Inflaton Quanta: A Window into Reheating?

Kunio Kaneta

NIIGATA UNIVERSITY

+ T. Takahashi (Saga U), N. Watanabe (Saga U) [2508.20402]

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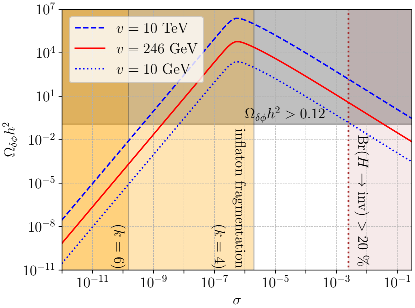
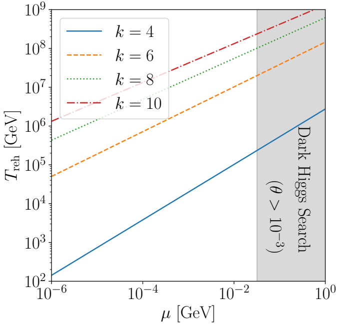
Outline



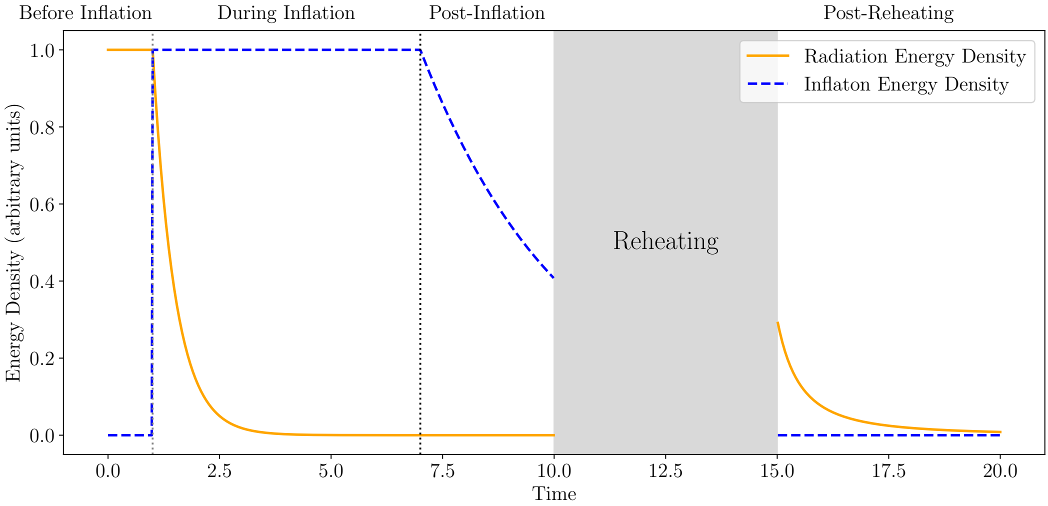


- Reheating problem
- Post-reheating inflaton production
  - $\sigma\phi^2|H|^2$ coupling
  - $\mu\phi|H|^2$ coupling
- Summary

Reheating problem

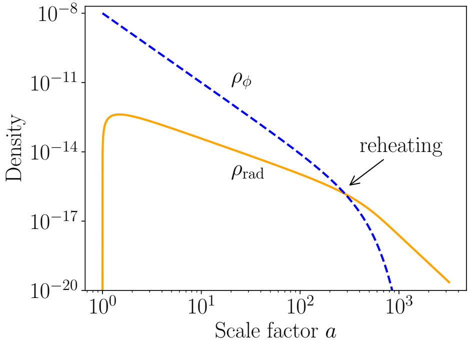
Missing link between inflation and hot big bang: reheating

- After inflation, the Universe is cold and empty
  - To realize the hot Big Bang, the Universe must be reheated
  - How can the radiation-dominated Universe be realized? $\Rightarrow$ Reheating problem



Purturbative reheating: Rayleigh dissipation

- Suppose a velocity-dependent friction term (Rayleigh dissipation)
  - EoM: $\ddot{\phi} + 3H\dot{\phi} + m_\phi^2\phi = 0 \quad \Rightarrow \quad \ddot{\phi} + (3H + \Gamma_\phi)\dot{\phi} + m_\phi^2\phi = 0$
  - ϕ-SM coupling? gauge inv. and renormalizability $\Rightarrow -\mathcal{L}_{\text{int}} \supset \sigma\phi^2|H|^2$ or $\mu\phi|H|^2$



