Primordial black holes and gravitational waves

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Refs.

M.Sasaki, TS, T.Tanaka, S.Yokoyama, PRL 117, 061101(2016) [arXiv:1603.08338]

B.Kocsis, TS, T.Tanaka, S.Yokoyama, arXiv:1709.09007

Plan of my talk

Background of this talk

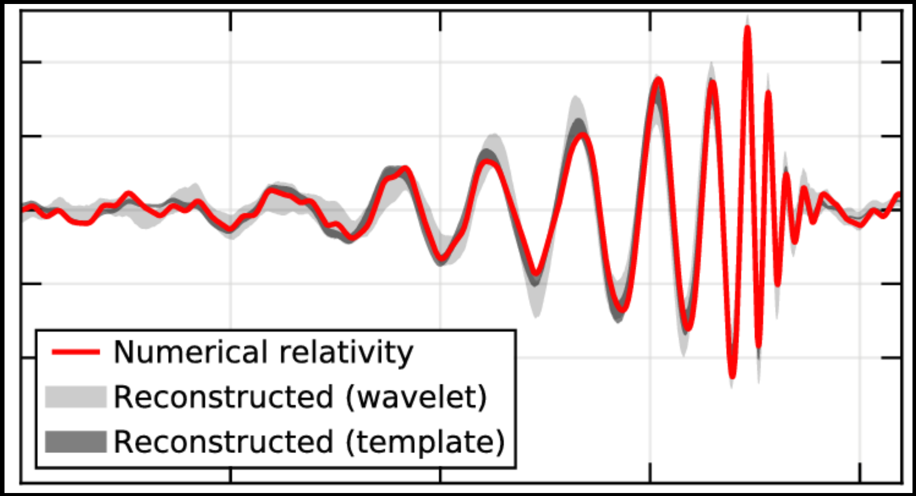
I present BHs observed by LIGO can be PBHs.

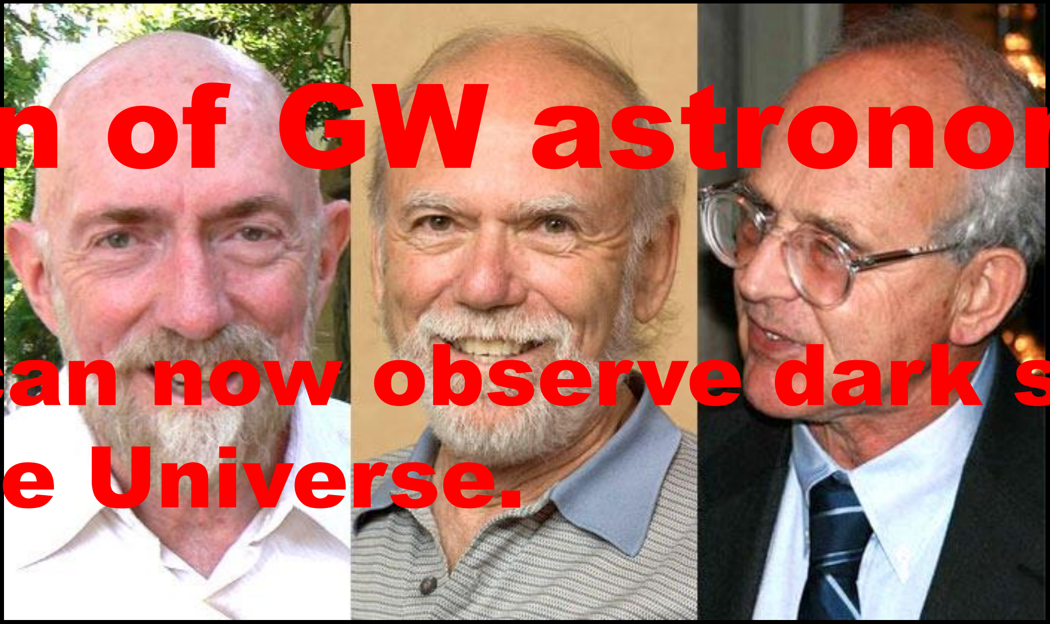
arXiv:1603.08338

I then show the PBH scenario can be tested by using the merger event distribution in the PBH mass plane.

