The Peculiar Motions of the BCGs in SPT Clusters

Raven Gassis + SPT Collaboration – mm Universe
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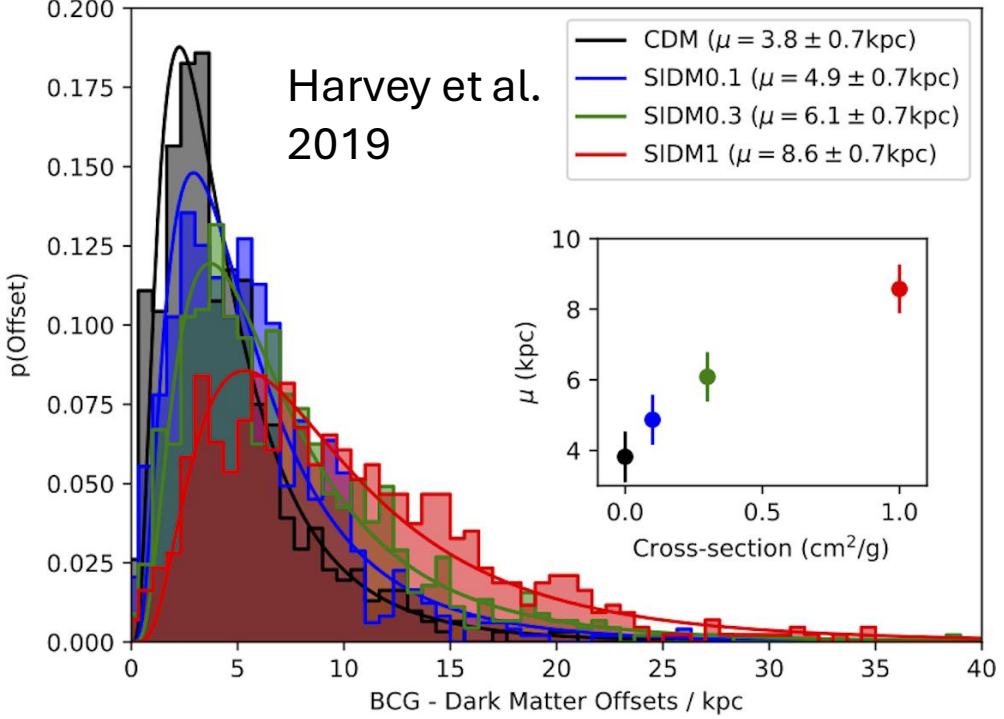
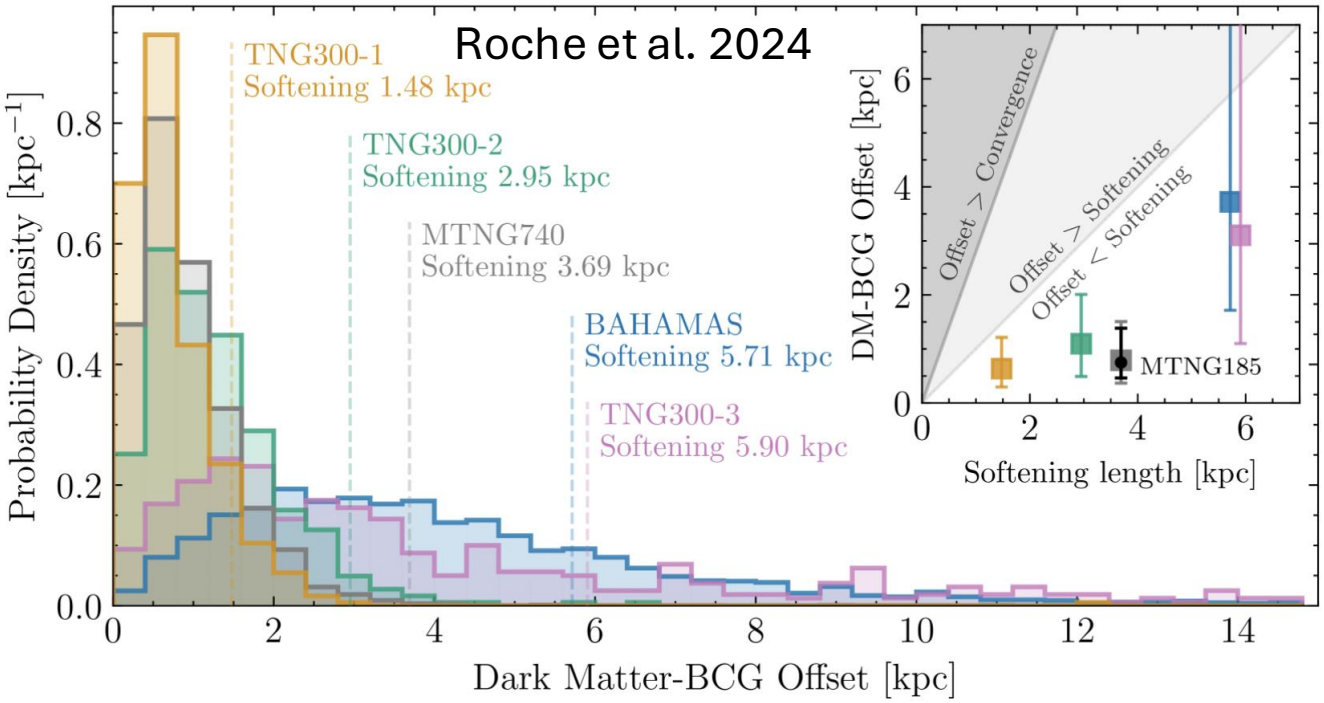
The Central Galaxy Paradigm

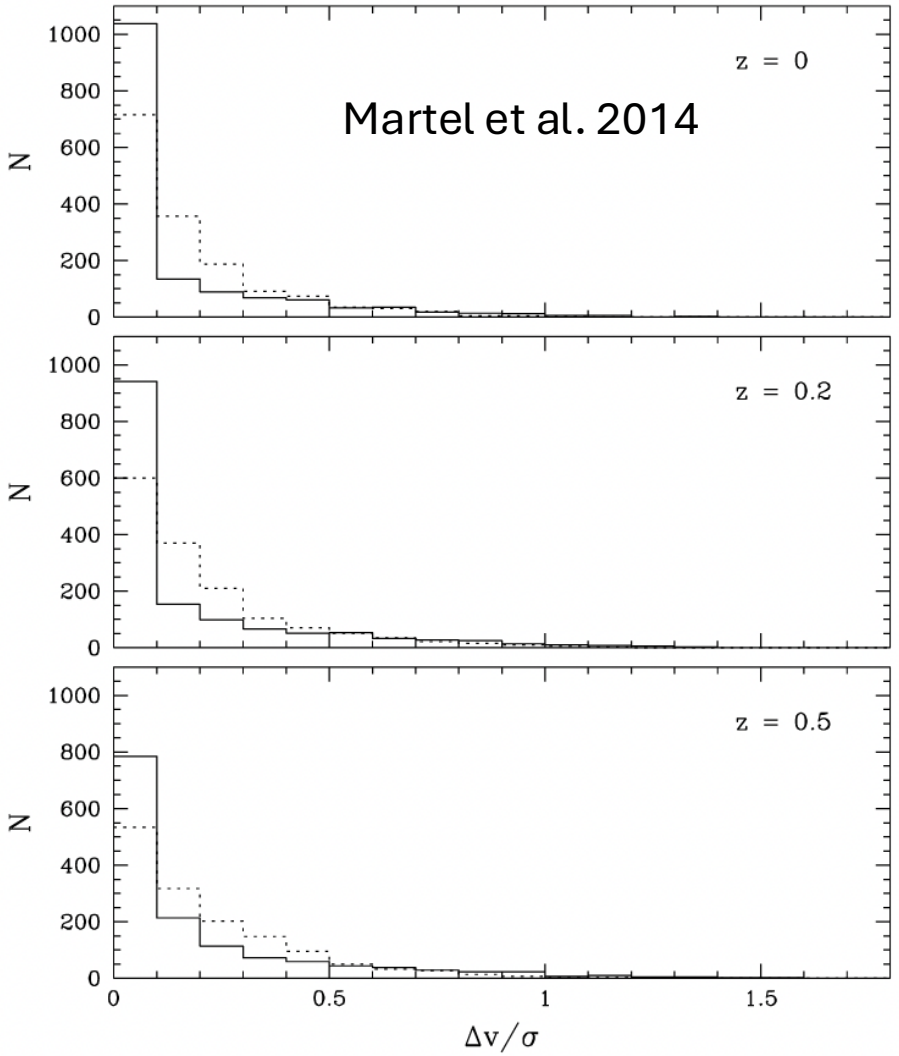
- Galaxy clusters form via hierarchical merger processes
- Dark Matter Halo defines cluster structure and gravitational potential
- Central Galaxy Paradigm (CGP): the Brightest Cluster Galaxy (BCG) should be at rest in the center of its host galaxy cluster
- BCG formation framework: a high gas accretion gas accretion phase at high z, a peak star formation phase and moderate z, and a merger and accretion phase at low
- Departure from the CGP→ post-galaxy formation mergers or alternative DM models

