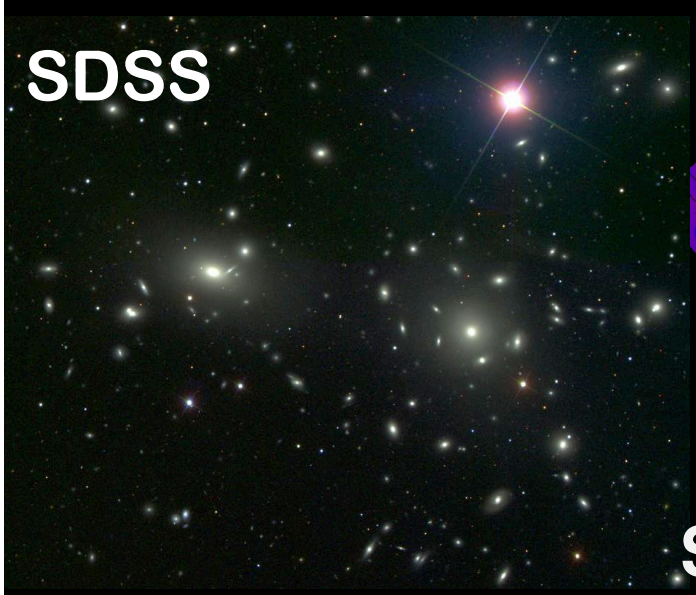
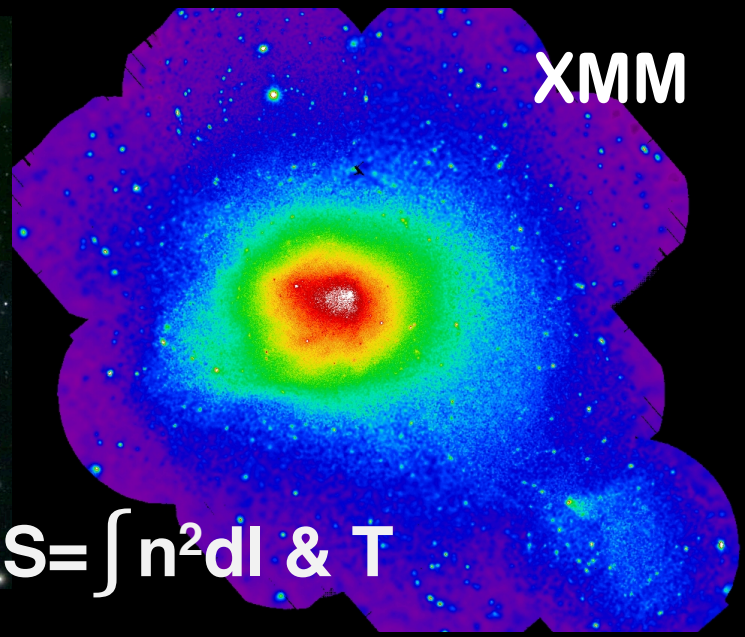
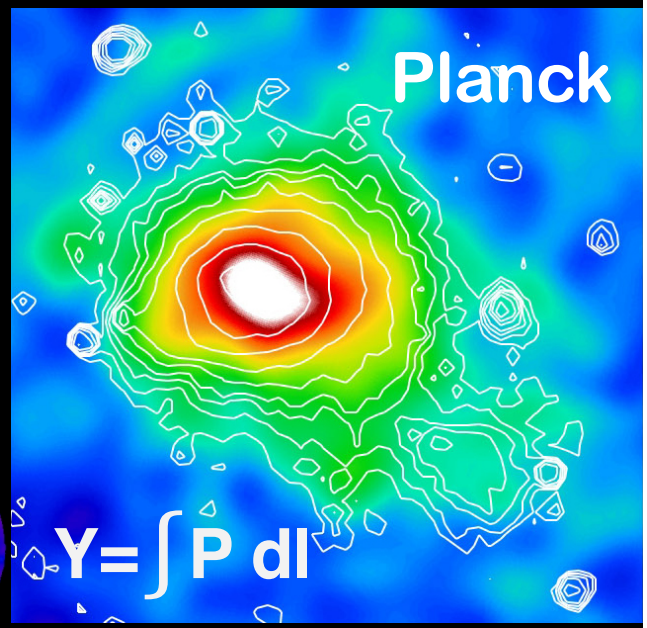
X-ray, SZ & dark matter in galaxy clusters

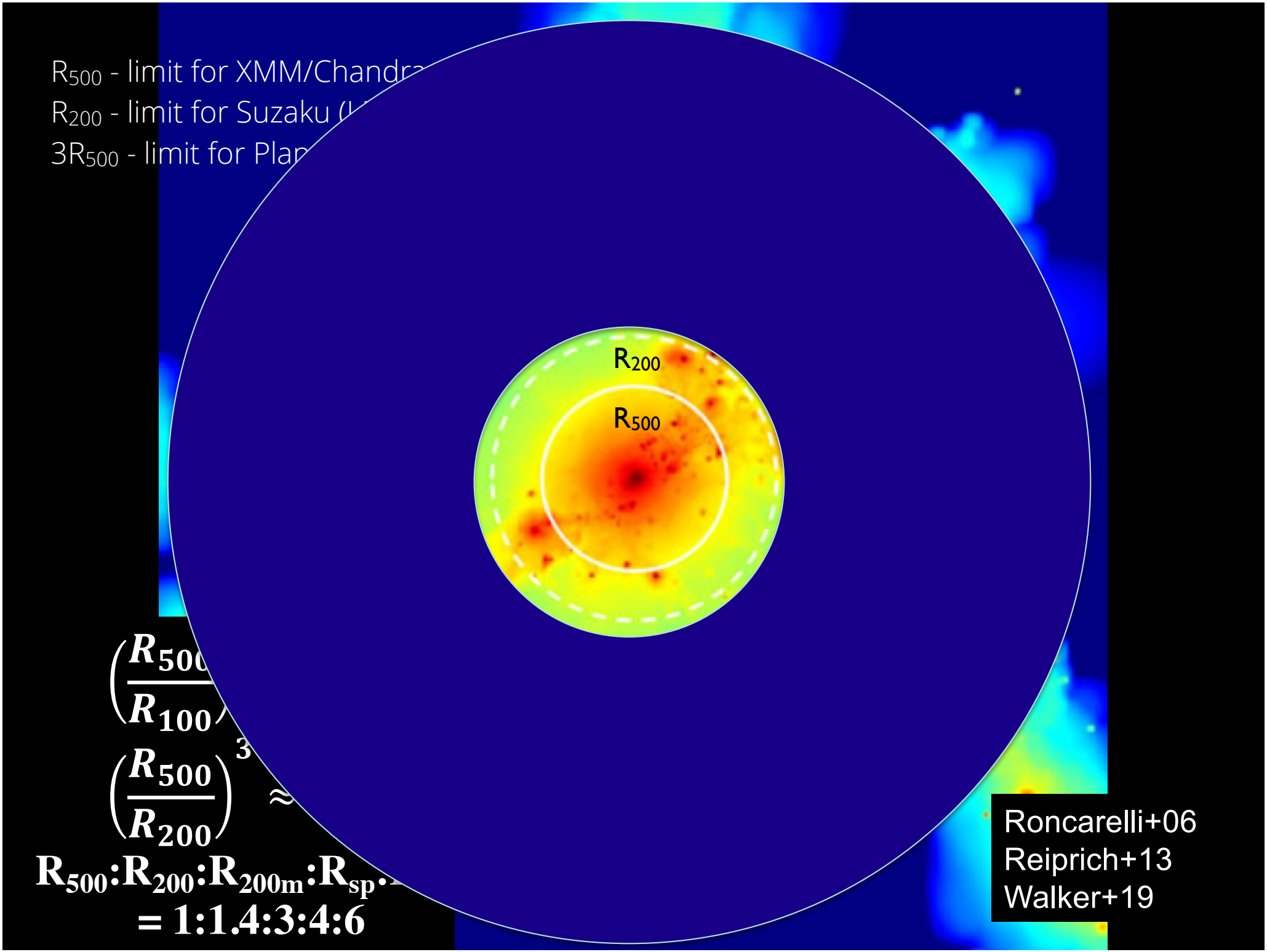
Stefano Ettori
INAF-OAS / INFN Bologna

D. Eckert (Uni Geneve), **V. Ghirardini** (CfA), **M. Sereno** (INAF-OAS Bo),
S. Molendi, E. Pointecouteau, F. Vazza et al.








R_{500} - limit for XMM/Chandra
R_{200} - limit for Suzaku
$3R_{500}$ - limit for Plan
R_{200}
R_{500}
$\left(\frac{R_{500}}{R_{100}}\right)$
$\left(\frac{R_{500}}{R_{200}}\right)^3 \approx$
$R_{500}:R_{200}:R_{200m}:R_{sp}$
$= 1:1.4:3:4:6$
Roncarelli+06
Reiprich+13
Walker+19

