PBH formation during preheating

Joaquim Iguaz Juan

with Pasquale Serpico, Marco Taoso
and Guillermo Ballesteros

Soon to appear on arXiv!

Napoli

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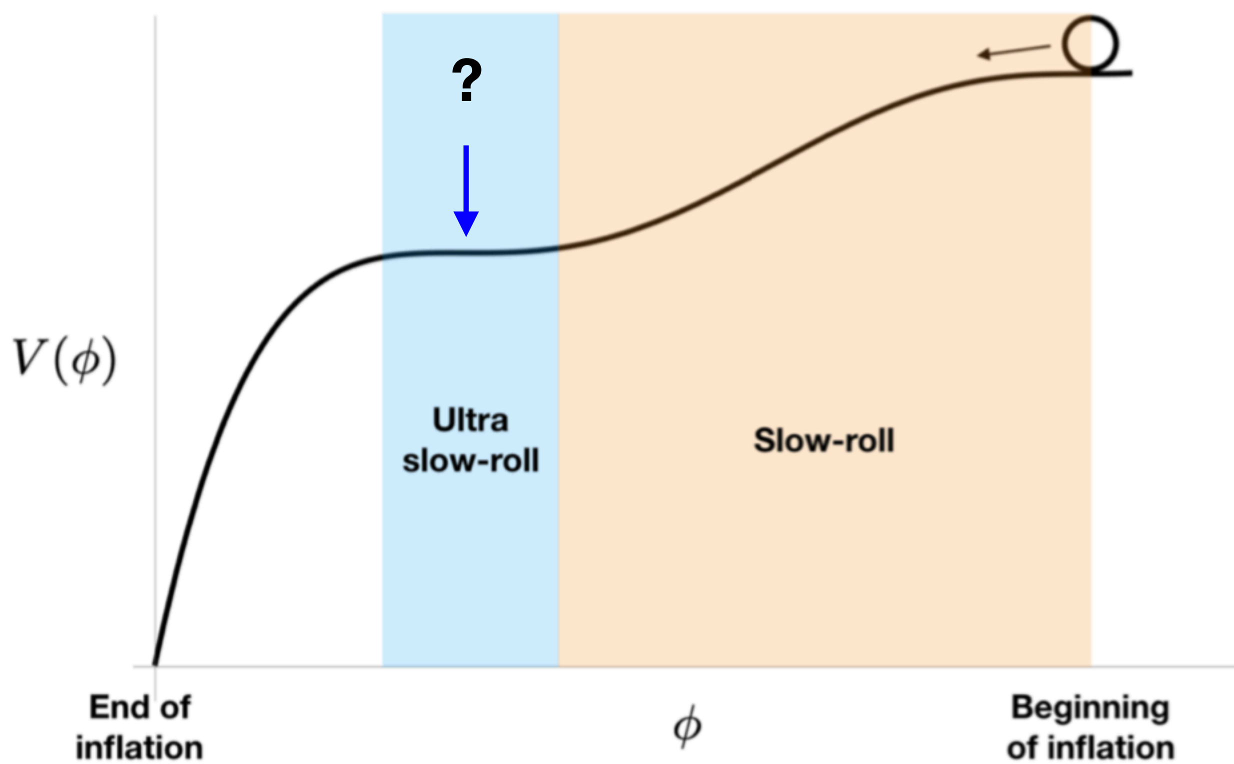
PBH formation: Fine-tuned?

