UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Département d'astronomie

Constraining the nature of dark matter and modified gravity in galaxy clusters

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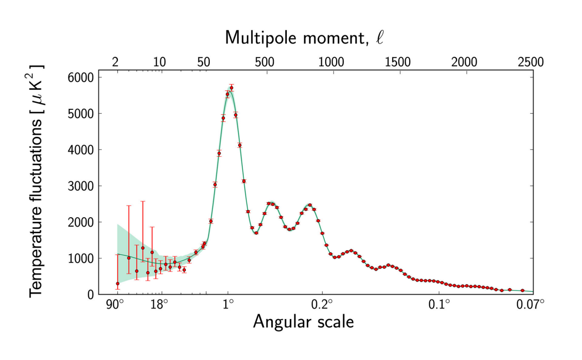
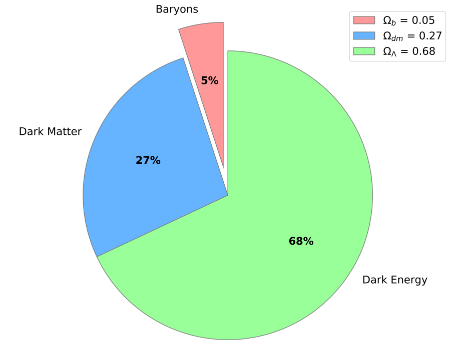
Eckert et al. 2022a, A&A 662, 123
Eckert et al. 2022b, A&A 666, 41

November 21, 2022

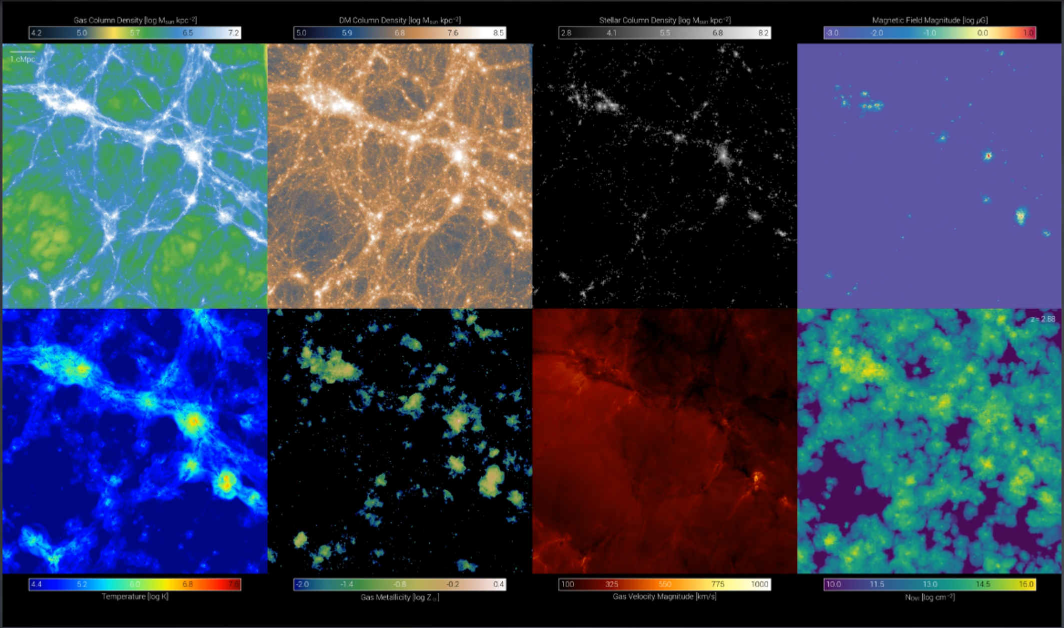
The dark sector conundrum





Our currently favored cosmological framework describes the Universe's LSS extremely well... but it contains 95% unknown stuff!

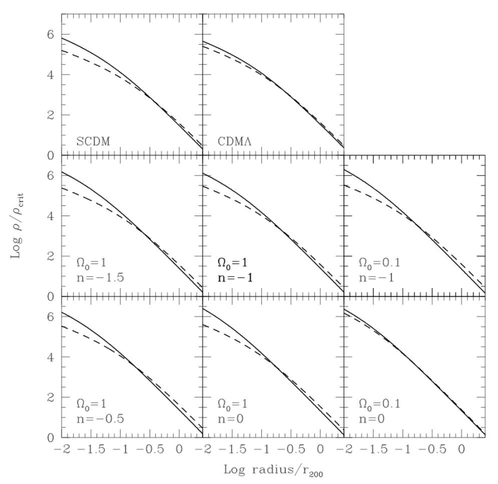
The formation and evolution of dark matter halos



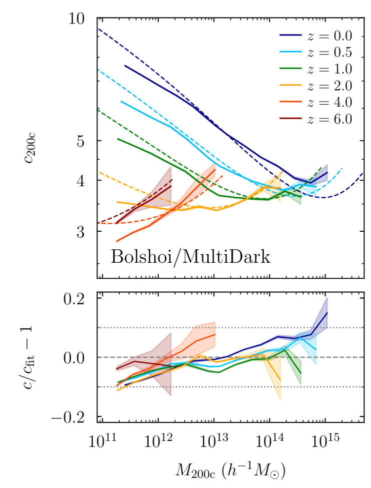
Illustris TNG Simulation

The mass profiles of collapsed halos in CDM

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



Navarro et al. 1997



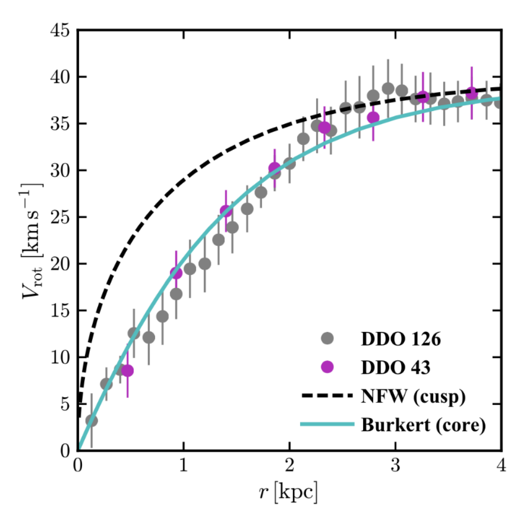
Diemer & Joyce 2018

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

$$c_{200} = \frac{r_s}{R_{200}}$$

The core-cusp problem

- The NFW model predicts $\rho(r) \propto r^{-1}$ in the central regions (*cusps*)
- In dwarf galaxies we often observe flat slopes of the gravitational field (*cores*) inconsistent with ΛCDM predictions
- Baryonic effects in dwarf galaxies are poorly understood; important to check this is in other mass ranges

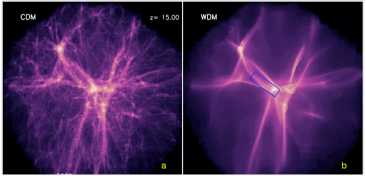


Bullock & Boylan-Kolchin 2017

Alternatives to Cold Dark Matter

Warm Dark Matter

$m_X \sim$ 1-100 keV



Moustakas et al. 2009

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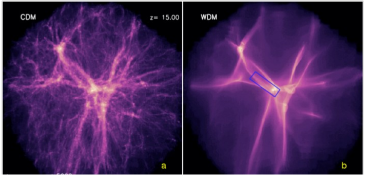
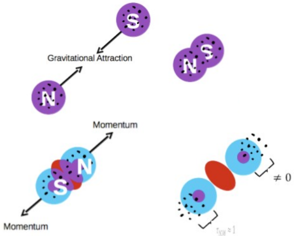


Moustakas et al. 2009

Self-Interacting Dark Matter

$\sigma_{DM\text{-}DM} > 0$



Wittman et al. 2018

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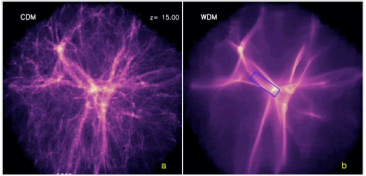

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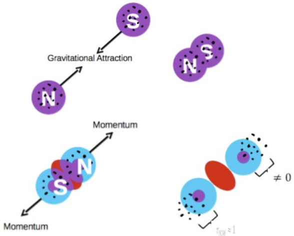
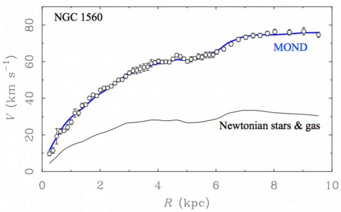


Wittman et al. 2018

Modification of gravity

$F_g \neq F_{Newton}$

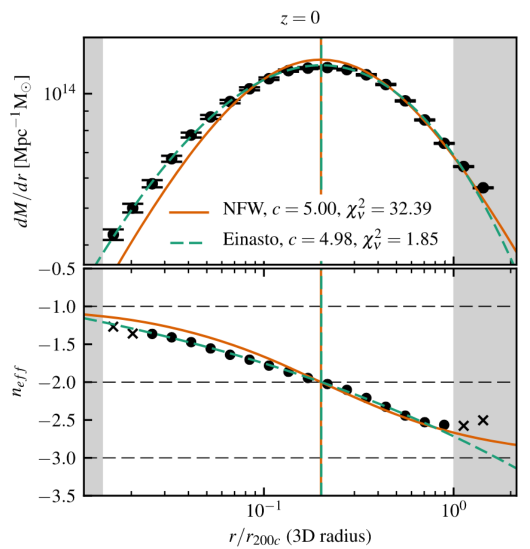


Begelman et al. 1991

The Einasto profile

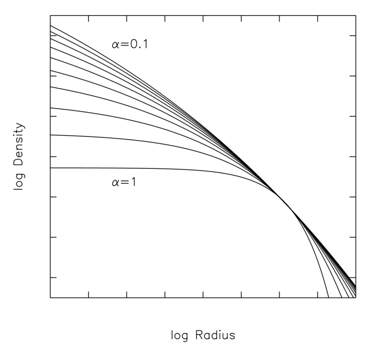
A more general form of DM profiles is the Einasto profile,

