Galaxy cluster masses using galaxy properties: how should we deal with dynamically disturbed clusters?

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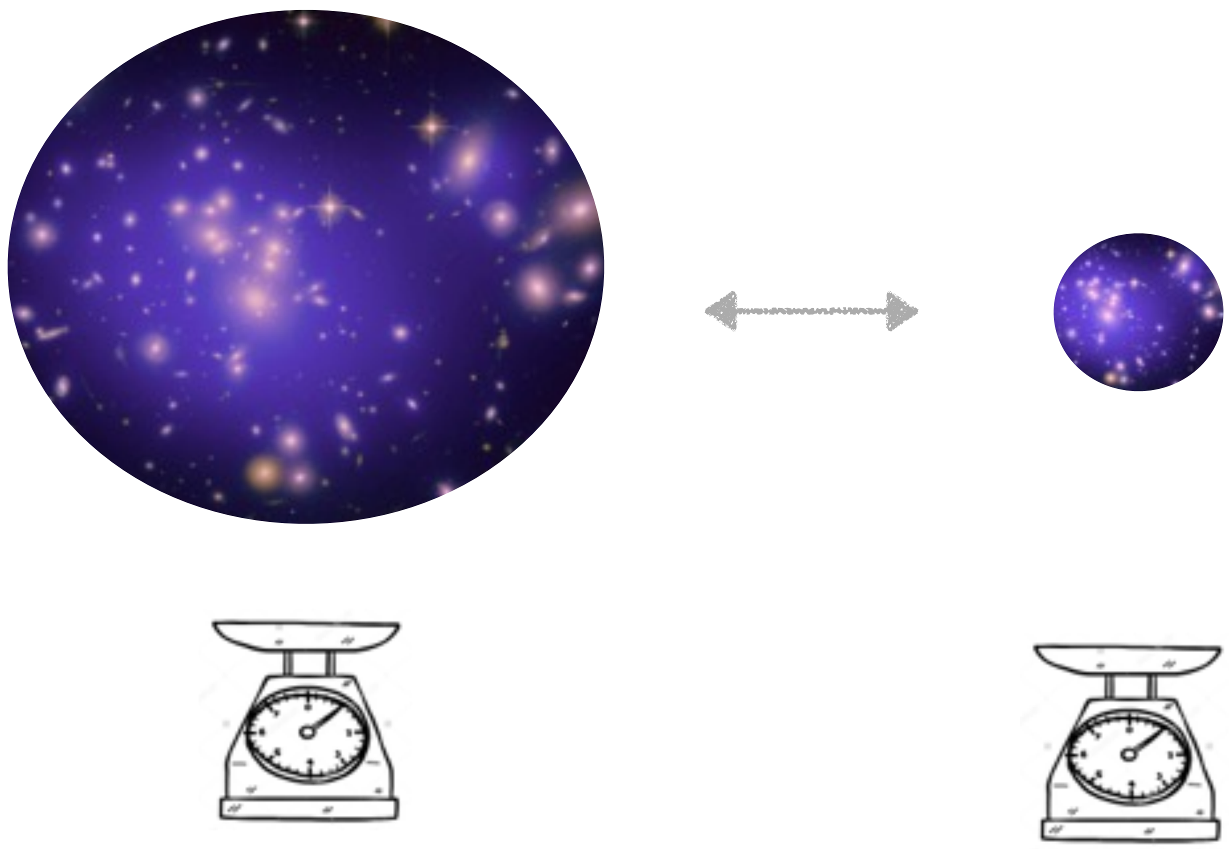
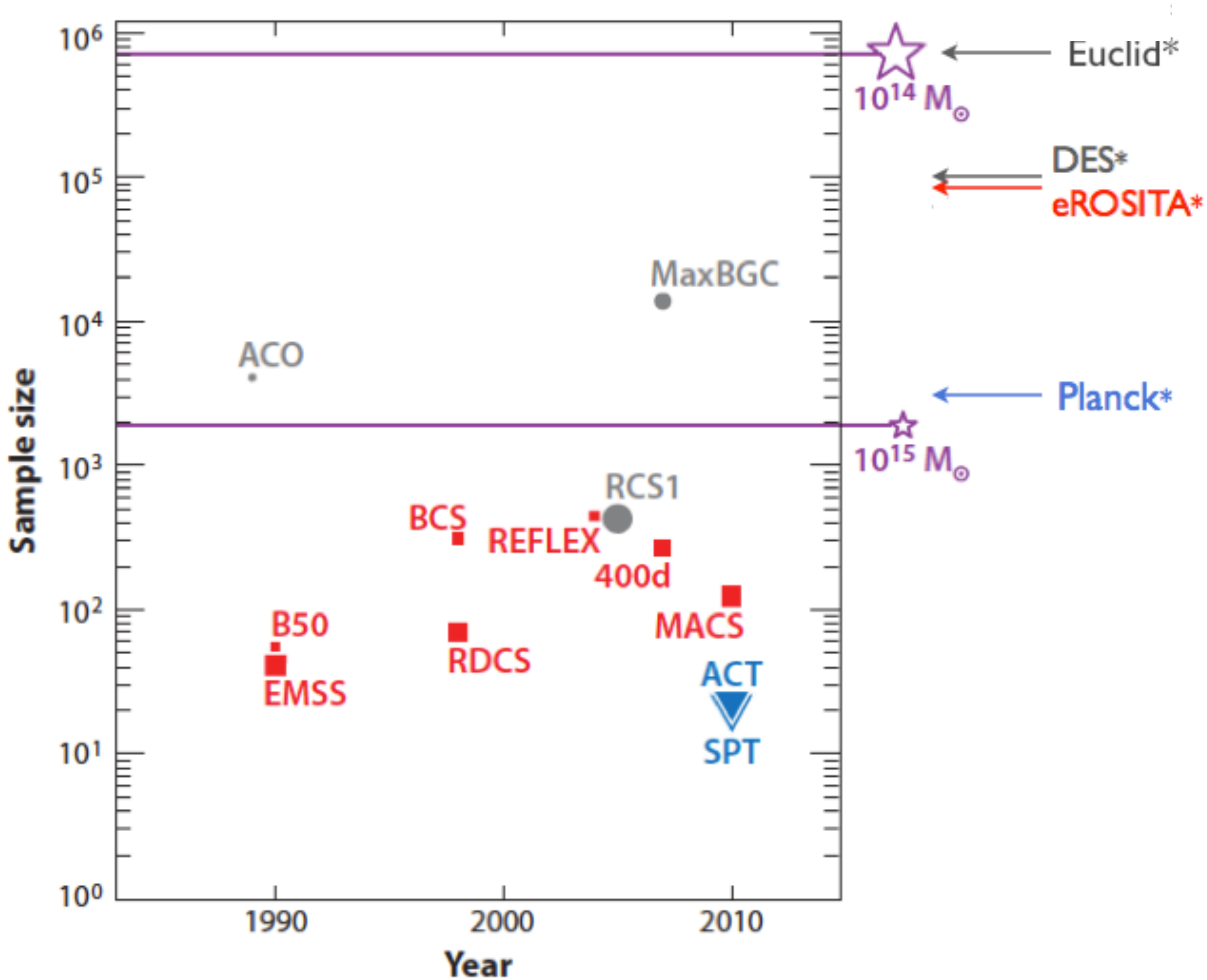


The Galaxy Cluster Mass Reconstruction Project: Radek Wojtak, Gary Mamon, Frazer Pearce, Ramin Skibba, Darren Croton, Meghan Gray, Richard Pearson, Trevor Ponman, Peter Behroozi, Reinaldo de Carvahlo, uan Muñoz-Cuartas, Daniel Gifford, Anja von der Linden, Mike Merrifield, Volker Müller, Eduardo Rozo, Eli Rykoff, Chris Power, Stuart Muldrew, Alex Saro, Tiit Sepp, Cristobal Sifón, Elmo Tempel, Elena Tundo & Yang Wang.

Modern cluster (cosmology) surveys



Adapted from Allen+2011

Galaxy-based methods

Any technique that uses galaxy properties as a mass proxy

e.g., positions, velocities, colours & luminosities

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Why do we care about them?

- Independent mass proxy
- Relatively inexpensive $!
- Extended galaxy distribution: clusters can be probed out to large radii e.g., $> R_{200c}$
- 2-for-1: dynamical analysis provides additional information about virialisation state

How do we define dynamical substructure observationally?

Some fraction of cluster population still have significant substructure i.e., unrelaxed, have undergone a recent merger, far from virialisation.

