A mechanism for protogalaxies nuclei formation from primordial black holes clusters

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Abstract. A model describing the formation of protogalaxies is developed. Compact supermassive clusters of primordial black holes assumed to act as a nuclei for the galaxy formation. The mechanism of PBH formation based on a collapse of massive walls of scalar field due to second order phase transition. Mass spectra of PBH are obtained analytically and shown possibility of the formation of PBH clusters with a total mass of $\sim 10^5 - 10^8 M_\odot$, having a size of $\sim 10$ parsec, in an amount of $\sim 10^{11}$, which corresponds to observational data on the value of galaxies on the visible Universe. The primary fractal structure of galaxies is naturally explained through the mechanism. Proposed approach is the cornerstone for a principally new scenario of the galaxy formation in the early Universe.

1. Introduction
Today, practically no one has any doubt that the centers of most galaxies contain supermassive black holes [1]. Nevertheless, the mechanism of galactic nuclei formation remains unclear. According to many studies, star formation and the formation of galactic nuclei were simultaneous [2]. The issue of the ”pre-star” origin of supermassive black holes in the centers of galaxies remains open. In addition, unlike the ”stellar” black holes, primordial black holes can have arbitrary mass.

One of the possibilities of how primordial black holes can form is the phase transitions during cosmological inflation. During inflation, quantum fluctuations of various fields very quickly ”swell” to macroscopic dimensions, forming primary inhomogeneities, including clusters of primordial black holes. These clusters may serve as a triggering mechanism for an accumulation baryons with further evolution in a protogalactic structure [3, 4].

2. Main Idea
Our calculations are based on the mechanism proposed in the works [5, 6]. We suppose that there is a field $\phi$ with the ”Mexican hat”-like potential:

$$V(\phi) = \lambda(|\phi|^2 - f^2/2)^2 + \Lambda^4(1 - \cos \theta),$$

where $\phi = r e^{i\theta}$, and $\Lambda^4(1 - \cos \theta)$ is the contribution of instanton effects in the renormalization of the Lagrangian. The potential is slightly inclined, so the minimum points are in $\theta = 2\pi n$. 

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It is assumed that during inflation this field is already in the ring minimum, and the radial component of the mass is quite large, so the field moves along the ring minimum.

![Figure 1](image.png)

**Figure 1.** The potential defined by the formula (1) and its possible states.

Because of quantum fluctuations during inflation, random walks occur in the phase $\theta$. We can obtain $f(\phi, t)$ - the distribution of the field $\phi$, due to its quantum fluctuations. This distribution function is a solution of the Fokker-Planck equation [7]. Let the initial value of the field $\theta_U$ be slightly different from the minimum. After inflation, the classical evolution of field will roll it down to a minimum. Some fluctuations transit the field through $\theta = \pi$. It leads field to roll down to the minimum on the other side and forms space region of false vacuum state. A massive potential wall appears between the different vacuums, capable of collapsing into a black hole.

At the time of inflation, the size of the horizon $H^{-1}$ is also the characteristic size of the fluctuations. After the end of inflation, a domain wall forms, separating the false vacuum. We can calculate the occurrence probability of critical fluctuations

$$P(t) = \int_0^\infty f(\theta, t) d\theta,$$

and, consequently, the rate at which the number of future domain walls increase:

$$\frac{dn}{dt} = \frac{dn_U}{dt} P(t) = 3He^{3Ht} P(t),$$

where $dn_U/dt$ is the the rate of increasing in the number of cause-independent areas in the observable Universe, $Ht_{in} = N$ the number of e-folds.

3. Mass spectra of PBH

Since we know the expansion rate of the Universe at the inflation stage, we can calculate the distribution of our regions in size because

$$\frac{dn}{dr} = \frac{dn}{dt} \frac{dt}{dr(t)},$$

where $r(t)$ is the expansion law at the time of inflation. And therefore we can calculate a mass spectra because the mass of primordial black hole

$$m = 4\pi r^2 \rho_S,$$

where $\rho_S = 4\lambda^2 f$ is an energy density of the potential wall between two vacuum states [5].

