A Multi-Probe Analysis of the 3D Shapes and Non-Thermal Pressure of Galaxy Clusters

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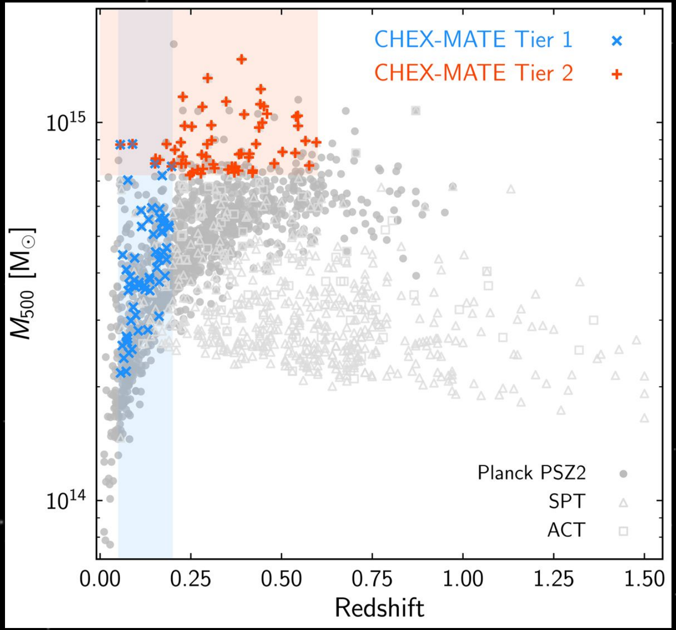
CHEX-MATE Collaboration

CHEX-MATE

- CHEX-MATE: The Cluster HEritage project with XMM-Newton - Mass Assembly and Thermodynamics at the Endpoint of structure formation (CHEX-MATE Collaboration 2021)
  - 3 Msec XMM-Heritage program
  - Planck SZ selected 118 clusters
  - Tier-1: volume-limited sample in the local universe
    $z < 0.2$ and $dec > 0$
    $2 \times 10^{14} M_{sun} < M_{500} < 9 \times 10^{14} M_{sun}$
  - Tier -2: sample of the most massive objects to have formed
    $z < 0.6$ and $M_{500} > 7.25 \times 10^{14} M_{sun}$



CHEX-MATE Collaboration (2021)

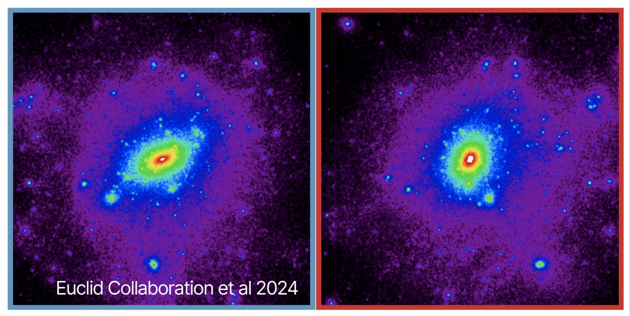
Science Goals

Shape Measurement

- Unbiased estimates of cluster properties require understanding of shape & orientation of halo

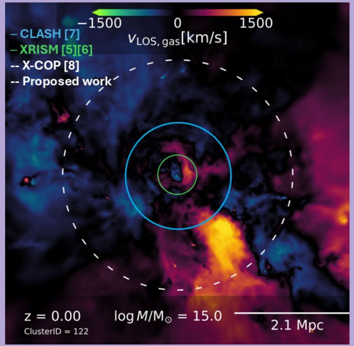
Spherical → Triaxial modeling

- Example: WL-derived masses are extremely sensitive to line of sight elongation



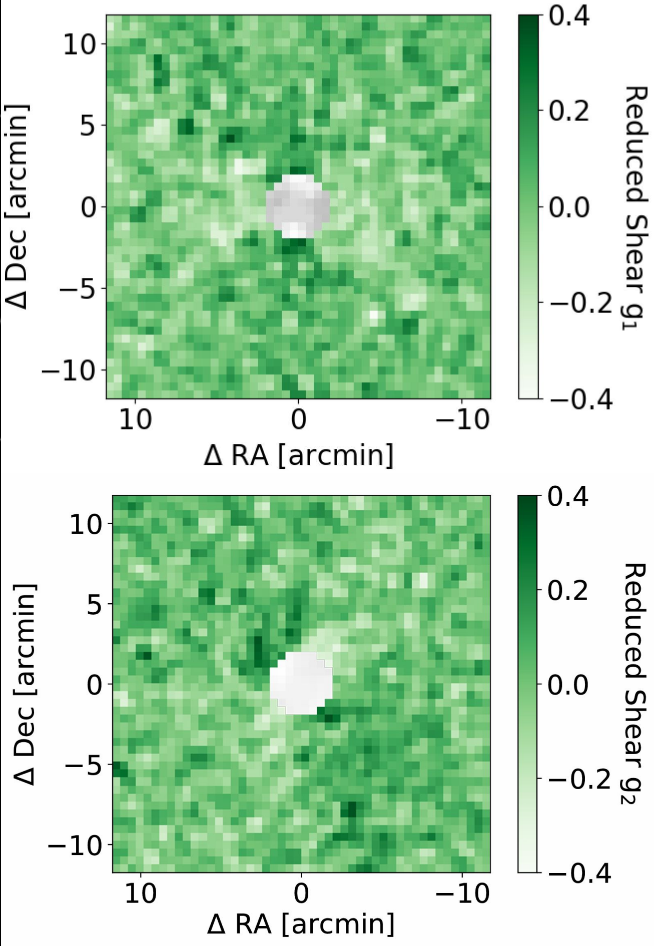
Non-thermal Pressure Support

- Assessing equilibrium status of cluster outskirts, where new material is being acccreted
- No large sample studies have probed the cluster outskirts → **CHEX-MATE dataset will enable measurement out to R_{200}**



