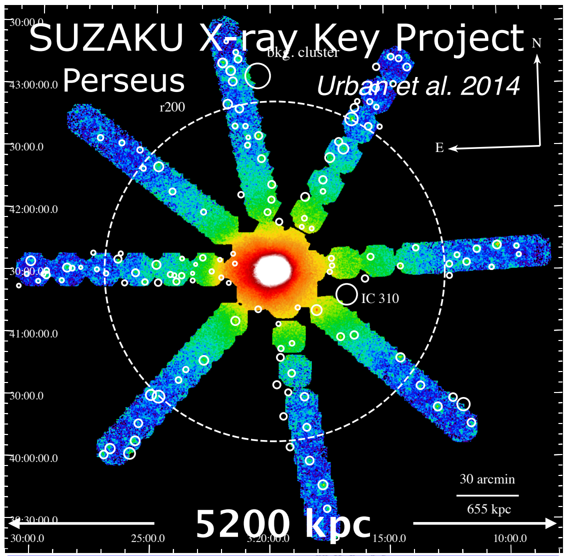
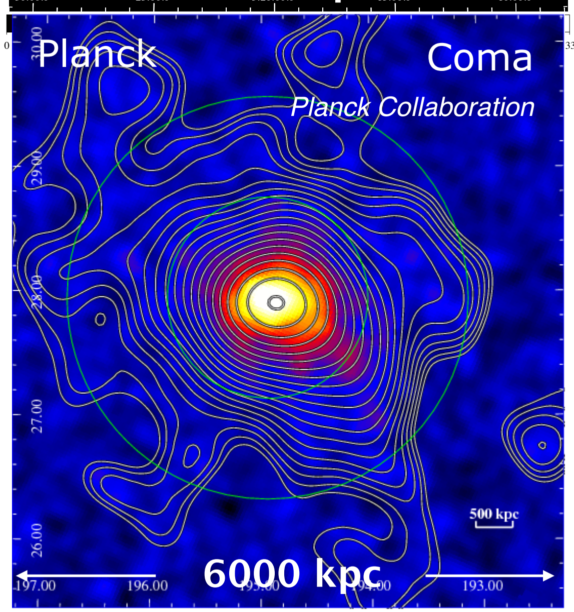
# *Galaxy Clusters Outskirts: New Frontier and Crossroads of Cosmology & Astrophysics*




## ✦Cluster Core ($r<0.2R_{500c}$)

Heating, Cooling, & Plasma physics

1. AGN feedback (Mechanical/CR heating)
2. Dynamical Heating, Gas sloshing
3. Thermal Conduction, Magnetic Field, He sedimentation

## ✦Cluster outskirts ($r>R_{500c}$)

Gas Accretion & Non-equilibrium phenomena

1. Gas motions
2. Gas clumping/inhomogeneities
3. Non-equilibrium electrons
4. Filamentary structure

## ✦Intermediate Region ($r\sim R_{500c}$)

Sweat Spot for Cluster Cosmology, but the physics of cluster cores and outskirts affects this region.

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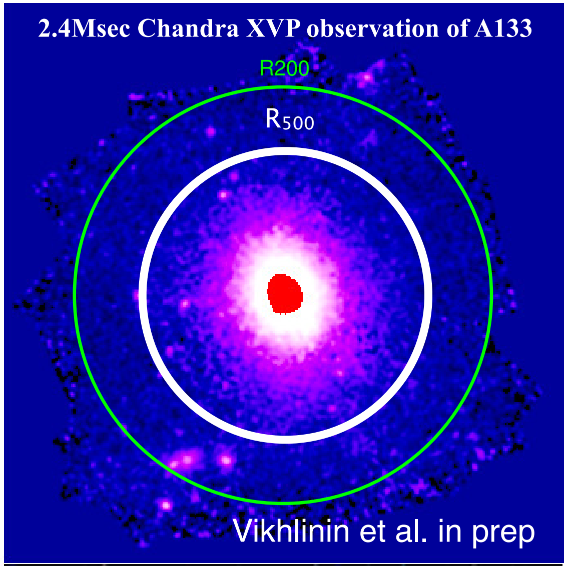