arXiv:1709.09007

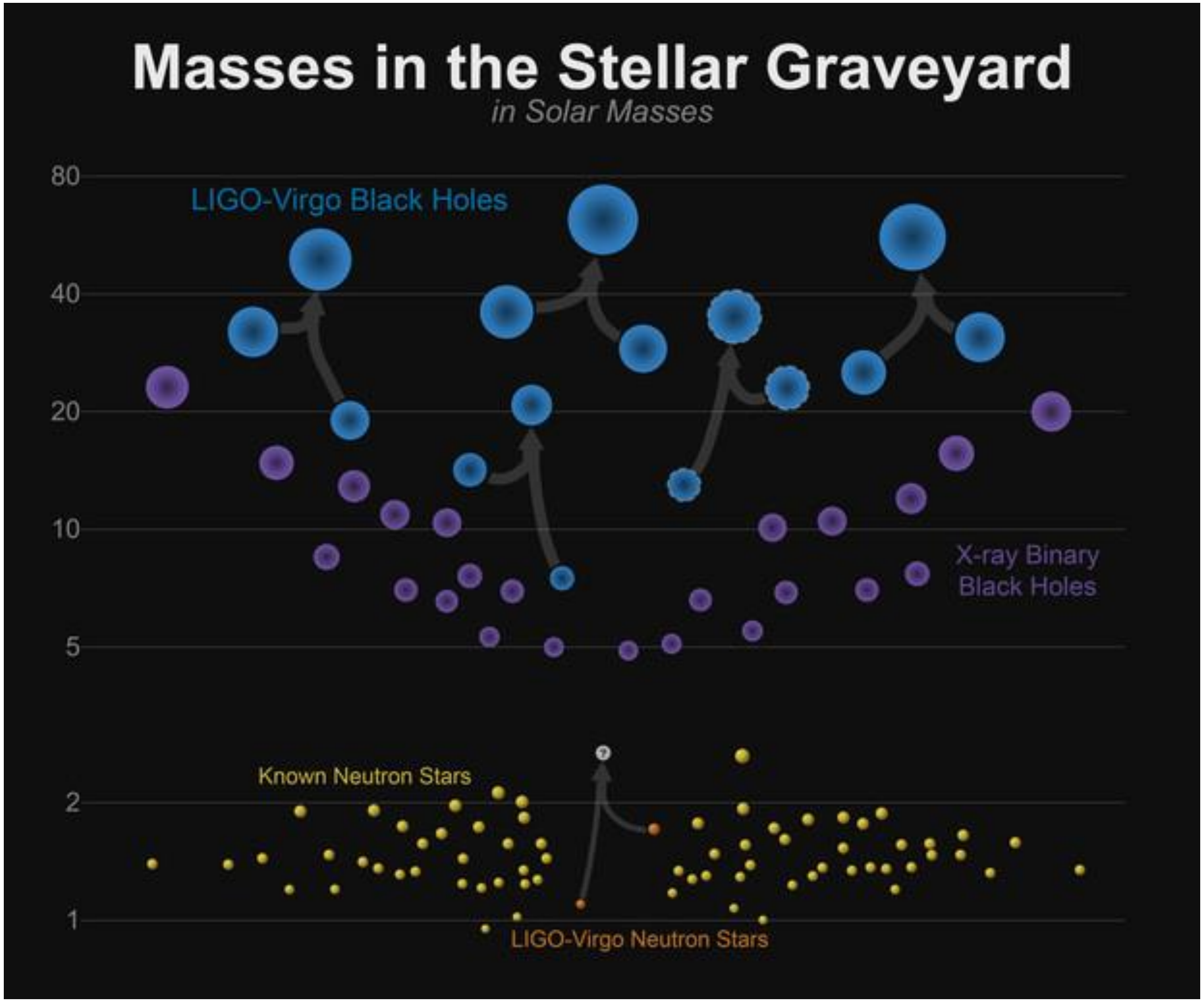
Discovery of BH binary by LIGO





Dawn of GW astronomy!!

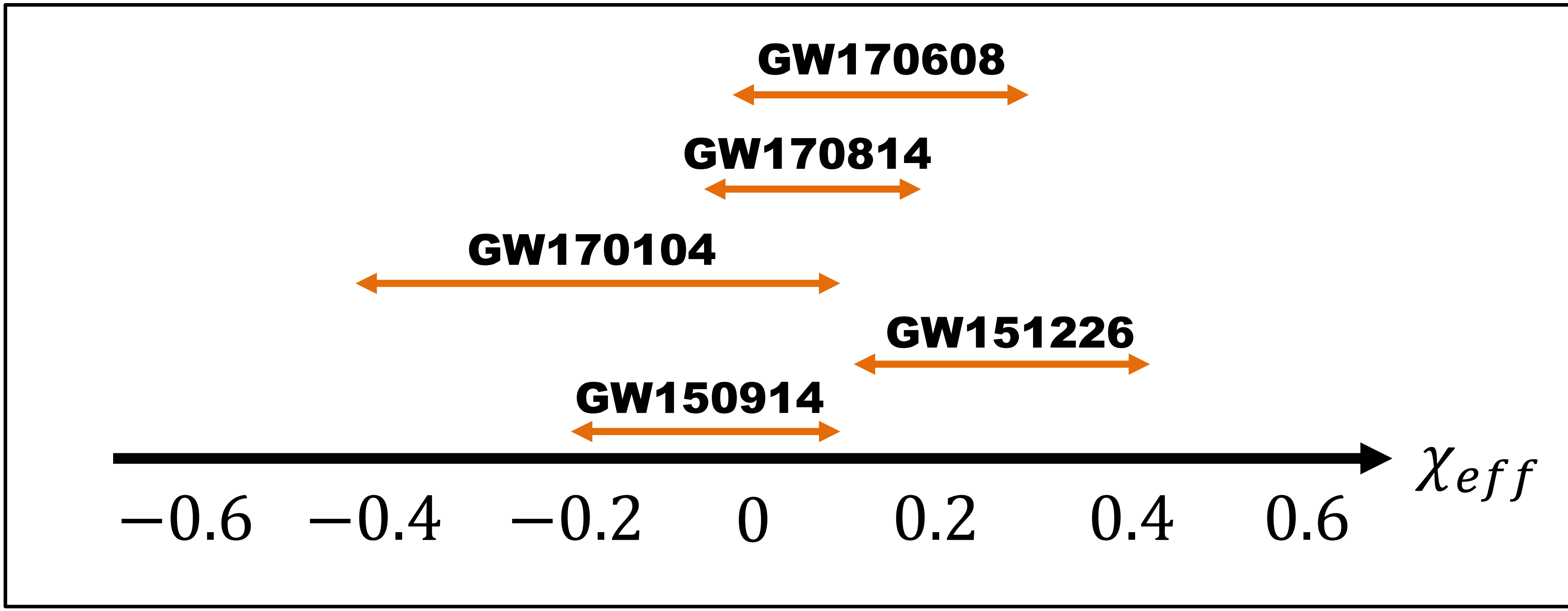
We can now observe dark side of the Universe.



LIGO BHs are anomalously heavy?

BH spin

$$\chi_{\text{eff}} = \frac{c}{GM}\left(\frac{\mathbf{S}_1}{m_1} + \frac{\mathbf{S}_2}{m_2}\right) \cdot \frac{\mathbf{L}}{|\mathbf{L}|} \qquad -1 \leq \chi_{eff} \leq 1$$



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!

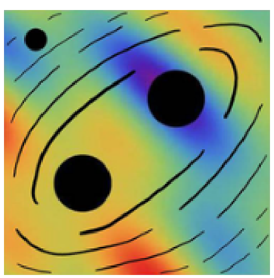
Editors' Suggestion

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.