Weak lensing shear

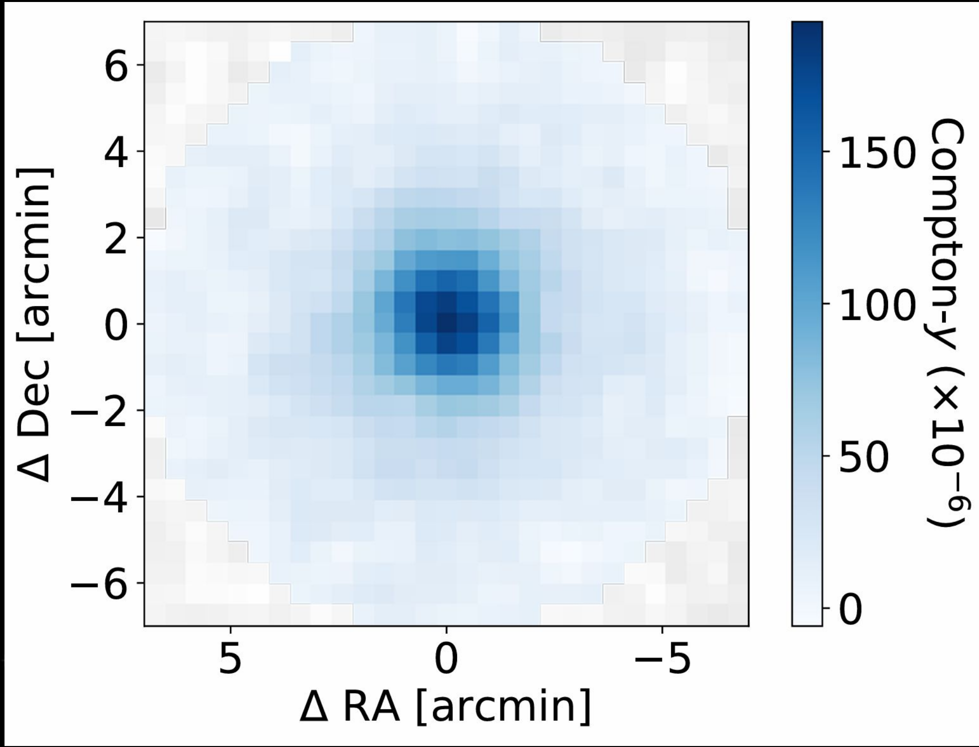
- Shear maps constructed from archival observations from the Subaru Suprime-Cam instrument
  - We use two component reduced shear maps
- Enables reconstruction of the total mass profile, providing constraints on the mass and concentration



Thermal SZ-y

- SZ Compton-y map from the combination of ACT and *Planck* measurements

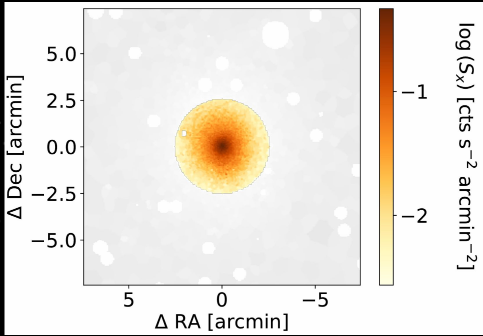
$$y \equiv \frac{\sigma_{\rm T}}{m_e c^2} \int_{\parallel} P_e dl = \frac{\sigma_{\rm T} k_{\rm B}}{m_e c^2} \int_{\parallel} n_e T_e dl,$$

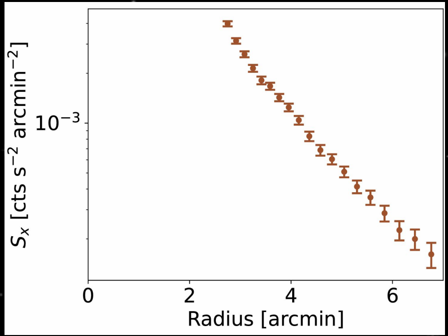


X-ray Surface Brightness and Temperature

- X-ray SB observations from XMM-*Newton* in [0.7-1.2] keV range
  - 2D data used in radial region that encloses 80% of the emission
  - 1D data used in exterior region to mitigate biases from gas clumping

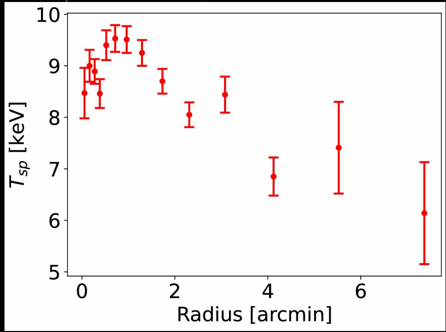
- Spectroscopic temperature measurements constructed via spectroscopic fits to SB data
  - Assume ICM is ideal gas to estimate electron temperature



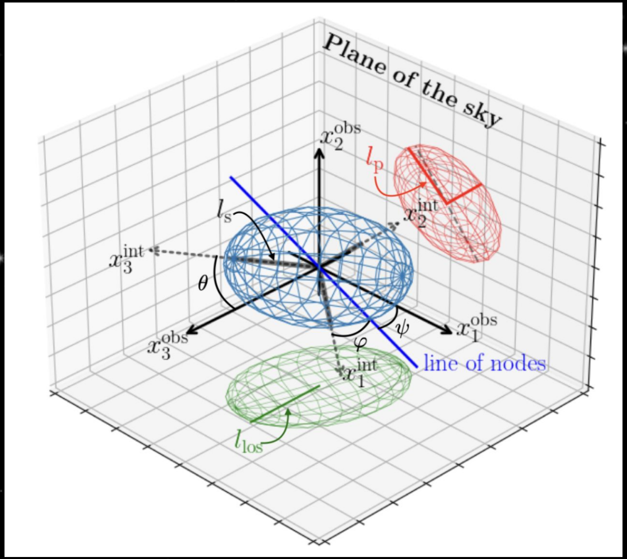


$$\mathrm{SB} = \frac{1}{4\pi(1+z)^3}\int_{\parallel} n_e^2 \Lambda_{\mathrm{eff}}(T_e, Z)\,dl$$

$$T_{\mathrm{sp}} = \frac{\int W T_e dV}{\int W dV}\ \mathrm{keV};\ W = \frac{n_e^2}{T_e^{3/4}},$$



