Primordial black holes in the era of gravitational wave astronomy

Teruaki Suyama

(Tokyo Institute of Technology)

<u>Refs.</u>

- •M.Sasaki, TS, T.Tanaka, S.Yokoyama, PRL 117, 061101(2016) [arXiv:1603.08338]
- B.Kocsis, TS, T.Tanaka, S.Yokoyama, ApJ 854, 41 (2018) [arXiv:1709.09007]
- •M.Sasaki, TS, T.Tanaka, S.Yokoyama, CQG 35, 063001(2018) [arXiv:1801.05235]
- ・日本物理学会誌72巻10月号(pp.723-727)、 「LIGOで検出された重力波は原始ブラックホールから?」



The 2017 Nobel Prize in Physics



"for decisive contributions to the LIGO detector and the observation of gravitational waves"

What is GWs?



Prediction of general relativity

Propagation of distortion of spacetime

Propagate at c, 2 DOFs, transverse

Detected 100 years after the birth of GR!!

I think over the coming decades we will see enormous numbers of things. Just as electromagnetic astronomy was begun in essence, at least modern astronomy, by Galileo pointing his telescope in the sky and discovering Jupiter's moons. This is the same thing but for gravitational waves. —Kip Thorne-

「ガリレオガリレイが自作の望遠鏡で初めて月を見 たことに対応する。その後の電磁波によって我々が 得た宇宙の知見は膨大である」

物理学会誌71巻4号 中村卓史(京大名誉教授)

GWs detected by LIGO

Hanford, Washington (H1)

Livingston, Louisiana (L1)





What emitted GWs?

Predicted by theory



GWs from black hole binary!!



GWs show that BH–BH binaries exit and they merge in the age of the Universe. (Until LIGO, we didn't know if they exist.)

PRL 116, 061102 (2016)

Selected for a Viewpoint in Physics PHYSICAL REVIEW LETTERS

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in

frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21} . It matches the waveform

predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the

resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a

false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater

than 5.1 σ . The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.08}_{-0.04}$.

In the source frame, the initial black hole masses are $36^{+5}_{-4}M_{\odot}$ and $29^{+4}_{-4}M_{\odot}$, and the final black hole mass is

 $62_{-4}^{+4}M_{\odot}$, with $3.0_{-0.5}^{+0.5}M_{\odot}c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals.

These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct

detection of gravitational waves and the first observation of a binary black hole merger.

week ending 12 FEBRUARY 2016

week ending 17 JUNE 2016

GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence

B.P. Abbott et al.*

(LIGO Scientific Collaboration and Virgo Collaboration) (Received 31 May 2016; published 15 June 2016)

We report the observation of a gravitational-wave signal produced by the coalescence of two stellar-mass black holes. The signal, GW151226, was observed by the twin detectors of the Laser Interferometer Gravitational-Wave Observatory (LIGO) on December 26, 2015 at 03:38:53 UTC. The signal was initially identified within 70 s by an online matched-filter search targeting binary coalescences. Subsequent off-line analyses recovered GW151226 with a network signal-to-noise ratio of 13 and a significance greater than 5 or. The signal persisted in the LIGO frequency band for approximately 1 s, increasing in frequency and amplitude over about 55 cycles from 35 to 450 Hz, and reached a peak gravitational strain of $3.4_{-0.9}^{+0.7} \times 10^{-22}$. The inferred source-frame initial black hole masses are $14.2_{-3.7}^{+8.3} M_{\odot}$ and $7.5_{-2.3}^{+2.3} M_{\odot}$. and the final black hole mass is $20.8^{+6.1}_{-1.7}M_{\odot}$. We find that at least one of the component black holes has spin greater than 0.2. This source is located at a luminosity distance of 440-180 Mpc corresponding to a redshift of 0.09^{+0.03}_{-0.04}. All uncertainties define a 90% credible interval. This second gravitational-wave observation provides improved constraints on stellar populations and on deviations from general relativity.

