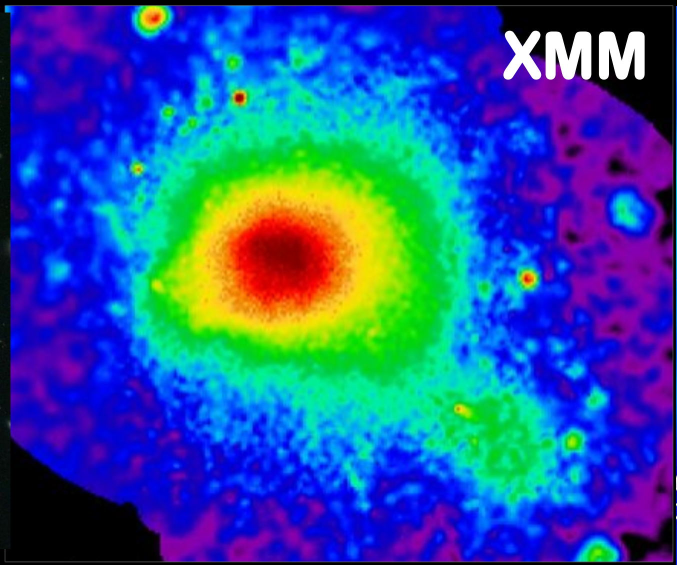
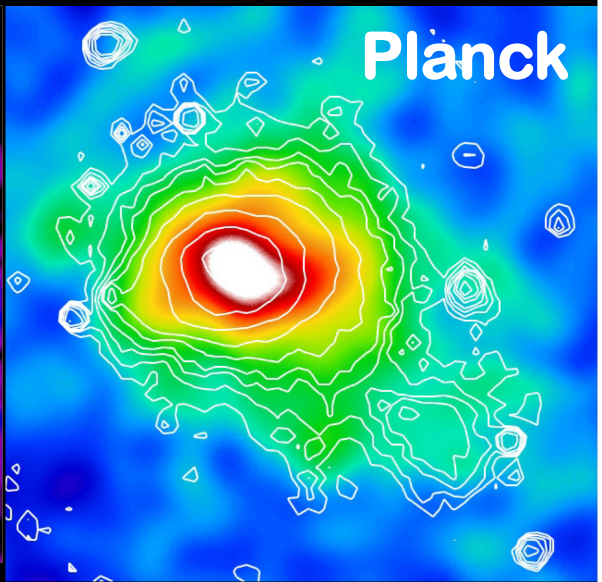
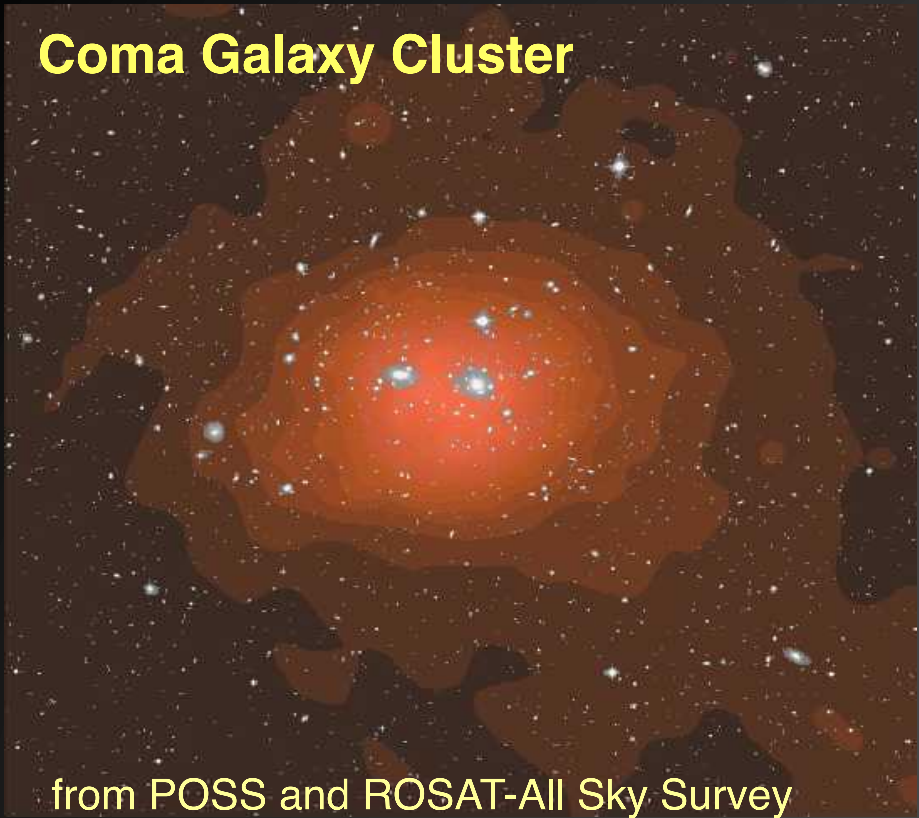
Cosmology & astrophysics with the thermal component of the Clusters of Galaxies

Stefano Ettori
INAF-OA / INFN Bologna



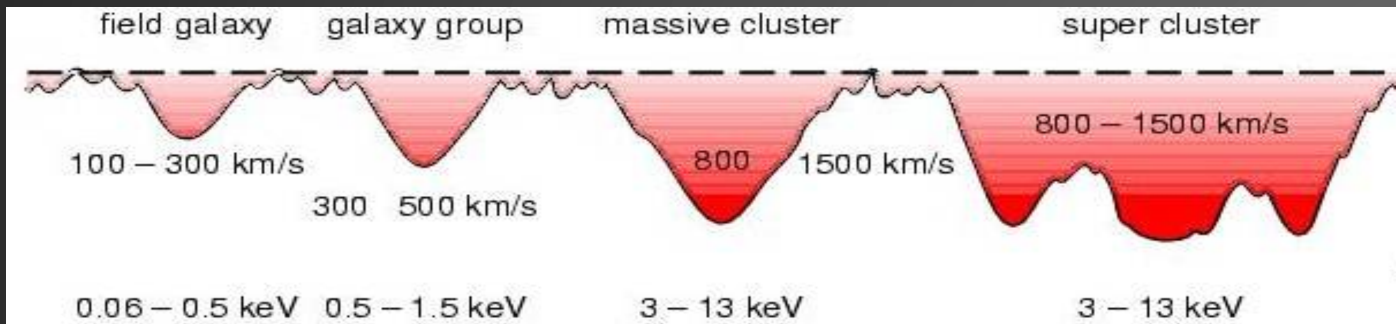


Clusters of galaxies

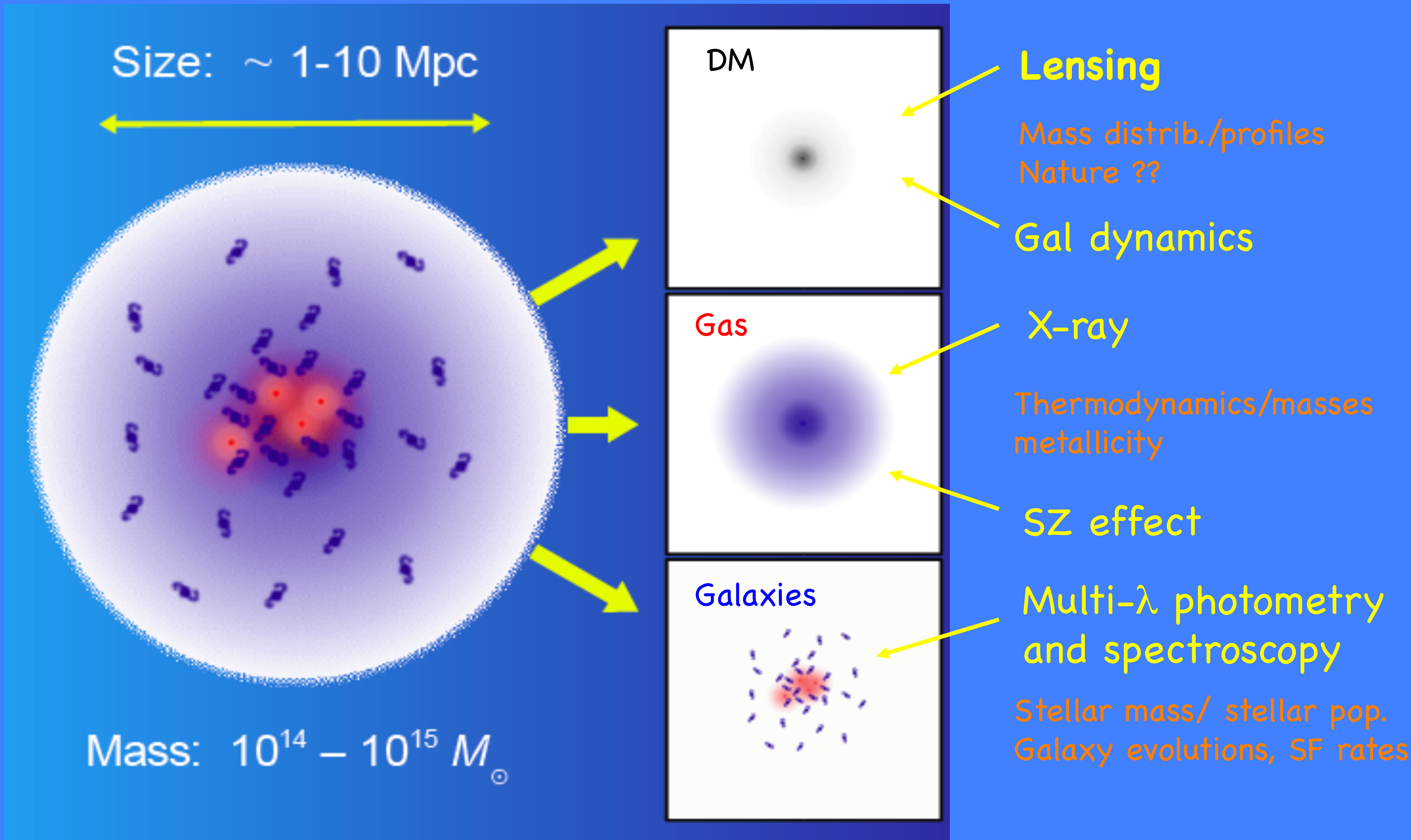


74 – 83% = Dark Matter
15 – 20% = *hot* ICM
2 - 6% = *cold* galaxies

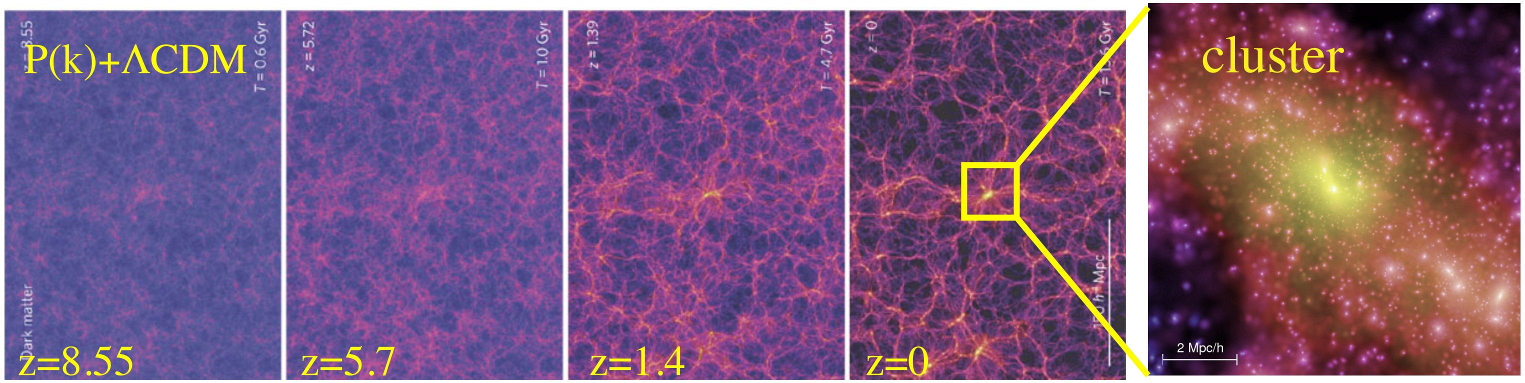
The hot gas is thermalized and trapped in the cluster potential well



