More robust astrophysical scaling relations with ML

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IAS

with

L. Thiele, F. Villaescusa-Navarro, J.C. Hill, M. Cranmer, D. Spergel,
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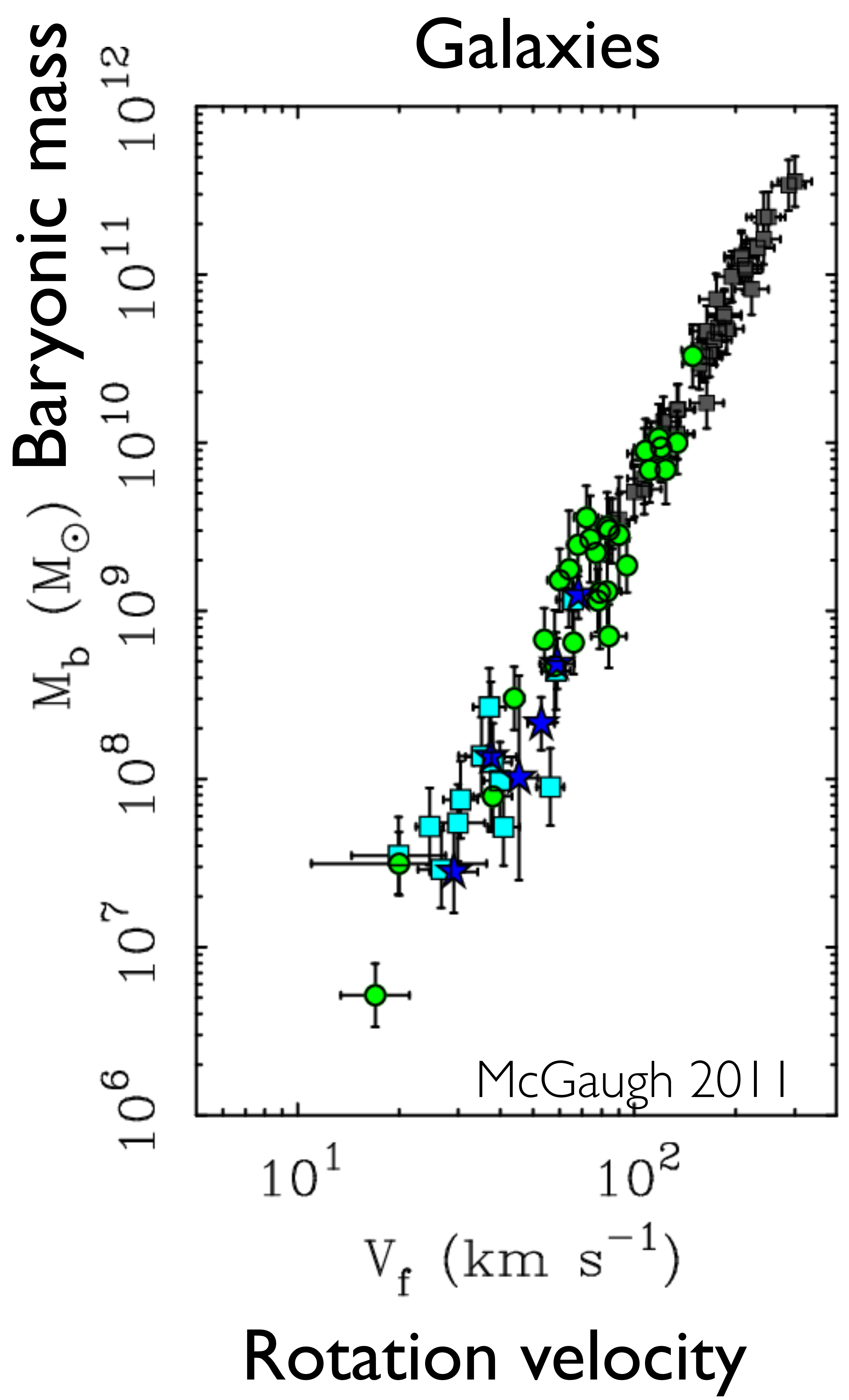
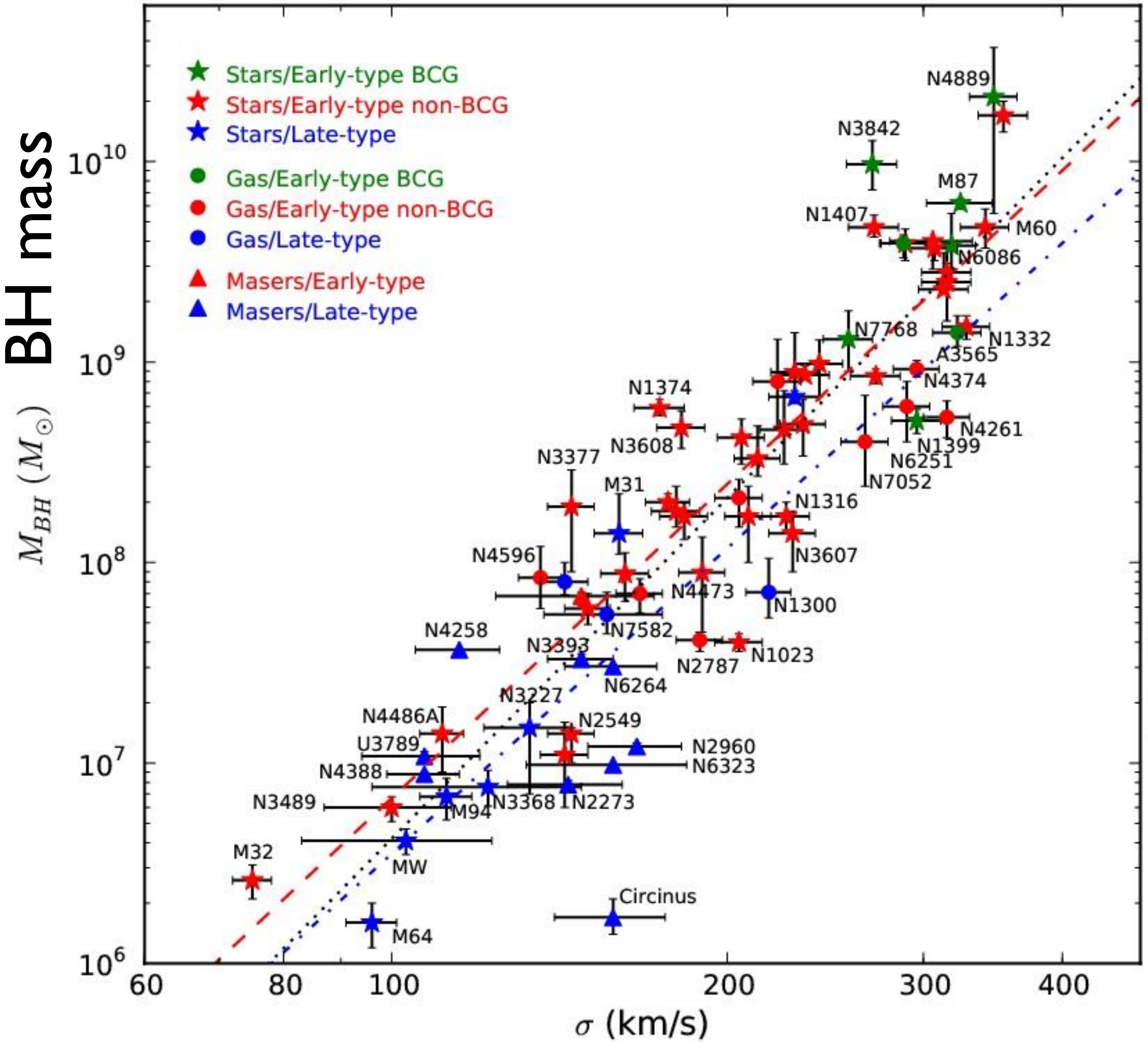
arXiv:2201.01305 & 2209.02075

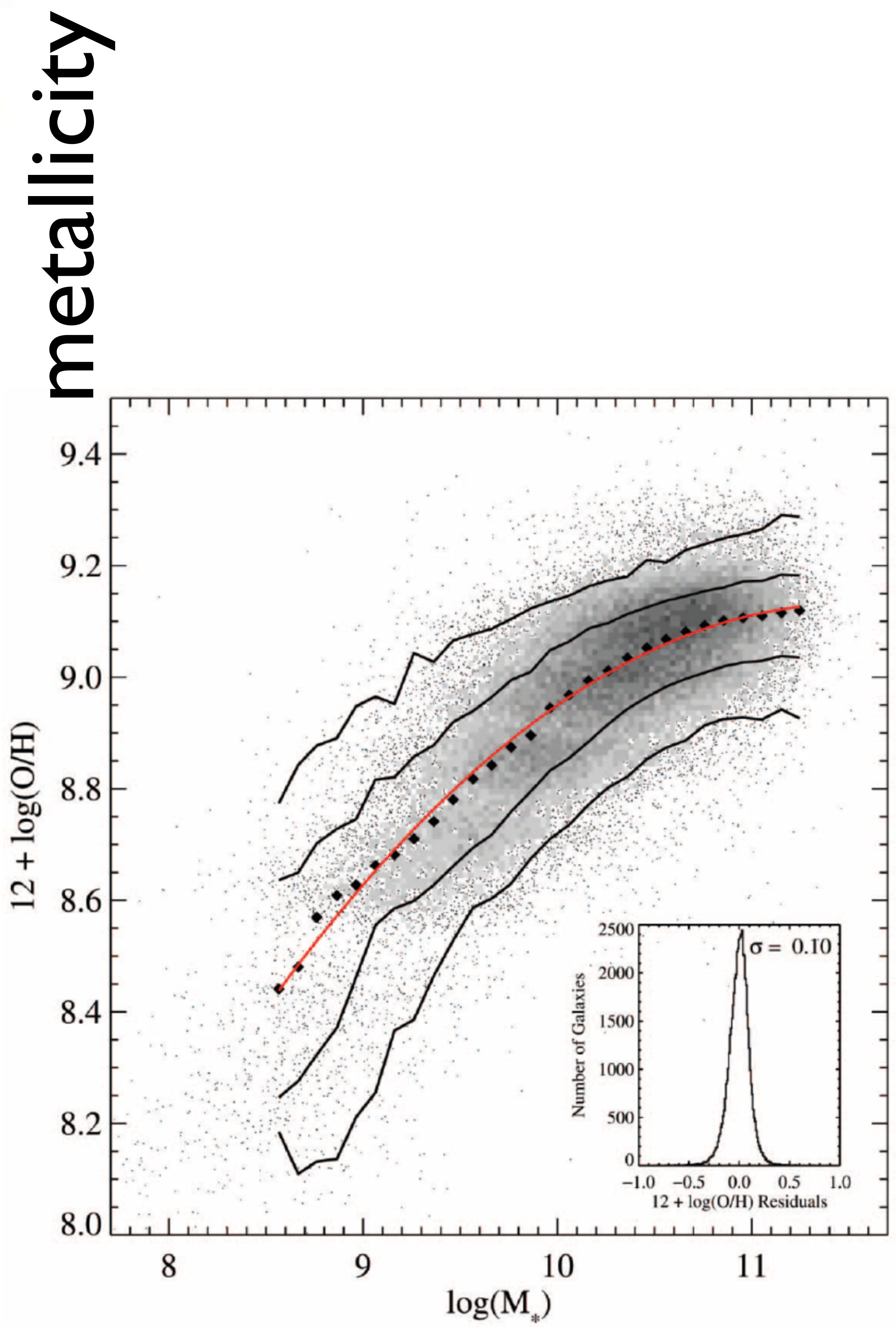
What are scaling relations?