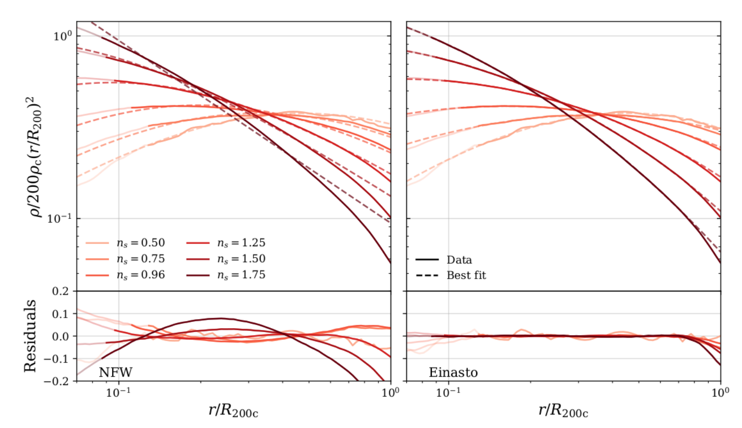
$$\rho(r) = \rho_{-2} \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{r_{-2}}\right)^{\alpha} - 1\right)\right]$$



Child et al. 2018

The Einasto profile



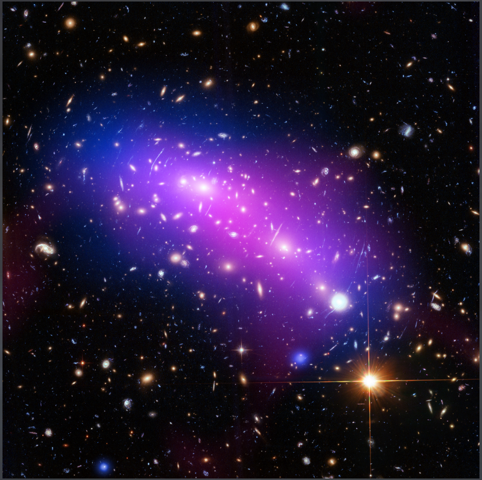


Brown et al. 2020

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

Galaxy clusters as the largest concentrations of dark matter

Given their masses galaxy clusters are "closed boxes" for dark matter and baryons alike



MACS 0416, Jauzac, DE, et al. 2015

Galaxy clusters can contain up to $10^{15} M_\odot$ of dark matter. They are the best place to search for deviations from ΛCDM!

Cluster mass profiles from hydrostatic equilibrium

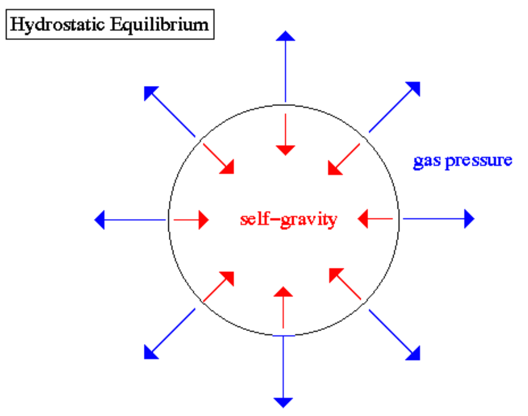
- The dynamics of the hot gaseous atmosphere follows the Euler equation,

$$\frac{\partial v}{\partial t} + (v \cdot \nabla) v = -\frac{1}{\rho} \nabla P - \nabla \Phi$$

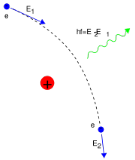
- After relaxation the velocity field is small and the halo is spherically symmetric,

$$\frac{dP}{dr} \approx -\rho \frac{d\Phi}{dr}$$

- If we can measure P, ρ then we can recover Φ



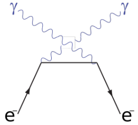
X-ray

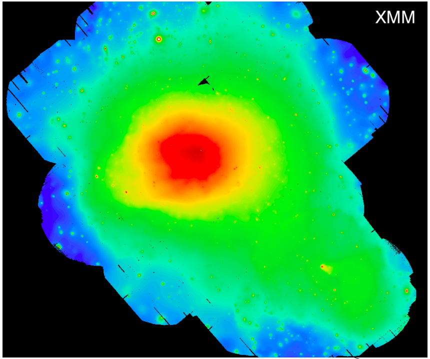


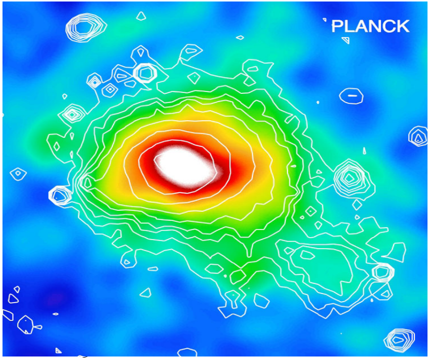
$$\epsilon_X \sim \int n_e^2 T^{1/2} dl$$

Sunyaev-Zel'dovich

$$y \sim \int P_e dl$$



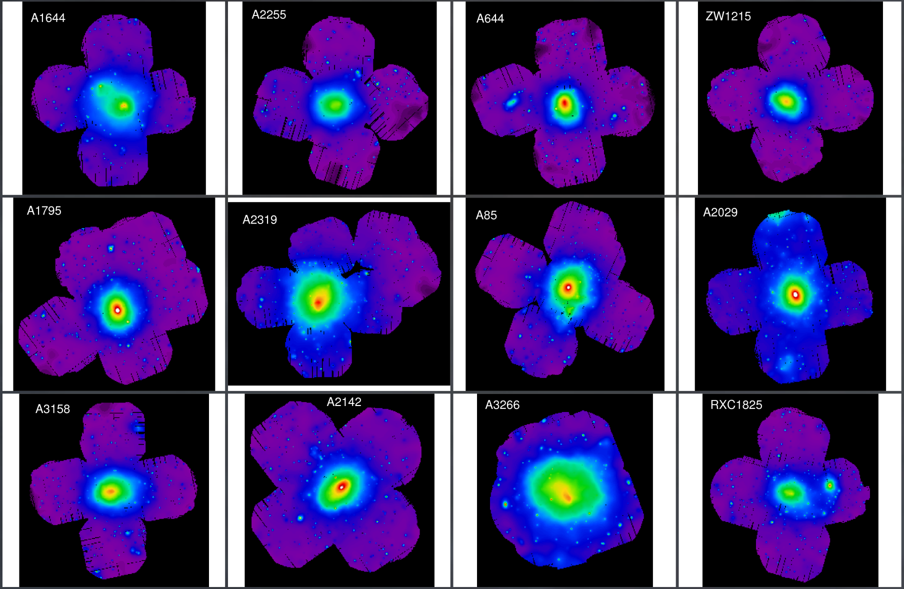




$$kT = P_{SZ}/n_X, K = P_{SZ} n_X^{-5/3}, \frac{dP_{SZ}}{dr} = -\rho_X \frac{GM(<r)}{r^2}$$

