Crossing the boundary of 2-point statistics in modified gravity and dark energy

Matteo Cataneo (he/him/his)
University of Edinburgh

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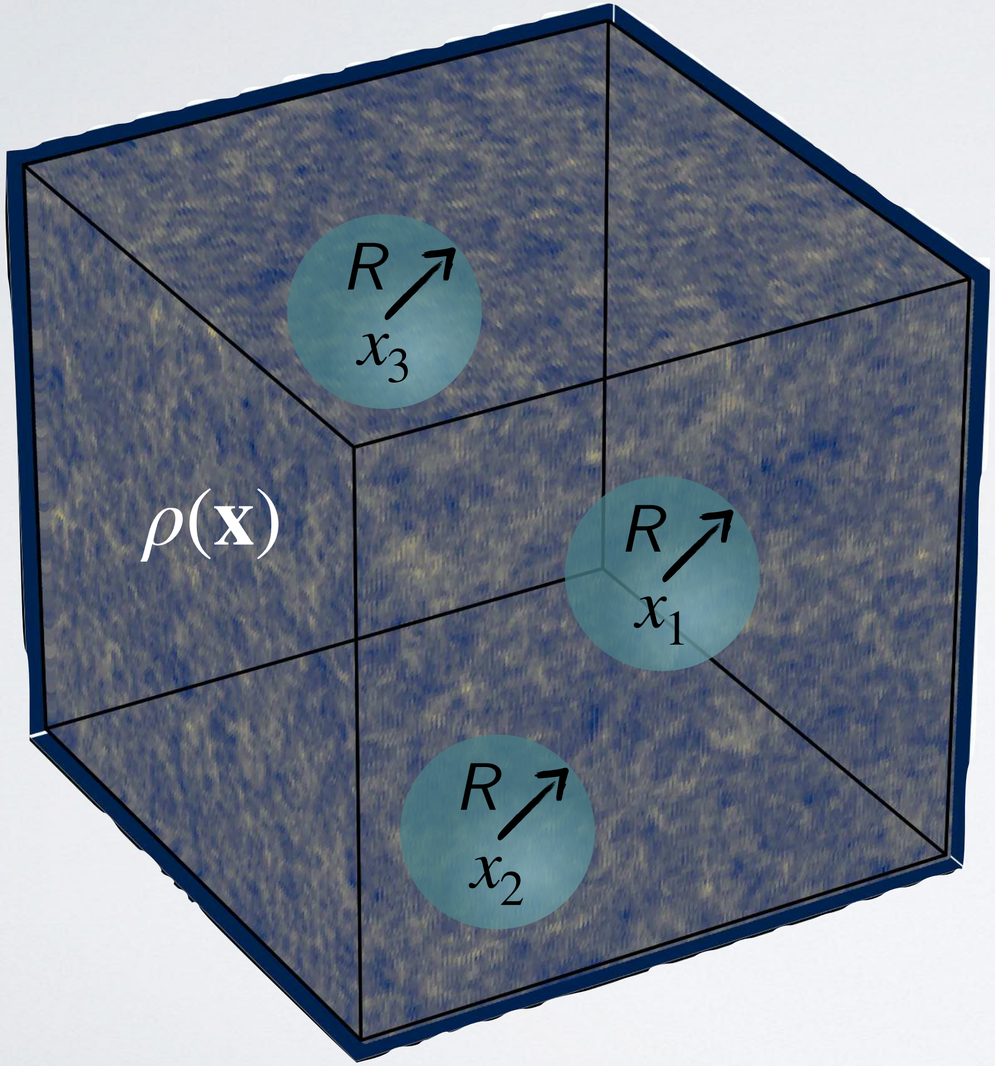
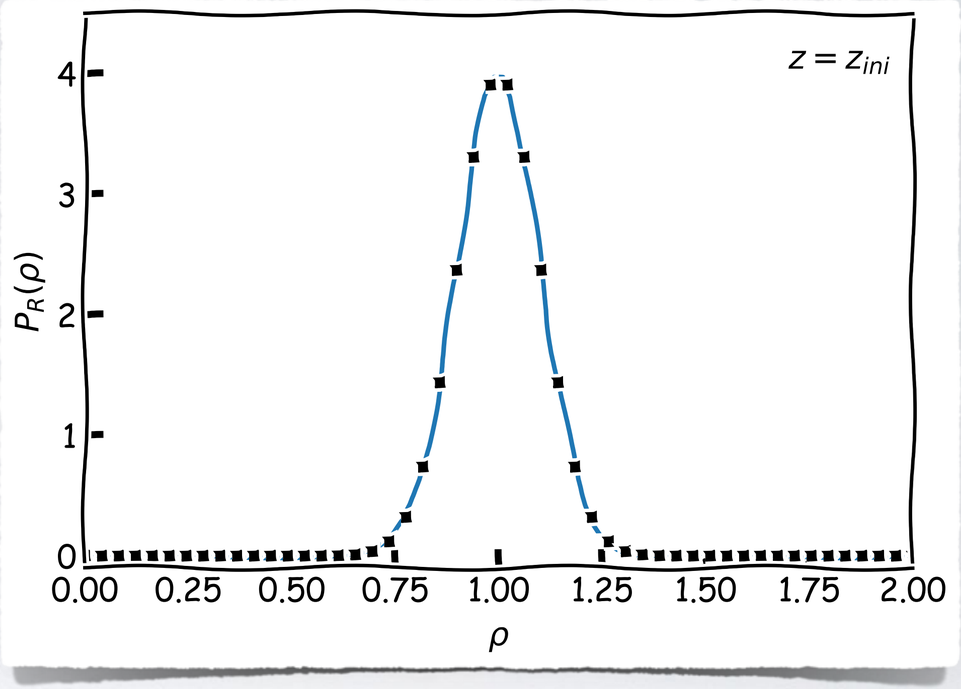
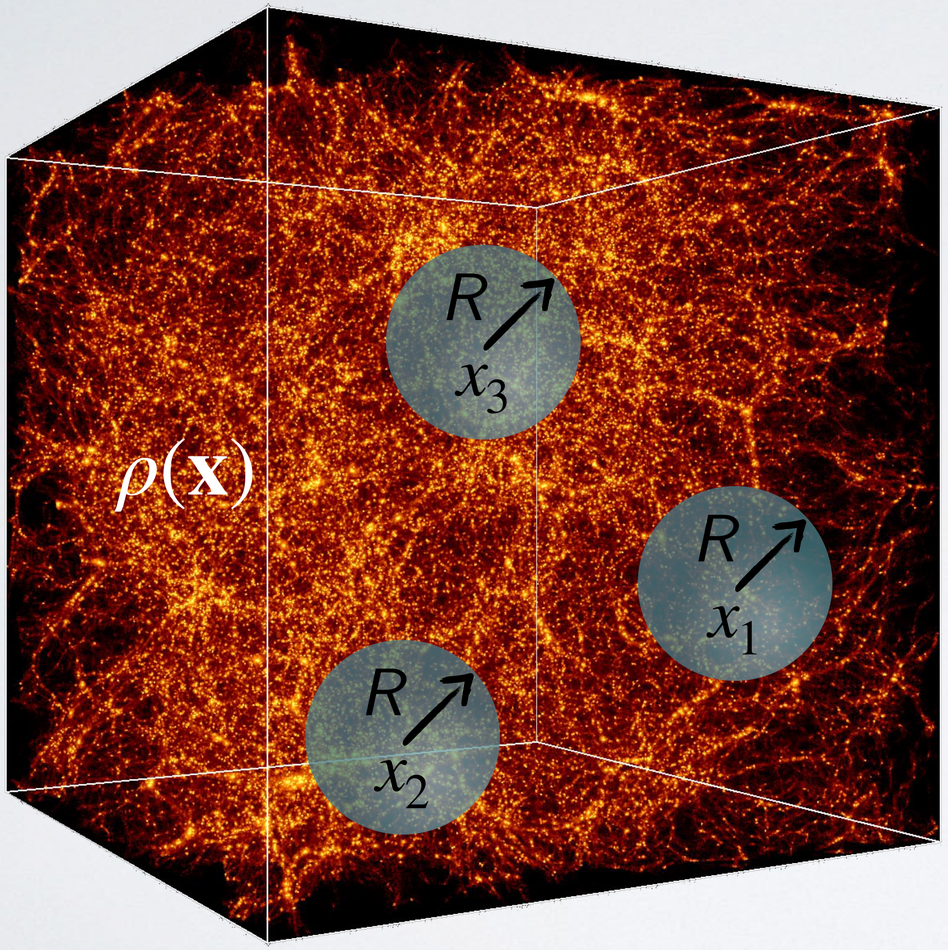
In collaboration with: Christian Arnold (Durham), Alex Gough (Newcastle), Catherine Heymans (Edinburgh), Baojiu Li (Durham) and Cora Uhlemann (Newcastle)

