Modified gravity and dark energy in higher-order scalar-tensor theories

Marco Crisostomi

SISSA

Atelier Théories de l'action Dark Energy - session 2 19/11/2019 IHP

In collaboration with:

Christos Charmousis, Ruth Gregory, Kazuya Koyama, David Langlois, Matt Lewandowski, Karim Noui, Dani Steer, Niko Stergioulas, Gianmassimo Tasinato, Filippo Vernizzi

DHOST

$$L = K + G_3\Box\phi + G.R + A_1\phi_{\mu\nu}\phi^{\mu\nu} + A_2(\Box\phi)^2 + A_3(\Box\phi)\phi^\mu\phi_{\mu\nu}\phi^\nu$$
$$+ A_4\phi^\mu\phi_{\mu\rho}\phi^{\rho\nu}\phi_\nu + A_5(\phi^\mu\phi_{\mu\nu}\phi^\nu)^2$$

[Langlois, Noui]

[MC, Koyama, Tasinato]

Impose the degeneracy conditions

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

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

[Langlois, Mancarella, Noui, Vernizzi]

Expand around FRW in the unitary gauge

$$S^{\rm quad} = \int d^3x\, dt\, a^3 \frac{M^2}{2}\left\{\delta K_{ij}\delta K^{ij} - \left(1+\frac{2}{3}\alpha_{\rm L}\right)\delta K^2 + (1+\alpha_{\rm T})\left(R\frac{\delta\sqrt{h}}{a^3} + \delta_2 R\right)\right.$$
$$\left. + H^2\alpha_{\rm K}\delta N^2 + 4H\alpha_{\rm B}\delta K\delta N + (1+\alpha_{\rm H})R\delta N + 4\beta_1\delta K\delta\dot{N} + \beta_2\delta\dot{N}^2 + \frac{\beta_3}{a^2}(\partial_i\delta N)^2\right\}$$

Non-linear perturbations: α_V

Gravitational wave constraints

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

Speed of gravity = Speed of light GW170817

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

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

Gravitational wave constraints

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

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

No decay of GW in DE

[Creminelli, Lewandowski, Tambalo, Vernizzi]

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

What is left?

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

$$\alpha_K \quad \alpha_B \quad \alpha_M \quad \beta_1$$

What about:

1 - Screening

2 - Self-acceleration

Screening

[MC, Koyama]

[MC, Lewandowski, Vernizzi]

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

$$\alpha_K \quad \alpha_B \qquad \alpha_M \qquad \beta_1$$

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

Region $(\alpha_M, \alpha_B, \beta_1)$ $\longrightarrow$ $\varepsilon_\Phi = \varepsilon_\Psi$ Vainshtein ✅

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

Screening ?

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

[MC, Koyama]

[MC, Lewandowski, Vernizzi]

α_K α_B α_M β_1

[Creminelli, Tambalo, Vernizzi, Yingcharoenrat]

Combination $(\alpha_M, \alpha_B, \beta_1) \lesssim 10^{-2}$

$\downarrow$

G_3

$0 \leq \beta_1 \lesssim 10^{-2}$

Self-acceleration

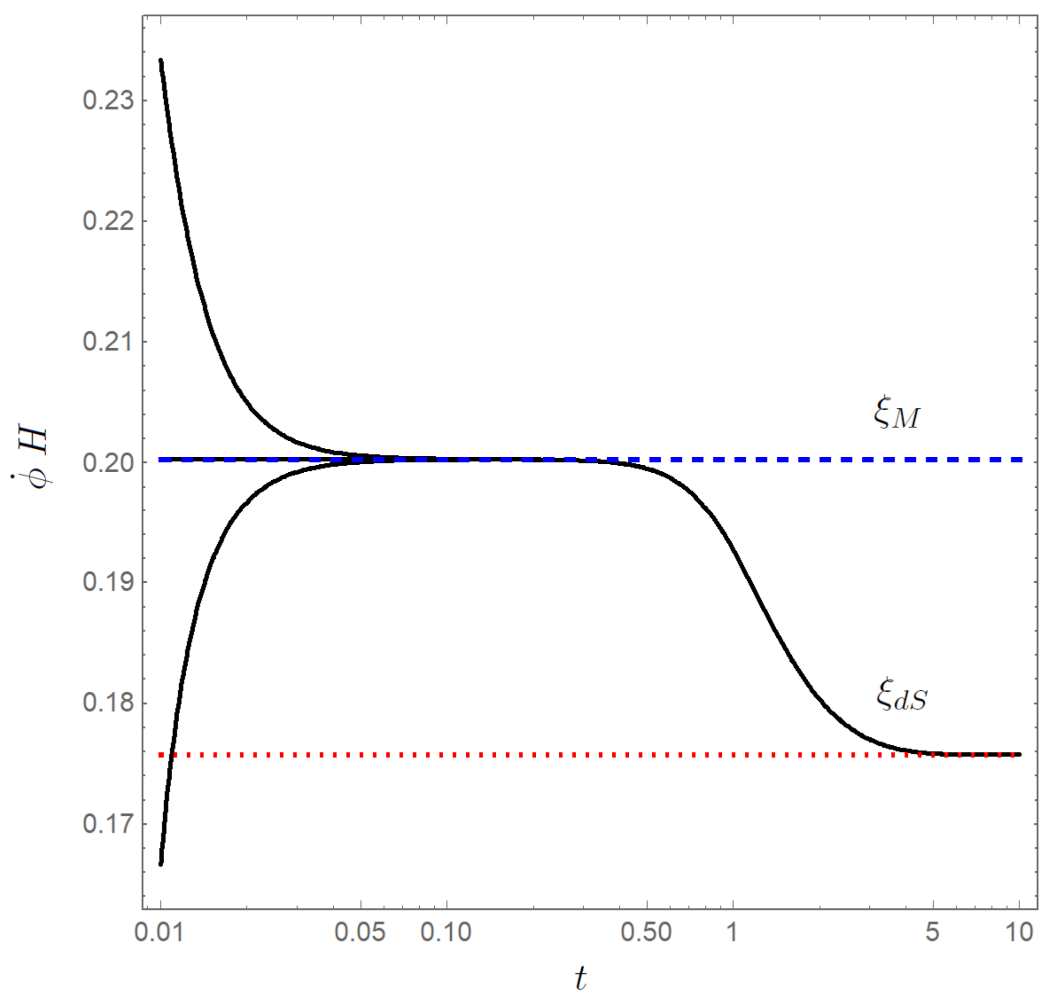
[MC, Koyama]

