Gravitational Wave Production right after a Primordial Black Hole Evaporation

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Based on PRD 101, 123533 (2020) (arXiv: 2003.10455)

Collaborators:

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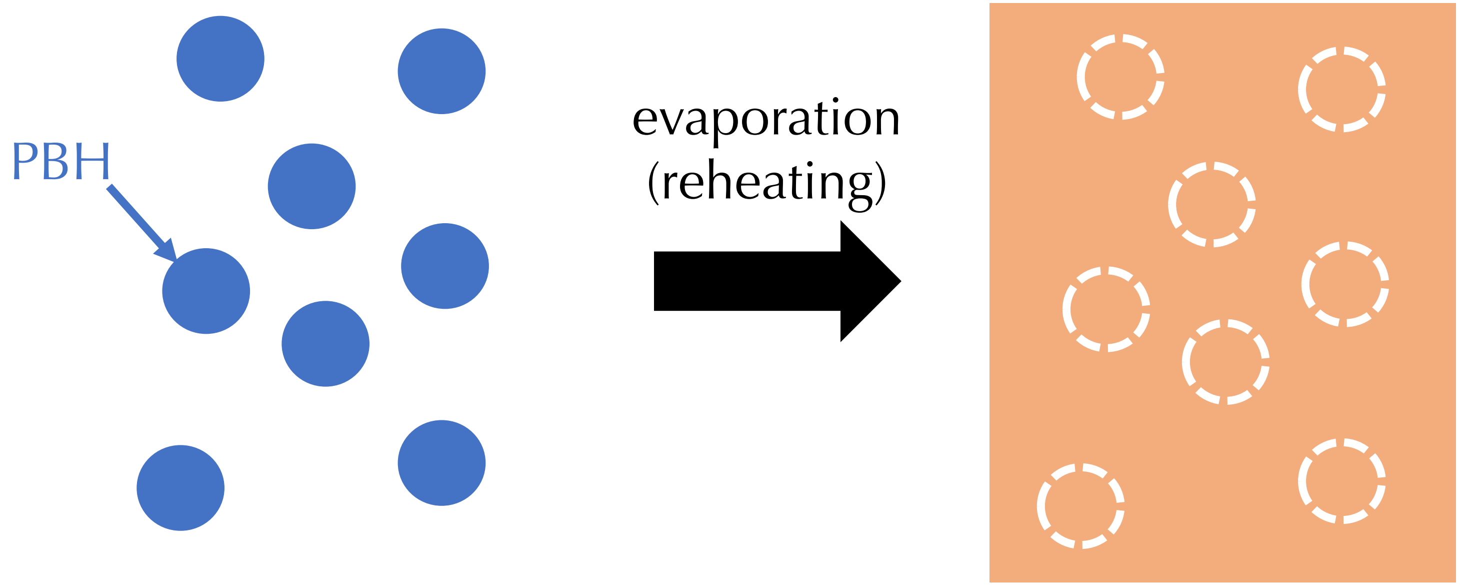
Overview of this talk

We show that large gravitational waves (GWs) can be produced right after PBH evaporation.



PBH dominated era
(early matter dominated era)

radiation dominated era

Evaporation of PBHs becomes faster as time goes by.

