WHEPP-2019

Origin of Primordial Black Holes from Warm Inflation

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Primordial Black Holes

Primordial Black Holes (PBHs) are the black holes that could have produced in the very early Universe.

Why PBHS are important to study?

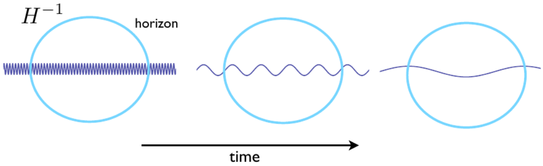
- They are probes to the early Universe physics, as they can provide constraints on the primordial power spectrum and the inflationary models.
- While CMB and LSS observations measure only the large scale modes ranging from $10^{-3} - 1$ Mpc^{-1}, PBHs span over a wide range of modes varying from $10^{-2} - 10^{23}$ Mpc^{-1}.
- PBHs are also the candidates for Dark Matter.

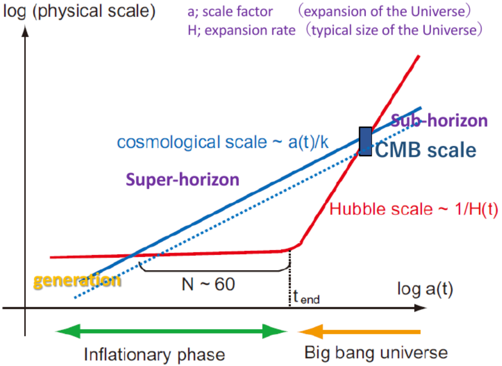
How do PBHs form?

PBHs can form in a number of ways. Here we consider the PBH generation

- by the collapse of overdensities generated during inflation

Primordial fluctuations during inflation





PBH formation via collapse of overdensities

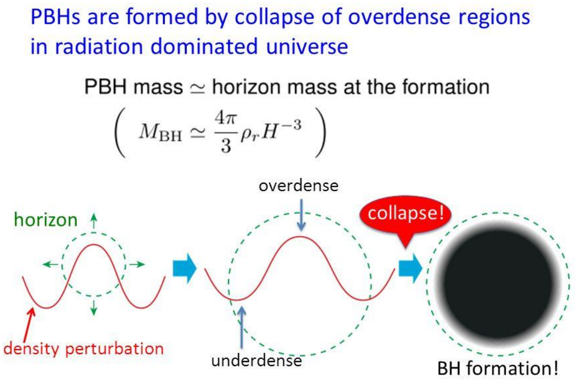


Figure : Source: www2.yukawa.kyoto-u.ac.jp/ ppp/PPP2012/slide/kitajima.pptx

Mass of the generated PBH

- The mass of a PBH depends on the epoch when it is formed.

$$M_{PBH}(k) \approx 5 \times 10^{15}\mathrm{g} \left(\frac{g_{*0}}{g_{*i}}\right)^{1/6} \left(\frac{10^{15}\mathrm{Mpc}^{-1}}{k}\right)^{2} \quad (1)$$

  Here g_{*0}, and g_{*i} are the relativistic degrees of freedom today and at the time of formation of PBH, respectively.

- Therefore, lighter PBHs form at large k (earlier in time), whereas the massive PBHs form at small k (later in time).
- Minimum mass of PBH $=10^{-5}$ g, Planck mass.
- PBHs with mass $M_{PBH} > 10^{15}$g are stable, whereas $M_{PBH} < 10^{15}$g would have evaporated into Hawking radiation by present time.

Initial mass fraction of PBH

It is the fraction of the energy density in the PBH at the time of its formation from the total energy density of the Universe at that epoch.

$$\beta(M_{PBH}) = \frac{\rho^i_{\rm PBH}(M_{PBH})}{\rho^i_{\rm total}} \tag{2}$$

$$= \frac{\Omega_{PBH0}(M_{PBH})}{\Omega_{r0}^{3/4}} \left(\frac{g_{*i}}{g_{*0}}\right)^{1/4} \left(\frac{M_{PBH}}{M_0}\right)^{1/2} \gamma^{-1/2}. \tag{3}$$

For different masses of PBH, there are observational bounds on Ω_{PBH0}, which can be further used to constraint $\beta(M_{PBH})$.

