# Measuring the masses of galaxy groups and clusters using galaxies

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UNIVERSITY OF TORONTO

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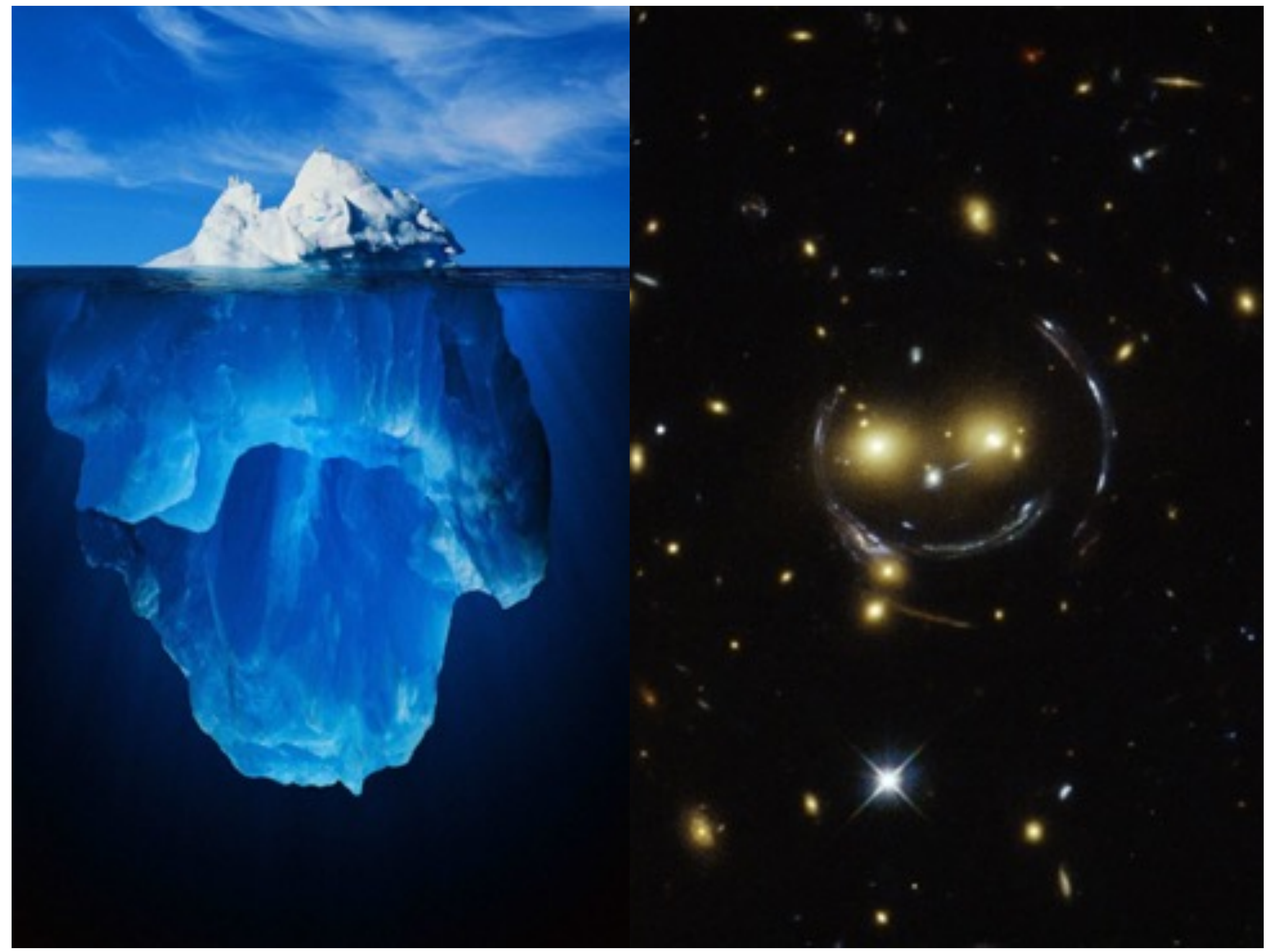
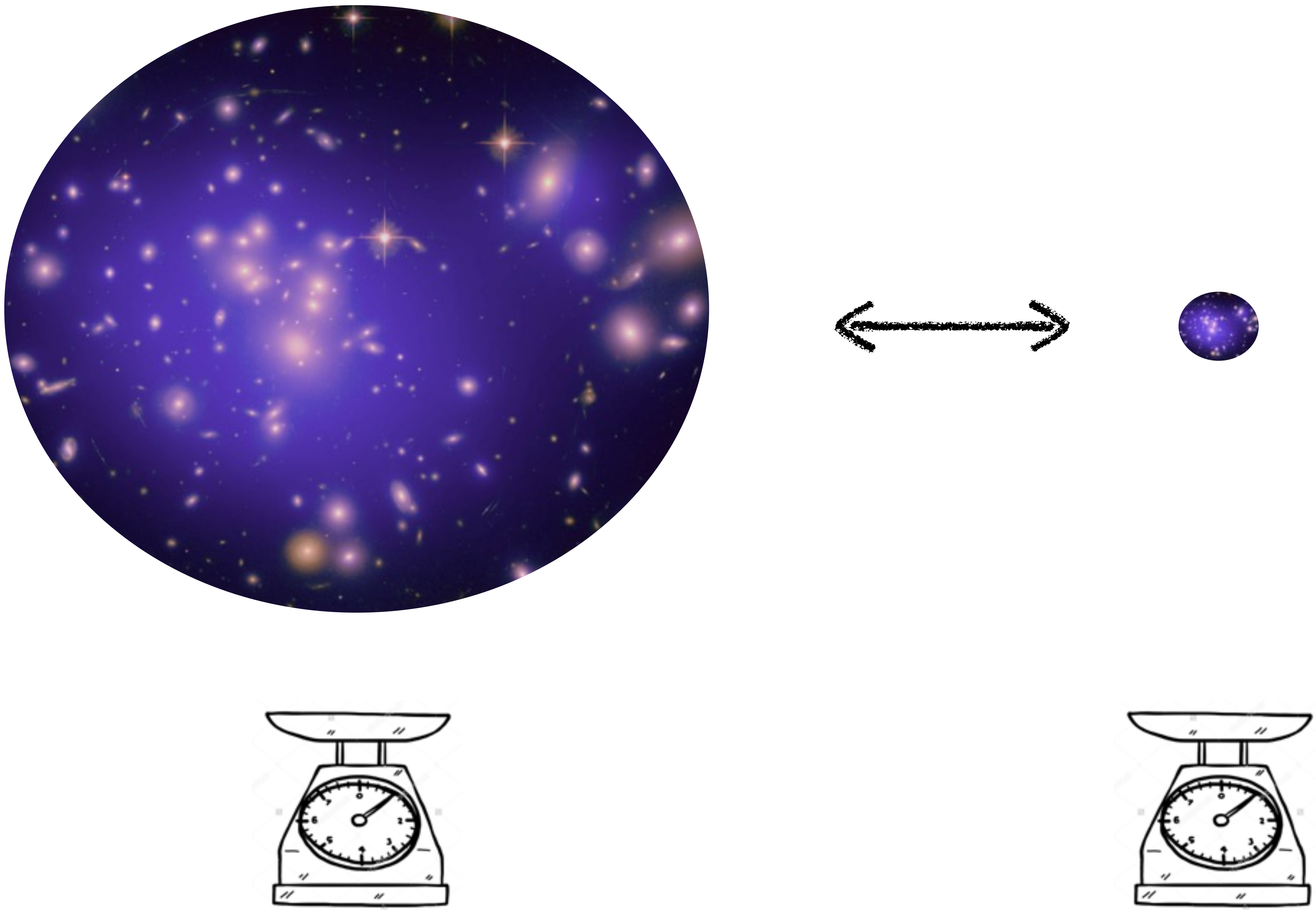


The Galaxy Cluster Mass Reconstruction Project: Radek Wojtak, Gary Mamon, Frazer Pearce, Ramin Skibba, Darren Croton, Meghan Gray, Richard Pearson, Trevor Ponman, Peter Behroozi, Reinaldo de Carvahlo, Juan Muñoz-Cuartas, Daniel Gifford, Anja von der Linden, Mike Merrifield, Volker Müller, Eduardo Rozo,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



# Galaxy-based methods

Abell 1689 ESA/Hubble

Any technique that uses galaxy properties as a mass proxy

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

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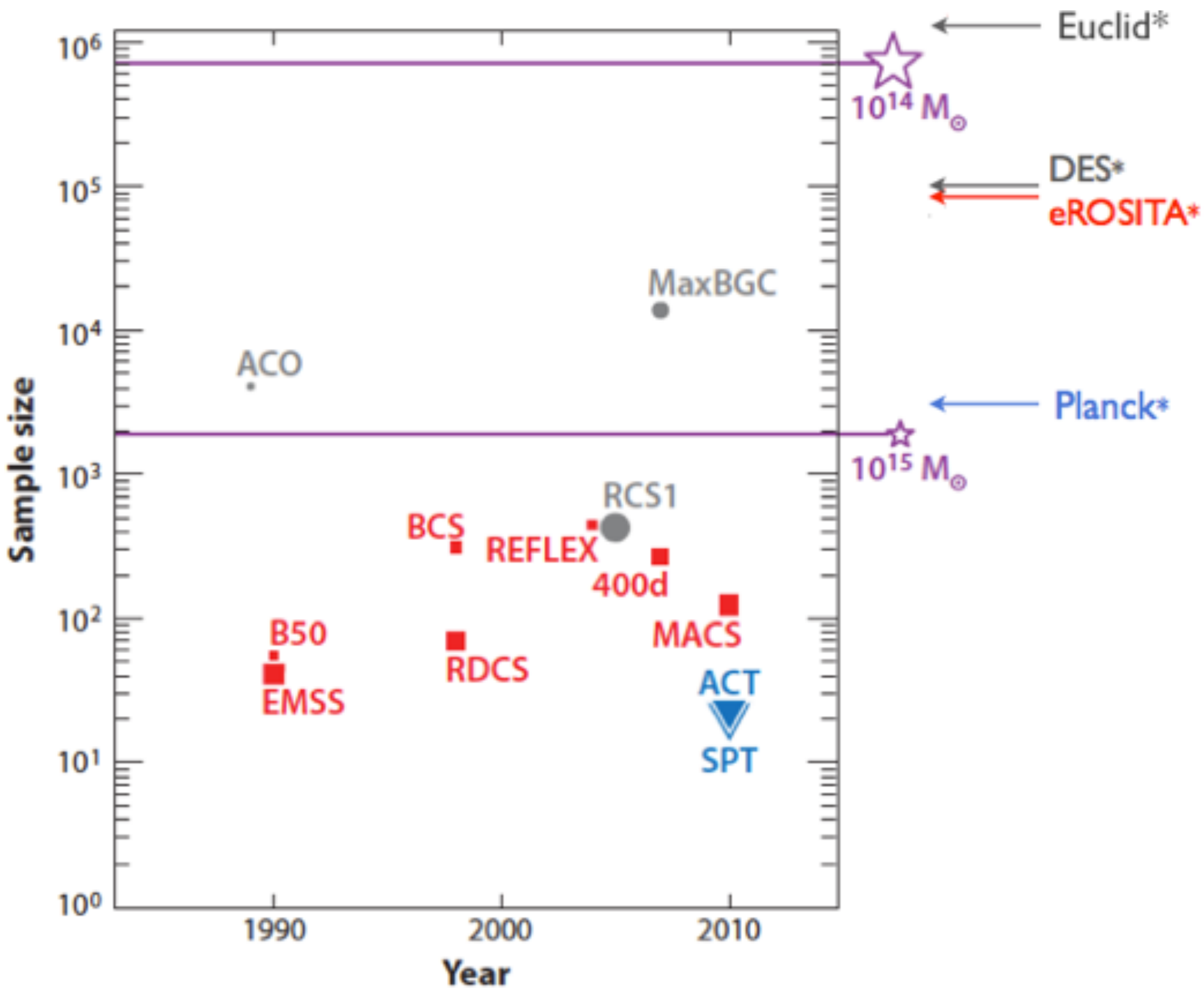
Any technique that uses galaxy properties as a mass proxy

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

# Why do we (still) care about them?

- Future data-sets: DES, Euclid etc.
- Independent mass proxy
- Some directly probe gravitational well
- $ inexpensive!
- Extended galaxy distribution: clusters can be probed out to large radii e.g., $> R_{200c}$
- Less sensitive to complex baryonic physics issues
- 2-for-1: dynamical analysis provides additional information about virialisation state

Modern cluster (cosmology) surveys




Adapted from Allen et. al., 2011

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We rely on galaxy-based group/cluster mass estimation techniques…

