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

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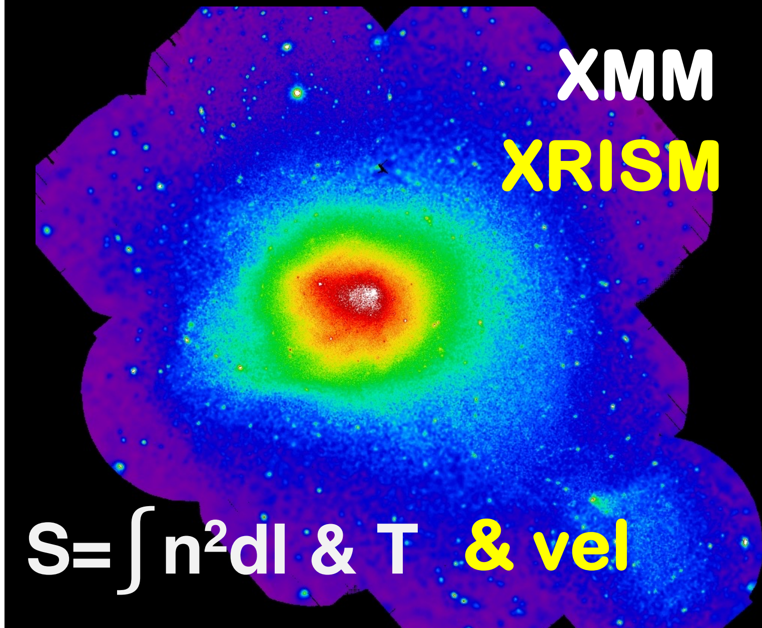
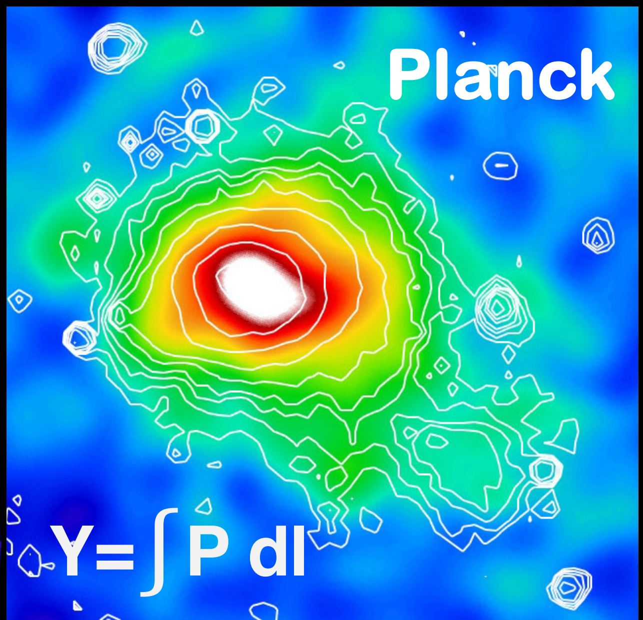
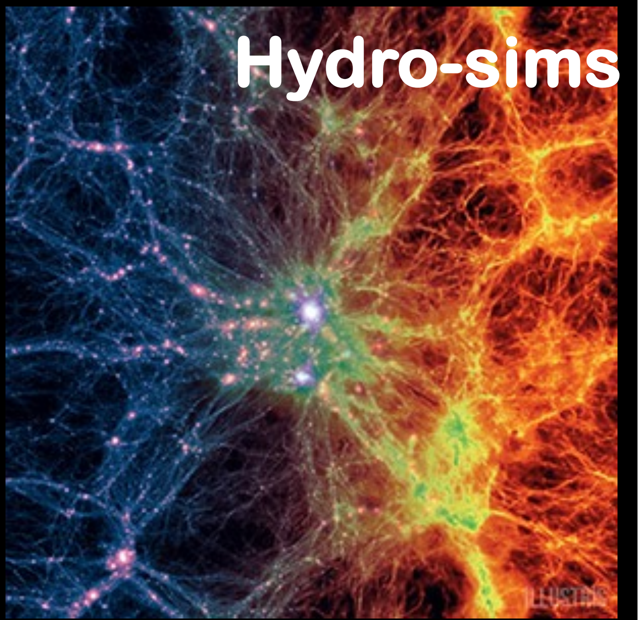






Clusters of Galaxies

- ***The largest gravitationally-bound structures in the universe;***
  "dunkle Materie" (Zwicky 1933) ➔ ~80% of M_{tot} (~15% hot gas; few % stars)

- **Cosmology from N(M), clustering** *& internal structure:*

Uno itinere non potest perveniri ad tam grande secretum

✓ **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+22*)
✓ **Bulleticity** ➔ *(SI)DM / MOND*
✓ *γ-ray signal from DM in clusters*
(➔ INAF-CTA AdR @OAS-Bologna)

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

Hydrostatic Mass, velocities & non-thermal pressure

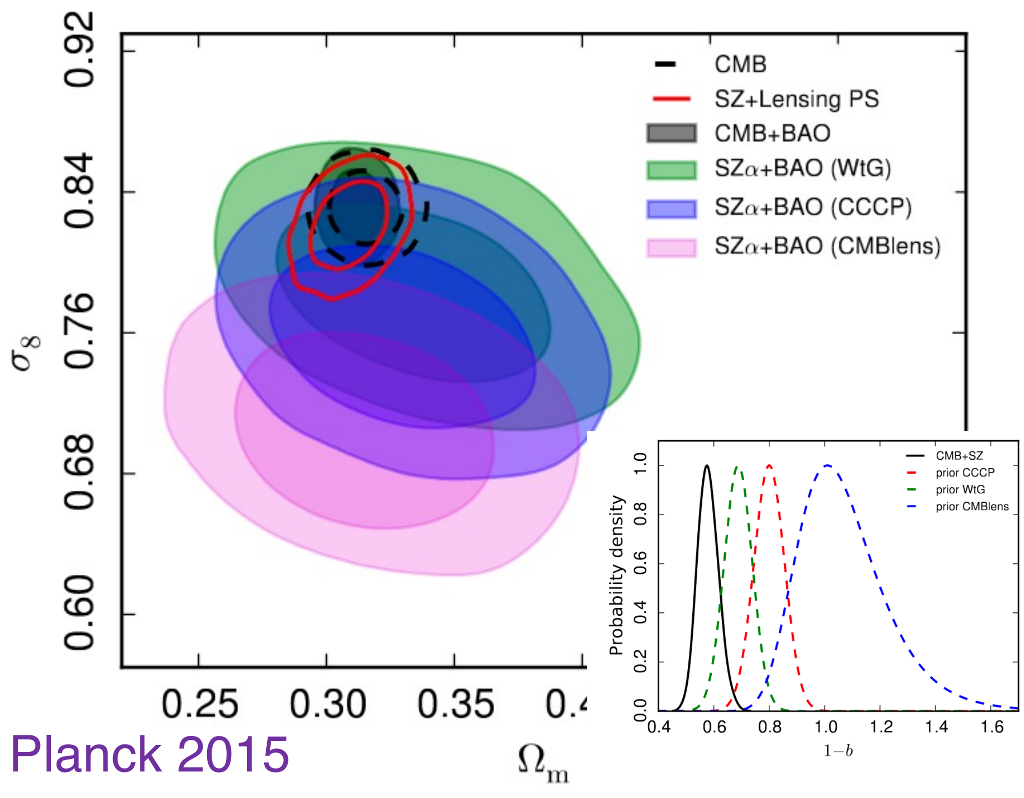
$$\frac{G\,M_{HE}(<r)}{r^2} = -\frac{dP_g}{dr}\frac{1}{\rho_g}$$

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

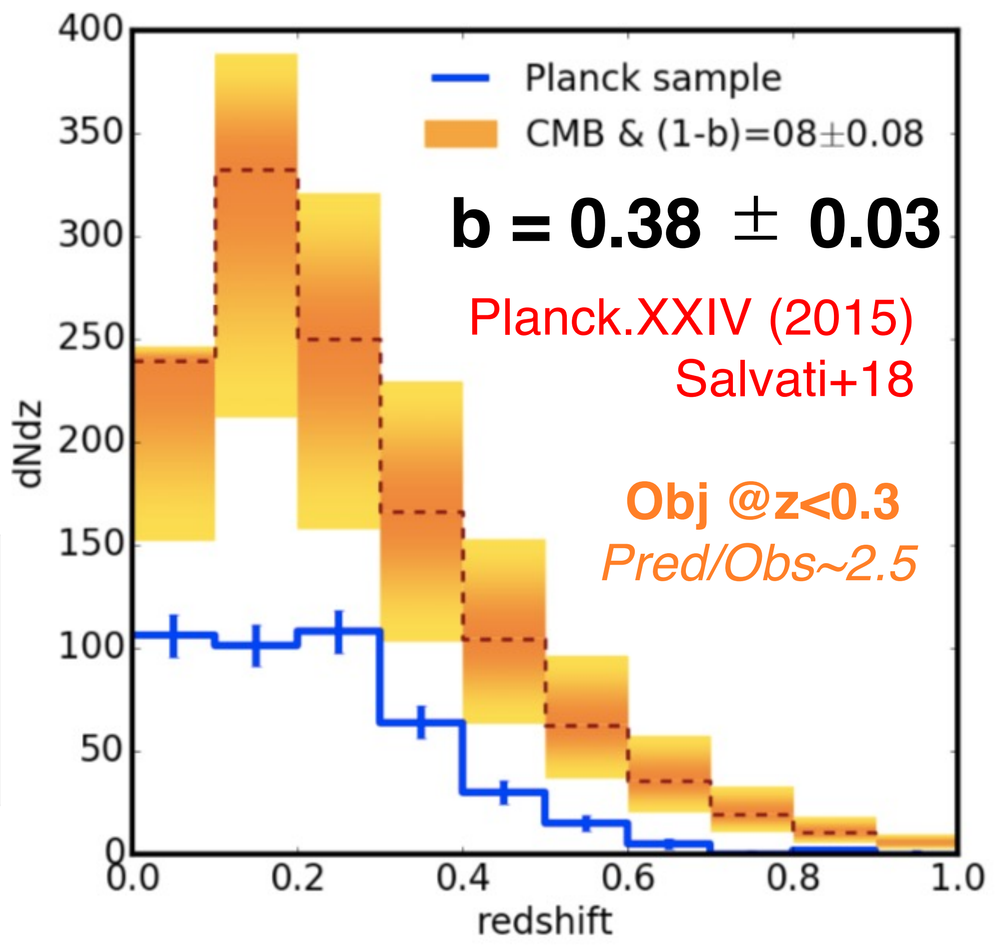
$$\ldots = -\frac{d(P_g+P_{NT})}{dr}\frac{1}{\rho_g} = -\frac{dP_{tot}}{dr}\frac{1}{\rho_g}$$

