K -mouflage cosmology: parameter constraints and forecasts

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K-mouflage

K-essence with non-minimal coupling to matter:

$$S = \int d^4x \sqrt{-\tilde{g}} \left[\frac{\tilde{M}_{\rm Pl}^2}{2} \tilde{R} + \mathcal{M}^4 K(\tilde{\chi}) \right] + \int d^4x \sqrt{-g} L_{\rm m}(\psi_i, g_{\mu\nu}) + \int d^4x \sqrt{-g} \frac{1}{4\alpha} F^{\mu\nu} F_{\mu\nu}$$

JF $\quad g_{\mu\nu} = A^2(\varphi)\, \tilde{g}_{\mu\nu} \quad$ **EF**

Model definition

Coupling function: $A(\varphi(a))$

Kinetic function: $K(\tilde{\chi}(a)), \quad \tilde{\chi} = -\frac{1}{2M^4} \partial^\mu \varphi \, \partial_\mu \varphi$

Mapping in the EFT action *Brax, P., & Valageas, JCAP 01 020 (2016)*

$$\begin{aligned} S = \int d^4x \sqrt{-g} \Big\{ & \frac{m_0^2}{2} [1 + \Omega(\tau)] R + \Lambda(\tau) - a^2 c(\tau) \delta g^{00} \\ & + \frac{M_2^4(\tau)}{2} (a^2 \delta g^{00})^2 - \cancel{\frac{\bar{M}_1^3(\tau)}{2} a^2 \delta g^{00} \delta K^\mu_\mu} - \cancel{\frac{\bar{M}_2^2(\tau)}{2} (\delta K^\mu_\mu)^2} - \cancel{\frac{\bar{M}_3^2(\tau)}{2} \delta K^\mu_\nu \delta K^\nu_\mu} \\ & + \cancel{\frac{a^2 \hat{M}^2(\tau)}{2} \delta g^{00} \delta R^{(3)}} + \cancel{m_2^2(\tau) (g^{\mu\nu} + n^\mu n^\nu) \partial_\mu (a^2 g^{00}) \partial_\nu (a^2 g^{00})} \Big\} + S_m[g_{\mu\nu}] \end{aligned}$$

K-mouflage

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Implemented in the EFTCAMB solver

EffectiveFieldTheory with CAMB

By B. Hu, M. Raveri, N. Frusciante and A. Silvestri

K-mouflage phenomenology

- **Background**

Modified expansion history

$$\frac{H^2}{H_0^2} = \frac{A^2}{(1-\epsilon_2)^2}\left[\frac{\Omega_{\rm m0}^{\rm K}}{a^3} + \frac{\Omega_{\gamma 0}^{\rm K}}{a^4} + \Omega_{\varphi 0}^{\rm K}\frac{\rho_\varphi}{\rho_{\varphi 0}}\right]$$

$$\rho_\varphi = \frac{\mathcal{M}^4}{A^4}(2\tilde{\chi}K' - K)$$

Running of the Planck mass

$$\epsilon_2 = \frac{d\ln A}{d\ln a} = -\frac{d\ln M_{\rm Pl}}{d\ln a}$$

$$A_0 \equiv A(z=0) = 1$$

- **Linear perturbations**

$$ds^2 = a^2\left[-(1+2\Phi)d\tau^2 + (1-2\Psi)d\mathbf{x}^2\right]$$

Late-time anisotropic stress

$$\Phi = (1+\epsilon_1)\Psi_{\rm N}, \quad \Psi = (1-\epsilon_1)\Psi_{\rm N}$$

Modified Poisson Eq. and
Weild potential

$$\mu(a) = \frac{-k^2\Phi}{4\pi G a^2\bar{\rho}_m\Delta_m} = (1+\epsilon_1)\bar{A}^2$$

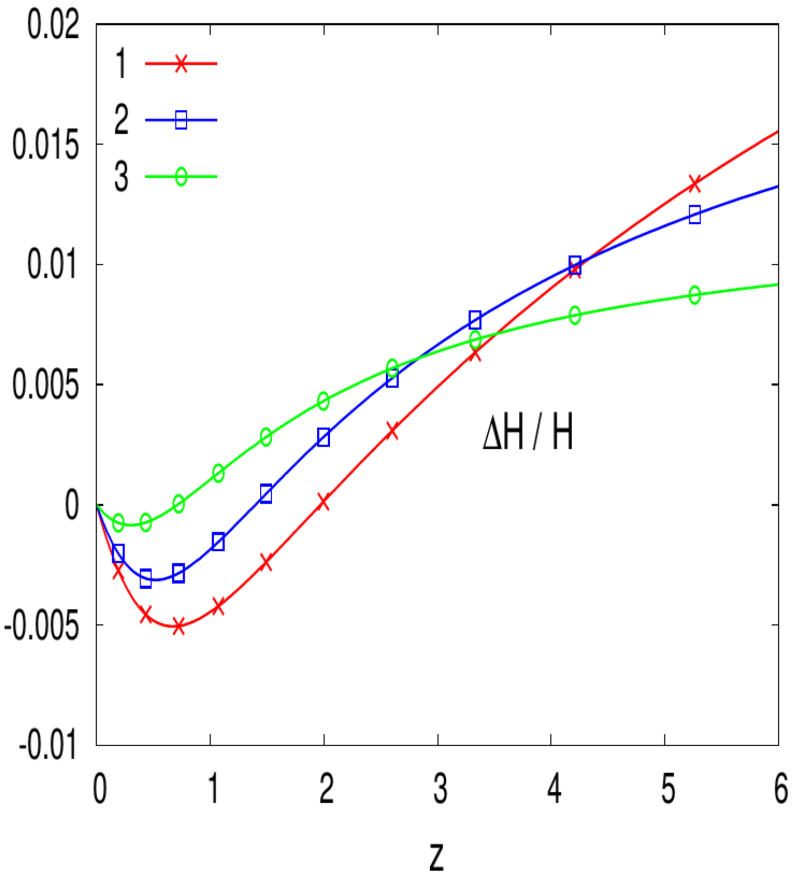
$$\Sigma(a) = \frac{-k^2(\Phi+\Psi)}{8\pi G a^2\bar{\rho}_m\Delta_m} = \bar{A}^2$$