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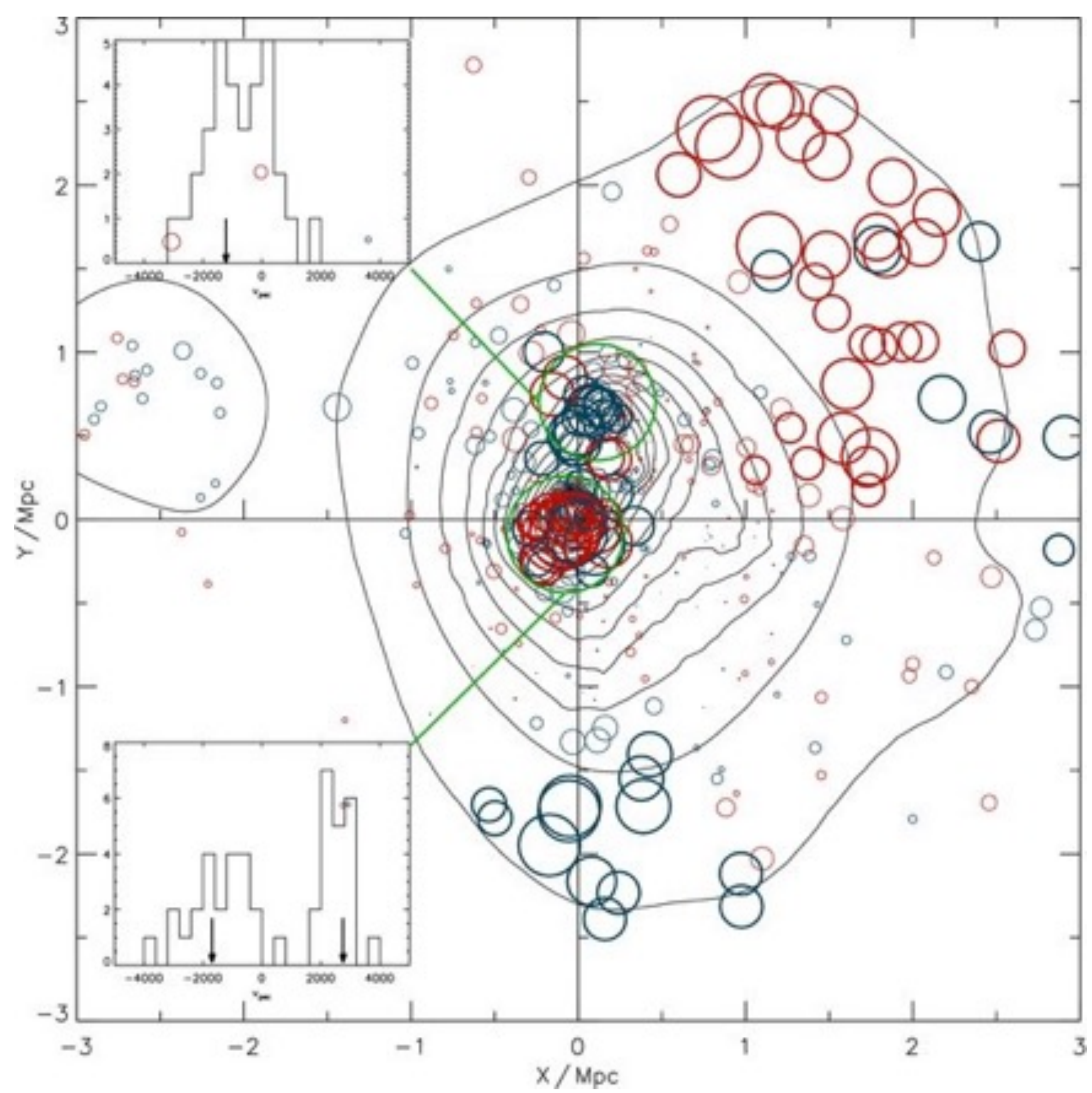

Owers et al., 2011, Abell 2744

Observational dynamical substructure detection

We use tests that aim to quantify difference between local ‘subgroups’ and global cluster phase-space properties

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Kappa test

$$\kappa_n = \sum_{i=1}^{n} -[\log(\mathrm{P_{KS}}(\mathrm{D_{sim}} > \mathrm{D_{Obs}})]$$

Velocity distribution of local subgroups are compared to cluster by measuring the max separation of the cumulative dist. functions (KS-test)

Colless & Dunn 1996

Dressler-Shectman test

$$\delta_{\mathrm{i}}^2 = (\frac{N_{\mathrm{nn}} + 1}{\sigma_{\mathrm{c}}})[(\overline{\nu}_{\mathrm{local}} - \overline{\nu}_{\mathrm{global}})^2 + (\sigma_{\mathrm{global}} - \overline{\nu}_{\mathrm{c}})^2]$$

where $N_{\mathrm{nn}} = \sqrt{n_{\mathrm{members}}}$

The DS statistic $\Delta = \sum_i \delta_i$

Dressler & Shectman 1988

The significance of the presence of 'significant substructure' in these tests are quantified by Monte Carlo 'shuffling' of the velocities.

Observational dynamical substructure detection

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3D tests such as DS, Kappa tests are found to be most reliable (Pinkney+1996, Hou+2012), but still can miss substructure e.g., viewing angle dependant (e.g., White+2010)

Dynamical substructure & cluster mass estimation

- Many studies have probed the frequency of dynamically disturbed clusters in their samples (e.g., Bird 1994, West et al. 2009, Einasto et al. 2012, Hou et al. 2012, Owers et al. 2017).

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- Some explore whether *measured* global cluster properties for highly substructured clusters differ from non-substructured clusters e.g.,

Strong difference	Small difference/inconclusive
Geller & Beers 1982	Biviano et al. 1993
Girardi et al. 1997	Fadda et al. 1996
Smith et al. 2005	Wing & Blanton 2012
Hou et al. 2012	Sifon et al. 2013

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Is it necessary to characterize all clusters in large samples and then exclude dynamically disturbed clusters?

Or better to include disturbed clusters in samples purely for the statistical benefit of having a large sample?

We don’t know whether including dynamically disturbed clusters in our samples for cosmology or galaxy environment studies is introducing biases via mass estimation.

↓

How can we probe this?

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1. Compare scaling relations between two different mass proxies for disturbed and relaxed clusters

- Lopes+2006: excluding substructured clusters doesn't improve correlation between X-ray luminosity and richness.
- Sifón+2013: hints that disturbed systems may bias the relation between dynamical and SZ mass, however, state the need for more clusters to be conclusive.

How can we figure this out?

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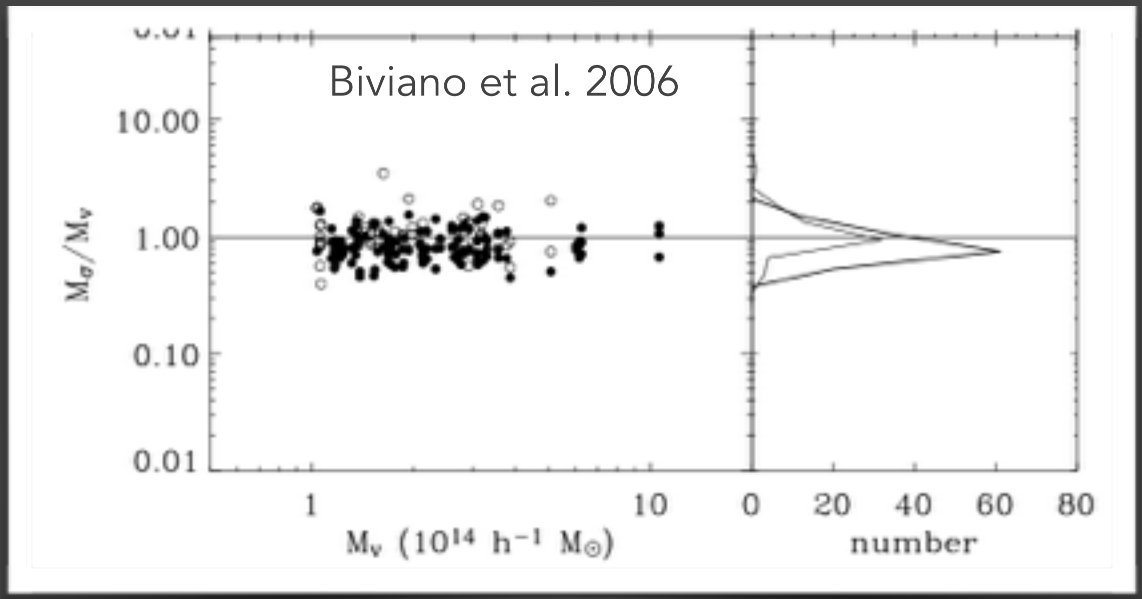
2. Use cosmological simulations where halo/cluster mass is known



- Biviano et al. 2006: hints that substructured cluster masses are biased high (white points).
- Pinkney et al. 1996: finds virial masses are overestimated by up to a factor of 2 for clusters undergoing mergers.

Limitations/Assumptions

1. Compare scaling relations between two different mass proxies for disturbed and relaxed clusters

↓

Substructure/relaxation state (not) correlated for different mass proxies?

2. Use cosmological simulations where halo/cluster mass is known

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Have to assume properties such as positions, velocities of mock cluster galaxies are realistic

This project!