Omitting the long calculation, the mass spectra of PBH:

$$\frac{dn}{dm} = \frac{3}{8} e^{3N} \sqrt{\frac{\pi^3 \rho_S^3}{H^6 N^6 m^7}} \text{Erfc} \left( \frac{2(\pi - \theta_U) \pi f}{H \sqrt{2N - \ln 2N \sqrt{\frac{m}{4\pi \rho_S}}}} \right).$$
Figure 2. The differential mass spectrum of the primordial black holes:

- \( f = 1.0H \),
- \( f = 1.6H \),
- \( f = 2.2H \).

Figure 2 shows the differential mass spectrum of the primordial black holes that appear in the model. We choose the following parameters of the model, consistent with the observed anisotropy of the background radiation: \( H = 10^{13} \) GeV, \( N = 60 \), field parameter \( \lambda = 5 \) and the initial value \( \theta_U = 0.05\pi \).

The number of PBHs in the observable Universe depends strongly on the value of \( f \), so that three values are chosen: \( f = 1.0H, f = 1.6H, f = 2.2H \). The model with \( f = 1.6H \) has the best correspondence with observational data.

4. Clusters of PBHs

Fluctuations that bring the field value to a false minimum are multiple. Therefore, a region with other false minima can be formed with greater probability within a region whose field value is already close to critical. So, the PBHs form clusters that have a fractal structure. We can use the already obtained formula (6) with the minor changes to calculate the spectra of clusters.

Figure 3. Mass spectra of PBHs clusters at \( f = 1.8H \):

a) Cluster with central BH mass \( 10^2 M_\odot \), cluster size 4 pc, cluster mass \( 2.6 \cdot 10^5 M_\odot \), number of clusters in the Universe \( 4.1 \cdot 10^8 \);
b) Cluster with central BH mass \( 10^5 M_\odot \), cluster size 40 pc, cluster mass \( 2.3 \cdot 10^8 M_\odot \), number of clusters in the Universe \( 8.1 \cdot 10^4 \).
Figure 4. Mass spectra of PBHs clusters at \( f = 1.6H \):

a) Cluster with central BH mass \( 10^2 M_\odot \), cluster size 4 pc, cluster mass \( 2.6 \cdot 10^5 M_\odot \), number of clusters in the Universe \( 2.9 \cdot 10^{11} \);

b) Cluster with central BH mass \( 10^5 M_\odot \), cluster size 40 pc, cluster mass \( 2.3 \cdot 10^8 M_\odot \), number of clusters in the Universe \( 1.1 \cdot 10^8 \).

Figures 3 and 4 show the PBH mass spectra of the cluster for different model parameters. It is seen that at \( f = 1.6H \) and central PBH mass \( \sim 10^2 M_\odot \) the number of clusters with total mass \( \sim 10^5 M_\odot \) corresponds to the number of galaxies in the observable Universe.

5. Conclusion

- Analytical mass spectra of primordial black holes for the observable Universe are obtained. With an appropriate choice of parameters, the model is consistent with the observational data.
- Primordial black holes form clusters have a fractal spatial structure. Most clusters are compact enough to form protogalactic nuclei.
- At \( f = 1.6H \) and central PBH mass \( \sim 10^2 M_\odot \) the number of clusters with total mass of \( \sim 10^5 M_\odot \) is of \( \sim 10^{11} \), so the model may explain forming the galactic nuclei in early Universe.

6. Forthcoming Research

It is planned to clarify in detail the spatial structure of the cluster (distribution with respect to \( r \)). In addition, we are going to simulate further movements of the PBHs in clusters to find out how they can form a supermassive black hole in the centers of future galaxies.

References

[1] Rosenberg D E and Rollino J 2000 Preprint astro-ph/0012023
[2] Veilleux S 2001 The starburst-agn connection Springer Proceedings in Physics: Starburst Galaxies: Near and Far (Springer) pp 8894
[3] Stiavelli M 1998 ApJL 495 L91
[4] Merrifield M, Forbes D A and Terlevich A 2000 MNRAS 313 L29L32
[5] Khlopov M Y, Konoplich R V, Rubin S G and Sakharov A S 2000 G&C 6 153156
[6] Dokuchaev V, Eroshenko Y N, Rubin S and Samarchenko D 2010 Astron. Lett. 36 773779
[7] Linde A D 1982 Phys. Lett. B 116 335339