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Primordial Black Holes in Matter Dominated Universe

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Why PBHs?

- We need 30 $M_\odot$ BHs to explain LIGO/VIRGO GW events
- We do not know the origin of 30 $M_\odot$ BHs to be astrophysical or cosmological.
- PBHs should be a good candidate for Cold Dark Matter (CDM), but we need to know the full cosmic history.
- Some inflation modes predict PBHs formed at small scales in the early Universe (before 1 sec)
- Scenarios have been constrained by BBN, CMB anisotropies, lensing、gamma-ray, and so on. Carr, Kohri, Sendouda, J.Yokoyama (2010)
- In future, scenarios can be investigated further by PIXIE (CMB μ-distortion), SKA/Ominiscope (21cm), CTA (gamma-ray), DECIGO (Gravitational Wave), …

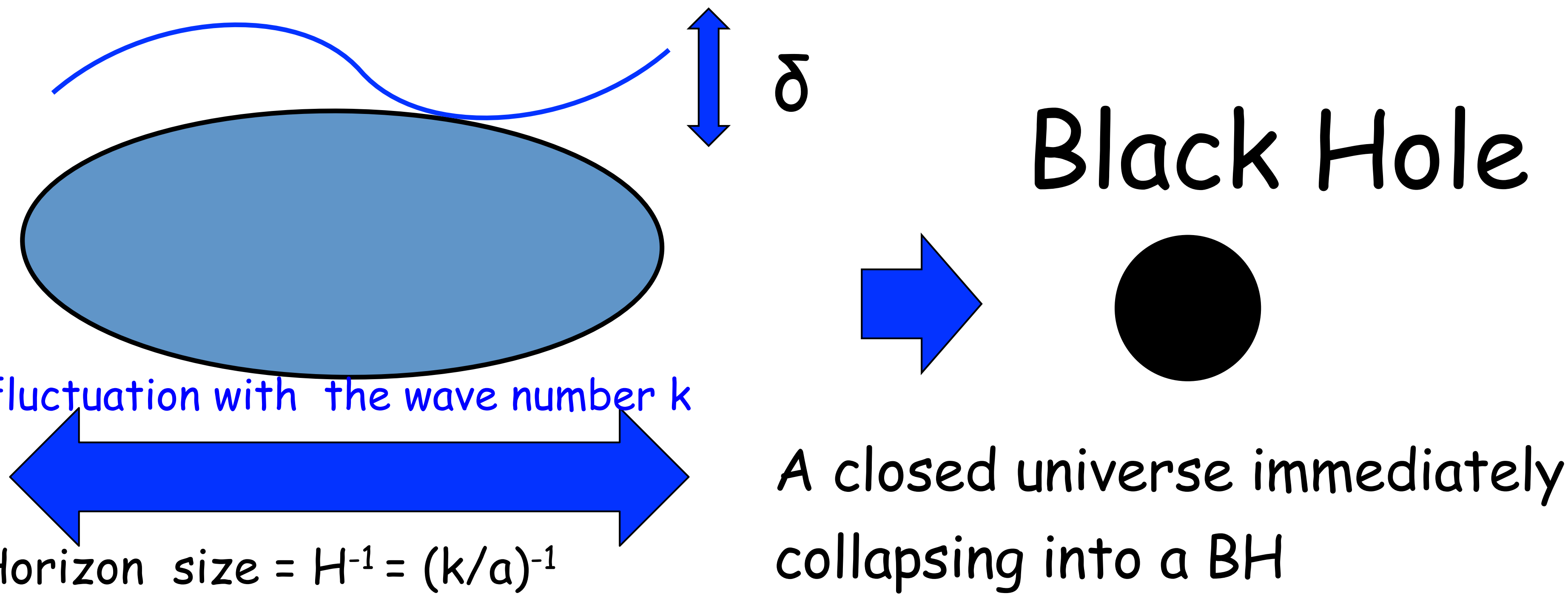
Conditions for a PBH formation in Radiation dominated (RD) Universe

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

Harada,Yoo and KK (2013)

- Gravity could be stronger than pressure

$$\delta > \delta_c \sim p/\rho \sim c_s^2 = w = 1/3$$



P_ζ (k) and PBH abundance β(M)

- Fraction of PBH to the total at its formation epoch with Gaussian fluctuation.

