大学共同利用機関法人
高エネルギー加速器研究機構

A02分担者

Primordial Black Hole in the Matter Dominated Universe

Kaz Kohri
郡　和範

KEK and Sokendai, Tsukuba, Japan

国立大学法人
総合研究大学院大学
THE GRADUATE UNIVERSITY FOR ADVANCED STUDIES [SOKENDAI]

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 (with accretion), 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), …

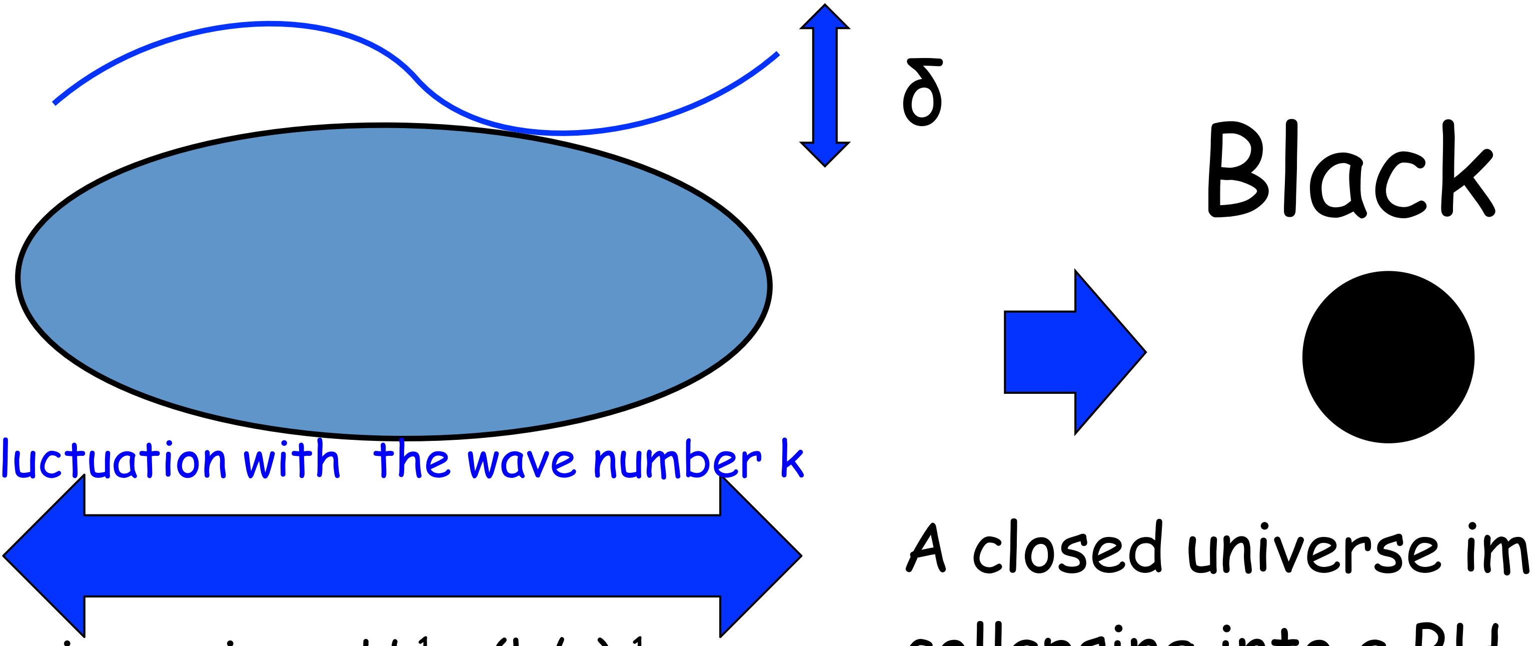
Conditions for a PBH formation in Radiation dominated (RD) Universe

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

Harada,Yoo and KK (2013)

- Gravity could be stronger than pressure

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



δ

Black Hole

A fluctuation with the wave number k

Horizon size = $H^{-1} = (k/a)^{-1}$

A closed universe immediately collapsing into a BH

P_ζ (k) and PBH abundance β(M)

