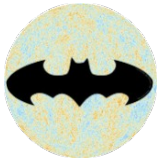
CHEX-MATE: towards a consistent universal pressure profile and cluster mass reconstruction

M. Muñoz Echeverría, et al.
CHEX-MATE and BATMAN collaborations



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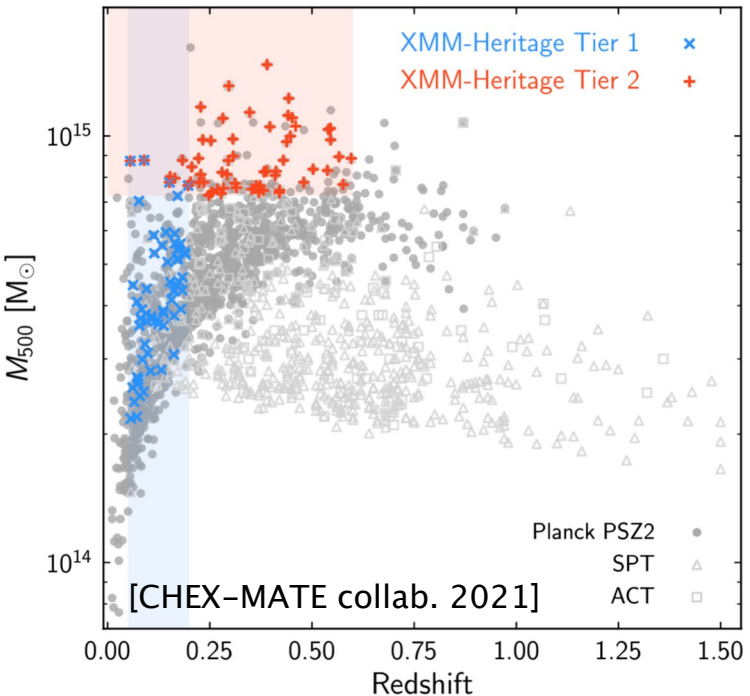
CHEX-MATE

The Cluster HEritage project with XMM-Newton: Mass Assembly and Thermodynamics at the Endpoint of structure formation



118 SZ selected clusters (PSZ2 SNR>6.5)

PIs: M. Arnaud/G. W. Pratt – S. Ettori

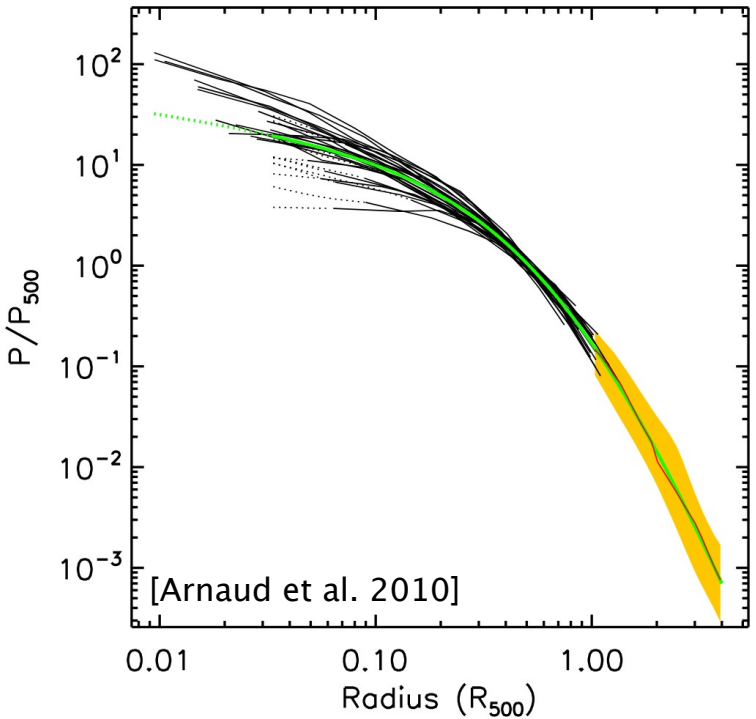
(some) Objectives:

- Understand interplay between gravitational collapse and baryonic effects
- Consistent picture of cluster mass estimates

→ Talk by S. Ettori

The universal pressure profile (UPP)

Clusters are self-similar when scaled in mass and redshift



Why important?

Used in:

- Cluster detection algorithms
- tSZ power spectrum cosmological analysis

But, P_{500} and R_{500} are functions of M_{500}

- Need to assume M_{500} to scale the profiles
- Which M_{500}?