The typical formation mechanism is the collapse of large overdensities in the early universe. However…



$$\beta = \mathrm{erfc}\left(\frac{\delta_c}{\sqrt{2\sigma^2}}\right)$$

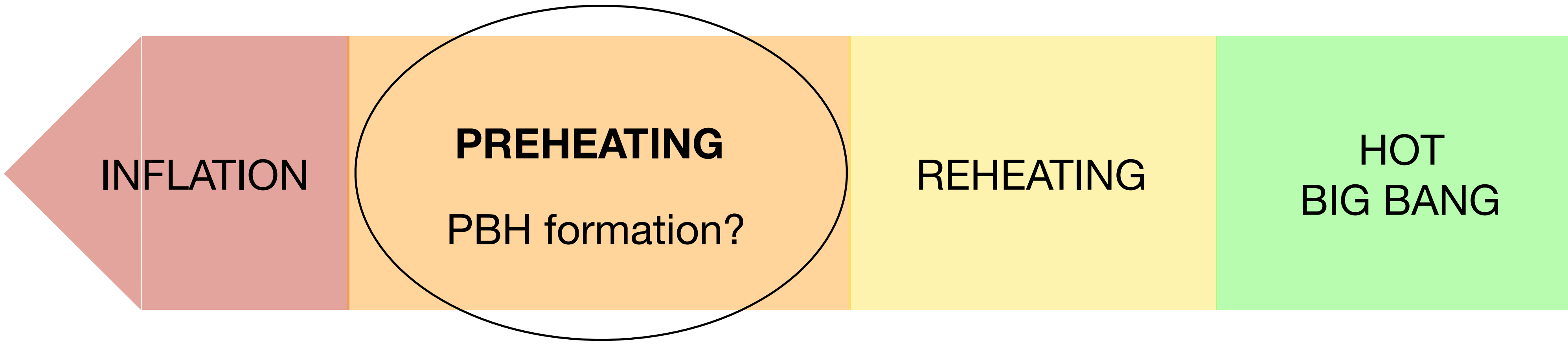
Error function!

Special features (such as an inflection point in USR) on the inflaton potential are placed at very specific locations.

The resulting PBH abundance depends very sensitively on the precise values for the parameters.

Alternative formation mechanism

An interesting opportunity for PBH formation may be at the end of inflation, in the non-perturbative phase preceding the hot big bang know as **preheating**.



Non-perturbative phenomena, such as parametric resonance, lead to the **exponential amplification** of inflaton perturbations.

It is a frequent claim (see *JCAP* 01 (2020) 024, *PRD* 64 (2001) 021301, *PRD* 71 (2005) 063507, *PRL* 121 (2018) 8 081306) that PBH formation is a **generic outcome** of such phenomenon.

IS PBH FORMATION A GENERIC FEATURE OF PREHEATING?

Parametric resonance

At the end of inflation:

Inflaton condensate + Fluctuations

$$\phi(t) \simeq \phi_0 \left(\frac{a_0}{a(t)}\right)^{3/2} \cos[m(t-t_0)]$$

$$\ddot{\chi}_k + \omega^2(k,t)\chi_k = 0$$

MATHIEU EQUATION

$$\frac{\mathrm{d}^2\chi_k}{\mathrm{d}z^2} + \Big[A(k) - 2q\cos(2z)\Big]\chi_k = 0$$

The solutions can exhibit a phenomenon called **parametric resonance:**

$$\chi_k = e^{\mu_k z}\mathcal{P}_{k+} + e^{-\mu_k z}\mathcal{P}_{k-} \qquad \Re(\mu_k) \neq 0 \implies$$

Exponential growth of *k* mode!

Parametric resonance: quadratic potential

JCAP 01 (2020) 024 and *PRD* 62 (2000) 083502

Inflaton + **metric perturbations** coupled via Einstein's equations

$$V(\phi) = \frac{1}{2} m_\phi^2 \phi^2$$

$$Q = \delta\phi + \frac{\dot{\phi}}{H}\Phi \qquad \tilde{Q} = a^{3/2} Q$$

$$\ddot{\tilde{Q}} + \left[m_\phi^2 + \frac{k^2}{a^2} + \frac{2m_\phi^2}{M_{\rm Pl}^2}\frac{\phi\dot{\phi}}{H} + \frac{3\dot{\phi}^2}{M_{\rm Pl}^2} - \frac{\dot{\phi}^4}{2H^2 M_{\rm Pl}^4} + \frac{3}{4M_{\rm Pl}^2} P_\phi \right] \tilde{Q} = 0$$

