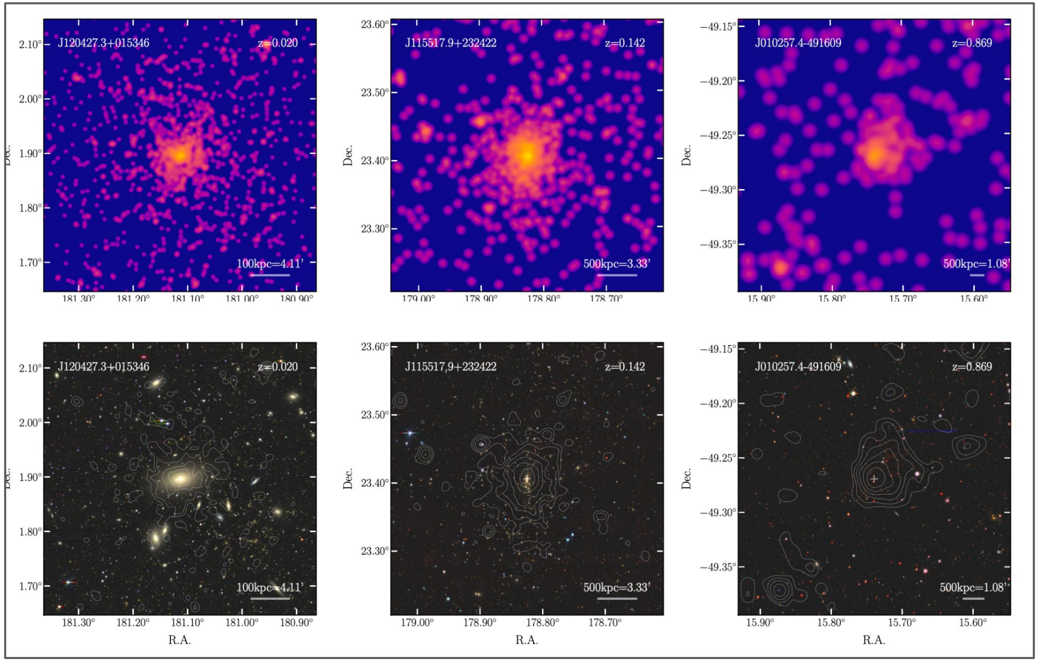
Modeling Population(s) of Galaxy Clusters

August (Gus) Evrard

Depts. of Physics and Astronomy,
Leinweber Center for Theoretical Physics
University of Michigan, Ann Arbor

First Results from the SRG/eROSITA All-Sky Survey: From Stars to Cosmology
Garching, Germany
18 September 2024



Bulbul+ 2024, A&A

Congratulations to Esra and the eRosita cluster team for all their efforts to publish the eRASS1 cluster catalog!

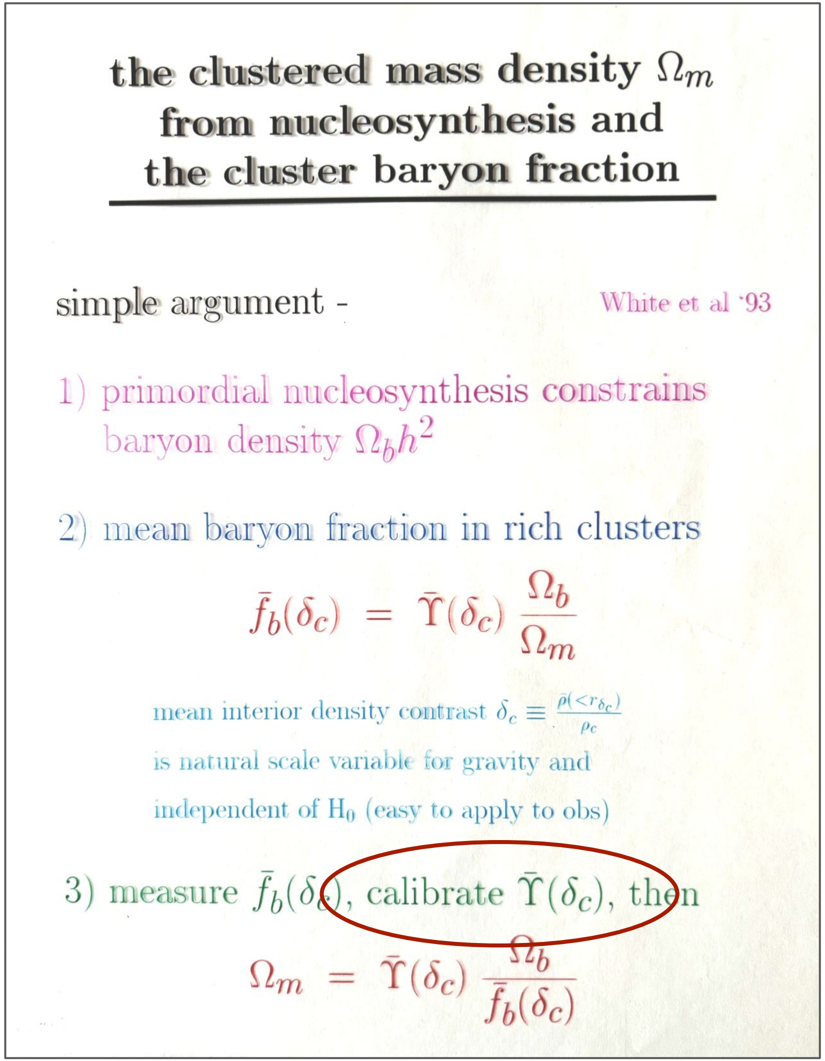
From the archives (literally…)

Image of a transparency from a 1998 talk

ROSAT observations had measured Coma’s baryon fraction

Briel, Henry + Bohringer 1992

How well would cluster gas trace the cosmic ratio? *Need Upsilon-bar!*



the clustered mass density Ω_m from nucleosynthesis and the cluster baryon fraction

simple argument -

White et al '93

1) primordial nucleosynthesis constrains baryon density $\Omega_b h^2$

2) mean baryon fraction in rich clusters

$$\bar{f}_b(\delta_c) = \bar{\Upsilon}(\delta_c)\,\frac{\Omega_b}{\Omega_m}$$

mean interior density contrast $\delta_c \equiv \frac{\bar{\rho}(<r_{\delta_c})}{\rho_c}$

is natural scale variable for gravity and

independent of H_0 (easy to apply to obs)

3) measure $\bar{f}_b(\delta_c)$, calibrate $\bar{\Upsilon}(\delta_c)$, then

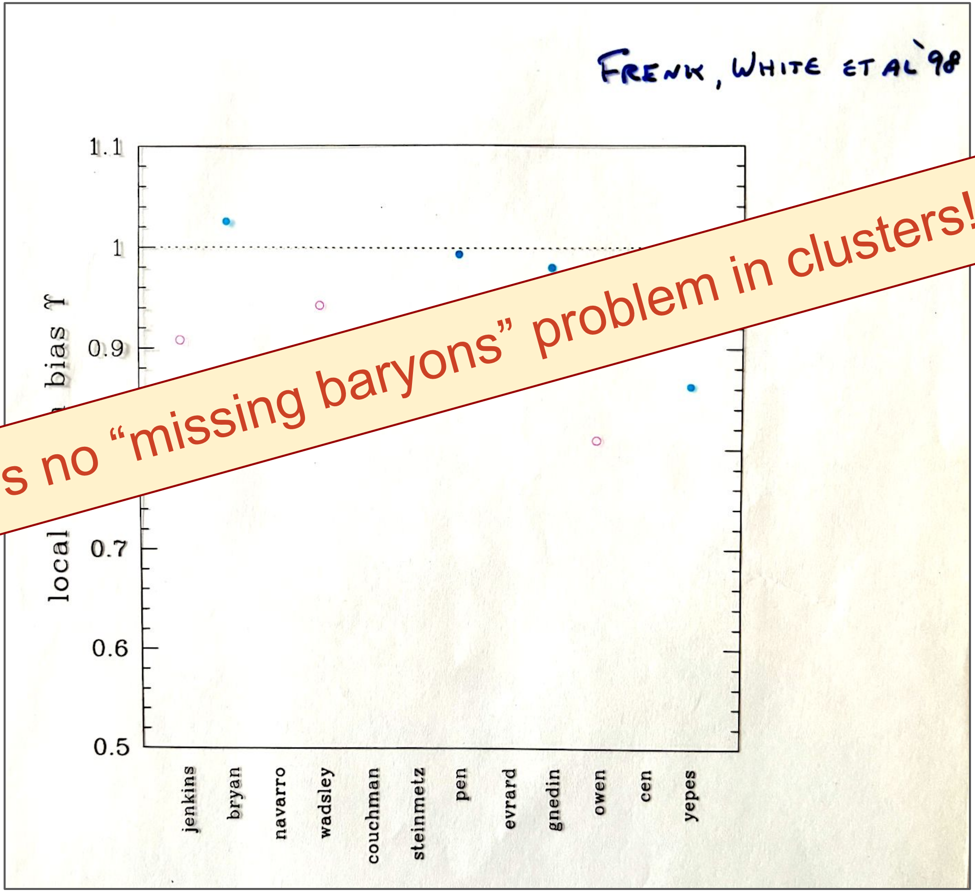
$$\Omega_m = \bar{\Upsilon}(\delta_c)\,\frac{\Omega_b}{\bar{f}_b(\delta_c)}$$

