A MASTER EQUATION FOR SCREENING IN LUMINAL HORNDESKI

SERGI SIRERA

PASCOS SHEFFIELD - 25 JUNE 2026

[2605.04154]: SS, TESSA BAKER, JAMES HALLAM, KRISHNA NAIDOO

THE ROYAL SOCIETY

UNIVERSITY OF PORTSMOUTH

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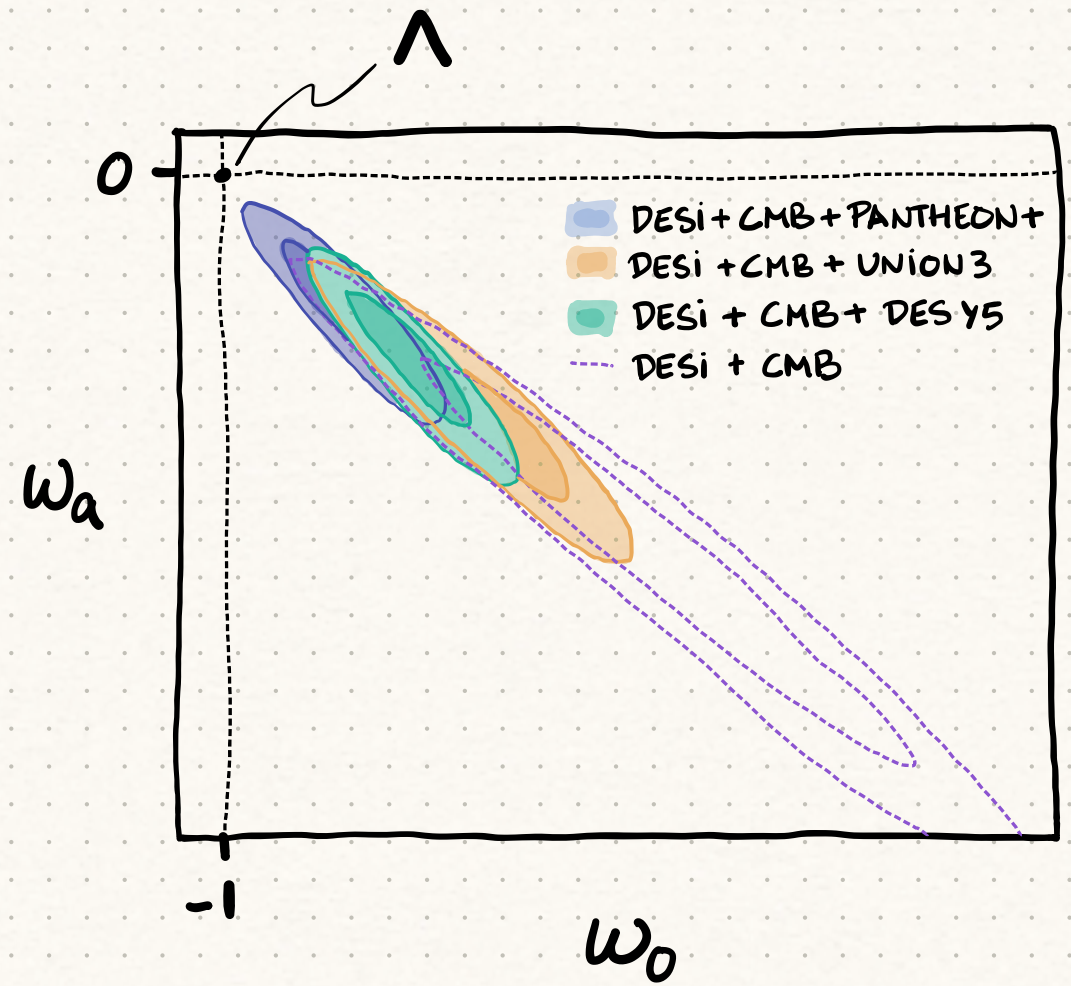
OUTLINE

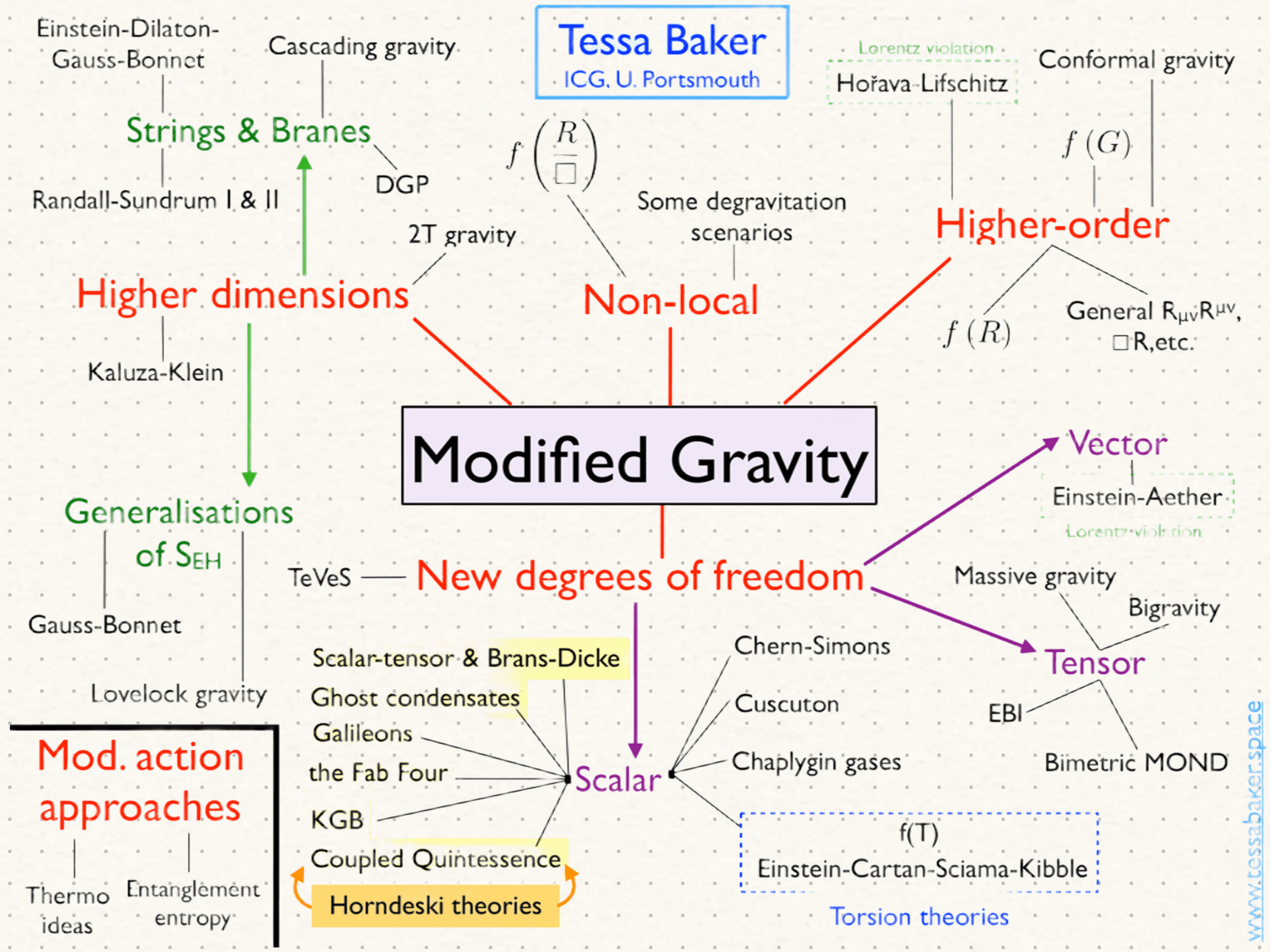
1. MOTIVATION: HOW DOES A THEORY SCREEN?
2. DERIVING MASTER EQUATION
3. SOLVING MASTER EQUATION
4. SUMMARY

- DARK ENERGY IS DYNAMICAL

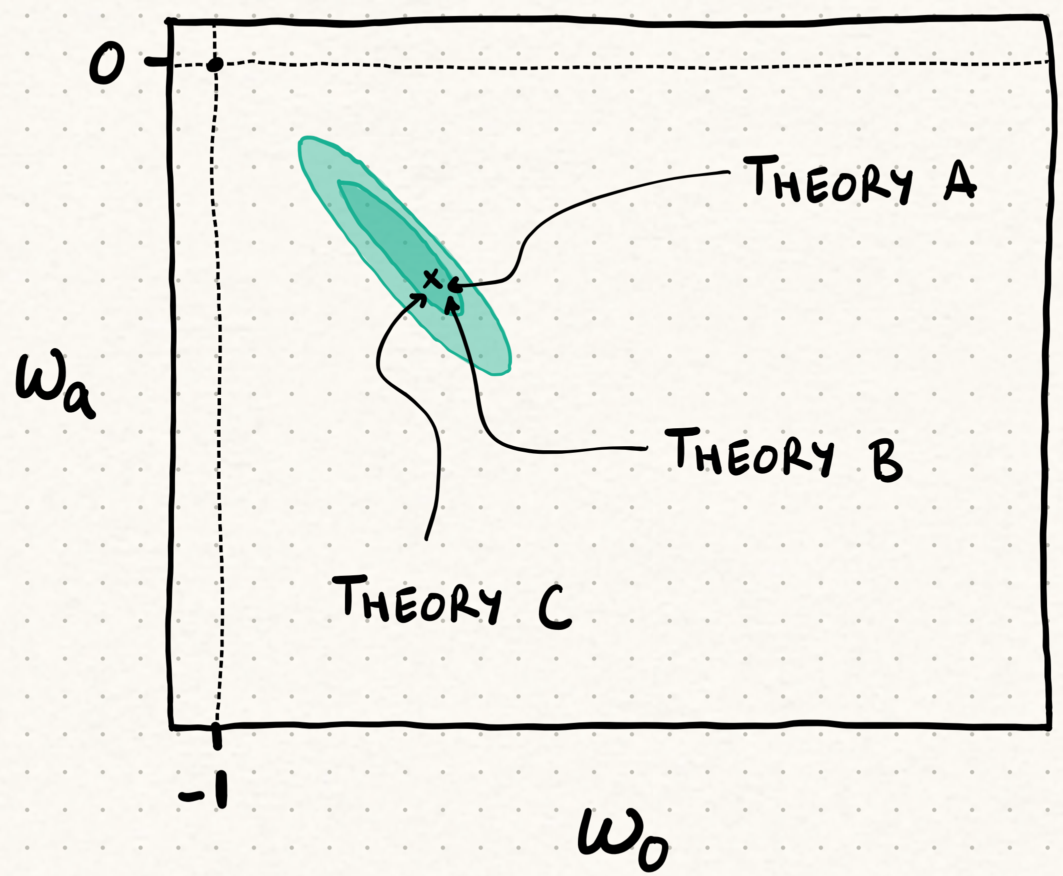


DESI DR2

- DARK ENERGY IS DYNAMICAL
- BUT, WHAT THEORY ?

