Cosmology with galaxy clusters: the role of X-rays

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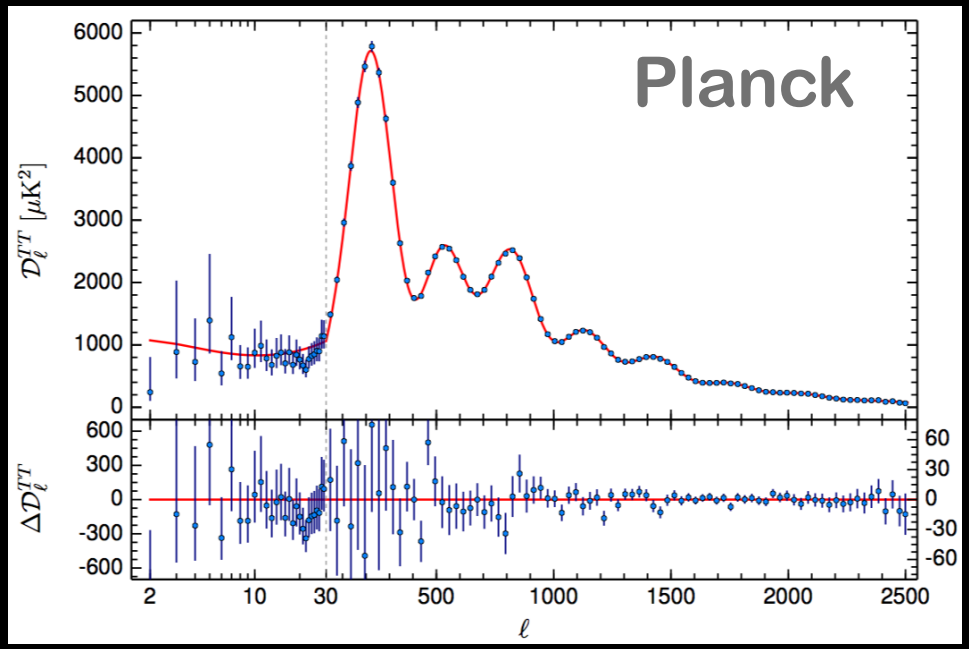
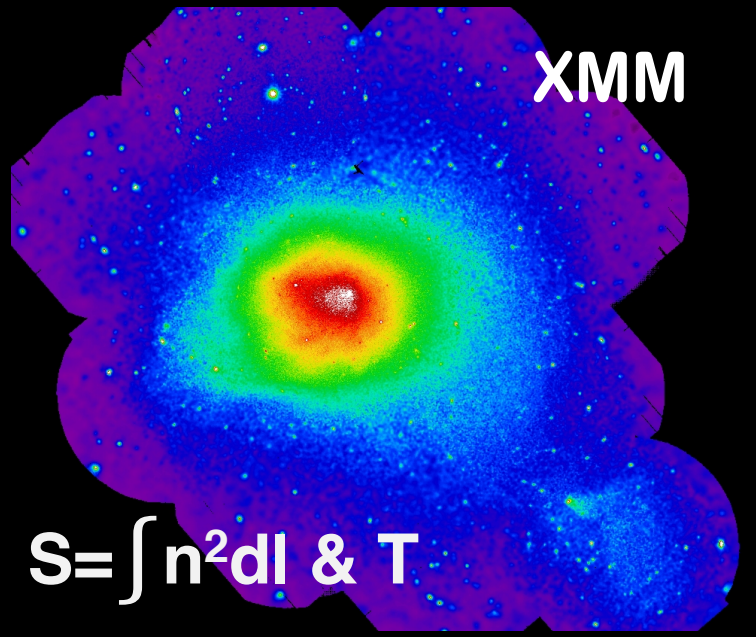




Clusters of Galaxies

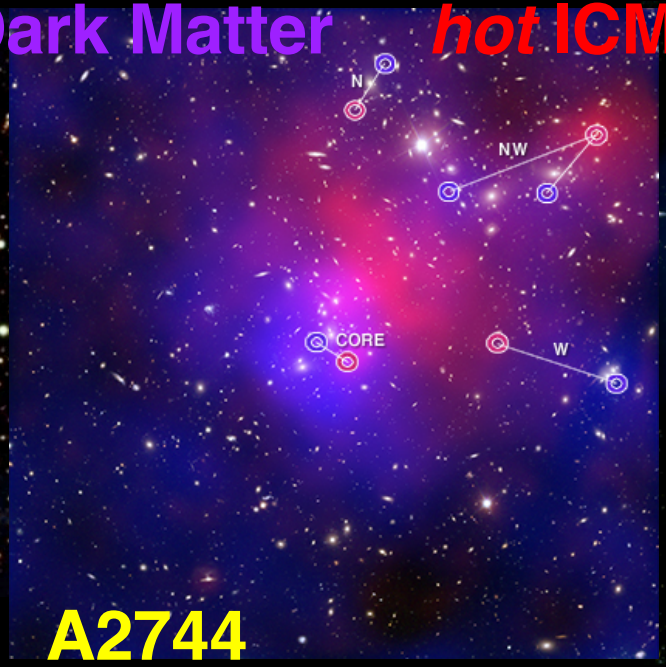
- ***The largest gravitationally-bound structures in the universe***
- ***"dunkle Materie"*** **(**Zwicky 1933**)**

~80% of total mass (~15% hot gas; few % stars)

- **DM halos: internal structure & properties**

Bullet cluster

Dark Matter ***hot*** **ICM**



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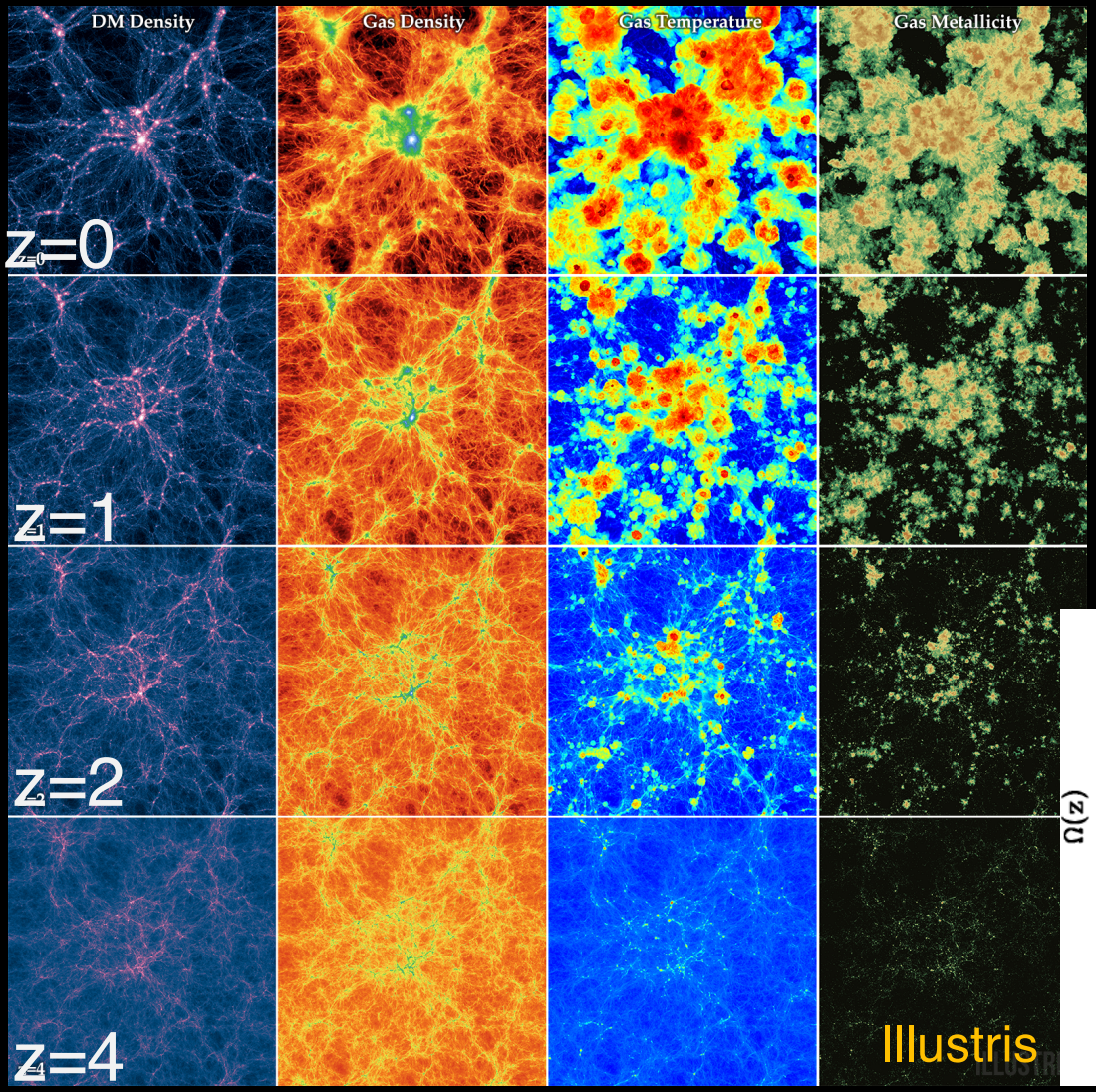
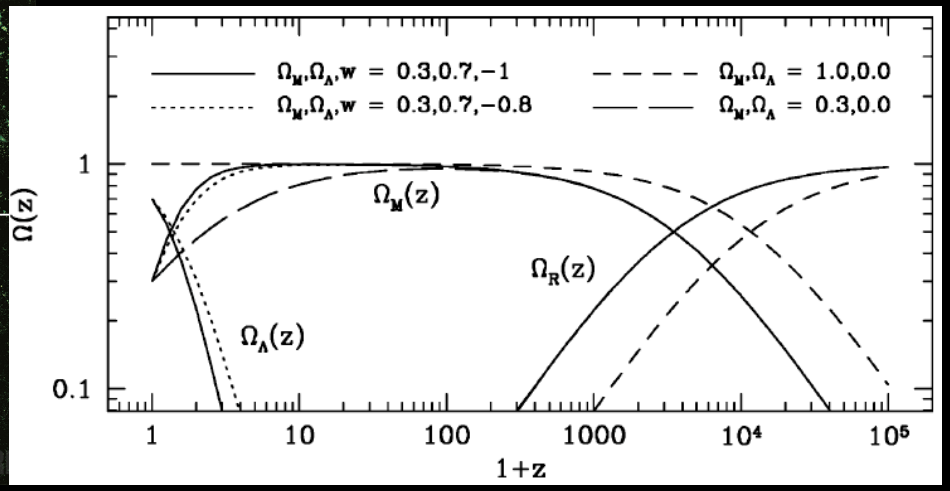
MACSJ0025

Large-scale Structure formation



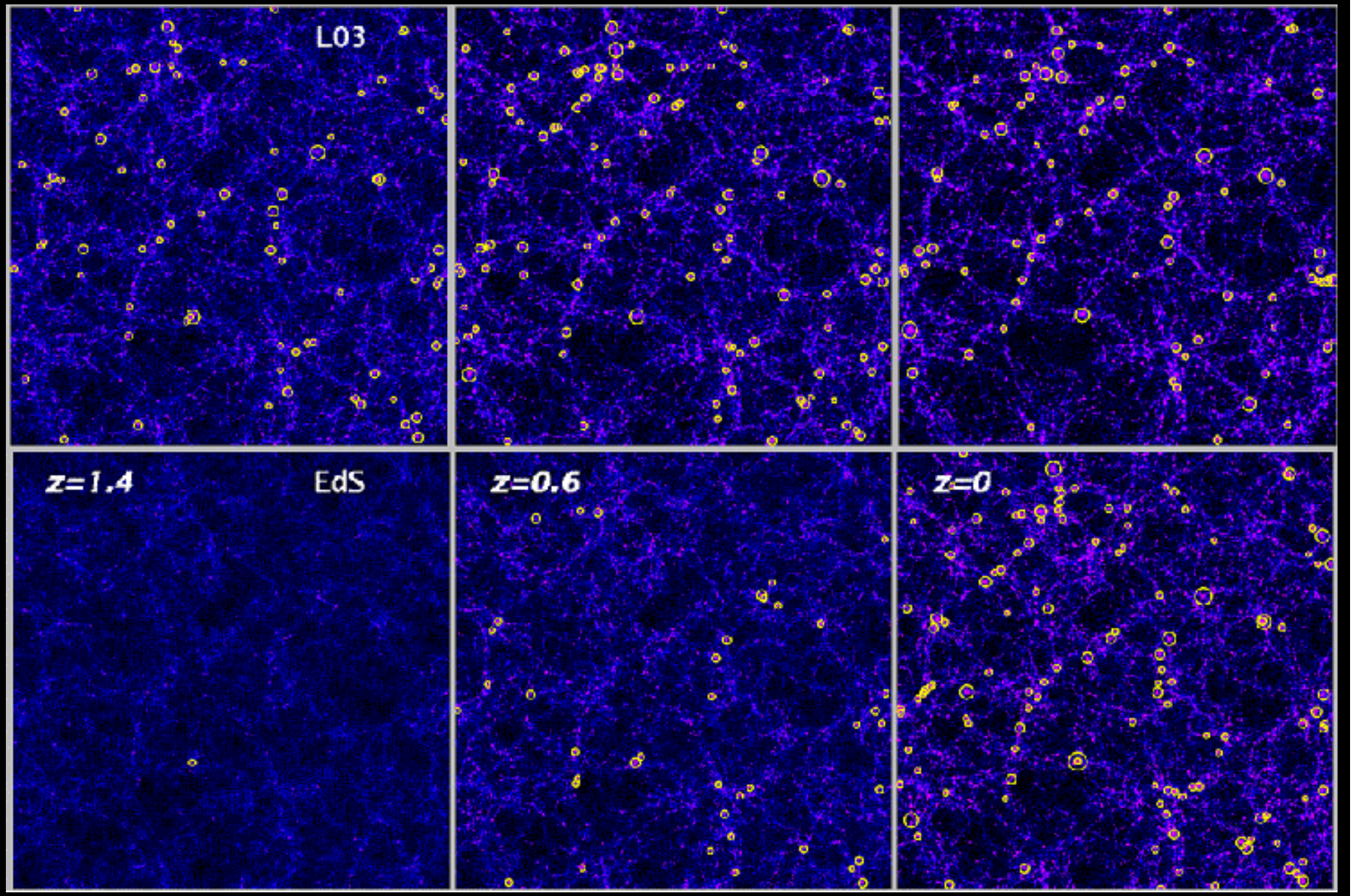
Voit05



Matter dominates the dynamics at **z>1**

Dark energy becomes relevant at **z<2**

Clusters of Galaxies & cosmology



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

What we need to do *cosmology with GC*

1. **robust cluster catalogs with large z leverage**

(with well understood purity and completeness; look for e.g. DES, SPT-3G, eROSITA, Euclid)

