Gravitational waves from Standard Model* Axion*Seesaw*Higgs portal inflation

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Introduction

Standard Model*Axion*Seesaw*Higgs portal inflation (SMASH) [1, 2] is a minimal extension of the Standard Model (SM) that addresses five fundamental problems of particle physics and cosmology (the origin of neutrino masses, strong CP problem, nature of inflation, generation of matter-antimatter asymmetry in the Universe, and identity of dark matter) in one stroke. An important aspect of the SMASH model is its predictivity. Because of its constrained framework, the model provides definite predictions for various cosmological observables that can be probed by upcoming experiments. Here we focus on the primordial gravitational waves (GWs) in the SMASH model and point out that there is indeed a unique prediction for the shape of the spectrum of GWs due to the nontrivial feature of the Peccei-Quinn (PQ) phase transition described in this model.

The SMASH model

In the SMASH model, the SM is extended by adding a new complex scalar field σ (the PQ field), three singlet neutrinos N_i with $i = 1, 2, 3$, and a vector-like quark Q. It is assumed that there is a global U(1) symmetry (PQ symmetry) which is spontaneously broken when the σ field acquires a vacuum expectation value v_σ. Axion arises as a Goldstone boson associated with the spontaneous breaking of the PQ symmetry, and it can be the main constituent of dark matter if a new intermediate scale becomes of order $v_\sigma \sim 10^{11}\,\mathrm{GeV}$. This new energy scale also provides large Majorana masses for heavy neutrinos, which explains the smallness of the SM neutrino masses through the seesaw mechanism and leads to the generation of baryon asymmetry of the Universe via the leptogenesis scenario. In this framework, inflation can arise from the dynamics of the Higgs and PQ fields in the presence of non-minimal couplings to gravity.

An intriguing prediction of the SMASH model is that there is nontrivial constraints on the nature of the PQ phase transition. It turns out that the rehearing temperature becomes sufficiently high such that the PQ symmetry is thermally restored after inflation and spontaneously broken afterwards, which goes as a second order phase transition. The critical temperature of the PQ phase transition can be estimated as [2]

$$\frac{T_c}{f_A} = \frac{2\sqrt{6\lambda_\sigma}}{\sqrt{8(\lambda_\sigma + \lambda_{H\sigma}) + \sum_i Y_{ii}^2 + 6y^2}}, \qquad (1)$$

where $f_A = v_\sigma$ is the axion decay constant, λ_σ the self-coupling of the PQ field, $\lambda_{H\sigma}$ the Higgs portal coupling, Y_{ii} and y the Yukawa couplings of N_i and Q, respectively. There are several constraints on these coupling parameters:

- The successful inflation requires $5\times 10^{-13} \lesssim \lambda_\sigma \lesssim 5\times 10^{-10}$.
- The requirement of vacuum stability implies $|\lambda_{H\sigma}| \lesssim Y_{ii}^2$ and $Y_{ii} \sim y \sim \lambda_\sigma^{1/4}$.
- Axions become the main constituent of dark matter if $f_A \sim 10^{11}\,\mathrm{GeV}$.

Combining these conditions, we obtain the following estimate of the critical temperature of the PQ phase transition,

$$\boxed{T_c \sim \lambda_\sigma^{1/4} f_A \sim \mathcal{O}(10^7\text{–}10^8)\,\mathrm{GeV}.} \qquad (2)$$

Around the critical temperature, there is a change in the equation of state of the Universe. Figure 1 shows a typical evolution of the effective degrees of freedom for the energy density and entropy density across the PQ phase transition.