$$z \equiv m(t - t_0) + 3\pi/4$$

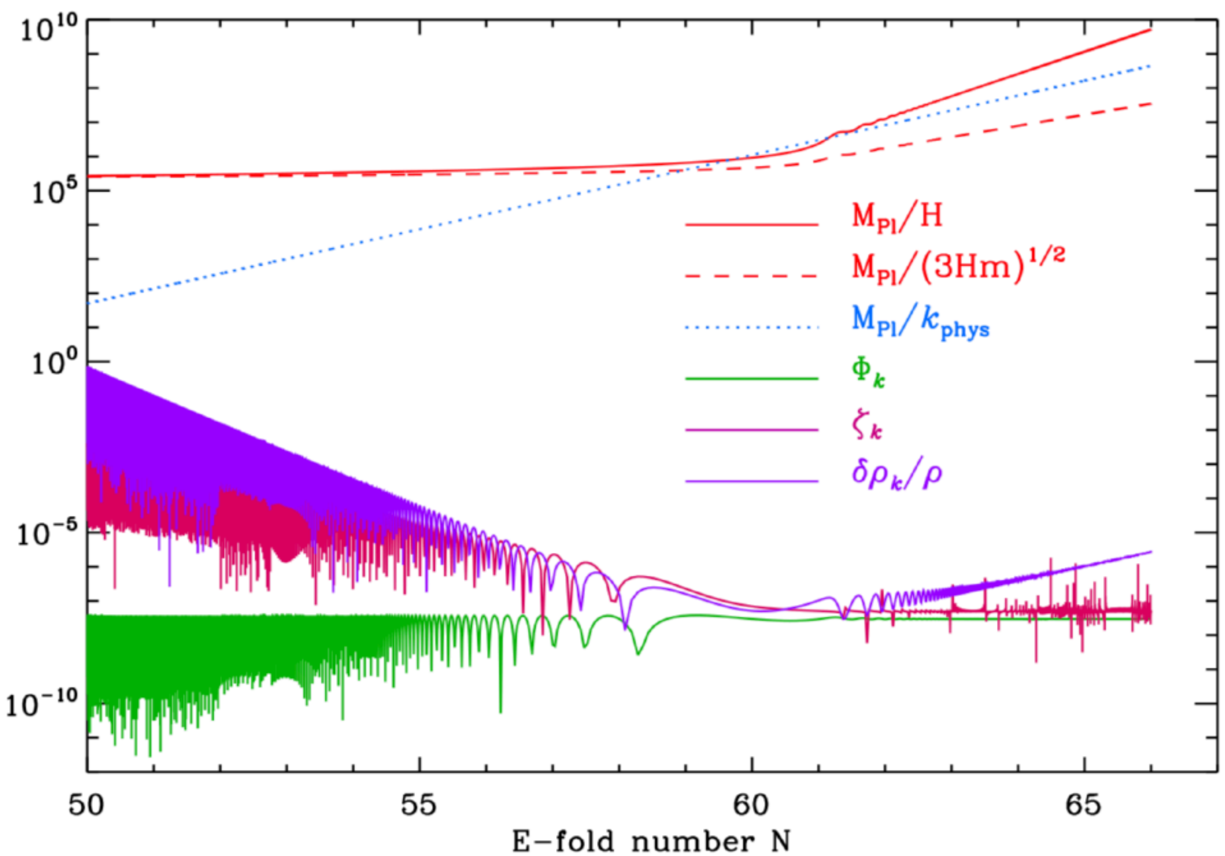
$$\frac{\mathrm{d}^2\tilde{Q}}{\mathrm{d}z^2} + \left[1 + \frac{k^2}{m_\phi^2 a^2} - \frac{\sqrt{6}\phi_0}{M_{\rm Pl}} \left(\frac{a_0}{a}\right)^{3/2} \cos(2z) \right] \tilde{Q} = 0$$

PBH formation: quadratic potential

$$V(\phi) = \frac{1}{2}m_\phi^2\phi^2$$

Linear analysis:
Jedamzik, Lemoine, and Martin. *JCAP* 09 (2010) 034.

$$\Longrightarrow \delta \propto a$$



Extrapolating to later times…

PBH formation!

