A new framework for testing gravity

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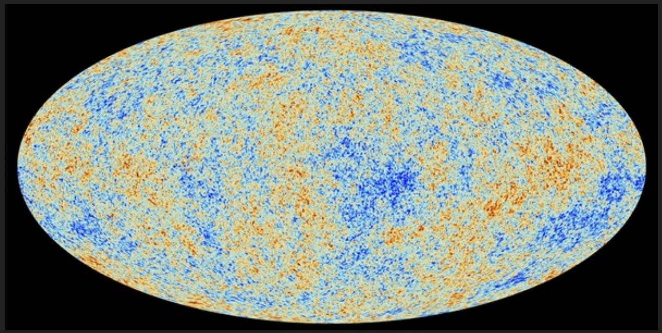
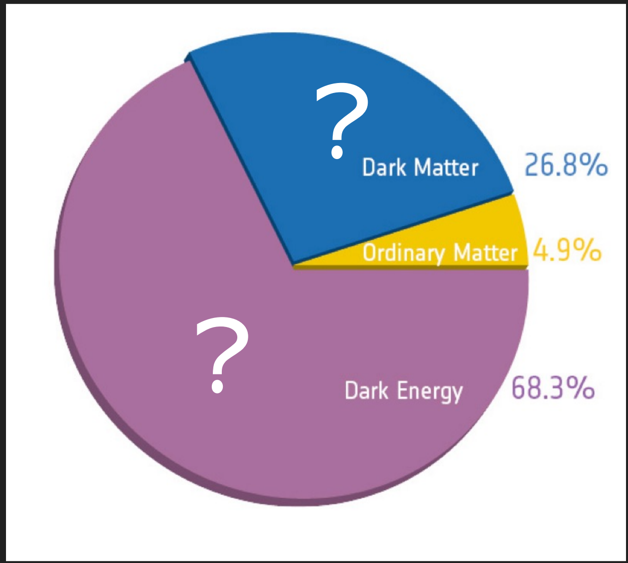
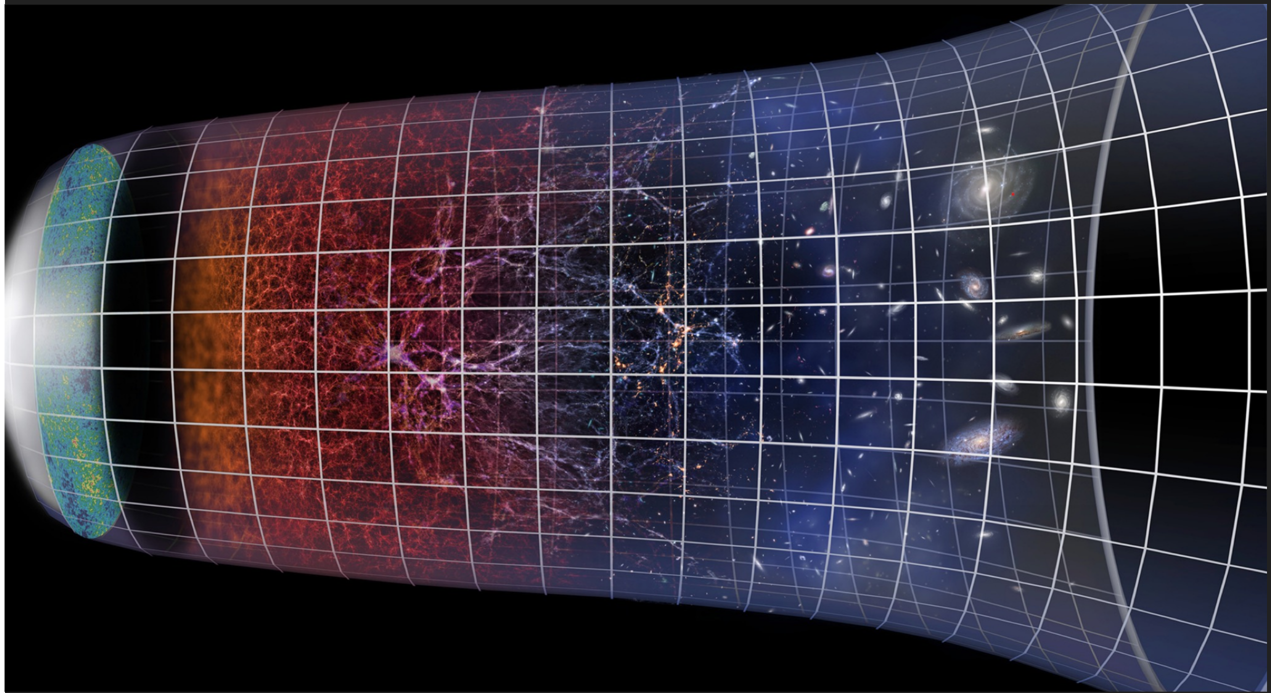
ΛCDM Universe







