The Dark Side of the Universe DSU 2022
5-9 December

Gravitational production during reheating phase: the possibility of purely Gravitational reheating

Md Riajul Haque
Department of Physics,
IIT Guwahati, Assam, India

- Motivation
- Is it possible to explain our current universe from purely gravitational production during reheating?
- Non-gravitational couplings: where do gravitational reheating lies?

Observational challenges in probing the early Universe

Our knowledge about the cosmic history of the Universe

Cosmic microwave background (CMB)

Provides evidence for an early inflationary phase with

- Energy scale $\sim 10^{16}$ GeV
- Duration $\Delta t_{\rm inf} \geq 10^{-36}$ Sec

Big-Bang Nucleosynthesis (BBN)

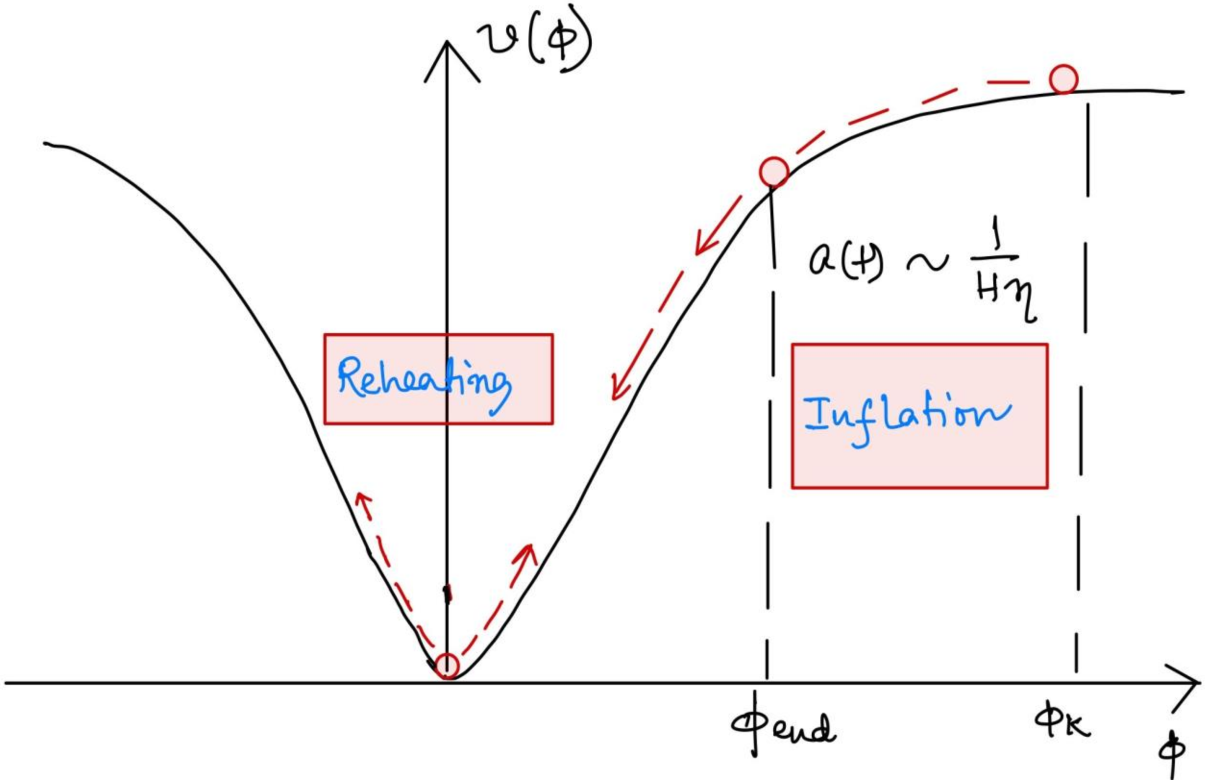
Predicts quantities such as light-element abundances

- Energy scale $E_{\rm BBN} \sim 1$ MeV
- Time scale $t_{\rm BBN} \sim 1$ Sec

- There is a massive gap in terms of energy (and time) scale between the periods of inflation and BBN, which is poorly understood from both theory and observation

