A new framework to testing modified gravity using galaxy surveys

Joaquin Armijo-Torres. IPMU postdoc colloquium

Hello!

New postdoc started in October!
I'm at A049, please pass by.
Interested in cosmology and the large-scale structure of the Universe.

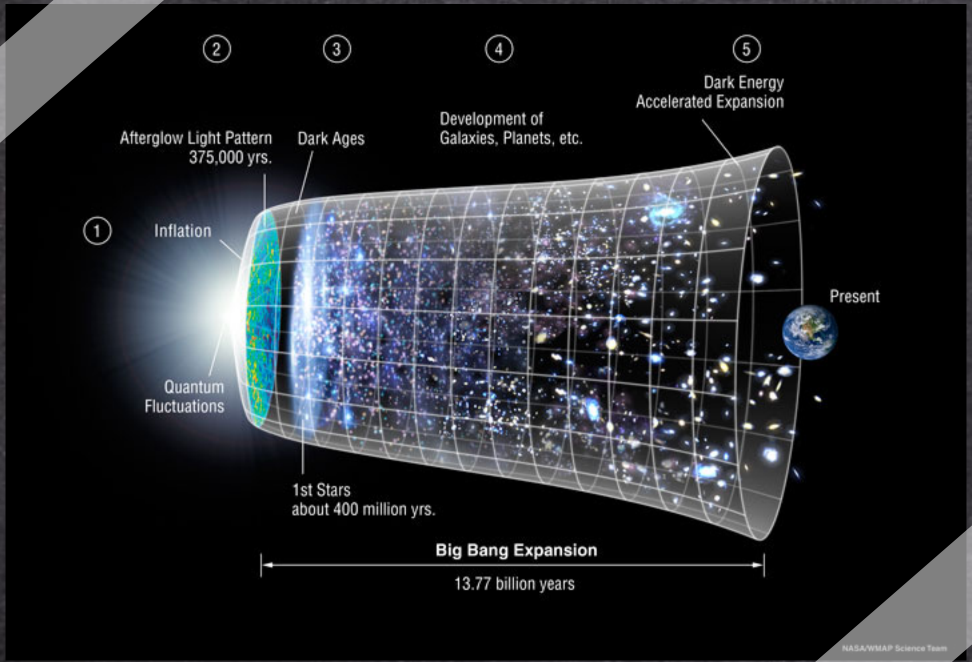
Outline of my talk.

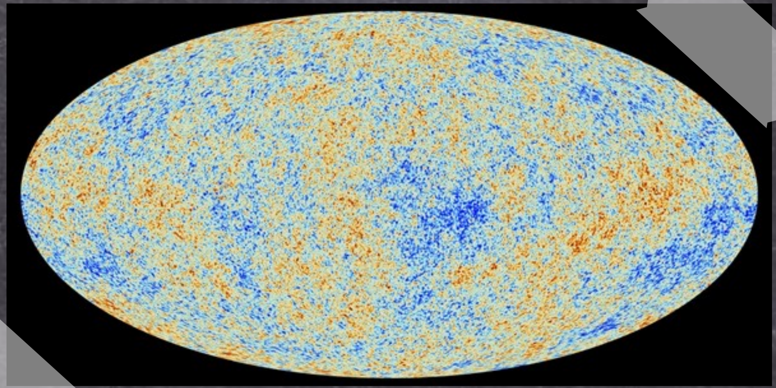
- Cold dark matter universe with and without cosmological constant: ΛCDM vs Modified gravity.
- GR and MG simulations and mock galaxy catalogues.
- Probes for modified gravity: what does the LSS tell us beyond 2-point statistics? A new approach.

01

ΛCDM vs. Modified gravity

The ΛCDM Universe





Λ drives dark energy which accounts for ~70% energy density budget. The rest comes from matter (25% dark matter, 5% baryons).

What about modified gravity?

Modified gravity

Ezquiaga & Zumalacarregui (2017)

	$c_g = c$	$c_g \neq c$
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], $f(\phi)$·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

Courtesy Baojiu Li

Modified gravity

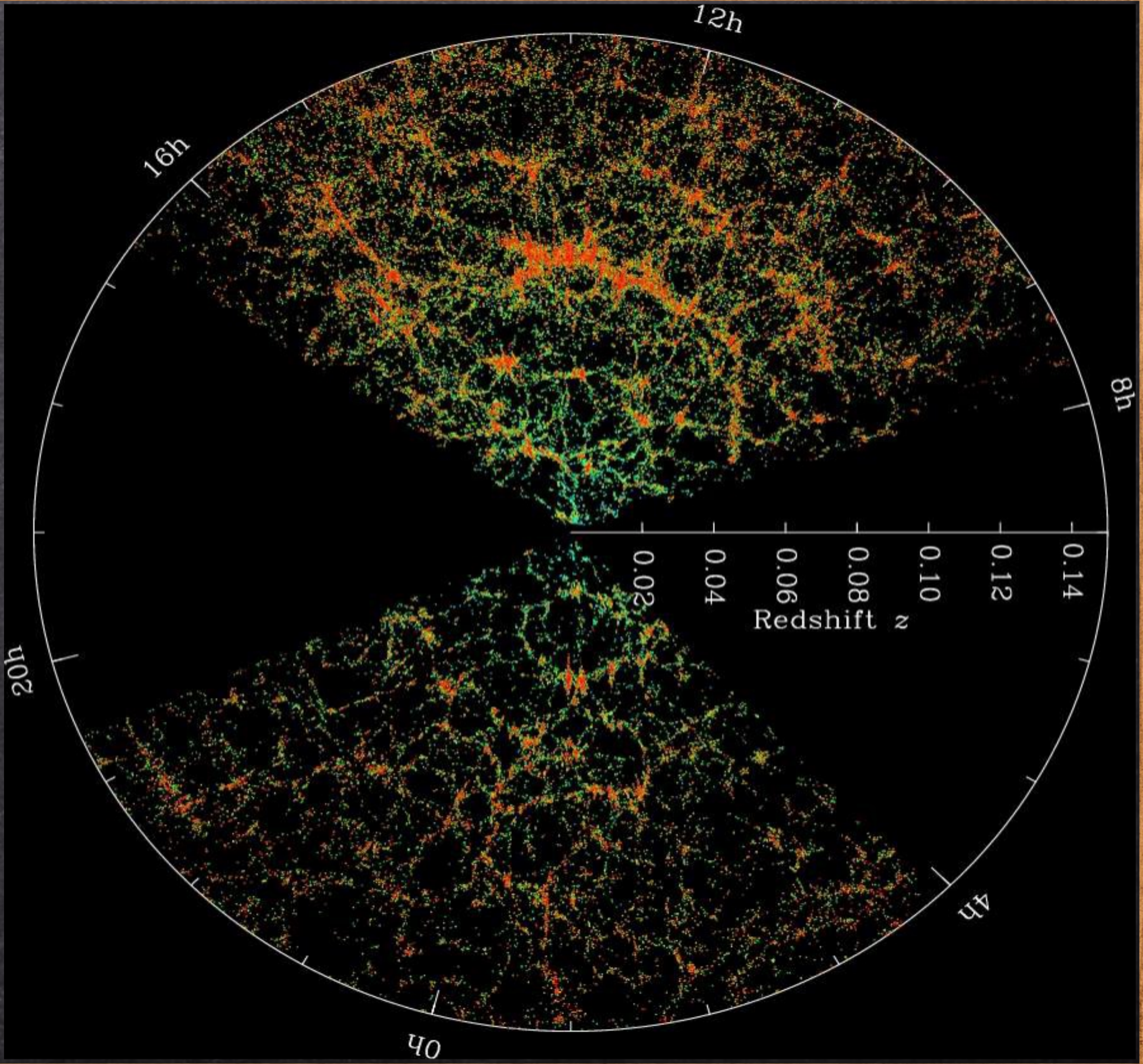
- Modified gravity can explain the cosmic acceleration without a cosmological constant.
- Scalar field coupled to matter or extra term in the Einstein-Hilbert action triggers extra fifth force that enhances gravity.
- Screening mechanism (Chameleon in f(R)) hides the fifth force in high density regions. This is needed to make observationally viable theory (solar system scale).
- The fifth force is screened in the early Universe (CMB is unchanged).
- Gravity needs to be probed at cosmic scale using the Large-scale structure.

Modified gravity

Matter density at $z \sim 0$ is highly non-linear.

It shows galaxies but not mass.

We understand roughly how galaxies populate the dark matter but with some few parameters.



$f(R)$ gravity

Replace the cosmological constant by $f(R)$ in the action:

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

where a modified Poisson equation can be obtained (varying the Action):

$$\vec{\nabla}^2 \Phi = 4\pi G a^2 \delta\rho_m - \frac{1}{2} \vec{\nabla}^2 f_R$$

The new term $f_R \equiv \frac{df}{dR}$ (the scalaron) is understand a new potential which mediates a new effective "fifth force". In the limit

$$\lim_{R \to \infty} f(R) = \text{const.}$$

When $f_R \to 0, f(R) = 2\Lambda$, which is the first condition for viable $f(R)$. The second limit is for $f_R \to 0$ when $\rho_m \to \infty$ (Chameleon mechanism).

The Hu & Sawicki model satisfy these conditions with $f(R)$ constant in the background cosmology throughout cosmic history.

