Decoding the reheating era through primordial gravitational waves

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What we know...

- Inflation successfully explains the initial stage of our universe.
- Success of Inflation : (a) solution of horizon and flatness problems, (b) generate a scale invariant curvature power spectrum from quantum vacuum.
- After the inflation, we know well about the standard Big-Bang cosmology (SBBC): radiation era and matter dominated era (forget about the DE at the moment).

What we “Probably” do not know...

- When do the normal matter fields create ? - Probably during the reheating era after the end of inflation.
- What are the essential parameters to describe the reheating stage ? - Probably the inflaton decay constant (Γ) and a reheating EoS parameter (ω).
- What are the possible values (or constraints) on Γ and ω ? - Do Not know.
- What is the mechanism for reheating era ? - Do Not know.

Motivations and approach in the present paper

- Clear motivation - Understanding the reheating era better.
- In the present paper, we provide a way to decode various informations of reheating phase through the "Primordial Gravitational Waves (PGWs)" spectrum.

Plan of today's talk

- 1st part: Background cosmological dynamics, mainly two types of reheating dynamics.
- 2nd part: Brief about GWs energy density.
- 3rd part: Decoding the reheating era by GWs spectrum today.

1st Part: Background cosmological dynamics.

- Action: $S = \int d^4x\sqrt{-g}\left[M_{\rm Pl}^2 R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)\right].$
- Potential: $V(\phi) = \Lambda^4\left[1 - \exp\left(-\sqrt{\frac{2}{3\alpha}}\frac{\phi}{M_{\rm Pl}}\right)\right]^{2n}.$

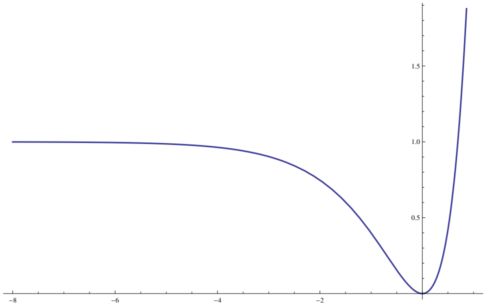


Figure: Inflaton potential.

Background Inflationary dynamics

- The presence of $V(\phi)$ in S ensures a viable slow roll inflation compatible with Planck constraints.

- Thus we take the background inflationary scale factor as a de-Sitter one:

$$a(\eta) = -1/\left(H_{\mathrm{I}}\eta\right) \tag{1}$$

- H_{I} - dS Hubble parameter and η - conformal time.

Reheating: R1 scenario

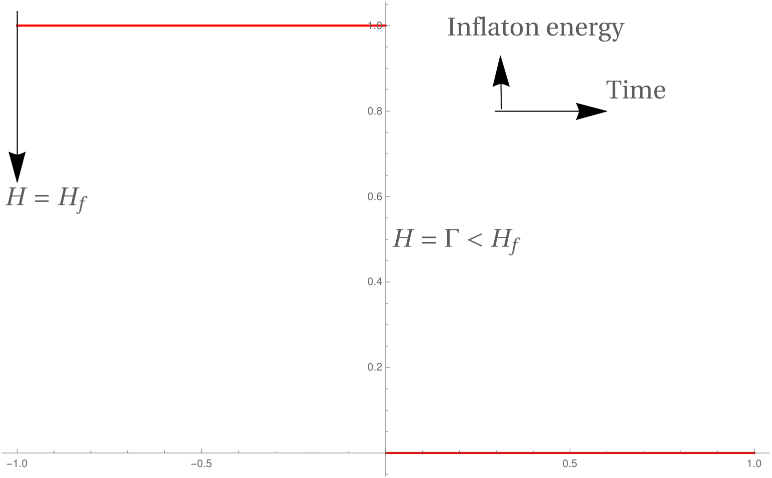


Figure: Inflaton energy density vs. time.

