Effects of a bare mass term on the reheating process

Simon Cléry

Astroparticle Symposium 2024

SC, Marcos A. G. Garcia, Yann Mambrini, Keith A. Olive, *Bare mass effects on the reheating process after inflation*, PRD (2024), arXiV:**2402.16958**

Introduction

Exact shape of inflaton potential around minimum, at the end of inflation, is quite unknown

➤ $V(\phi \ll M_P)$ can be approximated by some polynomial function of ϕ

➤ e.g Starobinsky includes a leading quadratic term $V(\phi \ll M_P) \sim m_\phi^2 \phi^2$ and a full serie of interaction terms suppressed after inflation

➤ *T* **α**-attractors models exhibits a leading monomial term $\boxed{V(\phi \ll M_P) \sim \lambda \phi^k M_P^{4-k}}$ for some self coupling λ and integer parameter k

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But, we cannot prevent the existence of a bare mass term $\boxed{\frac{1}{2} m_\phi^2 \phi^2}$

➤ May be present at tree level or may be generated radiatively

Inflaton mixed potential

We look at **mixed potential** after inflation, of the form

$$V(\phi \ll M_P) \sim \lambda \, \phi^k \, M_P^{4-k} + \frac{1}{2} m_\phi^2 \, \phi^2$$

- ➢ Consider *T* α-attractors as a benchmark with a subdominant mass term at the end of inflation

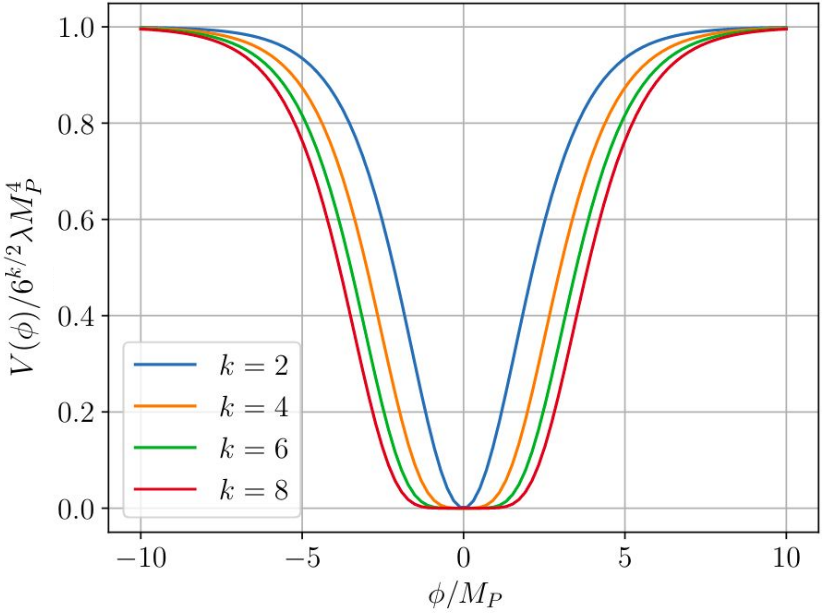
$$\lambda \phi_{\text{end}}^k M_P^{4-k} \gg \frac{1}{2} m_\phi^2 \phi_{\text{end}}^2$$

- ➢ Subsequent evolution can lead to the transition $\phi^k \to \phi^2$ during the oscillating regime

$$w_\phi = \frac{k-2}{k+2} \to 0$$

- ➢ Can drastically affect the reheating process

CMB constraints



T α-attractor potential

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

$$N_* \simeq \frac{1}{M_P^2}\int_{\phi_{\rm end}}^{\phi_*} \frac{V(\phi)}{V'(\phi)}d\phi \simeq \int_{\phi_{\rm end}}^{\phi_*} \frac{1}{\sqrt{2\epsilon}}\frac{d\phi}{M_P} \simeq \frac{3}{2k}\cosh\left(\sqrt{\frac{2}{3}}\frac{\phi_*}{M_P}\right)$$

$$A_{S*} \simeq \frac{V_*}{24\pi^2\epsilon_* M_P^4} \simeq \frac{6^{\frac{k}{2}}}{8k^2\pi^2}\lambda\sinh^2\left(\sqrt{\frac{2}{3}}\frac{\phi_*}{M_P}\right)\tanh^k\left(\frac{\phi_*}{\sqrt{6}M_P}\right)$$

➤ Constrained by the measurement of CMB scalar power spectrum

$$\lambda \simeq \frac{18\pi^2 A_{S*}}{6^{k/2}N_*^2}$$

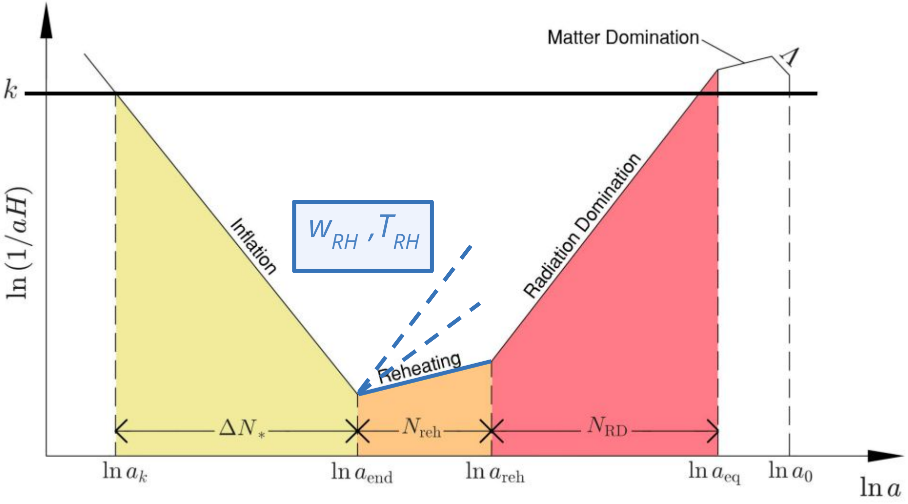
We focus on the mixed potential with $k=4$ and generalize some of the discussion to arbitrary k

CMB constraints

Determine N_* coherently from reheating temperature and average EoS

$$N_* = \ln\left[\frac{1}{\sqrt{3}}\left(\frac{\pi^2}{30}\right)^{1/4}\left(\frac{43}{11}\right)^{1/3}\frac{T_0}{H_0}\right] - \ln\left(\frac{k_*}{a_0 H_0}\right) + \frac{1}{4}\ln\left(\frac{V_*^2}{M_P^4 \rho_{\rm end}}\right) + \frac{1-3w_{\rm int}}{12(1+w_{\rm int})}\ln\left(\frac{\rho_{\rm RH}}{\rho_{\rm end}}\right) - \frac{1}{12}\ln g_{\rm reh}$$

$k = 4$ provides $N_\star = 56$ and $\lambda = 3.3 \times 10^{-12}$ independently of reheating



From *(P)reheating Effects of the Kähler Moduli Inflation I Model*, Islam Khan, Aaron C. Vincent and Guy Worthey, **2111.11050**

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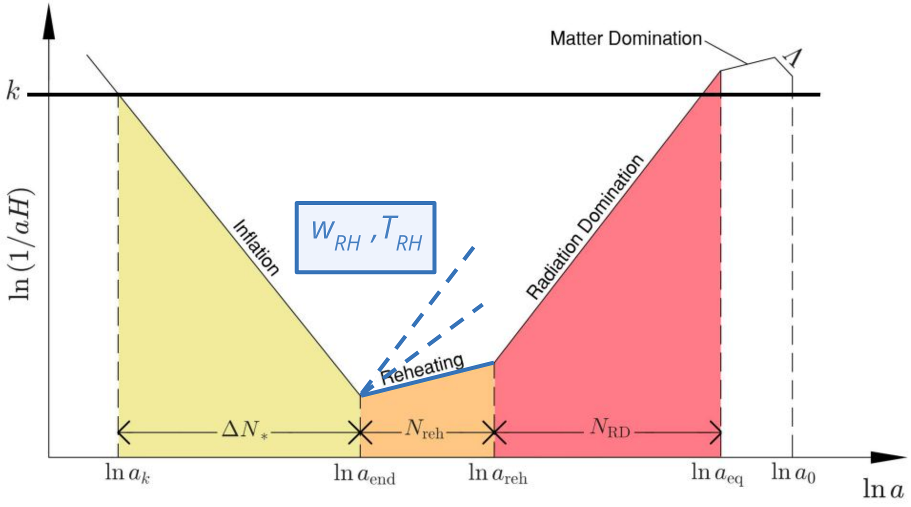

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➤ Bare mass term is subdominant at the end of inflation for $m_\phi \lesssim 9.3 \times 10^{12}\,\mathrm{GeV}$

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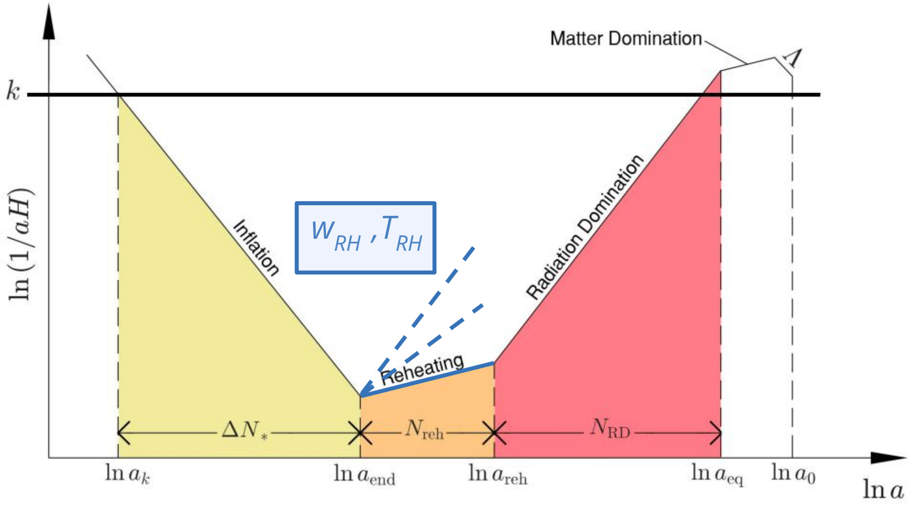
$$n_s = 1 - 6\epsilon_* + 2\eta_*$$
$$r = 16\epsilon_*$$



