Testing tension with GR using the mass profiles of galaxy clusters

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In collaboration with I. D. Saltas, K. Umetsu, L. Amendola, A. Biviano, B. Sartoris,

Tensions in Cosmology
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Osservatorio Astronomico della Regione Autonoma Valle d'Aosta Planetario di Lignan
Observatoire Astronomique de la Région Autonome Vallée d'Aoste Planétarium de Lignan
Région Autonome Vallée d'Aoste
Regione Autonoma Valle d'Aosta
Fondazione CRT

Outline of the talk

- Kinematic and lensing mass profiles of a galaxy cluster
- The MG-MAMPOSSt code
  - Forecasts: kinematic + (weak) lensing
  - Application to CLASH clusters
- Conclusions

Galaxy cluster mass profiles: dynamics vs lensing analysis

Spacetime of a galaxy cluster: linear perturbation of the Friedmann-Robertson-Walker metric

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

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

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

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

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Motion of galaxies (kinematic analysis)

⇩

TIME-TIME component of the metric $\mathbf{\Phi}$

Photons (lensing analysis)

⇩

TIME-TIME + **SPACE-SPACE** components of the metric $\mathbf{\Phi}_{lens} = \frac{1}{2}(\mathbf{\Phi} + \mathbf{\Psi})$

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LENSING AND **KINEMATIC** DETERMINATIONS OF A GALAXY CLUSTER MASS PROFILE COULD BE USED TO DETECT POSSIBLE SIGNATURES OF MODIFIED GRAVITY

The MG-MAMPOSSt code

Version of the **MAMPOSSt** code aimed at constraining modified gravity models using the internal kinematic of galaxy clusters

MAMPOSSt*= *Modelling Anisotropy and Mass Profile of Observed Spherical System

Developed Mamon, Biviano, Boué (MNRAS 429 (Mar., 2013)3079–3098**) to derive cluster mass profiles by the analysis of galaxies kinematics**

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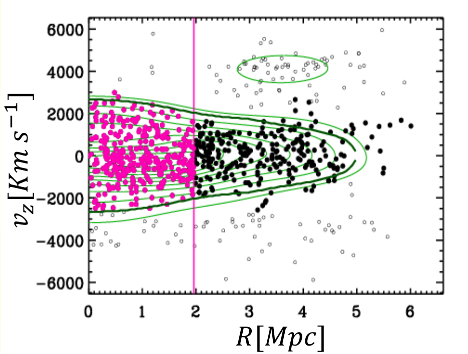
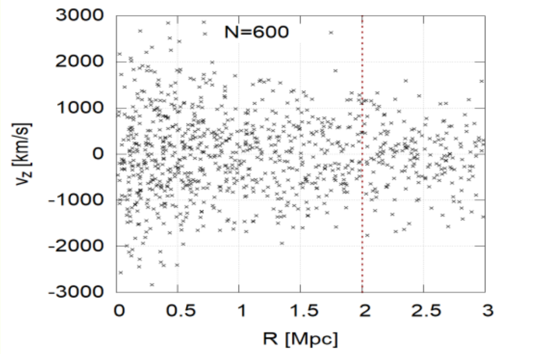
Jeans' equation solved in the projected phase-pace $(\boldsymbol{R}, \boldsymbol{v_z})$

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



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



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maximum likelihood fit to obtain the parameters of the mass profile and the anisotropy profile assuming a 3D velocity Gaussian distribution

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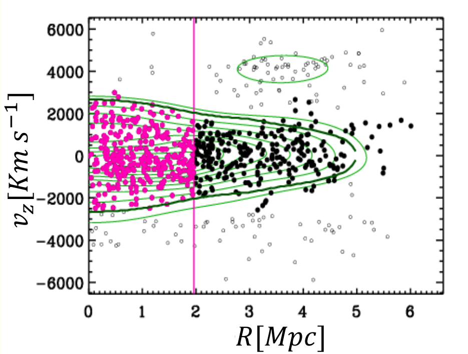