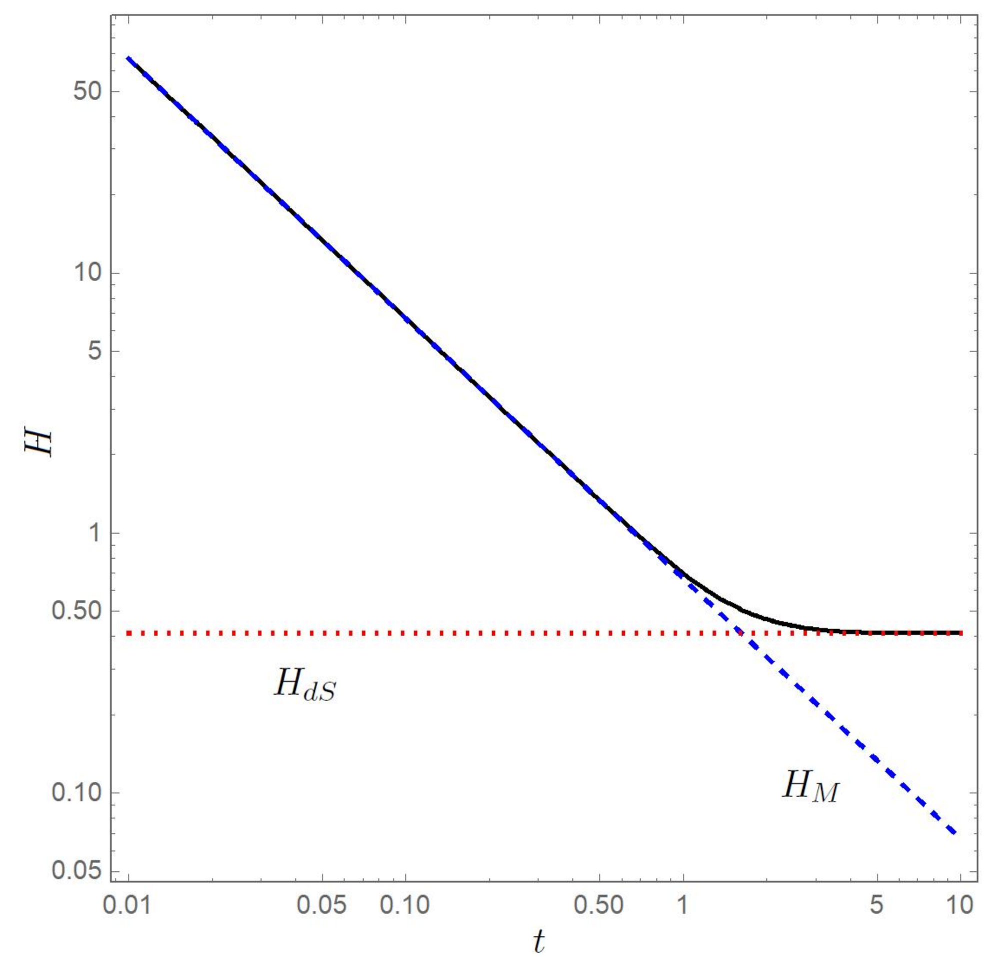
[MC, Koyama, Langlois, Noui, Steer]

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

Background effect

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





Self-acceleration

[MC, Koyama]