$$M_{HE}\,/(1-b) = M_{tot} \sim T^{3/2} \sim M_{gas} \sim L^{3/4} \sim Y^{3/5}$$

Hydrostatic bias: (1-b) = M_X/M_{500}



Planck 2015

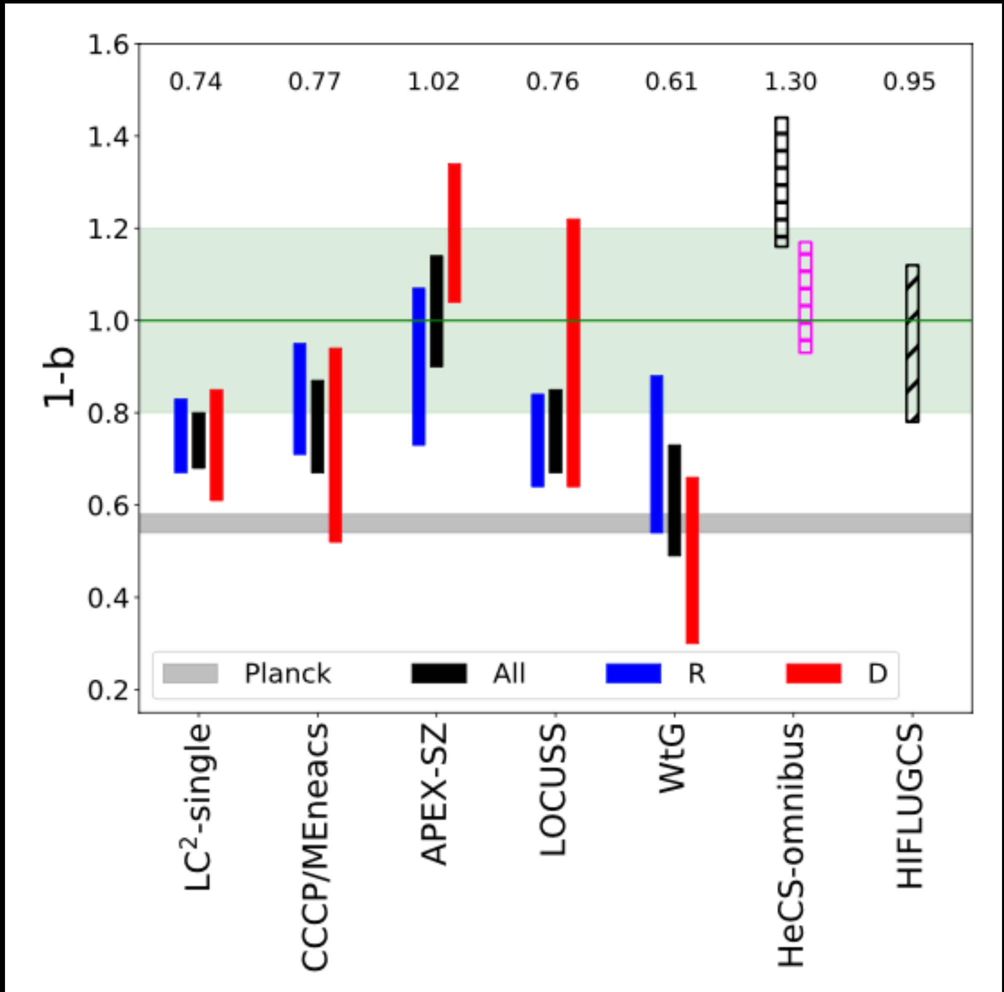


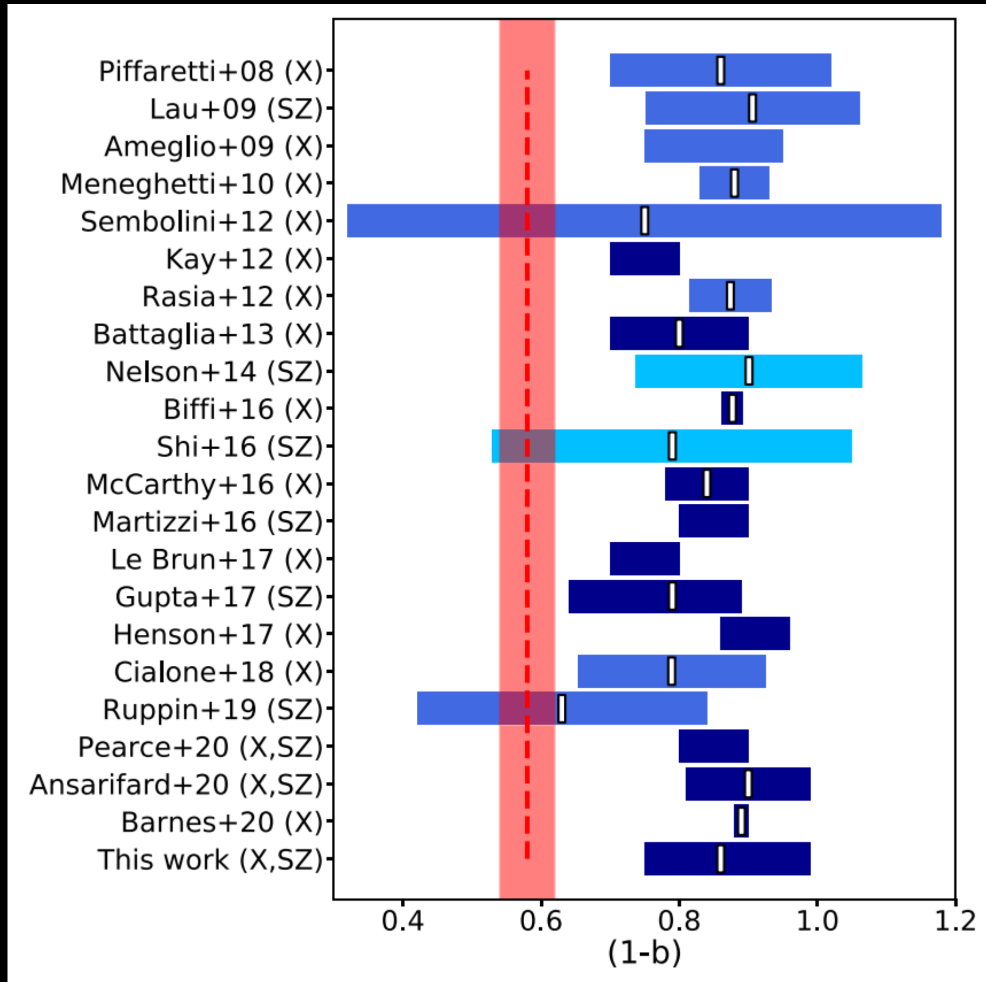
b = 0.38 ± 0.03

Planck.XXIV (2015)
Salvati+18

Obj @z<0.3
Pred/Obs~2.5

Hydrostatic bias: (1-b) = M_X/M_{500}

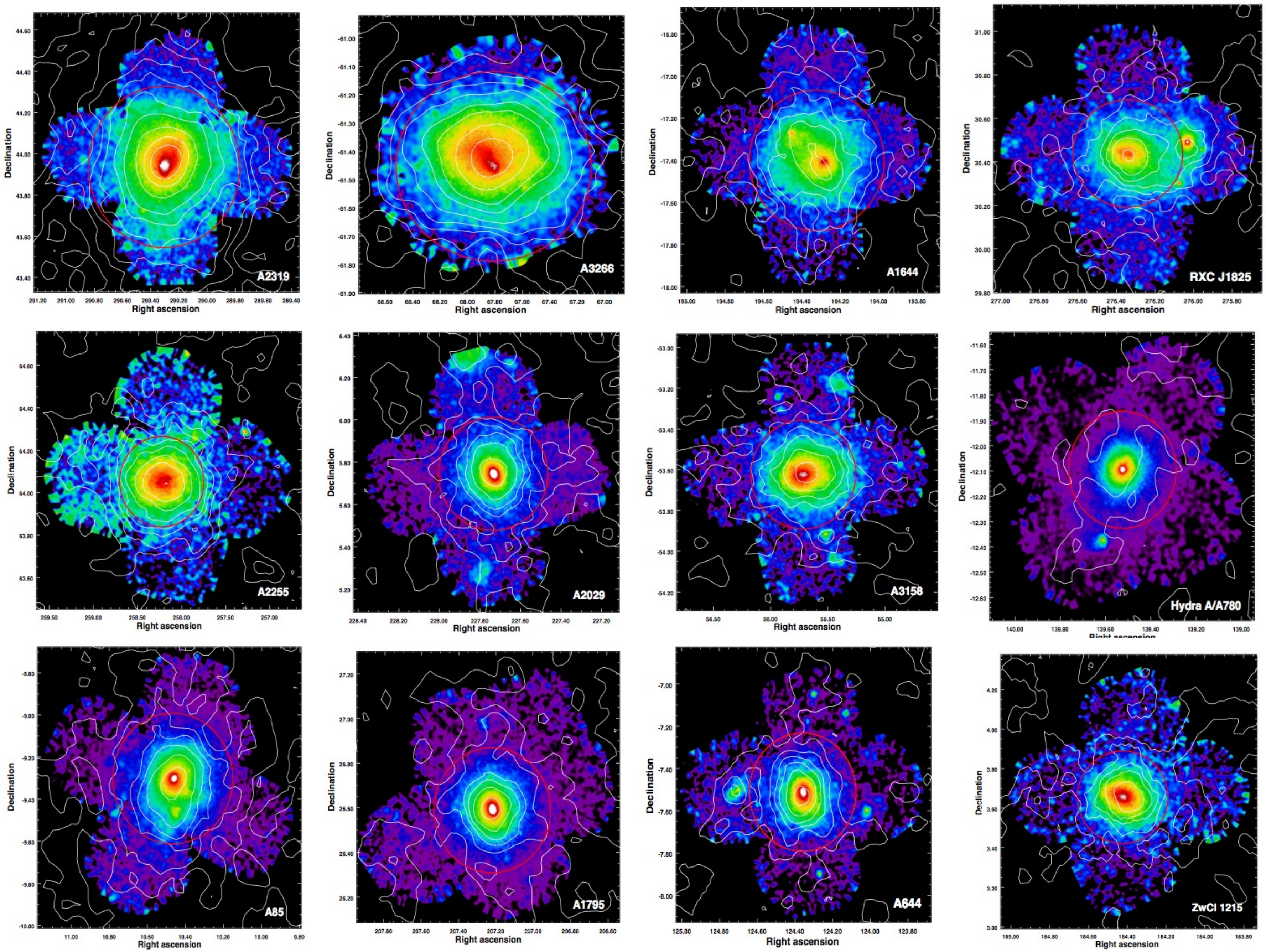




Planck ESZ sample (120 obj; ***Lovisari, Ettori+20***)

