Dark matter in galaxy clusters from **X-ray & SZ effect**

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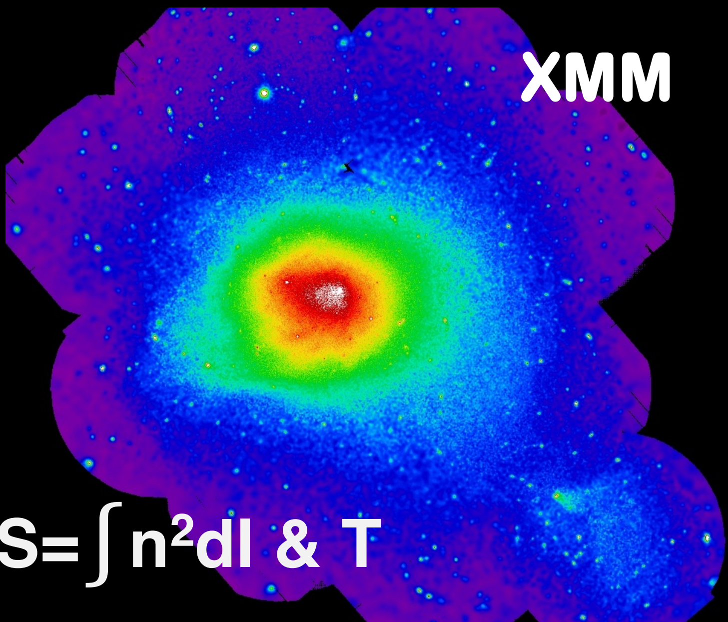
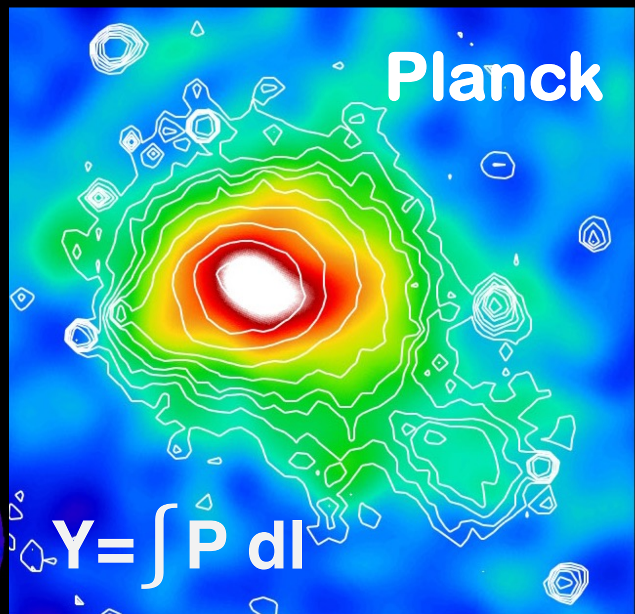
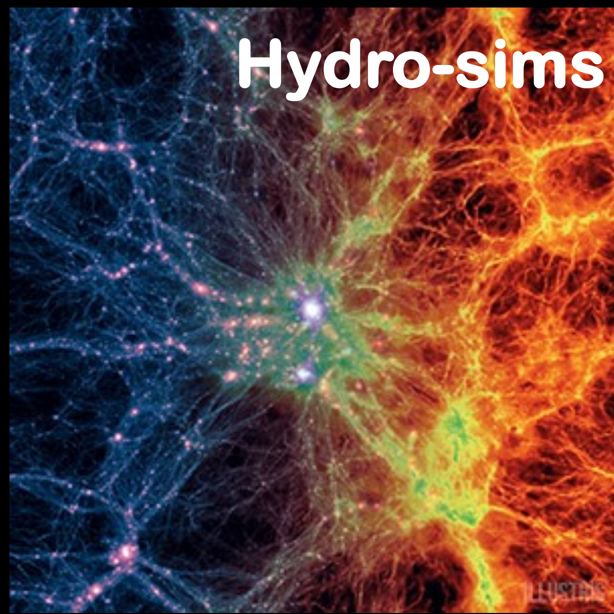






Clusters of Galaxies

- ***The largest gravitationally-bound structures in the universe***
- ***"dunkle Materie"*** (Zwicky 1933)
~80% of total mass (~15% hot gas; few % stars)
- **Properties of the DM**

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

Bullet cluster

A2744

MACSJ0025

Cosmology from the internal structures of Galaxy Clusters

- **Mass distribution ➔** *(SI)DM / MOND* (Ettori+19; Eckert+22)
- **Concentration/sparsity ➔** $\{\Omega_m; \sigma_8\}$ (Corasaniti+21, 22)
- **Triaxial shape ➔** consistency with ΛCDM (Sereno+18)
- **X/SZ pressure profiles ➔** H_0 (*Kozmanyan+19;* Ettori+20)
- **Gas mass fraction ➔** $\{\Omega_m; \Lambda, w\}$ (Ettori+10; *Mantz+21*)

➔ Reliable & robust reconstruction of the (total & baryonic) **mass distribution**

X-ray Galaxy Clusters:

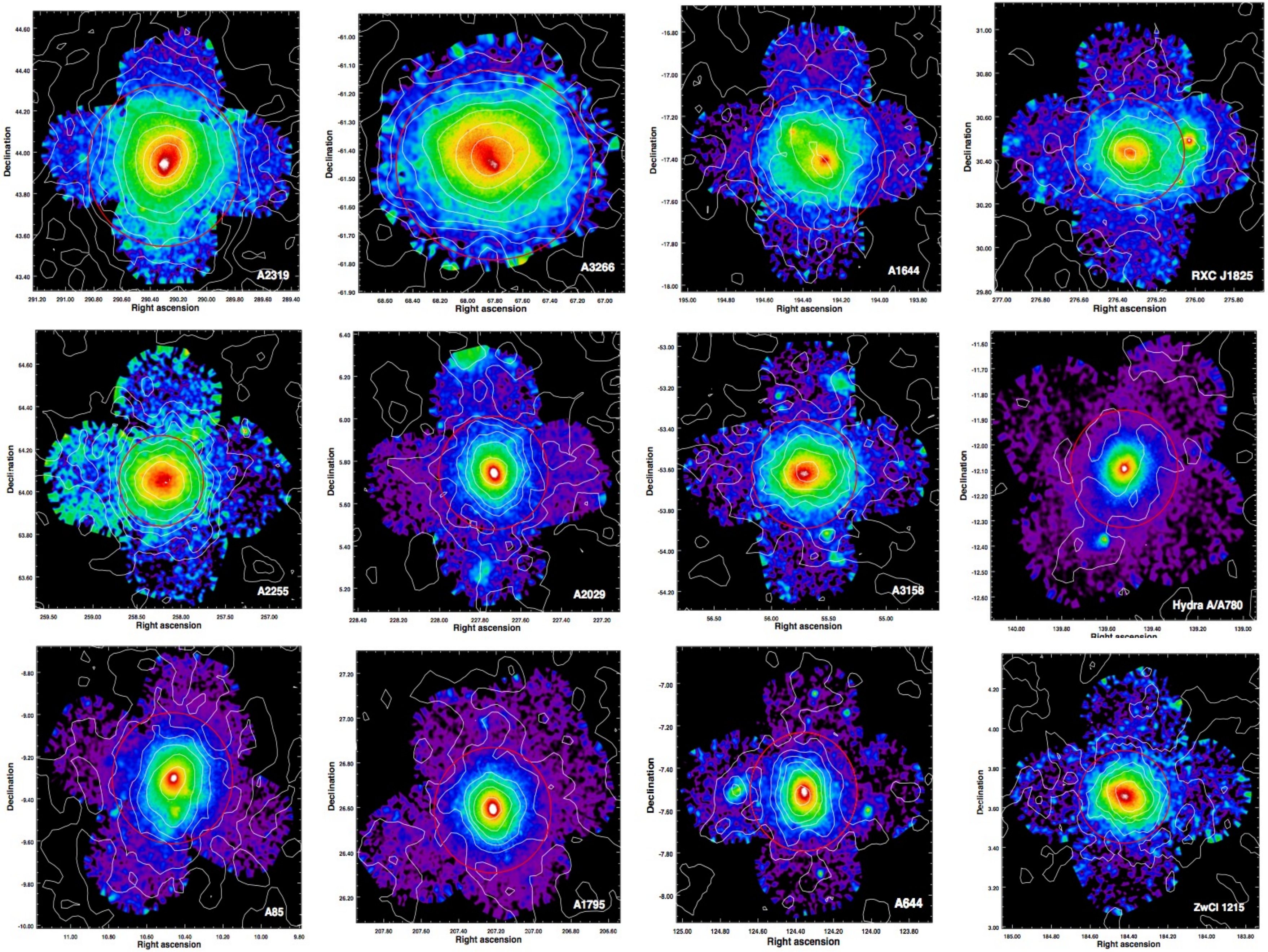
open problems on the mass distribution

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

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

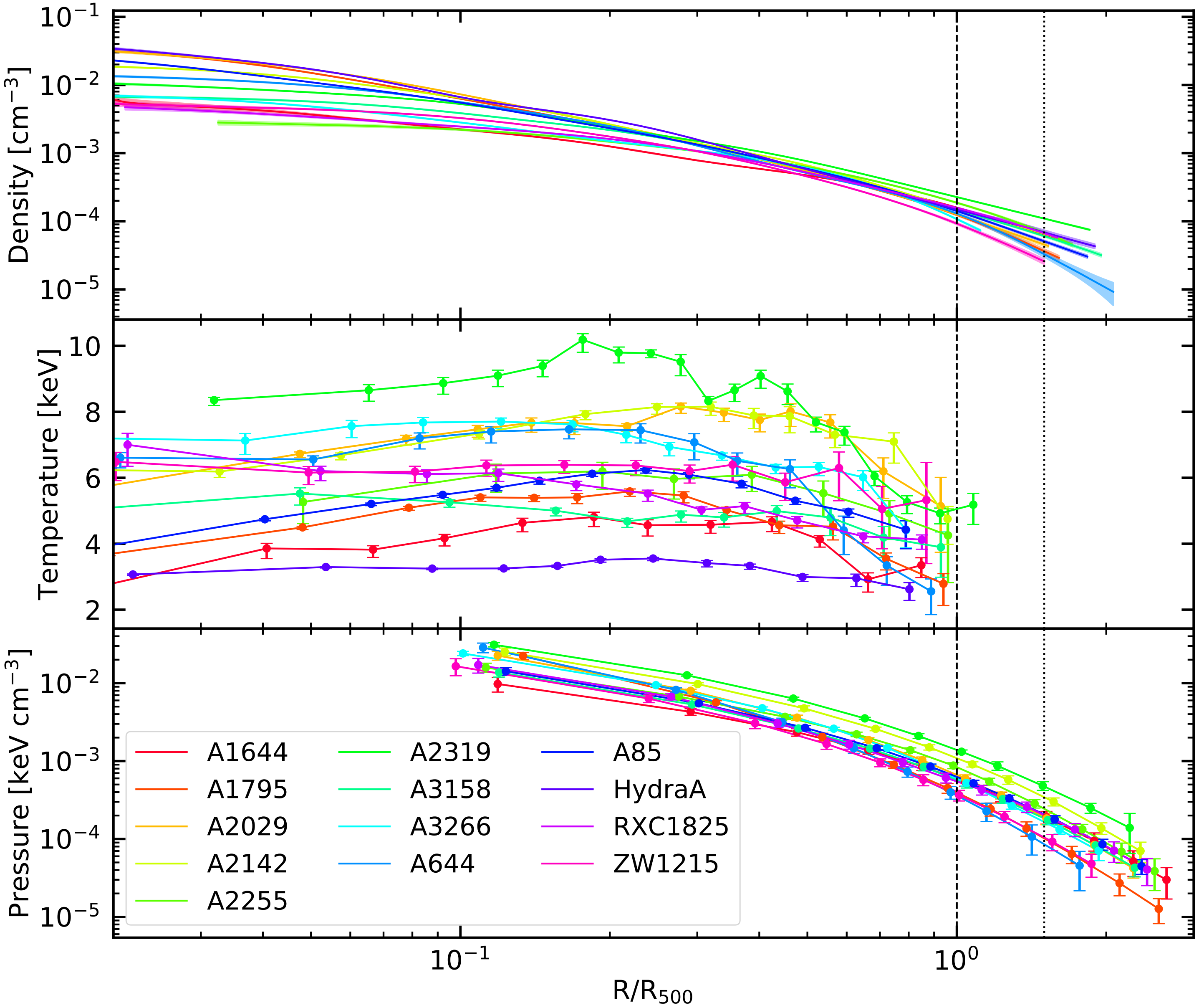
$$M_{tot} \sim R\ T \sim \mathbf{\Delta}\ R^3 \sim T^{3/2} \sim M_{gas} \sim L^{3/4} \sim Y^{3/5}$$

X-COP: *XMM* +*Planck* (Eckert+17)



X-COP: "universal" profiles

(& scatter; Ghirardini+19)



$T = P/n$

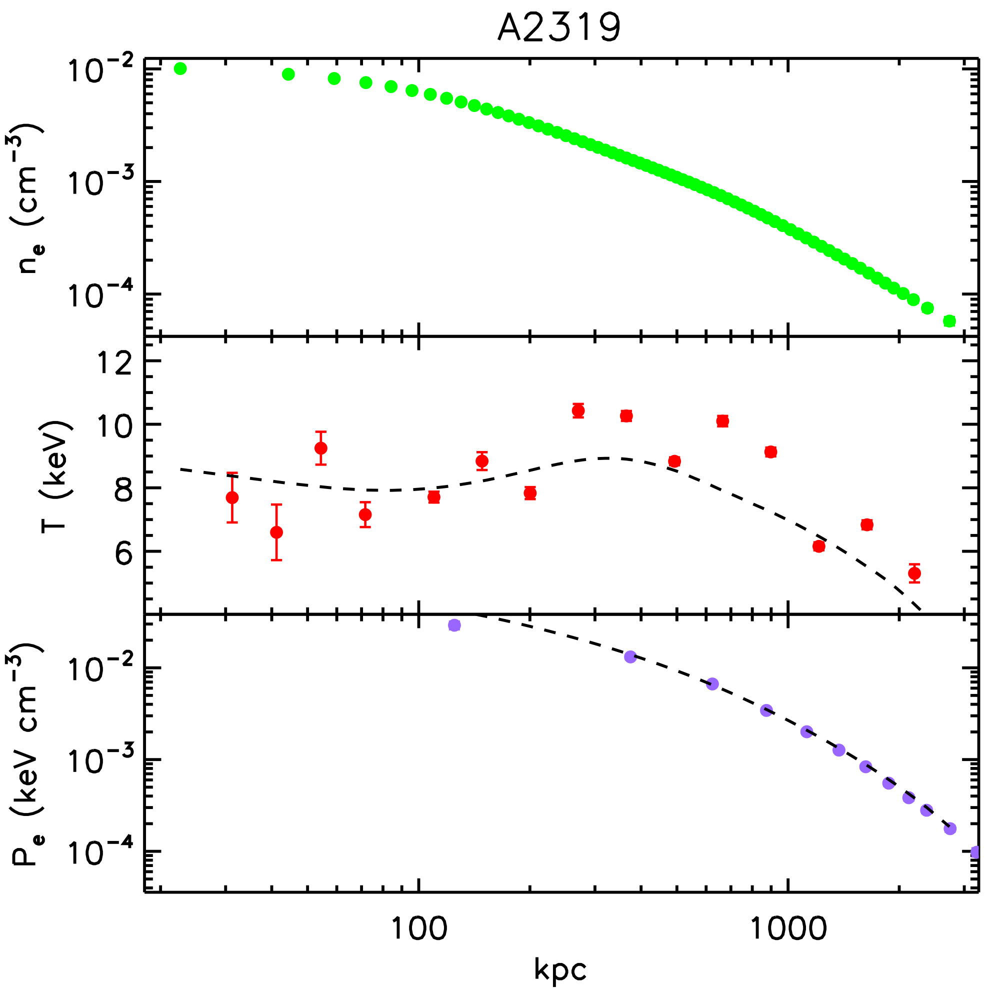
$K = P/n^{5/3}$

$M \sim -r^2/n \; dP/dr$

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

X-COP: mass profiles

$$M_{\mathrm{tot}}(<r) = -\frac{r\,P_{\mathrm{gas}}}{\mu m_{\mathrm{u}} G\, n_{\mathrm{gas}}}\frac{d\log P_{\mathrm{gas}}}{d\log r}$$

