A marked correlation function to test modified gravity

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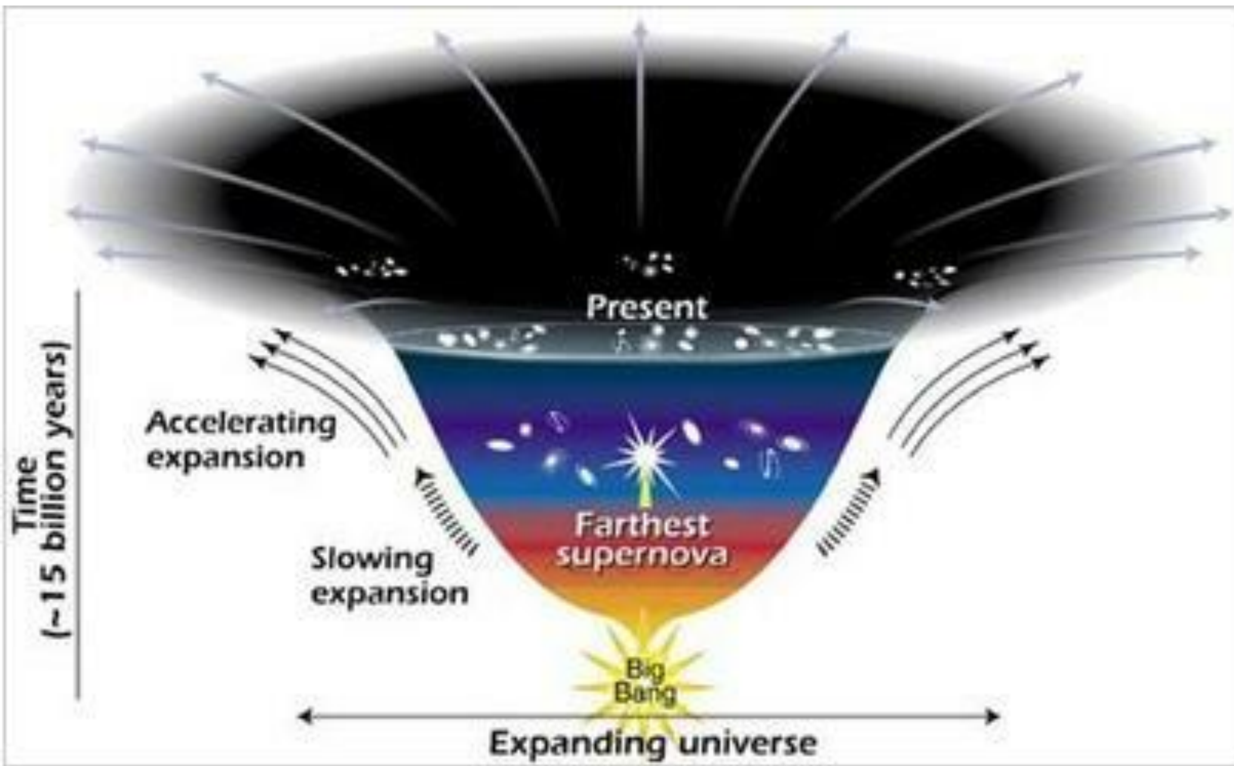
Beyond ΛCDM

Why?

Dark Energy

Modified Gravity



Modified gravity

After GW constraint

	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence [46] Brans-Dicke/$f(R)$ [47, 48] Kinetic Gravity Braiding [50]	quartic/quintic Galileons [13, 14] Fab Four [15] de Sitter Horndeski [49] $G_{\mu\nu}\phi^\mu\phi^\nu$ [51], $f(\phi)\cdot$Gauss-Bonnet [52]
beyond H.	Derivative Conformal (19) [17] Disformal Tuning (21) quadratic DHOST with $A_1 = 0$	quartic/quintic GLPV [18] quadratic DHOST [20] with $A_1 \neq 0$ cubic DHOST [23]
	Viable after GW170817	Non-viable after GW170817

Ezquiaga, Zumalacárregui (2017)

$$S = \int d^4x \sqrt{-g} \left\{ \frac{1}{2\kappa^2} \left[R + f(R) \right] + \mathcal{L}_m \right\}$$

The Hu & Sawicki $f(R)$ model

The election of the $f(R)$ from Hu and Sawicki (2007)

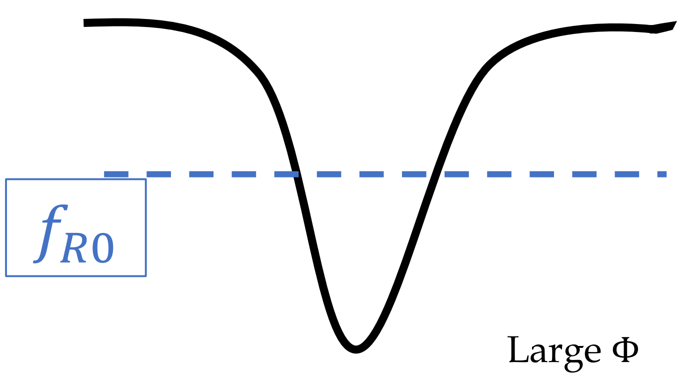
$$f(R) = -\frac{m^2 c_1 \left(-\frac{R}{m^2}\right)^n}{c_2 \left(-\frac{R}{m^2}\right)^n + 1},$$

For $n = 1$ the constraint is $|f_{R0}| \leq 10^{-4}$ (Schmidt, Vikhlinin and Hu, 2009).