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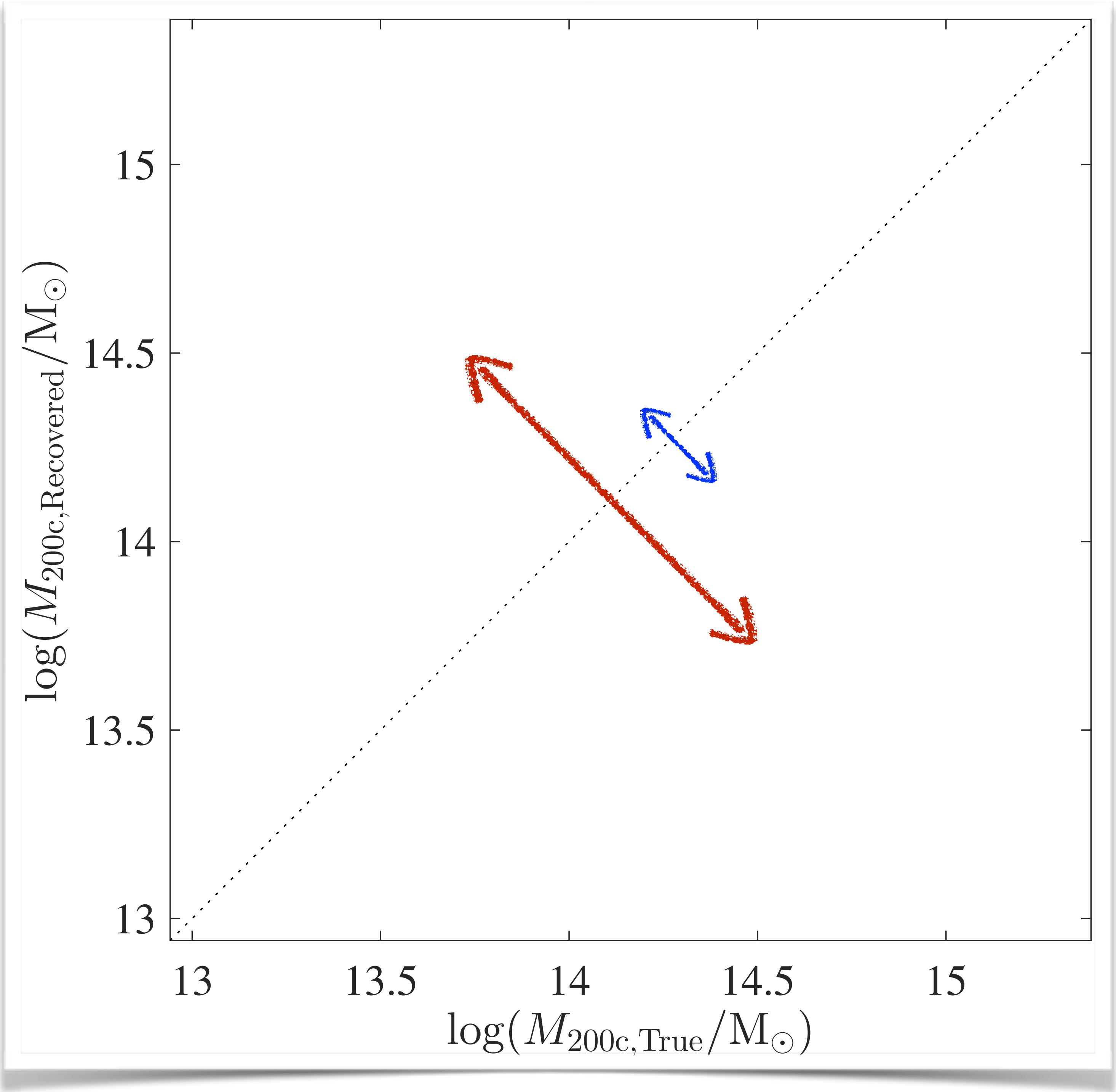
But do we know how well these techniques perform?

# How well do these techniques estimate mass?



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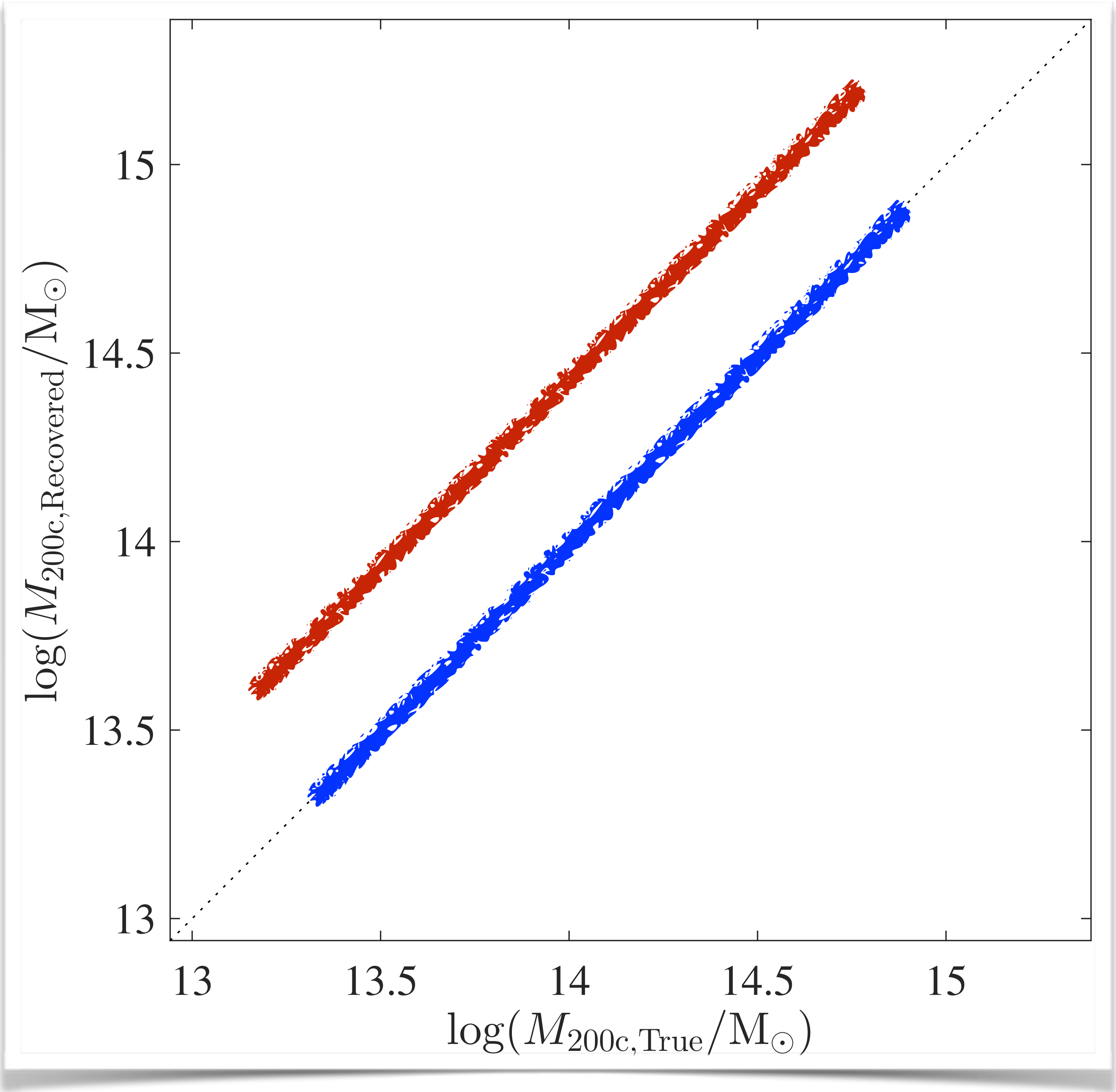

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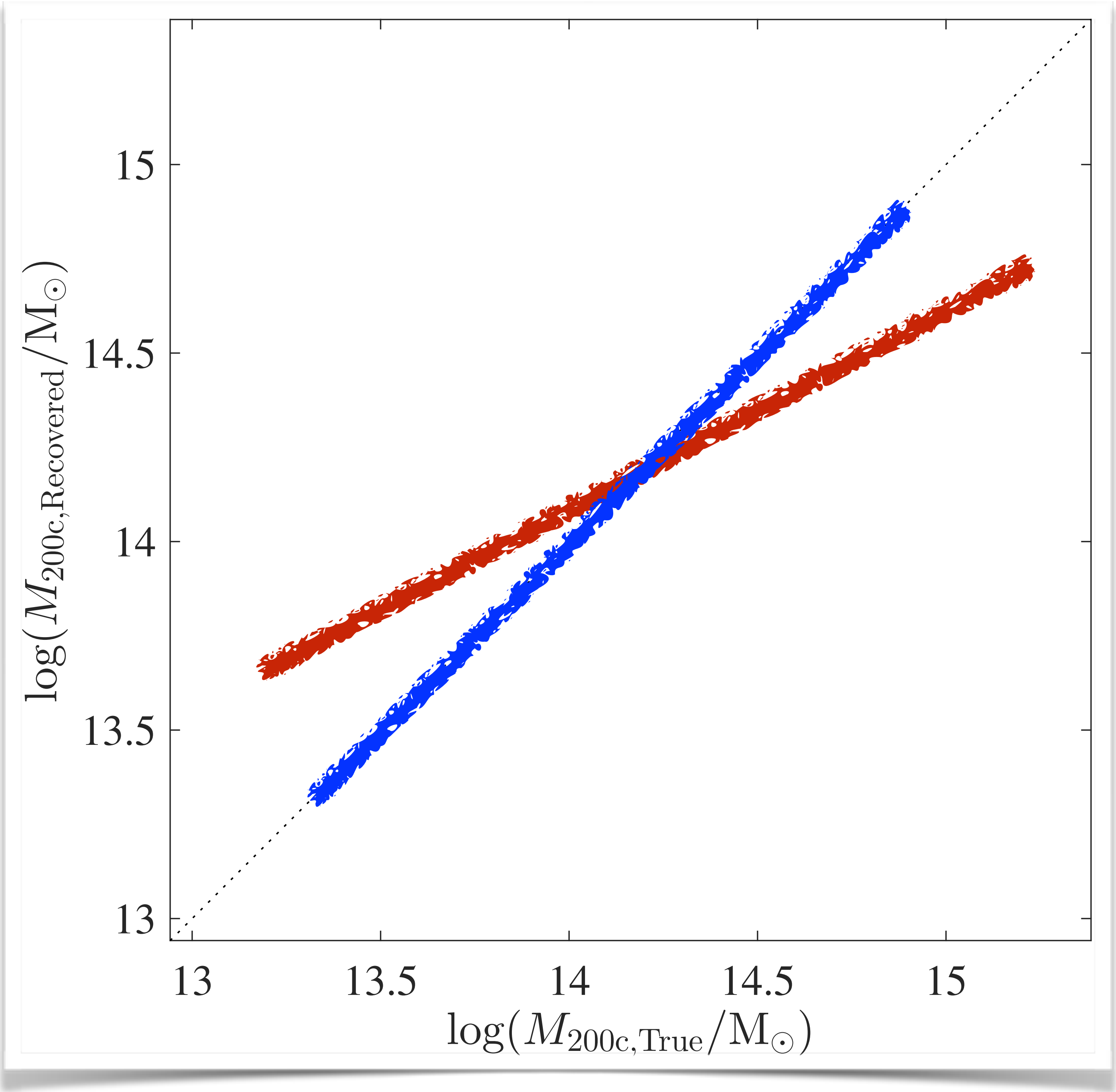

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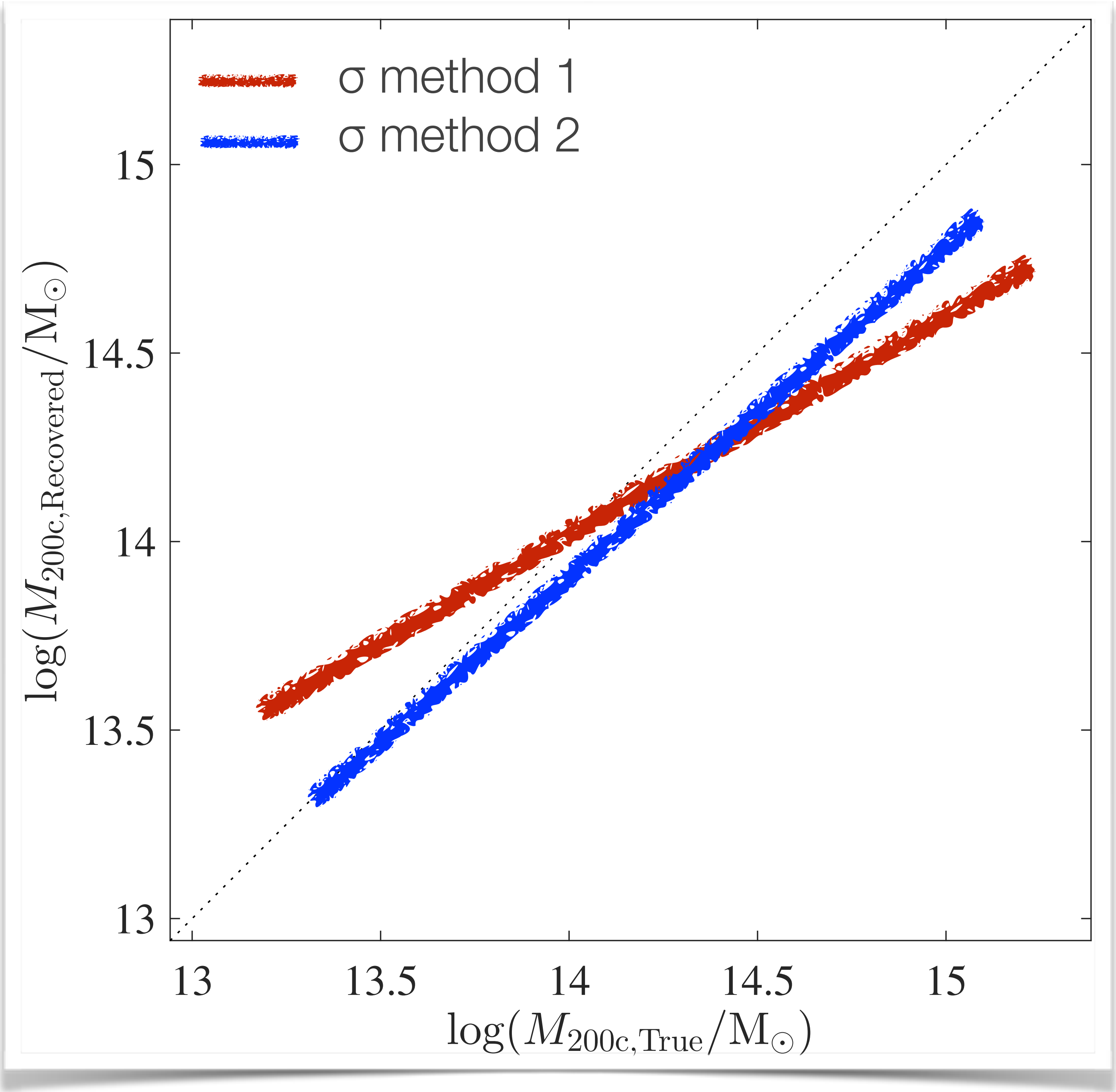


