TESTING GRAVITY WITH CROSS-CORRELATIONS OF CMB AND LSS

G. FRITTOLI[1,2,3], G. BENEVENTO[1,2], M. MIGLIACCIO[1,2], N. BARTOLO[2,4]

We aim to test gravity models by exploiting the additional information retained in the cross-correlations of CMB and the Large Scale Structure. In order to describe gravity, we adopt the Effective Field Theory of Dark Energy approach, which encapsulates a general modification of gravity, without being bound to a specific model. In this framework, we use the EFTCAMB Boltzman code to compute theoretical angular power spectra and the Fisher Information Matrix to forecast the ability to constrain cosmological parameters with present and future surveys.

START

Effective Field Theory (EFT) of Dark Energy

The EFT is a powerful framework that describes both dark energy and modified gravity. Its action recovers all single-field models in the regime where cosmological perturbation theory is applicable. **The DE action is written directly in terms of the perturbations of the metric field around a FRW solution.**

$$S = \frac{1}{2}\int d^4x\sqrt{-g}\{M_{pl}^2[(1+\Omega(t)]R + 2\Lambda(t) - 2c(t)\delta g^{00} + M_2^4(t)(\delta g^{00})^2 - M_1^3(t)\delta g^{00}\delta K - M_2^2(t)\delta K^2 - M_3^2(t)\delta K_\mu^\nu \delta K_\nu^\mu + \mu_1^2(t)\delta g^{00}\delta R + m_2^2(t)h^{\mu\nu}\partial_\mu g^{00}\partial_\nu g^{00}\}$$

- **Each operator is responsible for distinctive dynamical features** in the evolution of cosmological perturbations.
- Three operators, $\Omega(t)$, $c(t)$ and $\Lambda(t)$, also contribute to the background evolution.

At present, we specialised our study to the case of the Transitional Planck Mass (TPM) which is defined by a direct choice of the operators of the EFT action.

Transitional Planck Mass (TPM) Model

To obtain the TPM action we restrict our choice to the set of EFT functions that lead to the second-order equation of motion. Moreover, we impose that the speed of gravitational waves is constant and equal to the speed of light.

$$S = \int d^4x\sqrt{-g}\left\{\frac{m_0^2}{2}[(1+\Omega(t)]R + \Lambda(t) - c(t)\delta g^{00} + \frac{M_2^4(t)}{2}(\delta g^{00})^2 - \frac{M_1^3(t)}{2}\delta g^{00}\delta K\right\}$$