2. **accurate absolute mass calibration**

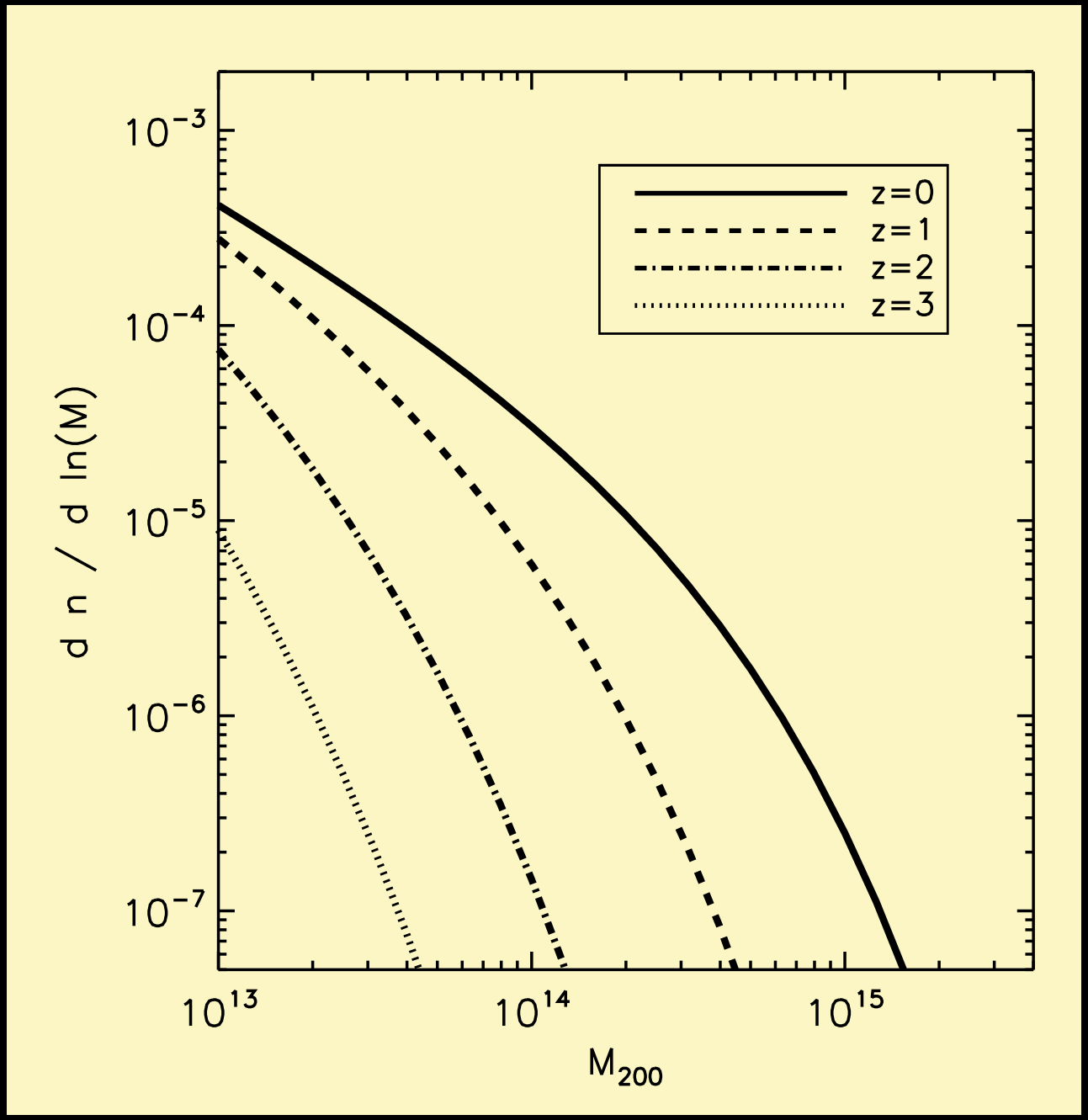
(from weak lensing or X-ray once b_{HE} is better characterized)

3. **sufficiently low-scatter mass proxy information**

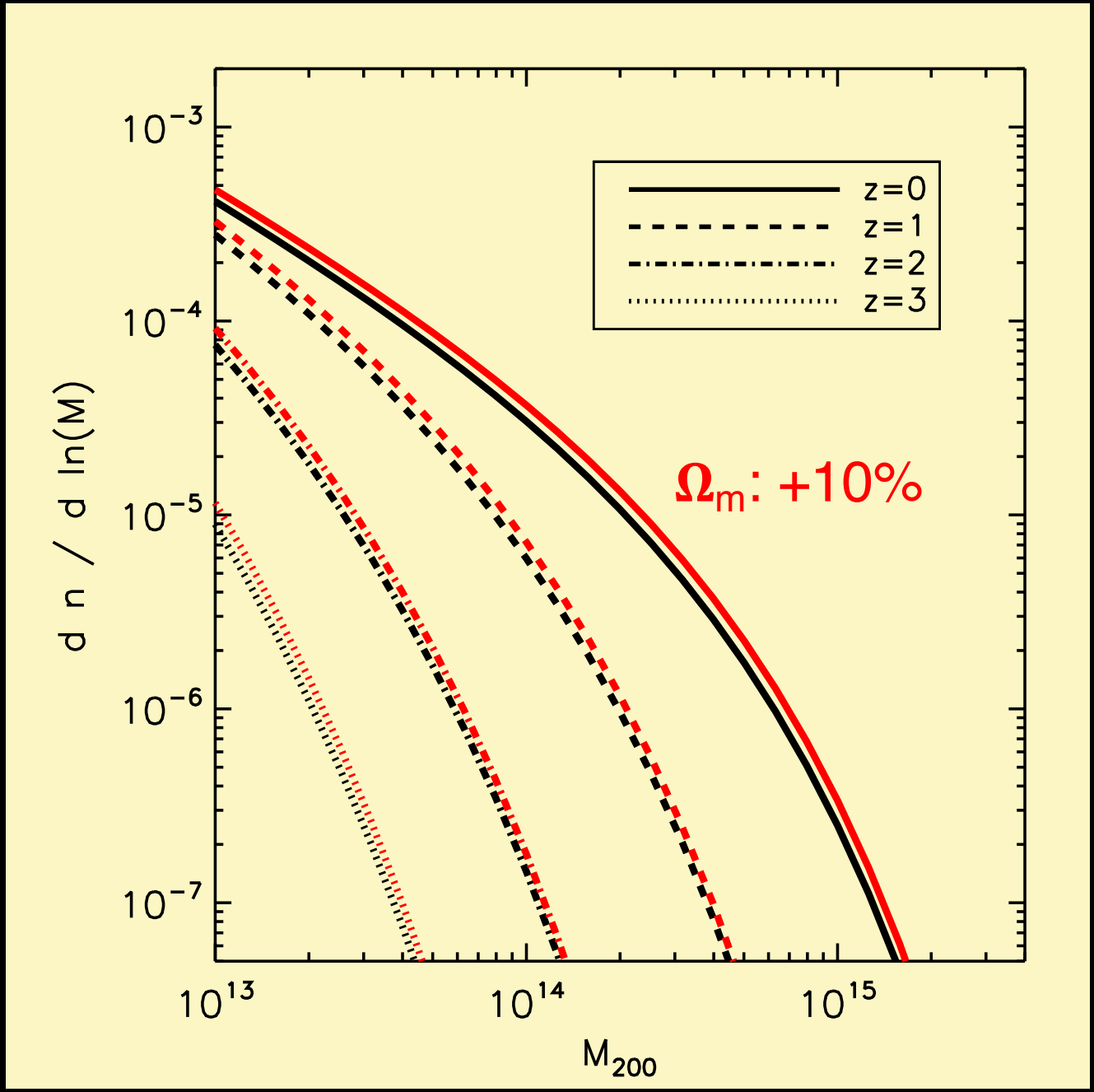
(mainly from X-ray and SZ follow-up; optical is more expensive and still affected from large scatter; ***Comalit*** *serie of papers by Sereno+15-19)*

Finally, we have to build a robust likelihood with N free parameters, where N = ***~6 cosmological parameters*** *&* ***~12-17 astrophysical ones*** *(e.g. Mantz+10, SPT-Bocquet+18)*