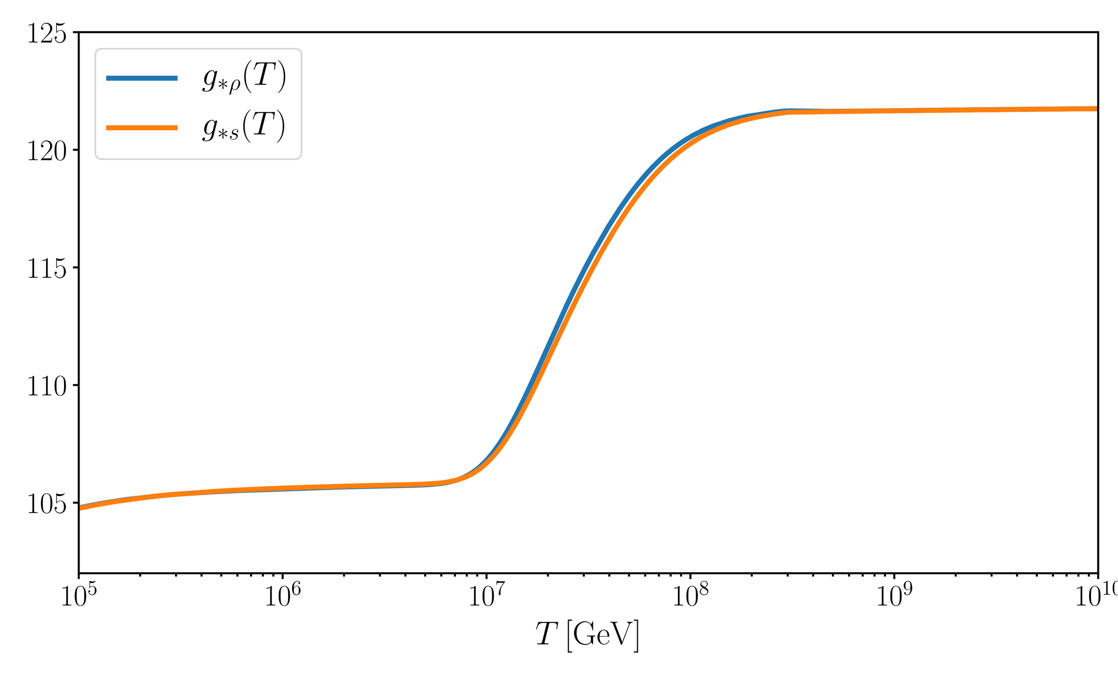

Figure 1: Temperature dependence of the effective degrees of freedom in the SMASH model.

Prediction for gravitational waves

The information about the thermal history of the Universe described above can be imprinted on the spectrum of primordial GWs. The GWs are originated from tensor fluctuations during inflation, and their spectrum at the present (conformal) time $\tau = \tau_0$ can be described as

$$\Omega_{\rm gw}(k) \equiv \frac{1}{\rho_{\rm crit}}\frac{d\rho_{\rm gw}(k)}{d\ln k} = T(k)\mathcal{P}_T(k), \quad T(k) \equiv \frac{1}{12a_0^2H_0^2}\left[\frac{d\chi(k,\tau_0)}{d\tau}\right]^2, \qquad (3)$$

where $\mathcal{P}_T(k)$ is the primordial tensor power spectrum, $T(k)$ the transfer function of GWs, and $\chi(k,\tau)$ the dimensionless tensor perturbations. $\mathcal{P}_T(k)$ is determined by the dynamics during inflation and becomes almost scale-invariant, as shown in Fig. 2. On the other hand, $T(k)$ represents the evolution of GWs after the modes reenter the horizon, and it contains information about thermal history of the Universe after inflation. In particular, changes in the effective degrees of freedom lead to modifications of the shape of $T(k)$ [3]. We note that there is a relation between the frequency of GWs and temperature $T_{\rm hc}$ at which the corresponding mode crosses the horizon,

$$f = \frac{k}{2\pi a_0} = \frac{H_{\rm hc}a_{\rm hc}}{2\pi\ a_0} \approx 2.65\,\mathrm{Hz}\left(\frac{g_{*\rho}(T_{\rm hc})}{106.75}\right)^{\frac{1}{2}}\left(\frac{g_{*s}(T_{\rm hc})}{106.75}\right)^{-\frac{1}{3}}\left(\frac{T_{\rm hc}}{10^8\,\mathrm{GeV}}\right), \qquad (4)$$

and hence the modifications in $T(k)$ (or $\Omega_{\rm gw}(f)$) at particular frequency ranges can be related to cosmological events occurring at corresponding temperatures.

By extending the formalism of Ref. [4] developed in the context of the SM, we compute the spectrum of GWs in the SMASH model. Figure 3 shows the result for the spectrum for a broad frequency interval compared to the sensitivities of various GW direct/indirect detection experiments. Note that ultimate DECIGO [5] can probe the primordial GWs at frequencies of $f \sim 0.1$–$1\,\mathrm{Hz}$, and such frequencies correspond to the modes that reenter the horizon around the epoch of the PQ phase transition, $T \sim 10^7$–$10^8\,\mathrm{GeV}$. The change of the effective degrees of freedom shown in Fig. 1 leads to a step in the GW spectrum at the corresponding frequency range, as shown in Fig. 4. We see that such a feature can be identified with the ultimate sensitivity of DECIGO, and hence there is a possibility to explore the nature of the PQ phase transition in a minimal model of particle cosmology in future high-sensitivity GW experiments.