Observable Properties of Clusters

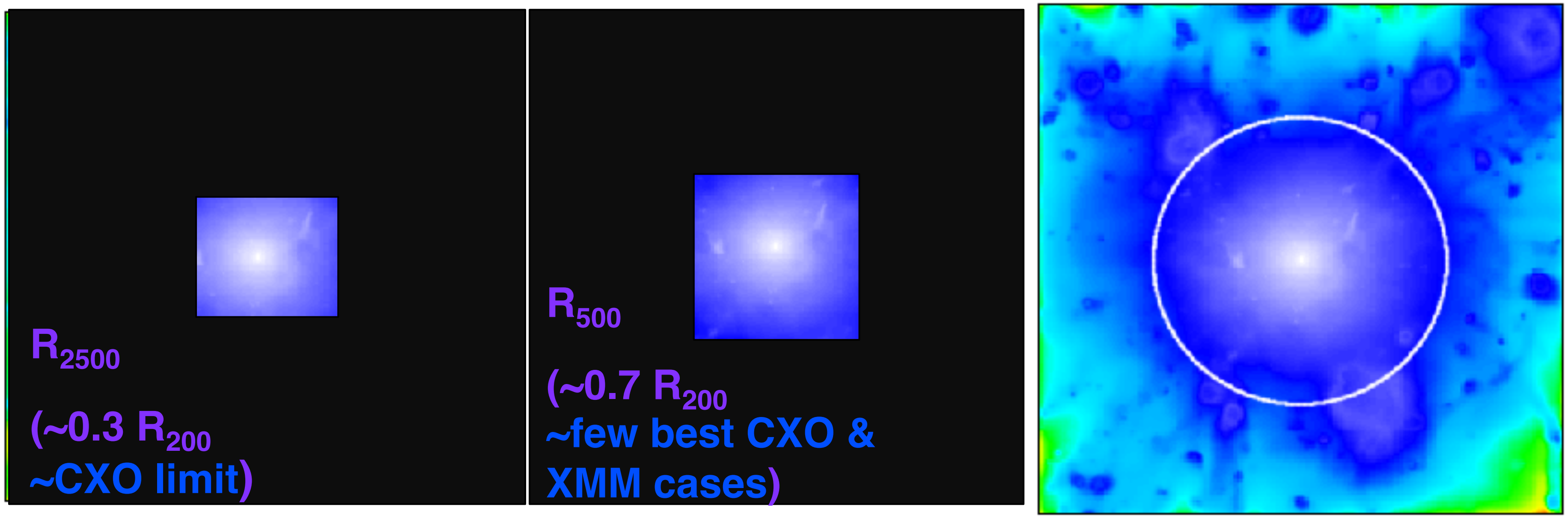


Structure formation in the Universe

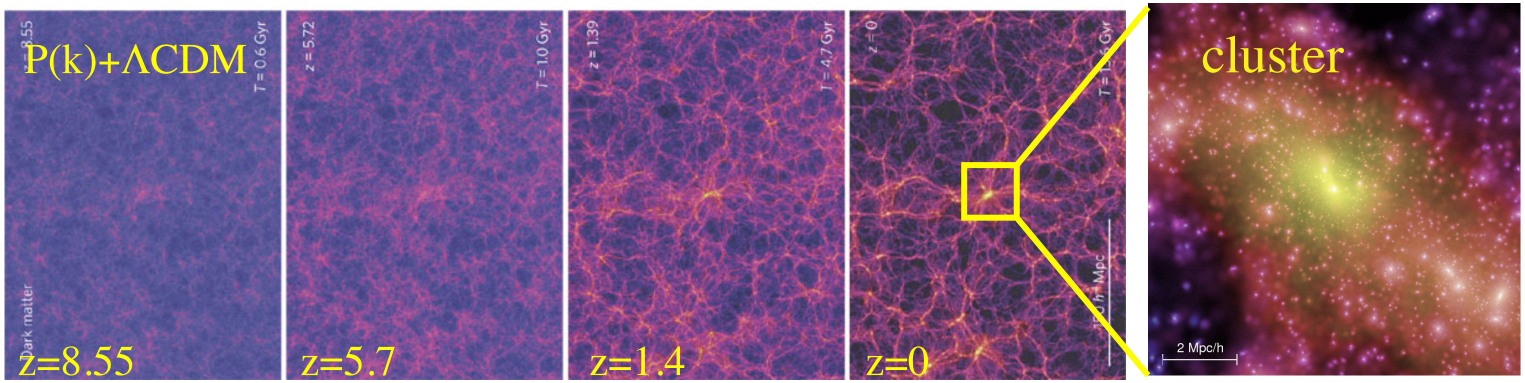


We know how the gravity forms structures on cluster scales.

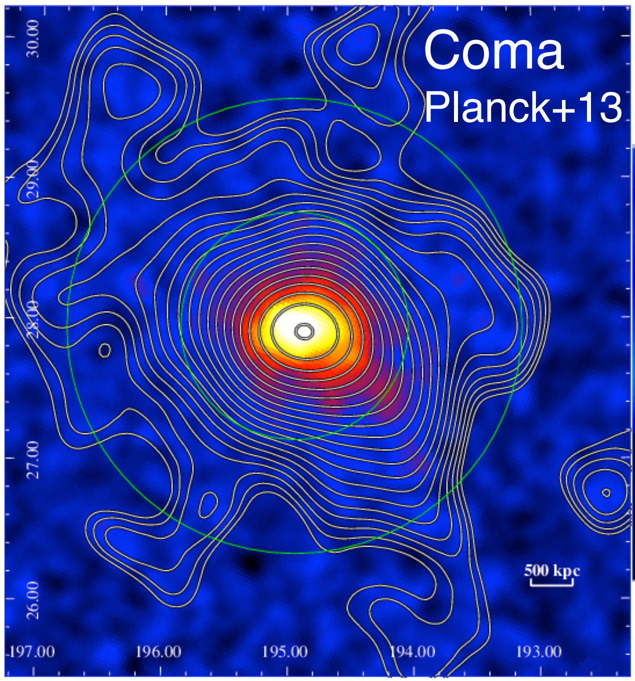
X-rays (SZ) provide a direct probe of the thermalized gas in a cluster's potential.

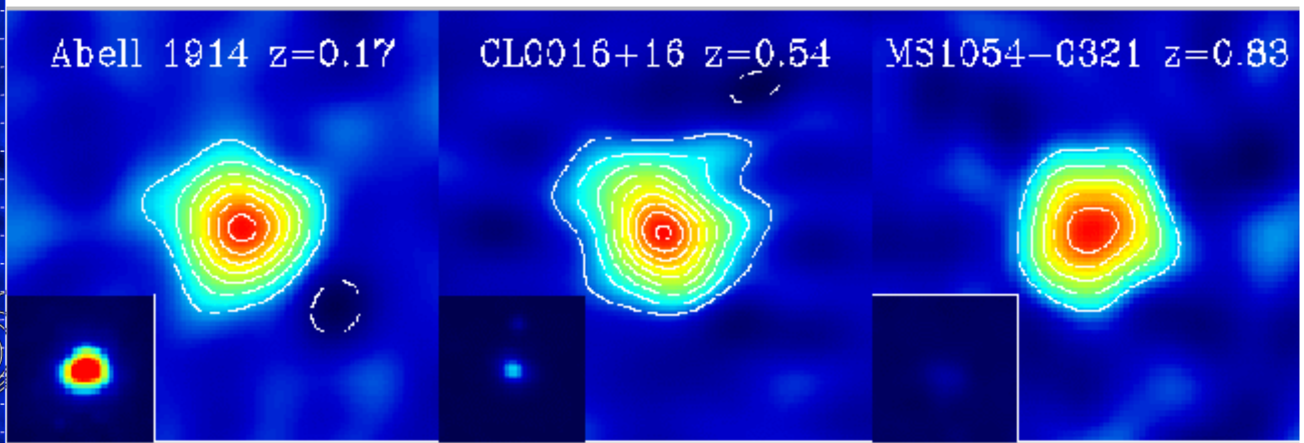


Structure formation in the Universe



We know how the gravity forms structures on cluster scales.
X-rays (SZ) provide a direct probe of the thermalized gas in a cluster's potential.





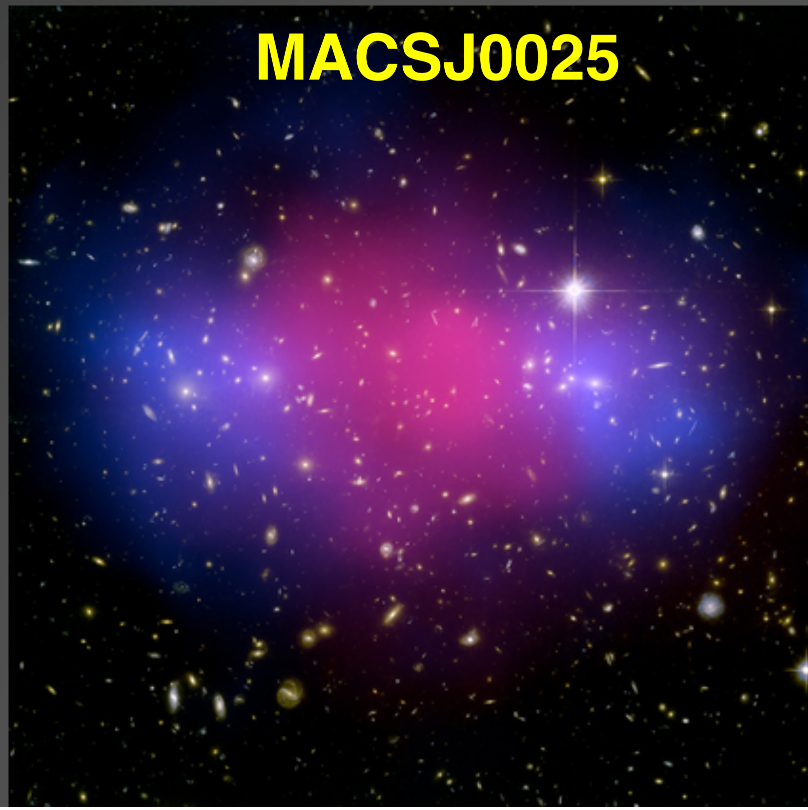
Clusters of galaxies: accretion

Dark Matter   *hot* ICM

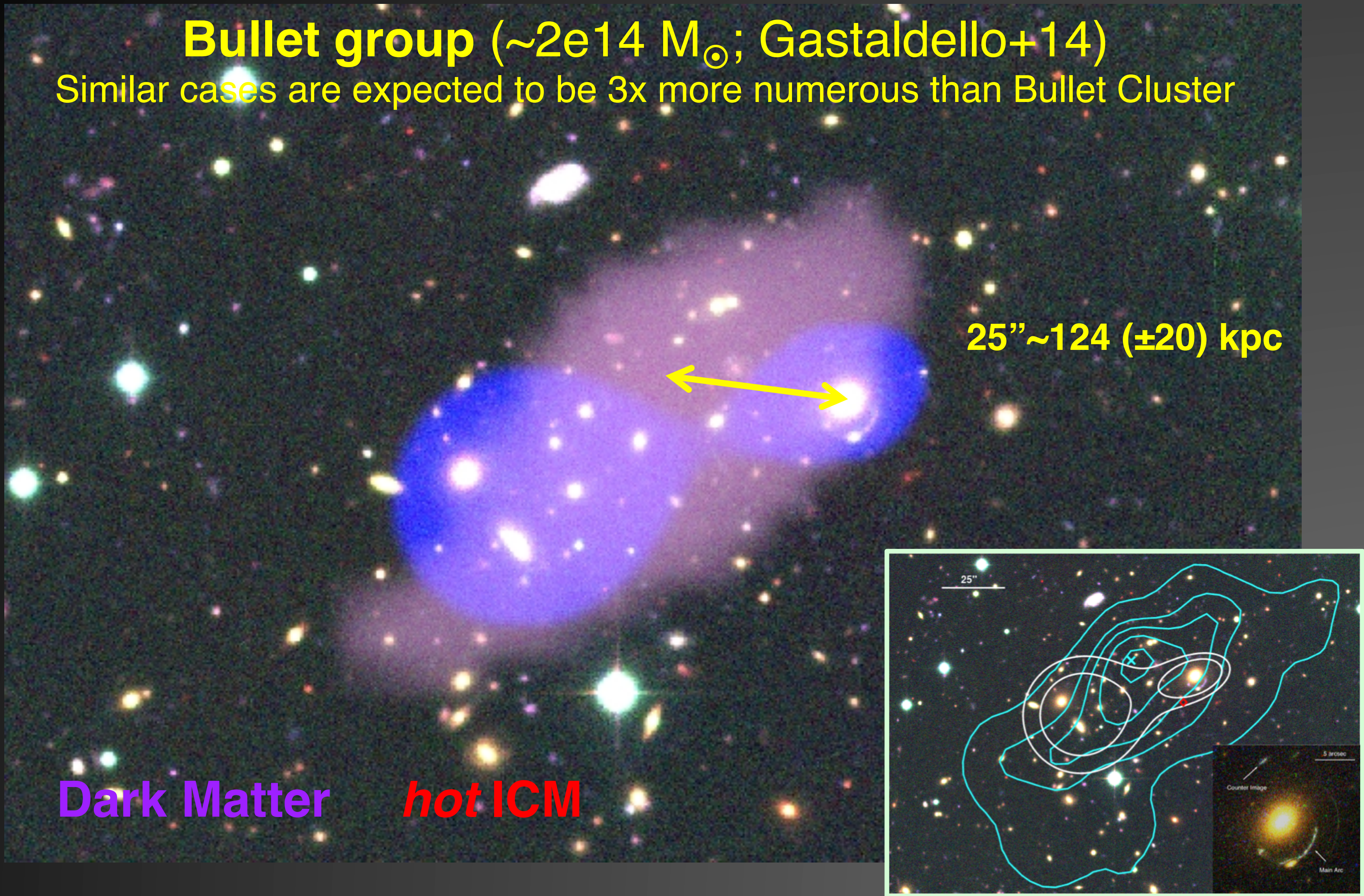
$\tau = \Sigma\sigma/m < 1$

$\sigma/m < 0.7\ cm^2 g^{-1}$

($10\ GeV\ /\ 10^{-23}\ cm^2$)