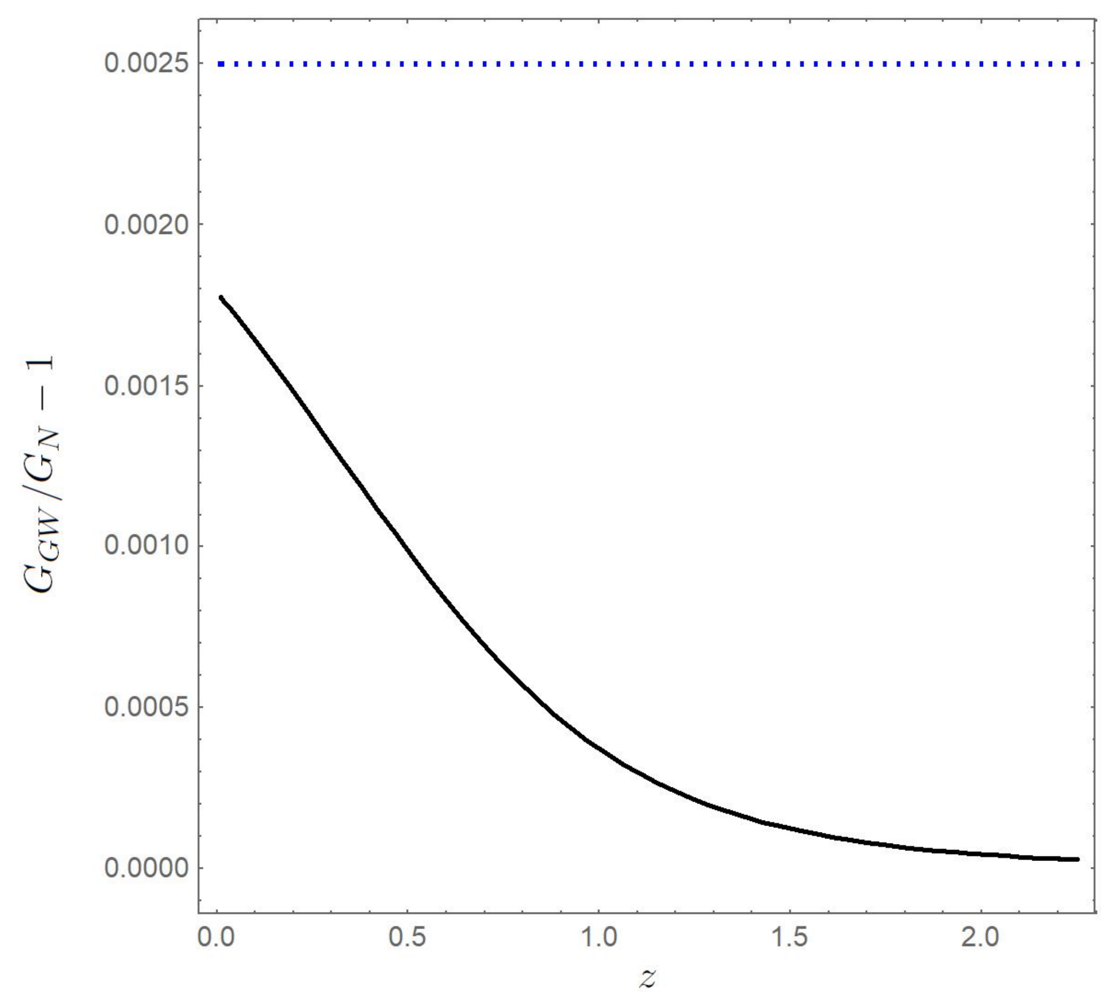
[MC, Koyama, Langlois, Noui, Steer]

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

Background effect

$$K = c_2 X\,, \quad G_3 = \frac{c_3}{\Lambda^3} X\,, \quad G = \frac{M_P^2}{2} + \frac{c_4}{\Lambda^6} X^2$$

$$c_2, c_3, c_4 \sim \mathcal{O}(1)$$



Signatures in LSS

[Kehagias, Riotto]

[Peloso, Pietroni]

[Creminelli, Norena, Simonovic, Vernizzi]

Consistency relations in LCDM

$$\langle \Phi_{\vec{q}}(\eta)\delta_{\vec{k}_1}(\eta_1)\cdots\delta_{\vec{k}_n}(\eta_n)\rangle'_{q\to 0} = P_\Phi(q)\sum_a \mathcal{O}_a \langle \delta_{\vec{k}_1}(\eta_1)\cdots\delta_{\vec{k}_n}(\eta_n)\rangle'$$

Consistency relations are broken in DHOST

[MC, Lewandowski, Vernizzi]

$$\delta^{(2)}(\vec{k},t) = \int_{\vec{k}_1,\vec{k}_2}^{\vec{k}} F_2(\vec{k}_1,\vec{k}_2;t)\,\delta^{(1)}(\vec{k}_1,t)\delta^{(1)}(\vec{k}_2,t)$$

$$F_2(\vec{k}_1,\vec{k}_2;t) = A_\alpha(t)\alpha_s(\vec{k}_1,\vec{k}_2) + A_\gamma(t)\gamma(\vec{k}_1,\vec{k}_2)$$

1 + DHOST

Always modified

$$\lim_{q\to 0}\frac{B(q,k_2,k_3)}{P_{11}(q)P_{11}(k)} \approx -2A_\alpha\left(\frac{1}{2}\frac{\vec{q}\cdot\vec{k}}{q^2} - \frac{1}{2}\frac{\vec{q}\cdot\vec{k}}{q^2}\right) = 0$$

Because of translation invariance!

$$\lim_{q\to 0}\frac{B^{\rm mml}(q,k_2,k_3)}{P_{11}(q)P_{11}(k)} \approx \left(L_{\rm lens}A_\alpha - A_\alpha^{\rm lens}\right)\frac{\vec{q}\cdot\vec{k}}{q^2}$$

Enhanced for different tracers

Signatures in LSS

Consistency relations are broken in DHOST

[MC, Lewandowski, Vernizzi]