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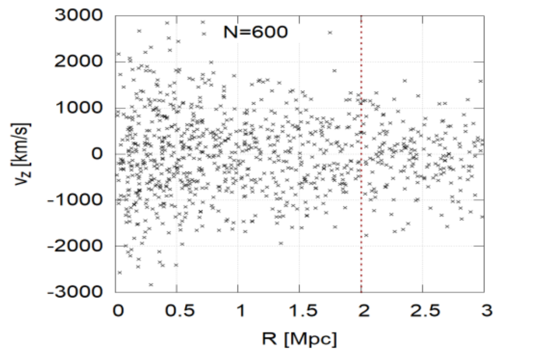

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$$\sigma_r^2(r) = \frac{1}{\nu(r)} \int_r^{\infty} ds \, \exp\left[2 \int_r^s \frac{\beta(t)}{t} dt\right] \nu(s) \frac{d\Phi}{ds}$$

parameter space: $r_s, r_{200}, r_\nu, \beta$

$\beta \rightarrow$ free parameter of the anisotropy profile

$r_\nu \rightarrow$ scale radius of the number density profile

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$$\mathcal{M}_i = \begin{cases} Y_1, Y_2 & VS \\ Q, \phi_\infty & CS \end{cases}$$

MG-MAMPOSSt:

- Chameleon screening, Vainshtein screening
- modified Newtonian potential (Navarro-Frenk-White)

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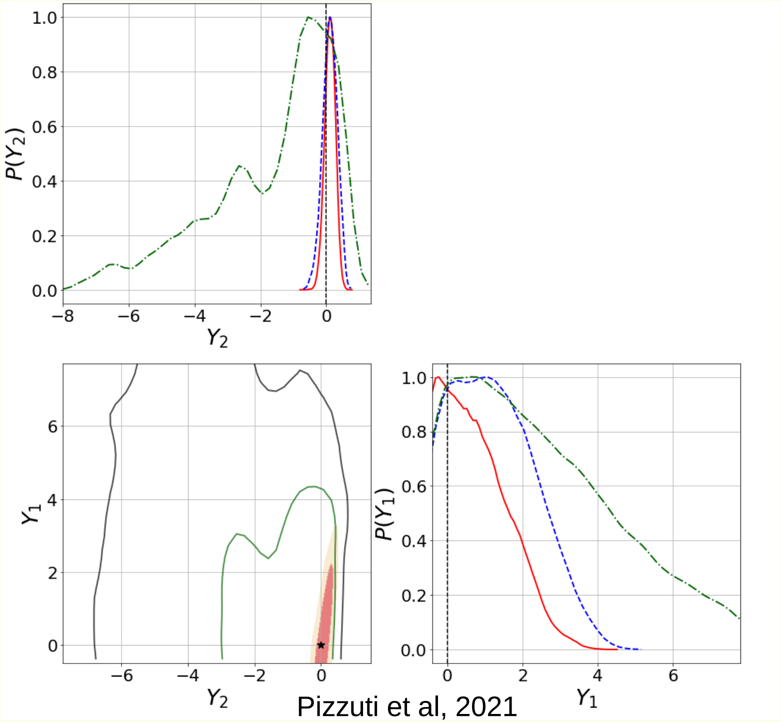
MG-MAMPOSSt:

- Chameleon screening, Vainshtein screening
- modified Newtonian potential (Navarro-Frenk-White)
- Grid /MCMC (Metropolis-Hastings) parameter space exploration. **Few hours for a complete MCMC run.**
- Simulated (weak) lensing information

Forecasts: Vainshtein screening

One cluster: **(weak) lensing** + **kinematics**
(600 tracers and 100 tracers)