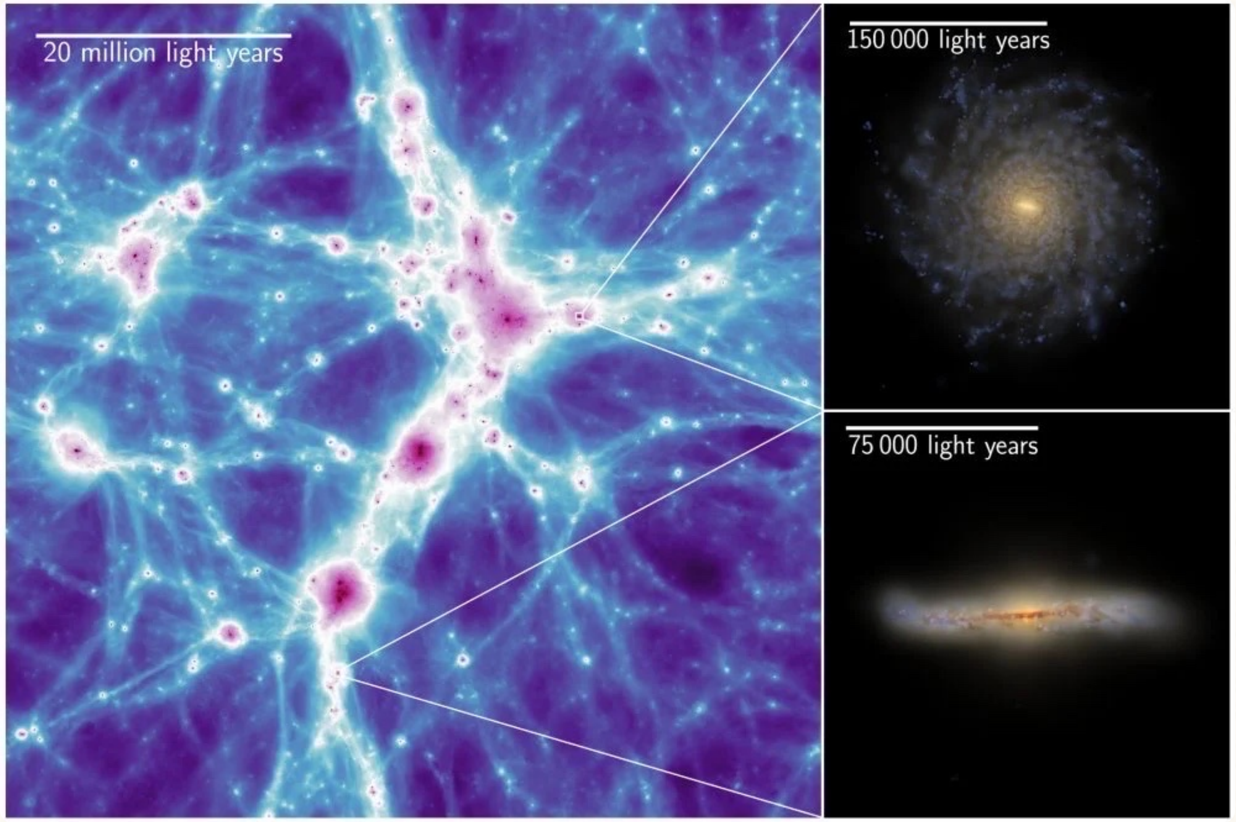


- DARK ENERGY IS DYNAMICAL
- BUT, WHAT THEORY?
  - UNDERDETERMINED AT BACKGROUND AND LINEAR LEVEL



- DARK ENERGY IS DYNAMICAL
- BUT, WHAT THEORY ?
  - UNDERDETERMINED AT BACKGROUND AND LINEAR LEVEL
- NONLINEAR REGIME REQUIRED

DIFFERENT THEORIES
↓
DIFFERENT SCREENING



[2508.21126] : COLIBRE PROJECT

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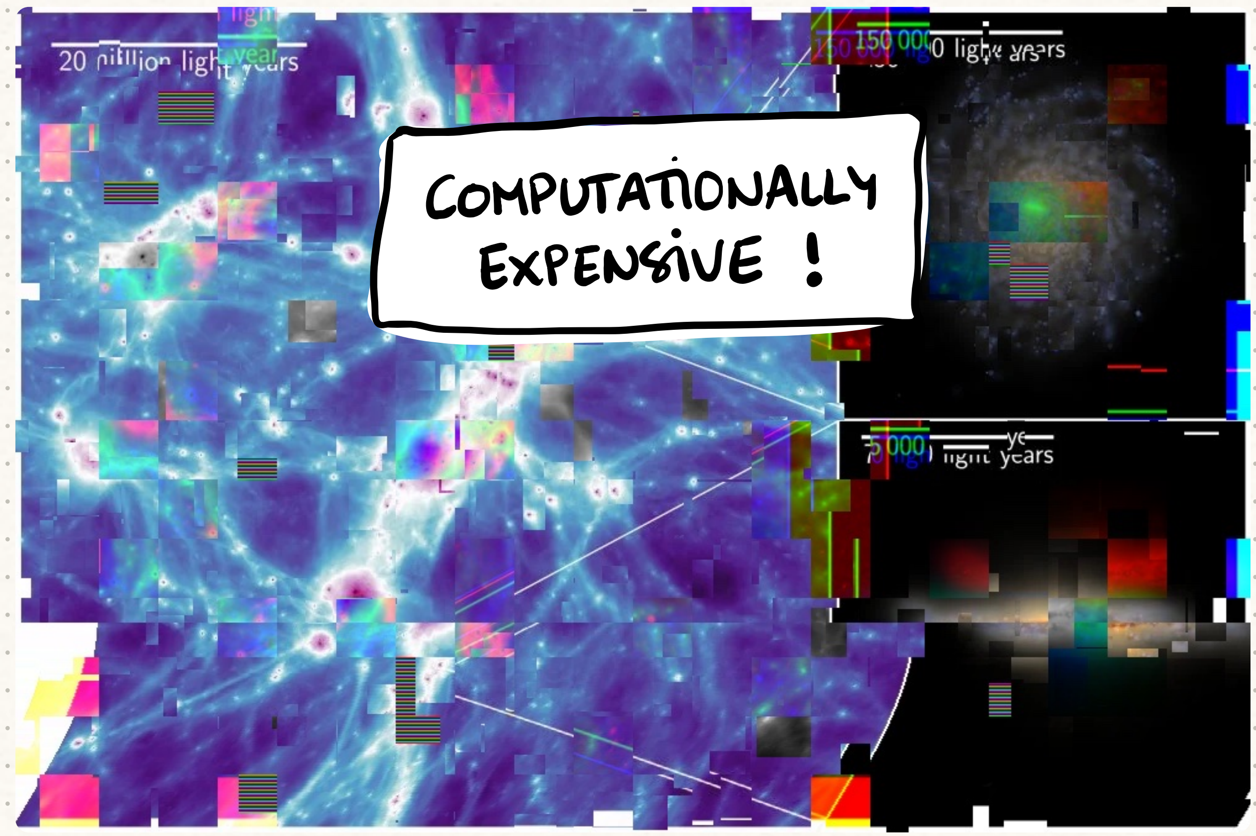

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  ↓

  DIFFERENT SCREENING

  - ANALYTICALLY COMPLEX

TYPICALLY BUILT SPECIFIC THEORIES WITH ONE ACTIVE SCREENING MECHANISM

- VAINSHTEIN

[1111.6749]: R. KIMURA, T. KOBAYASHI, K. YAMAMOTO

- CHAMELEON

[0902.0619]: K. KOYAMA, A. TARUYA, T. HIRAMATSU

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  DIFFERENT THEORIES

  ↓

  DIFFERENT SCREENING

  - ANALYTICALLY COMPLEX
- GOAL: UNIFIED SCREENING FRAMEWORK

MASTER SCREENING EQUATION

+

MODIFIED GRAVITY COSMOLOGICAL SIMULATIONS

[2209.01666]: B. WRIGHT, LSST

xALPHA: MATHEMATICA PACKAGE FOR COMPUTING NONLINEAR COSMOLOGICAL PERTURBATION EQUATIONS IN SCALAR-TENSOR THEORIES AND EXPRESSING THEM IN EFT ALPHA PARAMETERS: α_M, α_K, α_B.

GITHUB.COM/SERGISL/xALPHA

xAlpha

- Theory: Luminal Horndeski

$$S = \int d^4x \sqrt{-g}\,\Big[\underbrace{G_4(\phi)R}_{\text{non-minimal coupling}} + \underbrace{K(\phi, X)}_{\text{kinetic term}} + \underbrace{G_3(\phi, X)\Box\phi}_{\text{braiding}}\Big]$$

Speed of GWs = Speed of light (GW170817)

xAlpha

- Theory: Luminal Horndeski
- Background: FLRW + Perfect Fluid

Metric: $\bar{g}_{\mu\nu} = \begin{pmatrix} -1 & 0 \\ 0 & a^2(\tau)\delta_{ij} \end{pmatrix}$

Scalar: $\bar{\phi} = \bar{\phi}(\tau)$

Matter: $T_{\mu\nu} = (\rho + p) u_\mu u_\nu + p g_{\mu\nu}$

- THEORY: LUMINAL HORNDESKI
- BACKGROUND: FLRW + PERFECT FLUID
- PERTURBATIONS: NEWTONIAN GAUGE

$$
\left.\begin{array}{ll}
\text{METRIC:} & ds^2 = -(1+2\Phi)\,dt^2 + a^2(1-2\Psi)\,d\vec{x}^2 \\
\text{SCALAR:} & \phi = \bar{\phi}(t) + \delta\phi(t,\vec{x}) \longrightarrow Q = H\dfrac{\delta\phi}{\dot{\phi}} \\
\text{MATTER:} & \rho = \rho_m(1+\delta(t,\vec{x}))
\end{array}\right\}
\quad y^a = \begin{pmatrix} \Phi \\ \Psi \\ Q \end{pmatrix}
$$

xAlpha

- Theory: Luminal Horndeski
- Background: FLRW + Perfect Fluid
- Perturbations: Newtonian gauge
- Compute nonlinear equations of motion

Metric

$$\begin{bmatrix} \mathcal{E} + \epsilon \mathcal{E}^{(1)} + \epsilon^2 \mathcal{E}^{(2)} & \epsilon \mathcal{A}_i^{(1)} + \epsilon^2 \mathcal{A}_i^{(2)} \\ \epsilon \mathcal{A}_i^{(1)} + \epsilon^2 \mathcal{A}_i^{(2)} & a^2 \left(\delta_{ij} \mathcal{P} + \epsilon \mathcal{P}_{ij}^{(1)} + \epsilon^2 \mathcal{P}_{ij}^{(2)} \right) \end{bmatrix} = \begin{bmatrix} -\rho_m (1+\delta) & \delta T_{0i} \\ \delta T_{i0} & -p_m - \delta p_m^{(1)} \end{bmatrix}$$

Scalar

$$\mathcal{S} + \epsilon \mathcal{S}^{(1)} + \epsilon^2 \mathcal{S}^{(2)} = 0$$

xALPHA

$$Y^a = \begin{pmatrix} \Phi \\ \Psi \\ Q \end{pmatrix}$$

$$\tilde{\mathcal{E}}^{(1)} = \sum_a \left(H^2 A_1^a \cdot Y^a + H A_2^a \cdot \dot{Y}^a - \frac{1}{a^2} A_3^a \cdot \nabla^2 Y^a \right), \tag{1}$$

$$\begin{aligned}
\tilde{\mathcal{E}}^{(2)} = \sum_{a,b} \Bigg(& \frac{H^2}{2} A_1^{(ab)} \cdot Y^a Y^b + H A_2^{ab} \cdot \dot{Y}^a Y^b - 3 A_3^{(ab)} \cdot \dot{Y}^a \dot{Y}^b - \frac{2}{a^2} A_4^{ab} \cdot Y^a \nabla^2 Y^b - \frac{1}{2a^2} A_5^{(ab)} \cdot \partial_i Y^a \partial^i Y^b \\
& + \frac{1}{Ha^2} A_6^{ab} \cdot \dot{Y}^a \nabla^2 Y^b \Bigg),
\end{aligned}$$

$$\tilde{\mathcal{A}}_i^{(1)} = \sum_a \left(H B_1^a \cdot \partial_i Y^a - B_2^a \cdot \partial_i \dot{Y}^a \right),$$

$$\tilde{\mathcal{A}}_i^{(2)} = \sum_{a,b} \left(H B_1^{ab} \cdot Y^a \partial_i Y^b - B_2^{ab} \cdot \dot{Y}^a \partial_i Y^b - B_3^{ab} \cdot Y^a \partial_i \dot{Y}^b + \frac{1}{H} B_4^{ab} \cdot \dot{Y}^a \partial_i \dot{Y}^b - \frac{2}{Ha^2} B_5^{ab} \cdot \partial^j Y^a \mathcal{D}_{ij} Y^b \right),$$

