PONT AVIGNON 2017

DARK ENERGY WITH KINETIC MATTER MIXING

Based on 1609.01272 with G. D'Amico, Z. Huang, F. Vernizzi

Michele Mancarella
IPhT - CEA Saclay

ΛCDM and beyond

WHY ?

- ΛCDM predicts **unique** growth of structure. Compatible with data, but space for deviations
- Alternative models predict **more dynamics** (& free parameters) at the level of perturbations
- $10\text{-}10^2$ improvement expected in measurements of growth of structures. **Deviations testable**.

HOW ? EFFECTIVE THEORY OF DARK ENERGY

- Parametrizes linear perturbations in **single scalar field** models
- Simple, **minimal** way to bridge theory and observations. **Deviations from GR** as relevant parameters
- In this talk: effect of kinetic mixing between matter and scalar (Kinetic Matter Mixing-KMM)

Gravitational sector: a general action

- Scalar **breaks time diffs** and preserves times diffs - add all terms compatible with this pattern in unitary gauge & ADM (3+1) decomposition Creminelli *et al.*, hep-th/0606090 ; Cheung *et al.*, 0709.0293

- **Linear perturbations**, one d.o.f. without higher derivatives:

Gleyzes *et al.*, 1304.4840, Bellini & Sawicki, 1404.3713,

Running Planck mass

$$S^{(2)} = \int d^4x \, a^3 \frac{M^2(t)}{2} \left[\delta K_{ij} \delta K^{ij} - \delta K^2 + \delta_2 \left(\sqrt{h}/a^3 \, {}^{(3)}R \right) + \delta N \, {}^{(3)}R \right.$$

GR

$$\left. + \alpha_K(t) H^2(t) \, \delta N^2 + 4 \alpha_B(t) H(t) \, \delta N \delta K + \alpha_T(t) \, \delta_2 \left(\sqrt{h}/a^3 R \right) + \alpha_H(t) \, \delta N \, {}^{(3)}R \right]$$

Standard kinetic term (quintessence, k-essence)

Kinetic mixing gravity-scalar

Tensor speed excess

"Beyond Horndeski"/ GLPV

$$ds^2 = -N^2 dt^2 + h_{ij} \left(N^i dt + dx^i \right) \left(N^j dt + dx^j \right)$$

Lapse	N		$\dot{\phi}$	time kinetic energy of the scalar
Extrinsic curvature	K_{ij}	$\sim$	$\dot{h}_{ij}$	time kinetic energy of the metric
Intrinsic curvature	${}^{(3)}R_{ij}$	$\sim$	∇h_{ij}	spatial kinetic energy of the metric

Disformal couplings to matter

- Structure of the action unchanged under transformation:

Bettoni and Liberati '13, Gleyzes et al. '14, Domnech, Naruko, Sasaki'15

$$\tilde{g}_{\mu\nu} = C(\phi) g_{\mu\nu} + D(\phi, X) \partial_\mu \phi \partial_\nu \phi \qquad X \equiv g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi$$

$$S[g_{\mu\nu}, \alpha_I] = \tilde{S}[\tilde{g}_{\mu\nu}, \tilde{\alpha}_I] \qquad \tilde{\alpha}_I = \mathcal{F}_I (\alpha_J)$$

Disformal couplings to matter

- Structure of the action unchanged under transformation:

Bettoni and Liberati '13, Gleyzes et al. '14, Domnech, Naruko, Sasaki'15

$$\tilde{g}_{\mu\nu} = C(\phi) g_{\mu\nu} + D(\phi, X)\partial_\mu\phi\partial_\nu\phi \qquad X \equiv g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi$$

$$S[g_{\mu\nu}, \alpha_I] = \tilde{S}[\tilde{g}_{\mu\nu}, \tilde{\alpha}_I] \qquad \tilde{\alpha}_I = \mathcal{F}_I(\alpha_J)$$

- Couple matter to a Jordan frame metric of this form: $S_m = \int d^4x \mathcal{L}_m(\tilde{g}_{\mu\nu}, \psi_m)$

3 new parameters

$$\alpha_{C,m} = \frac{d\ln C_m}{d\ln a}\,, \quad \alpha_{D,m} = \frac{D_m}{C_m - D_m}\,, \quad \alpha_{X,m} = \frac{1}{C_m}\frac{\partial D_m}{\partial X}$$

1504.05481 with J. Gleyzes, D. Langlois, F. Vernizzi
1609.01272 with G. D'Amico, Z. Huang, F. Vernizzi

Kinetic Matter Mixing

- "Beyond Horndeski" = Kinetic Matter Mixing (KMM) with frame-invariant dispertion relation:

$$(\omega^2 - c_s^2 k^2)(\omega^2 - c_{\rm m}^2 k^2) = \lambda^2 c_s^2\, \omega^2 k^2$$

$$\lambda^2 \equiv \frac{1}{M^2 H^2\, \alpha c_s^2} \Big[\rho_{\rm m} + (1+\alpha_{D,{\rm m}}) p_{\rm m}\Big] \left(\alpha_H - \alpha_{X,{\rm m}}\right)^2$$

frame-invariant parameter measuring the degree of KMM

Kinetic Matter Mixing

- "Beyond Horndeski" = Kinetic Matter Mixing (KMM) with frame-invariant dispertion relation:

$$(\omega^2 - c_s^2 k^2)(\omega^2 - c_{\rm m}^2 k^2) = \lambda^2 c_s^2\, \omega^2 k^2$$

$$\lambda^2 \equiv \frac{1}{M^2 H^2\, \alpha c_s^2}\left[\rho_{\rm m} + (1+\alpha_{D,{\rm m}})p_{\rm m}\right](\alpha_H - \alpha_{X,{\rm m}})^2$$

frame-invariant parameter measuring the degree of KMM

$$\tilde{g}_{\mu\nu} = g_{\mu\nu} + D(\phi, X)\partial_\mu\phi\partial_\nu\phi \qquad \Rightarrow \qquad \tilde{\alpha}_{\rm H} = \frac{\alpha_{\rm H} - \alpha_{\rm X}}{1+\alpha_{\rm X}} \qquad \tilde{\alpha}_{\rm X,m} = \frac{\alpha_{\rm X,m} - \alpha_{\rm X}}{1+\alpha_{\rm X}}$$

