Primordial Black Holes from first-order phase transitions

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Introduction

Many models introduced to explain physics beyond Standard Model and its aspects such as dark matter or baryogenesis feature first-order phase transition at the early stage of the Universe. We inspect the possibility of Primordial Black Holes (PBHs) production during such transitions due to collapse of false vacuum remnants. First-order phase transitions proceeds through random nucleation of true vacuum bubbles, which predicts existence of regions where such nucleation is postponed. These false vacuum regions maintain constant energy density ΔV, while in the transitioned space outside energy redshifts as a^{-4}, causing false vacuum regions to become overdense and possibly collapse into Black Holes [1]. These Black Holes may provide an explanation of Dark Matter in our Universe, while various experiments constrain their total abundance in different mass ranges [2].

Characteristics of the transition

- strength of the transition $\alpha = \frac{\Delta V}{\rho_r} \gg 1$ (strongly supercoooled case),
- nucleation rate (expanded up to 2nd order)

$$\Gamma(t) = H_I^4 e^{\beta t\left[1-\frac{t}{2t_*}\right]},$$

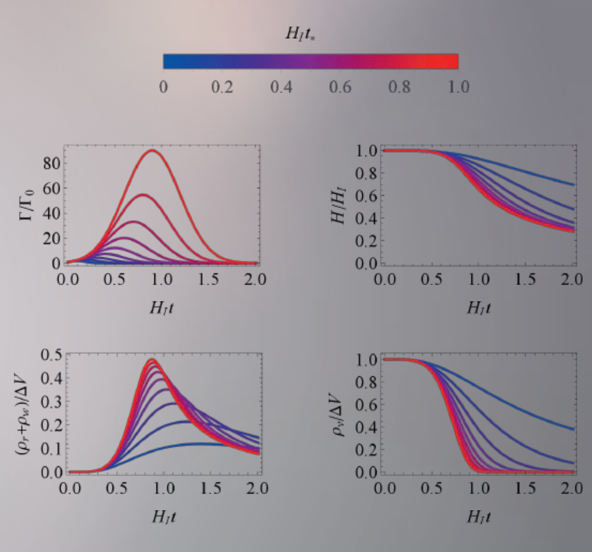
- Friedmann equations (bubble walls' energy density scales as radiation):

$$H^2 = \frac{1}{3M_P^2}(\rho_v + \rho_r + \rho_w),$$

$$\frac{\mathrm{d}(\rho_r+\rho_w)}{\mathrm{d}t} + 4H(\rho_r+\rho_w) = -\frac{\mathrm{d}\rho_v}{\mathrm{d}t},$$

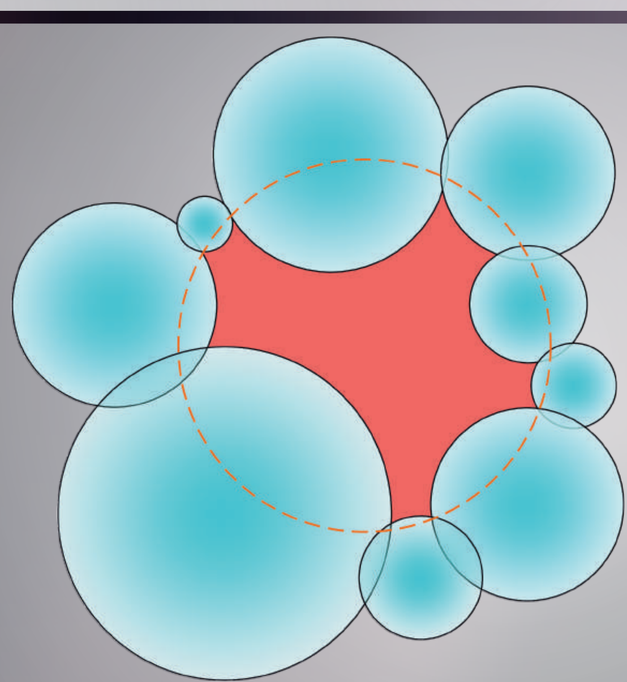
- fraction of the Universe in the false vacuum

$$P(t) = \exp\left[-\frac{4}{3}\pi\int_{-\infty}^{t}\mathrm{d}t_n\Gamma(t_n)a(t_n)^3R(t_n,t)^3\right].$$



Evolution of quantities demonstrating dynamics of the transition for fixed benchmark point $\beta/H_I = 10$. H_I is the initial value of Hubble parameter.

