Constraints on DHOST: GWs, Vainshtein and Cosmology

Marco Crisostomi

Université Paris Saclay — IPhT, DAp, LPT

Action Dark Energy theory group — IAP 20/05/2019

In collaboration with:

Matt Lewandowski, Filippo Vernizzi

Kazuya Koyama, David Langlois, Karim Noui, Dani Steer

Dark Energy as a Scalar Field

1961 — Brans-Dicke $L = f(\phi)R - \frac{1}{2}(\partial\phi)^2 - V(\phi)$ $\quad (\text{aka } f(R))$

t

Dark Energy as a Scalar Field

1961 — Brans-Dicke $L = f(\phi)R - \frac{1}{2}(\partial\phi)^2 - V(\phi)$ $(\text{aka } f(R))$

1974 — Horndeski

$$K(\phi, X) + G_3(\phi, X)\Box\phi + G_4(\phi, X)R - 2G_{4X}(\phi, X)[(\Box\phi)^2 - \phi_{\mu\nu}\phi^{\mu\nu}]$$

t

Dark Energy as a Scalar Field

1961 Brans-Dicke $L = f(\phi)R - \frac{1}{2}(\partial\phi)^2 - V(\phi)$ $(\text{aka} \;\; f(R))$

1974 Horndeski

$$K(\phi, X) + G_3(\phi, X)\Box\phi + G_4(\phi, X)R - 2G_{4X}(\phi, X)[(\Box\phi)^2 - \phi_{\mu\nu}\phi^{\mu\nu}]$$

1998 Dark Energy

Screening mechanisms

Self-acceleration

t

Dark Energy as a Scalar Field

- 1961 — Brans-Dicke $$L = f(\phi)R - \frac{1}{2}(\partial\phi)^2 - V(\phi) \qquad (\text{aka } f(R))$$
- 1974 — Horndeski $$K(\phi, X) + G_3(\phi, X)\Box\phi + G_4(\phi, X)R - 2G_{4X}(\phi, X)[(\Box\phi)^2 - \phi_{\mu\nu}\phi^{\mu\nu}]$$
- 1998 — Dark Energy

  Screening mechanisms

  Self-acceleration
- 2014 — beyond Horndeski $$F(\phi,\, X)[\Box\phi\, \phi^\mu \phi_{\mu\nu}\phi^\nu - \phi^\mu \phi_{\mu\rho}\phi^{\rho\nu}\phi_\nu]$$

t

Dark Energy as a Scalar Field

1961 — Brans-Dicke $L = f(\phi)R - \frac{1}{2}(\partial\phi)^2 - V(\phi)$ $\quad(\text{aka } f(R))$

1974 — Horndeski

$$K(\phi, X) + G_3(\phi, X)\Box\phi + G_4(\phi, X)R - 2G_{4X}(\phi, X)[(\Box\phi)^2 - \phi_{\mu\nu}\phi^{\mu\nu}]$$

1998 — Dark Energy

Screening mechanisms

Self-acceleration

2014 — beyond Horndeski $F(\phi,\ X)[\Box\phi\,\phi^\mu\phi_{\mu\nu}\phi^\nu - \phi^\mu\phi_{\mu\rho}\phi^{\rho\nu}\phi_\nu]$

2016 — DHOST $A_5(\phi,\ X)(\phi^\mu\phi_{\mu\nu}\phi^\nu)^2$

t

DHOST

$$L = K + G_3 \Box\phi + G.R + A_1[\phi_{\mu\nu}\phi^{\mu\nu} - (\Box\phi)^2] + A_3(\Box\phi)\phi^{\mu}\phi_{\mu\nu}\phi^{\nu}$$

$$+ f(G, A_1, A_3)\,\phi^{\mu}\phi_{\mu\rho}\phi^{\rho\nu}\phi_{\nu} + g(G, A_1, A_3)(\phi^{\mu}\phi_{\mu\nu}\phi^{\nu})^2$$

5 free functions

DHOST

$$L = K + G_3 \Box\phi + G.R + A_1[\phi_{\mu\nu}\phi^{\mu\nu} - (\Box\phi)^2] + A_3(\Box\phi)\phi^{\mu}\phi_{\mu\nu}\phi^{\nu}$$
$$+ f(G, A_1, A_3)\,\phi^{\mu}\phi_{\mu\rho}\phi^{\rho\nu}\phi_{\nu} + g(G, A_1, A_3)(\phi^{\mu}\phi_{\mu\nu}\phi^{\nu})^2$$

5 free functions

EFT of DE

Linear perturbations: α_K α_B α_M α_T α_H β_1

DHOST

$$L = K + G_3 \Box\phi + G.R + A_1[\phi_{\mu\nu}\phi^{\mu\nu} - (\Box\phi)^2] + A_3(\Box\phi)\phi^{\mu}\phi_{\mu\nu}\phi^{\nu}$$

$$+ f(G, A_1, A_3)\,\phi^{\mu}\phi_{\mu\rho}\phi^{\rho\nu}\phi_{\nu} + g(G, A_1, A_3)(\phi^{\mu}\phi_{\mu\nu}\phi^{\nu})^2$$

