Probing instant preheating by gravitational waves

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Based on

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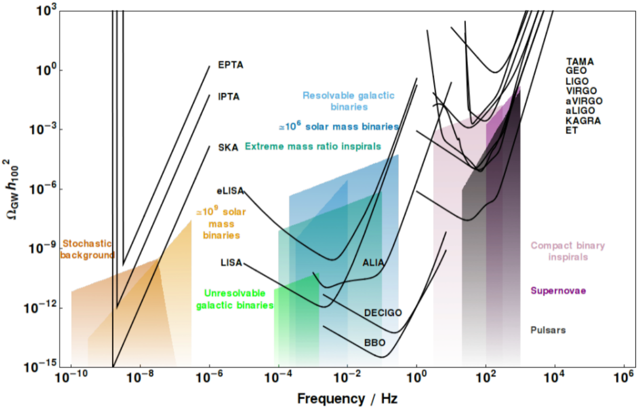
Dual Gravitational Wave Signatures of Instant Preheating, to appear.

Overview

Introduction

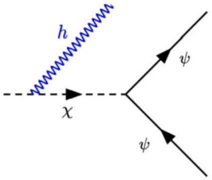
- Many proposals targeting at high frequency GWs, such as resonance cavities, superconducting rings, interferometers, see review 2011.12414

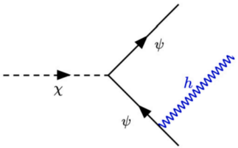


1408.0740

Introduction

1. In instant preheating, daughter particles can temporarily become superheavy, even approaching the Planck scale.
   $\phi \to \chi \to \psi\bar{\psi}$
2. Distinct GW signals can be produced in the process:
   graviton bremsstrahlung
   parametric resonance





Model

- Consider Lagrangian, Phys.Rev.D 60 (1999) 103505

$$\mathcal{L} \supset -\frac{1}{2}m_\phi^2\phi^2 - \frac{1}{2}\lambda^2\phi^2\chi^2 + y\chi\bar{\psi}\psi \ , \tag{1}$$

- The number density of the produced χ particles after just half of oscillation can be estimated as,

$$n_\chi \simeq \left(\frac{k_*}{2\pi}\right)^3 \ , \qquad k_* = \sqrt{\lambda m_\phi \phi_i} \ , \tag{2}$$

- From Yukawa coupling, the decay rate of χ is given by

$$\Gamma_{\chi\to\bar{\psi}\psi} = \frac{y^2 m_\chi}{8\pi} = \frac{y^2\lambda\phi(t)}{8\pi} \simeq \frac{y^2\lambda m_\phi \phi_i t}{8\pi} \ . \tag{3}$$

Energy loss

- The decay time is given by $t_{\rm dec} \simeq \sqrt{8\pi/(y^2 \lambda m_\phi \phi_i)}$
- Correspondingly, the mass of χ at the instance of its decay is given by

$$m_\chi(t_{\rm dec}) \simeq \lambda\phi(t_{\rm dec}) \simeq \sqrt{\frac{8\pi\lambda m_\phi \phi_i}{y^2}} \lesssim \lambda\phi_i \ . \tag{4}$$

- The energy loss of the inflaton in one half oscillation is then given by

$$\frac{\delta\rho_\phi}{\rho_\phi} \sim \frac{m_\chi(t_{\rm dec}) n_\chi}{\rho_\phi} \sim \frac{\lambda^2}{4\pi^3}\sqrt{\frac{8\pi}{y^2}} \lesssim \mathcal{O}(1) \times \lambda^{5/2} \ . \tag{5}$$

GWs production

- Two-body decay process $\chi \to \psi\bar{\psi}$ is associated with the three-body graviton bremsstrahlung process $\chi \to \psi\bar{\psi} + h$, whose differential decay rate is given by

$$\frac{d\Gamma_{\mathrm{brem}}}{d\ln E} = \frac{y^2}{64\pi^3}\frac{m_\chi^3}{M_{\mathrm{Pl}}^2}(1-2x)(1-2x+2x^2)\ , \tag{6}$$

  where $x \equiv E/m_\chi$.