which mimic the ΛCDM expansion history with

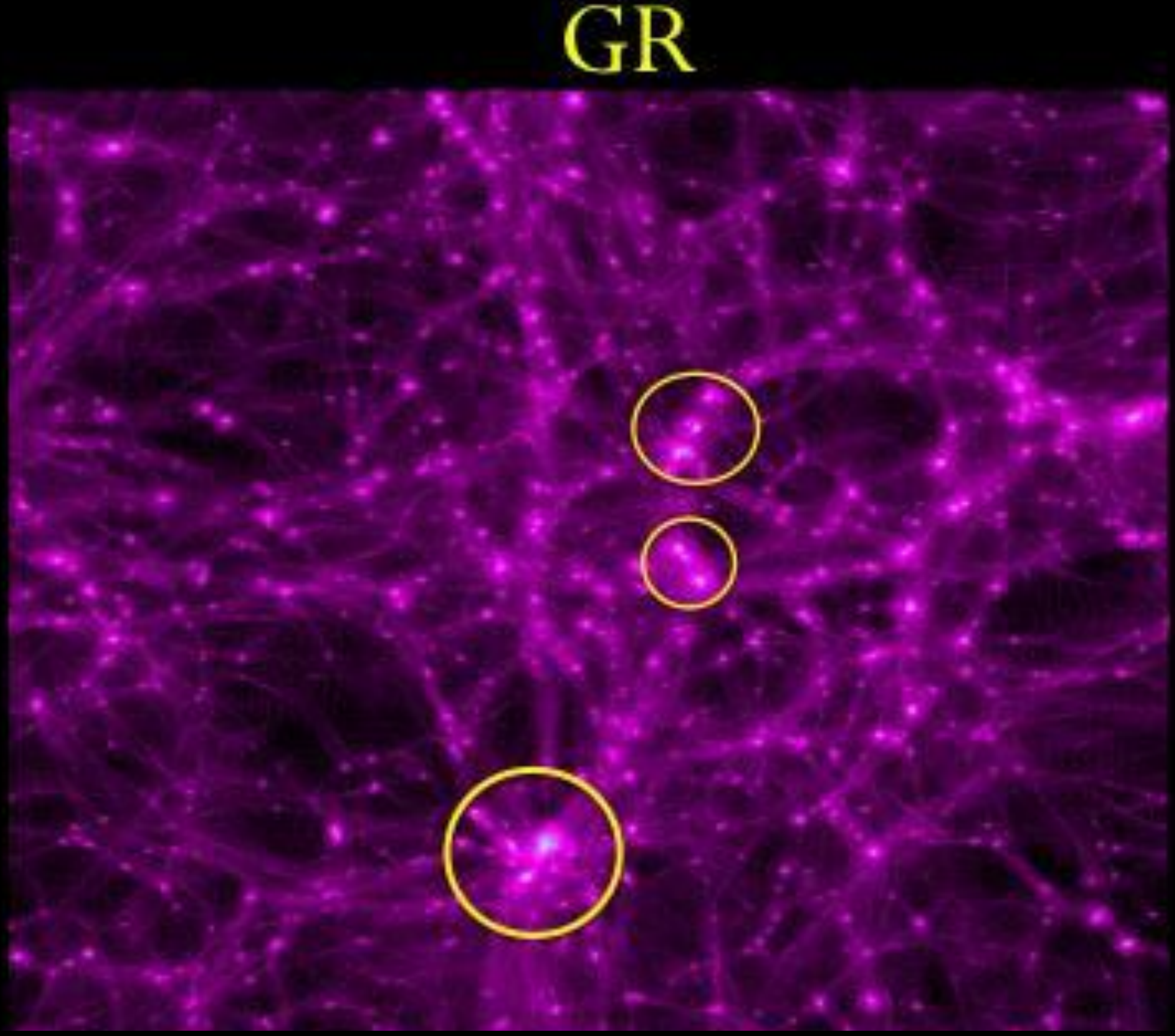
$$\frac{c_1}{c_2^2} = -\frac{1}{n}\left[3\left(1 + \frac{4\Omega_\Lambda}{\Omega_m}\right)\right]^{n+1} f_{R0}.$$

Chameleon mechanism:
Inside a deep Newtonian potential
$f_R \to 0$.