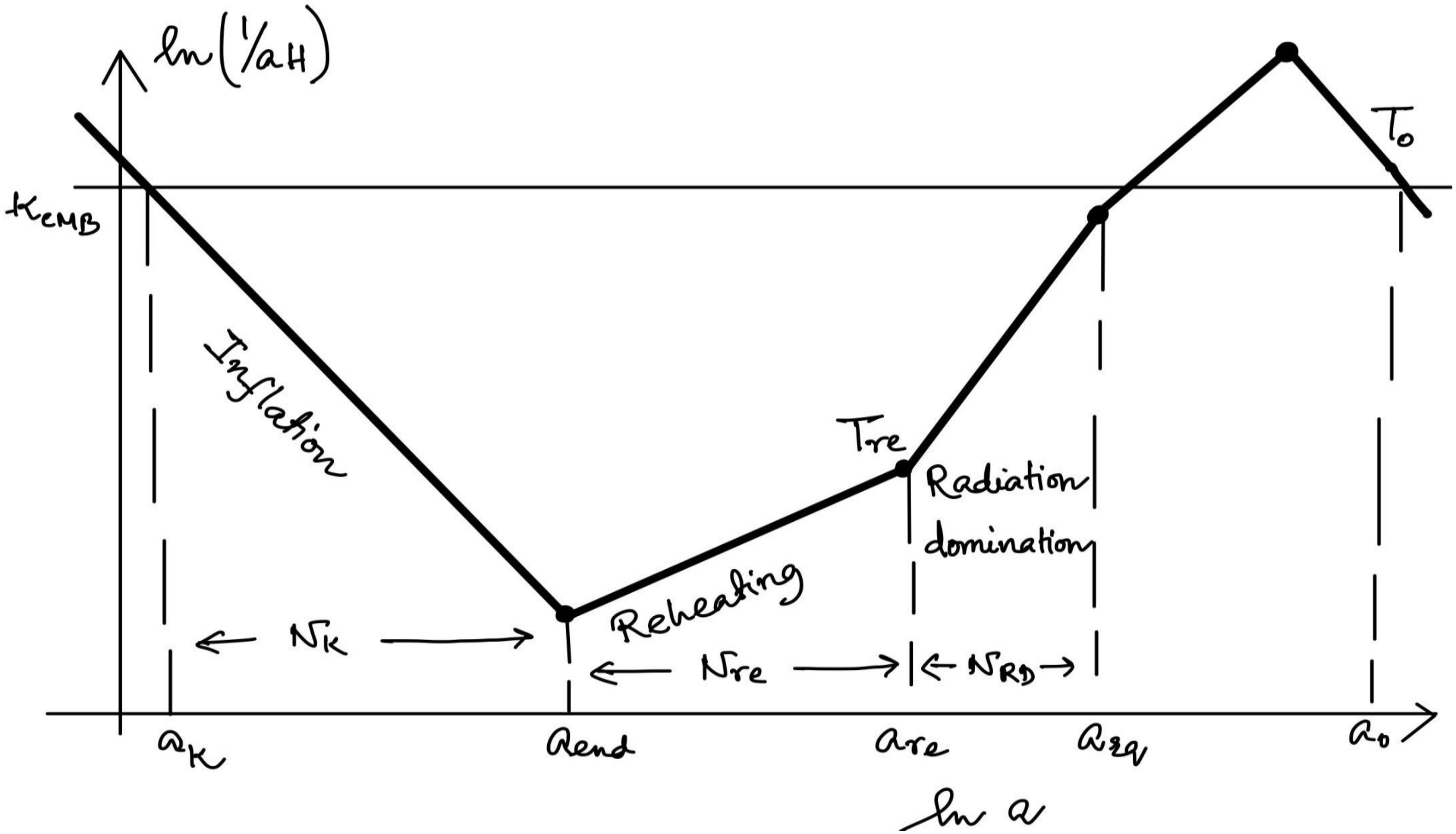
Why do we need reheating phase?

- ❑ The end point of inflation
  - ❖ The universe is cold, dark, and dominated by the homogeneous inflaton field.
- ❑ How does the Universe transition to a the hot, thermalized, radiation-dominated state after inflation, which is required for nucleosynthesis.
- ❑ Reheating!



- ❑ Natural consequence after inflation: fill the empty space with matter (**generate entropy)**

Schematic diagram of the evolution of the comoving Hubble radius



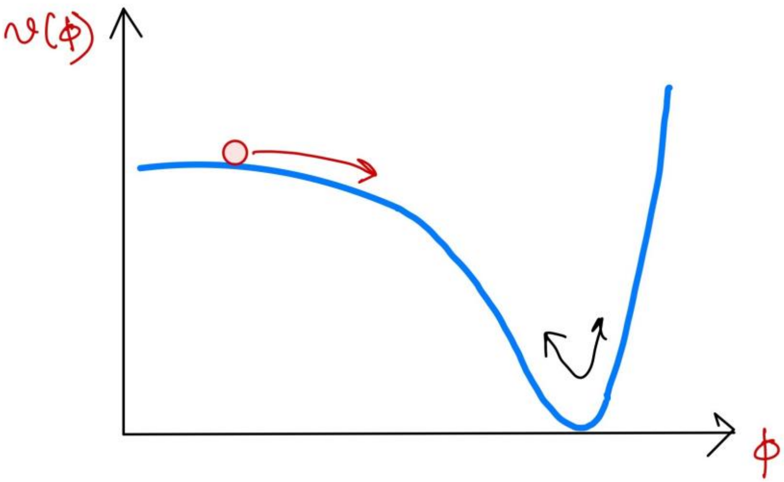
❖ We need to understand how the modified expansion history influences the prediction for cosmological observables.

