# Testing Gravity with CMB and LSS cross-correlation

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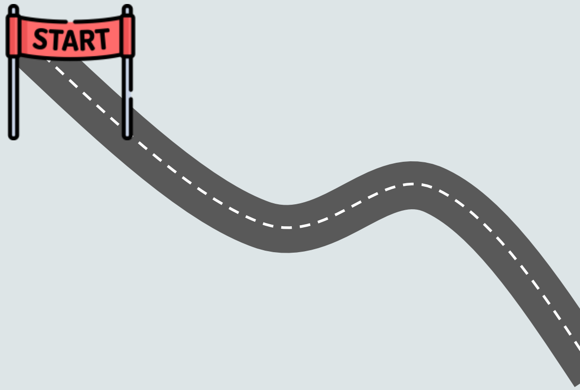
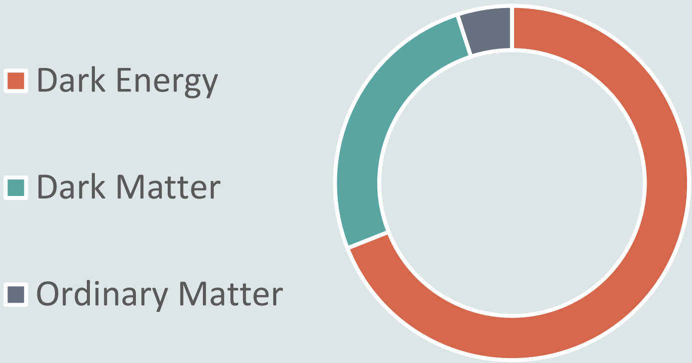
# ΛCDM and Dark Energy




General Relativity and ΛCDM work outstandingly well

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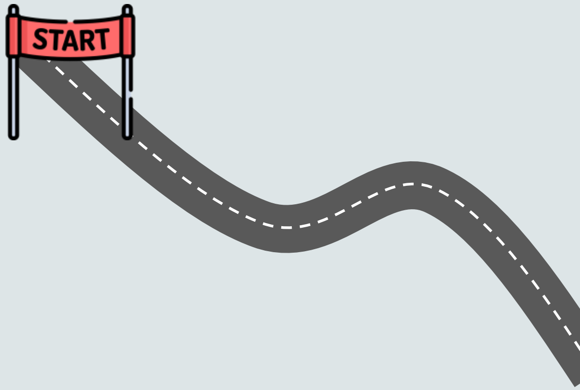
# ΛCDM and Dark Energy

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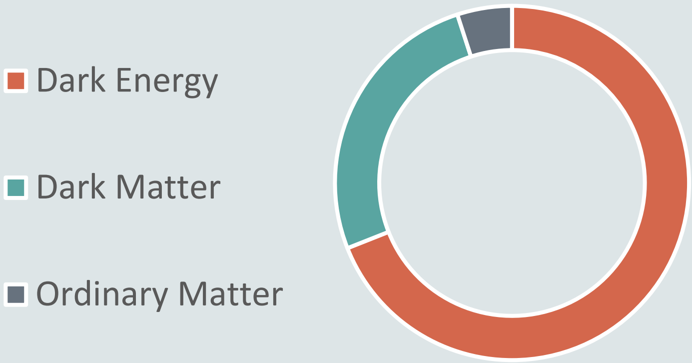


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- Describe theories of modified gravity: Transitional Planck Mass
- Assess the costraining power of future surveys: Fisher Forecasts

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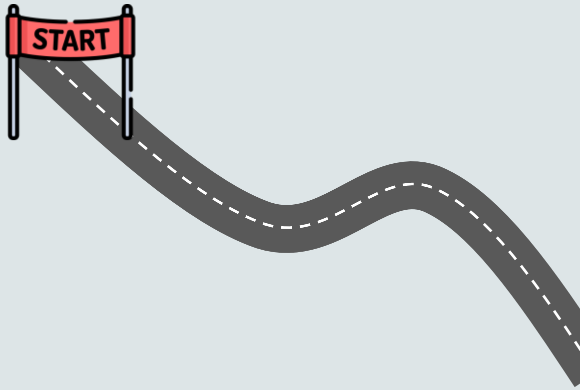


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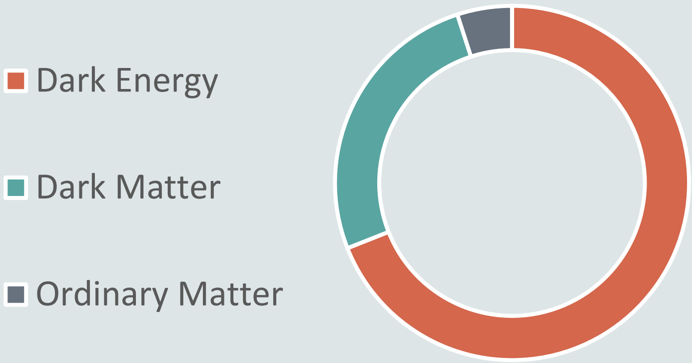