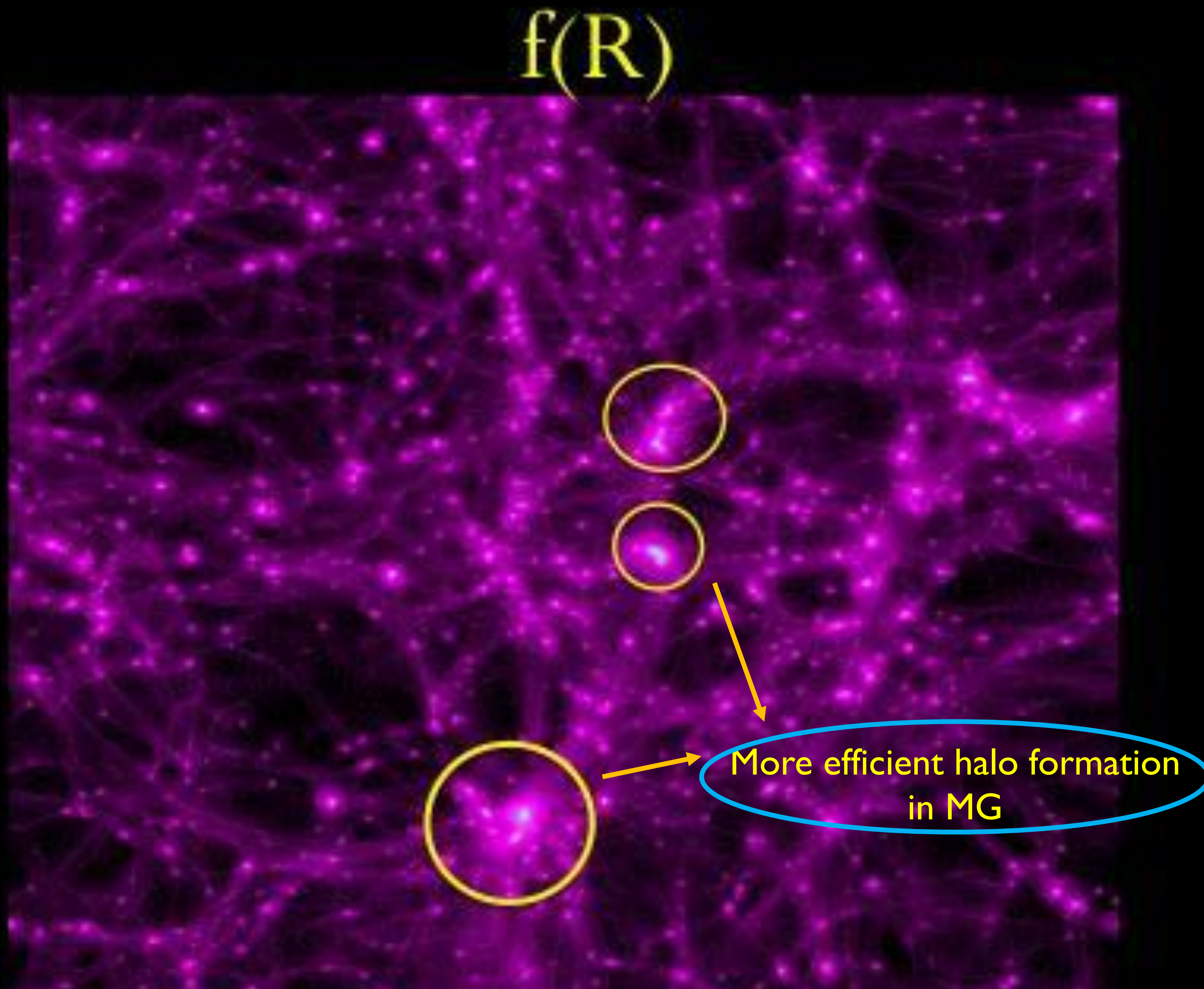


In the unscreened regime:

$$\Phi_{\mathrm{MG}} = \frac{4}{3}\Phi_{\mathrm{GR}}$$



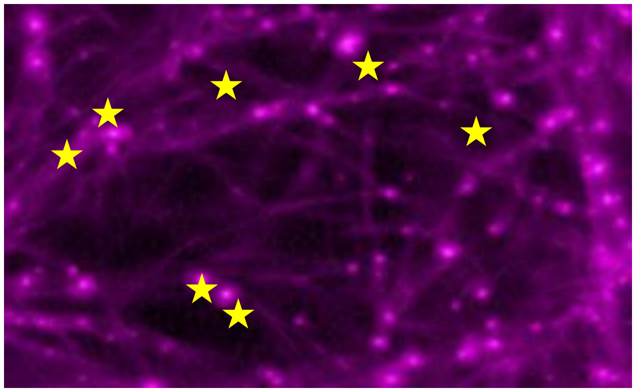
Gong-Bo Zhao 2011



Gong-Bo Zhao 2011

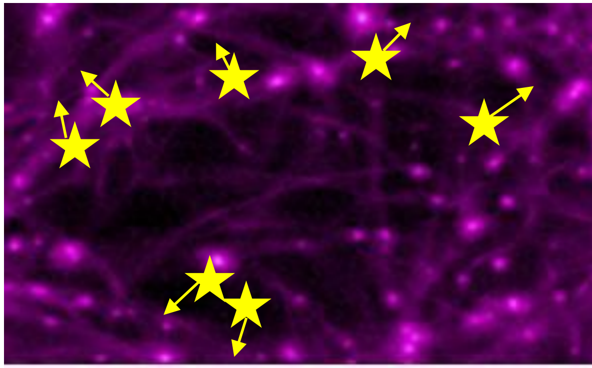
The marked correlation function

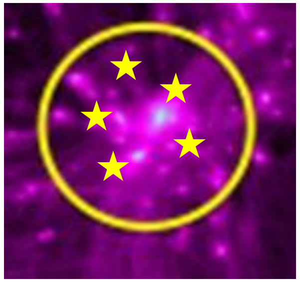
GR



Extra fifth force

MG





Enhancement of gravity in unscreened haloes

The marked correlation function

M. White (2016)

$$\mathcal{M} \equiv \frac{1+W}{1+\xi} = \frac{1}{n(r)\,\bar{m}^2} \sum_{ij} m_i m_j$$

