Modified gravity and dark energy from one point matter statistics

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The paper

On arXiv now (brand new!)

Cataneo et al. (2109.02636)

The matter density PDF for modified gravity and dark energy with Large Deviations Theory

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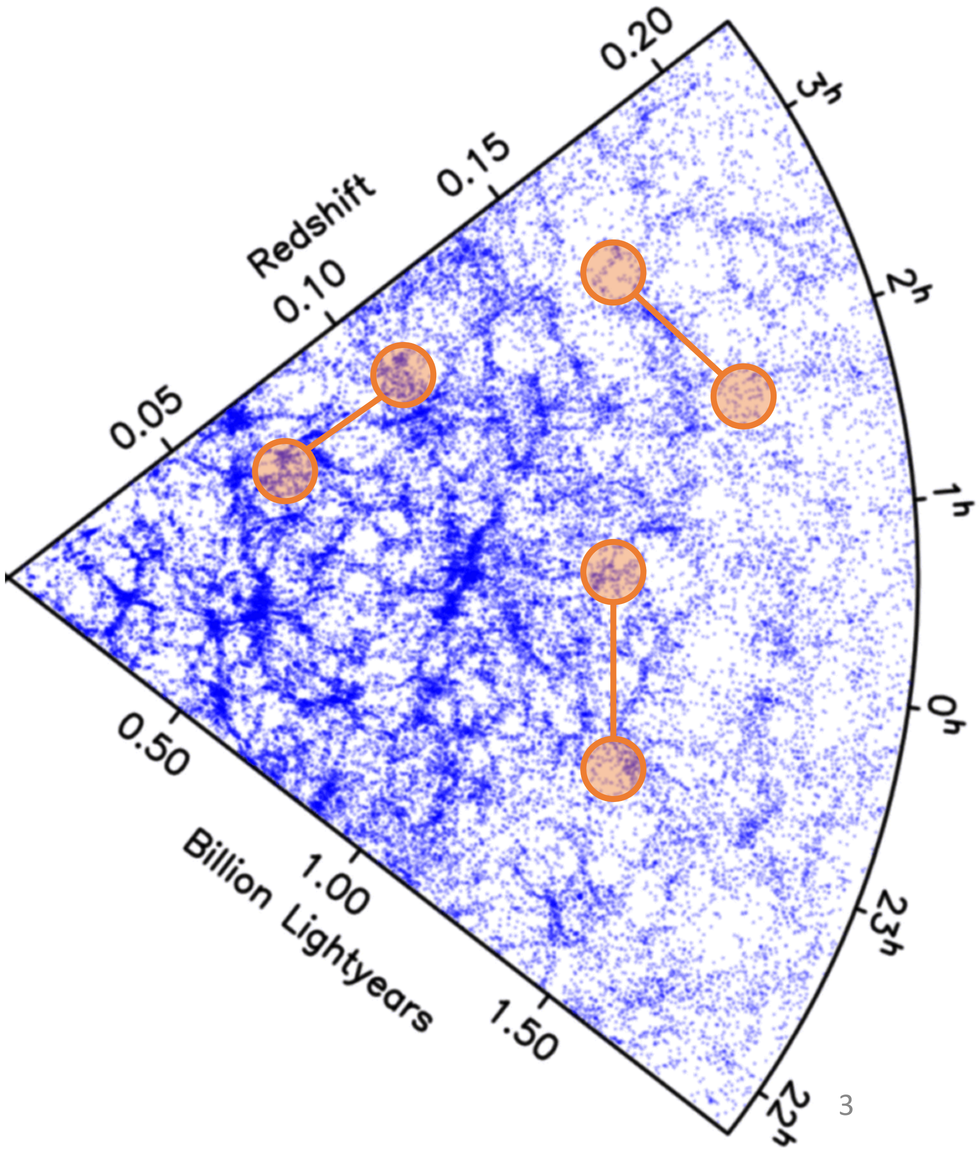
ABSTRACT

We present an analytical description of the probability distribution function (PDF) of the smoothed three-dimensional matter density field for modified gravity and dark energy. Our approach, based on the principles of Large Deviations Theory, is applicable to general extensions of the standard ΛCDM cosmology. We show that late-time changes to the law of gravity and background expansion can be included through Einstein-de Sitter spherical collapse dynamics combined with linear theory calculations and a calibration measurement of the non-linear variance of the smoothed density field from a simple numerical simulation. In a comparison to N-body simulations for $f(R)$, DGP and evolving dark energy theories, we find percent level accuracy around the peak of the distribution for predictions in the mildly non-linear regime. A Fisher forecast of an idealised experiment with a *Euclid*-like survey volume demonstrates the power of combining measurements of the 3D matter PDF with the 3D matter power spectrum. This combination is shown to halve the uncertainty on parameters for an evolving dark energy model, relative to a power spectrum analysis on its own. The PDF is also found to substantially increase the detection significance for small departures from General Relativity, with improvements of up to six times compared to the power spectrum alone. This analysis is therefore very promising for future studies including non-Gaussian statistics, as it has the potential to alleviate the reliance of these analyses on expensive high resolution simulations and emulators.

Information from cosmic fields

Cosmic fields are quantified by their *statistics*

- 2-point correlation functions (power spectra) are the standard tool
- For Gaussian fields, power spectra contains all the information, but late universe isn't Gaussian!

