Probing Modified Gravity Using Data From Large Scale Structure Surveys

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Plan

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.**

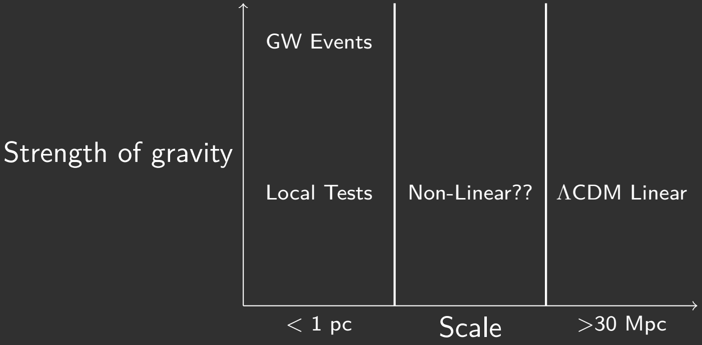
Problems with ΛCDM

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.**

Why modify gravity?

- The validity of GR as theory of gravity crucial ingredient in all evidence for existence of dark sector.
- Modify equations to naturally explain the effects of dark sector.



Vast model space

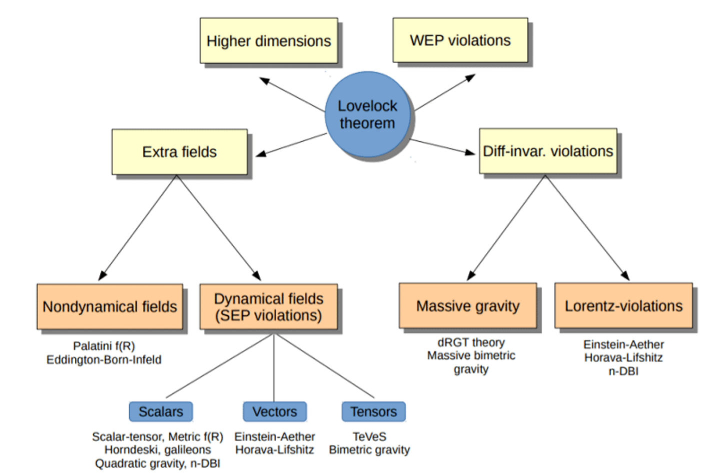


Figure courtesy Andrius Tamosiunas.

Parameterising Modified Gravity: Non-Linear Scales?

- Describe a large class of models using as few parameters as possible.
- Existing parameterisations [see Battye et al (2013), Gleyzes et al (2015)] [1] are designed and validated only on linear scales, i.e., on scales where $\delta \ll 1$.
- Future experiments will generate huge amount of data on **non-linear scales**.

[1] This list is by no means complete, this work has been going on for more than 2 decades now

Solution: Newtonian Approximation

- 'Newtonian Limit': limiting case where corrections to weak-field, low-velocity regime are negligible.
- Thomas (2020) (2004.13051) showed that it is possible to describe a large class of models using the Post-Friedmann formalism to obtain

$$\frac{1}{c^2}k^2\tilde{\phi}_{\mathrm{P}} = -\frac{1}{c^2}4\pi a^2\bar{\rho}G_{\mathrm{N}}\mu(a,k)\tilde{\Delta}\,, \tag{1}$$

$$\tilde{\psi}_{\mathrm{P}} = \eta(a,k)\tilde{\phi}_{\mathrm{P}}\,, \tag{2}$$

Note that Δ, the gauge-invariant density contrast need not be small, so these equations are valid on **all cosmological scales** relevant for N-body simulations.

Binning μ in redshift

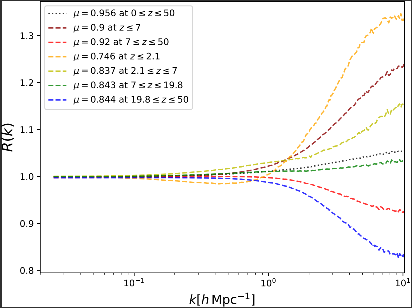
- $\mu(z)$ modelled as a step function, where in each simulation only one bin is 'switched on'.