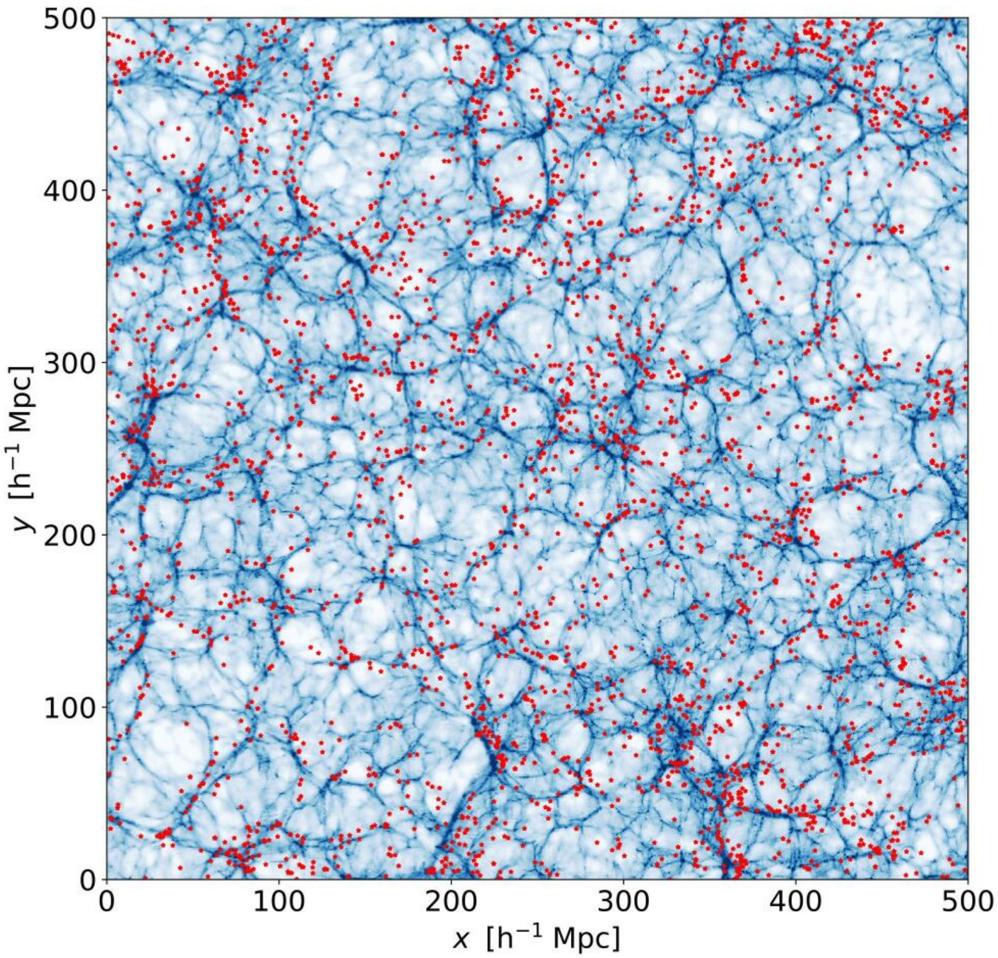
2-point correlation function

The definition of m depends on some environmental density property (Armijo et al, 2018; Hernandez-Aguayo et al. 2018.)

N-body simulations

ELEPHANT
Extended LEnsing PHysics with ANalytical ray Trancing
(ECOSMOG code. Li et al., 2012)

⋆ HOD galaxies



- 5 boxes, 3 models (GR, F6, F5)
- $\Omega_m = 0.281$ $\Omega_\Lambda = 0.719$
  $h = 0.697$ $n_s = 0.971$ $\sigma_8 = 0.820$

- HS $f(R)$ parameters:
  $n = 1$ $|f_{R0}| = 10^{-6}, 10^{-5}$

- $L_{\text{box}} = 1024\, h^{-1}$ Mpc
  $N_p = 1024^3$
  $m_p = 7.78 \times 10^{10} h^{-1} M_\odot$

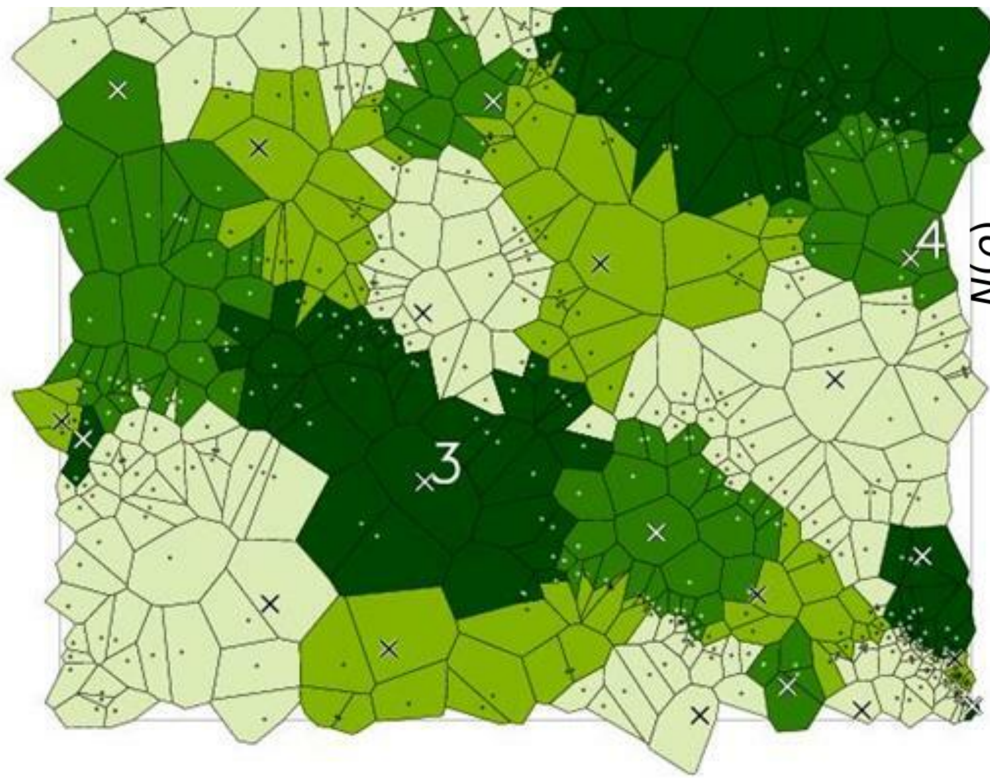
- HOD galaxy catalogues are calibrated to match, the galaxy number density and the real-space clustering in both GR and MG simulations (Hernandez-Aguayo et al. 2019).

