

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.**

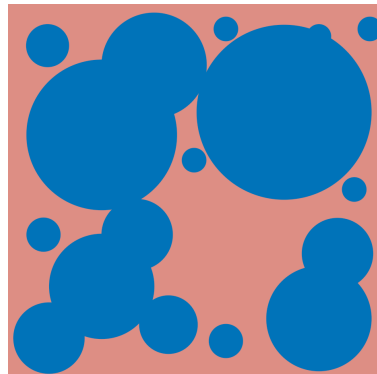


Figure 1: Vacuum bubbles and cosmological first-order phase transitions.

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.**

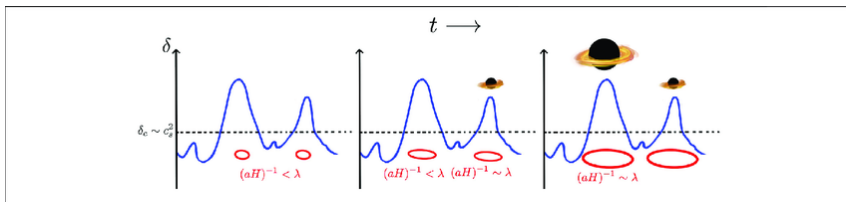


Figure 2: Sketch of PBH formations [11]

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.

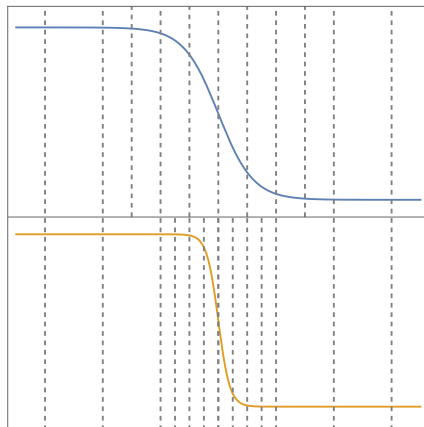


Figure 3: AMR applied on scalar bubble

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

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

where the potential for the scalar field reads

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

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.

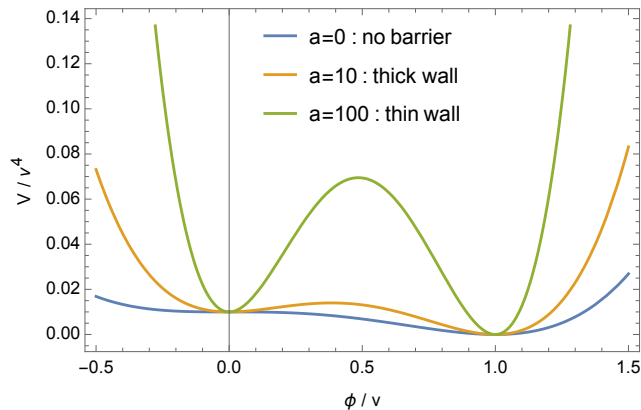


Figure 4: Potential for several possible parameters

Initial data

The initial scalar field profile takes the following ansatz,

$$\phi_i(r) = \frac{\phi_0}{2} \left(1 - \tanh \left(\frac{r - r_0}{D_0} \right) \right), \quad \dot{\phi}_i(r) = 0, \quad (3)$$

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 .

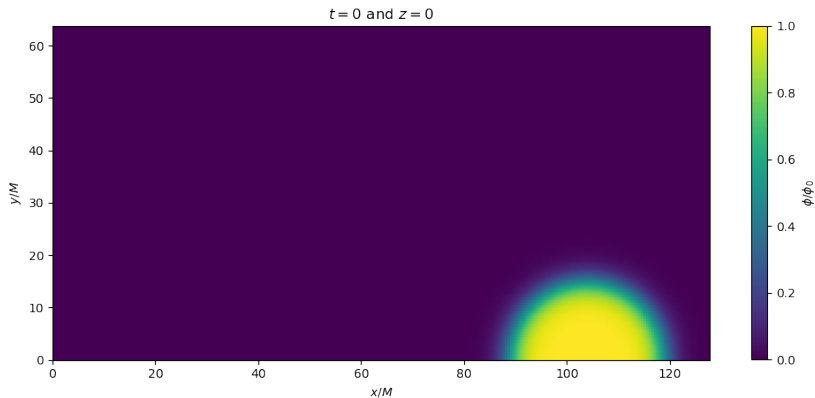


Figure 5: Initial configuration for the scalar field. Periodic boundary conditions along x -direction, reflective boundary conditions along y and z directions.