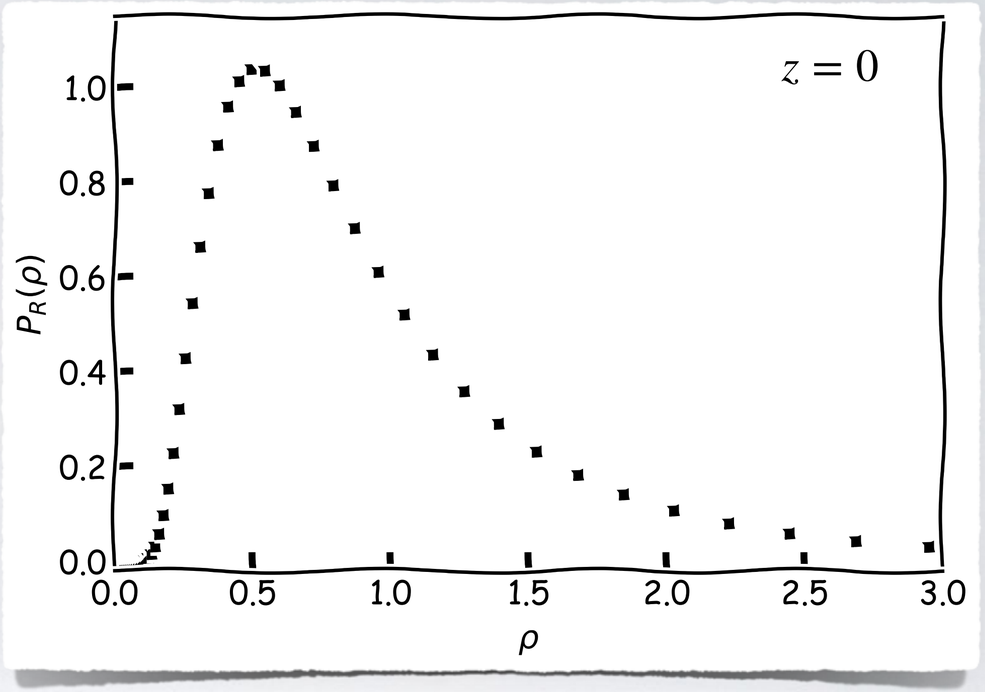
In the beginning it was Gaussian...



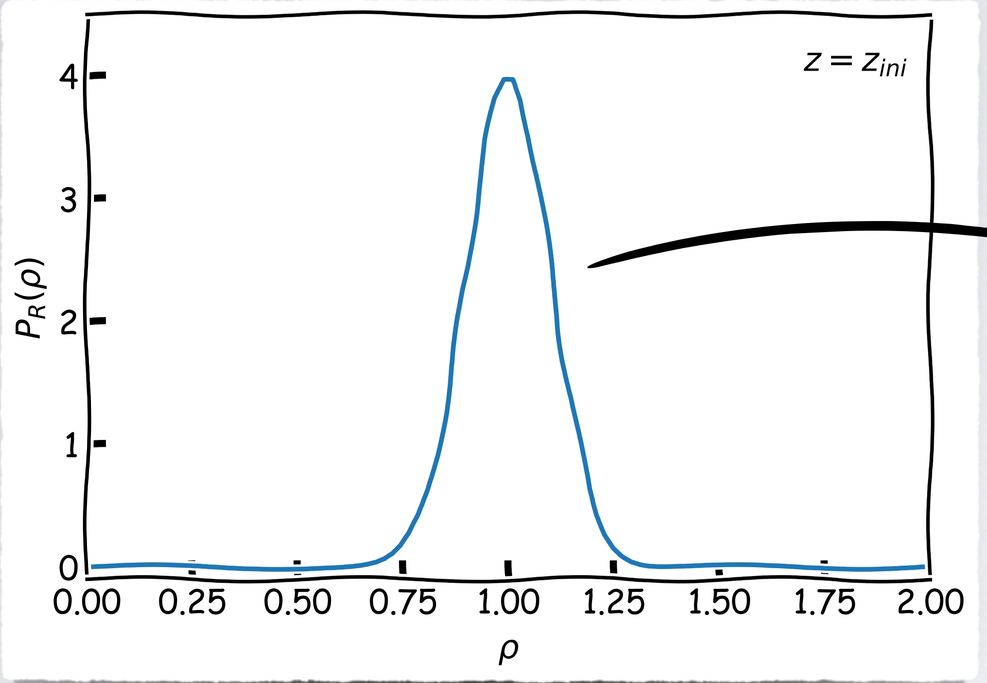


...later on, not so much!