Objectives

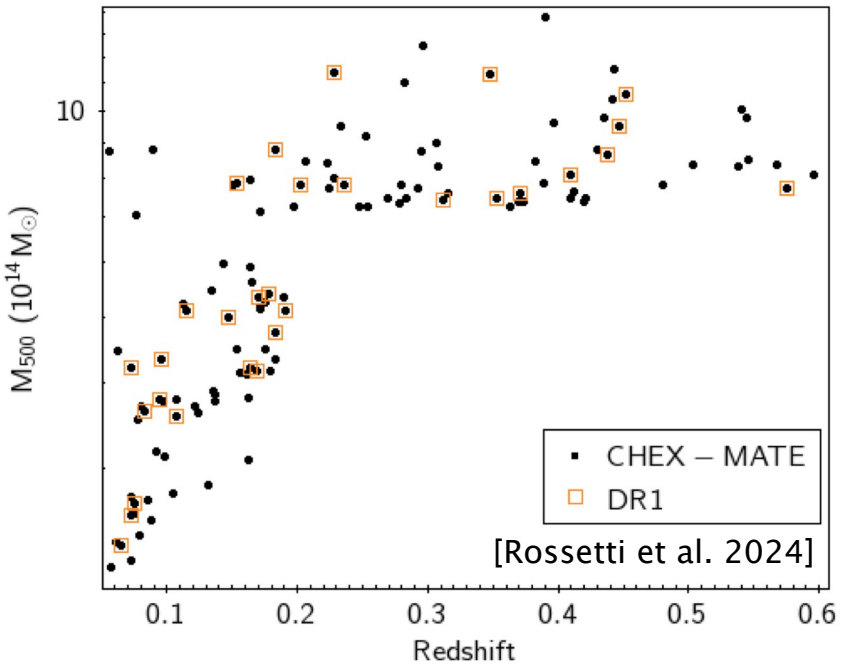
Towards the universal pressure profile with CHEX-MATE

- Build a **framework** for a consistent estimation of the **universal pressure profile (UPP)**
- Use the **best cluster M_{500} masses** to normalise the profiles
- **Propagate** the **uncertainties** of M_{500} and account for their **correlation** with the UPP
- **(Propagate** their impact on the estimation of the **tSZ PWS** and its use for **cosmology)**

Data and sample

Pressure profiles and M_{500} estimates

24 DR1 clusters



Thermal pressure profiles:

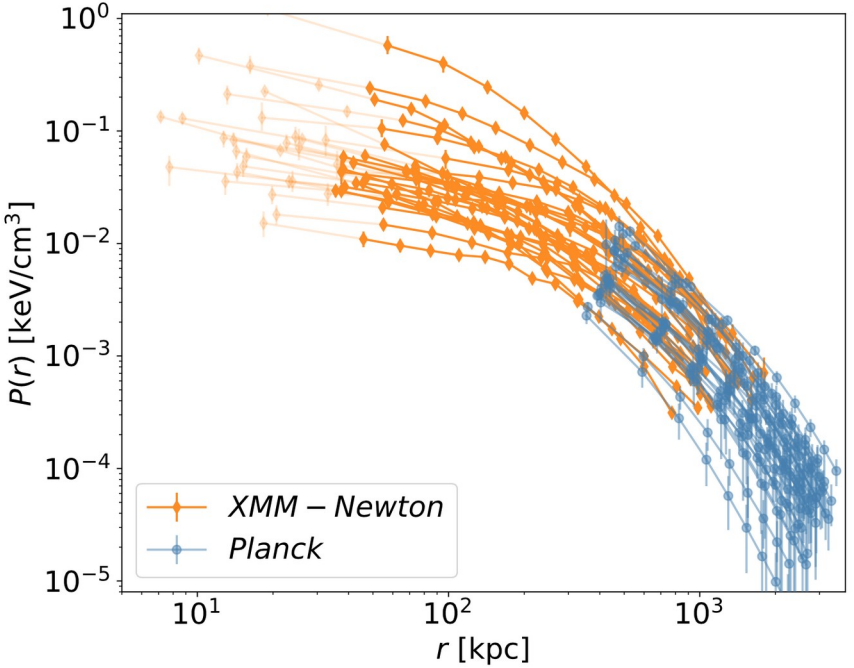
- XMM-Newton + Planck profiles
- Radial coverage: from 0.03 to 2.5 R_{500}

Individual cluster M_{500} estimates:

- Dynamical masses from Sereno et al. 2025

Data and sample

Pressure profiles and M_{500} estimates



Thermal pressure profiles:

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Model

$$P(r) = P_{500} \times \mathbb{P}(x)$$

$$x = r/R_{500}$$

$$P_{500} \propto M_{500}^{\delta}$$

A mass estimate M_{500} **per cluster**

The P_{500}–M_{500} scaling
If self-similar $\delta = 2/3$

Model

$$P(r) = P_{500} \times \mathbb{P}(x)$$

$$\mathbb{P}(x) = \frac{P_0}{(c_{500}x)^{\gamma}\,[1 + (c_{500}x)^{\alpha}]^{(\beta-\gamma)/\alpha}}$$

gNFW model for the UPP

Model

$$P(r) = P_{500} \times \mathbb{P}(x)$$

+ Intrinsic scatter with respect to the UPP: $\sigma_{\rm int}$

$$\sigma_{\rm int}(x) = \sigma_1 \exp\left[-\omega x\right] + \sigma_0 x$$

With a correlation length $\mathcal{L}_{\rm int}$

+ Ratio between X-ray and tSZ pressure: η_T

$$\eta_T \sim P^{\rm X} / P^{\rm tSZ}$$

Joint fit of the UPP and individual M_{500}

Free parameters of the model:

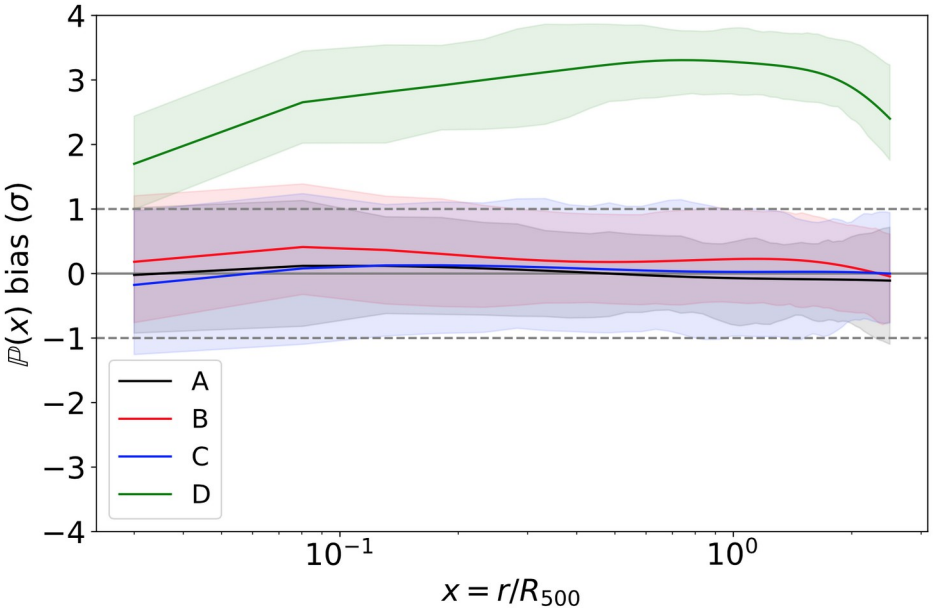
- **Global** parameters: P_{500}–M_{500} scaling relation (δ), gNFW, σ_{int}, L_{int}, η_T
- **Individual** parameters: mass M_{500} per cluster

Accounting for correlations and improving both $\mathbb{P}(x)$ and M_{500}

Strong correlations between parameters: priors on M_{500} needed

Validation on mock profiles

Joint fit of UPP and individual M_{500}



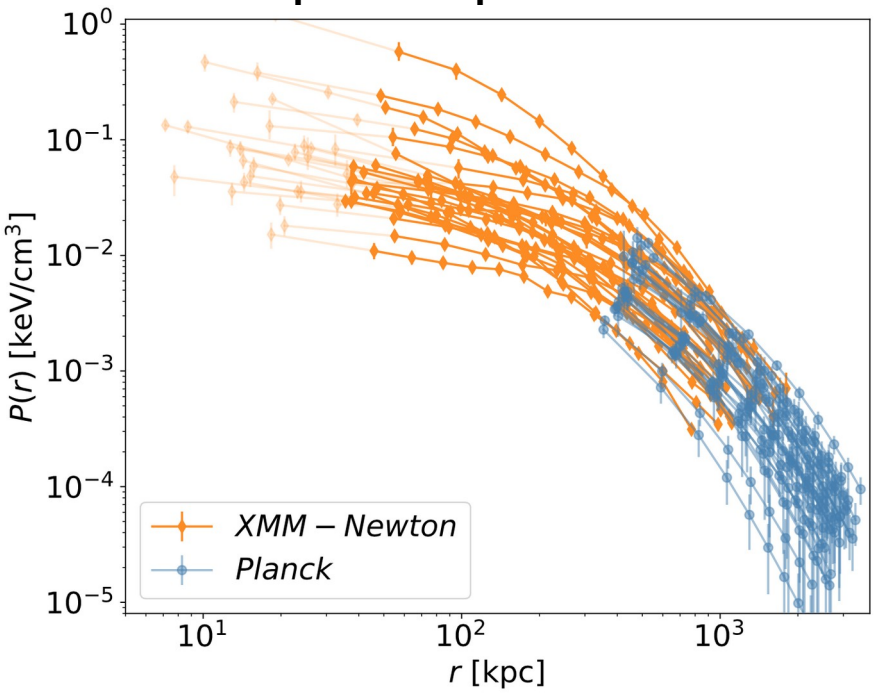
- (A) M_{500} priors centred on true M_{500}, δ fixed
- (B) M_{500} priors centred on true M_{500}, δ free
- (C) M_{500} priors scattered with respect to true M_{500}, δ fixed
- (D) M_{500} priors biased with respect to true M_{500}, δ fixed