$$\tilde{\mathcal{P}}_{ij}^{(1)} = \sum_a \left[\delta_{ij} \left(H^2 a^2 C_1^a \cdot Y^a + H a^2 C_2^a \cdot \dot{Y}^a - a^2 C_3^a \cdot \ddot{Y}^a \right) - C_4^a \cdot \mathcal{D}_{ij} Y^a \right],$$

$$\begin{aligned}
\tilde{\mathcal{P}}_{ij}^{(2)} = \sum_{a,b} \Bigg[& \delta_{ij} \Bigg(- H^2 a^2 C_1^{(ab)} \cdot Y^a Y^b + H a^2 C_2^{ab} \cdot Y^a \dot{Y}^b - a^2 C_3^{(ab)} \cdot \dot{Y}^a \dot{Y}^b + a^2 C_4^{ab} \cdot Y^a \ddot{Y}^b + \frac{a^2}{H} C_5^{ab} \cdot \dot{Y}^a \ddot{Y}^b \\
& + C_6^{(ab)} \cdot \partial_k Y^a \partial^k Y^b + \frac{2}{H} C_7^{ab} \cdot \partial_k Y^a \partial^k \dot{Y}^b \Bigg) + C_8^{(ab)} \cdot \partial_i Y^a \partial_j Y^b \\
& - \frac{1}{H} C_9^{ab} \cdot \partial_i Y^a \partial_j \dot{Y}^b + C_{10}^{ab} \cdot Y^a \mathcal{D}_{ij} Y^b \Bigg],
\end{aligned}$$

$$\tilde{\mathcal{S}}^{(1)} = \sum_a - \frac{H}{\dot{\phi}} \left(H^2 D_1^a \cdot Y^a + H D_2^a \cdot \dot{Y}^a + D_3^a \cdot \ddot{Y}^a + \frac{1}{a^2} D_4^a \cdot \nabla^2 Y^a \right),$$

$$\begin{aligned}
\tilde{\mathcal{S}}^{(2)} = \sum_{a,b} - \frac{H}{\dot{\phi}} \Bigg(& H^2 D_1^{(ab)} \cdot Y^a Y^b + 3H D_2^{ab} \cdot Y^a \dot{Y}^b + 3 D_3^{ab} \cdot \dot{Y}^a \dot{Y}^b + 3 D_4^{ab} \cdot Y^a \ddot{Y}^b - \frac{3}{2} D_5^{ab} \cdot \dot{Y}^a \ddot{Y}^b \\
& + \frac{1}{a^2} D_6^{ab} \cdot Y^a \nabla^2 Y^b + \frac{1}{a^2} D_7^{ab} \cdot \partial_i Y^a \partial^i Y^b + \frac{1}{a^2 H} D_8^{ab} \cdot \dot{Y}^a \nabla^2 Y^b - \frac{2}{a^2 H} D_9^{ab} \cdot \partial_i \dot{Y}^a \partial^i Y^b \\
& + \frac{1}{a^2 H^2} D_{10}^{ab} \cdot \ddot{Y}^a \nabla^2 Y^b - \frac{2}{a^2 H^2} D_{11}^{ab} \cdot \partial_i \dot{Y}^a \partial^i \dot{Y}^b - \frac{1}{2H^2 a^4} D_{12}^{ab} \cdot \mathcal{Y}^{a(2)} \Bigg),
\end{aligned}$$

xALPHA

Table 1: Linear coefficients.

Eqn	Term	Φ	Ψ	Q
$\mathcal{E}^{(1)}$	Y^a	A_1^Φ	–	A_1^Q
	$\dot{Y}^a$	–	A_2^Ψ	A_2^Q
	$\nabla^2 Y^a$	–	A_3^Ψ	A_3^Q
$\mathcal{A}_i^{(1)}$	$\partial_i Y^a$	B_1^Φ	–	B_1^Q
	$\partial_i \dot{Y}^a$	–	B_2^Ψ	B_2^Q
$\mathcal{P}_{ij}^{(1)}$	$\delta_{ij} Y^a$	C_1^Φ	–	C_1^Q
	$\delta_{ij} \dot{Y}^a$	C_2^Φ	C_2^Ψ	C_2^Q
	$\delta_{ij} \ddot{Y}^a$	–	C_3^Ψ	C_3^Q
	$\mathcal{D}_{ij} Y^a$	C_4^Φ	C_4^Ψ	C_4^Q
$\mathcal{S}^{(1)}$	Y^a	D_1^Φ	–	D_1^Q
	$\dot{Y}^a$	D_2^Φ	D_2^Ψ	D_2^Q
	$\ddot{Y}^a$	–	D_3^Ψ	D_3^Q
	$\nabla^2 Y^a$	D_4^Φ	D_4^Ψ	D_4^Q

Table 1: Second-order coefficients.

Eqn	Term	$\Phi\Phi$	$\Psi\Psi$	QQ	$\Phi\Psi$	ΦQ	ΨQ	$\Psi\Phi$	$Q\Phi$	$Q\Psi$
$\mathcal{E}^{(2)}$	$Y^a Y^b$	$A_1^{\Phi\Phi}$	–	A_1^{QQ}	–	$A_1^{\Phi Q}$	–		(sym)	
	$\dot{Y}^a Y^b$	–	$A_2^{\Psi\Psi}$	A_2^{QQ}	–	–	$A_2^{\Psi Q}$	$A_2^{\Psi\Phi}$	$A_2^{Q\Phi}$	–
	$\dot{Y}^a \dot{Y}^b$	–	$A_3^{\Psi\Psi}$	A_3^{QQ}	–	–	$A_3^{\Psi Q}$		(sym)	
	$Y^a \nabla^2 Y^b$	–	$A_4^{\Psi\Psi}$	A_4^{QQ}	$A_4^{\Phi\Psi}$	$A_4^{\Phi Q}$	$A_4^{\Psi Q}$	–	–	$A_4^{Q\Psi}$
	$\partial Y \partial Y$	–	$A_5^{\Psi\Psi}$	A_5^{QQ}	–	–	$A_5^{\Psi Q}$		(sym)	
	$\dot{Y}^a \nabla^2 Y^b$	–	–	A_6^{QQ}	–	–	–	–	–	–
$\mathcal{A}_i^{(2)}$	$Y^a \partial_i Y^b$	$B_1^{\Phi\Phi}$	–	B_1^{QQ}	–	$B_1^{\Phi Q}$	–	–	$B_1^{Q\Phi}$	–
	$\dot{Y}^a \partial_i Y^b$	–	$B_2^{\Psi\Psi}$	B_2^{QQ}	–	–	$B_2^{\Psi Q}$	$B_2^{\Psi\Phi}$	$B_2^{Q\Phi}$	–
	$Y^a \partial_i \dot{Y}^b$	–	$B_3^{\Psi\Psi}$	B_3^{QQ}	–	$B_3^{\Phi Q}$	–	–	–	$B_3^{Q\Psi}$
	$\dot{Y}^a \partial_i \dot{Y}^b$	–	–	B_4^{QQ}	–	–	–	–	–	–
	$\partial Y \mathcal{D} Y$	–	–	B_5^{QQ}	–	–	–	–	–	–
$\mathcal{P}_{ij}^{(2)}$	$\delta_{ij} Y Y$	$C_1^{\Phi\Phi}$	–	C_1^{QQ}	$C_1^{\Phi\Psi}$	$C_1^{\Phi Q}$	$C_1^{\Psi Q}$		(sym)	
	$\delta_{ij} Y \dot{Y}$	$C_2^{\Phi\Phi}$	–	C_2^{QQ}	$C_2^{\Phi\Psi}$	$C_2^{\Phi Q}$	$C_2^{\Psi Q}$	$C_2^{\Psi\Phi}$	$C_2^{Q\Phi}$	$C_2^{Q\Psi}$
	$\delta_{ij} \dot{Y} \dot{Y}$	–	$C_3^{\Psi\Psi}$	C_3^{QQ}	$C_3^{\Phi\Psi}$	$C_3^{\Phi Q}$	$C_3^{\Psi Q}$		(sym)	
	$\delta_{ij} Y \ddot{Y}$	–	–	C_4^{QQ}	$C_4^{\Phi\Psi}$	$C_4^{\Phi Q}$	$C_4^{\Psi Q}$	–	–	$C_4^{Q\Psi}$
	$\delta_{ij} \dot{Y} \ddot{Y}$	–	–	C_5^{QQ}	–	–	–	–	–	–
	$\delta_{ij} \partial Y \partial Y$	$C_6^{\Phi\Phi}$	$C_6^{\Psi\Psi}$	C_6^{QQ}	–	$C_6^{\Phi Q}$	–		(sym)	
	$\delta_{ij} \partial Y \partial \dot{Y}$	–	–	C_7^{QQ}	–	–	–	–	–	–
	$\partial_i Y \partial_j Y$	$C_8^{\Phi\Phi}$	$C_8^{\Psi\Psi}$	C_8^{QQ}	$C_8^{\Phi\Psi}$	$C_8^{\Phi Q}$	$C_8^{\Psi Q}$		(sym)	
	$\partial_i Y \partial_j \dot{Y}$	–	–	C_9^{QQ}	–	–	–	–	–	–
	$Y \mathcal{D}_{ij} Y$	$C_{10}^{\Phi\Phi}$	$C_{10}^{\Psi\Psi}$	C_{10}^{QQ}	–	–	–	–	$C_{10}^{Q\Phi}$	$C_{10}^{Q\Psi}$
$\mathcal{S}^{(2)}$	$Y^a Y^b$	$D_1^{\Phi\Phi}$	–	D_1^{QQ}	–	$D_1^{\Phi Q}$	–		(sym)	
	$Y^a \dot{Y}^b$	$D_2^{\Phi\Phi}$	–	D_2^{QQ}	–	$D_2^{\Phi Q}$	–		(sym)	
	$\dot{Y}^a \dot{Y}^b$	–	$D_3^{\Psi\Psi}$	D_3^{QQ}	$D_3^{\Phi\Psi}$	$D_3^{\Phi Q}$	$D_3^{\Psi Q}$	$D_3^{\Psi\Phi}$	$D_3^{Q\Phi}$	$D_3^{Q\Psi}$
	$Y^a \ddot{Y}^b$	–	$D_4^{\Psi\Psi}$	D_4^{QQ}	$D_4^{\Phi\Psi}$	$D_4^{\Phi Q}$	–	–	–	$D_4^{Q\Psi}$
	$\dot{Y}^a \ddot{Y}^b$	–	$D_5^{\Psi\Psi}$	D_5^{QQ}	$D_5^{\Phi\Psi}$	$D_5^{\Phi Q}$	$D_5^{\Psi Q}$	$D_5^{\Psi\Phi}$	$D_5^{Q\Phi}$	$D_5^{Q\Psi}$
	$Y^a \nabla^2 Y^b$	$D_6^{\Phi\Phi}$	$D_6^{\Psi\Psi}$	D_6^{QQ}	–	$D_6^{\Phi Q}$	$D_6^{\Psi Q}$	$D_6^{\Psi\Phi}$	$D_6^{Q\Phi}$	$D_6^{Q\Psi}$
	$\partial Y \partial Y$	$D_7^{\Phi\Phi}$	$D_7^{\Psi\Psi}$	D_7^{QQ}	$D_7^{\Phi\Psi}$	$D_7^{\Phi Q}$	$D_7^{\Psi Q}$		(sym)	
	$\dot{Y}^a \nabla^2 Y^b$	–	–	D_8^{QQ}	–	$D_8^{\Phi Q}$	$D_8^{\Psi Q}$	–	$D_8^{Q\Phi}$	–
	$\partial \dot{Y} \partial Y$	–	–	D_9^{QQ}	–	–	$D_9^{\Psi Q}$	–	–	$D_9^{Q\Psi}$
	$\ddot{Y}^a \nabla^2 Y^b$	–	–	D_{10}^{QQ}	–	–	–	–	–	–
	$\partial \dot{Y} \partial \dot{Y}$	–	–	D_{11}^{QQ}	–	–	–		(sym)	
	$\mathcal{Y}^{a(2)}$	–	–	D_{12}^{QQ}	–	–	–		(sym)	

