Impact of Cluster Structure and Dynamical State on Scatter in the SZ Flux-Mass Relation

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Galaxy cluster count is a powerful cosmological probe, but need to infer total mass *via M-Obs. Relations* (*Tx-M, Richness-M, Ysz-M…*)

\[ Y_{SZ} = \int y d\Omega \frac{k_B \sigma_T}{m_e c^2} \int n_e(l) T_e(l) dV \]

Need **accurate** and **unbiased** estimates of the form, norm, slope, and **scatter**!
Why study the origin of $\text{Y}_{sz}$-$M$ scatter?

(1) Reduce the scatter (e.g. CC exclusion, $Y_x=M_{tx}$)

(2) Quantify systematics
   - Self-calibration – lognormal? (Shaw+10)
   - Selection function – mergers? (Wik+08)
   - Multi-wavelength mass calibration – correlated error? (Cohn+09)

$Y_x$– $M$ Relation (Kravtsov+06)

Measure a non-Gaussian distribution with higher-order moments:

(3) Because we simply want to know why!

Skewness (1-sided):
$$\gamma = \frac{\langle (Y - \bar{Y})^3 \rangle}{\sigma^3}$$

Kurtosis (peaked and tailed):
$$\kappa = \frac{\langle (Y - \bar{Y})^4 \rangle}{\sigma^4} - 3.$$
Method

Cosmological Simulation

- N-body + adiabatic hydro
- FLASH (Fryxell et al. 2000)
- Box size = 256 Mpc/h,
  Resolution = 250 kpc/h
- 1024^3 particles (m_p = 1.3x10^9 M_{sun}/h)
- WMAP3 cosmological parameters

Find halos using FOF algorithm

Define mergers

- Merger tree analysis-- Mergers: <10:1 merger within 3 Gyrs
- Substructure measures – Centroid offset and Power ratios
Simulated Ysz-M Scatter

Examine if the scatter is lognormal by computing skewness and kurtosis

$lognormal: \gamma = 0, \kappa = 0$

Correlate with possible sources of scatter (dynamical state, halo concentration)

(R$_{500}$ is the radius enclosing 500 times the critical density of the universe.)
Non-negligible positive skewness and kurtosis (>0.5) for a wide range of limiting masses and redshifts, due to shape and projection effect

Need higher-moment parametrization in the form of Y-M scatter!
Do mergers bias the Ysz-M relation?

Weak correlation -- recently merged clusters tend to scatter low due to incomplete virialization
Do mergers bias the Ysz-M relation?

*Mergers do NOT bias the relation statistically!*

Why?

(1) Mergers are rare

(2) Shock heating effect is diluted
- hard to be captured in \( R_{500} \)
- incomplete thermalization operates in the opposite way

(3) Mergers move along the scaling relation

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**Distribution of Scatter**

- Dashed: mergers
- Solid: relaxed
Strong correlation with concentration!

Scatter is largely driven by variations in concentration!

Why?

Virial theorem:

\[ O_{\text{vir}} \propto M_{\text{vir}}^\alpha \]

\[ M_\Delta = f_1(c) \times M_{\text{vir}} \]

\[ O_\Delta = f_2(c, EOS) \times O_{\text{vir}} \]

\[ \Rightarrow O_\Delta \propto N(c, EOS) M_\Delta^\alpha \]

(R\textsubscript{200}/R\textsubscript{500} is monotonically decreasing with c)
Correct for the effect of concentration

\[ Y_{500} \quad \text{[Mpc]}^2 \]

\[ M_{500} \quad \text{[M}_\odot] \]

Smaller c

Larger c
Correct for the effect of concentration

Scatter reduced by ~40%!
Cross-calibrating mass with X-ray

Low-scatter X-ray mass proxy:

\[ Y_X \equiv M_g T_X \]

* Errors in \( M_{Y_{sz}} \) and \( M_{Y_x} \) are NOT correlated:

- Ysz-M outliers – shape & projection
- Yx-M outliers – dynamical state

* Cross-calibration can effectively remove outliers in the true Ysz-M relation
Summary

- The Y-M scatter is non-lognormal, with non-negligible positive skewness and kurtosis that can bias cosmological constraints.  
  \( \gg \) Higher-order moments need to be included in the form of scatter.

- The correlation with dynamical state is weak.  
  \( \gg \) Selection bias caused by mergers is negligible.

- There is a strong correlation with concentration.  
  \( \gg \) Corrections using such correlation can potentially be applied to observed clusters to reduce the scatter.

- Errors for SZ and X-ray predicted masses are not correlated.  
  \( \gg \) Cross-calibrating mass using X-ray data can effectively identify Ysz-M outliers.