5 free functions

EFT of DE

Linear perturbations: α_K α_B α_M α_T α_H β_1

kinetic term of the scalar

DHOST

$$L = K + G_3 \Box\phi + G.R + A_1[\phi_{\mu\nu}\phi^{\mu\nu} - (\Box\phi)^2] + A_3(\Box\phi)\phi^{\mu}\phi_{\mu\nu}\phi^{\nu}$$
$$+ f(G, A_1, A_3)\,\phi^{\mu}\phi_{\mu\rho}\phi^{\rho\nu}\phi_{\nu} + g(G, A_1, A_3)(\phi^{\mu}\phi_{\mu\nu}\phi^{\nu})^2$$

5 free functions

EFT of DE

Linear perturbations: α_K α_B α_M α_T α_H β_1

α_K: kinetic term of the scalar

α_B: kinetic mixing between metric and scalar

DHOST

$$L = K + G_3 \Box\phi + G.R + A_1[\phi_{\mu\nu}\phi^{\mu\nu} - (\Box\phi)^2] + A_3(\Box\phi)\phi^\mu\phi_{\mu\nu}\phi^\nu$$

$$+ f(G, A_1, A_3)\,\phi^\mu\phi_{\mu\rho}\phi^{\rho\nu}\phi_\nu + g(G, A_1, A_3)(\phi^\mu\phi_{\mu\nu}\phi^\nu)^2$$

5 free functions

EFT of DE

Linear perturbations: α_K α_B α_M α_T α_H β_1

- α_K: kinetic term of the scalar
- α_B: kinetic mixing between metric and scalar
- α_M: time variation of M_{Pl}

DHOST

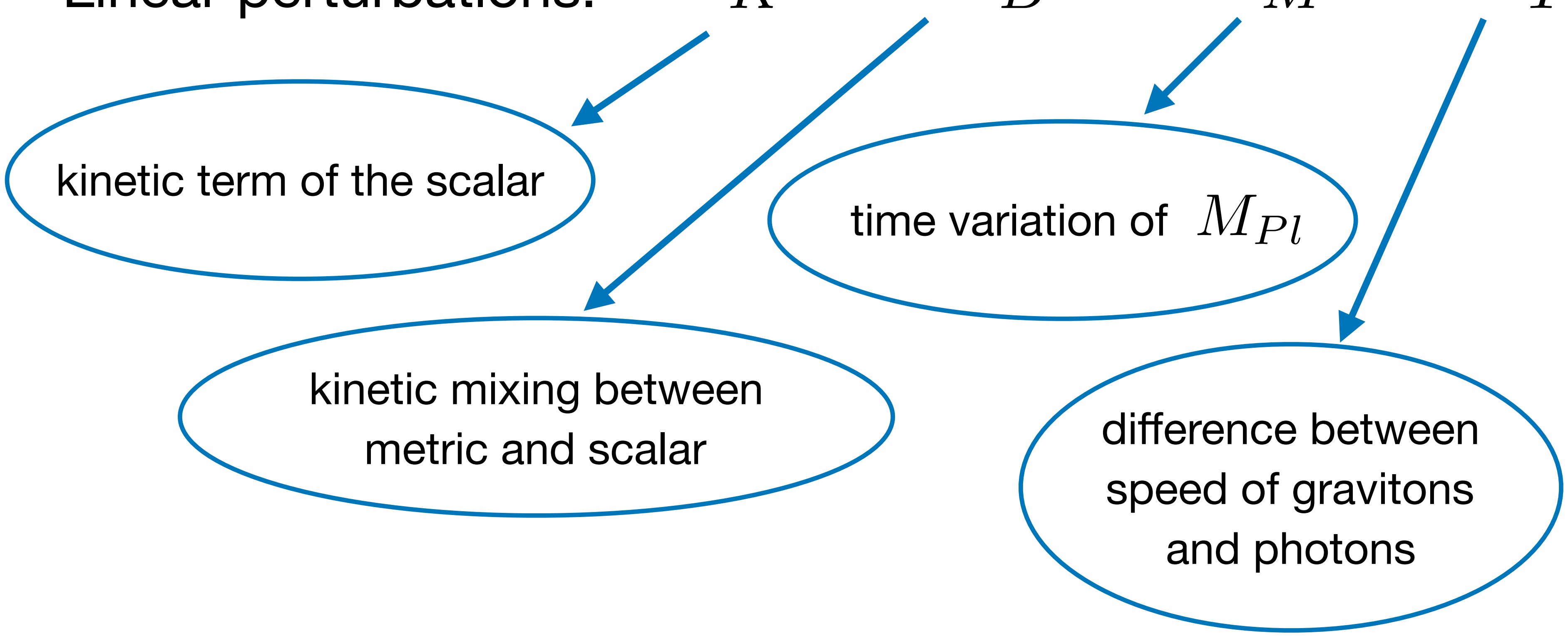
$$L = K + G_3 \Box\phi + G.R + A_1[\phi_{\mu\nu}\phi^{\mu\nu} - (\Box\phi)^2] + A_3(\Box\phi)\phi^\mu\phi_{\mu\nu}\phi^\nu$$