- STANDARD APPROXIMATIONS (WEAK FIELD LIMIT + QUASISTATIC APPROXIMATION)
- EFFECTIVE EQUATIONS OF MOTION
- REARRANGING, WE OBTAIN MASTER EQUATION

$$\underbrace{\Gamma \nabla^2 Q}_{\text{LINEAR}} - a^2 H^2 Q \left(M^2 + \underbrace{M_{nl}^2 Q}_{\text{CHAMELEON}}\right) + \underbrace{K_- Q \nabla^2 Q + K_+ (\partial_i Q)^2}_{\text{PHAEDRUS}} \underbrace{- \frac{1}{a^2 H^2} (\alpha_B + \alpha_M) \left[(\nabla^2 Q)^2 - (\partial_i \partial_j Q)^2 \right]}_{\text{VAINSHTEIN}} = \underbrace{- \frac{1}{2} (\alpha_B + 2\alpha_M) a^2 \tilde{\rho}_m}_{\text{MATTER SOURCE}}$$

EFFECTIVE PARAMETERS

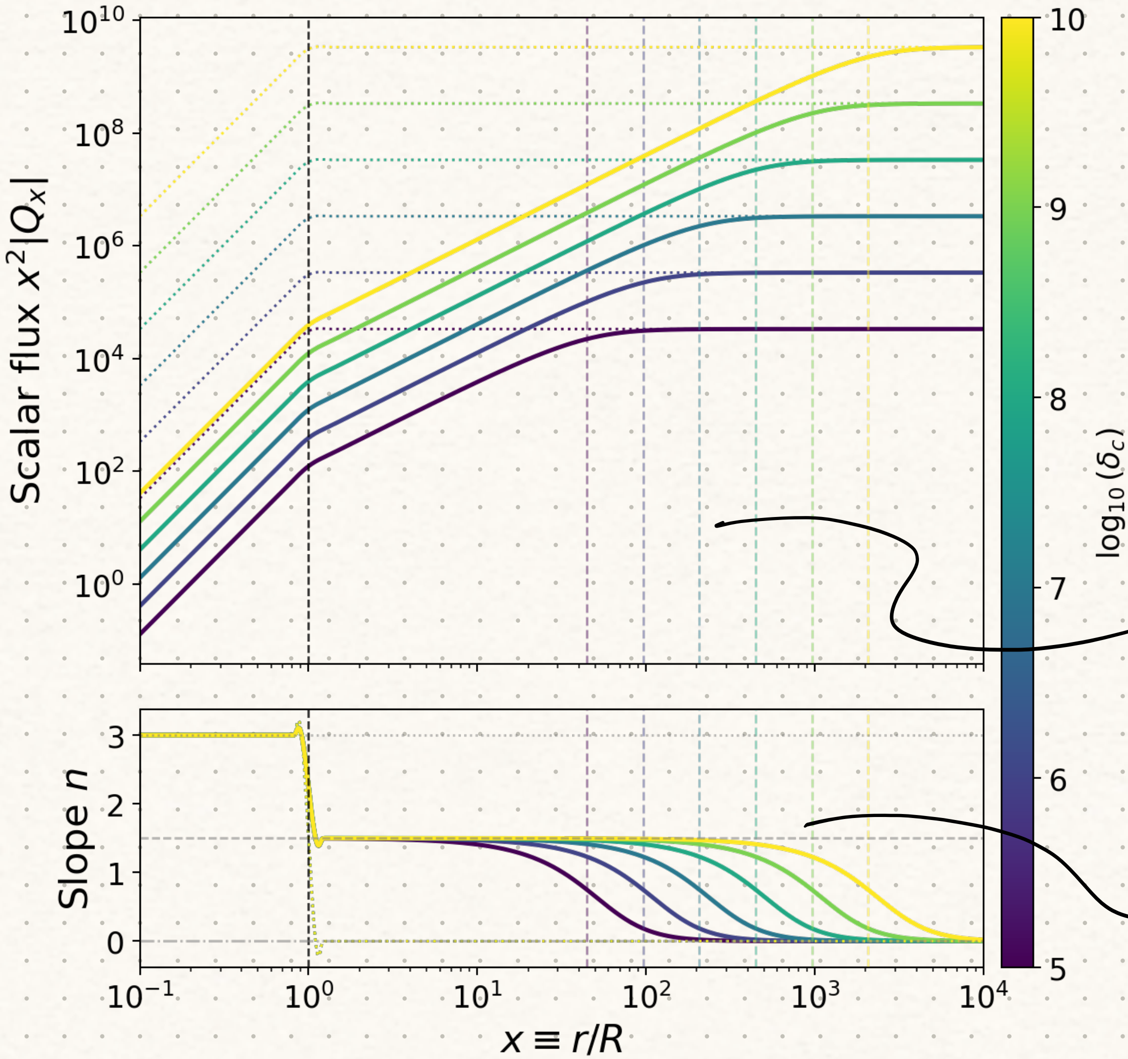
LINEAR	NONLINEAR
α_M, α_K, α_B	γ_B, γ_K, γ_M, γ_E, γ_X, γ_A, γ_D, γ_C

ESCUT : Equation For Screening With Unified Treatment

Python code to numerically Solve master equation

github.com/sergisl/escut

$$\underbrace{\Gamma\nabla^2 Q}_{\text{LINEAR}} - a^2H^2Q\,(M^2 + \underbrace{M_{nl}^2 Q}_{\text{CHAMELEON}}) + \underbrace{K_- Q\nabla^2 Q + K_+(\partial_i Q)^2}_{\text{PHAEDRUS}} \underbrace{- \frac{1}{a^2H^2}(\alpha_B+\alpha_M)\left[(\nabla^2 Q)^2 - (\partial_i\partial_j Q)^2\right]}_{\text{VAINSHTEIN}} = \underbrace{-\frac{1}{2}(\alpha_B+2\alpha_M)\,a^2\tilde{\rho}_m}_{\text{MATTER SOURCE}}$$



VAINSHTEIN

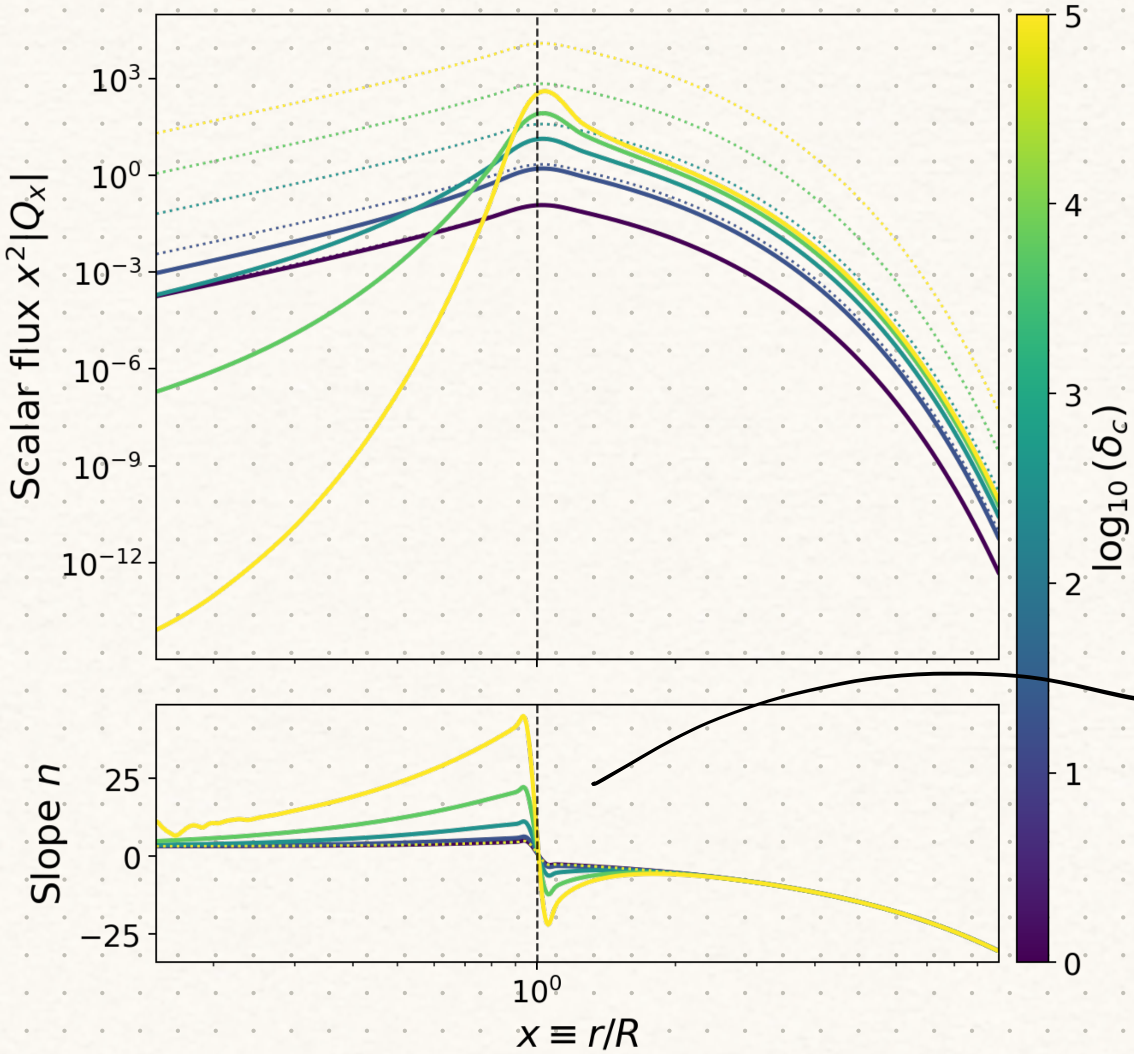
- NONLINEAR DERIVATIVES SUPPRESS 5TH FORCE IN HIGH-DENSITY ENVIRONMENTS

VAINSHTEIN RADIUS

$$\boxed{r_V^3 = \frac{4(\alpha_B+\alpha_M)(\alpha_B+2\alpha_M)}{\Gamma^2}\frac{M}{H^2}}$$

$$\frac{F_5}{F_N} \sim r^{1.5} \longrightarrow n = 1.5$$

$$\underbrace{\Gamma \nabla^2 Q}_{\text{LINEAR}} - a^2 H^2 Q \left(M^2 + \underbrace{M_{nl}^2 Q}_{\text{CHAMELEON}}\right) + \underbrace{K_- Q \nabla^2 Q + K_+ (\partial_i Q)^2}_{\text{PHAEDRUS}} - \underbrace{\frac{1}{a^2 H^2}(\alpha_B + \alpha_M)\left[(\nabla^2 Q)^2 - (\partial_i \partial_j Q)^2\right]}_{\text{VAINSHTEIN}} = \underbrace{-\frac{1}{2}(\alpha_B + 2\alpha_M) a^2 \tilde{\rho}_m}_{\text{MATTER SOURCE}}$$