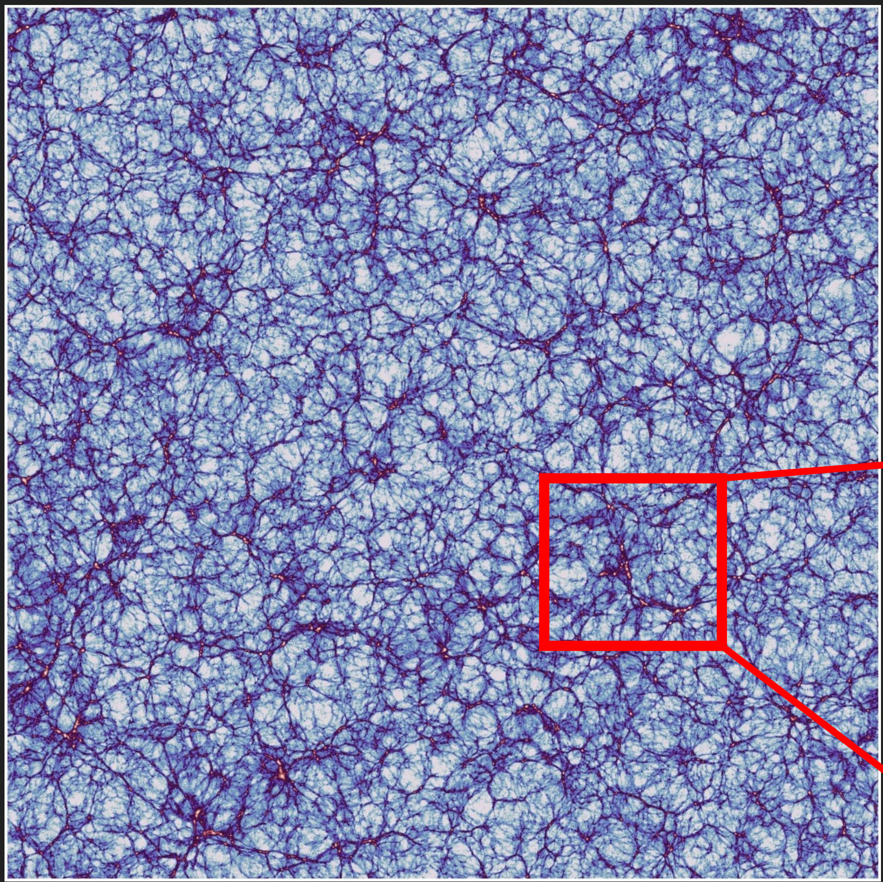
- The Universe is in accelerated expansion driven by the cosmological constant Λ.
- Composed by dark energy ~68%, dark matter 27% and baryons 5%.
- Not much is known about the dark components. Modified gravity can be a viable alternative.

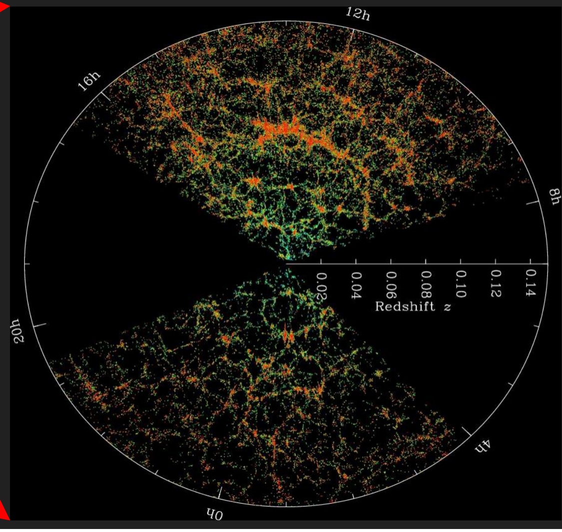
Surveying the LSS in the cosmic web

- At the early Universe matter fluctuations come from a **Gaussian** (random) distribution.

- Evolution of the matter field is shaped by both gravity and the effect of dark energy at late times z~0. It becomes **non-linear**.

- Only biased tracers (galaxies) of the field can be observed. Assuming a **connection** between haloes and galaxies.





Credits: SDSS

Modified gravity

Replacing the cosmological constant Λ by a function $f(R)$ in the action, leads to a modified Poisson equation which governs the EoM:

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

The new scalar field f_R mediates a new effective "fifth force".

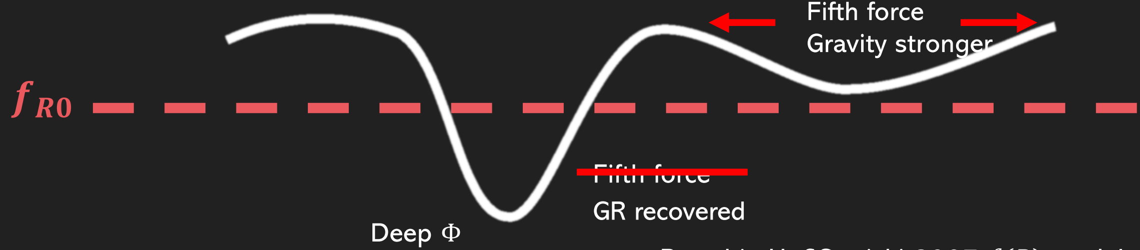
The Hu & Sawicki model satisfy these conditions with $f(R)$ constant in the background cosmology throughout cosmic history.

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

The $\frac{c_1}{c_2}$ term is set to replicate ΛCDM expansion history (same CMB). For $n=1$ we obtain $|f_{R0}| < 10^{-4}$ (Schmidt et al. 2009). Current constraints using abundance of clusters and weak lensing give $|f_{R0}| < 10^{-5}$ (Cataneo et al. 2015, Liu et al. 2019).

Testing gravity using the cosmic web

Environment is enhanced in MG due to action of a fifth force. However, is screened in high density regions (e.g inside a large halo). Mediated by a new scalar fied $f_{R0} = 10^{-5}, 10^{-6}$ (called F5, F6).

