Effects of Fragmentation on Post-Inflationary Reheating

Mathieu Gross, COSPT 2024 meeting, 01/02/2024

Based on

arXiv:2308.16231v1 with M. A. G. Garcia, Y. Mambrini, K. A. Olive, M. Pierre, and J.-H. Yoon

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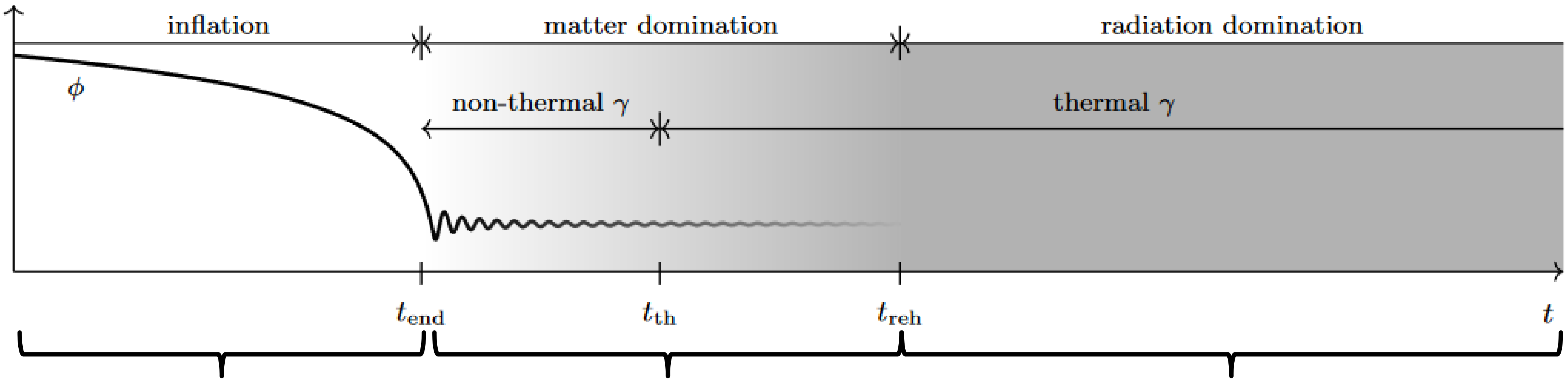
- Introduction: The standard reheating
- What is fragmentation?
- Numerical result and implications

Introduction



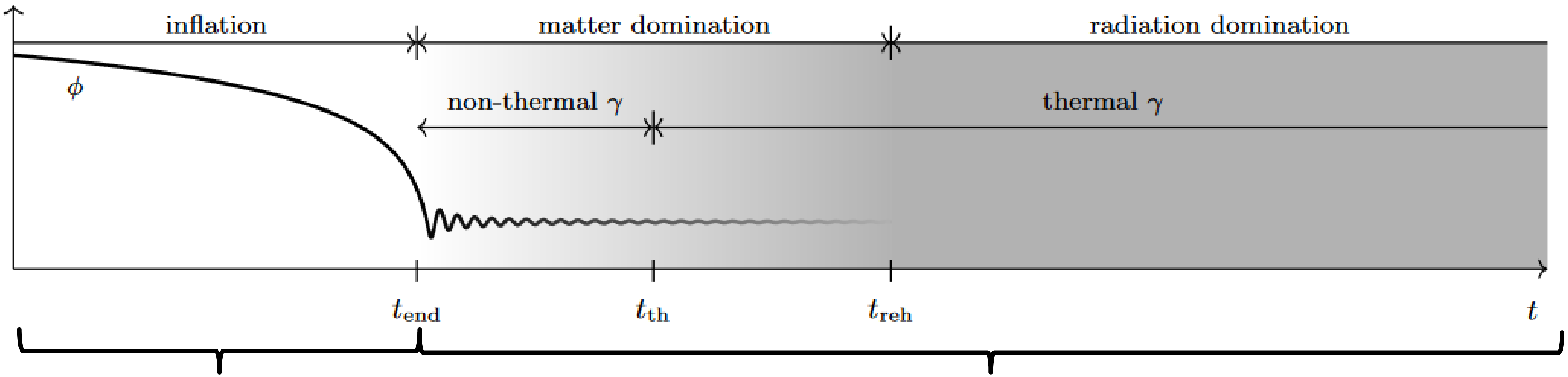
Accelerated expansion

Transition (reheating)

Thermal universe

arXiv:1806.01865v2 [hep-ph] 17 Dec 2018

Introduction



Production of particles/Dark matter

$$S = \int d^4x \sqrt{-g} \left(\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right)$$