Density mark

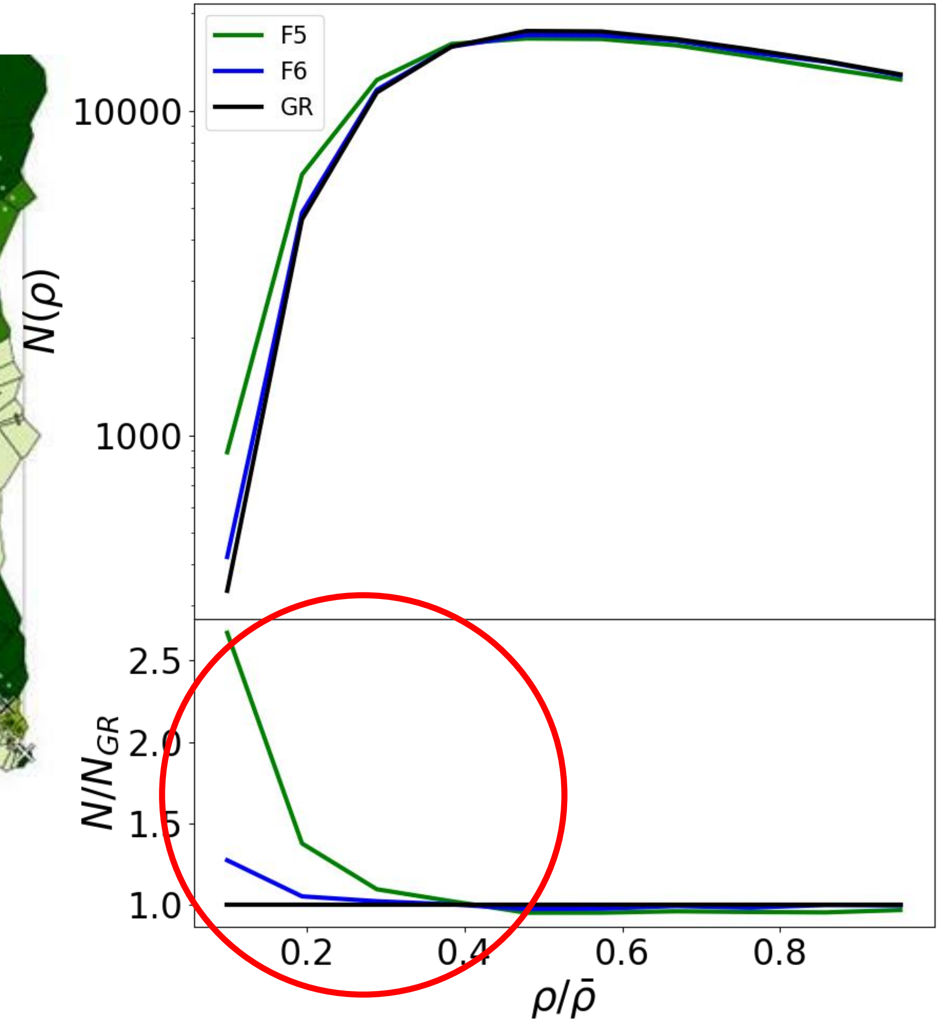
$m = \rho^p$

F5: $|f_{R0}| = 10^{-5}$
F6: $|f_{R0}| = 10^{-6}$

Neyrinck (2009)