Pizzuti et al, 2021

N_h clusters	$N = 600$ (joint) Y_1	$N = 600$ (joint) Y_2	$N = 100$ (joint) Y_1	$N = 100$ (joint) Y_2
1	$\lesssim 2.75$	$0.08^{+0.32}_{-0.28}$	$\lesssim 3.56$	$0.10^{+0.44}_{-0.40}$
5	$\lesssim 1.65$	$0.06^{+0.20}_{-0.18}$	$\lesssim 1.87$	$-0.08^{+0.31}_{-0.20}$
10	$\lesssim 1.24$	$-0.05^{+0.17}_{-0.13}$	$\lesssim 1.65$	$0.01^{+0.24}_{-0.17}$
15	$0.04^{+1.00}_{-0.39}$	$0.01^{+0.12}_{-0.09}$	$\lesssim 1.20$	$-0.01^{+0.19}_{-0.16}$
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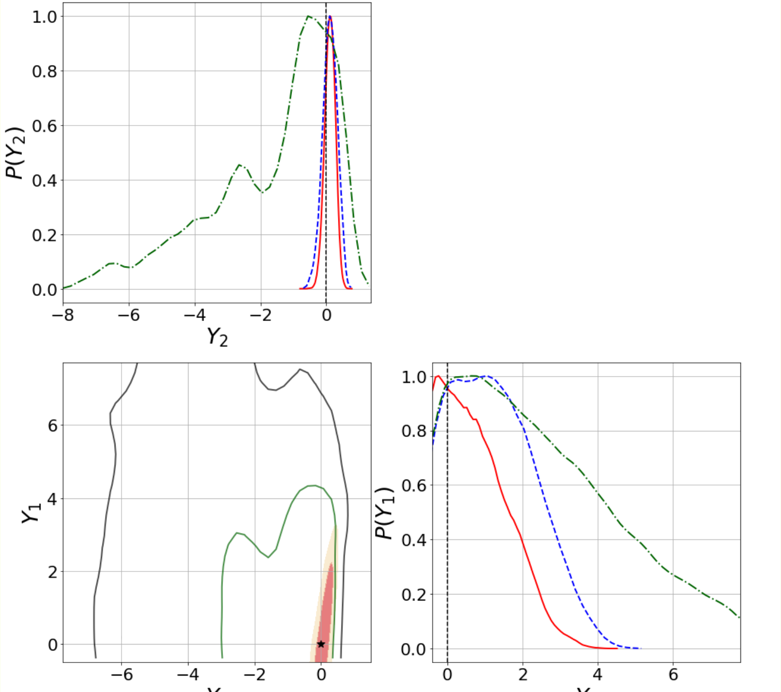

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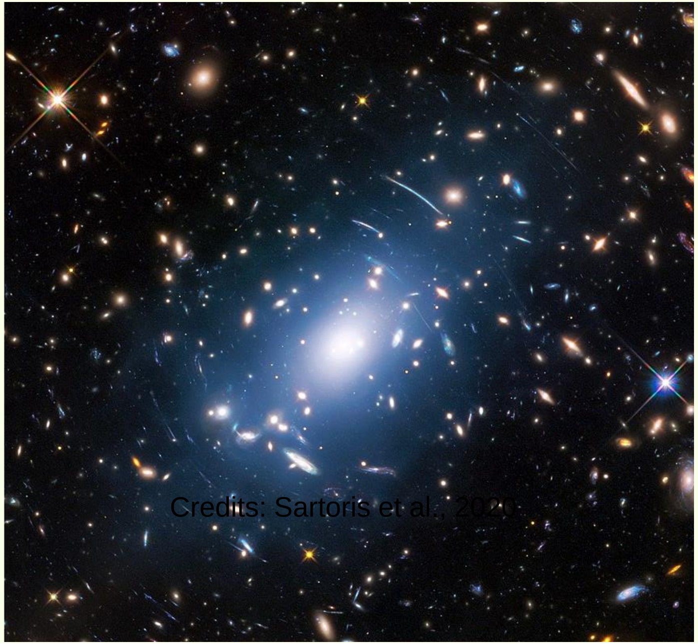
Example: DHOST – real data

MG-MAMPOSSt applied to p.p.s. of two massive clusters analysed within the **CLASH** and **CLASH-VLT** collaborations