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

$\delta_{\rm th} \sim 1/3 - 0.5$

- Finally we have a relation between β and fluctuation σ (or β and Ω)

$$\beta(M) \sim {\rm erfc}\left(\frac{\delta_{\rm th}}{\sqrt{2}\sigma}\right) \simeq \sqrt{\frac{2}{\pi}}\frac{\sigma}{\delta_{\rm th}} \exp\left(-\frac{\delta_{\rm th}^2}{2\sigma^2}\right)$$

$$= 1.5\times 10^{-18}\left(\frac{m_{\rm PBH}}{10^{15}g}\right)^{1/2}\left(\frac{\Omega_{\rm PBH}h^2}{0.1}\right)$$

$\sigma^2 \sim P_\zeta$

Typical quantities of PBHs in RD

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

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

- Lifetime

$$\tau_{PBH} \sim \frac{M_{PBH}^3}{M_{pl}^4} \sim 4\times 10^{17} sec \left(\frac{M_{PBH}}{10^{15} g}\right)^3 \sim 3\times 10^{68} yrs \left(\frac{M_{PBH}}{30 M_{\odot}}\right)^3$$

- Hawking Temperature

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

- Wave number of horizon length

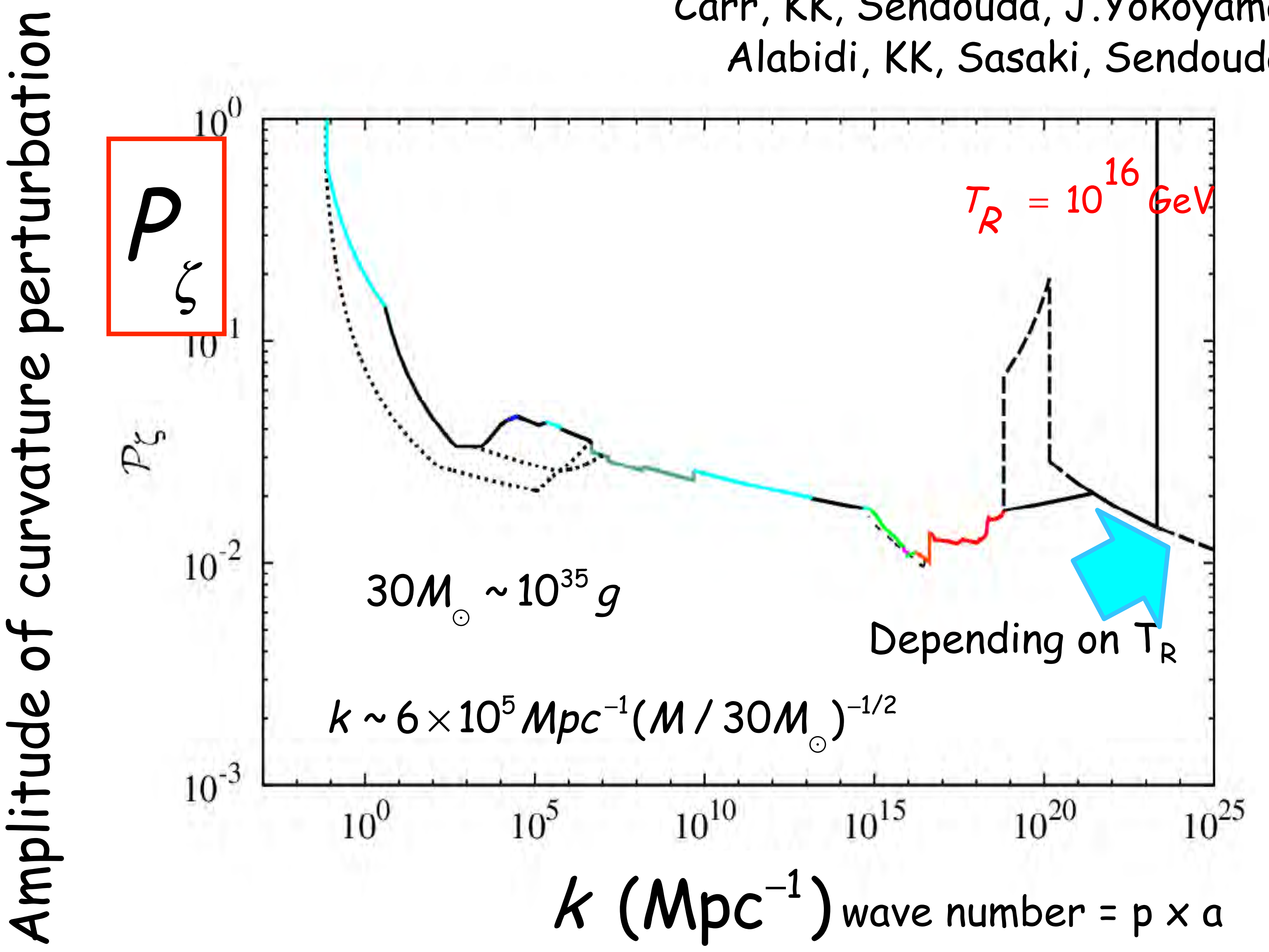
$$k = aH \sim 10^5 Mpc^{-1} \left(\frac{M_{PBH}}{10^4 M_{\odot}}\right)^{-1/2} \sim 10^5 Mpc^{-1} \left(\frac{T_{form}}{MeV}\right)^{+1}$$