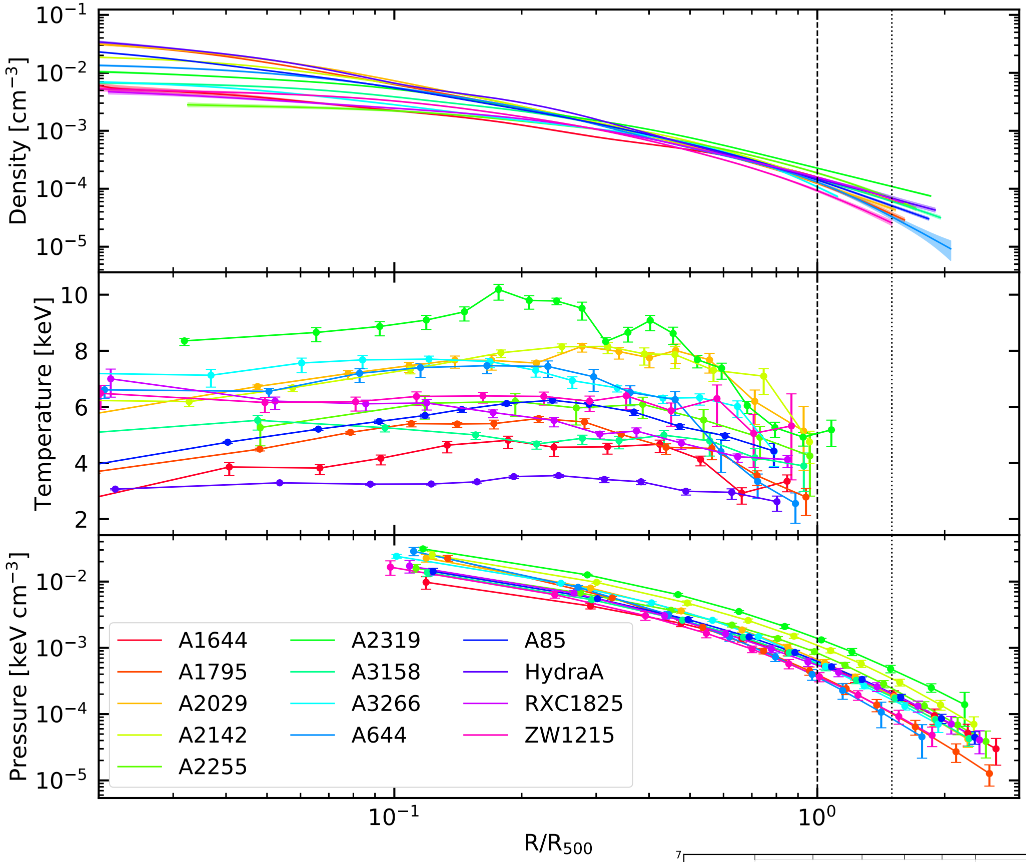
Gianfagna+21

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



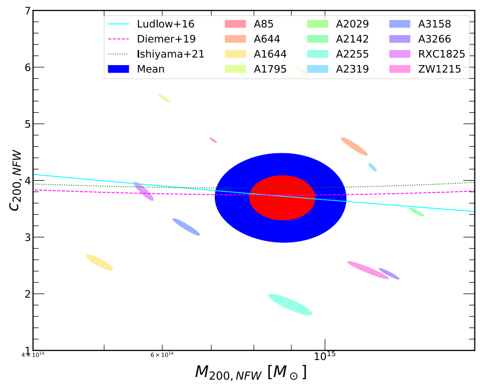
X-COP: thermodynamic profiles

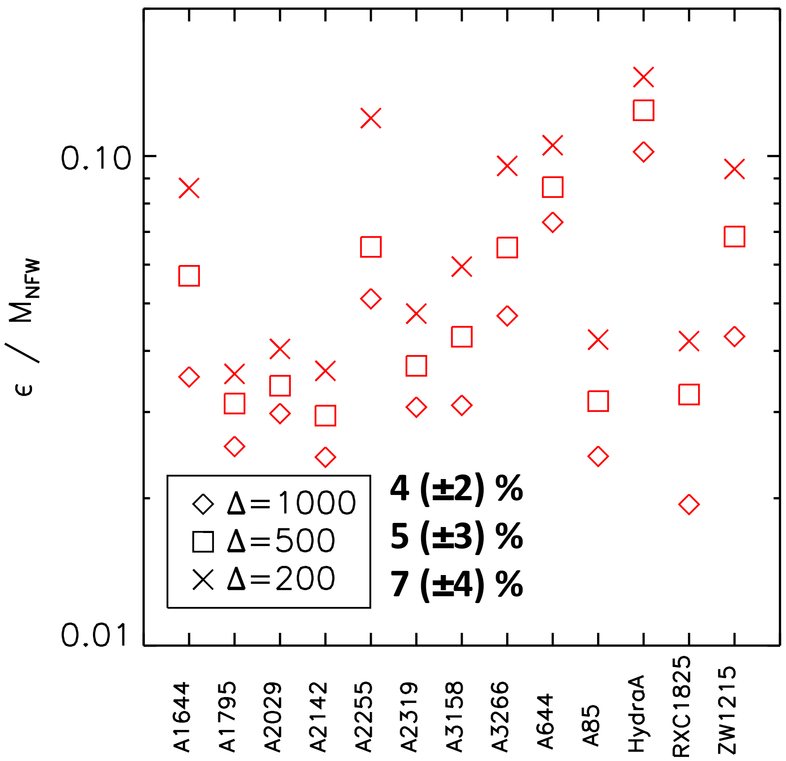
(Ghirardini+19; M_{HE}: Ettori+19; P_{NT}: Eckert+19)



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

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



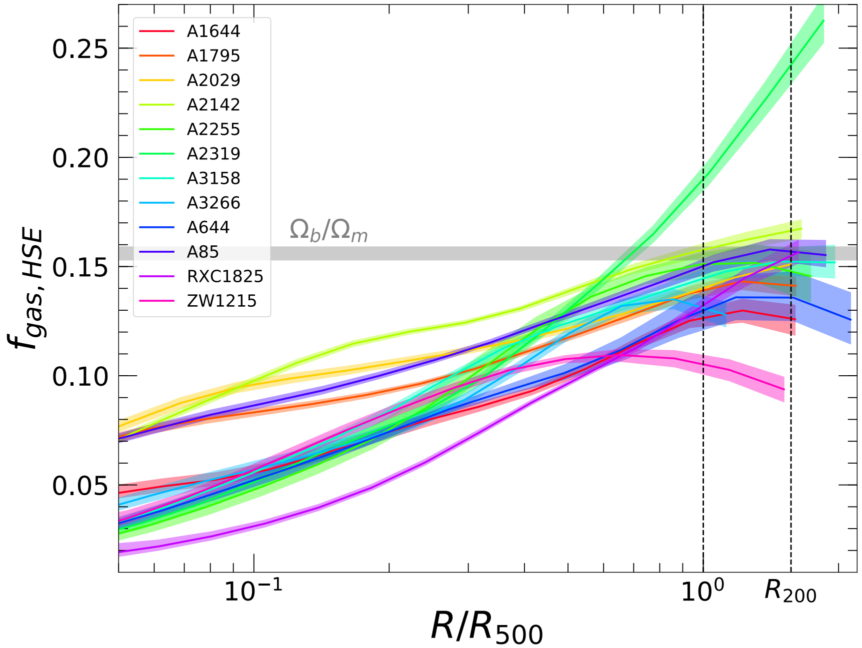


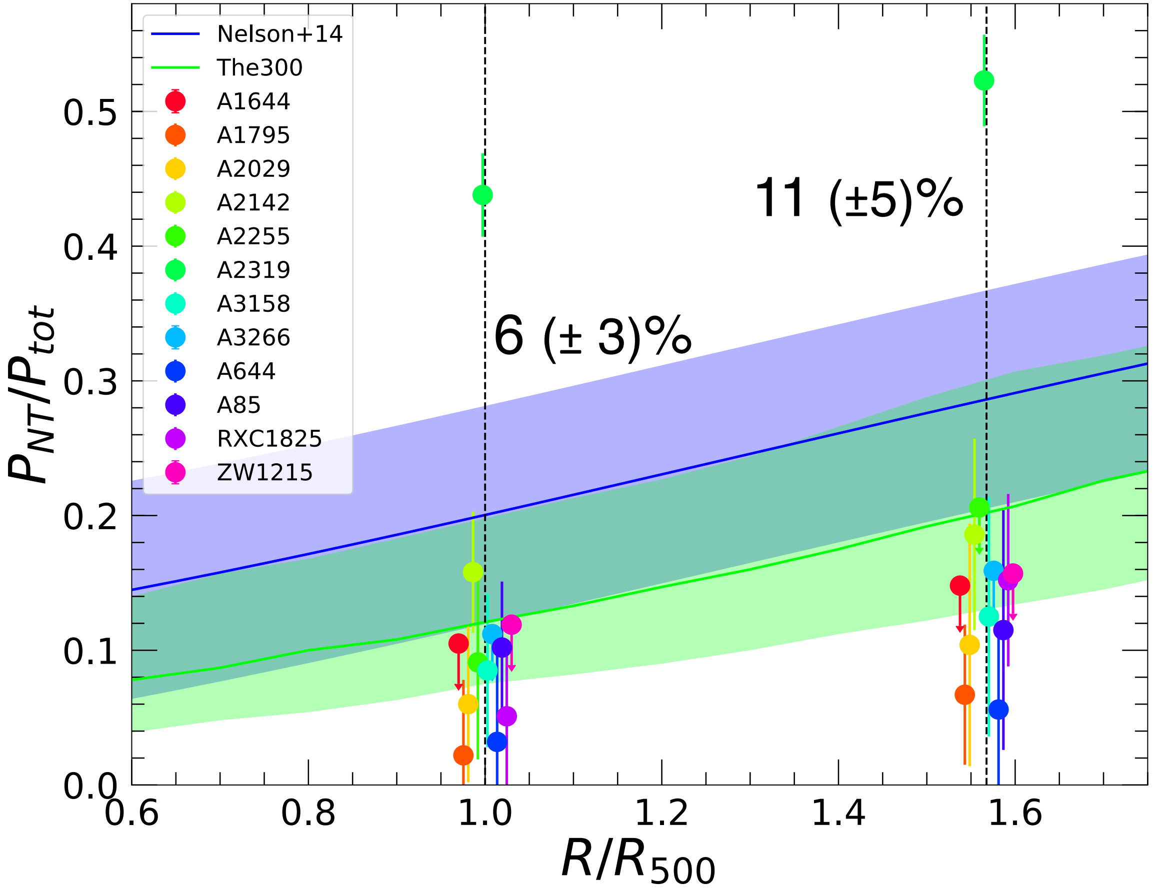
X-COP: non-thermal P

(Eckert+ 19 arXiv:1805.00034)

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

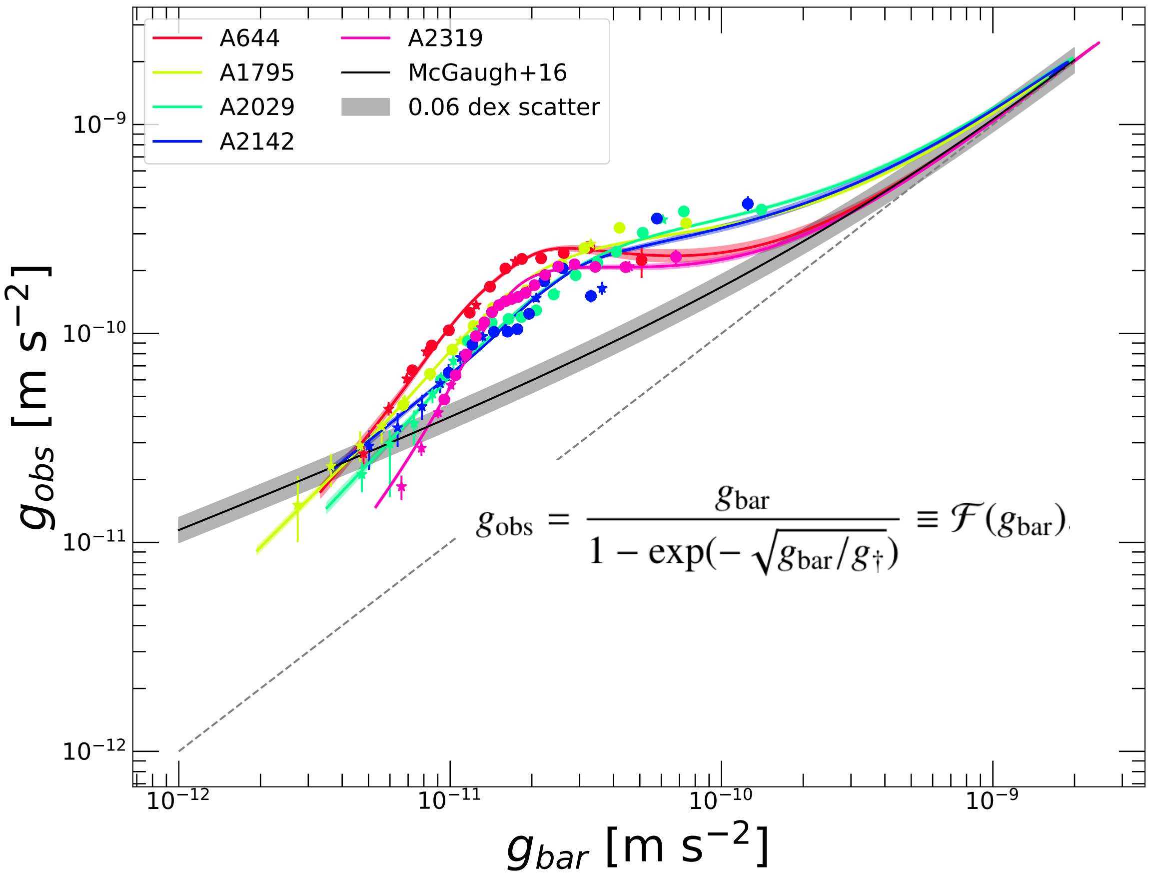
$$f_{\rm gas,univ}(r) = Y_b(r)\frac{\Omega_b}{\Omega_m} - f_\star$$

