11th Dec. 2021 @ DECIGO workshop

インフレーションの「現在」と重力波

多田 祐一郎（名古屋大学 YLC 特任助教）

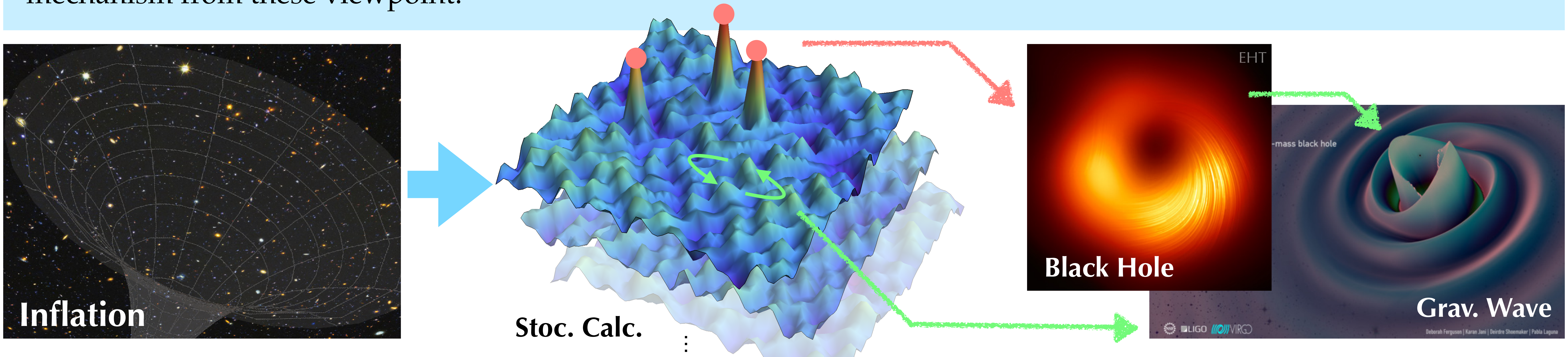
Yuichiro TADA (多田 祐一郎)

tada.yuichiro@e.mbox.nagoya-u.ac.jp

2017 Mar.	Ph.D. (Science)	The University of Tokyo (KavliIPMU & ICRR)
2017 Apr.	PD researcher	Institute d'Astrophysique de Paris
2018 Apr.	JSPS fellow (PD)	Nagoya University (C-lab.)
2021 Apr.	Designated Asst. Prof. (YLC)	Nagoya University (C-lab.)

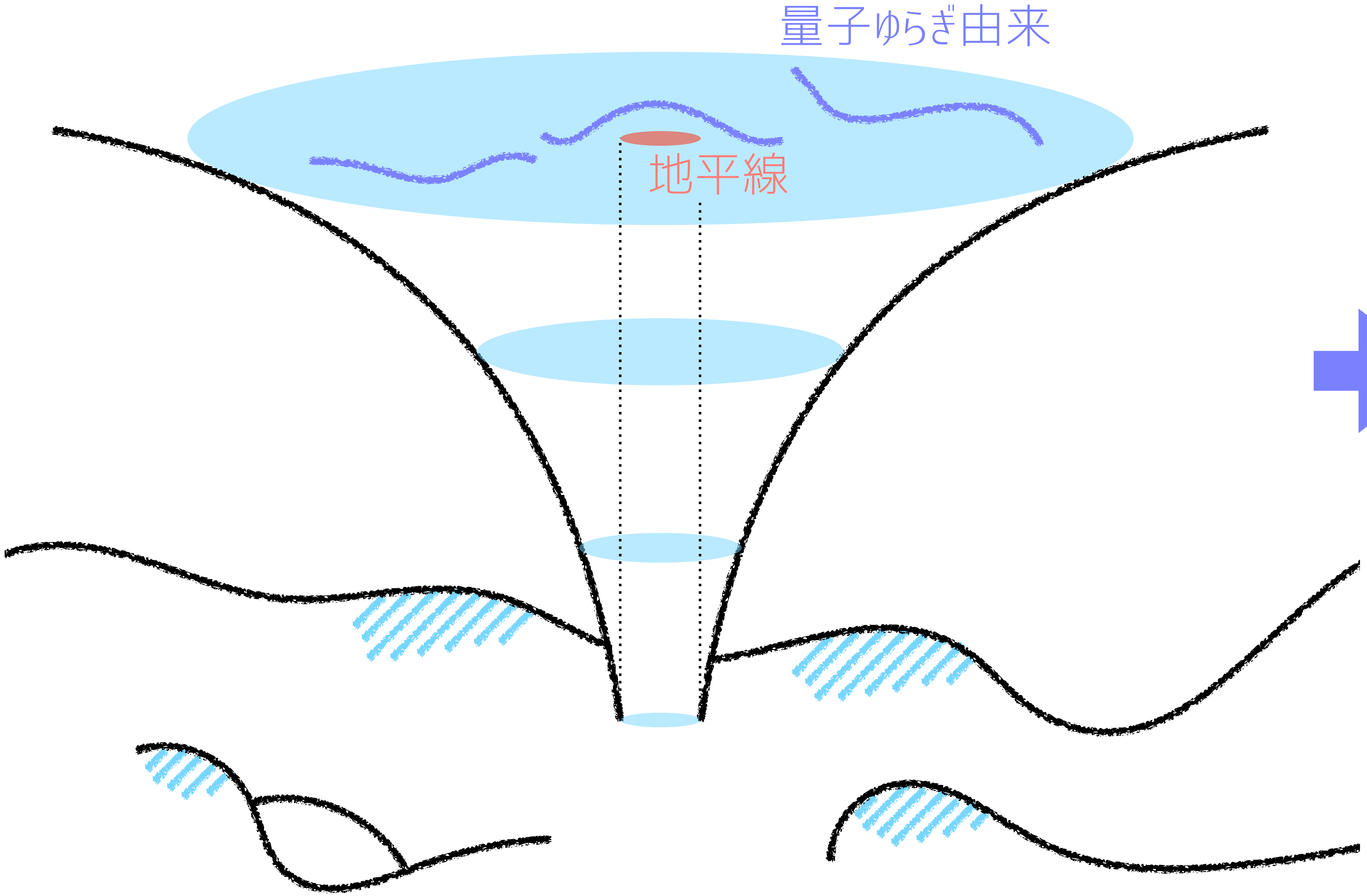
Research Topic: Approach to Cosmic Inflation in light of Stochastic Calc., Prim. Black Hole, and Grav. Wave

Our universe is thought to start with an accelerated expansion phase called **Inflation**. It can source various cosmic structures (e.g., galaxy) from quantum fluctuation, but its expansion mechanism has not been explained. As a possible sourced object, **Primordial Black Hole** (原始ブラックホール) has attracted attention as a candidate of **Dark Matter** (暗黒物質). **Gravitational Wave** (重力波) is also attractive because it can be directly detected now. I have proposed a powerful algorithm to evaluate their production by applying **Stochastic Calculus** (確率解析), and am approaching to the inflation mechanism from these viewpoint.



インフレーションとは

- 熱いビッグバン宇宙の前の加速膨張期



宇宙は
- 大局的には一様等方
- 局所的には豊かな構造
  （星，銀河，…）

インフレーションとは

- 量子ゆらぎの特徴量
  - 曲率ゆらぎ ζ ($\simeq$ 重力ポテンシャル, c.f. 密度ゆらぎ) のパワースペクトル $\mathscr{P}_\zeta(k)$

$$\mathscr{P}_\zeta(k = 0.05\,\mathrm{Mpc}^{-1}) = 2.1 \times 10^{-9} \sim \left(\frac{\Delta T_{\mathrm{CMB}}}{T_{\mathrm{CMB}}}\right)^2 \sim (10^{-5})^2$$

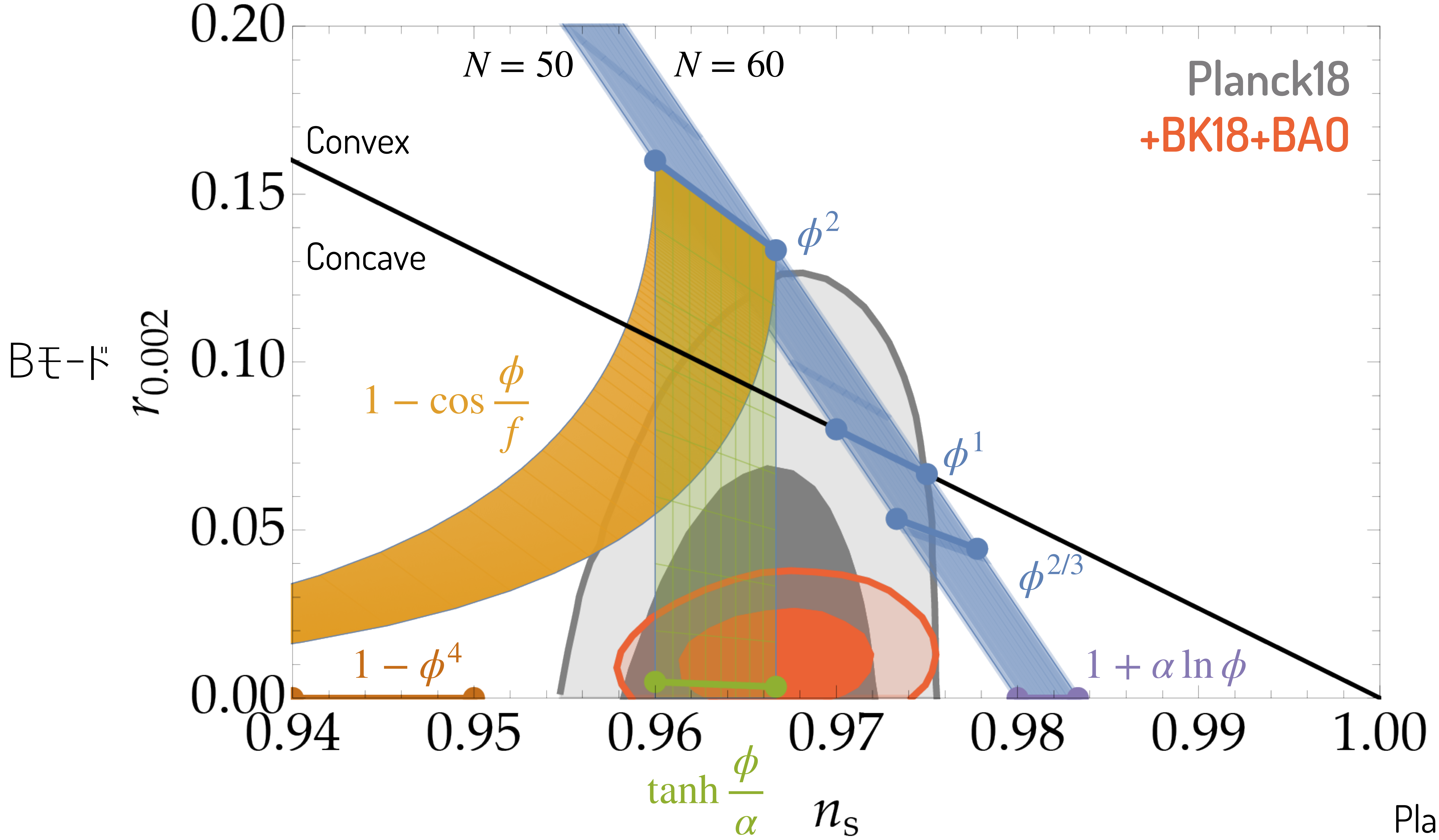
$$n_{\mathrm{s}} := 1 + \left.\frac{\mathrm{d}\ln \mathscr{P}_\zeta}{\mathrm{d}\ln k}\right|_{k=0.05\,\mathrm{Mpc}^{-1}}$$

  - 重力波 h のパワースペクトル $\mathscr{P}_h(k)$

$$r := \left.\frac{\mathscr{P}_h(k)}{\mathscr{P}_\zeta(k)}\right|_{k=0.05\,\mathrm{Mpc}^{-1}} = \frac{\mathscr{P}_h(k = 0.05\,\mathrm{Mpc}^{-1})}{2.1 \times 10^{-9}}$$

最新 CMB 制限

$$n_{\mathrm{s}} := 1 + \left.\frac{\mathrm{d}\ln \mathscr{P}_\zeta}{\mathrm{d}\ln k}\right|_{k=0.05\,\mathrm{Mpc}^{-1}} \qquad r_{0.002} := \left.\frac{\mathscr{P}_h(k)}{\mathscr{P}_\zeta(k)}\right|_{k=0.002\,\mathrm{Mpc}^{-1}}$$



Planck '18, BK '21

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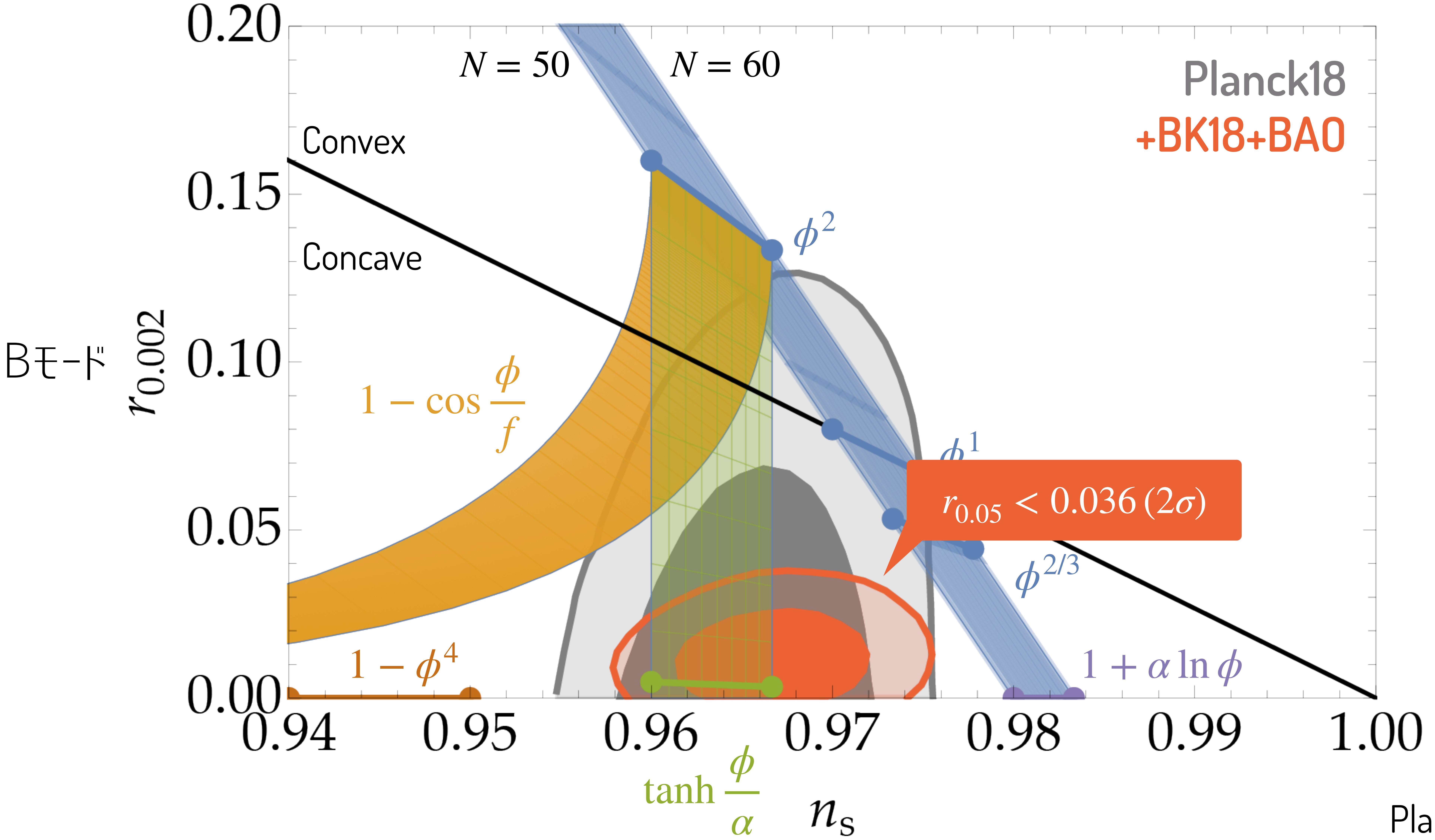
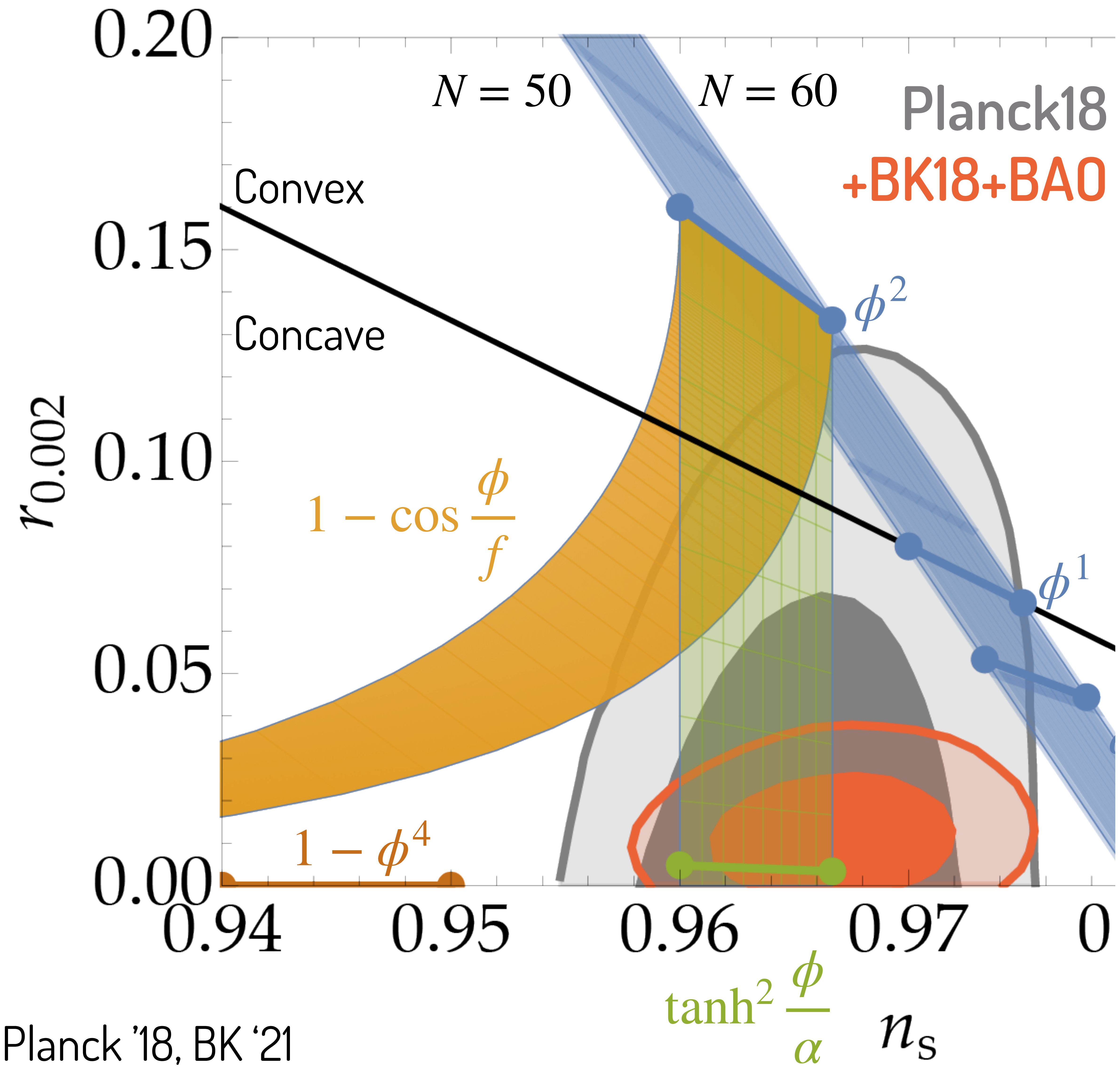