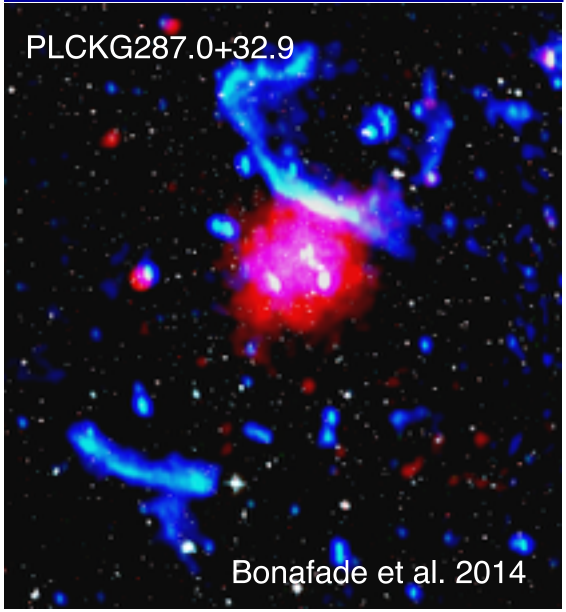


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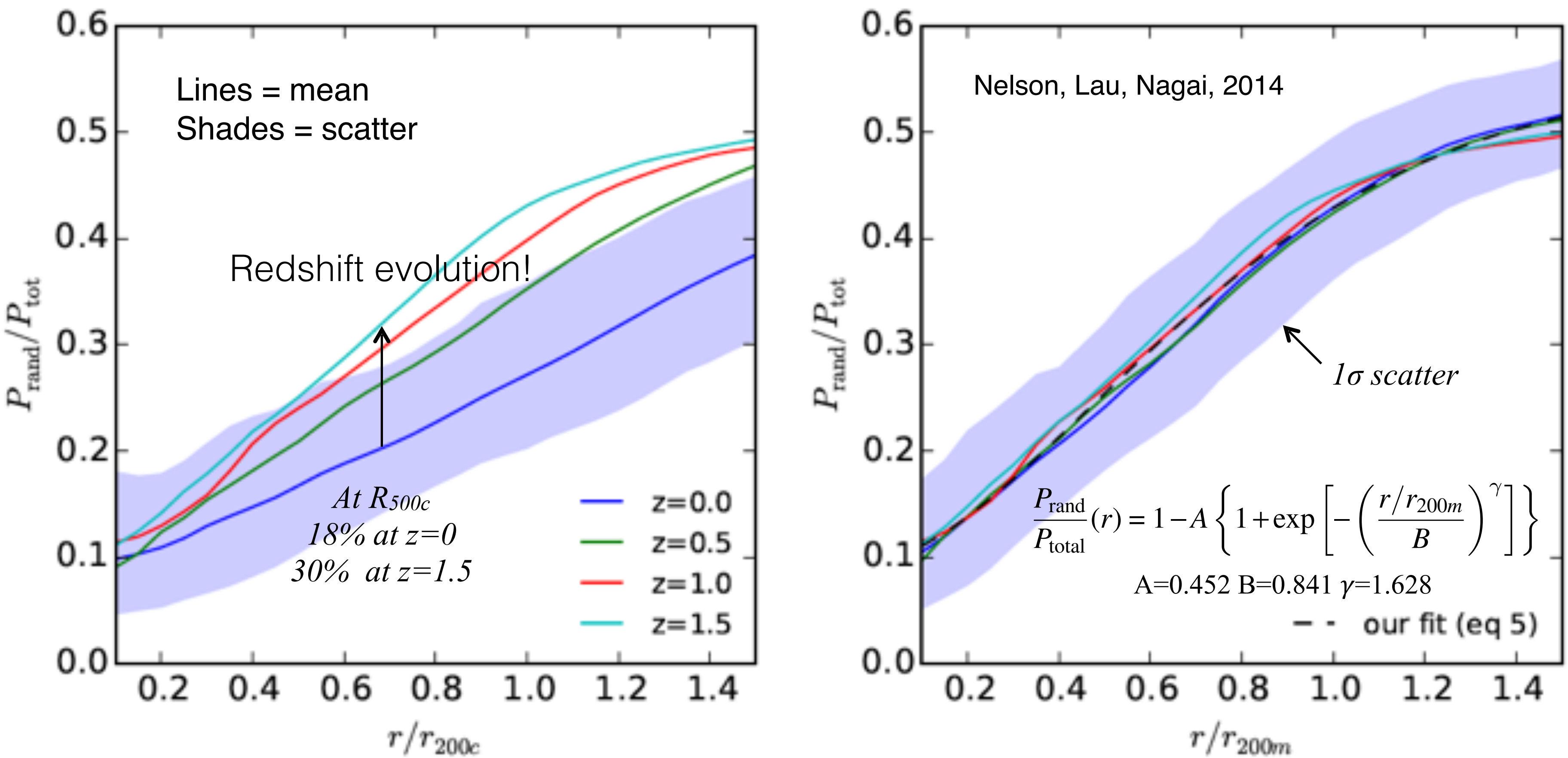
**Big Challenges (idea for the PIRE proposal):**
Understand ICM physics and control systematics in *mass calibration* & *selection function* at a few percent level

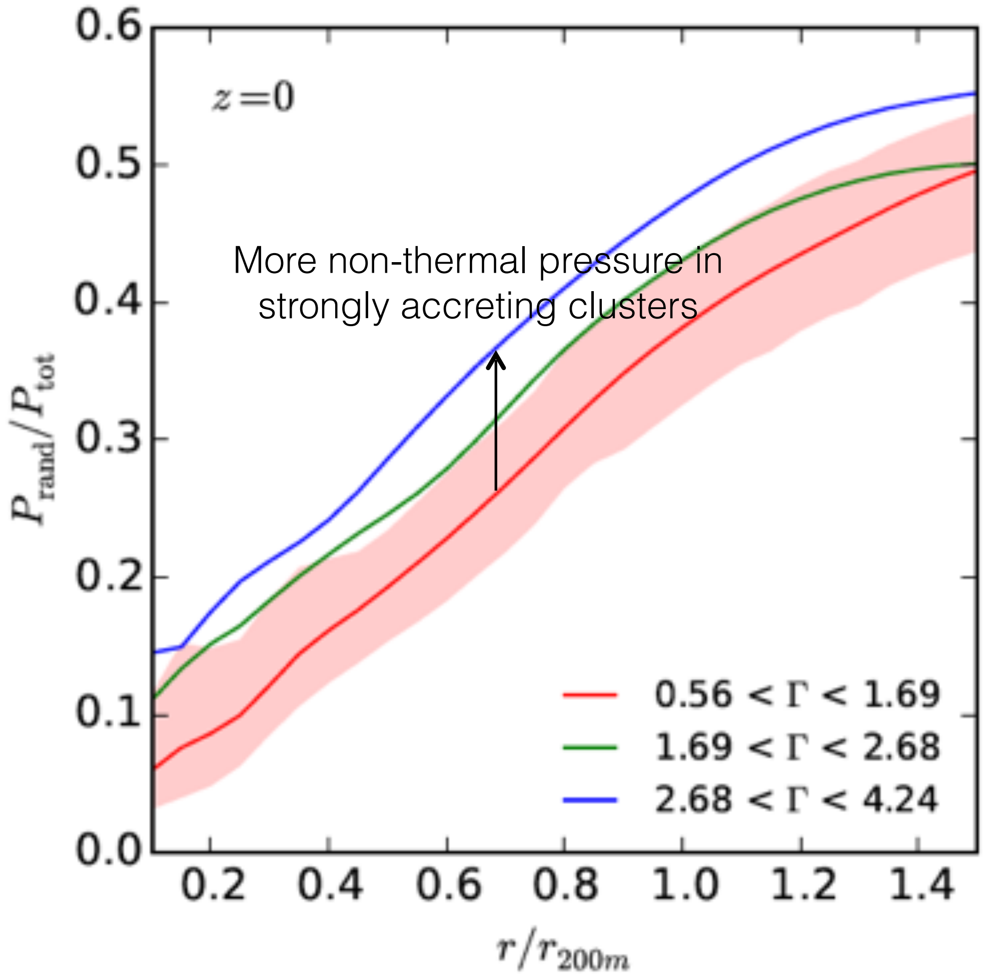
# Non-thermal Pressure Fraction Profiles

65 clusters from the Omega500 simulation




Non-thermal pressure fraction is more *universal* when halos are defined with respect to the *mean* density than the *critical* density.