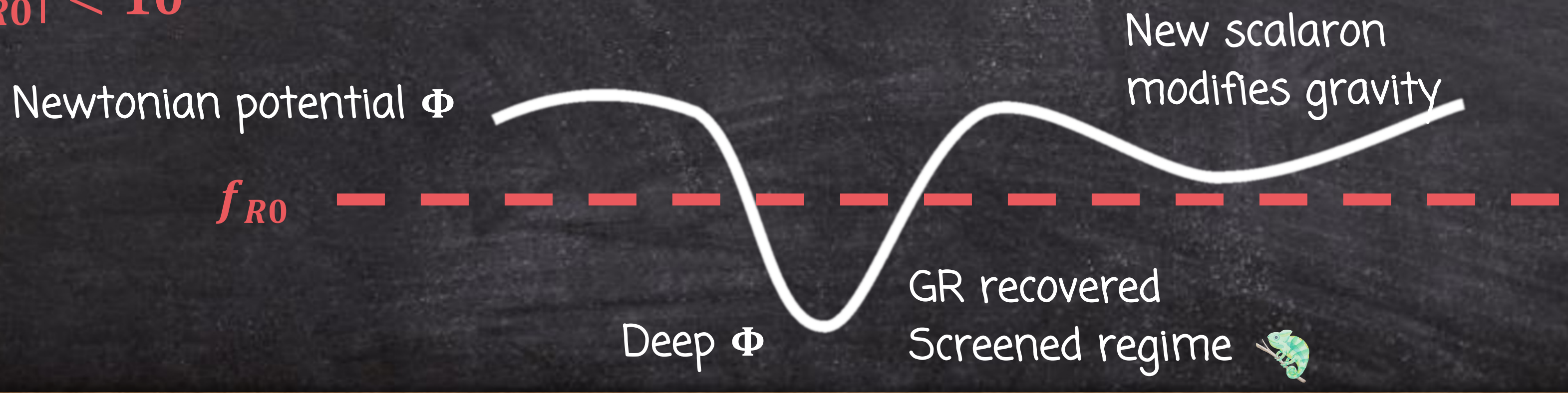
The Hu & Sawicki model

The function $f(R)$ takes the form: $f(R) = -m^2 \frac{c_1\left(\frac{R}{m^2}\right)^n}{c_2\left(\frac{R}{m^2}\right)^n+1}$, (Hu and Sawicki 2007)

Satisfying the previous limit for high curvature we can expand and solve for the background cosmology:

$$f(R) \approx \frac{c_1}{c_2} m^2 + \frac{c_1}{c_2^2} m^2 \left(\frac{m^2}{R}\right)^n, \text{ with } \frac{c_1}{c_2} = \frac{\Omega_{\Lambda,0}}{\Omega_{m,0}} \text{ and } \frac{c_1}{c_2^2} = -\frac{1}{n}\left[3\left(1 + 4\frac{\Omega_{\Lambda,0}}{\Omega_{m,0}}\right)\right]^{n+1} f_{R0}.$$

We can constraint the model based in 2 free parameters. For n=1 we obtain $|f_{R0}| < 10^{-4}$ (Schmidt et al. 2009). Current constraints using abundance of clusters and weak lensing give $|f_{R0}| < 10^{-5}$



02

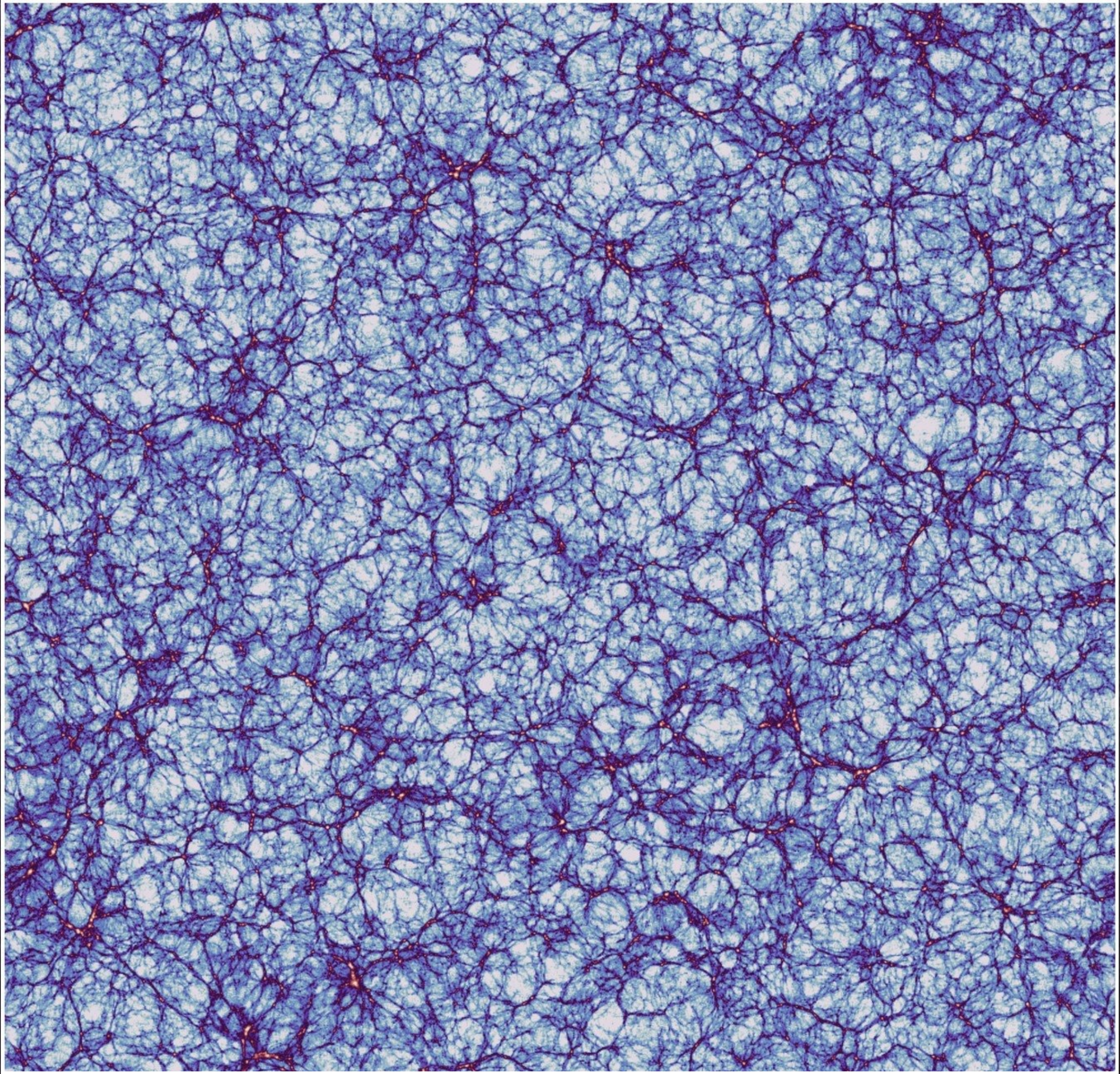
GR and MG simulations

Modified gravity simulations

Fully non-linear equations of motion for gravity $\boldsymbol{\Phi}$ and the scalaron $\boldsymbol{f_R}$ (Poisson equation).
Solutions to these equations using the ECOSMOG code (Li et al. 2012) and MG-GADGEGT (Arnold et al. 2018).

Simulations for GR and $\boldsymbol{f(R)}$ models with $|\boldsymbol{f_{R0}}| < \mathbf{10^{-5}}, \mathbf{10^{-6}}$ (F5, F6).

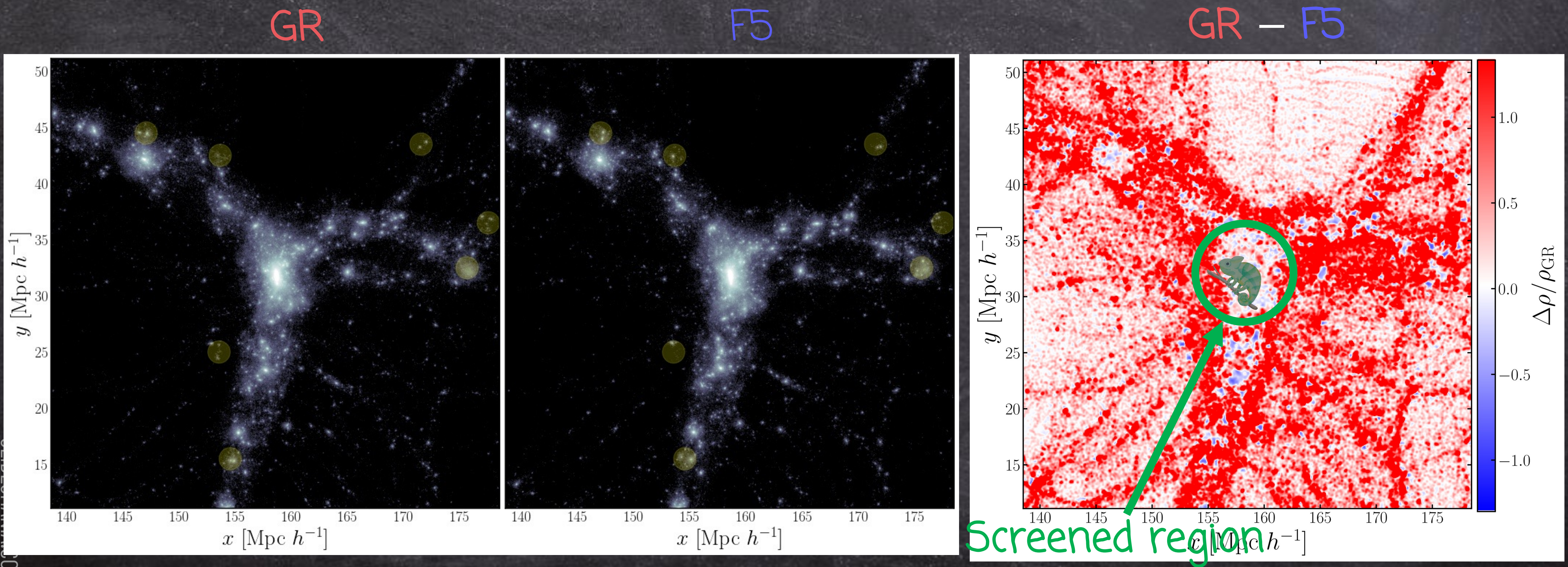
Simulations start from the same initial conditions.



