

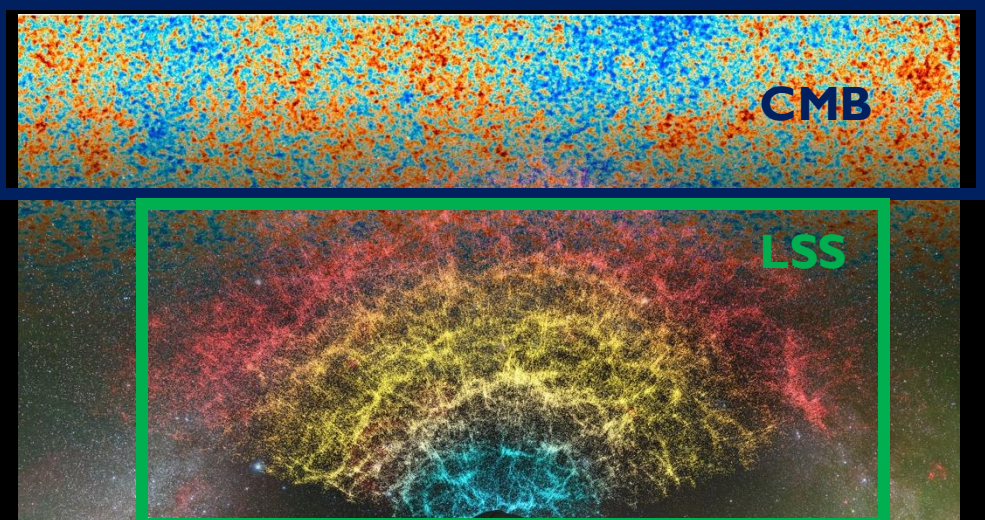


Mocking the Universe with numerical simulations: The case of modified gravity

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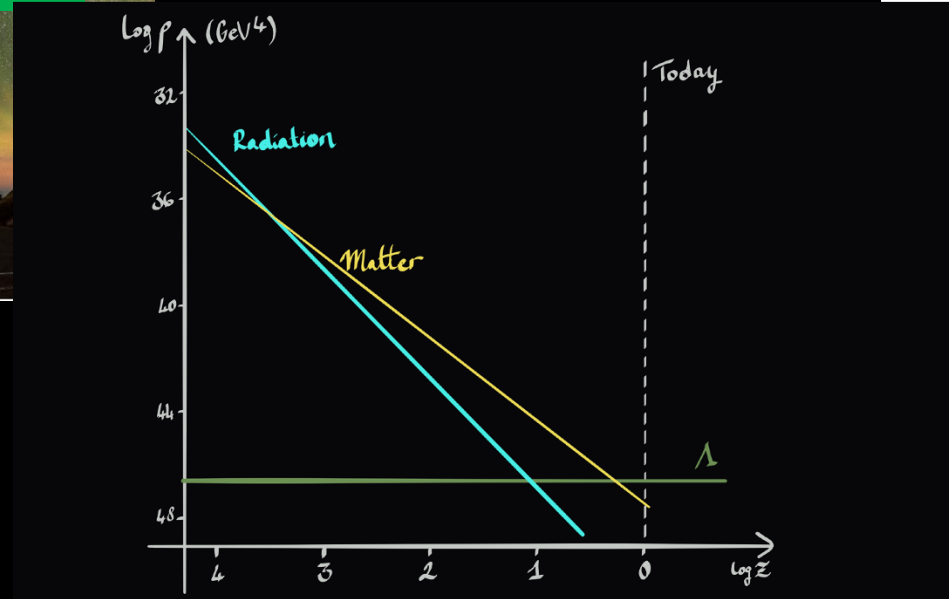
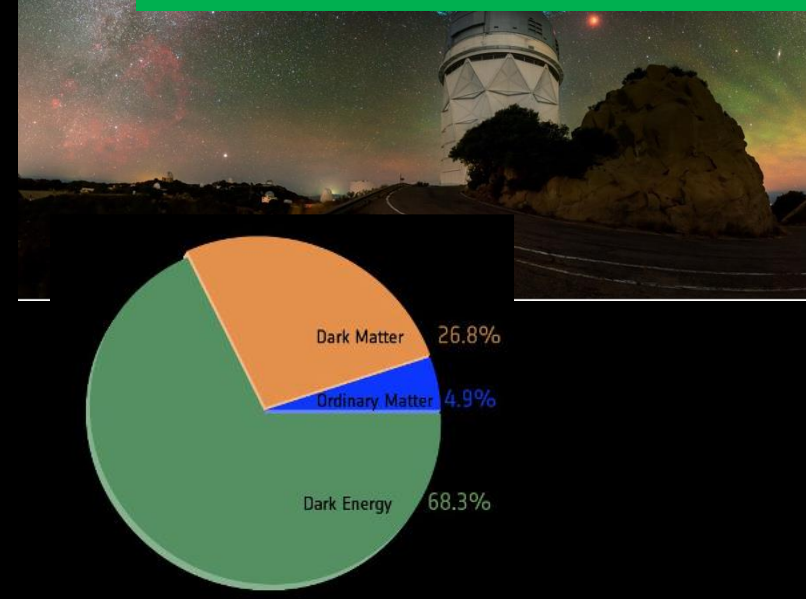
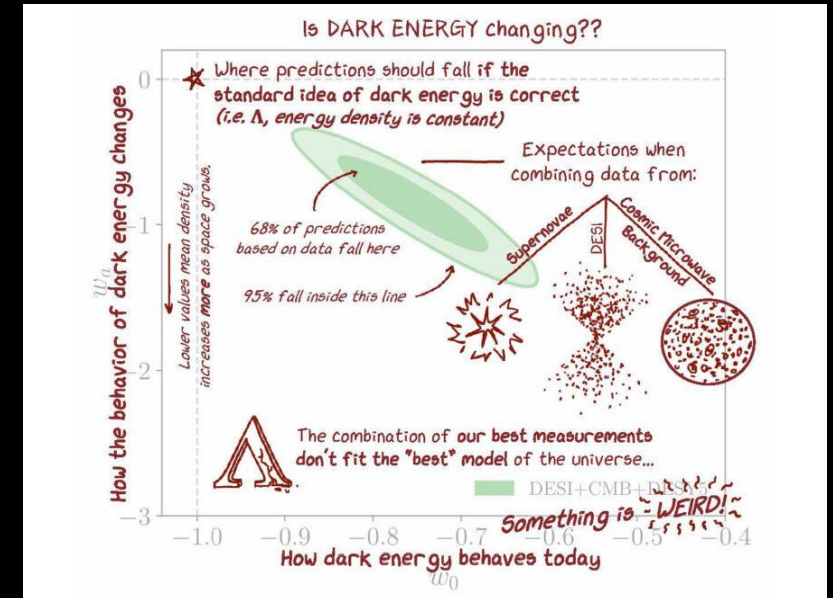
LeCosPA meets IPMU. Taipei. March-April 2025.

Precision cosmology



- Model with a few parameters
- Energy-density content.
- Data driven.