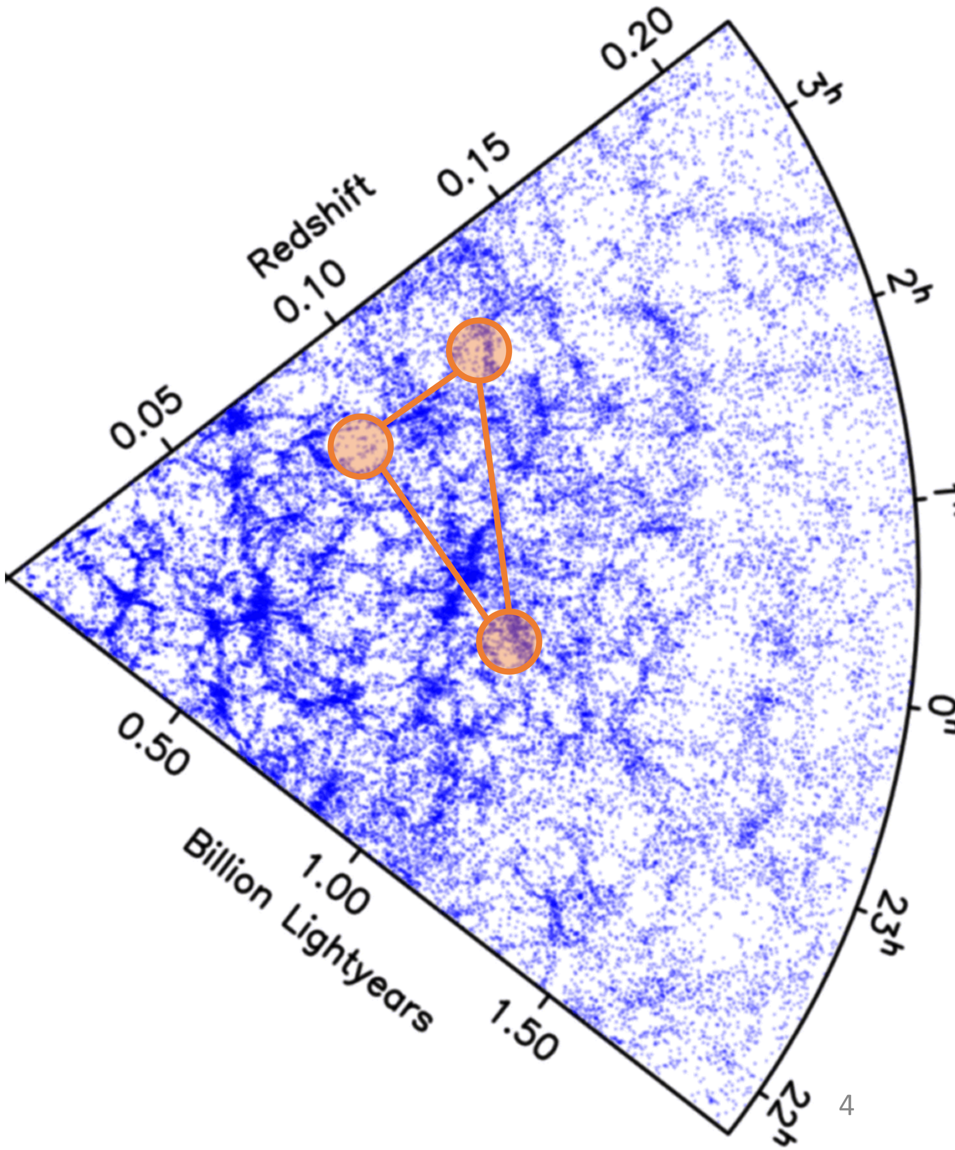


Information from cosmic fields

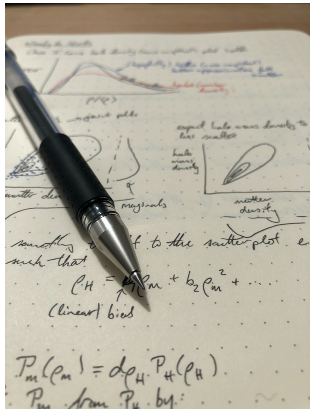
Non-Gaussian statistics

- can play same game with more points, generate N-point correlation functions
- N-point correlations functions hard to measure, have to account for shapes *and* separations

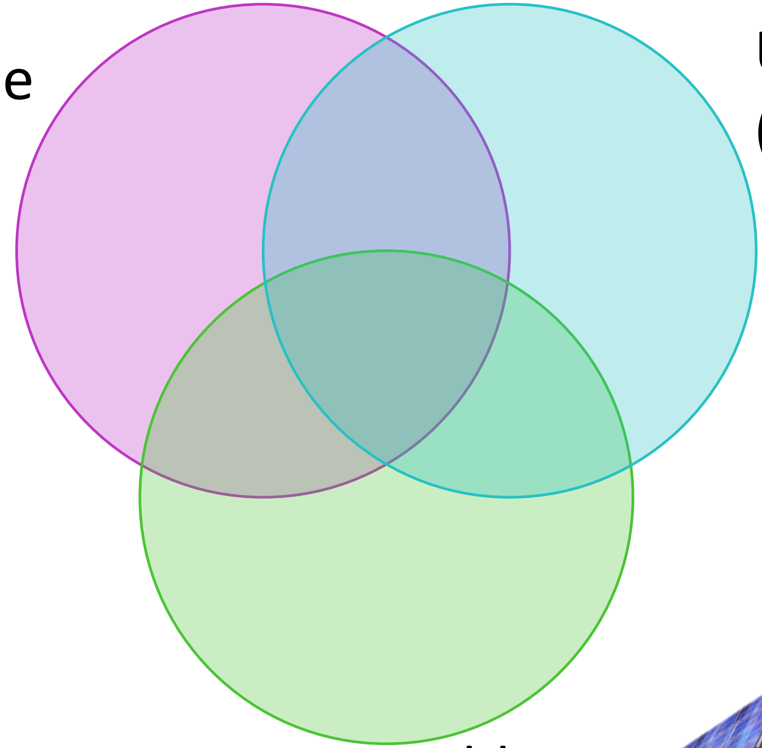
Is there a simpler non-Gaussian statistic which still captures lots of information?



Wishlist for our summary statistic

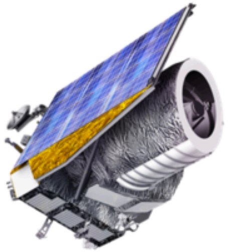


Predictable
(theory)

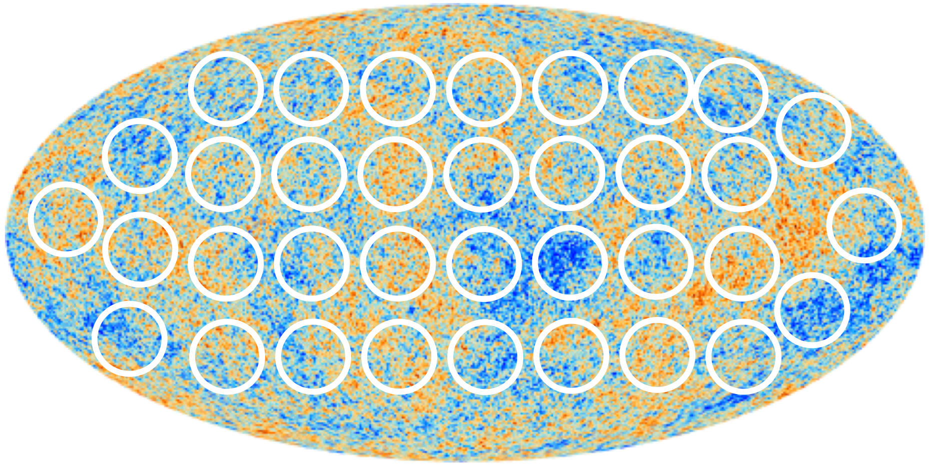


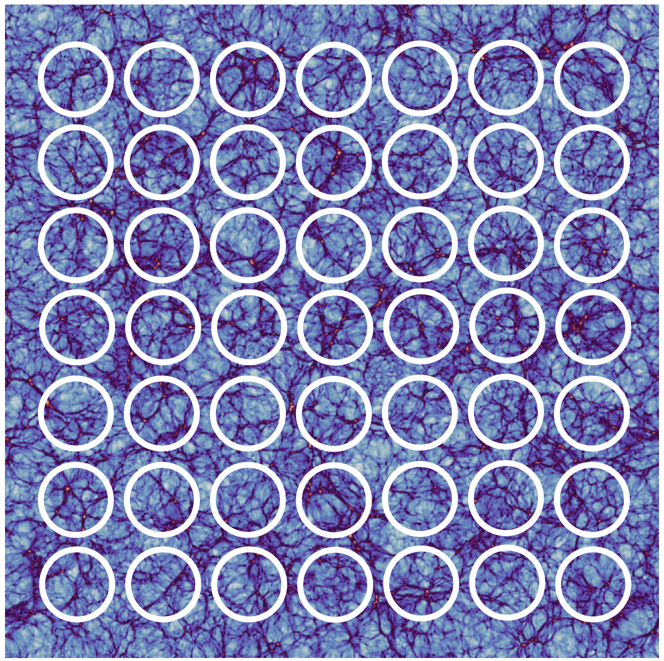
Useful
(physics)