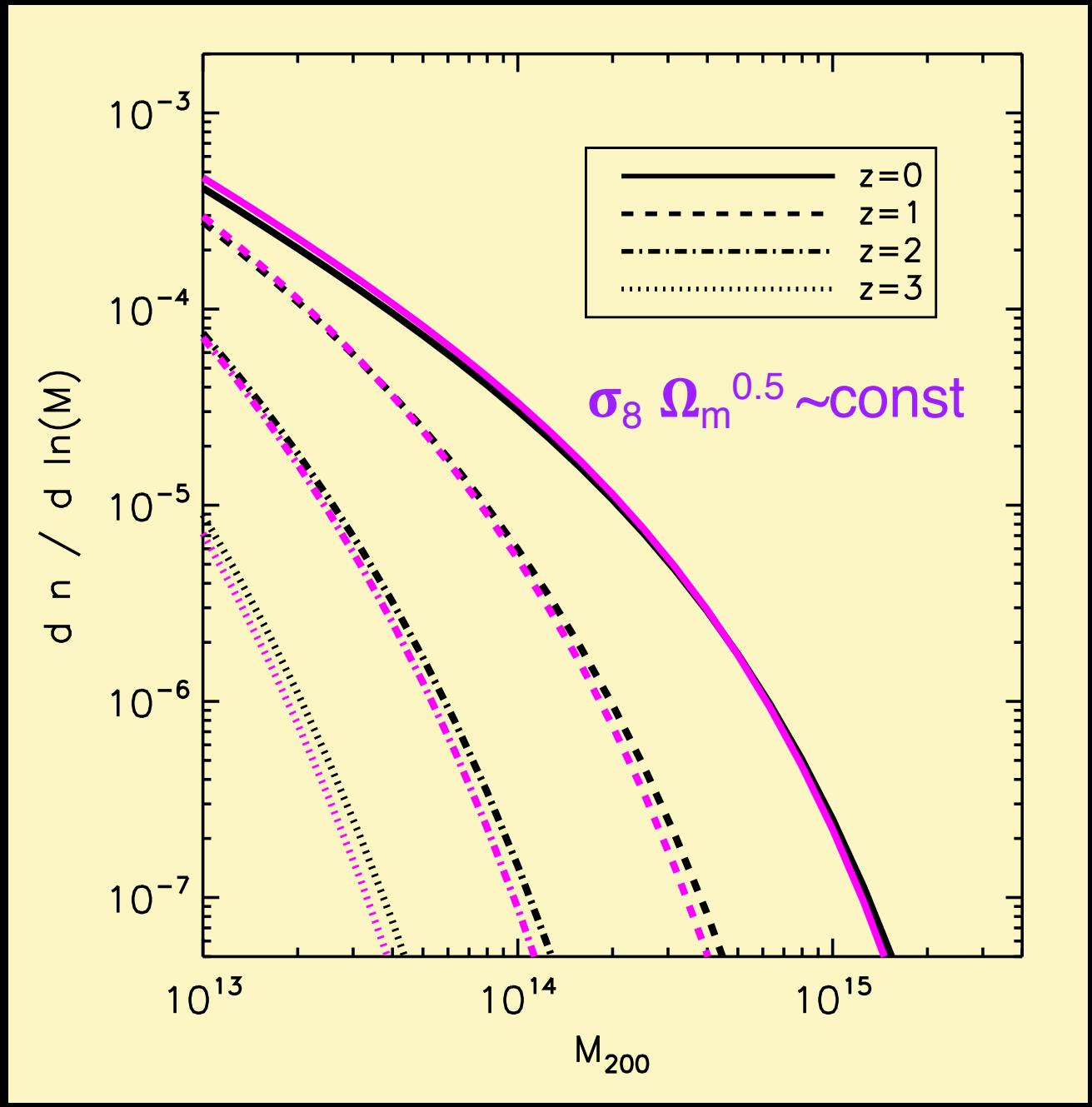
Clusters of Galaxies & cosmology



Clusters of Galaxies & cosmology



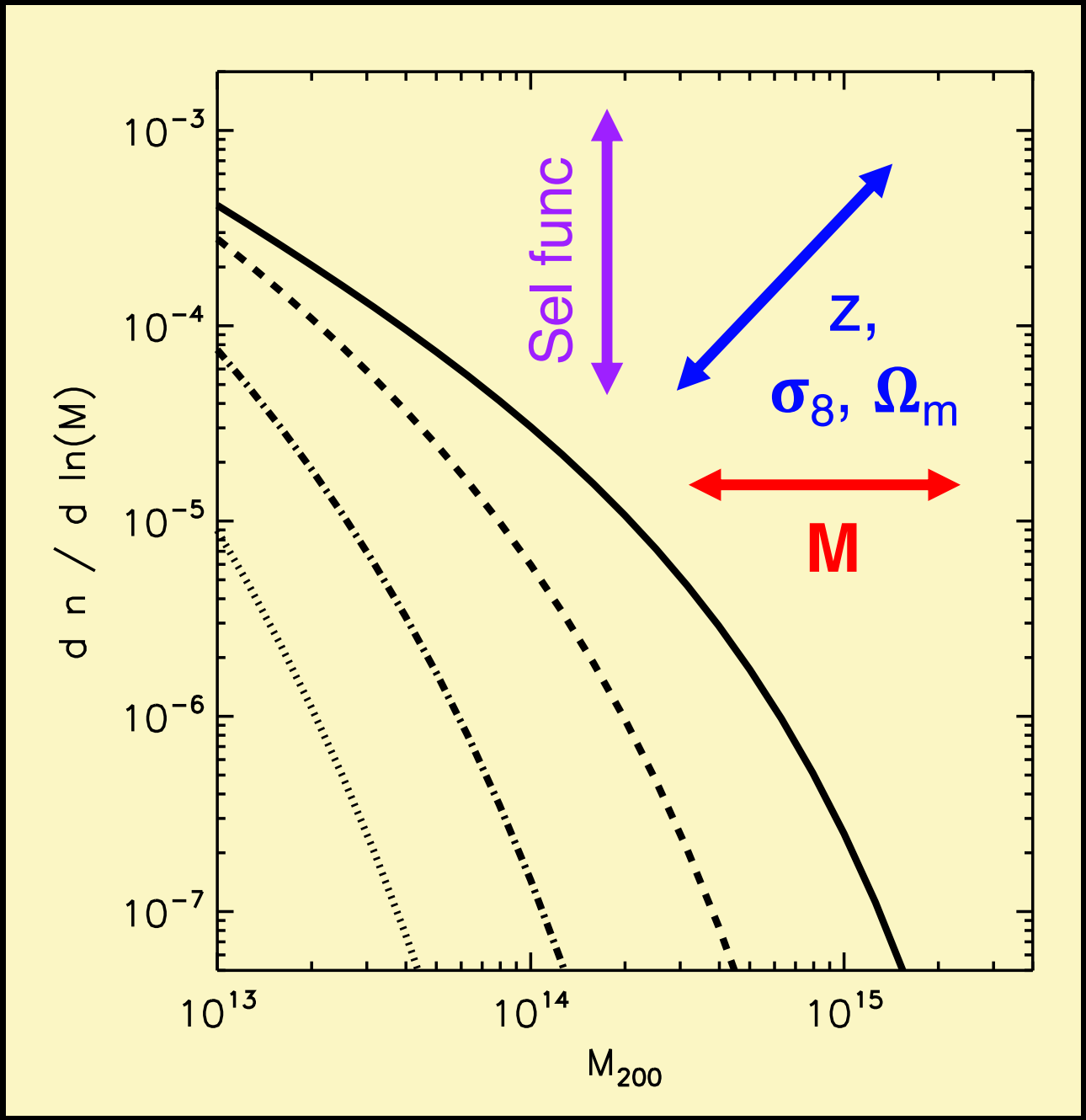
Clusters of Galaxies & cosmology



Locally one can determine $\sigma_8\Omega_m^{0.5}$, because only the amplitude on a given scale $R \approx (M/\Omega_m)^{1/3}$ can be measured

The degeneracy can be broken looking at the evolution of N(M)

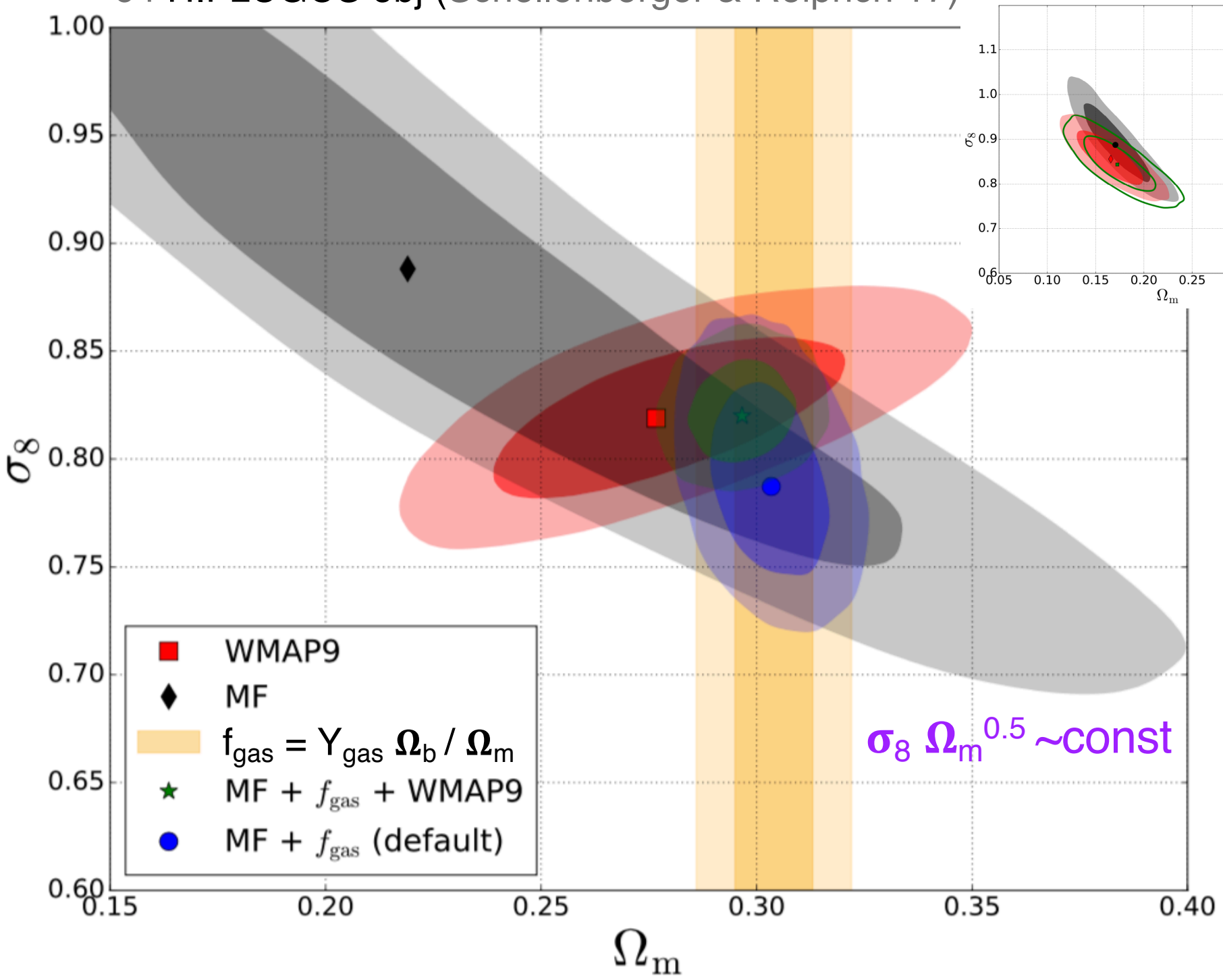
Clusters of Galaxies & cosmology



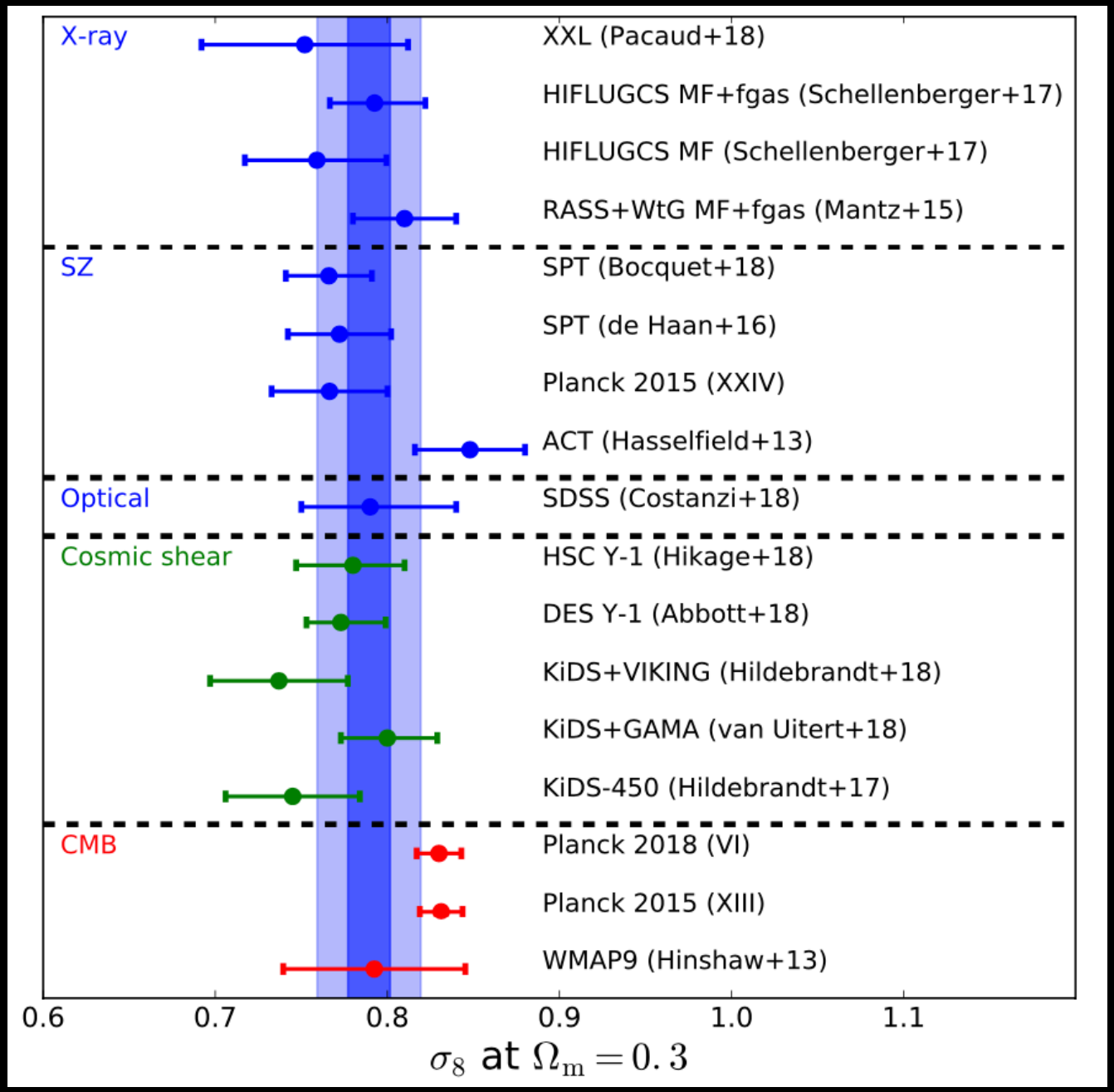
Amplitude @
$R \approx (M/\Omega_m)^{1/3}$
is dominated
by **groups**

Most massive
objects depend
on redshits

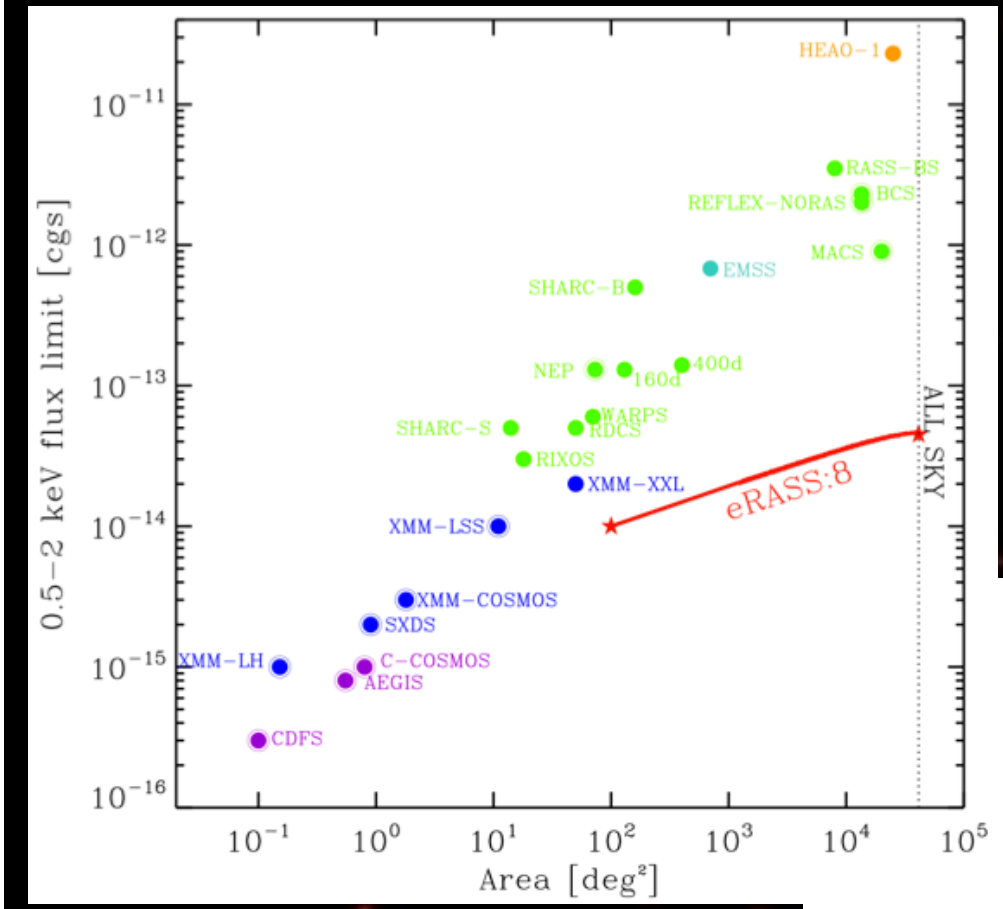
64 HIFLUGCS obj (Schellenberger & Reiprich 17)