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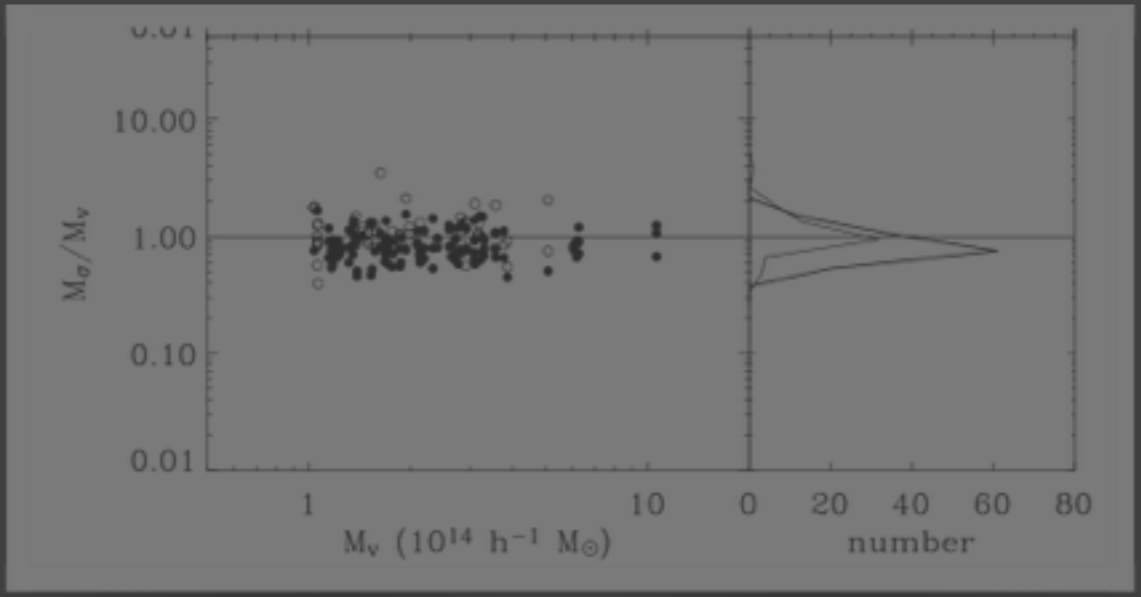

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Aim: test whether masses of dynamically disturbed clusters are measured to the same accuracy and precision as relaxed clusters for a range of galaxy-based cluster mass estimation techniques on the same set of mock clusters.

The Galaxy Cluster Mass Reconstruction Project dataset

Homogenous, blind test of galaxy-based cluster mass estimation techniques on mock clusters to get a handle on the scatter, biases we can expect from galaxy proxies.

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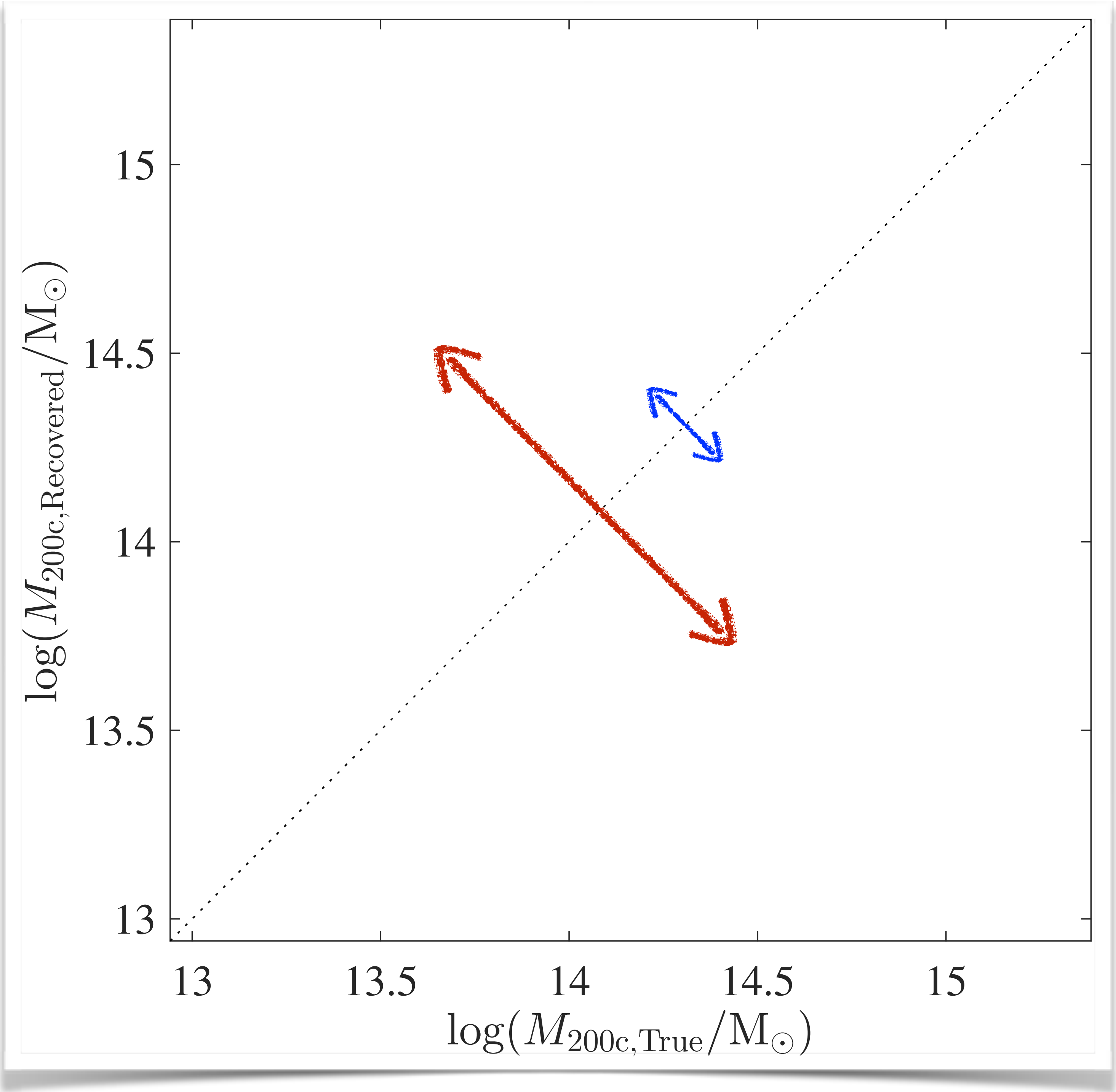

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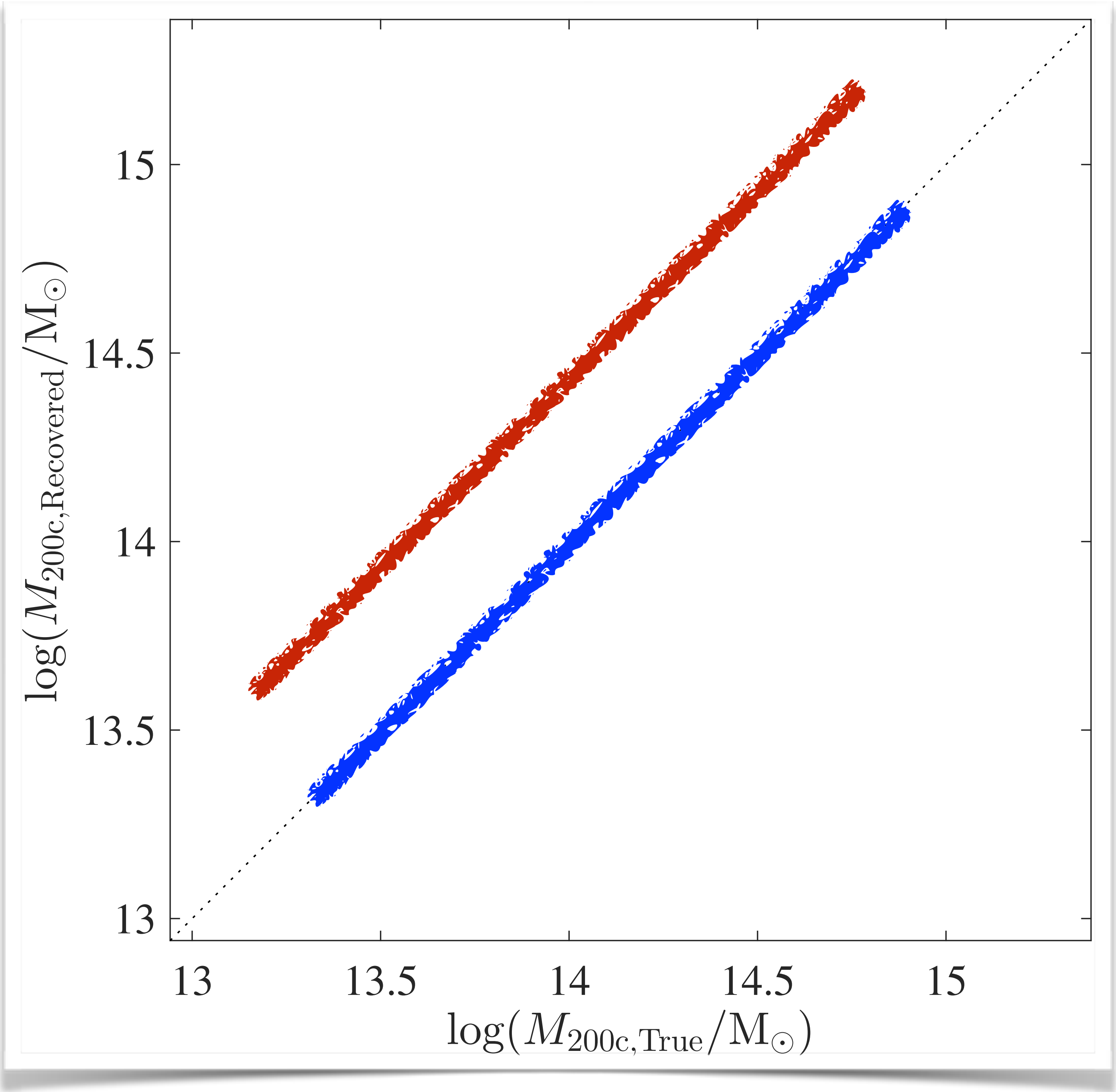

