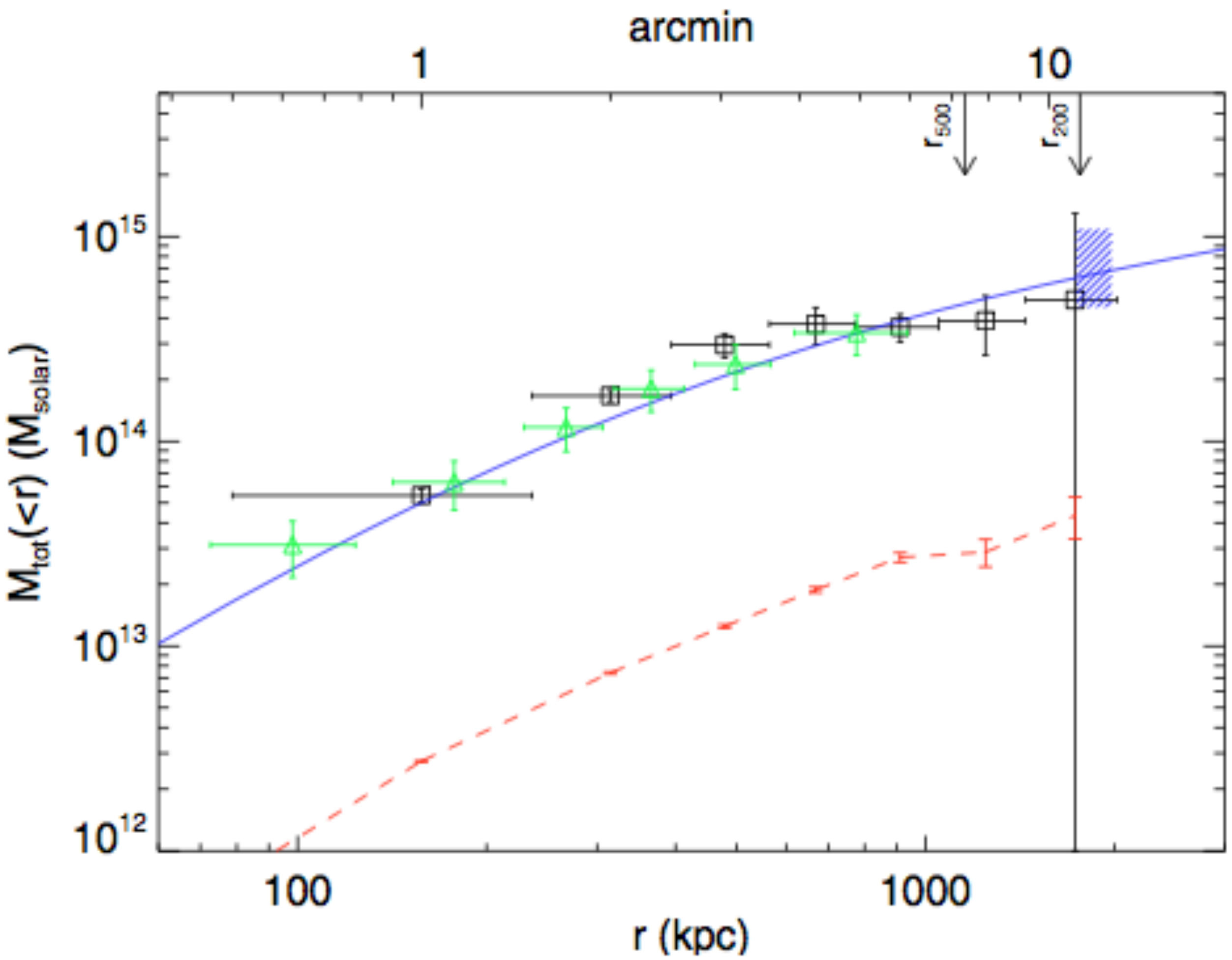
$$\mathrm{KE_{avg}} = -\frac{1}{2}\ \mathrm{GPE_{avg}}$$

The mass of a self-gravitating system in equilibrium:

$$M = RV^2/G$$

What are the assumptions in Zwicky's argument to reach the conclusion of dark matter?

Gas and total mass profiles



Mass profile in Abell 2204
(Basu et al. 2010)

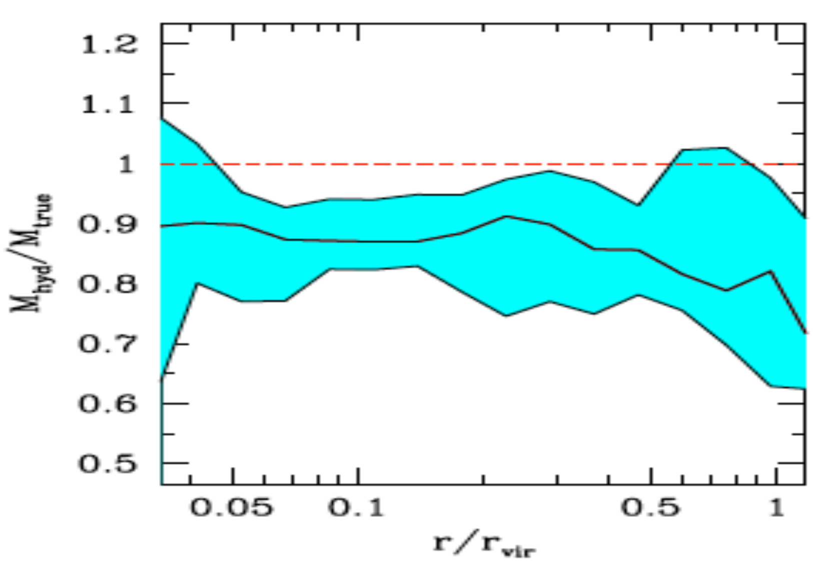
Hydrostatic (pressure) equilibrium

$$\nabla P = -\rho_g \nabla \phi(r),$$

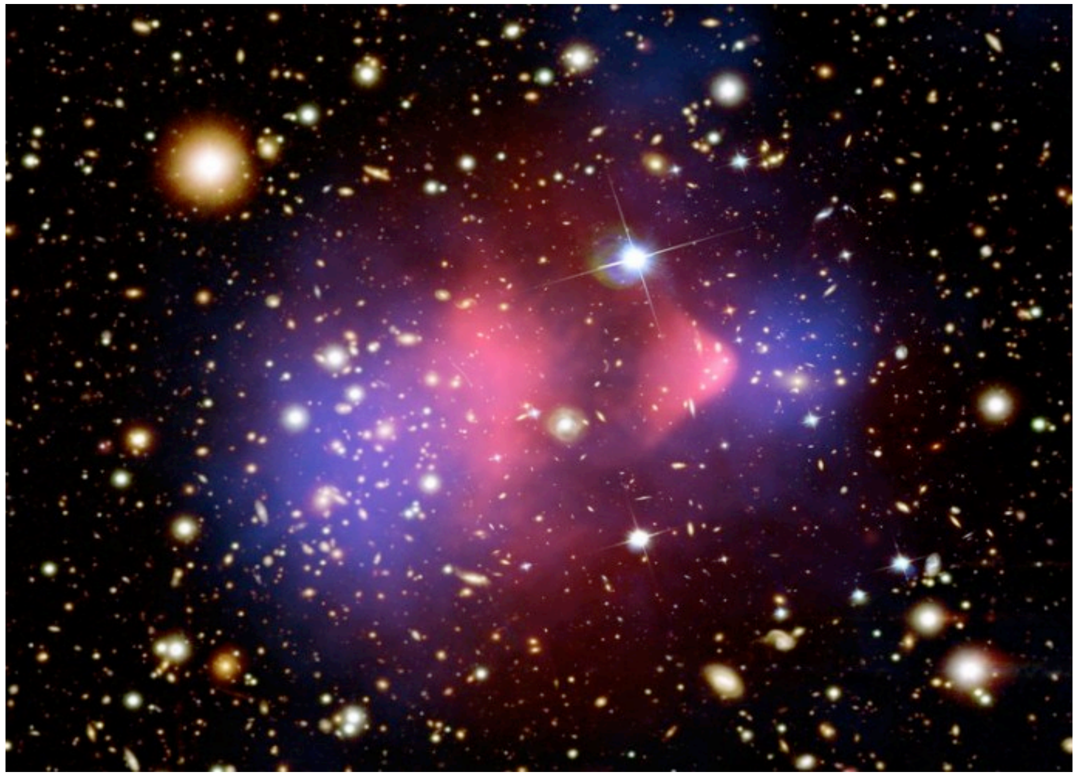
$$\frac{1}{\rho_g}\frac{dP}{dr} = -\frac{d\phi}{dr} = -\frac{GM(r)}{r^2},$$

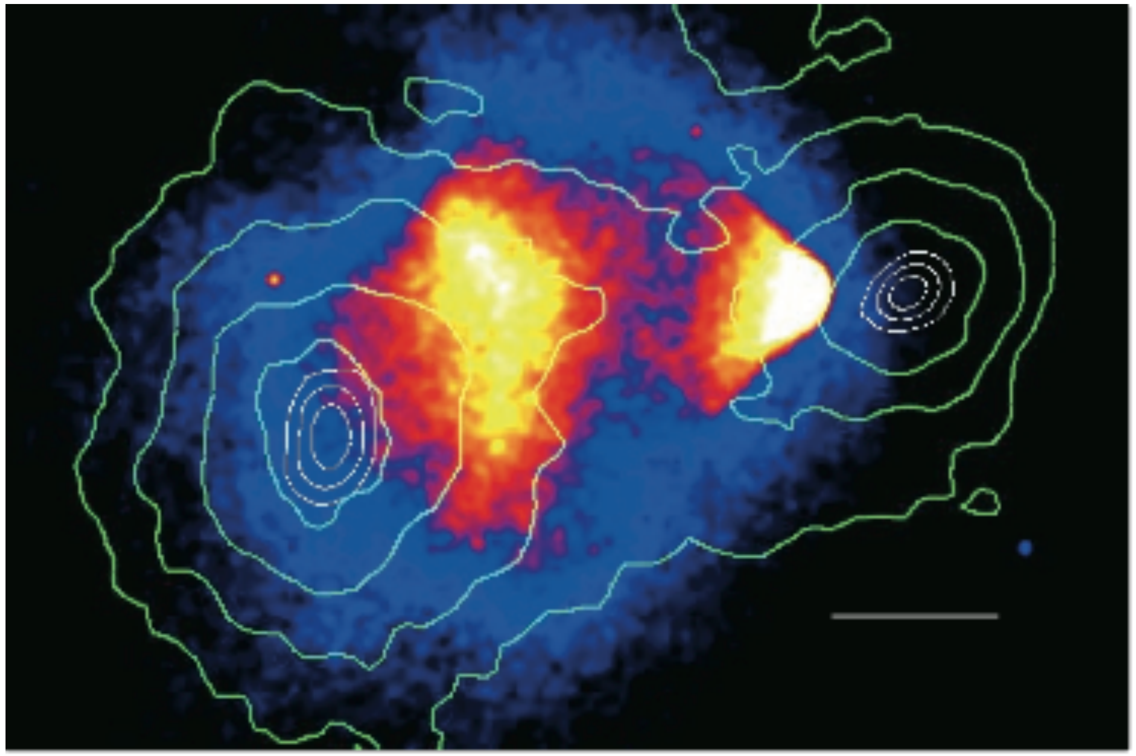
Derivation: multiply equation of hydrostatic equilibrium by r on both sides, integrate over sphere, and relate pressure to kinetic energy (easiest to verify for ideal gas).