Kinetic Matter Mixing

- "Beyond Horndeski" = Kinetic Matter Mixing (KMM) with frame-invariant dispertion relation:

$$(\omega^2 - c_s^2 k^2)(\omega^2 - c_{\rm m}^2 k^2) = \lambda^2 c_s^2\, \omega^2 k^2$$

$$\lambda^2 \equiv \frac{1}{M^2 H^2\, \alpha c_s^2}\Big[\rho_{\rm m} + (1+\alpha_{D,{\rm m}}) p_{\rm m}\Big]\,(\alpha_H - \alpha_{X,{\rm m}})^2$$

frame-invariant parameter measuring the degree of KMM

$$\tilde g_{\mu\nu} = g_{\mu\nu} + D(\phi, X)\partial_\mu\phi\partial_\nu\phi \qquad \Rightarrow \qquad \tilde\alpha_{\rm H} = \frac{\alpha_{\rm H} - \alpha_{\rm X}}{1+\alpha_{\rm X}} \qquad \tilde\alpha_{\rm X,m} = \frac{\alpha_{\rm X,m} - \alpha_{\rm X}}{1+\alpha_{\rm X}}$$

- Scalar-matter coupled system on sub-Hubble scales in Newtonian gauge:

$$\mathcal{L} = \frac{1}{2}\left\{\left(1 + \frac{c_s^2}{c_{\rm m}^2}\lambda^2\right)\dot\pi_{\rm c}^2 - c_s^2(\nabla\pi_{\rm c})^2 + \dot v_{\rm c}^2 - c_{\rm m}^2(\nabla v_{\rm c})^2 + 2\frac{c_s}{c_{\rm m}}\lambda\, \dot v_{\rm c}\, \dot\pi_{\rm c}\right\}$$

Kinetic Matter Mixing

- Growth of matter density contrast in Newtonian gauge & "quasi-static" limit ($k >> aHc_s^{-1}$):

$$\ddot{\delta}_m + (2+\gamma)\, H\dot{\delta}_m = \frac{3}{2}H^2\Omega_m \mu_\Phi \delta_m$$

ΛCDM: $\mu_\Phi = 1\,, \gamma = 0$

No KMM: $\mu_\Phi \geq 1\,, \gamma = 0$ KMM: can have $\mu_\Phi < 1$ & additional friction, $\gamma \neq 0$

Kinetic Matter Mixing

- Growth of matter density contrast in Newtonian gauge & "quasi-static" limit ($k >> aHc_s^{-1}$):

$$\ddot{\delta}_m + (2 + \gamma)\, H\dot{\delta}_m = \frac{3}{2} H^2 \Omega_m \mu_\Phi \delta_m$$

ΛCDM: $\mu_\Phi = 1\,, \gamma = 0$

No KMM: $\mu_\Phi \geq 1\,, \gamma = 0$ KMM: can have $\mu_\Phi < 1$ & additional friction, $\gamma \neq 0$

- **Time dependence** of the parameters: focus only on KMM, $\alpha_B = \alpha_T = 0\,, M(t) = M_{\rm Pl}$

$$H^2 = H_0^2 \left[\Omega_{\rm m0} a^{-3} + 1 - \Omega_{\rm m0}\right] \qquad \alpha_I(t) = \alpha_{I,0} \frac{1 - \Omega_{\rm m}(t)}{1 - \Omega_{\rm m,0}} \qquad I = K, H$$

Kinetic Matter Mixing

- Growth of matter density contrast in Newtonian gauge & "quasi-static" limit ($k >> aHc_s^{-1}$):

$$\ddot{\delta}_m + (2+\gamma)\, H\dot{\delta}_m = \frac{3}{2}H^2\Omega_m\mu_\Phi\delta_m$$

ΛCDM: $\mu_\Phi = 1\,, \gamma = 0$

No KMM: $\mu_\Phi \geq 1\,, \gamma = 0$ KMM: can have $\mu_\Phi < 1$ & additional friction, $\gamma \neq 0$

- **Time dependence** of the parameters: focus only on KMM, $\alpha_B = \alpha_T = 0\,, M(t) = M_{\rm Pl}$

$$H^2 = H_0^2\left[\Omega_{\rm m0}a^{-3} + 1 - \Omega_{\rm m0}\right] \qquad \alpha_I(t) = \alpha_{I,0}\frac{1-\Omega_{\rm m}(t)}{1-\Omega_{\rm m,0}} \qquad I = K, H$$

- **Stability conditions** (no ghost & gradients instabilities):

$$\alpha_K \geq 0\,, \quad 0 \leq \alpha_H \leq \frac{2}{3\Omega_m} \quad \Rightarrow \quad \mu_\Phi = 1 - \gamma \leq 1$$

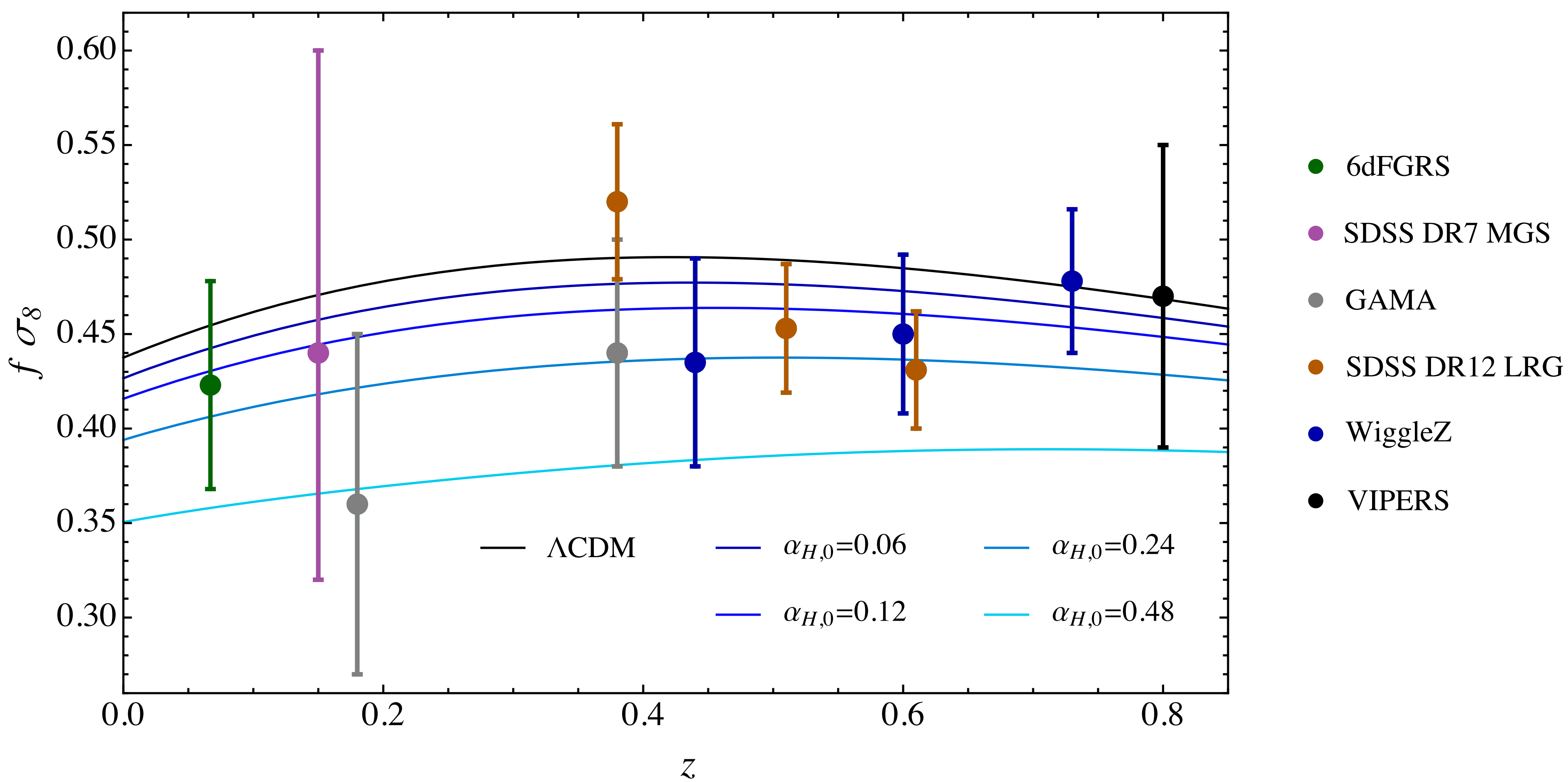
stability implies weakening of gravity!