➡ sudden reheating ➡ **large GWs produced!**

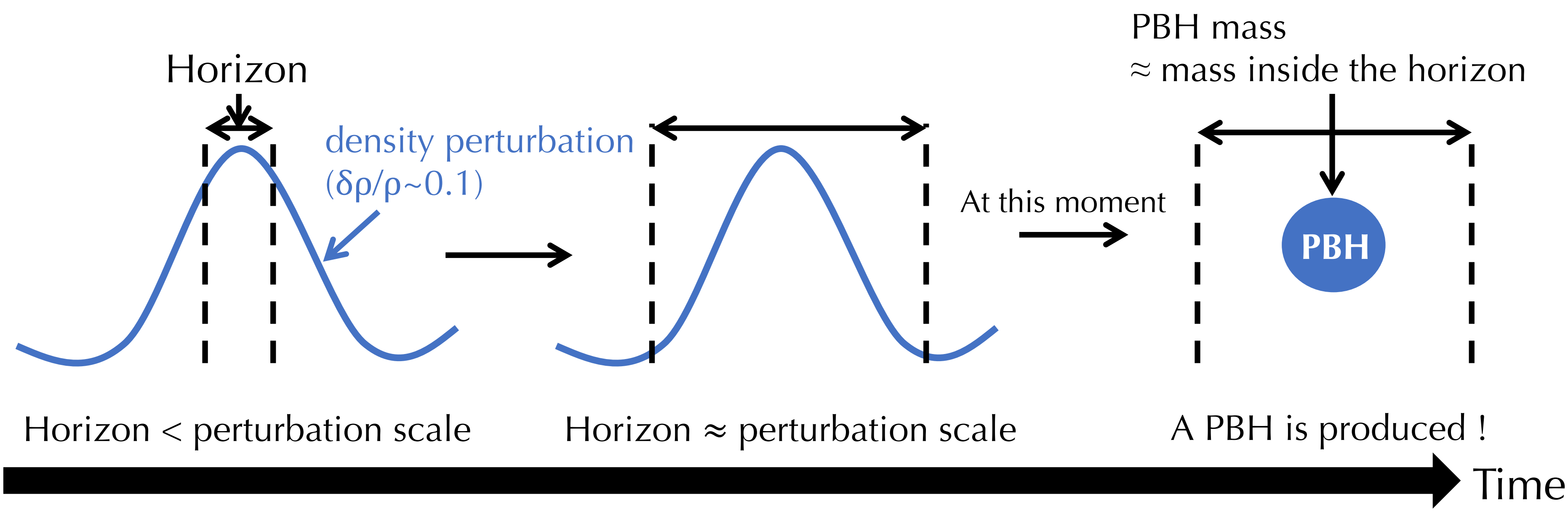
Outline of this talk

- Introduction of tiny PBHs
- GWs produced right after the evaporation
- Summary

Primordial Black Hole (PBH)

Primordial Black Hole (PBH) (Hawking 1971)

BH produced by a large density perturbation in the early Universe.



PBH can have a variety of masses:

$M_{PBH} \sim 30\ M_\odot$: PBHs for the LIGO-Virgo events

$M_{PBH} \sim 10^{20}$g : dark matter PBHs

$M_{PBH} \lesssim 10^{15}$g : PBHs that disappear by now through the Hawking evaporation

Scenario we consider

Inflation era

Reheating (inflaton decay)

Early radiation dominated (eRD) era

PBHs are produced

PBH dominated era (= early matter dominated era)

Reheating (PBH evaporation)

Radiation dominated (RD) era

(Late) matter dominated era (from z~3400)

Dark energy dominated era (from z~0.5)

Tiny PBHs

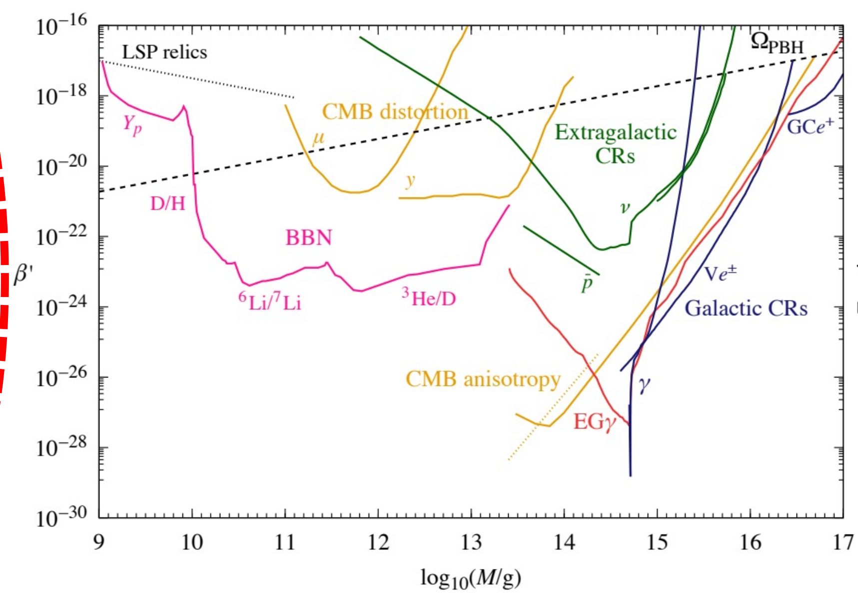
Mass of the PBHs dominating the universe must be $M_{\rm PBH} < \mathcal{O}(10^9)\,{\rm g}$

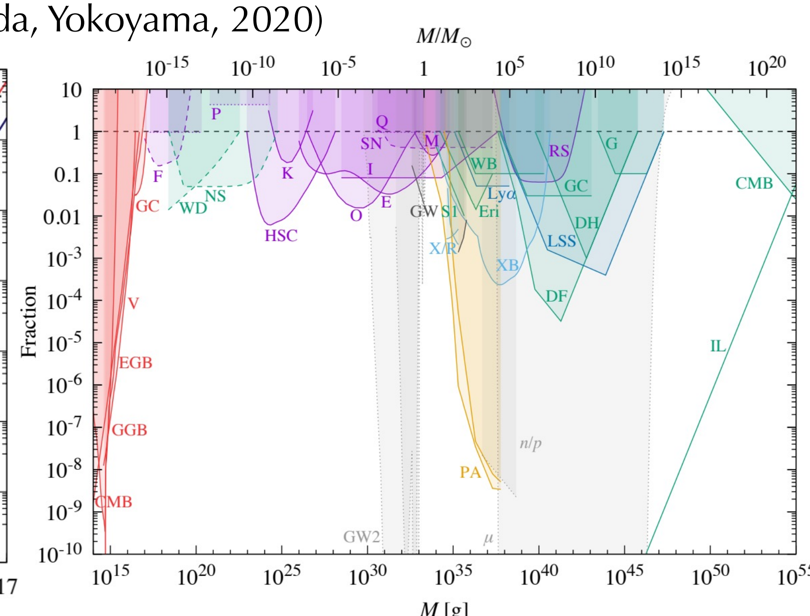
Because

Evaporation of the PBHs must finish before BBN.
Otherwise, the light elements are destroyed by the Hawking rad.