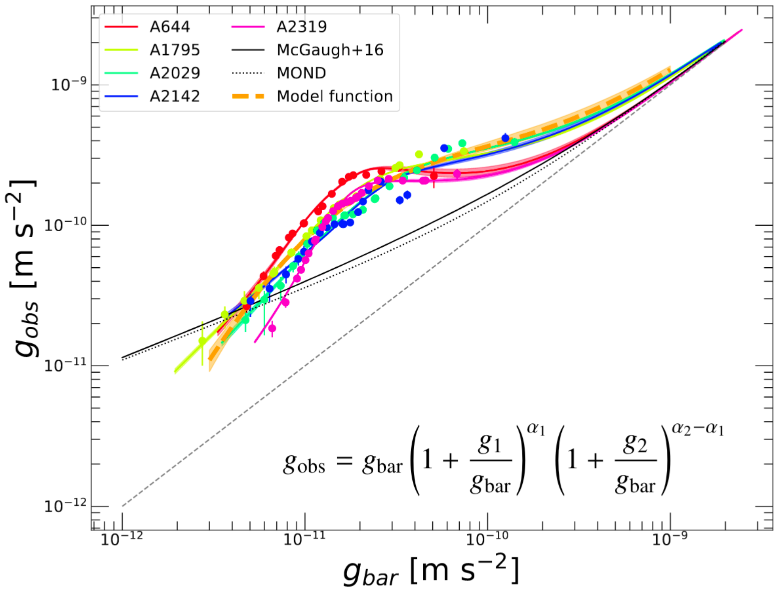


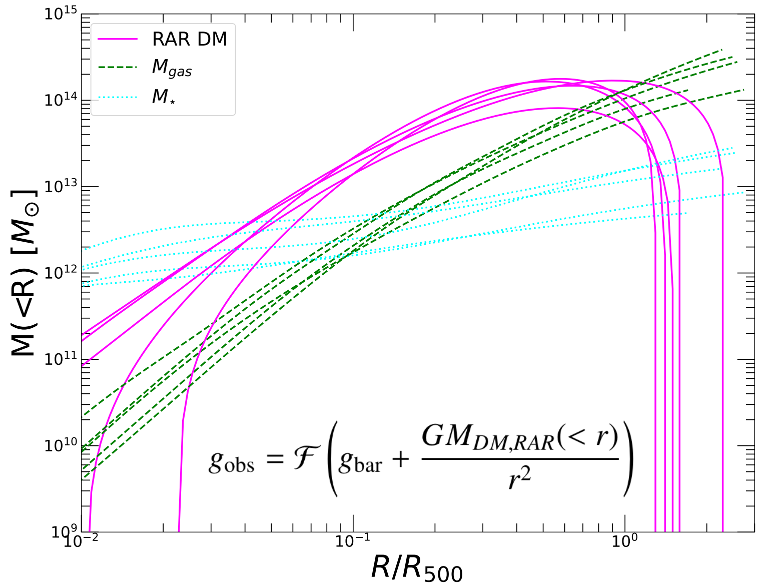


X-COP: Acceleration

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







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

X-COP: SIDM

(Eckert, Ettori, et al. 2022b)

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

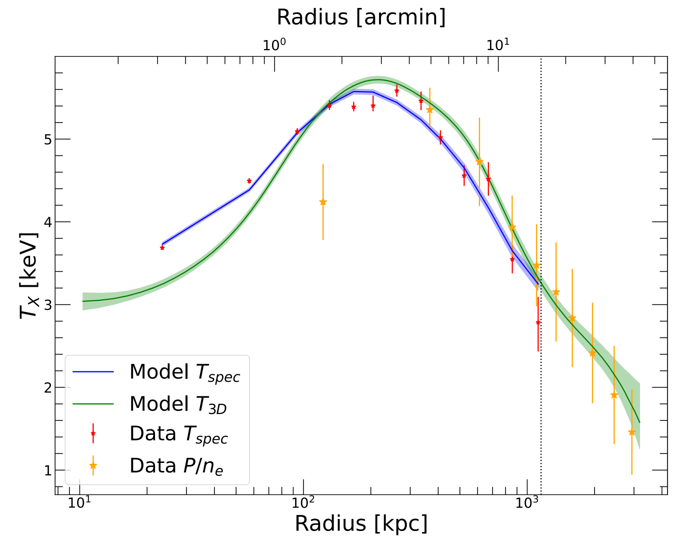
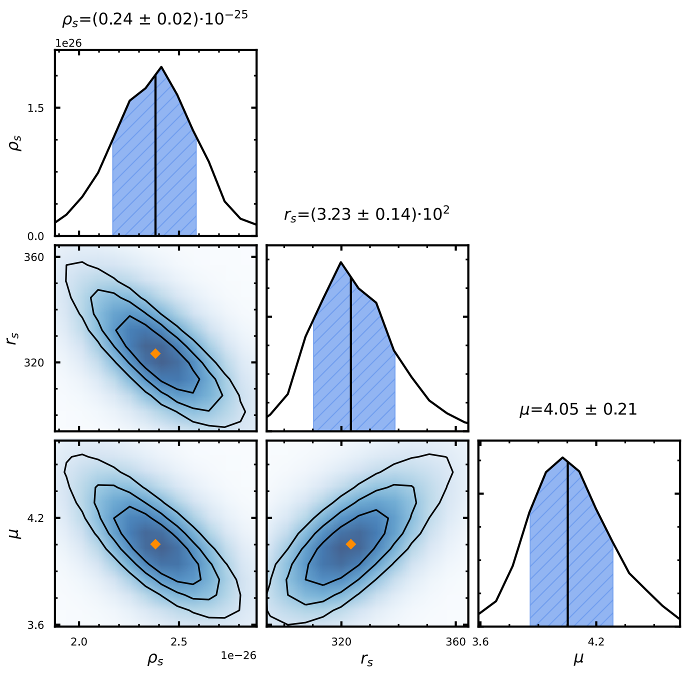
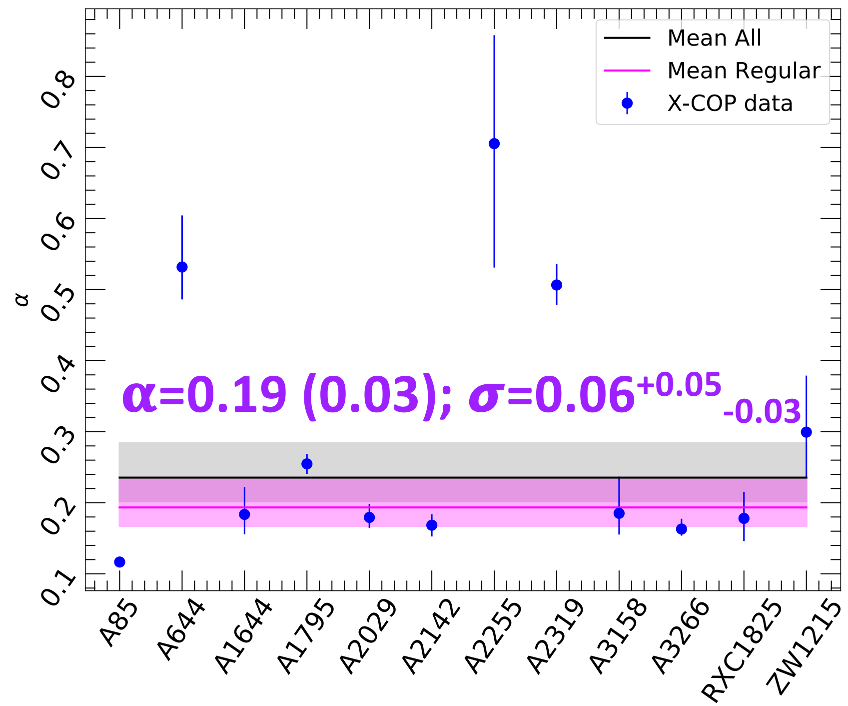


Table 1. Normal priors on the Einasto fit parameters. Here P_m and dP_m denote the outermost SZ pressure value and its error.

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	$P_m - 2dP_m$	$P_m + 2dP_m$