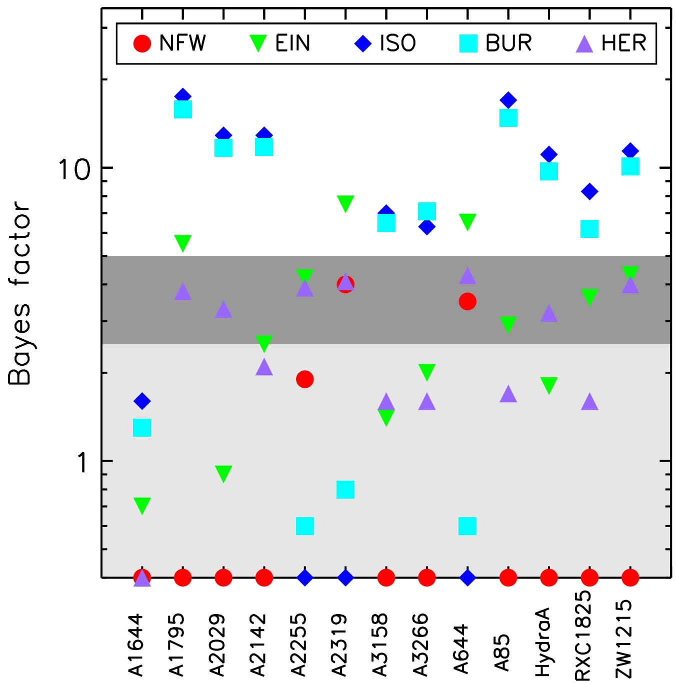


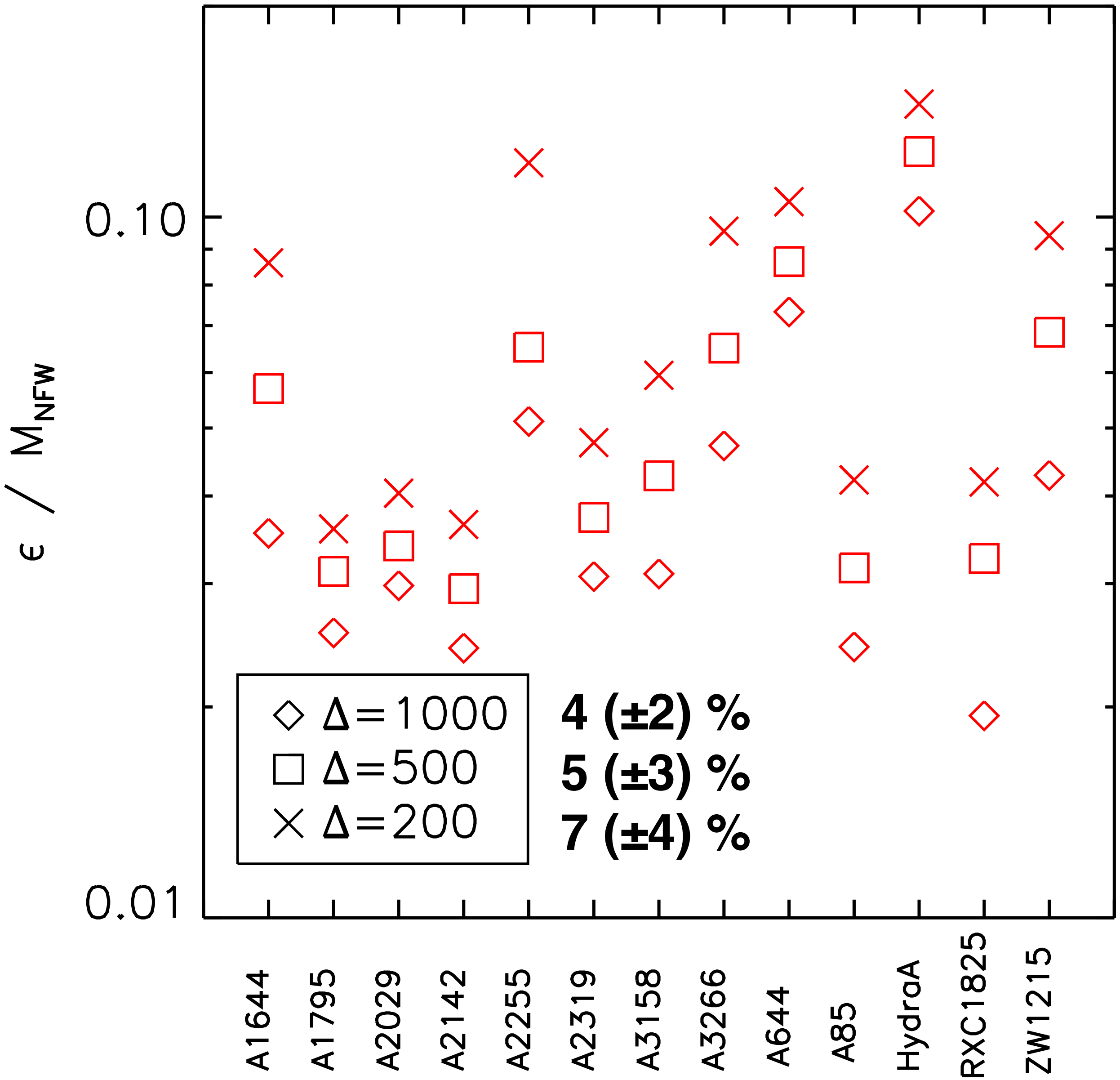
✓ Use of analytic mass models (e.g. NFW, ISO) by fitting T_{XMM} / P_{Planck} with values obtained from inversion of HE

$$\log\mathcal{L} = -0.5\left[(P-P_{model})\Sigma_{tot}^{-1}(P-P_{model})^T + n\log\left(\det\left(\Sigma_{tot}\right)\right)\right] - 0.5\sum_{i=1}^{n}\left[\frac{(T_i-T_{model,i})^2}{\sigma_{T,i}^2+[\sinh(\sigma_{int})\cdot T_{model,i}]^2} - \log\left(\frac{1}{\sigma_{T,i}^2+[\sinh(\sigma_{int})\cdot T_{model,i}]^2}\right)\right] - 0.5\left[\sum_{i=1}^{n}\frac{(\epsilon-\epsilon_{model,i})^2}{\sigma_{\epsilon,i}^2}\right]$$

X-COP: mass profiles

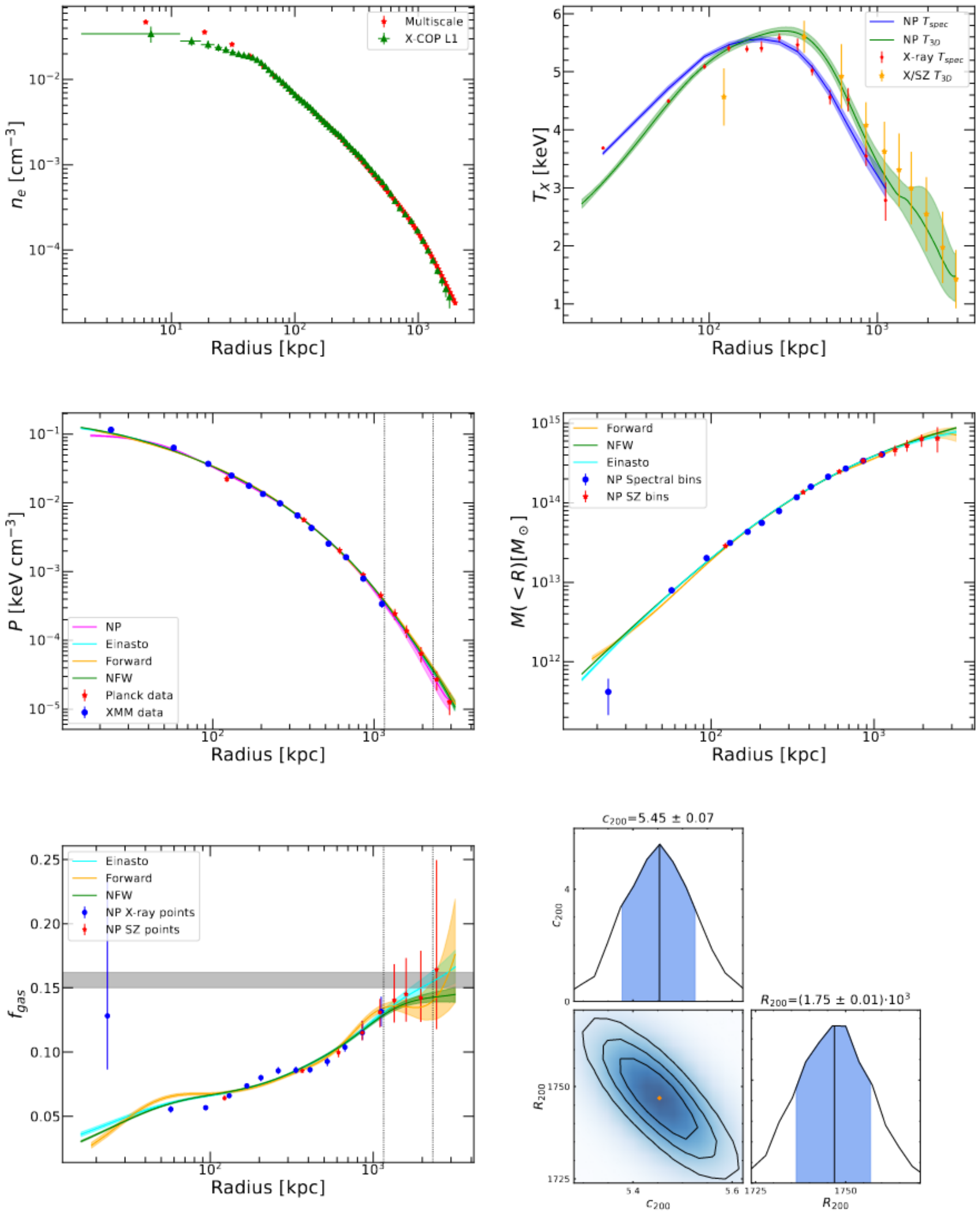
(Ettori+19)





X-COP: mass profiles

(Eckert, Ettori, et al. 2022a)



