

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

Kazunori Kohri

郡 和範

NAOJ/KEK/Sokendai/  
Kavli IPMU



理論センター  
THEORY CENTER



# 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**

# 17<sup>th</sup>, Dec, 2001 at Okazaki Baseball Stadium, Kyoto





18<sup>th</sup>, Oct, 2019 at Prof. Sasaki's office  
at LeCOSPAs, NTU, Taipei



Photos taken by K. Kohri



# 15<sup>th</sup>, Nov, 2012 at JGRG

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



# 22<sup>nd</sup>, March, 2014

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

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

Kodama, Sasaki, Katsuhiko Sato, Kei-ichi Maeda

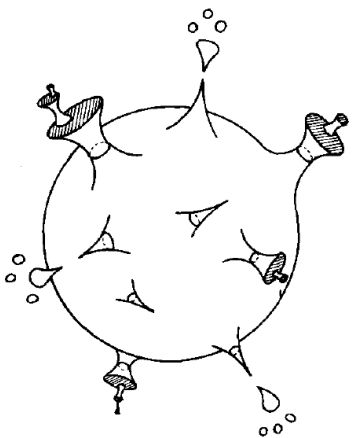


Fig. 2.



17<sup>th</sup>, Oct, 2019 at Taipei



Photo taken by K. Kohri



18<sup>th</sup>, Nov, 2019 at CosPA 2019/APPC14 hold by  
DACG/AAPPS, at Borneo Convention Center,  
Kuching, Sarawak, Malaysia