Show Abstract +

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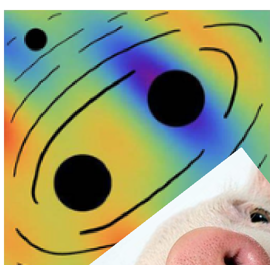


A theoretical analysis examines the possibility that the gravitational wave signal (GW150914) detected by LIGO was due to the coalescence of primordial black holes created by the extremely dense matter present in the early Universe.

Show Abstract +

What are primordial BHs?

PBHs=BHs that formed in the very early Universe

PBHs might comprise all/fraction of dark matter.

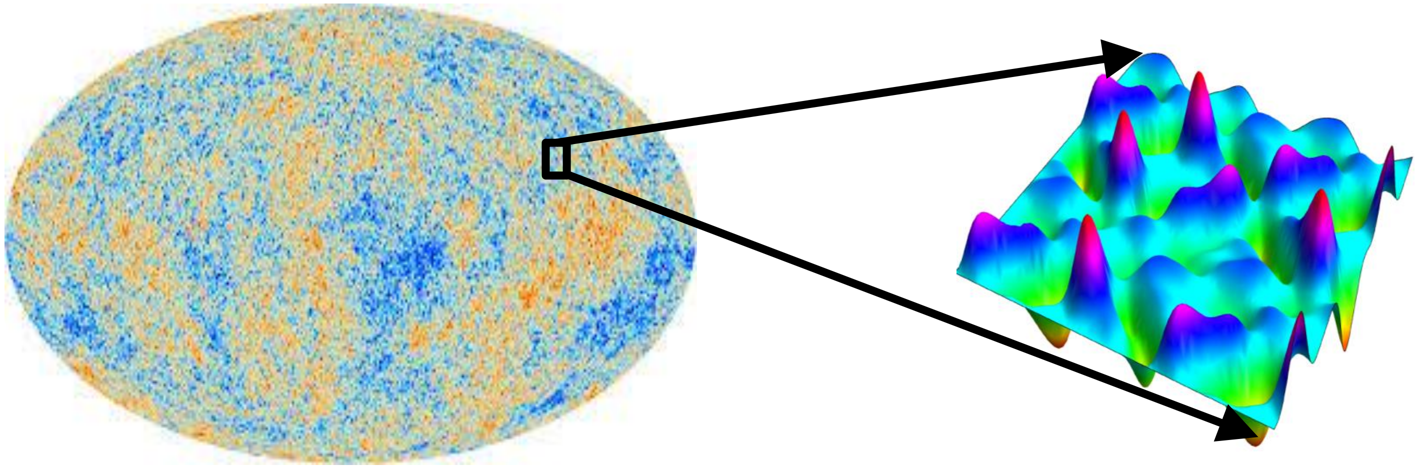
Popular formation mechanism S.Hawking 1971

Direct gravitational collapse of primordial density perturbation $\boldsymbol{\delta \sim 1}$

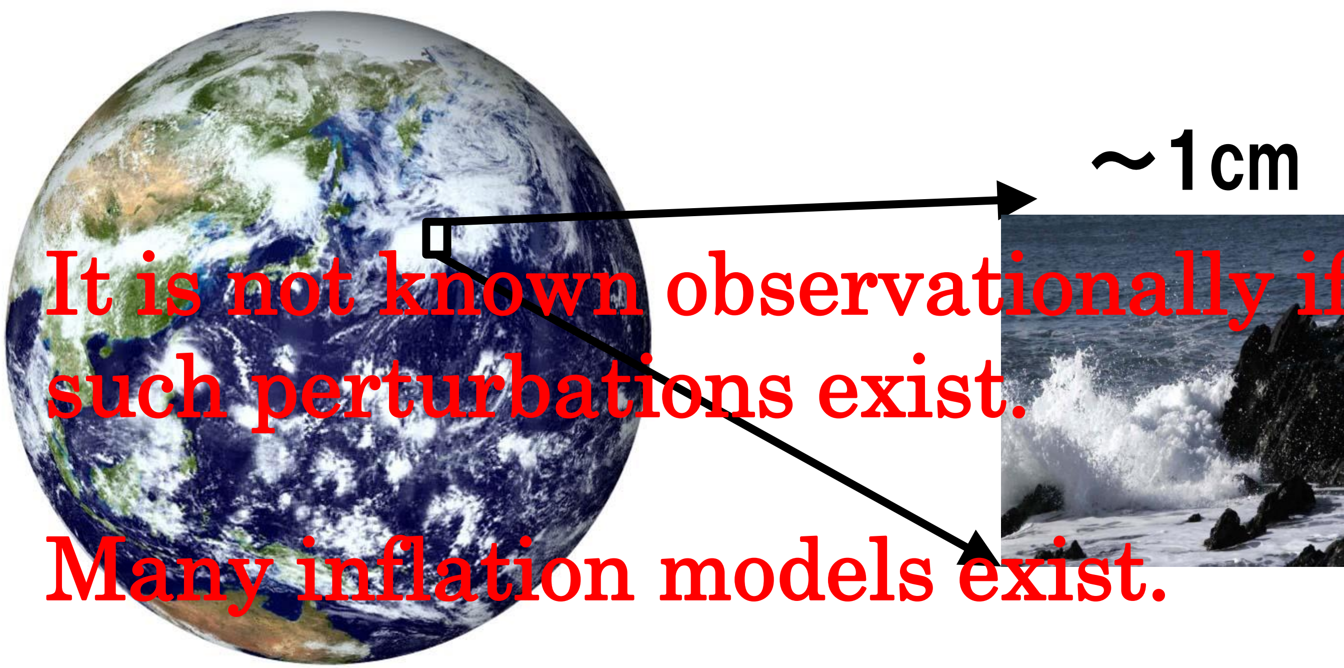
$$\boldsymbol{M_{\mathrm{PBH}} \sim \rho H^{-3} \sim 10\, M_{\odot} \left(\frac{t}{0.1\mathrm{ms}}\right)}$$

much before BBN era

Is $\delta \sim 1$ allowed observationally?



