Possibility of weakening the constraint on abundance of primordial black holes from Eridanus II

Krasnov M.A. [1], Belotsky K.M.[1]

[1]NRNU MEPhI, Department of elementary particle physics

Abstract

Stellar cluster, observed in dwarf galaxy Eridanus II, provides strong constraint on abundance of massive compact halo objects (MACHOs) of mass $10^3 M_\odot \leq M \leq 10^6 M_\odot$, so they cannot be the main component of dark matter. MACHO dark matter should dynamically heat the cluster, driving it to larger sizes and higher velocity dispersions until it dissolves into galaxy. Primordial black holes (PBH) are subject to this constraint. PBHs are now of special interest in connection to LIGO/Virgo results, early quasars observation, but historically first reason of very great interest to PBH is accounted for by dark matter (DM) problem. There have been plenty of works considering PBH as DM candidate, but, unfortunately, most of them just only put constraints overlapping each other on all relevant mass range. We consider cluster of PBHs of cluster mass within interval constrained from Eridanus.

Introduction

Primordial black holes (PBH) topic has received a huge wave of attention lately. The main reasons are last years discoveries of gravitation waves from black hole merging by LIGO/Virgo [10] and that early quasars can not be explained by stellar origin [1, 5]. There can be introduced other [9]. But starting with theoretical prediction of PBH itself, made by Ya.Zeldovich and I.Novikov in 1967 [11], and then especially after first results of MACHO [2, 3, 4], PBHs are considered as a candidate to dark matter (DM). By now an incredible number of works have been made on this topic but they basically restrict possible PBH abundance over all relevant mass range. Existing picture can be seen in one of the last review [8], though new constraints have had time to appear since that review. Nonetheless debates on whether or not PBHs can explain DM continue. In case of Eridanus II the constraint comes from observation of star cluster observed in Eri II, which would have to be destroyed if dark matter were composed of compact objects noticeably heavier than the stars. Since kinetic energy of such objects is mostly greater than that of star, they should heat up stellar cluster through gravitation interaction eventually destroying it. Parameters of the PBH clusters can be different but its mass $\sim 10^4 M_\odot$ can be of special interest as they can be supposed to be the seeds for quasars. If they are compact enough they will be subject to the aforementioned restriction. But they can be non-compact or (partially) destroyed in the course of their evolution or interaction with the star cluster and with each other. PBH cluster as a whole should heat up stellar cluster, its components should predominantly cool down.

Properties of clusters of primordial black holes

Clusters we analyze have power law mass distribution function [6]

$$\frac{dN}{dM} \propto \frac{1}{M^2}. \tag{1}$$

Where N is number of PBHs in cluster. We will use two parameters to describe PBH cluster. These are M_{min} and M_{cl} which mean mass of the lightest black hole in cluster and the cluster's mass. It is obvious to set three conditions for it.

$$\begin{cases} N = \displaystyle\int\limits_{M_{min}}^{M_{max}} \frac{dN}{dM}\, dM, \\ M_{cl} = \displaystyle\int\limits_{M_{min}}^{M_{max}} M \frac{dN}{dM}\, dM, \\ 1 = \displaystyle\int\limits_{M_{max}}^{\infty} \frac{dN}{dM}\, dM. \end{cases} \tag{2}$$

Diffusion treatment

We will assume an isotropic Maxwellian velocity distribution for the dark matter particles and a locally uniform dark matter density. Evolution of the stellar cluster of total energy $E_{\rm tot}$ can be described following representation of collision integral in Fokker-Planck equation through diffusion coefficient as the following

$$\frac{\dot{E}_{\rm tot}}{M_{\text{star cluster}}} = \frac{D[\Delta E]}{M_{\text{star cluster}}} = \frac{1}{2} D[(\Delta v^2)] + vD[\Delta v_{||}] = \\ = \frac{2\sqrt{2}\pi G^2 \rho M \ln\Lambda}{\sigma} \frac{\operatorname{erf}(X)}{X} - \frac{4\pi G^2 \rho v (m+M)\ln\Lambda}{\sigma^2} \mathrm{G}(X). \tag{3}$$