HSE mass bias:



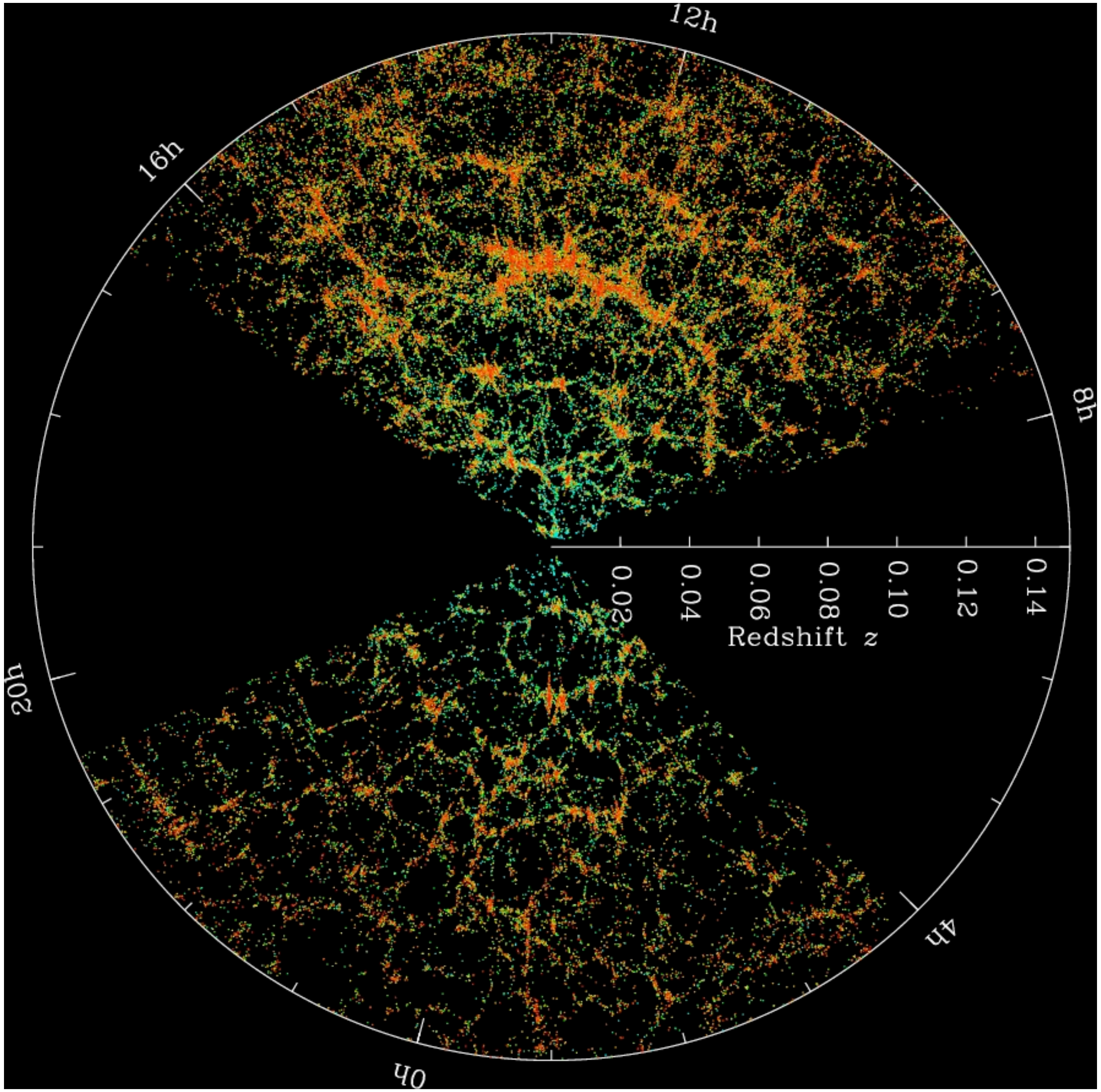
Dark matter with Bullet Cluster





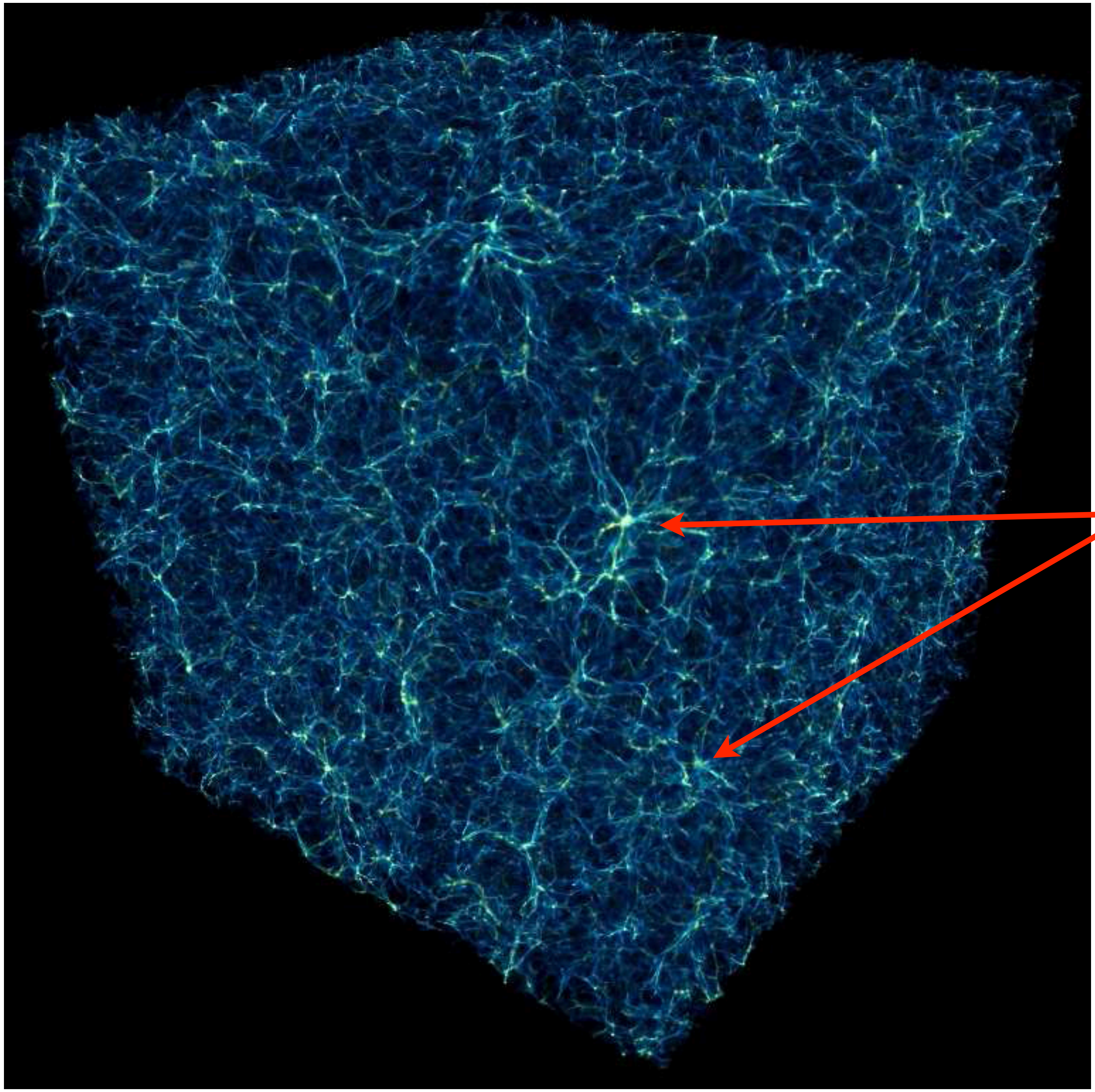
Clowe et al. 2006

Galaxy clusters from sky surveys



(c) SDSS collaboration

Galaxy clusters in simulations



700 Mpc comoving cube

Galaxy clusters: rare peaks in the density field

How many clusters?

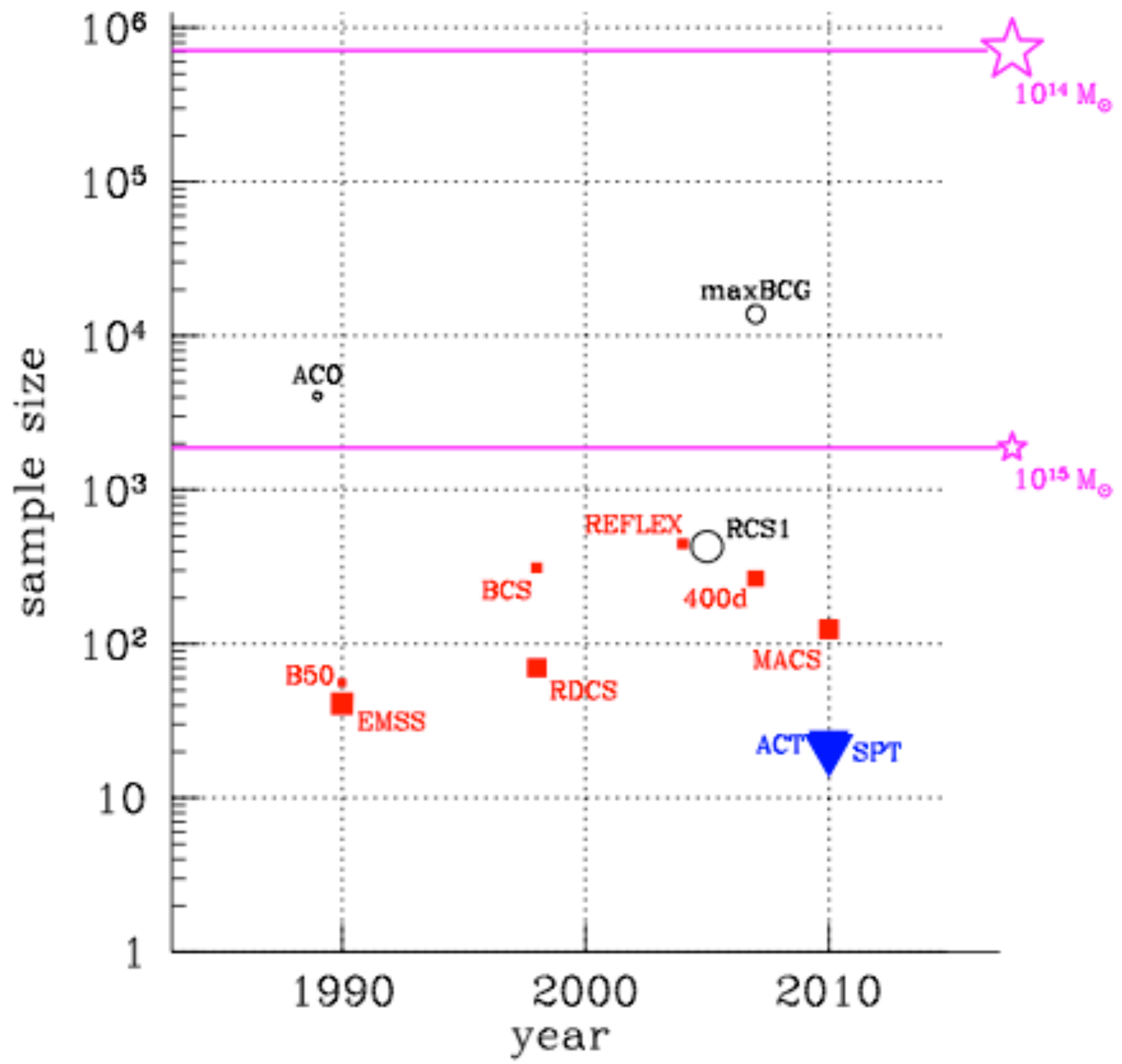


Figure 1: Yields from modern surveys of clusters used for cosmological studies are shown, with symbol size proportional to median redshift. Samples selected at optical (circles), X-ray (red squares), and mm (blue triangles) wavelengths are discussed in Section 3.2 . Stars and horizontal lines show full sky counts of halos expected in the reference ΛCDM cosmology (see Section 2) with masses above 10^{15} and 10^{14} $M_\odot$. Such halo samples have median redshifts of 0.4 and 0.8, respectively.