Clusters of galaxies: accretion

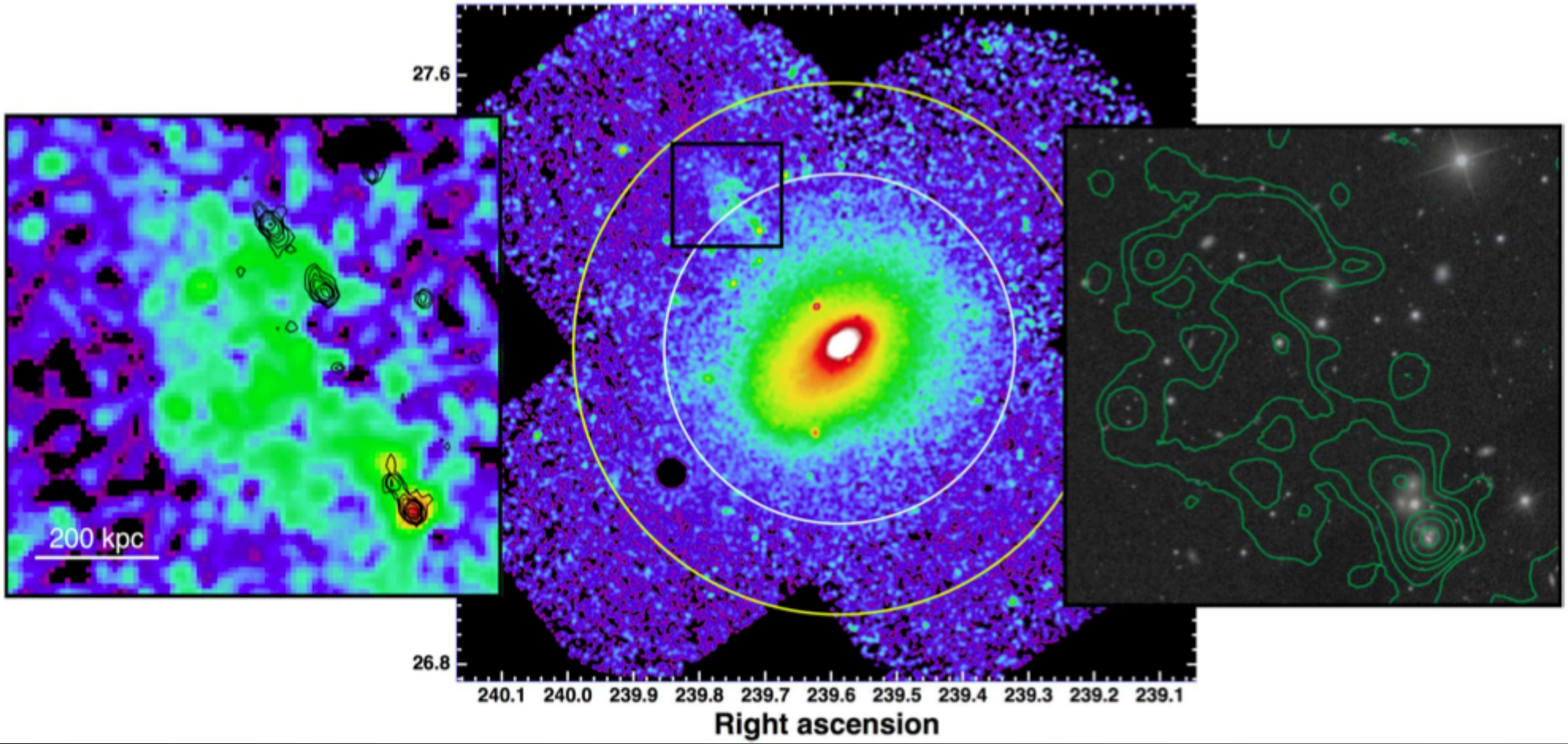


Clusters of galaxies: accretion

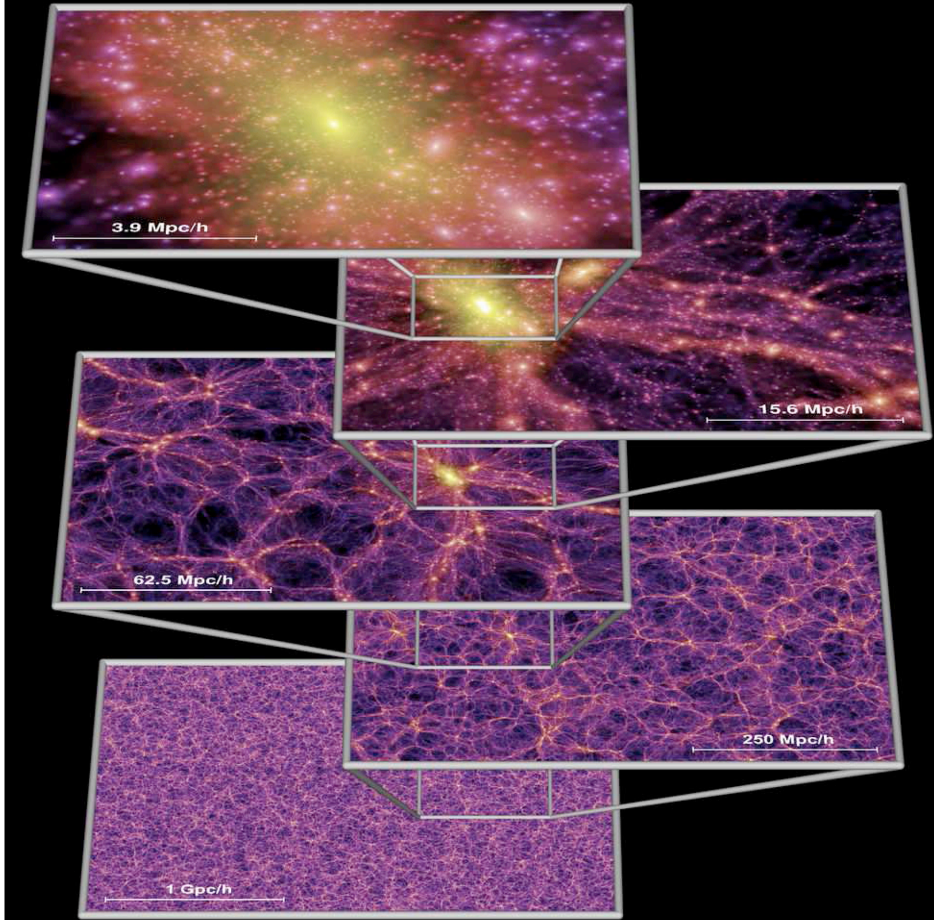
A2142 (~1.3e15 $M_{\odot}$; Eckert+14)

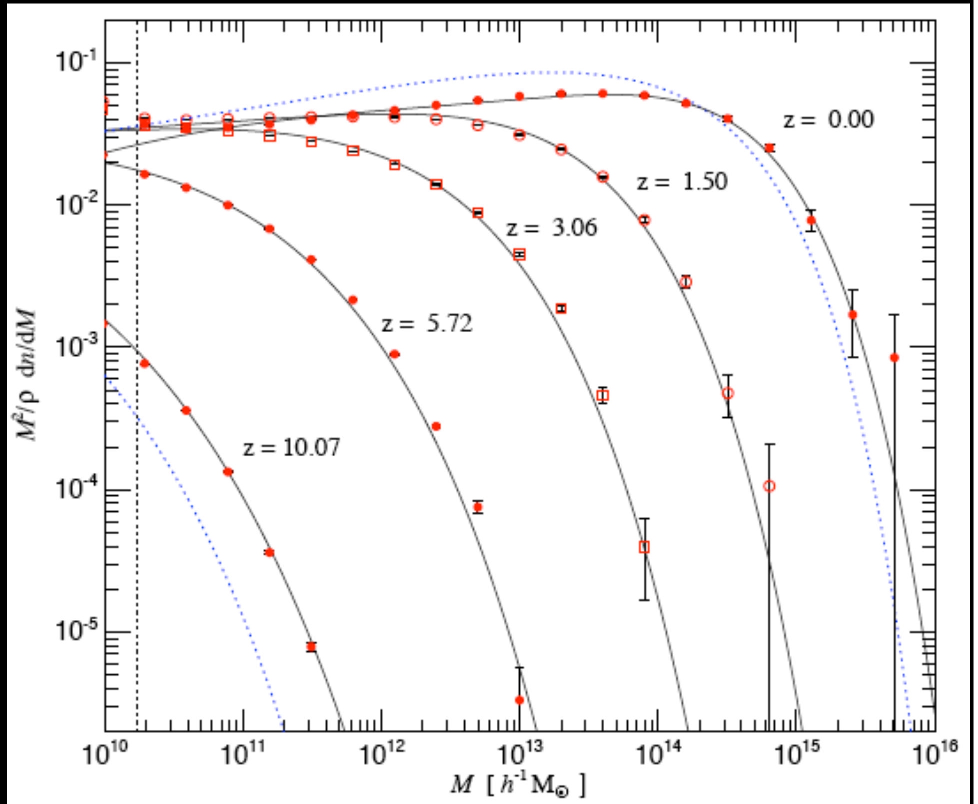
Direct observation of the accretion of a clump with M~1/100 M_{halo}

