Possible determination of the reheating temperature by direct detection of the inflationary gravitational wave background

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Abstract

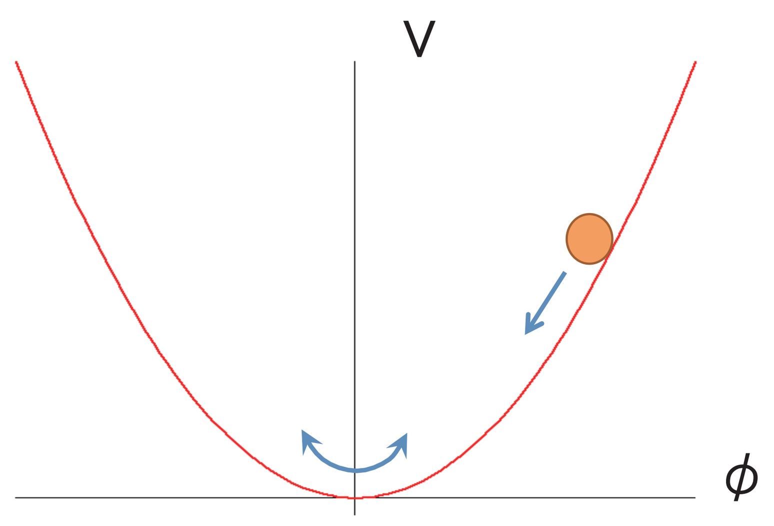
The gravitational wave background from inflation is expected to be a powerful tool to extract information not only on inflation but also on thermal history of the Universe after inflation. Most notably, reheating may have left its footprint on the shape of the inflationary gravitational wave background spectrum around the frequency where future gravitational wave direct detection experiments like DECIGO/BBO are targeting. The detectability of the reheating signature by future experiments is evaluated by calculating the Fisher information matrix.

Gravitational waves from inflation

- originate from quantum fluctuations in the space time metric during inflation
- propagate freely because of their weak interactions with matter = provide clean information about inflation.
- predicted to have an almost scale-invariant primordial spectrum.

The shape of the spectrum is affected by the history of the Hubble expansion.

Reheating after inflation



In the standard inflationary scenario, a slow-rolling scalar field (ϕ) drives inflation and it subsequently decays into radiation oscillating at the bottom of the potential. The Universe evolves like a matter-dominated universe during this oscillation phase, called reheating, and turns into a radiation-dominated era after reheating ends.

In the case of perturbative decay into light fermions, the equation take simple forms.

$$\ddot{\phi} + (3H+\Gamma)\dot{\phi} + \frac{\partial V(\phi)}{\partial \phi} = 0$$

$$\dot{\rho}_r + 4H\rho_r = \Gamma\rho_\phi$$

$$H^2 = \frac{8\pi}{3m_{Pl}^2}(\rho_\phi + \rho_r)$$

reheating temperature: $T_{RH} \simeq g_{*,RH}^{-(1/4)} \left(\frac{45}{8\pi^3}\right)^{1/4} (m_{Pl}\Gamma)^{1/2}$

Γ : decay rate of the scalar field

g_* : the effective number of degrees of freedom

The spectrum of the gravitational wave background

The intensity of a stochastic gravitational wave background is commonly characterized by the dimensionless quantity

$$\Omega_{GW} \equiv \frac{1}{\rho_c}\frac{d\rho_{GW}}{d\ln k}$$ (the gravitational wave energy density per logarithmic frequency in units of the critical density)

It is convenient to divide the spectrum of the gravitational wave background as $\Omega_{GW} = \frac{1}{12}\left(\frac{k}{aH}\right)^2 \Delta^2_{h,prim}(k) T_h^2(k)$