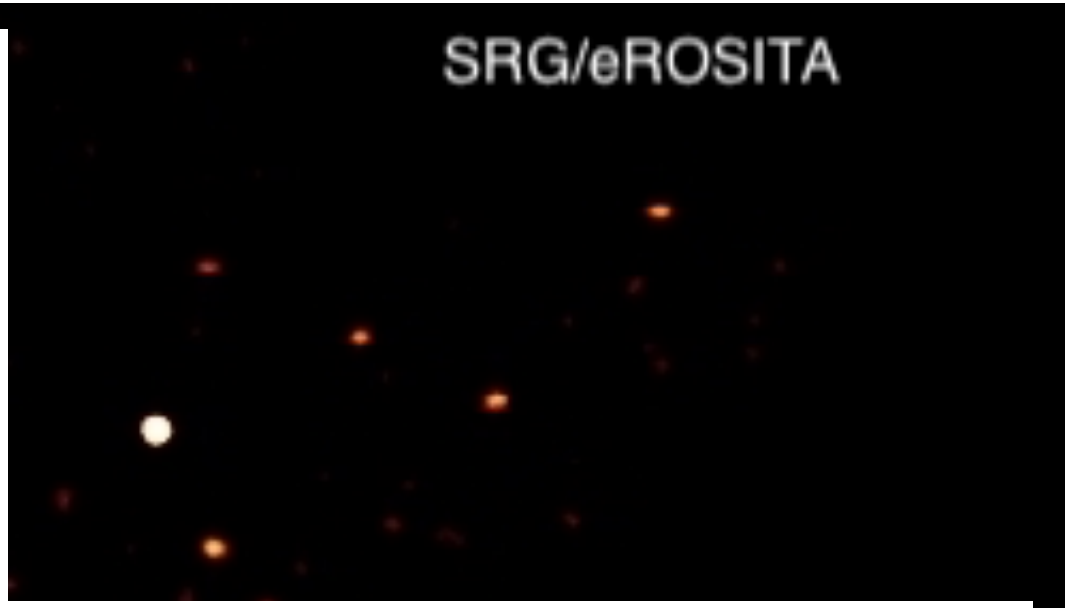


Clusters of Galaxies & cosmology



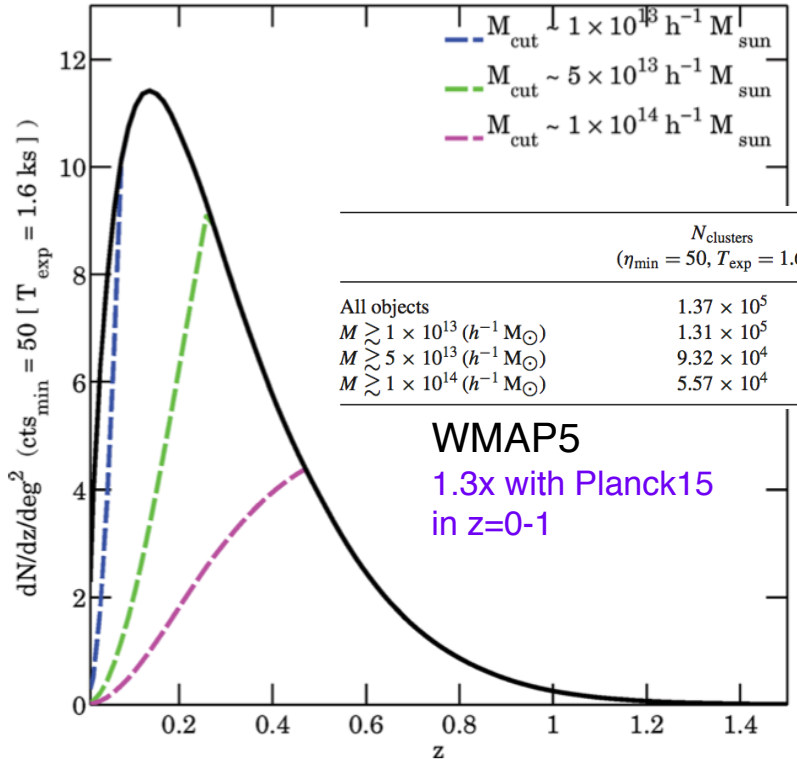
Pratt+19





Cluster Surveys: eROSITA

(Merloni+12, Pillepich+12, Borm+14)

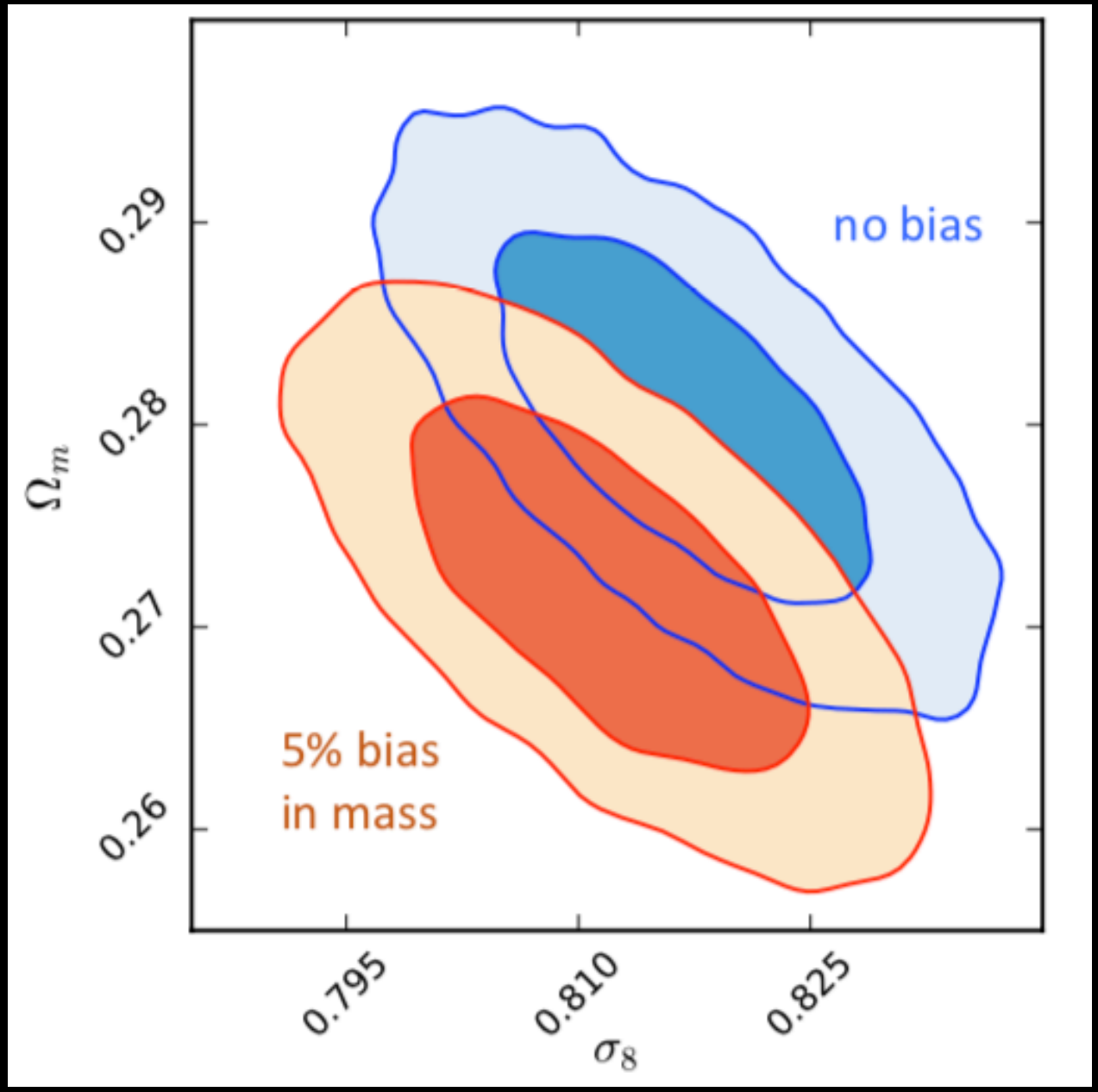


	$N_{clusters}$ ($\eta_{min} = 50$, $T_{exp} = 1.6$ ks)	z_{median}
All objects	1.37×10^5	0.25
$M \gtrsim 1 \times 10^{13}$ (h^{-1} $M_\odot$)	1.31×10^5	0.27
$M \gtrsim 5 \times 10^{13}$ (h^{-1} $M_\odot$)	9.32×10^4	0.35
$M \gtrsim 1 \times 10^{14}$ (h^{-1} $M_\odot$)	5.57×10^4	0.46

WMAP5

1.3x with Planck15 in z=0-1

Clusters of Galaxies & cosmology

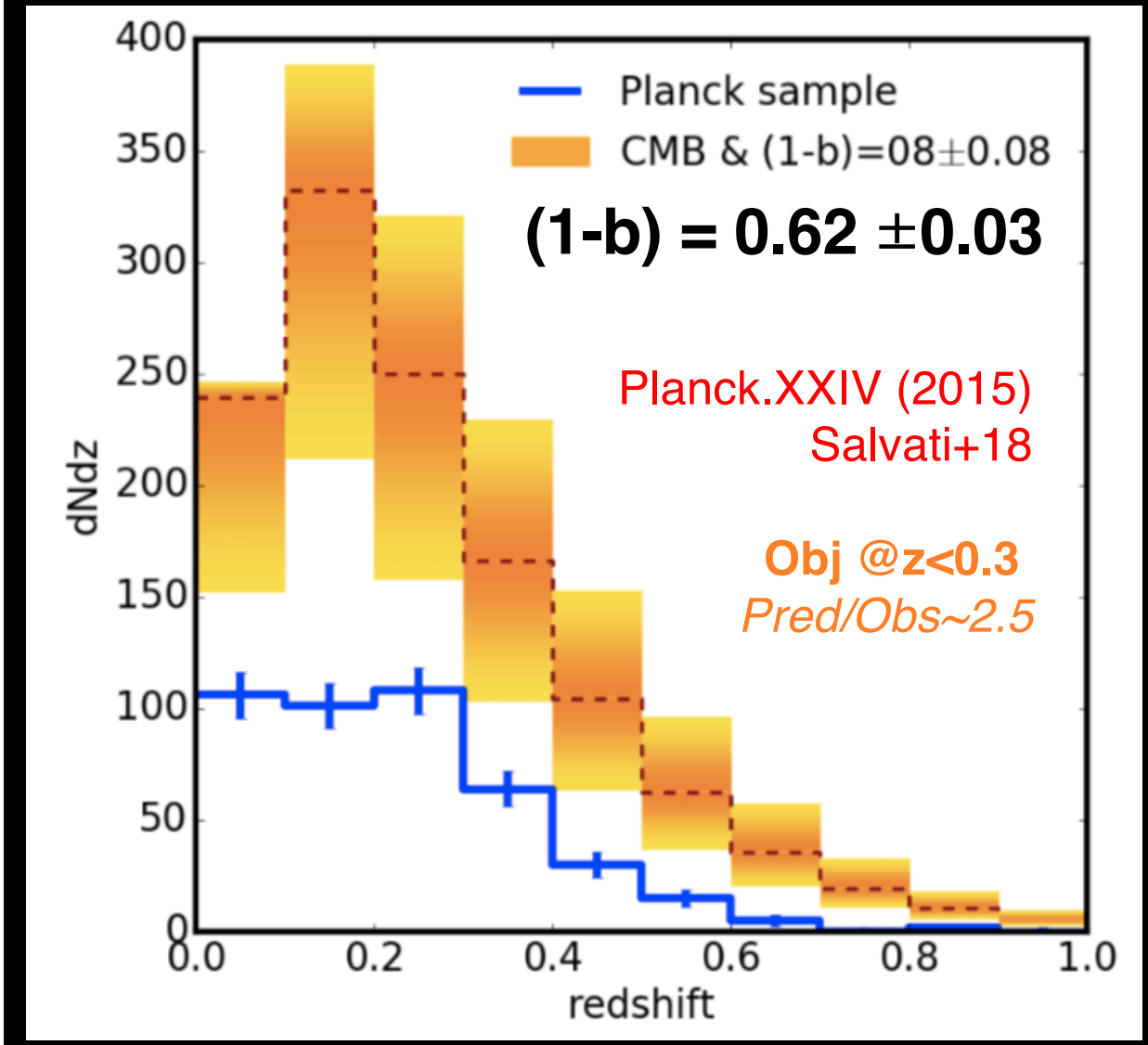


$\sigma_8 \sim (1\text{-}b)^{1/3}$

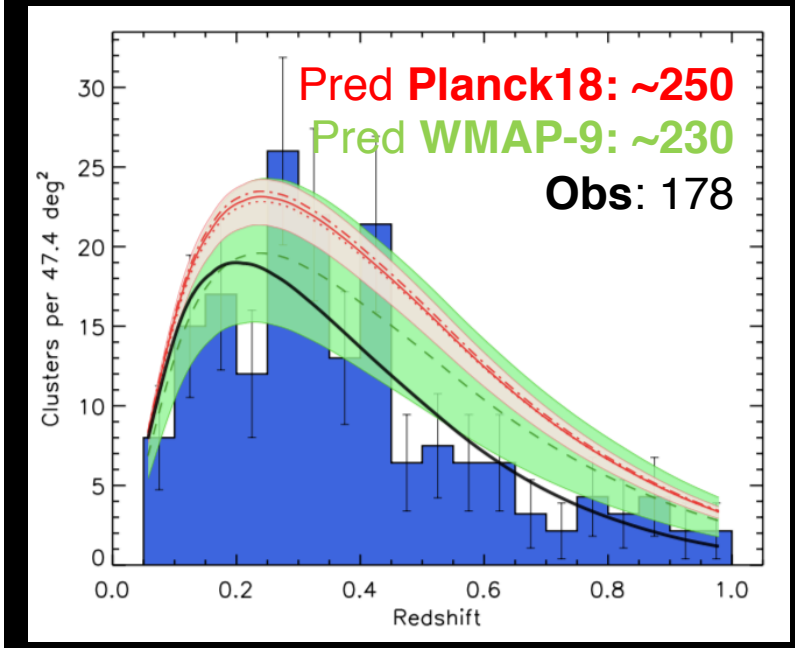
Predicted constraints from *eROSITA* cluster number counts (Borm+)