Allen, Evrard & Mantz 2011

Cosmology with galaxy clusters

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

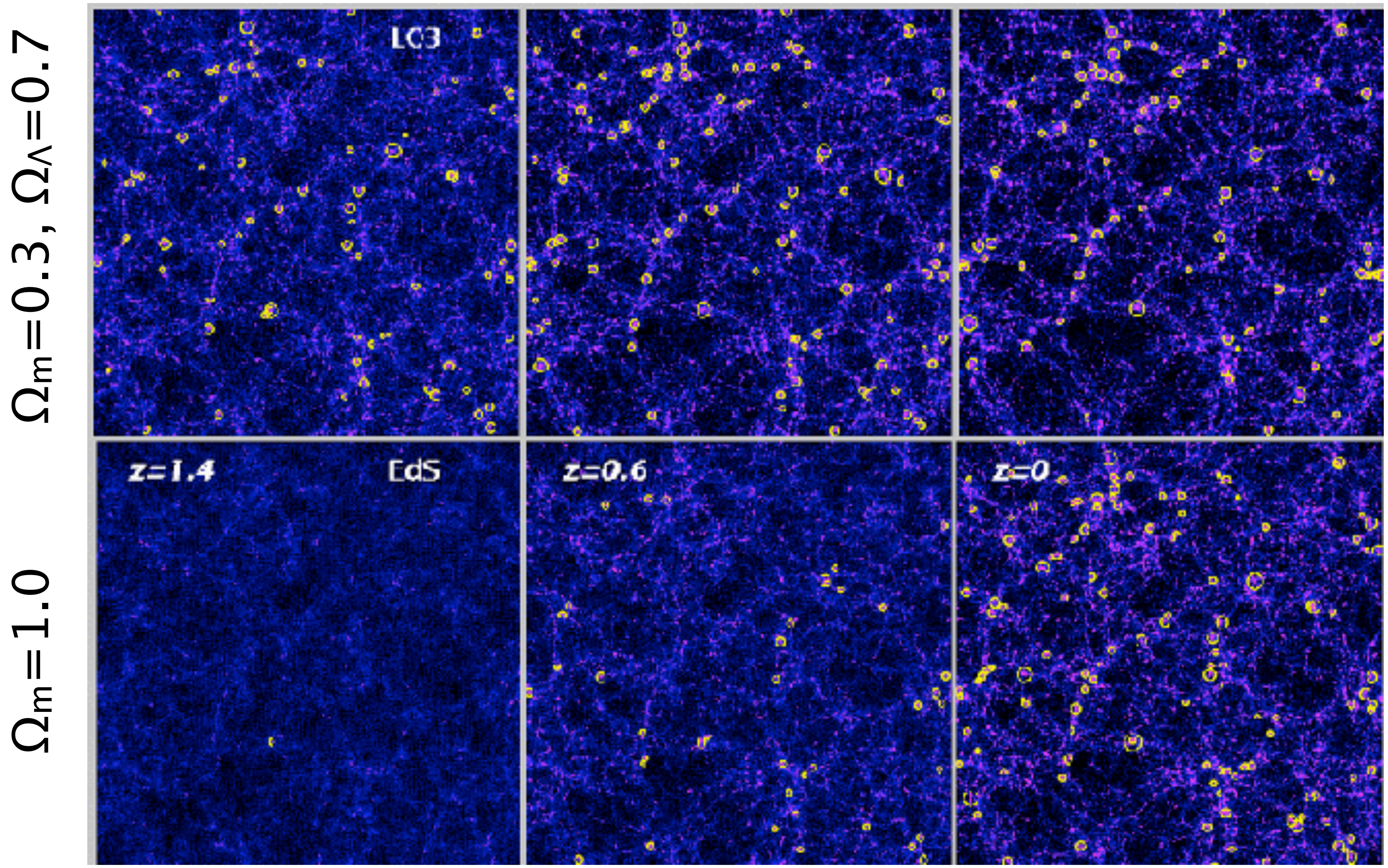
- Measuring distances using clusters as standard candles (joint X-ray/SZE)

- 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 galaxy cluster power spectrum

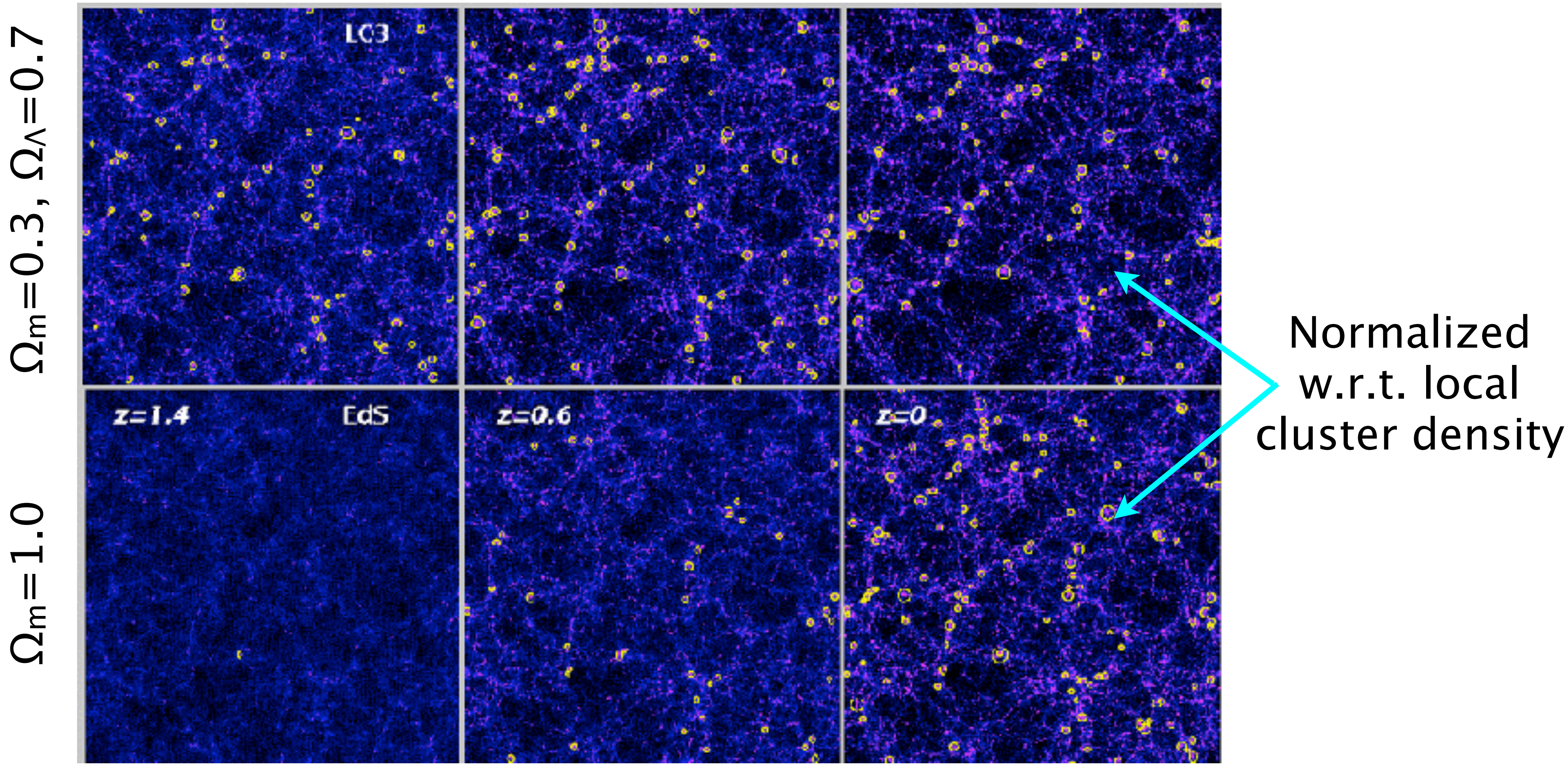
Growth of structures



Borgani & Guzzo, Nature, 2001

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

Growth of structures



Borgani & Guzzo, Nature, 2001

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

Space 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.

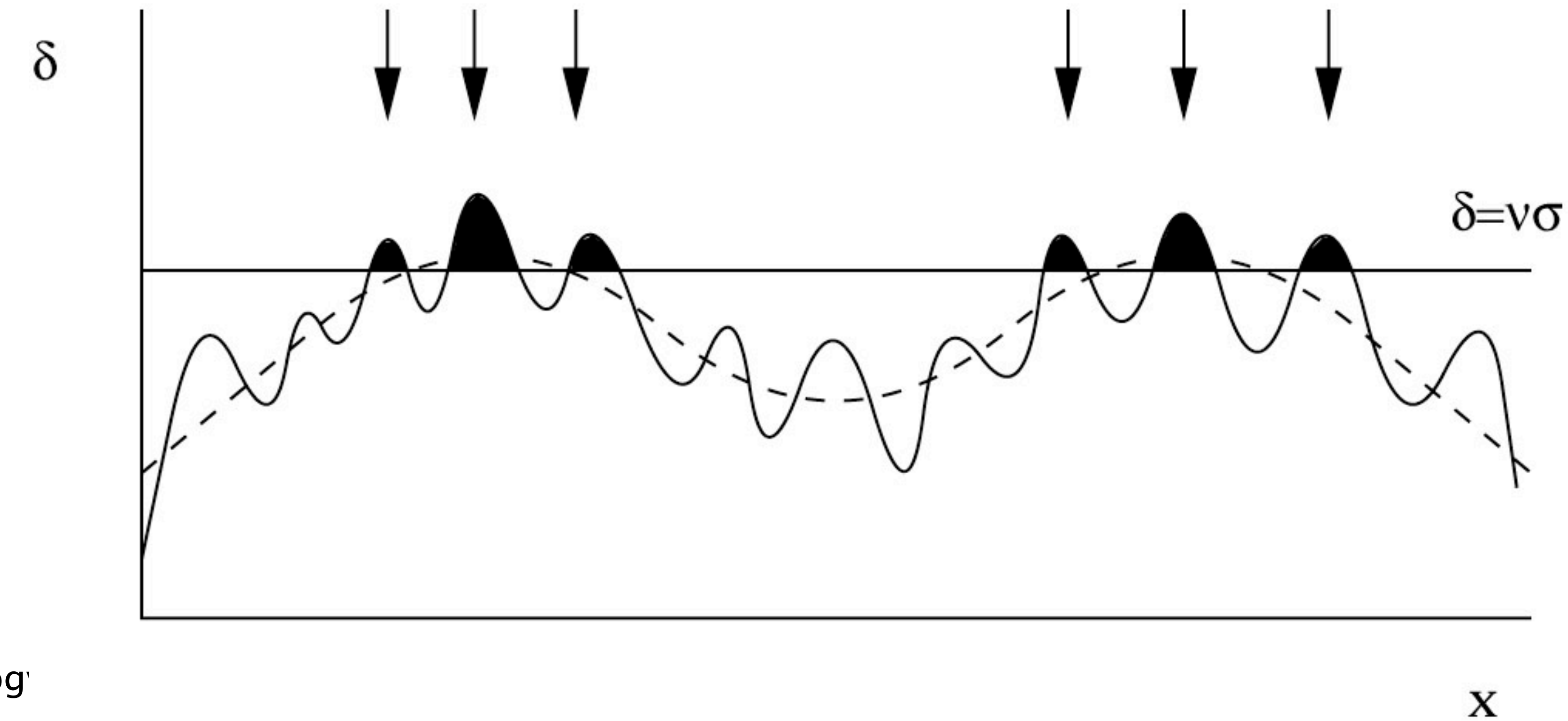
At scales below ~1 Mpc, the physics of baryons start to play an important role, and complicates the process.

