Intracluster medium properties and scaling relations from galaxy cluster simulations

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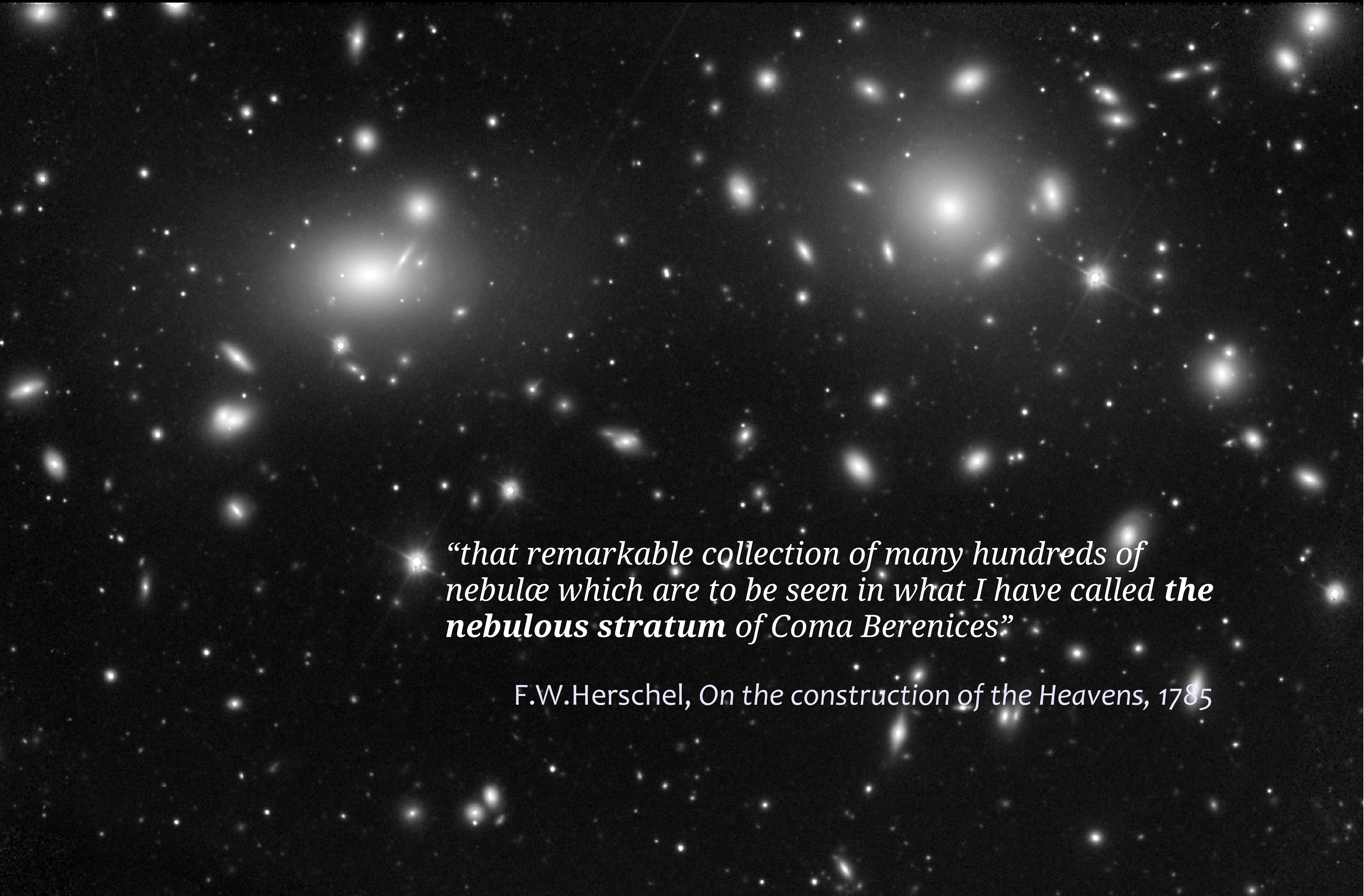
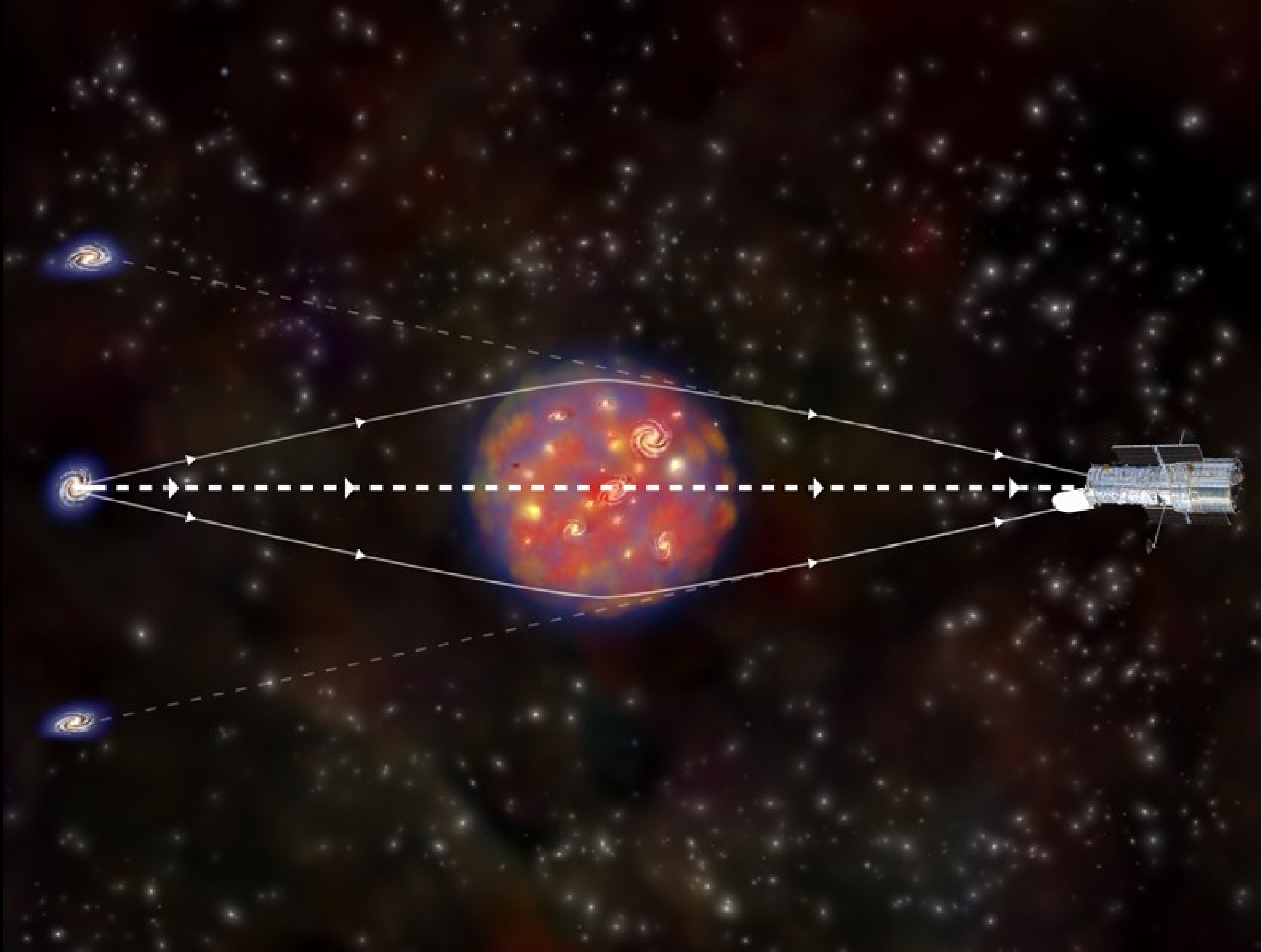
Galaxy groups and clusters



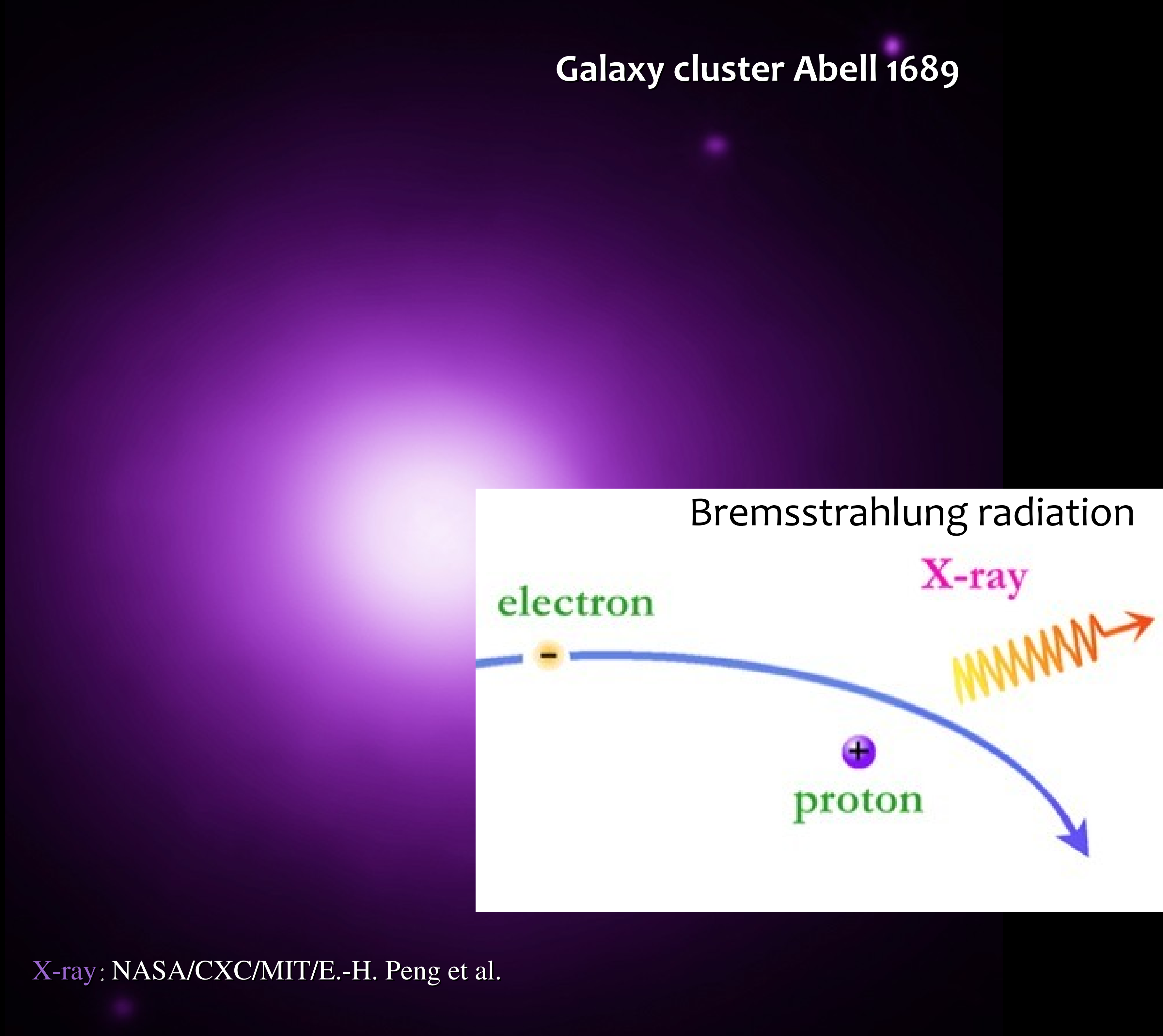
“that remarkable collection of many hundreds of nebulæ which are to be seen in what I have called ***the nebulous stratum*** *of Coma Berenices”*