An analytical prescription?



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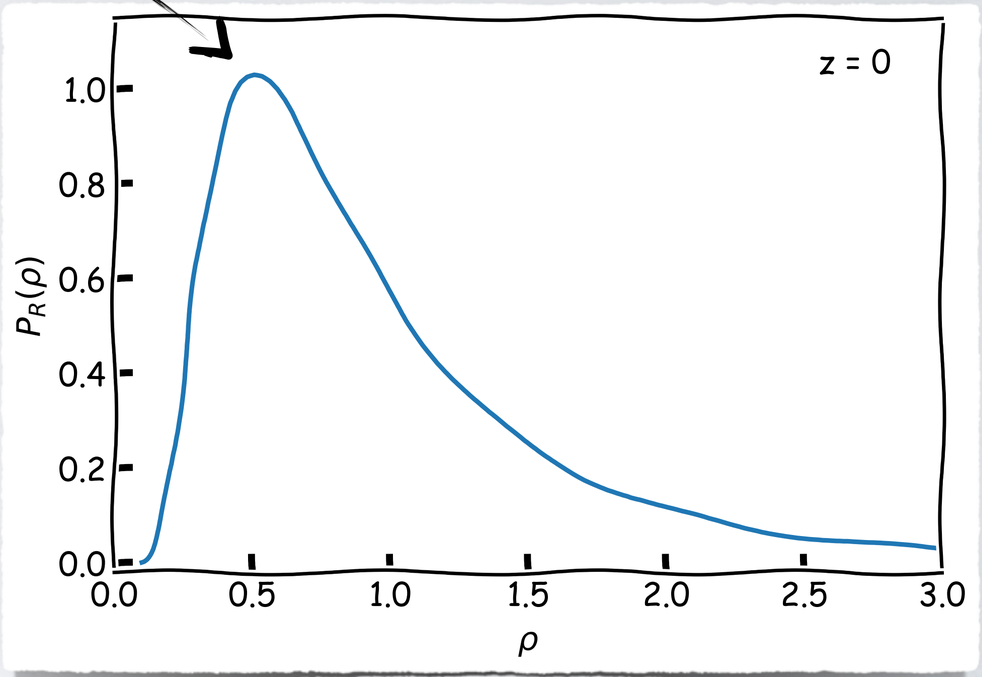

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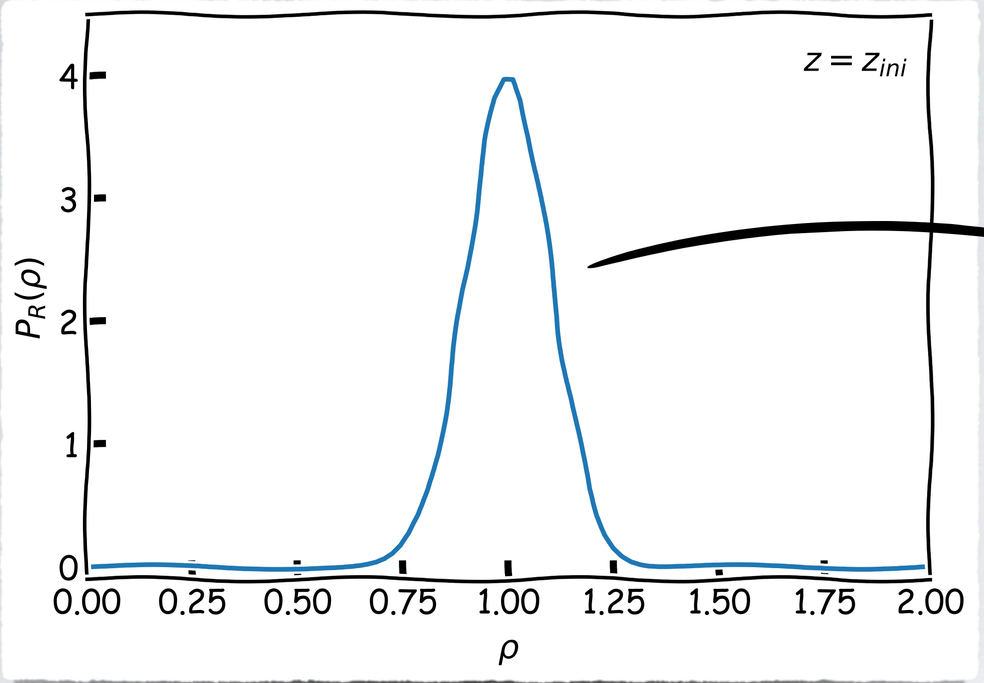
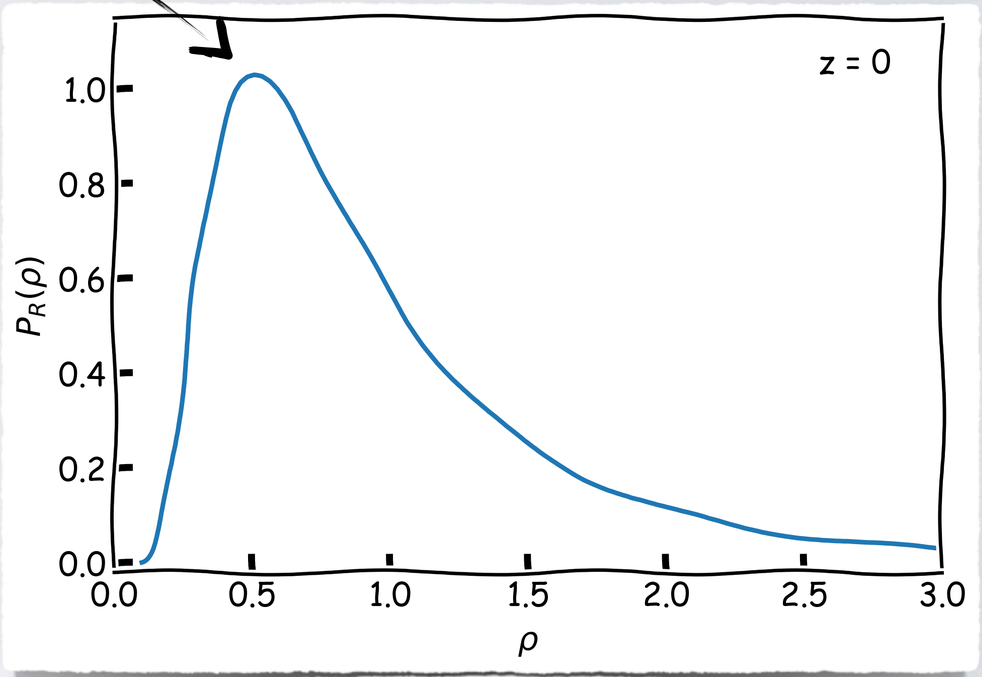