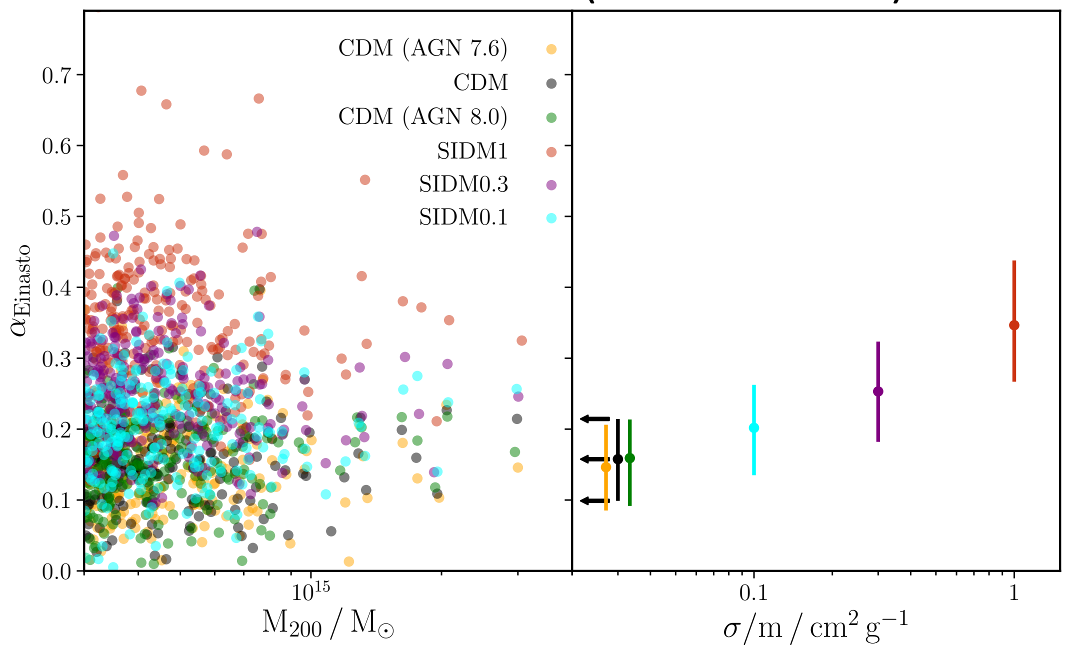


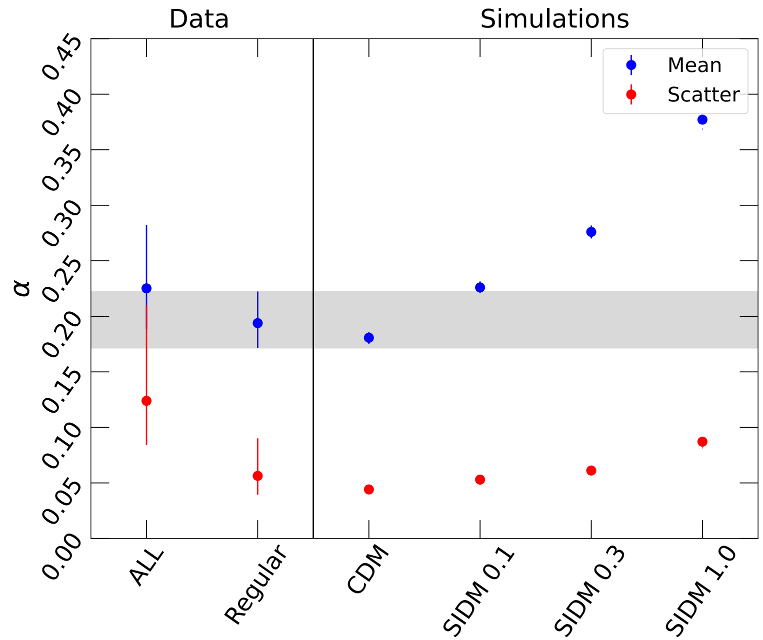


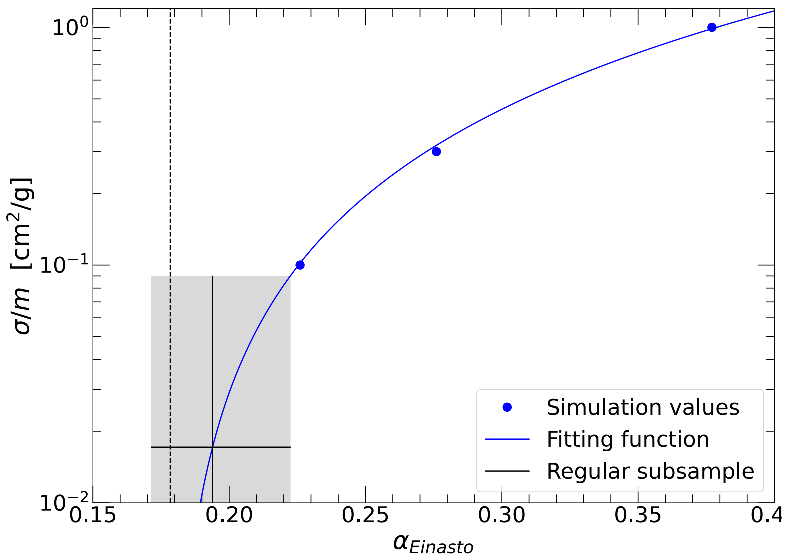
X-COP: SIDM

(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

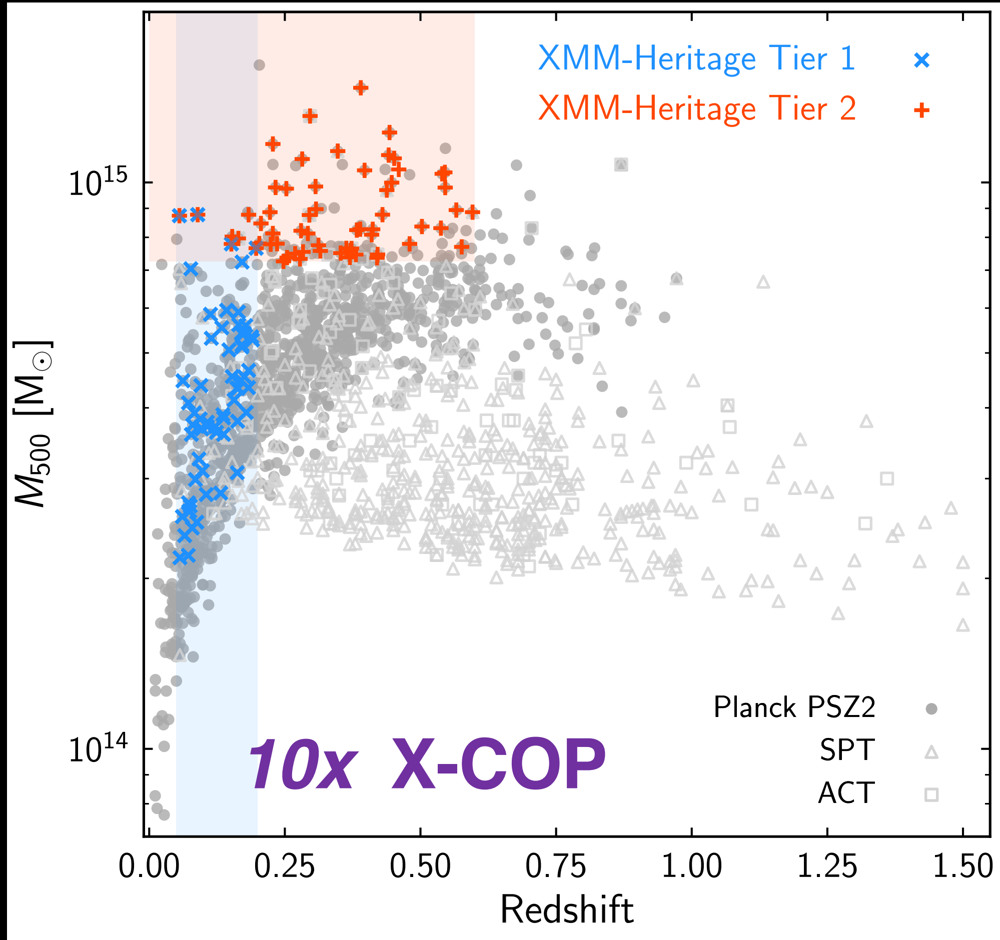
An XMM-Newton Multi-Year Heritage Program

Witnessing the culmination of structure formation in the Universe

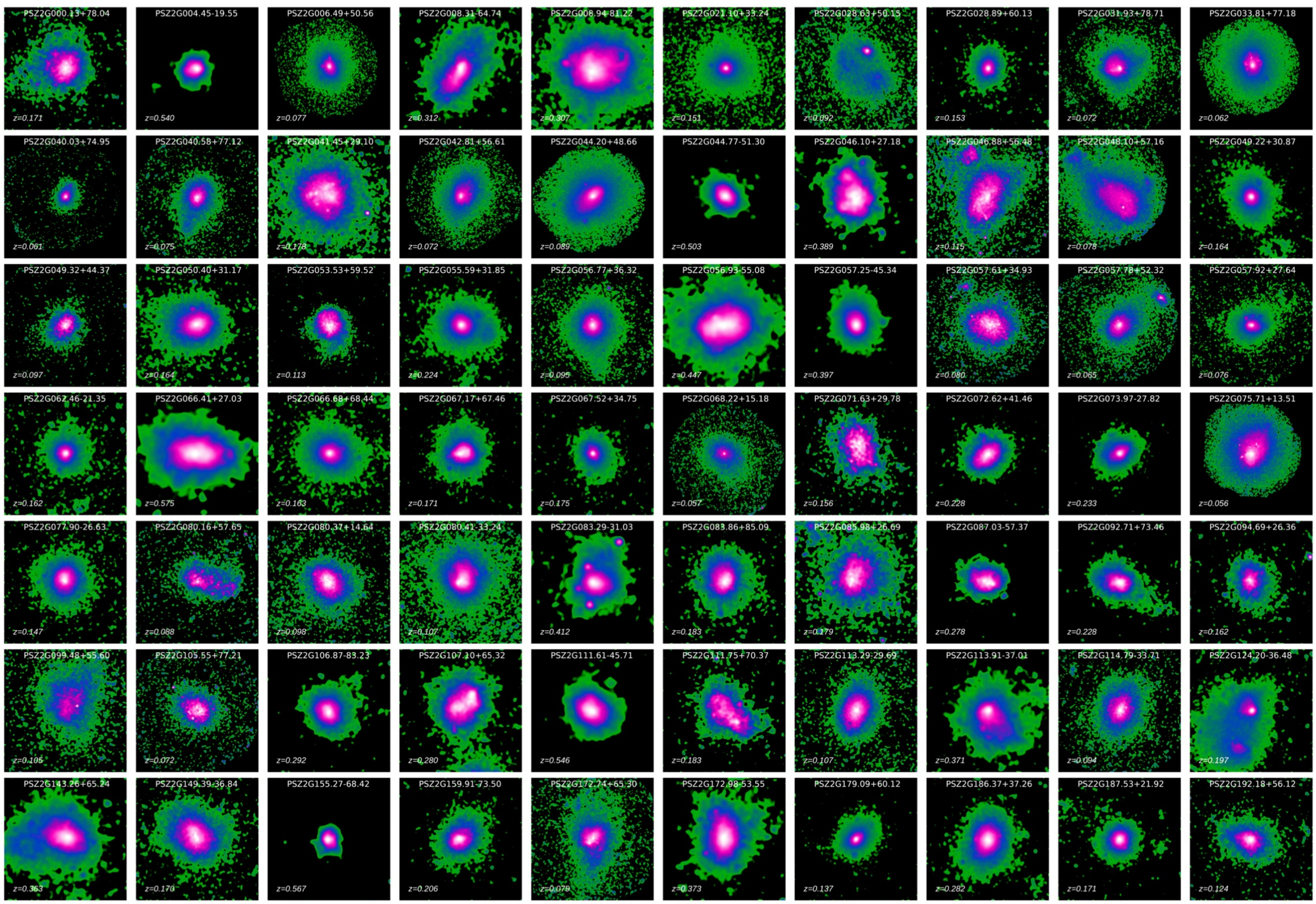
URL: xmm-heritage.oas.inaf.it

CHEX-MATE (the Cluster HEritage project with XMM-Newton: Mass Assembly and Thermodynamics at the Endpoint of structure formation; *PI Ettori & Pratt +~80 collaborators*): **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*