Inflationary parameters: Initial conditions for reheating

- Slow roll parameters: $\epsilon_v = \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2 \qquad \eta_v = M_p^2\left(\frac{V''}{V}\right)$

- e-folding number & inflationary energy scale :

$$N_k = \log\left(\frac{a_{end}}{a_k}\right) = \int_{\phi_k}^{\phi_{end}} \frac{|d\phi|}{\sqrt{2\epsilon_v}M_p}\ , H_k = \frac{\pi M_p \sqrt{r_k A_s}}{\sqrt{2}}$$



- CMB observable :

$$n_s = 1 - 6\epsilon_k(\phi_k) + 2\eta_k(\phi_k)\ ,\ r = 16\epsilon_k(\phi_k)$$

- End of inflation : Initial condition for reheating

$$\epsilon(\phi_{end}) = \frac{1}{2M_p^2}\left(\frac{V'(\phi_{end})}{V(\phi_{end})}\right)^2 = 1$$

Reheating phenomenology

- Usual approach: Through parametric resonance (Preheating)/ Perturbative decay → $g\phi S^2,\ g_1\phi^2 S^2,\ h\phi\bar{f}f, \ldots\ldots$

- Gravitational decay → $\sim \frac{1}{M_P} h_{\mu\nu} T_i^{\mu\nu}, i = S, f, X, \phi$

The gravitational decay channel was always ignored due to this Planck mass suppression. It was always thought that only gravitational production could not be sufficient to reheat the universe successfully.

Gravitational reheating set up

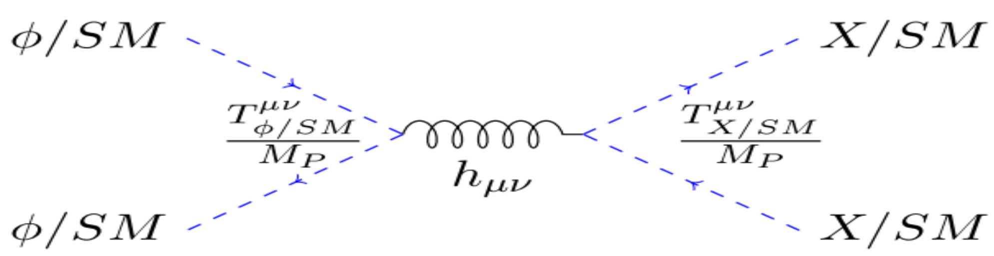
- Inflaton gravitationally decaying into Radiation (massless) + Dark matter (massive)

$$\dot{\rho}_\phi + 3H(1+\omega_\phi)\rho_\phi + \Gamma^T_\phi \rho_\phi(1+\omega_\phi) = 0\,,$$
$$\dot{\rho}_R + 4H\rho_R - \Gamma^{Rad}_{\phi\phi\to RR}\,\rho_\phi(1+\omega_\phi) = 0\,,$$
$$\dot{n}_Y + 3H n_Y - \frac{\Gamma^{DM}_{\phi\phi\to YY}}{m_\phi}\rho_\phi(1+\omega_\phi) = 0$$

$$\Gamma_{\phi\phi\to SS} = \frac{\rho_\phi\, m_\phi}{1024\,\pi\, M_p^4}\left(1+\frac{m_S^2}{2\,m_\phi^2}\right)\sqrt{1-\frac{m_S^2}{m_\phi^2}}\,,$$
$$\Gamma_{\phi\phi\to ff} = \frac{\rho_\phi\, m_f^2}{4096\pi\, M_p^4 m_\phi}\left(1-\frac{m_f^2}{m_\phi^2}\right)^{\frac{3}{2}}\,, \qquad (0.1)$$
$$\Gamma_{\phi\phi\to XX} = \frac{\rho_\phi\, m_\phi}{32768\,\pi\, M_p^4}\left(4+4\frac{m_X^2}{m_\phi^2}+19\frac{m_X^4}{m_\phi^4}\right)\sqrt{1-\frac{m_X^2}{m_\phi^2}}.$$

$$\Omega_X h^2 = \frac{\rho_X(T_F)}{\rho_R(T_F)}\frac{T_F}{T_{now}}\Omega_R h^2,$$
$$= \langle E_X\rangle \frac{X(T_F)}{R(T_F)}\frac{T_F}{T_{now}}\frac{A_F}{m_\phi}\Omega_R h^2$$