We focus on this range!

(Carr, Kohri, Sendouda, Yokoyama, 2020)





light PBH mass heavy

Motivations for tiny PBHs

Baryogenesis

Hawking evaporation can produce the right-handed neutrinos, whose non-thermal decay results in the leptogenesis. (e.g. Baumann, Steinhardt, Turok, 2007)

Relax Hubble tension

Hawking evaporation can produce dark radiation, which can relax the Hubble tension. (e.g. Hooper, Krnjaic, McDermott, 2019)

Predicted in some inflation models

Hybrid inflation model:
Mild water fall phase at the final stage of inflation can enhance perturbations.
(e.g. Garcia-Bellido, Linde, Wands, 1996)

Coupling between inflaton and gauge field:
Roll down of inflaton enhances the gauge field perturbations, which produce large scalar perturbations. (e.g. Linde, Mooij, Pajer, 2012)

What we do in this work

Scenario

Inflation era

Reheating (inflaton decay)

Early radiation dominated (eRD) era

tiny PBHs are produced

PBH dominated era (= early matter dominated era)

Reheating (PBH evaporation)

GW production!!

Radiation dominated (RD) era

We show large GWs can be produced right after the evaporation of the tiny PBHs.

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- <u>GWs produced right after the evaporation</u>
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GWs induced by scalar perturbations (Tomita 1967)

Scalar perturbations (related to curvature perturbations)

Metric perturbations:

$$ds^2 = a^2\left[-(1+2\Phi)d\eta^2 + \left((1-2\Phi)\delta_{ij} + \frac{1}{2}h_{ij}\right)dx^i dx^j\right]$$

Tensor perturbations (GWs)

$h^i_i = 0$

$\partial_i h^i_j = 0$

Einstein equation:

$$G_{\mu\nu} = \frac{1}{M_{\rm Pl}^2}T_{\mu\nu}$$

$$G^i_j = a^{-2}\left[\frac{1}{4}(h^{i\prime\prime}_j + 2\mathcal{H}h^{i\prime}_j - \Delta h^i_j) + 4\Phi\partial^i\partial_j\Phi + 2\partial^i\Phi\partial_j\Phi + A^i_j\right]$$

$$T^i_j = (\rho + P)\delta u^{,i}\delta u_{,j} + (P + \delta P)\delta^i_j$$

Terms irrelevant to tensor perturbations

E.o.m. for tensor perturbations:

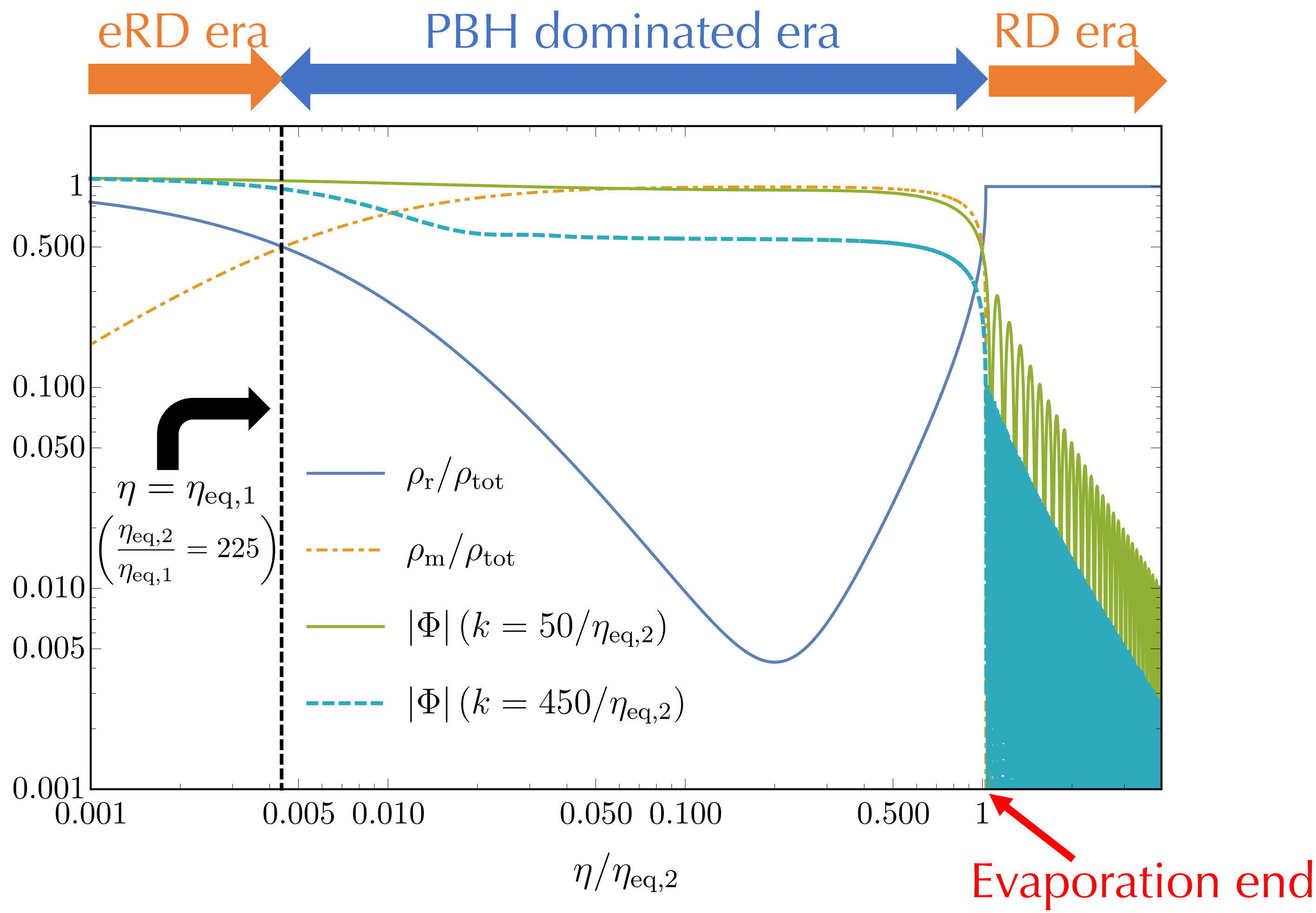
$$h''_{ij} + 2\mathcal{H}h'_{ij} - \Delta h_{ij} = -4\hat{\mathcal{T}}_{ij}^{\;\;lm}\mathcal{S}_{lm}$$