Triaxial Modeling



- Assumed thermodynamic profiles of ICM, the electron density (n_e) and electron pressure (P_e) are represented as functions of the ellipsoidal radius:

$$\zeta^2 = \frac{x_1^2}{q_1^2} + \frac{x_2^2}{q_2^2} + x_3^2$$

- Derive geometric properties of projected ellipse from intrinsic parameters of 3D ellipsoid when it is projected on the POS from any direction
  - ℓ_p = semi-major axis of ellipse
  - $e_{\parallel}$ = elongation
  - θ_ϵ = orientation angle

- SZ and X-ray SB redundantly probe the LOS extent of the ICM (ICM temp measured from X-ray)

$$S_X \propto \int n_e^2 \Lambda(T_e, Z) dl \quad + \quad B_{SZ} \propto \int n_e T_e dl \quad \longrightarrow \quad \Delta l \sim \frac{B_{SZ}^2 \Lambda(T_e, Z)}{S_X T_X^2} \sim \frac{B_{SZ}^2}{S_X T_X^2}$$

Mass Reconstruction

Choose to model the gravitational potential

$\nabla^2 \boldsymbol{\Phi} = 4\pi G \varrho$

Solve for $\boldsymbol{\Phi}$ numerically

Interpolate $\boldsymbol{\Phi}$ on a 3D ellipsoidal grid defined using axial ratios of the ICM

$\mathbf{q}_{pot} = \mathbf{q}_{ICM}$

Assume an NFW density profile

$$\rho(\zeta) = \frac{\rho_s}{(\zeta/\zeta_s)(1+\zeta/\zeta_s)^2}$$

Define elliptical analogs to $\mathbf{M}_{200}$ & $\mathbf{c}_{200} \rightarrow \mu_{200}$ & γ_{200}

$$\zeta_s = \frac{\zeta_{200}}{\gamma_{200}} \cong \frac{1}{\gamma_{200}} \left[\frac{3}{800\pi\rho_{cr}} \frac{1}{q_{\mathrm{pot},1} q_{\mathrm{pot},2}} \mu_{200} \right]^{1/3}$$

$$\rho_s = \frac{200}{3} \rho_{cr} \frac{\gamma_{200}^3}{ln(1+\gamma_{200}) - \gamma_{200}/(1+\gamma_{200})}$$

Make approx. in connecting μ_{200} & γ_{200} to ζ_s & ϱ_s: $\mathbf{q}_{mat} \sim \mathbf{q}_{pot}$

Use look-up table to convert $\mathbf{M}_{200}$ & $\mathbf{c}_{200} \rightarrow \mu_{200}$ & γ_{200} and fit directly for the spherical values

Projection

- To make models of our 2D observables, we must project the assumed 3D profiles describing the signal along the LOS:

$$F_{2D}(x_\xi; l_p, p_i) = 2 l_p e_\parallel \int_{x_\xi}^{\infty} F_{3D}(x_\zeta; l_s, p_i) \frac{x_\zeta}{\sqrt{x_\zeta^2 + x_\xi^2}} dx_\zeta$$

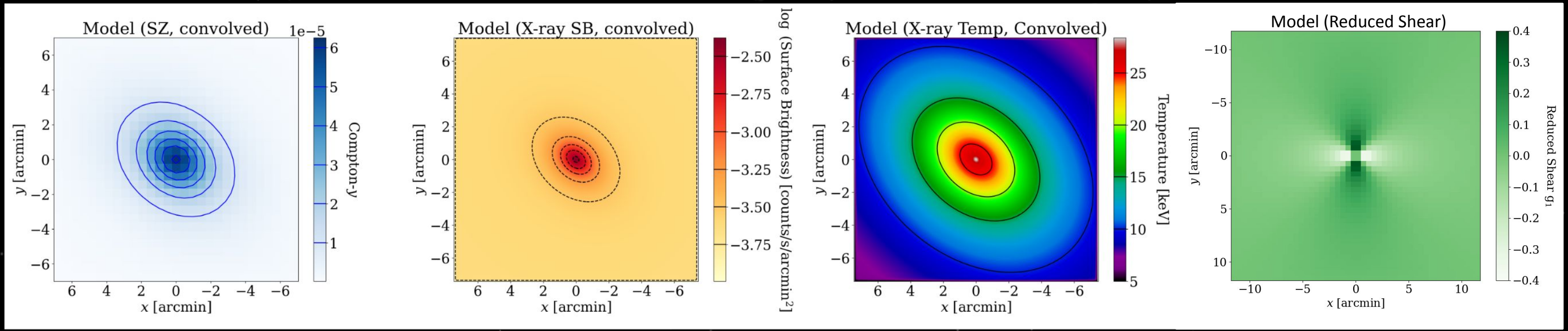
Direct observable

3D profile

P_e n_e Φ

$$\Psi = \frac{D_{LS}}{D_L D_S} \frac{2}{c^2} \int \Phi dl$$

$$\gamma_1 = \frac{1}{2}(\Psi_{11} - \Psi_{22}) \quad \text{and} \quad \gamma_2 = \Psi_{12} = \Psi_{21}$$



Non-Thermal Pressure Calculation

From gas analysis:

Can calculate elliptical gas density profile:

$$\rho_{gas} = \mu_e m_p n_e$$

Can calculate elliptical gas pressure profile:

$$P_{th} = P_e \frac{\mu_e}{\mu}$$

From addition of WL analysis:

Can calculate gravitational potential on triaxial ellipsoid.