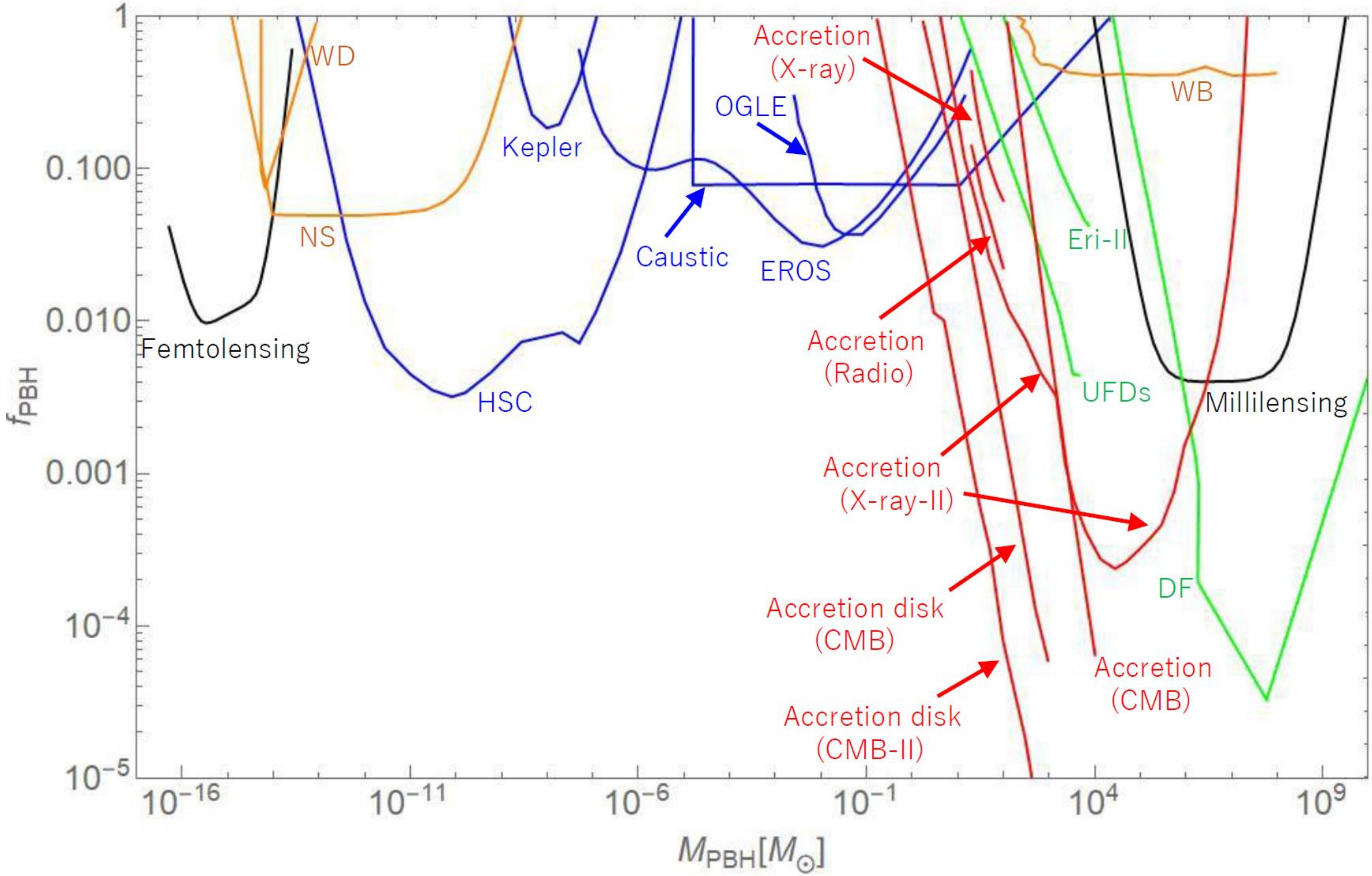
PBHs originate from very small-scale perturbations.



It is not known observationally if such perturbations exist.

Many inflation models exist.

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



Two things need to be explained.

How PBHs formed binaries?

Do their mergers explain the observed merger rate?

Binary formation in the RD era

THE ASTROPHYSICAL JOURNAL, 487:L139–L142, 1997 October 1

GRAVITATIONAL WAVES FROM COALESCING BLACK HOLE MACHO BINARIES

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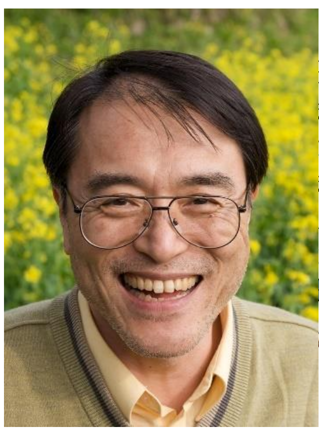
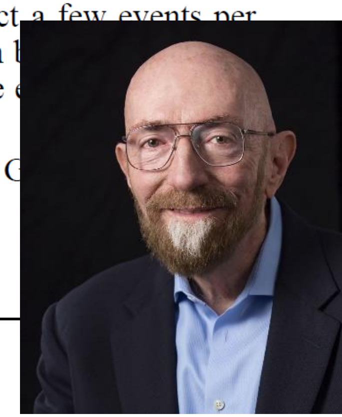
Received 1997 April 11; accepted 1997 July 23; published 1997 September 2