MACSJ-1206

- Subaru+HST
- VLT/VIMOS+MUSE

Abell S1063



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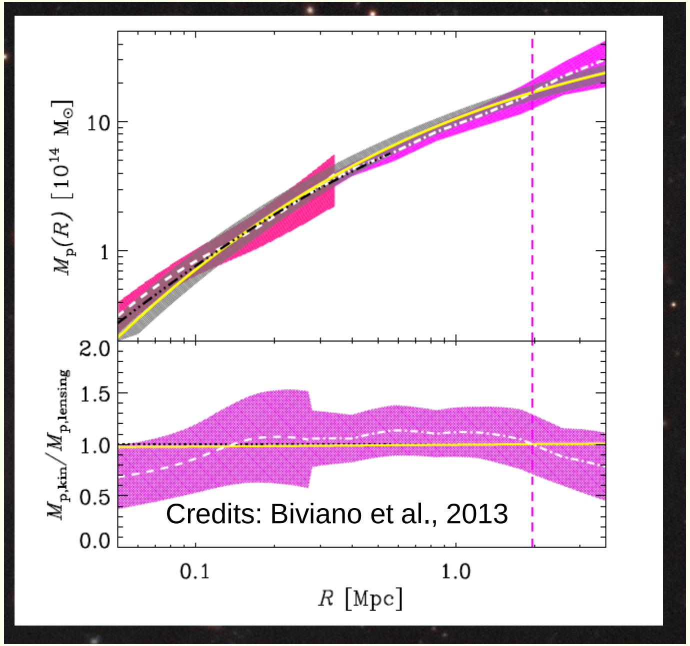

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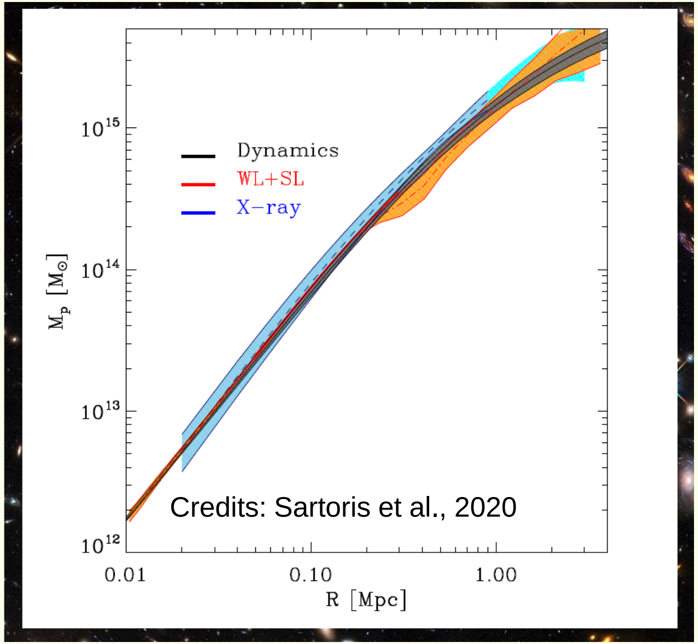

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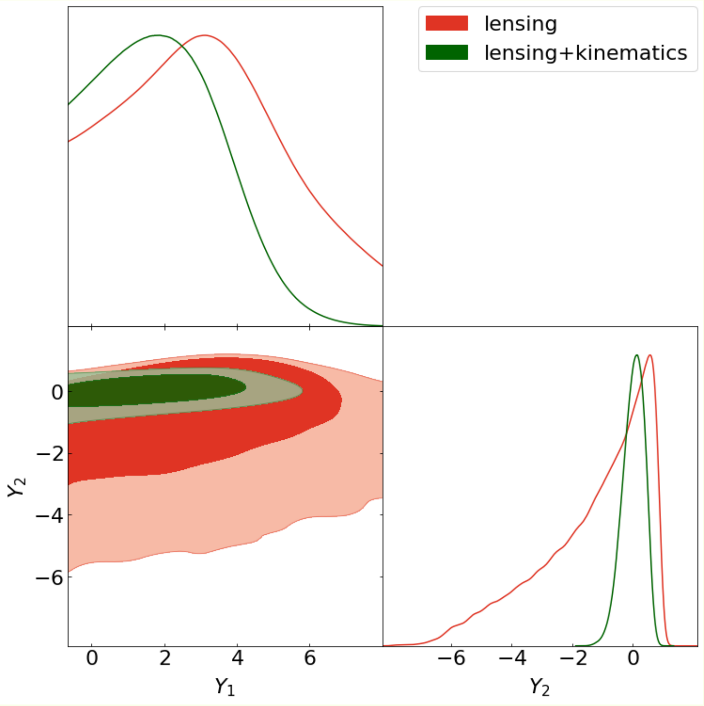