Assume generalized HSE

$$\nabla P_{\rm tot} = -\rho_{\rm gas} \nabla \Phi,$$

Undo this numerically to get the total pressure needed to offset gravity

Non-thermal pressure:

Spherically average the total pressure and thermal pressure, then:

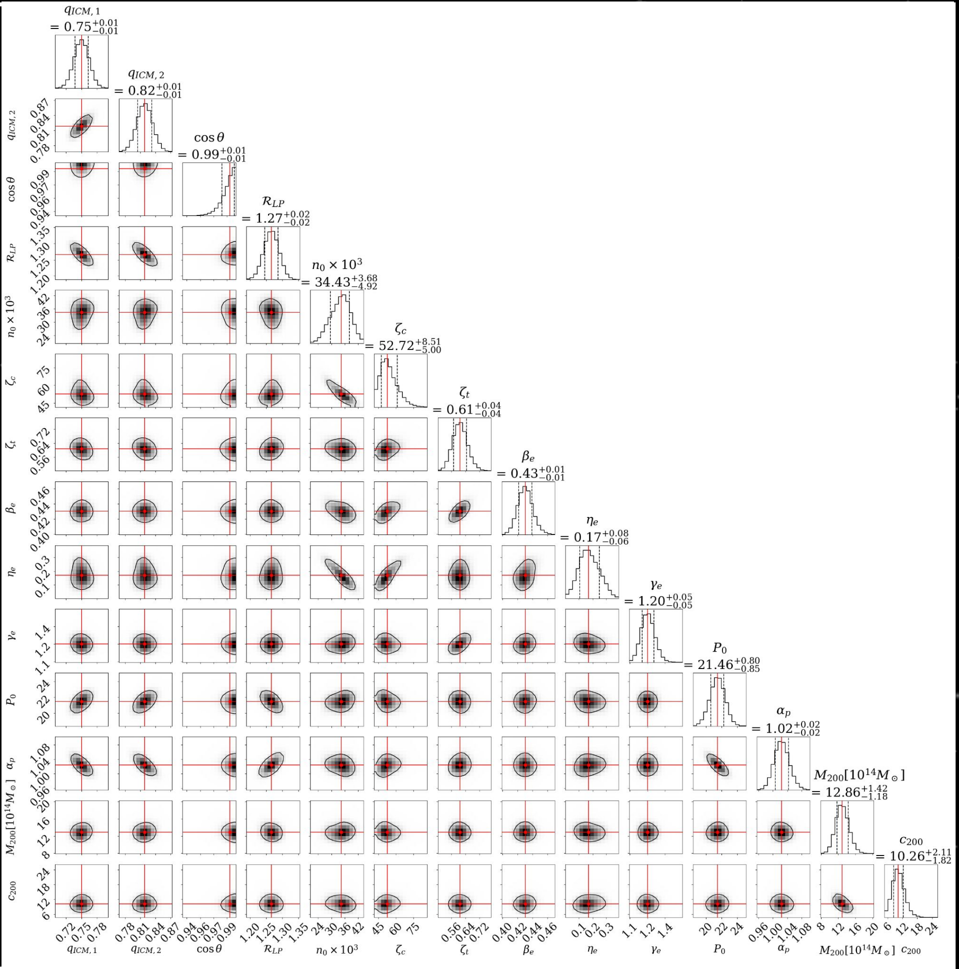
$$P_{nt} = P_{tot} - P_{th}$$

This calculation is computationally expensive, so it is done outside the fit

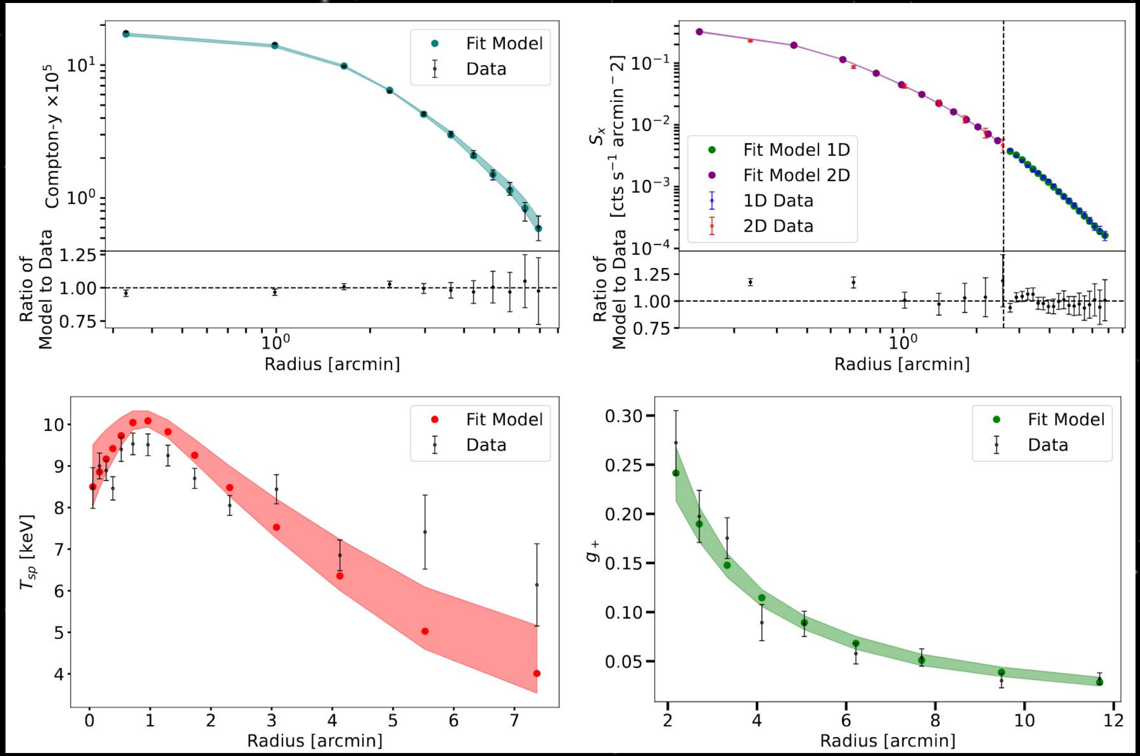
Demonstration on A1689

Multiprobe Fit

- Geometrical constraints are consistent with what is found in the literature
  - cosθ = 0.99 ⇒ A1689 is almost perfectly aligned with the line of sight
  - R_{LP} = 1.27 ⇒ A1689 is elliptical and elongated along the line of sight



