BiCoQ conference - 16/06/2026

TESTING GRAVITY THEORIES WITH GRAVITATIONAL REDSHIFT IN GALAXY CLUSTERS

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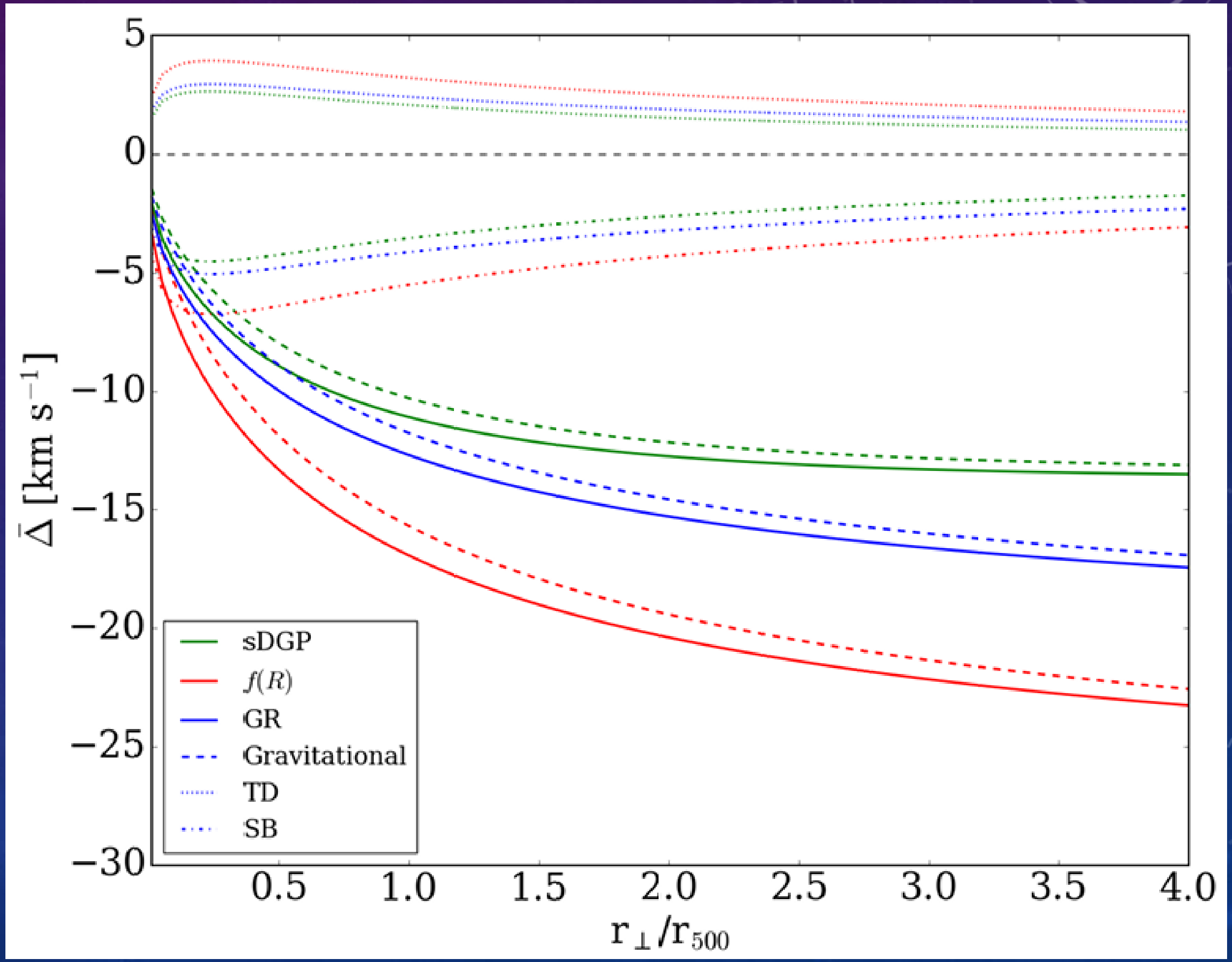
GRAVITATIONAL REDSHIFT: A PROBE FOR GALAXY CLUSTERS

Gravitational redshift (GRS) in galaxy clusters shifts the measured line-of-sight velocity values of cluster members

$$1 + z = \frac{\lambda_{obs}}{\lambda_{ref}} = \frac{\lambda_{cosm}}{\lambda_{ref}} \frac{\lambda_{pot}}{\lambda_{cosm}} \frac{\lambda_{obs}}{\lambda_{pot}} = (1 + z_{cosm})(1 + z_{GRS})(1 + \frac{v_{los}}{c})$$