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

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

$$\boxed{\sim 1/3 - 0.5}$$

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

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

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

$$\boxed{\sim P_\zeta}$$

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

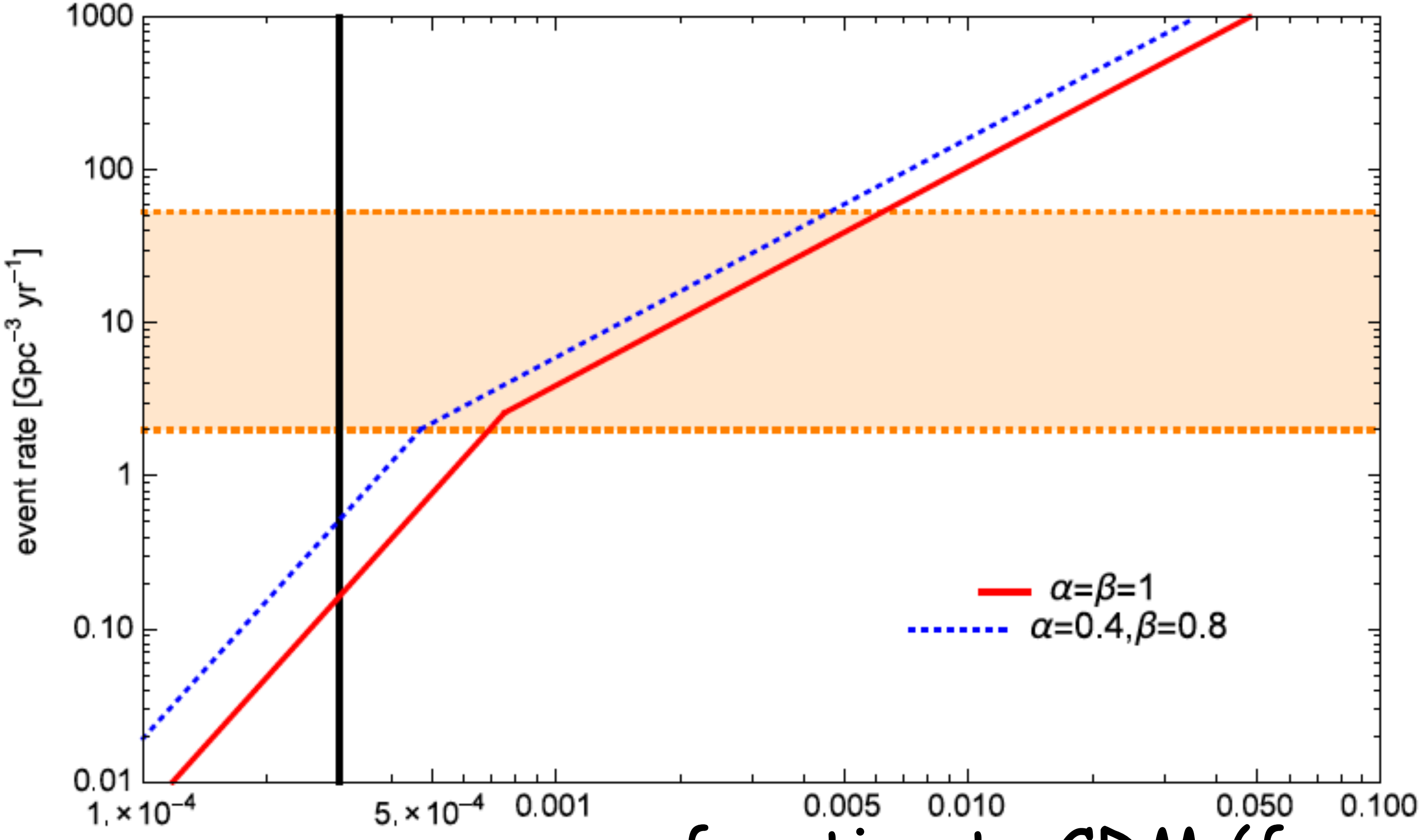
$$f_{fraction} \equiv \frac{\Omega_{PBH}}{\Omega_{CDM}} \sim \left(\frac{\beta}{10^{-18}}\right)\left(\frac{M_{PBH}}{10^{15} g}\right)^{-1/2} \sim \left(\frac{\beta}{10^{-8}}\right)\left(\frac{M_{PBH}}{30 M_{\odot}}\right)^{-1/2} \sim 10^8 \left(\frac{M_{PBH}}{30 M_{\odot}}\right)^{-1/2} \sqrt{P_{\delta}}\,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

GW150914 and its merger rate

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

3-body is important for the BBH formations

See also, Ali-Haimound, Kovetz and Kamionkowski (2017)

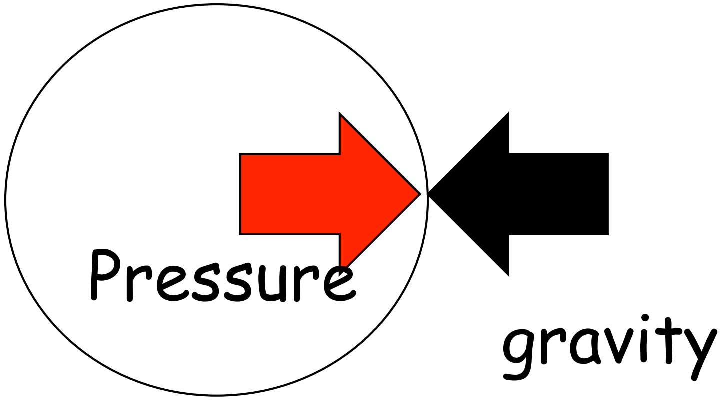


Rate of GW140914

fraction to CDM ($f_{fraction}$)