- **LCDM Limit:** $\bar{A}(a) \to 1, \quad \epsilon_2(a) \to 0, \quad \bar{\tilde{\chi}} \to 0, \quad \bar{K}' \to 0 \ \forall \ a$

K-mouflage phenomenology

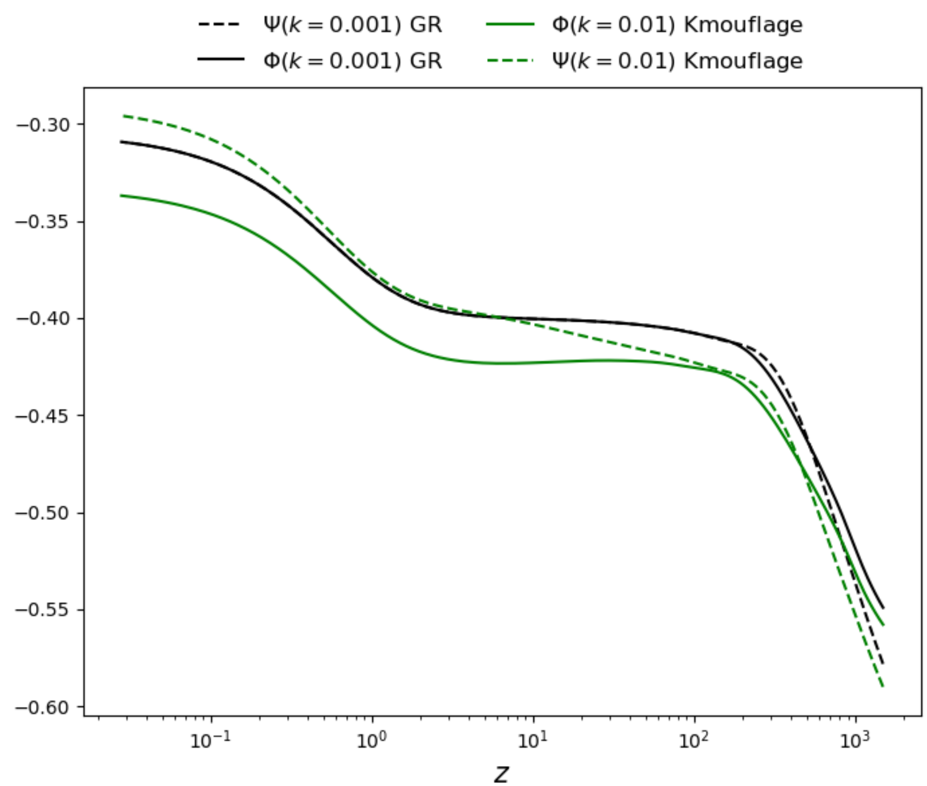
- **Background**

Modified expansion history



- **Linear perturbations**

$$ds^2 = a^2\left[-(1+2\Phi)d\tau^2 + (1-2\Psi)d\mathbf{x}^2\right]$$



- **LCDM Limit:** $\bar{A}(a) \to 1, \quad \epsilon_2(a) \to 0, \quad \bar{\bar{\chi}} \to 0, \quad \bar{K}' \to 0 \ \forall\ a$

Parameters of the model

A(a) and K(a) are parametrized in terms of the scale factor:

Brax, P., & Valageas, JCAP 01 020 (2016)

$$U(a) \equiv a^3 \sqrt{\bar{\tilde{\chi}}} \bar{K}' \propto \frac{a^2 \ln(\gamma_U + a)}{(\sqrt{a_{\rm eq}} + \sqrt{a}) \ln(\gamma_U + a) + \alpha_U a^2} \quad , \quad \frac{\mathrm{d}\bar{K}}{\mathrm{d}\tilde{\chi}} = \frac{U(a)}{a^3 \sqrt{\bar{\tilde{\chi}}}}$$