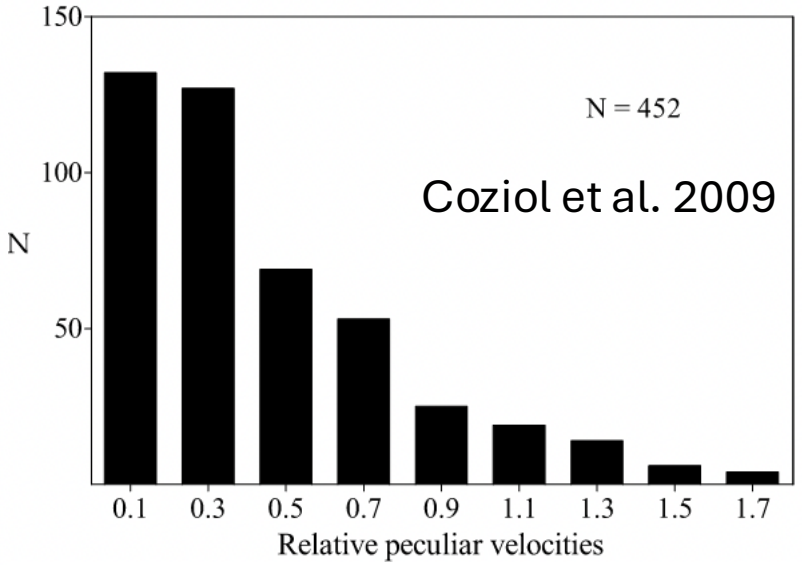


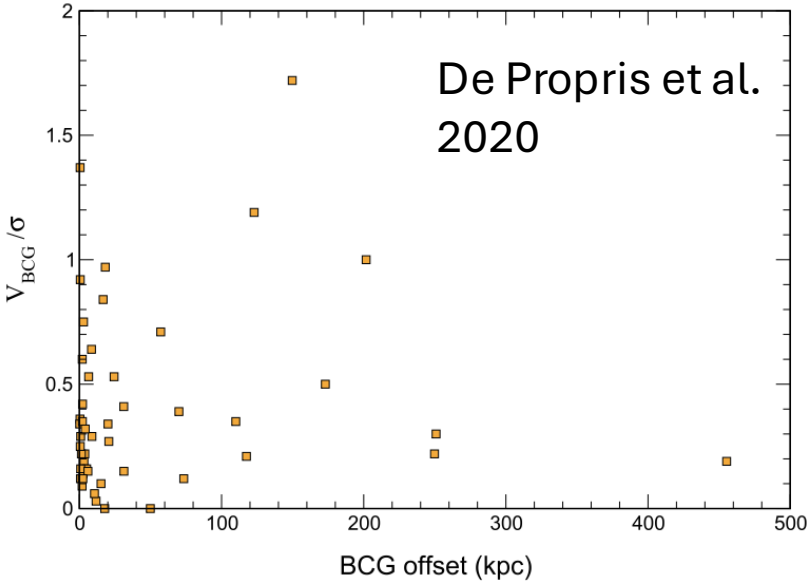


Peculiar Velocity as a test of ΛCDM

- 2 tests of CGP:
  - BCG peculiar velocity offset
  - BCG centroid offset
- De Propris sample:
  - 164 clusters from Planck Early SZ sample ($z \leq 0.35$) + a flux-limited X-ray sample of 100 clusters ($z \leq 0.3$).
- Martel Simulations:
  - Dashed line => values derived from all matter
  - Solid lines => values from galaxies only.
- Coziol sample:
  - 452 Abell clusters w/ $N_{mem}>10$ ($z \leq 0.2$)

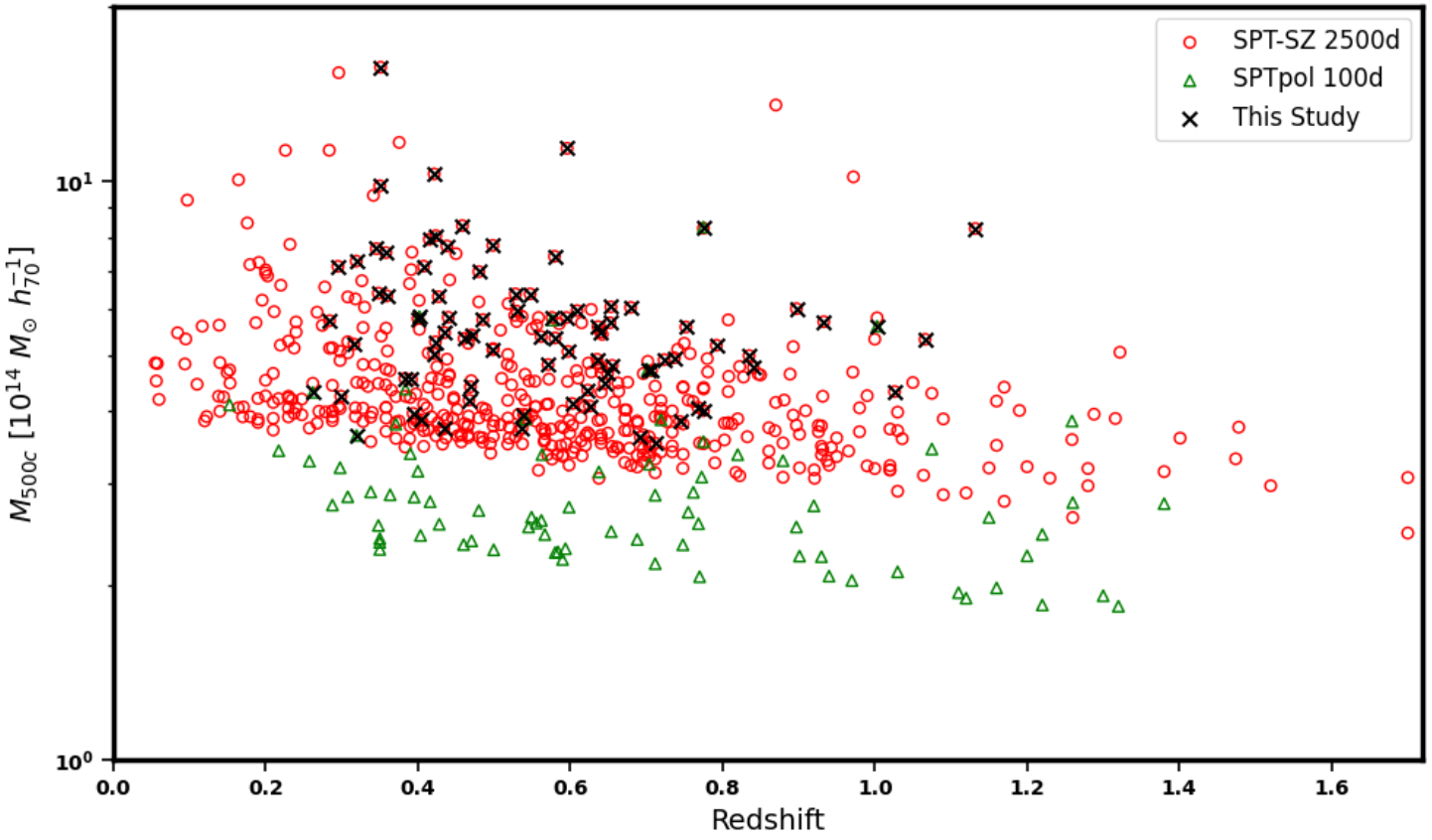


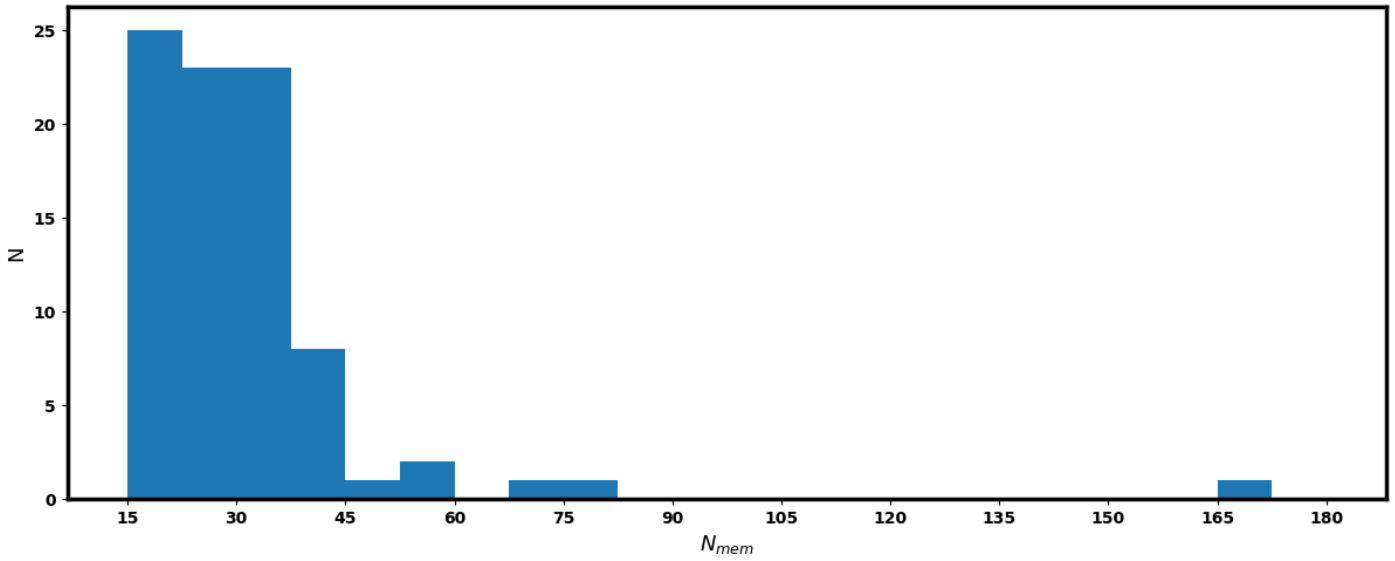




Project Subsample

- SPT spectroscopic catalogues:
  - v_p : BCG peculiar velocity
  - σ : cluster velocity dispersion
- BCG selection:
  - using automated algorithm (Noble et al. in prep, Somboonpanyakul et al. 2022)
  - lensing arcs
  - X-ray peaks
  - By-eye inspection
- 85 clusters with N_{mem}>15.