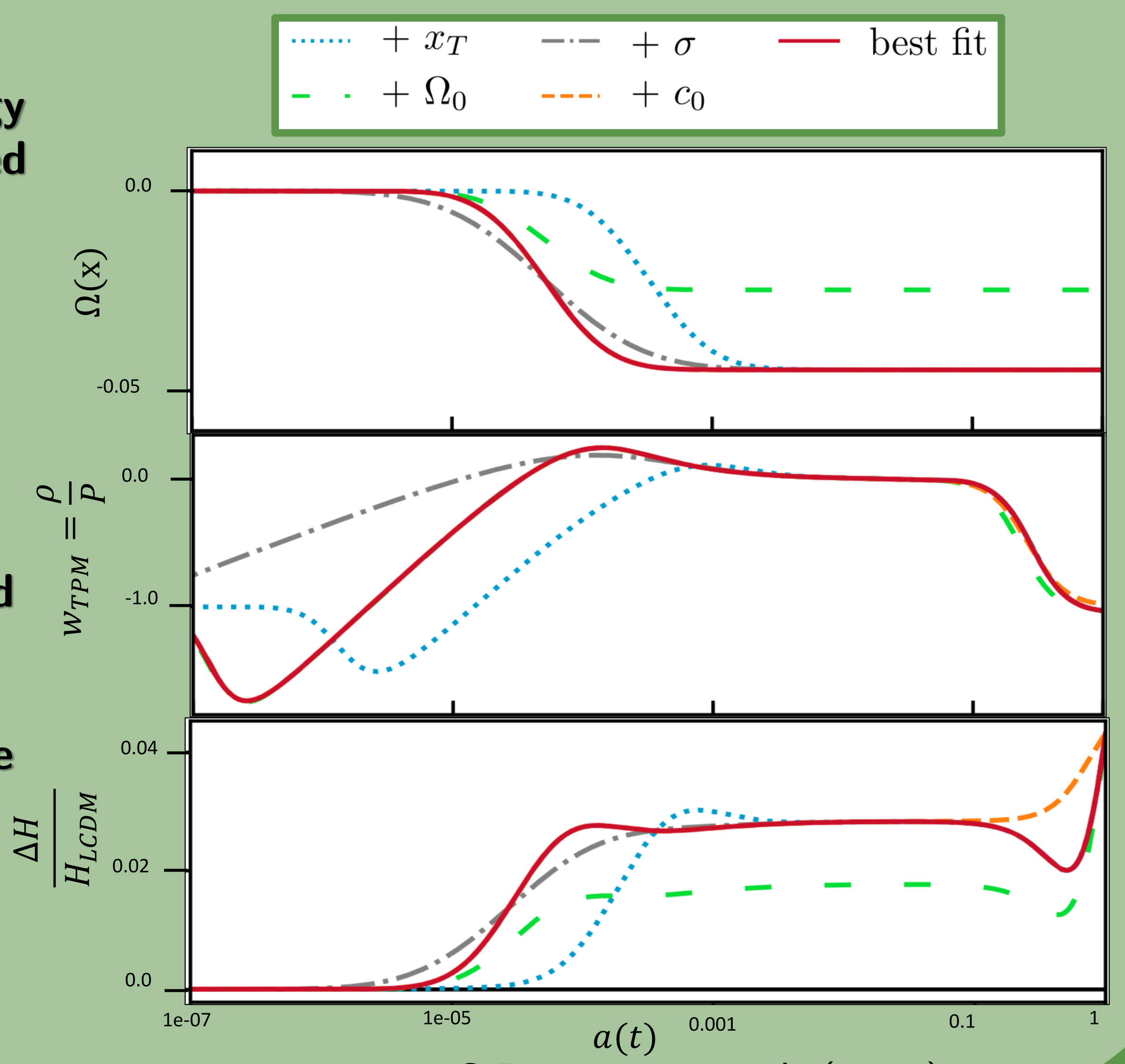
We consider a modified-gravity model that allows for a phenomenological shift (modeled as a step-like function) in the effective Planck Mass. We can set the EFT-functions accordingly:

$$\boldsymbol{\Omega(x) = \frac{\Omega_0}{2}\left(1 - \mathrm{erf}\left(\frac{\ln(a_T)-x}{\sqrt{2\pi}\sigma}\right)\right), \quad c(t) = c_0 = -\frac{M_2^4(t)}{3H_0^2m_0^2} = \frac{HM_1^3(t)}{6H_0^2m_0^2}}$$

The background evolution of the TPM model fixes $\Lambda(t)$ and $H(t)$, and can be described through an effective fluid with density and pressure:

$$\rho_{TPM} = 2c - \Lambda - 3m_0^2H^2(\Omega' + \Omega), \quad P_{TPM} = \Lambda + H^2m_0^2\left[\Omega'' + \Omega'\left(\frac{H'}{H}+2\right) + \Omega\left(2\frac{H'}{H}+3\right)\right]$$

The cosmology is parametrized by the 6 ΛCDM parameters, the c_0 parameter, which is relevant at late time, and the 3 parameters describing the transition ($\Omega_0, \sigma, x_T = \ln(a_T)$)



From G.Benevento et al. (2022).