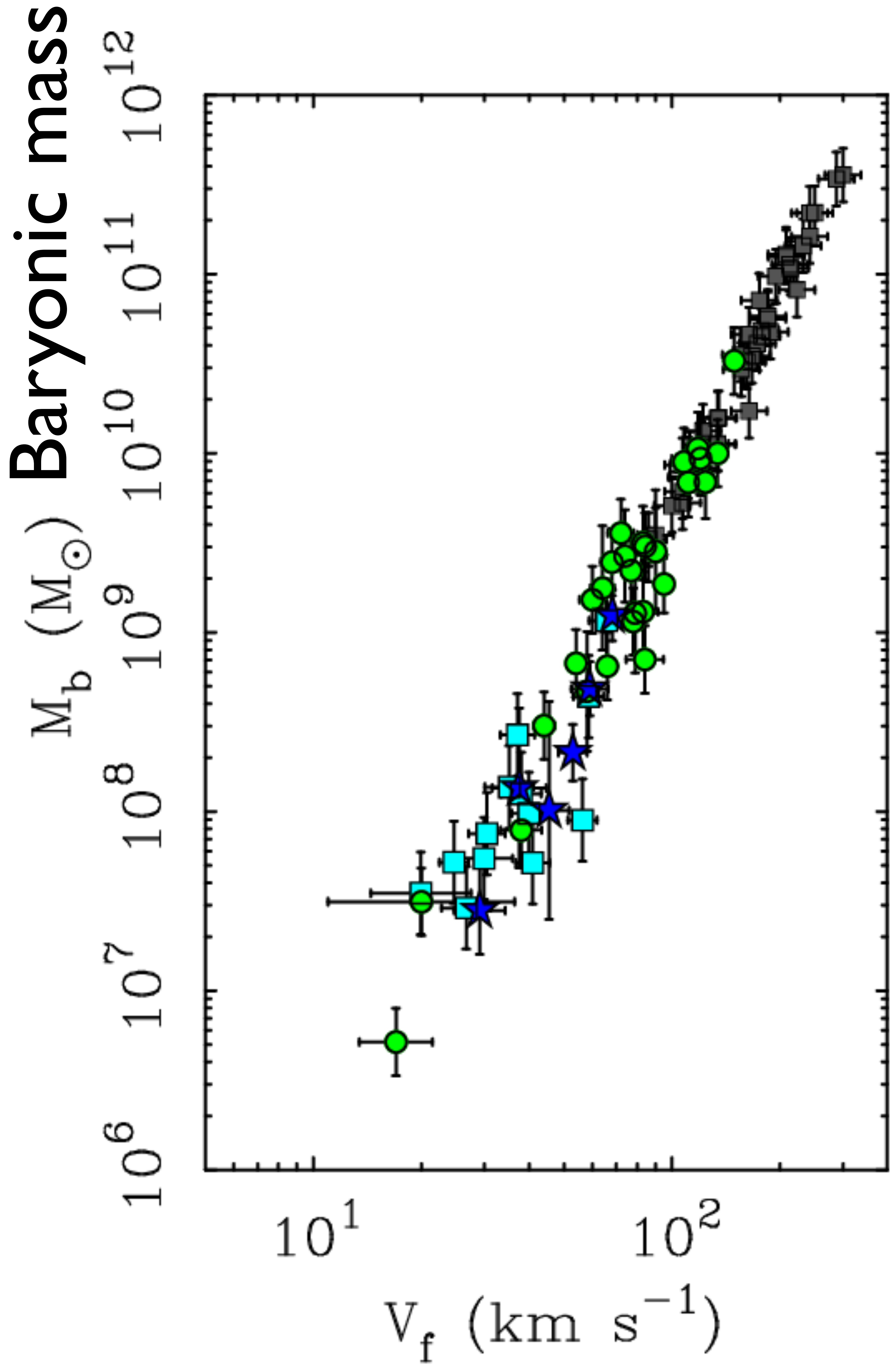


- Low-scatter relations between properties of complex astrophysical systems
- Often found empirically in observational/simulation data
- Often found by fitting power laws to 2D data