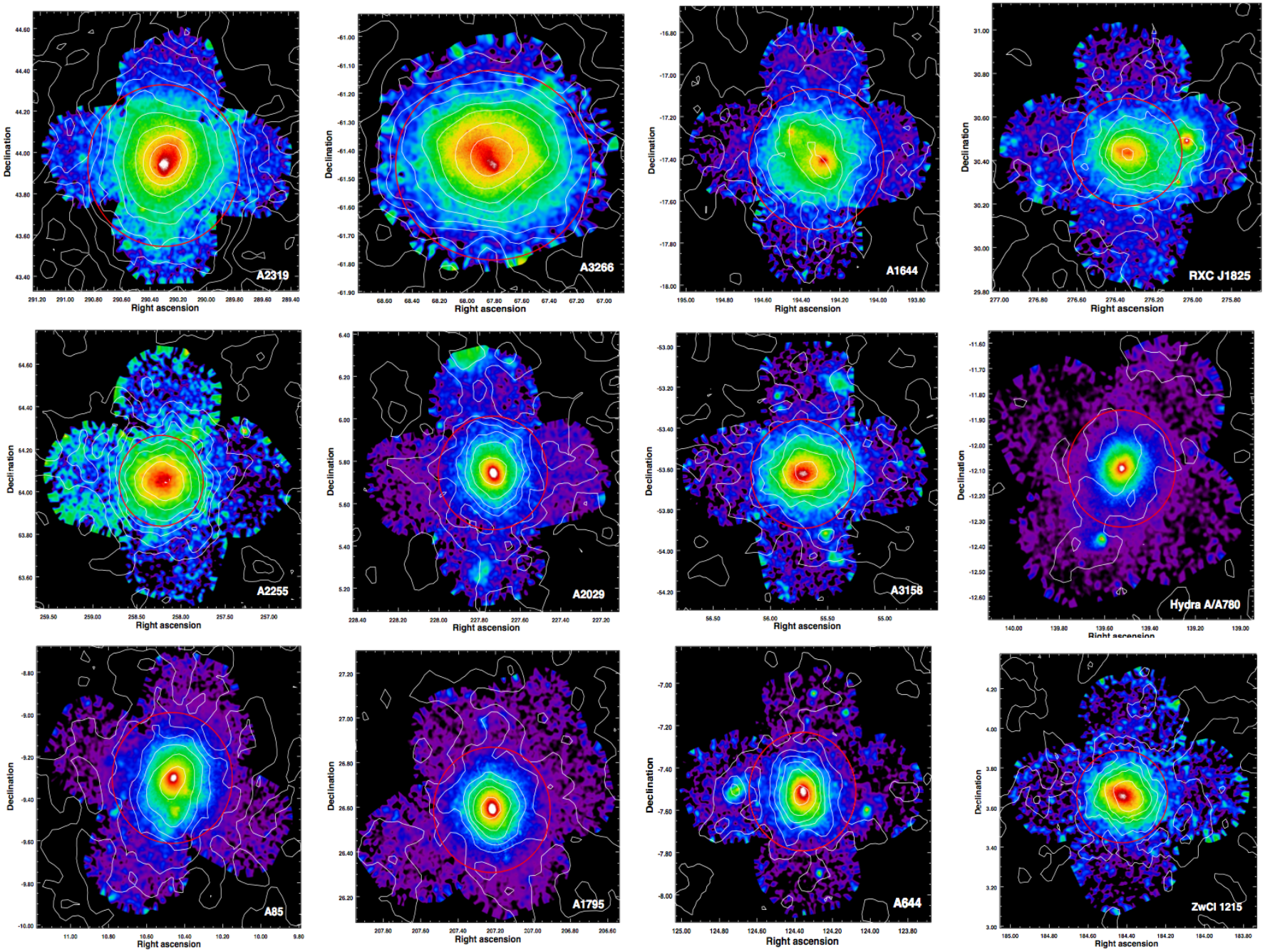
Problems

- Background
- Clumpiness
- Non thermal pressure support

X-COP The XMM Cluster Outskirts Project

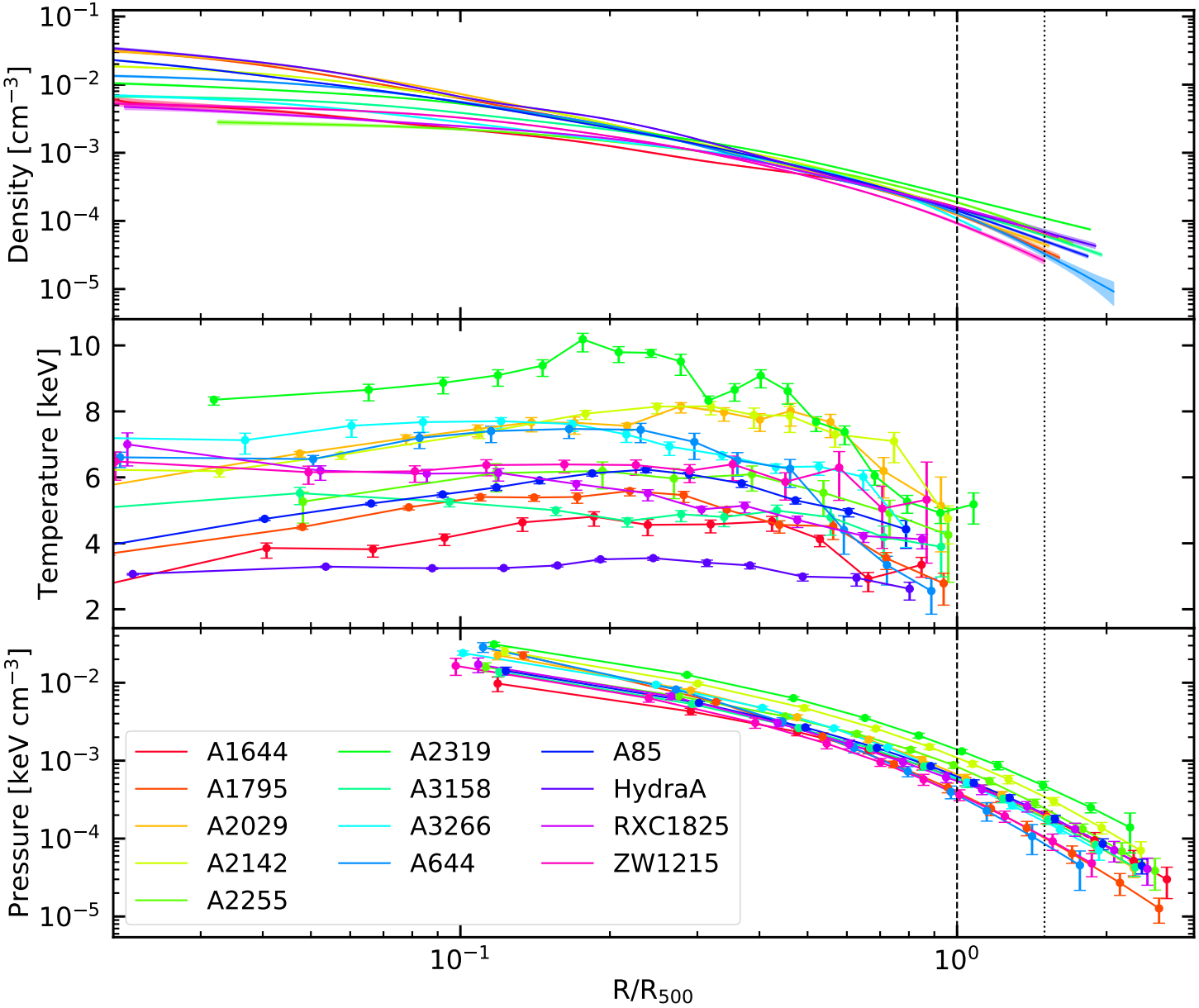
a ***very large program*** (PI: Eckert), approved in *XMM-Newton* AO-13 for a total observing time of 1.2 Msec, that targets the outer regions of a sample of 13 massive clusters ($M_{500} > 3 \times 10^{14}\ M_{\odot}$) in the redshift range 0.04-0.1 at uniform depth. The sample was selected based on the signal-to-noise ratio in the *Planck* Sunyaev-Zeldovich (SZ) survey with the aim of combining high-quality X-ray and SZ constraints throughout the entire cluster volume

X-COP: *XMM +Planck*



X-COP: "universal" profiles

(& scatter; Ghirardini+19 arXiv:1805.00042)



T = P/n

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

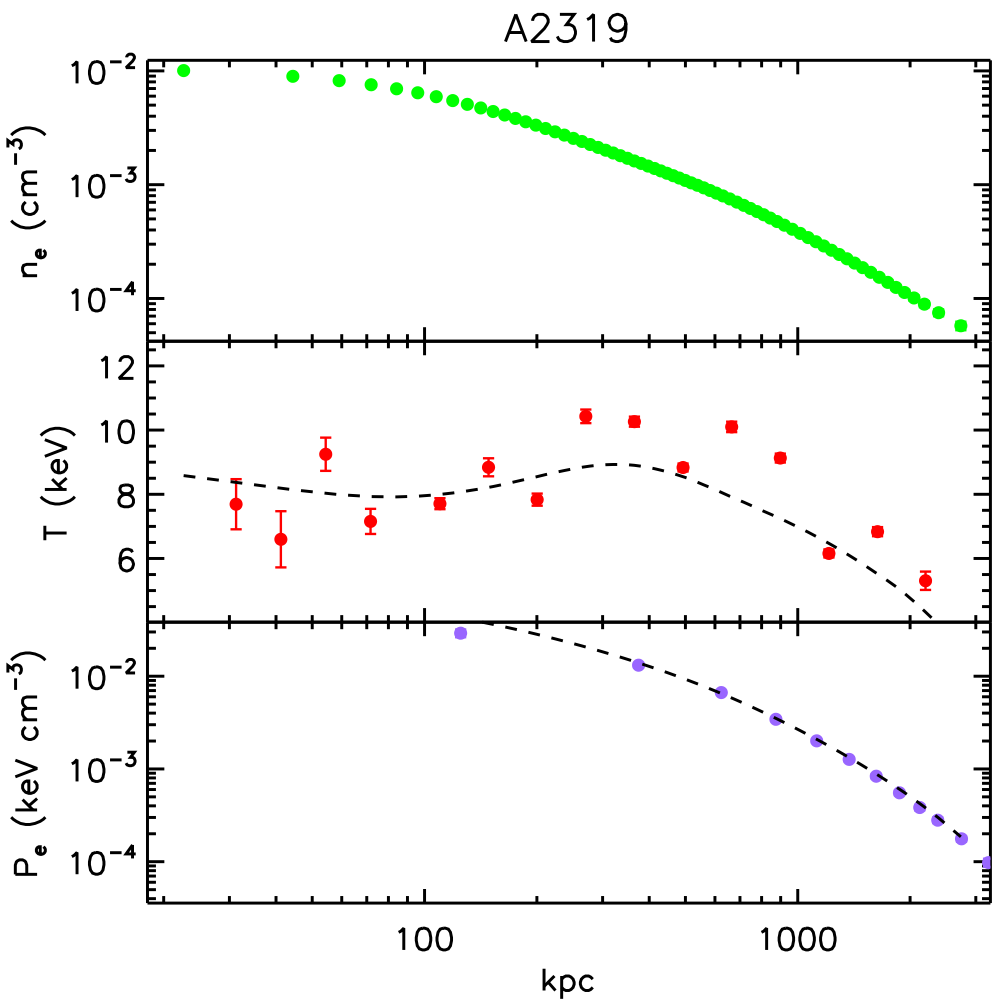
M ~ -r^2/n dP/dr

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

BTW in Ghirardini+19 (tomorrow on arXiv ?!?), we suggest a «better» modelization of **P as log(1+c*x)/x**

X-COP: mass profiles

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



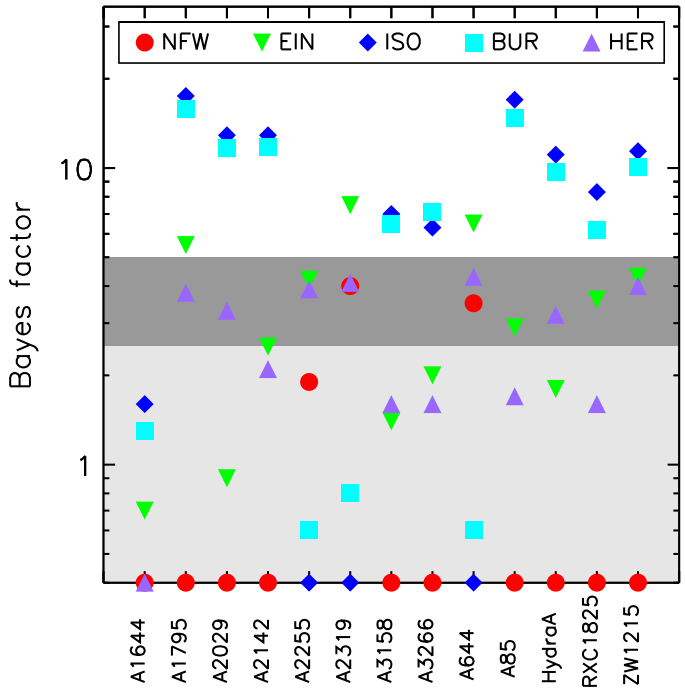
✓ Use of analytic mass models (e.g. NFW, ISO) by fitting T_{XMM} / P_{Planck} with values obtained from inversion of HE

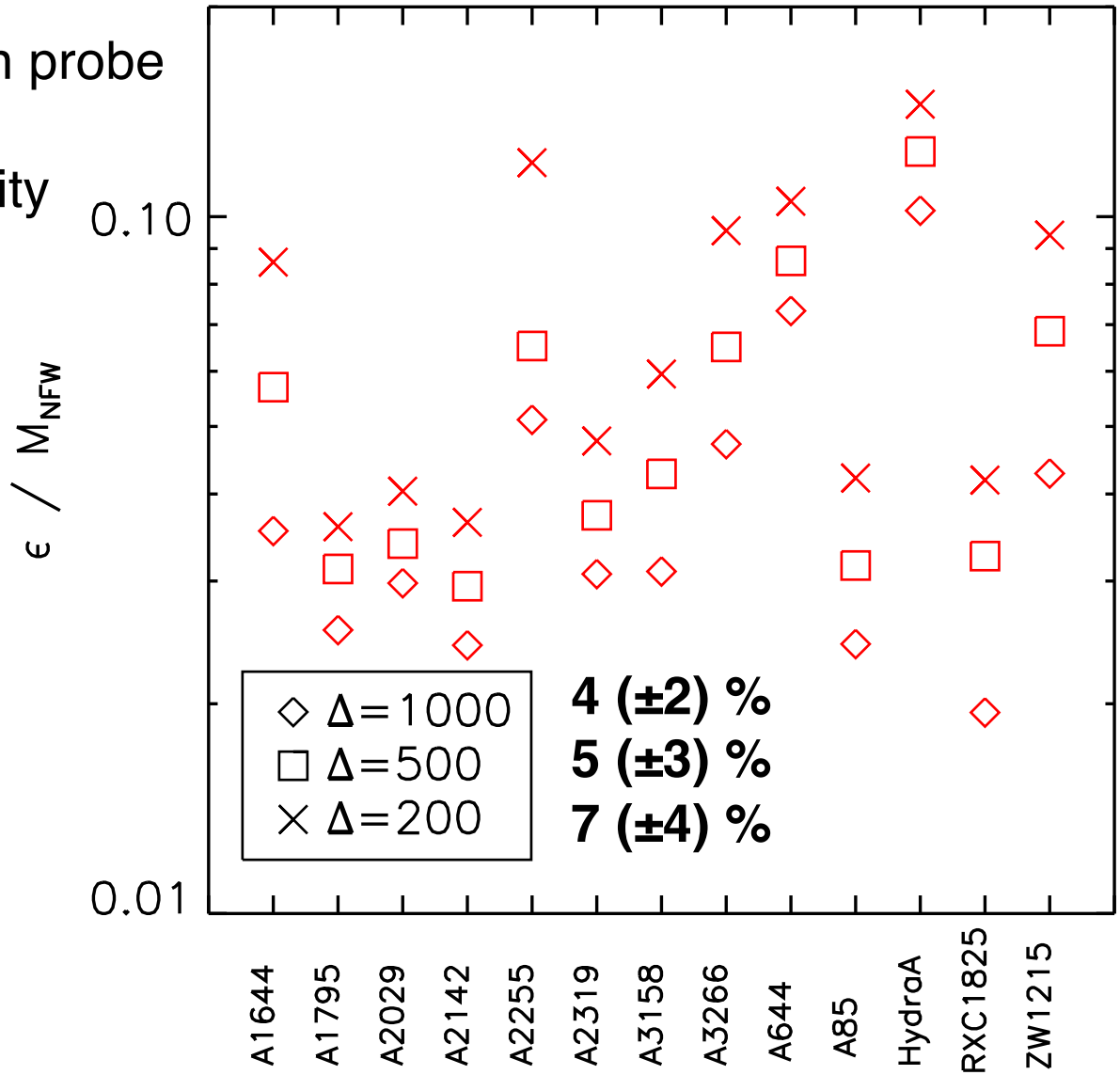
$$\log\mathcal{L} = -0.5\left[(P-P_{model})\Sigma_{tot}^{-1}(P-P_{model})^T + n\log\left(\det\left(\Sigma_{tot}\right)\right)\right]$$
$$-0.5\sum_{i=1}^{n}\left[\frac{(T_i-T_{model,i})^2}{\sigma_{T,i}^2+[\sinh(\sigma_{int})\cdot T_{model,i}]^2} - \log\left(\frac{1}{\sigma_{T,i}^2+[\sinh(\sigma_{int})\cdot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

X-COP: mass profiles

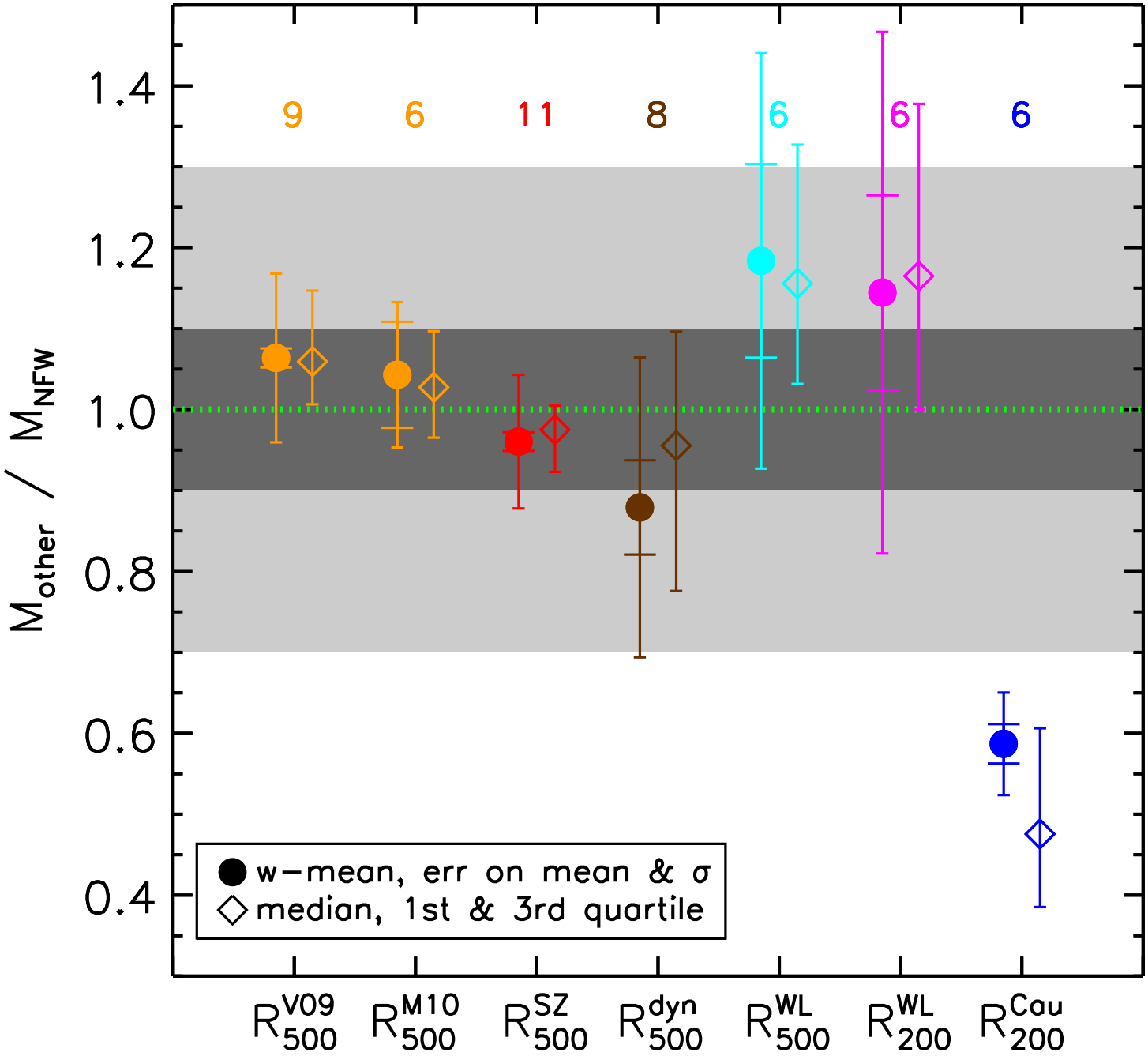
(Ettori+19 arXiv:1805.00035)