Effect of Kinetic Matter Mixing

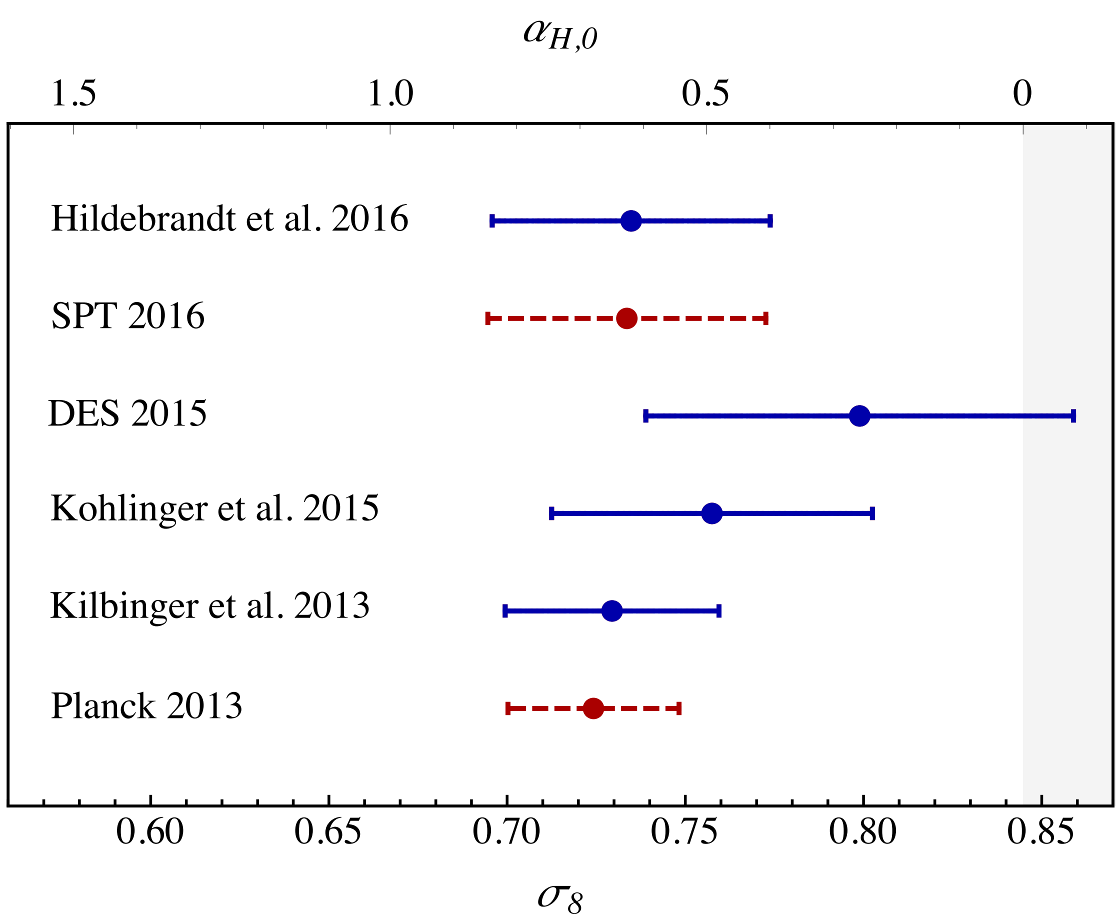
- Phenomenology beyond QS limit: Boltzmann codes. COOP (Huang), EFTCAMB (Hu, Raveri, Frusciante, Silvestri), hi_class (Zumalacarregui, Bellini, Sawicki, Lesgourgues)