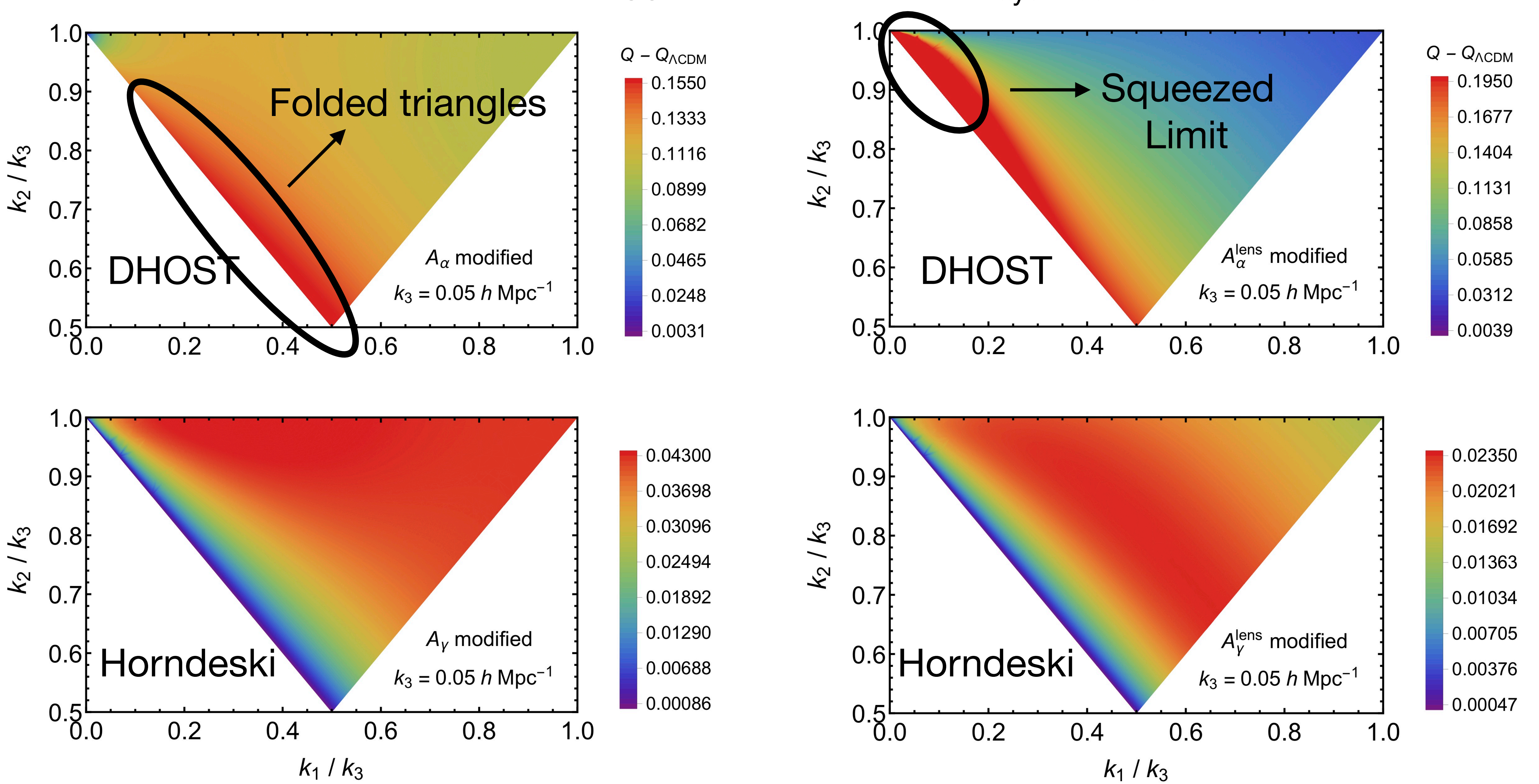
$$F_2(\vec{k}_1, \vec{k}_2; t) = A_\alpha(t)\alpha_s(\vec{k}_1, \vec{k}_2) + A_\gamma(t)\gamma(\vec{k}_1, \vec{k}_2)$$

1 + DHOST

Always modified

Auto-correlation

Cross-correlation



Stealth Black Holes

[Charmousis, MC, Gregory, Stergioulas]

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

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

$X \equiv \phi_\mu\phi^\mu = \text{const.}$ $\longrightarrow$ Relation between ϕ and the geodesic $x^\mu(\lambda)$

$$\phi^\mu \leftrightarrow \frac{dx^\mu}{d\lambda}$$

$$\nabla^\mu X = 0 \longrightarrow \frac{d^2x^\mu}{d\lambda^2} + \Gamma^\mu_{\rho\sigma}\frac{dx^\rho}{d\lambda}\frac{dx^\sigma}{d\lambda} = 0$$