Planck '18, BK '21

最新 CMB 制限



Planck '18, BK '21

✗

- Large-field $r \sim \mathcal{O}(0.1)$
  - chaotic
  - natural

✓

- Plateau-type $r \sim \mathcal{O}(10^{-3})$
  - Starobinsky

$$\mathscr{L} = \frac{1}{16\pi G}R + \alpha R^2$$

  - Higgs

$$\mathscr{L} = \left(\frac{1}{16\pi G} + \xi\mathscr{H}^2\right)R + \mathscr{L}_\mathrm{SM}$$

▲

- Small-field $r \ll 1$
  - hilltop

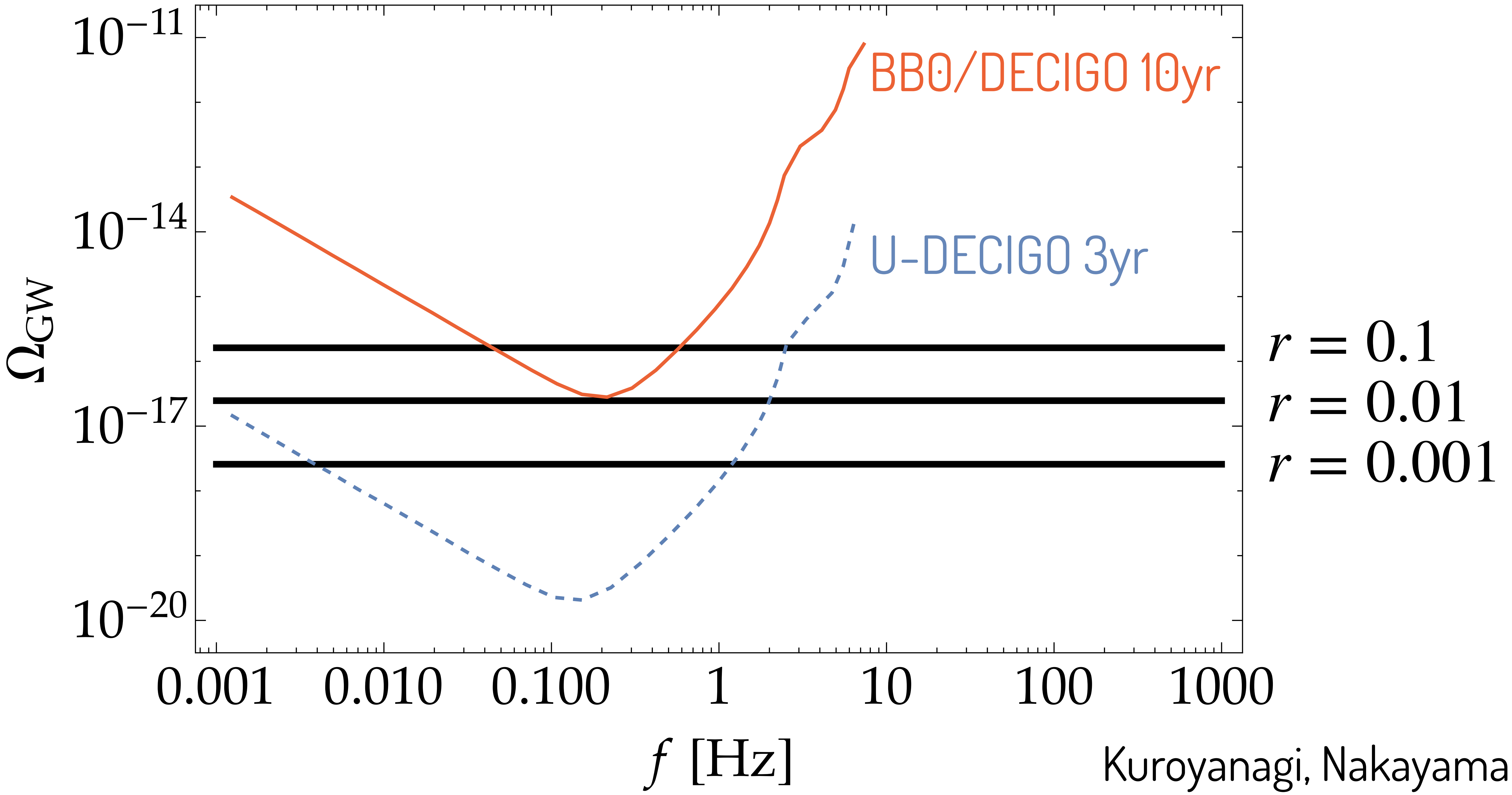
c.f. $1 - \phi^4 - \phi - \cdots$

(✓ – curvaton
check nonGauss

r in DECIGO?

- RD に horizon に入ってきた重力波

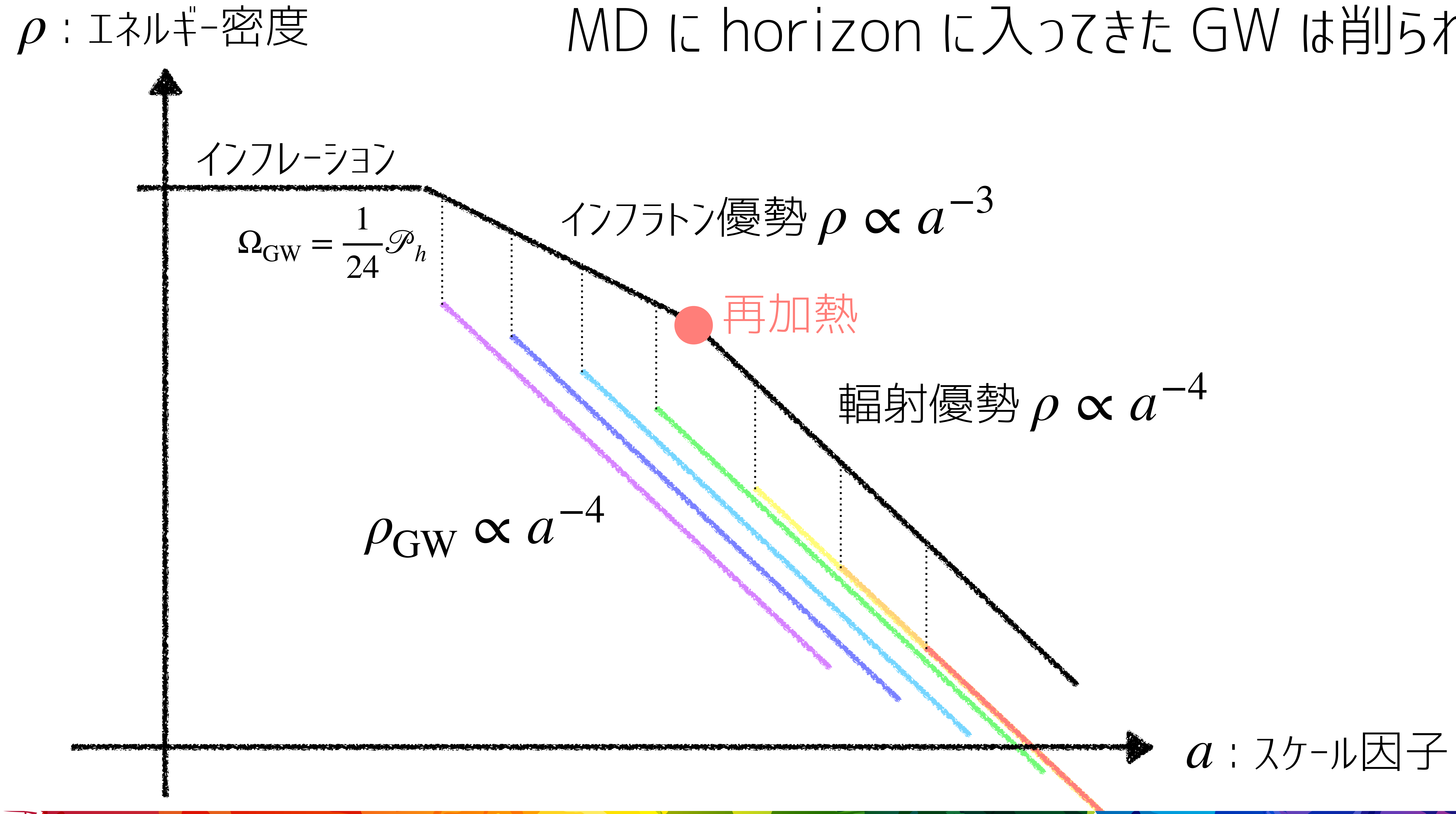
$$\Omega_{\rm GW}h^2 \simeq \frac{1}{24}\mathscr{P}_h \times \Omega_{\rm r}h^2 = 4\times 10^{-15} r \left(\frac{\mathscr{P}_\zeta}{2.1\times 10^{-9}}\right)\left(\frac{\Omega_{\rm r}h^2}{4.2\times 10^{-5}}\right)$$



Kuroyanagi, Nakayama, Saito '11

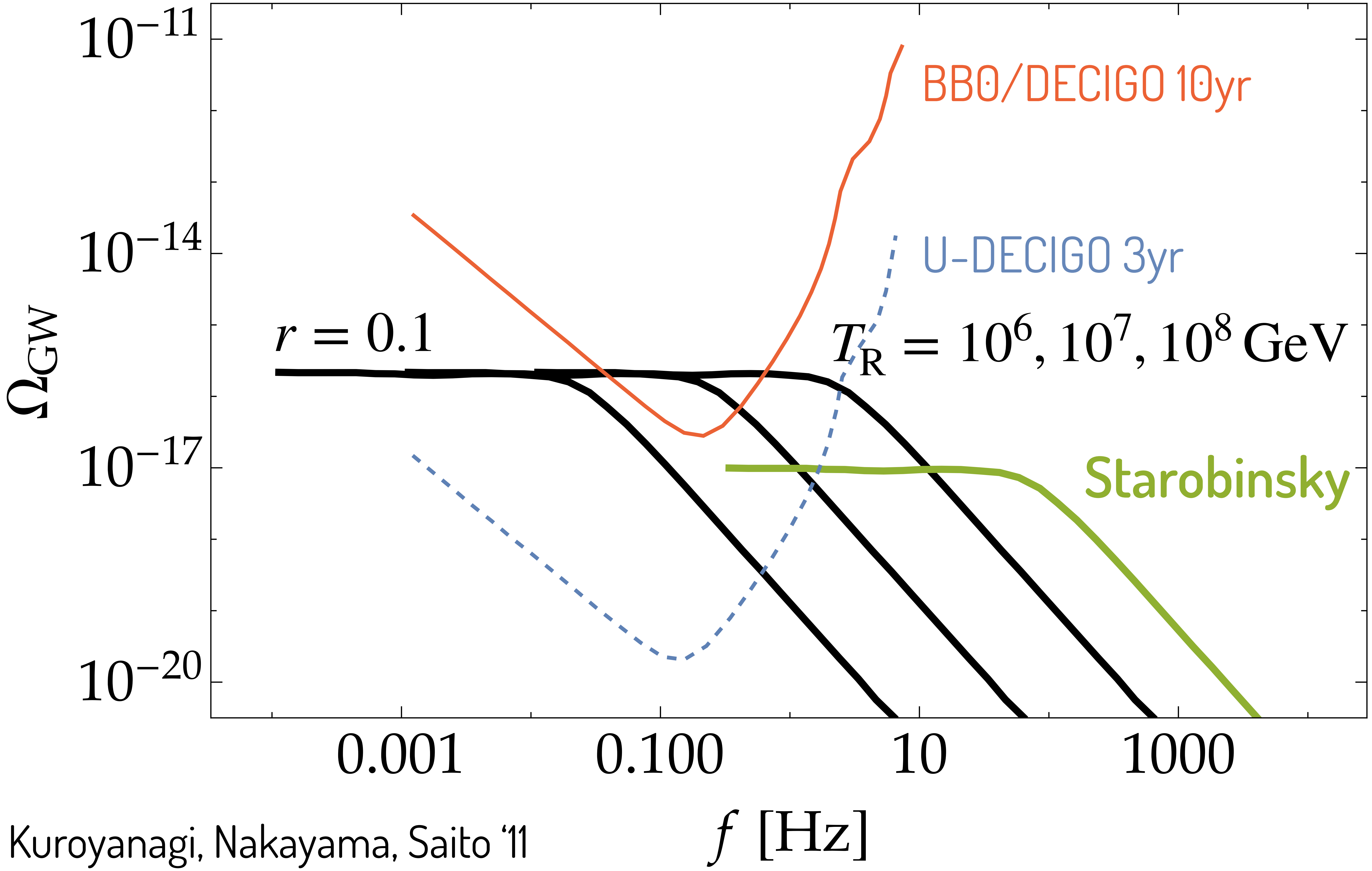
再加熱

MD に horizon に入ってきた GW は削られる



再加熱

MD に horizon に入ってきた GW は削られる



Kuroyanagi, Nakayama, Saito '11

$$r = 3 \times 10^{-3}$$

- Starobinsky

$$\mathscr{L} = \frac{1}{16\pi G} R + \alpha R^2 + \mathscr{L}_{\rm SM}$$

$\rightarrow$ $T_{\rm R} = 3 \times 10^9\,{\rm GeV}$

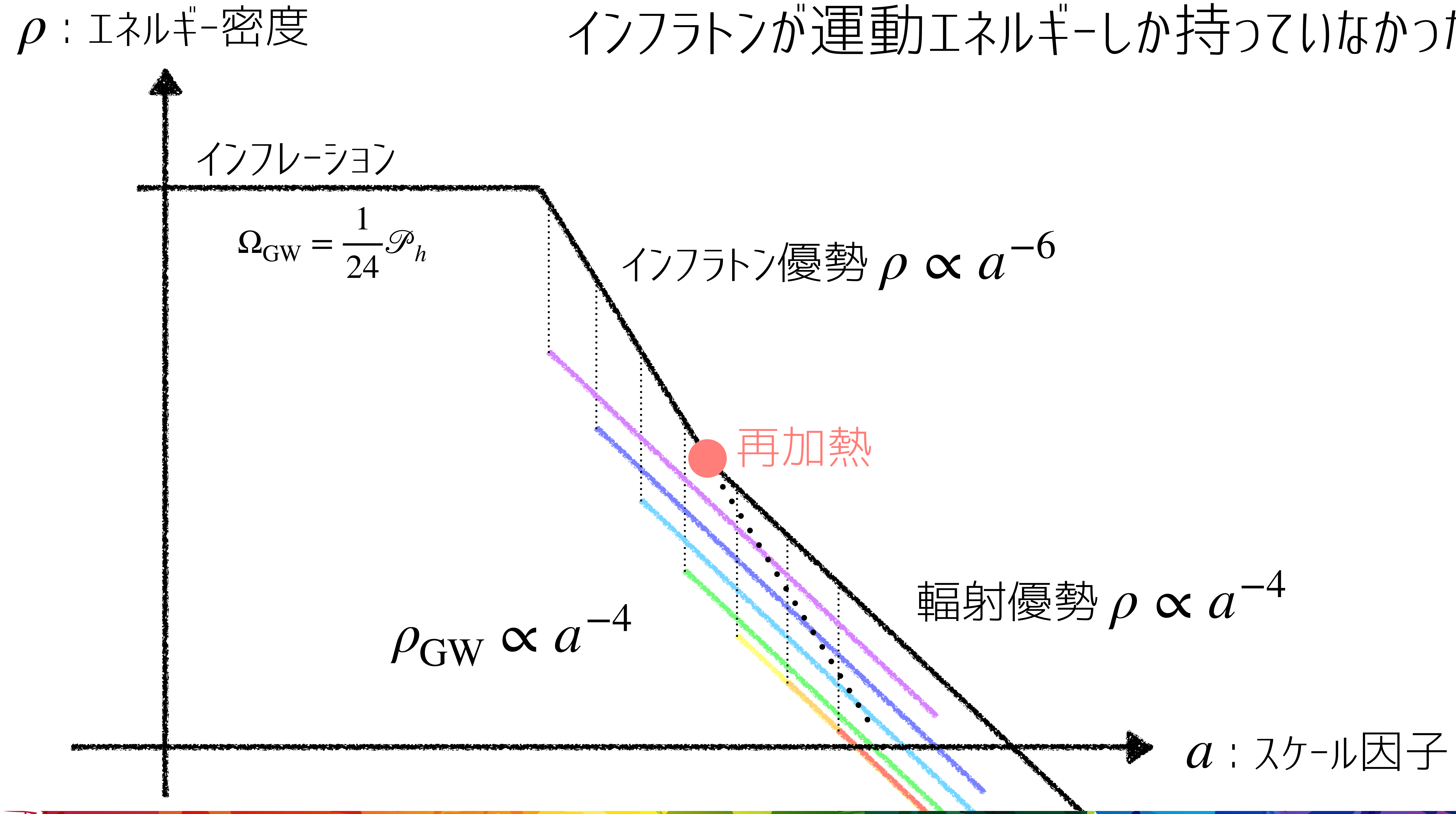
- Higgs

$$\mathscr{L} = \left(\frac{1}{16\pi G} + \xi \mathscr{H}^2 \right) R + \mathscr{L}_{\rm SM}$$