Features of PBH formations in RD

- Perfectly spherical due to radiation pressure

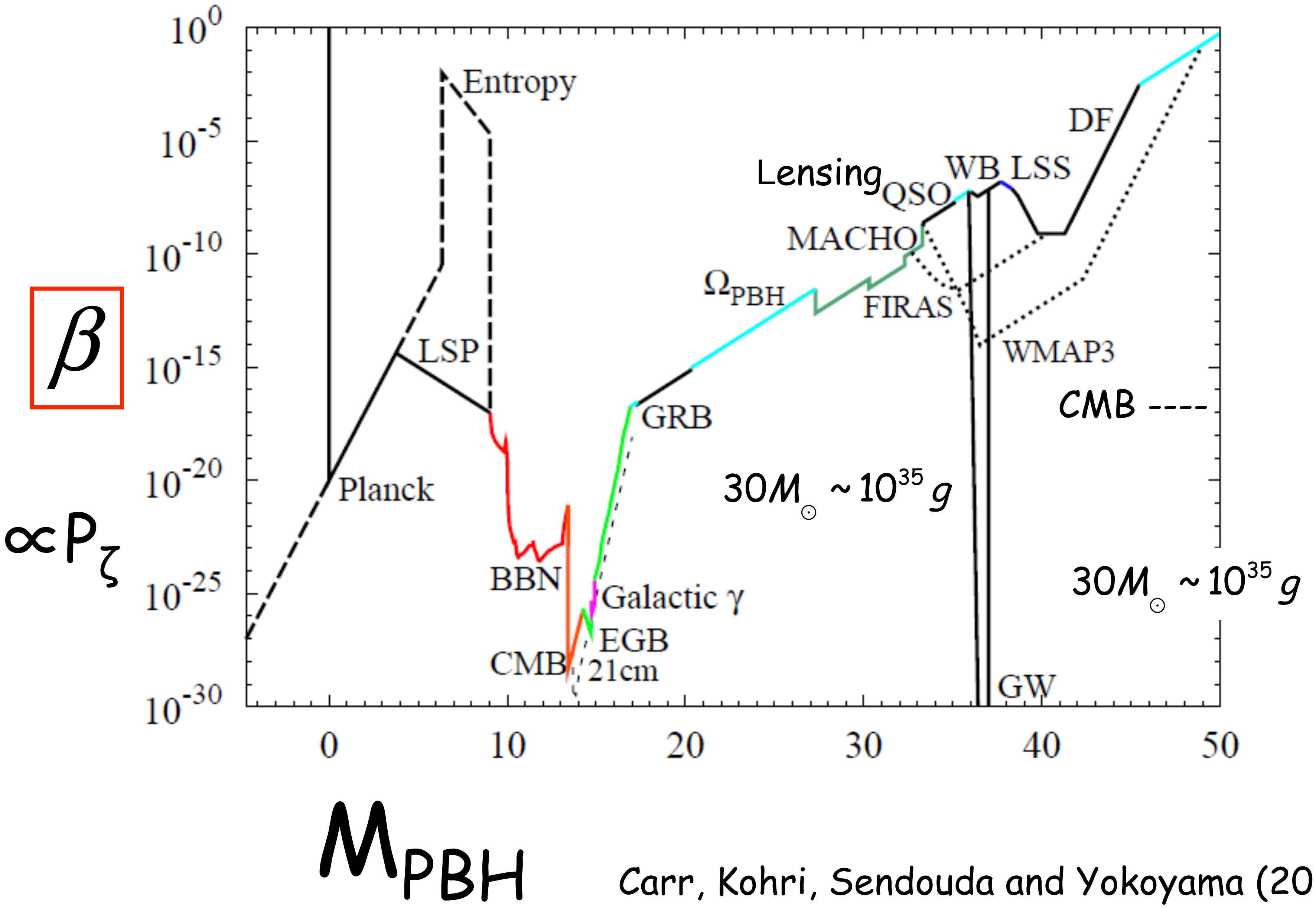


$(w \equiv p/\rho \sim 1/3)$

- No evolutions of density perturbations

- Small angular momentum

Upper bounds on β for PBH



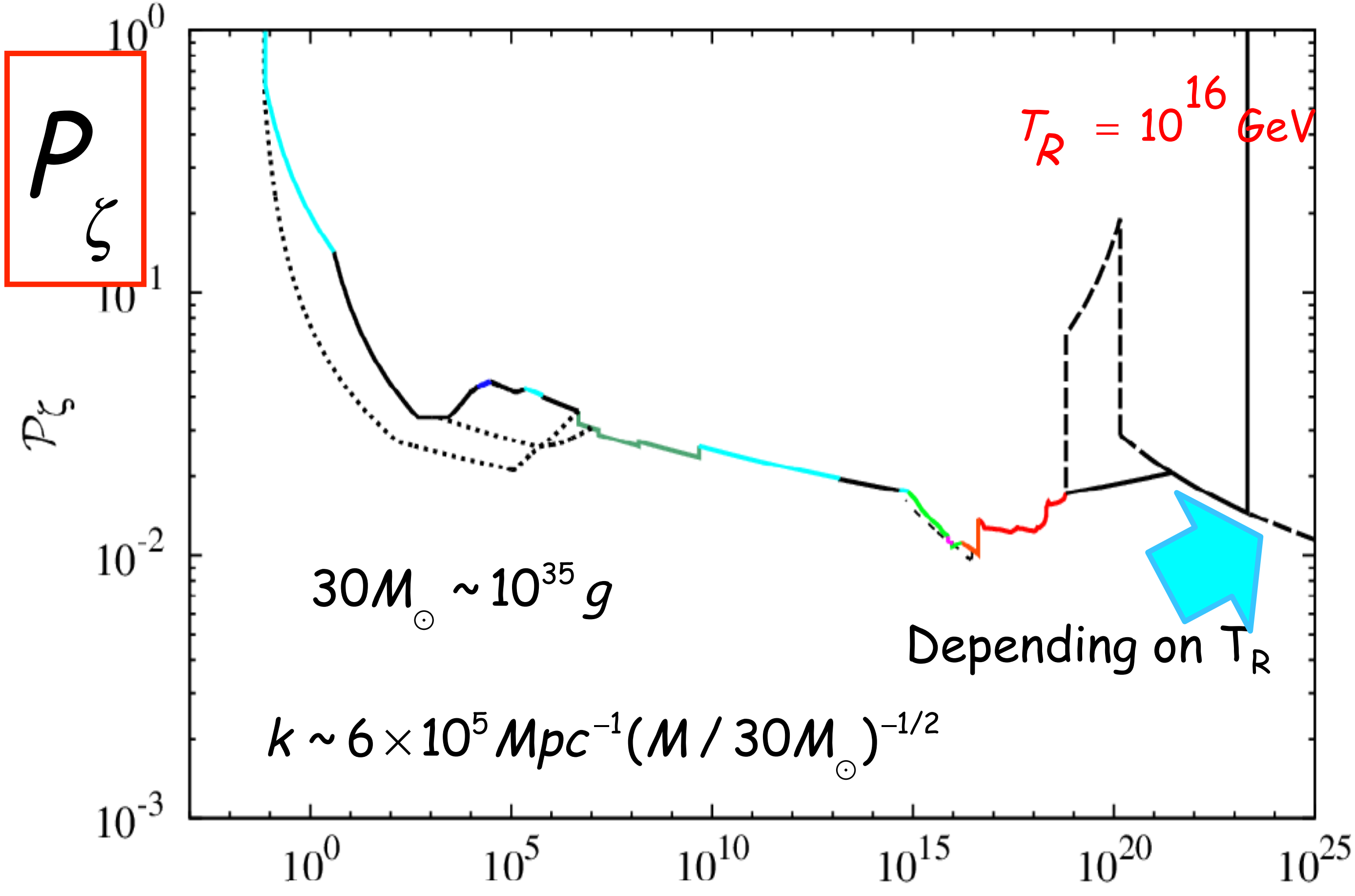
Carr, Kohri, Sendouda and Yokoyama (2010)
Josan, Green and Malik (2009)

Upper bounds on P_ζ for PBH

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

Amplitude of curvature perturbation

P_ζ



$30M_\odot \sim 10^{35} g$

$k \sim 6 \times 10^5 Mpc^{-1} (M / 30M_\odot)^{-1/2}$

Depending on T_R

$k\ (\mathrm{Mpc}^{-1})$ wave number k = p x a

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

ADAF-type disk-accretion

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

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

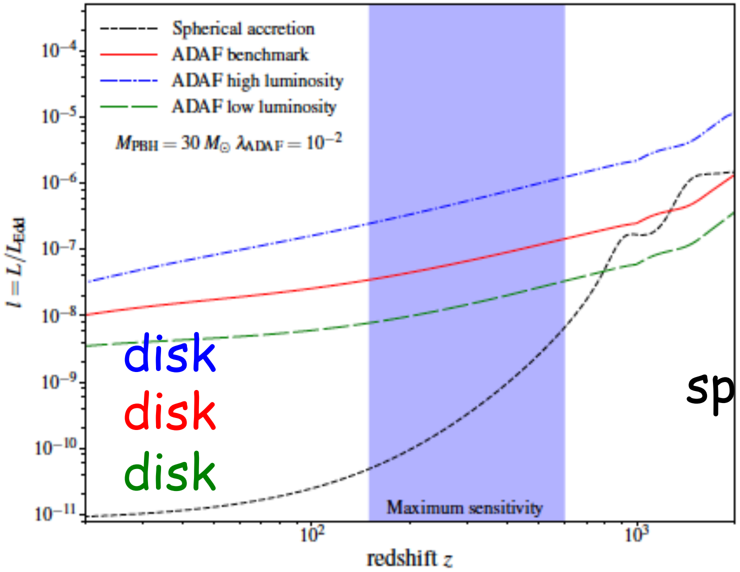
- CMB anisotropies/polarizations are affected