JCAP 01 (2020) 024

Parametric resonance: anharmonic corrections?

JCAP 01 (2020) 024 and *PRD* 62 (2000) 083502

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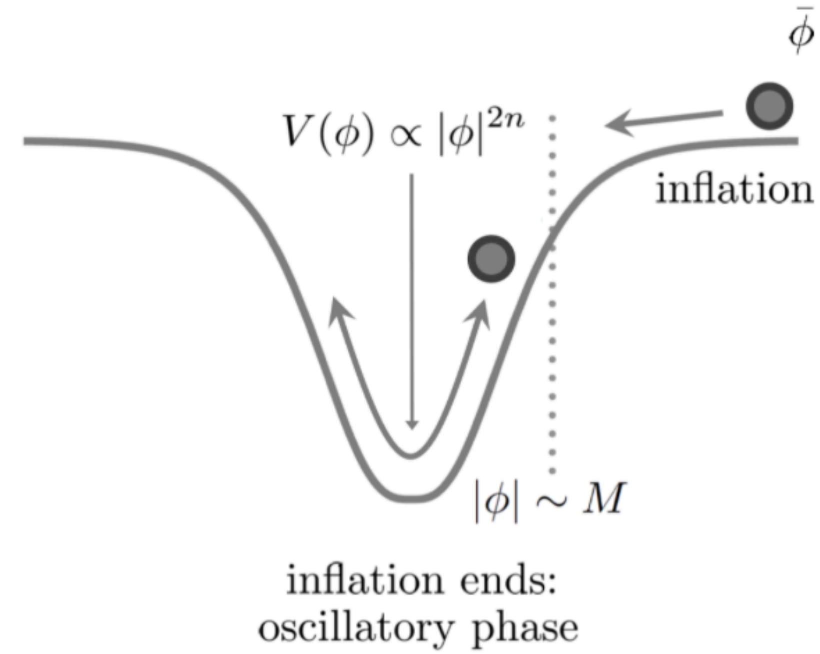
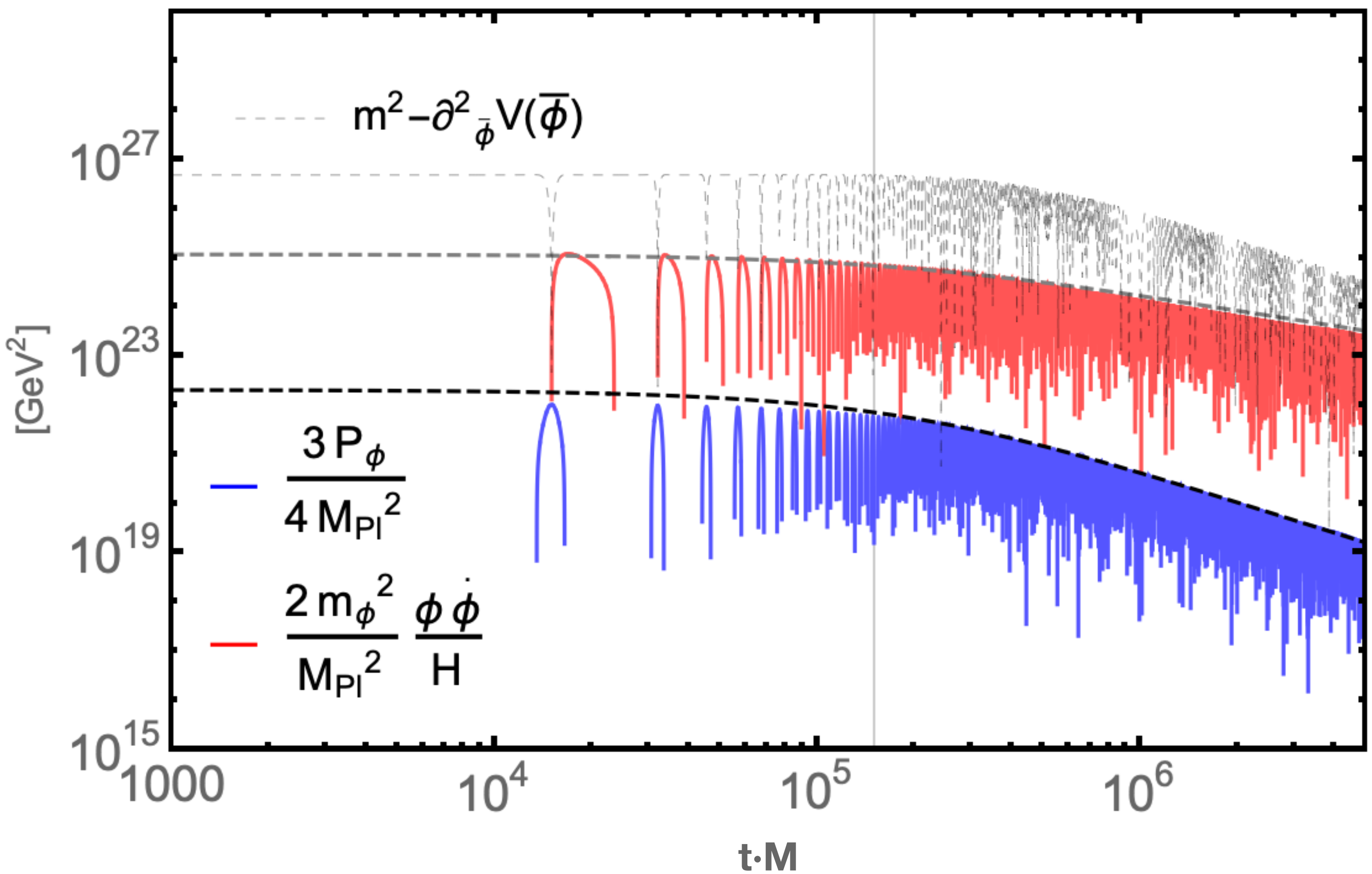
However, what about anharmonic correction?

