UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Département d'astronomie

Constraining the gravitational field of galaxy clusters through joint X-ray/SZ data

Dominique Eckert

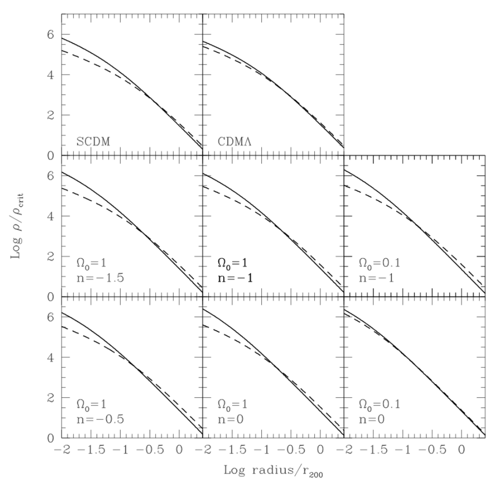
Department of Astronomy, University of Geneva

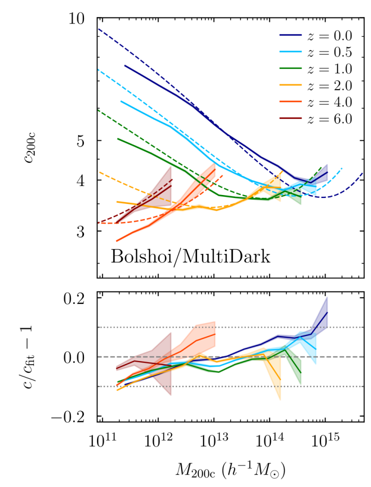
Main collaborators: S. Ettori, E. Pointecouteau, A. Robertson, R. Massey, R. Van der Burg, I. Loubser, H. Hoekstra, ...

June 30, 2021

The mass profiles of collapsed halos

ΛCDM predicts that halos of all scales should share the same structural properties





Navarro et al. 1997

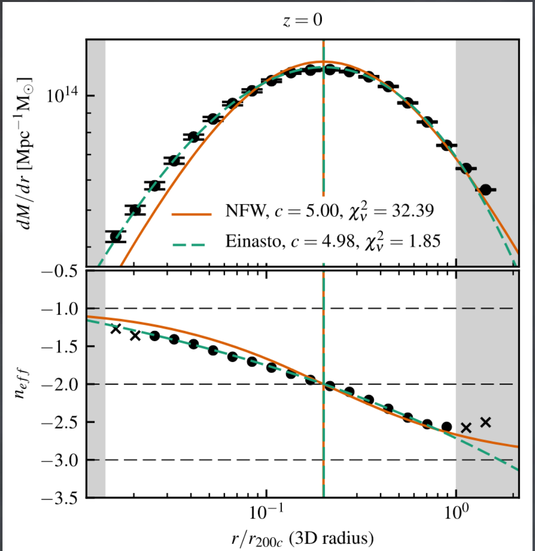
Diemer & Joyce 2018

$$\rho_{NFW}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

The Einasto profile

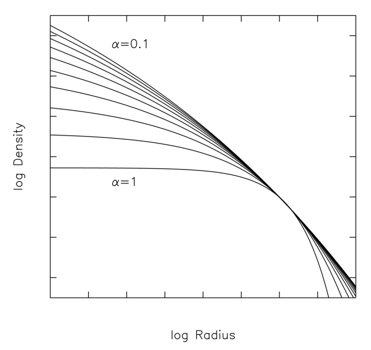
A more general form of DM profiles is the Einasto profile,

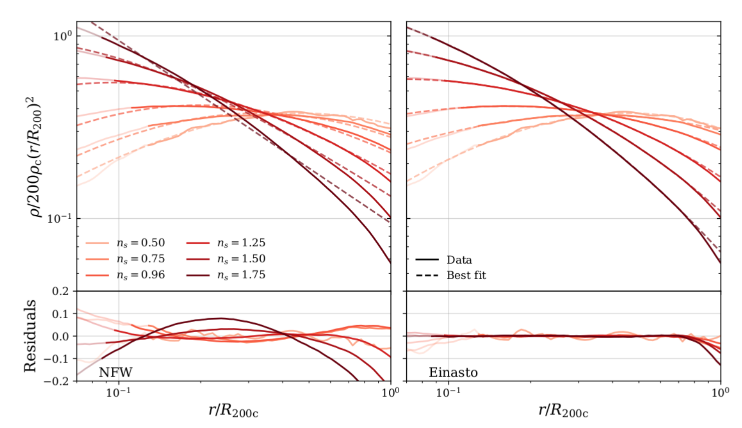
$$\rho(r) = \rho_{-2} \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{r_{-2}}\right)^{\alpha} - 1\right)\right]$$



Child et al. 2018

The Einasto profile



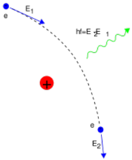


Brown et al. 2020

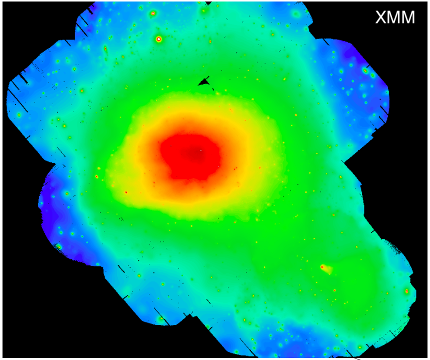
The Einasto index α depends on the slope of the primordial matter power spectrum n_s

Joint X-ray/Sunyaev-Zeldovich observations

X-ray

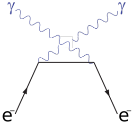


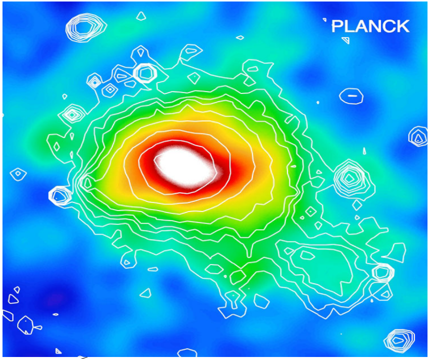
$$\epsilon_X \sim \int n_e^2 T^{1/2} dl$$



Sunyaev-Zel'dovich

$$y \sim \int P_e dl$$

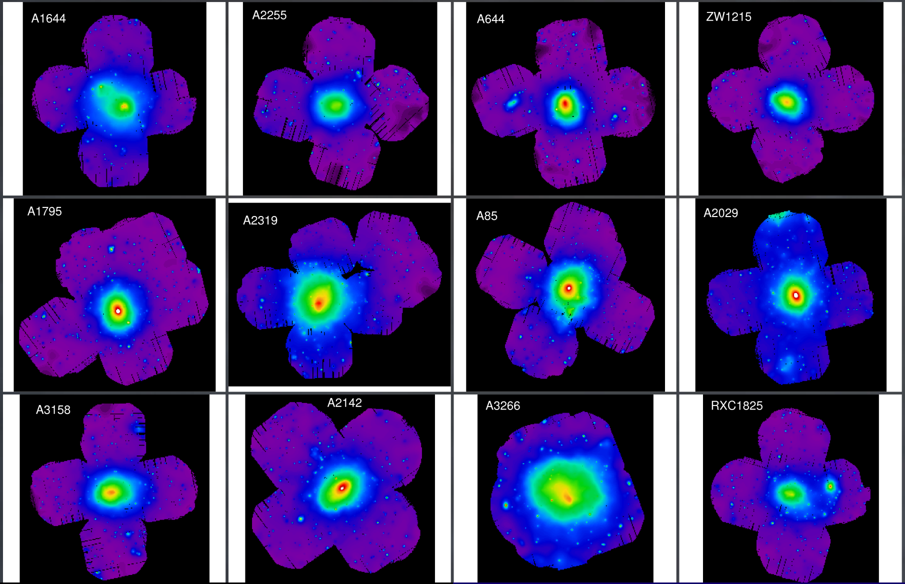




$$kT = P_{SZ}/n_X, K = P_{SZ} n_X^{-5/3}, \frac{dP_{SZ}}{dr} = -\rho_X \frac{GM(<r)}{r^2}$$