ϕ Is a classical field

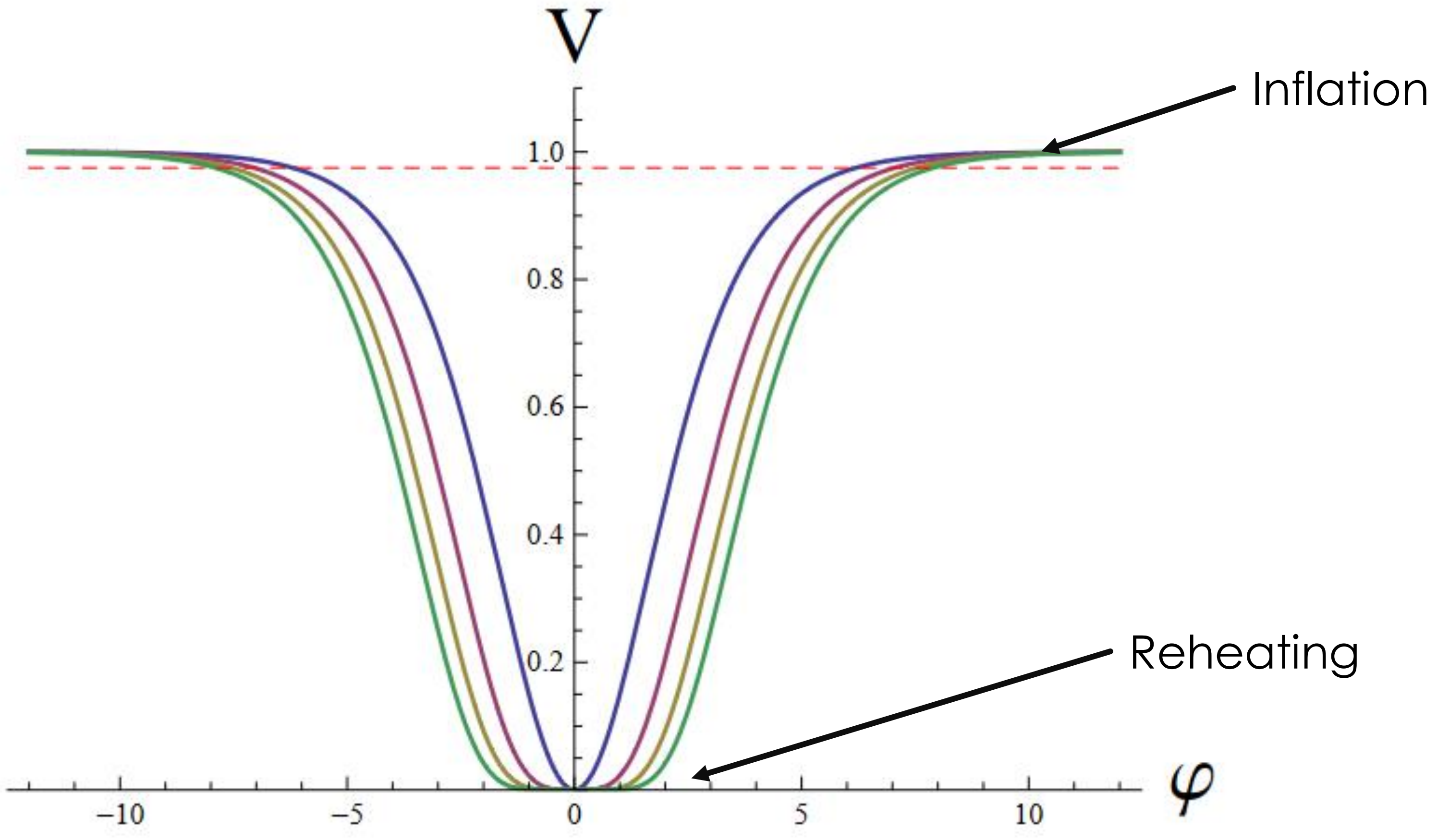
$$\mathcal{L} \supset \begin{cases} y\phi \bar{f} f & \phi \to \bar{f} f \\ \mu\phi bb & \phi \to bb \\ \sigma\phi^2 b^2 & \phi\phi \to bb \end{cases}$$

arXiv:1806.01865v2 [hep-ph] 17 Dec 2018

Introduction

$$V(\phi) = \lambda M_P^4 \left[\sqrt{6}\tanh\left(\frac{\phi}{\sqrt{6}M_P}\right)\right]^k$$

$$\lambda = \frac{18\pi^2 A_s}{6^{k/2} N_*^2}$$



k	λ
4	3.42×10^{-12}
6	5.70×10^{-13}
8	9.51×10^{-14}
10	1.58×10^{-14}

arXiv:1306.5220v3 [hep-th] 8 Sep 2013

Reheating the cosmological equations

Equation of motion for the homogeneous field

$$\ddot{\phi} + 3H\dot{\phi} + n\lambda m_{pl}^{4-k}\phi^{k-2}\phi = 0$$

Friedman's equations:

$$\dot{\rho}_\phi + 3H(1+w_\phi)\rho_\phi = -(1+w_\phi)\Gamma\rho_\phi$$

$$\dot{\rho}_R + 4H\rho_R = (1+w_\phi)\Gamma\rho_\phi$$

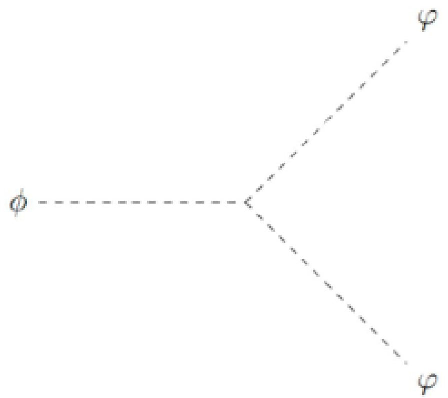
$$H^2 = \frac{\rho_R + \rho_\phi}{3m_{pl}^2}$$

Equation of state parameter:

$$w_\phi = \frac{P_\phi}{\rho_\phi} = \frac{k-2}{k+2}$$

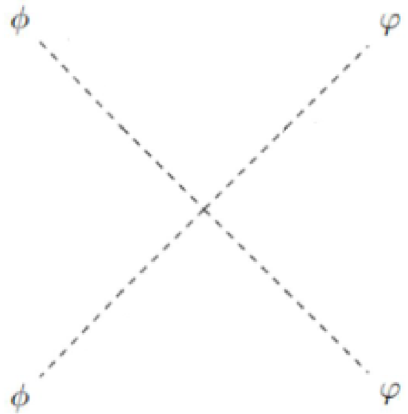
Reheating the microphysics

$$\mathcal{L} \supset -\mu\,\phi\,\varphi^2 - \sigma\,\phi^2\,\varphi^2 - y_\psi\,\overline{\Psi}\,\Psi\,\phi$$



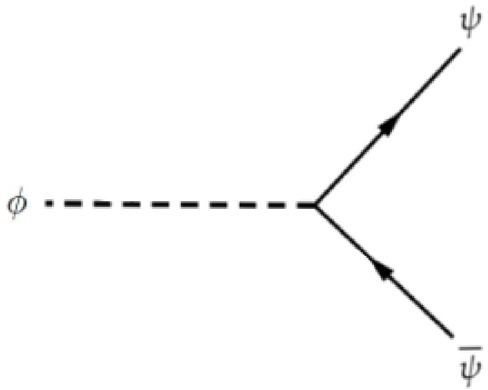
$$\Gamma^{1\to 2} \simeq \frac{m_\phi}{8\pi}\left(\frac{\mu_{\rm eff}}{m_\phi}\right)^2$$

Decay to bosons



$$\Gamma^{2\to 2} \simeq \frac{\sigma_{\rm eff}^2\,\rho_\phi}{8\pi\,m_\phi^3}$$

Scattering to bosons



$$\Gamma_{\phi\to\overline{\Psi}\Psi} = \frac{y_{\rm eff}^2}{8\pi} m_\phi$$

Decay to fermions

arXiv:2012.10756v2 [hep-ph] 7 Apr 2021

Solving the reheating

$$\rho_\phi = \rho_{end} \left(\frac{a_{end}}{a}\right)^{\frac{-6k}{k+2}} \longrightarrow \rho_R = \frac{1+\omega_\phi}{a^4} \int dln(a) \frac{\Gamma \rho_\phi a^4}{H}$$