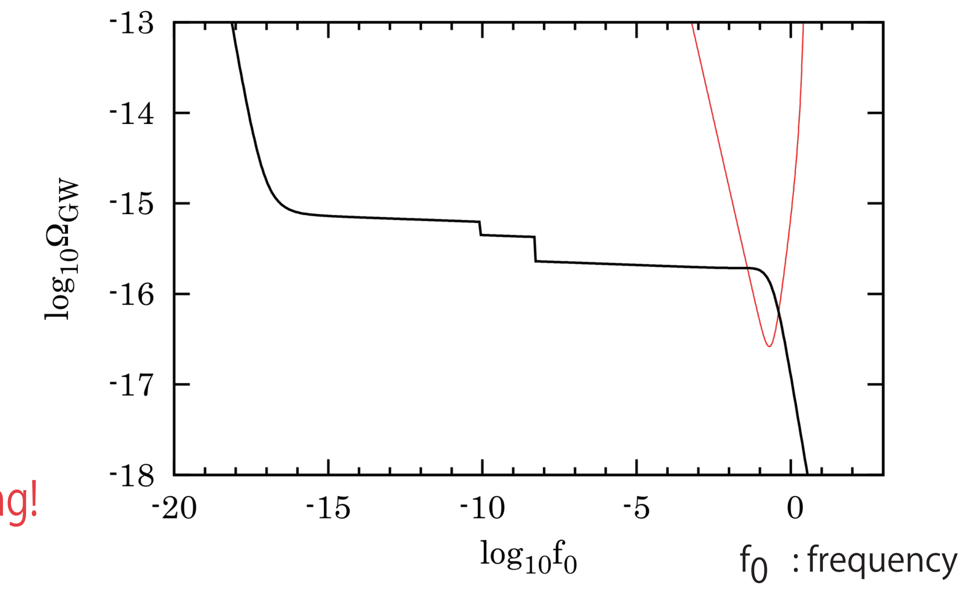
the initial power spectrum $\Delta^2_{h,prim}(k) \simeq r\Delta^2_{\zeta,prim} \exp\left[-\frac{r}{8}\ln\frac{k}{k_0} + \cdots\right]$

tensor to scalar ratio: $r \equiv \frac{\Delta_h^2(k_{CMB})}{\Delta_{\mathcal{R}}^2(k_{CMB})} \simeq 16\epsilon$

the transfer function $T_h^2(k) = (1-\Omega_\Lambda)^2 \left(\frac{g_*(T_{hc})}{g_{*0}}\right)\left(\frac{g_{*s0}}{g_{*s}(T_{hc})}\right)^{4/3}\left(\frac{3}{\sqrt{2}(k\tau_0)^2}\right)^2 (1+1.34x_{eq}+2.5x_{eq}^2)(1-0.32x_R+0.99x_R^2)^{-1}$ ← the effect of reheating!

$x_{eq} = k/k_{eq}$ $x_R = k/k_R$

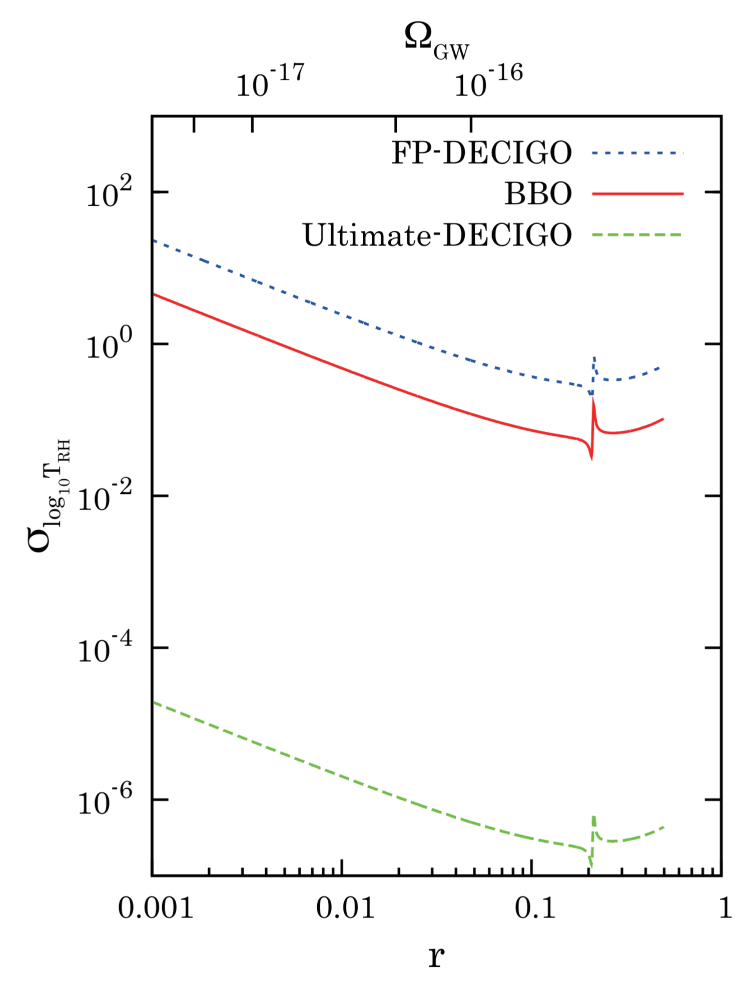
Theoretical prediction for the spectrum of the inflationary gravitational wave background for $T_{RH}=10^7$GeV