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DOI: 10.1103/PhysRevLett.116.061102

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5 V L,	GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2		
vit	(LIC (Rece	B. P. Abbott <i>et al.</i> * O Scientific and Virgo Collaboration) ived 9 May 2017; published 1 June 2017)	
7	We describe the observation of	GW170104, a gravitational-wave signal produced by the coales	gravitational-wave signal produced by the coalescence of
its	a pair of schlar-mass black holes. The signal was measured on January 4, 2017 at 101.1536 f UTC by the twin advanced detection of the Laster hieferenetic Gravitational-Ware Observatory during their second observing nut, with a network signal-to-noise natio of 13 and a fable alarm rate lass than 1 in 70.0000 years. The inferred component Black hole masses are $31.224M_{\odot}$ and $1434^{+2}M_{\odot}$ (at the 90% credible level). The black hole spins are best constrained through measurement of the effective impiral spin parameter, a mass-weighted combination of the spin components perpendicular to the orbital plane, $z_{\rm min} = 0.12^{+0.00}_{-0.00}$. This result implies that spin configurations with both component spin positively aligned with the orbital angular momentum and disforced. The source luminosity distance is 88925 Mpc corresponding to a		
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k	redshift of $z = 0.18^{+0.08}_{-0.07}$. We constrain the magnitude of modifications to the gravitational-wave dispersion relation and perform null tasts of annual relativity. A summing that gravitans an dispersed in unsumm like		apersion www.like
les	massive particles, we bound the graviton mass to $m_g \le 7.7 \times 10^{-23} \text{ eV}/c^2$. In all cases, we find that GW170104 is consistent with general relativity.		
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and has	I. INTRODUCTION	GW170104's source is a heavy bina	ry black hole system
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binary The first observing run of the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) their [1] identified two binary black hole coalescence signals with high statistical significance, GW150914 [2] and candi GW151226 [3], as well as a less significant candidate netic LVT151012 [4,5]. These discoveries ushered in a new era of observational astronomy, allowing us to investigate the previ astrophysics of binary black holes and test general relativity (GR) in ways that were previously inaccessible [6,7]. We now know that there is a population of binary black holes

Full with component masses $\geq 25M_{\odot}$ [5.6], and that merger rates are high enough for us to expect more detections [5,8].

Advanced LIGO's second observing run began on November 30, 2016. On January 4, 2017, a gravitational-Publ the C wave signal was detected with high statistical significance. Figure 1 shows a time-frequency representation of the data butio from the LIGO Hanford and Livingston detectors, with the the p signal GW170104 visible as the characteristic chirp of a binary coalescence. Detailed analyses demonstrate that GW170104 arrived at Hanford ~3 ms before Livingston, and originated from the coalescence of two stellar-mass black holes at a luminosity distance of ~3 × 109 light-years.

Full author list given at the end of the Letter.

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with a total mass of $\sim 50 M_{\odot}$, sugg subsolar metallicity environment [6]. Measurements of the black hole spins show a preference away from being (positively) aligned with the orbital angular momentum, but do not exclude zero spins. This is distinct from the case for GW151226, which had a strong preference for spins with positive projections along the orbital angular momen tum [3]. The inferred merger rate agrees with previous calculations [5,8], and could potentially be explained by binary black holes forming through isolated binary evolu tion or dynamical interactions in dense stellar clusters [6]. Gravitational-wave observations of binary black holes

are the ideal means to test GR and its alternatives. They provide insight into regimes of strong-field gravity where velocities are relativistic and the spacetime is dynamic. The tests performed with the sources detected in the first observing run showed no evidence of departure from GR's predictions [5,7]; GW170104 provides an opportunity to tighten these constraints. In addition to repeating tests performed in the first observing run, we also test for modifications to the gravitational-wave dispersion relation. Combining measurements from GW170104 with our previous results, we obtain new gravitational-wave constraints on potential deviations from GR.

