LIGO and Primordial Black Holes

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

Gravitational waves discovered!!

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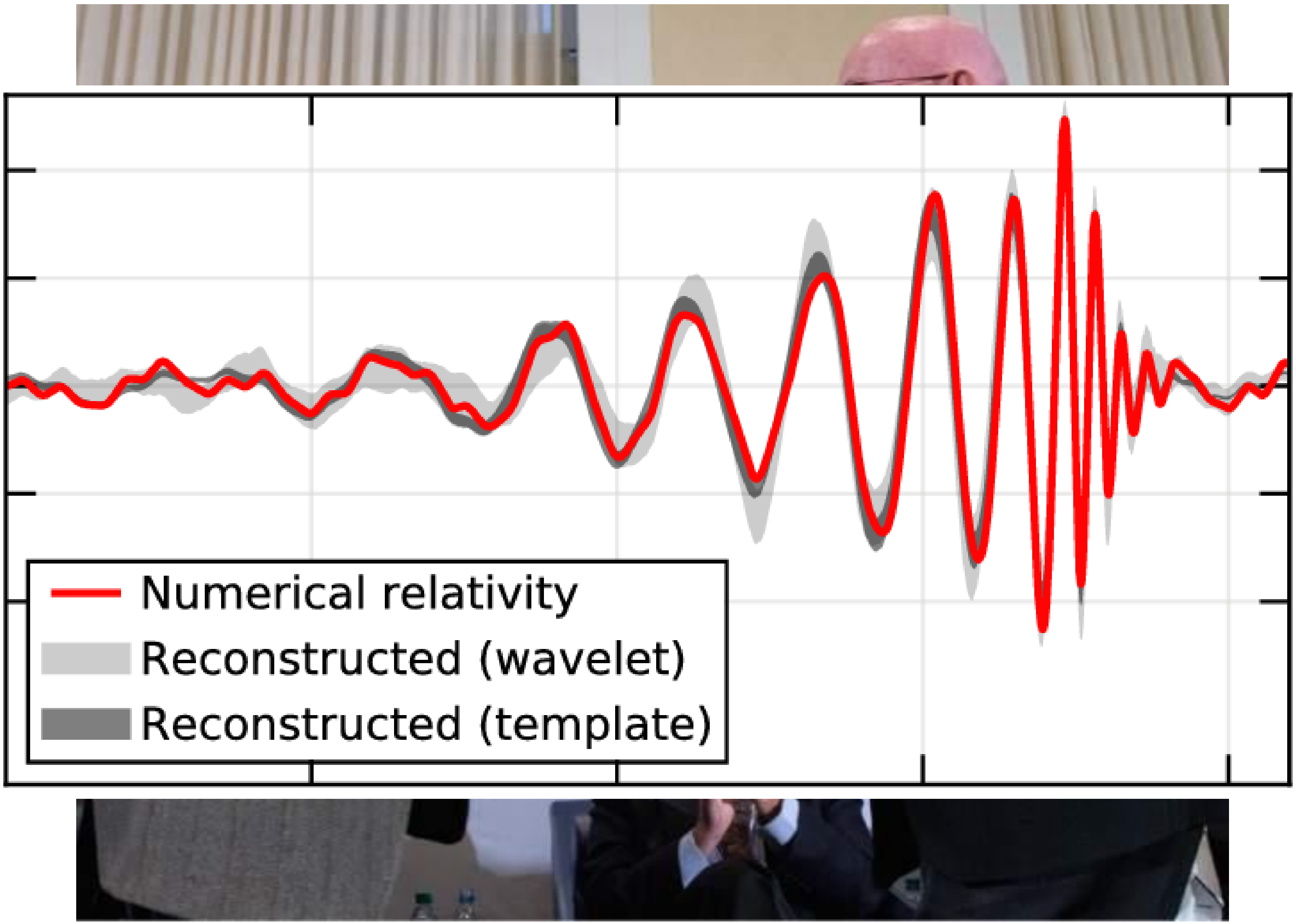


BH binary!!

