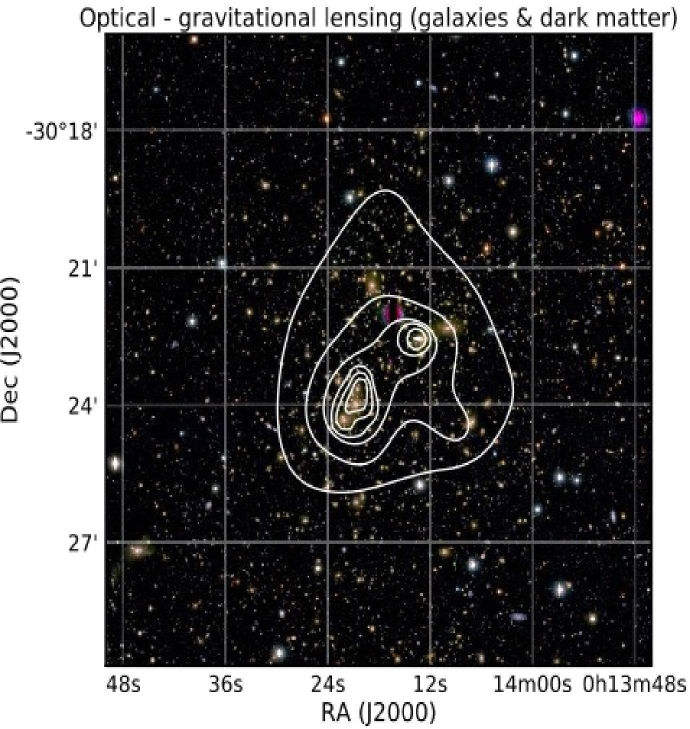
New Scaling Relations of Galaxy Cluster Radio Halos

Marco Balboni, *S. Ettori, F. Gastaldello, R. Cassano, A. Bonafede, V. Cuciti, A. Botteon et al. 2025,*
A&A, 695, A180

LOFAR Family Meeting - 22/09/2025

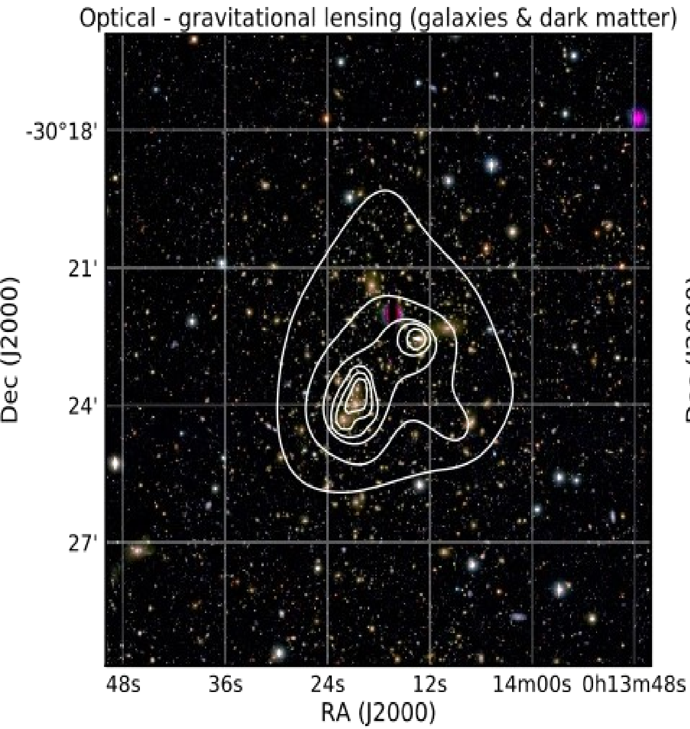
GCs multifrequency overview

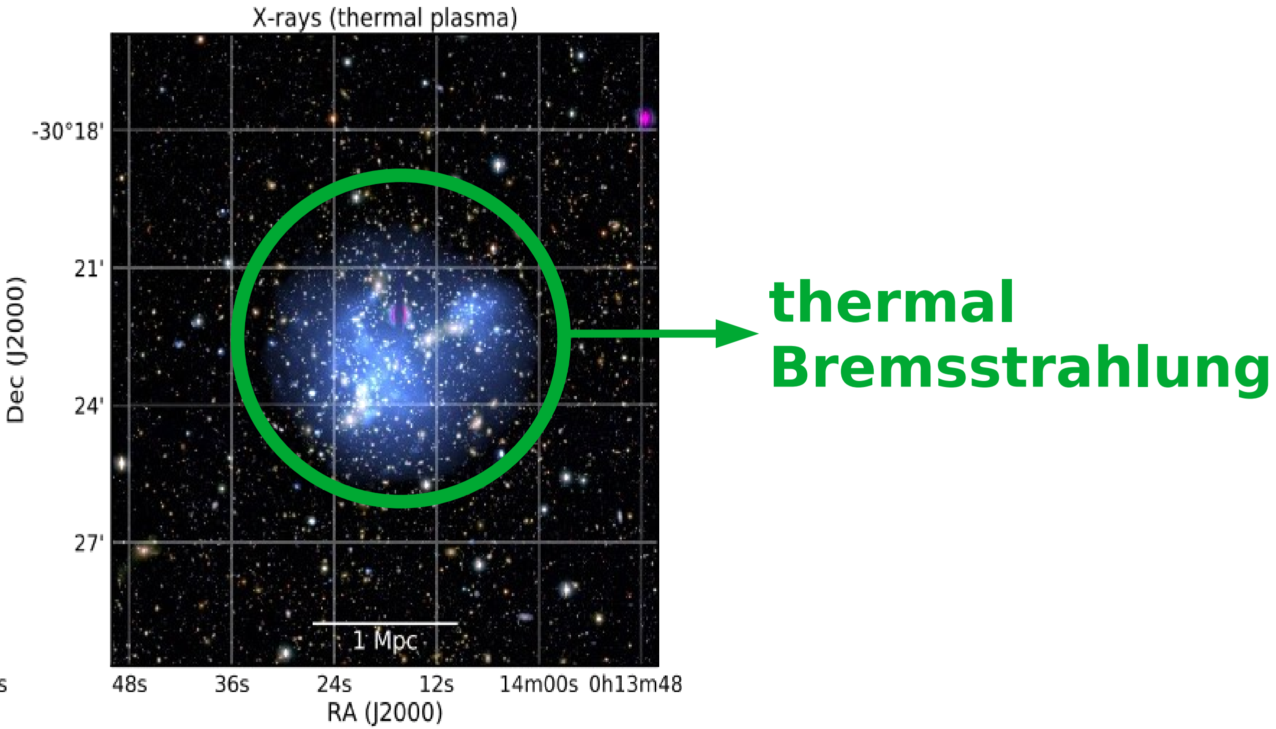


Clusters of galaxies are the largest objects in the Universe which are held together by their own gravity.

- Masses: $10^{14} – 10^{15}$ M_{sun} (~80% dark matter)
- Galaxies: 100s to 1000s
- Size: R~1 Mpc

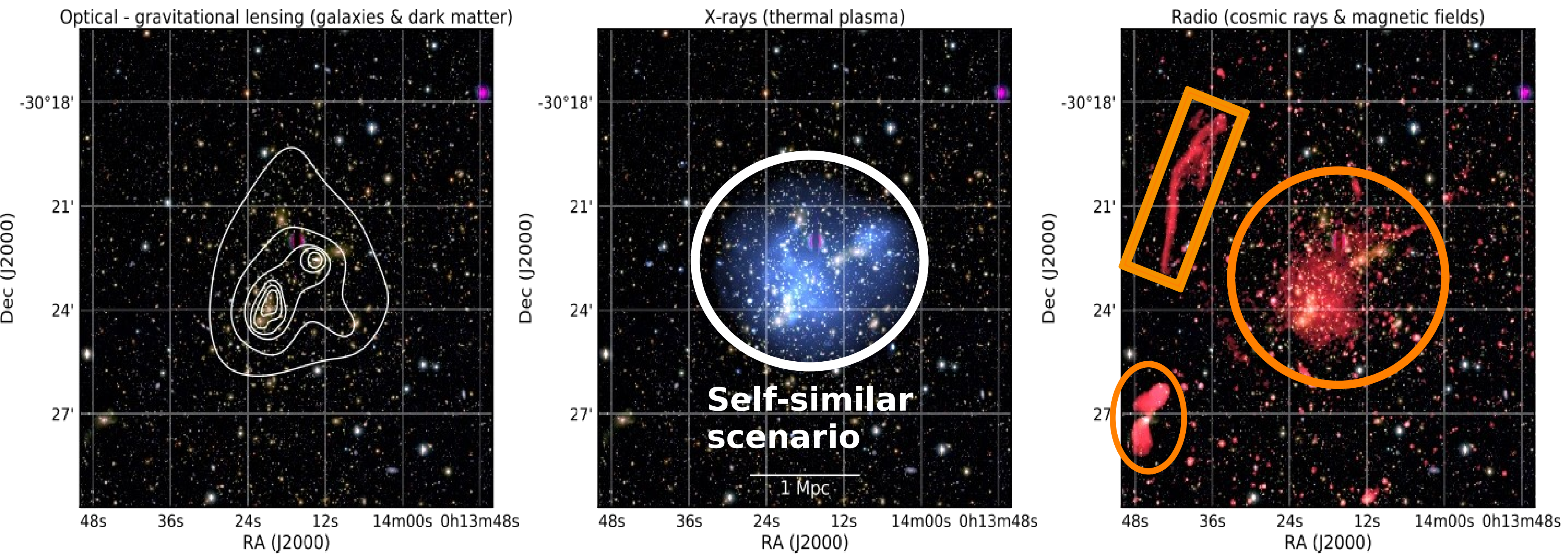
GCs multifrequency overview





GCs multifrequency overview

Synchrotron (CRe^{-} + weak B)