Simulations predict ~1 per local clusters



Large-scale Structure formation





Ω_m=0.25=1- Ω_Λ
h=0.73
σ_8=0.9

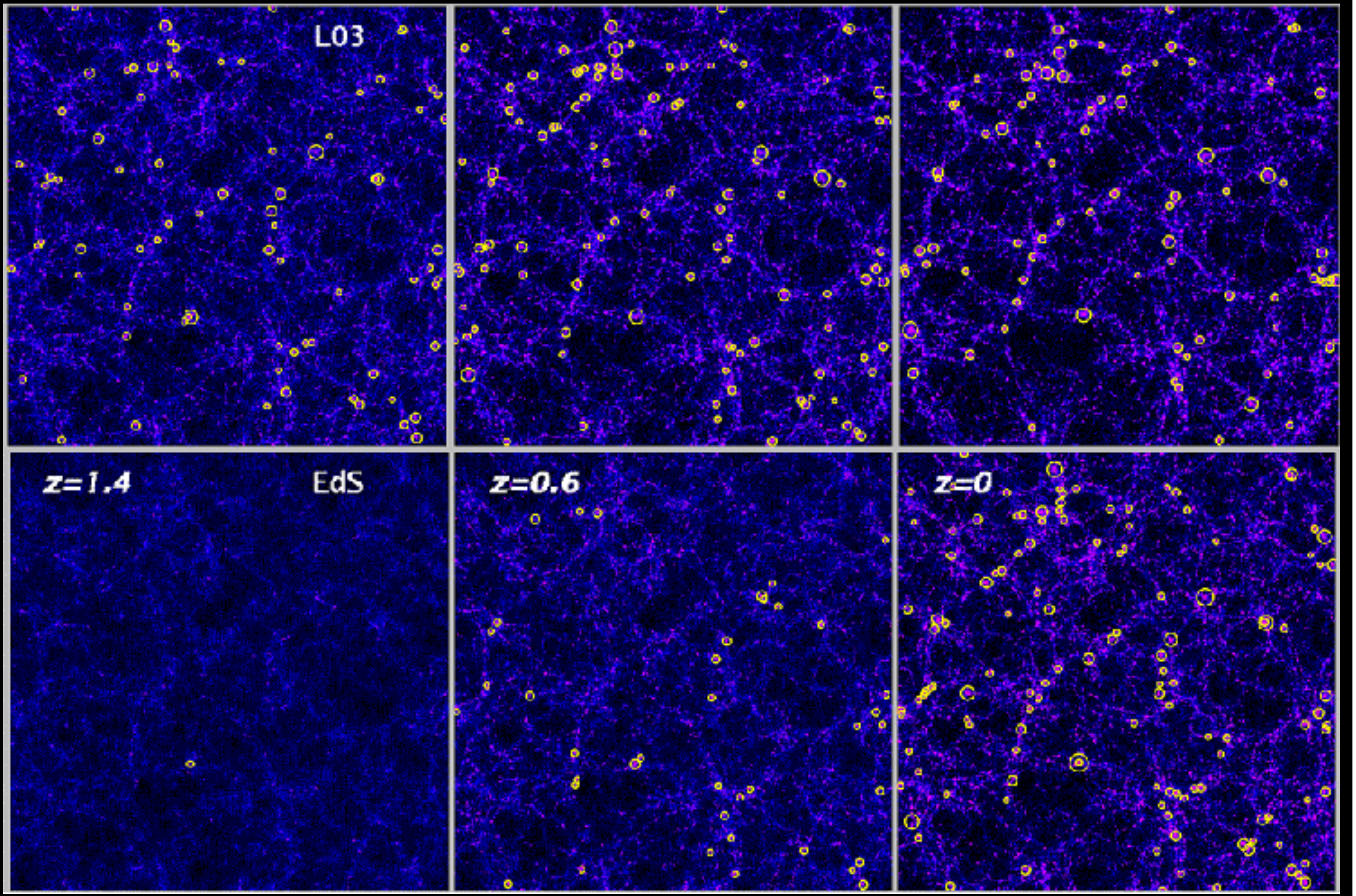
L=500/h Mpc

(*Springel et al. 2005*) Millennium simulations:
10^{10} particles of ~9e8 $M_\odot$/h

Dark Matter & X-ray clusters

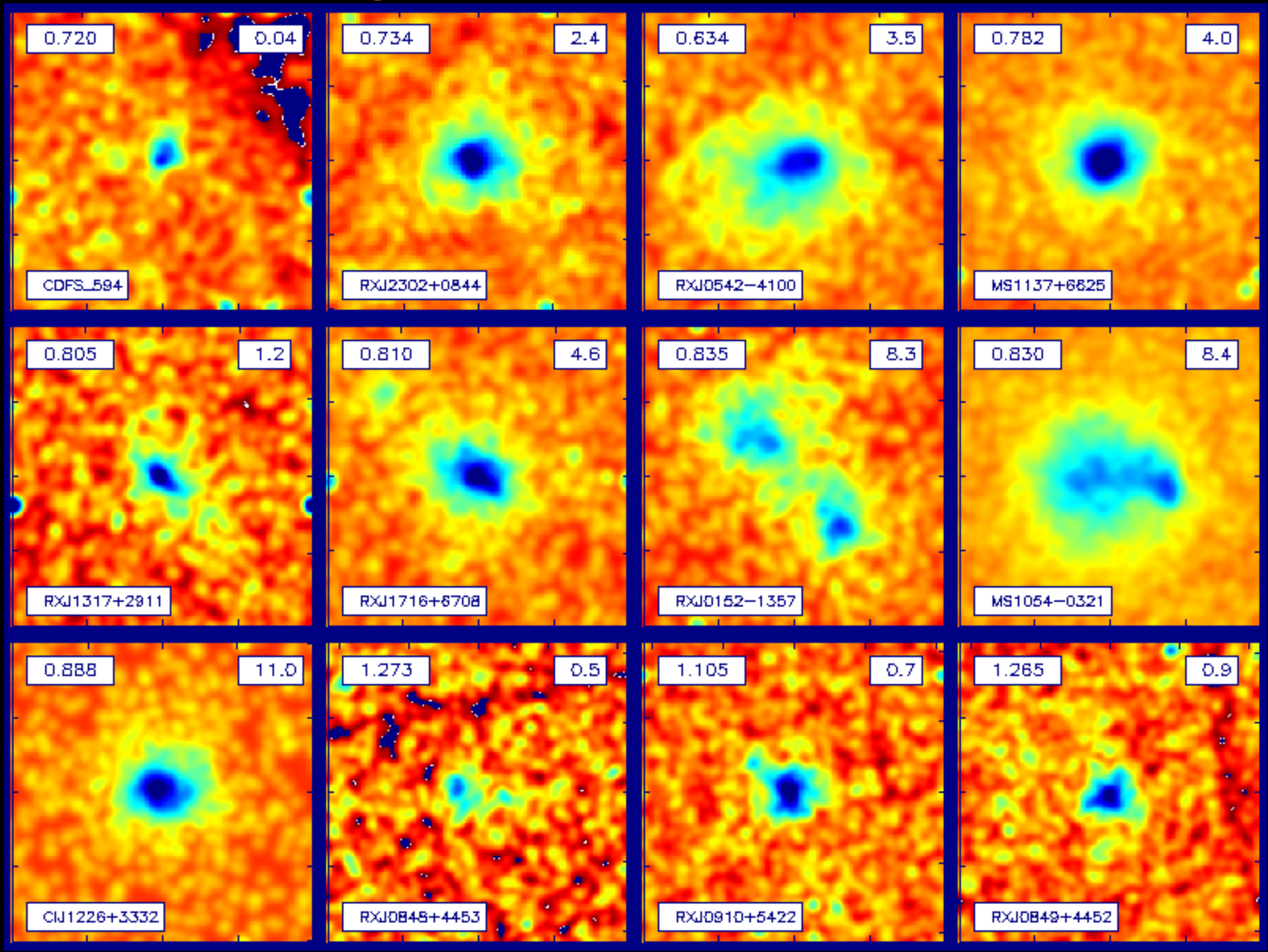
Ω_m=0.3
=1- Ω_Λ

EdS

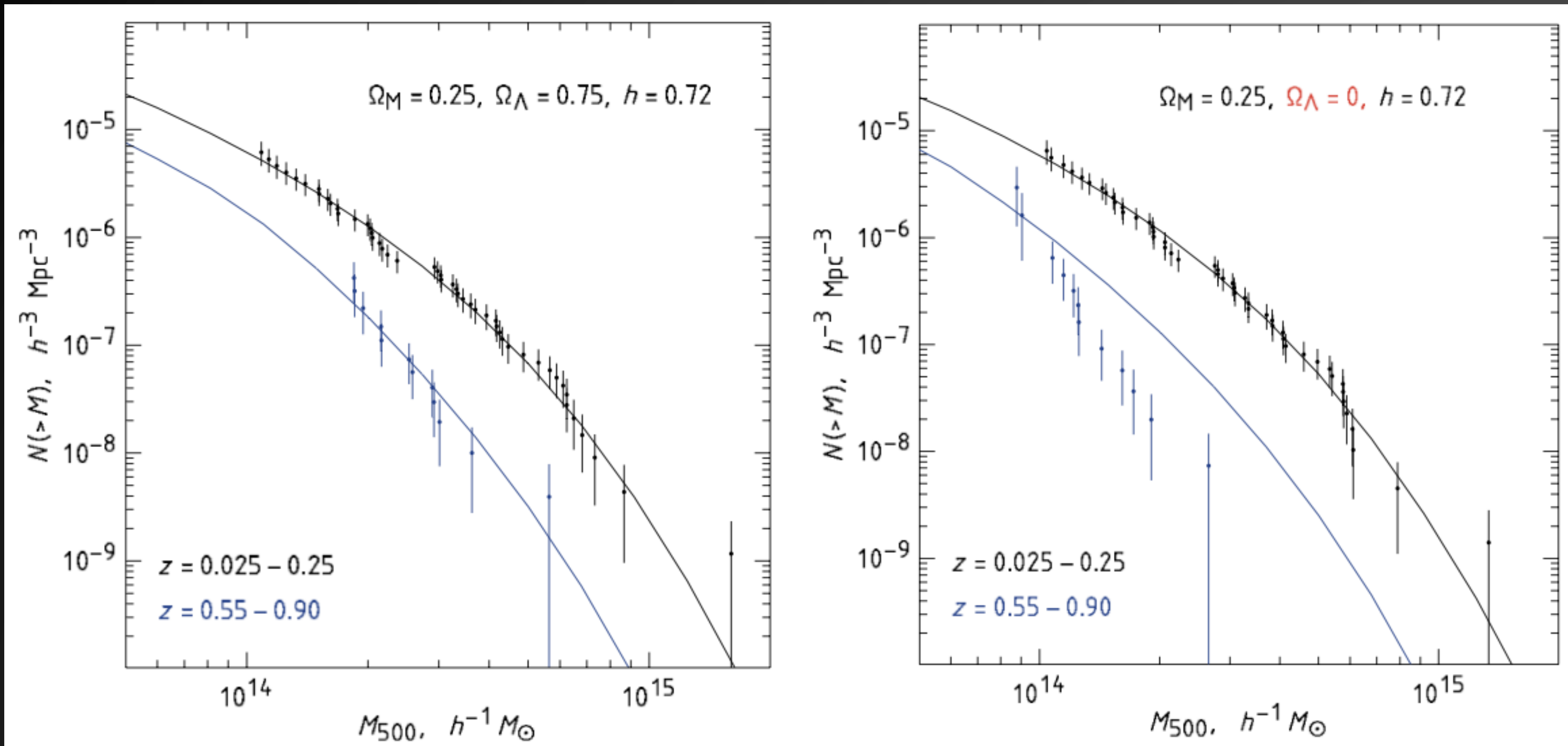


(*Borgani & Guzzo 2001*) Normalized to space density at z=0; **circles**: clusters with T>3 keV & $\propto$T

Chandra image of clusters at z>0.7 (>6 Gyr ago)