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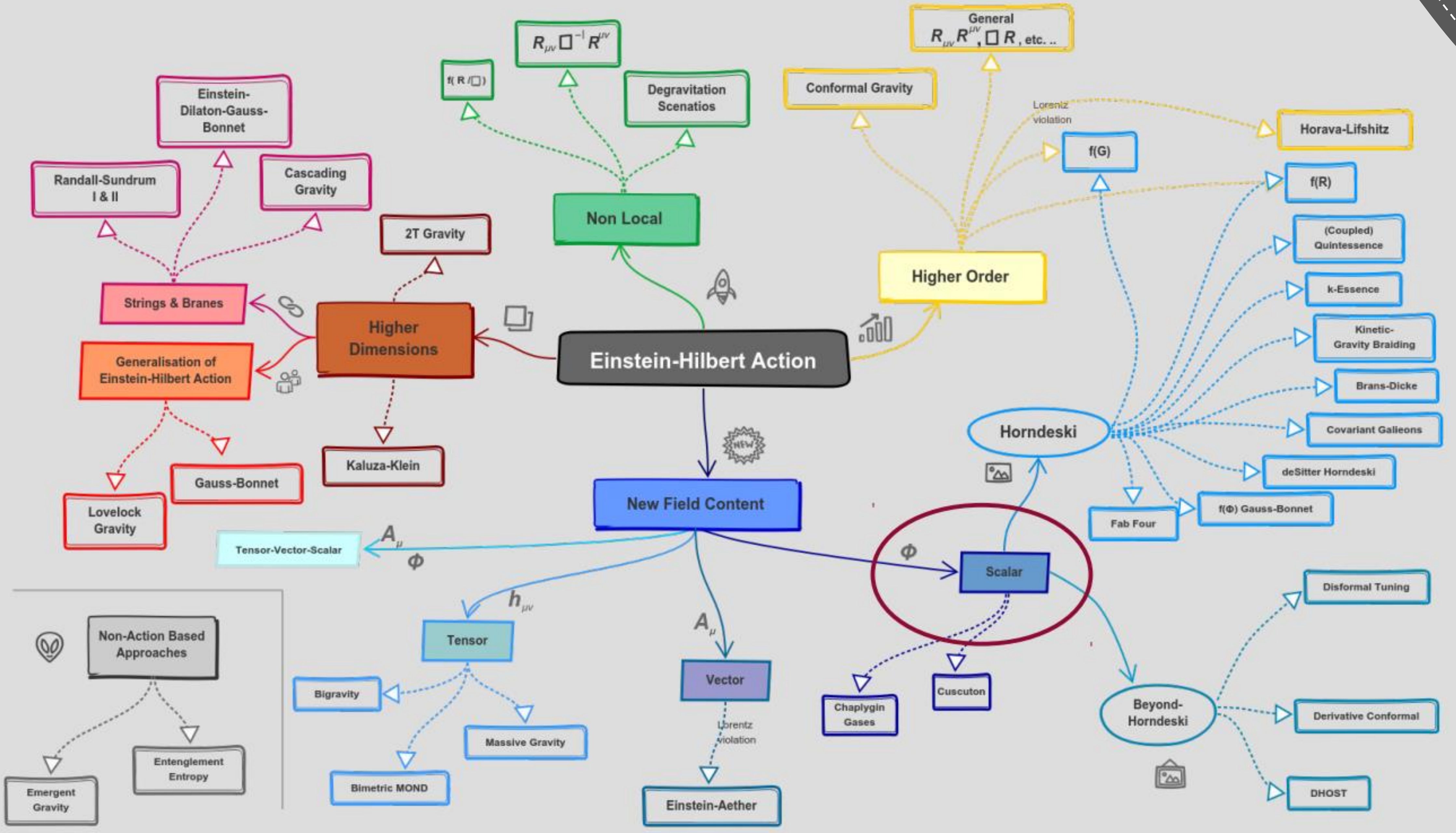
… but which models do we choose?




# !!! Overview incomplete !!!

Adapted from Tessa Baker, Fig. 3 in Bull et al. (2015)

There is a way to describe a whole plethora of theories:

# Effective Field Theory of Dark Energy (EFTofDE)

Aim: to establish a robust and economic way to connect data with fundamental theory

Big lesson from GR: in particle physics terms, no theory other than GR is compatible with the basic requisites of a single massless spin two field (the graviton) and recovering Lorentz invariance.

Lovelock's theorem: it implies that any infrared departure from GR must bring in new degrees of freedom.

Let me *just* add $\phi(x,t)$

The intuitive idea is to apply EFT directly to cosmological perturbations, by treating them as the Goldstone boson of spontaneously broken time-translations.

# Quick and Easy Recipy for the EFTofDE

1) Assume the WEP — Matter fields are coupled to the metric thorugh a matter action

2) Unitary Gauge — $\phi(x,t) = \bar{\phi}(t) + \cancel{\delta\phi(x,t)}$ — The scalar is *eaten* by the metric

3) FLRW line element

At this point you write and perturb all the operators compatible with the residual symmetries of unbroken spatial diffeomorphisms:

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

$$- M_2^2(t)\delta K^2 - M_3^2(t)\delta K^{\nu}_{\mu}\delta K^{\mu}_{\nu} + \mu_1^2(t)\delta g^{00}\delta R + m_2^2(t)h^{\mu\nu}\partial_\mu g^{00}\partial_\nu g^{00} + \cdots\Big\}$$

Where is the advantage in all of this?

# Effective Field Theory of Dark Energy

Aim: to establish a robust and economic way to connect data with fundamental theory

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

Transitional Planck Mass (TPM) Model

Fixing the speed of GW

Setting to Horndeski theories

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

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

Giampaolo Benevento will tell you more after lunch!

Parameters:

- 6 $\Lambda$CDM
- $c_0$ parameter (relevant at late times)
- 3 describing the transition $\Omega_o, \sigma, x_T=\log(a_T)$

# Let’s now test gravity: Fisher Forecasts

Fisher Forecasts are a powerful and economical tool to test the effectiveness of future surveys.

Def: $$F_{\alpha\beta} = -\left\langle \frac{\partial^2 \ln L}{\partial\theta_\alpha \partial\theta_\beta} \right\rangle_{at\ \theta=\theta_{fid}} \longrightarrow (F)^{-1}{}_{\alpha\beta} = B_{\alpha\beta} \longrightarrow \sigma_\alpha^2 = B_{\alpha\alpha}$$

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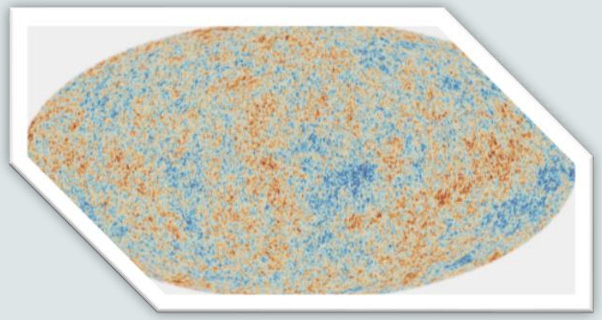
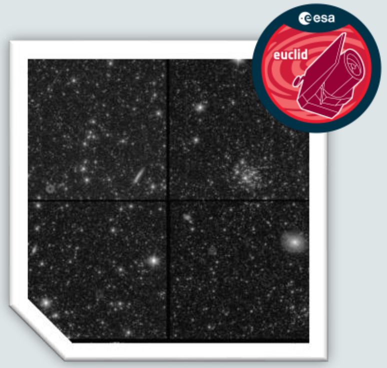
We can combine CMB and LSS also exploiting the additional information retained in their cross-correlations.