Statistic is so good that we can probe
- different mass models
- some theories of Mod Gravity



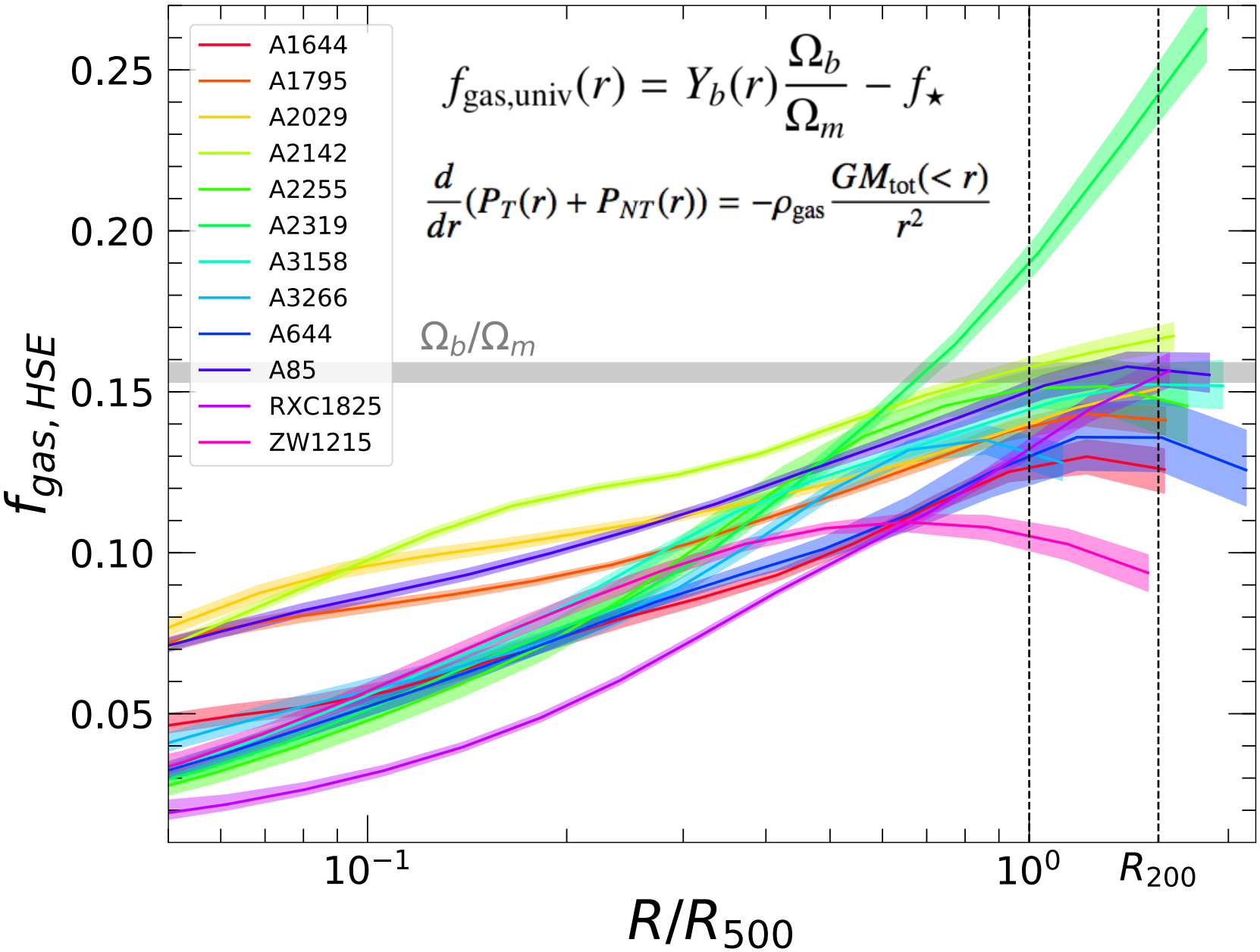


X-COP: mass profiles



X-COP: non-thermal P

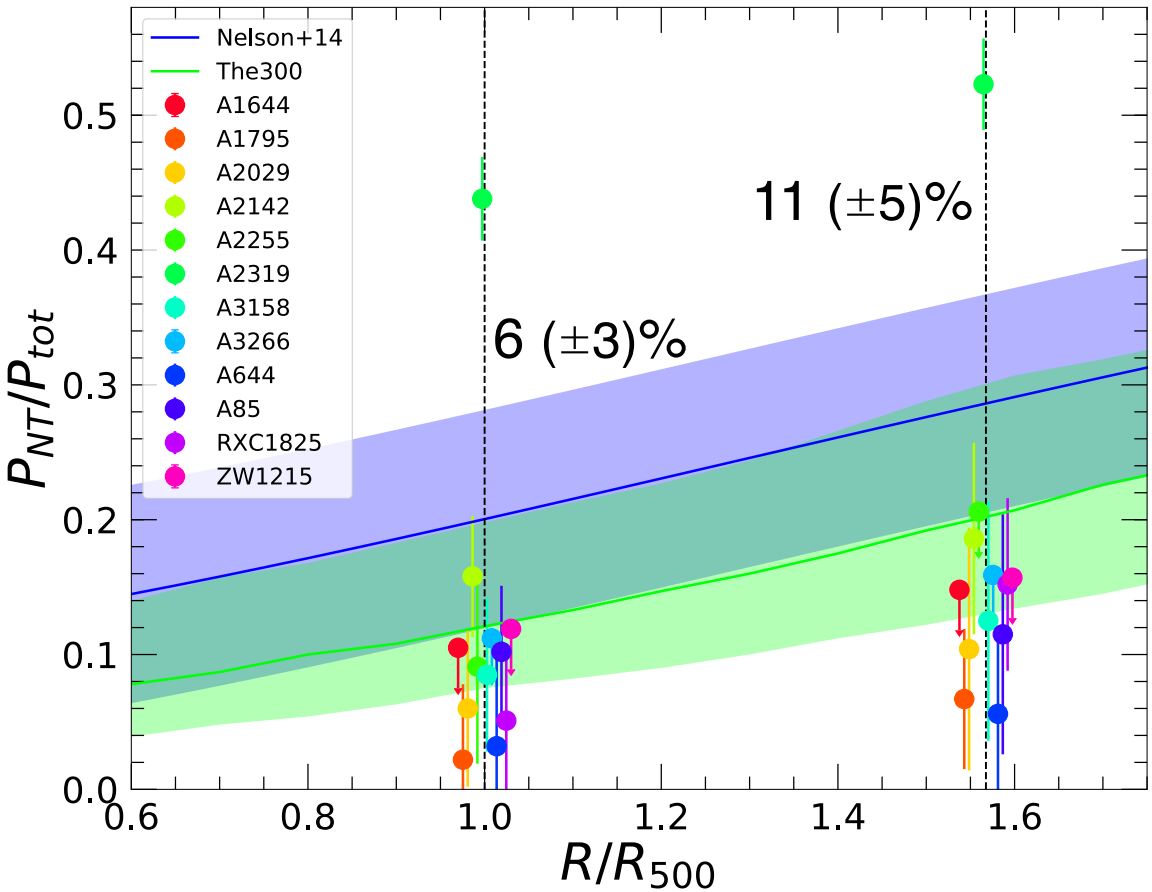
(Eckert+19 arXiv:1805.00034)



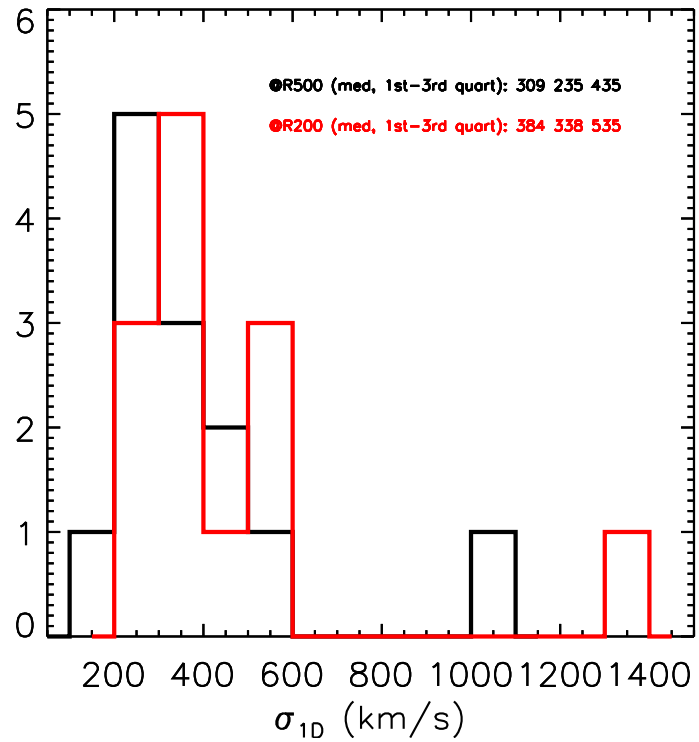
X-COP: non-thermal P

(Eckert+19 arXiv:1805.00034)

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



$$\alpha = \frac{P_{NT}}{P_{tot}} = \frac{\sigma_{1D}^2}{\sigma_{1D}^2 + kT/\mu m_p}$$



An XMM-Newton Heritage Program

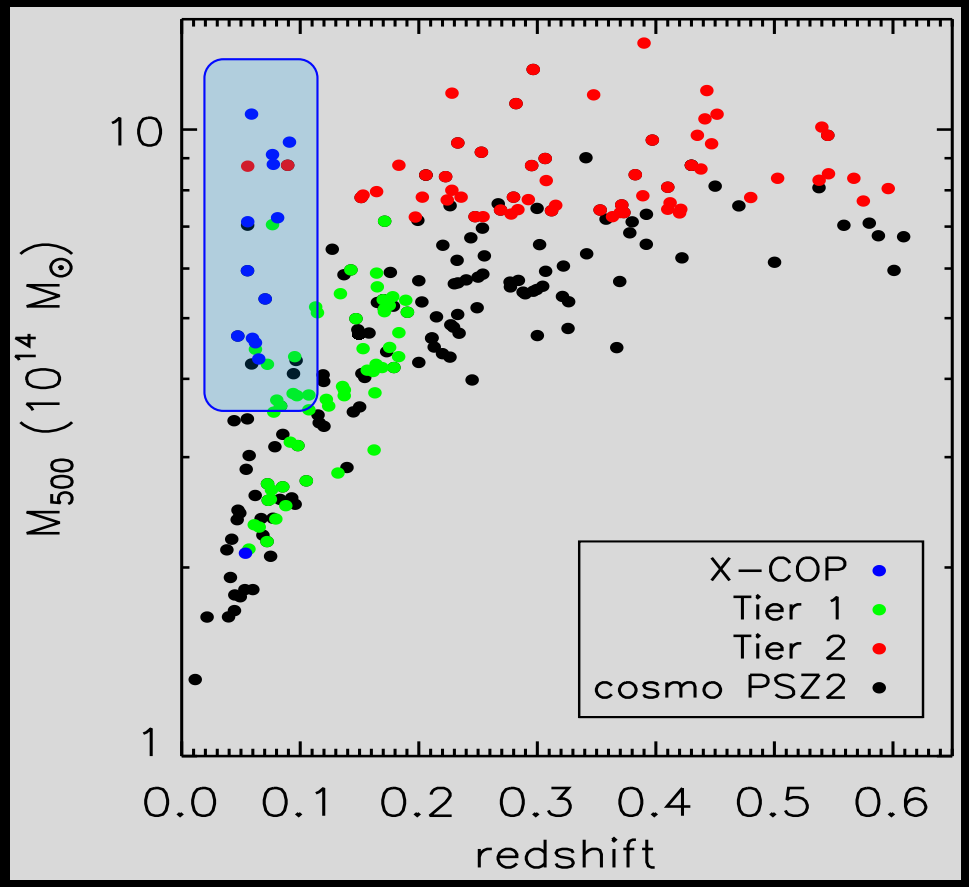
Witnessing the culmination of structure formation in the Universe

(PI: M. Arnaud & S. Ettori)

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

URL: xmm-heritage.oas.inaf.it

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

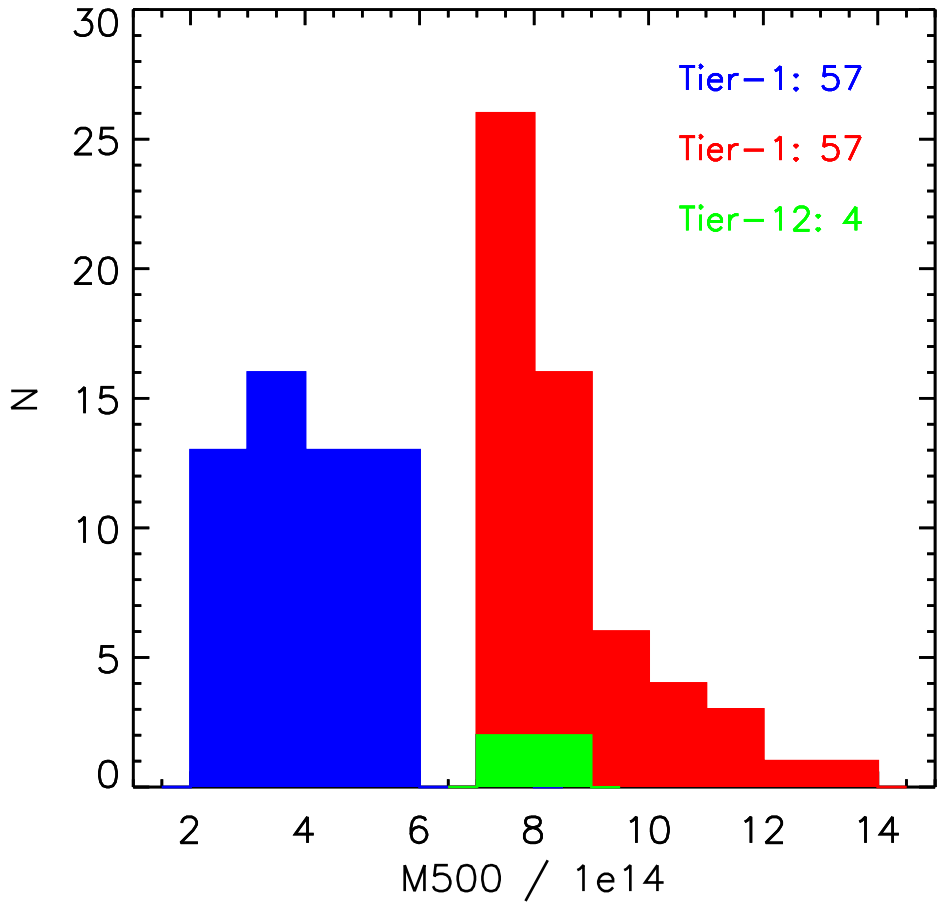
WG-radio (*chair:* ***Bonafede & Cassano***): Vazza; Venturi

