Primordial black holes
−perspectives in gravitational−wave astronomy−

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Topical Review

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Primordial black holes—perspectives in gravitational wave astronomy

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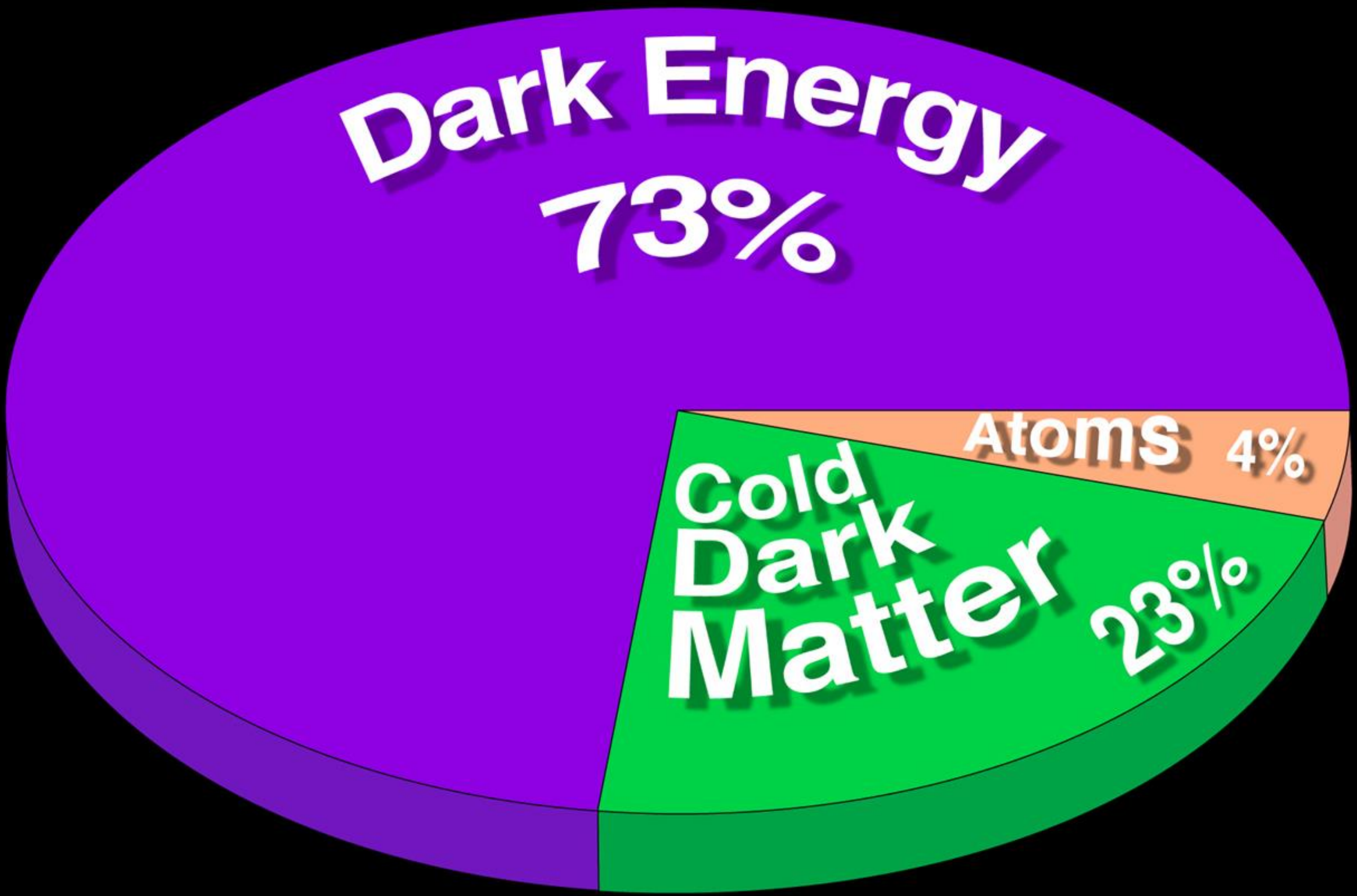
CrossMark

Abstract

This article reviews current understanding of primordial black holes (PBHs), with particular focus on those massive examples ($\gtrsim 10^{15}$ g) which remain at

What is the nature of dark matter?



New elementary particles?

No observational hints of the new particles may suggest that DM may be black holes.

Important question

Is dark matter made of BHs?

Astrophysical BHs cannot comprise dark matter.

If DM is made of BHs, they must be primordial BHs.

What are primordial BHs?

