NOWHERE TO HIDE: UNSCREENING CHAMELEONS WITH A BLACK HOLE

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Our code is available here!

https://github.com/andrei-v-frolov/accretion

COSMOLOGY SFU

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Contents:

- A lightning introduction to Modified Gravity
- Naive accretion dynamics in a non-vacuum environment
- Scalar field dynamics in Hu-Sawicki, Starobinsky and Symmetron models
- Results

Why studying Modified Gravity?

I don't know… Maybe Gravity is what we are not understanding!

IR problems:

- Dark matter: Local tests are not consistent with GR + standard matter sector…
- Dark energy and the Cosmological Constant problem: mismatch between the vacuum energy in QFT and the source of accelerated expansion. Does vacuum energy gravitates?

2-loop divergencies

UV problems:

- GR is non-renormalizable: it requires UV completion to be evaluated at the quantum limit.

It is also a partial consequence of this…

Completing both sides of the theory:

UV completion:

$$R + \frac{R^2}{M^2}$$

Starobinsky (1980)

IR completion:

$$R + \frac{\mu^4}{R}$$

Capozzielo, Carroll…

Why not introducing a generalized *free energy*? just as in thermodynamics:

$$S = \int d^4x \sqrt{-g} \left[\frac{f(R)}{16\pi G} + \mathcal{L}_m \right]$$

In that way, the coupling parameters will vary with the change in energy scales…

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We revisited two different models of f(R)...

For instance, we focus on the existing perspectives to solve problems (like the current cosmic acceleration) in the IR limit. These two models are designed to evade solar system tests:

Hu-Sawicki model:

$$f(R) = R - \frac{\alpha(R/R_0)^n}{1+\beta(R/R_0)^n} R_0$$

[0705.1158]

Starobinsky model:

$$f(R) = R + \lambda \left[\frac{1}{(1+(R/R_0)^2)^n} - 1 \right] R_0$$

[0706.2041]

f(R) theories will always contain more than one extra degree of freedom (apart from the ones in the metric), in many cases the existence of this extra degree of freedom is the key to solve problems in Cosmology. Even when these degrees of freedom generate extra forces which need to be screened.

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Equations of motion

Varying the action with respect to the metric, one obtains fourth-order equations of motion

$$f' R_{\mu\nu} - f'_{;\mu\nu} + \left(\Box f' - \frac{f}{2} \right) g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

One can find an extra scalar degree of freedom defined as $\phi \equiv f' - 1$

Its e.o.m is found by taking the trace of the equation above:

$$\Box f' = \underbrace{\frac{1}{3}\left(2f - f'R\right) + \frac{8\pi G}{3} T}_{U'_{\rm eff} \,\equiv\, \text{effective force}}$$

In that way, one can solve two second-order differential equations instead of one of fourth order!

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Needs to be determined!

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Species with traceless energy-momentum tensor (e.g. electromagnetic field) are not sources of this extra scalar of freedom.

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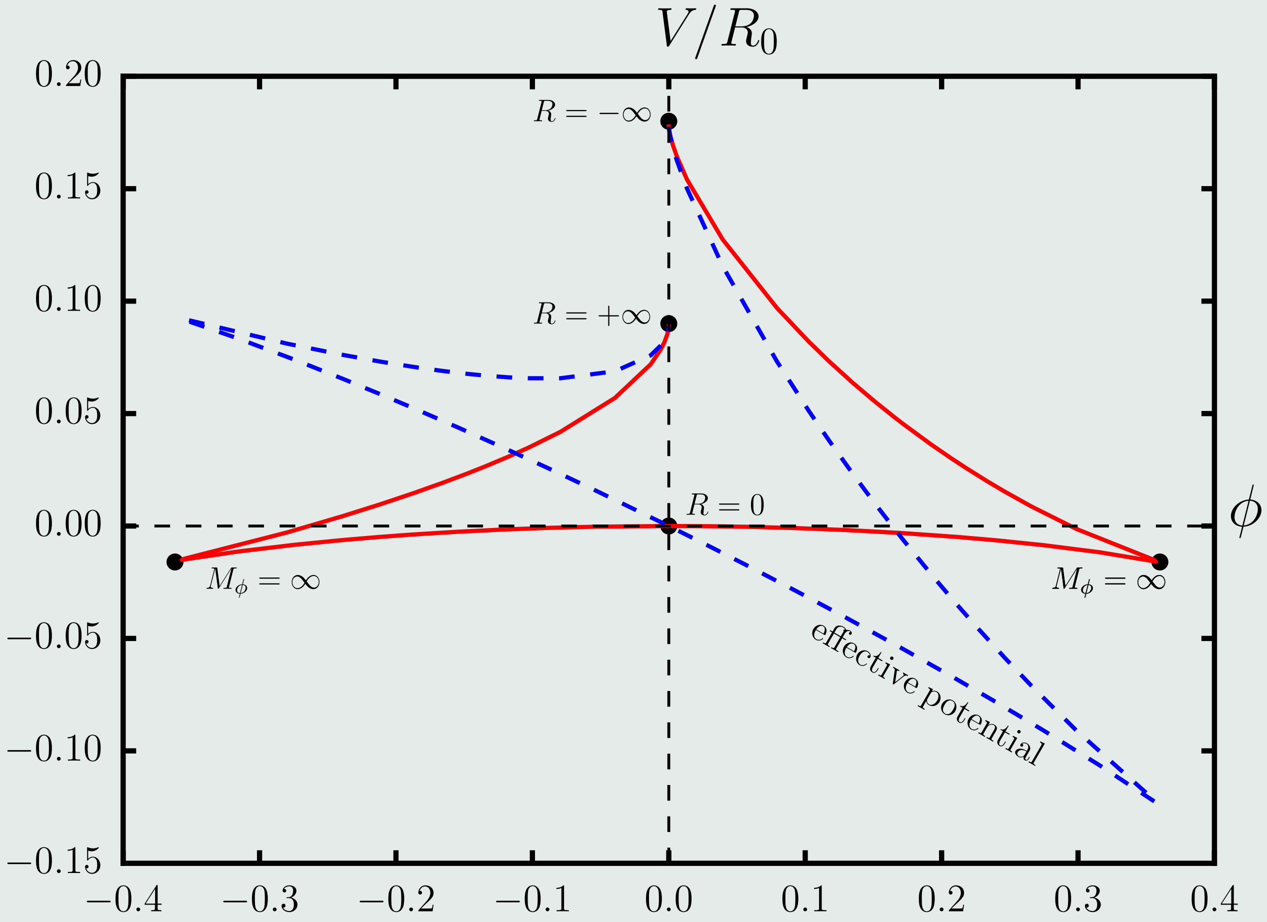
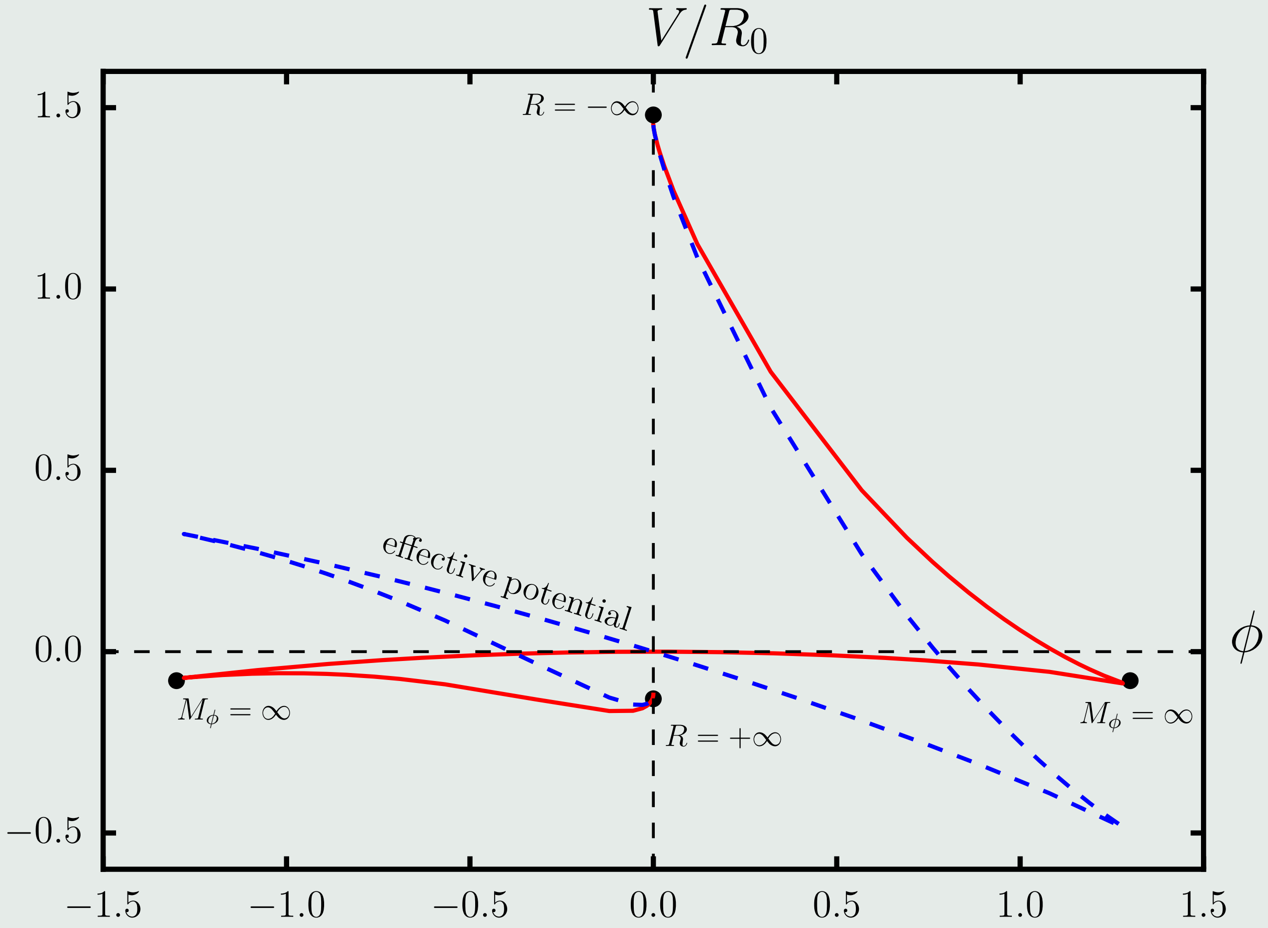
Accretion dynamics of a scalar field:

The effective potential $U_{\rm eff}(\phi)$ is represented by:



(Hu-Sawicki model)



(Starobinsky model)

In the presence of dust, matter density affects the effective potential increasing the field's mass, this type of behaviour is usually called Chameleon screening

How the matter profile looks?

Accreting matter in a spherically symmetric system: one particle at the time

Scheel, Shapiro and Teukolsky [hep-th/9411026] found that the Schwarzschild solution is an unavoidable final state of a spherically symmetric spacetime in this type of theories:

$$ds^2 = -\left(1-\frac{2M}{r}\right)dt^2 + \left(1-\frac{2M}{r}\right)^{-1}dr^2 + r^2\left(d\theta^2+\sin^2\theta d\phi^2\right)$$

Time and angle independence generate 2 conserved charges:

Energy

$$E = g_{tt}\,\xi^t\frac{dt}{d\tau} = -\left(1-\frac{2M}{r}\right)\frac{dt}{d\tau}$$

Angular momentum

$$L = g_{\phi\phi}\,\xi^\phi\frac{d\phi}{d\tau} = r^2\frac{d\phi}{d\tau}$$

(Working in the equatorial plane)

For a timelike curve $ds^2 = -d\tau^2$, we find:

$$\frac{E^2-1}{2} = \frac{1}{2}\left(\frac{dr}{d\tau}\right)^2 + \underbrace{\frac{L^2}{2r^2} - \frac{M}{r} - \frac{ML^2}{r^3}}_{V_{\rm eff}(r)}$$