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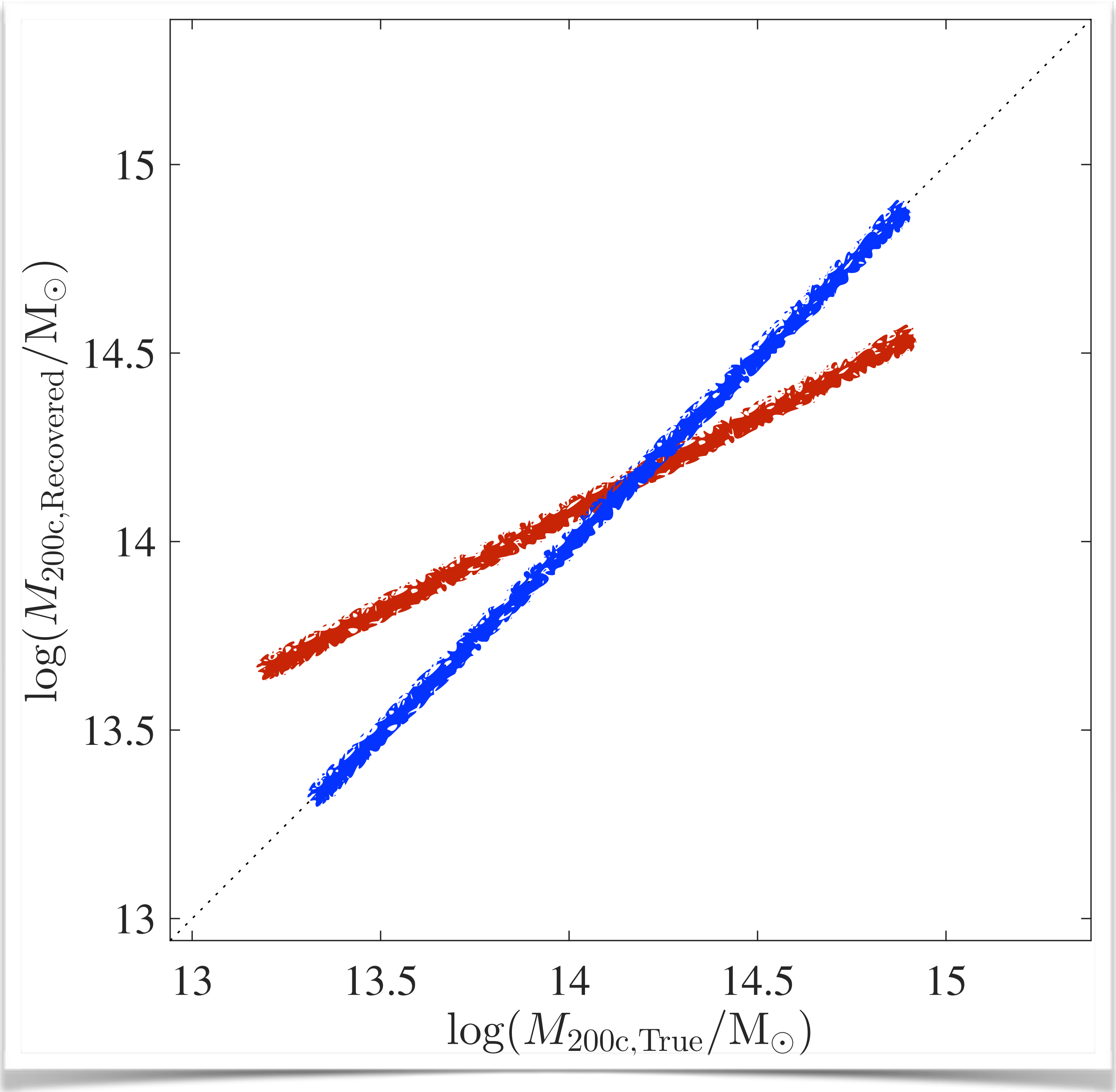
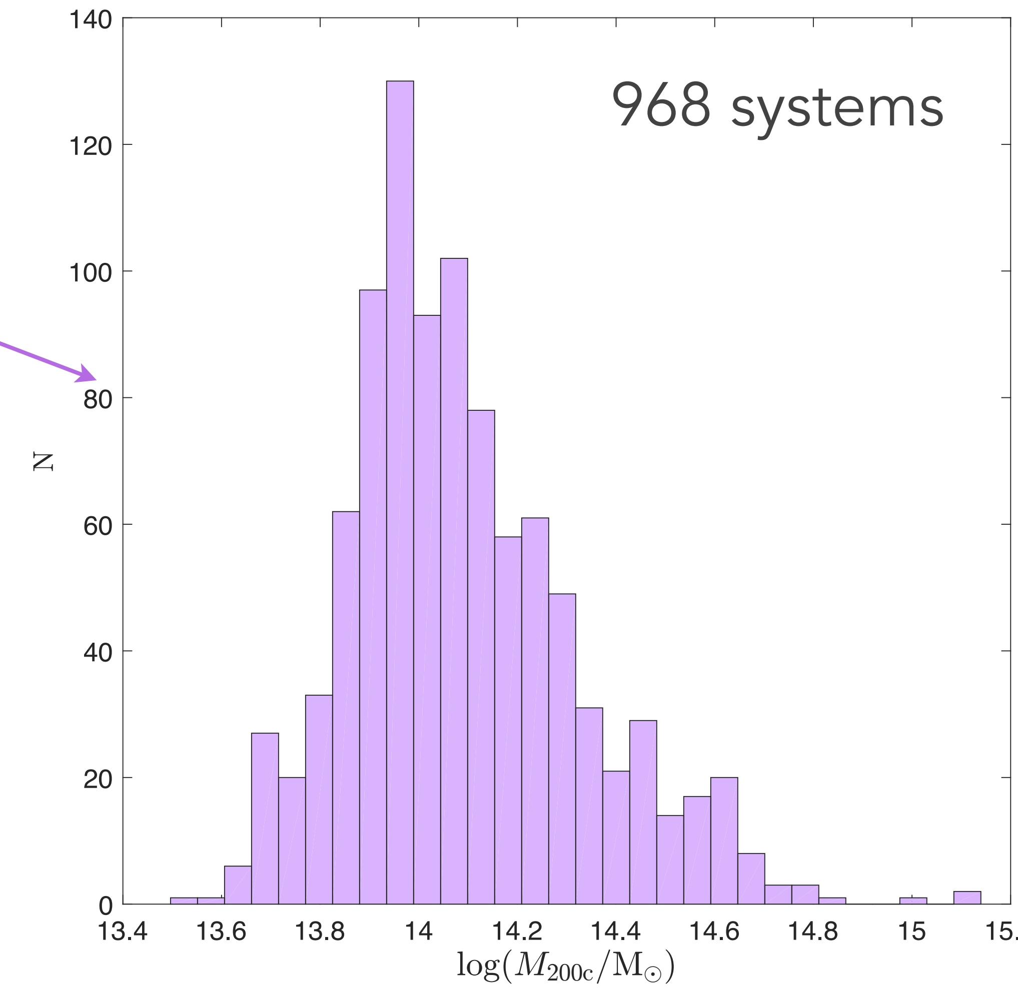


The Galaxy Cluster Mass Reconstruction Project dataset

DM only → Add galaxies - SAM & HOD models → 3 mock group/ cluster catalogues

577 clusters with log M_{200c} > 14 M_{solar}



The Galaxy Cluster Mass Reconstruction Project dataset

DM only → Add galaxies - SAM & HOD models → 3 mock group/ cluster catalogues

↓

Give participants only basic properties → Participants return membership & cluster parameters

For the 968 systems:

- M_{200c}
- Velocity dispersion
- Radius
- Galaxy membership

Workshop @ Univ. of Nottingham

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Galaxy-based mass estimation techniques

