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A new era for Galaxy Clusters

Testing gravity and the dark sector using mass profile reconstructions

16/06/2026

1° BiCoQ Conference: *from gravity to particles*

Anatomy of a galaxy cluster

- Typically a **few Mpc across**, $M \sim 10^{14} \div 10^{15}\, M_\odot$
- $10^2 \div 10^3$ **galaxies** ($\sim 5\%$ of the total mass)

Abell 2390 Credits: ESA/XMM-Newton/Euclid/Euclid Consortium/NASA

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- $10^{2} \div 10^{3}$ **galaxies** ($\sim 5\%$ of the total mass)
- Hot gas at $T \sim 10^{7} - 10^{8}\ K$: **Intra Cluster Medium (ICM),** X-ray emission via bremmstrahlung ($\sim 10 - 15\%$ of the total mass)
- **Cold Dark matter component** ($\sim 80 - 85\%$ of the total mass)

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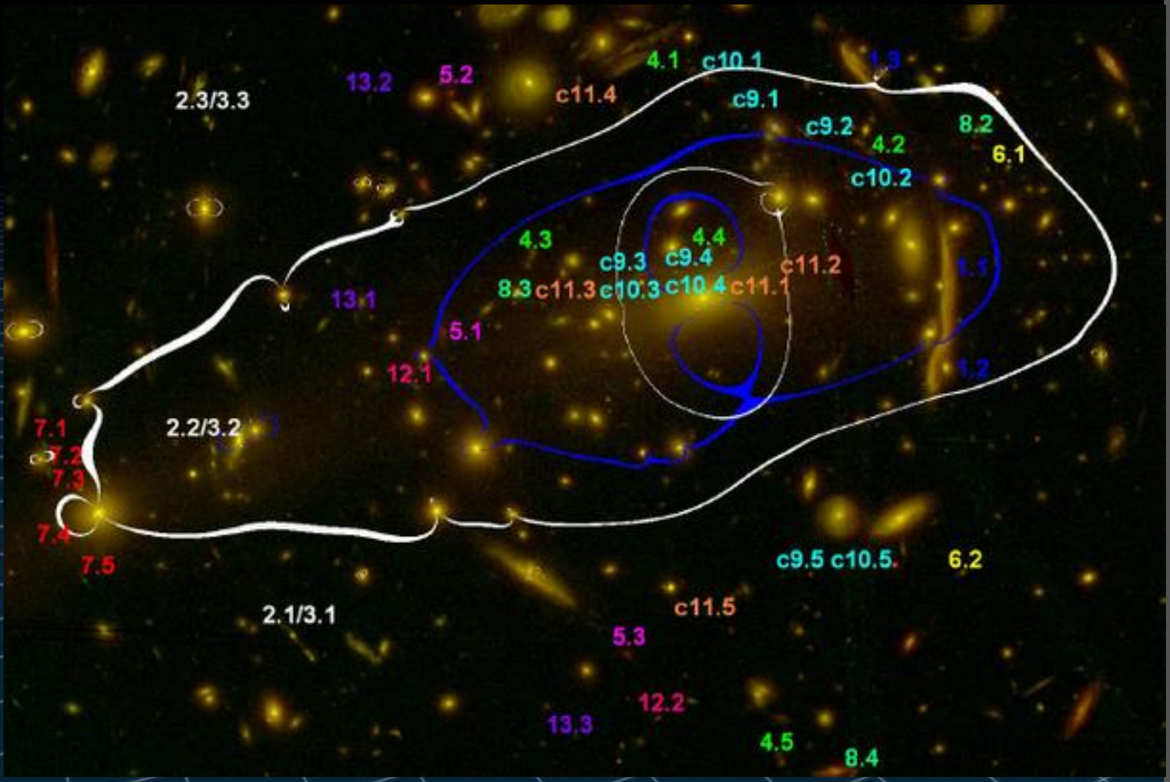
Excellent natural laboratories between cosmology and astrophysics

Galaxy cluster mass profiles: lensing



High-quality imaging and photometric data required

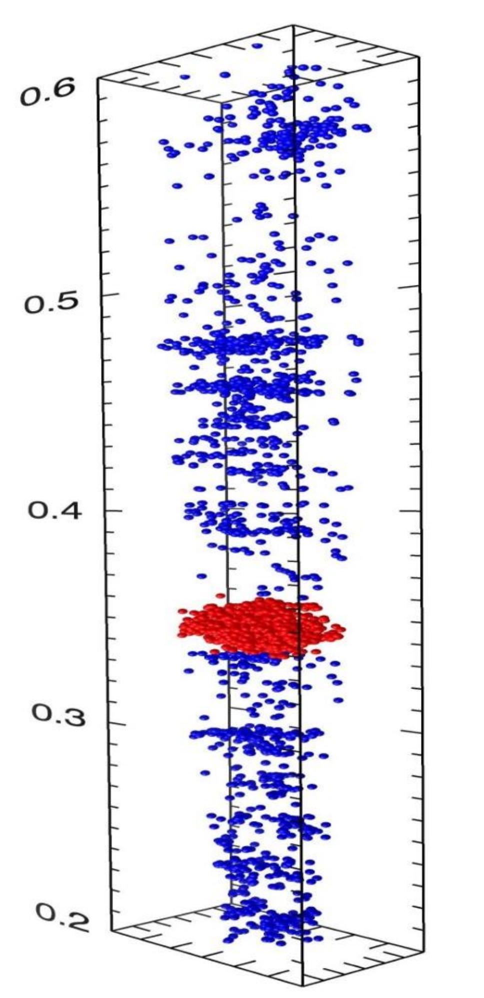
Light deflected by **gravitational potential** → estimation of mass by distortion of background sources

Strong lensing analysis: projected mass profile in the inner cluster region

Weak lensing analysis: projected mass profile in the outer cluster region

Assumptions in de-projection to recover the 3D mass

Galaxy cluster mass profiles: kinematics



Member galaxies of the cluster RXJ 2248 (red points)

Spherical Jeans' equation:

$$\frac{d}{dr}\left[\boldsymbol{\nu}(\boldsymbol{r})\sigma_r^2\right] + 2\boldsymbol{\beta}(\boldsymbol{r})\frac{\nu(r)\sigma_r^2}{r} = -\nu(r)\frac{\boldsymbol{d\Phi}}{\boldsymbol{dr}}$$

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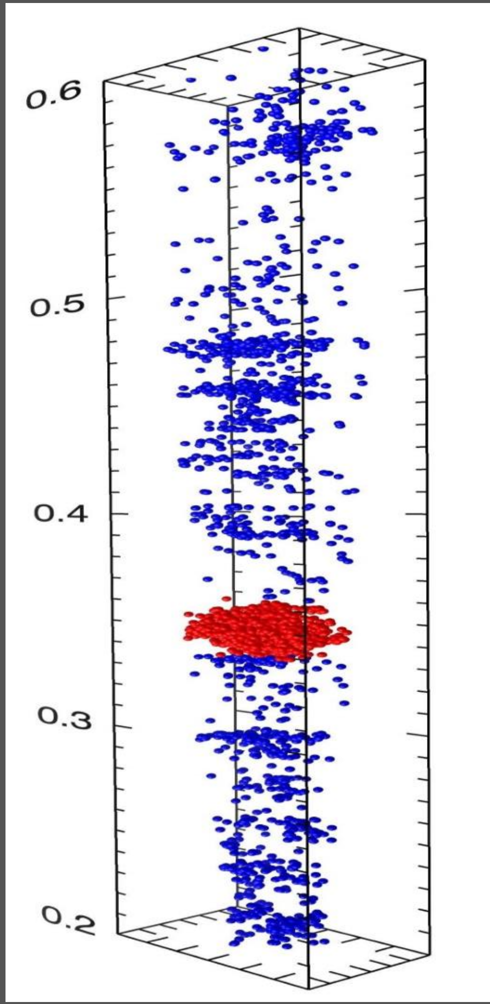