Hamilton-Jacobi method

$$\frac{\partial S}{\partial x^\mu} = p_\mu = g_{\mu\nu}\frac{dx^\nu}{d\lambda}$$

$$\phi \leftrightarrow S$$

Rotating Black Holes

[Charmousis, MC, Gregory, Stergioulas]

$$S = -E\,t + \cancel{L_z}\varphi + S_r(r) + S_\theta(\theta)$$

Carter 1968

$$S_r = \pm \int \frac{\sqrt{R}}{\Delta_r} dr\,, \qquad S_\theta = \pm \int \frac{\sqrt{\Theta}}{\Delta_\theta} d\theta$$

$$\begin{cases} \Delta_r = \left(1 - \frac{r^2}{\ell^2}\right)(r^2 + a^2) - 2Mr \\ \Delta_\theta = 1 + \frac{a^2}{\ell^2}\cos^2\theta \end{cases}$$

$$\Theta = a^2 m^2 \sin^2\theta \left(\Delta_\theta - \eta^2\right)\,,$$
$$R = m^2(r^2 + a^2)\left(\eta^2 (r^2 + a^2) - \Delta_r\right)$$

$$\eta = \eta_c \quad \longrightarrow \quad R(r_0) = 0$$

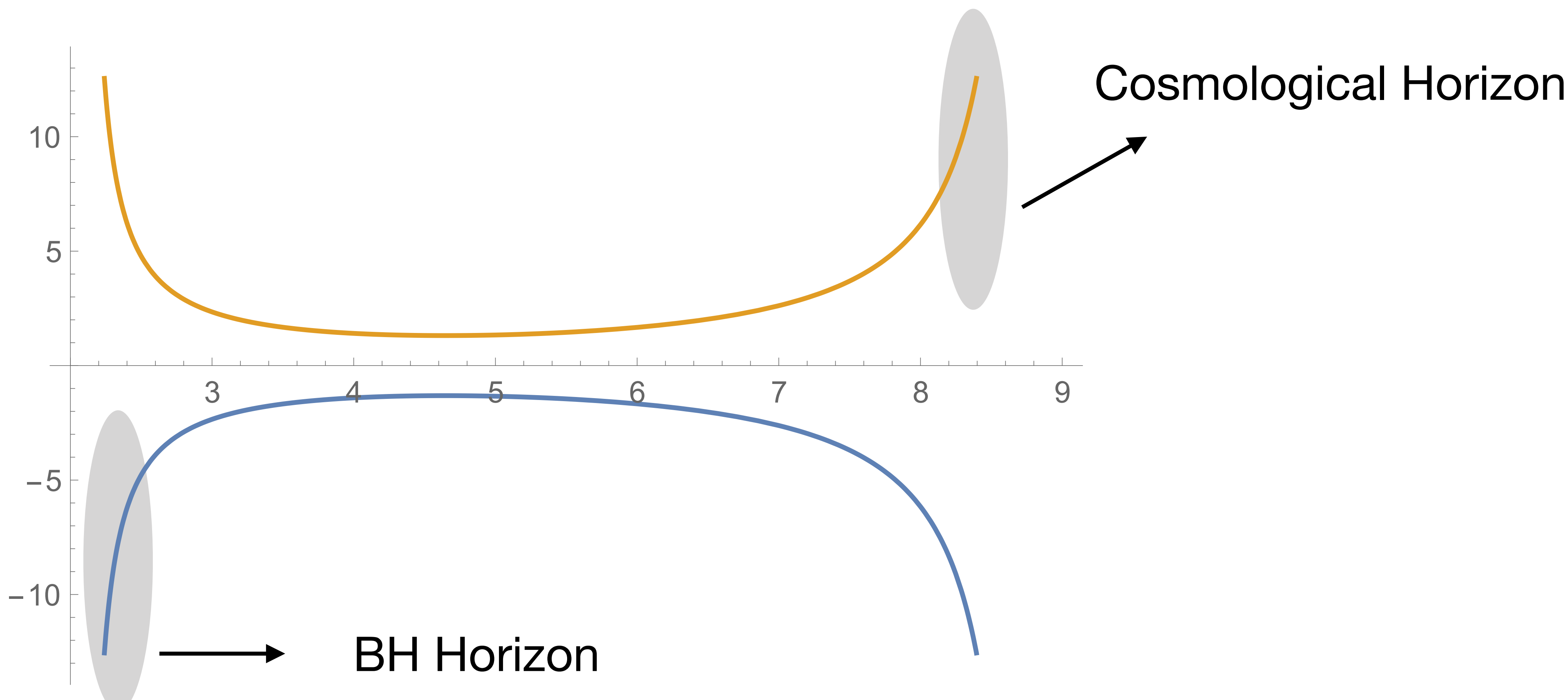
Rotating Black Holes

[Charmousis, MC, Gregory, Stergioulas]

$$S = -E\,t + \cancel{L_z}\varphi + S_r(r) + S_\theta(\theta)$$

Carter 1968

$$S_r = \pm \int \frac{\sqrt{R}}{\Delta_r} dr \qquad R = m^2(r^2+a^2)\left(\eta^2(r^2+a^2) - \Delta_r\right)$$