Some popular scaling relations



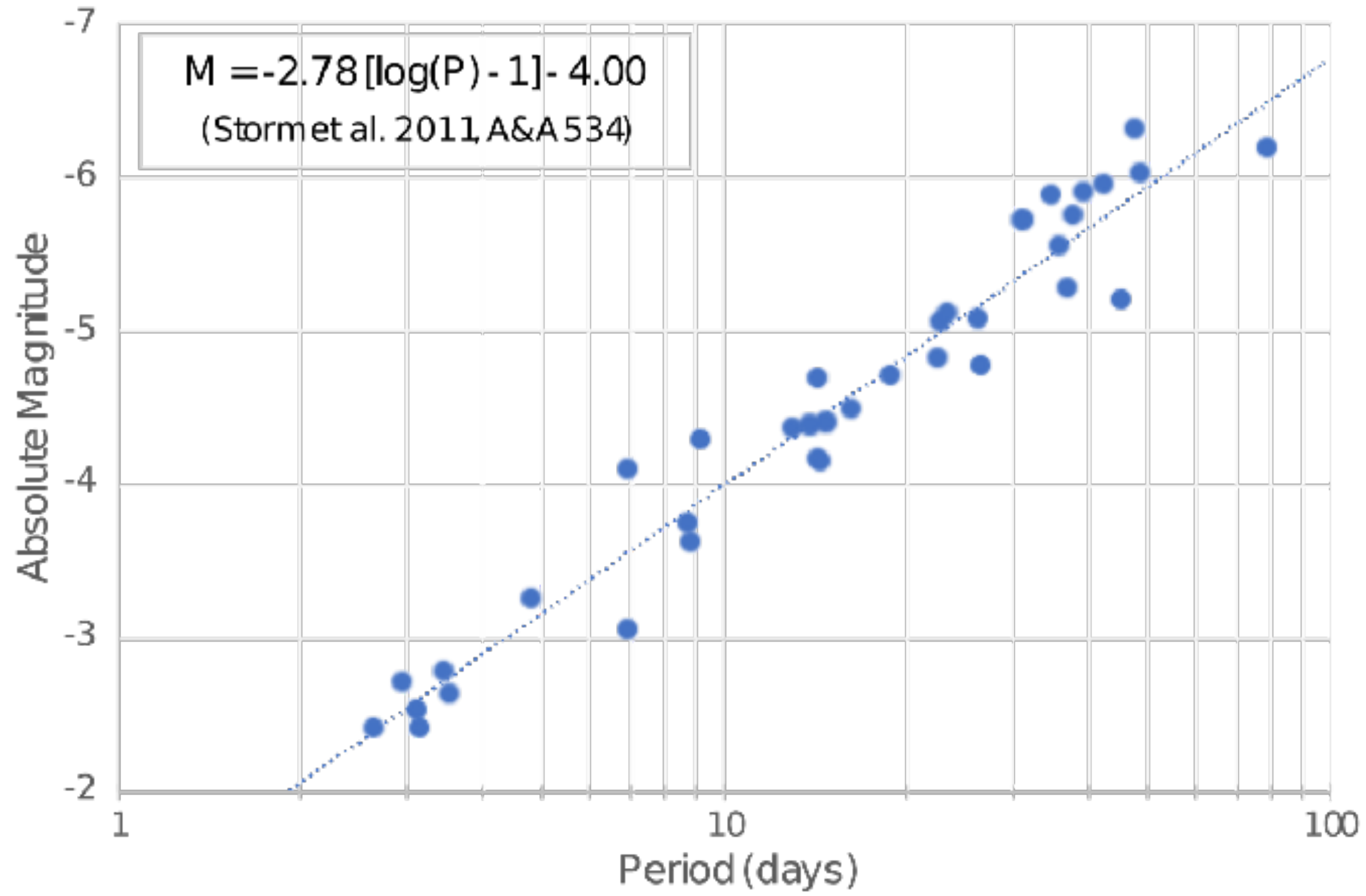




Important scaling relations for estimating cosmological distances

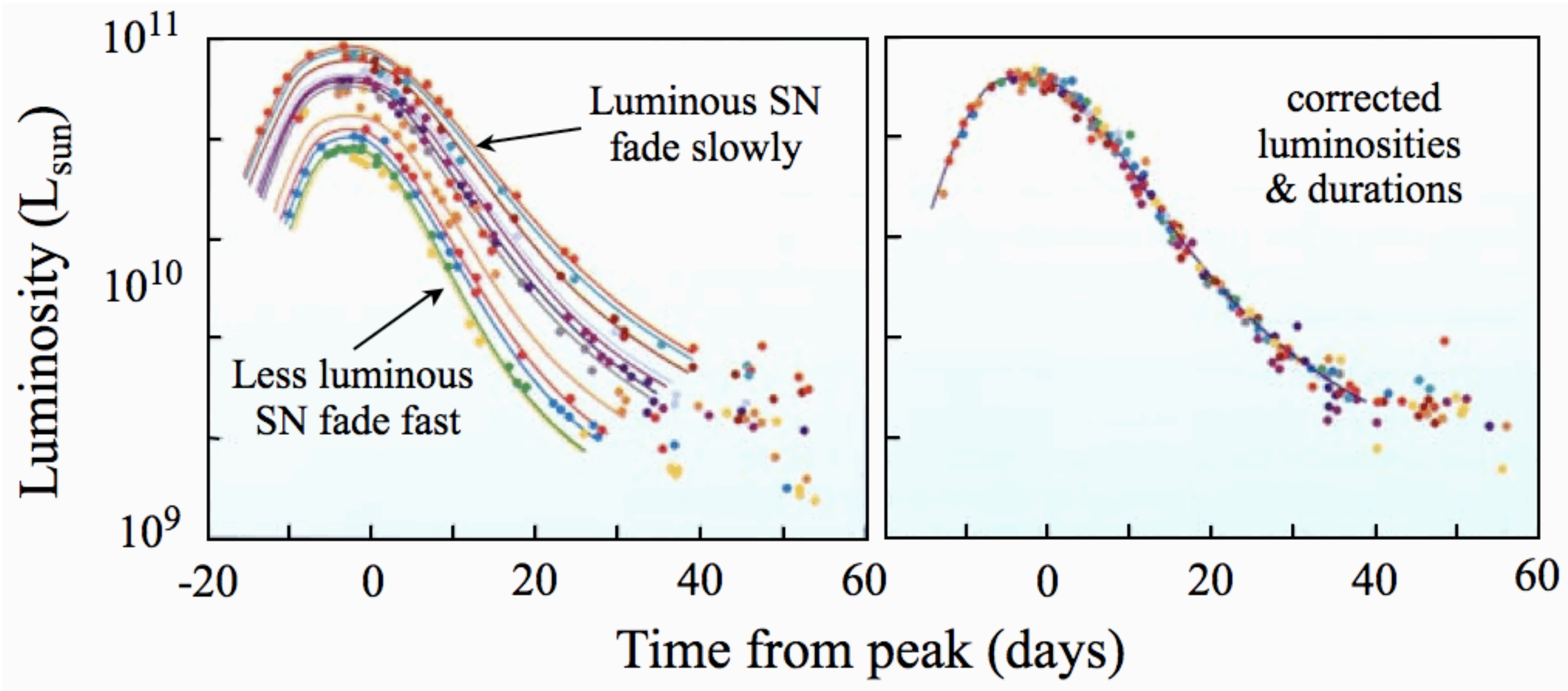
- Cepheid Period-Luminosity relation

$$M_v = A(\log_{10} P - 1) - B$$



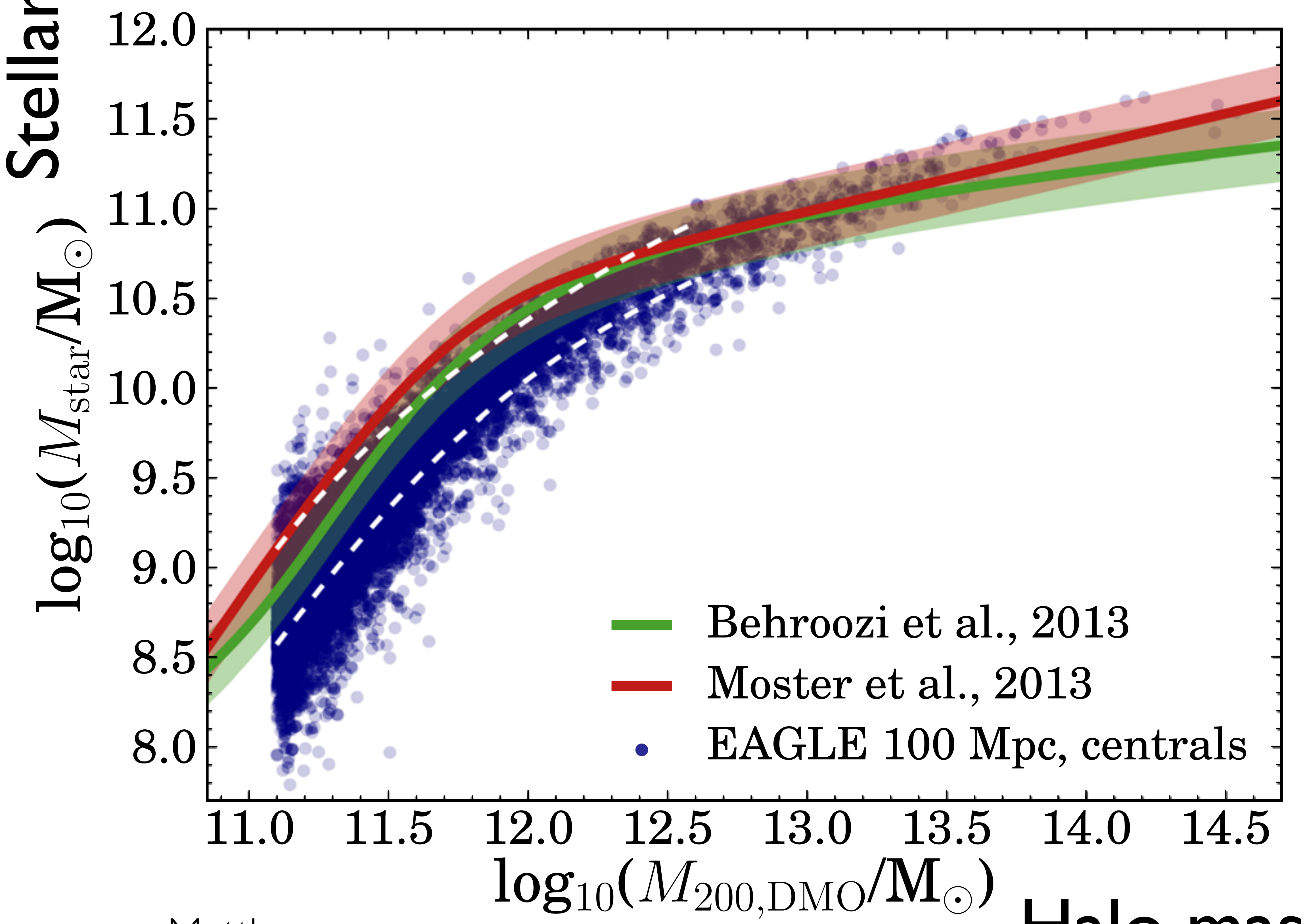
- Philips relation for supernovae

$$M_{max}(B) = -21.726 + 2.698\,\Delta m_{15}(B)$$



Scaling relations from simulations

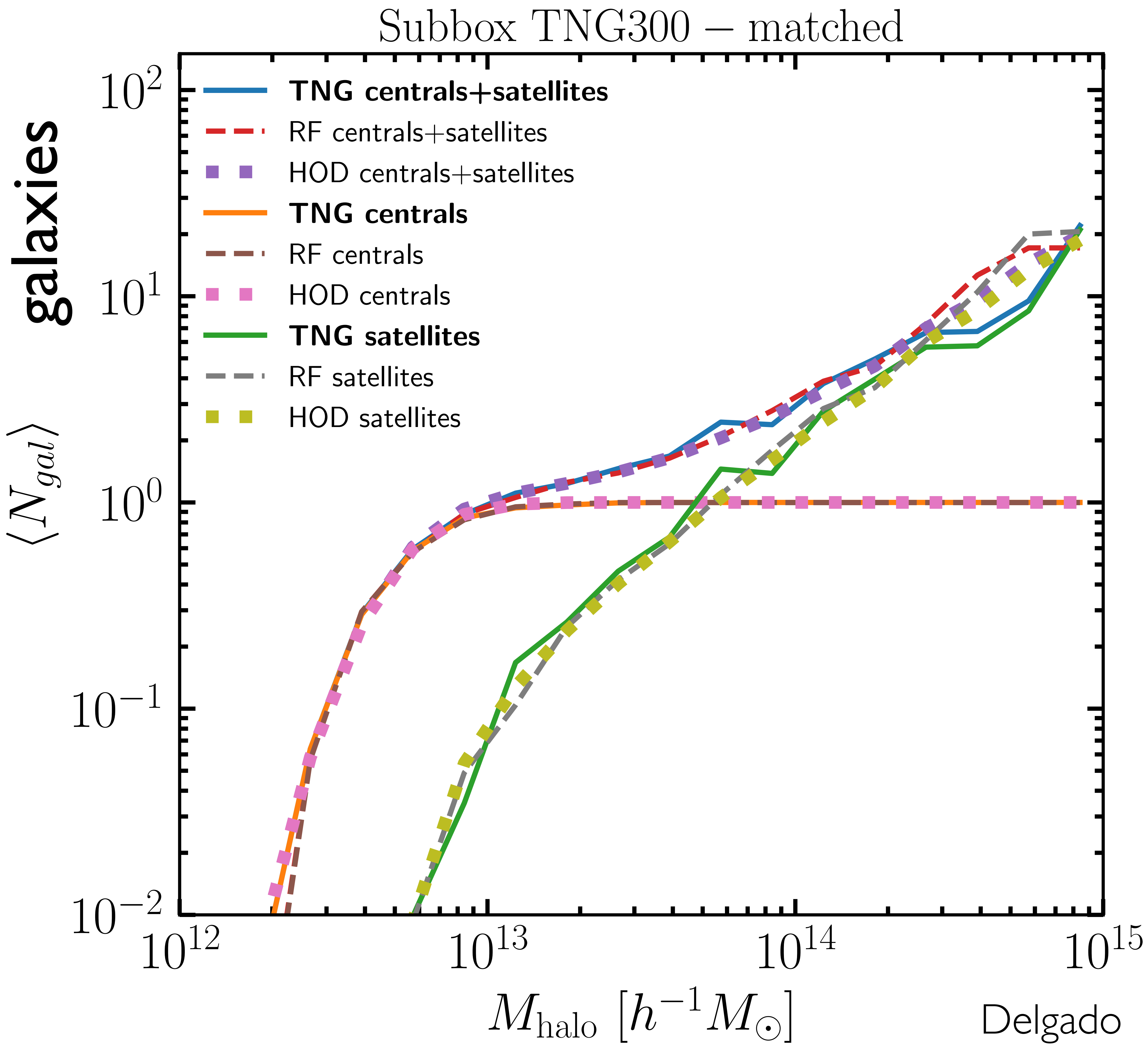
Stellar mass



Halo mass

Matthee et al. 17

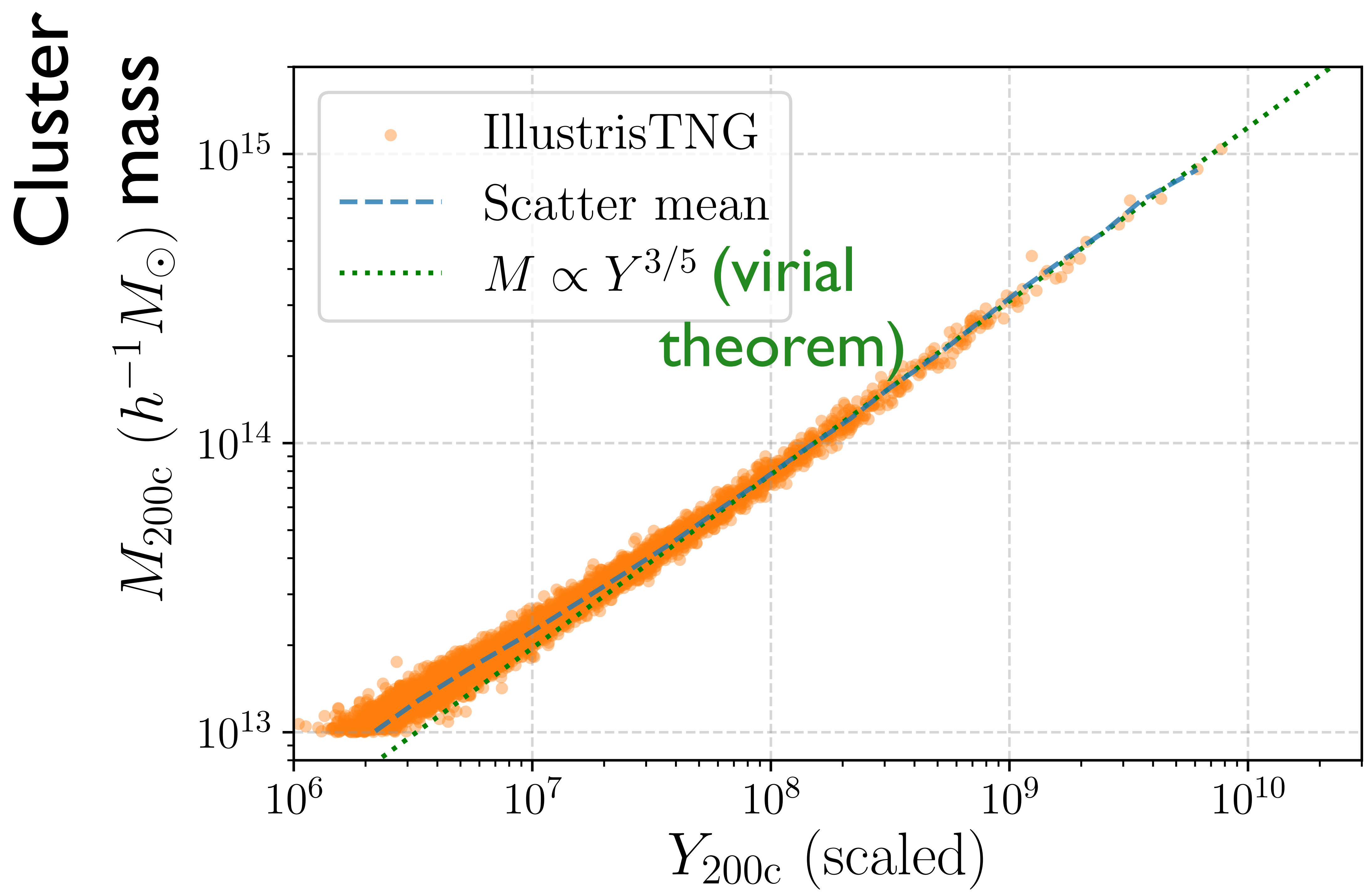
Number of galaxies



Delgado et al. 22

Halo mass