F.W.Herschel, *On the construction of the Heavens, 1785*

Fritz Zwicky (1898 - 1674)



Galaxy cluster Abell 1689

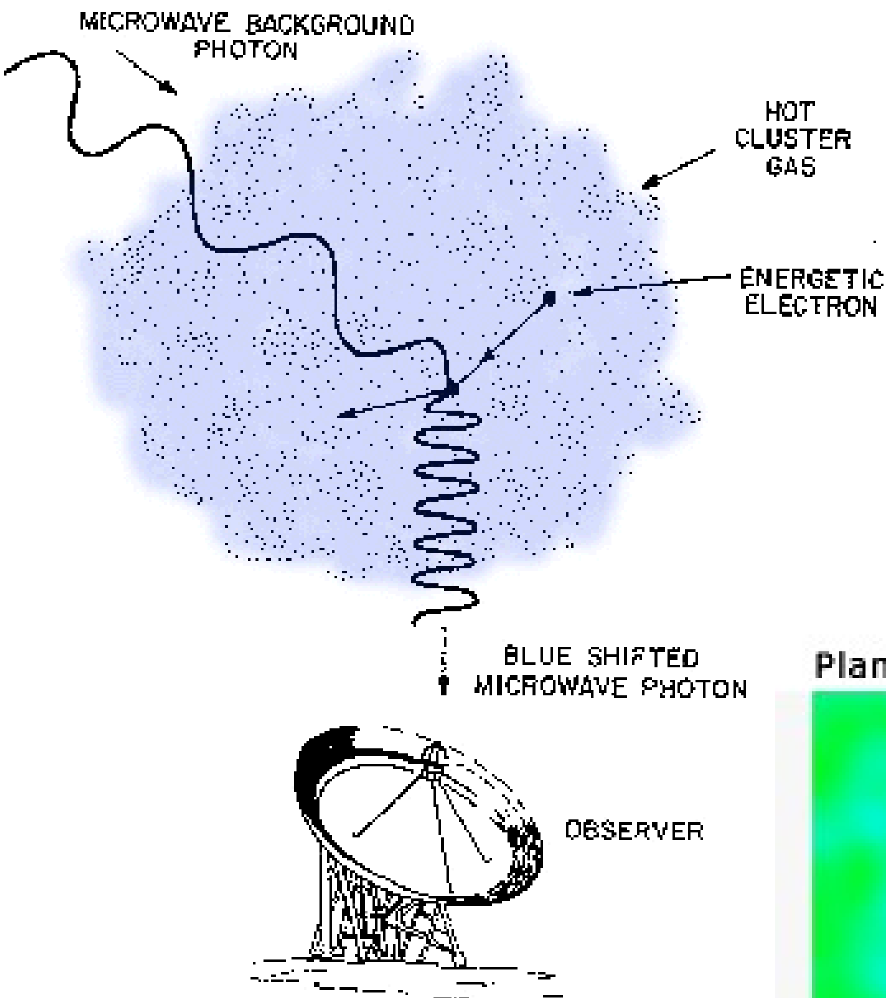


X-ray: NASA/CXC/MIT/E.-H. Peng et al.


Galaxy cluster Abell 1689
X-ray: NASA/CXC/MIT/E.-H. Peng et al.
Optical: NASA/STScI

Sunyaev-Zel'dovich effect (SZE)

inverse Compton scattering of
CMB photons on free electrons in the ICM



Adapted from L. Van Speybroeck

intensity decrement in the CMB is proportional to the Comptonization parameter y

temperature

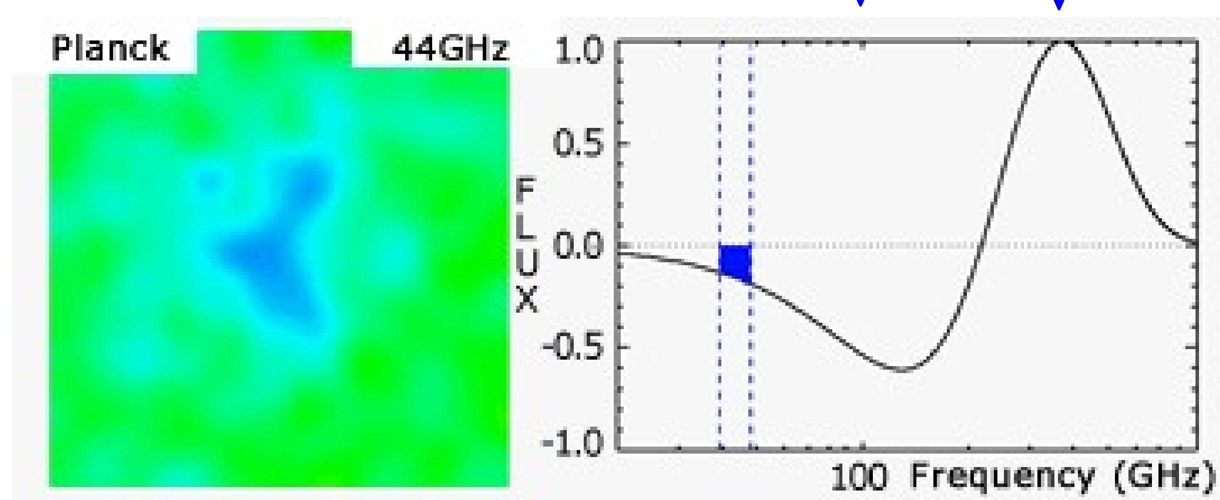
$$y = \int n_e(r)\, \sigma_T\, \frac{k_B T_e(r)}{m_e c^2}\, dl$$

gas density

--> integrated thermal pressure

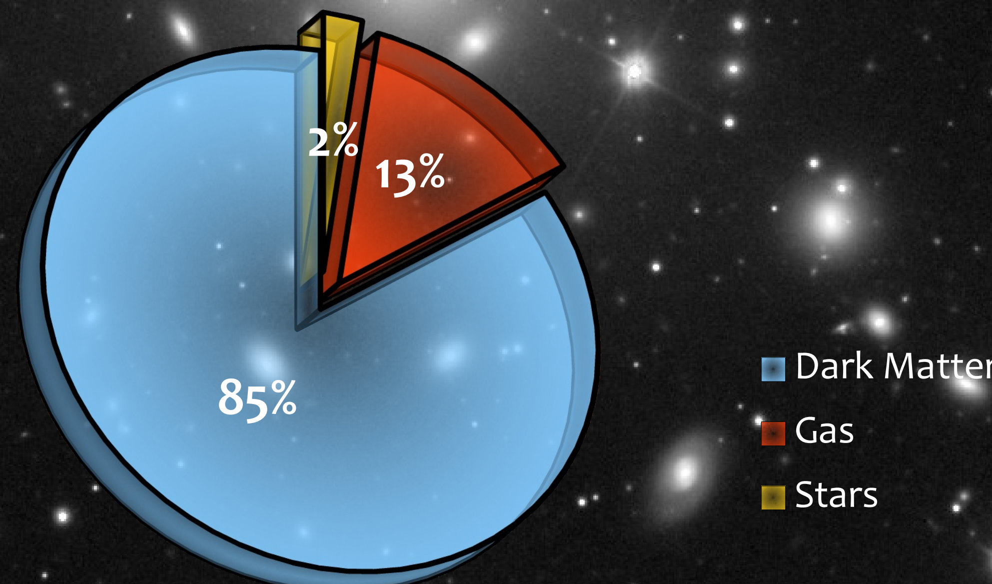
decrease in RJ regime

increase in Wien regime



ESA/Planck Collaboration

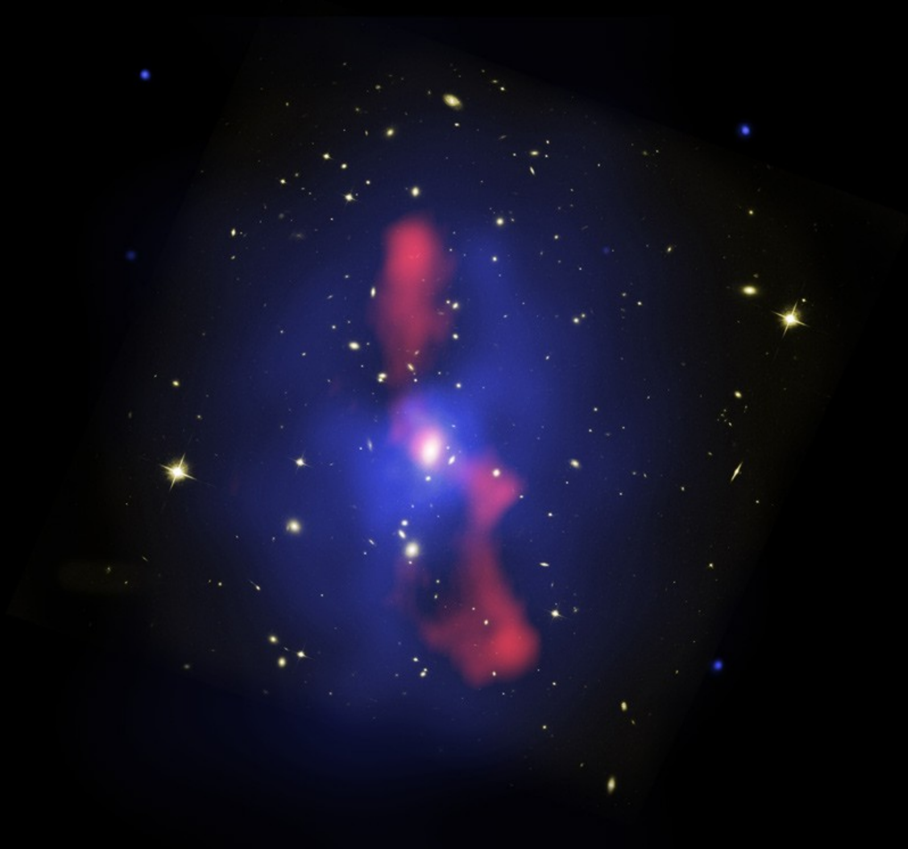
- largest virialized structures
- up to 1000 galaxies
- $M_{vir} = 10^{14}$-10^{15} M_{sun}
- R_{vir} = 900-1500 kpc
- $\sigma_{gal} \sim 1000$ km/s
- $T_{gas} \sim 10^7$-10^8 K