Parametric resonance: T-models

with M=7.75 10^{-3} M_{Pl} and n=1



$$V(\phi) = \Lambda^4 \tanh^{2n}\left(\frac{|\phi|}{M}\right)$$



$$m^2 - \frac{\partial^2 V(\bar{\phi})}{\partial \bar{\phi}^2} \sim \frac{M_{\rm Pl}^2}{M^2}\phi^2,$$

$$\frac{2m_\phi^2}{M_{\rm Pl}^2}\frac{\phi\dot{\phi}}{H} \sim M_{\rm Pl}\phi,$$

$$\frac{3}{4M_{\rm Pl}^2}P_\phi \sim \phi^2.$$

PBH formation: T-models

Results only valid in the linear regime: **backreaction** neglected!

Anharmonic corrections are also neglected!

$\Longrightarrow$ Need for numerical analysis (with CosmoLattice)

$$V(\phi) = \Lambda^4 \tanh^{2n}\left(\frac{|\phi|}{M}\right)$$

$\boldsymbol{\Lambda}$ fixed from CMB measurements

Most interesting regime: $M \ll M_{\rm Pl}$

↓

Strong resonance

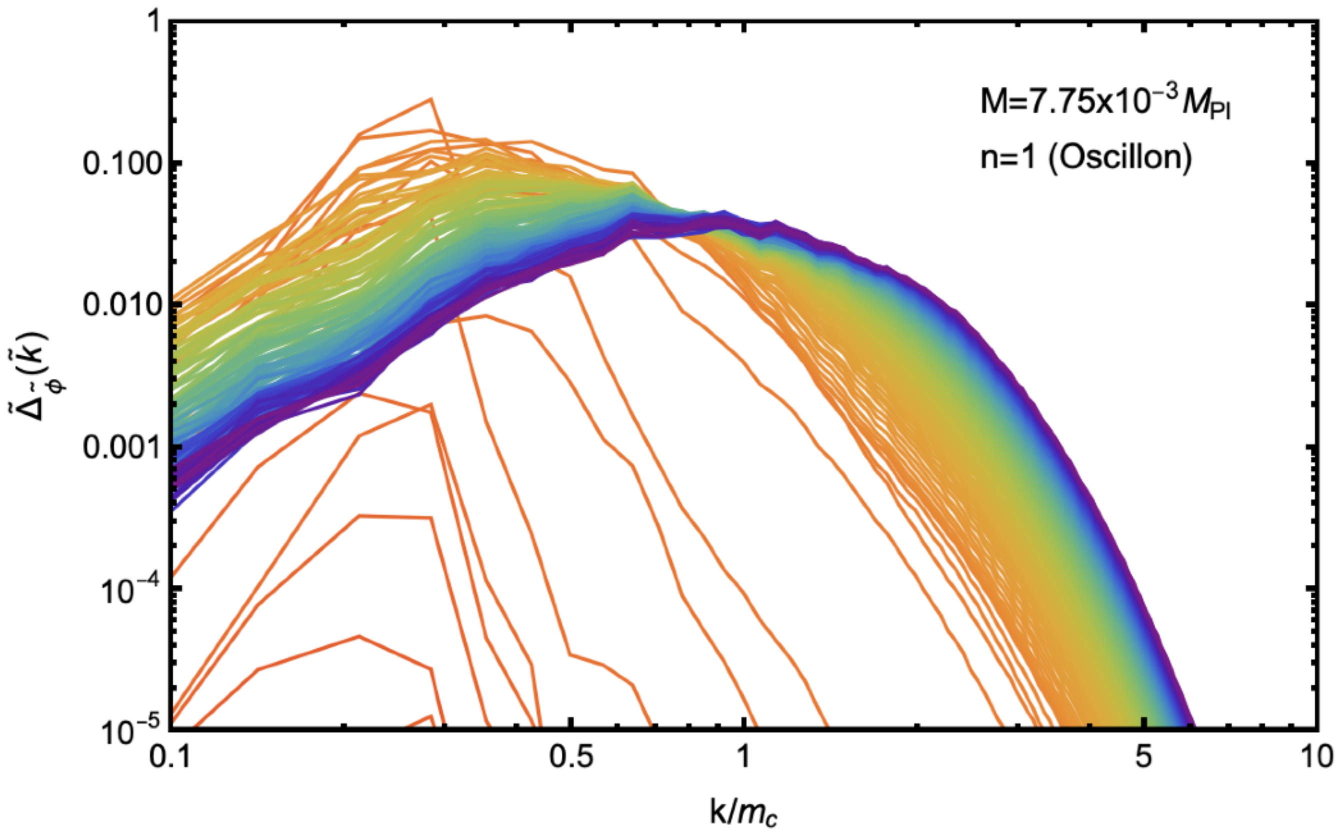
Lozanov and Amin. *PRD* 97 (2018) 2 023533.
Lozanov and Amin. *PRD* 99 (2019) 12 123504.