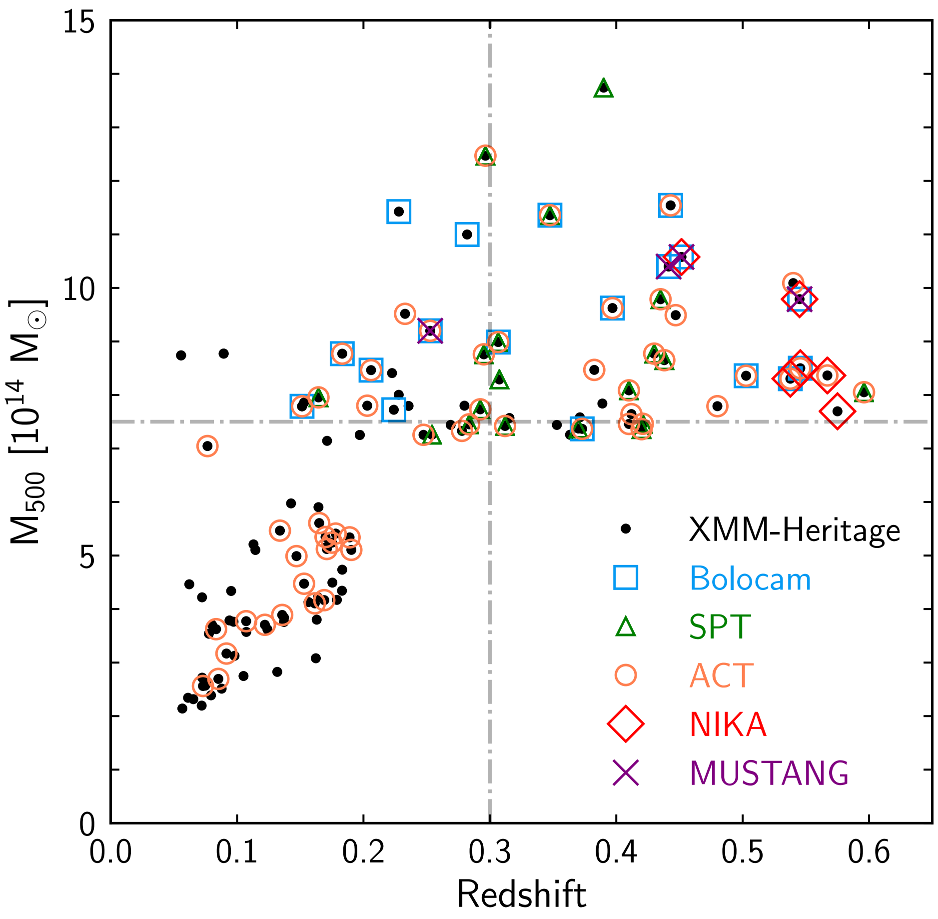


CHEX-MATE gallery *2021, A&A, 650, 104*

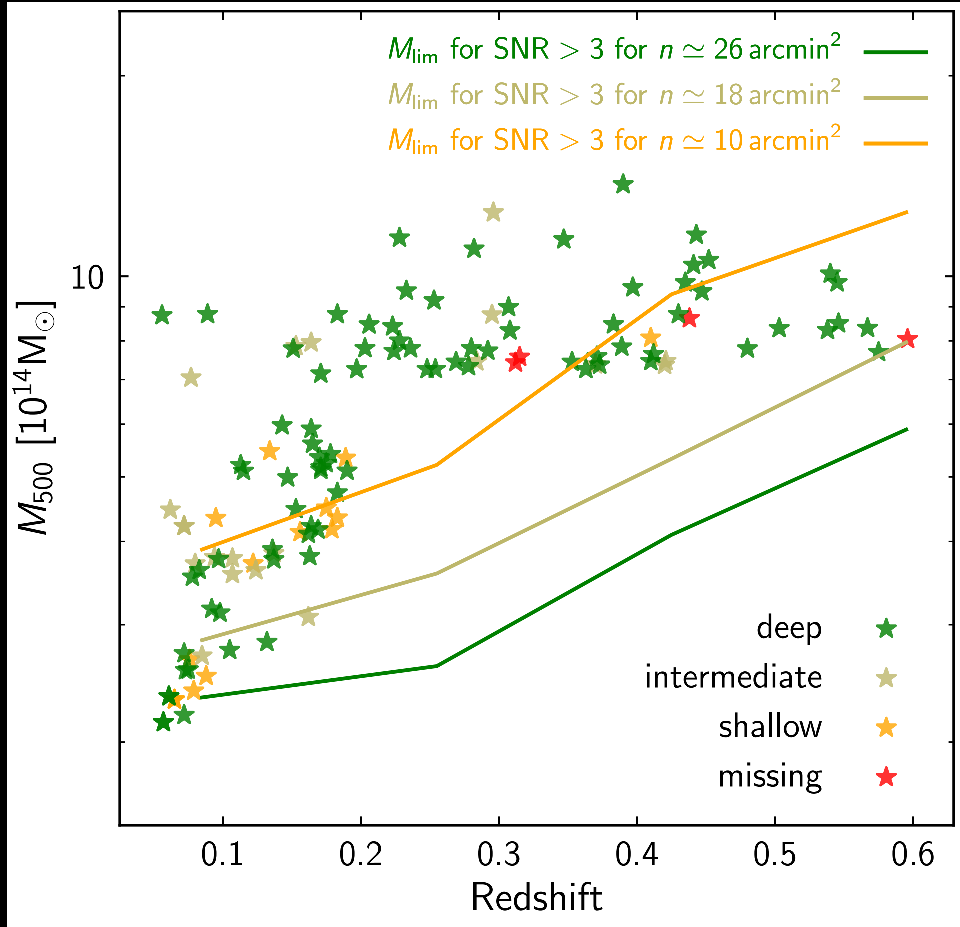


CHEX-MATE multi-λ *2021, A&A, 650, 104*

SZ



Lensing



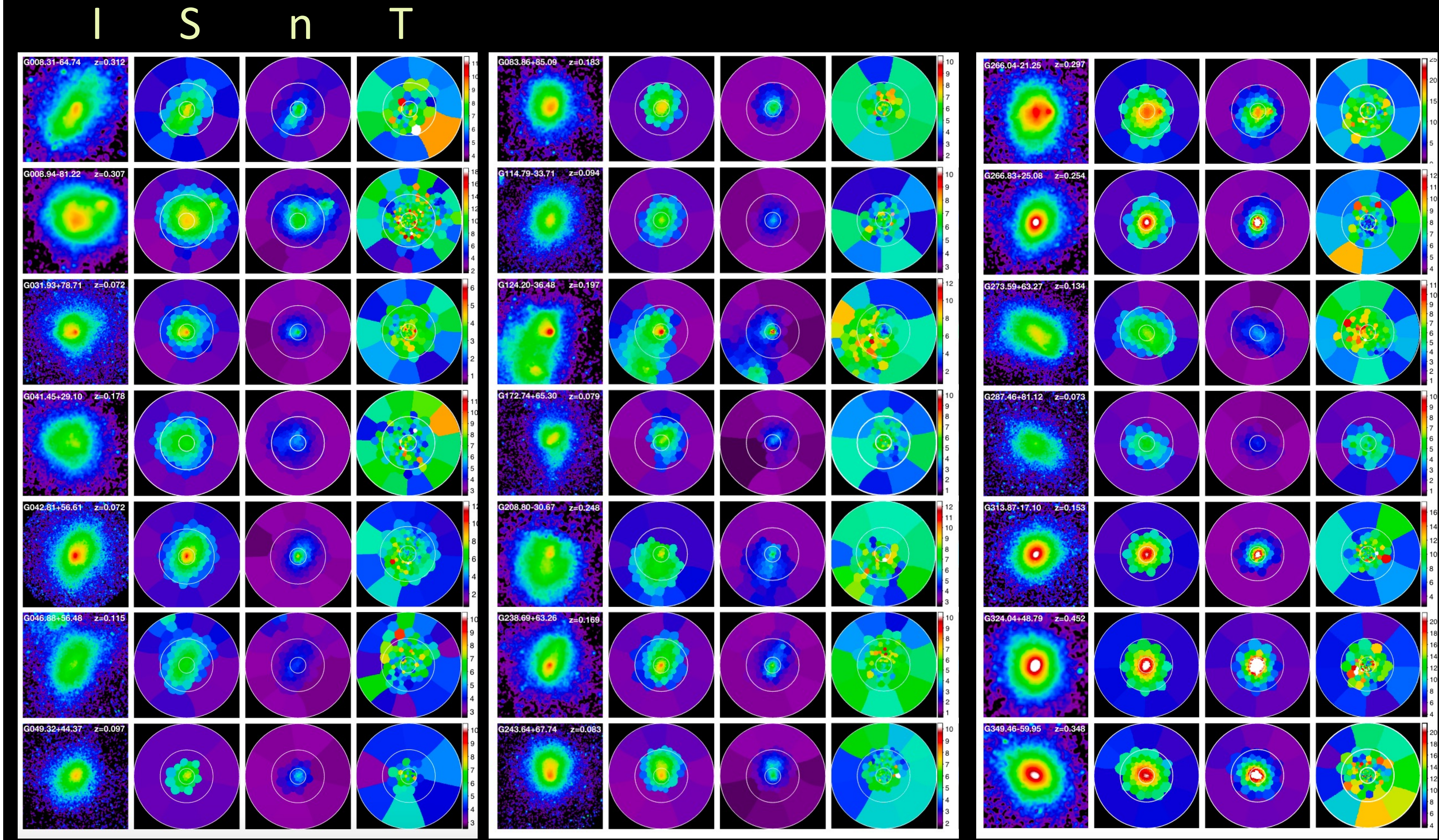
SZ data (including Planck) are public

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

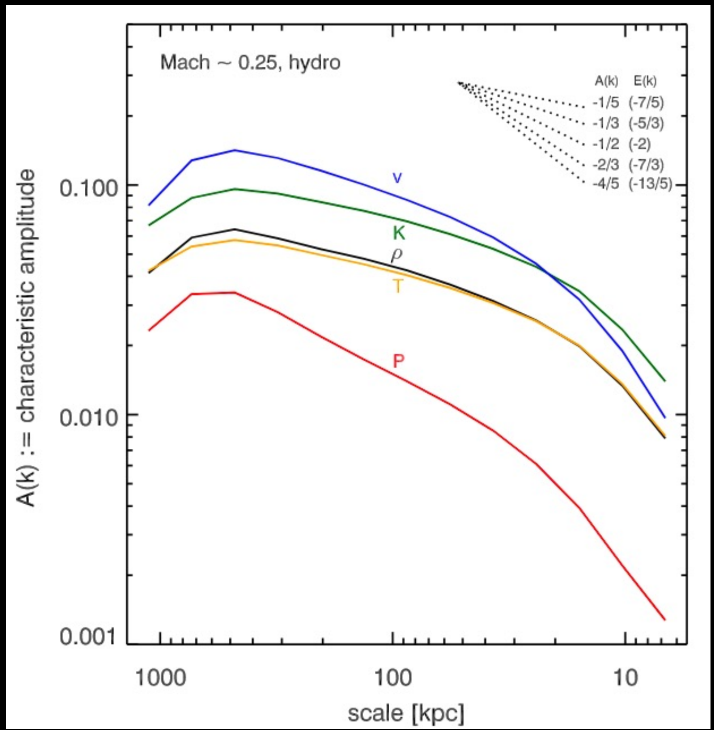
26+ objects will have dedicated proposals (*HSC/Subaru PI: Sayers; Megacam/CFHT, PI: Gavazzi/Umetsu; OmegaCam/VST PI: Sereno*)

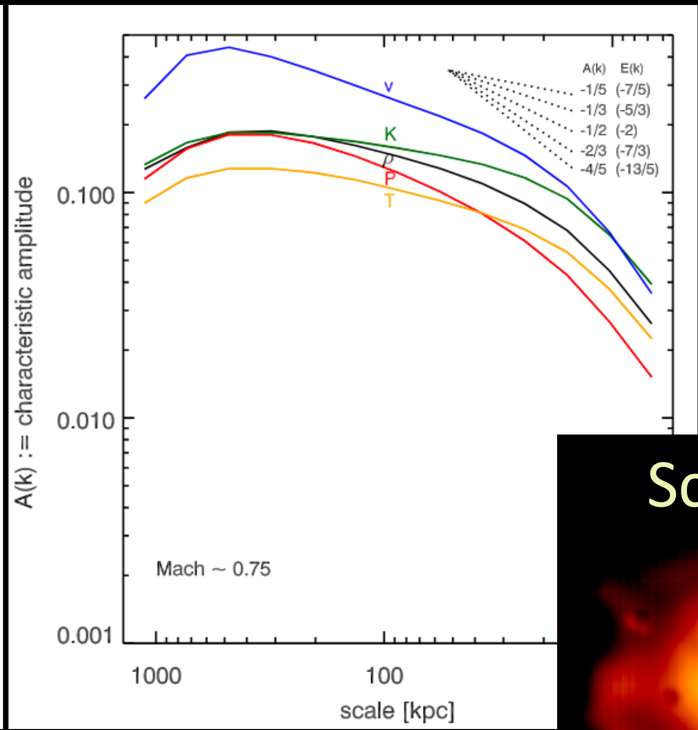
Temperature structure in the ICM

(Lovisari, Ettori et al. arXiv:2311.02176)



Velocities in the ICM



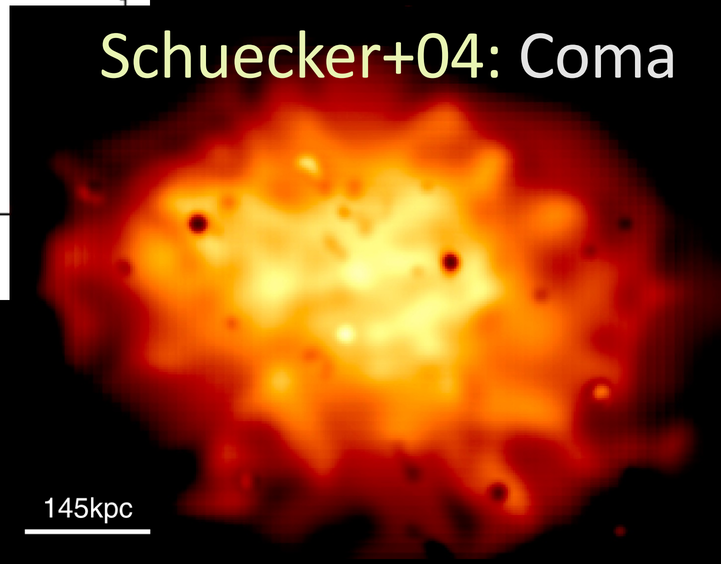


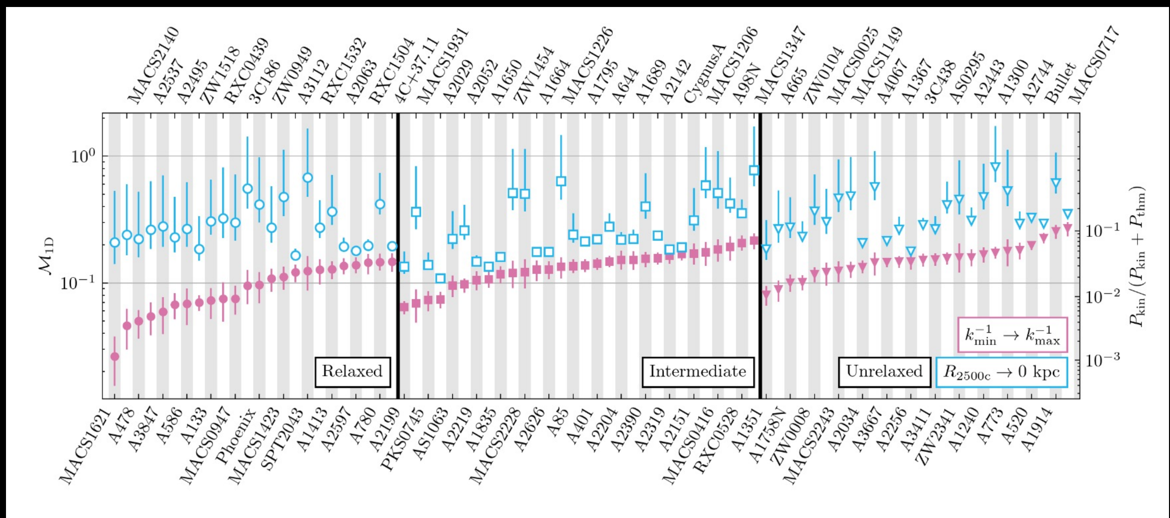
Gaspari+13-14, Zhuravleva+14:

low M flow ➔ δK

High M ➔ δP

Schuecker+04: Coma

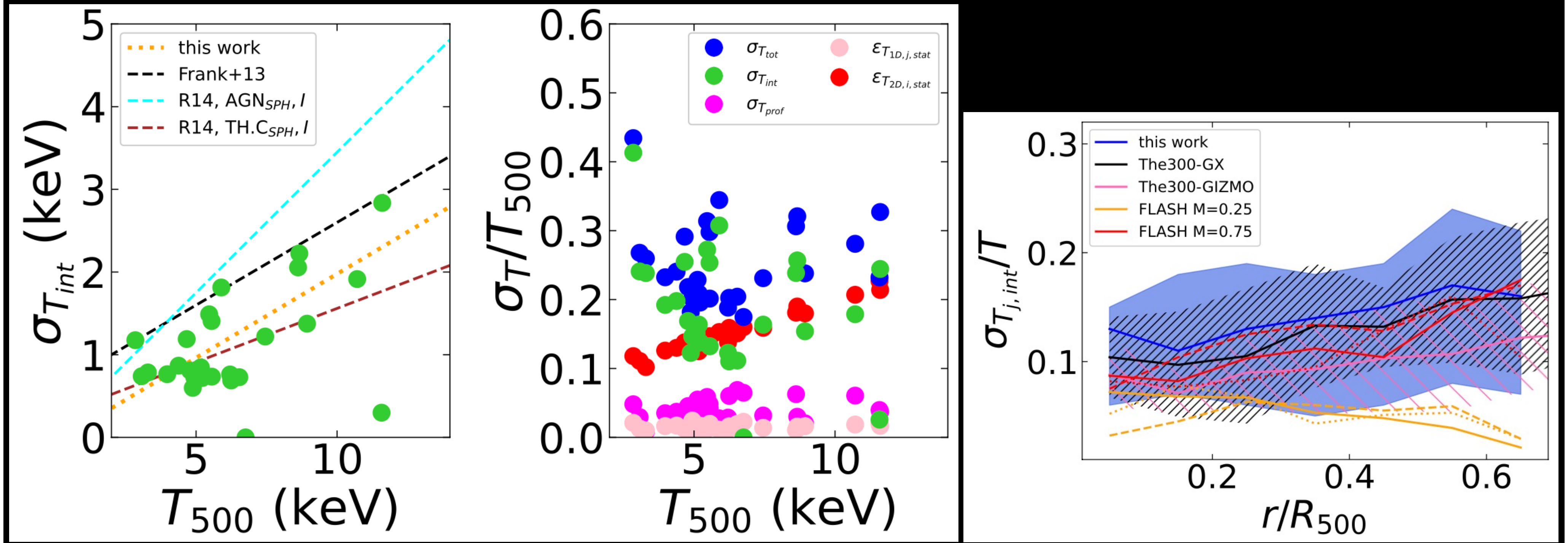




Heinrich+24: ICM density fluctuations in ~80 nearby (z<1) GCs

Temperature structure in the ICM

(Lovisari, Ettori et al. arXiv:2311.02176)

