Testing the Quasi-Static and Sub-Horizon Approximations in Horndesky Theories.

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Greco

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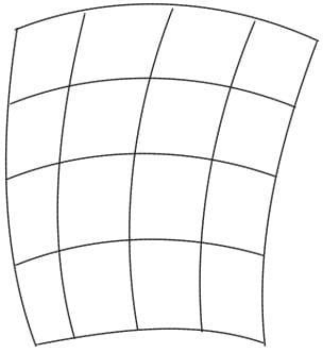
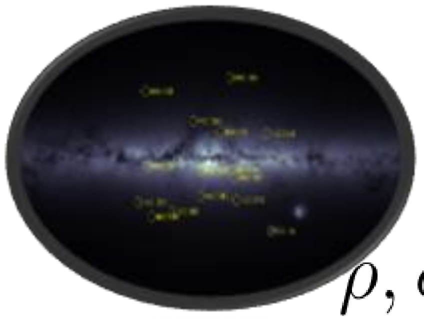
Universidad del Valle - Colombia

COSMOLOGY in COLOMBIA CoCo 2025

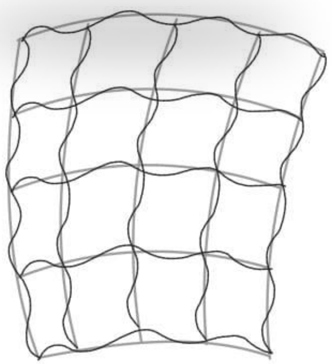
Universidad del Valle

Input





ρ, ϕ



SOLVERS

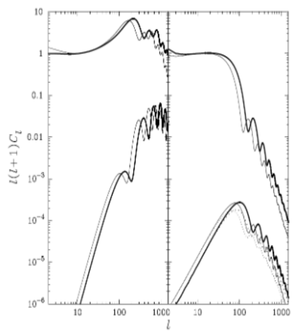
Horndeski in the Cosmic Linear Anisotropy Solving System

hi_class

CMBFAST

CLASS

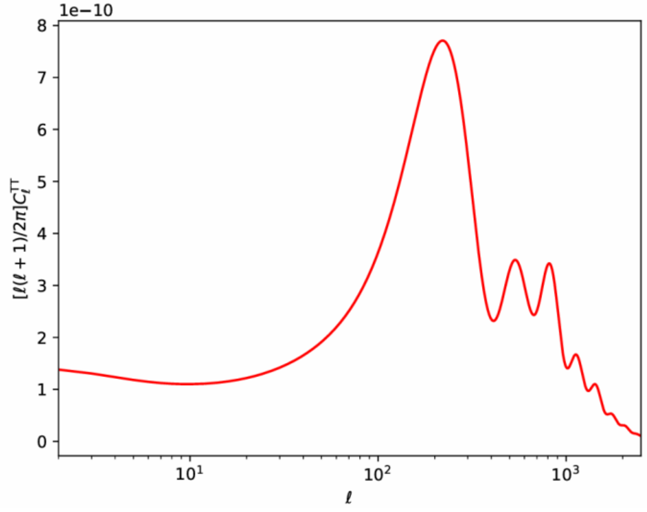
the Cosmic Linear Anisotropy Solving System