Targets of the Heritage Project

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

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

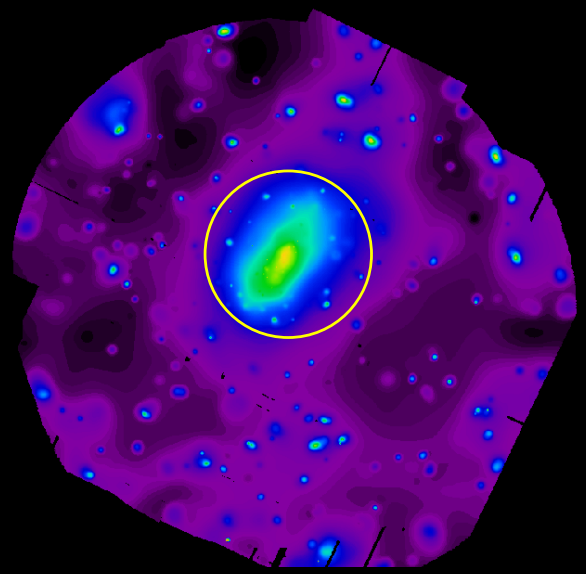
- Assess the relative importance of gravitational and non-gravitational processes in shaping cluster properties
- Probe the dynamical collapse of the gas on different scales
- Construct a consistent picture of cluster mass estimates
- Provide a unique reference for evolution studies and numerical modelling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