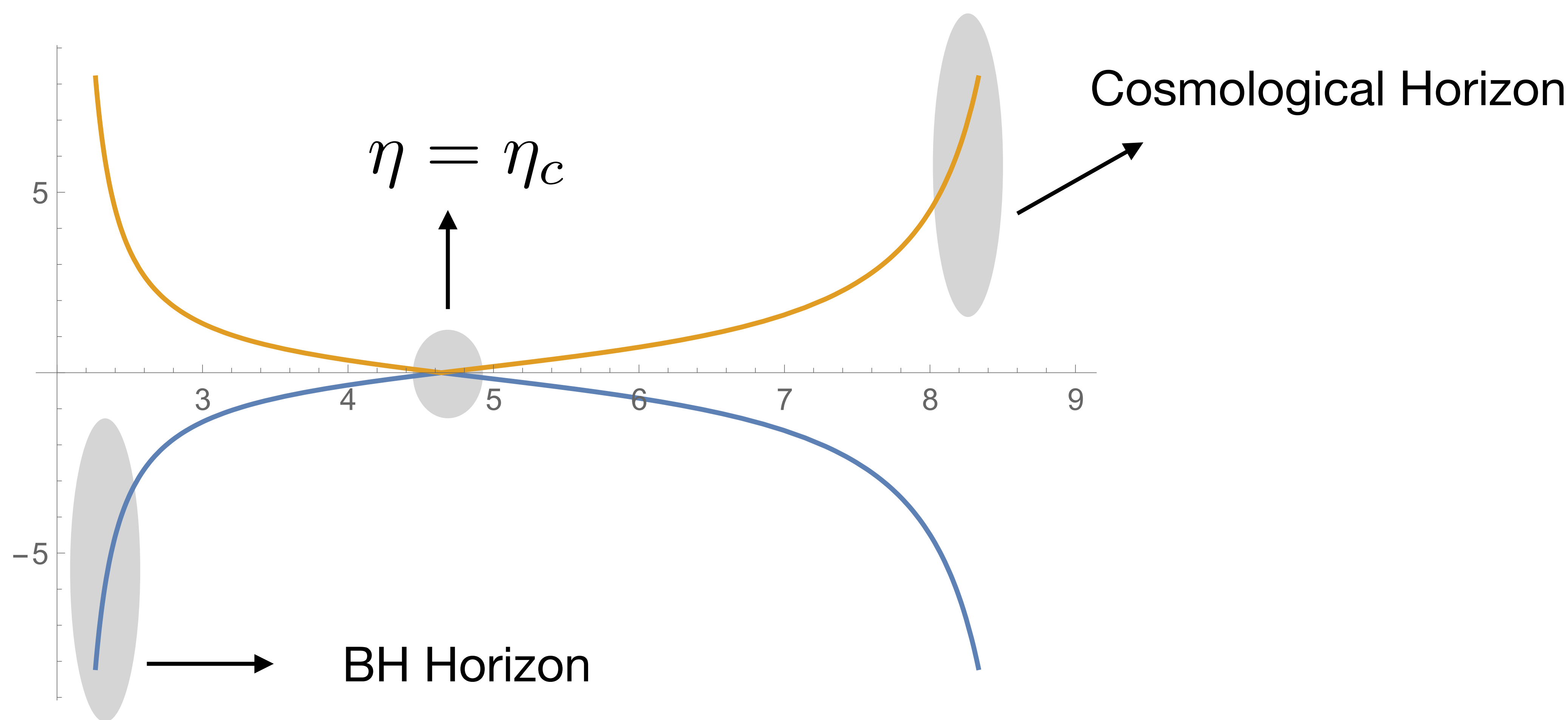
Rotating Black Holes

[Charmousis, MC, Gregory, Stergioulas]

$$S = -E\,t + \cancel{L_z}\varphi + S_r(r) + S_\theta(\theta)$$

Carter 1968

$$S_r = \pm \int \frac{\sqrt{R}}{\Delta_r} dr \qquad R = m^2(r^2+a^2)\left(\eta^2(r^2+a^2) - \Delta_r\right)$$



