Primordial Black Holes as Dark Matter: New Formation Scenarios and Astrophysical Effects

Alexander Kusenko

Abstract Scalar field instability can lead to a short matter dominated era, during which the matter is represented by large lumps of the scalar field, whose distribution exhibits large fluctuations, leading to copious production of primordial black holes (PBH). The PBH abundance can be sufficient to explain up to 100% of dark matter without violating observational constraints. Small PBH can destabilize neutron stars and contribute to r-process nucleosynthesis.

1 Introduction

Primordial black holes can account for all or part of dark matter in the early universe [1–6], and they can also seed supermassive black holes observed in centers of galaxies [7–10]. Furthermore, they could be responsible for some of the gravitational wave signals observed by LIGO [11–14].

The high-density environment in the early universe suggests that black holes may be produced if there is a sufficient degree of inhomogeneity [1–3]. However, the density perturbations that seeded the observed structures were too small for PBH formation. Some additional power could be generated on certain scales by inflaton dynamics [4], and many models have focused on this possibility [15, 16].

However, the presence of even a single scalar field (such as the Higgs field, if it has the right potential at large VEV, or some other fields, such as those predicted by supersymmetry) can result in large inhomogeneities on some scales. The origin of such inhomogeneities is in instability that causes fragmentation of a scalar condensate [17]. The instability leads to matter like state, in which the matter component is composed of large-mass lumps of the scalar field. Since the energy density in the matter component scales slower than the radiation matter density, the lumpy scalar

A. Kusenko (✉)
Department of Physics and Astronomy, University of California,
Los Angeles, CA 90095-1547, USA

Kavli Institute for the Physics and Mathematics of the Universe (WPI),
UTIAS The University of Tokyo, Kashiwa, Chiba 277-8583, Japan
e-mail: kusenko@ucla.edu

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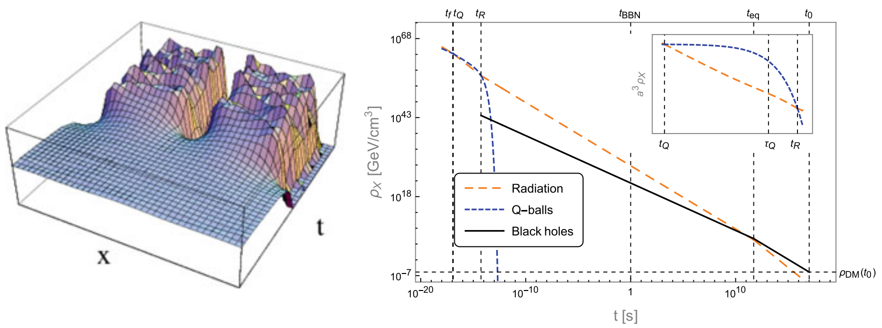

Fig. 1 Fragmentation of the scalar field (left panel, see Ref. [17]) can lead to a matter dominated stage with relatively few giant particles, which thus exhibit large density fluctuations [22, 23]. These density fluctuations, which lead to PBH production, are different from primordial density fluctuations seeding cosmic structures

field can come to dominate the energy density. The field lumps are large and relatively few, and the density fluctuations are much larger than in the case of matter made up of a huge number of small particles. Therefore, it is much more likely to find some patches of space in which the density contrast is of order one, which is necessary condition for PBH formation. Another condition, of near spherical symmetry, is also satisfied in some small subset of the universe.

2 Scalar Field Instability and PBH Formation

During inflation, scalar fields with masses smaller than the Hubble parameter develop large expectation values [18–21]. After inflation is over, the field relaxes to the minimum of its effective potential. There is a well-known instability that can set in during the coherent motion of the scalar field [17]. If the second derivative of the potential is sufficiently small or negative, an initially homogeneous condensate fragments into lumps of scalar field or Q-balls [21], as shown in the left panel of Fig. 1. The right panel shows the timeline of one such model [22], in which the scalar lumps come to dominate the energy density at time t_Q.

Eventually, the scalar lumps decay, and the radiation dominated era resumes. However, during the intermediate matter dominated era, PBH can be produced.