Radial Profiles



We find good agreement between the best fit model and the input data

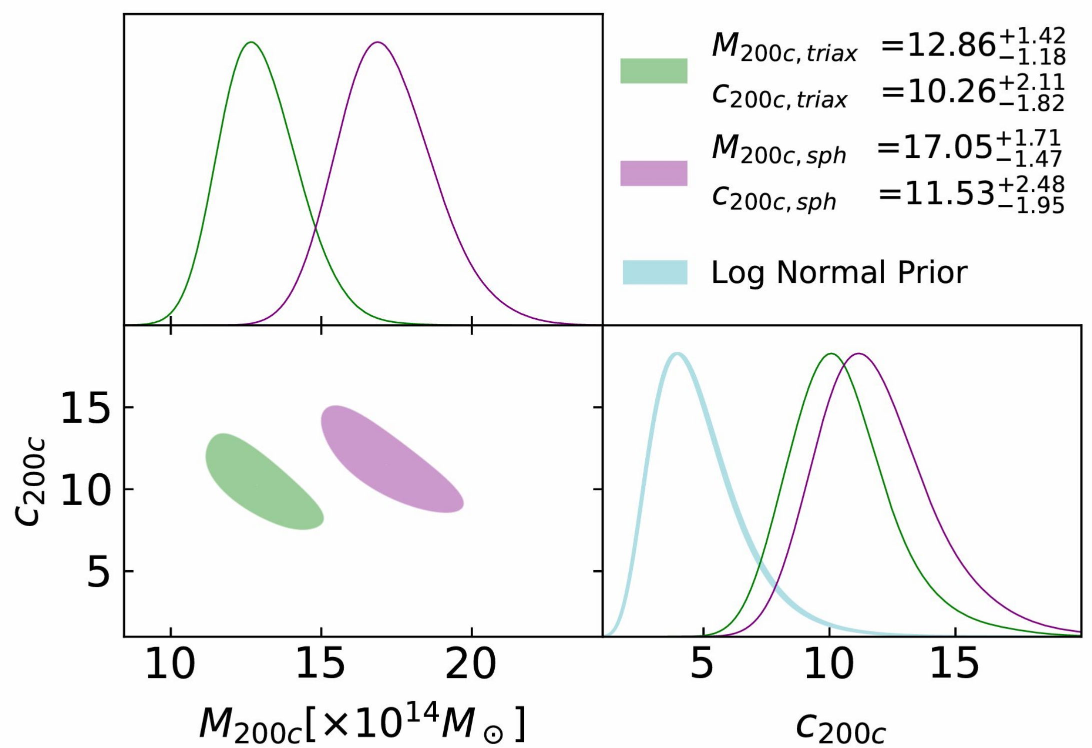
- Limited d.o.f. in model → two independent thermodynamic profiles shapes (density and pressure) must simultaneously describe three observables
- Higher S/N SZ data primarily constrain P_e
- Elongation ensures normalization of fitted temp profile is in agreement with obs data

WL Results

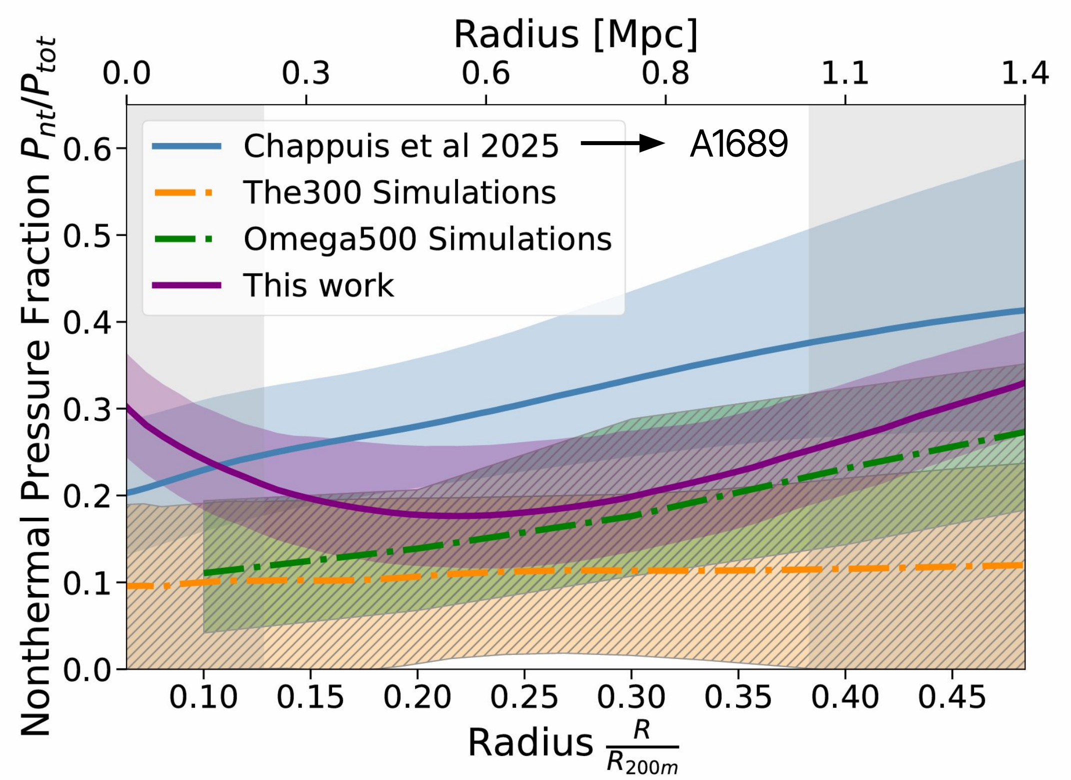
Prior spherical fits to A1689 suggested a high c_{200} for this system

- High c_{200} retained in triaxial fit → may be intrinsic rather than a result of projection

Higher mass obtained in spherical fit agrees with expectations from fitted geometry given LOS elongation = 1.27