$\rightarrow$ $T_{\rm R} \sim 10^{14}\,{\rm GeV}$

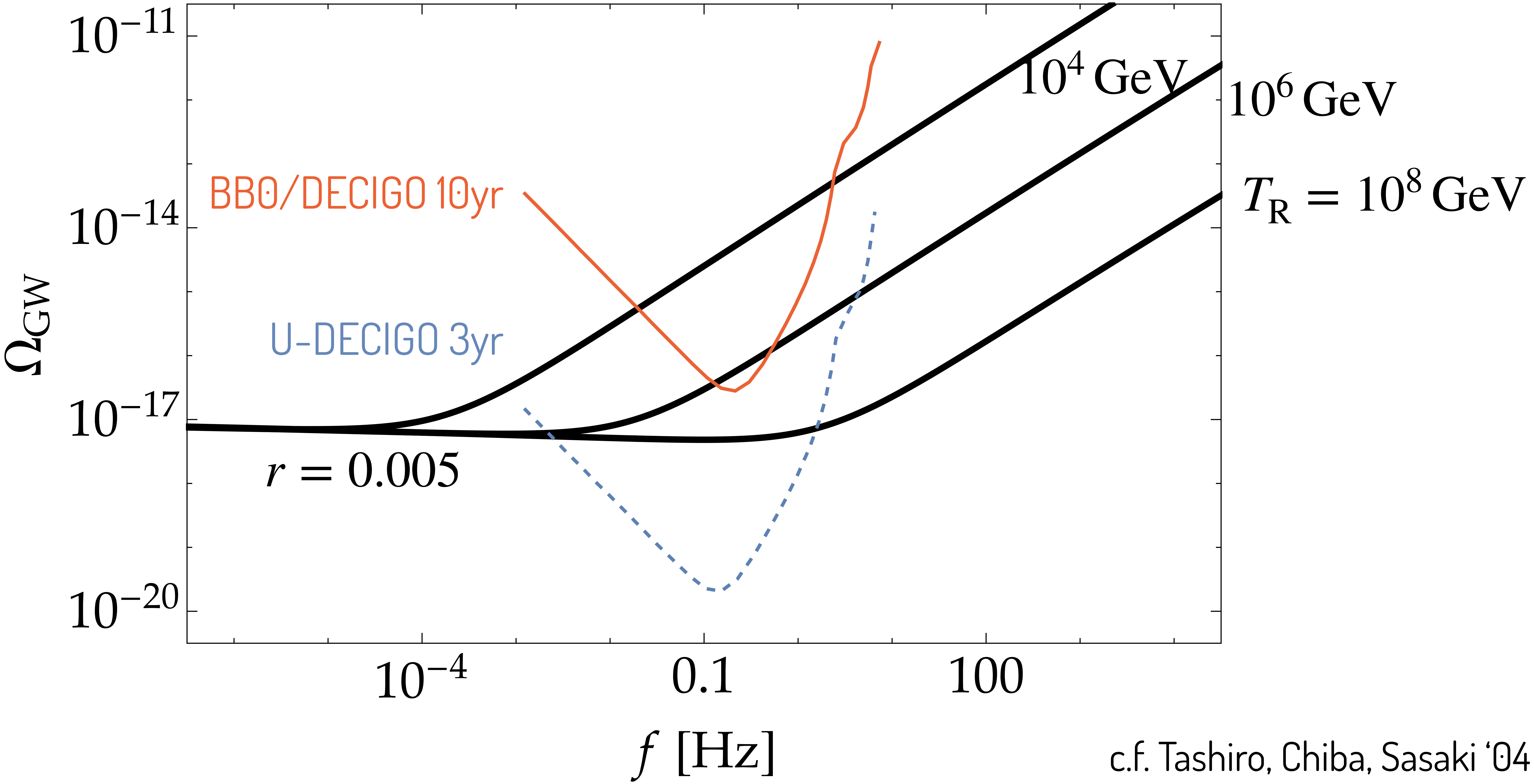
Kination

インフラトンが運動エネルギーしか持っていなかったら



Kination

インフラトンが運動エネルギーしか持っていなかったら

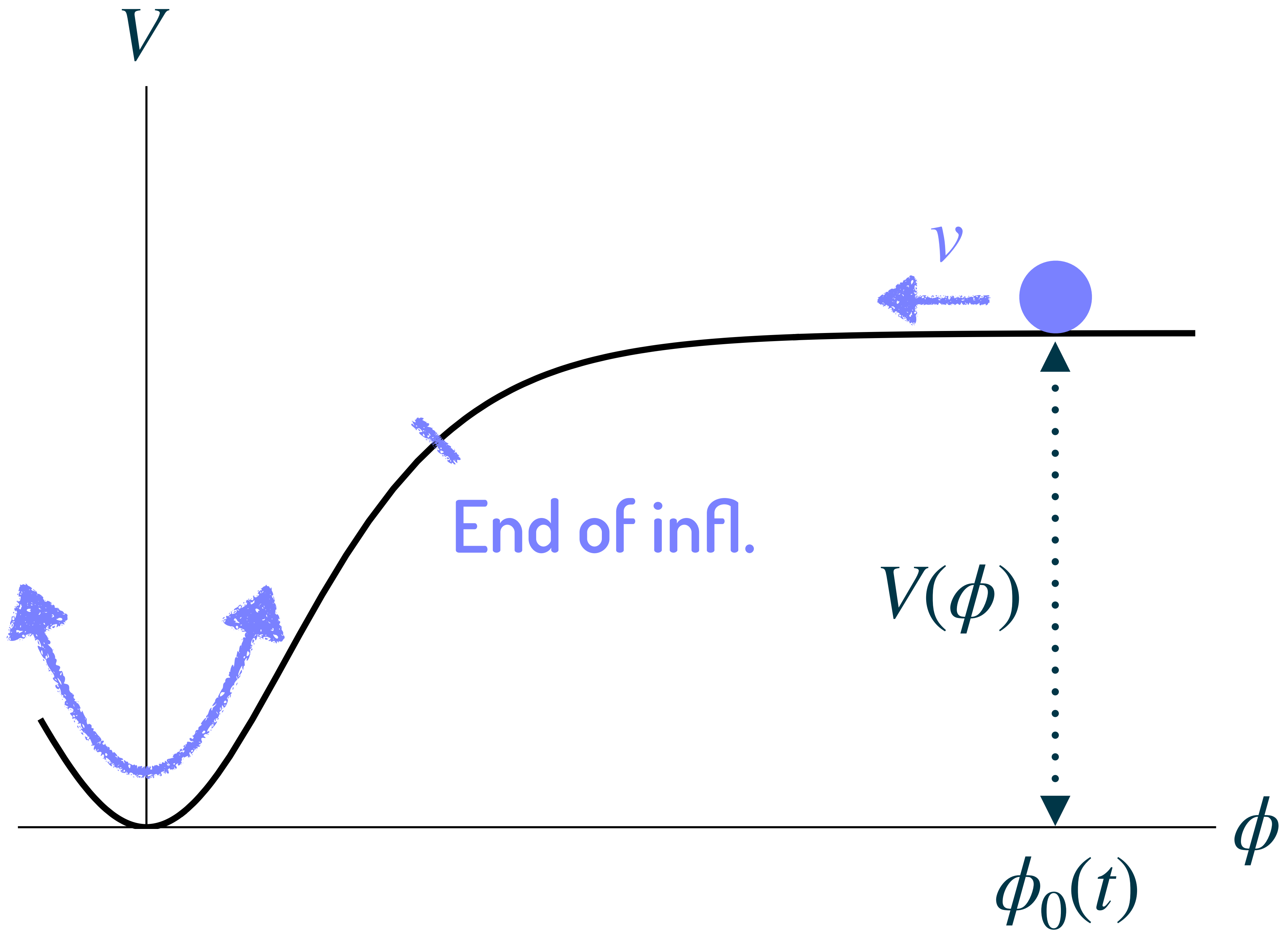


c.f. Tashiro, Chiba, Sasaki '04

k-inflation

Mukhanov+ '99

- 通常のインフレーション

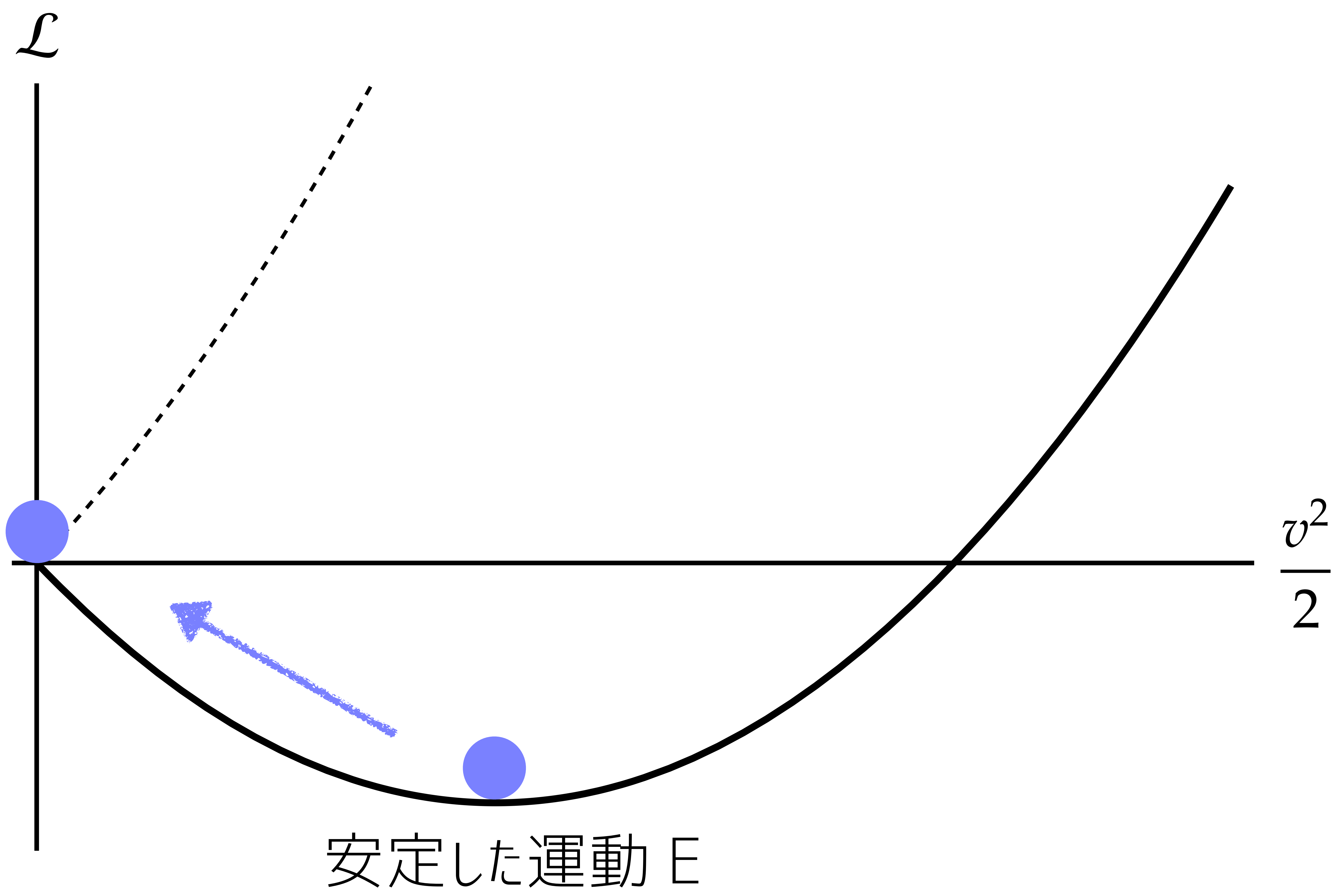


- インフラトンのポテンシャル E $\simeq$ 暗黒 E
- 運動 E $\dfrac{1}{2}v^2$ はすぐに薄まる

- k-inflation　　運動 E が薄まらない理論を作ればいい！

k-inflation

Mukhanov+ ‘99



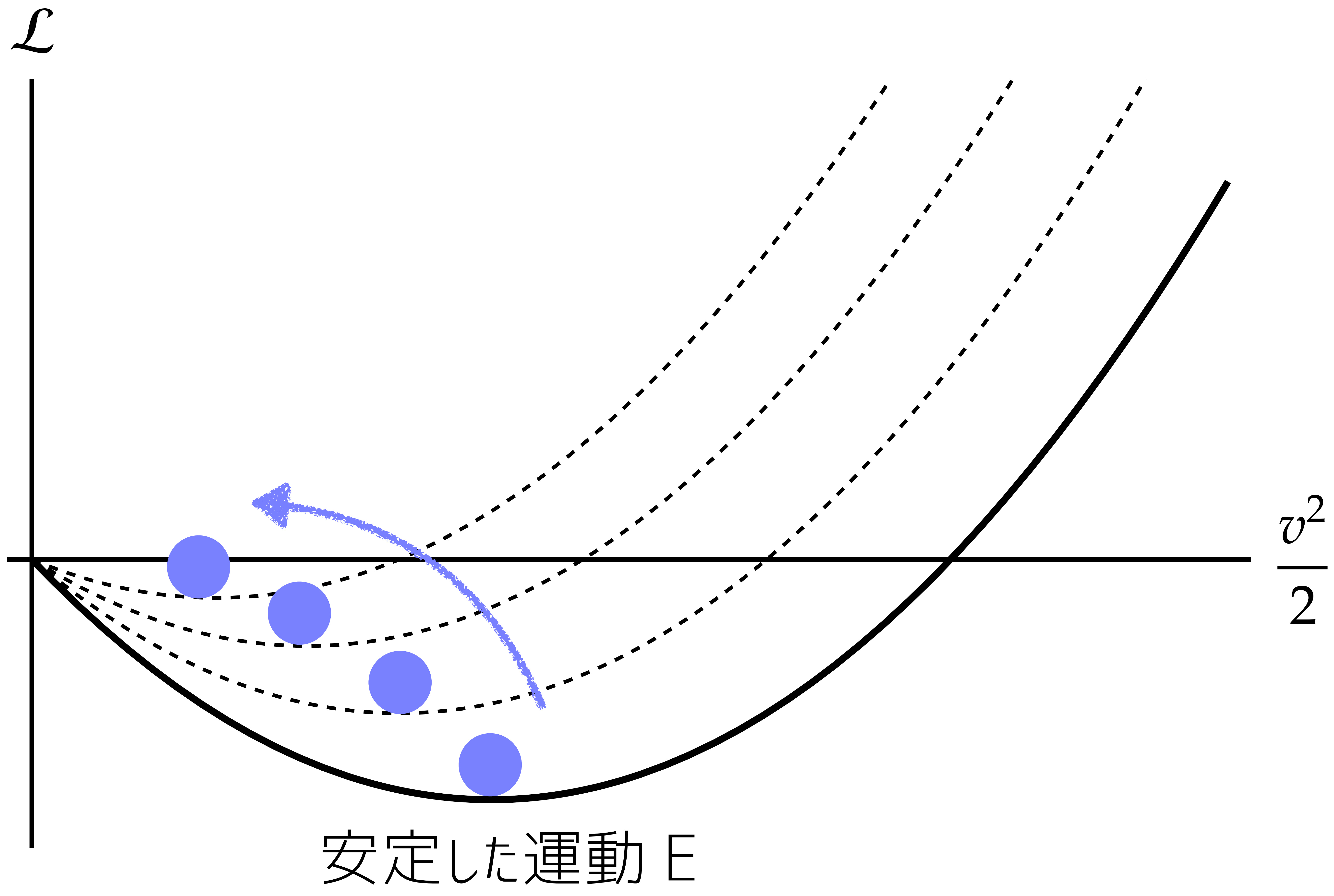
$$\mathscr{L} = -\left(\frac{1}{2}v^2\right) + \left(\frac{1}{2}v^2\right)^2$$

- インフラトンの音速が小さくなり
  ゆらぎの非ガウス性が大きくなる

→ CMB から棄却

minimal k

Mikura, YT, Yokoyama '21



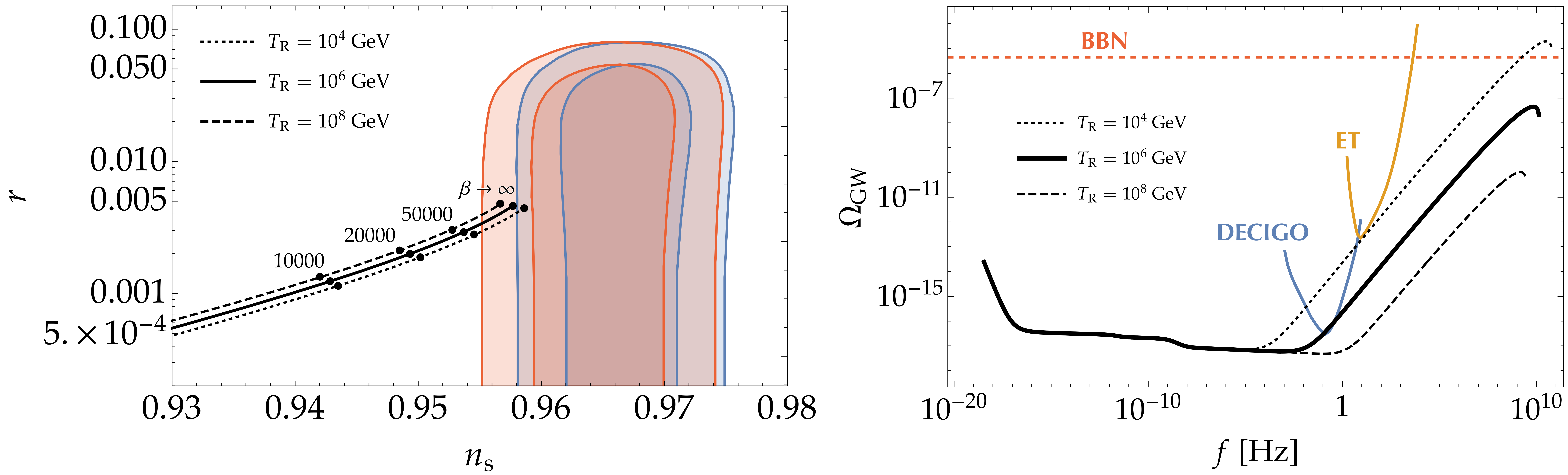
$$\mathscr{L} = -\phi \times \left(\frac{1}{2}v^2\right) + \left(\frac{1}{2}v^2\right)^2$$