The Halo Mass Function

of clusters per unit area and z:

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

- 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 of collapsed objects with mass M is then proportional to an integral over a Gaussian distribution



The Halo Mass Function

Observable

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

Theory

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)

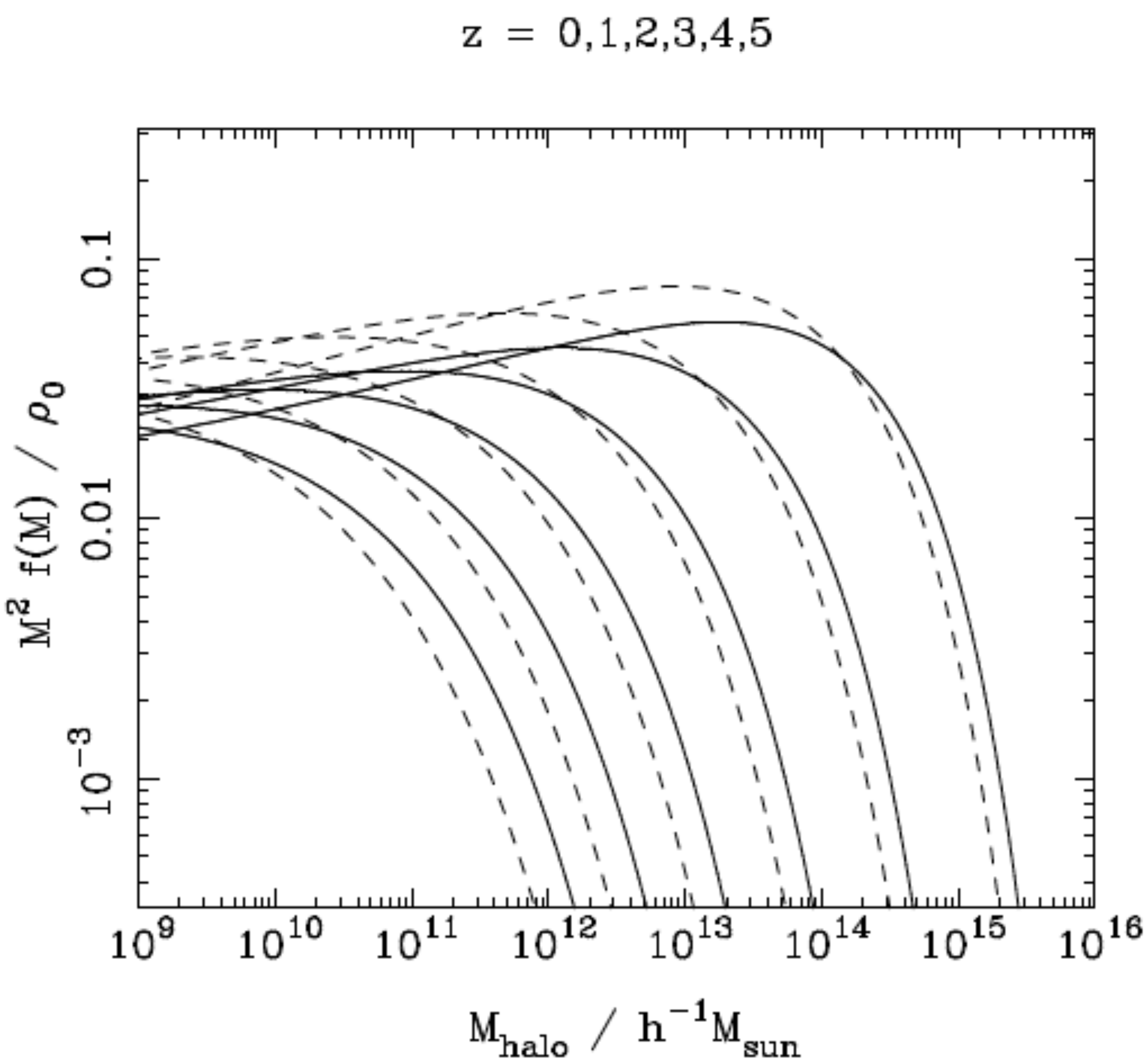
$$\frac{dn_M}{d\ln\sigma^{-1}} = A_J \frac{\Omega_M \rho_{cr0}}{M} \exp[-|\ln\sigma^{-1} + B_J|^{\epsilon_J}]$$

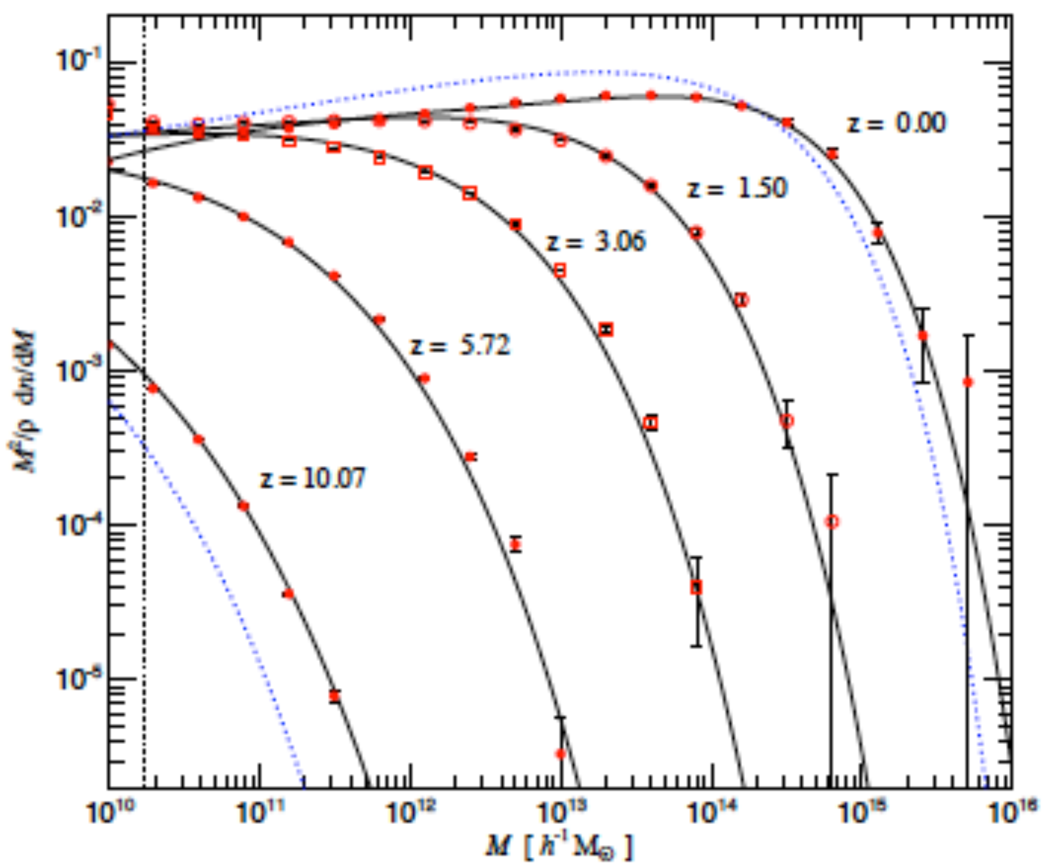
Cosmology predicts the variance on mass scale M:

$$\sigma^2(M,z) = \frac{D^2(z)}{(2\pi)^3} \int P(k)|W_k(M)|^2 d^3k,$$

The Halo Mass Function

Despite its very simple formalism, 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.





Cluster cosmology & astrophysics

Bayes' theorem makes clear that identifying the most likely cosmology is dependent on knowing how likely the observations are within that cosmological model:

$$P(C \mid R) \sim P(R \mid C)\, P_{prior}(C)$$

For galaxy clusters, nonlinear dynamics and astropysical uncertainties (e.g. uncertain baryonic physics) complicate the computation of the observable likelihood $P(R \mid C)$.

The question of computing the likelihood can be split into two parts:

- How many clusters of mass M exist in this cosmology at redshift z?

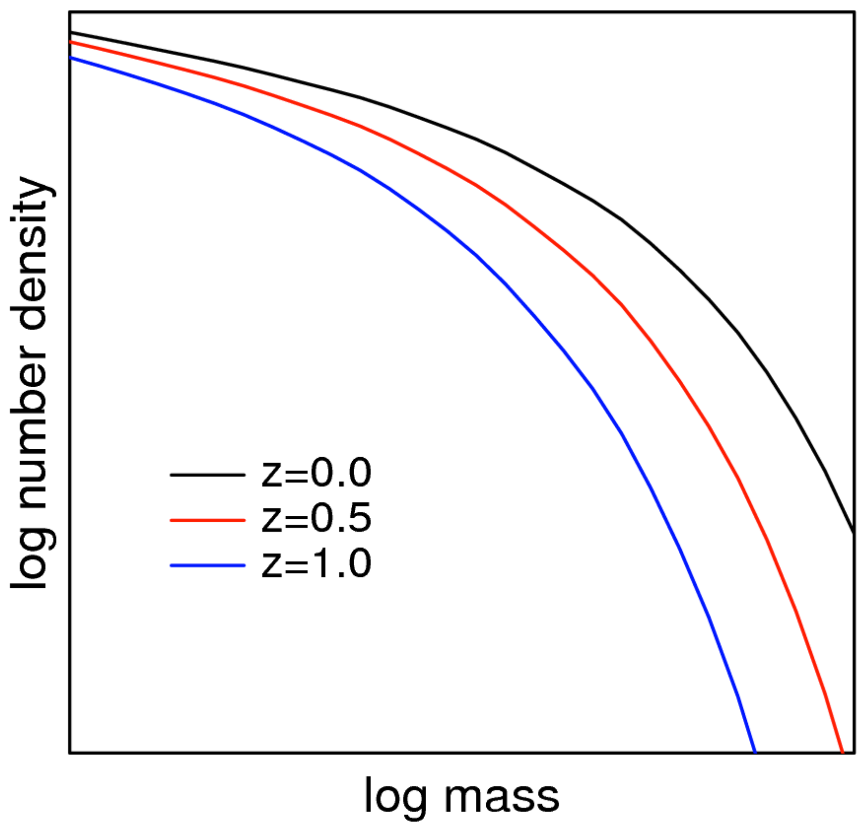
- What is the likelihood that a cluster of mass M at redshift z will have temperature T_x (or some other observable)