- Fraction to CDM

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

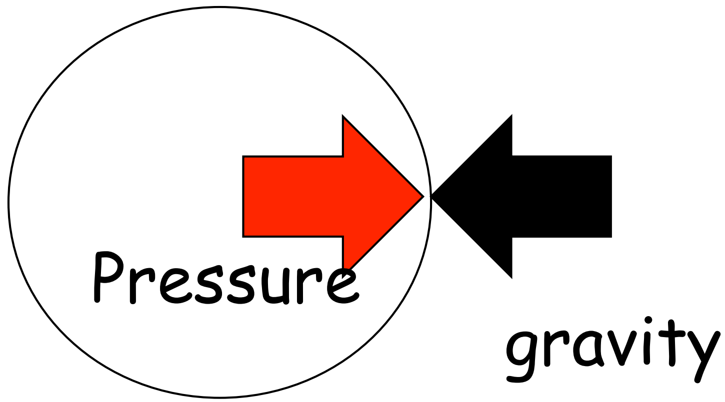
Upper bounds on P_ζ for PBH

Carr, KK, Sendouda, J.Yokoyama (2010)
Alabidi, KK, Sasaki, Sendouda (2012)



Features of PBH formations in RD

- Perfectly spherical due to radiation pressure



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

- No evolutions of density perturbations

- Small angular momentum

PBH formation at the (early) matter dominated (MD) Universe

Polnarev and Khlopov (1982)

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

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

- Density perturbations can evolve, which produces non-spherical objects and cannot be included inside the Horizon radius. That means less PBHs can be produced?

Matter domination

- Three radius in Lagrangian coordinate q_i

Zel'dovich Approximation

$$r_1 = (a - \alpha b) q_1$$
$$r_2 = (a - \beta b) q_2$$
$$r_3 = (a - \gamma b) q_3$$

- 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

$$\mathcal{C} = 16\left(1 - \frac{\gamma}{\alpha}\right) E\left(\sqrt{1 - \left(\frac{\alpha - \beta}{\alpha - \gamma}\right)^2}\right) r_f.$$

- Hoop conjecture for PBH production

$$\mathcal{C} \lesssim 2\pi r_g.$$

Abundance of PBHs formed in MD

- Probability distribution by peak statistics (BBKS)

Doroshkevich (1970)

$$
\begin{aligned}
&w(\alpha,\beta,\gamma)d\alpha d\beta d\gamma \\
&= -\frac{27}{8\sqrt{5}\pi\sigma_3^6}\exp\left[-\frac{1}{10\sigma_3^2}(\alpha+\beta+\gamma)^2-\frac{1}{4\sigma_3^2}\{(\alpha-\beta)^2+(\beta-\gamma)^2+(\gamma-\alpha)^2\}\right] \\
&\cdot(\alpha-\beta)(\beta-\gamma)(\gamma-\alpha)d\alpha d\beta d\gamma.
\end{aligned}
$$