R1 scenario - Continued

- The reheating is dominated by inflaton which instantaneously converts into radiation at the end of reheating.
- Constant EoS parameter of the inflaton field $= \omega$.
- Hubble parameter : $H = H_{\rm f} \left(\frac{a}{a_{\rm f}}\right)^{-\frac{3(1+\omega)}{2}}$.
- End of reheating : $H_{\rm re} = \Gamma$ (Decay constant).

R2 scenario

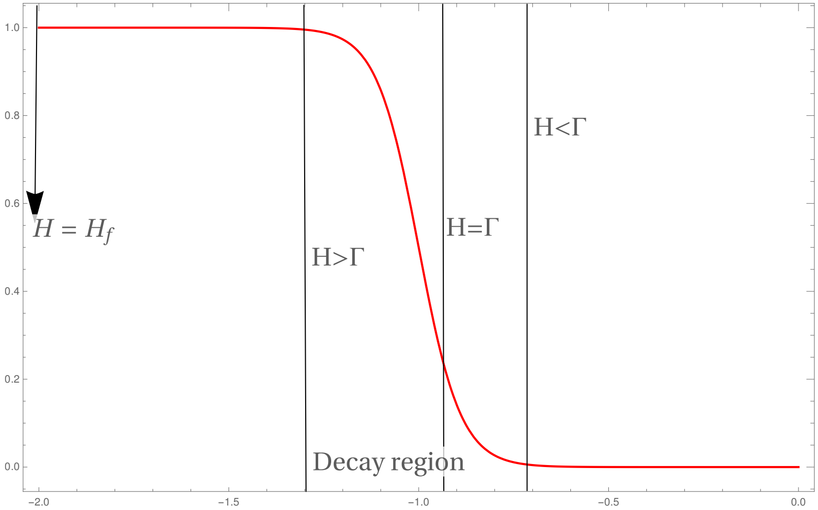


Figure: Inflaton energy density vs. time.

R2 scenario - Continued

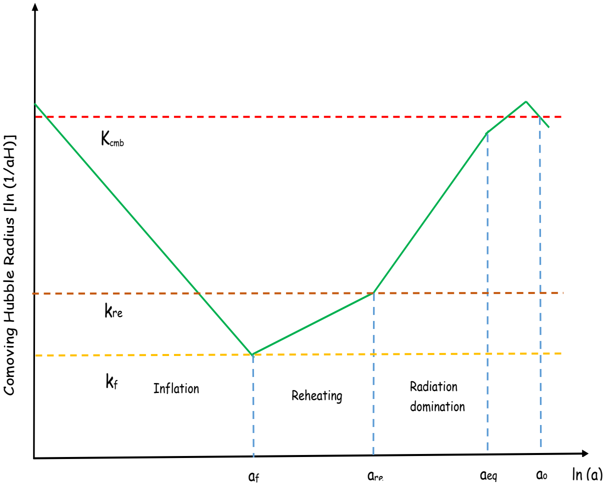
- The inflaton gradually decays into radiation.
- Effective EoS parameter during reheating: $\omega_{\rm eff} = \frac{3\omega\rho_\phi + \rho_{\rm r}}{3\left(\rho_\phi + \rho_{\rm r}\right)}$.
- During most of the reheating stage, $\rho_{\rm r} = 0$ and $\omega_{\rm eff} = \omega$ $\implies R1 \equiv R2$.
- Around the end of reheating, $\rho_{\rm r} \neq 0$ and $\omega_{\rm eff} \neq \omega$ $\implies R1 \neq R2$.
- Therefore, the R2 scenario differs from R1 around the end of reheating.

Background Radiation dynamics

- During reheating, the inflaton converts into radiation, which in turn indicates the beginning of the radiation when the EoS $= 1/3$.
- Thus the Hubble parameter during radiation epoch is given by,

$$H = H_{\rm re} \left(\frac{a}{a_{\rm re}} \right)^{-2}$$

2nd part: Brief about GWs energy density.