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

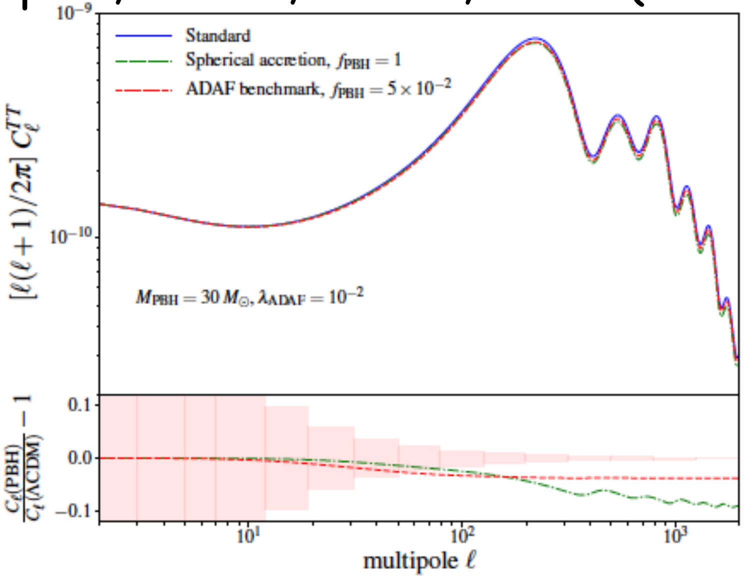
Modified CMB anisotropy

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

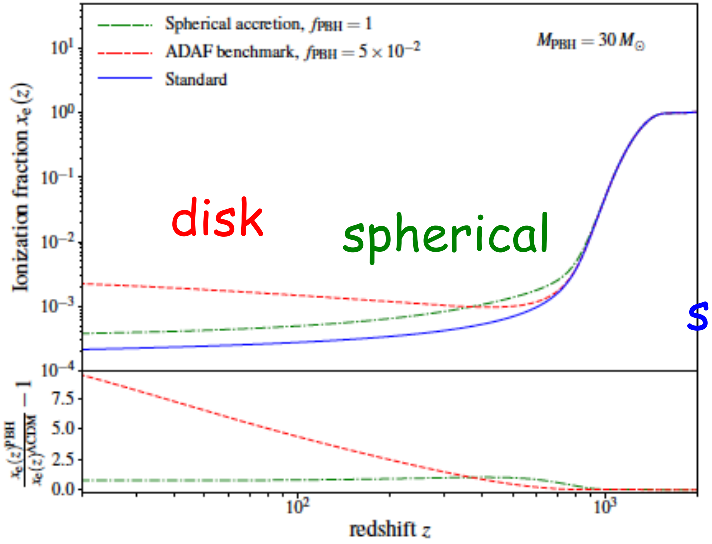
Luminosity



spherical



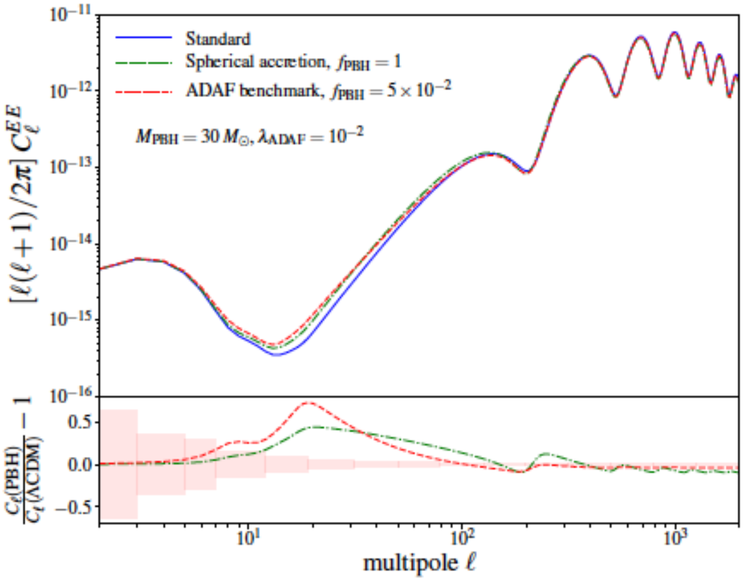
Ionization fraction



disk

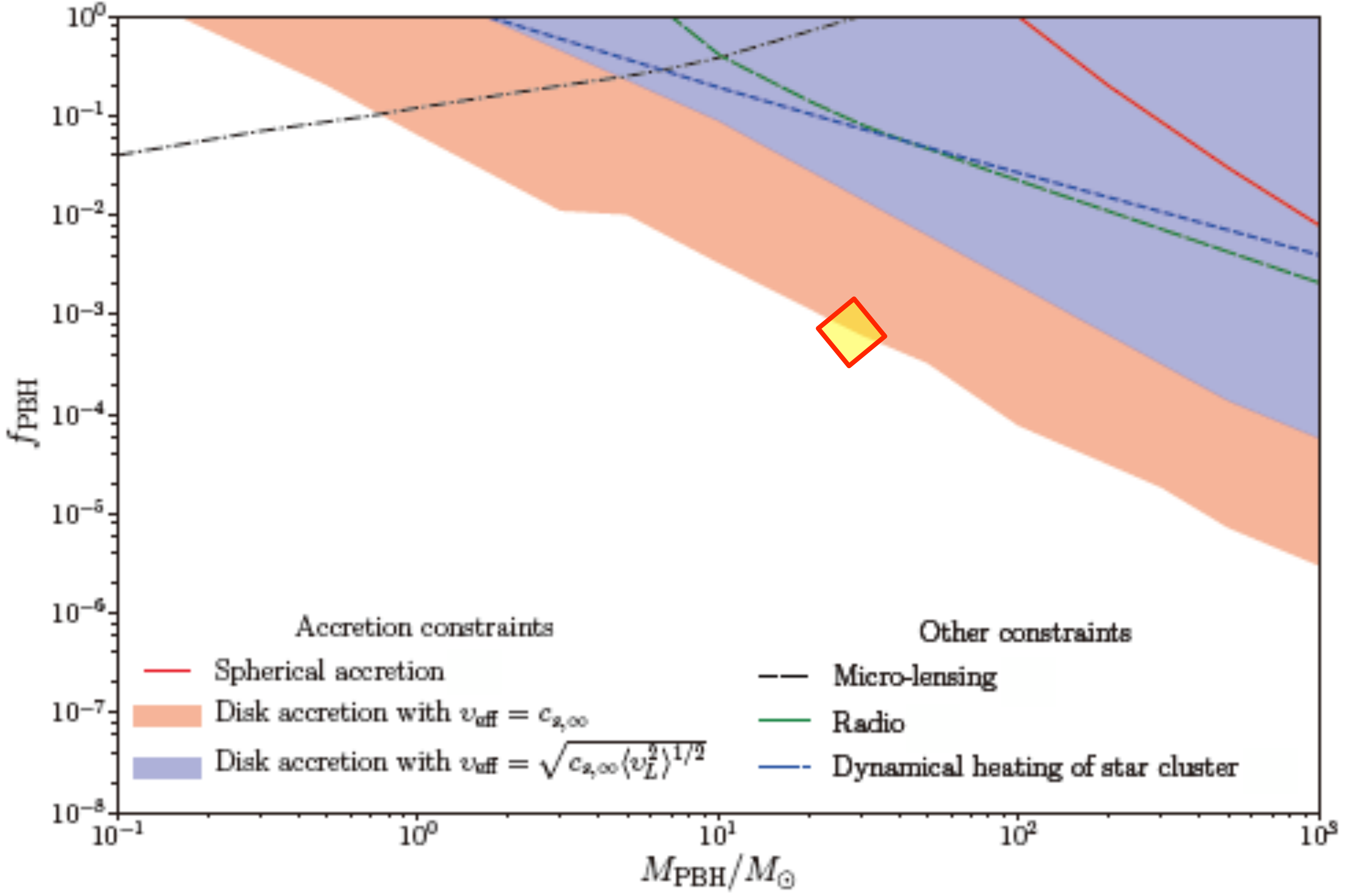
spherical

standard



CMB bound by disk-accretion in the latest MD epoch