Mass reconstruction in A1795

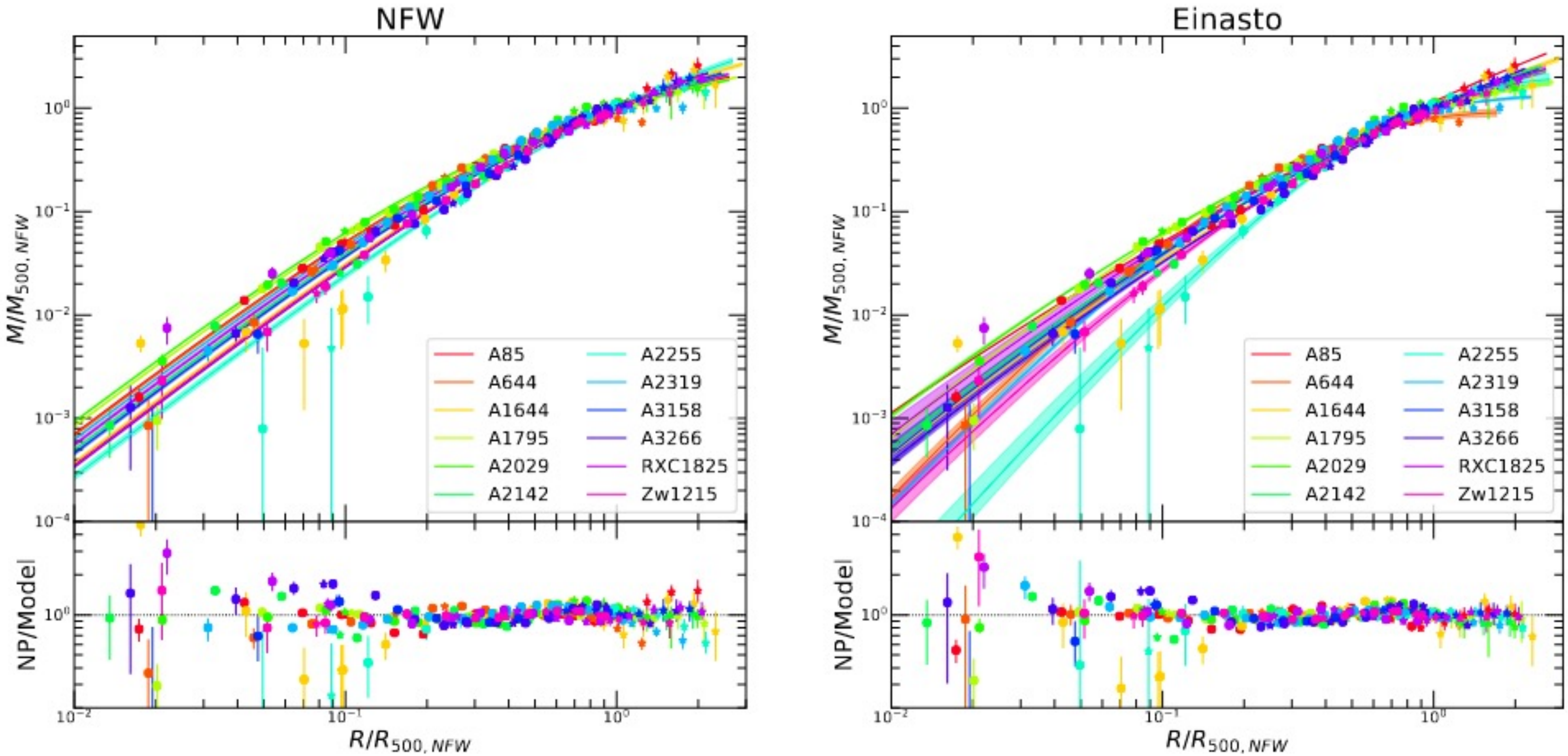
(i) n_e profile reconstructed with the multi-scale method;

(ii) non parametric reconstruction of the 3D temperature profile compared to the spectroscopic X-ray measurements and the 3D temperature profile obtained by dividing the SZ pressure by the X-ray density (projected, spec-w, PSF convolved T)

(iii) mass profiles obtained with different reconstructions (NFW, Einasto, Forward, and NP) ➔ *https://github.com/domeckert/hydromass*

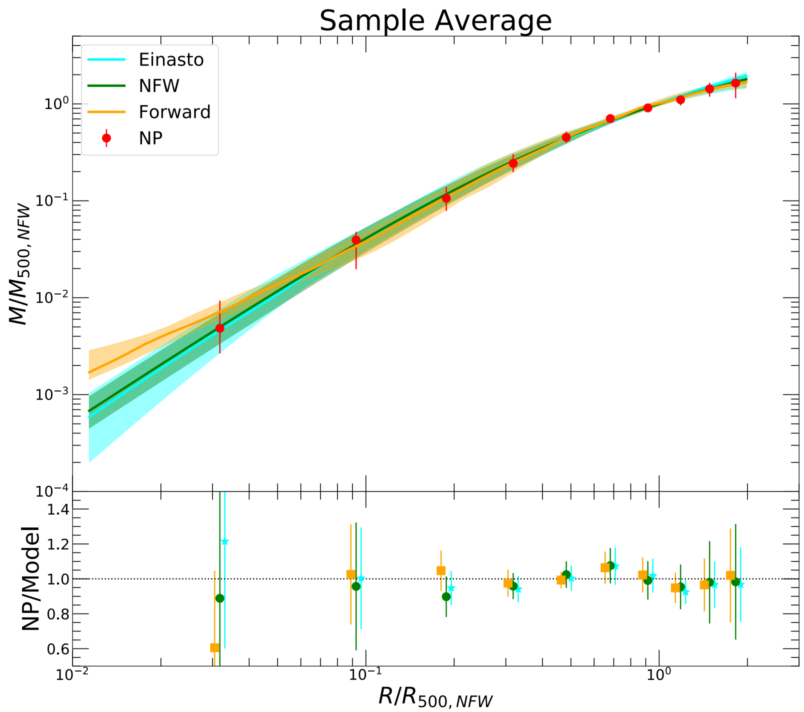
X-COP: mass profiles

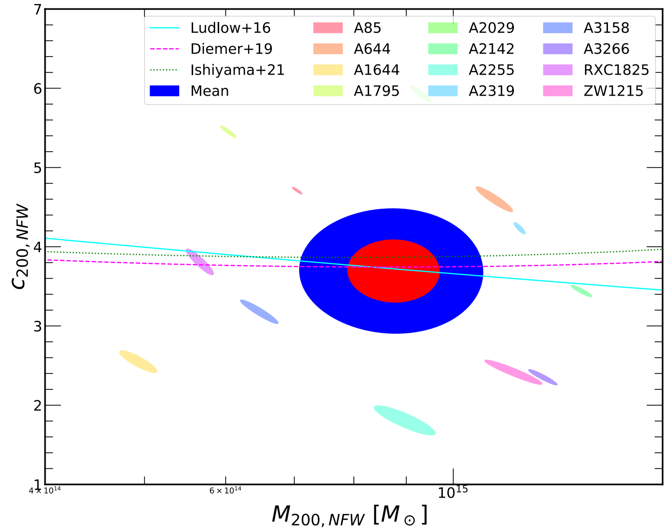
(Eckert, Ettori, et al. 2022a)

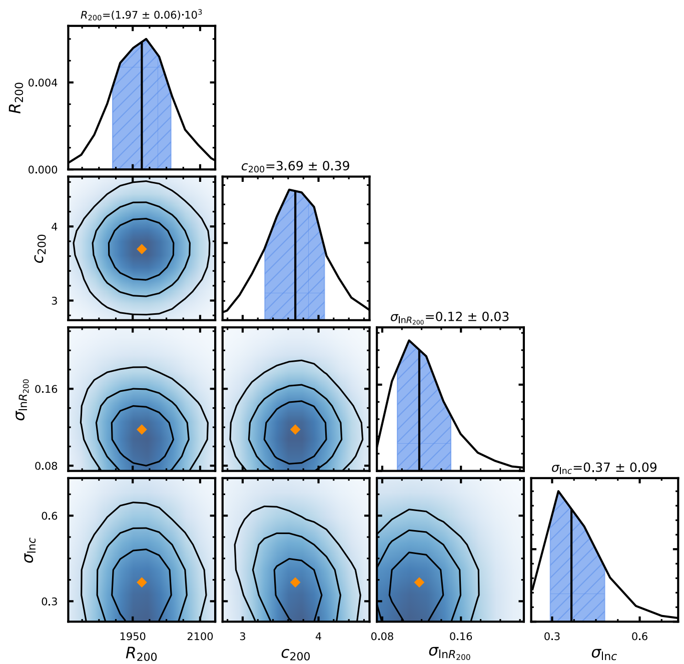


X-COP: mass profiles

(Eckert, Ettori, et al. 2022a)