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$\nu(r) \rightarrow$ **number density** profile of the tracers

$\sigma_r^2(r) \rightarrow$ **velocity dispersion** along the radial direction

$\beta(r) = 1 - (\sigma_\phi^2 + \sigma_\theta^2)/2\sigma_r^2 \rightarrow$ **velocity anisotropy** profile

$\frac{d\Phi}{dr} = \frac{GM(r)}{r^2} \rightarrow$ **gravitational potential**

Needed velocities: spectroscopic redshift data required

Assumption of **dynamical relaxation** and **spherical symmetry**

Galaxy cluster mass profiles: dynamics vs lensing analysis

Spacetime of a galaxy cluster**: linear perturbation** of FRW metric

$$\boldsymbol{ds^2 = a^2(\tau)\left[-\left(1+\frac{2\Phi}{c^2}\right)c^2 d\tau^2 + \left(1-\frac{2\Psi}{c^2}\right)dl^2\right]},$$

$\Phi, \Psi \sim 10^{-4} c^2$ gravitational potentials

In standard GR: $\Phi = \Psi \equiv \Phi_N$

$\Phi \neq \Psi \rightarrow$ Signatures of modified gravity

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Constrain Φ, Ψ → Constrain deviation from General Relativity

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Constrain Φ, Ψ ⇨ Constrain deviation from General Relativity

Motion of galaxies (kinematic analysis): **TIME-TIME Φ**

Photons (lensing analysis): **TIME-TIME** + **SPACE-SPACE** $\Phi_{lens} = \frac{1}{2}(\Phi + \Psi)$

MG-MAMPOSSt

MAMPOSSt = Modelling Anisotropy and Mass Profile of Observed Spherical System

Developed by *Mamon, Biviano, Boué* (MNRAS 429 (Mar. 2013)3079–3098)

Jeans' equation solved in the **projected phase-pace** $(\boldsymbol{R}, \boldsymbol{v_z})$

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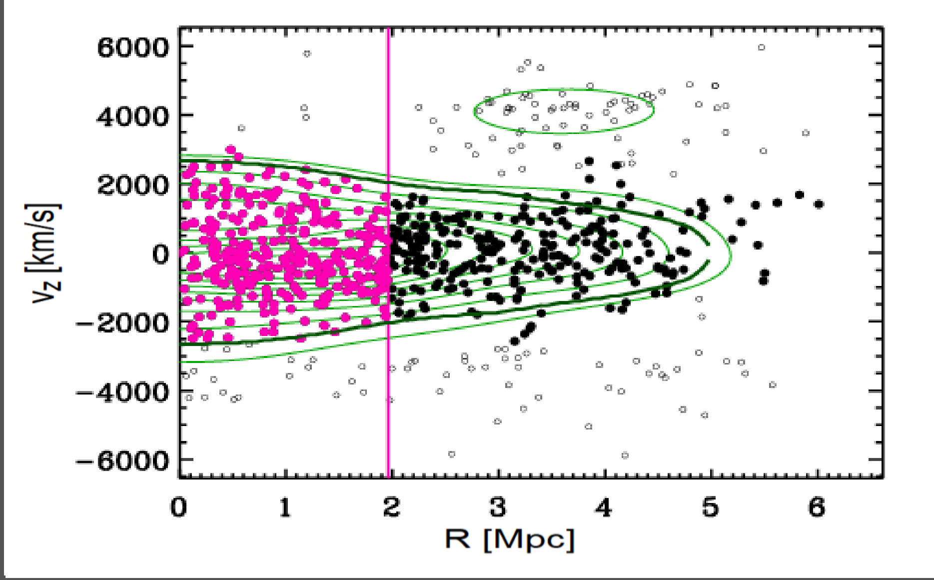
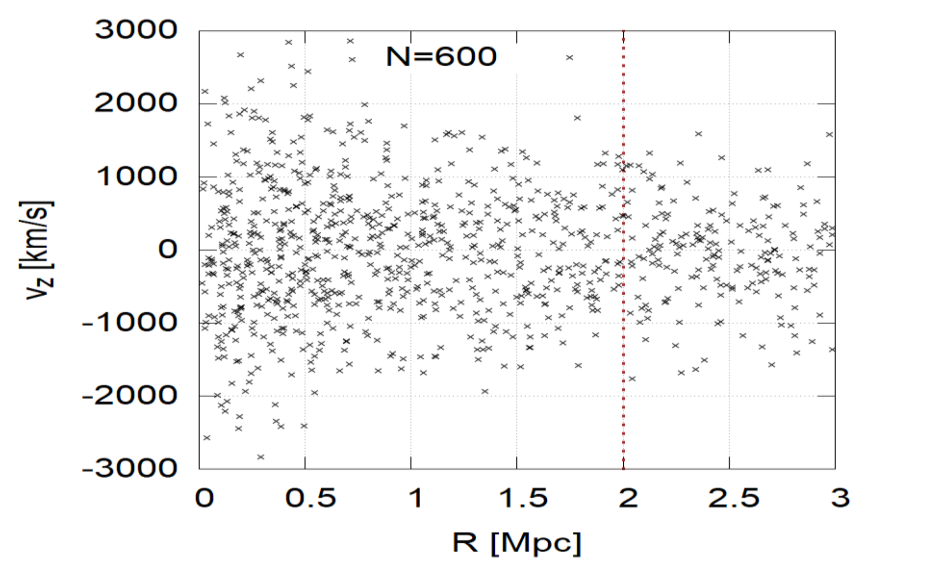
Real cluster MACS 1206 (Biviano et al., 2013)



Synthetic cluster N=600 (Pizzuti et al., 2021)



Maximum Likelihood fit to obtain the parameters of kinematics quantities

MG-MAMPOSSt ([Pizzuti L., Saltas I.D., Amendola L., 2021])

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

$\beta(r) \rightarrow$ anisotropy profile

$\nu(r) \rightarrow$ number density profile

Parameter space: GR

MG-MAMPOSSt:

- **Modified Newtonian potential**
- **Chameleon** screening, **Vainshtein** screening (DHOST)
- **Grid /MCMC** (Metropolis-Hastings) parameter space exploration.
- Simulated (weak) lensing information
- **Generalised anisotropy and BCG dynamics**

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$$\mathcal{M}_i = \begin{cases} Y_1, Y_2 & VS \\ Q, \phi_\infty & CS \\ \epsilon_0, \rho_c, Q & RG \\ f_{DE}\ c_s^2 & CDE \end{cases}$$

Parameter space: GR + non-standard params: $\mathcal{M}_1, \mathcal{M}_2, \mathcal{M}_3$

MG-MAMPOSSt:

- **Modified Newtonian potential**
- **Chameleon** screening, **Vainshtein** screening (DHOST), Refracted Gravity, Clustering DE
- **Grid /MCMC** (Metropolis-Hastings) parameter space exploration.
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An overview of what we can do…

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- Lensing + kinematics (+X-ray?)
- Test idealised scenarios (simulations) to explore new models

Constrain MG and DE models

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Constrain matter distributions in clusters

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Analysis of orbits
Mass estimations

- Mass and orbits of the CHEX-MATE clusters
- Mass and orbits of the VIRGO cluster

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Constrain alterantives to dark matter

