Testing GR using Large Scale Structure: A Pixelised Approach

Rencontres Du Vietnam 2025

Collaborators: Daniel Thomas, Richard Battye, Peter Taylor, Francesco Pace
*(Based on 2004.13051, 2103.05051, 2306.17240, **2409.06569**)*

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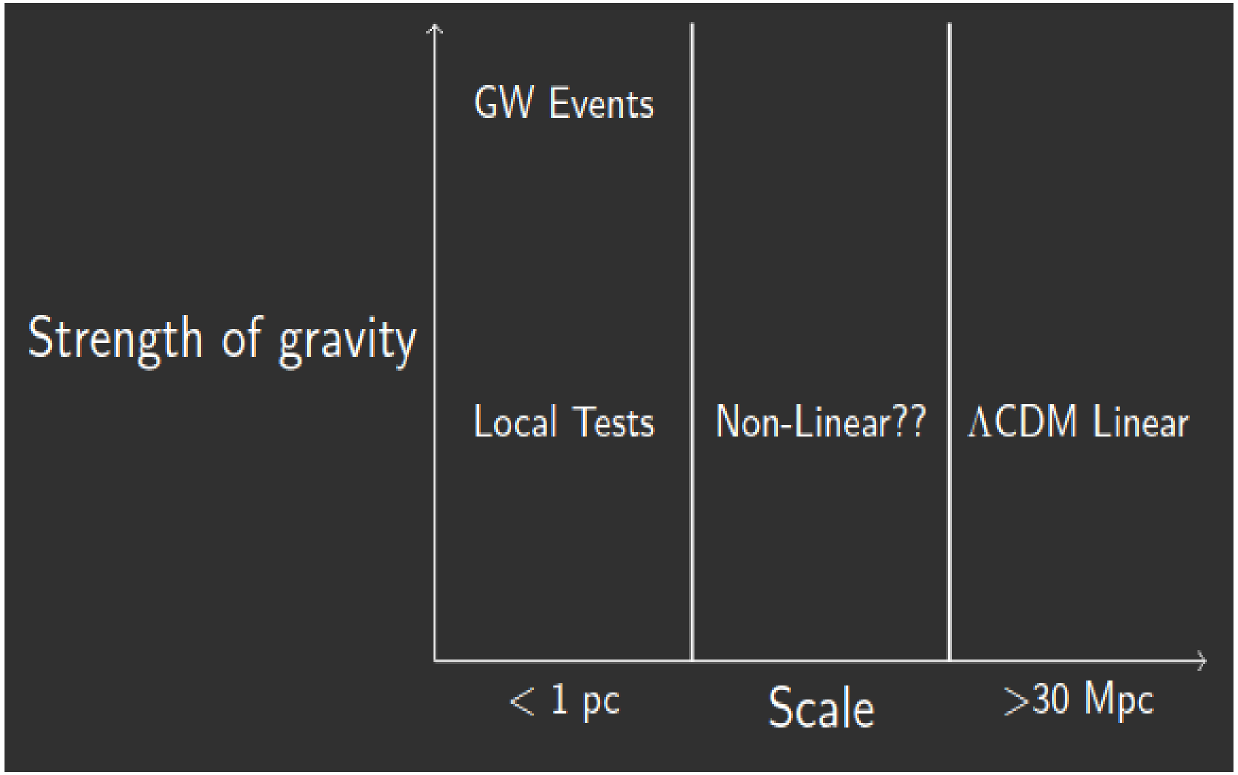
Some Problems with ΛCDM

- **Some major issues that (should) keep cosmologists up at night:**
- The unknown nature of the main ingredients of the model, dark matter and dark energy.

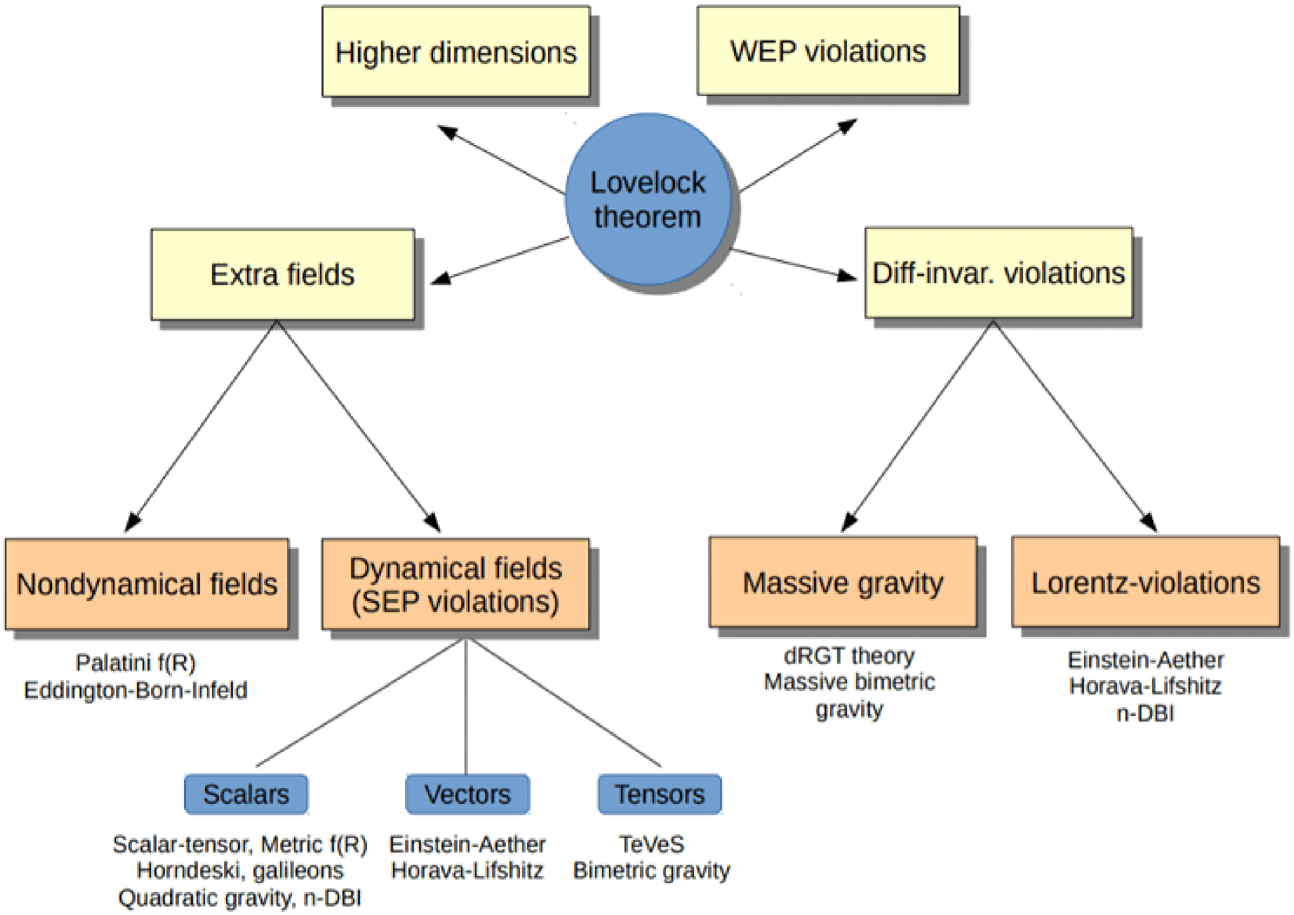
Some Problems with ΛCDM



Some major issues that (should) keep cosmologists up at night:

- The unknown nature of the main ingredients of the model, dark matter and dark energy.
- Validity of general relativity (GR) assumed over a huge range of scales where it hasn't been tested

Vast model space



Post-Friedmann Formalism: Pixelized Poisson Eqn.

- Post-Friedmann $1/c^2$ expansion of FLRW metric
- Quasi-static limit (weak-field, low velocity regime)

$$\begin{aligned} k^2\tilde{\phi} &= 4\pi a^2 G_{\rm N}\mu(a,k)\tilde{\Delta}\,, \\ \tilde{\psi} &= \eta(a,k)\tilde{\phi} \end{aligned}$$

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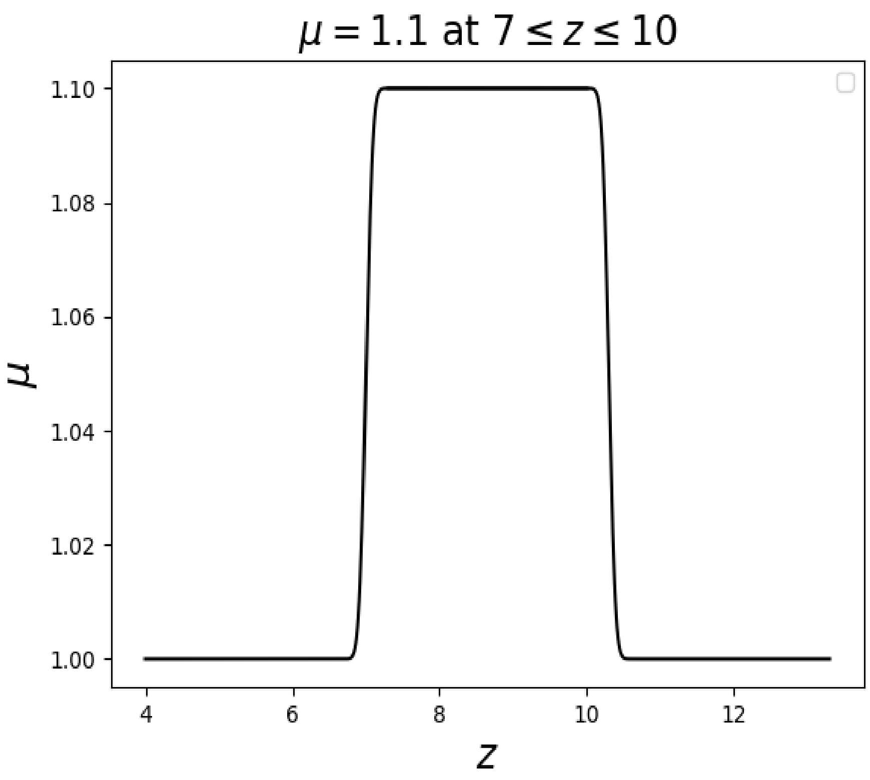

N-body simulations: Measuring $P(k)$ for binned μ

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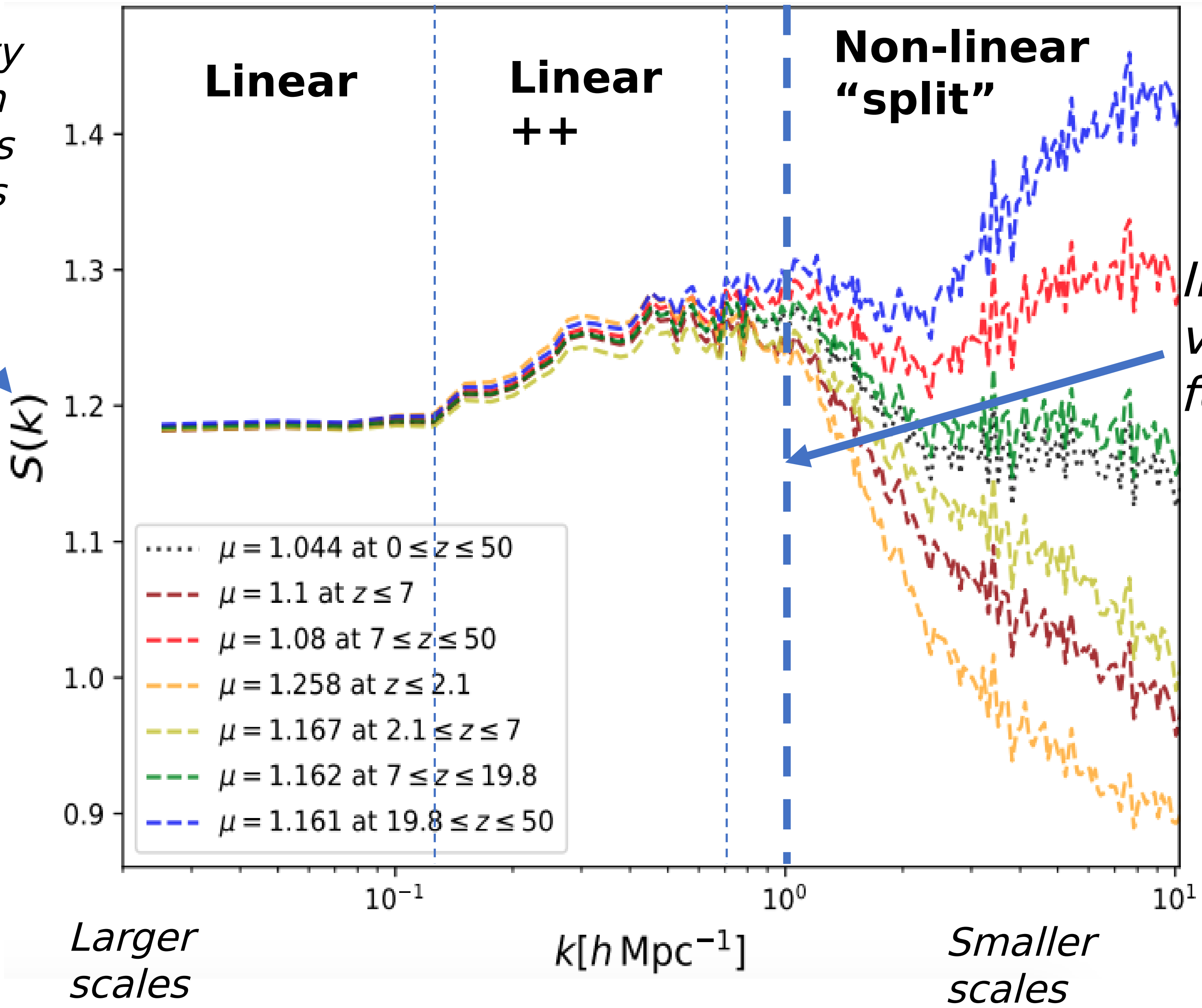
Number of bins	Redshift	μ	
1	0-50	1.044	0.956
2	0-7.0	1.100	0.900
	7.0-50	1.080	0.920
4	0-2.1	1.256	0.746
	2.1-7.0	1.167	0.837
	7.0-19.2	1.162	0.842
	19.2-50.0	1.161	0.843