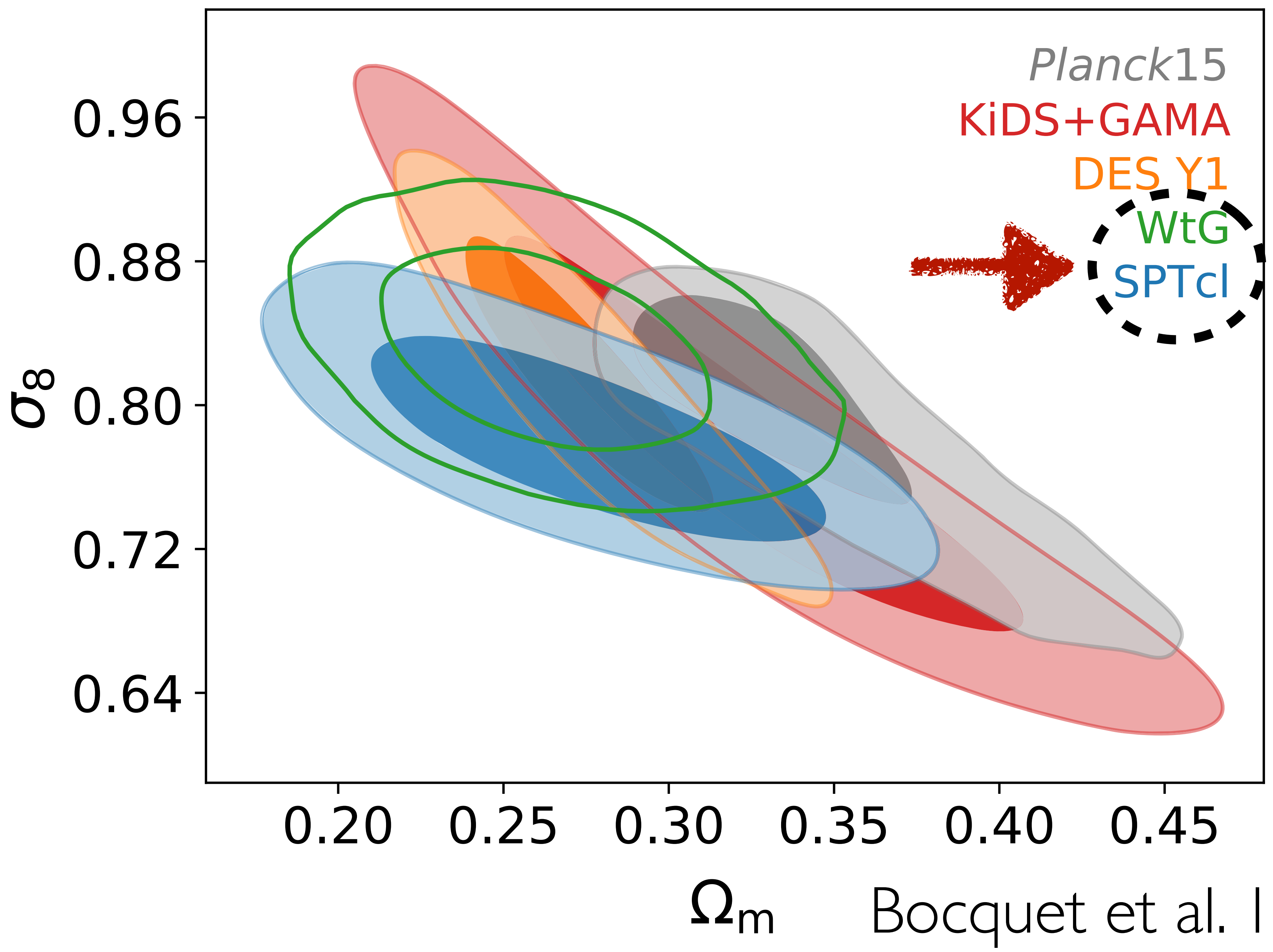
Scaling relations for cluster cosmology



$$Y \propto \int_0^{R_{200c}} P_e(r)dV$$

$$\propto M_{\rm gas}T_{\rm gas}$$

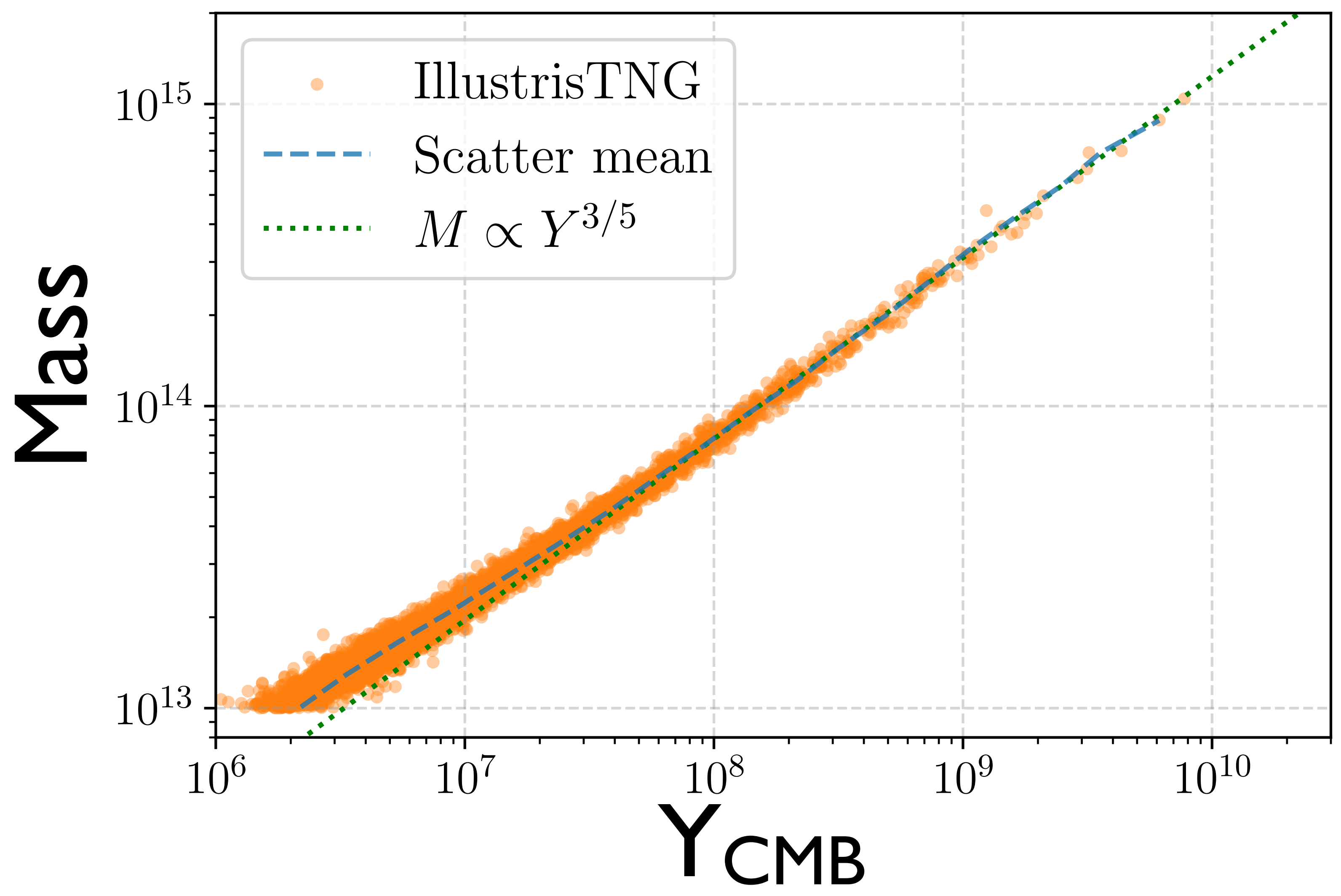
(thermal energy of ionized gas)



Bocquet et al. 19

Problem statement for ML

$$M_{\mathrm{cluster}} = f\,(\,Y_{\mathrm{CMB}}^{3/5}\ \ ,\ \text{other observables??}\,)$$

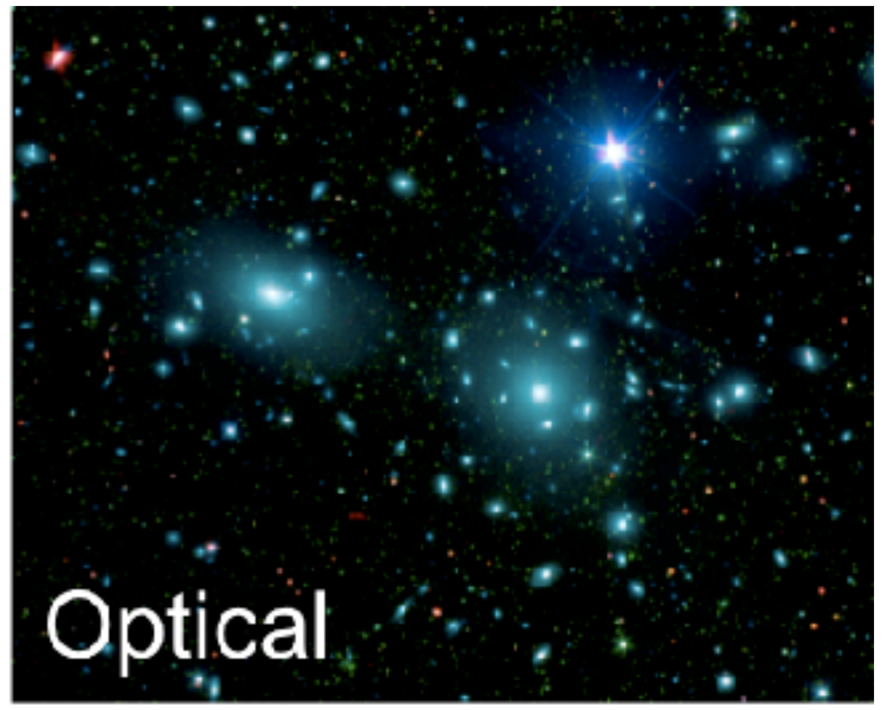


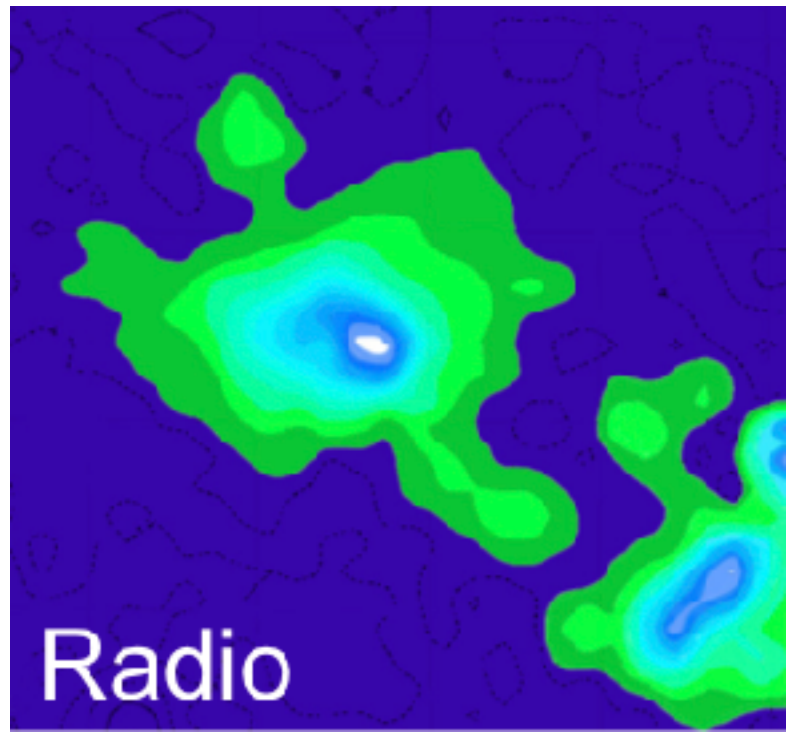
- X-ray/CMB surveys

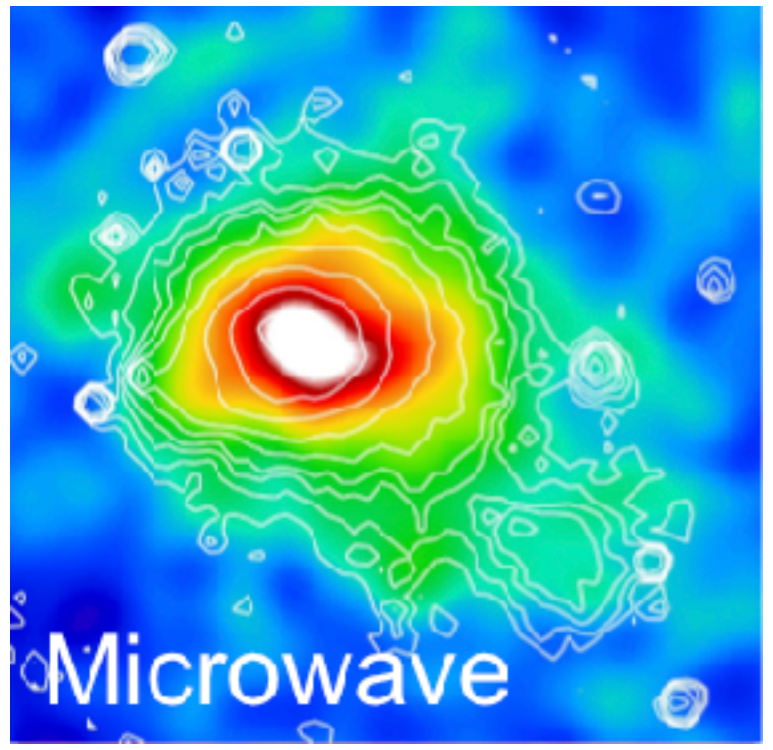
- Gas density/pressure profile
- Luminosity profile
- Spectral temperature
- Gas concentration/ellipticity
- ……