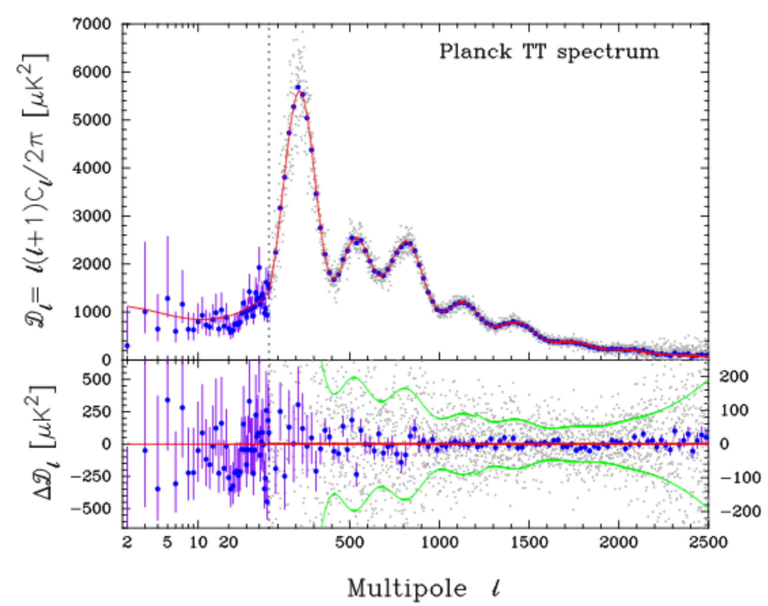


Galaxy clusters & cosmology



Vikhlinin et al. 09

Cosmology in the Planck era



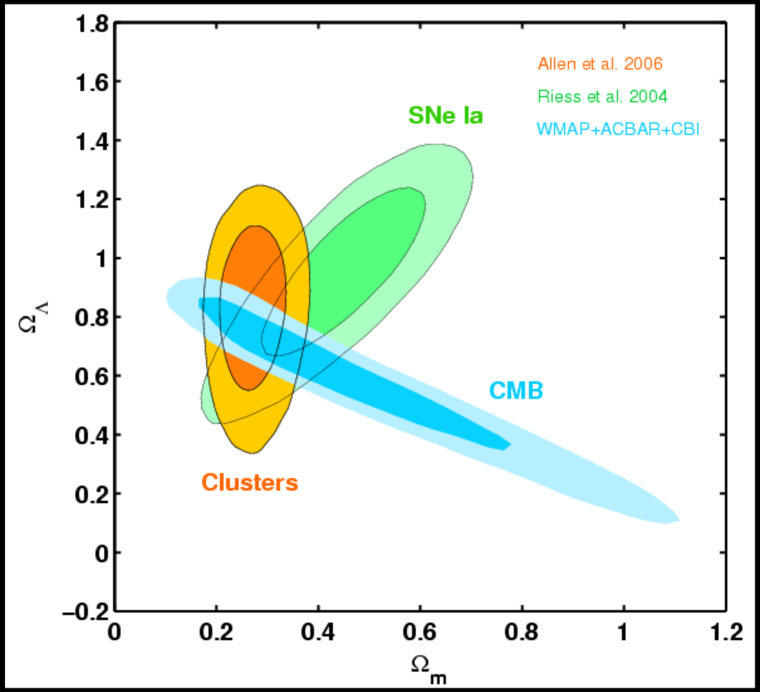
Parameter	*Planck* Best fit	*Planck* 68% limits	*Planck*+lensing Best fit	*Planck*+lensing 68% limits	*Planck*+WP Best fit	*Planck*+WP 68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	2.23 ± 0.16	2.215	$2.19^{+0.12}_{-0.14}$	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14300	0.1423 ± 0.0029	0.14094	0.1414 ± 0.0029	0.14305	0.1426 ± 0.0025
$\Omega_m h^3$	0.09597	0.09590 ± 0.00059	0.09603	0.09593 ± 0.00058	0.09591	0.09589 ± 0.00057
Y_P	0.247710	0.24771 ± 0.00014	0.247785	0.24775 ± 0.00014	0.247695	0.24770 ± 0.00012
Age/Gyr	13.819	13.813 ± 0.058	13.784	13.796 ± 0.058	13.8242	13.817 ± 0.048
z_*	1090.43	1090.37 ± 0.65	1090.01	1090.16 ± 0.65	1090.48	1090.43 ± 0.54
r_*	144.58	144.75 ± 0.66	145.02	144.96 ± 0.66	144.58	144.71 ± 0.60
$100\theta_*$	1.04139	1.04148 ± 0.00066	1.04164	1.04156 ± 0.00066	1.04136	1.04147 ± 0.00062
z_{drag}	1059.32	1059.29 ± 0.65	1059.59	1059.43 ± 0.64	1059.25	1059.25 ± 0.58
r_{drag}	147.34	147.53 ± 0.64	147.74	147.70 ± 0.63	147.36	147.49 ± 0.59
k_D	0.14026	0.14007 ± 0.00064	0.13998	0.13996 ± 0.00062	0.14022	0.14009 ± 0.00063
$100\theta_D$	0.161332	0.16137 ± 0.00037	0.161196	0.16129 ± 0.00036	0.161375	0.16140 ± 0.00034
z_{eq}	3402	3386 ± 69	3352	3362 ± 69	3403	3391 ± 60
$100\theta_{eq}$	0.8128	0.816 ± 0.013	0.8224	0.821 ± 0.013	0.8125	0.815 ± 0.011
$r_{drag}/D_V(0.57)$	0.07130	0.0716 ± 0.0011	0.07207	0.0719 ± 0.0011	0.07126	0.07147 ± 0.00091

15.5-months results of the temperature anisotropies in the CMB from Planck (Planck 2013 results. XVI) put ***alone*** constraints on $\Omega_b h^2$, $\Omega_m h^2$ at ~2% level (1σ) *on ΛCDM*

Galaxy clusters & cosmology

- The ***amplitude of P(k)*** on cluster scale

- There is degeneracy in the determination of the cosmological parameters… ***complementarity***

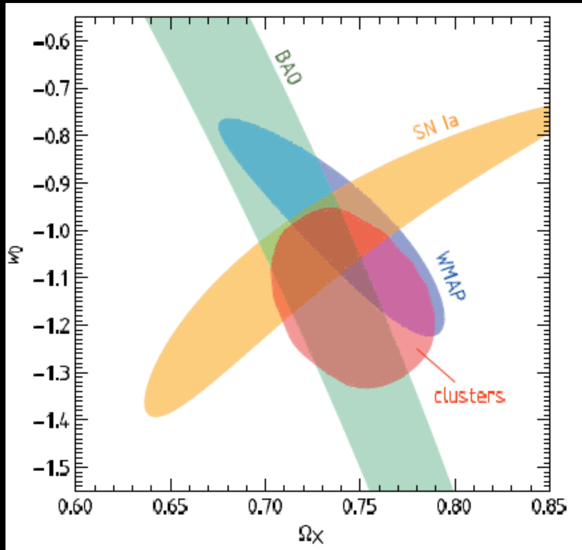


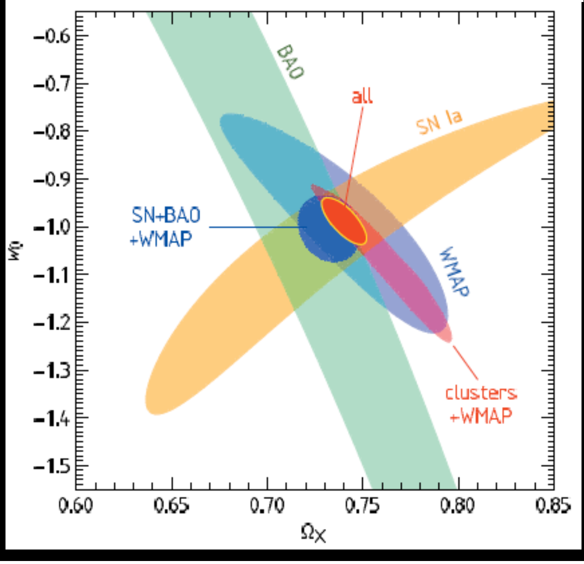
Galaxy clusters & cosmology

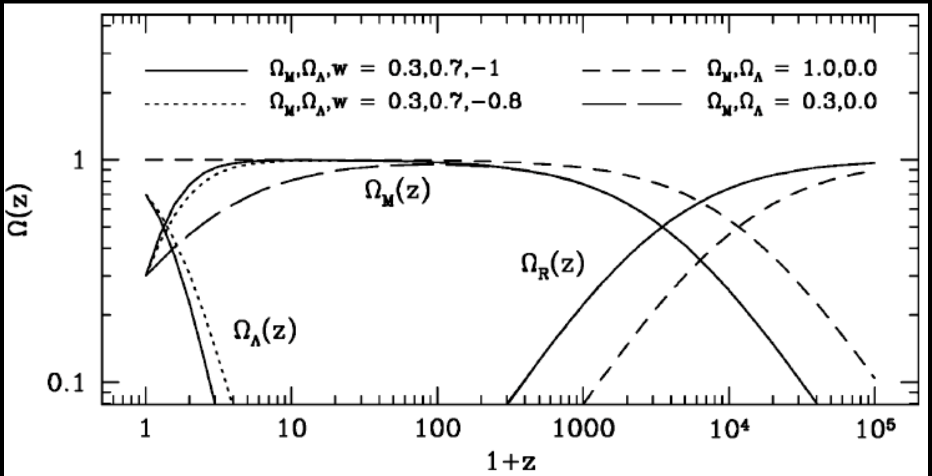
- The ***amplitude of P(k)*** on cluster scale

- There is degeneracy in the determination of the cosmological parameters… ***complementarity***

- The ***equation of state of the Dark Energy*** & its evolution with redshift is unknown

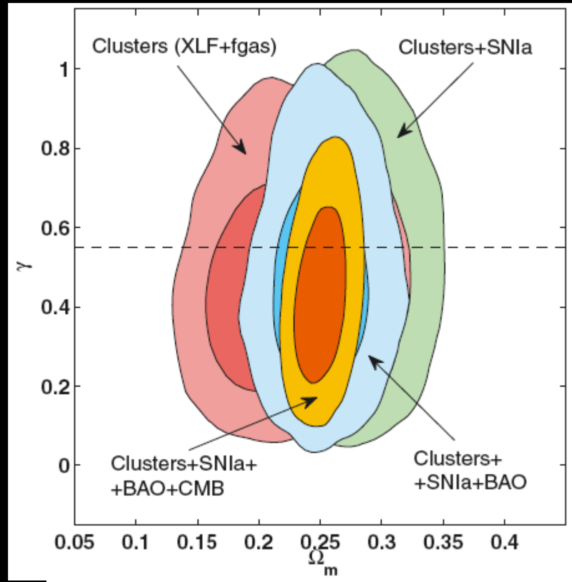


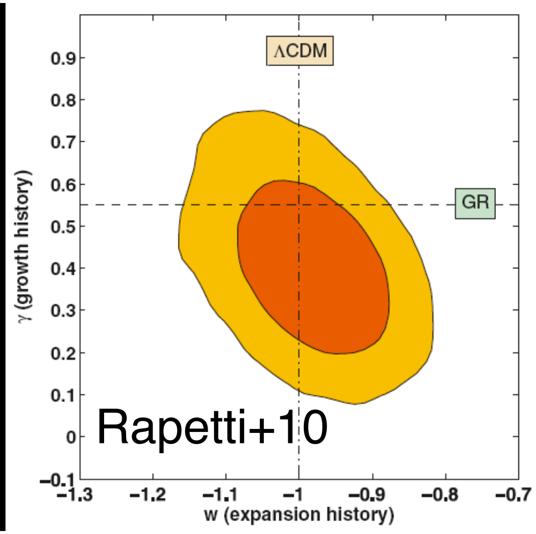




Galaxy clusters & cosmology

- The ***amplitude of P(k)*** on cluster scale
- There is degeneracy in the determination of the cosmological parameters… ***complementarity***
- The ***equation of state of the Dark Energy*** & its evolution with redshift is unknown
- Testing ***GR*** on GC scales



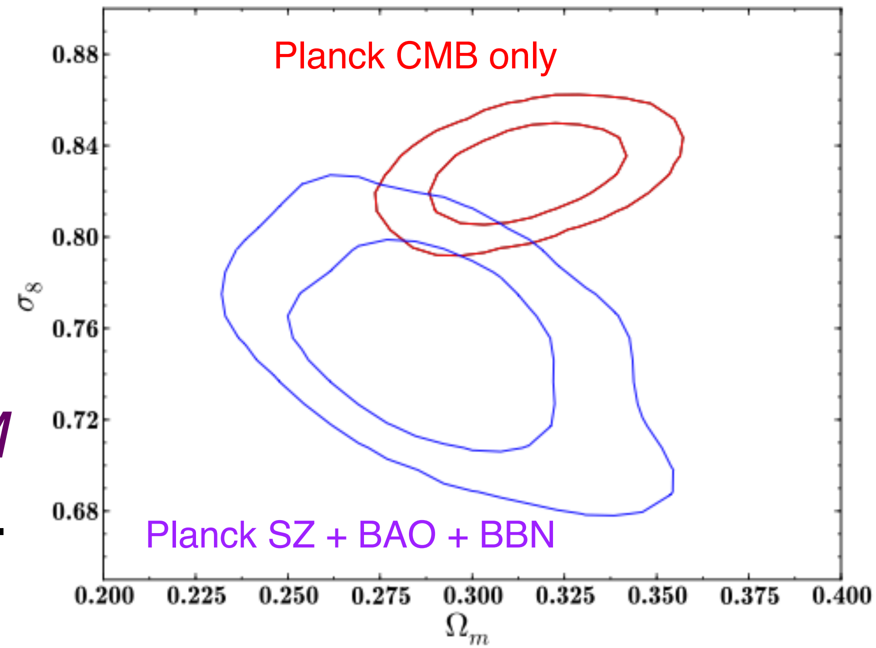


Cosmology with GC: note

X-ray: constraints also on w_o(~20% at 1 σ) using 90-240 well-studied obj (*out of X-ray known1743 clusters, Piffaretti+11*)

Optical: constraints only on "local" cosmology ($\sigma_{8,}$ Ω_m; *no on w*) using 1e4 SDSS-MaxBCG clusters (*Rozo+10*)

SZ: present surveys provide ~1000 detections all-sky; *1st cosmological constraints with a sample of ~190 obj* (*Planck 2013 XX*) still to be refined (***tension with CMB:*** *bias in X-ray based M by ~40%* or *Σm_ν=0.20±0.09 eV*?).
NB: they rely on Y_{SZ} – M_X scaling laws



Total mass from X-rays

X-ray total mass is a fundamental tool to use Galaxy clusters as cosmological probes