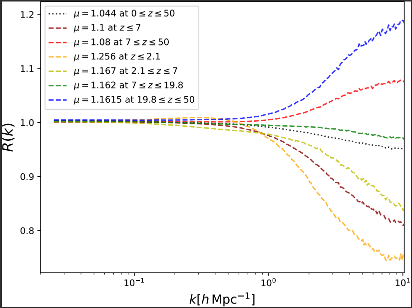
Number of bins	Redshift	μ	
1	0-50	1.044	0.956
2	0-7.0	1.100	0.900
	7.0-50	1.080	0.920
4	0-2.1	1.256	0.746
	2.1-7.0	1.167	0.837
	7.0-19.2	1.162	0.842
	19.2-50.0	1.161	0.843

Figure: Binning of μ adopted in Srinivasan et. al. (2021) (2103.05051), where bin width is varied to keep $D(z=0)$.

Impact of μ on $P(k)$

"Split" behaviour on small (non-linear) scales, where the power depends on the range of redshifts over which the modified gravity effects were switched on

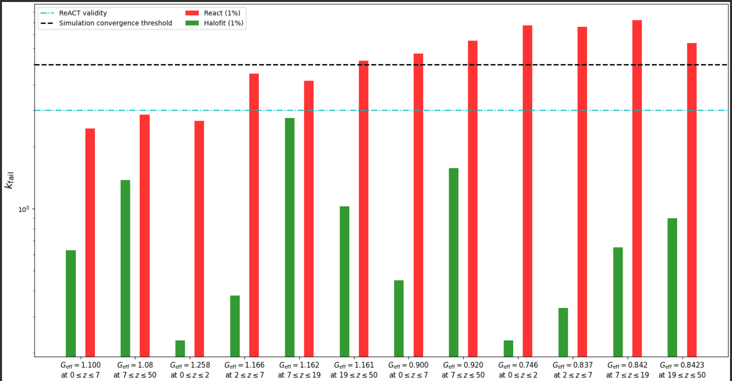




Where $R(k)$ is the ratio relative to re-scaled ΛCDM power spectrum to match linear growth at $z = 0$.

Comparison of fitting functions

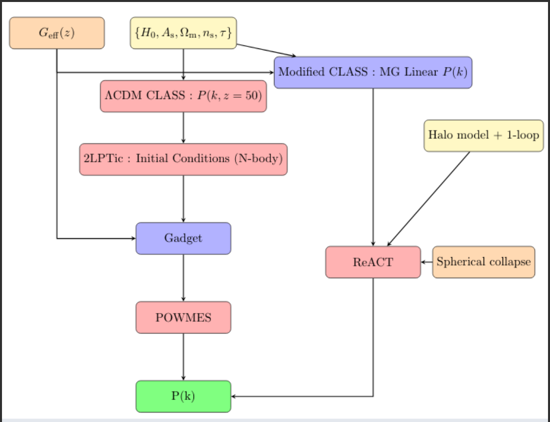
ReACT [Cataneo et al (2018), Bose et al 2020]: Halo model + Spherical collapse



$k_{\rm fail} \equiv k$ at which $R(k)$ predicted by fitting function deviates from $R(k)$ calculated from simulations

Euclid Pipeline Results

Euclid $\mu - \sigma$ parameterisation forecast paper with current pipeline



Computing the weak-lensing convergence power spectrum

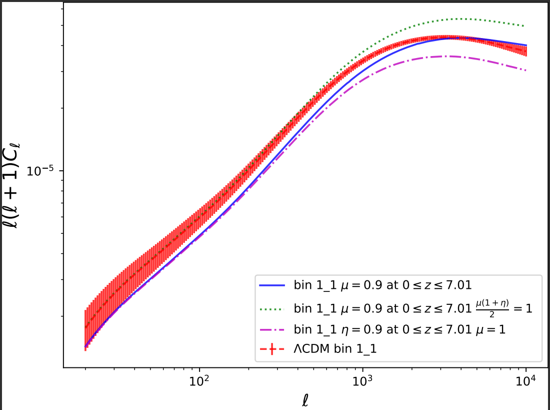
The weak-lensing convergence power spectrum can be computed from the matter power spectrum and the modified gravity parameters