Comoving Hubble Radius [ln (1/aH)]
Kcmb
kre
kf
Inflation
Reheating
Radiation domination
af
are
aeq
a0
ln (a)

- Tensor perturbation or GWs variable: $h_{ij}(\eta, \vec{x})$ or $h_k(\eta)$:

$$ds^2 = a^2(\eta)\left[-d\eta^2 + (\delta_{ij} + h_{ij})\, dx^i dx^j\right]$$

- Equation of GWs variable:

$$h_k''(\eta) + \frac{2a'}{a} h_k' + k^2 h_k = 0$$

- GWs energy density: $\rho_{\rm GW}(k, \eta) = \frac{M_{\rm Pl}^2}{a^2} \frac{k^3}{4\pi^2}\left[\left|h_k'\right|^2 + k^2 \left|h_k\right|^2\right]$.

- Dimensionless GWs energy density: $\Omega_{\rm GW}(k, \eta) = \rho_{\rm GW} / \left(3 M_{\rm Pl}^2 H^2\right)$.

- Interested to determine: $\Omega_{\rm GW}\big|_0$.

3rd Part (A): Decoding the R1 reheating by GWs spectrum.

GWs during inflation

- GWs energy density during inflation:

$$\rho_{\rm GW}(k,a) \propto H_{\rm I}^2 \left(\frac{k^2}{a^2}\right) \left[1 + 2\left(\frac{k}{H_{\rm I}a(\eta)}\right)^2\right]$$

- At super-horizon scale, $k \ll H_{\rm I}a$:

$$\rho_{\rm GW}(k,a) \propto H_{\rm I}^2 \left(\frac{k^2}{a^2}\right)$$

- Therefore the comoving GWs energy density increases with time during inflation.

GWs during R1 reheating

- GWs energy density during reheating for $k < k_{\rm re}$:

$$\rho_{\rm GW}(k,a) \propto H_{\rm I}^2 \left(\frac{k^2}{a^2}\right)$$

- GWs energy density during reheating for $k > k_{\rm re}$:

$$\rho_{\rm GW}(k,a) \propto H_{\rm I}^2 \left(\frac{k^2}{a^4}\right) \cos^2\left(\frac{k}{\gamma k_{\rm f}} a^{\gamma}\right) \left[\left|C_k\right|^2 + \left|D_k\right|^2\right]$$

- Therefore the comoving GWs energy density - (a) increases for $k < k_{\rm re}$ and (b) oscillates with almost constant amplitude for $k > k_{\rm re}$.

GWs during radiation

- GWs energy density during radiation:

$$\rho_{\mathrm{GW}}(k, a) \propto H_{\mathrm{I}}^2 \left(\frac{k^2}{a^4}\right) \left[\left|E_k\right|^2 + \left|F_k\right|^2\right]$$

- Therefore the comoving GWs energy density becomes constant during radiation.

Dimensionless GWs energy density today

- For $k < k_{\rm re}$: $\Omega_{\rm GW} = \Omega_R \left(\frac{H_{\rm I}^2}{12\pi^2 M_{\rm Pl}^2}\right)$.

- For $k_{\rm re} < k < k_{\rm f}$:
$$\Omega_{\rm GW} h^2 = \Omega_R h^2 \left(\frac{H_{\rm I}^2}{12\pi^2 M_{\rm Pl}^2}\right) \Gamma^2 \left(1 + \frac{\nu}{\gamma}\right) \left(\frac{k}{k_{\rm re}}\right)^{n_{\rm GW}}.$$

- $n_{\rm GW} = \frac{2(3\omega - 1)}{(3\omega + 1)}$.

- Three cases:
  1. $n_{\rm GW} < 0$ for $\omega < 1/3$; Red tilted spectrum.
  2. $n_{\rm GW} > 0$ for $\omega > 1/3$; Blue tilted spectrum.
  3. $n_{\rm GW} = 0$ for $\omega = 1/3$; Flat spectrum.