The MG lightcone project (Arnold et al. 2018)$z = 0, L_{\mathrm{box}} = 768\ \mathrm{Mpc}\ h^{-1}$

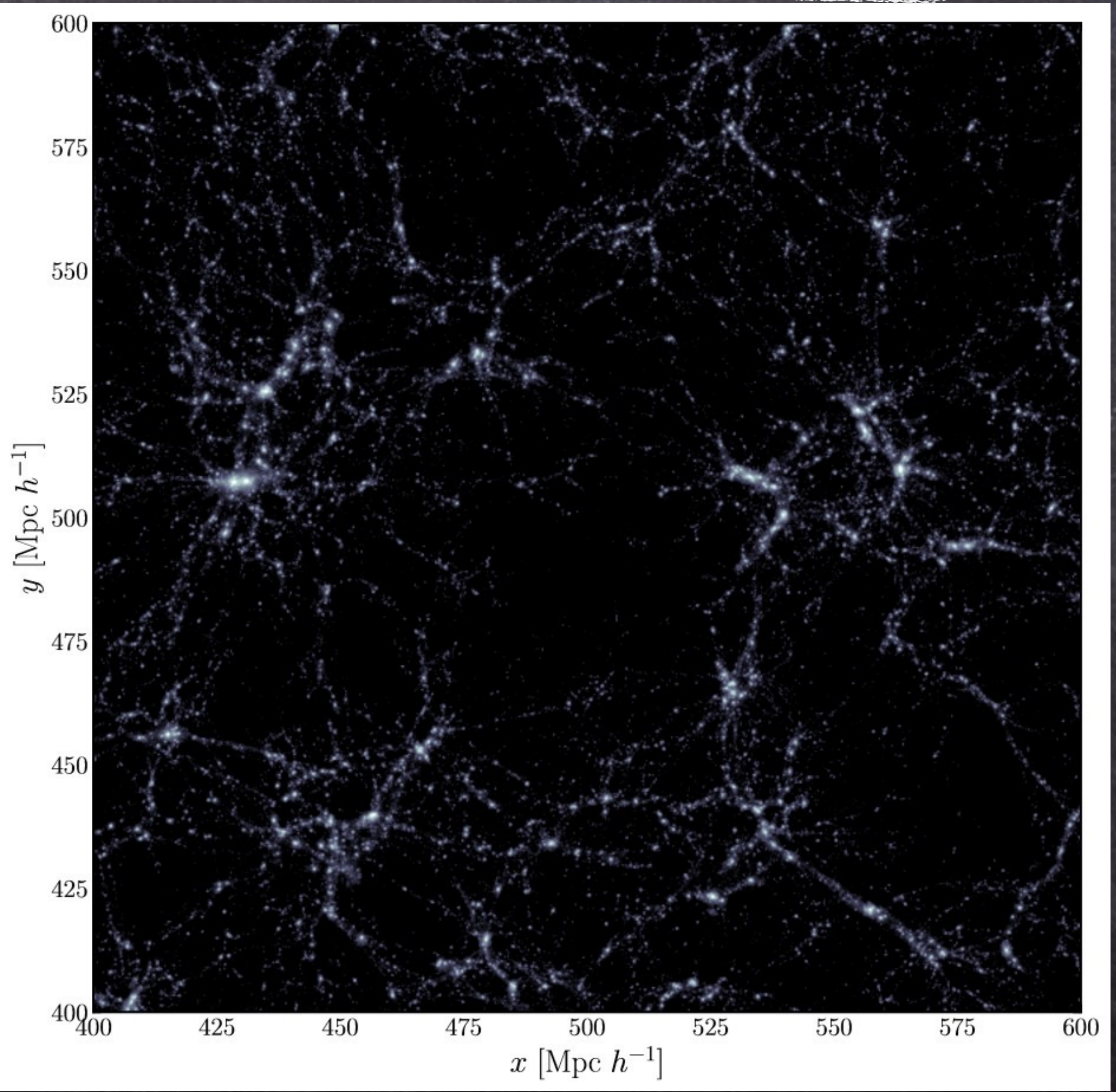
Modified gravity simulations

Chameleon mechanism: Gravity is modified, however screened in high-density regions (e.g. inside a large mass halo)



Testing gravity using the cosmic web

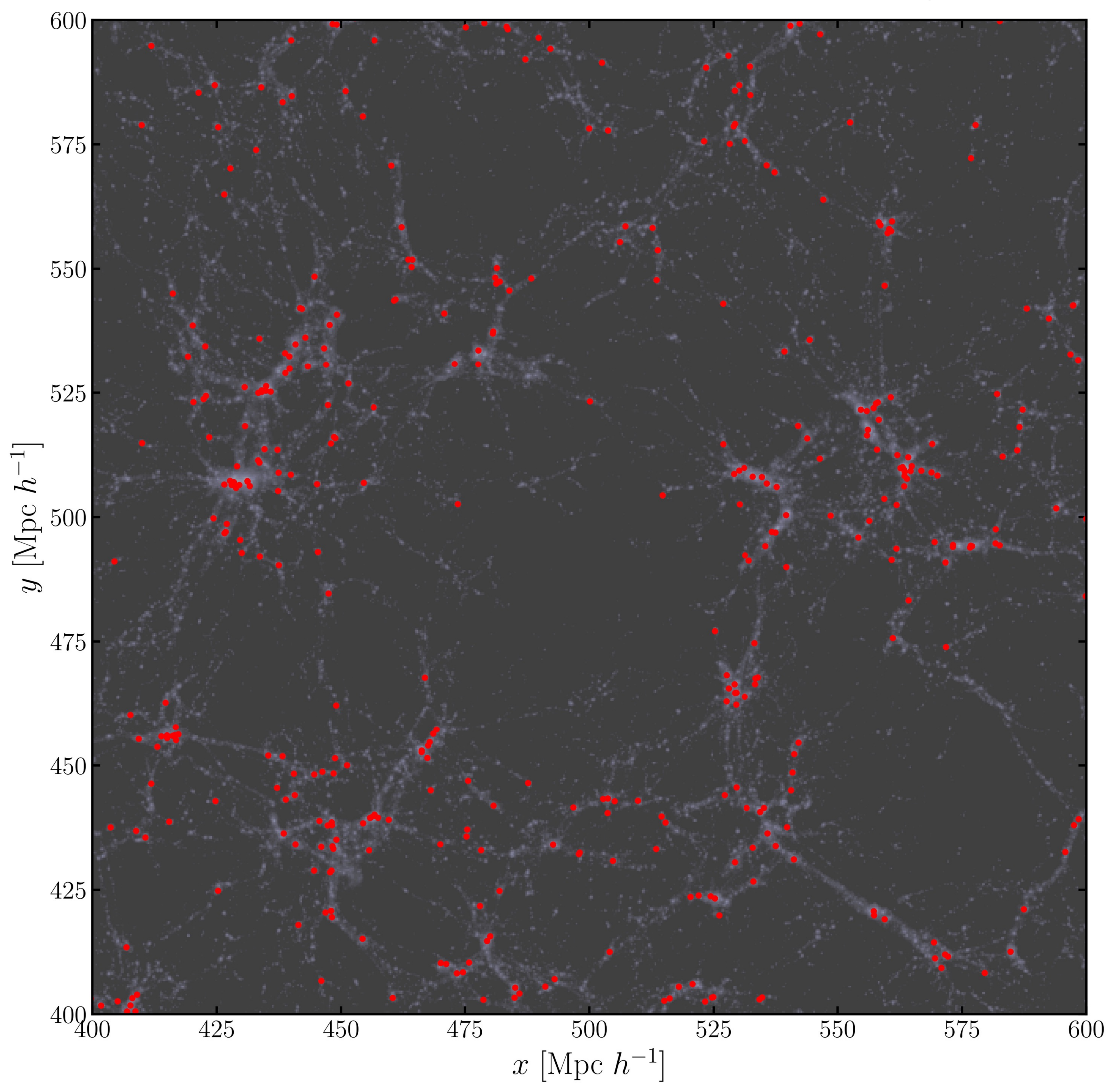
- The distribution of matter at late times forms large-scale structures.
- These structures are shaped mainly by gravity and the late cosmic acceleration, creating different environments where galaxies live.
- Nodes, filaments, walls and voids can be found in the cosmic web.



Testing gravity using the cosmic web

We observe galaxies:

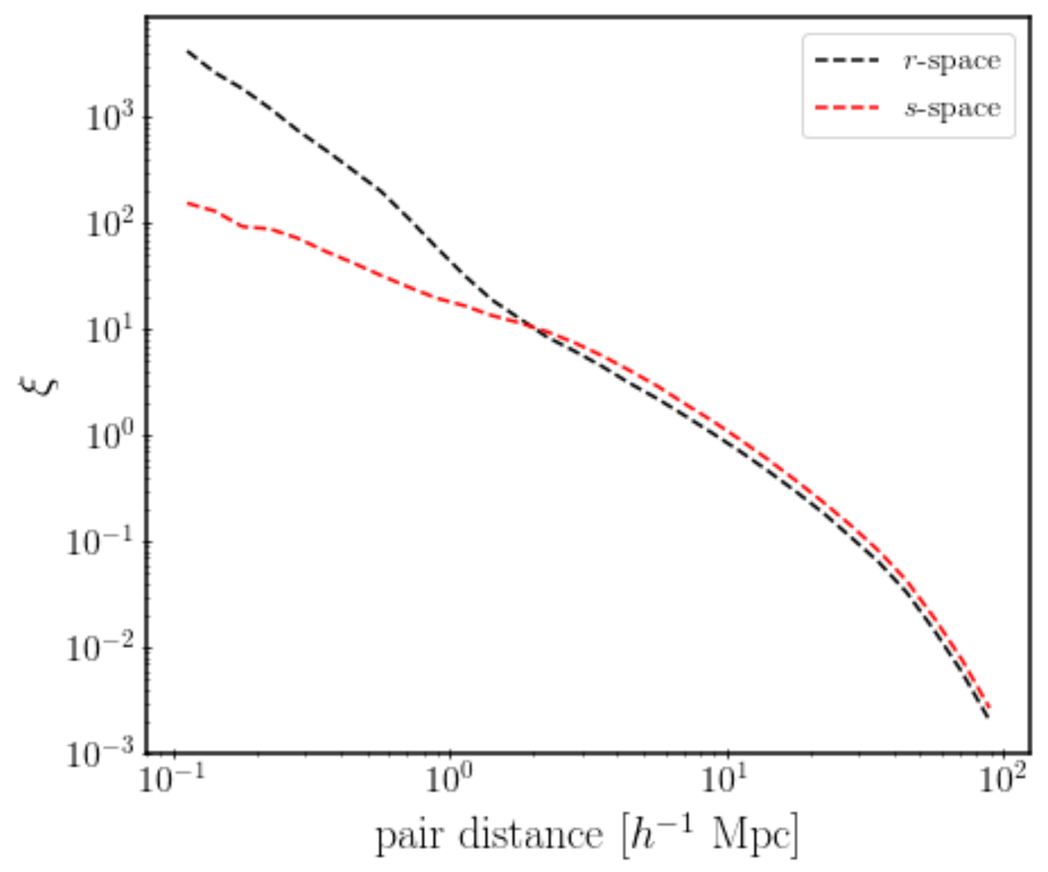
- Galaxies trace the underlying matter distribution assuming a non-linear and stochastic bias relation $\delta_g = b\delta_m$.
- They follow the formation of the same structures as the cosmic web formed by matter.
- Studying the connection between dark matter (haloes) and galaxies help us to understand the cosmological model.