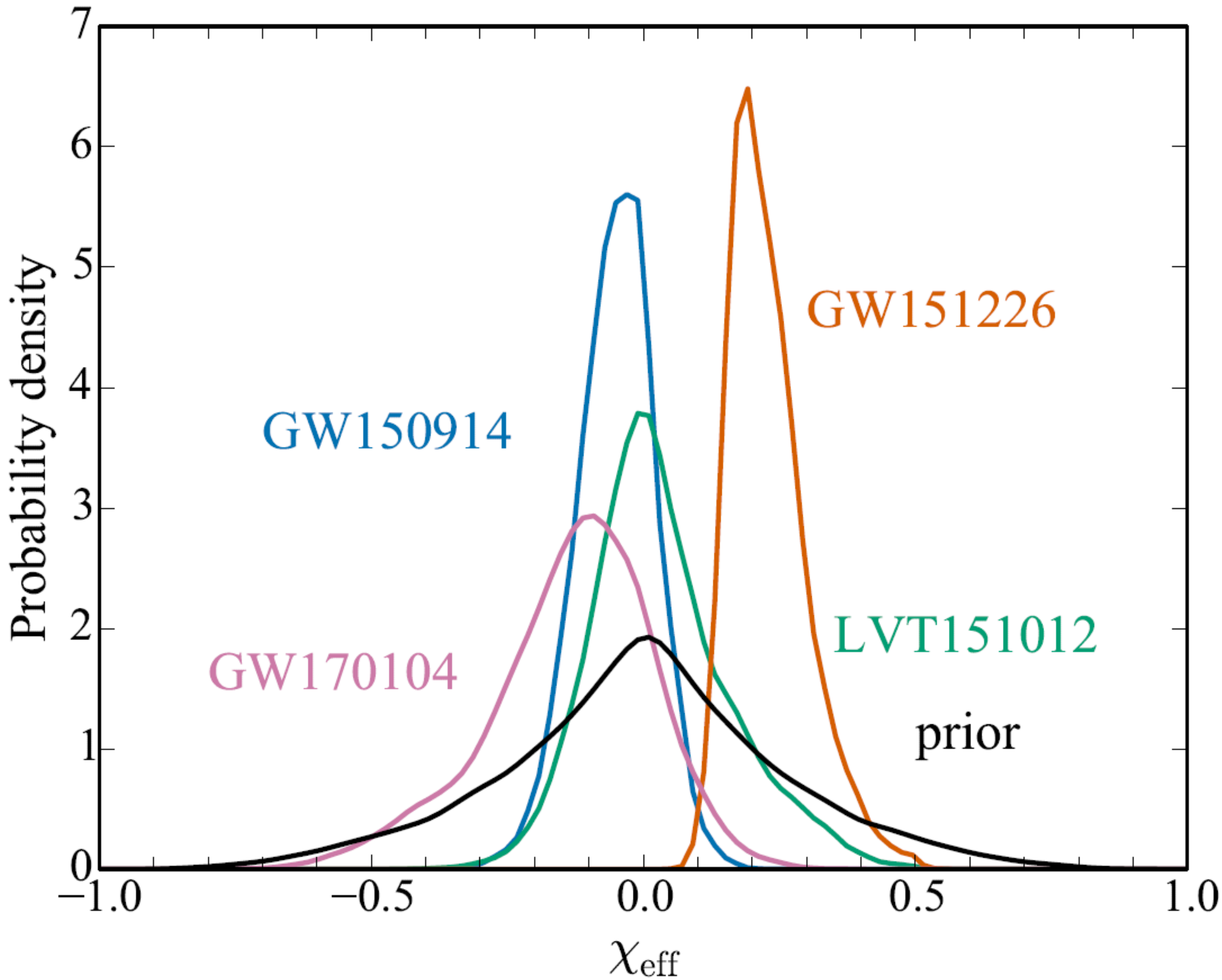
(LIGO)

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

So far, 3 events have been detected.

Event name	BH mass ($M_\odot$)
GW150914	(36, 29)
GW151226	(14, 8)
GW170104	(31, 19)

They are surprisingly heavy.



It appears spins of BHs are not so big.

What we know after LIGO

There are many BH binaries.

They are heavy and low spin.

They can merge within Hubble time.

What we don't know after LIGO

Where do they come from?

Questions

What is the origin of such heavy BHs?

What is the mechanism of the binary formation?