Planck 2018
- Temperature
- Polarization
- CMB lensing




Euclid survey
- Galaxy Clustering
- Weak Lensing

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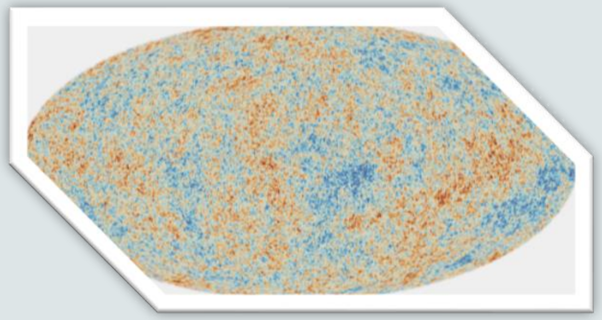

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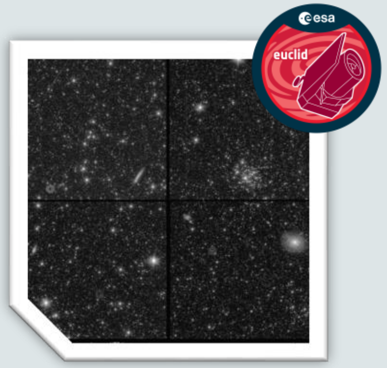

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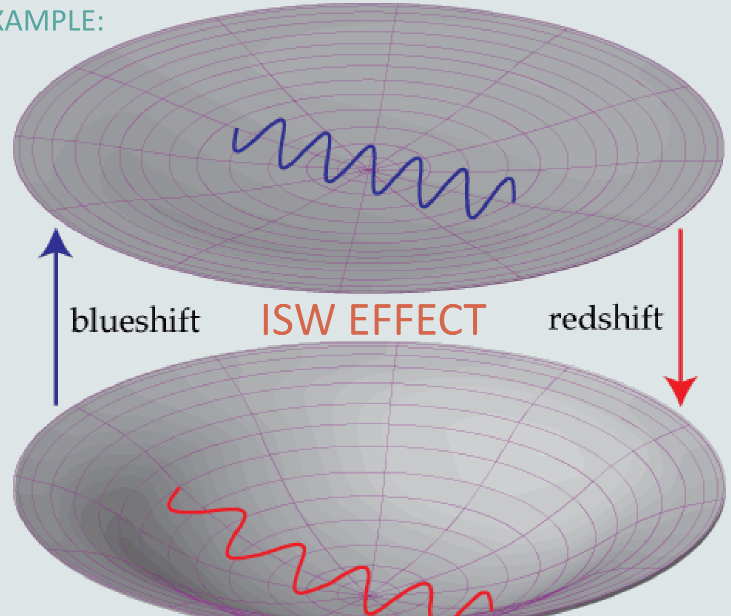
Why the cross-correlation?

EXAMPLE:



# Blueprint of the project

$$F_{\alpha\beta} = \sum_{X,Y,X',Y' \ in \ M} \sum_{\ell} \frac{\partial C_\ell^{XY}}{\partial \theta_\alpha} \left[ Cov\left( C_\ell^{XY}, C_\ell^{X'Y'} \right) \right]^{-1} \frac{\partial C_\ell^{X'Y'}}{\partial \theta_\beta}$$

$\Lambda$CDM and MG forecasts

## Blueprint of the project

EFTCAMB

$$C_\ell^{XY} = \left\langle (a_\ell^X)^*, a_\ell^Y \right\rangle$$

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$\Lambda$CDM and MG forecasts

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Include here all the noises and surveys specifications

FE FORECAST CODE

$$Cov\left(C_\ell^{XY}, C_\ell^{X'Y'}\right)$$

EFTCAMB

$$\frac{\partial C_\ell^{XY}}{\partial \theta_\alpha} = \frac{C_\ell^{XY}(\theta_\alpha + \epsilon) - C_\ell^{XY}(\theta_\alpha - \epsilon)}{2\epsilon}$$