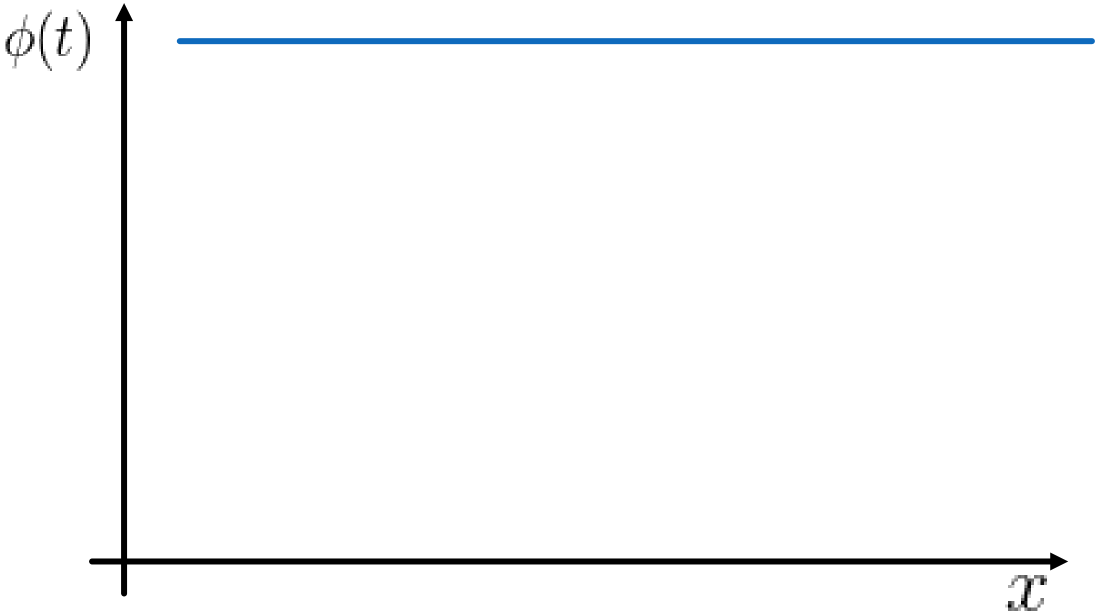
Define the reheating time : $\rho_R(a_{RH}) = \rho_\phi(a_{RH})$

Define the reheating Temperature: $T_{RH} \sim \rho_R(a_{RH})^{\frac{1}{4}}$

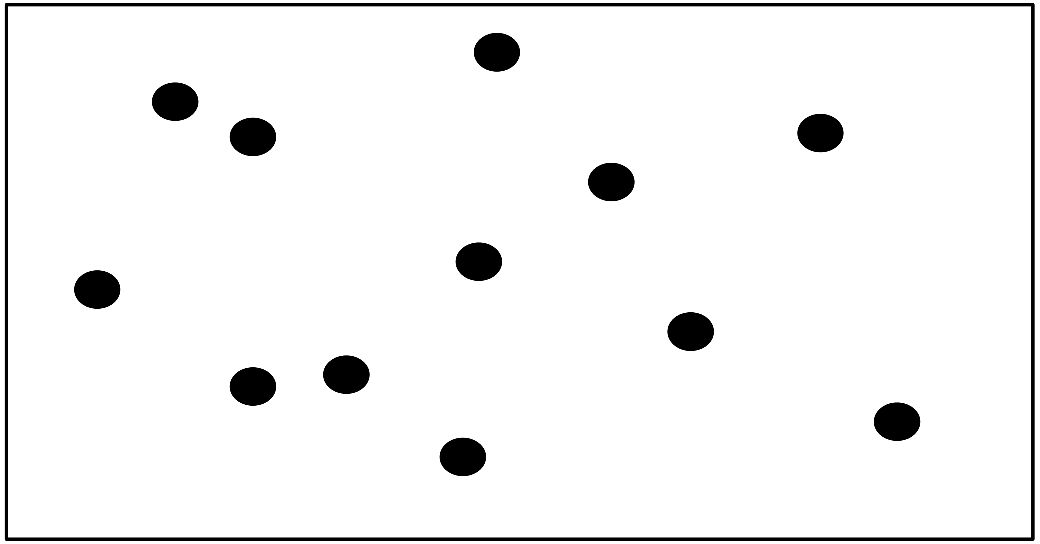
The issue of fluctuation

$\phi(t)$ $+$ $\delta\phi(t, x)$

Condensate: Classical field that oscillate at a frequancy m_ϕ uniformly in space



Particle: Non homogeneous quantum field (usual particles)



What is fragmentation?

$$\phi(t,x) = \bar{\phi}(t) + \delta\phi(t,x) \longrightarrow V(\phi) = \lambda M_{pl}^{4-k} \sum_{l=1}^{k} \binom{k}{l} \phi^{k-l} \delta\phi^{l}$$

Introduce new couplings !

New EOM:

$$\ddot{\phi} - \frac{\Delta\phi}{a^2} + 3H\phi + V_{,\phi}(\phi) = 0 \longrightarrow \ddot{\delta\phi} + 3H\dot{\delta\phi} - \frac{\nabla^2\delta\phi}{a^2} + k(k-1)\lambda M_P^2 \left(\frac{\phi(t)}{M_P}\right)^{k-2} \delta\phi = 0$$