- Srinivasan et. al. (2021) (2103.05051), where bin-width is varied to keep D(z = 0) constant.

z=0 phenomenology (ratio of matter power spectrum in MG to GR)

Ratio of density fluctuations on different scales today in MG vs GR



Indicative validity of formula

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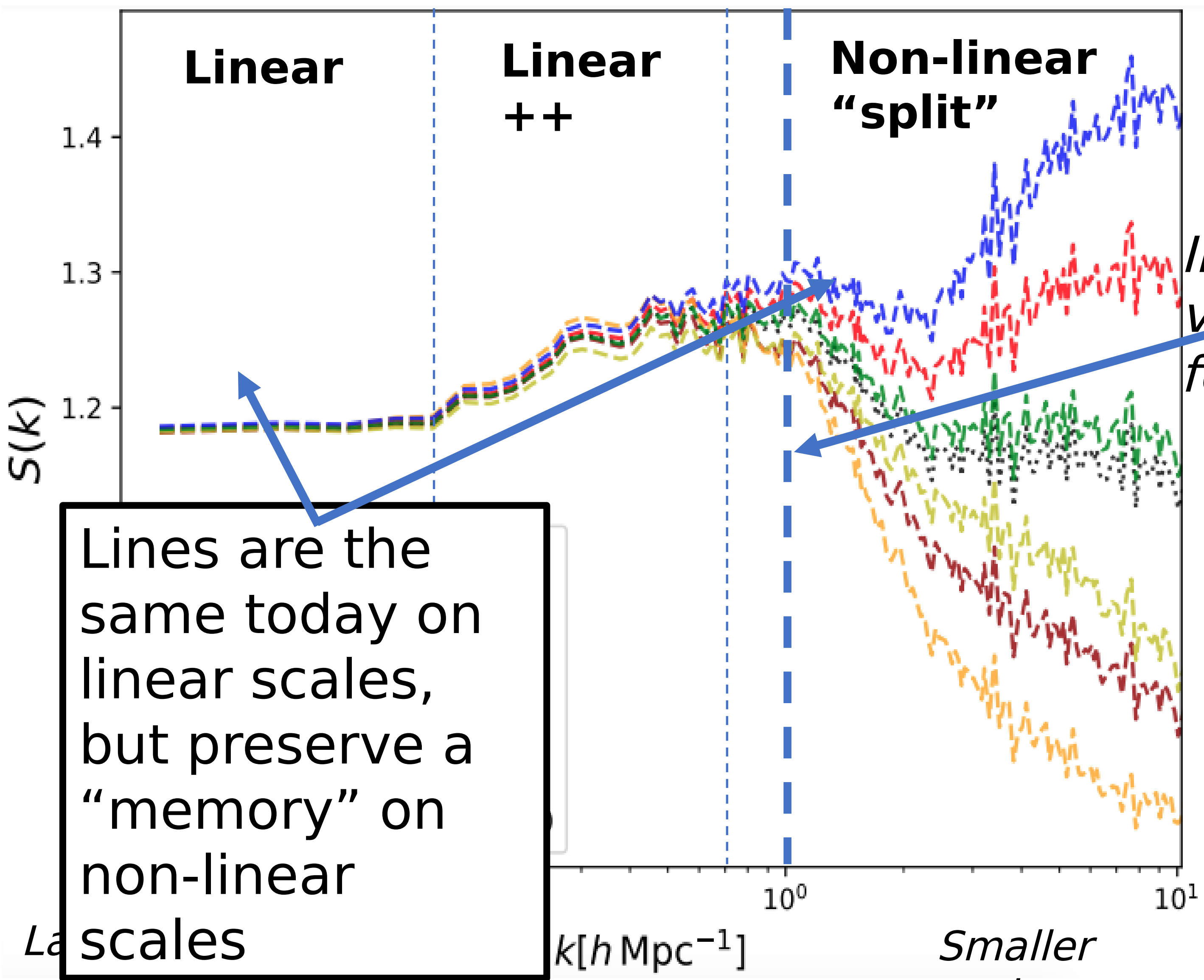


Lines are the same today on linear scales, but preserve a "memory" on non-linear scales