# 18<sup>th</sup>, July, 2022 during COVID at IPMU

Work from home  
and refrain from nonessential and  
nonurgent activities



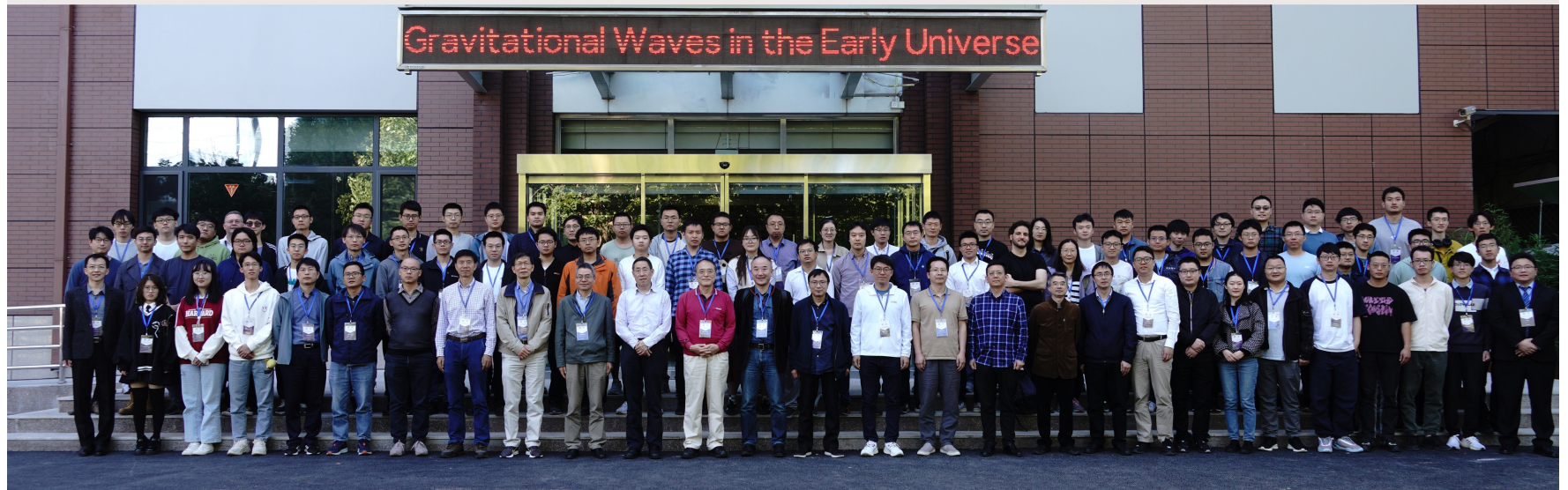


# Workshop organized by Shi Pi at 14<sup>th</sup>, Oct, 2023, Beijing, China



## International Mini-Workshop Gravitational Waves in the Early Universe

13-16 Oct. 2023  