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



Fraction to CDM

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

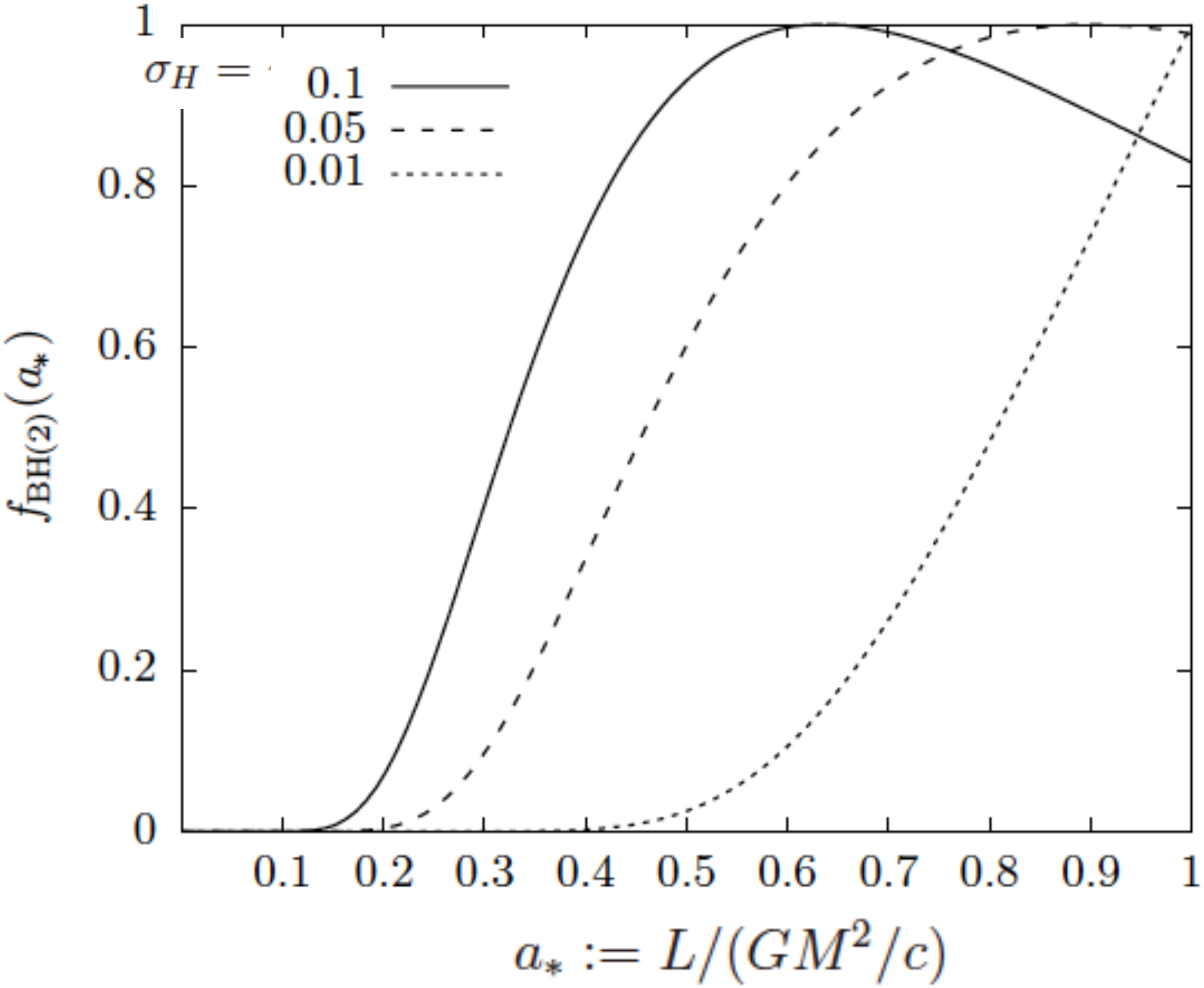
$$\beta_0 \simeq \int_0^\infty d\alpha \int_{-\infty}^\alpha d\beta \int_{-\infty}^\beta d\gamma \theta[\delta_H(\alpha,\beta,\gamma)-\delta_{\mathrm{th}}]\theta[1-h(\alpha,\beta,\gamma)]w(\alpha,\beta,\gamma)$$