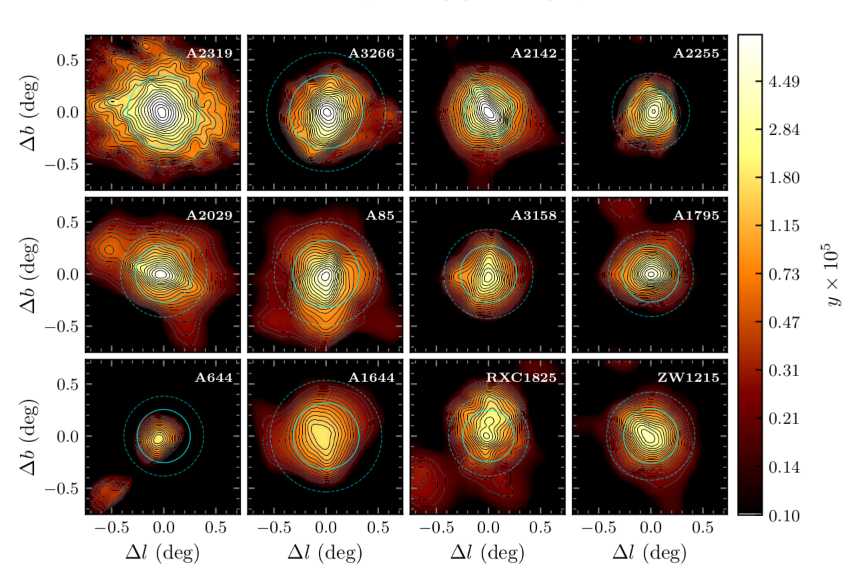
The X-COP project

X-COP (PI: Eckert) is a very large program on XMM to follow up Planck clusters with the highest S/N



SZ observations with Planck

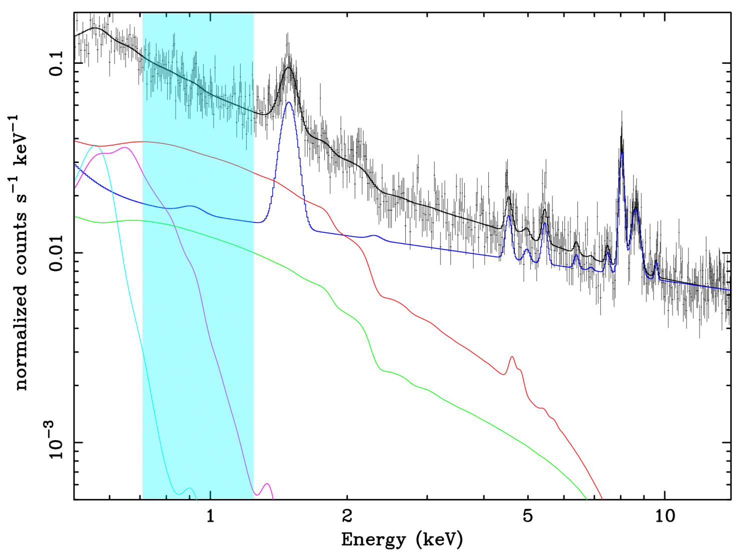
All our targets are spatially resolved by *Planck*



Baldi, ..., DE, ..., 2019

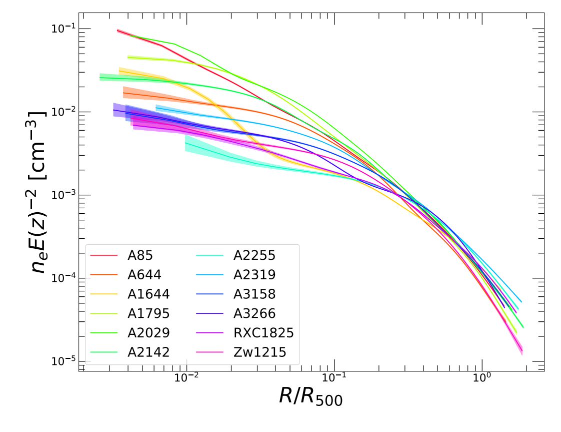
The X-COP strategy

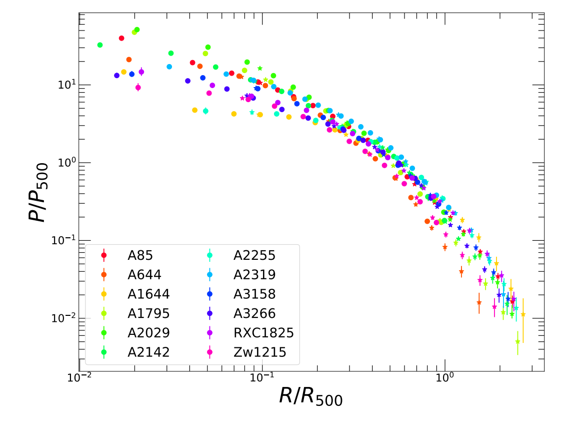
XMM has a large FOV and collecting area... but also a high and variable background



In the [0.7-1.2] keV band the signal-to-background ratio is maximized

X-ray and SZ profiles

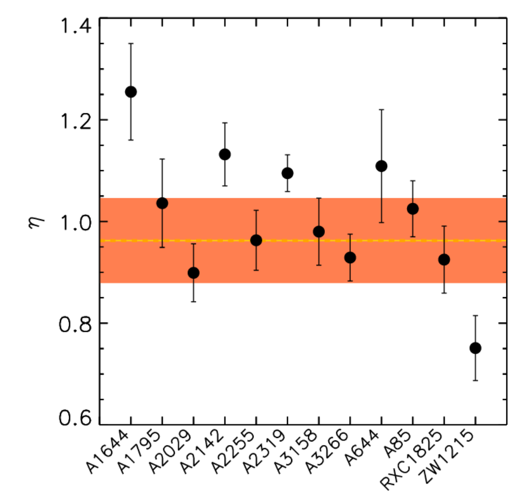


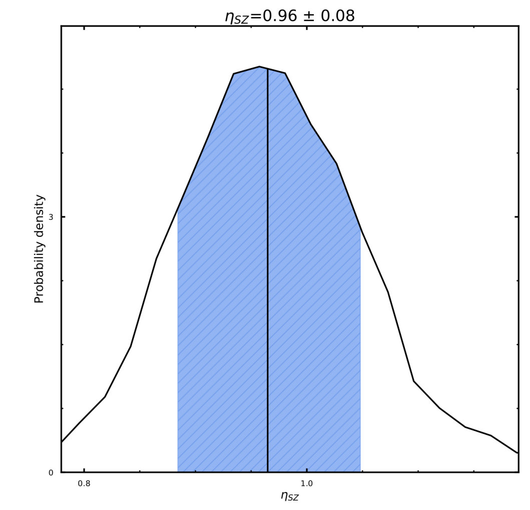


Ghirardini, DE et al. 2019

Our profiles extend to $1.8 R_{500}$ (n), $2.3 R_{500}$ (P), and $0.9 R_{500}$ (T)