(Credit: Claire Lamman/DESI collaboration)

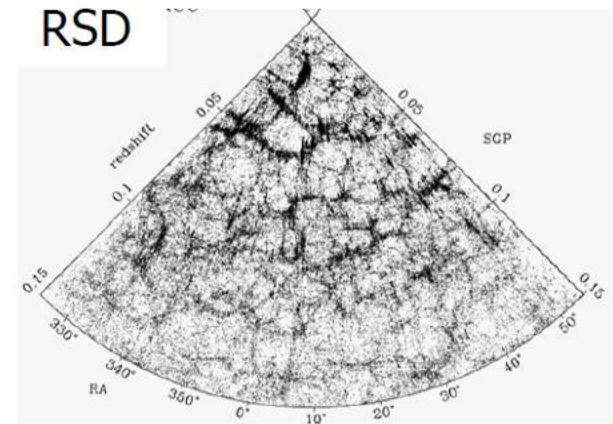
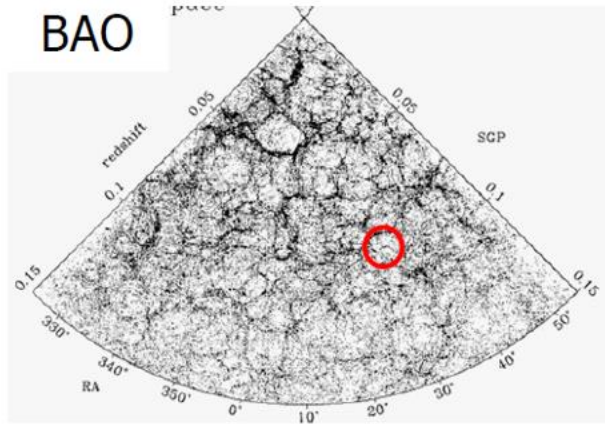


- Physics beyond Λ CDM ?
- Tension between early and late Universe ?
- Is Dark Energy dynamical ?

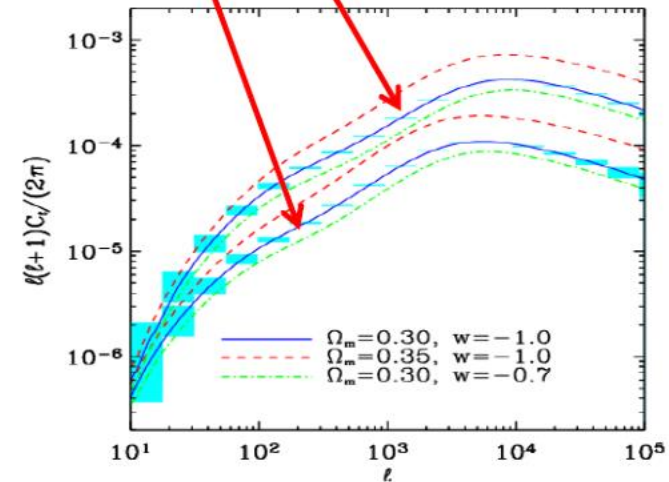
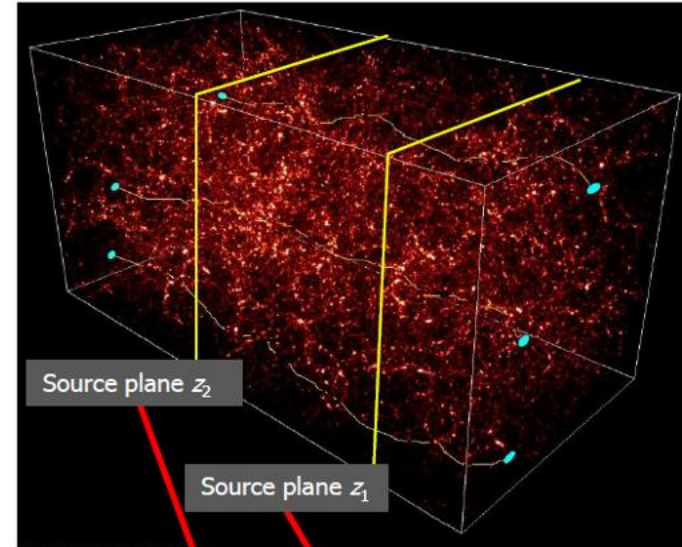
Cosmology with the large-scale structure of the Universe

BAO, RSD and WL over 15,000 deg²

50 million galaxies with redshifts

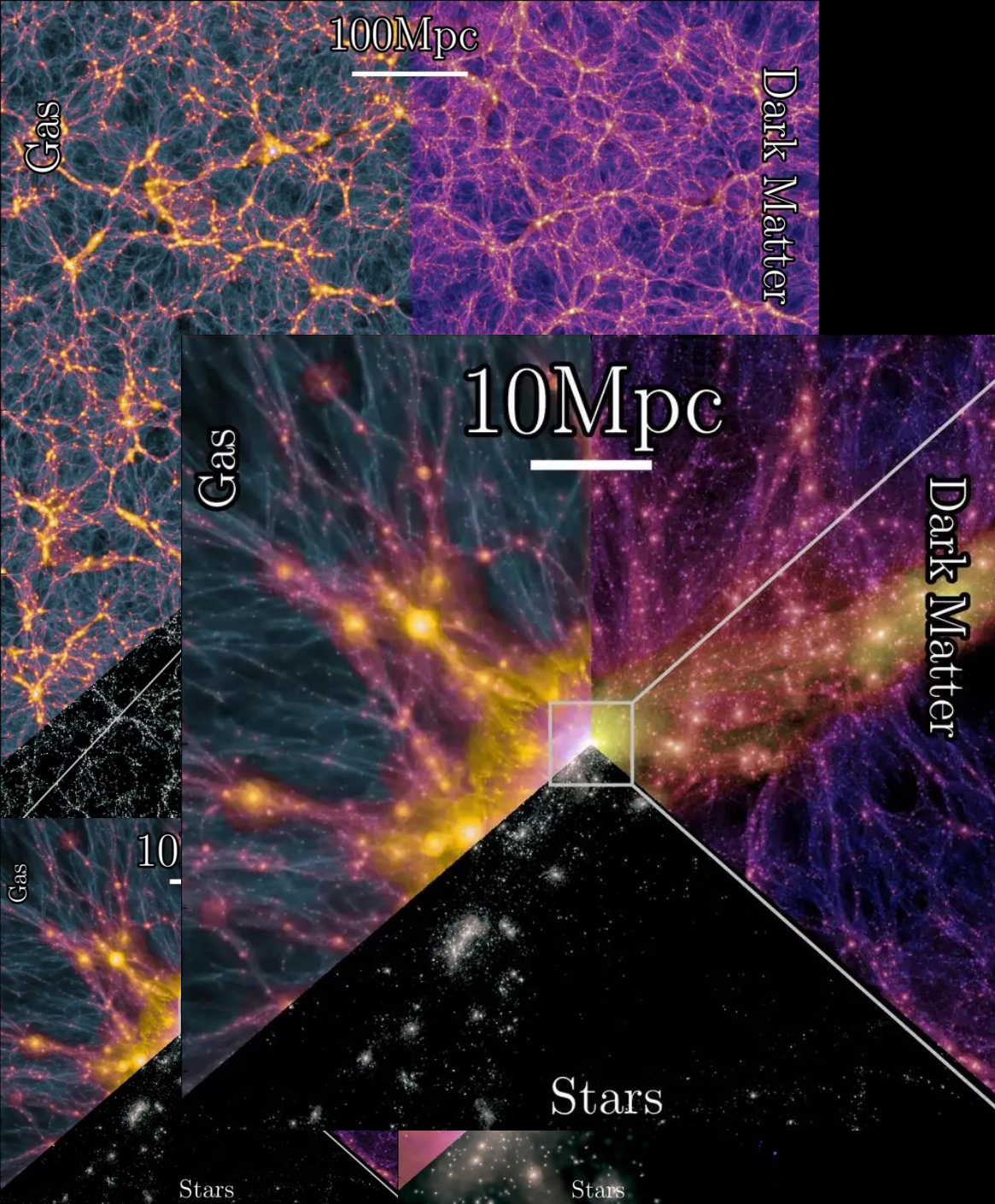


1.5 billion sources with shapes, 10 slices



(Credit: Linda Blot)