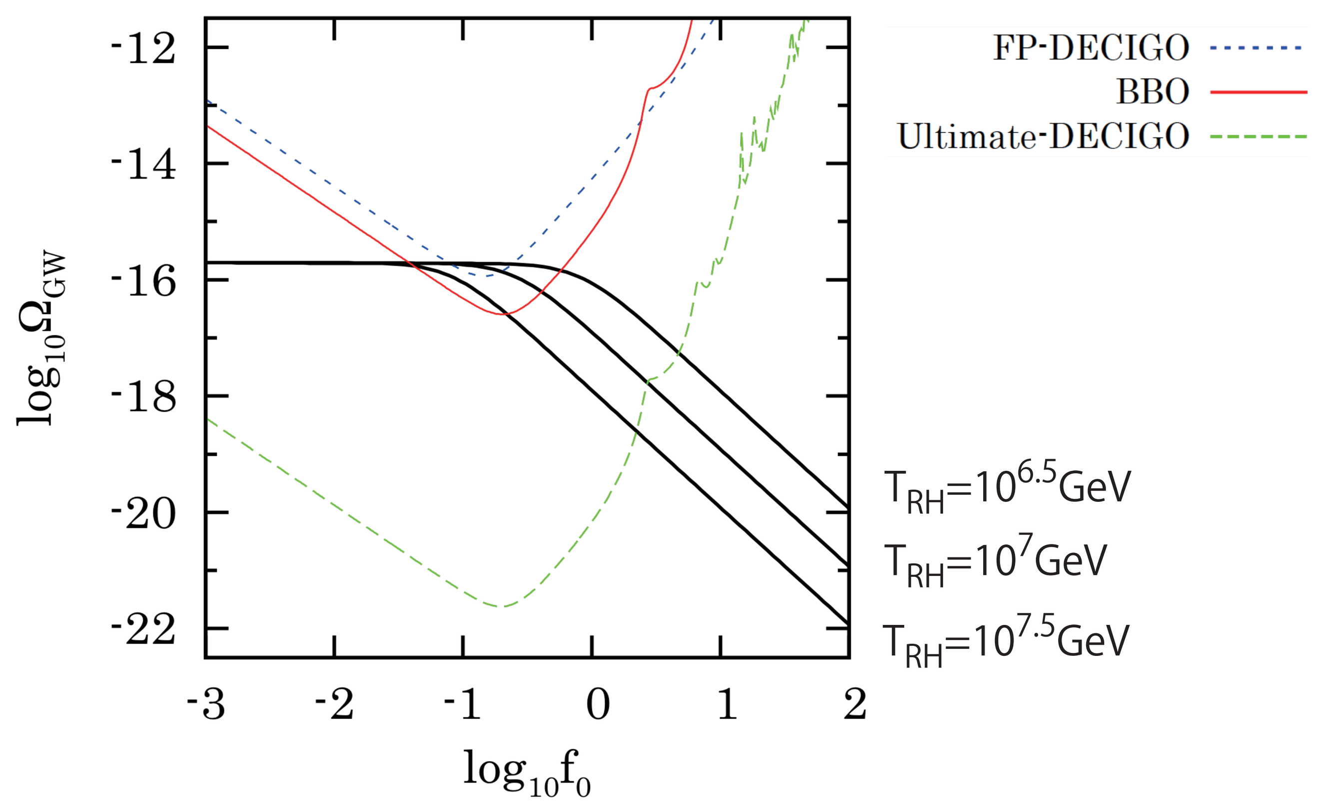
Forecast based on the Fisher matrix analysis

errors on the reheating temperature T_R
(10 year obserbation, $T_{RH}=10^7$GeV)