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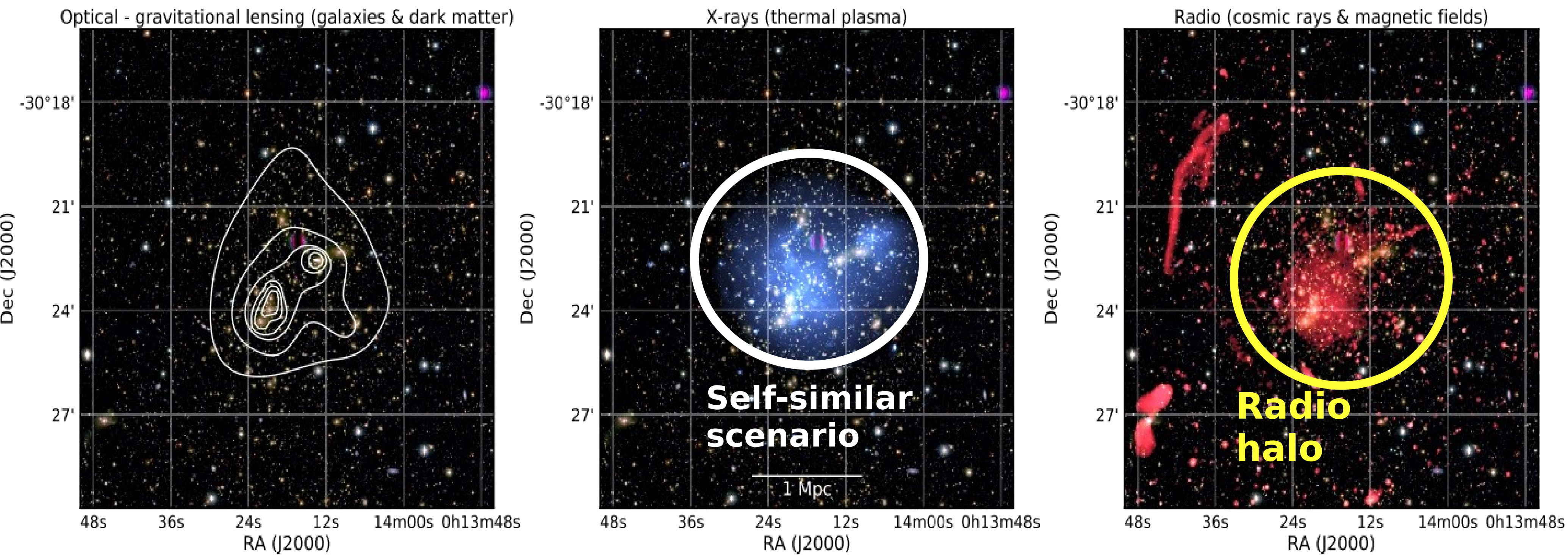
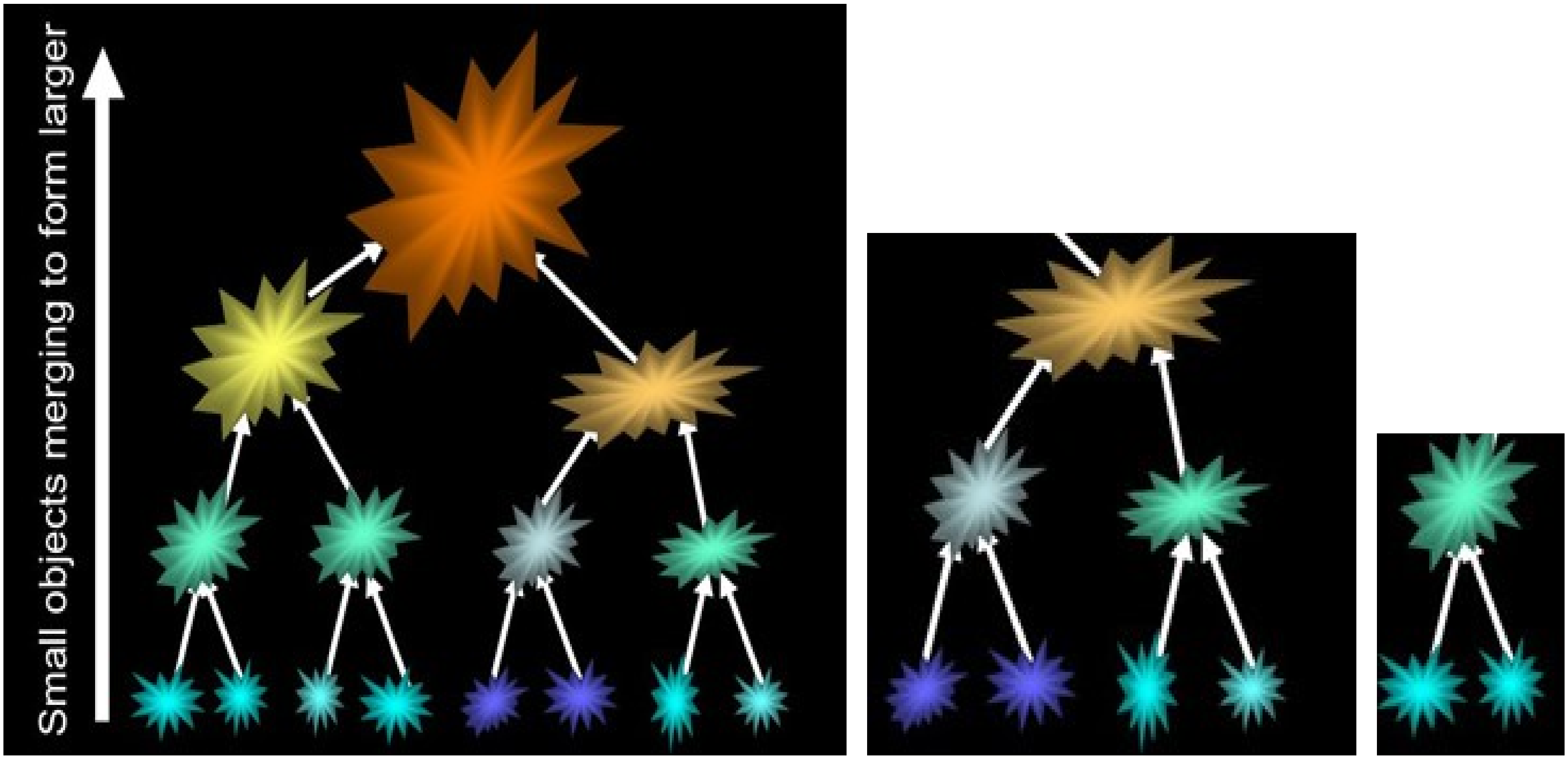


Self-similar scenario

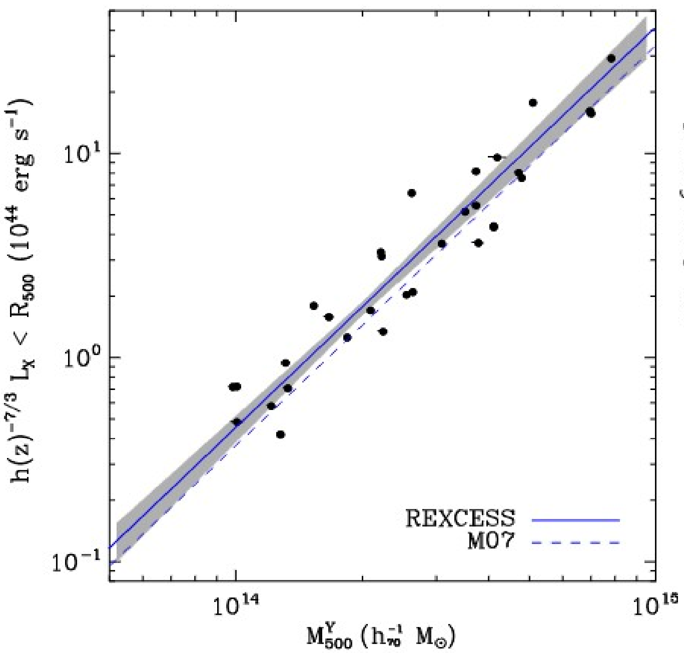
- At cluster scales gravity dominates causing a self-similar evolution

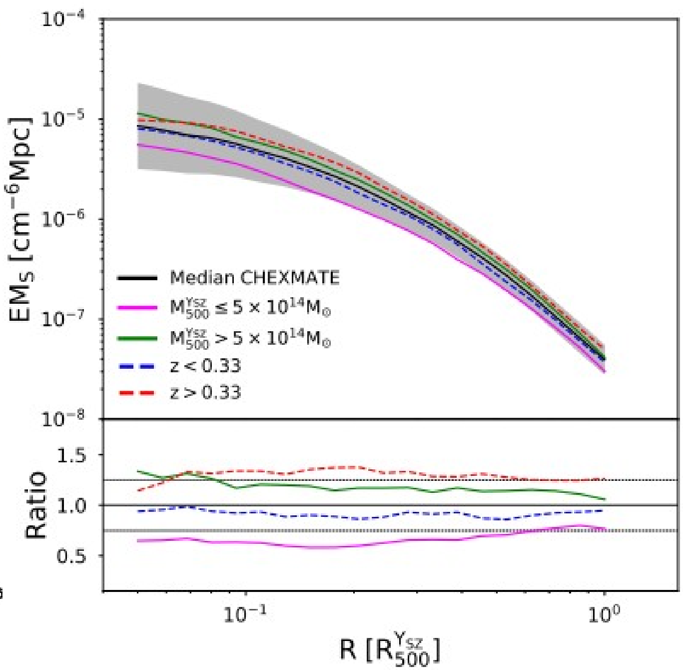


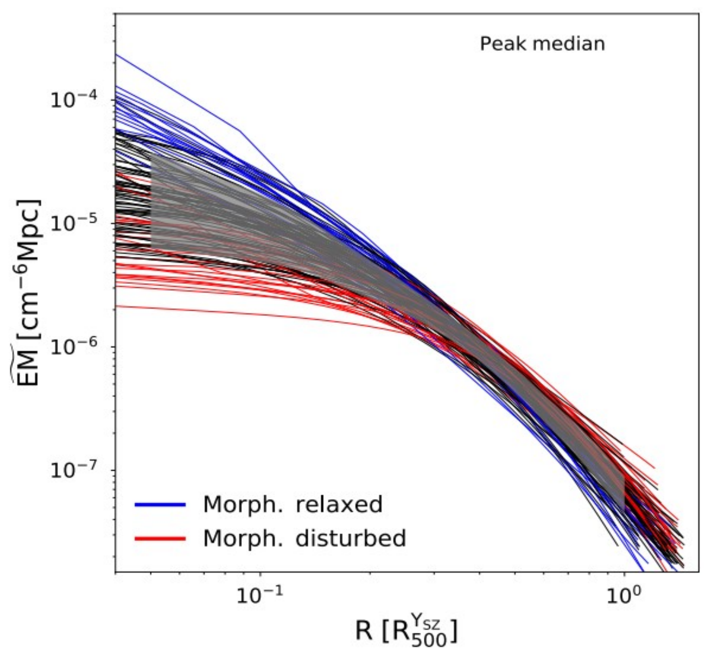
Credits: https://astronomy.swin.edu.au/cosmos/*/Hierarchical+Clustering

Self-similar scenario

- At cluster scales gravity dominates causing a self-similar evolution
- Well studied through X-ray observations of ICM:
  - Scaling relations among global properties, L_X – M, T – M, L_X – T (e.g. Pratt+09, Lovisari+2015) and resolved ones, ρ(r), T(r) (e.g. Arnaud+2010, Rossetti+24)

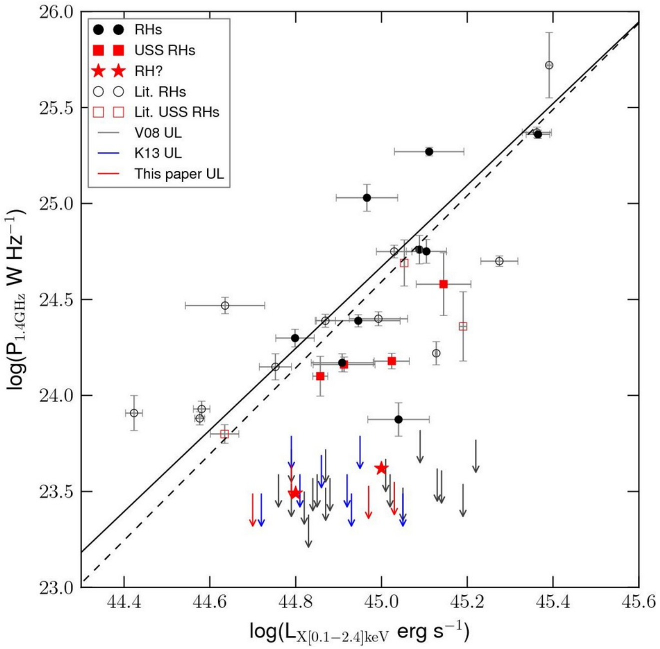


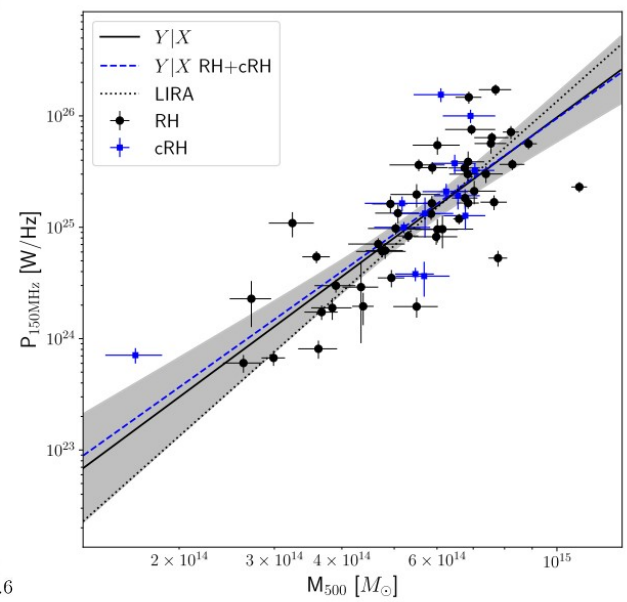


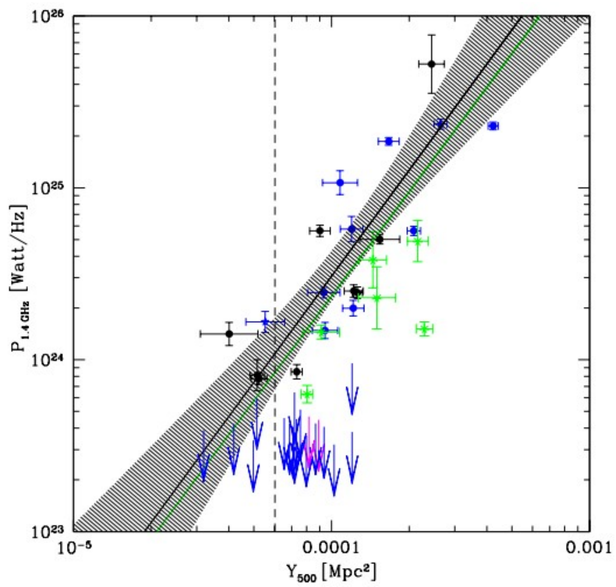


Scaling laws in radio

- Non-thermal component scaling relations have been studied for integrated quantities: $P_R - L_X$, P_R - M, $P_R - Y_{SZ,500}$ (e.g Cassano+13, Kale+15, Cuciti+23)







