

Do you believe that primordial
black holes could form during the
early matter-dominated epoch?

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THEORY CENTER

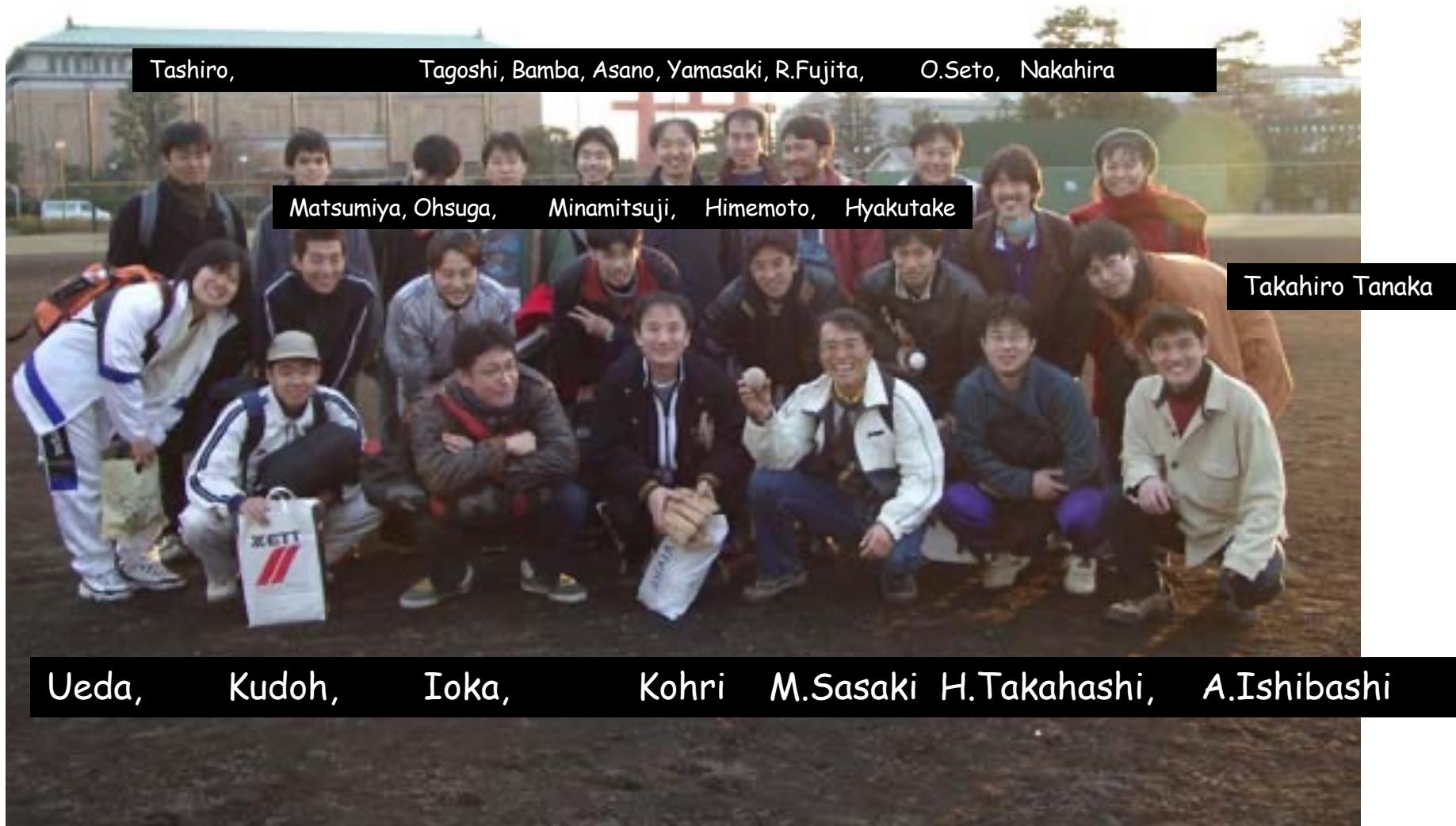
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Abstract

- Congratulations on your graduation from Kavli IPMU, Misao
- Misao has served as a hub for research on cosmology and gravity at Kavli IPMU or in the world
- Even after moving to or during APCTP, please continue to serve as a hub researcher for research in Asia or for research worldwide