Beijing, China



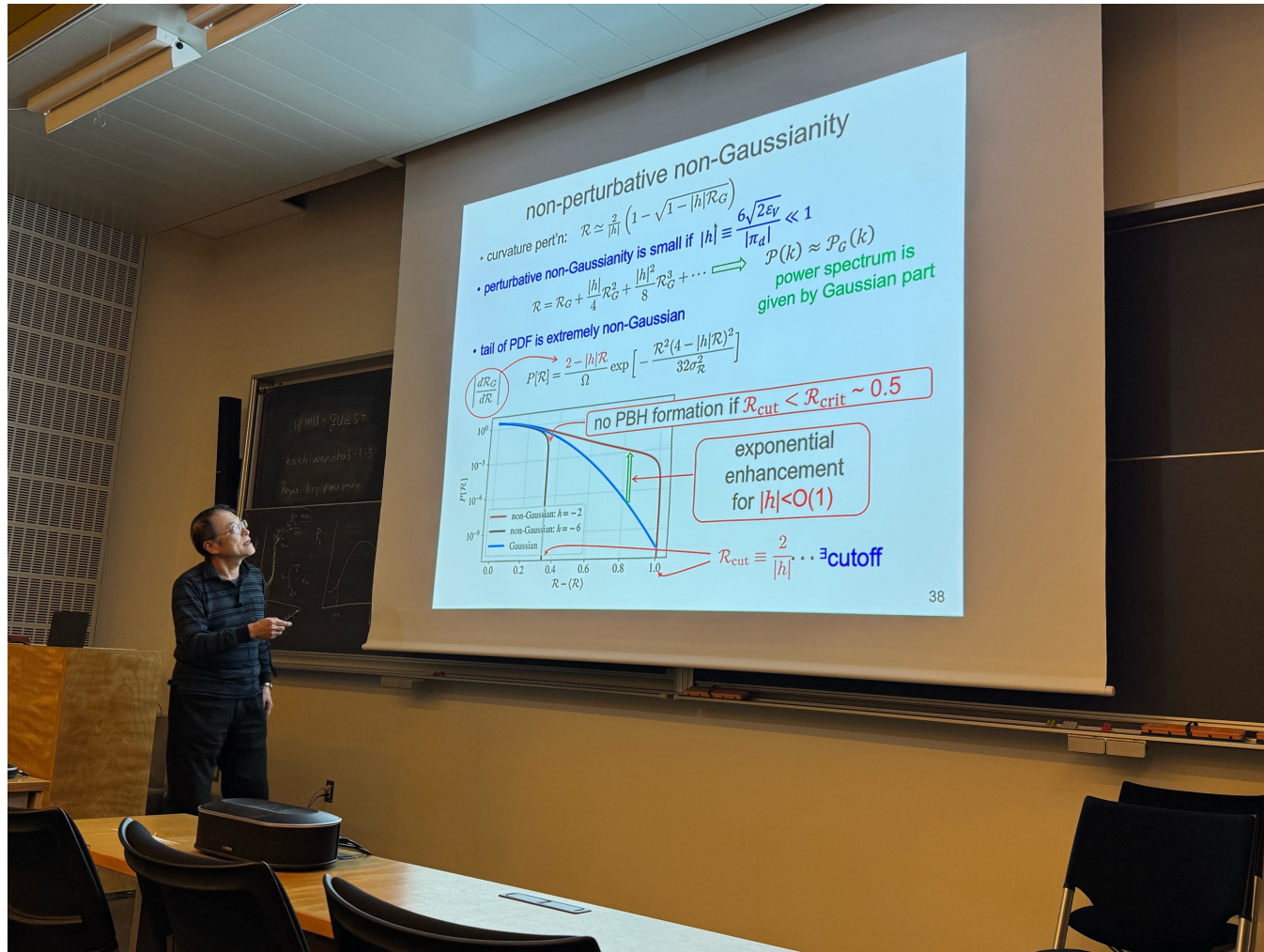


# LeCOSPA-IPMU workshop at 2<sup>nd</sup>, April, 2025, NTU, Taipei





# On Misao's final Lectures at IPMU 9<sup>th</sup>, 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, ...



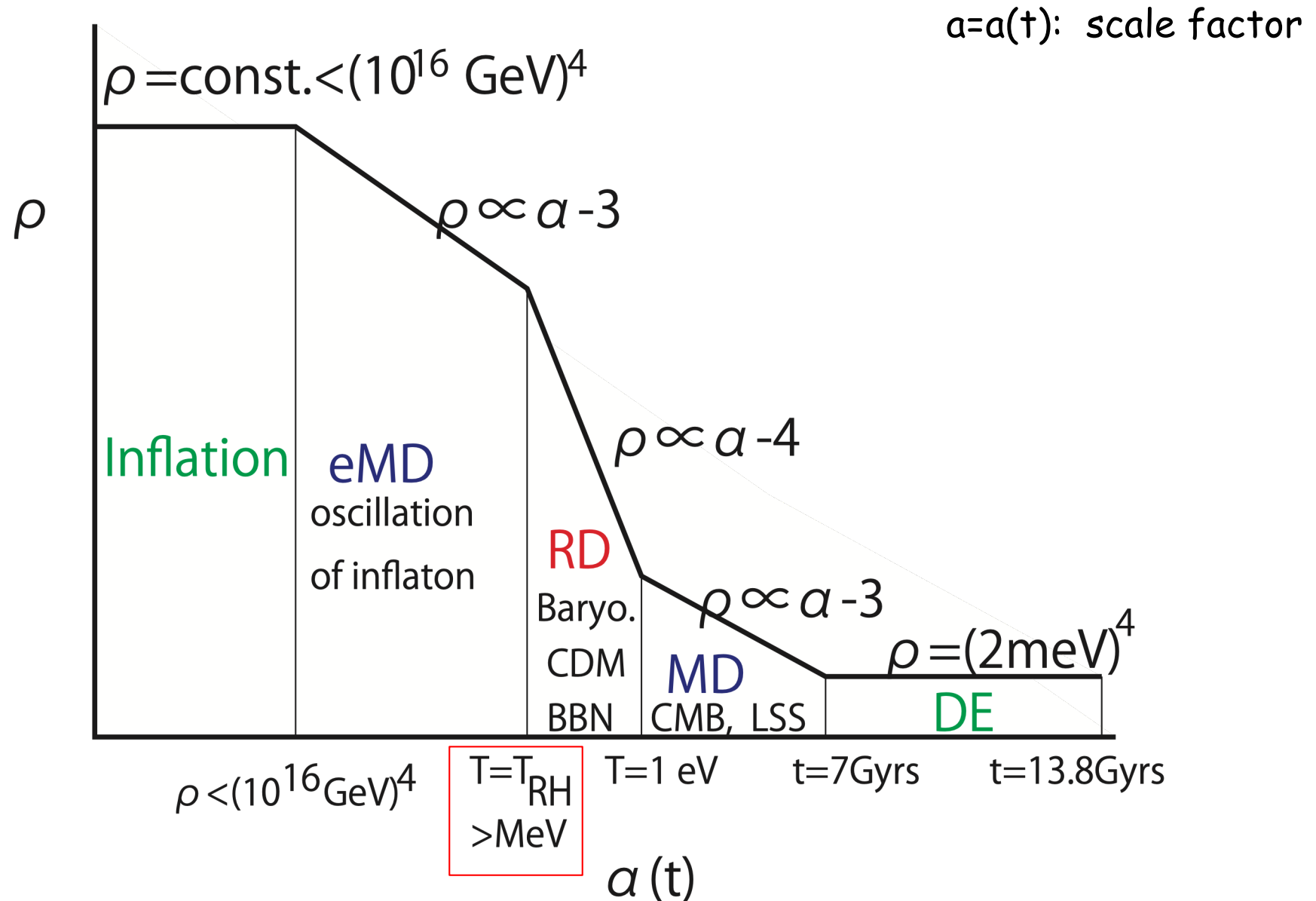
Formations of PBHs in the **early**  
**Matter Dominated** epoch