# The Galaxy Cluster Mass Reconstruction Project

The first homogenous, blind study of galaxy-based mass estimation techniques

# The Galaxy Cluster Mass Reconstruction Project

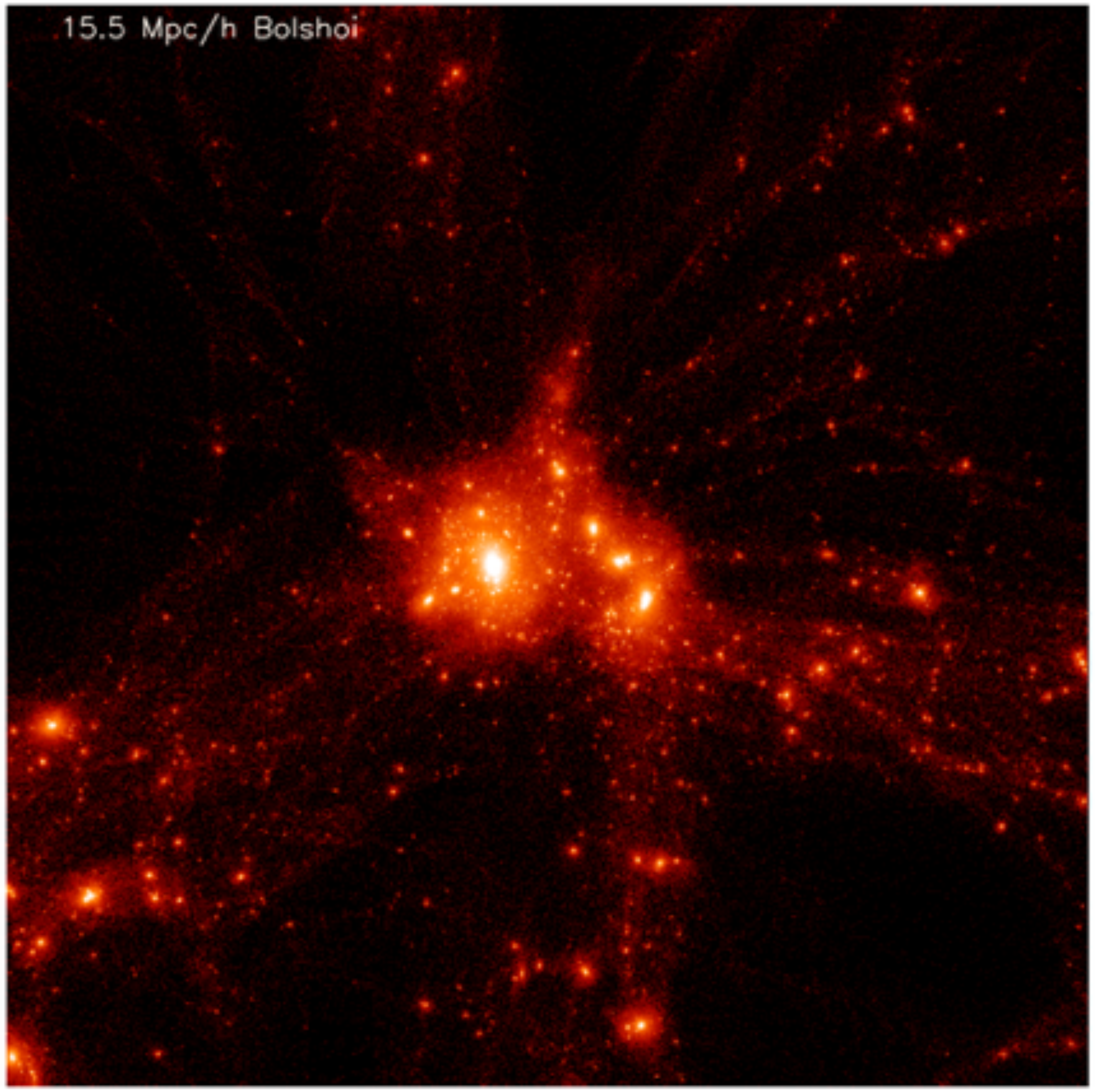
The first systematic, homogenous study of galaxy-based mass estimation techniques

↓

- Primary aim: how much scatter in log $M_{200c}$ do we expect?
- Which method is best for given data-set?
- Long-term goal: how can we improve these methods?

# The Galaxy Cluster Mass Reconstruction Project

DM only



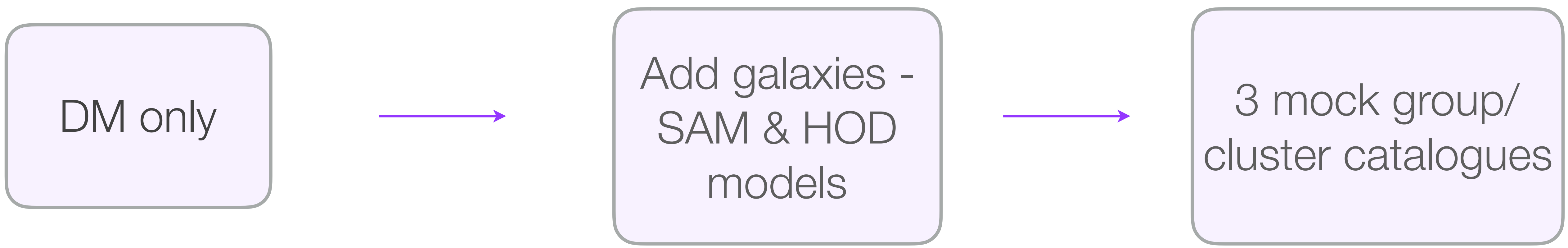

Millennium Simulation (Springel et al., 2005), Bolshoi (Klypin et al., 2011)

# The Galaxy Cluster Mass Reconstruction Project

DM only → Add galaxies - SAM & HOD models

SAM - Darren Croton
HOD - Ramin Skibba

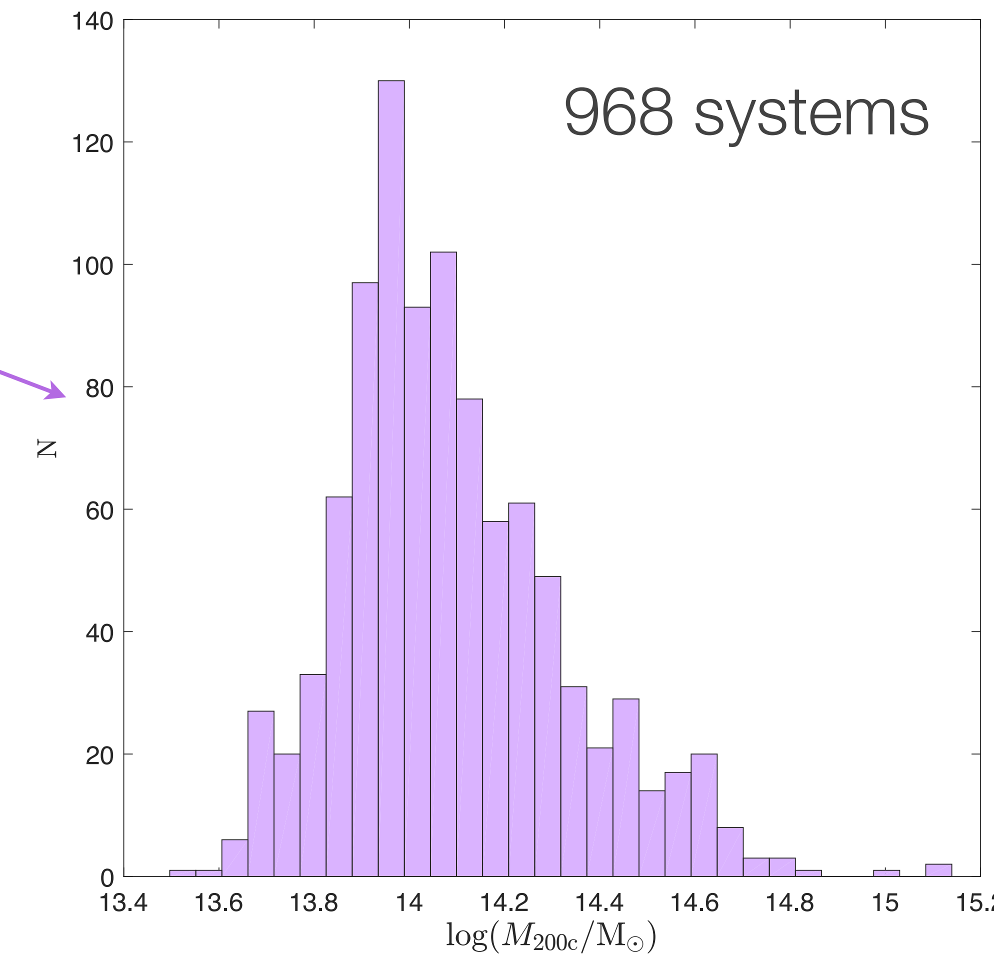
# The Galaxy Cluster Mass Reconstruction Project



# The Galaxy Cluster Mass Reconstruction Project

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

391 systems with log $M_{200c} \leq 14$ $M_{solar}$



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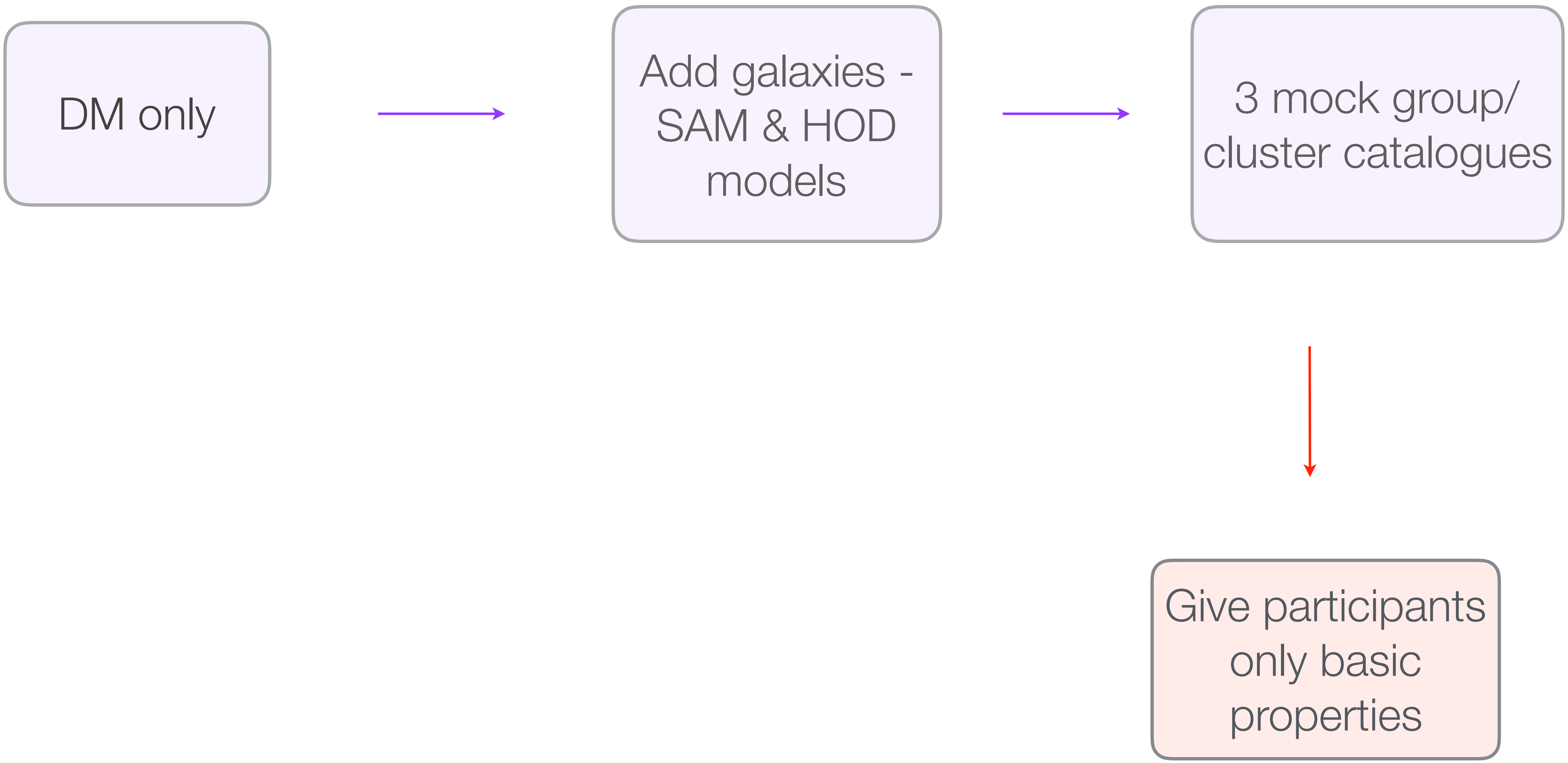