17th, Dec, 2001

at Okazaki Baseball Studium, Kyoto



18th, Oct, 2019 at Prof. Sasaki's office
at LeCOSPA, NTU, Taipei



Photos taken by K. Kohri

15th, Nov, 2012 at JGRG

60th birthday (being considered a rebirth/reborn in Japan)



Kodama, Kei-ichi Maeda Sasaki,

Photo taken by K. Kohri

22nd, March, 2014

at Commendation of Prof. Katsuhiko Sato as a Person of Cultural Merit Award
(文化功労者顕彰)

K. Sato(Kyoto U.), H. Kodama(Kyoto U.), M. Sasaki(Kyoto U., Yukawa Inst., Kyoto), K. Maeda(Kyoto U.), Phys. Lett.B 108 (1982) 103-107



17th, Oct, 2019 at Taipei



Photo taken by K. Kohri

18th, Nov, 2019 at CosPA 2019/APPC14 hold by
DACG/AAPPS, at Borneo Convension Center,
Kuching, Sarawak, Malaysia



18th, July, 2022 during COVID at IPMU

Work from home
and refrain from nonessential and
nonurgent activities



Workshop organized by Shi Pi at 14th, Oct, 2023, Beijing, China

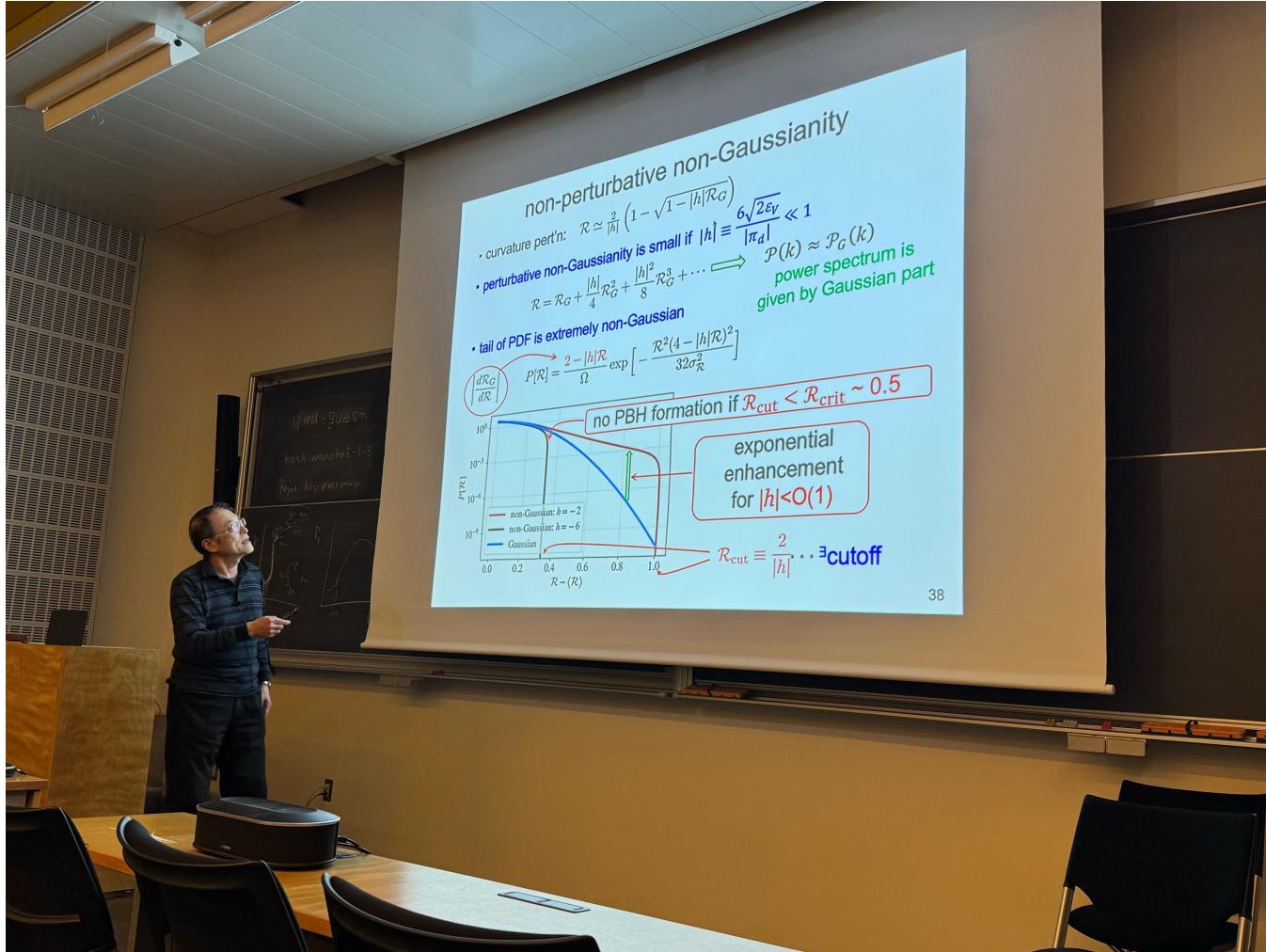


LeCOSPA-IPMU workshop

at 2nd, April, 2025, NTU, Taipei



On Misao's final Lectures at IPMU 9th, Feb, 2026



Do you believe that
primordial black
holes could form
during the early
matter-dominated
epoch?

Yes

Misao told us,

No.

He did not
believe it at all

until 2019

Now

Yes. we believe

it is possible,

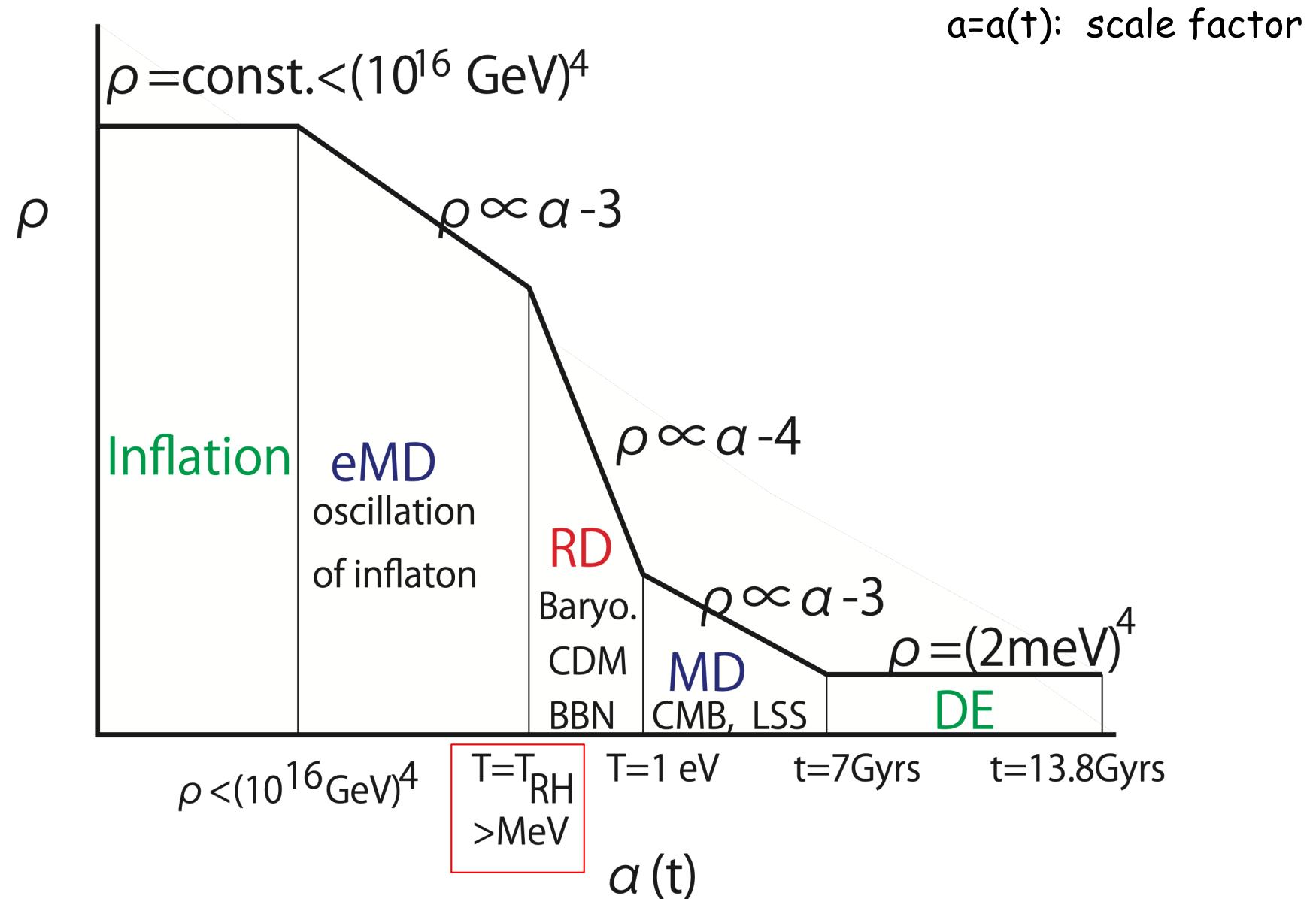
but, ...