$\hat{\mathcal{T}}_{ij}^{\;\;lm}$: Projection operator onto the transverse and traceless tensor

$$S_{ij} \equiv 4\Phi\partial_i\partial_j\Phi + 2\partial_i\Phi\partial_j\Phi - \frac{4}{3(1+w)\mathcal{H}^2}\partial_i(\Phi' + \mathcal{H}\Phi)\partial_j(\Phi' + \mathcal{H}\Phi) \qquad (w = P/\rho)$$

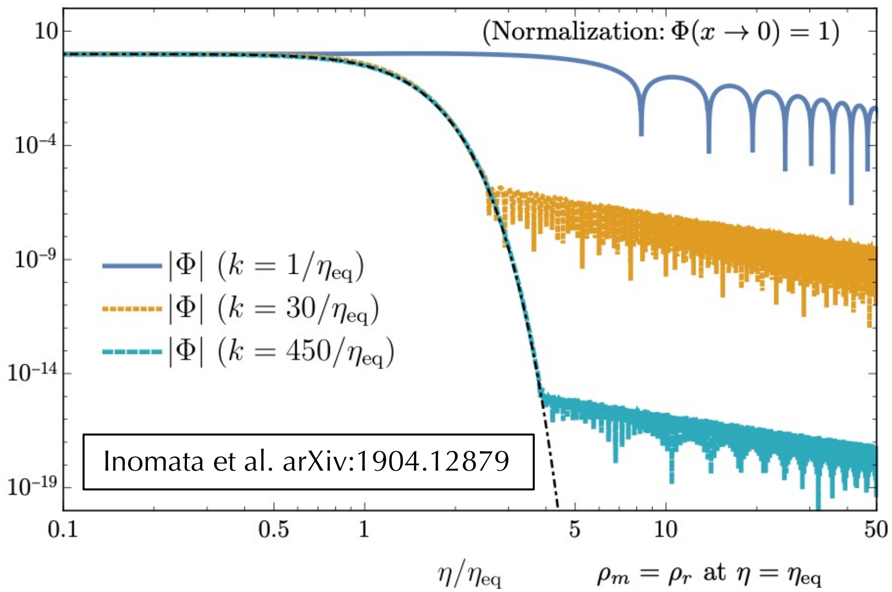
Point Scalar perturbations can induce GWs at second order.