Consistency between X-ray and SZ data

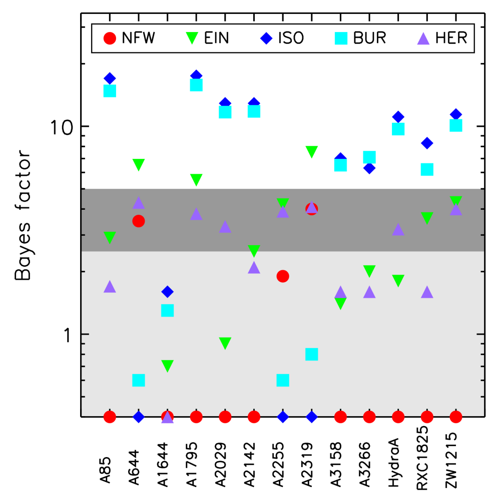


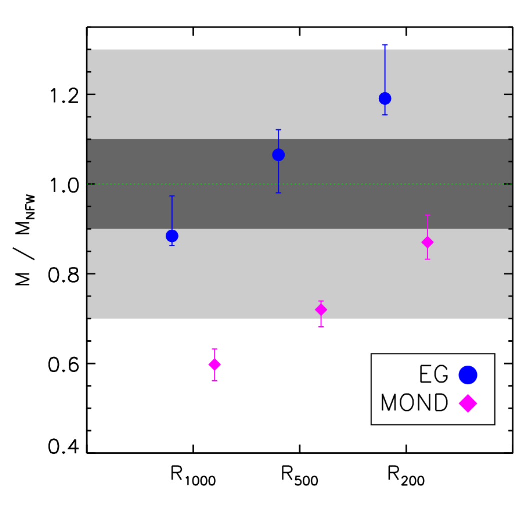


We measure on average $\eta_{SZ} = \frac{P_{SZ}}{k_B T_X n_e} = 0.96 \pm 0.08$

Mass profile comparison

In Ettori et al. 2019 we found that NFW is generally a better fit to the X-COP data than competing models



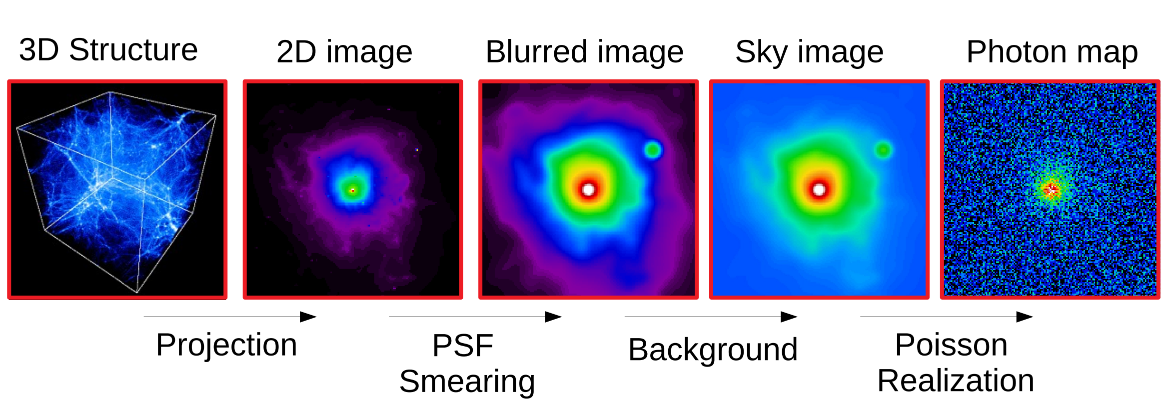


Ettori, DE, et al. 2019

Here the Einasto index was fixed to $\alpha = 0.2$

Derojection and PSF deconvolution

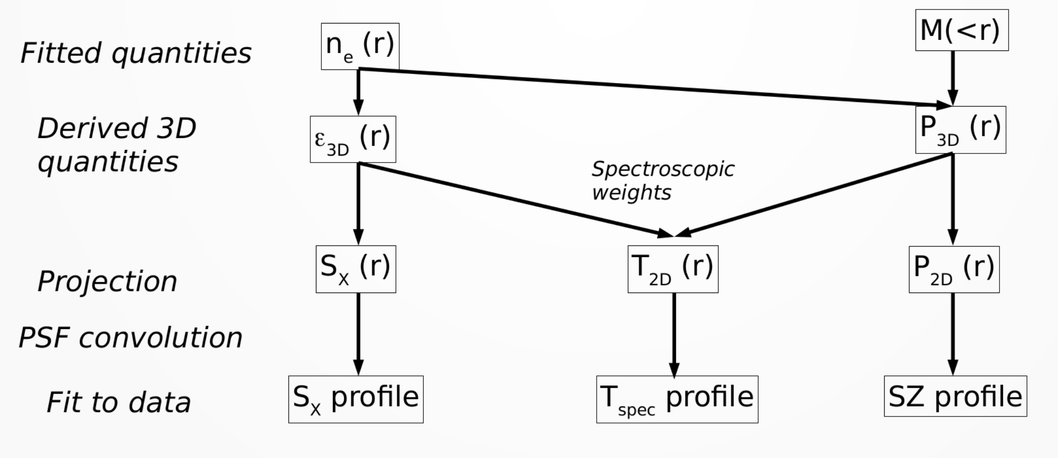
In practice we have access to *projected* and *PSF-blurred* quantities



Eckert et al. 2020

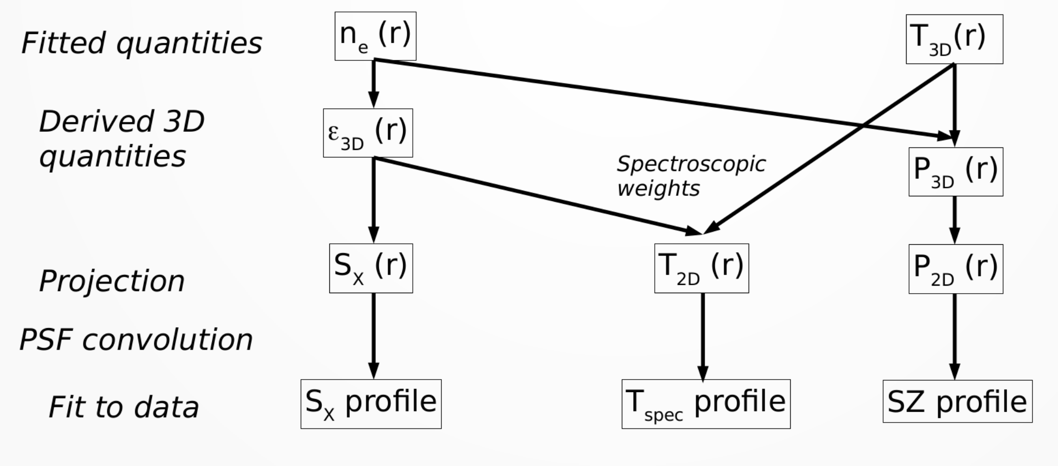
We decompose the 3D profile as a linear combination of basis functions and forward fit the model to the observed counts

Mass modeling scheme



We assume a functional form for the mass (Einasto, NFW) and forward-model it to the data, jointly fitting X-ray and SZ observables