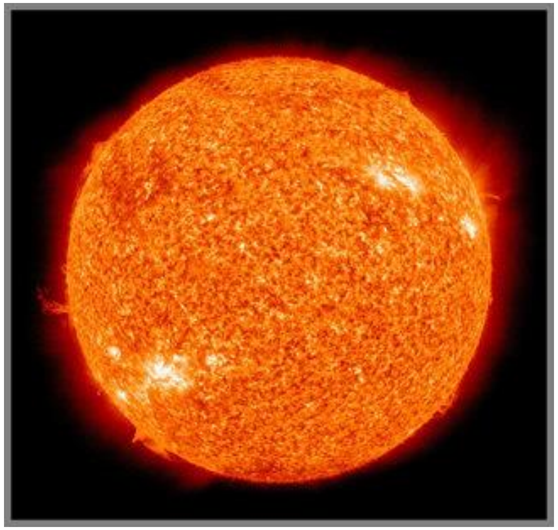
Basic strategy

propose scenarios as many as possible

propose many ideas to test them

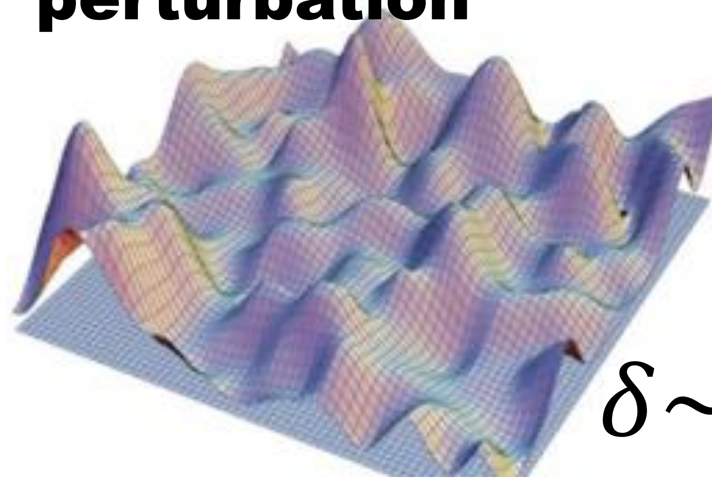
test them by real data.

Maybe, primordial BHs!



Astrophysical BH

Primordial density perturbation



$\delta \sim 0.3$

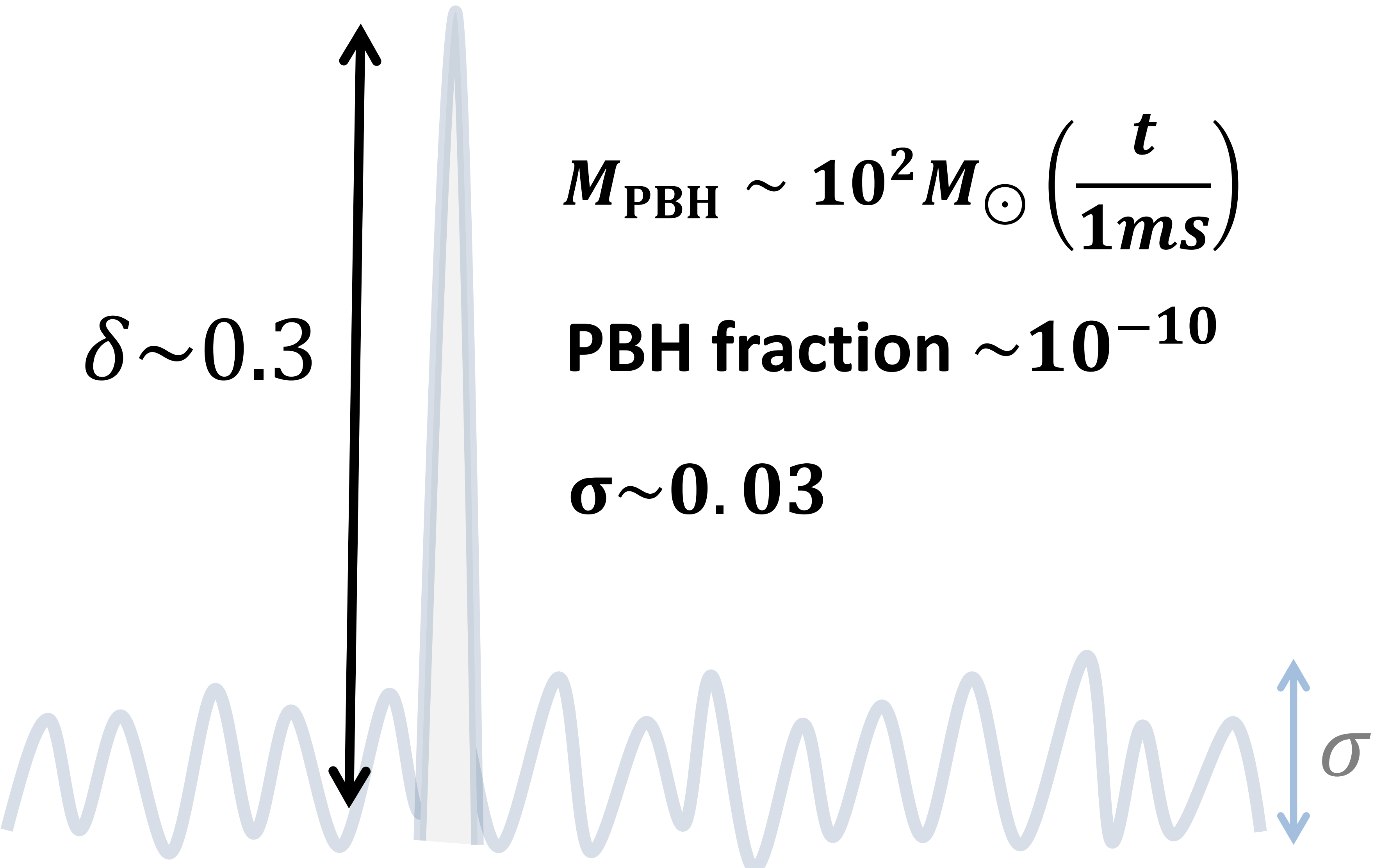
PBH

PBH forms out of rare high-σ peak of small-scale perturbation (~pc)