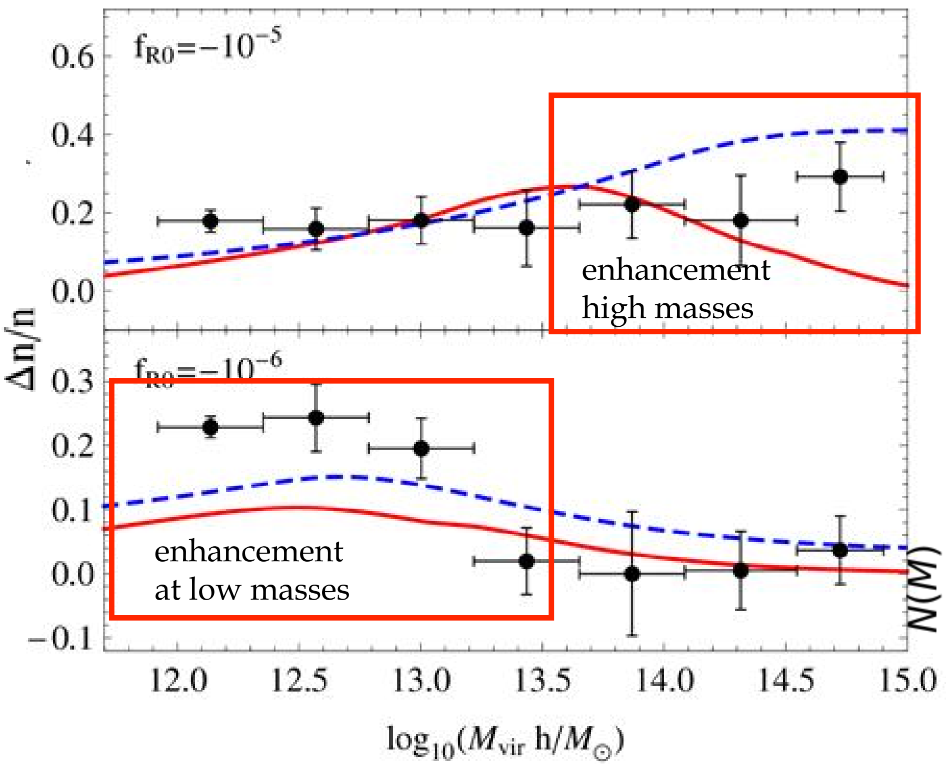
Armijo et al. (2018)



- Bigger cells
- Smaller density
- Higher mark

Halo mass mark

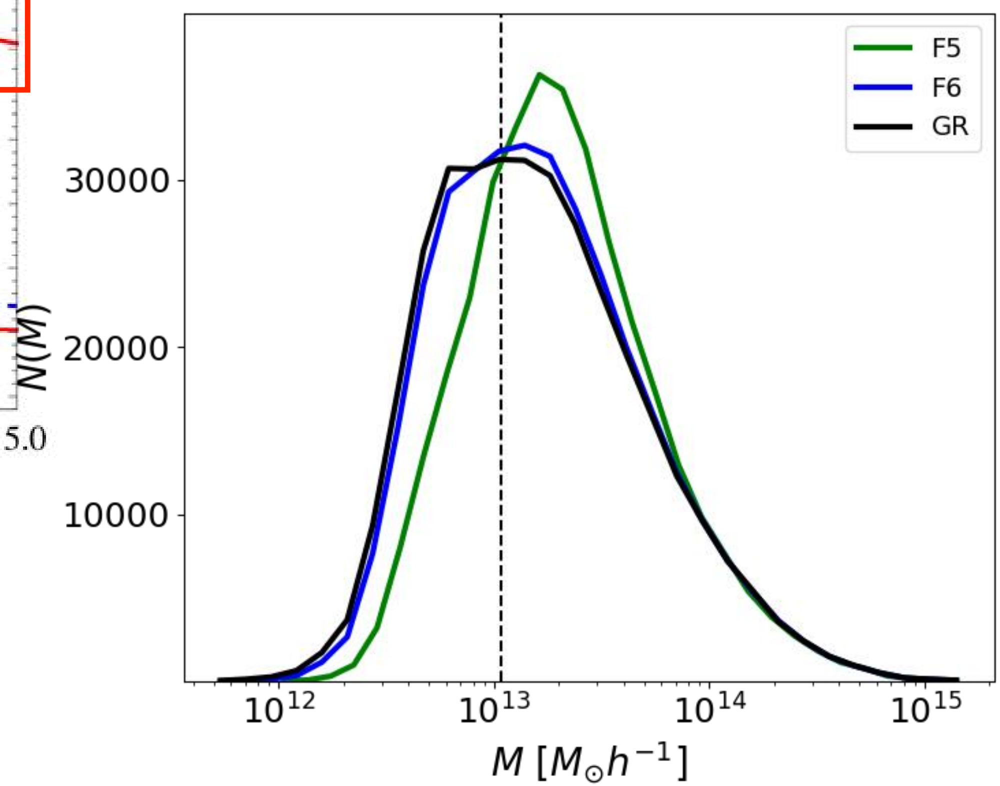
F5: $|f_{R0}| = 10^{-5}$
F6: $|f_{R0}| = 10^{-6}$



Lombriser et al. (2013)