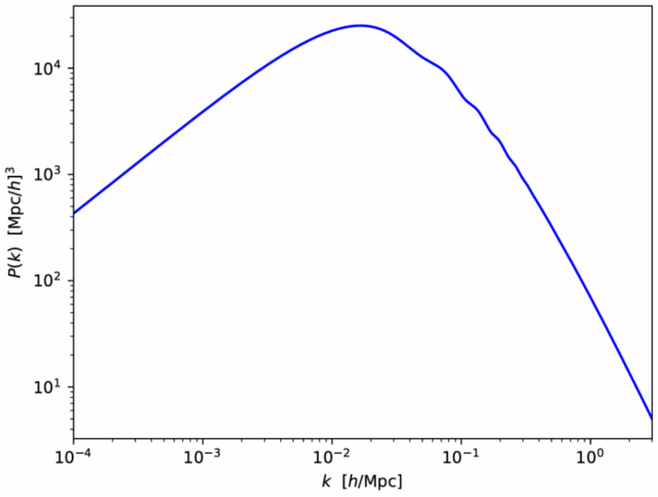


MGCAMB

Code for Anisotropies in the Microwave Background

Output

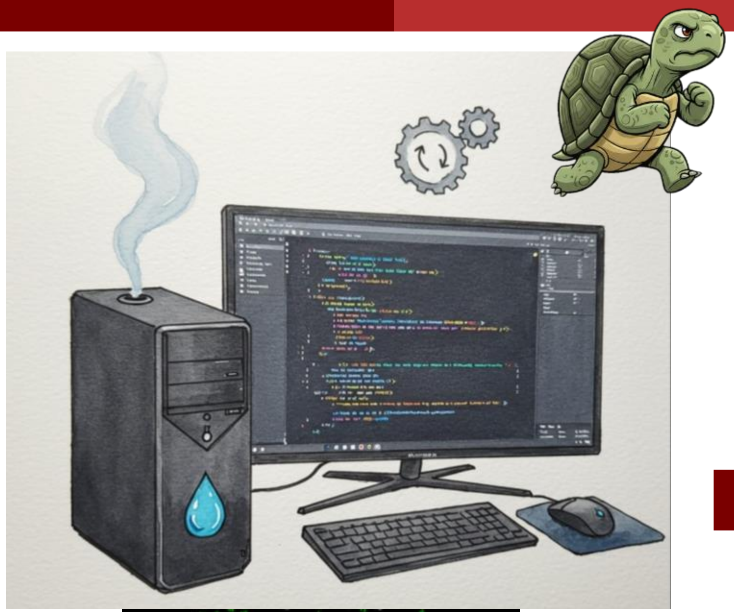




FULL

Horndeski

FULL



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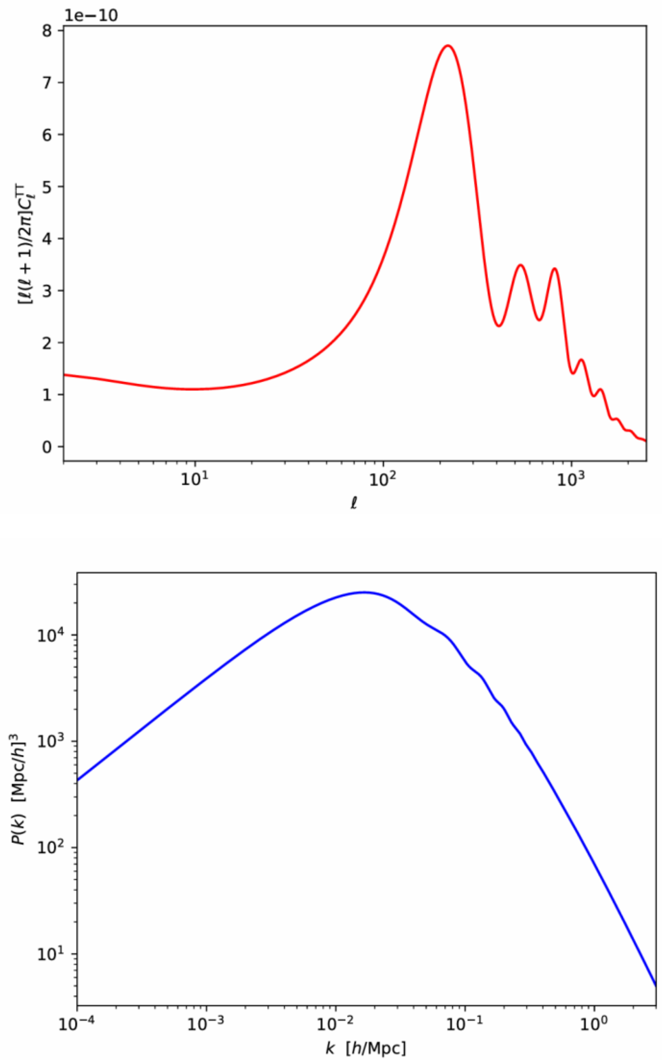
Output