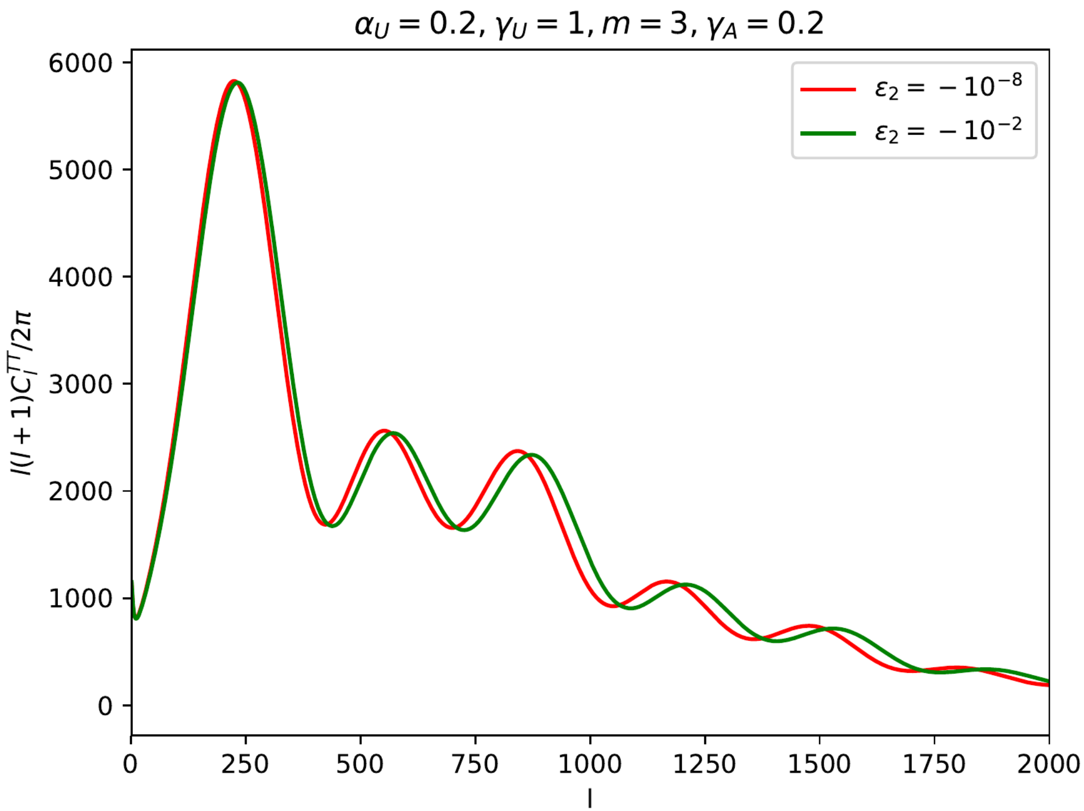
$$\bar{A}(a) = 1 + \alpha_A - \alpha_A \left[\frac{(\gamma_A + 1)a}{\gamma_A + a} \right]^{\nu_A} \qquad \alpha_A = -\frac{\epsilon_{2,0}(\gamma_A + 1)}{\gamma_A \nu_A}$$

- Very week dependence of cosmology on γ_U We fix it to: $\gamma_U = 1$
- α_U sets the transition to the DE dominated epoch. We choose: $0 < \alpha_U < 5$
- If we assume $\tilde{\chi} \gg 1: \quad K(\tilde{\chi}) \sim \tilde{\chi}^m$, then: $\nu_A = \frac{3(m-1)}{2m-1}$ $m > 1$
- γ_A sets the transition to the DE dominated epoch $0 < \gamma_A < 20$
- $\boxed{\epsilon_{2,0} \equiv \epsilon_2(a = 1)}$ Controls the running of Plank mass and the deviation from LCDM $|\epsilon_{2,0}| < 0.01$

(solar system bounds)

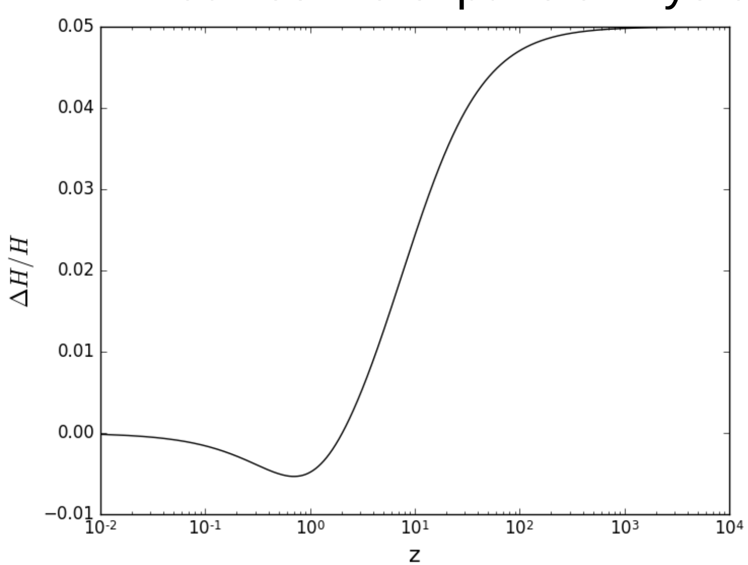
CMB acoustic peaks shift

Acoustic peaks appears shifted toward higher multipoles, ~10% deviation for $\epsilon_{2,0}$ = -0.01



$$l_{first\ peak} \simeq 0.75\,\pi\left(\eta_0 - \eta_{rec}\right)/r_s\left(\eta_{rec}\right)$$

K-m modifies the expansion hystory



- Higher Hubble rate at high redshift
- Smaller Sound Horizon
- Similar distance to last-scattering
- Oscillations projected on higher multipoles

(K)-mimic the LCDM expansion

If we require the Hubble rate to follow the LCDM solution:

$$\begin{cases} \dfrac{H^2}{H_0^2} = \dfrac{A^2}{(1-\epsilon_2)^2}\left[\dfrac{\Omega^{\mathrm{K}}_{\mathrm{m}0}}{a^3} + \dfrac{\Omega^{\mathrm{K}}_{\gamma 0}}{a^4} + \Omega^{\mathrm{K}}_{\varphi 0}\dfrac{\rho_\varphi}{\rho_{\varphi 0}}\right] = \dfrac{\hat{\Omega}_{\mathrm{m}0}}{a^3} + \dfrac{\hat{\Omega}_{\gamma 0}}{a^4} + \hat{\Omega}_{\Lambda 0} \\ -\dfrac{2}{3H_0^2}\dfrac{dH}{dt} = \dfrac{A^2}{1-\epsilon_2}\left[\dfrac{\Omega^{\mathrm{K}}_{\mathrm{m}0}}{a^3} + \dfrac{4\Omega^{\mathrm{K}}_{\gamma 0}}{3a^4} + \Omega^{\mathrm{K}}_{\varphi 0}\dfrac{\rho_\varphi + p_\varphi}{\rho_{\varphi 0}}\right] + [\ldots] = \dfrac{\hat{\Omega}_{\mathrm{m}0}}{a^3} + \dfrac{4\hat{\Omega}_{\gamma 0}}{3a^4} \end{cases}$$