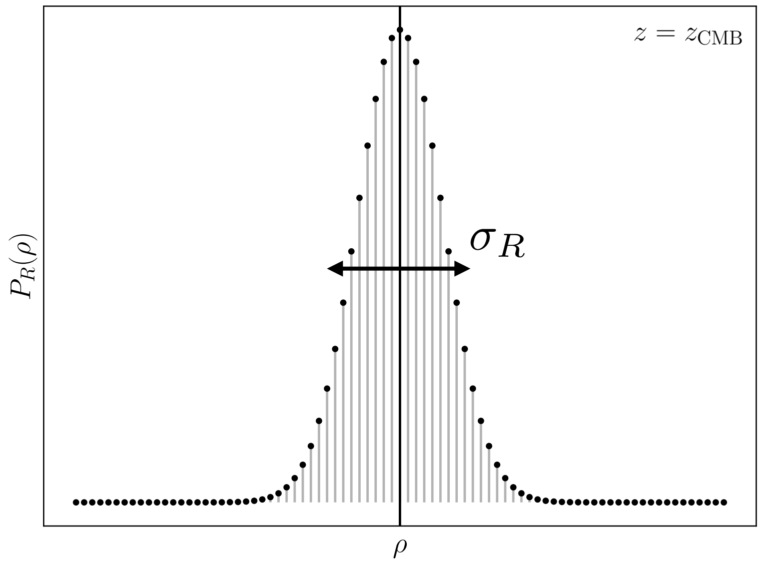
Measurable
(experiment)

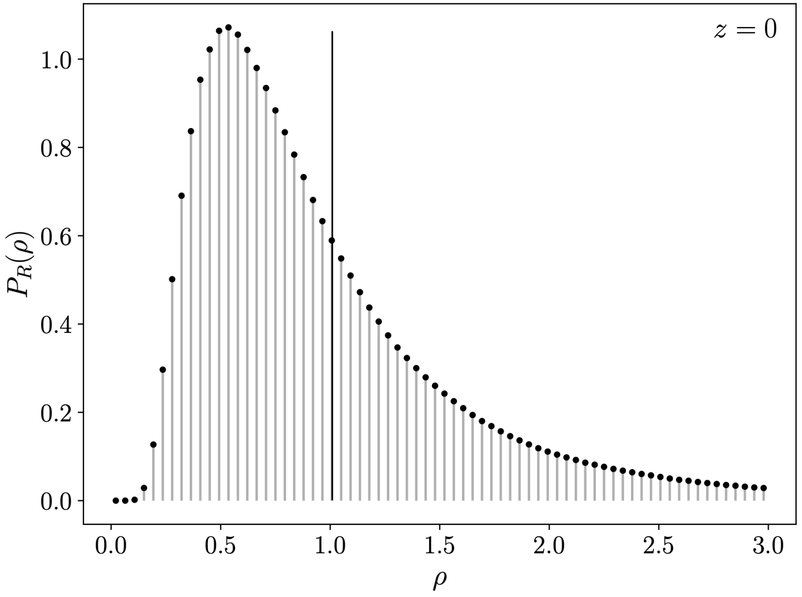


Our choice: one point function

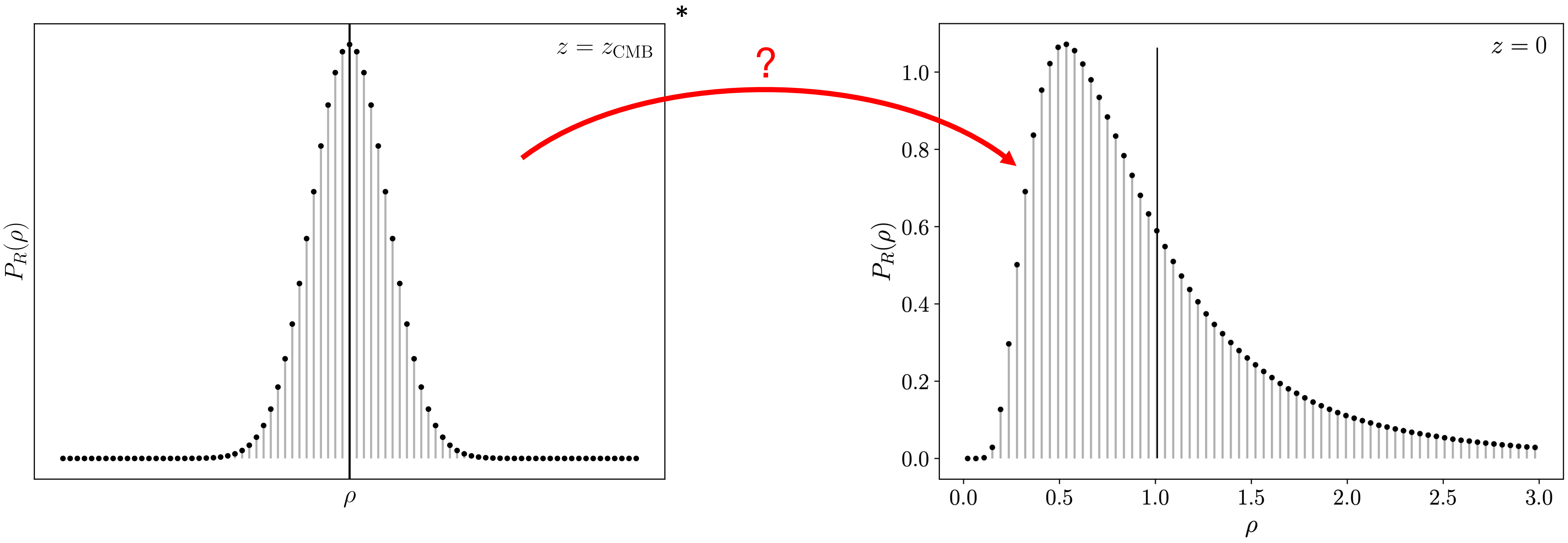






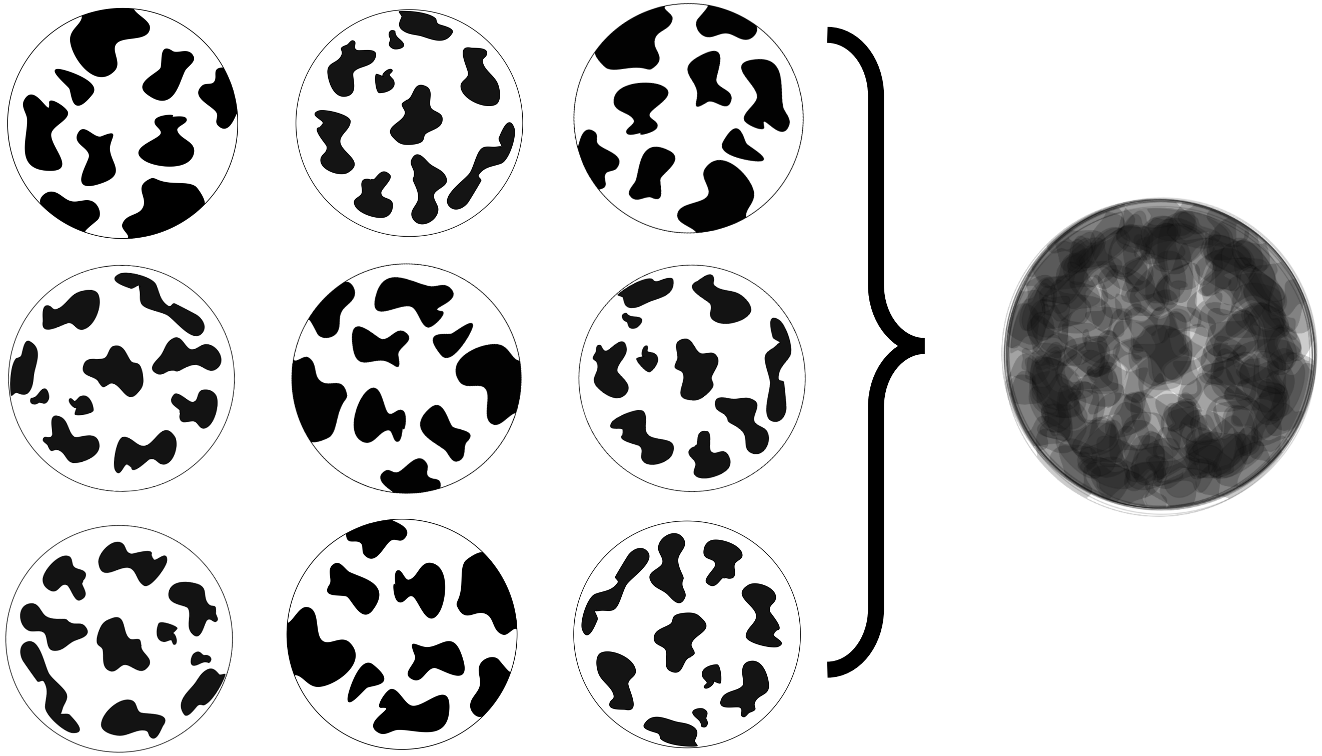


Analytic prediction?



