# Formations and evolutions of PBHs in the matter-dominated Universe

Kaz Kohri

和範

## KEK / Sokendai / Kavli IPMU



## Why PBHs?

# LIGO and Virgo have detected gravitational wave signals from Binary Black Holes

https://www.youtube.com/watch?v=1agm33iEAuo



#### GW150914 and its merger rates for 30 M<sub>solar</sub> masses BBH

M. Sasaki, T. Suyama, T. Tanaka and S. Yokoyama (2016).



## Upper bounds on the fraction to CDM Carr, Kohri, Sendouda, J.Yokoyama (2009)(2019)





#### Evaporating PBHs through Hawking Process



# DECIGO discriminates BPBHs from the normal BBHs

Takashi Nakamura et al, arXiv:1607.00897 [astro-ph.HE]



Primordial Black Hole (PBH)

 Large perturbation at small scales was produced by Inflation at around
 > 10<sup>-36</sup> second



# Conditions for a PBH formation in Radiation dominated (RD) Universe

Zel'dovich and Novikov (1967), Hawking (1971), Carr (1975)

Harada, Yoo and KK (2013)

Gravity could be stronger than pressure



## $P_{\zeta}$ (k) and PBH abundance $\beta(M)$

• Fraction of PBH to the total with Gaussian Statistics

For Peak Statistics, e.g., see Yoo, Harada, Garriga, Kohri, 2018

$$\beta(M) \equiv \frac{\rho_{\rm PBH}(M)}{\rho_{\rm tot}} = 2 \int_{\delta_{\rm th}}^{\infty} d\delta \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{\delta^2}{2\sigma^2}\right) = \operatorname{erfc}\left(\frac{\delta_{\rm th}}{\sqrt{2\sigma}}\right)$$

• Relation between  $\beta$  and fluctuation  $\sigma$  (or  $\beta$  and  $\Omega)$ 

$$\beta(\mathcal{M}) \sim \operatorname{erfc}\left(\frac{\delta_{\mathrm{th}}}{\sqrt{2}\sigma}\right) \simeq \sqrt{\frac{2}{\pi}} \frac{\sigma}{\delta_{\mathrm{th}}} \exp\left(-\frac{\delta_{\mathrm{th}}^2}{2\sigma^2}\right)$$
$$= 1.5 \times 10^{-18} \left(\frac{m_{\mathrm{PBH}}}{10^{15} \,\mathrm{g}}\right)^{1/2} \left(\frac{\Omega_{\mathrm{PBH}}h^2}{0.1}\right) \sim P_{\zeta}$$

 $\beta = \rho_{\text{PBH}} / \rho_{\text{tot}} \text{ vs } M_{\text{PBH}}$ 

Carr, Kohri, Sendouda, J.Yokoyama (2019) in preparation



#### Typical quantities of PBHs in RD

• Mass (horizon mass = $\rho(t_{form}) H(t_{form})^{-3}$ )

$$M_{\text{PBH}} \sim M_{p/}^2 t_{\text{from}} \sim \frac{M_{p/}^3}{T_{\text{form}}^2} \sim 10^{15} g \left(\frac{T_{\text{form}}}{3 \times 10^8 \text{GeV}}\right)^{-2} \sim 30 M_{\odot} \left(\frac{T_{\text{form}}}{40 \text{MeV}}\right)^{-2}$$

• Lifetime

$$\tau_{_{\mathrm{PBH}}} \sim \frac{\mathcal{M}_{_{\mathrm{PBH}}}^3}{\mathcal{M}_{_{p/}}^4} \sim 4 \times 10^{17} \sec\left(\frac{\mathcal{M}_{_{\mathrm{PBH}}}}{10^{15} \,\mathrm{g}}\right)^3 \sim 3 \times 10^{68} \,\mathrm{yrs}\left(\frac{\mathcal{M}_{_{\mathrm{PBH}}}}{30 \,\mathrm{M}_{_{\odot}}}\right)^3$$

• Hawking Temperature

$$T_{PBH} \sim \frac{M_{pl}^2}{M_{PBH}} \sim 0.1 \text{MeV} \left(\frac{M_{PBH}}{10^{15} g}\right)^{-1} \sim 3 \times 10^{-11} K \left(\frac{M_{PBH}}{30 M_{\odot}}\right)^{-1}$$

• Fraction to CDM

$$f_{\text{fraction}} \equiv \frac{\Omega_{\text{PBH}}}{\Omega_{\text{CDM}}} \sim \left(\frac{\beta}{10^{-18}}\right) \left(\frac{M_{\text{PBH}}}{10^{15} g}\right)^{-1/2} \sim \left(\frac{\beta}{10^{-8}}\right) \left(\frac{M_{\text{PBH}}}{30M_{\odot}}\right)^{-1/2} \sim 10^8 \left(\frac{M_{\text{PBH}}}{30M_{\odot}}\right)^{-1/2} \sqrt{P_{\delta}} \exp\left[-\frac{1}{18P_{\delta}}\right]$$

#### Features of PBH formations in RD

• Spherical due to radiation pressure



 $(w\equiv p\,/\,\rho\sim 1\,/\,3)$ 

• Negligible evolutions of density perturbations

• Quite a small angular momentum

See, T.Chiba and S.Yokoyama, 2017 De Luca et al, 2019

#### Cosmic history of energy density

a=a(t): scale factor



#### PBH formation at the (early) matter dominated (MD) Universe Polnarev and Khlopov (1982)

Harada, Yoo, KK, Nakao, Jhingan (2016)

 Pressure is negligible, which could induce an immediate collapse and producing more PBHs?

