Effects of Fragmentation on Post-Inflationary Reheating

Mathieu Gross, RPP 2024 meeting, Jussieu 24/01/2024

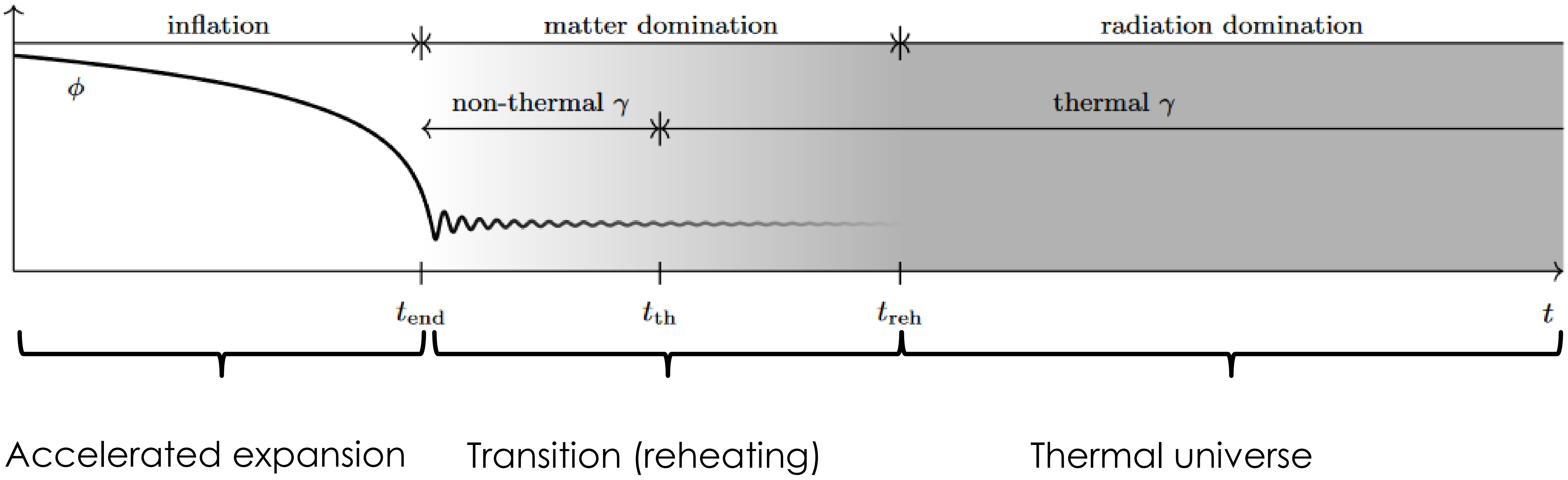
Based on

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

Content

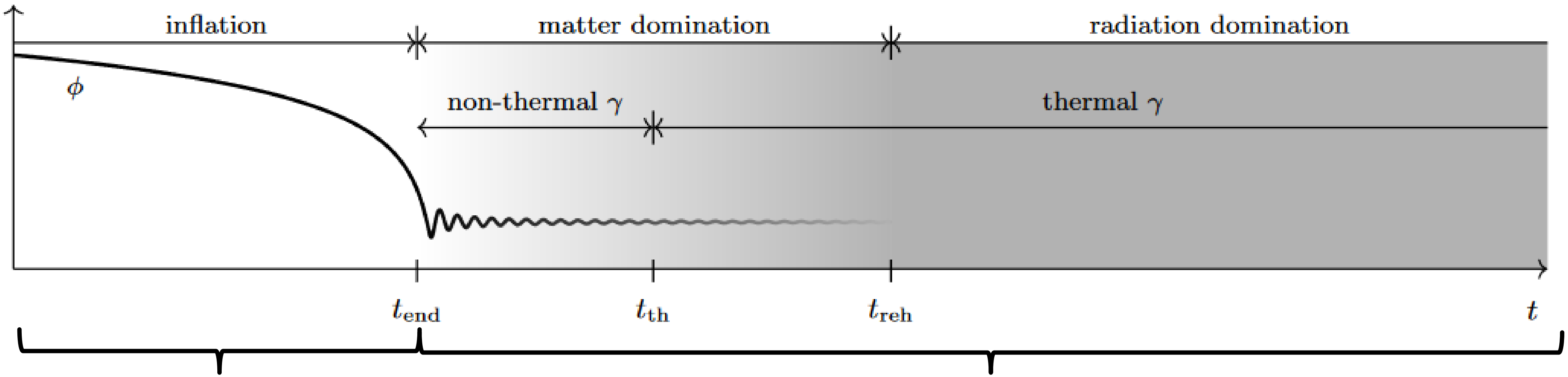
- Introduction: The standard reheating
- What is fragmentation?
- Numerical result and implications