X-ray Subsample

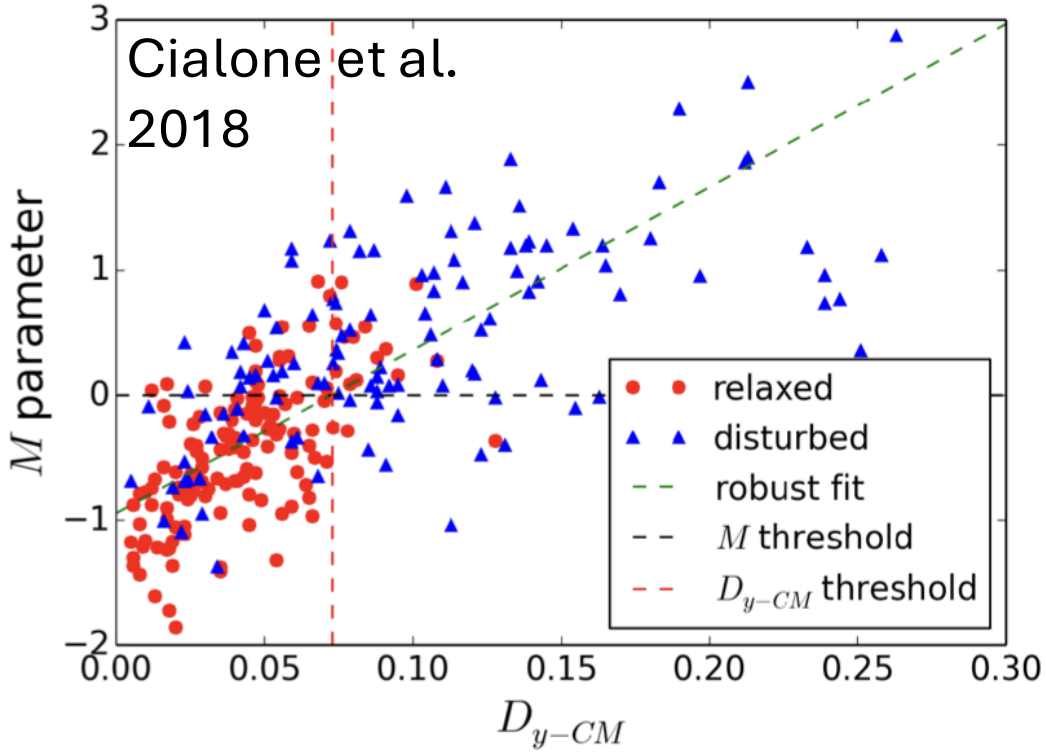
$$c_{[\mathrm{R500}]} = \frac{Flux(\mathrm{r} < 0.2 * \mathrm{R500})}{Flux(\mathrm{r} < \mathrm{R500})}$$

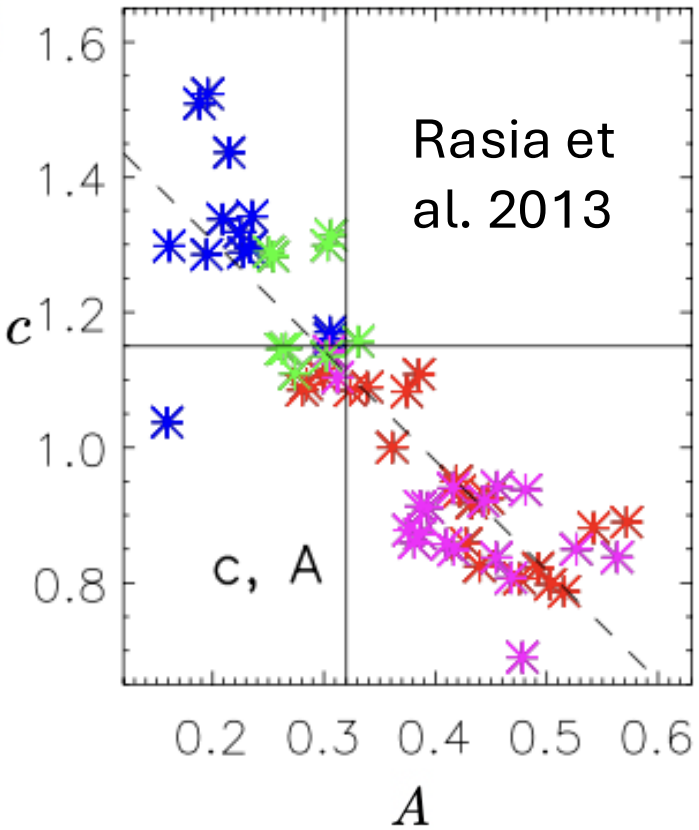
$$D[kpc] = d_A \sqrt{((\alpha_{ICM} - \alpha_{BCG}) * cos(\delta_{BCG}))^2 + (\delta_{ICM} - \delta_{BCG})^2}$$

$$A = \frac{\sum(|I - R|)}{\sum I}$$

$$M = \frac{1}{N_{par}} \sum_{par} (A_{par} \times \frac{par - L_{par}}{|q_{par} - m_{par}|})$$

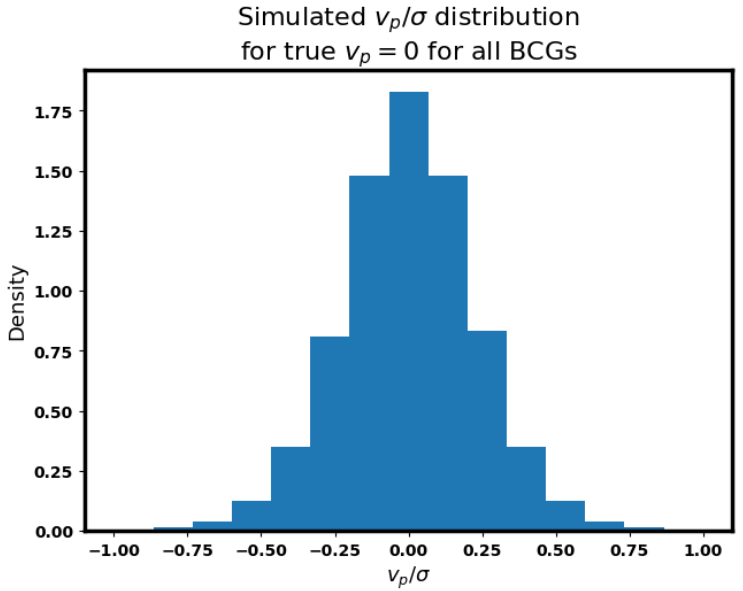
- 73 Clusters have either XMM and/or Chandra follow-up data
- Measure:
  - A: asymmetry parameter
  - c: concentration parameter
  - D: centroid separation between BCG and X-ray distribution
  - M: combined relaxation parameter
  - L_{par}:cut value
  - q_{par}: 1st/3rd quartile (par<m_{par}/par>m_{par})

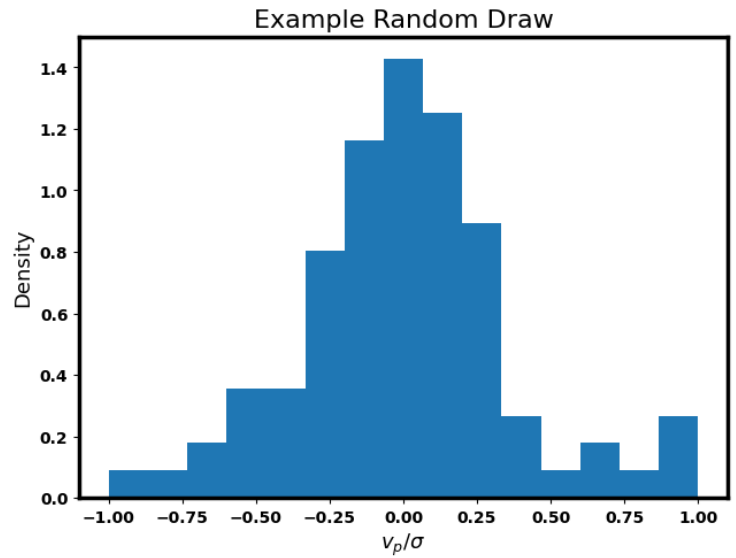


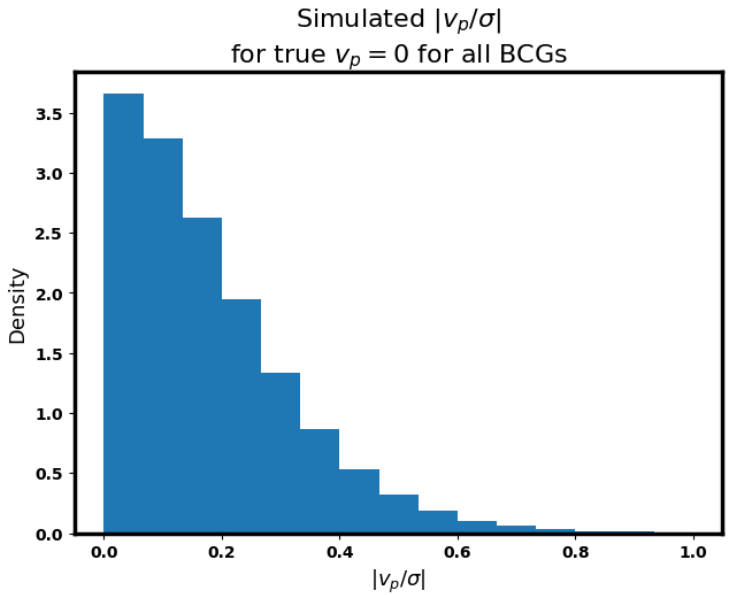


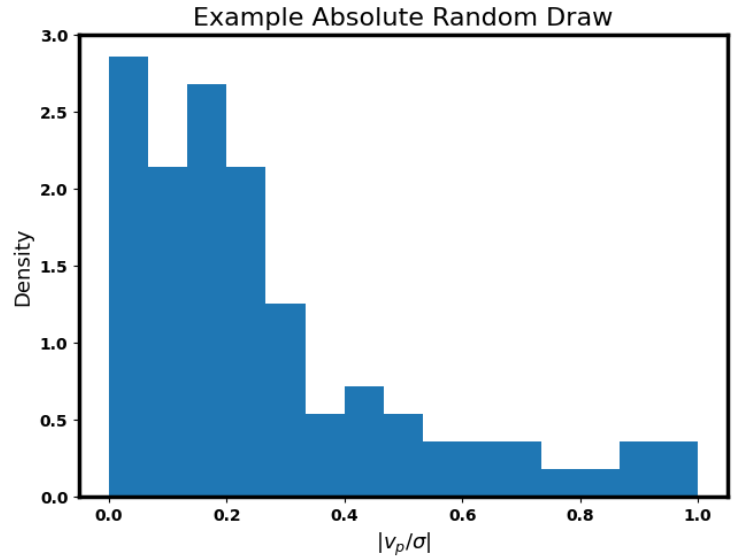
Measuring BCG Peculiar Motion

- v_p/σ: "BCG peculiar motion"
- Normal Distribution ND with μ=0: the Idealized case.
- K-S test of 1000 random draws and 100 different time seeds.
- Med_{err}: median of the measurement error distribution
- σ_{err}: the confidence interval from the non-Gaussian measurement error distribution