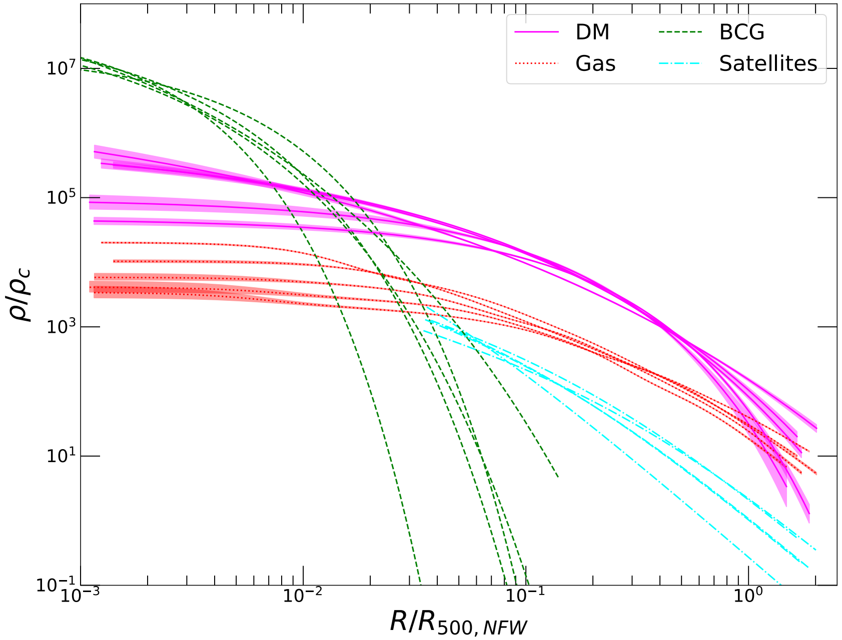


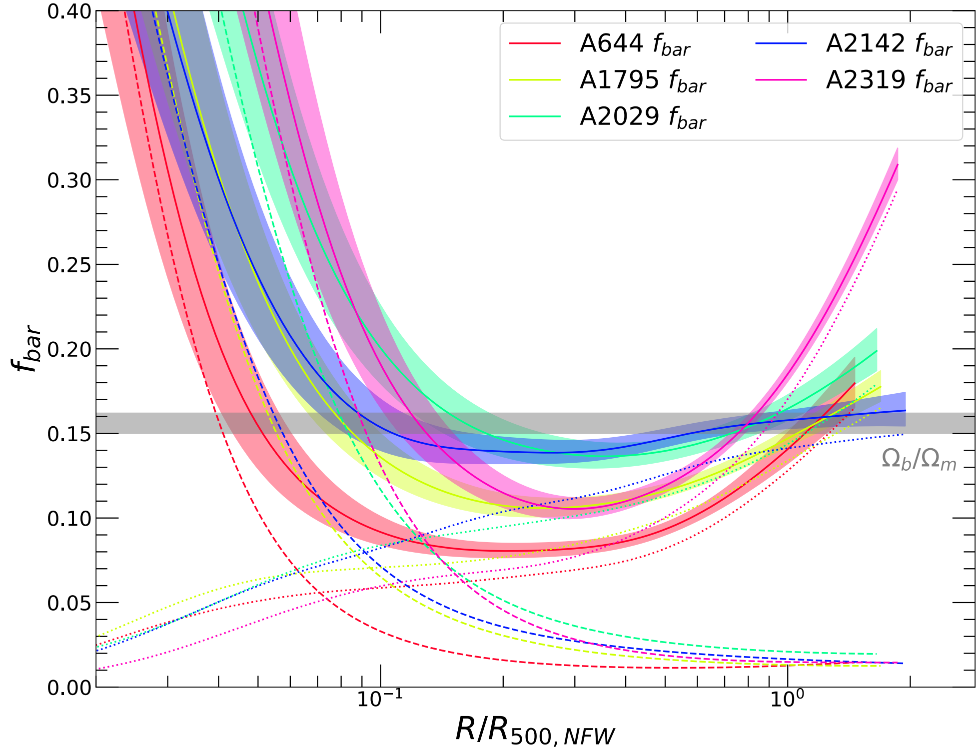


- NFW profile provides an excellent description: deviations of less than 10% over a wide radial range; but more diversity in individual shape
- The average NFW concentration and its scatter agree very well with the prediction of the ΛCDM framework

X-COP: mass profiles

(Eckert, Ettori, et al. 2022a)



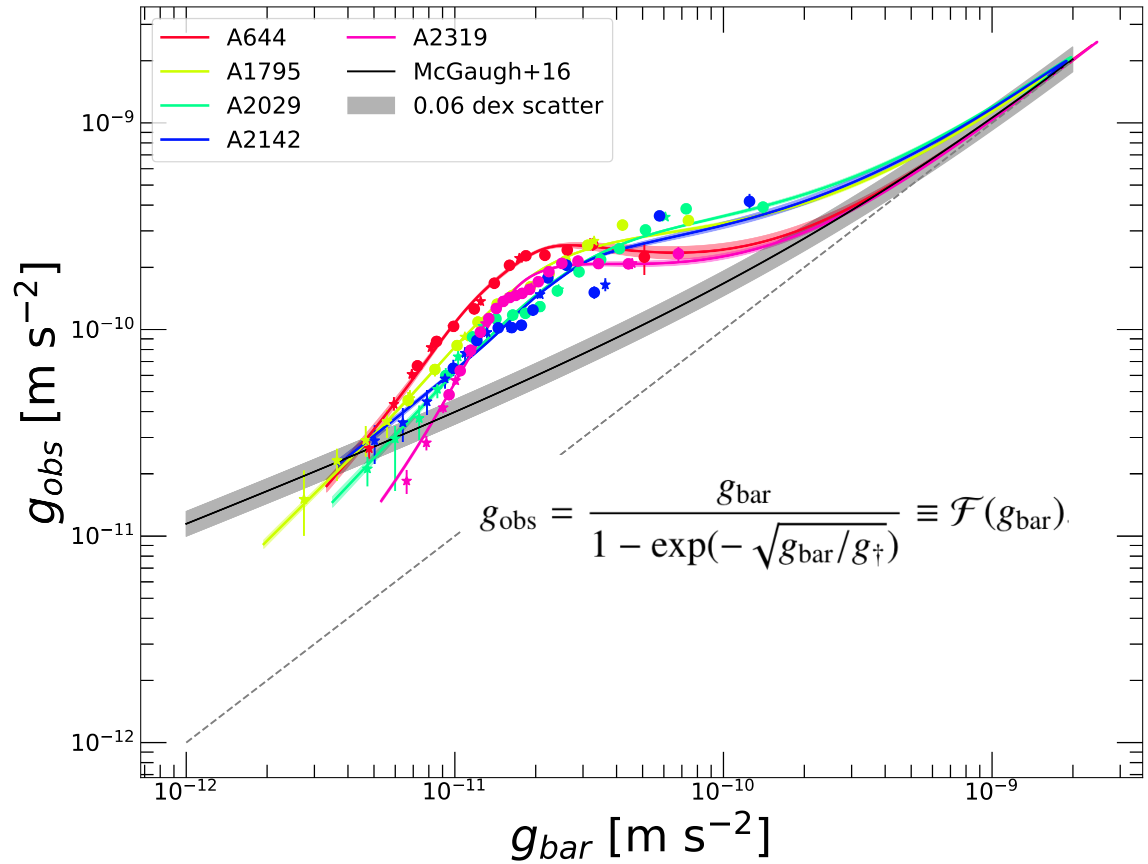


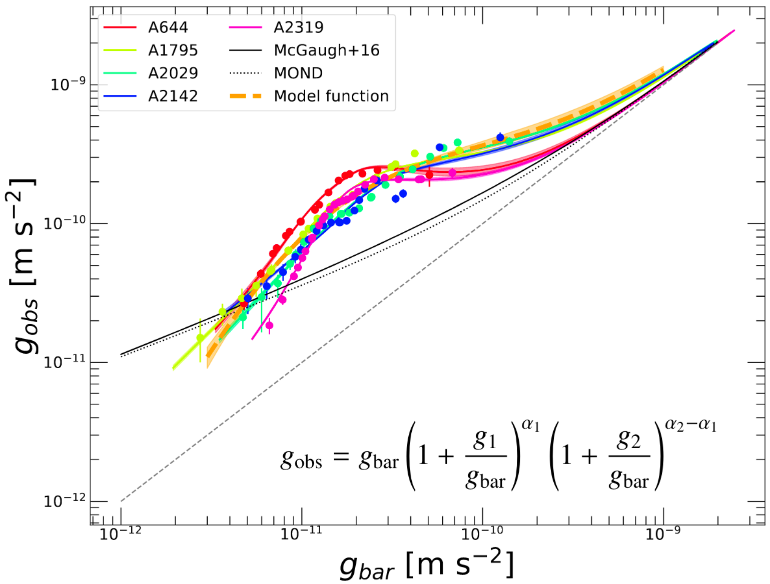
$M_{tot}(r) = \mathbf{M_{DM}(r)} + M_{gas}(r) + M_{BCG}(r) + M_{sat}(r)$
stellar mass distributions from CFHT r-band imaging (Loubser+20)