$$+ f(G, A_1, A_3)\, \phi^\mu\phi_{\mu\rho}\phi^{\rho\nu}\phi_\nu + g(G, A_1, A_3)(\phi^\mu\phi_{\mu\nu}\phi^\nu)^2$$

5 free functions

EFT of DE

Linear perturbations: α_K α_B α_M α_T α_H β_1



DHOST

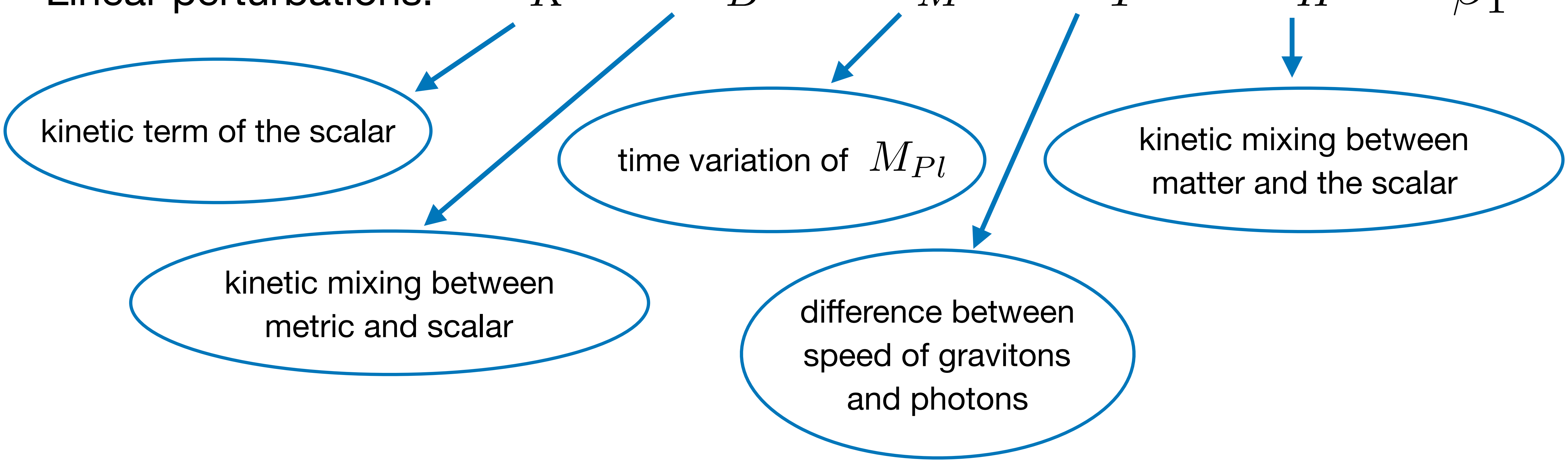
$$L = K + G_3 \Box\phi + G.R + A_1[\phi_{\mu\nu}\phi^{\mu\nu} - (\Box\phi)^2] + A_3(\Box\phi)\phi^{\mu}\phi_{\mu\nu}\phi^{\nu}$$

$$+ f(G, A_1, A_3)\, \phi^{\mu}\phi_{\mu\rho}\phi^{\rho\nu}\phi_{\nu} + g(G, A_1, A_3)(\phi^{\mu}\phi_{\mu\nu}\phi^{\nu})^2$$

