CMB constraints on K-mouflage models.

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Based on: Benevento et al., in prep.

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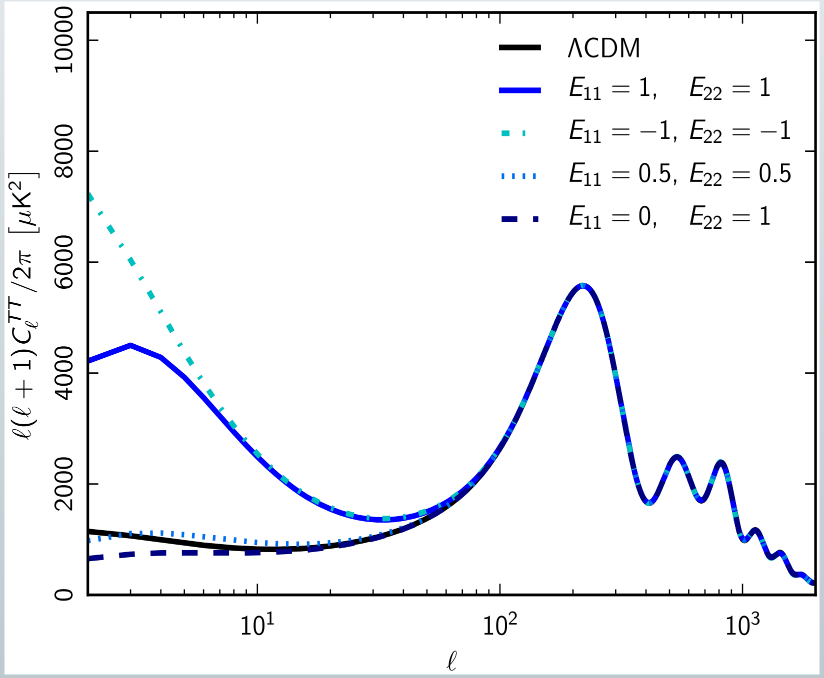
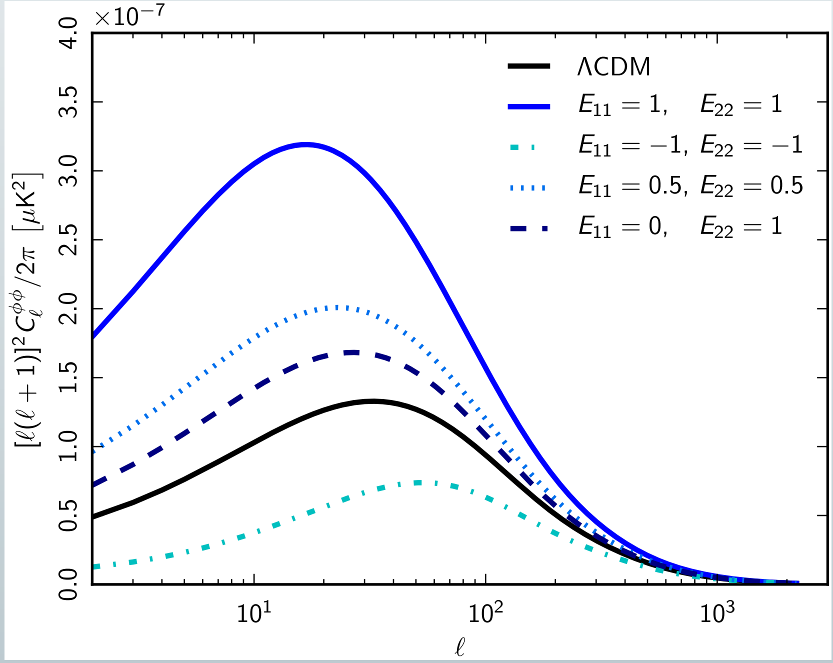
Effects of DE/MG on CMB

DE/MG can impact CMB observations in a variety of model dependent ways. Focusing on scalar perturbations:

- Modifications of background evolution: shift of peaks (projection effects)
- Late time decay of potentials: ISW effect => cross-correlation CMB-LSS
- Modifications of lensing potential.
- Modifications of growth factor => mismatch between A_s and σ_8 .