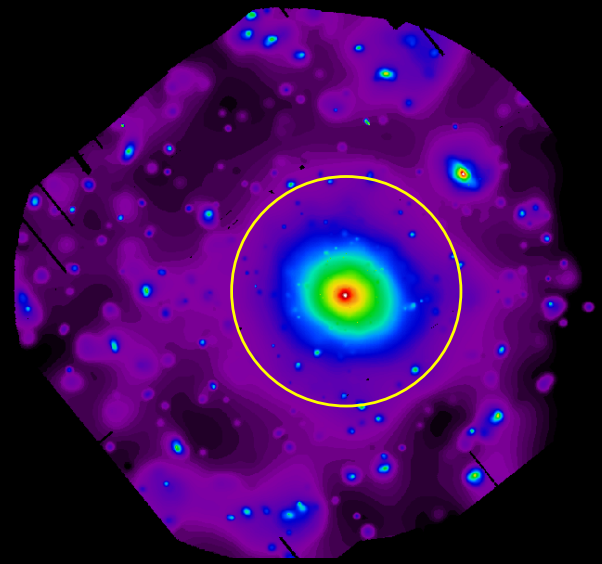
The XMM-Newton Heritage Project

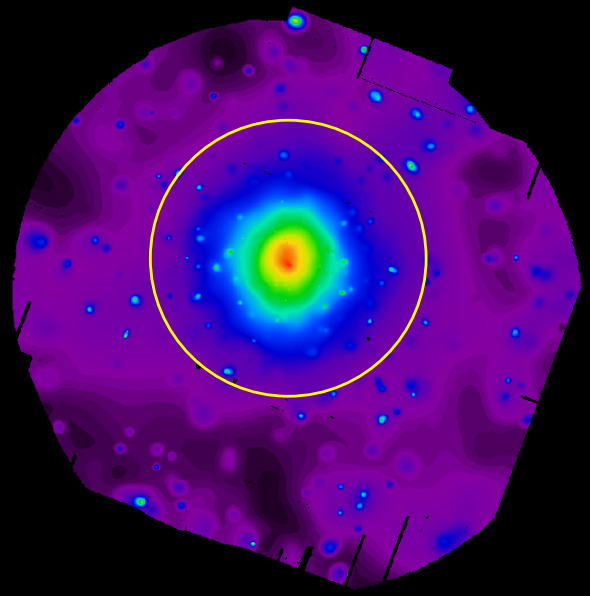
PSZ2G008, **z=0.312**, M_{500}=7.4e14

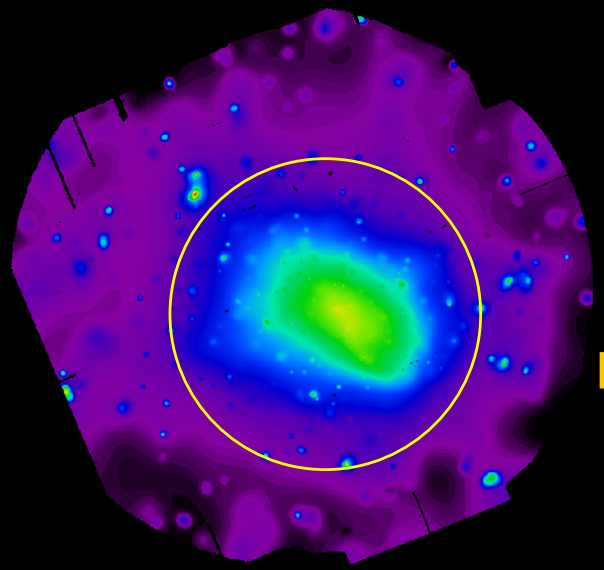
PSZ2G066, **z=0.163**, M_{500}=3.8e14



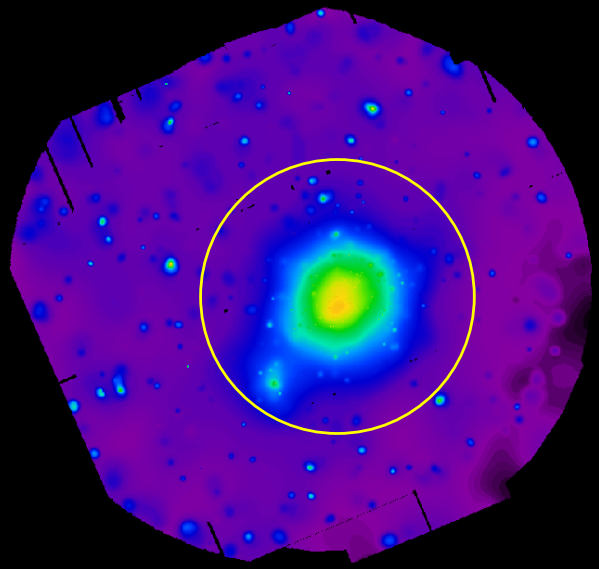
Statistical error (1 σ) on M_{500}~20%







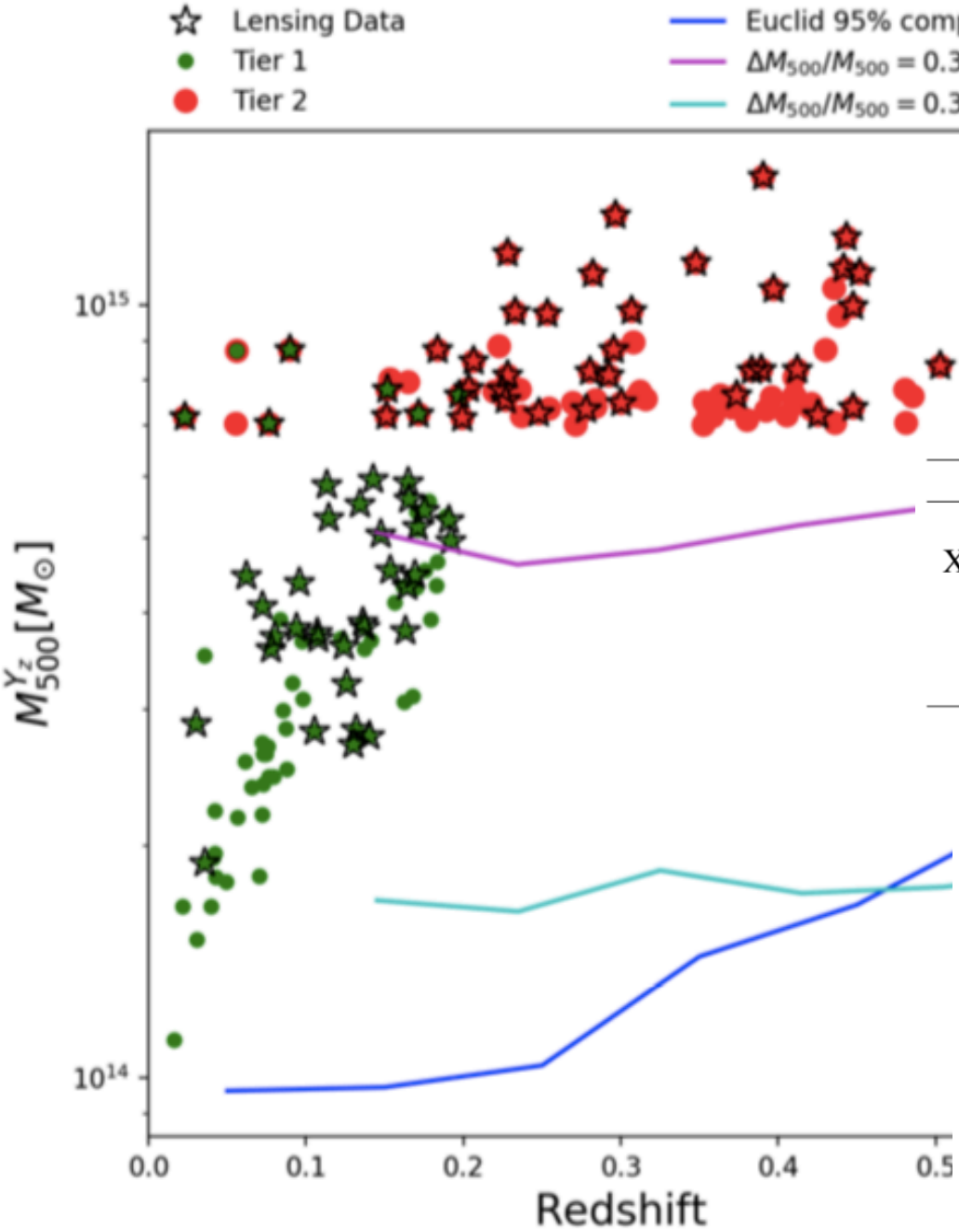
PSZ2G077, **z=0.147**, M_{500}=5e14



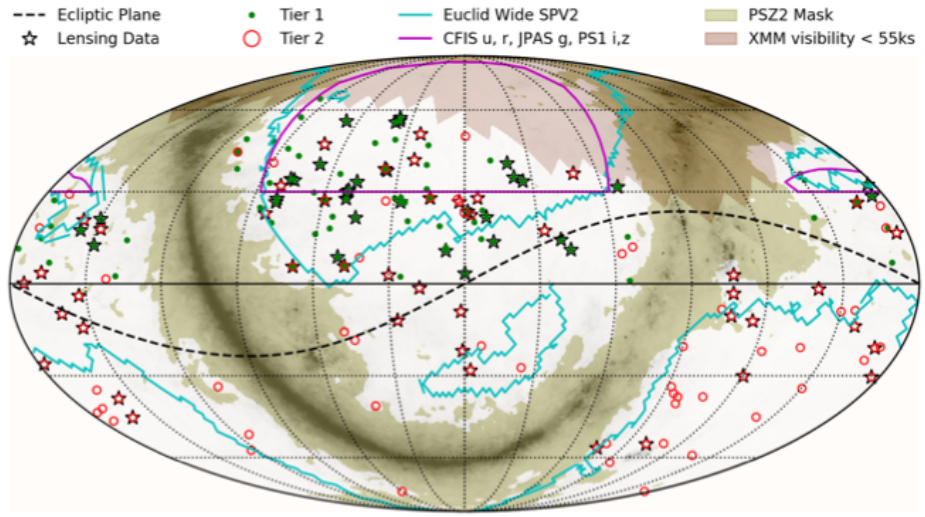
PSZ2G273, **z=0.134**, M_{500}=5.5e14

PSZ2G285, **z=0.165**, M_{500}=6.5e14

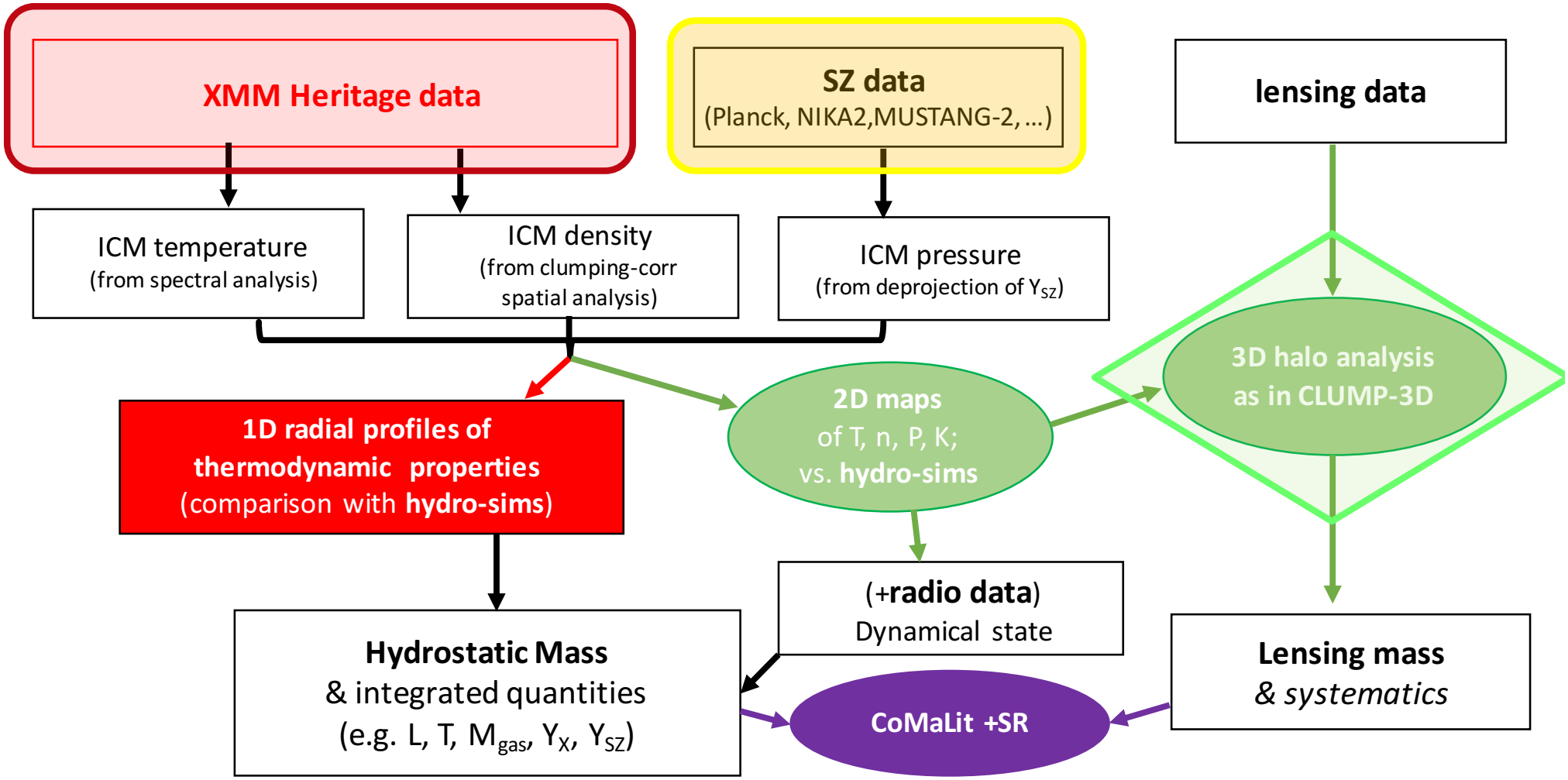
Targets of the Heritage Project

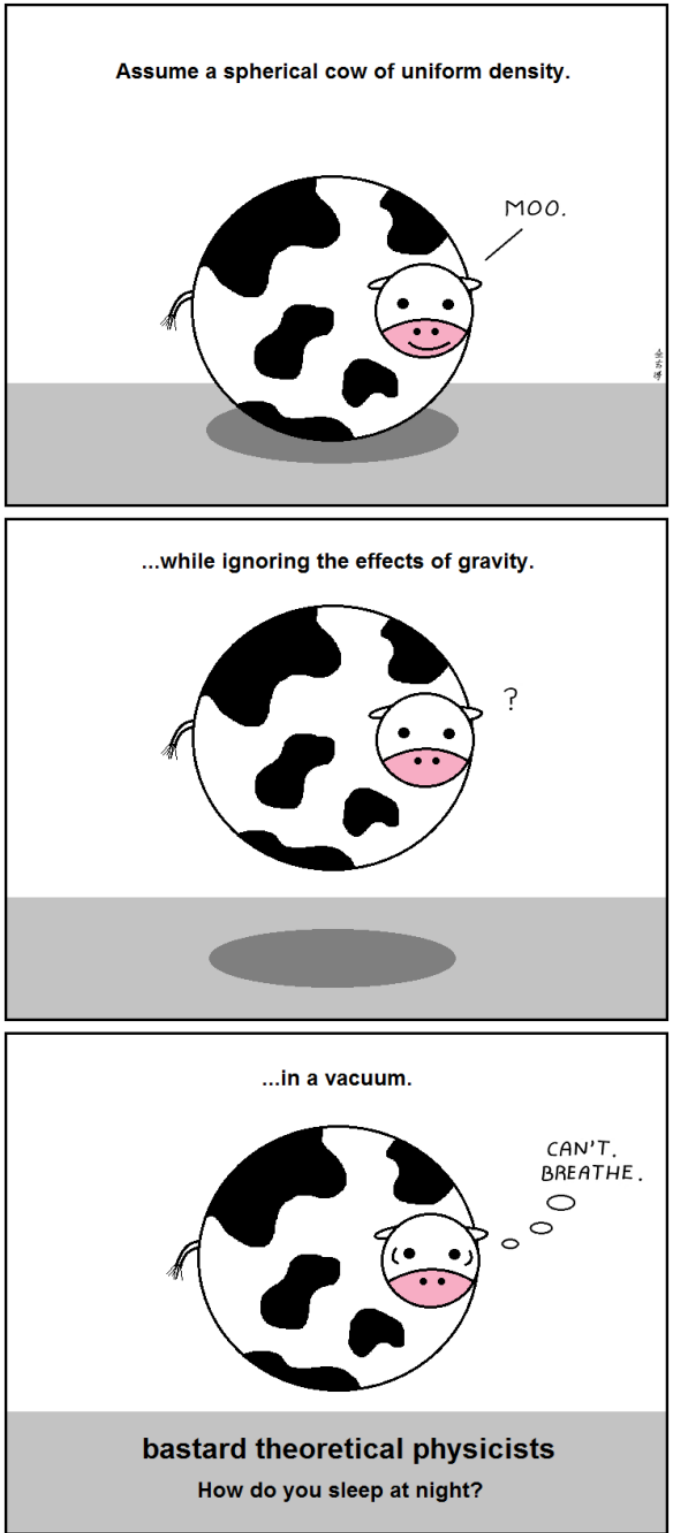


	tot	archive	1st-yr	2nd-yr	3rd-yr
X-ray	118	38	30 (68)	27 (95)	23 (118)
XMM time (ksec)	5304	2304	1000	1000	1000
WL-only	–	79	7 (86)	16 (102)	16 (118)
WL+X	–	33	20 (53)	27 (80)	38 (118)

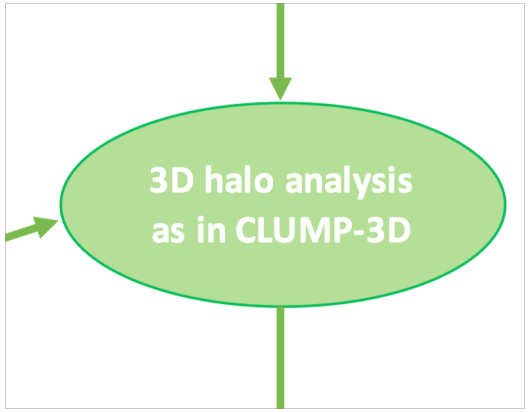


Flowchart of (possible) analysis





3D halo analysis: making a *cow not spherical*



Shape & orientation of gas & total mass distrib

(Sereno, Ettori & Baldi … **1109.2732 X+SZ →**
Sereno & Umetsu … **1105.4994: W+S le**
Sereno, Ettori et al. **1210.3359: joint**

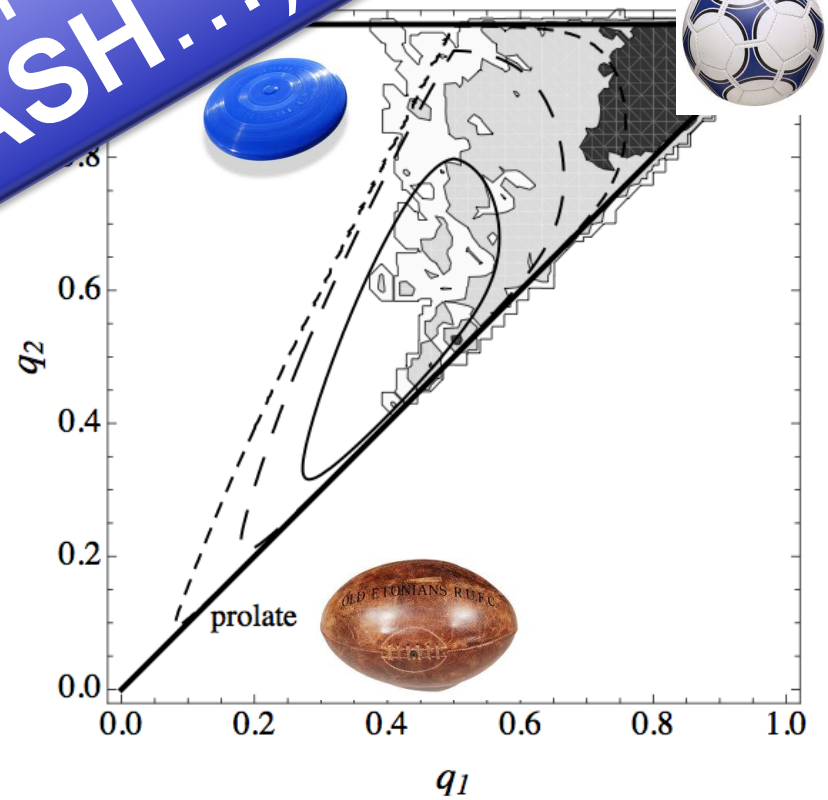
Method: the distributions of total
are approximately ellipsoid
they have different, co
share the same d

- *Weak and*
  featu

ntation of
ky
es the elongation of
ne of sight
Th s are deprojected thanks to
Bay erence.

BUT … possible for only few objetcs with enough high-quality data (before CLASH…)

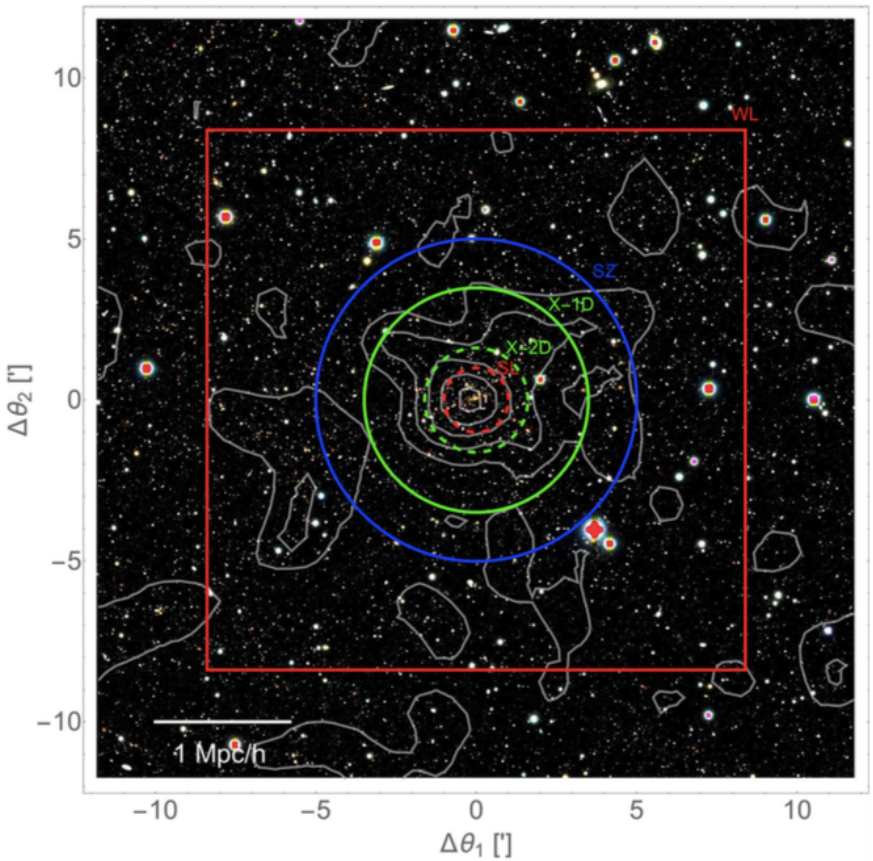
1689

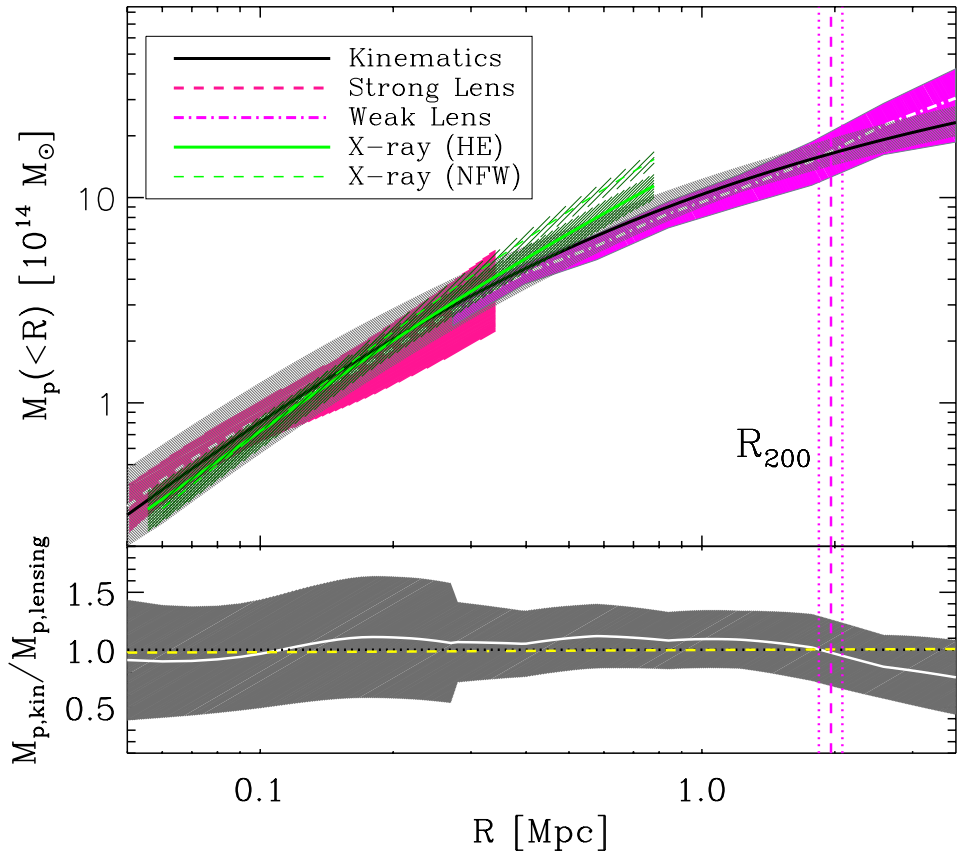


MACS1206 (M_{200}~$10^{15}M_{\odot}$, z=0.439)