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

Spin distribution

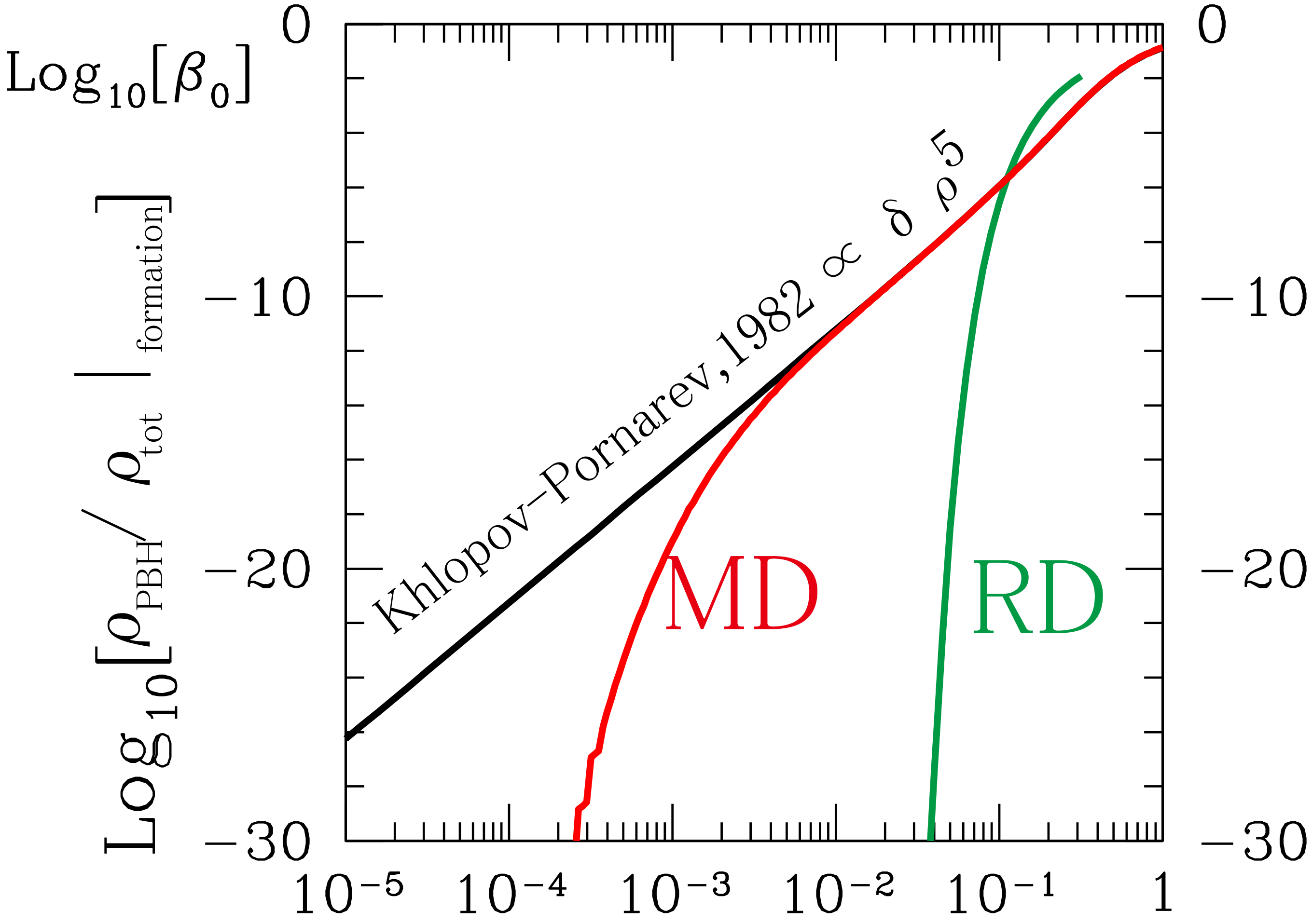
More highly-spinning halos cannot collapse into PBHs, which means that the PBHs produced tend to have high spins in MD

Harada, Yoo, KK, Nakao (2017)



Beta in matter-domination

Harada, Yoo, KK, Nakao (2017)