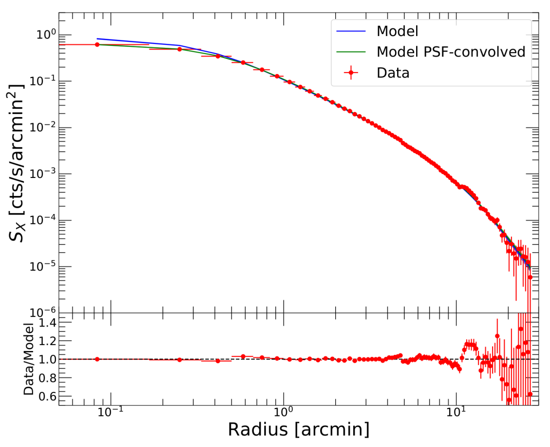
Non-parametric Gaussian Process reconstruction

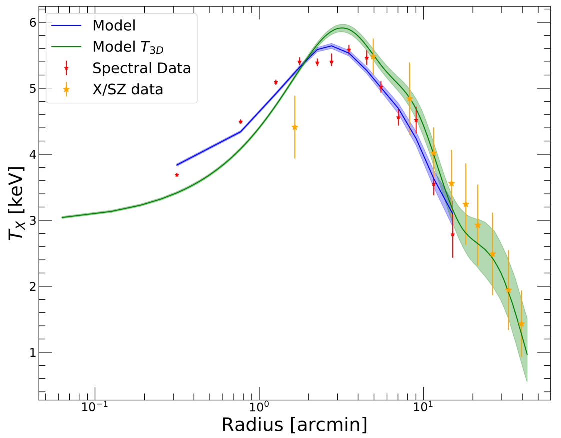


As a comparison point we apply a *non-parametric* method by describing the 3D temperature profile as a linear combination of Gaussians

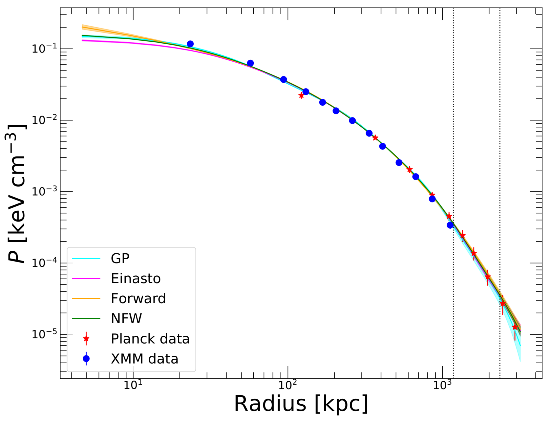
$$T_{3D}(r) = \sum G_i \mathcal{N}(\mu_i, \sigma_i^2)$$