- The branching ratio of χ to the graviton bremsstrahlung is

$$\mathrm{Br}_{\chi\to\psi\bar{\psi}h} \simeq \frac{1}{8\pi^2}\left(\frac{m_\chi}{M_{\mathrm{Pl}}}\right)^2 \tag{7}$$

  Therefore, heavier χ will result in more significant amount of produced GWs in the Universe.

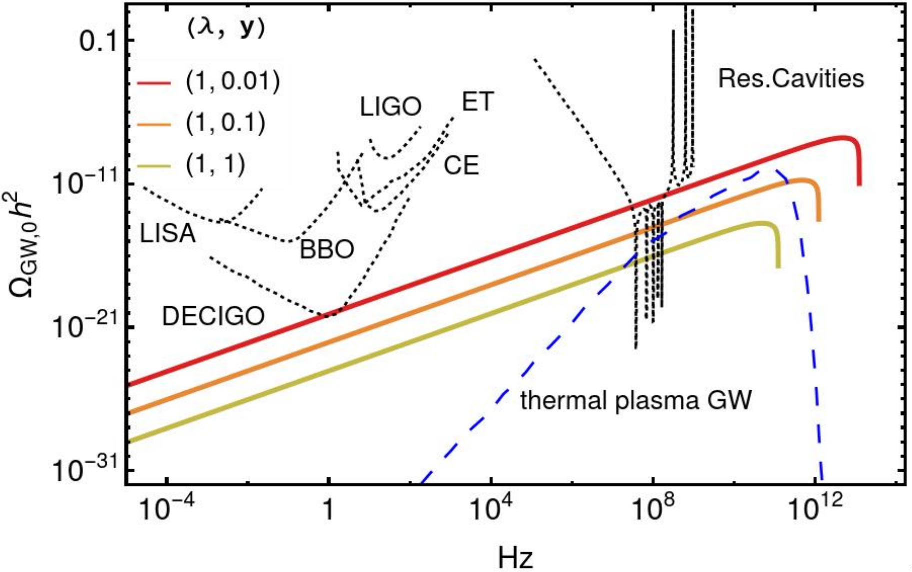
Graviton Bremsstrahlung

- The present-day GW spectrum can be estimated as,

$$\frac{d\Omega_{\rm GW}}{d\ln E_0} = \epsilon\,\Omega_{\rm rad}\left(\frac{g_*}{g_{*0}}\right)\left(\frac{g_{*s0}}{g_{*s}}\right)^{\frac{4}{3}}\left(\frac{m_\chi n_\chi}{\rho_{\rm tot}}\right)_{z_{\rm dec}} \times {\rm Br}_{\chi\to\psi\bar{\psi}h} \times x(1-2x)(1-2x+2x^2)\,, \tag{8}$$

$$f_p \simeq 4.6\times 10^{13}\,{\rm Hz}\times\left(\frac{a_{\rm dec}}{a_{\rm reh}}\right)\left(\frac{m_\chi}{M_{\rm Pl}}\right)\left(\frac{10^{15}\,{\rm GeV}}{T_{\rm reh}}\right). \tag{9}$$

GW Spectrum


(λ, y)
(1, 0.01)
(1, 0.1)
(1, 1)
LIGO
ET
CE
Res.Cavities
LISA
BBO
DECIGO
thermal plasma GW
0.1
10^{-11}
10^{-21}
10^{-31}
$\Omega_{GW,0}h^2$
10^{-4}
1
10^{4}
10^{8}
10^{12}
Hz