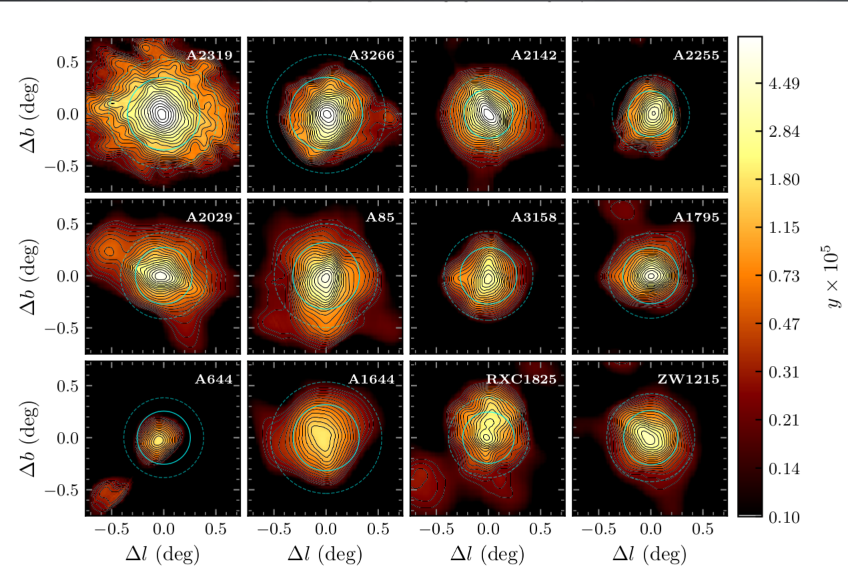
The X-COP project

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



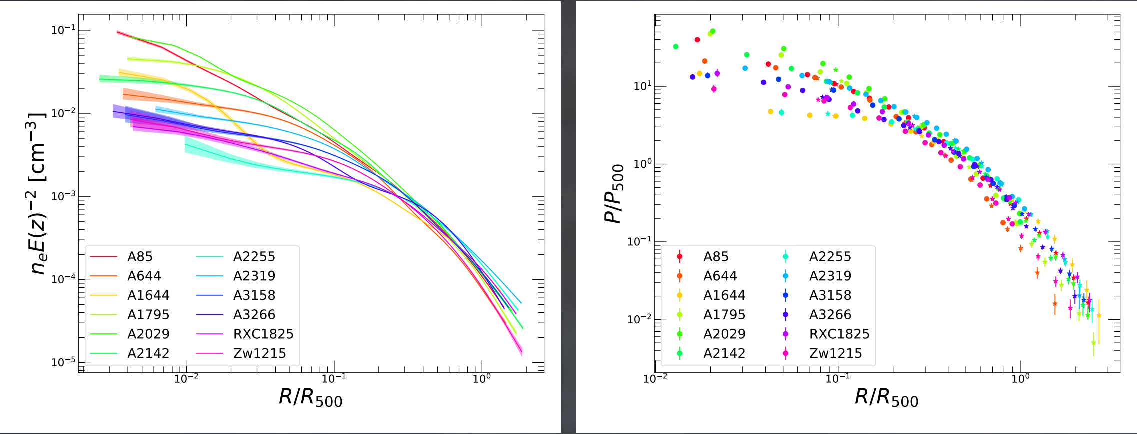
SZ observations with Planck

All our targets are spatially resolved by *Planck*



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

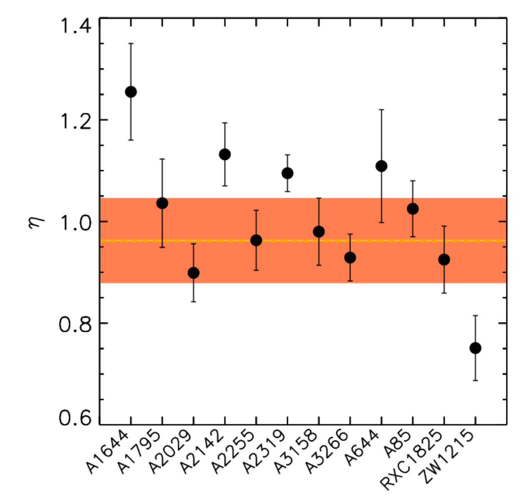
X-ray and SZ profiles

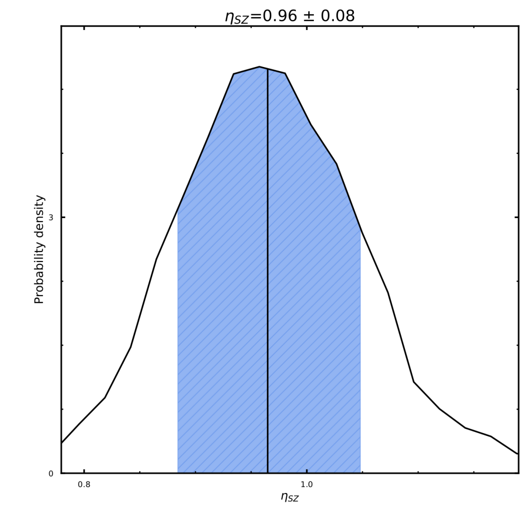


Ghirardini, DE et al. 2019

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

Consistency between X-ray and SZ data

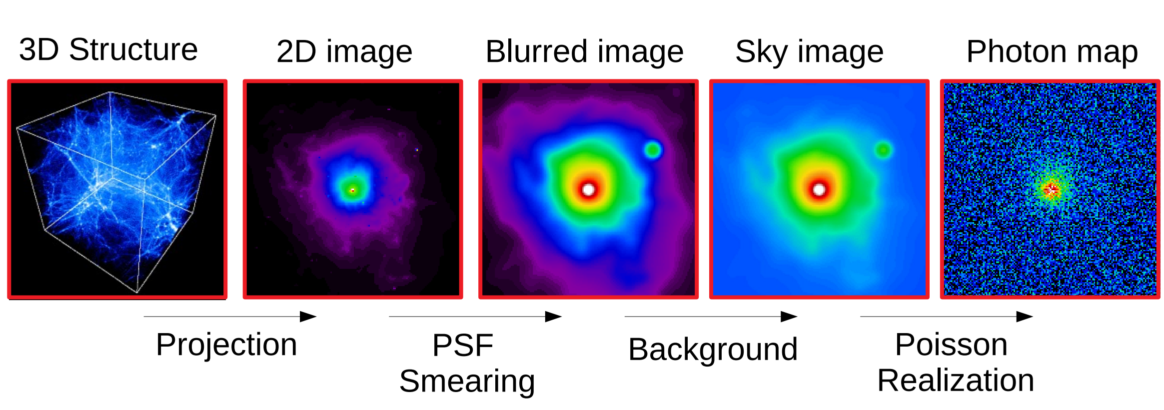




We measure on average $\eta_{SZ} = \frac{P_{SZ}}{k_B T_X n_e} = 0.96 \pm 0.08$

Mass Reconstruction using Bayesian Forward Modelling

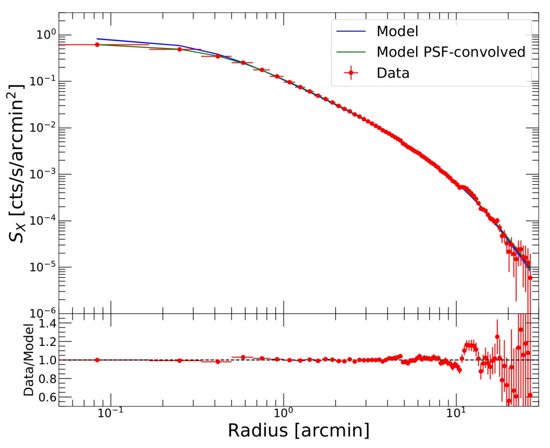
In practice we have access to *projected* and *PSF-blurred* quantities

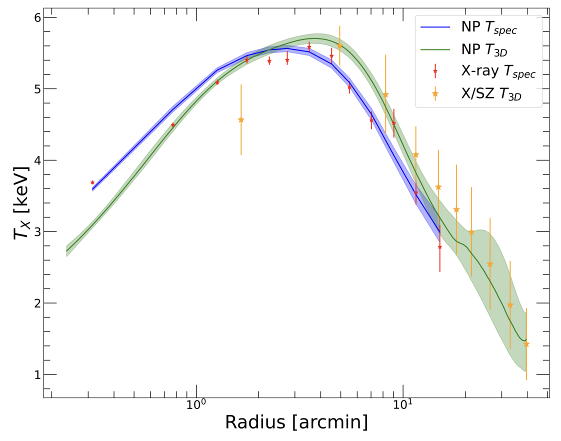


Eckert et al. 2020

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

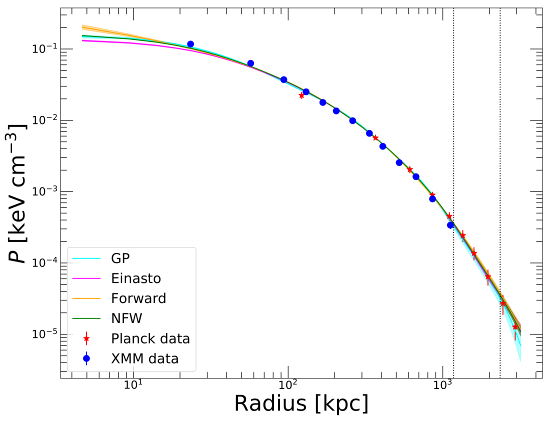
Example mass reconstruction: A1795

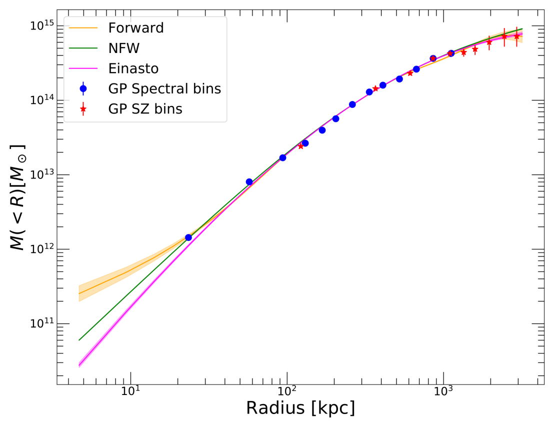




Eckert et al. 2022a

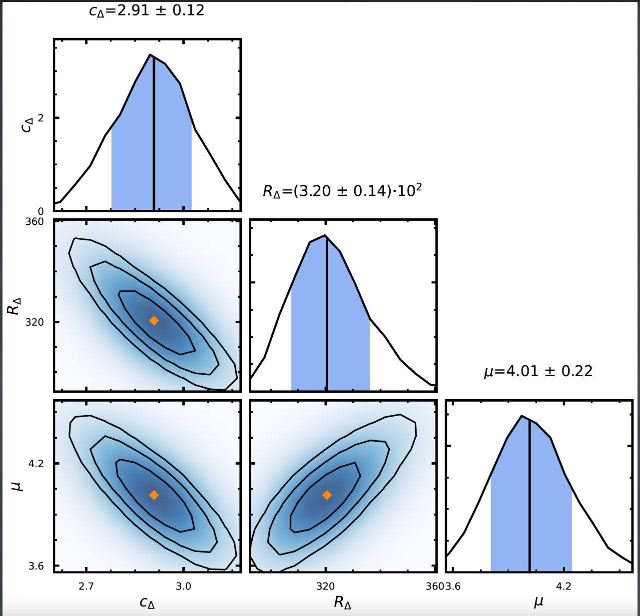
Example mass reconstruction: A1795





Eckert et al. 2022a

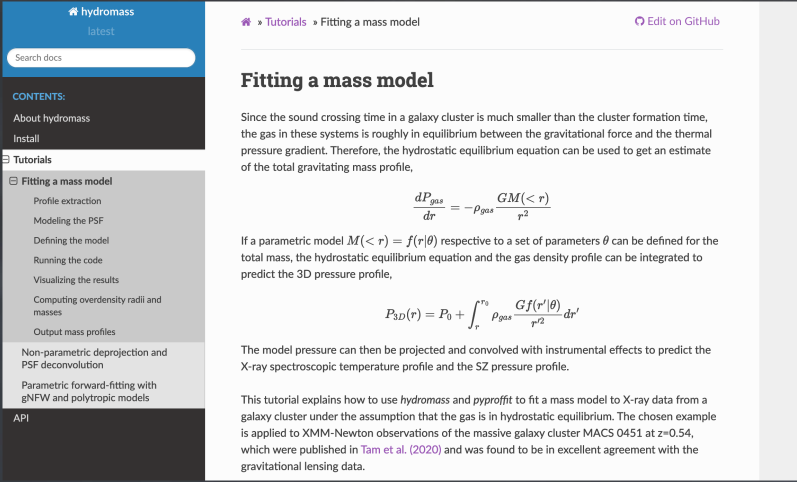
Example mass reconstruction: A1795



Eckert et al. 2022a

Public code and documentation

All the code is public! Check out the Python packages pyproffit (surface brightness, density, imaging) and hydromass (deprojection, mass modeling)



Fitting a mass model

Since the sound crossing time in a galaxy cluster is much smaller than the cluster formation time, the gas in these systems is roughly in equilibrium between the gravitational force and the thermal pressure gradient. Therefore, the hydrostatic equilibrium equation can be used to get an estimate of the total gravitating mass profile,

$$\frac{dP_{gas}}{dr} = -\rho_{gas}\frac{GM(<r)}{r^2}$$

If a parametric model $M(<r) = f(r|\theta)$ respective to a set of parameters θ can be defined for the total mass, the hydrostatic equilibrium equation and the gas density profile can be integrated to predict the 3D pressure profile,

