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Primordial black hole constraints for extended mass functions

B. Carr, M. Raidal, T. Tenkanen, V.V. and H. Veermäe, arXiv:1705.05567.
M. Raidal, V.V. and H. Veermäe, arXiv:1707.01480.

by

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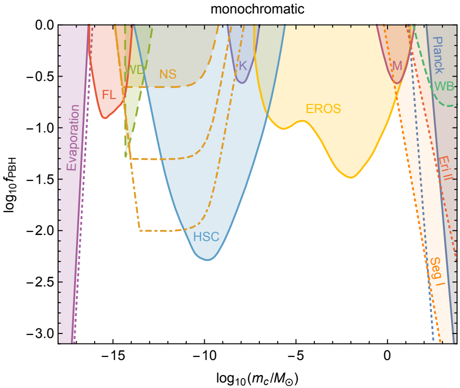
Introduction

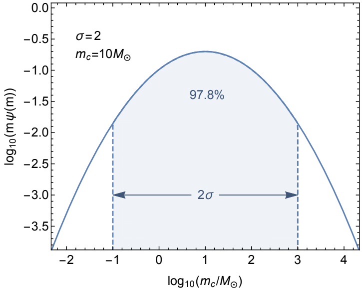
- Monochromatic PBH mass function: $\psi(m) = f_{\rm PBH}\delta(m - m_c)$, $f_{\rm PBH} \equiv \Omega_{\rm PBH}/\Omega_{\rm DM}$.



Extended PBH mass function

- An extended PBH mass function arises naturally.
- Assuming that all BHs observed by LIGO are primordial, the observations favour extended PBH mass function.
- We consider as a simple example a lognormal mass function:

$$\psi(m) = \frac{f_{\rm PBH}}{\sqrt{2\pi}\sigma m} \exp\left(-\frac{\log^2(m/m_c)}{2\sigma^2}\right) .$$



Extracting constraints

- Consider an observable $A[\psi(m)]$ to which PBHs of different mass contribute independently:

$$A[\psi(m)] = A_0 + \int \mathrm{d}m\, \psi(m) K_1(m)\,.$$

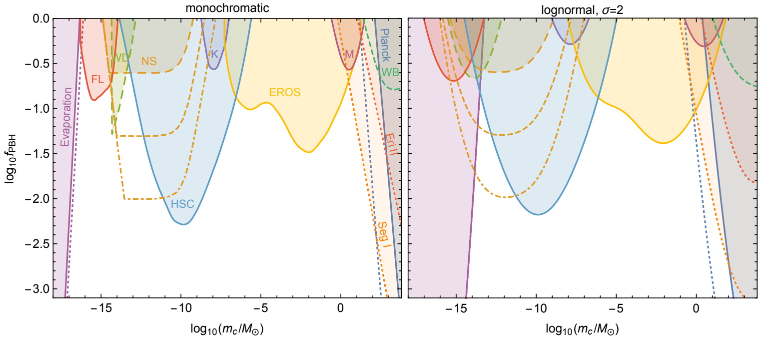
- For a monochromatic mass function at m_c a bound $A \leq A_{\rm exp}$ can be written as

$$f_{\rm PBH}(m_c) \leq \frac{A_{\rm exp} - A_0}{K_1(m_c)} \equiv f_{\rm max}(m_c)\,,$$

so

$$\int \mathrm{d}m \frac{\psi(m)}{f_{\rm max}(m)} \leq 1\,.$$

Constraints for lognormal MF



- The effect of the extension is to 'smooth' the constraints.
- The regions allowing a relatively large PBH fraction are reduced.

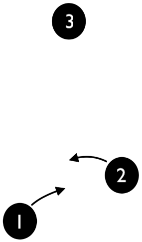
GW background

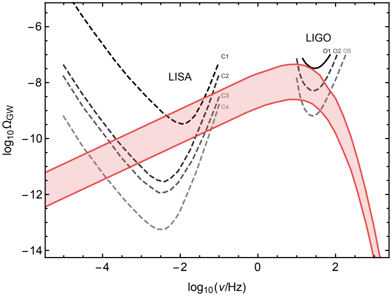
- The GWs from the unobservable events combine to create a stochastic GW background.
- Non-observation of the GW background constrains the PBH abundance.
- PBH binaries are formed in the early Universe dominantly by three-body interactions.