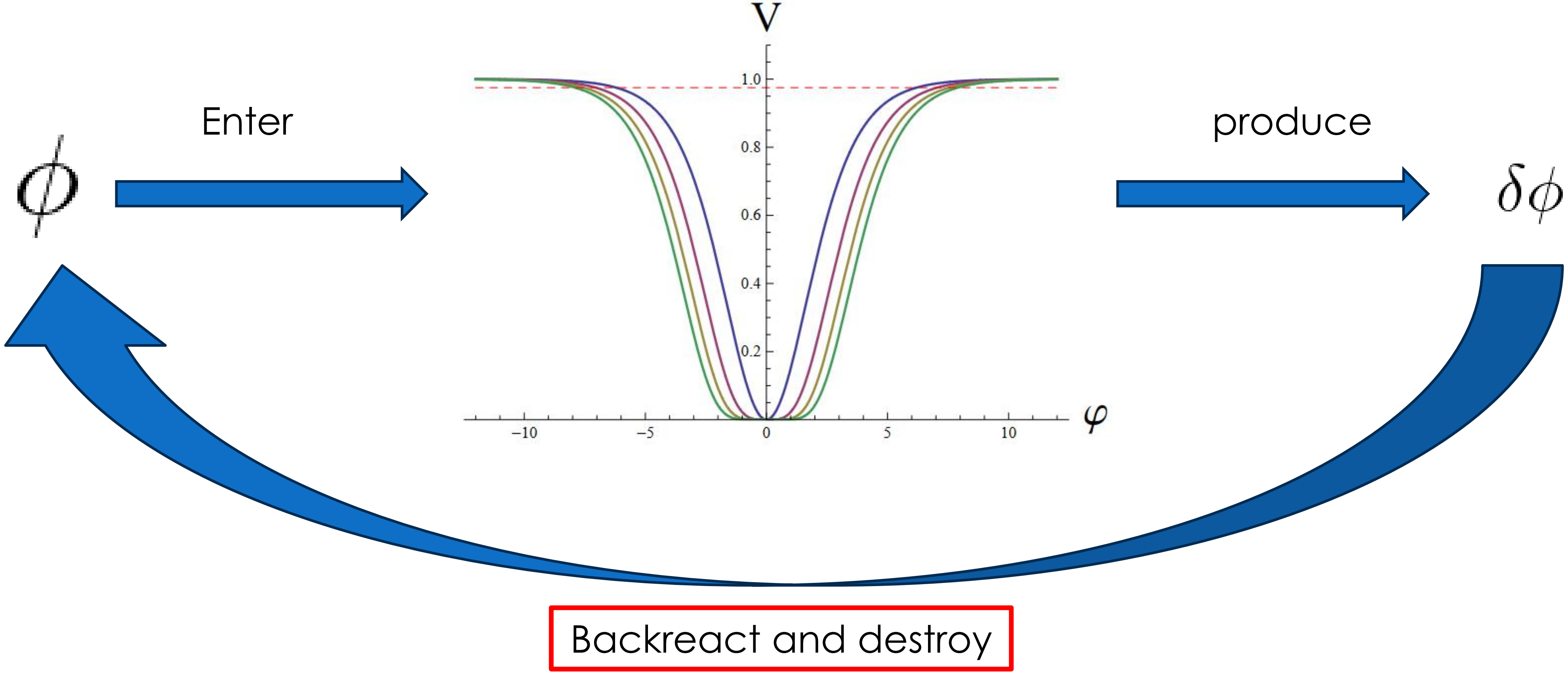
Up to first order

Valid until : $\delta\phi \sim \phi$ after that we need to solve the full non-linear dynamics

Fragmentation is the moment when the perturbation energy density take over the inflaton energy density.

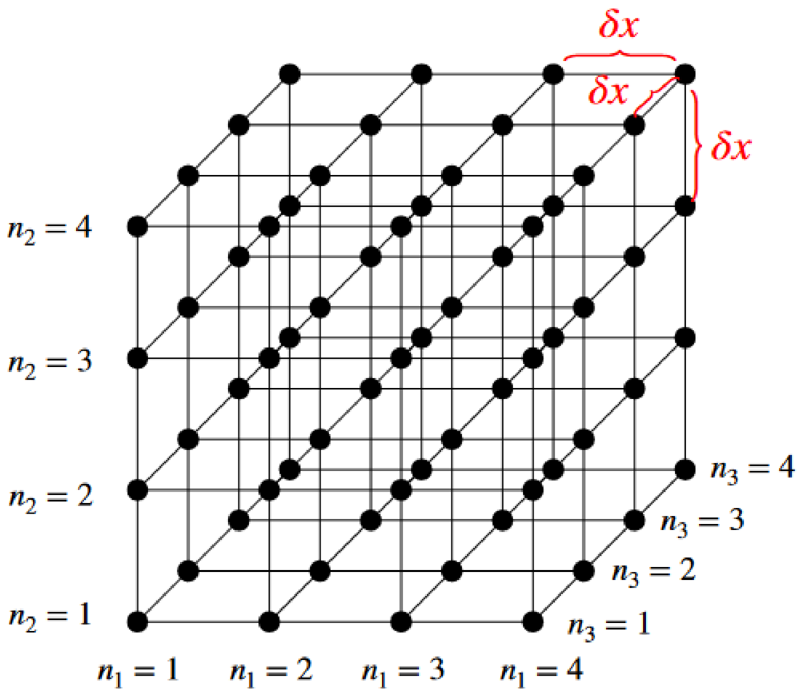
$$\rho_\phi = \overline{\frac{1}{2}\dot{\phi}^2 + \frac{1}{2a^2}(\nabla\phi)^2 + V(\phi)} \qquad \rho_{\bar{\phi}} = \frac{1}{2}\dot{\bar{\phi}}^2 + V(\bar{\phi}) \qquad \rho_\phi = \rho_{\bar{\phi}} + \rho_{\delta\phi}$$

What is fragmetation



Numerical Simulation

CosmoLattice

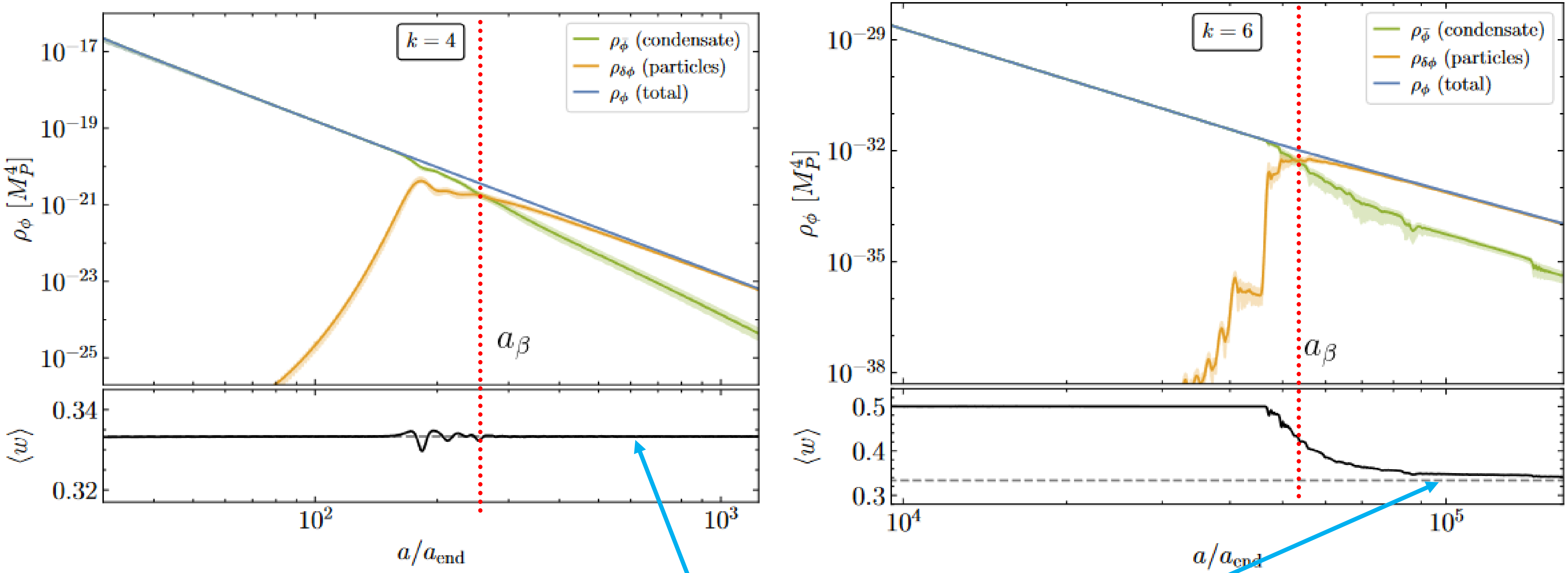


User Manual: arXiv:2102.01031v2

Review of the simulation techniques: arXiv:2006.15122v3

The following numerical results only take into account the self motion of the inflaton field