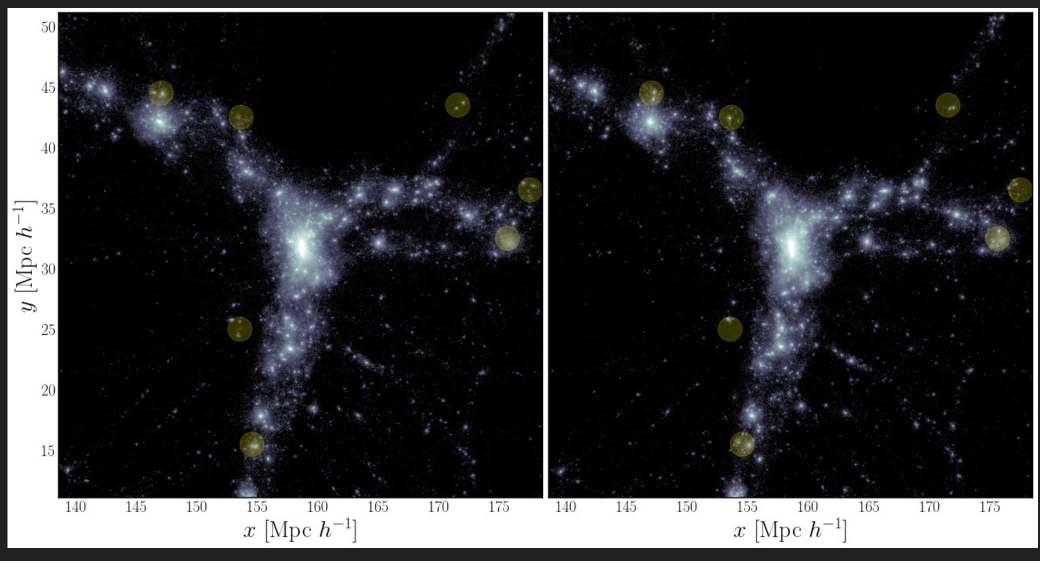


Based in Hu&Sawicki 2007 $f(R)$ model

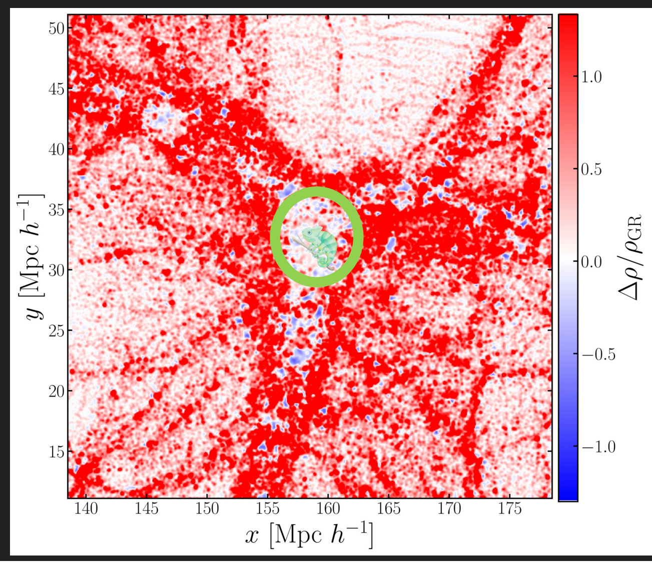
$f(R)$ acts for a range of scales, from collapsing structures to non-linear regime, but with a complex density-dependent screening mechanism.

Lightcone MG-simulations from Arnold et al 2019.