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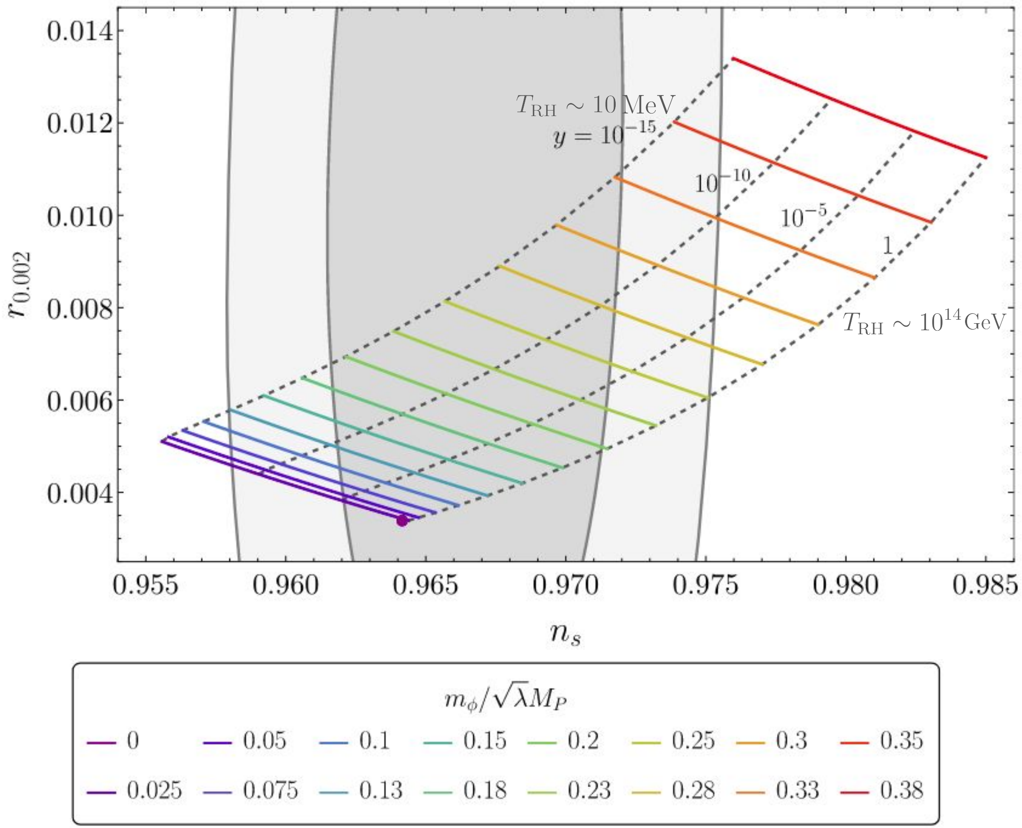
- ➤ Presence of a bare mass term can still importantly modify inflaton dynamics
- ➤ Change the equation of state during reheating $w_\phi = \frac{1}{3} \to 0$ as $\phi^4 \to \phi^2$

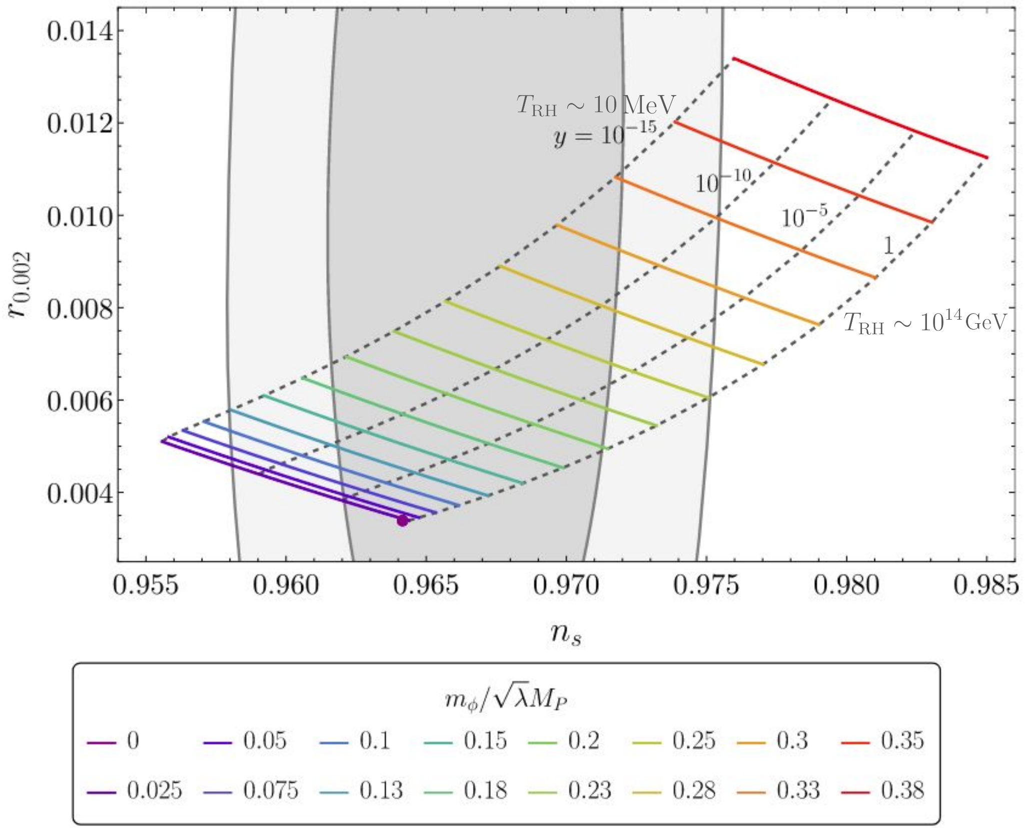
CMB constraints



$$V(\phi) = \lambda M_P^4 \left[\sqrt{6}\tanh\left(\frac{\phi}{\sqrt{6}M_P}\right)\right]^4 + \frac{1}{2}m_\phi^2\,\phi^2$$

- ➤ Larger m_ϕ increases overall n_s and r
- ➤ A matter domination induces a $T_{\rm RH}$ dependence of $N_\star$
- ➤ In this case: larger $T_{\rm RH}$ induces lower r but larger n_s

CMB constraints



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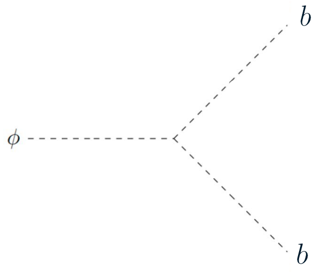
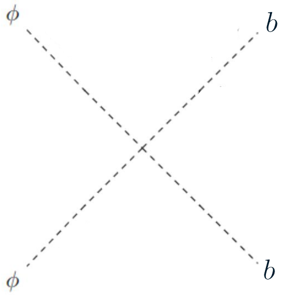
➤ In this case: larger $T_{\rm RH}$ induces lower r but larger n_s

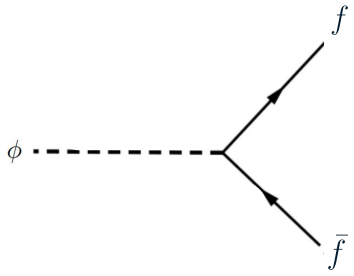
$$m_\phi < 1.6 \times 10^{12}\ {\rm GeV}$$

Inflaton couplings

$$\mathcal{L} \supset -\mu\,\phi\,b^2 \;-\sigma\,\phi^2\,b^2 \;-y\,\phi\,f\,\bar{f}$$







$$\Gamma_{\phi b^2} = \frac{\mu_{\text{eff}}^2}{8\pi m_{\phi(t)}}$$

$$\Gamma_{\phi^2 b^2} = \frac{\sigma_{\text{eff}}^2}{8\pi}\frac{\rho_\phi}{m_{\phi(t)}^3}$$

$$\Gamma_{\phi\to\bar{f}f} = \frac{y_{\text{eff}}^2}{8\pi} m_{\phi(t)}$$

- ➤ $m_\phi^2(t) = V''(\phi(t))$ time dependent inflaton effective mass
- ➤ **Effective couplings** from oscillations average of decay rates
- ➤ Time dependent **effective masses of final state particles** induced by the couplings

Impact of $\phi^k \to \phi^2$ on Reheating

$$\frac{1}{2}m_\phi^2\phi_0^2(a_m) = \lambda M_P^{4-k}\phi_0^k(a_m)$$

Impact of $\phi^k \rightarrow \phi^2$ on Reheating

$$\frac{1}{2}m_\phi^2\phi_0^2(a_m) = \lambda M_P^{4-k}\phi_0^k(a_m)$$

$$\rho_\phi \propto a^{-3}$$

$$\rho_\phi \propto a^{-6k/k+2}$$

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$$\rho_\phi \propto a^{-3}$$

$$\rho_\phi \propto a^{-6k/k+2}$$

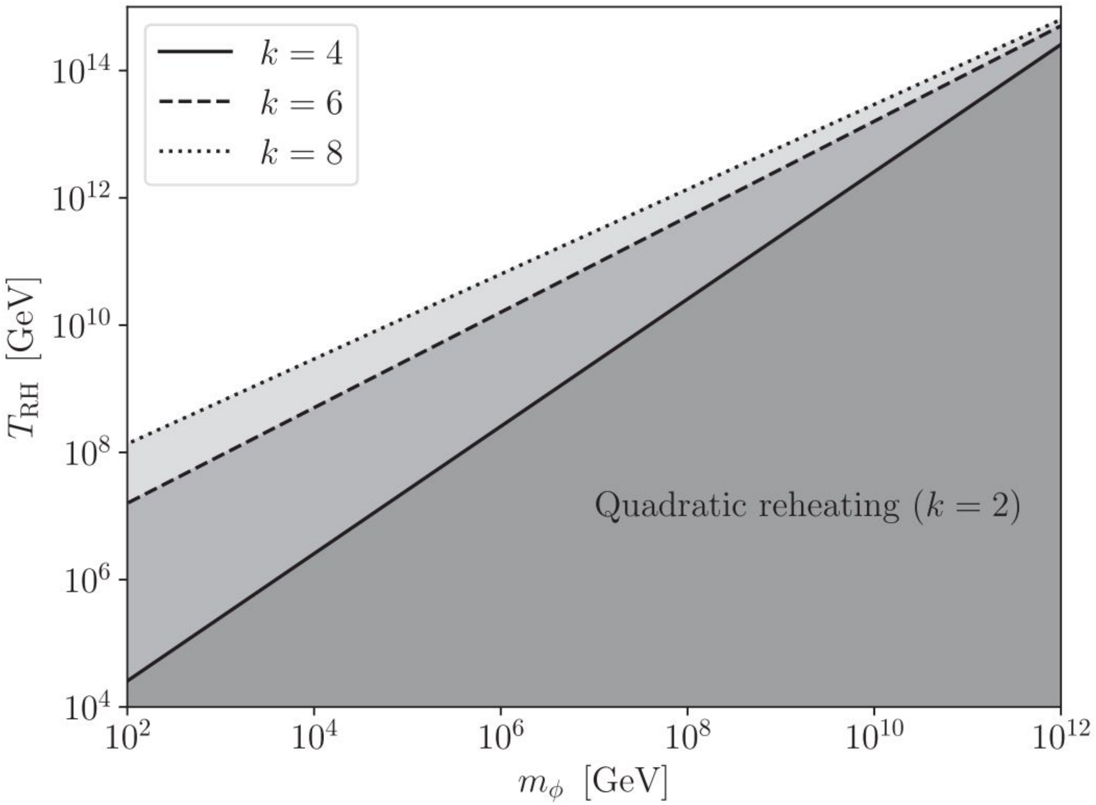
$$\rho_\phi(a_m) = 2\left(\frac{m_\phi^2}{2}\right)^{\frac{k}{k-2}} \lambda^{\frac{-2}{k-2}} M_P^{\frac{2(k-4)}{k-2}}$$

