LIGO Detected Primordial Black Holes?

In September 2015, gravitational waves (GWs) were detected for the first time by the LIGO detectors, the two laser interferometers in the United States. It was found that detected GWs originate from the coalescence of two black holes (BHs) in a binary, each weighing about 30 times the mass of the Sun (30 solar mass). Although there have been indirect observations of BHs in the X-ray binaries, their masses are at most 15 solar masses. Furthermore, theory of stellar evolution suggests that the mass of the BH that forms after the death of the star is around 10 solar masses even if the star was much heavier at its birth. Thus, the discovery of such heavy BHs was an unexpected event. After this discovery, elucidating the scenario for the origin of such BHs and the formation of a binary has become one of the most important topics in astrophysics.

Dr.Teruaki Suyama at Research Center for the Early Universe and his collaborators have proposed a novel scenario [1] that the detected gravitational waves were caused by the coalescence of primordial BHs (PBHs), hypothetical BHs that formed just after the Big-Bang. Since everywhere in the Universe in its early stage was extremely dense, if there is a certain level of denser regions, such a region could undergo gravitational collapse and turn into a BH. In order to produce 30 solar mass PBH, the collapse must occur when the Universe is merely about 0.1 milliseconds old after the Big-Bang. This is what general relativity tells us. What general relativity does not tell us is whether such denser regions suitable for the PBH formation actually existed in the Universe. The answer must be given by cosmology, but cosmology is not yet mature enough to offer the definite answer due to our incomplete understanding of the primordial inhomogeneities from both theoretical and observational points of view.

Instead of adopting a specific theoretical model explaining the origin of inhomogeneities necessary for PBH formation, Suyama *et al.* started from the simple and

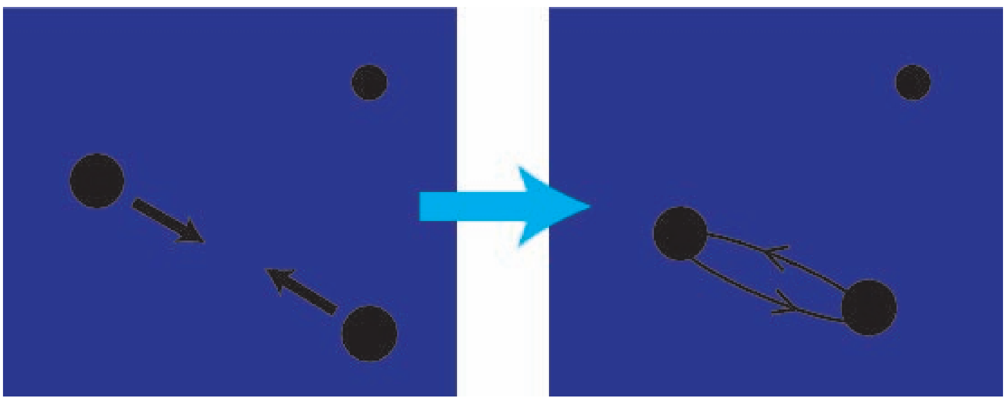

Fig. 1: Two neighboring PBHs come closer by their gravitational force (left panel). Due to the influence of the nearest third PBH, the two PBHs form a binary with large eccentricity (right panel).

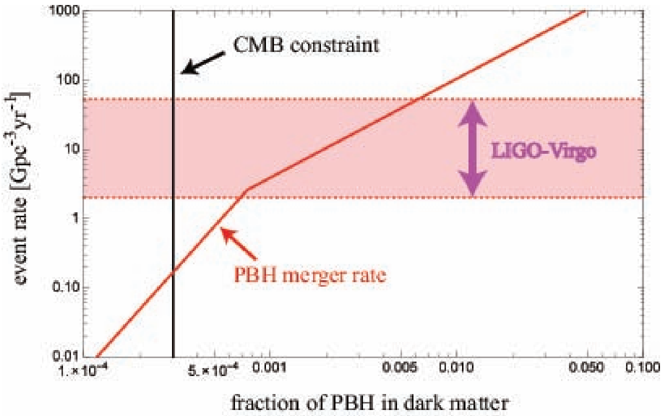

Figure 2: Estimated coalescence rate (red curve) of PBH binaries as a function of the fraction of PBH in dark matter. The colored band labeled "LIGO-Virgo" represents the statistical uncertainty of the coalescence event rate. The vertical black line is the upper limit set by the non-detection of the distortion of the CMB spectrum.

phenomenological assumption that all PBHs have the same mass, 30 solar mass, and distributed randomly in space in the early Universe. In this framework, the only free parameter left is the number density of PBHs. One of the attractive features in the PBH scenario is that formation of the PBH binary occurs naturally by the simple physical mechanism, as was first pointed out by Nakamura *et al.* in [2]. The mechanism is as follows. Since PBHs distribute randomly in space, there is a small but non-vanishing probability that two neighboring PBHs happen to be much closer than the mean distance. Such PBHs, as a pair, defeat the expansion of space and start to attract each other by the gravitational force between them. While the two PBHs are getting closer, the other PBHs, especially the nearest PBH, give an angular momentum to the colliding PBHs. As a result, a head-on collision is circumvented and a binary with large eccentricity forms (Fig. 1). Because of the large eccentricity, the PBH binary can coalesce within the age of the Universe.

With this simple picture, Suyama *et al.* computed the probability distribution of the size and the eccentricity of the resultant binaries and converted it to the PBH coalescence rate at the present time (Fig. 2) [1]. It was then found that the PBH scenario can explain the event rate obtained by the LIGO-Virgo Collaborations within statistical uncertainty if the PBHs constitute about one-thousandth of dark matter, corresponding to about 30 million PBHs in the Milky Way galaxy.

PBHs of about 30 solar mass are known to distort the blackbody spectrum of the cosmic microwave background (CMB) by the radiation emitted by the accreting gas surrounding the PBH. No such distortion has been observed down to the level of one ten-thousandth. This limit can be converted into the upper limit on the adundance of PBHs as several ten-thousandths in terms of their fraction in dark matter [3] (see also Fig. 2). Taking it as face value, this already excludes the PBH scenario. However, this upper limit is derived with approximations made to deal with the complex process of accretion and it is not certain how robust the limit is. In light of this situation, it is concluded in [1] that the gravitational-wave event detected by LIGO can be caused by the merger of PBHs.

In the PBH scenario, both binary formation and coalescence within the age of the Universe are naturally realized by the simple physical mechanism mentioned above, which makes the PBH scenario attractive. In the near future, GW detectors will be upgraded and many more BH binaries will surely be detected. Vast information about BH binaries such as mass, spin, eccentricity and spatial distribution will then become available. This information will enable us to test the PBH scenario and pave a new way to probe the early Universe.

References

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