Large-deviation theory



Large-deviation theory 101

[excellent review by Touchette (2009)]

- Describes the exponential decay of the probability of large fluctuations in stochastic processes

driving parameter

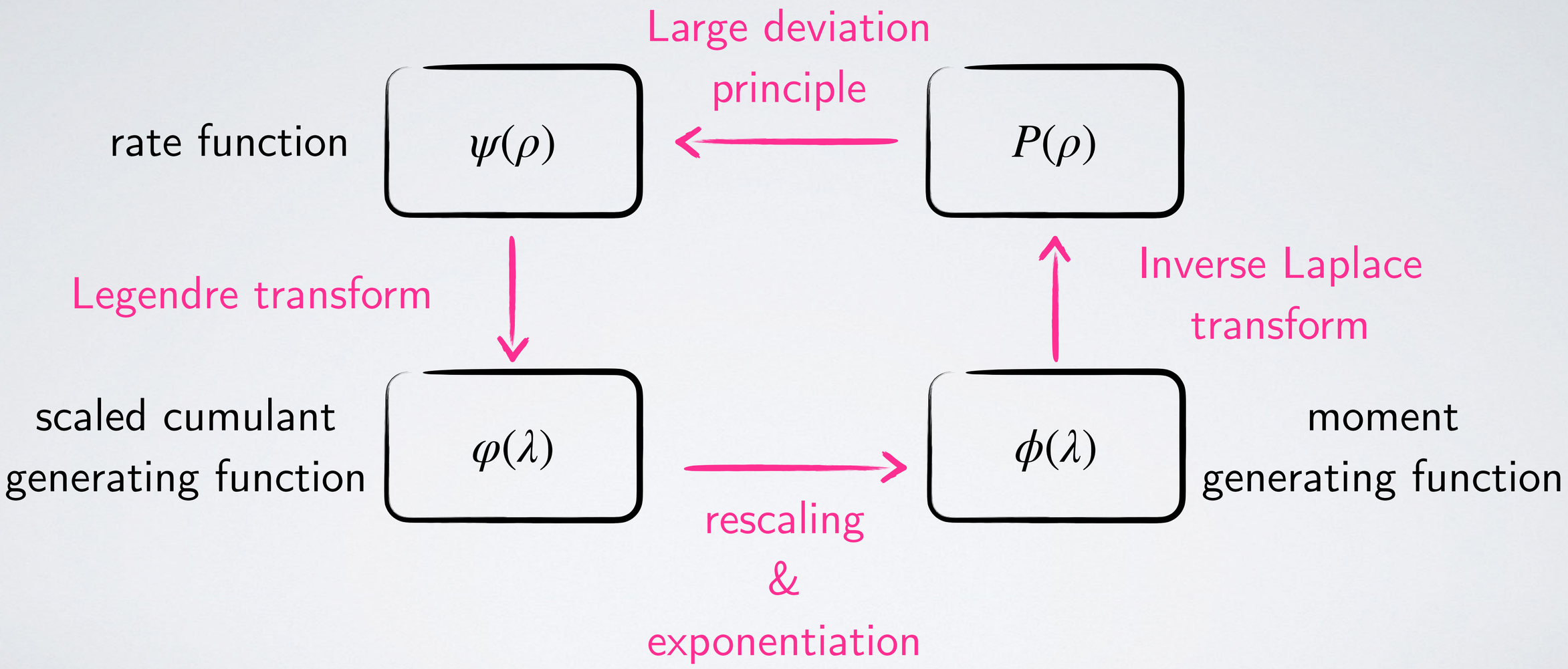
$$P(x) \sim e^{-N\psi(x)}$$

decay-rate function

- A generalisation of the Central Limit Theorem

$$\psi(x) \approx \frac{1}{2}\psi''(x^*)(x - x^*)^2$$

From rate functions to PDFs (and back)



Contractions, saddles and probabilities

[Bernardeau & Reimberg (2016), Uhlemann et al. (2016)]

Rate function of the cosmic density field (contraction principle)

linear theory

Einstein-de Sitter sph. dynamics

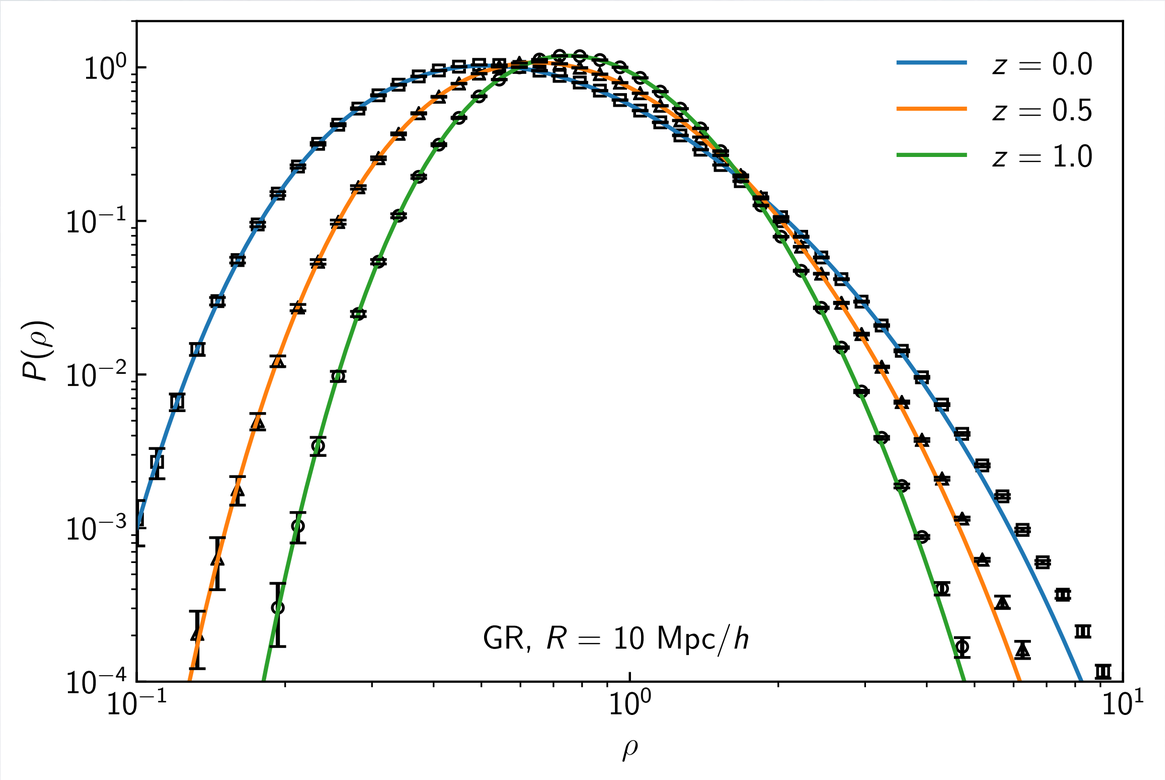
$$\psi_R(\rho) = \frac{\sigma_{\rm L}^2(R)}{\sigma_{\rm L}^2(R\rho^{1/3})} \frac{\tau_{\rm EdS}^2(\rho)}{2}$$