transition to a matter dominated era

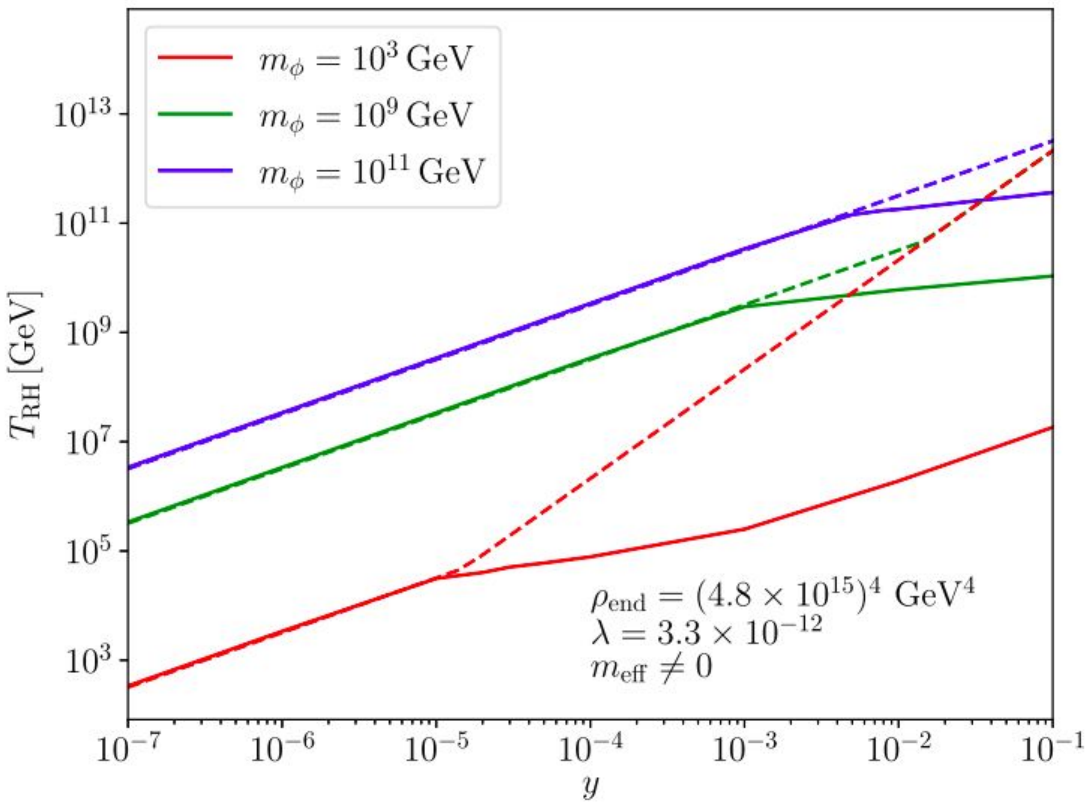
Impact of $\phi^k \to \phi^2$ on Reheating

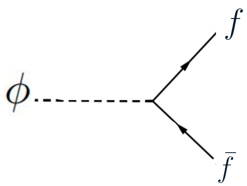
$$T_{\rm RH} \lesssim \left(\frac{1}{\alpha}\right)^{\frac{1}{4}} \left(\frac{m_\phi M_P^{\frac{k-4}{k}}}{(2\lambda)^{\frac{1}{k}}}\right)^{\frac{k}{2(k-2)}}$$

➤ Reheating happens in quadratic potential for large bare mass or low reheating temperature



Impact of $\phi^4 \to \phi^2$ on Reheating





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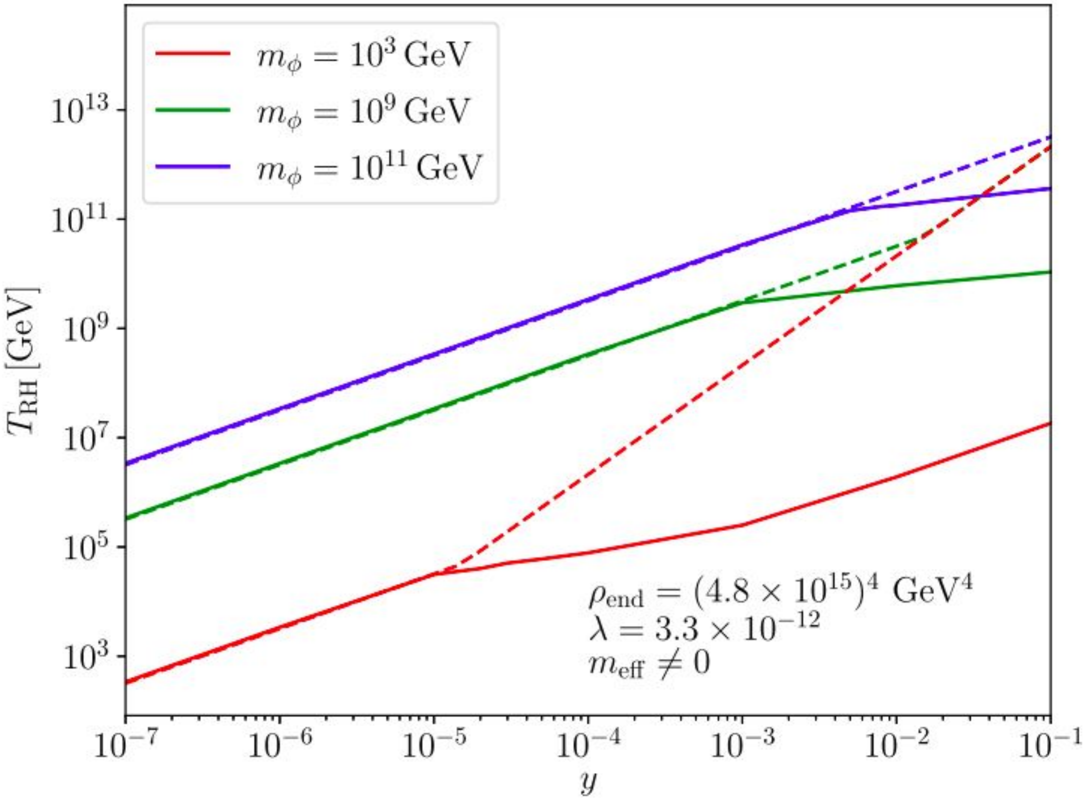
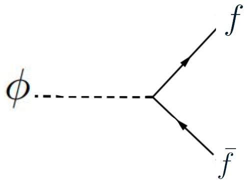




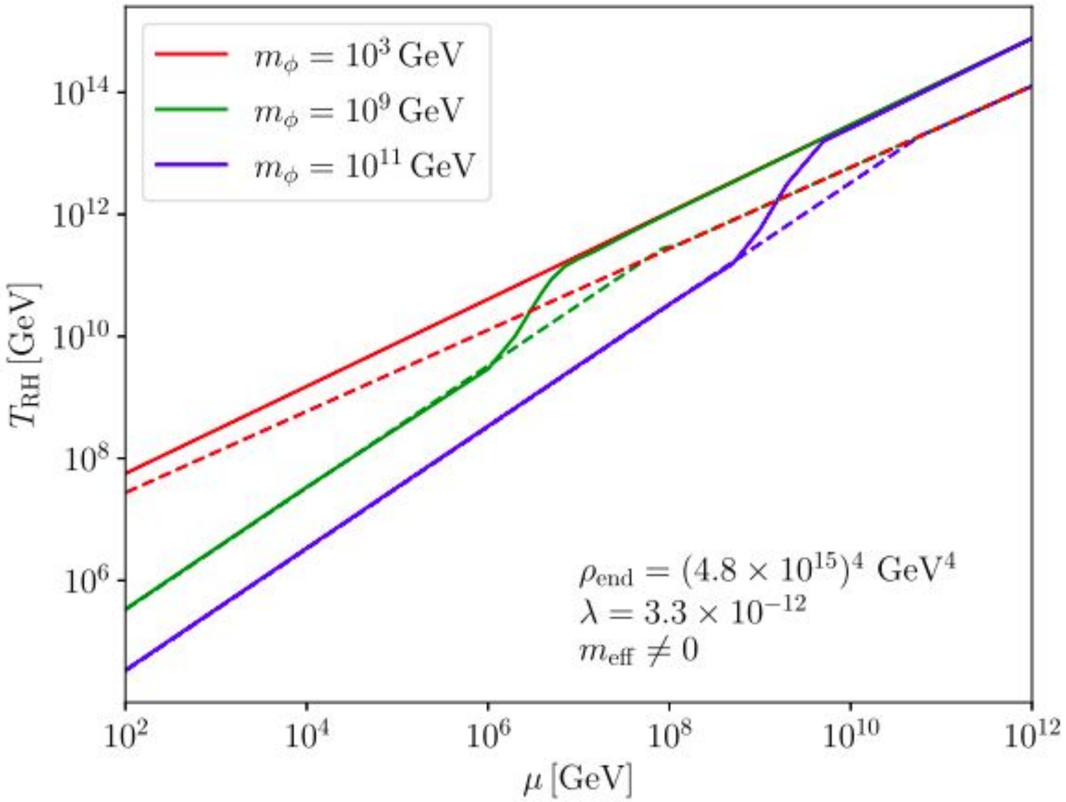
➢ low y : reheating in the **quadratic potential** with **no suppression** from effective mass of fermions

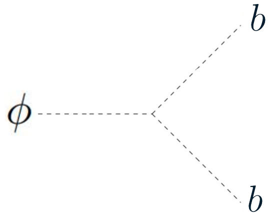
➢ larger y : effective mass **suppression**, reheating still takes place **in quadratic potential**

➢ largest y : effective mass **suppression,** reheating occurs either in **quadratic (large m_ϕ)** or **quartic (low m_ϕ)**