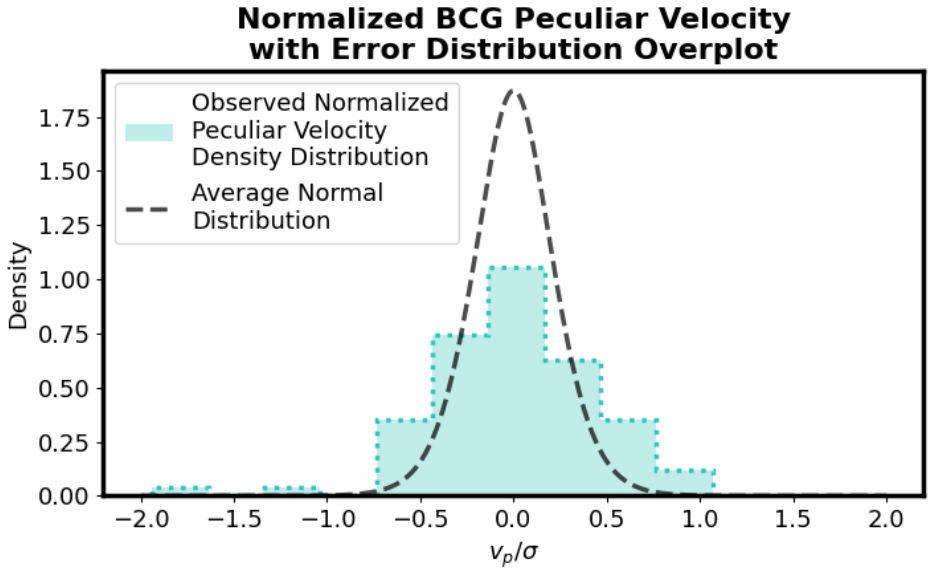


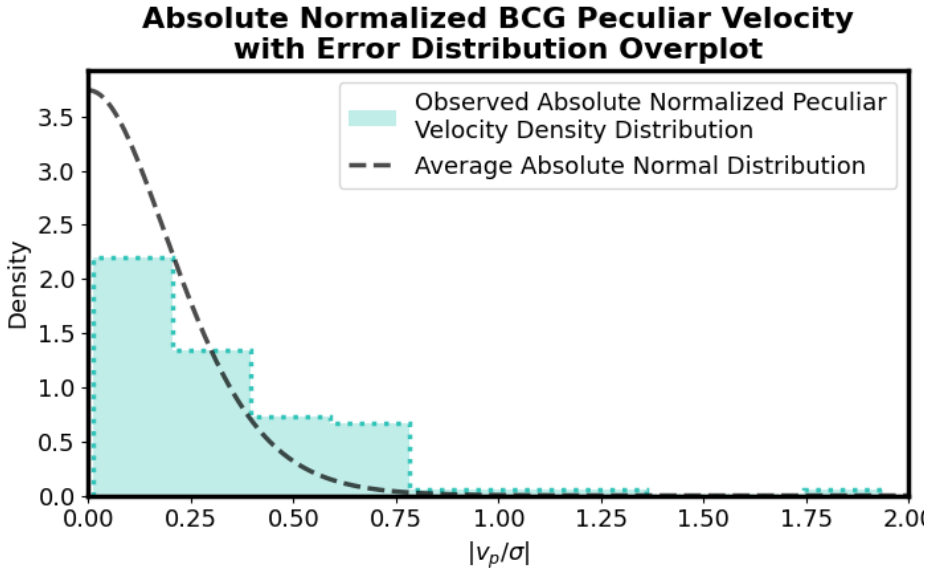


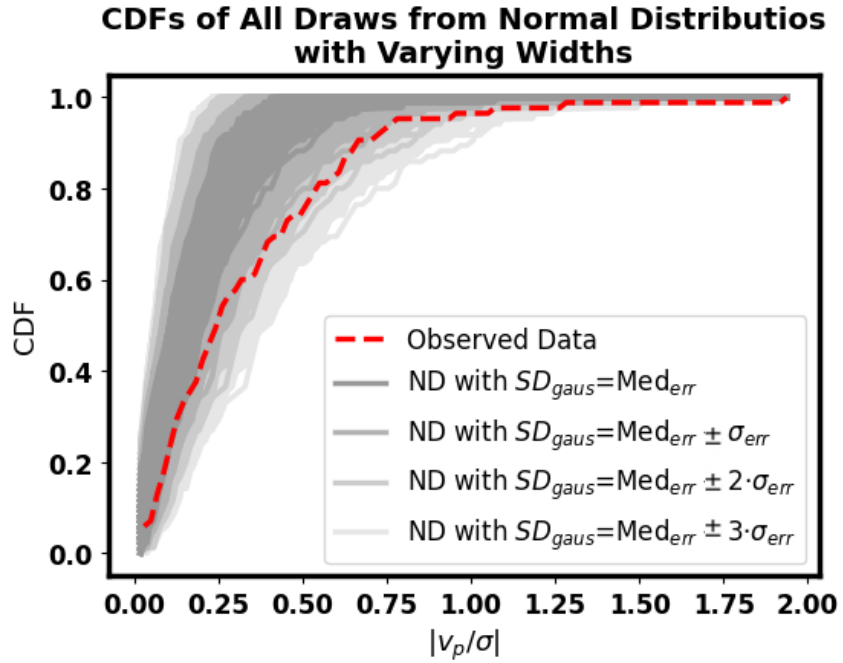


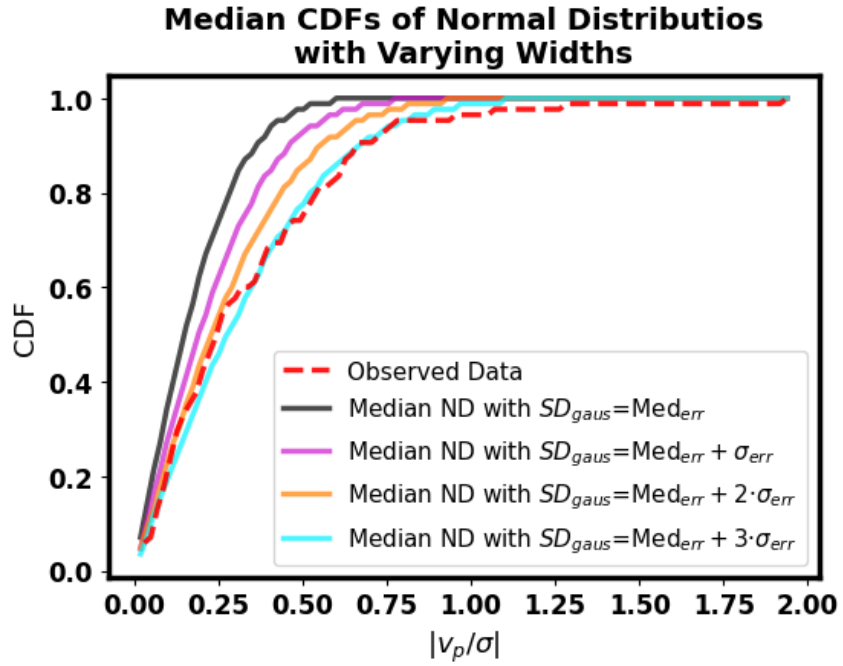
Observed vs. Theorized Offsets

- SD_{gaus}: standard deviation of the Normal Distribution (ND)
- K-S Null Hypothesis Rejection Rate:
  - ND and observed values are from same parent distribution: $(25.1^{+1.2}_{-1.2})$
  - Absolute ND values are greater than the observed values: $(100^{+0.0}_{-0.1})$