3 PBH Formation During a Lump-Dominated Epoch

When the “matter” is composed of relatively few giant “particles” (scalar lumps), the density fluctuations can be large. The regions of high density can give rise to black holes. This mechanism is very different from models that rely on primordial density fluctuations generated during inflation [1–6, 15]. It is also different from a model

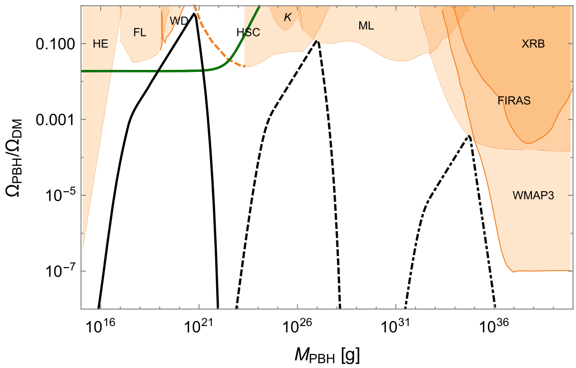

Fig. 2 PBH mass function in a model of Ref. [22]. See Refs. [22, 23, 26] for discussion of constraints and mass functions in other models. Solid green line indicates the parameter space where neutron star disruptions by PBH can produce up to 100% of r-process material needed to explain heavy element abundances [27]

based on inhomogeneous baryogenesis [24], in which the scalar dynamics lead to formation of high-baryon-number bubbles, which collapse to black holes.

The presence of a sufficient density contrast is not yet sufficient for a black hole formation. The mass distribution in the overdense region should be spherically symmetric to a high degree [25]. The PBHs form from a small subset of the overdense regions (which, in turn, are a small subset of the total). Even though the PBH-forming configurations are rare, there is a sufficient number of them to account for all dark matter [22, 23].

The mass function of PBH produced from scalar instability is shown in Fig. 2. The PBH abundance can account for all dark matter in the mass window of 10^{20-23} g, where there are no strong constraints on the abundance of PBHs. There can also be black holes with 1–10 solar masses, which can contribute to the gravitational waves observed by LIGO. A similar scenario exists for the inflaton field, which can fragment into oscillons [26].

4 Neutron Star Genocide and Other Astrophysical Effects of PBH

Neutron stars can capture PBH, in which case the neutron star is destroyed eventually by a black hole eating it from the inside [28]. The last stages of the neutron star demise can be accompanied by a massing release of cold nuclear matter [27], which can contribute to the r-process nucleosynthesis. Rapid-capture (r-process) nucleosynthesis is needed to explain the observed abundances of heavy elements, including gold, platinum, and uranium. However, the site of r-process remains unknown, while neutron star collisions can release some neutron-rich matter, other sources may contribute to r-process. In the part of the parameter space shown in Fig. 2, neutron star genocide by PBH can account for up to 100% of the needed r-process.

PBH contribution to r-process nucleosynthesis is consistent with the observed distribution of heavy elements in dwarf spheroidal galaxies [29]: since the capture of a PBH on a neutron star is a rare event, one expects that roughly one in ten ultrafaint dwarfs should have a high abundance of heavy elements [27].

In addition to r-process nucleosynthesis, the presence of PBH can result in several additional astrophysical effects. The last stages of neutron star destructions cause the magnetic field of the star to undergo a transformation on the time scales of a few milliseconds. This results in a radio pulse whose duration and energy are consistent with observed fast radio bursts.

Released nuclear matter, heated by beat decays, reaches temperatures at which some fraction of positrons can be produced. These low-energy positrons eventually annihilate, and their population can explain the observed 511 keV line from the Galactic Center [27].

Regardless of their initial size, small PBH captured on neutron stars transform into black holes with masses from 1 to 2 $M_{\odot}$ [27, 30]. Since astrophysical black holes are expected to have larger masses, detection of a population of black holes with masses $(1-2)M_{\odot}$ would imply the existence of PBH.

5 All Dark Matter in the Form of PBH?

There is an open mass window, shown in Fig. 2, in which all dark matter can be made up by primordial black holes. Several techniques used to rule out PBH at masses below $10^{-13}M_{\odot}$ and above $10^{-10}M_{\odot}$ are ineffective in this mass window. For example, optical microlensing does not work for black holes whose event horizons are smaller than the wavelength of light [31, 32]. PBH in this mass window can be produced in the early universe in a number of models that make few assumptions beyond inflation and, possibly, an additional scalar field [22, 23, 26].

6 Conclusion

A new class of models for PBH formation, based on the scalar field instability in the early universe, makes PBH formation a natural and fairly generic phenomenon. There is a scalar field in the Standard Model, namely, the Higgs field, and theories beyond the Standard Model typically predict a large number of scalar fields, for example, from supersymmetry.