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

- Probability

$$\beta_0 = \int_0^\infty d\alpha \int_{-\infty}^{\alpha} d\beta \int_{-\infty}^{\beta} d\gamma\, \theta(1-h(\alpha,\beta,\gamma))w(\alpha,\beta,\gamma)$$

$$h(\alpha,\beta,\gamma) = \frac{2}{\pi}\frac{\alpha-\gamma}{\alpha^2}E\left(\sqrt{1-\left(\frac{\alpha-\beta}{\alpha-\gamma}\right)^2}\right)$$

$$h(\alpha,\beta,\gamma) := \mathcal{C}/(2\pi r_g)$$

Effects by finite angular momentum

Harada, Yoo, KK, Nakao (2017)

- Probability distribution

$$a_* := L/(GM^2/c)$$

$$f_{\mathrm{BH}(2)}(a_*)da_* \propto \frac{1}{a_*^{5/3}} \exp\left(-\frac{1}{2\sigma_H^{2/3}}\left(\frac{2}{5}\mathcal{I}\right)^{4/3}\frac{1}{a_*^{4/3}}\right) da_*$$

- Probability

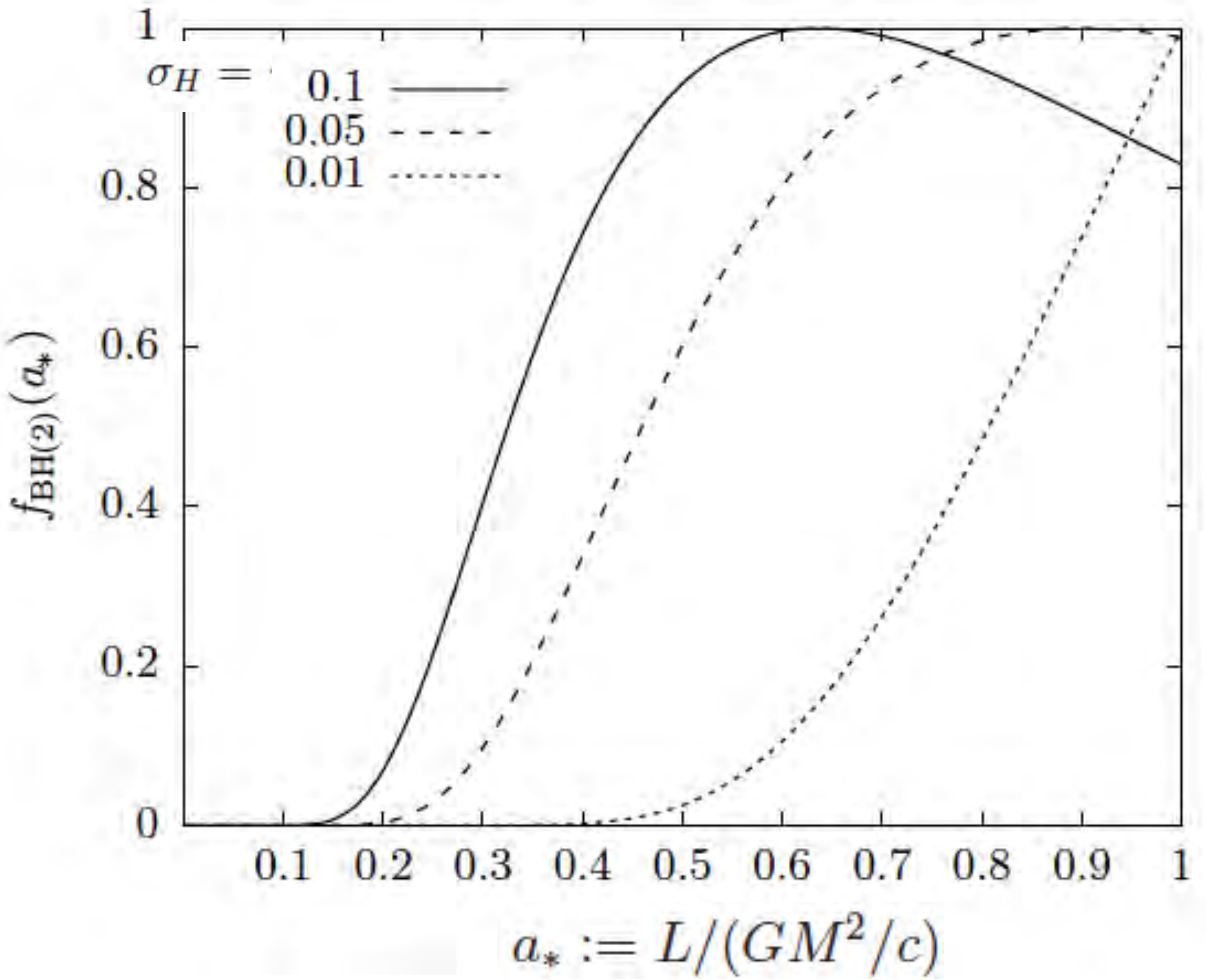
$$\beta_0 \simeq \int_0^\infty d\alpha \int_{-\infty}^{\alpha} d\beta \int_{-\infty}^{\beta} d\gamma \theta[\delta_H(\alpha,\beta,\gamma) - \delta_{\mathrm{th}}]\theta[1 - h(\alpha,\beta,\gamma)]w(\alpha,\beta,\gamma)$$