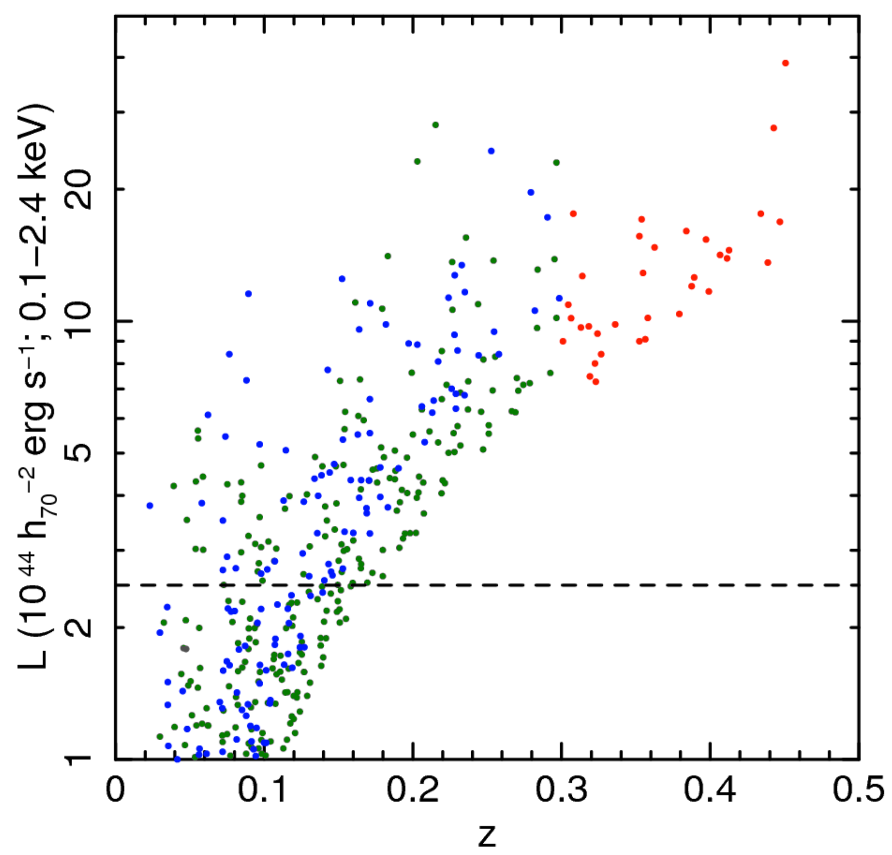
Scaling relations

Prediction in terms of mass

Detection via X-ray flux, SZ flux, optical richness

$dN / \; dz \, dM \quad \rightarrow \quad dN / dz \, dF$

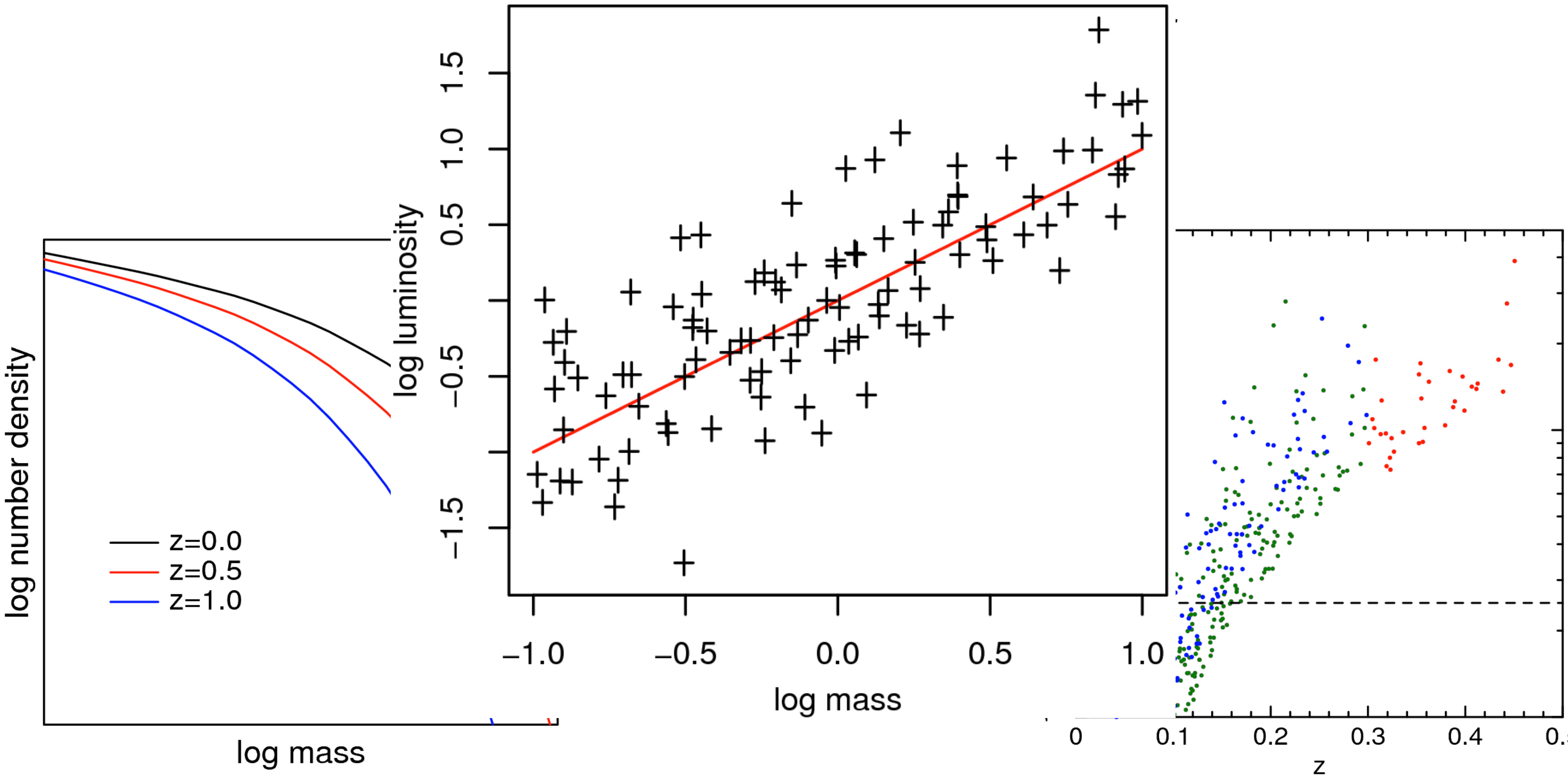




Scaling relations

Prediction in terms of mass

Detection via X-ray flux,
SZ flux, optical richness



Self-similar scaling

The simplest model to explain the physics of the ICM is based on the assumption that only gravity determines its properties.

This makes clusters a scaled version of each other.

X-ray temperature specifies the thermal energy per gas particle.

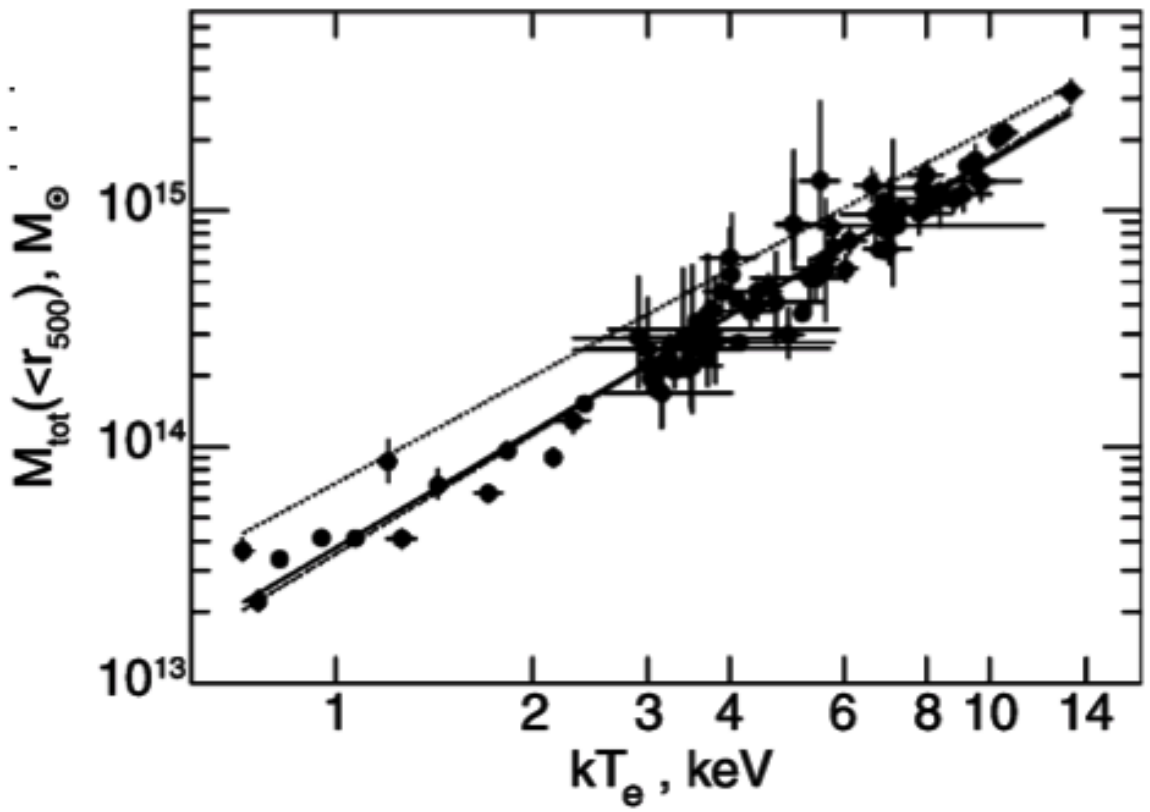
For hydrostatic equilibrium: $T \propto \frac{M}{r}$

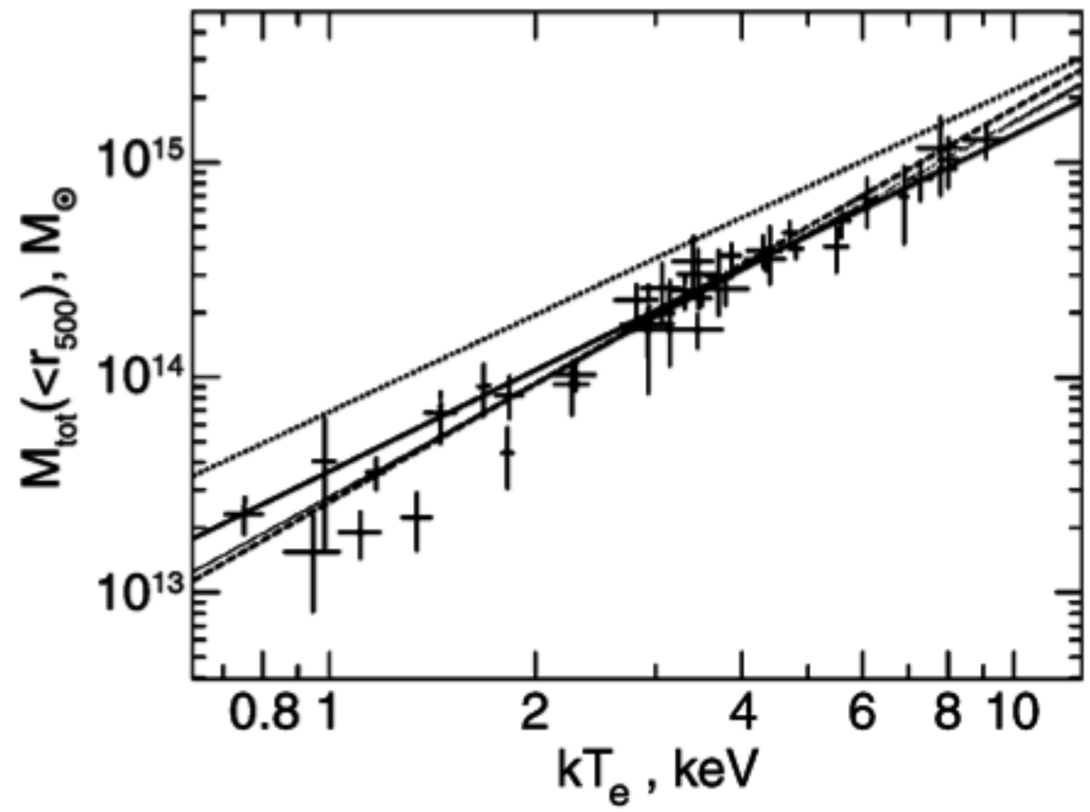
$$M_{200} = \frac{4\pi}{3} \Delta_c \rho_{\rm crit} r_{200}^3$$

$$T \propto = \frac{M_{200}}{r_{200}} \propto r_{200}^2 \propto M^{2/3}$$

M–T scaling relation

$$T \propto = \frac{M_{200}}{r_{200}} \propto r_{200}^2 \propto M^{2/3}$$





$$M_{500} = 3.57 \times 10^{13}\, M_\odot \left(\frac{kT}{1\, keV}\right)^{1.58}$$

X-ray temperature is good measure of virial mass (better than velocity dispersion).