From the archives…

Image of a transparency from a 1998 talk

Multiple simulators had run the reference "Santa Barbara cluster"
Frenk et al 1999

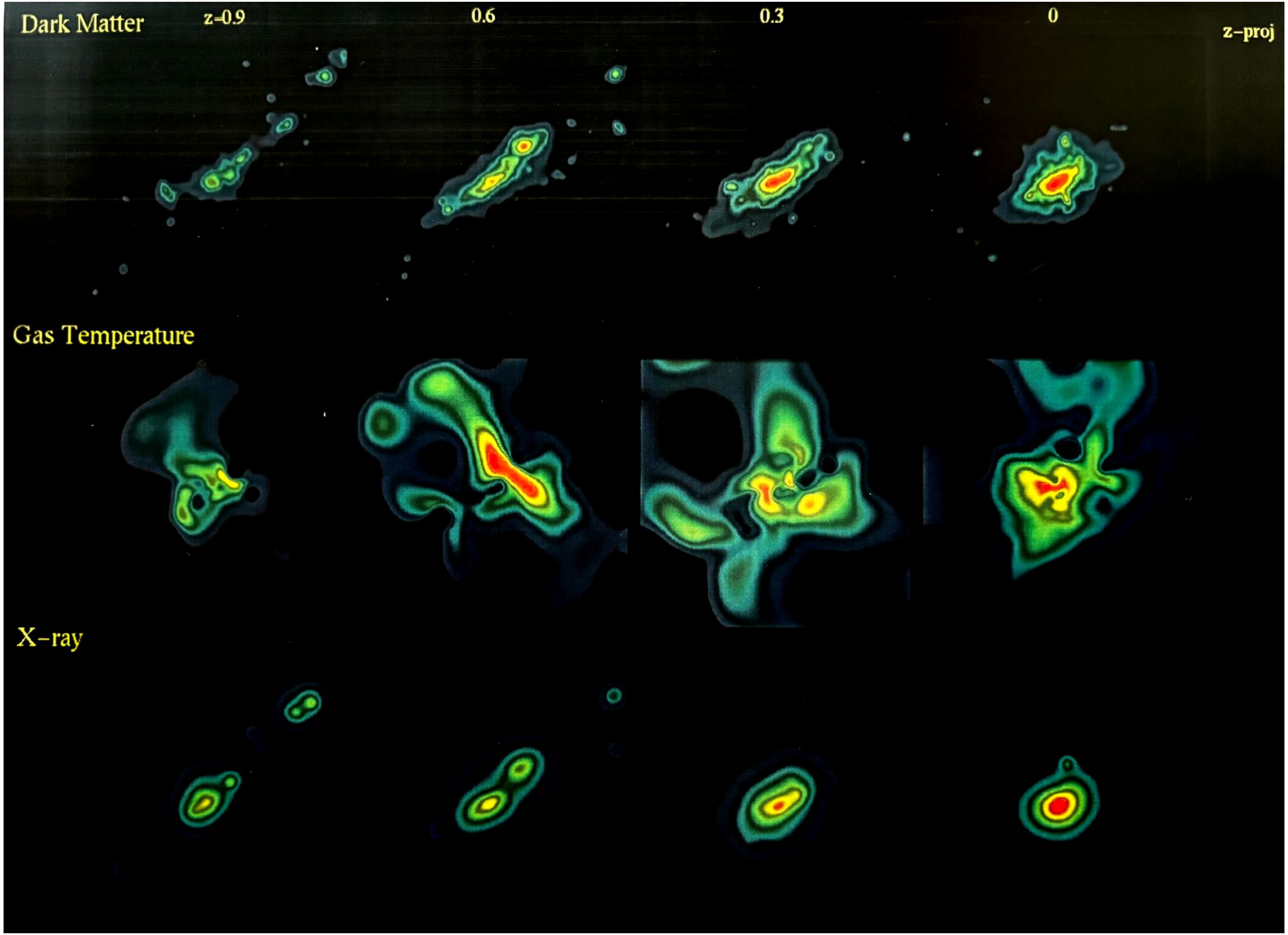
Local baryon fraction not strongly biased wrt the cosmic value
    Upsilon-bar ~ 1



There's no "missing baryons" problem in clusters!

From the archives…

Insights into component dynamics and thermal structure



Evrard & Gioia 1998

The Galaxy Cluster – Massive Halo Connection

Galaxy Clusters at the crossroads (2011 KITP image)

Cosmology:

$\Omega_m - \sigma_8$
gravity, D(z)
GR extensions
SIDM
f_{nl}

+ complementarity

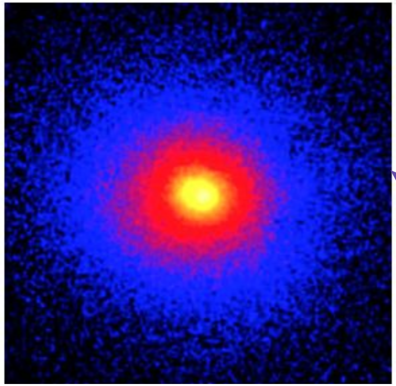
Astrophysics:

most massive galaxies
(+ descendents of first galaxies)
most massive SMBHs
plasma processes
chemistry
galaxy mergers
strong lensing of high-z structures

+ lots more!

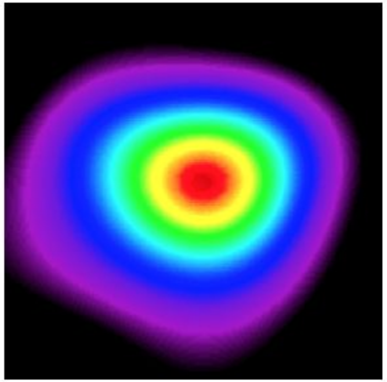
Background image credit:
Gustavo Yepes (Universidad Autonoma Madrid) and MultiDark collaboration.

Clusters are massive, multicomponent cosmic halos

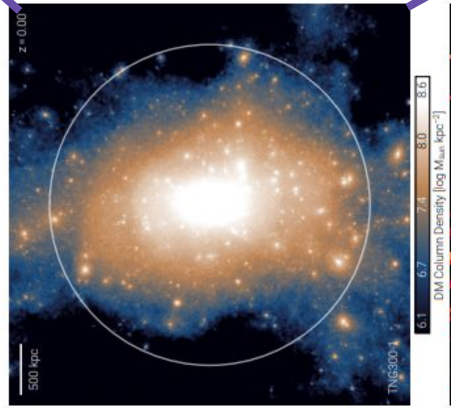


X-ray flux
from hot gas bremsstrahlung
best for identifying clusters (least projection)

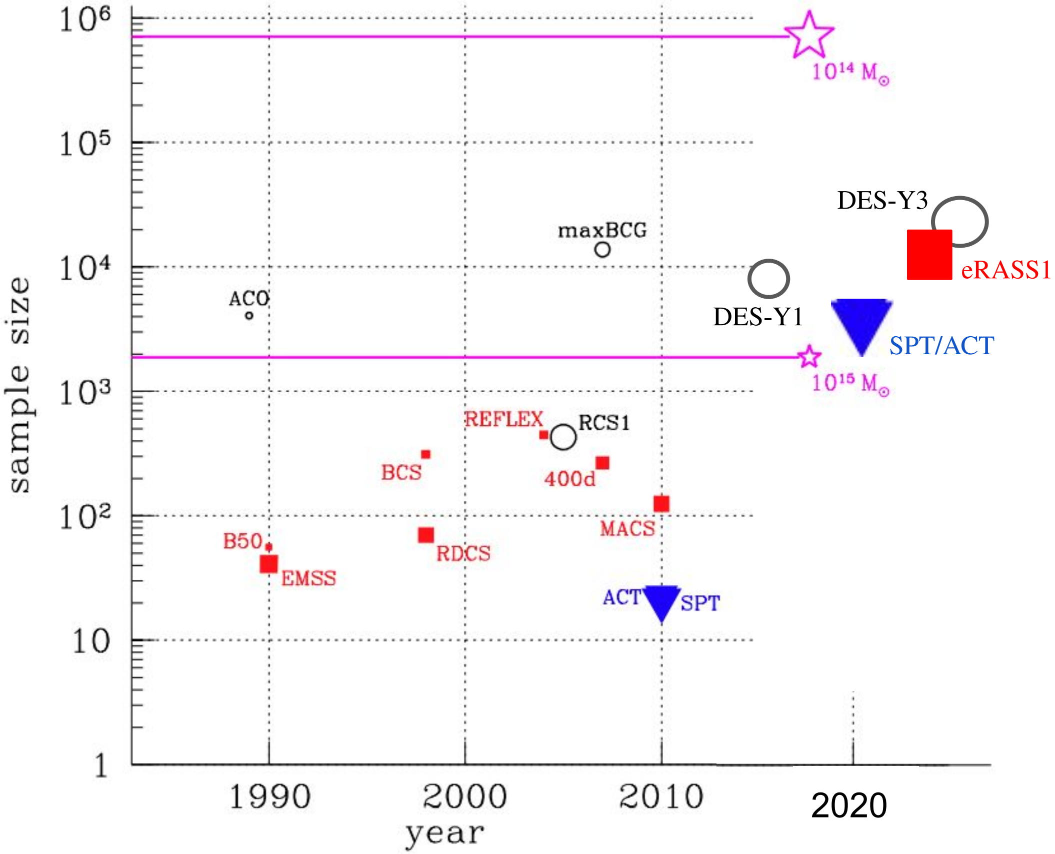
Stars
redshifts!