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- No systematic studies have been made on the scaling of spatially resolved properties (but also on the P_R redshift dependence)

Datasets

UNIFORM DEPTH

CHEX-MATE

- Representative PSZ sample of 118 GC
- Homogeneous X-ray coverage
- Low and high redshift objects (Tier1 and Tier2)

Aims:

- Cluster absolute mass scale
- Cluster statistical properties
- How cluster properties changes over the time

CHEX-MATE Collaboration et al. 2021
Campitiello et al. 2022

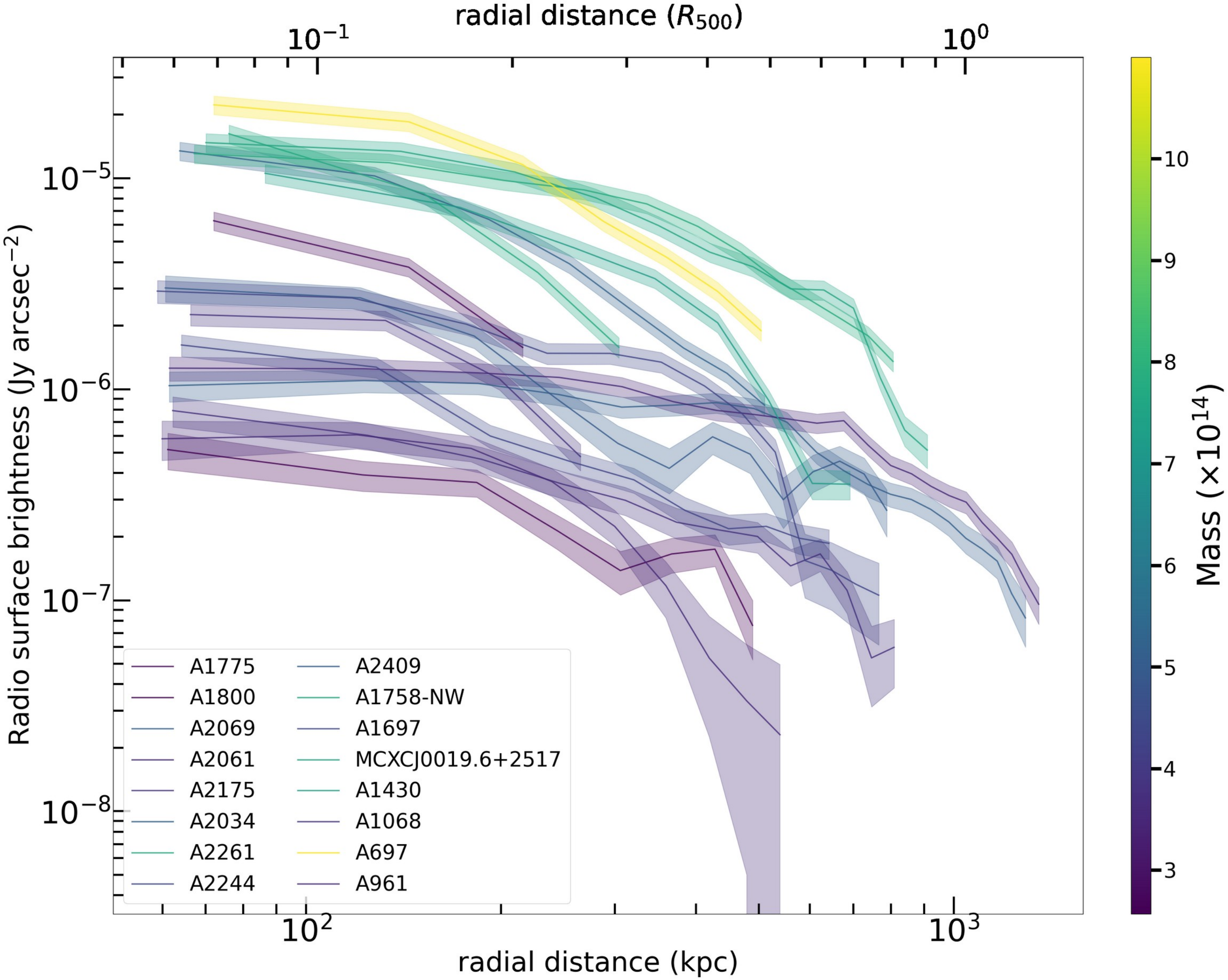
LoTSS DR2

- Deep 120-168 MHz survey of the Northen sky
- High sensitivity (100 muJy/beam)
- Ideal for halos studies (83 so far)

Botteon et al. 2022
Bruno et al. 2023
Zhang et al. 2023
Cassano et al. 2023
Cuciti et al. 2023
Jonese et al. 2023

Radio re-scaling

- Extracted the radial profiles from the 16 CHEX-MATE - LoTSS DR2 (z<0.4)



Radio re-scaling

- Extracted the radial profiles from the 16 CHEX-MATE - LoTSS DR2 (z<0.4)
- Derived the expected scaling in mass for the profiles assuming $R_H \sim M^\beta E_z^\beta$. Compared the mass expected dependence with the best-fit scaling

$$P_{150} = 4\pi D_L^2 \frac{S_{150}}{(1+z)^{\alpha+1}}$$

$$P_R \propto (M E_z)^{\alpha_M}$$

$$S_{150} \sim I_{150} R_{halo}^2 \left(\frac{D_L}{D_\theta}\right)^2 \sim I_{150} M^{-2\beta_M} E_z^{-2\beta_z} (1+z)^4$$

$$\boxed{I_{150}(r) \propto (M)^{\alpha_M - 2\beta_M} E_z^{\alpha_M - 2\beta_z} (1+z)^{-(3+\alpha)}}$$

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$$\boxed{\begin{aligned} I_{150}(r) &\propto (M)^{\alpha_M - 2\beta_M} E_z^{\alpha_M - 2\beta_z} (1+z)^{-(3+\alpha)} \\ &= I_0 e^{\left(-A \frac{r}{r_{500}}\right)} M^{\gamma_M} E_z^{\gamma_z} (1+z)^{-(3+\alpha)} \end{aligned}}$$

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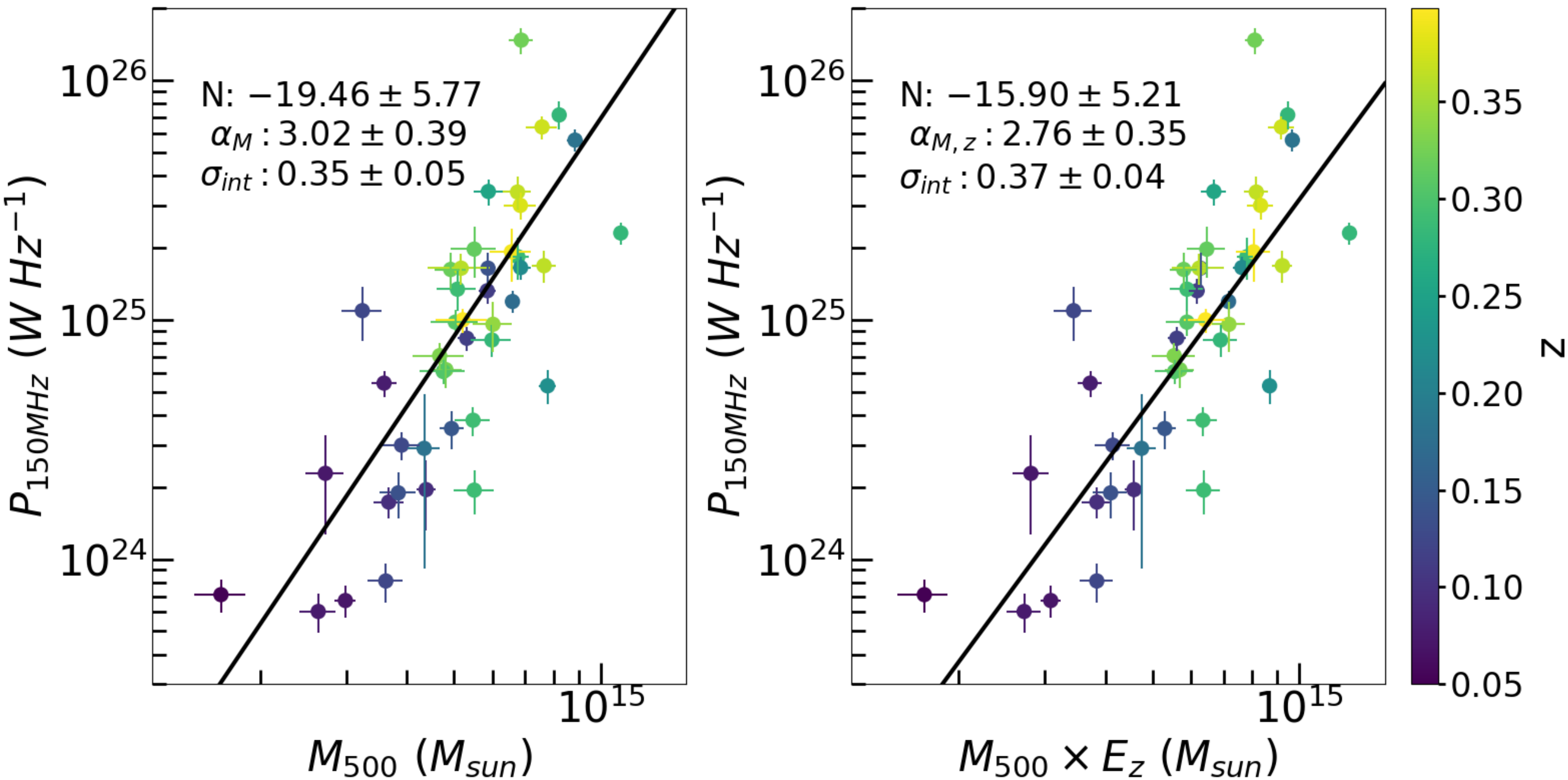
- Exploited the Cuciti+23 RH sample to derive mass and redshift dependence