M–L and L–T relations

$$T \propto= \frac{M_{200}}{r_{200}} \propto r_{200}^2 \propto M^{2/3}$$

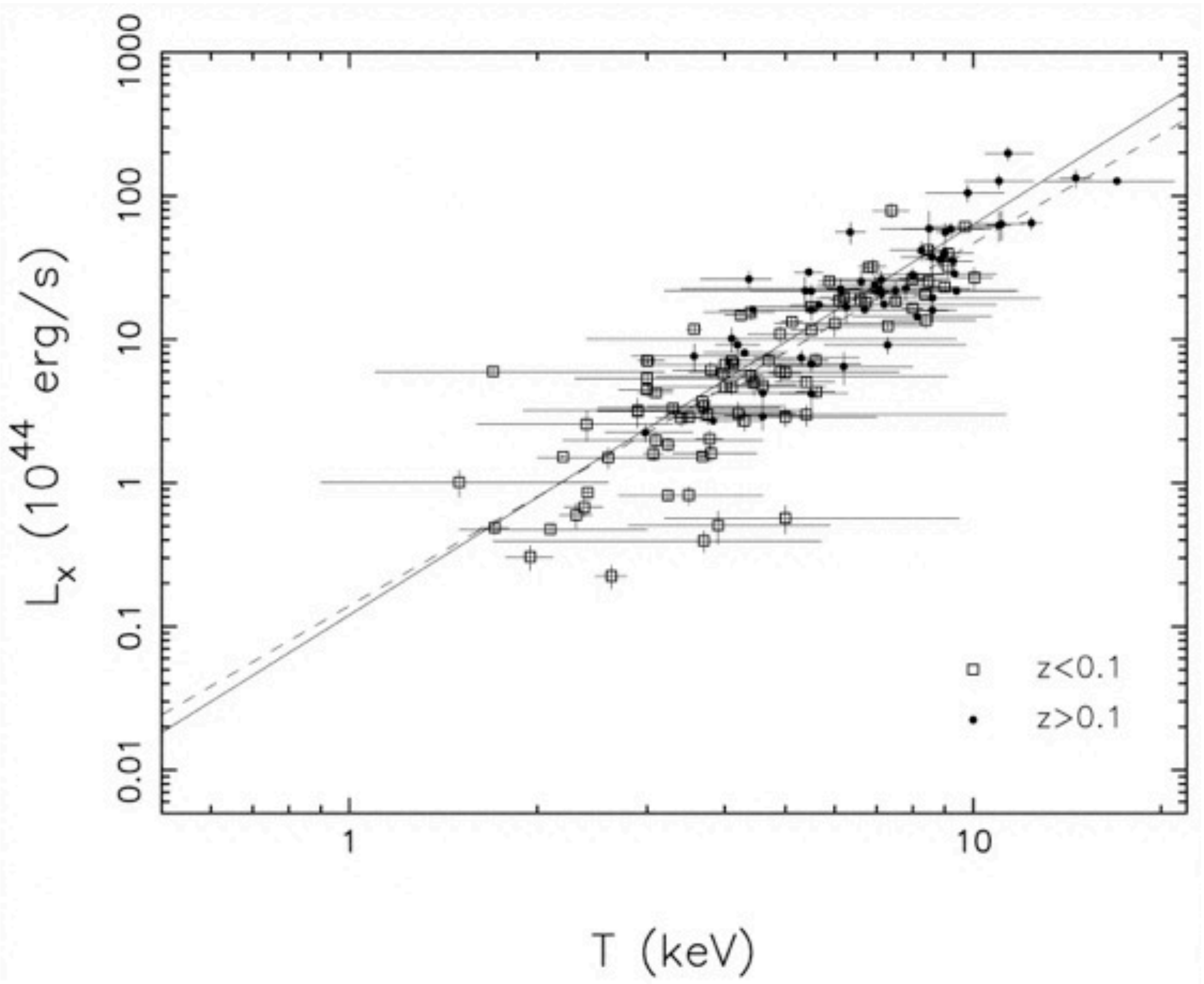
From Bremmstrahlung radiation, we have:

$$L_X \propto \rho_g^2 T^{1/2} r_{\rm vir}^3 \propto \rho_g^2 T^{1/2} M_{\rm vir}$$

$$\rho_g \sim M_g r_{\rm vir}^{-3} = f_g M_{\rm vir} r_{\rm vir}^{-3}$$

where $f_g = M_g/M_{vir}$ is the gas fraction.

$$L_X \propto f_g^2 M_{\rm vir}^{4/3} \propto f_g^2 T^2$$



Measured slopes are L ~ T^A with A=2.5-2.9.

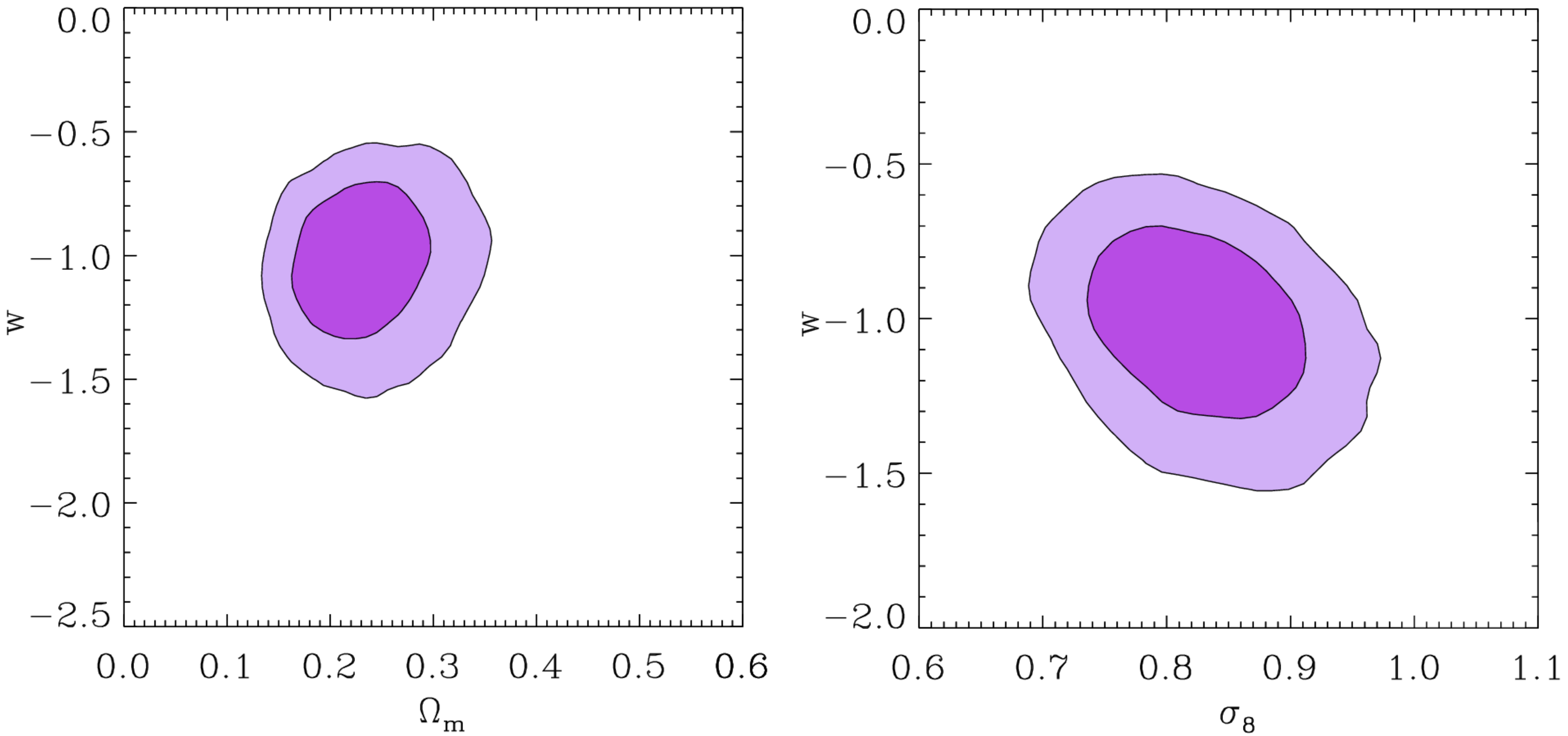
Results for cosmology

Table 2: Recent cosmological results from galaxy clusters[a,b]

Reference[c]	Data	σ_8	Ω_m	Ω_{DE}	w	h
Local abundance and evolution[d]						
M10	X-ray	0.82 ± 0.05	0.23 ± 0.04	$1 - \Omega_m$	-1.01 ± 0.20	
V09	X-ray	0.81 ± 0.04	0.26 ± 0.08	$1 - \Omega_m$	-1.14 ± 0.21	
Local abundance only						
R10	optical	0.80 ± 0.07	0.28 ± 0.07	$1 - \Omega_m$	-1	
H09	X-ray	0.88 ± 0.04	0.3	$1 - \Omega_m$	-1	
Local abundance and clustering						
S03	X-ray	$0.71^{+0.13}_{-0.16}$	$0.34^{+0.09}_{-0.08}$	$1 - \Omega_m$	-1	
Gas-mass fraction						
A08	X-ray		0.27 ± 0.06	0.86 ± 0.19	-1	
A08	X-ray		0.28 ± 0.06	$1 - \Omega_m$	$-1.14^{+0.27}_{-0.35}$	
E09	X-ray		0.32 ± 0.05	$1 - \Omega_m$	$-1.1^{+0.7}_{-0.6}$	
L06	X-ray+SZ		$0.40^{+0.28}_{-0.20}$	$1 - \Omega_m$	-1	
XSZ distances						
B06	X-ray+SZ		0.3	$1 - \Omega_m$	-1	$0.77^{+0.11}_{-0.09}$
S04	X-ray+SZ		0.3	$1 - \Omega_m$	-1	0.69 ± 0.08