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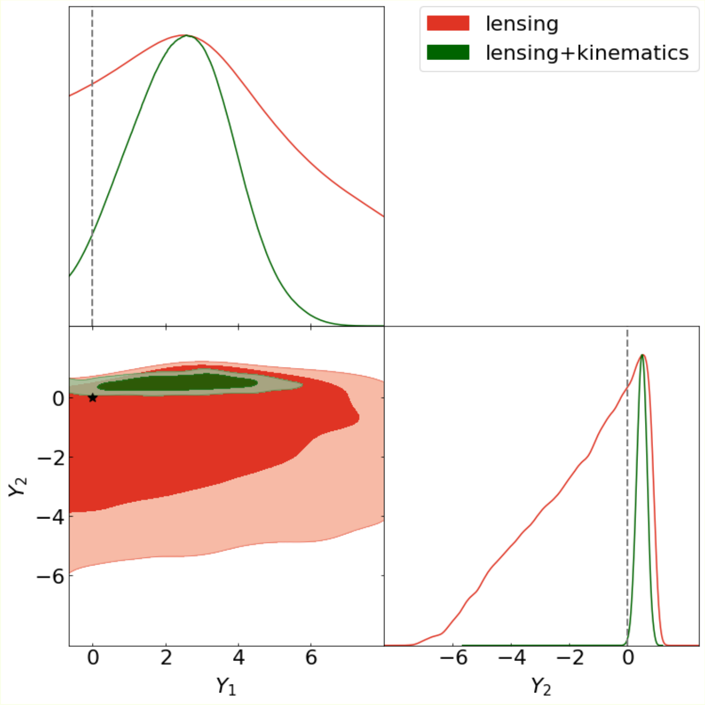

Pizzuti et al, 2022a

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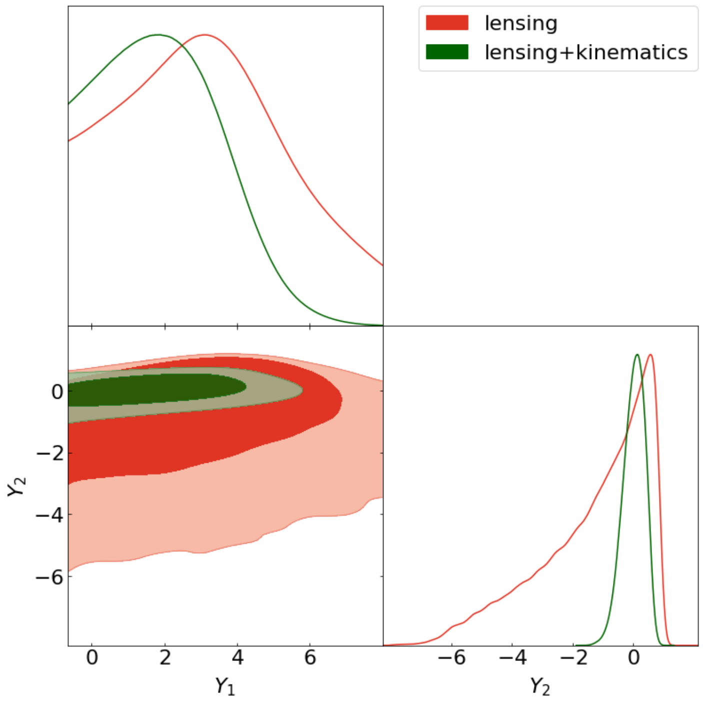

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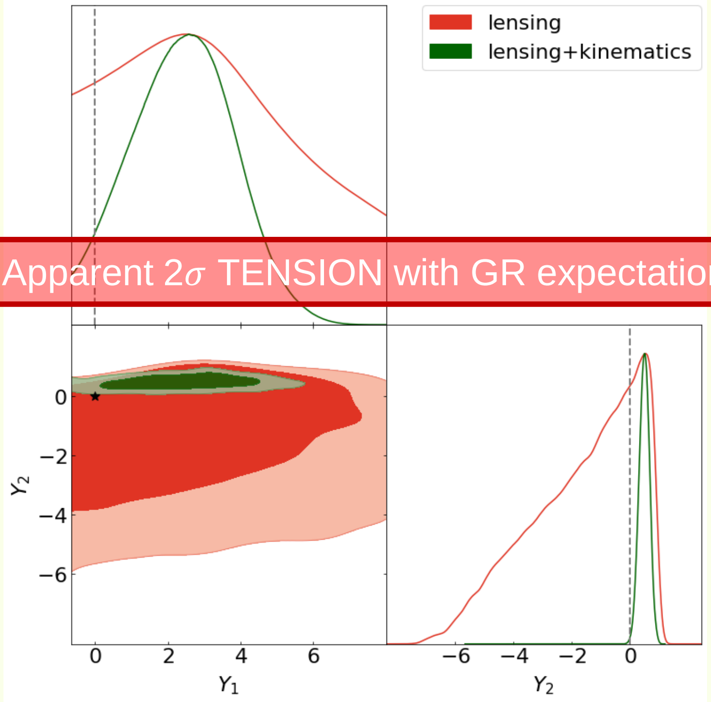