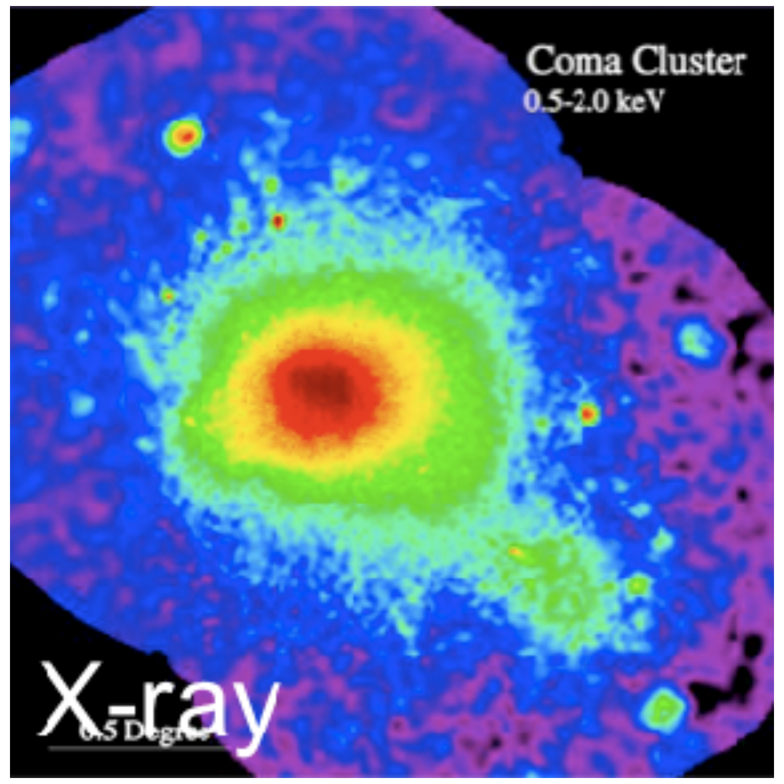
- Galaxy surveys

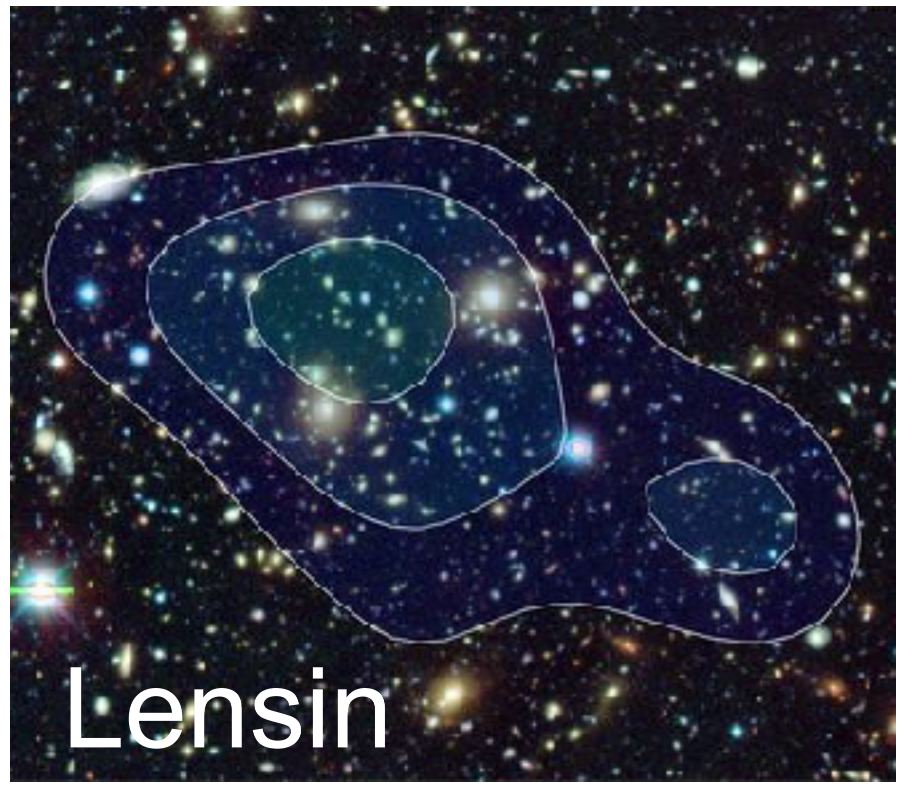
- Richness
- Galaxy colors (e.g. fraction of red galaxies)
- Stellar mass
- …….





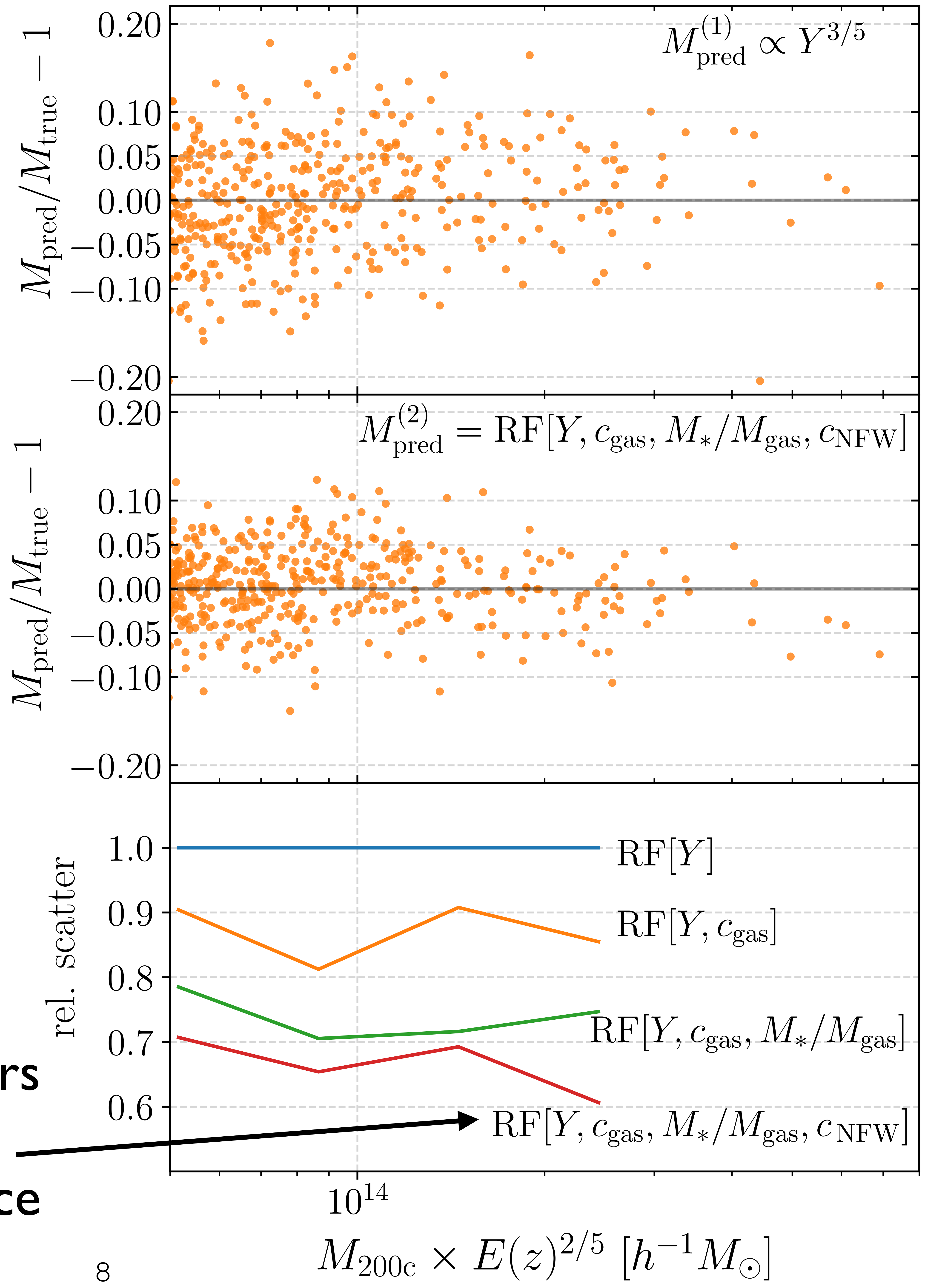






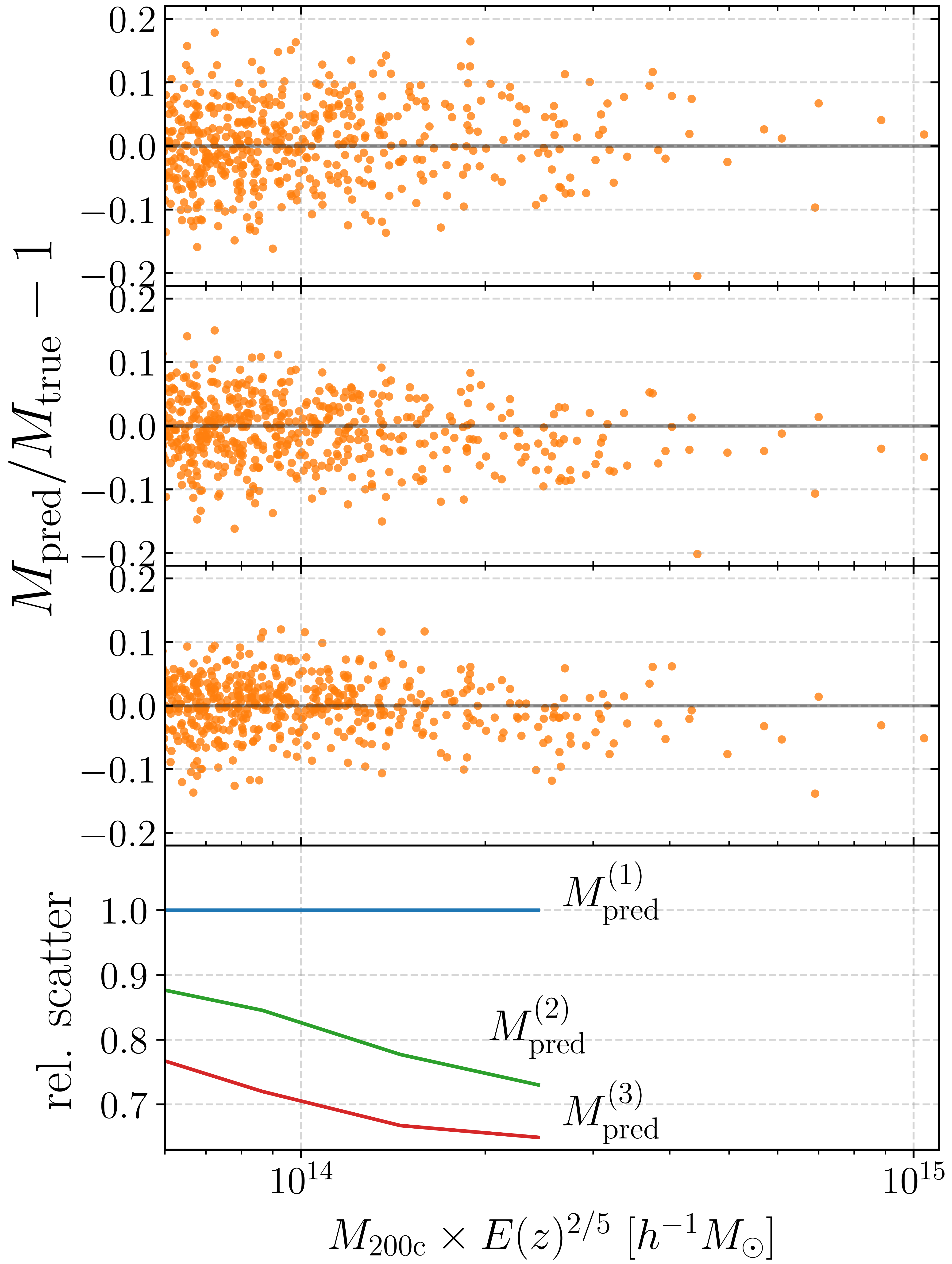
First step:

Use Random Forest (RF) to narrow down the parameter space



We found adding more parameters [M_{gas} , axiality, richness,…] does not improve the performance

IllustrisTNG data



Second step: Symbolic regression

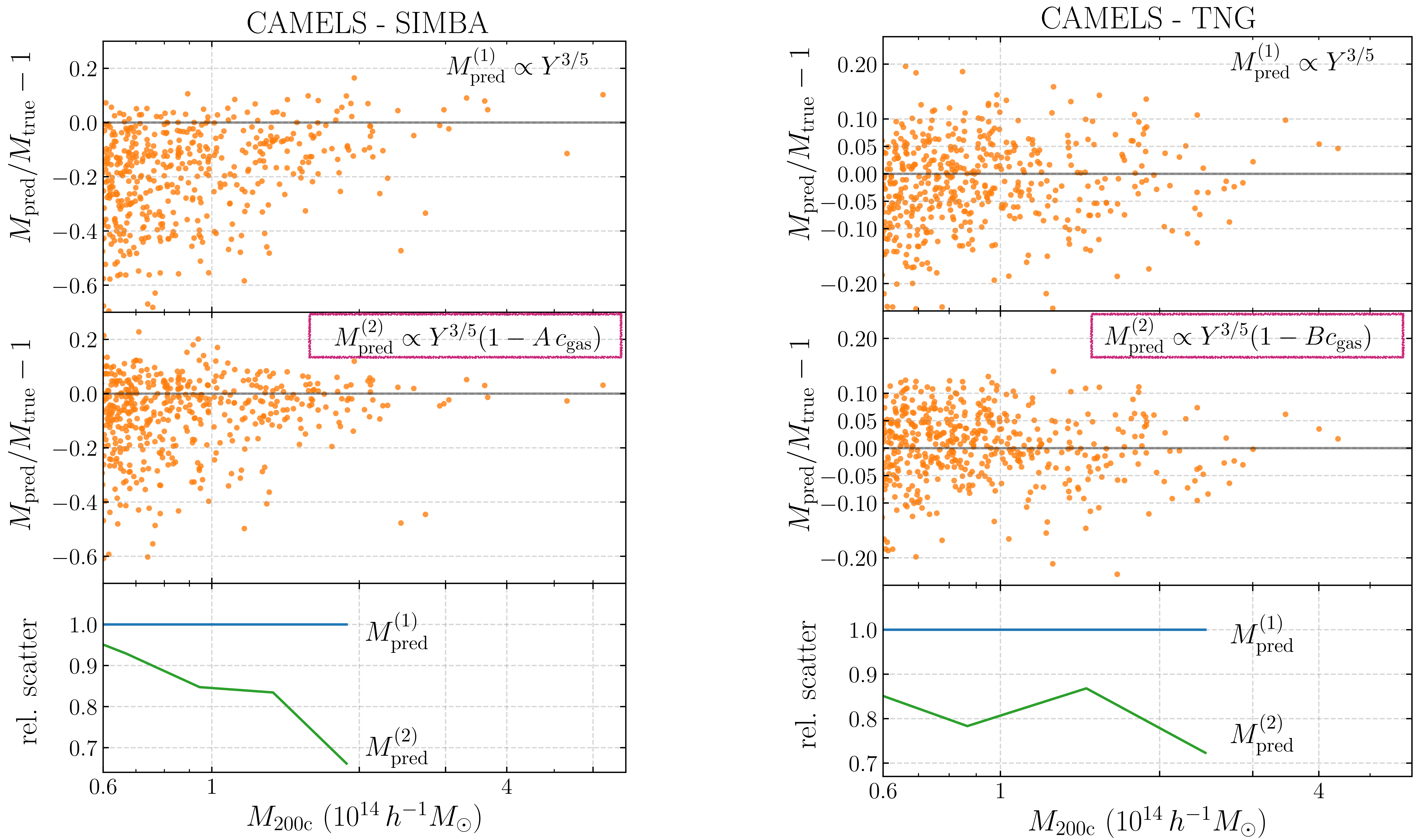
$$M^{(1)}_\mathrm{pred} \propto Y^{3/5}$$

$$M^{(2)}_\mathrm{pred} \propto Y^{3/5}\,(1 - A\,c_\mathrm{gas})$$

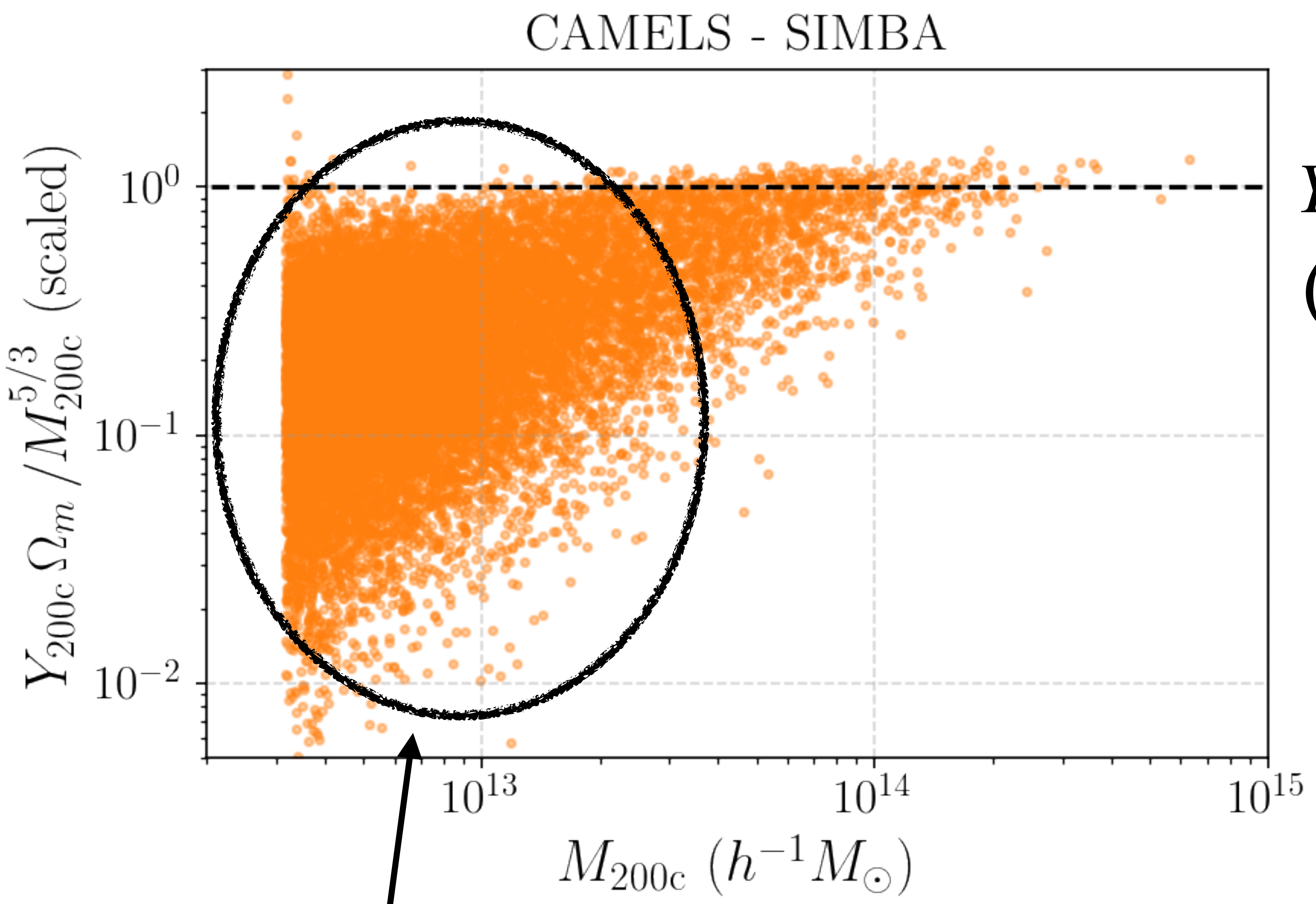
$$c_\mathrm{gas} \equiv \frac{M_\mathrm{gas}(r < R_{200c}/2)}{M_\mathrm{gas}(r < R_{200c})}$$

$$M^{(3)}_\mathrm{pred} \propto Y^{3/5}\left(\frac{B}{c_\mathrm{NFW}}\right)^{M_*/M_\mathrm{gas}}$$

Using CAMELS to test robustness w.r.t feedback



Part II : Reducing deviation from self-similarity (pow. law)

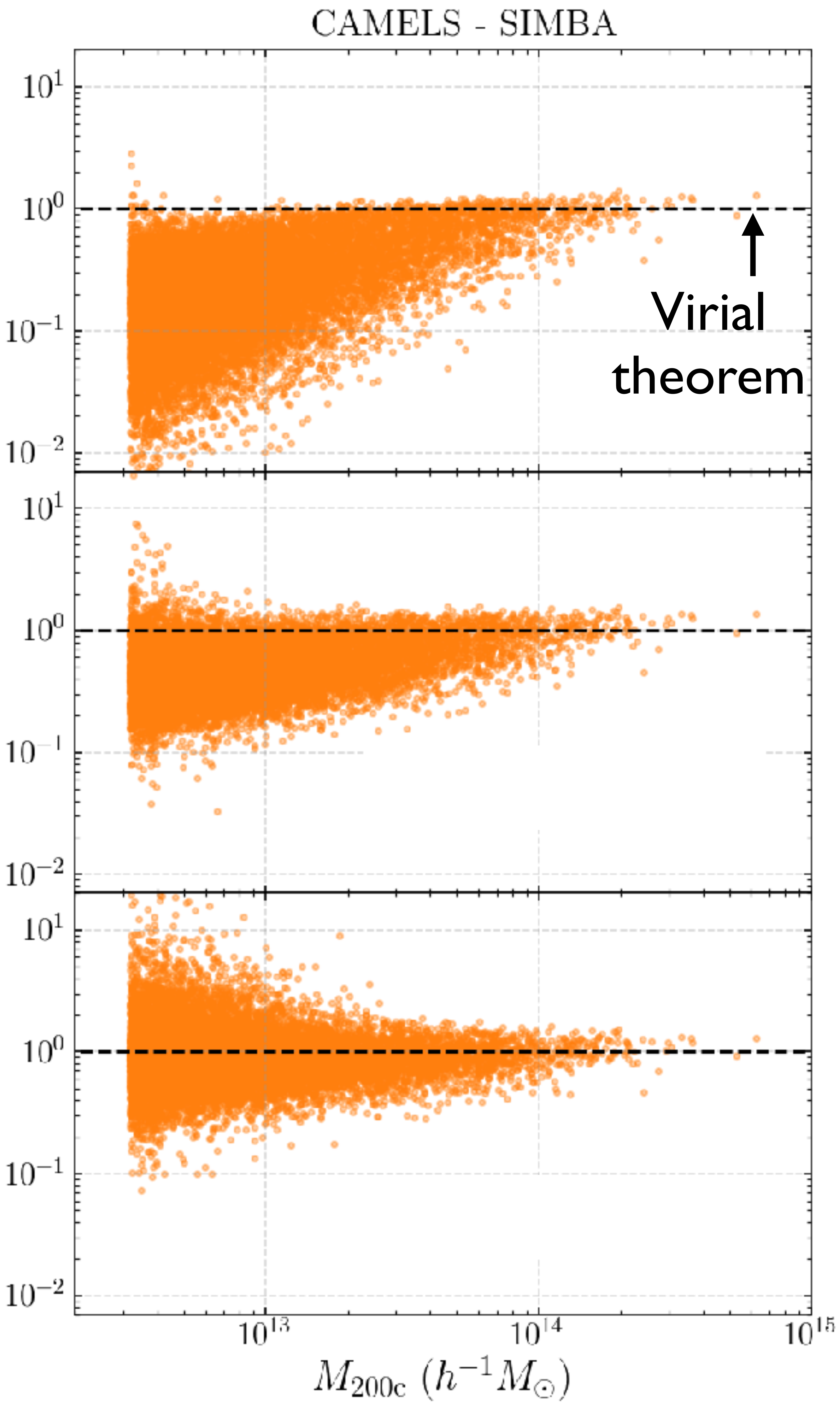


$Y \propto M^{5/3}$

(virial theorem)