With unbiased & scattered M_{500} priors: we recover unbiased UPP and M_{500}

Joint UPP and M_{500} measurement

Fit to CHEX-MATE data with dynamical M_{500} priors

Thermal **pressure profiles**

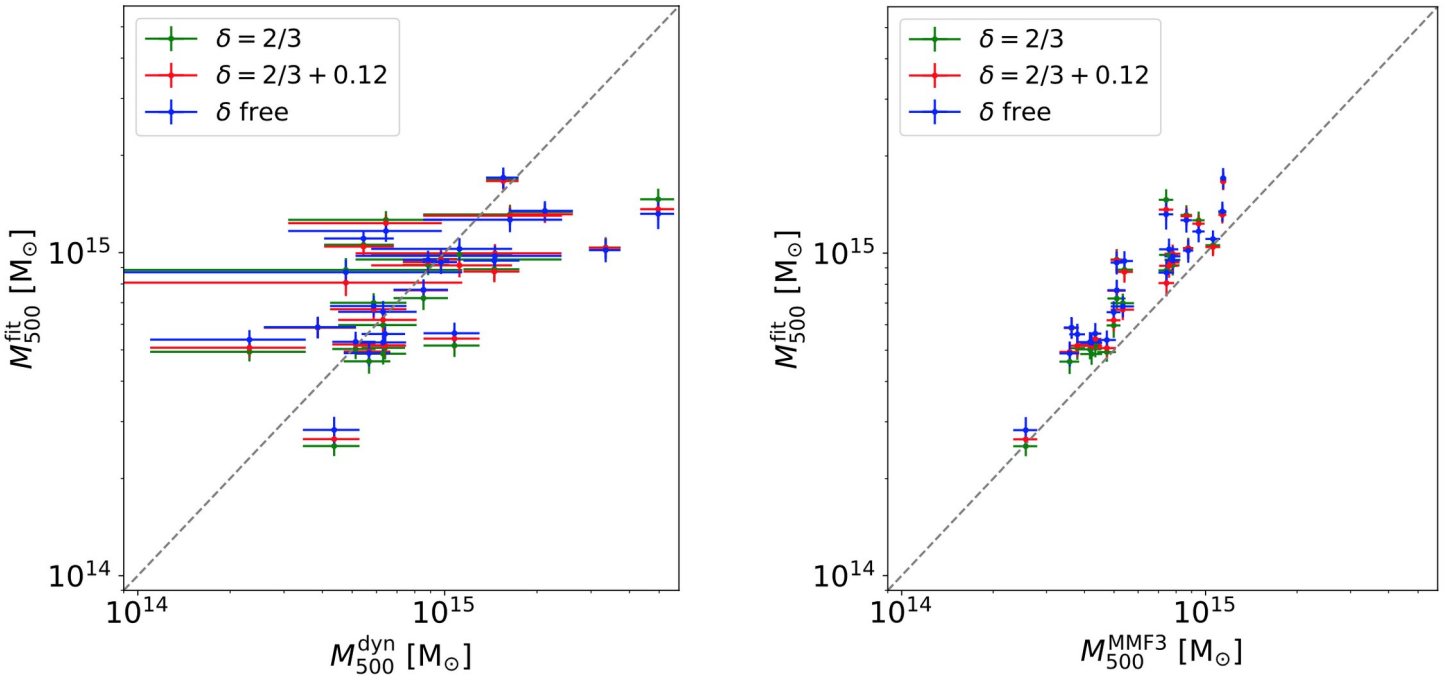


Gaussian **priors** on M_{500}, centred on their **dynamical** estimates from Sereno et al. 2025