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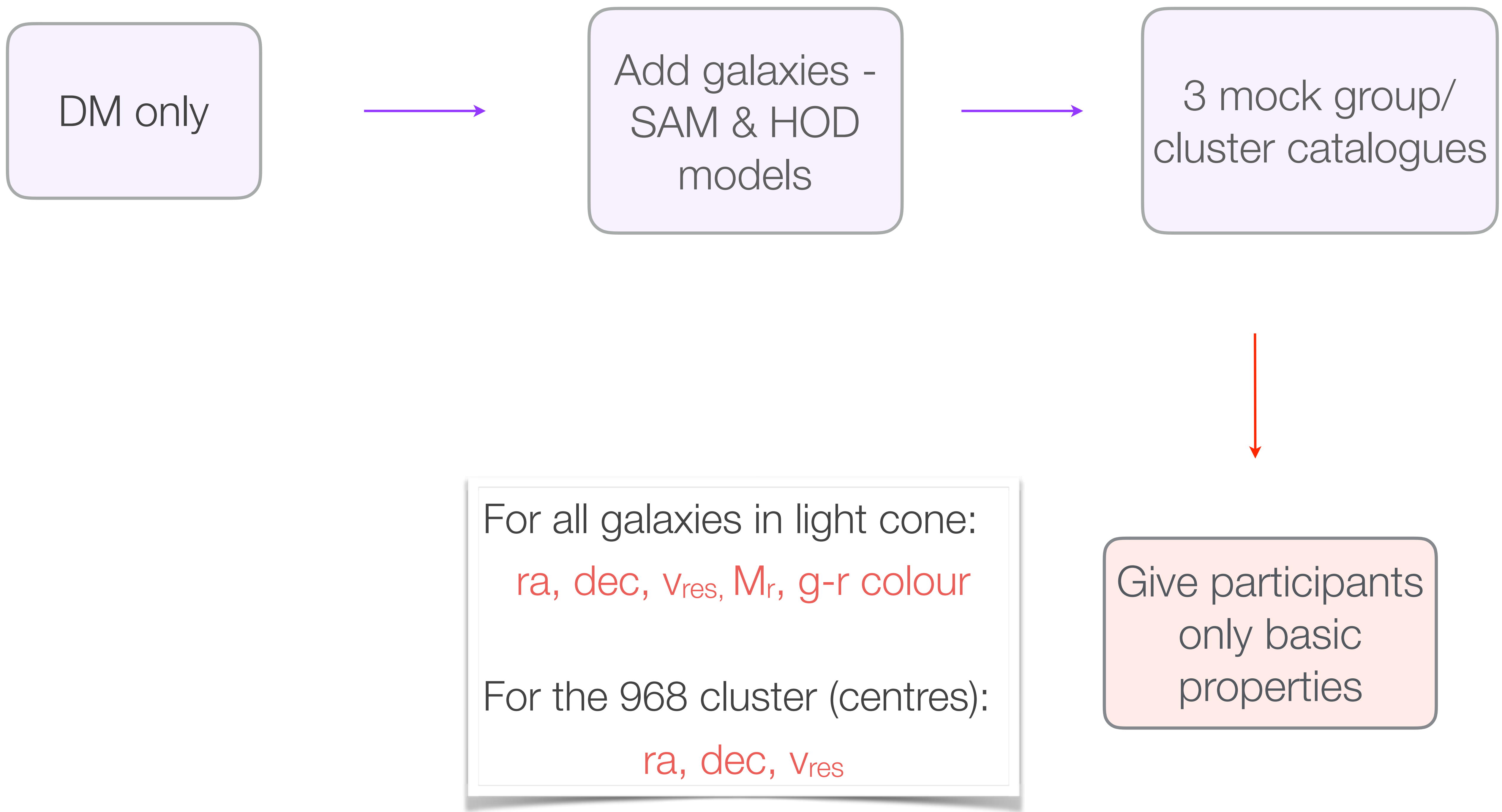


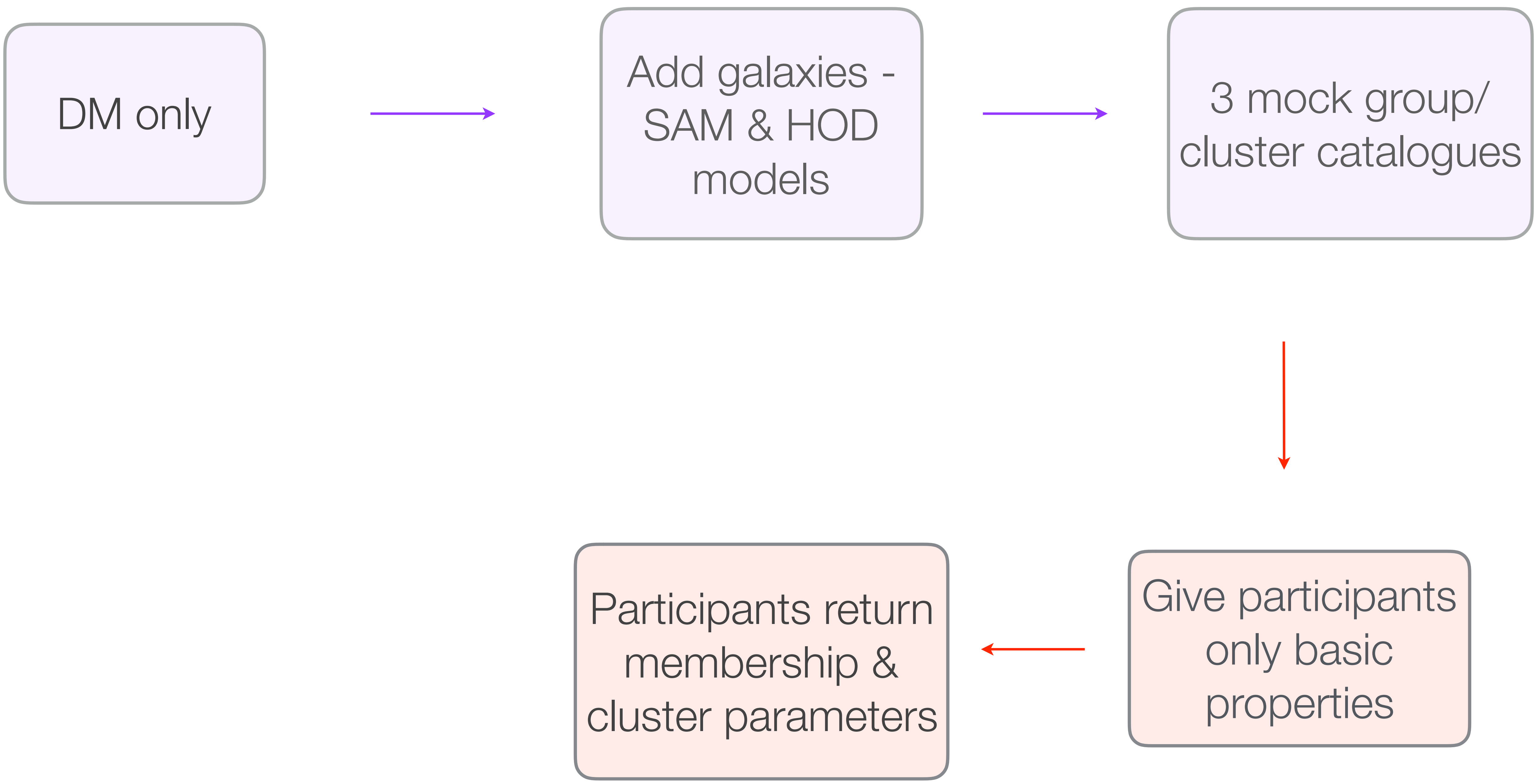
# The Galaxy Cluster Mass Reconstruction Project

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

→ Give participants only basic properties


Workshop @ Univ. of Nottingham

# The Galaxy Cluster Mass Reconstruction Project



# The Galaxy Cluster Mass Reconstruction Project

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

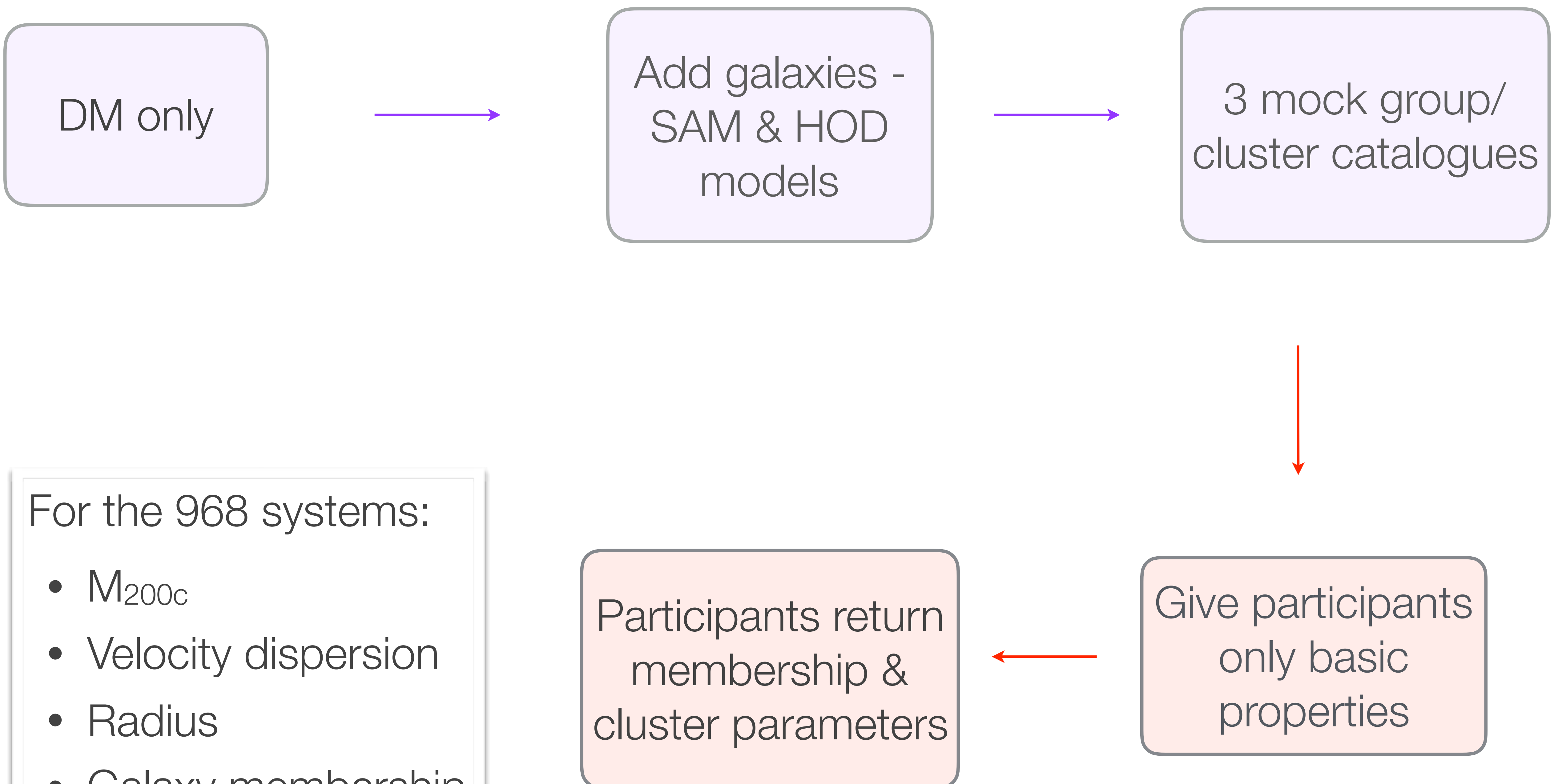
↓

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

For the 968 systems:

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

# The Galaxy Cluster Mass Reconstruction Project

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- $M_{200c}$
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# Galaxy-based mass estimation techniques

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| Method | Initial galaxy selection | Mass estimation | Type of data required | Reference |
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| PCN | Phase space | Richness | Spectroscopy | Pearson et al. (in preparation) |
| PFN* | FOF | Richness | Spectroscopy | Pearson et al. (in preparation) |
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| RM1 | Red sequence | Richness | Multiband photometry, sample of central spectra | Rykoff et al. (2014) |
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# Galaxy-based mass estimation techniques

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

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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

## Step 2

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Number of galaxies above a given luminosity threshold

Positions & velocities of galaxies

RMS radius/ DM profile fitted to obtain radius.