GR F5



F5 - GR



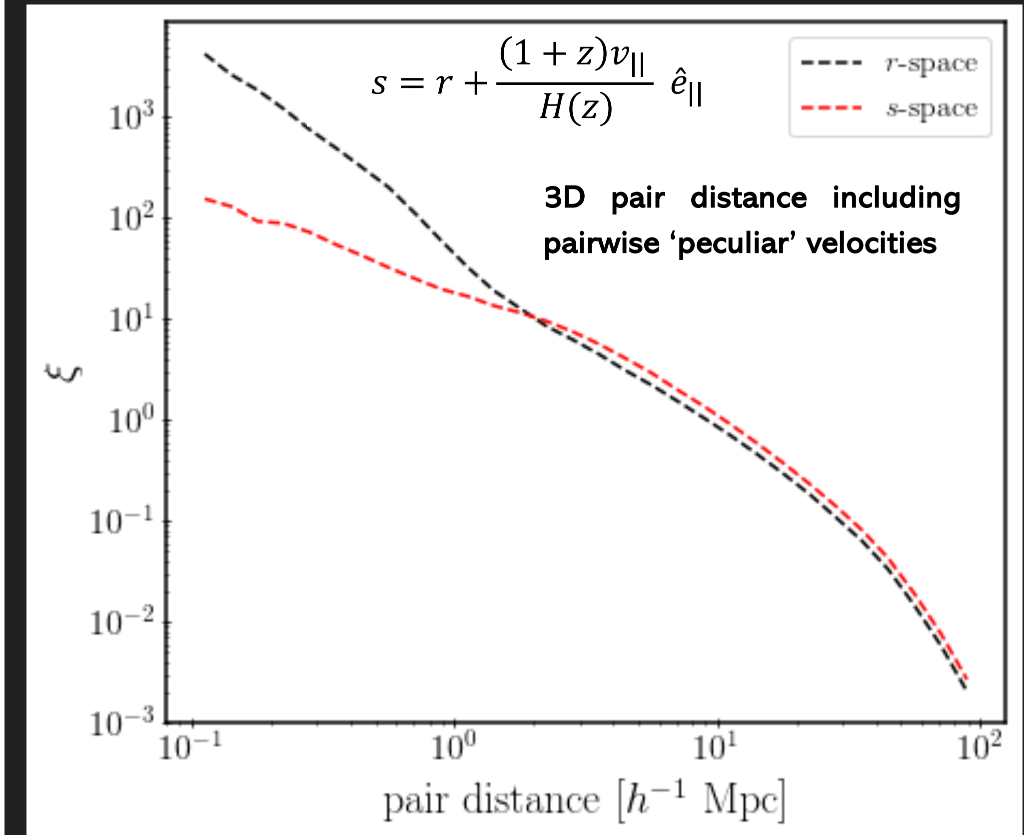
MG enhanced

GR and MG predict the same

MG enhanced

Probing the cosmic web using galaxy surveys

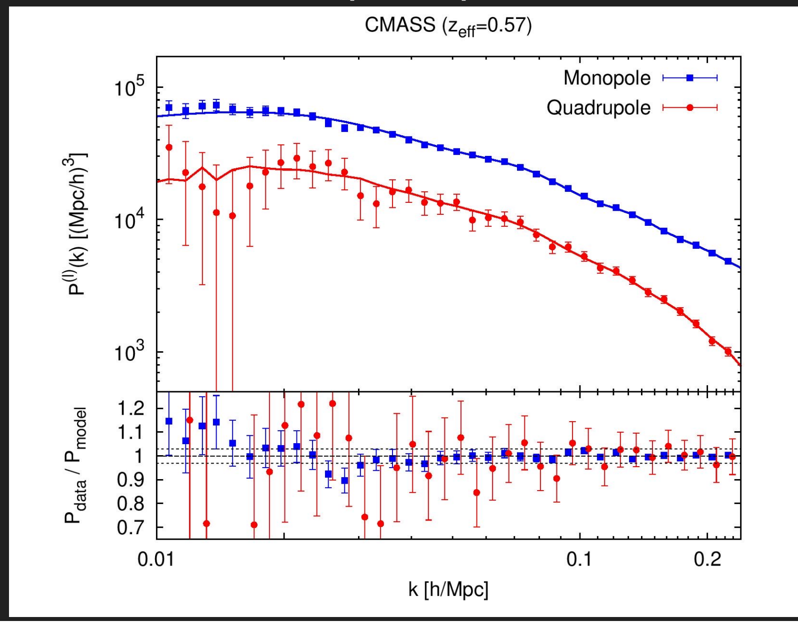
Galaxy clustering:
2PCF relates the number of galaxy pairs in comparison to a random distribution of pairs



(FT)

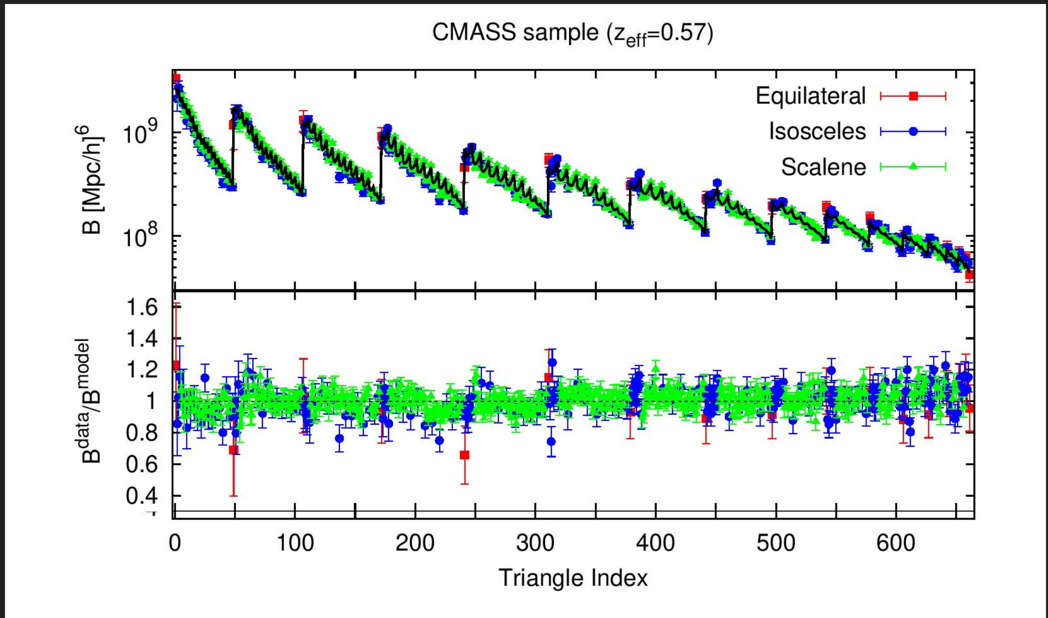
Measured accurately by spec-z surveys, such as SDSS-BOSS (DESI measuring it now).
When studying the shape of the Universe, mocks might replicate this observations, including those from modified gravity (HOD tunning, Cautun et al. 2017).

The power spectrum



Gil-Marin et al. BOSS DR12

Beyond 2-point: Higher-order statistics

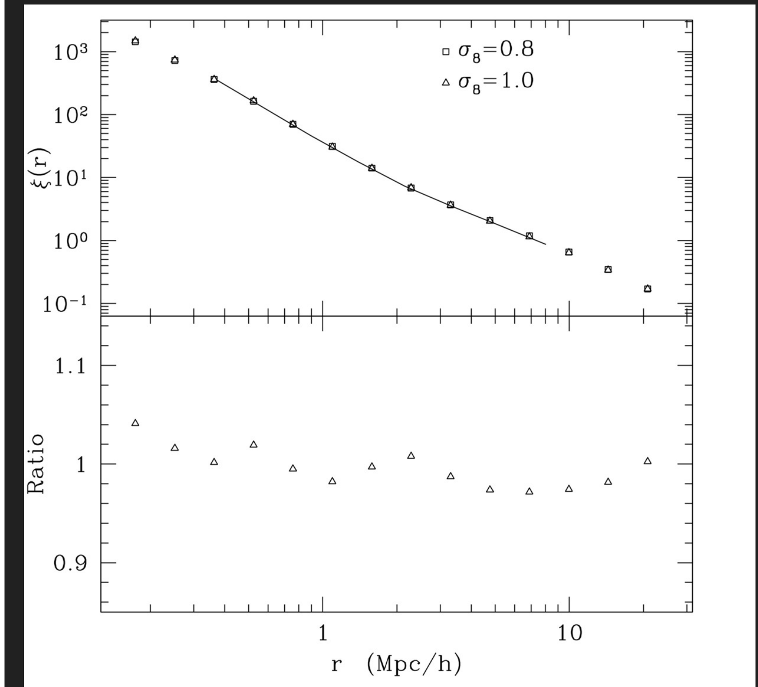


- Higher moments are needed to describe non-gaussian density field: 3-point functions (bispectrum) and beyond.
- For higher-order it can be expensive to calculate, specially for large samples.
- Non-Gaussian statistics also can do the job.