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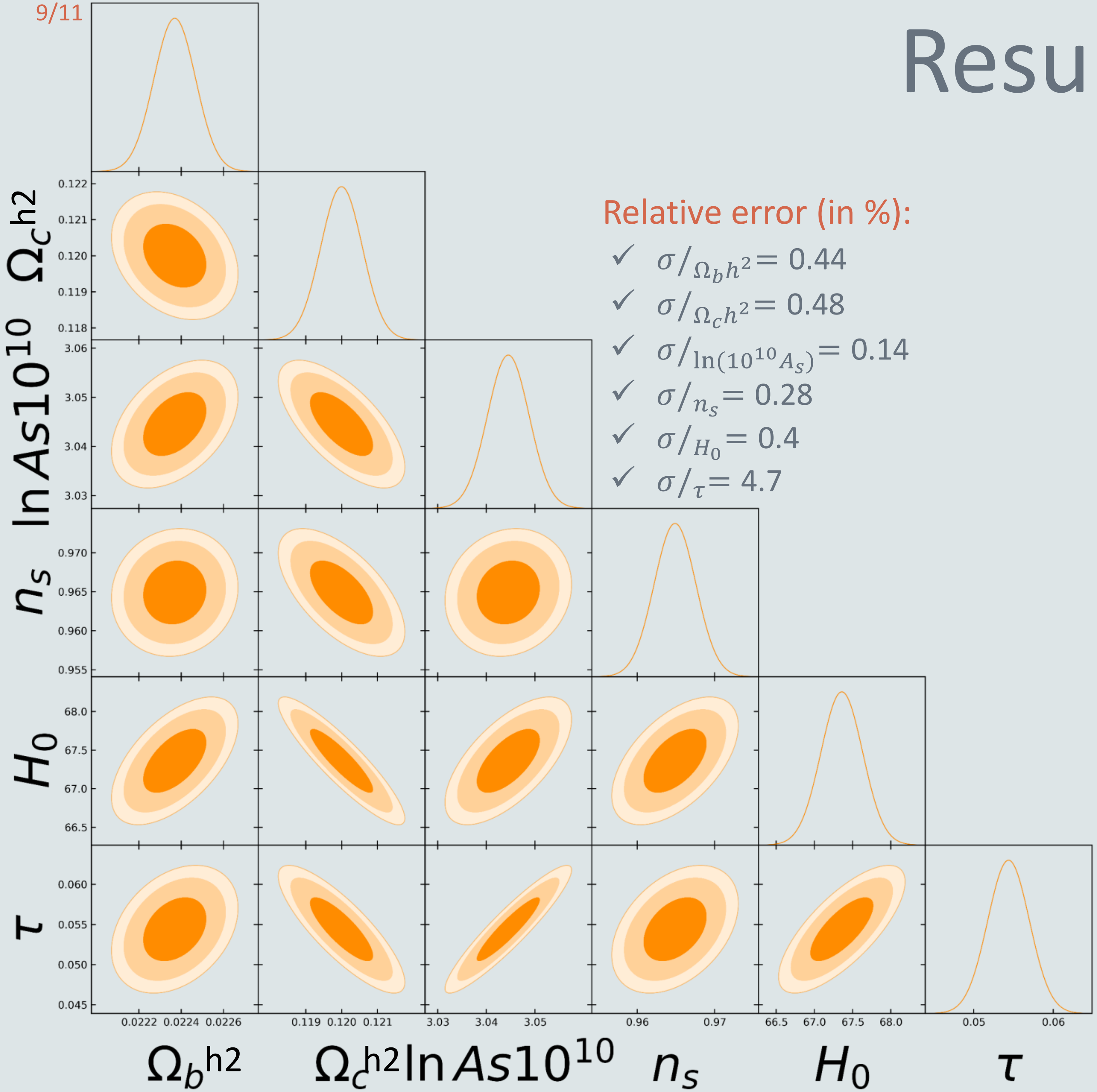
$\Lambda$CDM and MG forecasts

Study the impact of relativistic contributions

- CLASS/CAMB agreement
- Limber/non-Limber difference

# Results: ΛCDM




Relative error (in %):

- ✓ $\sigma/_{\Omega_b h^2} = 0.44$
- ✓ $\sigma/_{\Omega_c h^2} = 0.48$
- ✓ $\sigma/_{\ln(10^{10} A_s)} = 0.14$
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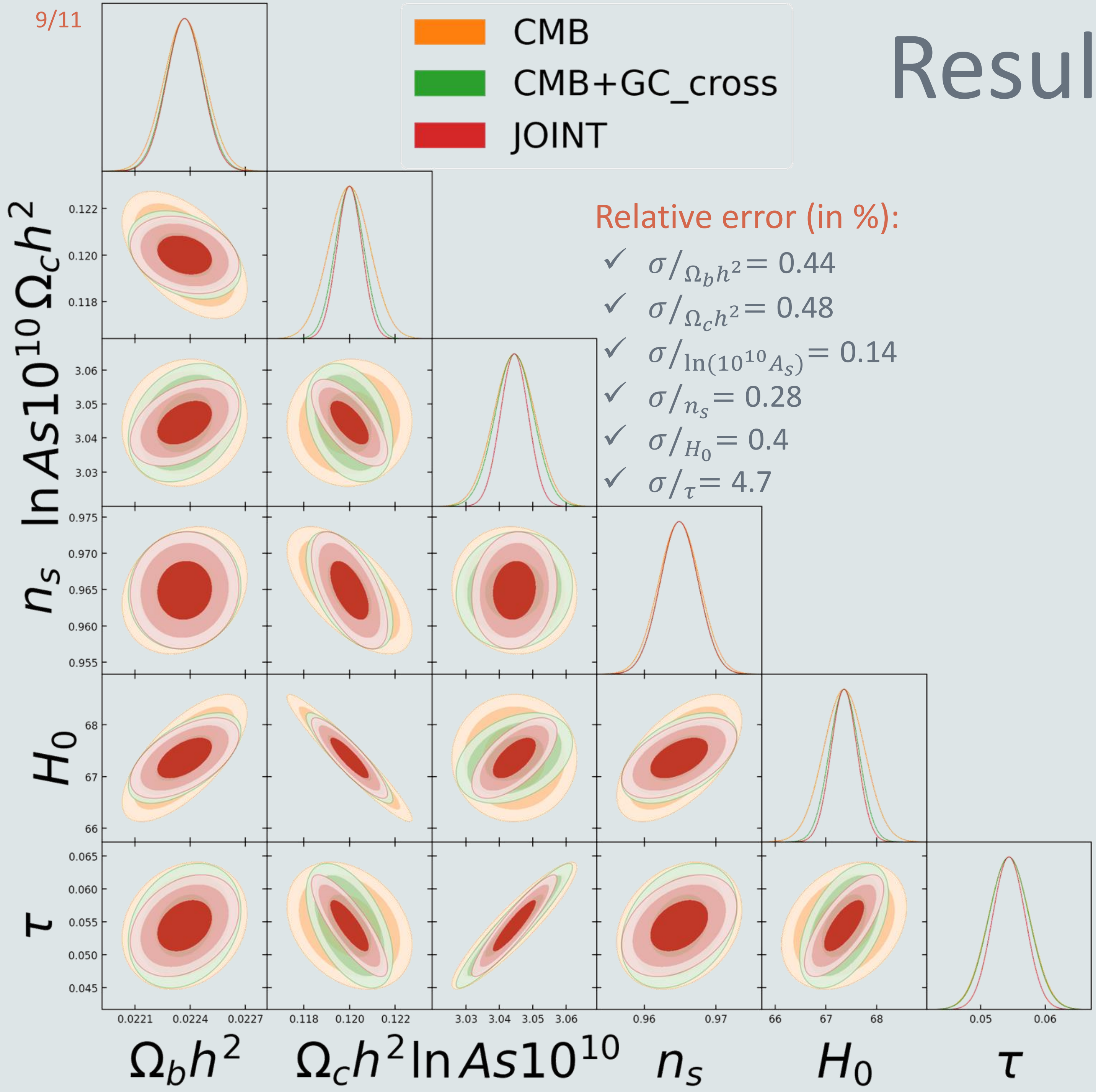


