Title: Constraining modified gravity models using galaxy cluster masses

Speakers: Minahil Adil Butt

Collection/Series: 50 Years of Horndeski Gravity: Exploring Modified Gravity

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Abstract:

We present a comprehensive joint analysis of two distinct methodologies for measuring the masses of galaxy clusters: hydrostatic measurements and caustic techniques. We show that by including cluster-specific assumptions obtained from hydrostatic measurements in the caustic method, the potential mass bias between these approaches can be significantly reduced. While this may appear to diminish the caustic method as a technique independent of the dynamical state of a cluster, it provides a means to refine mass constraints and offers an avenue for scrutinizing modifications to gravity. Applying this approach to two well-observed massive galaxy clusters A2029 and A2142, we find no discernible mass bias, affirming the method's validity. We draw a similar conclusion when applying this approach to modified gravity models. Specifically, our implementation allows us to investigate Chameleon and Vainshtein screening mechanisms, enhancing our understanding of these modified gravity scenarios.

Furthermore, we explore the prospect of achieving more precise constraints with fewer systematic errors by exclusively employing the caustic method to constrain screening mechanisms on a larger scale, encompassing several hundred stacked galaxy clusters.

Constraining Modified Gravity using Galaxy Cluster Masses

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Motivation

Accurate Mass Measurements

Biases in Mass Measurements

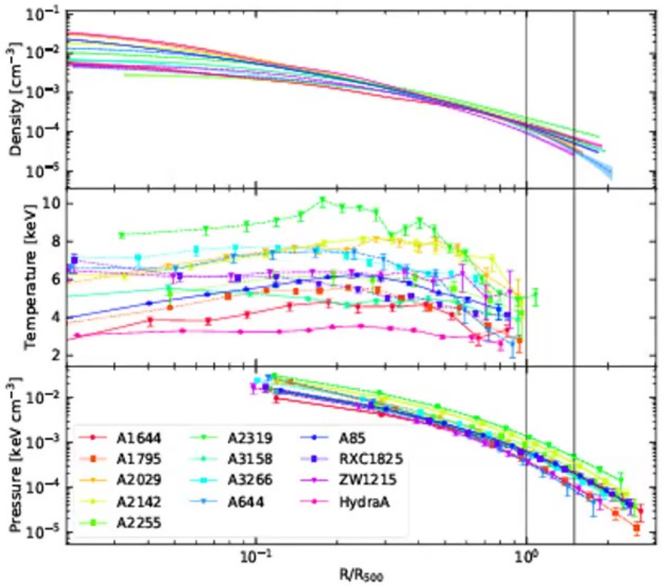
Modified Gravity in Mass Measurements

Research Objective

- A comprehensive joint analysis of two distinct methodologies
- Including cluster-specific assumptions obtained from hydrostatic measurements in the caustic method
- Applying this approach to two well-observed massive galaxy clusters A2029 and A2142, and then to stacked clusters
- Applying this approach to modified gravity models, Chameleon and Vainshtein screening, to enhance our understanding of these models