5 free functions

EFT of DE

Linear perturbations: α_K α_B α_M α_T α_H β_1



DHOST

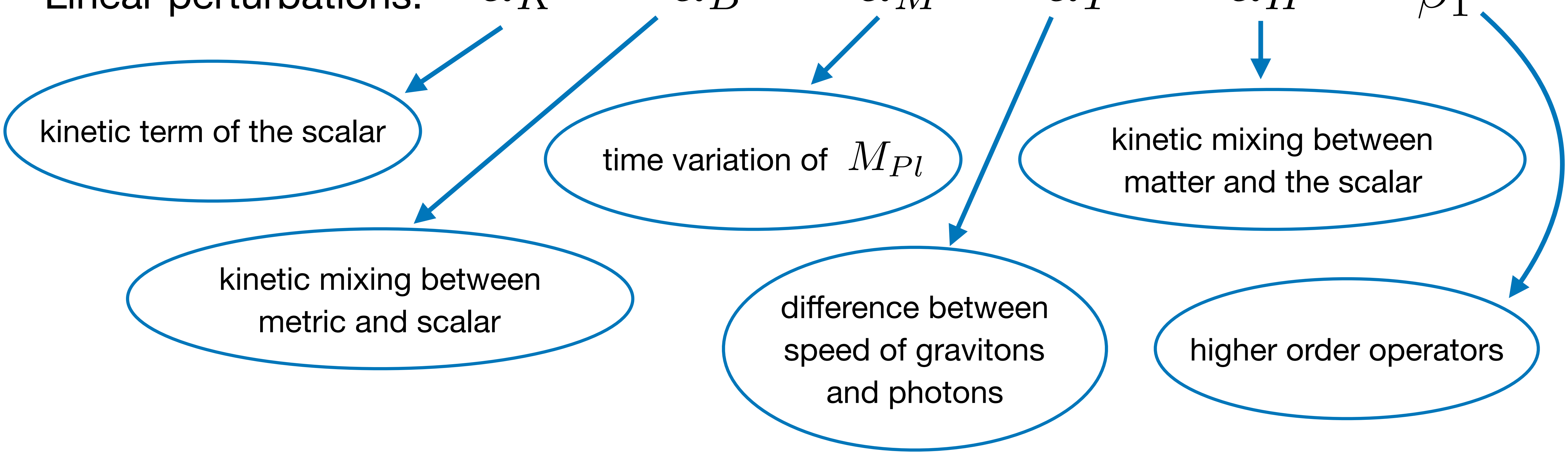
$$L = K + G_3 \Box\phi + G.R + A_1[\phi_{\mu\nu}\phi^{\mu\nu} - (\Box\phi)^2] + A_3(\Box\phi)\phi^\mu\phi_{\mu\nu}\phi^\nu$$

$$+ f(G, A_1, A_3)\,\phi^\mu\phi_{\mu\rho}\phi^{\rho\nu}\phi_\nu + g(G, A_1, A_3)(\phi^\mu\phi_{\mu\nu}\phi^\nu)^2$$

5 free functions

EFT of DE

Linear perturbations: α_K α_B α_M α_T α_H β_1



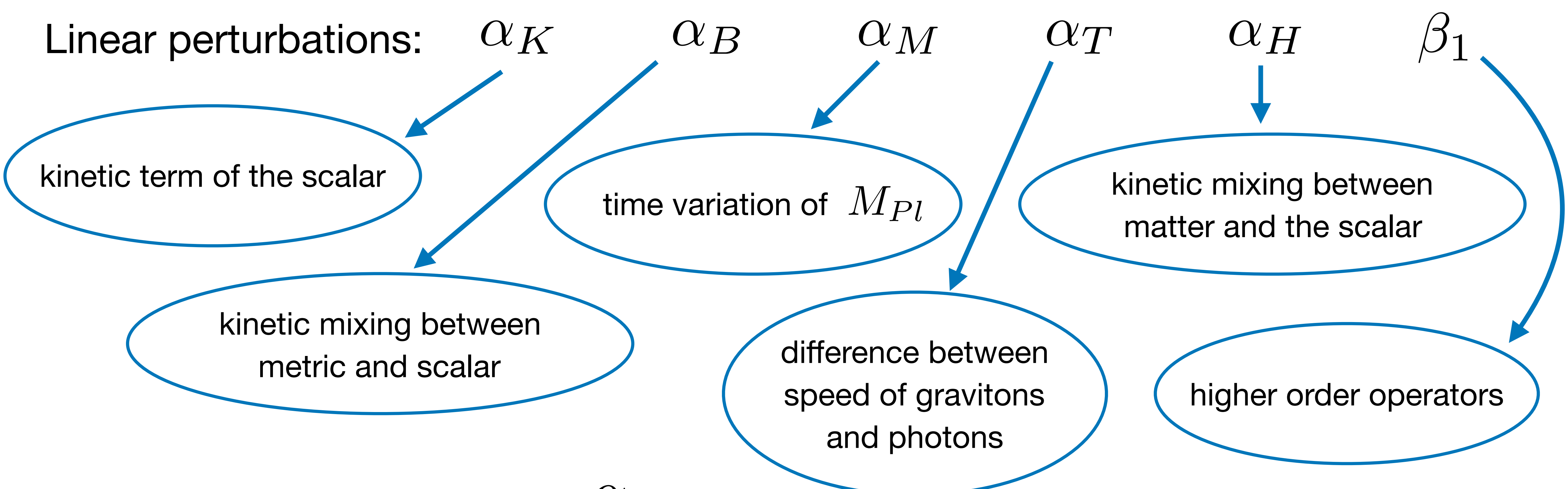
DHOST

$$L = K + G_3 \Box\phi + G.R + A_1[\phi_{\mu\nu}\phi^{\mu\nu} - (\Box\phi)^2] + A_3(\Box\phi)\phi^{\mu}\phi_{\mu\nu}\phi^{\nu}$$

$$+ f(G, A_1, A_3)\,\phi^{\mu}\phi_{\mu\rho}\phi^{\rho\nu}\phi_{\nu} + g(G, A_1, A_3)(\phi^{\mu}\phi_{\mu\nu}\phi^{\nu})^2$$

