Probing Gravity using Large Scale Structure: A Model-Agnostic Approach

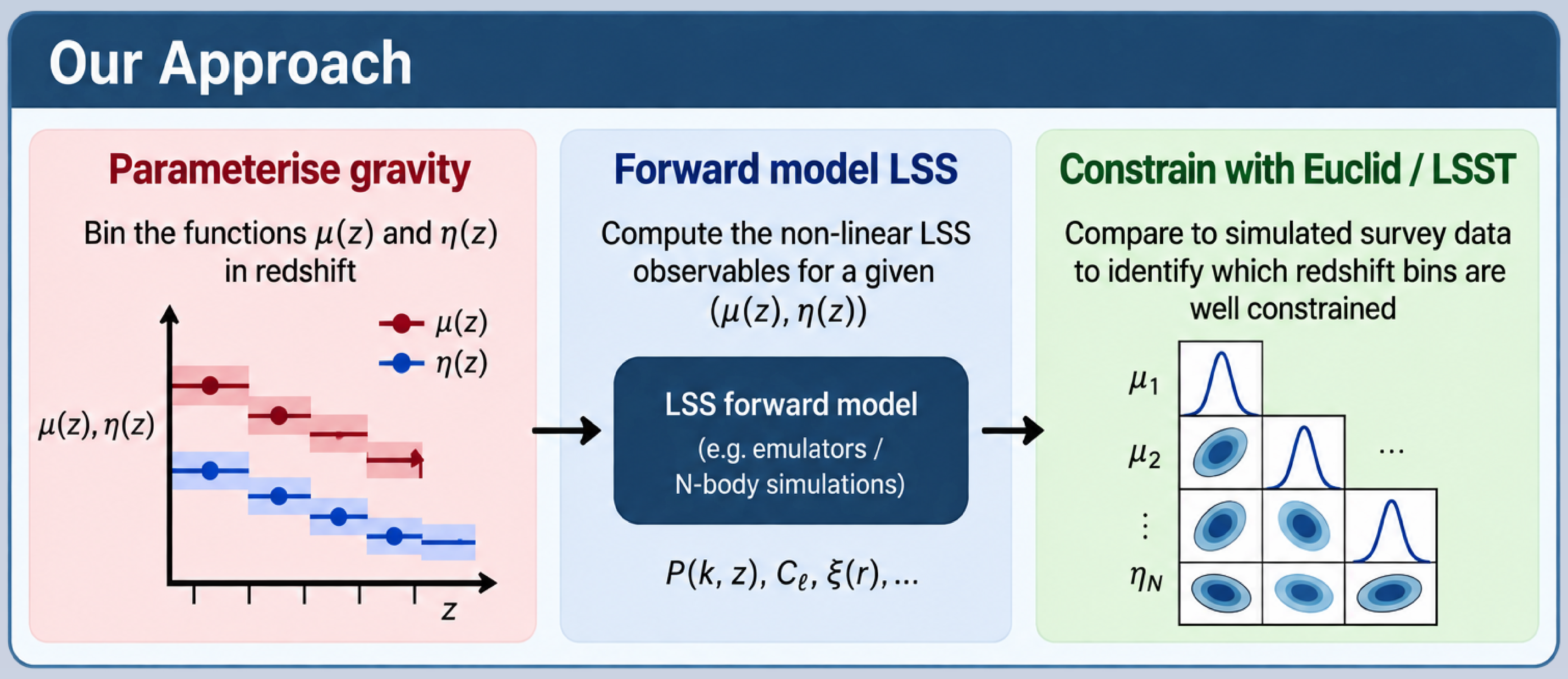
Sankarshana Srinivasan
P4F Fellow, CEICO, FZU Institute of Physics, Prague, Czechia
srinivasan@fzu.cz
Collaborators: Daniel Thomas, Kai Lehman, Shreya Prabhu, Richard Battye, Jochen Weller, Peter Taylor, Ajiv Krishnan, Francesco Pace

Introduction

Large-scale structure (LSS) surveys probe gravity on cosmological scales, but constraints so far are largely limited to the linear regime. Upcoming surveys (LSST, Euclid) are sensitive to non-linear growth expensive to model for most modified gravity (MG) models. We introduce a model-agnostic parameterisation, adding two free functions μ(a,k) and η(a,k) that capture deviations from GR without assuming a specific theory:

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

This approach is advantageous for several reasons. Most importantly, one is interested in capturing deviations from General Relativity (GR) without knowledge of the underlying theory. If one can compute non-linear structure, one can constrain models that predict deviations from GR in the LSS.