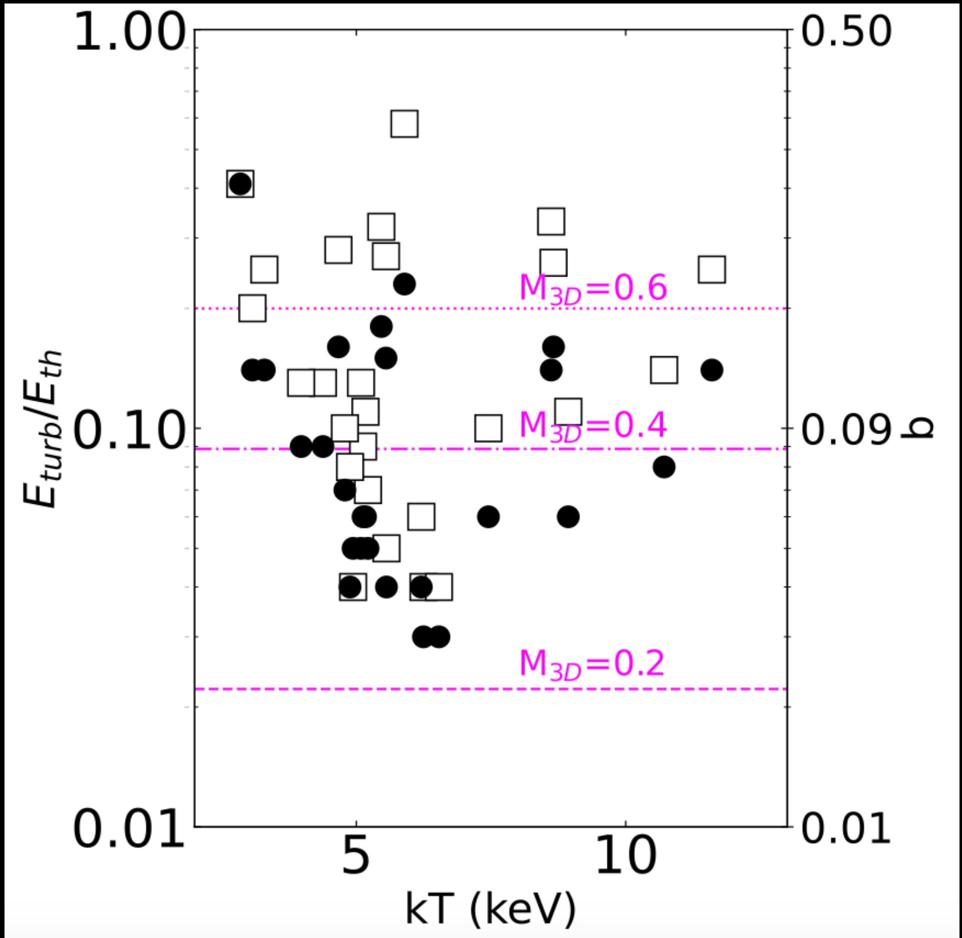


➔ **M =v/c$_s$ ~σ_T/T**

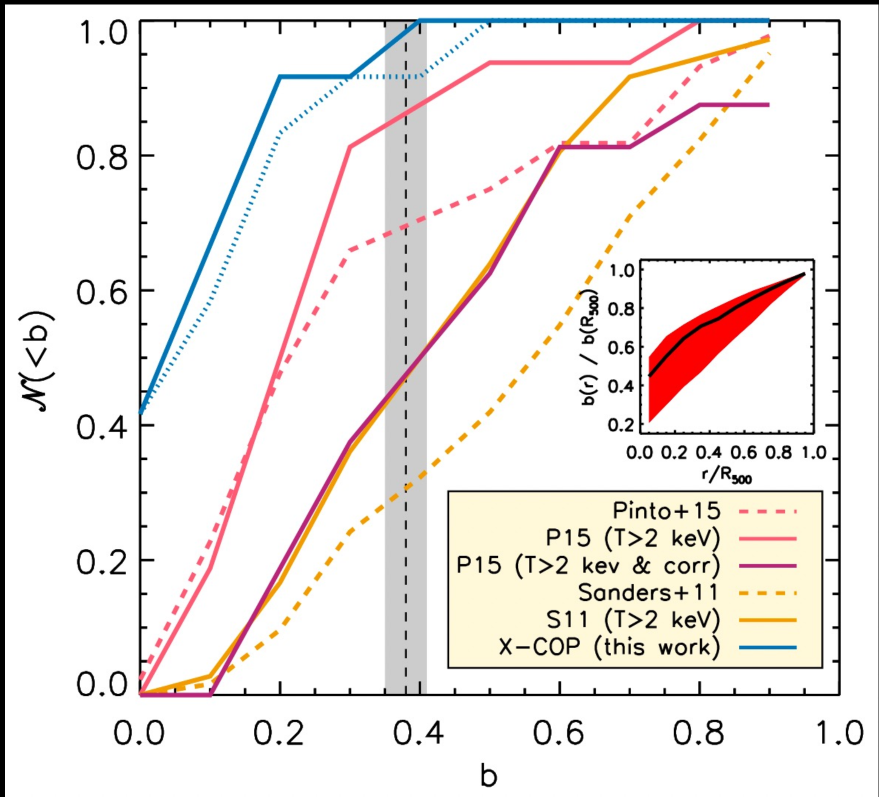
➔ $E_{turb} / E_{therm} = 0.5\,\gamma\,(\gamma-1)\,(3\,M_{1D}^2) = 0.5\,\gamma\,(\gamma-1)\,M^2$

Temperature structure in the ICM

(Lovisari, Ettori et al. arXiv:2311.02176)



Ettori & Eckert 22

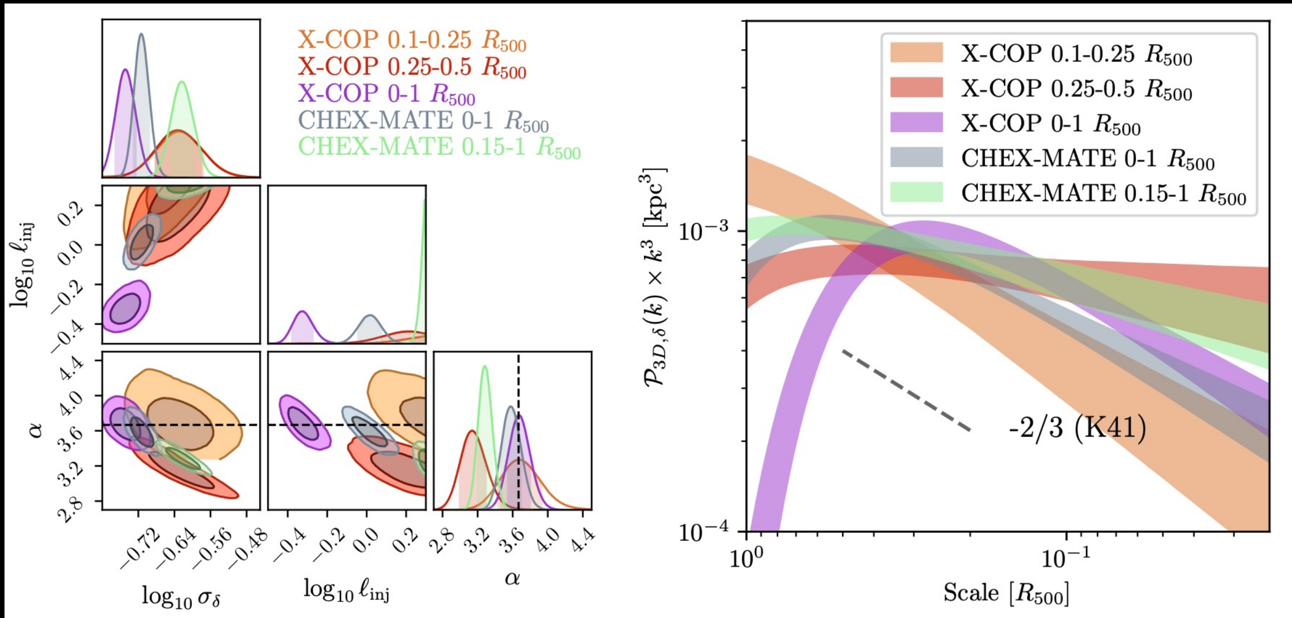


$$b = 1 - M_{HE}/M_{tot} = (E_{th}/E_{turb} + 1)^{-1}$$

~0.06 **[0.03-0.13]** / *after integration: 0.11 [0.04-0.22]*

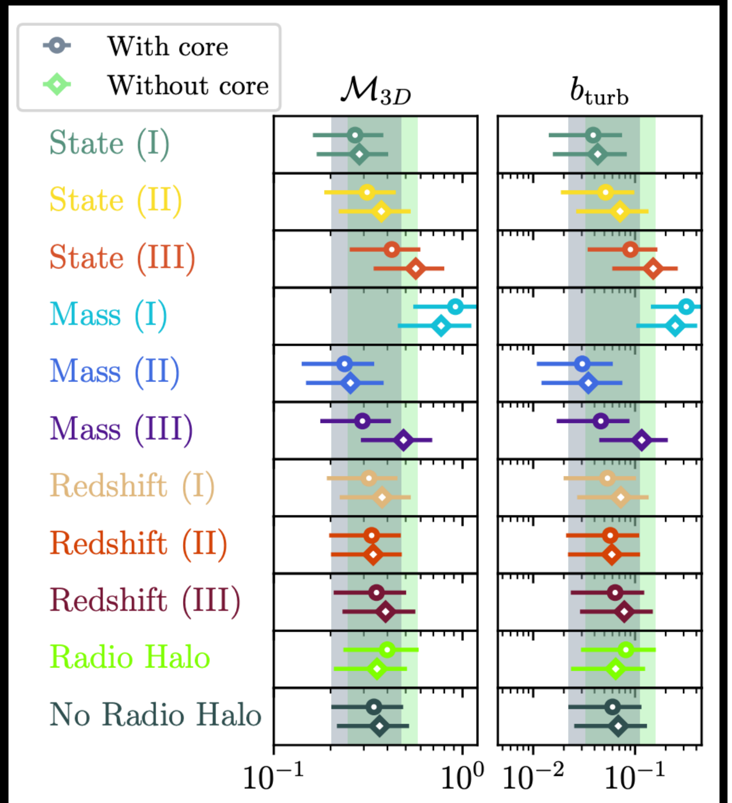
S_X fluctuations in the ICM

(Dupourqué, Clerc et al. arXiv:2403.03064)



$$\mathcal{M}_{3D} \approx \sqrt{3} \times (1 \pm 0.4)\, \sigma_\delta$$

$$\frac{P_{\rm turb}}{P_{\rm tot}} = \frac{\mathcal{M}_{3D}^2 \gamma}{\mathcal{M}_{3D}^2 \gamma + 3}$$