Due to ejection of gas from clusters/groups due to AGN/SN feedback

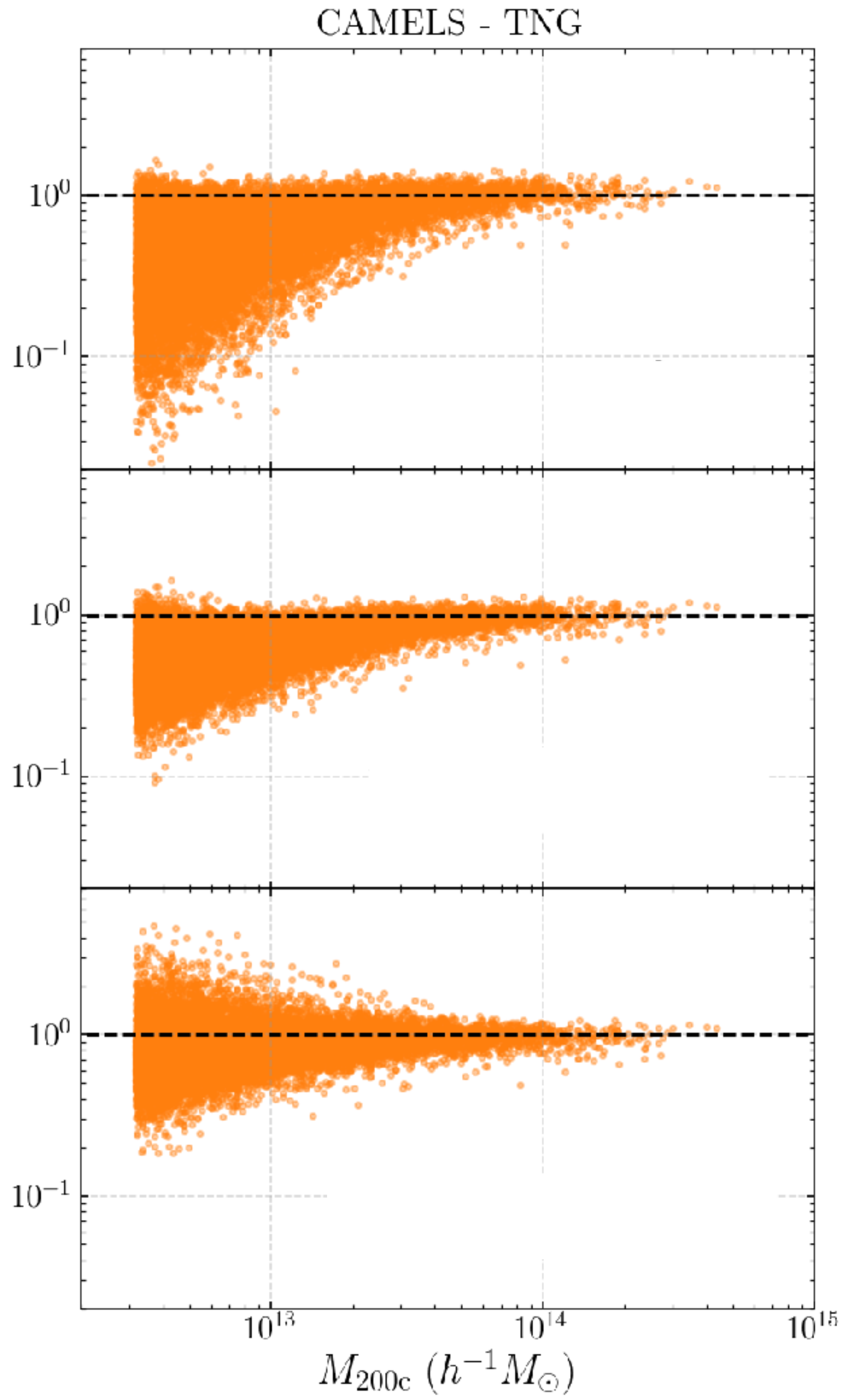
Results



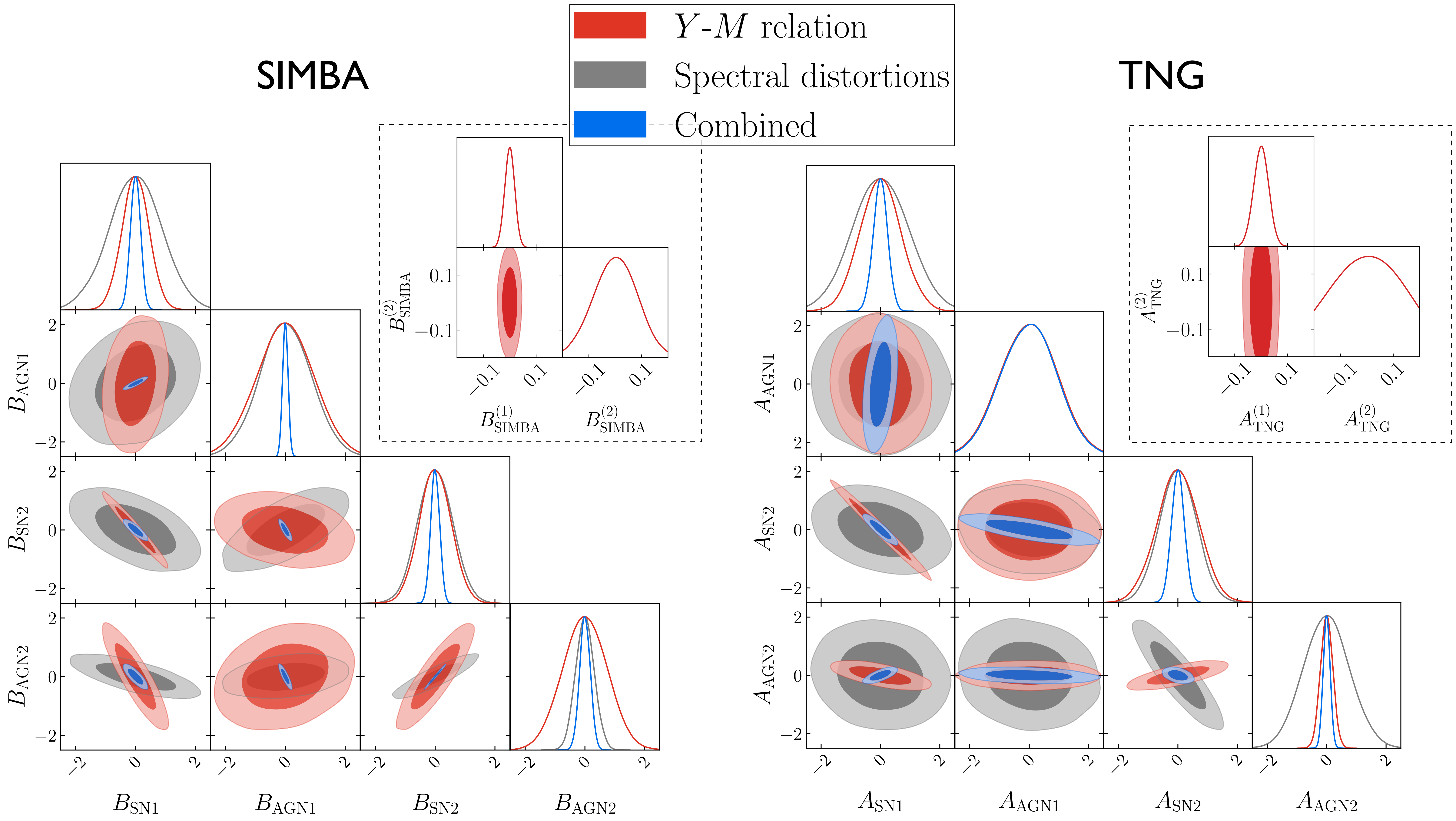
Y

$$Y\left(1+\frac{M_*(r<R)}{M_{\rm gas}(r<R)}\right)$$

$$Y\left[1+\frac{M_*(r<R/2)}{M_{\rm gas}(r<R/2)}\right]$$



Constraining baryonic feedback in hydro sims with the Y-M relation



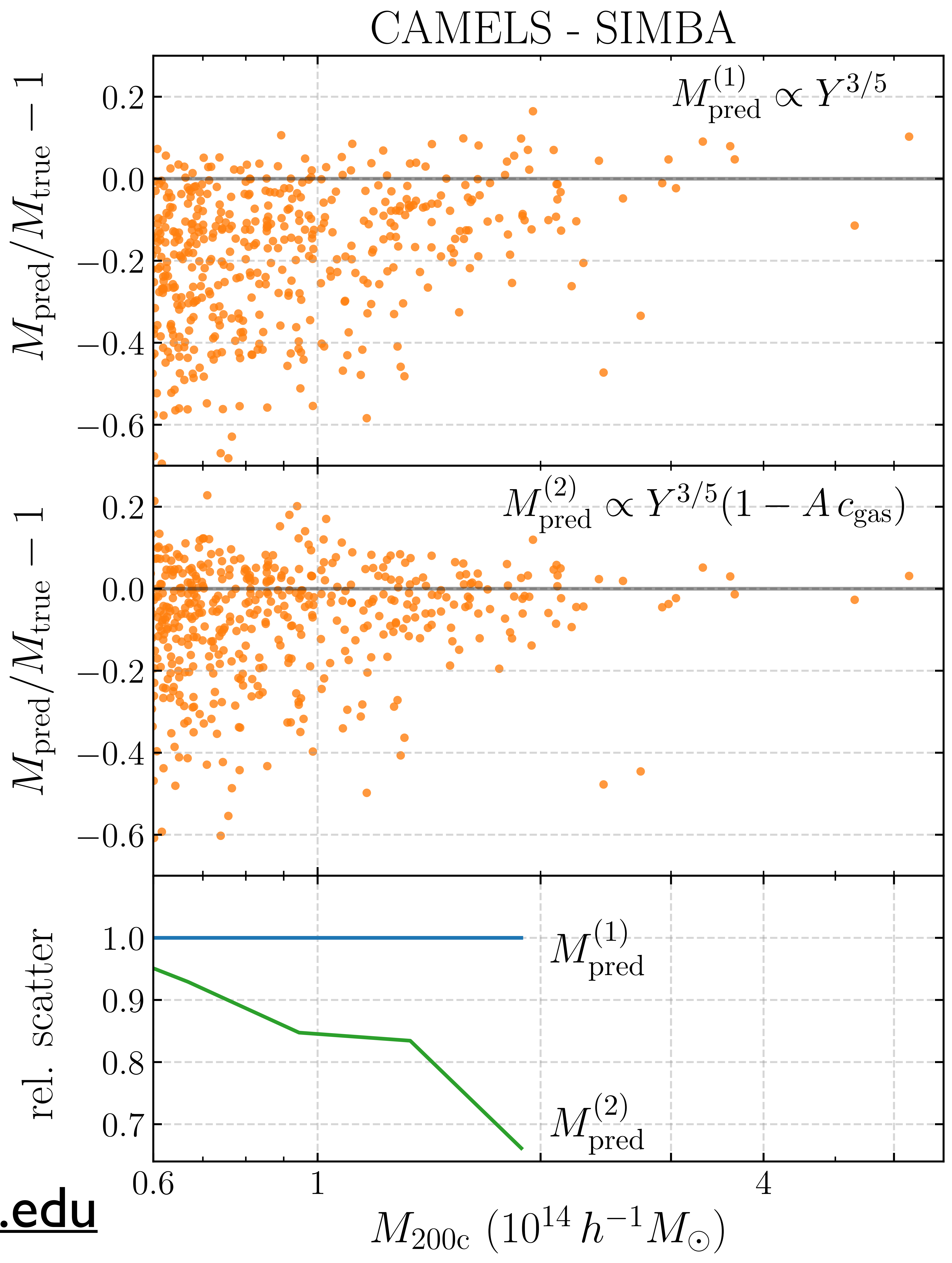
Summary

★ ML tools like symbolic regression can be used to improve astrophysical scaling relations

- Using gas conc. reduces scatter in SZ mass estimates by 20-30% for large clusters

- Including stellar to gas mass ratio reduces deviation from self-similarity by factor >2

➡ Suggestions for other scaling relations?



