Primordial Black Hole Scenario for the Gravitational-Wave Event GW150914

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Discovery of BH binary by LIGO

GW from the merger of a BH binary was detected for the first time in Sep 14, 2015 (GW150914).

BH mass: $36 M_\odot$, $29 M_\odot$

Source redshift: 0.09

Event rate: $0.6-12 \text{ /Gpc}^3 \text{ /yr}$
The origin of GW150914 is not known yet.

Questions

What is the origin of such heavy BHs?

What is the mechanism of the binary formation?

It is important 1) to propose possible scenarios as many as we can, and 2) to propose many ideas to test them and 3) to test them by real data.
We proposed a scenario that the detected GW was caused by the merger of two primordial black holes (PBHs).

This result was also covered by NHK, several newspapers, Newton, Nikkei-Science, Science News, Association of Asia Pacific Physical Societies, European Physical Society etc.
Formation of PBHs

Collapse of primordial density perturbation

\[ \rho(1 + \delta) \]

\[ H^{-1} = a/k \]

If density contrast is \( \sim 1 \) at the horizon reentry, the overdense region collapses to BH.

\[ r_{\text{SCH}} \sim GM \sim G\rho H^{-3} \sim H^{-1} \sim t \]

Shortly after the overdensity starts to contract, it falls within its Schwarzschild radius. So the mass is roughly determined by the horizon mass:

\[ M_{\text{PBH}} \sim \rho H^{-3} \sim \frac{1}{GH} \sim 10^5 M_\odot \left( \frac{t}{1\text{s}} \right) \sim 20M_\odot \left( \frac{k}{1\text{pc}^{-1}} \right)^{-2} \]
Since its original proposal in 70s, PBH has been studied both theoretically and observationally.

- PBH with any mass can be produced in the early Universe.
- Small PBH ($\lesssim 10^{15} g$) evaporates by now by the Hawking radiation.
- Large PBH ($\gtrsim 10^{15} g$) behaves as dark matter.
- No detection of PBHs and only upper limits on PBH abundance exist.
Requirements for success

Formation of about $30M_\odot$ BHs.

Formation of about $30M_\odot$ BH binaries.

Merger of BH binaries consistent with LIGO observation.

In the PBH scenario, these requirements can be naturally satisfied.
Requirements for success

**Formation of about $30M_\odot$ BHs.**

Entirely depends on inflation models.

There are inflation models that predict PBHs.

**Formation of about $30M_\odot$ BH binaries.**

Simple physical mechanism exists.


**Merger of BH binaries consistent with LIGO observation.**

Formation of binary with large eccentricity.

Required abundance of PBHs is consistent with other existing upper limit.
An inflation model predicting PBHs

(Kawasaki, Kusenko, Yanagida, 2012)

\[ V = V_H + V_N + V_{HN}, \]

\[ V_H(\phi, \psi) = \left(1 + \frac{\phi^4}{8} + \frac{\psi^2}{2}\right) \left(-\mu^2 + \frac{\psi^4}{16 M^2}\right)^2 + \frac{\phi^2 \psi^6}{16 M^4}, \]

\[ V_N(\varphi) = \nu^4 \left(1 - \frac{\kappa}{2} \varphi^2\right) - \frac{g^2}{2} \nu^2 \varphi^4 + \frac{g^2}{16} \varphi^8, \]

\[ V_{HN}(\phi, \psi, \varphi) = \left(-\mu^2 + \frac{\psi^4}{16 M^2}\right)^2 \frac{\varphi^2}{2} - \left(-\mu^2 + \frac{\psi^4}{16 M^2}\right) \nu^2 \phi \varphi, \]
Another inflation model predicting PBHs

(Kawasaki et al. 2016)

\[
W_{\text{new}} = v^2 \phi - \frac{g}{n+1} \phi^{n+1} + c,
\]

\[
K_{\text{new}} = |\phi|^2 + \frac{\kappa}{4} |\phi|^4 + \cdots,
\]

\[
V(\varphi) \simeq v^4 - 2\sqrt{2}cv^2 \varphi - \frac{\kappa}{2} v^4 \varphi^2 - \frac{g}{2^{\frac{n}{2} - 1}} v^2 \varphi^n + \frac{g^2}{2^n} \varphi^{2n} + V_{\text{pre}} \left( 1 + \frac{1}{2} \varphi^2 \right).
\] (10)
Requirements for success

Formation of about \(30M_\odot\) BHs.

Entirely depends on inflation models.

There are inflation models that predict PBHs.

Formation of about \(30M_\odot\) BH binaries.

Simple physical mechanism exists.


Merger of BH binaries consistent with LIGO observation.