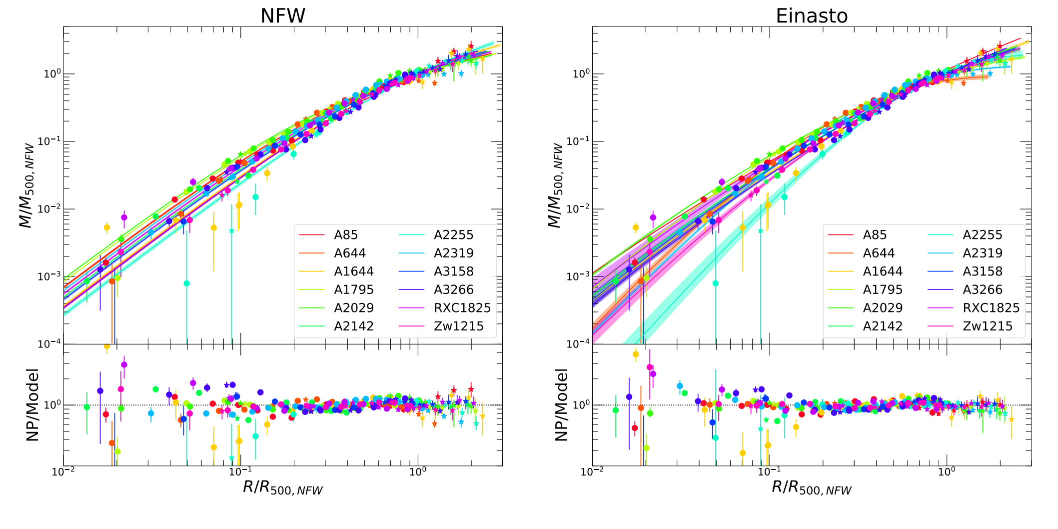
$$P_{3D}(r) = P_0 + \int_r^{r_0} \rho_{gas}\frac{Gf(r'|\theta)}{r'^2}dr'$$

The model pressure can then be projected and convolved with instrumental effects to predict the X-ray spectroscopic temperature profile and the SZ pressure profile.

This tutorial explains how to use *hydromass* and *pyproffit* to fit a mass model to X-ray data from a galaxy cluster under the assumption that the gas is in hydrostatic equilibrium. The chosen example is applied to XMM-Newton observations of the massive galaxy cluster MACS 0451 at z=0.54, which were published in Tam et al. (2020) and was found to be in excellent agreement with the gravitational lensing data.

https://hydromass.readthedocs.io https://pyproffit.readthedocs.io

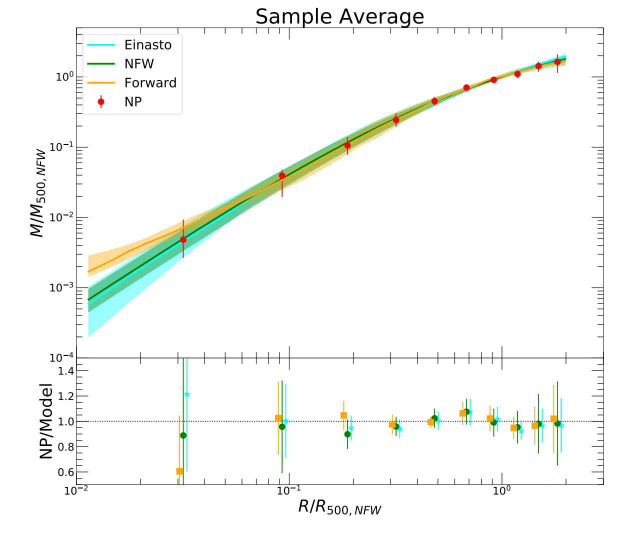
Einasto vs NFW reconstruction



Eckert et al. 2022a

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

NFW closely traces the average mass profiles

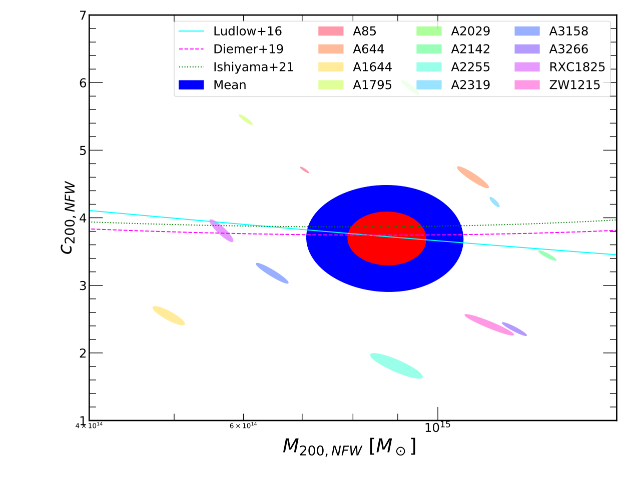


Eckert et al. 2022a

The median profiles look closely like NFW, differences less than 10% at all radii

The mass-concentration relation

In ΛCDM the relation between halo mass and NFW concentration should follow a well know relation

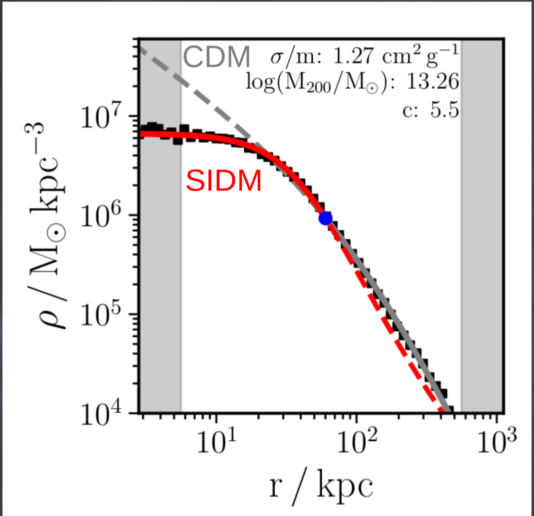


Eckert et al. 2022a

Our measurements exactly match the predictions of the ΛCDM paradigm

Mass profiles in self-interacting DM

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



Robertson et al. 2020

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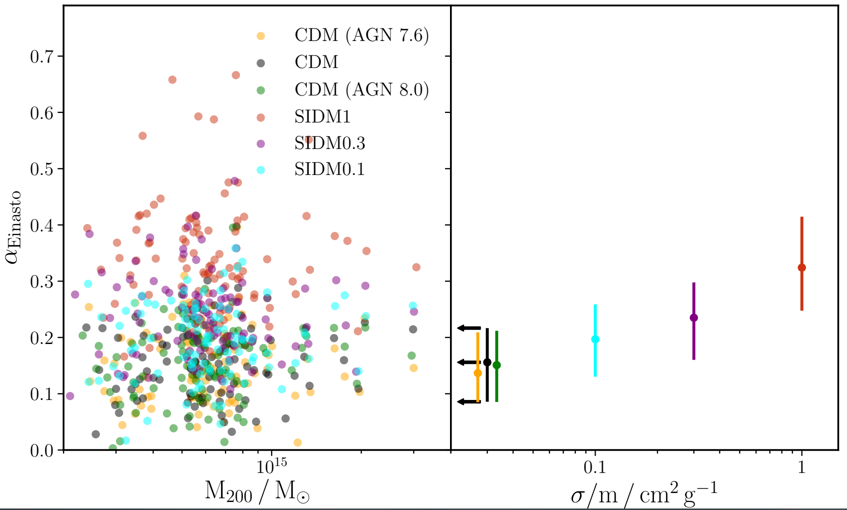
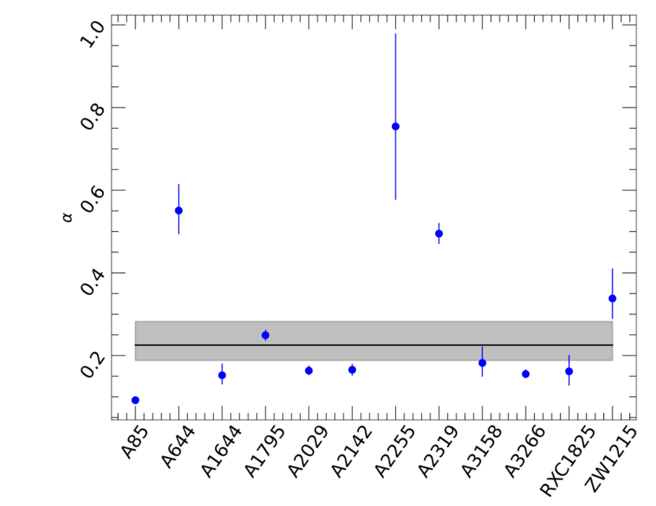


Robertson et al. 2020

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



Eckert et al. 2022b

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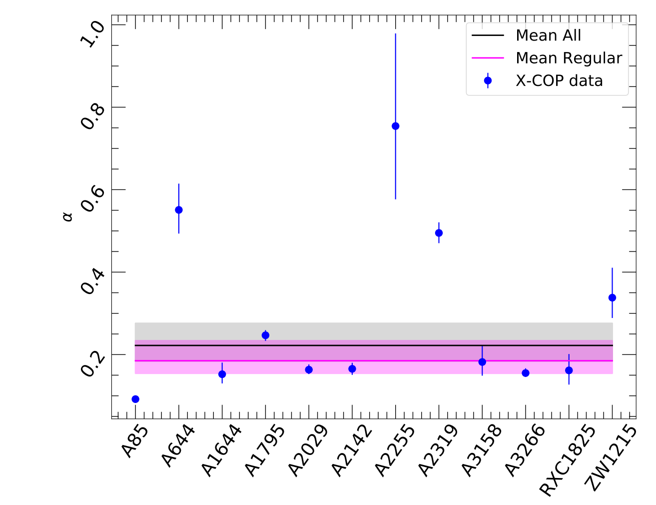
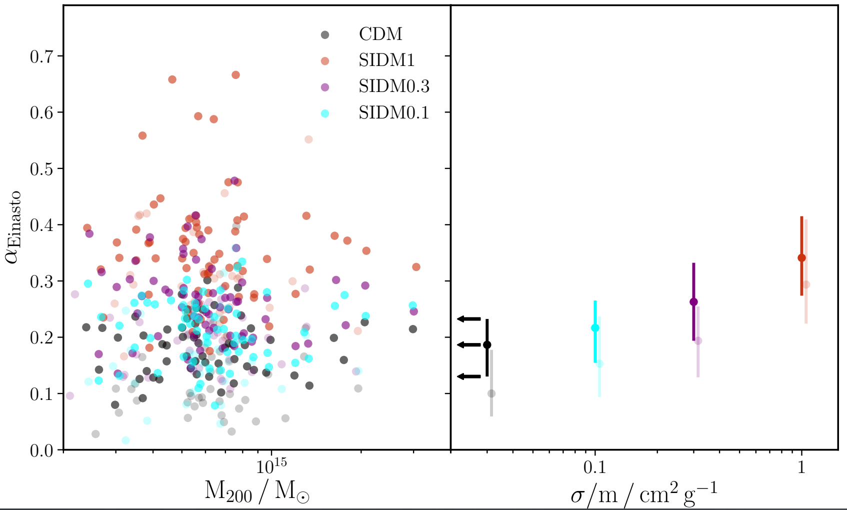