For reviews see Biviano 2000, Voit 2005, Kravtsov & Borgani 2012

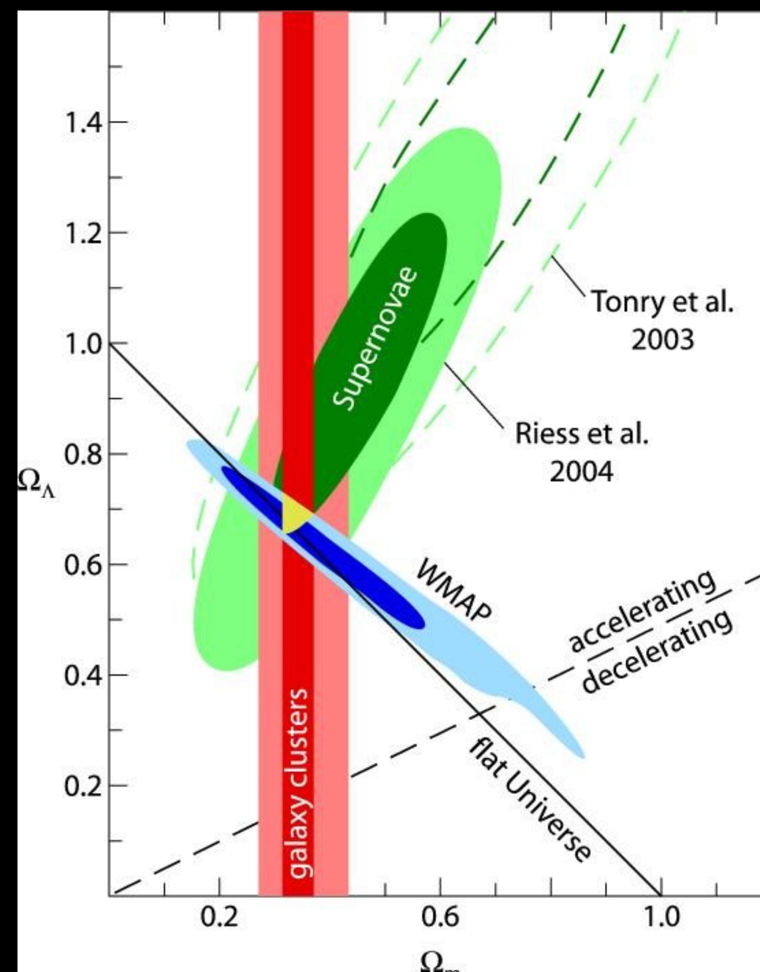
why are galaxy clusters important?

Astrophysical laboratories



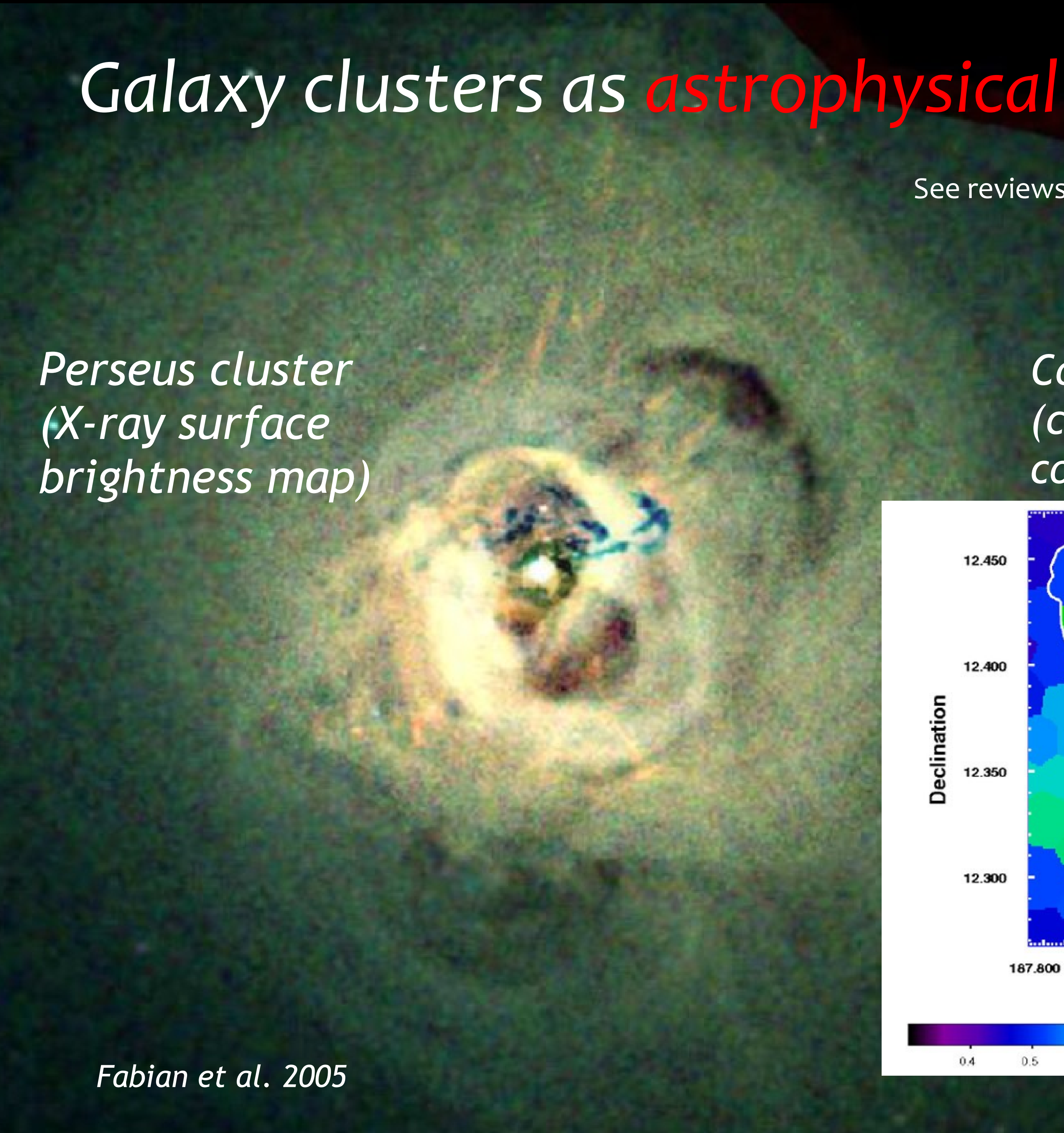
galaxy cluster MS 0735.6+7421
(optical/X-ray/radio image)

Cosmological probes



Galaxy clusters as *astrophysical laboratories*

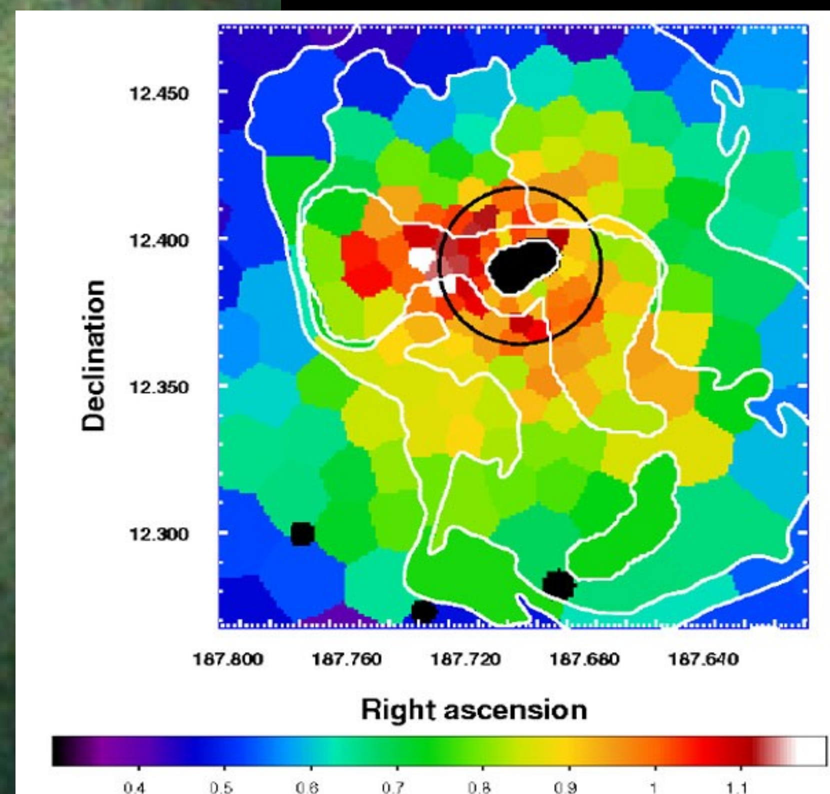
See reviews from McNamara & Nulsen 2007
and Boehringer & Werner 2010



Perseus cluster
(X-ray surface brightness map)