$$P_\kappa(\ell) \propto \int_0^{\chi_{\max}} W(\chi) \frac{\mu^2(1+\eta)^2}{4} P_\delta(\ell/\chi)\,, \tag{3}$$

where P_δ is the matter power spectrum, η is the second modified gravity parameter that affects the photon geodesics and χ is the comoving distance to the source along the line of sight.

How important are non-linear scales?

- Future missions will rely on their modelling of non-linear scales to maximise their constraining power.
- Degeneracies between modified gravity models can be broken by explicitly including non-linear scales in the analysis.



Impact of μ on $P(k)$

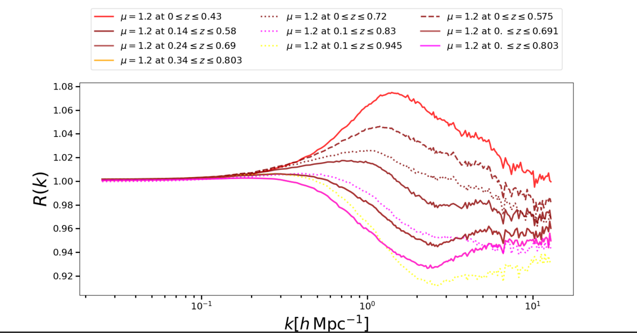
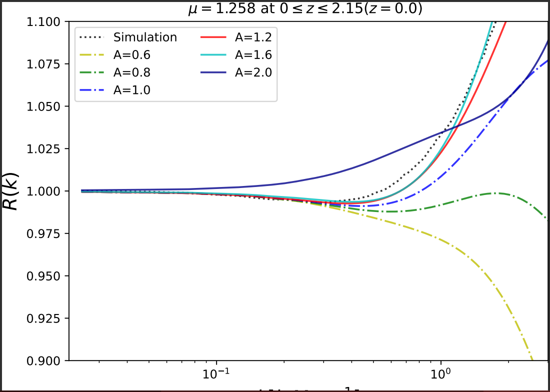


Figure: The power spectrum from the simulations with the μ modified in the redshift range containing the transition from matter-domination to dark energy domination.

A better fit?

- Modifying gravity will modify halo density profiles.
- The concentration c scales with halo mass as a weak negative power law $(\alpha \ -0.13)$.
- Modifying $c(M)$ relation in ReACT leads to a better fit to $P(k)$ in simulation(s)



Results from ongoing work

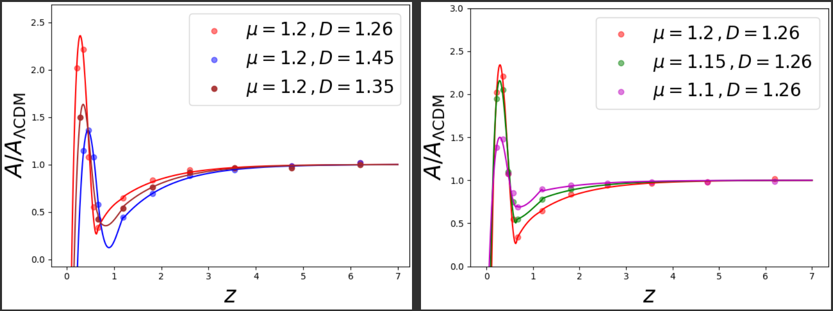


Figure: The variation in fitting parameters is consistent across the (μ, D) parameter space probed in our simulations (Paper to be submitted this month!).