Allen, Evrard & Mantz 2011

Results for cosmology

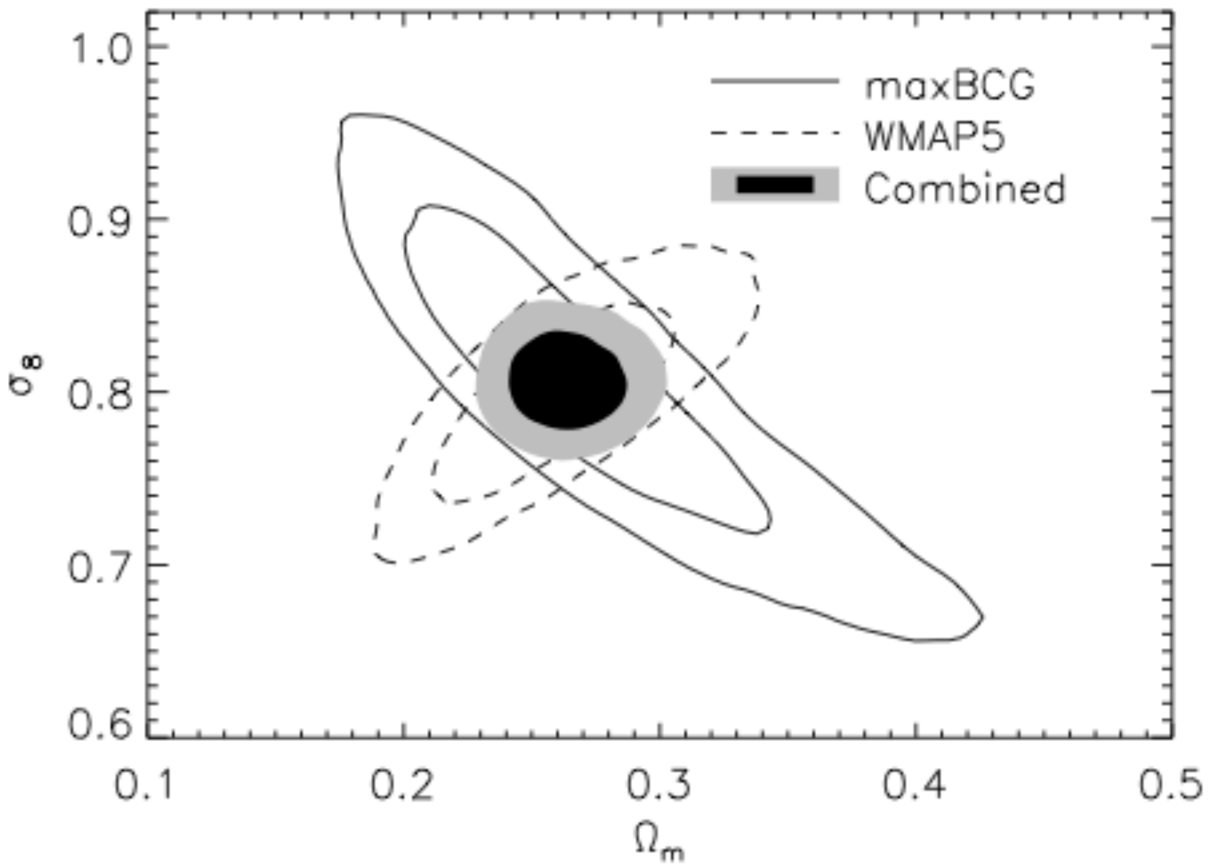


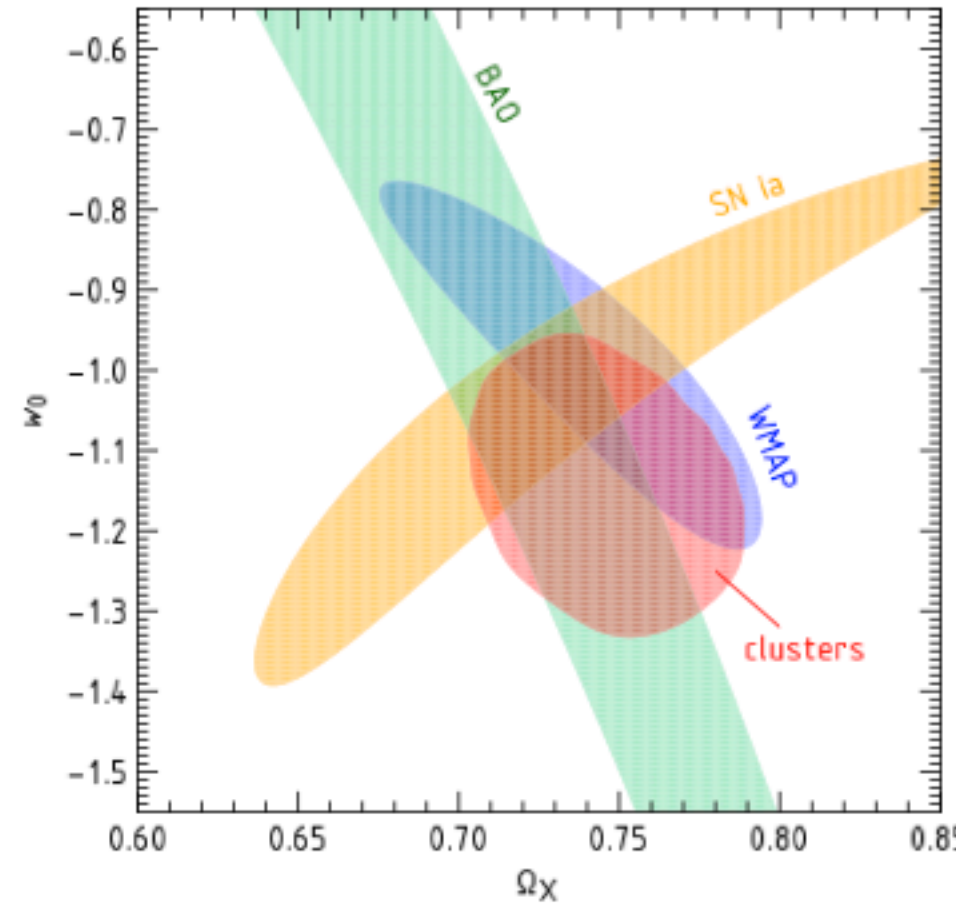
Mantz, Allen, Ebeling et al.