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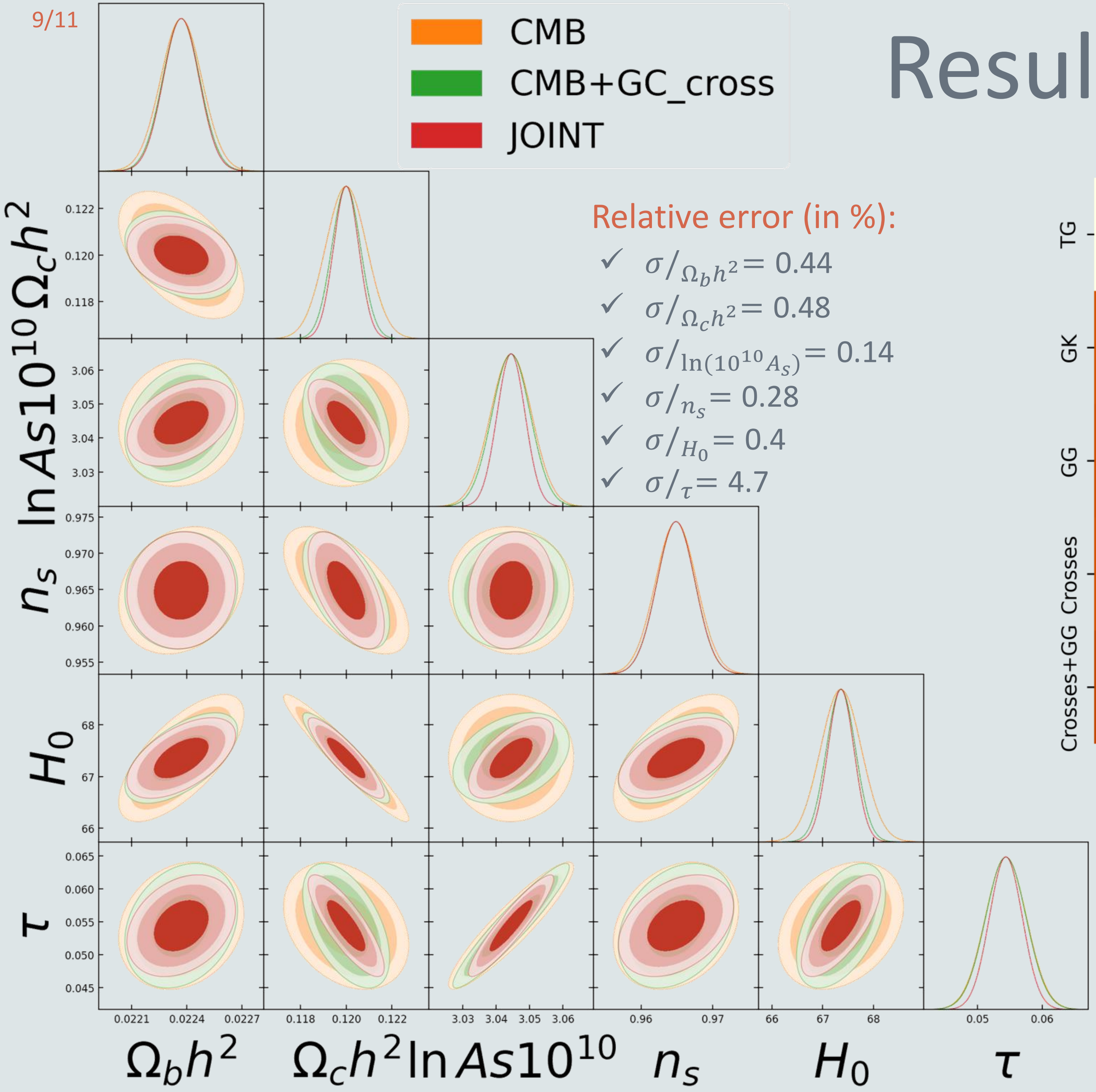