From Planck 2015 results. XIV.

K-mouflage

K-mouflage: k-essence models with universal coupling.

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

$$ds^2 = A^2(\varphi) d\tilde{s}^2 \longrightarrow \text{EF}$$

$$\downarrow$$

JF

P. Brax and P. Valageas, JCAP 01 (2016) 020
P. Brax and P. Valageas, Phys. Rev D 90, 023507 (2014)

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$$\underbrace{ds^2}_{\text{JF}} = \underbrace{A^2(\varphi)}_{\text{Coupling function}}d\tilde{s}^2 \longrightarrow \text{EF}$$

$$\tilde{\chi} = -\frac{\tilde{g}^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi}{2\mathcal{M}^4} \sim \rho_\Lambda \text{today}$$

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ds^2: JF

$A^2(\varphi)$: Coupling function

$$\tilde{\chi} = -\frac{\tilde{g}^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi}{2\mathcal{M}^4}$$

$\mathcal{M}^4 \sim \rho_\Lambda$ today

Screening condition: $$\nabla\Psi_N \geq \frac{M^2}{2\beta M_{Pl.}}$$

Screening in regions of large acceleration. In a cosmological setting: recovers GR in the Early Universe.

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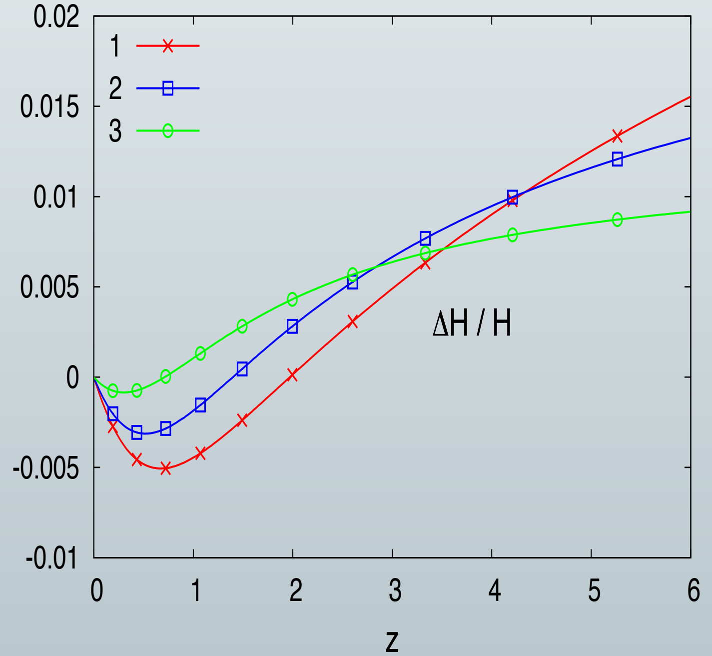
Background evolution

- Friedmann equation (note: deviations from LCDM evolution)

$$3M_{\rm Pl}^2 H^2 (1-\epsilon_2)^2 = \bar\rho + \bar\rho_{\rm rad} + \bar\rho_\varphi \,, \qquad \epsilon_2 = \frac{d\ln\bar A}{d\ln a}$$

- KG equation:

$$\frac{d}{dt}\left[\bar A^{-2} a^3 \frac{d\bar\varphi}{dt}\bar K'\right] = -a^3\bar\rho\frac{d\ln\bar A}{d\bar\varphi} = -\frac{\beta\bar\rho_0}{\tilde M_{\rm Pl}} \,, \qquad \beta(a) \equiv \tilde M_{\rm Pl}\frac{d\ln\bar A}{d\bar\varphi}$$



Parametrization in terms of scale factor:

$$U(a) \equiv a^3\sqrt{\bar{\bar\chi}}\bar K'$$

$$\propto \frac{a^2\ln(\gamma_U + a)}{(\sqrt{a_{\rm eq}}+\sqrt{a})\ln(\gamma_U+a)+\alpha_U a^2}$$

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

Perturbations

At the linear level, in the non-relativistic, linear regime, deviations from GR are governed by the parameter ε_1, defined in terms of the coupling function and kinetic term:

$$\epsilon_1 = \frac{2\beta^2}{\bar{K}'}, \qquad \Phi = (1+\epsilon_1)\Psi_{\rm N}, \quad \Psi = (1-\epsilon_1)\Psi_{\rm N}$$

Growth factor evolution

$$\frac{d^2 D}{d(\ln a)^2} + \left(2 + \frac{1}{H^2}\frac{dH}{dt}\right)\frac{dD}{d\ln a} - \frac{3}{2}\Omega_{\rm m}(1+\epsilon_1)D = 0$$

Screening (at linear level) when $\varepsilon_1 << 1$ => K' >> 1 => Early Universe background.