Fabian et al. 2005

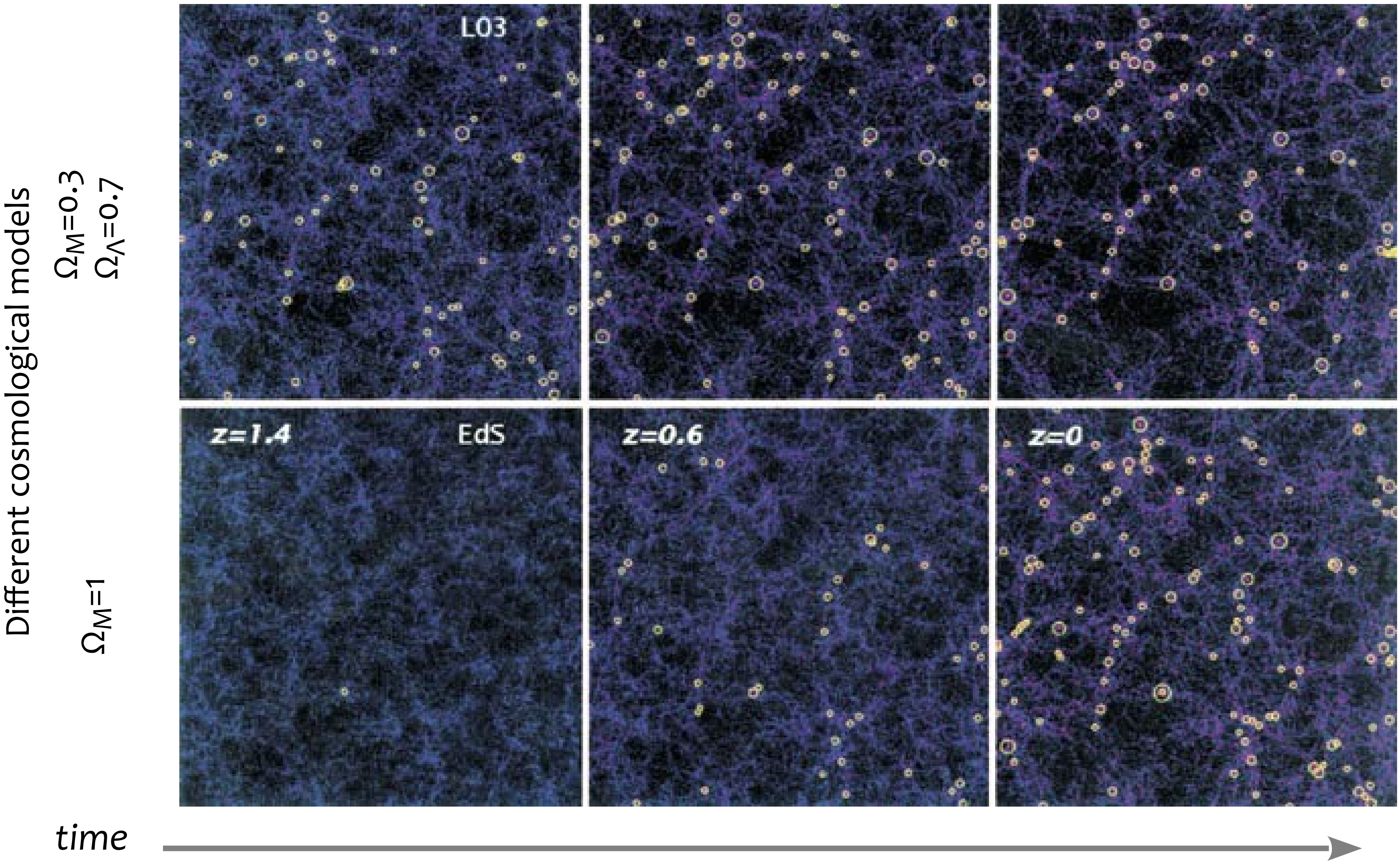
Coma cluster
(color: metallicity map contours: radio emission)



Simionescu et al. 2009

Galaxy clusters as cosmological probes

--> evolution of the cluster mass function



Borgani & Guzzo (Nature) 2001

From observations to cluster total mass

Masses of individual clusters:

- tracing dynamics of galaxies in clusters
- measuring X-ray/radio properties of the Intracluster medium
- strong (and weak) gravitational lensing measurements

Extremely good characterisation...

...but observationally expensive!

From observations to cluster total mass

Scaling relations

- power law relations providing direct link between observables and cluster masses
- self-similar model (Kaiser 1986)
  - neglecting dissipative, non-gravitational effects, the dimensionless properties are expected to be self-similar* in time
- <u>ideal mass proxy</u> has:
  - low intrinsic scatter
  - insensitive to cluster dynamical state

Simulations of galaxy clusters

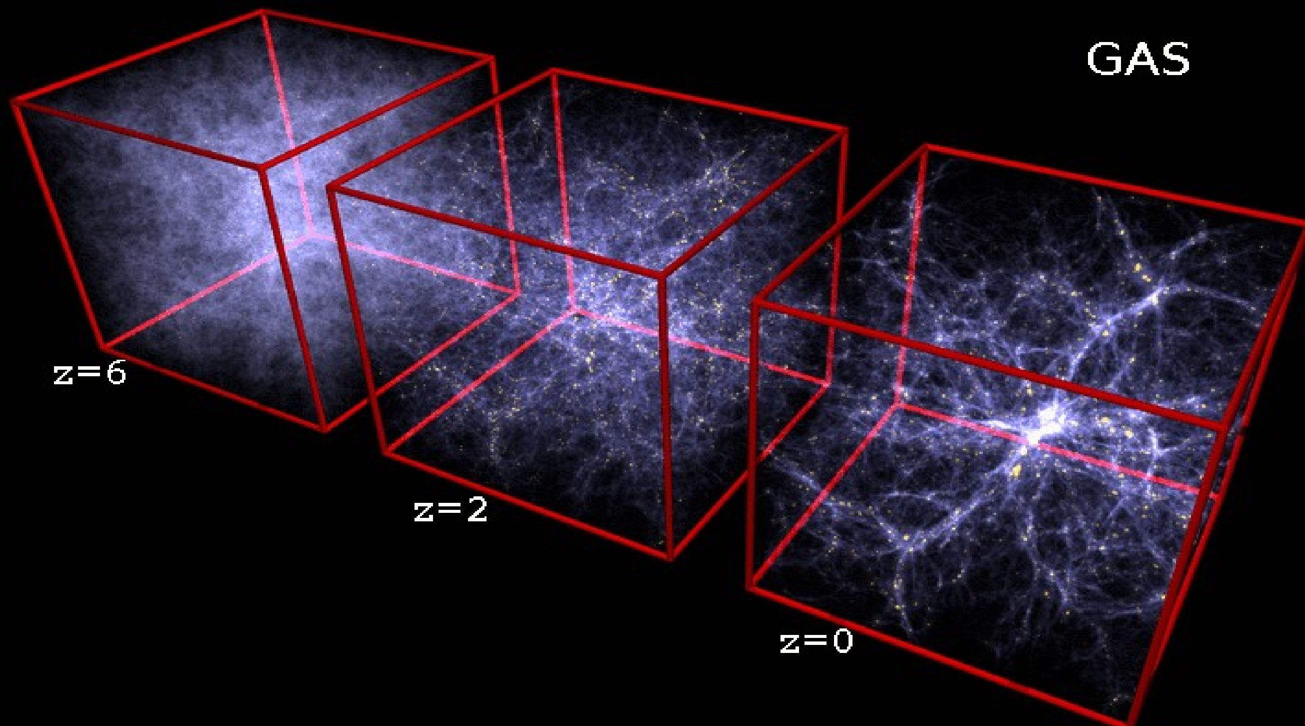
**smallest structures are expected to be scaled down versions of larger ones*

Main goal:

- **stability and robustness**
of scaling relations with respect to ICM physics
- **evolution/redshift dependence**
of scaling relations
- **observational systematics**

Fabjan et al. (2011), Planelles et al. (2013), Fabjan et al. (in prep)

Cosmological simulations



Credit: Volker Springel

- TREE-PM SPH code GADGET-3 (Springel 2005)
- Λ-CDM cosmology
- Star formation from a subresolution multiphase model (*Springel & Hernquist 2003*)
- Metal production from SN Ia, SN II, intermediate and low mass stars (*Tornatore et al. 2007*)
- Kinetic and mechanical feedback (e.g. supernovae driven winds, feedback from active galactic nuclei)

Cluster samples

Large statistical cluster sample

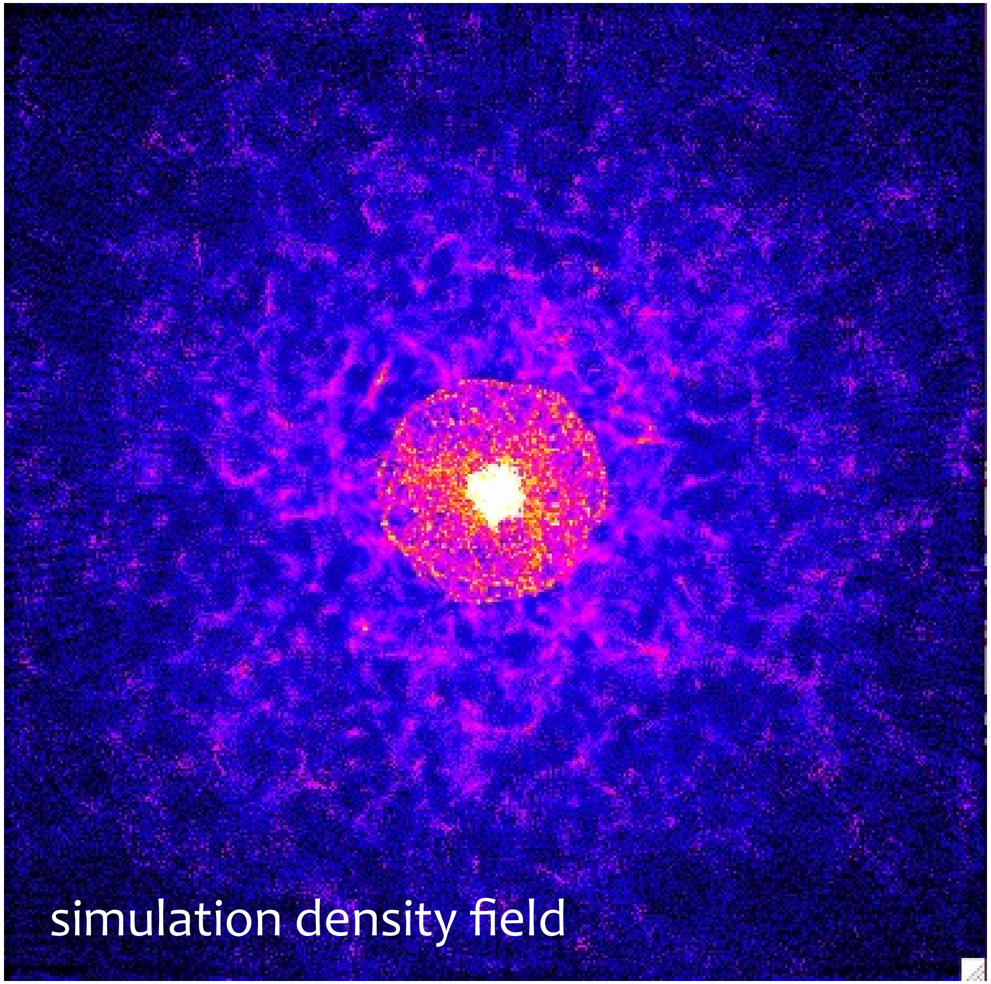
Cosmo box:

1 Gpc/h; 1024^3 particles

29 Lagrangian regions

(~160 clusters,

$M_{vir} > 3 \cdot 10^{13}\ M_{sun}/h$)



- non-radiative simulations:
  NR
- radiative simulations:
  CSF - radiative cooling
  + star formation
  + galactic winds

Bonafede et al. (2011)

Cluster samples

Cosmo box:

479 Mpc/h; 1024^3 particles

9 Lagrangian regions:

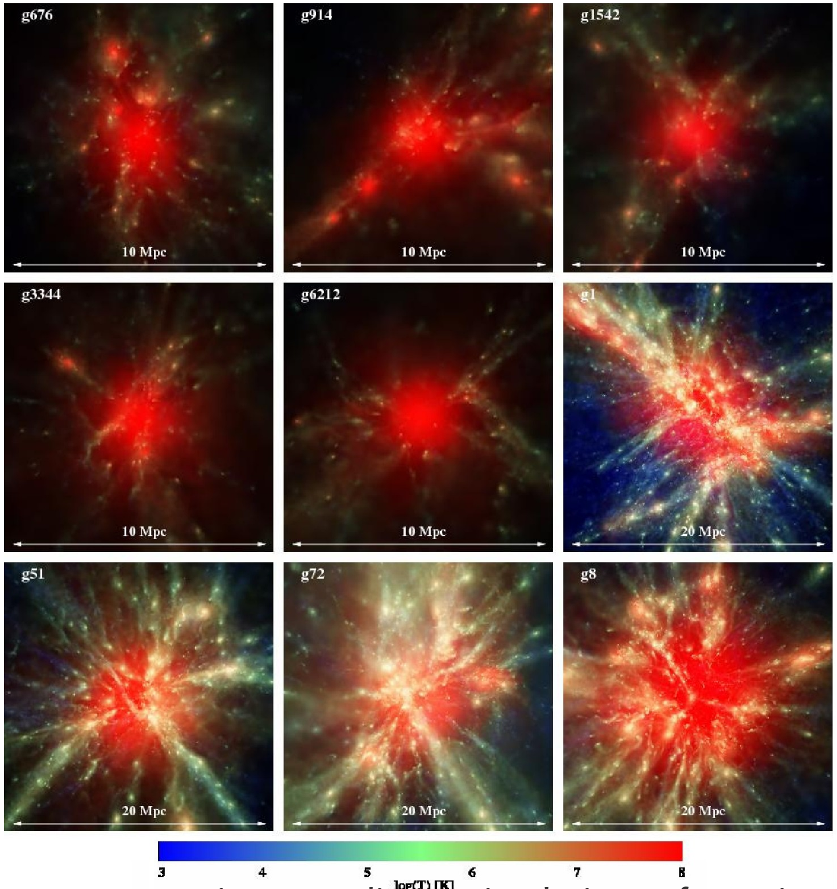
(18 clusters,

$M_{vir} > 5 \cdot 10^{13}\ M_{sun}$)

- non-radiative simulations:
  NR
- radiative simulations:
  CSF - radiative cooling
  + star formation + galactic winds

  AGN - radiative cooling
  + star formation(+ galactic winds)
  + AGN feedback

Small cluster sample
with different ICM physics



Gas temperature in non-radiative simulations of 9 regions
visualized with ray-tracing software SPLOTCH (*Dolag et al. 2009*)

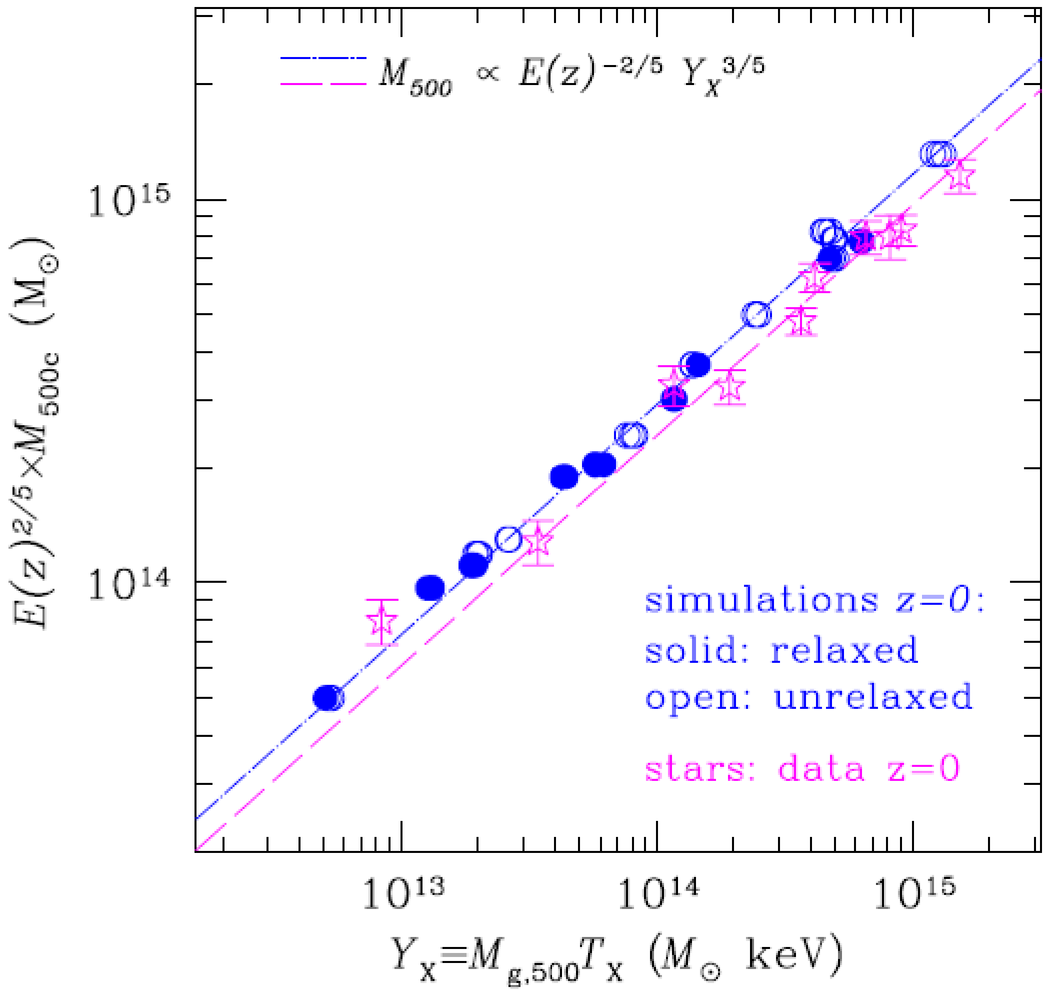
X-ray scaling relations

Kravtsov et al. (2006),
Chandra data from Vikhlinin et al. 2006

X-ray temperature
- sensitive to substructures
- sensitive to dynamical state

Gas mass
- needs X-ray spectroscopy
- less sensitive to cluster mergers

$Y_X = M_{gas}\, T_X$
- ICM total thermal energy
- low scatter mass proxy (5-7%)
- insensitive to mergers
- self-similar slope and redshift evolution



$$M_\Delta = \Delta\, \rho_c(z)\, (4\pi/3) R_\Delta^3$$

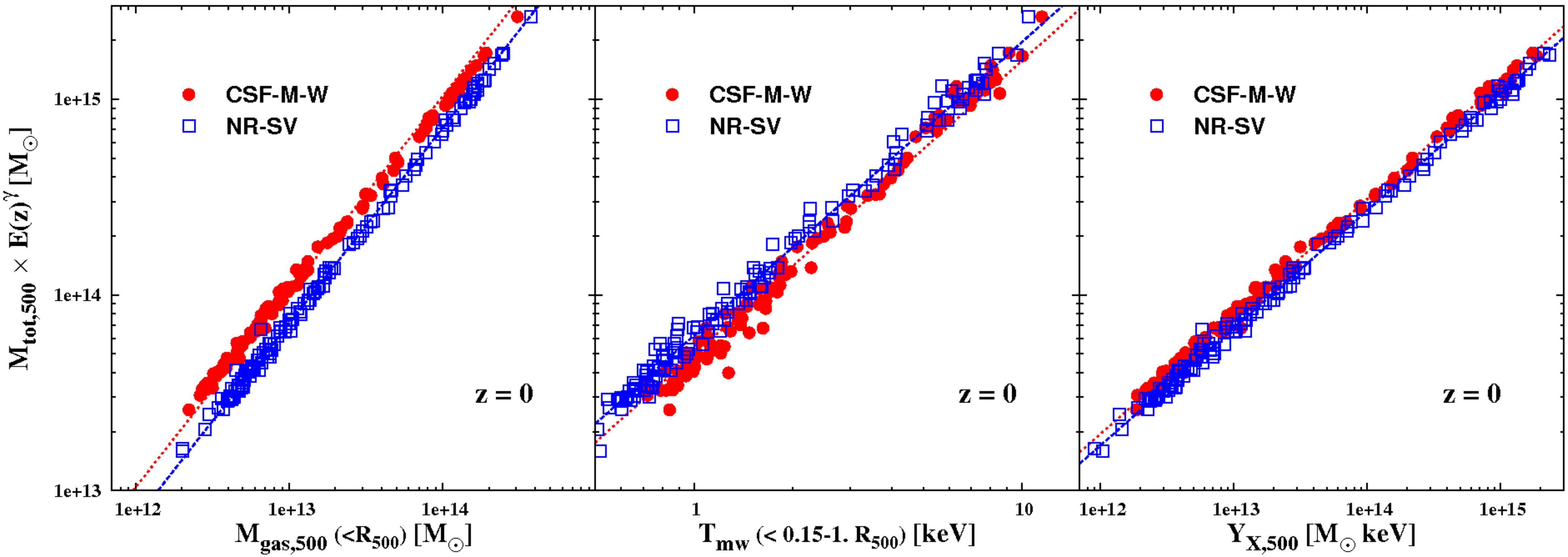
$$\rho_c(z) = 3 H_0^2 E(z)^2 / 8\pi G$$

$$E(z) \equiv H(z)/H_0 = \left[(1+z)^3 \Omega_m + \Omega_\Lambda\right]^{1/2}$$

(see Pratt et al. 2009, O'Hara et al. 2006, Ettori et al. 2006,Rasia et al. 2010, Vikhlinin et al. 2009a)