Sereno, Ettori et al. 2017 arXiv:1702.00795

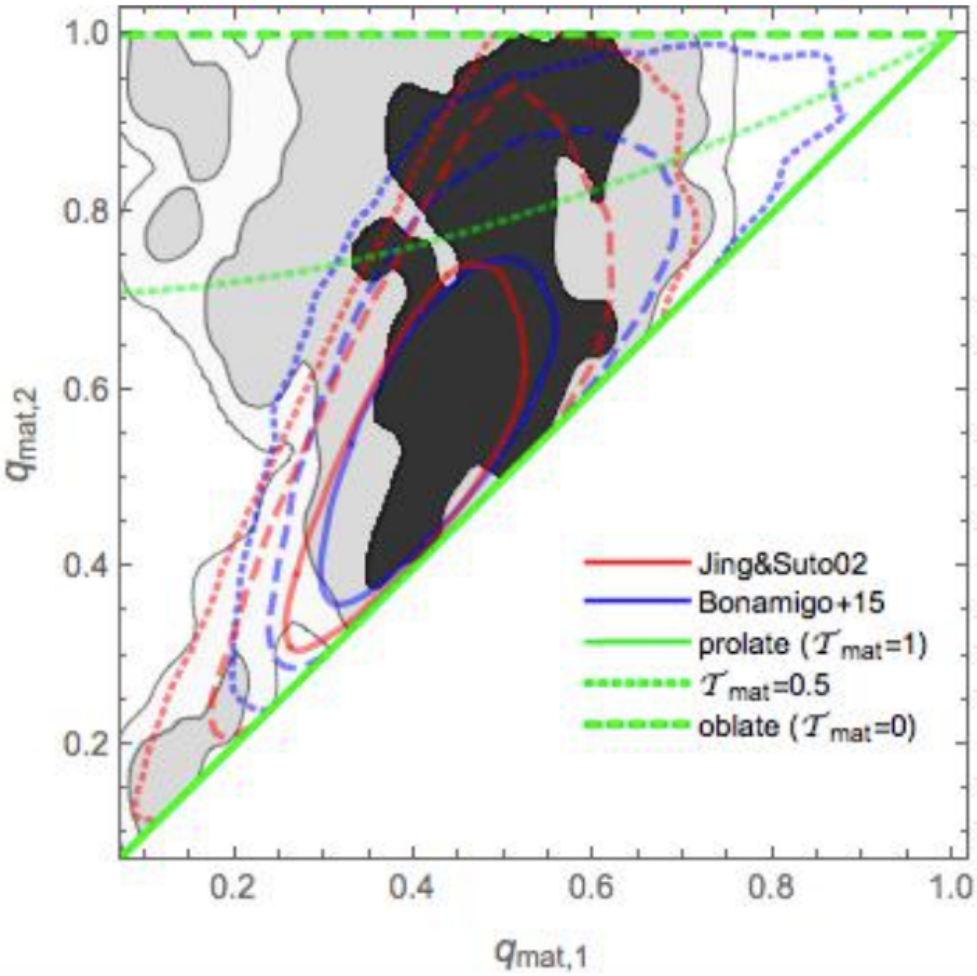
We started the ***CLUster Multi-Probes in Three Dimensions (CLUMP-3D)*** project to get the unbiased intrinsic properties (i.e with no assumption of *spherical symmetry or HE)* by exploiting rich datasets ranging from X-ray, to optical, to radio λ

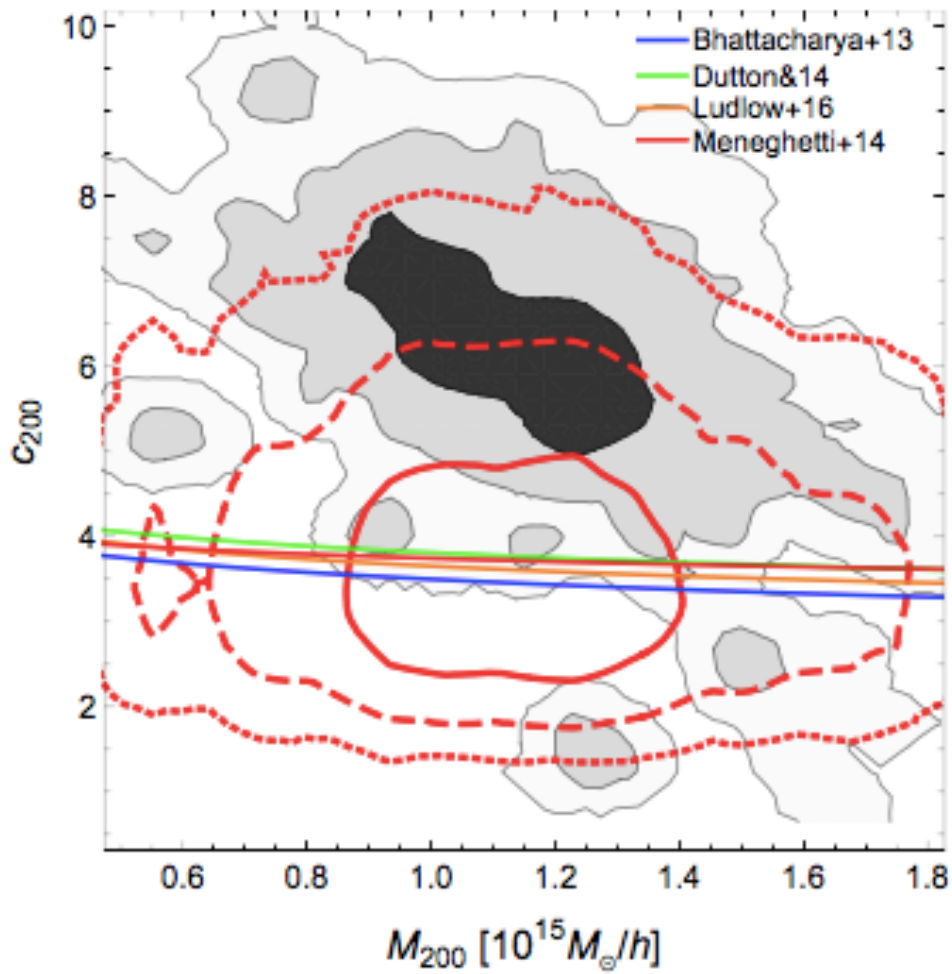




MACS1206 (M_{200}~$10^{15}M_{\odot}$, z=0.439)

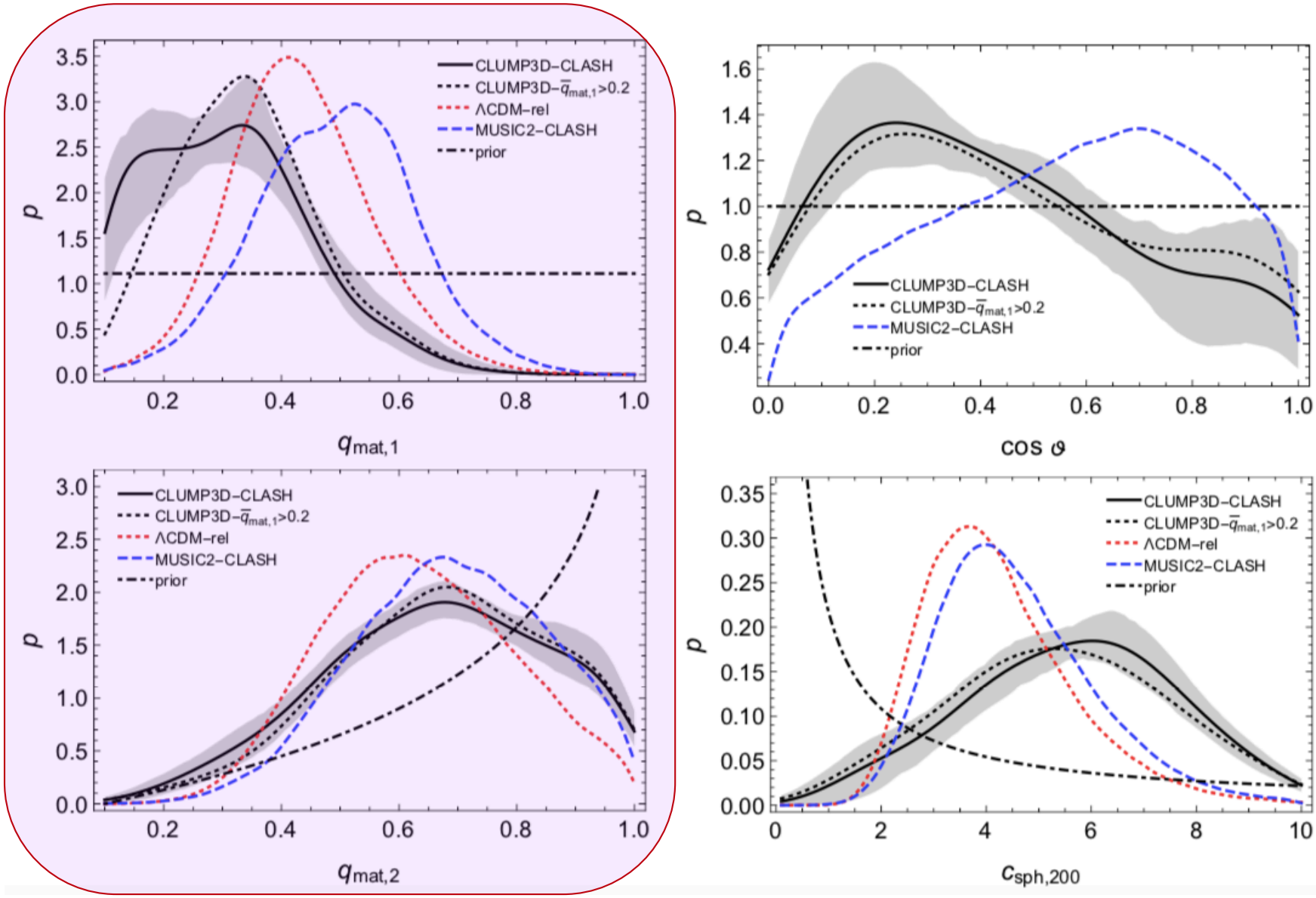
Sereno, Ettori et al. 2017 arXiv:1702.00795





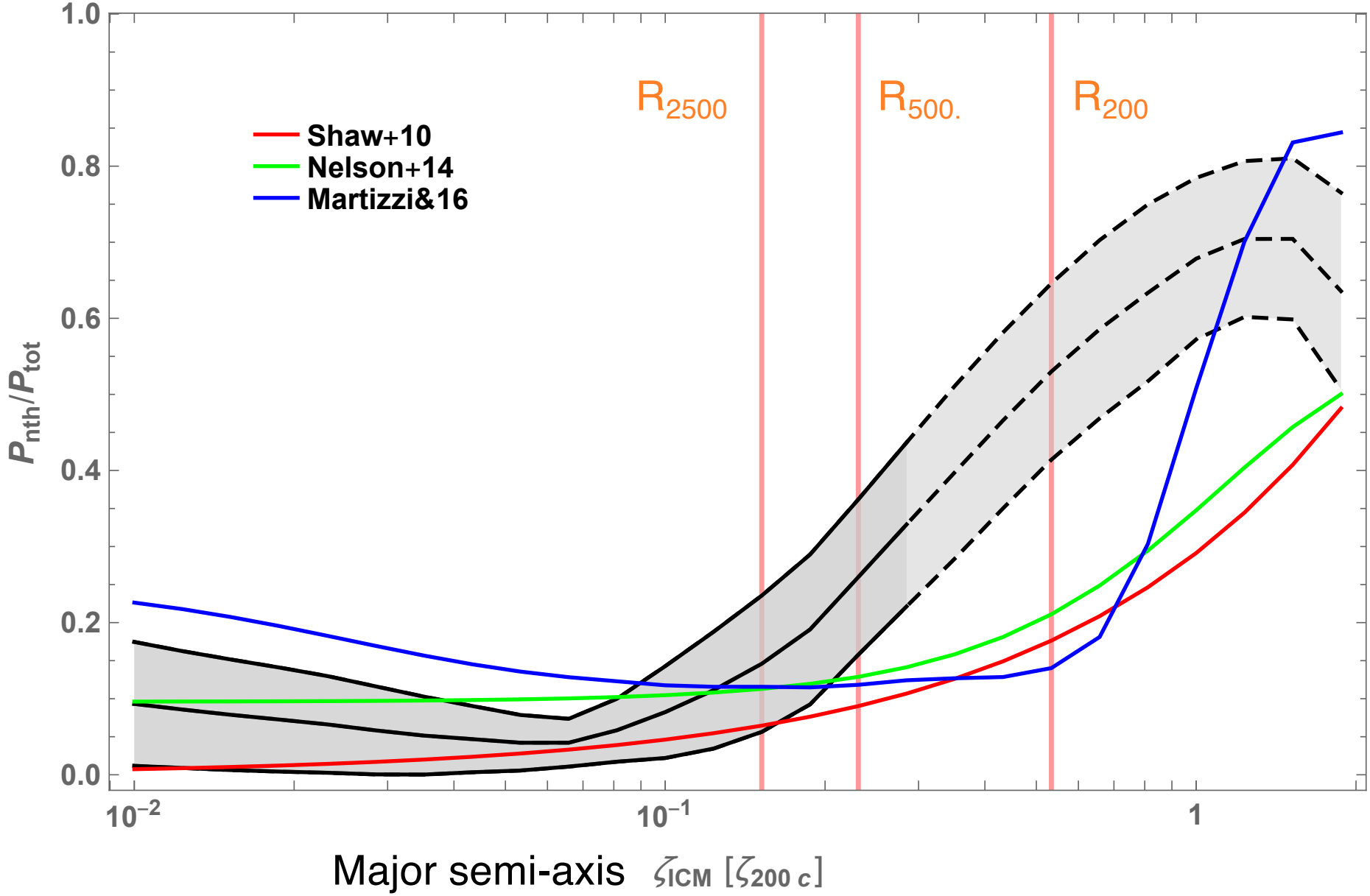
CLUMP-3D on CLASH objects

Umetsu+18 arXiv:1804:00664, Chiu+18 arXiv:1804:00676, Sereno+18 arXiv:1804.00667



CLUMP-3D on CLASH objects

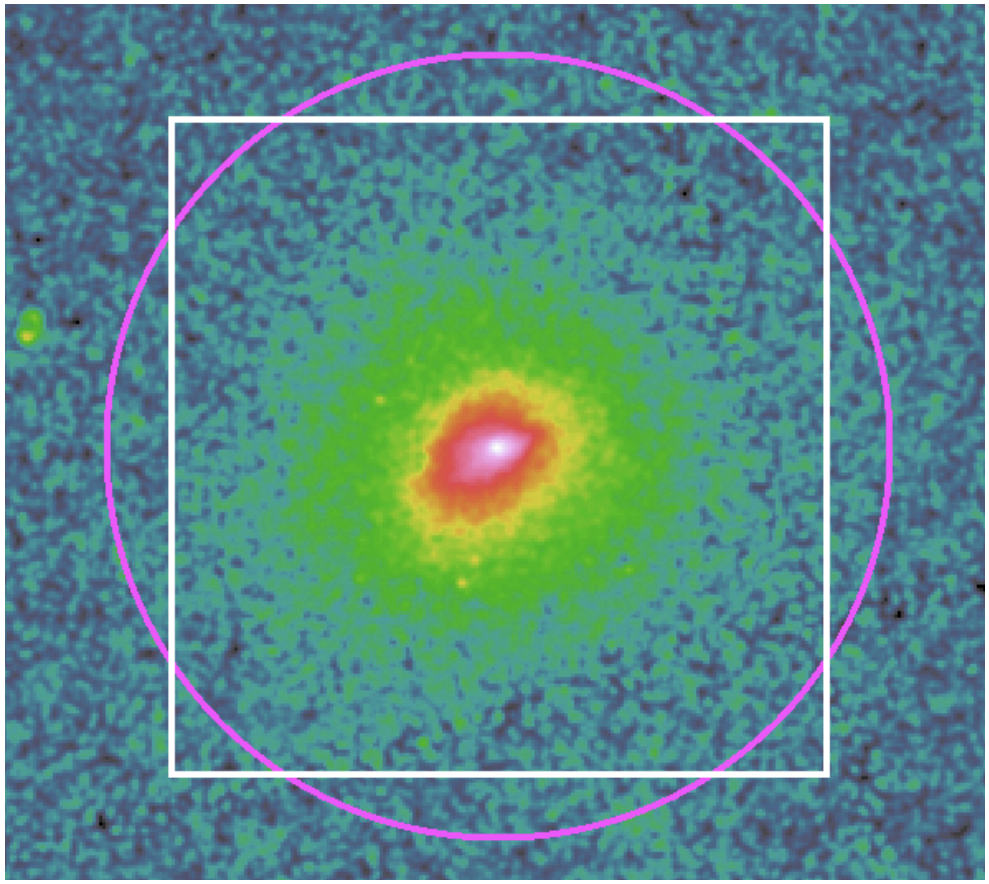
Sereno, Ettori+ in prep.