II. DETECTORS AND DATA QUALITY

The LIGO detectors measure gravitational-wave strain using two dual-recycled Fabry-Perot Michelson interfer-ometers at the Hanford and Livingston observatories [1,10].

6 OCTOBER 2017 PRL 119, 141101 (2017) PHYSICAL REVIEW LETTERS \mathcal{G} GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence

B P Abbott et al (LIGO Scientific Collaboration and Virgo Collaboration) (Received 23 September 2017; published 6 October 2017)

On August 14, 2017 at 10:30:43 UTC, the Advanced Virgo detector and the two Advanced LIGO detectors coherently observed a transient gravitational-wave signal produced by the coalescence of two stellar mass black holes, with a false-alarm rate of \$1 in 27 000 years. The signal was observed with a three-detector network matched-filter signal-to-noise ratio of 18. The inferred masses of the initial black holes are 30.5^{+5.7}₋₁₀M_☉ and 25.3^{+2.8}_{-4.2}M_☉ (at the 90% credible level). The luminosity distance of the source is 540^{+130}_{-20} Mpc, corresponding to a redshift of $z = 0.11^{+0.03}_{-0.01}$. A network of three detectors improves the sky localization of the source, reducing the area of the 90% credible region from 1160 deg² using only the two LIGO detectors to 60 deg² using all three detectors. For the first time, we can test the nature of gravitational-wave polarizations from the antenna response of the LIGO-Virgo network, thus enabling a new class of phenomenological tests of gravity.

DOI: 10.1103/PhysRevLett.119.141101

I INTRODUCTION

TAMA The era of gravitational-wave (GW) astronomy began rferom with the detection of binary black hole (BBH) mergers, by the Advanced Laser Interferometer Gravitational-Wave e Unite Observatory (LIGO) detectors [1], during the first of the se dete Advanced Detector Observation Runs. Three detections. GW150914 [2], GW151226 [3], and GW170104 [4], and a 2011. lower significance candidate, LVT151012 [5], have been e sour announced so far. The Advanced Virgo detector [6] joined the second observation run on August 1, 2017 Ad var

On August 14, 2017, GWs from the coalescence of two sensiti black holes at a luminosity distance of 540+130 Mpc, with masses of $30.5^{+5.7}_{-3.0}M_{\odot}$ and $25.3^{+2.8}_{-4.2}M_{\odot}$, were observed in all ions [three detectors. The signal was first observed at the LIGO amental Livingston detector at 10:30:43 UTC, and at the LIGO ort the Hanford and Virgo detectors with a delay of ~8 ms and ~14 ms_respectively first

The signal-to-noise ratio (SNR) time series, the timenerging frequency representation of the strain data, and the time series data of the three detectors together with the inferred rovide GW waveform, are shown in Fig. 1. The different sensitivities and responses of the three detectors result in the GW

producing different values of matched-filter SNR in each detector Three methods were used to assess the impact of the

Virgo instrument on this detection. (a) Using the best fit

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waveform obtained from analysis of the LIGO detectors' data alone, we find that the probability, in 5000 s of data around the event, of a peak in SNR from Virgo data due to noise and as large as the one observed, within a time window determined by the maximum possible time of flight, is 0.3%. (b) A search for unmodeled GW transients demonstrates that adding Advanced Virgo improves the false-alarm rate by an order of magnitude over the two-detector network. (c) We compare the matched-filter marginal likelihood for a model with a coherent BBH signal in all three detectors to that for a model assuming pure Gaussian noise in Virgo and a BBH signal only in the LIGO detectors: the three detector BBH signal model is preferred with a Bayes factor of more than 1600.

Until Advanced Virgo became operational, typical GW position estimates were highly uncertain compared to the fields of view of most telescopes. The baseline formed by the two LIGO detectors allowed us to localize most mergers to roughly annular regions spanning hundreds to about a thousand square degrees at the 90% credible level [7-9]. Virgo adds additional independent baselines, which in cases such as GW170814 can reduce the positional uncertainty by an order of magnitude or more [8].