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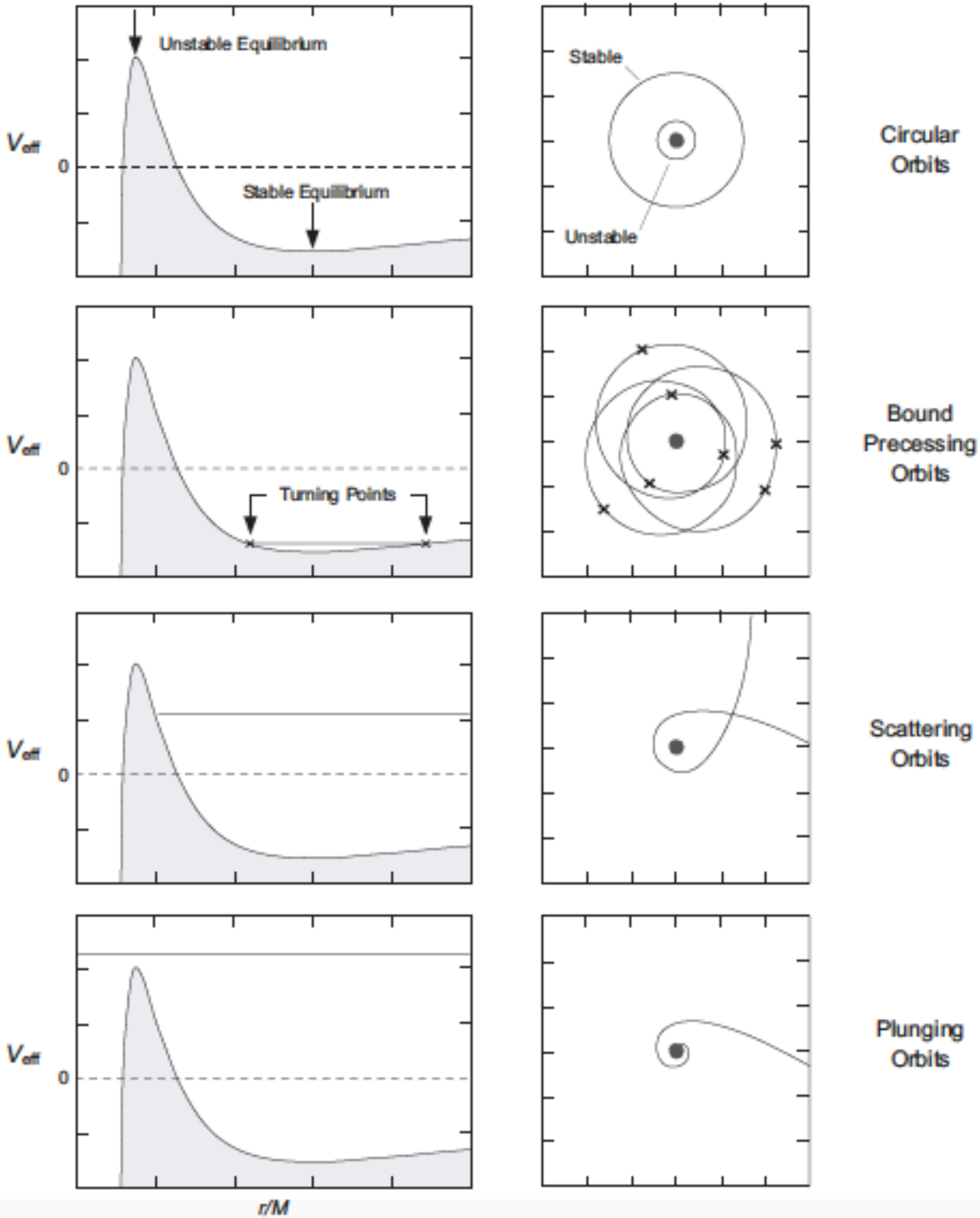

Just as in Classical Mechanics: we plot the effective potential as a function of the radius to see the possible orbits.

The radius and energy of the innermost stable circular orbit (ISCO) is:

$$r_{\mathrm{ISCO}} = 6M$$
$$E_{\mathrm{ISCO}} = \sqrt{\frac{8}{9}}$$

- It is not possible to form stable circular orbits at r < ISCO.
- Eccentric trajectories contribute minimally to the overall shape of the matter distribution: angular momentum conservation reduces the time spent at r < ISCO. This is the zone with the lowest matter density.

The change in mass (and geometry) can be naively evaluated by the luminosity:

$$\dot{M} = \frac{L}{\left(1 - \sqrt{\frac{8}{9}}\right)}$$

Supermassive black holes can change their mass in 1% in 10^7 years!

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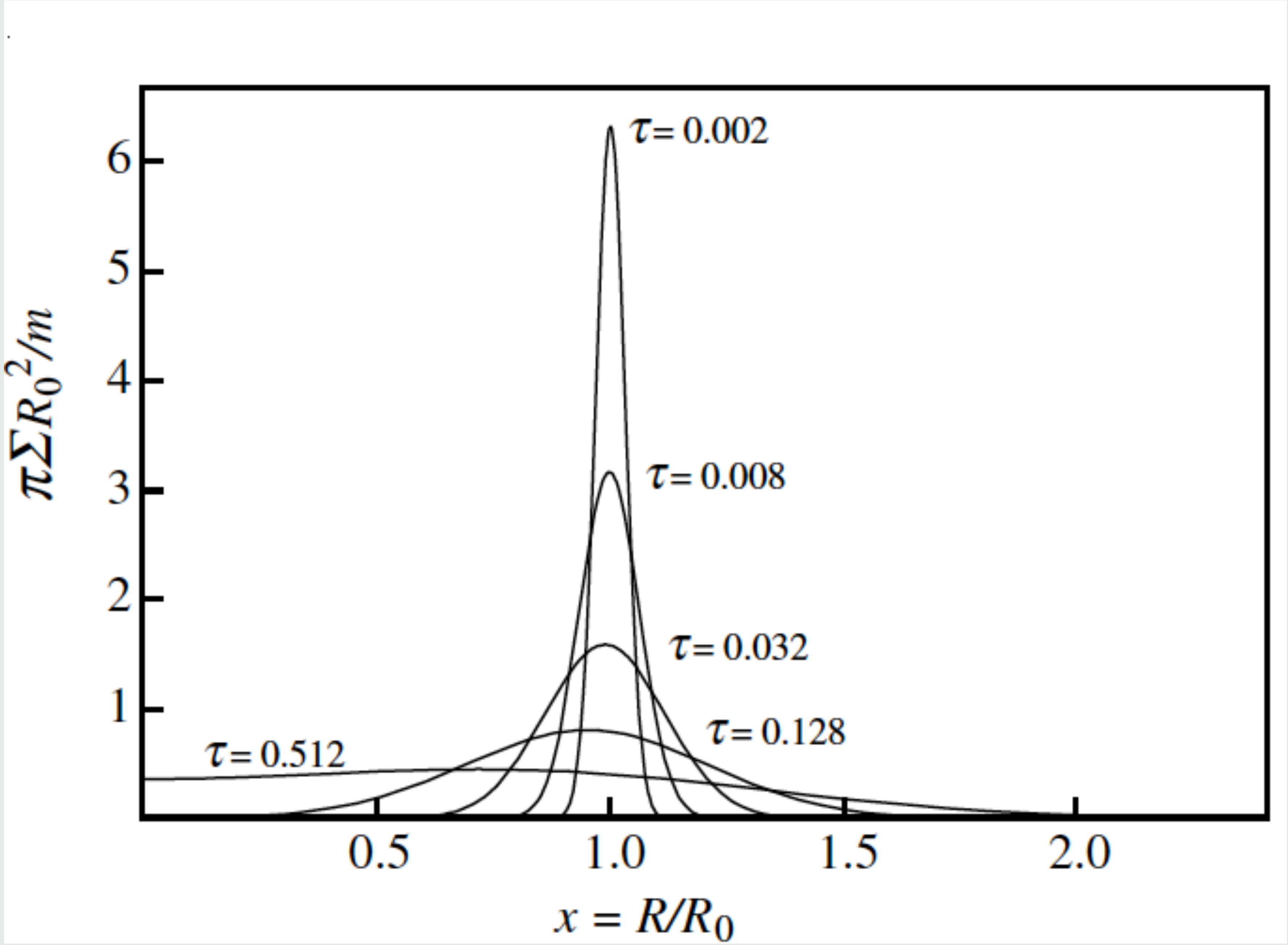
For r > ISCO, structure equations can be extremely complicated. Assuming that molecular friction dominates (which is not true) one can see that radial inhomogeneities spread rapidly:



Frank, King & Raine (2002)

Results

Previously:

We currently consider that there is (at least) one supermassive black hole at the core of every active galaxy:

$$M_{BH} \approx 10^7 - 10^9 M_\odot$$

Naively, in such an environment, we should not expect any effect coming from extra degrees of freedom in modified gravity…

Let's consider the simplest case: a spherically symmetric Black Hole

$$g_{\mu\nu} = -\left(1 - \frac{2M}{r}\right)\delta^t_\mu \delta^t_\nu + \left(1 - \frac{2M}{r}\right)^{-1} \delta^r_\mu \delta^r_\nu + r^2 (\delta^\theta_\mu \delta^\theta_\nu + \sin^2\theta \delta^\phi_\mu \delta^\phi_\nu)$$

From the previous part, we consider the following as the matter density background

$$\rho(r) = \rho_0 \theta\left(r - r_{\mathrm{ISCO}}\right)$$

(Davis et al. '14)

The semi-linear equation of motion for the extra scalar in f(R) is

$$\Box\phi - U'_{\mathrm{eff}}(\phi) = 0$$

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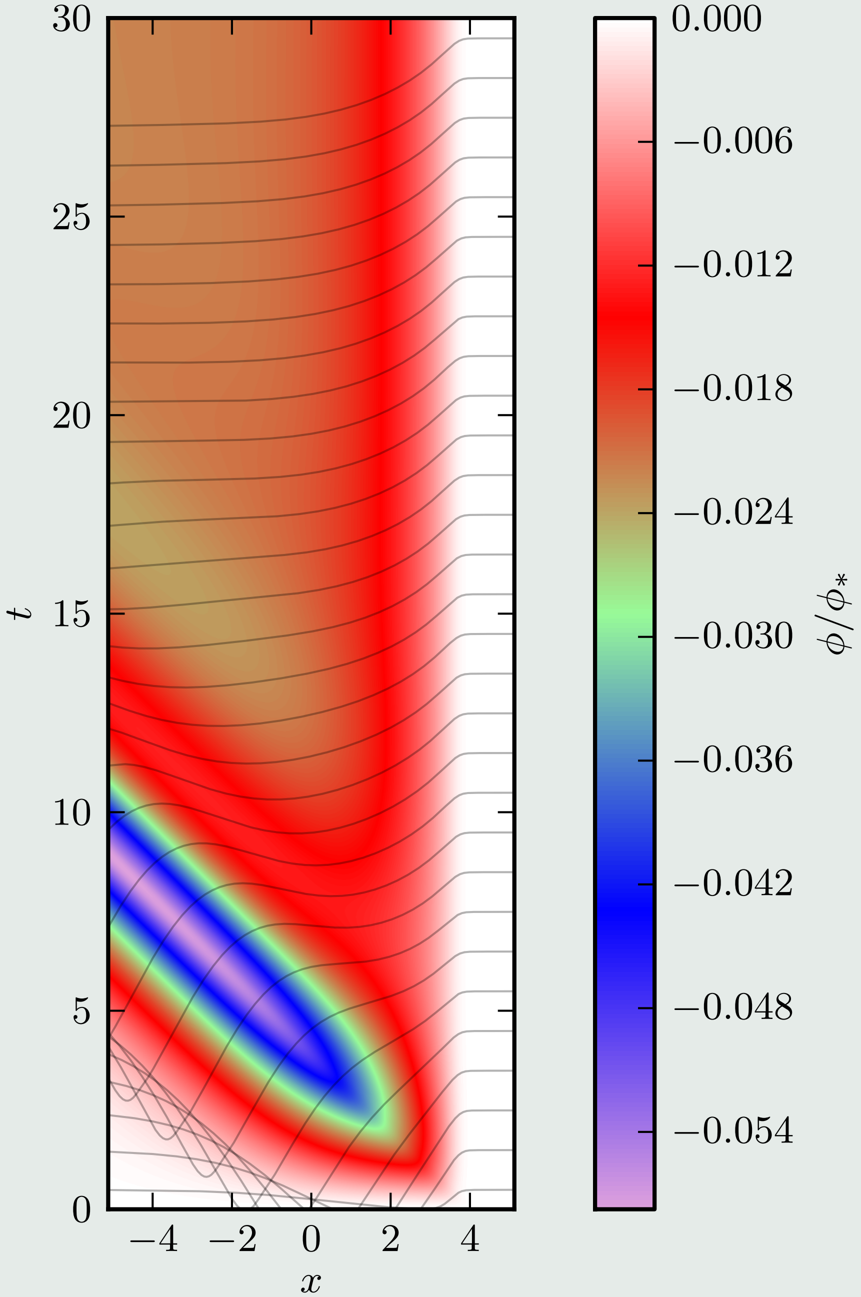
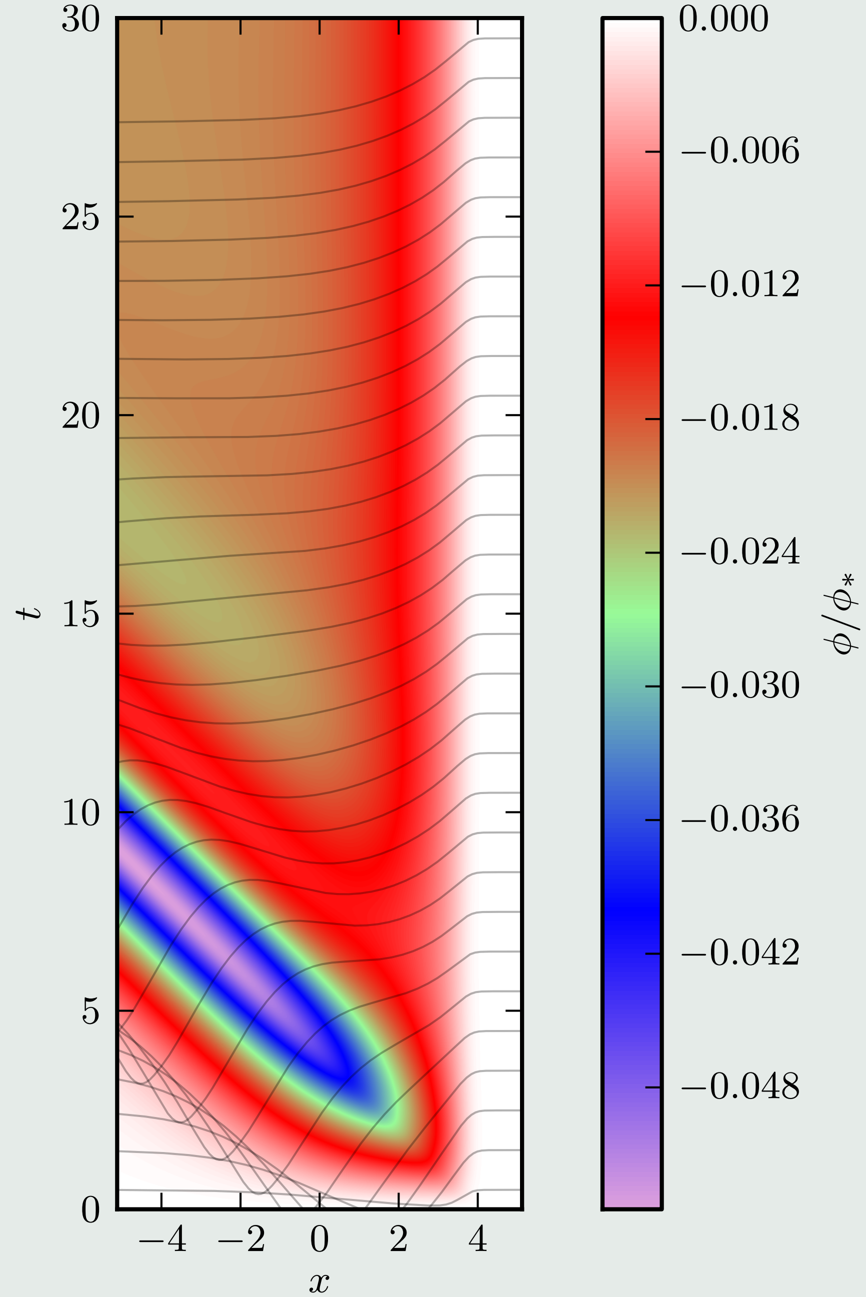
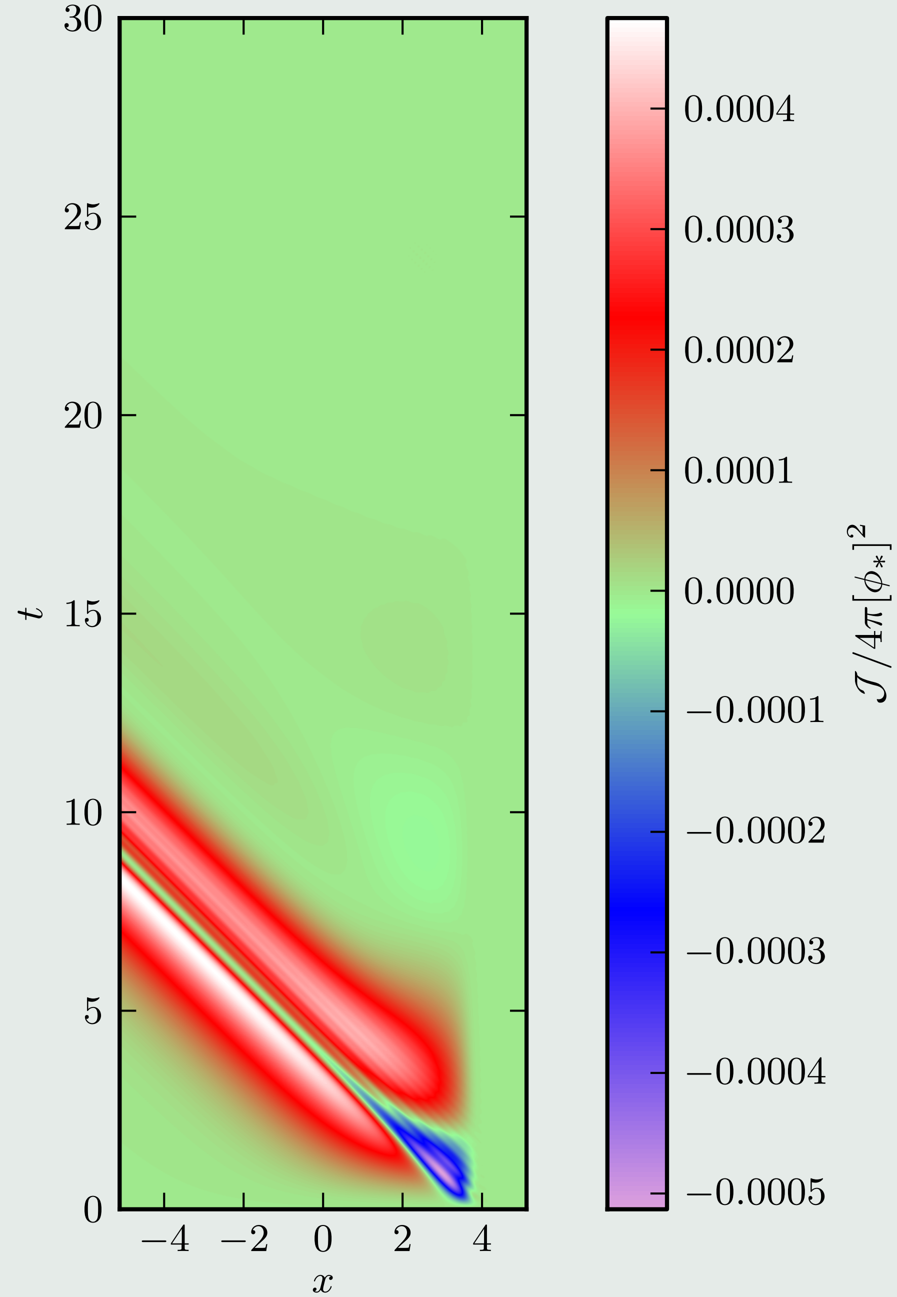