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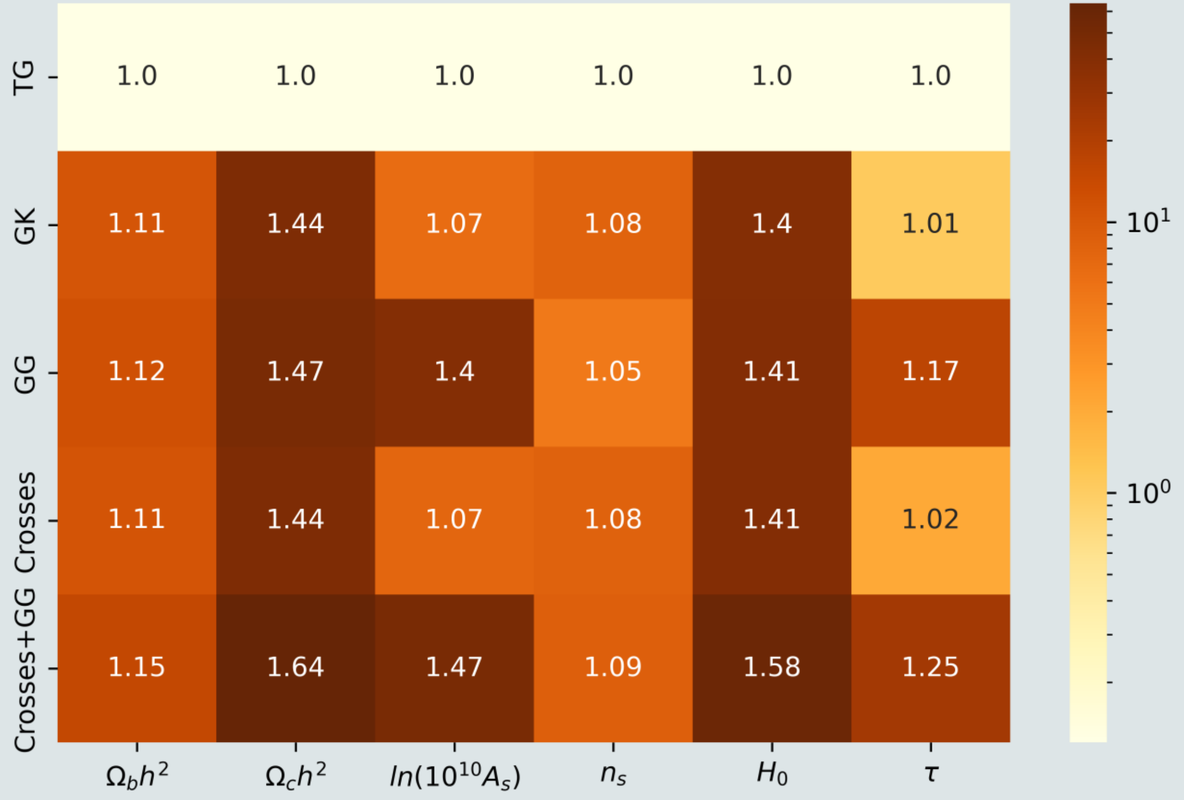



From a baseline of forecasts with CMB probes, we add Galaxy Counts

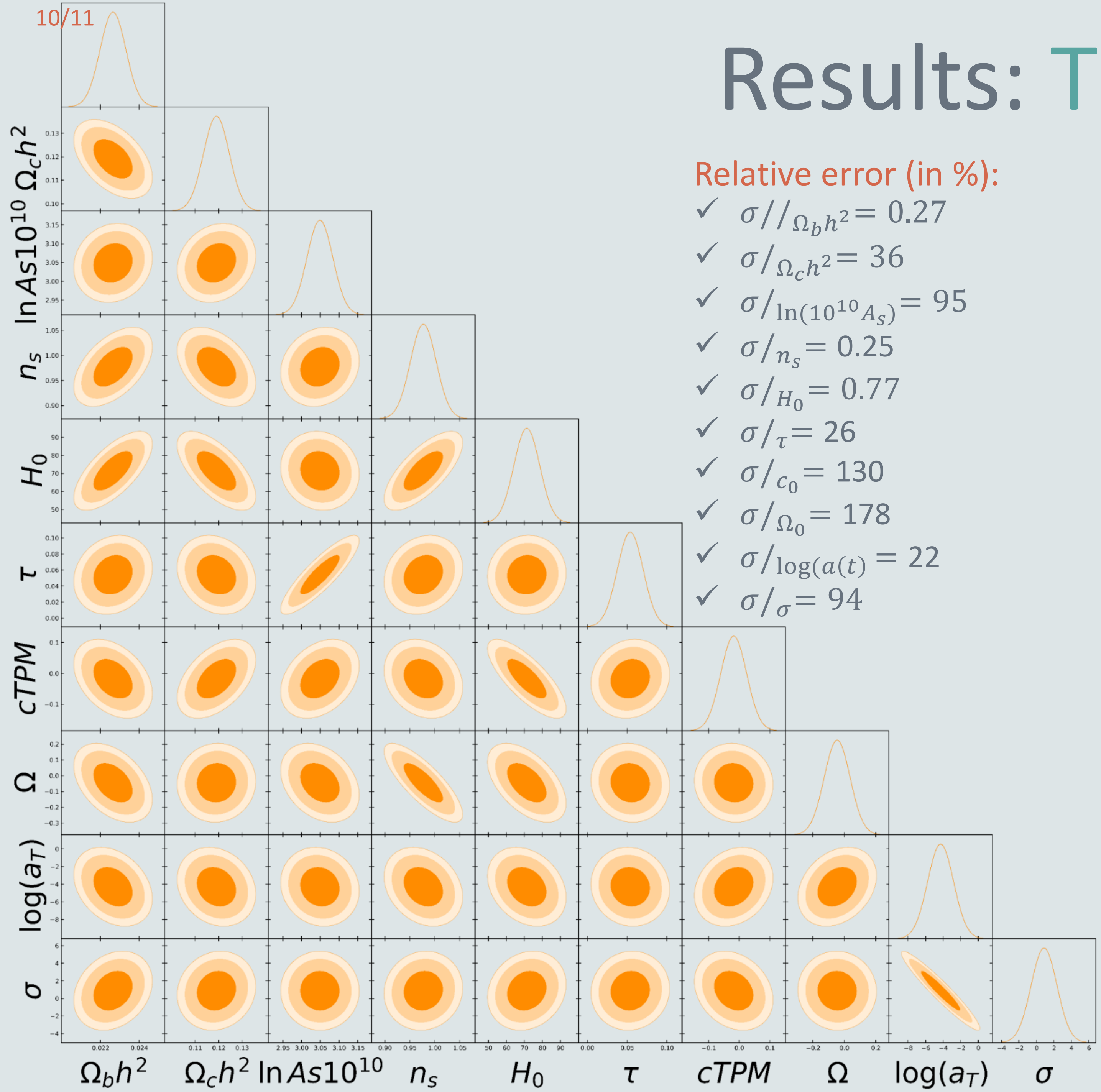
Color scale

$$\left[\left(\frac{\sigma_{\text{before}}}{\sigma_{\text{after}}} - 1\right) \times 100\right]$$