Here $D[(\Delta v^2)]$ and $vD[\Delta v_{||}]$ are the diffusion coefficients of the squared star velocity and its radial component, m and M in this formula are the masses respectively of star and MACHO (the objects on which the stars scatter as on whole), ρ is the density of MACHO, σ is their velocity dispersion, $\ln\Lambda \sim 30$ is the Coulomb logarithm. Function $G(x)$ under accepted assumptions is

$$\mathrm{G}(X) = \frac{1}{2X^2}\left[\operatorname{erf}(X) - \frac{2X}{\sqrt{\pi}} e^{-X^2}\right], \tag{4}$$

with v being here star velocity, $X = v/\sqrt{2}\sigma$, and ρ is the density of PBH clusters in the galaxy what is the total (averaged) PBH density in the galaxy. The potential energy per unit mass for Eridanus II's cluster is given by

$$\frac{U}{M_{\text{star cluster}}} = \text{const} + \beta G \rho r_h^2 - \alpha \frac{G M_*}{r_h}, \tag{5}$$

where $\alpha \approx 0.36$ and $\beta \approx 7.2$. Now replace ρ with $\rho_{DM} \cdot f_{DM}$. Using virial theorem

$$E_{\rm tot} = \frac{1}{2} U. \tag{6}$$

And equation (5) we obtain the equation for $\dot{r}_h$. Now we differentiate equation (6) and divide both sides by $M_{\text{star cluster}}$.

$$\frac{\dot{E}_{\rm tot}}{M_{\text{star cluster}}} = \frac{1}{2} \frac{\dot{U}}{M_{\text{star cluster}}}. \tag{7}$$

$\dot{E}$ connected with diffusion coefficients in this way:

$$\dot{E} = M_{\text{star cluster}} \left(vD\left[\Delta v_{||}\right] + \frac{1}{2} D\left[(\Delta v^2)\right] \right), \tag{8}$$

Let's look at cooling effect described by first-order diffusion coefficient:

$$vD\left[\Delta v_{||}\right] = -\frac{4\pi v G^2 \rho_{cl} (m_* + M_{cl}) \ln\Lambda}{\sigma^2} G(X), \tag{9}$$

due to the $G(X)$ this effect is negligible. $G(X) \sim 10^{-3}$. This was cooling effect from cluster as whole. If we summarize effects of any PBH so we get

$$vD_\Sigma\left[\Delta v_{||}\right] = -\frac{4\pi v G^2 \rho_{cl} (m_* + M') \ln\Lambda}{\sigma^2} G(X), \tag{10}$$

Where M' is given by 13. It's obvious this is also negligible since $M' < M_{cl}$. Then replace the left side with (3). Since heating is much stronger than cooling we get

$$D\left[(\Delta v^2)\right] = \frac{\dot{U}}{M_{\text{star cluster}}}. \tag{11}$$

If we choose PBHs distribution function as $f(m,v) = \sum_i g_i(v)\delta(m - m_i)$, where $g_i(v)$ is Maxwellian velocity distribution. m_i are distributed by power law (1) and each of $g_i(v)$ is normalized so that $\int d^3\vec{v}\, g_i(v) = n_i$ where n_i is number density of PBHs with mass m_i. In order to go to an extended mass spectrum, consider the sum

$$\sum_i n_i M_i^2 = \int \frac{dn}{dM} M^2\, dM = \frac{\rho}{\int \frac{dn}{dM} M\, dM} \int \frac{dn}{dM} M^2\, dM = \rho M', \tag{12}$$

where M' is given by

$$M' = \frac{\int dN/dM\, M^2\, dM}{\int dN/dM\, M\, dM}, \tag{13}$$

where dN/dM is the mass-spectrum of PBHs. In the case $dN/dM \propto M^{-2}$:

$$M' = \frac{M_{max} - M_{min}}{\ln(M_{max}/M_{min})}. \tag{14}$$

And after all

$$\dot{r}_h \left(\alpha \frac{M_*}{\rho_{DM} r_h^2} + 2\beta r_h \right) = \frac{4\sqrt{2}\pi G f_{DM} \ln\Lambda}{\sigma} M', \tag{15}$$