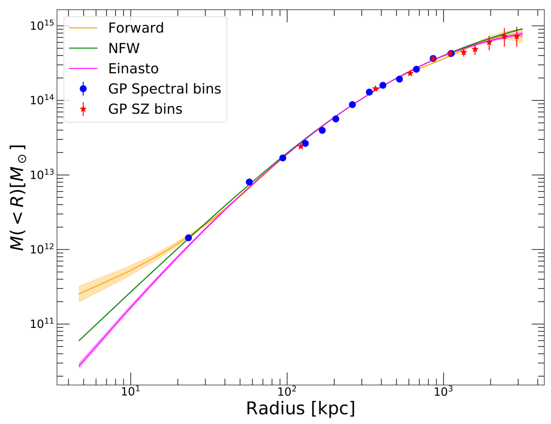
Example: A1795



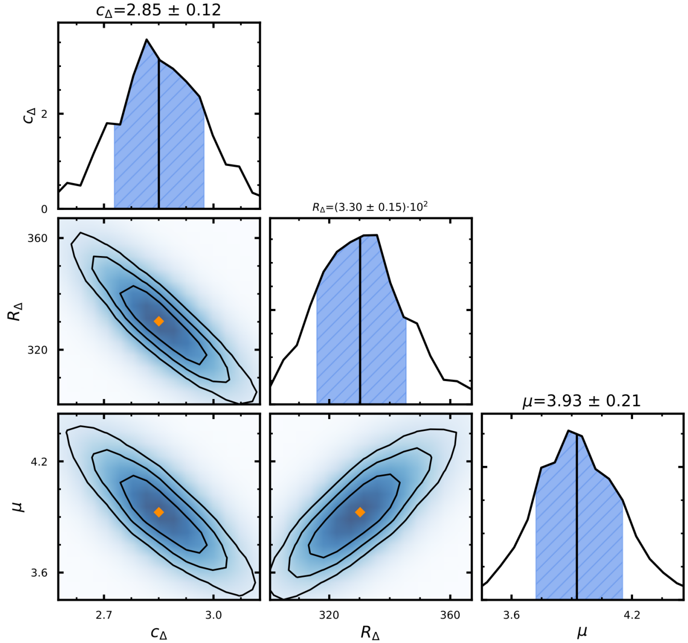


Example: A1795

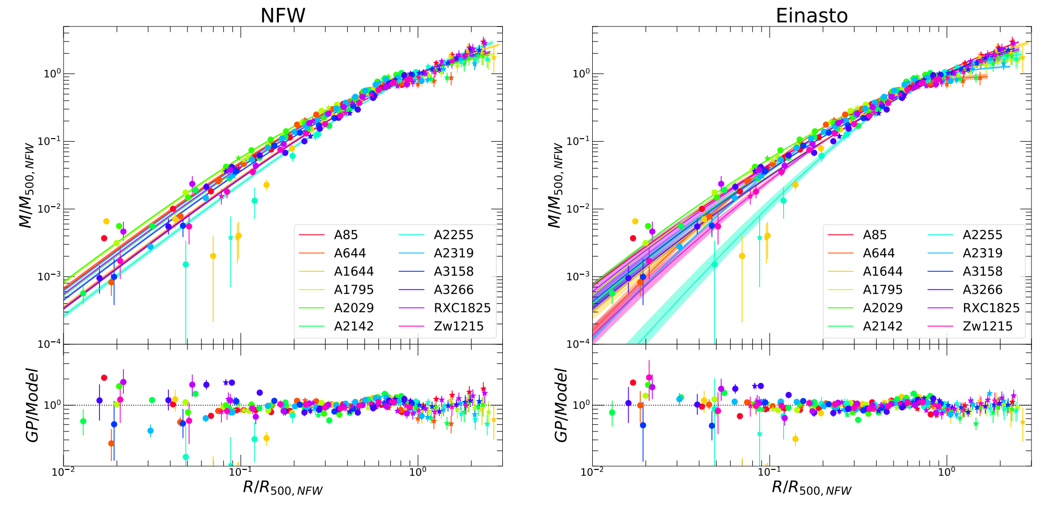




Example: A1795



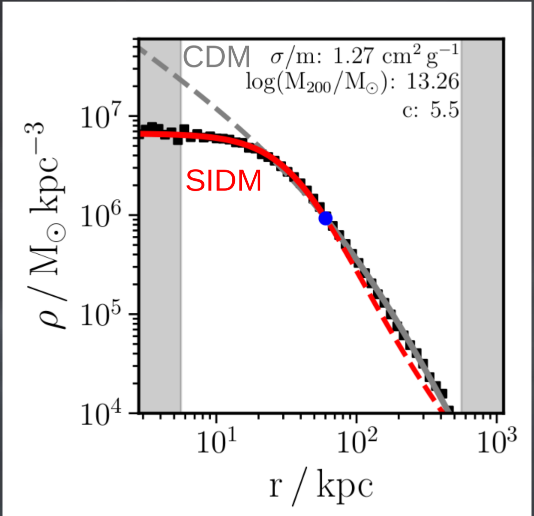
Einasto vs NFW reconstruction



There is *more variety* in the DM profiles than can be captured with NFW only

Mass profiles in self-interacting DM

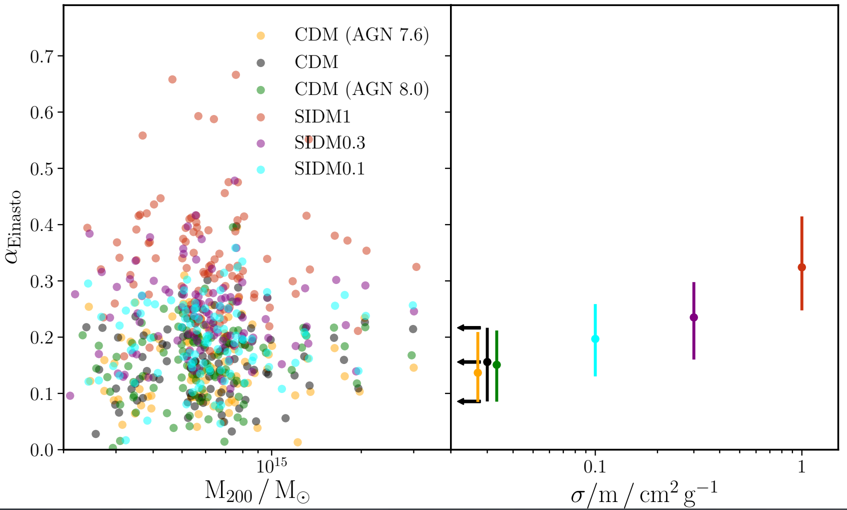
DM self-interaction ($\sigma_{DM-DM} > 0$) modifies the shape of DM halos



Robertson et al. 2020

Mass profiles in self-interacting DM

DM self-interaction ($\sigma_{DM-DM} > 0$) modifies the shape of DM halos

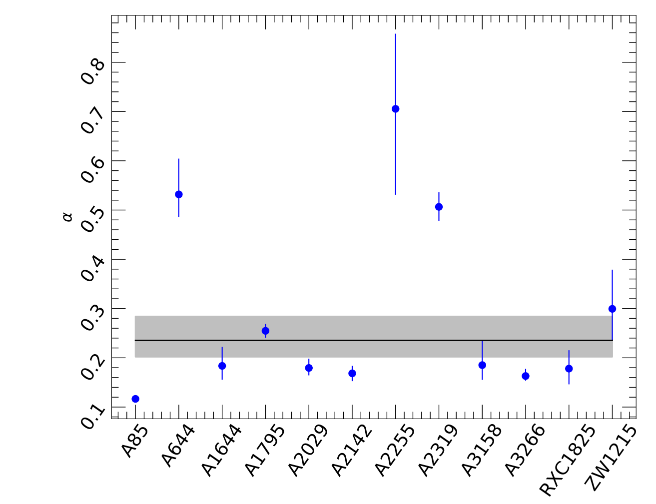


Robertson et al. 2020

The Einasto index α is sensitive to σ_{DM-DM}

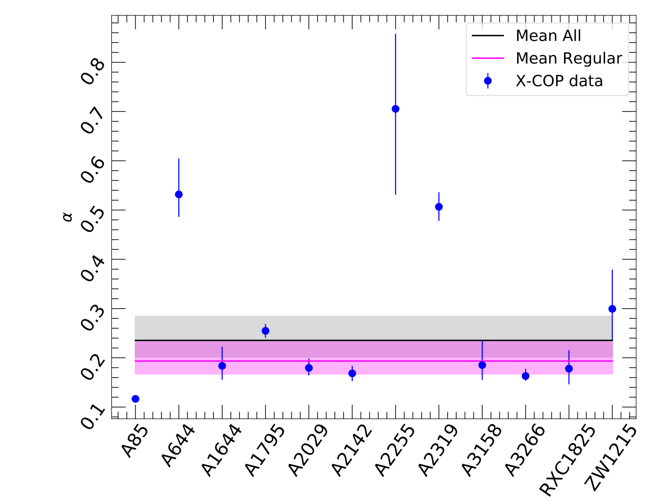
Einasto index of X-COP clusters

We were able to measure α with good precision for all systems



Einasto index of X-COP clusters

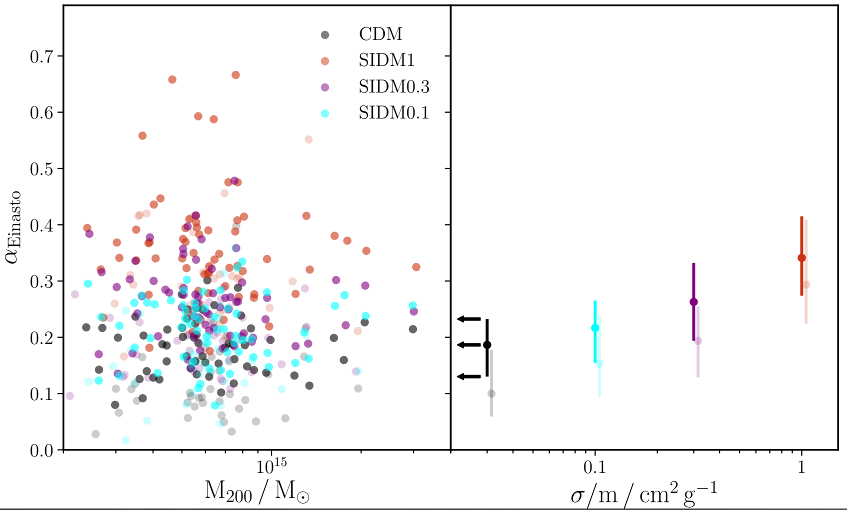
We were able to measure α with good precision for all systems



To minimize systematics (mis-centering, HSE bias, deviations from sphericaly symmetry...) we select only the regular X-ray clusters, $w < 0.02$

Comparison with numerical simulations

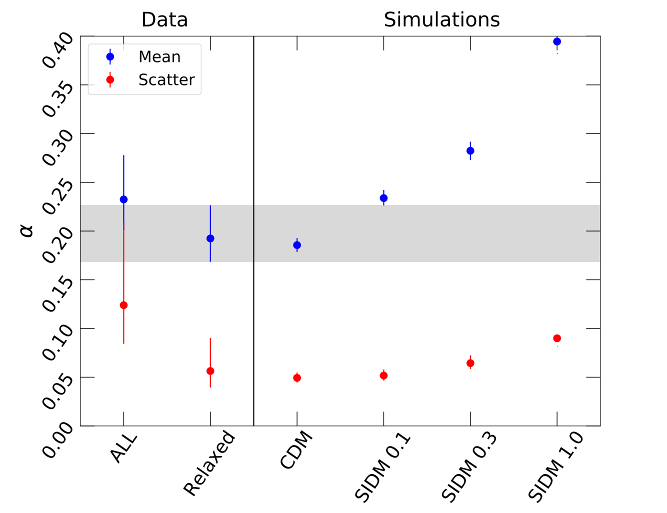
For an appropriate comparison we select only *relaxed* systems in numerical simulations ($X_{off} < 0.05$)



Eckert et al. in prep.

