Formation and evolution of primordial black hole binaries

VV and H. Veermäe, arXiv: 1908.09752
M. Raidal, C. Spethmann, VV and H. Veermäe, arXiv: 1812.01930
M. Raidal, VV and H. Veermäe, arXiv: 1707.01480

by

Ville Vaskonen

Gravitational waves from the early universe, Nordita, August 29, 2019

Outline

1. Introduction
2. PBH binary formation
3. Numerical simulations
4. Survival of the binaries
5. Constraints from LIGO/Virgo
6. Summary

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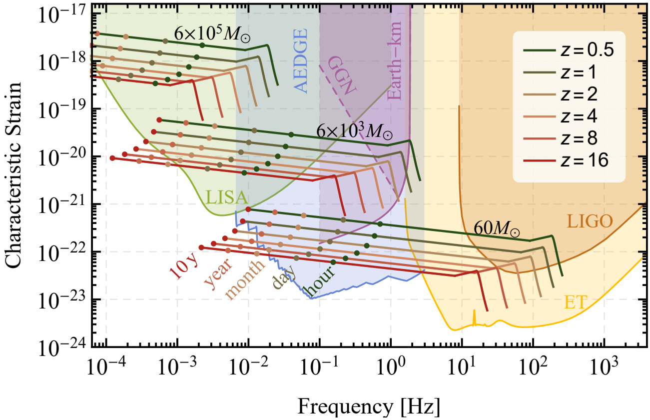
Introduction

Motivation

1. dark matter
2. supermassive black holes
3. LIGO-Virgo observations

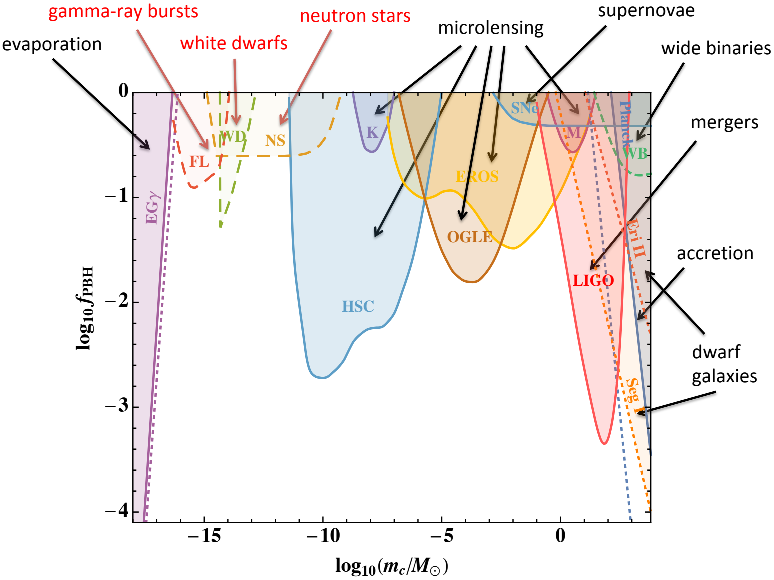
[Astrophys. J. 875 (2019) L1]

Motivation



Characteristic Strain
Frequency [Hz]
$6\times10^5 M_\odot$
$6\times10^3 M_\odot$
$60 M_\odot$
AEDGE
GGN
Earth-km
LISA
LIGO
ET
10 y
year
month
day
hour
$z=0.5$
$z=1$
$z=2$
$z=4$
$z=8$
$z=16$

PBH constraints



Extended PBH mass function

- Constraints for extended mass functions:

  [B. Carr, M. Raidal, T. Tenkanen, VV and H. Veermäe, arXiv: 1705.05567.]