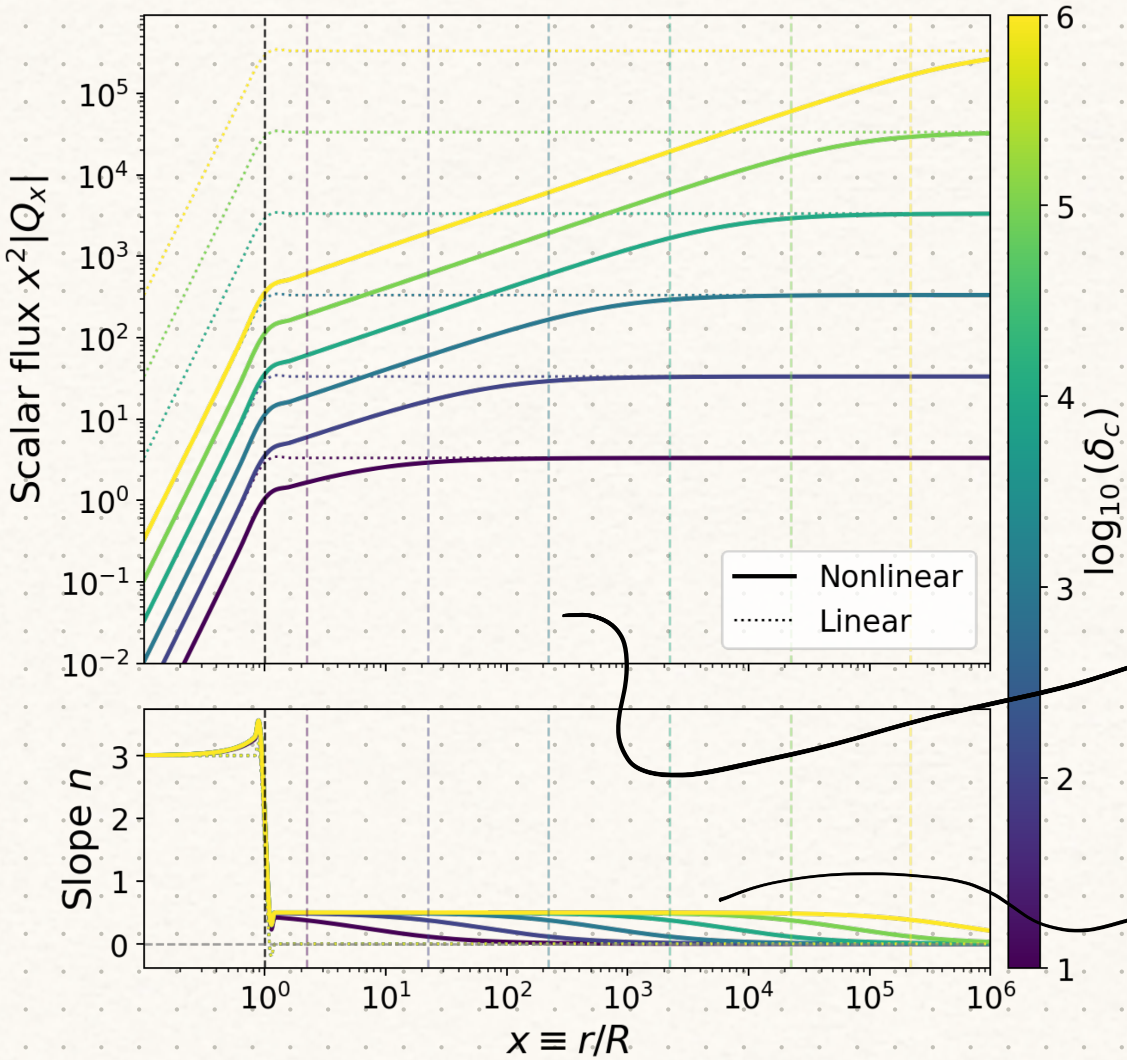
CHAMELEON

- SCALAR FIELD ACQUIRES LARGE MASS IN HIGH-DENSITY ENVIRONMENTS

THIN SHELL

$$\boxed{\mu_{\text{eff}} = \mu \frac{3\Delta R}{R}}$$

$$\underbrace{\Gamma \nabla^2 Q}_{\text{LINEAR}} - a^2H^2Q\,\underbrace{(M^2 + M_{n\ell}^2 Q)}_{\text{CHAMELEON}} + \underbrace{K_- Q \nabla^2 Q + K_+(\partial_i Q)^2}_{\text{PHAEDRUS}} - \underbrace{\frac{1}{a^2H^2}(\alpha_B + \alpha_M)\left[(\nabla^2 Q)^2 - (\partial_i \partial_j Q)^2\right]}_{\text{VAINSHTEIN}} = \underbrace{-\frac{1}{2}(\alpha_B + 2\alpha_M)\,a^2 \tilde{\rho}_m}_{\text{MATTER SOURCE}}$$



PHAEDRUS

- SUPPRESSING 5TH FORCE THROUGH FIELD-DEPENDENT NON-CANONICAL KINETIC TERMS

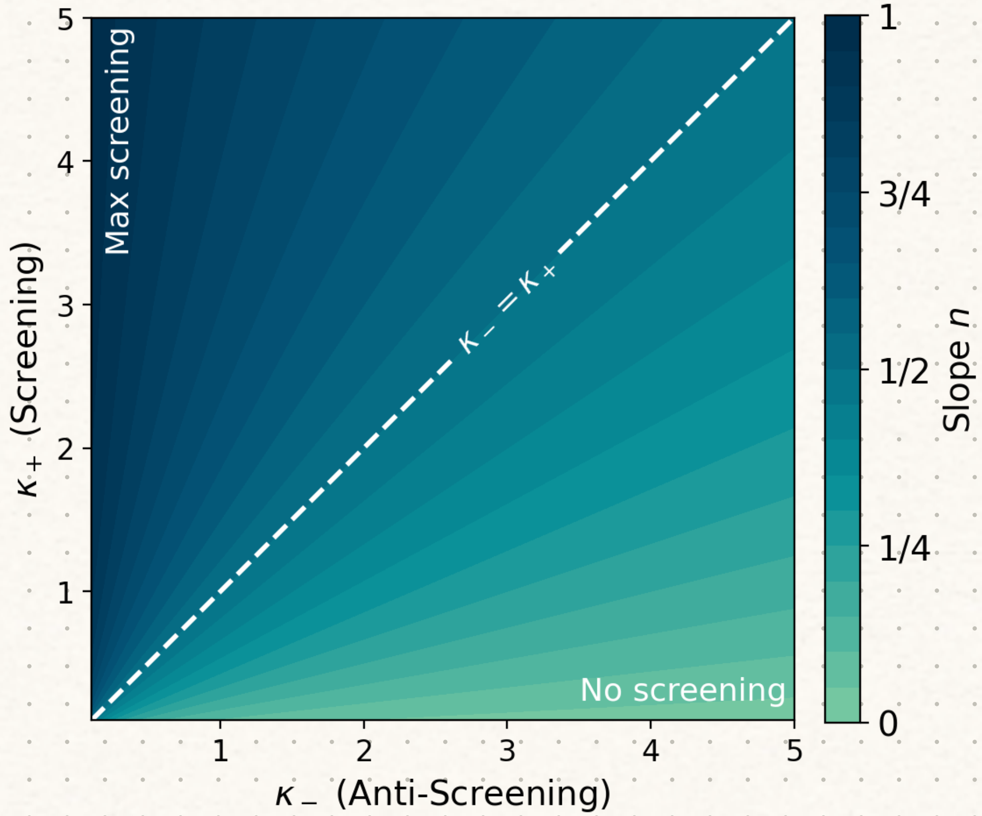
$$\boxed{\text{PHAEDRUS RADIUS} \quad r_p = \frac{2K(\alpha_B + 2\alpha_M)\mu}{\Gamma^2}}$$