Galaxy clustering: The 2-point correlation function

$$1 + \xi = \frac{DD}{RR}$$

Estimator: relates the number of galaxy pairs DD in comparison to a random distribution of pairs RR

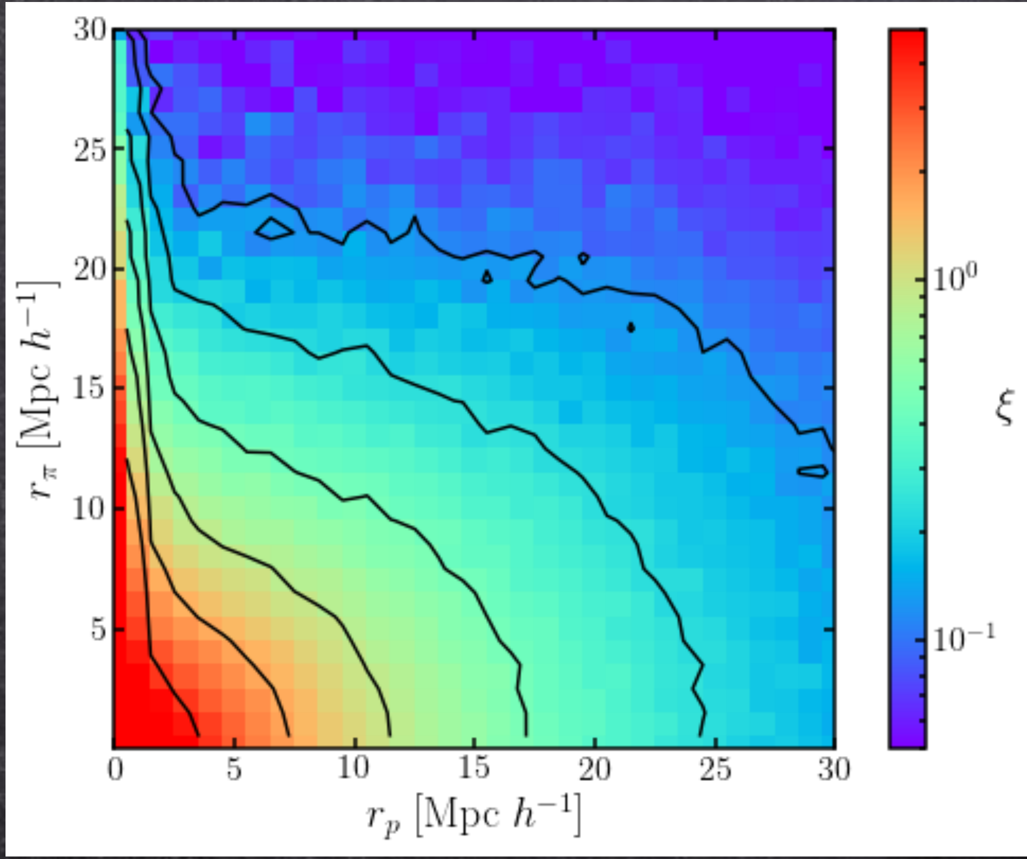


$$s = r + \frac{(1+z)v_{||}}{H(z)}\,\hat{e}_{||}$$

3D pair distance including pairwise 'peculiar' velocities

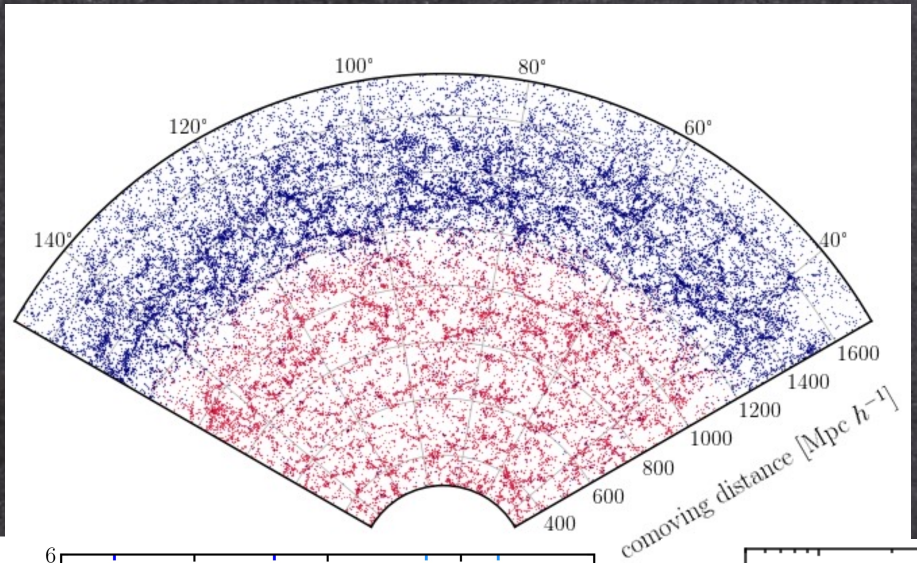
$$\frac{w_p(r_p)}{r_p} = \frac{1}{r_p}\int_{-\infty}^{\infty} dr_\pi\, \xi(r_p, r_\pi)$$