➢ larger m_ϕ leads to larger $T_{\rm RH}$ in quadratic potential

Impact of $\phi^4 \to \phi^2$ on Reheating





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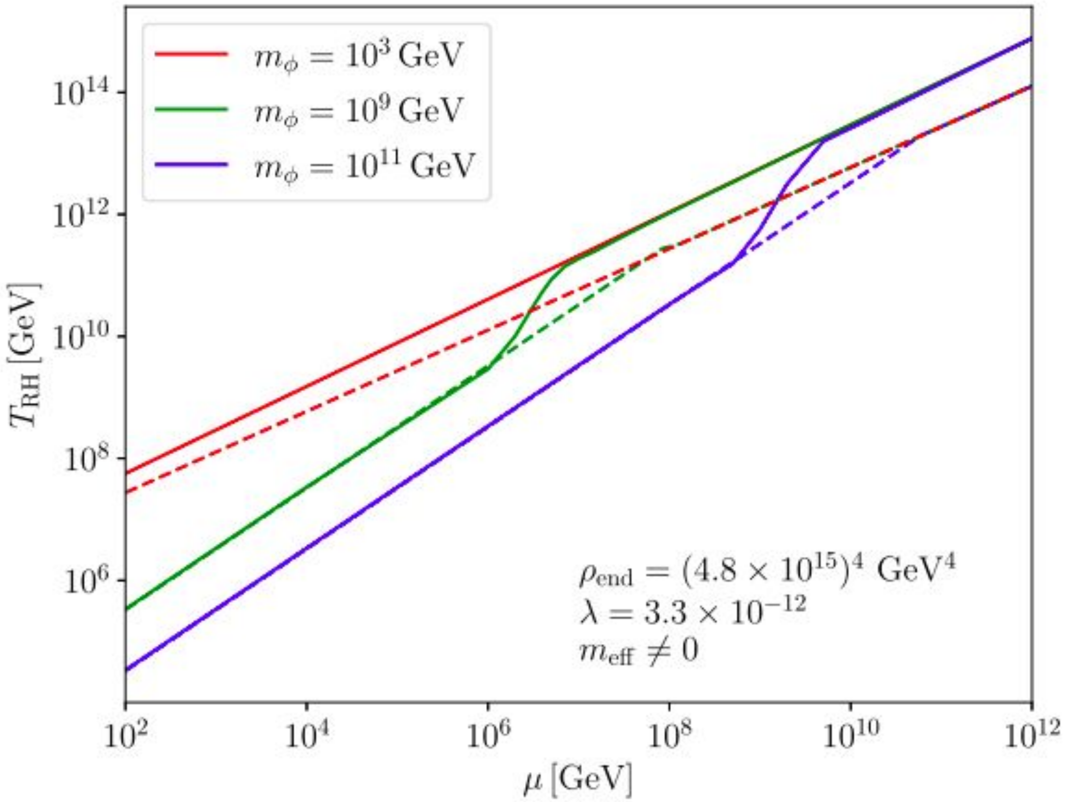
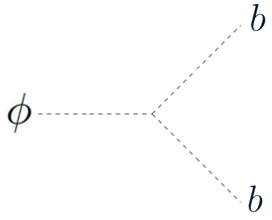




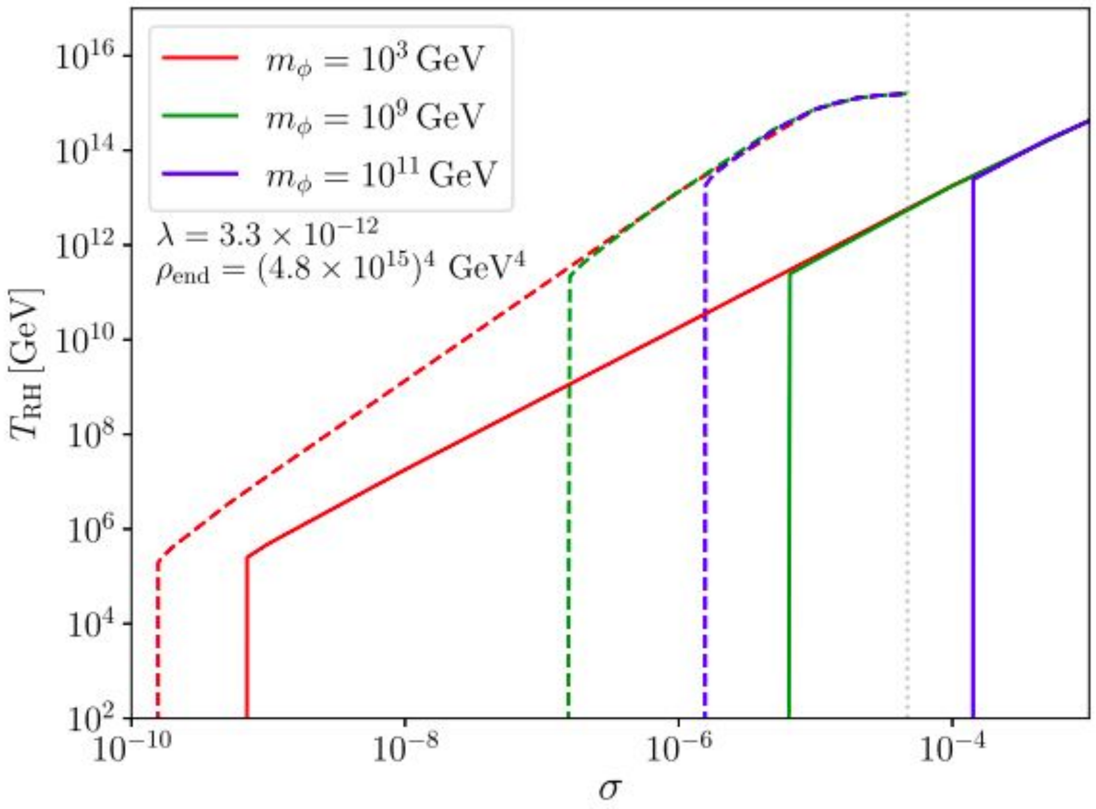
➤ low μ : reheating in the **quadratic potential** with **no enhancement** from effective mass of bosons

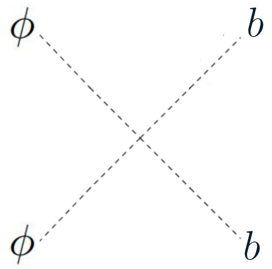
➤ larger μ : effective mass **enhancement,** reheating still takes place in **quadratic potential**

➤ largest μ : effective mass **enhancement,** reheating occurs in **quartic** potential

➤ larger m_ϕ leads to smaller $T_{\rm RH}$ in quadratic potential

Impact of $\phi^4 \to \phi^2$ on Reheating





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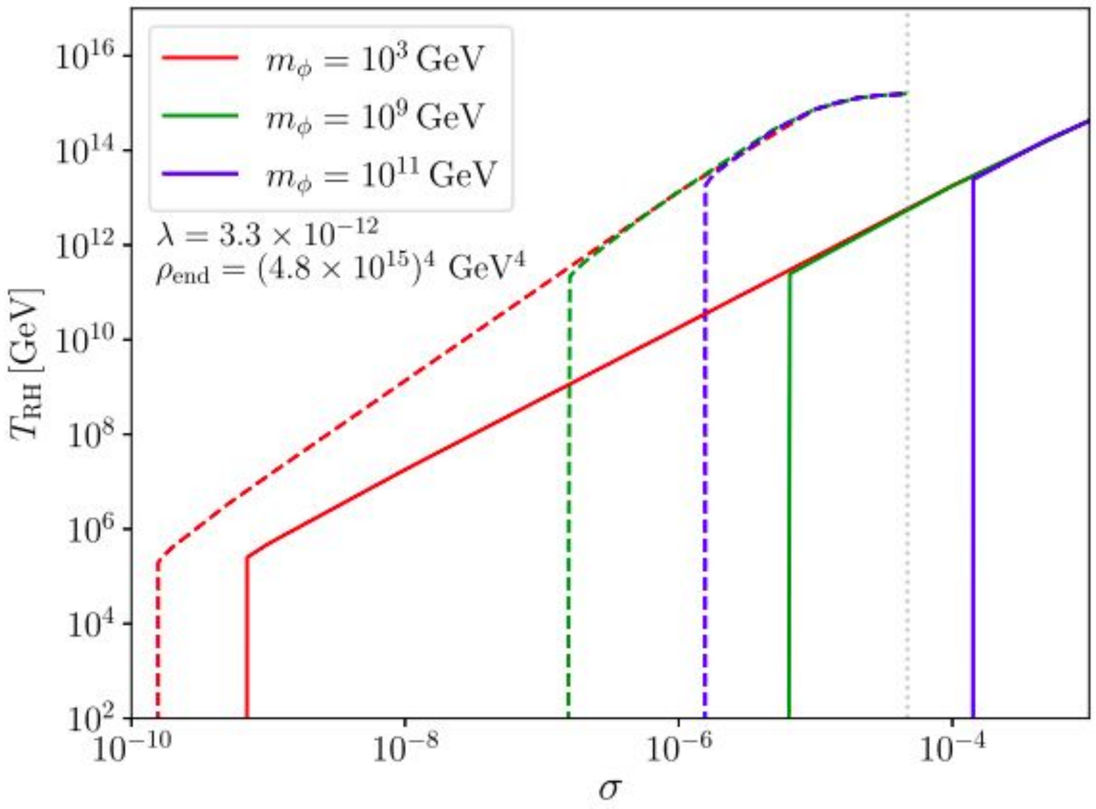
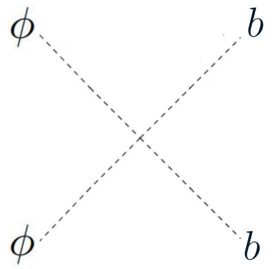


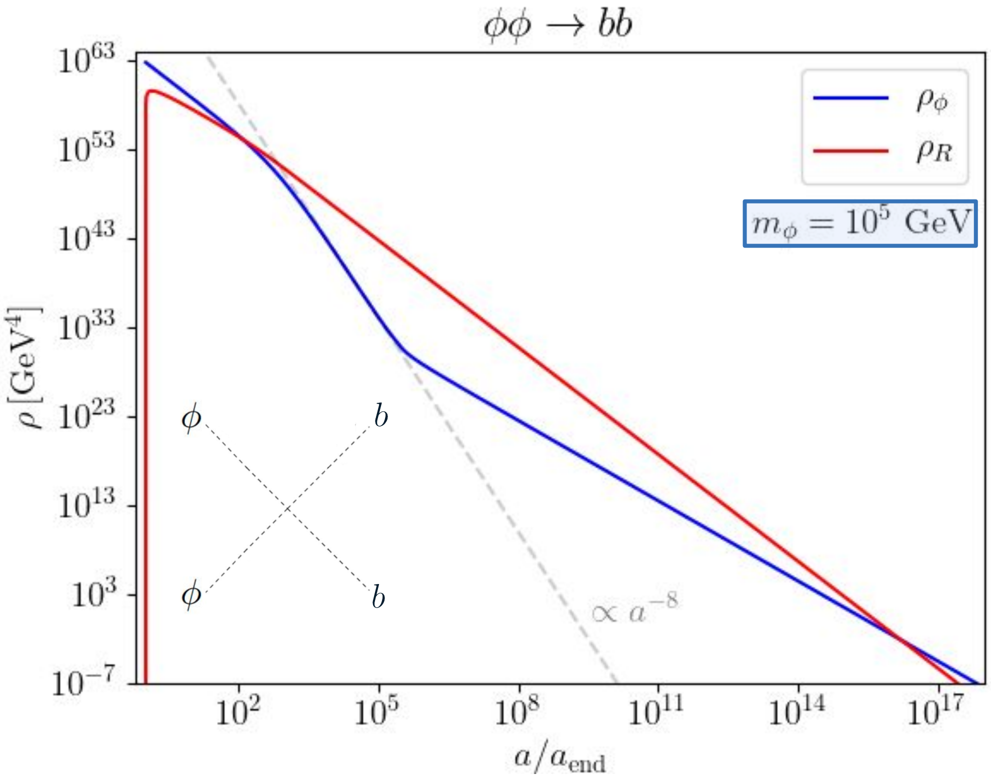


➤ low σ : **no reheating in quadratic potential**

➤ larger σ : reheating takes place in **quartic potential** with effective mass **suppression**