*for extensions to non-Gaussian initial conditions see 1708.02206 and 1912.06621

Resort to spherical cows



One point function lumps spheres of the same density together, which results in a spherical symmetry.

Can we leverage this symmetry into dynamics?

Individual spheres of the same density

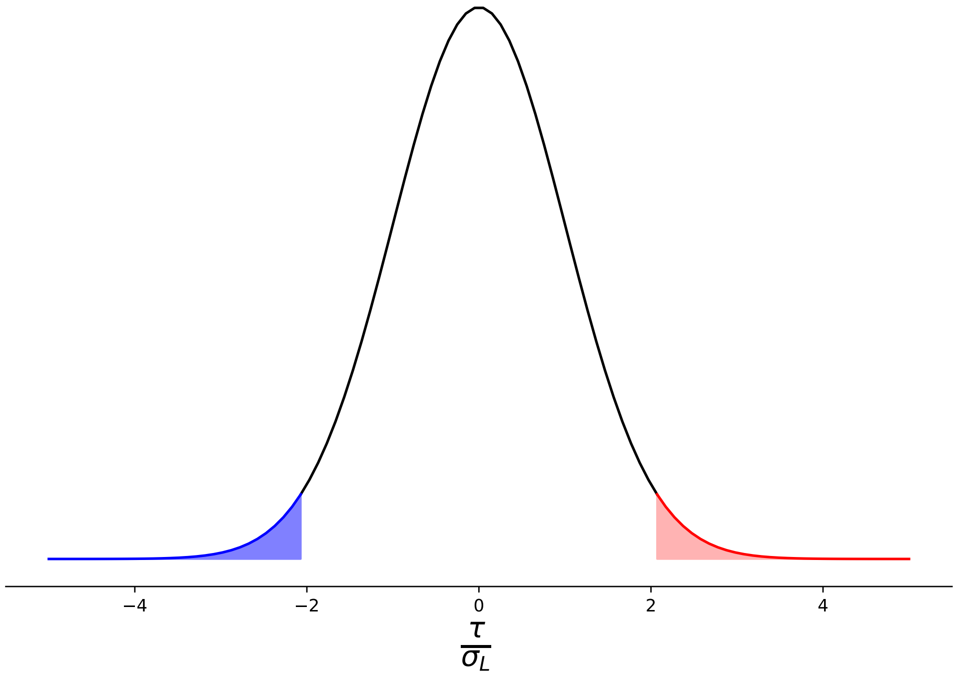
Large deviation theory

A theory dealing with exponential decay of probabilities of large fluctuations (review: Touchette 2009, Phys. Rep.)

$$P(x) \sim e^{-N\psi(x)}$$

Driving parameter → N

Rate function → $\psi(x)$



The key result for our purposes is the following:

Symmetry in statistic ⟷ Symmetry in dynamics

$P_R(\rho)$ $\qquad$ $\tau \mapsto \rho_{\mathrm{SC}}(\tau)$

Results from LDT

Result of applying LDT (Bernardeau & Reimberg (2016), Uhlemann et al (2016))

$$P_R(\rho) = \sqrt{\frac{\psi''_R(\rho) + \psi'_R(\rho)/\rho}{2\pi}} e^{-\psi_R(\rho)}$$

Structure of the rate function

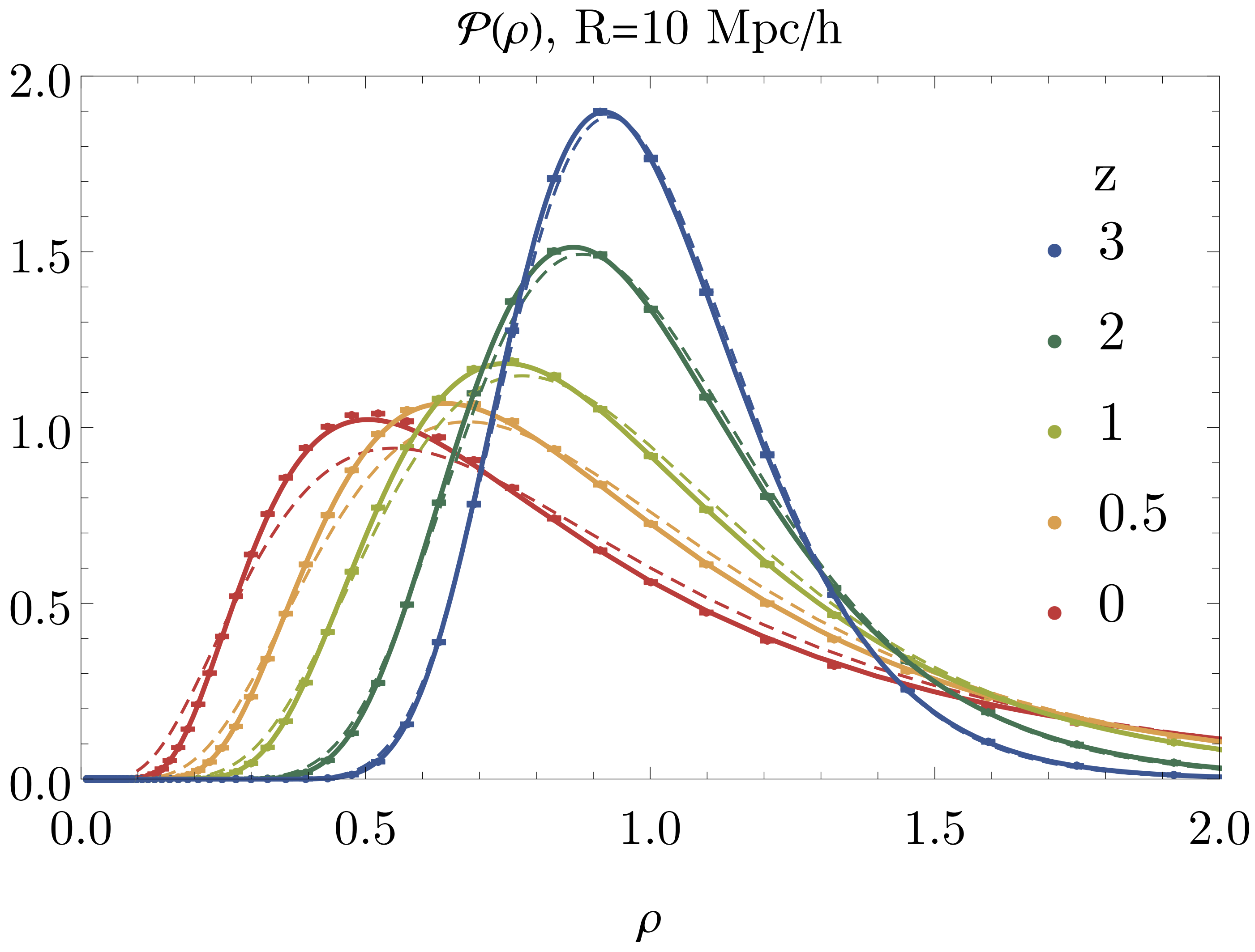
$$\psi_R(\rho) = \frac{\sigma^2_{\mathrm{L}}(R)}{\sigma^2_{\mathrm{L}}(R\rho^{1/3})} \frac{\tau^2(\rho)}{2\sigma^2_{\mathrm{NL}}(R)}$$

Spherical collapse

Linear theory

Parameter: measure from simulation

Success of LDT in ΛCDM



- Mild theoretical assumptions.
- Analytic ingredients, from underlying physics principles.
- Better fit to simulations than phenomenology curve (lognormal).