- Boltzmann equations

$$\dot{\rho}_\phi + 3H\rho_\phi = -\Gamma_\phi\rho_\phi$$
$$\dot{\rho}_{\text{rad}} + 4H\rho_{\text{rad}} = +\Gamma_\phi\rho_\phi$$
$$H^2 = \frac{\rho_\phi + \rho_{\text{rad}}}{3M_P^2}$$

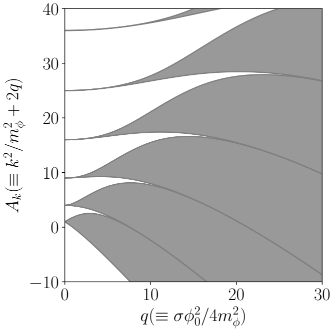
- Reheating temperature:

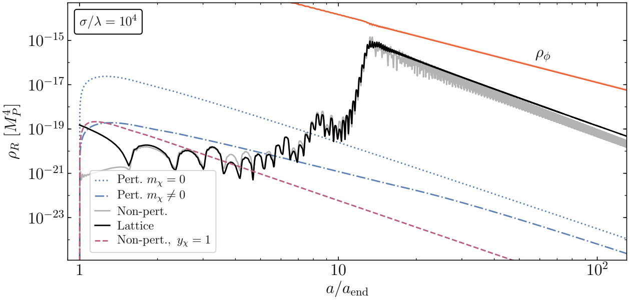
$$\rho_\phi(a_{\text{reh}}) = \rho_{\text{rad}}(a_{\text{reh}}) \equiv \frac{\pi^2}{30} g_*(T_{\text{reh}}) T_{\text{reh}}^4$$

Non-perturbative reheating: preheating

- If coupling is large, parametric amplification of particle production is non-negligible

$$\mathcal{L}_{\rm int} \supset -\sigma\phi^2\chi^2 \quad \Rightarrow \quad \ddot{\chi}_k + 3H\dot{\chi}_k + \left(\frac{k^2}{a^2} + \sigma\phi^2(t)\right)\chi_k = 0$$





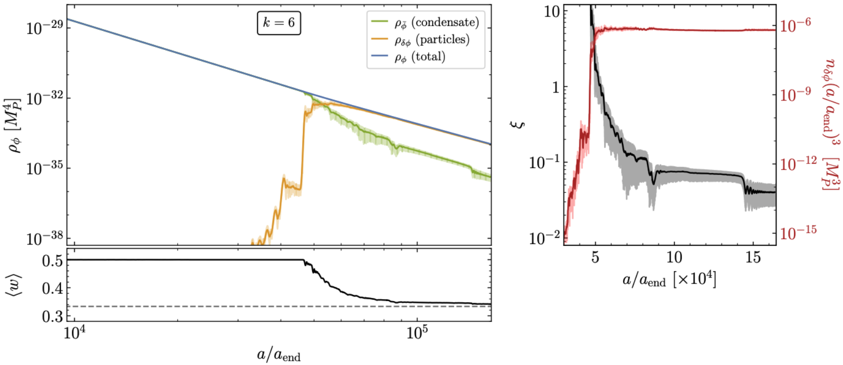
[Garcia, KK, Mambrini, Olive, Verner '22]

Fragmentation of inflaton condensate

- If inflaton has self-interaction, inflaton condensate fragments during reheating

$$V(\phi \ll M_P) = \lambda M_P^4 \left(\frac{\phi}{M_P}\right)^k, \quad \lambda \simeq 10^{-12} - 10^{-14} (\text{depending on } k)$$

$$\phi = \bar{\phi}(t) + \delta\phi(t, \vec{x}) \quad \Rightarrow \quad \delta\ddot{\phi}_k + 3H\delta\dot{\phi}_k + \left(\frac{k^2}{a^2} + V''(\bar{\phi})\right)\delta\phi_k = 0$$



[Garcia, Gross, Mambrini, Olive, Pierre, Yoon '23]

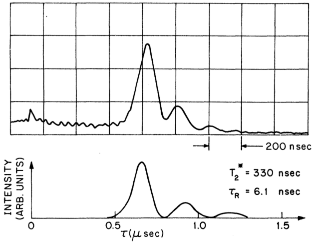
Yet another non-perturbative reheating: superradiance

PHYSICAL REVIEW VOLUME 93, NUMBER 1 JANUARY 1, 1954

Coherence in Spontaneous Radiation Processes

R. H. Dicke
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received August 25, 1953)

- Spontaneous emission
  - excited atoms
  - separation between atoms $\gg$ photon wave length
  - $\Rightarrow$ exponential decay
- Super-radiant emission
  - if phase-aligned
  - separation between atoms $\ll$ photon wave length
  - $\Rightarrow$ pulse-like burst