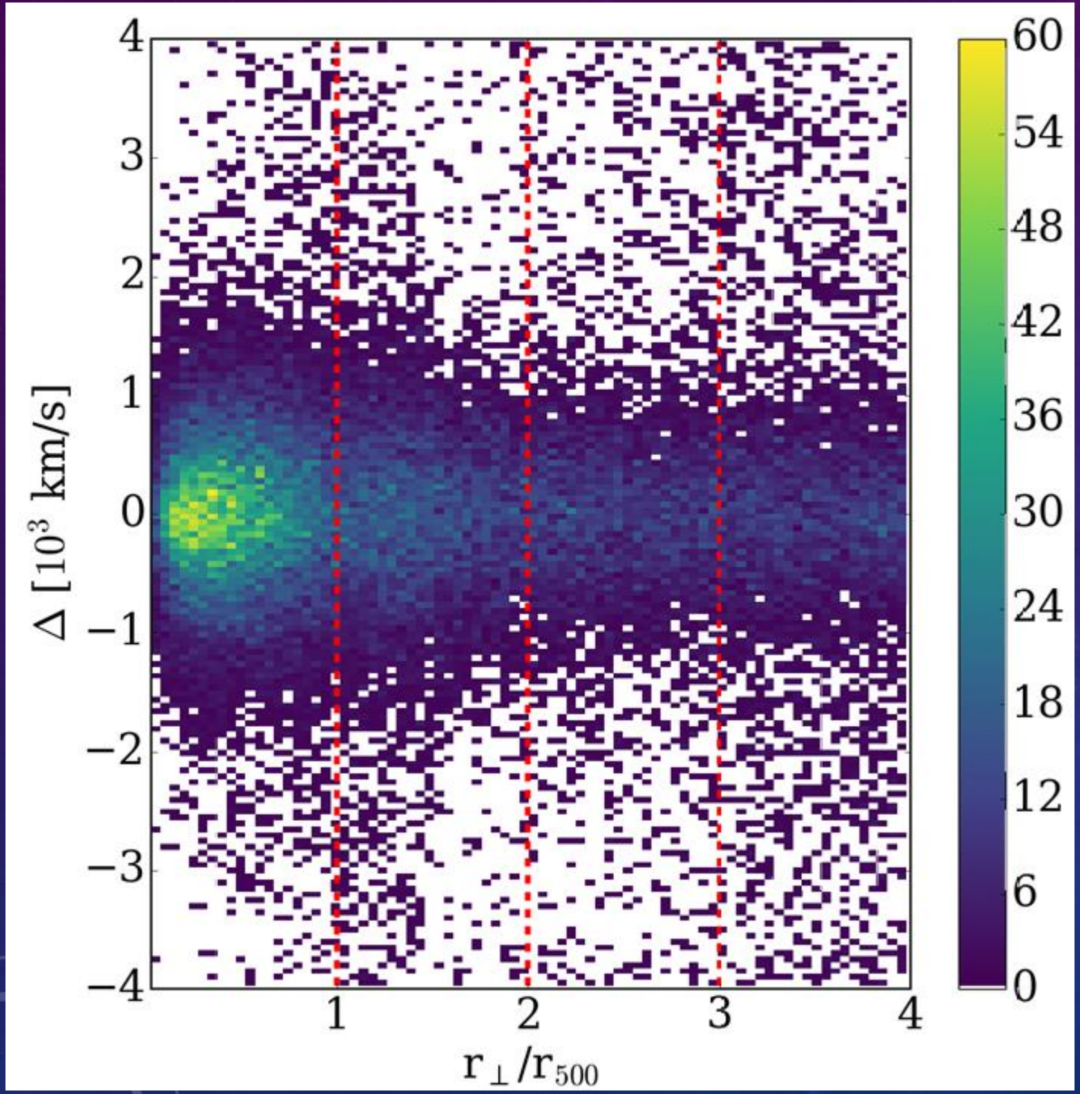
$$z_{GRS} = \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}} \simeq \frac{\Phi(\boldsymbol{x}_{obs}) - \Phi(\boldsymbol{x}_{em})}{c^2}$$

The predicted GRS is strongly dependent on the selected gravity model, thus a precise measurement of GRS-induced shifts can probe deviations from General Relativity



Rosselli et al. 2023, A&A, Volume 669, id.A29

DIRECT DETECTION METHOD



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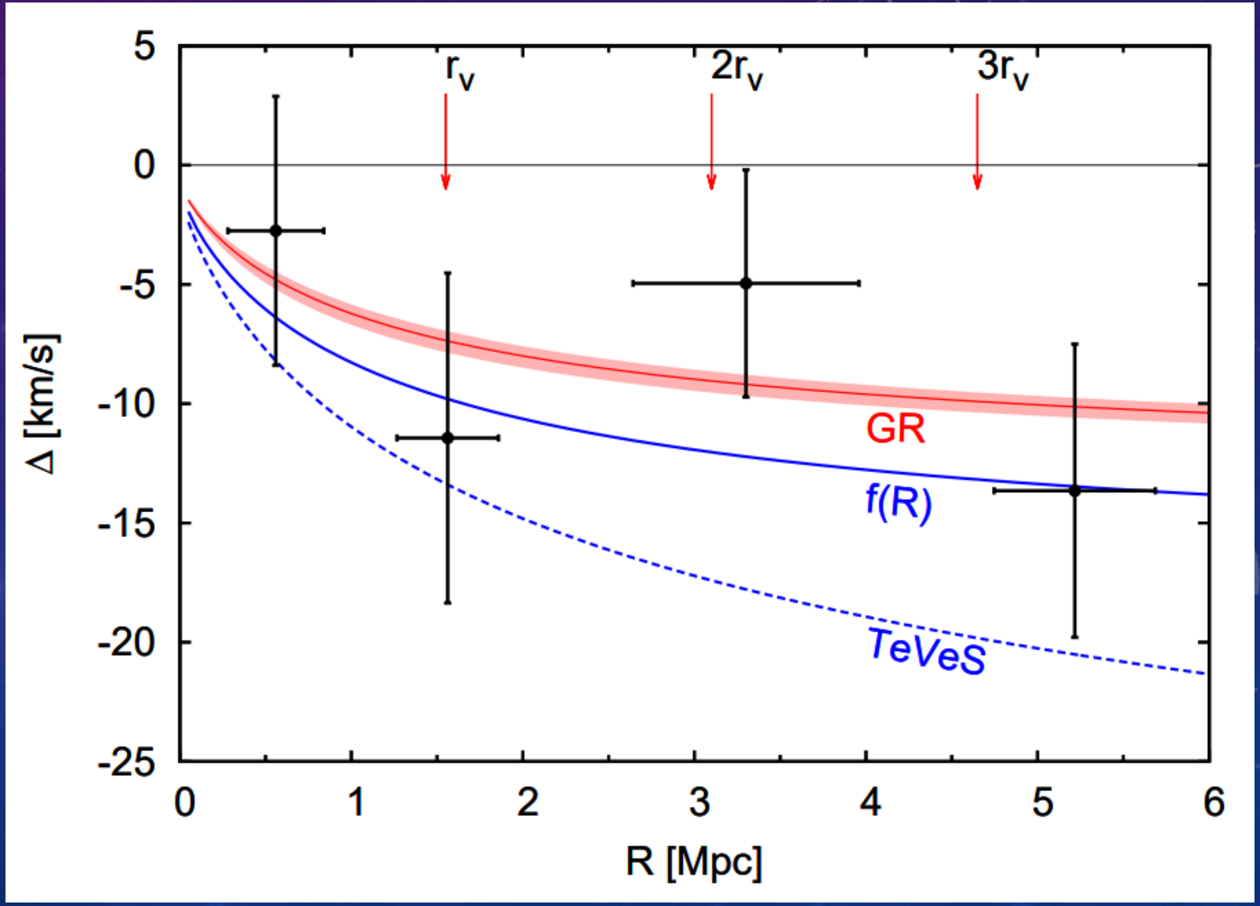
Direct detection is done by stacking large cluster member samples ($\approx 10^5$) in the same projected phase-space (PPS)