Mass Measurement Methods

• Hydrostatics



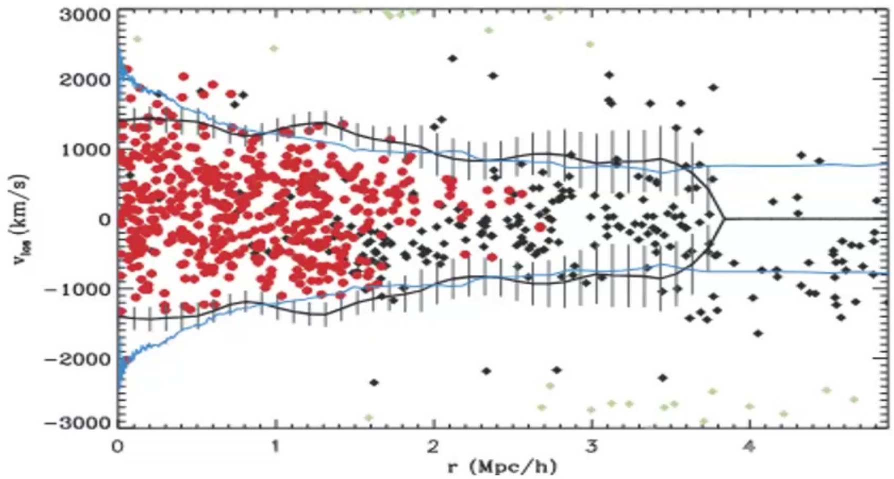
Laudato’21, Ettori’18, Butt et al.’ 21

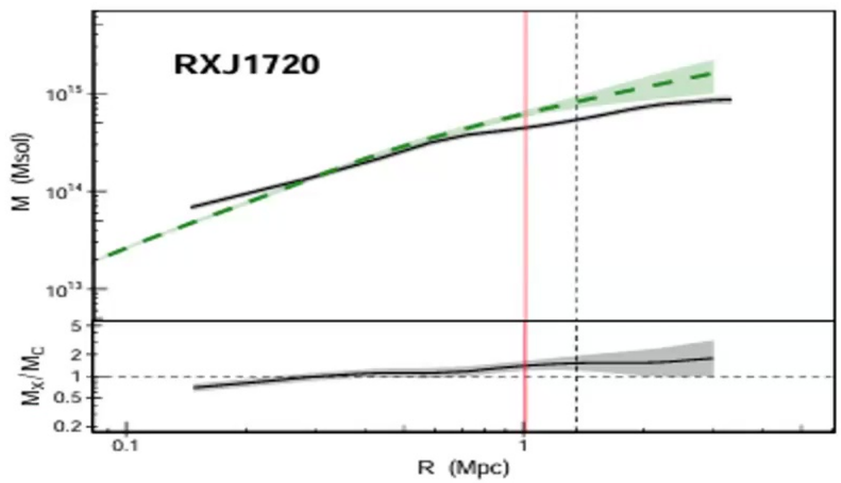
• Caustics

- Relies on the formation of density caustics in phase space to infer cluster mass.
- Independent of the dynamical state of the cluster and effective for individual cluster analysis.
- Dependent on accurate galaxy velocity measurements and limited by the number of spectroscopically confirmed members.

The Caustic Method

- Measures the mass profile of galaxy clusters beyond the virial radius without assuming dynamical equilibrium.
- It is possible to extract the escape velocity of galaxies from the redshift diagram.





Serra’10, Maughan’16

The Caustic Method

- The mass of an infinitesimal shell is given by:

$$Gdm = -2\Phi(r)\mathcal{F}(r)dr = \mathcal{A}^2(r)g(\beta)\mathcal{F}(r)dr$$

where

$$\mathcal{F}(r) = -2\pi G\ \frac{\rho(r)r^2}{\Phi(r)},$$

$$< v^2_{esc,los}(r) > = \mathcal{A}^2(r).$$

- Therefore,

$$GM(< r) = \int_0^r \mathcal{A}^2(r)\mathcal{F}_\beta(r)dr$$

Diaferio'09

The Caustic Method: Modified Gravity

- $\mathcal{F}_{NFW} = \frac{r^2}{2(r+r_s)^2} \frac{1}{\ln(1+\frac{r}{r_s})}$ is a slowly changing function of r. So is $\mathcal{F}_\beta(r)$ if g_β is.
- Hence, we can assume that $\mathcal{F}_\beta(r)$= $\mathcal{F}_\beta$.
- Therefore, $GM(< r) = \mathcal{F}_\beta \int_0^r \mathcal{A}^2(r)dr$.
- Most literature takes $\mathcal{F}_\beta = 0.5$ or $\mathcal{F}_\beta = 0.65$.
- We wish to observe whether taking the complete expression for $\mathcal{F}_\beta(r)$ in GR and MG models will influence the caustic mass and in turn, the mass bias.

$$\mathcal{F}(r) = -2\pi G \frac{\rho(r)r^2}{\Phi(r)}$$

Diaferio'09

Chameleon Screening

- Range of the fifth force depends on the local density.

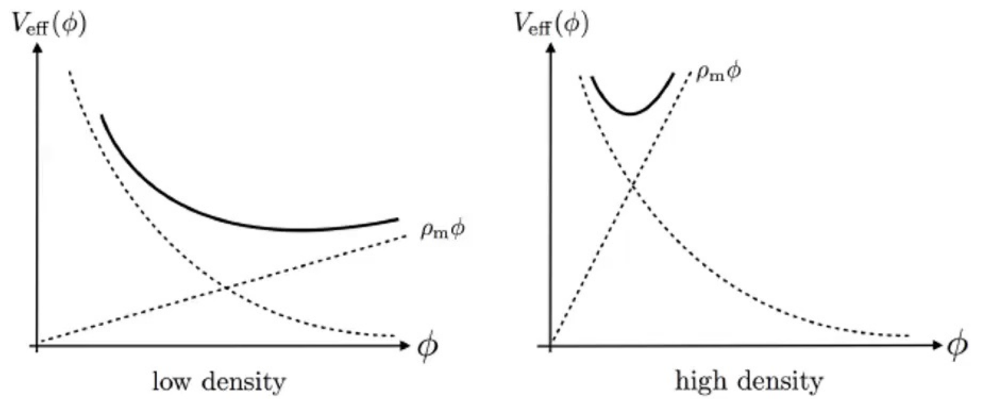


Fig. 3.2 Effective potential for *a*) low ambient matter density and *b*) high ambient density. As the density increases, the minimum of the effective potential, $\phi_{\rm min}$, shifts to smaller values, while the mass of small fluctuations, m_ϕ, increases.