➤ larger m_ϕ does not change $T_{\rm RH}$ at fixed σ, but **prevents reheating for low σ**

Impact of $\phi^4 \to \phi^2$ on Reheating



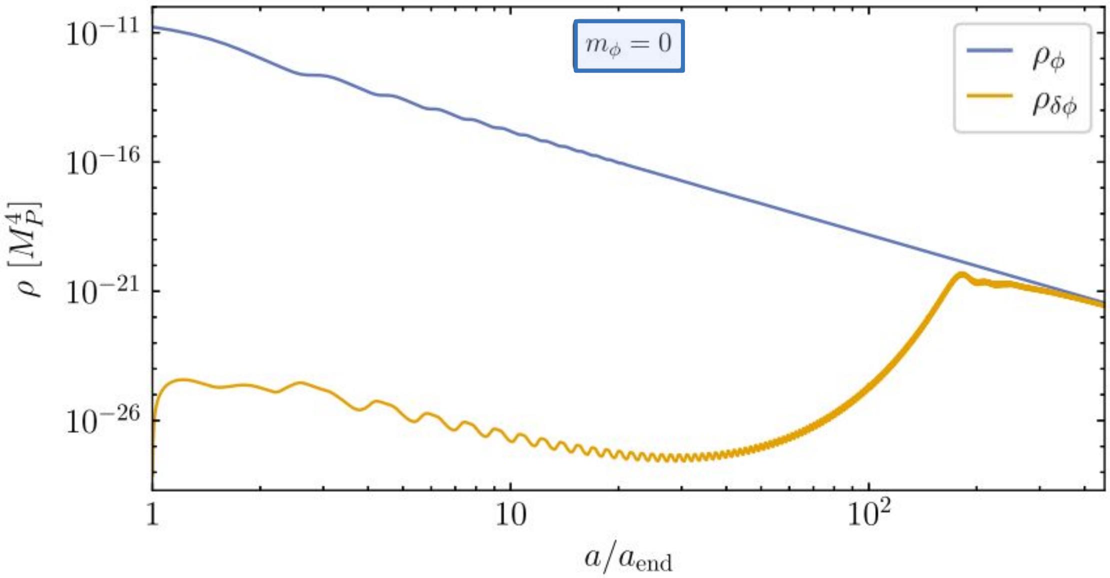
➤ Large σ to ensure **reheating in quartic** potential leads to **cold inflaton relic**

$$\Omega_\phi h^2 = 1.6\left(\frac{m_\phi}{1\ \mathrm{GeV}}\right)^{\frac{5}{2}}\left(\frac{10^{10}\ \mathrm{GeV}}{T_{\mathrm{RH}}}\right)^{\frac{3}{2}}$$

➤ Strongly constrain the bare mass to avoid overclosing the Universe

$$m_\phi < 0.35\left(\frac{T_{\mathrm{RH}}}{10^{10}\ \mathrm{GeV}}\right)^{\frac{3}{5}}\ \mathrm{GeV}$$

Impact of $\phi^k \to \phi^2$ on fragmentation



➤ Self-interactions result in an inflaton-particles bath (**fragmentation**)

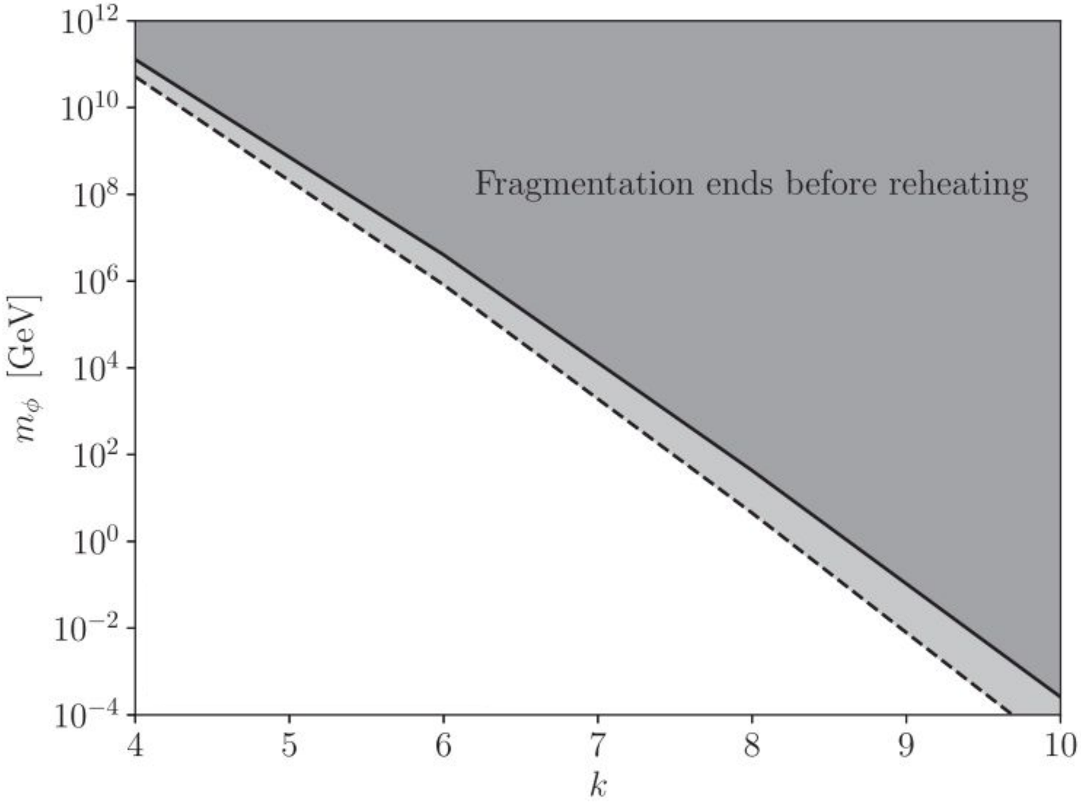
$$\ddot{\delta\phi} + 3H\dot{\delta\phi} - \frac{\nabla^2 \delta\phi}{a^2} + V''(\bar{\phi})\delta\phi = 0$$

$$V''(\bar{\phi}) \simeq k(k-1)\lambda\bar{\phi}^{k-2}M_P^{4-k}$$

➤ Leave almost massless inflaton particles that decay slowly, modifying importantly reheating process

See Garcia, Gross, Mambrini, Olive, Pierre, Yoon, *Effects of fragmentation on post-inflationary reheating,* **2308.16231**, for a recent numerical analysis using `Cosmolattice`

Impact of $\phi^k \to \phi^2$ on fragmentation



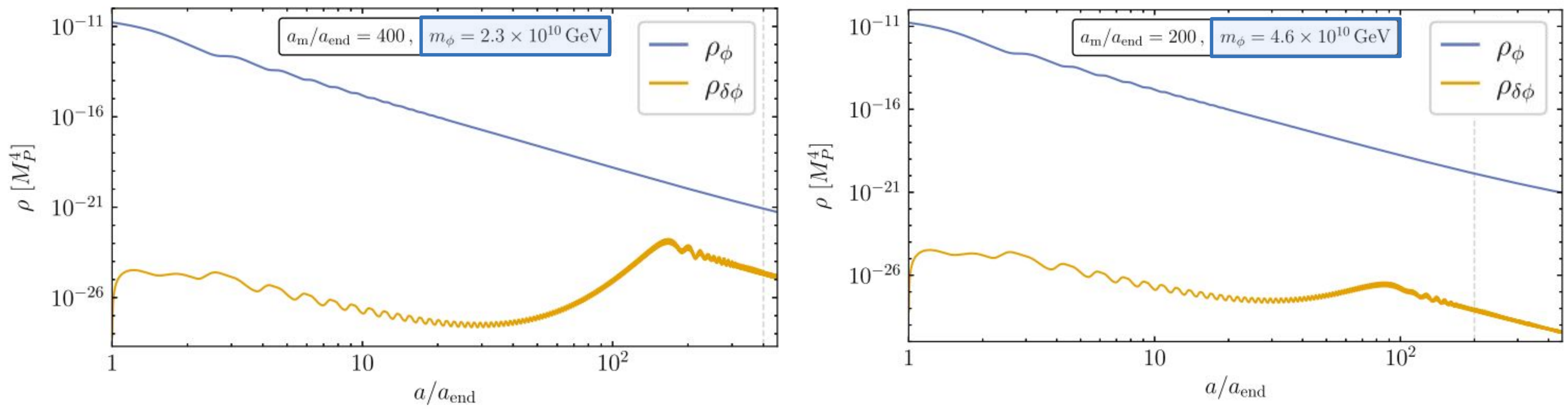
$$V''(\bar{\phi}) \simeq k(k-1)\lambda\bar{\phi}^{k-2}M_P^{4-k} + m_\phi^2$$

➤ Bare mass term can dominate before fragmentation destroys the condensate

➤ Suppression of the parametric resonances for inflaton perturbations

➤ Large bare mass **can end fragmentation before reheating** proceeds

Impact of $\phi^4 \to \phi^2$ on fragmentation



- ➢ Numerical simulations indicate that fragmentation ends even before bare mass term dominates
- ➢ Large bare mass may prevent generation of inflaton particles after inflation

Conclusion

- ➤ Upper limit on the inflaton bare mass sets by CMB observables

- ➤ Oscillations in a mixed potential can lead to transition from higher EoS to matter dominated era

- ➤ Strong impact on the reheating temperature, depending on the dominant channel

- ➤ Leaves a cold inflaton relic for annihilations without decays, while still reheating the Universe

- ➤ Can prevent the condensate from fragmenting, even in presence of dominating self-interactions at the end of inflation

Thank you !