PBHs=BHs that formed in the very early Universe

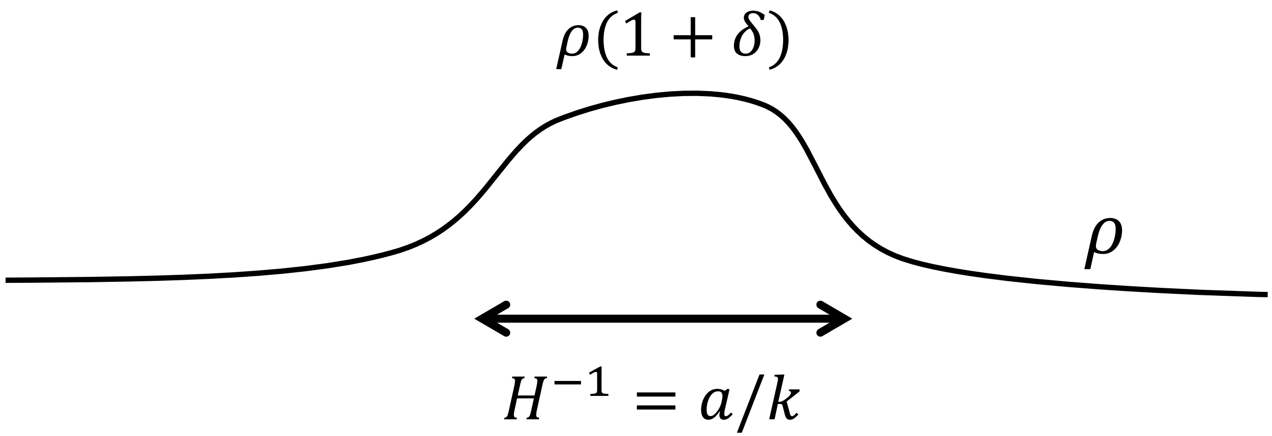
S.Hawking 1971

Formation mechanism of PBHs

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

Formation of PBHs

Collapse of primordial density perturbation



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

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

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

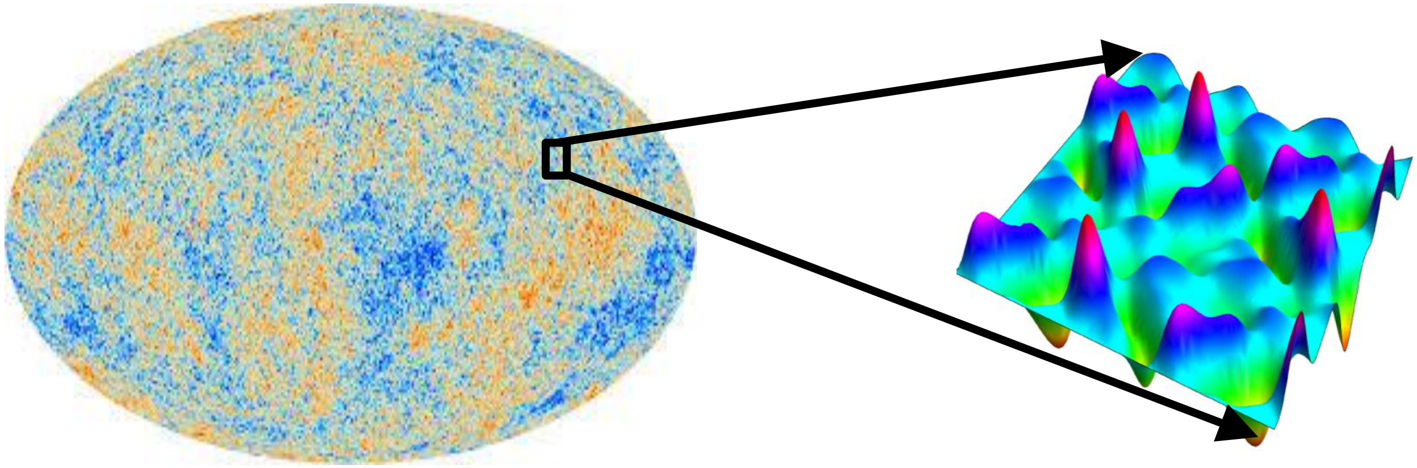
$$M_{\mathrm{PBH}} \sim \rho H^{-3} \sim \frac{1}{GH} \sim 10 M_{\odot} \left(\frac{t}{0.1 ms}\right) \sim 10 M_{\odot} \left(\frac{k}{1\mathrm{pc}^{-1}}\right)^{-2}$$

Length scale of the density perturbations determines the mass of PBHs

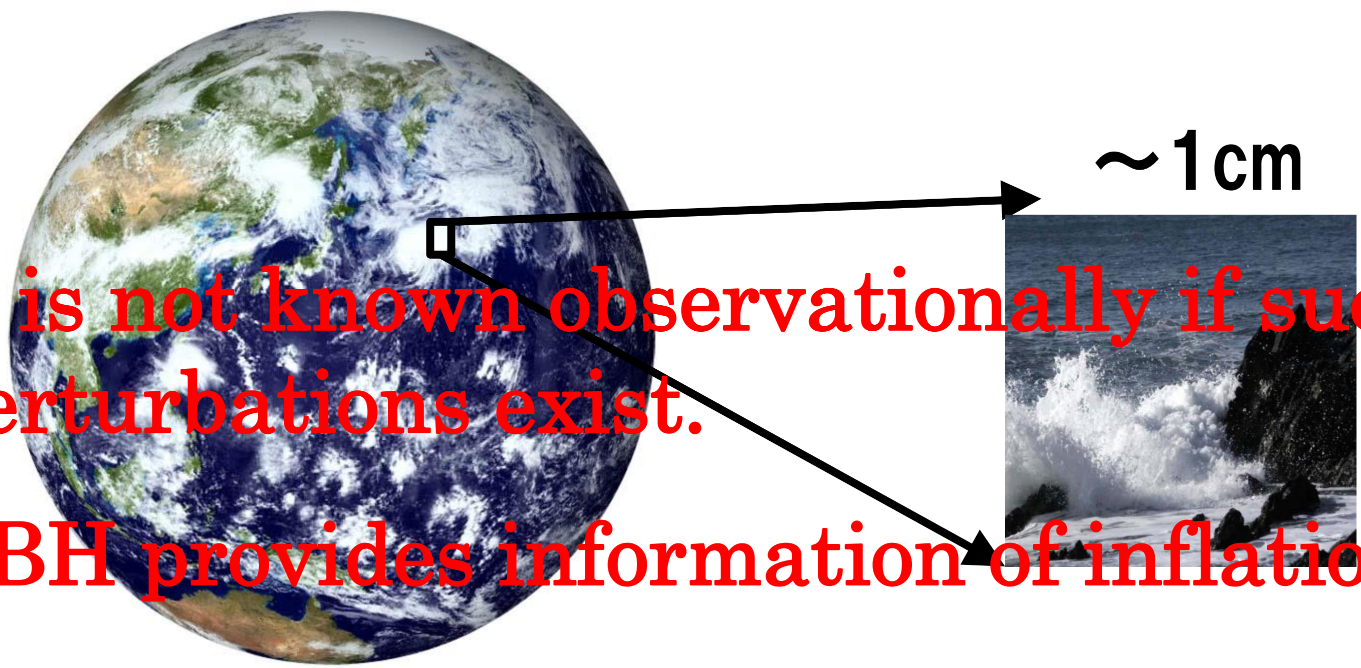
$$\boldsymbol{M_{\mathrm{PBH}} \sim 10 M_{\odot} \left(\frac{k}{1\mathrm{pc}^{-1}} \right)^{-2}}$$

Contrary to the astrophysical BHs, PBHs (much) lighter than the Sun can be produced.

Is δ~1 allowed observationally?



PBHs originate from very small-scale perturbations.



It is not known observationally if such perturbations exist.

PBH provides information of inflation.

An inflation model predicting PBHs

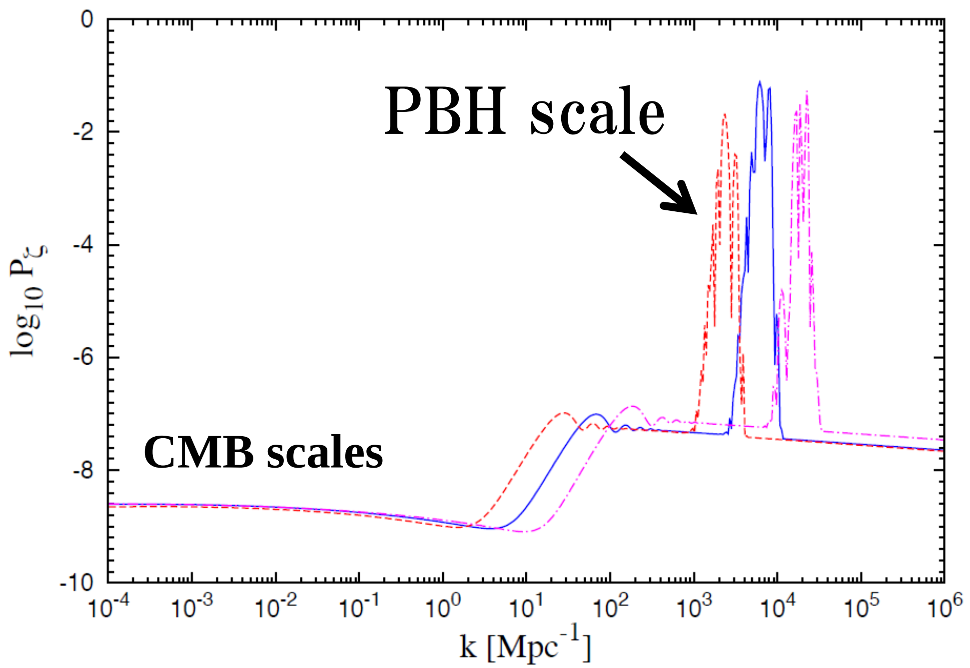
(Kawasaki, Kusenko, Yanagida, 2012)