5 free functions

EFT of DE



Non-linear perturbations: α_V

Gravitational wave constraints

$$L = K + G_3 \Box\phi + G.R + A_1[\phi_{\mu\nu}\phi^{\mu\nu} - (\Box\phi)^2] + A_3(\Box\phi)\phi^{\mu}\phi_{\mu\nu}\phi^{\nu}$$

$$+ f(G, A_1, A_3)\,\phi^{\mu}\phi_{\mu\rho}\phi^{\rho\nu}\phi_{\nu} + g(G, A_1, A_3)(\phi^{\mu}\phi_{\mu\nu}\phi^{\nu})^2$$

1) Speed of gravity = Speed of light

Gravitational wave constraints

$$L = K + G_3 \Box\phi + G.R + A_1[\phi_{\mu\nu}\phi^{\mu\nu} - (\Box\phi)^2] + A_3(\Box\phi)\phi^{\mu}\phi_{\mu\nu}\phi^{\nu}$$

$$+ f(G, A_1, A_3)\,\phi^{\mu}\phi_{\mu\rho}\phi^{\rho\nu}\phi_{\nu} + g(G, A_1, A_3)(\phi^{\mu}\phi_{\mu\nu}\phi^{\nu})^2$$

1) Speed of gravity = Speed of light

$$\ddot{h}_{ij} + (3 + \alpha_{_M})H\dot{h}_{ij} + (1 + \alpha_{_T})k^2 h_{ij} = 0$$

Gravitational wave constraints

$$L = K + G_3 \Box\phi + G.R + A_1[\phi_{\mu\nu}\phi^{\mu\nu} - (\Box\phi)^2] + A_3(\Box\phi)\phi^{\mu}\phi_{\mu\nu}\phi^{\nu}$$

$$+ f(G, A_1, A_3)\,\phi^{\mu}\phi_{\mu\rho}\phi^{\rho\nu}\phi_{\nu} + g(G, A_1, A_3)(\phi^{\mu}\phi_{\mu\nu}\phi^{\nu})^2$$

1) Speed of gravity = Speed of light

$$\ddot{h}_{ij} + (3 + \alpha_M)H\dot{h}_{ij} + (1 + \alpha_T)k^2 h_{ij} = 0 \qquad \alpha_V = -\alpha_H$$

Gravitational wave constraints

$$L = K + G_3 \Box\phi + G.R + A_1[\phi_{\mu\nu}\phi^{\mu\nu} - (\Box\phi)^2] + A_3(\Box\phi)\phi^\mu\phi_{\mu\nu}\phi^\nu$$

$$+ f(G, A_1, A_3)\,\phi^\mu\phi_{\mu\rho}\phi^{\rho\nu}\phi_\nu + g(G, A_1, A_3)(\phi^\mu\phi_{\mu\nu}\phi^\nu)^2$$

1) Speed of gravity = Speed of light

$$\ddot{h}_{ij} + (3+\alpha_M)H\dot{h}_{ij} + (1+\alpha_T)k^2 h_{ij} = 0 \qquad \alpha_V = -\alpha_H$$

$$L = (G - XA_1)K_{ij}K^{ij} + G^{(3)}R + \ldots$$

Gravitational wave constraints

$$L = K + G_3 \Box\phi + G.R + A_1[\phi_{\mu\nu}\phi^{\mu\nu} - (\Box\phi)^2] + A_3(\Box\phi)\phi^{\mu}\phi_{\mu\nu}\phi^{\nu}$$

$$+ f(G, A_1, A_3)\,\phi^{\mu}\phi_{\mu\rho}\phi^{\rho\nu}\phi_{\nu} + g(G, A_1, A_3)(\phi^{\mu}\phi_{\mu\nu}\phi^{\nu})^2$$

1) Speed of gravity = Speed of light

$$\ddot{h}_{ij} + (3+\alpha_M)H\dot{h}_{ij} + (1+\alpha_T)k^2 h_{ij} = 0 \qquad \alpha_V = -\alpha_H$$

$$L = (G - XA_1)K_{ij}K^{ij} + G^{(3)}R + \ldots$$

Gravitational wave constraints

$$L = K + G_3 \Box\phi + G.R + A_1[\phi_{\mu\nu}\phi^{\mu\nu} - (\Box\phi)^2] + A_3(\Box\phi)\phi^\mu\phi_{\mu\nu}\phi^\nu$$

$$+ f(G, A_1, A_3)\,\phi^\mu\phi_{\mu\rho}\phi^{\rho\nu}\phi_\nu + g(G, A_1, A_3)(\phi^\mu\phi_{\mu\nu}\phi^\nu)^2$$