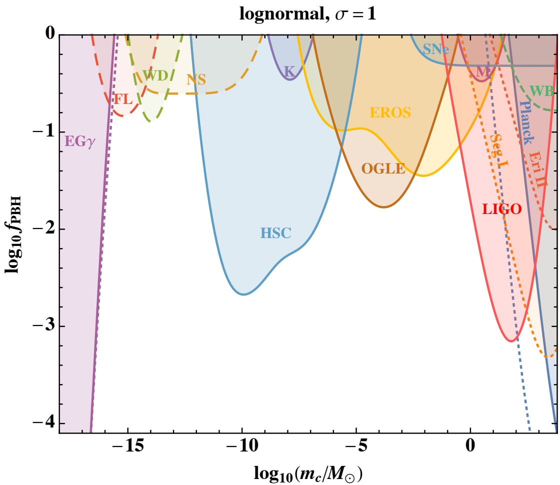
$$f_{\rm PBH} \leq \left(\int {\rm d}m \frac{\psi(m)}{f_{\rm max}(m)} \right)^{-1} .$$

- Lognormal mass function:

$$\psi(m) = \frac{1}{\sqrt{2\pi}\sigma m} \exp\left(-\frac{\log^2(m/m_c)}{2\sigma^2} \right) ,$$

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

Constraints for lognormal ψ



Wider mass function $\implies$ smaller maximal PBH abundance.

PBH Formation

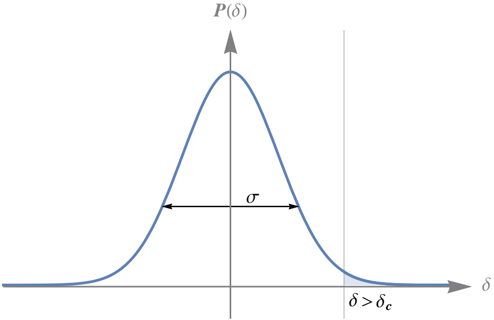
[B. Carr, Astrophys. J. 201, 1 (1975).]

- Large density perturbations collapse into BHs at horizon re-entry,

$$M \sim M_H \,.$$

- PBH abundance:

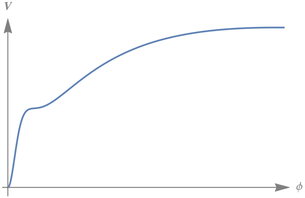
$$\frac{\rho}{\rho_{\rm tot}} \sim \int_{\delta_c} {\rm d}\delta P(\delta) \,.$$

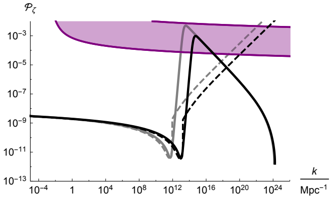


Examples

- Single field double inflation:

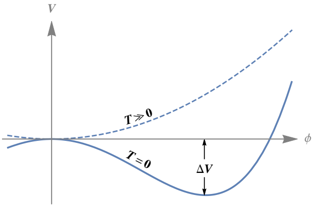
  [K. Kannike, L. Marzola, M. Raidal and H. Veermäe, arXiv: 1705.06225]

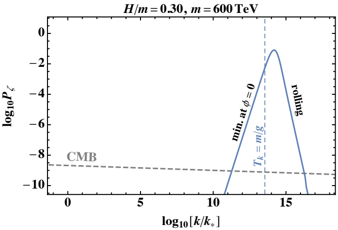




- Thermal inflation:

  [K. Dimopoulos, T. Markkanen, A. Racioppi and VV, arXiv: 1903.09598]





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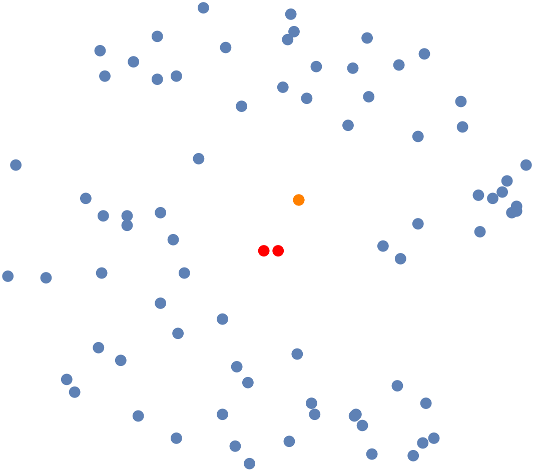
PBH binary formation

Initial state

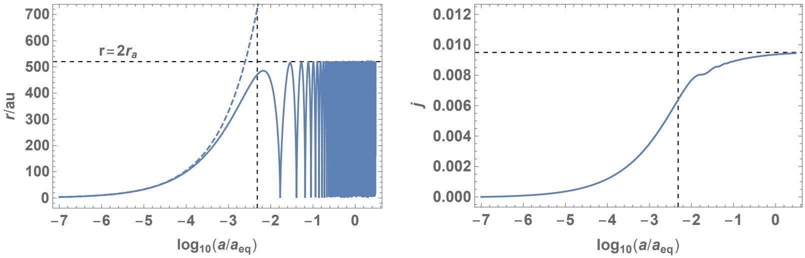
[T. Nakamura, M. Sasaki, T. Tanaka and K. S. Thorne, astro-ph/9708060.]