Effect of Kinetic Matter Mixing

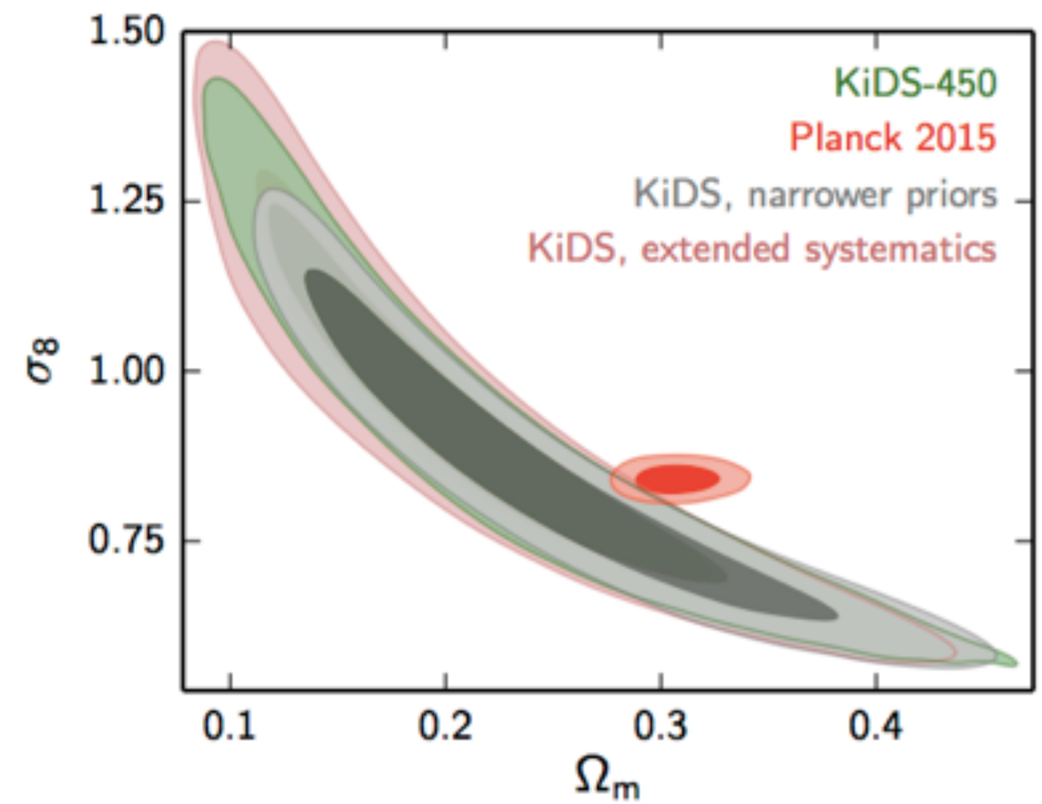
- Phenomenology beyond QS limit: Boltzmann codes. COOP (Huang), EFTCAMB (Hu, Raveri, Frusciante, Silvestri), hi_class (Zumalacarregui, Bellini, Sawicki, Lesgourgues)



Effect of Kinetic Matter Mixing

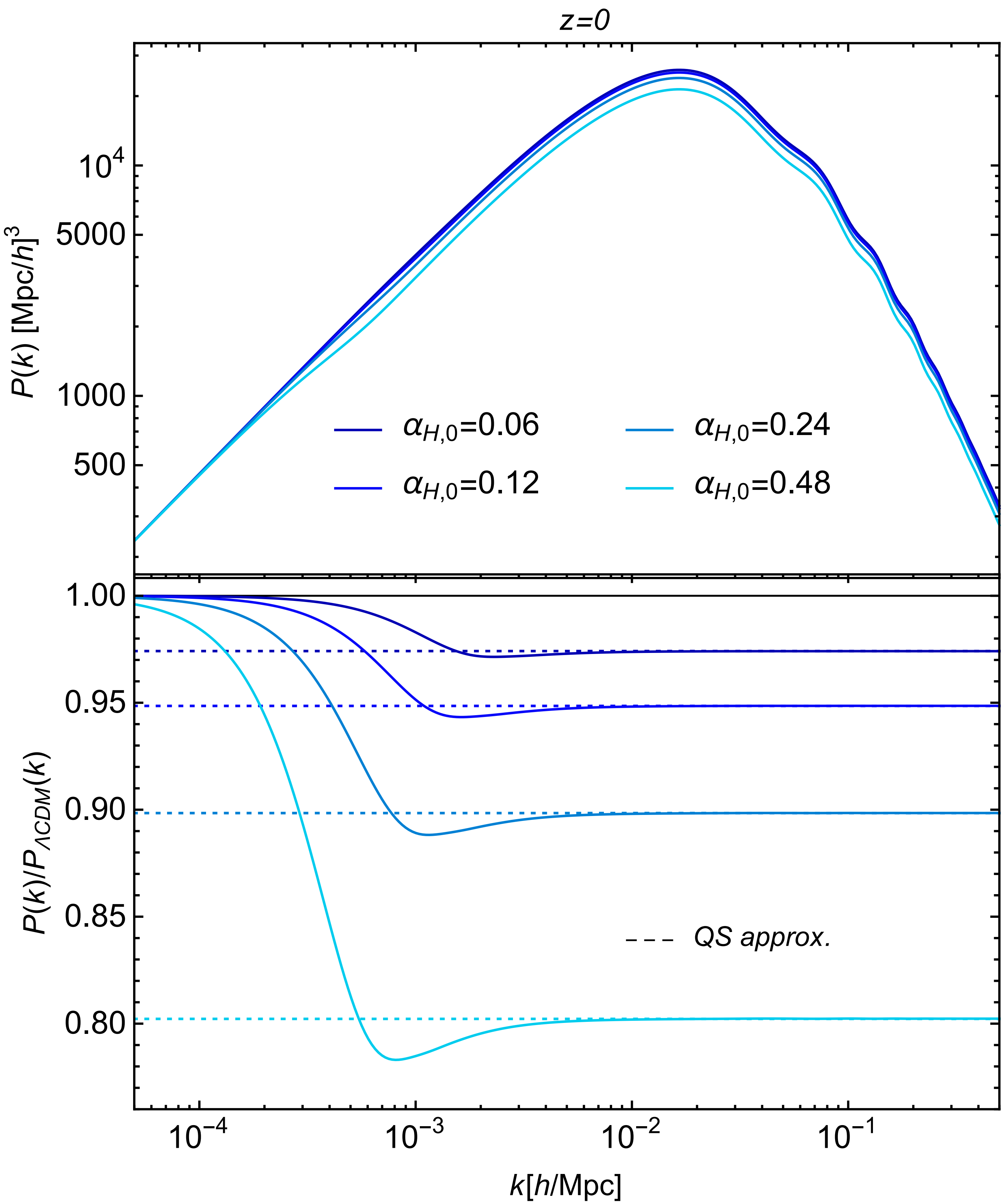


Joudaki et al '16



- The effect of KMM goes in the direction of alleviating the tension between the Planck satellite measurements and lensing observations

Power Spectrum



- Excellent agreement with QS solution of

$$\ddot{\delta}_m + (2+\gamma)\, H\dot{\delta}_m = \frac{3}{2} H^2 \Omega_m \mu_\Phi \delta_m$$

Conclusions

- Effective Theory of Dark Energy: a unifying description of scalar-tensor theories of gravity, **general** but **effective** (stability, parametrise deviations from GR at perturbative level), based on symmetries