Uhlemann et al. (2020)

What needs to change going to MG/DE?

In principle need to update:

- linear theory

  ➡ Easy! Do this with your favourite extended cosmology.

- non-linear variance

  ➡ Run many MG simulations…expensive to test lots of cosmologies/models.

  ➡ Use lognormal approximation (accurate to 1% on scales considered).

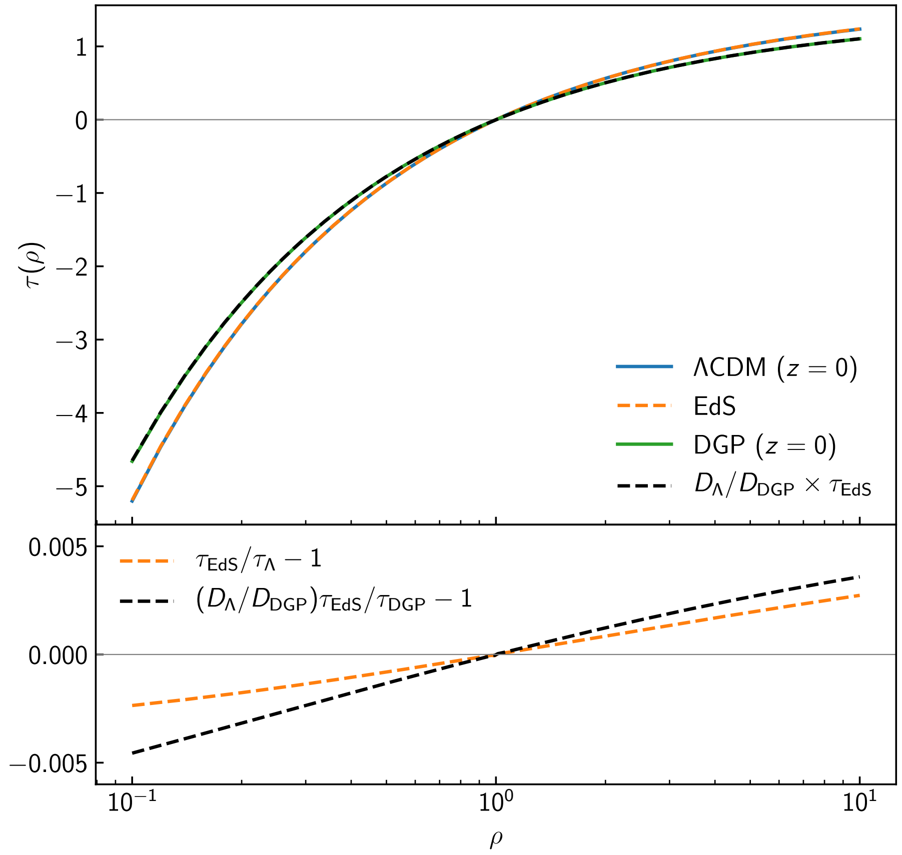
$$\sigma^2_{\rm NL} \approx \frac{\ln[1+\sigma^2_{\rm L}]}{\ln[1+\sigma^2_{\rm L,fid}]}\sigma^2_{\rm NL,fid}$$

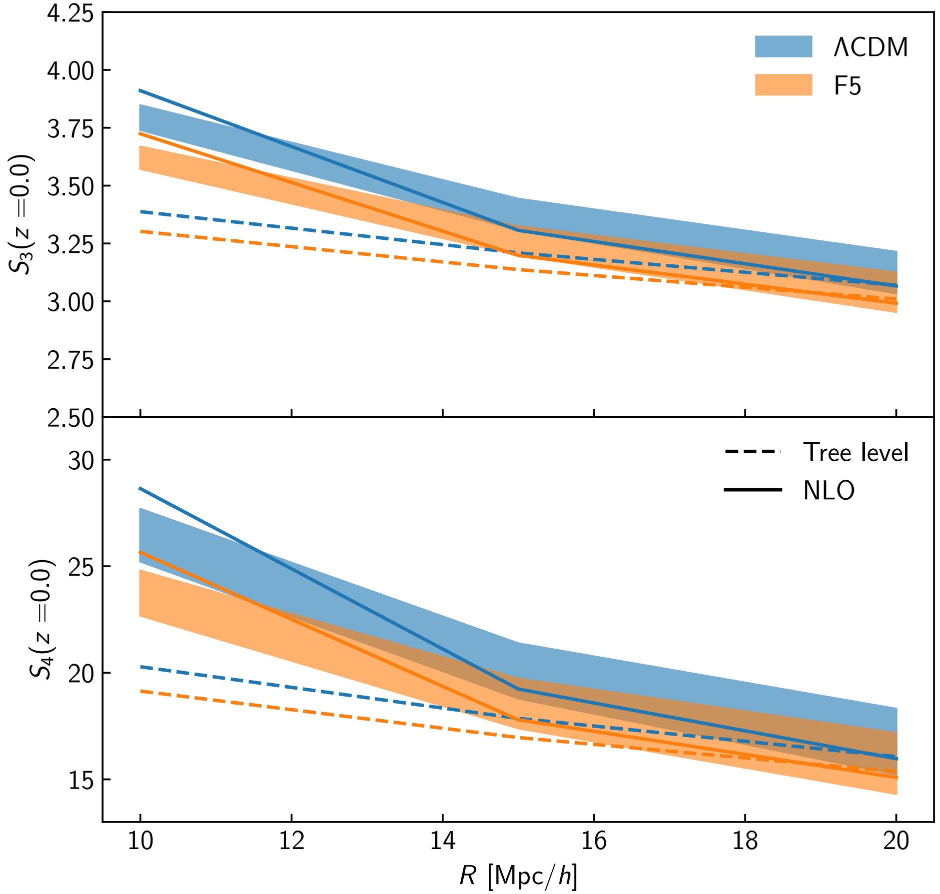
- spherical collapse

  ➡ In principle tricky for MG/DE theories.

  ➡ If we restrict to scales >10 Mpc/h we can use the same mapping as in GR.