Introduction



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

Introduction



Production of particles/Dark matter

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

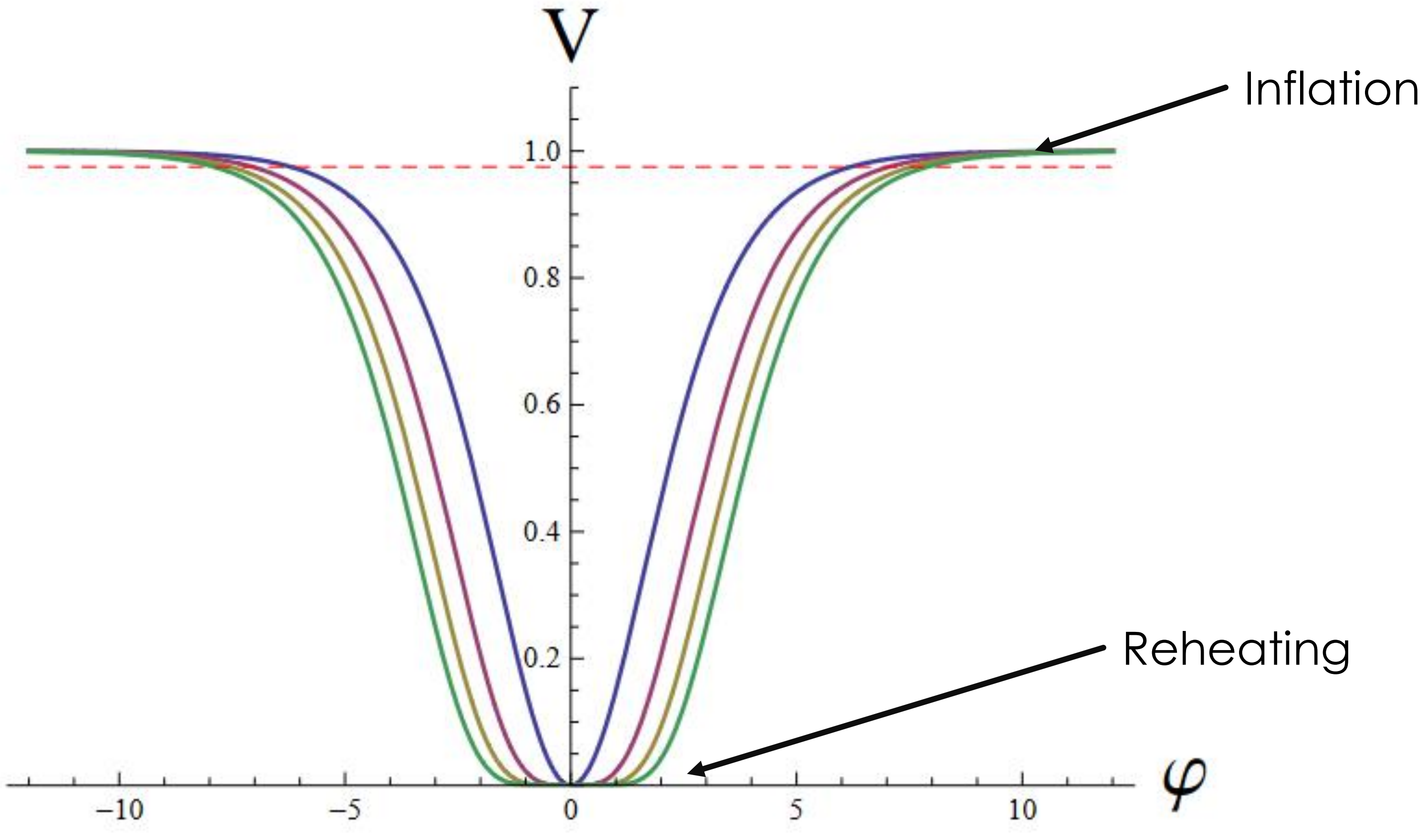
$$\mathcal{L} \supset \begin{cases} y\phi \bar{f} f & \phi \to \bar{f} f \\ \mu \phi b b & \phi \to bb \\ \sigma \phi^2 b^2 & \phi\phi \to bb \end{cases}$$

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

Usual treatment

Equation of motion for the homogeneous field

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

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

Friedman's equations:

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

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

Equation of state parameter:

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

What is fragmentation?

$$\phi(t,x) = \bar{\phi}(t) + \delta\phi(t,x)$$

$$\ddot{\phi} - \frac{\Delta\phi}{a^2} + 3H\phi + V_{,\phi}(\phi) = 0$$

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

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.

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

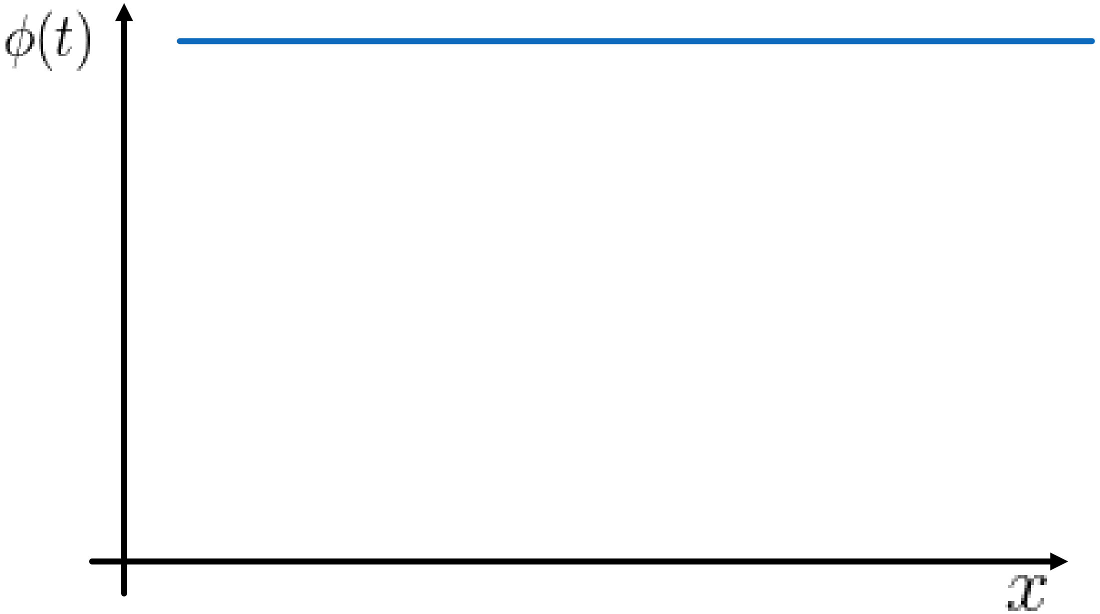
$$\rho_{\bar{\phi}} = \frac{1}{2}\dot{\bar{\phi}}^2 + V(\bar{\phi})$$

