Bubbles kick off primordial black holes to form more binaries

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First-order Phase Transition

Cosmological first-order phase transition (FOPT) [1, 2, 3, 4] is a possible phenomenon in the early universe to go beyond the Standard Model and to probe new physics with associated productions of stochastic gravitational-wave backgrounds (SGWBs) [5, 6]. The energy scale for a FOPT ranges widely from inflation to QCD phase transitions.

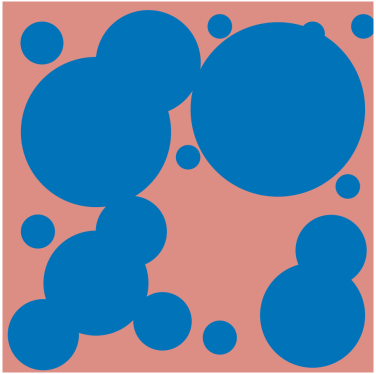


Figure 1: Vacuum bubbles and cosmological first-order phase trnasitions.

Primordial black hole collapsing

Primordial black holes (PBHs) can naturally arise from many scenarios [7, 8, 9, 10]. The quantum fluctuations during inflation rapidly froze because of the shrinking of the comoving Hubble horizons, which resulted in classical over-dense regions. The energy scale for a PBH formation mechanism ranges widely from inflation to BBN and even later.

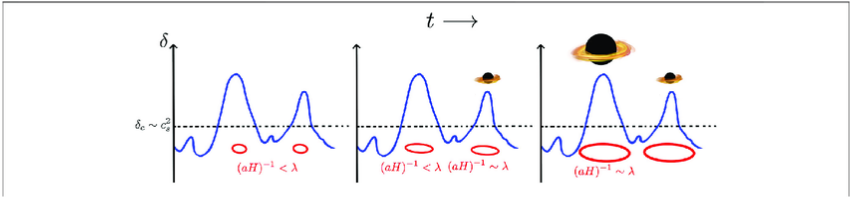


Figure 2: Sketch of PBH formations [11]

What about the interactions between the black holes and the bubbles? A Numerical Relativity simulation is needed!

Since the width of the bubble wall shrinks when expanding, mesh refinement is required in the simulation.

We use GRChombo[12, 13], a AMR based open-source code for numerical relativity simulations.

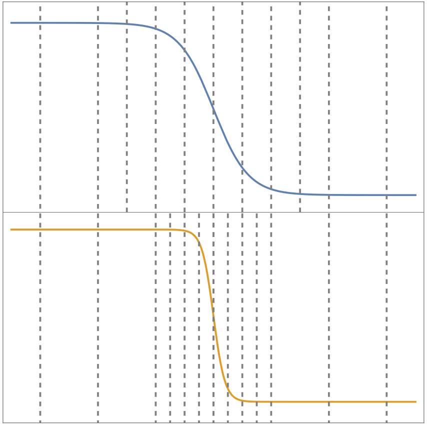


Figure 3: AMR applied on scalar bubble

We consider a universe with a PBH suffering FOPT, which is described by a real scalar field,

$$S = \int \mathrm{d}^4 x \sqrt{-g} \left(\frac{1}{M_{\mathrm{pl}}^2} R - \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right), \tag{1}$$

where the potential for the scalar field reads

$$V(\phi) = \left(1 + a \left(\frac{\phi}{\phi_0} \right)^2 - (2a - 4) \left(\frac{\phi}{\phi_0} \right)^3 + (a + 3) \left(\frac{\phi}{\phi_0} \right)^4 \right) (V_F - V_T) + V_T. \tag{2}$$

This potential has a local minimum V_F at $\phi = 0$ and a global minimum V_T at $\phi = \phi_0$, corresponding to the false vacuum and true vacuum respectively.

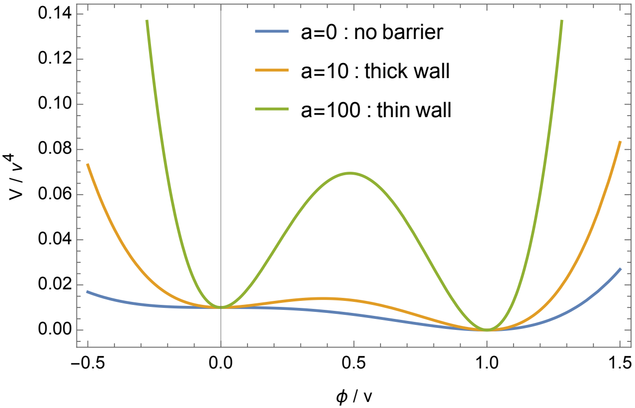


Figure 4: Potential for several possible parameters

Initial data

The initial scalar field profile takes the following ansatz,

$$\phi_{\mathrm{i}}(r) = \frac{\phi_0}{2}\left(1 - \tanh\left(\frac{r - r_0}{D_0}\right)\right), \quad \dot{\phi}_{\mathrm{i}}(r) = 0, \tag{3}$$

where r_0 and D_0 are the radius and width of the bubble respectively.