Tests of general relativity (GR) in the strong field regime have been performed with the signals from the BBH mergers detected by the LIGO interferometers [2-5,10]. In GR, GWs are characterized by two tensor (spin-2) polarizations only, whereas generic metric theories may allow up to six polarizations [11,12]. As the two LIGO instruments have similar orientations, little information about polarizations can be obtained using the LIGO detectors alone. With the addition of Advanced Virgo we can probe, for the first time, gravitational-wave polarizations geometrically by projecting the wave's amplitude molice 120 221 no lotini tr 124 201

GW170608: Observation of a 19 Solar-mass Binary Black Hole Coalescence

LIGO Scientific Collaboration and Virgo Collaboration (See the end matter for the full list of authors.)

Received 2017 Novamber 14; revised 2017 Novembar 30; accepted 2017 December 2; published 2017 December 18

Abstract

On 2017 June 8 at 02:01:16:49 UTC, a gravitational-wave (GW) signal from the merger of two stellar-mass black holes was observed by the two Advanced Laser Interferometer Gravitational-Wave Observatory detectors with a network signal-to-noise ratio of 13. This system is the lightest black hole binary so far observed, with component masses of $12^{+7}_{-2}M_{\odot}$ and $7^{+2}_{-2}M_{\odot}$ (90% credible intervals). These lie in the range of measured black hole masses in low-mass X-ray binaries, thus allowing us to compare black holes detected through GWs with electromagnetic observations. The source's luminosity distance is 340^{+140}_{-140} Mpc, corresponding to redshift 0.07^{+000}_{-000} . We verify that the signal waveform is consistent with the predictions of general relativity. Key words: binaries: general - gravitational waves - stars: black holes

1. Introduction

THE ASTROPHYSICAL JOURNAL LETTERS 851:L35 (11pp) 2017 December 20

OPEN ACCESS

The first detections of binary black hole mergers were made by the Advanced Laser Interferometer Gravitational Wave Observatory (LIGO; Aasi et al. 2015; Abbott et al. 2016a) during its first observing run (O1) in 2015 (Abbott et al. 2016b, 2016c, 2016d) Following a commissioning break, LIGO undertook a second observing run (O2) from 2016 November 30 to 2017 August 25 with the Advanced Vinzo detector (Acemese et al. 2015) joining the run on 2017 August 1. Two binary black hole mergers (Abbott et al. 2017a, 2017b) and one binary neutron star merger (Abbott et al. 2017c) have been reported in O2 data. Here, we describe GW170608, a binary black hole merger with likely the lowest mass of any so far observed by LIGO.

GW170608 was first identified in data from the LIGO Livingston Observatory (LLO), which was in normal observing mode. The LIGO Hanford Observatory (LHO) was operating stably with a sensitivity typical for O2, but its data were not analyzed automatically as the detector was undergoing a routine angular control procedure (Section 2 and the Appendix). Matchedfilter analysis of a segment of data around this time revealed a candidate with source parameters consistent between both LIGO detectors; further offline analyses of a longer period of data confirmed the presence of a gravitational-wave (GW) signal from the coalescence of a binary black hole system, with high statistical significance (Section 3).

The source's parameters were estimated via coherent Bayesian analysis (Veitch et al. 2015; Abbott et al. 2016e). A degeneracy between the component masses m1, m2 prevents precise determination of their individual values, but the chirp mass $\mathcal{M} = (m_1 m_2)^{3/5} (m_1 + m_2)^{-1/5}$ is well measured and is the smallest so far observed for a merging black hole binary system, with the total mass $M = m_1 + m_2$ also likely the lowest so far observed (Section 4). Individual black hole spins are poorly constrained; however, we find a slight preference for a small positive net component of spin in the direction of the binary orbital angular momentum

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Similarly to GW151226 (Abbott et al. 2016c), this system' black holes found in X-ray binaries (Section 5) and below those seen in other LIGO-Virgo black hole binaries,

https://doi.org/10.3847/2041-8213/sef

We also test the consistency of the observed GW signal with the predictions of general relativity (GR); we find no deviations from those predictions.