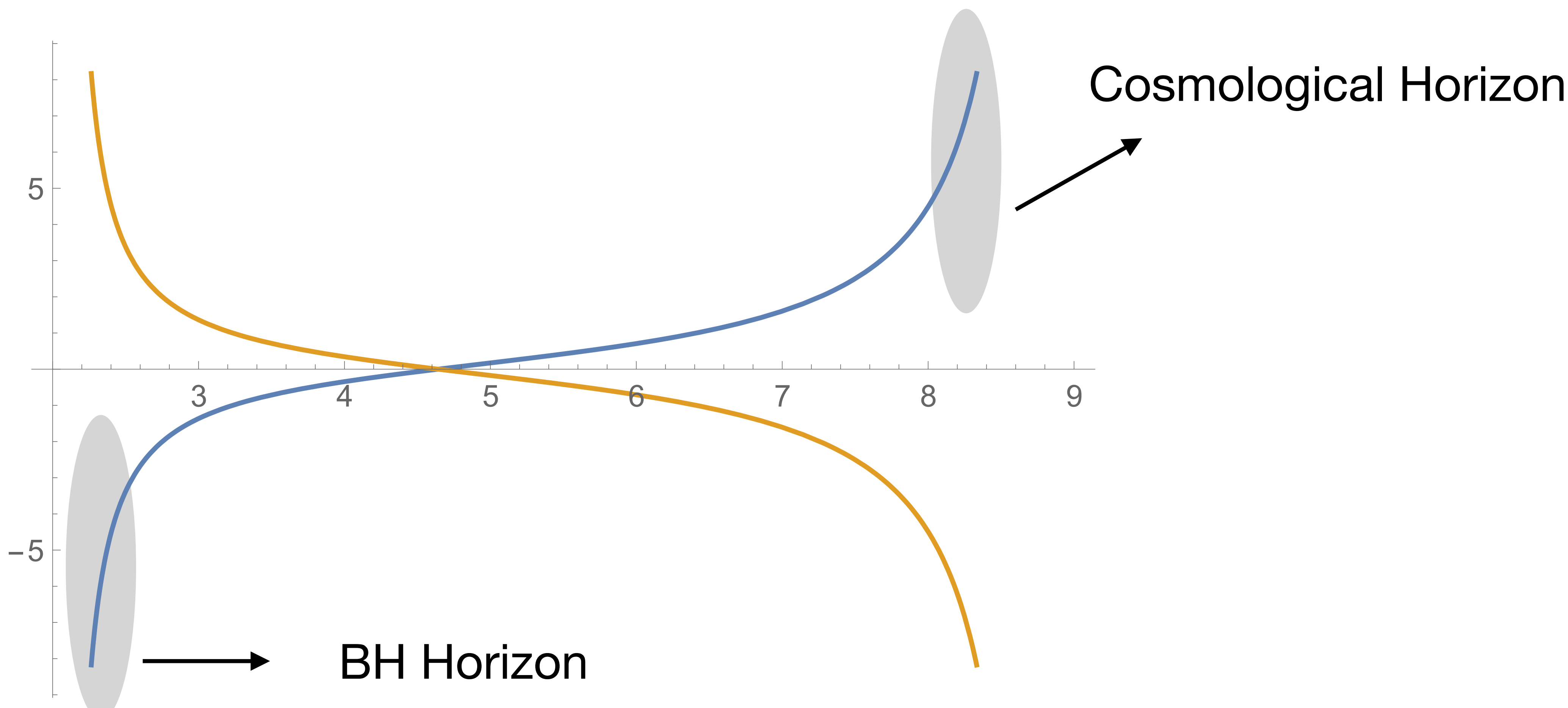
Rotating Black Holes

[Charmousis, MC, Gregory, Stergioulas]

$$S = -E\,t + \cancel{L_z}\varphi + S_r(r) + S_\theta(\theta)$$

Carter 1968

$$S_r = \pm \int \frac{\sqrt{R}}{\Delta_r} dr \qquad R = m^2(r^2+a^2)\left(\eta^2(r^2+a^2) - \Delta_r\right)$$