PBH cluster, being compact enough, can play the role of MACHO. But PBHs themselves which constitute it should play this role too. It does not matter whether or not PBHs are collected in clusters (we will refer to this case as separate PBHs). This is true if we ignore collective gravity effects of PBHs. It is easy to show that in this case effect depends on the mean PBH density and, so, does not depend on their space distribution. Collective gravitational effect will change velocity parameters like v and σ. It will lead to weakening of cooling effect when PBH cluster is more dense, PBH cluster escape velocity becomes bigger. It is shown in Appendix A. But it is not significant if we take all the velocity parameters (dispersion of PBHs in their cluster, dispersion of stars in their cluster and velocity in galaxy) being of the same order of magnitude. In Fig.1 and Fig.2 we take in case of separate PBHs in the form

$$\sigma' = \sqrt{v^2 + \sigma^2}. \tag{16}$$

We are interested in f_{DM}, equation (15) allow us to get it. We know parameters of Eridanus II's cluster, so just integrate in certain limits. We will use only $\sigma = 10\,\frac{\text{km}}{s}$ because it weakens the cooling. All constraints come from requiring that the timescale to grow from initial $r_h = 2$ pc to current 13 pc is equal to star cluster's age. So integrate one side with respect to r_h and the other side with respect to t in stated limits. After all just take out f_{DM}. Fig.1 and Fig.2 are made for Eridanus II's star cluster 12 Gyr old and its stellar mass $M_* = 6000 M_\odot$. Dot-dashed lines are presented for case of modificated velocity dispersion chosen in the form (16).

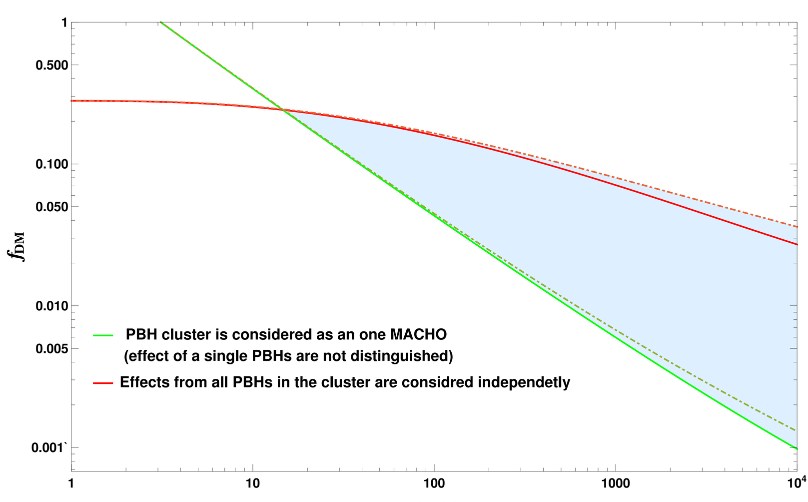

Figure 1: Constraints for clusters with lightest PBH with mass $10 M_\odot$. Eridanus II's star cluster is assumed to be 12 Gyr old and $\rho_{DM} = 1\,\frac{M_\odot}{pc^3}$.

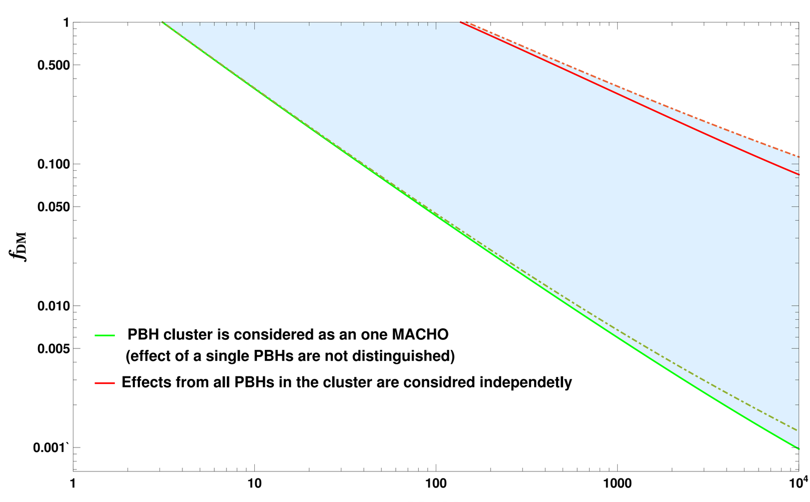

Figure 2: Constraints for clusters with lightest PBH with mass $0.1 M_\odot$. Eridanus II's star cluster is assumed to be 12 Gyr old and $\rho_{DM} = 1\,\frac{M_\odot}{pc^3}$.