- Refracted Gravity
- Boson stars and solitonic objects
- MOND-like models

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Constrain matter distributions in clusters

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Data from **CLASH** and **CLASH-VLT** collaborations

MACSJ-1206

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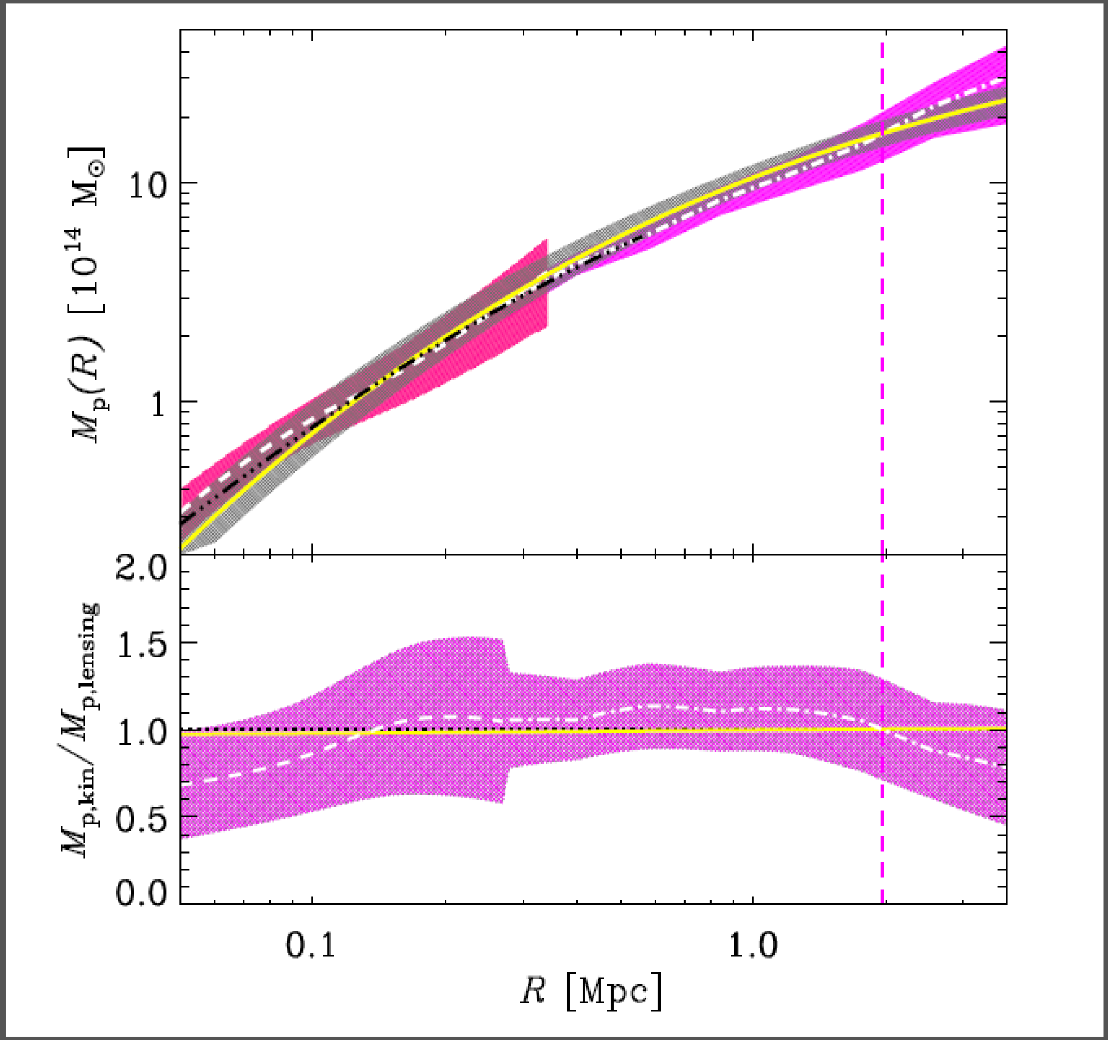
MACSJ-1206