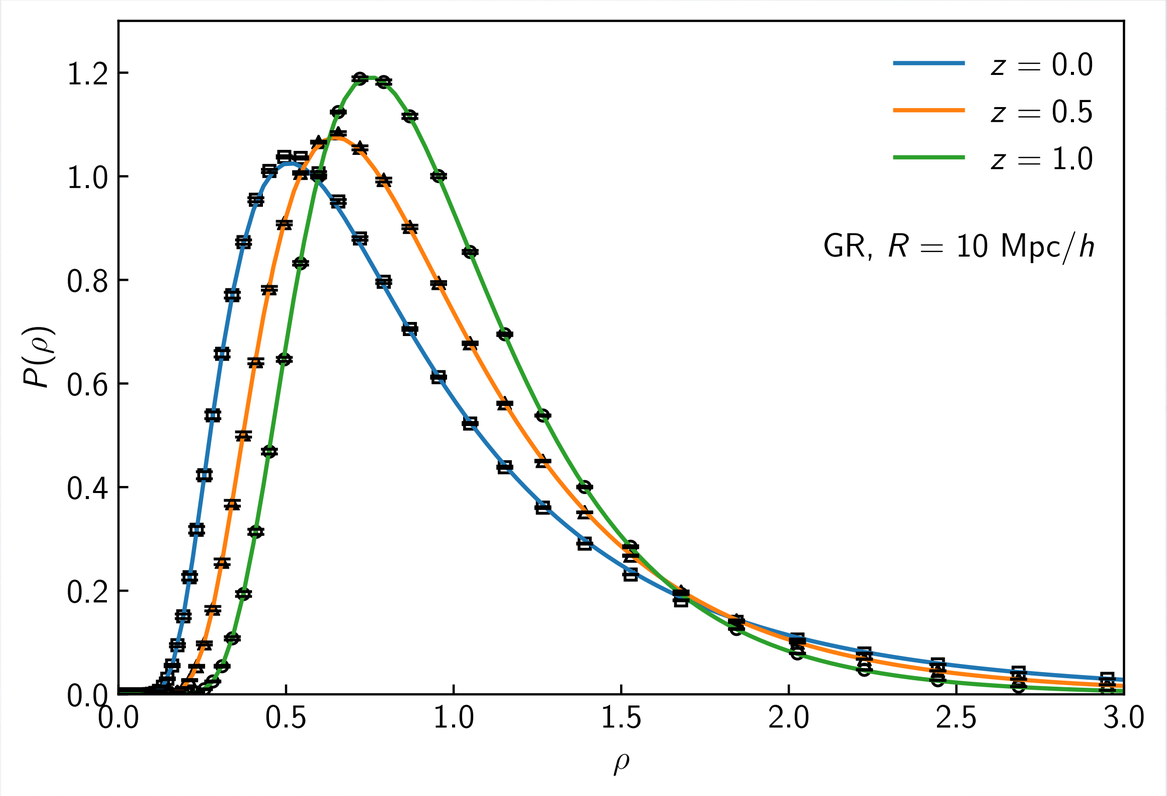
From the rate function to the PDF (contraction + saddle-point approx.)

$$\mathscr{P}_{R,z}(\rho) = \sqrt{\frac{\psi_R''(\rho) + \psi_R'(\rho)/\rho}{2\pi\sigma_{\ln\rho}^2(R,z)}} \exp\left[-\frac{\psi_R(\rho)}{\sigma_{\ln\rho}^2(R,z)}\right]$$

non-linear clustering

Matter PDF in ΛCDM





Uhlemann et al. (2016)

What about MG and DE?

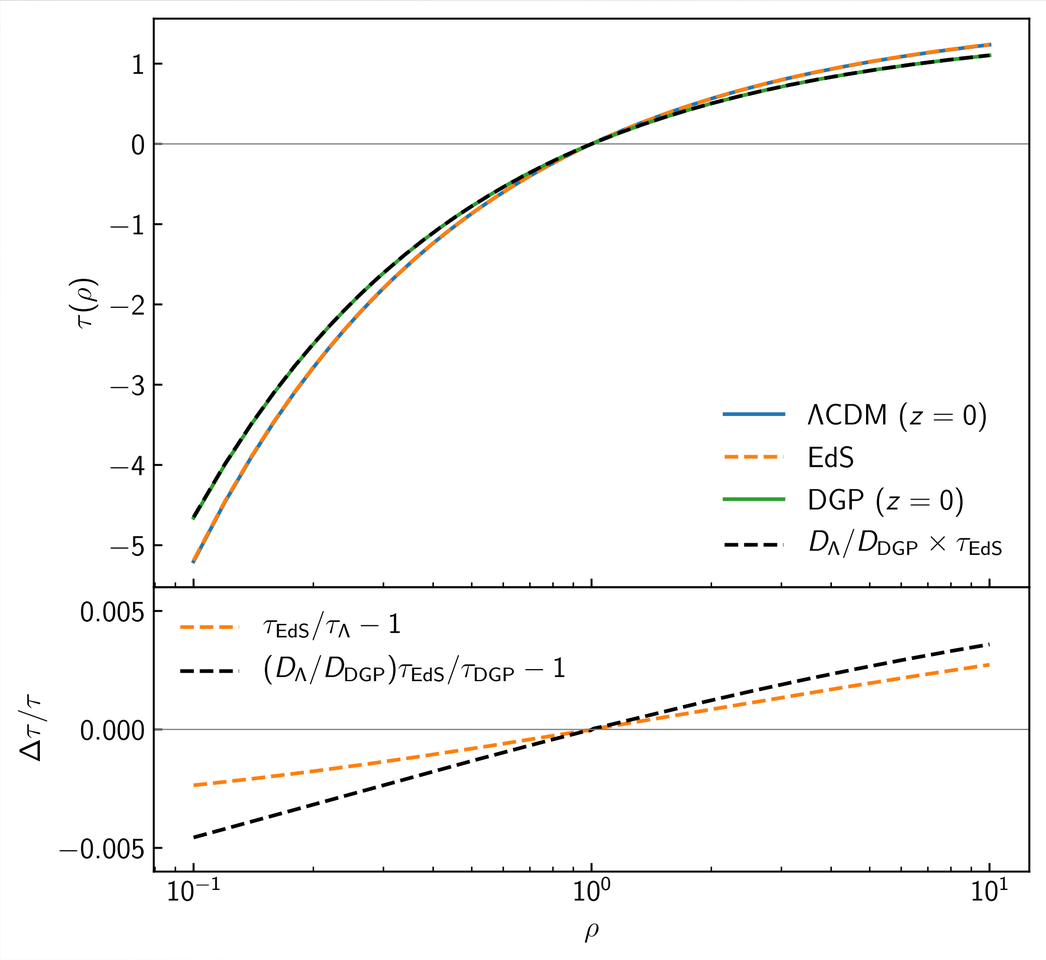
On sufficiently large scales ($R \gtrsim 10\ \mathrm{Mpc}/h$)