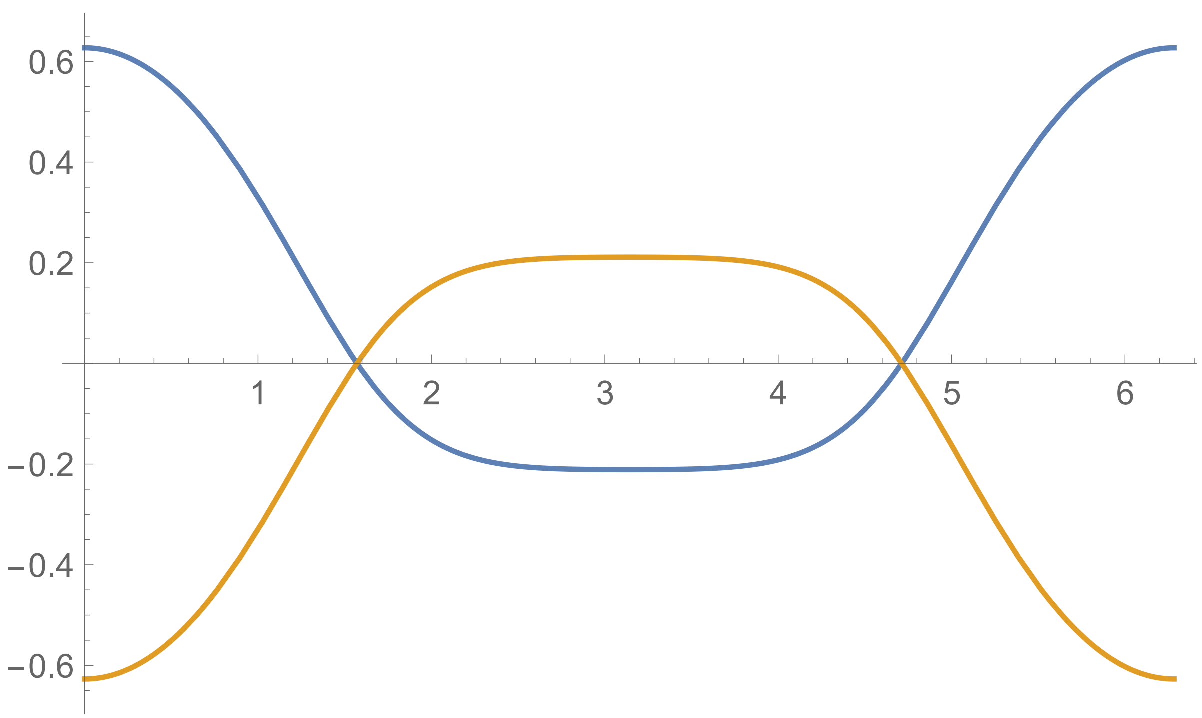
Rotating Black Holes

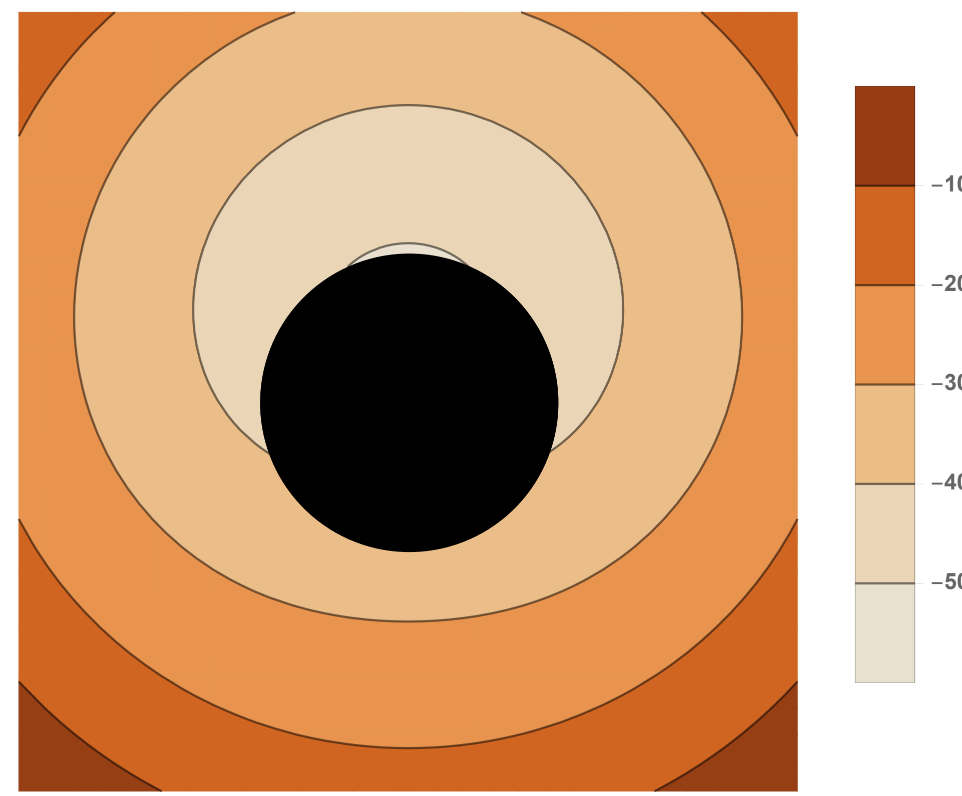
[Charmousis, MC, Gregory, Stergioulas]

$$S = -E\,t + \cancel{L_z}\varphi + S_r(r) + S_\theta(\theta)$$

Carter 1968

$$S_\theta = \pm \int \frac{\sqrt{\Theta}}{\Delta_\theta} d\theta \qquad\qquad \Theta = a^2 m^2 \sin^2\theta \left(\Delta_\theta - \eta^2\right)$$





Rotating Black Holes

[Charmousis, MC, Langlois, Noui]

$$S = -E\,t + \cancel{L_z}\varphi + S_r(r) + S_\theta(\theta)$$

Carter 1968

Perturbations

GR:

$$\psi(r,\theta)\, e^{-i\omega t + im\varphi} \qquad \mathscr{O}(\omega,m)\psi = 0$$

$$\mathscr{O}(\omega,m) = \mathscr{O}_r(\omega,m) + \mathscr{O}_\theta(\omega,m) \longrightarrow \psi(r,\theta) = \psi_r(r)\psi_\theta(\theta)$$

DHOST:

$$\mathscr{O}(\omega,m)\psi = \mathcal{T} \qquad \begin{cases} \delta G_{\mu\nu} = \delta T_{\mu\nu} \equiv \dfrac{1}{2}\Xi\,\overline{\phi}_\mu\overline{\phi}_\nu\,\delta X \\ \overline{\nabla}_\mu\left(\Xi\,\overline{\phi}^\mu\,\delta X\right) = 0 \end{cases}$$

Rotating Black Holes

[Charmousis, MC, Langlois, Noui]

$$S = -E\,t + \cancel{L_z}\varphi + S_r(r) + S_\theta(\theta)$$

Carter 1968

Perturbations

DHOST:

$$\overline{\nabla}_\mu \left(\Xi\, \overline{\phi}^\mu\, \delta X \right) = 0$$

$$\chi = \sum_m \int d\omega\, \chi_{m,\omega}(r,\theta) e^{-i\omega t + im\varphi}$$

$$I(r) \equiv -\int dr\, \frac{(r^2+a^2)^2}{\Delta(r)\sqrt{R(r)}}$$

$$\chi_{m,\omega}(r,\theta) = \frac{C_{m,\omega}(\theta)}{\sqrt{R(r)}} \exp\left[i\varepsilon \left(-\omega I(r) - \omega \sin^2\theta J(r) + mK(r) \right) \right]$$

$$J(r) \equiv \int dr\, \frac{a^2}{\sqrt{R(r)}}\,,$$

$$K(r) \equiv -\int dr\, \frac{2Mar}{\Delta(r)\sqrt{R(r)}}$$

Conclusions

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

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

- 3 free functions ($\alpha_K \quad \alpha_B \quad \alpha_M \quad \beta_1$)
- Screening is OK (hopefully)
- Self-acceleration is OK
- Distinctive signatures in LSS
- QNM & Ringdown

Thanks!