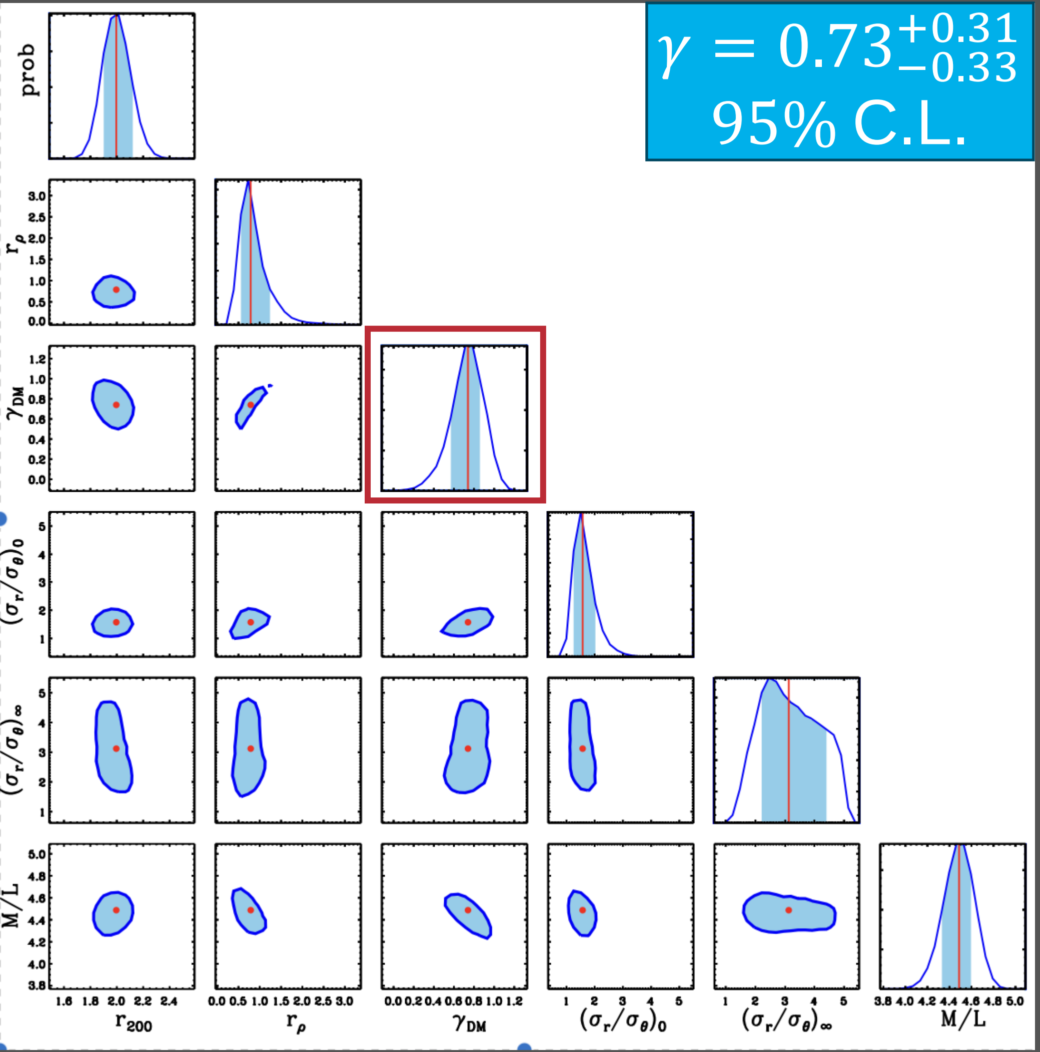
Subaru+HST. **+** VLT/VIMOS +MUSE



Credits: Biviano et al., 2013

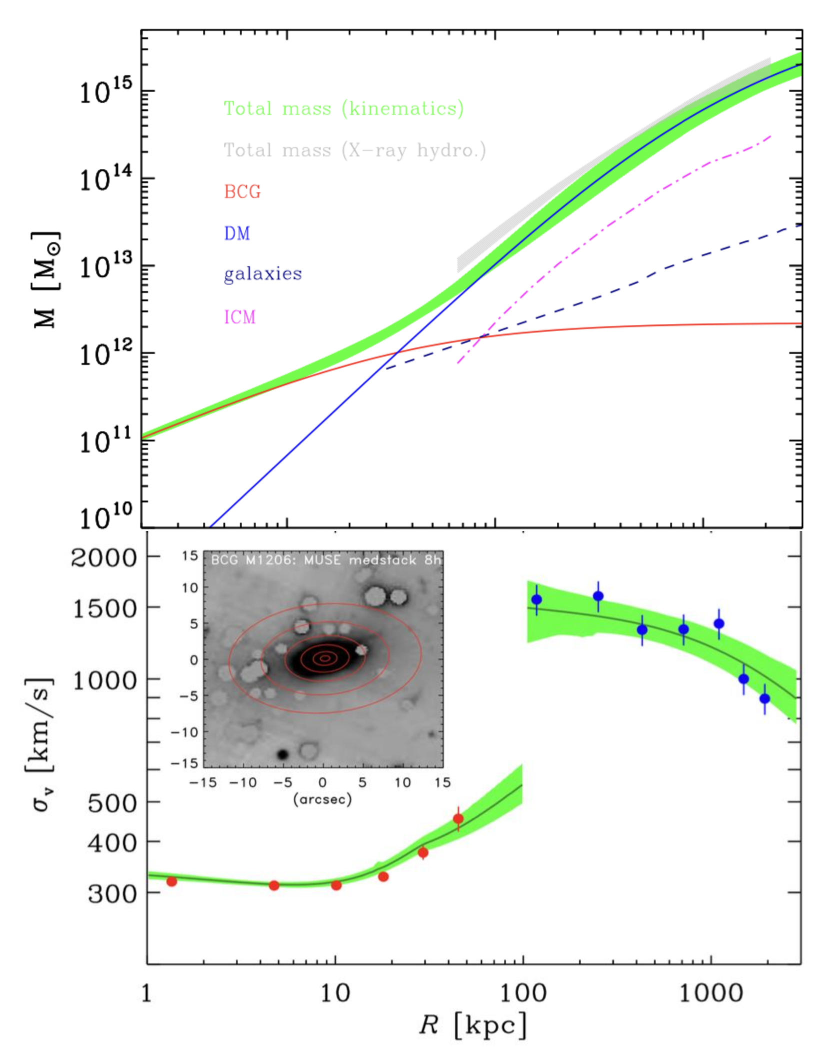
What if we further have the velocity dispersion of the BCG?

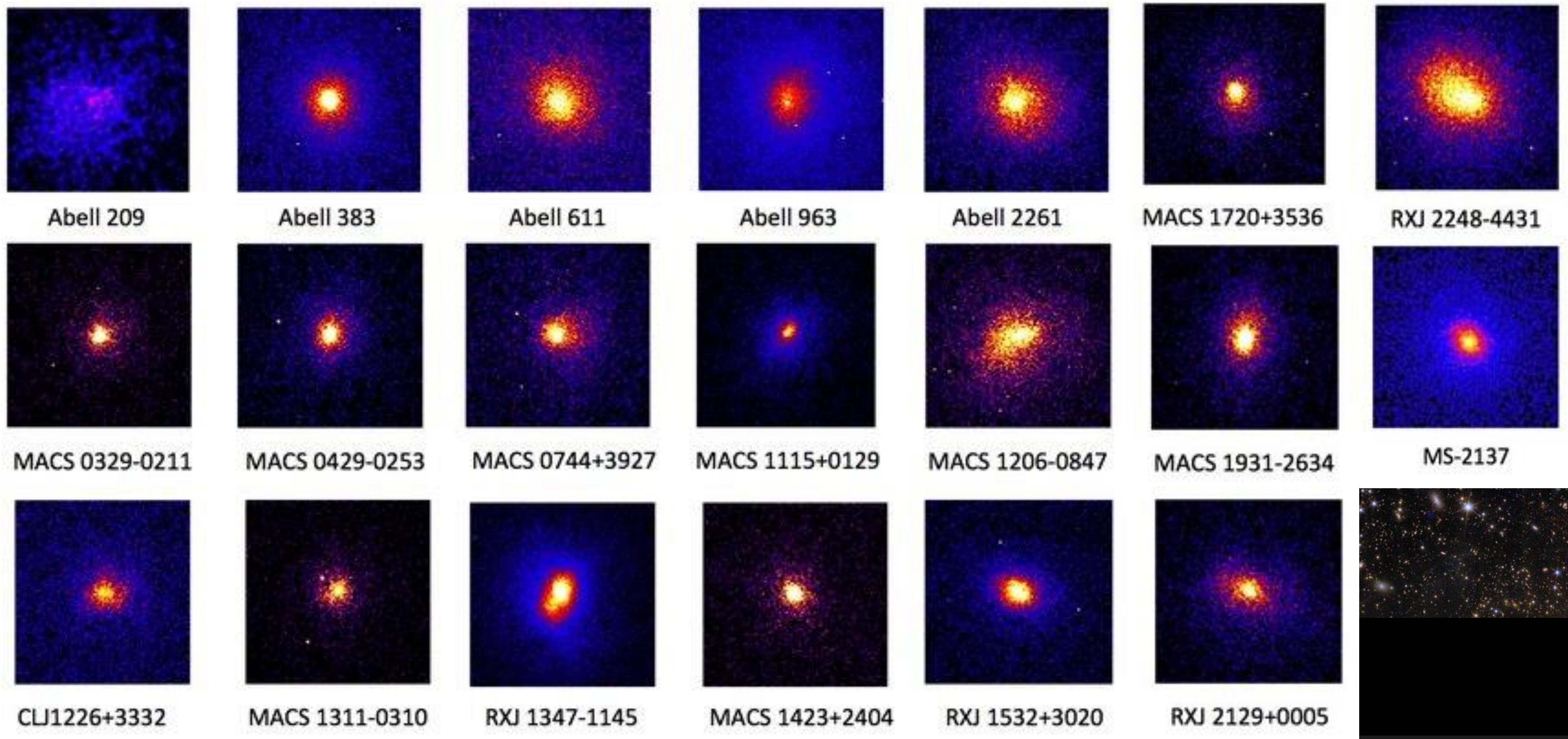
A. Biviano, **LP,** et al., 2023 [10.3847/1538-4357/acf832](https://doi.org/10.3847/1538-4357/acf832)



$\gamma = 0.73^{+0.31}_{-0.33}$
95% C.L.

$$\rho_{gNFW}(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^{\gamma}\left(1+\frac{r}{r_s}\right)^{3-\gamma}}$$