SZ effect from upscattering of CMB photons
extends to high-z easily



“dark matter” **halo**



Allen, Evrard, Mantz 2011, ARAA

Galaxy Cluster/Halo catalogs:

Optical/IR
X-ray
Sunyaev-Zel'dovich (SZ)
Theory (all sky, M_{200m})

– Increasing size and depth using both hot gas and galaxies as tracers.

– Growing **spectroscopic coverage**

– z>1 is no longer the frontier
Spitzer: SPARCS, GOGREEN, +

– z>~3 is now the frontier
Protoclusters: MAHALO, BOSS, +

Key to cluster science: exploit overlapping, multi-wavelength surveys

Population Model Ingredients:
Halo mass function (HMF) &
Scaling Relations (MPRs/MORs)

Population modeling I. Halo Mass Function (HMF)

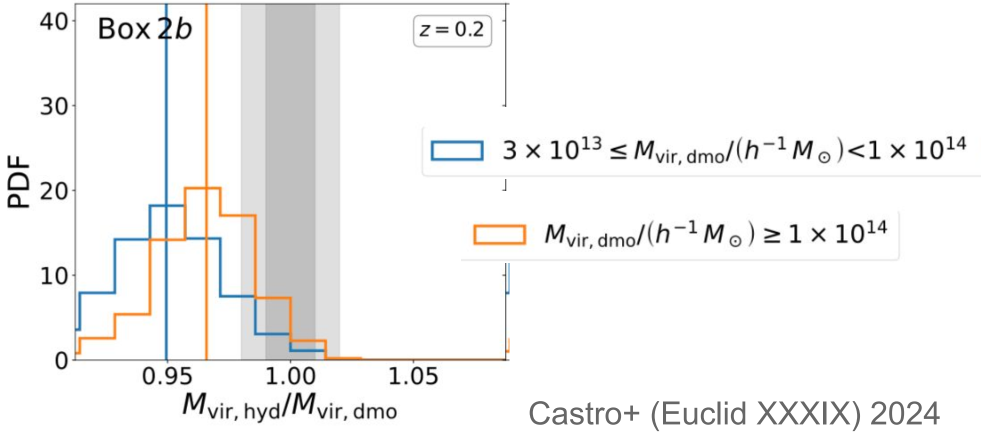
Press & Schechter 1974	**Analytic form** + 1e3 particle N-body (**4600+ citations!**)
Jenkins+ (Virgo Cons.) 2001	*Hubble Volume* (1e9) and other N-body → **fit parameters** (1500)
Tinker+ 2008	Multiple 1e9 N-body → **fit parameters (+ ext.)** (1600)
Bocquet+ 2020	Multiple 1e12 N-body → **emulator** (~100)
Castro+ (Euclid XXIV) 2023	Multiple 1e12 N-body → **fit parameters** (~30)

Precise calibrations must be weighed against this:

DM-only universes are not ours!

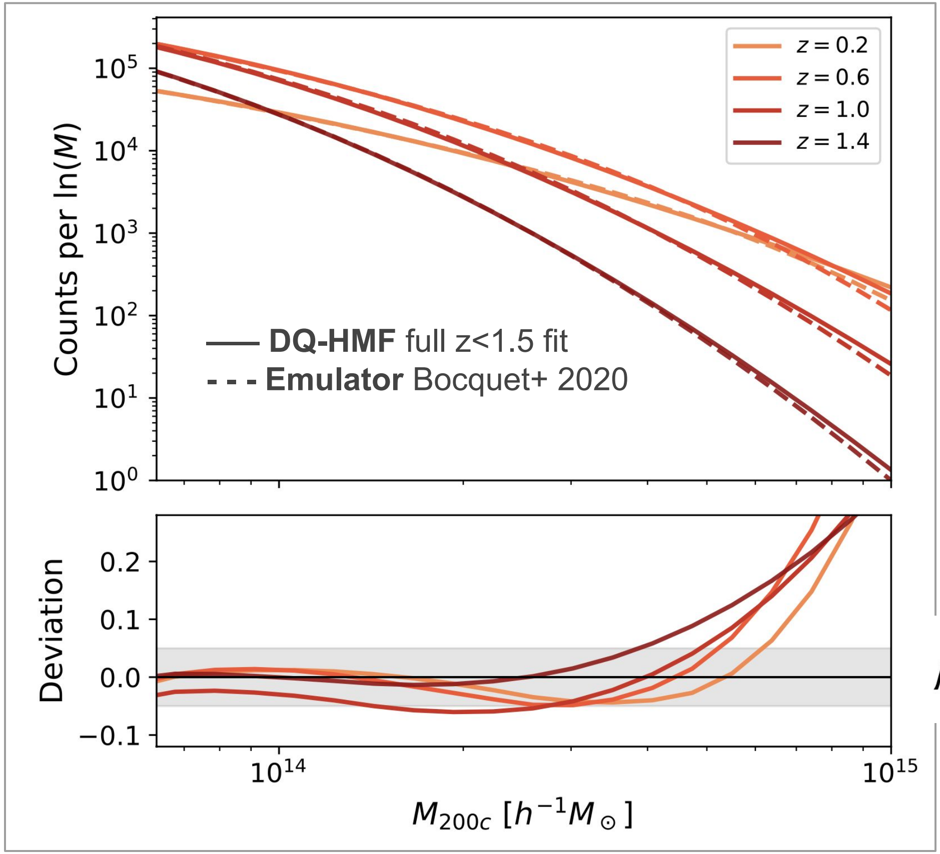
Galaxy formation drives **baryon loss**, reducing total halo mass.

A "**world estimate**" requires multiple, independent simulations.



Castro+ (Euclid XXXIX) 2024

Modest alternative: simple, dual-quadratic form (DQ-HMF)



Norton, Evrard & Adams 2024, MNRAS

Define mass relative to a pivot value

$$\mu \equiv \ln(M/M_p)$$

Expand log of space density as a quadratic

$$\ln\left[\frac{dn(\mu,z)}{d\mu}\right] = -\sum_{i=0}^{2} \frac{1}{i!}\,\beta_i(z)\,\mu^i$$

Normalization and slope at the pivot-mass behave quadratically with z

$$\beta_i(z) = \beta_{i,n} + \beta_{i,z}\,(z - z_p) + \frac{1}{2}\beta_{i,z2}\,(z - z_p)^2 \;\; ; \; i \in \{0, 1\},$$

while curvature is linear.

$$\beta_2(z) = \beta_{2,n} + \beta_{2,z}\,(z - z_p).$$

DQ-HMF benefits from simplicity

- **Eight, directly interpretable parameters**
- Computationally efficient for MCMC chains
- Convolution with log-normal mass-observable relation is **analytic**

Parameter	Definition
$\beta_i(z)$	HMF evolving shape in μ, $i \in [0, 2]$
$\beta_{i,n}$	normalization of β_i at z_p
$\beta_{i,z}$	redshift gradient of β_i at z_p
$\beta_{i,z2}$	redshift curvature of β_i at z_p
M_p	pivot mass
z_p	pivot redshift

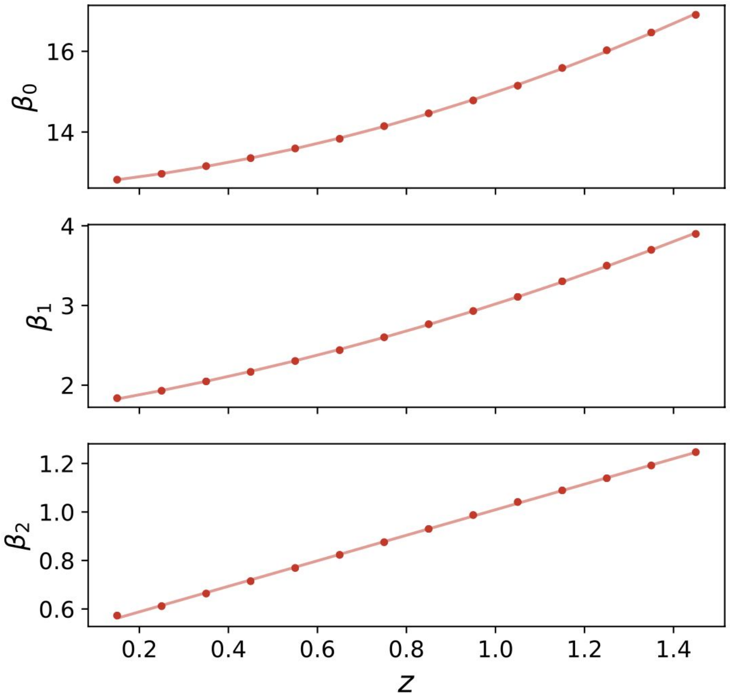


Figure 2. DQ-HMF model parameters, $\beta_i(z)$, derived from fitting the Mira-Titan HMF at the redshifts shown as points. Lines show the fits to equations (2) and (3), with parameter values given in Table 2.1.