非ガウス性許容範囲！

$c_s \sim 0.03 > 0.021\ (2\sigma)$

minimal k

Mikura, YT, Yokoyama ‘21

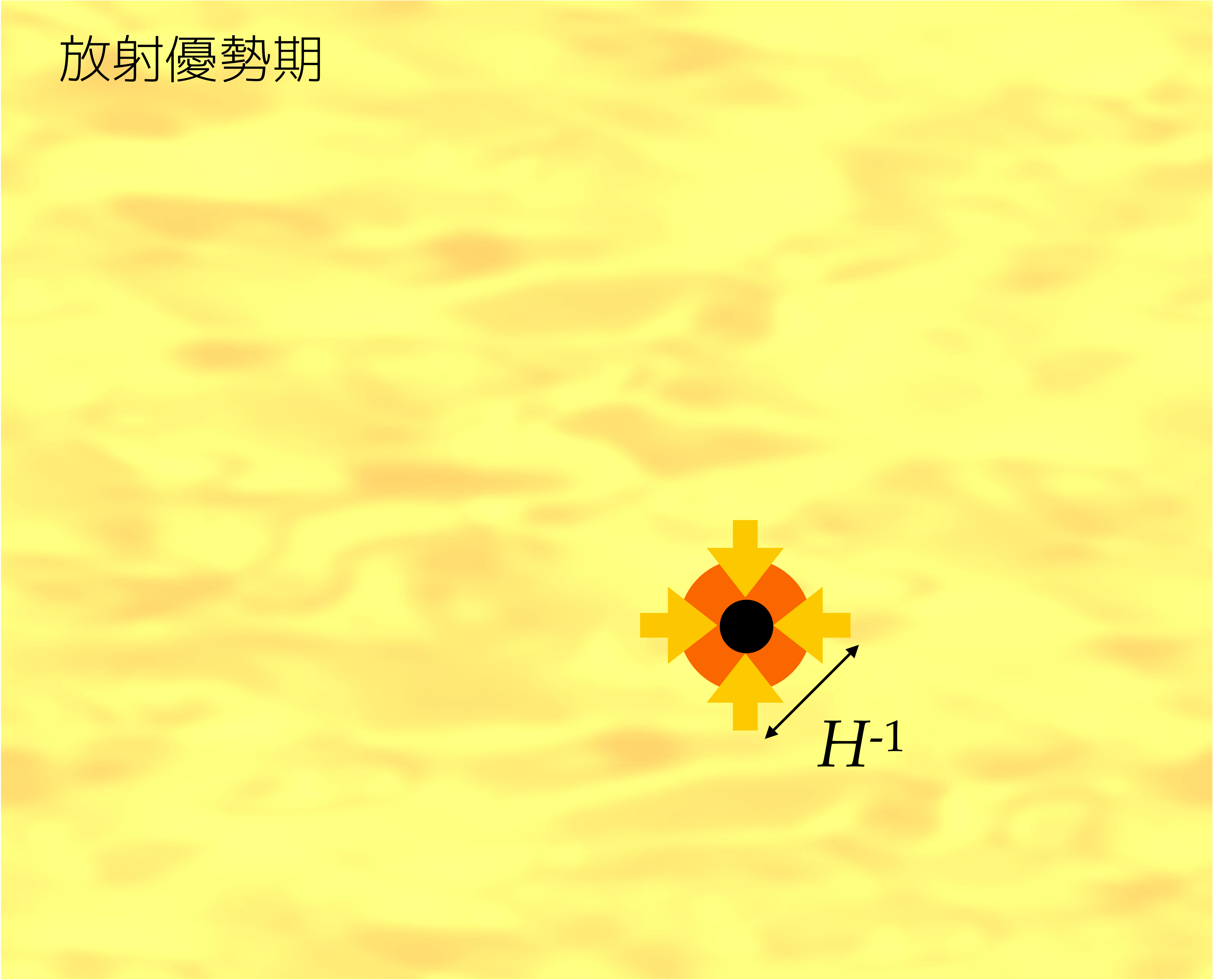


小まとめ

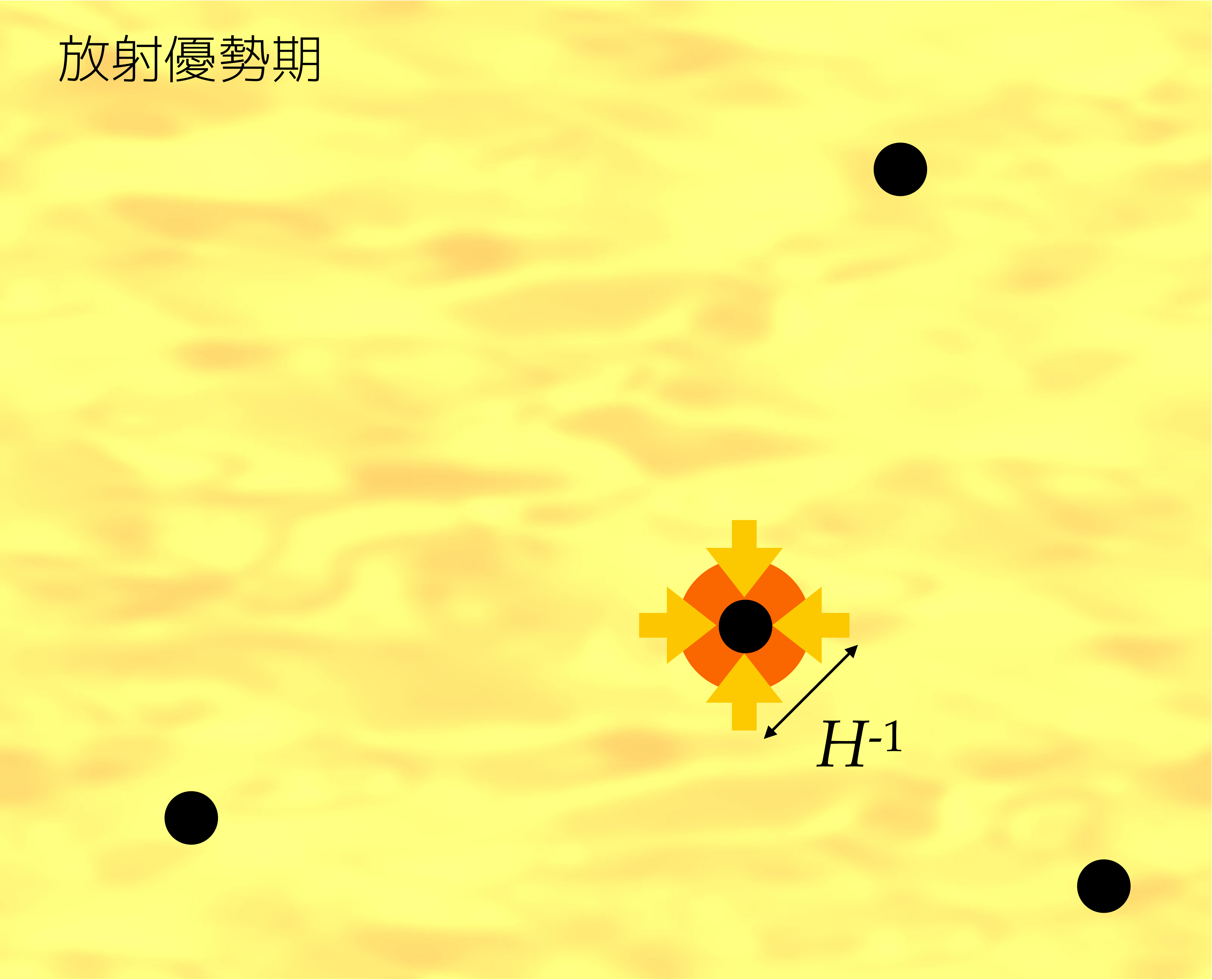
- Planck + BK でインフレーション理論に強い制限 ($r < 0.036$)
- 有望な理論 $r \sim \mathcal{O}(0.001) \Leftrightarrow \Omega_{\mathrm{GW}} \sim \mathcal{O}(10^{-17})$
- kination 期があると GW は増幅できる

原始ブラックホール Carr & Hawking 1974

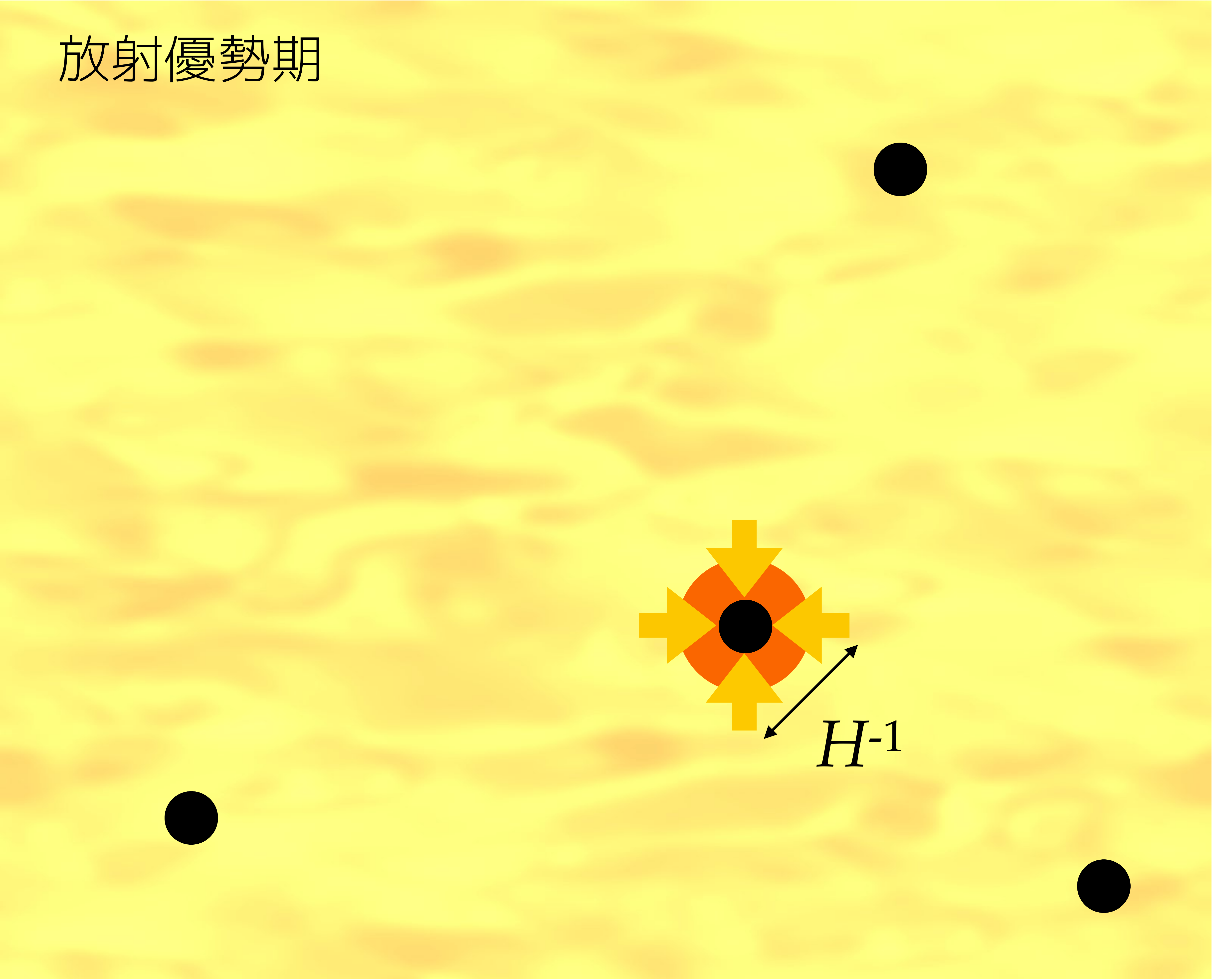
原始ブラックホール Carr & Hawking 1974



原始ブラックホール Carr & Hawking 1974



原始ブラックホール Carr & Hawking 1974



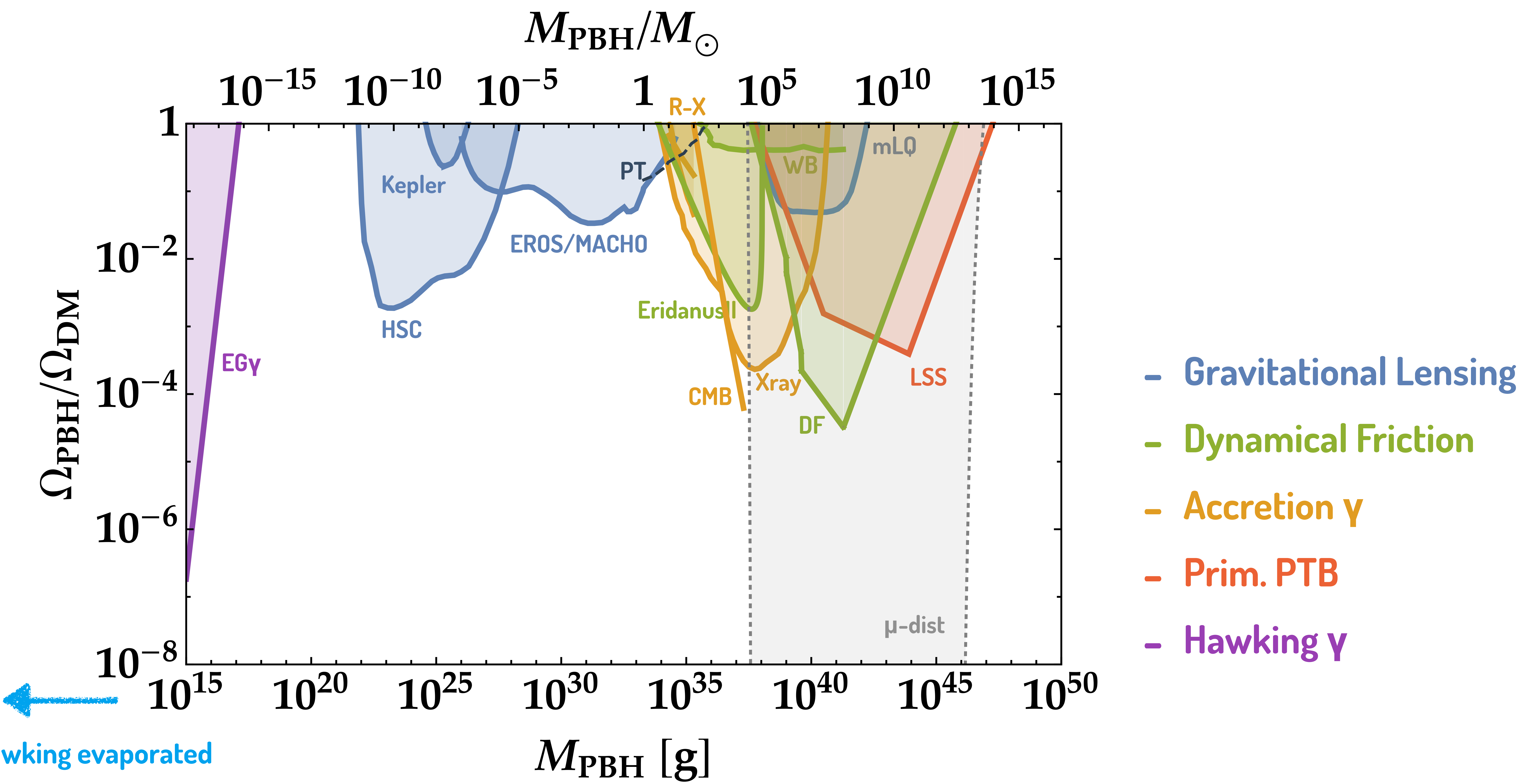
- PBH質量

$$M_{\mathrm{PBH}} \sim M_{\mathrm{H}} = \frac{4\pi}{3}\rho H^{-3} = \frac{1}{2GH}$$
$$\sim M_{\odot}\left(\frac{t_{\mathrm{PBH}}}{10^{-5}\,\mathrm{s}}\right)$$
$$\sim M_{\odot}\left(\frac{k_{\mathrm{PBH}}}{4\,\mathrm{pc}^{-1}}\right)^{-2}$$