1) Speed of gravity = Speed of light

$$\ddot{h}_{ij} + (3 + \alpha_M)H\dot{h}_{ij} + (1 + \alpha_T)k^2 h_{ij} = 0 \qquad \alpha_V = -\alpha_H$$

$$L = (G - XA_1)K_{ij}K^{ij} + G^{(3)}R + \ldots$$

2) No decay of GW in DE

P. Creminelli, M. Lewandowski, G. Tambalo, and F. Vernizzi, "Gravitational Wave Decay into Dark Energy," *JCAP* **1812** (2018), no. 12 025, 1809.03484.

$$\alpha_H + 2\beta_1 = 0$$

Gravitational wave constraints

$$L = K + G_3 \Box\phi + G.R + A_1[\phi_{\mu\nu}\phi^{\mu\nu} \quad (\Box\phi)^2] + A_3(\Box\phi)\phi^{\mu}\phi_{\mu\nu}\phi^{\nu}$$

$$+ f(G, A_1, A_3)\,\phi^{\mu}\phi_{\mu\rho}\phi^{\rho\nu}\phi_{\nu} + g(G, A_1, A_3)(\phi^{\mu}\phi_{\mu\nu}\phi^{\nu})^2$$

1) Speed of gravity = Speed of light

$$\ddot{h}_{ij} + (3 + \alpha_M)H\dot{h}_{ij} + (1 + \alpha_T)k^2 h_{ij} = 0 \qquad \alpha_V = -\alpha_H$$

$$L = (G - XA_1)K_{ij}K^{ij} + G^{(3)}R + \dots$$

2) No decay of GW in DE

P. Creminelli, M. Lewandowski, G. Tambalo, and F. Vernizzi, "Gravitational Wave Decay into Dark Energy," *JCAP* **1812** (2018), no. 12 025, `1809.03484`.

$$\alpha_H + 2\beta_1 = 0 \qquad A_3 = g = 0$$

Gravitational wave constraints

$$L = K + G_3 \Box\phi + G.R + \cancel{A_1[\phi_{\mu\nu}\phi^{\mu\nu} - (\Box\phi)^2]} + \cancel{A_3(\Box\phi)\phi^\mu\phi_{\mu\nu}\phi^\nu}$$

$$+ f(G, A_1, A_3)\,\phi^\mu\phi_{\mu\rho}\phi^{\rho\nu}\phi_\nu + \cancel{g(G, A_1, A_3)(\phi^\mu\phi_{\mu\nu}\phi^\nu)^2}$$

1) Speed of gravity = Speed of light

$$\ddot{h}_{ij} + (3 + \alpha_M)H\dot{h}_{ij} + (1 + \cancel{\alpha_T})k^2 h_{ij} = 0 \qquad \alpha_V = -\alpha_H$$

$$L = (G - X\cancel{A_1})K_{ij}K^{ij} + G^{(3)}R + \dots$$

2) No decay of GW in DE

P. Creminelli, M. Lewandowski, G. Tambalo, and F. Vernizzi, "Gravitational Wave Decay into Dark Energy," *JCAP* **1812** (2018), no. 12 025, `1809.03484`.

$$\alpha_H + 2\beta_1 = 0 \qquad A_3 = g = 0$$

Assumption: EFT of DE still trustable at LIGO/Virgo frequencies

Solar System constraints

$$L = K + G_3 \Box\phi + G.R + \frac{3G_X^2}{2G}\phi^\mu \phi_{\mu\rho}\phi^{\rho\nu}\phi_\nu$$

α_K α_B α_M β_1

Solar System constraints

$$L = K + G_3 \Box\phi + G.R + \frac{3G_X^2}{2G}\phi^\mu \phi_{\mu\rho}\phi^{\rho\nu}\phi_\nu$$

α_K α_B α_M β_1

gravitational potentials for a spherically symmetric matter source

$$\Phi' = \frac{G_*(1+\varepsilon_\Phi)m}{r^2}\,, \qquad \Psi' = \frac{G_*(1+\varepsilon_\Psi)m}{r^2}$$

Solar System constraints

$$L = K + G_3 \Box\phi + G.R + \frac{3G_X^2}{2G}\phi^\mu \phi_{\mu\rho}\phi^{\rho\nu}\phi_\nu$$

α_K α_B α_M β_1

gravitational potentials for a spherically symmetric matter source

$$\Phi' = \frac{G_*(1+\varepsilon_\Phi)m}{r^2}\,, \qquad \Psi' = \frac{G_*(1+\varepsilon_\Psi)m}{r^2}$$

CASSINI $-0.2\times 10^{-5} < \varepsilon_\Psi - \varepsilon_\Phi < 5.5\times 10^{-5}$ → $0 \le \beta_1 \lesssim 10^{-5}$

Solar System constraints

$$L = K + G_3 \Box\phi + G.R + \frac{3G_X^2}{2G}\phi^\mu \phi_{\mu\rho}\phi^{\rho\nu}\phi_\nu$$