Apparent 2σ TENSION with GR expectation

Pizzuti et al, 2022a

Understanding the systematics: cosmological simulations

In a GR Universe $\sim 70\%$ of the cluster population leads to spurious detections of MG

2 observational criteria related to systematics DIRECTLY from the projected phase space (pps)

Anderson-Darling coefficient A^2 → deviations from Gaussianity of the los velocity distribution:

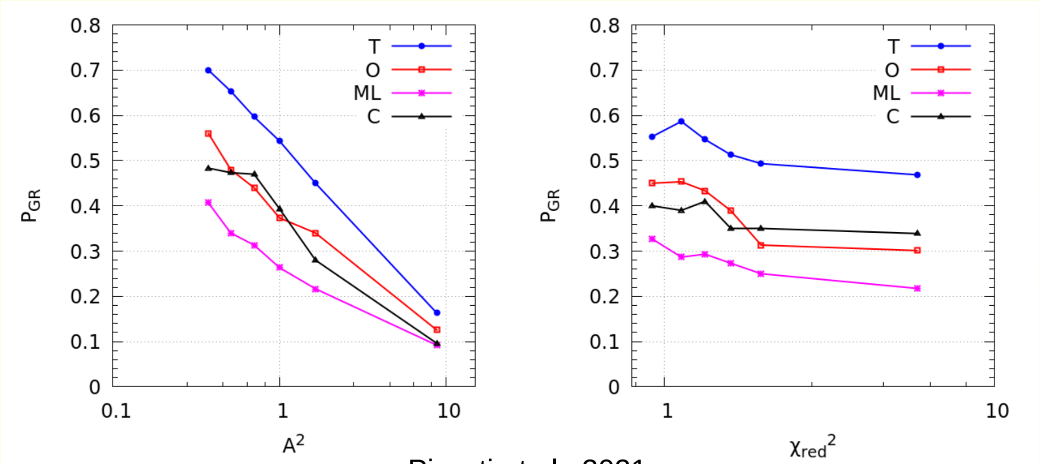
$$A^2 = -n - \frac{1}{n}\sum_{i=1}^{n}(2i-1)[\ln\Phi(x_i) + \ln(1-\Phi(x_{n+1-i}))]$$

χ^2 from fitting the projected number density with a pNFW profile →
- deviations from sph. symmetry,
- parametrization of the profile,
- substructures in the pps

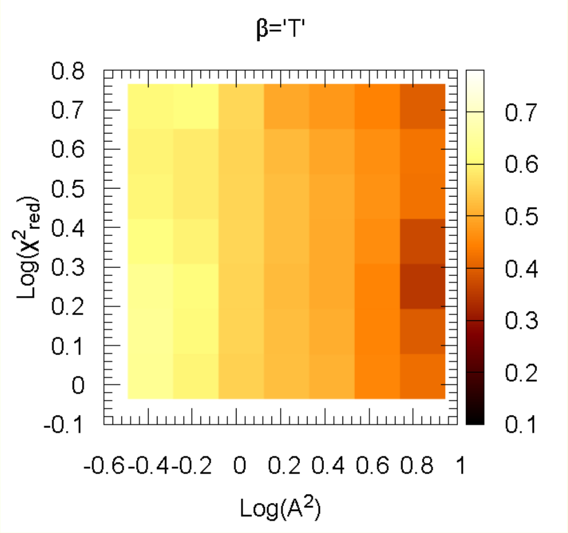
Understanding the systematics: cosmological simulations

Systematics related to the lack of the main assumptions: **dynamical relaxation** and **sph. symmetry**