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

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

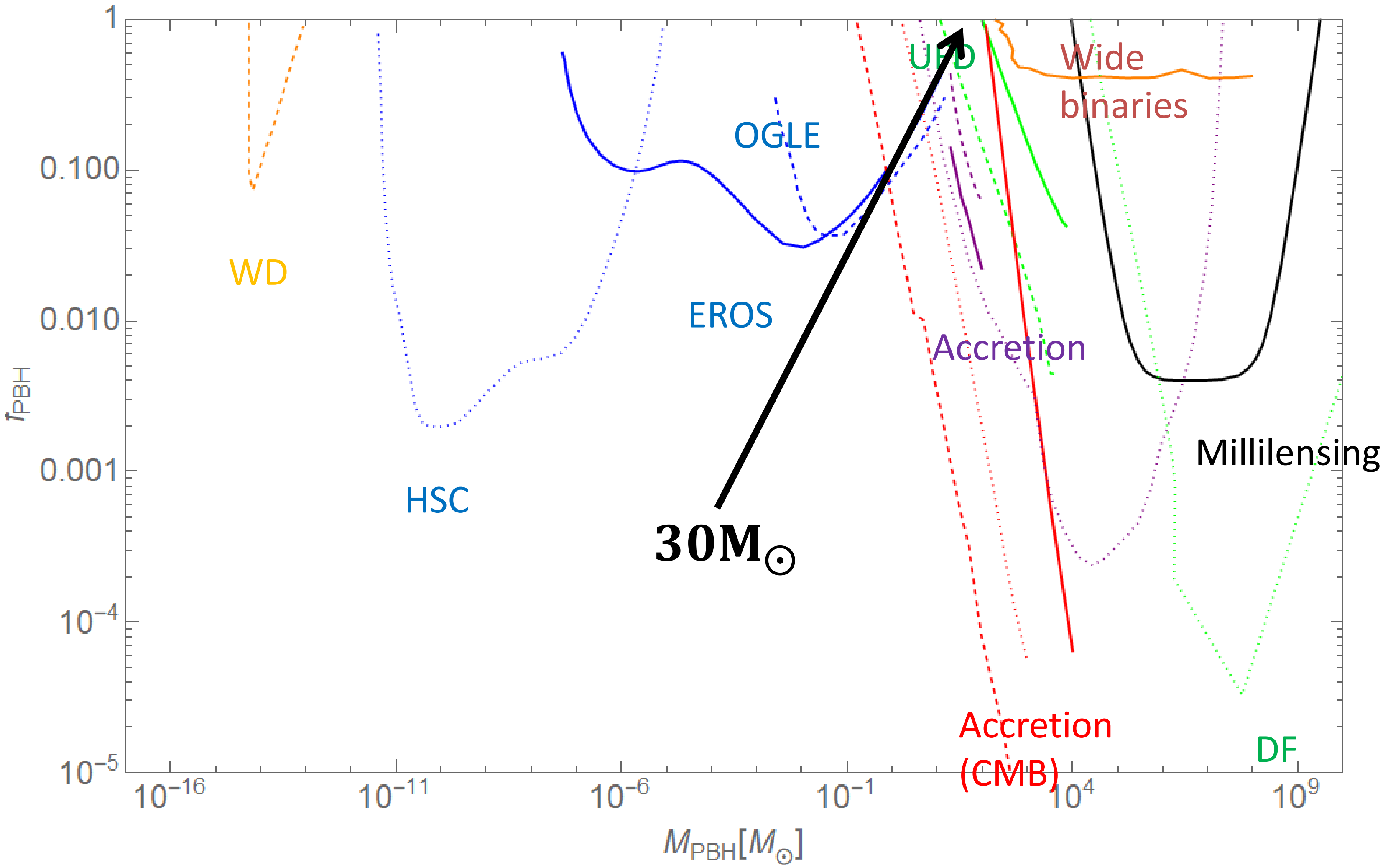
$$V_{\mathrm{N}}(\varphi) = v^4\left(1 - \frac{\kappa}{2}\varphi^2\right) - \frac{g}{2}v^2\varphi^4 + \frac{g^2}{16}\varphi^8,$$

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



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

(by electromagnetic observations)



※*Monochromatic mass function is assumed.*

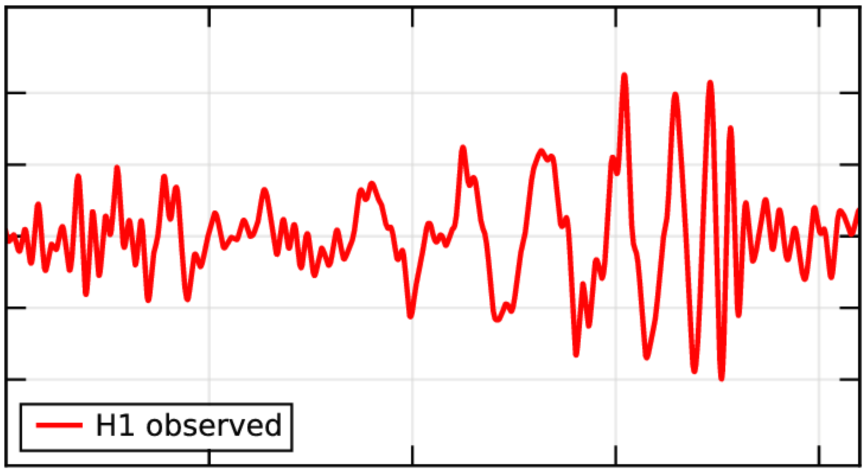
Message

Observations of GWs can add new constraints on the constraint figure for PBH mass range in

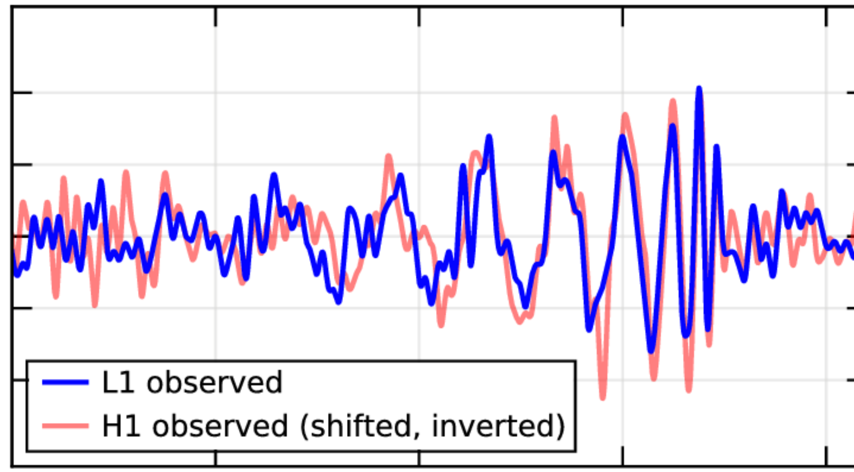
- 0.2-300 $M_\odot$
- $10^{17}\mathrm{g} - 10^{19}\mathrm{g}, 10^{20}\mathrm{g} - 10^{22}\mathrm{g}$

GWs from BH binaries

Hanford, Washington (H1)



Livingston, Louisiana (L1)



PBHs form binaries in the radiation dominated era and merge at present epoch.