Comparison with numerical simulations

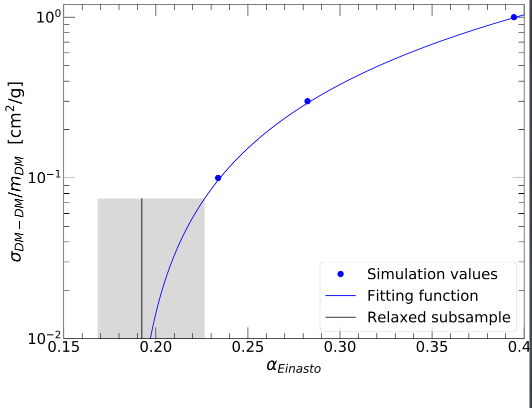
For an appropriate comparison we select only *relaxed* systems in numerical simulations ($X_{off} < 0.05$)



Eckert et al. in prep.

Constraints on σ_{DM-DM}

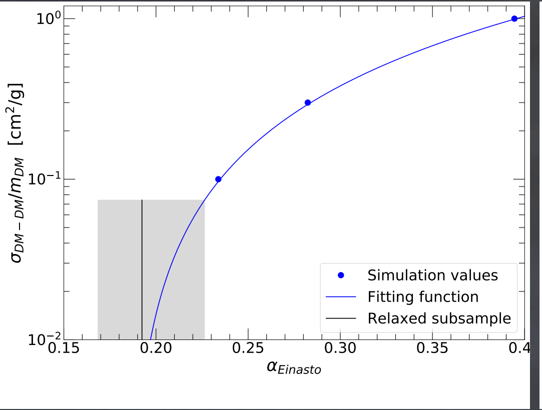
For every value of α we can associate a value of σ_{DM-DM} and draw a posterior PDF

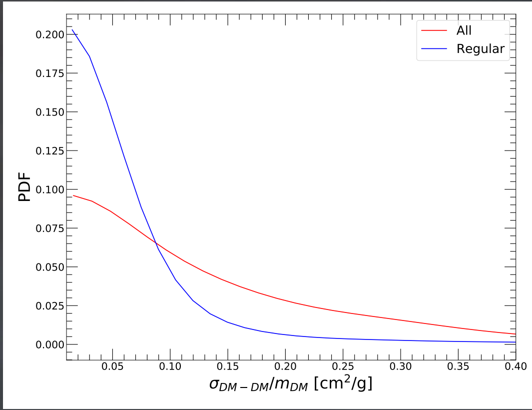


Eckert et al. in prep.

Constraints on σ_{DM-DM}

For every value of α we can associate a value of σ_{DM-DM} and draw a posterior PDF



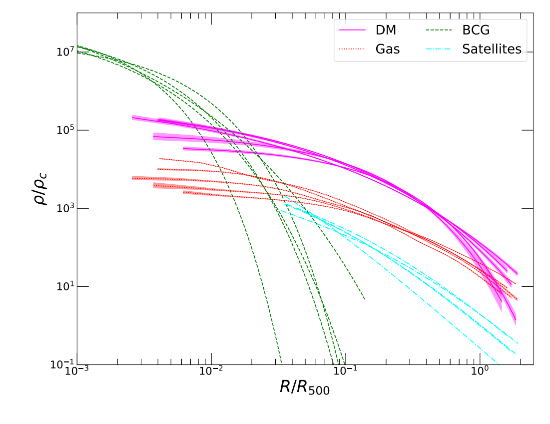


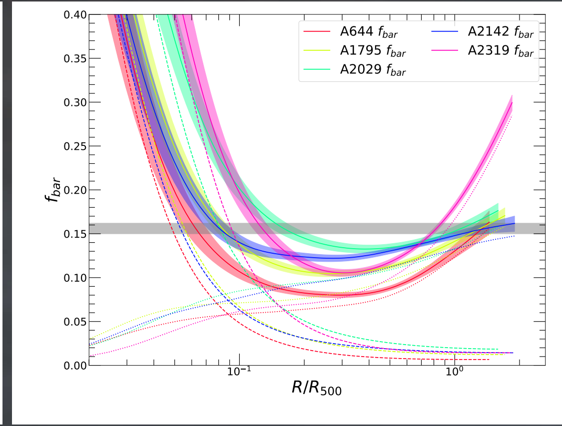
Eckert et al. in prep.

Using the regular sample we set an upper limit $\sigma_{DM-DM} < 0.13$ cm^2/g

DM vs baryonic components

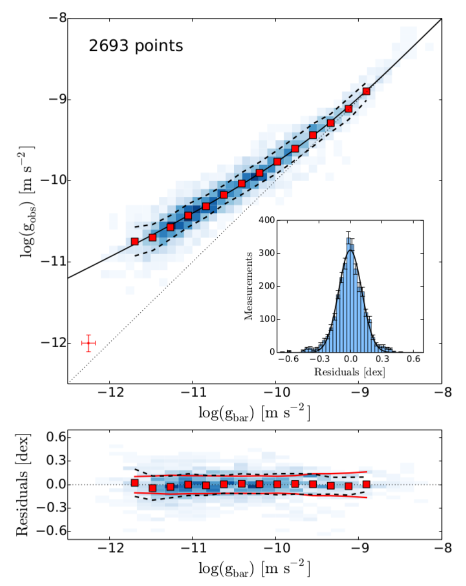
For a subset of systems we directly measured all the relevant baryonic components: gas, BCG, and satellites





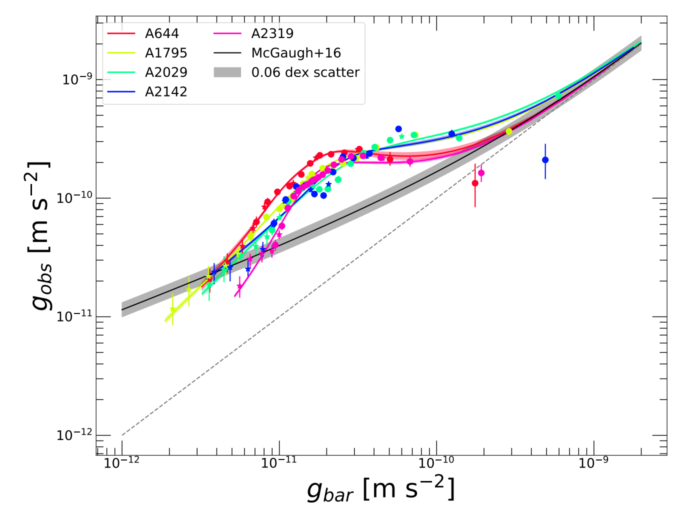
A universal radial acceleration relation?

- Similar calculations were made for galaxy rotation curves, i.e. comparing the observed gravitational force with that expected from baryons only
- When plotted in terms of gravitational force, it looks like the scale where deviation from baryonic expectations occurs doesn't depend on galaxy mass or type (McGaugh et al. 2016)



McGaugh et al. 2016

What about galaxy clusters?

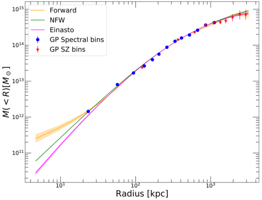


Eckert et al. in prep.