- Scattered, but (almost) no bias
- (almost) Uncorrelated to pressure profiles

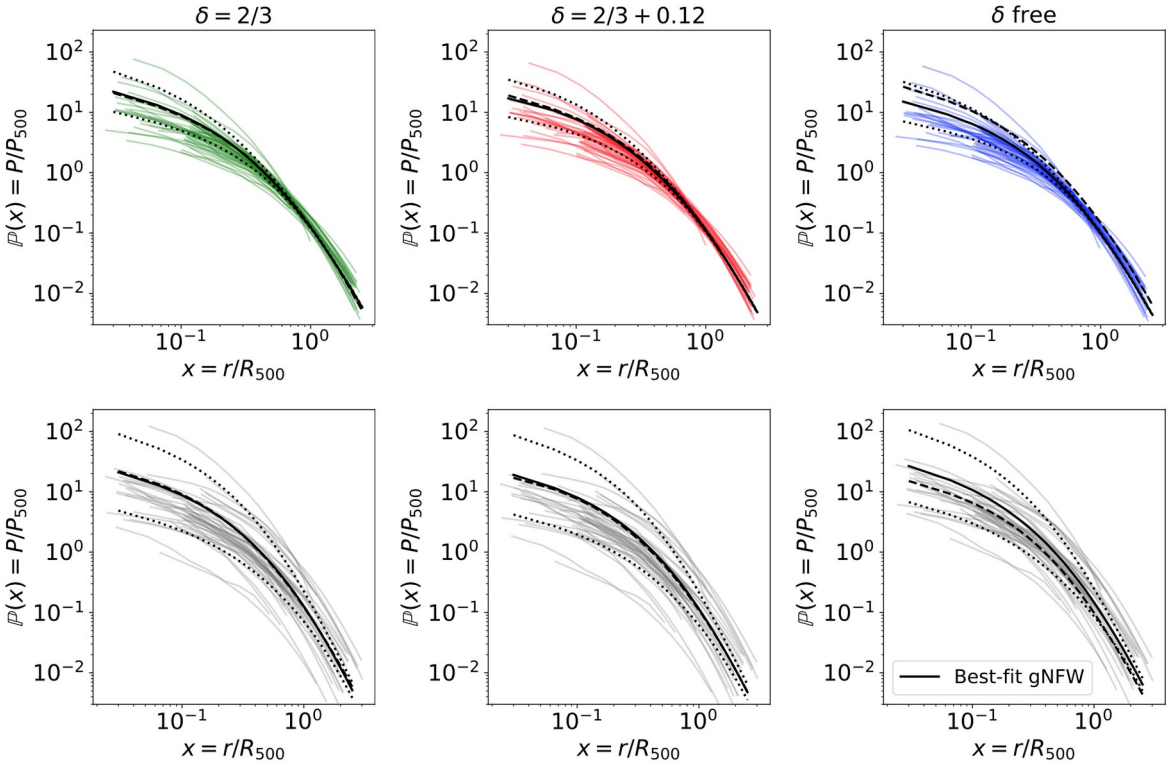
Joint UPP and M_{500} measurement

Fit to CHEX-MATE data with dynamical M_{500} priors



Dynamical M_{500} are refined to scale the pressure profiles the best

Joint UPP and M_{500} measurement



M_{500} fitted

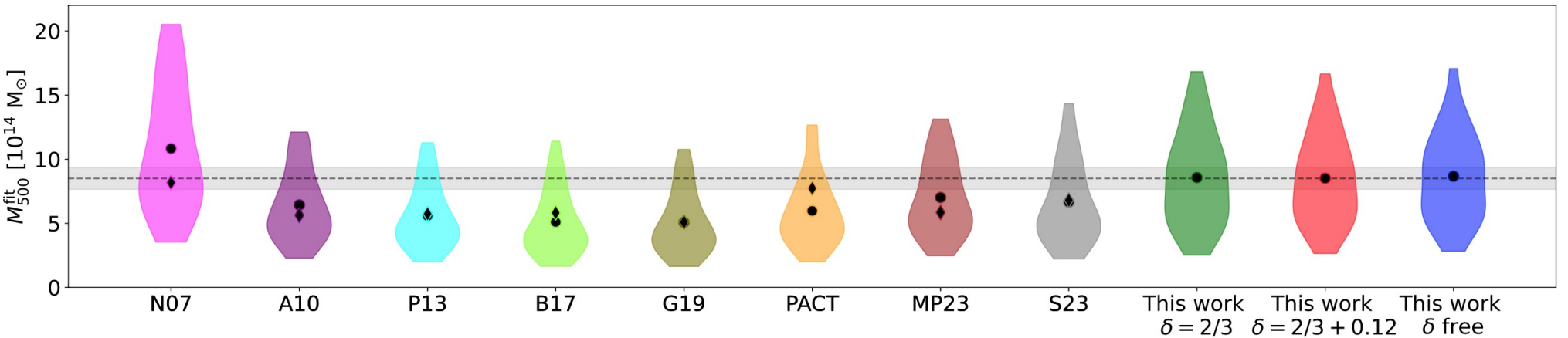
M_{500} fixed

Refined M_{500}: same accuracy and better precision

M_{500} uncertainties propagated to the UPP

Impact of the UPP on the M_{500} determination

Fitting M_{500} by assuming UPPs from the literature



Impact of the UPP shape and δ on the measured signal
→ **coherent UPP, δ, and M_{500} needed for unbiased cosmology!**