$$\frac{F_5}{F_N} \sim r^{0.5} \longrightarrow n = 0.5$$

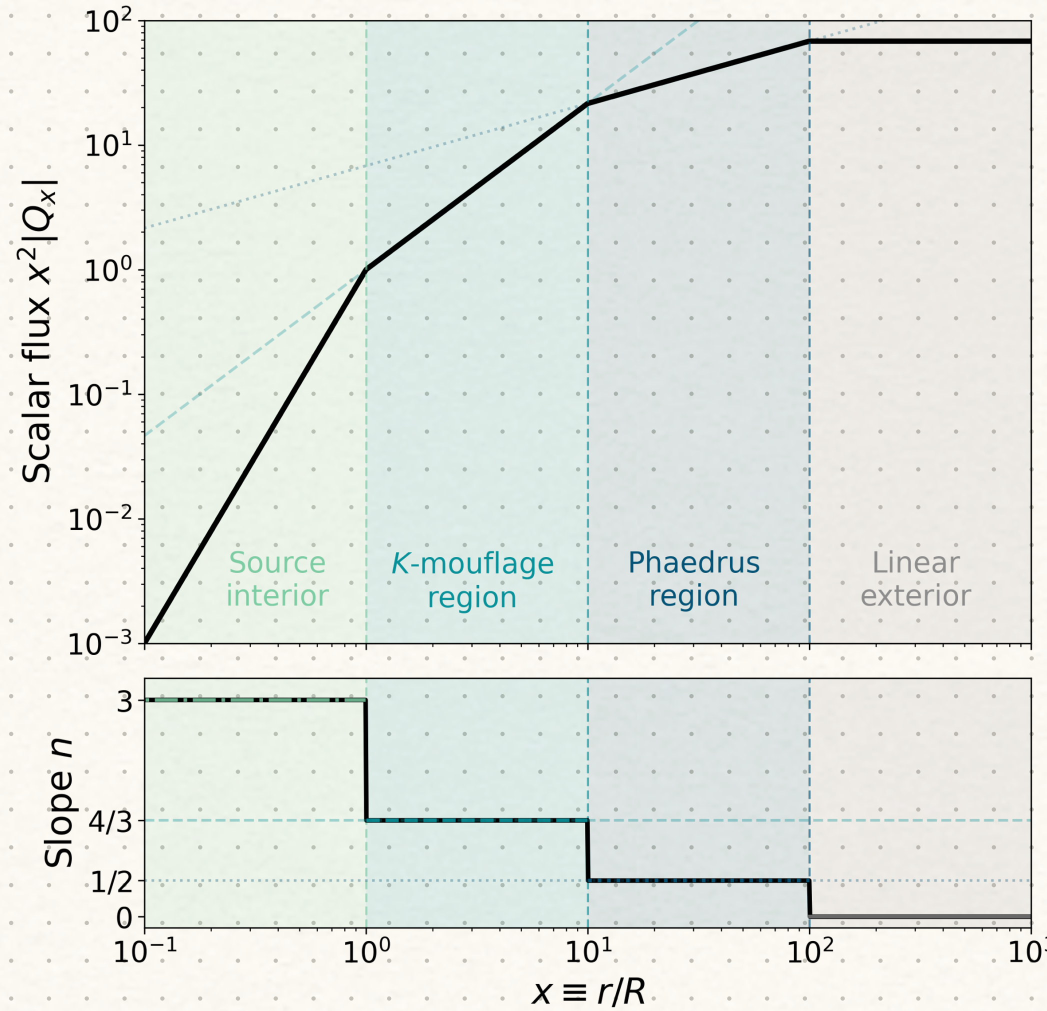
Phaedrus

Varying slope

$$n = \frac{\kappa_+}{\kappa_- + \kappa_+}$$



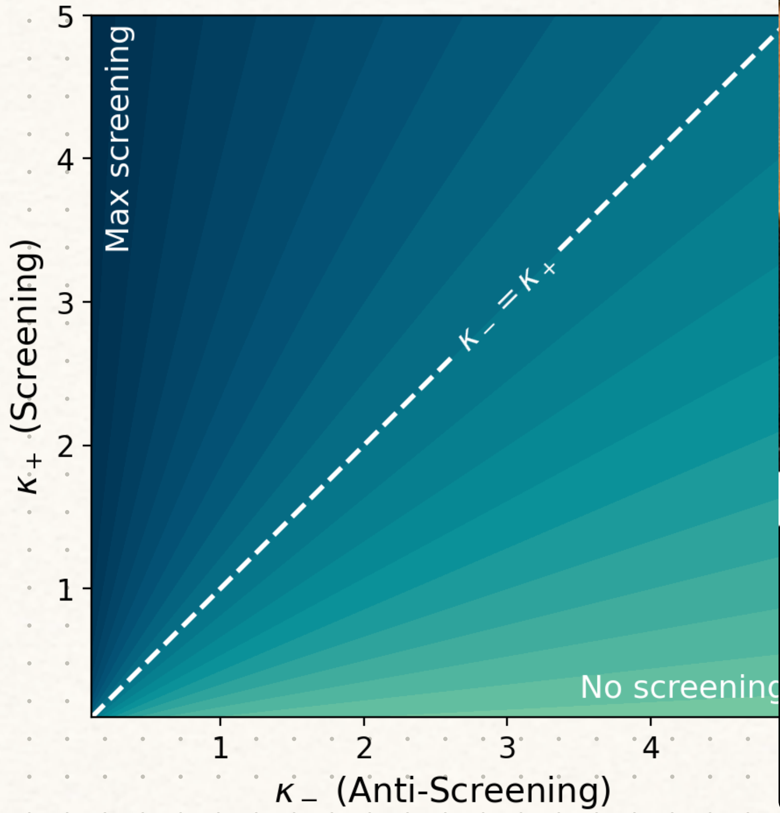
Envelope structure

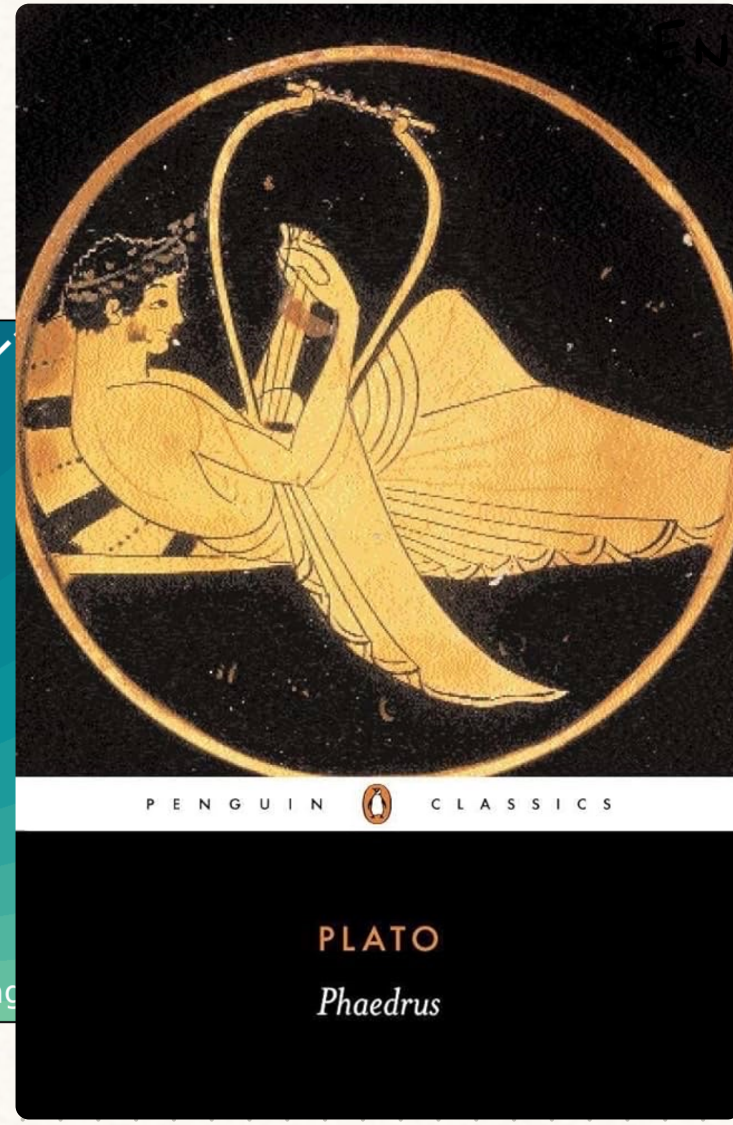


Phaedrus

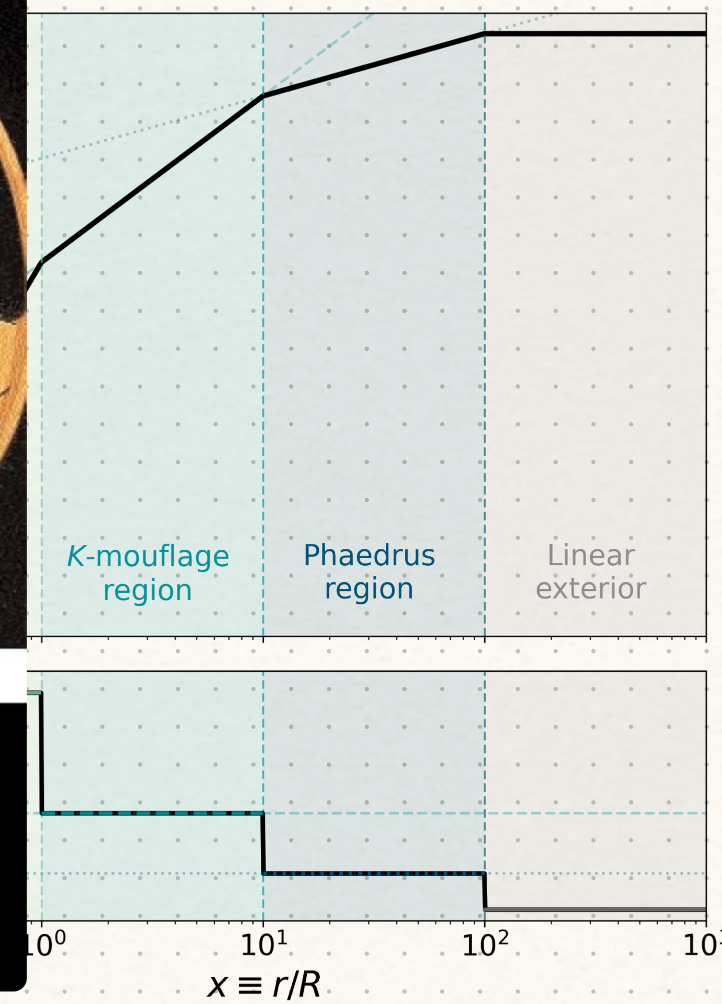
Varying slope

$$n = \frac{\kappa_+}{\kappa_- + \kappa_+}$$





Envelope Structure



- Derived and organised nonlinear equations for luminal Horndeski
- Constructed Unified Screening Framework
  - Enables cosmological simulations of large classes of modified gravity
- Recovered Vainshtein and Chameleon simultaneously
- Identified new screening regime : Phaedrus
- Introduced two new open-source packages

xAlpha ESCUT

github.com/sergisl

Thank you !

BACKUP SLIDES

- STANDARD APPROXIMATIONS

① WEAK FIELD LIMIT $|\Phi| \sim |\Psi| \ll 1$, BUT $|\nabla^2 \Phi| \sim |\nabla^2 \Psi| \sim 1$

② QUASISTATIC APPROXIMATION

→ HUBBLE TIMESCALE $|\dot{Y}| \lesssim H|Y|$

→ SUB-HORIZON SCALES $|\nabla^2 Y| \gg H^2 |Y|$

- STANDARD APPROXIMATIONS

  ↓

- EFFECTIVE EQUATIONS OF MOTION

METRIC:

$$2\nabla^2\Psi + \alpha_B \nabla^2 Q = a^2 \tilde{\rho}_m \delta$$

$$\nabla^2 (\Psi - \Phi - \alpha_M Q) = 0$$

SCALAR:

$$[\gamma_B - \gamma_E - 2(\alpha_B - \alpha_M)]\nabla^2 Q + \alpha_B \nabla^2 \Phi + 2\alpha_M \nabla^2 \Psi$$

$$- a^2 H^2 Q (M^2 + M_{nl}^2 Q) + d_2 Q \nabla^2 Q + d_3 (\partial_i Q)^2 - \frac{1}{a^2 H^2}(\alpha_B + \alpha_M)\left[(\nabla^2 Q)^2 - (\partial_i \partial_j Q)^2\right] = 0$$

α - PARAMETERS

LINEAR:

$\alpha_M \longrightarrow$ PLANCK-MASS RUNNING

$\alpha_K \longrightarrow$ KINETICITY

$\alpha_B \longrightarrow$ BRAIDING

NONLINEAR:

γ_B, γ_K, γ_M, γ_E,

γ_X, γ_A, γ_D, γ_C

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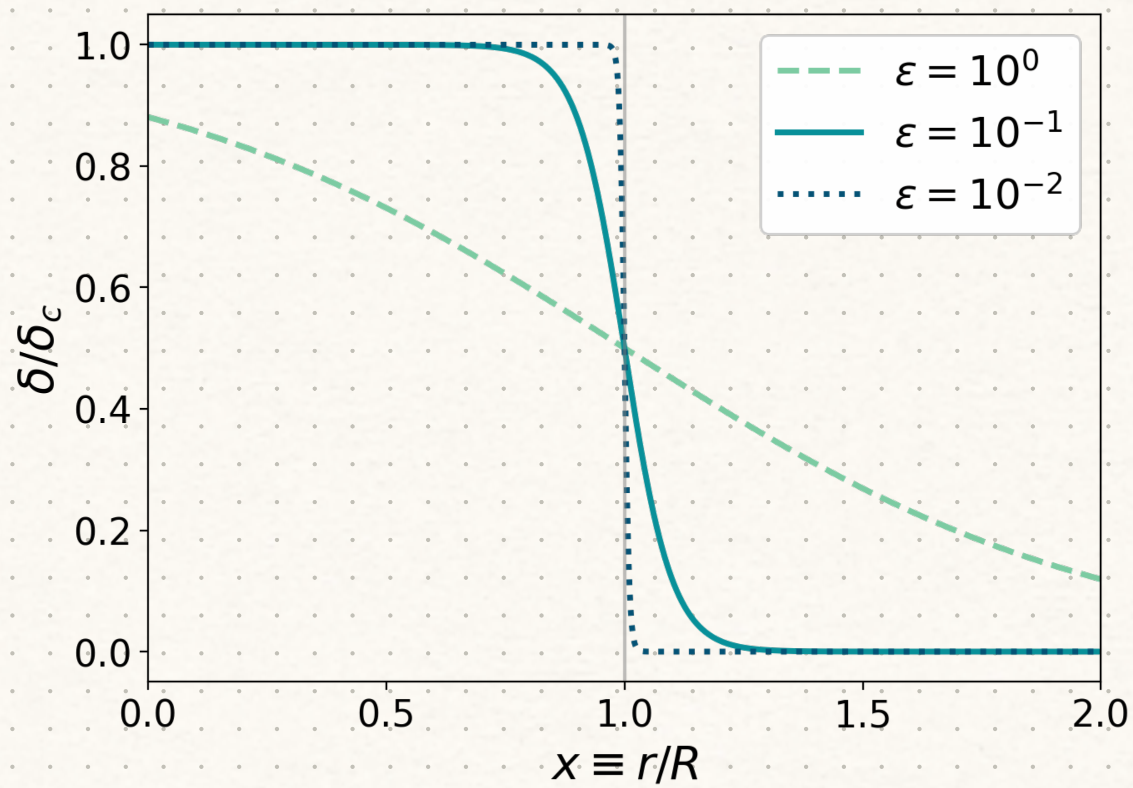
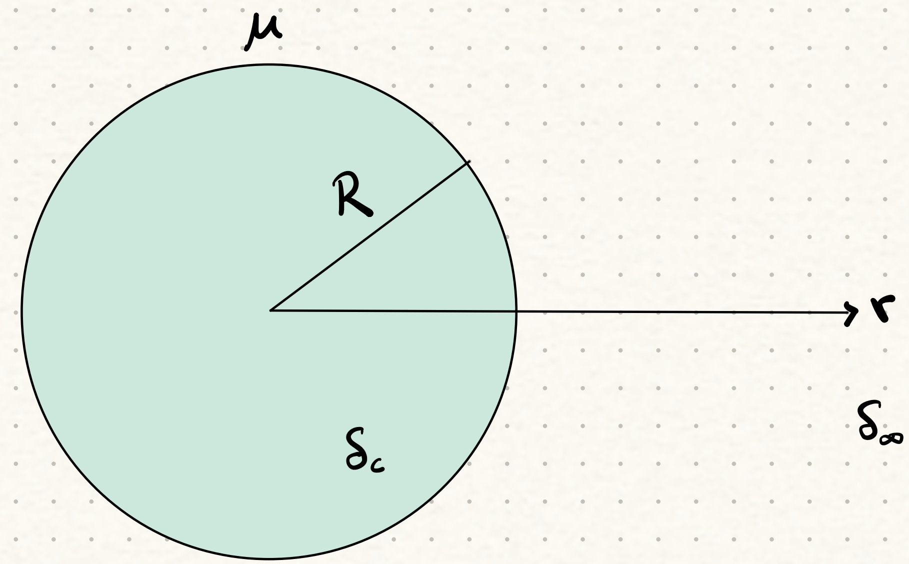
- MATTER SOURCE - SPHERICAL SYMMETRY