$$V_{eff}(\phi) = V(\phi) + \frac{g\phi}{M_{Pl}}\rho_m$$

$$\lambda_{eff} = \min\left(\frac{\partial^2 V_{eff}}{\partial\phi^2}\right)^{-\frac{1}{2}}$$

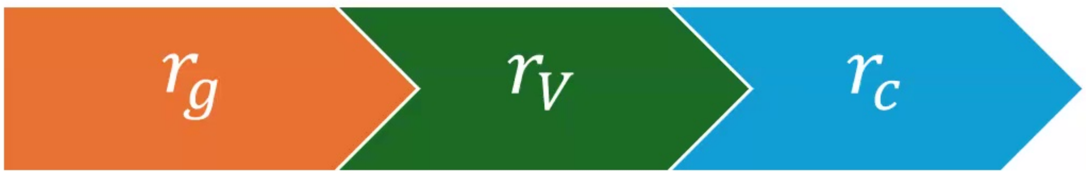
$$m_\phi^2 = V_{,\phi\phi}(\phi_{min})$$

$$\lambda = \frac{h}{mc}$$

Khoury’13

Vainshtein Screening

- Screening is determined by the curvature of the object.



$$r_V = \left(\frac{8\, r_c^2 r_g}{9}\right)^{\frac{1}{3}}$$

$$r_g = 2GM$$

Langlois'18, Dima'18, Crisostomi'17, Haridasu'21

The Modified Potentials

- Chameleon Screening

$$\frac{d\Phi}{dr} = \frac{G\mathcal{M}(<r)}{r^2} + \frac{\beta}{M_{Pl}}\frac{d\phi}{dr}$$

- Vainshtein Screening

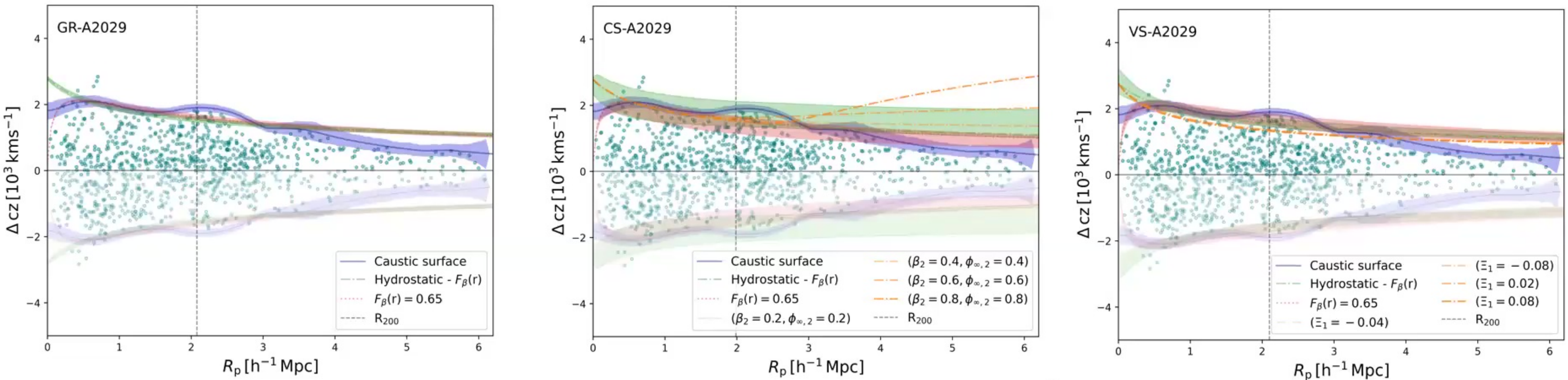
$$\frac{d\Phi}{dr} = \frac{G_N^{eff}\mathcal{M}(<r)}{r^2} + \Xi_1 G_N^{eff}\frac{d^2\mathcal{M}(<r)}{dr^2}$$