$m = M^p$

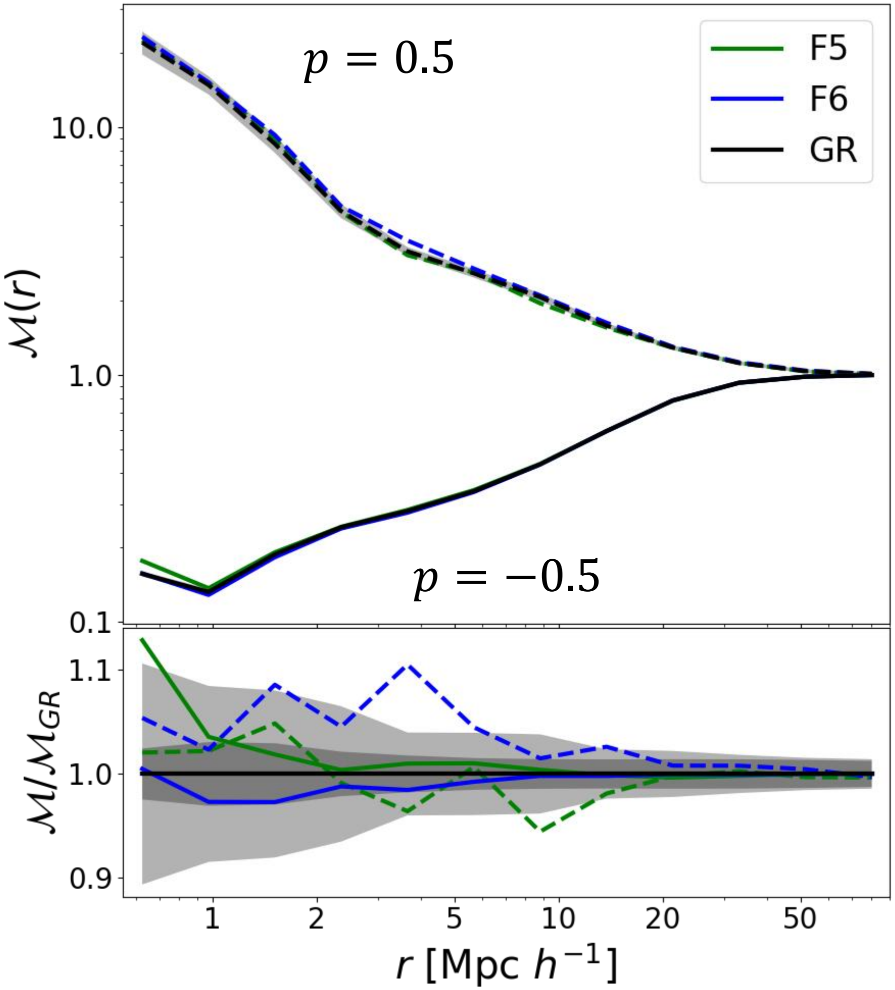
Armijo et al. (2018)