Besides the vacuum bubble, a PBH is assumed to exist and stay in the false vacuum, where the universe is dominated by the potential V_F.

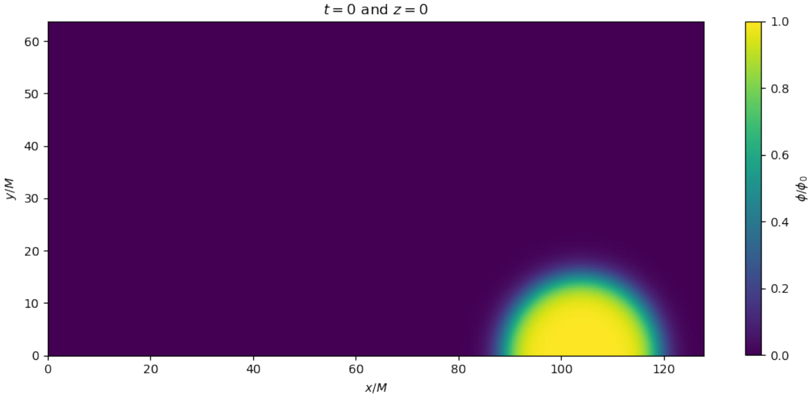


Figure 5: Initial configuration for the scalar field. Periodic boundary conditions along x-direction, reflective boudary conditions along y and z directions.

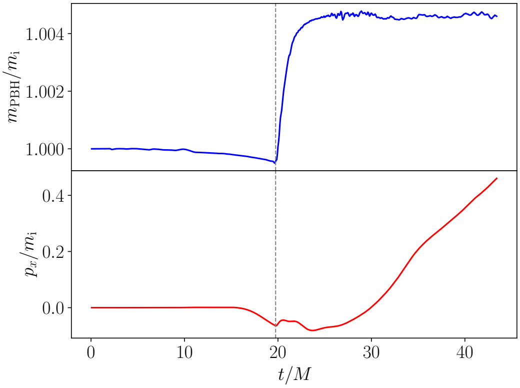


Figure 6: The time evolution for the PBH mass $m_{\rm PBH}$ and momentum along x-direction p_x. The gray dashed line denotes the collision time for the vacuum bubble and the PBH.

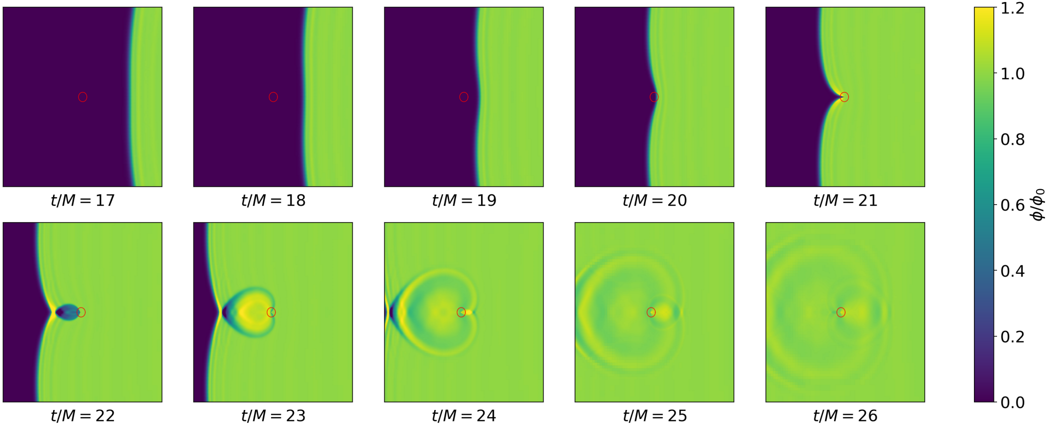


Figure 7: Scalar field profile when the vacuum bubble crosses the PBH at around $t = 20M$, whose apparent horizon is painted in red circles.