We obtain an equation for the Kinetic function:

$$\Omega_{\varphi 0}\bar{K} = A^2(1-\epsilon_2)\left(-\hat{\Omega}_{\Lambda 0} + \frac{\hat{\Omega}_{\gamma 0}}{3a^4}\right) - A^4\frac{\Omega_{\gamma 0}}{3a^4} + \frac{A^2(1-\epsilon_2)}{3}\left(\epsilon_2 + \frac{2}{1-\epsilon_2}\frac{d\epsilon_2}{d\ln a}\right)\left(\frac{\hat{\Omega}_{\mathrm{m}0}}{a^3} + \frac{\hat{\Omega}_{\gamma 0}}{a^4} + \hat{\Omega}_{\Lambda 0}\right)$$

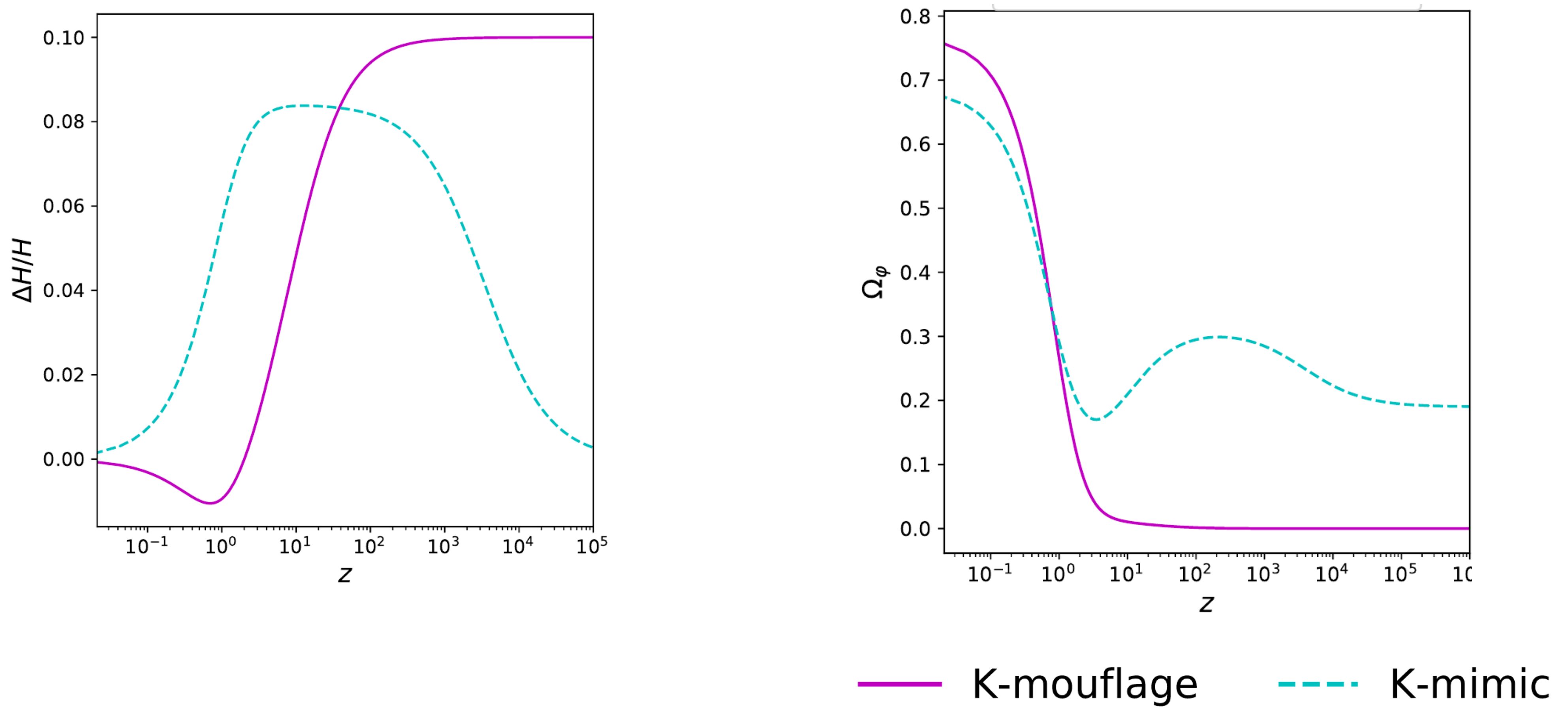
The background evolution is completely degenerate with LCDM if: $\hat{\Omega}_i = \Omega_i$

K-mimic, background evolution

Theoretical stability (no ghost) requirements impose:

$$\tilde{\chi} > 0 \qquad K' > 0 \qquad A > 0$$

can be satisfied picking $\hat{\Omega}_{\gamma 0} = \Omega_{\gamma 0}$, and $\epsilon_2 > 0$, but: $\boxed{\hat{\Omega}_{m0} > \frac{\Omega_{m0}}{1 - \epsilon_{2,0}}}$