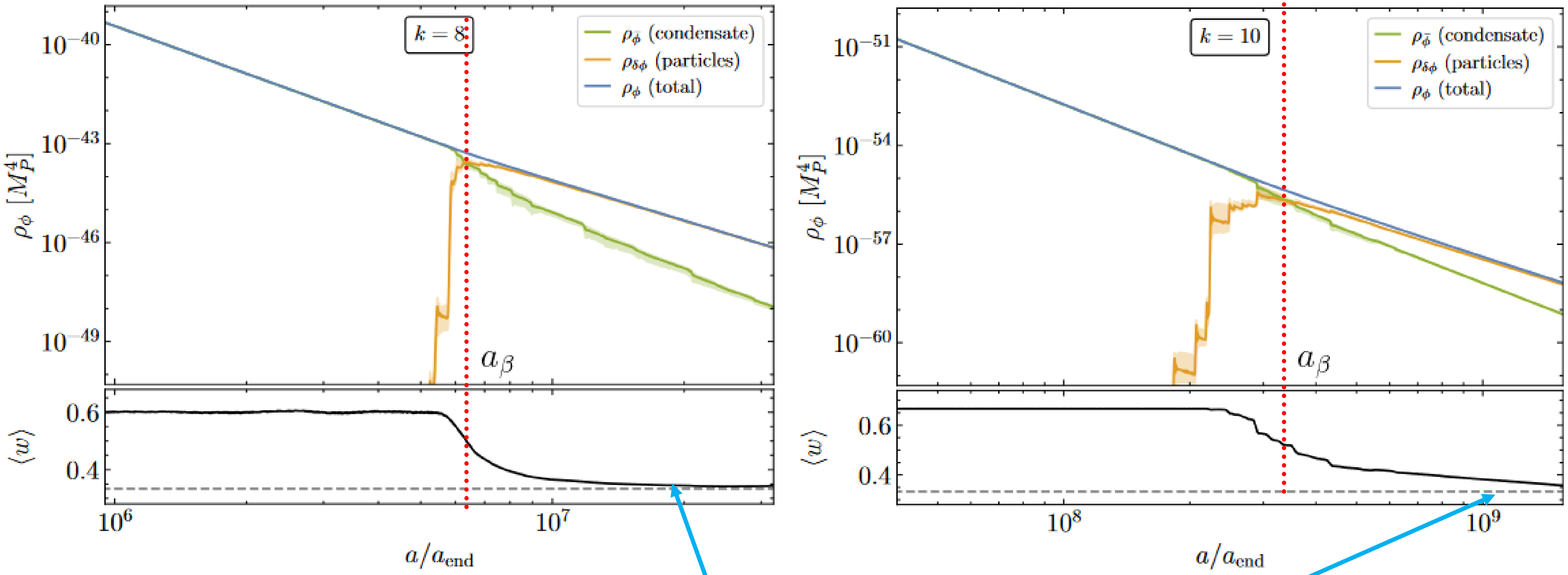
Simulation result



$w_\phi = \frac{1}{3}$ radiation (massless particles)

Energy density and equation of state parameter as a function of the scale factor for various power of the potential

Simulation result



$w_\phi = \frac{1}{3}$ radiation (massless particles)

Energy density and equation of state parameter as a function of the scale factor for various power of the potential

How to avoid fragmentation

$$\dot{\rho_\phi} + 3H(1+w_\phi)\rho_\phi = -(1+w_\phi)\Gamma\rho_\phi$$

$$\dot{\rho_R} + 4H\rho_R = (1+w_\phi)\Gamma\rho_\phi$$

$$H^2 = \frac{\rho_R + \rho_\phi}{3m_{pl}^2}$$

+

$$\Gamma_\phi = \begin{cases} \frac{y_{\rm eff}^2(k)}{8\pi} m_\phi(t) & \phi \to \bar{f}f \\ \frac{\mu_{\rm eff}^2(k)}{8\pi m_\phi(t)} & \phi \to bb \\ \frac{\sigma_{\rm eff}^2}{8\pi} \frac{\rho_\phi(t)}{m_\phi^3(t)} & \phi\phi \to bb. \end{cases}$$

Solve and require to reheat before fragmentaion

k	$y_{\rm eff}$	$\mu_{\rm eff}$	$\sigma_{\rm eff}$	$T_{\rm RH}$
4	1.61×10^{-1}	3.57×10^{10} GeV	3.57×10^{-6}	1.14×10^{13} GeV
6	1.58×10^{-2}	1.84×10^{5} GeV	5.37×10^{-10}	1.19×10^{10} GeV
8	1.32×10^{-3}	6.33×10^{-1} GeV	9.59×10^{-15}	1.50×10^{7} GeV
10	3.62×10^{-5}	1.49×10^{-6} GeV	6.47×10^{-20}	1.80×10^{4} GeV

Problematic?

Depending on the potential what are the allowed processes to produce matter in the early universe?

$$V(\phi) \implies \mathcal{L}_{int}\,?$$

Reheating after fragmentation

We define the energy ratio: $\xi \equiv \frac{\rho_{\bar{\phi}}}{\rho_{\delta\phi}}$ and compute the remaining energy tranfert using latice data.