EFT of K-mouflage

General EFT action

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

EFT of K-mouflage

Mapping K-mouflage

$$S = \int d^4x \sqrt{-g} \left\{ \frac{m_0^2}{2} \left[1 + \Omega(\tau)\right] R + \Lambda(\tau) - a^2 c(\tau) \delta g^{00} \right.$$
$$+ \frac{M_2^4(\tau)}{2} (a^2 \delta g^{00})^2 - \cancel{\frac{\bar{M}_1^3(\tau)}{2} a^2 \delta g^{00} \delta K_\mu^\mu} - \cancel{\frac{\bar{M}_2^2(\tau)}{2} (\delta K_\mu^\mu)^2} - \cancel{\frac{\bar{M}_3^2(\tau)}{2} \delta K_\nu^\mu \delta K_\mu^\nu}$$
$$\left. + \cancel{\frac{a^2 \hat{M}^2(\tau)}{2} \delta g^{00} \delta R^{(3)}} + \cancel{m_2^2(\tau) (g^{\mu\nu} + n^\mu n^\nu) \partial_\mu (a^2 g^{00}) \partial_\nu (a^2 g^{00})} \right\} + S_m[g_{\mu\nu}]$$

$$\Omega(a) = \bar{A}^{-2} - 1$$

$$\frac{\Lambda(a) a^2}{m_0^2} = \frac{a^2 \mathcal{M}^4 \bar{K}}{m_0^2 \bar{A}^4} - \frac{3 \mathcal{H}^2 \epsilon_2^2}{\bar{A}^2}$$

$$\frac{c(a) a^2}{m_0^2} = \frac{a^2 M^4 \bar{\tilde{\chi}} \frac{\mathrm{d}\bar{K}}{\mathrm{d}\tilde{\chi}}}{m_0^2 \bar{A}^4} - \frac{3 \epsilon_2^2 \mathcal{H}^2}{\bar{A}^2}$$

$$\gamma_1(a) = \frac{M_2^4}{m_0^2 H_0^2} = \frac{\mathcal{M}^4 A^{-4} \bar{\tilde{\chi}}^2 \frac{\mathrm{d}^2 \bar{K}}{\mathrm{d}\tilde{\chi}^2}}{m_0^2 H_0^2}$$

- Mapping implemented in EFTCAMB
- Planck 2015 analysis sets background to ΛCDM and $M_2^4 = 0$

Data analysis

Approaches to CMB data analysis:

- Model dependent. Choose a specific model and fit parameters to the data
- Phenomenological parametrization. Parametrize (usually) Newtonian Gauge potentials and use parametrizations to constrain deviations from expected behaviour in GR., e.g.

$$-k^2\Psi \equiv 4\pi G a^2 \mu(a,\boldsymbol{k})\rho\Delta$$

$$-k^2(\Phi+\Psi) \equiv 8\pi G a^2 \Sigma(a,\boldsymbol{k})\rho\Delta$$

$$\eta(a,\boldsymbol{k}) \equiv \Phi/\Psi$$

- Theory-driven parametrization: EFT, Horndeski.

In this analysis we take a “hybrid” approach: EFT mapping of a specific class of models, namely K-mouflage.
We will consider a general parametrization of K and A.

Choice of parameters and priors

$$\frac{1}{U} \propto \frac{\sqrt{a_{\rm eq}}}{a^2} + \frac{1}{a^{3/2}} + \frac{\alpha_U}{\ln(\gamma_U + a)}$$

- General parametrization producing the behaviour U(a) ~ t(a) (if not, energy density of ϕ dominates over matter at early times).