[Skribanowitz et al, '73]

- First observation by MIT group [Skribanowitz et al, '73]
  - Irradiated atoms emit pulse-like light in a particular direction (single photon process)
  - Two-photon processes may extend the super-radiant region (macro-coherence)

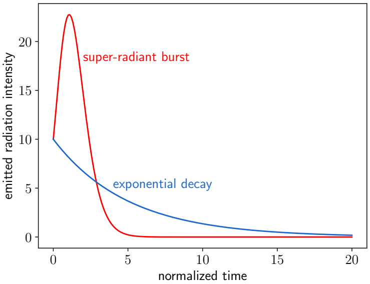
    [Yoshimura et al, '08]

Parametrically amplified superradiance

- Hamiltonian of χ (neglecting expansion): $H = \int d^3x \frac{1}{2}\left[\pi_\chi^2 + (\vec{\nabla}\chi)^2 + m_\chi^2(t)\chi^2\right]$
  - For each Fourier mode χ_k, the wave functional ψ satisfies the Schrödinger equation:

$$i\frac{\partial\psi}{\partial t} = \frac{1}{2}\left[-\frac{\partial^2}{\partial\chi_k^2} + \omega_k^2(t)\chi_k^2\right]\psi \quad \Rightarrow \quad \psi(\chi_k, t) = \left(\frac{\mathrm{Re}D}{\pi}\right)^{1/4} e^{-\frac{1}{2}D(t)\chi_k^2}$$

  - Phase of ψ aligned during preheating: $\mathrm{Im}D \sim$ const. $\Rightarrow$ superradiance
- Inflaton may decay faster than exponential [Yoshimura, KK, Oda '24]



  - Decay time: $\tau_D \simeq \frac{\ln\mathcal{N}}{\mathcal{N}} \times \frac{1}{\Gamma_\phi}$ (Γ_ϕ: perturbative decay rate)
  - $\mathcal{N}$: number of particles in the coherent state

$$\mathcal{N} \sim \underbrace{\mathcal{N}_\phi}_{\text{number of inflaton per Hubble volume}} \times \underbrace{M_P/m_\phi}_{\text{number of levels}}$$

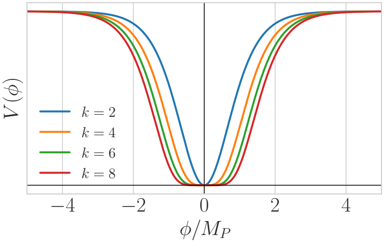
$$\sim 10^{17}$$

- In any case, reheating should be completed $\Longleftrightarrow \rho_{\mathrm{rad}} \gg \rho_\phi (\to 0)$

Post-reheating inflaton production

Inflaton mass dissapearance

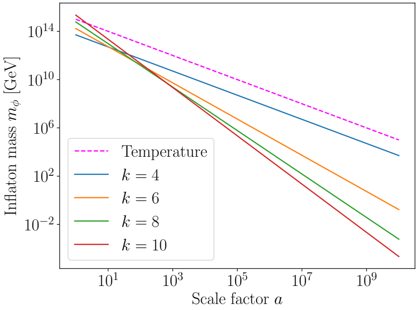
- Extended T-model as an example



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

$$= \begin{cases} 6^{k/2}\lambda M_P^4 & (|\phi| \gg M_P) \\ \lambda M_P^4 (\phi/M_P)^k & (|\phi| \ll M_P) \end{cases}$$

$$\Rightarrow \quad m_\phi^2 = V''(\phi) = k(k-1)\lambda M_P^2 \left(\frac{\phi}{M_P}\right)^{k-2}$$

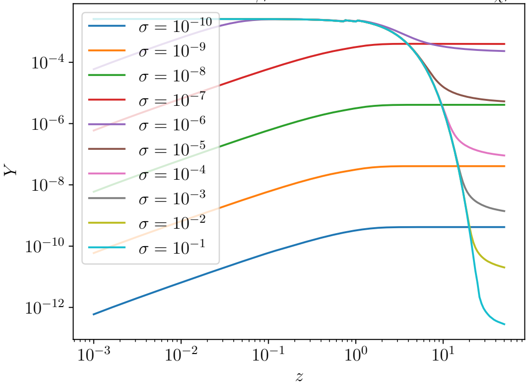


- $k = 2$: $m_\phi = $ const.
- $k > 2$: $m_\phi^2 = V''(\phi) \propto \phi^{k-2} \to 0$ as $\phi \to 0$
- inflaton mass disappears after reheating!
  $\Rightarrow$ $m_\phi(a) < T$ for $k \geq 4$ at some point