# Origin of Scatter in the Non-thermal Pressure Profiles



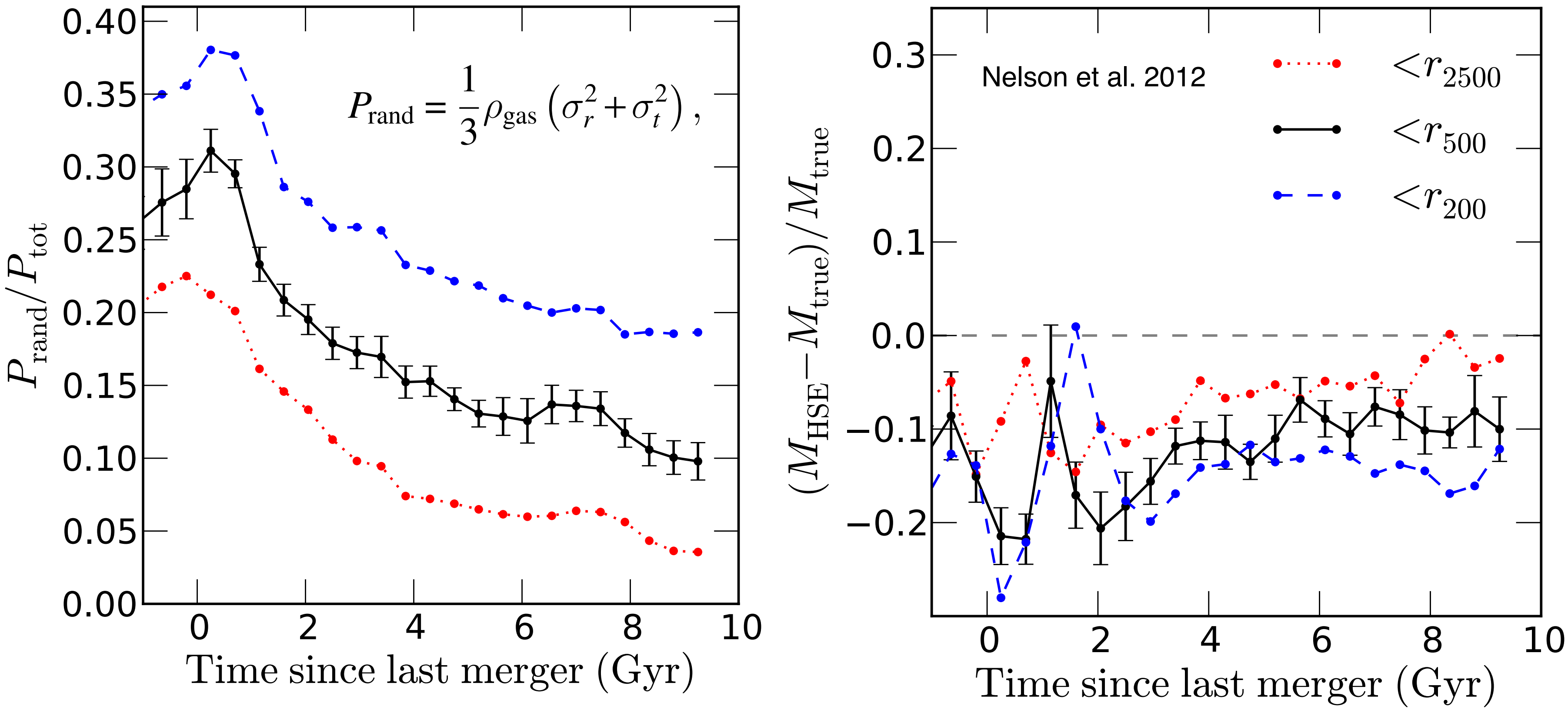

**Mass Accretion Rate**

$$\Gamma_{200m} \equiv \frac{\Delta \log_{10} M_{200m}}{\Delta \log_{10} a}$$

between z=0 and 0.5
(Diemer & Kravtsov 2014)

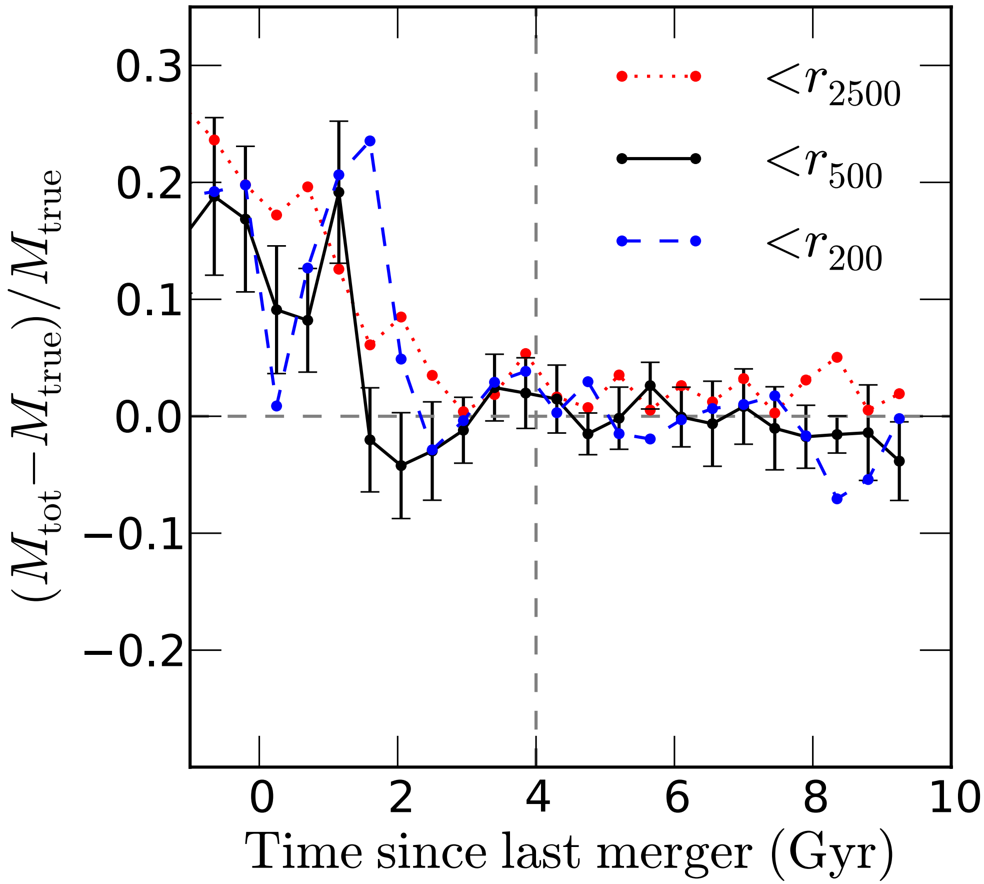
Strong dependence on the mass accretion history of clusters.
Important implications for the HSE mass bias and the Y-M relation.