  Very weak dependence of cosmology on γ_U. We fix **$\gamma_U = 1$** .
  $\alpha_U \sim 1$ sets transition into dark energy era. We choose **$0 < \alpha_U < 10$**

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

- If $K \sim \chi^m$, then $\nu_A = \dfrac{3(m-1)}{2m-1}$, **$m > 1$**.

  γ_A sets transition into DE era, $\gamma_A \sim 1$. We set **$0 < \gamma_A < 20$**

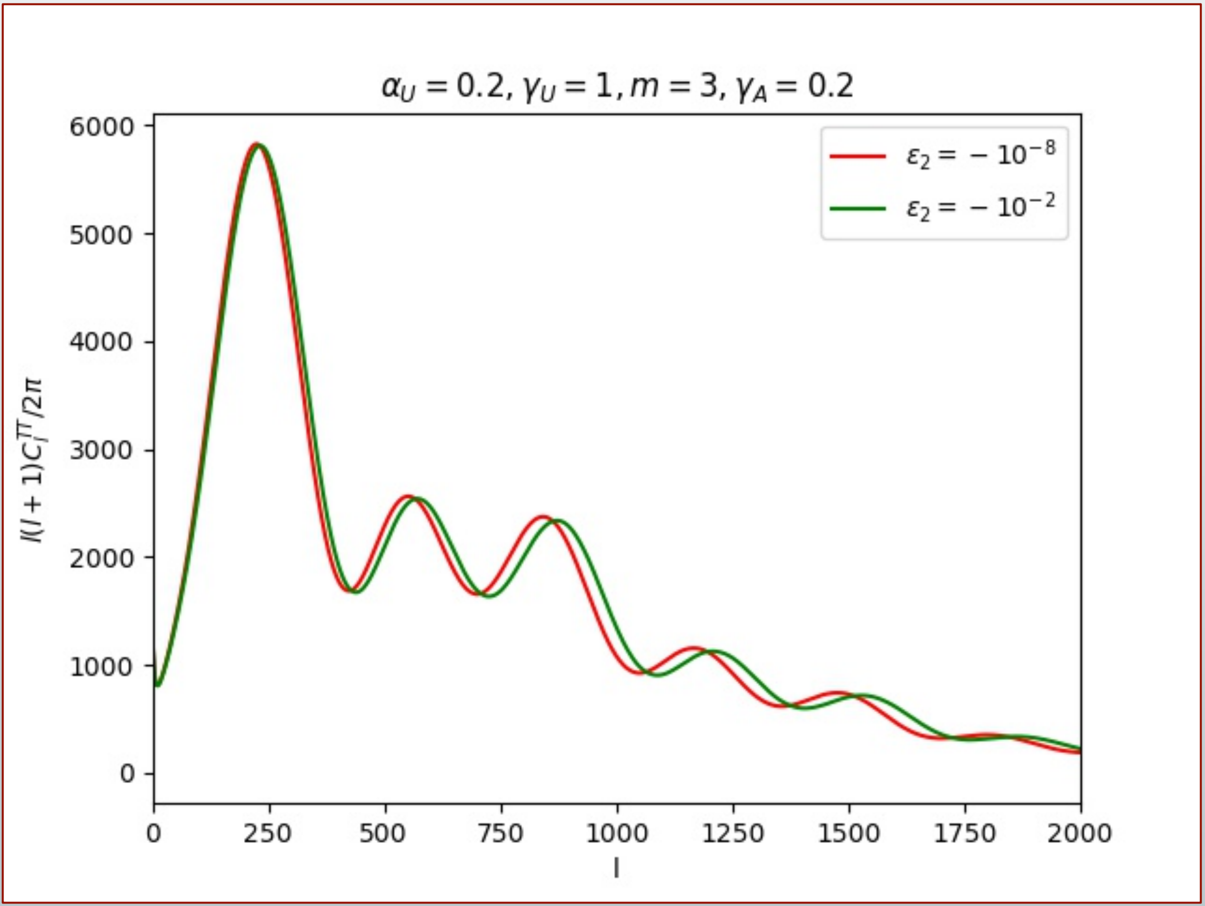
- **$-0.01 < \epsilon_{2,0} < 0$** (solar system bounds), $\epsilon_{2,0} = -\dfrac{\alpha_A \gamma_A \nu_A}{\gamma_A + 1}$