M_{gas}, T_{mw} and Y_X at z=0

non radiative runs have slope close to the self-similar one



$$M_{tot}=C\left(\frac{M_{gas}}{2.e13\ M_{sun}}\right)^a$$
self-similar slope: *a=1*

$$M_{tot}E(z)=C\left(\frac{T_{mw}}{3\ keV}\right)^a$$
self-similar slope: *a=1.5*

$$M_{tot}E(z)^{2/5}=C\left(\frac{Y_X}{4.e13\ M_{sun}\ keV}\right)^a$$
self-similar slope: *a=0.6*

Residuals from M_{gas} and T

best fit relation with fixed self-similar slope

Pearson correlation r = - 0.18

CSF

NR

Pearson correlation r = - 0.57

Residuals from M_{gas} and T

best fit relation with fixed self-similar slope

- $M > 5x10^{14} M_{sun}$
- $M < 10^{14} M_{sun}$

CSF

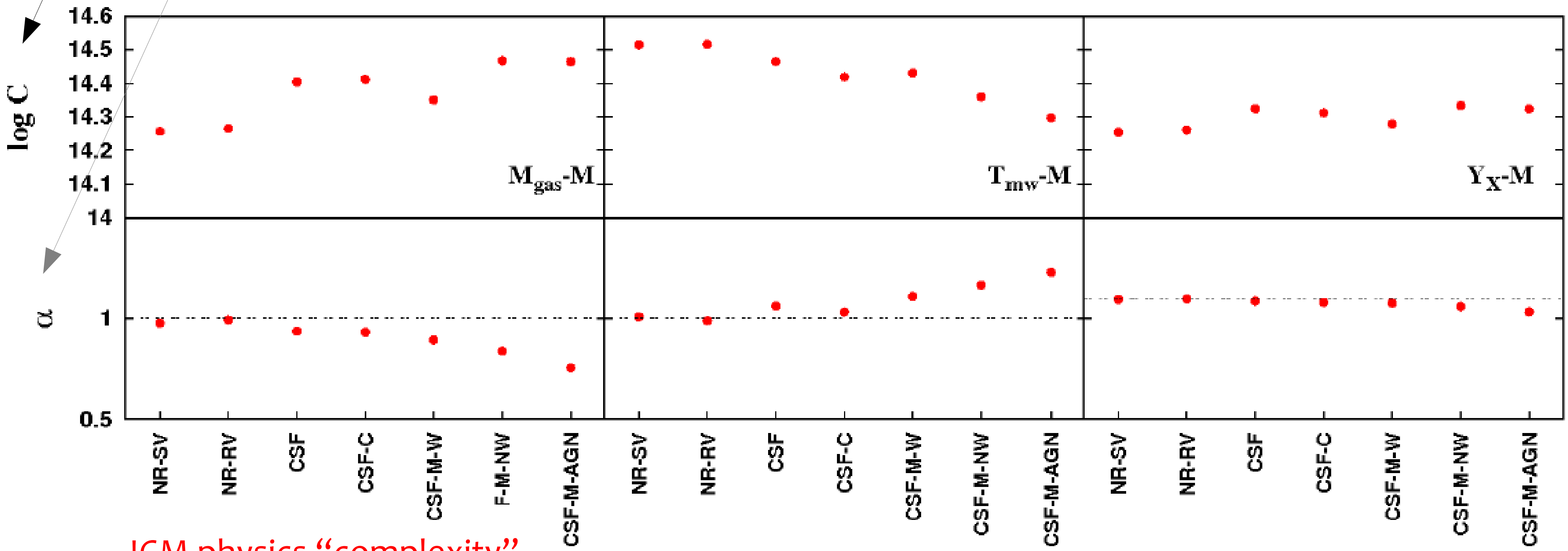
NR

Effect of ICM physics

(normalisation)

(slope)

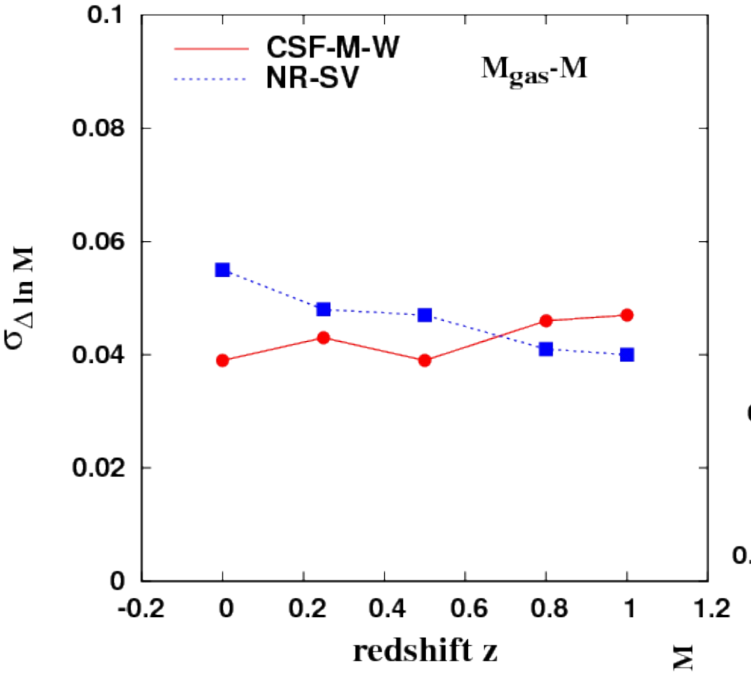
$$\log C(z) = \log C_0(z) + \beta_1 (1+z)\,;$$
$$\alpha(z) = \alpha_0 + \beta_2 (1+z)\,.$$

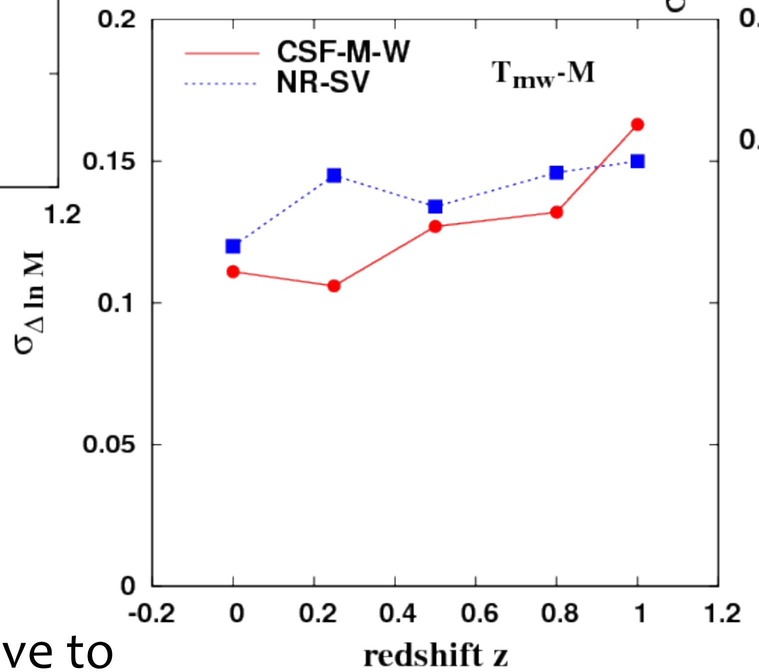


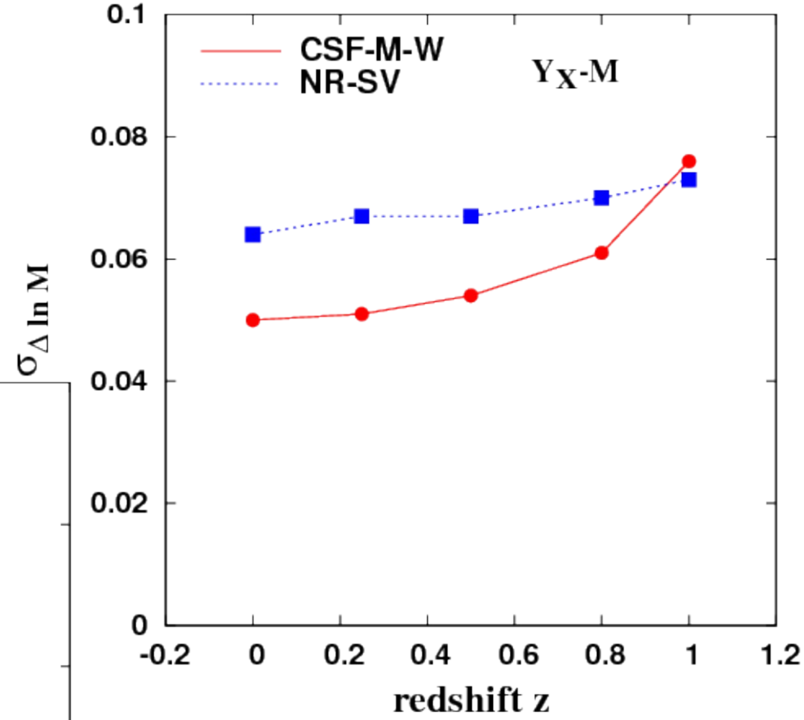
ICM physics "complexity"

- for radiative simulations the slope changes significantly with respect to the self-similar prediction
- Y_X is the mass proxy less sensitive to the included physics