$$G_N^{eff} = \frac{\gamma_N G_N}{1-\alpha_H-3\beta_1}$$

$$\Xi_1 = -\frac{(\alpha_H-\beta_1)^2}{2(\alpha_H+2\beta_1)}$$

Langlois'18, Dima'18, Crisostomi'17, Haridasu'21

Caustics and Modified Gravity



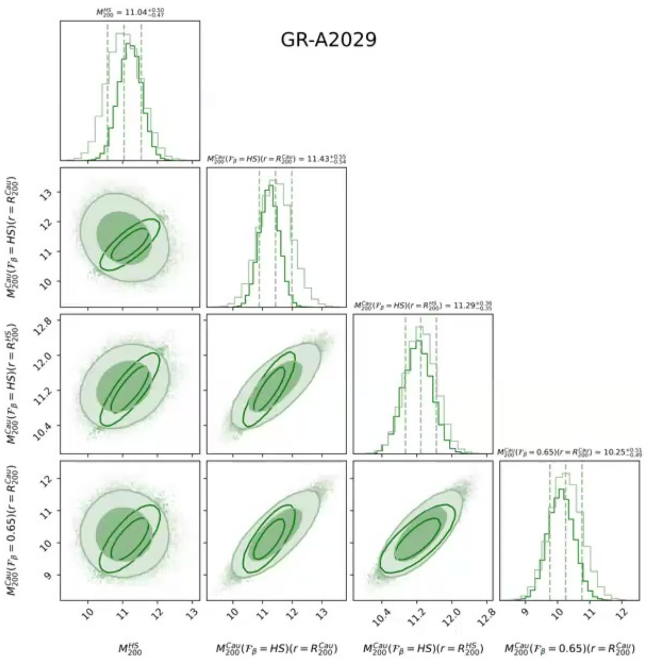
$$-2\Phi(r) = \mathcal{A}^2(r)g(\beta) \equiv \Phi_\beta(r)g(\beta)$$

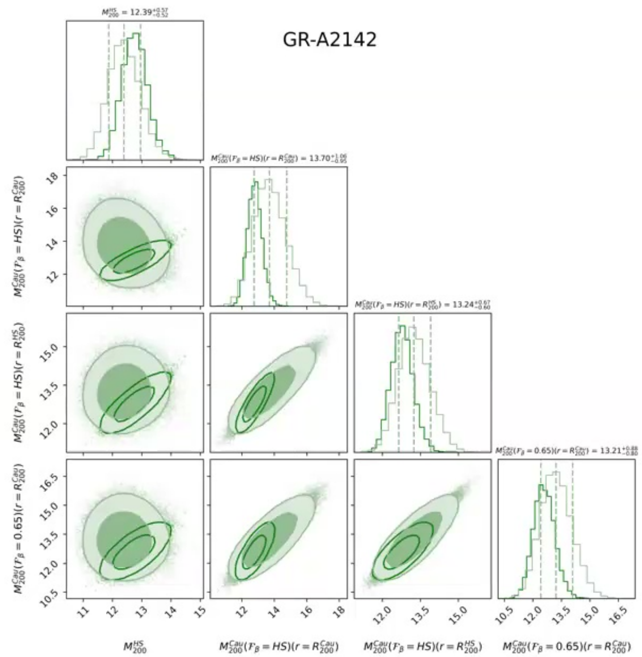
$$g(\beta) = \frac{3 - 2\beta(r)}{1 - \beta(r)}$$