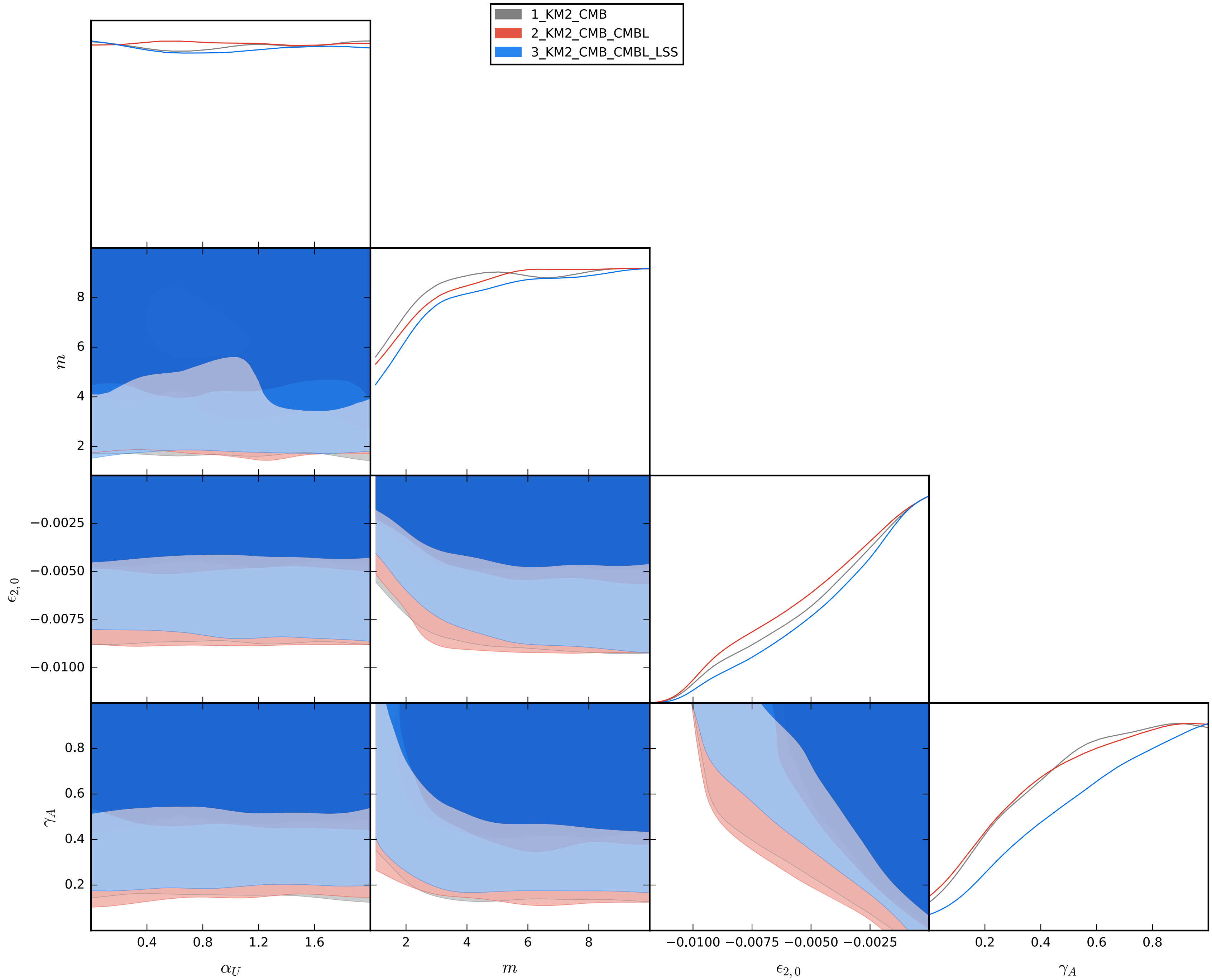
- Growth of perturbations is governed by ε_1. It is possible to show that ε_1 and ε_2 are related

$$\epsilon_1(a) = -\,\epsilon_2\,\frac{2\left(-3\epsilon_2 + \frac{d\ln U}{d\ln a}\right)}{3\Omega_{\rm m}}$$

Projection effects

Main effect: shift of the peaks toward higher l, due to changes in background evolution.