$$M_{\mathrm{PBH}} \sim 10^2 M_\odot \left(\frac{t}{1ms}\right)$$

PBH fraction $\sim 10^{-10}$

$$\sigma \sim 0.03$$

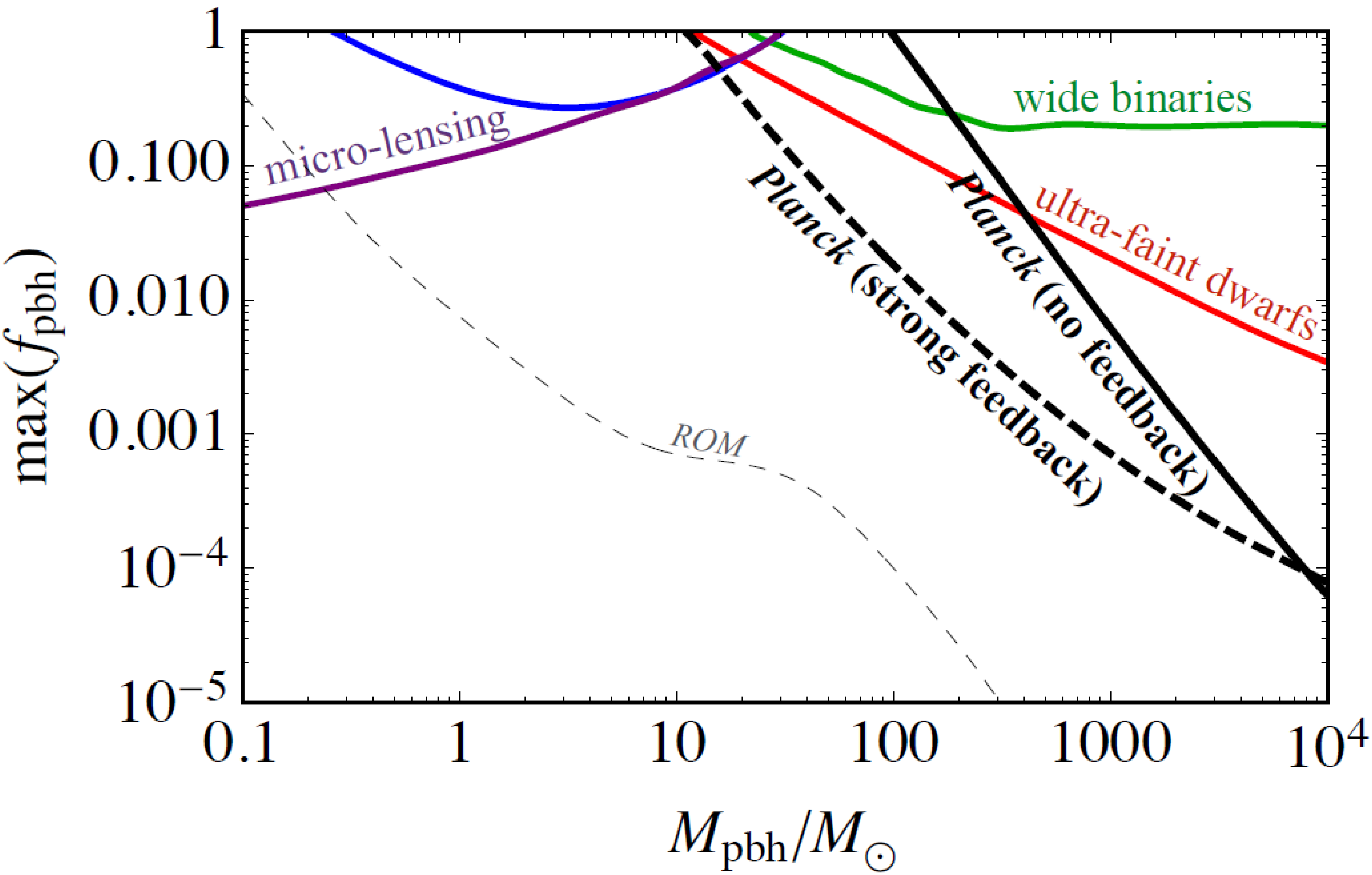


If PBHs, it's exciting!