Formations of PBHs in the **early** **Matter Dominated** epoch

Mechanisms **suppressing** the formation of Primordial Black Holes

- Anisotropy Polnarev and Khlopov (1982)
Tomohiro Harada, Chul-Moon Yoo, Kazunori Kohri, Ken-ichi Nakao, Sanjay Jhingan, arXiv:1609.01588 [astro-ph.CO]
- Inhomogeneity Polnarev and Khlopov (1982)
T. Kokubu, K. Kyutoku, K. Kohri, T. Harada, arXiv:1810.03490
- Spin? Weitao Ye, Yungui Gong, Tomohiro Harada, Zhaofeng Kang, Kazunori Kohri, Daiki Saito, Chul-Moon Yoo, arXiv:2508.10070 [gr-qc]
- **Velocity dispersion (Virialization)** with Misao Sasaki
Tomohiro Harada, Kazunori Kohri, Misao Sasaki, Takahiro Terada, Chul-Moon Yoo, arXiv:2211.13950 [astro-ph.CO]
• see also, Luis E. Padilla, Juan Carlos Hidalgo, Karim A. Malik, arXiv:2110.14584 [astro-ph.CO]
- ...

Cosmic history of energy density



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

Polnarev and Khlopov (1982)

Tomohiro Harada, Chul-Moon Yoo, Kazunori Kohri, Ken-ichi Nakao, Sanjay Jhingan,

arXiv:1609.01588 [astro-ph.CO]

1. **Pressure is negligible**, which could induce an immediate collapse (e.g., $\delta_{\text{th}}=w \rightarrow 0?$), and then 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_i

$$r_1 = (a - \alpha b)q_1 \quad \text{Zel'dovich Approximation}$$

$$r_2 = (a - \beta b)q_2$$

$$r_3 = (a - \gamma b)q_3$$

- 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 with 2nd Elliptic funciton $E(x)$

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

- Hoop conjecture for PBH production

$$C \lesssim 2\pi r_g.$$

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

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

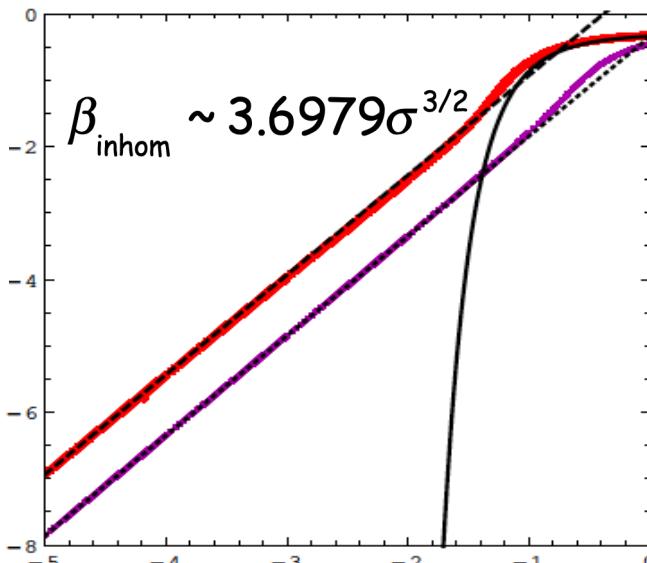
$$\begin{aligned} h(\alpha, \beta, \gamma) &= \frac{2}{\pi} \frac{\alpha - \gamma}{\alpha^2} E \left(\sqrt{1 - \left(\frac{\alpha - \beta}{\alpha - \gamma} \right)^2} \right) \\ h(\alpha, \beta, \gamma) &:= \mathcal{C} / (2\pi r_g) \end{aligned}$$