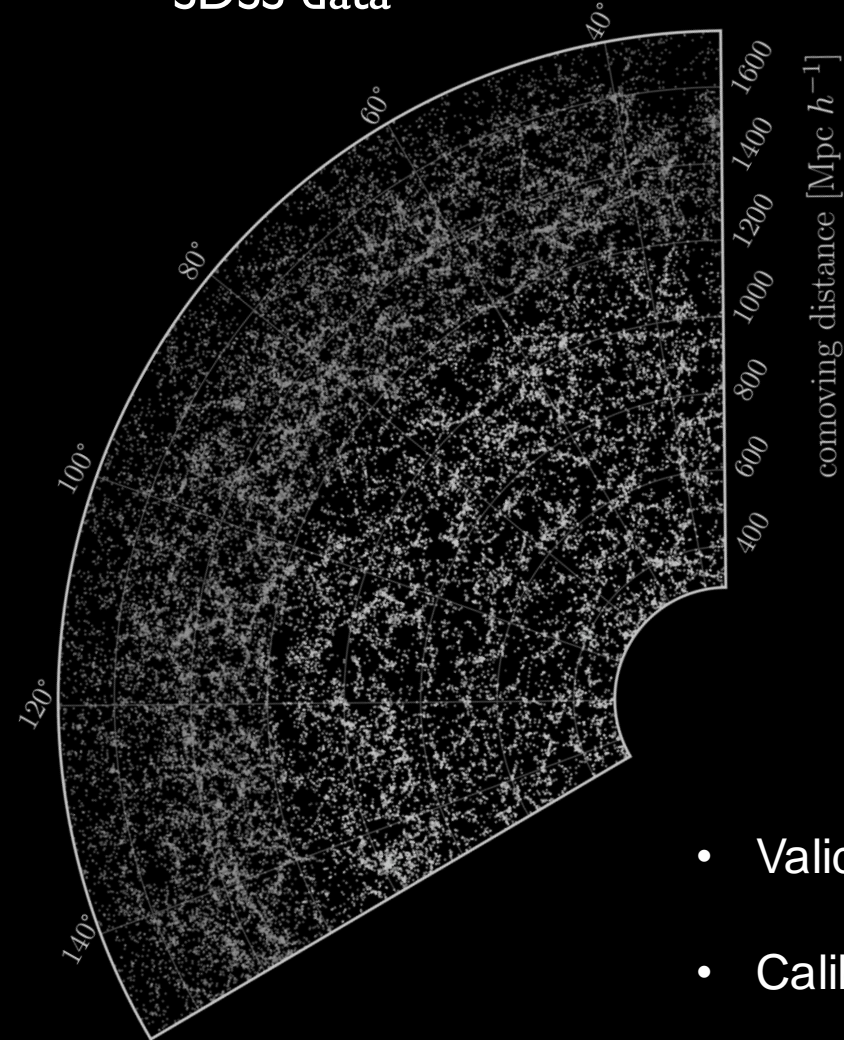
Mocking the Universe with LSS simulations



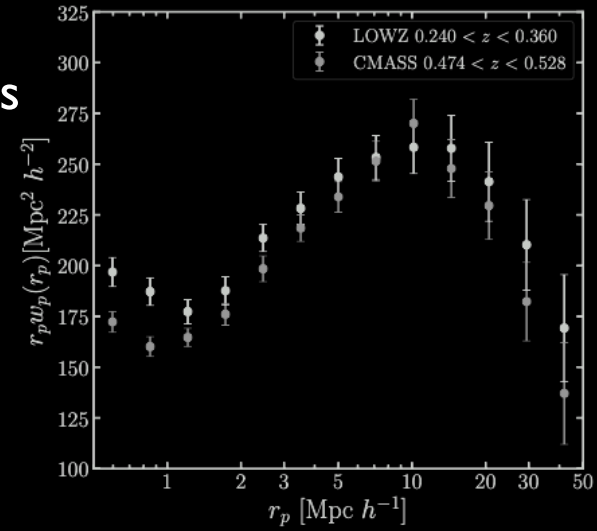
- Large volume of the Universe
- Random initial conditions statistically compatible with CMB
- Follow gravitational collapse in an expanding background assuming a cosmological model
- Non-linear regime.
- Non-gaussian density field.

From observations to constraints

SDSS data



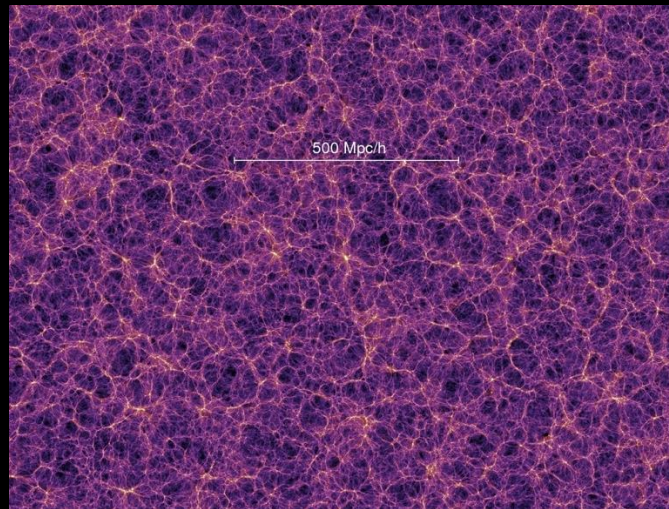
Summary statistics



Probability of observed events given a theory.

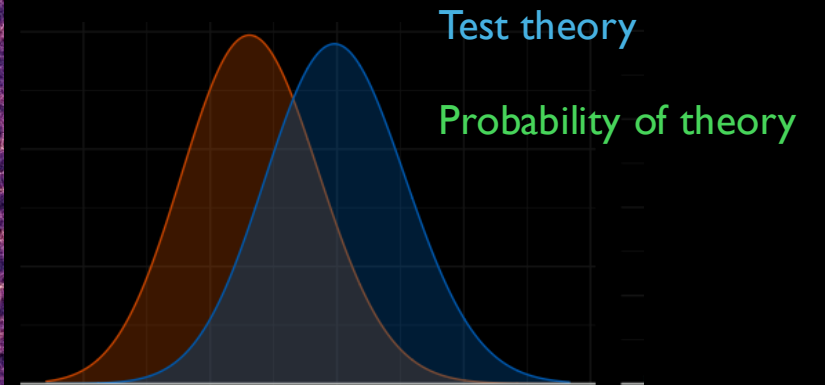
Probability of multiple theories given the observed data.

Simulations



Likelihood

- Validation
- Calibration
- Emulators



Testing modified gravity using LSS simulations

Modified gravity $f(R)$

Motivated to explain cosmic expansion without cosmological constant

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.