It accounts for (some fraction of) dark matter. Many papers appeared last year.

It gives strong restriction on inflation.

Upper bound on PBH abundance



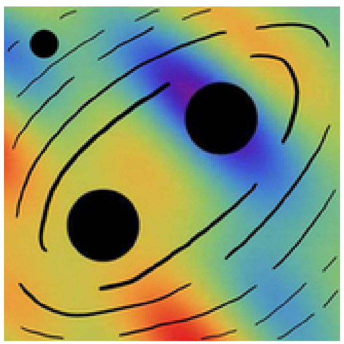
Ali-Haimoud, Kamionkowski, 1612.05644

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 +

It is assumed that all PBHs have 30 $M_{\odot}$.

I am currently investigating the case where the PBH mass function is non-monochromatic.

Necessary conditions

Formation of about $30M_\odot$ BHs.

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

Merger rate consistent with LIGO observation.

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

Necessary conditions

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.

Merger rate consistent with LIGO observation.

An inflation model predicting PBHs

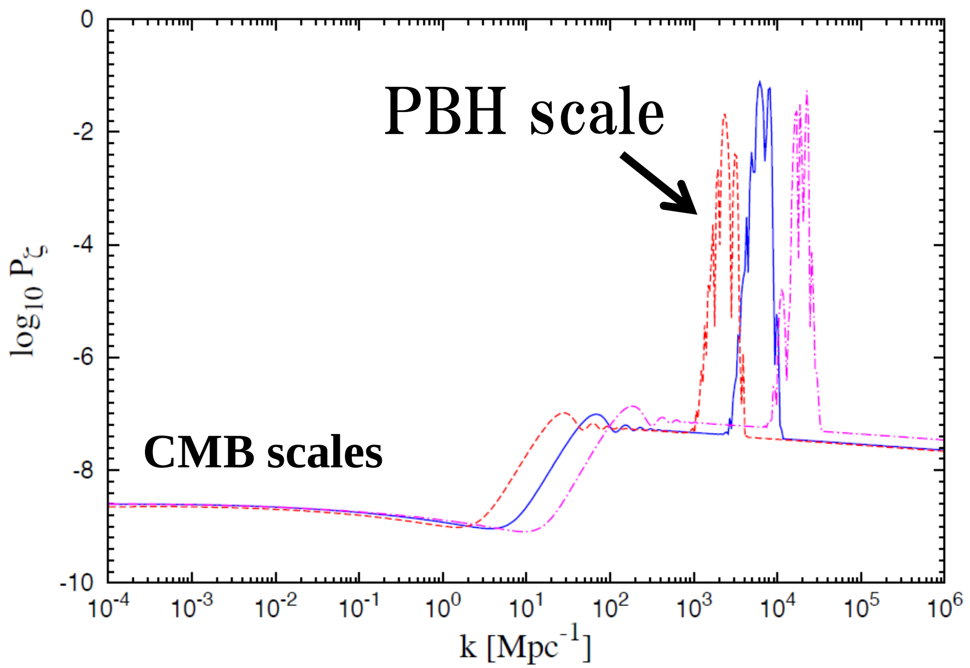
(Kawasaki, Kusenko, Yanagida, 2012)

$$V = V_{\rm H} + V_{\rm N} + V_{\rm HN},$$

$$V_{\rm H}(\phi,\psi) = \left(1 + \frac{\phi^4}{8} + \frac{\psi^2}{2}\right)\left(-\mu^2 + \frac{\psi^4}{16M^2}\right)^2 + \frac{\phi^2\psi^6}{16M^4},$$

$$V_{\rm N}(\varphi) = v^4\left(1 - \frac{\kappa}{2}\varphi^2\right) - \frac{g}{2}v^2\varphi^4 + \frac{g^2}{16}\varphi^8,$$

$$V_{\rm HN}(\phi,\psi,\varphi) = \left(-\mu^2 + \frac{\psi^4}{16M^2}\right)^2\frac{\varphi^2}{2} - \left(-\mu^2 + \frac{\psi^4}{16M^2}\right)v^2\phi\varphi,$$



Necessary conditions

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 but inevitable physical mechanism exists.

(T.Nakamura, M.Sasaki, T.Tanaka, K.Thorne, 1997)
(K.Ioka, T.Chiba, T.Tanaka, T.Nakamura, 1998)

Merger of rate consistent with LIGO observation.

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

GRAVITATIONAL WAVES FROM COALESCING BLACK HOLE MACHO BINARIES

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ABSTRACT

If MACHOs are black holes of mass ~0.5 $M_\odot$, they must have been formed in the early universe when the temperature was ~1 GeV. We estimate that in this case in our Galaxy's halo out to ~ 50 kpc there exist ~5 × 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 ~5 × 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

PBH binary formation ($\sim 0.5 M_\odot$) is considered.