Wojtak et al. 2011, Nature, Volume 477, Issue 7366, pp. 567-569

SYSTEMATICS AND OBSERVATIONAL EFFECTS

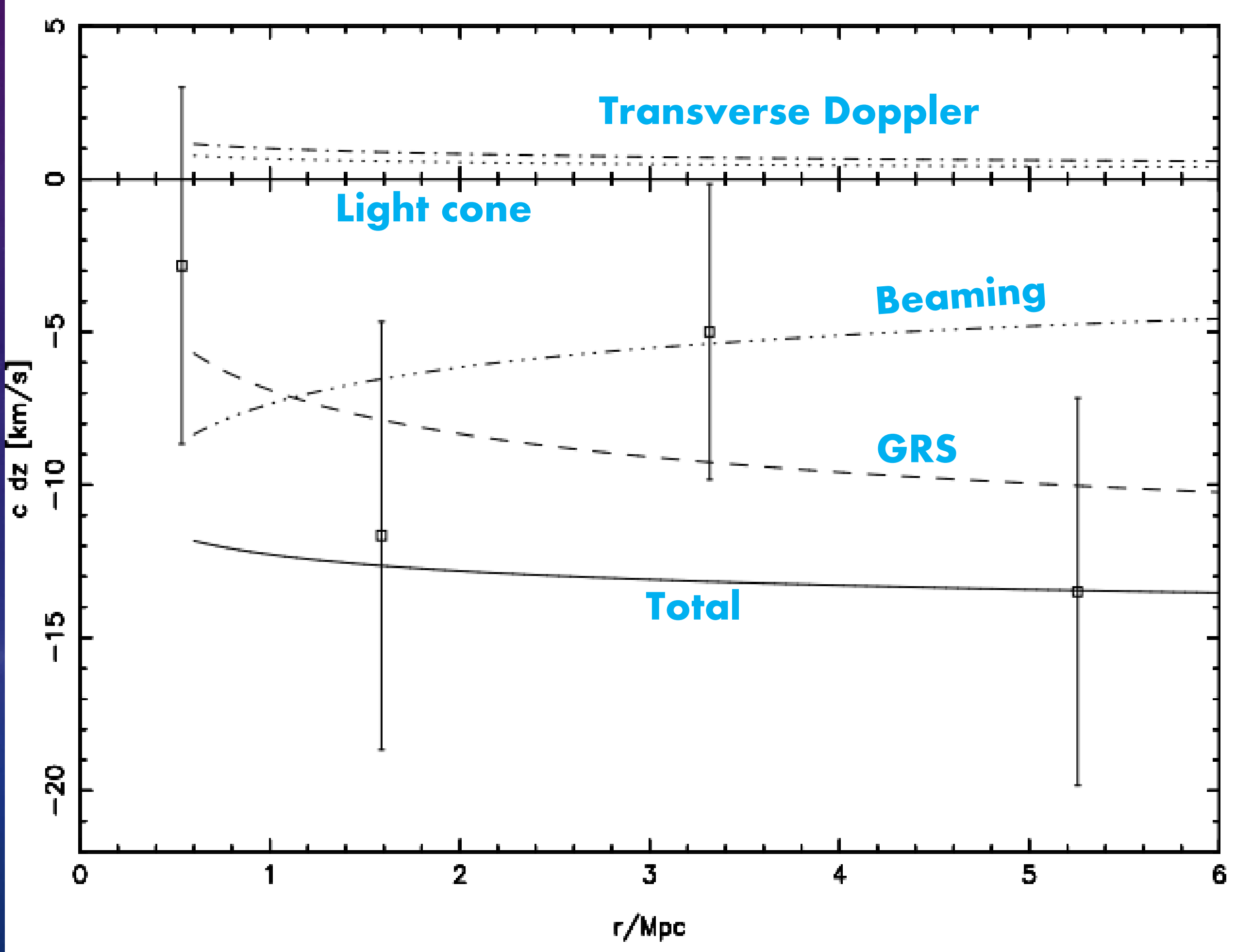
The PPS distortions are induced by the way we define the galaxy cluster rest-frame

Choosing the ***BCG redshift*** or the ***mean redshift*** makes all of the difference!!!

$$v_{\rm meas} = \frac{z - z_{\rm cosm}}{1 + z_{\rm cosm}} \equiv \frac{z - z_{\rm ref}}{1 + z_{\rm ref}}$$

$$v_{\rm meas} = c(z_{\rm GRS} - z_{\rm GRS}^{\rm max}) + v_{\rm los} - v_{\rm BCG}$$

$$v_{\rm meas} = \left[z_{\rm GRS} - \langle z_{\rm GRS}\rangle + \frac{v_{\rm los}}{c}\right] c$$