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

Simple parameterization of running of spectral indexes

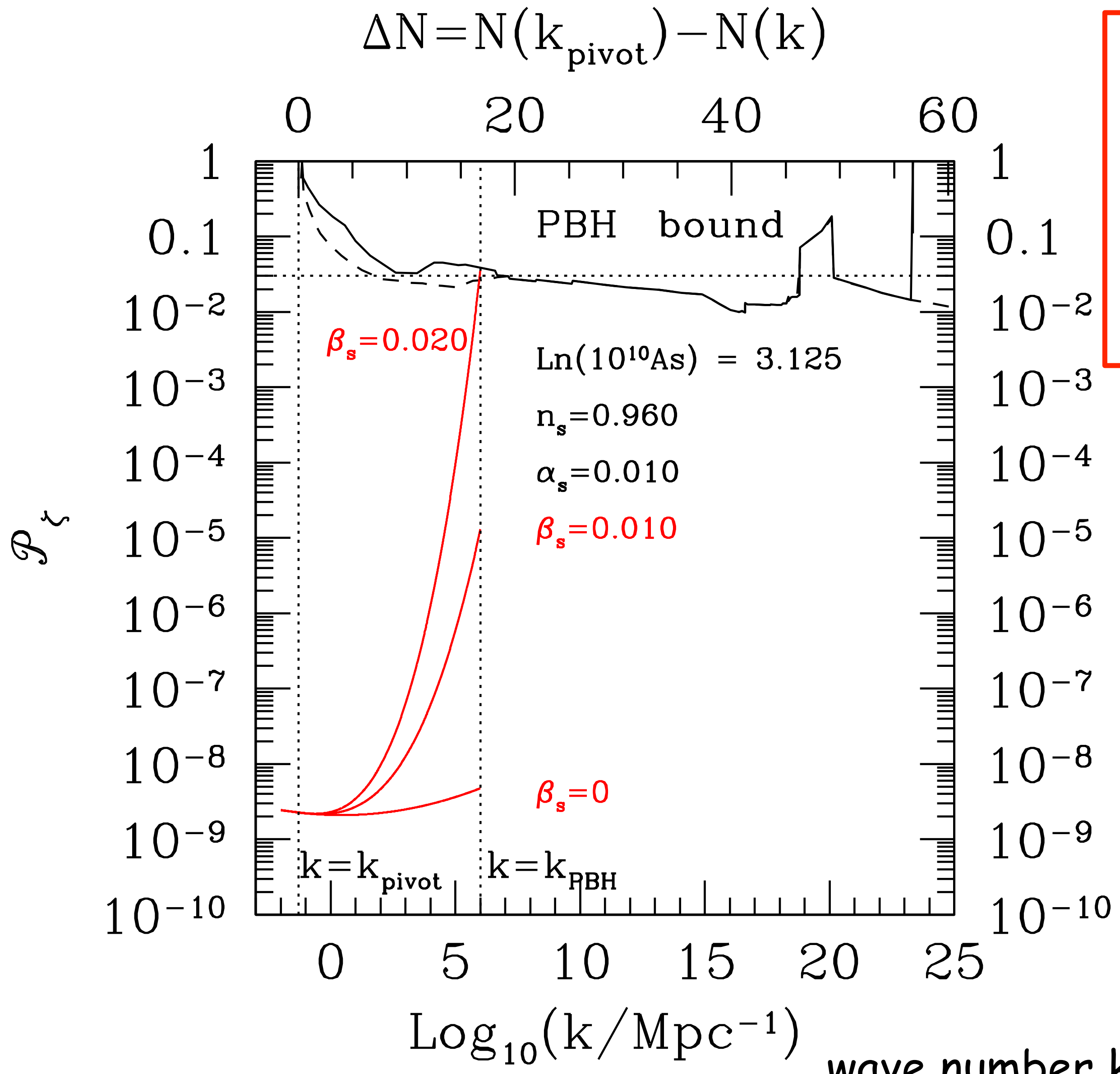
KK and T.Terada, 2018

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

P_ζ vs k

KK and T.Terada, 2018

Amplitude of curvature perturbation



Planck (2015)

$n_s = 0.9586 \pm 0.0056,$

$\alpha_s = 0.009 \pm 0.010,$

$\beta_s = 0.025 \pm 0.013.$

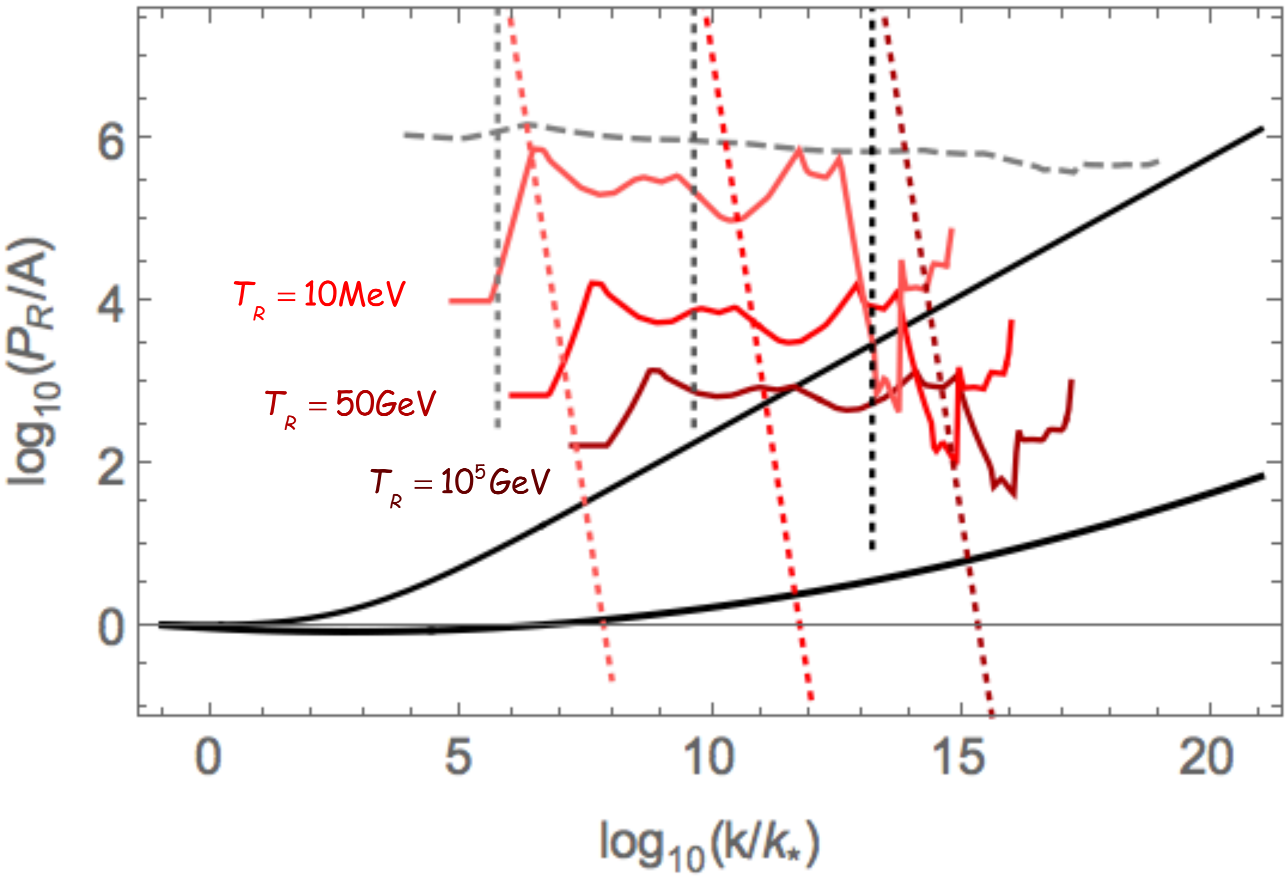
at 68% C.L.