Radio re-scaling

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	σ_{int}	Δ_σ	γ_M	$\Delta\,\gamma_M$	γ_z	$\Delta\,\gamma_z$
$I_{150MHz} \propto M^{\gamma_M}$	0.22	0.05	3.68	0.43	0 (fixed)	/
$I_{150MHz} \propto M^{\gamma_M}\ E_{z,\mathrm{fixed}}^{4/3}$	0.24	0.04	3.41	0.38	4/3 (fixed)	/
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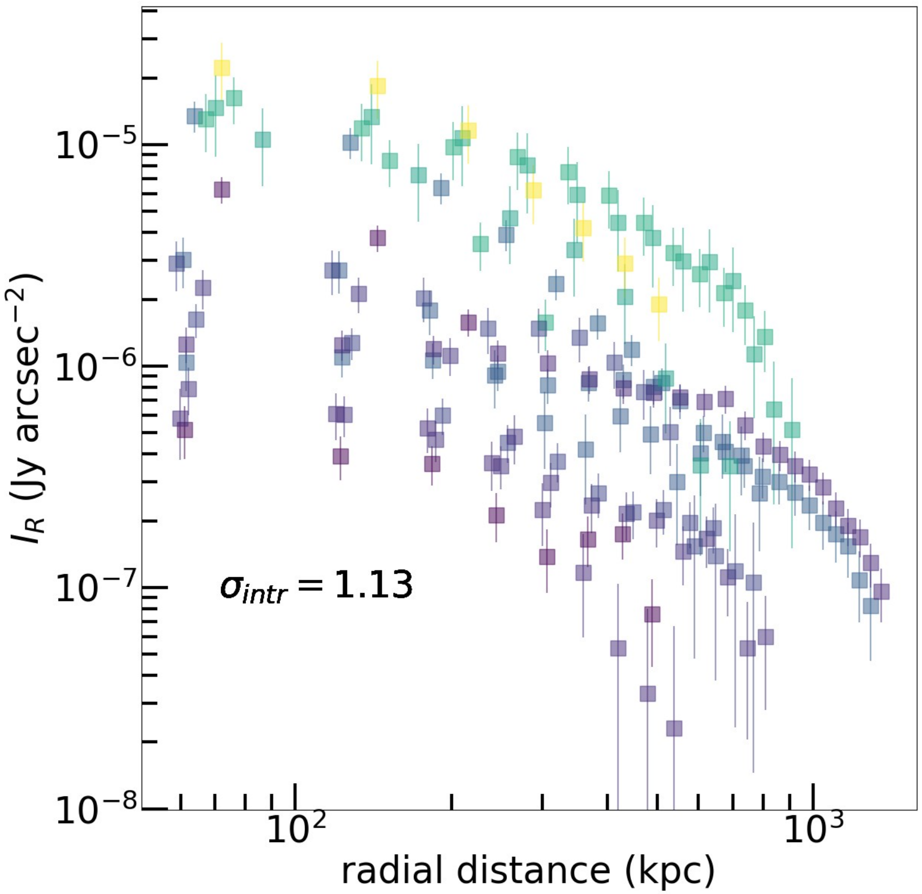

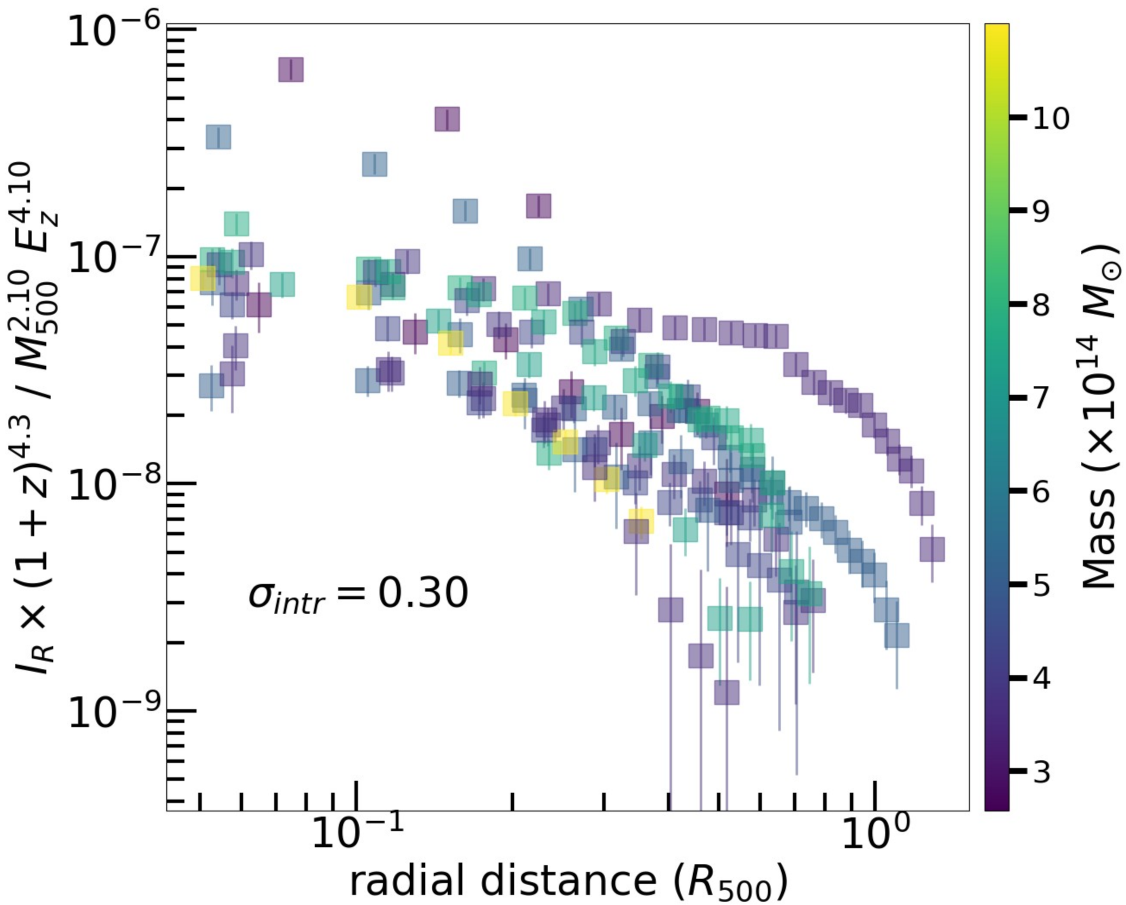

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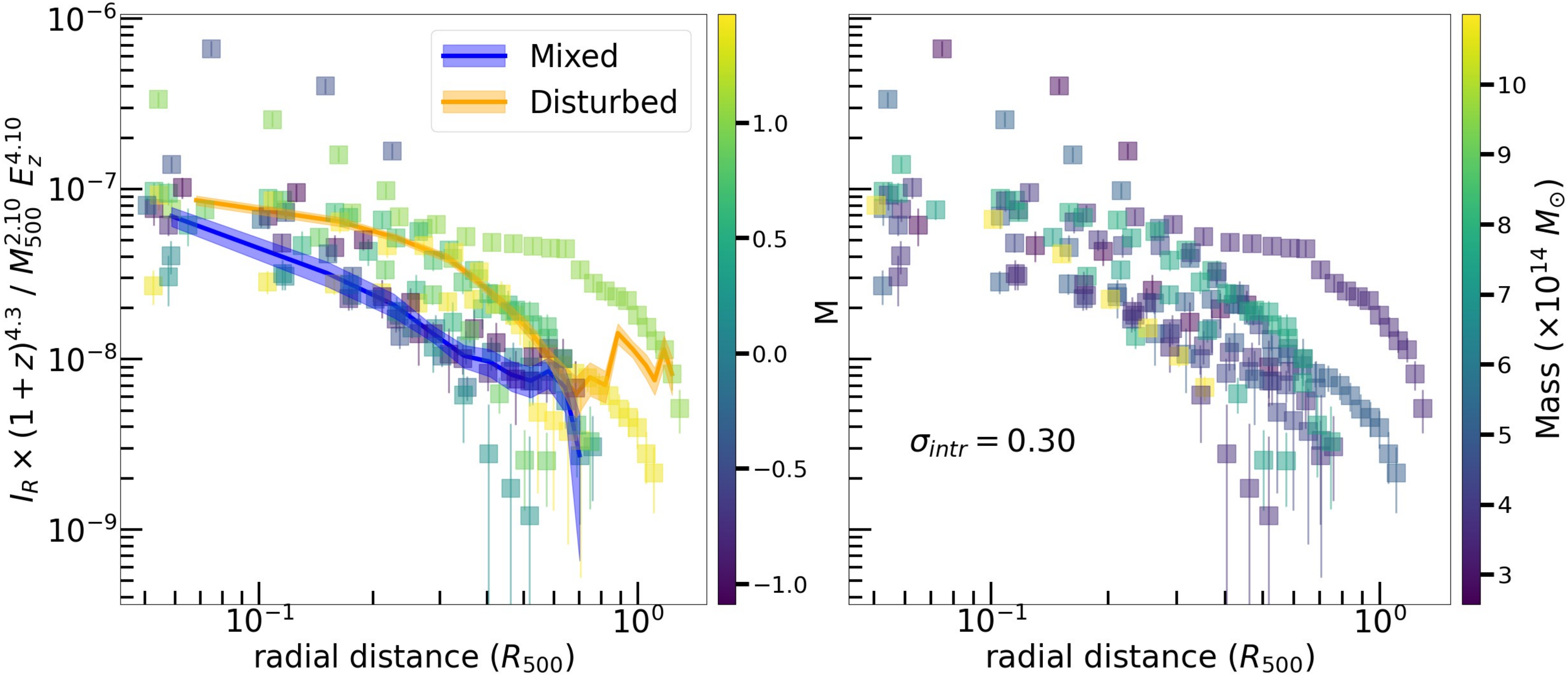

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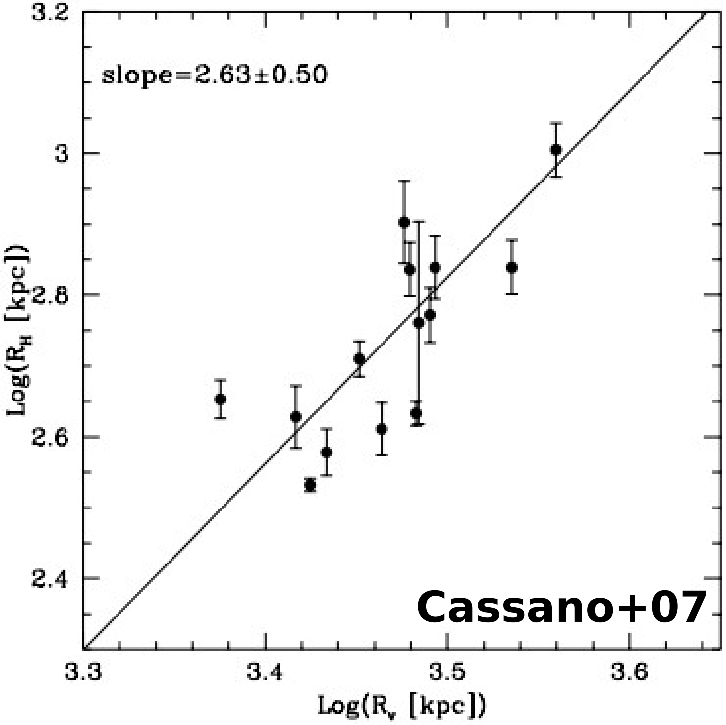