- *low counts statistic*: **scaling relations**

(for galaxy clusters mass function: M_{tot} vs L/T/M_{gas}/Y_X *or* ***a combination of these***…)

Ettori et al. 2012; Ettori 2013 & 2014

$$M_{tot} \propto \Delta R_{\Delta}^{3} \Rightarrow \propto L^{3/4} \propto M_{g} \propto T^{3/2} \propto Y_{SZ}^{3/5}$$

Total mass from X-rays

X-ray total mass is a fundamental tool to use Galaxy clusters as cosmological probes

- *low counts statistic*: **scaling relations**

(for galaxy clusters mass function: M_{tot} vs $L/T/M_{gas}/Y_X$ *or* ***a combination of these***…)

Ettori et al. 2012; Ettori 2013 & 2014

$$M_{tot} \propto L^{\alpha} \, M_g{}^{\beta} \, T^{\gamma}; \quad 4\alpha + 3\beta + 2\gamma = 3$$

The ***self-similar*** prediction on **normalization & slope** can fully explain the ***observed X-SZ SL*** once $\{f_g(M), \beta_P(M), C\}$ are considered

Total mass from X-rays

X-ray total mass is a fundamental tool to use Galaxy clusters as cosmological probes

- *low counts statistic*: **scaling relations**

(for galaxy clusters mass function: M_{tot} vs L/T/M_{gas}/Y_X *or* ***a combination of these***…)
Ettori et al. 2012; Ettori 2013 & 2014

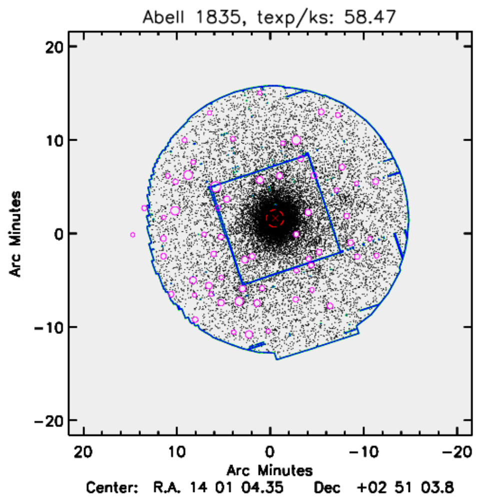
$$M_{tot} \propto L^{\alpha} \; M_g^{\;\beta} \; T^{\gamma}; \quad 4\alpha + 3\beta + 2\gamma = 3$$

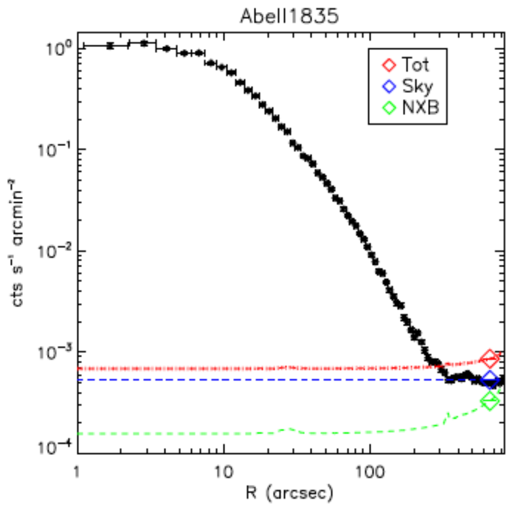
- *high counts statistic*: **mass profiles**

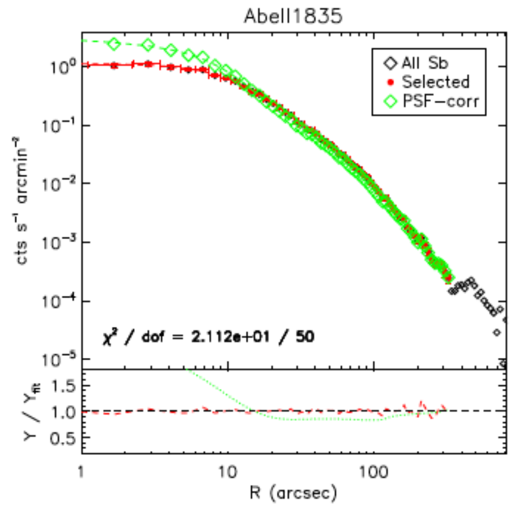
(calibration & hydrostatic bias; *~200 out of 1743 obj known*, *Piffaretti et al. 11*)
Ettori et al., 2013, SSRv, 177, 119 (arXiv:1303.3530)

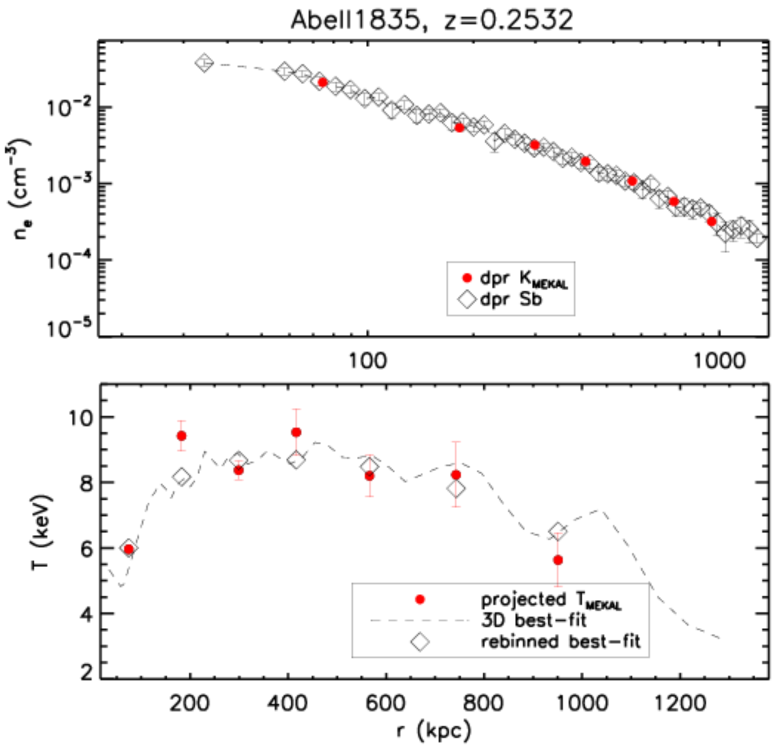
$$M_{tot}(< r) = -\frac{kT_{gas}(r)\; r}{G\mu m_p}\left(\frac{\partial \ln n_{gas}}{\partial \ln r} + \frac{\partial \ln T_{gas}}{\partial \ln r}\right)$$