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

$$\beta \equiv \frac{\rho_{\text{PBH}}}{\rho_{\text{tot}}}$$



$$\beta_{\text{aniso}} \simeq 0.05556 \sigma^5$$

$$\sigma \sim \overline{\delta \rho / \rho}$$

$$\text{Log}_{10}[\sigma]$$

$$\beta_{\text{inhom+aniso}} \simeq \beta_{\text{inhom}} \times \beta_{\text{aniso}} = 0.2055 \sigma^{13/2}$$

Velocity Dispersion and PBH formation

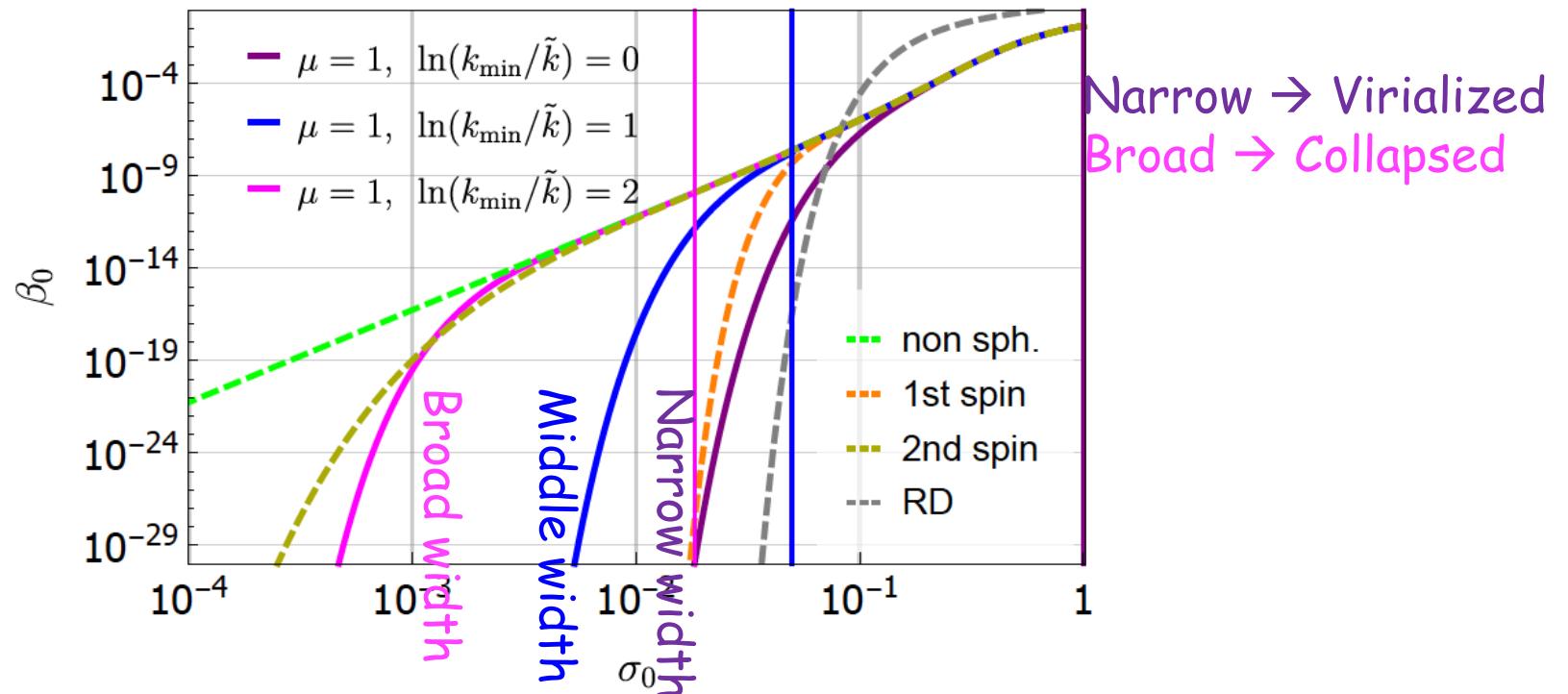
Tomohiro Harada, Kazunori Kohri, Misao Sasaki, Takahiro Terada, Chul-Moon Yoo, arXiv:2211.13950 [astro-ph.CO]