ABSTRACT

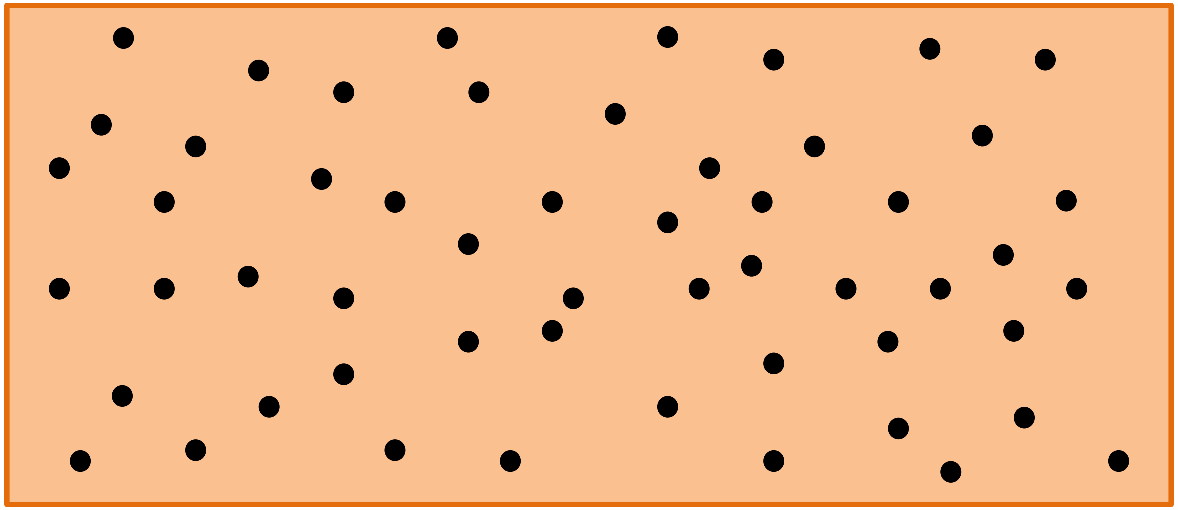
HOs are black holes of mass ~0.5 $M_\odot$ they must have been formed in the early uni
e was ~1 GeV. We estimate that in this case in our Galaxy's halo out to ~ 50 kpc there exist ~5 ×
hole binaries the coalescence times of which are comparable to the age of the universe, so that the
e rate will be ~5 × 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 b
tion of interferometers in the LIGO/VIRGO/TAMA/GEO network. Therefore, the
HOs can be tested within the next 5 yr by gravitational waves.



dings: black hole physics — dark matter — gravitation — gravitational lensing — G

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.

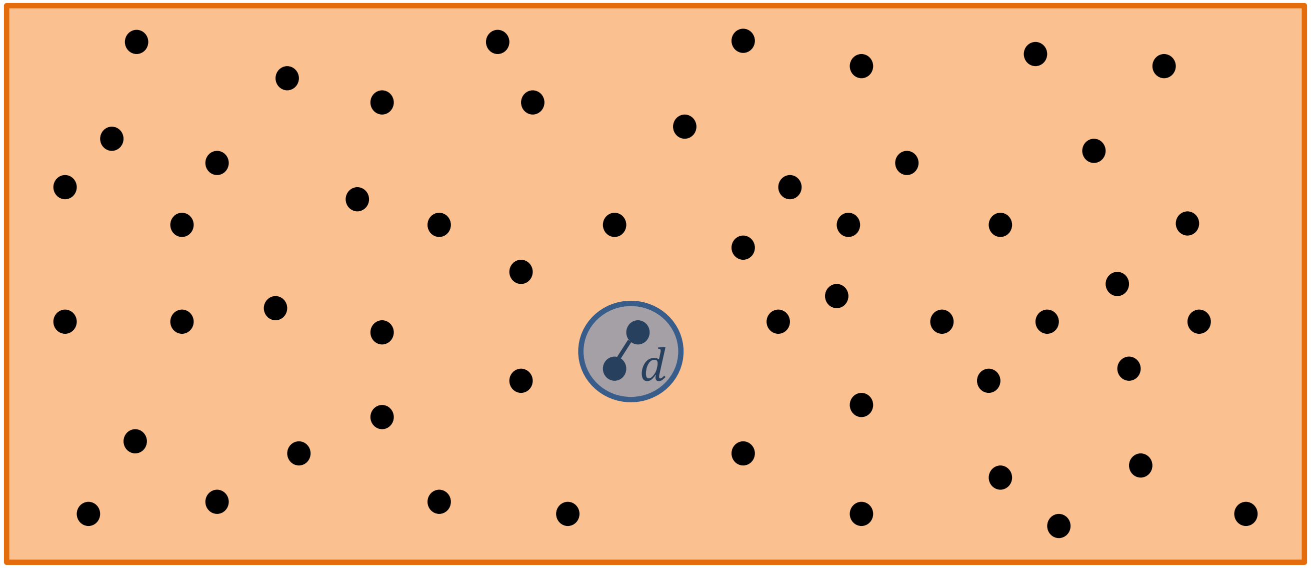
2. All PBHs have the same mass

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.