Non-thermal Pressure Fraction



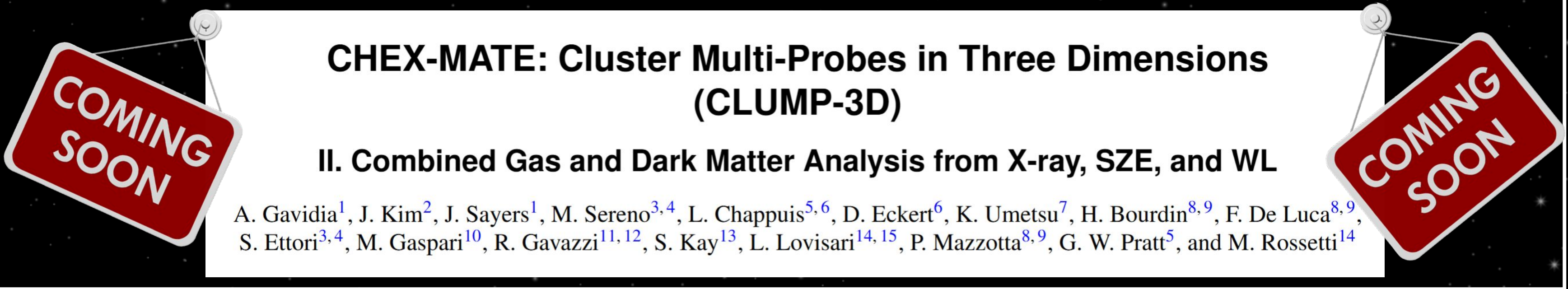
We obtain a non-thermal pressure fraction with ≲10% uncertainty

- Chappuis et al 2025 is a 1D analysis that uses the same CHEX-MATE data but different modeling formalism
- Green and yellow lines are independent analyses of simulated clusters showing ensemble average profiles

Conclusions

- We are capable of measuring spherical and triaxial masses
  - Will investigate the spherical-triaxial mass bias in the full CHEX-MATE sample
- We obtain a radial profile of the non-thermal pressure fraction with ≲10% uncertainty
  - Will apply pipeline to full CHEX-MATE sample to obtain an ensemble average radial profile

- Next steps:
  - Apply pipeline to sample of ~50 simulated clusters from The300 to investigate any bias introduced by the fit
  - Apply pipeline to sub-sample of CHEX-MATE clusters



CHEX-MATE: Cluster Multi-Probes in Three Dimensions (CLUMP-3D)

II. Combined Gas and Dark Matter Analysis from X-ray, SZE, and WL

A. Gavidia[1], J. Kim[2], J. Sayers[1], M. Sereno[3,4], L. Chappuis[5,6], D. Eckert[6], K. Umetsu[7], H. Bourdin[8,9], F. De Luca[8,9], S. Ettori[3,4], M. Gaspari[10], R. Gavazzi[11,12], S. Kay[13], L. Lovisari[14,15], P. Mazzotta[8,9], G. W. Pratt[5], and M. Rossetti[14]

Extra Slides

Mock Data Fits

Fitting to toy model data generated using model equations tests how well the pipeline returns known input parameters

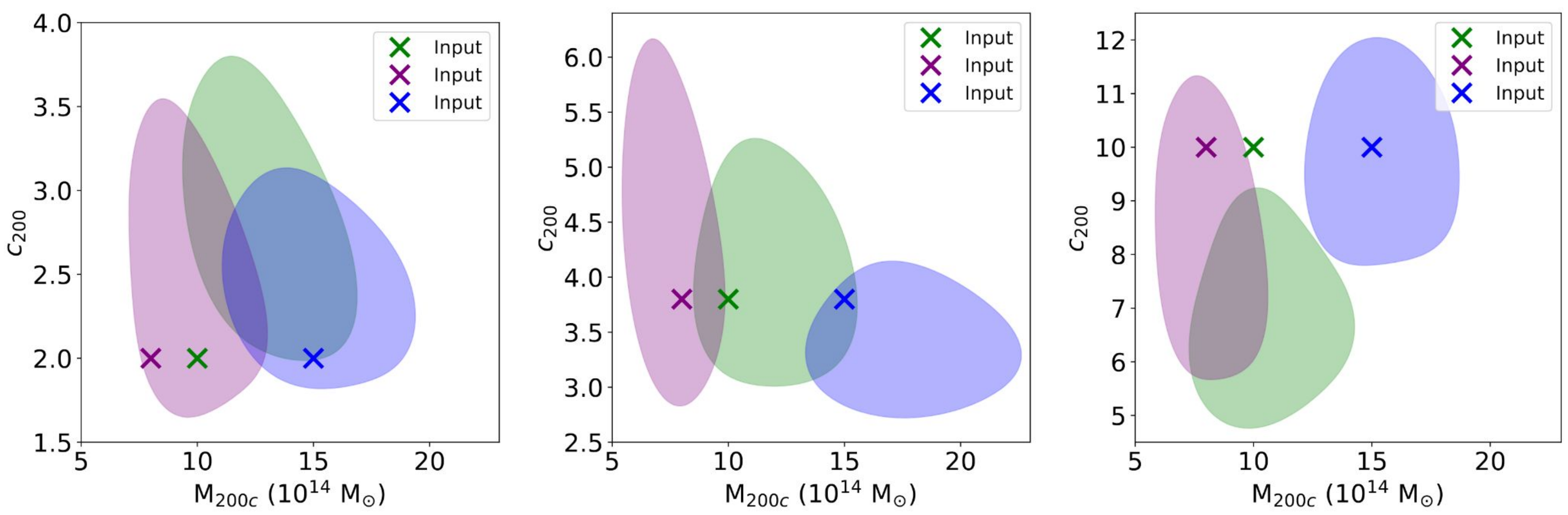
M_{200} [10^{14} M_{sun}]	c_{200}
8	3.8
10	3.8
15	3.8