$$\sigma_{\delta, \text{ent}}^2(k) = \sigma_0^2 \exp \left\{ -2\mu \left[\ln \left(\frac{k}{\tilde{k}} \right) \right]^2 \right\}, \quad (16)$$

or equivalently,

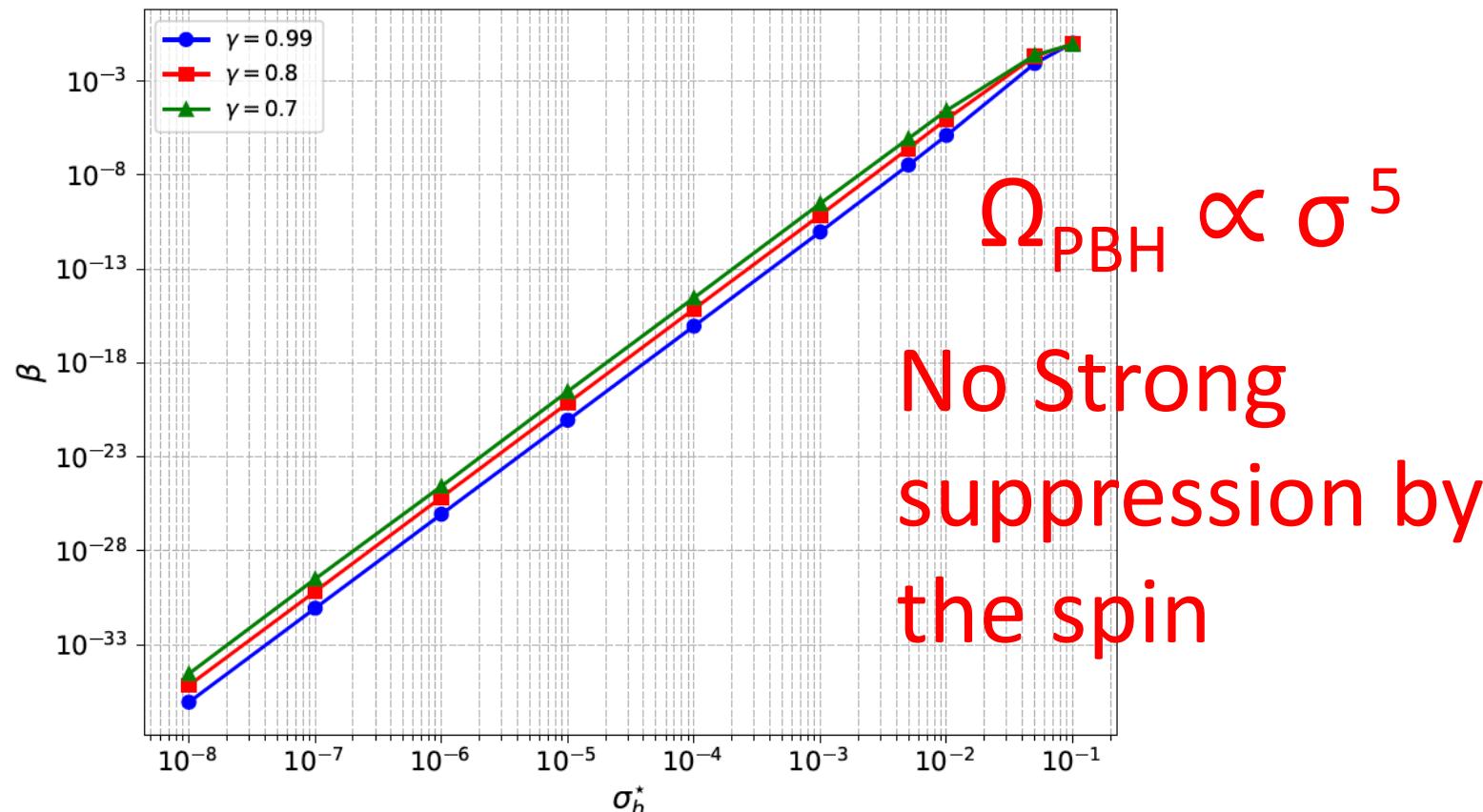
$$\ln \sigma_{\delta, \text{ent}}(k) = -\mu \left[\ln \left(\frac{k}{\tilde{k}} \right) \right]^2 + \ln \sigma_0, \quad (17)$$

where μ is the non-dimensional parameter characterizing the width of the log-normal distribution.