Decoupling from expansion

$$\mathbf{F}/\mu = \underbrace{\mathbf{r}\ddot{a}/a}_{\text{Hubble flow}} - \underbrace{M\hat{\mathbf{r}}/r^2}_{\text{self-gravity}} + \underbrace{(\hat{\mathbf{r}}\cdot\mathbf{T}\cdot\mathbf{r})\hat{\mathbf{r}}}_{\text{radial tidal forces}} + \underbrace{(\mathbf{r}\times(\mathbf{T}\cdot\mathbf{r}))}_{\text{tidal torque}}\times(\hat{\mathbf{r}}/r)\,,$$

$$\mathbf{T}_{i,j} = \partial_i\partial_j\phi(\mathbf{r}_c)$$



Coalescence time

- GW emission $\implies$

  [P. C. Peters, Phys. Rev. 136 B1224 (1964).]

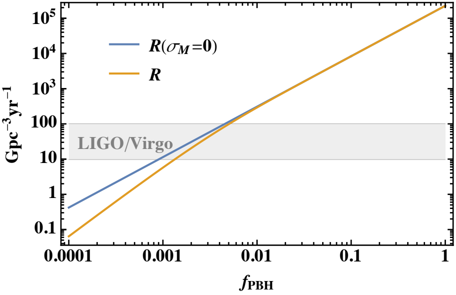
$$\tau = \frac{3}{85}\frac{r_a^4}{\eta M^3} j^7 \,.$$

For example $m_1 = m_2 = 10M_\odot$, $j = 0.01$ and $r_a = 260\,\mathrm{au}$ gives $\tau \simeq 10^{10}\,\mathrm{yr} \simeq$ age of the universe.

- To get the merger rate we need
  - the PBH mass function,
  - the distribution of initial binary separation and
  - the distribution of tidal torques.

Merger rate

- Torques from all PBHs and other matter inhomogeneities:
  [Y. Ali-Haïmoud, E. D. Kovetz and M. Kamionkowski, 1709.06576.]



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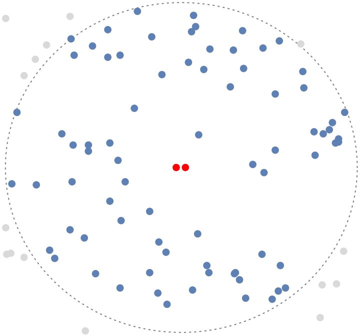
Numerical simulations

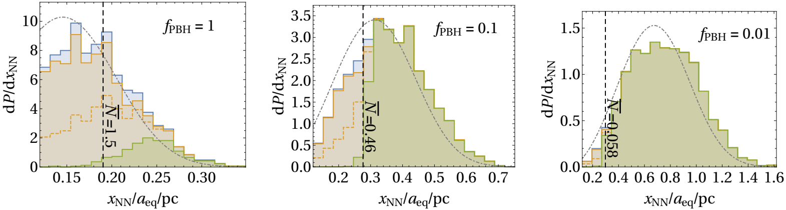
N-body simulation

- $N - 2$ randomly distributed PBHs in a sphere.
- A central PBH pair that will form a binary with lifetime $\tau = t_0$
- We simulated $N = 70$ bodies from $a_{\rm beg} = 10^{-3} a_{\rm eq}$ to $a_{\rm end} = 3a_{\rm eq}$.
- The expansion of the universe is accounted by including a Hubble acceleration, $\ddot{r} = \ddot{a} r / a$.
- The gravitational attraction of PBHs outside the sphere is approximated by a uniform mass density.