$$GM(<r) = \int_0^r \mathcal{A}^2(r)\mathcal{F}_\beta(r)dr$$

Butt'24

The Joint Analysis - GR Masses

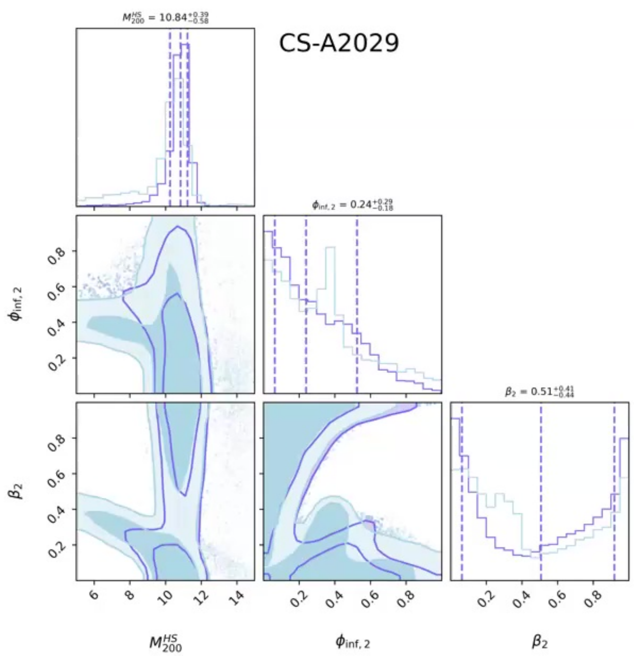


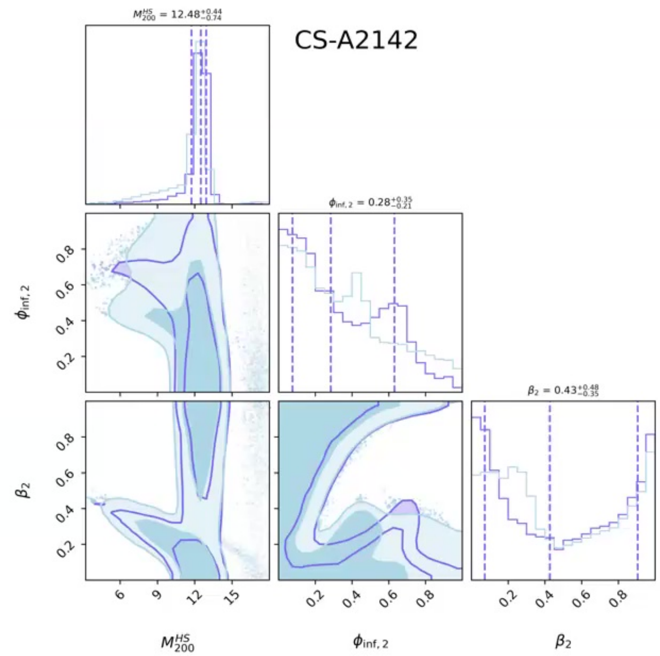


Cluster	$R_{200}^{\rm HS}$ (Mpc)	$M_{200}^{\rm HS}$ $(10^{14} M_{\odot})$	$\mathcal{F}_{\beta}(r)$	$R_{200}^{\rm Cau}$ (Mpc)	$M_{200}^{\rm Cau}$ $(10^{14} M_{\odot})$	$M_{200}^{\rm Joint}$ $(10^{14} M_{\odot})$	$M_{200}^{\rm HS}/M_{200}^{\rm Cau}$
A2029	$2.08^{+0.03}_{-0.03}$	$11.04^{+0.50}_{-0.47}$	HS	$2.11^{+0.03}_{-0.03}$	$11.43^{+0.55}_{-0.54}$	$11.21^{+0.33}_{-0.34}$	$0.97^{+0.07}_{-0.07}$
			0.65	$2.02^{+0.03}_{-0.03}$	$10.25^{+0.51}_{-0.49}$	$10.79^{+0.39}_{-0.38}$	$1.08^{+0.07}_{-0.07}$
			0.50	$1.86^{+0.03}_{-0.03}$	$7.89^{+0.39}_{-0.38}$	$9.76^{+0.05}_{-0.11}$	$1.40^{+0.09}_{-0.09}$
A2142	$2.15^{+0.03}_{-0.03}$	$12.39^{+0.57}_{-0.52}$	HS	$2.23^{+0.06}_{-0.03}$	$13.70^{+1.06}_{-0.95}$	$12.75^{+0.43}_{-0.43}$	$0.90^{+0.09}_{-0.08}$
			0.65	$2.20^{+0.04}_{-0.04}$	$13.20^{+0.84}_{-0.79}$	$12.63^{+0.47}_{-0.44}$	$0.94^{+0.07}_{-0.07}$
			0.50	$2.02^{+0.04}_{-0.04}$	$10.16^{+0.65}_{-0.61}$	$11.62^{+0.41}_{-0.40}$	$1.22^{+0.10}_{-0.09}$