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

$M \propto \sigma^3$

# Statistics I'll refer to a lot…

RMS: root-mean-square difference between the recovered and true log mass

Overall uncertainty i.e., inc. bias, normalization

$\sigma_{MRec}$: scatter about the recovered log mass

Intrinsic scatter i.e., exc. bias, normalization

# Results!

# HOD2 catalogue

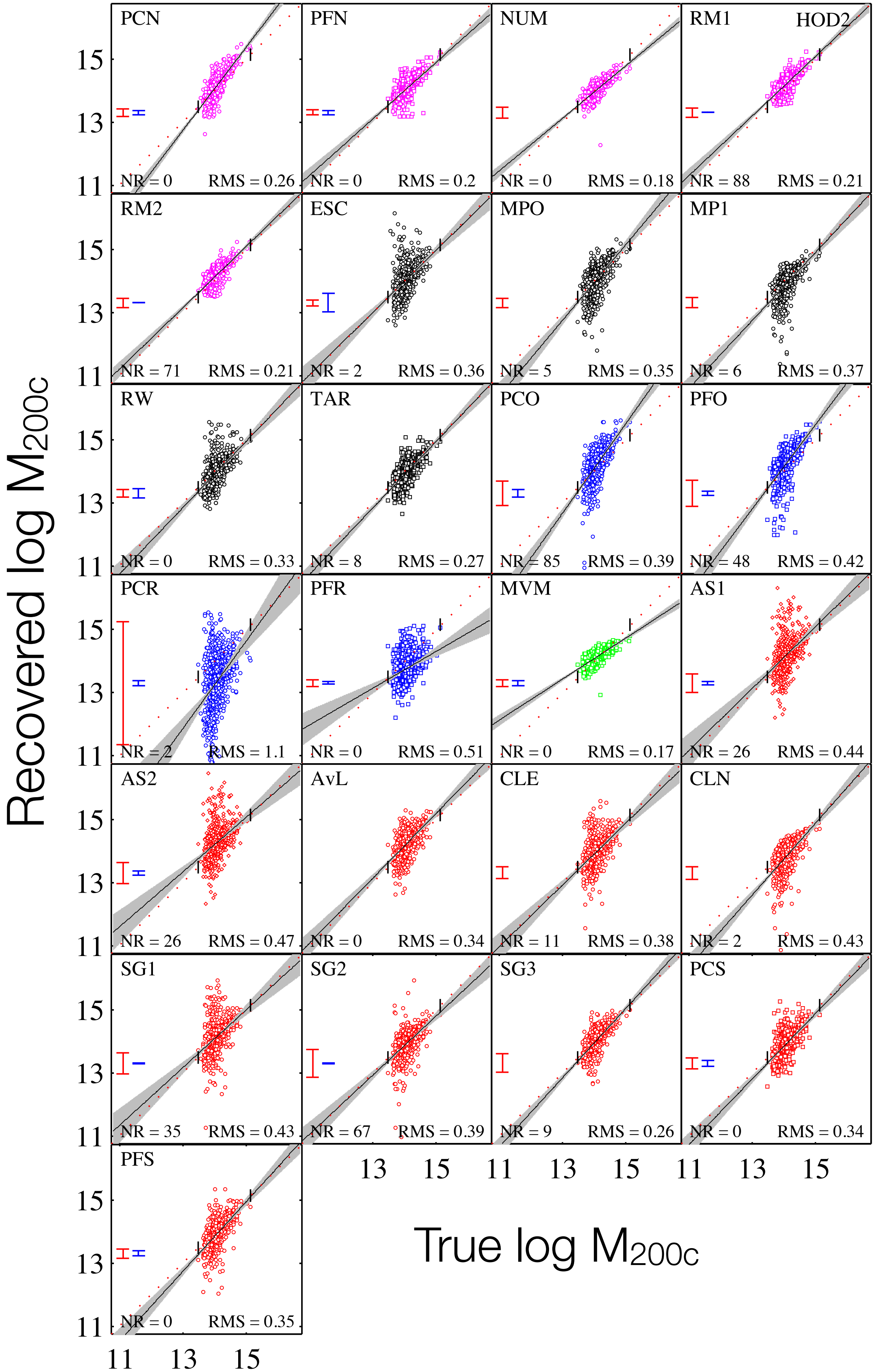
Richness

Phase space

Radial

Abundance matching

Velocity dispersion




Old et al., 2015

Richness

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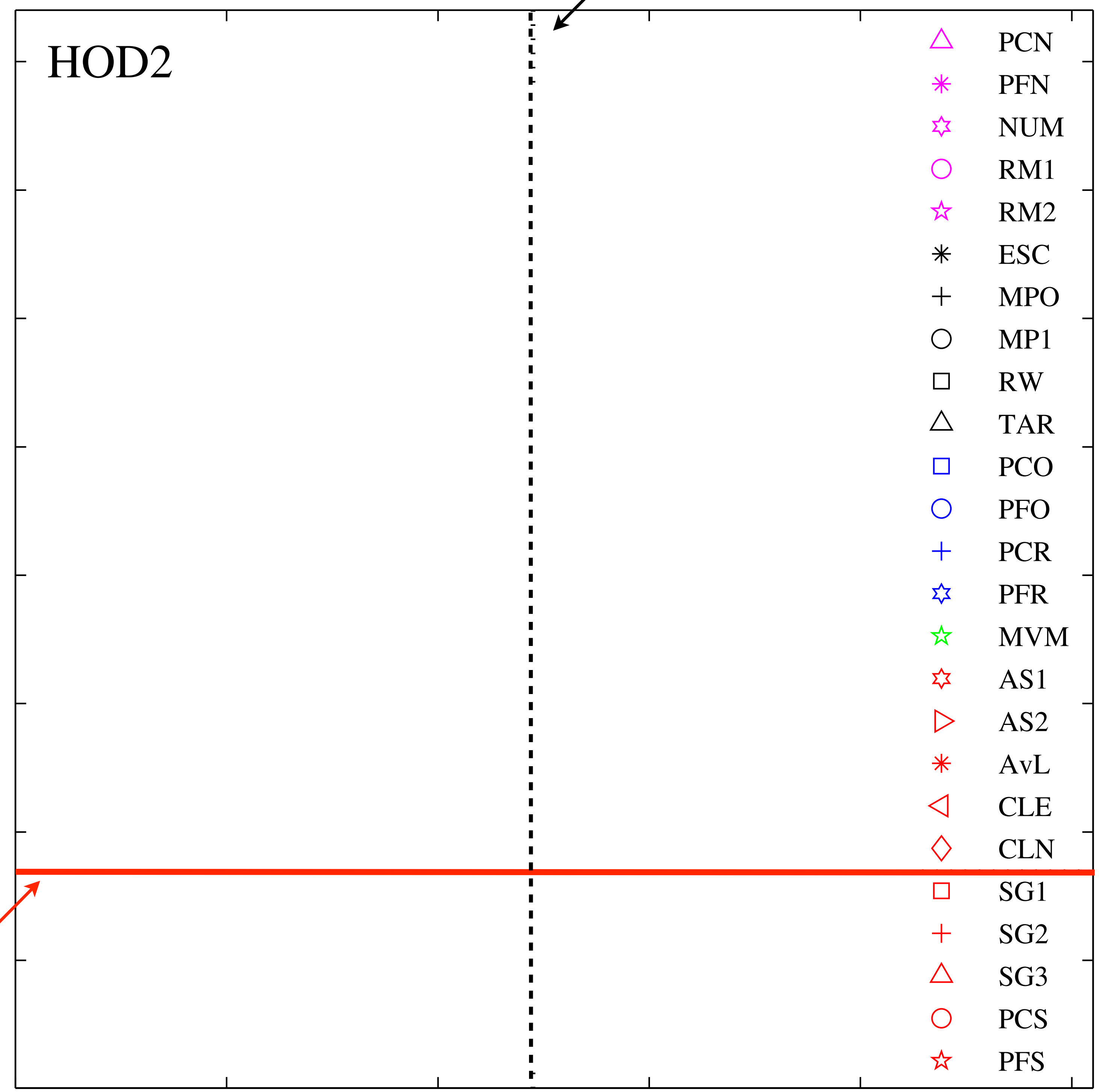
Mean true log $M_{200c}$




RMS (dex)

Mean Recovered log $M_{200c}$

Assuming uniform $M_{200c}$!

Note: PCR lies beyond the axes of this figure with RMS = 1.08, log M200c = 13.37.

Mean true log $M_{200c}$

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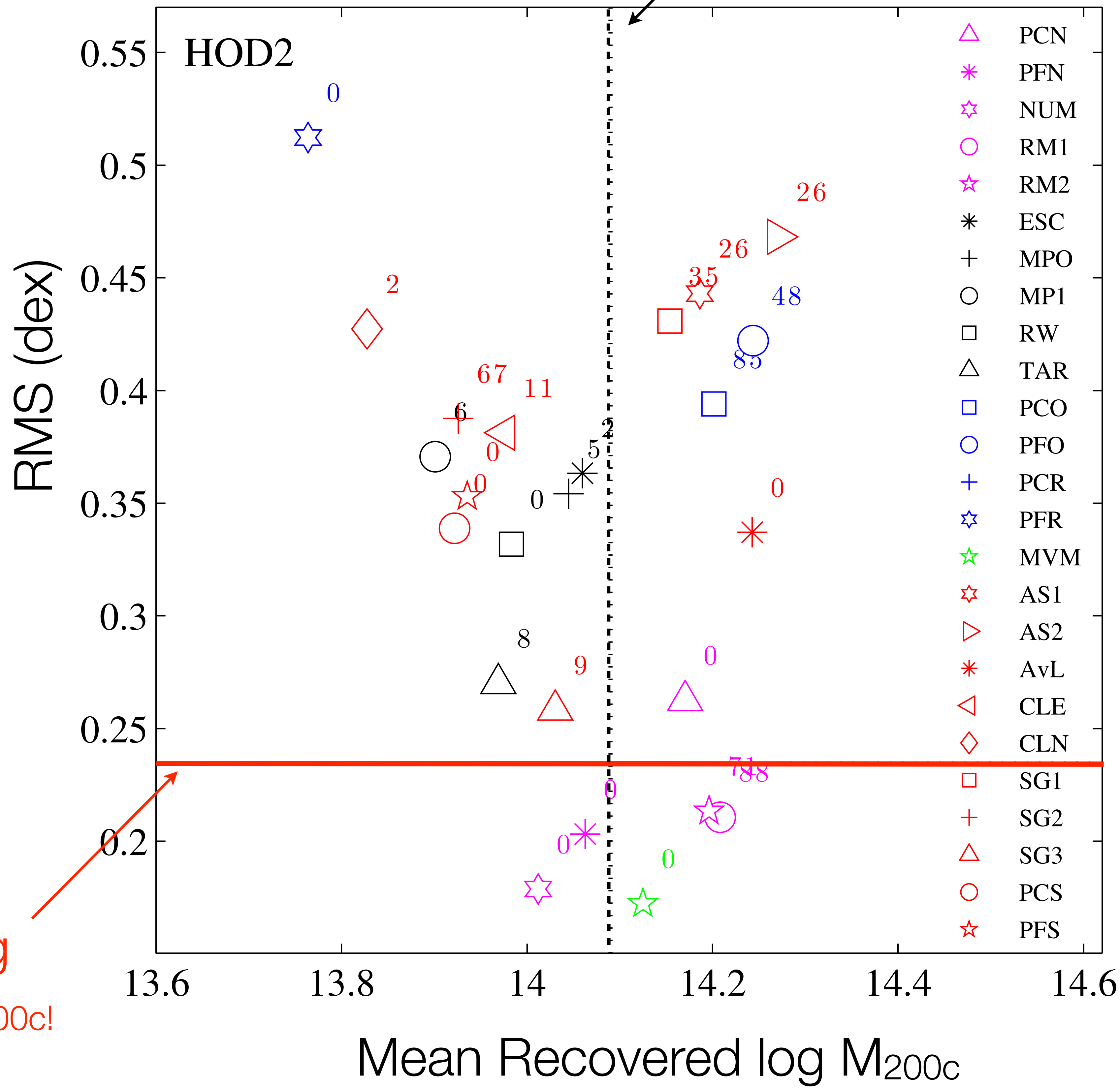