Evolution of intrinsic scatter

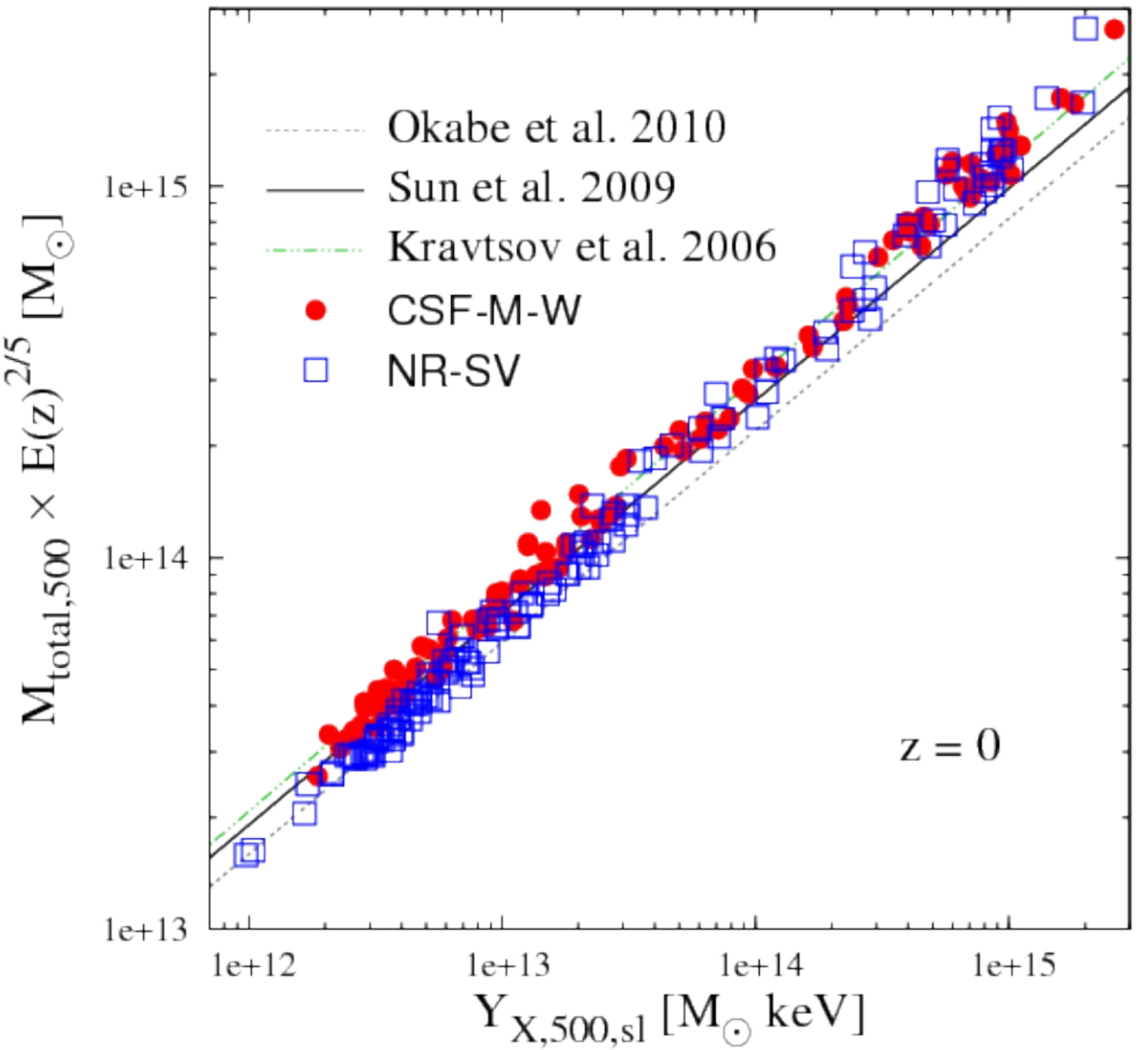






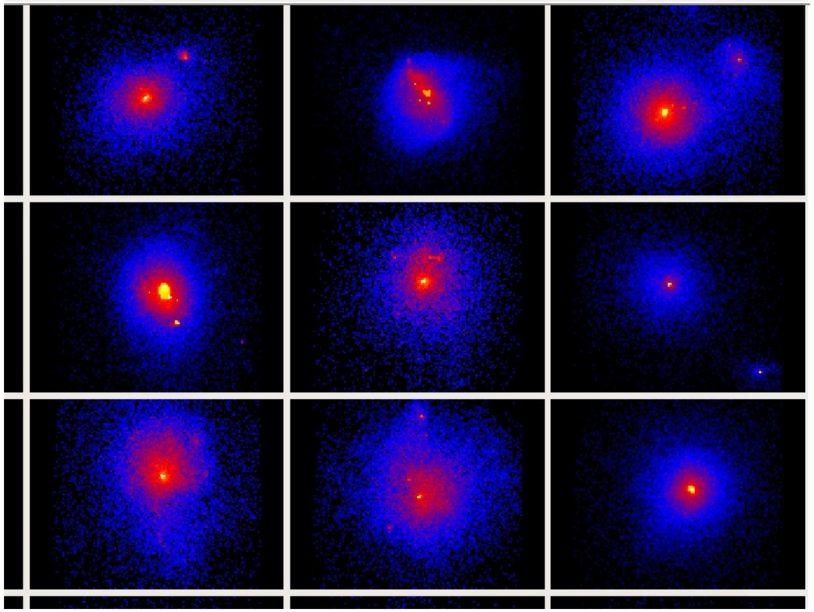
- gas mass with $\sigma_{\ln M}$ 4-5%
- temperature more sensitive to substructures at higher redshift
- Y_X increases intrinsic scatter with redshift

Observational systematics



Spectroscopic-like temperature
(Mazzotta et al. 2004, Vikhlinin 2006)

- larger scatter 6-->10% CSF, 5-->8% NR
- discrepancy with observations at the high mass end

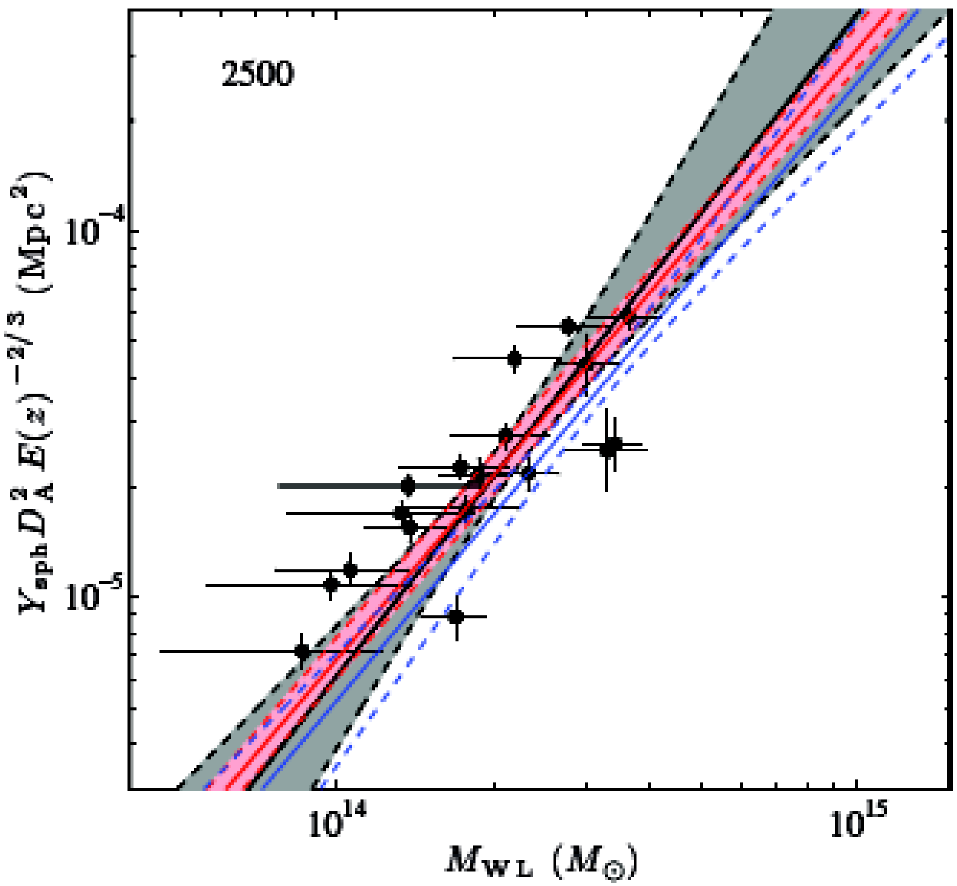


mock X-ray observations
(Rasia, Fabjan et al. in prep.)

SZE scaling relations

Y_{SZ} (integrated SZE signal)
→ proportional to the *thermal energy content of ICM*

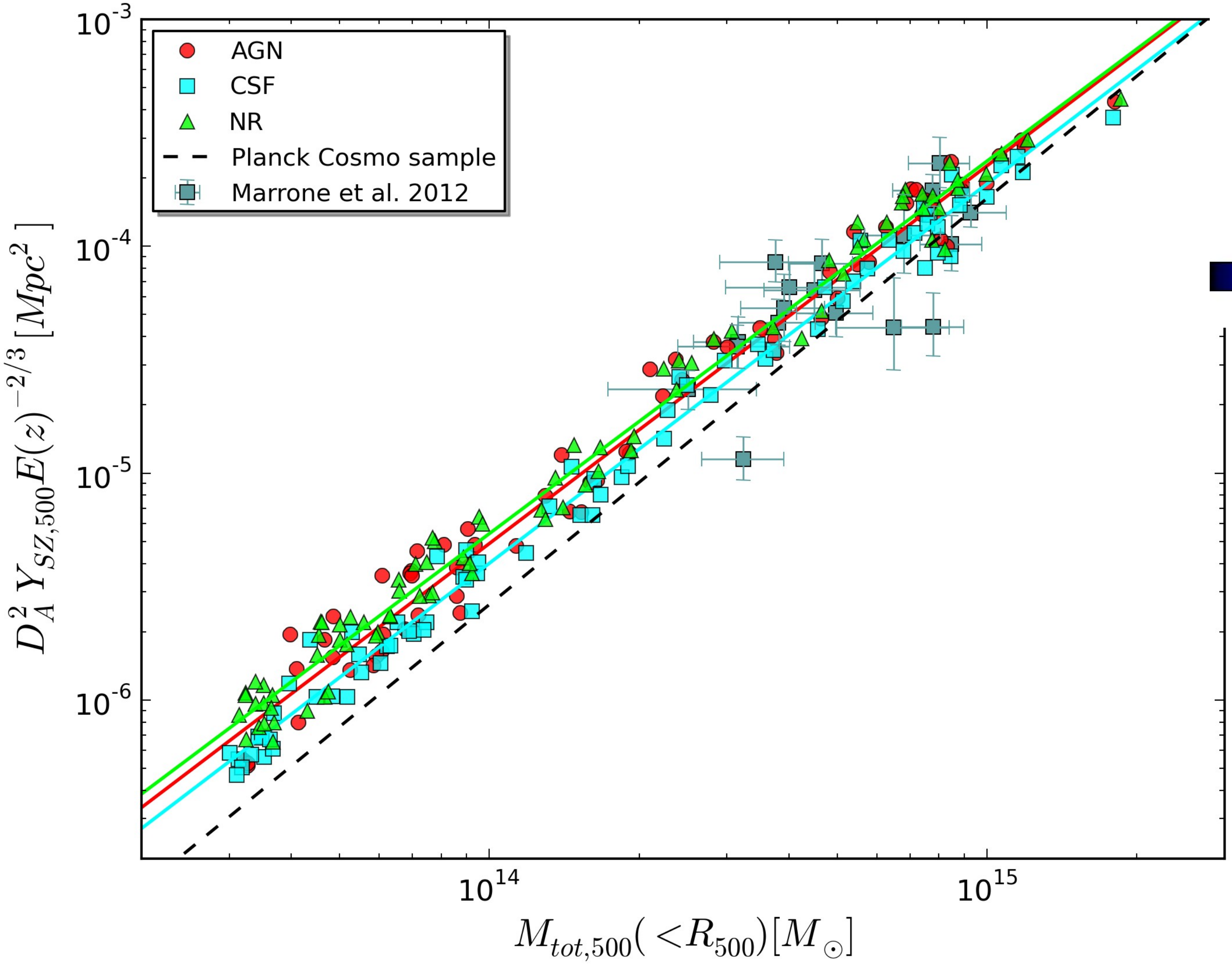
- Y as excellent mass proxy if measured on sufficiently large scales
- low intrinsic scatter regardless of cluster dynamical state
- cluster physics affects the normalization and the scatter