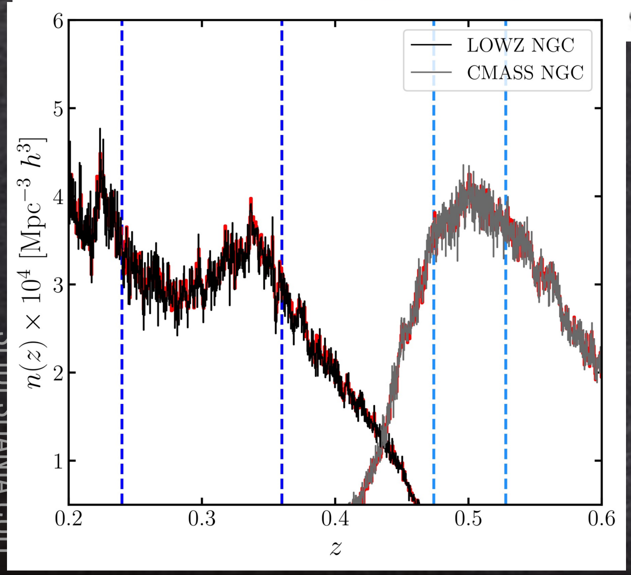
The projected-correlation function

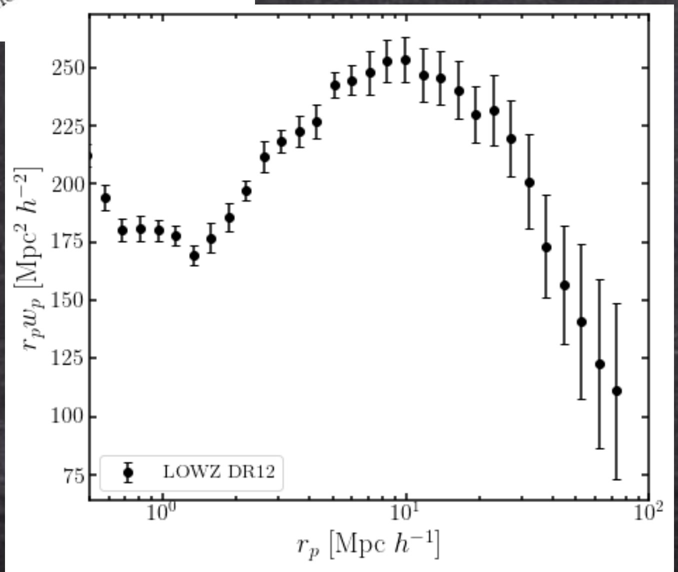


Large-scale galaxy surveys

SDSS-III BOSS



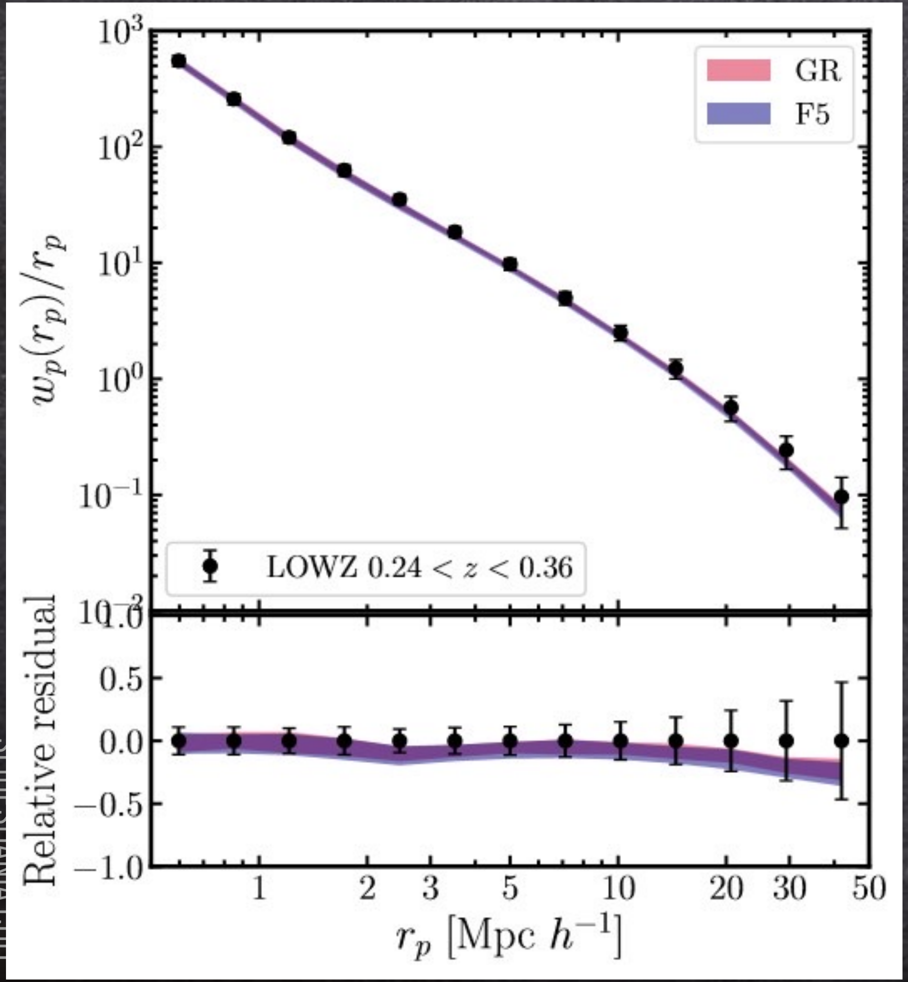


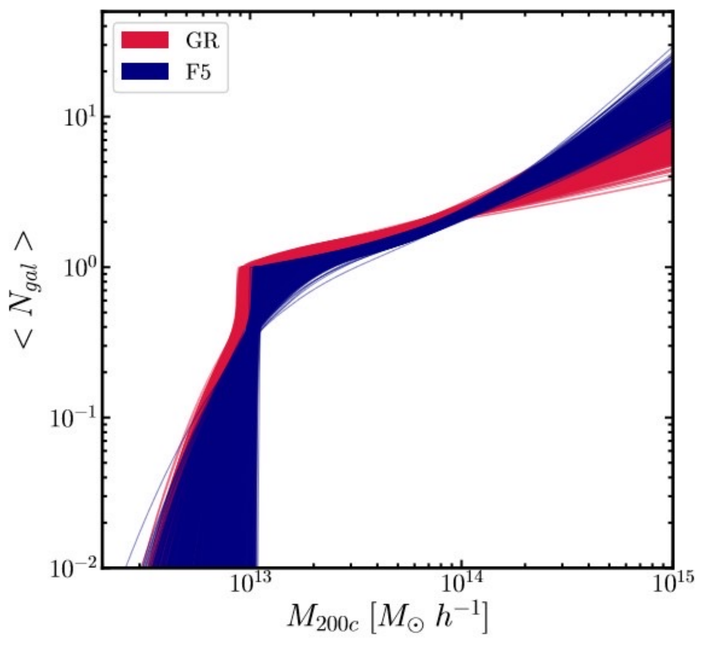


- Currently 1- and 2-point functions are measured accurately in a large range of scales.
- When creating mock galaxy catalogues from simulations (GR and MG) we are forced to reproduce both $n(z)$ and he projected 2-point clustering.
- We can rely in the fine tunning of parameters of the halo-galaxy models to generate such observational constraints. (Cautun et al. 2017, Armijo et al. 2018, Paillas et al. 2019)

Can we replicate these results directly in the simulations? That's the neat part! Absolutely yes!

We need to create galaxy mock catalogues





The Halo occupation distribution (HOD) model:

Average number of galaxies inside a dark matter halo as function of its mass:

$$\langle N_c \rangle = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{\log M_{min} - M}{\sigma_{\log M_{min}}}\right)\right]$$

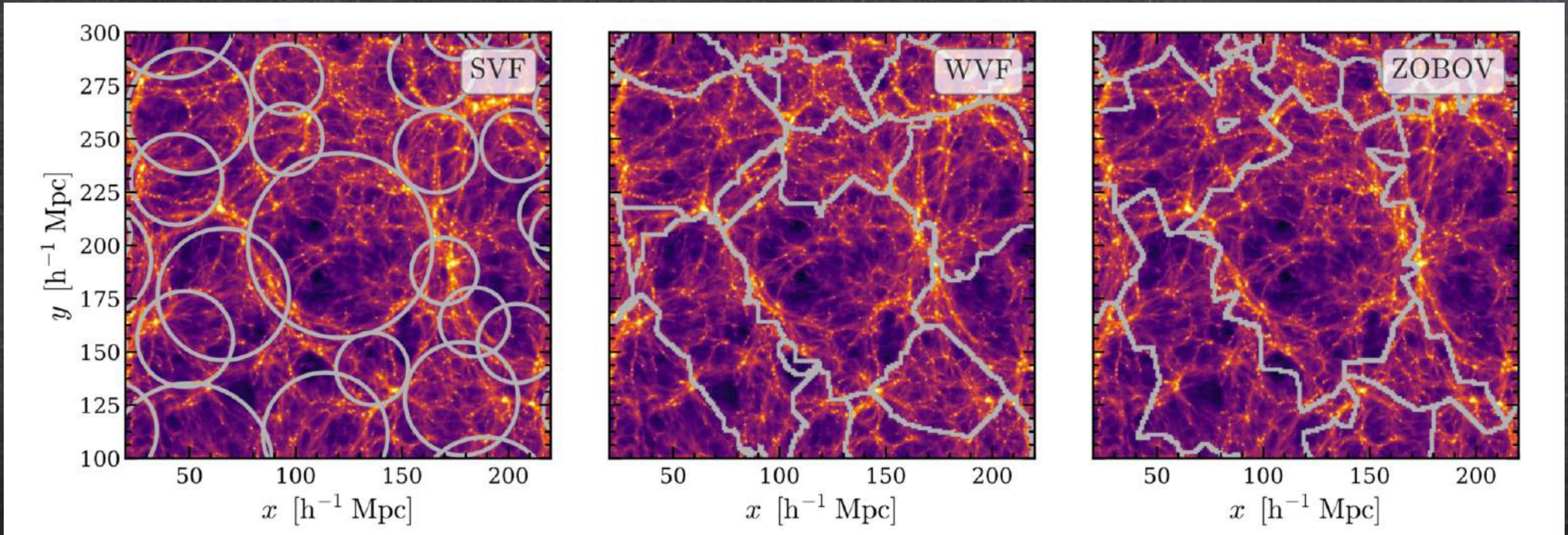
$$\langle N_s \rangle = \langle N_c \rangle \left(\frac{M - M_0}{M_1}\right)^{\alpha}$$

(caveat) the HOD function (5 parameters) is degenerated with the number density of galaxies n_{gal} and the clustering ξ.

03 Probes for modified gravity

Weak lensing in cosmic voids

- Finding void regions in the cosmic web and comparing void finders: 7 void finders (4 3D-VF, 3 2D-VF).
- Using galaxies in voids to measure weak lensing statistics and compare it for different gravity models.

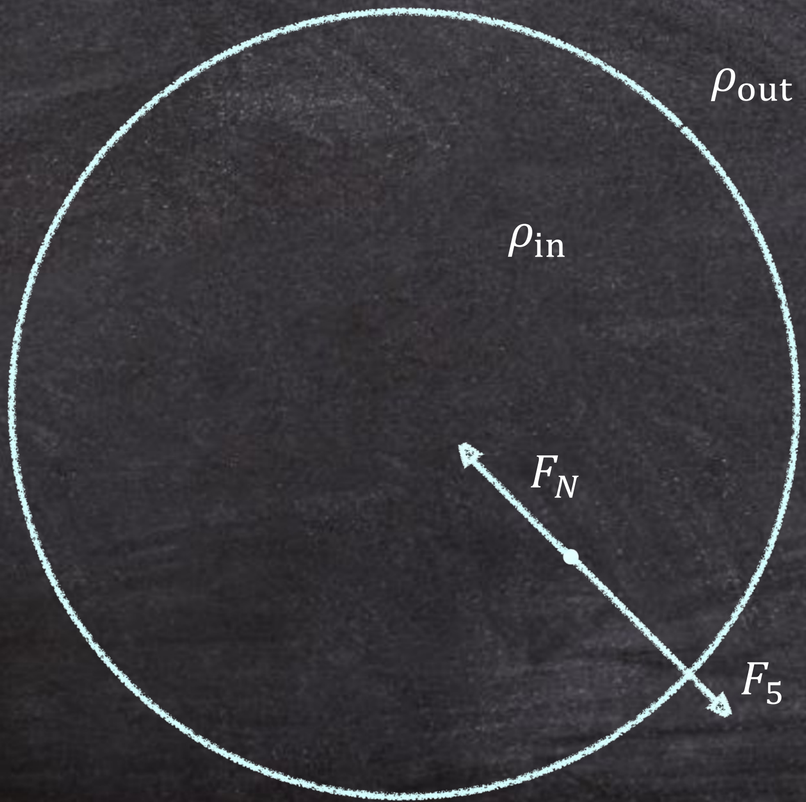


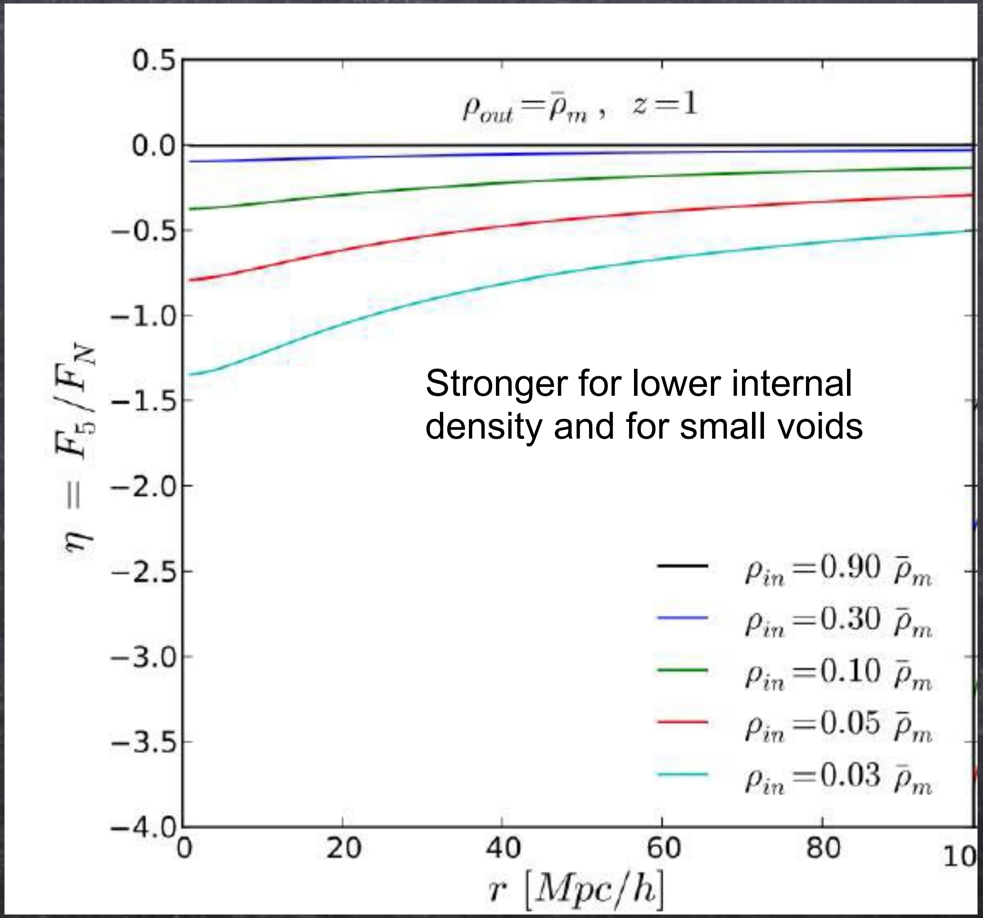
The SHED collaboration: Cautun et al. 1710.01730; Paillas et al. 1810.02864

$f(R)$ voids: prediction using the spherical top-hat model:

Clampitt et al. 2013 calculate the Newtonian and fifth force for a top-hat empty region

Negative fifth force inside voids acting in opposite Direction to Newtonian



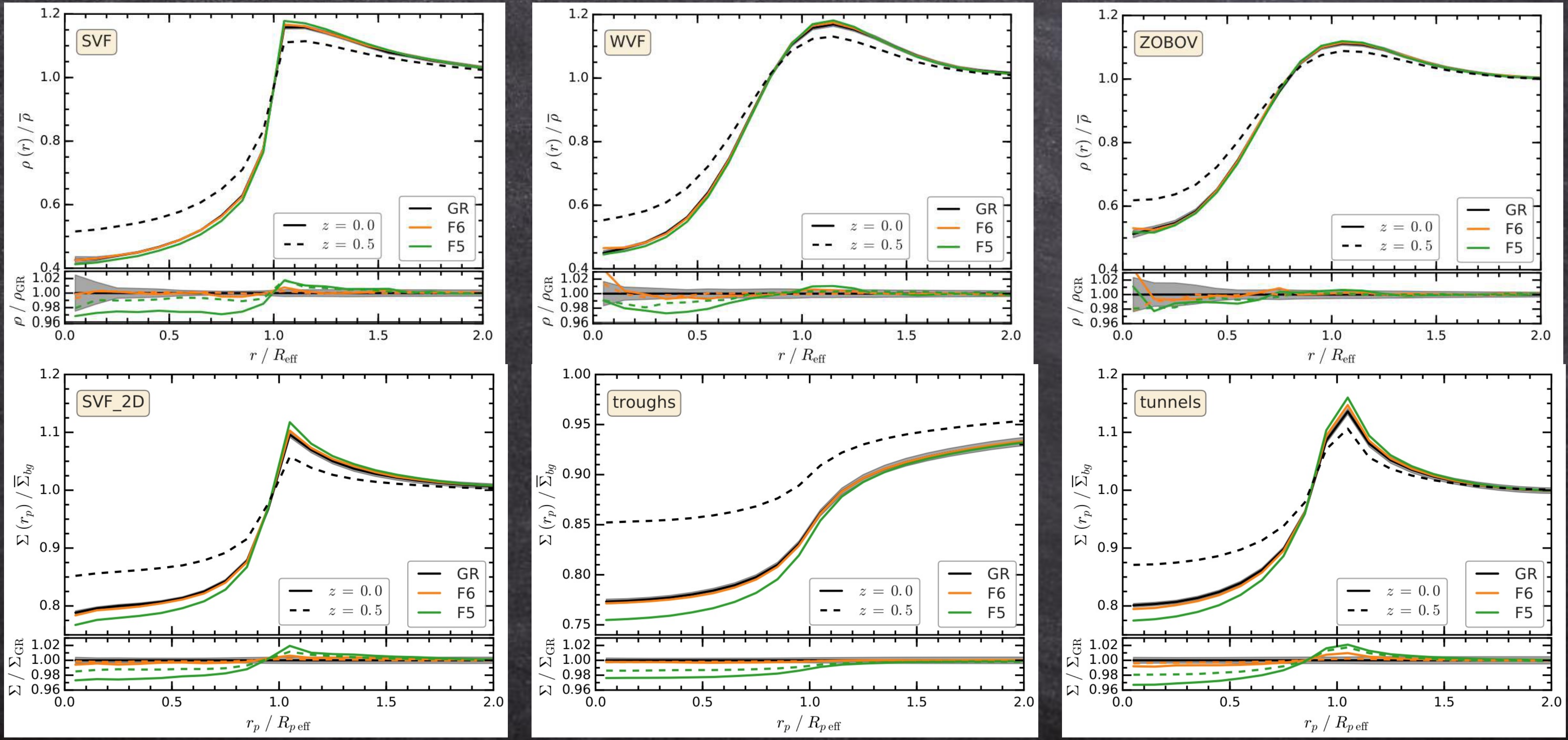


Void stacked mass profiles

$$
\begin{aligned}
\rho(r) &= \overline{\rho}_{bg}(1+\xi_{vm;\,3D}) \\
\Sigma(r) &= \overline{\Sigma}_{bg}(1+\xi_{vm;\,2D})\,,
\end{aligned}
$$

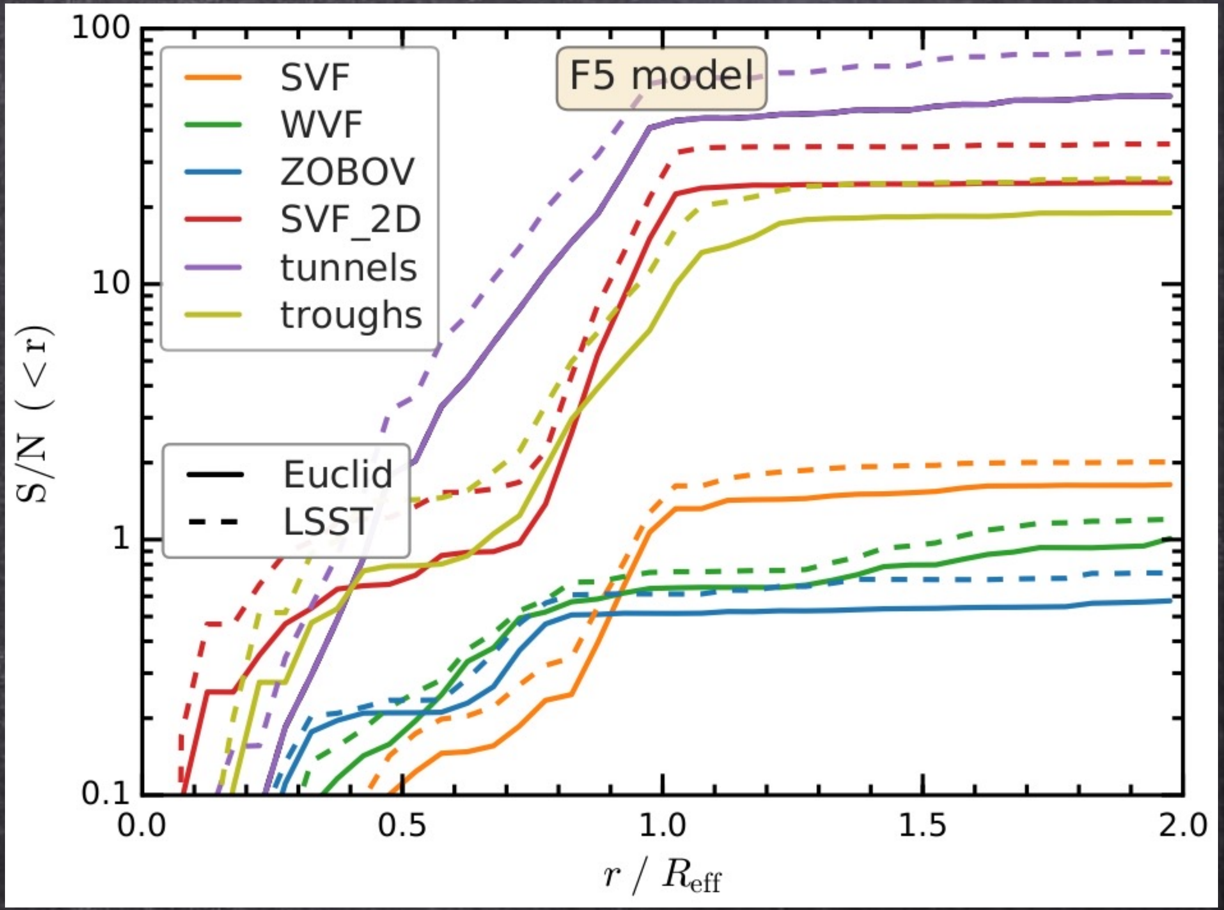
3D voids

2D voids



Testing MG with voids in the LSST era

- Lensing can be used to detect $f(R)$ with LSST especially with 2D VF.
- DM profiles confirm emptier voids in MG models.
- These results are found for models even with the same 2-point clustering.

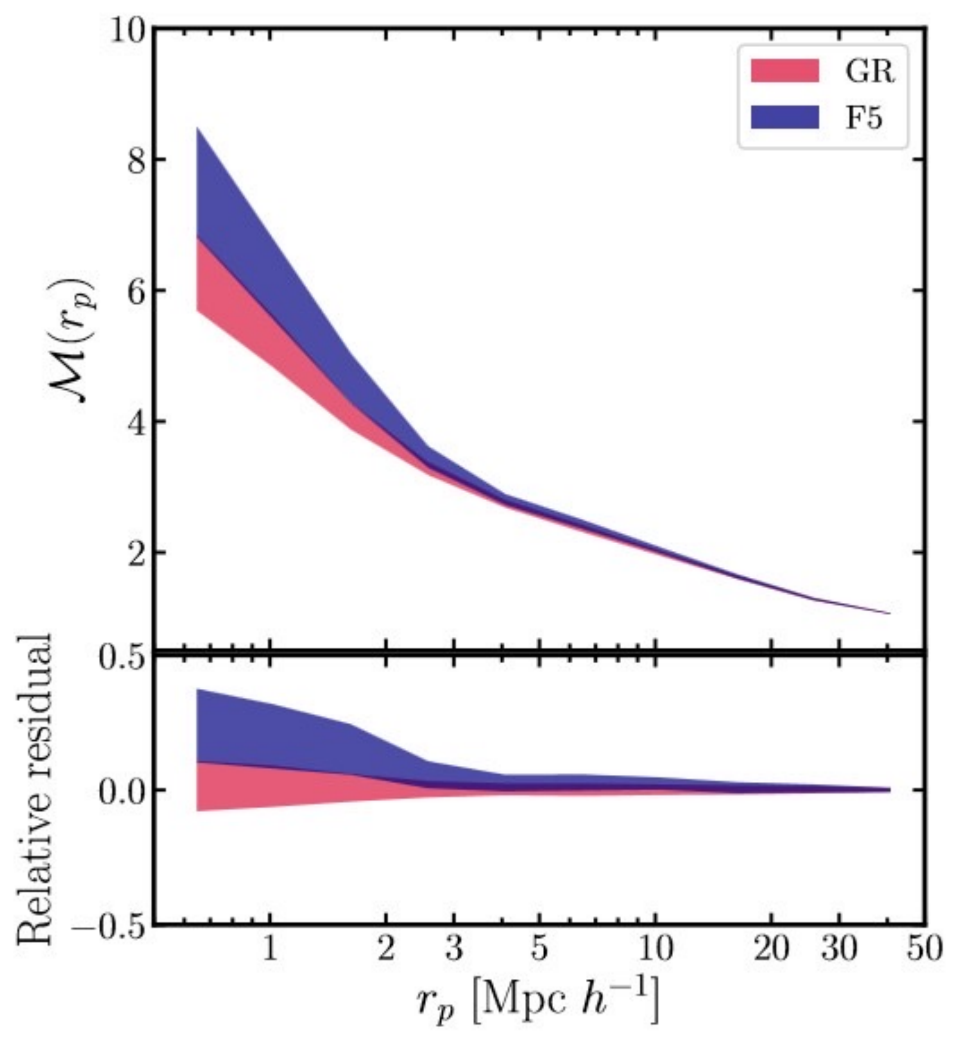


Marked statistics

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

$$m = \left(\frac{\rho}{\bar{\rho}}\right)^p$$

- "Marks" can be used in two-point statistics to upweight models given a density environmental property.
- The marked correlation function can be used to break degeneracies in HOD modeling (White et al. 2008).
- The marked correlation function has been used to distinguish between standard GR and MG (Armijo et al. 2018).