Horndeski

Horndeski

$QSA - SHA$

Horndeski

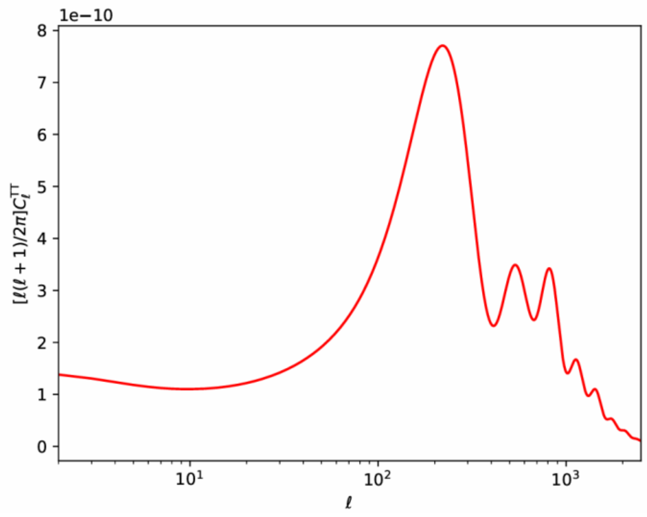
$QSA - SHA$

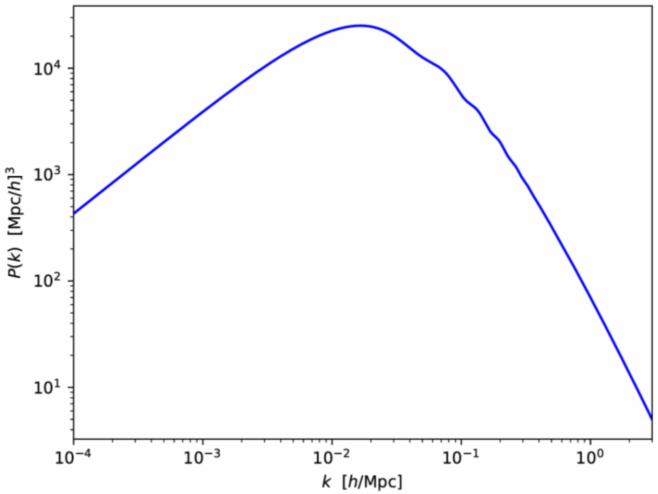
hi_class

Einstein Boltzmann solver

$\approx$

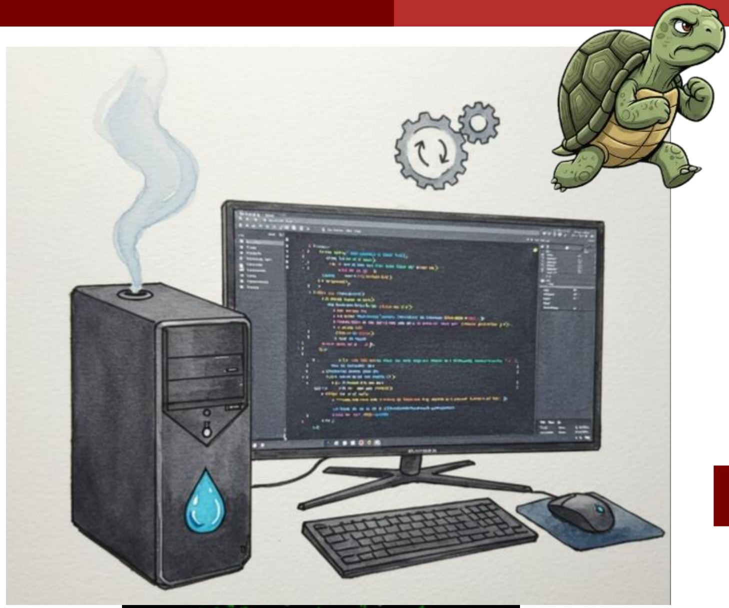
Output





Horndeski

FULL →



hi_class

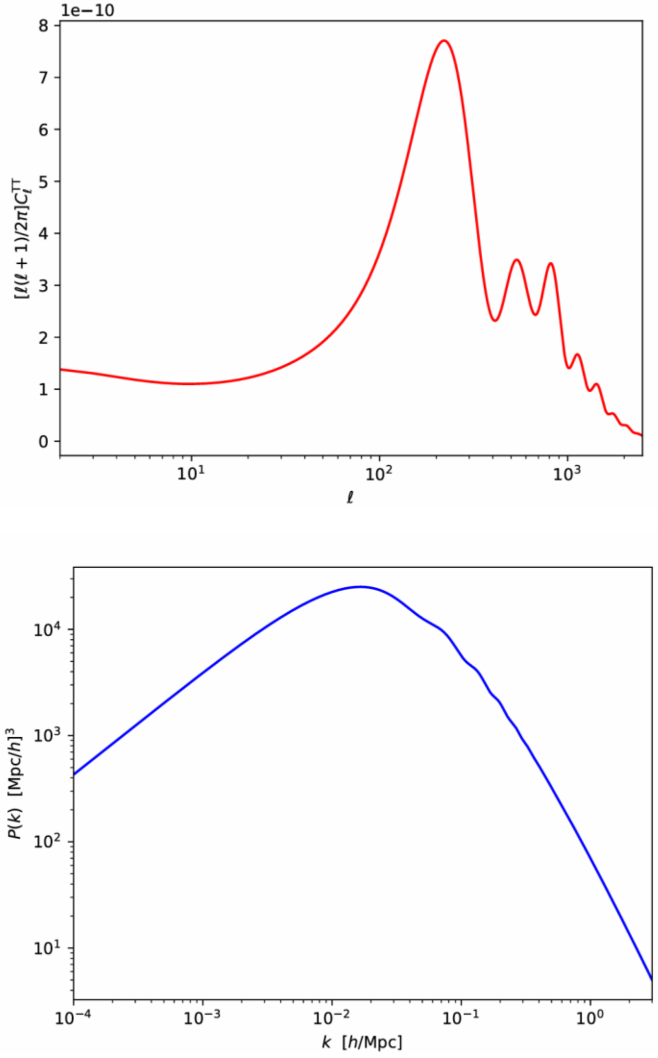
$QSA - SHA$ →

Einstein Boltzmann solver

= →

≈ →

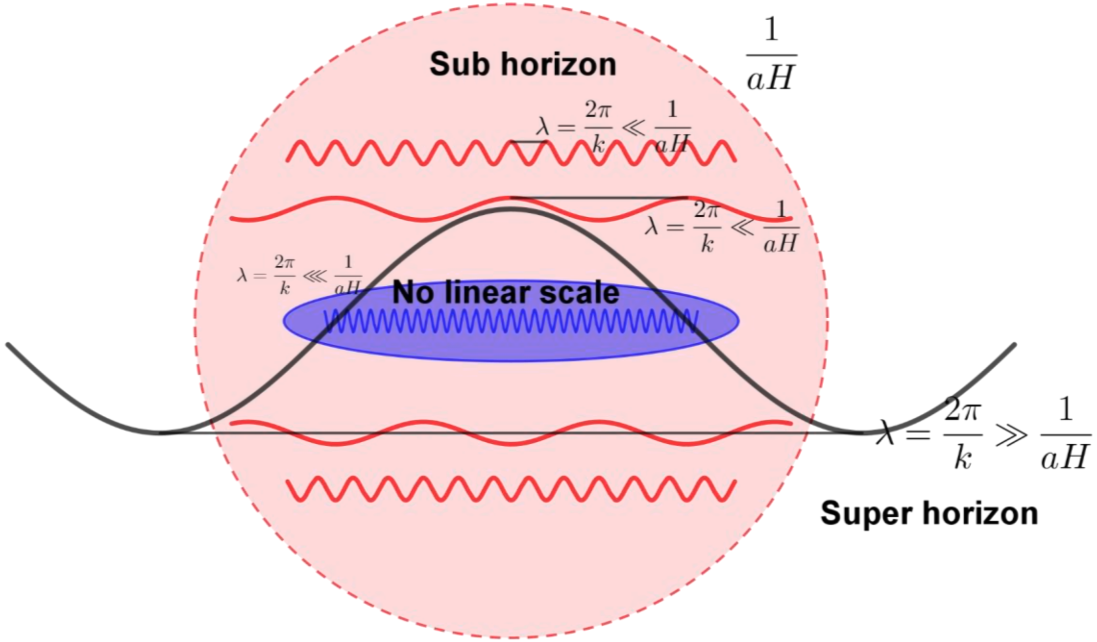
Output



What is the QSA and SHA?