Parameters: $H_{end},\ \omega_\phi,\ M_{DM}$ $\quad \Gamma^{Rad} = (\Gamma^S + \Gamma^f + \Gamma^X)$



M. R. Haque and D. Maity [arXiv:2201.02348
Y. Mambrini and K. A. Olive [Phys.Rev.D 103 (2021) 11, 115009]

Initial conditions and constraints

- Initial conditions : $\rho_{\phi}^{in} = 3M_p^2 H_{end}^2, \rho_R = \rho_{DM} = 0$

- Constraint conditions: Present state of our universe

1. Entropy conservation

$$T_{re} = \left(\frac{43}{11\, g_*^{re}}\right)^{1/3} \left(\frac{a_0\, H_{end}}{k}\right) e^{-(N_k+N_{re})}\, T_0\,,$$

with $k/a_0 = 0.05\ \mathrm{Mpc}^{-1}$, $T_0 = 2.725^0\ \mathrm{K}$

2. Present DM abundance $\Omega_X h^2 = 0.12$

3. Universe must be radiation dominated before $T_{re} > T_{BBN} \sim 10 MeV$

4. Upper limit on Inflationary energy scale $H_{end}^{max} > \pi M_p \sqrt{r\, A_s/2} \sim 5 \times 10^{13} GeV$

Present state of the universe is completely fixed by $H_{end},\ \omega_\phi,\ M_{DM}$

L. Dai, M. Kamionkowski and J. Wang, PRL. 113, 041302 (2014)
J. L. Cook, etal JCAP 1504 (2015) 047

Model independent predictions

- Assuming Slow-roll inflation (with out taking any particular model)

$$m_\phi^{end} \simeq \sqrt{(1+\omega_\phi)(4+12\omega_\phi)/(1-\omega_\phi)^2}\, H_{end}$$

$$N_{re} = \frac{1}{3\omega_\phi - 1} \ln\left(\frac{512\,\pi\, M_p^2\,(1+15\,\omega_\phi)}{3\,(1+\gamma) H_{end}\, m_\phi^{end}\,(1+\omega_\phi)}\right)$$

$$T_{re} = \left(\frac{9\,(1+\gamma)\, H_{end}^3\, m_\phi^{end}\,(1+\omega_\phi)}{512\,\beta\,\pi\,(1+15\omega_\phi)}\, e^{-4\,N_{re}}\right)^{1/4}$$

$$n_f^{com} \simeq \frac{3H_{end}^3}{2048\pi}\frac{1+\omega_\phi}{1-\omega_\phi}\left(\frac{m_f}{m_\phi^{end}}\right)^2\left(1-e^{-\frac{3N_{re}}{2}(1-\omega_\phi)}\right),$$

$$n_S^{com} = 8n_X^{com} = \frac{3H_{end}^3\,(1+\omega_\phi)}{512(\pi+3\pi\omega_\phi)},$$

Gravitational Reheating prediction:

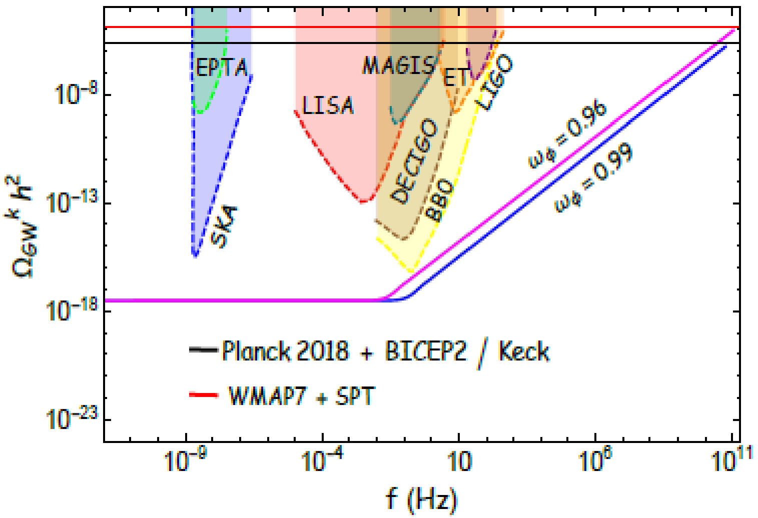
Dark matter sector

- Fermionic DM: $2\times10^5 < m_f < 3\times10^8\ GeV$

Inflaton sector

- Inflaton equation of state $\omega_\phi = (0.6, 0.99)$
- Energy scale $H_{end} = (1\times10^9, 5\times10^{13})\ GeV$
- Inflationary e-folds $62 < N_{efold} < 63$