$M_{\odot} \simeq 2\times 10^{33}\,\mathrm{g}$

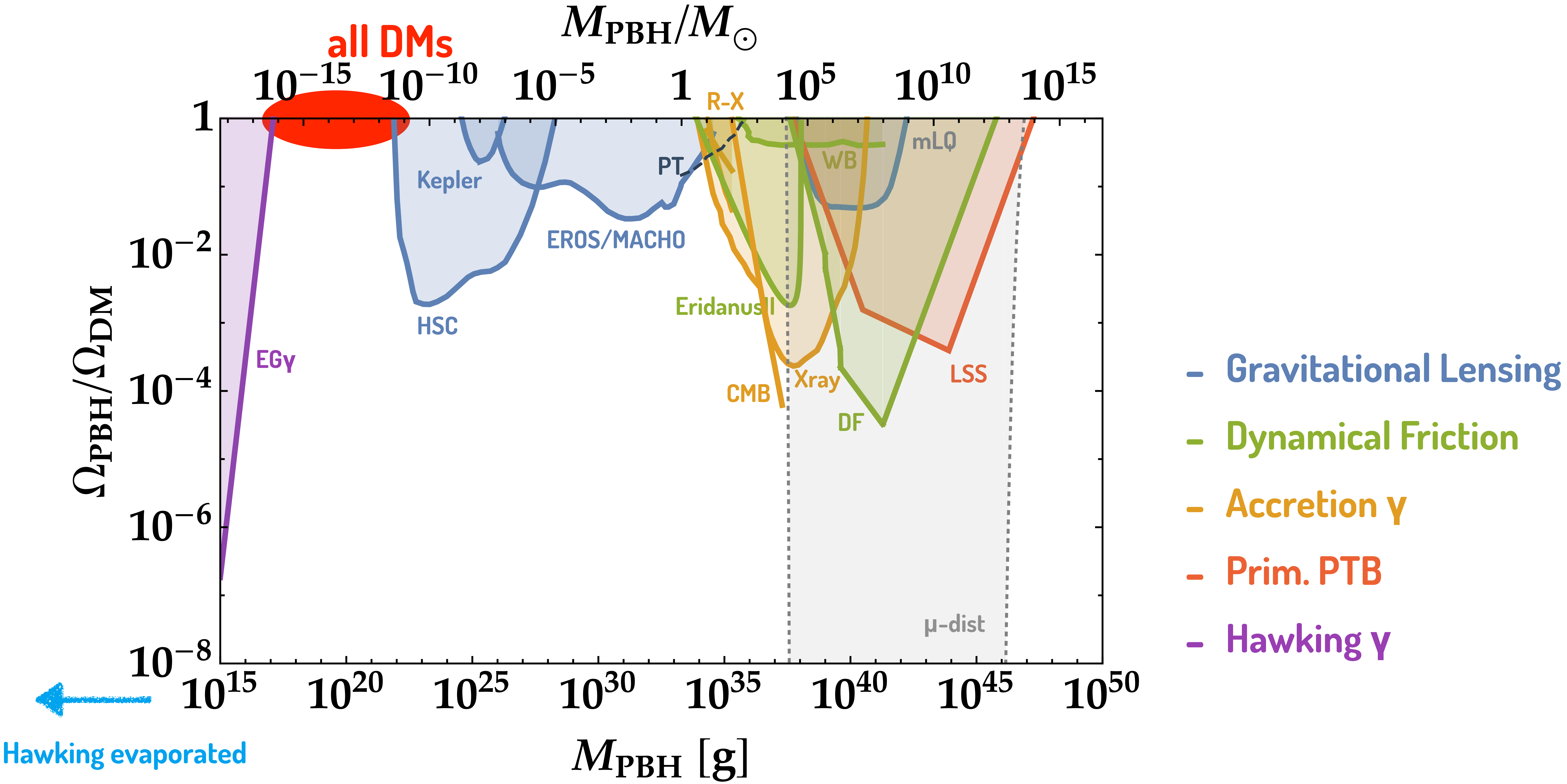
$$M_{\mathrm{Pl}} \simeq 2\times 10^{-5}\,\mathrm{g} \lesssim M_{\mathrm{PBH}} \lesssim 10^{15} M_{\odot}$$

観測的制限および動機

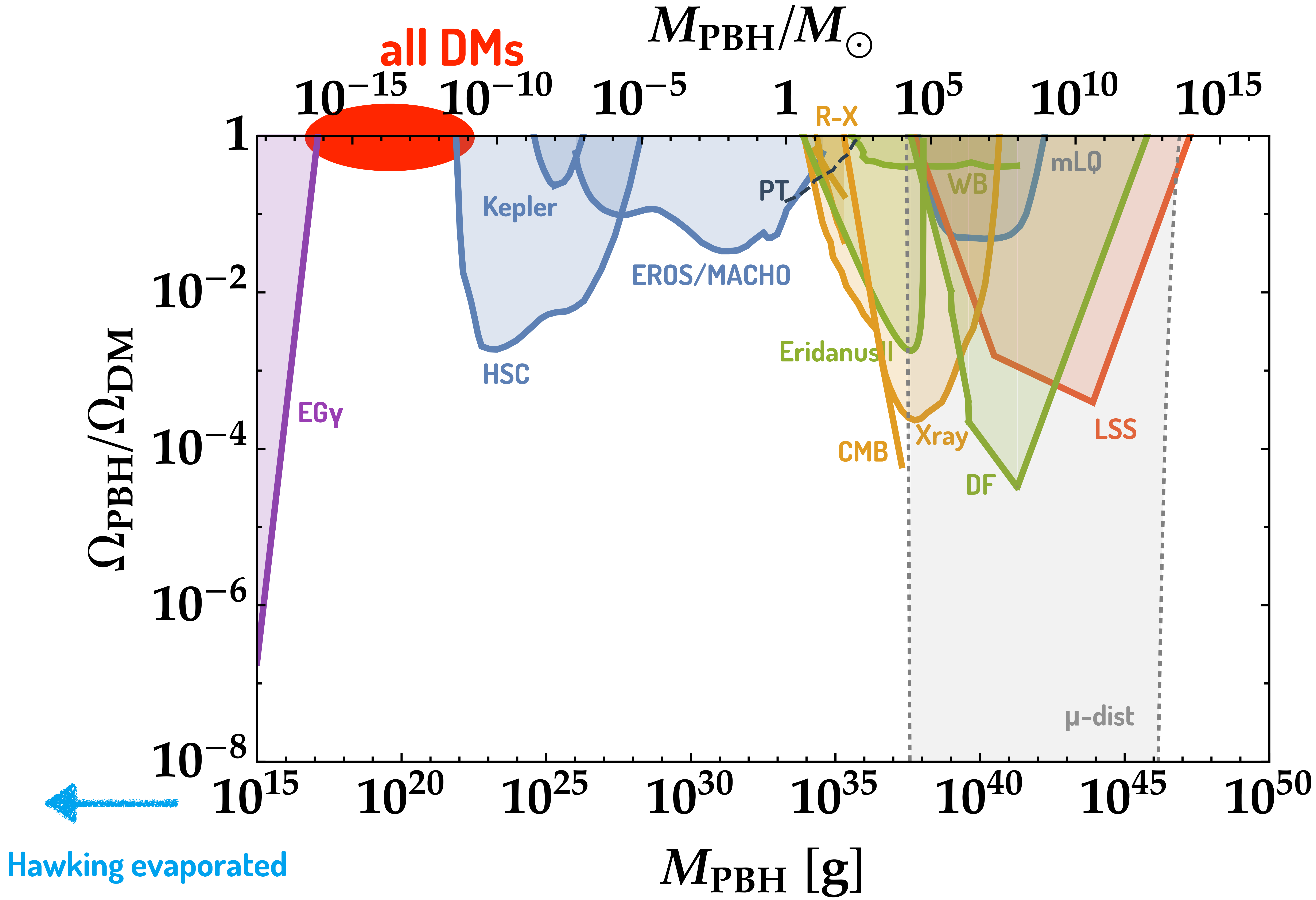


Hawking evaporated

観測的制限および動機

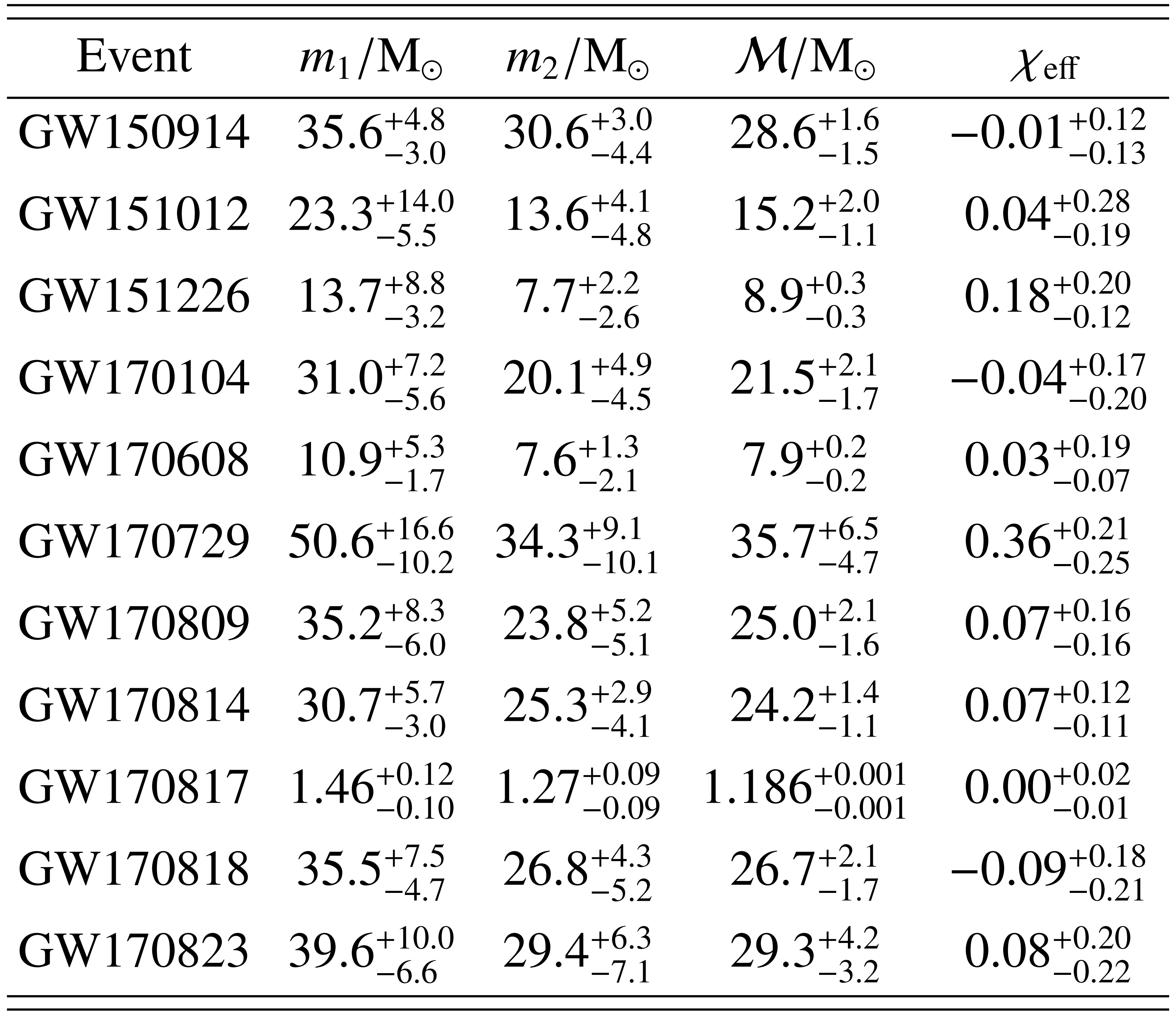

all DMs
$M_{\rm PBH}/M_\odot$
10^{-15}
10^{-10}
10^{-5}
1
10^{5}
10^{10}
10^{15}
R-X
PT
Kepler
EROS/MACHO
HSC
EGγ
WB
mLQ
Eridanus II
CMB
Xray
DF
LSS
μ-dist
$\Omega_{\rm PBH}/\Omega_{\rm DM}$
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{15}
10^{20}
10^{25}
10^{30}
10^{35}
10^{40}
10^{45}
10^{50}
$M_{\rm PBH}$ [g]
Hawking evaporated
Gravitational Lensing
Dynamical Friction
Accretion γ
Prim. PTB
Hawking γ

観測的制限および動機



通常よりやや重いBH

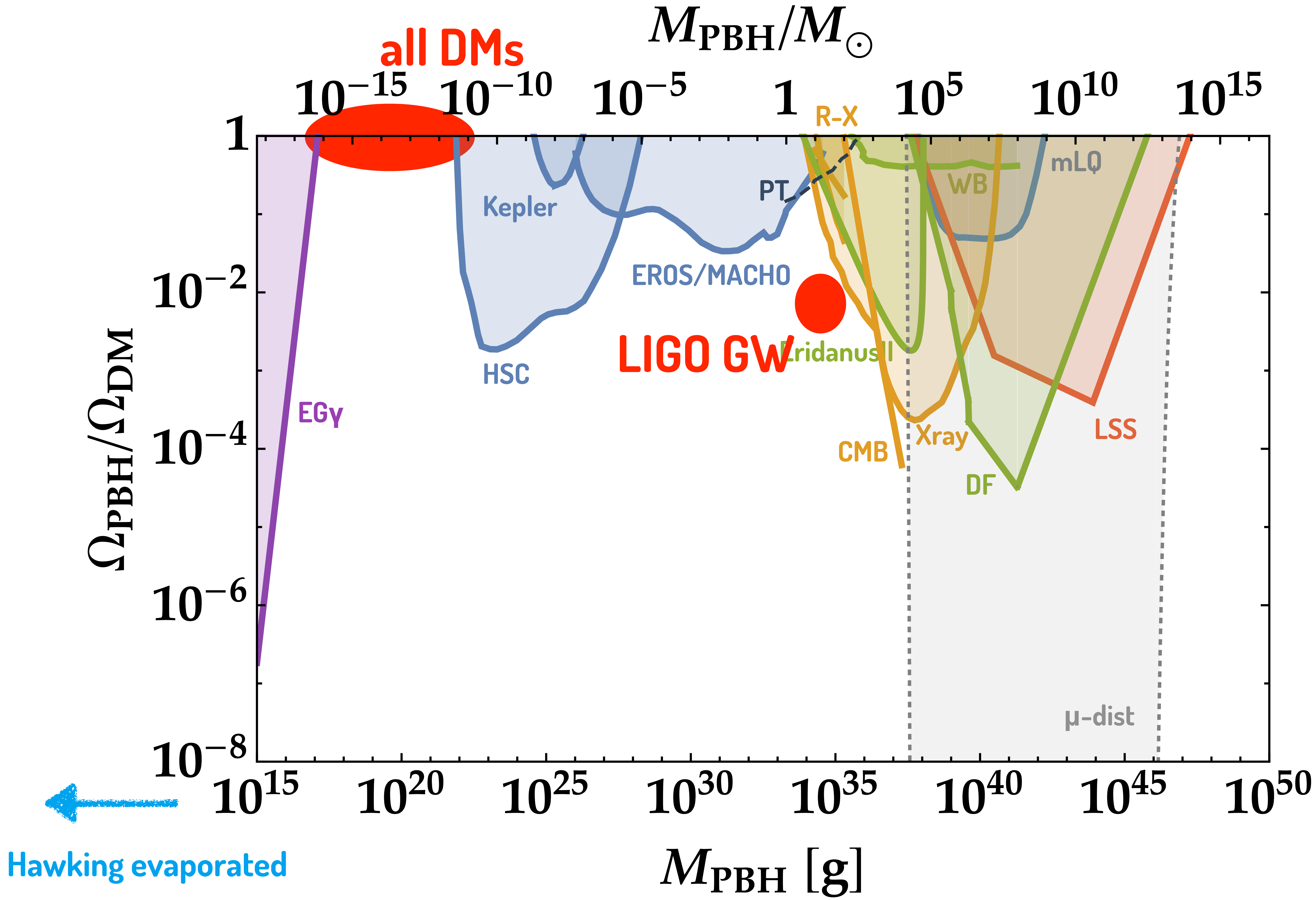
スピンなし



Event	$m_1/\mathrm{M}_\odot$	$m_2/\mathrm{M}_\odot$	$\mathcal{M}/\mathrm{M}_\odot$	$\chi_{\rm eff}$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.1}$	$0.04^{+0.28}_{-0.19}$
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$35.7^{+6.5}_{-4.7}$	$0.36^{+0.21}_{-0.25}$
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.16}_{-0.16}$
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$24.2^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$0.08^{+0.20}_{-0.22}$