Checking spherical collapse

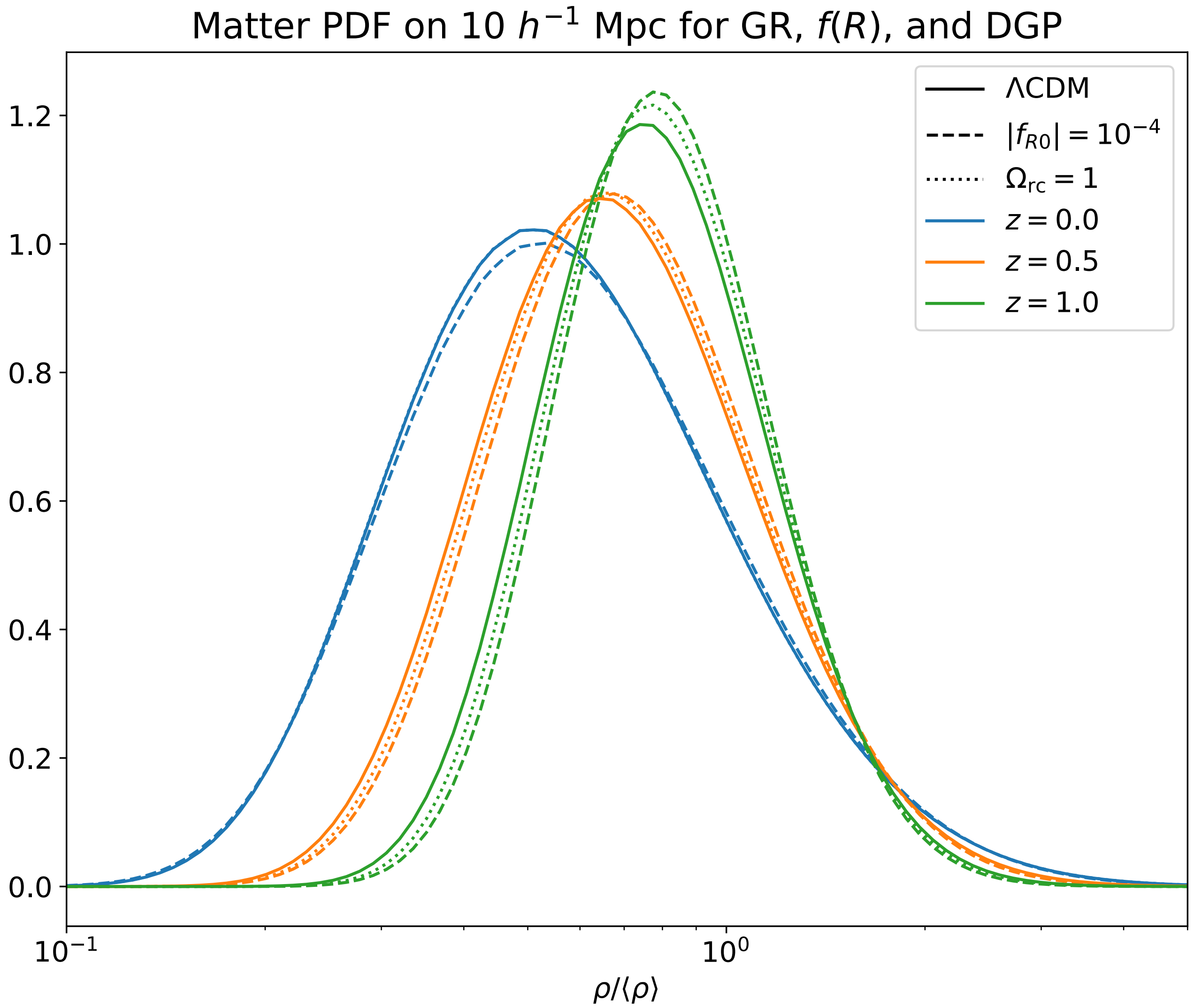




$$\psi_R^{\rm MG}(\rho) = \frac{\sigma^2_{\rm L,MG}(R)}{\sigma^2_{\rm L,MG}(R\rho^{1/3})} \frac{\tau^2_{\rm GR}(\rho)}{2\sigma^2_{\rm NL,MG}(R)}$$

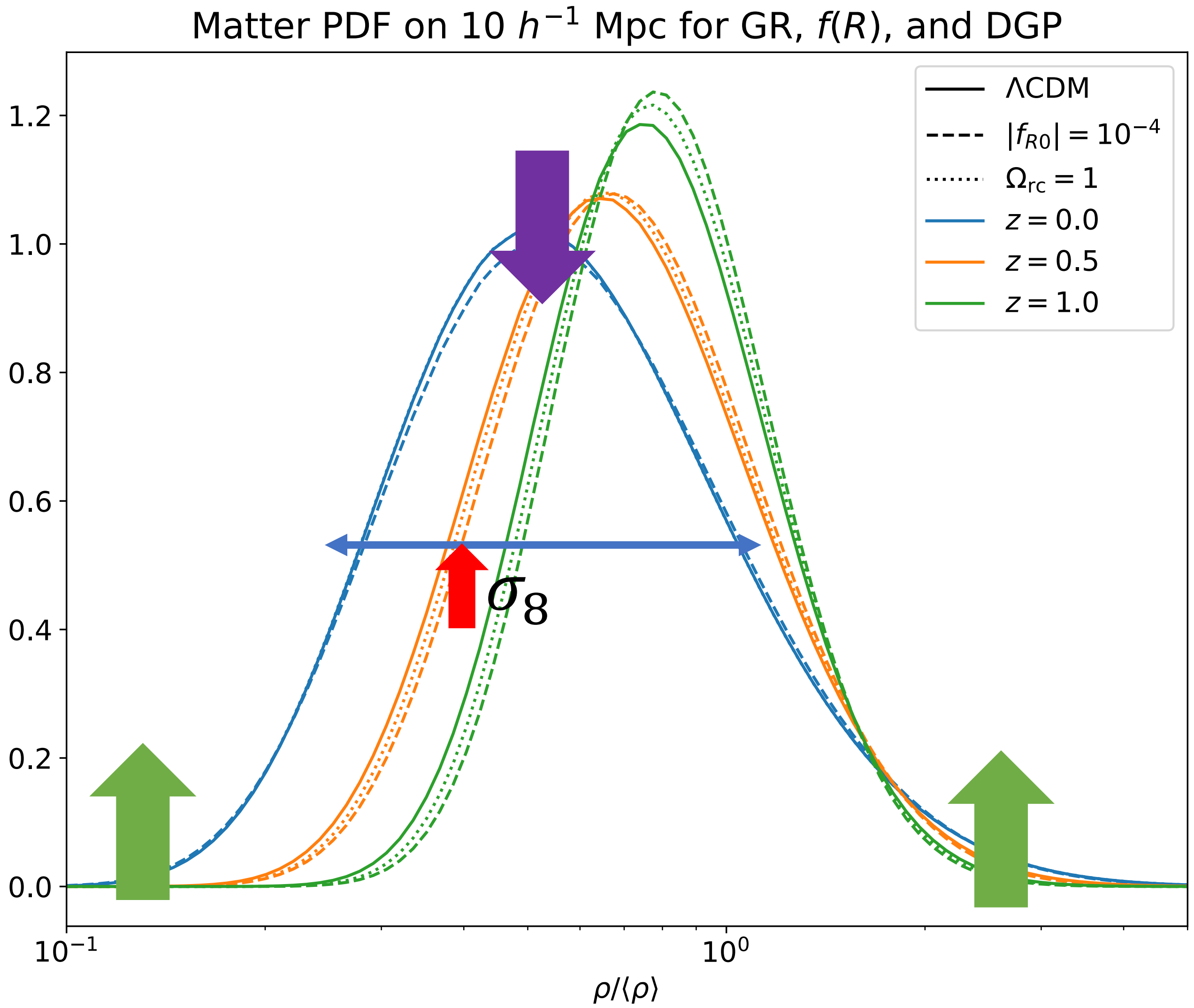
Cataneo et al. (2021)