Gil-Marin et al. (2016)

Non-gaussian test: Marked statistics

White & Padmanabhan (2008)

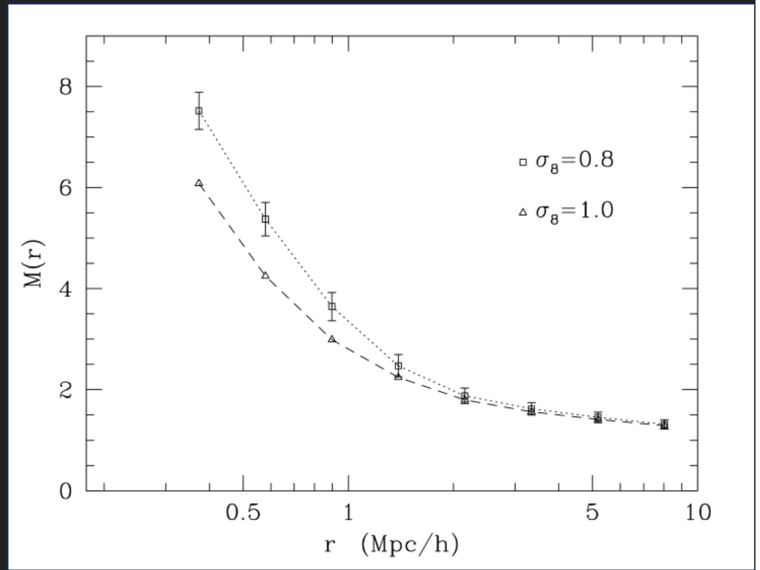


- The idea is simple, but quite informative: Add an additional weight when computing the (standard) 2PCF.

- The 'mark' can be an (arbitrary) function of the density field, conveniently defined to up-weight over-density or under-densities.

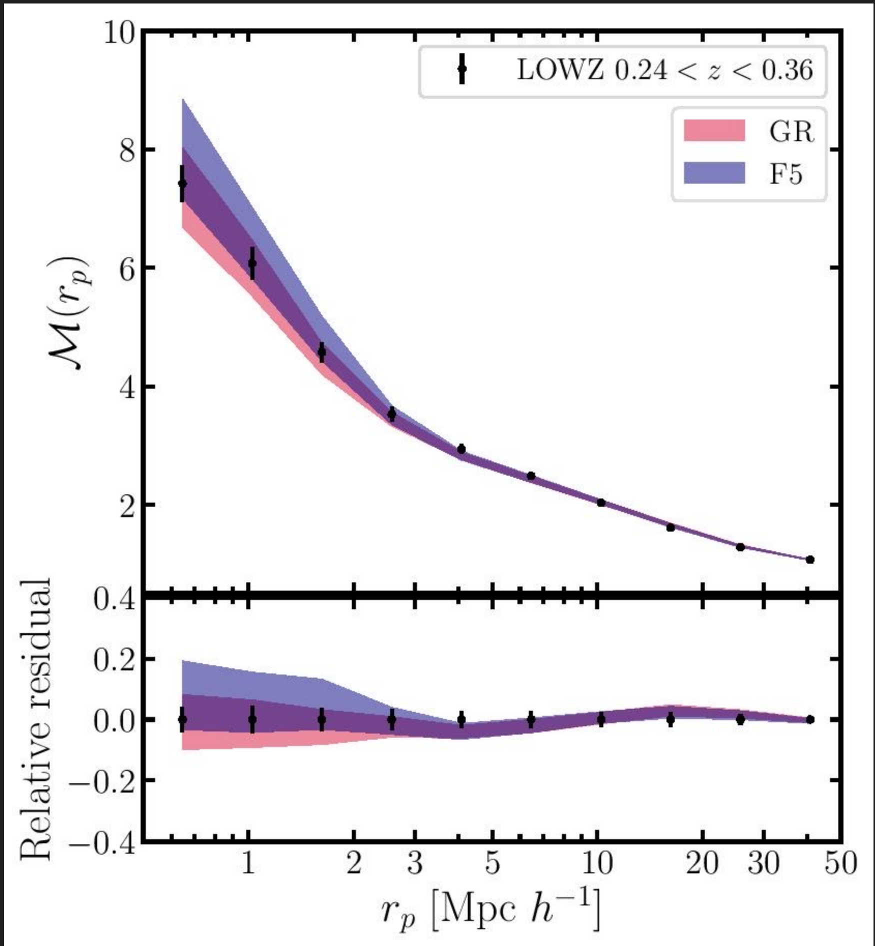
- Informative even when 1,2-point functions are the same.

- As a density dependent test, is sensitive to cosmology ($\sigma_8, \Omega_\mathrm{m}$), modified gravity and environment (Armijo et al. 2018).