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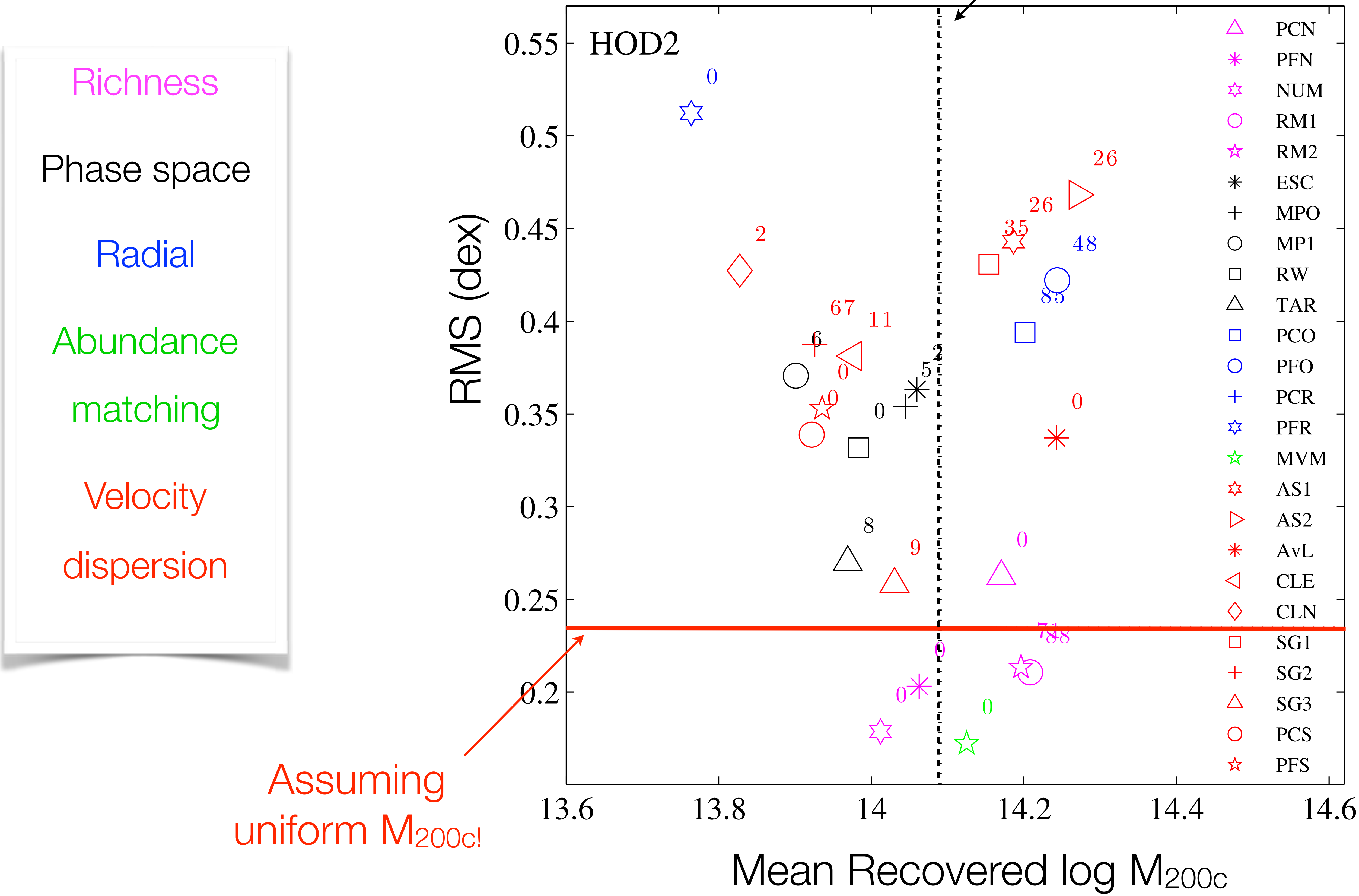


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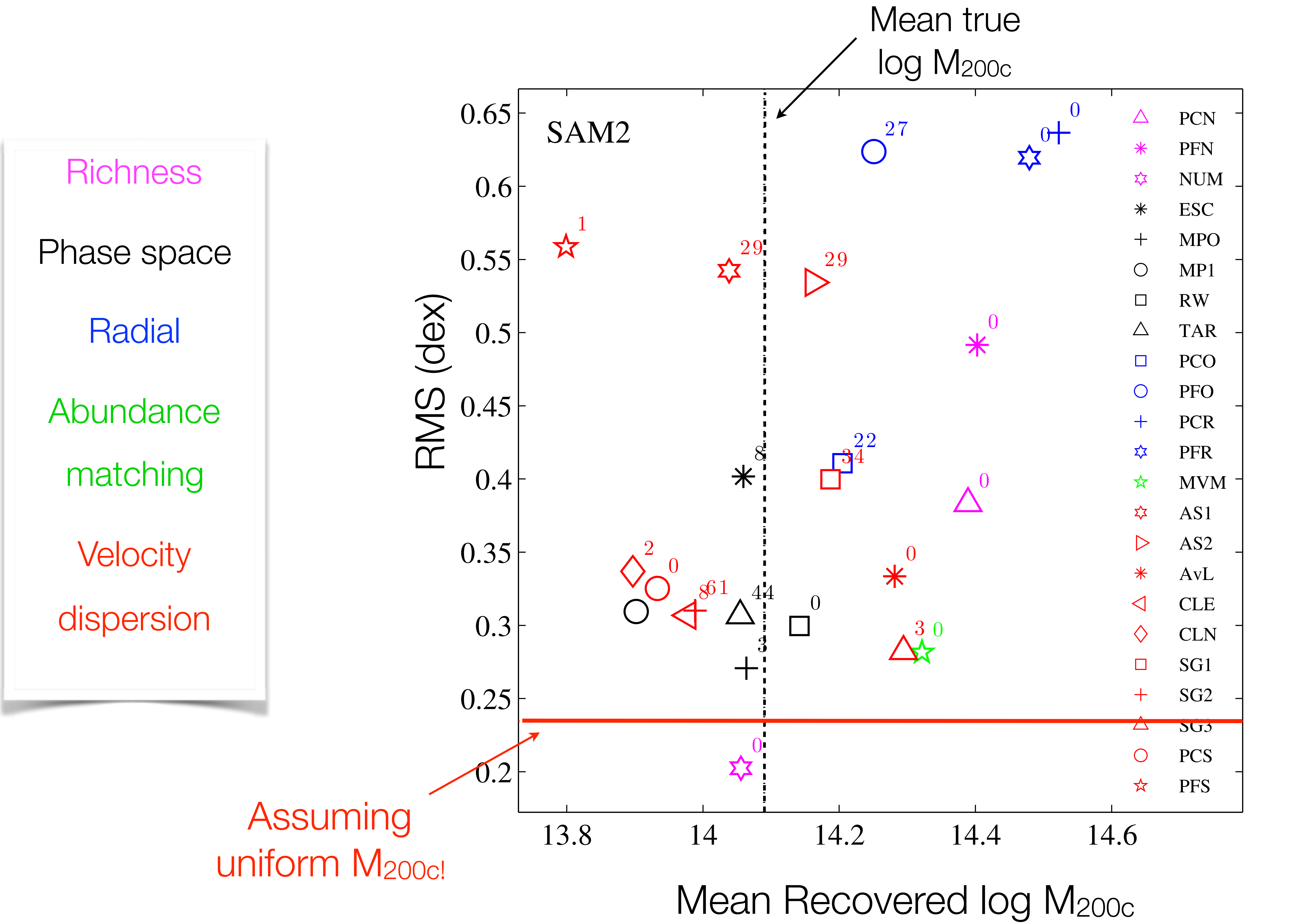

Richness
Phase space
Radial
Abundance
matching
Velocity
dispersion
Mean true
log M200c
SAM2
RMS (dex)
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Assuming
uniform M200c!
PCN
PFN
NUM
ESC
MPO
MP1
RW
TAR
PCO
PFO
PCR
PFR
MVM
AS1
AS2
AvL
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CLN
SG1
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SG3
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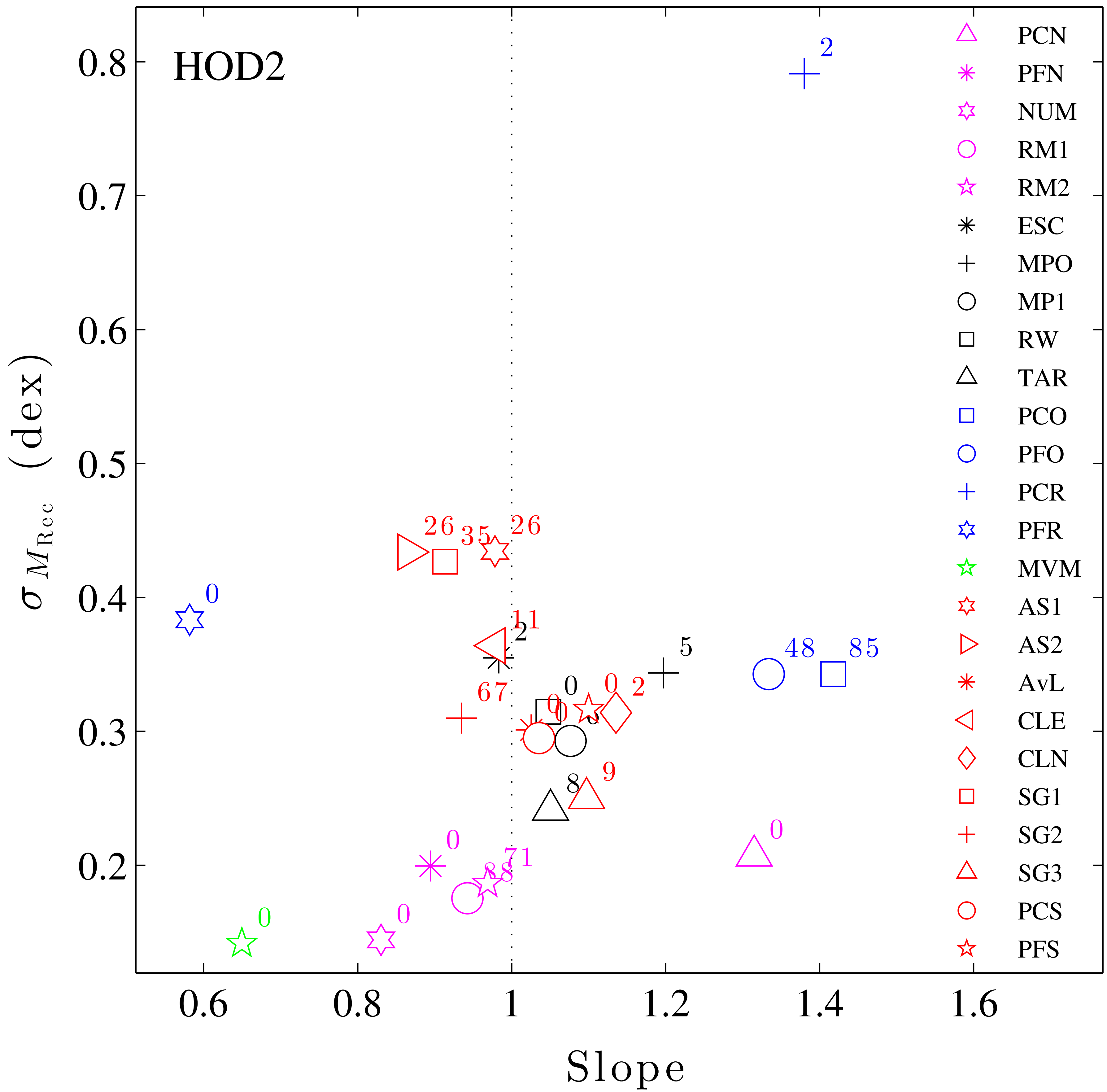