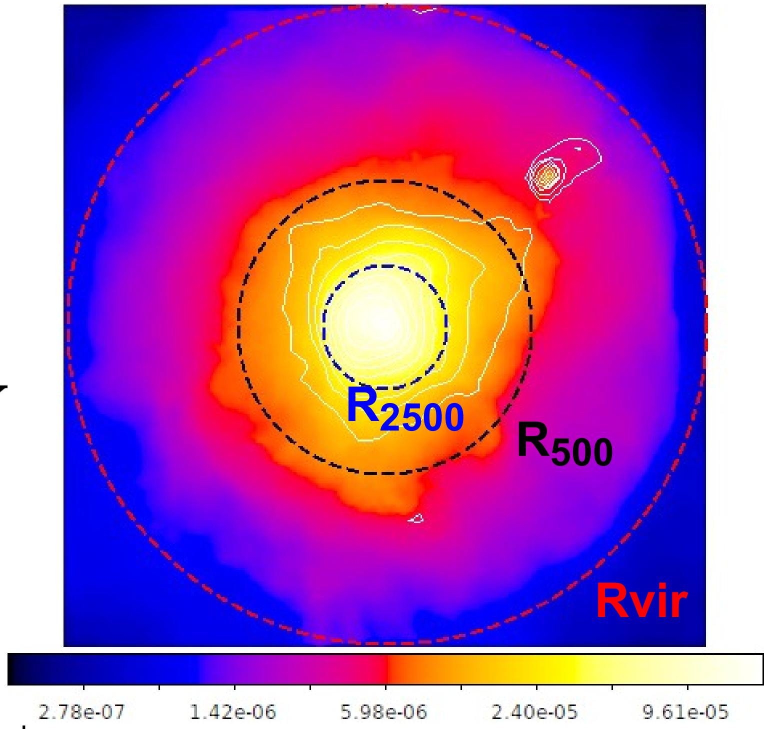


Marrone et al. (2012)

see Motl et al. 2005, Nagai 2006, Bonaldi et al. 2007, Shaw et al. 2008

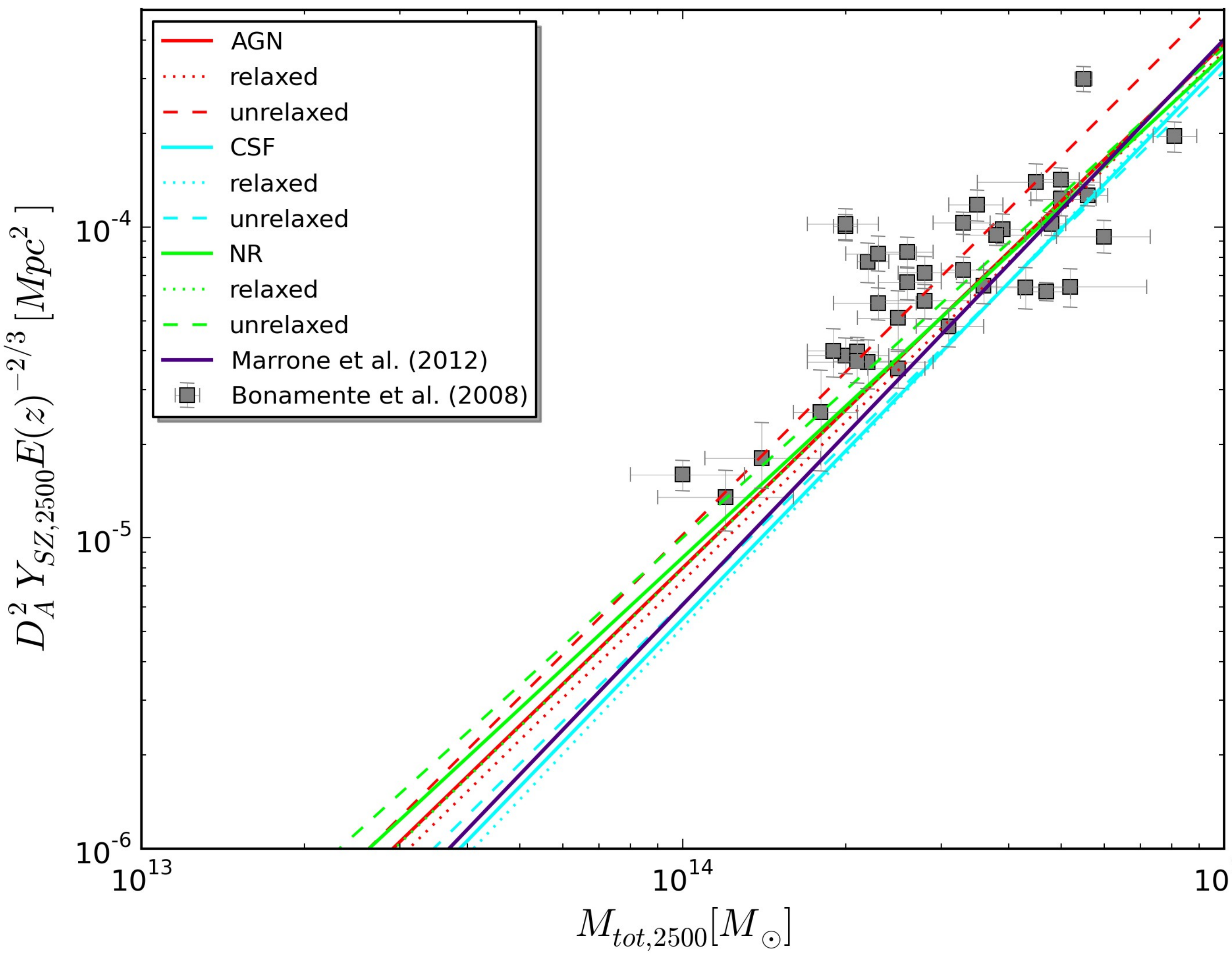
$Y_{SZ}(<R_{500})$ at z=0

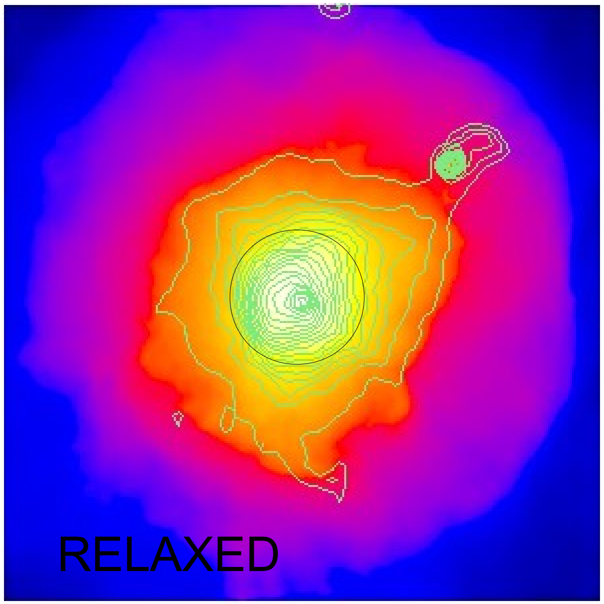


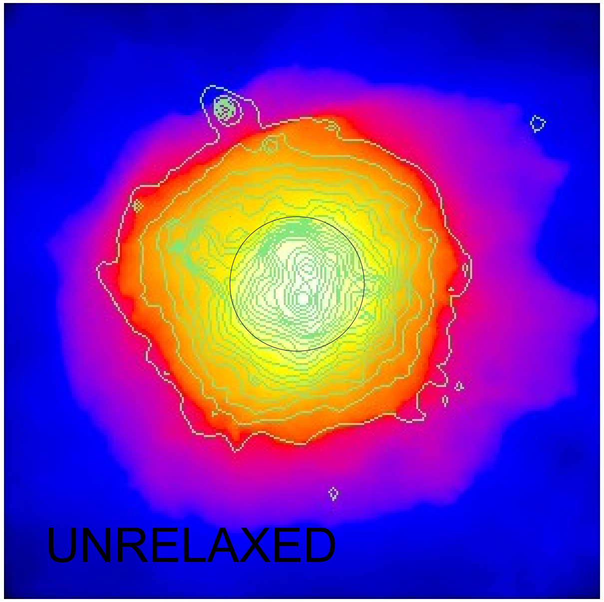


- low intrinsic scatter (cca. 10-12%)
- lower normalization for CSF simulations
- discrepancy with data at group scales

$Y_{SZ}(<R_{2500})$ at z=0







Short summary

Galaxy clusters can be used as **cosmological probes**

- need precise measurements of cluster masses
- two approaches:
  - detailed study of nearby clusters with different methods
  - mass proxies (large samples)

Scaling relations (M_{gas},T,Y_X,Y_{sz}) from simulated clusters:

- *non radiative simulations* follow the self-similar prediction
- in *radiative simulations* relations with M_{gas} and T_{mw} have opposite deviation from self-similarity → M-Y_X has a nearly self-similar slope
- **M_{gas}** is a low scatter mass proxy, with **constant scatter** with redshift
- **Y_X** is the **most stable** against ICM physics
- **mock observations** show an **increase in the scatter** of scaling relations
- **Ysz** has **low intrinsic scatter** with higher normalization with respect to observational data


THANK YOU