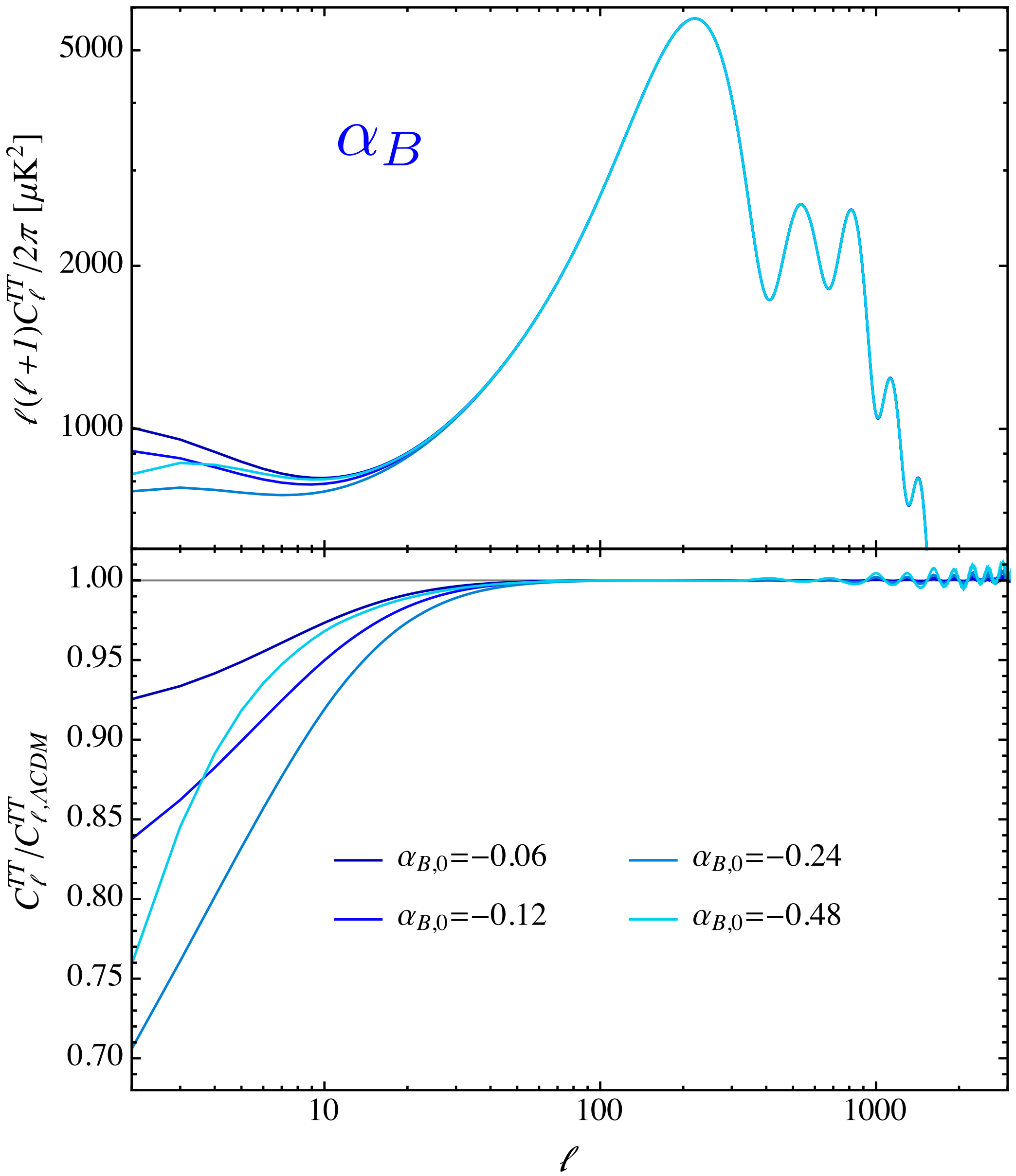
- Impact on observables: we can find dark energy in perturbations!

- We can fully solve equations at all scales thanks to Boltzmann codes

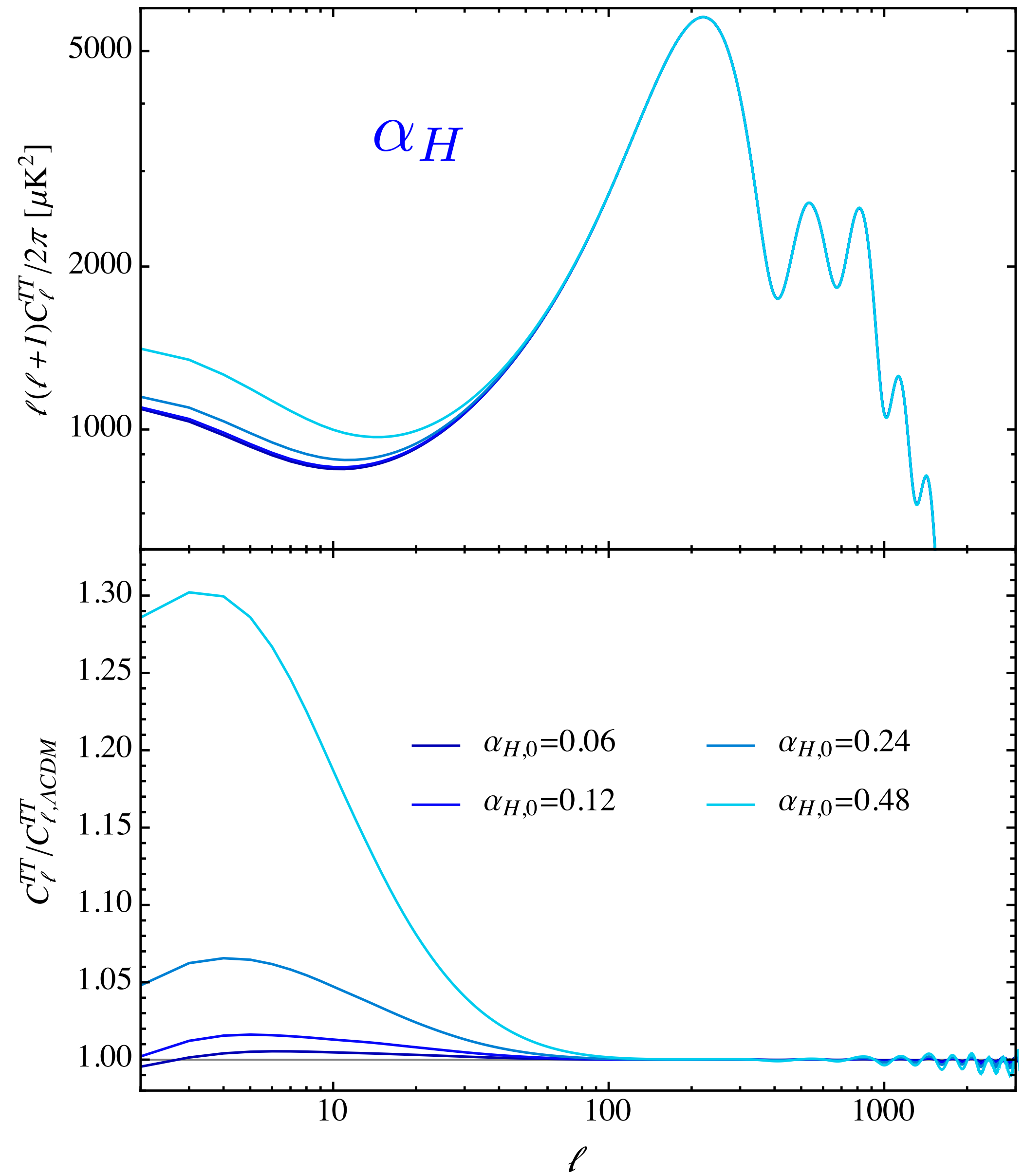
- Kinetic Matter Mixing: weakens gravity when stability conditions are imposed. A way to alleviate tensions?