238 clusters, z < 0.5 (XLF), including systematics

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

Results for cosmology

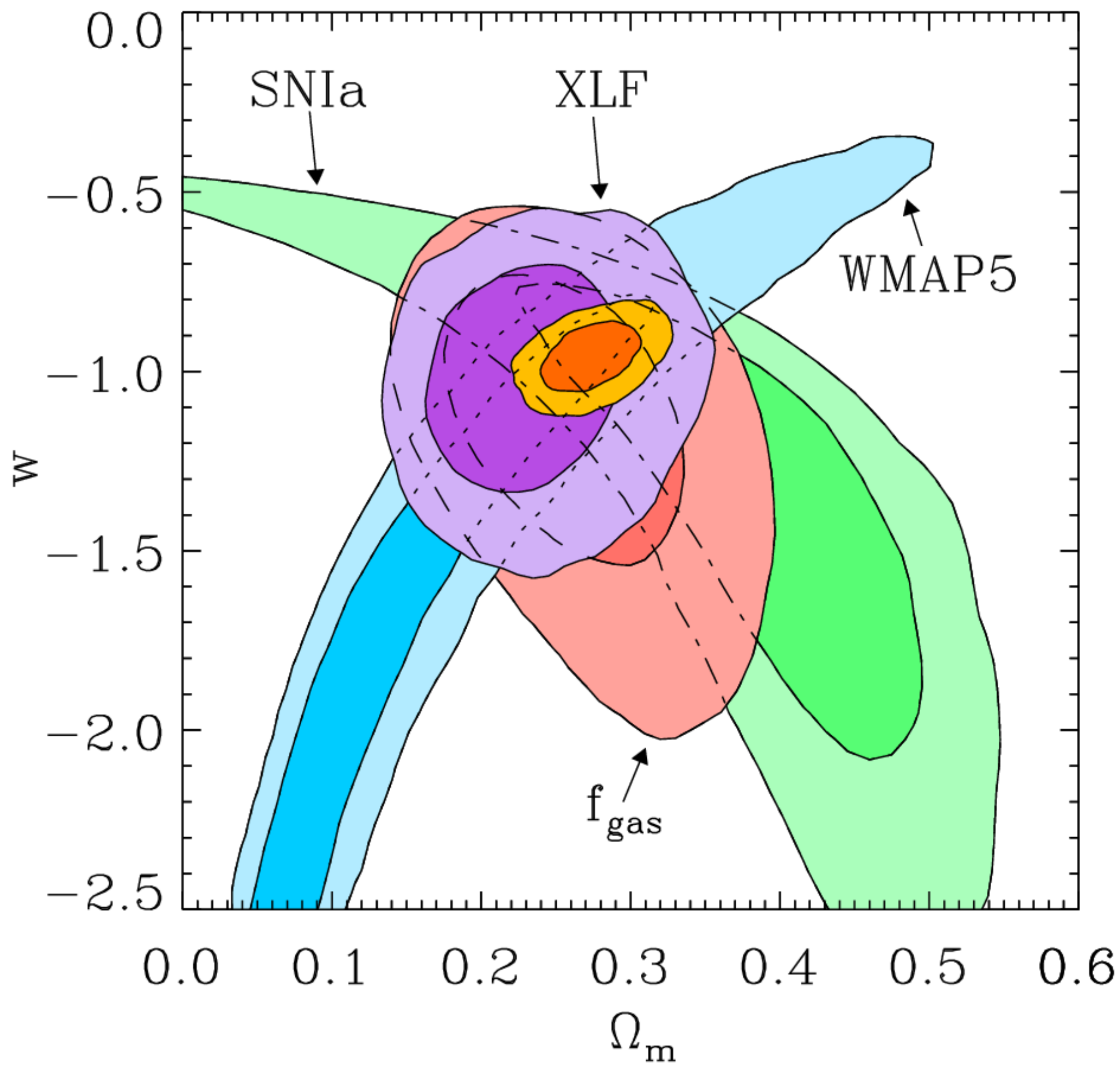


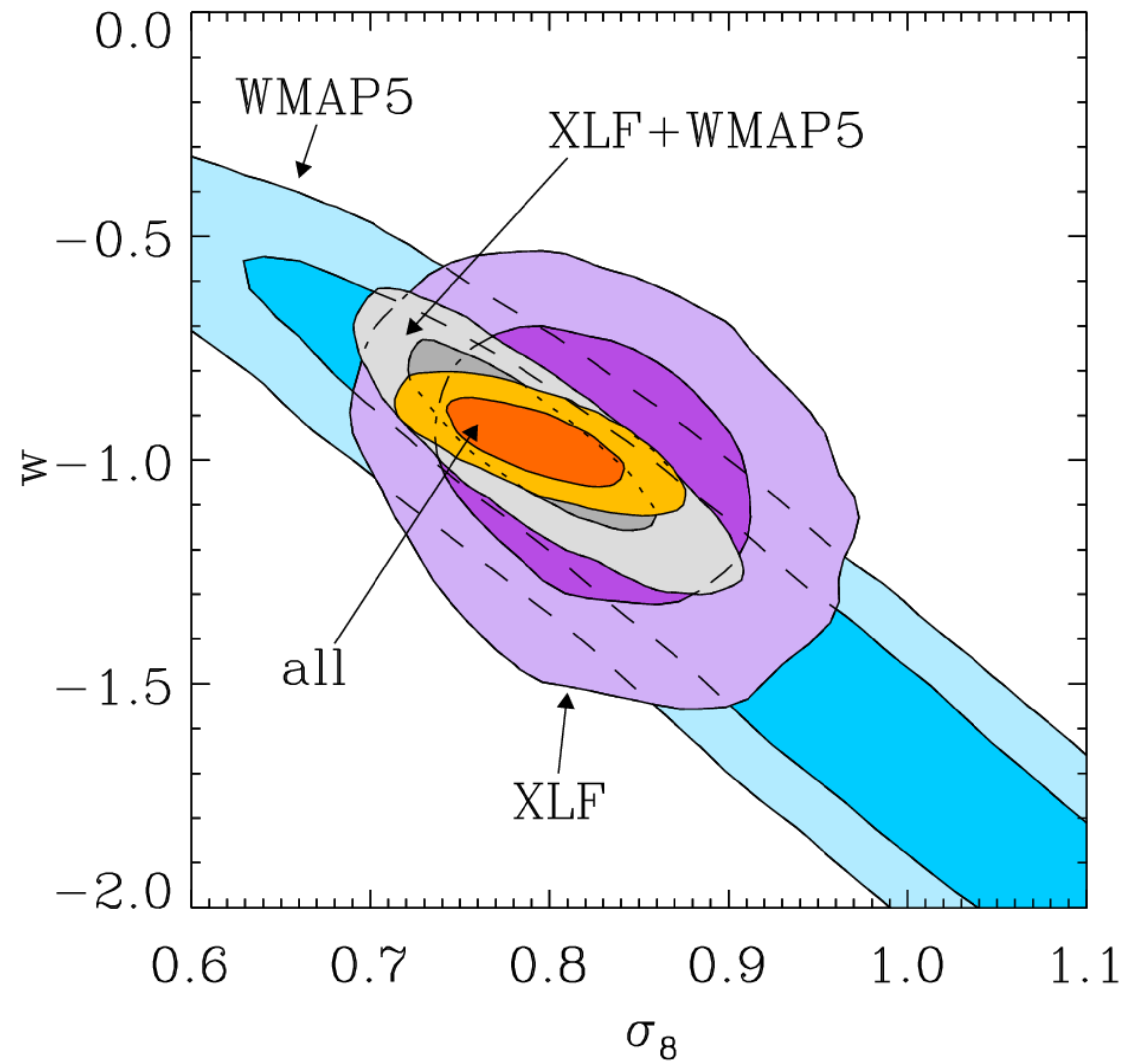


Left: Optical maxBCG sample with WMAP (Dunkley et al. 2009)

Right: 400 sq. deg. X-ray sample + others (Vikhlinin et al. 2009)

Results for cosmology





Mantz, Allen, Ebeling et al.

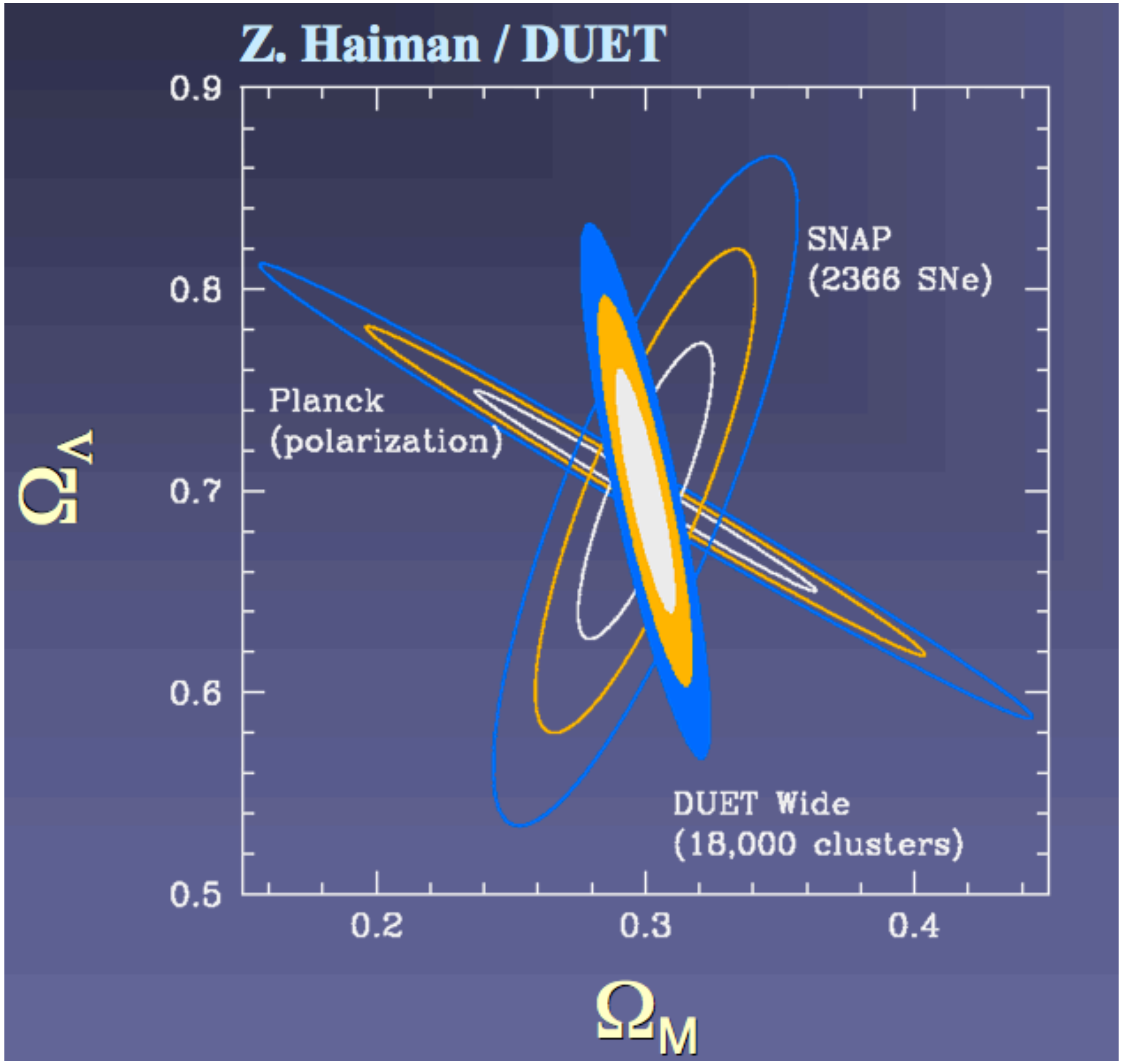
238 clusters, $z < 0.5$ (XLF)
Including systematics

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

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

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

Future constraints



Constraints using dN/dz of ~18,000 clusters in a wide angle X-ray survey (SPT gives similar results)

<u>Power comparable</u> to:

Planck measurements of CMB anisotropies

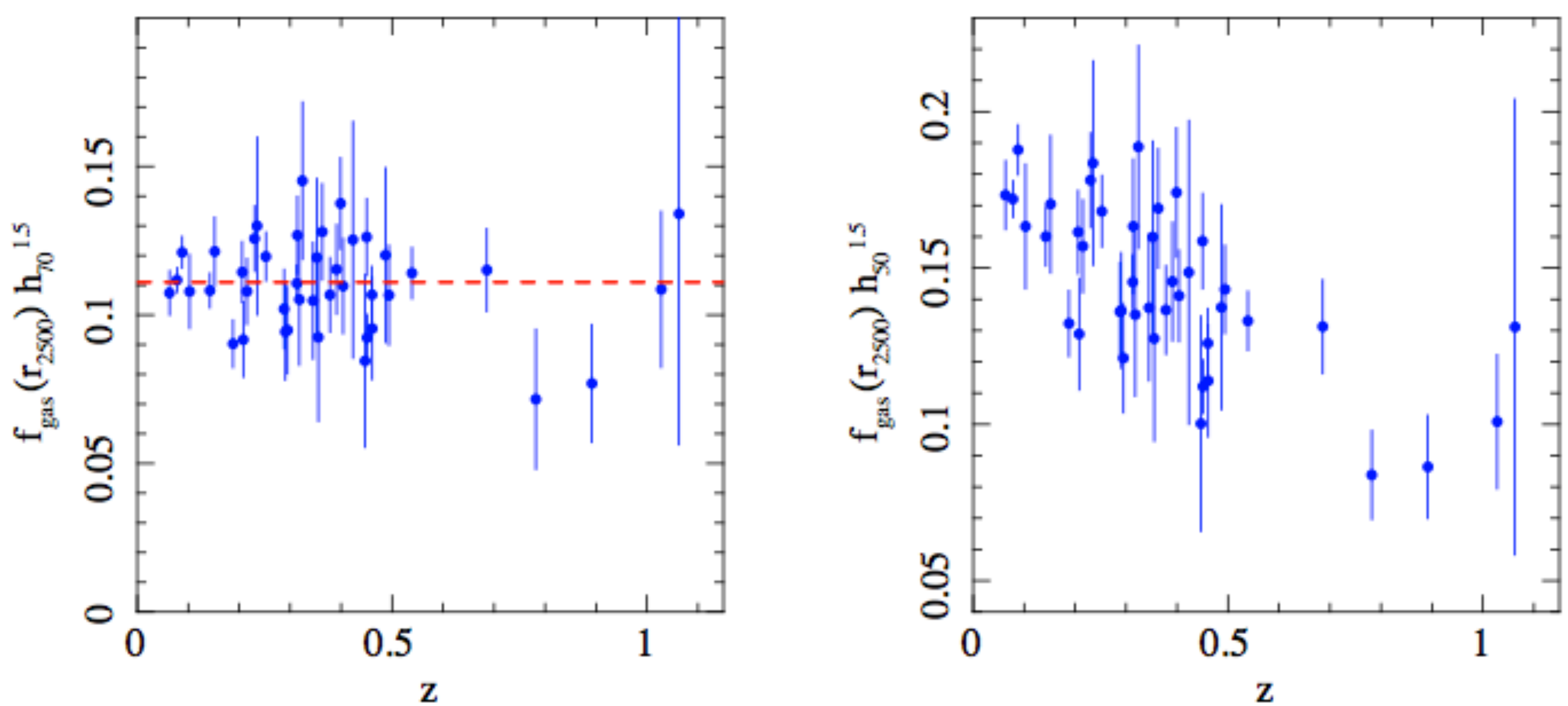
2,400 Type Ia SNe from SNAP

- Ω_M to ~1%
- Ω_Λ to ~5%

Gas mass fraction

Since galaxy clusters collapse from a scale of ~10 Mpc, they are expected to contain a fair sample of the baryonic content of the universe (mass segregation is not believed to occur at such large scales).

The gas mass fraction, f_{gas}, is therefore a reasonable estimate of the baryonic mass fraction of the cluster. It should also be reasonable approximation to the universal baryon mass fraction, $f_B = \Omega_B / \Omega_m$



Allen et al. 2008

Gas mass fraction

Since galaxy clusters collapse from a scale of ~10 Mpc, they are expected to contain a fair sample of the baryonic content of the universe (mass segregation is not believed to occur at such large scales).

The gas mass fraction, f_{gas}, is therefore a reasonable estimate of the baryonic mass fraction of the cluster. It should also be reasonable approximation to the universal baryon mass fraction, $f_B = \Omega_B / \Omega_m$

Mantz, Allen et al.