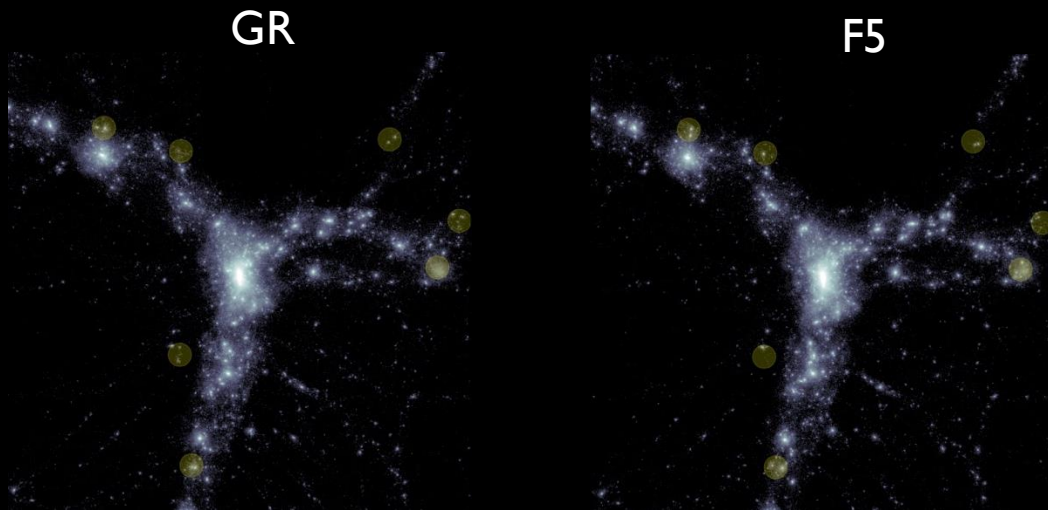
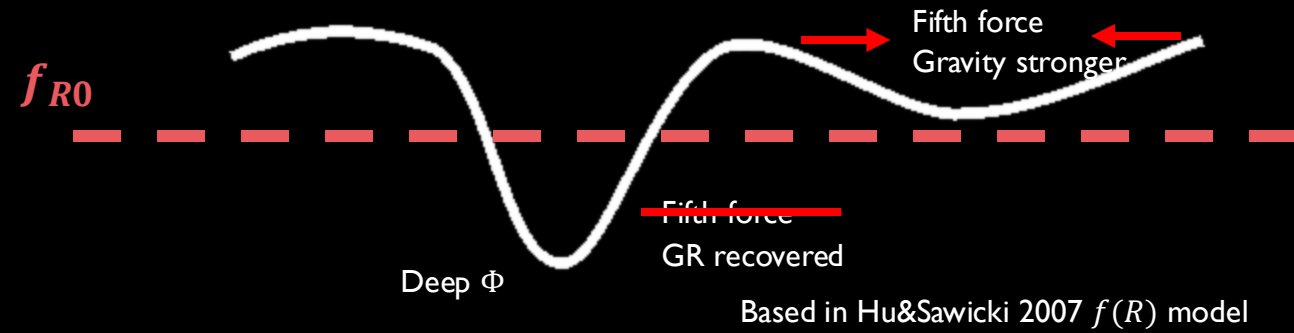
$$f(R) \approx \frac{c_1}{c_2} m^2 + \frac{c_1}{c_2^2} m^2 \left(\frac{m^2}{R}\right)^n, \text{ with } \frac{c_1}{c_2} = \frac{\Omega_{\Lambda,0}}{\Omega_{m,0}} \text{ and } \frac{c_1}{c_2^2} = -\frac{1}{n} \left[3 \left(1 + 4 \frac{\Omega_{\Lambda,0}}{\Omega_{m,0}}\right)\right]^{n+1} f_{R0}.$$

The $\frac{c_1}{c_2}$ term is set to replicate Λ CDM 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).

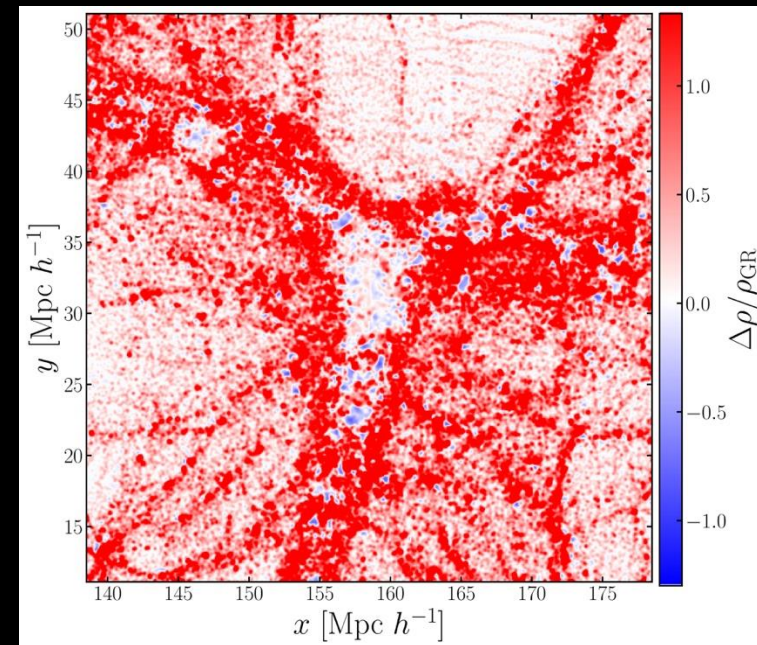
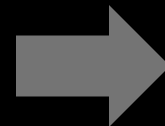
Simulations of $f(R)$ gravity

- **Environment is enhanced** in MG due to action of a fifth force $f_{R0} = 10^{-5}, 10^{-6}$ (called **F5, F6**).
- Screened in high density regions (e.g inside a large halo).
- Both enhancement and screening are scale-dependent dominant at small scales.