LIGO/Virgo 2018

観測的制限および動機



通常よりやや重いBH

スピンなし

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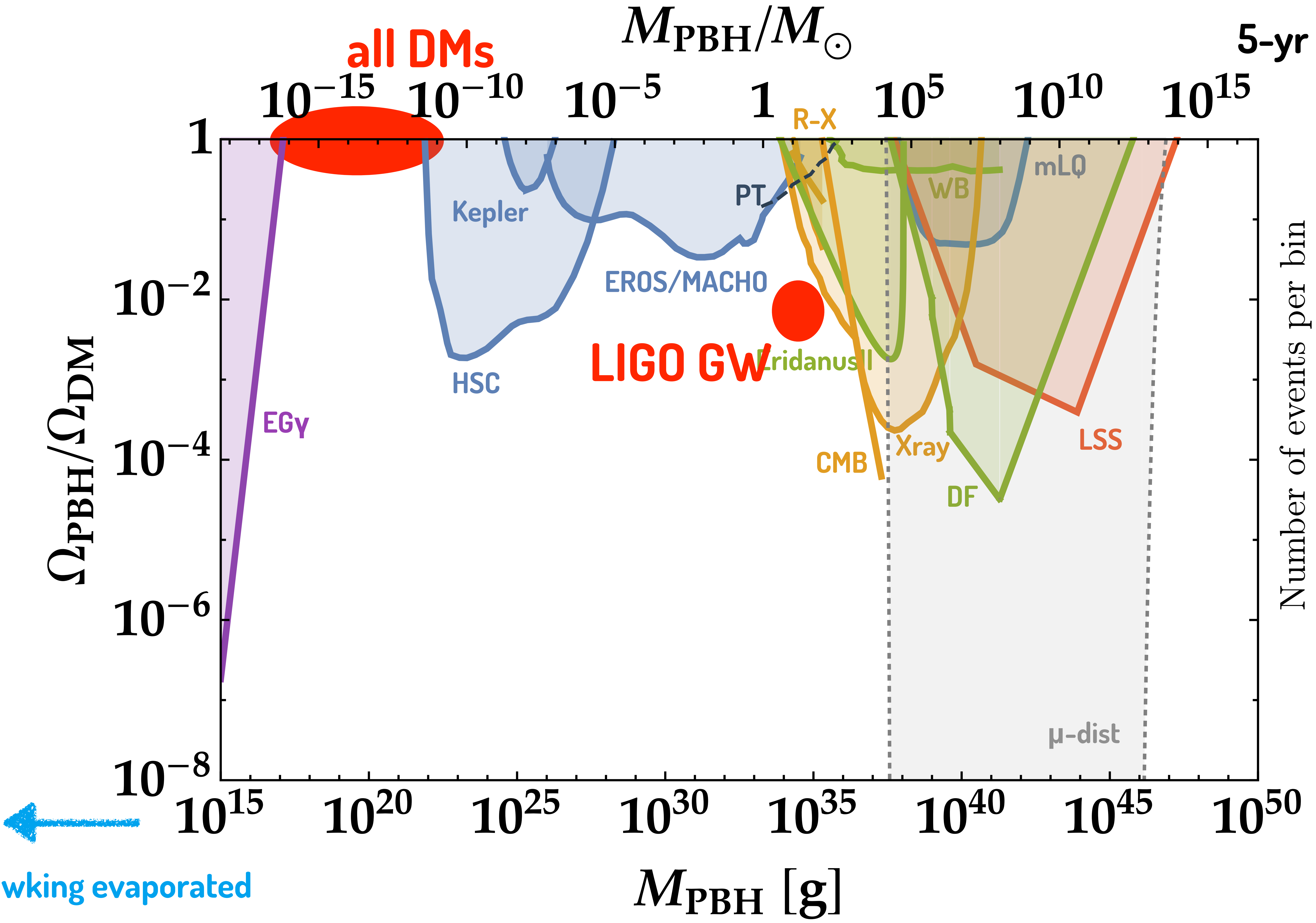
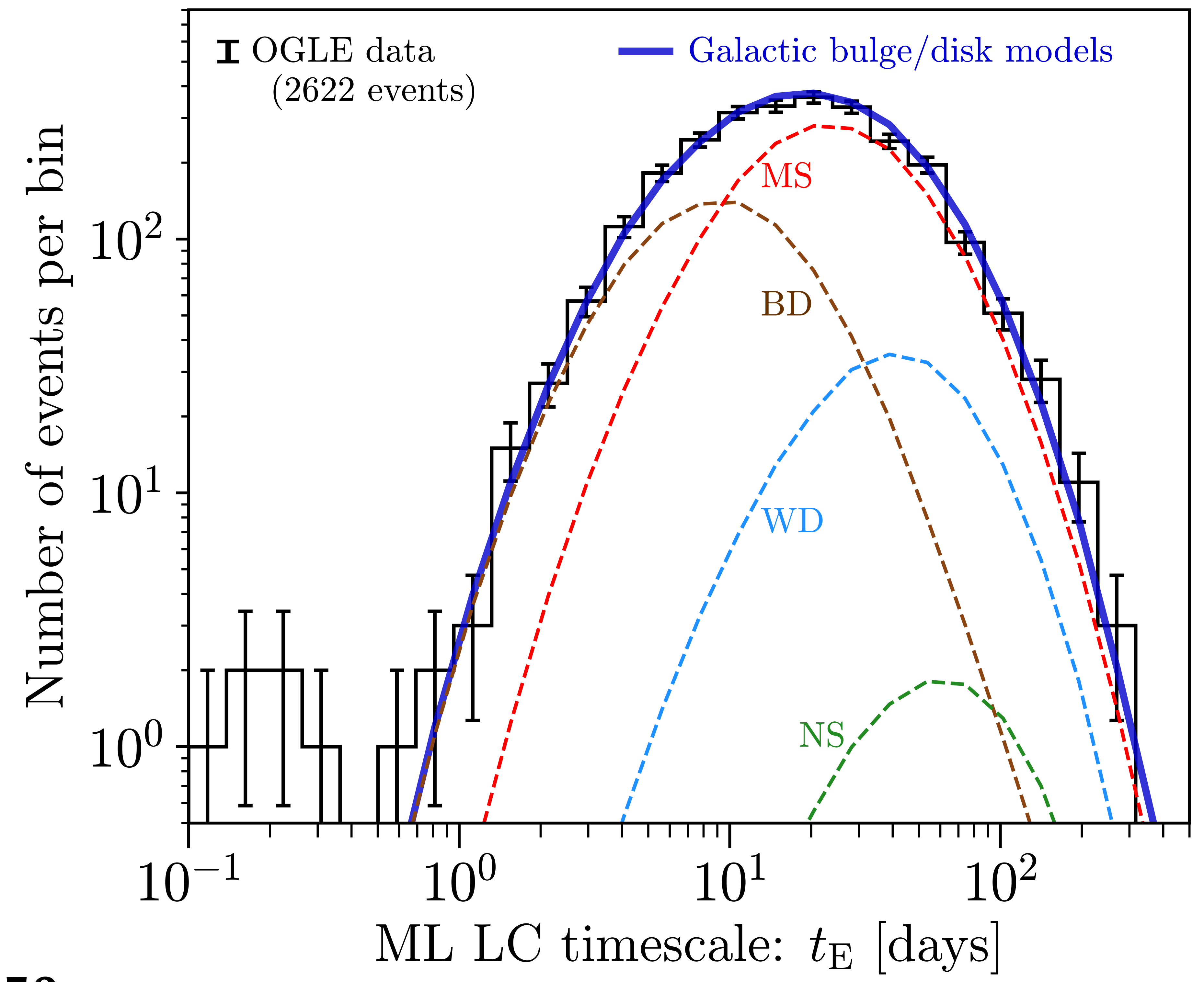


Hawking evaporated

5-yr Optical Gravitational Lensing Experiment (OGLE)

Niikura+ 2019



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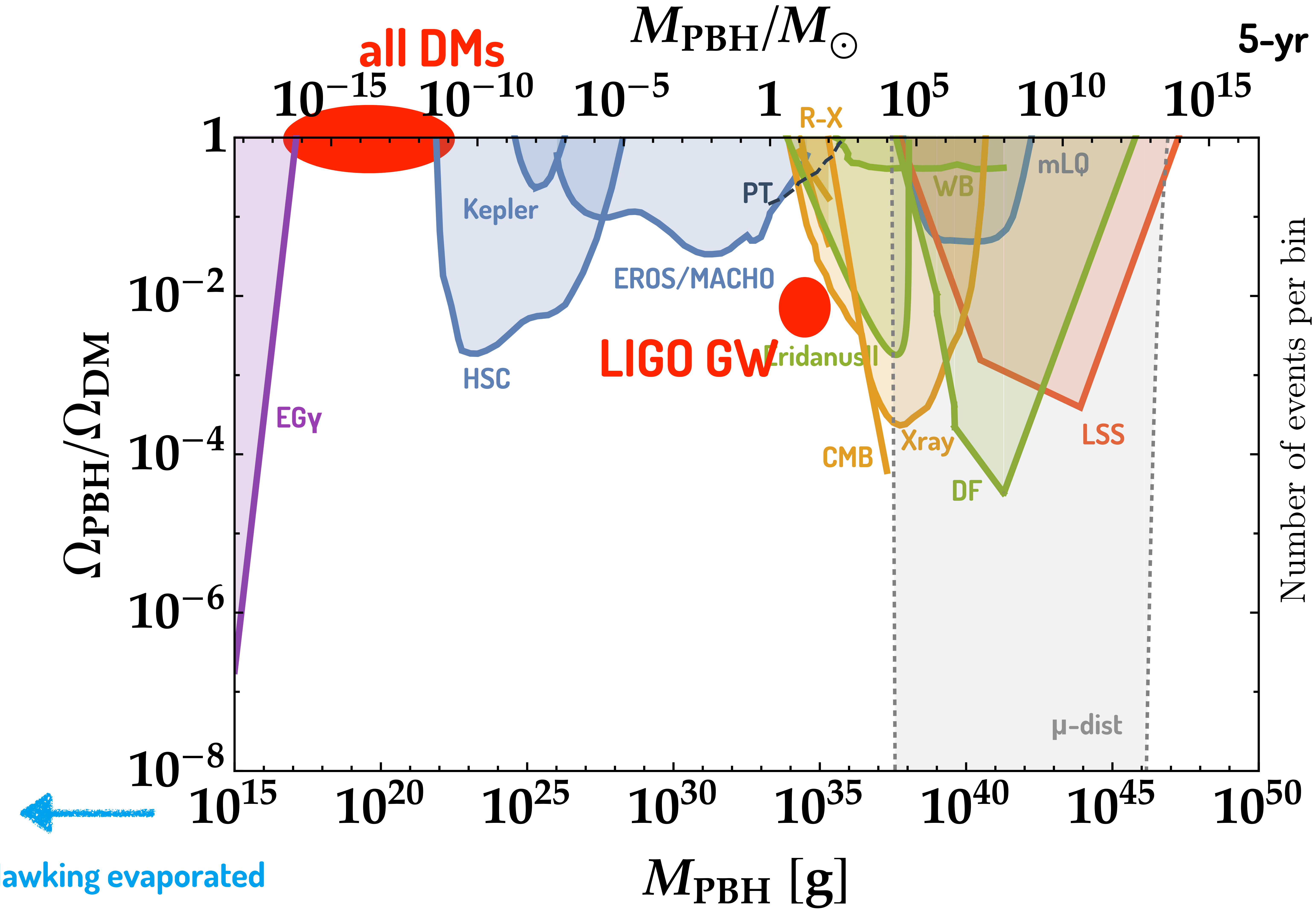

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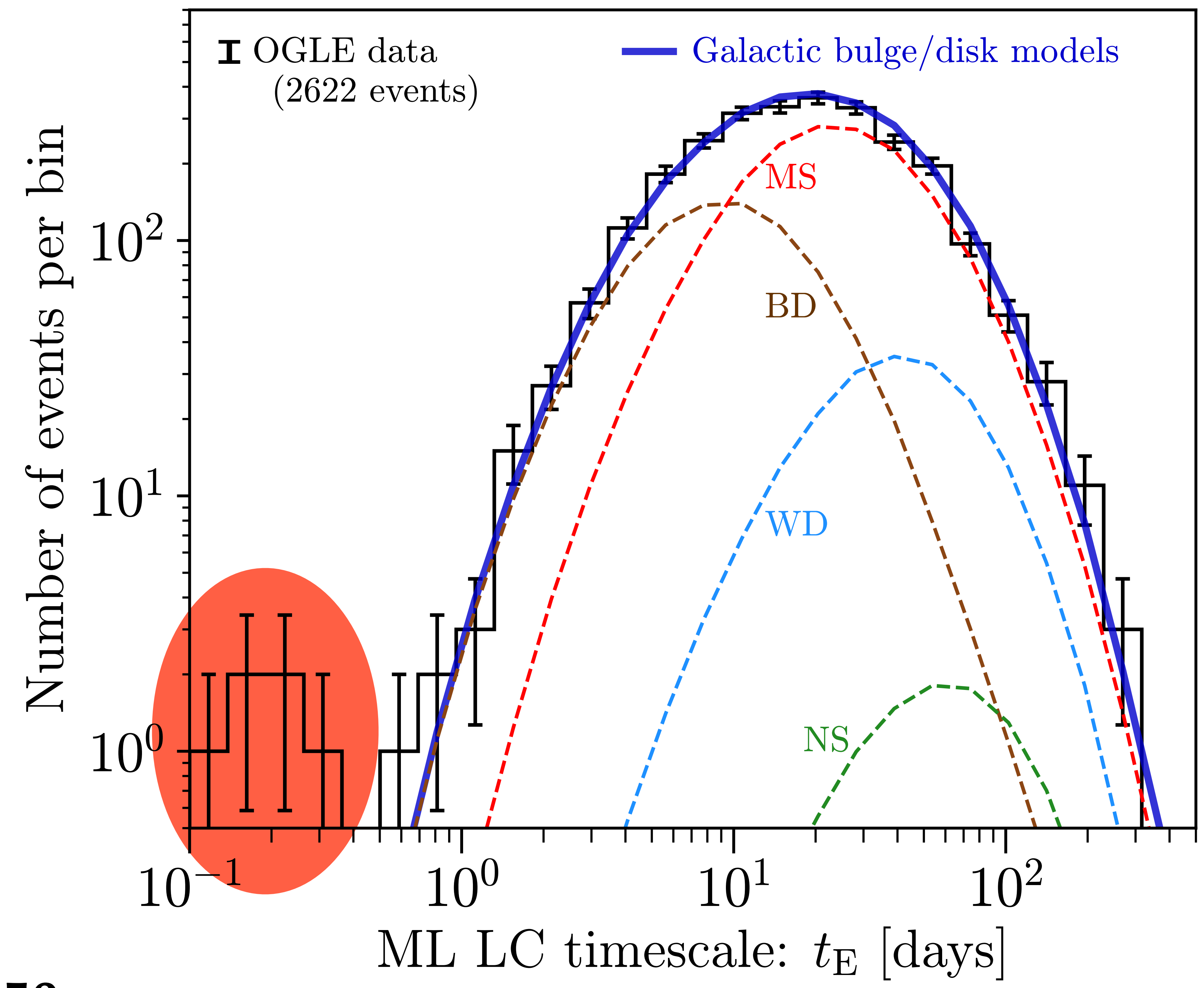

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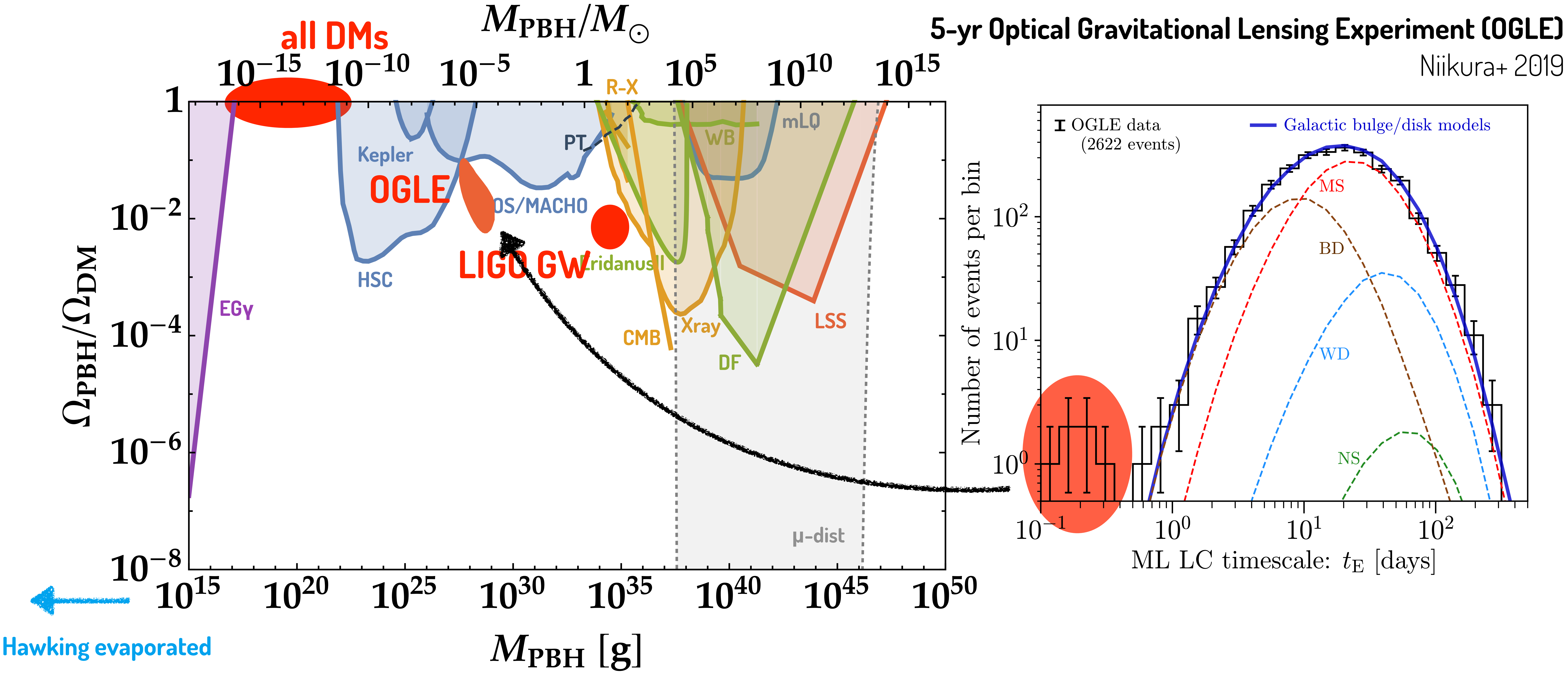

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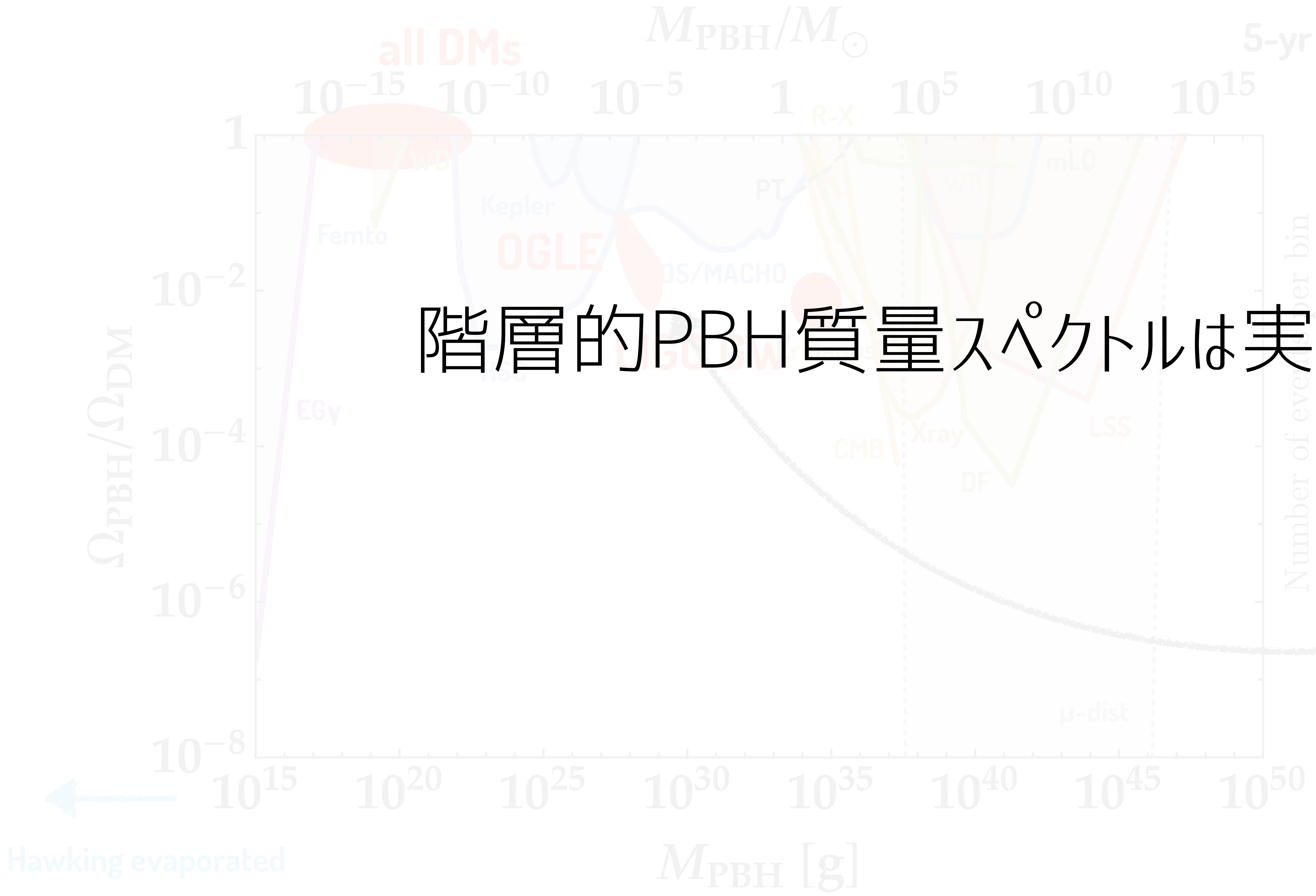