~~Step 1 = cluster finding~~ Step 2 = members Step 3 = mass

Method	Initial Galaxy Selection	Mass Estimation	Type of data required	Reference
PCN	Phase space	Richness	Spectroscopy	Pearson et al. (2015)
PFN*	FOF	Richness	Spectroscopy	Pearson et al. (2015)
NUM	Phase space	Richness	Spectroscopy	Mamon et al. (in prep.)
ESC	Phase space	Phase space	Spectroscopy	Gifford & Miller (2013)
MPO	Phase space	Phase space	Multi-band photometry, spectroscopy	Mamon et al. (2013)
MP1	Phase space	Phase space	Spectroscopy	Mamon et al. (2013)
RW	Phase space	Phase space	Spectroscopy	Wojtak et al. (2009)
TAR*	FOF	Phase space	Spectroscopy	Tempel et al. (2014)
PCO	Phase space	Radius	Spectroscopy	Pearson et al. (2015)
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PFR*	FOF	Radius	Spectroscopy	Pearson et al. (2015)
MVM*	FOF	Abundance matching	Spectroscopy	Muñoz-Cuartas & Müller (2012)
AS1	Red Sequence	Velocity dispersion	Spectroscopy	Saro et al. (2013)
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Galaxy-based mass estimation techniques

Step 2 = members

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Friends-Of-Friends algorithm

Phase space: within a certain distance and velocity from cluster centre

Red sequence: selecting galaxies of a certain colour

Galaxy-based mass estimation techniques

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Number of galaxies above a given luminosity threshold

Positions & velocities of galaxies e.g., caustics

RMS radius/ DM profile fitted to obtain radius.

Matching using theoretical halo mass function & cluster r-band luminosity function

$$M \propto \sigma^3$$

What did we find?

- Scatter in M_{200c} for majority of galaxy-based mass estimation techniques is high, factor of ~2-12.
- Scatter is generally higher for lower mass clusters for majority of methods.
- Methods using same proxy e.g., σ do not necessarily perform consistently.
- Stronger correlation of the recovered to true N_{gal} in comparison with M_{200c}.
- Many methods overestimate high mass clusters - implications due to steeply falling cluster mass function.

Old+2014, 2015

Cluster sample & analysis for this project

- We only use data from the SAM (SAGE) catalogue where the dynamical properties of galaxies are taken directly from the underlying N-body dark matter subhaloes, i.e., they retain 'dynamical memory' of the merging history of the clusters (phase-space properties of galaxies have primarily evolved over time due to the influence of gravity).

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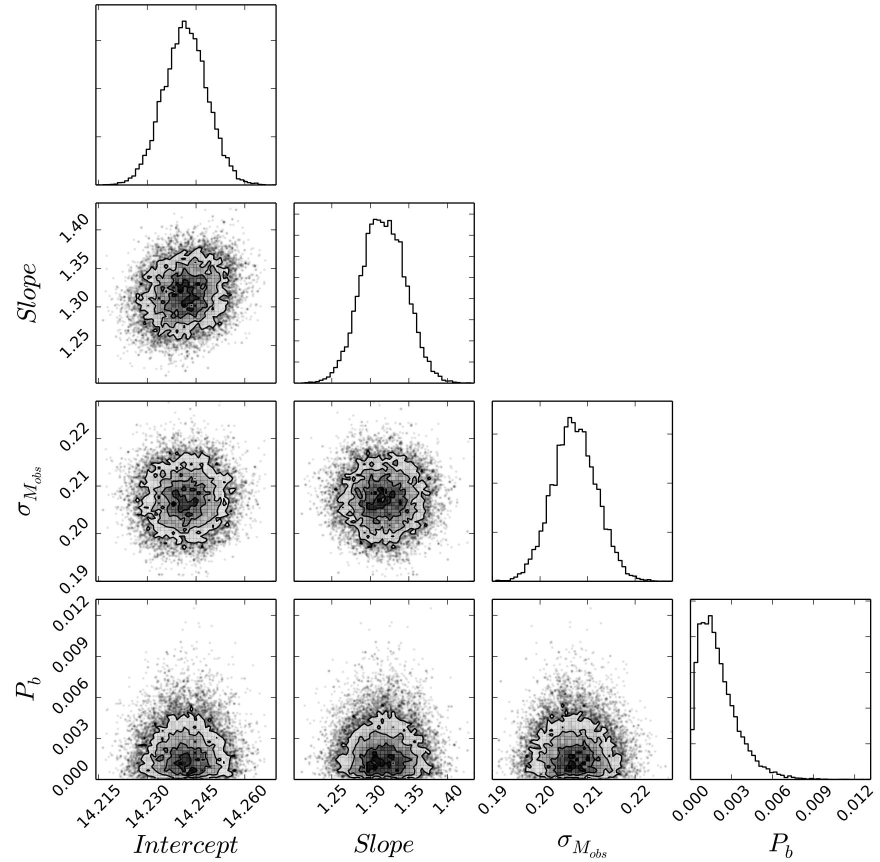
- Clusters are deemed in the substructured sample if either DS or Kappa-test identify substructure: 257 of the 943 clusters (~27%).
- The substructure tests identify a higher fraction substructured clusters as a function of cluster mass.
- We therefore need to control the two samples by mass & (iteratively) randomly select the minimum number of clusters in a given mass bin.

Cluster sample & analysis for this project

- For each set of sub-samples, we quantify differences between the two samples in terms of the relation between the underlying and recovered clusters masses.

- We perform a likelihood fitting analysis assuming a model where there is a linear relationship between log $M_{200,rec}$ and log $M_{200,true}$ log and residual offsets in the recovered mass are drawn from a normal distribution.

- We use the parallel-tempered MCMC sampler *emcee* (Foreman & Mackay 2013) to efficiently sample the parameter space & produce posterior probability distributions for the fit parameters.



Results!

Is there a difference in scatter in the M_{rec} - M_{true} relation?

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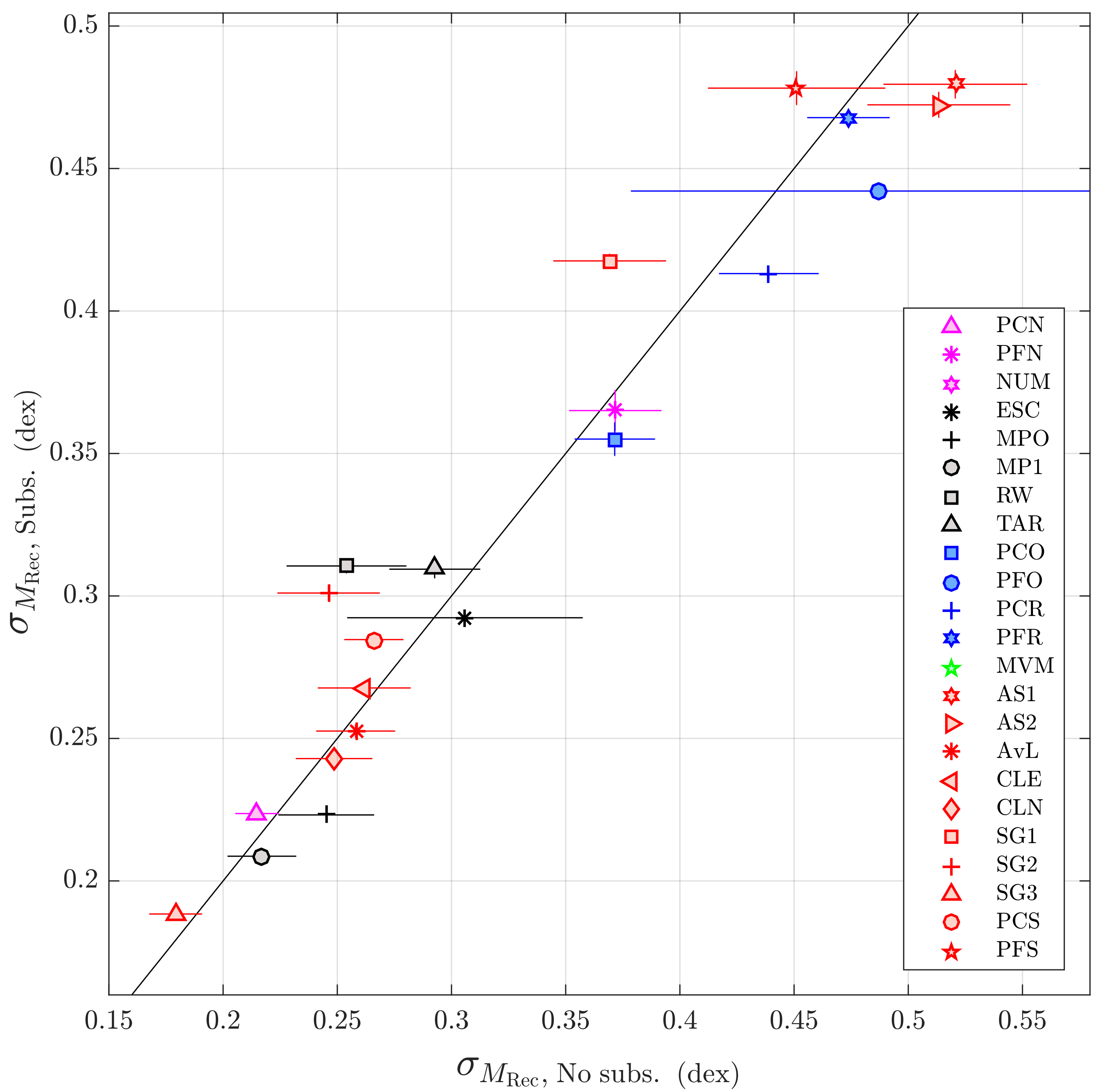
Scatter in M_{rec} for Subs. clusters