wave number k = p x a

Upper bounds on curvature perturbation in MD

Carr, Tenkanen and Vaskonen (2017)
KK and T.Terada, 2018

$\log_{10}[P_\zeta / P_{\zeta,\mathrm{observed}}]$

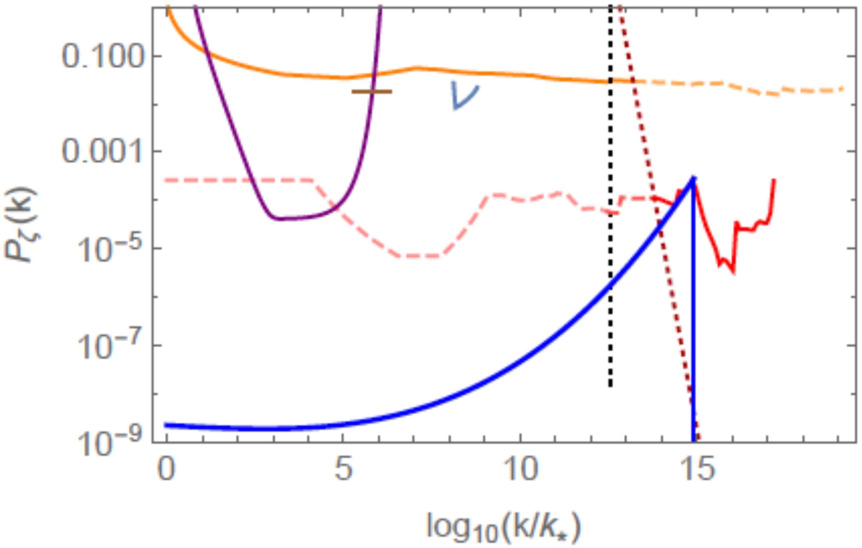


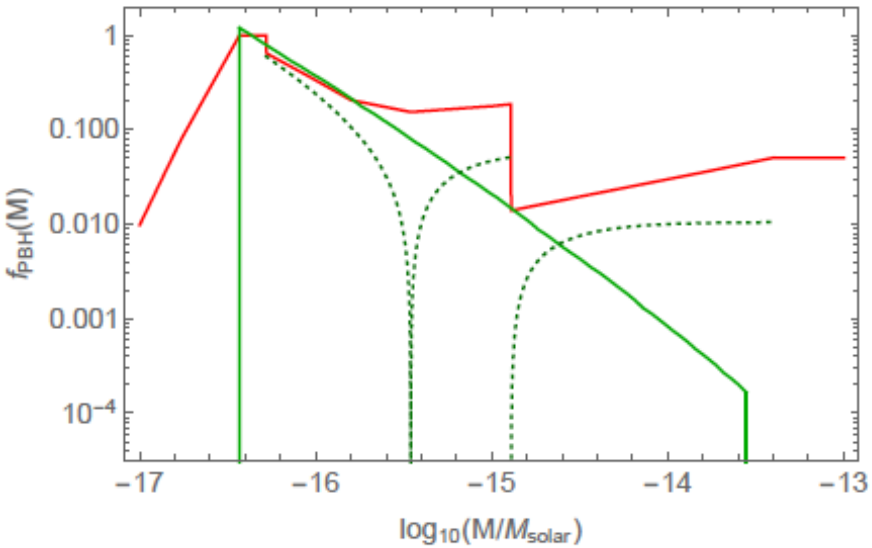
100% MD before reheating

100 % Dark Matter by PBHs

KK and T.Terada, 2018

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





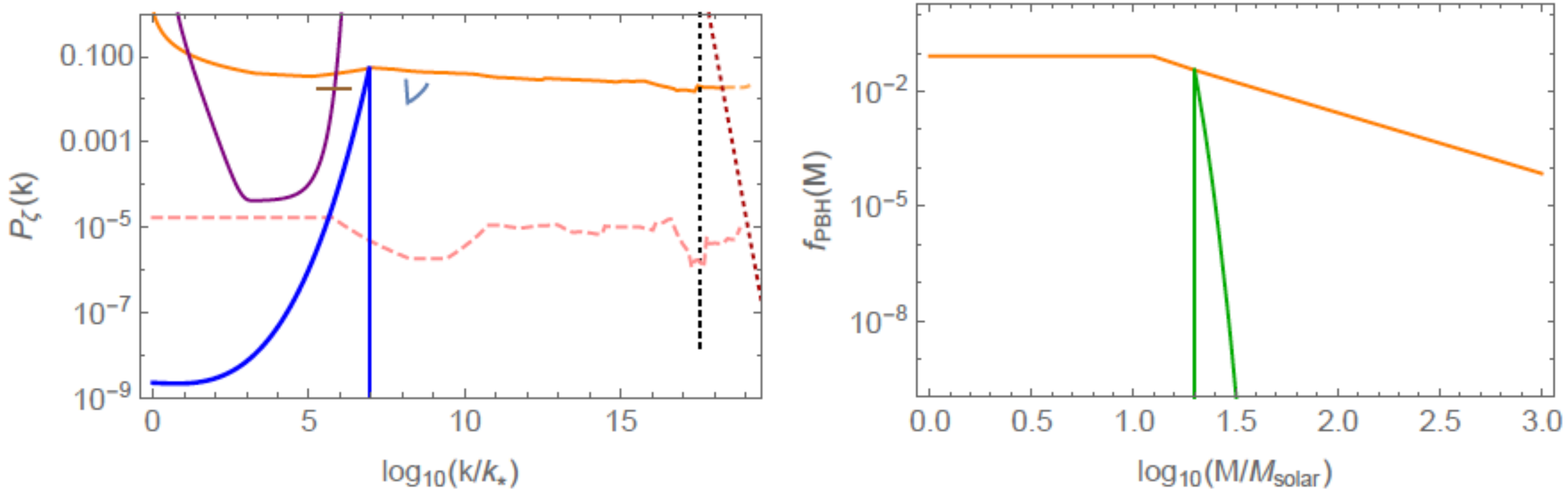
black dotted line shows

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

LIGO/VIRGO event

KK and T.Terada, 2018

$$n_s = 0.96, \alpha_s = 0, \beta_s = 0.026.$$



black dotted line shows the reheating at $T_R = 10^9\mathrm{GeV}$

Summary

- PBH can be formed at small scales even in both radiation and matter dominated epochs
- More PBHs can be 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)…