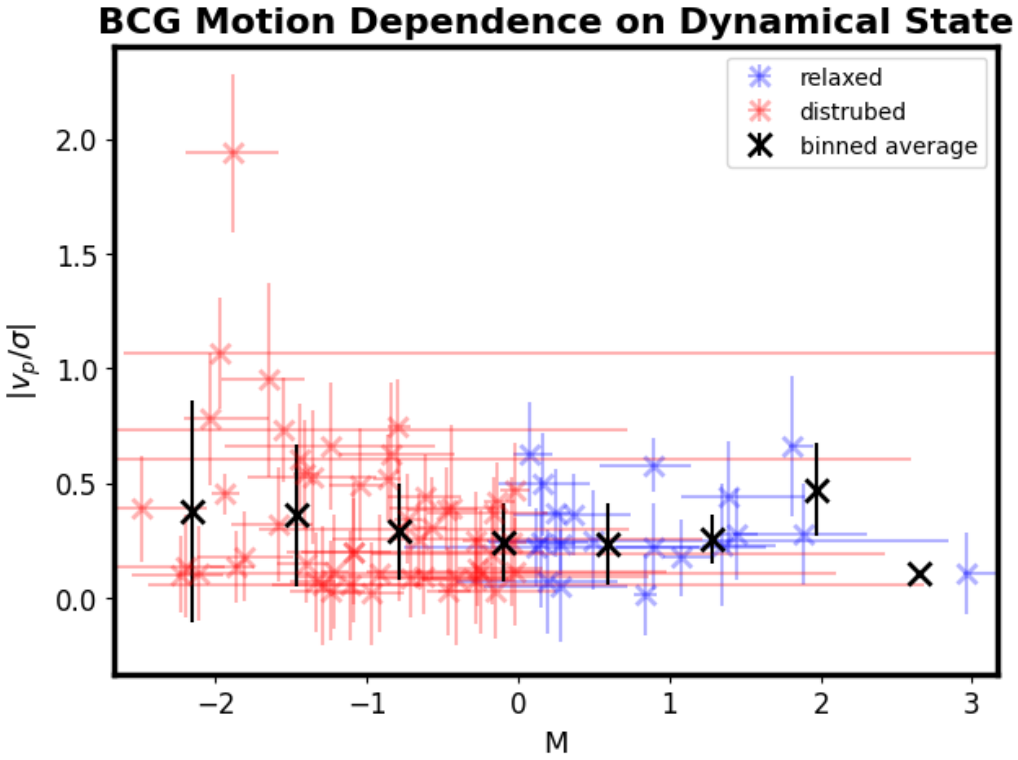


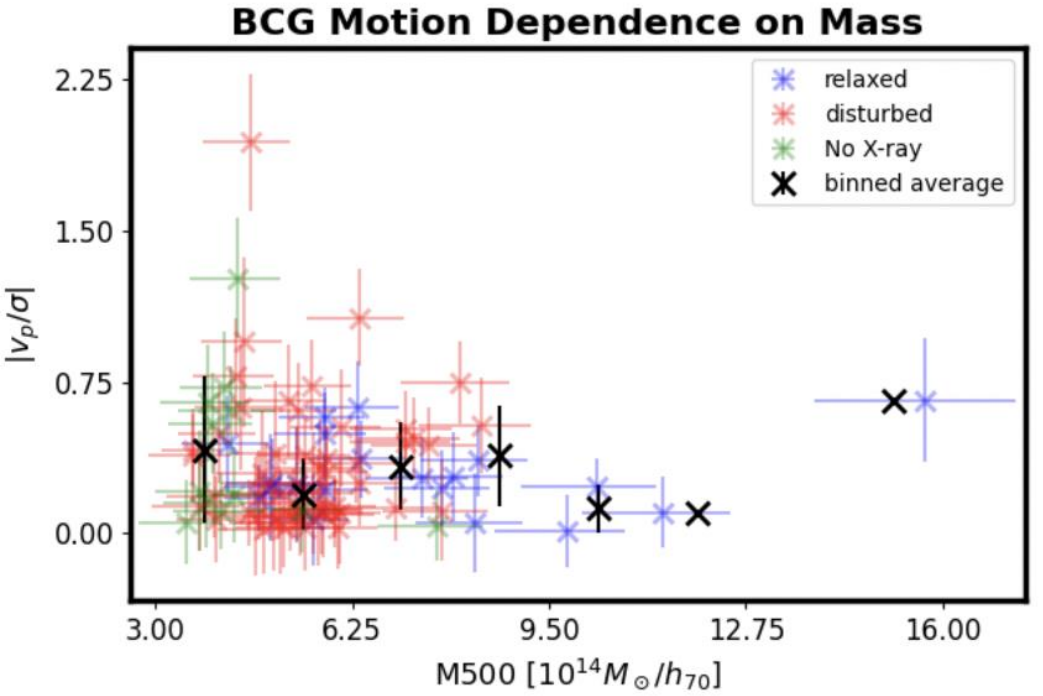


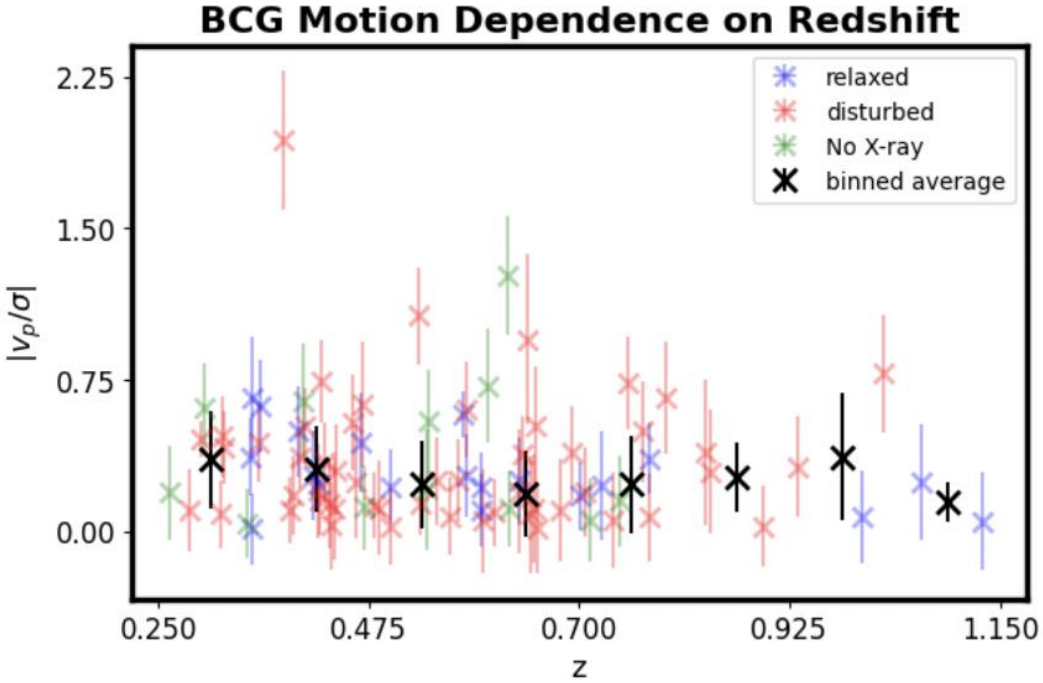


Dynamical State, Redshift, and Mass

parameters	r	p
$\lvert v_p/\sigma \rvert$ vs. M	0.054	0.651
$\lvert v_p/\sigma \rvert$ vs. z	-0.114	0.297
$\lvert v_p/\sigma \rvert$ vs. M500 $[10^{14} M_\odot/h_{70}]$	-0.009	0.935