CMB

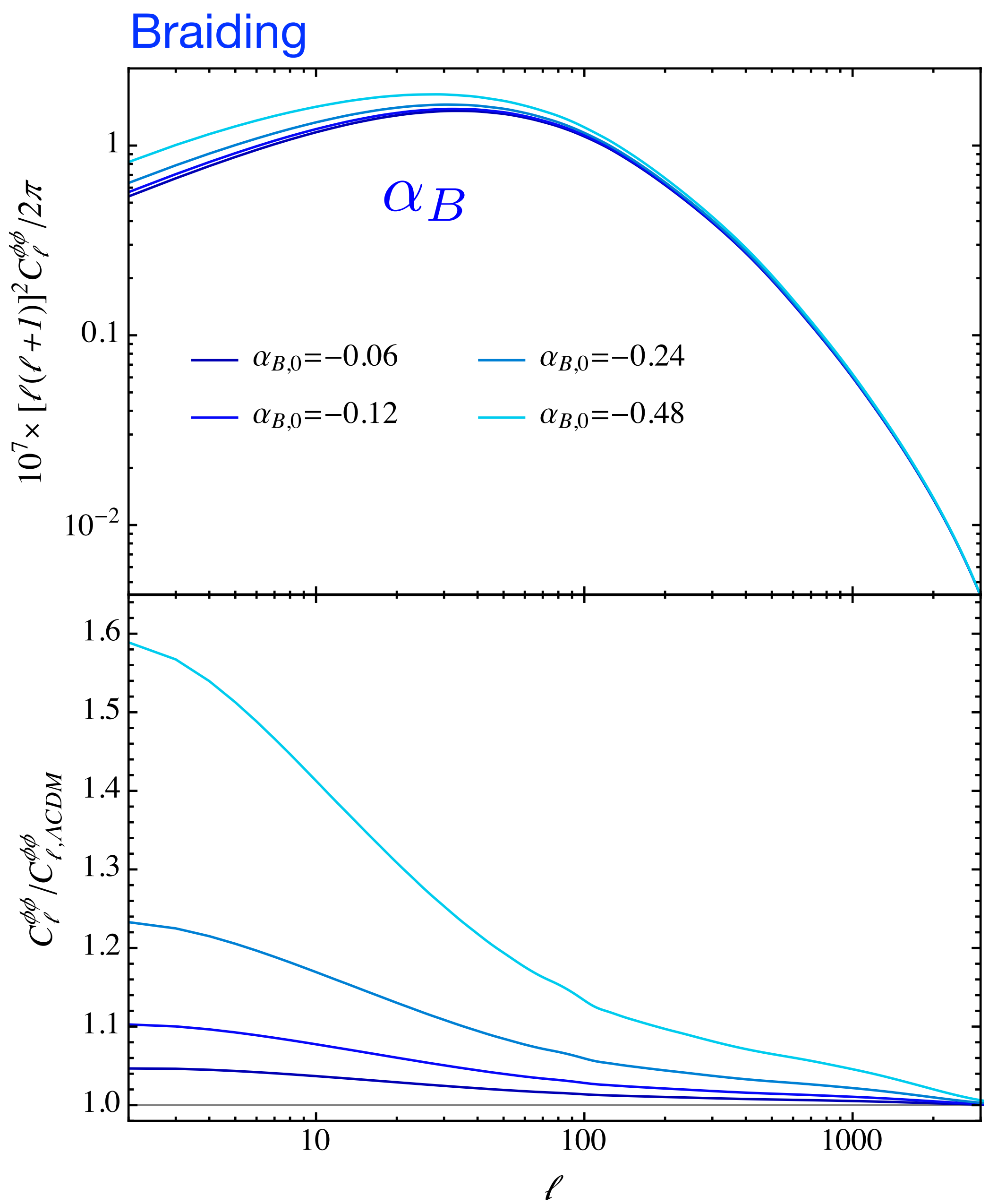
Braiding



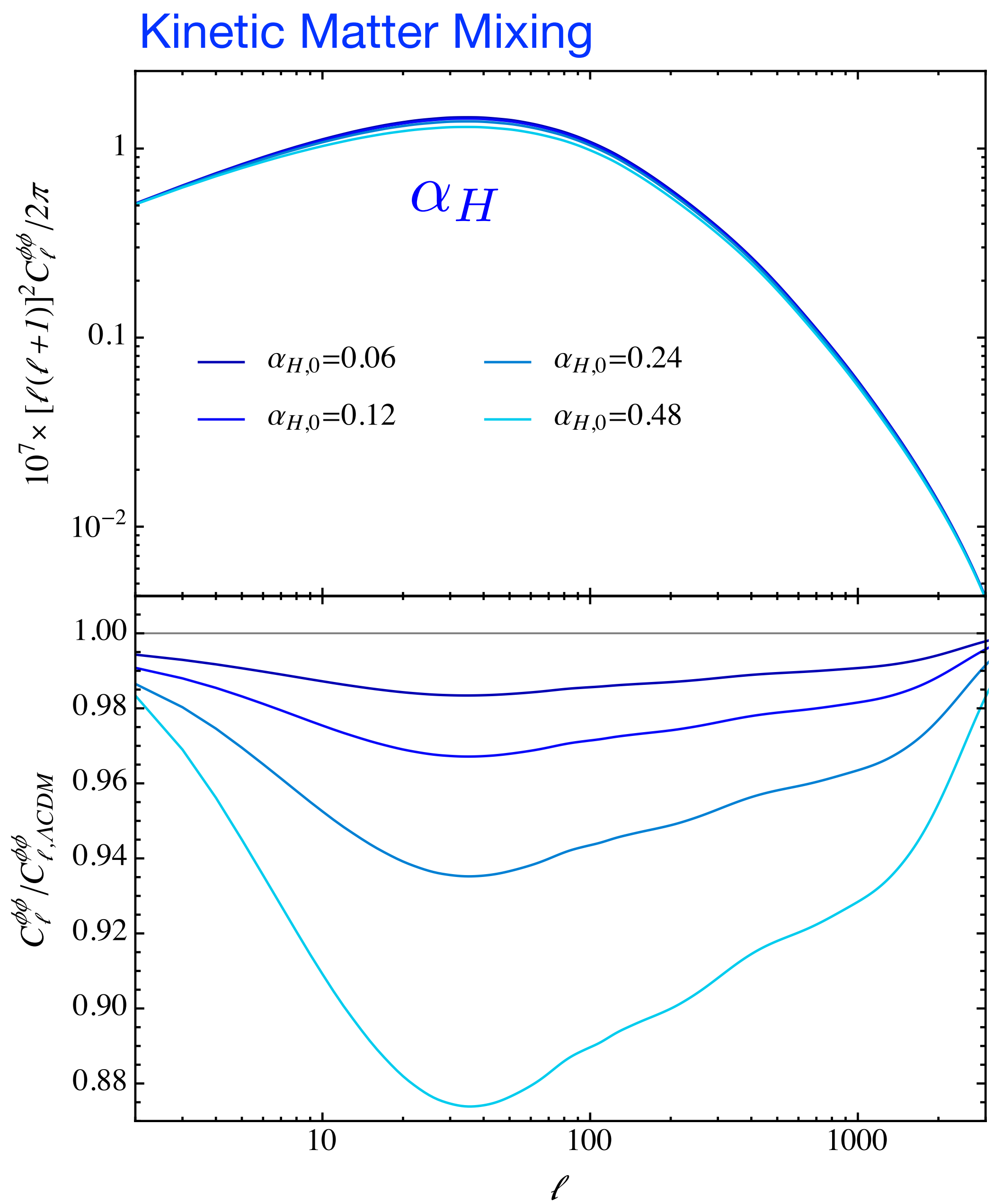
Kinetic Matter Mixing



Lensing

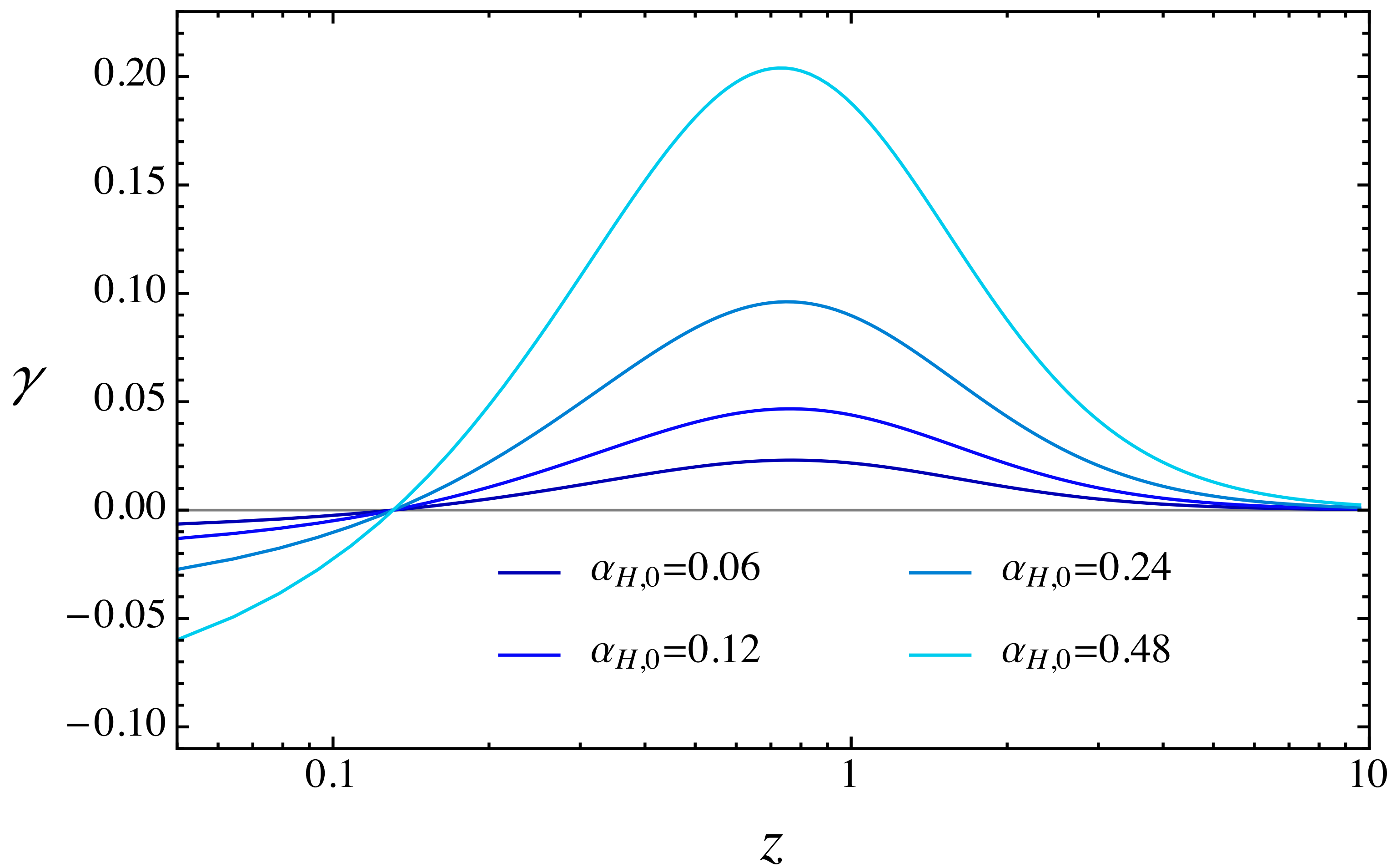


Braiding
α_B
1
0.1
10^{-2}
$10^7 \times [\ell(\ell+1)]^2 C_\ell^{\phi\phi}/2\pi$
$\alpha_{B,0}$=−0.06
$\alpha_{B,0}$=−0.12
$\alpha_{B,0}$=−0.24
$\alpha_{B,0}$=−0.48
1.6
1.5
1.4
1.3
1.2
1.1
1.0
$C_\ell^{\phi\phi}/C_{\ell,\Lambda CDM}^{\phi\phi}$
10
100
1000
ℓ