$$\mathrm{d}s^2 = -\{1 + 2\Psi(\boldsymbol{x}, t)\}\mathrm{d}t^2 + a(t)^2\{1 + 2\Phi(\boldsymbol{x}, t)\}\delta_{ij}\, \mathrm{d}x^i\, \mathrm{d}x^j$$

$$k \gg aH, \quad \Phi \gg \frac{\dot{\Phi}}{H}, \quad \Psi \gg \frac{\dot{\Psi}}{H}$$



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$$k \gg aH, \quad \Phi \gg \frac{\dot{\Phi}}{H}, \quad \Psi \gg \frac{\dot{\Psi}}{H}$$

$$\delta R = 6\ddot{\Phi} + 24H\dot{\Phi} - 6H\dot{\Psi} + 4\frac{k^2}{a^2}\Phi + \left(2\frac{k^2}{a^2} - 12\dot{H} + 24H^2\right)\Psi$$

What is the QSA and SHA?

$$ds^2 = -\{1 + 2\Psi(\boldsymbol{x}, t)\}dt^2 + a(t)^2\{1 + 2\Phi(\boldsymbol{x}, t)\}\delta_{ij}\, dx^i\, dx^j$$

$$k \gg aH, \quad \Phi \gg \frac{\dot{\Phi}}{H}, \quad \Psi \gg \frac{\dot{\Psi}}{H}$$

$$\delta R = \cancel{6\ddot{\Phi}} + \cancel{24H\dot{\Phi}} - \cancel{6H\dot{\Psi}} + 4\frac{k^2}{a^2}\Phi + \left(2\frac{k^2}{a^2} - 12\dot{H} + 24H^2\right)\Psi$$

$$\overset{\text{QSA}}{\approx} 4\frac{k^2}{a^2}\Phi + \left(2\frac{k^2}{a^2} - 12\dot{H} + 24H^2\right)\Psi$$

What is the QSA and SHA?

$$\mathrm{d}s^2 = -\{1 + 2\Psi(\boldsymbol{x}, t)\}\mathrm{d}t^2 + a(t)^2\{1 + 2\Phi(\boldsymbol{x}, t)\}\delta_{ij}\, \mathrm{d}x^i\, \mathrm{d}x^j$$