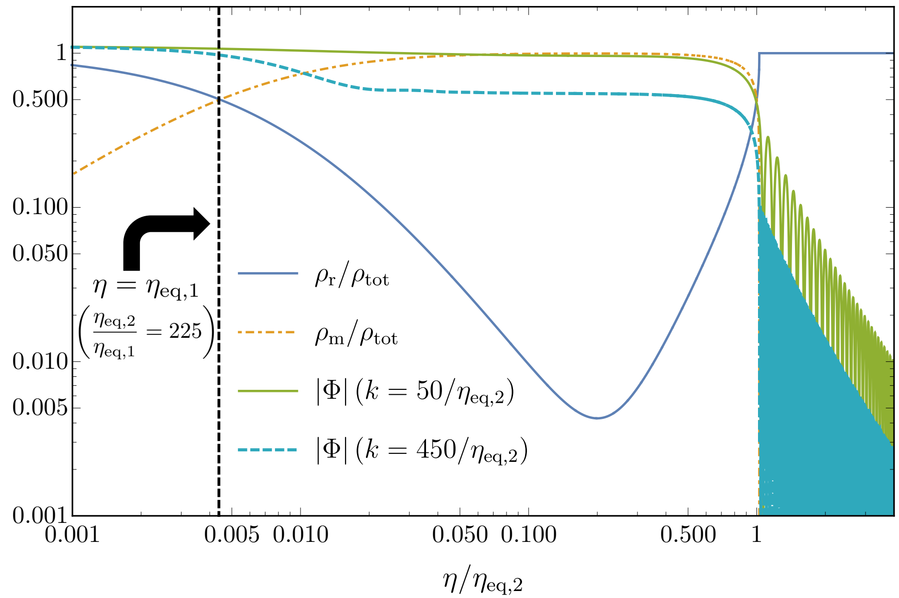
Scalar perturbation evolution



Gravitational potential oscillates rapidly soon after the evaporation.

Comparison with a gradual reheating





$$\Gamma = \text{const.}$$

(perturbative decay of inflaton)

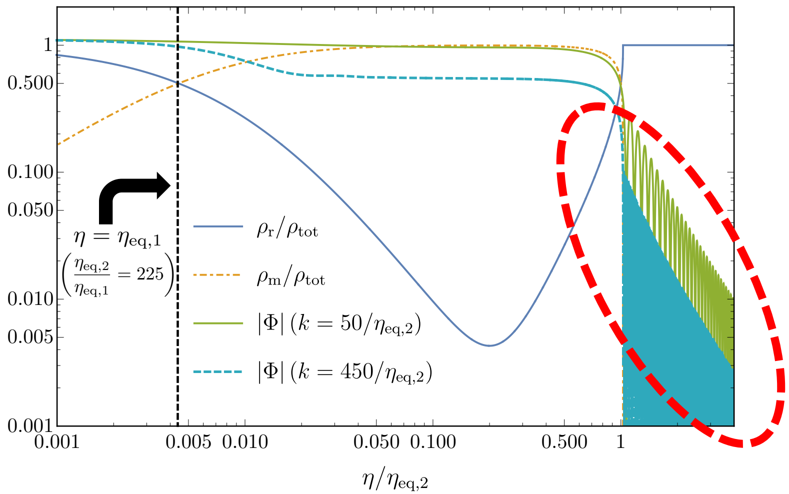
$$\Gamma \propto M_{\rm PBH}^{-3} \propto (t_{\rm eva} - t)^{-1}$$

(PBH evaporation)

During the reheating, the fluid deviates from the perfect fluid because PBHs and emitted radiation are not strongly coupled.

→ The short reheating period leads to the unsuppressed amplitudes.

Why are large GWs produced?



The rapid oscillation is the main source for the GW production.

E.o.m. for tensor perturbations: $h''_{ij} + 2\mathcal{H}h'_{ij} - \Delta h_{ij} = -4\hat{\mathcal{T}}_{ij}{}^{lm}\mathcal{S}_{lm}$

$$S_{ij} \equiv 4\Phi\partial_i\partial_j\Phi + 2\partial_i\Phi\partial_j\Phi - \frac{4}{3(1+w)\mathcal{H}^2}\partial_i(\Phi' + \mathcal{H}\Phi)\partial_j(\Phi' + \mathcal{H}\Phi)$$