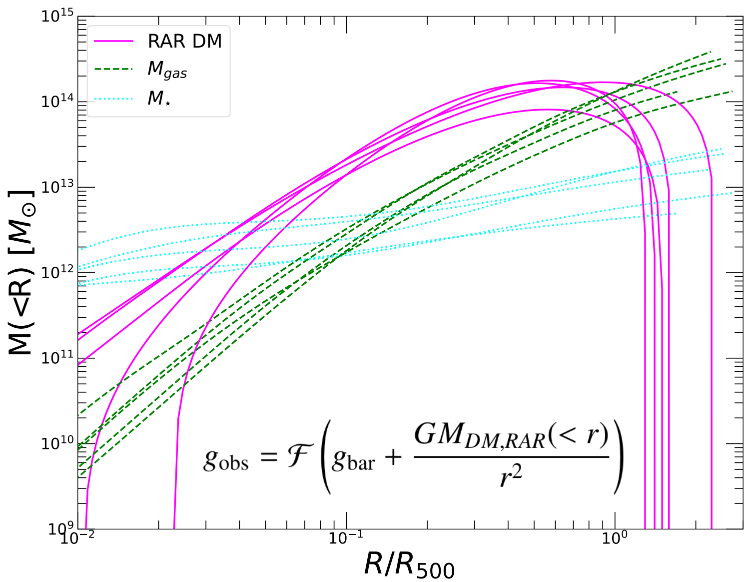
Cluster	$f_{gas,2500}$	$f_{\star,2500}$	$f_{bar,2500}$	$f_{gas,500}$	$f_{\star,500}$	$f_{bar,500}$	$f_{gas,200}$	$f_{\star,200}$	$f_{bar,200}$
A644	7.7 ± 0.1	1.2 ± 0.4	8.9 ± 0.5	12.8 ± 0.6	1.3 ± 0.5	14.1 ± 1.1	16.9 ± 1.2	1.5 ± 0.6	18.4 ± 1.7
A1795	9.6 ± 0.1	1.7 ± 0.6	11.3 ± 0.6	13.4 ± 0.3	1.3 ± 0.5	14.7 ± 0.7	15.8 ± 0.5	1.3 ± 0.4	17.1 ± 1.0
A2029	11.1 ± 0.1	2.8 ± 0.9	13.8 ± 1.1	14.4 ± 0.3	2.1 ± 0.7	16.5 ± 1.0	17.1 ± 0.7	2.0 ± 0.7	19.1 ± 1.4
A2142	12.0 ± 0.1	2.3 ± 0.8	14.3 ± 0.9	14.1 ± 0.2	1.7 ± 0.6	15.8 ± 0.8	14.7 ± 0.5	1.5 ± 0.5	16.2 ± 1.0
A2319	9.2 ± 0.1	2.0 ± 0.7	11.3 ± 0.8	17.0 ± 0.2	1.5 ± 0.5	18.5 ± 0.7	24.9 ± 0.5	1.5 ± 0.5	26.4 ± 1.0

X-COP: Acceleration

$$\frac{G\, M_{tot}(< r)}{r^2} = g$$







Eckert+22a; Ettori+19 & +17 on RAR/MOND/EG

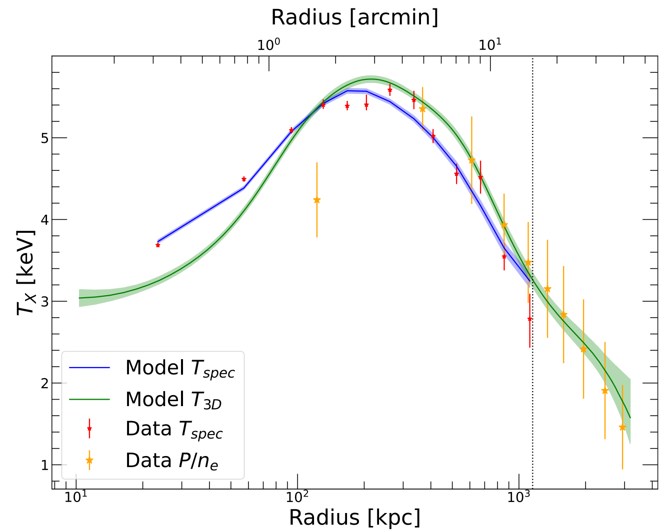
X-COP: SIDM

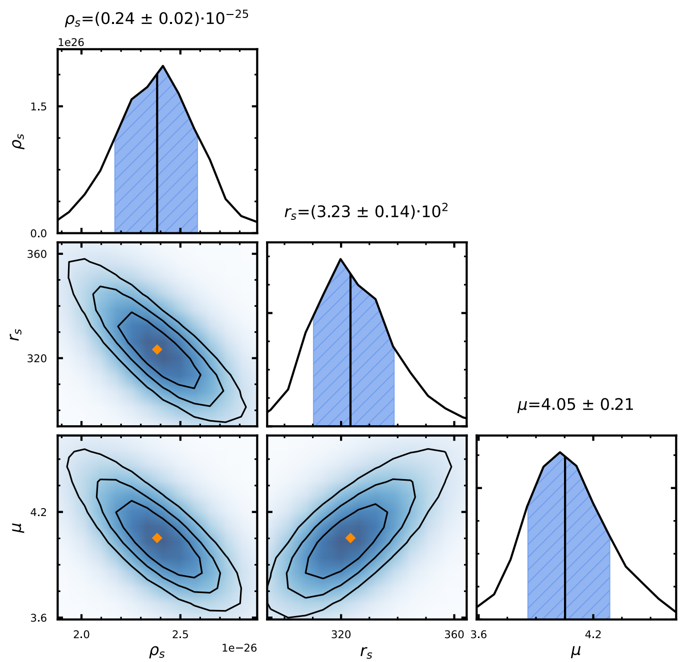
(Eckert, Ettori, et al. 2022b)

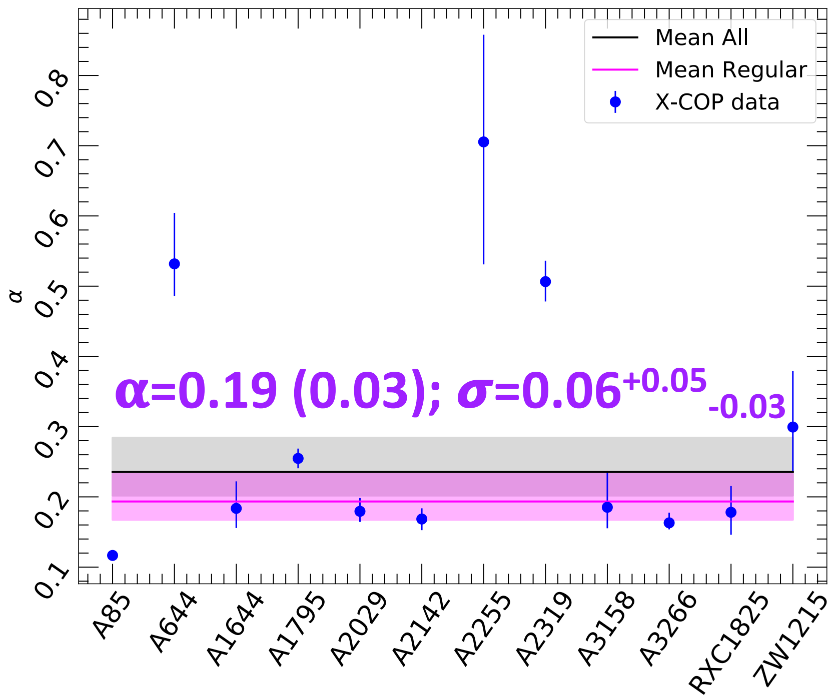
$$\rho_{\rm Einasto}(r) = \rho_s \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{r_s}\right)^{\alpha} - 1\right)\right]$$

Table 1. Normal priors on the Einasto fit parameters. Here P_m and dP_m denote the outermost SZ pressure value and its error.

Parameter	Mean	σ	Min	Max
r_s [kpc]	700	300	100	3000
c	1.8	1.5	0	10
μ	5	3	0.2	20
P_0	P_m	dP_m	$P_m - 2dP_m$	$P_m + 2dP_m$