Conclusion

We have find that PBH cluster predominantly consisting of light BHs (power law distribution is considered here) may allow circumventing constraints on PBH mass equal to the PBH cluster mass. We have achieved the weakening of constraints on MACHO dark matter, what is accounted for by finite (big) size of PBH cluster. In this case dynamic friction of star crossing it plays significant role.

The next step is to find how long clusters of PBHs could live before complete disruption. In complete analysis of PBH and stellar clusters interaction, there should be the following effects to be taken into account:

- Scattering of stars on PBH cluster as a whole (as on point-like one)[1],
- Tidal forces effects due to finite size of PBH cluster,
- Dynamical friction of stars inside PBH cluster.

Here third effect alone was taken into account and compared with first one [7]. That is we compared maximal and minimal limiting cases in sense of constraining PBH abundance. The work on complete analysis is in progress.

References

[1] J. Aird et al. "The evolution of the X-ray luminosity functions of unabsorbed and absorbed AGNs out to z 5". English. In: *Monthly Notices of the Royal Astronomical Society* 451.2 (Aug. 2015). 36 pages, 20 figures, 11 tables. A casual reader is directed to figures 7, 8, 9 and 20. Updated to version accepted for publication in MNRAS, pp. 1892–1927.

[2] C. Alcock et al. "The MACHO Project First-Year Large Magellanic Cloud Results: The Microlensing Rate and the Nature of the Galactic Dark Halo". In: *The Astrophysical Journal* 461 (Apr. 1996), p. 84.

[3] C. Alcock et al. "The MACHO Project Large Magellanic Cloud Microlensing Results from the First Two Years and the Nature of the Galactic Dark Halo". In: *The Astrophysical Journal* 486.2 (Sept. 1997), pp. 697–726.

[4] C. Alcock et al. "The MACHO Project: Microlensing Results from 5.7 Years of Large Magellanic Cloud Observations". In: *The Astrophysical Journal* 542.1 (Oct. 2000), pp. 281–307.

[5] E. Bañados et al. "An 800-million-solar-mass black hole in a significantly neutral Universe at a redshift of 7.5". In: *Nature* 553.7689 (Dec. 2017), pp. 473–476.

[6] K. M. Belotsky et al. "Clusters of Primordial Black Holes". In: *The European Physical Journal C* 79.3 (Mar. 2019).

[7] T. D. Brandt. "CONSTRAINTS ON MACHO DARK MATTER FROM COMPACT STELLAR SYSTEMS IN ULTRA-FAINT DWARF GALAXIES". In: *The Astrophysical Journal* 824.2 (June 2016), p. L31.

[8] B. Carr, F. Kühnel, and L. Visinelli. "Constraints on stupendously large black holes". In: *Monthly Notices of the Royal Astronomical Society* 501.2 (Nov. 2020), pp. 2029–2043.

[9] S. Clesse and J. García-Bellido. "Seven hints for primordial black hole dark matter". In: *Physics of the Dark Universe* 22 (2018), pp. 137–146.

[10] t. V. C. The LIGO Scientific Collaboration and the KAGRA Collaboration. "All-sky search for short gravitational-wave bursts in the third Advanced LIGO and Advanced Virgo run". In: *Phys. Rev. D* 104 (12 Dec. 2021), p. 122004.

[11] Y. Zel'dovich and I. Novikov. "The Hypothesis of Cores Retarded during Expansion and the Hot Cosmological Model". In: *Sov. Ast* (1967), p. 602.

[1]in other words, dynamical friction of PBH cluster inside stellar cluster