# Effects of Non-thermal pressure on the HSE mass bias



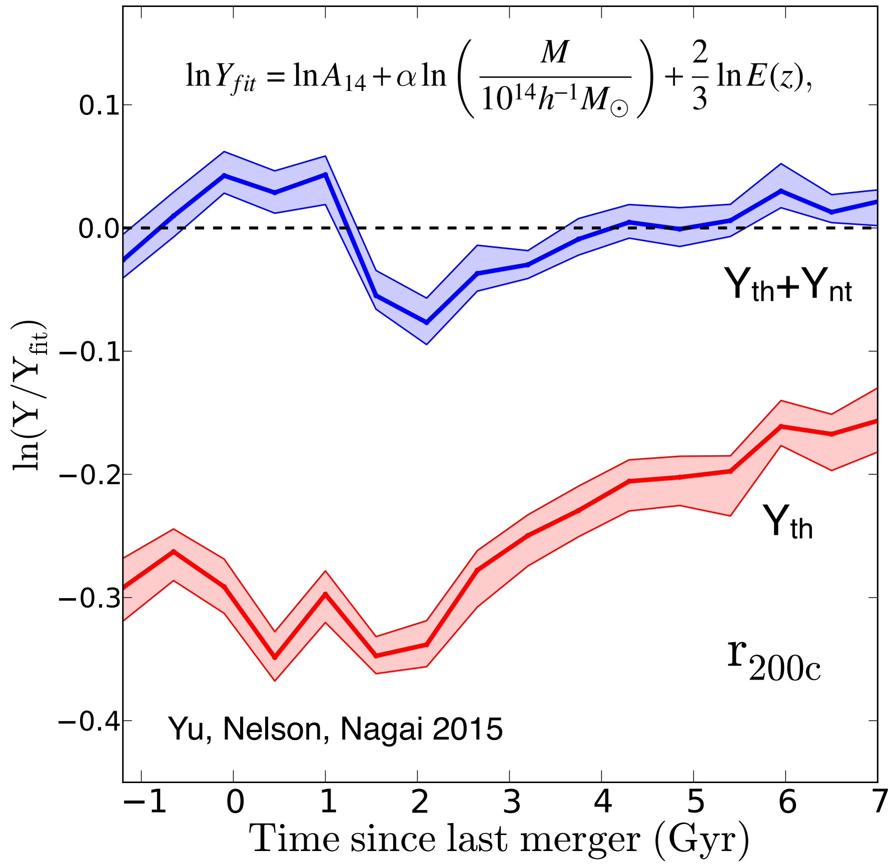

Non-thermal pressure due to random gas motions is one of the most dominant sources of systematic uncertainties in the HSE mass estimates of galaxy clusters.