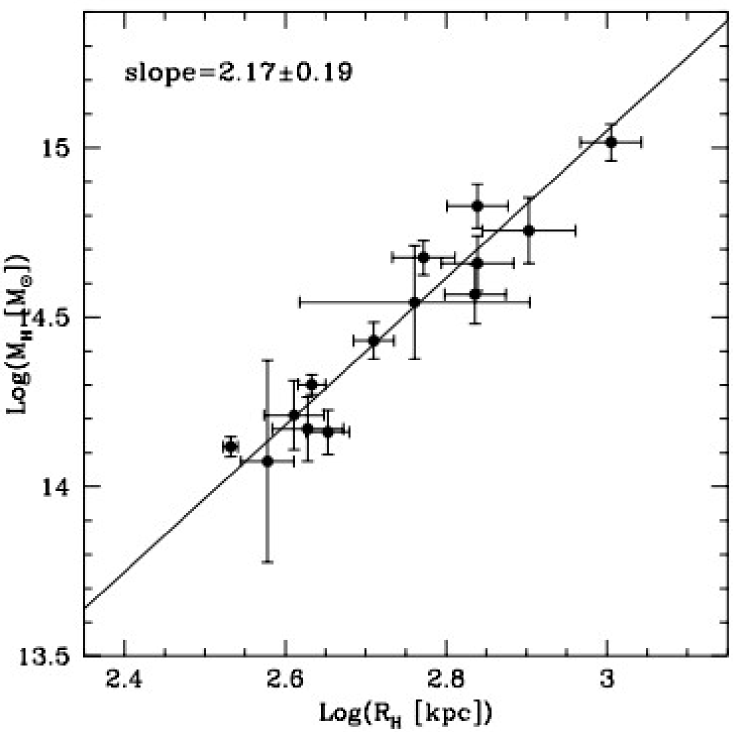

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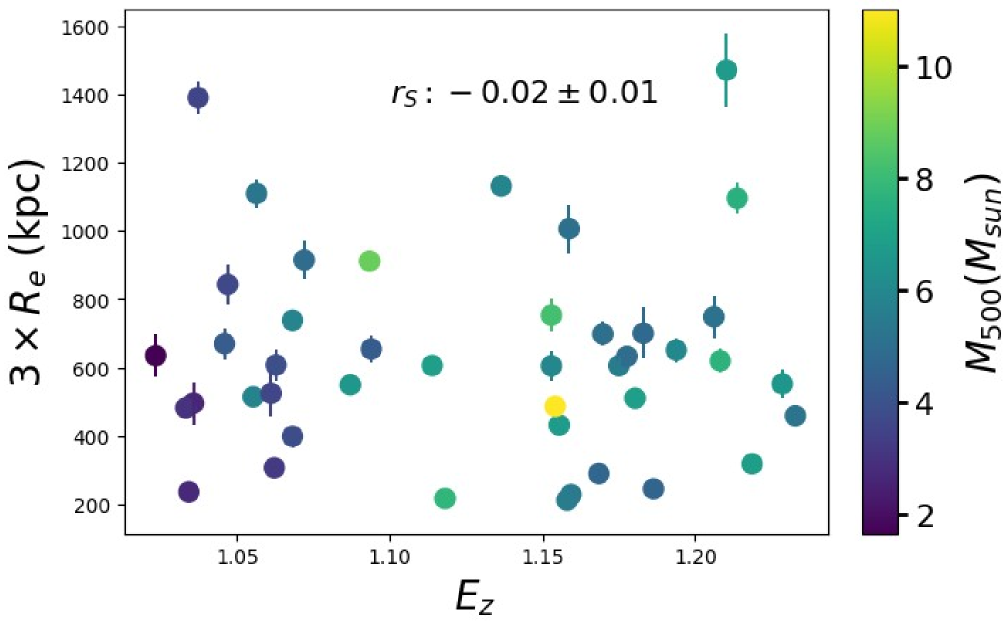

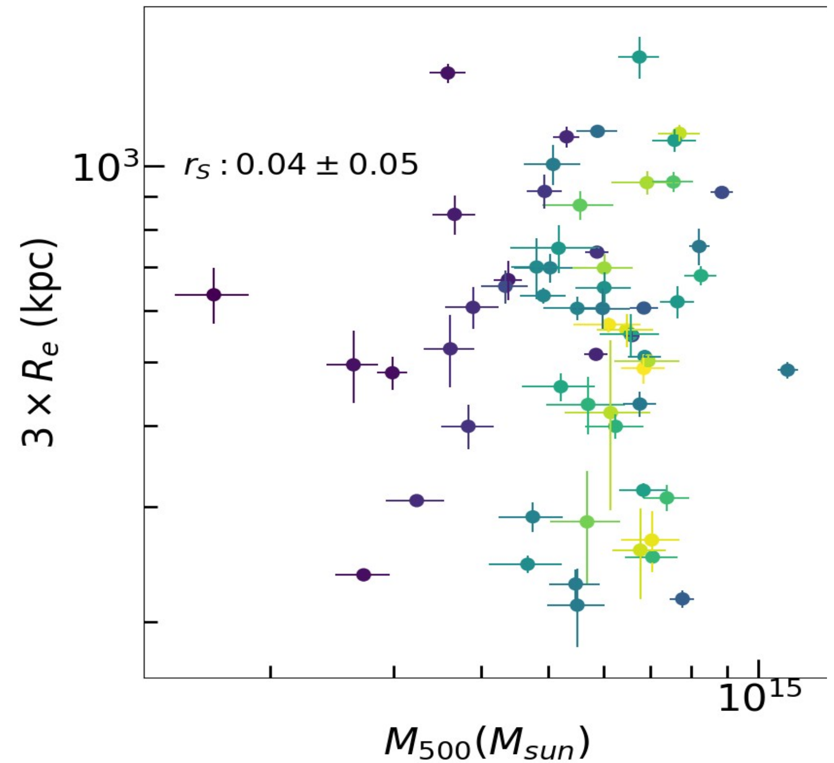

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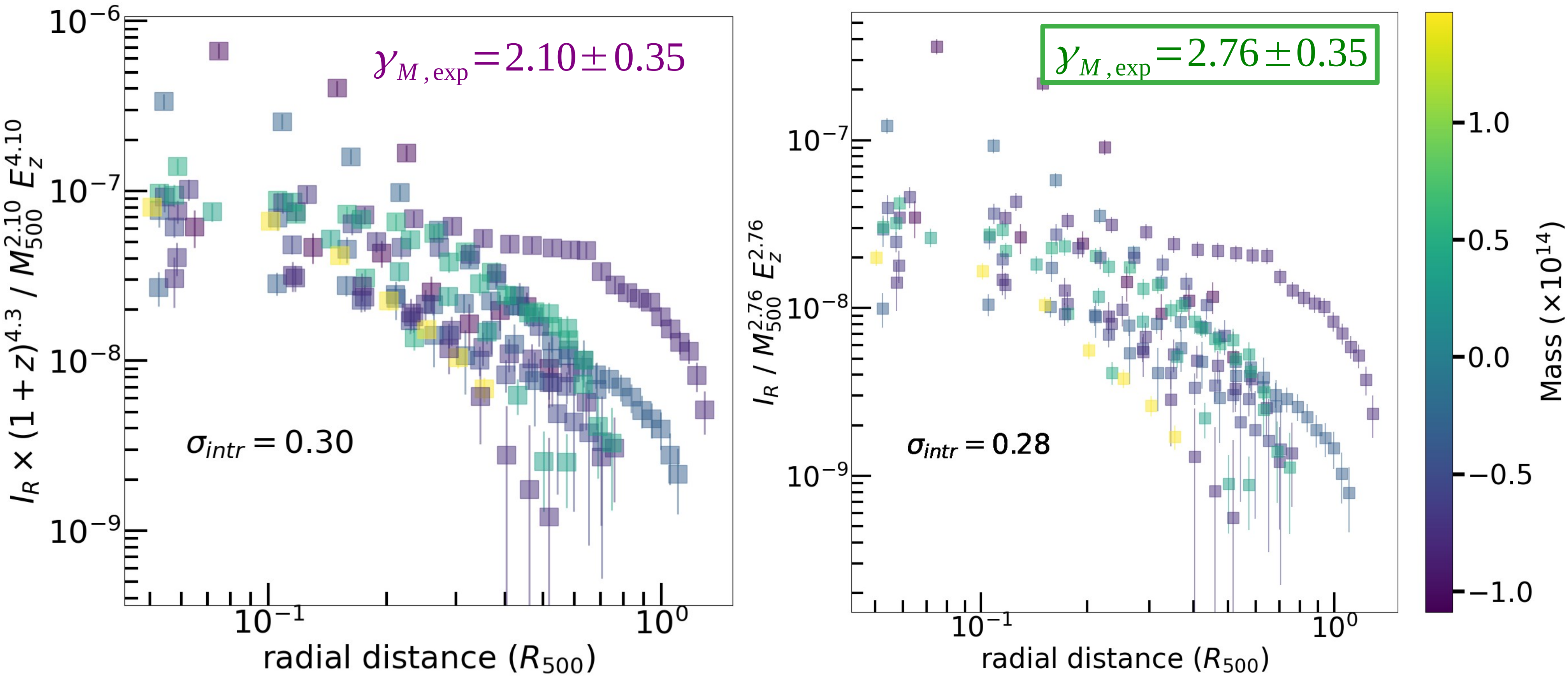
$I_{150MHz} \propto (ME_z)^{\gamma_M}$	0.26	0.04	2.88	0.31	/	/



The role of B

The radio halo power

$$P_R = f(M, z)$$

In the context of turbulent re-acceleration (Cassano+05,06)

$$\boxed{P_R \propto M^{2-\Gamma} \frac{B^2 n_{e,r}}{(B^2 + B_{IC}^2)^2}}$$

If $B = B_{M'} \left(\frac{M}{M'} \right)^b$:

$$\log(P_{150}) = N + \left(\frac{4}{3} - 2b \right) \log\left(\frac{M}{M'} \right) - 2 \log\left[1 + \left(\frac{B_{CMB,0}}{B_{M'}} \right)^2 \frac{(1+z)^4}{(M/M')^{2b}} \right]$$

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b	$U(0, 10)$	2.05 ± 0.36
$B_{M'}$	$U(0, 10)$	2.53 ± 0.61
N	$U(0, 10)$	2.82 ± 0.83
σ_{int}	$HC(0.5)$	0.95 ± 0.13
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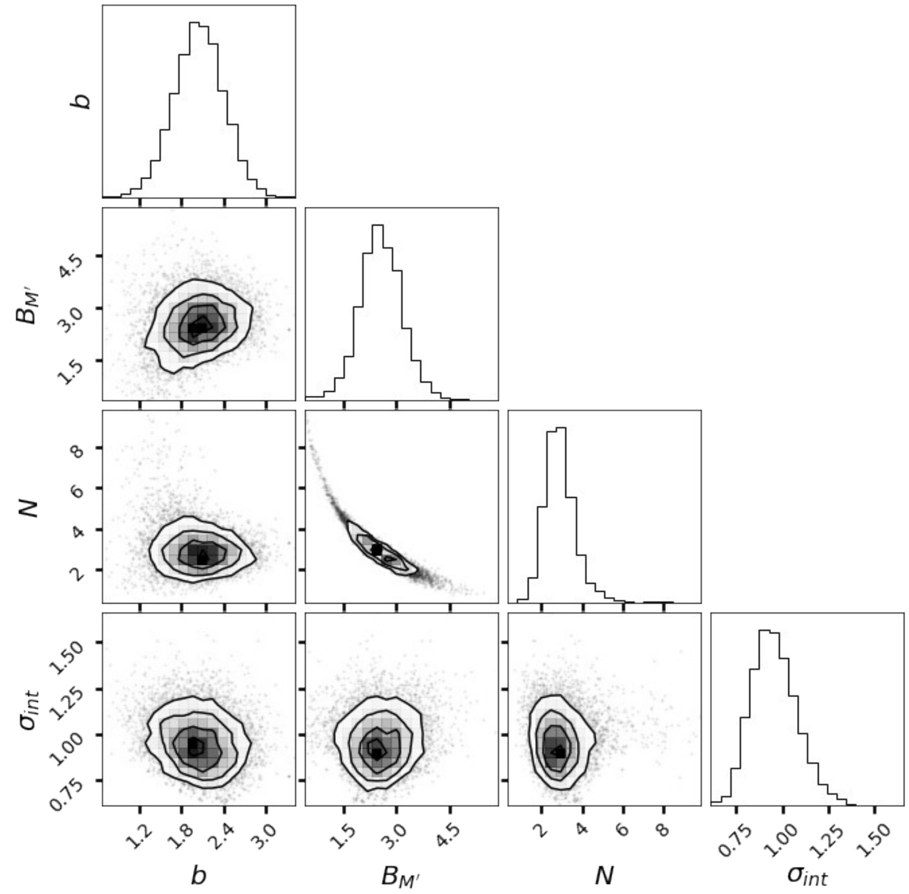