Here $\Omega_{r0} \approx 5.38 \times 10^{-5}$, $M_0 = \frac{4\pi}{3}\rho_{cr}H_0^{-3} \approx 4.62 \times 10^{22} M_\odot$, $\gamma = 0.2$, $g_{*i} = 200$, $g_{*0} = 3.36$

Press-Schechter theory for PBH formation

- Initial Gaussian perturbation, with overdensity $\delta > \delta_c$.
- Using this theory, the initial mass fraction of a PBH is given as

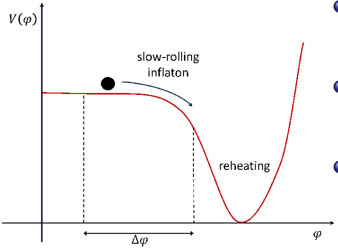
$$\beta(M_{PBH}) = \frac{2}{\sqrt{2\pi}\sigma(R)} \int_{\delta_c}^{1} \exp\left(\frac{-\delta^2(R)}{2\sigma^2(R)}\right) d\delta(R) = \operatorname{erfc}\left(\frac{\delta_c}{\sqrt{2}\sigma(R)}\right) \quad (4)$$

where erfc is the complimentary error function, and $\delta_c \sim \mathcal{O}(1)$, and $\sigma^2(R)$ is the mass variance, calculated for a given form of the primordial power spectrum.

Cosmic Inflation

Phase of accelerated expansion in the early Universe that lasted for a brief duration.

In the standard description of inflation,



- The inflaton couplings are negligible during inflation.
- As a result, the Universe supercools when inflates.
- There is a *reheating* phase after inflation during which the particles are created.

Warm Inflation

Warm Inflation is an alternate description of inflation in which,

- The inflaton dissipates to the other fields both during and after inflation.
- The Universe has a thermal bath of particles throughout.
- E.o.m of inflaton is modified

$$\ddot{\phi} + 3H\dot{\phi} + \Upsilon\dot{\phi} + V'(\phi) = 0$$

- Dissipation parameter $Q \equiv \frac{\Upsilon}{3H}$.

Primordial power spectrum for warm inflation

The primordial power spectrum for warm inflation is given as[1]

$$P_{\mathcal{R}}(k) = \left(\frac{H_k^2}{2\pi\dot{\phi}_k}\right)^2 \left[1 + 2n_k + \left(\frac{T_k}{H_k}\right)\frac{2\sqrt{3}\pi Q_k}{\sqrt{3+4\pi Q_k}}\right] G(Q_k).$$

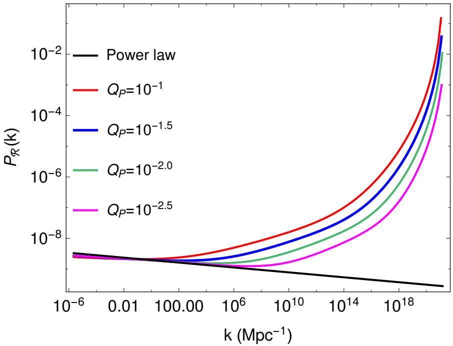
- It has contributions from thermal bath with temperature T and the dissipation parameter Q.
- Here $G(Q)$ is the growth factor [2],

$$G(Q_k) = 1 + 4.981\, Q_k^{1.946} + 0.127\, Q_k^{4.330}.$$

[1] S. Bartrum et al, PLB 732, 116 (2014).
[2] M. Benetti and R. O. Ramos, PRD 95 no. 2, (2017) 023517.

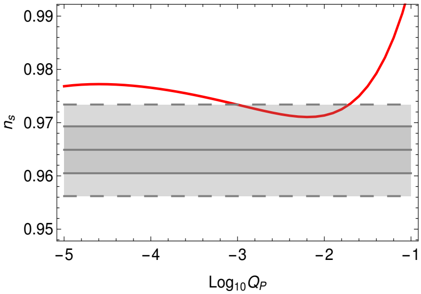
Our warm inflation model

We consider inflationary potential $\lambda\phi^4$ with $\Upsilon \propto T^3$.(Arya et al, JCAP02 (2018) 043)



- The primordial curvature power spectrum has a blue-tilt ($n_s > 1$) for the PBH scales (large k).
- For large dissipation, the amplitude of the primordial power spectrum is larger as compared to the smaller dissipation case.