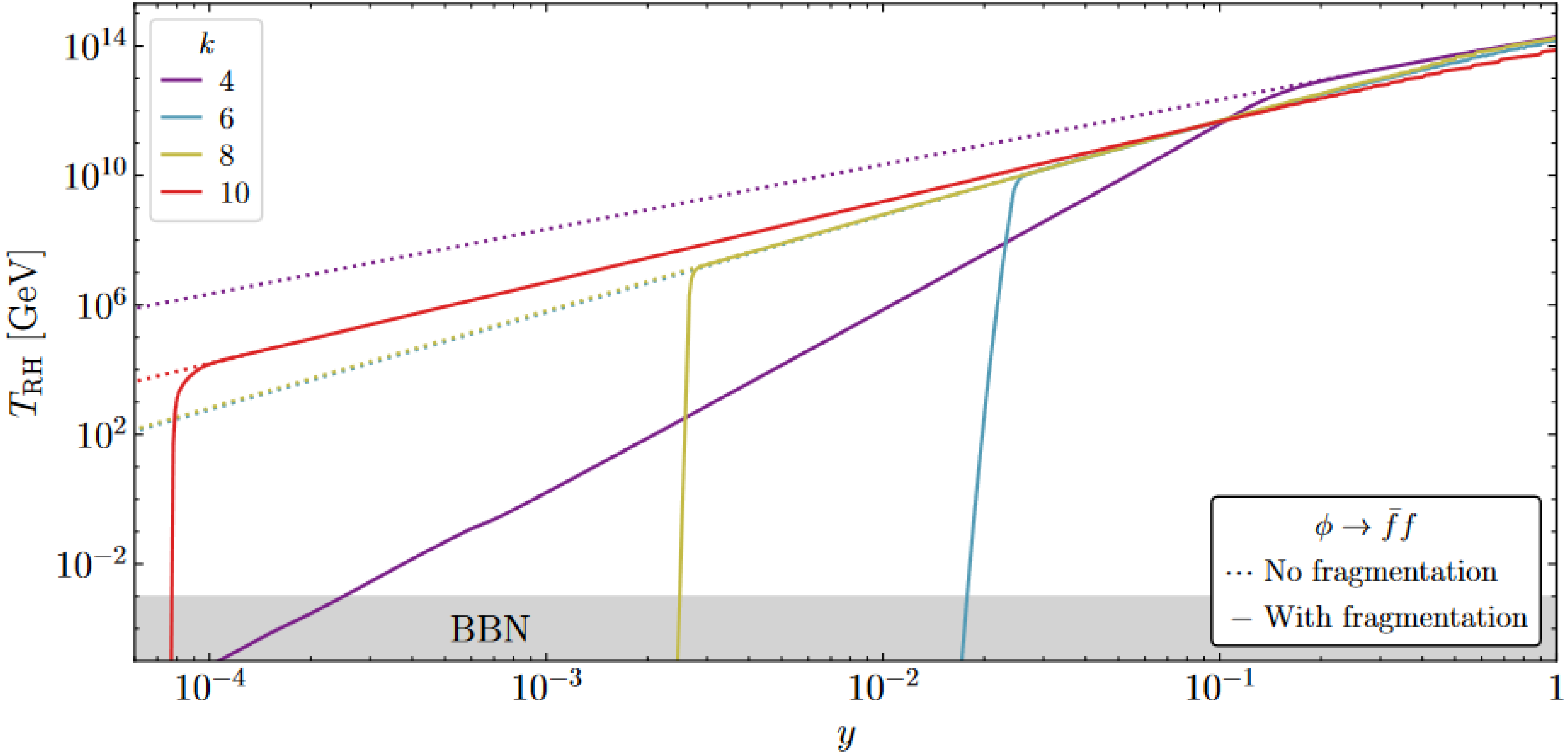
After fragmentation : $\begin{cases} \rho_{\bar{\phi}} \sim O(1\%) \\ \rho_{\delta\phi} \sim O(99\%) \end{cases}$

$\phi \to \bar{f} f$
$$T_{\rm RH}^{(\beta)} = \left(\frac{30}{g_\rho \pi^2}\right)^{\frac{1}{4}} M_P (\sqrt{3} c_k \xi^{\frac{k-2}{k}})^{\frac{k+2}{12(6-k)}} \left(\frac{\rho_{\rm end}}{M_P^4}\right)^{\frac{2k^2-12k+16}{12k(k-6)}} \beta^{-\frac{(k-2)(k-4)}{(k+2)(k-6)}}$$

$\phi \to bb$
$$T_{\rm RH}^{(\beta)} = \left(\frac{30}{g_\rho \pi^2}\right)^{\frac{1}{4}} M_P \left(\sqrt{3}\frac{\mu^2}{8\pi c_e M_P^2}\right)^{\frac{1}{3}}$$

$\phi\phi \to bb.$
$$T_{\rm RH}^{(\beta)} = M_P \left(\frac{30}{g_\rho \pi^2}\right)^{\frac{1}{4}} \left(\frac{\sigma^2 \tilde{c}\sqrt{3}}{8\pi}\right)$$