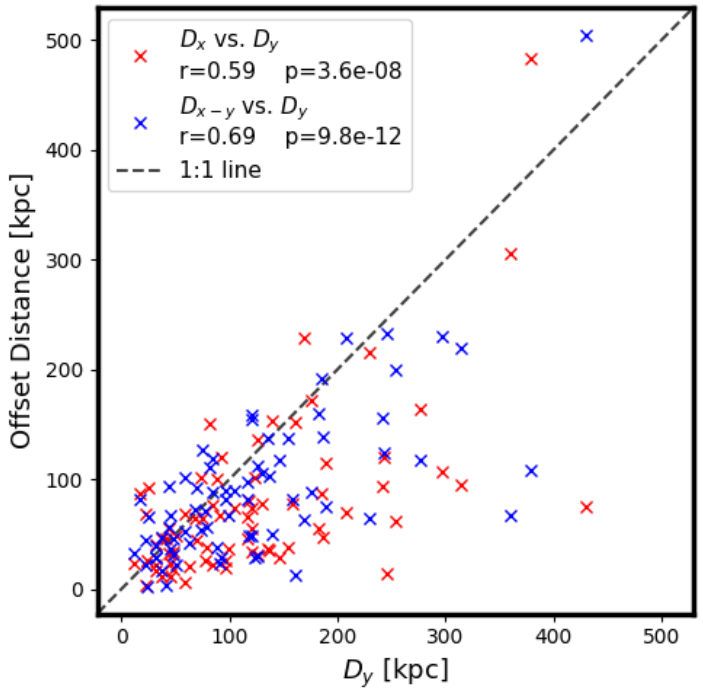


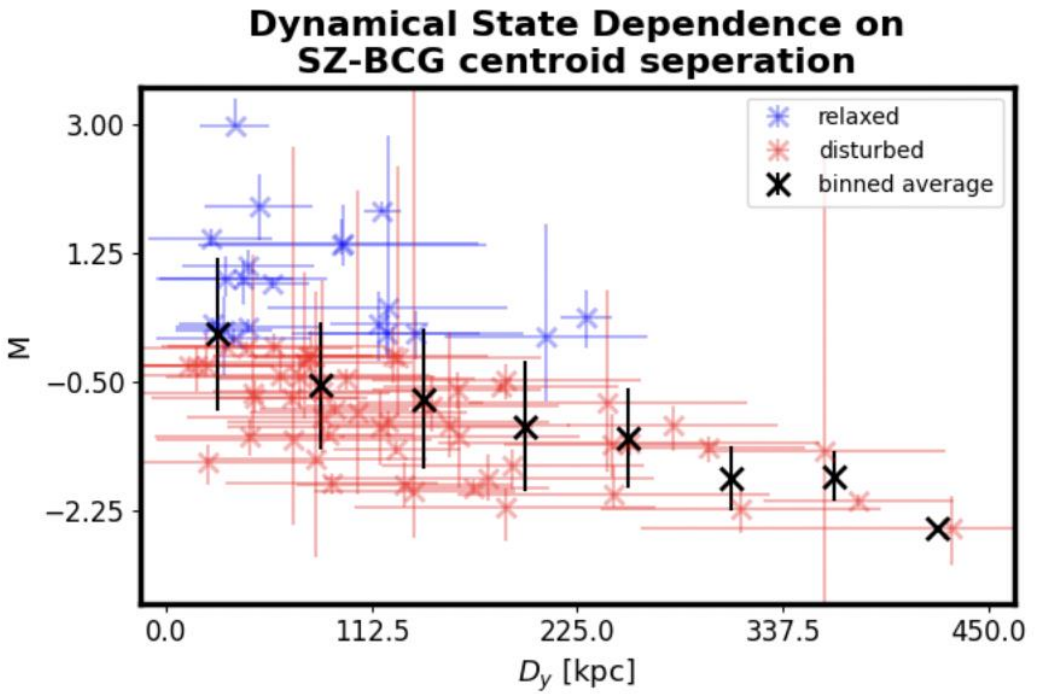


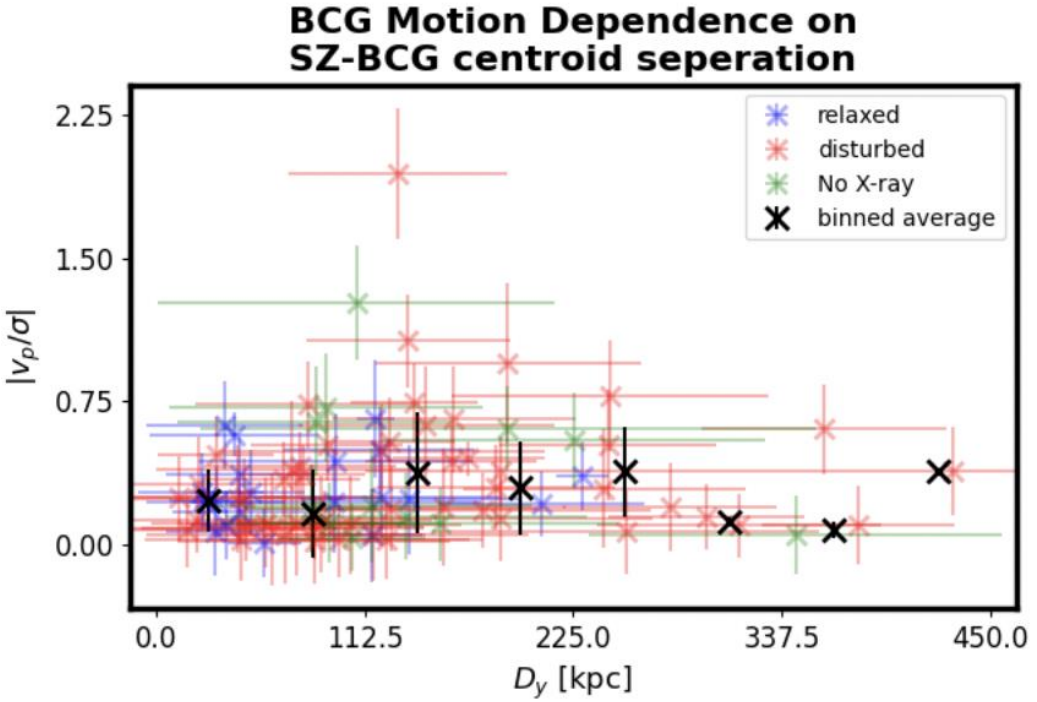
BCG-SZ Offset

- D_x=BCG-Xray centroid offset
- D_y=BCG-SZ centroid offset
- D_{x-y}=Xray-SZ centroid offset

parameters	r	p
$\|v_p/\sigma\|$ vs. D_y [kpc]	0.022	0.839
M vs. D_y [kpc]	-0.534	1e-06
$\|v_p/\sigma\|$ vs. A	0.016	0.893
$\|v_p/\sigma\|$ vs. c	0.076	0.523
$\|v_p/\sigma\|$ vs. $D_x[kpc]$	-0.081	0.496
$\|v_p/\sigma\|$ vs. M	0.054	0.651







Conclusions

- We find that the observed BCG peculiar motion is larger than what it would be if the observed v_p/σ was due to measurement uncertainty alone
- We do not find a very significant correlation between BCG peculiar motion and dynamical state, mass, or redshift.
- D_y acts as a viable dynamical state proxy in cases where we do not have X-ray follow up data.

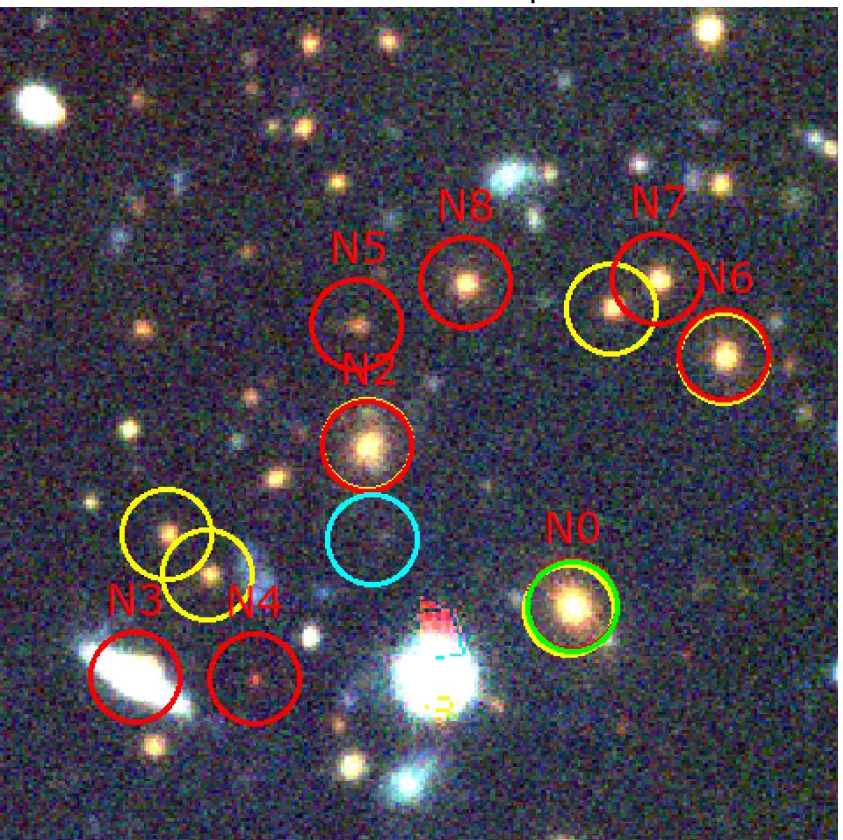
Secret Bonus Slides

High $|v_p/\sigma|$

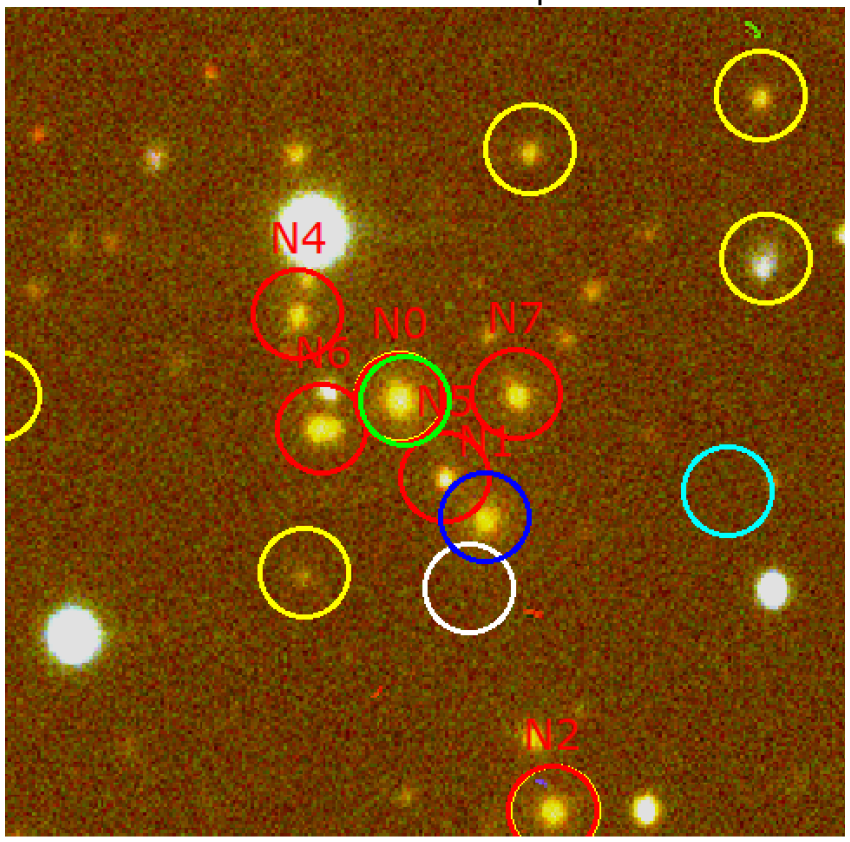
Name	Selected BCG	Probability	2nd Choice BCG	Probability
SPT-CLJ2146-4846	N0	57.14%	N2	13.8%
SPT-CLJ2022-6323	N0	69.93%	N1	8.01%
SPT-CLJ2035-5251	N1	27.59%	N0	39.16%

red	Automated algorithm selection
green	Blind selection
blue	Zenteno et al. 2020 selection
magenta	Calzadilla et al. 2023 selection
yellow	Redshift measured
cyan	SZ center
white	X-ray center