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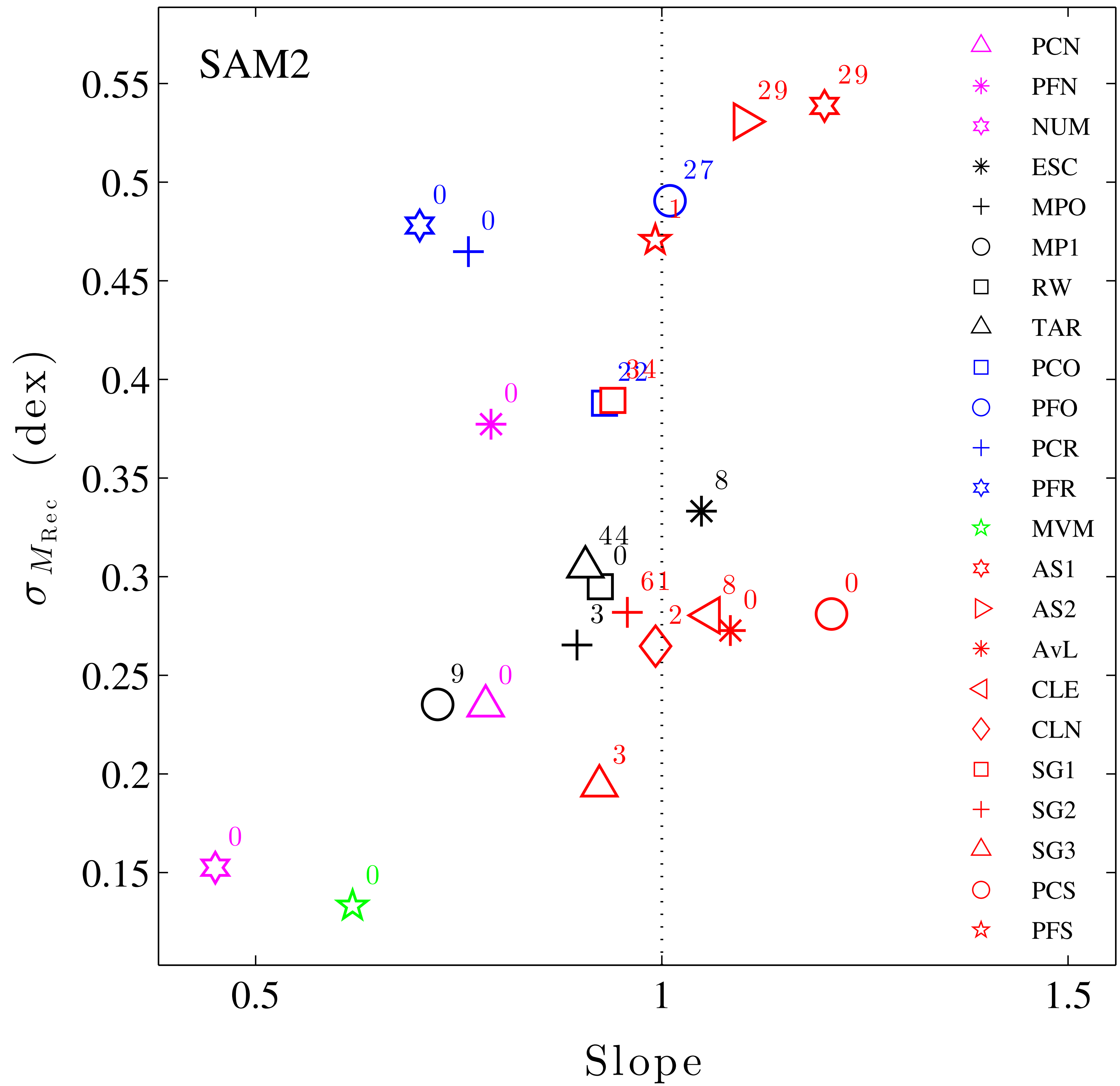

# HOD2 catalogue

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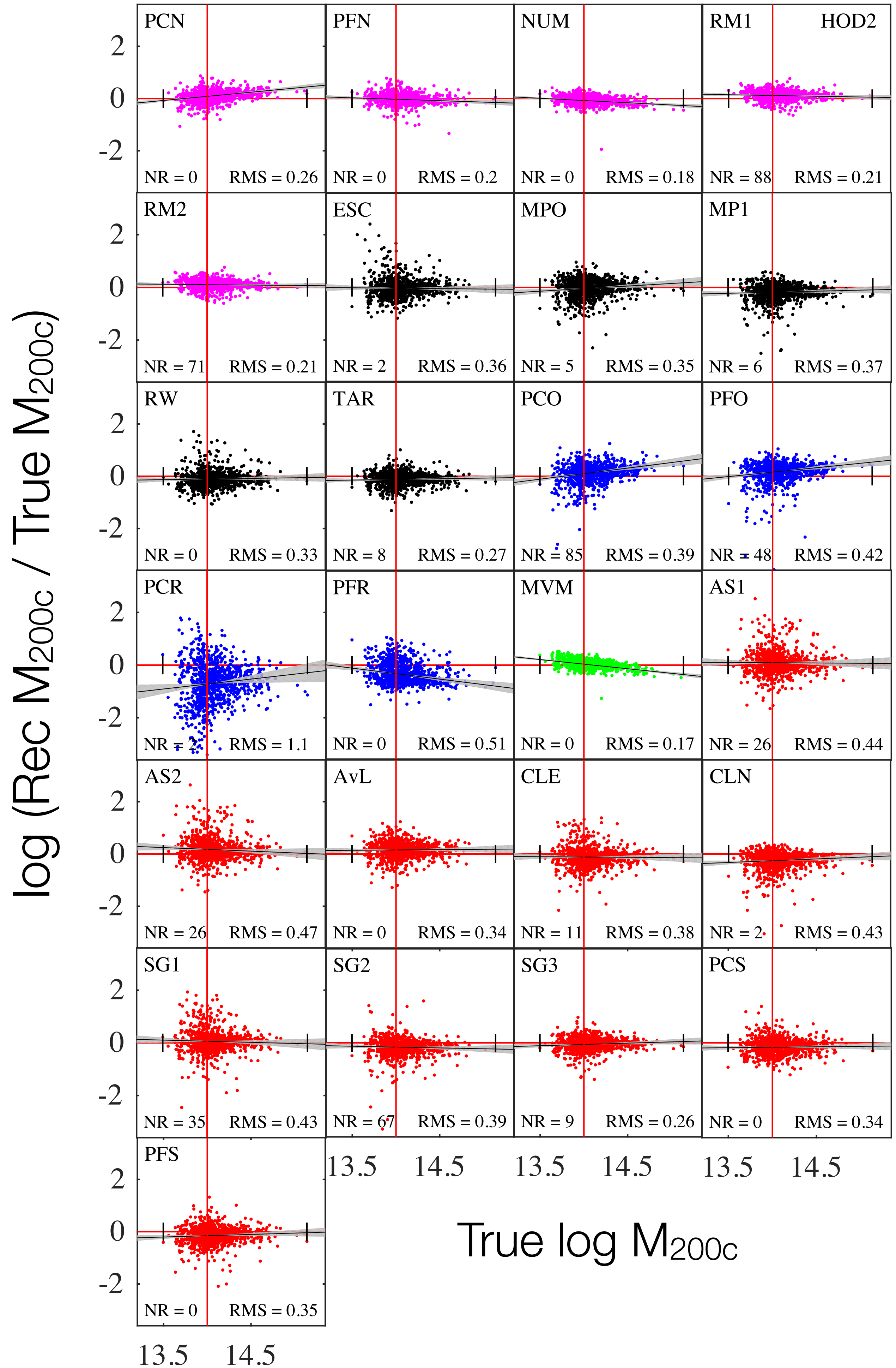


Higher scatter in $M_{200c}$ for less massive objects

# SAM2 catalogue

Richness

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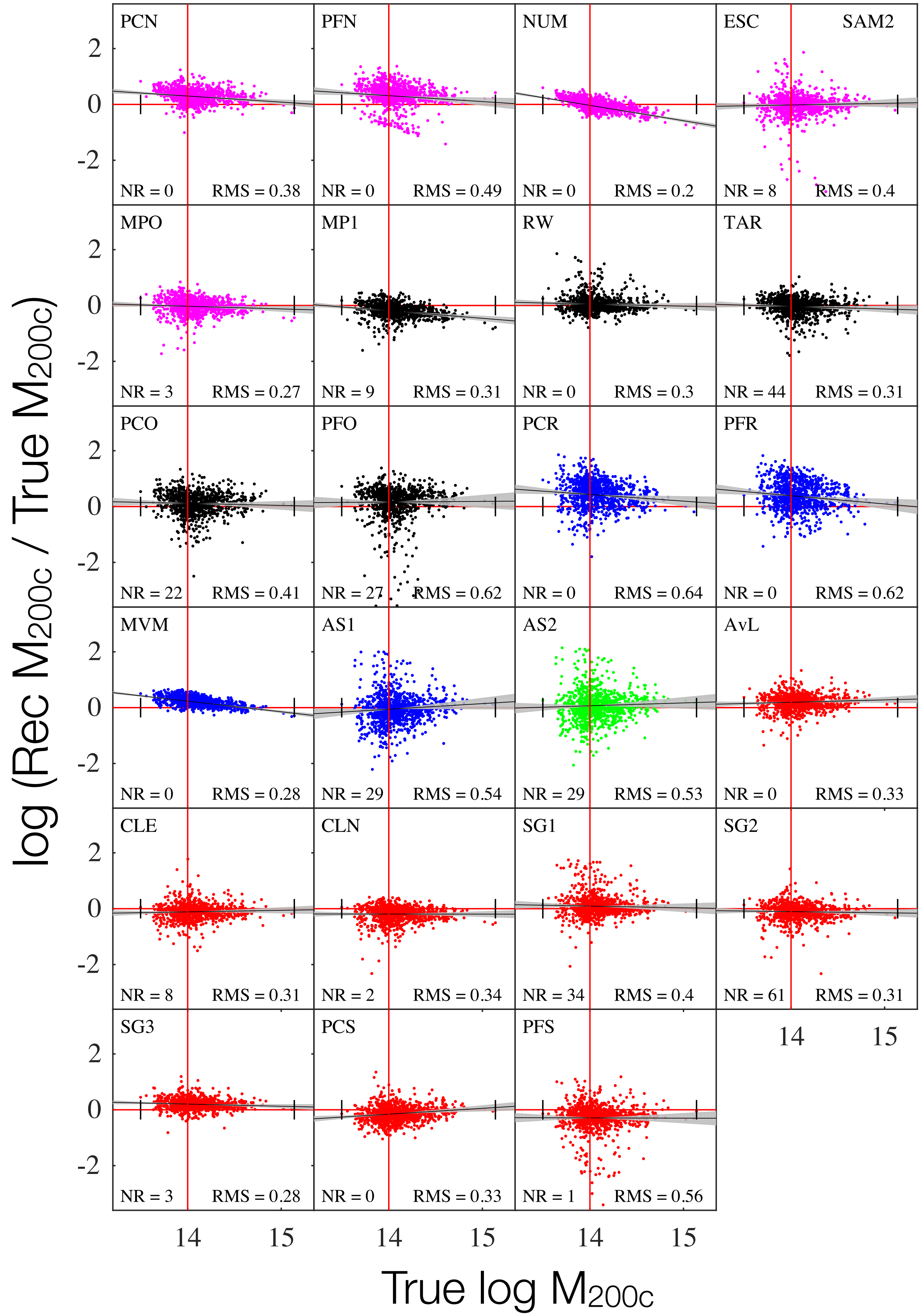
Radial