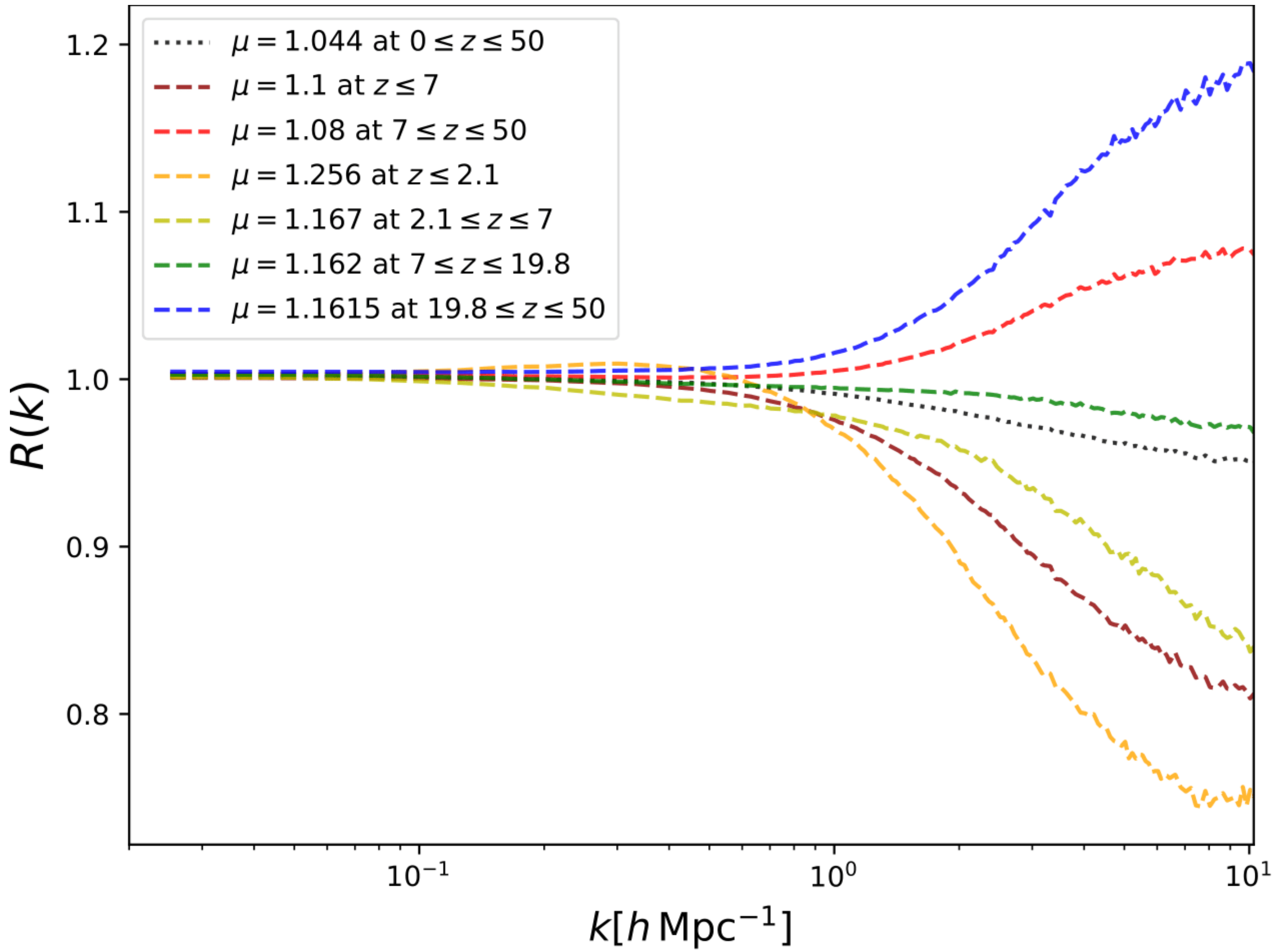
Indicative validity of formula

La
scales

Smaller scales

N-body simulations: Measuring $P(k)$ for binned μ

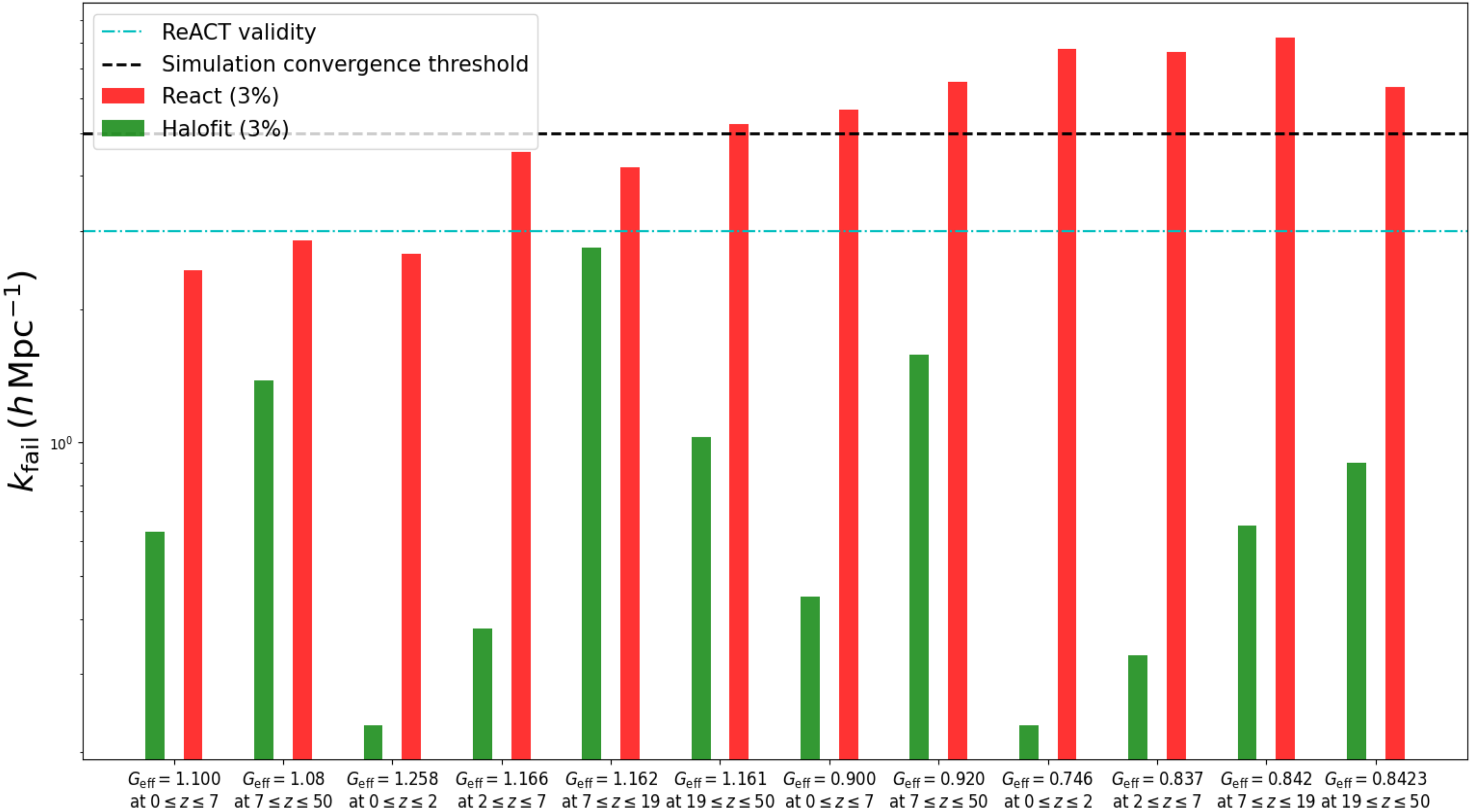
- So-called **Reaction** $[R(k)]$, ratio of P(k) in MG relative to re-scaled ΛCDM