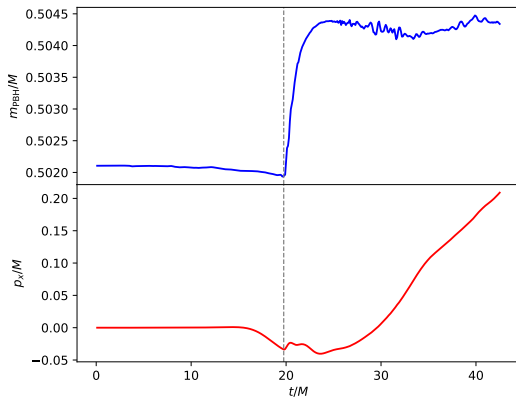


Figure 6: The time evolution for the PBH mass m_{PBH} and momentum along x -direction p_x . The gray dashed line denotes the collision time for the vacuum bubble and the PBH.

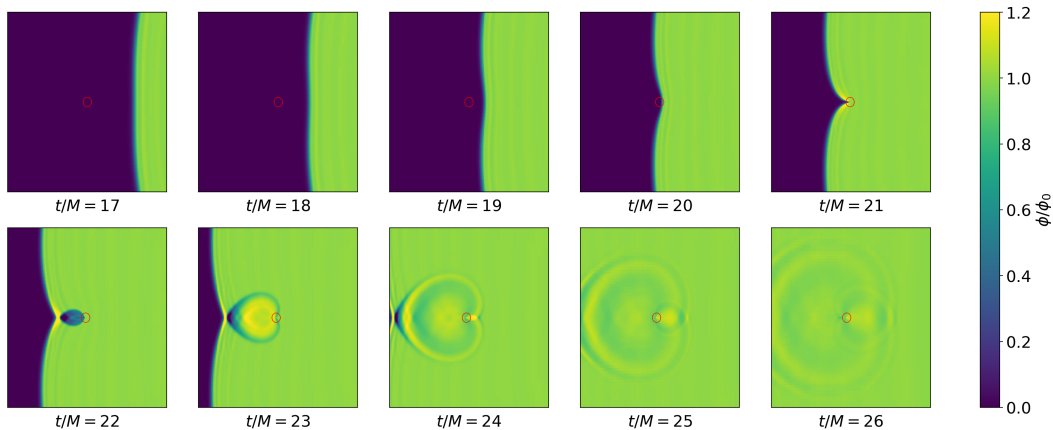


Figure 7: Scalar field profile when the vacuum bubble crosses the PBH at around $t = 20M$, whose apparent horizon is painted in red circles.

- 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.**

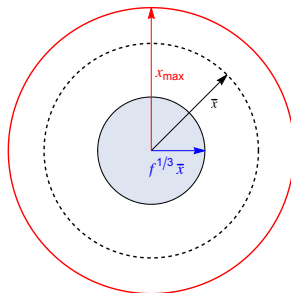
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Let us focus on the second phenomenon which modifies the binary formation rate for the PBHs. For PBHs with masses m_{PBH} separated by a comoving distance x , **the decoupling happens if $m_{\text{PBH}} \cdot (ax)^{-3} > \rho$** , where ρ is the energy 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

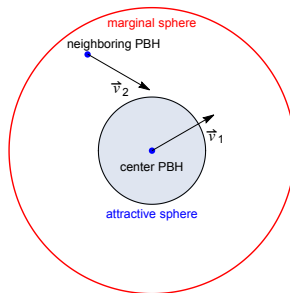
$$f \cdot \left(\frac{\bar{x}}{x}\right)^3 > 1. \quad (4)$$

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

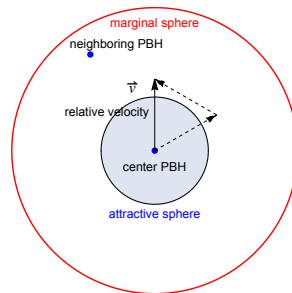
$$f = \frac{m_{\text{PBH}}}{\frac{4\pi}{3}(a_{\text{eq}}\bar{x})^3} \left(\frac{1}{2} \frac{3H_{\text{eq}}^2}{8\pi G}\right)^{-1} = \frac{2\gamma H_{\text{PBH}}^{-1} H_{\text{eq}}^{-2}}{(a_{\text{eq}}\bar{x})^3}. \quad (5)$$