$$\delta_H(\alpha,\beta,\gamma) = \alpha + \beta + \gamma \qquad \delta_{\mathrm{th}} := \left(\frac{2}{5}\mathcal{I}\sigma_H\right)^{2/3}$$

Spin distribution

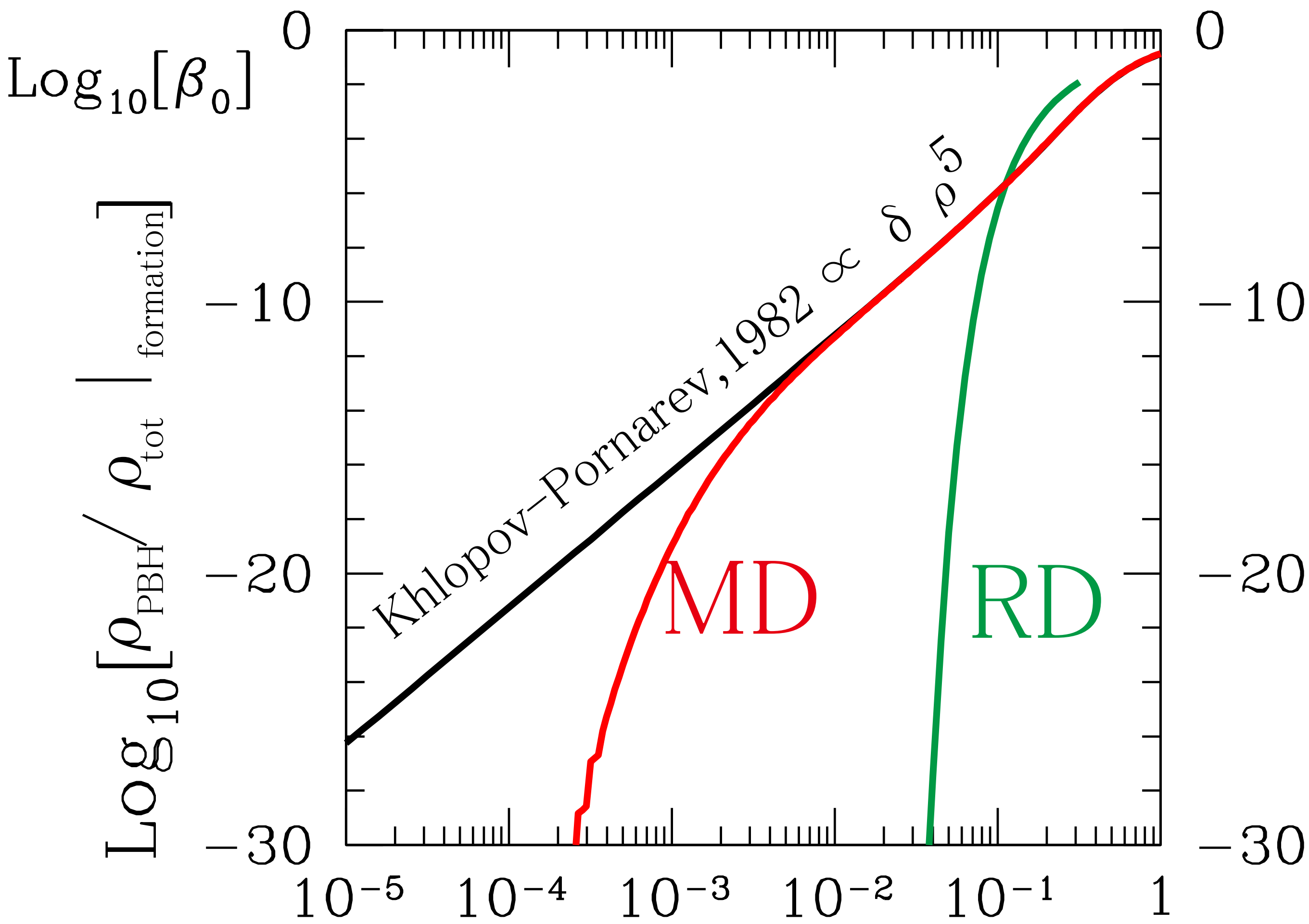
More highly-spinning halos cannot collapse into PBHs, which means that the PBHs produced tend to have high spins in MD