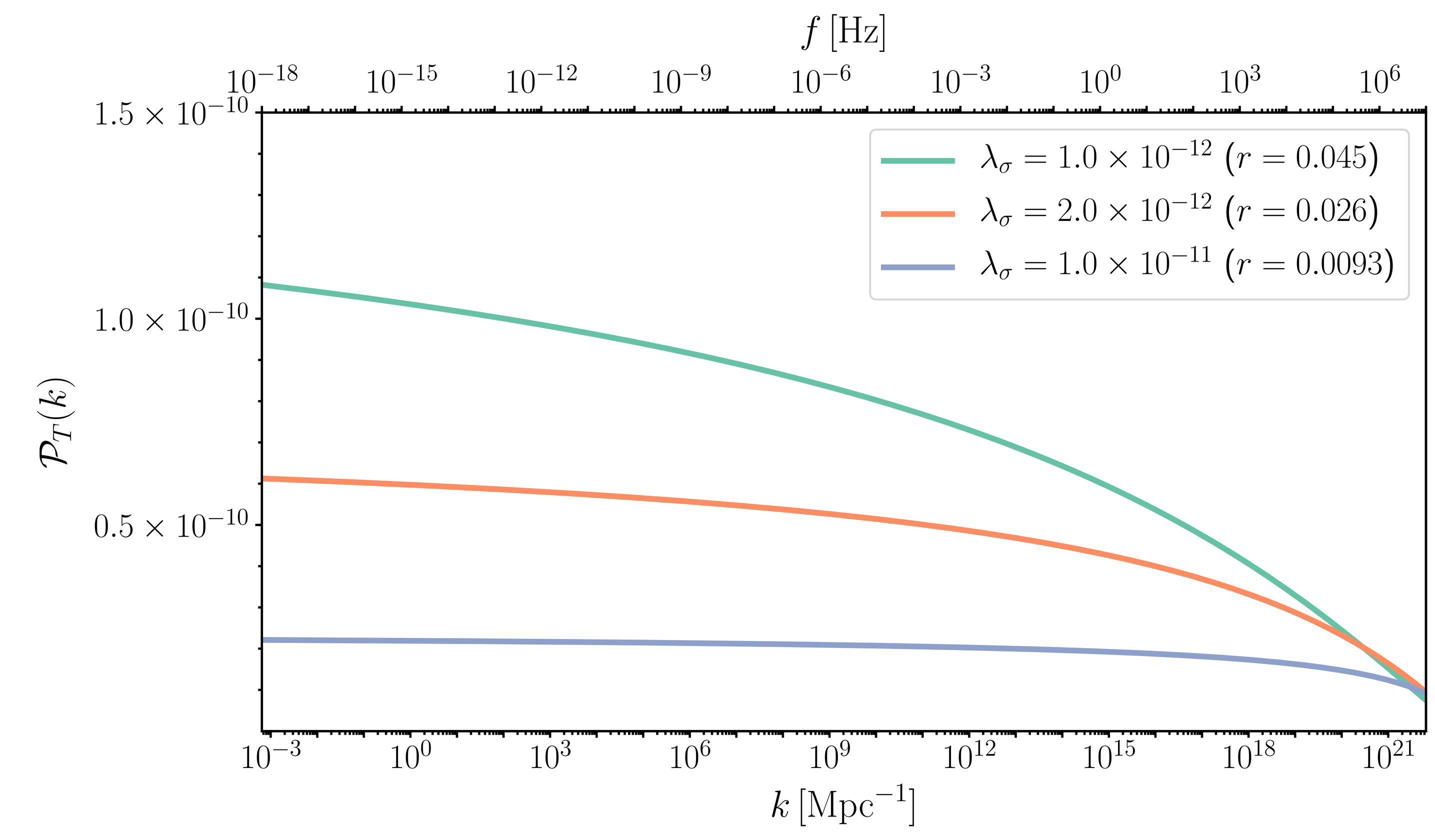

Figure 2: The primordial tensor power spectrum in the SMASH model.