Methodology

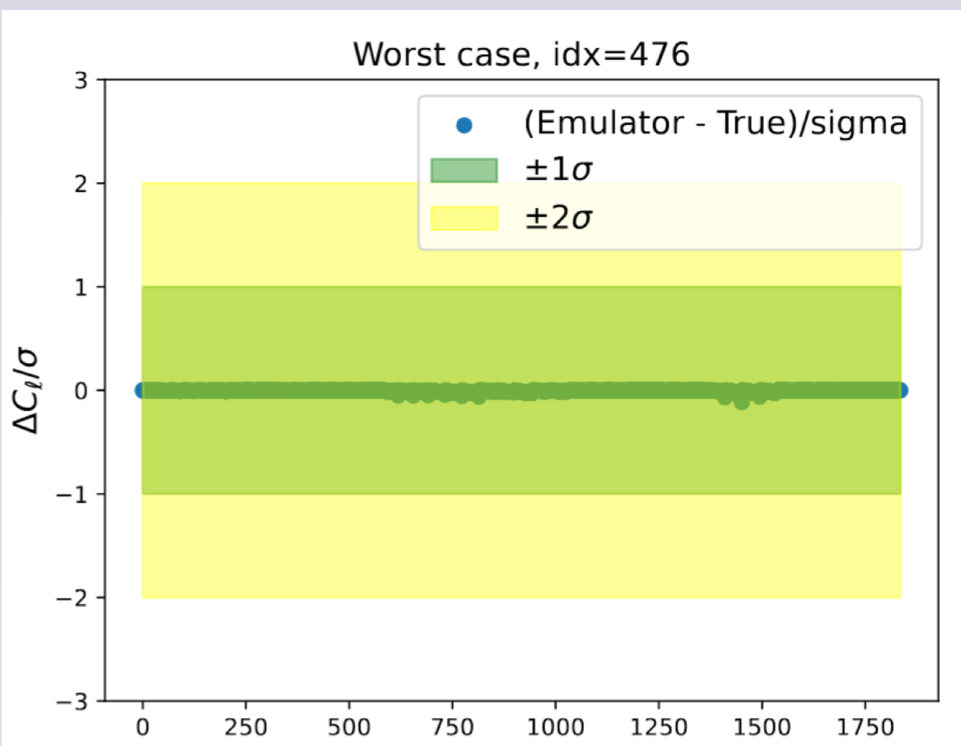
The challenge: Non-linear LSS forward modelling requires expensive N-body simulations.

Our solution: We use COLA to generate fast approximate N-body simulations, reproducing full N-body results to $k{=}1\,h$ Mpc^{-1}. Instead of emulating (P(k)) directly, we emulate the MG boost:

$$B(k) = \frac{P_{\rm MG}(zk)}{P_{\Lambda{\rm CDM}}(z,k)}$$

Boost → PCA Compression → Gaussian Process/ Neural Network

$$C_{ij}^{XY}(\ell) = c\int_{z_{\rm min}}^{z_{\rm max}} {\rm d}z\frac{W_i^X(z)W_j^Y(z)}{H(z)r^2(z)}P(k_\ell,z)$$



New improved emulator priors
(wider parameter space)

Parameter	Fiducial	Lower bound	Upper bound
$\Omega_{\rm m}$	0.3156	0.24	0.40
$\Omega_{\rm b}$	0.0492	0.04	0.055
h	0.6727	0.65	0.75
$n_{\rm s}$	0.9645	0.80	1.20
$\ln 10^{10}A_{\rm s}$	3.0587	2.944439	3.218876
μ	1.0	0.9	1.1
η	1.0	0.9	1.1