Predictions from primordial gravitational waves



Spectrum of the gravitational today

$$\Omega^k_{GW} h^2 \simeq \Omega_R h^2 P_T(k) \frac{4\mu^2}{\pi} \Gamma^2 \left(\frac{5+3\omega_\phi}{2+6\omega_\phi}\right) \left(\frac{k}{2\mu k_{re}}\right)^{n_{GW}}$$

$$\mu = \frac{1}{2}(1+3\omega_\phi) \quad P_T(k) = H^2_{end}/12\pi^2 M_p^2.$$

Index of the GW spctrum:

$$n_{GW} = \frac{(6\omega_\phi - 2)}{(3\omega_\phi + 1)}$$

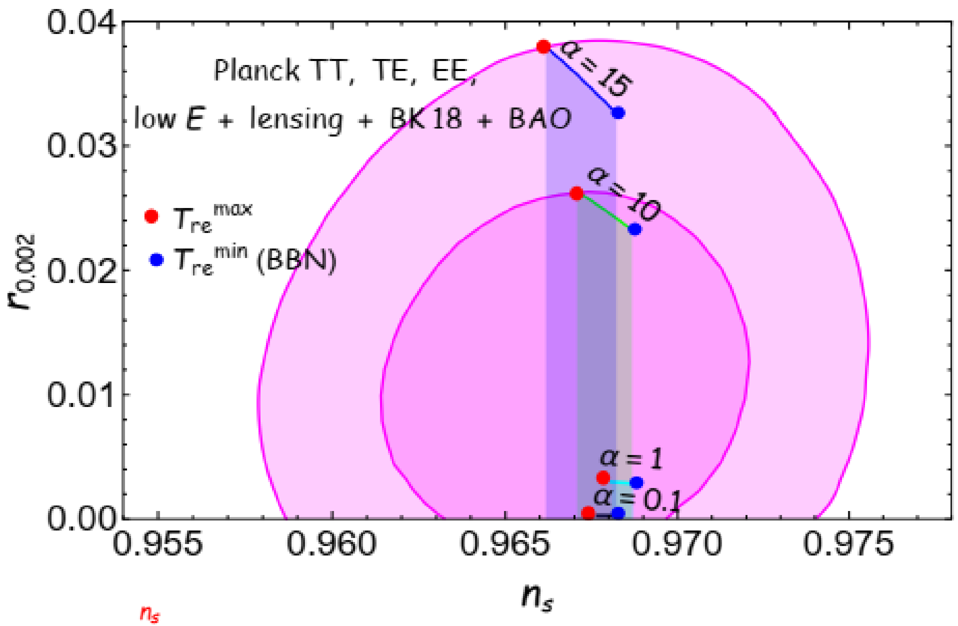
From BBN bounds set by Plank 2018 data:

$$\boxed{\omega_\phi \to 0.98 \sim 1.0}$$

R. Haque, DM, S. T. Paul, L. Sriramkumar, Phys.Rev.D 104 (2021) 6, 063513

Constraining specific models

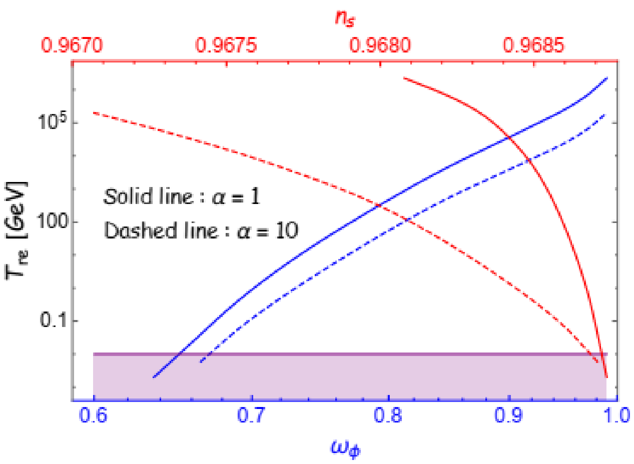
$$V(\phi) = \Lambda^4 \left[1 - e^{-\sqrt{\frac{2}{3\alpha}}\phi/M_p}\right]^{2n}$$

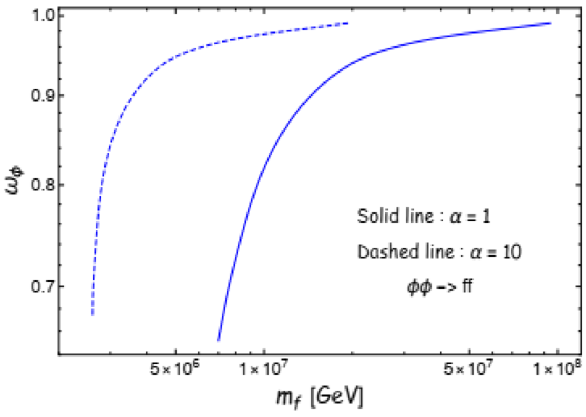


Predictions:

$$\alpha = 1 \rightarrow 0.9681 \leq n_s \leq 0.9687$$
$$n \geq 4.75$$
$$7 \times 10^6 < m_f < 9 \times 10^7\ GeV$$

$$\alpha = 10 \rightarrow 0.9611 \leq n_s \leq 0.9687$$
$$n \geq 5.15$$
$$3 \times 10^6 < m_f < 2 \times 10^7\ GeV$$