Coherence-check: when UPP fixed to A10, compatible with MMF3

Summary & conclusions

- Framework to jointly fit the UPP and clusters' M_{500}
  - Dynamical M_{500} as priors: **scattered & unbiased**, **uncorrelated** to pressure
  - **Improve M_{500}** based on the thermal pressure distribution
  - **Propagate** the M_{500} **uncertainties** to the UPP → cosmology
- **Strong correlation** between UPP and M_{500}: **self-consistent** framework **needed**

Backups

Covariance matrix modelling

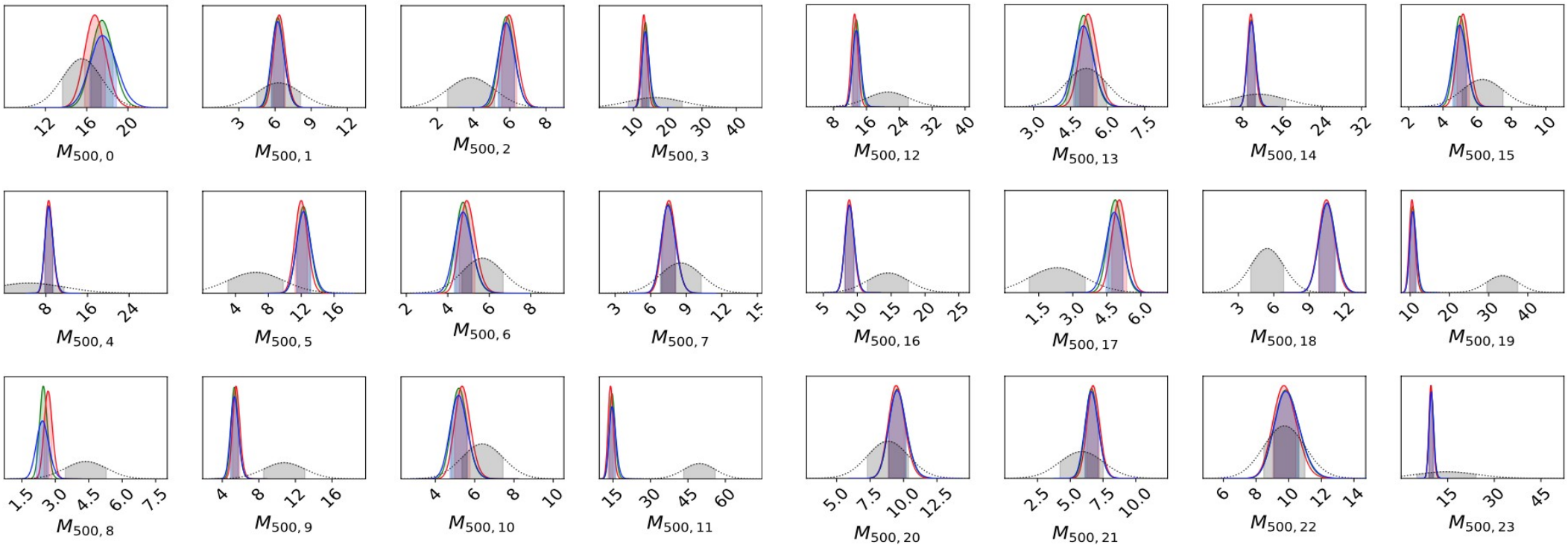
$$C_i(\theta) = \Sigma_{\text{data},i} + \Sigma_{\text{int},i}(\theta)$$

Intrinsic scatter covariance matrix:

$$\begin{aligned}\Sigma^{k,k}_{\text{int},i}(\theta) &= \left[P_{\text{mod},i}(r_{i,k},\theta) \times \sigma_{\text{int}}(r_{i,k},\theta)\right]^2 \\ &= \left[P_{500,i}(\theta)\ \mathbb{P}(r_{i,k},\theta) \times \sigma_{\text{int}}(r_{i,k},\theta)\right]^2\end{aligned}$$