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



MG Lightcone



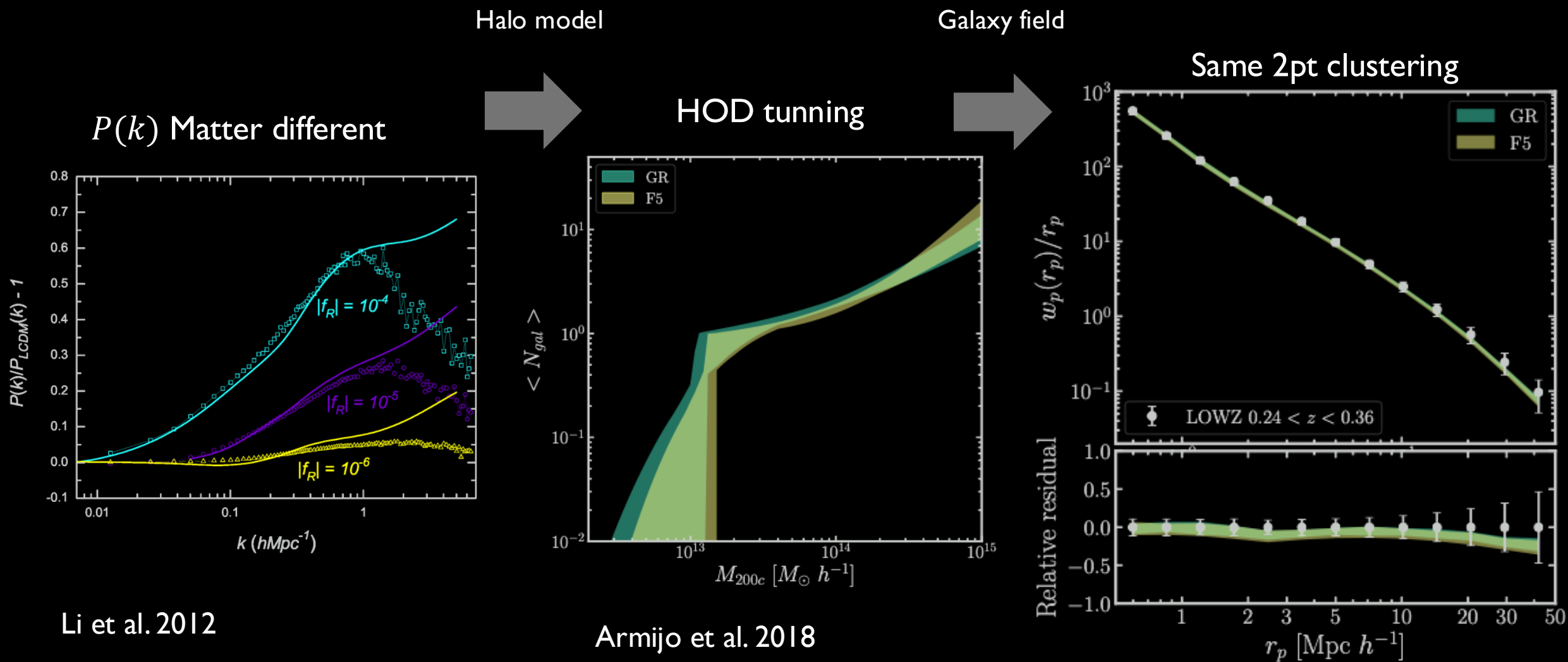
F5 - GR

MG enhanced

GR and MG predict the same

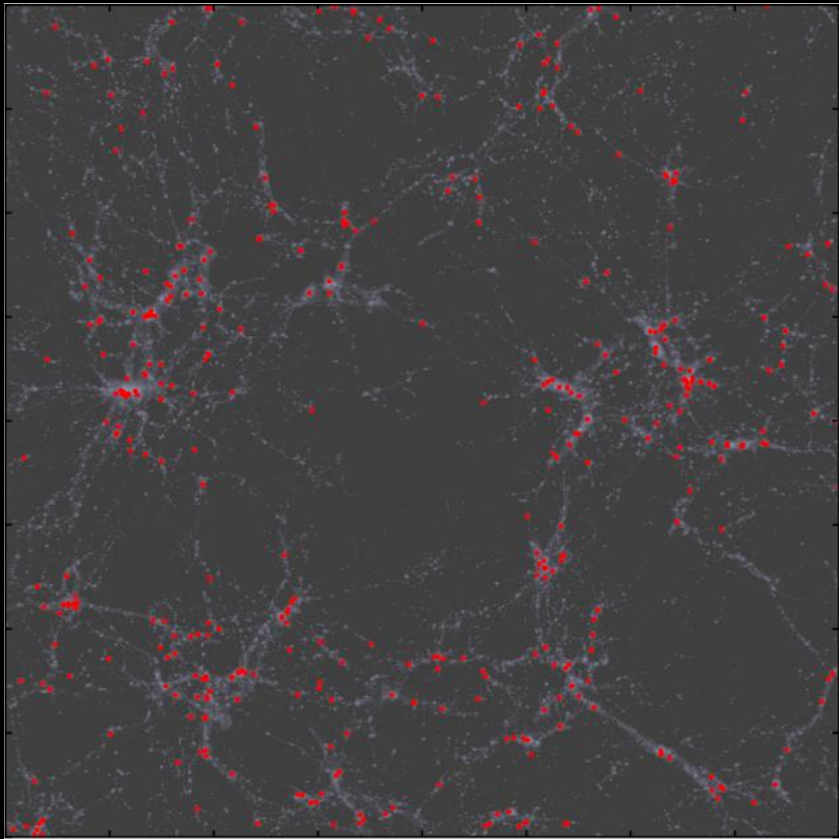
MG enhanced

Testing modified gravity with marked statistics



Testing modified gravity with marked statistics

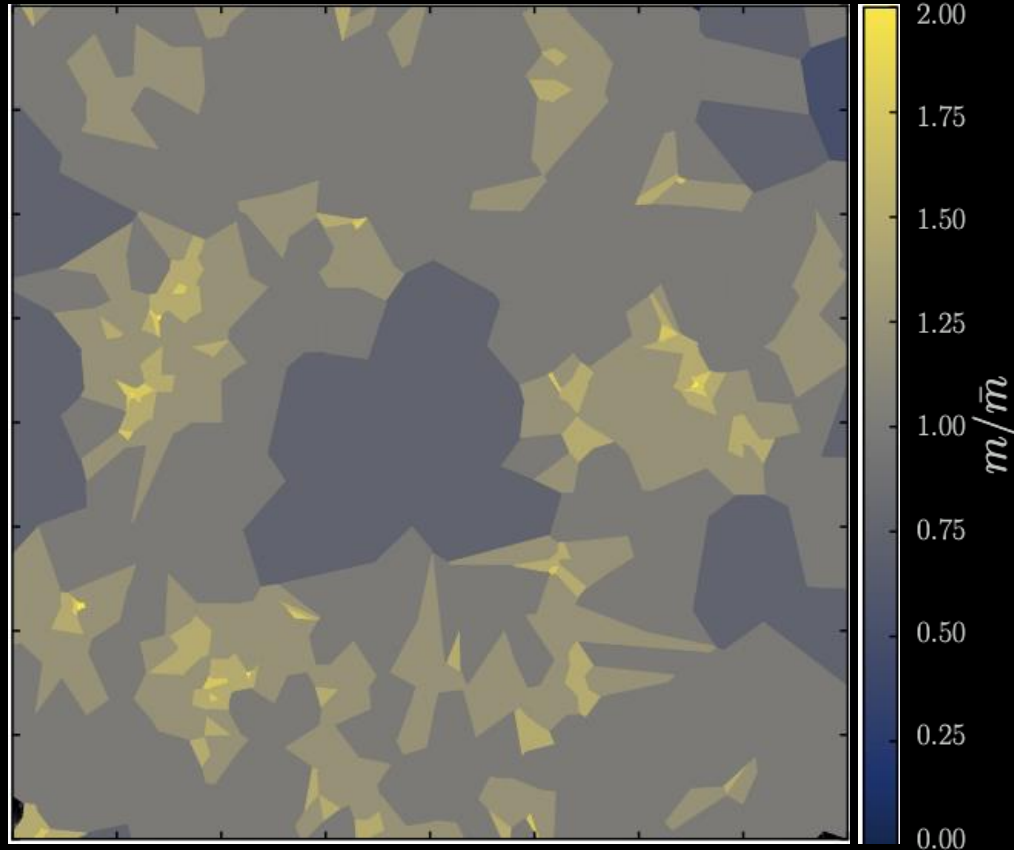
GR and F5 simulations
populated with HOD galaxies



Both simulations have same n_{gal} and 2PCF w_p (HOD tuned)

Armijo et al. 2024a

Density field reconstruction



Voronoi density field

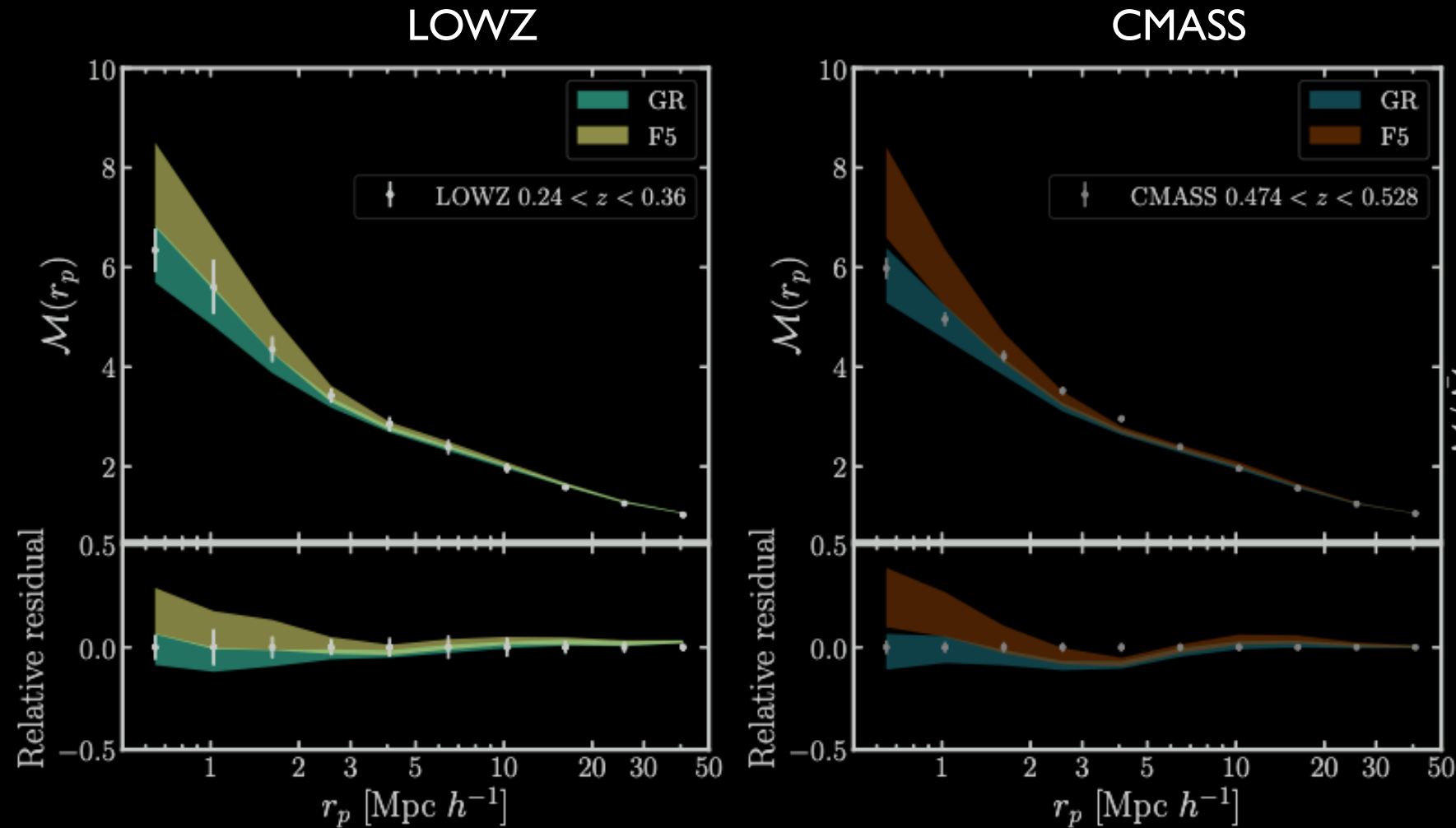
Combine clustering with
density dependent
information (matter field)