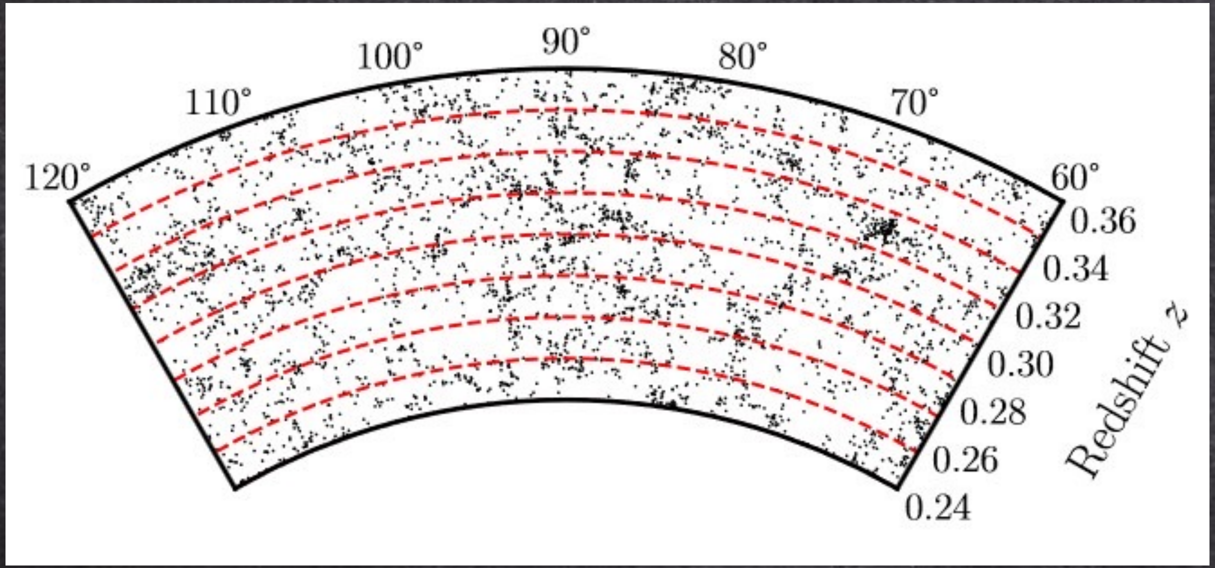
White et al. (2008)

Testing modified gravity using the marked correlation function

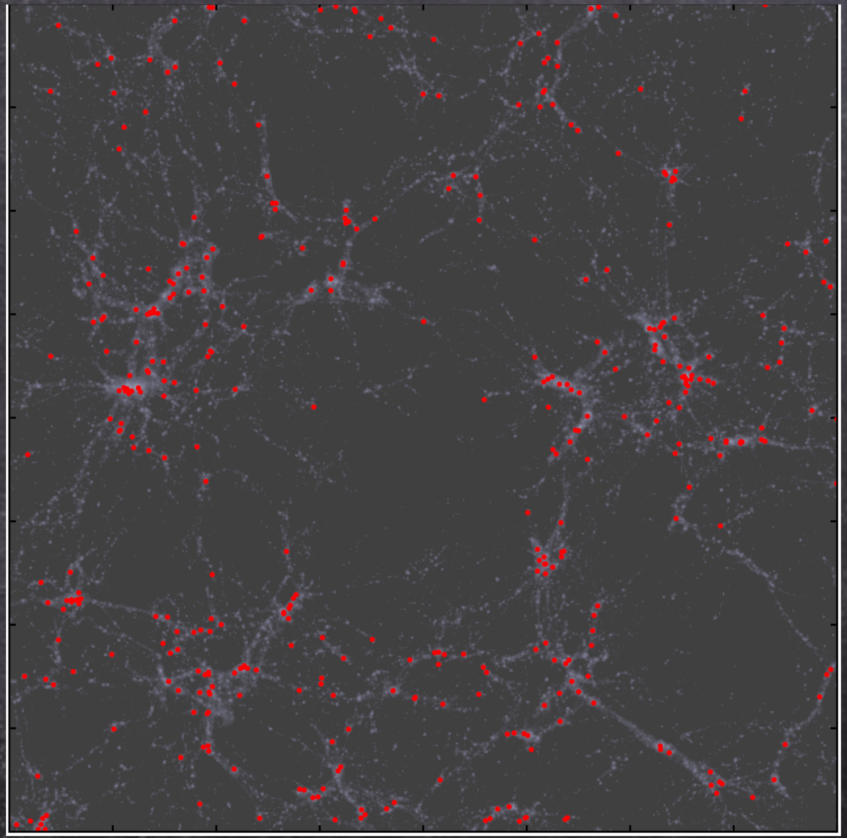
Marks:

based in the local density marks defined in White et al. (2016), We estimate the local density using the Voronoi tessellation method

Survey data: (RA, Dec, z)



Project in 2D-plane



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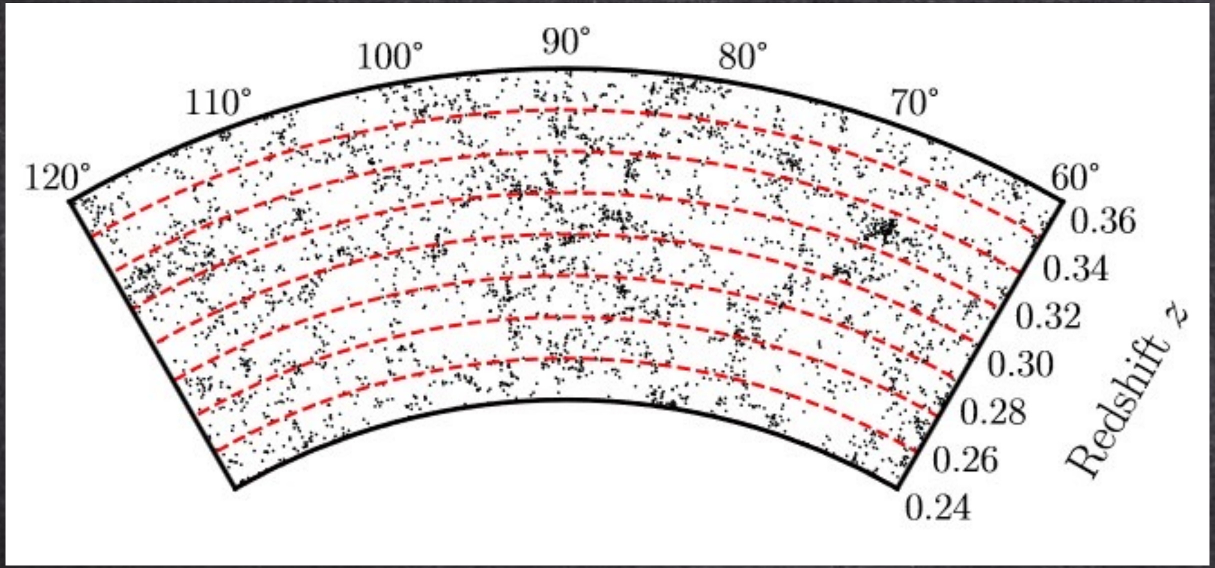

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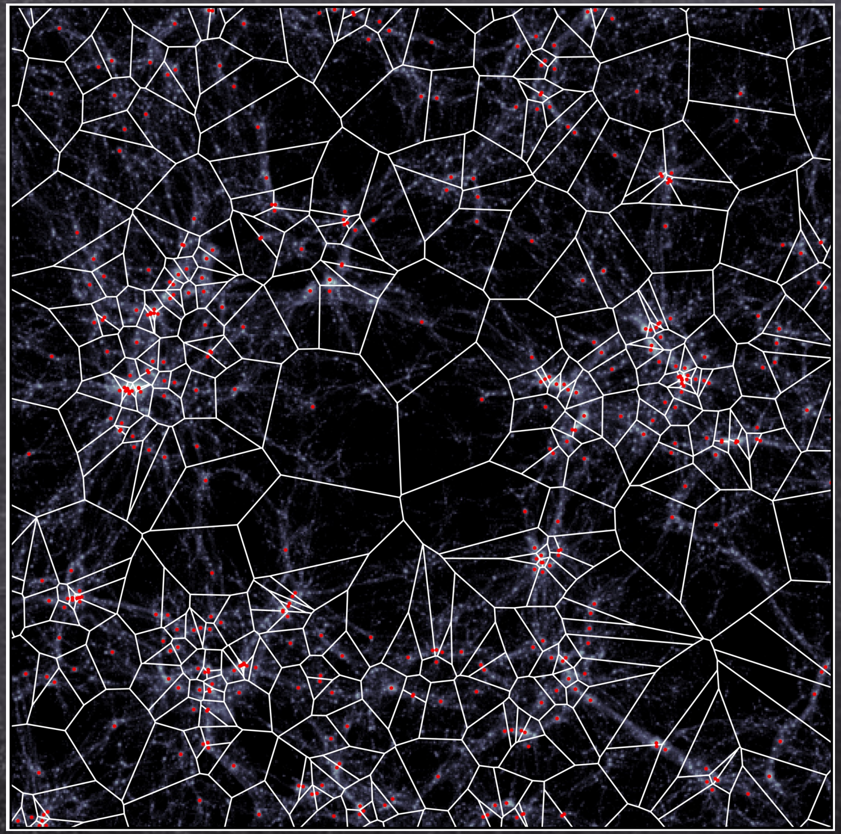