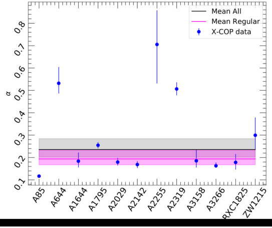
The relation between baryonic and total acceleration *is not universal*, and thus it does not derive from a fundamental property of gravity

Take home message

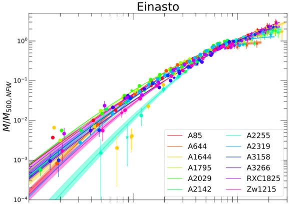
We put together a framework to set constraints on the gravitational field from joint X-ray and SZ data



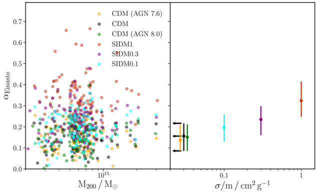
With X-COP data we provide precise measurements of the Einasto index α



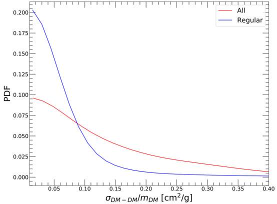
There is more diversity in the DM density profiles than can be described by NFW



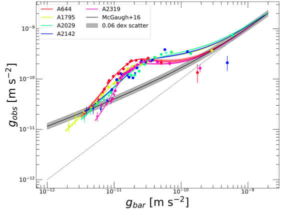
The Einasto index α is sensitive to the dark matter self-interaction cross section



We set an upper limit on the DM self-interaction cross section of $\sigma_{DM\text{-}DM}$ < 0.13 cm^2/g (90 % c.l.)

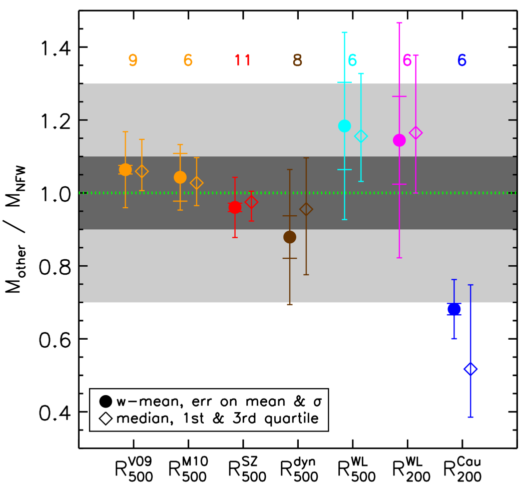


The relation between baryonic and total acceleration is not a fundamental property of gravity

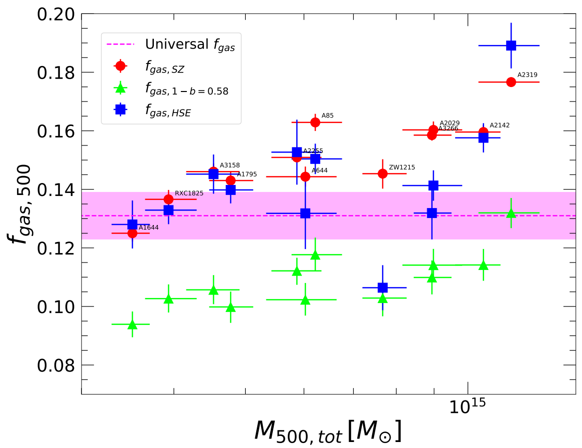


Backup Slides

HSE bias in X-COP clusters



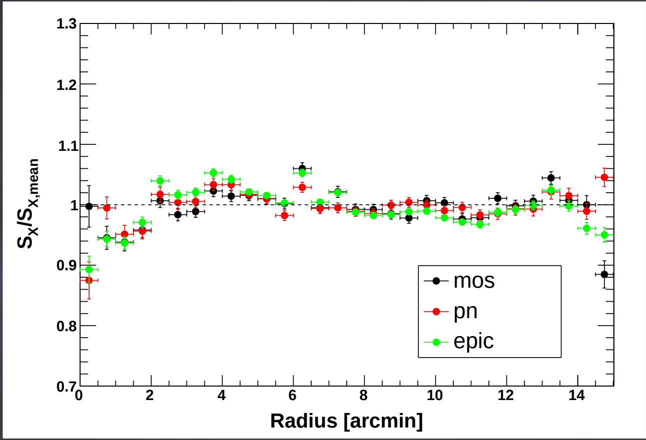
Ettori et al. 2019



Eckert et al. 2019

Beating systematics in background subtraction

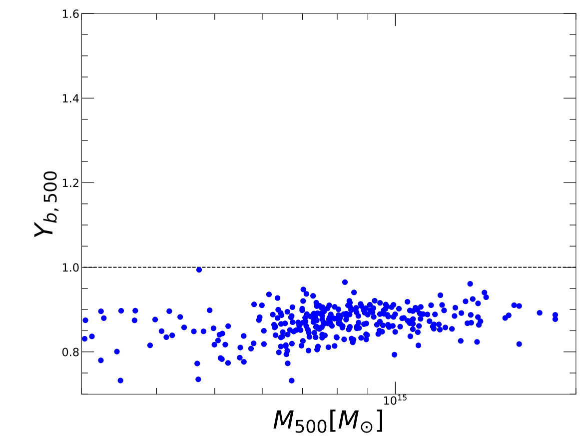
We analyzed a set of ~ 500 blank-sky XMM pointings and estimated the reproducibility of the background



When modeling all known XMM background components we reach a precision of 3% on background subtraction

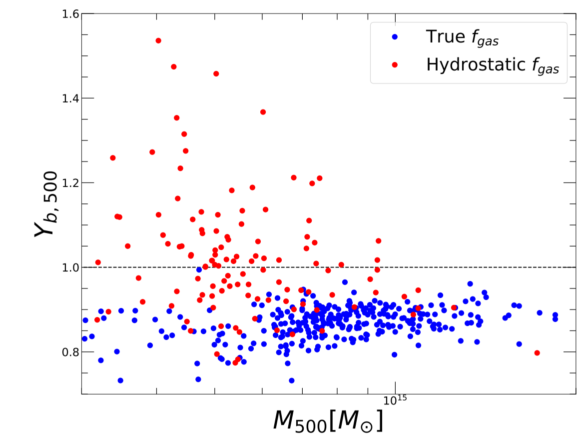
Universal gas fraction

We used a large set of ~ 300 simulated clusters (Rasia et al. in prep.) to determine the baryon depletion Y_b



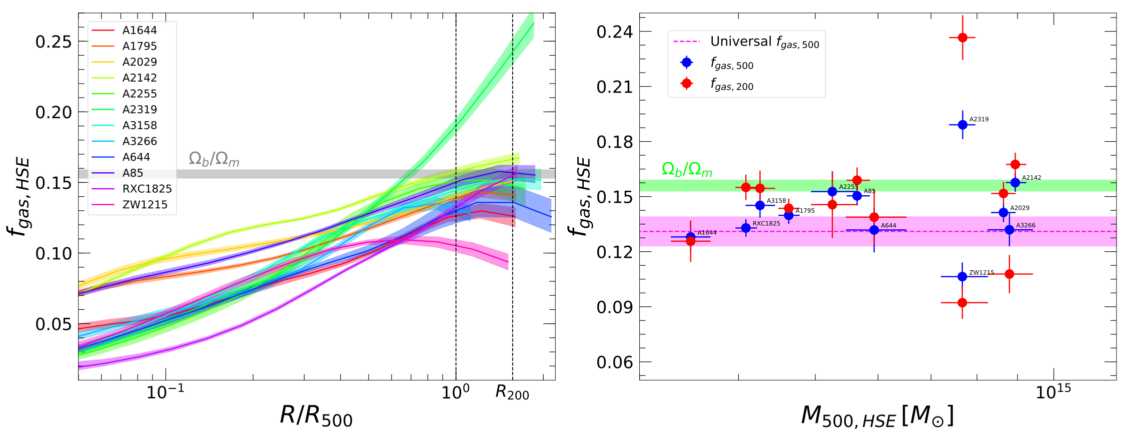
Universal gas fraction

We used a large set of ~ 300 simulated clusters (Rasia et al. in prep.) to determine the baryon depletion Y_b