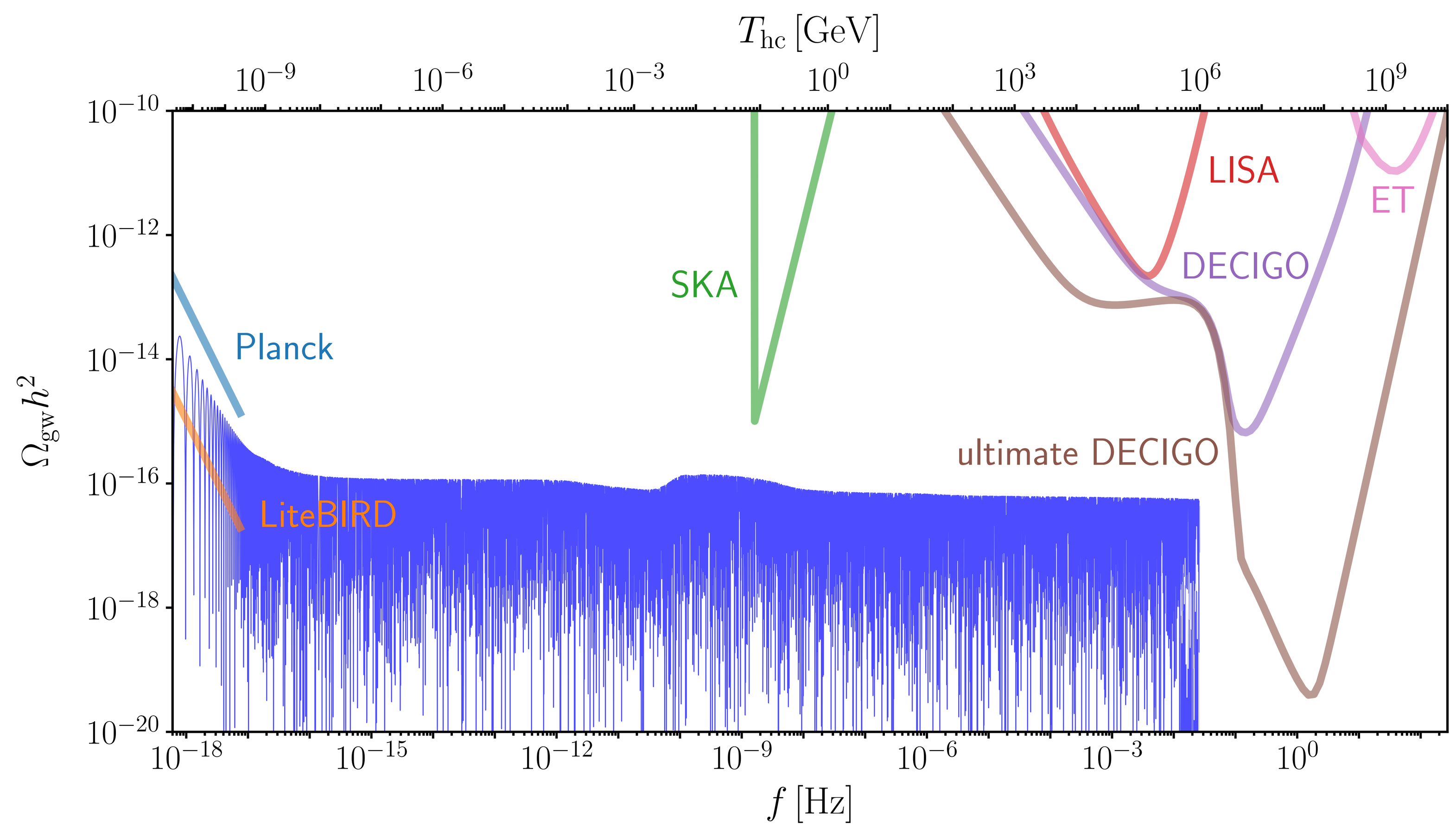

Figure 3: The spectrum of GWs in the SMASH model and various experimental sensitivities.