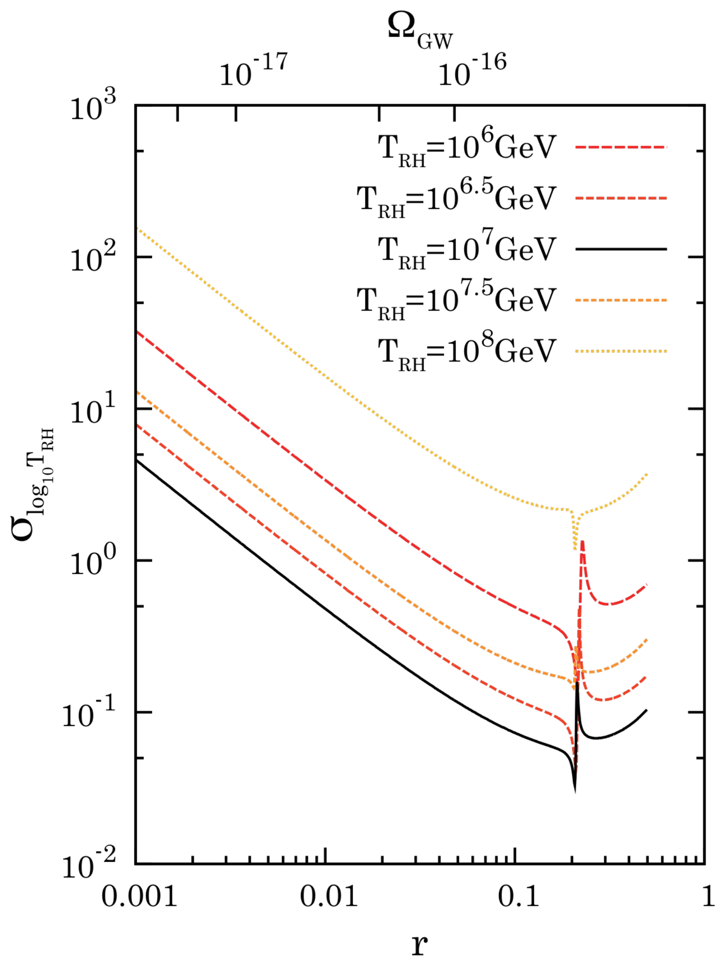
The signature of reheating is detectable with BBO if r>0.1, and the reheating temperature is determined with the accuracy of about 10%.



The spectrum of the inflationary gravitational wave background for several reheating temperatures and sensitivity curves of the future experiments