(Dynamics of the Hu-Sawicki Chameleon)

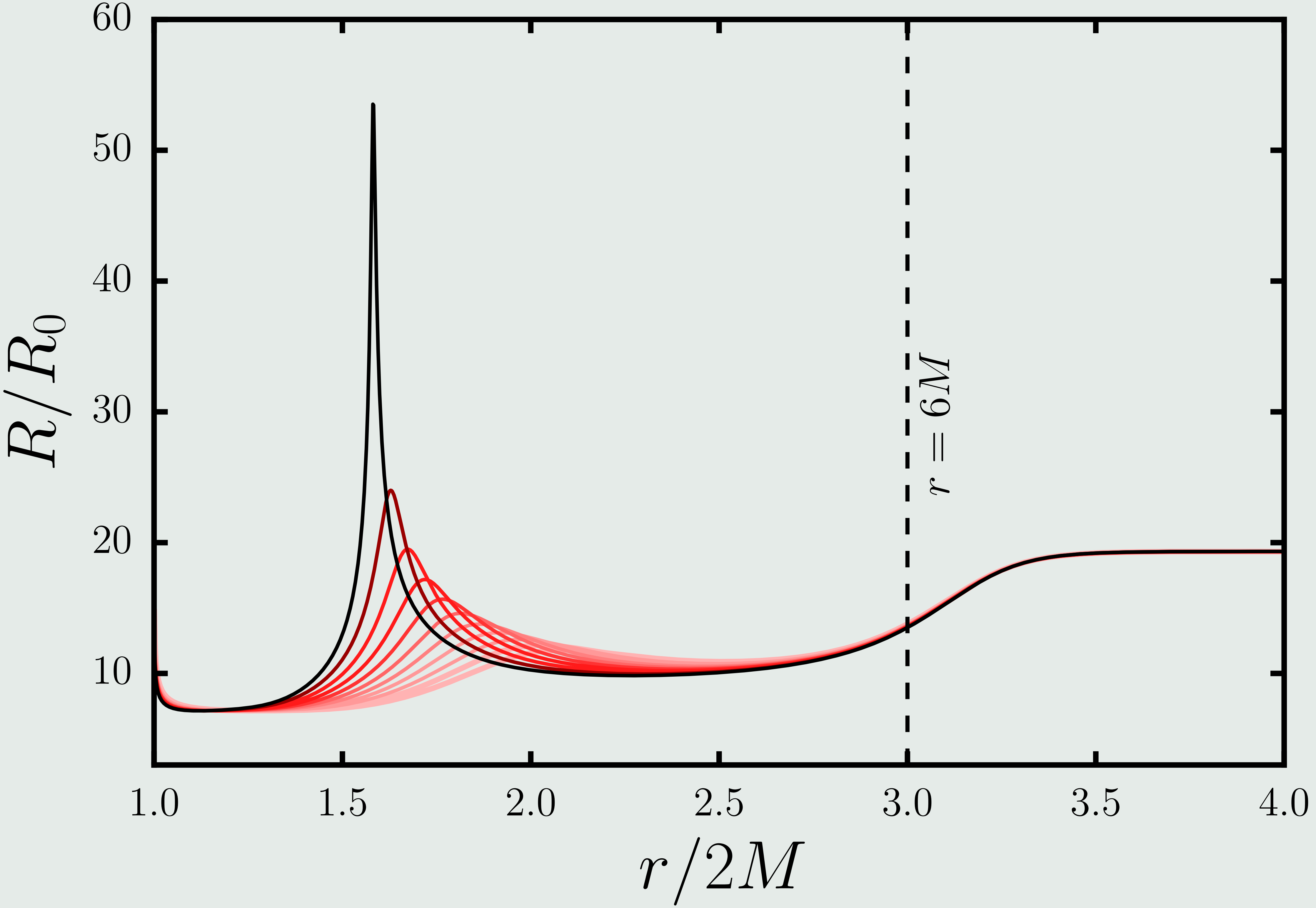


(Dynamics of the Starobinsky chameleon)



(Flux of the Hu-Sawicki Chameleon)

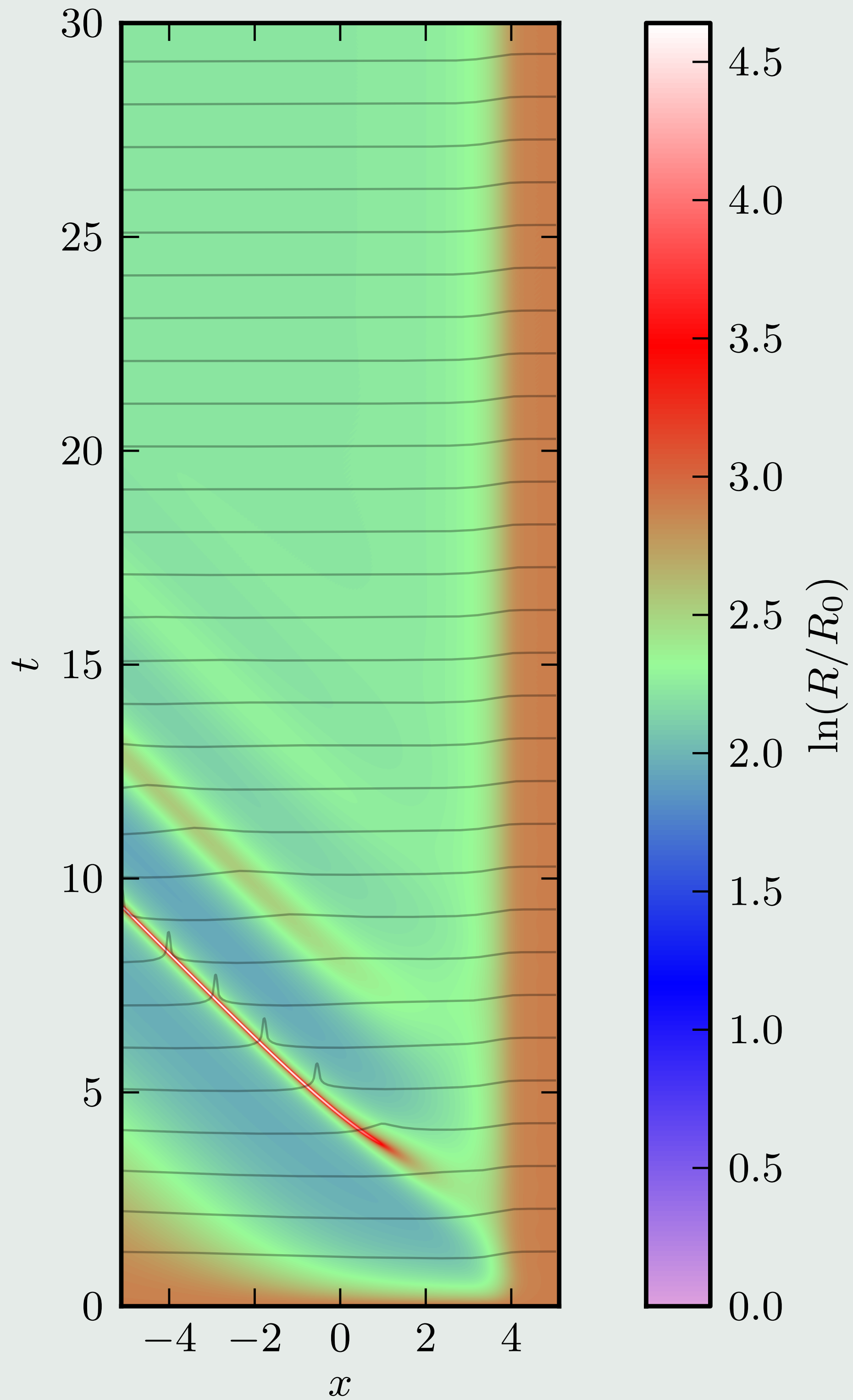
Formation of naked singularities:



Curvature singularities can be removed!