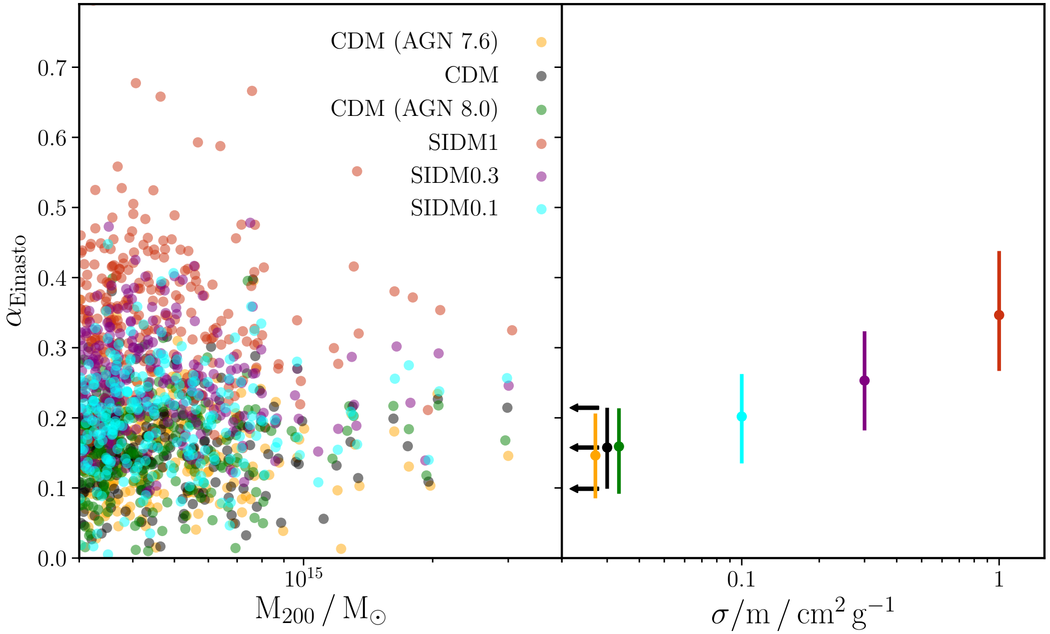


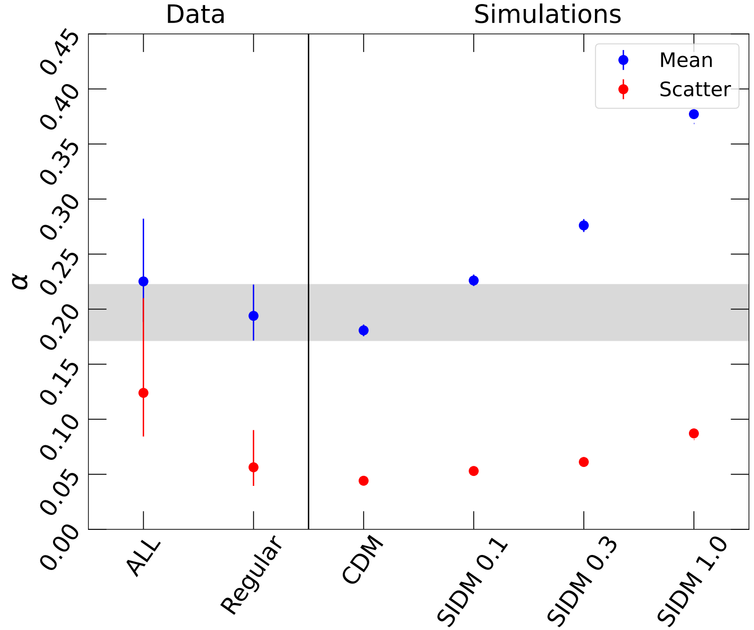


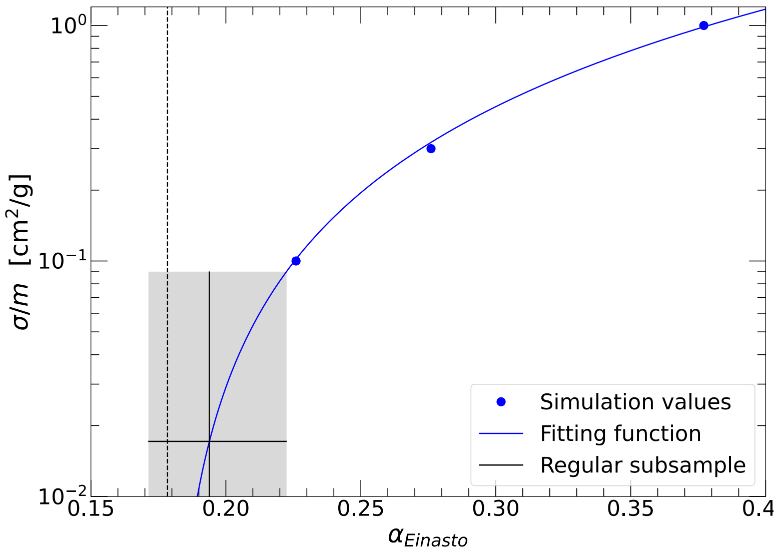
X-COP: SIDM

(Eckert, Ettori, et al. 2022b)

BAHAMAS-SIDM (Robertson+21)







$$\alpha_{\rm Einasto} = \alpha_0 + \alpha_1 \left(\frac{\sigma/m}{1\ {\rm cm}^2/{\rm g}} \right)^{\gamma}$$

σ/m < 0.19 cm^2/g (95% c.l.)

at collision velocity v_{DM-DM} ~ 1000 km/s

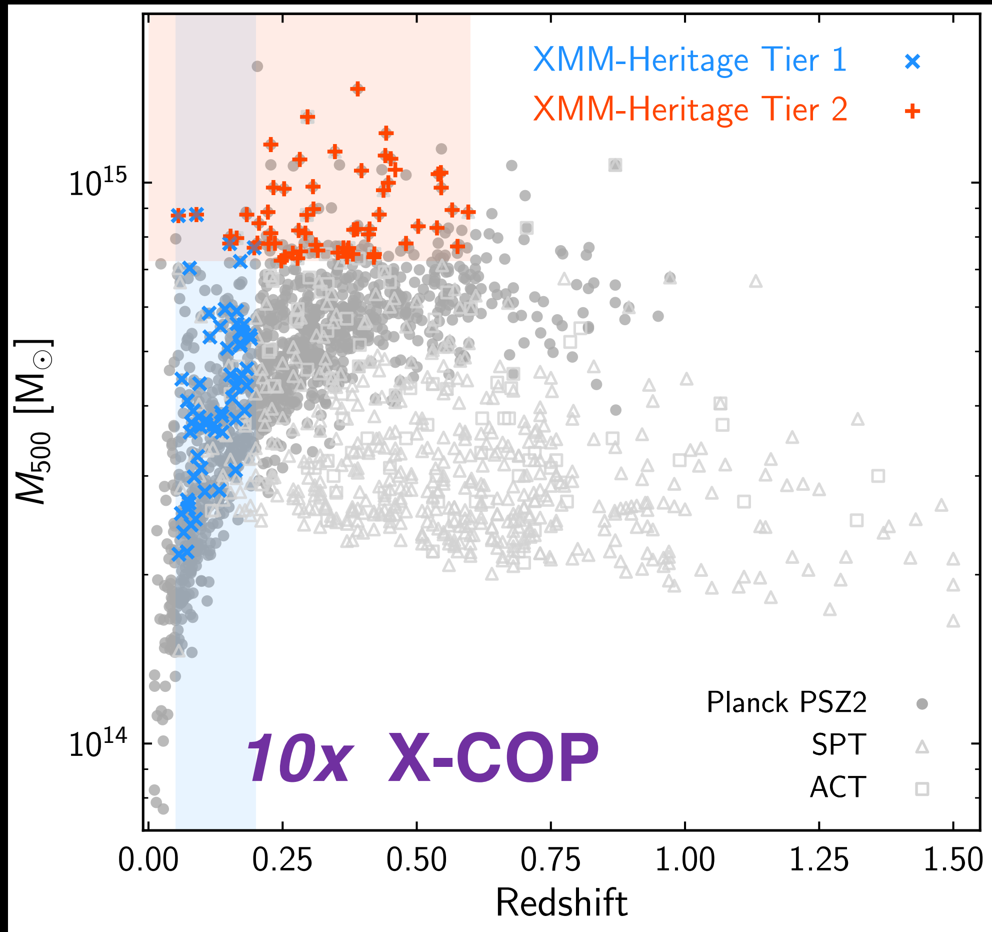
An XMM-Newton Multi-Year Heritage Program