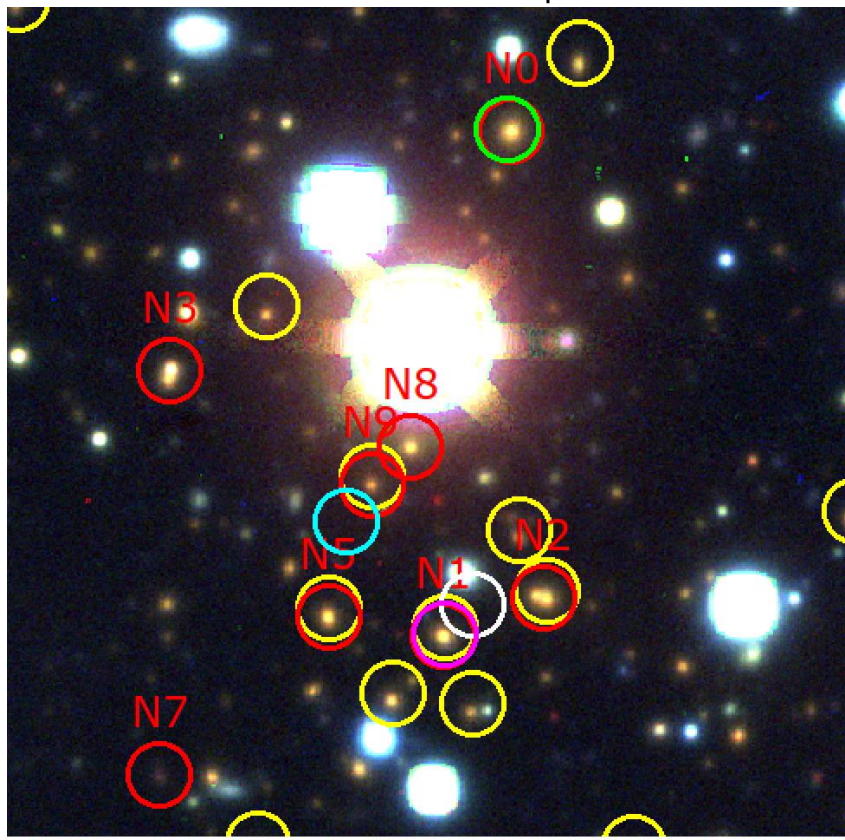
SPT-CLJ2146-4846, v_p/σ = -1.27



SPT-CLJ2022-6323, v_p/σ = -1.94

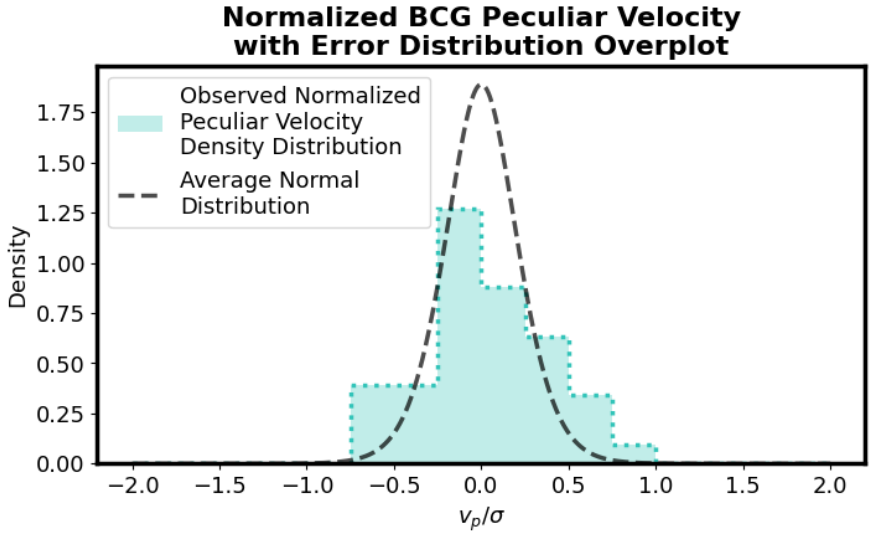


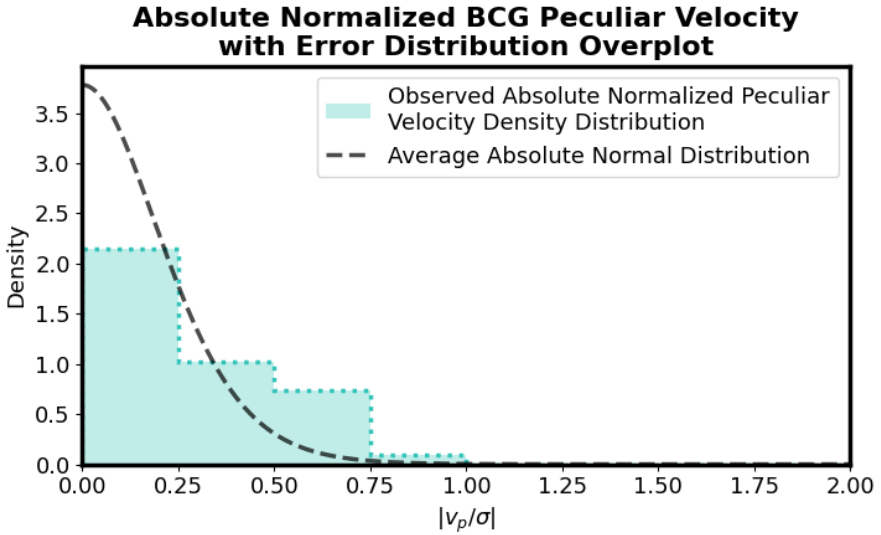
SPT-CLJ2035-5251, v_p/σ = 1.07

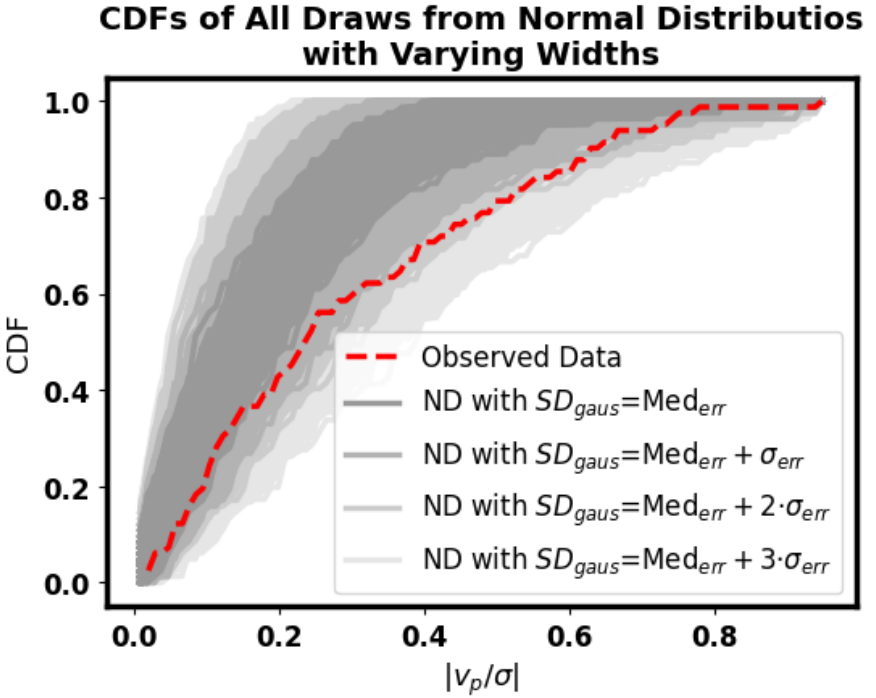


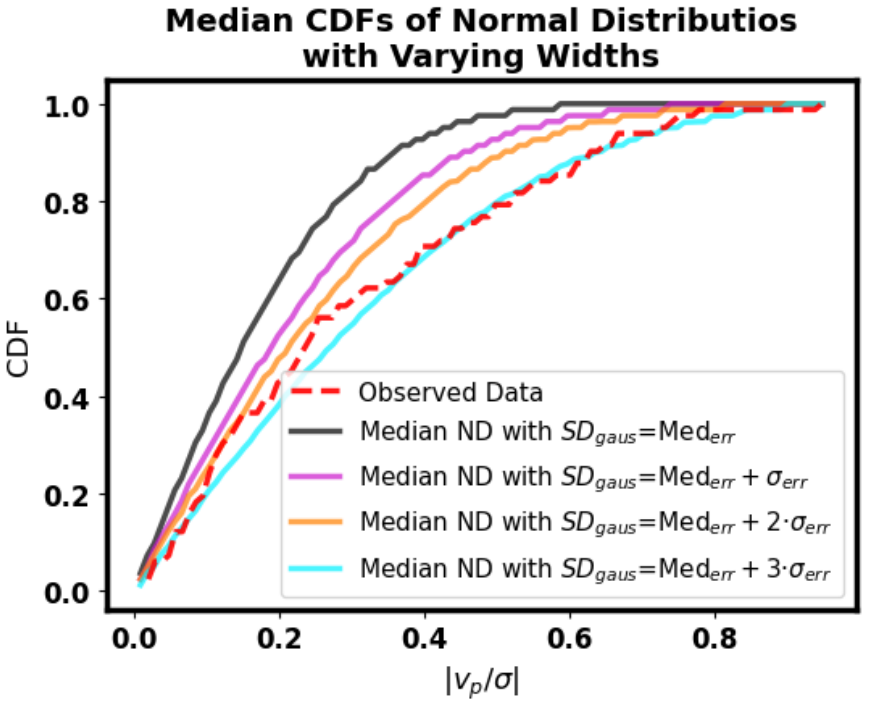
Observed vs. Theorized Offsets (High $|v_p/\sigma|$ Removed)

- The removal of the 3 high $|v_p/\sigma|$ does not qualitatively change our conclusions.
- K-S Null Hypothesis Rejection Rate:
  - ND and observed values are from same parent distribution: $(13.65^{+1.08}_{-1.15})$
  - Absolute ND values are greater than the observed values: $(99.4^{+0.23}_{-0.2})$