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

A new framework for testing gravity



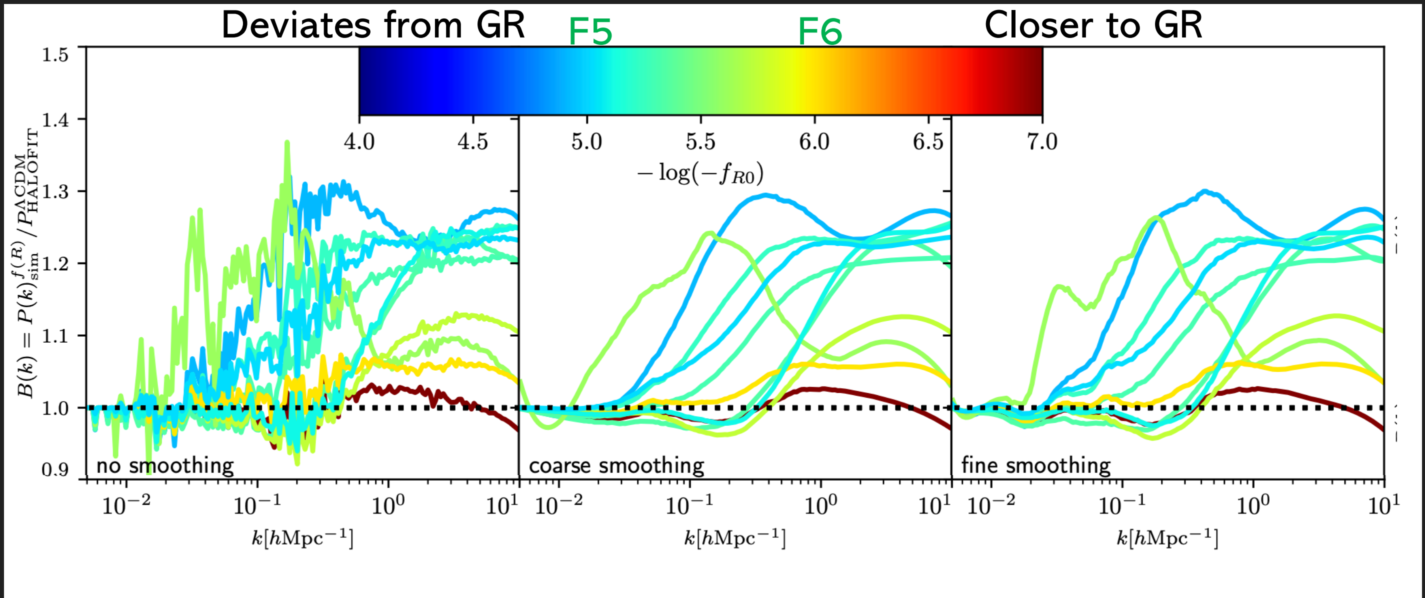
Armijo et al. (2023)

- We measured the marked correlation function for LOWZ galaxies (LRGs). No evidence of modified gravity is found, but not possible to rule out F5.
- Need more data (CMASS sample was inconclusive), DESI could provide a good constraint for $f(R)$ gravity.
- Halo model can introduce uncertainties larger than MG features.
- This is valid only for a MG model with the fiducial cosmology. Do we understand degeneracies between MG and cosmological parameters?

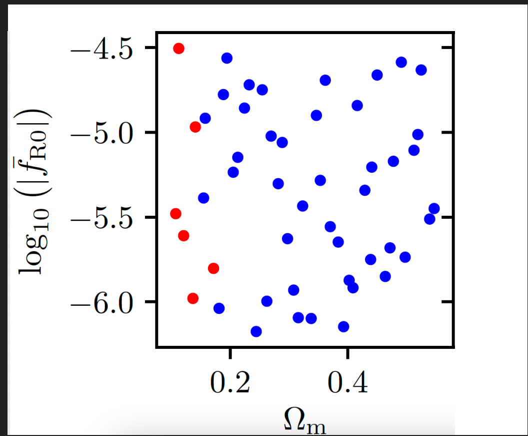
A new framework for testing ~~gravity~~ cosmology

FORGE: F-Of-R Gravity Emulator (Arxiv: [2109.04984](https://arxiv.org/abs/2109.04984))

Makes possible to explore fifth force parameter in contrast with different cosmologies.