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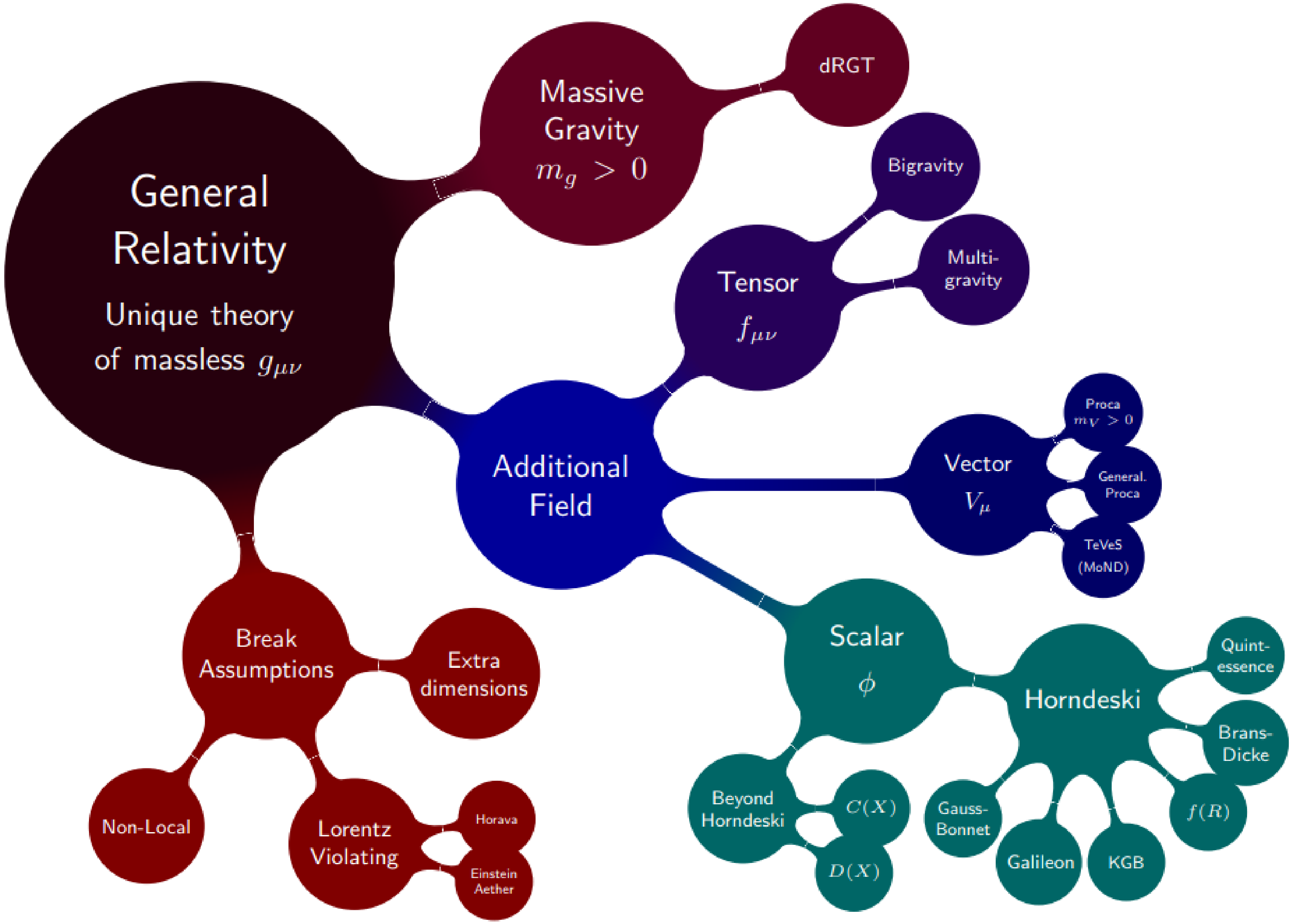
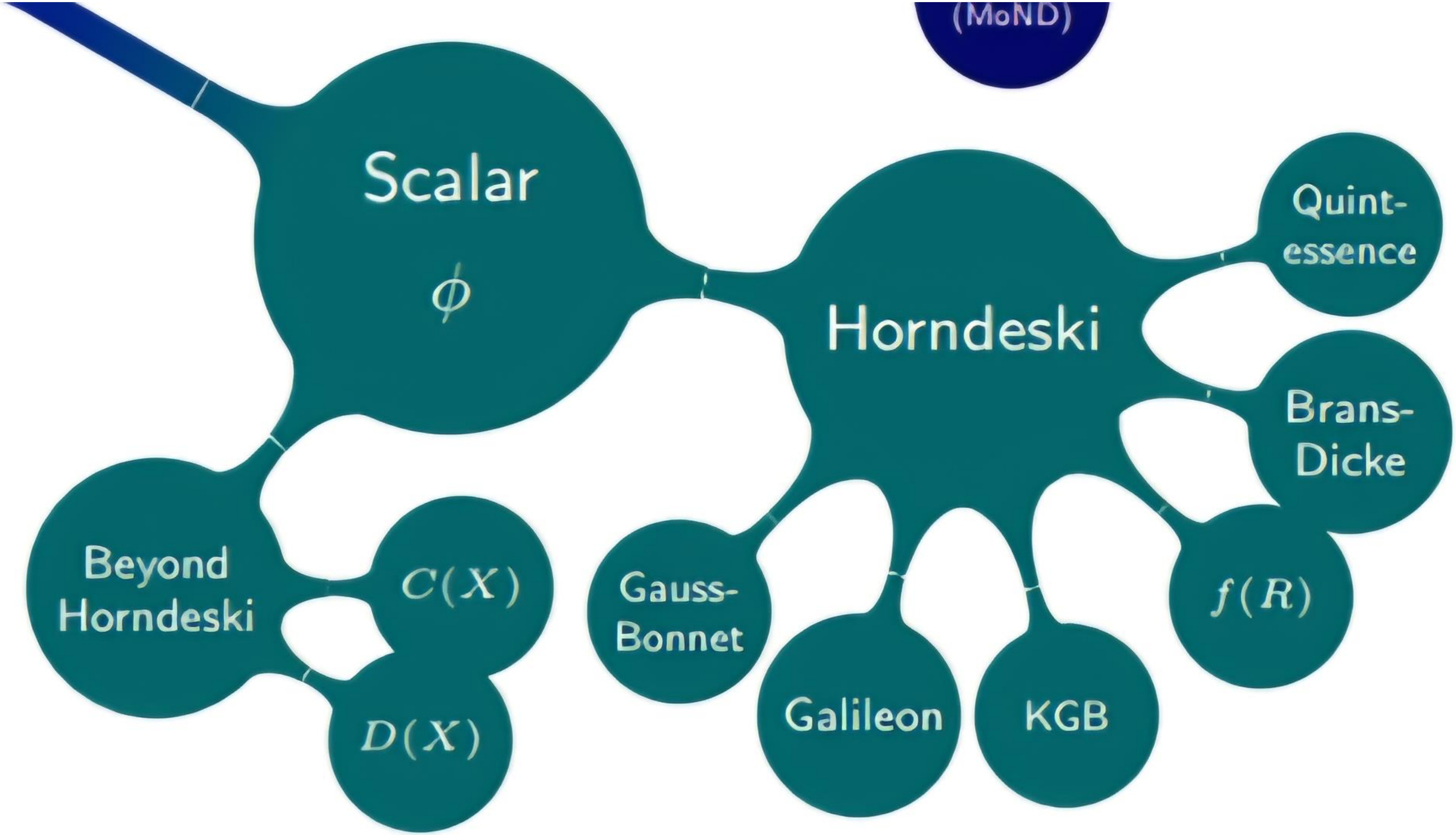
$$\overset{\mathrm{QSA}}{\approx} \quad 4\frac{k^2}{a^2}\Phi + \left(2\frac{k^2}{a^2} - 12\dot{H} + 24H^2\right)\Psi$$

$$\overset{\mathrm{SHA}}{\approx} \quad 4\frac{k^2}{a^2}\Phi + 2\frac{k^2}{a^2}\Psi.$$