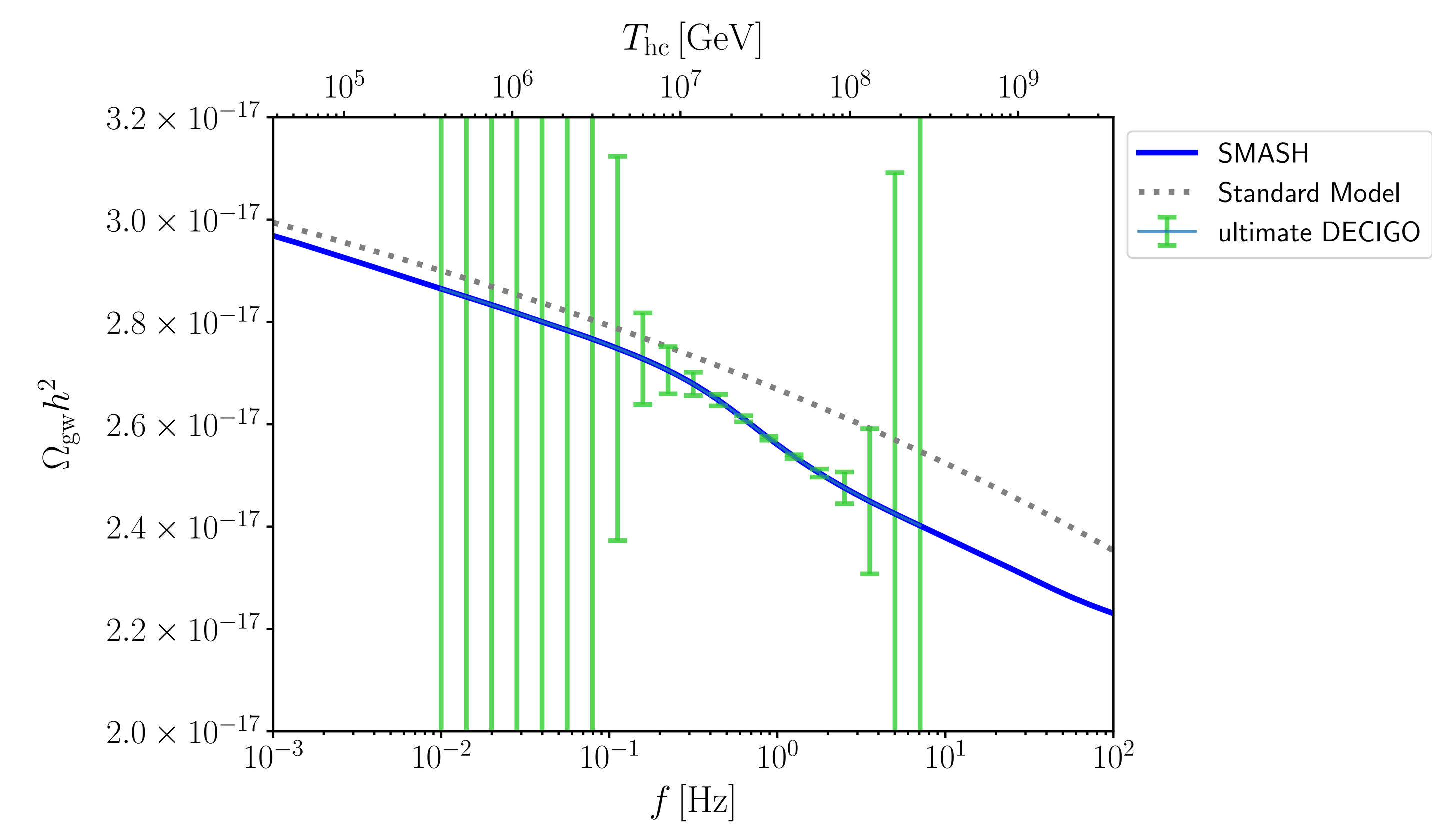

Figure 4: The spectrum of GWs at a higher frequency range and sensitivity of ultimate DECIGO.

Summary

- The SMASH model gives a unique prediction for the critical temperature of the PQ phase transition, $T_c \sim \mathcal{O}(10^7\text{–}10^8)\,\mathrm{GeV}$.
- The temperature range $T_c \sim \mathcal{O}(10^7\text{–}10^8)\,\mathrm{GeV}$ corresponds to the frequency of GWs $f \sim 0.1$–$1\,\mathrm{Hz}$, which is the best frequency range probed by future space-borne GW interferometers.
- The change of the equation of state around the PQ phase transition leads to a step in the spectrum of primordial GWs, and such a feature can be tested by ultimate DECIGO.

References

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