$M_X \equiv M_{tot}$ *or not?*

Cluster f(M) from Y_{SZ} calibrated vs M_X & $M_X/M_{500} = (1-b)$



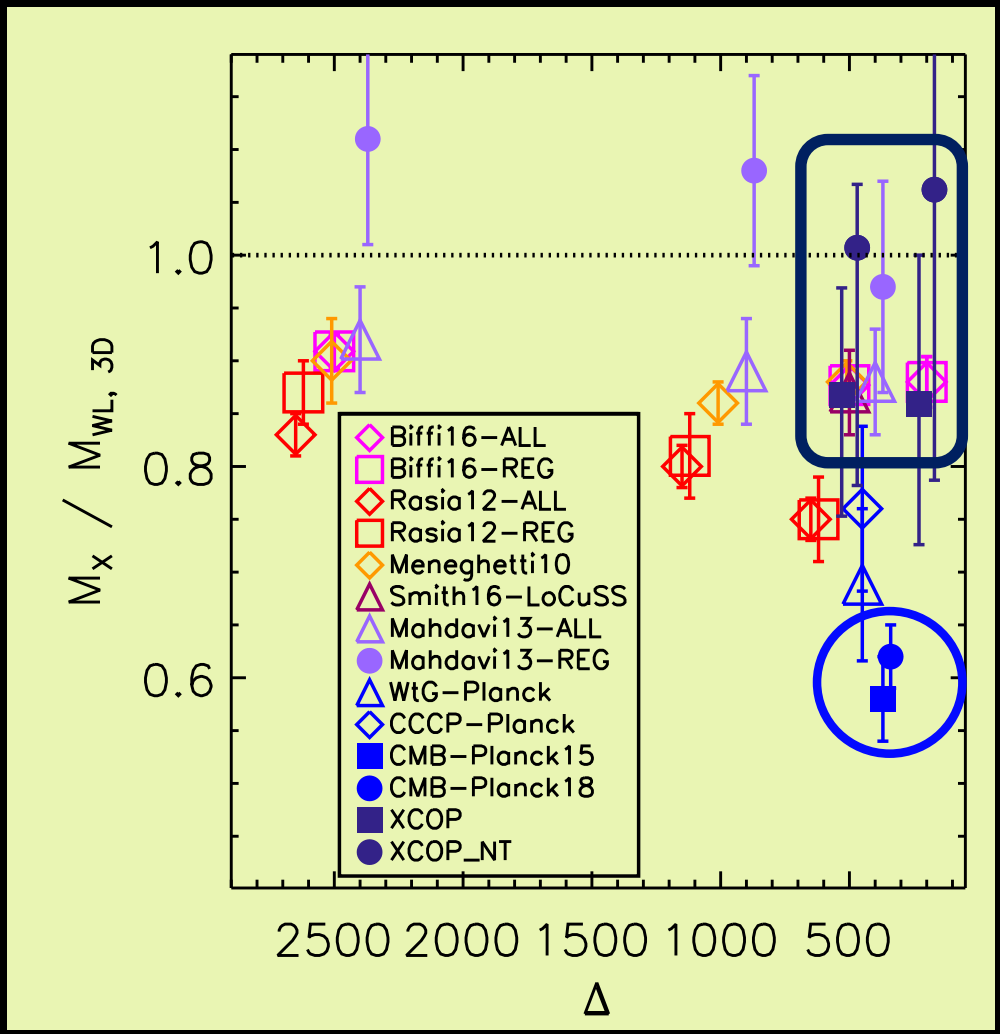
XXL (Pacaud+18)



$M_X \equiv M_{tot}$ *or not?*

Cluster f(M) from Y_{SZ} calibrated vs M_X & **$M_X/M_{500} = (1-b)$**

But "In summary, accurate calibrations of cluster masses are essential if cluster counts are to be used as cosmological probes. Given the uncertainties in these calibrations, we do not use cluster counts in our main parameter grid."
(**Planck 2018 results VI**)



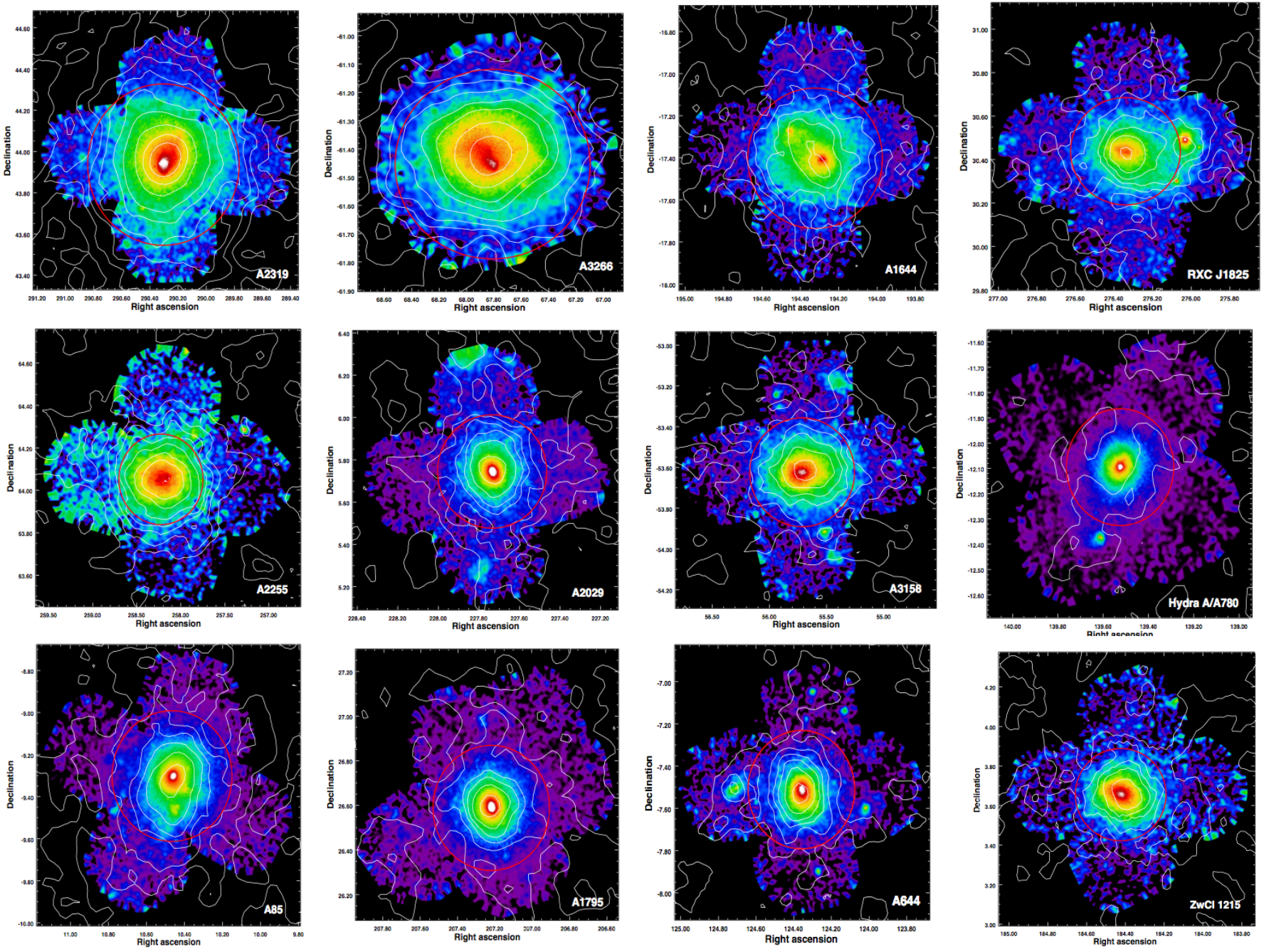
Total mass from SZ/X-rays

$$\frac{G\,M_{tot}(<r)}{r^2} = -\frac{dP_g}{dr}\frac{1}{\rho_g} - \frac{dv}{dt}$$

$$M_{tot}(<r) = -\frac{kT_g\ r}{G\mu m_p}\left(\frac{\partial \ln n_g}{\partial \ln r} + \frac{\partial \ln T_g}{\partial \ln r}\right)$$

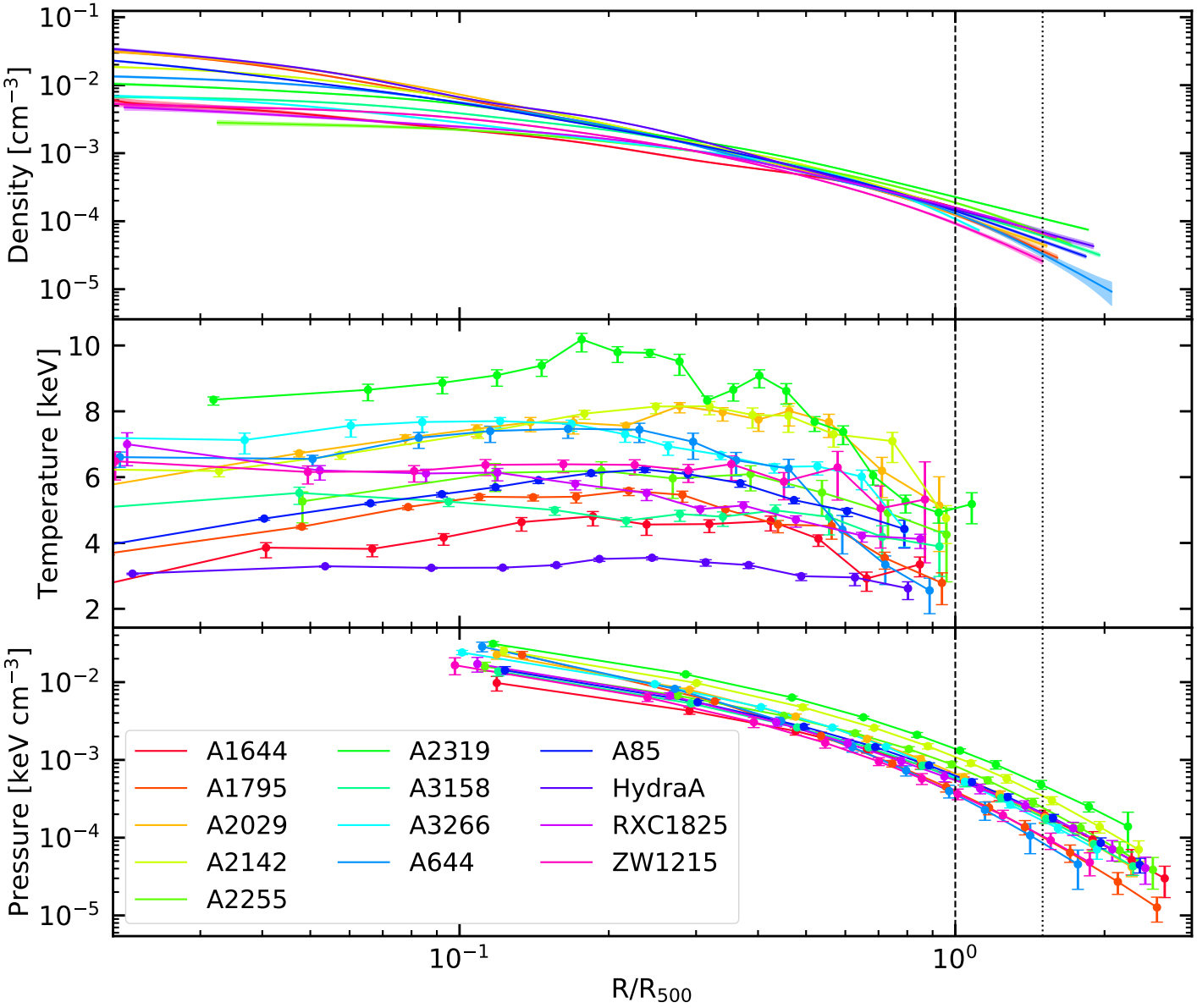
$$M_{tot} \sim R\ T \sim \Delta\ R^3 \sim T^{3/2} \sim M_{gas} \sim L^{3/4} \sim Y^{3/5}$$

X-COP: *XMM +Planck*



X-COP: "universal" profiles

(& scatter; Ghirardini+19 arXiv:1805.00042)