Reheating after fragmentation

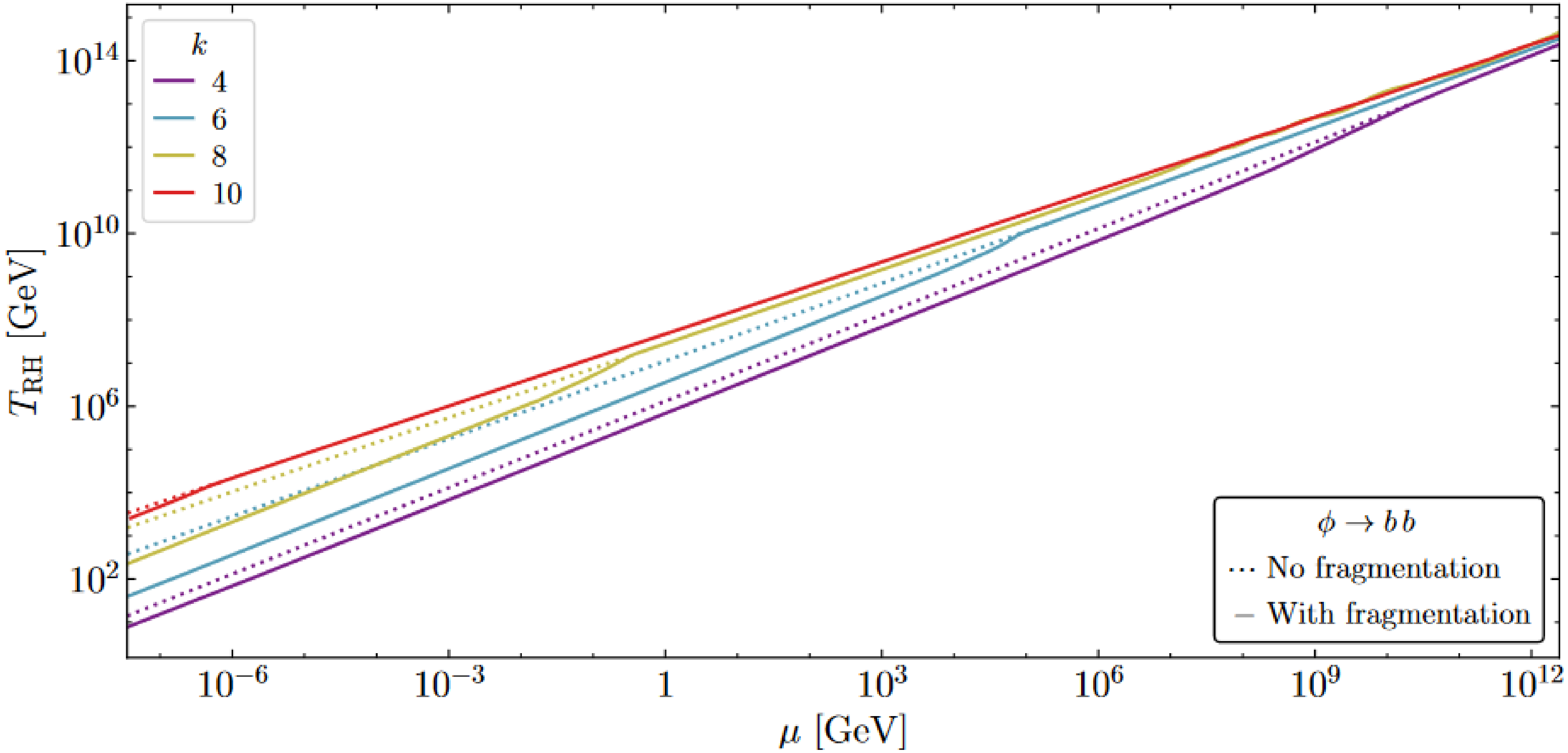


Reheating temperature as a function of the coupling for various power of the potential

arXiv:2308.16231v1

Fragmentation exclude reheating via decay to fermion if k>2

Reheating after fragmentation

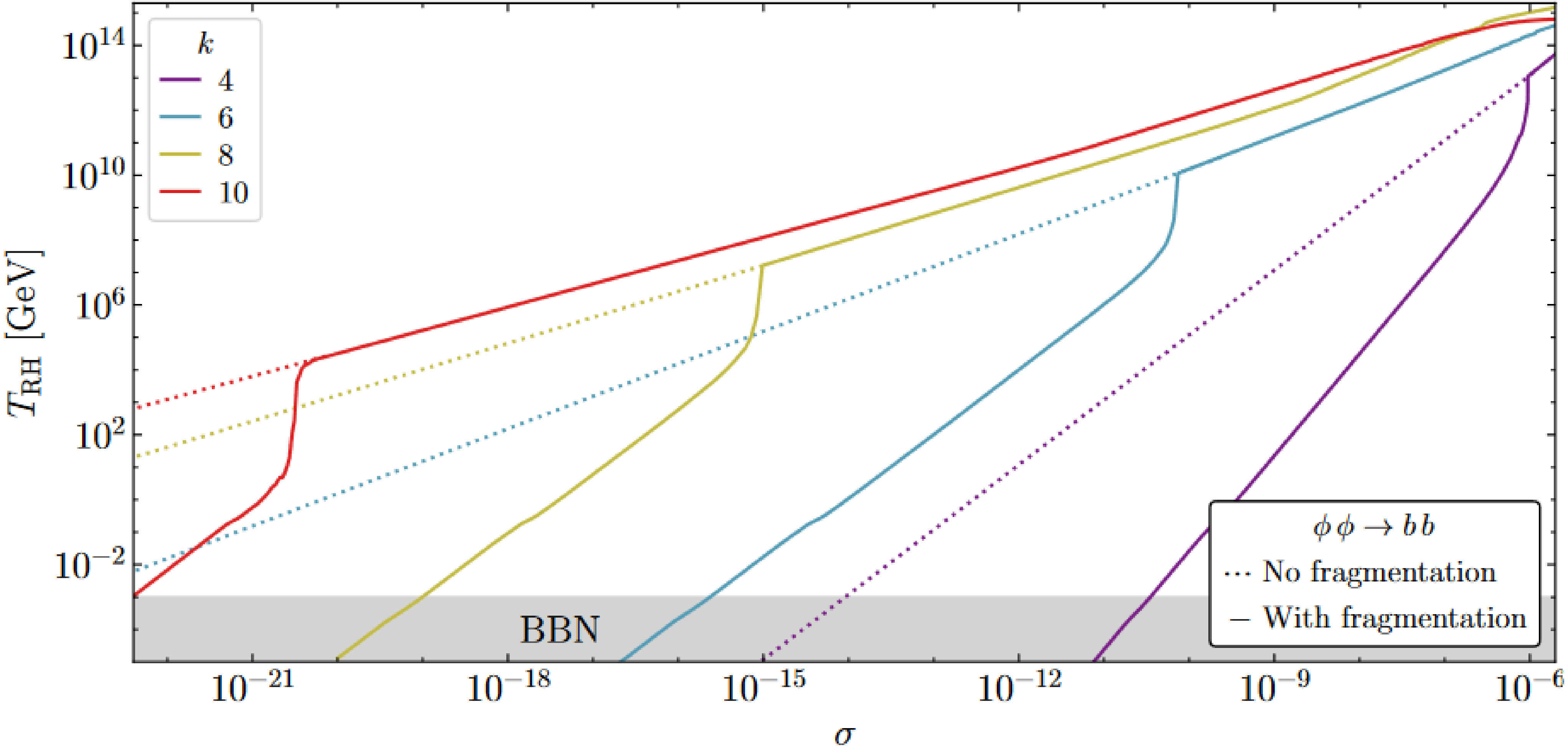


Reheating temperature as a function of the coupling for various power of the potential

arXiv:2308.16231v1

There is no fragmentation problem for decay to boson.

Reheating after fragmentation



Reheating temperature as a function of the coupling for various power of the potential

Fragmentation has an important effect for the bound on the minimum value required for the coupling

arXiv:2308.16231v1

Conclusion

- Non linearities in the early universe can produce a massive amount of perturbation leading to radiation dominated universe.
- The pertubations affects the processes that produce matter and add constrains for reheating to happend in a specific way depending on the model

Thank you!