Results from ongoing work

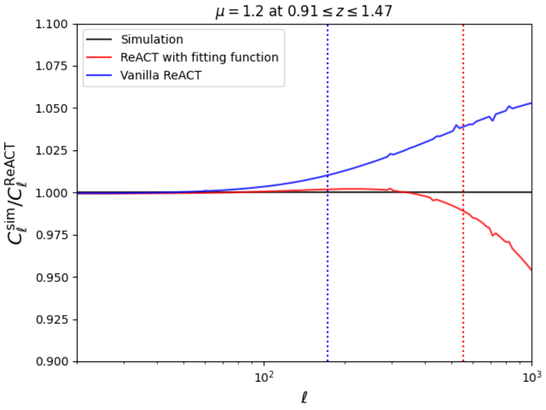
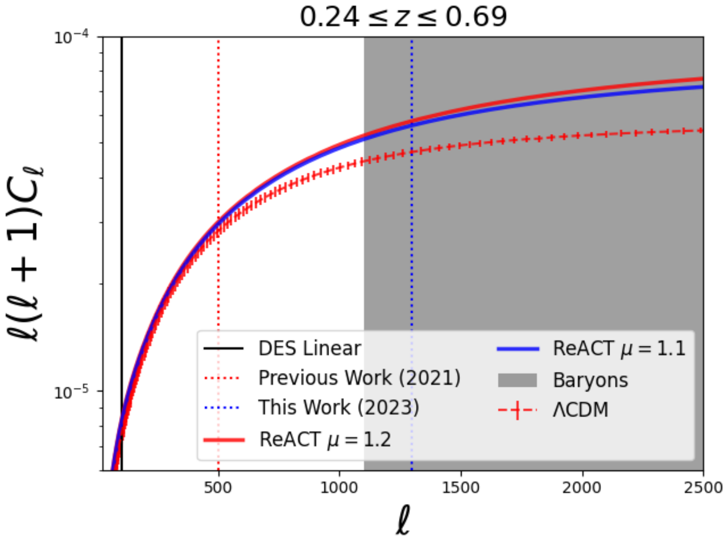


Figure: The weak-lensing convergence power spectrum compared to simulations from the the standard implementation of ReACT and with our fitting function implemented. Vertical lines correspond to 1% disagreement.

Results from ongoing Work



Future Directions

- Release of `ReACT` with binned fitting function as a publicly available tool -> Rubin Forecast with Dan Thomas, Agnes Ferte
- $k-$cut cosmic shear (Peter Taylor)
- Speeding up simulations with COLA (allows building of emulators, faster exploration of wider parameter space)
- Measure the density profiles in halos (possible splashback signature?)

Summary

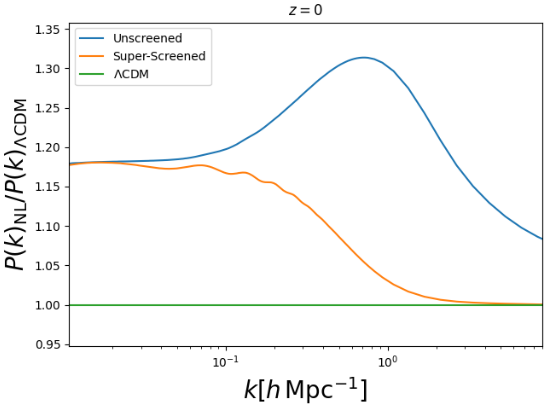
Most important results:

- Important to parameterise models on non-linear scales to take advantage of bulk of data produced by future galaxy surveys.
- We also showed that computing observables from our model-independent simulations allows exploration of full parameter space and degeneracy breaking.
- Goal: Validate `ReACT`, implement c(M) modification and perform non-linear model-independent forecasts.

Euclid Pipeline Results

Pipeline applied to so-called late time parametrisation, given by

$$\mu(z) = 1 + E_{11}\Omega_\Lambda(z) \quad (4)$$



Two extreme regimes identified: Super-screened and and Un-screened.

BWAB (But What About Baryons?)

Bose et al (2021) releases an update to the ReACT code that incorporated Baryonic feedback (fit from Mead et al (2021))