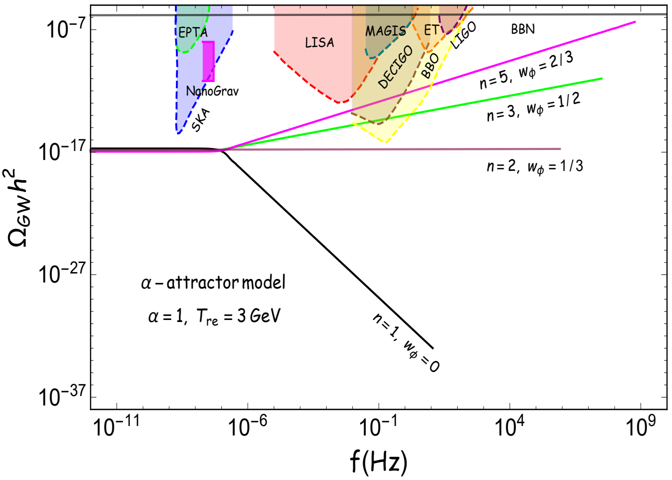


Figure: $\Omega_{\rm GW}$ (today) for different reheating EoS parameter.

Probing the R1 reheating scenario by GWs spectrum

- From the slope of $\Omega_{\rm GW}$, we can probe the inital value of the reheating EoS.
- The break of $\Omega_{\rm GW}$ occurs at $k = k_{\rm re}$. Thus the $\Omega_{\rm GW}$ can extract $k_{\rm re}$, which will probe the $H_{\rm re}$ or equivalently Γ (the decay rate of inflaton).

3rd Part (B): Decoding the R2 reheating by GWs spectrum.

GWs spectrum for R2 reheating

- During inflation, ρ_{GW} have the same evolution as earlier.
- During the R2 reheating era, we numerically solve the tensor perturbation equation, by using the background evolution.
- During radiation era, ρ_{GW} have the same evolution as earlier.
- Consequently, we arrive at Ω_{GW} at present epoch.

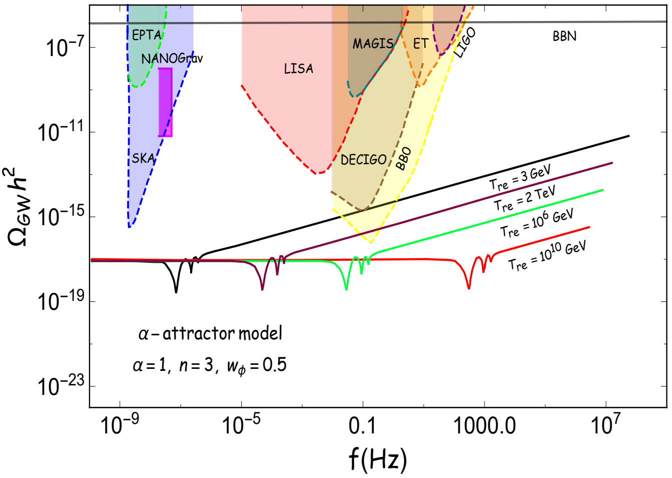


Figure: $\Omega_{\rm GW}$ (today) for different reheating EoS parameter.

The absence or presence of oscillation will help to confirm the R1 or R2 scenario respectively.

TAKE HOME MESSAGE

- The reheating era connects the inflationary universe with the standard Big-Bang cosmology.
- However our understanding of the reheating era is still at its novice stage in terms of both theory and observations.
- We provide a possible way to probe the reheating phase from GWs spectrum.

TAKE HOME MESSAGE

- Discussed how the GWs spectrum (if observed) can probe the reheating EoS parameter and / or the inflaton decay rate during the reheating stage.

- Discussed how to probe a particular reheating mechanism by PGWs.

- Consistency with NANOGrav - please see our paper Phys.Rev.D 104 (2021) 6, 063513.

THANK YOU

HAVE A NICE DAY