# 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  $q_i$

$$r_1 = (a - \alpha b)q_1$$

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 2<sup>nd</sup> Elliptic function  $E(x)$

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

- 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

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

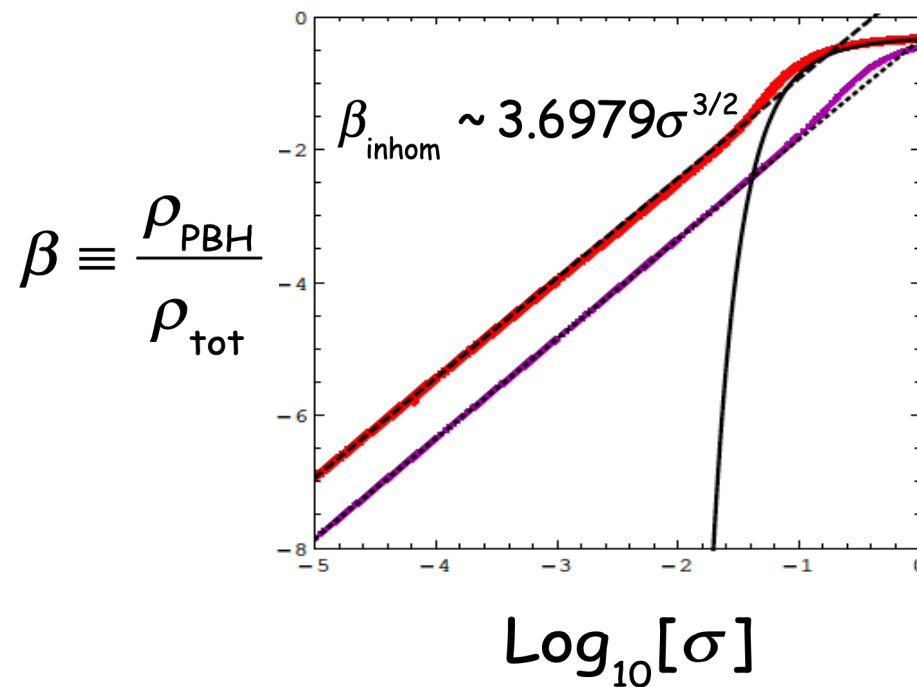
$$\begin{aligned}
 h(\alpha, \beta, \gamma) &= \frac{2}{\pi} \frac{\alpha - \gamma}{\alpha^2} E \left( \sqrt{1 - \left( \frac{\alpha - \beta}{\alpha - \gamma} \right)^2} \right) \\
 h(\alpha, \beta, \gamma) &:= \mathcal{C} / (2\pi r_g)
 \end{aligned}$$



# 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



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

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

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

# Velocity Dispersion and PBH formation

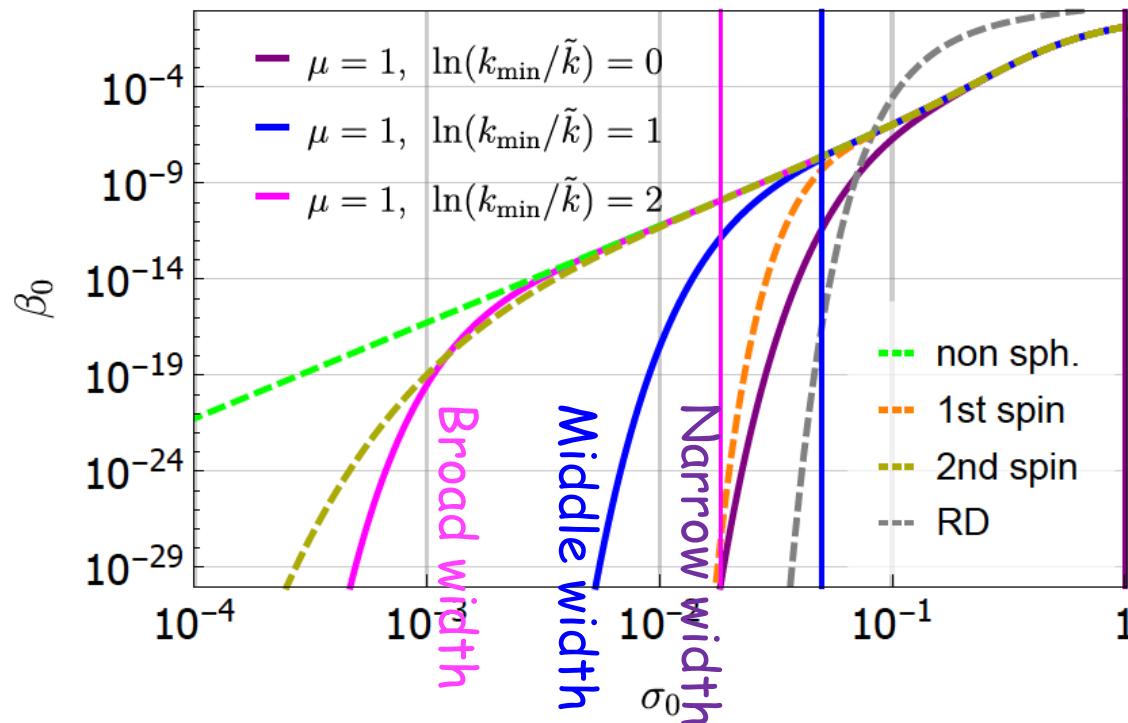
Tomohiro Harada, Kazunori Kohri, Misao Sasaki, Takahiro Terada, Chul-Moon Yoo, arXiv:2211.13950 [astro-ph.CO]