Eckert et al. 2022b

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. 2022b

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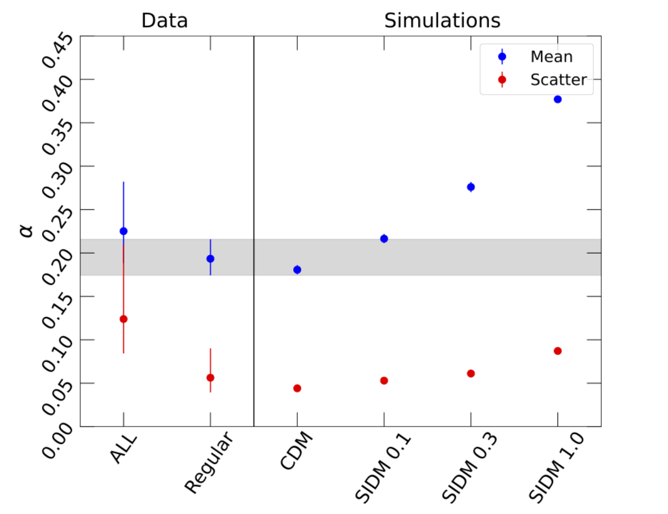
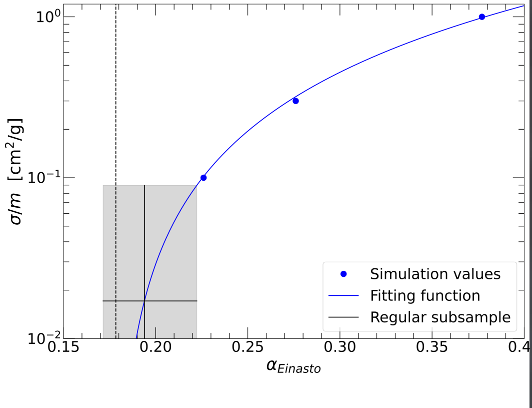


Eckert et al. 2022b

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. 2022b

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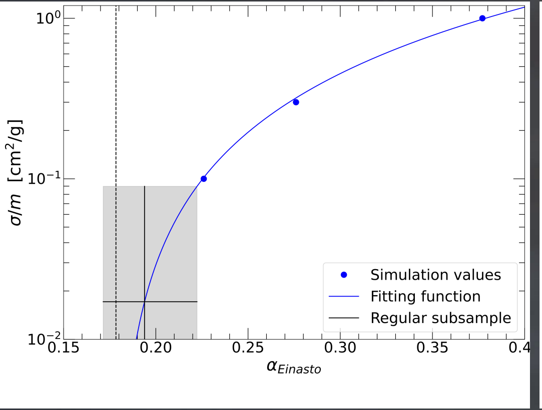
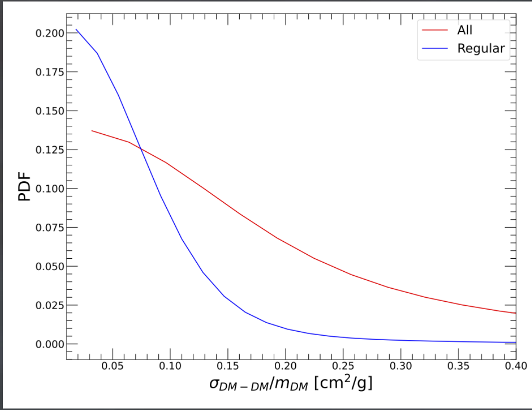


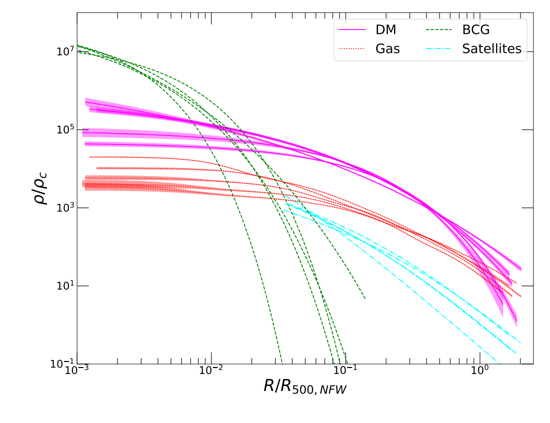


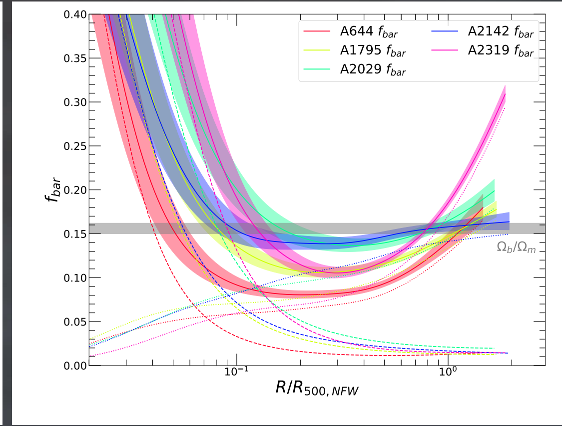
Eckert et al. 2022b

Using the regular sample we set an upper limit $\sigma_{DM-DM} < 0.13$ cm^2/g (90% c.l.)

DM vs baryonic components

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

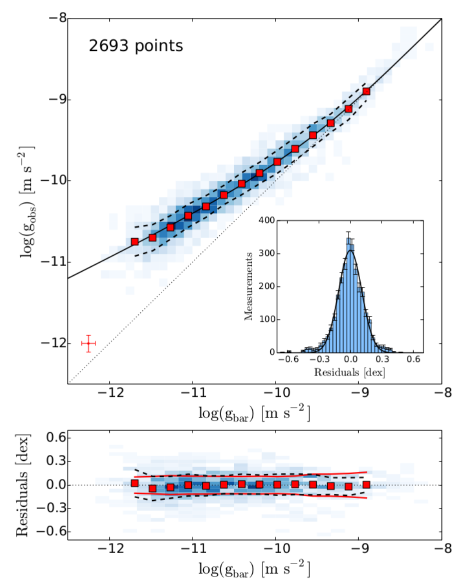




Eckert et al. 2022a

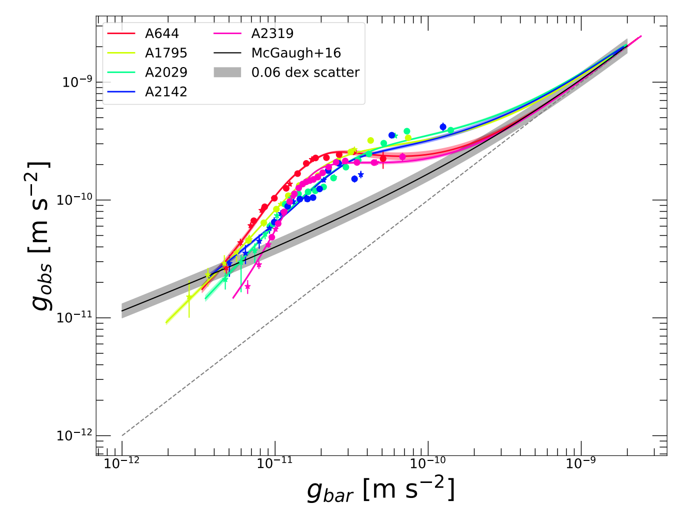
A universal radial acceleration relation?

- 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?

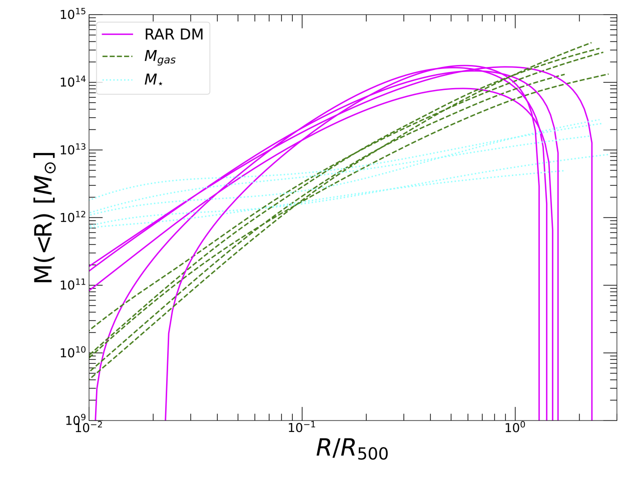


Eckert et al. 2022a

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

A missing mass component in MOND?