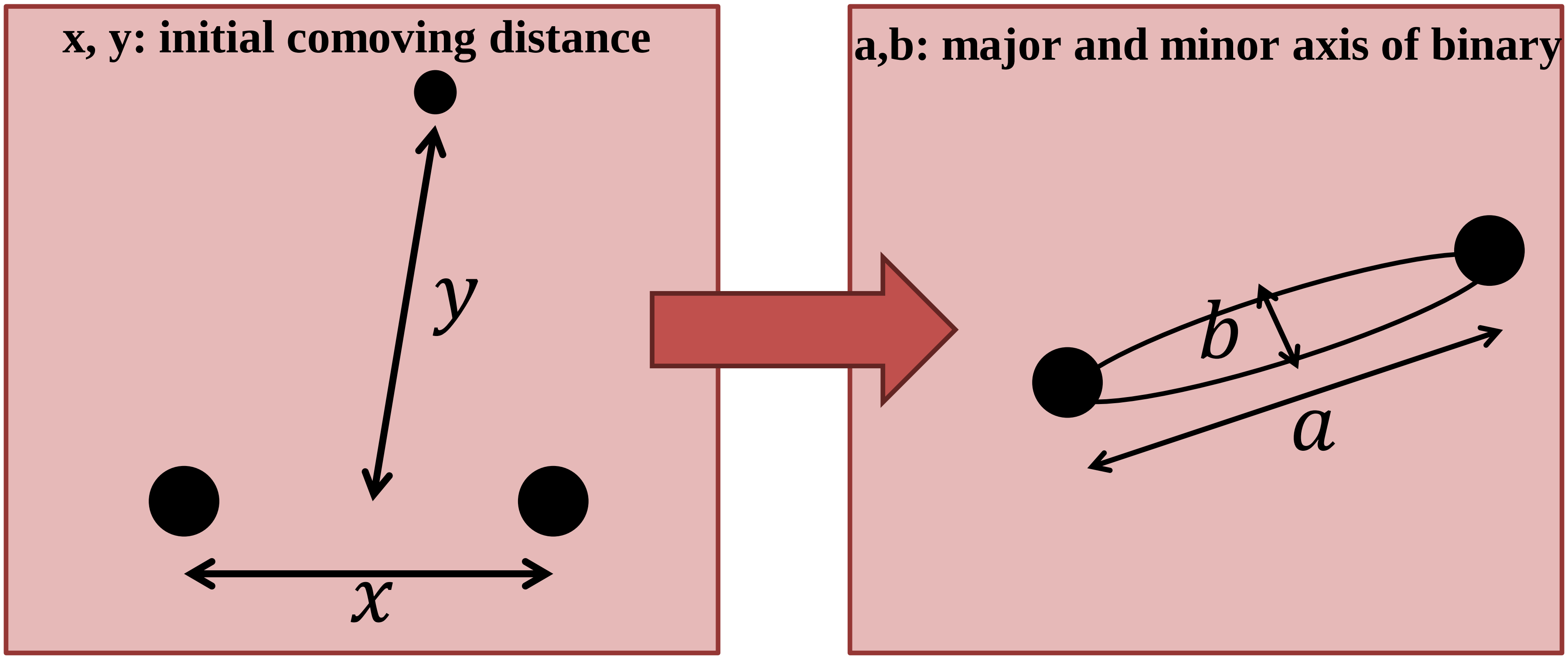
When the PBH energy $2\,M_{BH}$ in the volume $\sim d^3$ exceeds $\rho_{rad} d^3$, the PBHs in pair decouple from cosmic expansion and start to come closer by the gravitational force. (Ioka et al. 1998, Ali-Haimoud et al. 2017)



This can happen only in the RD era.

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

The nearest third PBH (but distant) gives angular momentum to the bound system.

