Probing the Origin of Primordial Black holes using Gravitational Waves

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Gravitational Wave Probes of Physics Beyond Standard Model 2023

1. Introduction
2. Main Scheme
3. Creation Mechanism
4. Creation of Secondary SGWB
5. Cumulative SGWB

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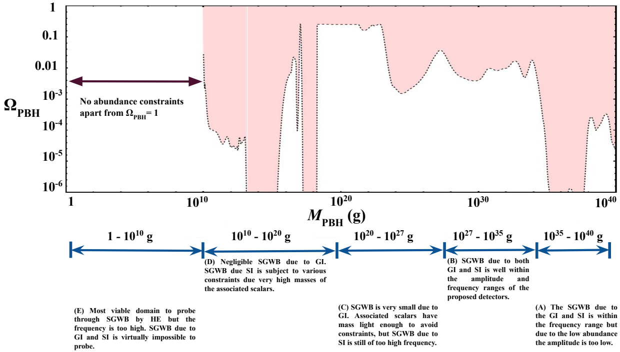
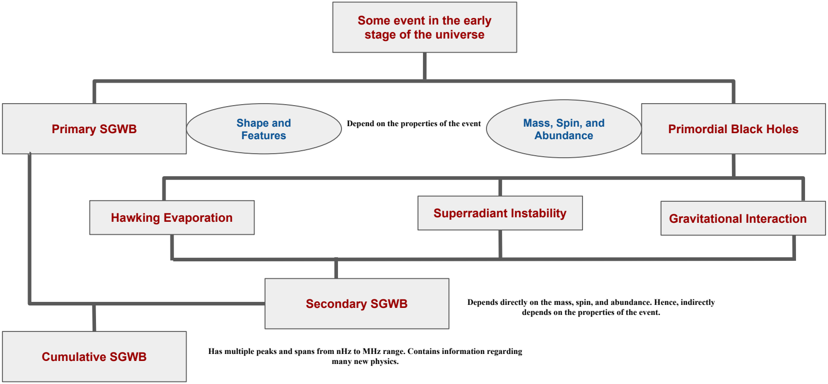
- PBHs can originate from inflation, cosmic strings, first order phase transitions (FOPT), etc

- PBHs can, in principle, be probed from the HE and SI, and gravitational interaction (GI) depending on their mass and spin. HE and SI can create both particles and gravitational waves (GW), whereas GI can create GW.




Some event in the early stage of the universe
Primary SGWB
Shape and Features
Depend on the properties of the event
Mass, Spin, and Abundance
Primordial Black Holes
Hawking Evaporation
Superradiant Instability
Gravitational Interaction
Secondary SGWB
Depends directly on the mass, spin, and abundance. Hence, indirectly depends on the properties of the event.
Cumulative SGWB
Has multiple peaks and spans from nHz to MHz range. Contains information regarding many new physics.

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   - Creation of PBH
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Creation of PBH

- PBHs can be created by curvature perturbations due to inflation, cosmic strings, FOPT, etc.
- In this study, we consider the delayed vacuum decay during a FOPT as the mechanism that creates PBH.
- PBH mass depends on the transition temperature, whereas the PBH abundance and spin depend on the strength of the FOPT (α), the inverse time scale of the FOPT (β), and the transition temperature.
- $\{T, \alpha, \beta/H\} \rightarrow \{M_{\rm PBH}, f_{\rm PBH}\}$
  $\{10 \text{ GeV}, 2.135, 16\} \rightarrow \{4.6 \times 10^{-4} M_\odot, 0.01\}$
  $\{1 \text{ GeV}, 1.2, 10\} \rightarrow \{0.046 M_\odot, 0.02\}$
  $\{0.039 \text{ GeV}, 1, 8\} \rightarrow \{30 M_\odot, 0.006\}$

Creation of Primary SGWB

- During a FOPT, SGWB can be created from the collision of bubble walls, sound waves, and magnetohydrodynamics.
- In this work, we consider the SGWB due to the bubble wall collision which can be expressed as

$$\Omega_{\rm GW}(f) = 1.67\times10^{-5}\left(\frac{H}{\beta}\right)^2\left(\frac{\kappa\alpha}{1+\alpha}\right)^2\frac{0.11v_w^2}{0.42+v_w^3}\left(\frac{100}{g_*}\right)^{1/3}\frac{3.8(f/f_p)^{2.8}}{1+2.8(f/f_p)^{3.8}},$$