PBH 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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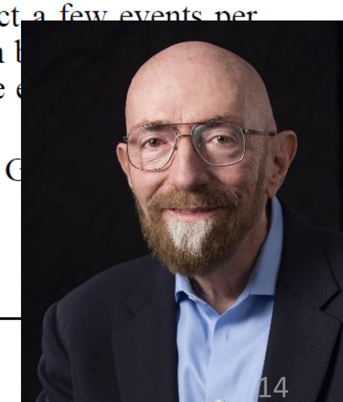
ABSTRACT

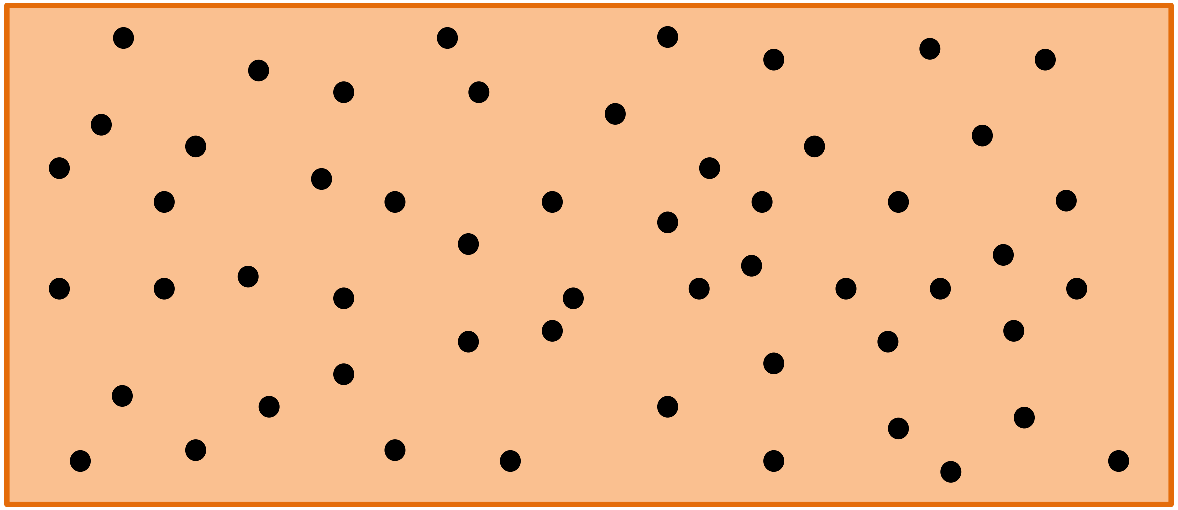
HOs are black holes of mass ~0.5 $M_\odot$ they must have been formed in the early uni
e was ~1 GeV. We estimate that in this case in our Galaxy's halo out to ~ 50 kpc there exist ~5 ×
hole binaries the coalescence times of which are comparable to the age of the universe, so that the
e rate will be ~5 × 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 — C



Two assumptions **(Nakamura et al. 1997)**

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

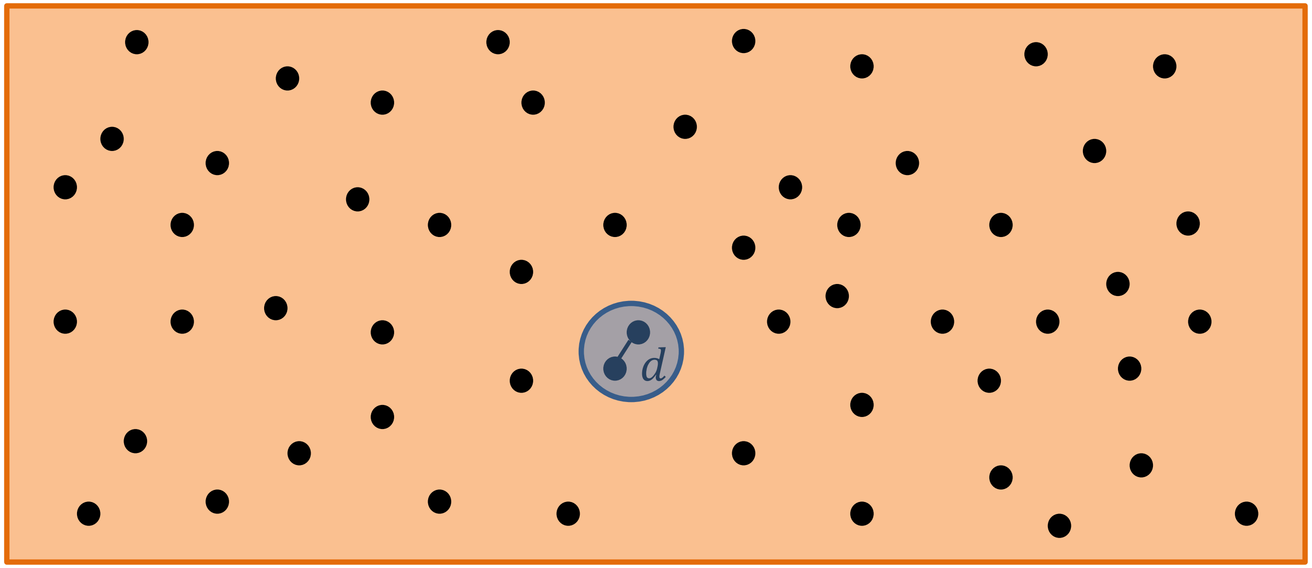


Initially, PBHs are on the flow of the cosmic expansion.

2. All PBHs have the same mass

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

(The rest is not assumption but physical consequence.)



When $2\ M_{BH} > \rho_{rad} d^3$, the PBHs in pair becomes bound.

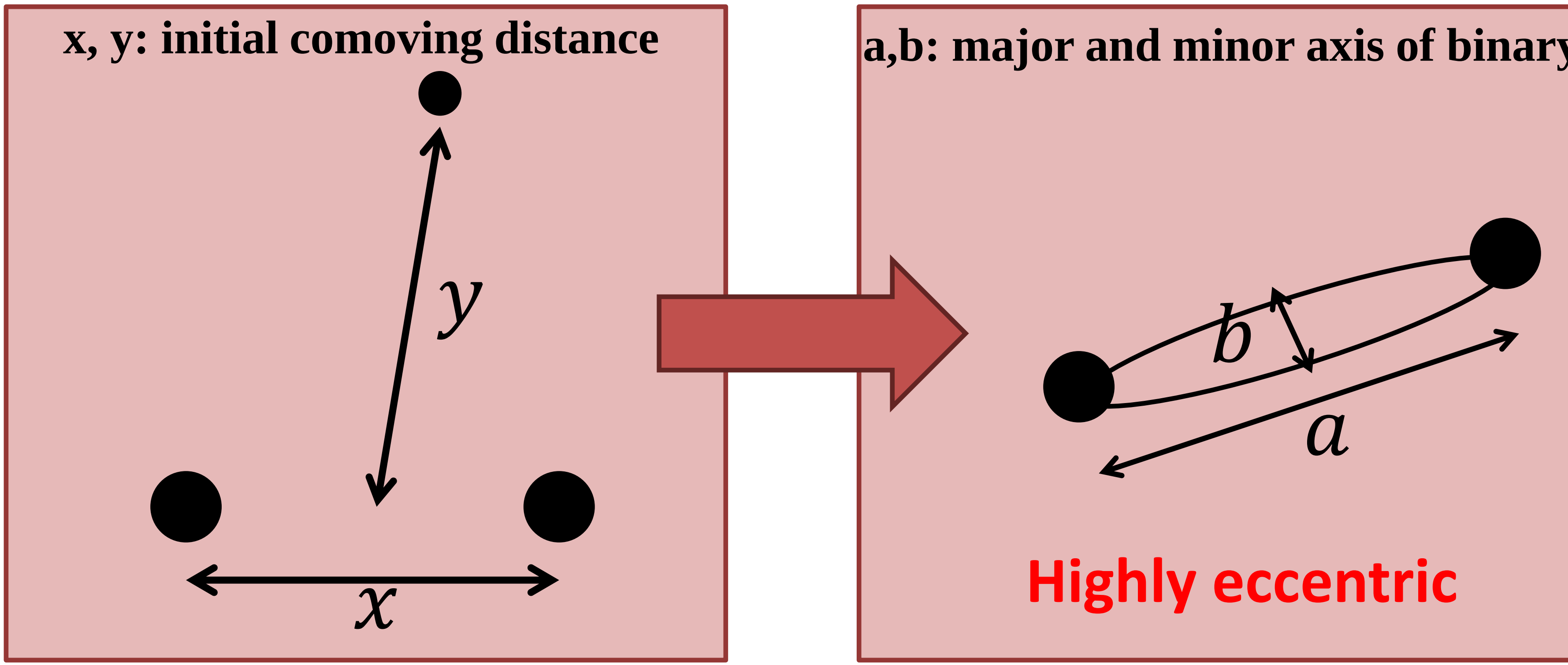
This happens for $d < f_{PBH}{}^{1/3} \ell_{PBH}$ and in the RD era. $\left(f_{PBH} = \frac{\Omega_{PBH}}{\Omega_{DM}}\right)$