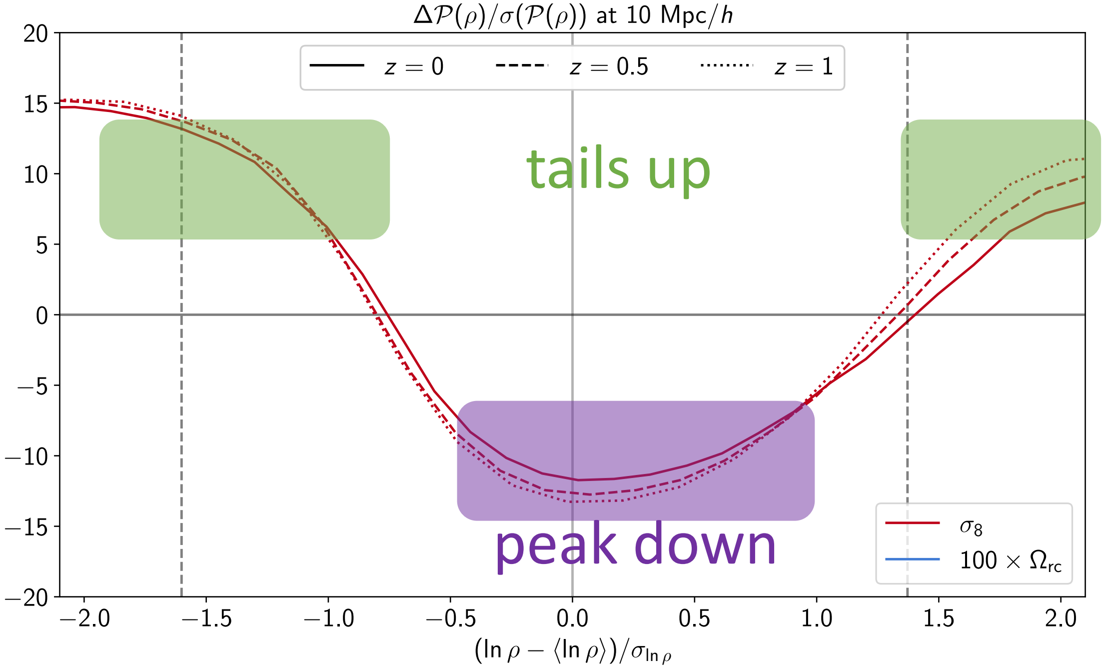
Going beyond LCDM



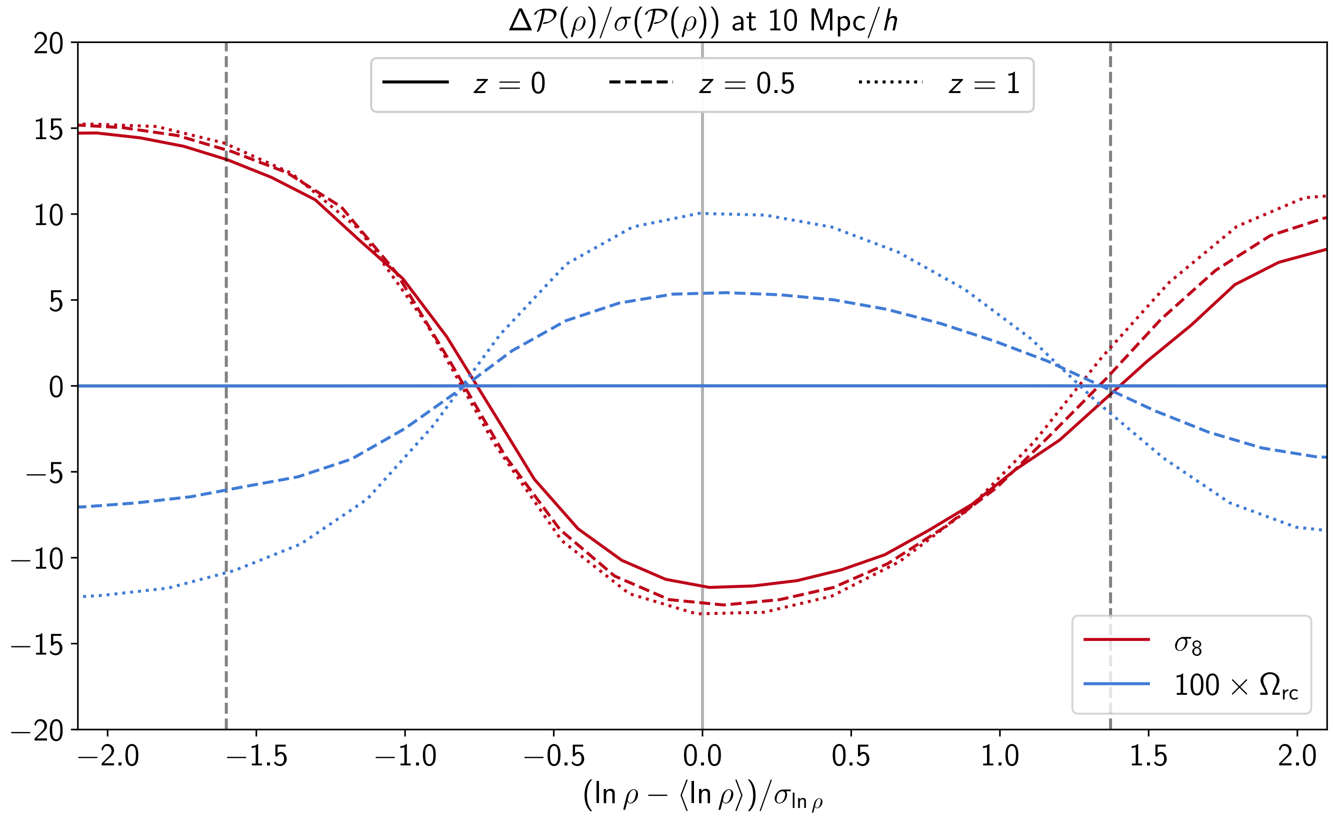
- Modified gravity changes the width and shape of the PDF.
- Fixing σ_8 normalizes this width, tilt and redshift dependence more apparent.