Norton, Evrard & Adams 2024, MNRAS

Population modeling II. Scaling Relations

Intrinsic **halo** scaling: **Mass-Property Relations (MPRs)**

- Available from "full-physics" simulations of large cosmic volumes (or "zooms")
- Constant power law (PL) forms are rare, but **running PL in {M, z}** ok
- Scatter is **log-normal** to first order, skew-normal for some properties

---

Observed **cluster** scaling: **Mass-Observable Relations (MORs)**

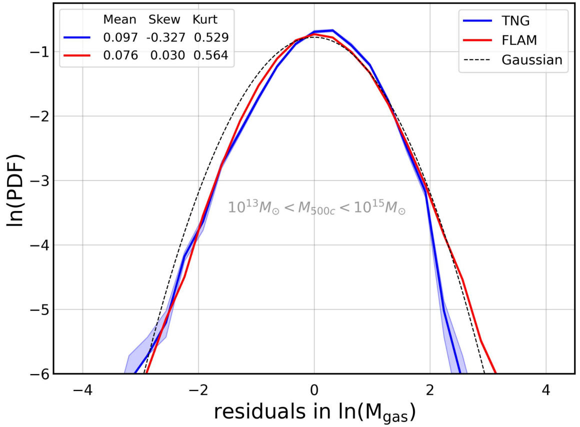
- Build from light-cone outputs of "full-physics" simulations (or N-body + baryon pasting)
- **Projection often adds skew to Pr(obs | M,z)**, less so for X-ray flux!
- Mis-centering must be modeled for optical (& SZ) clusters
- Not generic: form of Pr(obs | M,z) must be tailored to a survey/selection specifics

Evidence for log-normal MPRs

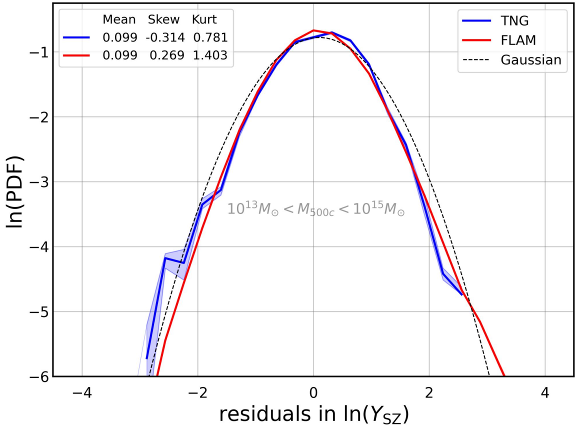
Illustris-TNG&Cluster + FLAMINGO sims: **normed residuals from KLLR mean**

Eddie Aljamal

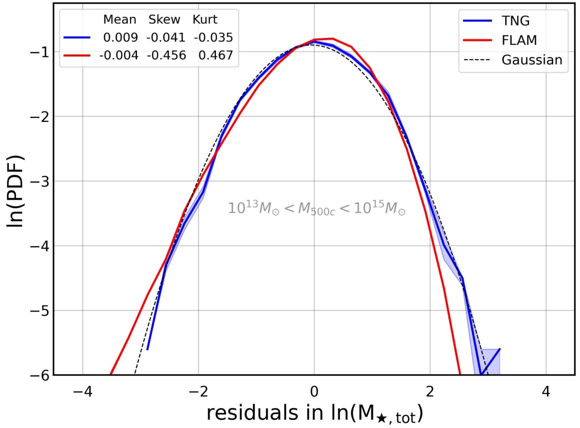
M_{gas}



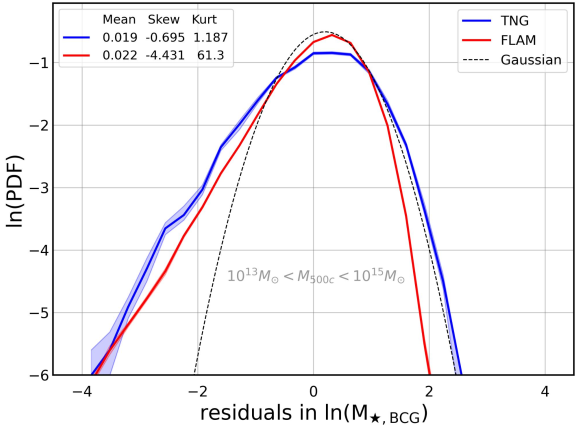
Y_{SZ}



$M_{star,tot}$



$M_{star,BCG}$



DQ-HMF & PL + log-normal MPR → *analytic forms*

Log-normal property kernel

s = ln(property) in appropriate units

$$P(s|\mu) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left\{-\frac{[s-\langle s\rangle(\mu)]^2}{2\sigma^2}\right\},$$

After convolution, find

$$\langle s\rangle(\mu) = \varpi + \alpha\,\mu.$$ power law mean

Space density

$$\ln\left[\frac{dn(s,z)}{ds}\right] = \ln A - \beta_0(z) - \frac{\beta_2(z)(s-\varpi)^2 + 2\alpha\beta_1(z)(s-\varpi) - \beta_1^2(z)\sigma^2}{2(\alpha^2+\beta_2(z)\sigma^2)},$$

Mean mass selected by property

$$\ln\langle M \mid s, z\rangle = \frac{(s-\varpi)/\alpha - (\beta_1(z)-1/2)\sigma^2/\alpha^2}{1+\beta_2(z)\sigma^2/\alpha^2}.$$

$$A = \frac{1}{\sqrt{\alpha^2+\beta_2(z)\sigma^2}}.$$

Explicit mixing of HMF shape and MPR parameters → **cosmo/astro degeneracies**

Norton, Adams, Evrard 2024, MNRAS

Which *Intrinsic* Properties are the Best Proxies for Total Halo Mass?

Mass Proxy Quality of IllustrisTNG & FLAMINGO halos

Eddie Aljamal

Focus: Scatter in true halo mass given one or more properties.

Explicit mass dependence via KLLR on halo populations at discrete redshift.

$$\sigma^2_{M_{500c}|\mathbf{s}} = \left(\alpha(\mu, z)^T \mathbf{C}^{-1}(\mu, z)\alpha(\mu, z)\right)^{-1}$$

Steeper scalings (higher alpha) or (and?) **low intrinsic scatter** are best, and strong anti-correlations.

Table 3. Sample sizes for halos with $M_{500c} > 10^{13}\,M_\odot$

Redshift	TNG300-1	TNG-Cluster	FLAM-L1_m8
2	299	318	10 288
1.0/1.05[a]	1 290	351	42 337
0.5	2 015	352	71 171
0	2 548	341	91 242

Table 1. Definition of gas properties used in this work.

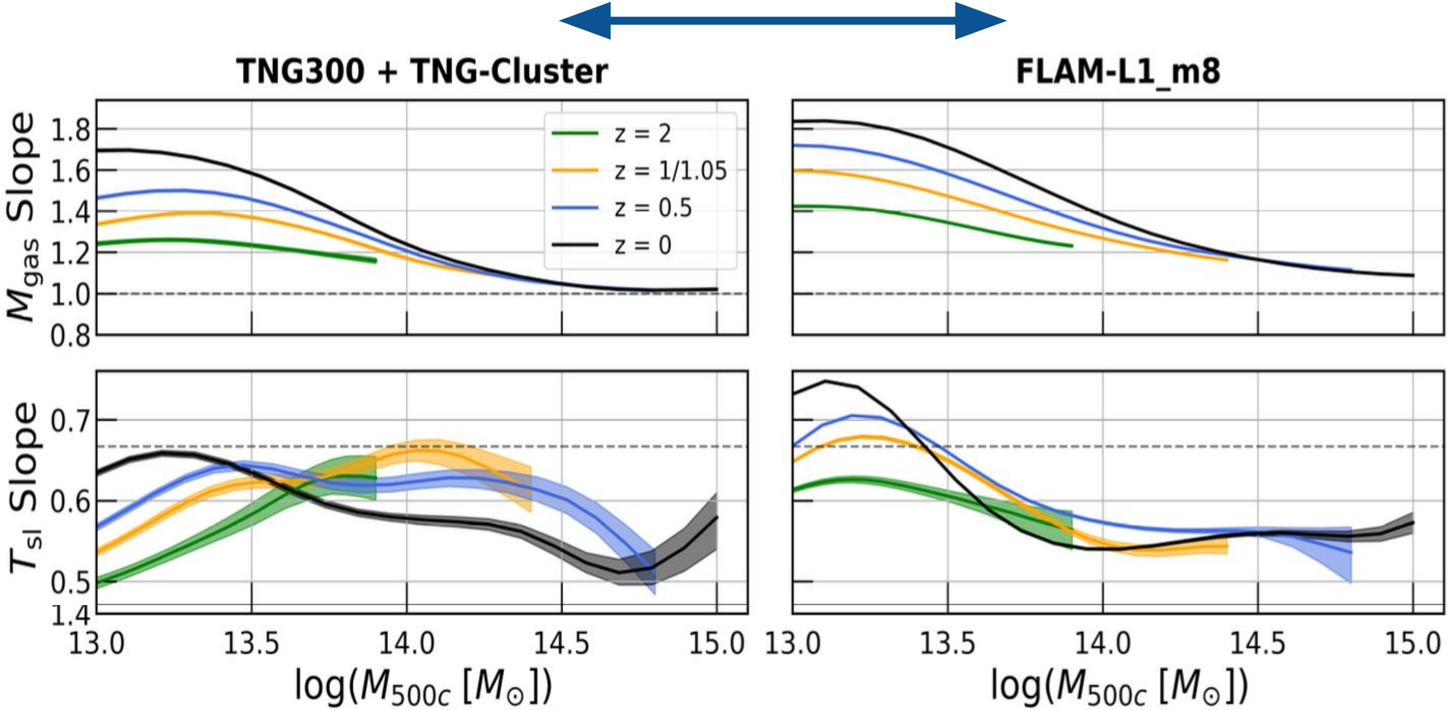
Property	Definition
M_{gas}	Total hot gas mass ($T > 10^5$ K) within R_{500c}
T_{sl}	Core-excised spectroscopic-like temperature for gas with $k_B T \geq 0.1$ keV and $0.15R_{500c} < r < R_{500c}$, eq. (2)
T_{mw}	Mass-weighted average temperature of hot gas within R_{500c}, eq. (3)
Y_X	X-ray pressure of gas in R_{500c}, eq. (9)
Y_{SZ}	tSZ pressure of gas in R_{500c}, eq. (8)

Aljamal, AE+TNG+FLAMINGO teams, 2024, in prep.