Only a fraction of PBHs (f_{PBH}) form a bound system.

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.

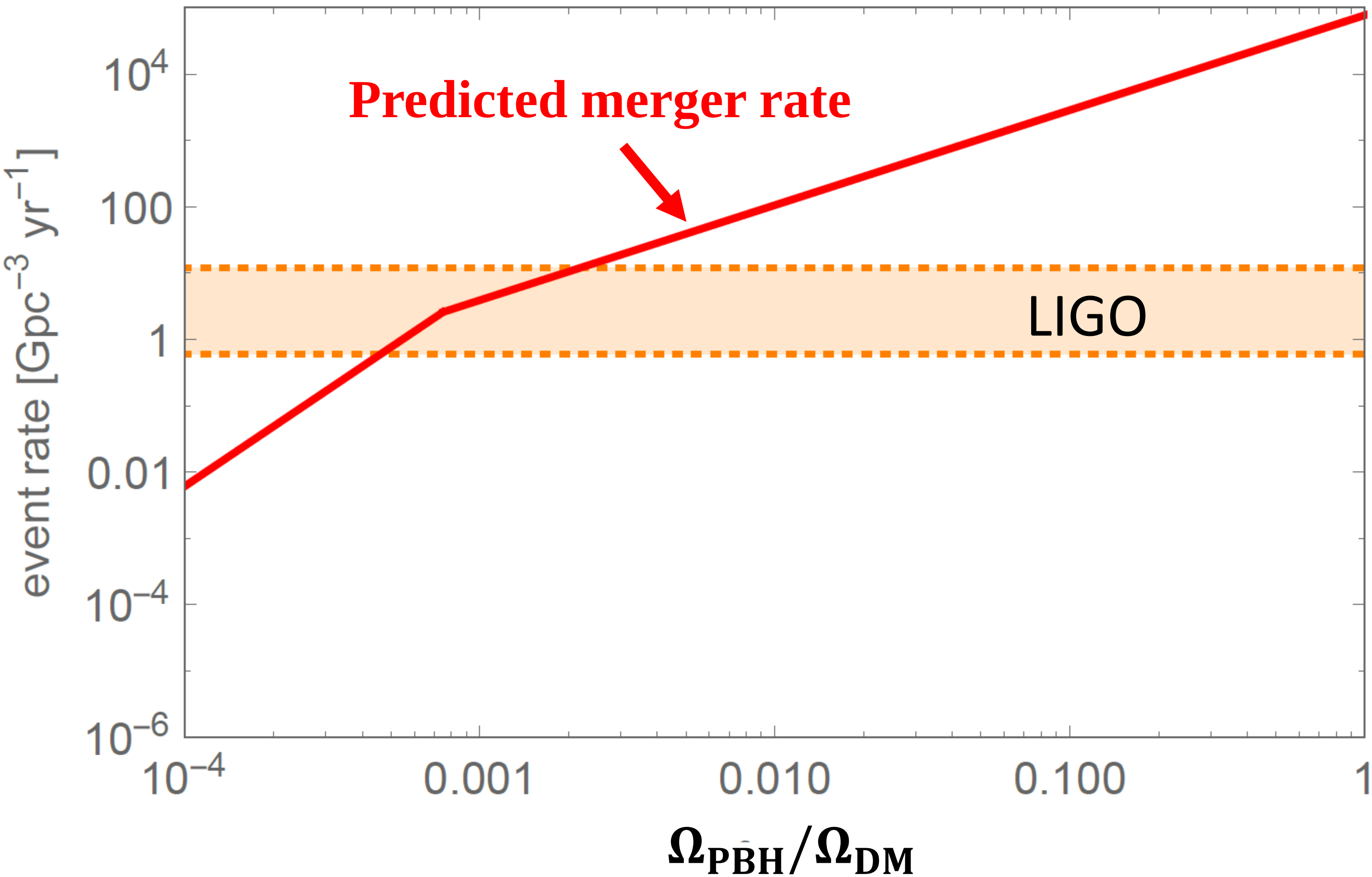
(Binary formation!)



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

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

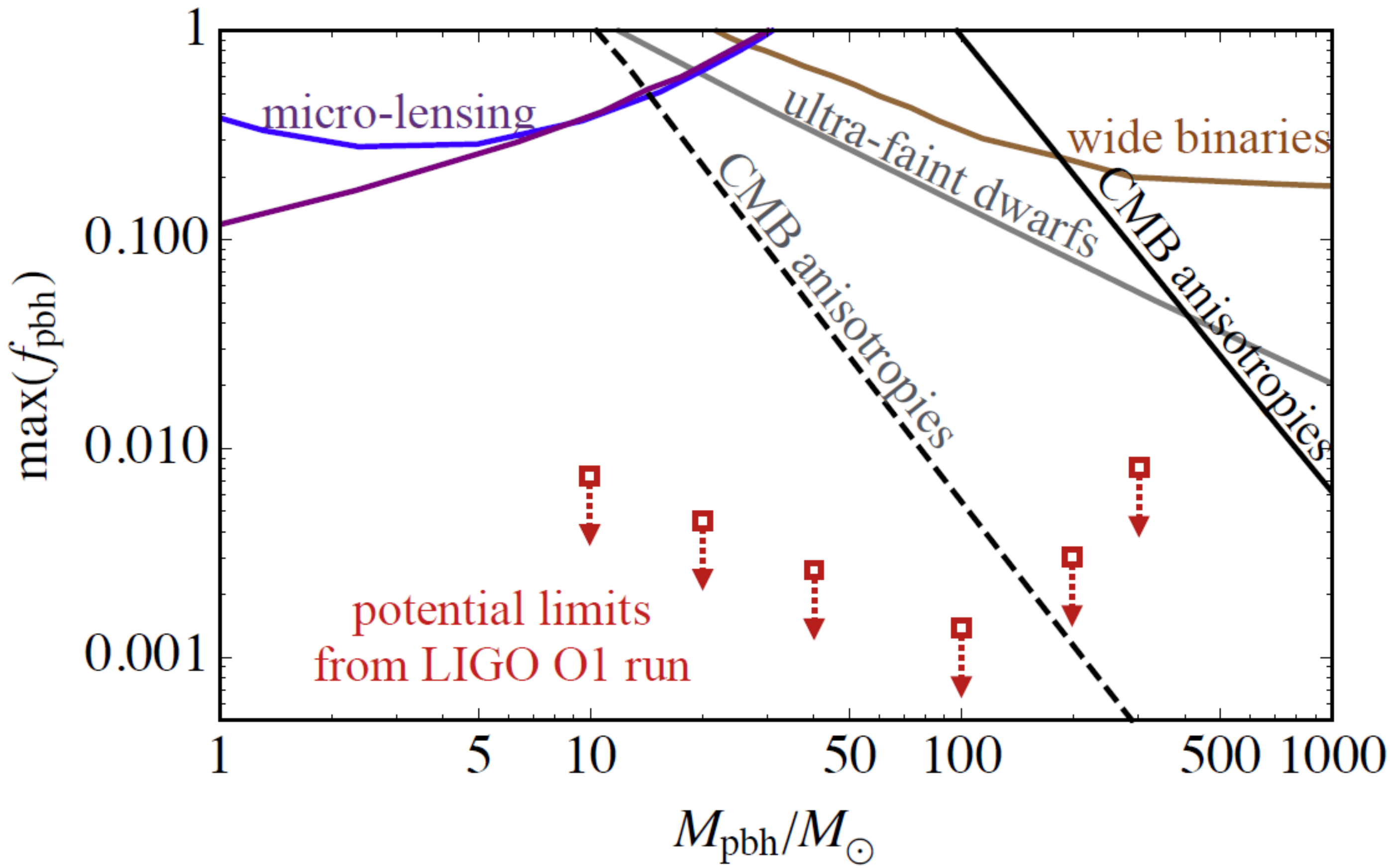
Merger event rate (Sasaki et al. 2016)