$\mathbf{T = P/n}$

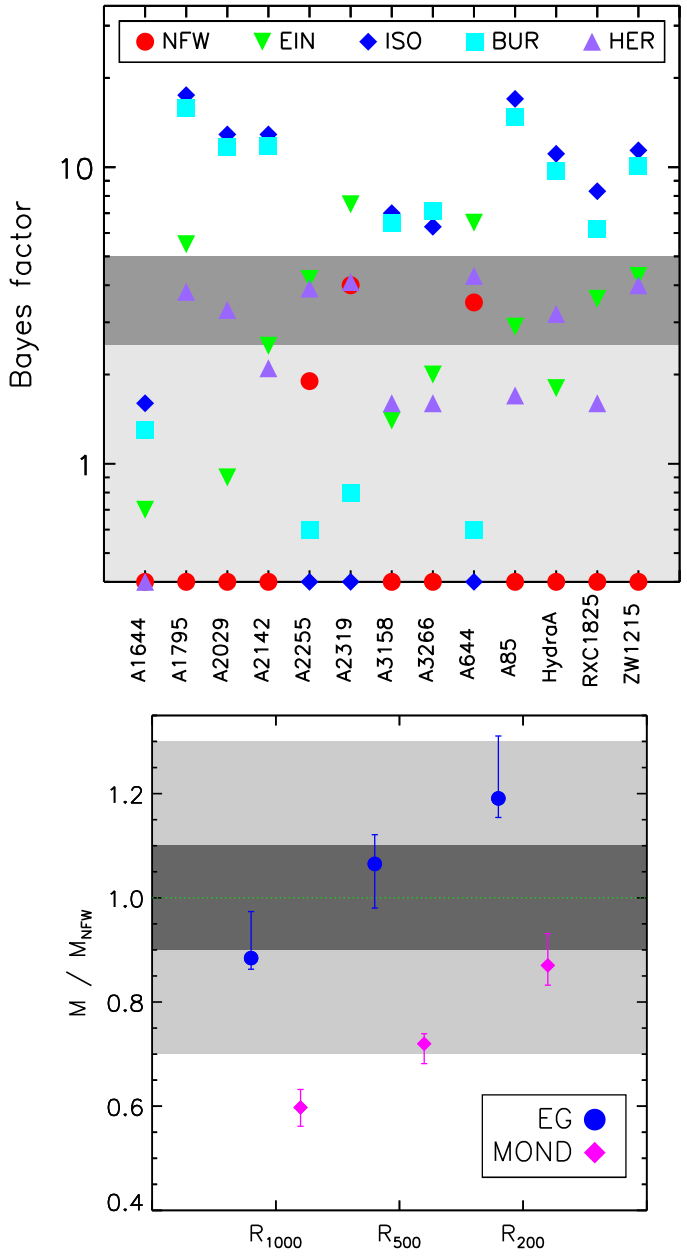
$\mathbf{K = P/n^{5/3}}$

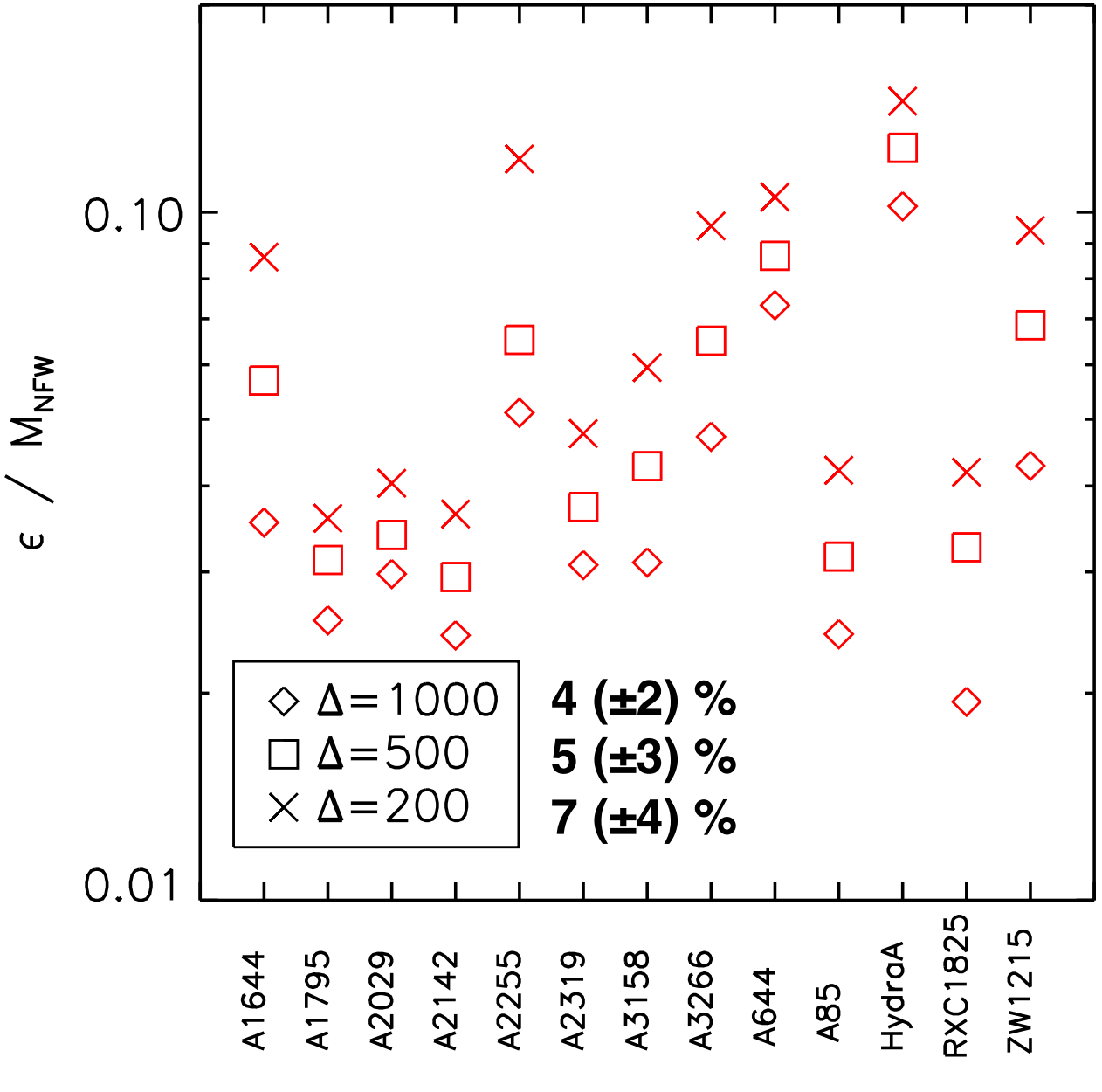
$\mathbf{M \sim -r^2/n\ dP/dr}$

(see also Ameglio+07, 09, Shitanishi+18)

X-COP: mass profiles

(Ettori+19 arXiv:1805.00035)





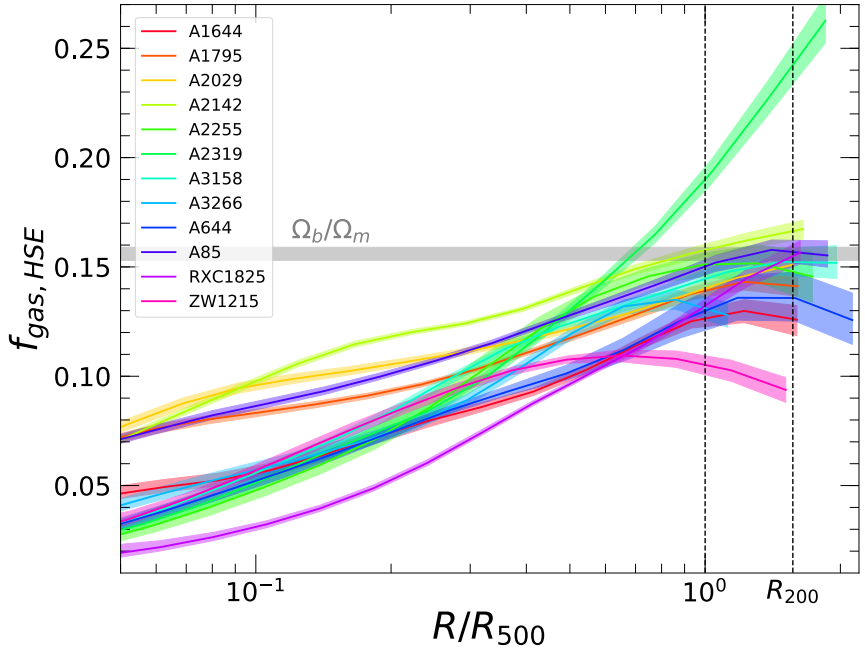
X-COP: non-thermal P

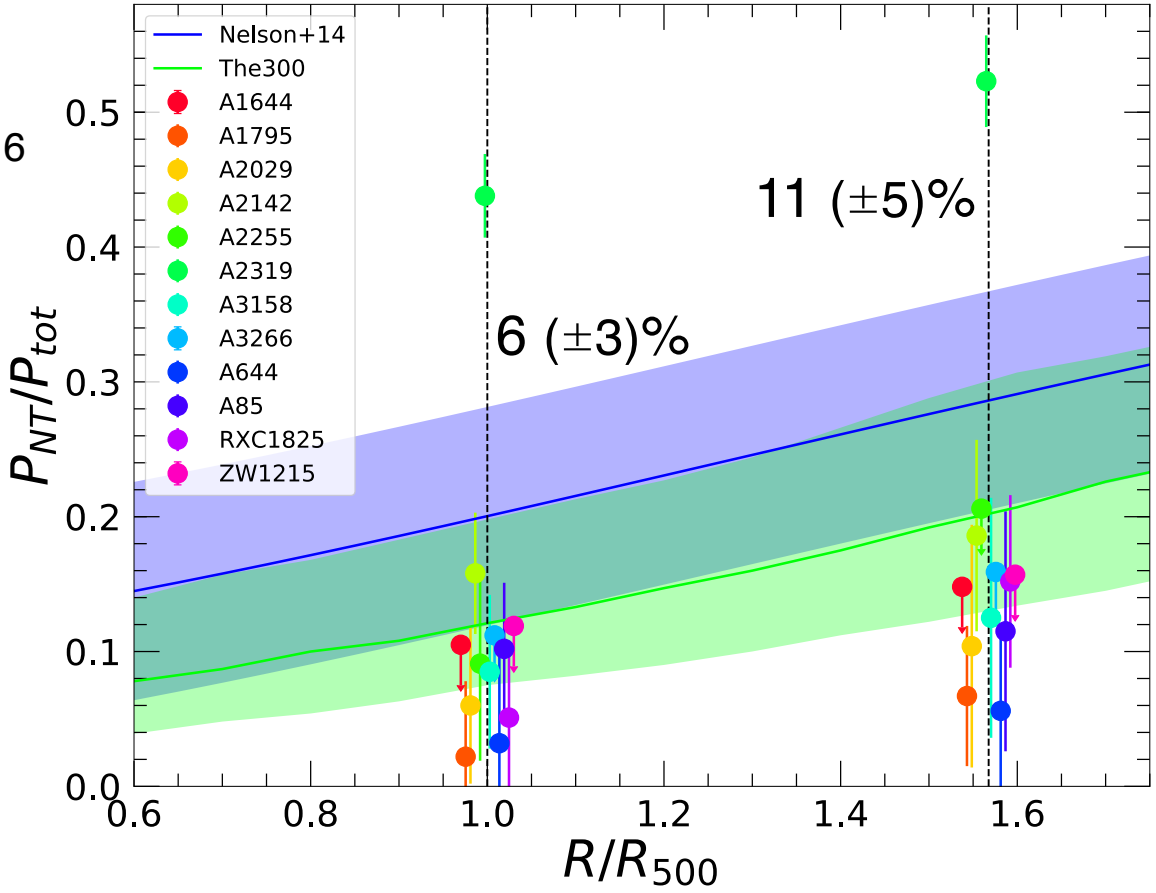
(Eckert+19; see also Lau+13, Nelson+14, Biffi+16, Vazza+18)

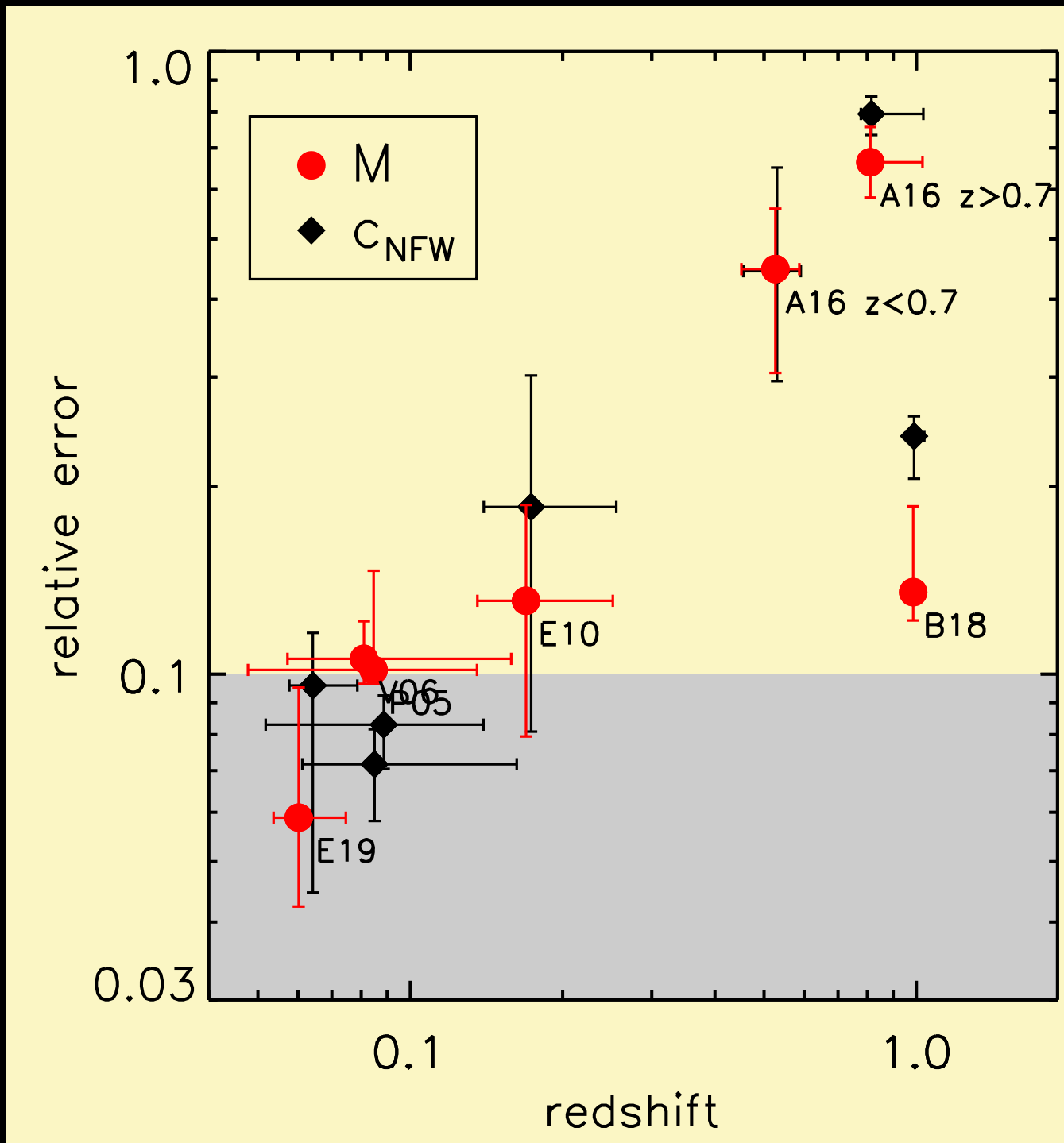
$$\frac{d}{dr}(P_{th}(r) + P_{NT}(r)) = -\rho_{\rm gas}\frac{GM_{\rm tot}(<r)}{r^2}$$