Hot gas scaling relations: gas mass & temp. slopes

Eddie Aljamal

Robustness to numerical method



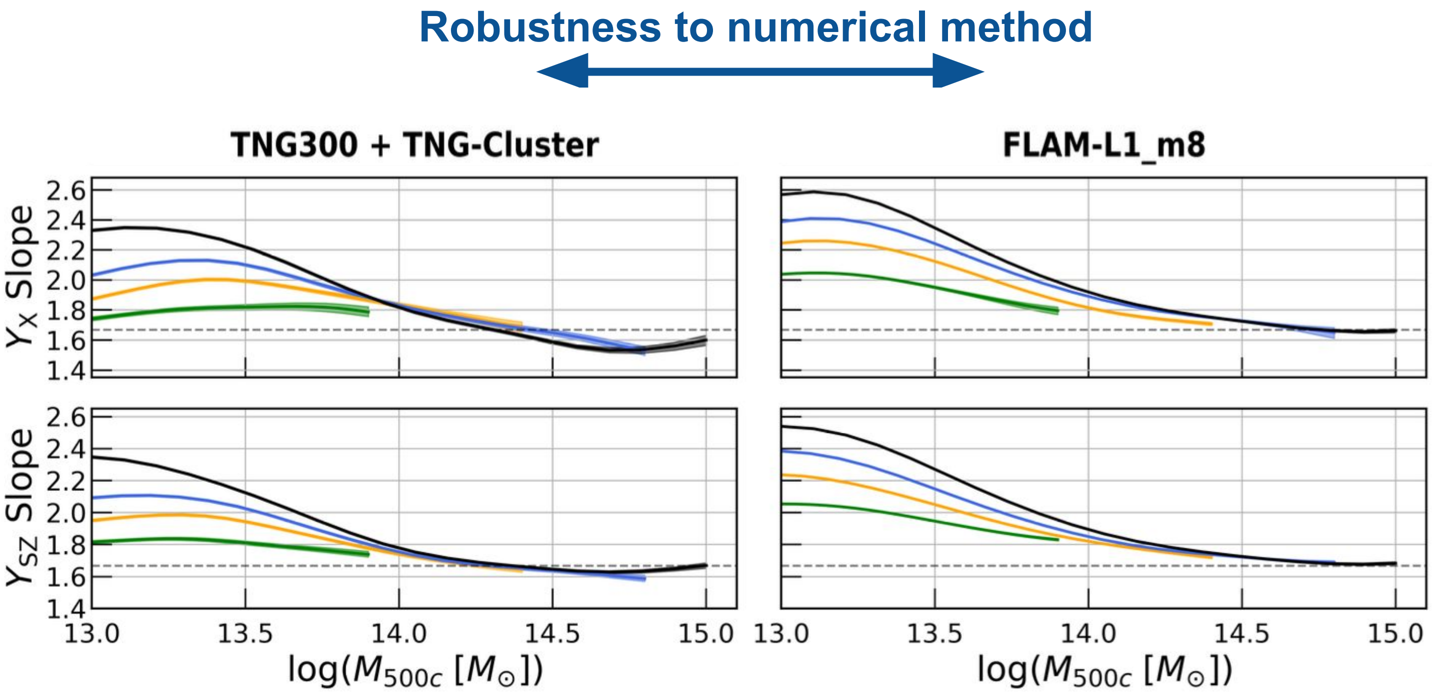
– Approaches self-similar value (1)
– Group slope steepens with time

– Cluster value consistently below self-similar (2/3)
– Weak redshift dependence

Aljamal, AE+TNG+FLAMINGO teams, 2024, in prep.

Hot gas scaling relations: **pressure (2 types) slopes**

Eddie Aljamal

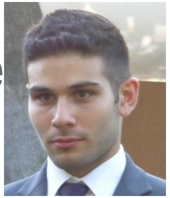


– Approaches self-similarity (5/3) @high masses

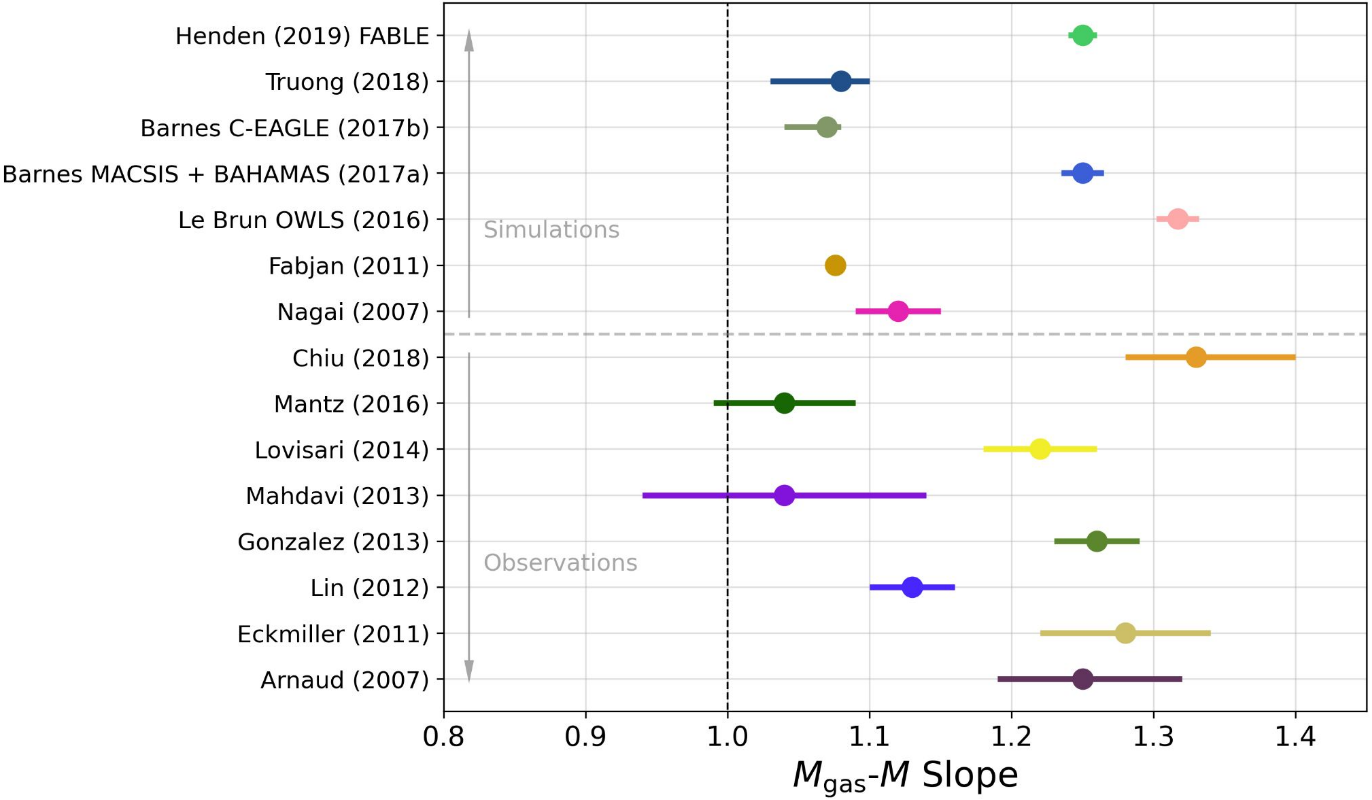
– Group slope steepens with time

Aljamal, AE+TNG+FLAMINGO teams, 2024, in prep.

Compendium of literature slopes: gas mass (incomplete



Eddie
Aljamal



Super-linear due to less efficient star formation in high mass halos.