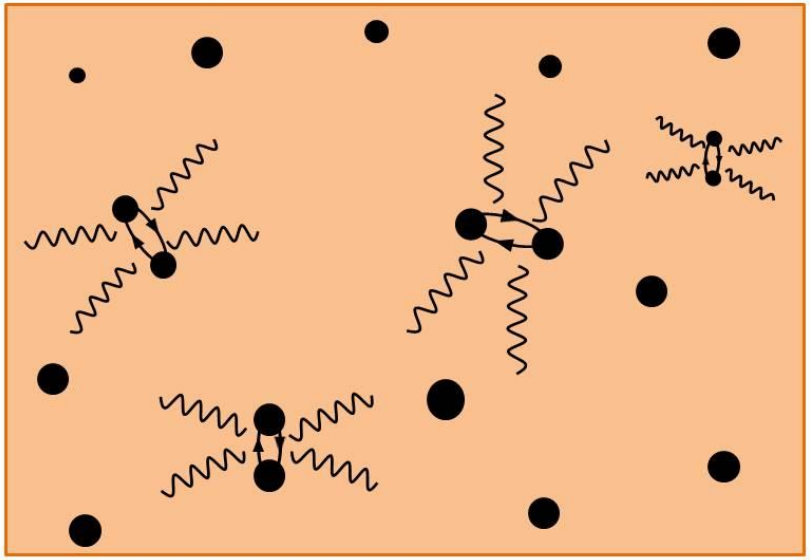


Once x and y are fixed, a and b are determined as

$$a = \frac{1}{f_{\rm PBH}} \frac{x^4}{\bar{x}^3} \qquad b = \frac{x^3}{y^3} a$$

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

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



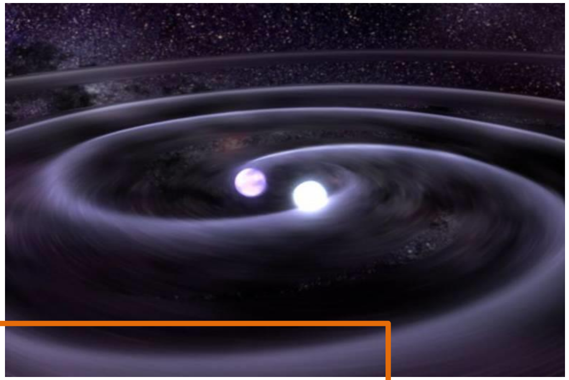
Uniform distribution

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

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



GR prediction

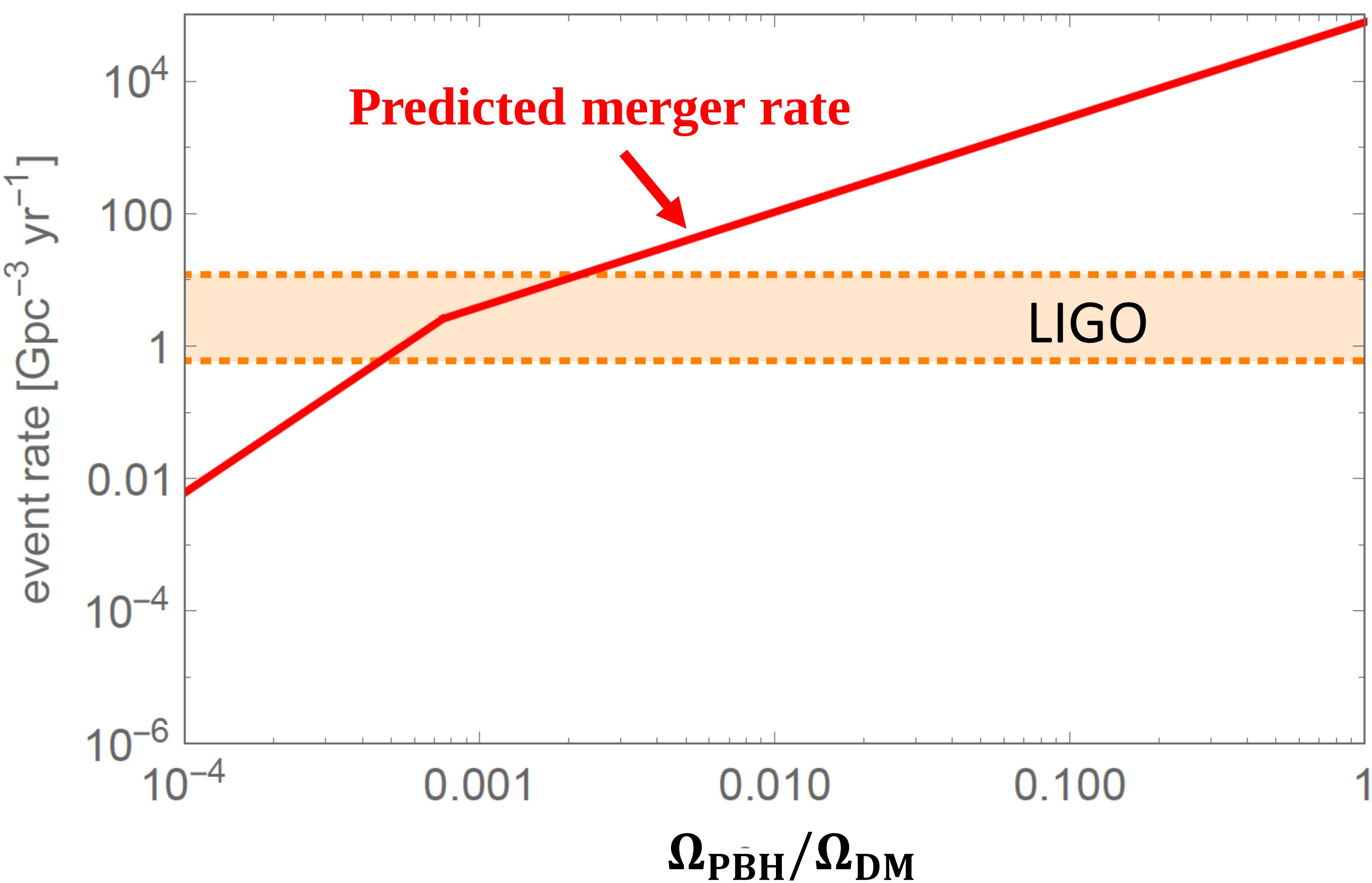
$$\text{Merger time} = \frac{3}{170}\frac{a^4}{(GM_{BH})^3}(1-e^2)^{7/2}$$

Pdf in (a, e) to the merger probability in $(t, t+dt)$.

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

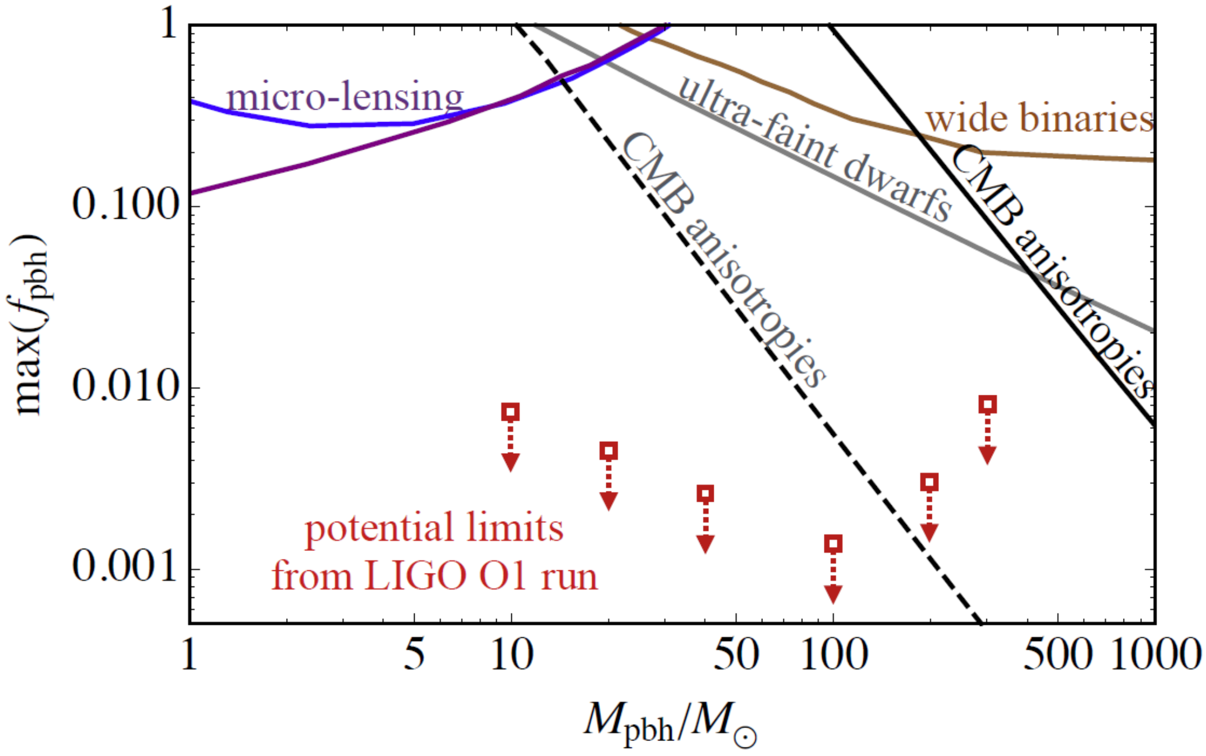
In the paper by Sasaki et al. 2016, $M_{BH} = 30M_{\odot}$ and the formula was extended to the case $\Omega_{PBH} < \Omega_{DM}$.