α_K α_B α_M β_1

gravitational potentials for a spherically symmetric matter source

$$\Phi' = \frac{G_*(1+\varepsilon_\Phi)m}{r^2}, \qquad \Psi' = \frac{G_*(1+\varepsilon_\Psi)m}{r^2}$$

CASSINI $-0.2\times 10^{-5} < \varepsilon_\Psi - \varepsilon_\Phi < 5.5\times 10^{-5}$ ⟶ $0 \leq \beta_1 \lesssim 10^{-5}$

Tuning $(\alpha_M, \alpha_B, \beta_1)$ ⟶ $\varepsilon_\Phi = \varepsilon_\Psi$ Vainshtein ✅

Hulse-Taylor $-2.5\times 10^{-3} \leq \varepsilon_\Phi \leq 7.5\times 10^{-3}$ ⟶ $0 \leq \beta_1 \lesssim 10^{-2}$

Cosmological constraints

$$L = K + G_3 \Box\phi + G.R + \frac{3G_X^2}{2G}\phi^{\mu}\phi_{\mu\rho}\phi^{\rho\nu}\phi_{\nu}$$

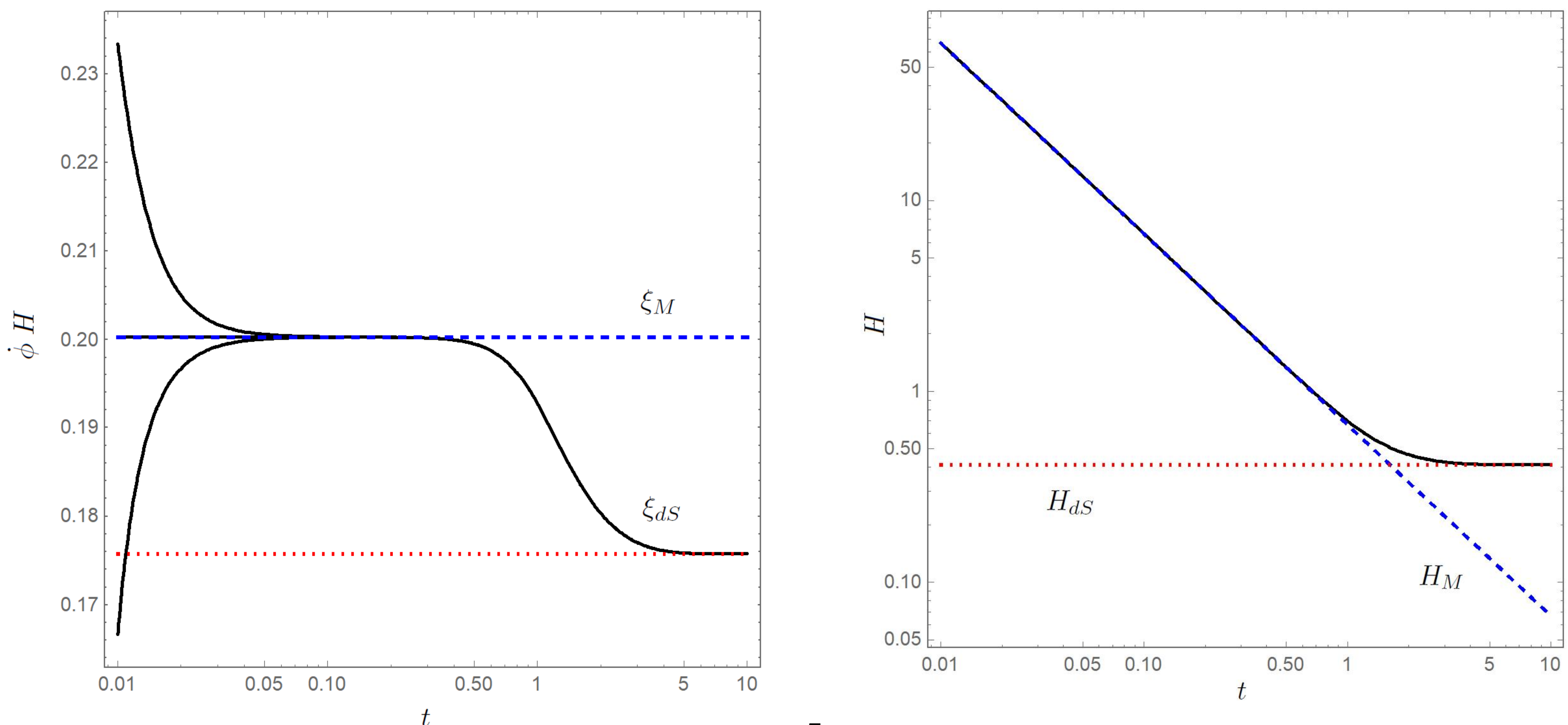
Background effects ⟶ Self-acceleration

Cosmological constraints

$$L = K + G_3 \Box\phi + G.R + \frac{3G_X^2}{2G}\phi^\mu \phi_{\mu\rho}\phi^{\rho\nu}\phi_\nu$$