$$\rho_\phi = \rho_{\bar{\phi}} + \rho_{\delta\phi}$$

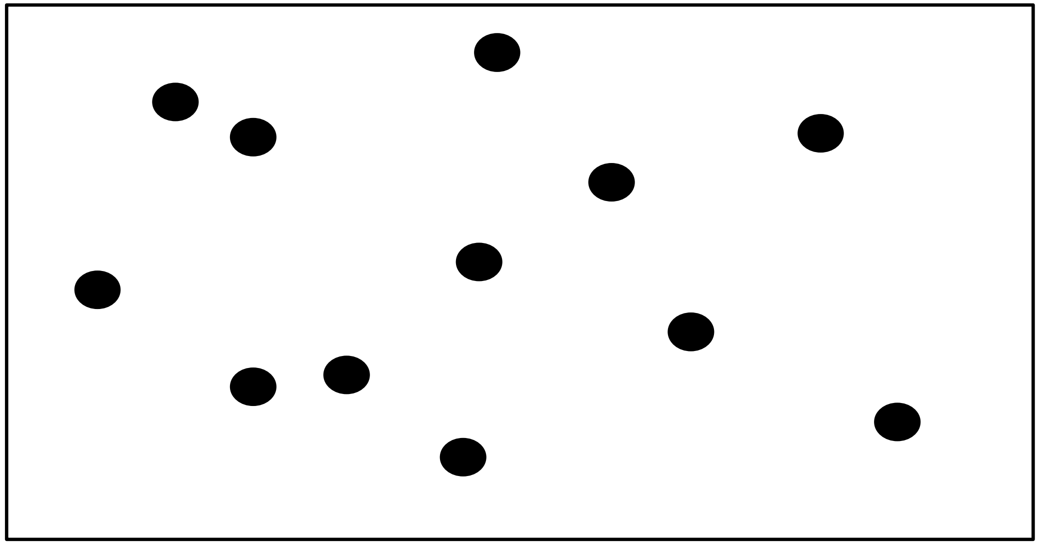
Condensate or particles ?

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

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

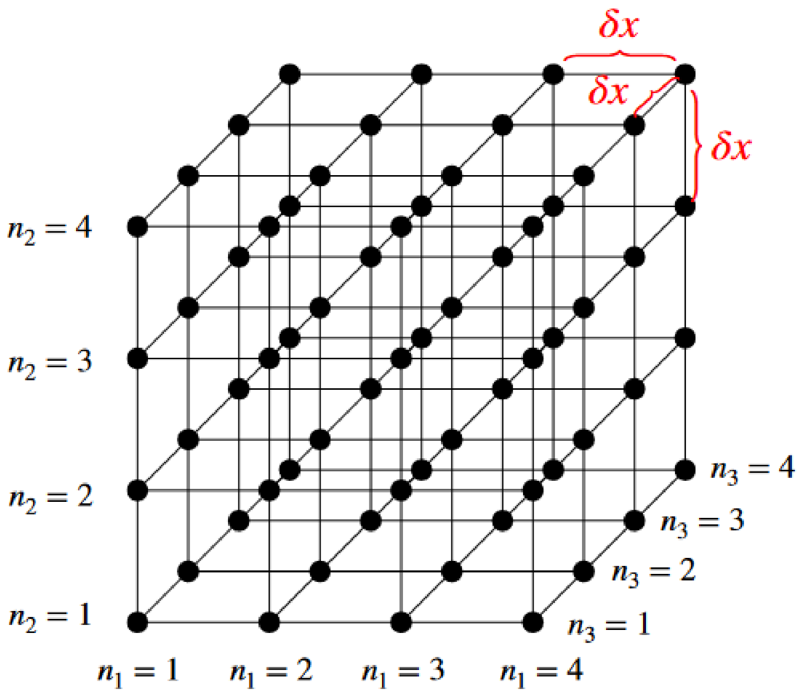


Particle: Non homogeneous quantum field (usual particles)