2. Detector Operation

The LIGO detectors measure GW strain using dual-recycled Michelson interferometers with Fabry-Perot arm cavities (Assi et al. 2015; Abbott et al. 2016a). During O2, the horizon distance for systems with component masses similar to GW170608-the distance at which a binary merger optimally oriented with respect to a detector has an expected signal-to-noise ratio (S/N) of (Allen et al. 2012; Chen et al. 2017)—peaked at ~1 Gpc for LLC and at ~750 Mpc for LHO.

At the time of GW170608, LLO was observing with sensitivity close to its peak. LHO was operating in a stable configuration with a sensitivity of ~650 Mpc; a routine procedure to minimize angular noise coupling to the strain measurement wa being performed (Kasprzack & Yu 2016). Although such times are in general not included in searches, it was determined that LHO strain data were unaffected by the procedure at frequencies above 30 Hz and may thus be used to identify a GW source and measure its properties. More details on LHO data are given in th

Similar procedures to those used in verifying previous GW detections (Abbott et al. 2017b) were followed and indicate that no disturbance registered by LIGO instrumental or environ mental sensors (Effler et al. 2015) was strong enough to hav caused the GW170608 signal.

Calibration of the LIGO detectors is performed by inducing test-mass motion using photon pressure from modulated auxiliary lasers (Karki et al. 2016; Abbott et al. 2017d; Cahilland et al. 2017). The maximum 1σ calibration uncertainties for strair data used in this analysis are 5% in amplitude and 3° in phase

over the frequency range 20-1024 Hz. The Advanced Virgo detector was, at the time of the event, i observation mode with a horizon distance for signals comparable to GW170608 of 60-70 Mpc. However, this was during an early

We now know that many BH-BH mergers are occurring in the Universe.



When and where did those BHs form and how did they form binaries?







LIGO BHs are anomalously heavy?

BH spin

$$\chi_{\text{eff}} = \frac{c}{GM} \left(\frac{S_1}{m_1} + \frac{S_2}{m_2} \right) \cdot \frac{L}{|\mathbf{L}|} \qquad -1 \le \chi_{eff} \le 1$$



BHs have low spin? BH spins are misaligned?

What is the origin of LIGO BHs?

- list possible scenarios as many as we can.
- propose many ideas of how to test and distinguish them observationally.

The seemingly unusual features may suggest that those BHs are new population.

Maybe, primordial black holes!

Editors' Suggestion

PDF HTML

Primordial Black Hole Scenario for the Gravitational-Wave Event GW150914

Misao Sasaki, Teruaki Suyama, Takahiro Tanaka, and Shuichiro Yokoyama Phys. Rev. Lett. **117**, 061101 (2016) – Published 2 August 2016



A theoretical analysis examines the possibility that the gravitational wave signal (GW150914) detected by LIGO was due to the coalescence of primordial black holes created by the extremely dense matter present in the early Universe.

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A theoretical analysis examines the possibility that the gravitational wave signal (GW150914) detected by LIGO was due to the coalescence of primordial black holes created by the extremely dense matter present in the early Universe.

What are primordial BHs?

PBHs=BHs that formed in the very early Universe S.Hawking 1971

PBHs might comprise all/fraction of dark matter.

Several formation mechanism of PBHs

- Direct gravitational collapse of primordial density perturbation. (widely investigated)
- Collapse of cosmic strings
- Creation of vacuum bubbles
- •

PBHs are fossils of high energy physics such as inflation¹⁶



If density contrast is ~ 1 at the horizon reentry, the overdense region collapses to BH.

 $r_{\rm SCH} \sim GM \sim G\rho H^{-3} \sim H^{-1} \sim t$

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

$$M_{\rm PBH} \sim \rho H^{-3} \sim \frac{1}{GH} \sim 10 M_{\odot} \left(\frac{t}{0.1 ms}\right) \sim 10 M_{\odot} \left(\frac{k}{1 {\rm pc}^{-1}}\right)^{-2}$$

Formation of PBH

It has been confirmed by simulations that BH forms out of primordial overdense region.