Witnessing the culmination of structure formation in the Universe

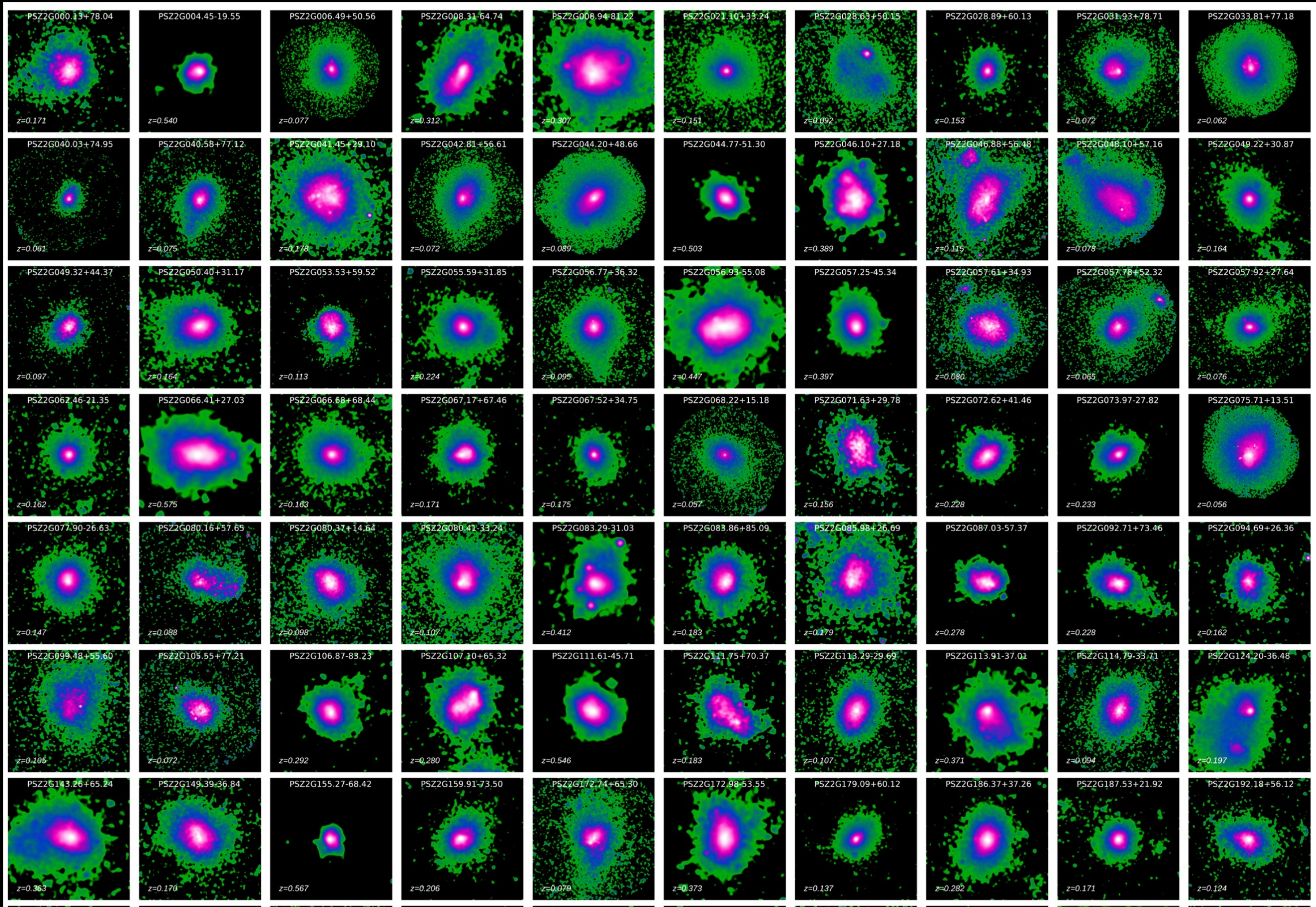
URL: xmm-heritage.oas.inaf.it

CHEX-MATE (the Cluster HEritage project with XMM-Newton: Mass Assembly and Thermodynamics at the Endpoint of structure formation): **3 Msec** over the period 2018-21 to survey ***homogenously*** 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*

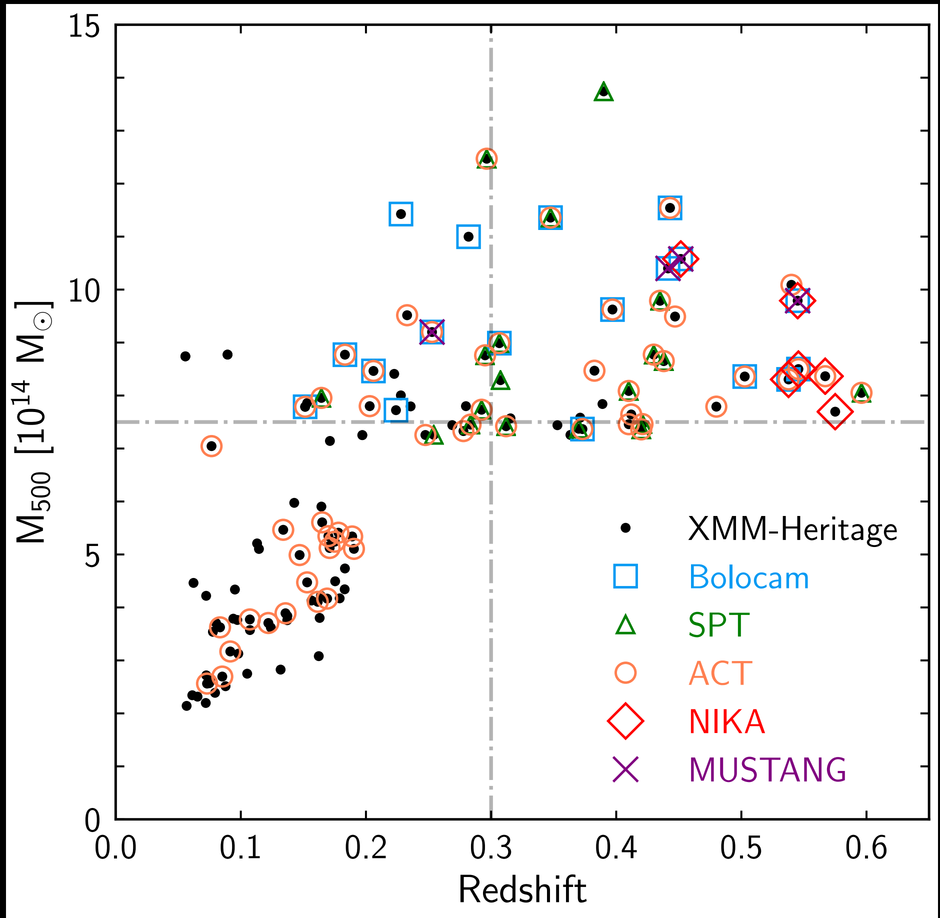


CHEX-MATE gallery *2021, A&A, 650, 104*

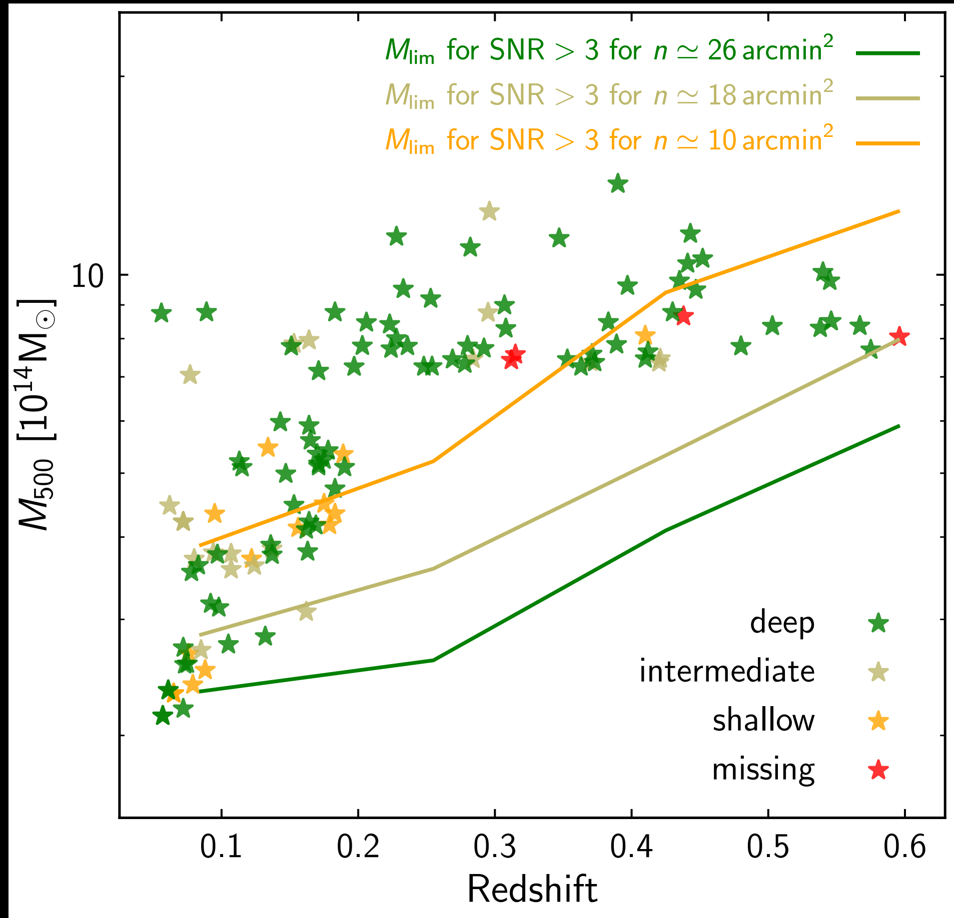


CHEX-MATE multi-λ *2021, A&A, 650, 104*

SZ



Lensing



SZ data (including Planck) are public

62 objects with published WL analysis (*see LC² catalog, Sereno 15*);

26+ objects will have dedicated proposals (*HSC/Subaru PI: Sayers; Megacam/CFHT, PI: Gavazzi/Umetsu; OmegaCam/VST PI: Sereno*)

Goals of CHEX-MATE

Selection for the 3 Msec ***program:***

SNR>6.5; $z \in [0.05, 0.6]$; M_{Tier-2}>7.25e14

- Assess the relative importance of gravitational and non-gravitational processes in shaping cluster properties
- Probe the dynamical collapse of the gas on different scales
- Construct a consistent picture of cluster mass estimates
- Provide a unique reference for evolution studies and numerical modelling
- Legacy for Next Generation missions