- The PBH extracts energy from the bubble wall, leading to a mass enhancement by about 0.5%. This phenomenon is expected to be more significant for a late time expansion when the energy density on the bubble wall is large.
- The strong collision with the scalar field brings momentum to the PBH. An interesting phenomenon is that the bubble does not push the black hole away, but rather pulls it towards the center of the bubble.
- Interactions between the PBH and the scalar field disrupts the spherical symmetry of the bubble wall, which leads to GW radiation both from the bubble and from the PBH. The scalar field oscillates at length scale comparable to the radius of the PBH, which corresponds to a high-frequency GW radiation.

Let us focus on the second phenomenon which modifies the binary formation rate for the PBHs. For PBHs with masses $m_{\rm PBH}$ separated by a comoving distance x, the decoupling happens if $m_{\rm PBH} \cdot (ax)^{-3} > \rho$, where ρ is the energy density of the background cosmic fluid [14, 15], which can not be satisfied in radiation-dominated epoch. In matter-dominated epoch, the condition for forming a binary would be

$$f \cdot \left(\frac{\bar{x}}{x}\right)^3 > 1. \tag{4}$$

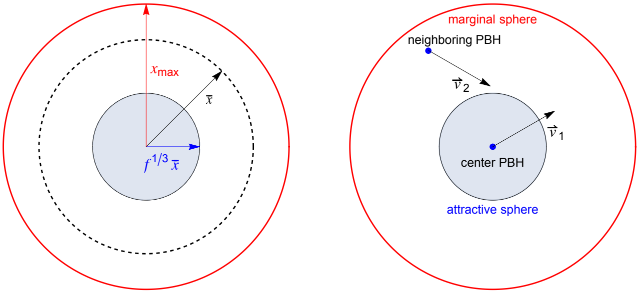
The average comoving distance $\bar{x}$ could be estimated from the definition of f at matter-radiation equality,

$$f = \frac{m_{\rm PBH}}{\frac{4\pi}{3}(a_{\rm eq}\bar{x})^3}\left(\frac{1}{2}\frac{3H_{\rm eq}^2}{8\pi G}\right)^{-1} = \frac{2\gamma H_{\rm PBH}^{-1} H_{\rm eq}^{-2}}{(a_{\rm eq}\bar{x})^3}. \tag{5}$$

As PBHs gained veolcities during FOPTs, we'd like to know how they move in an expanding background with $\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2\mathrm{d}\mathbf{x}^2$. We can solve the geodesic equation for the x-directional 4-velocity of a massive particle as

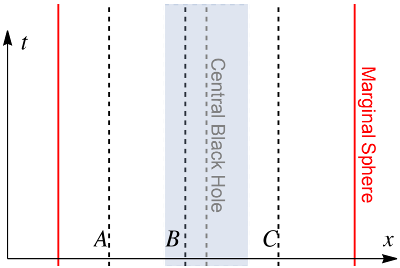
$$u^\mu \equiv \frac{\mathrm{d}x^\mu}{\mathrm{d}\tau} = \left(\sqrt{\frac{(a_{\mathrm{PT}}v)^2}{(a/a_{\mathrm{PT}})^2}+1}, \frac{v}{(a/a_{\mathrm{PT}})^2}, 0, 0\right), \tag{6}$$

where a_{PT} is the scale factor around the FOPT, and v is a constant, while the dimensionless term $a_{\mathrm{PT}}v$ can be interpreted as the "physical velocity" of the PBH when $1/\sqrt{1-(a_{\mathrm{PT}}v)^2} \sim O(1)$.

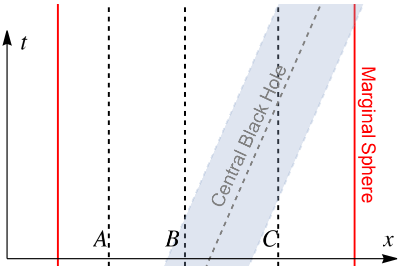


(a) Initial case (b) PBHs gain velocity (c) Relative velocity

Figure 8: How velocity modifies the binary formation criterion.