BH forms at around $\delta = 0.4 \sim 0.5$

Consistent with analytic estimation T.Harada, C.Yoo, K.Kohri 2013

Is $\delta \sim 1$ allowed observationally?



PBHs originate from very small-scale perturbations.



PBH can constrain primordial perturbation on small scales.



An inflation model predicting PBHs

(Kawasaki, Kusenko, Yanagida, 2012)

$$\begin{split} V &= V_{\rm H} + V_{\rm N} + V_{\rm HN}, \\ V_{\rm H}(\phi, \psi) &= \left(1 + \frac{\phi^4}{8} + \frac{\psi^2}{2}\right) \left(-\mu^2 + \frac{\psi^4}{16M^2}\right)^2 + \frac{\phi^2 \psi^6}{16M^4}, \\ V_{\rm N}(\varphi) &= v^4 \left(1 - \frac{\kappa}{2}\varphi^2\right) - \frac{g}{2}v^2\varphi^4 + \frac{g^2}{16}\varphi^8, \\ V_{\rm HN}(\phi, \psi, \varphi) &= \left(-\mu^2 + \frac{\psi^4}{16M^2}\right)^2 \frac{\varphi^2}{2} - \left(-\mu^2 + \frac{\psi^4}{16M^2}\right)v^2\phi\varphi, \end{split}$$



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 ($\leq 10^{15}g$) evaporates by now by the Hawking radiation.
- Large PBH ($\gtrsim 10^{15}g$) behaves as (cold) dark matter.
- No detection of PBHs and only upper limits on PBH abundance exist.

Observational limits on $f_{PBH} = \Omega_{PBH} / \Omega_{DM}$



Coming back to LIGO BHs, two things need to be explained before including the PBH as a possible explanation of LIGO events.

- How PBHs formed binaries?
- Do their mergers explain the observed merger rate?

Binary formation in the RD era

(candidate of my master thesis)

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GRAVITATIONAL WAVES FROM COALESCING BLACK HOLE MACHO BINARIES

TAKASHI NAKAMURA Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606, Japan MISAO SASAKI AND TAKAHIRO TANAKA

Department of Earth and Space Science, Osaka University, Toyonaka 560, Japan

AND

KIP S. THORNE Theoretical Astrophysics, California Institute of Technology, Pasadena, CA 91125 Received 1997 April 11; accepted 1997 July 23; published 1997 September 2

ABSTRACT



HOs are black holes of mass $\sim 0.5 M_{\odot}$ they must have been formed in the early united was ~ 1 GeV. We estimate that in this case in our Galaxy's halo out to ~ 50 kpc there exist $\sim 5 \times 10^{-10}$ the binaries the coalescence times of which are comparable to the age of the universe, so that the

e rate will be $\sim 5 \times 10^{-2}$ events yr⁻¹ per galaxy. This suggests that we can expect a few events per

15 Mpc. The gravitational waves from such coalescing black hole MACHOs can be tion of interferometers in the LIGO/VIRGO/TAMA/GEO network. Therefore, the HOs can be tested within the next 5 yr by gravitational waves.

idings: black hole physics — dark matter — gravitation — gravitational lensing — C

Nobel Prize again?



Two assumptions (Nakamura et al. 1997)

1. After PBHs are formed (by some mechanism), they distribute uniformly in space (Poisson).



Initially, PBHs are on the flow of the cosmic expansion.

2. All PBHs have the same mass

Binary formation in RD era (Nakamura et al. 1997)

(The rest is not assumption but physical consequence.)

As the universe expands, distance between PBHs becomes smaller than the Hubble horizon.