Fisher Forecasts (FF)

The information on a vector of cosmological parameter θ_i that can be extracted from a subset M of all the auto- and cross- spectra **can be estimated using the Fisher Information Matrix** $F_{\alpha\beta}$, with L the likelihood, and the expectation value evaluated at the fiducial values $\theta_{i.fid}$:

$$F_{\alpha\beta} = -\left\langle\frac{\partial^2 \ln L}{\partial\theta_\alpha\partial\theta_\beta}\right\rangle_{at\ \theta=\theta_{fid}} \xrightarrow{\text{For power spetra, in practice:}} = \sum_{X,Y,X',Y'\ in\ M}\sum_\ell \frac{\partial C_\ell^{XY}}{\partial\theta_\alpha}\left[Cov\left(C_\ell^{XY}, C_\ell^{X'Y'}\right)\right]^{-1}\frac{\partial C_\ell^{X'Y'}}{\partial\theta_\beta}$$

with:

$$Cov\left(C_\ell^{XY}, C_{\ell'}^{X'Y'}\right) = \frac{\delta_{\ell\ell'}^K}{(2\ell+1)f_{sky}}\left\{\left[C_\ell^{XX'} + N_\ell^{XX'}\right]\left[C_{\ell'}^{YY'} + N_{\ell'}^{YY'}\right] + \left[C_\ell^{XY'} + N_\ell^{XY'}\right]\left[C_{\ell'}^{YX'} + N_{\ell'}^{YX'}\right]\right\}$$

By virtue of the Cramér-Rao inequality, **we obtain a lower bound on the covariance $B_{\alpha\beta}$ of our parameters:**

$$(F)^{-1}{}_{\alpha\beta} = B_{\alpha\beta} \xrightarrow{\text{For diagonal elements:}} \sigma_\alpha^2 = B_{\alpha\alpha}$$

and the square root of its diagonal elements yields the 1σ marginalised uncertainties on each parameter.

EFTCAMB & FF Code

EFTCAMB is an extension of the publicly available Einstein-Boltzmann solver, CAMB. **EFTCAMB implements the EFT approach,** and it allows to:

- ✓ study the linear cosmological perturbations in a model-independent framework or of specific single scalar field DE/MG models via the mapping EFT procedure.
- ✓ evolve the full perturbation equations on all linear scales without relying on any quasi-static approximation.
- ✓ check the stability conditions of perturbations.
- ✓ specify the expansion history by choosing a DE equation of state

We built a Fisher Forecast code in python3

- ✓ It interfaces directly with EFTCAMB. However, it can accept any spectra from files.
- ✓ **The covariance matrix with all cross-spectra is automatically computed given a set of probes and their noises.**
- ✓ It allows for the selection of specific probes (include or exclude probes at will)
- ✓ It allows for the selection of the multipole range in which the probes are considered