(a) Black holes with no velocities



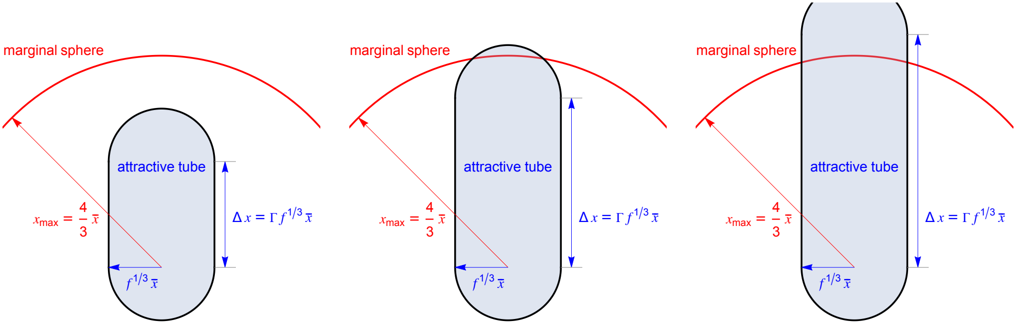
(b) The central black hole moves with an relative velocity

Figure 9: An $1+1$ dimensional view of how the relative velocity gained by the central PBH modifies the decoupling region.

We denote the comoving distance moved by a massive particle with velocity v from matter-radiation equality $t_{\rm eq}$ to nowadays t_0 as Δx, Comparing it with the average distance $\bar{x}$ gives a clear picture of how far a PBH moves,

$$\frac{\Delta x}{\bar{x}} = \frac{3}{2}(a_{\rm PT}v)\left(\frac{f}{2\gamma}\right)^{1/3}\left(\frac{a_{\rm eq}}{a_{\rm PBH}}\right)^{2/3}\left(\frac{a_{\rm PT}}{a_{\rm eq}}\right) \equiv \Gamma f^{1/3}. \tag{7}$$

For QCD phase transition $a_{\rm PT}/a_{\rm eq} \simeq 10^8$, PBHs formed before EW scale $a_{\rm PBH}/a_{\rm eq} \simeq 10^{12}$ with efficiency $\gamma = 0.2$ and velocity $a_{\rm PT}v = 0.3$, one obtains a rough estimation $\Gamma \sim O(1)$ and $\Delta x \simeq f^{1/3}\bar{x}$.



(a) $f^{1/3} < \frac{4}{3}(\Gamma+1)^{-1}$ (b) $\frac{4}{3}(\Gamma+1)^{-1} < f^{1/3} < \frac{4}{3}(\Gamma^2+1)^{-1/2}$ (c) $f^{1/3} > \frac{4}{3}(\Gamma^2+1)^{-1/2}$

Figure 10: Three situations of the relation between the attractive tube and the marginal sphere.

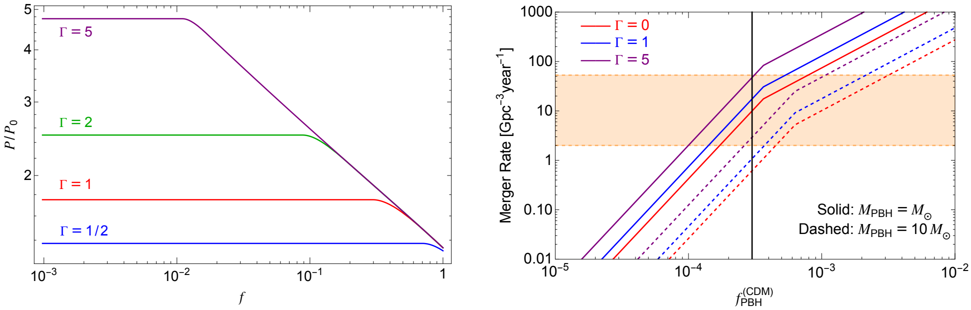


Figure 11: Left: The ratios P/P_0 for different Γ. The ratio returns to 1 as $\Gamma \to 0$ corresponding to $v = 0$. Right: Modified merger rate as a function of $f_{\rm PBH}^{\rm (CDM)} = f\Omega_{\rm m}/\Omega_{\rm CDM}$. The horizontal shaded region in orange is the LIGO-Virgo constraint on the event rate $2 \sim 53\ {\rm Gpc}^{-3}{\rm year}^{-1}$ [16], while the vertical black line at $f_{\rm PBH}^{\rm (CDM)} \simeq 3 \times 10^{-4}$ is the upper limit from non-detection of CMB distortion [17].

Simulation

Three phenomena:

- Mass enhancement. Depending on the separation and mass of the black hole.
- GW radiation. May be related to the QNMs of the black hole.
- Momentum transfer. May be more significant for a lighter black hole.

$\Longrightarrow$ Higher PBH binary formation rate.
$\Longrightarrow$ Stronger constraints on PBH abundance.

Modified binary formation rates

There are several basic assumptions in the estimation:

- Uniformly distribution of PBHs with no clustering. Results may be dramatically changed if PBHs are clustered, which is more difficult to consider.
- Monochromatic PBHs are considered, so that the velocities are assumed to be the same.

Thanks!

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