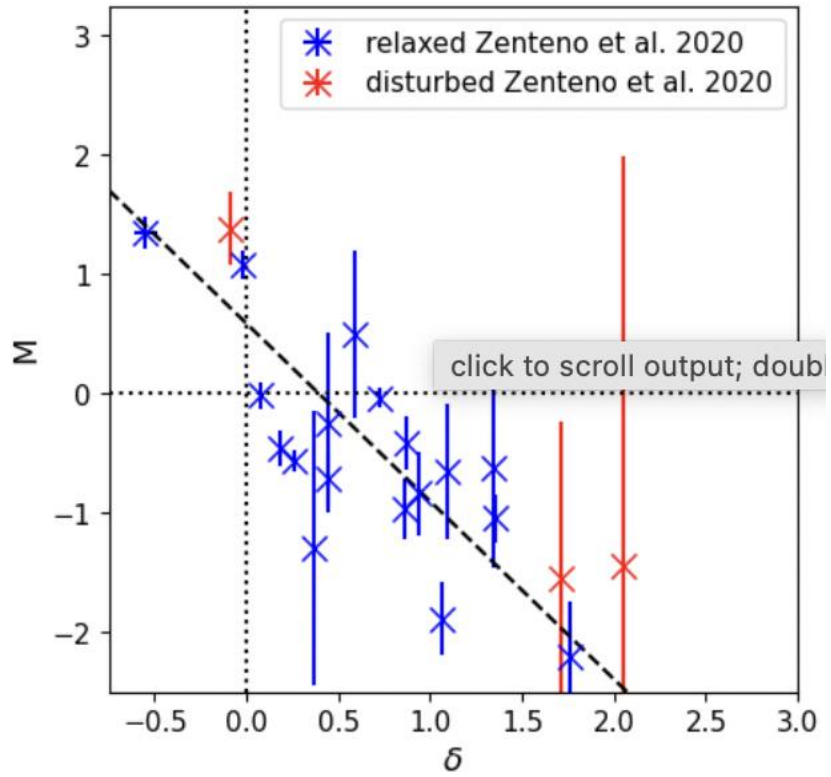


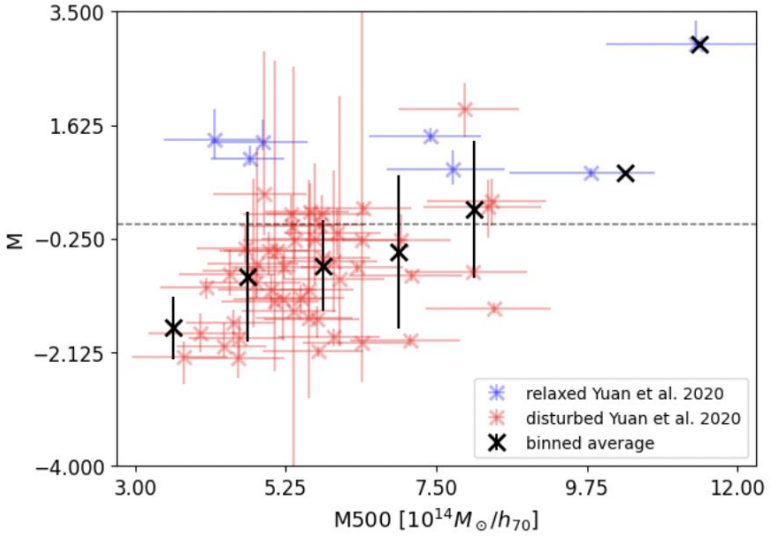


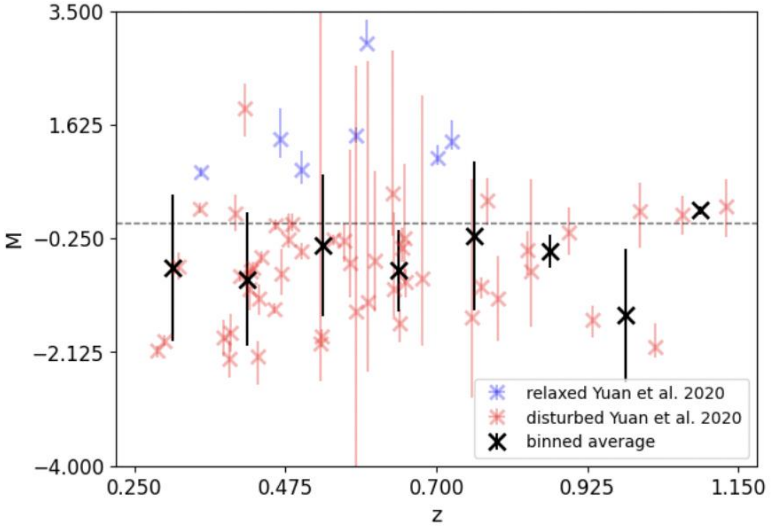
X-ray Comparisons and Evolution

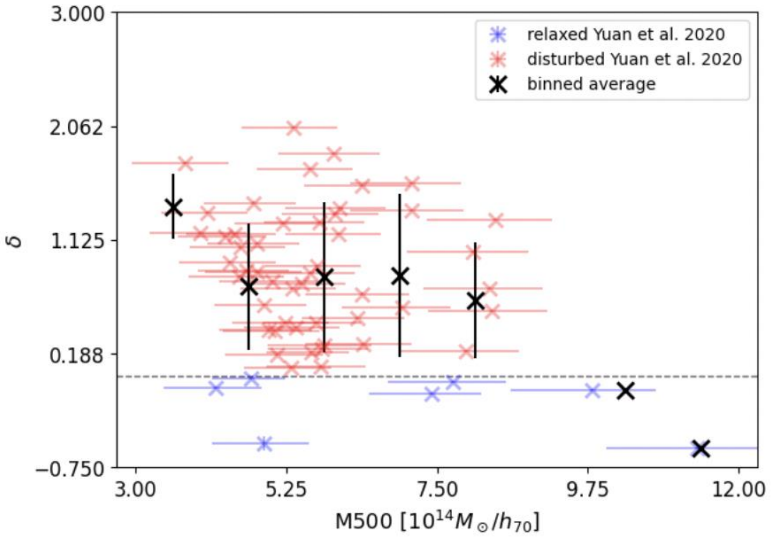
Catalogue A – Catalogue B	# Common Clusters	% Classification Match	% Classification Mismatch
This Work - Yuan et al. 2020	56	85.71%	14.29%
This Work - Zenteno et al. 2020	29	31.03%	68.97%
Yuan et al. 2020 - Zenteno et al. 2020	21	19.05%	80.95%

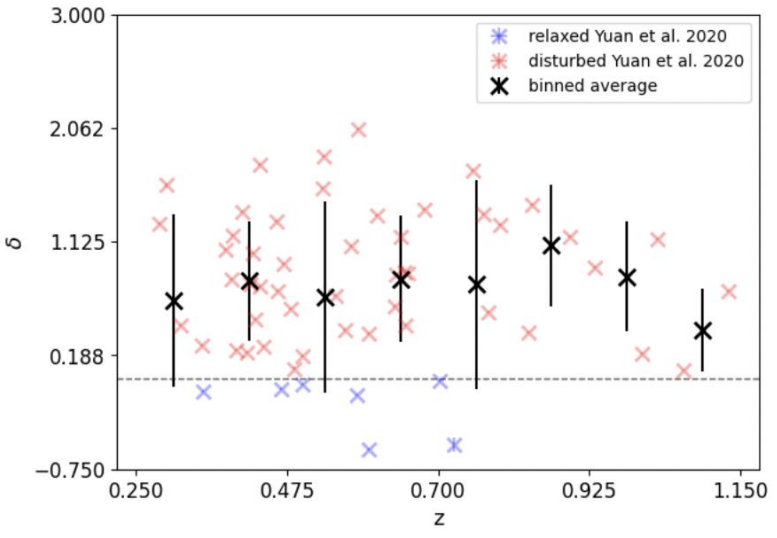
parameters	r	p
M vs. M500 $[10^{14} M_{\odot}/h_{70}]$	0.486	0.00014
δ vs. M500 $[10^{14} M_{\odot}/h_{70}]$	-0.289	0.031
M vs. z	0.11	0.42
δ vs. z	-0.007	0.96











Important parameters and bins

Parameter	Value
Min_{err}	0.09
$\mathrm{Med}_{err} - 3\sigma_{err}$	0.119
$\mathrm{Med}_{err} - 2\sigma_{err}$	0.134
$\mathrm{Med}_{err} - \sigma_{err}$	0.177
Med_{err}	0.222
$\mathrm{Med}_{err} + \sigma_{err}$	0.285
$\mathrm{Med}_{err} + 2\sigma_{err}$	0.344
$\mathrm{Med}_{err} + 3\sigma_{err}$	0.413
Max_{err}	0.42

bin #	M bins	z bins	M500 bins $[10^{14} M_{\odot}/h_{70}]$
1	$-2.5 < M < -1.8125$	$0.25 < z < 0.3625$	$3.0 < M500 < 4.625$
2	$-1.8125 < M < -1.125$	$0.3625 < z < 0.475$	$4.625 < M500 < 6.25$
3	$-1.125 < M < -0.4375$	$0.475 < z < 0.5875$	$6.25 < M500 < 7.875$
4	$-0.4375 < M < 0.25$	$0.5875 < z < 0.7$	$7.875 < M500 < 9.5$
5	$0.25 < M < 0.9375$	$0.7 < z < 0.8125$	$9.5 < M500 < 11.125$
6	$0.9375 < M < 1.625$	$0.8125 < z < 0.925$	$11.125 < M500 < 12.75$
7	$1.625 < M < 2.3125$	$0.925 < z < 1.0375$	$12.75 < M500 < 14.375$
8	$2.3125 < M < 3.0$	$1.0375 < z < 1.15$	$14.375 < M500 < 16.0$