A^2, χ^2_ν →**help in selecting suitable halos**



Pizzuti et al., 2021

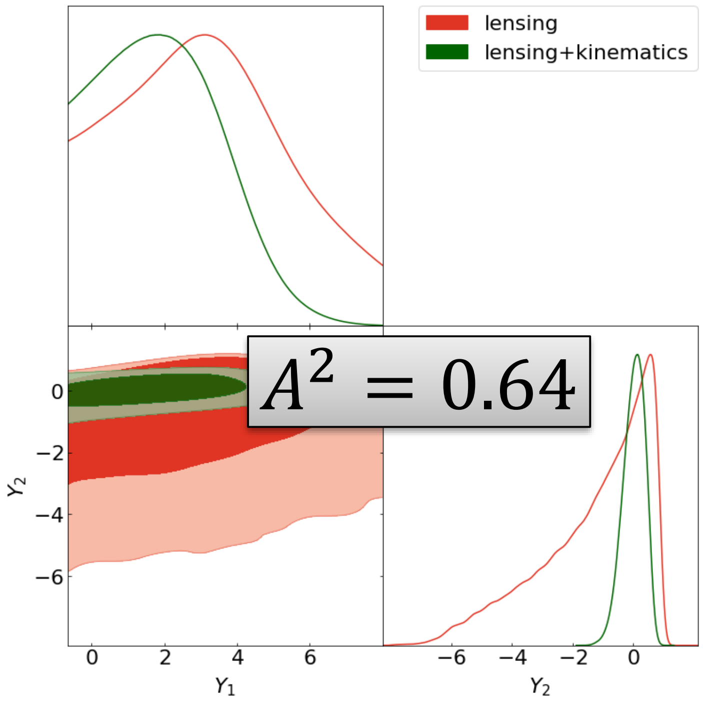


Percentage of spurious detection lowered **down to $\sim$ 20%** for $A^2 < 1, \chi^2_{red} < 0.5$

TREND INDEPENDENT OF THE ANISOTROPY MODEL

Example: DHOST – real data

MACSJ-1206



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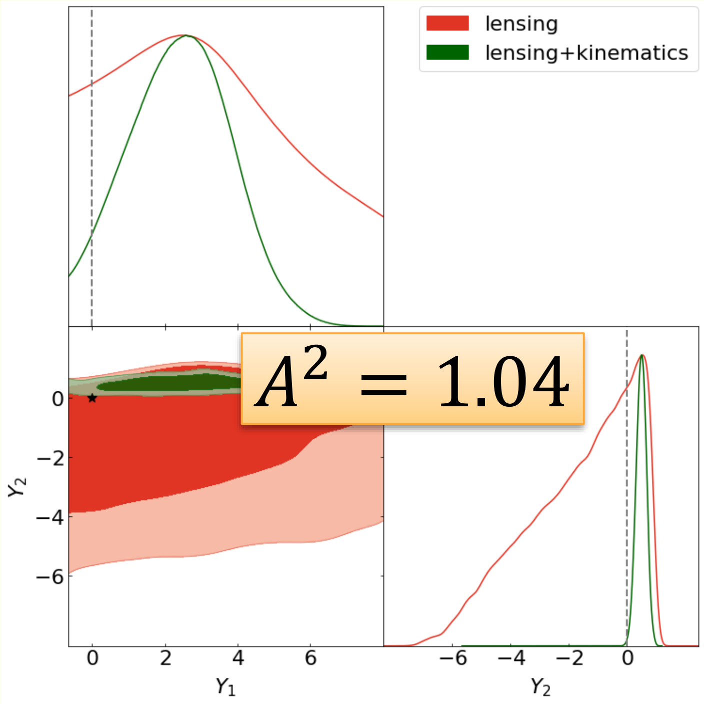


Pizzuti et al, 2022a

Summary and conclusions

- **MG-MAMPOSSt**: powerful tool to constrain modified gravity models **when combined with other probes** (such as lensing information). Available on https://github.com/Pizzuti92/MG-MAMPOSSt/

- Applied in the case of **Vainsthein screening (DHOST)** to CLASH clusters: $\boldsymbol{Y_2 \sim -0.12^{+0.66}_{-0.67}}$ for MACS 1206