Nakamura, Sasaki, Tanaka, Thorne, astro-ph/9708060.

Ioka, Chiba, Tanaka, Nakamura, astro-ph/9807018.

Sasaki, Suyama, Tanaka, Yokoyama, 1603.08338.





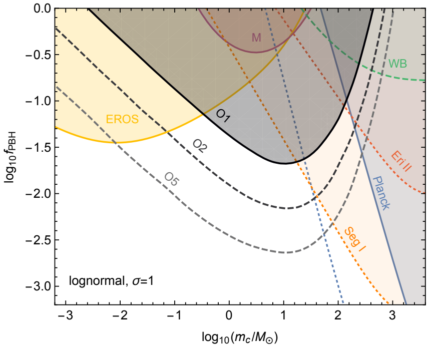
Constraints from LIGO

- The observable is of the form

$$A[\psi(m)] = \int \mathrm{d}m_1 \mathrm{d}m_2 \mathrm{d}m_3 \psi(m_1)\psi(m_2)\psi(m_3) K_1(m_1, m_2, m_3) + \ldots$$

$\implies$ the constraint must be calculated separately for each mass function.

- LIGO gives the strongest constraint for $m_c \sim 1 - 10 M_\odot$:



Summary

1. If PBHs of different mass contribute independently on the observable, the constraints for extended PBH mass function can be extracted from those for monochromatic ones.

2. The wider the mass function is, the smaller is the maximal allowed PBH abundance.

3. The non-observation on the GW background from PBH mergers by LIGO gives the dominant constraint for $m_c \sim 1 - 10 M_\odot$.

Lognormal mass function

For the lognormal mass function

$$\psi(m) = \frac{f_{\rm PBH}}{\sqrt{2\pi}\sigma m} \exp\left(-\frac{\log^2(m/m_c)}{2\sigma^2}\right)$$

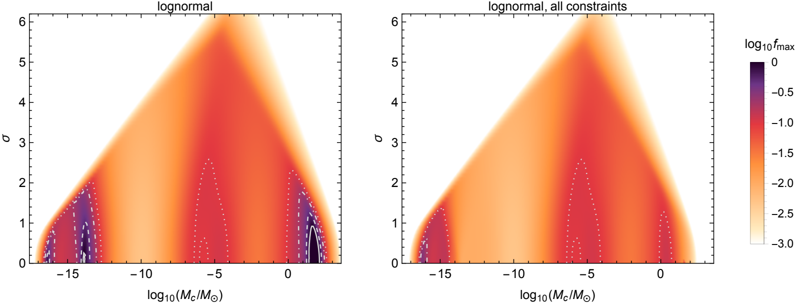
$\log m_c$ and σ^2 are the mean and variance of the $\log m$ distribution:

$$\log m_c \equiv \langle \log m \rangle_\psi , \quad \sigma^2 \equiv \langle \log^2 m \rangle_\psi - \langle \log m \rangle_\psi^2 ,$$

where

$$\langle X \rangle_\psi \equiv \frac{1}{f_{\rm PBH}} \int {\rm d}M \, \psi(M) X(M) .$$

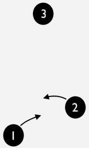
PBH constraints



PBH binary formation

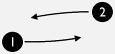
Early Universe

$$\frac{R_3(t_0)}{\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}} \approx 5.1\times 10^4 \delta_{\rm dc}^{\frac{16}{37}} f_{\rm PBH}^{\frac{53}{37}} \left(\frac{m_c}{30M_\odot}\right)^{-\frac{32}{37}}$$



Late Universe

$$\frac{R_2(t_0)}{\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}} \approx 3.7\times 10^{-7} \delta_0 f_{\rm PBH}^2 \left(\frac{v_{\rm PBH}}{10\,\mathrm{km/s}}\right)^{-\frac{11}{7}}$$



$\implies$ R_3 dominates over R_2 unless $\delta_0 \gtrsim 10^{11}$.

PBH mergers and LIGO

- LIGO events and PBH constraints indicate that $\sigma \approx 0.3 - 3$ and $m_c \approx 0.1 - 60 M_\odot$.
- For $(m_c, \sigma) = (30 M_\odot, 1)$ the LIGO rate $12 - 213\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ is obtained for $f_{\rm PBH} = 0.0045 - 0.024$.