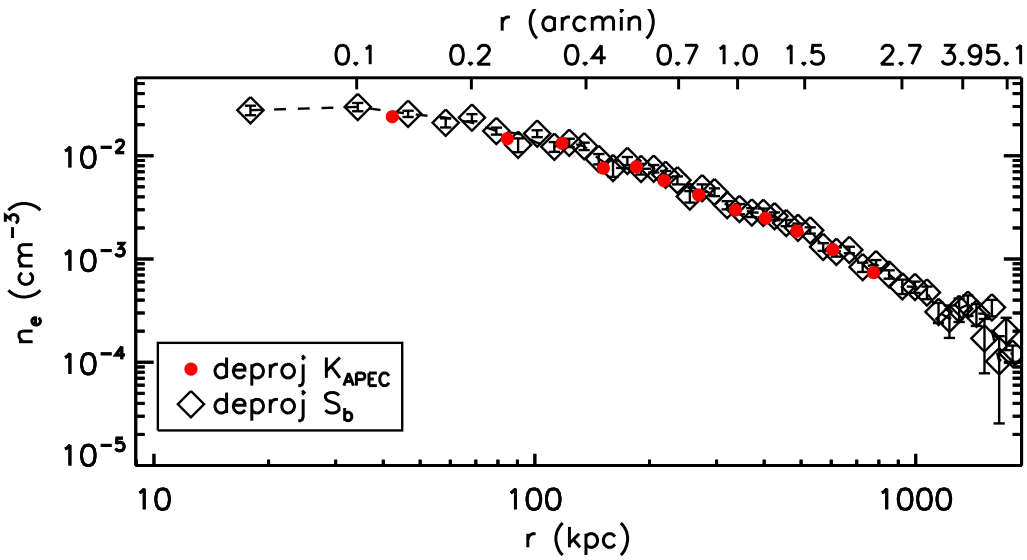


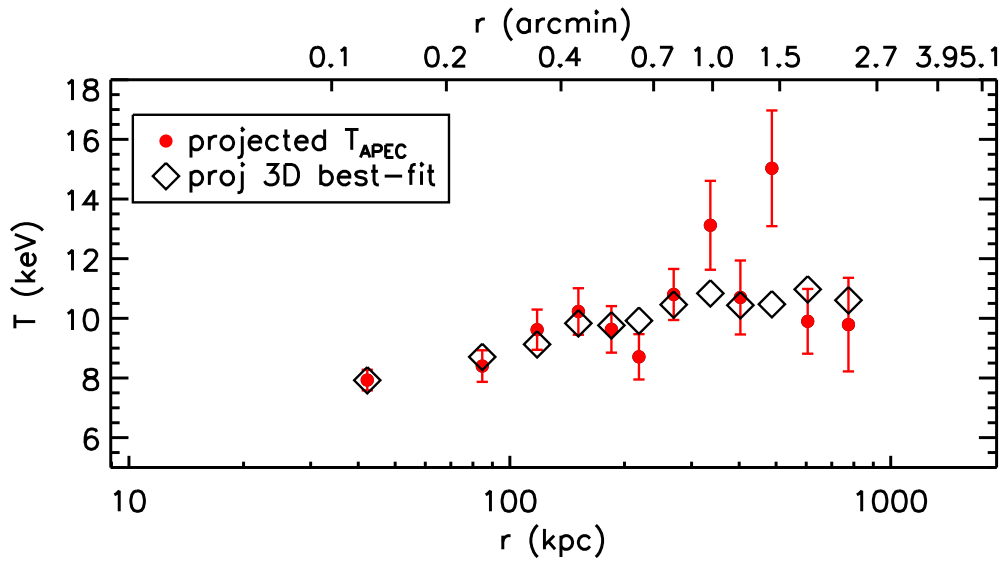
MACS1206

new 180 ksec Chandra in AO19

(last 42 ksec on June 1st)