Consistent with LIGO if $30M_{\odot}$PBHs constitute about 0.1% of dark matter.

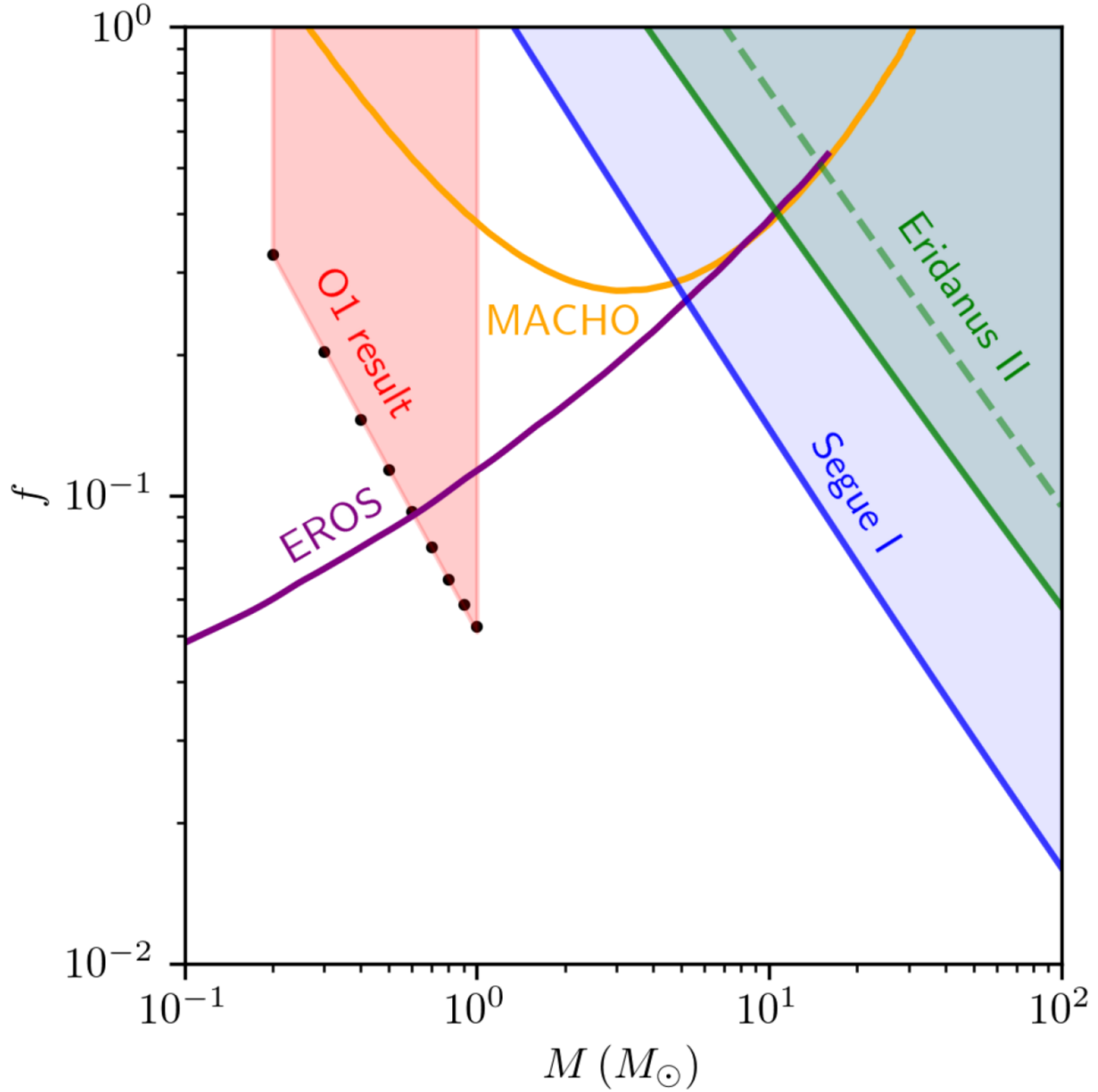
Recently, the same formula has been used to place upper limit on Ω_{PBH} from the LIGO observation.

(Ali-Haimoud, Kovetz, Kamionkowski 2017)



Recently, LIGO-Virgo team placed upper limit on the subsolar-mass PBHs.