Trapped False Vacuum Domains



A schematic picture of False Vacuum Domain (FVD) consisting of false vacuum region (red) trapped in between true vacuum bubbles (blue). To describe nonsphericity of FVD, we introduce parameters ϵ and r_0.

Collapse into PBHs

We determine whether false vacuum domains collapse into PBHs by the hoop conjecture. We check whether radius of region with excess mass

$$\delta m(r,t) = m(r,t) - \frac{4\pi}{3}r^3 a(t)^3\rho_B(t)$$

is smaller than Schwarzschild radius for δm:

$$r < r_s(\delta m) = \frac{\delta m(r,t)}{4\pi a(t)M_P^2}.$$

$m(r,t)$ is a sum of three contributions:

- mass of the false vacuum part of the FVD

$$m_1(r,t) = \frac{4\pi}{3}\epsilon(t)a(t)^3 r(t)^3\Delta V,$$

- mass of bubble walls (σ - bubble's surface tension, $\bar{\gamma}$ - average Lorentz factor, calculated within thin wall approximations [3])

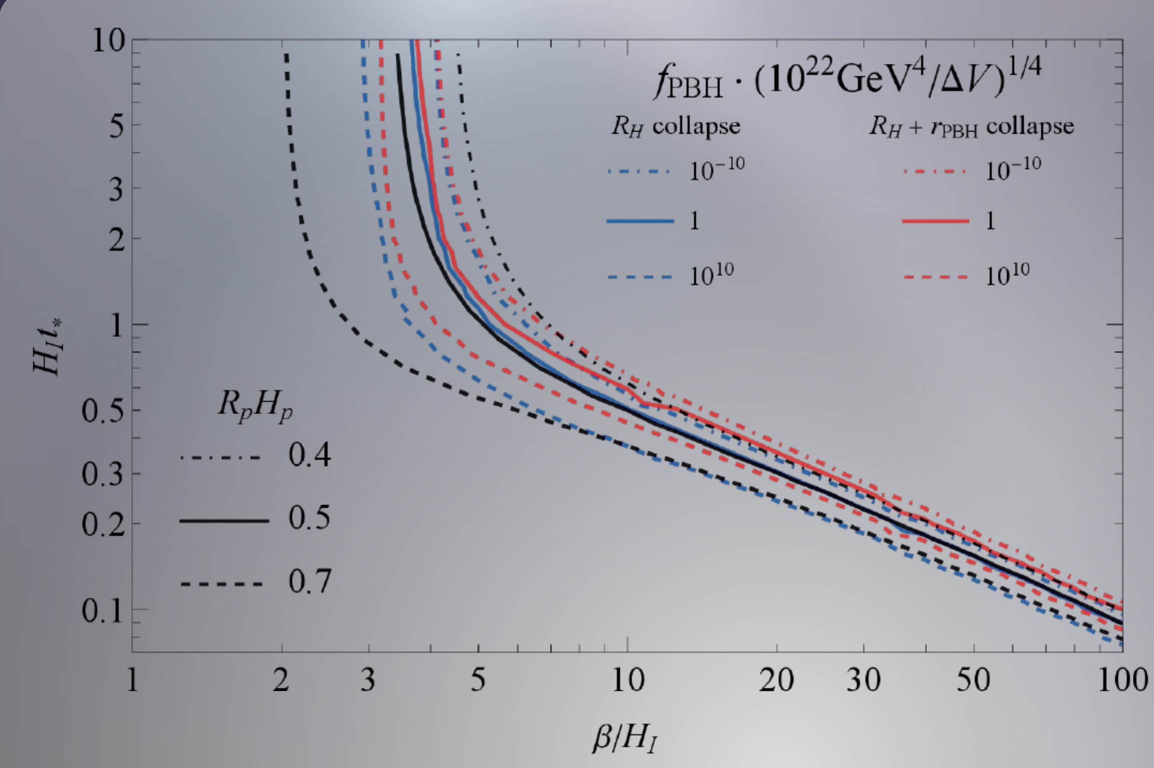
$$m_2(r,t) = 4\pi a(t)^2 r(t)^2\sigma\bar{\gamma}(t),$$