Background effects → Self-acceleration

$$K = c_2 X\,, \quad G_3 = \frac{c_3}{\Lambda^3}X\,, \quad G = \frac{M_P^2}{2} + \frac{c_4}{\Lambda^6}X^2 \qquad c_2, c_3, c_4 \sim \mathcal{O}(1)$$

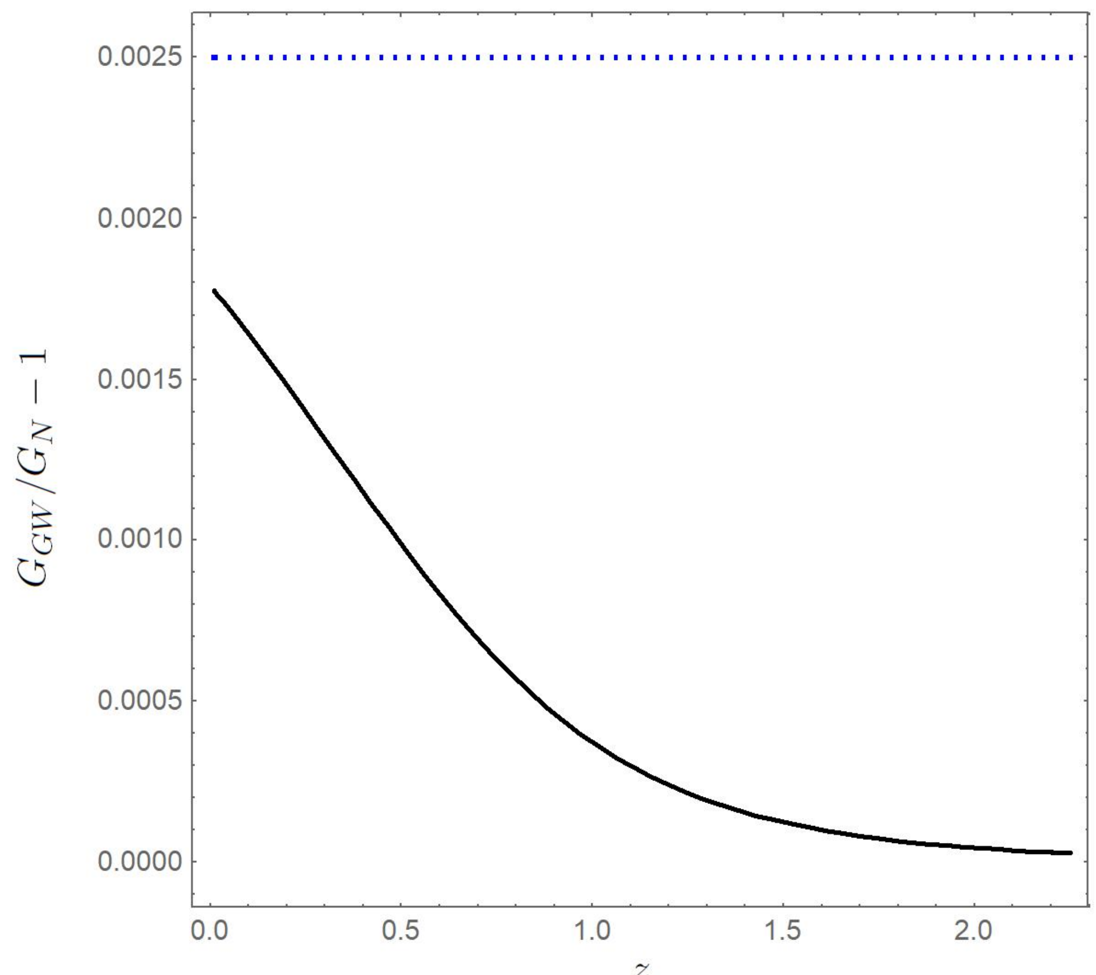


Cosmological constraints

$$L = K + G_3 \Box\phi + G.R + \frac{3G_X^2}{2G}\phi^\mu \phi_{\mu\rho}\phi^{\rho\nu}\phi_\nu$$

Background effects → Self-acceleration

$$K = c_2 X\,, \quad G_3 = \frac{c_3}{\Lambda^3}X\,, \quad G = \frac{M_P^2}{2} + \frac{c_4}{\Lambda^6}X^2 \qquad c_2, c_3, c_4 \sim \mathcal{O}(1)$$



Conclusions

$$L = K + G_3 \Box\phi + G.R + \frac{3G_X^2}{2G}\phi^\mu \phi_{\mu\rho}\phi^{\rho\nu}\phi_\nu$$

- 3 free functions of ϕ and X

- Screening and self-acceleration are OK

- Cosmological constraints from the background

Thanks!