Richness

Phase space

Radial

Abundance matching

Velocity dispersion

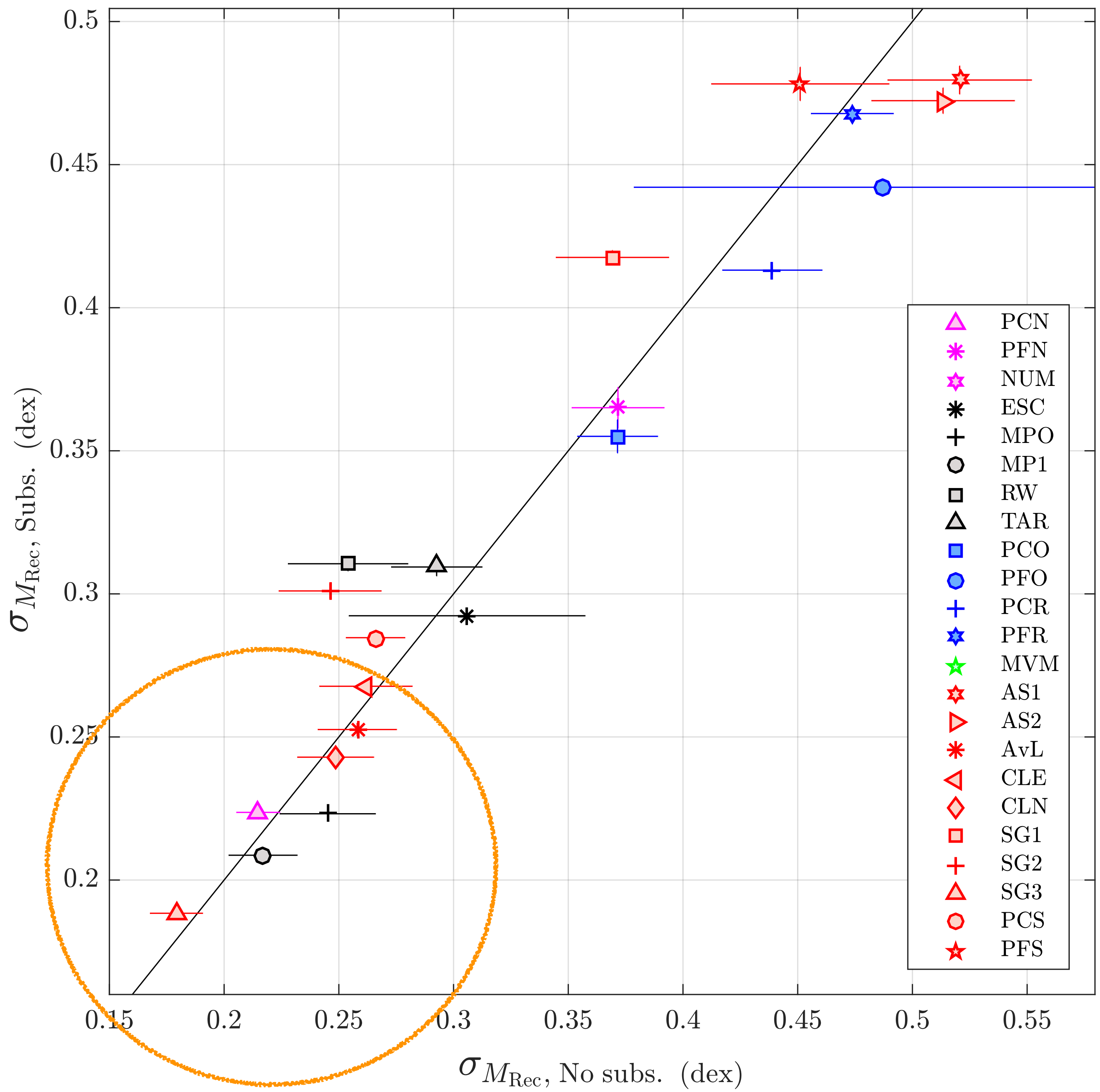
Scatter in M_{rec} for Non subs. clusters

Old+in prep

Is there a difference in scatter in the M_{rec} - M_{true} relation?

Scatter in M_{rec} for Subs. clusters

Not really!



Richness

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Scatter in M_{rec} for Non subs. clusters

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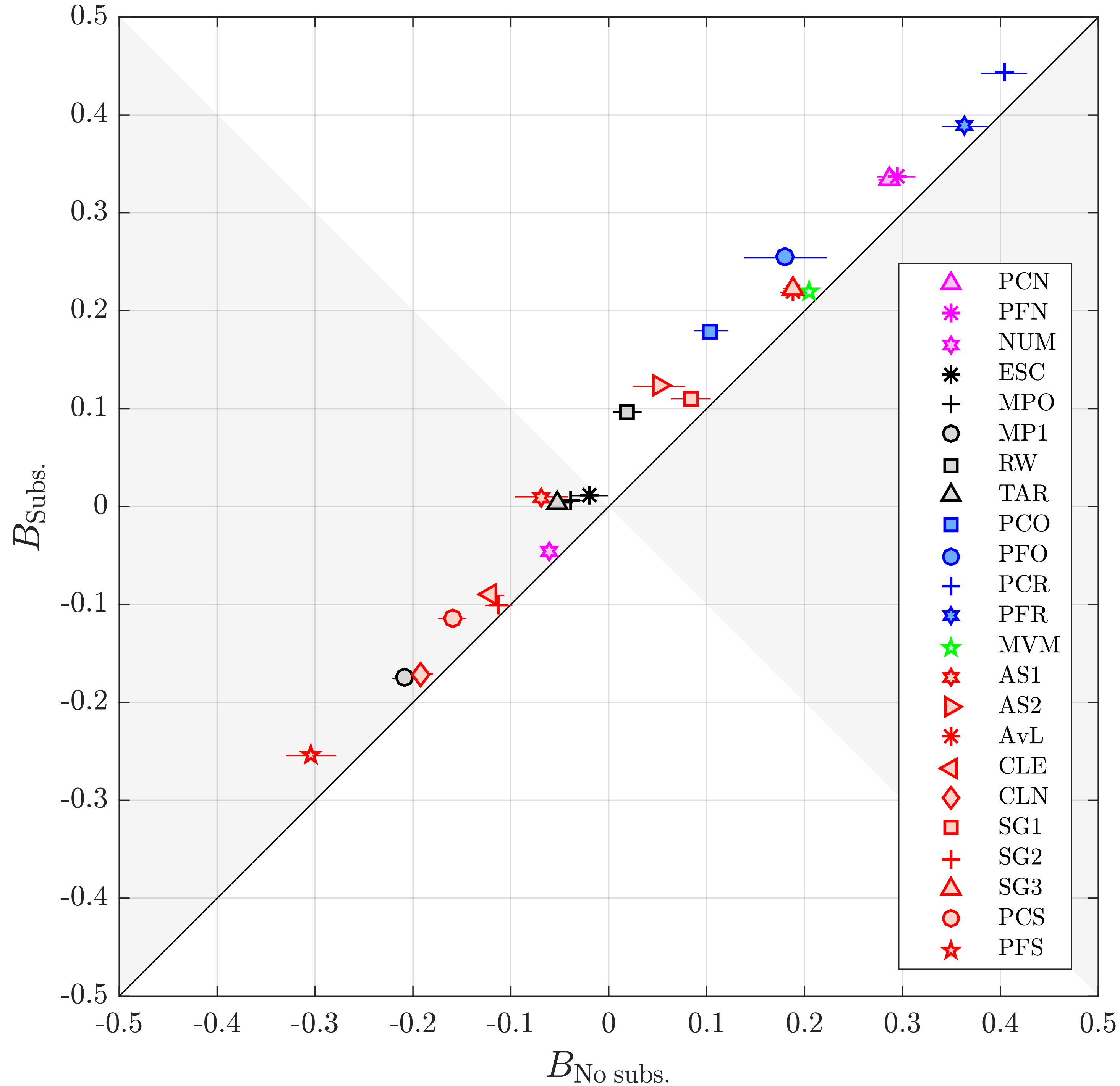
PRELIMINARY

Is there a difference in bias in the M_{rec} - M_{true} relation?