It is assumed that dark matter entirely consists of PBHs.

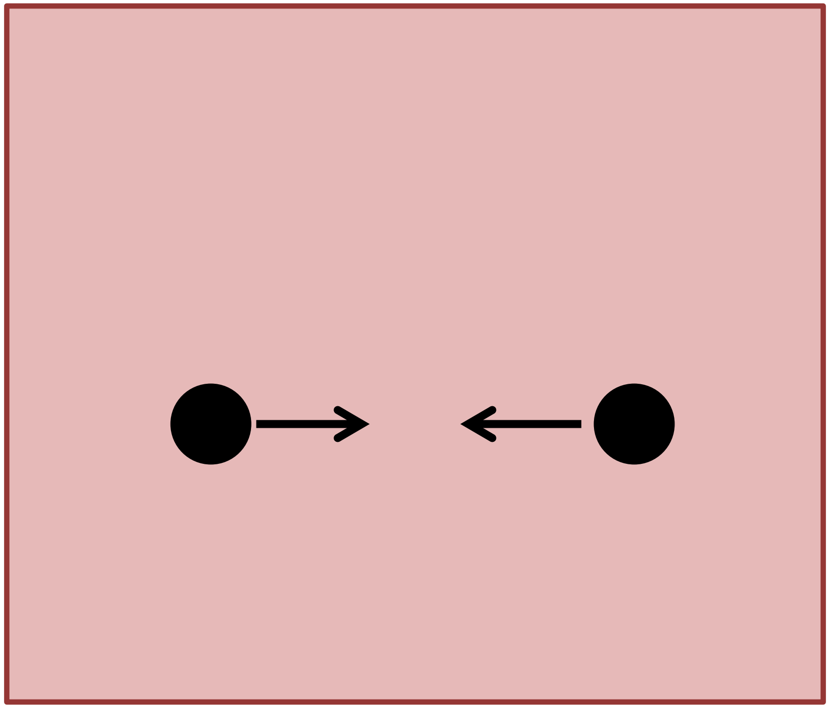
BH binaries in the PBH scenario

(T.Nakamura, M.Sasaki, T.Tanaka, K.Thorne, 1997)

Assumptions

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

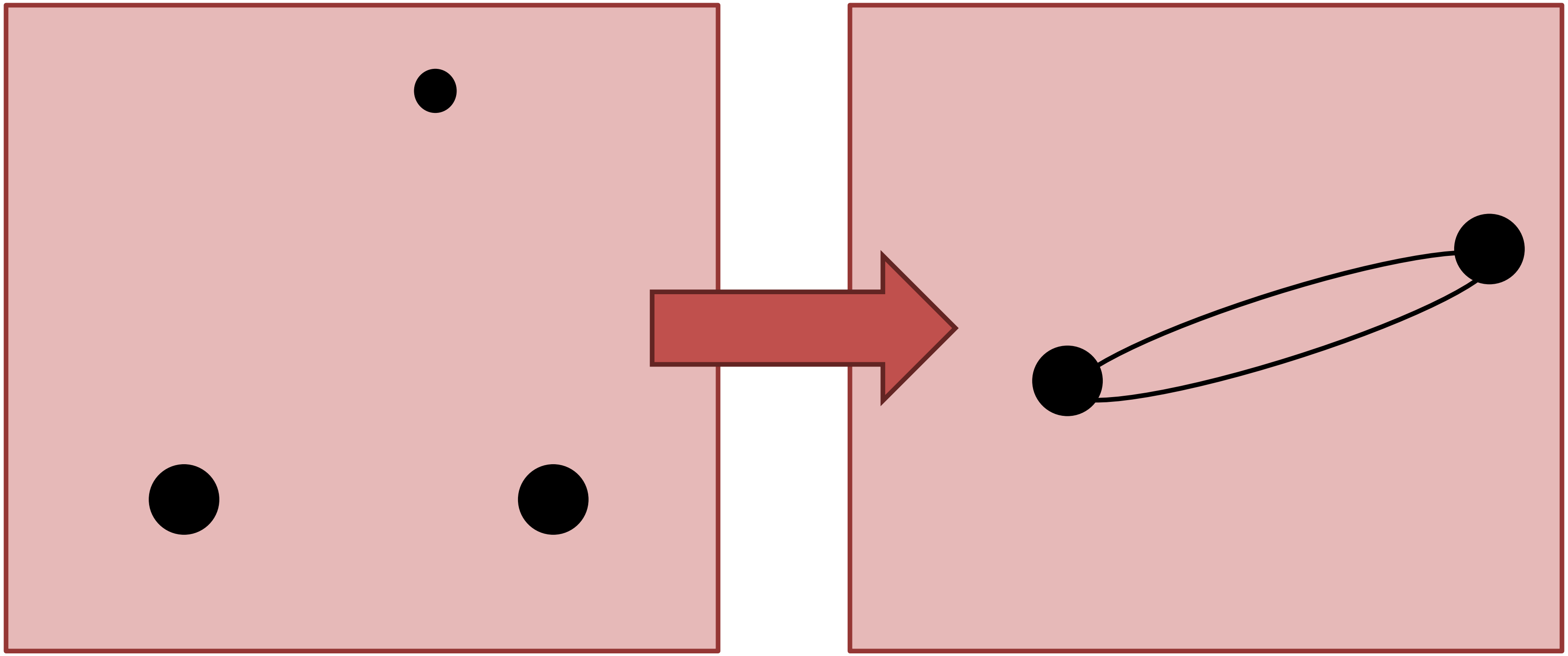
Two neighboring PBHs come closer by gravity.