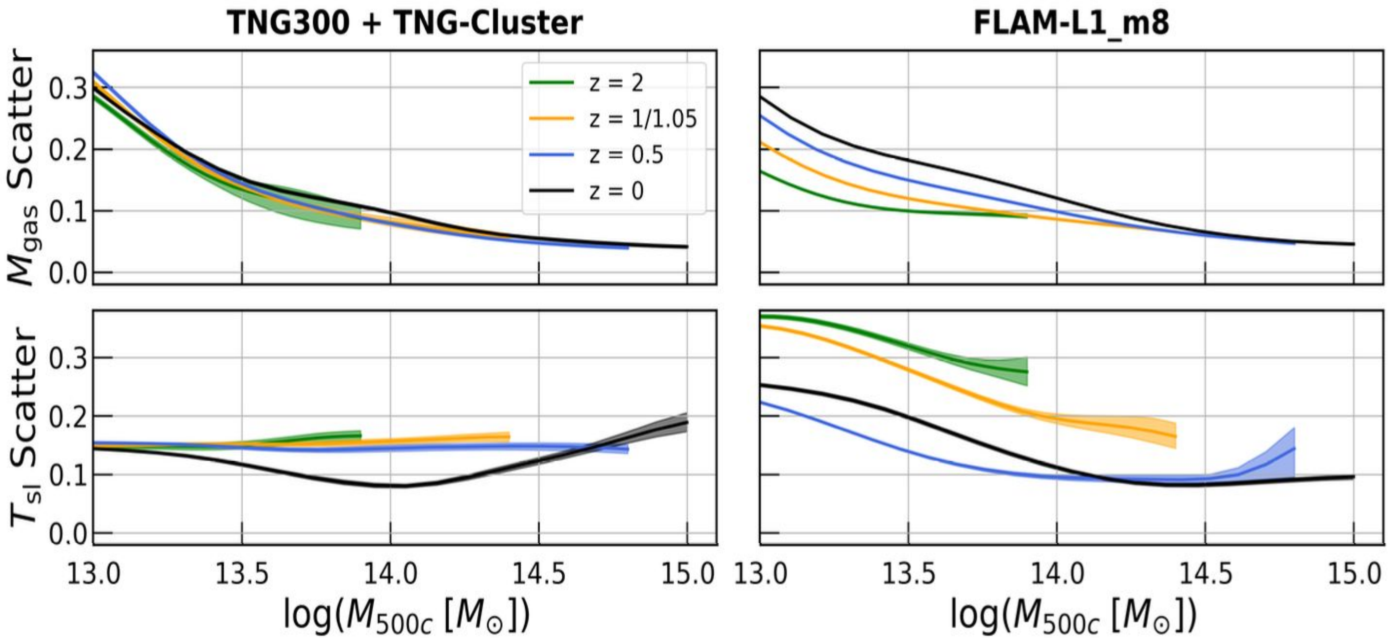
Good consistency but does not reflect

– sample selection/ mass coverage
– systematic errors

Aljamal, AE+TNG+FLAMINGO teams, 2024, in prep.

Hot gas scaling relations: **gas mass & temp. scatter**

Eddie Aljamal



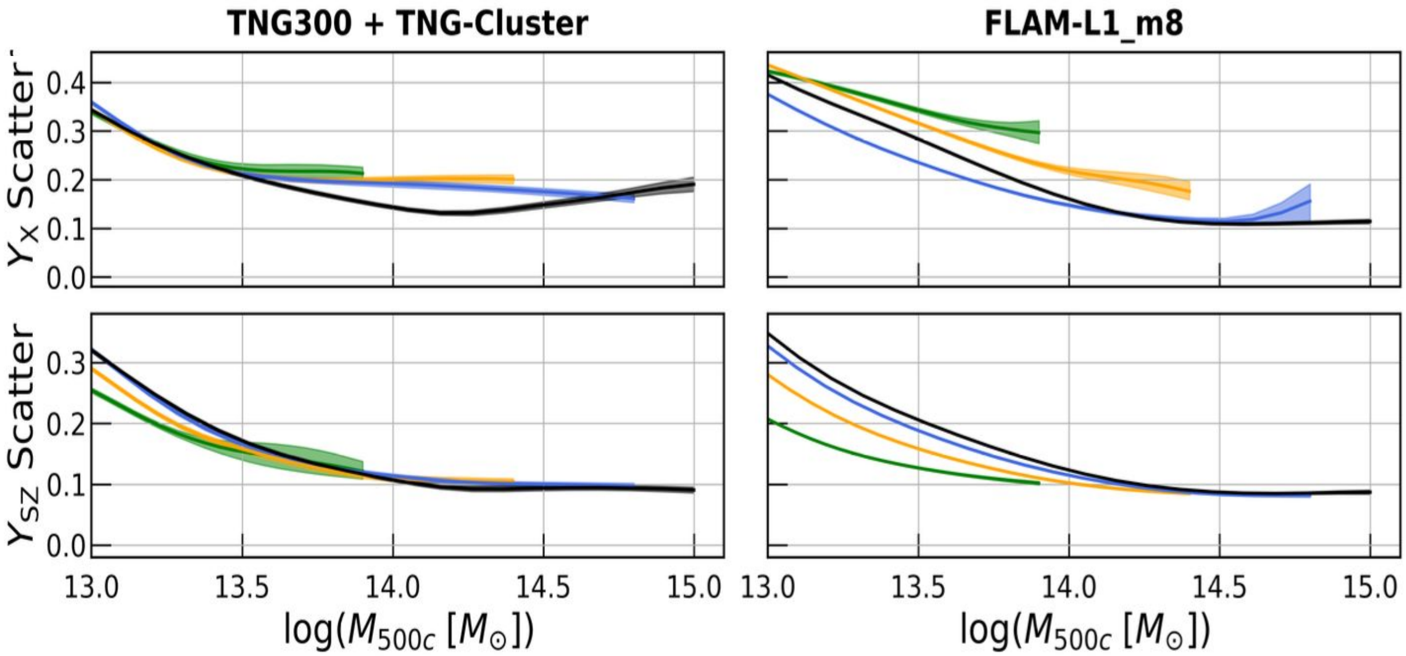
Strong mass dependence in M_{gas}
Only 5% @1e15

More z-evolution in FLAM than TNG at the group scale.

Aljamal, AE+TNG+FLAMINGO teams, 2024, in prep.

Hot gas scaling relations: **pressure scatter**

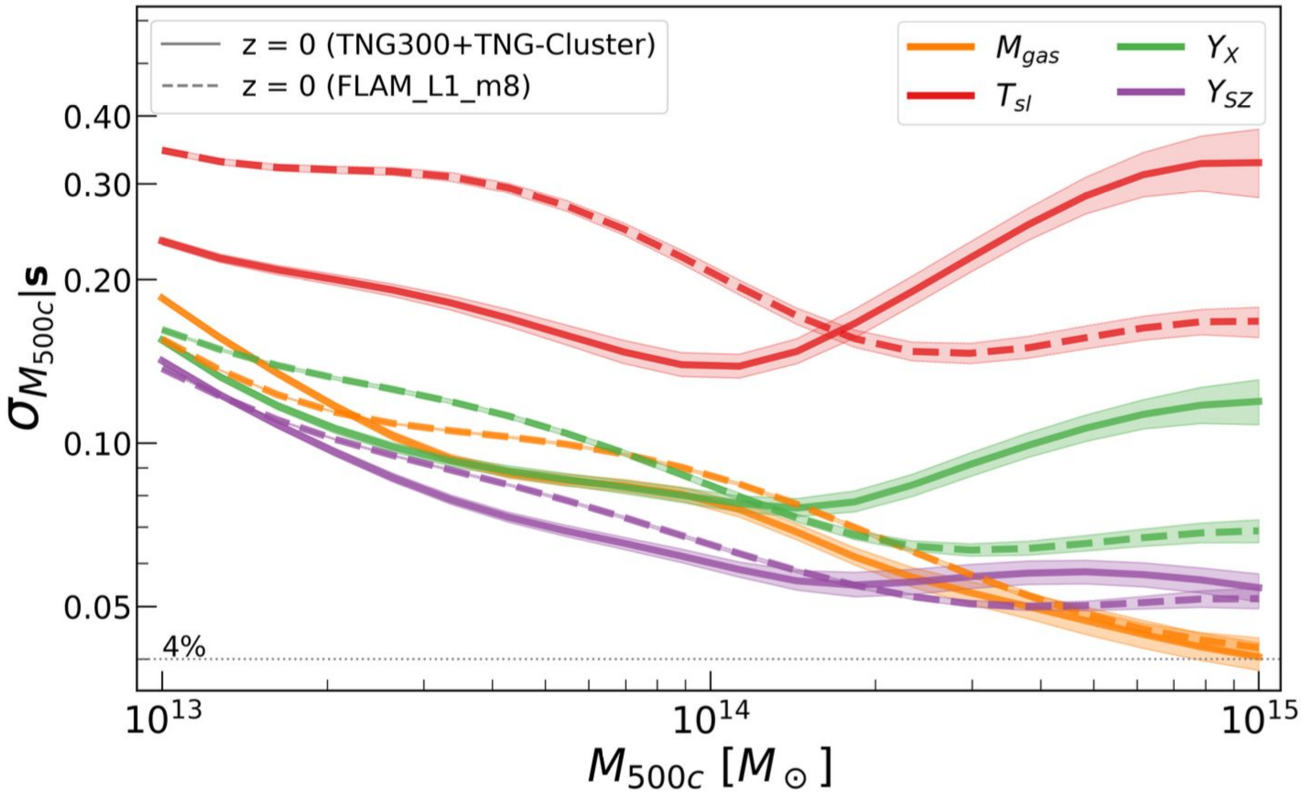
Eddie Aljamal



Asymptotes to 10% at cluster masses (>1e14)

Aljamal, AE+TNG+FLAMINGO teams, 2024, in prep.