(a) Initial case

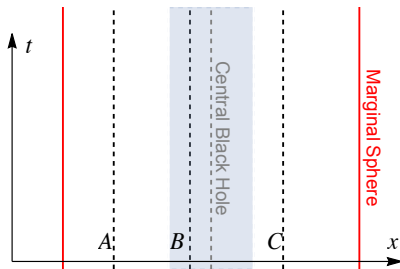


(b) PBHs gain velocity

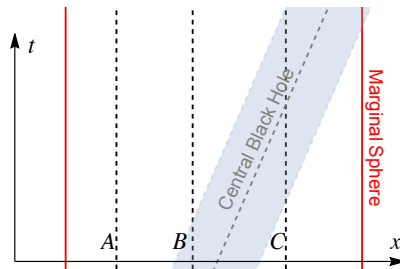


(c) Relative velocity

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_{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,

$$\frac{\Delta x}{\bar{x}} = \frac{3}{2}(a_{\text{PT}}v) \left(\frac{f}{2\gamma}\right)^{1/3} \left(\frac{a_{\text{eq}}}{a_{\text{PBH}}}\right)^{2/3} \left(\frac{a_{\text{PT}}}{a_{\text{eq}}}\right) \equiv \Gamma f^{1/3}. \quad (6)$$

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

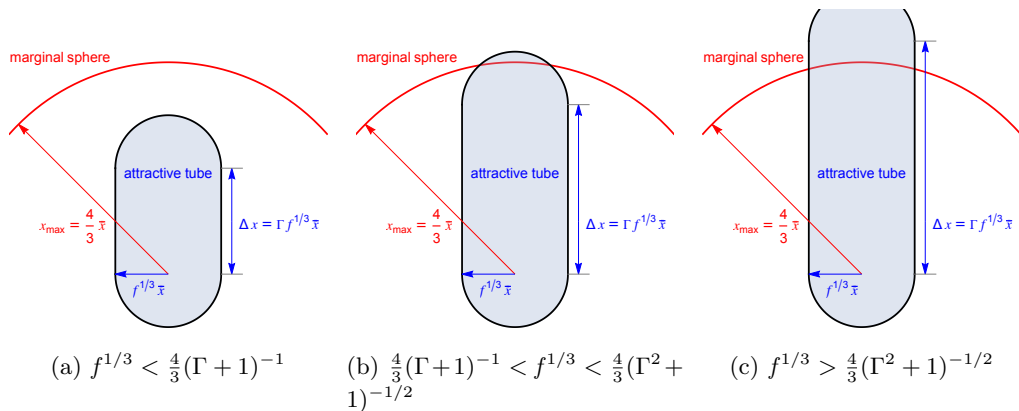


Figure 10: Three situations of the relation between the attractive tube and the marginal sphere.

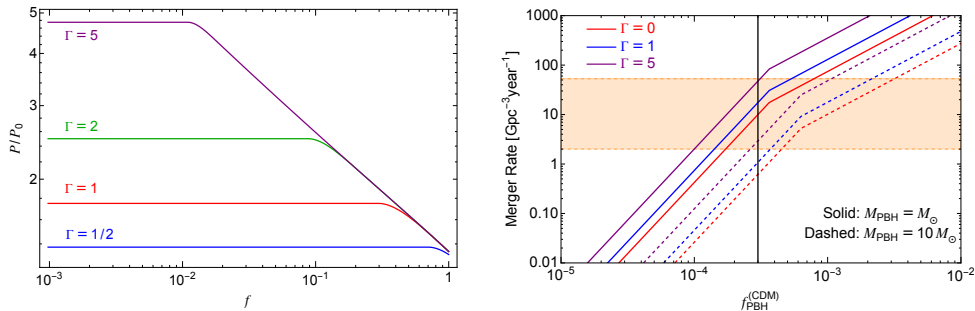


Figure 11: Left: The ratios P/P_0 for different Γ . The ratio returns to 1 as $\Gamma \rightarrow 0$ corresponding to $v = 0$. Right: Modified merger rate as a function of $f_{\text{PBH}}^{(\text{CDM})} = f\Omega_{\text{m}}/\Omega_{\text{CDM}}$. The horizontal shaded region in orange is the LIGO-Virgo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

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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.

⇒ Higher PBH binary formation rate.

⇒ 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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