Harada, Yoo, KK, Nakao (2017)



Beta in matter-domination

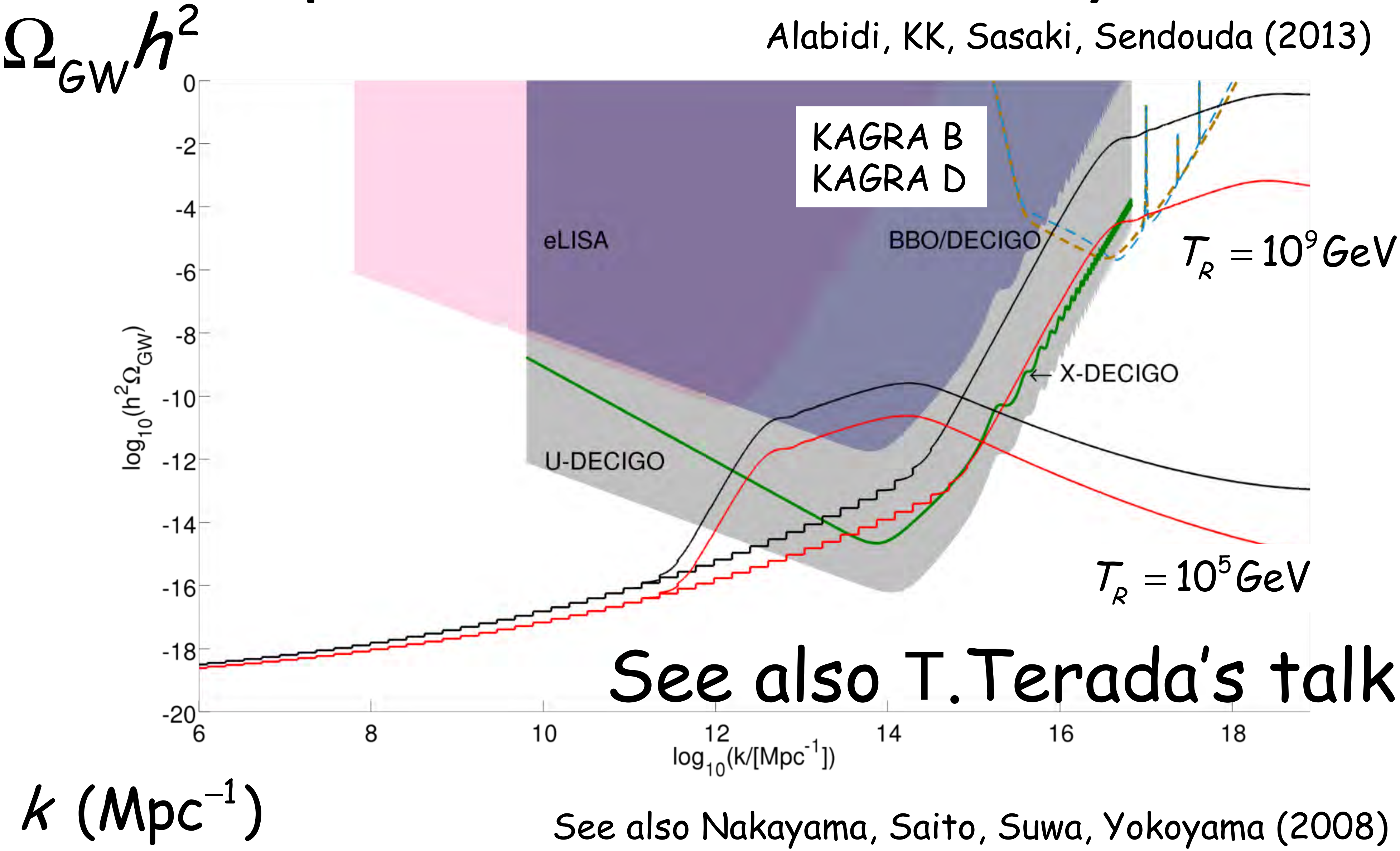
Harada, Yoo, KK, Nakao (2017)