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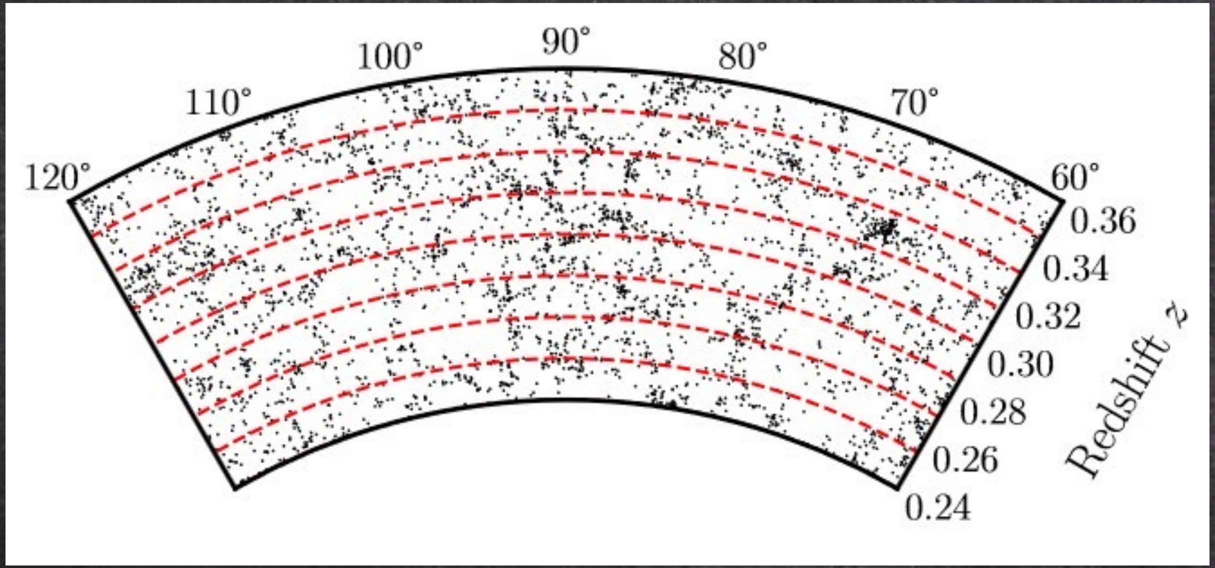

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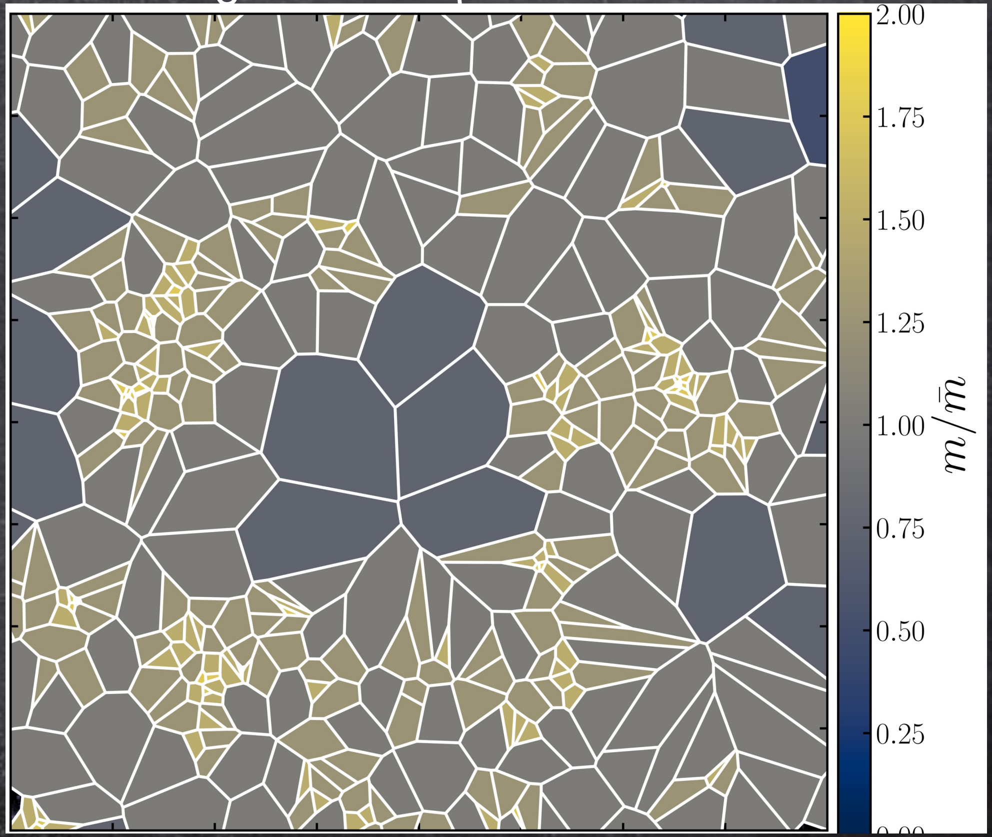

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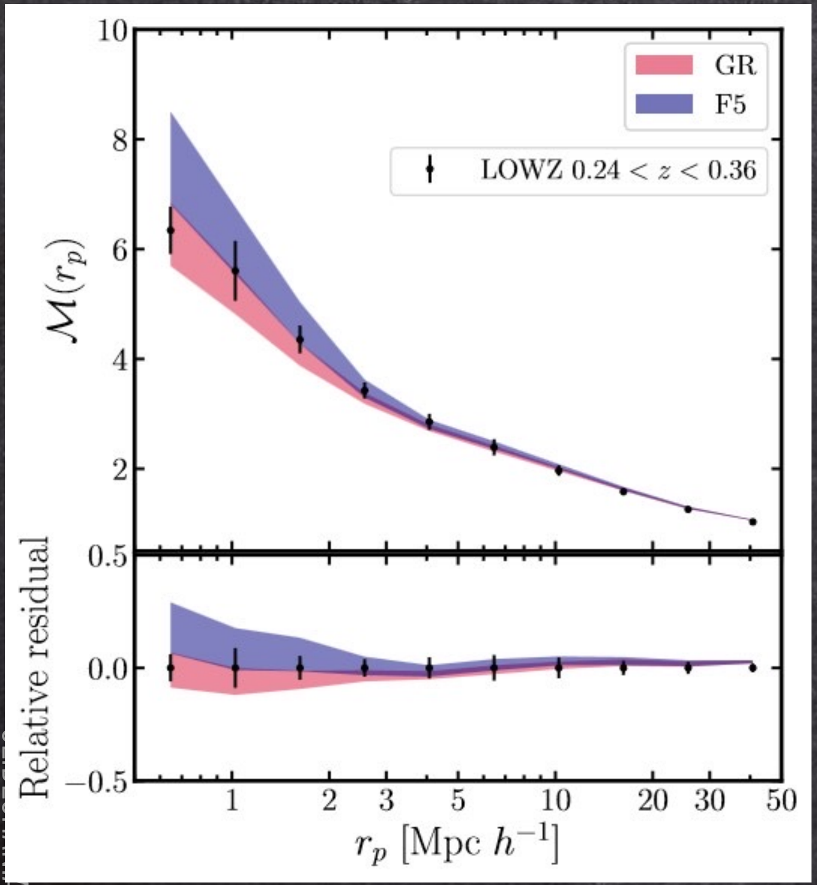

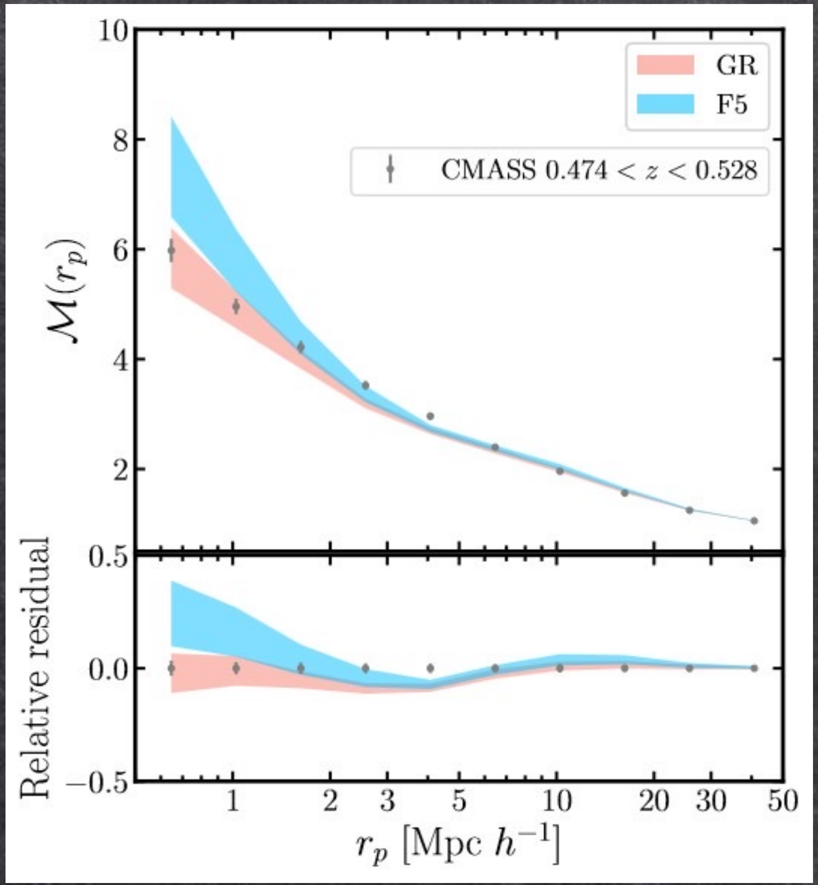

$$\mathcal{M}(r) = \frac{1+W}{1+\xi}$$

- We measure $\mathcal{M}(r_p)$ for LOWZ and CMASS. We can constrain the HOD model with the data but not rule out modified gravity.
- Although CMASS agrees better with GR, some disagreement is found at $3 < r_p/\mathbf{Mpc}\, h^{-1} < 5$.
- Future LRG sample (DESI survey) could improve this measurement.

Summary and Conclusions

- In the search for the elusive camouflaged fifth force in modified gravity. Looking into the predicted modified environments where $f(R)$ gravity acts.
- Into the void: emptier voids in MG models might be a key to constraint the fifth force.
- Marked statistic to test gravity on large-scales and understand the halo model. It helps to break the degeneracy between MG and the HOD modelling. Future data such DESI-LRG will be relevant for this test.

Thank you!

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