Divergent curvatures can be controlled by adding a higher-curvature correction in the Hu-Sawicki (or Starobinsky) [Kobayashi & Maeda 2009] action. Such a modification must not affect the low R behaviour of the model:

$$f(R) = R - \frac{\alpha(R/R_0)^n}{1+\beta(R/R_0)^n} R_0 + \mu\left(\frac{R}{R_0}\right)^2$$



(Curvature cusps form and get absorbed)

… and the Symmetron model (as a bonus track)

Khoury and Hinterbichler [1001.4525] showed a very simple mechanism to "hide" extra degrees of freedom in different types of theories. This is based on spontaneous symmetry breaking:

$$\int d^4x\sqrt{-g}\left[\frac{R}{16\pi G}-\frac{1}{2}\partial_\mu\phi\partial^\mu\phi-\frac{1}{4}\lambda\phi^4+\frac{1}{2}\mu\phi^2+\frac{\mathcal{L}_m(A^2(\phi)g_{\mu\nu})}{\sqrt{-g}}\right]$$

($\mathbb{Z}_2$ Symmetron)

The field assumes different vacuum expectation (VEV) values at different regions: A very low VEV in a high density environment, and a higher value when is surrounded by a low matter density.

This will evolve in the same non-trivial matter density background:

$$\rho(r)=\rho_0\theta\left(r-r_{\rm ISCO}\right)$$

The equation of motion for the symmetron is also semi-linear:

$$\Box\phi-U'_{\rm eff}(\phi)=0$$

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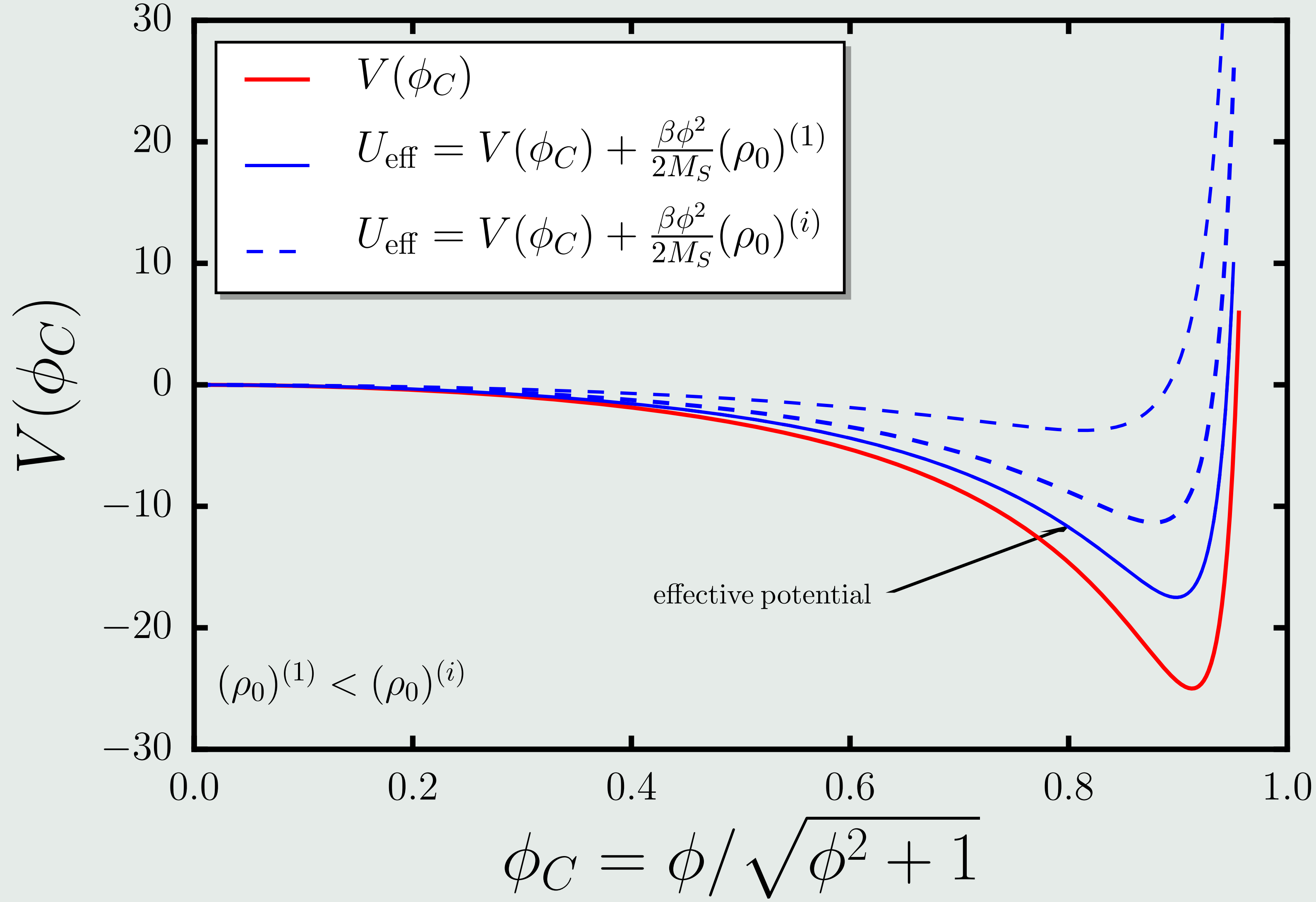
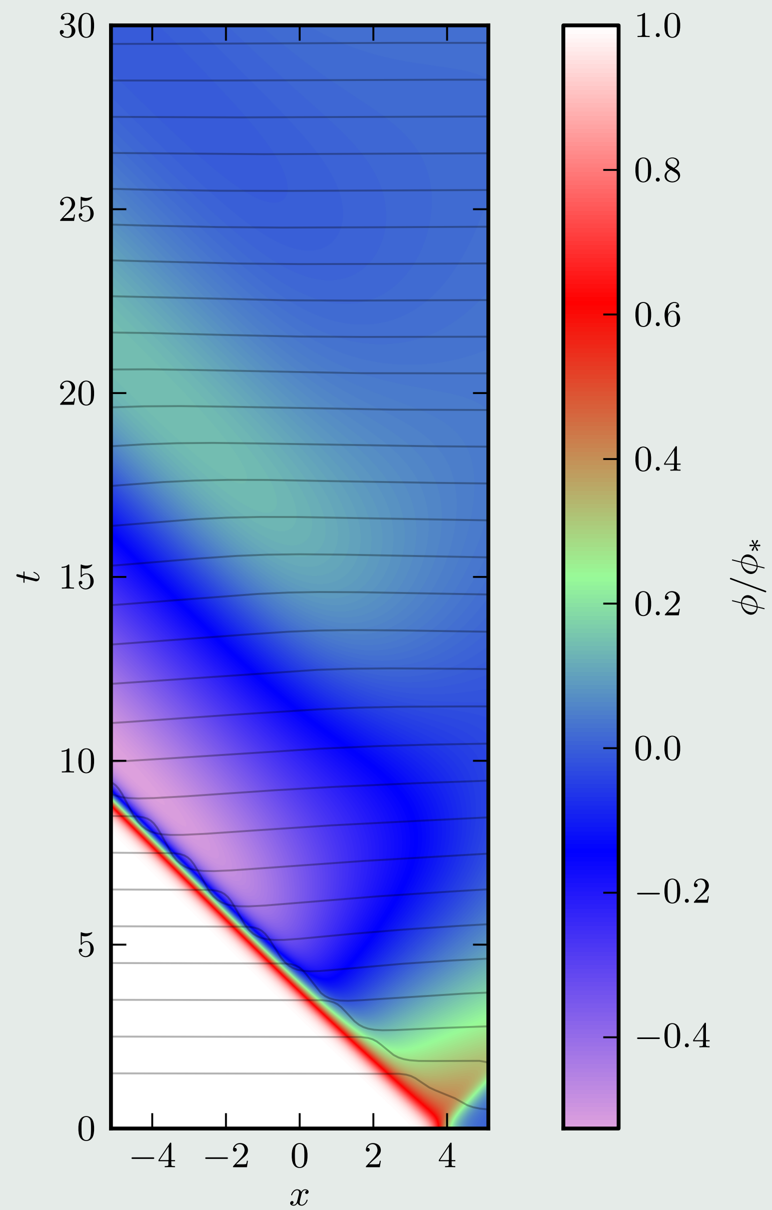
Symmetron screening:

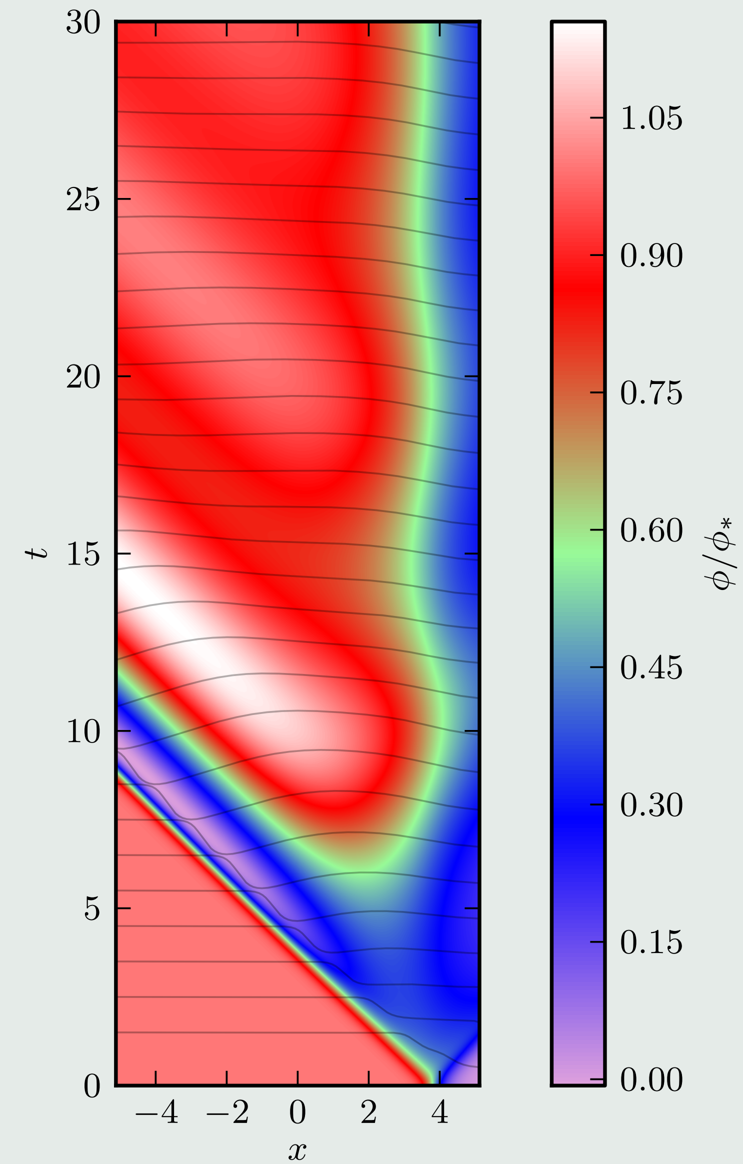
The effective potential $U_{\text{eff}}(\phi)$ is represented by:



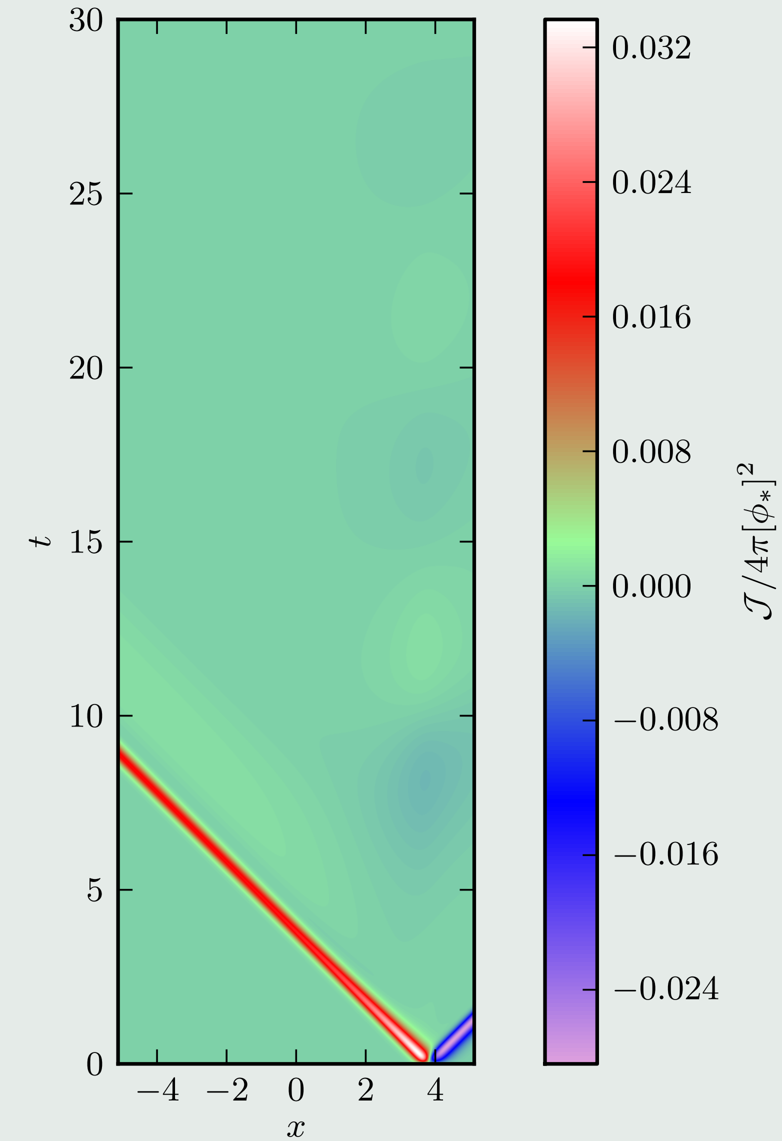
In contrast with the chameleon, matter density affects the effective potential in a way it decreases the field's mass, this type of behaviour is usually called symmetron screening.



(Case I: Dynamics of the symmetron)



(Case II: Dynamics of the symmetron)



(Flux of the symmetron)