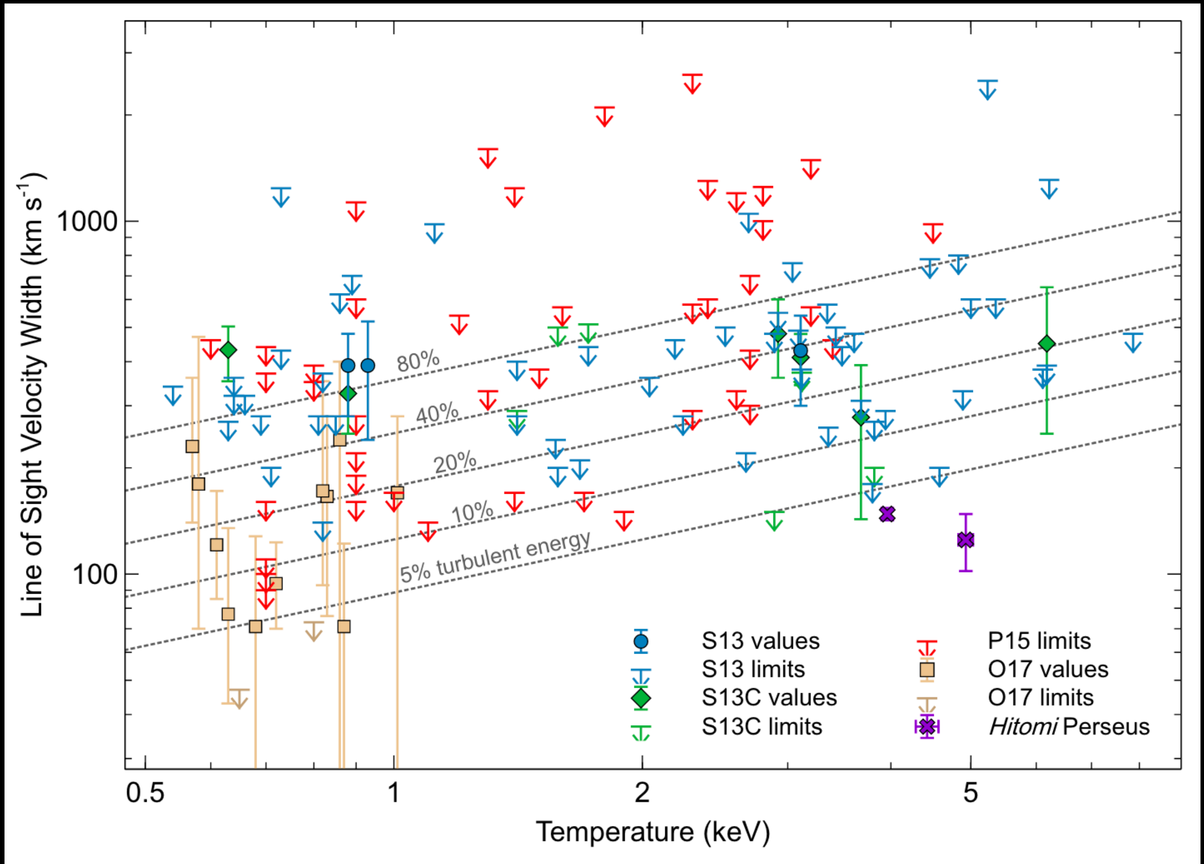
➔ $b_{turb} = 0.09 \pm 0.06$

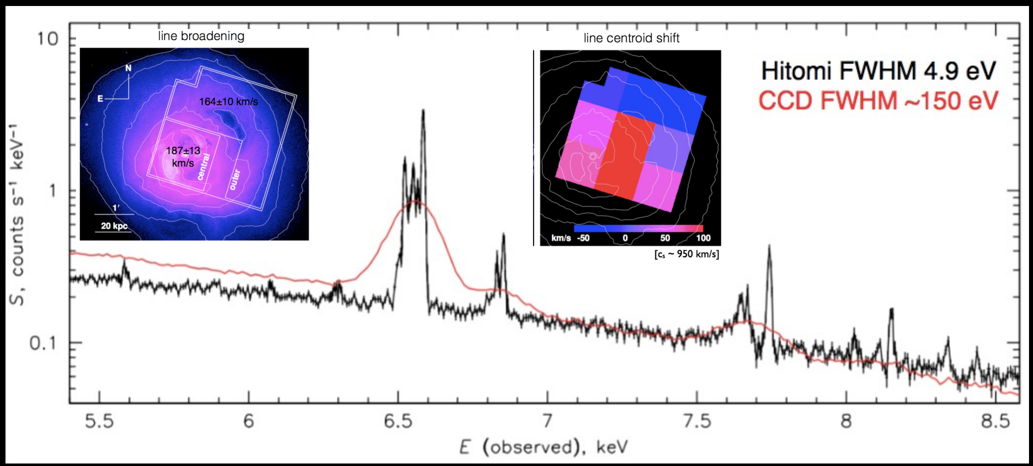
6 September 2023, 23:42 UTC

XRISM/SLIM successful launch

Velocities in the ICM

Compilation of v_{ICM}
(mostly 1 σ upper limits)
(Sanders arXiv:2301.12791)



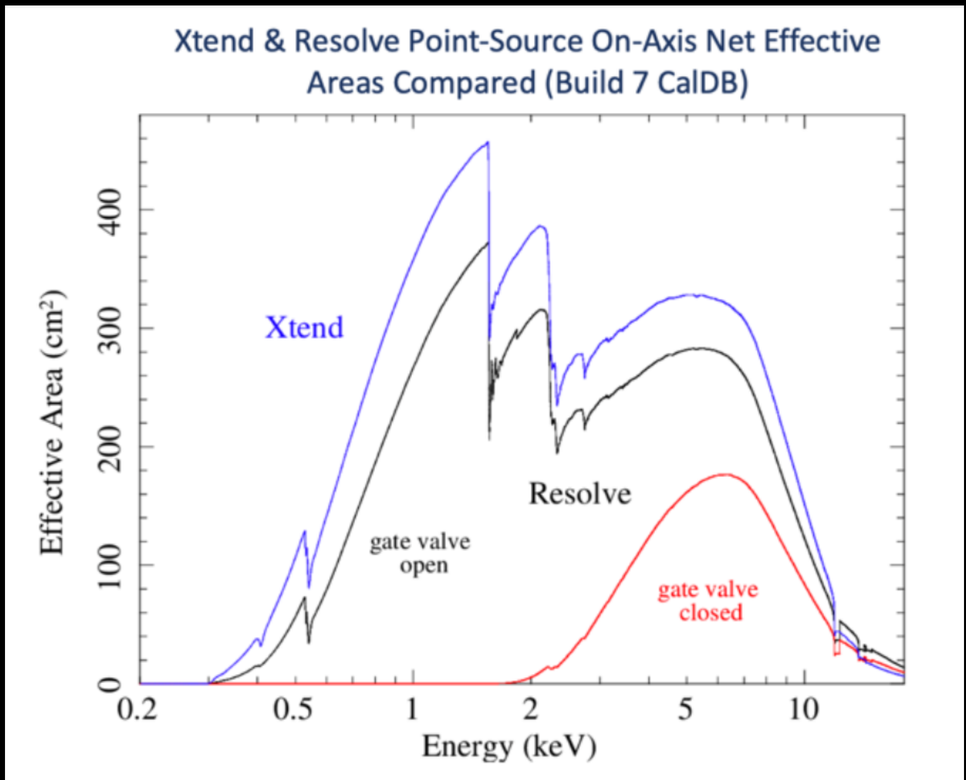


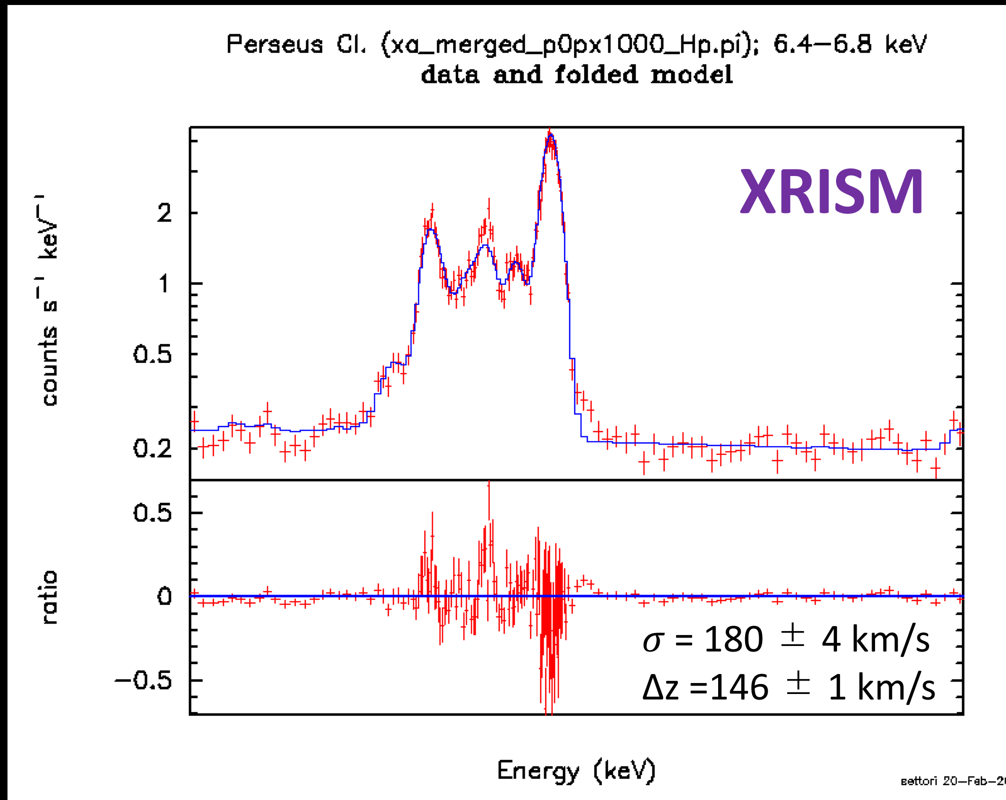
Hitomi collaboration, Nature 2016

Velocities in the ICM: XRISM

PV: Perseus (5 pointings), Coma (2), M87 (4), Centaurus, A3667, **A2029 (3),** (A2319 as a test)

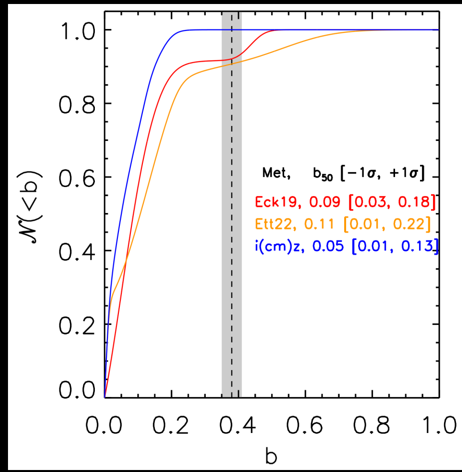
AO1 (~**30% of t_{exp}**; ESA: 8%, 7x more time requested): Phoenix, The toothbrush, Ophiuchus, A85, A496, A754, A1060/Hydra-A, A1413, ***A1689***, A1914, A2034, A2052, ***A2142***, A2163, A2199, A3395, A3571, MKW4, more on Perseus, Coma, Centaurus, A3667, …





Take-home messages on P_{NT}

- Analytic model (Ettori & Eckert 22) of P_{NT} ➔ b_{HE}, σ_{turb}
- **i(cm)z** (Ettori+20, 23): a semi-analytic model based on P_{univ} + *cMz;* reproduce spatially-resolved & integrated quantities ➔ forecasting b_{HE} (vel_{bapec})



- ✓ in relaxed objects (X-COP): *b_{50}~0.1 (<0.2)*
- ✓ (CHEX-MATE; M_{Planck}): *b_{50}~0.1 (<0.3)*
- ✓ Required: $b_{Planck} = 0.38 \pm 0.03$

❖ Hydrodynamic simulations (from e.g. Magneticum, the300, ENZO) convolved with SIXTE-like tools are needed to infer correlation between intrinsic and observed properties *(turbulence, bulk motions, structure functions, true b_{HE})*