J. M. Ezquiaga and M. Zumalacárregui (2018,



J. M. Ezquiaga and M. Zumalacárregui (2018,

$$g_{\mu\nu} \to \bar{g}_{\mu\nu} + \delta g_{\mu\nu} \qquad G_{\mu\nu} \to \bar{G}_{\mu\nu} + \delta G_{\mu\nu} \qquad T_{\mu\nu} \to \bar{T}_{\mu\nu} + \delta T_{\mu\nu}$$

$$0 = -\kappa \bar{\rho}_m \delta_m + A_1 \dot{\Phi} + A_2 \dot{\Psi} + \left(A_3 + A_4 \frac{k^2}{a^2} \right) \Phi + \left(A_5 + A_6 \frac{k^2}{a^2} \right) \Psi,$$

$$0 = -\frac{a \kappa \bar{\rho}_m V_m}{k^2} + C_1 \dot{\Phi} + C_2 \dot{\Psi} + C_3 \Phi + C_4 \Psi,$$

$$0 = B_1 \ddot{\Phi} + B_2 \ddot{\Psi} + B_3 \dot{\Phi} + B_4 \dot{\Psi} + B_5 \Phi + B_6 \Psi,$$

$$0 = D_1 \ddot{\Phi} + D_2 \dot{\Phi} + D_3 \dot{\Psi} + \left(D_4 + D_5 \frac{k^2}{a^2} \right) \Phi + \left(D_6 + D_7 \frac{k^2}{a^2} \right) \Psi.$$

Designing Horndeski and the effective fluid approach

Rubén Arjona,* Wilmar Cardona,† and Savvas Nesseris‡ arXiv:1904.06294v2

$$g_{\mu\nu} \to \bar{g}_{\mu\nu} + \delta g_{\mu\nu} \qquad G_{\mu\nu} \to \bar{G}_{\mu\nu} + \delta G_{\mu\nu} \qquad T_{\mu\nu} \to \bar{T}_{\mu\nu} + \delta T_{\mu\nu}$$

$$A_3 \frac{k^2}{a^2}\Psi + A_6 \frac{k^2}{a^2}\delta\phi - \kappa\rho_m\delta_m \simeq 0,$$

$$B_6 \frac{k^2}{a^2}\Psi + B_8 \frac{k^2}{a^2}\Phi + B_7 \frac{k^2}{a^2}\delta\phi \simeq 0,$$

$$D_7 \frac{k^2}{a^2}\Psi + \left(D_9 \frac{k^2}{a^2} - M^2\right)\delta\phi + D_{10}\frac{k^2}{a^2}\Phi \simeq 0,$$

$$G_4(\Psi + \Phi) + G_{4\phi}\delta\phi = 0$$

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$$G_4(\Psi + \Phi) + G_{4\phi}\delta\phi = 0$$

$$D_9 = -K_X + 2G_{3\phi} - 4H\dot{\phi}G_{3X} - \ddot{\phi}\left(2G_{3X} + \dot{\phi}^2 G_{3XX}\right) - \dot{\phi}^2 G_{3\phi X}$$

Designing Horndeski and the effective fluid approach

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QSA-SHA coeffiecients

$$\varepsilon \equiv \frac{aH}{k}, \qquad \delta \equiv \frac{\dot{\varepsilon}}{\varepsilon H}, \qquad \xi \equiv \frac{\ddot{\varepsilon}}{\varepsilon H^2}, \quad \chi \equiv \frac{\dddot{\varepsilon}}{\varepsilon H^3},$$

$$\varepsilon_\Phi \equiv \frac{\dot{\Phi}}{\Phi H}, \quad \varepsilon_\Psi \equiv \frac{\dot{\Psi}}{\Psi H}, \quad \chi_\Phi \equiv \frac{\dot{\varepsilon}_\Phi}{\varepsilon_\Phi H}, \quad \chi_\Psi \equiv \frac{\dot{\varepsilon}_\Psi}{\varepsilon_\Psi H}.$$

Tracking the validity of the quasi-static and sub-horizon approximations in modified gravity

J. Bayron Orjuela-Quintana, Savvas Nesseris arXiv:2303.14251 **[gr-qc]**

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$$\kappa\delta\rho_{\rm DE} = W_1\dot{\Phi} + W_2\dot{\Psi} + \left(W_3 + W_4\frac{k^2}{a^2}\right)\Phi + \left(W_5 + W_6\frac{k^2}{a^2}\right)\Psi,$$
$$\kappa\delta P_{\rm DE} = Y_1\ddot{\Phi} + Y_2\ddot{\Psi} + Y_3\dot{\Phi} + Y_4\dot{\Psi} + \left(Y_5 + Y_6\frac{k^2}{a^2}\right)\Phi + \left(Y_7 + Y_8\frac{k^2}{a^2}\right)\Psi,$$
$$\frac{a\kappa\bar{\rho}_{\rm DE}}{k^2}V_{\rm DE} = Z_1\dot{\Phi} + Z_2\dot{\Psi} + Z_3\Phi + Z_4\Psi,$$
$$\kappa\bar{\rho}_{\rm DE}\pi_{\rm DE} = -\frac{k^2}{a^2}(\Phi + \Psi),$$