Angus et al. (2010) postulate that a missing mass component (e.g. sterile neutrino) in clusters could make up for the missing acceleration



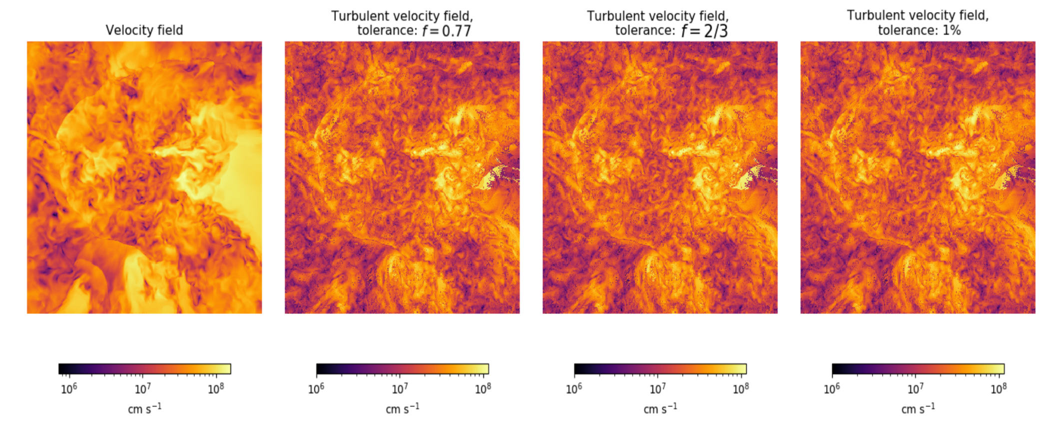
Eckert et al. 2022a

The missing mass should have an *unphysically decreasing* shape on large scales

Beyond hydrostatic equilibrium

In practice the velocity field in clusters cannot be completely neglected

$$\frac{\partial v}{\partial t} + (v \cdot \nabla) v = -\frac{1}{\rho} \nabla P - \nabla \Phi$$



Angelinelli et al. 2020

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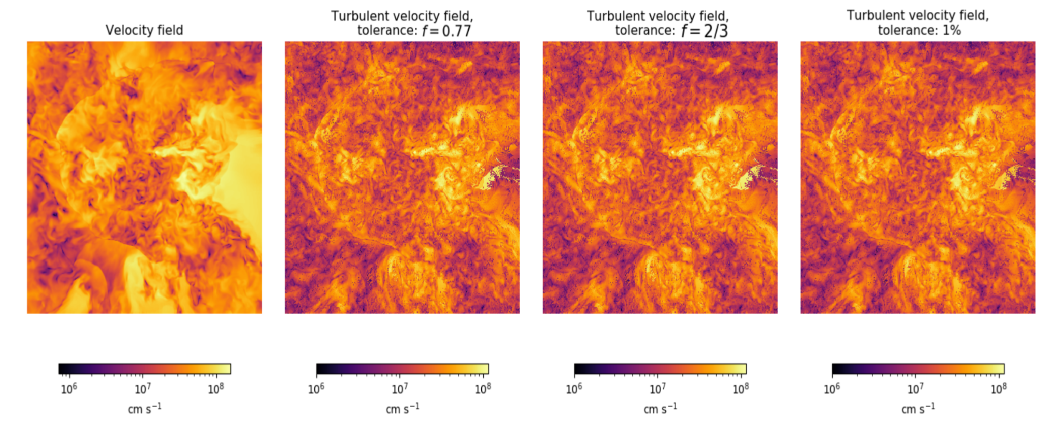
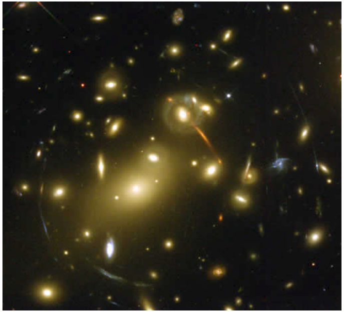


Angelinelli et al. 2020

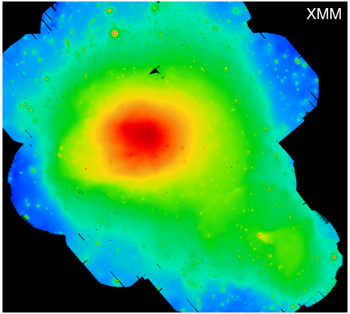
Random gas motions (a.k.a. turbulence) act as an *extra* pressure term

Lensing



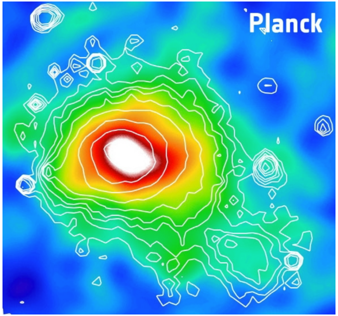
$$\Sigma_{mat} \propto \int_{\parallel} \rho_{mat}\, dl$$

X-ray



$$\epsilon_X \propto \int_{\parallel} n_e^2\, dl \qquad T_X \propto \frac{\int_{\parallel} w\, T\, dl}{\int_{\parallel} w\, dl}$$

SZ

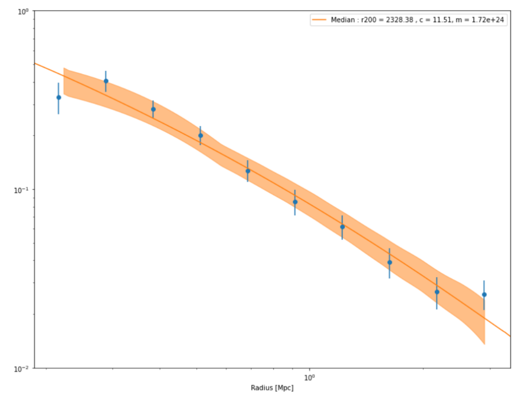


$$y_{SZ} \propto \int_{\parallel} n_e\, T\, dl$$

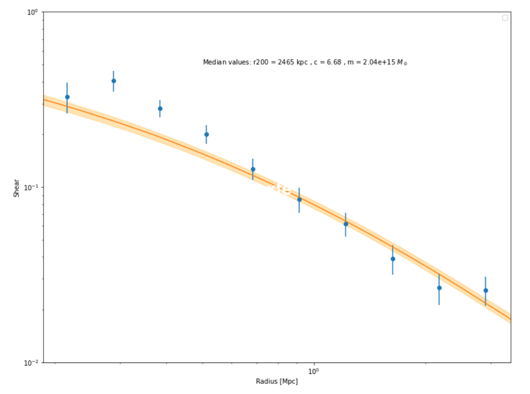
The weak gravitational lensing signal is independent of the hydrostatic assumption; however, strong dependence on l.o.s. structure

Joint analysis with weak lensing and non-thermal pressure

WL only

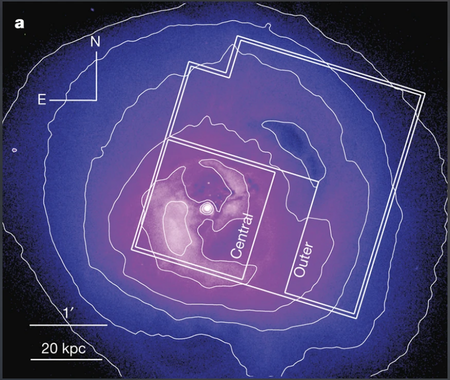


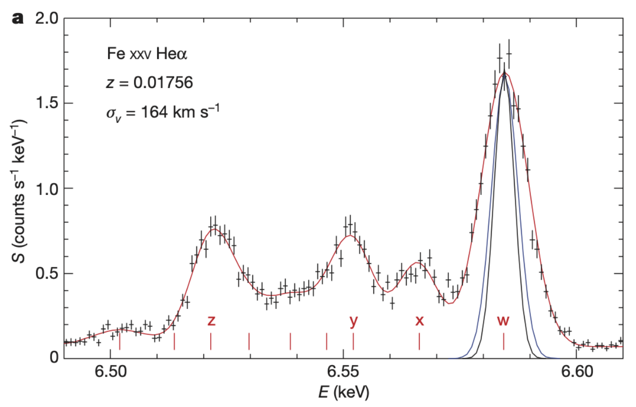
WL+X-ray



A1689, Loris Chappuis's MSc thesis

Hitomi has given us a short preview of the amazing things we can expect from microcalorimeters

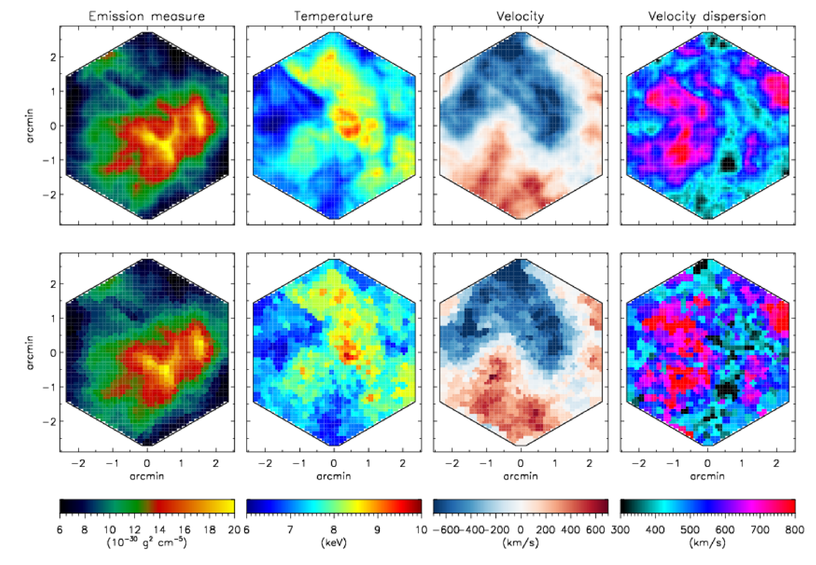




Perseus cluster, Hitomi Collaboration 16

A line broadening of 164 ± 10 km/s is detected; $P_{\rm turb} \approx 4\% P_{\rm thermal}$

Mapping gas motions with Athena/X-IFU

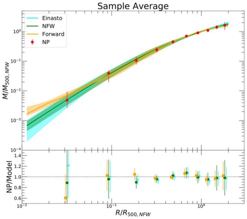


Simulation of a fiducial cluster at z=0.1, Roncarelli et al. 2018

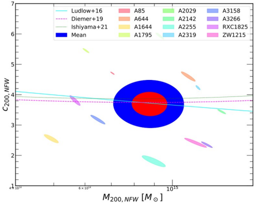
We need the X-IFU to accurately map gas motions and measure accurate DM profiles!