Kaiser 2013, MNRAS, Volume 435, Issue 2, p.1278-1286

THE GRAGAS METHOD

I developed a new approach, sensitive to the slight *deformation* of a cluster projected phase-space (PPS) induced by gravitational redshift, that exploits all the PPS points *without* any binning

➡ **Gravitational Redshift Analysis in GAlaxy clusters Software (GRAGAS)**

$$v_{\mathrm{RF}} - \Delta_{\mathrm{GRS}}(R, \vec{\theta}) = \mathcal{N}(0, \sigma_{\mathrm{LOS}}(R))$$

⬇

$$\mathcal{L}_{\mathrm{tot}}(r_0, \boldsymbol{\theta}) = \prod_{i=1}^{N} \frac{1}{\sqrt{2\pi\sigma^2_{\mathrm{tot},i}(R_i, \boldsymbol{\theta})}} \exp\left\{-\frac{[v_{\mathrm{meas},i} - \Delta_{\mathrm{GRS}}(R_i, r_0, \boldsymbol{\theta})]^2}{2\sigma^2_{\mathrm{tot},i}(R_i, \boldsymbol{\theta})}\right\}$$

THE GRAGAS METHOD

GRAGAS performs a parametric fit of the PPS:

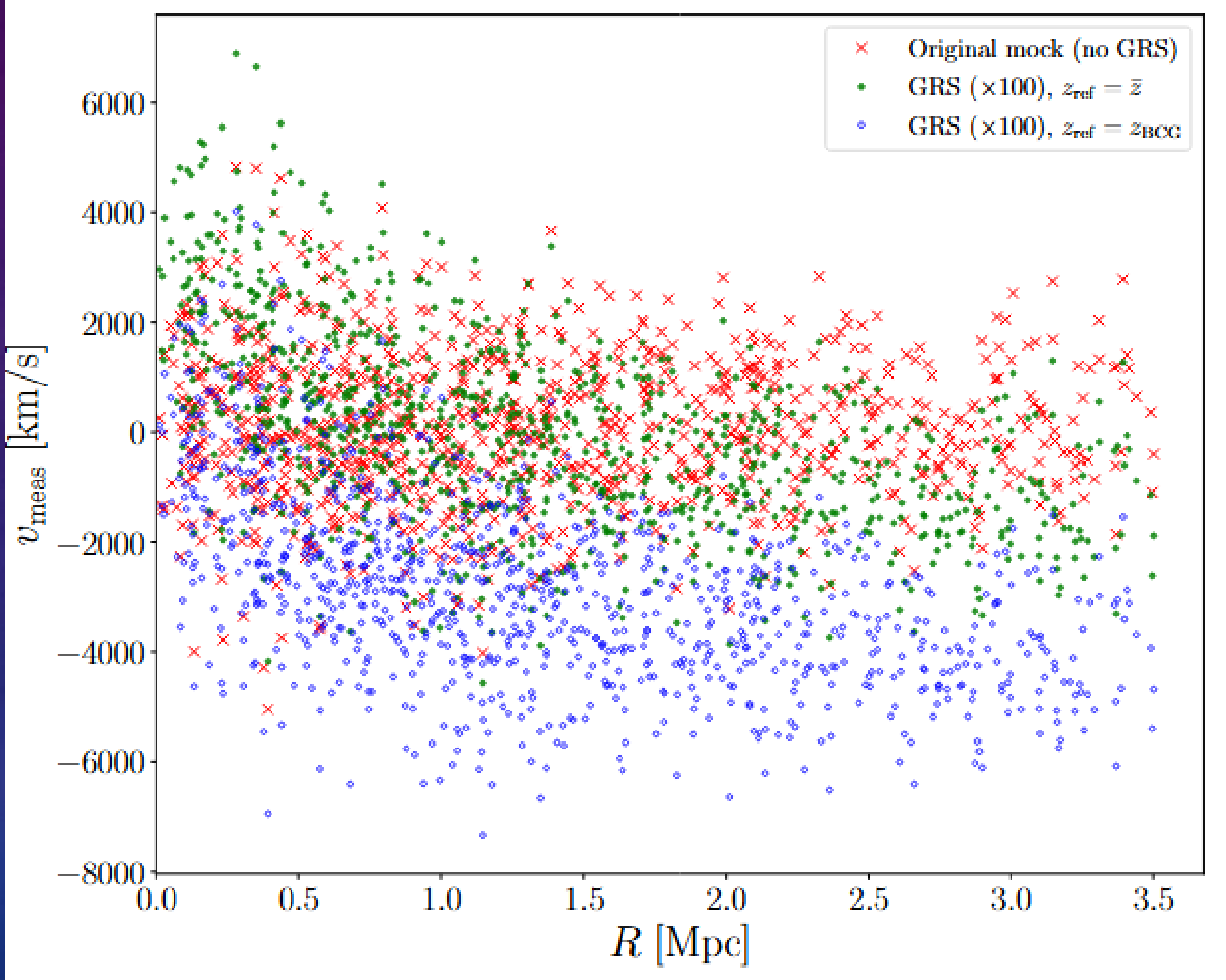
$$\Sigma(R)\,\sigma_z^2(R) \;=\; 2\int_R^\infty \nu\sigma_r^2\left[1-\beta(r)\frac{R^2}{r^2}\right]\frac{r\,\mathrm{d}r}{\sqrt{r^2-R^2}}$$

$$\sigma_r^2(r) = \frac{1}{\nu(r)}\int_r^\infty \exp\left[2\int_r^s \beta(t)\frac{\mathrm{d}t}{t}\right]\nu(s)\frac{GM(s)}{s^2}\,\mathrm{d}s$$

$$\Delta_\mathrm{s}(R) = \frac{2}{c\Sigma(R)}\int_R^\infty [\Phi(r)-\Phi(0)]\frac{\rho(r)r\mathrm{d}r}{\sqrt{r^2-R^2}}$$