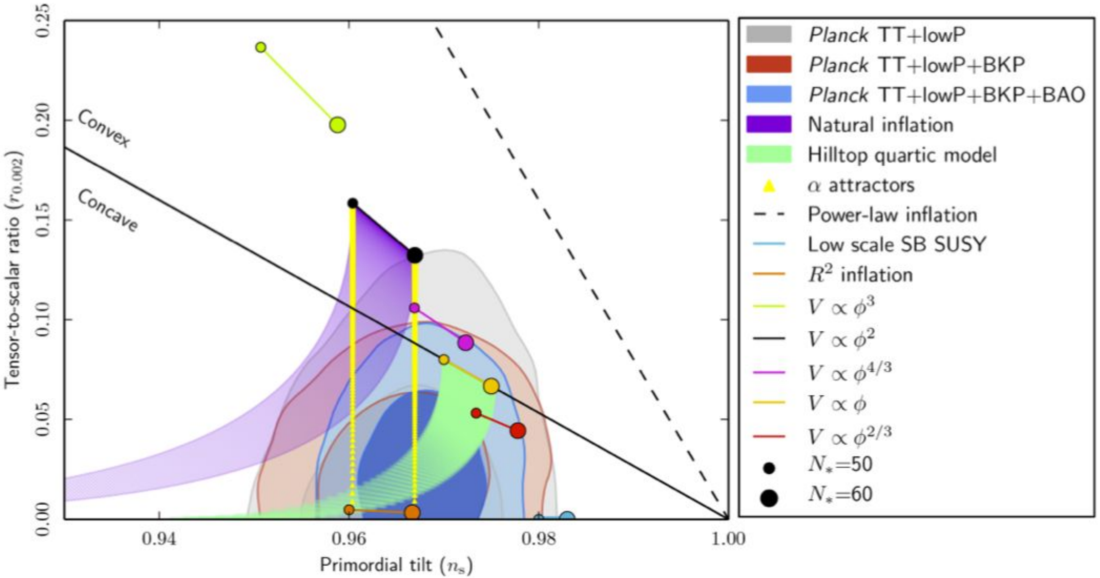
Backup

Inflaton potential

Large field inflation models can predict observables in agreement with CMB data

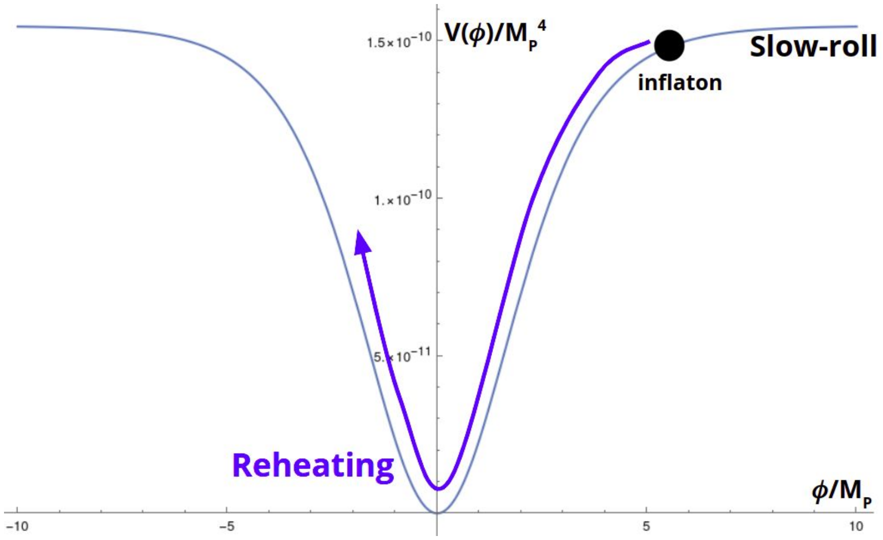
- key examples are R^2 inflation models such as Starobinsky
- other examples such as α-attractors can accommodate similar predictions for (n_s, r)

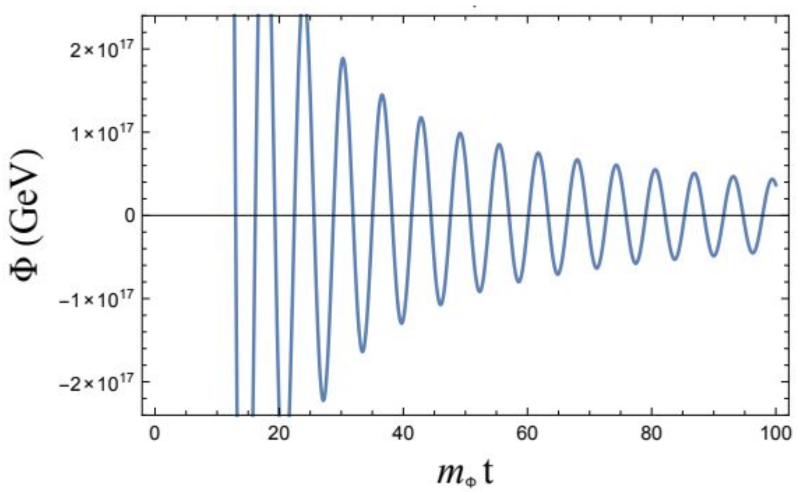
$$n_s = 1 - 6\epsilon_* + 2\eta_*$$
$$r = 16\epsilon_*$$



First CMB Constraints on the Inflationary Reheating Temperature, Martin, Ringeval, **1004.5525**

Inflaton oscillations





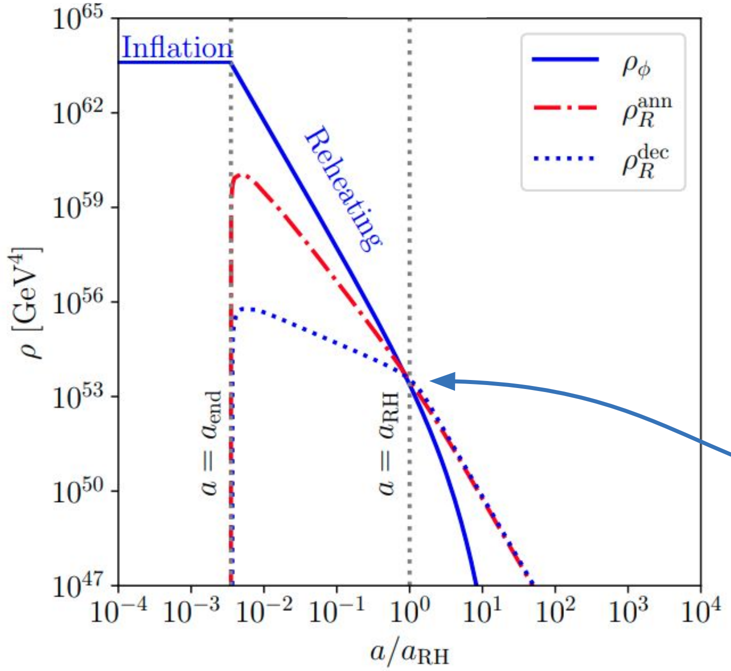
$$\ddot{\phi}(t) + 3H\dot{\phi}(t) + \Gamma\dot{\phi}(t) + V'(\phi(t)) = 0$$

➤ Couplings of the inflaton with the other fields induce transfer of energy during the oscillations : reheating

➤ Redshifted envelop and frequency of oscillations depend on the shape of the potential near the minimum

Reehating

➤ Perturbative particle production and SM particles thermalize to constitute the thermal bath



➤ Solve Boltzmann equations for energy densities

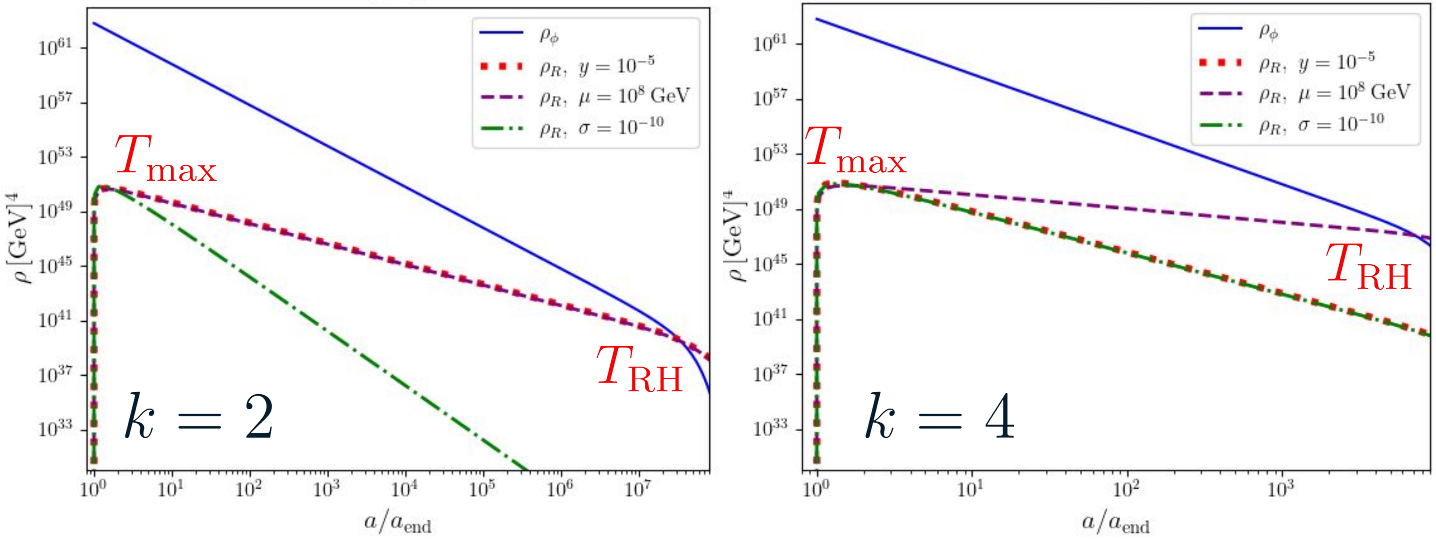
$$\frac{d\rho_\phi}{dt} + 3H(1+w_\phi)\rho_\phi \simeq -(1+w_\phi)\Gamma_\phi\rho_\phi$$
$$\frac{d\rho_R}{dt} + 4H\rho_R \simeq (1+w_\phi)\Gamma_\phi\rho_\phi\,.$$

$$\rho_R(T_{\rm RH}) = \rho_\phi(T_{\rm RH}) = 3\,M_P^2\,H_{\rm RH}^2$$

➤ Define the end of the reheating at equality between energy densities

Reheating

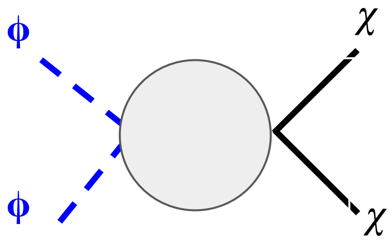
$\mu\,\phi\,b^2$ - - - - $\sigma\,\phi^2\,b^2$ -·-·- $y\,\phi\,f\bar{f}$ · · · ·



- ➢ Different "redshifts" of produced energy density from $T_{\rm max}$ to $T_{\rm RH}$
- ➢ $T_{\rm RH}$ depends importantly both on couplings and shape of inflaton potential

Boltzmann approach

Assuming that the local background geometry is Minkowskian, we compute transition probability



Initial state inflaton ϕ as a coherently oscillating homogeneous condensate with no momentum

Production rate can be computed which is the right hand side of the Boltzmann equations

$$\dot{n}_\chi + 3Hn_\chi = R^{(\mathrm{N})}_{\phi\phi\to\chi\chi}$$

$$\frac{d\rho_\phi}{dt} + 3H(1+w_\phi)\rho_\phi \simeq -(1+w_\phi)\Gamma_\phi\rho_\phi$$

$$\frac{d\rho_R}{dt} + 4H\rho_R \simeq (1+w_\phi)\Gamma_\phi\rho_\phi\,.$$

See Boltzmann or Bogoliubov? Approaches Compared in Gravitational Particle Production, Kaneta, Lee, Oda, **2206.10929**