Higgs portal coupling: quadratic case (1)

- ϕ-SM coupling: $-\mathcal{L}_{\rm int} = \sigma \phi^2 |H|^2$
  - After EWSB $\Rightarrow$ $m_\phi = \sqrt{\sigma} v$ ($v = 246$ GeV)
  - Pair production of inflaton particles from thermal Higgs annihilation: $h\, h \to \delta\phi\, \delta\phi$

Evolution of $Y = n_{\delta\phi}/s$ as a function of $z = m_\chi/T$

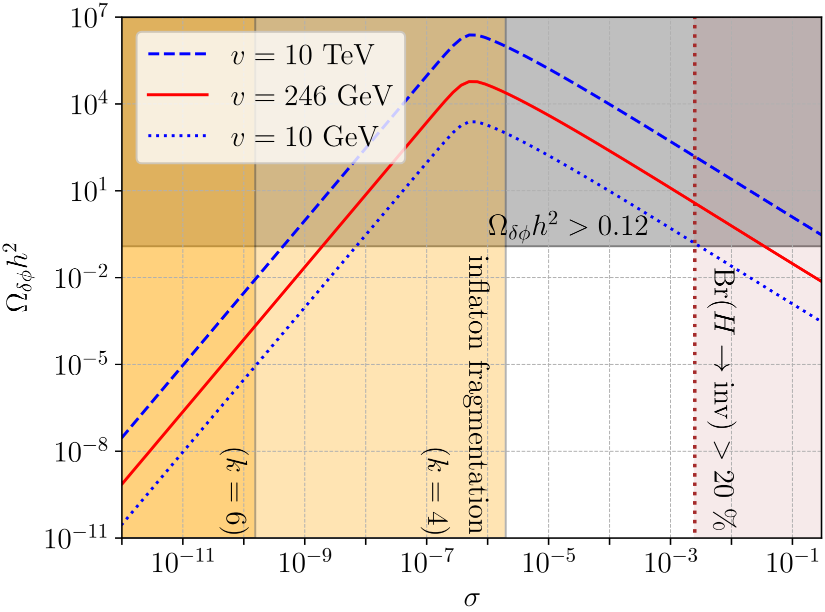


- Boltzmann equation

$$\dot{n}_{\delta\phi} + 3Hn_{\delta\phi} = \langle \sigma v \rangle (n_{h,\rm eq}^2 - n_{\delta\phi}^2)$$

  - initial condition: $n_{\delta\phi}(a_{\rm ini}) = 0$
  - thermal $\delta\phi$ ($\sigma \gtrsim 10^{-6}$)
    $\Rightarrow$ independent from I.C.
    $\Rightarrow$ **"Freeze-out" DM**
  - nonthermal $\delta\phi$ ($\sigma \lesssim 10^{-6}$)
    $\Rightarrow$ sensitive to I.C.
    $\Rightarrow$ **"Freeze-in" DM**

Higgs portal coupling: quadratic case (2)



Higgs portal coupling: linear case (1)

- ϕ-SM coupling: $-\mathcal{L}_{\rm int} = 2\mu\phi|H|^2$
  - m_ϕ from radiative correction:

$$V_{\rm CW} = \frac{(2\mu\phi)^2}{16\pi^2}\left(\ln\frac{2\mu\phi}{\Lambda^2} - \frac{3}{2}\right), \quad (\Lambda : \text{renormalization scale})$$

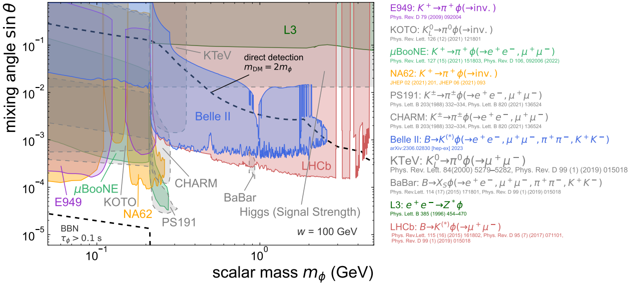
  - minimizing $V_{\rm inf} + V_{\rm CW} \Rightarrow m_\phi \simeq \mu/\pi$