$(\boldsymbol{r_0})$

6 free parameters: $R_{200}, r_\nu, r_s, \beta_0, \beta_\infty, r_0$



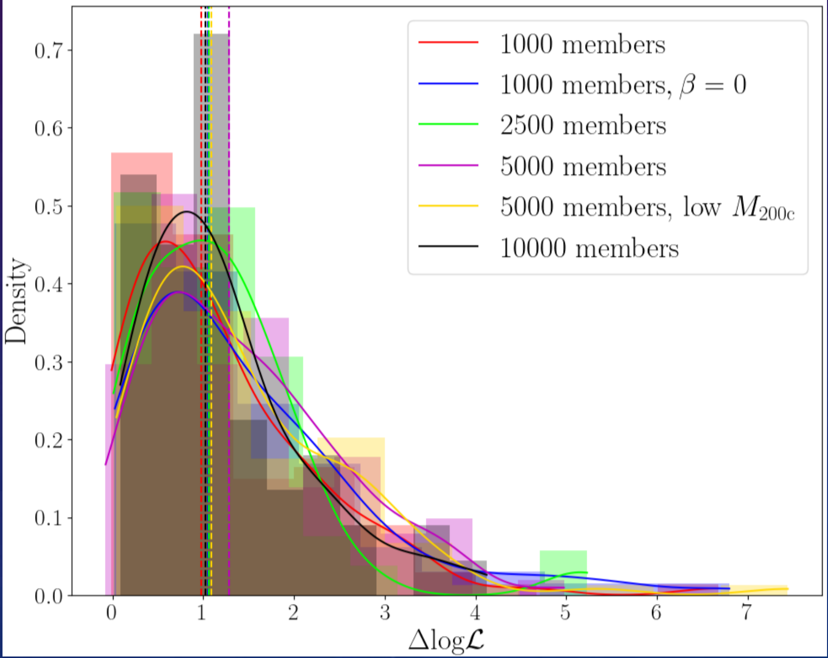
Maraboli et al., in prep.

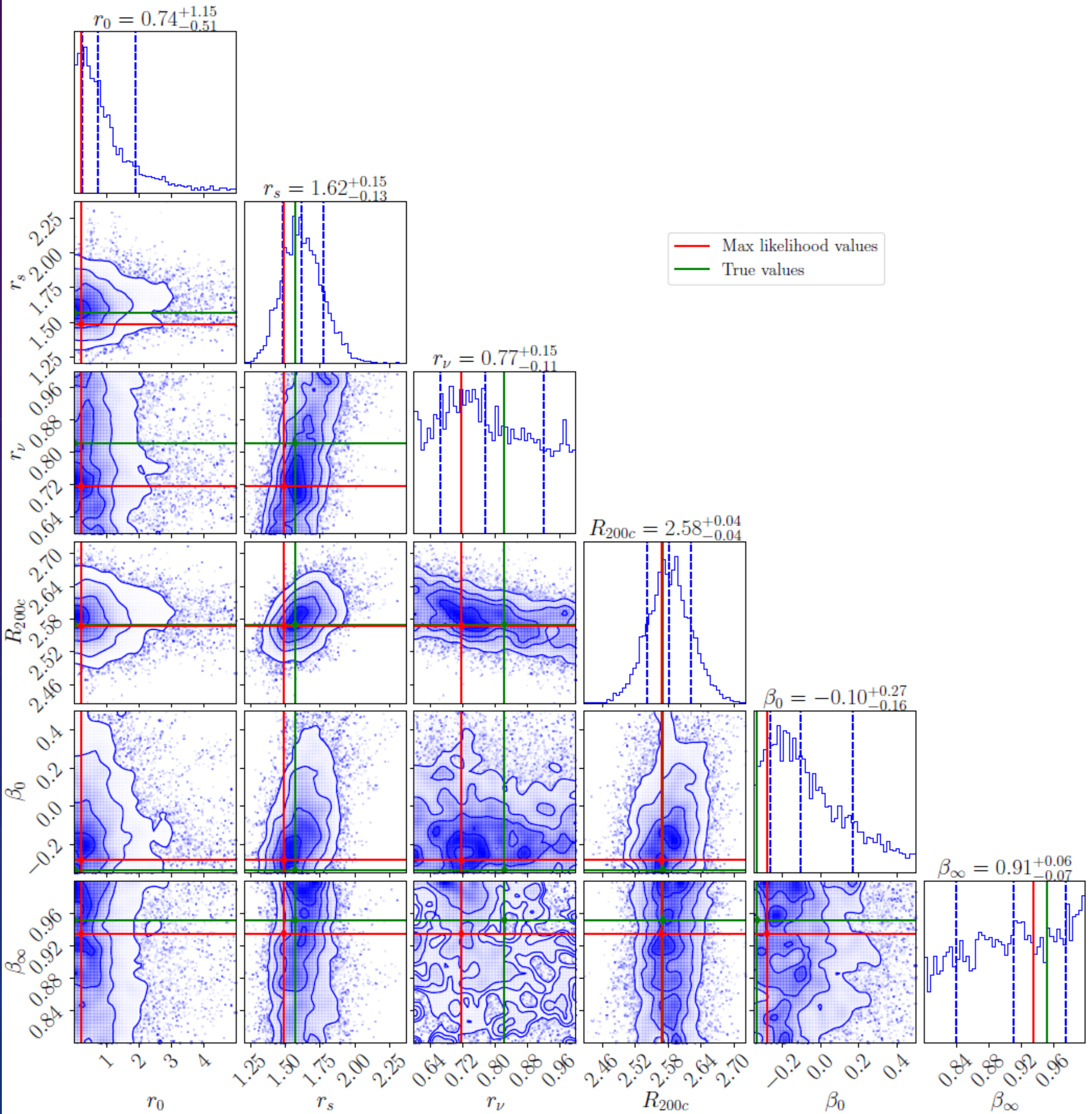
GRAGAS VALIDATION

GRAGAS performances were evaluated on different sets of *mock galaxy clusters*

N_{mem}	M_{200c} [$M_\odot$]	r_ν [Mpc]	r_s [Mpc]	β_0	β_∞
1000	2.57×10^{15}	0.82	1.54	-0.33	0.95
1000	2.57×10^{15}	0.82	1.54	0	0
2500	2.57×10^{15}	0.82	1.54	-0.33	0.95
5000	2.57×10^{15}	0.82	1.54	-0.33	0.95
5000	1.14×10^{15}	0.82	1.4	0.4	0.9
10 000	2.57×10^{15}	0.82	1.54	-0.33	0.95