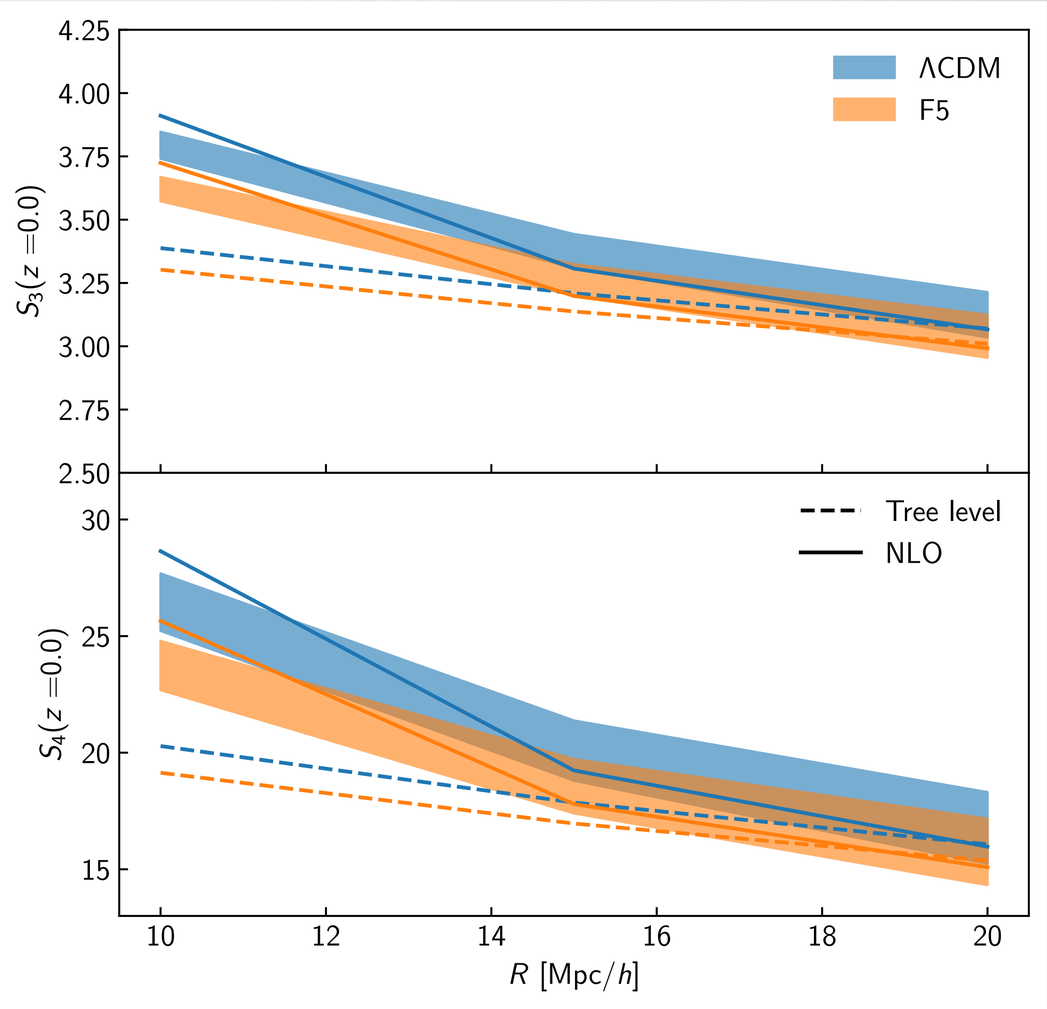
1. MG phenomenology (i.e. fifth force and screening mechanisms)
2. DE changes to background expansion

have ***negligible impact on the evolution of spherical fluctuations*** (cf. Brax & Valageas 2012).

Cataneo et al. in prep.

Einstein-de Sitter approximation





Cataneo et al. in prep.

The matter density PDF in MG and DE

Rate function (contraction principle)