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

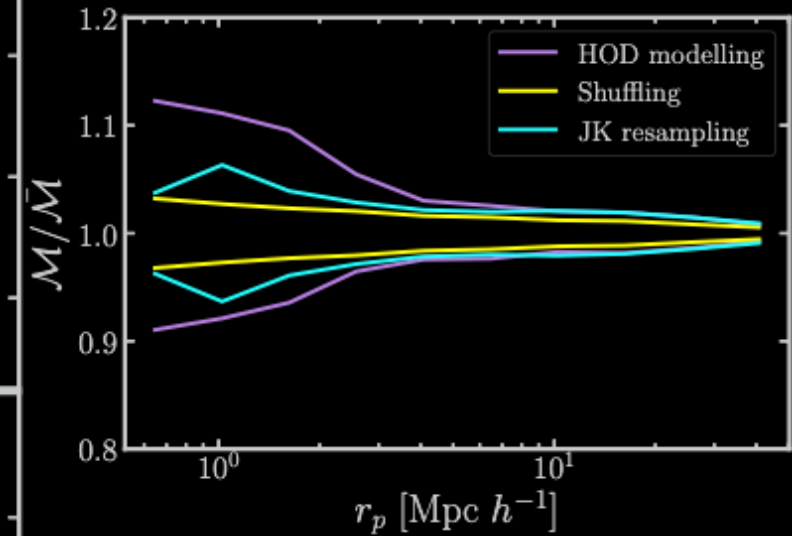
Ratio between ξ
weighted and
standard ξ .

Marked statistics
(see Jess's talk)

Testing modified gravity: Application to BOSS-LRGs

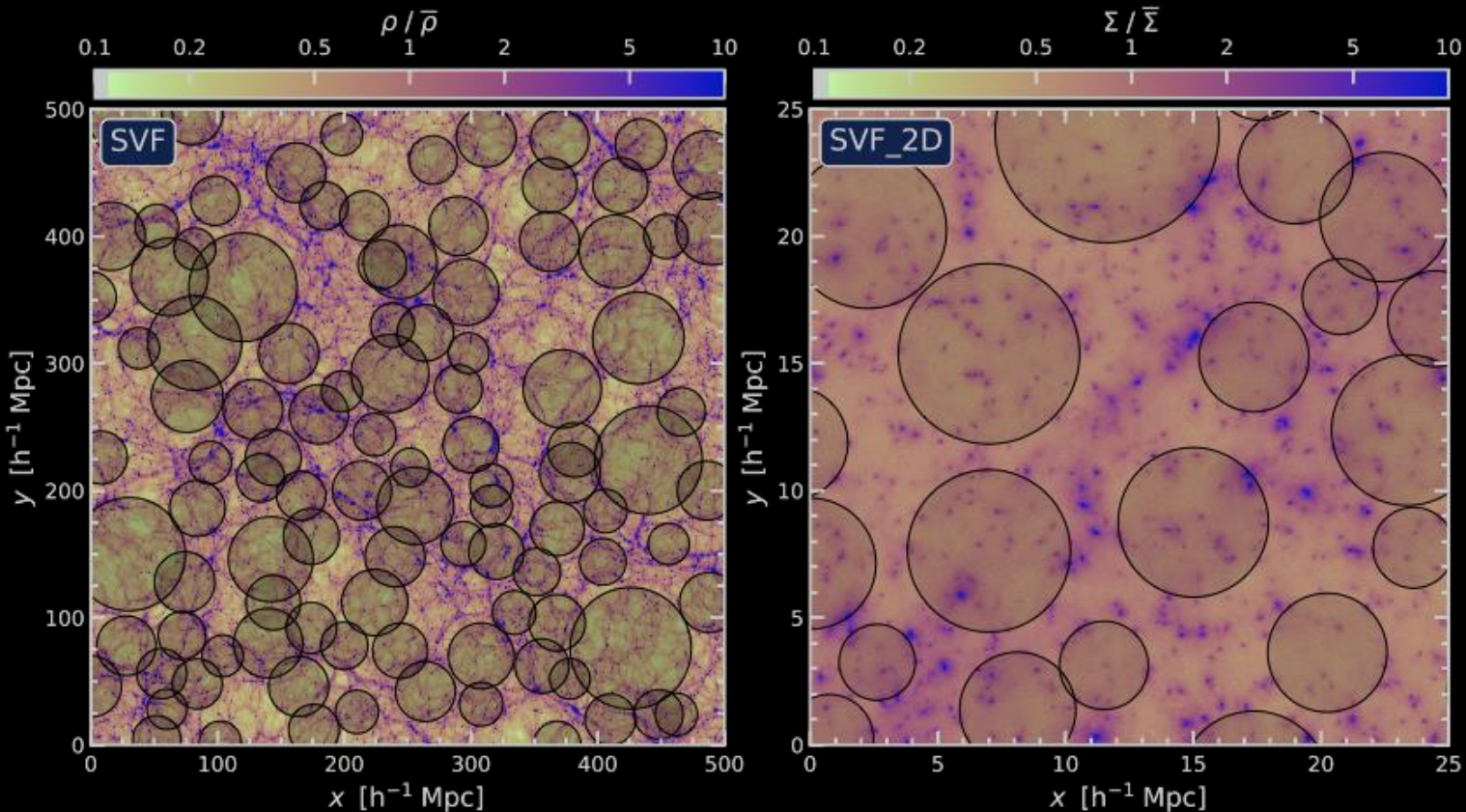


Data prefers GR rather than F5. Not significant for LOWZ data, but more conclusive for CMASS.