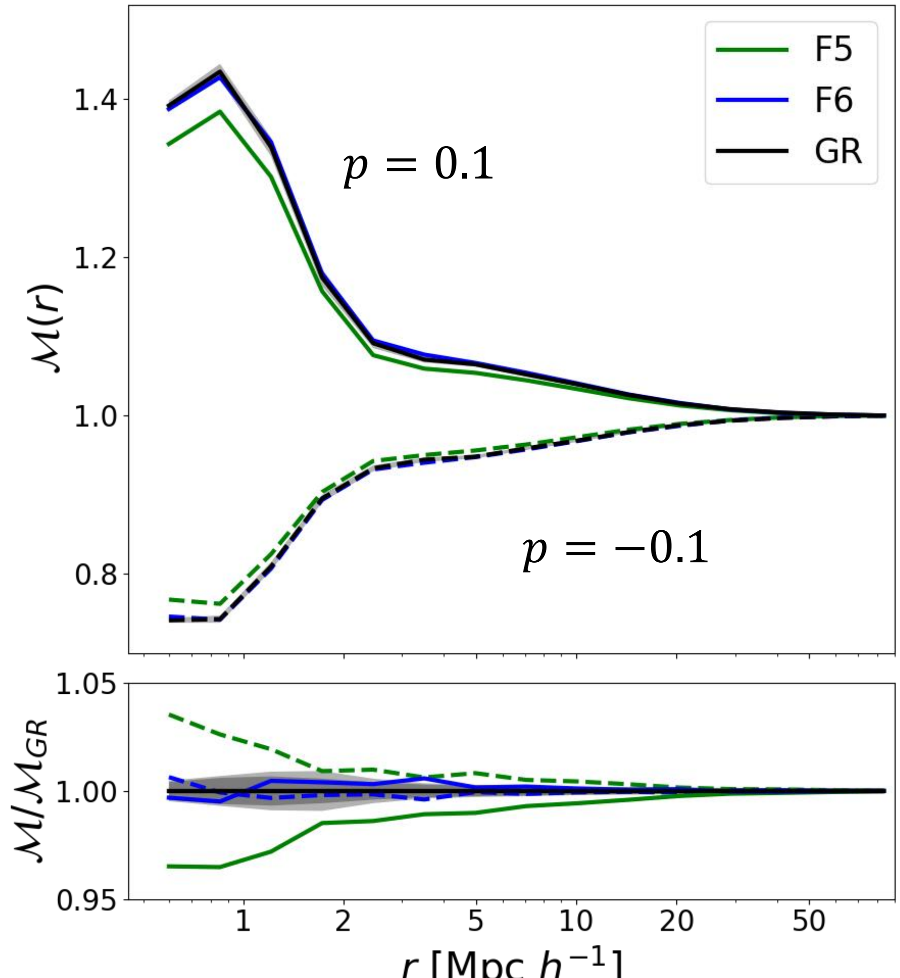
Marked statistics

F5: $|f_{R0}| = 10^{-5}$
F6: $|f_{R0}| = 10^{-6}$

Density-marked correlation function



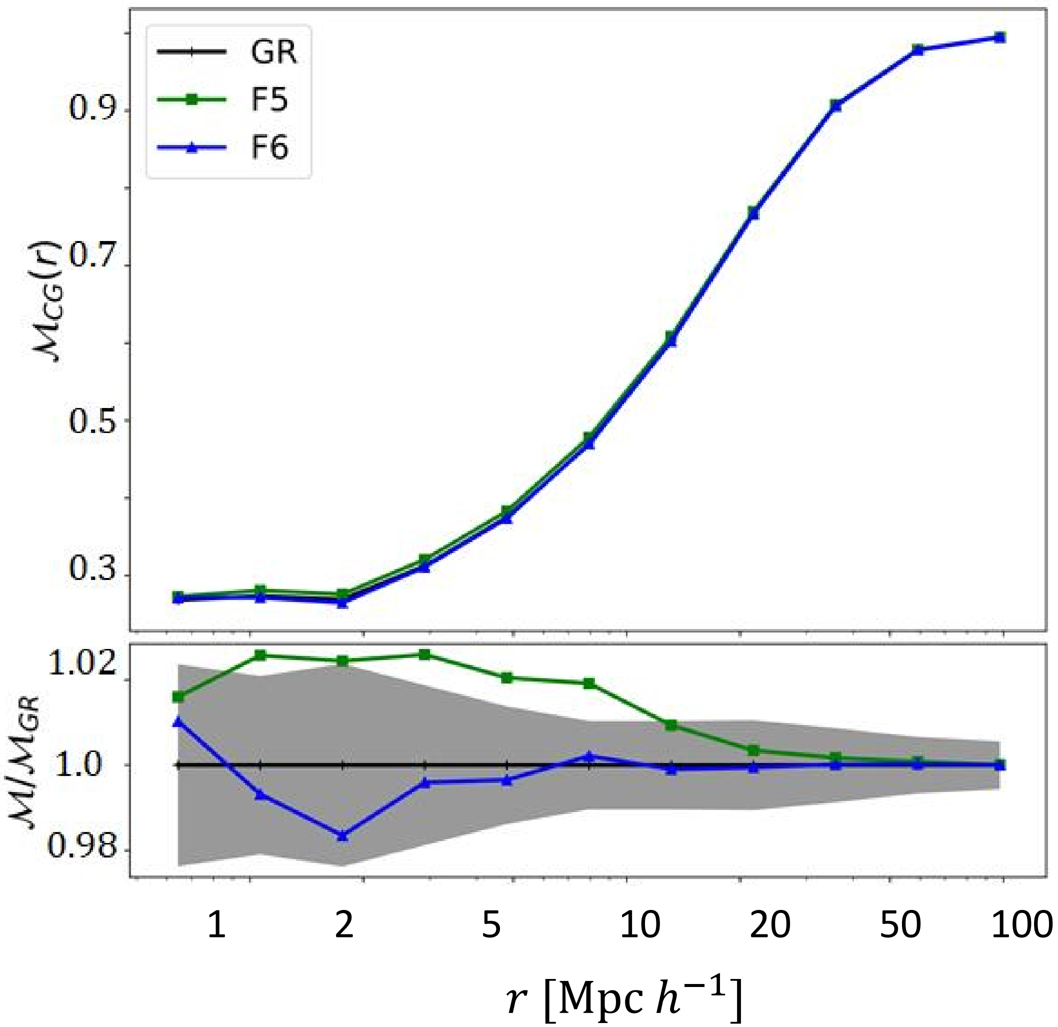
Mass-marked correlation function

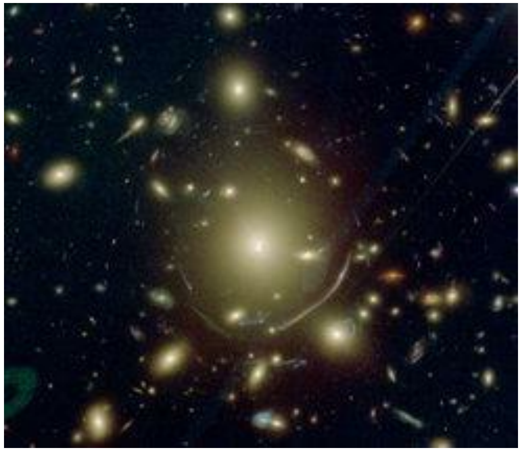


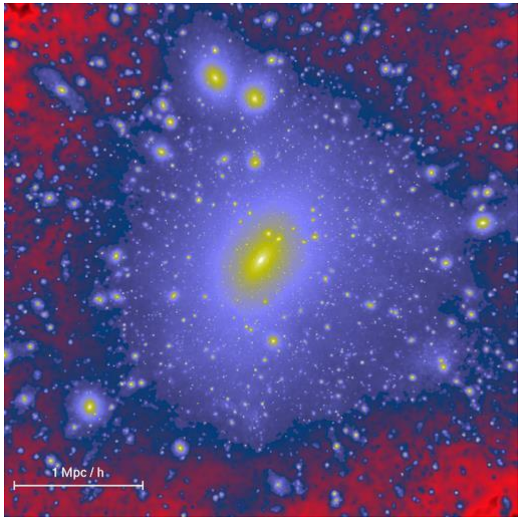
Marked statistics

What else?

$$m_c = M^p; m_g = \rho^q$$







Marked statistics

Why clusters?

Largest gravitationally-bound objects. Ideal laboratories to test gravity in this regime (~1-20 Mpc/h) (Schmidt et al., 2009).

More massive haloes are predicted in $f(R)$ gravity (Lombrisier et al. 2013)

Constraint $f(R)$ parameters from observational data (Cataneo et al. 2015)

Modelling of cluster physics in $f(R)$ gravity (Mitchell et al. 2019)

Future datasets will improve the constraints

Everybody loves galaxy clusters

Summary and conclusions

- Models of modified gravity with screening mechanism are proposed to test gravity at large scales ($\sim 1 - 20$ Mpc/h).
- The marked correlation function can be used to unveil MG where the structure formation deviates from ΛCDM, even if the 2-point correlation function is the same.
- Using either the local density or the host halo mass as marks encode extra information, showing evidence of the presence of the fifth force in the unscreened regime in MG models.