K-mouflage VS K-mimic

General properties

- **Effective Newton constant higher than GR**

$$\epsilon_2 < 0,\ A > 1,\ 0 < a < 1$$

- **Scalar field energy negligible at high z**

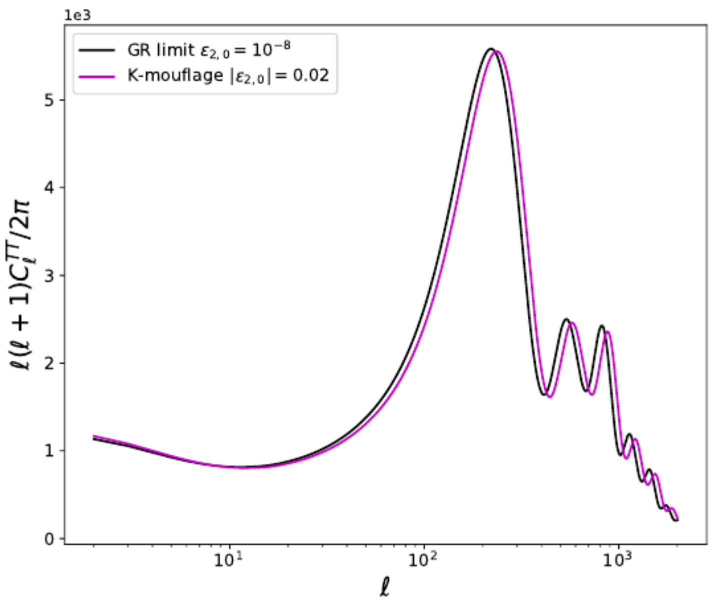
- **Effective Newton constant lower than GR**

$$\epsilon_2 > 0,\ A < 1,\ 0 < a < 1$$

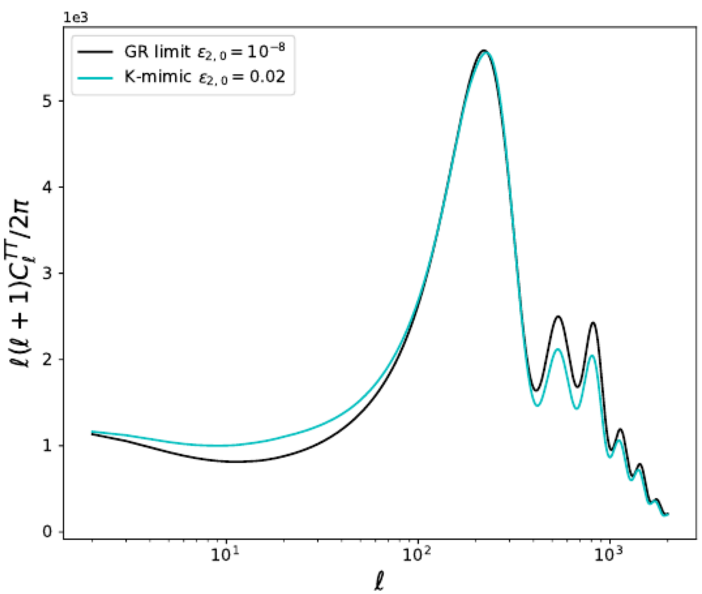
- **Scalar field never subdominant**

Observational imprints

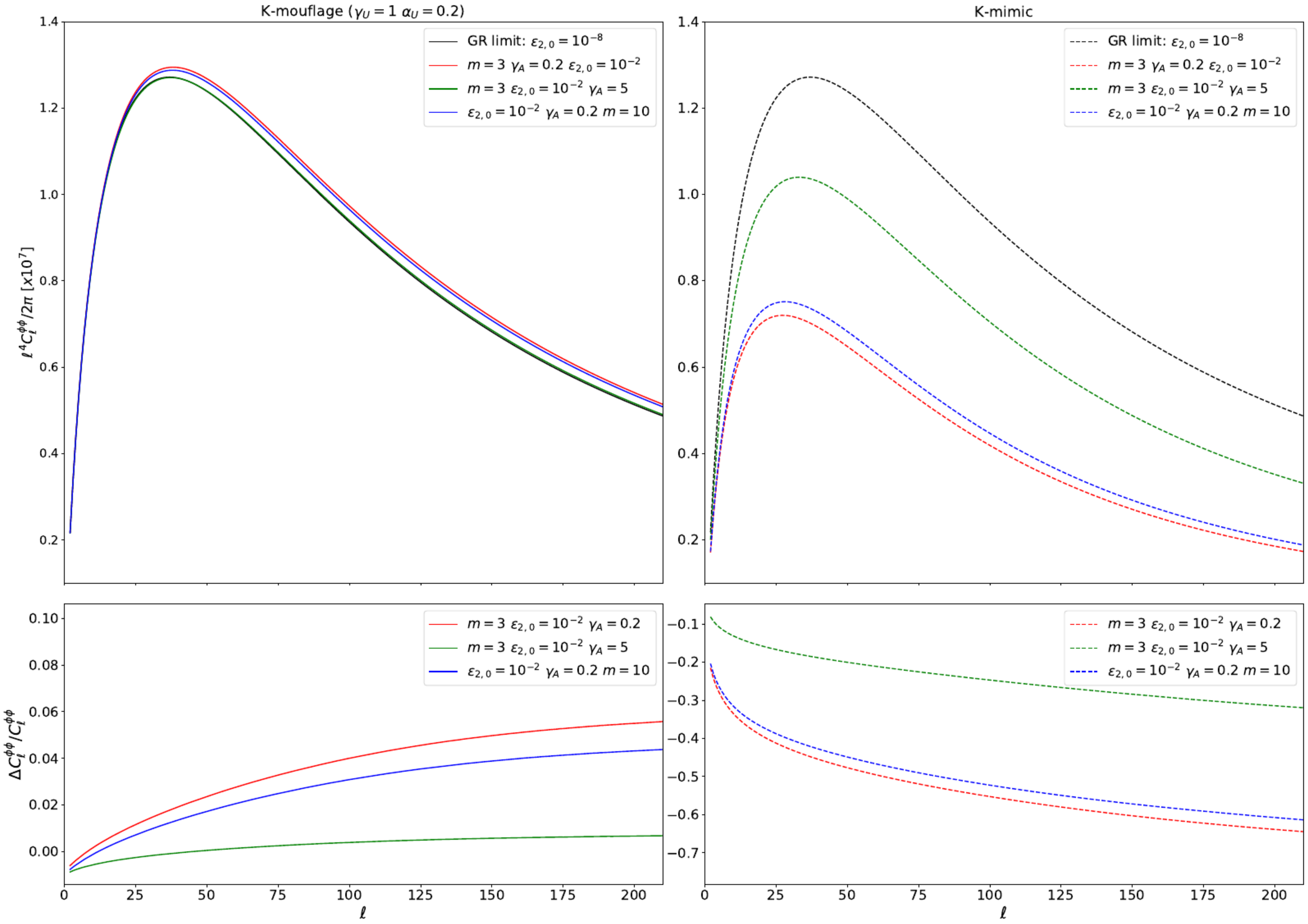
- **Shift in the acoustic peaks**
- **Weak growth enhancement**