- After EWSB, ϕ mixes with h

$$\text{mixing angle: } \theta \simeq \frac{2\mu v}{m_h^2}$$

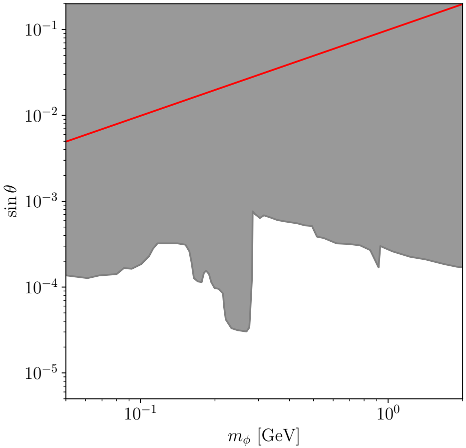
  (assume $m_\phi \ll m_h$)

- can be tested by the dark Higgs search



[Ferber, Grohsjean, Kahlhoefer '23]

Higgs portal coupling: linear case (2)



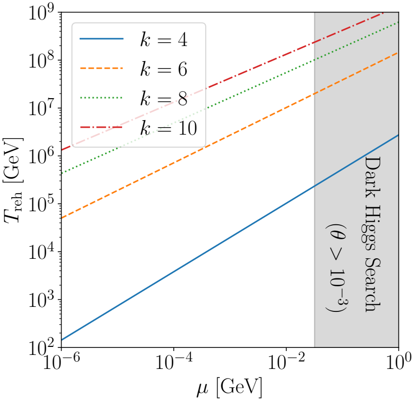
- mass-mixing relation:

$$m_\phi \simeq \frac{\mu}{\pi} \quad \Rightarrow \quad \theta \simeq \frac{2\pi m_\phi v}{m_h^2} \simeq \frac{m_\phi}{10\ \text{GeV}}$$

  - Already excluded by meson-decay measurements
- how to avoid the constraint?
  - need m_ϕ independent from μ
  - e.g. $\sigma\phi^2|H|^2$ term or bare mass term
- constraint $\theta \simeq 2\mu v/m_h^2 \lesssim 10^{-3}$:

$$\mu \lesssim 10^{-3}\frac{m_h^2}{2v} \simeq 0.032\ \text{GeV}$$

Higgs portal coupling: linear case (3)



- reheating by $\phi \to hh$ decay

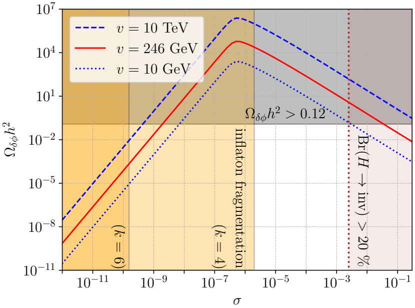
$$\dot{\rho}_\phi + 3(1 + w_\phi) H \rho_\phi = -\Gamma_\phi \rho_\phi$$
$$\dot{\rho}_{\rm rad} + 4H\rho_{\rm rad} = +\Gamma_\phi \rho_\phi$$
$$\Gamma_\phi \simeq \frac{\mu^2}{8\pi m_\phi(t)}$$
$$\Rightarrow \quad \rho_\phi(T_{\rm reh}) = \rho_{\rm rad}(T_{\rm reh}) \equiv \frac{\pi^2}{30} g_*(T_{\rm reh}) T_{\rm reh}^4$$

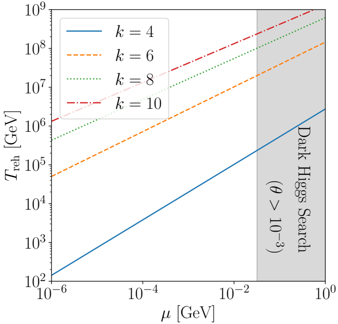
- upper bound on $\mu \Rightarrow$ upper bound on $T_{\rm reh}$

k	4	6	8	10
$T_{\rm reh}^{\rm max}$	2.4×10^5 GeV	2.0×10^7 GeV	1.0×10^8 GeV	2.4×10^8 GeV

■ Summary

Summary





- Inflaton generation even after reheating completes ($k \geq 4$)
- Two types of inflaton-SM coupling
- $\sigma\phi^2|H|^2$ coupling
  - can be DM via freeze-in or freeze-out
  - tested by Higgs invisible decay
- $\mu\phi|H|^2$ coupling
  - need to avoid mass-mixing relation
  - can be tested by dark Higgs search
  - upper bound on T_{reh}