# Correcting the HSE mass bias



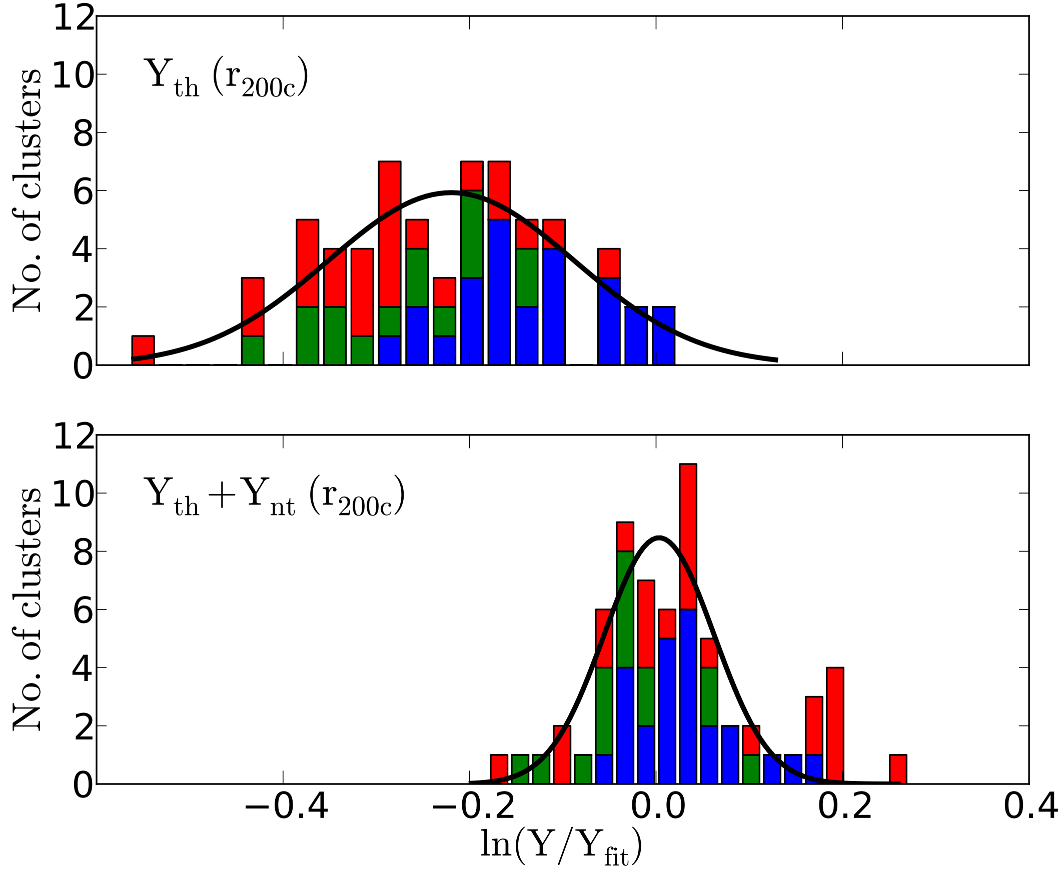

By accounting for non-thermal pressure from random gas motions, it is possible to recover the true mass for clusters with $t_{merge}$>4Gyr.

# *Effects of Non-thermal pressure on the Y-M relation*




Evolution of non-thermal pressure drives deviations of Y-M relation from the self-similar relation

# *Effects of Non-thermal pressure on scatter of the Y-M relation*




$\sigma = 0.123$

$\sigma = 0.085$

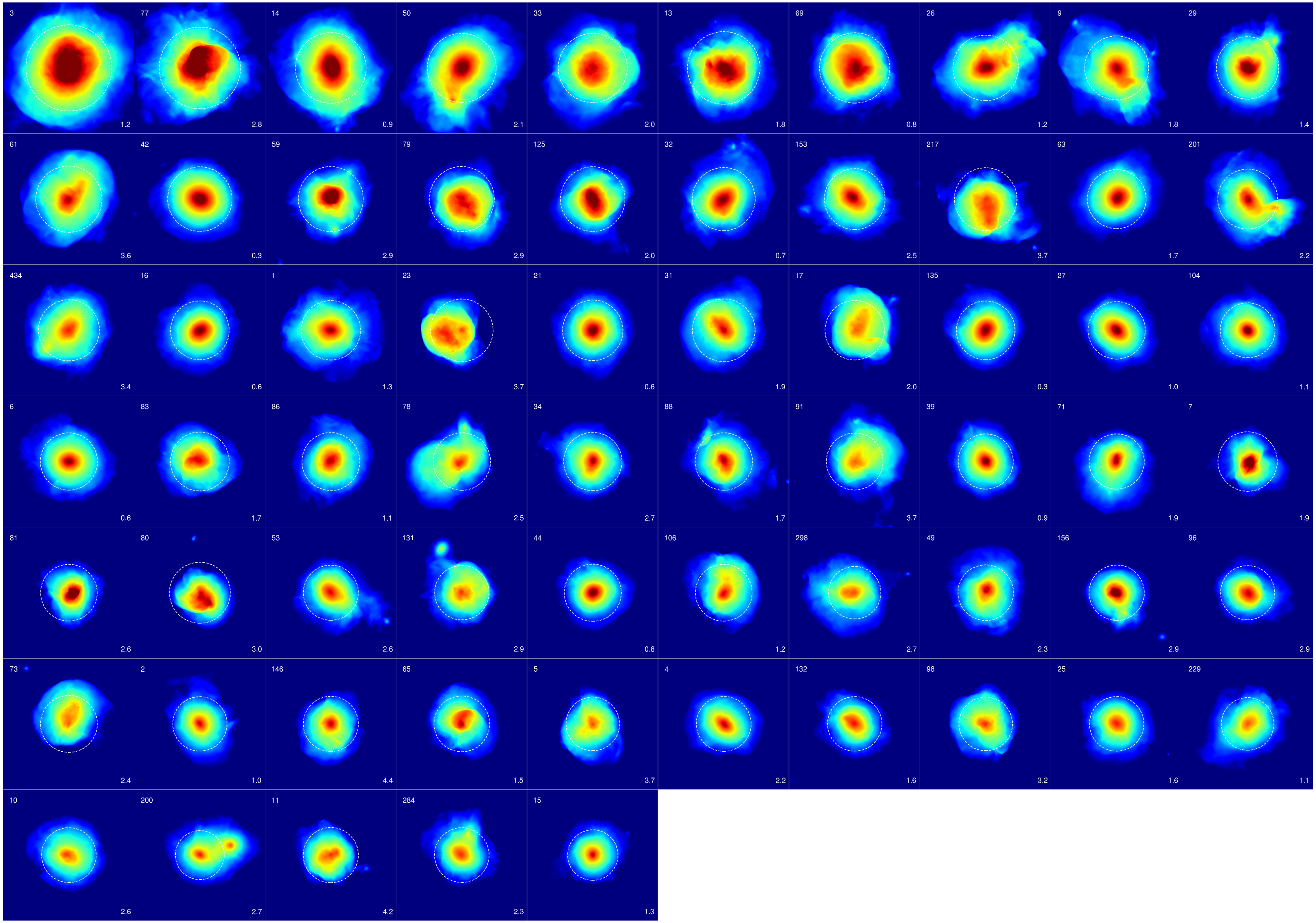
Relaxed Only:

$\sigma = 0.054$

More relaxed clusters lie preferentially above the relation, unrelaxed below.
Including non-thermal pressure removes this dependence.