Dissipation parameter consistent with CMB



- A small range of Q_P values are consistent with the CMB observations.
- For $Q_P > 10^{-1.7}$, the value of n_s is disallowed from Planck. Therefore we do not consider those cases.

Initial Mass Fraction versus Mass of the generated PBH

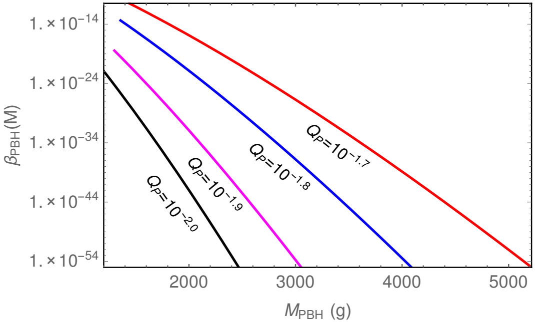


Figure : Plot of initial mass fraction $\beta(M)$ versus M_{PBH} (g).

- Large dissipation leads to more massive PBH formation, whereas small dissipation produces small mass PBHs.

Constraints on the abundance of PBHs formed

- The order of mass of the PBH formed from our warm inflation model, $M_{PBH} \sim 10^3$ g. Such a tiny mass of PBH would have evaporated into Hawking radiation by now (lifetime $\sim 10^{-19}$ sec).
- We find that for the cases with $Q_P = 10^{-1.8}, 10^{-1.9}, 10^{-2}$, the obtained initial mass fraction is in accordance with the upper limit ($\beta(M_{PBH}) < 10^{-14}$) obtained from the abundance of stable and long lived decaying particles produced by evaporating PBHs [3].
- The case with $Q_P = 10^{-1.7}$ overproduces PBHs, which is inconsistent with the upper bounds on β, and hence should be ruled out.

[3] A. M. Green, PRD60 (1999) 063516, M. Lemoine, PLB 481 (2000) 333338, M. Yu. Khlopov, A. Barrau, and J. Grain, Class. Quant. Grav. 23 (2006) 18751882

Generated PBHs as constituent of dark matter

- It is also argued that PBH evaporation ceases when PBH mass gets close to the Planck mass, and such Planck mass relics can thus constitute the present dark matter [4].
- The present density of the Planck mass relics should be less than the cold dark matter density, so that it does not overclose the Universe today.
- For our warm inflation models with $Q_P = 10^{-1.9}$, and $Q_P = 10^{-2}$, we find that the calculated initial mass fraction lies within the limit [5] ($\beta(10^3 g) < 10^{-16}$), and hence the possibility to form DM remains valid. However, Planck mass relics are extremely tiny and almost impossible to detect by non-gravitational measures.

[4] J. H. MacGibbon, Nature 329 (1987) 308309.

[5] B. J. Carr, J. H. Gilbert, and J. E. Lidsey, PRD50 (1994) 48534867

Summary

- PBHs are a remarkable probe to the physics of early Universe, particularly inflation.
- We discussed the PBH generation from a model of warm inflation.
- The primordial power spectrum has a blue-tilt at the small scales, with a large amplitude required for PBH generation.
- For various cases of dissipation, PBHs of mass $\mathcal{O}(10^3\ \mathrm{g})$ are formed.
- The initial mass fraction of PBHs is observationally constrained, and for one case of our model, the PBHs are overproduced, hence should be ruled out.
- There is also a possibility that the Planck mass remnants of the evaporating PBHs constitute the dark matter.

Thank you

Backup

On smoothening the density perturbations using a Gaussian window function, the probability distribution for a smoothed density contrast over a radius $R = (aH)^{-1}$ is given as

$$p(\delta(R)) = \frac{1}{\sqrt{2\pi}\sigma(R)} \exp\left(\frac{-\delta^2(R)}{2\sigma^2(R)}\right). \tag{5}$$

$$\sigma^2(R) = \int_0^\infty \tilde{W}^2(kR) P_\delta(k) \frac{dk}{k} \tag{6}$$

where $P_\delta(k)$ is the matter power spectrum, and $\tilde{W}(kR)$ is the Fourier transform of the window function

$$\tilde{W}(kR) = \exp(-k^2R^2/2). \tag{7}$$

$$P_\delta(k) = \frac{4(1+w)^2}{(5+3w)^2} \left(\frac{k}{aH}\right)^4 P_{\mathcal{R}}(k), \tag{8}$$