- mass of true vacuum bubbles contained inside FVD sphere

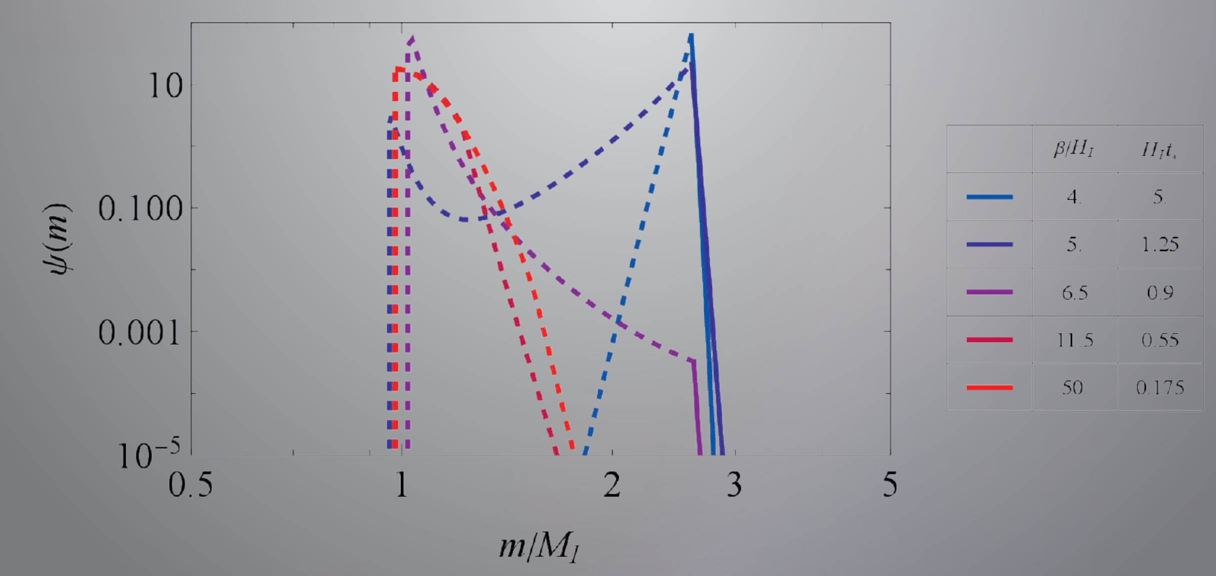
$$m_3(r,t) = \frac{4\pi}{3}(1-\epsilon(t))a(t)^3 r(t)^3\rho_B(t).$$

Schwarzschild condition then gives a lower bound on r of collapsing region, which we call $r_{PBH}(t)$.

Results



The PBH abundance today normalised to that of DM, f_{PBH}, as a function of the bubble nucleation parameters β and t_*. The blue lines include only large regions collapsing immediately on horizon crossing while the red ones also include the population of smaller regions collapsing as their compactness grows. The black lines show the average bubble radius normalised to the horizon radius, R_pH_p.



The normalised PBH mass function produced for a set of transitions with different values of the bubble nucleation rate parameters β and t_*. The examples here are chosen to lay along the $f_{PBH} = 1$ line for $\Delta V = 10^{22}\mathrm{GeV}^4$. M_I denotes initial mass of the Hubble horizon.

Conclusions

As we have shown, supercooled phase transitions provide an elegant mechanism leading to production of PBHs. We have estimated their population and examined how constraints on PBHs abundance translate into constraints on phase transitions' parameter space. We found that the shape of the bubble nucleation rate affects the final PBH mass function, while the potential energy difference ΔV roughly determines the mass of the produced Black Holes.

References

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Acknowledgements

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