Numerical Simulation

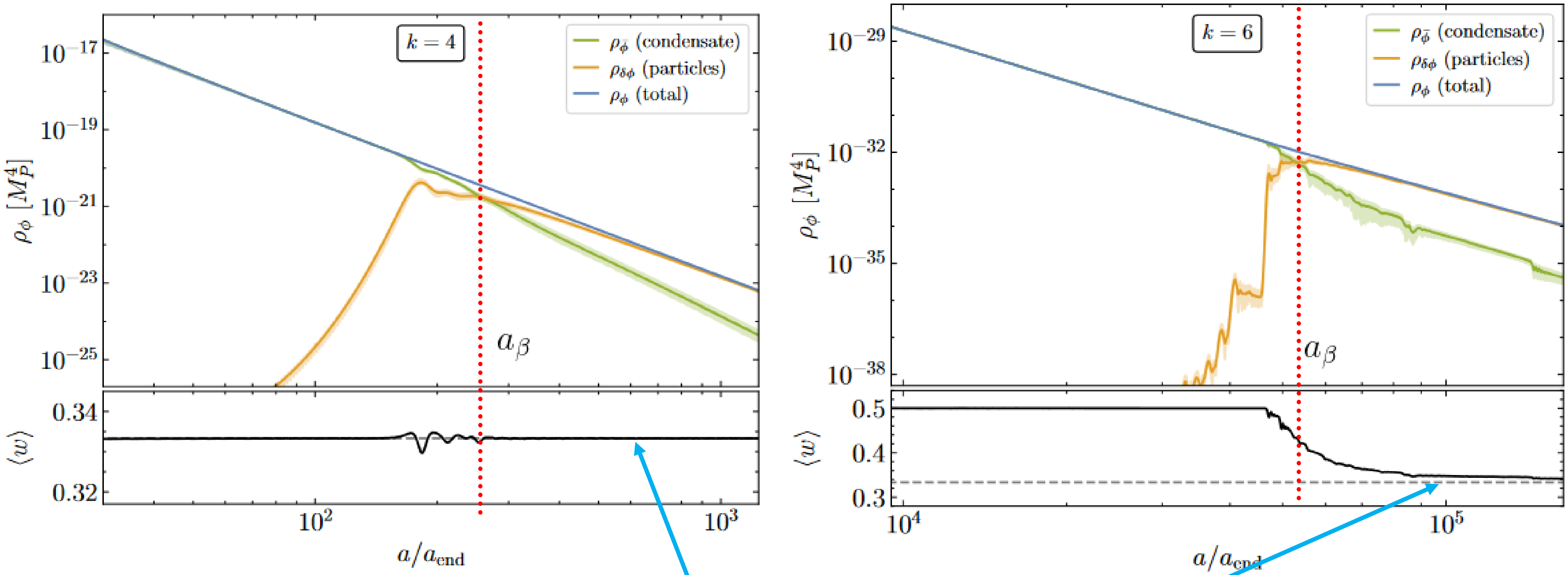
CosmoLattice



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

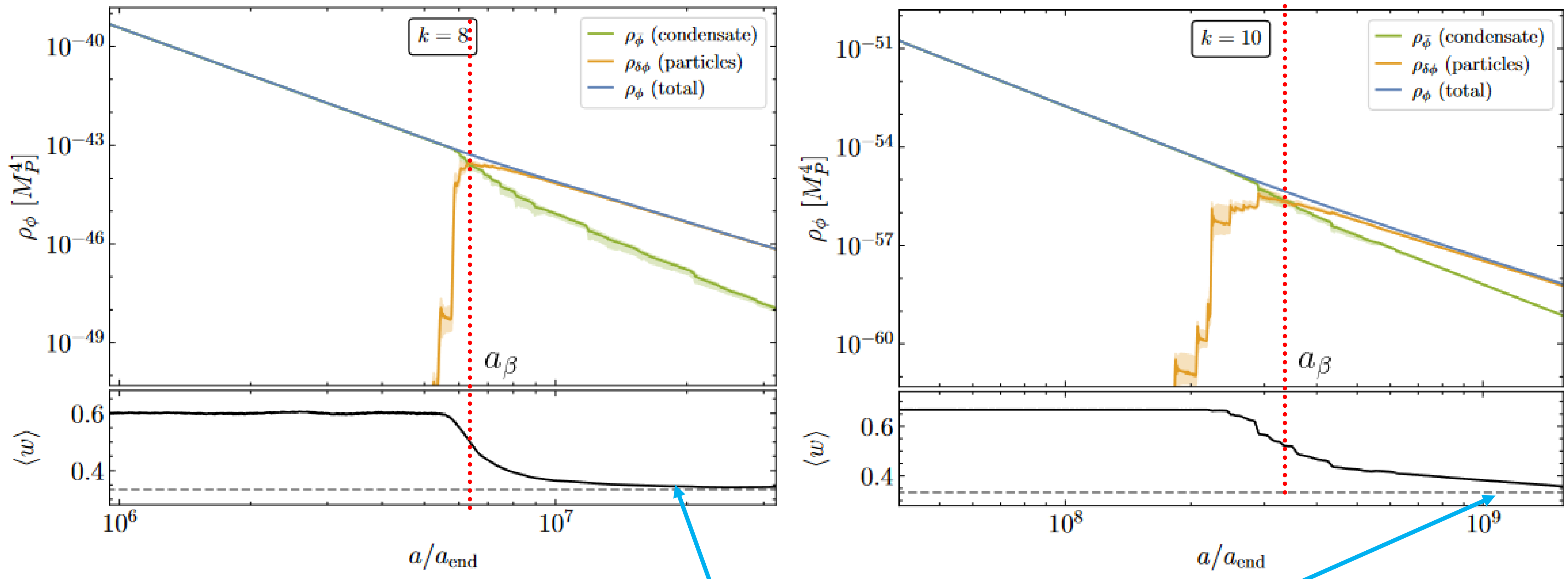
Simulation result



$w_\phi = \frac{1}{3}$ 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)