Bias at M_{pivot} for Subs. clusters



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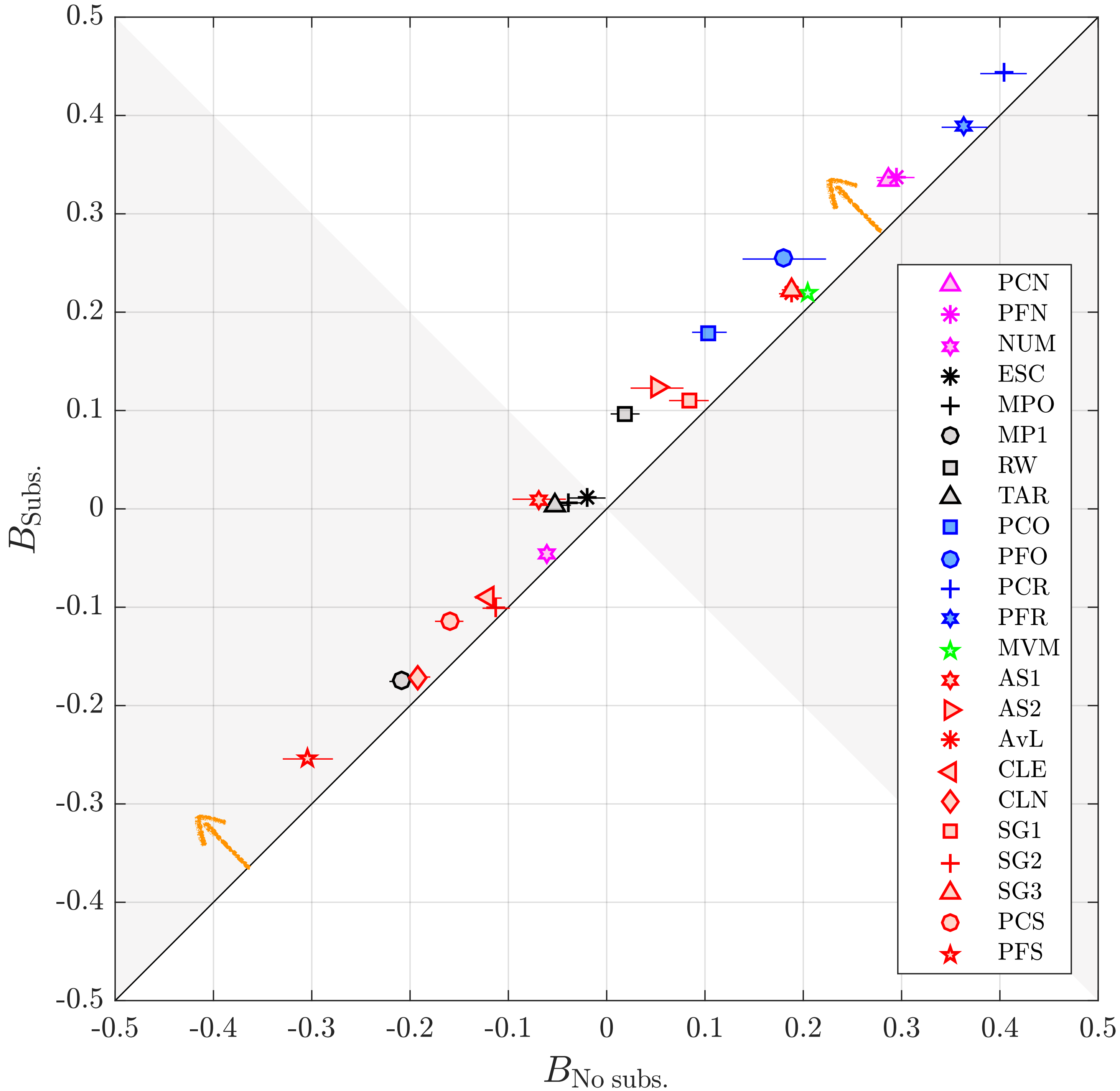
PRELIMINARY

Is there a difference in bias in the M_{rec} - M_{true} relation?

Bias at M_{pivot} for Subs. clusters

Small systematic overestimation at M_{pivot}



Richness

Phase space

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Bias at M_{pivot} for Non subs. clusters

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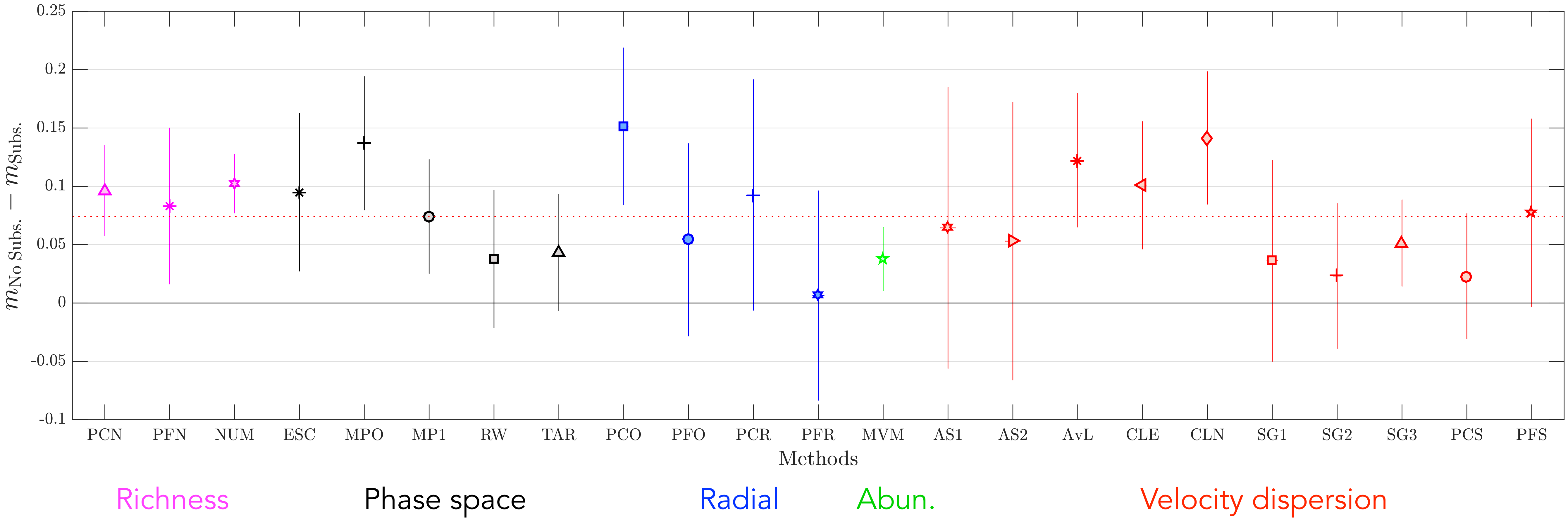
Difference in the slope of the M_{rec} - M_{true} relation?



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PRELIMINARY

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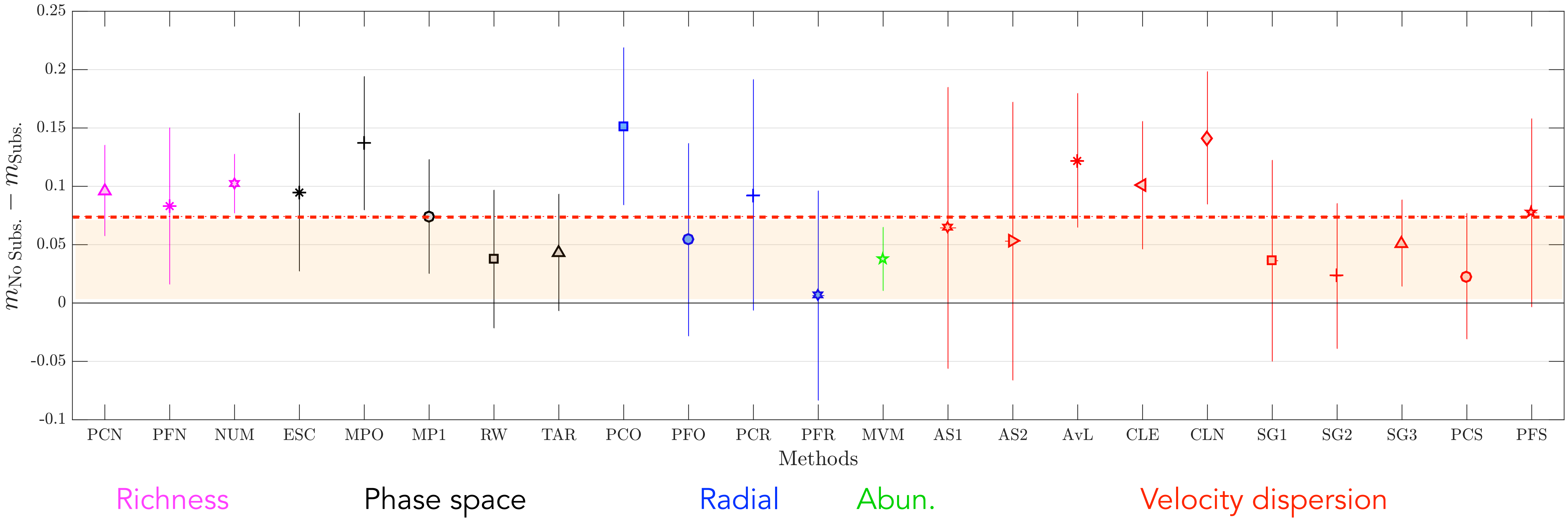

Slope of Mrec -Mtrue relation is generally flatter for substructured clusters

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How would the bias we see translate to shift in cosmo. parameters?