Butt'24

The Joint Analysis - CS Masses

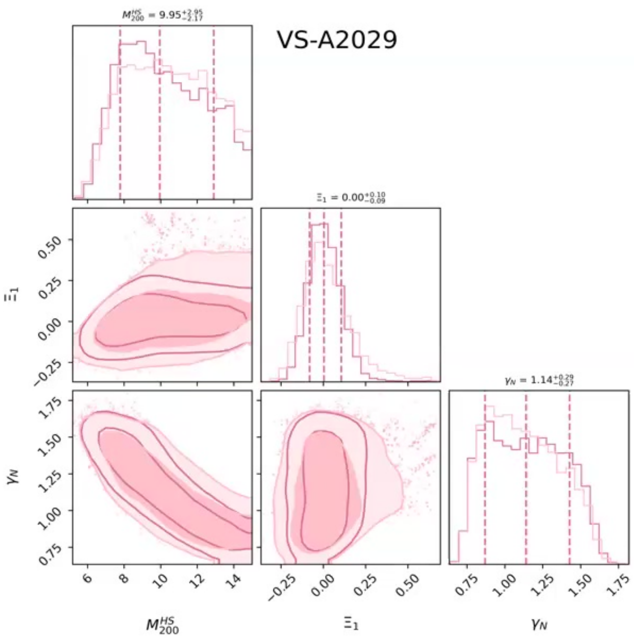


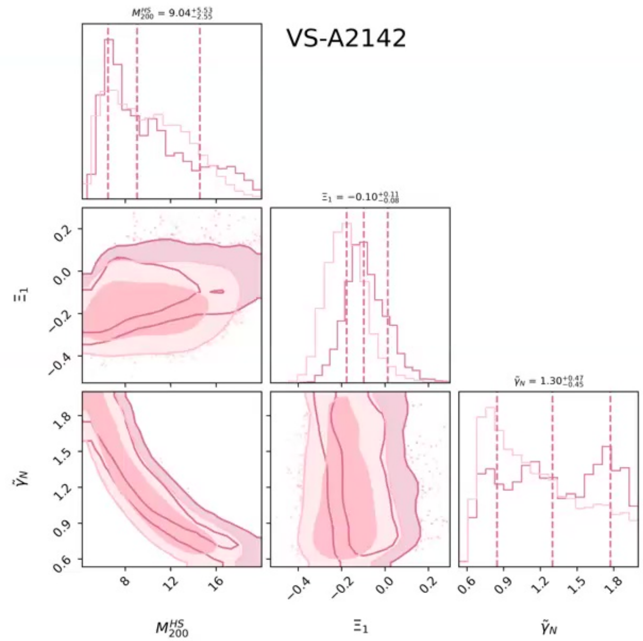


Cluster	$R_{200}^{\rm HS}$ (Mpc)	$M_{200}^{\rm HS}$ $(10^{14}M_\odot)$	$\mathcal{F}_\beta(r)$	$R_{200}^{\rm Cau}$ (Mpc)	$M_{200}^{\rm Cau}$ $(10^{14}M_\odot)$	$M_{200}^{\rm Joint}$ $(10^{14}M_\odot)$	$\phi_{\infty,2}$ $\beta=\sqrt{\frac{1}{6}}$	β_2	$M_{200}^{\rm HS}/M_{200}^{\rm Cau}$
A2029	$2.04^{+0.04}_{-0.13}$	$10.41^{+0.62}_{-1.91}$	HS	$2.08^{+0.05}_{-0.10}$	$11.02^{+0.75}_{-1.57}$	$10.84^{+0.39}_{-0.58}$	$0.24^{+0.29}_{-0.18}$	…	$0.94^{+0.13}_{-0.12}$
			0.50	$1.86^{+0.04}_{-0.03}$	$7.83^{+0.38}_{-0.37}$	$7.87^{+0.42}_{-0.46}$	$0.36^{+0.12}_{-0.03}$	$0.28^{+0.03}_{-0.03}$	$1.32^{+0.12}_{-0.23}$
A2142	$2.14^{+0.03}_{-0.13}$	$12.20^{+0.53}_{-2.13}$	HS	$2.20^{+0.07}_{-0.13}$	$13.19^{+1.20}_{-2.21}$	$12.48^{+0.44}_{-0.74}$	$0.28^{+0.35}_{-0.21}$	…	$0.91^{+0.15}_{-0.10}$
			0.50	$2.02^{+0.04}_{-0.04}$	$10.18^{+0.59}_{-0.65}$	$10.28^{+0.78}_{-0.64}$	$0.45^{+0.36}_{-0.12}$	$0.22^{+0.04}_{-0.04}$	$1.18^{+0.11}_{-0.19}$