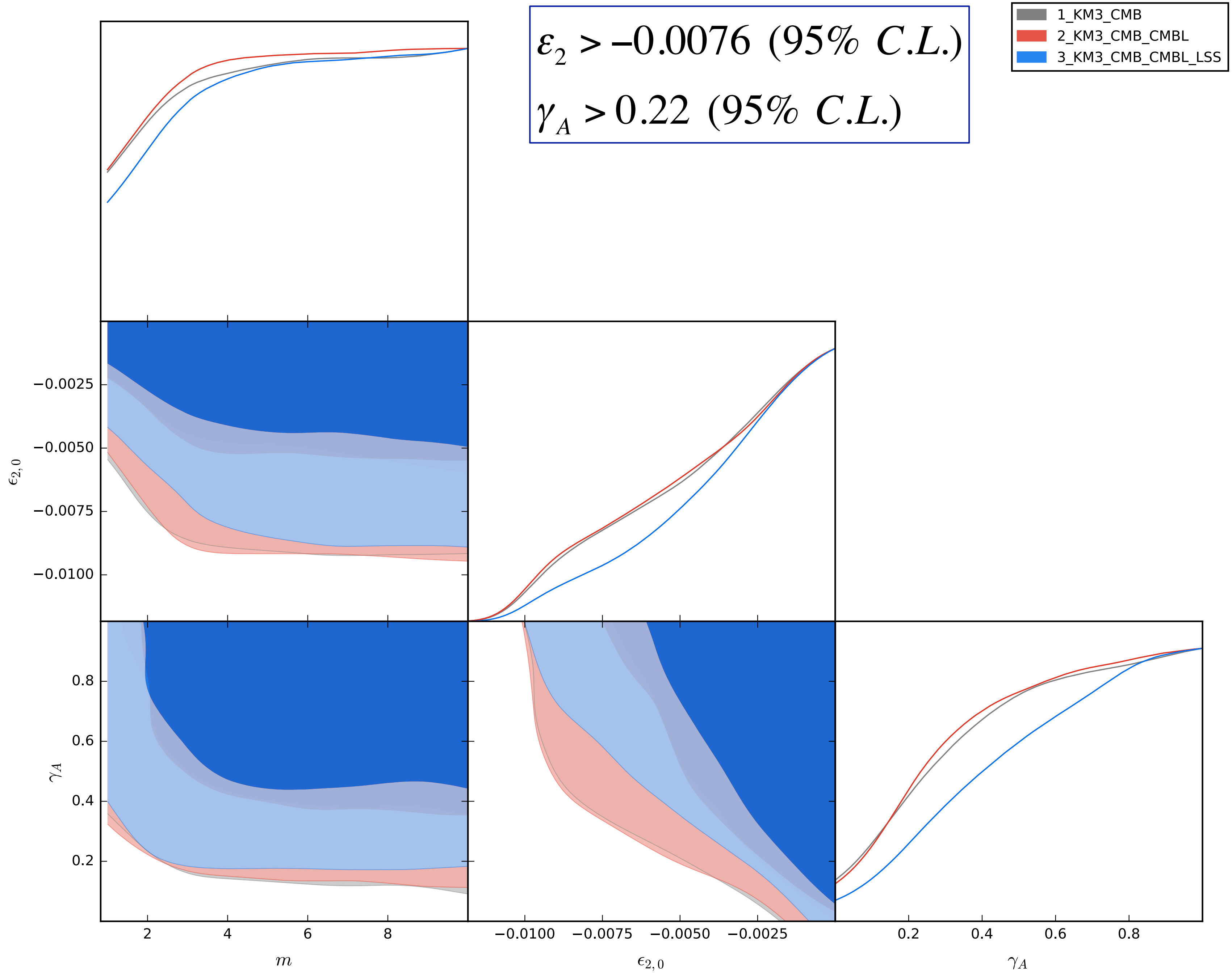




1_KM2_CMB
2_KM2_CMB_CMBL
3_KM2_CMB_CMBL_LSS
m
$\epsilon_{2,0}$
γ_A
α_U
0.4
0.8
1.2
1.6
2
4
6
8
−0.0025
−0.0050
−0.0075
−0.0100
0.2
0.4
0.6
0.8