2. Density perturbations can evolve, which produces non-spherical objects and cannot be enclosed by the Horizon. That means less PBHs can be produced?

#### Matter Domination

• Three radius in Lagrangian coordinate q<sub>i</sub>

 $r_1 = (a - lpha b)q_1$  Zel'dovich Approximation  $r_2 = (a - eta b)q_2$  $r_3 = (a - \gamma b)q_3$ 

- Eccentricity  $e^2 = 1 \left(\frac{r_2(t_c)}{r_3(t_c)}\right)^2 = 1 \left(\frac{\alpha \beta}{\alpha \gamma}\right)^2$
- Hoop with 2<sup>nd</sup> Elliptic function E(x)  $C = 16 \left(1 - \frac{\gamma}{\alpha}\right) E \left(\sqrt{1 - \left(\frac{\alpha - \beta}{\alpha - \gamma}\right)^2}\right) r_f$
- Hoop conjecture for PBH production

 $C \leq 2\pi r_g$ .

#### Abundance of PBHs formed in MD

Probability distribution by peak statistics (BBKS)
 Doroshkevich (1970)

$$w(\alpha,\beta,\gamma)d\alpha d\beta d\gamma$$

$$= -\frac{27}{8\sqrt{5}\pi\sigma_3^6} \exp\left[-\frac{1}{10\sigma_3^2}(\alpha+\beta+\gamma)^2 - \frac{1}{4\sigma_3^2}\{(\alpha-\beta)^2 + (\beta-\gamma)^2 + (\gamma-\alpha)^2\}\right]$$

$$\cdot (\alpha-\beta)(\beta-\gamma)(\gamma-\alpha)d\alpha d\beta d\gamma.$$

$$\sigma_H = \sqrt{5}\sigma_3$$

• Probability

$$\begin{split} \beta_0 &= \int_0^\infty d\alpha \int_{-\infty}^\alpha d\beta \int_{-\infty}^\beta d\gamma \; \theta(1 - h(\alpha, \beta, \gamma)) w(\alpha, \beta, \gamma) \\ h(\alpha, \beta, \gamma) &= \frac{2}{\pi} \frac{\alpha - \gamma}{\alpha^2} E\left(\sqrt{1 - \left(\frac{\alpha - \beta}{\alpha - \gamma}\right)^2}\right) \\ h(\alpha, \beta, \gamma) &:= \mathcal{C}/(2\pi r_g) \end{split}$$

#### Angular momentum produced by perturbations

Harada, Yoo, KK, nad Nakao (2017)

• Angular momentum

$$\mathbf{L}_{c} = \int_{a^{3}V} \rho \mathbf{r} \times \mathbf{v} d^{3}\mathbf{r} = \rho_{0}a^{4} \left( \int_{V} \mathbf{x} \times \mathbf{u} d^{3}\mathbf{x} + \int_{V} \mathbf{x} \delta \times \mathbf{u} d^{3}\mathbf{x} \right)$$

$$= \mathsf{Dencity porturbation} \delta^{1^{\text{st}} \text{ order effects}} 2^{\text{nd}} \text{ order effects}$$

- Density perturbation δ<sup>1</sup>
- (Peculiar) Velocity perturbation  $\mathbf{u} := aD\mathbf{x}/Dt$

$$\mathbf{u}_1 = -\frac{t}{a} \nabla \psi_1$$

 $\psi := \Psi - \Psi_0$ 

• Potential perturbation

#### Effects by finite angular momentum

Harada, Yoo, KK, Nakao (2017)

• Probability distribution

$$a_* := L/(GM^2/c)$$
  
$$f_{\text{BH}(2)}(a_*)da_* \propto \frac{1}{a_*^{5/3}} \exp\left(-\frac{1}{2\sigma_H^{2/3}} \left(\frac{2}{5}\mathcal{I}\right)^{4/3} \frac{1}{a_*^{4/3}}\right) da_*$$

• Probability

 $\beta_0 \simeq \int_0^\infty d\alpha \int_{-\infty}^\alpha d\beta \int_{-\infty}^\beta d\gamma \theta [\delta_H(\alpha,\beta,\gamma) - \delta_{\rm th}] \theta [1 - h(\alpha,\beta,\gamma)] w(\alpha,\beta,\gamma)$ 

$$\delta_{H}(lpha,eta,\gamma) = lpha + eta + \gamma \qquad \delta_{ ext{th}} \quad := \left(rac{2}{5}\mathcal{I}\sigma_{H}
ight)^{2/3}$$

#### Spin distribution

More highly-spinning halos cannot collapse into PBHs, which means that the PBHs produced tend to have high spins in MD Harada, Yoo, KK, Nakao (2017)



