Formation of primordial black holes after Starobinsky inflation in a single field model

Daniel Frolovsky

Tomsk State University

Faculty of Physics, Quantum Field Theory Department

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Motivation

Formation of primordial black holes (PBH):

- Our aim is to get a single-field model that describes the formation of primordial black holes and keeps successes of inflation and the standard cosmology.

What inflation model should we consider for it?

- The Starobinsky model (1980) perfectly fits current observations of the CMB radiation but does not lead to PBH production, so we should consider more general $F(R)$-gravity.
- We need model with double inflation for large scalar perturbations collapsing to PBH later.

Choice of the new viable $F(R)$-gravity function is non-trivial:

- has to obey no-ghost or stability conditions;
- should not lead to singularities in cosmological evolution;
- should agree with observations.

The single-field models of PBH production:

- lead to the related decrease in the value of the tilt n_s of CMB scalar perturbations.

J. Garcia-Bellido and E. Ruiz Morales (2017);
I. Dalianis, A. Kehagias, and G. Tringas (2019);
H. V. Ragavendra, P. Saha, L. Sriramkumar, and J. Silk (2021).

The model

Appleby, Battye and Starobinsky (2010) proposed a viable $F(R)$-gravity model with the action

$$S = \frac{M_{\rm Pl}^2}{2} \int d^4x \sqrt{-g} F(R), \tag{1}$$

$$F(R) = \frac{1}{2} M_{\rm Pl}^2 \left(\epsilon_{AB} g \ln \left(\frac{\cosh\left(\frac{R}{\epsilon_{AB}} - b\right)}{\cosh(b)} \right) + (1-g)R + \frac{R^2}{6M^2} \right), \tag{2}$$

$$\epsilon_{AB} = \frac{R_0}{2g \ln(1 + e^{2b})}. \tag{3}$$

Here, $M_{\rm Pl} \sim 10^{18}$ GeV is the Planck mass, $M \sim 10^{-5} M_{\rm Pl} \sim 10^{13}$ GeV, g and b are dimensionless parameters, and R_0 is a vacuum value of the scalar curvature with $\sqrt{R_0} \sim 10^{-33}$ eV.

We use the same $F(R)$-function but instead of describing the dark energy we want to describe PBH production.

- The power spectrum of scalar perturbations is well constrained on the CMB scale by observations, but not on smaller scales.

Thus, we can assume much higher value of R_0, $\sqrt{R_0} < H_{\text{inf}} \sim 10^{14}$ GeV.

- This difference of physical scales is the important one in the physical interpretation of the model.

The standard conversion from $F(R)$ to canonical inflaton scalar field ϕ with the potential V is given by

$$\phi = \sqrt{\frac{3}{2}} M_{\rm Pl}^2 \ln\left(\frac{2}{M_{\rm Pl}^2} F'\right), \quad V(R) = M_{\rm Pl}^4 \frac{F'R - F}{4(F')^2}, \tag{4}$$

$$g = 0.41, \quad b = 2.89247, \quad R_0 = 0.1 \cdot M^2.$$

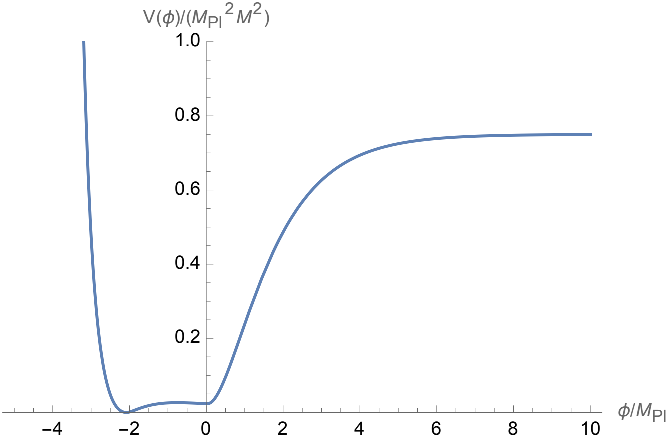

Figure: 1

Zooming the potential $V(\phi)$ for the selected values of the inflaton field ϕ:

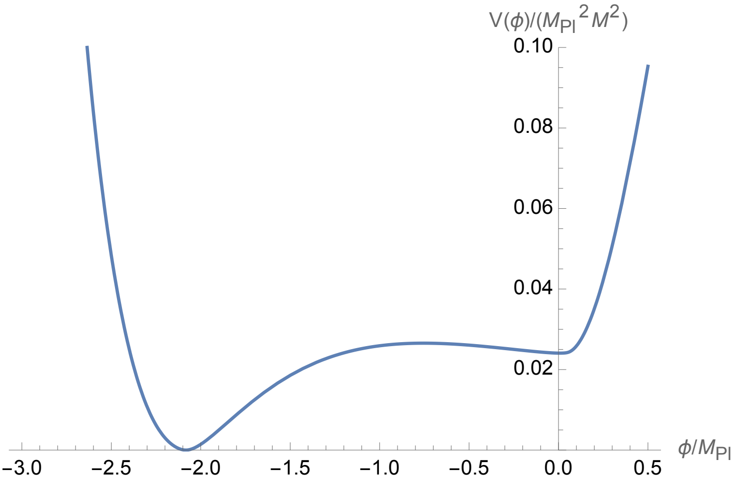

Figure: 2

Double inflation

The equations of motion are given by

$$\ddot{\phi}+3H\dot{\phi}+V'(\phi)=0,\ \ H^2=\frac{1}{3M_{\rm Pl}^2}\left(\frac{1}{2}\dot{\phi}^2+V(\phi)\right),\ \ \dot{H}=-\frac{1}{2M_{\rm Pl}^2}\dot{\phi}^2,\quad (5)$$

where $H(t)$ is the Hubble function, and $\phi_{\rm in}=\phi(0)=5.17\cdot M_{\rm Pl}$, $\phi'(0)=0$.