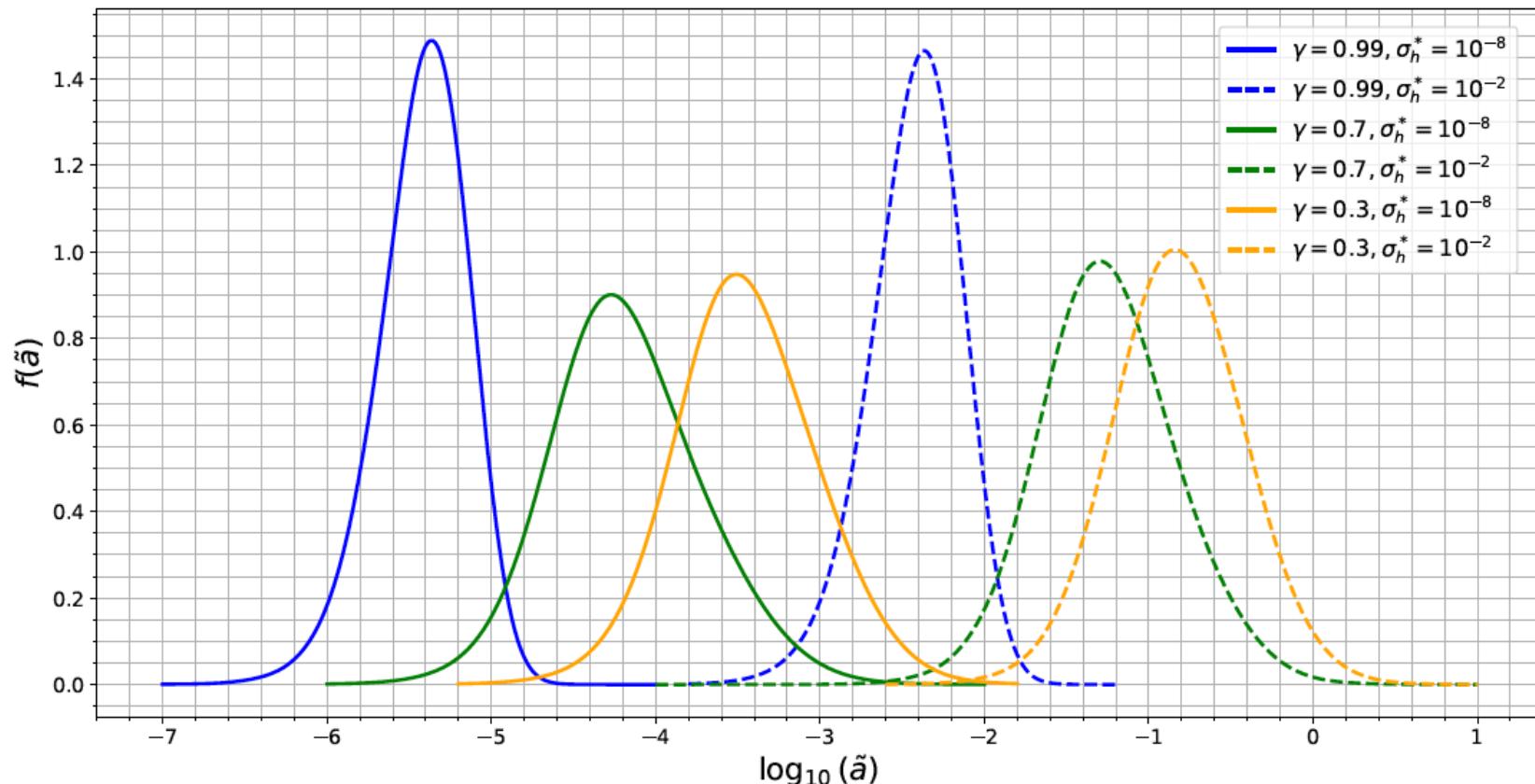
Suppressing PBH formation by anisotropy in the early matter dominated epoch (eMD)