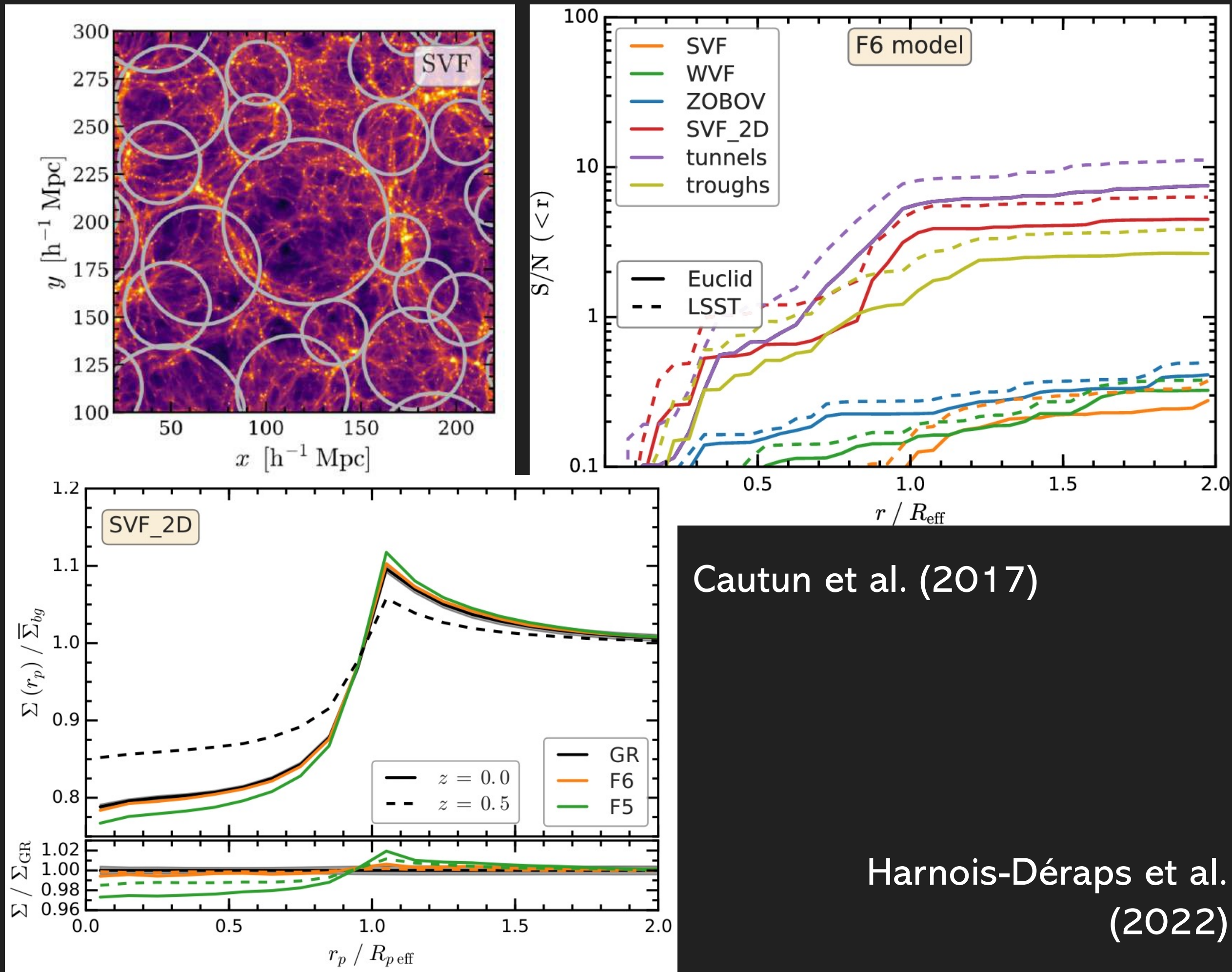


Also varying h, σ_8.



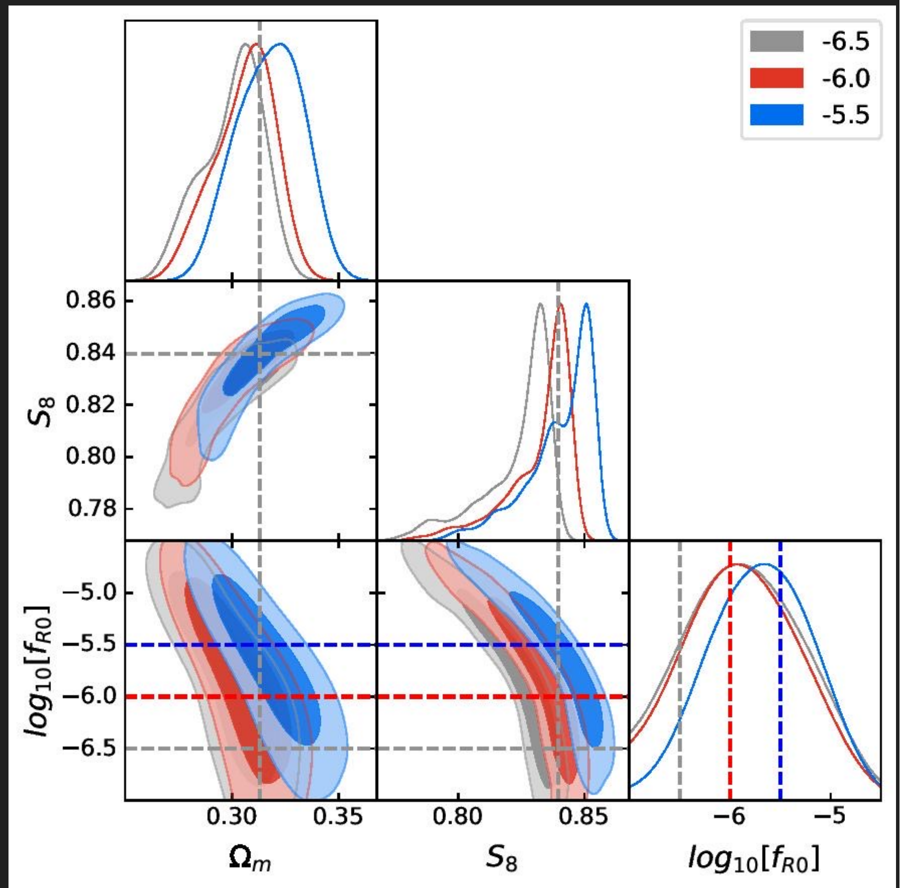
Arnold et al. (2021)

Cosmology in the next (current) generation survey era



Cautun et al. (2017)