Tidal force from the third BH

(T.Nakamura, M.Sasaki, T.Tanaka, K.Thorne, 1997)

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



Binary is formed.

Necessary conditions

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 but inevitable physical mechanism exists.

(T.Nakamura, M.Sasaki, T.Tanaka, K.Thorne, 1997)
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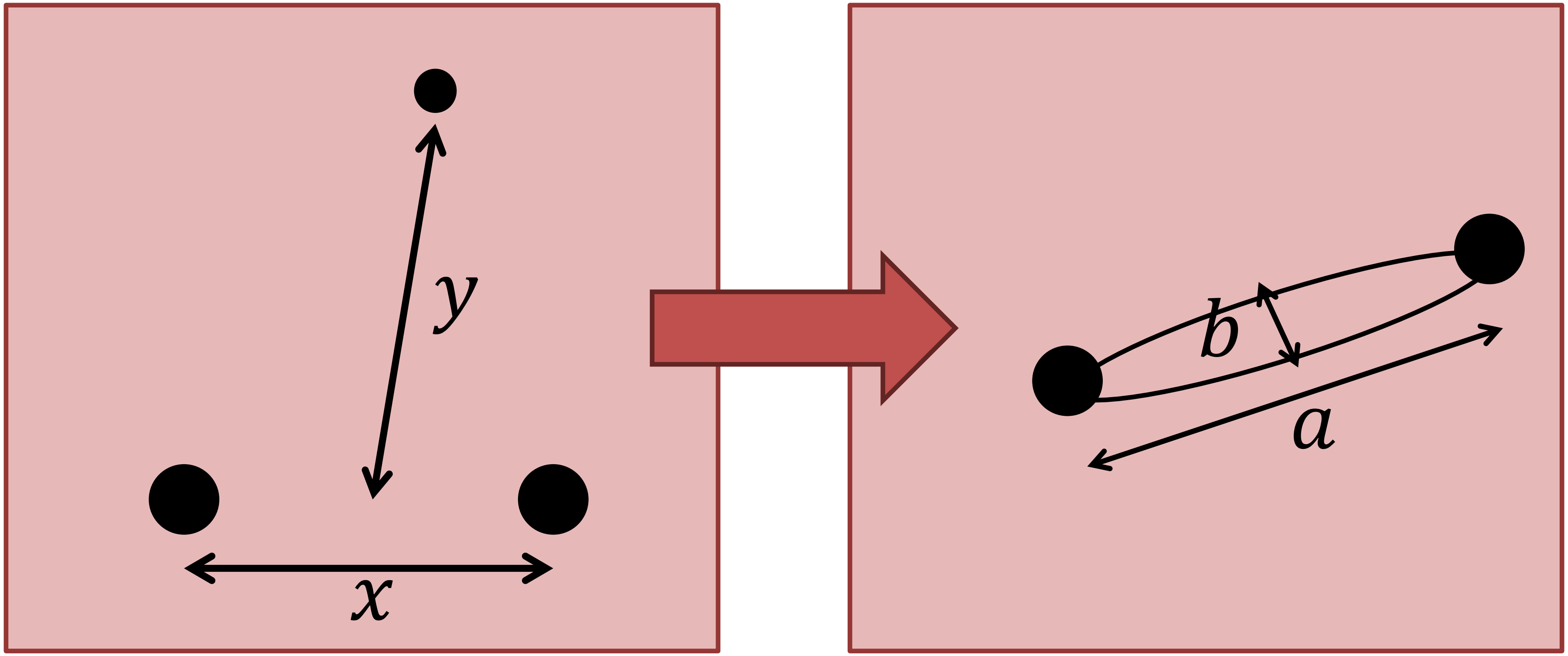
Merger rate consistent with LIGO observation.

Binaries can merge within the age of the Universe thanks to the large eccentricity.