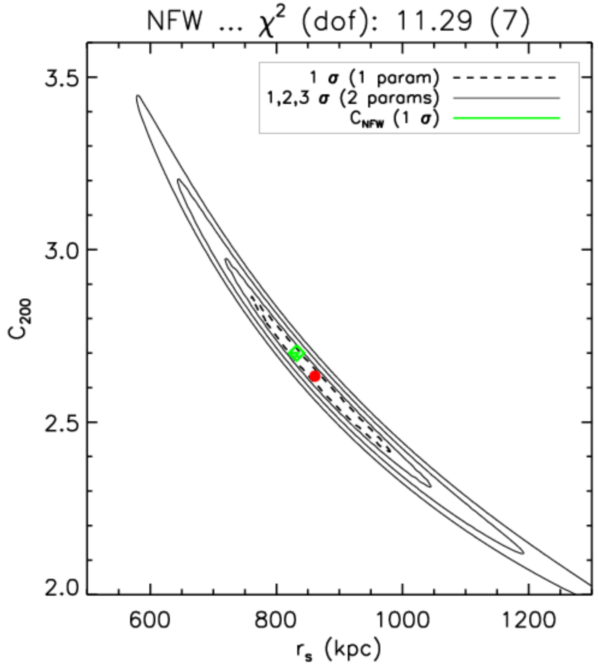
Mass profiles: c-M relation



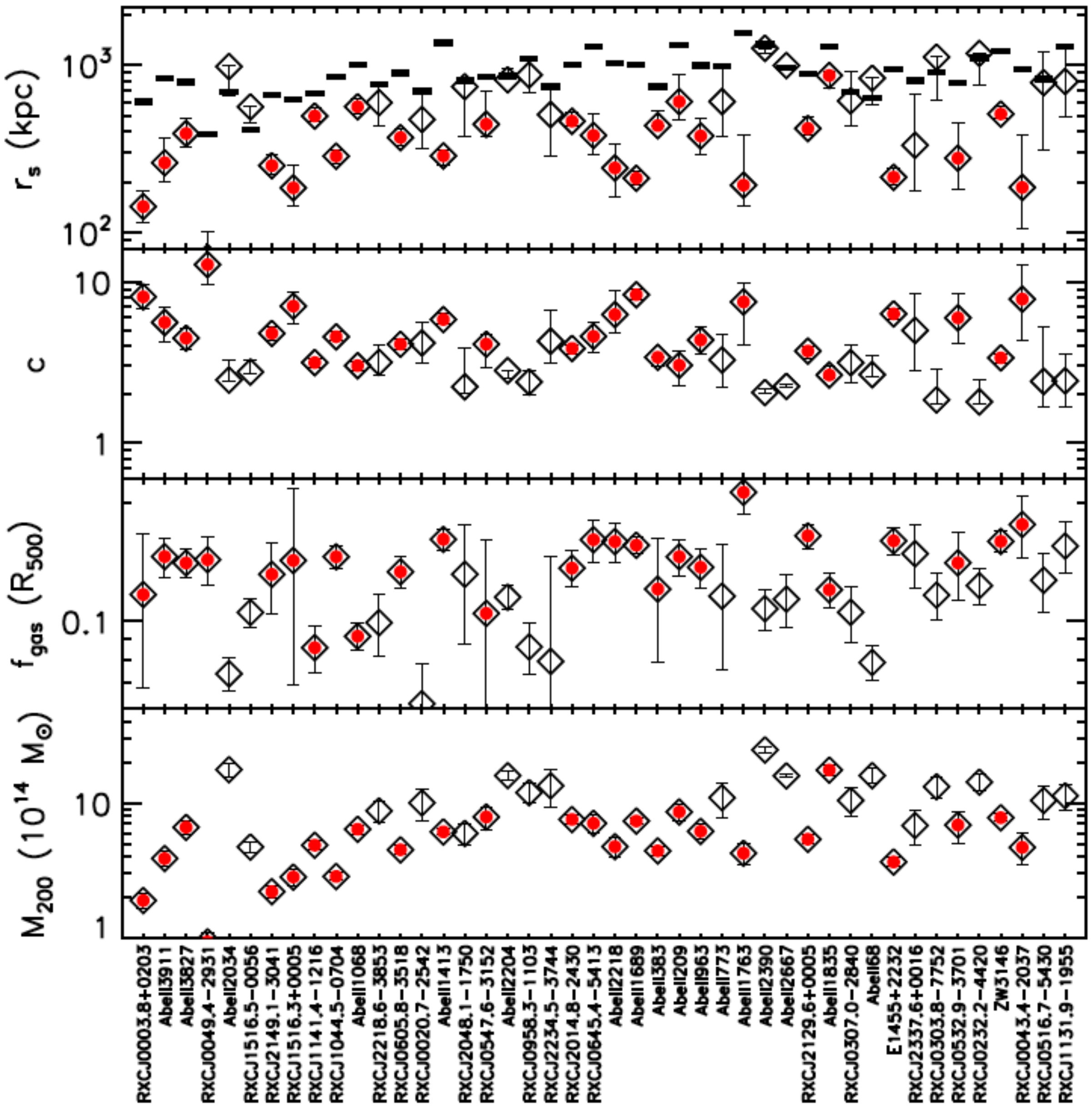








Results on {c, M, f_{gas}}



$c = R_{200}/r_s$

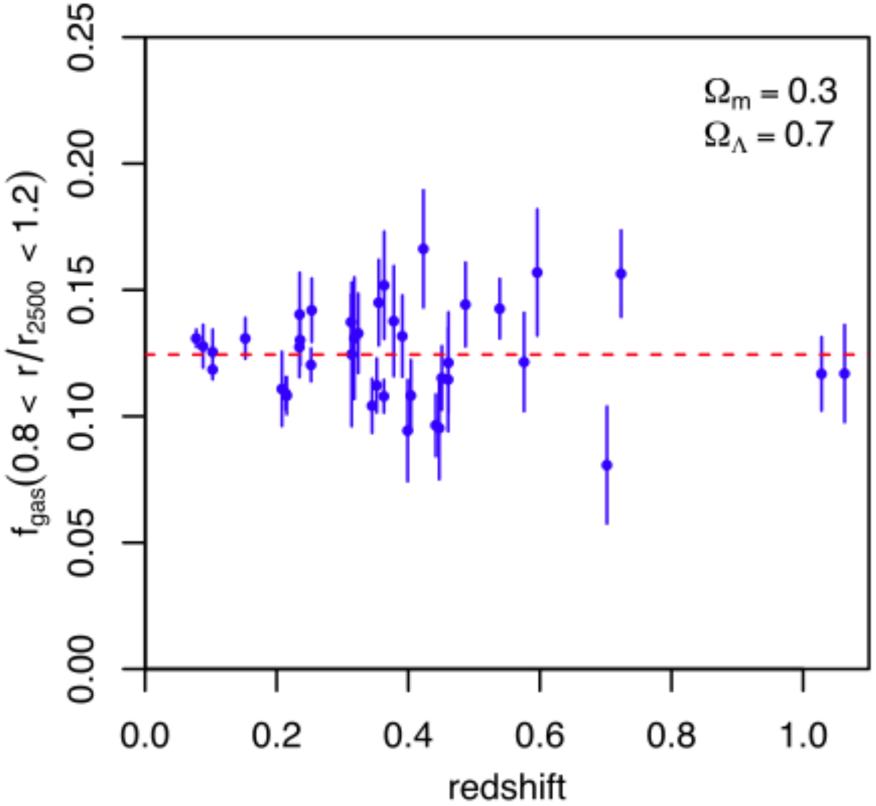
$f_{gas} = M_{gas}/M_{tot}$

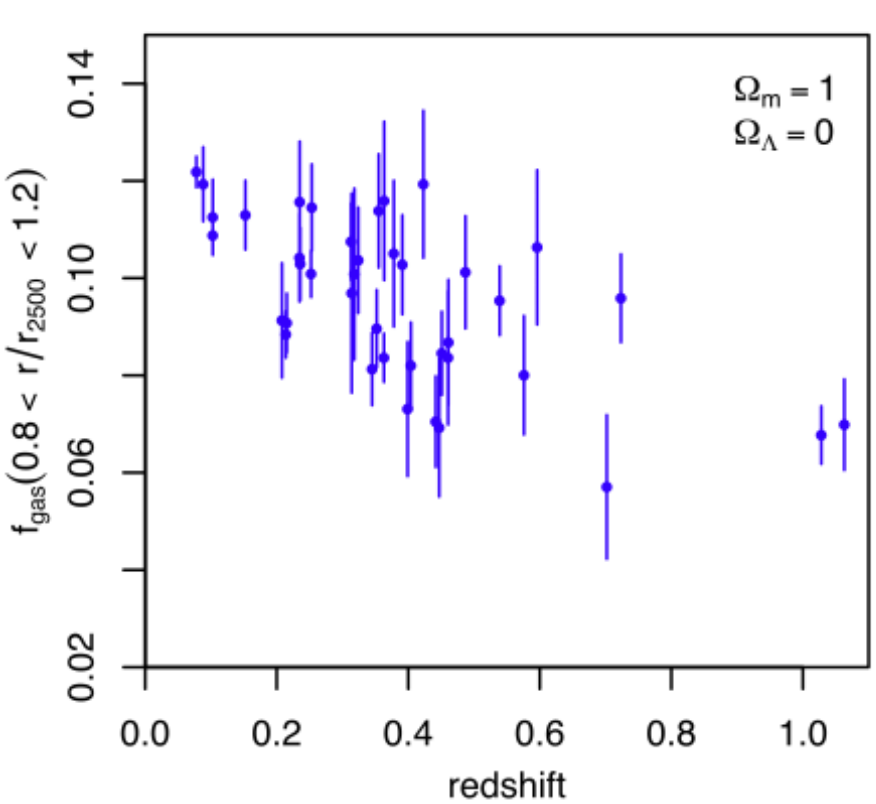
$M_{200} = 200\rho_c(z)\ V$

$V = 4/3\pi R_{200}^3$

Gas mass fraction

$f_{gas}(<R_{500}) = M_{gas}/\ M_{tot} \propto n_{gas}R^3/R \propto d_{ang}\,(\Omega_m,\ \Omega_\Lambda,\ w)^{3/2}$

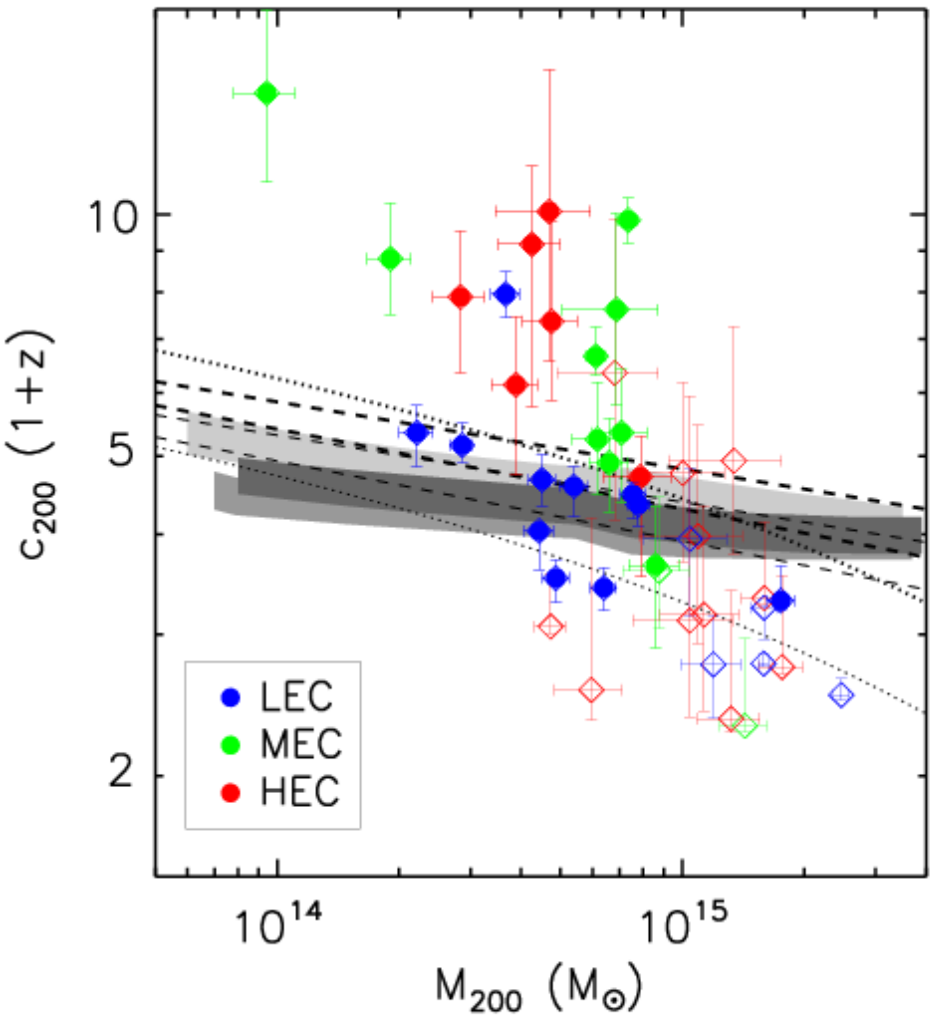


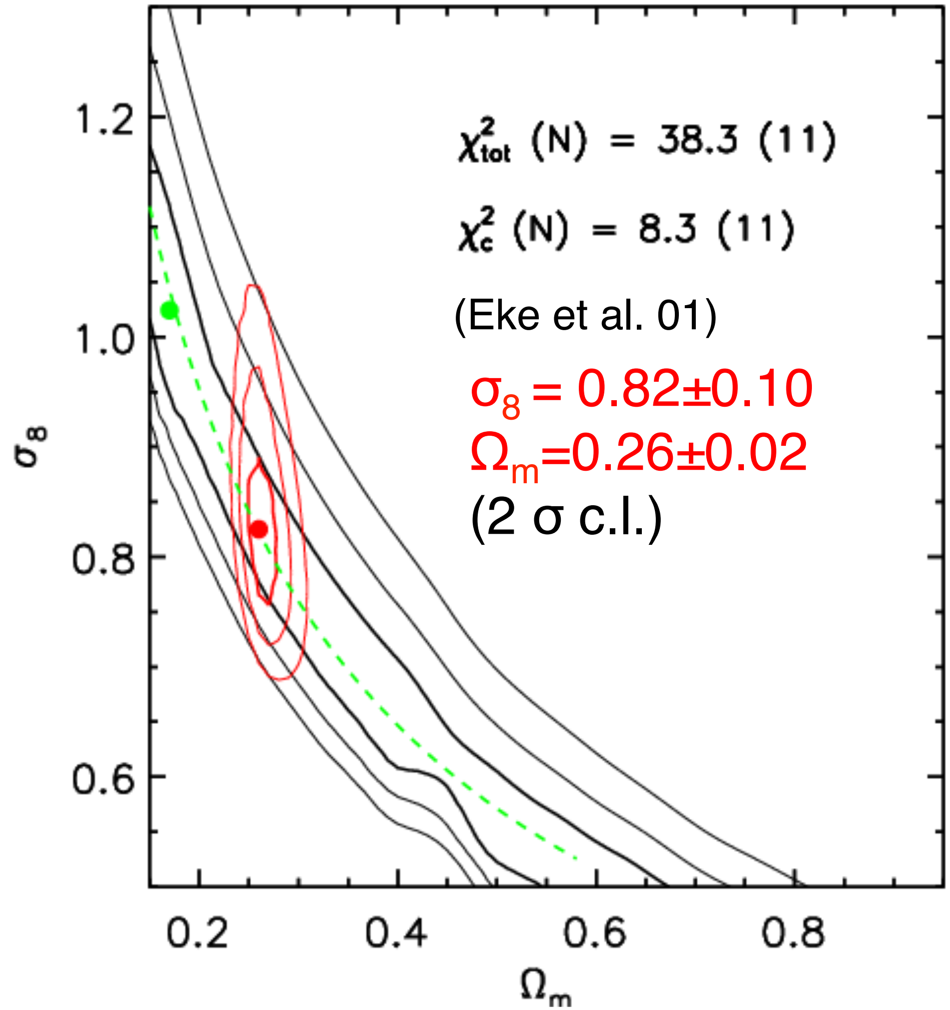


Mantz et al. (2014):
40 obj with T>5 keV observed with Chandra @z=0.08-1.06

➔ $\varepsilon_{\Omega m}$~14%, ε_w~27% , Ω_Λ>0 @99.99% l.c.

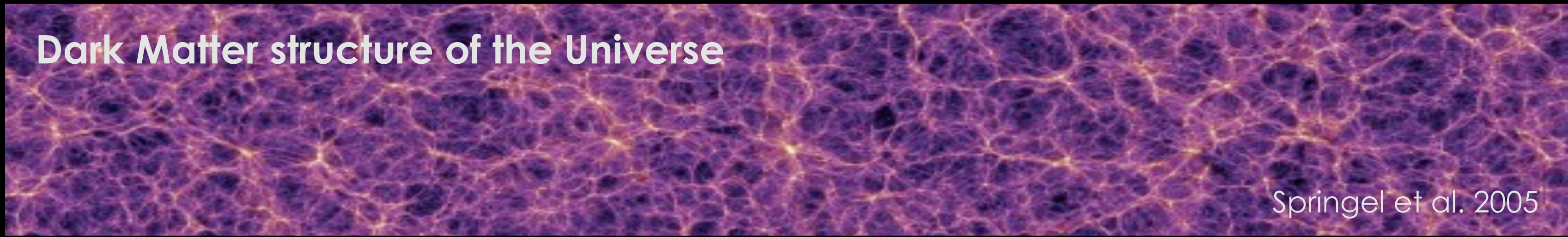
c-M relation: $\sigma_8 - \Omega_m$





ATHENA+

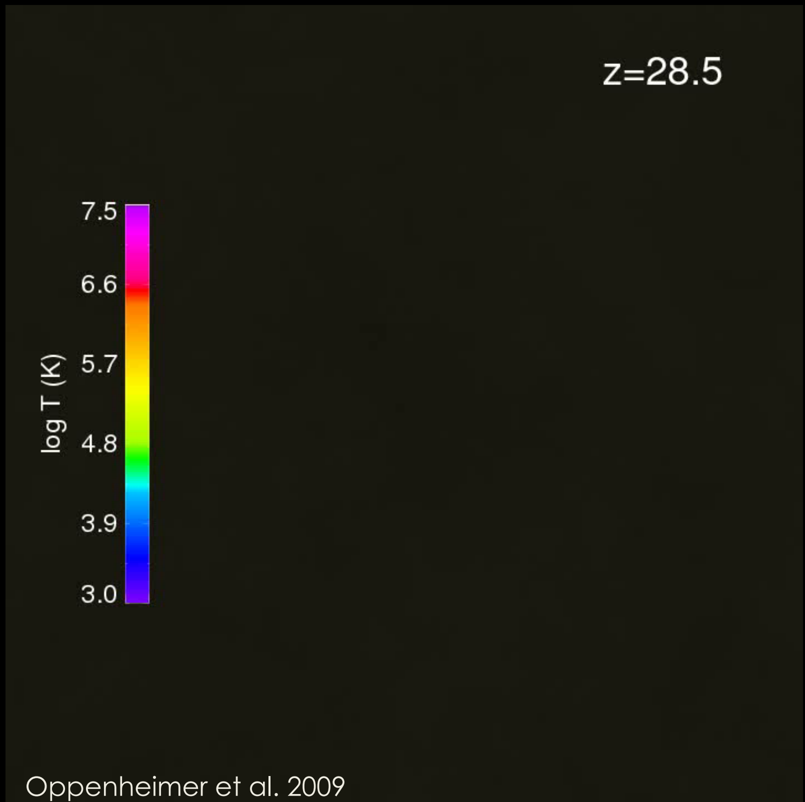
Why does the observable universe look the way it does?