Merger event rate (Sasaki et al. 2016)



Consistent with LIGO if $30M_{\odot}$PBHs constitute about a few × 0.1% of 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)



Stellar mass PBHs as the dominant dark matter is strongly disfavored.

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**

1709.09007

HIDDEN UNIVERSALITY IN THE MERGER RATE DISTRIBUTION IN THE PRIMORDIAL BLACK HOLE SCENARIO

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Draft version September 27, 2017

ABSTRACT

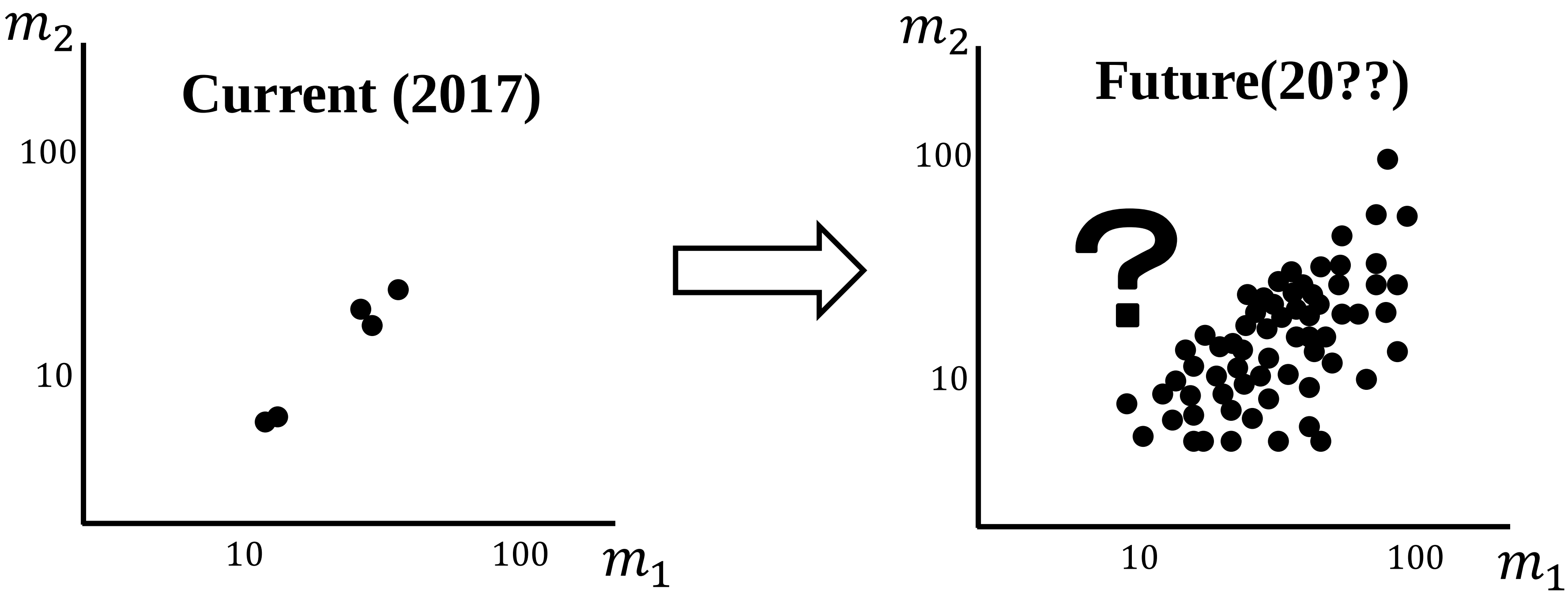
Primordial black holes (PBHs) form binaries in the radiation dominated era. Once formed, some fraction of them merge within the age of the Universe by gravitational radiation reaction. We investigate the merger rate of the PBH binaries when the PBHs have a distribution of masses around $\mathcal{O}(10)\mathrm{M}_\odot$, which is a generalization of the previous studies where the PBHs are assumed to have the same mass. After deriving a formula for the merger time probability distribution in the PBH mass plane, we evaluate it under two different approximations. We identify a quantity constructed from the mass-distribution of the merger rate density per unit time and volume $\mathcal{R}(m_1,m_2)$, $\alpha = -(m_1+m_2)^2\partial^2 \ln\mathcal{R}/\partial m_1 \partial m_2$, which universally satisfies $0.97 \lesssim \alpha \lesssim 1.05$ for all binary masses independently of the PBH mass function. This result suggests that the measurement of this quantity is useful for testing the PBH scenario.

How do we test the PBH scenario?

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 $\boldsymbol{f(m_{BH})}$.

Assumption

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

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

Merger event rate distribution in (m_1, m_2) plane

Mass function

$$\mathcal{R}(m_1, m_2, t) = \frac{1}{2n_{\rm PBH}} \mathcal{R}_{\rm intr}(m_1, m_2, t) f(m_1) f(m_2)$$

Observable in the future

Probability that given BH pair (m_1, m_2) form a binary and merge at time t.

We evaluated R_{intr} basically following the approach of Nakamura et al.1997.

Result

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

$C, \tilde{f}(m)$: sensitive to the PBH mass function

$$0.97 < \alpha < 1.05$$

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 scenario predicts

$$0.97 \lesssim \alpha \lesssim 1.05$$

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)**

Summary

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.