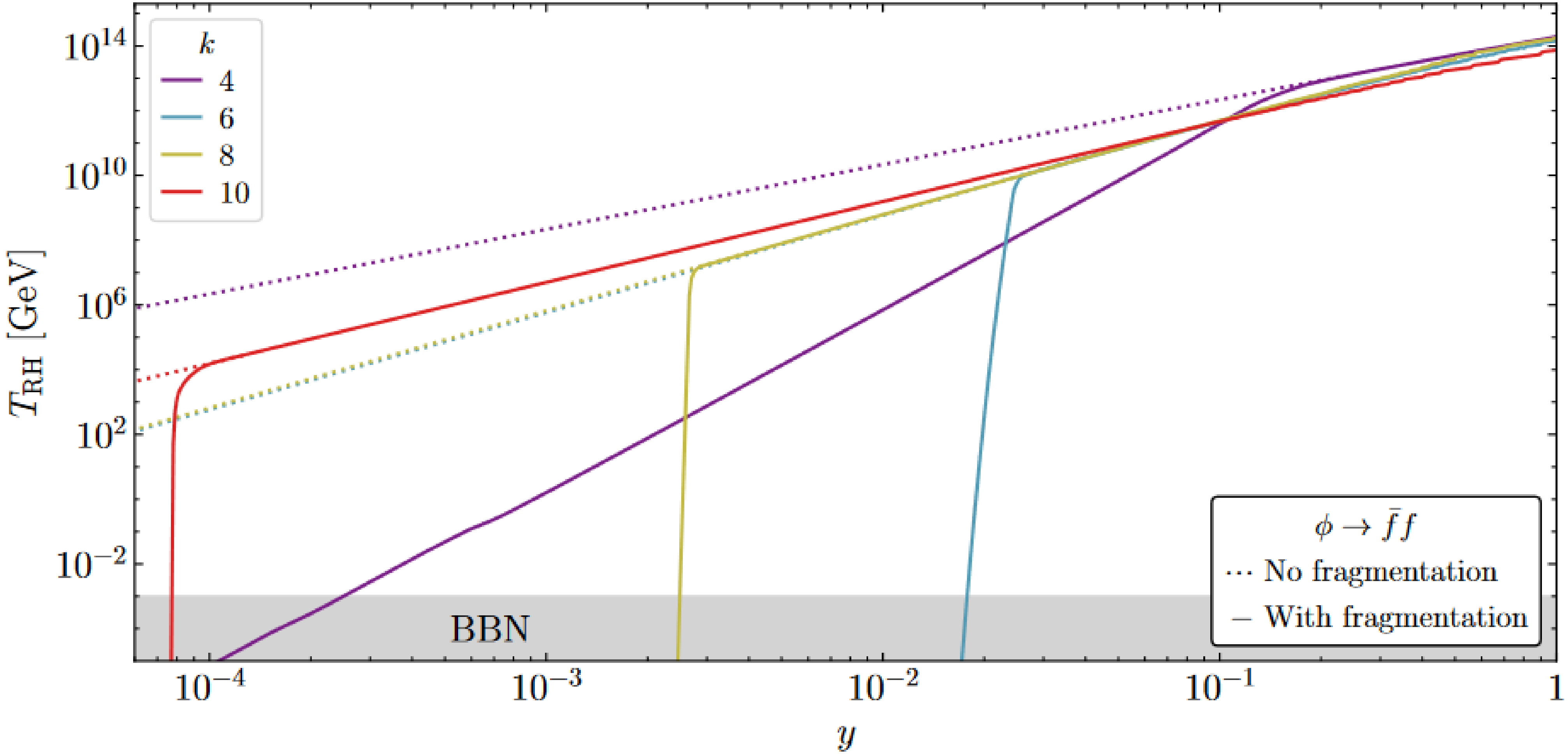
Energy density and equation of state parameter as a function of the scale factor for various power of the potential