$$\mathcal{H}^{-2}(\Phi')^2 \sim (k\eta)^2\Phi^2$$

oscillation time scale is ~1/k

kη >> 1 for rapid oscillation

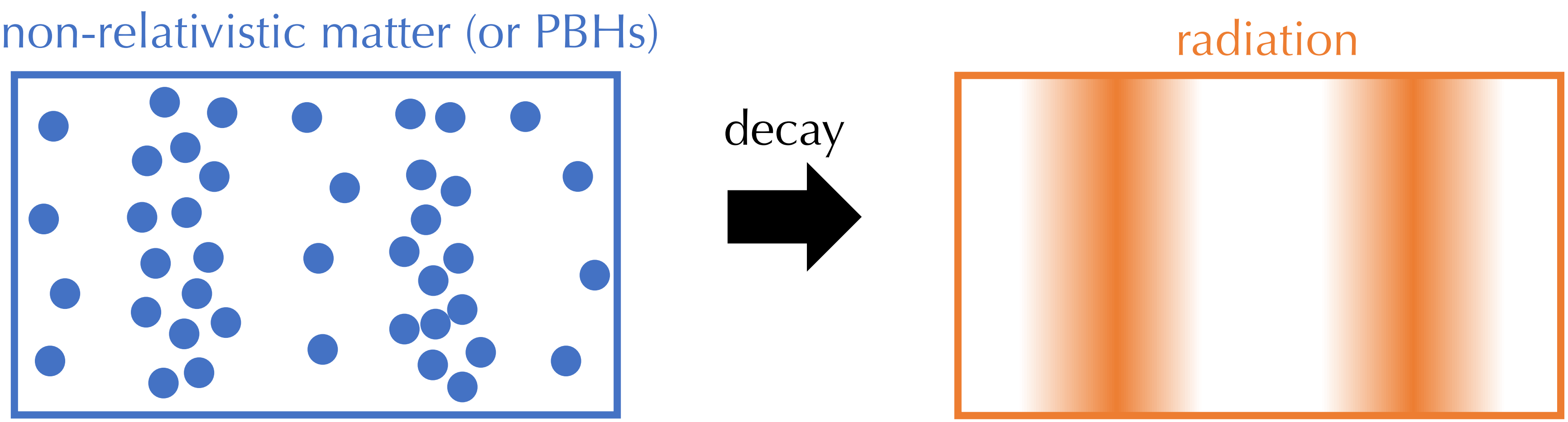
Large GWs are produced !

Poltergeist mechanism

Logo (credit: Takahiro Terada)

Poltergeist
mechanism for gravitational wave production

We name this enhancement mechanism the "Poltergeist mechanism".



After the decay, "ghosts" of the non-relativistic matter "make a noise" in the thermal bath.

"ghosts" = produced radiation,
"make a noise" = oscillation of radiation sound wave

Then, large GWs are produced !

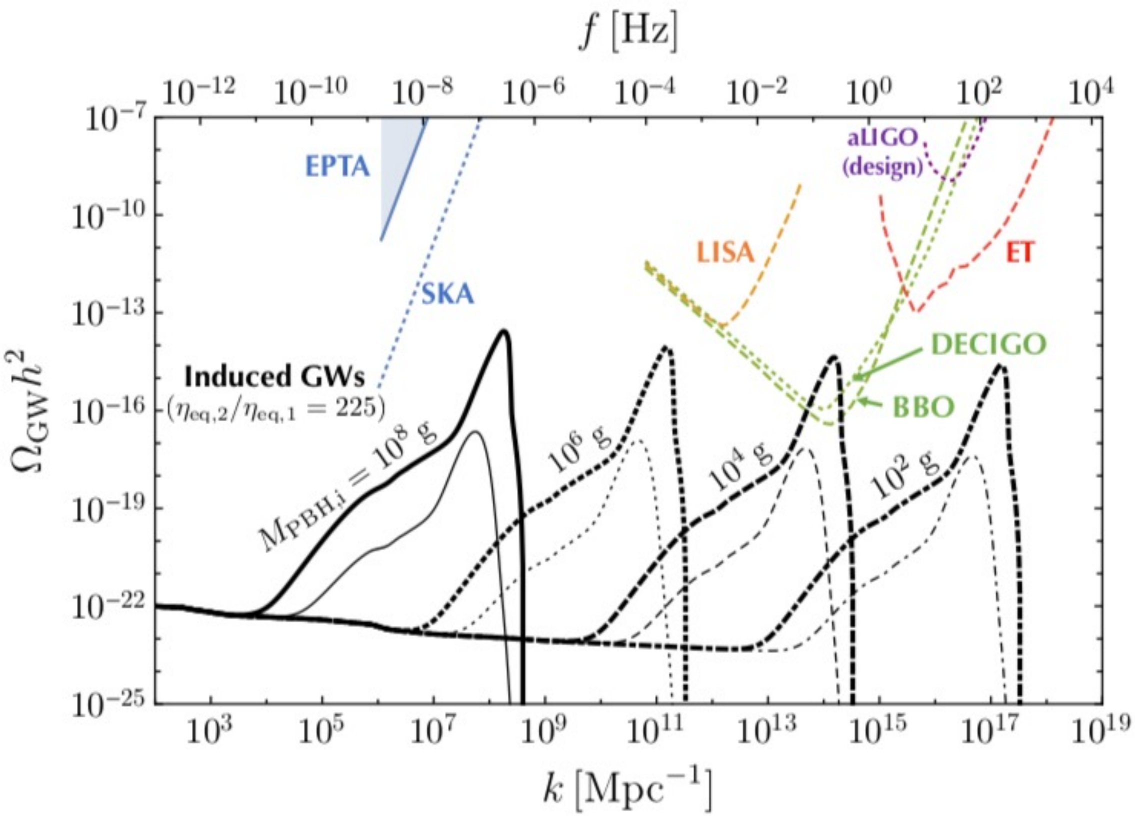
GW spectrum

We consider the following power spectrum of curvature perturbations.

$$\mathcal{P}_\zeta(k) = \Theta(k_{\rm NL} - k) A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

$(A_s = 2.1 \times 10^{-9}, n_s = 0.96)$

$k_{\rm NL}$ corresponds to the scale where the matter perturbation become non-linear at the evaporation.