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$$V_{\rm DE} = \frac{a\dot{F}}{2F}\frac{F + 6\frac{k^2}{a^2}F_R}{3\frac{k^2}{a^2}F_R + F}\frac{\bar{\rho}_m}{\bar{\rho}_{\rm DE}}\delta_m \approx 0$$

$$\dot{F}\delta_m \approx 0$$

$$\dot{F} \propto H \times \text{Perturbation} \sim 0$$

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QSA-SHA "0-order"

$$V_{\mathrm{DE}} = \frac{a\dot{F}}{2F} \frac{F + 6\frac{k^2}{a^2}F_R}{3\frac{k^2}{a^2}F_R + F} \frac{\bar{\rho}_m}{\bar{\rho}_{\mathrm{DE}}} \delta_m \qquad \dot{F} = 6\frac{k^3}{a^3}(\delta + \xi - 2)F_R \varepsilon^3$$

$$V_{\mathrm{DE}} = \frac{a}{F\left(F + 3\frac{k^2}{a^2}F_R\right)} \left\{ F(F-1) + \frac{k^2}{a^2}(3F-4)F_R \right\} \frac{\bar{\rho}_m}{\bar{\rho}_{\mathrm{DE}}} \delta_m \frac{k}{a} \varepsilon$$

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QSA-SHA coeffiecients

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$$\varepsilon_\Phi \equiv \frac{\dot{\Phi}}{\Phi H}, \quad \varepsilon_\Psi \equiv \frac{\dot{\Psi}}{\Psi H}, \quad \chi_\Phi \equiv \frac{\dot{\varepsilon}_\Phi}{\varepsilon_\Phi H}, \quad \chi_\Psi \equiv \frac{\dot{\varepsilon}_\Psi}{\varepsilon_\Psi H}.$$

- Standar approach $V_{\mathrm{DE}} \sim \mathcal{O}(\epsilon^3)$
- QSA-SHA coeffiecients $V_{\mathrm{DE}} \sim \mathcal{O}(\epsilon)$

Tracking the validity of the quasi-static and sub-horizon approximations in modified gravity

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Horndeski

$QSA - SHA$

Coefficients
0 - order

$$\varepsilon \equiv \frac{aH}{k}, \qquad \delta \equiv \frac{\dot{\varepsilon}}{\varepsilon H},$$
$$\xi \equiv \frac{\ddot{\varepsilon}}{\varepsilon H^2}, \qquad \chi \equiv \frac{\dddot{\varepsilon}}{\varepsilon H^3},$$
$$\varepsilon_\Phi \equiv \frac{\dot{\Phi}}{\Phi H}, \qquad \varepsilon_\varphi \equiv \frac{\dot{\varphi}}{\varphi H},$$
$$\chi_\Phi \equiv \frac{\dot{\varepsilon}_\Phi}{\varepsilon_\Phi H}, \qquad \chi_\varphi \equiv \frac{\dot{\varepsilon}_\varphi}{\varepsilon_\varphi H}.$$

- $\pi_{DE} = 0$

$$\varepsilon \equiv \frac{aH}{k}, \qquad \delta \equiv \frac{\dot{\varepsilon}}{\varepsilon H},$$
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- $\pi_{DE} \neq 0$

Coefficients for Horndesky

- $\pi_{DE} \neq 0$

$$\varepsilon \equiv \frac{aH}{k}, \quad \delta \equiv \frac{\dot{\varepsilon}}{\varepsilon H}, \quad \xi \equiv \frac{\ddot{\varepsilon}}{\varepsilon H^2}, \quad \chi \equiv \frac{\dddot{\varepsilon}}{\varepsilon H^3},$$
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$$A = A_0 + \frac{k^2}{a^2}A_1 + \left(A_1 + \frac{k^2}{a^2}A_2 + \frac{k^4}{a^4}A_3\right)\varepsilon + \mathcal{O}\left(\varepsilon^2, \varepsilon_\Psi, \varepsilon_\Psi\right)$$

- $\pi_{DE} = 0$

$$\varepsilon \equiv \frac{aH}{k}, \quad \delta \equiv \frac{\dot{\varepsilon}}{\varepsilon H}, \quad \xi \equiv \frac{\ddot{\varepsilon}}{\varepsilon H^2}, \quad \chi \equiv \frac{\dddot{\varepsilon}}{\varepsilon H^3},$$
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$$A = A_0 + \frac{k^2}{a^2}A_1 + \left(A_1 + \frac{k^2}{a^2}A_2 + \frac{k^4}{a^4}A_3\right)\varepsilon + \mathcal{O}\left(\varepsilon^2, \varepsilon_\varphi, \varepsilon_\Phi\right)$$