DENSITY PROFILE





- BASICS OF SCREENING

GRAVITATIONAL POTENTIAL $\Phi_T = \Phi_N + \alpha Q$ → SCALAR PERTURBATION

↳ NEWTONIAN

$\nabla^2 \Phi_N = 4\pi G \rho$

GRAVITATIONAL FORCE $F_T = -m \nabla \Phi_T = -m \nabla \Phi_N - m\alpha \nabla Q = F_N + F_5$

$$\frac{F_5}{F_N} = \frac{\alpha \nabla Q}{\nabla \Phi_N} = S(\alpha)\, r^n$$

→ SCREENING EFFICIENCY

↳ $n=0$ UNSCREENED

↳ $n>0$ SCREENED

↳ $n=1.5$ VAINSHTEIN

↳ $n=1.33$ K-MOUFLAGE

↳ $n=0\text{-}1$ PHAEDRUS

- LINEAR REGIME

$$\Gamma \frac{1}{r^2}(r^2 Q')' - H^2 M^2 Q = -\frac{1}{2}(\alpha_B + 2\alpha_M)\tilde{\rho}_m \delta$$

$$\downarrow$$

$$Q_{\text{LIN}} = \frac{(\alpha_B + 2\alpha_M)\mu}{\Gamma r} e^{-m_{\text{eff}} r} \longrightarrow m_{\text{eff}}^2 = \frac{H^2 M^2}{\Gamma}$$

CHAMELEON $m_{\text{eff}}^2 \neq 0$

VAINSHTEIN/K-MOUFLAGE $m_{\text{eff}}^2 \approx 0$

$$\frac{F_5}{F_N} \sim \frac{\nabla Q}{\nabla \Phi_N} \sim \frac{r^{-2}}{r^{-2}} \sim r^0 \rightarrow n = 0$$

NO SCREENING

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- VAINSHTEIN
  - NONLINEAR DERIVATIVES SUPPRESS 5TH FORCE IN HIGH-DENSITY ENVIRONMENTS

MASTER EQUATION

$$\Gamma\,(r^2 Q')' - \frac{2}{H^2}(\alpha_B + \alpha_M)\left[r^2 (Q')^2\right]' = -\frac{1}{2}(\alpha_B + 2\alpha_M)\, r^2 \tilde{\rho}_m \delta$$

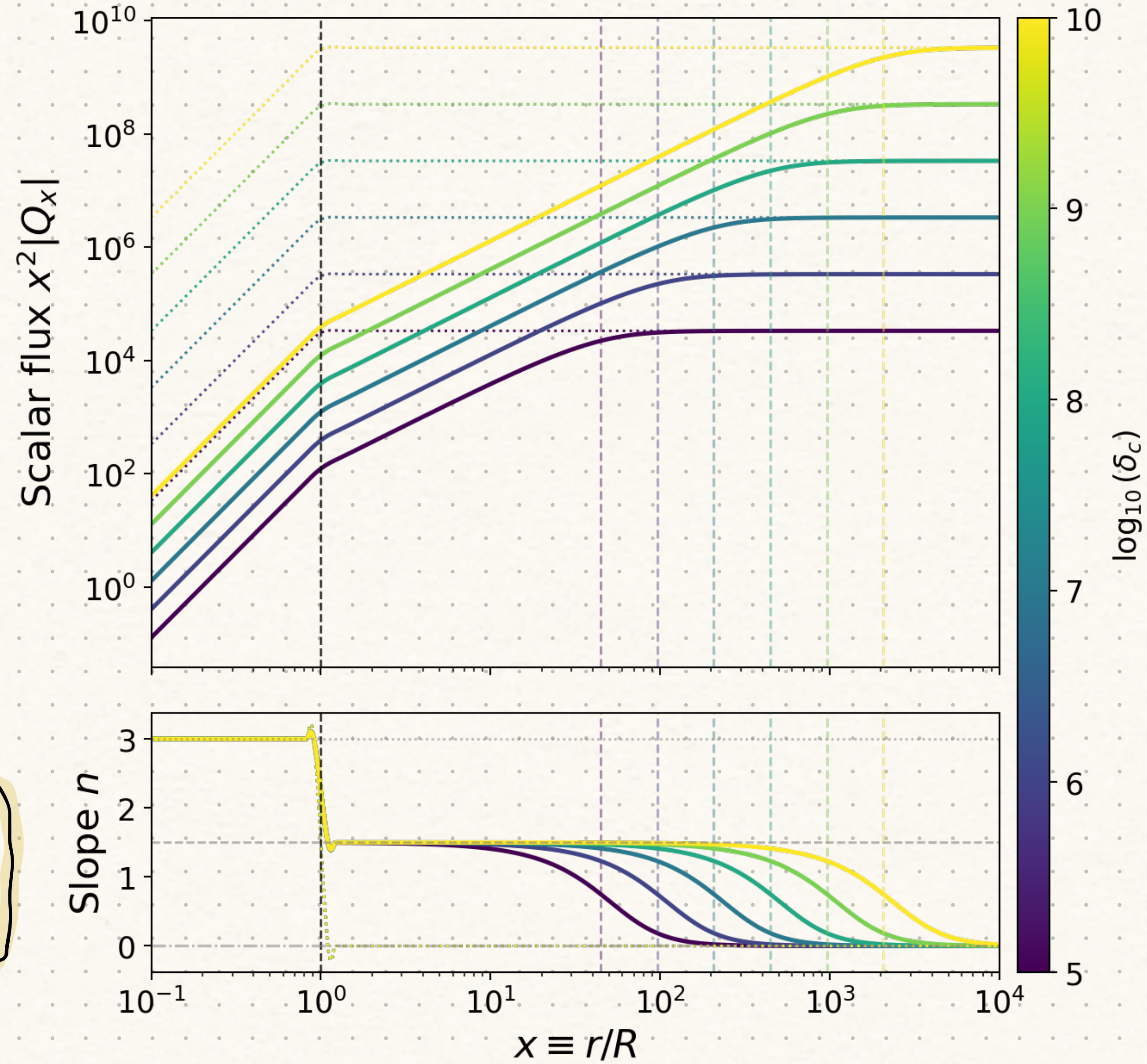
SOLUTION

$$Q_V = Q_0 - \frac{\Gamma H^2}{2(\alpha_B + \alpha_M)}\sqrt{2\, r_V^3\, r}$$

VAINSHTEIN RADIUS

$$\boxed{r_V^3 = \frac{4(\alpha_B + \alpha_M)(\alpha_B + 2\alpha_M)}{\Gamma^2}\frac{\mu}{H^2}}$$

$$\frac{F_5}{F_N} \sim \frac{r^{-1/2}}{r^{-2}} \sim r^{1.5} \longrightarrow n = 1.5$$



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- CHAMELEON
  - SCALAR FIELD ACQUIRES LARGE MASS IN HIGH-DENSITY ENVIRONMENTS

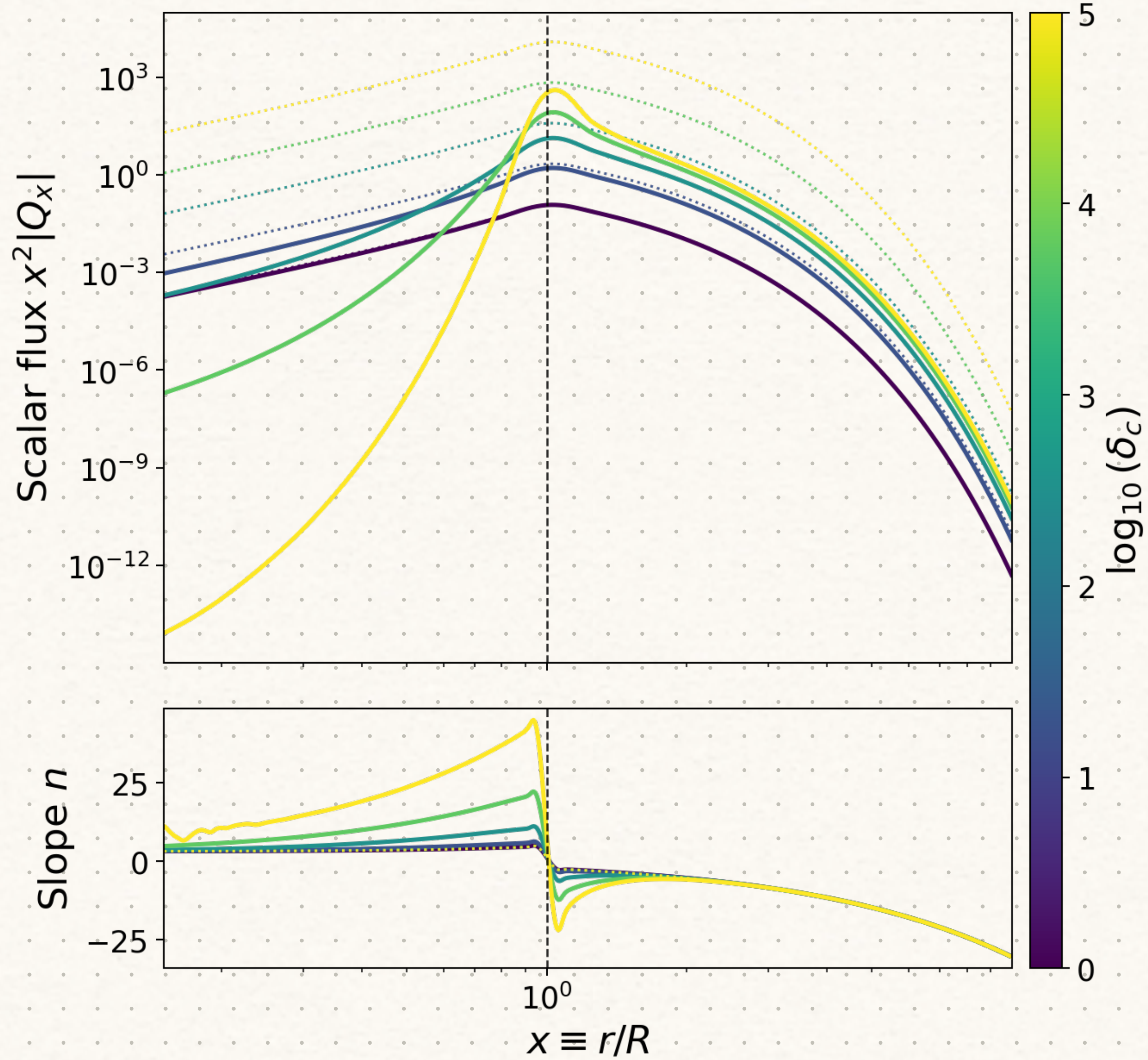
MASTER EQUATION

$$\Gamma\,(r^2 Q')' - r^2 H^2 Q\left(M^2 + M_{nl}^2 Q\right) = -\frac{1}{2}(\alpha_B + 2\alpha_M)\, r^2 \tilde{\rho}_m \delta$$