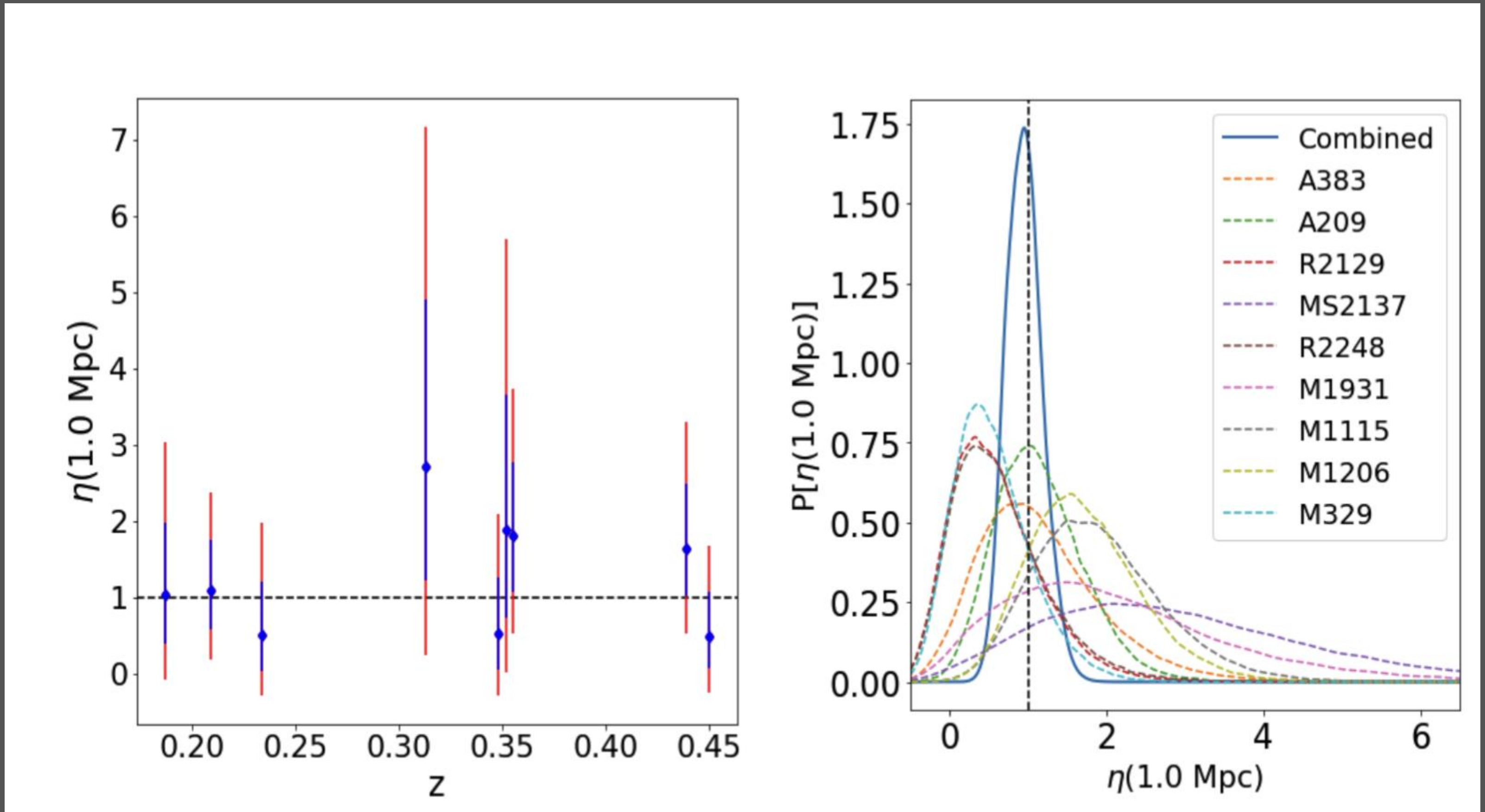




More statistics! The CLASH sample

Testing genuine departures from GR using nine CLASH clusters

Ratio between the scalar potentials of the perturbed metric of a cluster: $\eta = \frac{\Psi}{\Phi}$



$$\eta(r = 1\ \mathrm{Mpc}) = 0.93^{+0.48}_{-0.40}\ (stat, 2\sigma) \pm 0.47\ (syst)$$

Pizzuti et al., 2026a, *JCAP* 03 (2026) 022

Combined distribution: in agreement with GR expectation ($\eta = 1$)

NFW mass profile: on average best fit for the *total* mass of each cluster.

Lensing data from Umetsu et al., 2016
Kinematics data from the CLASH-VLT team

THE CHEX-MATE SAMPLE

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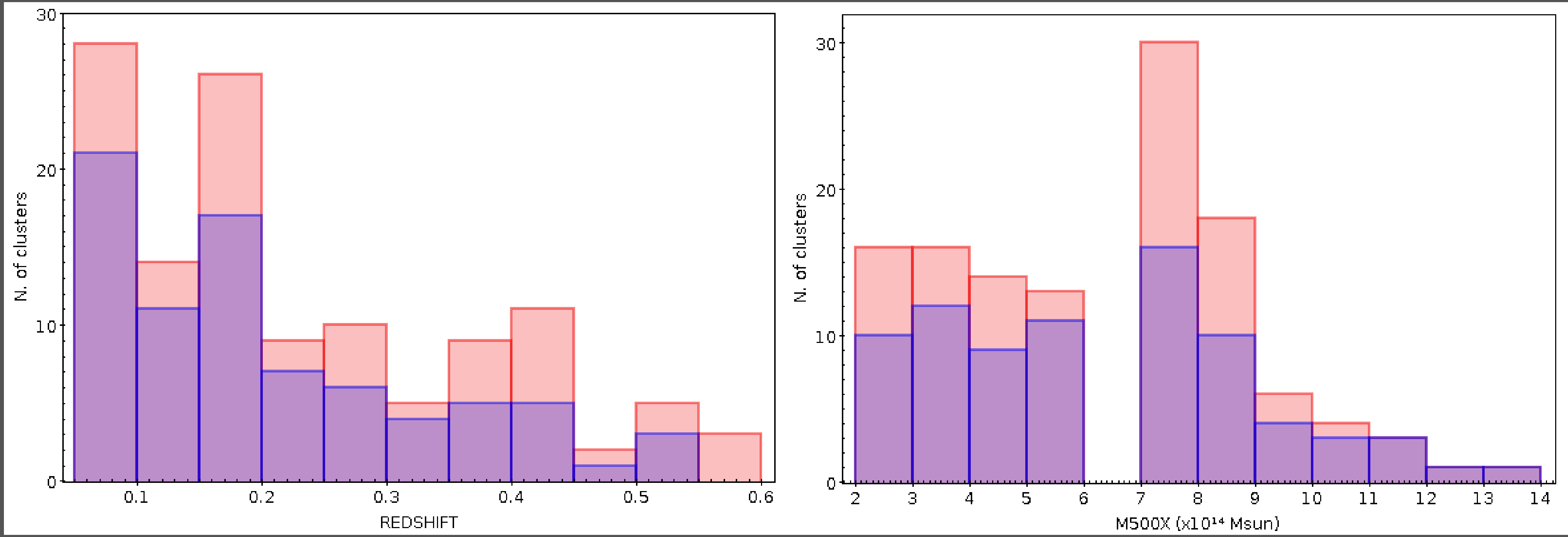
Cluster HEritage project with XMM-Newton – Mass Assembly and Thermodynamics at the Endpoint of structure formation (CHEX – MATE)

118 cluster SZ-selected (SNR > 6.5). Two subsamples: **Tier 1** (z <0.2), **Tier 2** (z > 0.2)



We consider a total of 75 clusters with at **least 50 confirmed members** within $R = r_{200c,ap}$ (Members selected with CLEAN, see Sereno+25)

MG-MAMPOSSt fit: mass estimates

For all clusters, we run a MCMC with 110000 points (10000 burn-in). **Flat uninformative priors (except for r_ν)**