- **No shift in the acoustic peaks**
- **Strong growth suppression**



Late-time probes: CMB lensing



Constraints on K-mouflage

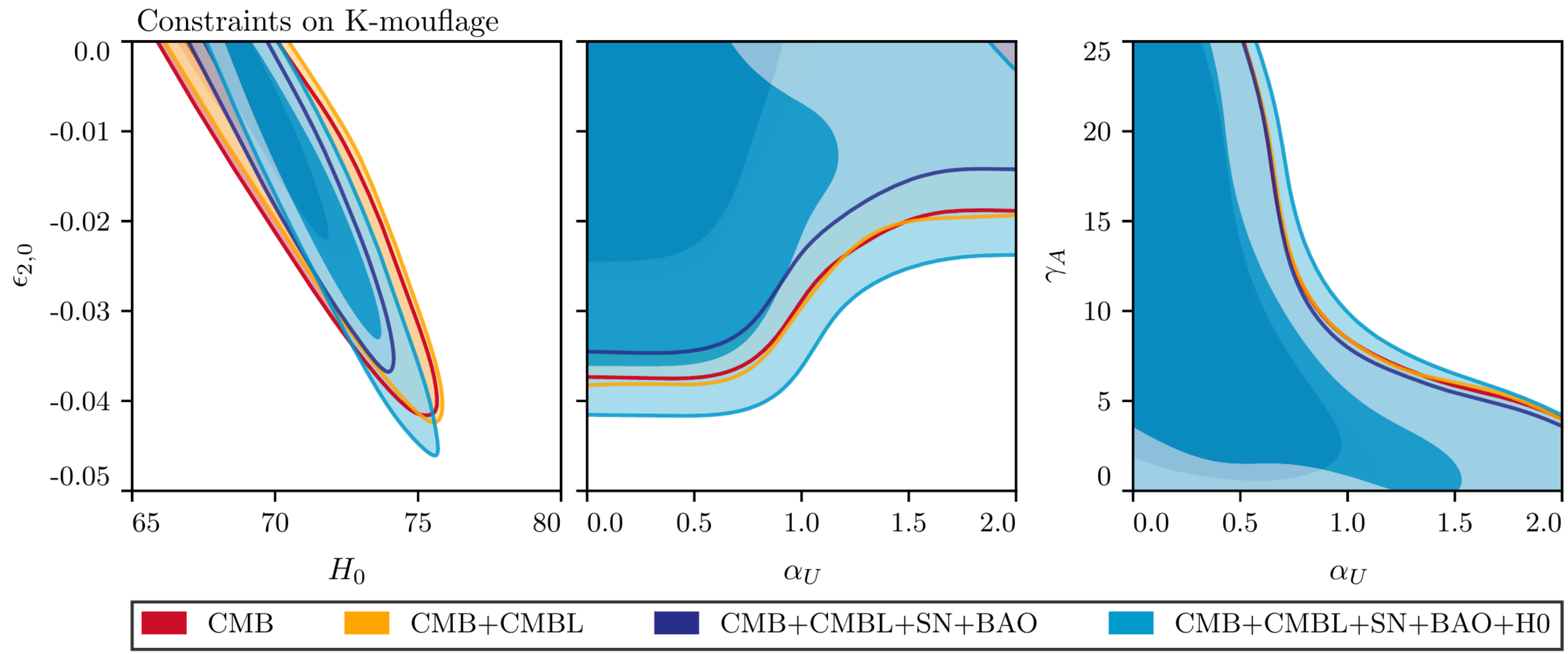


Table 4. 2σ constraints on K-mouflage parameters

parameter	CMB	CMB+CMBL	CMB+CMBL+SN+BAO	CMB+CMBL+SN+BAO+H_0
$\epsilon_{2,0}$	$-0.012^{+0.012}_{-0.02}$	$-0.012^{+0.012}_{-0.02}$	$-0.012^{+0.012}_{-0.02}$	$-0.02^{+0.02}_{-0.022}$
γ_A	$10.0^{+15.0}_{-10.0}$	$10.0^{+15.0}_{-10.0}$	$11.0^{+14.0}_{-11.0}$	$11.0^{+14.0}_{-11.0}$
α_U	$0.4^{+1.0}_{-0.42}$	$0.4^{+1.0}_{-0.42}$	$0.31^{+0.59}_{-0.31}$	$0.41^{+0.91}_{-0.41}$
γ_U	$5.7^{+4.3}_{-4.7}$	$5.7^{+4.3}_{-4.7}$	$5.6^{+4.4}_{-4.6}$	$5.5^{+4.5}_{-4.5}$
m	$5.2^{+4.8}_{-4.2}$	$5.2^{+4.8}_{-4.2}$	$5.3^{+4.7}_{-4.3}$	$5.4^{+4.6}_{-4.4}$