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

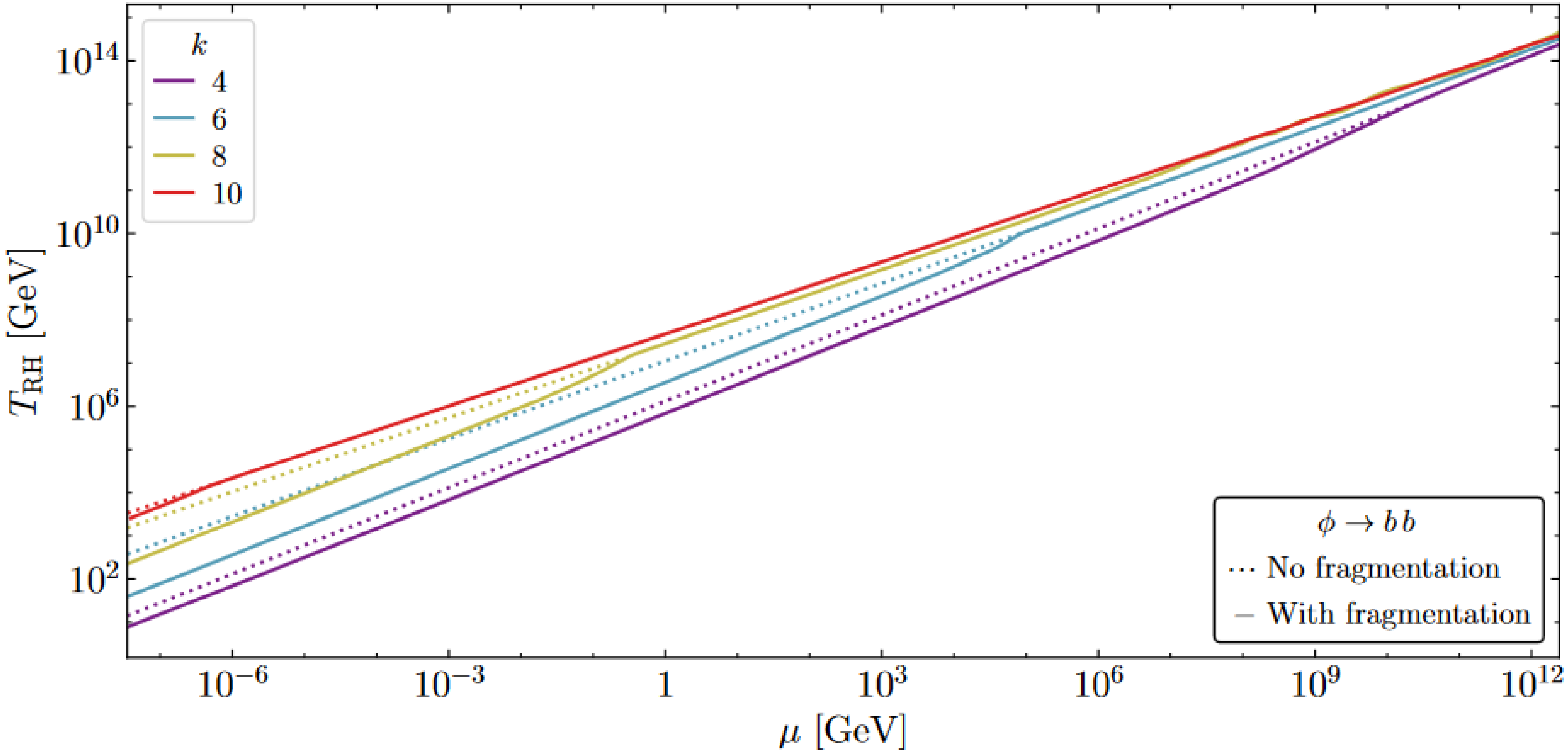


Reheating temperature as a function of the coupling for various power of the potential