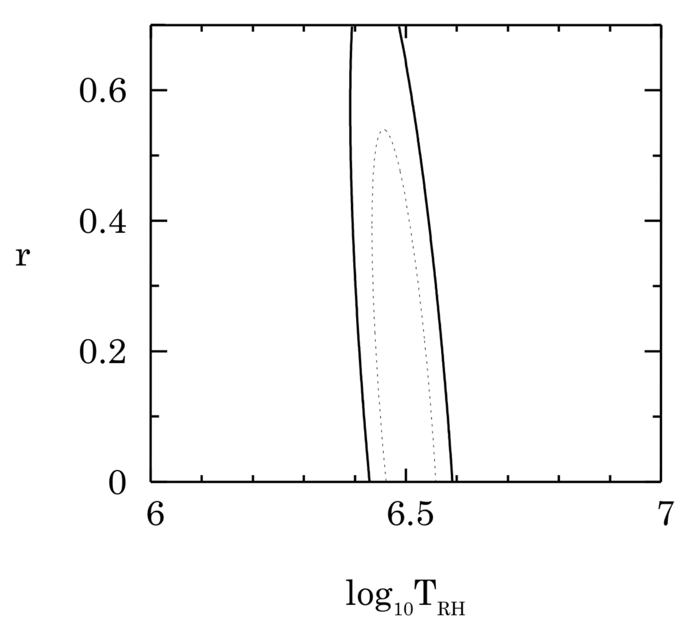


Dependence on reheating temperature



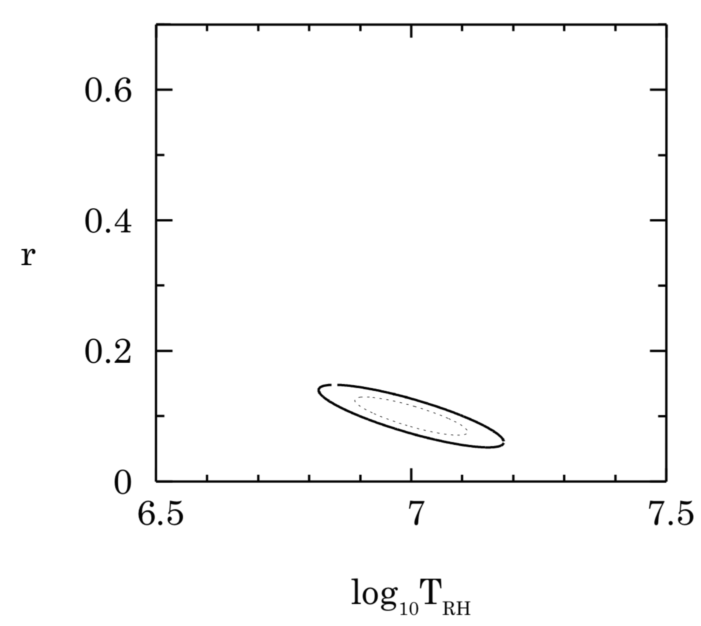
(BBO 10 year obserbation, r=0.1)

$T_{RH}=10^{6.5}$GeV
signal to noise ratio: 6.5



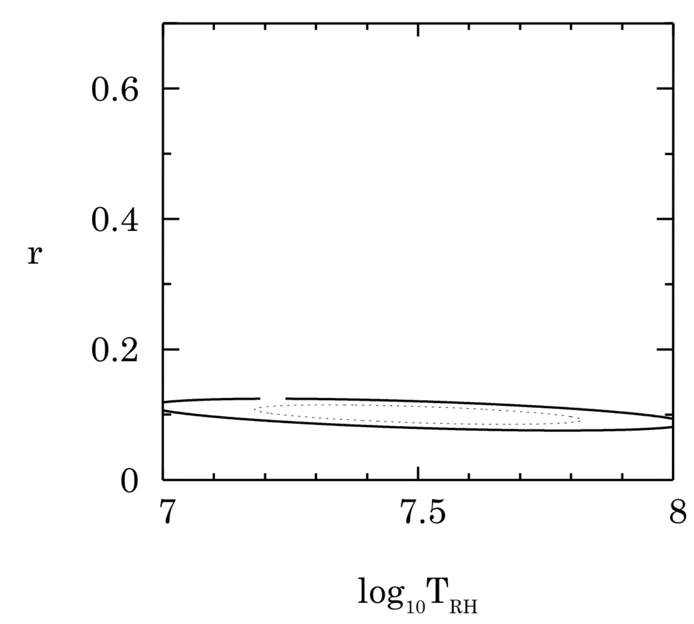
low signal to noise ratio
→ less power to determine the amplitude (r)

$T_{RH}=10^{7}$GeV
signal to noise ratio: 16.8



The edge is just on the sensitive spot
→ tight constraint on the reheating temperature

$T_{RH}=10^{7.5}$GeV
signal to noise ratio: 22.0



almost flat spectrum inside the sensitivity curve
→ cannot determine the reheating temperature

Summary

The matter-dominat phase during reheating would be imprinted in the spectrum of the inflationary gravitational wave background, the frequency of which strongly depends on the reheating temperature. We have performed a Fisher matrix analysis to predict the possibility of detecting the signature of reheating by future direct detection gravitational wave experiments, and discussed how well it can determine the reheating temperature. Although the sensitivity range of direct detection experiments is not wide enough to search the reheating signature, the future experiments have potential to find the evidence of reheating if the reheating temperature is around 10^7GeV.

Reference: K. Nakayama, S. Saito, Y. Suwa and J. Yokoyama, J. Cosmol. Astropart. Phys. 06 (2008) 020, K. Nakayama, S. Saito, Y. Suwa and J. Yokoyama, Phys. Rev. D 77, 124001 (2008). S. Kuroyanagi, T. Chiba and N. Sugiyama, Phys. Rev. D 79, 103501 (2009).