SOLUTION

$$Q_c \simeq \begin{cases} \dfrac{1}{2M_{nl}^2}\left[-M^2 + \sqrt{M^4 + 2M_{nl}^2(\alpha_B + 2\alpha_M)\,\tilde{\rho}_m \delta}\,\right], & r \ll R \\[2ex] \dfrac{(\alpha_B + 2\alpha_M)\,\mu_{eff}}{8\pi \Gamma r}\,\dfrac{e^{-m_{eff}(r-R)}}{m_{eff}R + 1}, & r \gg R \end{cases}$$

$$\boxed{\text{THIN SHELL}: \ \mu_{eff} = \mu\,\frac{3\Delta R}{R}}$$



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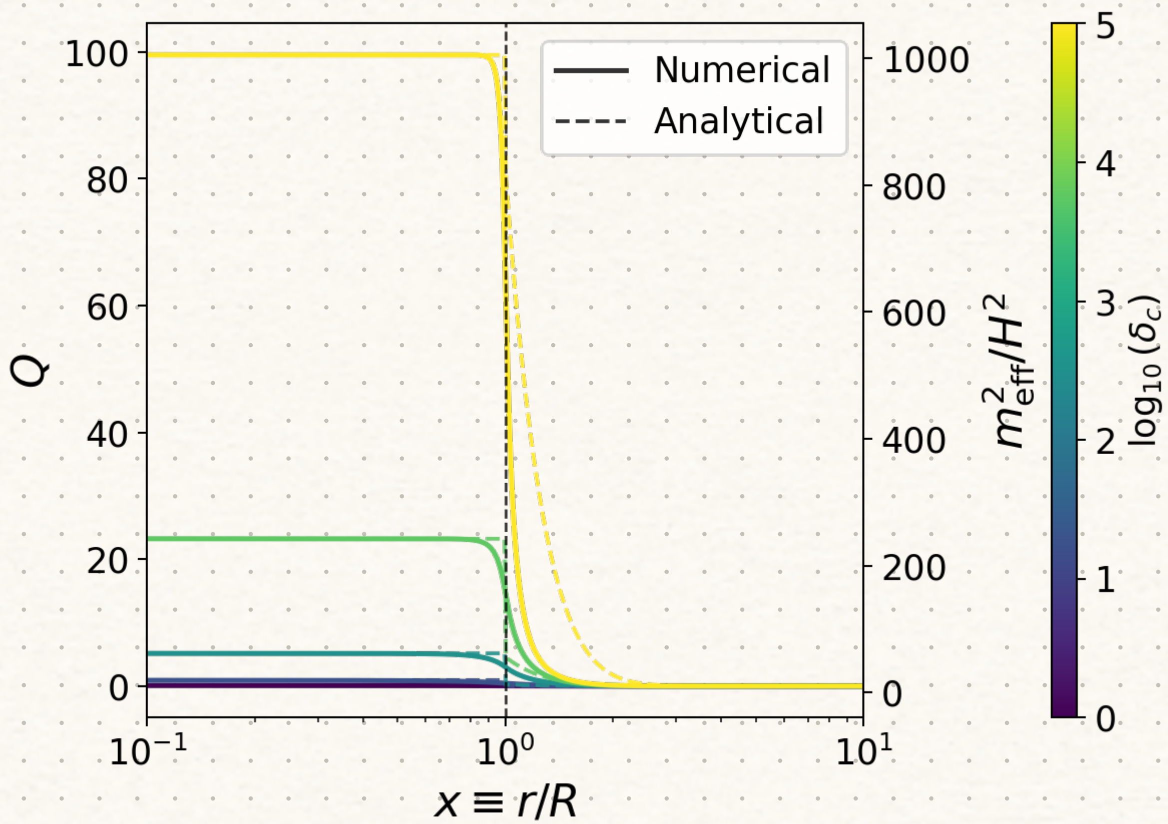
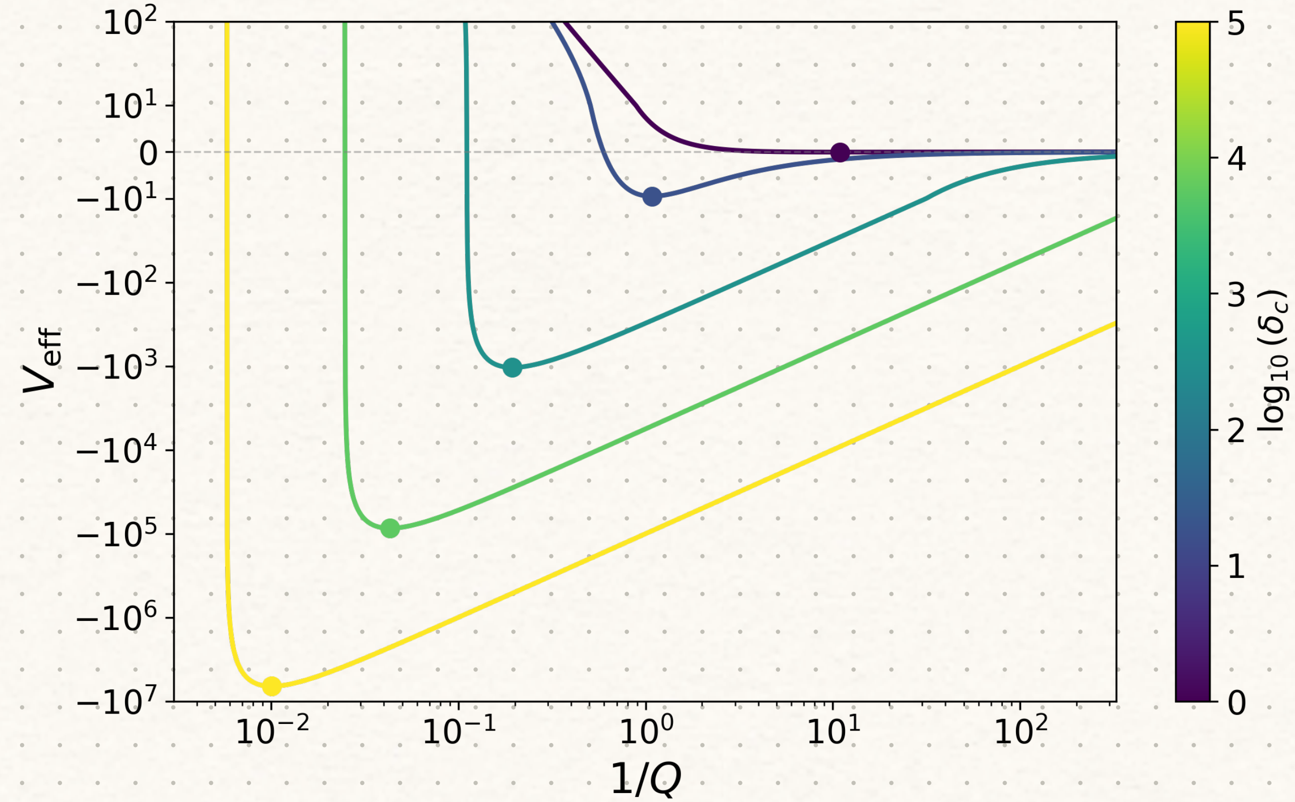
CHAMELEON





$$m_{eff}^2 = \frac{1}{\Gamma}\left(M^2 + M_{nl}^2 Q\right)$$

$$V_{eff} = \frac{Q}{2\Gamma}\left[M^2 Q + \frac{2}{3} M_{nl}^2 Q^2 - (\alpha_B + 2\alpha_M)\tilde{\rho}_m \delta\right]$$

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- PHAEDRUS
  - SUPPRESSING 5TH FORCE THROUGH FIELD-DEPENDENT NON-CANONICAL KINETIC TERMS

MASTER EQUATION

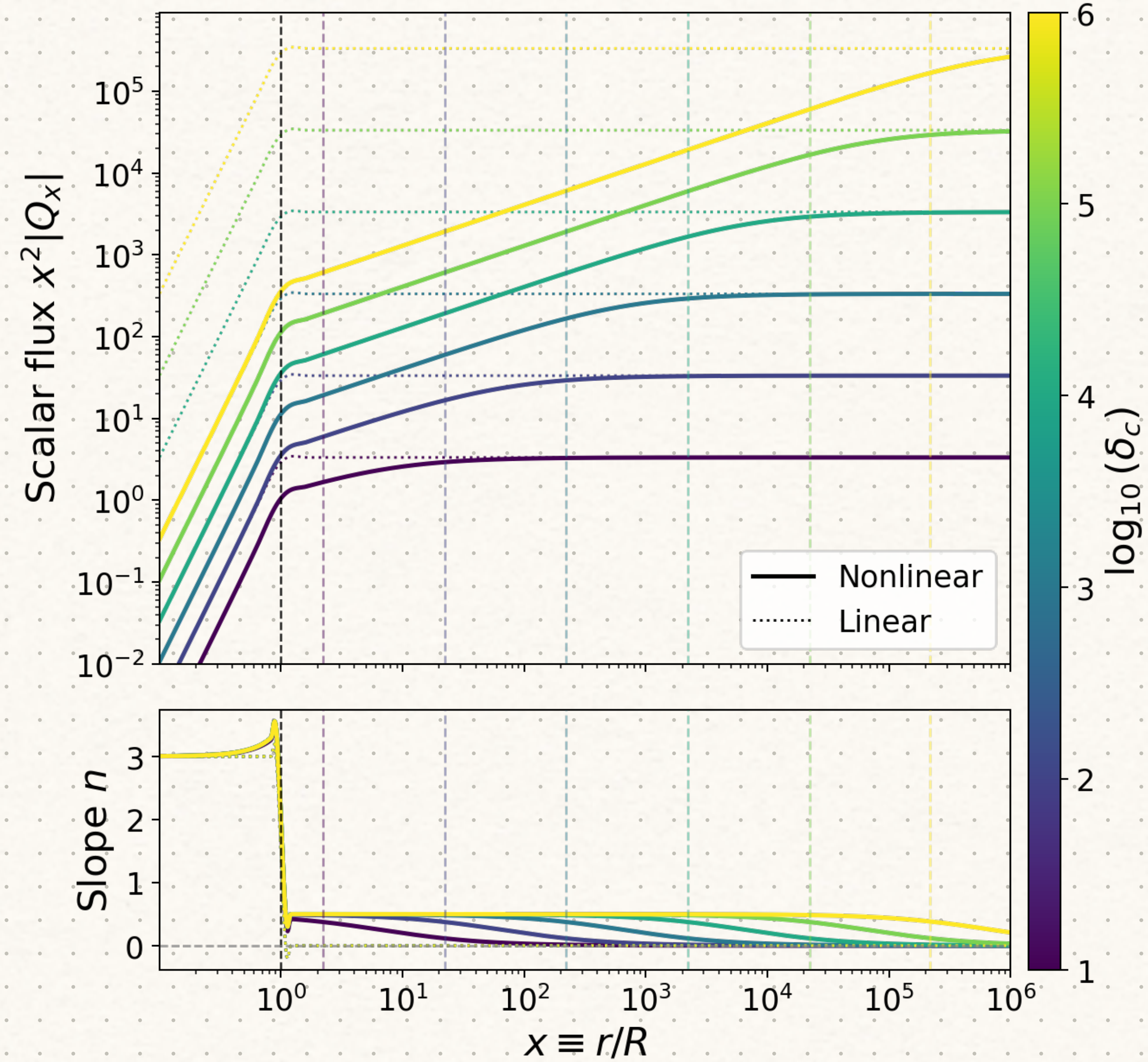
$$\Gamma (r^2 Q')' + K_- Q (r^2 Q')' + K_+ r^2 (Q')^2 = -\frac{1}{2}(\alpha_B + 2\alpha_M) r^2 \tilde{\rho}_m \delta$$

SOLUTION $K_- = K_+ = K$

$$Q = -\frac{\Gamma}{K}\left[1 - \sqrt{1 + \frac{r_P}{r}}\right]$$

$$\boxed{\text{PHAEDRUS RADIUS}: \quad r_P = \frac{2K(\alpha_B + 2\alpha_M)\mu}{\Gamma^2}}$$

$$\frac{F_5}{F_N} \sim \frac{r^{-3/2}}{r^{-2}} \sim r^{0.5} \rightarrow n = 0.5$$



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- CONVERGENCE TESTS