arXiv:2308.16231v1

Fragmentation exclude reheating via decay to fermion if k>2

Reheating after fragmentation

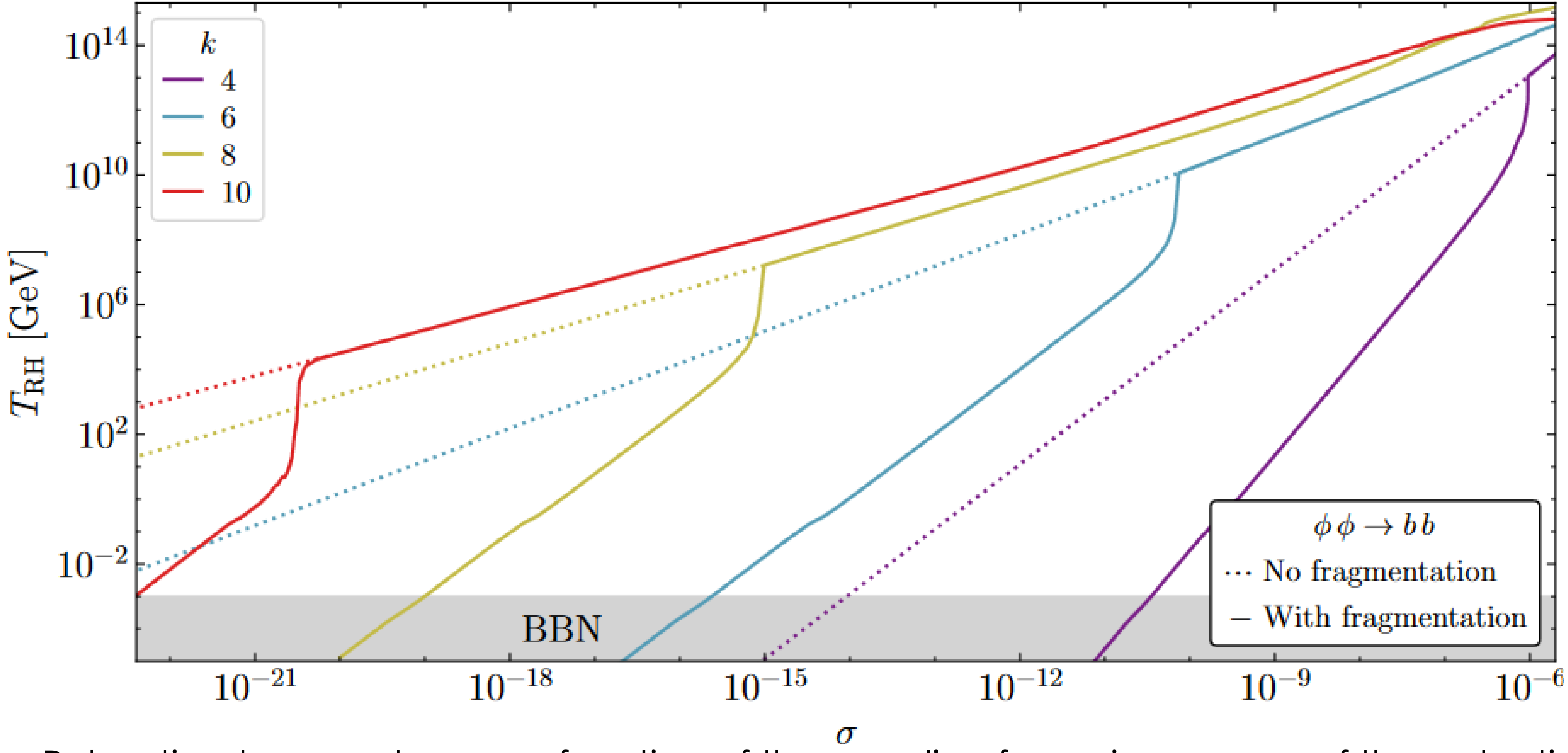


Reheating temperature as a function of the coupling for various power of the potential

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

$$\Gamma_\phi = \gamma_\phi \left(\frac{\rho_\phi}{M_P^4} \right)^l ,$$

$$\gamma_\phi = \begin{cases} \sqrt{k(k-1)}\lambda^{1/k} M_P \frac{y_{\rm eff}^2}{8\pi} , & \phi \to \bar{f} f , \\ \frac{\mu_{\rm eff}^2}{8\pi\sqrt{k(k-1)}\lambda^{1/k} M_P} , & \phi \to bb , \\ \frac{\sigma_{\rm eff}^2 M_P}{8\pi[k(k-1)]^{3/2}\lambda^{3/k}} , & \phi\phi \to bb , \end{cases}$$

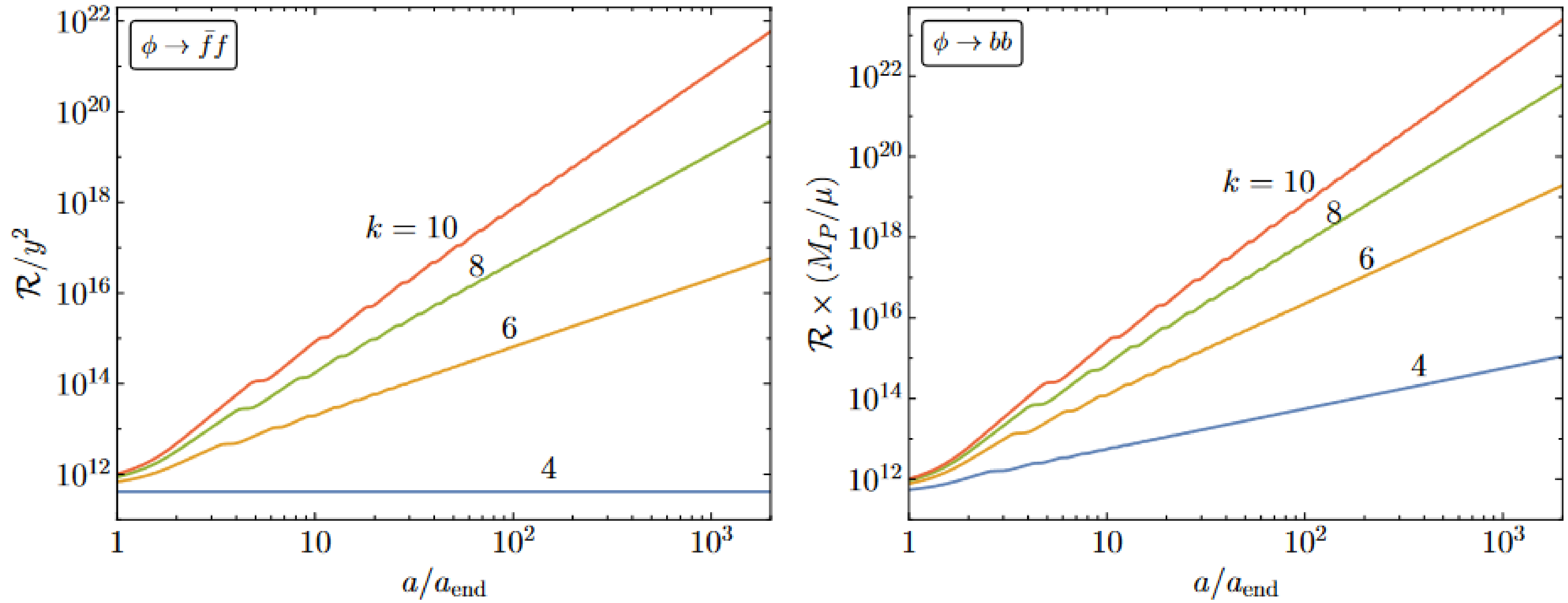


Figure 2: Kinematic parameter $\mathcal{R}$ as a function of the scale factor, for $k = 4, 6, 8, 10$. Left: fermionic decays. The channel $\phi\phi \to bb$ can be recovered from these results upon changing $y^2 \to 2\sigma$. Right: bosonic decays.