$\sigma_H = \sqrt{5}\sigma_3$ = $\delta\rho/\rho$

In Hilltop models with low reheating temperature with the early MD

Alabidi, KK, Sasaki, Sendouda (2013)



See also T.Terada's talk

See also Nakayama, Saito, Suwa, Yokoyama (2008)

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

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

- A non-spherical accretion disk around a PBH caused by an angular momentum emits radiation

$$\dot{M}_{\rm HB} \equiv 4\pi\lambda\,\rho_\infty v_{\rm eff} r_{\rm HB}^2 \equiv 4\pi\lambda\,\rho_\infty \frac{(GM)^2}{v_{\rm eff}^3}$$

$$l \simeq \omega\, r_{\rm HB}^2 \simeq \left(\frac{\delta\rho}{\rho} + \frac{\delta v}{v_{\rm eff}}\right) v_{\rm eff} r_{\rm HB}$$

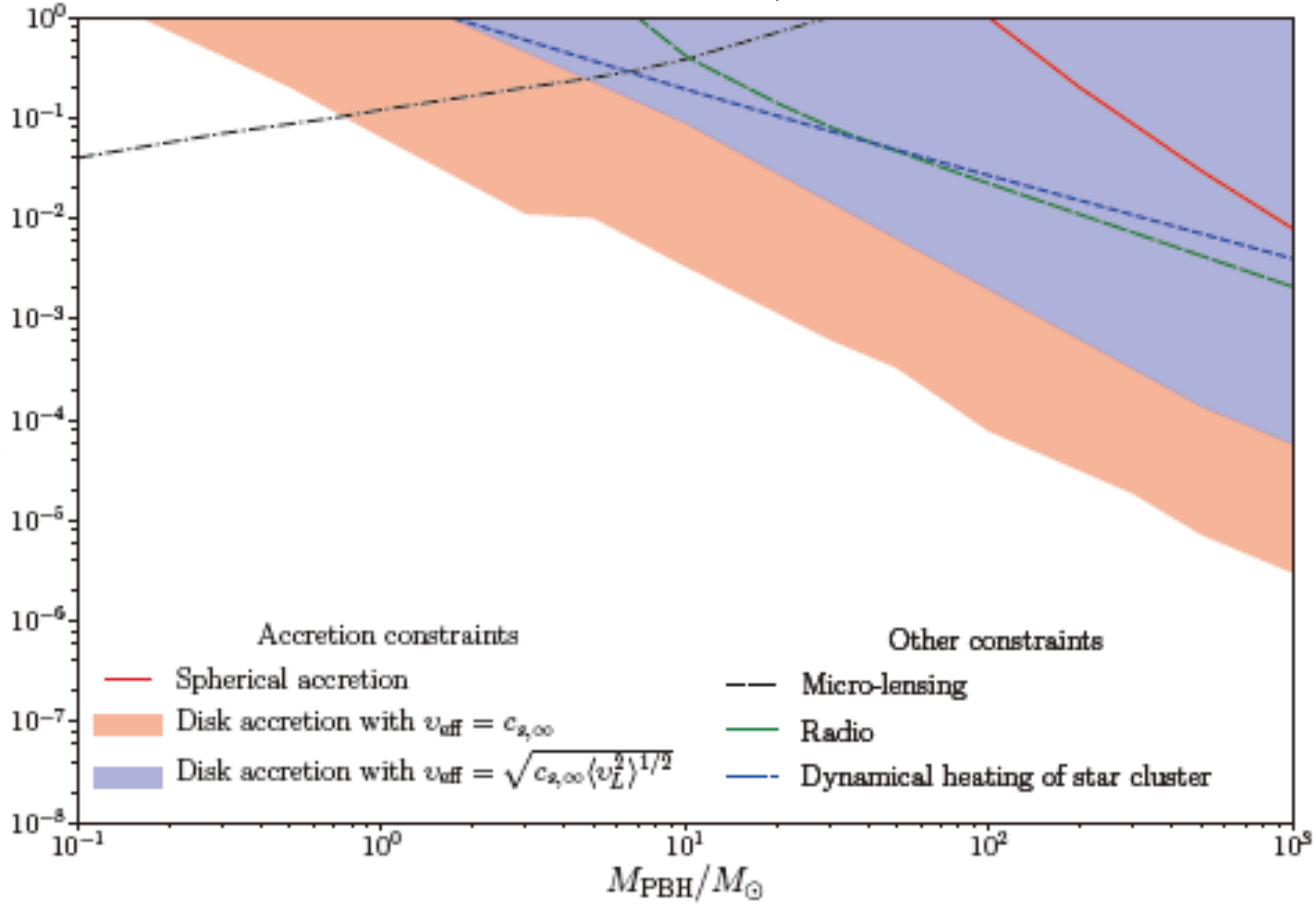