Take home message

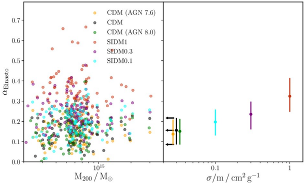
The average mass profiles look closely like an NFW, with deviations smaller than 10 % at all radii



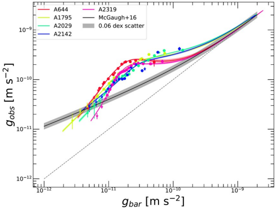
The structural properties of galaxy clusters closely match ΛCDM predictions



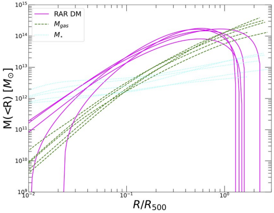
The Einasto index α is sensitive to the dark matter self-interaction cross section ; we set $\sigma_{DM\text{-}DM} < 0.13\ cm^2/g$ (90 % c.l.)



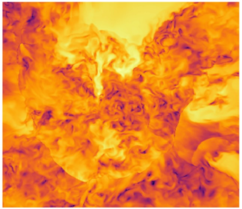
The relation between baryonic and total acceleration is not a fundamental property of gravity



The shape of the measured gravitational field is inconsistent with MOND predictions

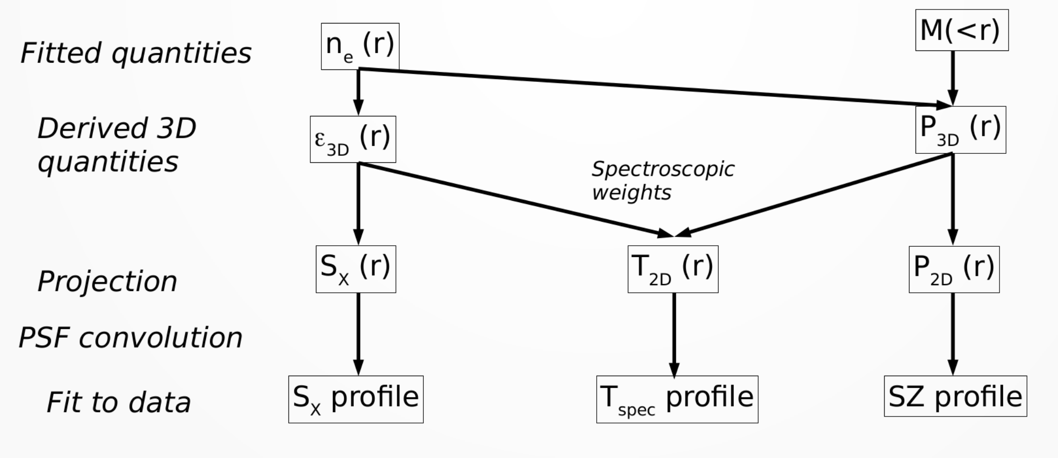


We need Athena/X-IFU to determine the velocity field and accurately measure the gravitational field



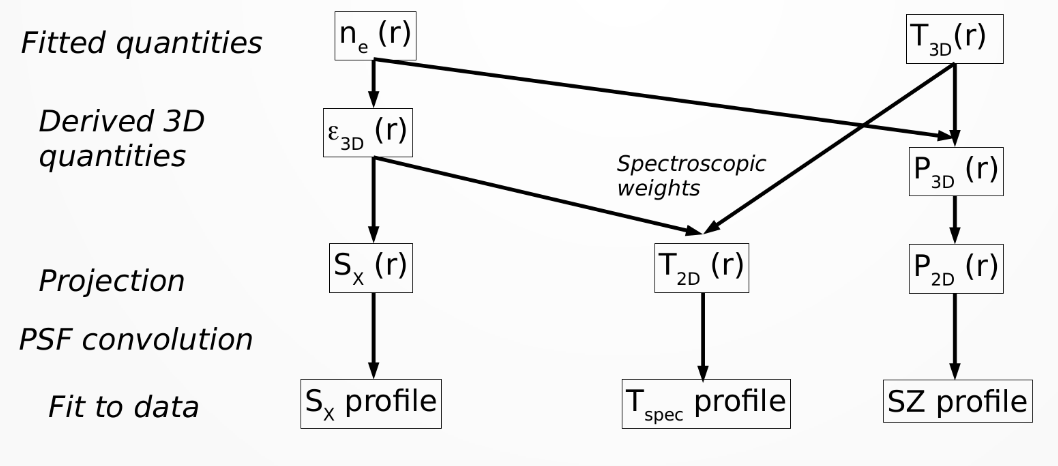
Backup Slides

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

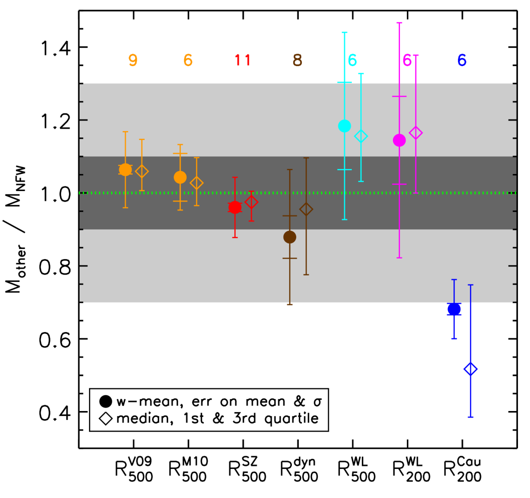
Non-parametric lognormal mixture reconstruction



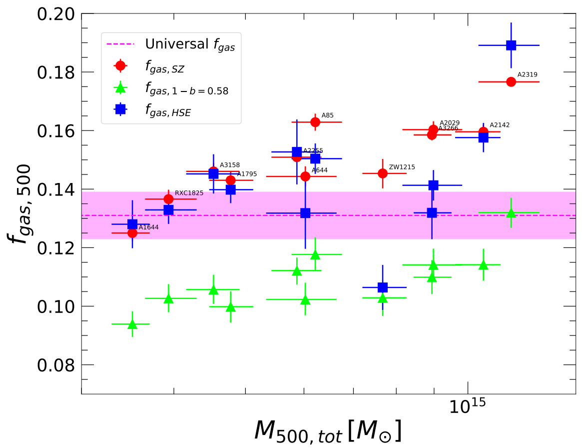
As a comparison point we apply a *non-parametric* method by describing the 3D temperature profile as a linear combination of Gaussians

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

HSE bias in X-COP clusters



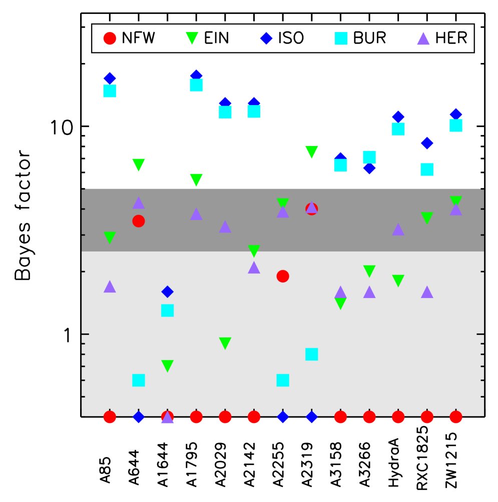
Ettori et al. 2019

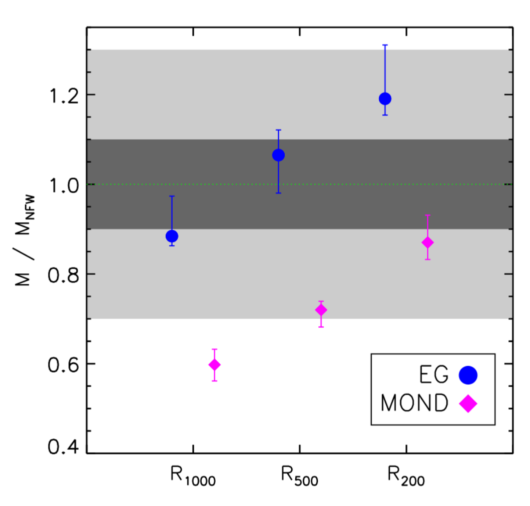


Eckert et al. 2019

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



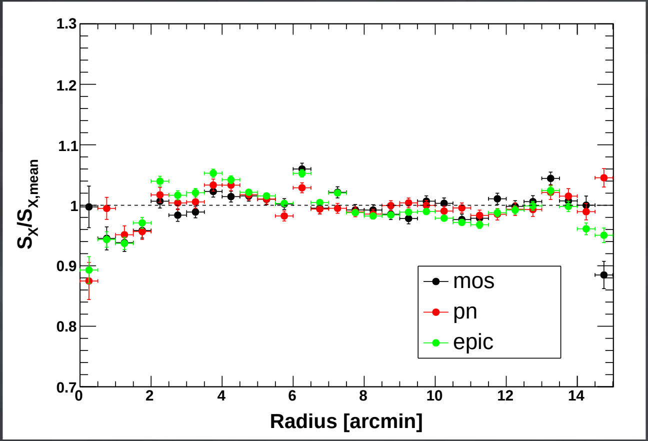


Ettori, DE, et al. 2019

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

Beating systematics in background subtraction

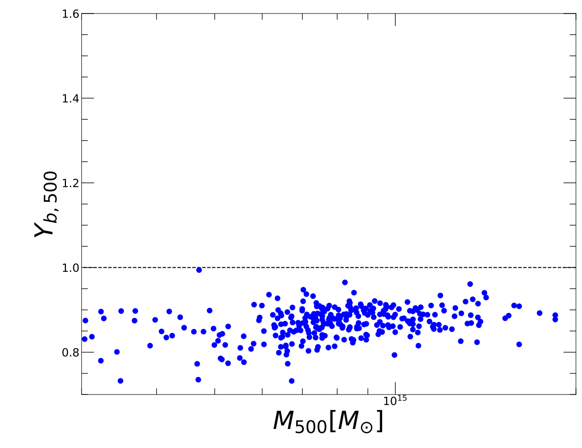
We analyzed a set of ~ 500 blank-sky XMM pointings and estimated the reproducibility of the background