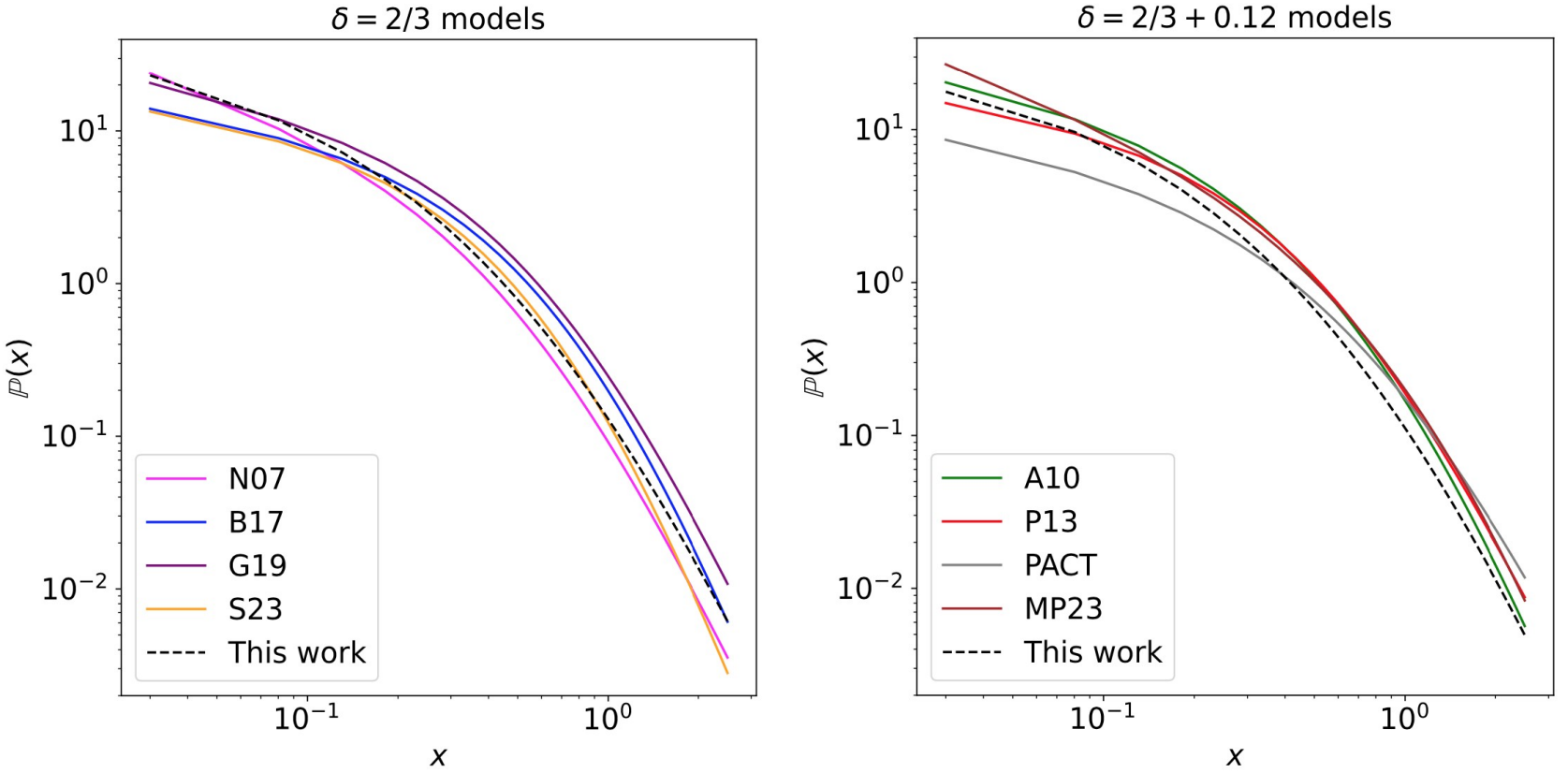
$$\Sigma^{k,l}_{\text{int},i}(\theta) = \sqrt{\Sigma^{k,k}_{\text{int},i}\Sigma^{l,l}_{\text{int},i}}\exp\left[-\frac{(x_{i,k}-x_{i,l})^2}{2L^2_{\text{int}}}\right]$$