Required abundance of PBHs is consistent with other existing upper limit.
Pioneering paper

GRAVITATIONAL WAVES FROM COALESCING BLACK HOLE MACHO BINARIES

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ABSTRACT

If MACHOs are black holes of mass \( \sim 0.5 \, M_\odot \), they must have been formed in the early universe when the temperature was \( \sim 1 \, \text{GeV} \). We estimate that in this case in our Galaxy’s halo out to \( \sim 50 \, \text{kpc} \) there exist \( \sim 5 \times 10^8 \) black hole binaries the coalescence times of which are comparable to the age of the universe, so that the coalescence rate will be \( \sim 5 \times 10^{-2} \) events yr\(^{-1} \) per galaxy. This suggests that we can expect a few events per year within 15 Mpc. The gravitational waves from such coalescing black hole MACHOs can be detected by the first generation of interferometers in the LIGO/VIRGO/TAMA/GEO network. Therefore, the existence of black hole MACHOs can be tested within the next 5 yr by gravitational waves.

Subject headings: black hole physics — dark matter — gravitation — gravitational lensing — Galaxy: halo
BH binaries in the PBH scenario

Assumptions

PBHs distributed randomly in the early Universe (no clustering).
All PBHs have $30M_\odot$.

Tidal force from the third BH

Binary with large eccentricity is formed in the radiation dominated universe.

\[ a = \frac{\alpha x^4}{f \bar{x}^3}, \quad b = \beta \left(\frac{x}{y}\right)^3 a \]
Probability distribution of binary parameters

\[ dP = \frac{9}{\bar{x}^6} x^2 y^2 \, dx \, dy \quad 0 < x < y < \bar{x} \]

Probability in \((a, a + da)\) and \((e, e + de)\)

\[ dP = \frac{3}{4} f^{3/2} \bar{x}^{-3/2} a^{1/2} e (1 - e^2)^{-3/2} \, da \, de. \]
Requirements for success

**Formation of about $30M_\odot$ BHs.**

Entirely depends on inflation models.
There are inflation models that predict PBHs.

**Formation of about $30M_\odot$ BH binaries.**

Simple physical mechanism exists.

**Merger of BH binaries consistent with LIGO observation.**

There is a space for $\Omega_{PBH}(<1)$ consistent with LIGO.
Life time of the binary

Life time of the binary is a function of major axis $a$ and eccentricity $e$.

\[ t = Q a^4 (1 - e^2)^{7/2}, \quad Q = \frac{3}{170} (GM_{\text{BH}})^{-3} \]
Merger probability

\[ dP = \frac{3}{16} \left( \frac{t}{T} \right)^{3/8} e(1 - e^2)^{-\left(\frac{45}{16}\right)} \frac{dt}{t} \, de, \quad T \equiv \frac{\bar{x}^4 Q}{f^4}. \]

Integrating this over the eccentricity gives the probability of merger occurring in \((t, t + dt)\).

Two quantities determining the maximum of \(e\).

- Distance to third BH \(y\) (case A)
- Major axis \(a\) (case B)
Meger event rate

- Consistent with LIGO if PBH constitutes about 0.1% of dark matter.
- $30M_\odot$ PBH as whole dark matter was excluded only from the observation of GWs.
Remark 1


Different binary formation mechanism is considered.

\[ \sigma = \pi \left( \frac{85\pi}{3} \right)^{2/7} R_s^2 \left( \frac{v_{\text{pbh}}}{c} \right)^{-18/7} \]

\[ = 1.37 \times 10^{-14} M_{30}^2 v_{\text{pbh} - 200}^{-18/7} \text{ pc}^2 \]
Remark 1


\[ \mathcal{V} = 2f\left(\frac{M_c}{400M_\odot}\right)^{-11/21} \text{ Gpc}^{-3} \text{ yr}^{-1}, \]

Consistent with LIGO if PBH is whole dark matter
Remark 2

Previous CMB constraint may be too strong.

Cosmic microwave background limits on accreting primordial black holes

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Interest in the idea that primordial black holes (PBHs) might comprise some or all of the dark matter has recently been rekindled following LIGO’s first direct detection of a binary-black-hole merger. Here we revisit the effect of accreting PBHs on the cosmic microwave background (CMB) frequency spectrum and angular temperature/polarization power spectra. We compute the accretion rate and luminosity of PBHs, accounting for their suppression by Compton drag and Compton cooling by CMB photons. We estimate the gas temperature near the Schwarzschild radius, and hence the free-free luminosity, accounting for the cooling resulting from collisional ionization when the background gas is mostly neutral. We account approximately for the velocities of PBHs with respect to the background gas. We provide a simple analytic estimate of the efficiency of energy deposition in the plasma. We find that the spectral distortions generated by accreting PBHs are too small to be detected by FIRAS, as well as by future experiments now being considered. We analyze Planck CMB temperature and polarization data and find, under our most conservative hypotheses, and at the order-of-magnitude level, that they rule out PBHs with masses $\gtrsim 10^2 \, M_\odot$ as the dominant component of dark matter.

1612.05644
Remark 2
Summary

LIGO opened a new way to probe the early Universe.

LIGO might have detected PBHs for the first time.

If PHB constitutes about thousandth of whole dark matter, the merger event rate is consistent with the LIGO result.

The proof of the presence of PBHs has great impact on cosmology.