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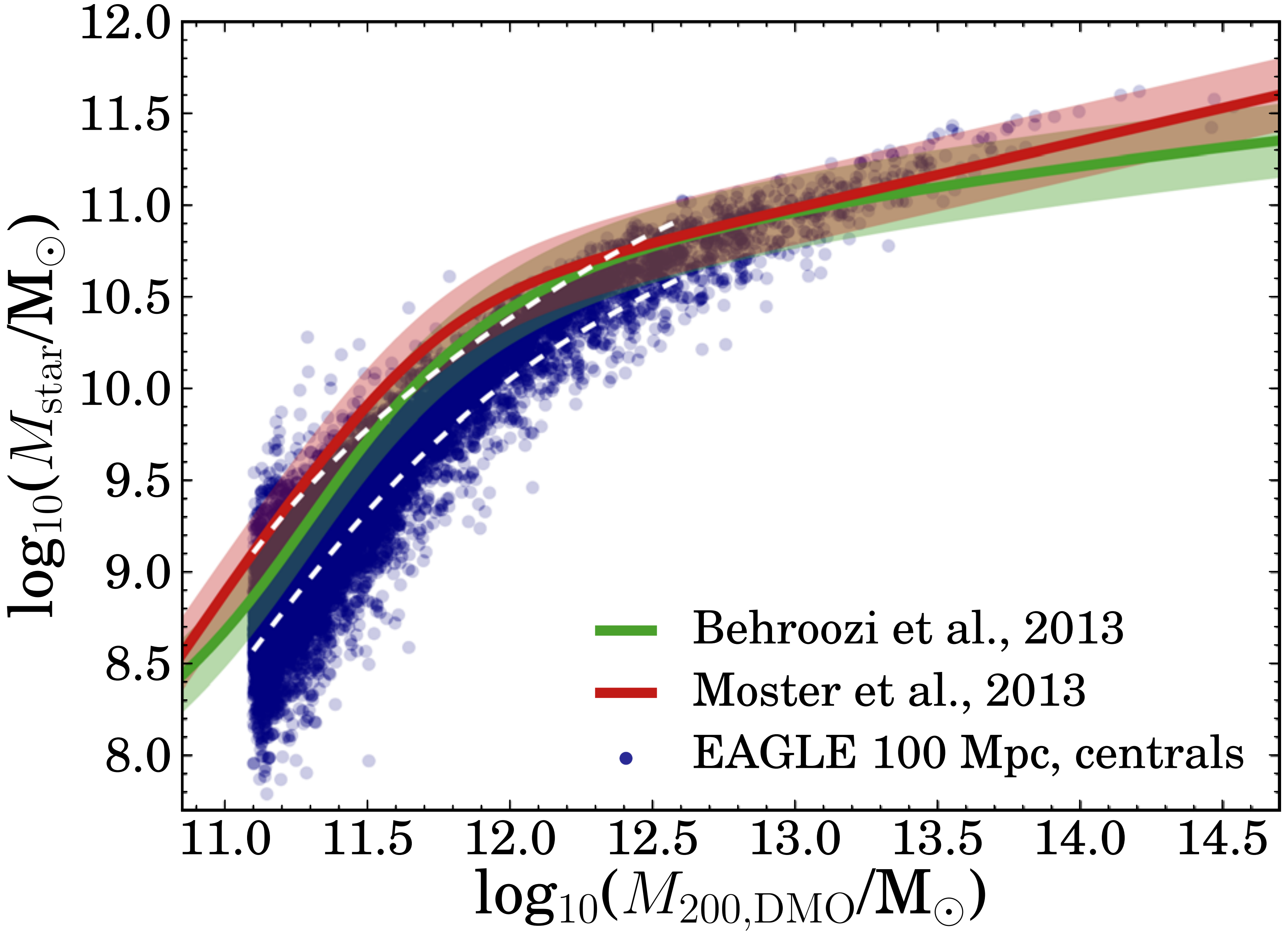
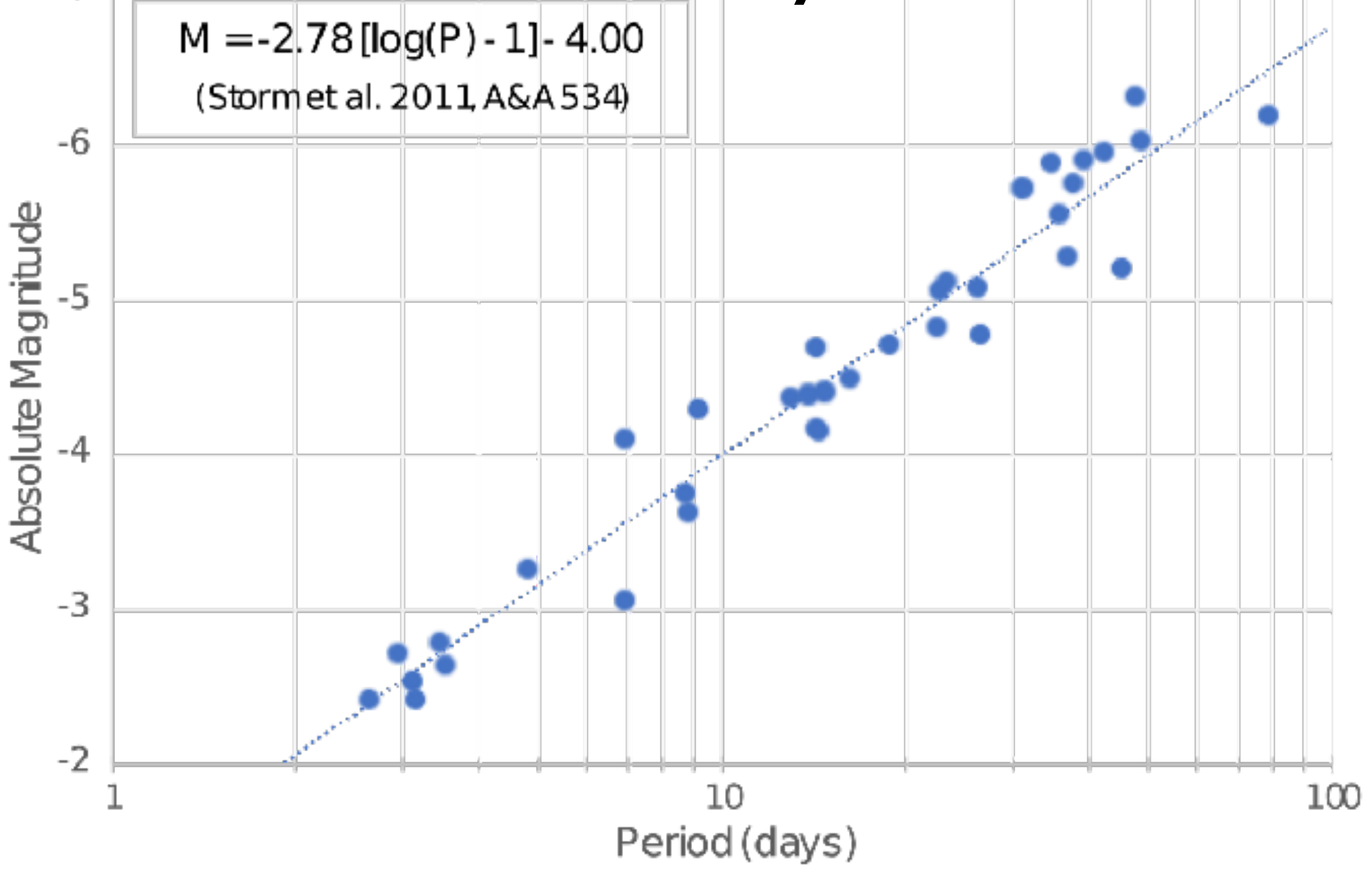
Application to other scaling relations?

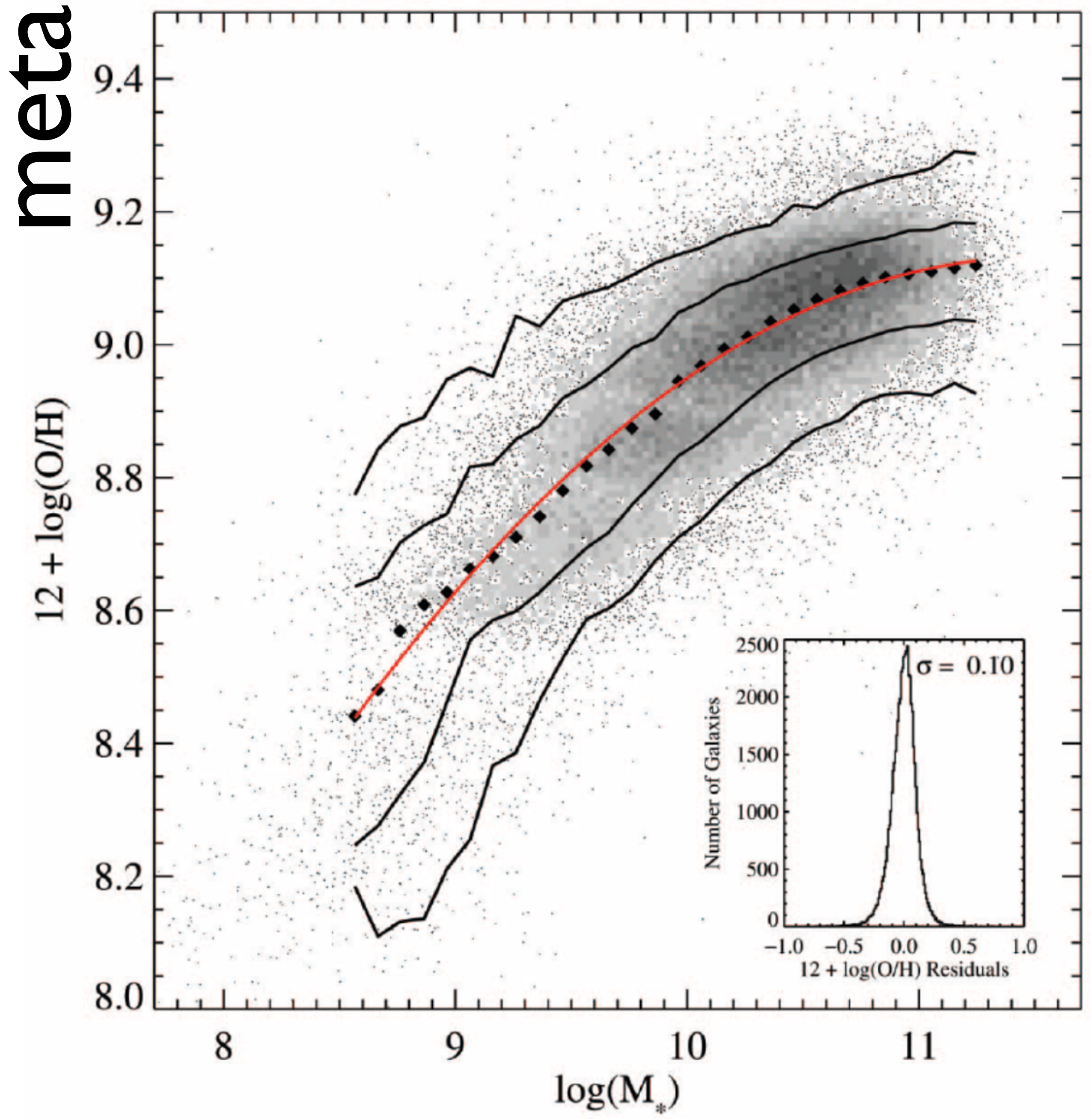
Stellar-halo mass relation



Cepheid Period
-Luminosity rel.



metallicity



Stellar mass