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

or equivalently,

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

where  $\mu$  is the non-dimensional parameter characterizing the width of the log-normal distribution.

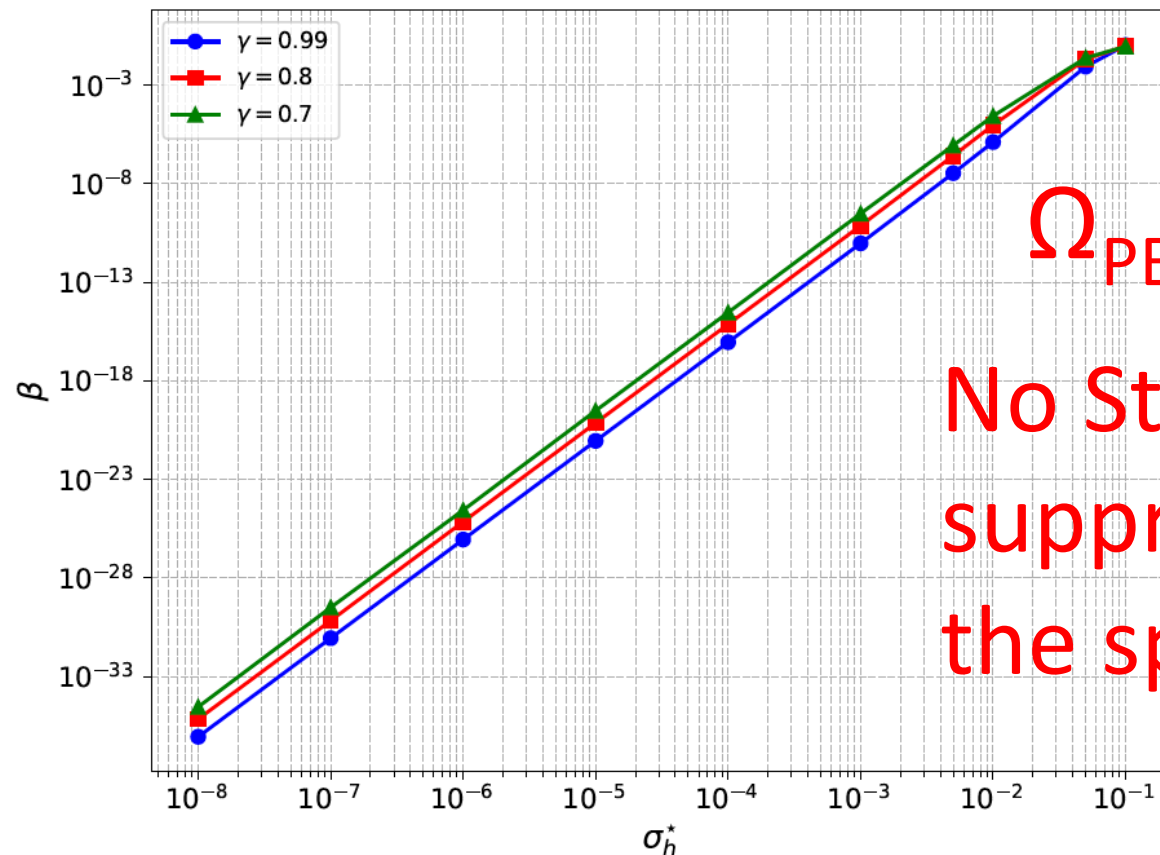


Narrow → Virialized  
Broad → Collapsed