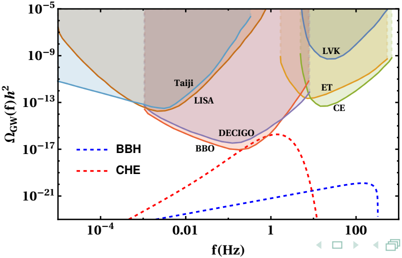
where,

$$f_p = \frac{0.62}{1.8-0.1v_w+v_w^2}\left(\frac{\beta}{H}\right)\frac{T}{100\ {\rm GeV}}\left(\frac{g_*}{100}\right)^{1/6}\times1.65\times10^{-5}\ {\rm Hz},$$

is the peak frequency.

- Secondary SGWB from PBHs can be created from HE, SI, and GI.
- However, HE works best for very light PBHs whereas SI and GI work best for heavy PBHs.
- In 2305.07569 we had considered GI of PBH as the source, whereas in 2311.xxxxx we have considered SI as the source.

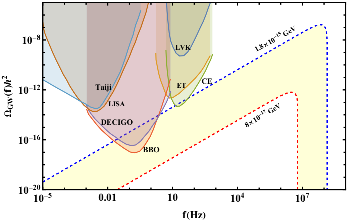
- If PBHs of certain mass range exists and they are abundant enough, then they interact among themselves and with other astrophysical black holes (ABH) to create SGWB.
- These interactions could be of two different types, (1) Close Hyperbolic Encounters, and (2) Formation of Binary Black Holes.
- The magnitude of the resulting SGWB from both these processes are proportional to $M_{\rm PBH}^2$ and $f_{\rm PBH}^2$.
- For the three benchmark cases that we had considered, only the lowest temperature one will create PBHs heavy enough.

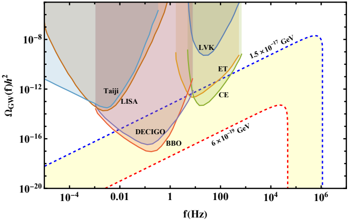


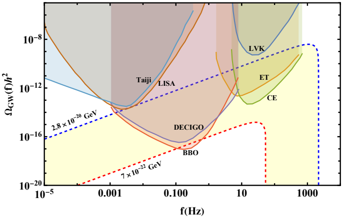
- If PBHs have appreciable spin, then ULBs can extract energy and angular momentum from the PBH and amplify. This is called superradiant instability.
- The energy transfer from this ULB-PBH system as GW depends on the gravitational fine structure constant, which is defined as, $\alpha_g = GM_{\rm PBH} m_a/\hbar c$.
- Unlike the previous case, a SGWB of very high magnitude can be created from superradiant instabilities of PBHs.
- However, this is subject to many conditions, i.e. spin of the PBH, existence of ultra light bosons (ULB) of a certain mass range, etc.
- The initial spin of these PBHs are very low, [1]therefore, we only consider the remnants of PBH-PBH mergers as the source of such superradiant instability.

[1]We have shown the values of the initial spin to be $\mathcal{O}(0.001)$ for the realistic cases in our recent work 2311.xxxxx.

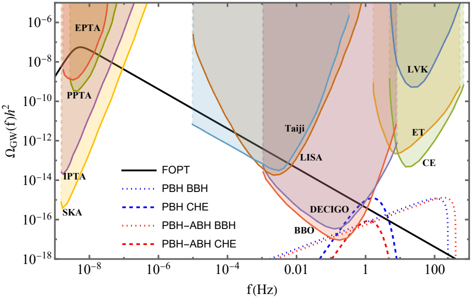
- For all the three benchmark cases that we had considered, detectable SGWB will be created if the relevant ULB of a certain mass range exist.





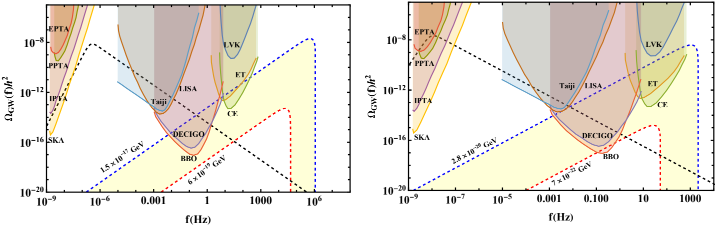


- Now, if we combine the two, we extract more information regarding the creation of PBHs from this process.
- If suitable ULBs are not there, then the combination only takes the *secondary* SGWB from the GI into account.