The dynamical analyses on the mock clusters showed a mild preference for a GRS-including model, thus indicating an indirect detection through likelihood comparison





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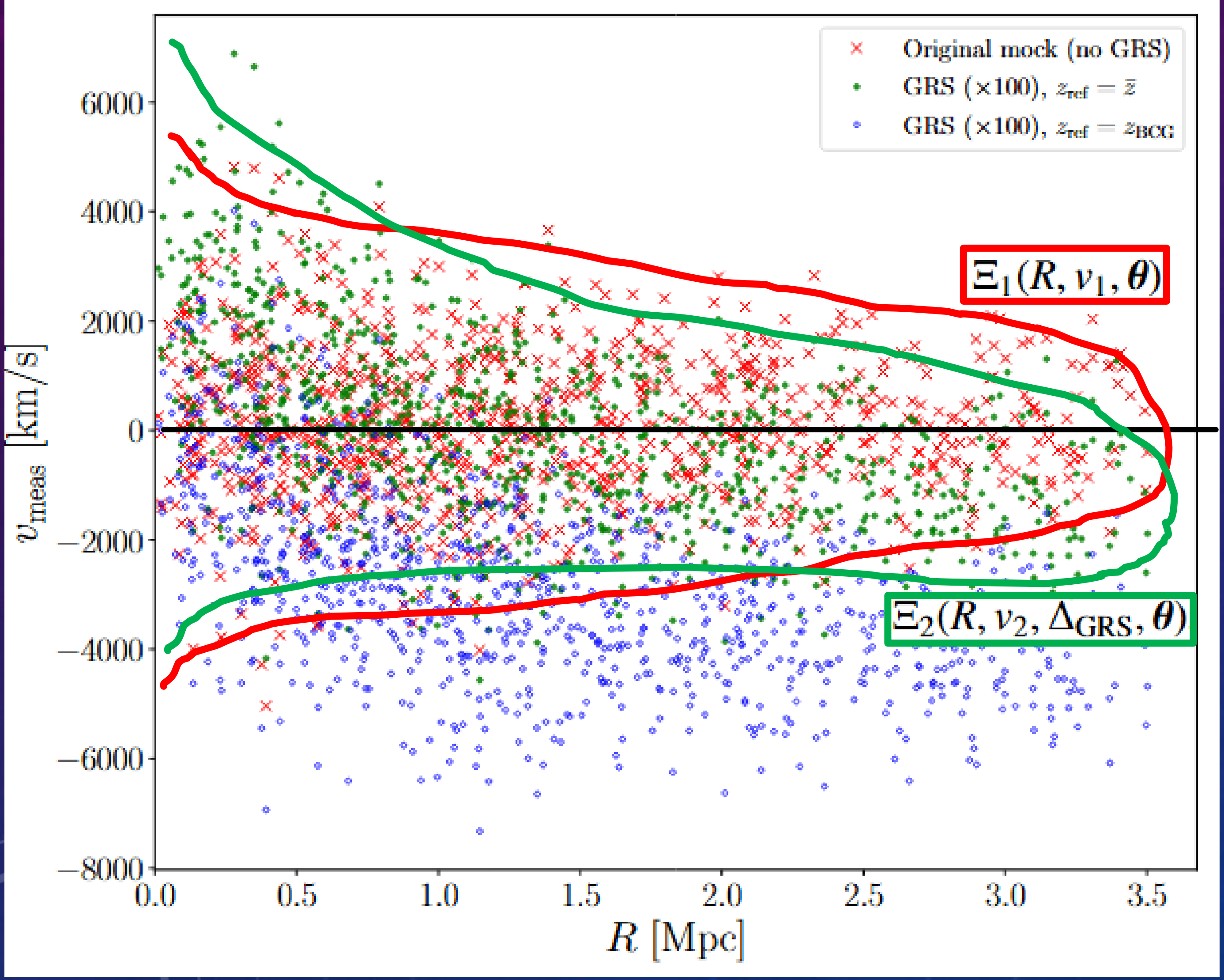
OVERESTIMATE OF LOS VELOCITY DISPERSION



At any projected radius:

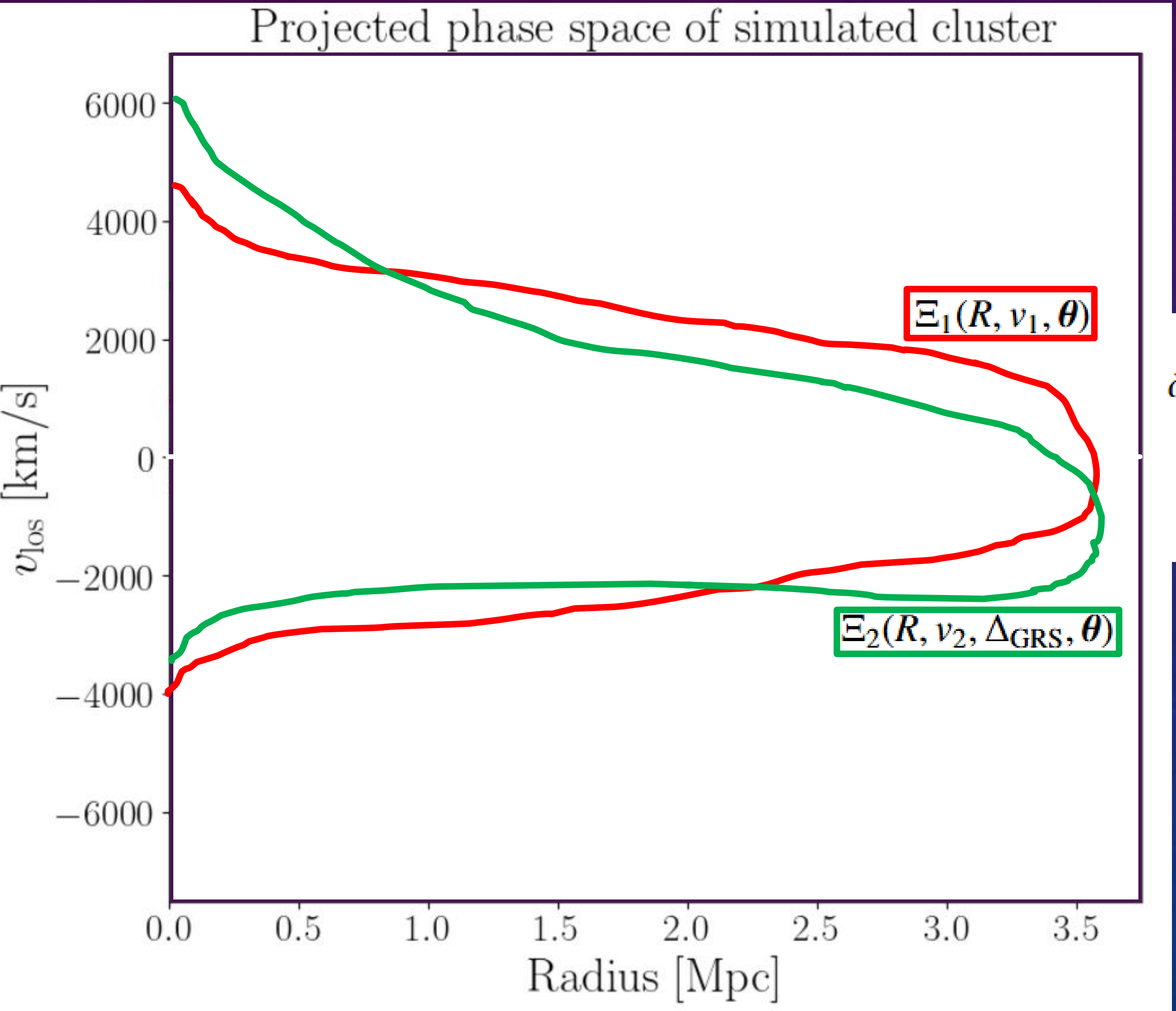
$$v_{1,i} \; : \; \mathbb{E}(v_1) \propto \int_{-\infty}^{+\infty} v_1 \Xi_1 \mathrm{d}v_1 = 0$$

$$v_{2,i} \; : \mathbb{E}(v_2) \propto \int_{-\infty}^{+\infty} v_2 \Xi_2 \mathrm{d}v_2 = \Delta_{GRS}$$

By construction:

$$\sigma_2^2 = \sigma_1^2 \propto \int_{-\infty}^{+\infty} [v_1 - \mathbb{E}(v_1)]^2 \Xi_1 \mathrm{d}v_1 = \int_{-\infty}^{+\infty} [v_2 - \mathbb{E}(v_2)]^2 \Xi_2 \mathrm{d}v_2$$

OVERESTIMATE OF LOS VELOCITY DISPERSION



$$\tilde{\sigma}_2^2 = \frac{1}{N}\int_{-\infty}^{+\infty}[v_2 - \mathbb{E}(v_1)]^2 \Xi_1 dv_2 =$$

$$= \frac{1}{N}\int_{-\infty}^{+\infty}[v_1 + \Delta_{GRS}]^2 \Xi_1 dv_1 = \sigma_1^2 + \frac{\Delta_{GRS}^2}{N} \geq \sigma_1^2$$

Possible overestimate of virial mass!!!