Non-gravitational couplings

- Non-gravitational decay rate (Taking the effect of both Bose enhancement and Pauli blocking)

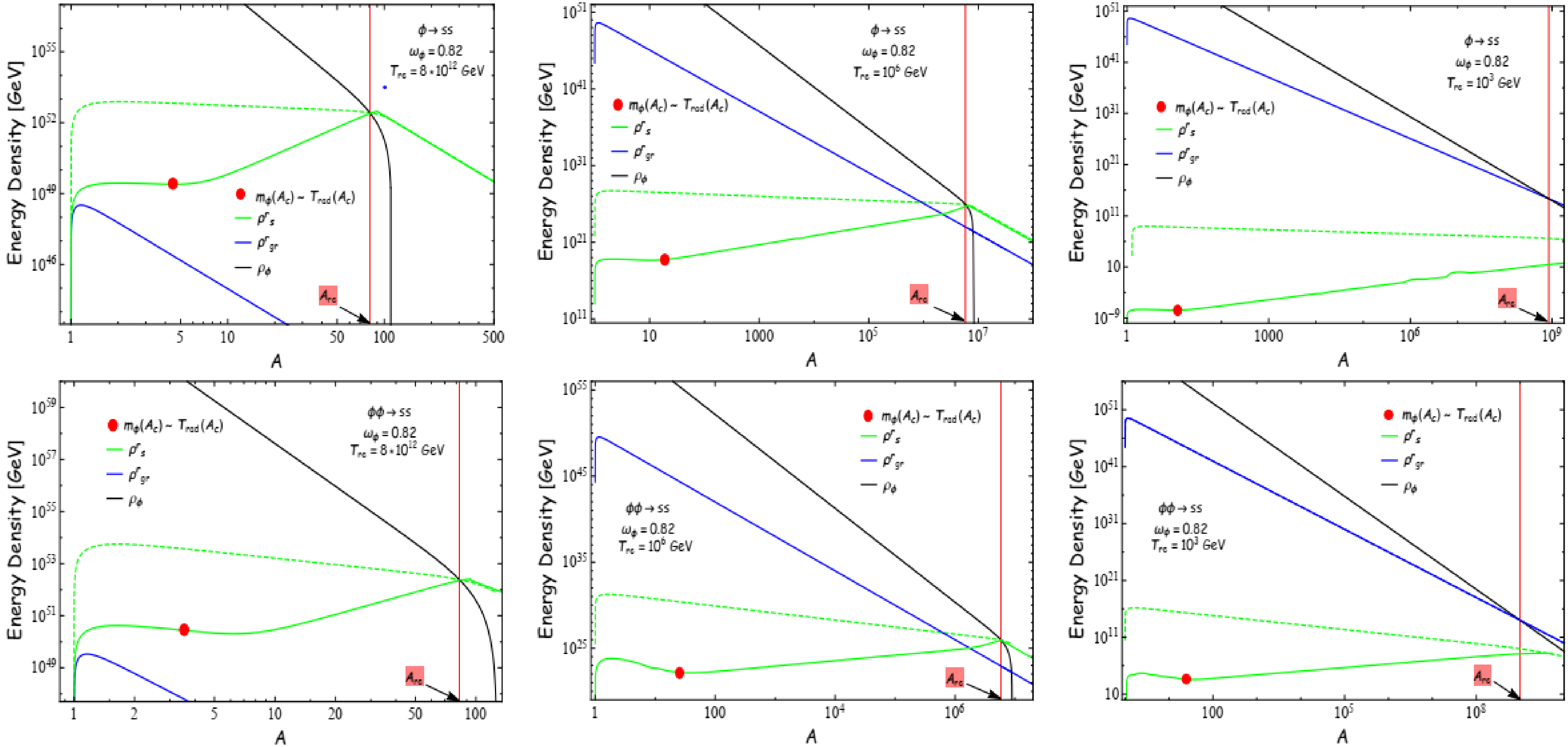
$$\Gamma_{s/f} = \begin{cases} \Gamma_{\phi\to ss} & = \frac{(g_1^r)^2}{8\pi m_\phi(t)}(1+2f_B(m_\phi/2T))\,, & \text{for} \quad g_1^r \phi s^2 \\ \Gamma_{\phi\phi\to ss} & = \frac{(g_2^r)^2 \rho_\phi(t)}{8\pi m_\phi^3(t)}(1+2f_B(m_\phi/T))\,, & \text{for} \quad g_2^r \phi^2 s^2 \\ \Gamma_{\phi\to \bar{f}f} & = \frac{h^2}{8\pi} m_\phi(t)(1-2f_F(m_\phi/2T))\,, & \text{for} \quad h^r \phi \bar{f} f \end{cases}$$

$$f_{B/F}(w) = \frac{1}{e^w \mp 1}$$

- Based on their dominating effect, we find three distinct regions of coupling where reheating evolution will be different:

1) **Case-I:** Entire reheating dynamics will be dominated by direct non-gravitational coupling.
2) **Case-II:** Both the decay processes will partially dominate the reheating dynamics.
3) **Case-III:** Entire reheating dynamics will be dominated by gravity mediated process (Gravitational reheating).

Evolution of inflaton and radiation energy density as a function of normalized scale factor (Bosonic reheating)



Left panel: Coupling is in the range of $g_i^r > \mathscr{G}_{ci}^{1,\,th}$. **Middle panel:** Coupling is in the range of $\mathscr{G}_{ci}^{2,\,th}/\mathscr{G}_{ci}^{2} < g_i^r < \mathscr{G}_{ci}^{1,\,th}$. **Right panel:** Coupling is in the range of $g_i^r < \mathscr{G}_{ci}^{2,\,th}/\mathscr{G}_{ci}^{2}$.

Variation of the radiation temperature with respect to the scale factor

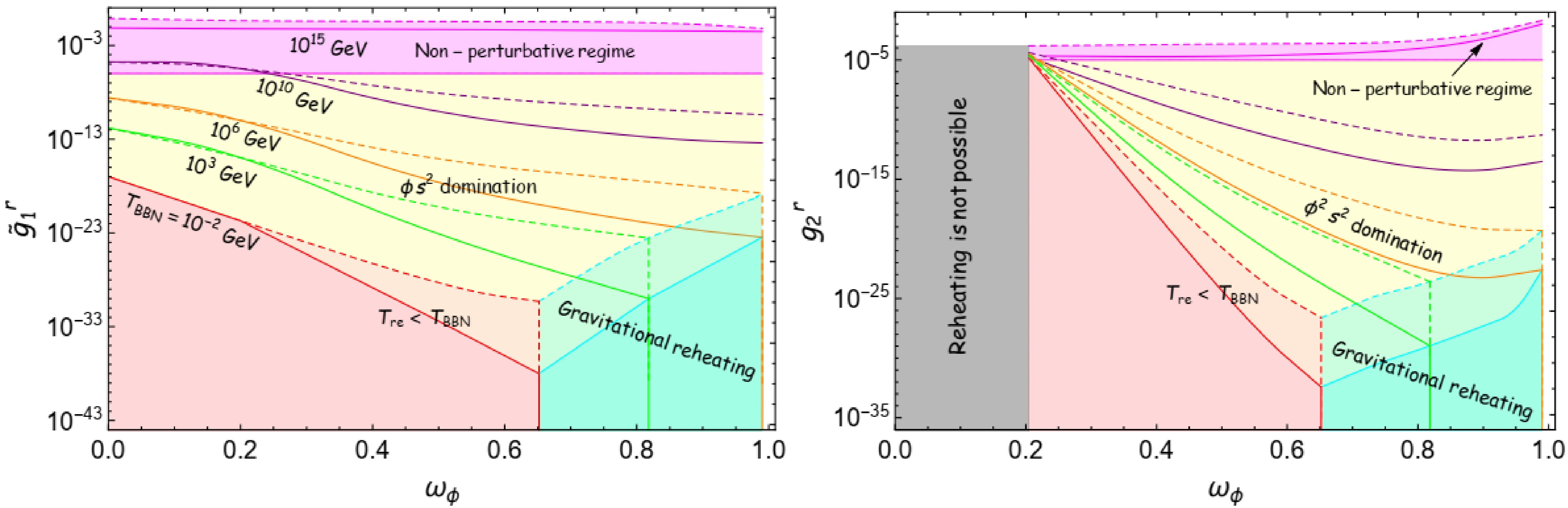
- **Bosonic reheating**

Channel	$T \ll m_\phi(t)$ (Without thermal effect)		$T \gg m_\phi(t)$ (With thermal effect)	
	Non-gravitational	Gravitational	Non-gravitational	Gravitational
$\phi \to ss$	$A^{-\frac{3(1-w_\phi)}{8}}$	A^{-1}	$A^{-\frac{(1-3w_\phi)}{2}}$	A^{-1}
$\phi\phi \to ss$	$A^{-\frac{9(1-w_\phi)}{8}}$	A^{-1}	$A^{-\frac{(3-5w_\phi)}{2}}$	A^{-1}