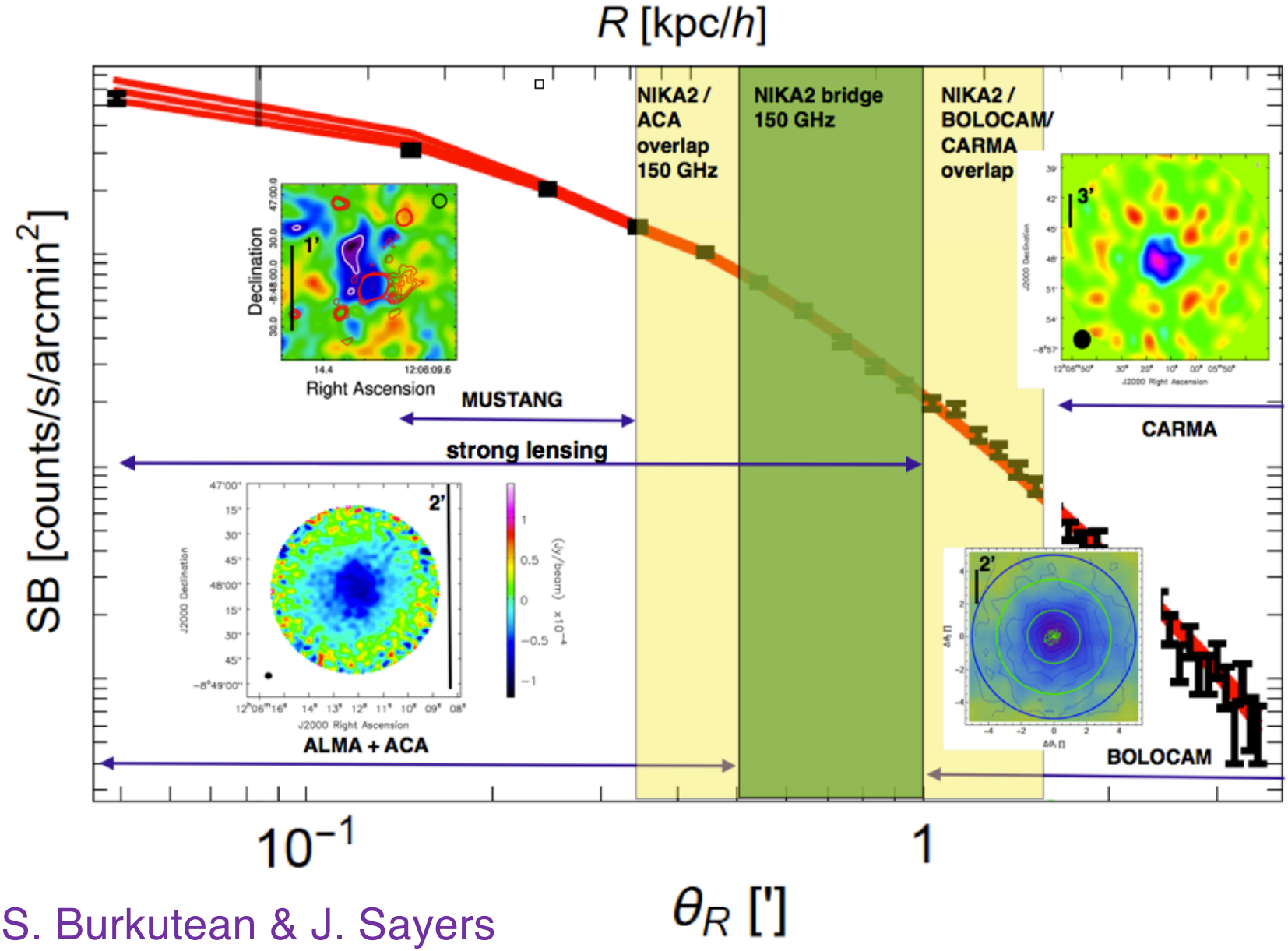






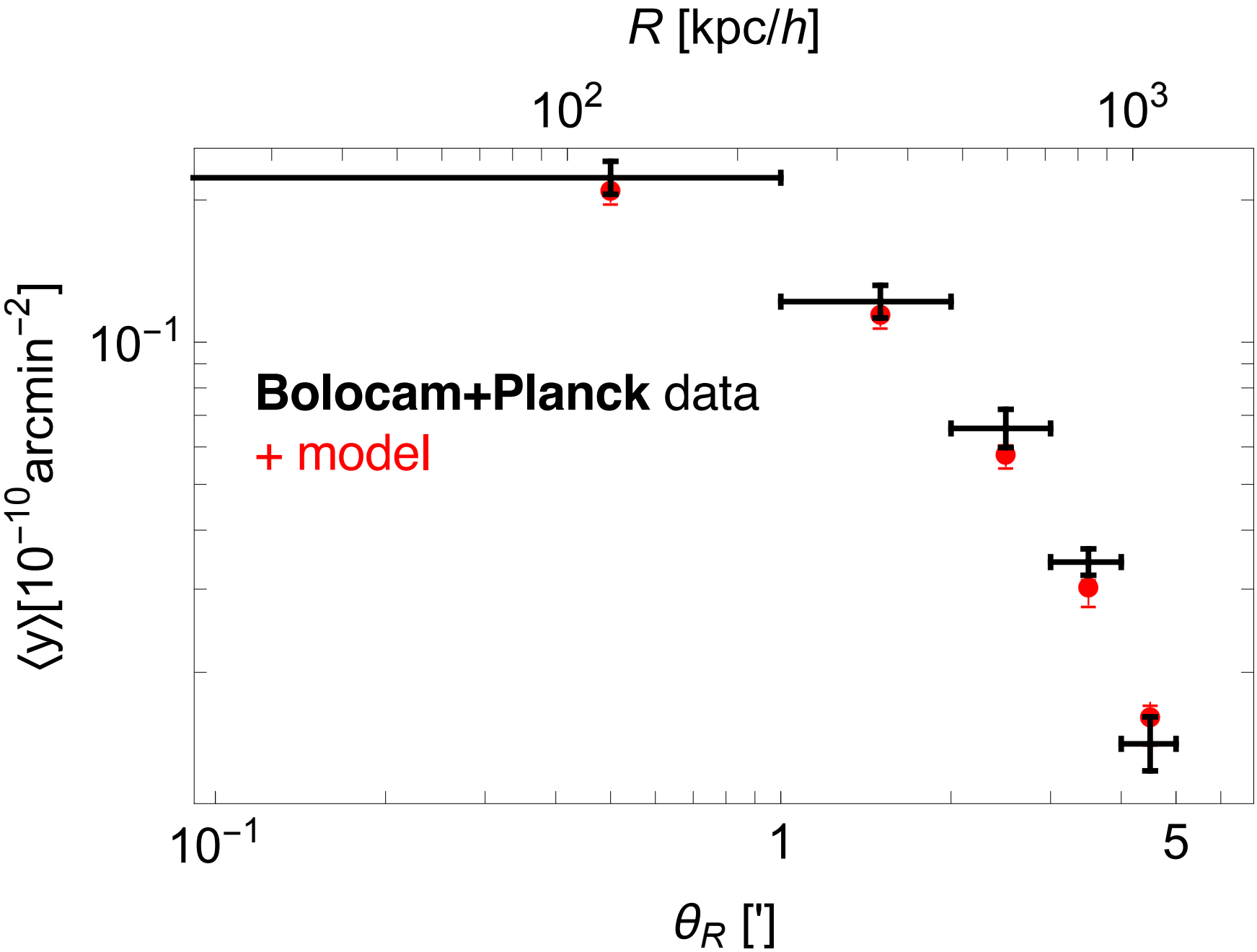
MACS1206

+14hrs ALMA/ACA & 19hrs NIKA2/IRAM

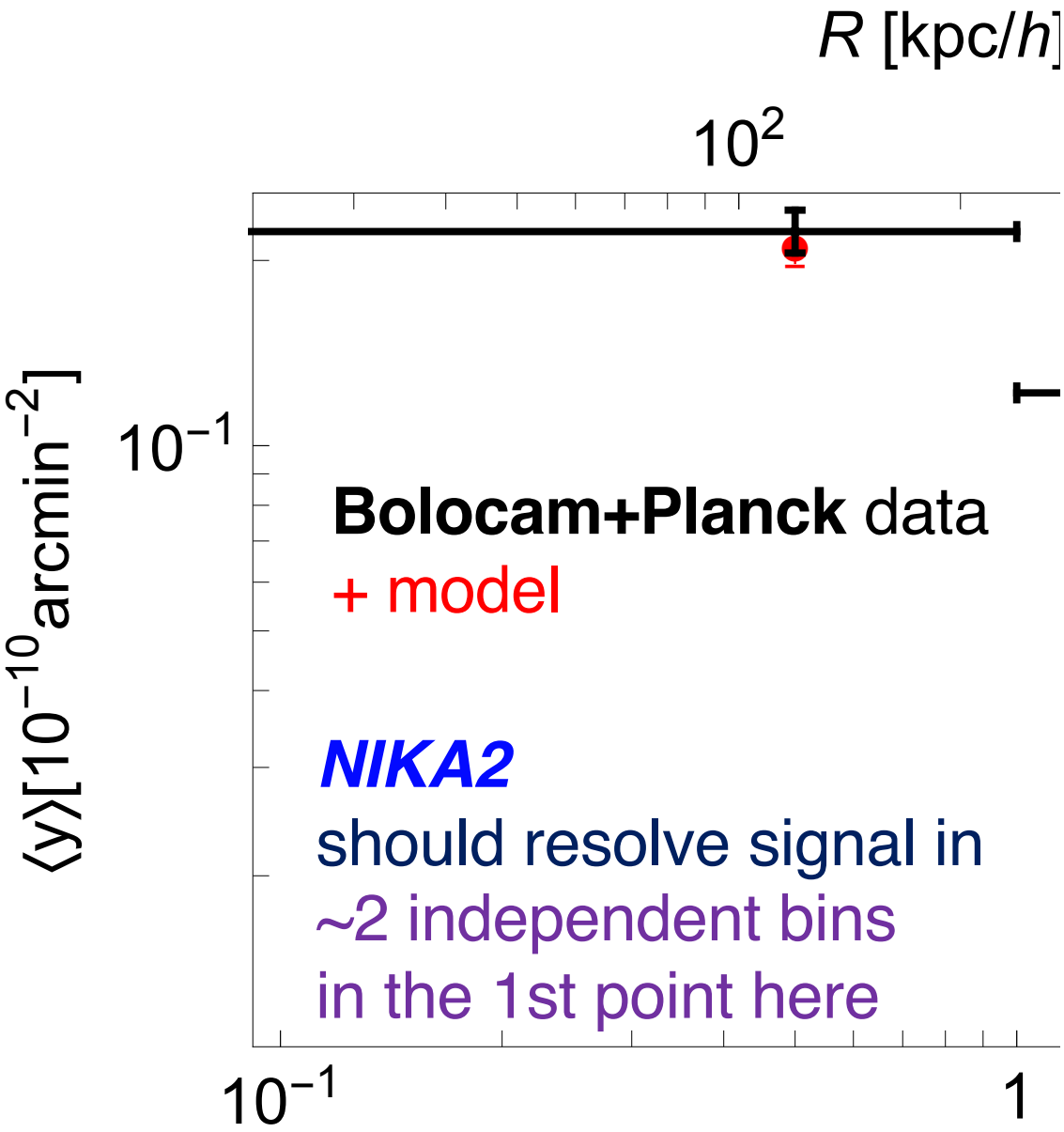


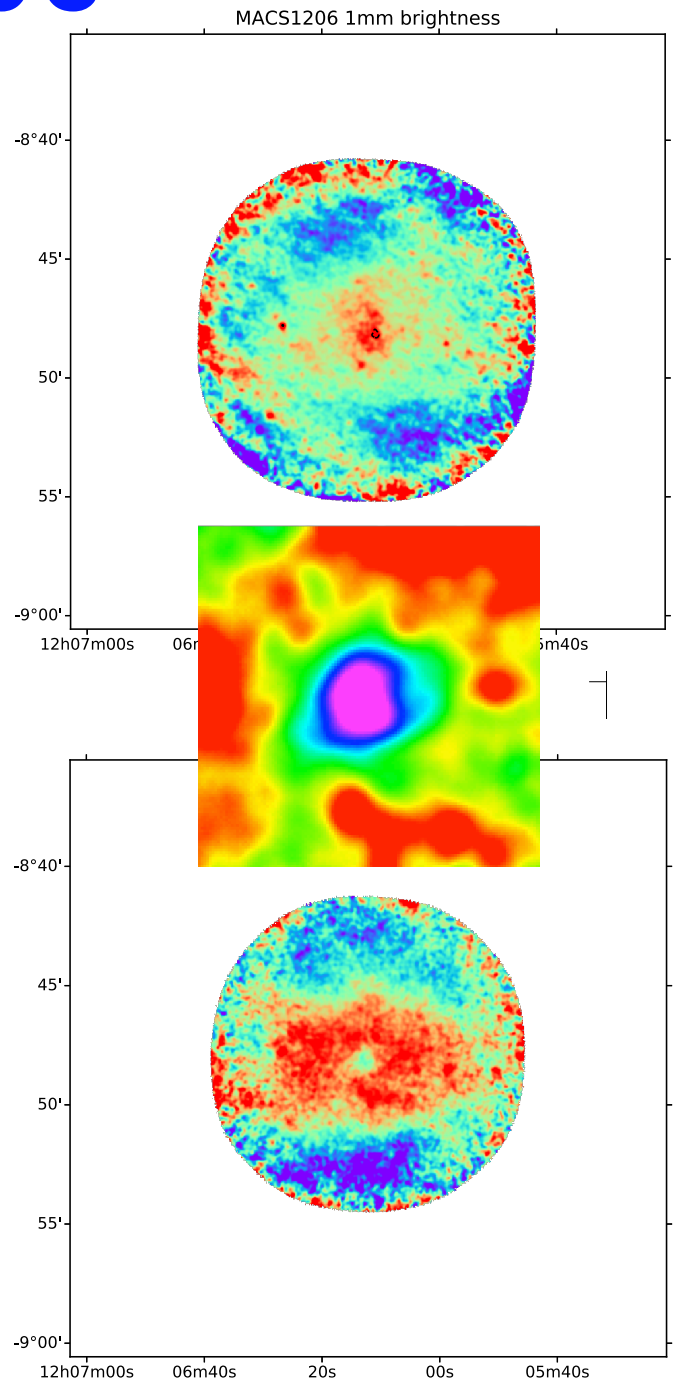
With S. Burkutean & J. Sayers

MACS1206


R [kpc/h]
10^2
10^3
10^-1
⟨y⟩[10^-10 arcmin^-2]
Bolocam+Planck data
+ model
10^-1
1
5
θ_R ['']

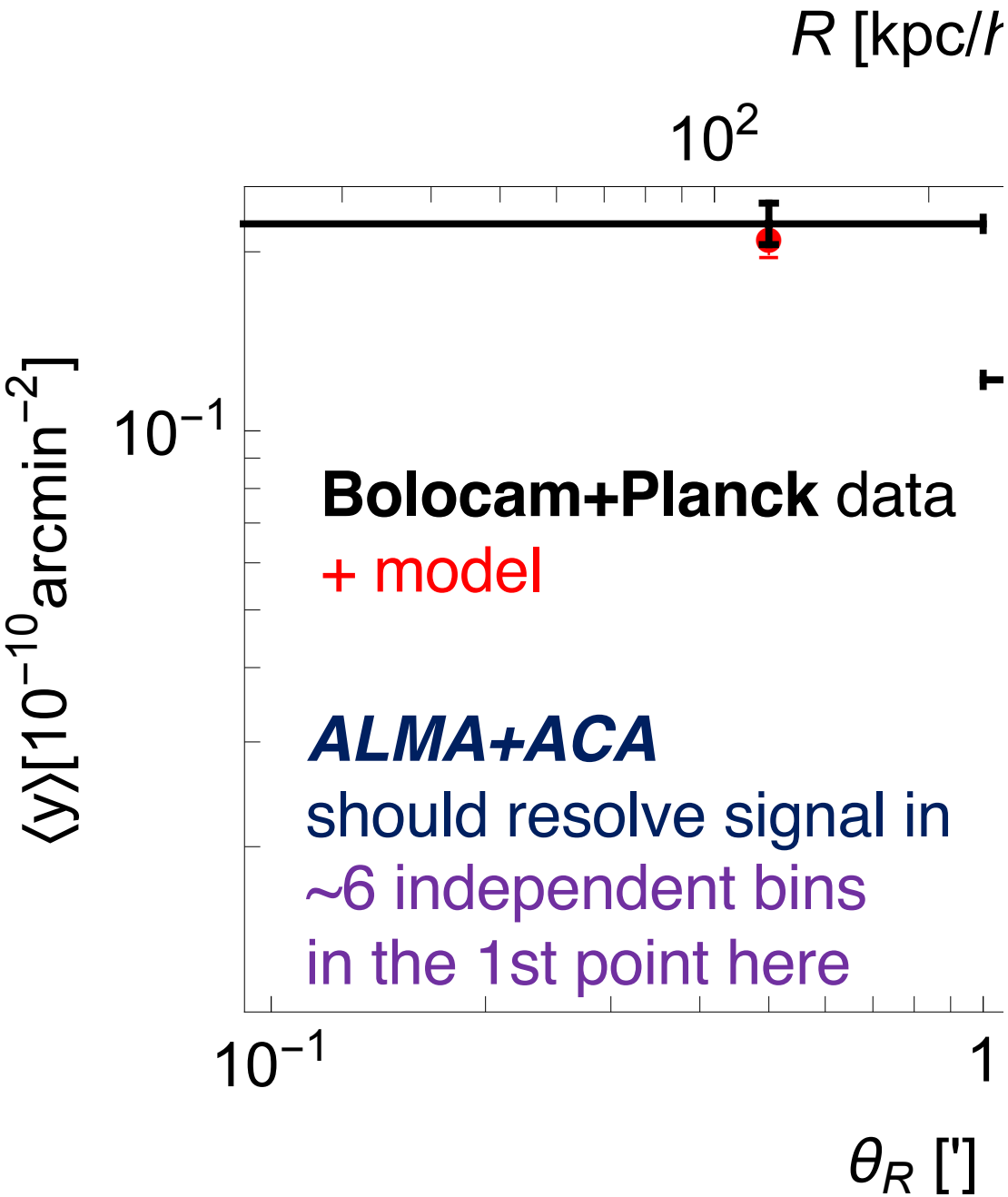
MACS1206

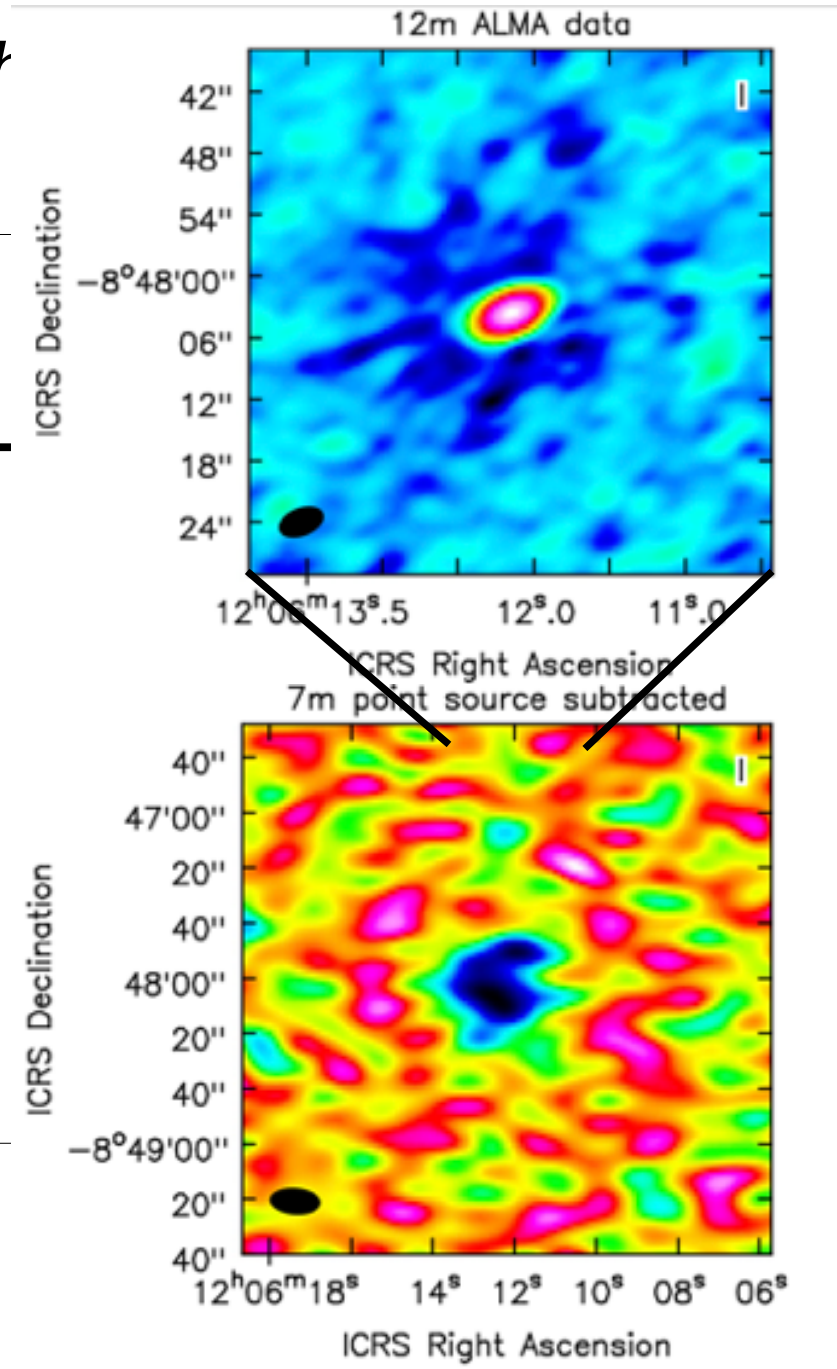




Thanks to B. Ladjelate & IRAM+NIKA2 teams

MACS1206


R [kpc/h
10^2
10^{-1}
$\langle y \rangle [10^{-10} \mathrm{arcmin}^{-2}]$
Bolocam+Planck data
+ model
ALMA+ACA
should resolve signal in
~6 independent bins
in the 1st point here
10^{-1}
1
θ_R ['']


12m ALMA data
ICRS Declination
42''
48''
54''
−8°48'00''
06''
12''
18''
24''
12h06m13s.5
12s.0
11s.0
ICRS Right Ascension
7m point source subtracted
40''
47'00''
20''
40''
48'00''
20''
40''
−8°49'00''
20''
40''
12h06m18s
14s
12s
10s
08s
06s
ICRS Right Ascension

Conclusions

- Combining ***X-ray+SZ*** profiles is a very efficient tool to recover (*clumping-free spatially-resolved*) cluster physical quantities (***X-COP*** & ***XCOP2***, ***Heritage*** & ***CLUMP-3D*** *on the gas & DM halo's triaxility*)
- *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*)
- From **mass** to **cosmology & astrophysics:** accurate modelization of the scatter & covariance (as done in ***CoMaLit*** framework) to control systematics

Galaxy clusters *as cosmological probes & astrophysical laboratories*

- ***[3-5 years]*** *Define what is the* ***true cluster mass scale****; define the* ***scatter*** *in the observed (spatially-resolved) quantities* from "universal" (n/T/P) profiles, we recover observables (like Sx, L, M_{gas}) for a given {z, M} and propagate the relative scatter (***XMM-Heritage/2018-20***; ***eROSITA/*****Jun 2019**; ***Euclid/*****2022**)

- ***[3-10 years]*** *Understand the role & components of of* $\boldsymbol{P_{NT}}$ How is the energy of matter's infall and virialization distributed in cluster's potential? How important are the details of the ICM microphysics in describing plasma (dis)homogeneities? To be investigated with future X-ray instruments (***XRISM /*****2021**; ***Athena/*****2030**); *for now, analysis of hydro-simulations (e.g. Angelinelli+19 arXiv:1905.04896)*