- The value of Y_{bar} is nearly independent of the adopted baryonic physics (Planelles et al. 2014)
- Considering the (well-measured) stellar fraction, we set $f_{gas} = Y_b \frac{\Omega_b}{\Omega_m} - f_\star$

Testing hydrostatic equilibrium with f_{gas}

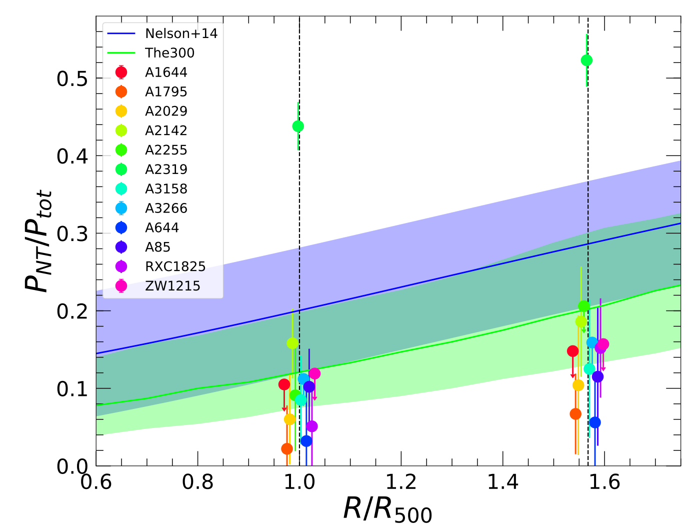


Eckert et al. 2019

Median [percentiles] for the full sample:

- $f_{gas,500} = 0.141\ [0.131, 0.154]$
- $f_{gas,200} = 0.149\ [0.121, 0.161]$

Non-thermal pressure support vs simulations



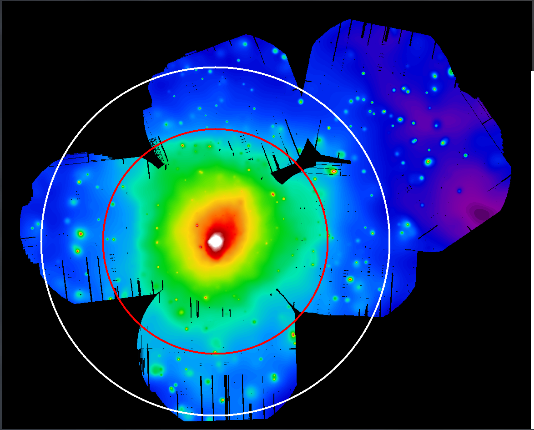
Eckert et al. 2019

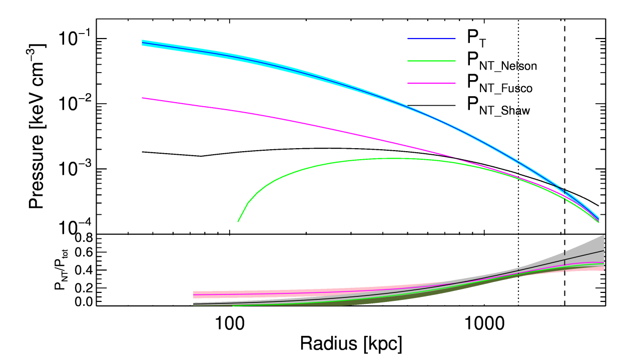
With one exception (A2319) the level of NT pressure is *lower* than predicted

Median $P_{NT,500} = 6\%$, $P_{NT,200} = 10\%$

The case of A2319

A2319 is a head-on merger with 3:1 mass ratio

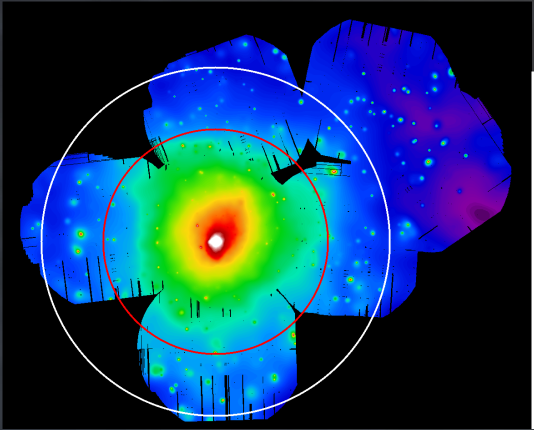


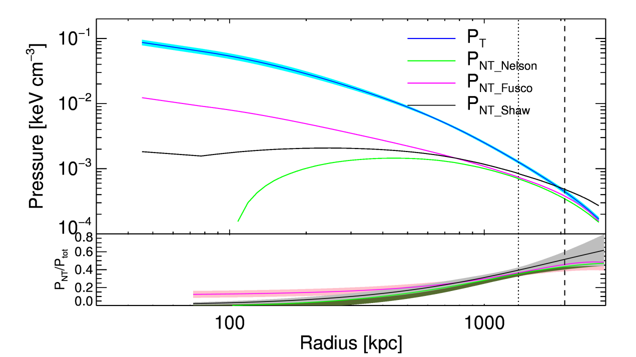


Ghirardini, Ettori, DE et al. 2018

The case of A2319

A2319 is a head-on merger with 3:1 mass ratio



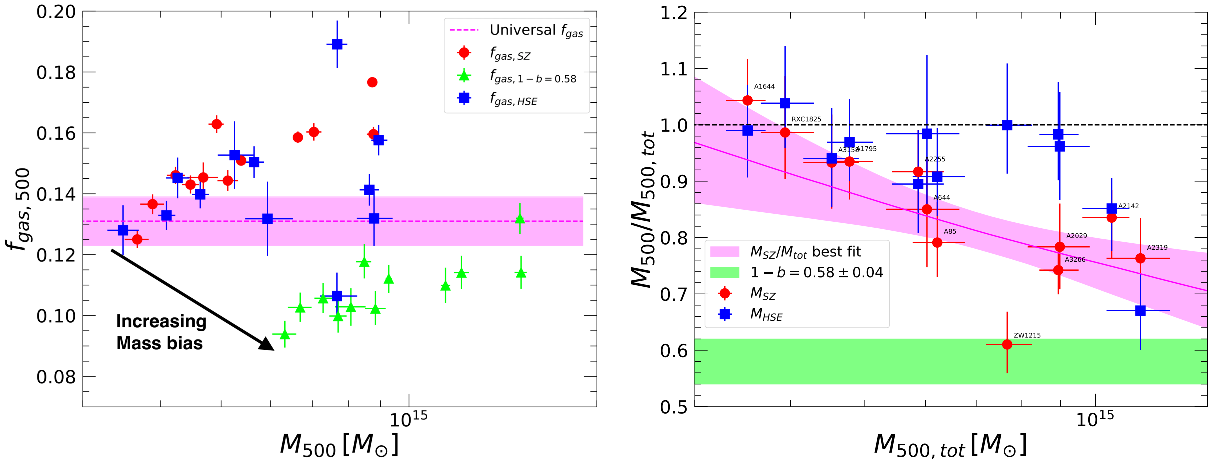


Ghirardini, Ettori, DE et al. 2018

A2319 is probably in a transient phase of high NT pressure ($\sim$ 40%)

Non-thermal pressure and hydrostatic bias

We compared our masses corrected for NT pressure with hydrostatic masses



Eckert et al. 2019

- On average we measure $M_{HSE}/M_{tot} = 0.94 \pm 0.04$
- *Planck* masses are slightly biased low, $M_{SZ}/M_{tot} = 0.85 \pm 0.05$
- $1 - b = 0.58 \pm 0.04$ would imply a very low $f_{gas} = 10.5\%$