- CMB anisotropies are affected

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

CMB bound by disk-accretion in the latest MD epoch

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

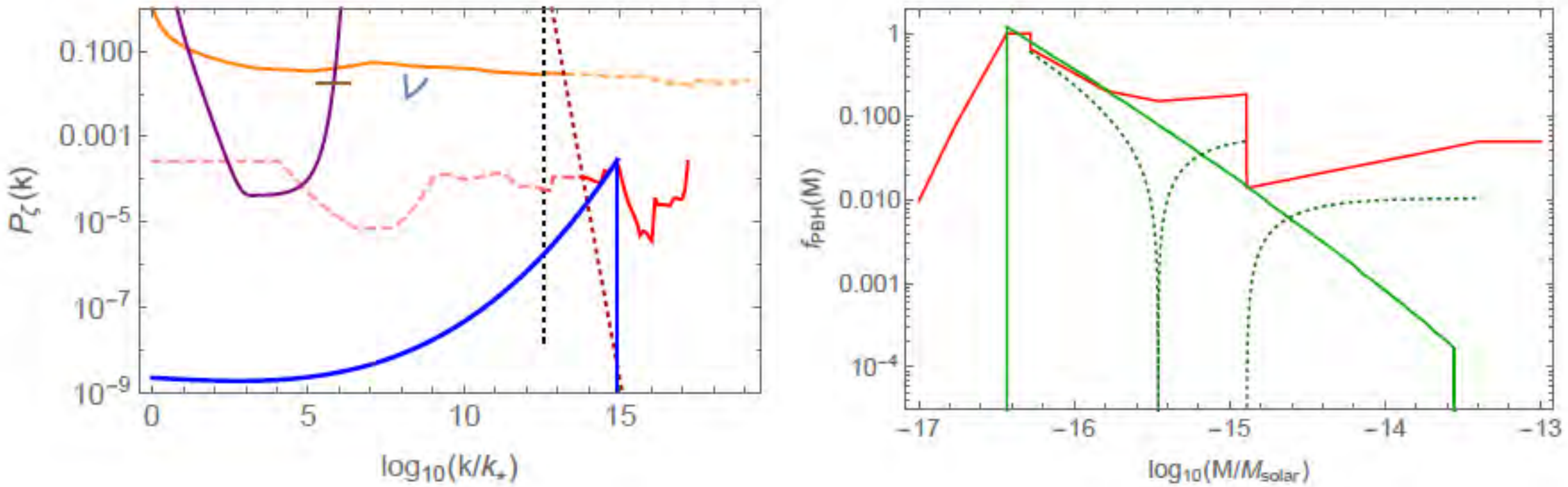
Fraction to CDM



100 % Dark Matter by PBHs

KK and T.Terada, 2018

$$n_s = 0.96, \alpha_s = 0, \beta_s = 0.0019485$$



black dotted line shows

$T_R = 10^4\text{GeV}$

Summary

- PBH can be formed at small scales even in both radiation and matter dominated epochs
- More PBHs are produced in MD
- We may detect gravitational wave signals secondarily-induced by large SCALAR fluctuations at small scales by e.g., aLIGO, KAGRA, DECIGO …
- 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 (GW)…