# Physics of SZ Cluster Selection

Thermal SZ effect images of 65 galaxy clusters from the Omega500 simulation project ordered by Ysz($<3r_{500c}$)



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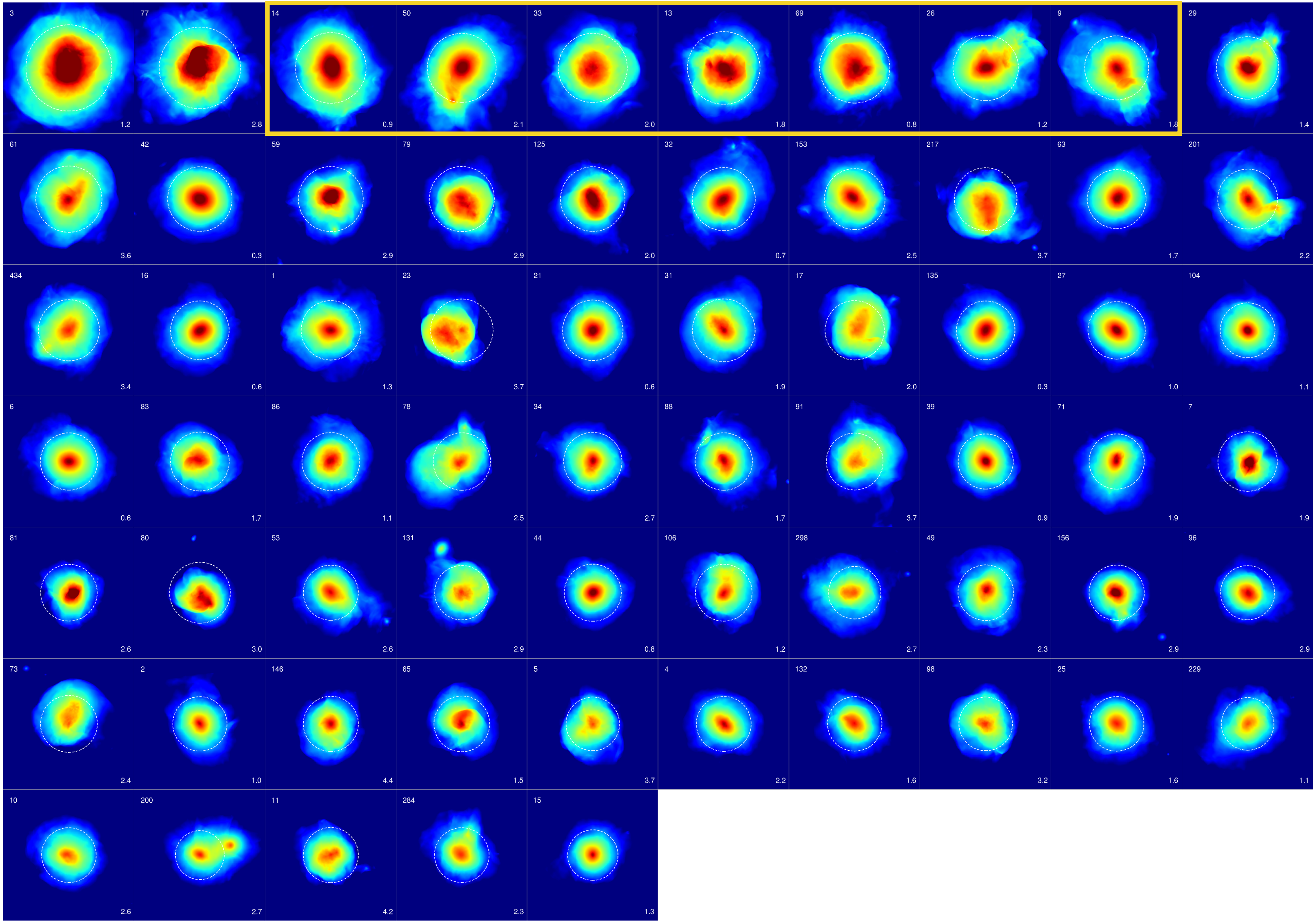
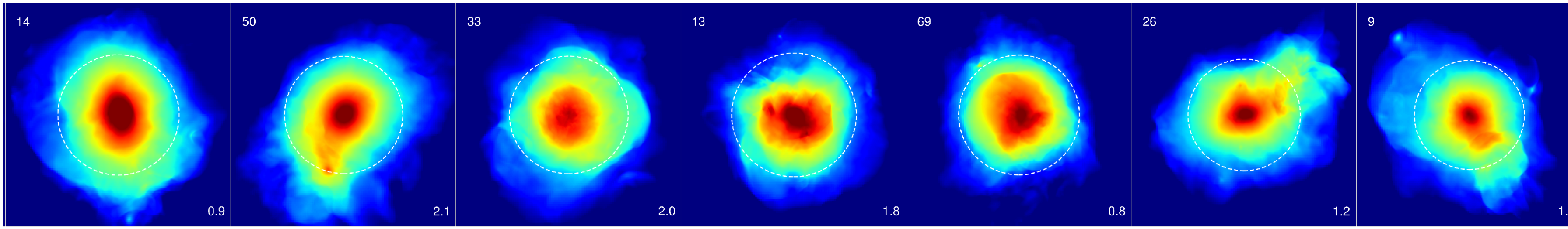
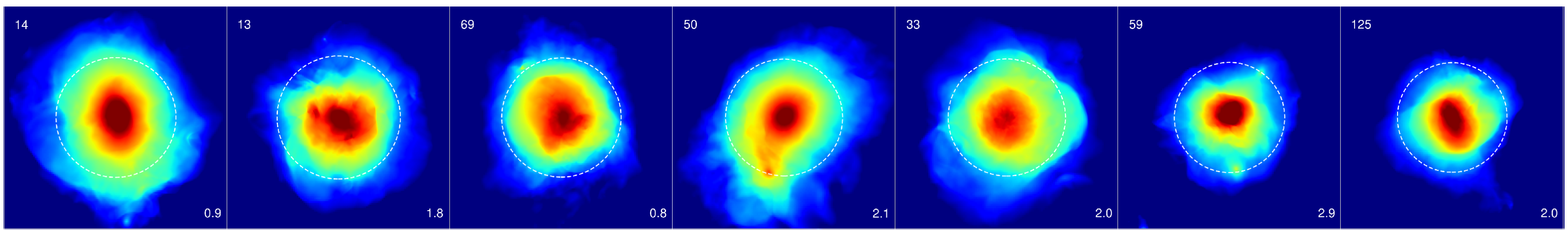