$$\varepsilon_2 > -0.0076 \ (95\% \ C.L.)$$

$$\gamma_A > 0.22 \ (95\% \ C.L.)$$



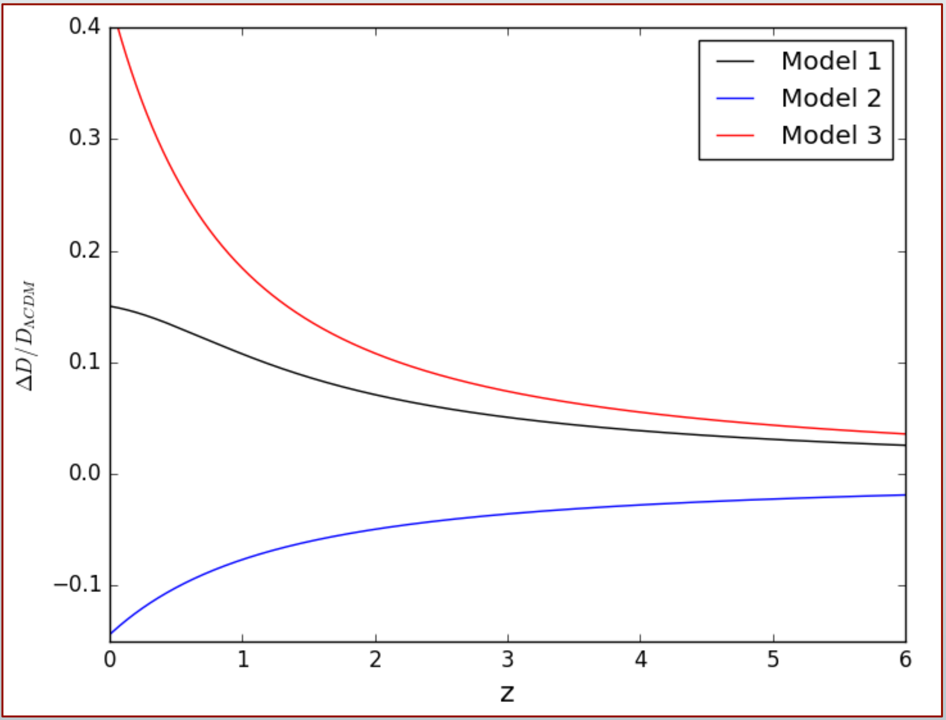
Forecasts

	Fiducial	Planck	COrE
α_U	0.2	10912	25.18
γ_U	1	54562	194.52
m	3	5411	378
ε_2	-10^{-8}	1.68×10^{-3}	0.000103
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}	1.9110^{-3}
A_s	2.10×10^{-9}	1.83×10^{-11}	8.30×10^{-12}