Weitao Ye, Yungui Gong, Tomohiro Harada, Zhaofeng Kang, Kazunori Kohri, Daiki Saito, Chul-Moon Yoo, arXiv:2508.10070 [gr-qc]
Tomohiro Harada, Chul-Moon Yoo, Kazunori Kohri, Ken-ichi Nakao, Sanjay Jhingan, arXiv:1609.01588 [astro-ph.CO]



Spin distribution of PBHs formed in the early matter dominated epoch (eMD)

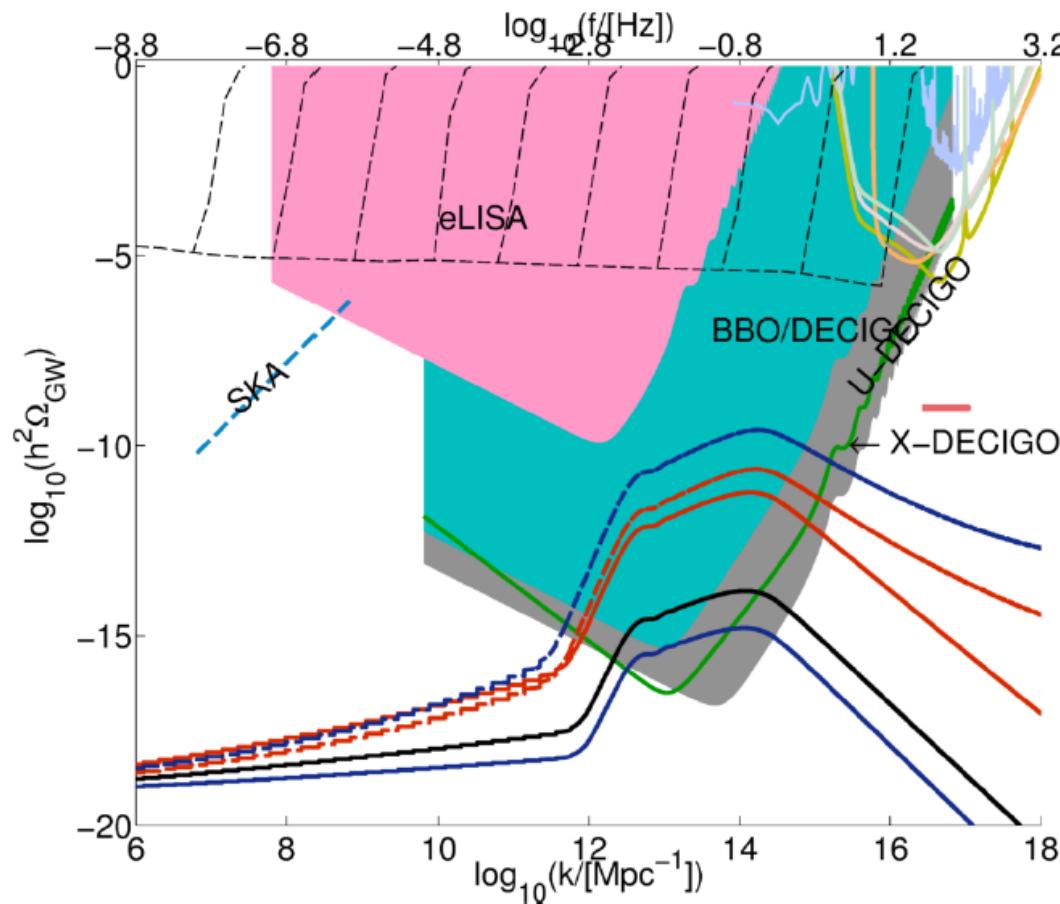
Weitao Ye, Yungui Gong, Tomohiro Harada, Zhaofeng Kang, Kazunori Kohri, Daiki Saito, Chul-Moon Yoo, arXiv:2508.10070 [gr-qc]



Another topics

Enhanced IGW? at the sudden transition from eMD to RD

Laila Alabidi, Kazunori Kohri, Misao Sasaki, Yuuiti Sendouda,
arXiv:1303.4519 [astro-ph.CO]



This work gave us a part of the idea that would later be named **the poltergeist mechanism** proposed by Inomata, Kohri, Nakama and Terada

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