Hot gas properties: **Mass Proxy Quality** @z=0



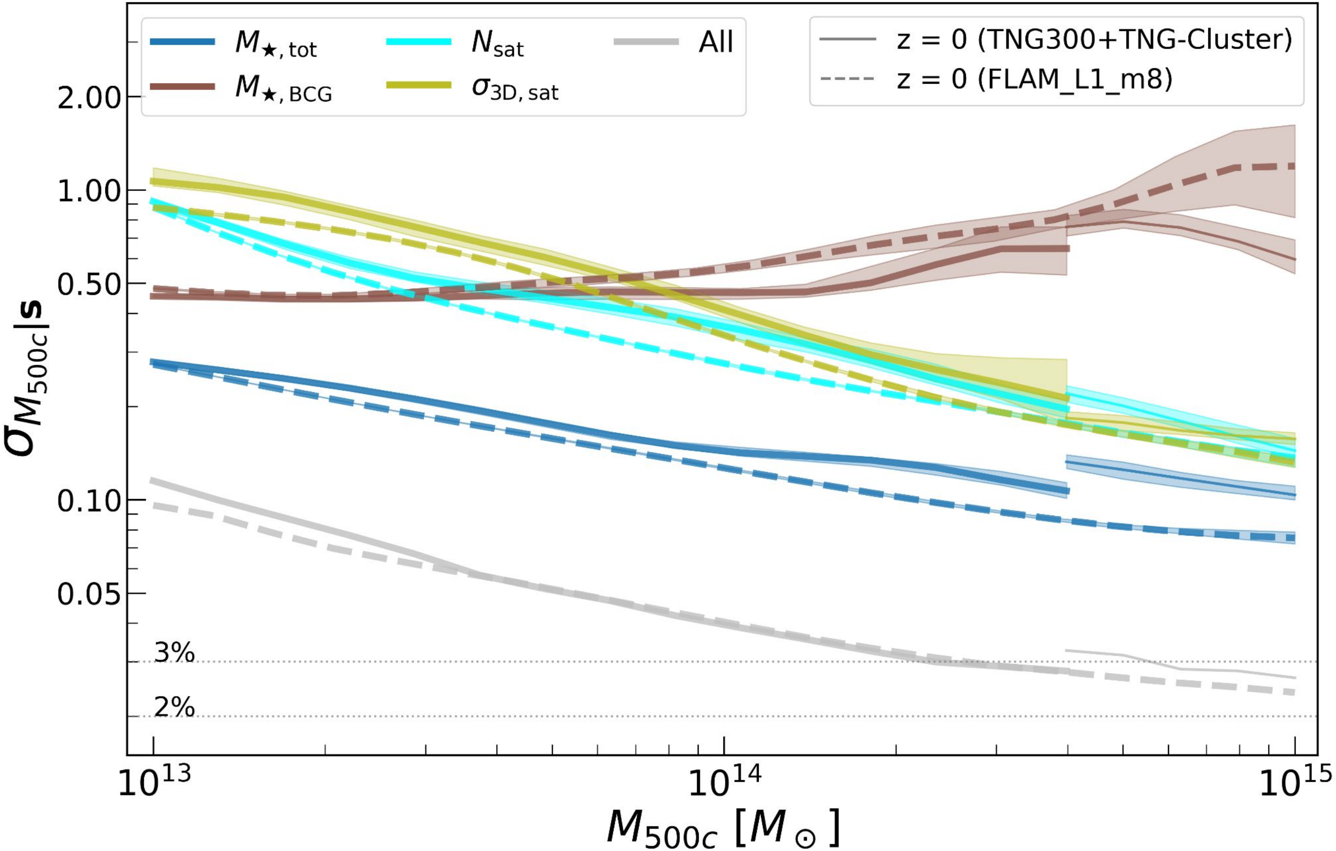
Eddie Aljamal

Gas Mass and **SZ Pressure** are the best proxies of halo mass.

Robust across redshift.

Aljamal, AE+TNG+FLAMINGO teams, 2024, in prep.

What about **Galaxy properties?**

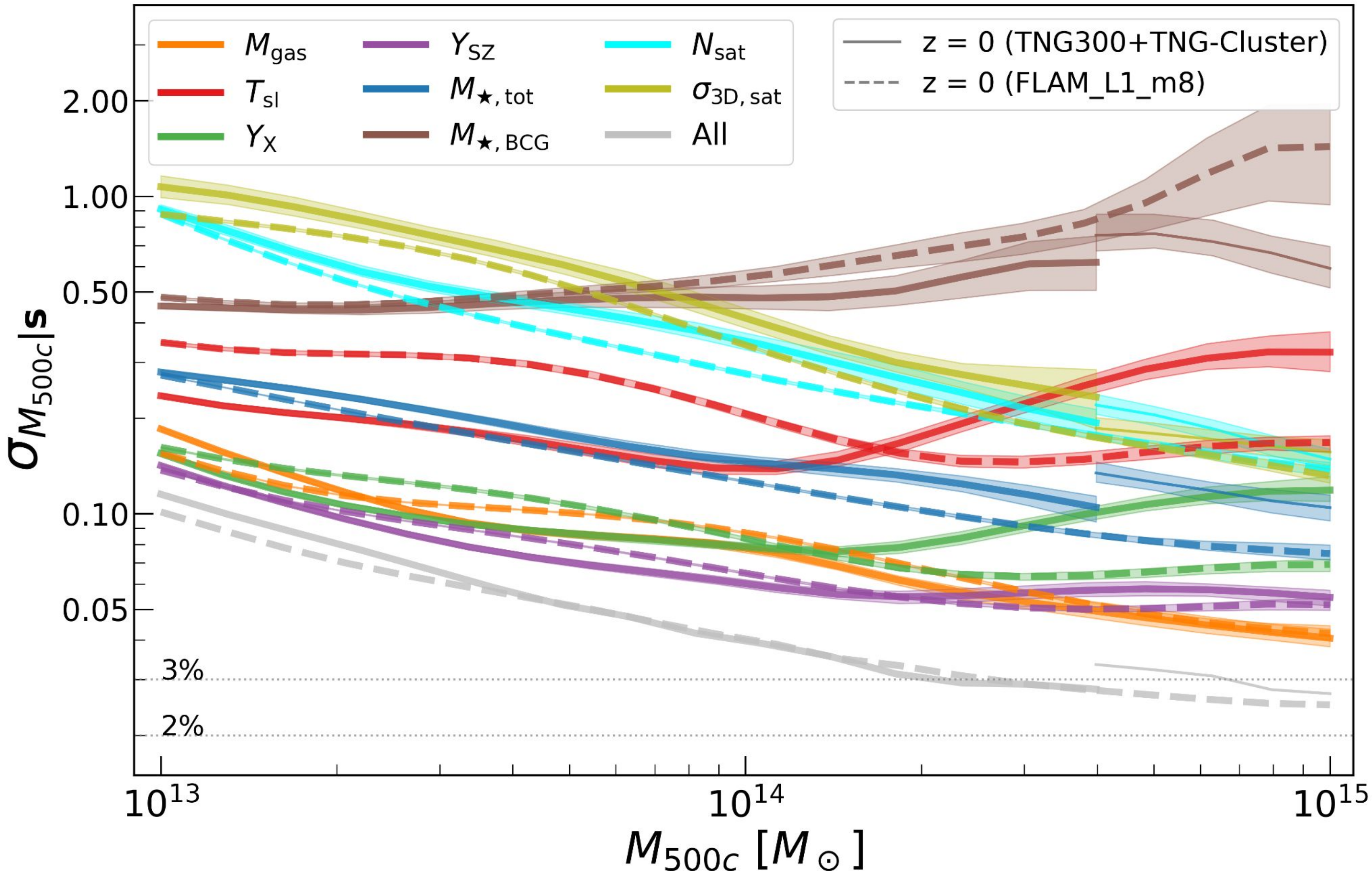


Eddie Aljamal

Total stellar mass is the best, reaching 10% for the largest clusters.

BCG stellar mass is relatively poor at high mass.

Aljamal, AE+TNG+FLAMINGO teams, 2024, in prep.



What if you had it all?

3% mass scatter is achieved at the cluster scale by combining all properties.

What can be achieved in practice?

Summary

Synergies between simulations and observations of galaxy clusters have been expanding and deepening for decades, and will continue to do so in the eRosita era.