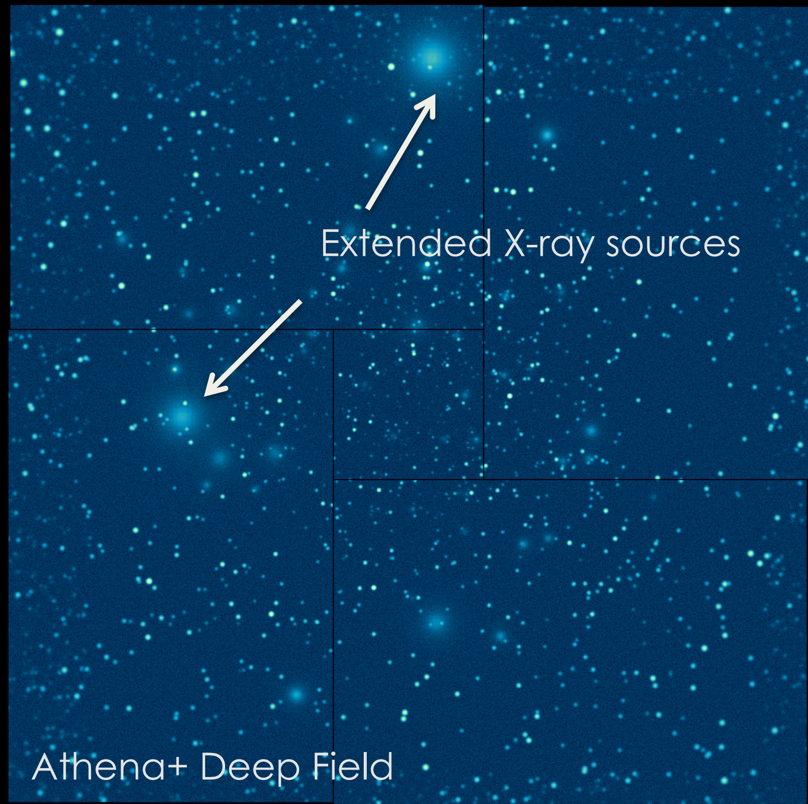


ATHENA+

Key questions for observational astrophysics in 2028

1. How does ordinary matter assemble into the large scale structures we see today?



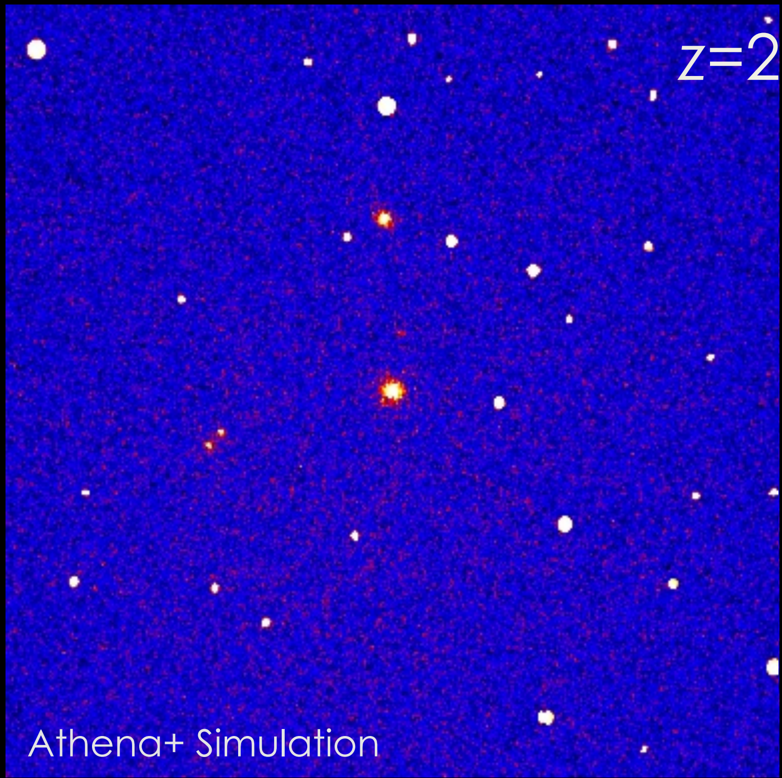


Pointecouteau, Reiprich et al., 2013 arXiv1306.2319

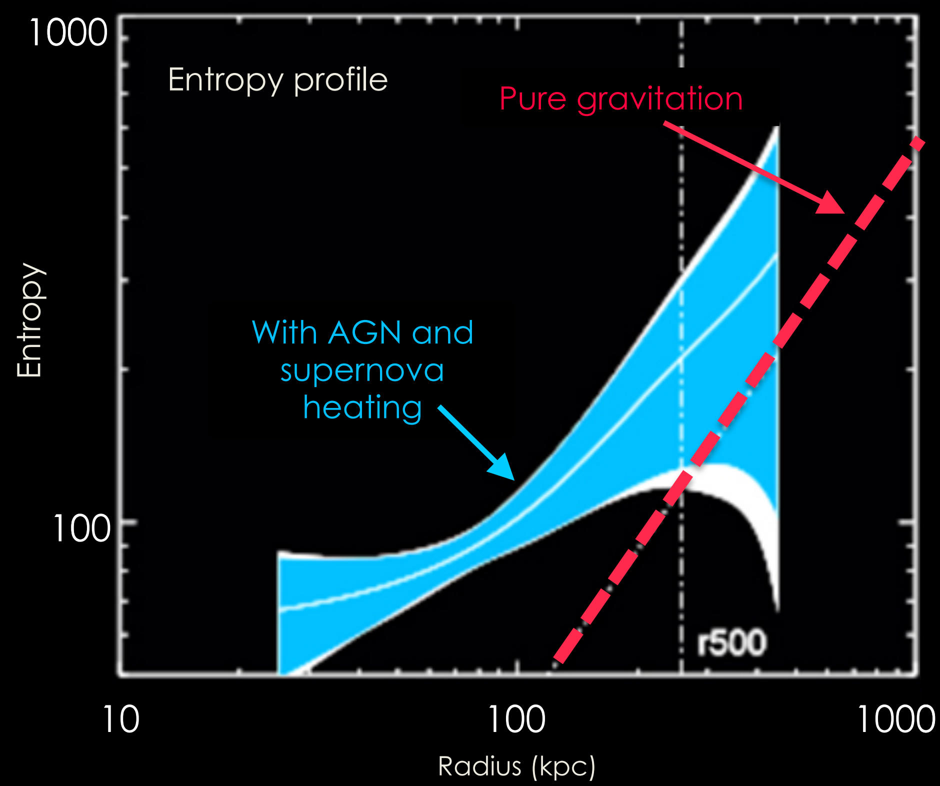
ATHENA+

The formation and evolution of clusters and groups of galaxies

How and when was the energy contained in the hot intra-cluster medium generated?



Pointecouteau, Reiprich et al., 2013 arXiv1306.2319



How does ordinary matter assemble into the large-scale structures that we see today?

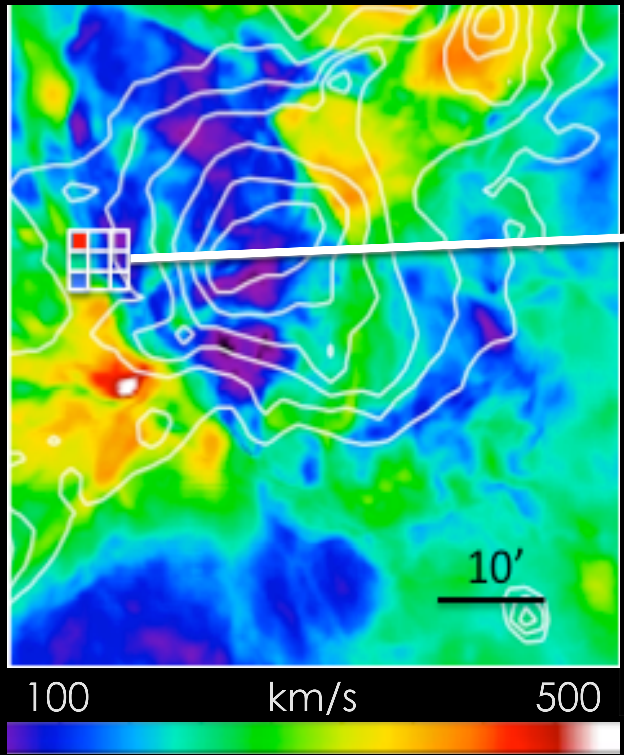
ATHENA+

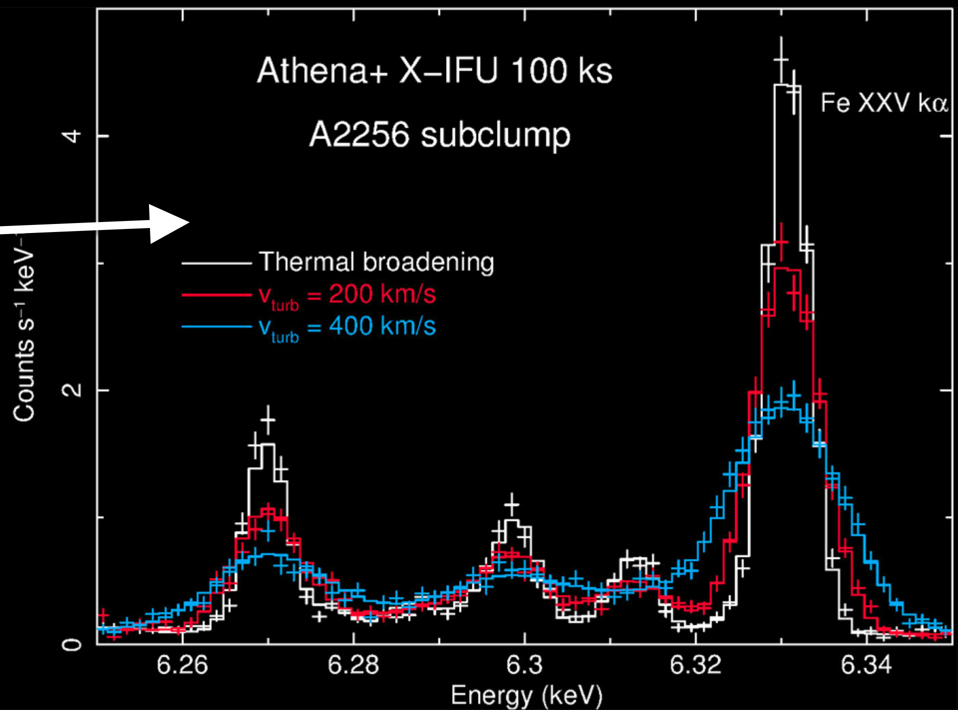
The formation and evolution of clusters and groups of galaxies

How and when was the energy contained in the hot intra-cluster medium generated?

Simulated Velocity map

Ettori, Pratt, et al., 2013 arXiv1306.2322





How does ordinary matter assemble into the large-scale structures that we see today?

ATHENA+

Athena+ science in context

Athena+ is a crucial part of the suite of large observatories needed to reach the science objectives of astronomy in the coming decades