Forecasts Results

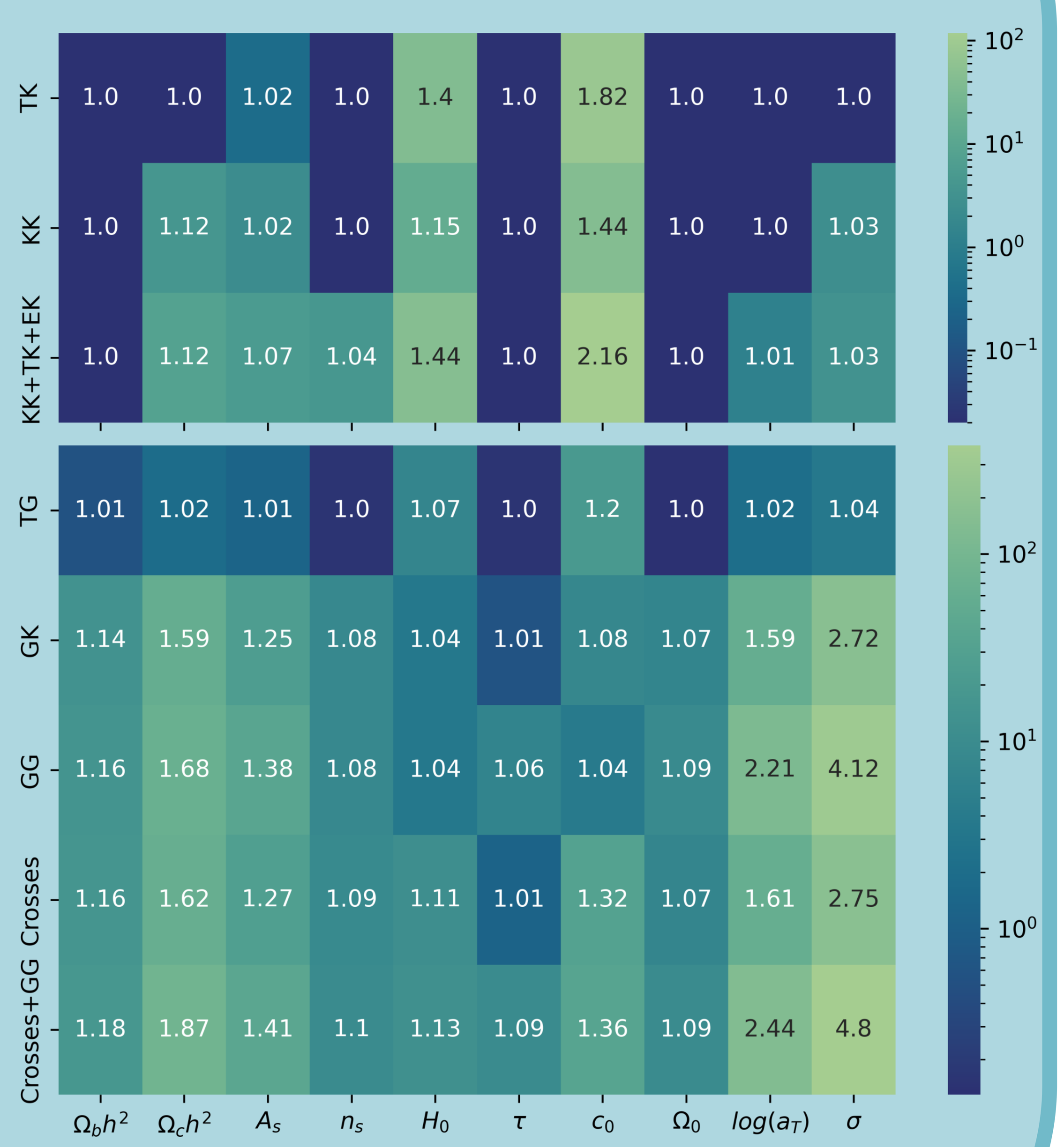
We start by considering the constraints that can be obtained with CMB temperature and polarization spectra TT,TE,EE assuming Planck specifications.

Then, we add the CMB lensing convergence KK and its cross-correlations. We can already see an improvement in the late time parameters, including c_0

The annotations are given by: $\frac{\sigma_{before}}{\sigma_{after}}$

The color scale is given by: $\left[\left(\frac{\sigma_{before}}{\sigma_{after}} - 1\right)\times 100\right]$

Finally, we also add Galaxy Clustering for a Euclid-like photometric survey without considering tomography. We can see an improvement on σ and $\ln(a_T)$ which were otherwise unconstrained.



Next Steps:

- **Tomography is under testing**
- Add Cosmic Shear as a probe
- Extend to other CMB and Galaxy surveys
- Consider other EFT parametrizations

[1]Università Roma Tor Vergata [2]Istituto Nazionale di Fisica Nucleare [3]Università Roma La Sapienza [4]Università degli Studi di Padova

EMAIL: guglielmo.frittoli@roma2.infn.it