When the PBH energy 2 M_{BH} in the volume $\sim d^3$ exceeds $\rho_{rad}d^3$, the PBHs in pair decouple from cosmic expansion and start to come closer by the gravitational force. (Ioka et al. 1998, Ali-Haimoud et al. 2017)



This can happen only in the RD era. 27

Binary formation in RD era (Nakamura et al. 1997) The surrounding PBHs (especially the nearest one) exert torque and the bound system acquires the angular momentum. (Binary formation!) x, y: initial comoving distance a,b: major and minor axis of binary ${\mathcal X}$ Once x and y are fixed, a and b are determined as x^3 __4

$$\frac{1}{\bar{x}_{\text{PBH}}} \frac{x^{-}}{\bar{x}^{3}} \qquad b = b$$

Binary formation in RD era (Nakamura et al. 1997)

We can compute probability distribution of (a,e).



Uniform distribution

$$dP = \frac{9}{\bar{x}^6} x^2 y^2 dx dy \qquad 0 < x < y < \bar{x}$$

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

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

Life time of the binary

The next thing to do is to convert the probability in (a, e) to the merger probability in (t, t + dt).



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

$$t = Qa^4(1 - e^2)^{7/2}, \qquad Q = \frac{3}{170}(GM_{\rm BH})^{-3}$$

In the paper by Nakamura et al. 1997, $M_{BH} = 0.5M_{\odot}$ and $\Omega_{PBH} = \Omega_{DM}$ was considered.

In the paper by Sasaki et al. 2016, $M_{BH} = 30 M_{\odot}$ and the formula was extended to the case $\Omega_{PBH} < \Omega_{DM}$.

Merger event rate (Sasaki et al. 2016)



0.1% of dark matter.

Remark



Remark

PBH paper S.Bird et al. PRL 116, 201301(2016).



Consistent with LIGO if PBH is whole dark matter

Recently, the same formula has been used to place upper limit on Ω_{PBH} from the LIGO observation.

(Ali-Haimoud, Kovetz, Kamionkowski 2017)



It is important to keep in mind that monochromatic mass function is assumed. Additional consideration is necessary for the extended mass function. (Carr et al. 2017)

PBH hypothesis LIGO BHs could be primordial BHs.

Editors' Suggestion

Primordial Black Hole Scenario for the Gravitational-Wave Event GW150914

Misao Sasaki, Teruaki Suyama, Takahiro Tanaka, and Shuichiro Yokoyama Phys. Rev. Lett. **117**, 061101 (2016) – Published 2 August 2016



A theoretical analysis examines the possibility that the gravitational wave signal (GW150914) detected by LIGO was due to the coalescence of primordial black holes created by the extremely dense matter present in the early Universe. Show Abstract +

By testing this scenario, we get more knowledge about the condition of the extremely early universe.

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Various effects that are ignored have been evaluated in

other papers. (Ioka et al. 1998, Hayasaki et al. 2009, Sasaki et al. 2016, Eroshenko 2016, Ali-Haimoud et al. 2017)

- Tidal force from outer BHs
- Initial peculiar velocity of PBHs
- Three body collisions
- Additional tidal force from dark matter perturbations
- Encounters of other PBHs (later time effect)
- Tidal force from halos (later time effect)
- Dynamical friction from DM and baryon (later time effect)

Simple analytical estimation suggest that those effects do not lead to the significant change of the result.

We have to keep in mind that these studies adopt the two assumptions.

How do we test the PBH scenario?

- Cosmic evolution of merger rate T.Nakamura et al. 2016
- Spin distribution

T.Chiba and S.Yokoyama 2016

- Stochastic GWs K.Ioka et al 1999, S.Wang et al. 2016, M.Raidal et al. 2017
- Event distribution in BH mass plane

B.Kocsis, TS, T.Tanaka, S.Yokoyama 2017



We can test the PBH scenario by observing the merger rate at high-z.