1808.04771

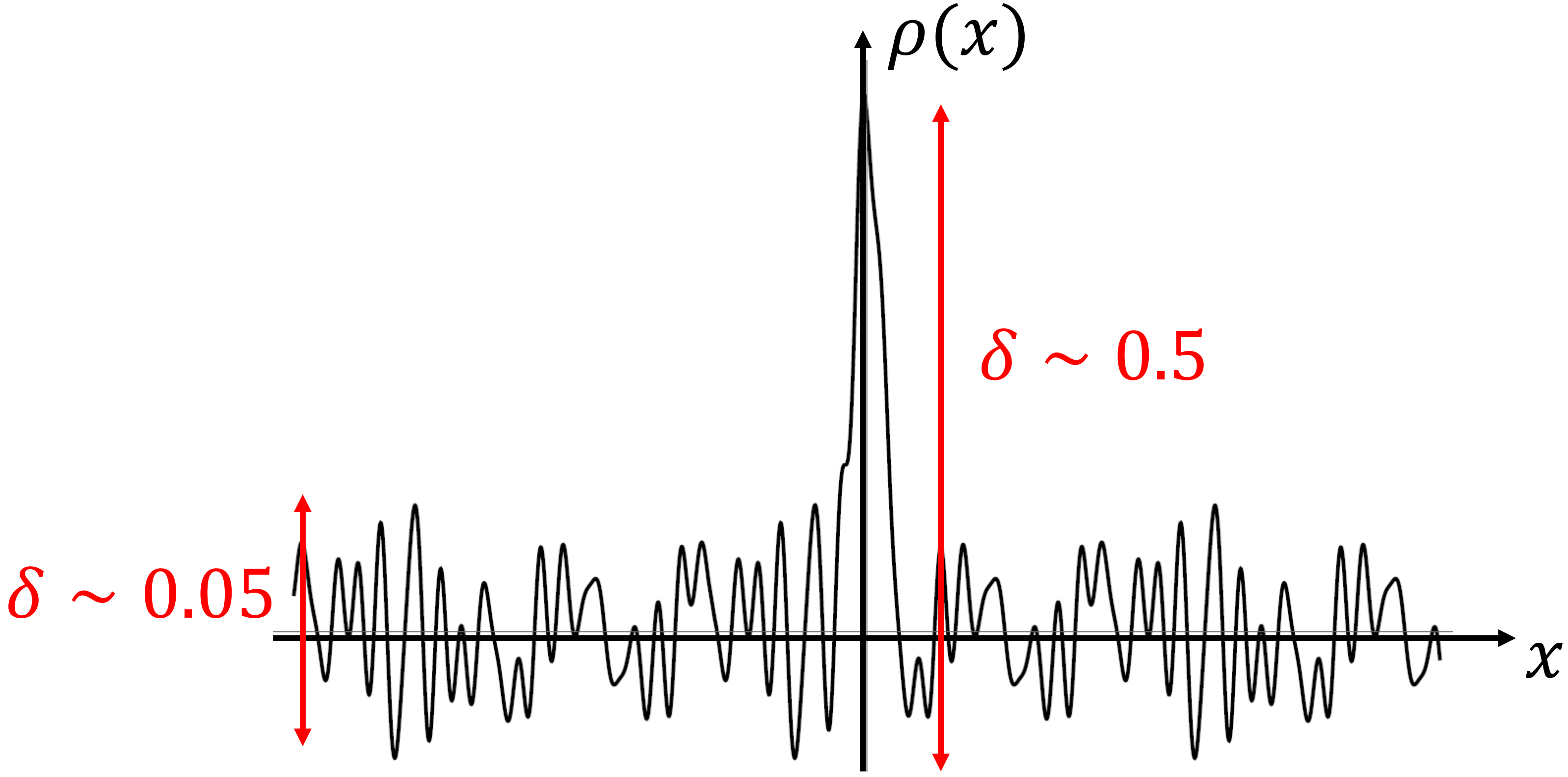


GW astronomy is already quite powerful to probe stellar-mass PBHs.

GWs as a probe of small PBHs

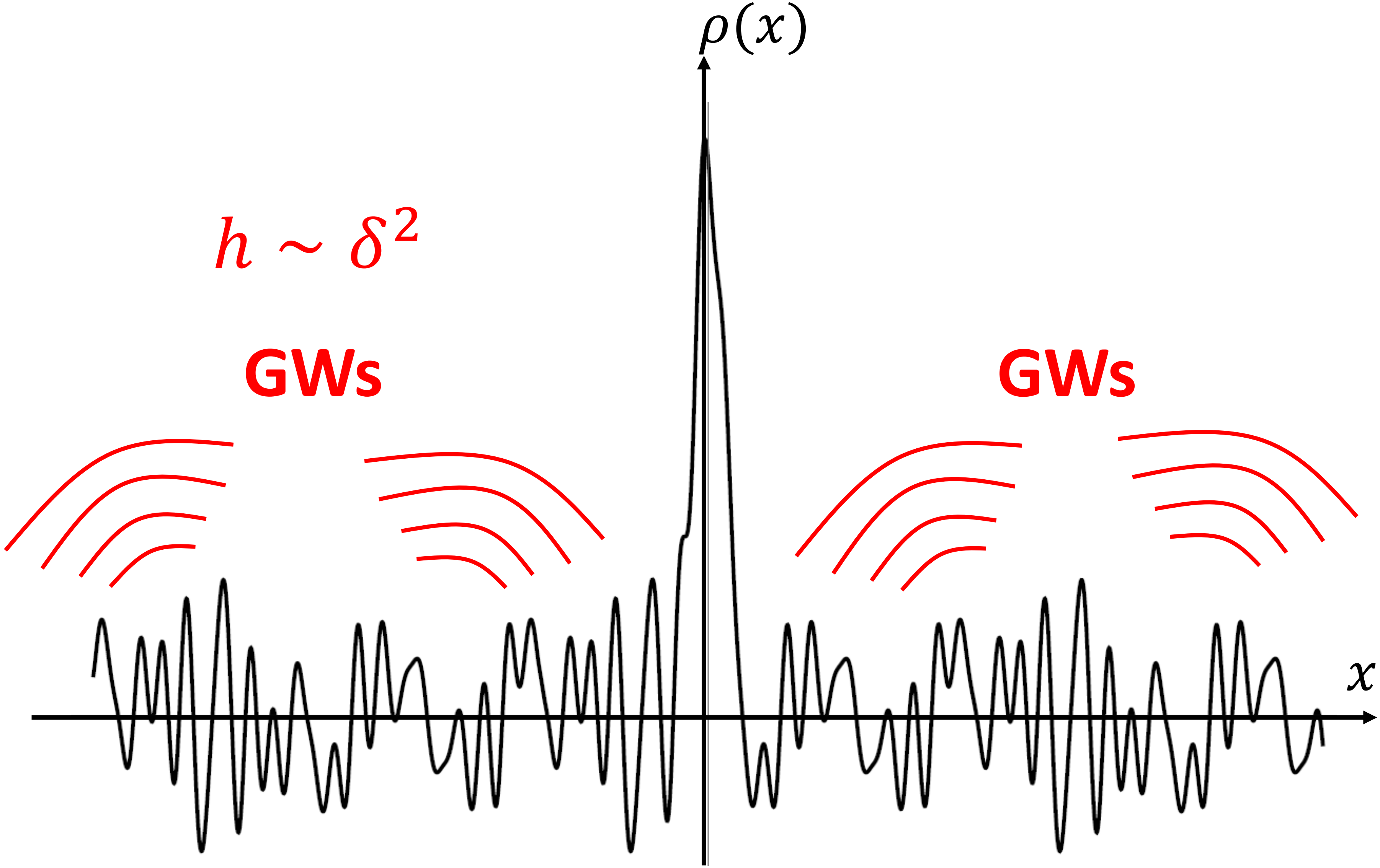
Saito, Yokoyama 2008

($10^{17}\mathrm{g} - 10^{19}\mathrm{g}, 10^{20}\mathrm{g} - 10^{22}\mathrm{g}$)



PBHs form only at high-σ.