Butt'24

The Joint Analysis - VS Masses

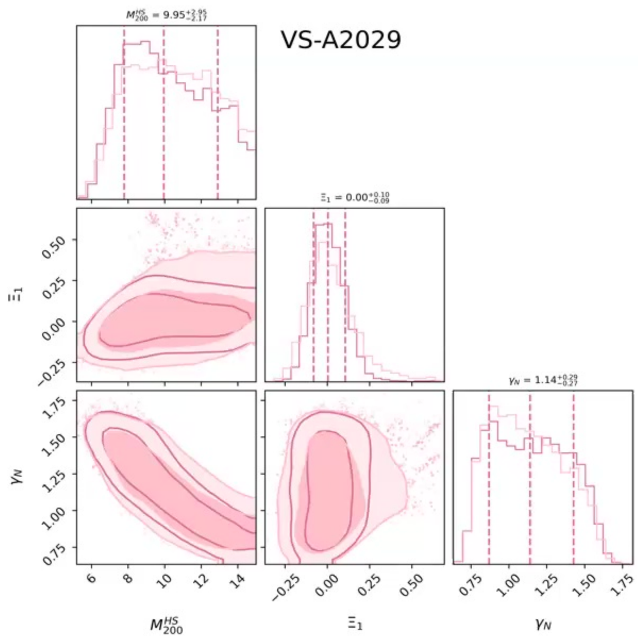


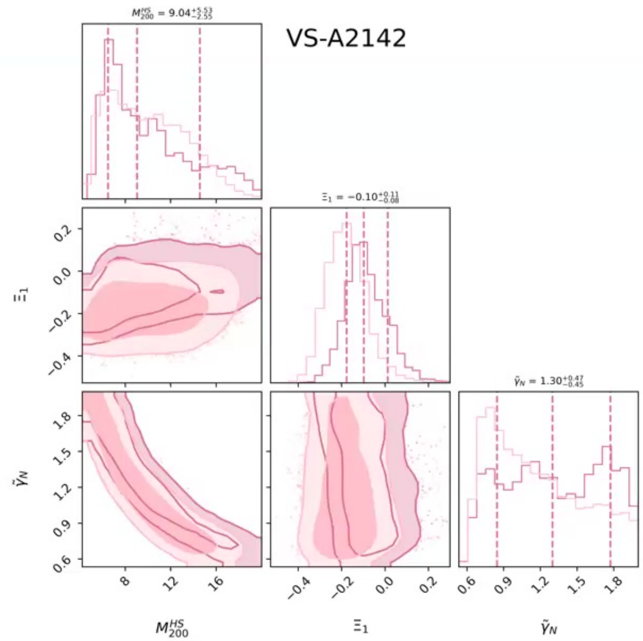


Cluster	$R_{200}^{\rm HS}$ (Mpc)	Ξ_1	$\tilde{\gamma}_{\rm N} M_{200}^{\rm HS}$	$\mathcal{F}_\beta(r)$	$R_{200}^{\rm Cau}$ (Mpc)	$\tilde{\gamma}_{\rm N} M_{200}^{\rm Cau}$ $(10^{14} M_\odot)$	$\tilde{\gamma}_{\rm N} M_{200}^{\rm Joint}$ $(10^{14} M_\odot)$	Ξ_1	$M_{200}^{\rm HS}/M_{200}^{\rm Cau}$
A2029	$2.09^{+0.11}_{-0.09}$	$-0.04^{+0.19}_{-0.12}$	$11.16^{+1.92}_{-1.40}$	HS	$2.10^{+0.04}_{-0.04}$	$11.32^{+0.68}_{-0.64}$	$11.15^{+1.15}_{-1.01}$	$-0.00^{+0.10}_{-0.09}$	$0.98^{+0.15}_{-0.11}$
				0.50	$1.86^{+0.03}_{-0.03}$	$7.84^{+0.39}_{-0.38}$	$8.78^{+0.53}_{-0.44}$	$-0.18^{+0.06}_{-0.06}$	$1.43^{+0.25}_{-0.19}$
A2142	$2.04^{+0.07}_{-0.06}$	$-0.20^{+0.10}_{-0.08}$	$10.50^{+1.04}_{-0.87}$	HS	$2.19^{+0.05}_{-0.05}$	$13.01^{+0.96}_{-0.90}$	$11.80^{+1.05}_{-0.94}$	$-0.10^{+0.11}_{-0.06}$	$0.81^{+0.09}_{-0.07}$
				0.50	$2.01^{+0.04}_{-0.04}$	$10.04^{+0.64}_{-0.62}$	$10.21^{+0.60}_{-0.58}$	$-0.21^{+0.07}_{-0.06}$	$1.05^{+0.13}_{-0.11}$