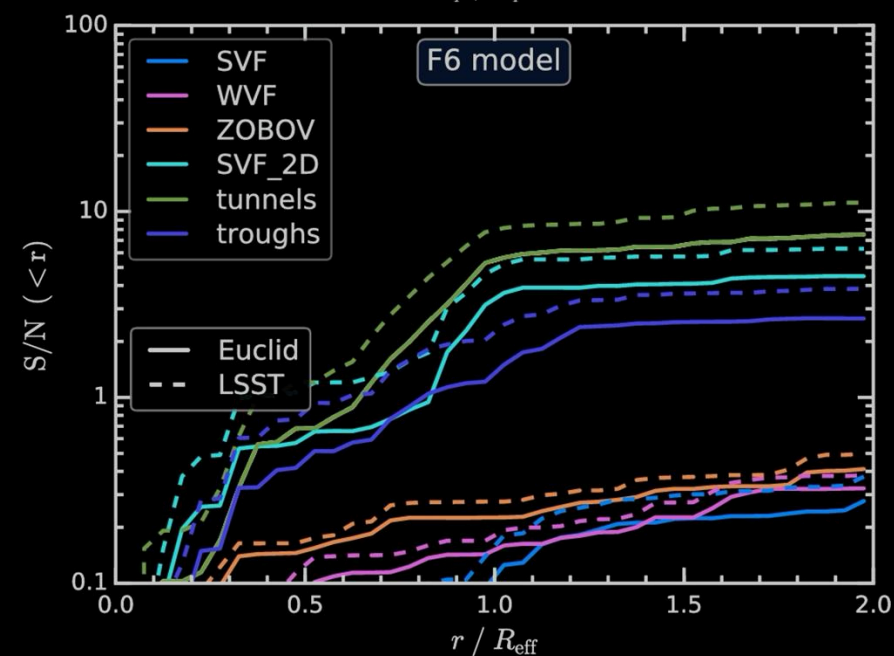
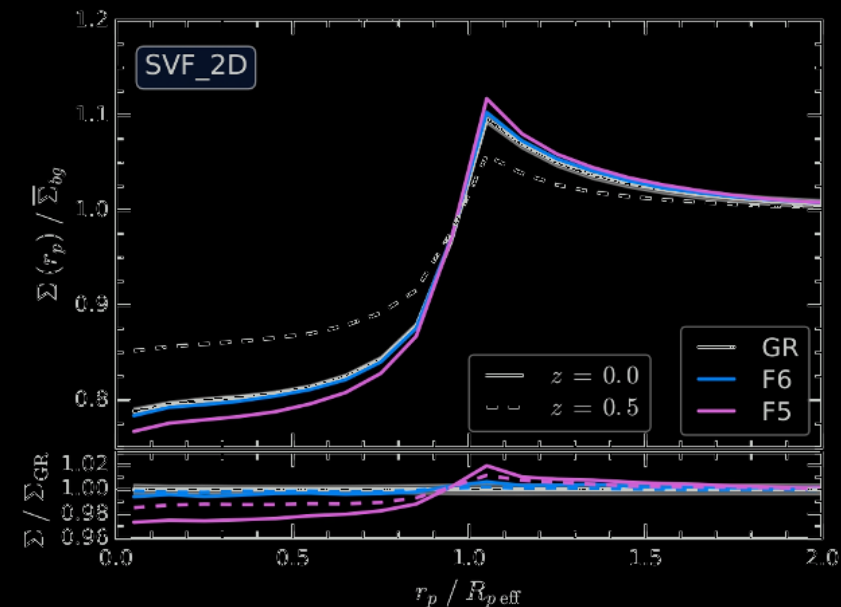
Error budget is dominated by HOD modelling.

Future constraints for stage-IV surveys using higher-order statistics



Voids grow emptier in MG models even in 2D fields (weak lensing).
 Future Euclid and LSST might constraint the amplitude of the fifth force.
 Estimating the excess of tangential shear for MG models (level at 10^{-6}).

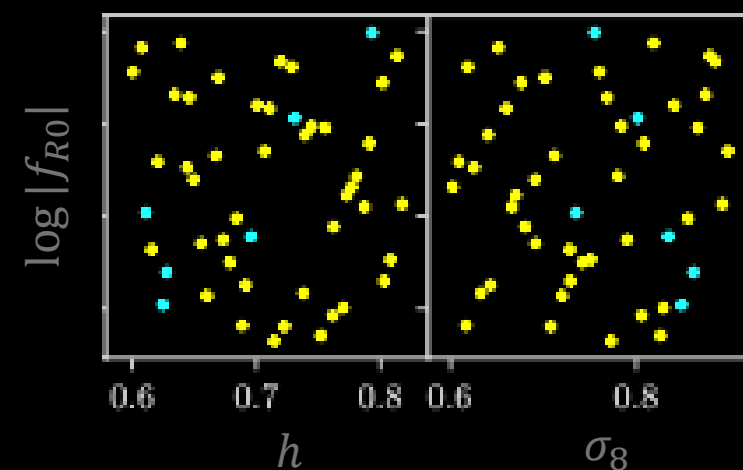
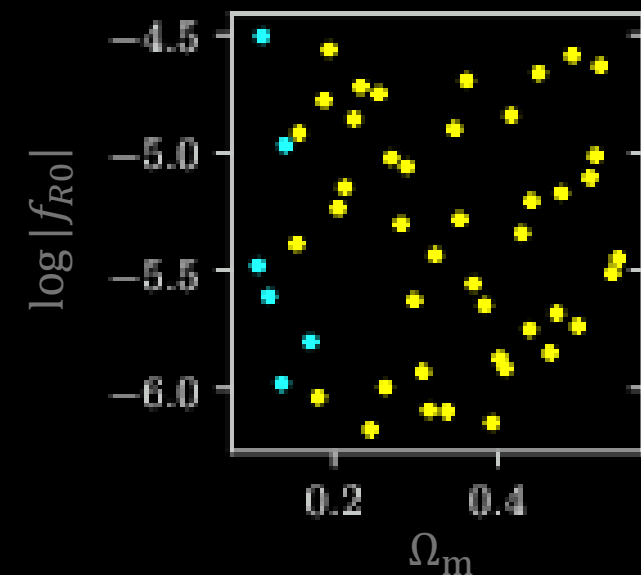
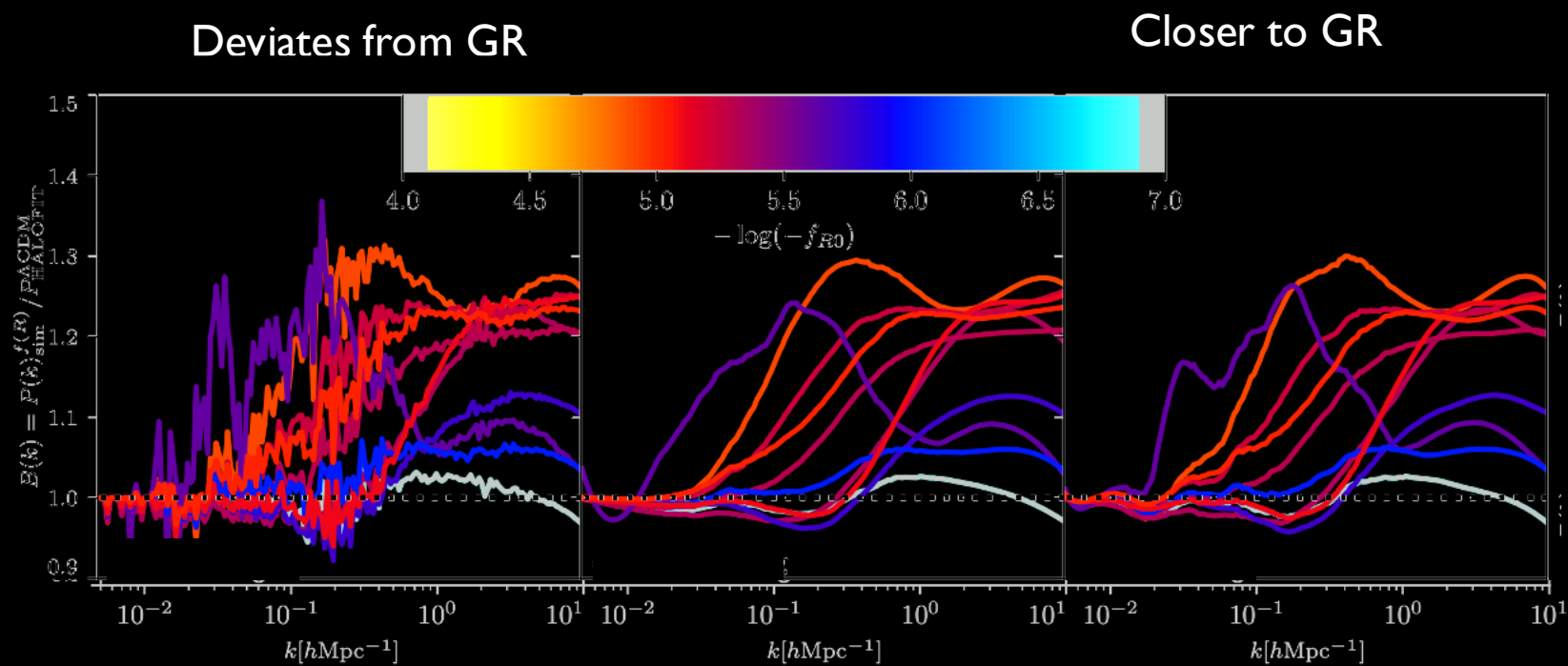
Cautun et al. (2017)



Future constraints for stage-IV surveys using higher-order statistics

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.