#### Beta in matter-domination

Harada, Yoo, KK, Nakao (2017)



### Simple parameterization of running of spectral indexes of curvature perturbation

KK and T.Terada, 2018

$$P_{\zeta}(k) = A_{\rm s} \left(\frac{k}{k_*}\right)^{n_{\rm s}-1+\frac{\alpha_{\rm s}}{2}\ln\left(\frac{k}{k_*}\right)+\frac{\beta_{\rm s}}{6}\left(\ln\left(\frac{k}{k_*}\right)\right)^2$$



Amplitude of curvature perturbation

#### Upper bounds on curvature perturbation in MD



100% MD before reheating



#### LIGO/VIRGO event with 30 Msolar

KK and T.Terada, 2018





# CMB bound on PBHs by disk-accretion in the late MD epoch

Poulin, Serpico, Calore, Clesse, KK (2017)

 A non-spherical accretion disk (ADAF(slim) + Standard disk) around a PBH caused by an angular momentum emits radiation

$$\begin{split} \dot{M}_{\rm HB} &\equiv 4\pi\lambda\,\rho_{\infty}v_{\rm eff}r_{\rm HB}^2 \equiv 4\pi\lambda\,\rho_{\infty}\frac{(GM)^2}{v_{\rm eff}^3}\\ l &\simeq \omega\,r_{\rm HE}^2 \simeq \left(\frac{\delta\rho}{\rho} + \frac{\delta v}{v_{\rm eff}}\right)v_{\rm eff}r_{\rm HB} \end{split}$$

CMB anisotropies are affected



• From observations, we can constrain the number density of PBHs.

### An accretion disk around a black hole

Kohri, Mineshige, 2002 Kohri, Narayan, Piran, 2005

- Viscous heating process  $\Leftrightarrow$  Various cooling processes
  - i. Standard Accretion Disk (Standard Disk)
    - Radiative Cooling
  - ii. Advection Dominated Accretion Flow (ADAr)
    - Advective cooling (entropy going into BH) gives RIAF (optically thin) or Slim Disk (optically-thick)
  - iii. Convection Dominated Accretion Flow (CDAF)
    - Convective cooling
  - iv. Neutrino-Dominated Accretion Disk (NDAF)



Neutrino Cooling

V. ..

#### Modified CMB anisotropy

Poulin, Serpico, Calore, Clesse, Kohri (2017)



Luminosity

Ionization fraction

#### Modified CMB anisotropy

Poulin, Serpico, Calore, Clesse, Kohri (2017)



# CMB bound by disk-accretion in the latest MD epoch

Poulin, Serpico, Calore, Clesse, KK (2017)



### PBHs are clustering?

Matsubara, Terada, Kohri, S. Yokoyama, 1909.06048 See also, Suyama and S. Yokoyama (2019) See also Suyama's talk Tada and S.Yokoyama (2015)

![](_page_32_Figure_2.jpeg)

# Effects of Inhomogeneity on PBH formations in Matter Domination

T.Kokubu, K.Kyutoku, K.Kohri, T.Harada, arXiv:1810.03490

Singularity should be enclosed by (apparent) horizon

![](_page_33_Figure_3.jpeg)

# Higgs stabilization due to evaporating PBHs?

![](_page_34_Picture_1.jpeg)

• Potential with finite-temperature corrections

 $V_{\text{eff}}(\phi) \simeq \frac{1}{2} \left( \lambda_{\text{eff}} T_{\text{H}}^2 + \kappa^2 T_{\text{H}}^2 \right) \phi^2 + \frac{\lambda_{\text{eff}}}{4} \phi^4 \\ \phi_{\text{max}}^2 / T_{\text{H}}^2 \approx \mathcal{O}(10)$ 

• Probability to get over the potential

$$P(\phi > \phi_{\max}) \simeq \frac{\sqrt{2\langle \delta \phi^2 \rangle_{ren}}}{\pi \phi_{\max}} \exp\left(-\frac{\phi_{\max}^2}{2\langle \delta \phi^2 \rangle_{ren}}\right) \quad \left< \delta \phi^2 \right>_{ren} / T_{\rm H}^2 \simeq \mathcal{O}(0.1)$$
  
This gives,  
$$\phi_{\max}^2 / \left< \delta \phi^2 \right>_{rem} \sim 10^2$$

$$\mathcal{N}_{\text{PBH}} \cdot P(\phi > \phi_{\text{max}}) \lesssim 1$$
$$\beta \lesssim \mathcal{O}\left(10^{-21}\right) \left(\frac{m_{\text{PBH}}}{10^9 \text{g}}\right)^{3/2}$$

or

### Summary

- PBH can be formed at small scales even in both radiation and matter dominated epochs
- More PBHs can be produced in MD for  $\delta p/p \ll 1$
- We may detect gravitational wave signals secondarilyinduced by large SCALAR fluctuations at small scales by e.g. DECIGO/BBO ...
- We will be able to distinguish a model from others by using future small-scale probes such as PIXIE-like satellite (CMB µ-distortion), SKA/Ominiscope (21cm,Pulsar timing), CTA (gamma-ray), DECIGO/BBO (GW)...