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

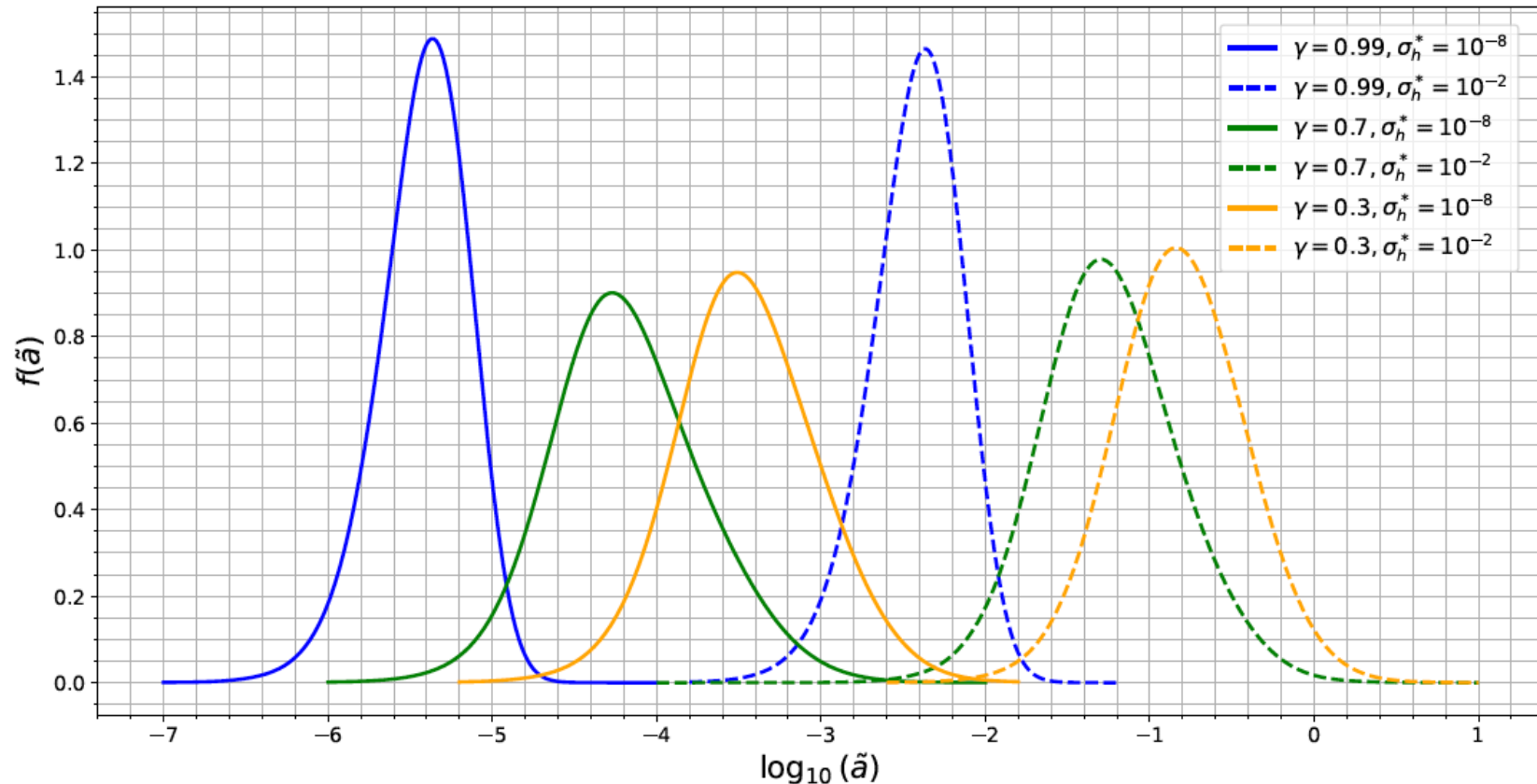
Weitao Ye, Yungui Gong, Tomohiro Harada, Zhaofeng Kang, Kazunori Kohri, Daiki Saito, Chul-Moon Yoo, arXiv:2508.10070 [gr-qc]  
Tomohiro Harada, Chul-Moon Yoo, Kazunori Kohri, Ken-ichi Nakao, Sanjay Jhingan, arXiv:1609.01588 [astro-ph.CO]