M_{200} [10^{14} M_{sun}]	c_{200}
8	10
10	10
15	10

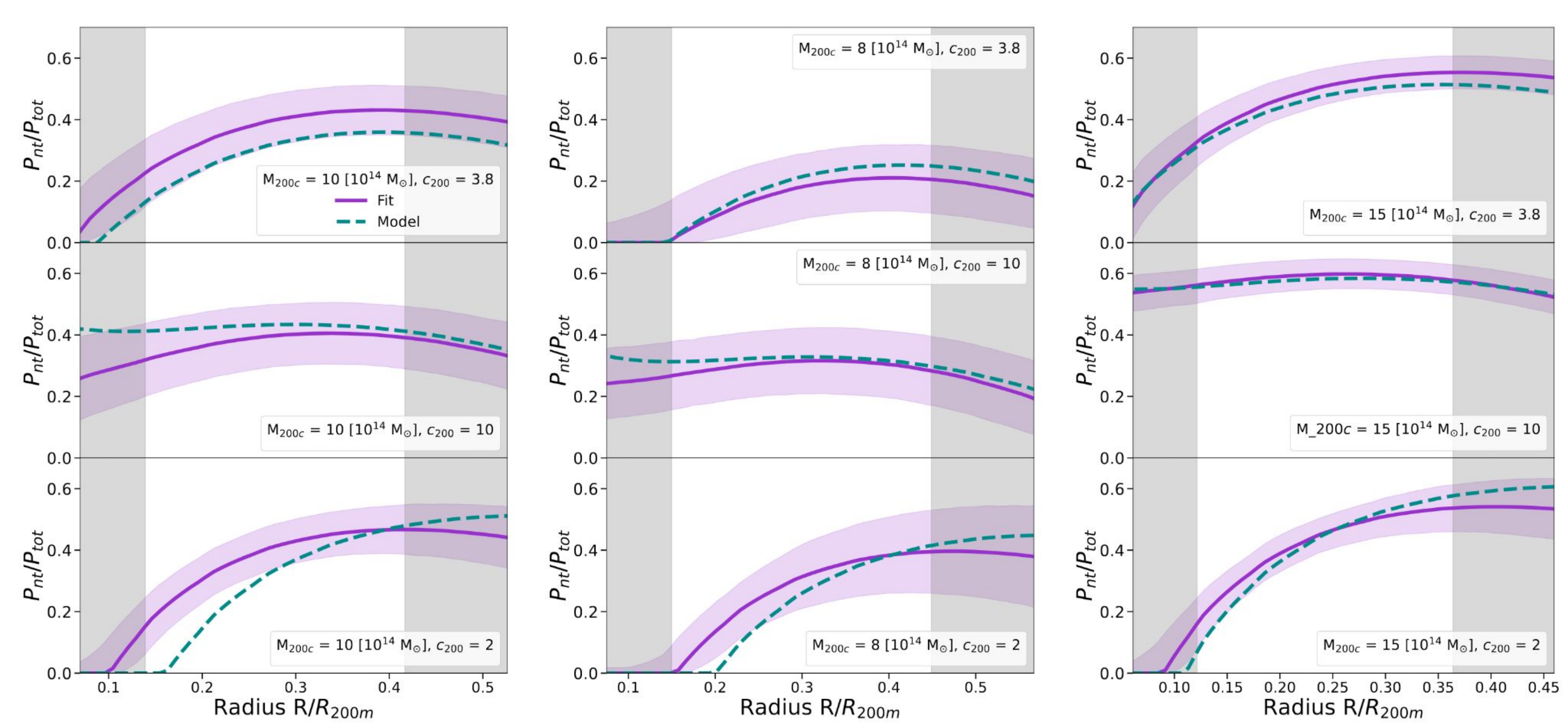
M_{200} [10^{14} M_{sun}]	c_{200}
8	2
10	2
15	2

q_1	0.60
q_2	0.75
$\cos\theta$	0.6
φ	-25
Ψ	60
n_0	0.01 cm^3
ζ_c	200 kpc
ζ_t	2.5 Mpc
β_e	0.65
η_e	0.60
γ_e	4.2
P_0	30
α_p	0.8