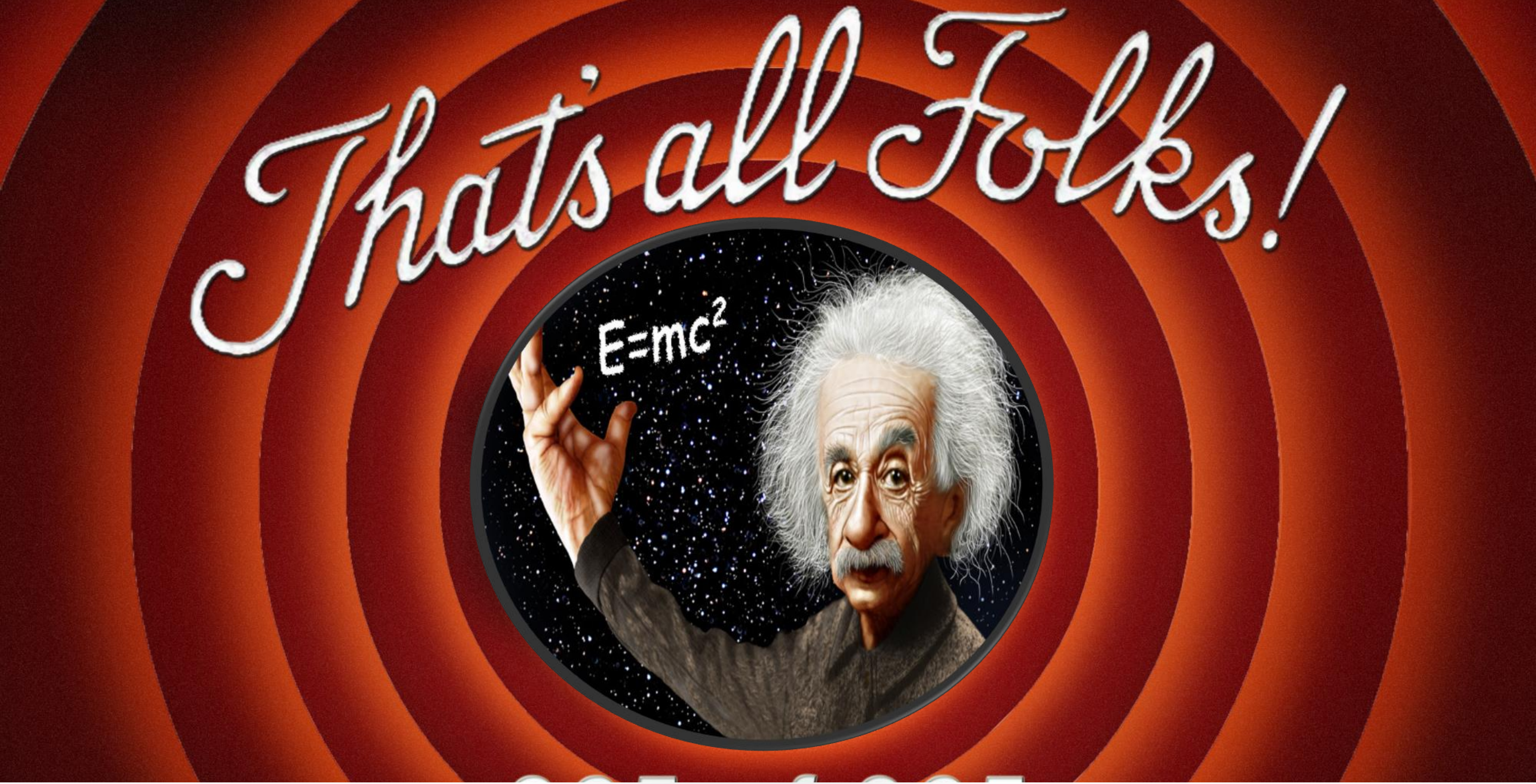
- **Apparent tension with GR expectation $\boldsymbol{Y_2 = 0}$** for Abell S1063 which can be **fully explained in terms of systematics**

NEXT…

- A few (suitable) dozen clusters are sufficient to bring down the uncertainties by one order of magnitude
  Accurate systematics calibration is necessary!

- Explore other mass parametrisations and new models (work in progress!)

Thanks for your attention


That's all Folks!
$E=mc^2$