Kinetic Matter Mixing
α_H
1
0.1
10^{-2}
$10^7 \times [\ell(\ell+1)]^2 C_\ell^{\phi\phi}/2\pi$
$\alpha_{H,0}$=0.06
$\alpha_{H,0}$=0.12
$\alpha_{H,0}$=0.24
$\alpha_{H,0}$=0.48
1.00
0.98
0.96
0.94
0.92
0.90
0.88
$C_\ell^{\phi\phi}/C_{\ell,\Lambda CDM}^{\phi\phi}$
10
100
1000
ℓ

Friction with KMM



$$\ddot{\delta}_m + (2 + \gamma)\, H\dot{\delta}_m = \frac{3}{2} H^2 \Omega_m \mu_\Phi \delta_m$$

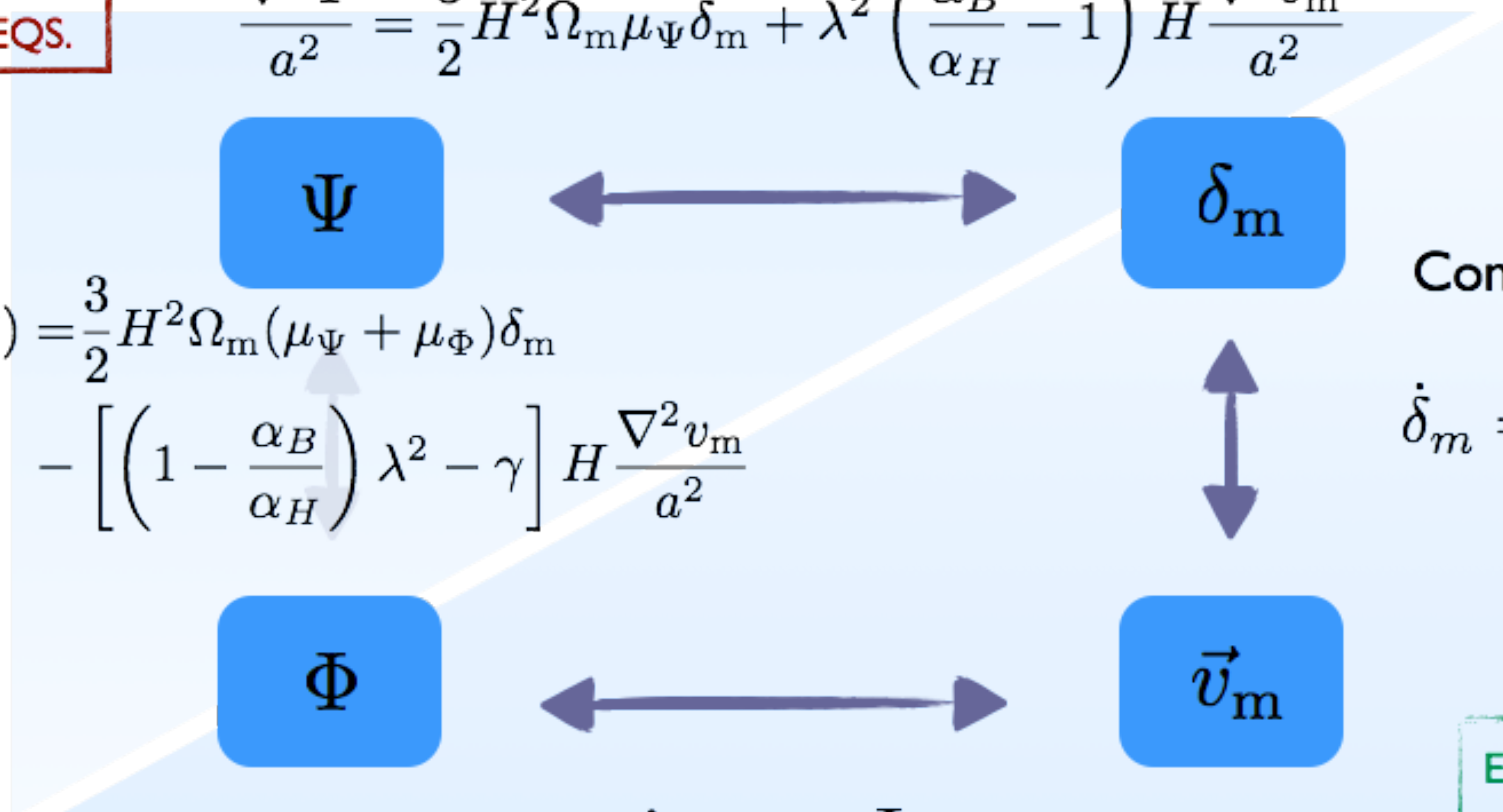
$$\gamma = \frac{\log(1 + \lambda^2)}{d \log a} \qquad \lambda^2 = \frac{3\,(\rho_m + p_m)}{M^2 H^2 \alpha c_s^2} \alpha_H^2$$

Modified Gravity+KMM

$$ds^2 = -(1+2\Phi)dt^2 + a^2(t)(1-2\Psi)d\vec{x}^2$$

EINSTEIN EQS.

$$\frac{\nabla^2\Psi}{a^2} = \frac{3}{2}H^2\Omega_{\rm m}\mu_\Psi\delta_{\rm m} + \lambda^2\left(\frac{\alpha_B}{\alpha_H}-1\right)H\frac{\nabla^2 v_{\rm m}}{a^2}$$



$$\frac{\nabla^2}{a^2}(\Phi+\Psi) = \frac{3}{2}H^2\Omega_{\rm m}(\mu_\Psi+\mu_\Phi)\delta_{\rm m} - \left[\left(1-\frac{\alpha_B}{\alpha_H}\right)\lambda^2 - \gamma\right]H\frac{\nabla^2 v_{\rm m}}{a^2}$$

Continuity equation:

$$\dot{\delta}_m = -\frac{\nabla^2 v_{\rm m}}{a^2}$$

Euler equation: $\dot{v}_{\rm m} = -\Phi$

ENERGY-MOMENTUM CONSERVATION