There is a space for $\Omega_{PBH}(< 1)$ consistent with LIGO.

Simple Newtonian analysis



$$a = \frac{\alpha}{f}\frac{x^4}{\bar{x}^3}, \quad b = \beta\left(\frac{x}{y}\right)^3 a$$

Binary with large eccentricity is formed.

Probability distribution function

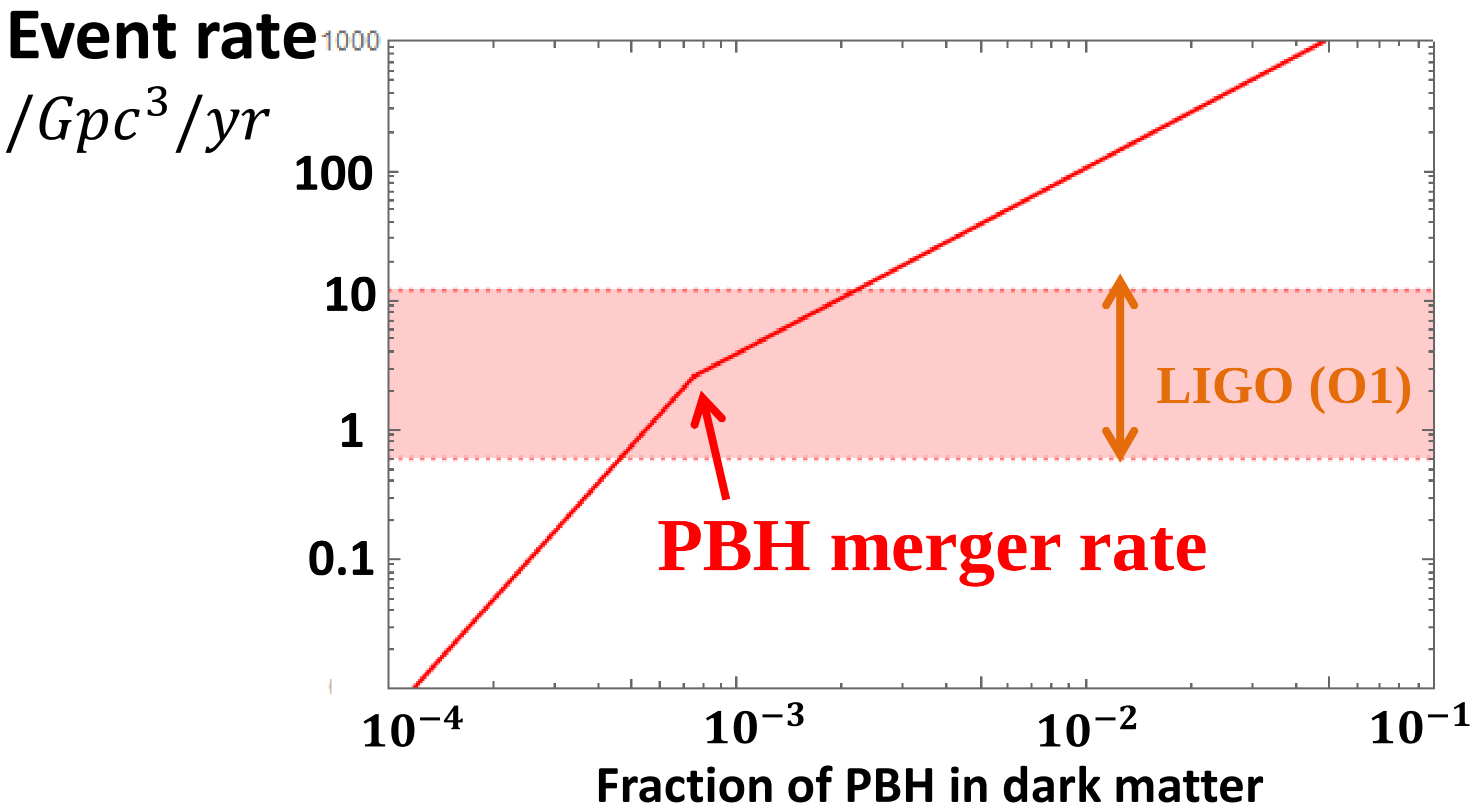
$$dP = \frac{9}{\bar{x}^6} x^2 y^2 dx dy \qquad 0 < x < y < \bar{x}$$

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

$$t = Q a^4 (1 - e^2)^{7/2}, \qquad Q = \frac{3}{170} (G M_{\mathrm{BH}})^{-3}$$

After integrating over the eccentricity, we obtain the probability that merger occurs in the interval $(t, t + dt)$.

Merger event rate



- Consistent with LIGO if PBH constitutes about 0.1% of dark matter (no inconsistency with other obs).

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.