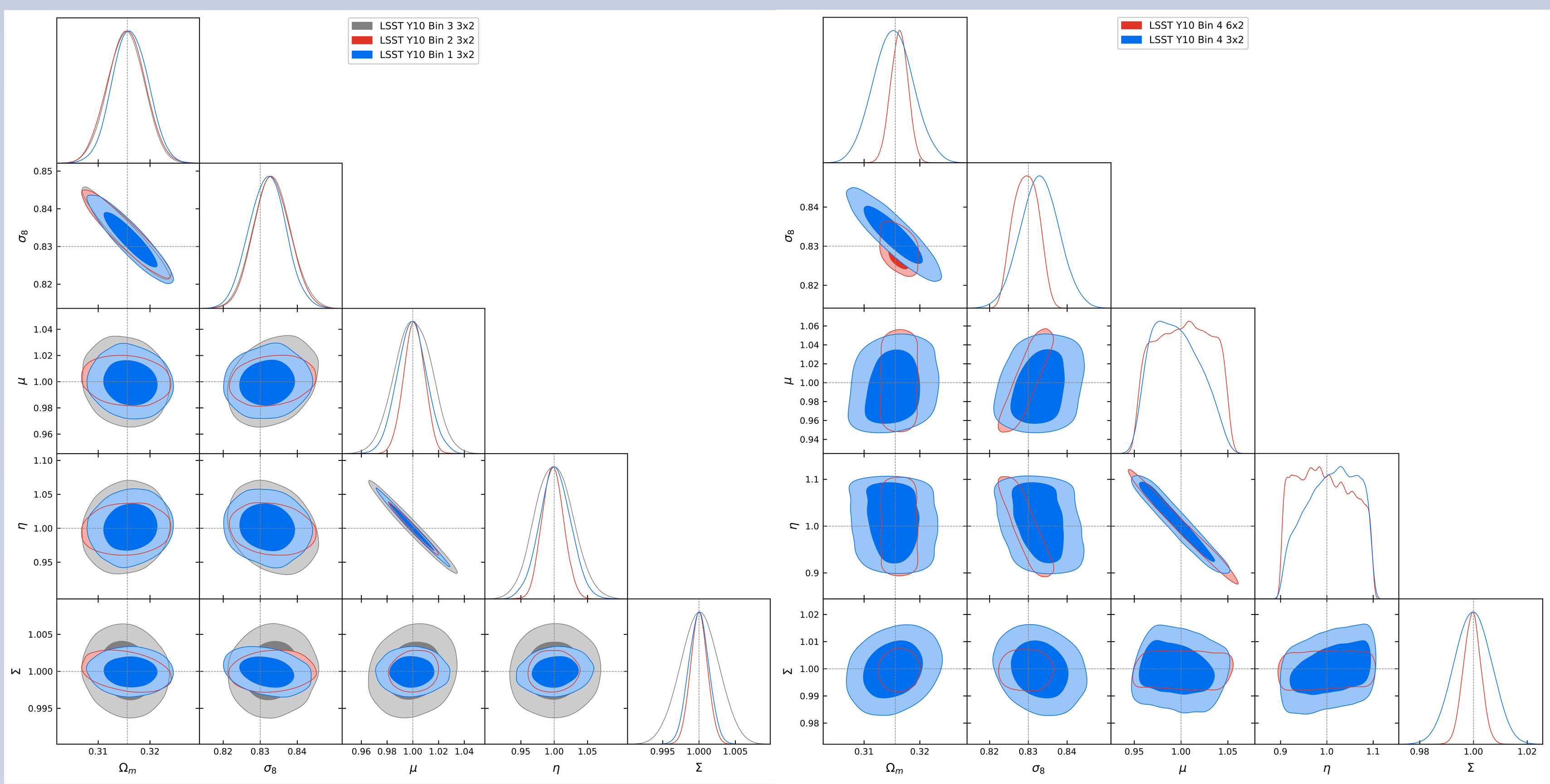
Results

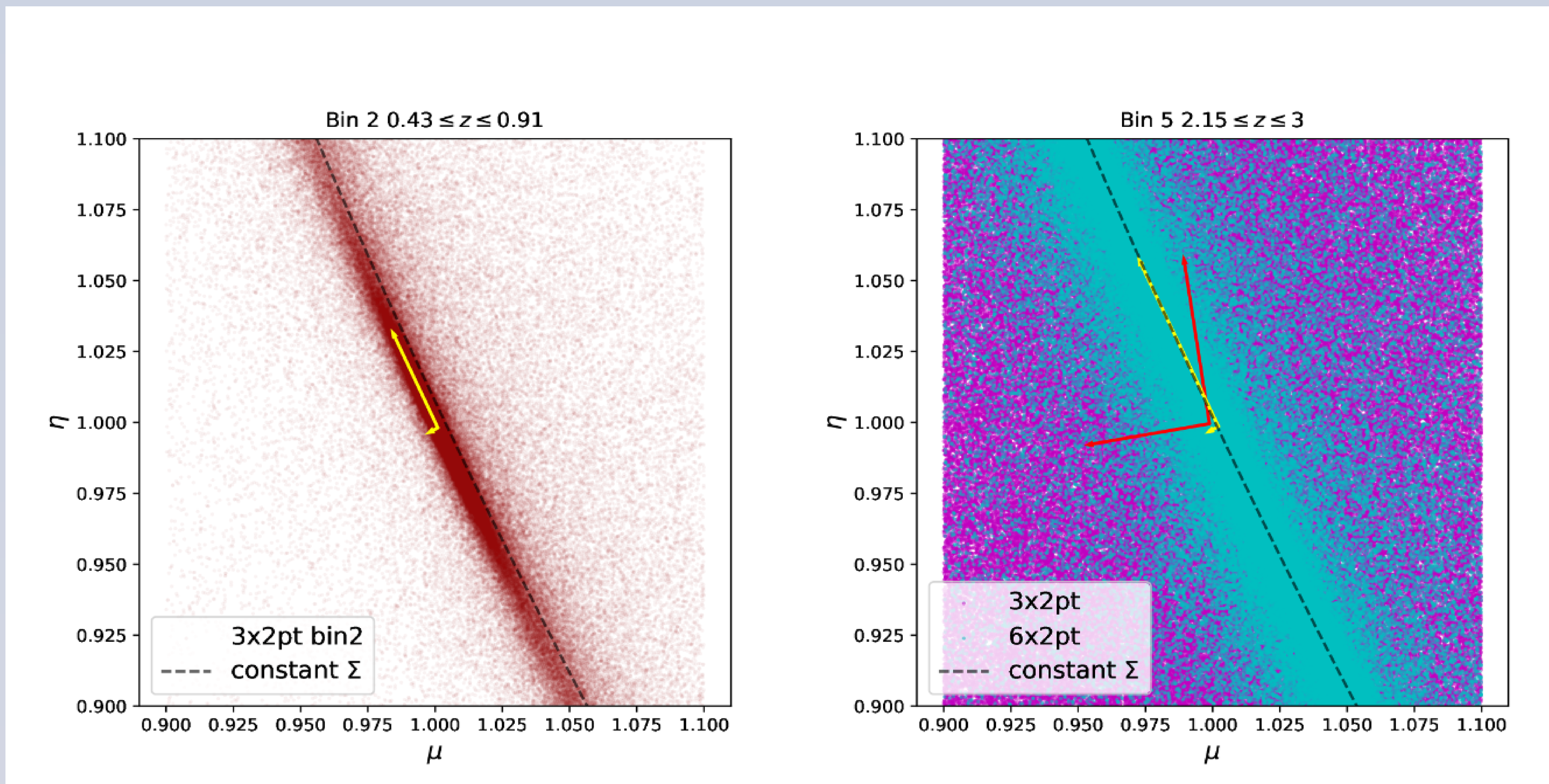
Simulated LSST Y10 X Simons Observatory 6x2pt data.

- 31 Nuisance parameters: bin-wise bias b_i, linear alignment amplitude A_{IA}, 3 baryonic feedback parameters photo-z errors, shear calibration parameters.
- 5 redshift bins for μ and η. We fix the redshift bin, vary MG + cosmological params. **Best constrained principal component:** $\Sigma{=}\mu(1{+}\eta)/2$
- **CMB lensing allows constraints on MG at z>1.5, albeit only via Σ.**

Bin	Data vector	μ	η	Σ
1	3×2pt	1.00 ± 0.020	1.00 ± 0.045	1.00 ± 0.005
1	6×2pt	1.00 ± 0.020	1.00 ± 0.045	1.00 ± 0.004
2	3×2pt	1.00 ± 0.012	1.00 ± 0.025	1.00 ± 0.003
2	6×2pt	1.00 ± 0.015	1.00 ± 0.025	1.00 ± 0.003
3	3×2pt	1.00 ± 0.030	1.00 ± 0.048	1.00 ± 0.005
3	6×2pt	1.00 ± 0.035	1.00 ± 0.05	1.00 ± 0.005
4	3×2pt	1.00 ± 0.04	Prior-Dominated	1.00 ± 0.015
4	6×2pt	1.00 ± 0.06	Prior-Dominated	1.00 ± 0.009
5	3×2pt	Prior-Dominated	Prior-Dominated	Prior-Dominated
5	6×2pt	Prior-Dominated	Prior-Dominated	1.00 ± 0.009

Bin 1	$0\leq z<0.43$
Bin 2	$0.43\leq z<0.91$
Bin 3	$0.91\leq z<1.47$
Bin 4	$1.47\leq z<2.15$
Bin 5	$2.15\leq z<3.0$





Conclusions

1. Model-agnostic gravity tests constrain redshift-dependent deviations from GR using μ and η.

2. Nonlinear information matters Our framework enables inference using nonlinear LSS information, which allows degeneracy breaking between MG and cosmological parameters.

3. Lensing probes Σ = μ(1+η)/2 which is substantially better constrained than μ alone.

4. CMB lensing extends the redshift reach sensitivity to z>1.5.

5. Results are qualitatively consistent with DES Y3 analysis, which also showed sensitivity to Σ