- A simple way to estimate the expected relative bias in Ω_m and σ_8 is to determine the two cosmological parameters for which the corresponding mass function matches the mass function computed for a fixed, fiducial cosmology, but shifted along the mass axis by a range of mass biases.

- We adopt a Planck cosmology (Planck+2016) with Ω_m=0.31 and σ_8=0.83 as a reference model and a universal fitting formula for the mass function from Tinker +2008.

Analysis by Radek Wojtak @ SLAC

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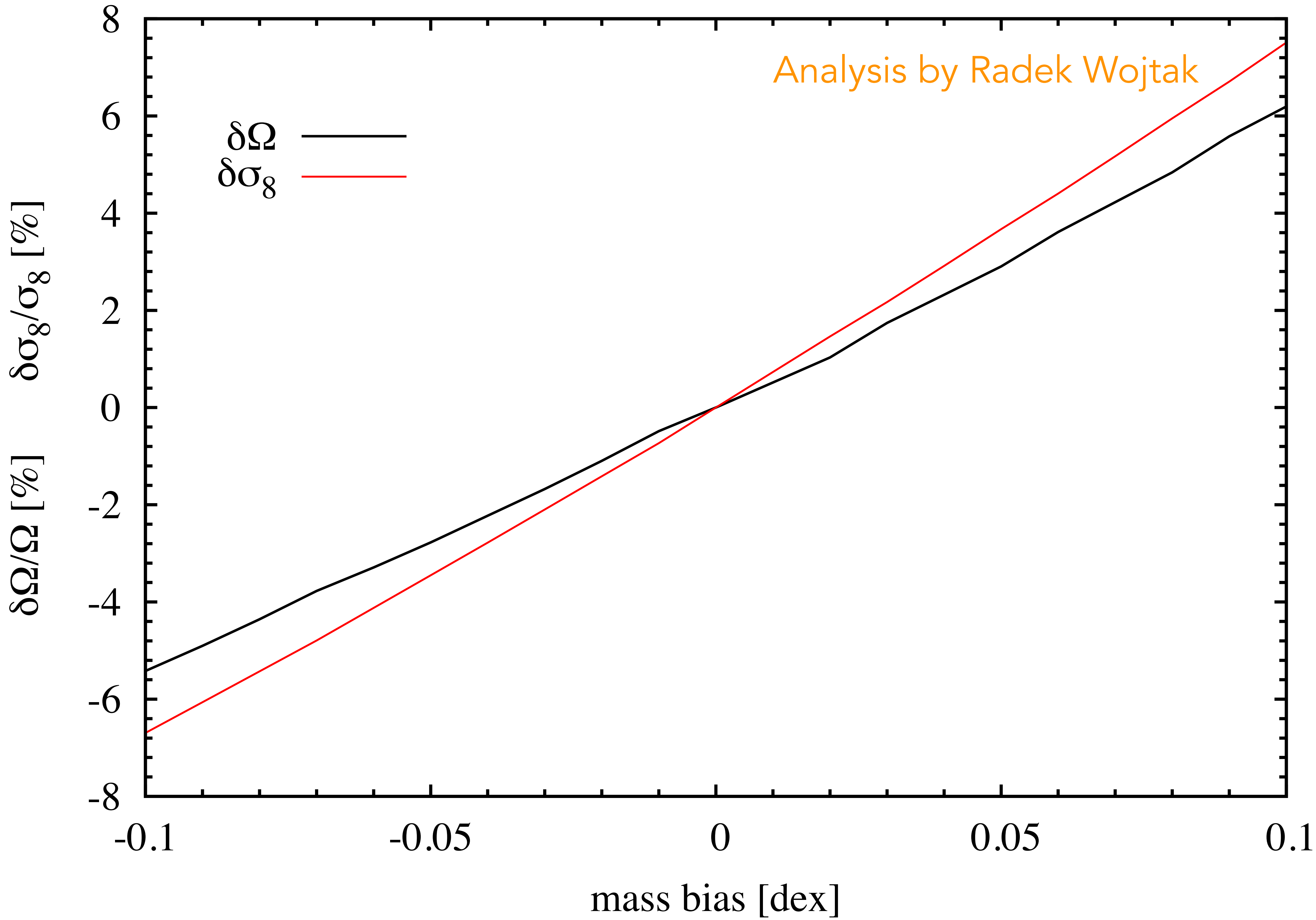

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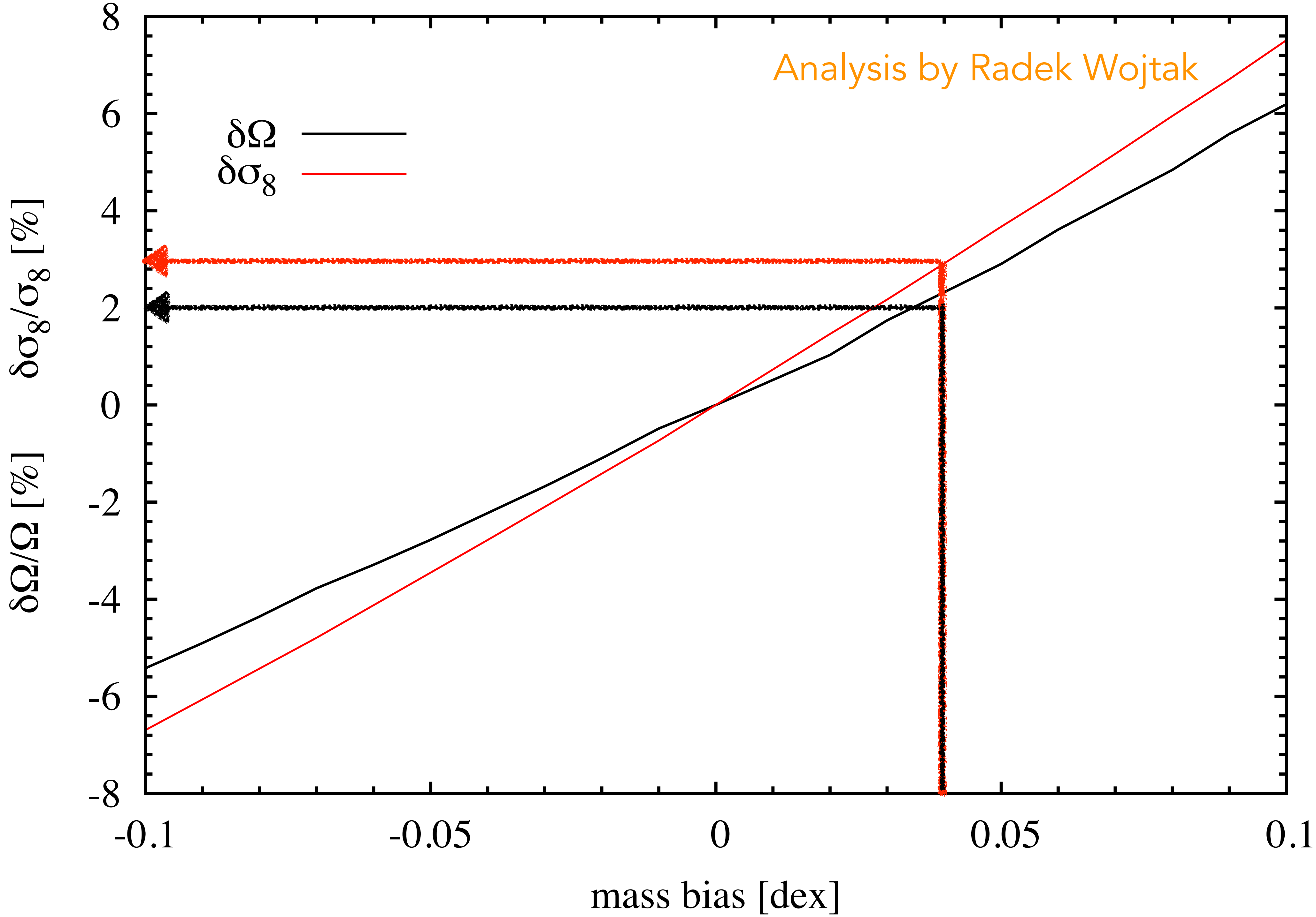

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Take home points

- Little difference in scatter in Mrec -Mtrue relation for highly-substructured cluster samples*.
- Small systematic increase (~10%) in bias at the median mass of the sample for all techniques for the subs clusters vs. non-subs clusters.
- Slope of Mrec -Mtrue relation is generally flatter for substructured clusters.
- Is this taking the extreme case? On the one hand yes (comparing subs. vs. non subs), but on the other, no (contamination in non subs. sample).
- Should we exclude galaxy disturbed clusters in dynamical cluster cosmology samples… TBD, but at the very least, we recommend dynamical state properties of used for scaling relations match application samples.