Disruption of the binaries

x_{NN} = the initial comoving distance of the PBH nearest to the binary.
$z_{\rm end} \simeq 1000$:



1. If the initial configuration contains a third PBH close to the PBH pair that is expected to form a binary, it is very likely that it collides with the binary.
2. PBHs will form dense clusters relatively early, and binaries absorbed by these clusters are likely to be disrupted.

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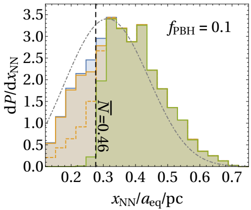
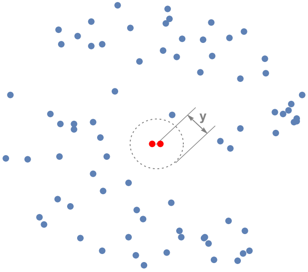
Survival of the binaries

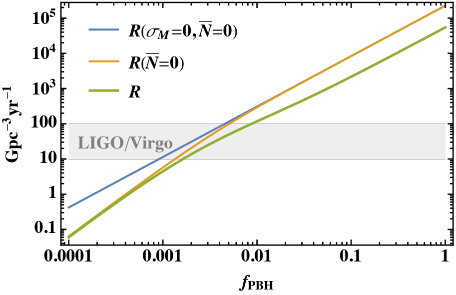
Disruption by the nearest PBH

To avoid disruption by the PBH nearest to the binary, we require that the average number of PBHs inside a sphere of radius y is

$$\bar{N}(y) \simeq \frac{M}{\langle m \rangle} \frac{f_{\rm PBH}}{f_{\rm PBH} + \sigma_{\rm M}} \,.$$



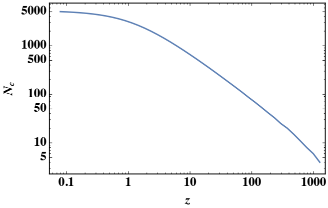


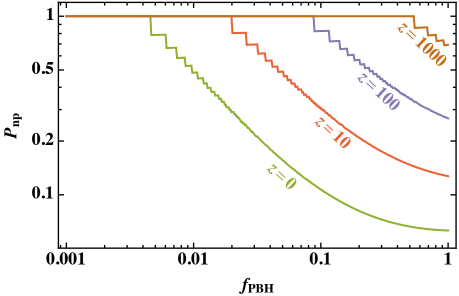


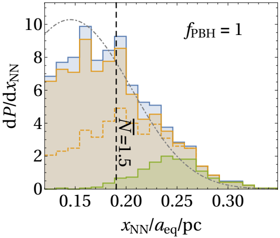
Disruption in a cluster

- Halos with $N < N_c(z)$ PBHs have collapsed before redshift z.
- All binaries in clusters that collapse are disrupted $\implies$ survival probability

$$P_{\rm np}(z) = \sum_{N=N_c(z)}^{\infty} P_N \,.$$







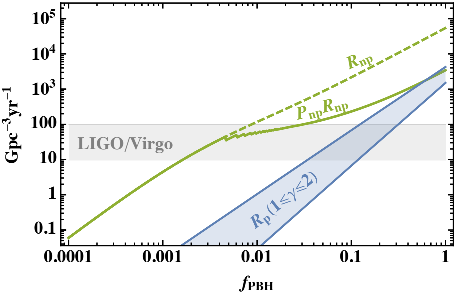
Contribution of the perturbed binaries

Binary-PBH interactions increases

- the binding energy E of the binary by $\mathcal{O}(1)$ factor,
- the angular momentum j of the binary by $\mathcal{O}(10)$ factor.

$$\tau = \frac{3}{1360}\frac{M}{\eta E^4} j^7 \,.$$

$\Longrightarrow$ τ increases by several orders of magnitude.
$\Longrightarrow$ Disrupted binaries that initially had a very short lifetime can contribute to the present merger rate.