- four mass models: **NFW**, **Burkert**, **Hernquist**, **Einasto** $m = 3$
- two number density models: **pNFW**, **pHernquist**
- one general anisotropy model: **generalized Tiret**

→ **Eight different combinations for each cluster in the sample**

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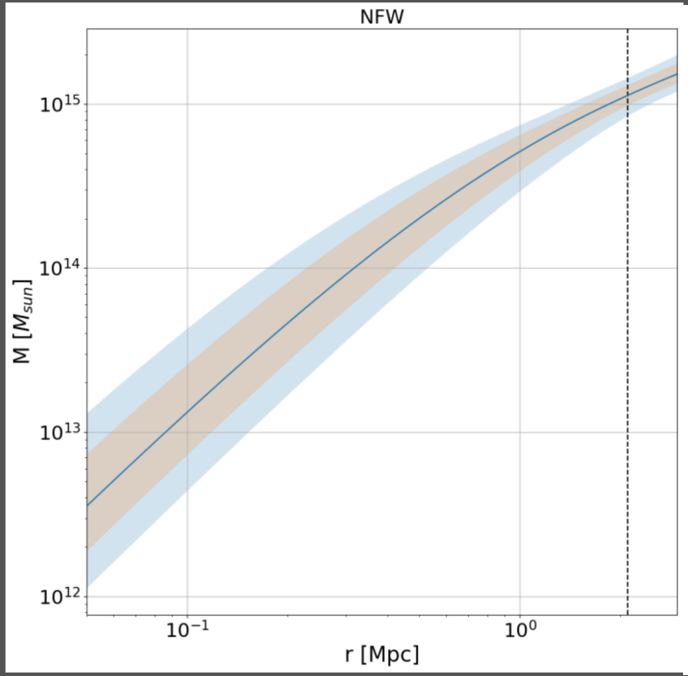
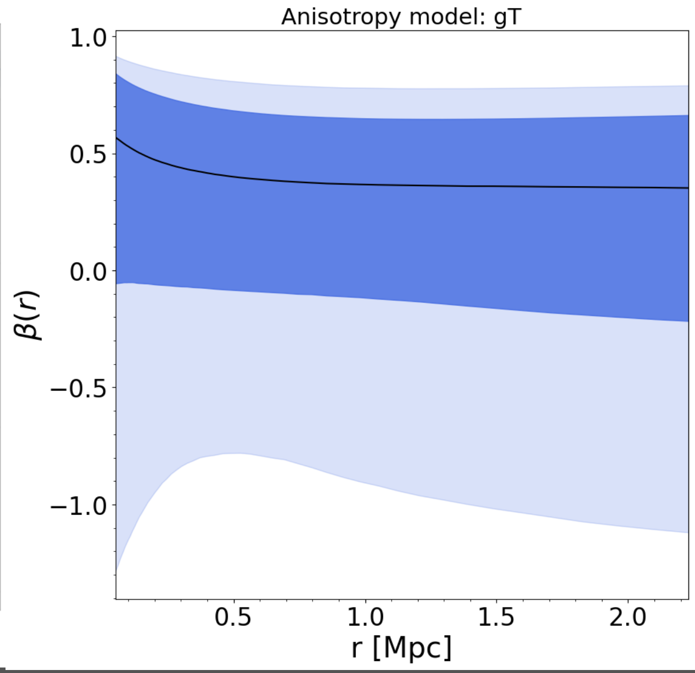
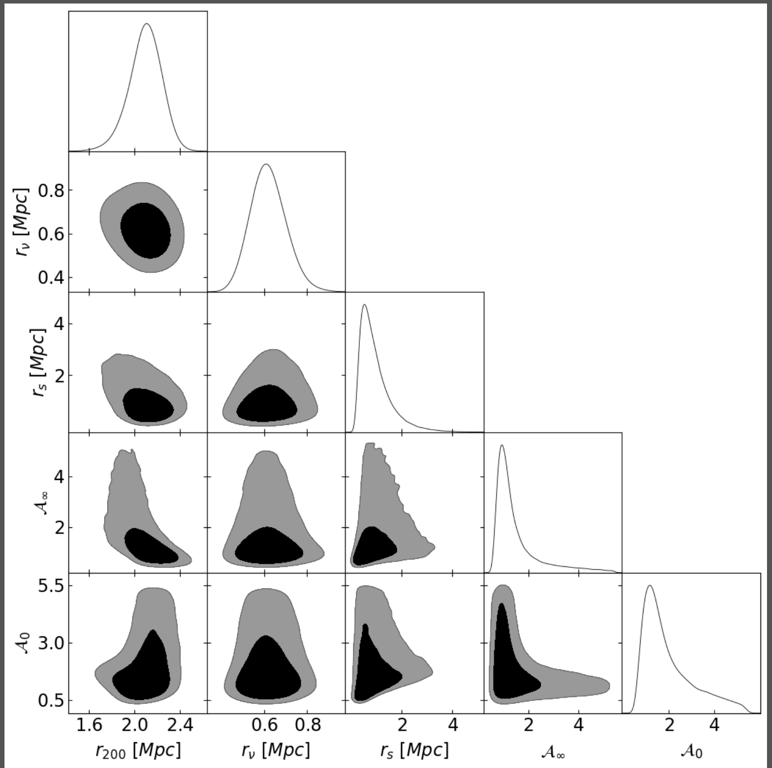
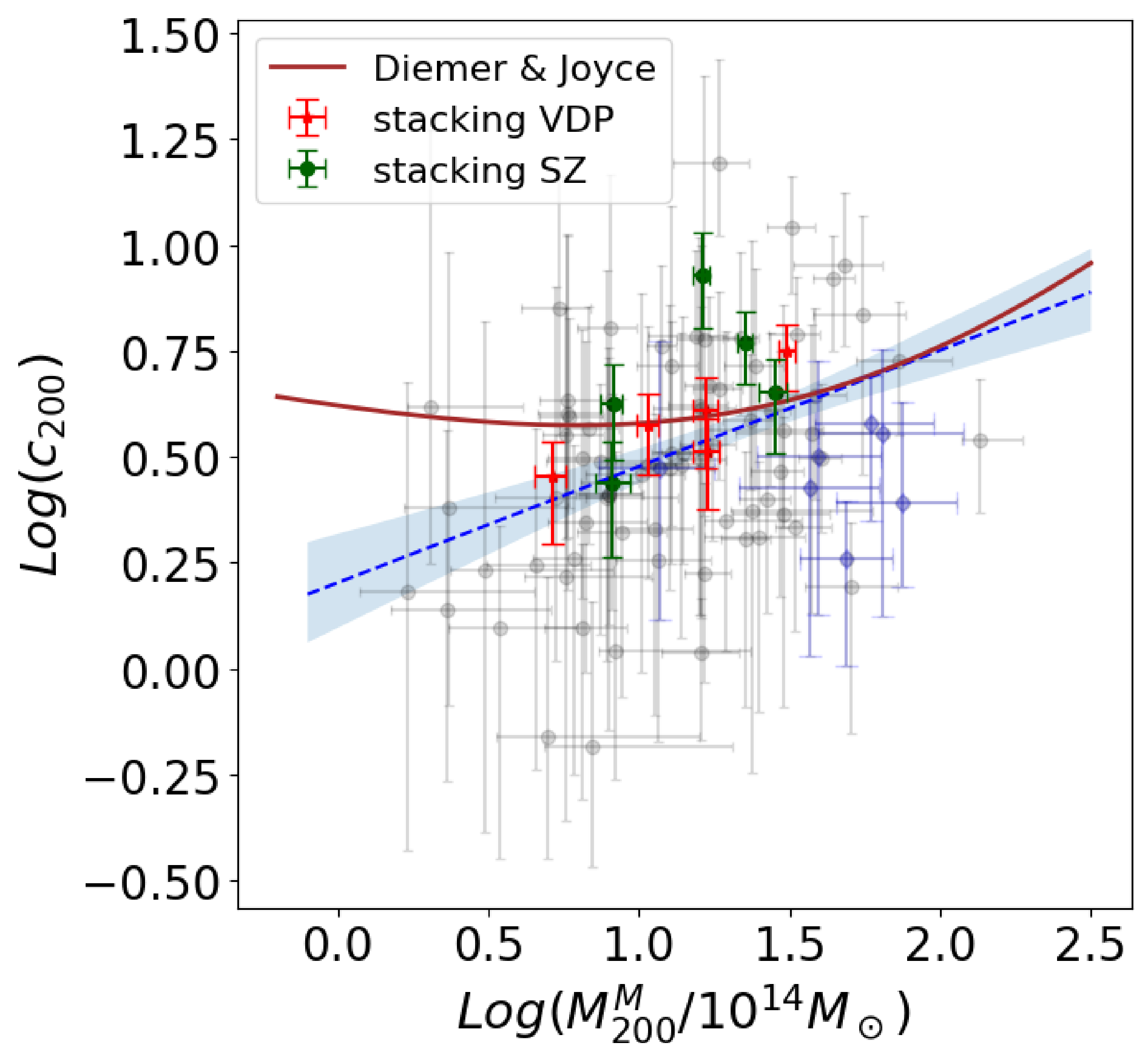
Example: cluster PSZ2 G049.22+30.87