N-body simulations: Validating ReACT for binned μ

- ReACT: Code that implements halo model reaction formalism (see Cataneo et al (2019), Bose et al (2020), Bose et al 2021) to compute $R(k)$

N-body simulations: Validating ReACT for binned μ



N-body simulations: Computing 3x2pt observables

- From the standard Limber approximation, the 2-D projection can be computed from the matter power spectrum and the modified gravity parameters

$$C_{ij}(\ell) = \int_{z_{\min}}^{z_{\max}} dz \frac{W_i(z)W_j(z)}{H(z)\chi^2(z)} P(k_\ell, z)$$

Where the **clustering kernel** is:

$$W_i^{\mathrm{G}}(z) \quad = \quad b_i(k,z)\frac{n_i(z)}{\bar{n}}H(z) = W_{i,\Lambda\mathrm{CDM}}^{\mathrm{G}}(z)$$

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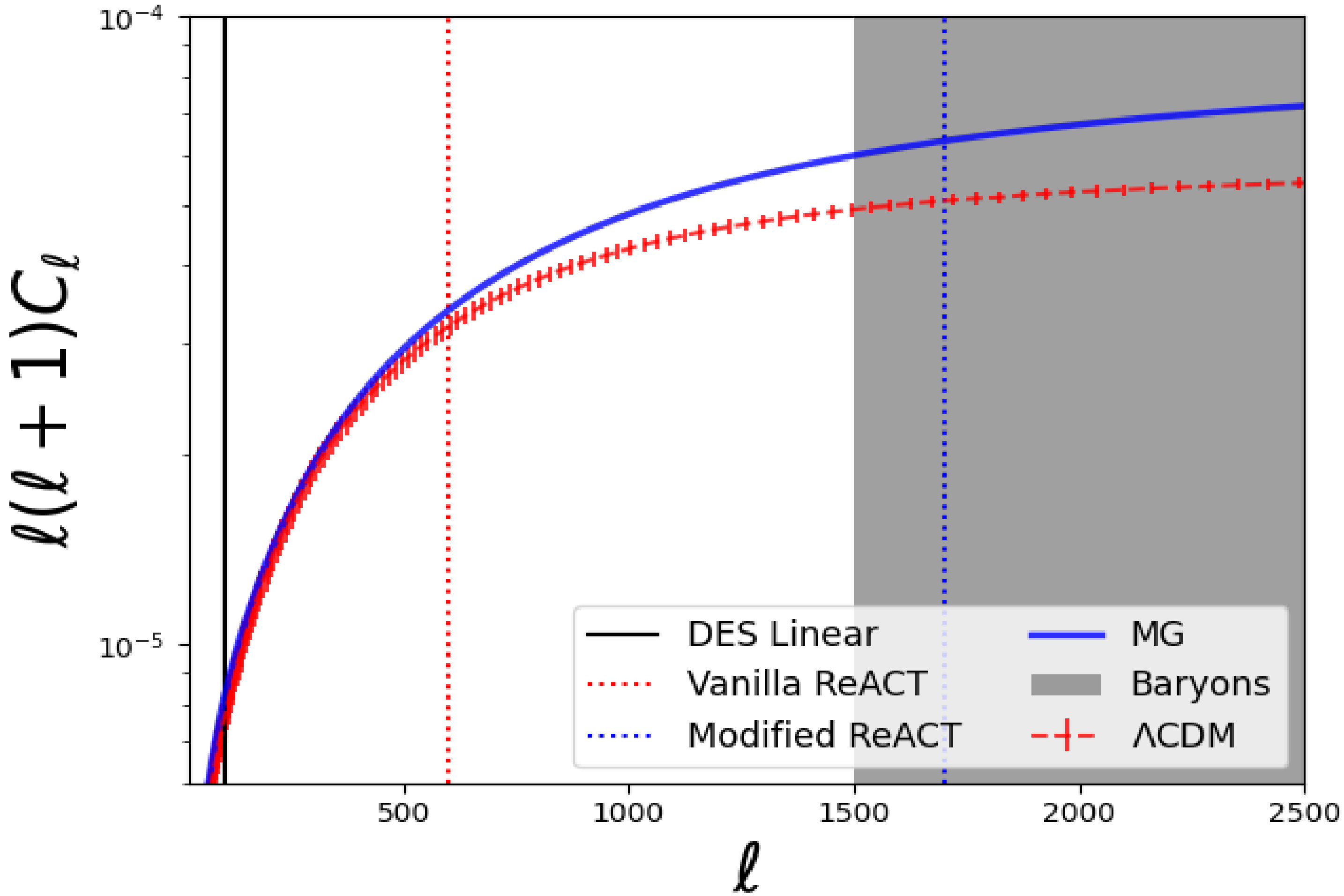
Where the **lensing kernel** is:

$$W_i^{\mathrm{L}}(z) \quad = \quad W_{i,\Lambda\mathrm{CDM}}^{\mathrm{L}} \frac{\mu(z)[1+\eta(z)]}{2} + W_i^{\mathrm{IA}}(k, z)\,,$$

N-body simulations: Validating ReACT for binned μ

- **Srinivasan et al (2024): Validate ReACT for a relevant part of (μ, D) parameter space**



Fisher Forecasts

- Pipeline : Compute non-linear $P(k)$ with ReACT v1 and ReACT v2 [modified *c(M*, $\boldsymbol{\mu}, \boldsymbol{D}$)]
- Limber : $P(k) \Longrightarrow C(\ell)$
- Obvious fiducial point : ΛCDM
- LSST Y-10 like survey, 10 lens bins and 5 source bins
- Nuisance parameters: bin-wise bias b_i , linear alignment amplitude $A_{\rm IA}$, baryonic feedback parameter $T_{\rm AGN}$, photo-z errors, shear calibration parameters (29 in total)
- **4 redshift bins for μ and η.**

Fisher Forecasts

Key questions are:

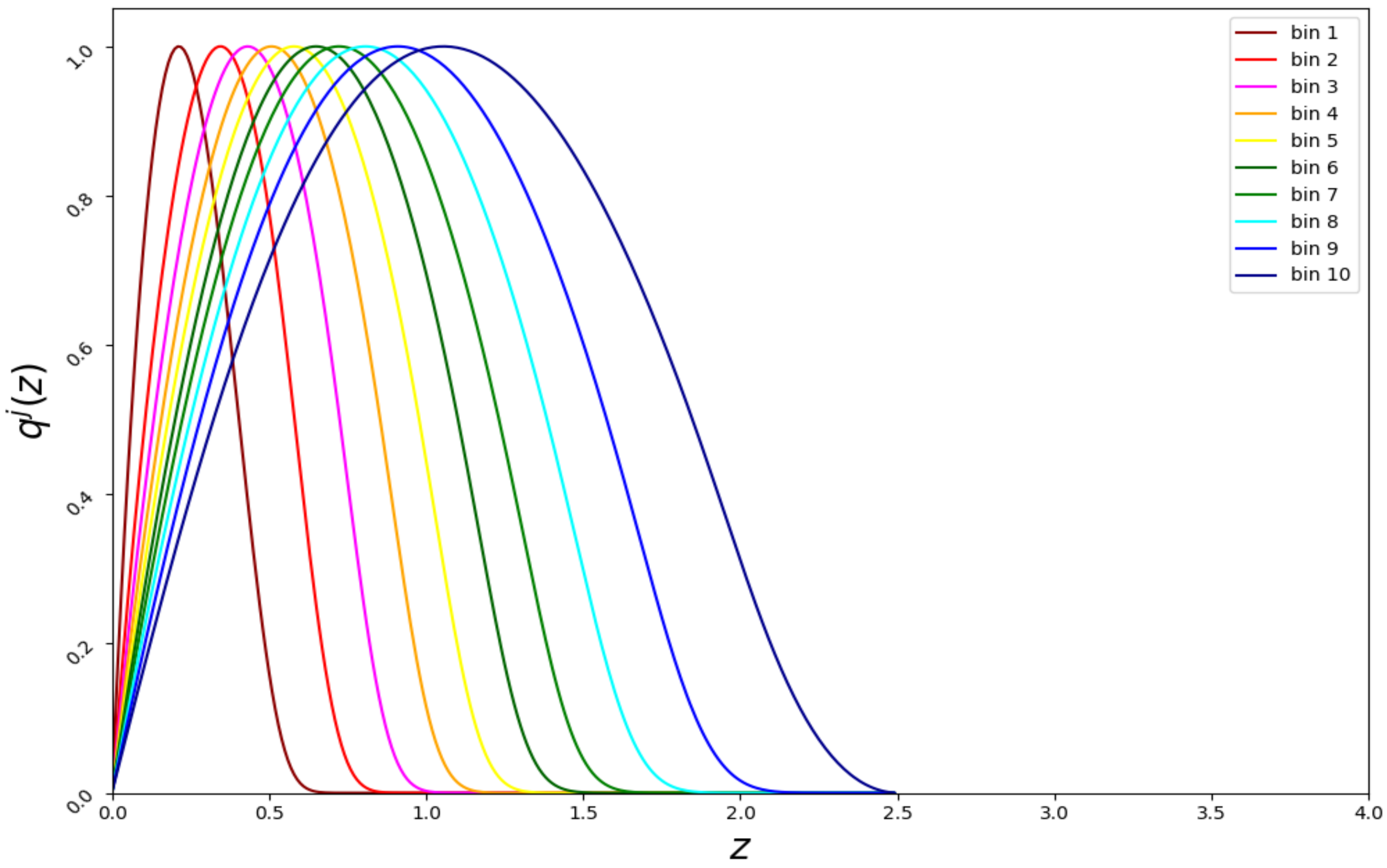
- How much can we push into non-linear scales without having to worry about baryonic feedback/other small scale uncertainties?

Fisher Forecasts

Key questions are:

- How much can we push into non-linear scales without having to worry about baryonic feedback/other small scale uncertainties?
- What’s the most efficient binning scheme to maximise constraining power? How does this change as a function of MG params and scale-cut?