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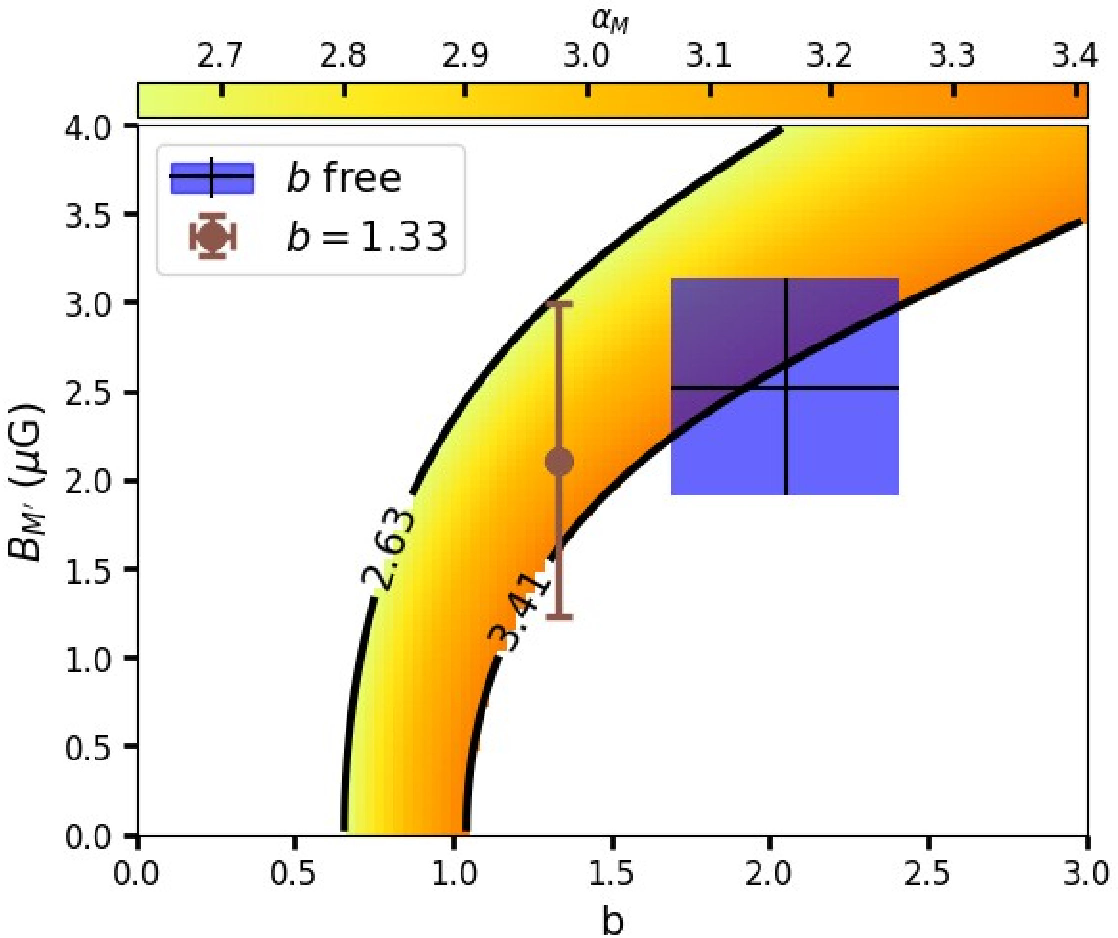
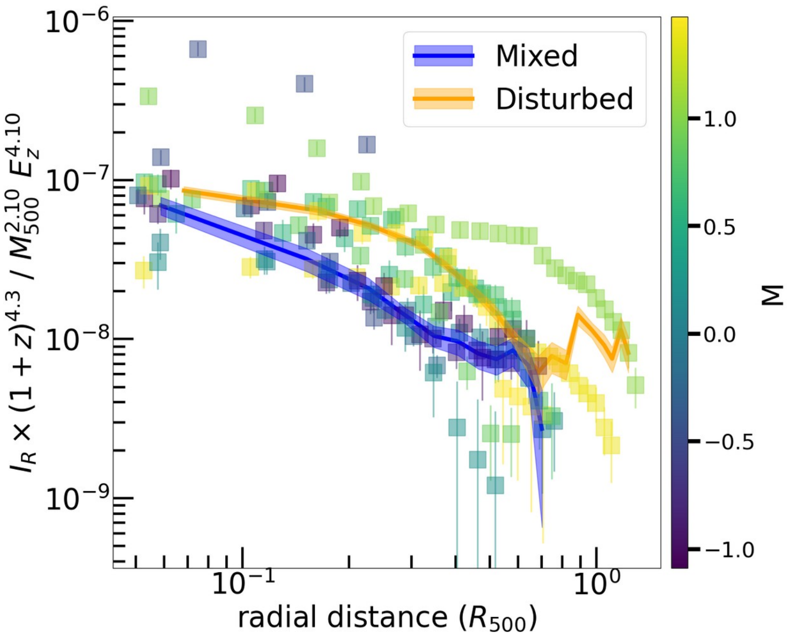
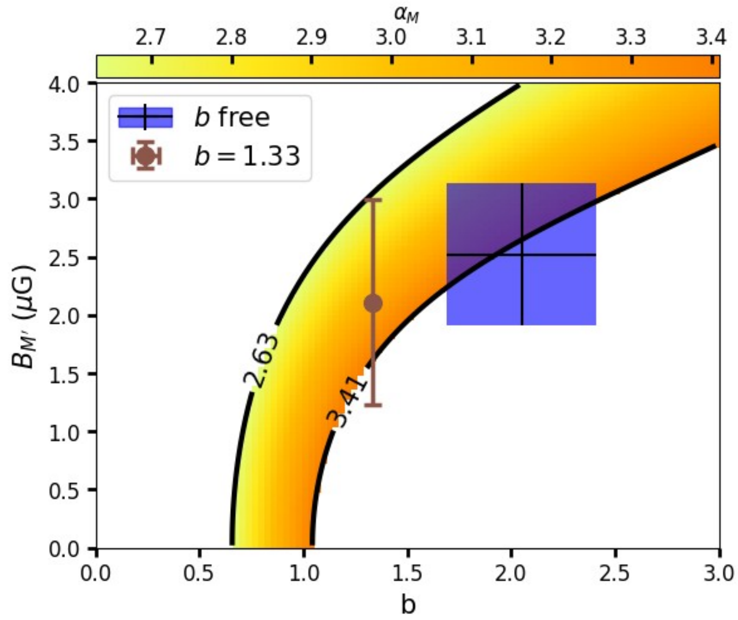


Summary

We studied the scaling properties of radio halo profiles finding:

- Strong cluster's mass depenced of the profiles from I_R-M(z) relation
- The profile scatter to be singificantly reduced by M & z rescaling
- A residual dependence of the scaled profiles on the cluster dynamical state
- Evidence for no R_H-M relation, which, when taken into account allows to reconcile predictions and observations
- A strong (~2) mass dependence of the global cluster B





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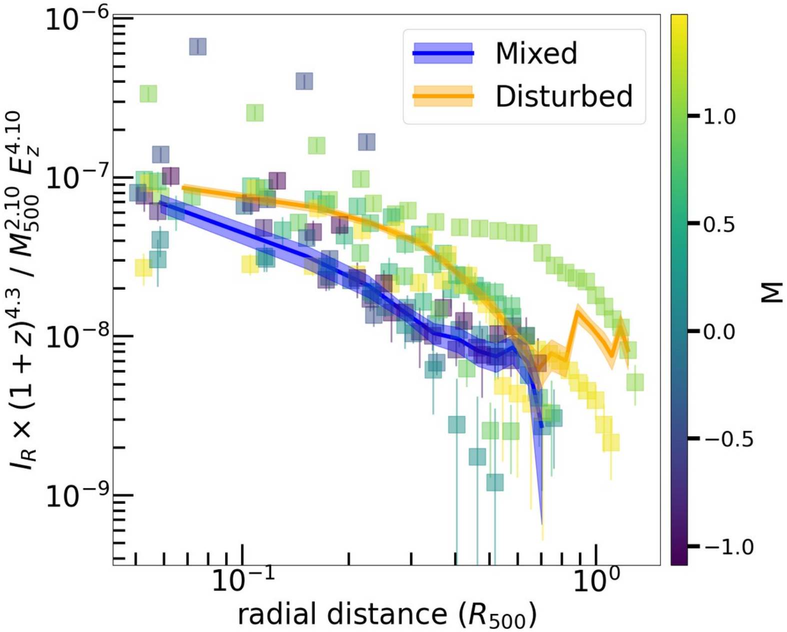

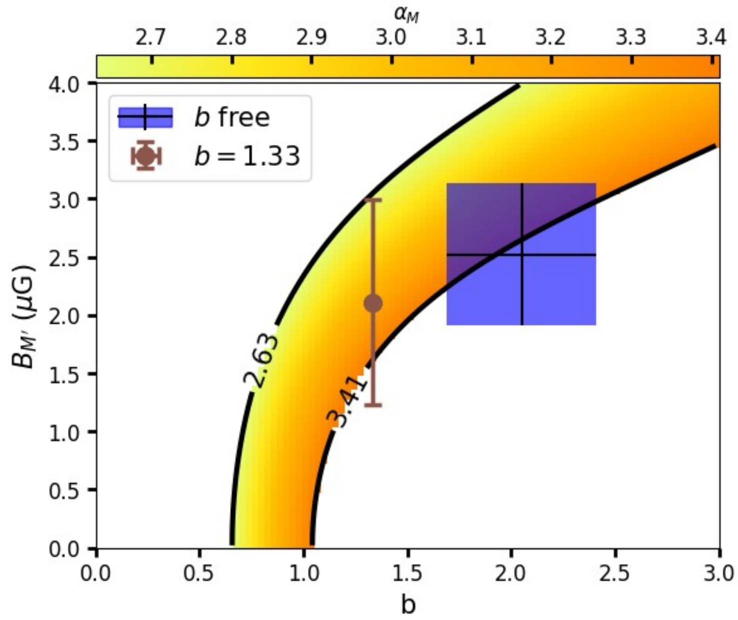

Thank you for the attention!