MG-MAMPOSSt fit: c-M relation

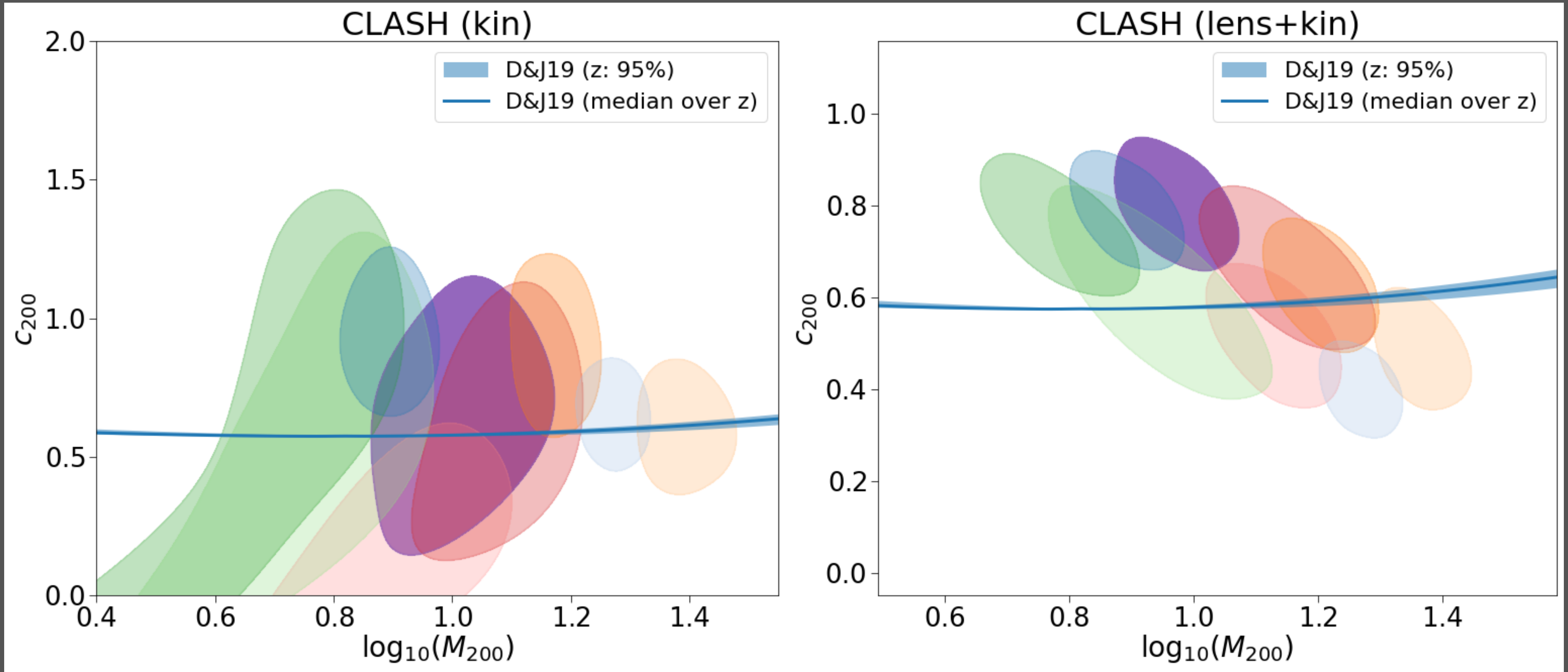


- Slightly rising trend found by a ODR linear fit
- In agreement with theoretical prediction of Diemer&Joyce, 2019
- Red points from vdp stacking analysis

Preliminary: the CLASH c-M relation

.While kinematics seems to be consistent with Diemer&Joyce, combined lensing+kinematic analysis shows a **decreasing trend**

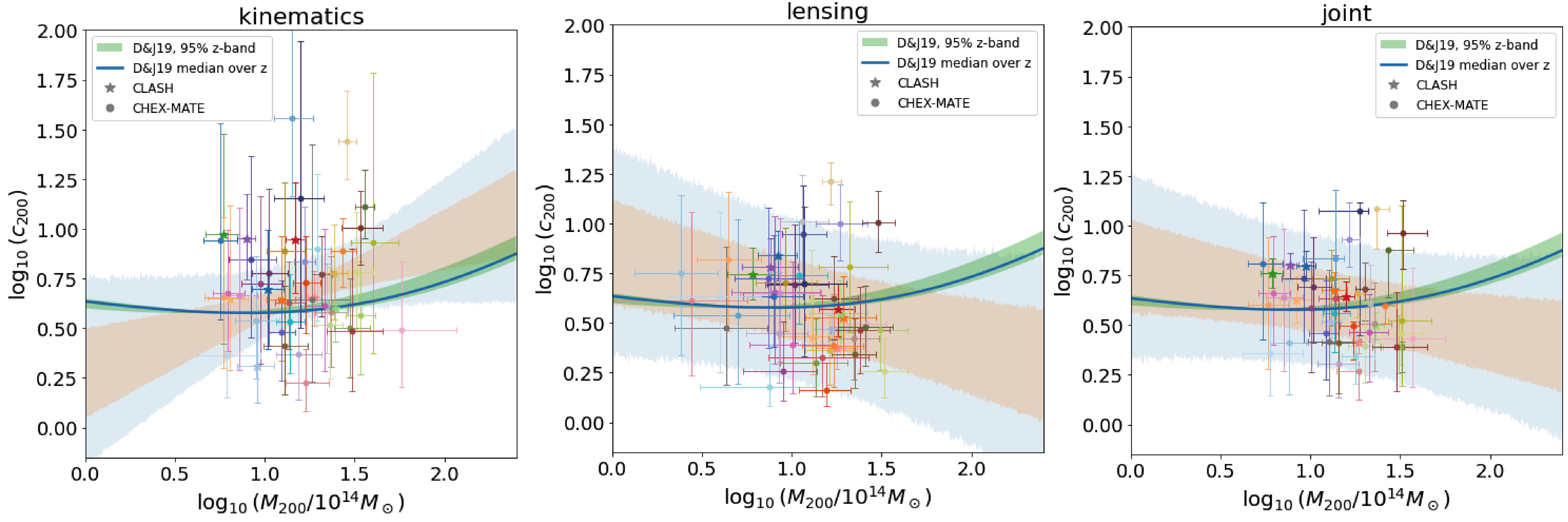
Is this an effect of kinematic mass measurements?