Parametric Resonance

- χ' parametric resonance $\ddot{\chi}_{\boldsymbol{k}} + 3H\delta\dot{\chi}_{\boldsymbol{k}} + \left(\frac{k^2}{a^2} + \lambda^2\phi^2(t)\right)\delta\chi_{\boldsymbol{k}} = 0.$
- In order to obtain GW from parametric resonance, we have developed our own code to conduct the simulations including field dynamics and GW extraction.
- EoM

$$\ddot{\phi} + 3H\dot{\phi} - \frac{1}{a^2}\nabla^2\phi + \frac{\partial V}{\partial\phi} = 0, \tag{10}$$

$$\ddot{\chi} + (3H + \Gamma)\dot{\chi} - \frac{1}{a^2}\nabla^2\chi + \frac{\partial V}{\partial\chi} = 0, \tag{11}$$

$$\dot{\rho}_{\mathrm{R}} + 3H(1+\omega)\rho_{\mathrm{R}} = \left\langle \Gamma\dot{\chi}^2 \right\rangle, \tag{12}$$

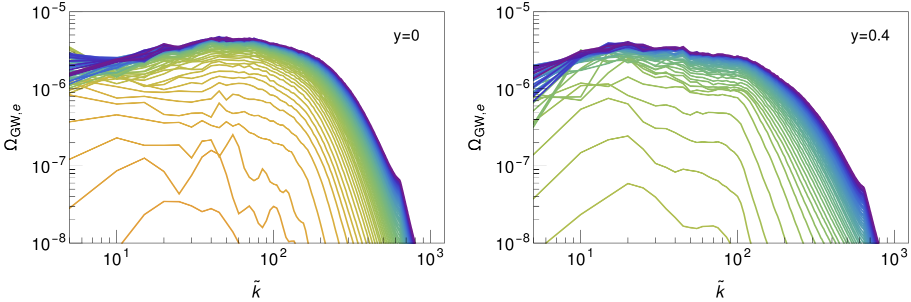
$$\frac{\ddot{a}}{a} = \frac{1}{6M_{\mathrm{Pl}}^2}\left[-\bar{\rho} - 3\bar{p}\right], \tag{13}$$

$$H^2 = \frac{\bar{\rho}}{3M_{\mathrm{Pl}}^2}. \tag{14}$$

GW Production

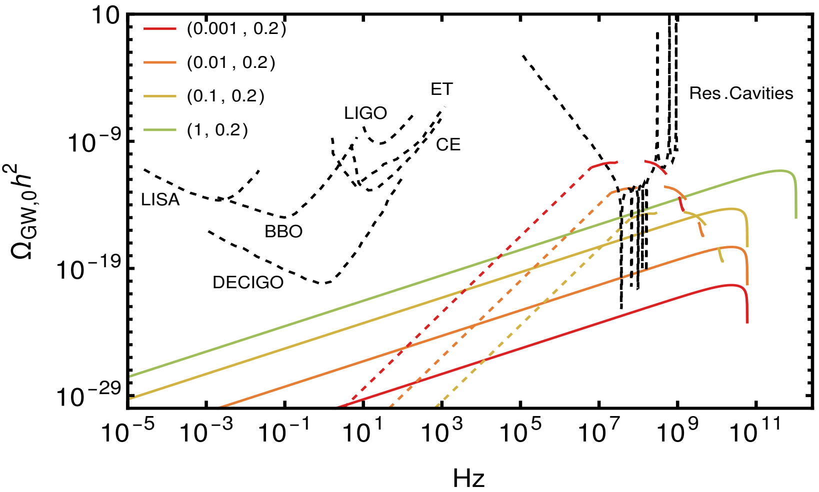
- EoM of tensor perturbation h_{ij} in FLRW spacetime,

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{1}{a^2}\nabla^2 h_{ij} = \frac{2}{m_{pl}^2}\Pi_{ij}^{TT}, \tag{15}$$



GW Spectra Today

- Eventually, we obtain the GW energy spectra today,



Conclusion

- In instant preheating, superheavy particles decay happens and GW from graviton bremsstrahlung can be a direct probe of such physics.
- The peak frequency of GW from graviton bremsstrahlung is 10^{10}Hz – 10^{11}Hz.
- As the Yukawa coupling y increases, the frequency of GW generated by parametric resonance redshifts, around 10^7 Hz – 10^9 Hz.
- Observing these two signals provides a GW detection method for probing instant preheating.

Thanks for your listening!