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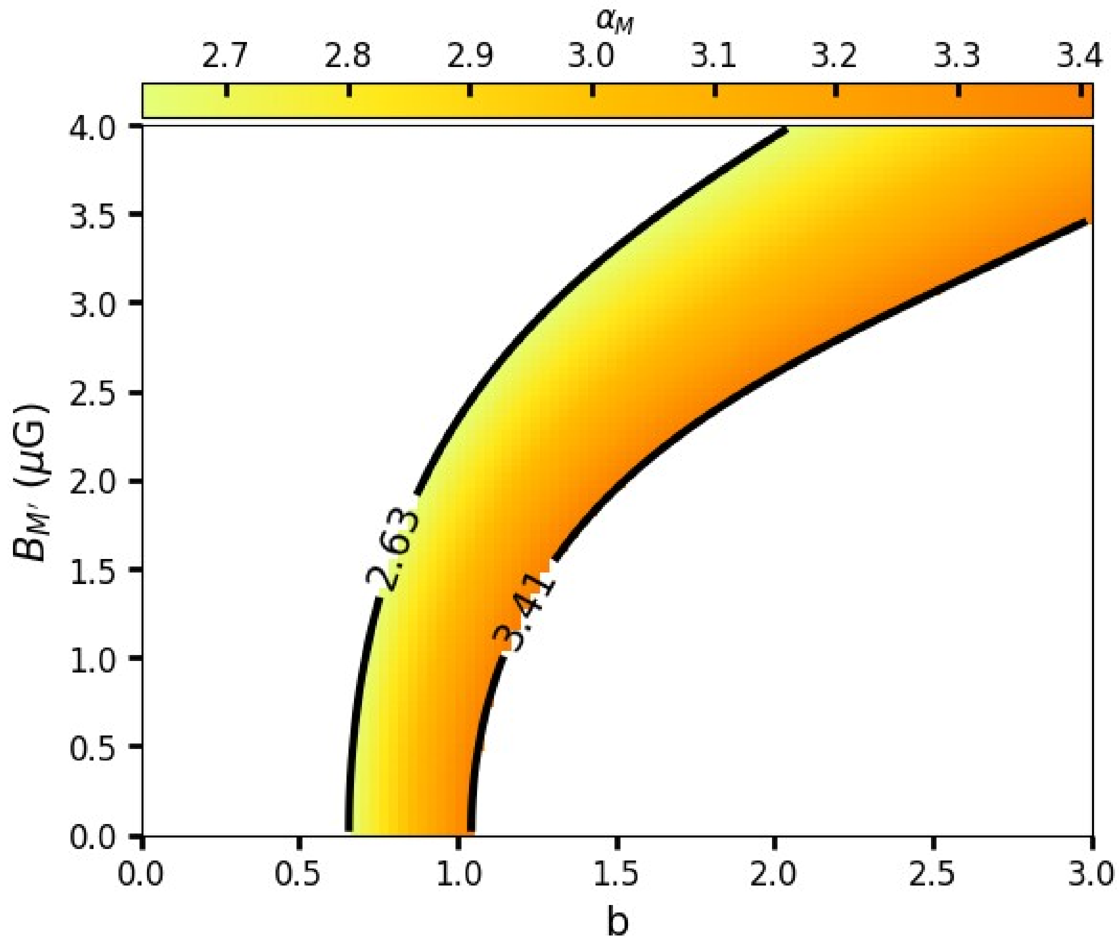
Constrained from the observed P-M relation



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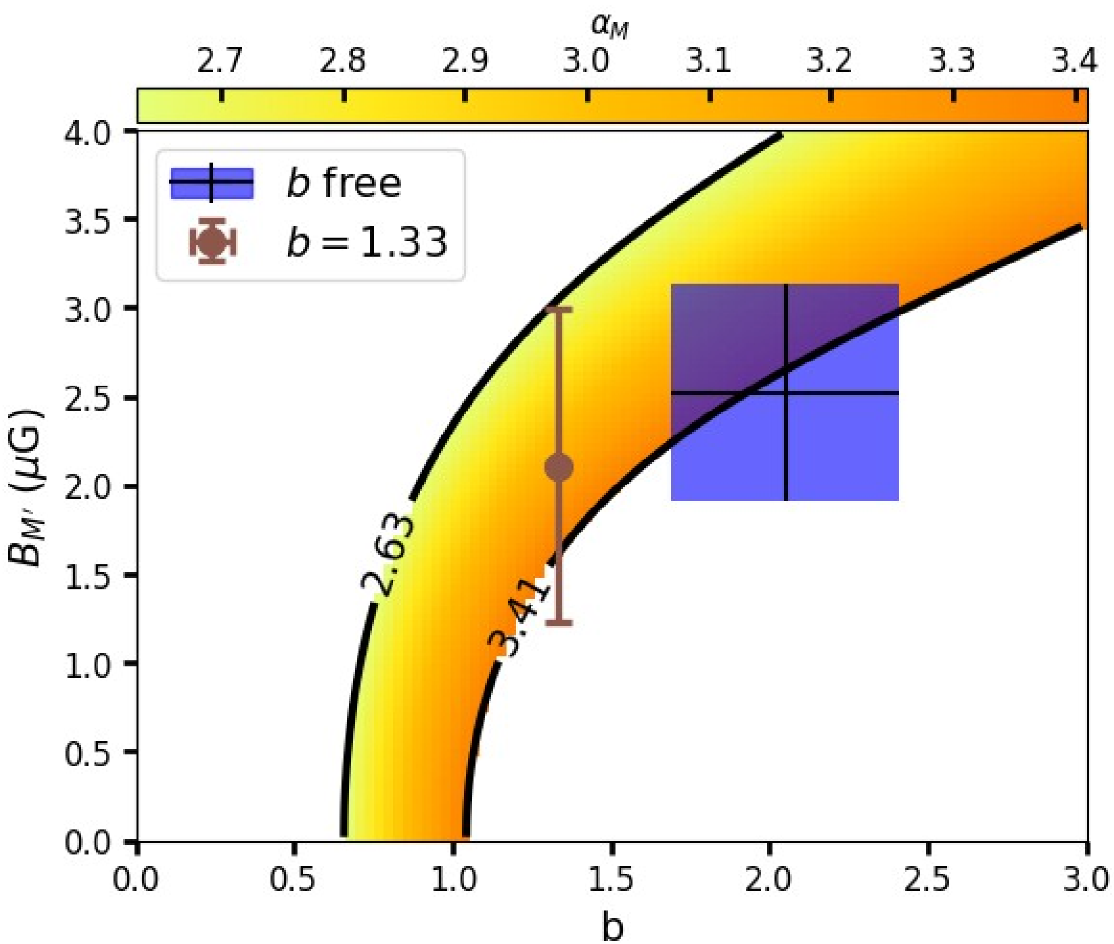

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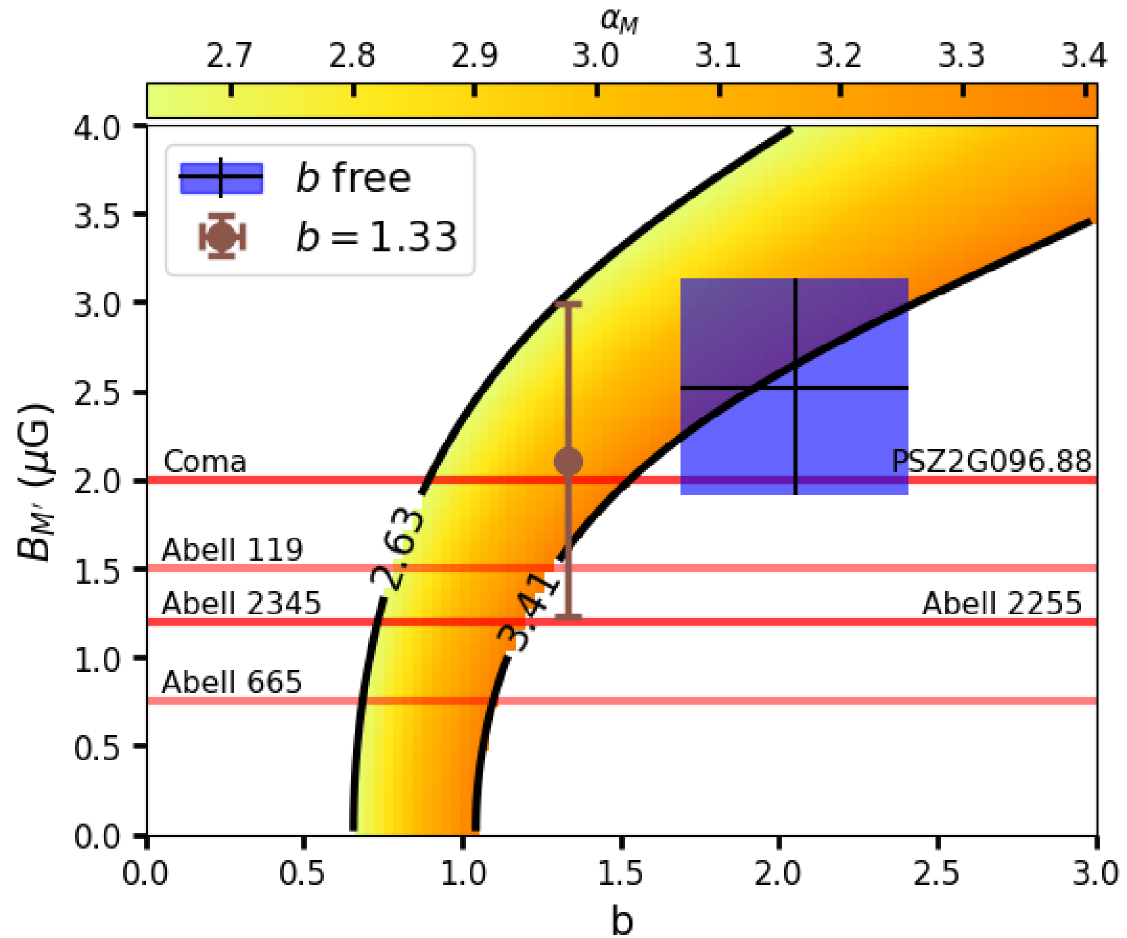
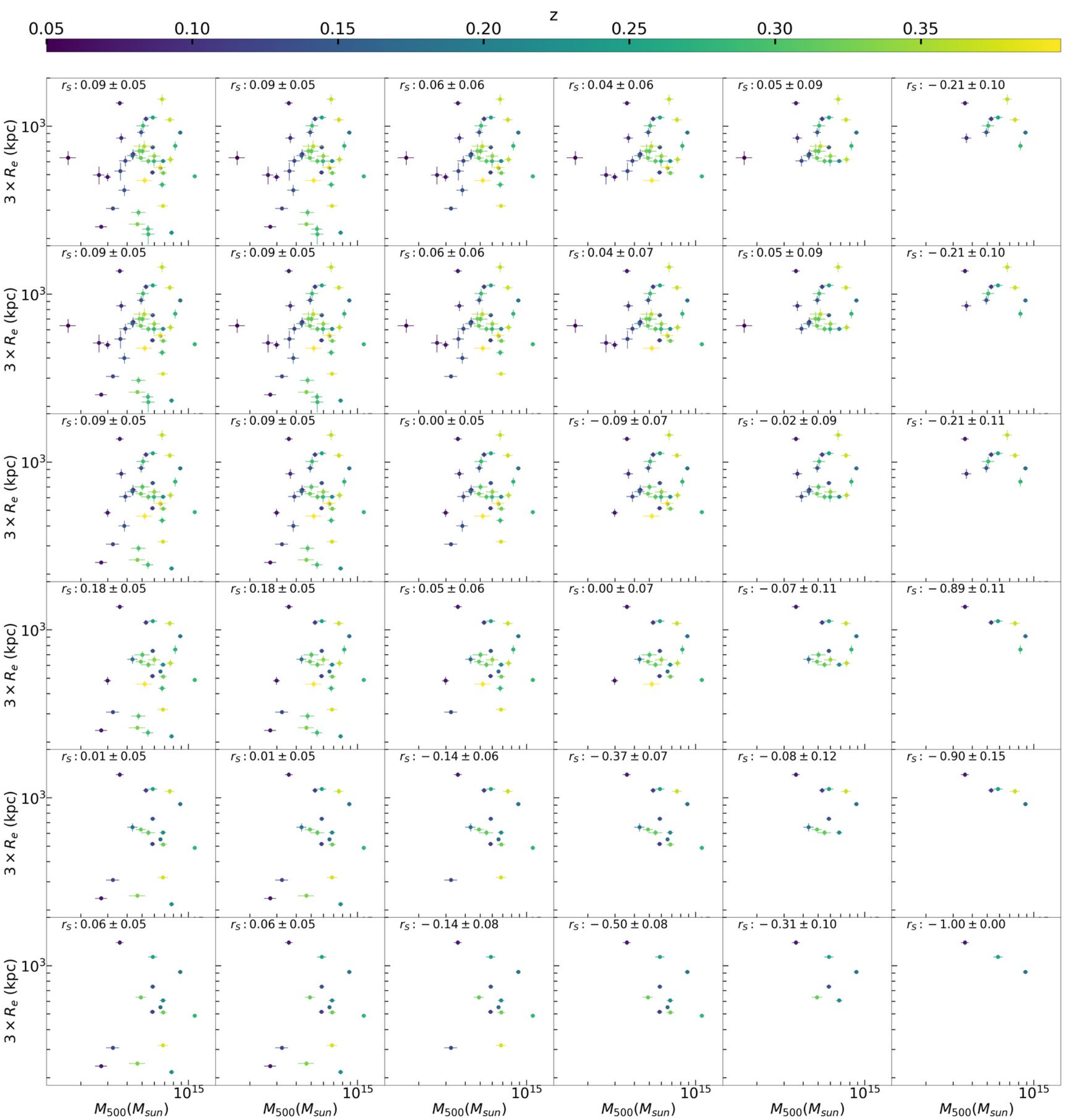
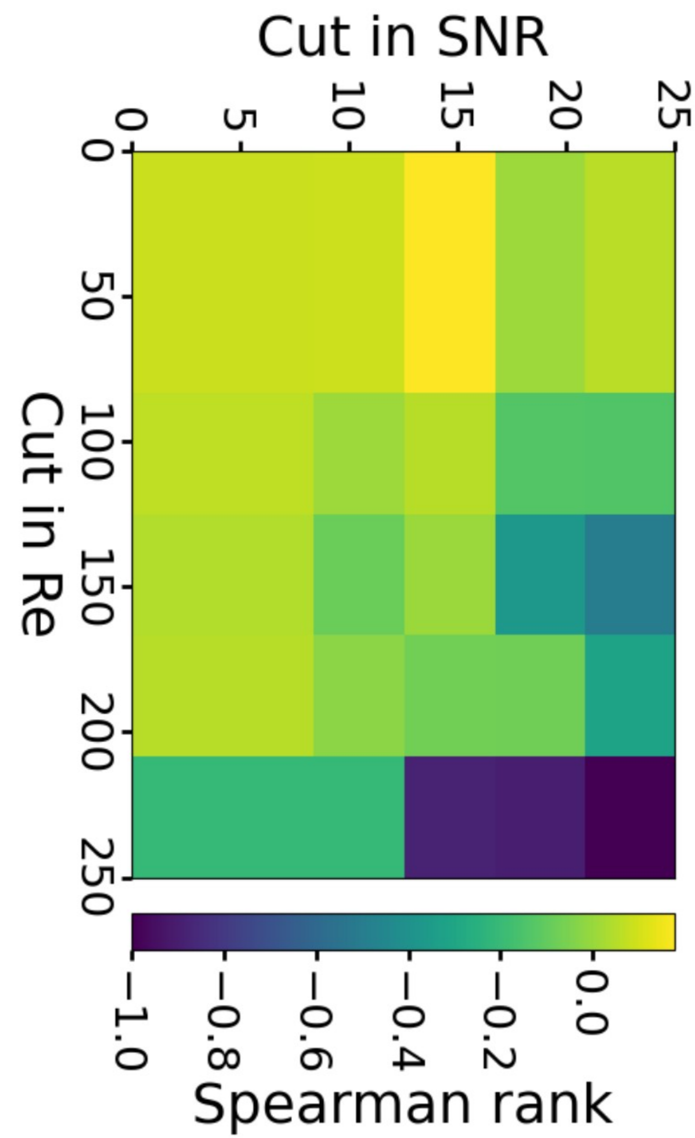