Fourier modes

Potential near the minimum is a power k-dependent monomial

$$V(\phi) = \lambda \frac{\phi^k}{M_P^{k-4}}, \quad \phi \ll M_P$$

➤ Treat time dependent condensate as a time dependent coupling with an amplitude and quasi-periodic

$$\phi(t) \ = \ \phi_0(t) \cdot \mathcal{P}(t)$$

Expand the quasi-periodic function in Fourier modes

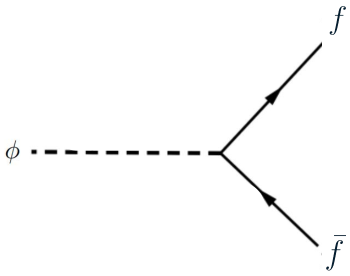
$$\mathcal{P}(t) = \sum_{n=-\infty}^{\infty} \mathcal{P}_n e^{-in\omega t}$$

with $\omega = m_\phi \sqrt{\frac{\pi k}{2(k-1)}} \frac{\Gamma(\frac{1}{2}+\frac{1}{k})}{\Gamma(\frac{1}{k})}$

➤ Each Fourier mode adds its contribution to the scattering amplitude with its energy *En* = *n*.ω

Gravitational portals in the early Universe, **SC,** Mambrini, Olive, Verner, **2112.15214**

Inflaton decay to fermions



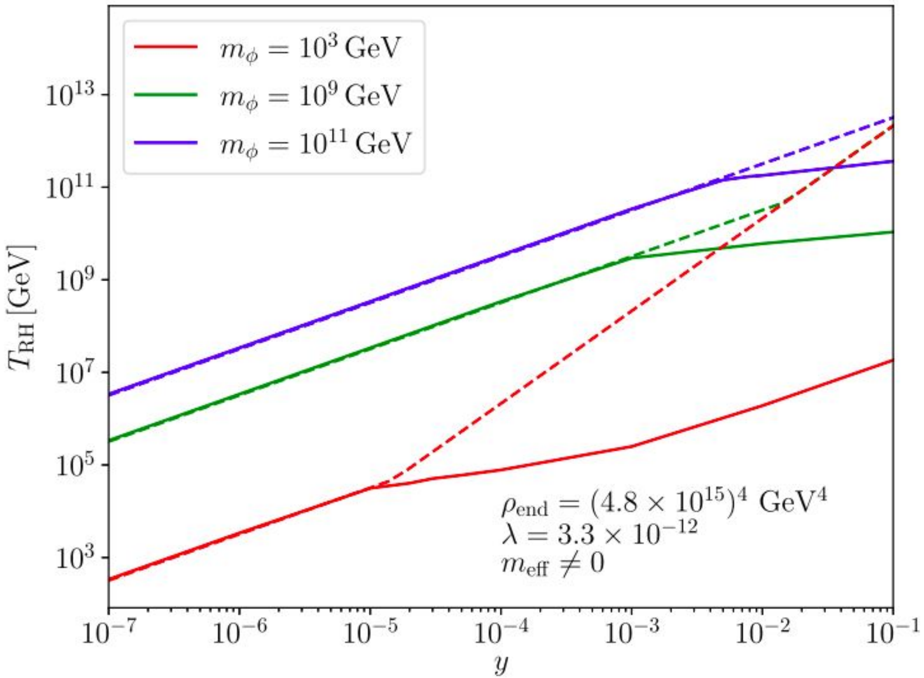
$$\Gamma_{\phi\to\bar{f}f} = \frac{y_{\rm eff}^2}{8\pi} m_\phi$$

$$T_{\rm RH} = \begin{cases} \left(\frac{\lambda}{\alpha}\right)^{\frac{1}{4}} \frac{y_{\rm eff}^2}{\pi} M_P \simeq 4.2\times10^{14}\, y_{\rm eff}^2\, \text{GeV} & k=4 \\ \left(\frac{3}{\alpha}\right)^{\frac{1}{4}} \left(\frac{y_{\rm eff}^2 m_\phi M_P}{20\pi}\right)^{\frac{1}{2}} \simeq 3.3\times10^{12}\, y_{\rm eff} \sqrt{\frac{m_\phi}{10^9\,\text{GeV}}}\,\text{GeV} & k=2 \end{cases}$$

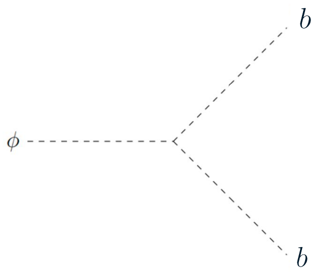
$$y_{\rm eff} \simeq \frac{1}{2}\times\frac{y}{\mathcal{R}^{\frac{1}{4}}} \simeq 6\times10^{-4}\sqrt{y} \quad (k=4)$$

$$y_{\rm eff} = 6.7\times10^{-3}\left(\frac{m_\phi}{10^9\ \text{GeV}}\right)^{\frac{1}{4}} y^{\frac{1}{4}} \quad (k=2)$$

$$\mathcal{R} \propto m_{\rm eff}^2/m_\phi^2 \gg 1$$

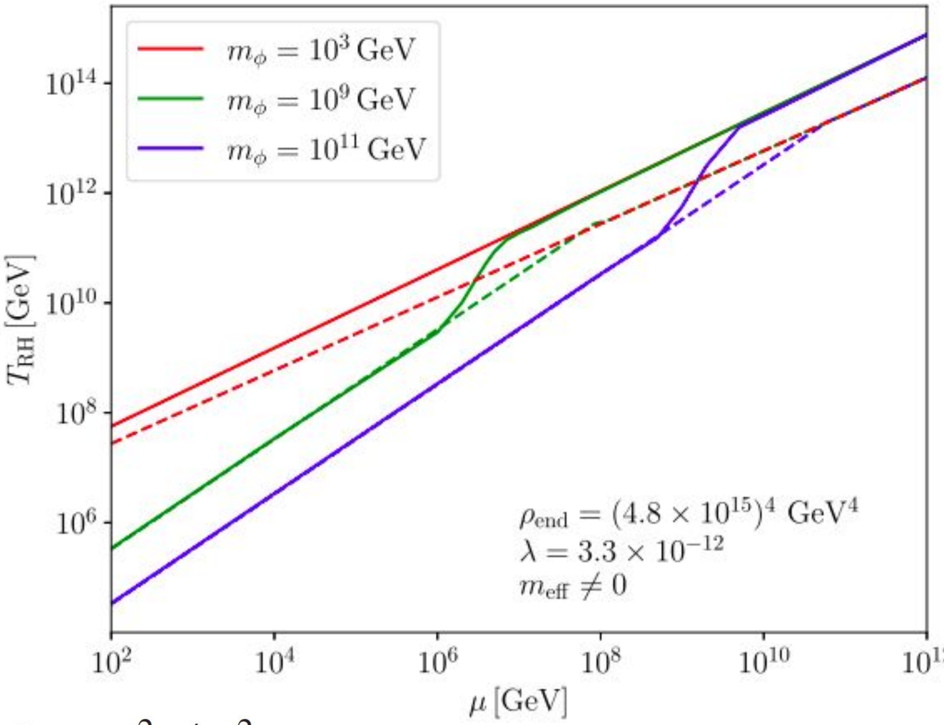


Inflaton decay to bosons



$$\Gamma_{\phi b^2} = \frac{\mu_{\rm eff}^2}{8\pi m_\phi}$$

$$T_{\rm RH} = \begin{cases} \left(\frac{1}{\alpha}\right)^{\frac{1}{4}} \left(\frac{\mu_{\rm eff}^2}{36\pi M_P^2}\right)^{\frac{1}{3}} \lambda^{-\frac{1}{12}} M_P \simeq 1.8\times 10^{18} \left(\frac{\mu_{\rm eff}}{M_P}\right)^{\frac{2}{3}} \text{GeV} & k=4 \\ \left(\frac{3}{\alpha}\right)^{\frac{1}{4}} \left(\frac{M_P}{20\pi m_\phi}\right)^{\frac{1}{2}} \mu_{\rm eff} \simeq 3.3\times 10^{3} \mu_{\rm eff} \sqrt{\frac{10^9\,\text{GeV}}{m_\phi}} & k=2 \end{cases}$$

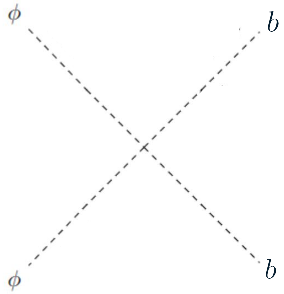


$$\mu_{\rm eff} \simeq 3.3\times 10^{-10}\ \text{GeV} \left(\frac{10^9\ \text{GeV}}{m_\phi}\right)^2 \left(\frac{\mu}{\text{GeV}}\right)^{\frac{5}{2}} \qquad k=2$$

$$\mu_{\rm eff} \simeq 2.5\ \text{GeV} \left(\frac{\mu}{\text{GeV}}\right)^{\frac{15}{14}} \qquad k=4$$

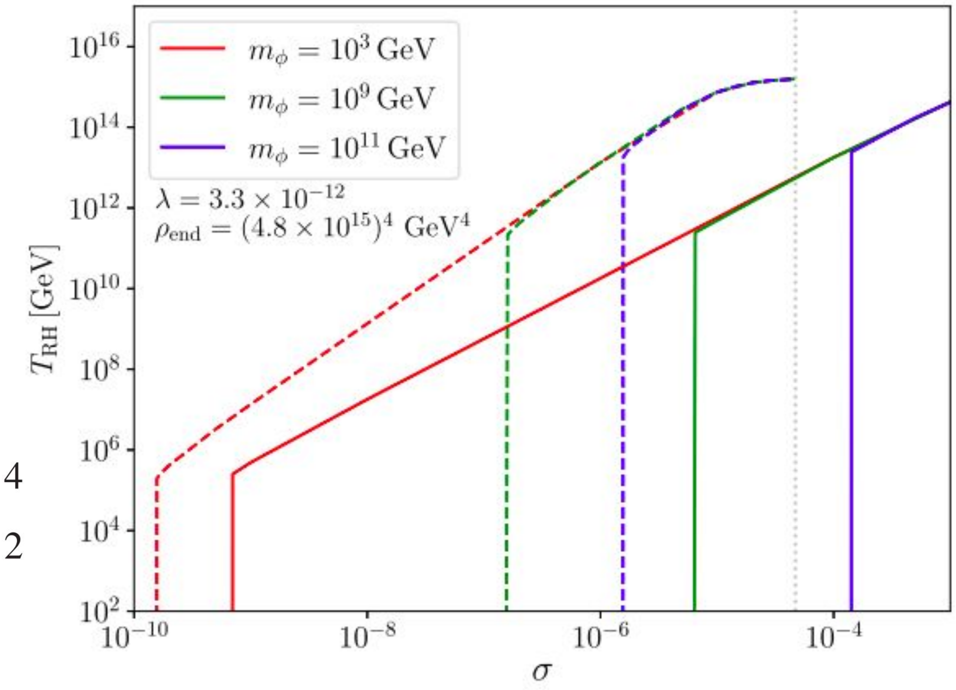
$$\mathcal{R} \propto m_{\rm eff}^2/m_\phi^2 \gg 1$$