Length of PBH dominated era is fixed.

Thick: monochromatic mass function

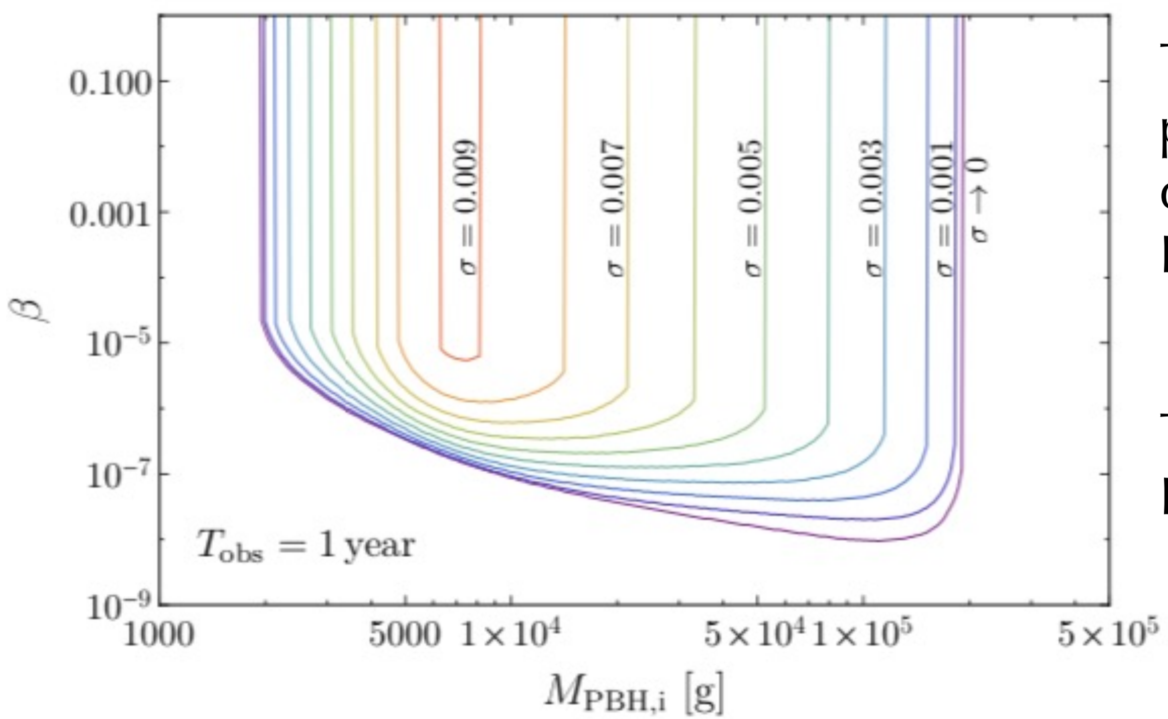
Thin: finite-width mass function $(\sigma = 0.01)$

$$\rho_{\rm PBH,i}(M_{\rm PBH,i}) = \frac{\rho_{\rm PBH,i}}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(\ln(M_{\rm PBH,i}/M_{\rm PBH,i0}))^2}{2\sigma^2}\right)$$

PBH abundance constraints

The GW spectrum depends on the PBH mass and the length of PBH dominated era, which is determined by the initial fraction of PBHs.

$$\beta = \left. \frac{\rho_{\rm PBH}}{\rho_{\rm tot}} \right|_{t=t_{\rm form}}$$



The regions above lines predict the enhanced GWs detectable by DECIGO or BBO.

The abundance of the tiny PBHs could be constrained!