Backup slides

All from: arXiv:2308.16231v1

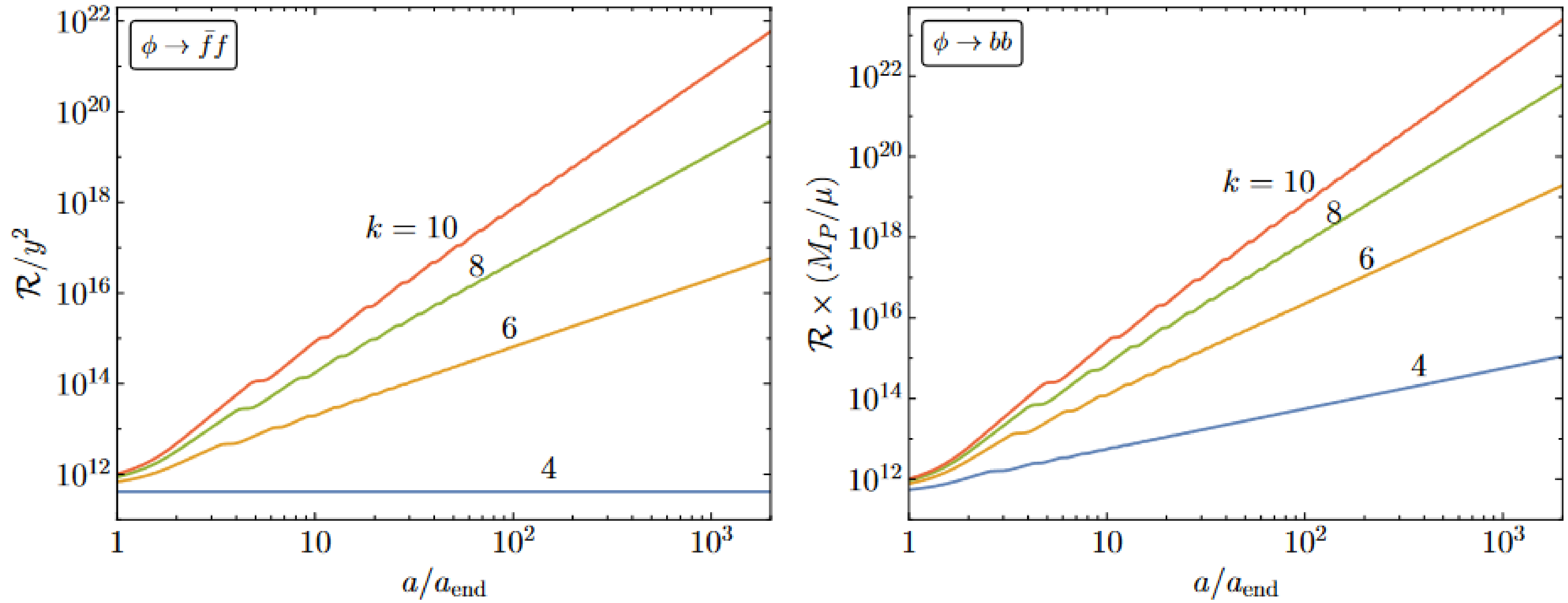


Figure 2: Kinematic parameter $\mathcal{R}$ as a function of the scale factor, for $k = 4, 6, 8, 10$. Left: fermionic decays. The channel $\phi\phi \to bb$ can be recovered from these results upon changing $y^2 \to 2\sigma$. Right: bosonic decays.

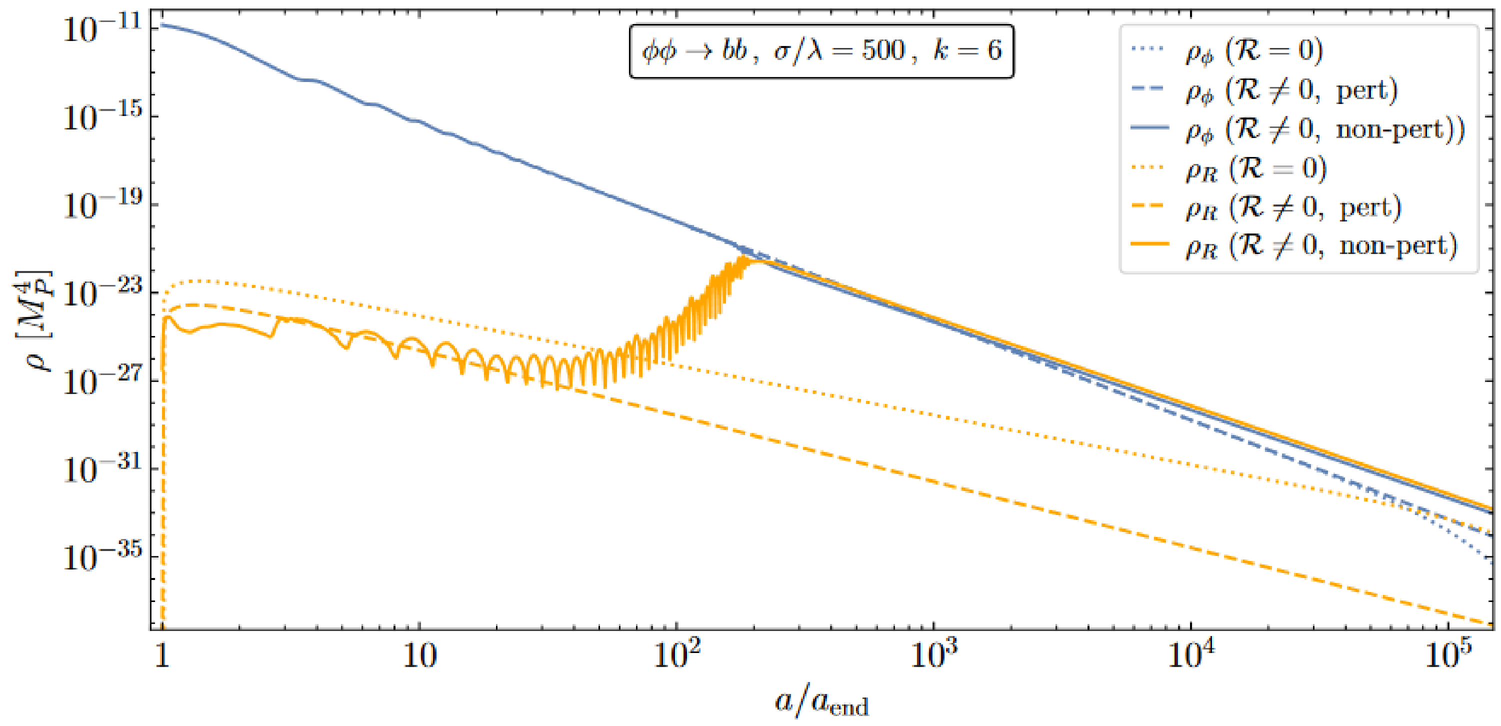


Figure 3: Dependence on the induced mass $m_{\rm eff}$ of the inflaton and radiation energy densities, for the $\phi\phi \to bb$ decay channel. The solid lines are computed by matching results using the Hartree approximation prior to strong parametric resonance to results from a lattice simulation for the backreaction regime.