Butt'24

The Joint Analysis - VS Masses

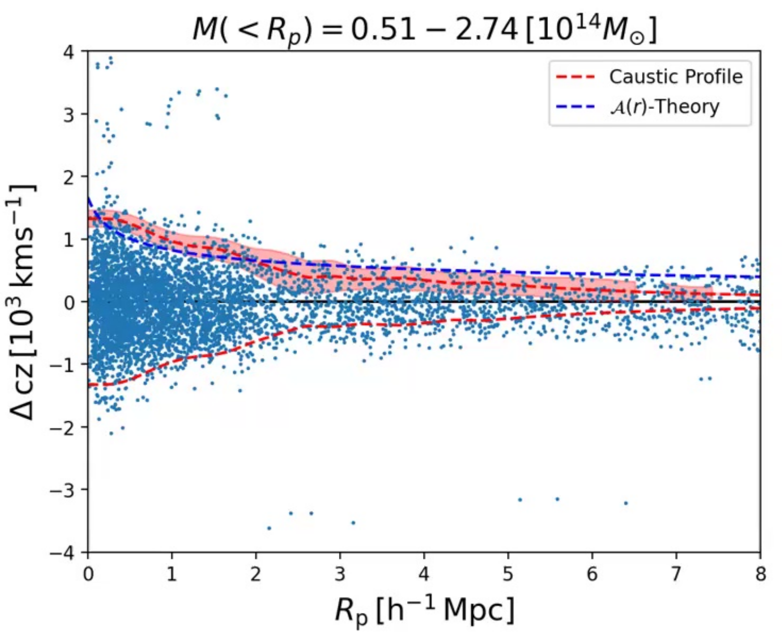




Cluster	$R_{200}^{\rm HS}$ (Mpc)	Ξ_1	$\tilde{\gamma}_{\rm N} M_{200}^{\rm HS}$	$\mathcal{F}_\beta(r)$	$R_{200}^{\rm Cau}$ (Mpc)	$\tilde{\gamma}_{\rm N} M_{200}^{\rm Cau}$ $(10^{14} M_\odot)$	$\tilde{\gamma}_{\rm N} M_{200}^{\rm Joint}$ $(10^{14} M_\odot)$	Ξ_1	$M_{200}^{\rm HS}/M_{200}^{\rm Cau}$
A2029	$2.09^{+0.11}_{-0.09}$	$-0.04^{+0.19}_{-0.12}$	$11.16^{+1.92}_{-1.40}$	HS	$2.10^{+0.04}_{-0.04}$	$11.32^{+0.68}_{-0.64}$	$11.15^{+1.15}_{-1.01}$	$-0.00^{+0.10}_{-0.09}$	$0.98^{+0.15}_{-0.11}$
				0.50	$1.86^{+0.03}_{-0.03}$	$7.84^{+0.39}_{-0.38}$	$8.78^{+0.53}_{-0.44}$	$-0.18^{+0.06}_{-0.06}$	$1.43^{+0.25}_{-0.19}$
A2142	$2.04^{+0.07}_{-0.06}$	$-0.20^{+0.10}_{-0.08}$	$10.50^{+1.04}_{-0.87}$	HS	$2.19^{+0.05}_{-0.05}$	$13.01^{+0.96}_{-0.90}$	$11.80^{+1.05}_{-0.94}$	$-0.10^{+0.11}_{-0.06}$	$0.81^{+0.09}_{-0.07}$
				0.50	$2.01^{+0.04}_{-0.04}$	$10.04^{+0.64}_{-0.62}$	$10.21^{+0.60}_{-0.58}$	$-0.21^{+0.07}_{-0.06}$	$1.05^{+0.13}_{-0.11}$

Butt’24

Stacked Clusters - Methodology



$$-2\Phi(r) = \mathcal{A}^2(r)g(\beta) \equiv \Phi_\beta(r)g(\beta)$$

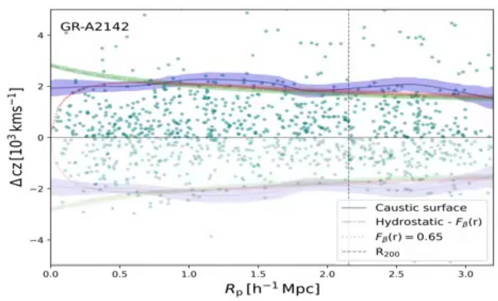
$$GM(<r) = \int_0^r \mathcal{A}^2(r)\mathcal{F}_\beta(r)dr$$

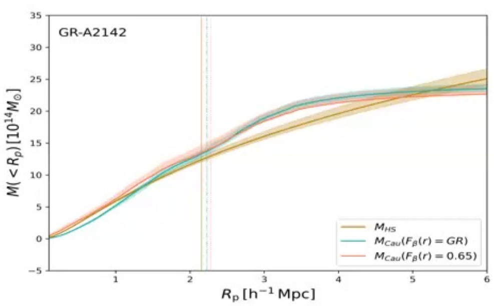
$$g(\beta) = \frac{3 - 2\beta(r)}{1 - \beta(r)}$$

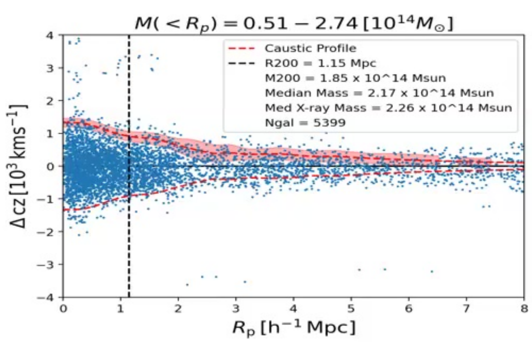
On Stacked Clusters!

Without hydrostatic data!

$$\mathcal{A}^2(r)(M_{200}, c_{200})$$







Summary

- Alleviated the mass bias between hydrostatic and caustic mass by applying cluster specific assumptions from the hydrostatic technique within the caustic technique.
- Applied this method to clusters A2029 and A2142 in the GR, CS and VS scenarios.
- Applying a similar formalism, without hydrostatic data, to stacked galaxy clusters to obtain tighter constraints.