Abundance matching

Velocity dispersion

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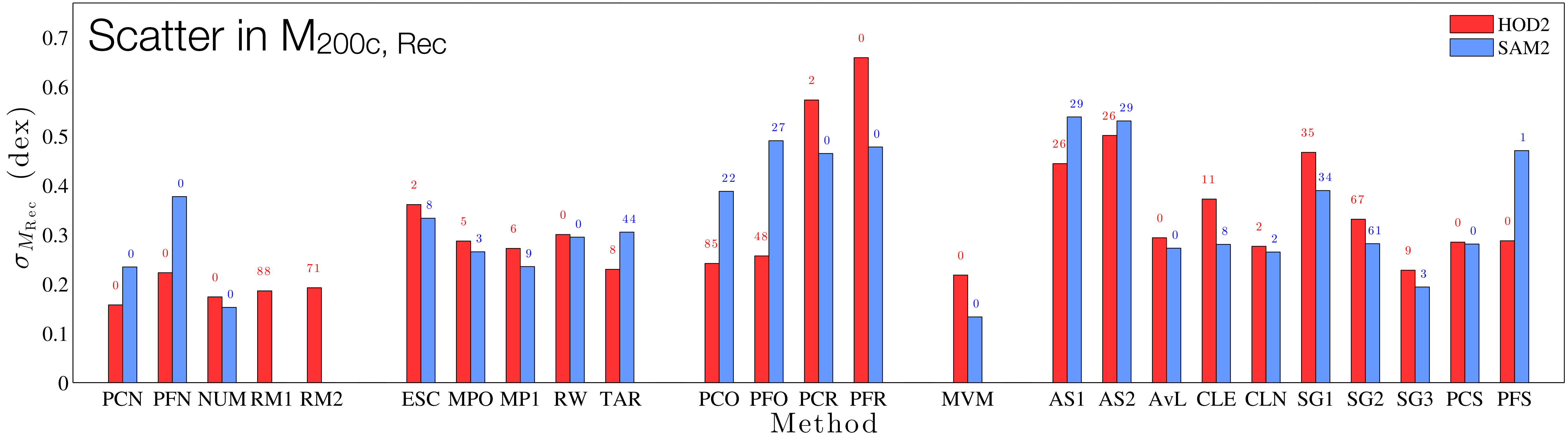
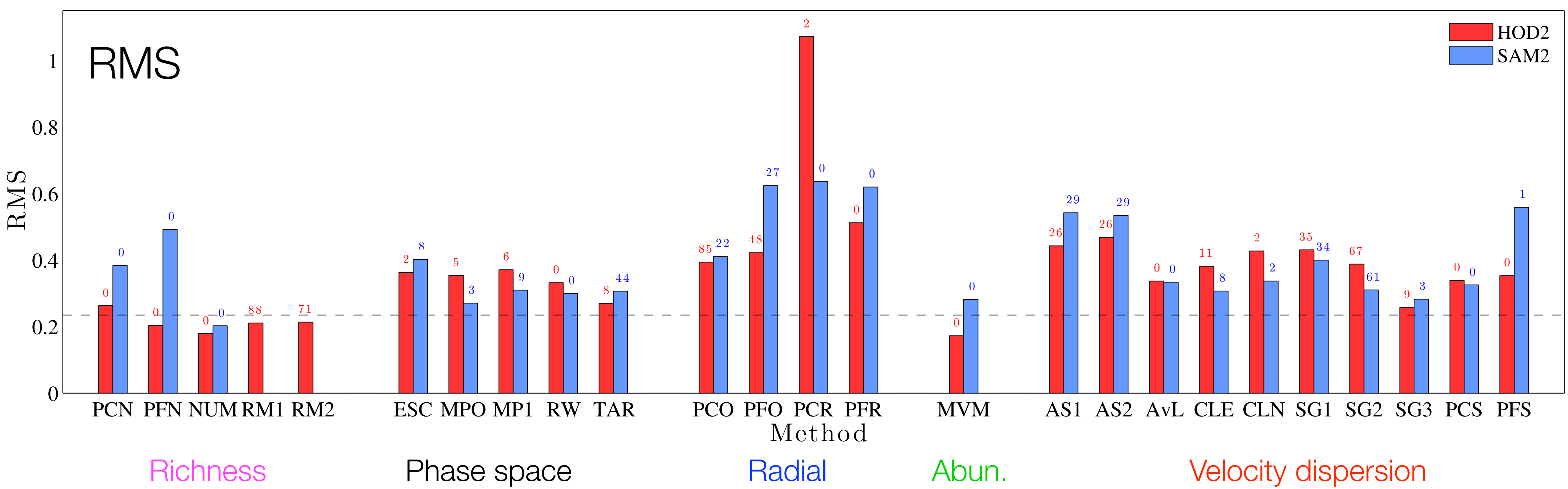
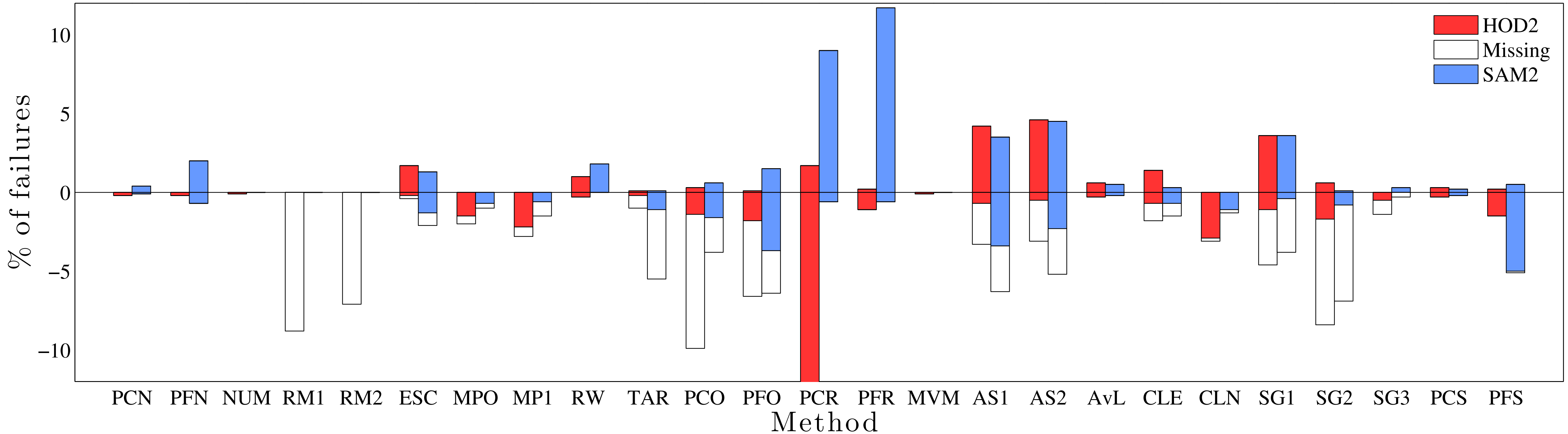



HOD & SAM catalogues producing, on average, qualitatively similar level of scatter & bias



# Catastrophic failures

Fraction of clusters whose mass is wrong by > a factor of 10




Richness Phase space Radial Abun. Velocity dispersion

Outliers over-predicting mass will be detrimental due to steeply falling high mass end of cluster mass function

# Other GCMRP projects in progress…

- Dynamical substructure & mass estimation
  (Old et. al, in prep.)

- Mass bias due to contamination & incompleteness
  (Wojtak et. al, in prep.)

# Dynamical substructure & mass estimation

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

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# Dynamical substructure & mass estimation

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Q. Do we really need to exclude heavily substructured clusters from our cluster (cosmology) samples?

Q. Are mass proxies strongly affected (i.e., increased scatter or biased) by significant substructure?

Strong effect: Geller & Beers 1982, Girardi et al. 1997, Smith et al. 2005, Hou et al., 2012.

Little effect: Biviano et al. 1993, Fadda et al. 1996, Wing & Blanton 2012, Sifon et al., 2013.

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# Observational detection: Dressler-Shectman test

Quantifies difference between local ‘subgroups’ and global cluster properties

$\delta_{\rm i}^2 = (\frac{N_{\rm nn}+1}{\sigma_{\rm c}})[(\overline{\nu}_{\rm local} - \overline{\nu}_{\rm global})^2 + (\sigma_{\rm global} - \overline{\nu}_{\rm c})^2]$ , where $N_{\rm nn} = \sqrt{n_{\rm members}}$

Correction made to original test (Pinkney et al. 1996; Hou et al. 2012)

The DS statistic $\Delta = \sum_i \delta_i$ Dressler & Shectman 1988

The significance of the presence of ‘significant substructure’ is quantified by Monte Carlo ‘shuffling’ of the velocities.

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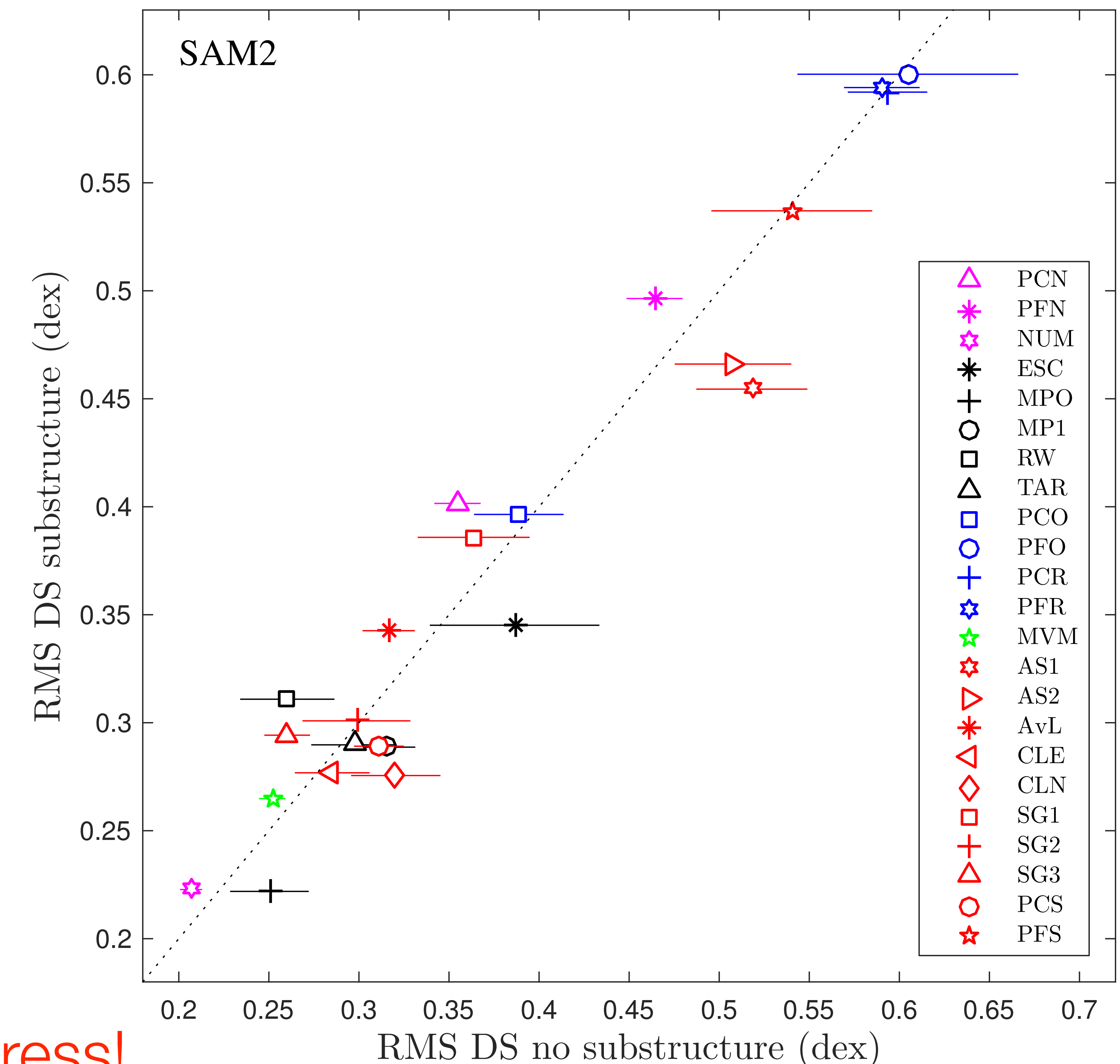
Correction made to original test (Pinkney et al. 1996; Hou et al. 2012)

The DS statistic $\Delta = \sum_i \delta_i$ Dressler & Shectman 1988

The significance of the presence of ‘significant substructure’ is quantified by Monte Carlo ‘shuffling’ of the velocities.

DS test is most reliable obs. substructure indicator according to Pinkney et al., 1996, Hou et. al 2012, however, viewing-angle dependent etc. (White et. al 2010, Cohn et. al 2012).

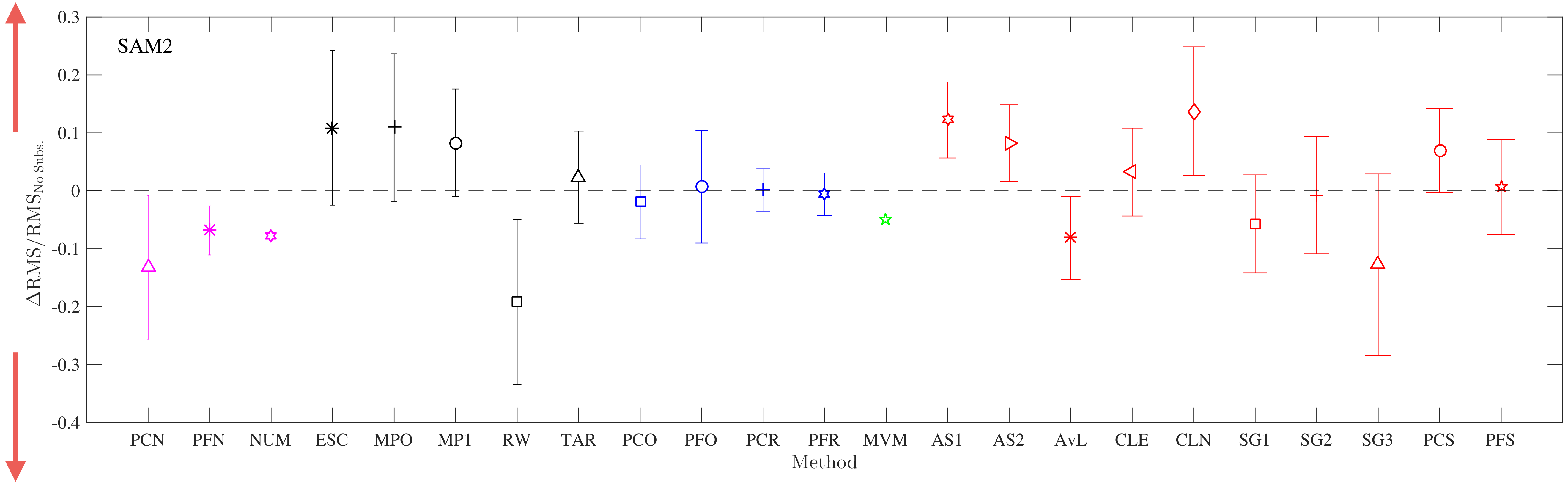
# Significant dynamical substructure & overall uncertainty in mass




Work in Progress!

# Significant dynamical substructure & overall uncertainty in mass

Increase




Richness　Phase space　Radial　Abun.　Velocity dispersion

Decrease

Work in Progress!

# Measuring galaxy cluster masses using galaxies

## Take home points

- Scatter in $M_{200c}$ for majority of galaxy-based mass estimation techniques is high, factor of ~2-12.
- Scatter is generally higher for groups than 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.

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## Future work

- Does significant substructure increase scatter/bias in mass estimation? (Old et al., in prep.)
- Contamination/incompleteness of methods (Wojtak et al., in prep)
- Mass recovery at:
  - high-z
  - different phases of cluster evolution (pre-mergers, mergers)
  - multi-wavelength (X-ray, SZ)?