MGLenS forecast for cosmological inference



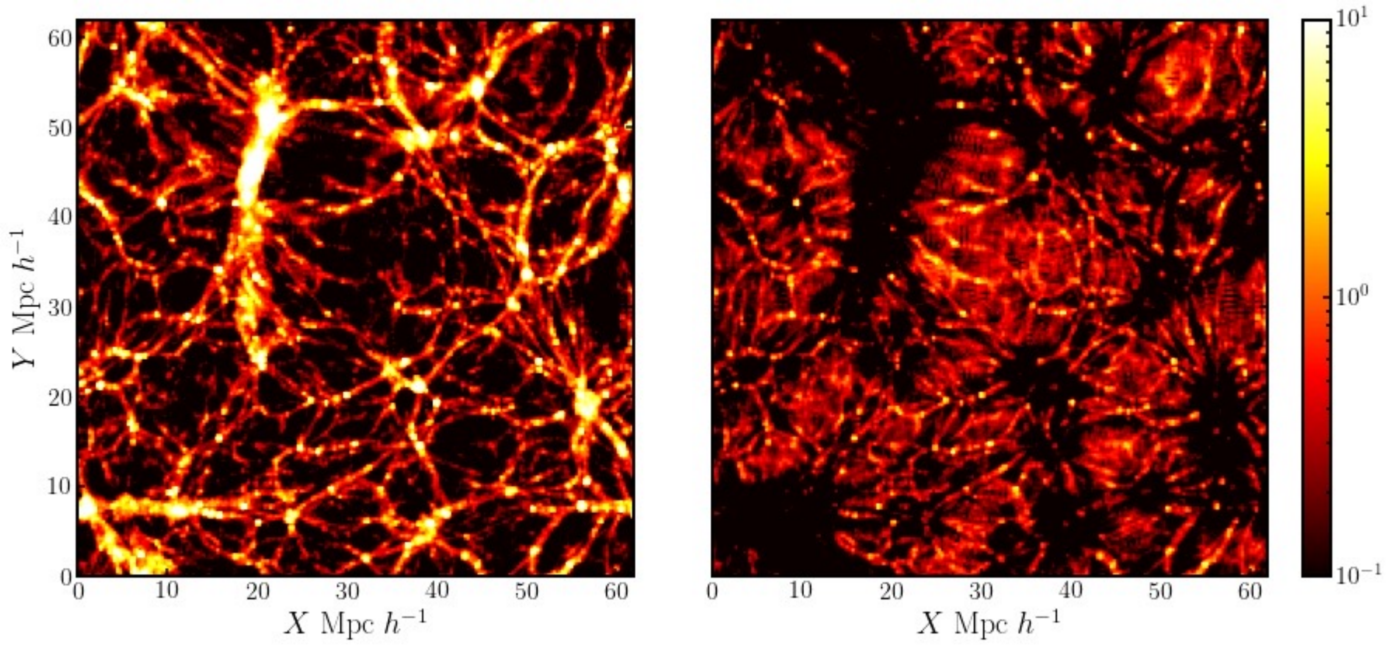
Harnois-Déraps et al. (2022)

Marked power spectrum

$$\delta_M(\mathbf{x}) \equiv \frac{\rho_M(\mathbf{x}) - \langle \rho_M \rangle}{\langle \rho_M \rangle} = \frac{1}{\bar{m}} m(\mathbf{x}) \left[1 + \delta(\mathbf{x})\right] - 1.$$

$$m(\mathbf{x}) = \left(1 + \frac{\delta_R(\mathbf{x})}{1 + \delta_s}\right)^{-p}$$

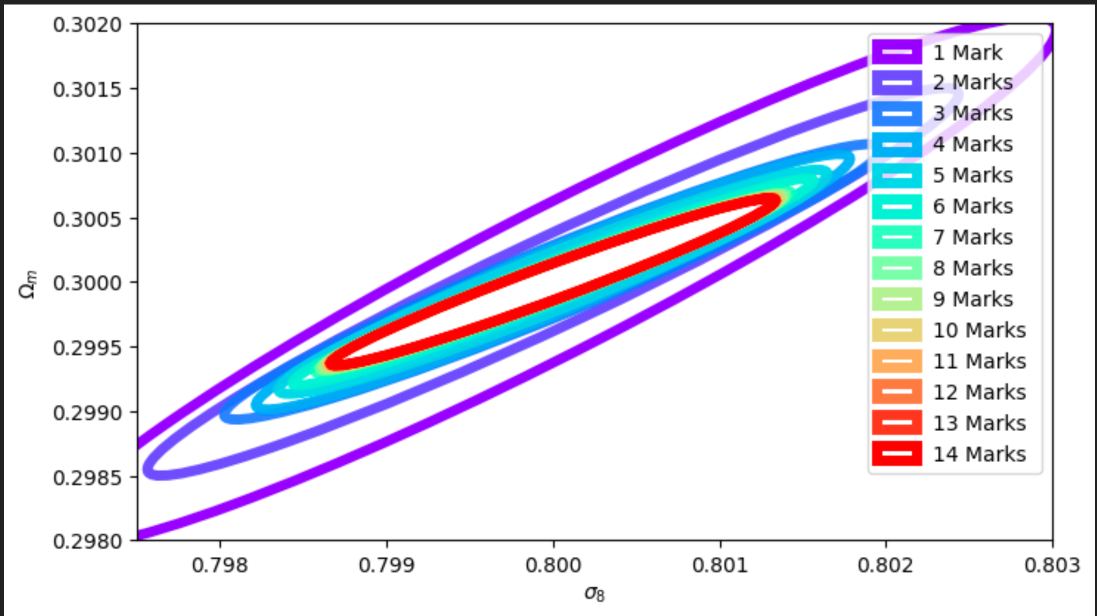
$p < 0$ $p > 0$



- Marked PS can be tuned to focus on different scales. Different values of power law param. '*p*'
- Like 2-point statistics but with information for higher-orders (Philcox et al. 2020).
- It has been showed to be sensitive to neutrino mass (Massara et al 2023).
- Can be extended for weak lensing statistics using the convergence field.

Marked power spectrum

Preliminary Fisher analysis



Credits: Jess Cowell

- Constraints can be improved by combining marks.
- Currently being testes on HSC-Y1 data. Using Rubin-LSST in the future.
- New marks can be defined. Using halo masses or secondary properties.

Summary and conclusions

- Modified gravity models that can reproduce ΛCDM cosmic expansion predict modified environments enhanced by the fifth force.
- Non-Gaussian features of the density field can be revealed by higher-order statistics information. The marked CF/PS can be used to reveal MG in such scales.
- Halo occupation introduces uncertainties! Weak lensing statistics could be more helpful to test the density field.
- Marked PS is more sensitive to modified gravity, neutrinos, baryonic physics. Ready to be used in future cosmological analysis.

Thank you!