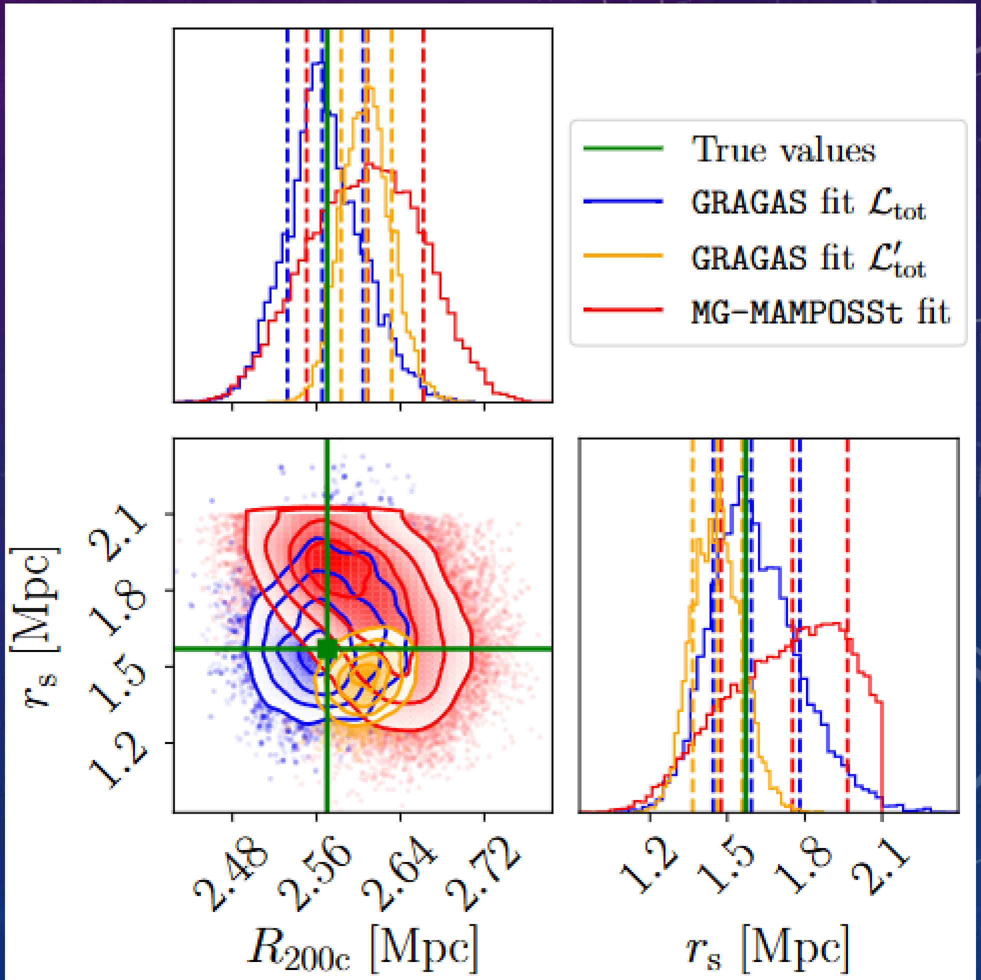
GRS, VIRIAL MASSES AND ANISOTROPY VALUES

The GRS-induced distortion, if not accounted for with a dedicated model, may introduce a bias on $\boldsymbol{M_{200}}$ measurements

Depending on the algorithm, the σ_{LOS} overestimate can bias both velocity anysotropy measurements and virial mass measurements

When virial quantities are biased, empirically I find a ≈**1.7%** difference in R_{200}

This translates roughly in ≈**5% overestimate of** $\boldsymbol{M_{200}}$**!**



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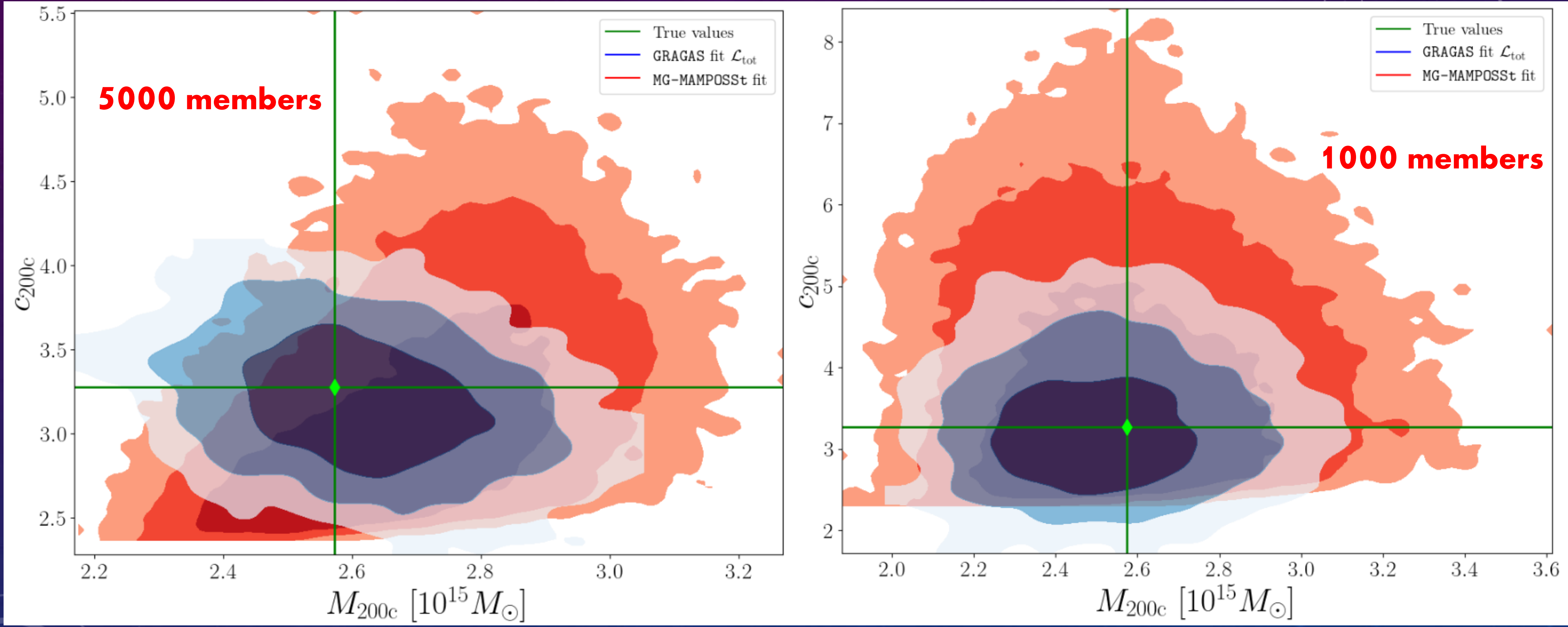
EFFECTS ON COSMOLOGICAL CONSTRAINTS



TAKE-HOME MESSAGES

Hire me!
I'm on the job market!

- GRAGAS is sensitive to the GRS-induced distortions of the PPS (validated on mock galaxy clusters), thus it provides a more accurate and refined dynamical model
- Not accounting for GRS effects in massive galaxy clusters may lead to a $\approx 5\%$ overestimate of M_{200}!
- GRS has to be accounted for advanced calibrations of cosmological scaling relations (e.g. mass-concentration relation)

THANK YOU!