Label in the boxes

$$\frac{\sigma_{\text{before}}}{\sigma_{\text{after}}}$$

# Results: TPM

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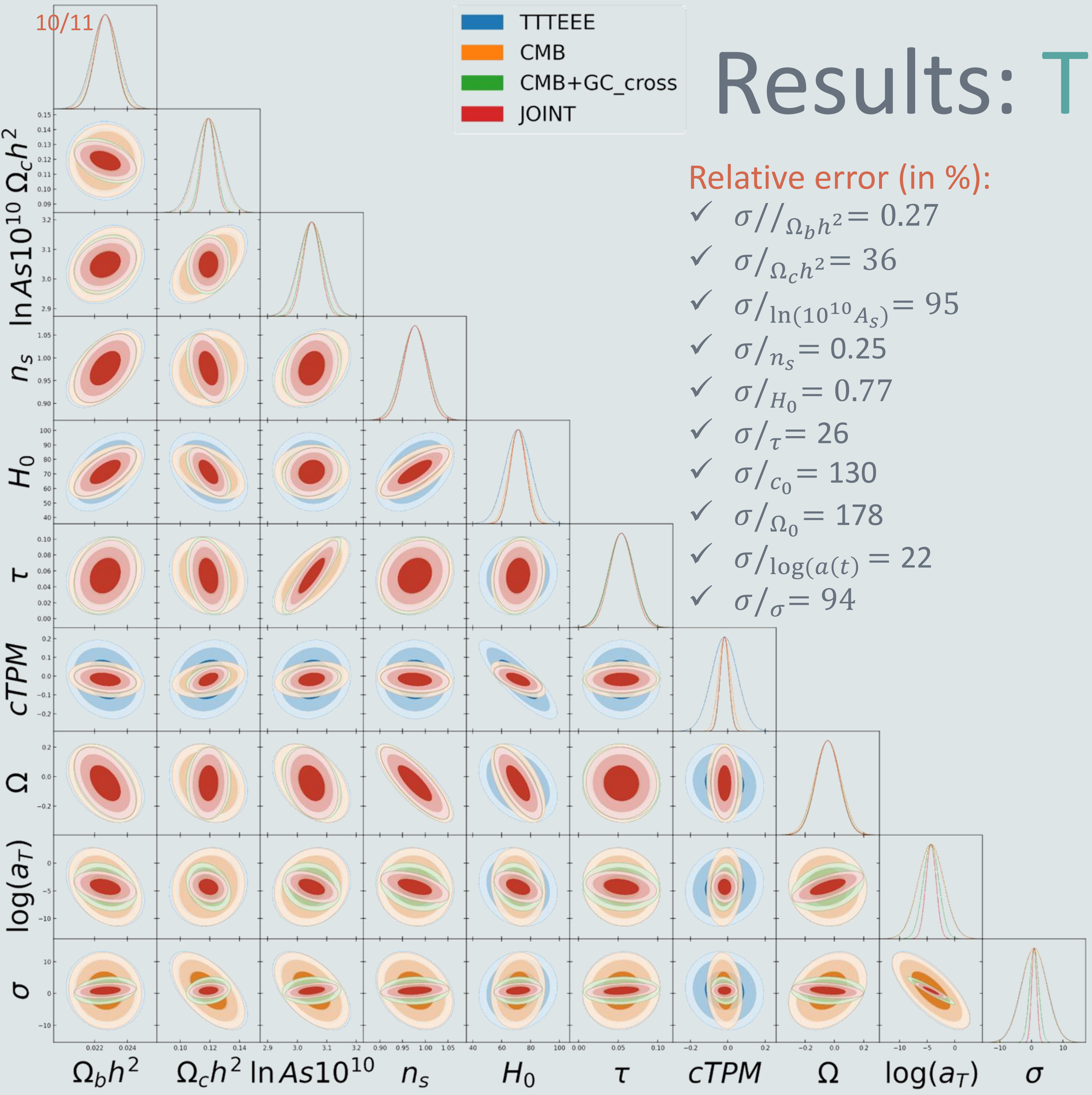


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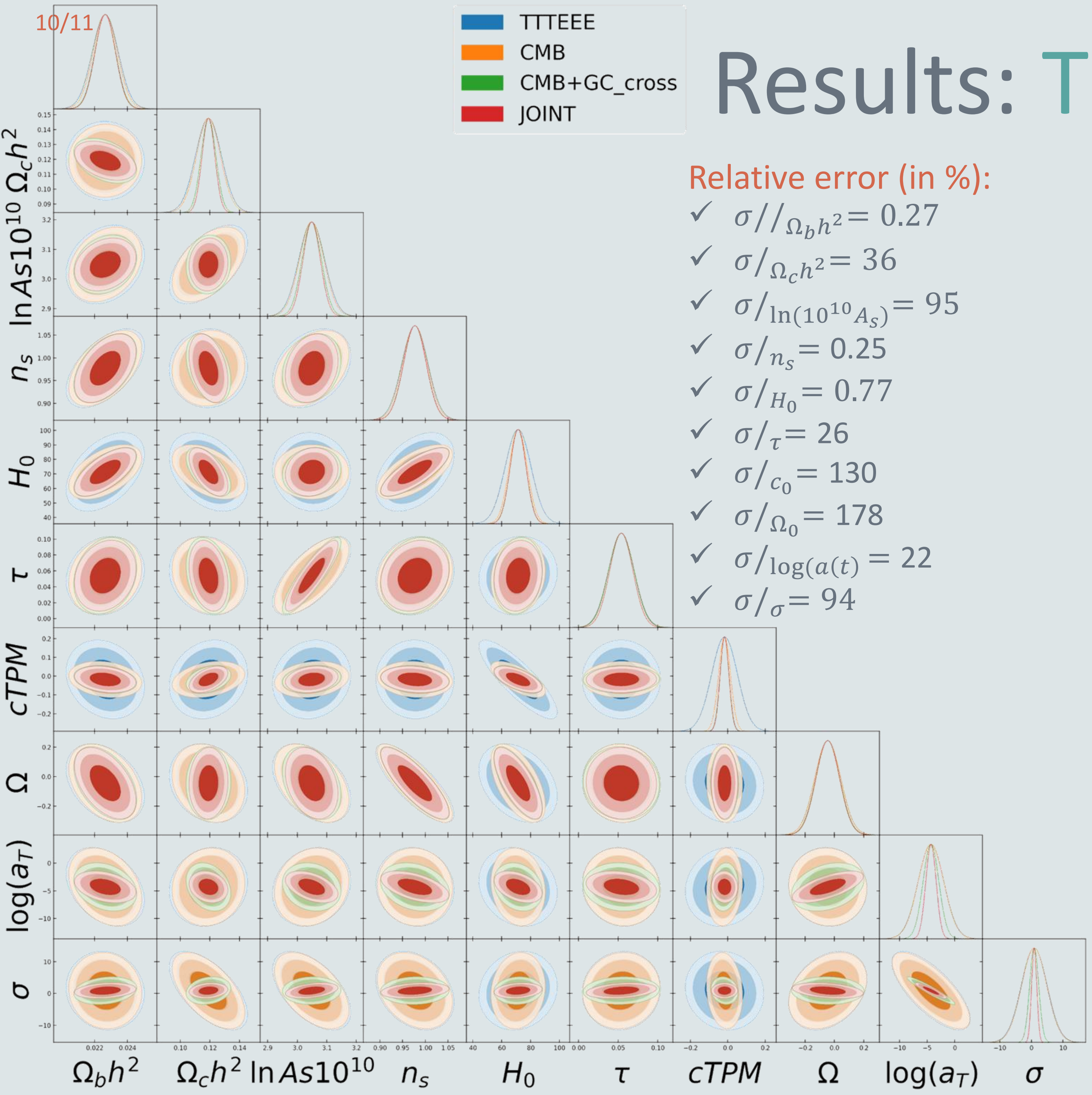