5-yr Optical Gravitational Lensing Experiment (OGLE)

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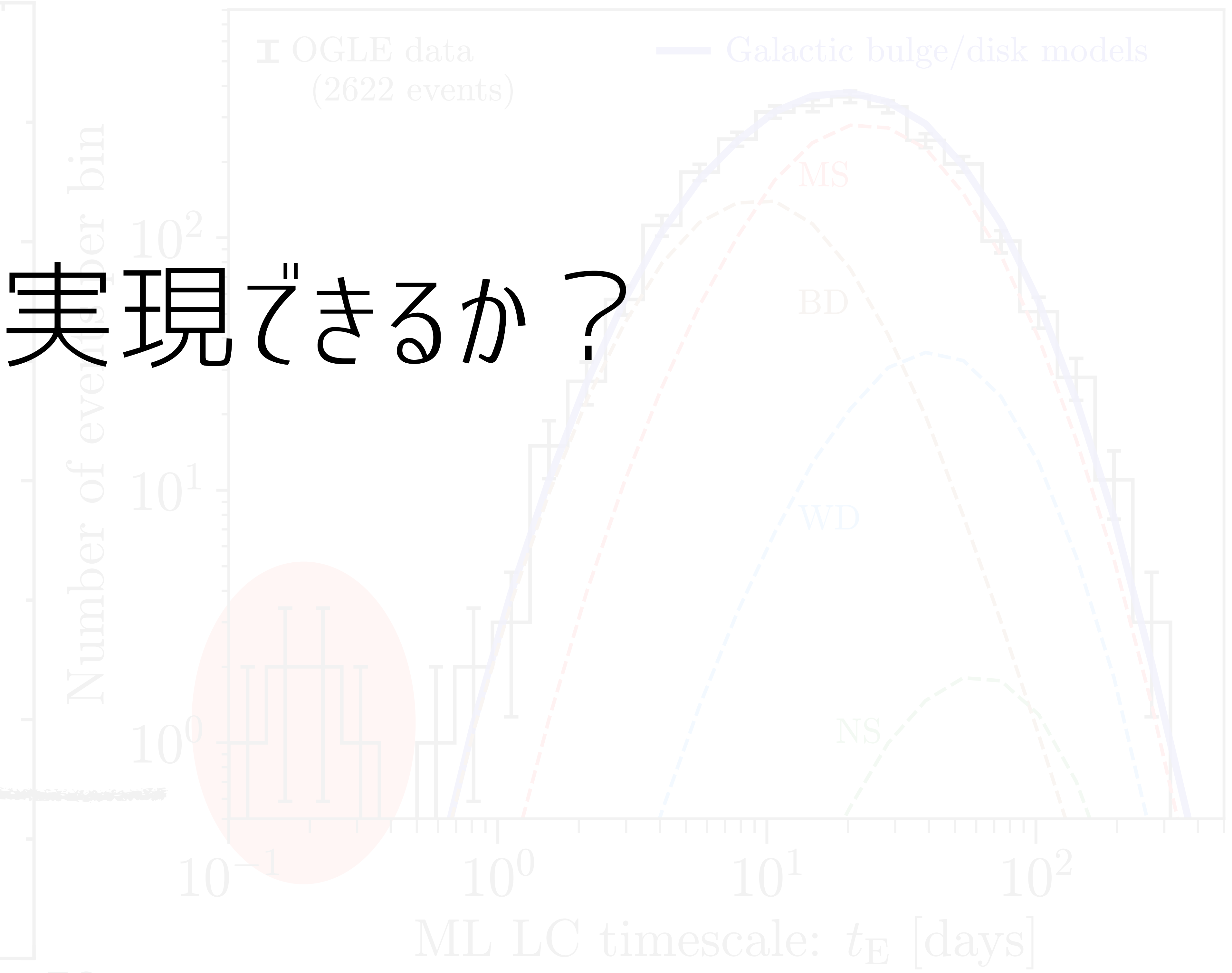
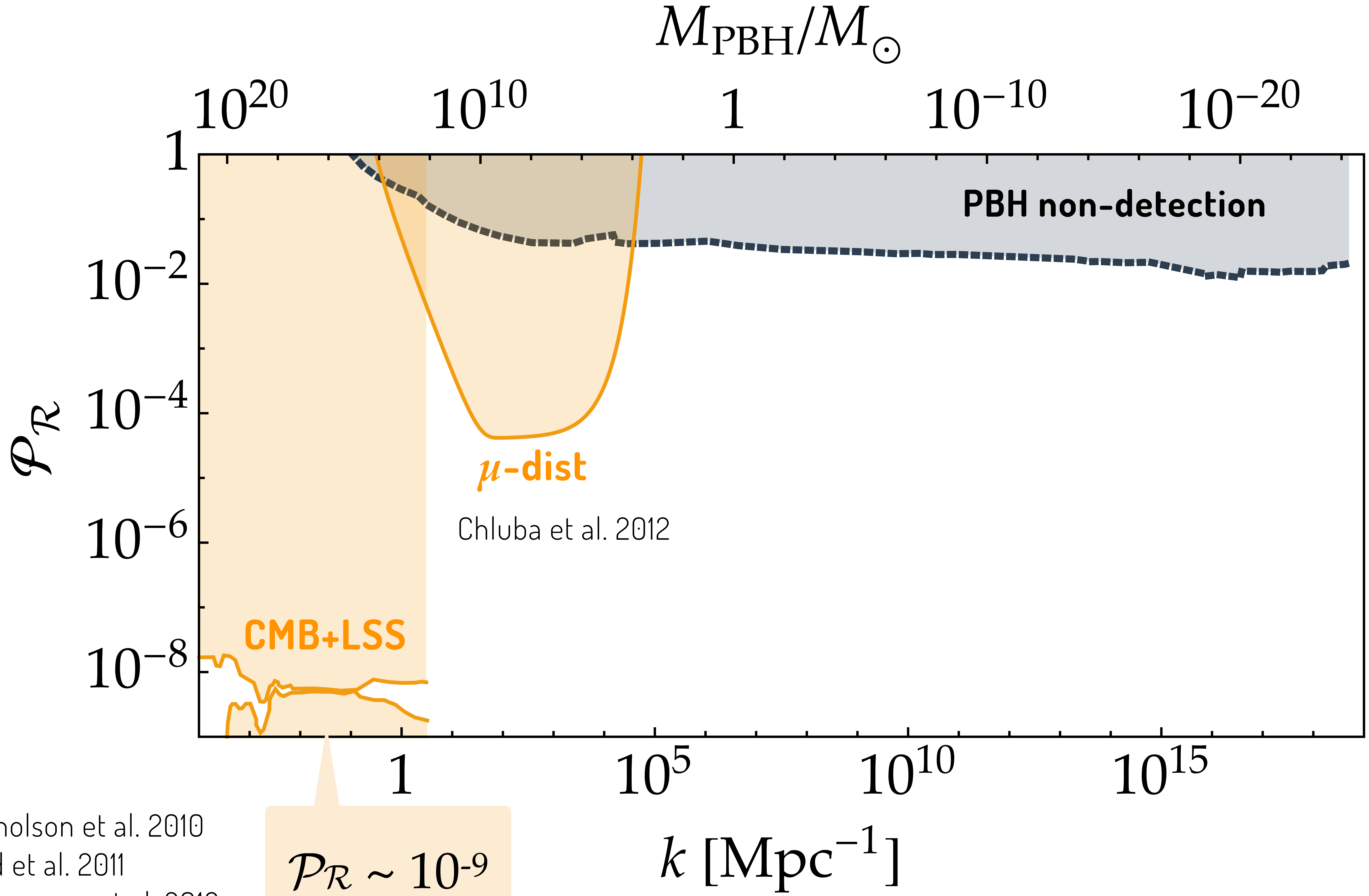