K-m shifts peaks, but also H_0 does, and in the same direction

Constraints on K-mimic

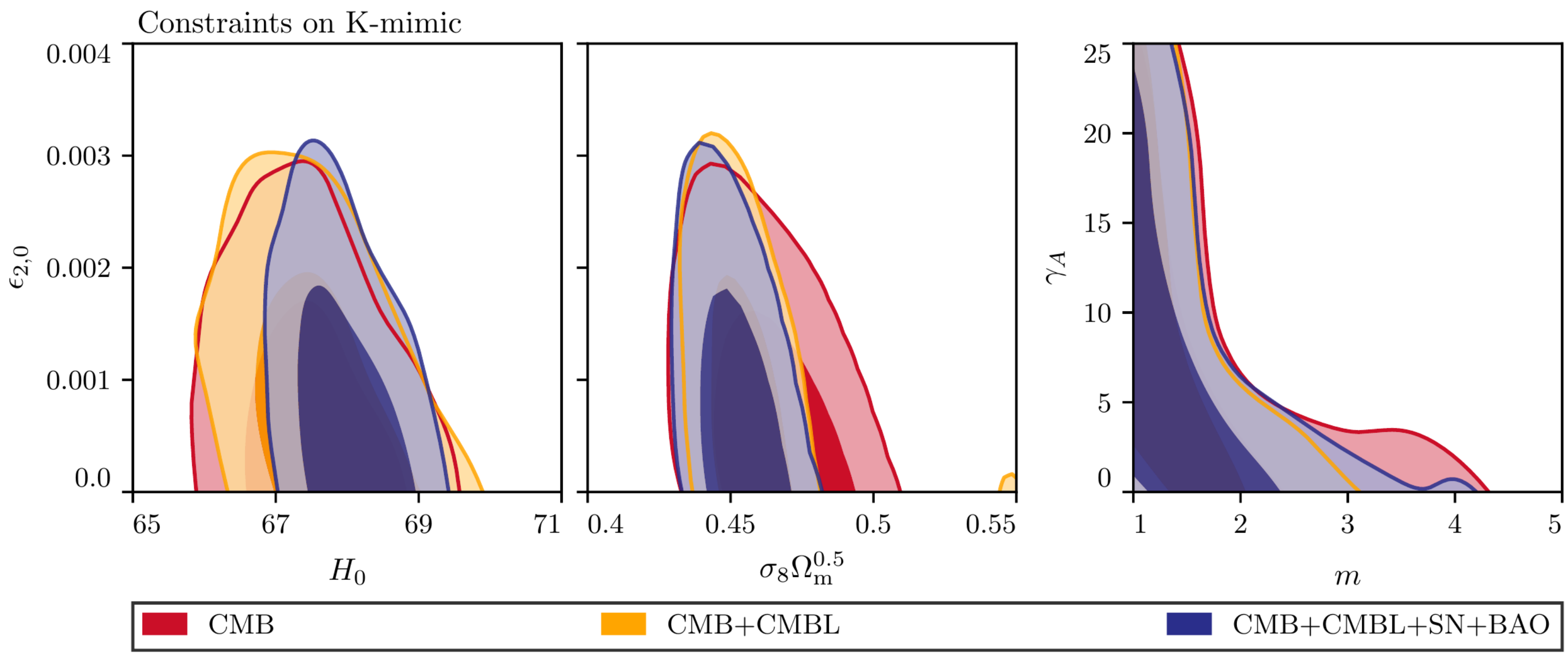


Table 5. 2σ constraints on K-mimic parameters

parameter	CMB	CMB+CMBL	CMB+CMBL+SN+BAO
$\epsilon_{2,0}$	$0.0008^{+0.0013}_{-0.00083}$	$0.001^{+0.0014}_{-0.00096}$	$0.0009^{+0.0014}_{-0.00091}$
γ_A	$8.0^{+17.0}_{-8.2}$	$9.0^{+16.0}_{-9.2}$	$8.0^{+14.0}_{-7.7}$
m	$1.6^{+1.9}_{-0.61}$	$1.4^{+1.1}_{-0.44}$	$1.5^{+1.3}_{-0.53}$

Fisher matrix forecasts

CMB experimental specifications			
Parameter	Fiducial value	σ_{Planck}	σ_{COrE}
α_U	0.1	10912	25.18
γ_U	1	54562	194
m	3	5411	378
ϵ_2	-10^{-8}	1.68×10^{-3}	1.03×10^{-4}
γ_A	0.2	39.52	17.23
$\Omega_b h^2$	0.0226	2.12×10^{-4}	2.58×10^{-5}
$\Omega_c h^2$	0.112	1.48×10^{-3}	4.99×10^{-4}
H_0	70	2.51	0.227
n_s	0.96	5.91×10^{-3}	1.41×10^{-3}
τ	0.09	4.23×10^{-3}	1.91×10^{-3}
A_s	2.10×10^{-9}	1.83×10^{-11}	8.30×10^{-12}

CONCLUSIONS

SUMMARY:

- We have analysed K-mouflage models, considering a generic parametrizations of the kinetic and coupling functions, and K-mimic models fixing the kinetic function to stay close to LCDM.