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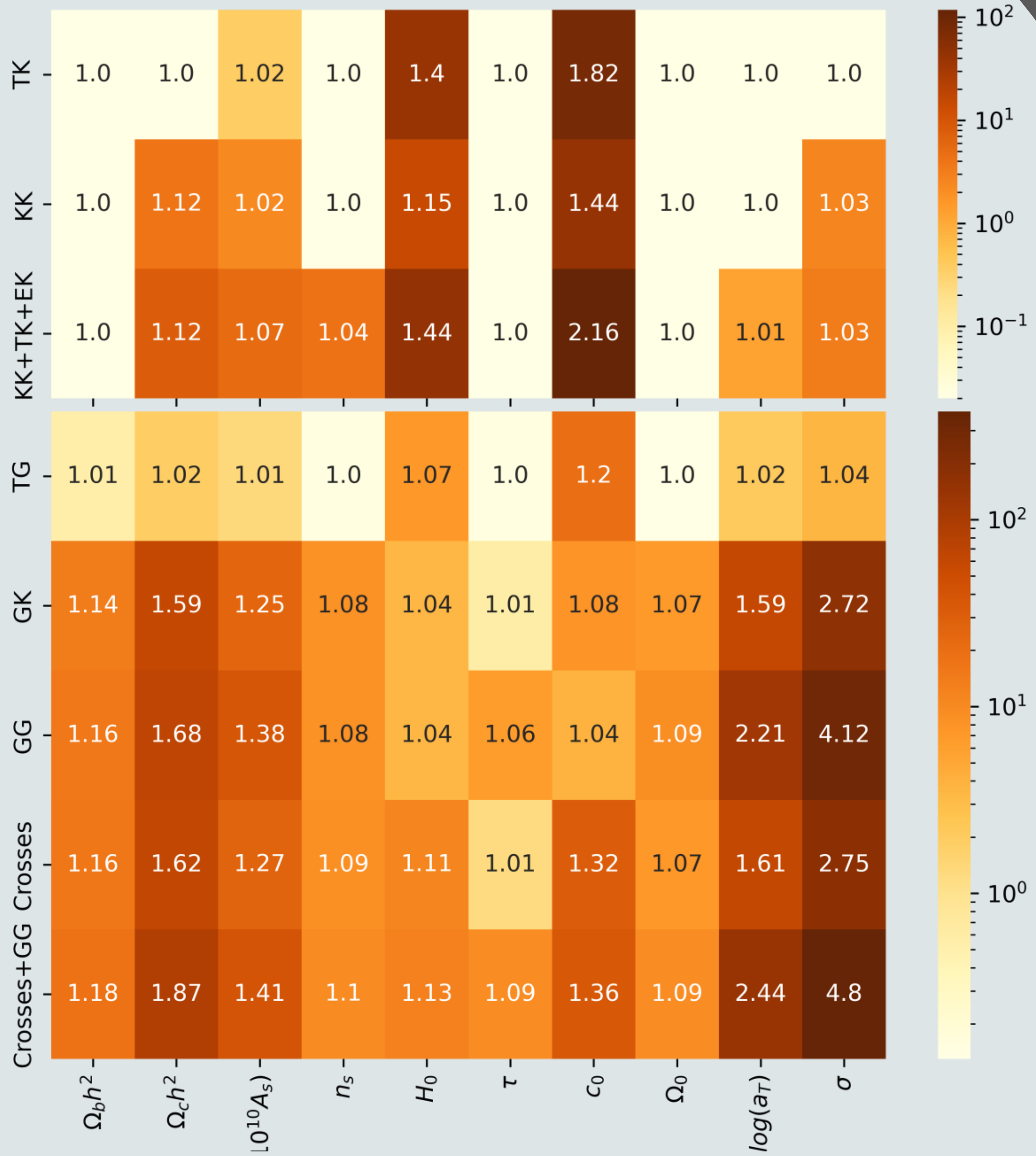

# At present

- Exploited the EFTofDE: it is powerful tool and in combination with EFTCAMB we explored the study-case of the TPM
- Forecasted uncertanties with various set of probes, both from CMB and LSS, finding better costraints

# Forecasts for the future

- Finalize Tomography: it is added and under testing
- Add galaxy weak lensing to the set of probes used for the forecasts
- Include nuisance parameters (e.g. bias parameters)
- Assess the impact of relativistic contributions in galaxy counts
- Extend to other CMB and Galaxy surveys
- Explore different models using the EFT formalisms