Coefficients for Horndesky

$$\frac{G}{G_N} \propto \mathcal{D}\mathbf{5}^{(0)} + \frac{k^2\mathcal{D}\mathbf{6}^{(0)}}{a^2} + \left(\frac{k^2\mathcal{D}\mathbf{8}^{(0)}}{a^2} + \mathcal{D}\mathbf{7}^{(0)}\right)\frac{k\varepsilon}{a} + \frac{k^2\mathcal{D}\mathbf{9}^{(0)}\varepsilon^2}{a^2} + \frac{k^3\mathcal{D}\mathbf{10}^{(0)}\varepsilon^3}{a^3}$$

$$\Bigg/ \left(\mathcal{F}\mathbf{1}^{(\theta)} + \frac{\mathrm{k}^4\mathcal{F}\mathbf{3}^{(\theta)}}{\mathrm{a}^4} + \frac{\mathrm{k}^2\mathcal{F}\mathbf{2}^{(\theta)}}{\mathrm{a}^2} + \left(\frac{\mathrm{k}^5\mathcal{F}\mathbf{6}^{(\theta)}}{\mathrm{a}^5} + \frac{\mathrm{k}^3\mathcal{F}\mathbf{5}^{(\theta)}}{\mathrm{a}^3} + \frac{\mathrm{k}\mathcal{F}\mathbf{4}^{(\theta)}}{\mathrm{a}}\right)\varepsilon\right.$$

$$+ \left(\frac{\mathrm{k}^4\mathcal{F}\mathbf{8}^{(\theta)}}{\mathrm{a}^4} + \frac{\mathrm{k}^2\mathcal{F}\mathbf{7}^{(\theta)}}{\mathrm{a}^2}\right)\varepsilon^2 + \left(\frac{\mathrm{k}^5\mathcal{F}10^{(\theta)}}{\mathrm{a}^5} + \frac{\mathrm{k}^3\mathcal{F}\mathbf{9}^{(\theta)}}{\mathrm{a}^3}\right)\varepsilon^3$$

$$\left. + \frac{\mathrm{k}^4\mathcal{F}11^{(\theta)}\varepsilon^4}{\mathrm{a}^4} + \frac{\mathrm{k}^5\mathcal{F}12^{(\theta)}\varepsilon^5}{\mathrm{a}^5}\right)$$

Coefficients for Horndesky

$$\frac{G}{G_N} \propto \mathcal{D}\mathbf{5}^{(0)} + \frac{k^2\mathcal{D}\mathbf{6}^{(0)}}{a^2} + \left(\frac{k^2\mathcal{D}\mathbf{8}^{(0)}}{a^2} + \mathcal{D}\mathbf{7}^{(0)}\right)\frac{k\varepsilon}{a} + \frac{k^2\mathcal{D}\mathbf{9}^{(0)}\varepsilon^2}{a^2} + \frac{k^3\mathcal{D}\mathbf{10}^{(0)}\varepsilon^3}{a^3}$$

$$\Bigg/ \left(\mathcal{F}\mathbf{1}^{(\theta)} + \frac{\mathrm{k}^4\mathcal{F}\mathbf{3}^{(\theta)}}{\mathrm{a}^4} + \frac{\mathrm{k}^2\mathcal{F}\mathbf{2}^{(\theta)}}{\mathrm{a}^2} + \left(\frac{\mathrm{k}^5\mathcal{F}\mathbf{6}^{(\theta)}}{\mathrm{a}^5} + \frac{\mathrm{k}^3\mathcal{F}\mathbf{5}^{(\theta)}}{\mathrm{a}^3} + \frac{\mathrm{k}\mathcal{F}\mathbf{4}^{(\theta)}}{\mathrm{a}}\right)\varepsilon\right.$$

$$+ \left(\frac{\mathrm{k}^4\mathcal{F}\mathbf{8}^{(\theta)}}{\mathrm{a}^4} + \frac{\mathrm{k}^2\mathcal{F}\mathbf{7}^{(\theta)}}{\mathrm{a}^2}\right)\varepsilon^2 + \left(\frac{\mathrm{k}^5\mathcal{F}10^{(\theta)}}{\mathrm{a}^5} + \frac{\mathrm{k}^3\mathcal{F}\mathbf{9}^{(\theta)}}{\mathrm{a}^3}\right)\varepsilon^3$$

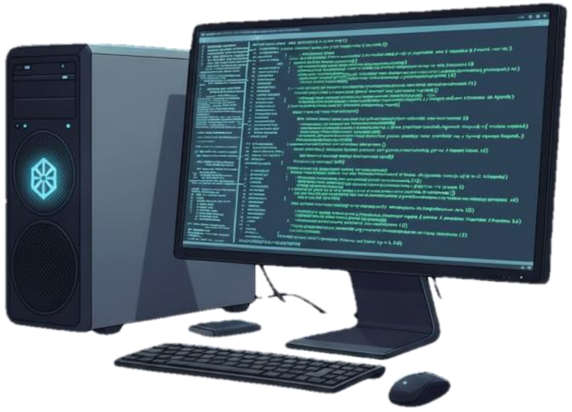
$$\left. + \frac{\mathrm{k}^4\mathcal{F}11^{(\theta)}\varepsilon^4}{\mathrm{a}^4} + \frac{\mathrm{k}^5\mathcal{F}12^{(\theta)}\varepsilon^5}{\mathrm{a}^5}\right)$$

Horndeski

FULL

hi_class

$QSA - SHA$



Einstein Boltzmann solver

$=$

$\approx$

Φ, Ψ, P(k), C(l), …

DESCUBRE EL CONOCIMIENTO

HECHO EN UNIVALLE

QUE TRANSFORMA VIDAS