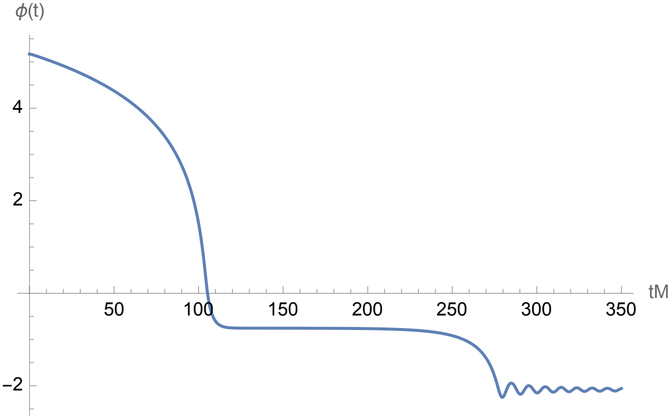

Figure: 3

There is the double inflation indeed, with the two plateaus leading to slow-roll of the inflaton:

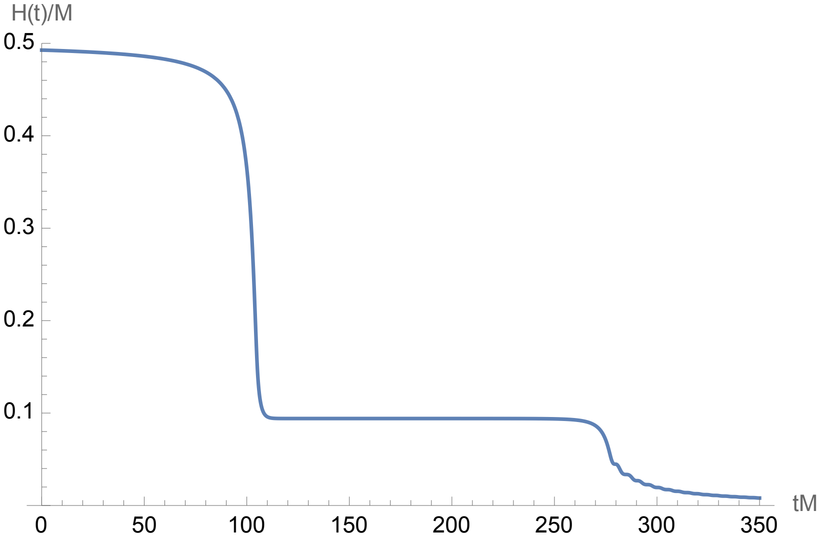

Figure: 4

Power spectrum of perturbations and PBH masses

$$P_R(t) = \frac{H^2(t)}{8M_{\text{Pl}}^2\pi^2\epsilon(t)}, \quad (6)$$

where $\epsilon(t) = -\frac{\dot{H}}{H^2}$, $k = aH = \dot{a}$.

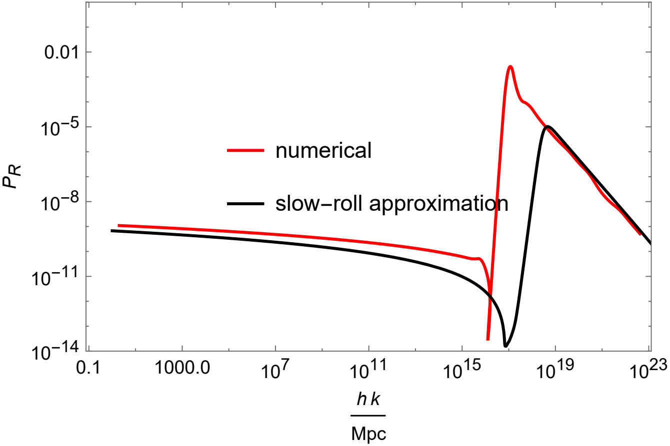

Figure: 5

$$M_{\mathrm{PBH}} \simeq \frac{M_{\mathrm{Pl}}^2}{H(t_{\mathrm{peak}})} \exp\left[2(N_{\mathrm{total}} - N_{\mathrm{peak}}) + \int_{t_{\mathrm{peak}}}^{t_{\mathrm{end}}} \epsilon(t) H(t) dt\right] \qquad (7)$$

ϕ_{in}	n_s	ΔN	r	N_{end}	M_{PBH}
5.099	0.95657	21	0.00532	65.03	$2.17 \cdot 10^{19}$ g
5.120	0.95737	20	0.00514	65.09	$5.72 \cdot 10^{18}$ g
5.146	0.95831	19	0.00492	65.03	$8.41 \cdot 10^{17}$ g
5.170	0.95915	18	0.00473	65.02	$1.43 \cdot 10^{17}$ g
5.095	0.95646	16	0.00536	60.01	$3.89 \cdot 10^{15}$ g
5.120	0.95738	15	0.00514	60.01	$7.38 \cdot 10^{14}$ g

$$b = 2.89, \quad g = 0.41$$

The value of the index n_s of scalar perturbations agrees with the PLANCK measurements (2020):

$$n_s = 0.9649 \pm 0.0042 \quad (1\sigma), \quad r < 0.036 \quad (2\sigma). \qquad (8)$$

Conclusion

- We adapted the ABS $F(R)$-gravity model for double inflation and PBH production.
- The PBH can have masses $10^{17} - 10^{19}$ g, so that they can also survive in the present universe and may form part of CDM.
- Our results agree with the current measurements of cosmic microwave background radiation within 3σ but require fine-tuning of the parameters.

THANK YOU FOR YOUR ATTENTION!