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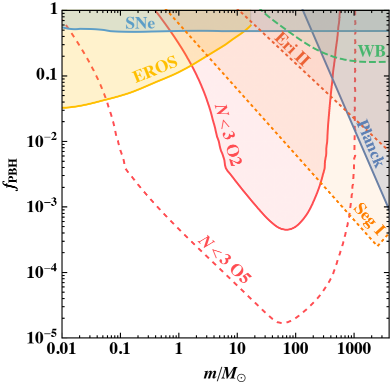
Constraints from LIGO/Virgo observations

No PBHs

- Expected number of events:

$$N = \Delta t \int \mathrm{d}R(m_1, m_2, z)\mathrm{d}V_c(z)\theta(\rho(m_1, m_2, z) - \rho_c)\,.$$

- Assume Poisson statistics: $N < 3$.

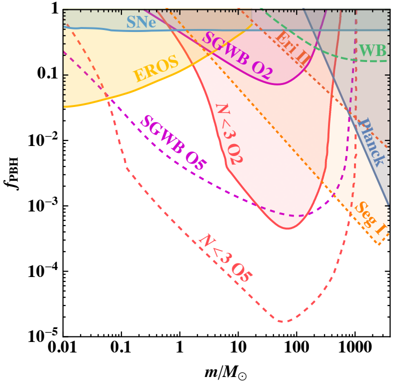


No SGWB

- Expected stochastic GW background:

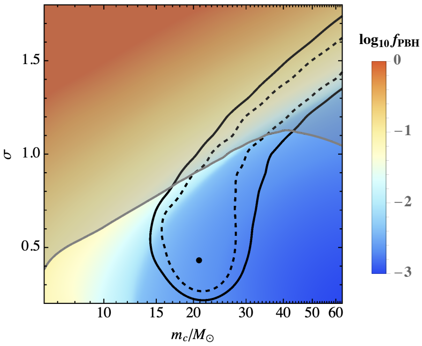
$$\Omega_{\rm GW}(\nu) = \frac{\nu}{\rho_c} \int \frac{{\rm d}R(m_1,m_2,z)\,{\rm d}z}{(1+z)H(z)} \frac{{\rm d}E_{\rm GW}(\nu_r)}{{\rm d}\nu}\, \theta(\rho_c - \rho(m_1,m_2,z))\,,$$

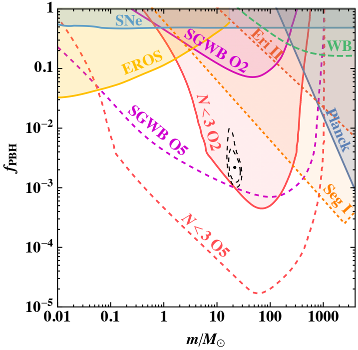
- Require that SNR<8:



Fit for lognormal mass function

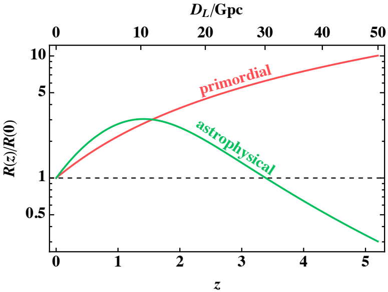
- $N_{\rm obs} = 10$ BH-BH merger events in $\Delta t \simeq 165$ days.
- A likelihood fit for the masses and event rate: $m_c \simeq 20 M_\odot$, $\sigma \simeq 0.4$, $f_{\rm PBH} \simeq 0.002$.

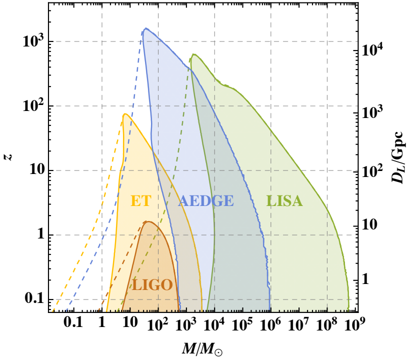




Separating PBBHs from ABBHs

Different behaviour of the merger rates as a function of z allows us to separate the primordial and astrophysical origins of the events:





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Summary

Summary

- A population of PBH binaries is formed before matter-radiation equality from large Poisson fluctuations.
- Many of these binaries are disrupted by a nearby PBH or a small cluster of PBHs.
- The present merger rate for $f_{\rm PBH} \simeq 1$ still is well above the observed one.
- LIGO/Virgo observations give the strongest constraint on $f_{\rm PBH}$ in the mass range $2 - 120 M_\odot$.
- Future GW experiments can tell the origin of the observed BH binary population.