The Bernardeau-Nimishi-Taruya (BNT) Transform



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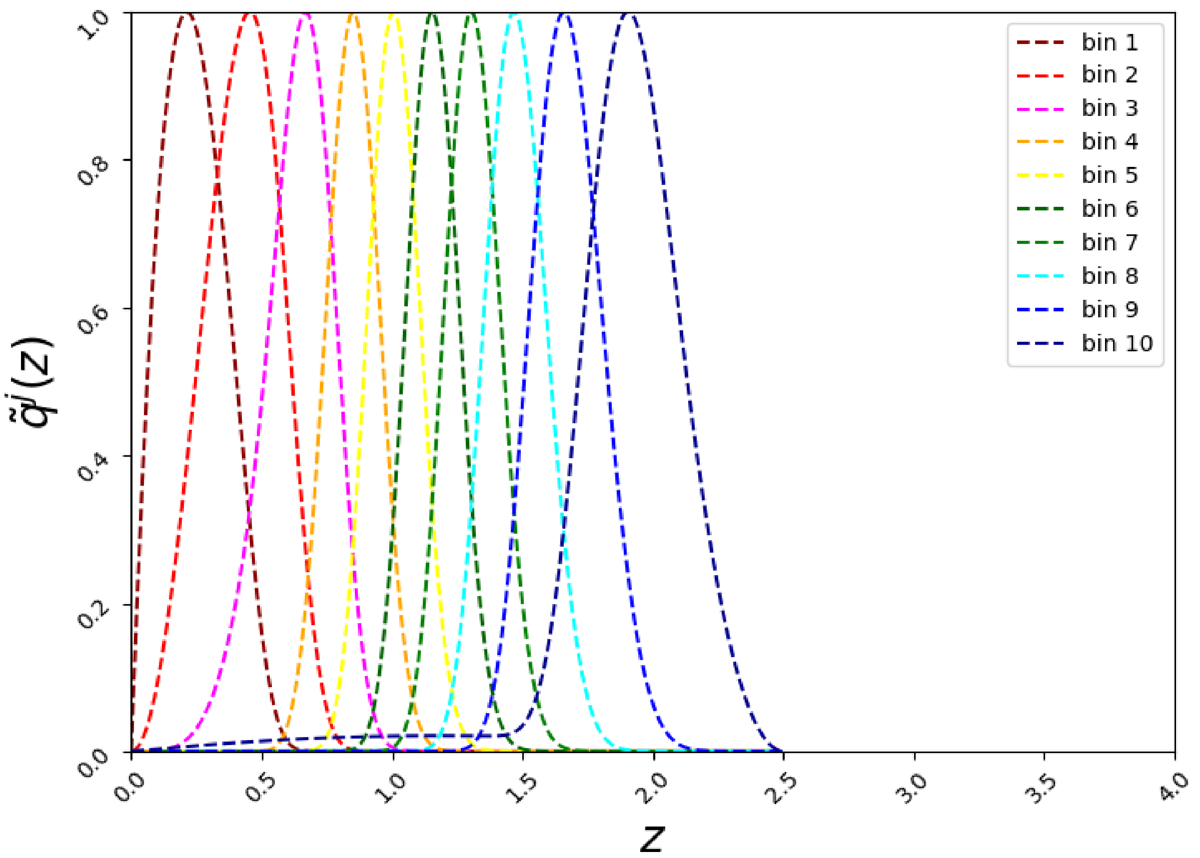
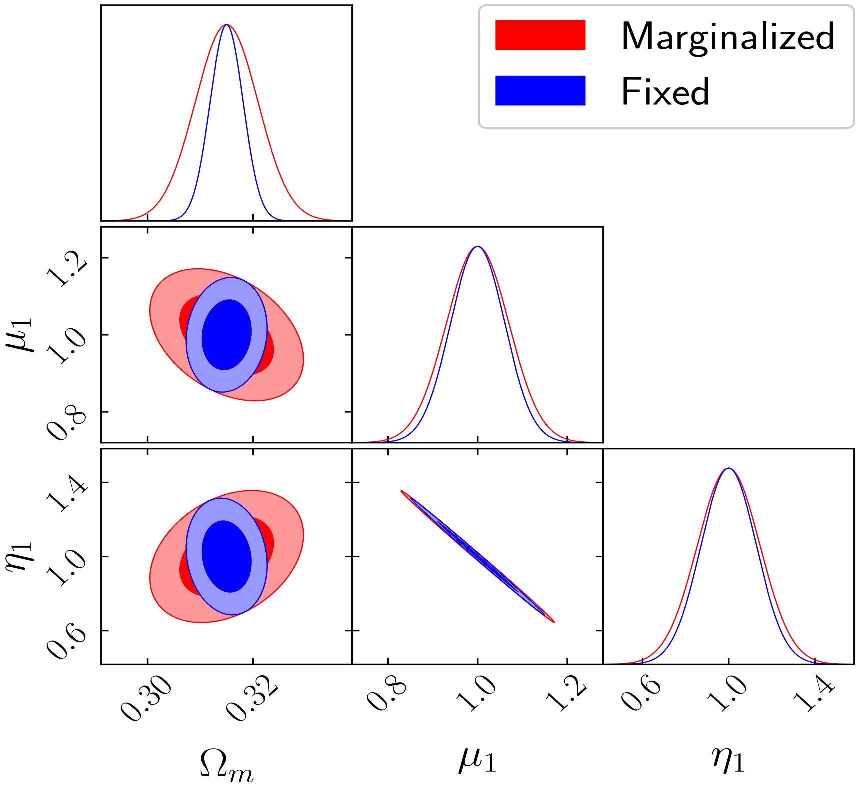
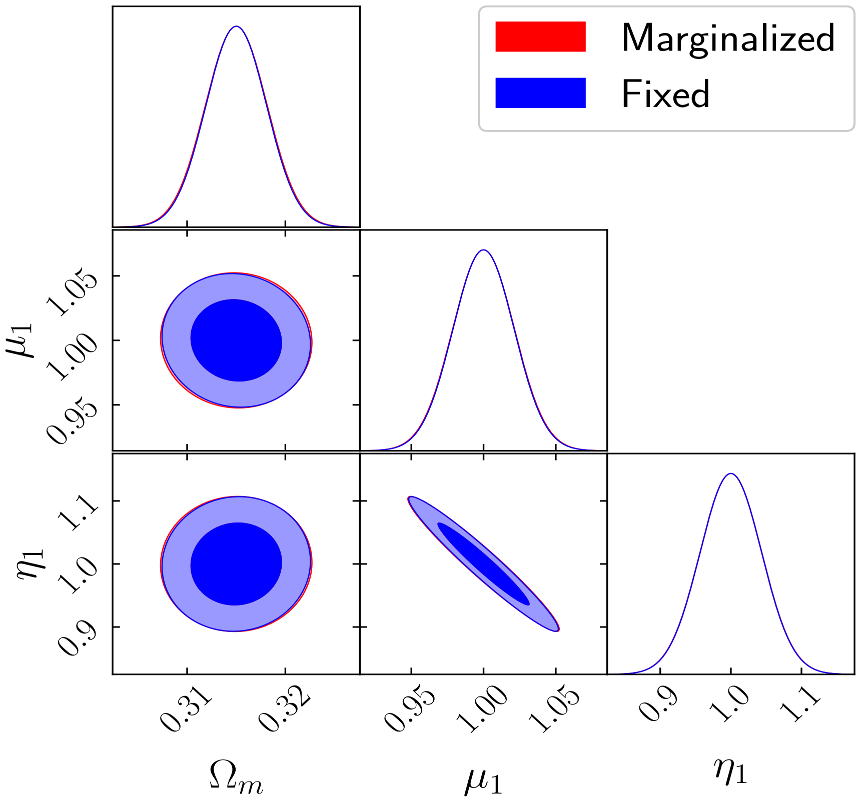