$$m_{\text{eff}}^2(t) \equiv \begin{cases} y^2\phi^2\,, & \phi \to \bar{f}f\,, \\ 2\mu\phi\,, & \phi \to bb\,, \\ 2\sigma\phi^2\,, & \phi\phi \to bb\,. \end{cases}$$

$$\mathcal{R} \equiv \frac{8}{\pi k^2 \lambda} \left(\frac{\Gamma(\frac{1}{k})}{\Gamma(\frac{1}{2} + \frac{1}{k})} \right)^2 \times \begin{cases} y^2 \left(\frac{\phi_0(t)}{M_P} \right)^{4-k}\,, & \phi \to \bar{f}f\,, \\ 2\frac{\mu}{M_P} \left(\frac{\phi_0(t)}{M_P} \right)^{3-k}\,, & \phi \to bb\,, \\ 2\sigma \left(\frac{\phi_0(t)}{M_P} \right)^{4-k}\,, & \phi\phi \to bb\,, \end{cases}$$

In the case of fermionic decays, or scattering depletion, the decay rate acquires a correction $\Gamma_\phi \propto \mathcal{R}^{-1/2}$ if $\mathcal{R} \gg 1$, resulting in a reduced efficiency of the inflaton decay. On the other hand, for $\phi \to bb$, due to the tachyonic nature of the effective mass of b during half of the inflaton oscillation, an enhancement of the dissipation rate appears, $\Gamma_\phi \propto \mathcal{R}^{1/2}$ for $\mathcal{R} \gg 1$.

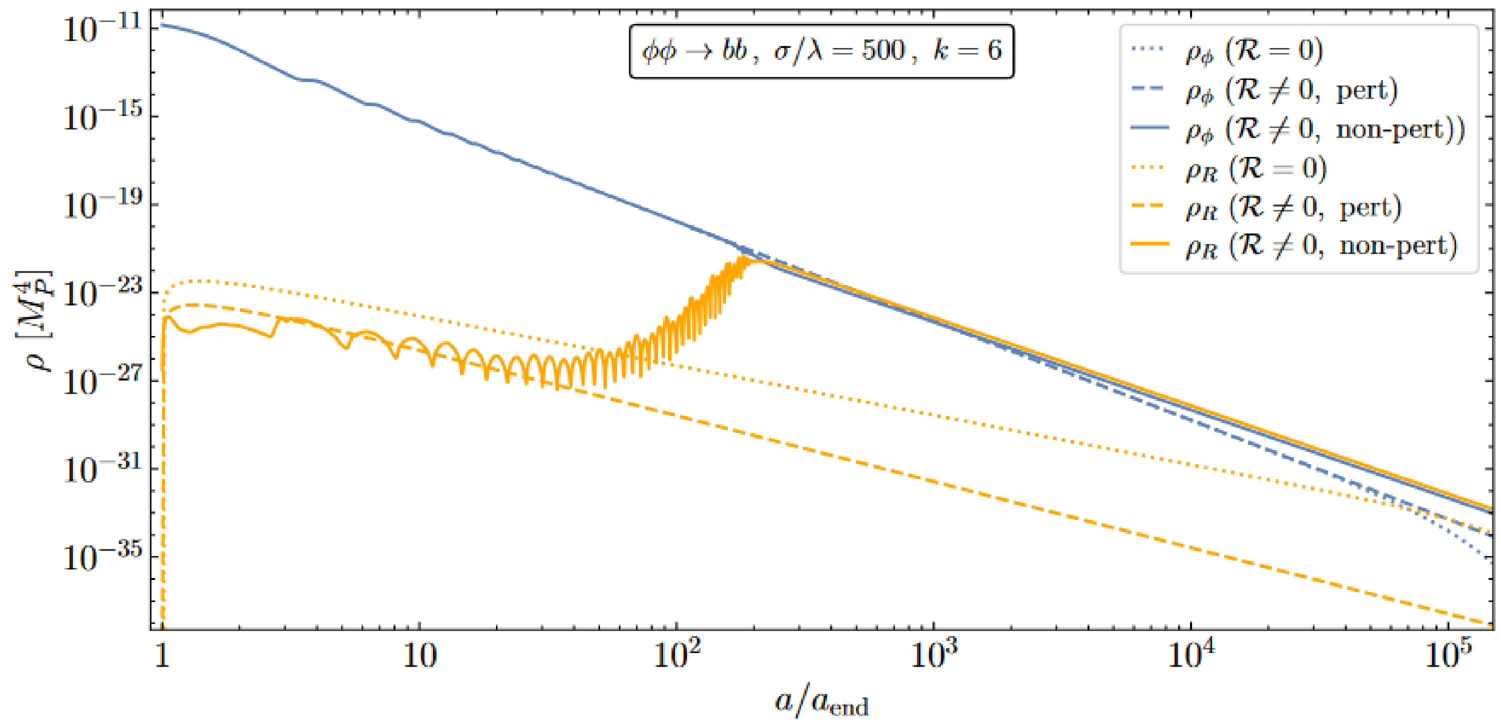


Figure 3: Dependence on the induced mass $m_{\rm eff}$ of the inflaton and radiation energy densities, for the $\phi\phi \to bb$ decay channel. The solid lines are computed by matching results using the Hartree approximation prior to strong parametric resonance to results from a lattice simulation for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