Here we show the cumulative SGWB from a FOPT ($T = 60$ MeV, $\alpha = 1$, $\beta/H = 3.5$) that creates PBHs of $40M_\odot$ and $f_{\rm PBH} = 0.005$.

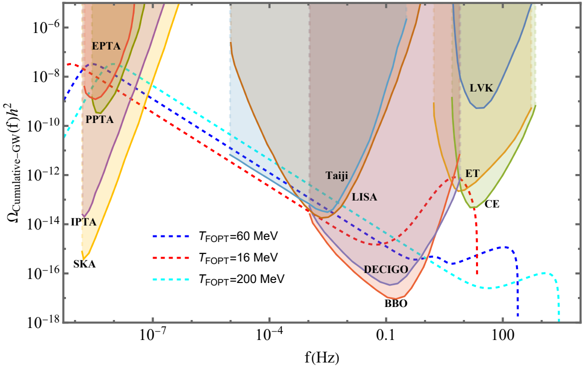
- However, in case there are ULBs of relevant mass scale, the *secondary* SGWB due to SI completely overshadows the one due to GI.



Here we show the cumulative SGWB from (Left) a FOPT ($T = 1$ GeV, $\alpha = 1.2$, $\beta/H = 10$) that creates PBHs of $0.046 M_\odot$ and $f_{\rm PBH} = 0.02$, (right) a FOPT ($T = 39$ MeV, $\alpha = 1$, $\beta/H = 8$) that creates PBHs of $30 M_\odot$ and $f_{\rm PBH} = 0.006$.

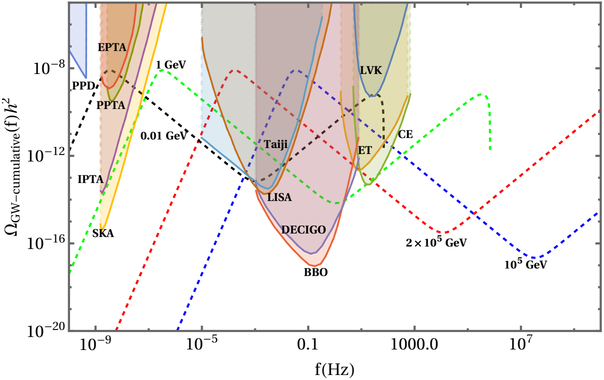
- The *primary* SGWB depends directly on the transition parameters.
- The *secondary* SGWB's dependence on the transition parameter is indirect, i.e., the dependence comes through the PBH mass and abundance.
- In our study, we take the transition temperature as the most pivotal transition parameter and show how the cumulative SGWB depends on the transition temperature.

- In case there are no ULBs of relevant mass scale present, then the cumulative SGWB will be a sum of the SGWB due to FOPT and the GI.



In all of these cases we have taken $\alpha = 1,\ \beta/H = 3.5,\ f_{\text{PBH}} = 0.005$

- However, in the presence of the ULBs with the right mass, we consider the SGWB due to the FOPTs and the ones from the SI of the PBHs.



In all of these cases we have taken

$$\alpha = 1,\ \beta/H = 3.5,\ f_{\rm PBH} = 0.005,\ \alpha_g = 0.5$$

- Supercooled cases, for which the order of the nucleation and the percolation temperatures are different than that of the critical temperature, might give rise to different temperature dependence.
- Non-standard cosmology can result in different scaling of the SGWBs with respect to the red-shift.
- FOPTs in some early matter-dominated era may give rise to PBH with high initial spin, resulting in stronger SGWBs from SI.

Thanks!

Backup

- **2106.05637:** J. Liu, L. Bian, R.-G. Cai, Z.-K. Guo and S.-J. Wang, *Primordial black hole production during first-order phase transitions*
- **2212.14037:** K. Kawana, T. Kim and P. Lu, *PBH Formation from Overdensities in Delayed Vacuum*
- **2305.04924:** M. Lewicki, P. Toczek and V. Vaskonen, *Primordial black holes from strong first-order phase*
- **2305.04942:** Y. Gouttenoire and T. Volansky, *Primordial Black Holes from Supercooled Phase Transitions* transitions Transitions