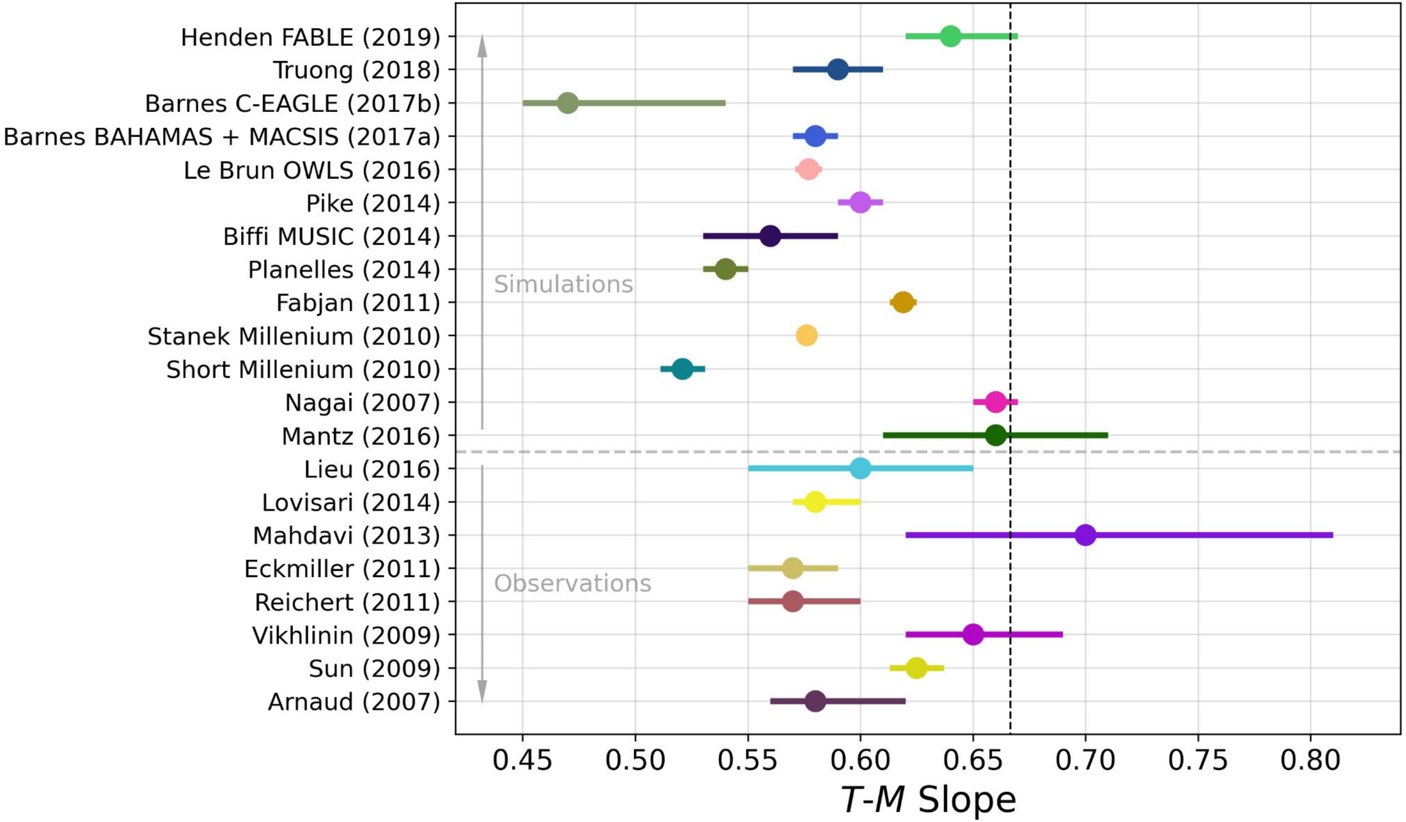
Multiwavelength studies are essential.

A verification study of two “full physics” cosmological simulations shows:

- Good agreement in hot gas property statistics,
- Mass and redshift dependence of slope and scatter, esp. at group scale,
- Gas mass and pressure are the best halo mass proxies.

Thank you!

Compendium of literature slopes: Temperature



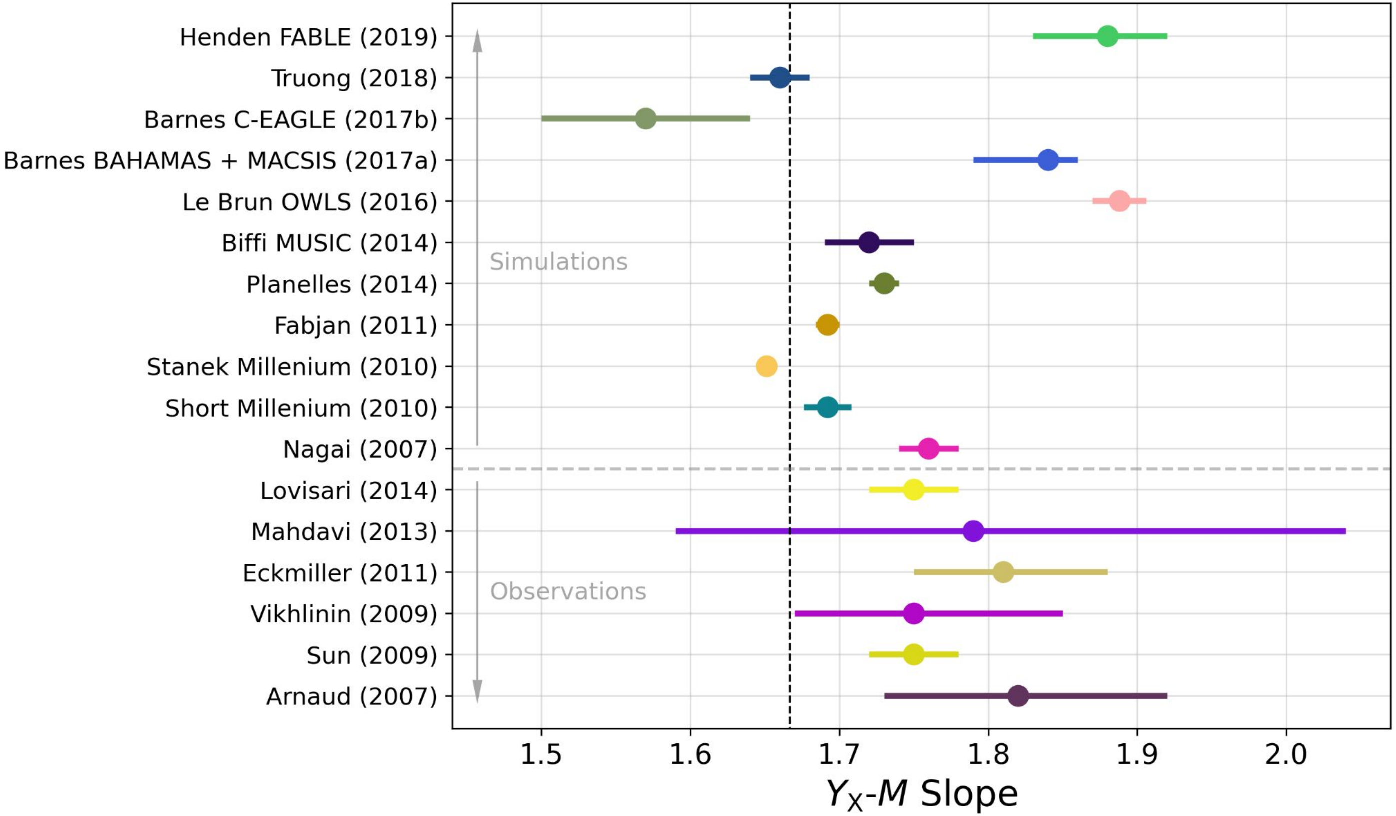
Sub-self-similar due to more efficient star formation in low mass halos.

Fair consistency but does not reflect

– sample selection
– systematic errors

Aljamal, AE+TNG+FLAMINGO teams, 2024, in prep.

Compendium of literature slopes: Electron Pressure



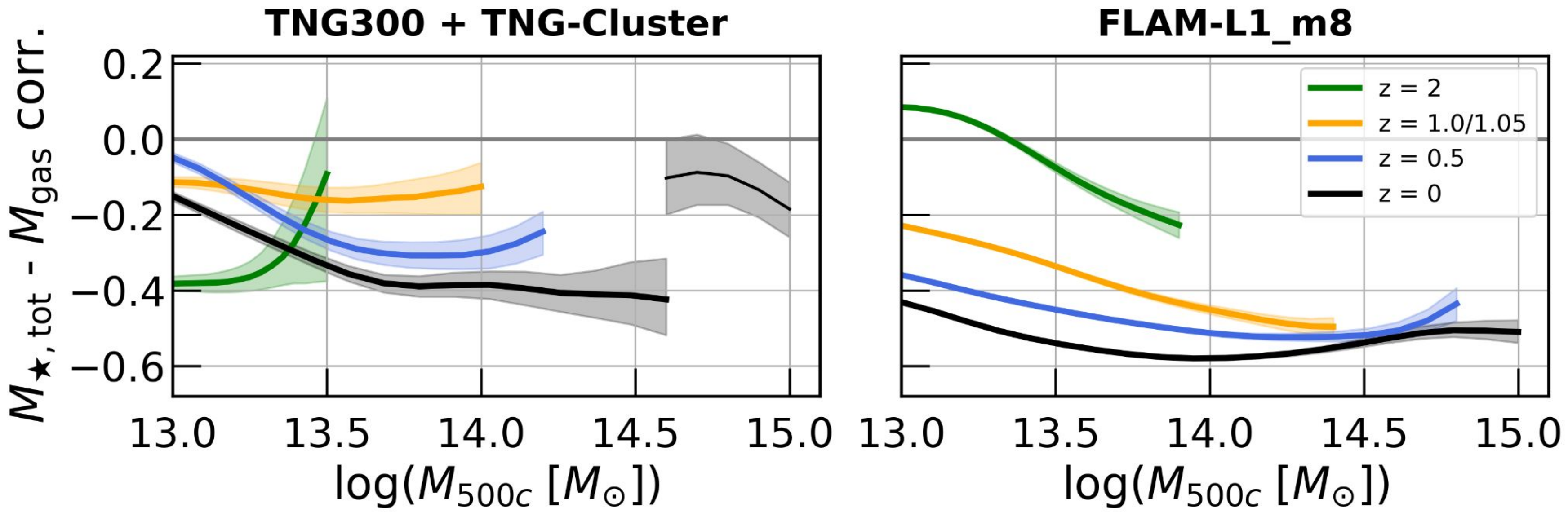
Super-self-similar due primarily to Mgas slope >1.

Fair consistency but does not reflect

– sample selection
– systematic errors

Aljamal, AE+TNG+FLAMINGO teams, 2024, in prep.

Property covariance: Mstartot and Mgas



Property covariances: T and Mgas