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



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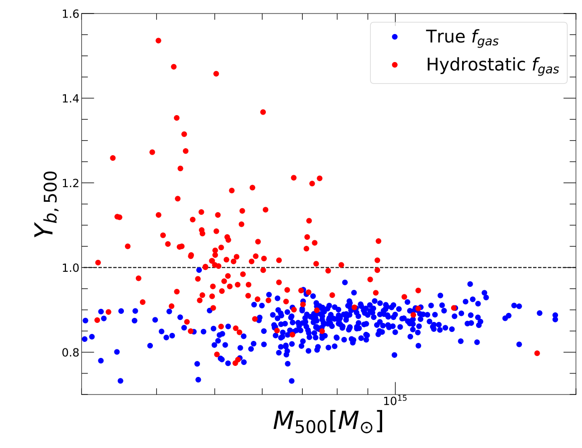
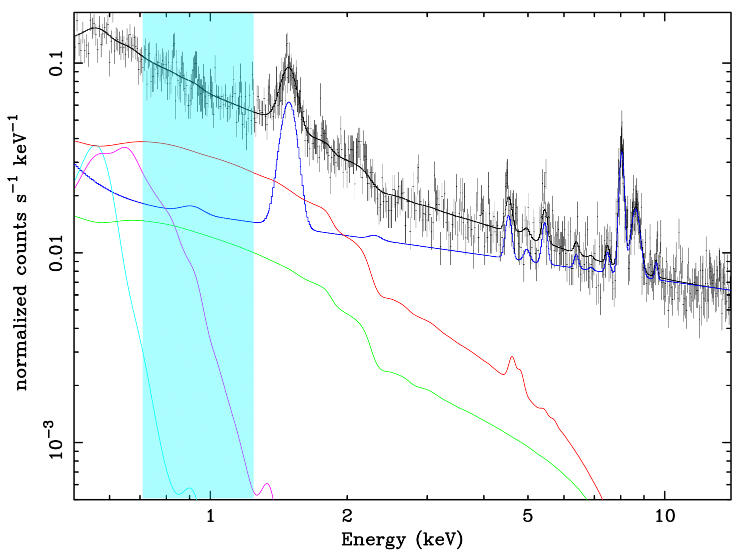


- The value of Y_{bar} is nearly independent of the adopted baryonic physics (Planelles et al. 2014)
- Considering the (well-measured) stellar fraction, we set $f_{gas} = Y_b \frac{\Omega_b}{\Omega_m} - f_\star$

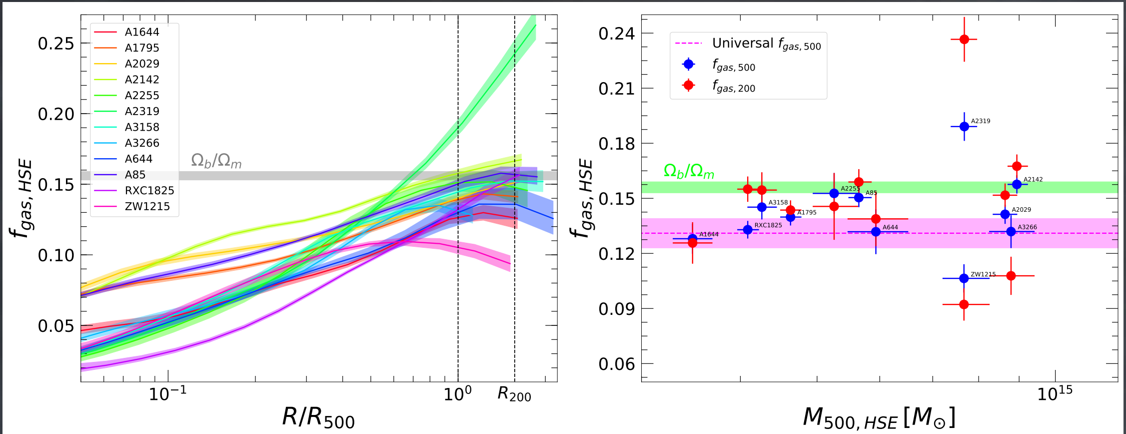
The X-COP strategy

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

Testing hydrostatic equilibrium with f_{gas}

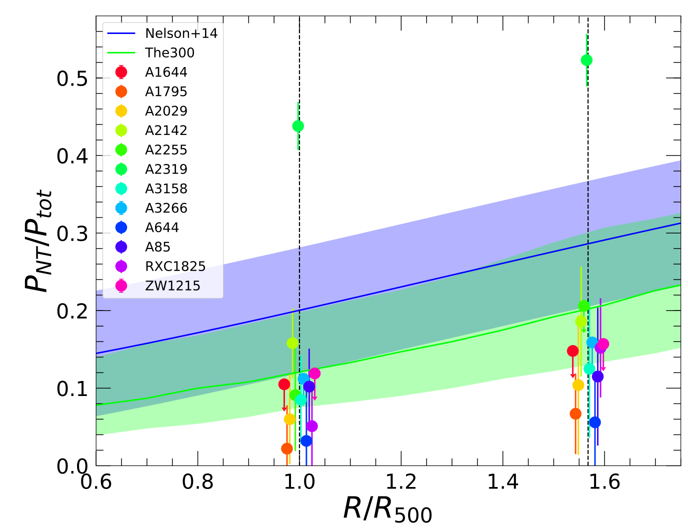


Eckert et al. 2019

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

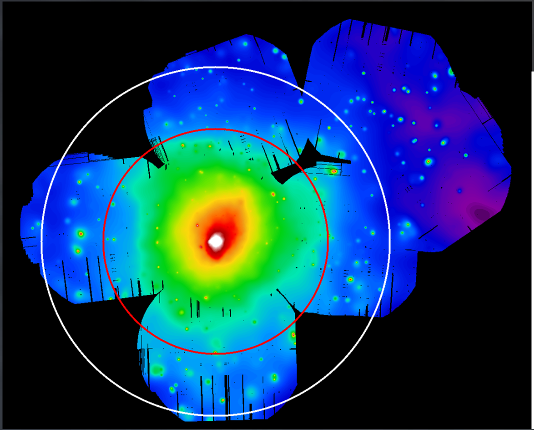


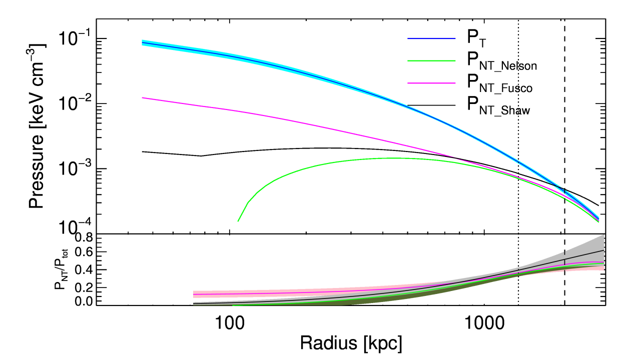
Eckert et al. 2019

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

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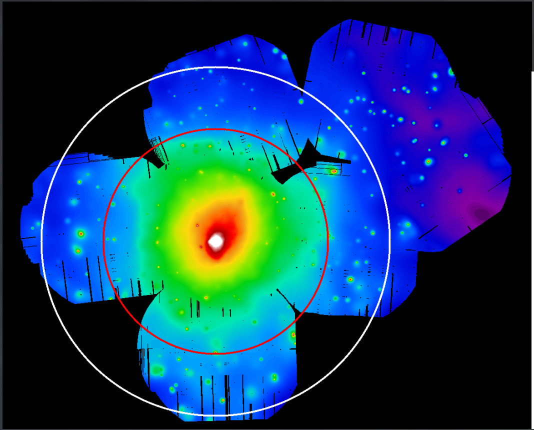
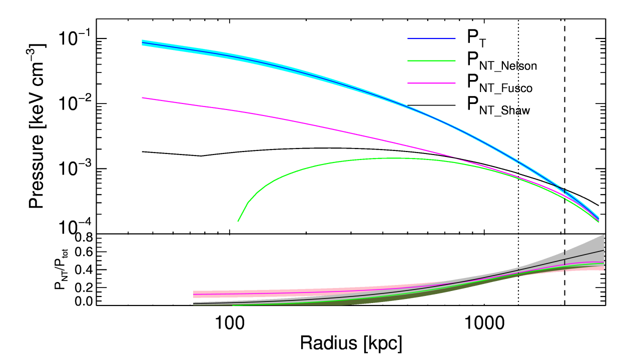


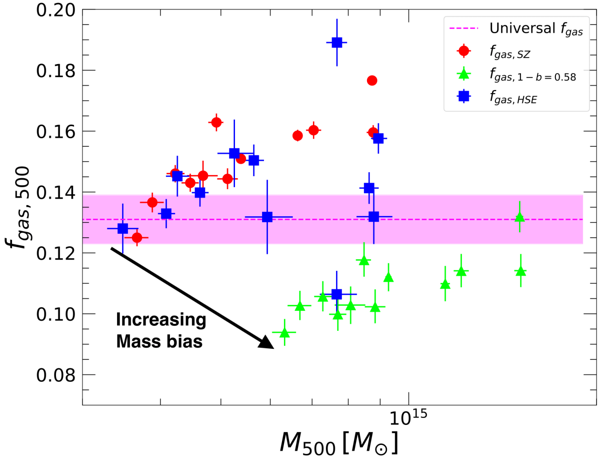


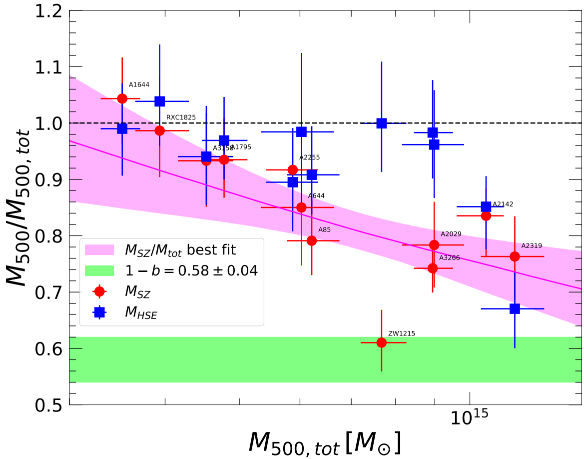
Ghirardini, Ettori, DE et al. 2018

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 $f_{gas} = 10.5\%$