Backup slides





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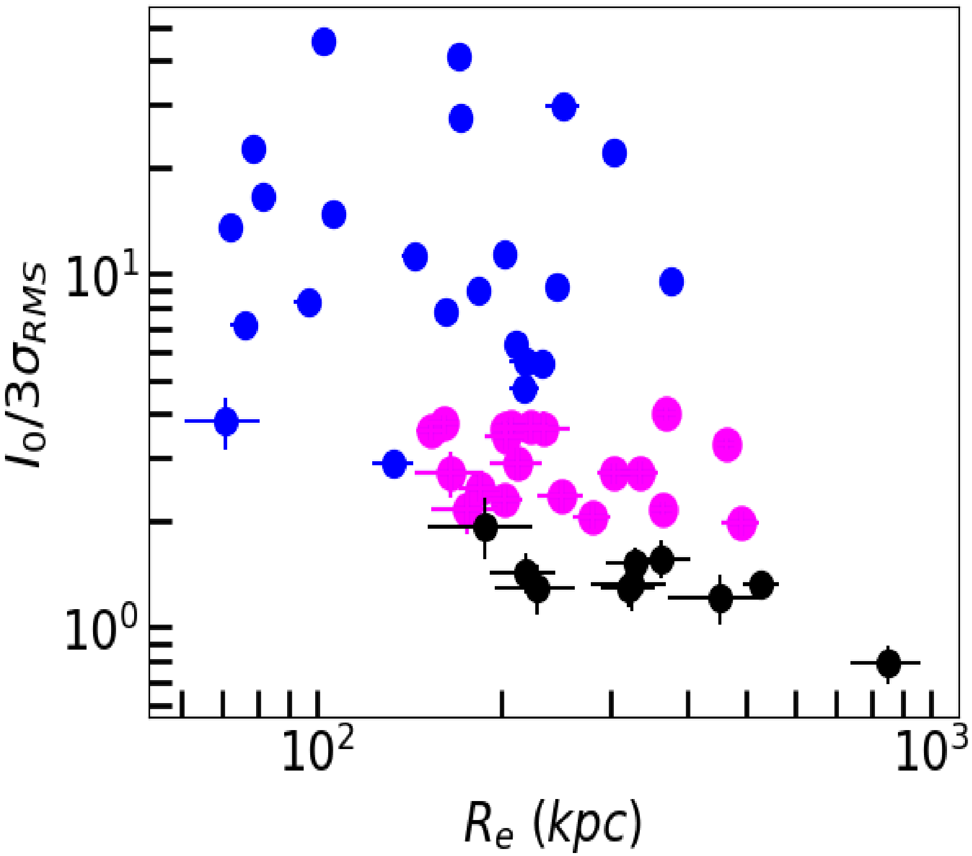
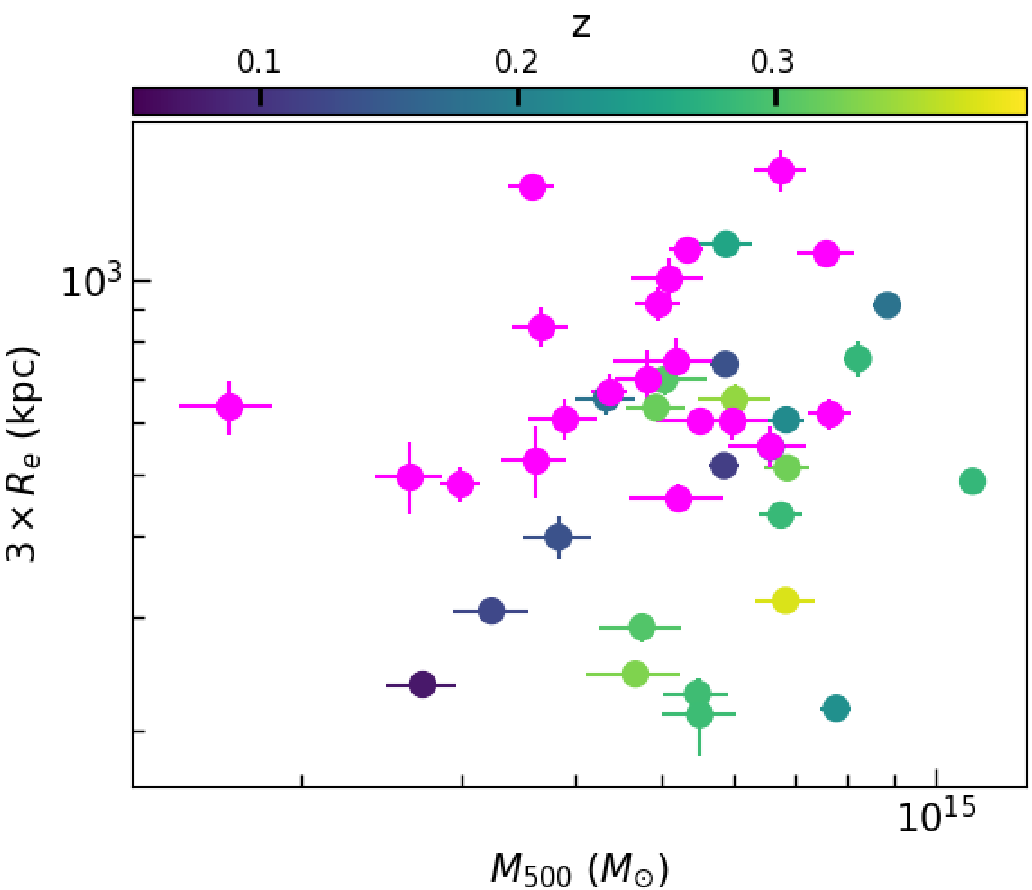
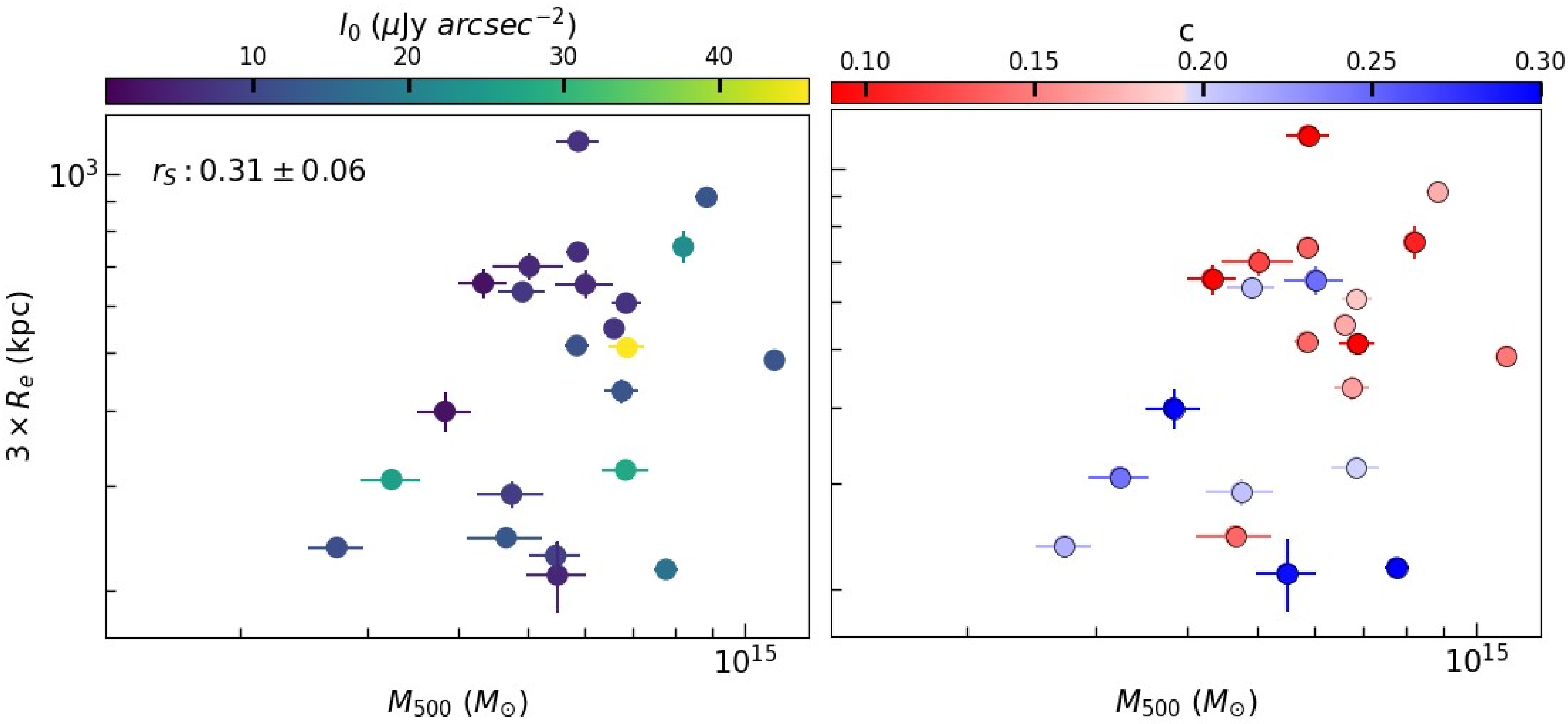




Backup slides



Backup slides