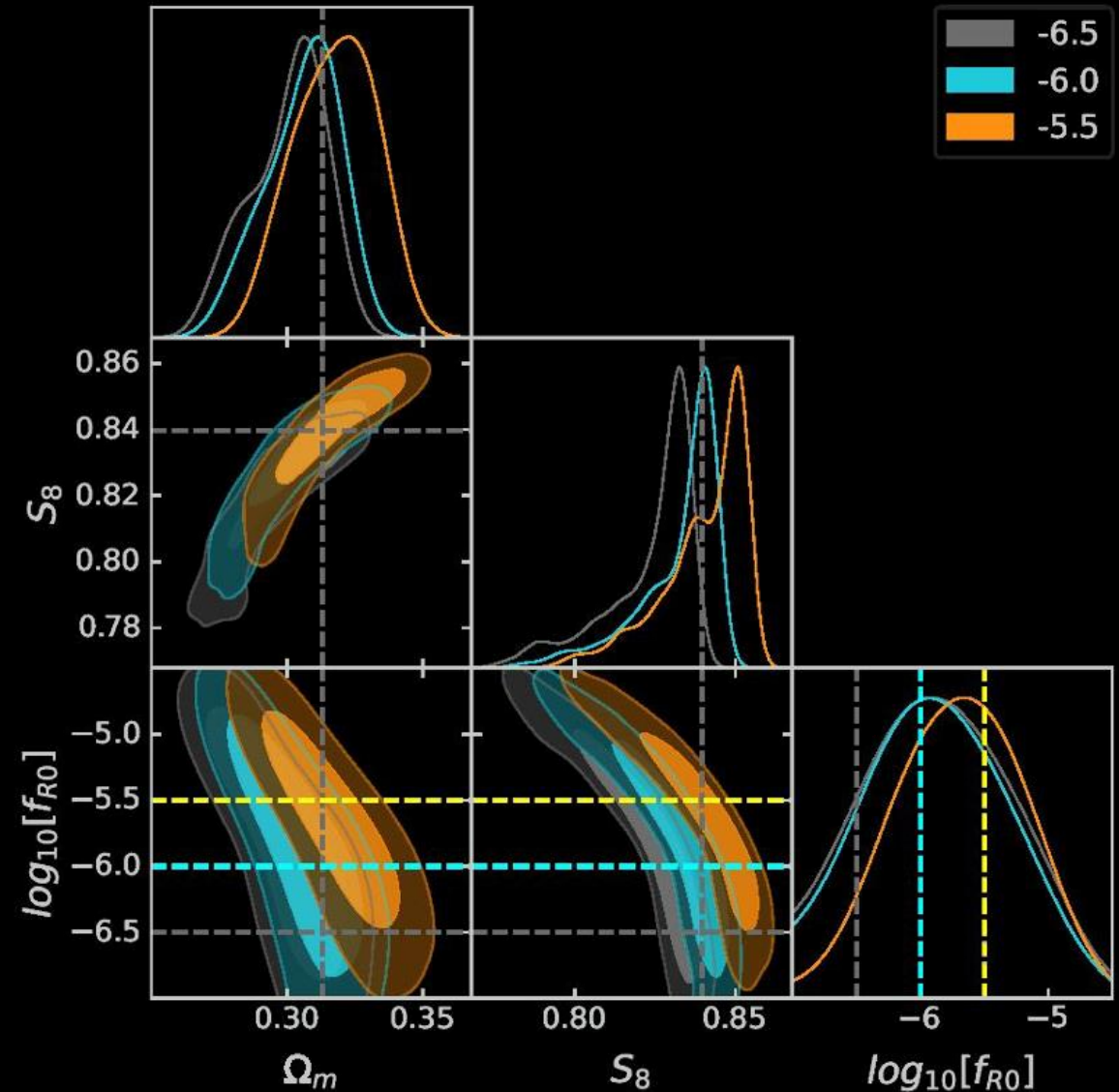
Arnold et al. (2021)

Future constraints for stage-IV surveys using higher-order statistics

MGLenS forecast for cosmological inference using angular power spectrum (C_ℓ):

- Evaluating emulator with theory data vector.
- Explore constraining power of fifth force against different cosmological parameter (introduces degeneracies).
- Requires adding very small scales $\ell \sim 3000$ (needs stage-IV surveys).

Need to explore higher-order statistics!



Prospects for $f(R)$ gravity

SPT-clustersxWL+CMB (FORGE informed HMF)

SPT-clustersxWL+CMB (semi-analytical HMF)

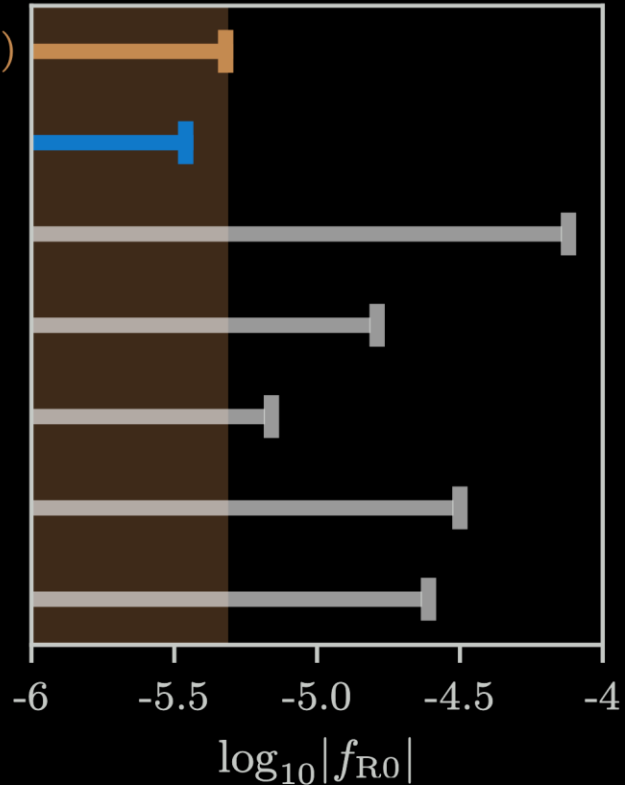
eROSITA-clusters (Artis+24)

ROSAT-clusters+CMB+SN+BAO (Cataneo+15)

WLpeaks+Planck15priors (Liu+16)

galaxyWL+CMB+SN+BAO (Hu+16)

3x2pt+CMB (Kou+23)



- Current constraints of fifth force are derived using clusters.
- Simulations provide a framework to include more constraints.
- Emulator alone (MGLenS) forecast constraints at the same level $\log |f_{R0}| \lesssim -5.3$.

Summary and conclusions

- Simulations are at the core of large-scale structure analyses.
- Useful to test physics beyond Λ CDM. Modified gravity as an alternative for cosmological constant introduces scale dependent physics.
- Elusive fifth force must be studied with density dependent tests including non-Gaussian statistics.
- For future stage-IV cosmic shear surveys (Euclid, LSST) simulations are pivotal for a complete analysis.
- Emulator approach can provide powerful constraints on the amplitude of the fifth force.

Thank you!