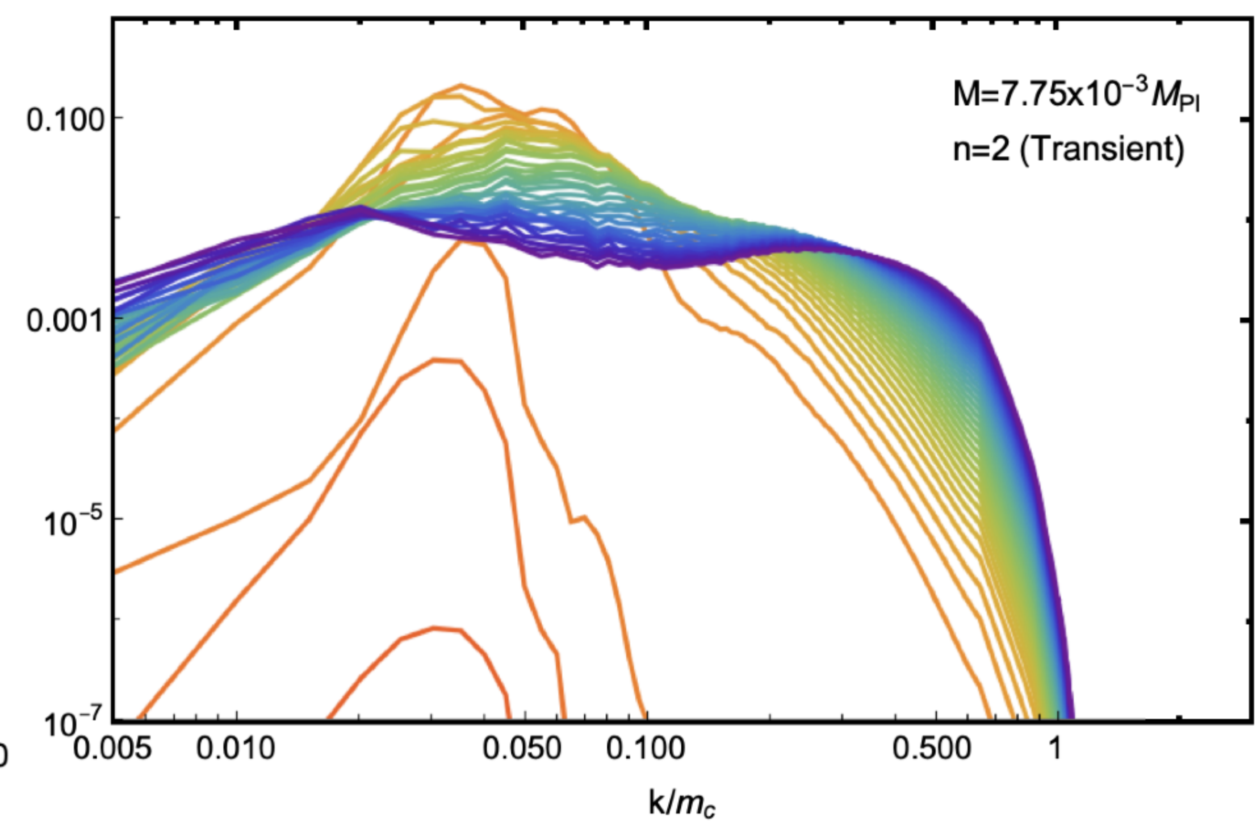
Numerical results: Oscillons

It turns out that backreaction of inflaton perturbations onto their own growth shuts off the resonant amplification.

It prevents PBH formation! However, metastable structures (oscillons and transients) are formed.

t: EARLY ⟶ LATE





$$\tilde{k} \equiv k/m_c = kM^n\Lambda^{-2}\phi_{in}^{1-n} \qquad \Delta_\phi \equiv \tilde{\Delta}_{\tilde{\phi}}\phi_{in}^2$$

Conclusions

PBH formation has been recently argued to be a generic outcome at preheating.

We introduced the physical phenomenon behind the possible formation of PBHs, namely resonant amplification sourced by the oscillating inflaton background.

1. **ANHARMONICITY**

For inflaton potentials not ruled out by CMB data (α-attractor T-models), anharmonicity provides the leading contribution to parametric resonance.

2. **BACKREACTION**

Backreaction effects: The growth of perturbations is eventually shut off well before PBH form. However, metastable structures in the form of oscillons form.