Individual cluster masses

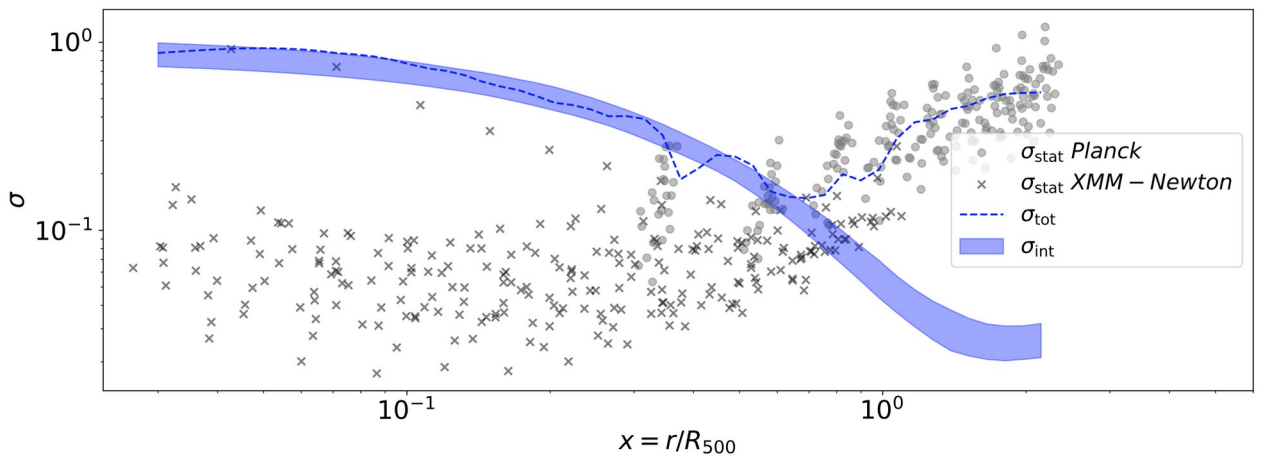


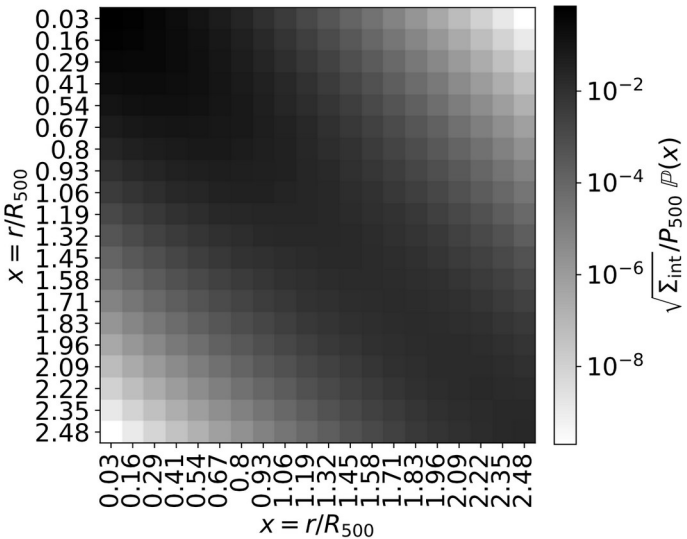
Posterior distributions

Universal Pressure Profiles



Intrinsic scatter





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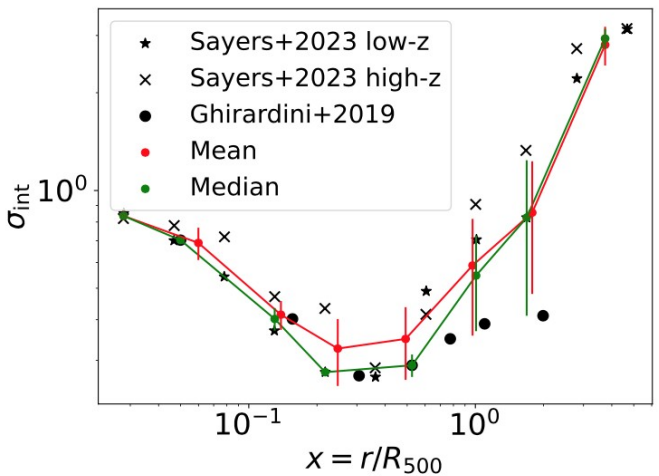

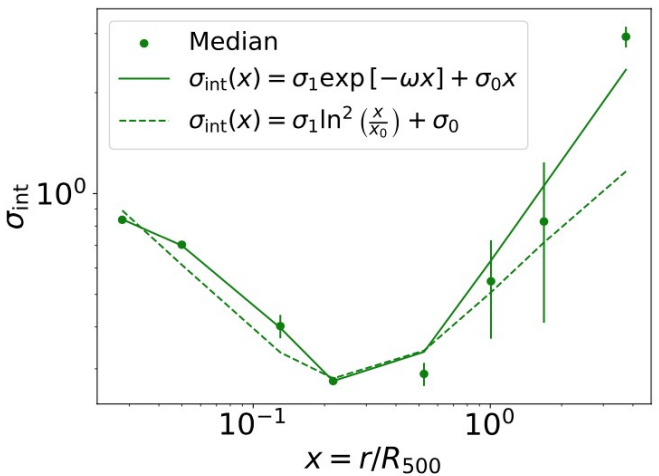

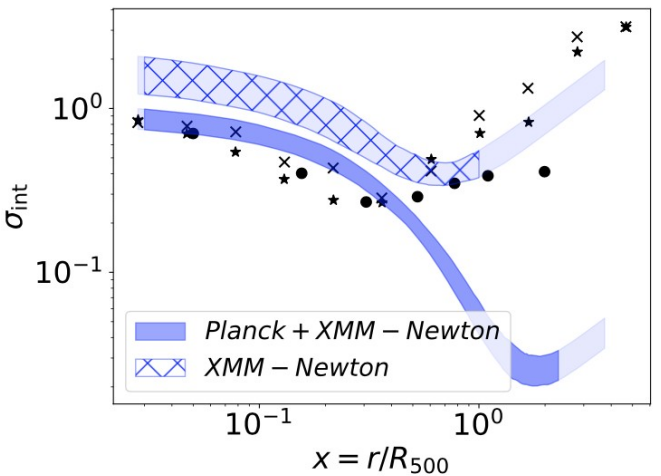

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Joint fit of UPP and individual M_{500}