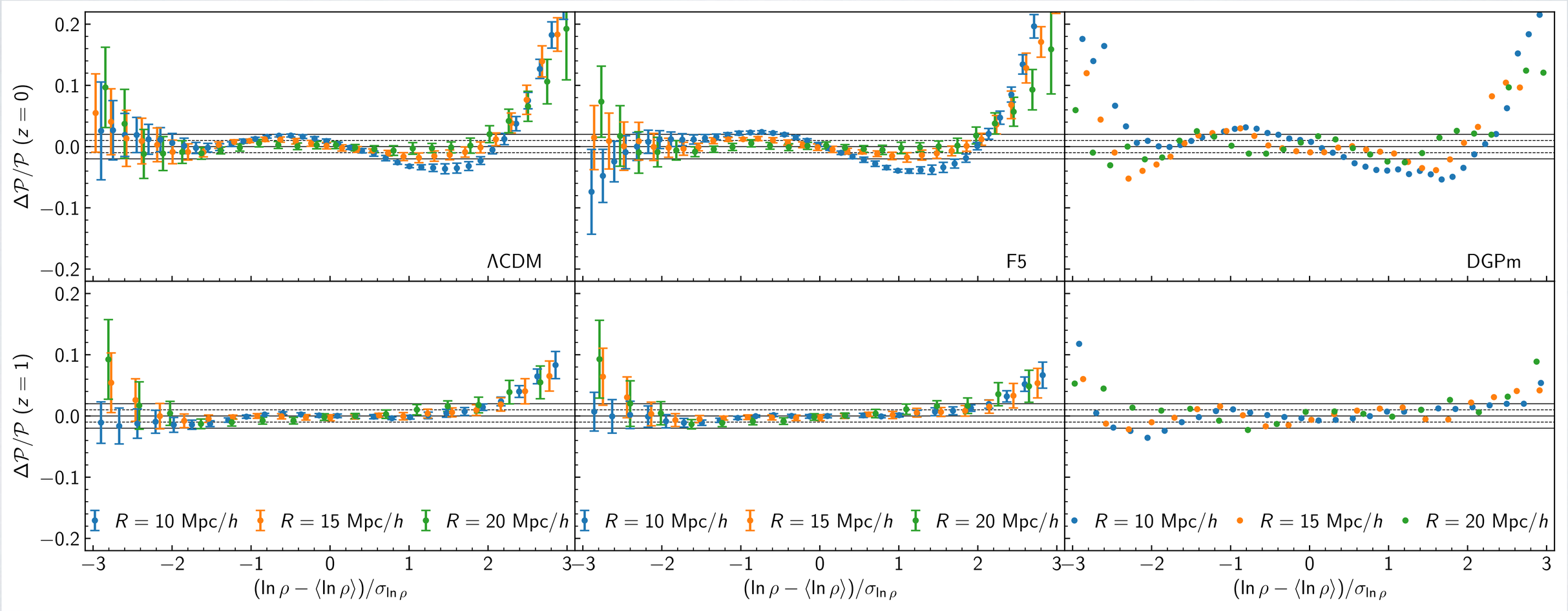
$$\psi_{R,z}(\rho) = \frac{\sigma^2_{\mathrm{L,ext}}(R,z)}{\sigma^2_{\mathrm{L,ext}}(R\rho^{1/3},z)} \frac{\tau^2_{\mathrm{EdS}}(\rho)}{2}$$

From rate function to PDF (contraction + saddle-point approx.)

$$\mathscr{P}_{R.z}(\rho) = \sqrt{\frac{\psi''_{R,z}(\rho) + \psi'_{R,z}(\rho)/\rho}{2\pi\sigma^2_{\ln\rho,\mathrm{ext}}(R,z)}} \exp\left[-\frac{\psi_{R,z}(\rho)}{\sigma^2_{\ln\rho,\mathrm{ext}}(R,z)}\right]$$

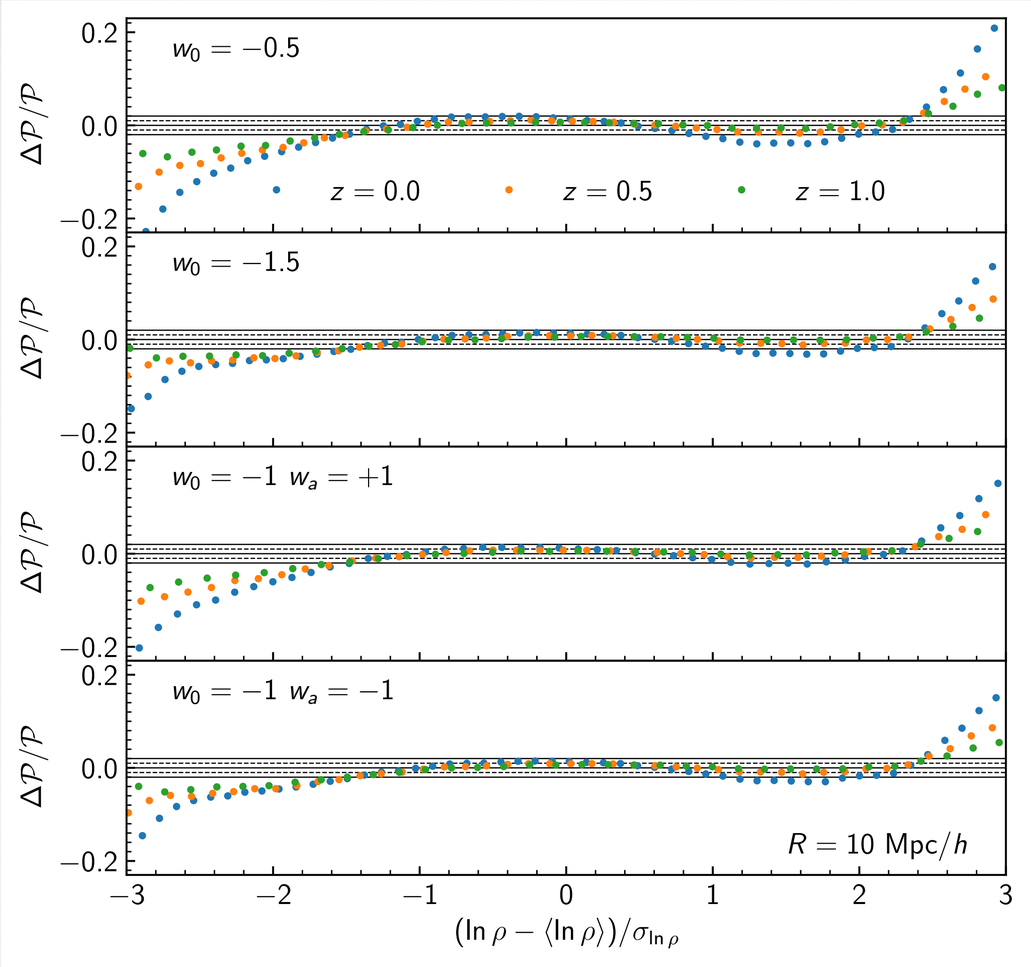
Cataneo et al. in prep.

LDT v simulations: Modified Gravity



Cataneo et al. in prep.