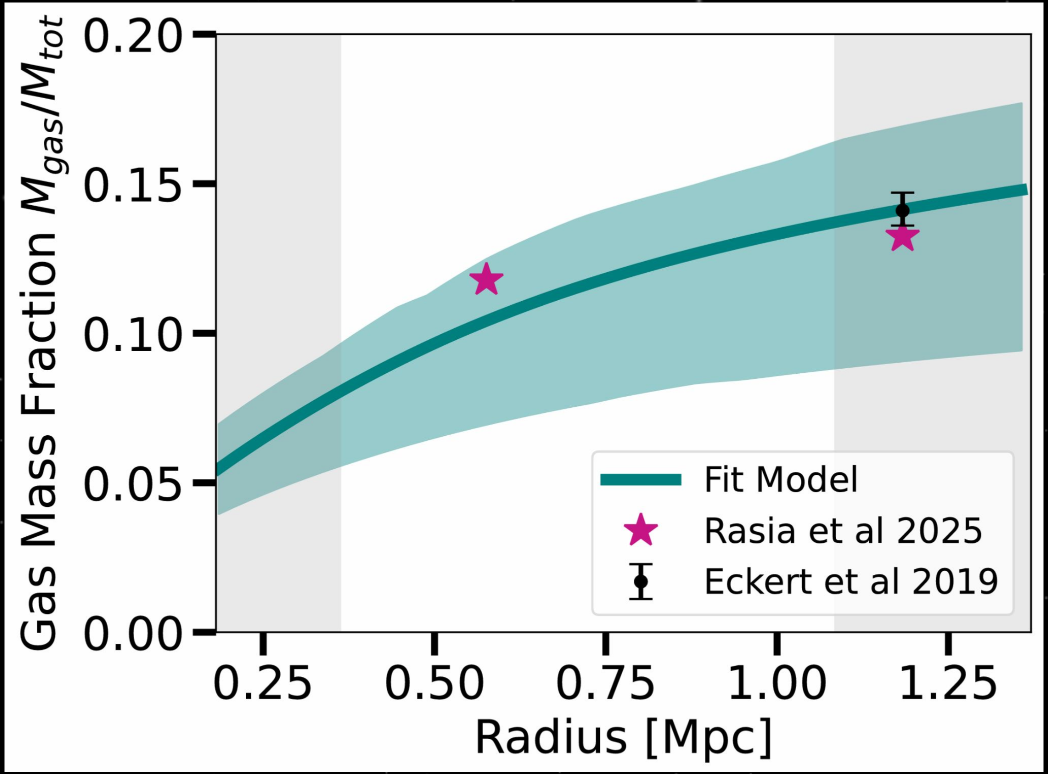
Mock Data Fits



Mock Data Fits



Gas Mass Fraction



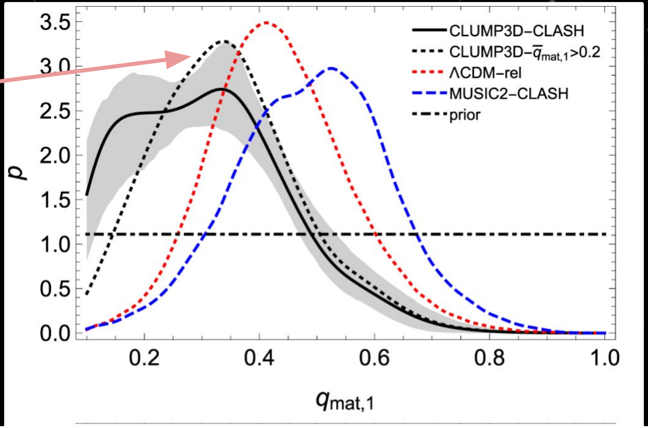
Science Goal: Shape Measurement

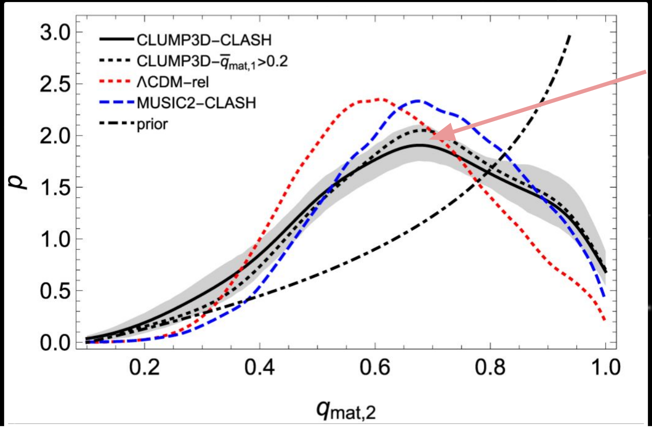
- What is the distribution of three-dimensional shapes of galaxy clusters?
  - Knowledge of the mass and concentration of cluster crucial for understanding formation & evolution
    - Unbiased estimates require understanding of shape & orientation of halo

Spherical → Triaxial modeling

  - Cosmological models make strong prediction for the shape of DM halos (e.g., Yoshida et al. 2000)
    - CLASH results (Sereno et al. 2018) potentially suggest more extreme axial ratios compared to simulations
    - CLASH measurement has lower $q_{mat,1}$ → more recent formation time than in simulation?
  - Larger axial ratios could potentially point to a non-zero self-interaction cross-section for dark matter

Smaller q_1 than expected





Larger q_2 than expected

Sereno et al. 2018

Triaxial Gas Analysis

- Assume the following model profiles:
  - Electron density profile (Vikhlinin et al. 2006; Ettori et al. 2009)

$$n_e(\zeta) = n_0 \left(\frac{\zeta}{\zeta_c}\right)^{-\eta_e} \left[1 + \left(\frac{\zeta}{\zeta_c}\right)^2\right]^{-3\beta_e/2+\eta_e/2} \left[1 + \left(\frac{\zeta}{\zeta_t}\right)^3\right]^{-\gamma_e/3} \quad \mathrm{cm}^{-3}$$

  - Gas pressure profile: gNFW (Nagai et al. 2007; Arnaud et al. 2010)

$$\frac{P_e(x)}{P_{500}} = \frac{P_0}{(c_{500}x)^{\gamma_p}[1 + (c_{500}x)^{\alpha_p}]^{(\beta_p-\gamma_p)/\alpha_p}} \qquad x = \zeta/R_{500}$$

- SZ and X-ray SB redundantly probe the LOS extent of the ICM

$$S_X \propto \int n_e^2 \Lambda(T_e, Z) dl \; + \; B_{SZ} \propto \int n_e T_e dl \longrightarrow \Delta l \sim \frac{B_{SZ}^2 \Lambda(T_e, Z)}{S_X T_X^2} \sim \frac{B_{SZ}^2}{S_X T_X^2}$$

Triaxial Total Mass Reconstruction

- We assume an NFW density profile to model the total matter distribution and that the gravitational potential resulting from it is elliptically symmetric
  - Allows us to assume $q_{pot} = q_{ICM}$ (motivated by simulation)

$$\Phi(\zeta) = 4\pi G \Delta^{-1} \rho(\zeta') = 4\pi G \Delta^{-1} \left[\frac{\rho_s}{(\zeta'/\zeta_s)(1+\zeta'/\zeta_s)^2} \right]$$

- Define μ_{200} and γ_{200} as elliptical analogs to $\mathbf{M_{200c}}$ and $\mathbf{c_{200c}}$. These parameters are defined exactly w.r.t the axial ratios of the matter distribution
  - For computational efficiency, make approximation in connecting μ_{200} and γ_{200} to ζ_s and ρ_s that $q_{mat} \sim q_{pot}$

$$\zeta_s = \frac{\zeta_{200}}{\gamma_{200}} \cong \frac{1}{\gamma_{200}} \left[\frac{3}{800\pi\rho_{cr}} \frac{1}{q_{\text{pot},1} q_{\text{pot},2}} \mu_{200} \right]^{1/3} \qquad \rho_s = \frac{200}{3} \rho_{cr} \frac{\gamma_{200}^3}{ln(1+\gamma_{200}) - \gamma_{200}/(1+\gamma_{200})}$$

- Convert $\mathbf{M_{200c}}$ and $\mathbf{c_{200c}} \rightarrow \mu_{200}$ and γ_{200} using a look-up table

Science Goal: Shape Measurement

- Unbiased estimates of cluster properties require understanding of shape & orientation of halo

  Spherical → Triaxial modeling
- **Cluster abundance cosmology**
  - Slight "**S_8 tension**" between cluster measurements and other probes such as the CMB, with cluster measurements producing lower values of S_8
    - **Most likely explanation is mass calibration**
  - Simulations used to quantify the mass bias due to the assumption of spherical symmetry to calibrate WL-derived masses
    - **An observationally derived benchmark to compare with simulations does not yet exist**