$$f_{\rm gas,univ}(r) = Y_b(r)\frac{\Omega_b}{\Omega_m} - f_\star$$

f_b from Planelles+13, LeBrun+14, Sembolini+16







Amodeo+16
Bartalucci+18
Ettori+10, 19
Pointecouteau+05
Vikhlinin+06

An XMM-Newton Heritage Program

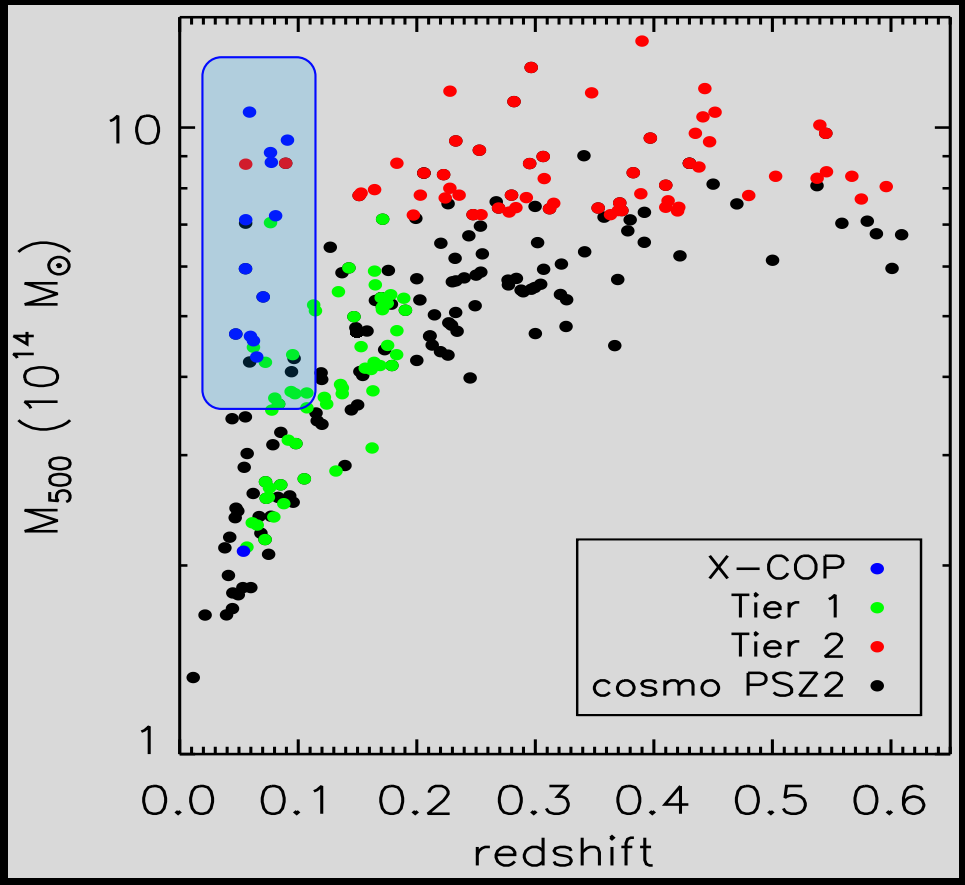
Witnessing the culmination of structure formation in the Universe

URL: xmm-heritage.oas.inaf.it

10x X-COP

➔ **3 Msec** over the next *3 years* to survey 118 Planck-SZ selected objects comprising an unbiased census of:

- *the population of clusters at the most recent time (z < 0.2),*
- *the most massive objects to have formed thus far in the history of the Universe*



An XMM-Newton Heritage Program

Witnessing the culmination of structure formation in the Universe

(PI: M. Arnaud & S. Ettori)

Steering Committee: M. Arnaud **(PI)**, S. Ettori **(PI)**, D. Eckert, F. Gastaldello, R. Gavazzi, S. Kay, L. Lovisari, B. Maughan, E. Pointecouteau, G. Pratt, M. Rossetti, M. Sereno

Core X-ray (*chair:* ***Eckert & Pratt***): SC members; Bartalucci; Bourdin; Buote; De Grandi; Donahue; Duffy; Ghirardini; Ghizzardi; Jones; Mazzotta; Molendi; Paltani; Schellenberger; Tozzi

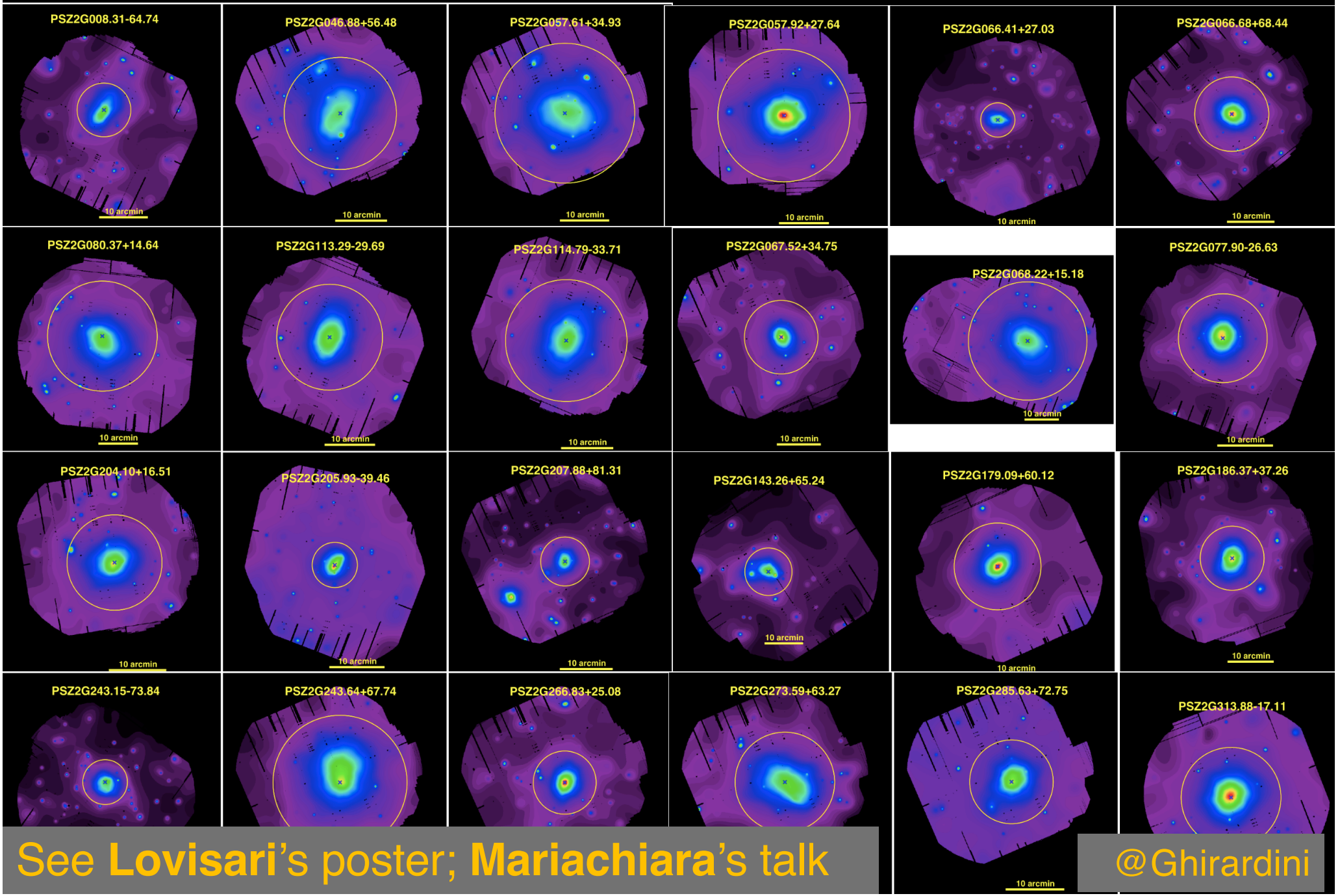
WG-lensing (*chair:* ***Gavazzi & Sereno***): IAC; Jauzac; Maurogordato; Okabe; Pires; Umetsu; van der Burg

WG-hydrosims (*chair:* ***Kay & Rasia***): Borgani; Dolag; Gaspari; LeBrun; Yepes; Vazza

WG-SZ (*chair:* ***Pointecouteau & Sayers***): Bourdin; Burkutean; Clerc; Macias; Mayet; Mazzotta; Melin; Mroczkowski; Perotto