Mitigating Baryonic Feedback



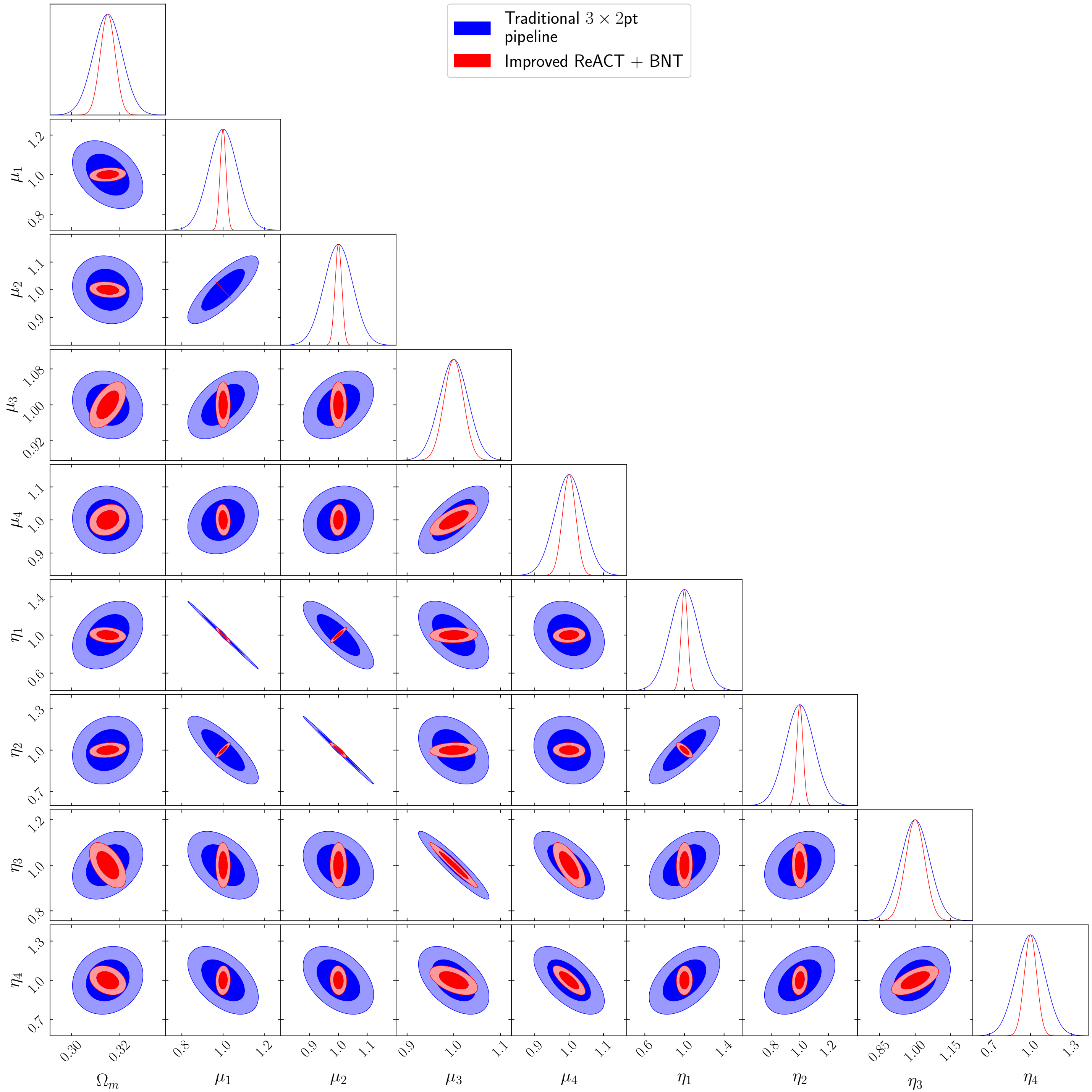
$k_{\rm cut} = 0.5\,h$ Mpc^{-1} (GC, GGL)
Corresponding $\ell_{\rm cut}$ (Shear)

$\Longrightarrow$
BNT



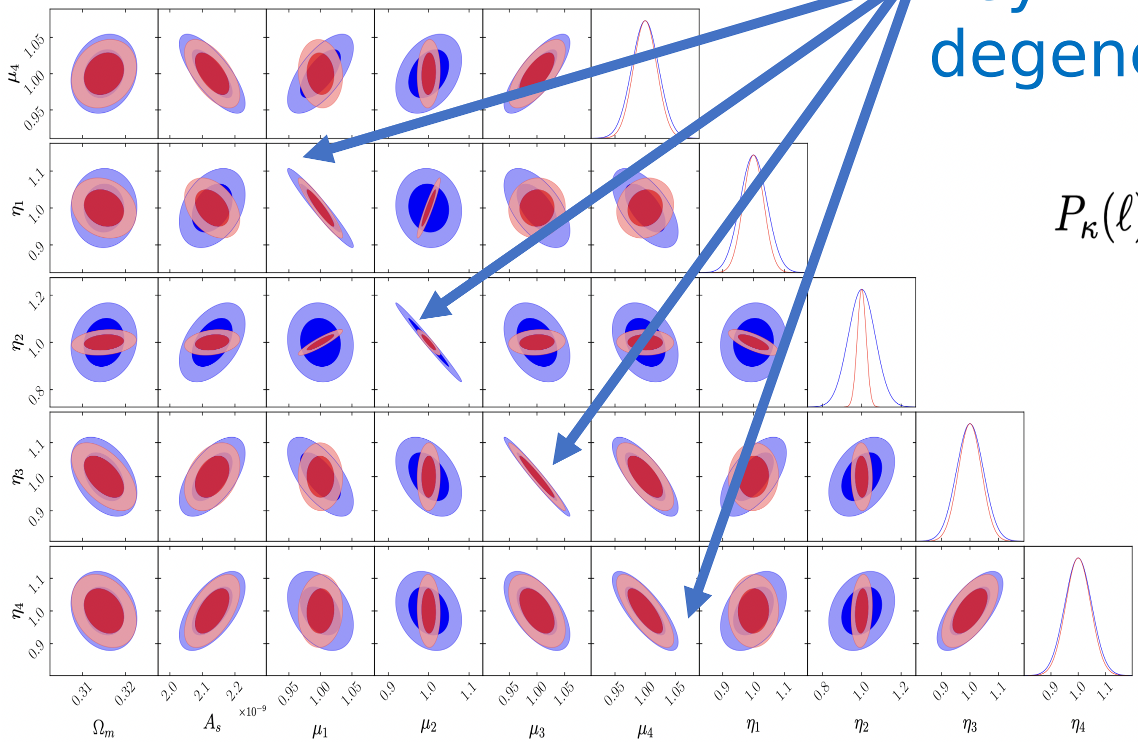
$k_{\rm cut} = 0.5\,h$ Mpc^{-1}

Improvement from NL modelling



Degeneracies

- Key degeneracy is μ-η in same redshift bin:
  - Exact degeneracy in linear theory in lensing. In principle non-linear info breaks this.
  - When lensing dominates the 3x2pt data vector (low *z*), this degeneracy is more prominent.
  - Non-linear effects reduce this degeneracy, but not as much as hoped (even with concentration).
- Degeneracies with LCDM parameters are smaller than in linear theory.



Key degeneracy

$$P_\kappa(\ell) = \frac{9H_0^4\Omega_\mathrm{m}^2}{4c^4}\int_0^{\chi_\mathrm{max}} \mathrm{d}\chi \frac{1}{a^2(\chi)} g^2(z) \frac{\mu^2(1+\eta)^2}{4} P_\delta(\ell/\chi)$$

On non-linear scales, μ also has an effect on this part.

What next?

- ReACT is slow! Needs emulation. Validation required for multiple bins, scale dependence
- Is COLA a reasonable validation tool in the range of scales we care about for binned $\mu{-}\eta$?
- Other observables from sims, voids/clusters (splashback, counts)?

Summary

- Large scale structure allows precision tests of gravity on non-linear cosmological scales.
- Model-agnostic approach: bin MG parameters in scale and time!
- BNT allows control over range of scales entering analysis → better constraining power due to better control of uncertainties in the modelling of small scales.
- We achieve factor $\sim$ 20 improvement in the MG parameter constraints relative to the linear only case (see **2409.06569** for more details).