- K-mouflage predicts early-time deviations in the background and horizontal shift in the CMB power spectrum

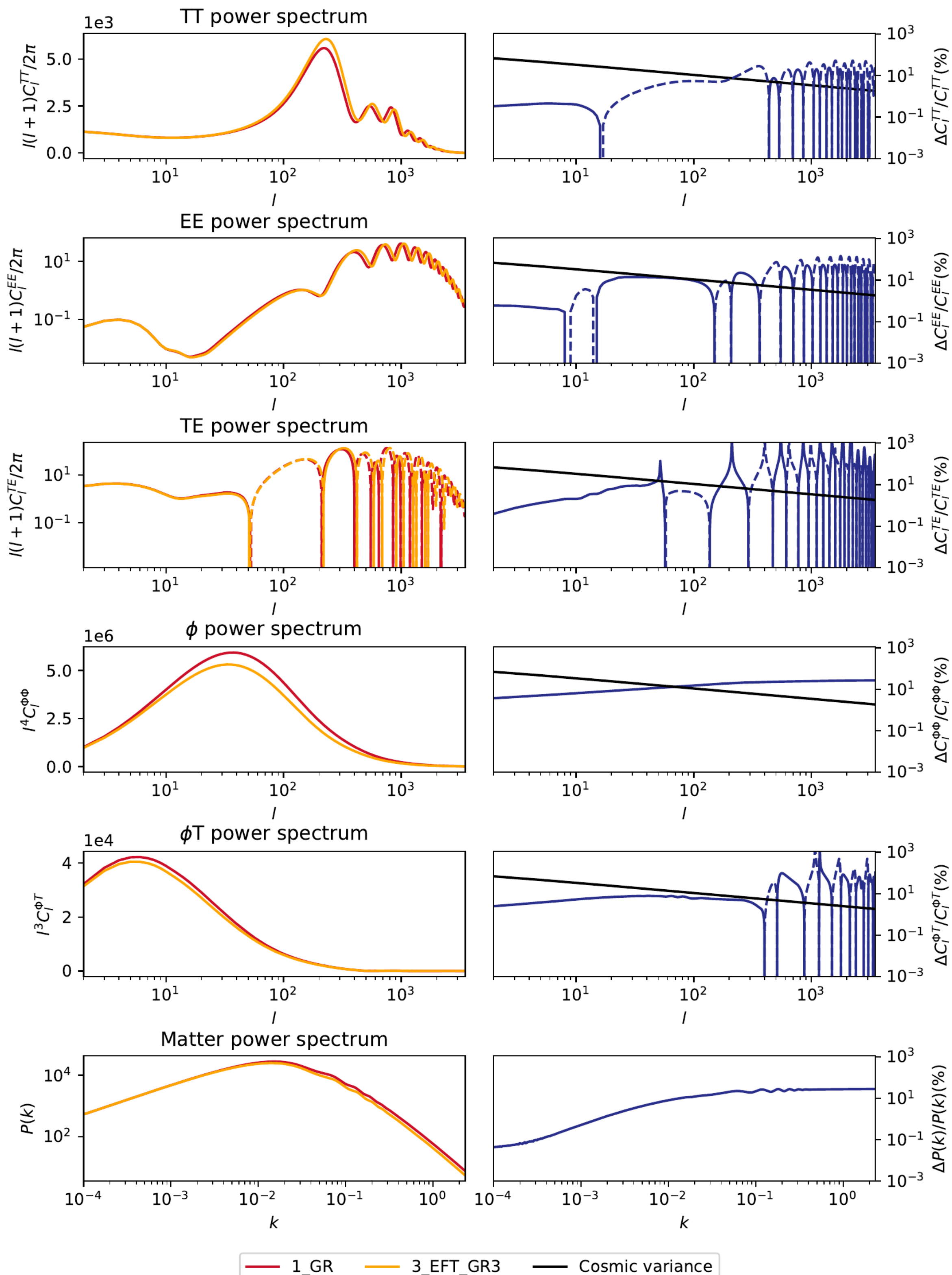
- K-mimic shows deviations in the CMB power sectrum and a strong growth suppression (very constrained by data)

- Cosmological probconstraints are complementay to Solar-System constraints

- K-mouflage models can possibly alleviate the H0 tension with local measurements

ONGOING WORK:

- Produce forecasts for upcoming surveys (e.g. Euclid)
- Analize degeneracies massive neutrinos


TT power spectrum
EE power spectrum
TE power spectrum
ϕ power spectrum
ϕT power spectrum
Matter power spectrum
1e3
1e6
1e4
$l(l+1)C_l^{TT}/2\pi$
$l(l+1)C_l^{EE}/2\pi$
$l(l+1)C_l^{TE}/2\pi$
$l^4C_l^{\Phi\Phi}$
$l^3C_l^{\Phi T}$
$P(k)$
$\Delta C_l^{TT}/C_l^{TT}(\%)$
$\Delta C_l^{EE}/C_l^{EE}(\%)$
$\Delta C_l^{TE}/C_l^{TE}(\%)$
$\Delta C_l^{\Phi\Phi}/C_l^{\Phi\Phi}(\%)$
$\Delta C_l^{\Phi T}/C_l^{\Phi T}(\%)$
$\Delta P(k)/P(k)(\%)$
l
k
1_GR
3_EFT_GR3
Cosmic variance