- **Fermionic reheating**

Channel	$T \ll m_\phi(t)$ (Without thermal effect)		$T \gg m_\phi(t)$ (With thermal effect)	
	Non-gravitational	Gravitational	Non-gravitational	Gravitational
$\phi \to \bar{f}f$	$A^{-\frac{3(1+3w_\phi)}{8}}$ (A^{-1}) for $w_\phi < 5/9 (> 5/9)$	A^{-1}	$A^{-\frac{3(1+5w_\phi)}{10}}$ (A^{-1}) for $w_\phi < \frac{7}{15} (> \frac{7}{15})$	A^{-1}

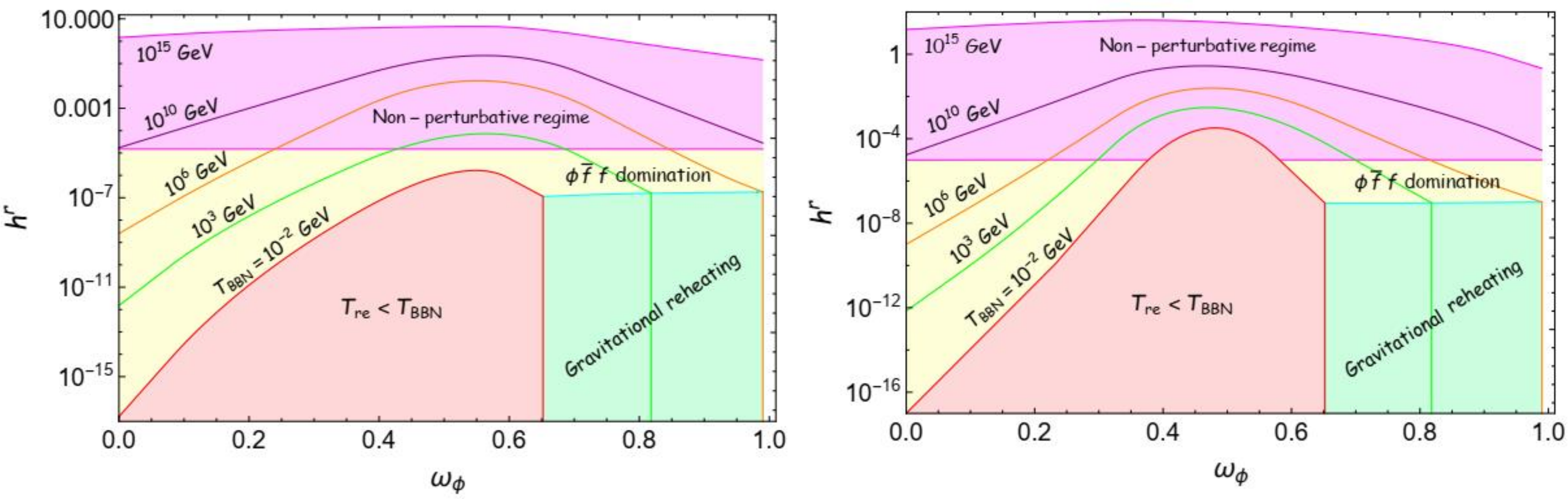
Variation of the dimensionless bosonic coupling parameters as a function of inflaton EoS (Bosonic reheating)



❖ The pink-shaded region corresponds to the non-perturbative regime where bounds on coupling $\tilde{g}_1^r \geq \left(V_{end}^{1/2} m_\phi^{end}/(24 M_p \phi_{end}^2)\right)^{1/2}$ and $g_2^r \geq (V_{end}^{1/8}/\phi_{end}) \left(V_{end}^{1/2} (m_\phi^{end})^3/(\sqrt{2} M_p \phi_{end}^4)\right)^{1/4}$ are obtained from resonance condition of Mathieu equation for scalar field.

L. Kofman, A. D. Linde and A. A. Starobinsky, Phys. Rev. D **56**, 3258-3295 (1997)

Variation of the fermionic coupling parameters as a function of inflaton EoS (Fermionic reheating)



- For the Bosonic reheating, Bose enhancement factor induces the decay rate, which decreases the lower limit of inflaton-Boson coupling above which the Boson decay dominated reheating (bosonic reheating) is possible.

- On the other hand, for fermionic decay of inflaton, the thermal bath induces an additional Pauli blocking factor into the decay rate, which requires a higher value of coupling *h* for successful fermionic reheating.

Summary

- I initially provided a brief description about the importance of reheating.
- Then discuss a model-independent approach to acquire a precise cosmological prediction. We switch off all possible unknown parameters, implying that the inflaton sector is coupled with the observable sector only through gravitational interaction.
- Finally, discussed where do gravitational reheating lie with respect to different non-gravitational couplings.

Thank You