LDT v simulations: Dark Energy



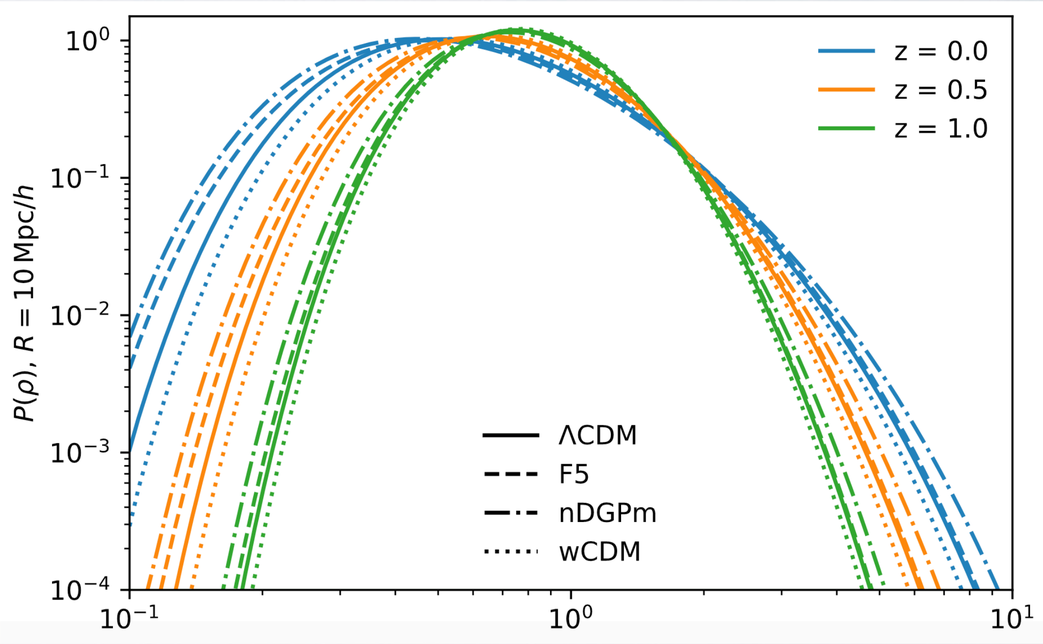
Cataneo et al. in prep.

pyLDT

- Computes 3D matter density PDF
- ΛCDM, w_0w_aCDM, DGP and f(R) gravity
- Can easily implement new models just by adding linear growth equation
- PDFs for 3 redshifts and 3 smoothing radii in ~1 sec (most of it CAMB)
- Includes log-normal approximation

$$\sigma^2_{\ln\rho}(R,z) = \frac{\ln\left[1+\sigma^2_{\rm L}(R,z)\right]}{\ln\left[1+\sigma^2_{\rm L,fid}(R,z)\right]}\sigma^2_{\ln\rho,\rm fid}(R,z)$$

- Soon available on GitHub together with example notebook



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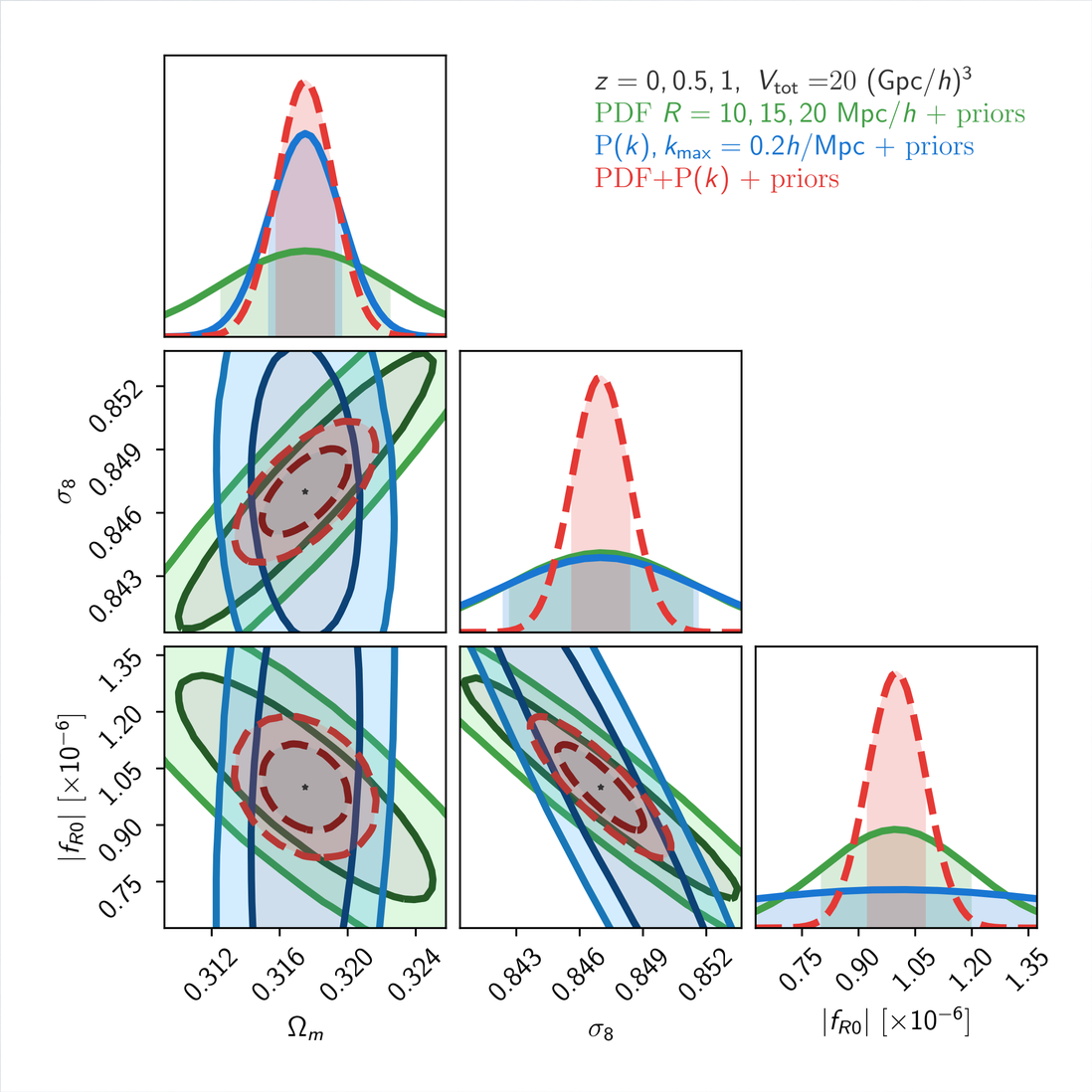
$\mathscr{P}(\rho)$-$P(k)$ complementarity



	F6 detection
PDF $\mathcal{P}_R(\rho)$ 3 scales + prior	5.15σ
$P(k)$, $k_{\rm max} = 0.2h/$Mpc + prior	2.01σ
PDF + $P(k)$ + prior	13.40σ

Watch Alex Gough's Flash Talk for more!

Cataneo et al. in prep.

Summary & Outlook

- LDT works for matter density PDF of MG and DE cosmologies
- No knowledge of spherical evolution dynamics required in the mildly non-linear regime
- Only need linear theory + non-linear variance
- Substantial information gain from $P(k)$ + PDF combination

- Extend to biased tracers in redshift space (Uhlemann et al. 2017)
- Extend to lensing convergence PDF (Barthelemy et al. 2020, Boyle et al. 2020) and combine with Reaction framework (Cataneo et al. 2019)
- Applications to density split statistics (Friedrich et al. 2018, Gruen et al. 2018) and combine with Reaction framework