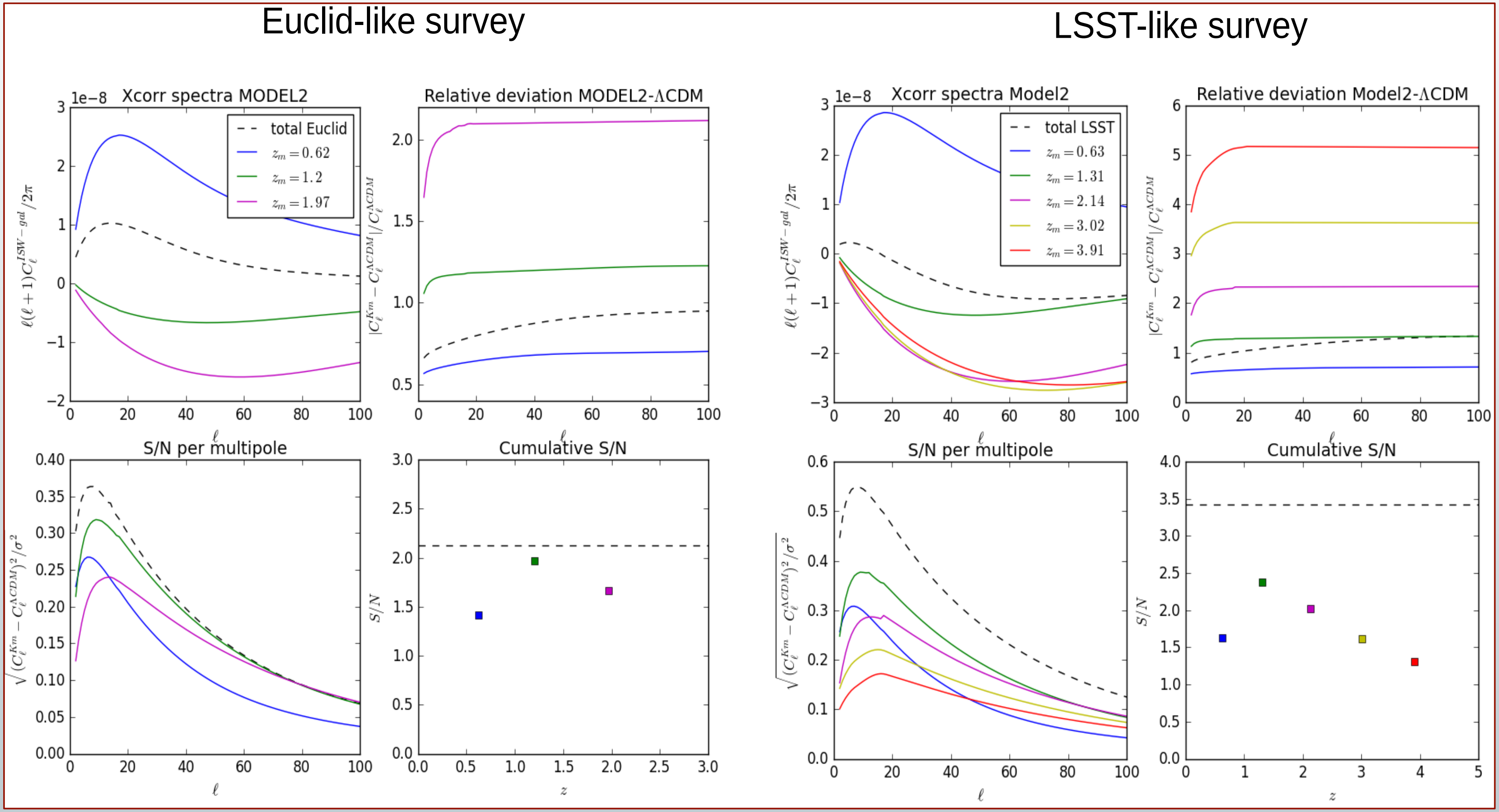
ISW-galaxy

	Kinetic term	Coupling function	β	m	K_0
Model 1	$-1+\chi+K_0\chi^m$	$A = e^{\beta\varphi\sqrt{8\pi G}}$	0.3	3	1
Model 2	$-1+\chi+K_0\chi^m$	$A = e^{\beta\varphi\sqrt{8\pi G}}$	0.3	3	-5
Model 3	$-1+\chi-\chi^2+\chi^3/4$	$A = e^{\beta\varphi\sqrt{8\pi G}}$	0.3	-	-

Growth factor: K-mouflage vs. ΛCDM



ISW-tomography (model 2)



Conclusions

- We have analyzed K-mouflage models, considering a general parametrization of the kinetic and coupling functions.

- Steps:
  - Describe linear perturbations in K-mouflage in EFT framework
  - Map model in EFTCAMB
  - MCMC (CMB + lensing + BAO + SN)

- Most of the constraining power comes from non-trivial background evolution, up to high redshift. Shifting of the peaks.

- Forecasts for future generation CMB surveys shows possible order of magnitude improvement in constraining power for crucial parameters.

- Growth factor evolution differs from LCDM also in matter domination. ISW tomography can be interesting with future LSS surveys (model dependent analysis so far)

- And of course still need to check other LSS observables.