How $P_R(\rho)$ depends on cosmology





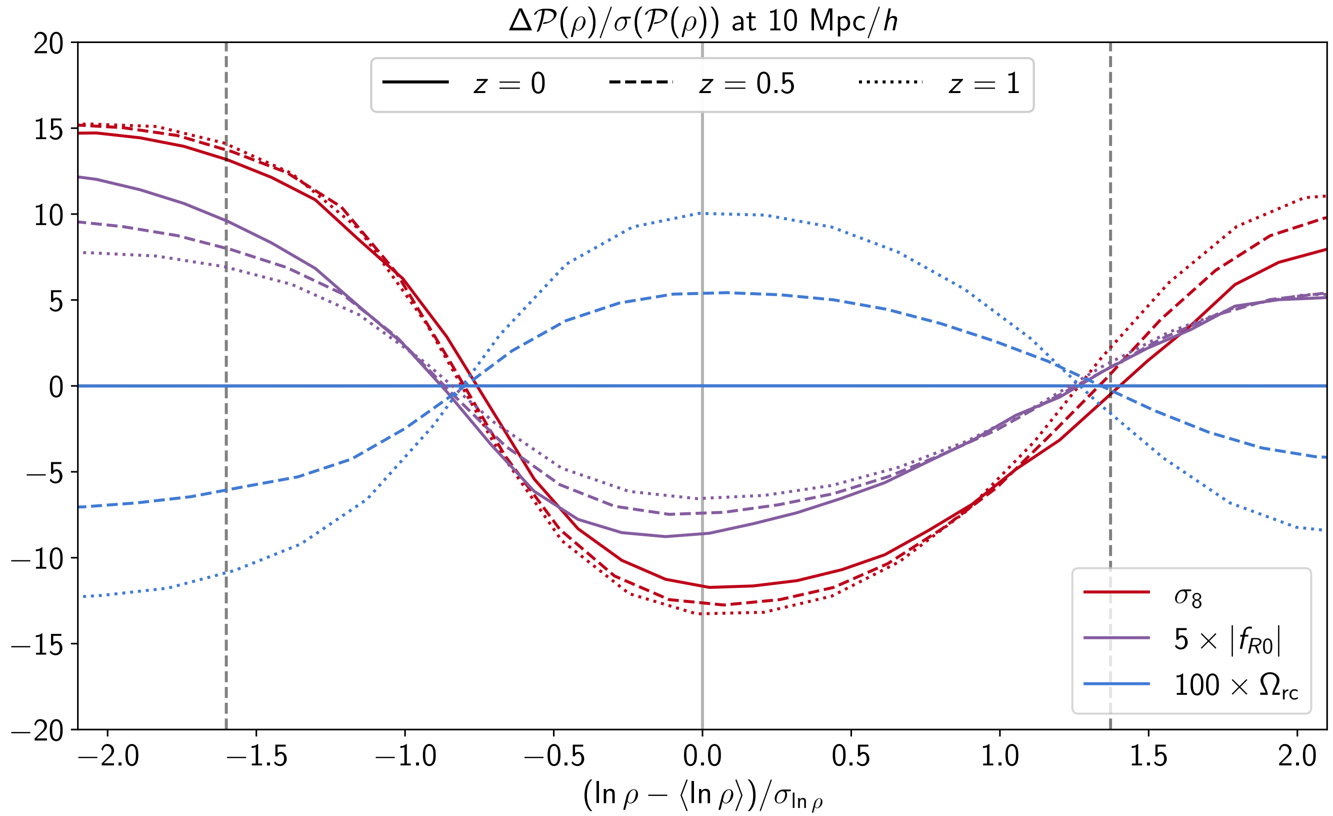
Derivative plots



- DGP gravity changes to the PDF come from modifying expansion history.
- DGP and σ_8 have very different redshift dependence.
- Story similar with changing dark energy.

Cataneo et al. (2021)

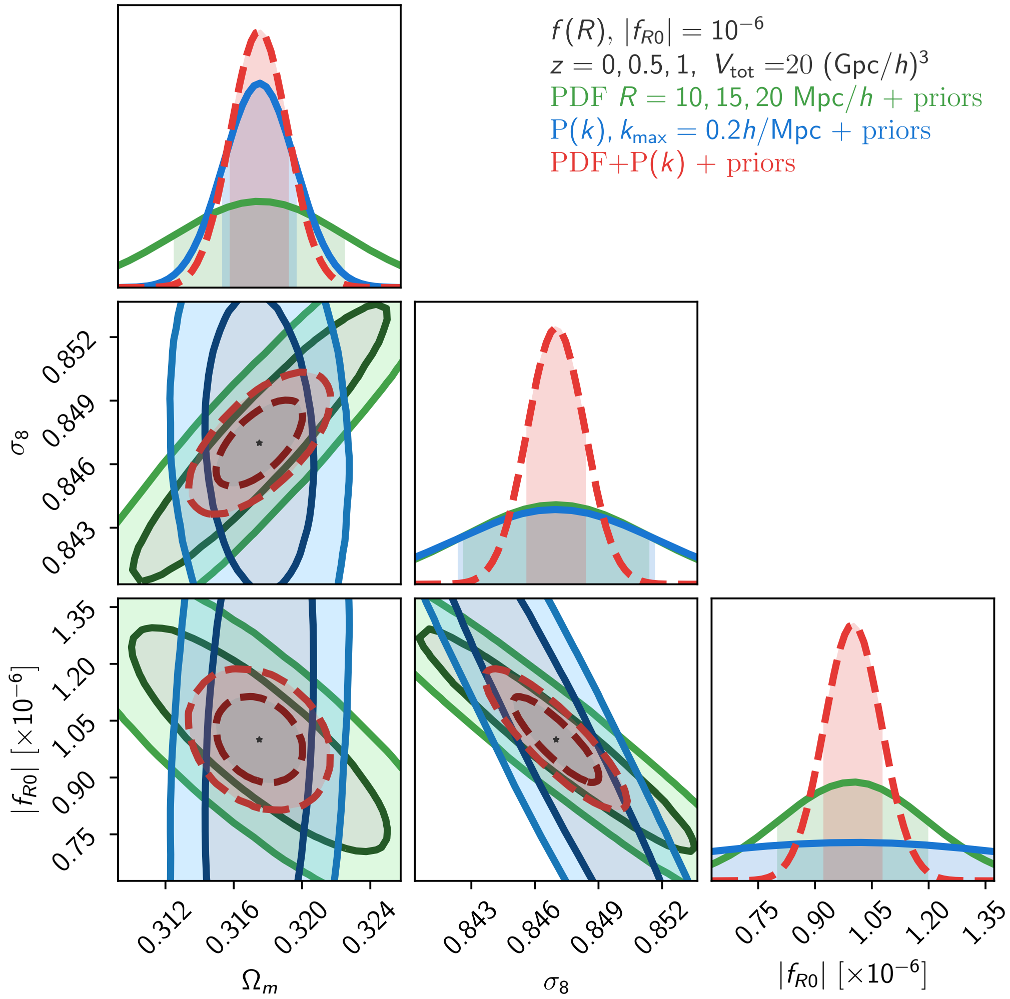
Derivative plots



- DGP gravity changes to the PDF come from modifying expansion history.
- DGP and σ_8 have very different redshift dependence.
- Story similar with changing dark energy.
- $f(R)$ gravity induces additional skewness from scale-dependent fifth-force.

Cataneo et al. (2021)

Results



MG results

	DGP detection	$f(R)$ detection
PDF (10, 15, 20 Mpc/h)	1.17σ	5.15σ
$P(k)$, $k_{\rm max} = 0.2\ h/$Mpc	2.42σ	2.01σ
PDF + $P(k)$	5.19σ	13.40σ

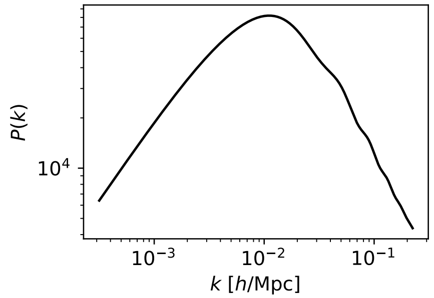
$w_0 w_a$CDM results

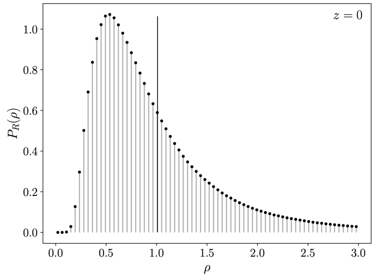
	Factor improvement
σ_8, w_0, w_a	$\times 2.5$
FoM	$\times 5$

Cataneo et al. (2021)

Takeaways

- The matter PDF can be accurately predicted using LDT in MG and DE cosmologies.
- The matter PDF + $P(k)$ at least doubles constraining power.
- Code pyLDT available now! Comes with 4 models out of the box (GR, $f(R)$, DGP, w_0w_aCDM) but can add your own by adding linear equations. PDFs for all models at 3 scales + 3 redshifts in $\sim$1 second.
- The matter PDF can be mapped to observables e.g. weak lensing (Barthelemy et al. 2020, Boyle et al. 2020) or biased tracers (Uhlemann et al. 2017).





Model	Improvement
DGP	$\times 2$ (5.19σ)
$f(R)$	$\times 6$ (13.4σ)
w_0w_aCDM	$\times 5$ (FoM)

https://github.com/mcataneo/pyLDT-cosmo