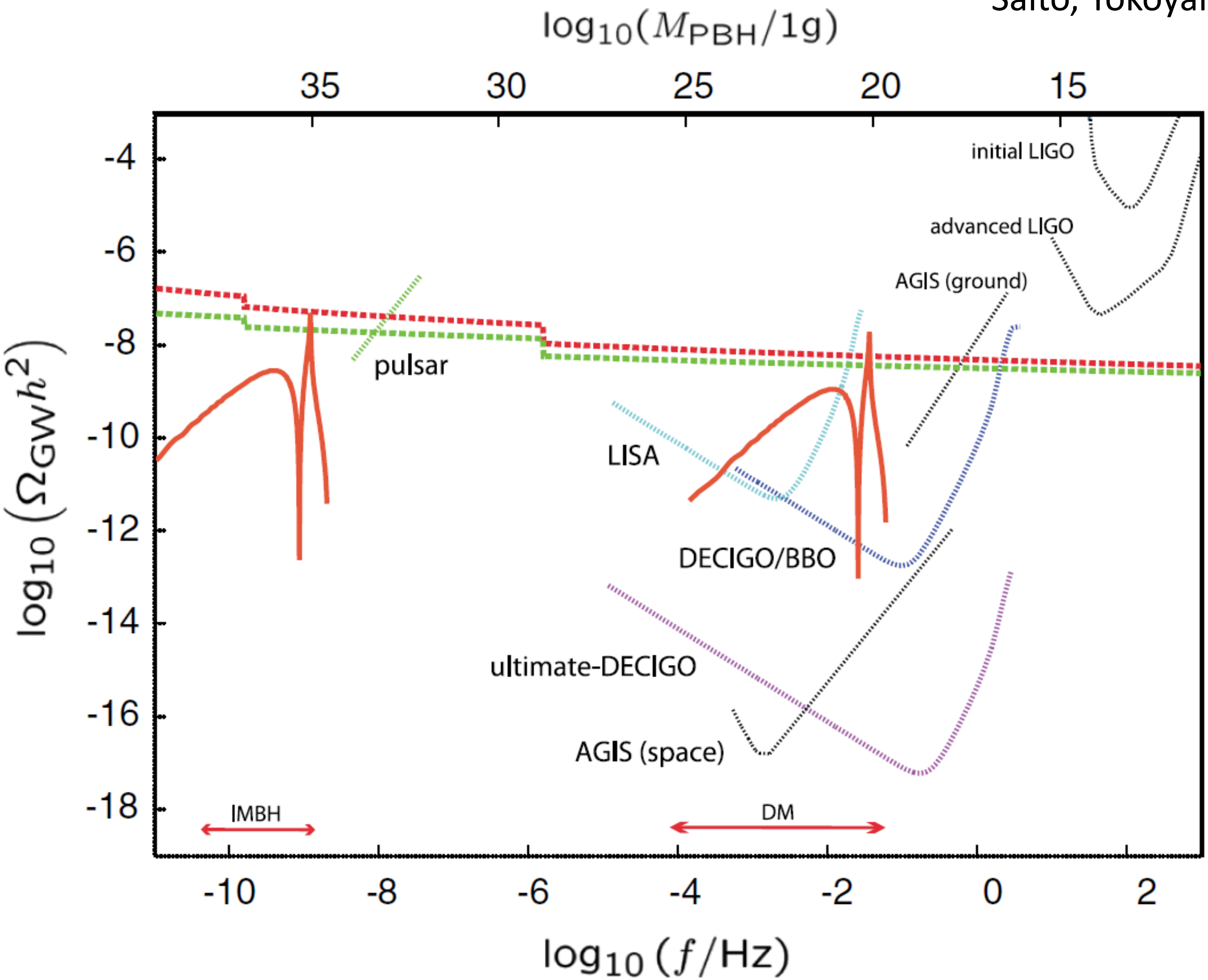
Density perturbations at other sites are still relatively large.



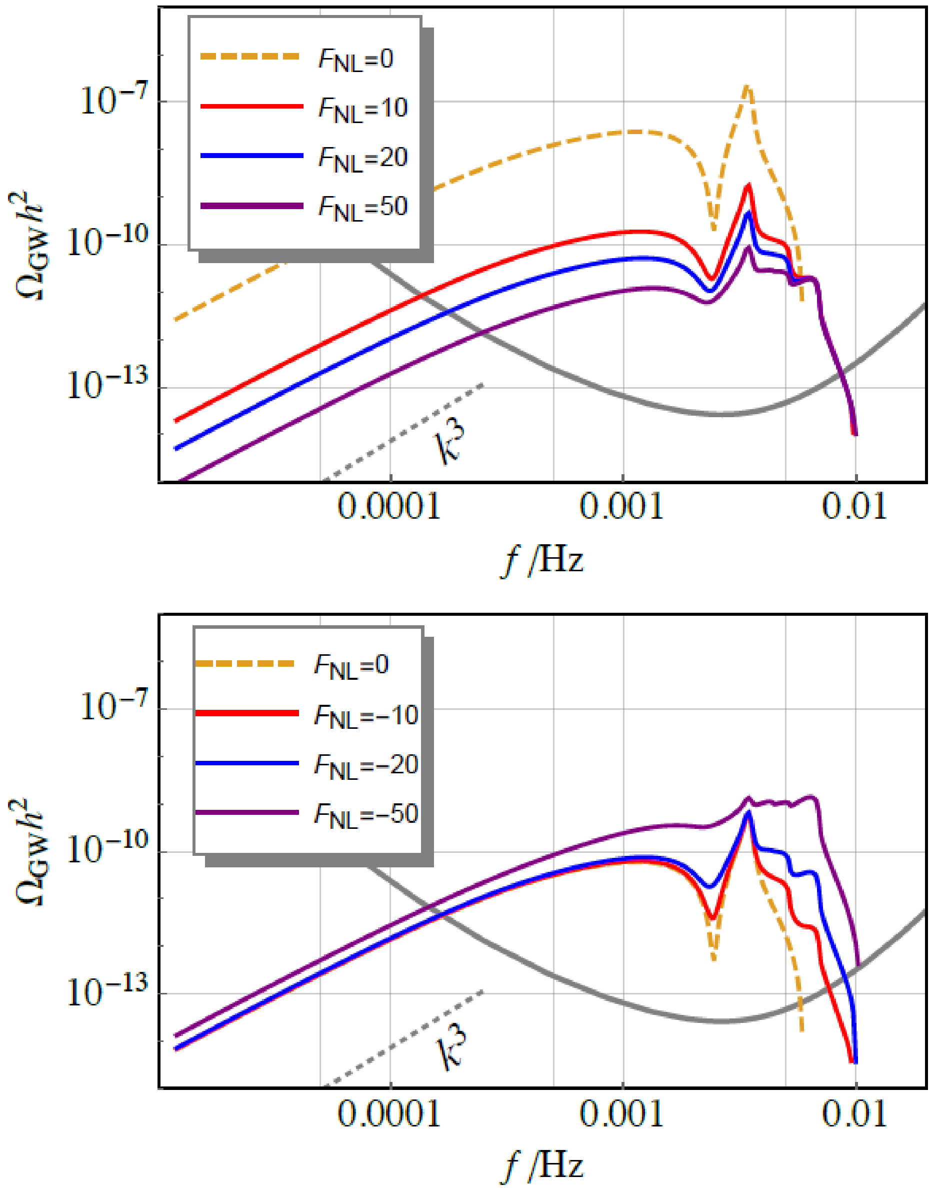
Stochastic GWs are generated.

$$f_{\rm GW} = 0.03 \ {\rm Hz} \left(\frac{M_{\rm PBH}}{10^{20} \ {\rm g}}\right)^{-1/2} \left(\frac{g_{*p}}{106.75}\right)^{-1/12}$$

Saito, Yokoyama 2008



LISA/DECIGO can test the PBH DM scenario!



Cai, Pi, Sasaki 2018

LISA/DECIGO can test the PBH DM scenario even when the perturbations are non-Gaussian!

Summary

GW astronomy has just begun.

GW astronomy will bring us new information about PBHs.

LIGO might have detected PBHs for the first time.