WG-radio (*chair:* ***Bonafede & Cassano***): Vazza; Venturi

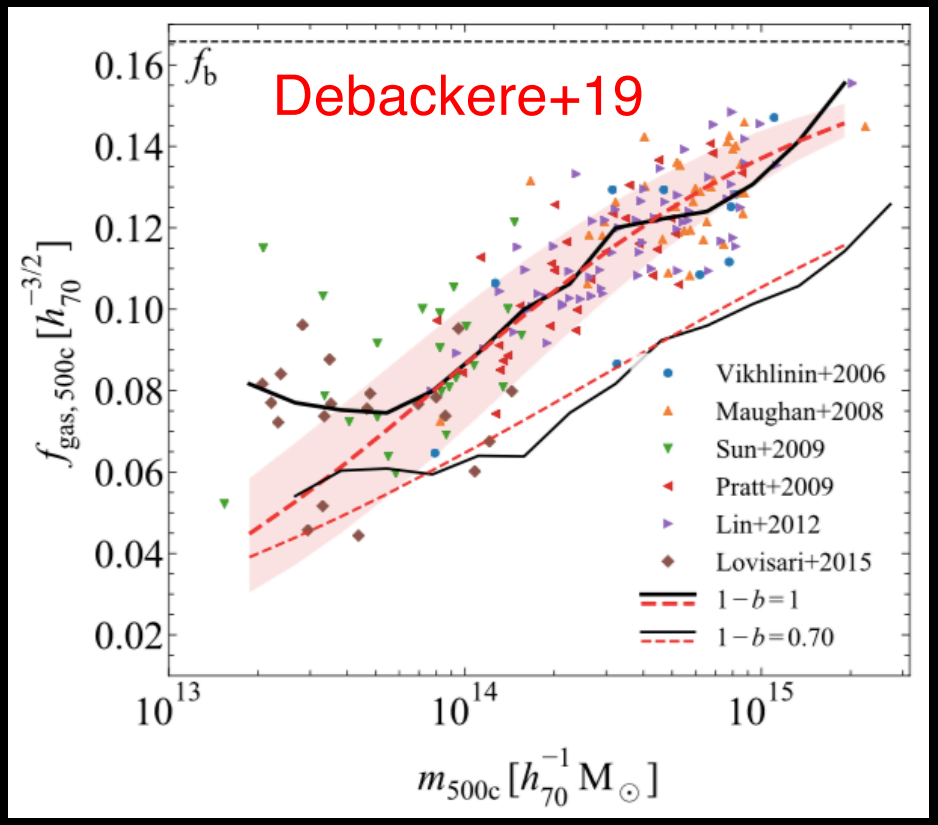
XMM-Newton Heritage Cluster Project

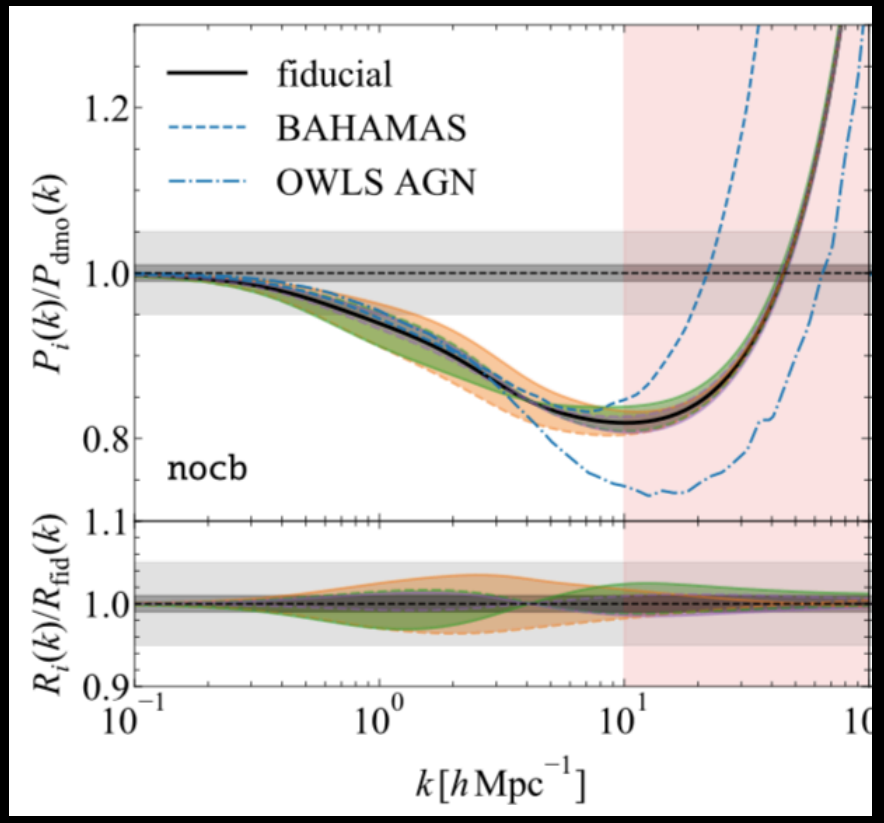


See **Lovisari**'s poster; **Mariachiara**'s talk

@Ghirardini

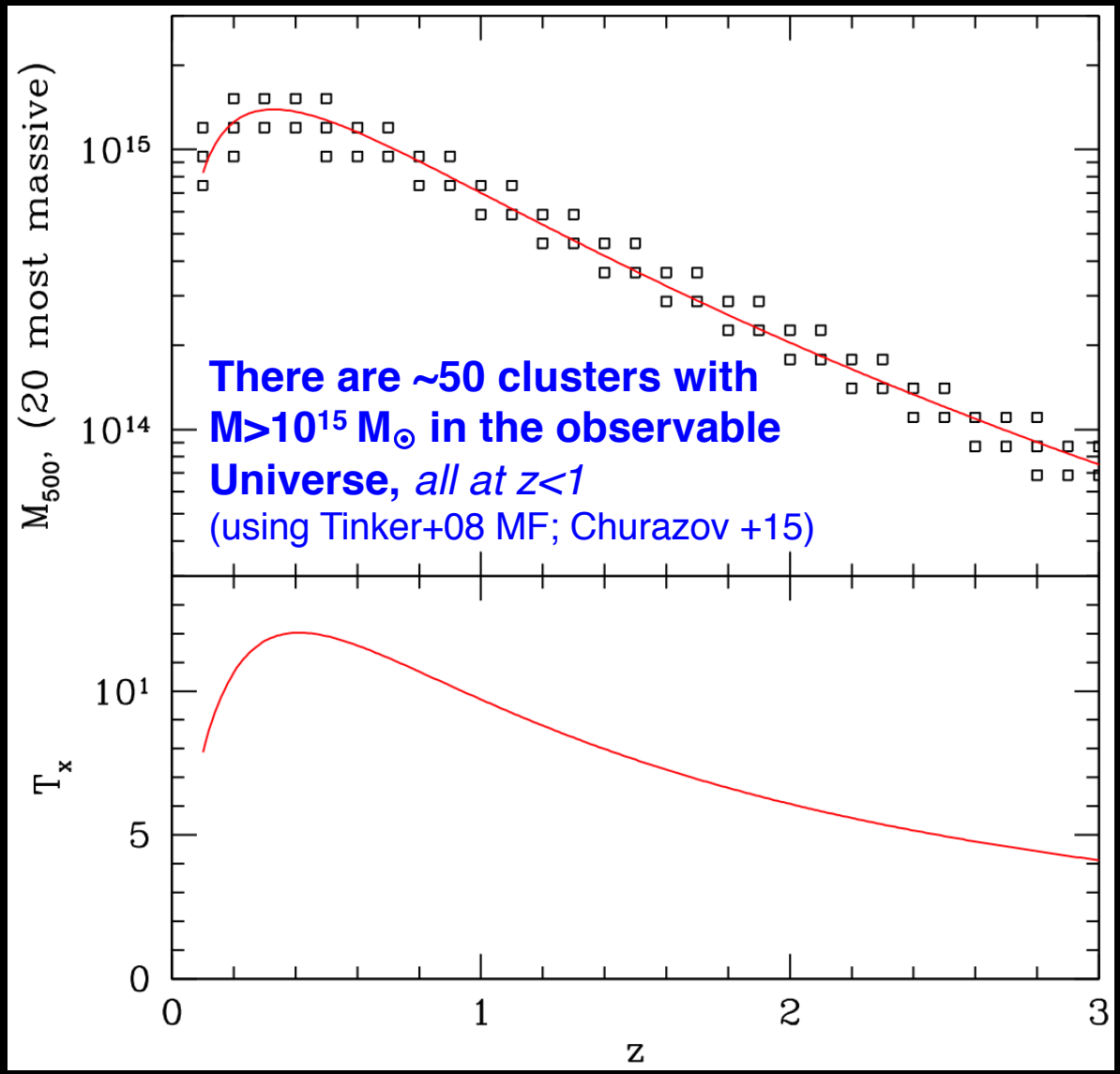
Gas fraction & P_k





X-ray can constrain hot gas in groups/clusters that dominate P_k at k<10 causing power suppression of **few %** at k~0.3-2 where **sub%** is required

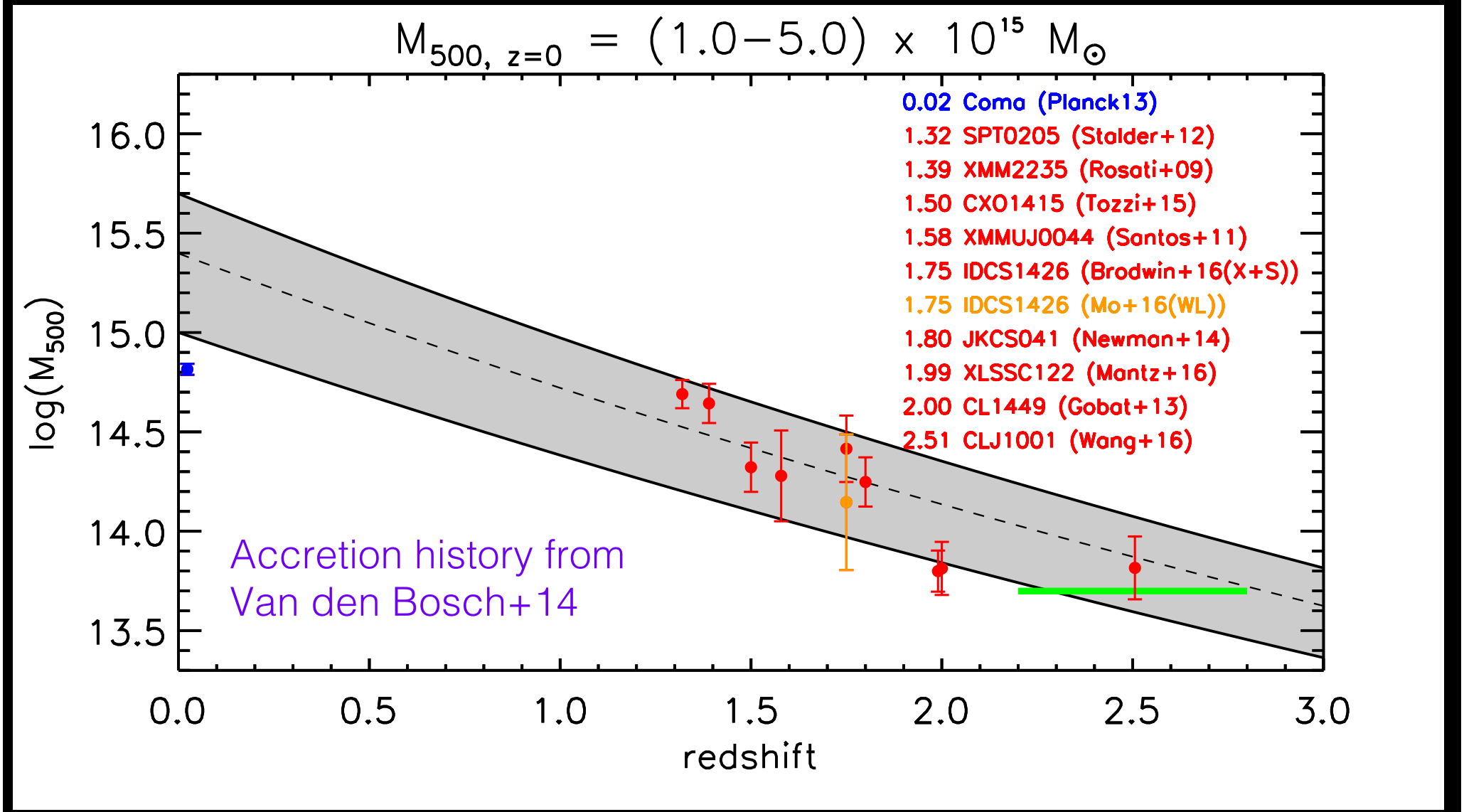
The most massive clusters



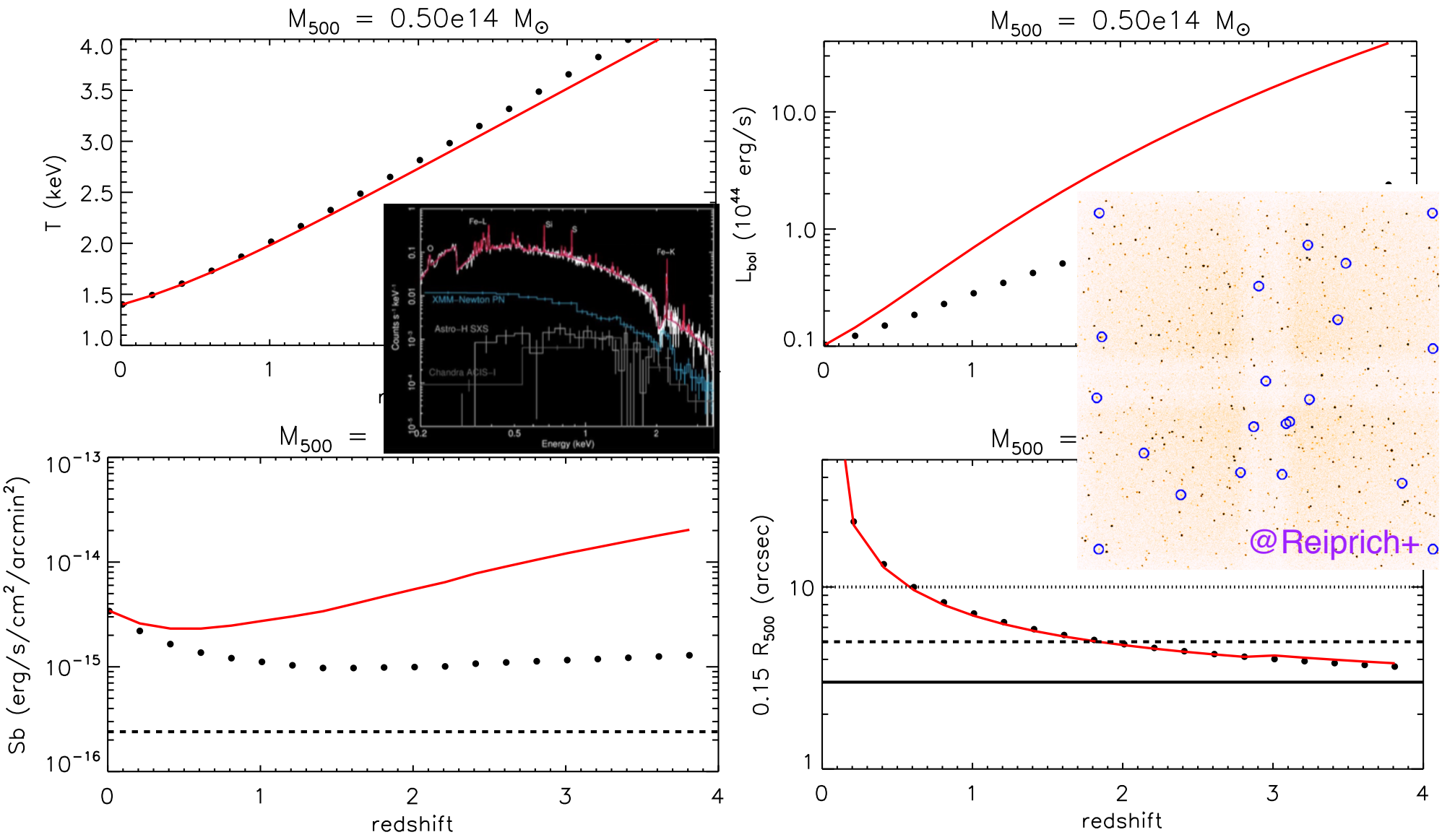
# of objects with $M_{500}/M_\odot$ > 5e13 (>1.4e14):

All sky
58e3 (600) @z>2
6100 (21) @z>2.5

The most massive clusters



Properties of a object with M_{500}~5e13 Msun



Take-home points

- ✓ *We are in condition to define a **complete error budget** on M_{hyd}* (~5% statistical; 5% systematic due to different methods) & use mass distribution in cluster's halos as probe of ΛCDM (c-M-z relation *-Ettori+10;* sparsity *-Corasaniti+18;* ***CLUMP-3D*** *– Sereno et al. 17-19*)

- ➢ *[<0.5 XUB] Define what is the **true cluster mass scale**, the impact of the scatter in the observed (spatially-resolved) quantities* from "universal" (n/T/P) profiles *& **{M,z} evolution*** (***XMM-Heritage/2018-20***; ***eROSITA*/2019**; ***Euclid*/2022**)

- ➢ *[1-1.5 XUB] Define the constituents of P_{NT}* How is the energy of matter's infall and virialization distributed in cluster's potential? To be investigated with hydro-sims & future X-ray instruments (***XRISM*/2022; *Athena*/2030**)

Still open questions
on structure formation & evolution

- How is matter funneled into the most massive knots of the cosmic web? How and when does the accreted matter mix with the rest of the ICM?
- *How does the ongoing accretion shape the kinematic properties of the ICM near and beyond R_{vir}? To what extent is the dissipation of turbulence a potential heating source that supplements the virial shocks?*
- What is the role of non-eq physics responsible for the formation of the cosmic structures?
- *How & when did the first collapsed groups appear?*

Work for ***Athena*** and any future *Cosmic Web Explorer*

(see e.g. Simionescu, Ettori et al. 2019 arXiv:1908.01778)

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