$\Omega_{\text{PBH}} \propto \sigma^5$   
No Strong  
suppression by  
the spin

# 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]

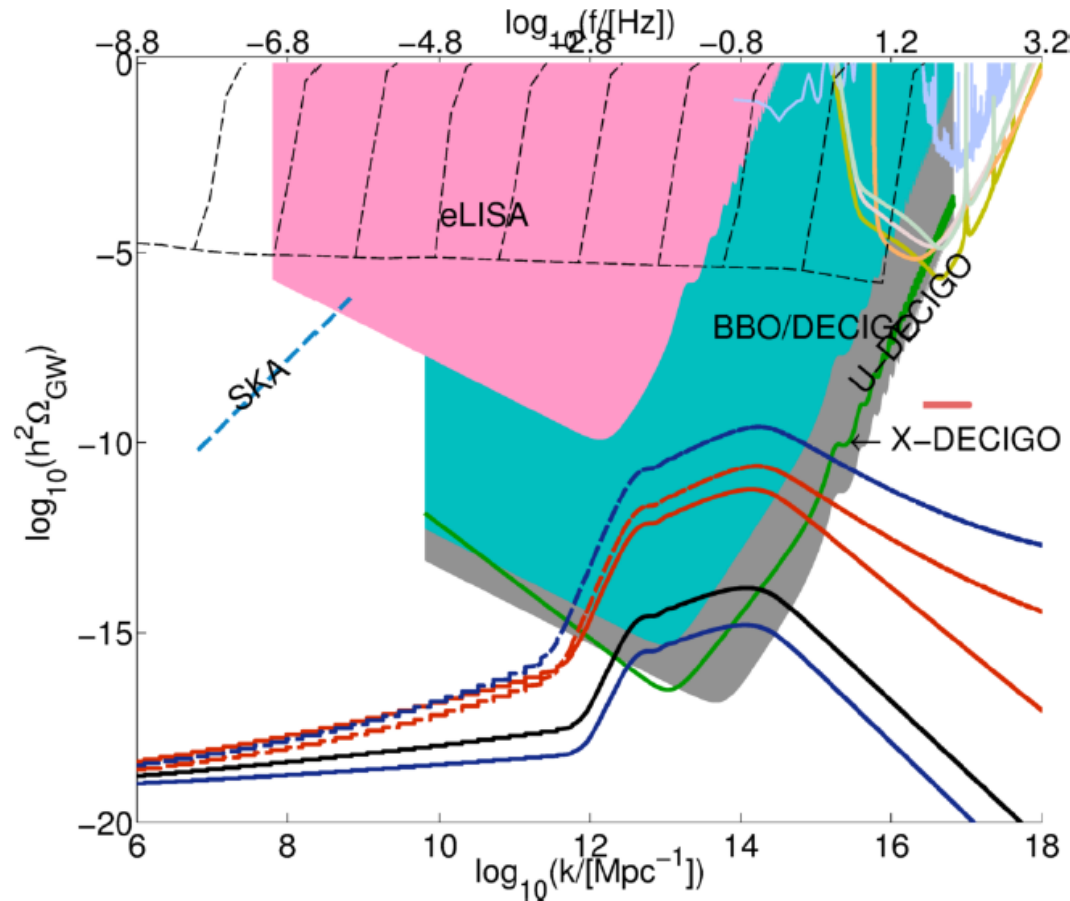




Another topics

# 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

# Summary

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