# Physics of SZ Cluster Selection

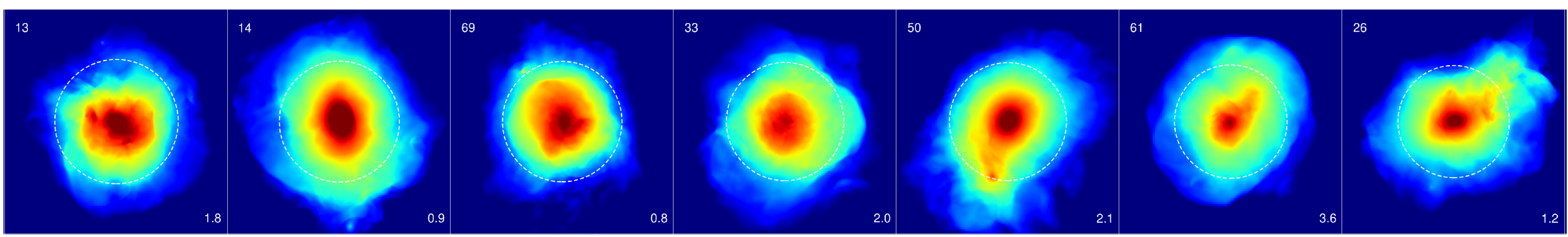
## Selection based on Ysz($<3r_{500c}$) - Planck




## Selection based on Ysz($<r_{500c}$) - ACT/SPT

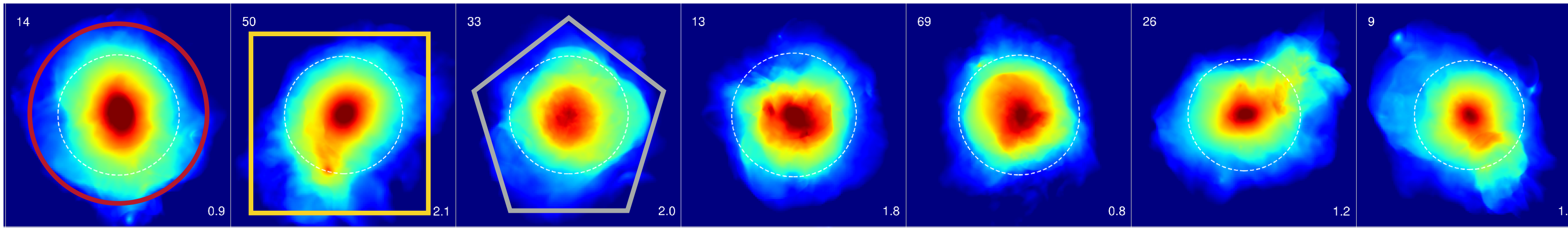



## Selection based on M($<r_{500c}$)

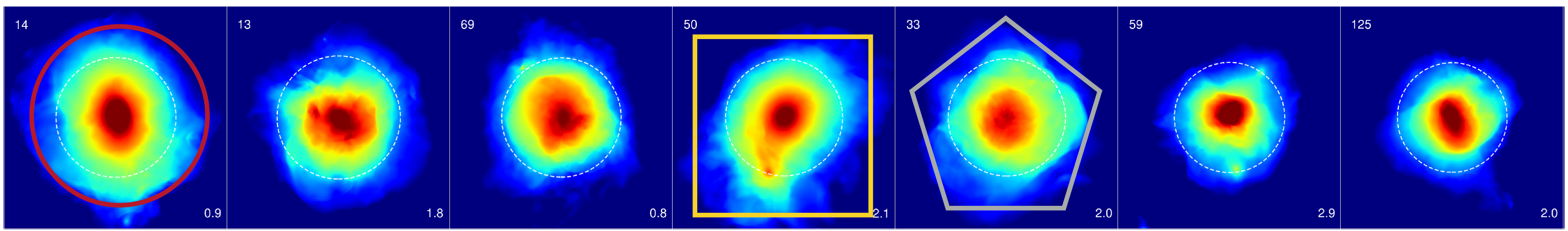


# Physics of SZ Cluster Selection

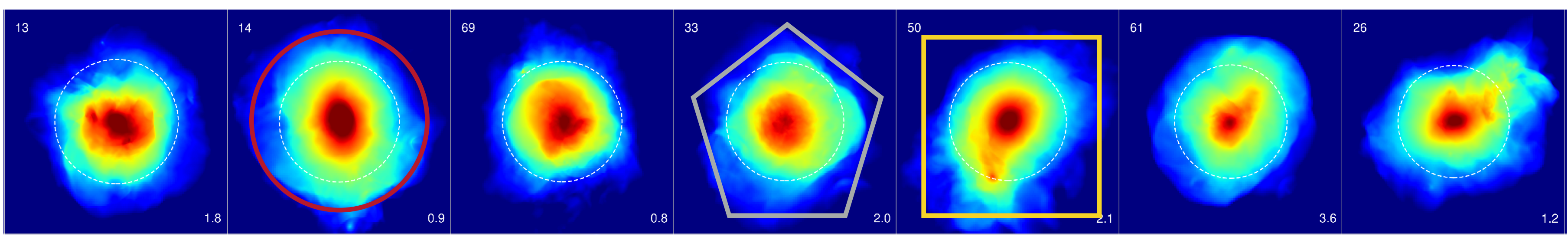
Selection based on Ysz(<3$r_{500c}$) - Planck




Selection based on Ysz(<$r_{500c}$) - ACT/SPT



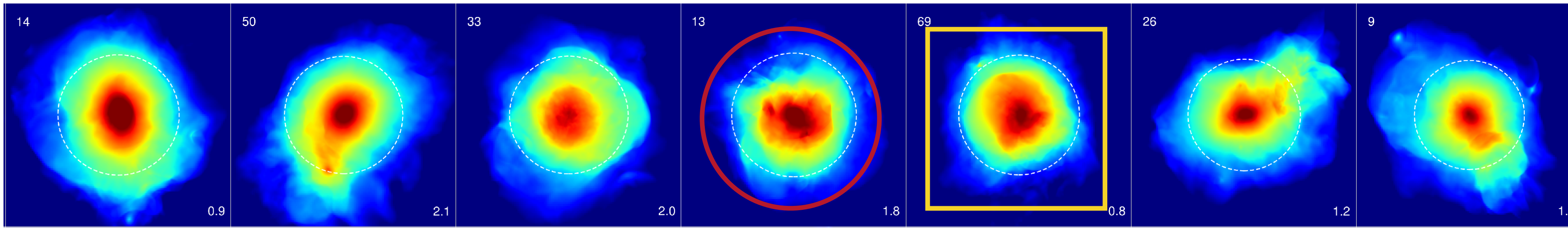

Selection based on M(<$r_{500c}$)