When statistics grows…

.Full kinematics+lensing combined analysis of 45 clusters between CHEX-MATE and CLASH-VLT

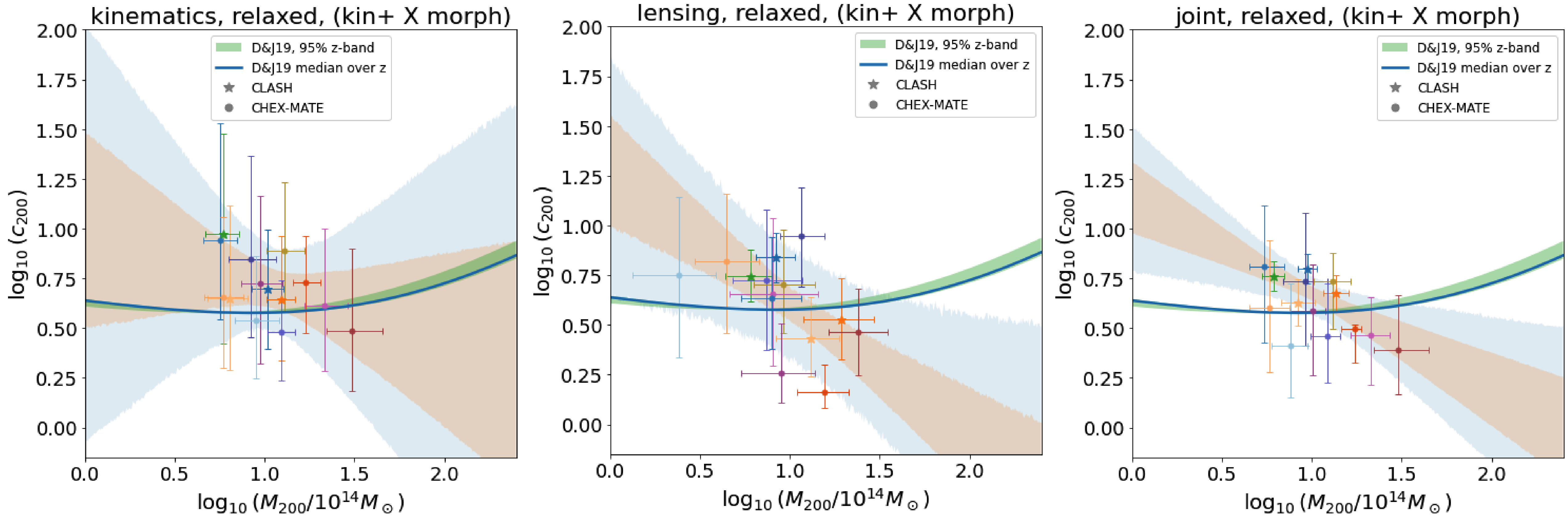
Again, the kinematic-only measurements show a mild increasing trend which disappears in the joint analysis…



A joint lensing+kinematics c-M relation

.Full kinematics+lensing combined analysis of 45 clusters between CHEX-MATE and CLASH-VLT

EFFECT OF DISTURBED CLUSTERS: when selecting only relaxed systems the trend completely disappears



Conclusions: what next?

- **MG-MAMPOSSt**: powerful tool to explore interesting physics at cluster scales

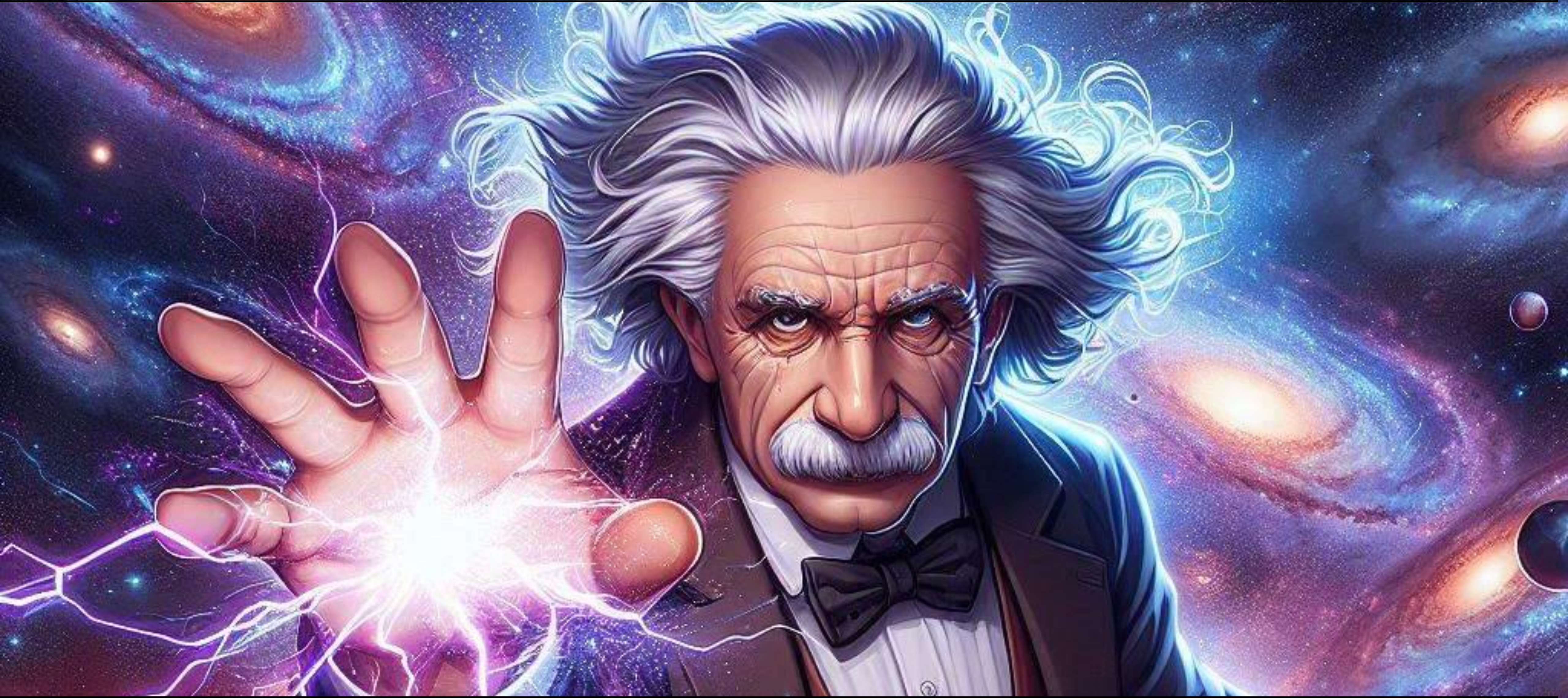
  Available on GitHub (Pizzuti et al, 2023a)
  https://github.com/Pizzuti92/MG-MAMPOSSt/

- Combine other information from different probes (lensing, X-rays) to get tight constraints on gravity, the dark sector but also galaxy evolution in dense environments.

- Extend to many clusters: accurate **selection/calibration of systematics** needed

- Next step: **many models** to test! Results are coming soon…

THAT’S ALL FOLKS!



Thank you!