Inflaton scattering to bosons



$$\Gamma_{\phi^2 b^2} = \frac{\sigma_{\text{eff}}^2}{8\pi}\frac{\rho_\phi}{m_\phi^3}$$

$$T_{\text{RH}} = \begin{cases} \left(\frac{1}{\alpha}\right)^{\frac{1}{4}} \left(\frac{\sigma_{\text{eff}}^2}{144\pi}\right) \lambda^{-\frac{3}{4}} M_P \simeq 8.9 \times 10^{23} \sigma_{\text{eff}}^2 \,\text{GeV} & k = 4 \\ \text{no reheating} & k = 2 \end{cases}$$



$$\sigma_{\text{eff}}^2 \simeq 16\mathcal{R}^{-1/2}\sigma^2 \simeq 9.6\sqrt{\lambda}\sigma^{\frac{3}{2}}, \quad k=4$$

$$\mathcal{R} \propto m_{\text{eff}}^2 / m_\phi^2 \gg 1$$

Inflaton decay to vectors

In SUGRA embeddings of inflation, kinetic terms for gauge fields can depend on the inflaton

$$\mathcal{L} \supset -\frac{g}{4M_P}\phi F_{\mu\nu}F^{\mu\nu} - \frac{\tilde{g}}{4M_P}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

See Garcia, Kaneta, Ke, Mambrini, Olive, Verner, *The Role of Vectors in Reheating,* **2311.14794** for a further discussion of such couplings

$$\Gamma_{\phi\to A_\mu A_\mu} = \frac{\alpha_{\rm eff}^2 m_\phi^3}{M_P^2} \longrightarrow T_{\rm RH} = \begin{cases} \boxed{\text{no reheating}} & k=4 \\ \left(\frac{3}{\alpha}\right)^{\frac{1}{4}}\left(\frac{2m_\phi^3}{5M_P^3}\right)^{\frac{1}{2}}\alpha_{\rm eff}M_P \simeq 7.0\times 10^3 \alpha_{\rm eff}\left(\frac{m_\phi}{10^9\ \text{GeV}}\right)^{\frac{3}{2}} \text{GeV} & k=2 \end{cases}$$

$$\alpha_{\rm eff}^2 = (g_{\rm eff}^2 + \tilde{g}_{\rm eff}^2)/(64\pi)$$

➤ **no effective masses of vectors generated**

$$\boxed{m_\phi \gtrsim 40\alpha_{\rm eff}^{-\frac{2}{3}}\ \text{TeV}}$$

➤ Ensure sufficient reheating temperature

Inflaton scattering to vectors

In SUGRA embeddings of inflation, kinetic terms for gauge fields can depend on the inflaton

$$\mathcal{L} \supset -\frac{\kappa}{4M_P^2}\phi^2 F_{\mu\nu}F^{\mu\nu} - \frac{\tilde{\kappa}}{4M_P^2}\phi^2 F_{\mu\nu}\tilde{F}^{\mu\nu}$$

See Garcia, Kaneta, Ke, Mambrini, Olive, Verner, *The Role of Vectors in Reheating,* **2311.14794** for a further discussion of such couplings

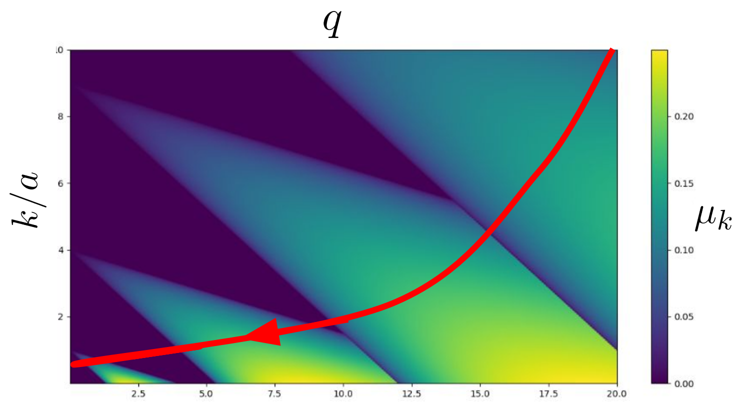
$$\Gamma_{\phi\phi\to A_\mu A_\mu} = \frac{\beta^2 \rho_\phi}{M_P^4} m_\phi$$

$$\beta^2 = (\kappa_{\text{eff}}^2 + \tilde{\kappa}_{\text{eff}}^2)/(4\pi)$$

$$\longrightarrow \quad T_{\text{RH}} = \begin{cases} \boxed{\text{no reheating}} & k=4 \\ \boxed{\text{no reheating}} & k=2 \end{cases}$$

➢ **no effective masses of vectors generated**

Preheating through non-perturbative processes

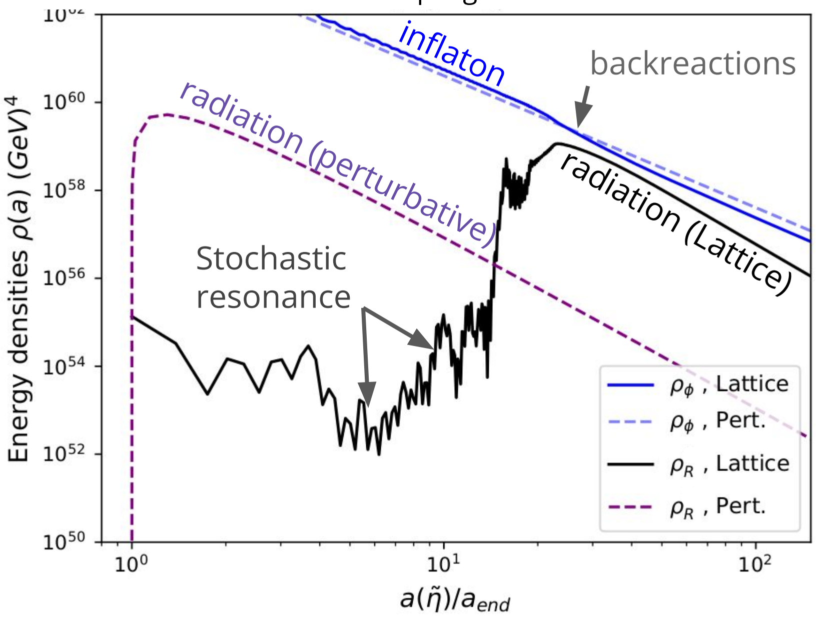


Instabilities in the colored regions

➤ number of occupation increasing

$\chi_k \propto \exp\left[\mu_k t\right]$

coupling σ ~10^{-6}



Preheating corresponds to the first oscillations ➜ resonances and exponential production

For large couplings, reach a regime of large backreactions of the fields on the background ➜ Lattice

Freeze-in from preheating, Garcia, Kaneta, Mambrini, Olive, Verner, **2109.13280**

Preheating through non-perturbative processes

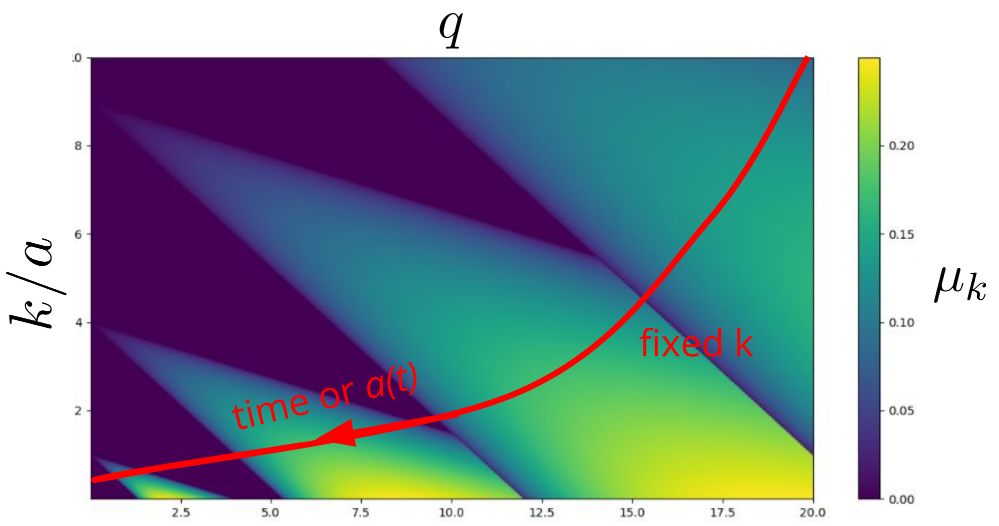
Time dependent background coupled to fields can lead to parametric resonance or tachyonic instability

$$\mathcal{L} \supset \sigma\phi^2\chi^2$$

$$\chi_k'' + \left(\frac{k^2}{m_\phi^2 a^2} + 2q - 2q cos(2z)\right)\chi_k = 0$$

EOM for Fourier modes in the oscillating background

$$q \equiv \frac{\sigma\phi_0^2}{2m_\phi^2} \sim \frac{\sigma}{\lambda}$$



Instabilities in the colored regions

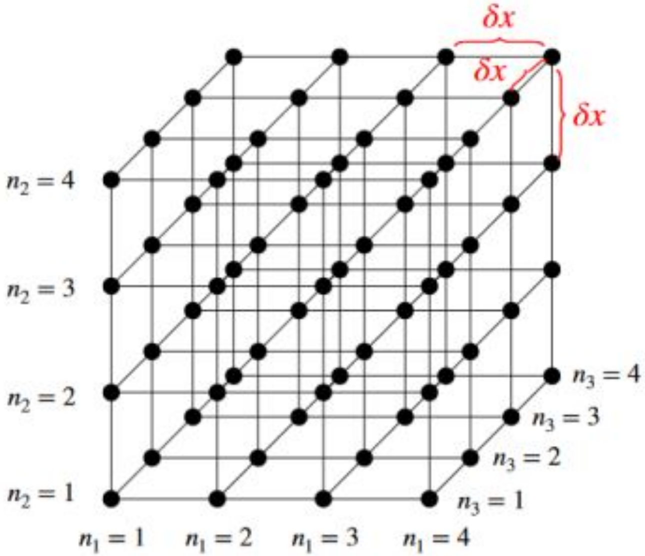
➤ increasing occupation number of the modes

$$\chi_k \propto \exp\left[\mu_k t\right]$$

Freeze-in from preheating, Garcia, Kaneta, Mambrini, Olive, Verner, **2109.13280**

Numerical Lattice simulations

CosmoLattice



The art of simulating the early Universe, Figueroa, Florio, Torrenti, Valkenbug, **2006.15122**

CosmoLattice: A modern code for lattice simulations of scalar and gauge field dynamics in an expanding universe, Figueroa, Florio, Torrenti, Valkenbug, **2102.01031**