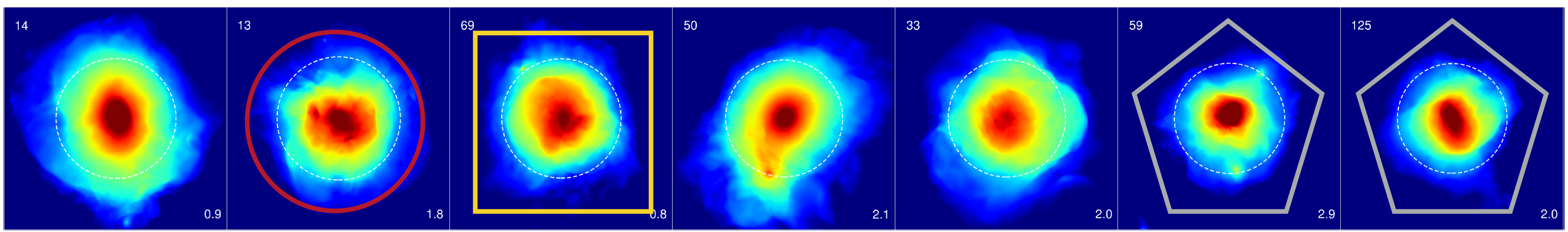

Planck select clusters with high degree of thermalization with extended pressure envelope

# Physics of SZ Cluster Selection

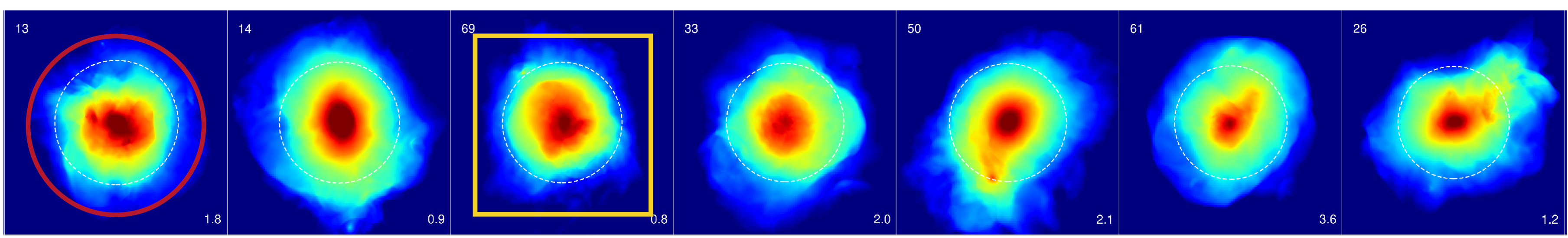
Selection based on Ysz($<3r_{500c}$) - Planck




Selection based on Ysz($<r_{500c}$) - ACT/SPT




Selection based on M($<r_{500c}$)




ACT & SPT select merging clusters with high pressured cores

# *Challenges & Questions*

1. Mass Calibration: How robust is the theoretical estimate of the HSE mass bias (e.g., non-thermal pressure, ICM density/temperature inhomogeneities, profile fitting techniques)? Can we use them to correct for the HSE mass bias or check with lensing? What observations do we need (lensing mass calibration, ASTRO-H, Pressure/SB fluctuations)?

2. Can we improve on the robust mass proxy (e.g., Yx-M)? Are the ICM profiles really "universal" (critical vs. mean, dependence on dynamical states/MAH, clumps/filaments)? Can correct for the non-thermal pressure to make the profiles and scaling relations more self-similar and/or reduce scatter? Why mass? What about gravitational potential?

3. Irreducible biases: e.g., undetected gas clumps/filaments and gas accelerations. Can we measure them or need inputs from simulations? Are simulations sufficiently reliable?

4. Selection function: X-ray/SZ/optical surveys select different clusters! Key: dynamical states and cool core (CC) fractions and their evolution. How to characterize dynamical states (morphological classification, radio relics)? Can we model CC fraction and evolution?

5. Alternative approaches for cluster cosmology: SZ power spectrum, higher-order moments, cross-correlations? No cluster mass! More than a nice cross-check?

# *Challenges & Questions*

6. Physics of Cluster Outskirts: How well do we understand the physics of cluster outskirts? Non-thermal pressure, ICM inhomogeneities in density, temperature and metallicity, e-p process and filaments. Small effect (<10%) at $R_{500c}$ and larger in outskirts. What else? How well do simulations and observations agree?

7. Do clusters have a well-defined edge? Shock radius (for gas) & Splash-back radius (for DM)? Is $R_{shock} \approx R_{sp}$? Can model this analytically? How do clusters accrete mass and shape the structure and dynamics of dark matter and gas in cluster outskirts?

8. Bulk and turbulent gas motions: How robust are the model predictions (viscosity, MTI instability)? Need observational constraints at large radii! ASTRO-H? Pressure/SB fluctuations? kSZ imaging? SZ power spectrum? Athena+/SMART-X? Radio/$\gamma$-ray?

9. Impact of AGN feedback: What is the sphere of influence of AGN feedback? Does it affect the ICM properties in cluster outskirts (e.g., Planck pressure profile, small-scale gas clumps, metallicity)? Also need to model CC and NCC. What is the minimalistic AGN feedback model?

10. ICM micro-physics: How well can we model ICM micro-physics (e.g., viscosity, conduction, magnetic field, cosmic-rays, e-p equilibration, plasma instabilities) ab initio? How well can we constrain them observationally (radio/X-ray/$\gamma$-ray)?