Spin distribution

$$\chi_{\text{eff}} = \frac{c}{GM} \left(\frac{S_1}{m_1} + \frac{S_2}{m_2} \right) \cdot \frac{L}{|\mathbf{L}|}$$



Spin distribution of PBHs (formed in RD)



PBHs are expected to be slowly rotating. (simply because rotation requires more δ to form PBH) Positive χ_{eff} and negative one are equally likely.

GWs from many PBH binaries (Stochastic GWs)

V.Mandic, S.Bird, I.Cholis, 1608.06699 S.Clesse, J.Garcia-Bellido, 1609.03565 S.Wang et al., 1610.08725



I.Cholis, 1609.03565

V.Mandic et al., 1608.06699

S.Wang et al., 1610.08725

Distinguishing from stellar-origin BHs is crucial.

How do we test the PBH scenario?

-Merger event distribution in mass plane-

Main message

Merger rate distribution in the PBH mass plane has hidden universality and is an interesting observable to address this question.

B.Kocsis, TS, T.Tanaka, S.Yokoyama 2017



In the future, we will have observed many merger events and will be able to discuss about the distribution in the PBH mass plane (m_1, m_2) .

In order to investigate what kind of feature appears in the distribution in the mass plane in the PBH scenario, we first generalized the formula to the case of the extended PBH mass function $f(m_{BH})$.

Assumption

In Kocsis et al.2017, we considered the extended mass function which is not so broad (≤ 10) since it is not clear at all if the same mechanism of the binary formation can still work dominantly for very broad mass function.

No correlation between different PBH masses.

Apart from this, we do not assume a specific form of f(m).

Merger event rate distribution in (m_1, m_2) plane



Non-trivial task is to evaluate \mathcal{R}_{intr} .

To derive the merger rate for given (m_1, m_2) , we need to know the probability distribution of (a, e).

Distribution of (a, e) is determined by statistical variables: x, y_i, M_i, e_i

$$a = Ax^{4}, A = \frac{1}{1 + z_{eq}} \frac{\rho_{c} \Omega_{m}}{m_{1} + m_{2}}$$
$$1 - e^{2} = \frac{9}{4}\zeta^{2}, \quad \zeta = \sum_{i=1}^{N} \frac{x^{3}}{y_{i}^{3}} \frac{M_{i}}{m_{t}} \sin(2\theta_{i}) \frac{(e_{z} \times e_{i})}{|e_{z} \times e_{i}|},$$





We evaluated the merger rate under two different approximations.

- Nearest BH only (N = 1), analytically
- Flat mass function (numerically)

Flat mass function



We found an approximate fitting formula for the probability distribution of the eccentricity.

In both cases, we found that the merger rate distribution is given by

$$\mathcal{R}(m_1, m_2, t) = C\tilde{f}(m_1)\tilde{f}(m_2)(m_1 + m_2)^{\alpha}$$

C, $\tilde{f}(m)$: sensitive to the PBH mass function Dependence on the total mass is not

sensitive to the mass function!!

$$0.97 < \alpha < 1.05$$

 $\ln \mathcal{R} = \ln \mathcal{C} + \ln \tilde{f}(m_1) + \ln \tilde{f}(m_2) + \alpha \ln(m_1 + m_2)$



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Hidden Universality of $R(m_1, m_2, t)$ Statement

Construct a quantity α out of the distribution $R(m_1, m_2, t)$ as

$$\alpha(m_1, m_2, t) \equiv -(m_1 + m_2)^2 \frac{\partial^2}{\partial m_1 \partial m_2} \ln \mathcal{R}(m_1, m_2, t)$$

Then, the PBH mergers in the present mechanism predict $0.97 \leq \alpha \leq 1.05$

for any PBH mass function (as long as it is not broad).

Different formation mechanisms predict different value

- $\alpha \approx 1.43$ PBH binary formation at low redshift. (Bird et al. 2016, Clesse, Garcia-Bellido 2016)
- $\alpha \sim 4$ Dynamical formation scenario (astrophysics BHs)



GW astronomy has just begun.

LIGO might have detected PBHs for the first time.

The PBH scenario can be tested in the future by GW data.