階層的PBH質量スペクトルは実現できるか？

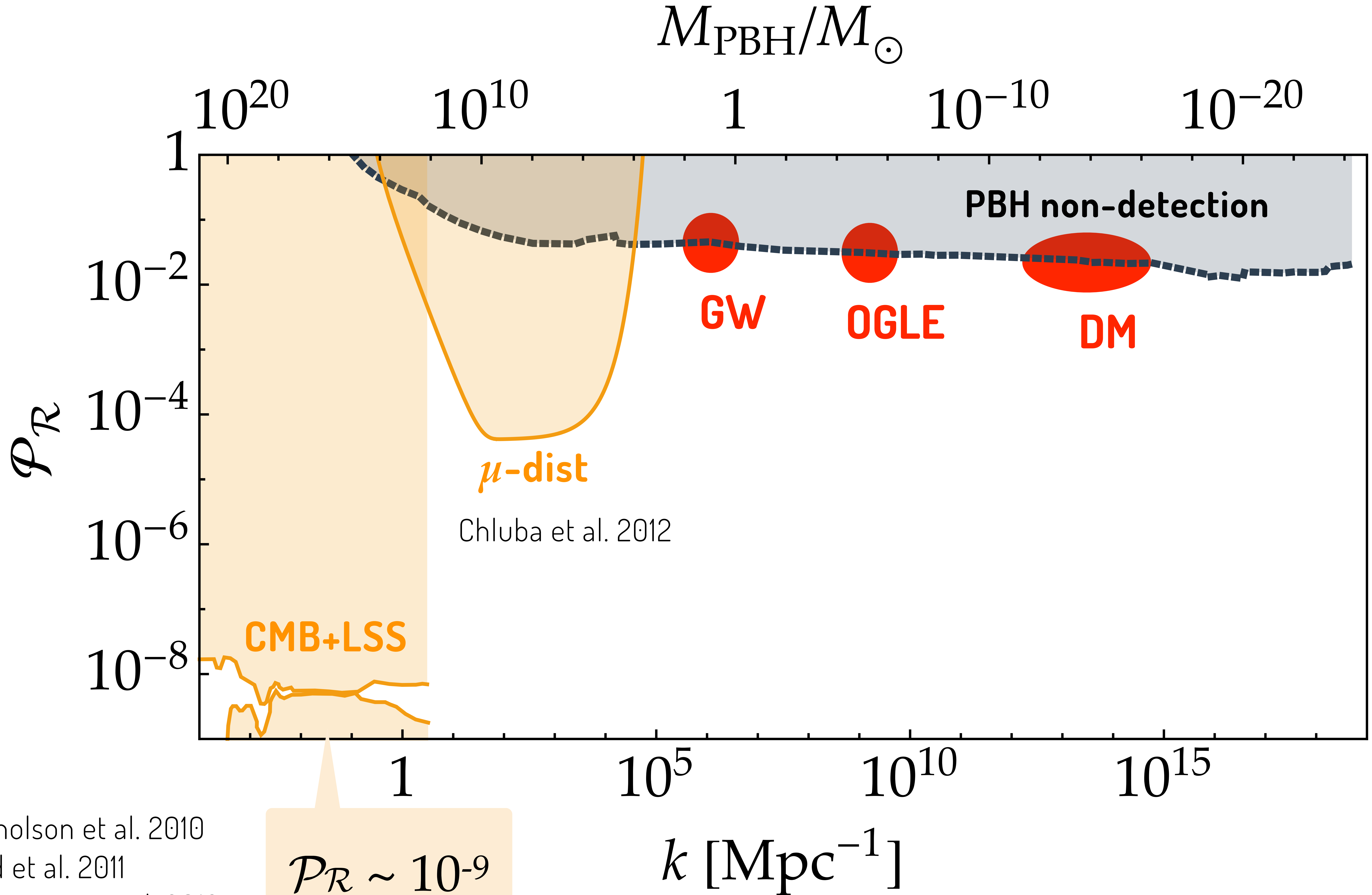


Chluba et al. 2012

$\mathcal{P}_\mathcal{R}$ ~ 10^{-2}

$\mathcal{P}_\mathcal{R}$ ~ 10^{-9}

Nicholson et al. 2010
Bird et al. 2011
Bringmann et al. 2012

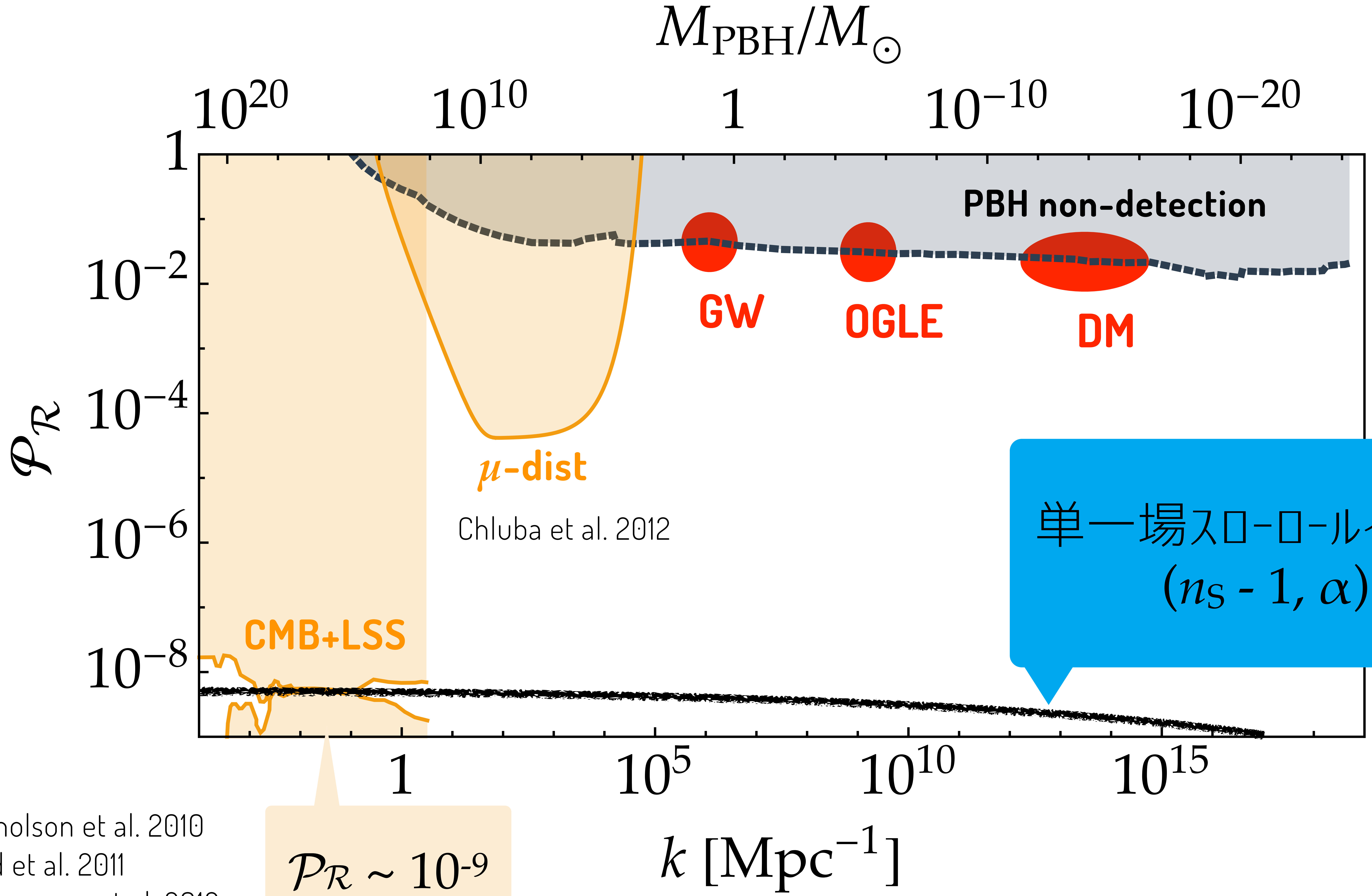


Chluba et al. 2012

$\mathcal{P}_\mathcal{R} \sim 10^{-2}$

Nicholson et al. 2010
Bird et al. 2011
Bringmann et al. 2012

$\mathcal{P}_\mathcal{R} \sim 10^{-9}$



Chluba et al. 2012

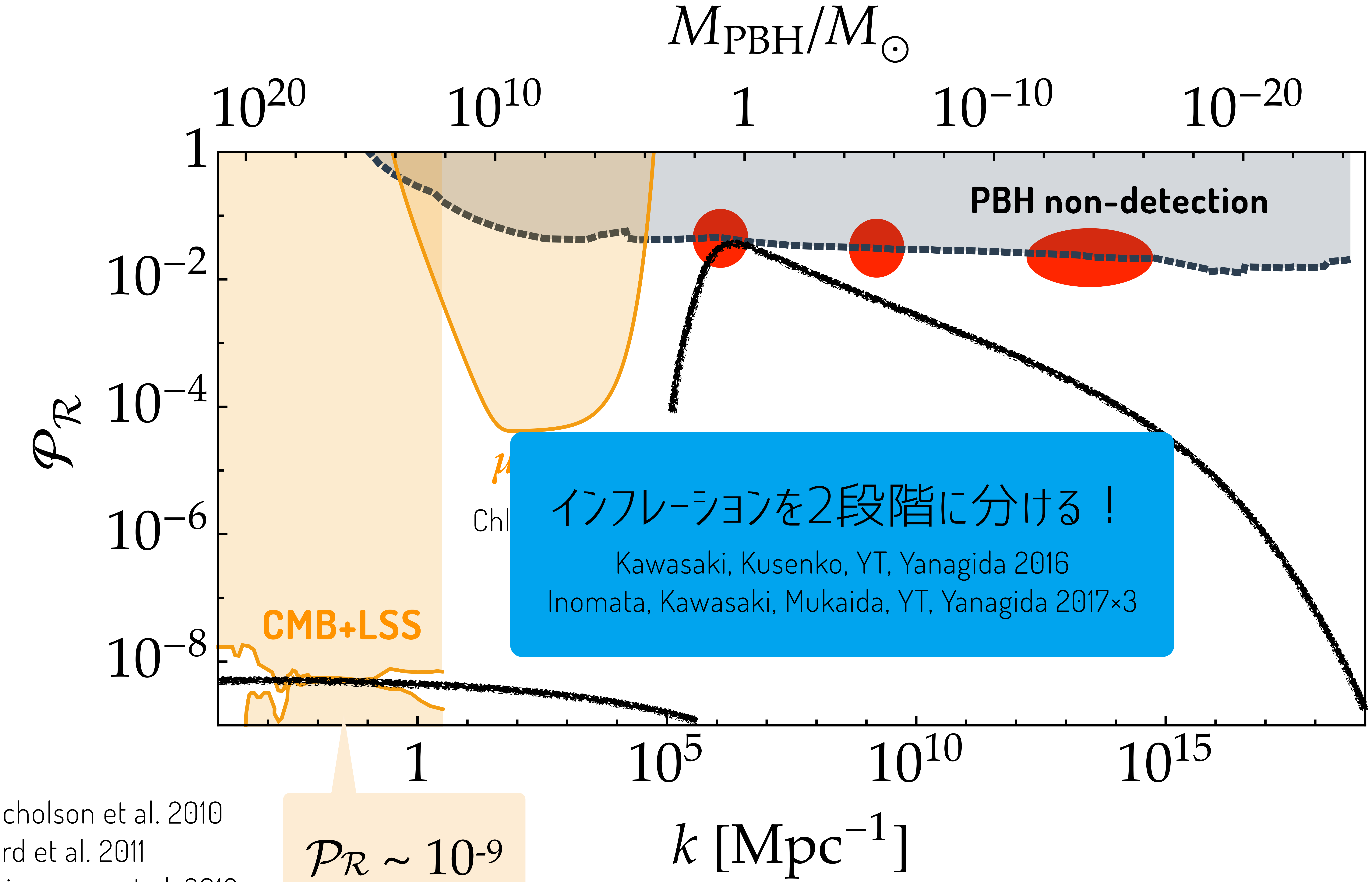
$\mathcal{P}_\mathcal{R} \sim 10^{-2}$

単一場スローロールインフレーションでは

$(n_S - 1, \alpha) \sim \mathcal{O}(\varepsilon)$

Nicholson et al. 2010
Bird et al. 2011
Bringmann et al. 2012

$\mathcal{P}_\mathcal{R} \sim 10^{-9}$



インフレーションを2段階に分ける！

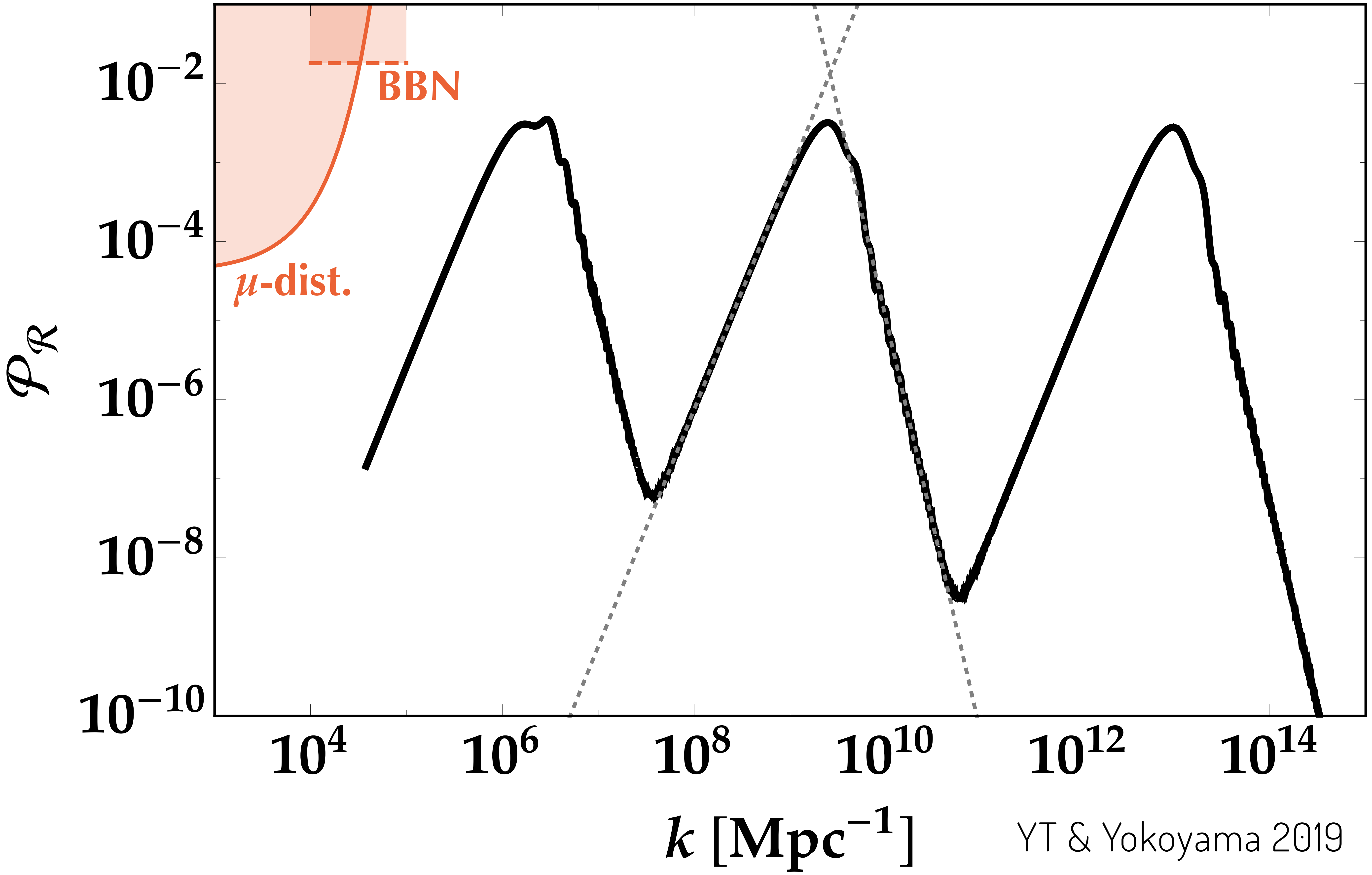
Kawasaki, Kusenko, YT, Yanagida 2016
Inomata, Kawasaki, Mukaida, YT, Yanagida 2017×3

$\mathcal{P}_\mathcal{R} \sim 10^{-2}$

$\mathcal{P}_\mathcal{R} \sim 10^{-9}$

Nicholson et al. 2010
Bird et al. 2011
Bringmann et al. 2012

極端な例



YT & Yokoyama 2019

- 4つの hilltop inflation

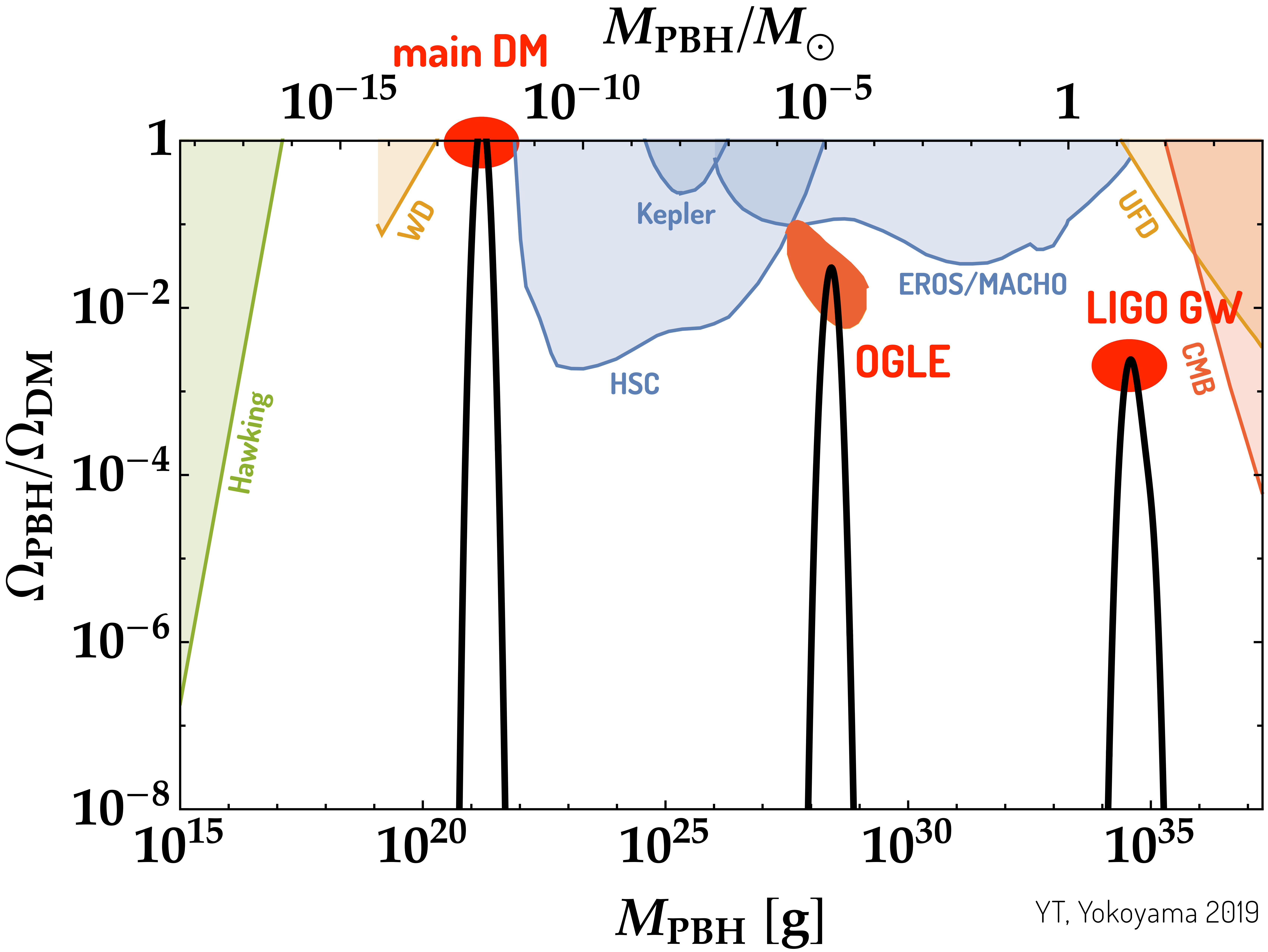
$$V_{\mathrm{hill}} = \sum_{i=1}^{4} V_{\mathrm{hill},i}$$

$$+$$

- 固定項

$$V_{\mathrm{stab}} = \sum_{i\neq j} \frac{c_{ij}}{2} V_{\mathrm{hill},i} \frac{\phi_j^2}{M_{\mathrm{Pl}}^2}$$

  - 段階-i 中:
    ϕ_{i+1} をポテンシャル上に固定
  - $V_{\mathrm{hill},i}$ の減衰後:
    段階-$(i+1)$ が始まる



YT, Yokoyama 2019

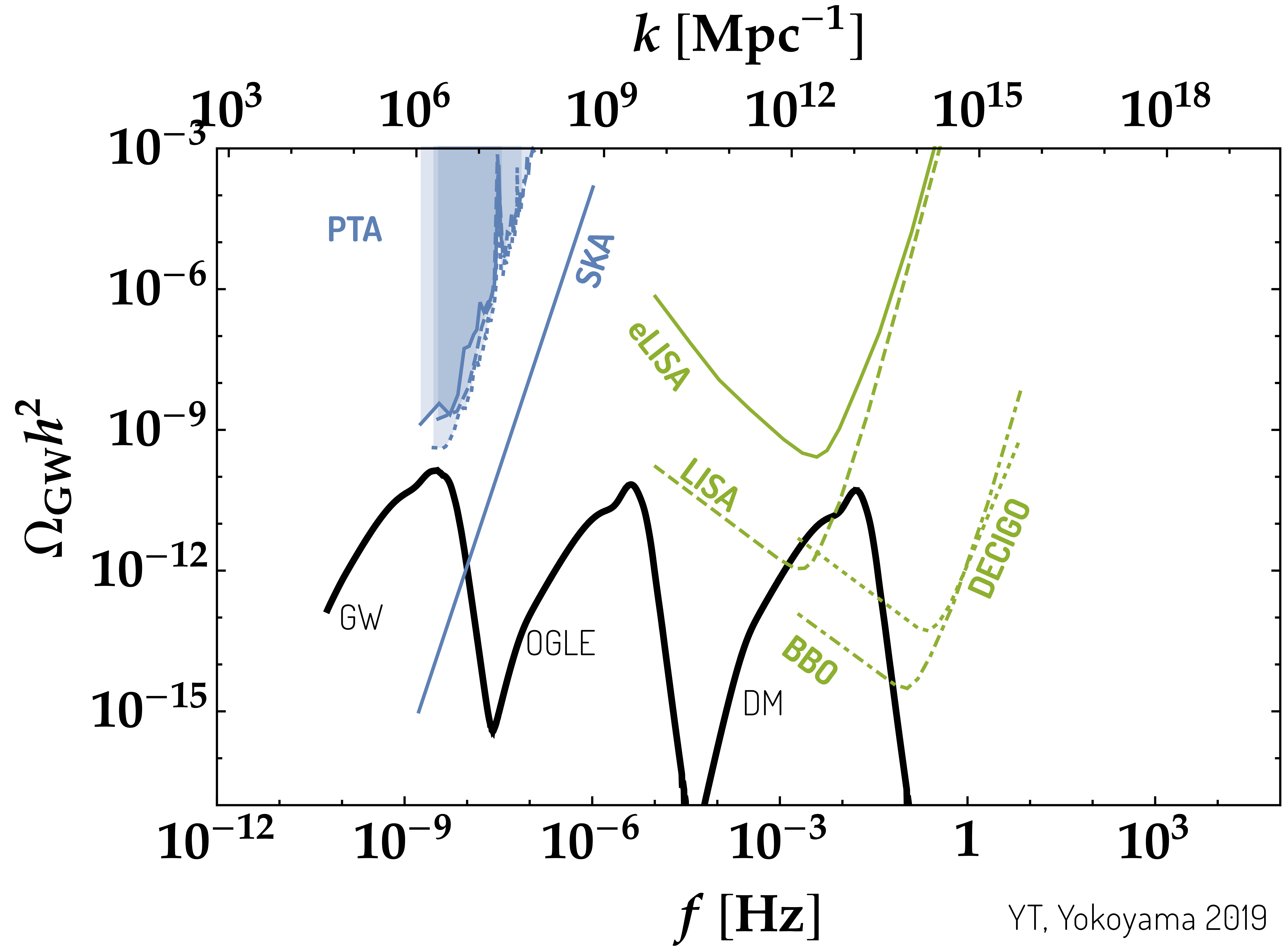
クロスチェック

大きいスカラー（密度）ゆらぎ

↓

摂動の2次でテンソルゆらぎ
（背景重力波）

$$\Omega_{\rm GW}h^2 \sim 10^{-9}\left(\frac{\mathscr{P}_{\mathscr{R}}}{10^{-2}}\right)^2$$



YT, Yokoyama 2019

超弦理論への示唆？

dS swampland conjecture　Ooguri & Vafa+ 2018

「*UV* 完備な *EFT* では *dS* 真空は安定にならない？」

$$\epsilon_V = \frac{M_{\rm Pl}^2}{2}\left(\frac{V'}{V}\right)^2 \gtrsim \mathscr{O}(1) \quad \text{or} \quad \eta_V = M_{\rm Pl}^2\frac{V''}{V} \lesssim -\mathscr{O}(1)$$

各インフレーション相は長く続かない → 多段階にして合わせて 60 e-folds

- CMB scale?

インフラトンがゆらぎを作るとすると

$$-0.035 \ \text{✗}\ \frac{\mathrm{d}\log\mathscr{P}_\zeta}{\mathrm{d}\log k}(k_{\rm CMB}) = n_{\rm s} - 1 \simeq -6\epsilon_V + 2\eta_V$$

Planck 2018

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- CMB scale?

カーバトンなら Kogai, YT '20

$$-0.035 \simeq \frac{\mathrm{d}\log\mathscr{P}_\zeta}{\mathrm{d}\log k}(k_{\mathrm{CMB}}) = n_{\mathrm{s}} - 1 \simeq -2\epsilon_V + \frac{2}{3}\frac{m_\sigma^2}{H^2}$$

Planck 2018

まとめ

- Planck + BK でインフレーション理論に強い制限 ($r < 0.036$)
- 有望な理論 $r \sim \mathcal{O}(0.001) \ \Leftrightarrow \ \Omega_{\rm GW} \sim \mathcal{O}(10^{-17})$
- kination 期があると GW は増幅できる
- PBH-DM $\ \Leftrightarrow \ \Omega_{\rm GW}(f \sim 10\,{\rm mHz}) \sim 10^{-9}$