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References

1. Y.B. Zel'dovich, I.D. Novikov, Sov. Astron. **10**, 602 (1967)
2. S. Hawking, Mon. Not. Roy. Astron. Soc. **152**, 75 (1971)
3. B.J. Carr, S.W. Hawking, Mon. Not. Roy. Astron. Soc. **168**, 399 (1974)
4. J. Garcia-Bellido, A.D. Linde, D. Wands, Phys. Rev. D **54**, 6040 (1996). https://doi.org/10.1103/PhysRevD.54.6040
5. P.H. Frampton, M. Kawasaki, F. Takahashi, T.T. Yanagida, JCAP **1004**, 023 (2010). https://doi.org/10.1088/1475-7516/2010/04/023
6. K. Inomata, M. Kawasaki, K. Mukaida, Y. Tada, T.T. Yanagida (2016)
7. R. Bean, J. Magueijo, Phys. Rev. D **66**, 063505 (2002). https://doi.org/10.1103/PhysRevD.66.063505
8. M. Kawasaki, A. Kusenko, T.T. Yanagida, Phys. Lett. B **711**, 1 (2012). https://doi.org/10.1016/j.physletb.2012.03.056
9. S. Clesse, J. García-Bellido, Phys. Rev. D **92**(2), 023524 (2015). https://doi.org/10.1103/PhysRevD.92.023524
10. A.D. Dolgov, Usp. Fiz. Nauk **188**(2), 121 (2018).https://doi.org/10.3367/UFNe.2017.06.038153. [Phys. Usp.61,no.2,115(2018)]
11. S. Clesse, J. García-Bellido, Phys. Dark Univ. **15**, 142 (2017). https://doi.org/10.1016/j.dark.2016.10.002
12. S. Bird, I. Cholis, J.B. Muñoz, Y. Ali-Haïmoud, M. Kamionkowski, E.D. Kovetz, A. Raccanelli, A.G. Riess, Phys. Rev. Lett. **116**(20), 201301 (2016). https://doi.org/10.1103/PhysRevLett.116.201301
13. M. Sasaki, T. Suyama, T. Tanaka, S. Yokoyama, Phys. Rev. Lett.**117**(6), 061101 (2016).https://doi.org/10.1103/PhysRevLett.121.059901, https://doi.org/10.1103/PhysRevLett.117.061101. [Erratum: Phys. Rev. Lett.121,no.5,059901(2018)]
14. J. Georg, S. Watson, JHEP **09**, 138 (2017). https://doi.org/10.1007/JHEP09(2017)138. [JHEP09,138(2017)]
15. MYu. Khlopov, Res. Astron. Astrophys. **10**, 495 (2010). https://doi.org/10.1088/1674-4527/10/6/001
16. B. Carr, T. Tenkanen, V. Vaskonen, Phys. Rev. D **96**(6), 063507 (2017). https://doi.org/10.1103/PhysRevD.96.063507
17. A. Kusenko, M.E. Shaposhnikov, Phys. Lett. B **418**, 46 (1998). https://doi.org/10.1016/S0370-2693(97)01375-0
18. T.S. Bunch, P.C.W. Davies, Proc. Roy. Soc. Lond. **A360**, 117 (1978). https://doi.org/10.1098/rspa.1978.0060
19. A.D. Linde, Phys. Lett. B **116**, 335 (1982). https://doi.org/10.1016/0370-2693(82)90293-3
20. A.A. Starobinsky, J. Yokoyama, Phys. Rev. D **50**, 6357 (1994). https://doi.org/10.1103/PhysRevD.50.6357
21. M. Dine, A. Kusenko, Rev. Mod. Phys. **76**, 1 (2003). https://doi.org/10.1103/RevModPhys.76.1
22. E. Cotner, A. Kusenko (2016)
23. E. Cotner, A. Kusenko, Phys. Rev. D **96**(10), 103002 (2017). https://doi.org/10.1103/PhysRevD.96.103002
24. F. Hasegawa, M. Kawasaki (2018)
25. A.G. Polnarev, M. Yu. Khlopov, Sov. Phys. Usp. **28**, 213 (1985).https://doi.org/10.1070/PU1985v028n03ABEH003858. [Usp.Fiz.Nauk145,369(1985)]
26. E. Cotner, A. Kusenko, V. Takhistov (2018)
27. G.M. Fuller, A. Kusenko, V. Takhistov, Phys. Rev. Lett. **119**(6), 061101 (2017). https://doi.org/10.1103/PhysRevLett.119.061101
28. C. Kouvaris, P. Tinyakov, Phys. Rev. D **90**(4), 043512 (2014). https://doi.org/10.1103/PhysRevD.90.043512
29. A.P. Ji, A. Frebel, A. Chiti, J.D. Simon, Nature **531**, 610 (2016). https://doi.org/10.1038/nature17425

30. V. Takhistov, Phys. Lett. B **782**, 77 (2018). https://doi.org/10.1016/j.physletb.2018.05.026
31. R. Takahashi, T. Nakamura, Astrophys. J. **595**, 1039 (2003). https://doi.org/10.1086/377430
32. N. Matsunaga, K. Yamamoto, JCAP **0601**, 023 (2006). https://doi.org/10.1088/1475-7516/2006/01/023