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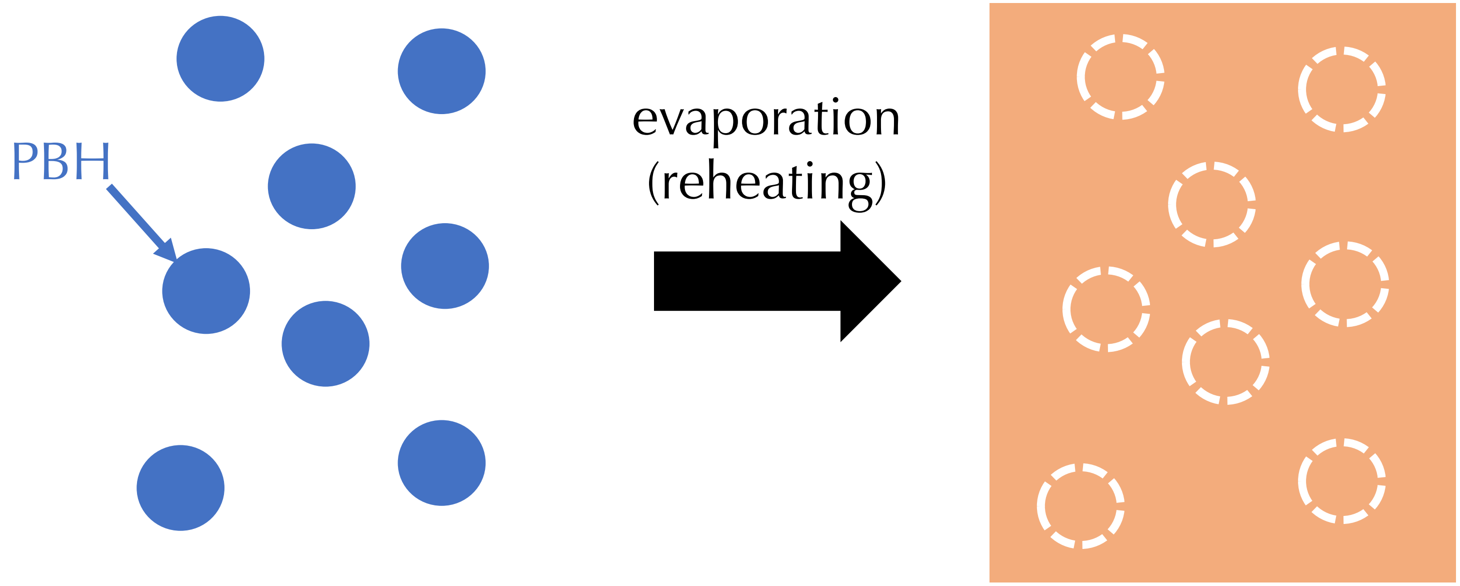
Summary of this talk

We have shown that large GWs can be produced right after PBH evaporation.



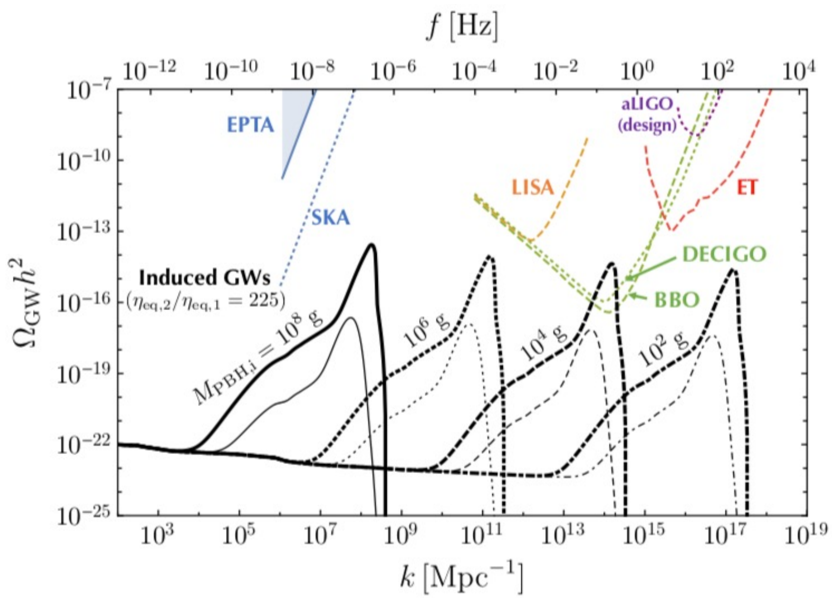
PBH dominated era
(early matter dominated era)

radiation dominated era

Evaporation of PBHs becomes faster as time goes by.

→ sudden reheating → **large GWs produced!**

Result summary



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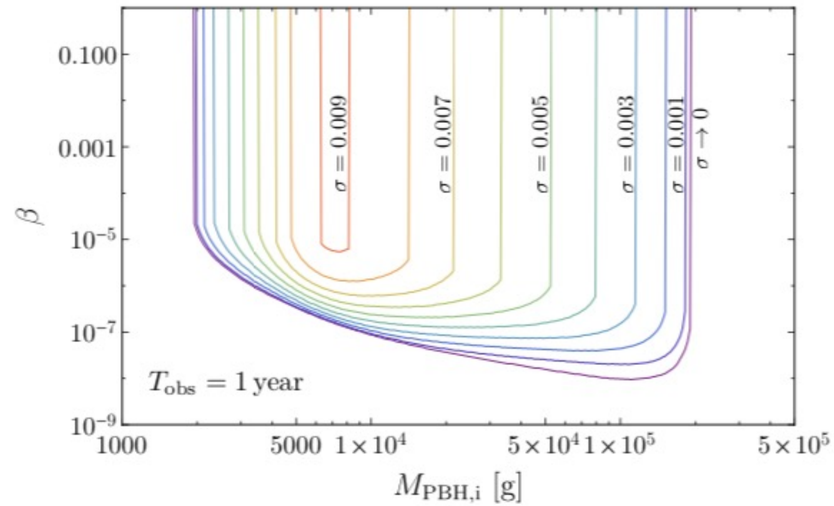
The near future observations could investigate the abundance of the tiny PBHs!



See also follow-up works:
Domenech, Takhistov, Sasaki, 2105.06816
White et al., 2105.11655