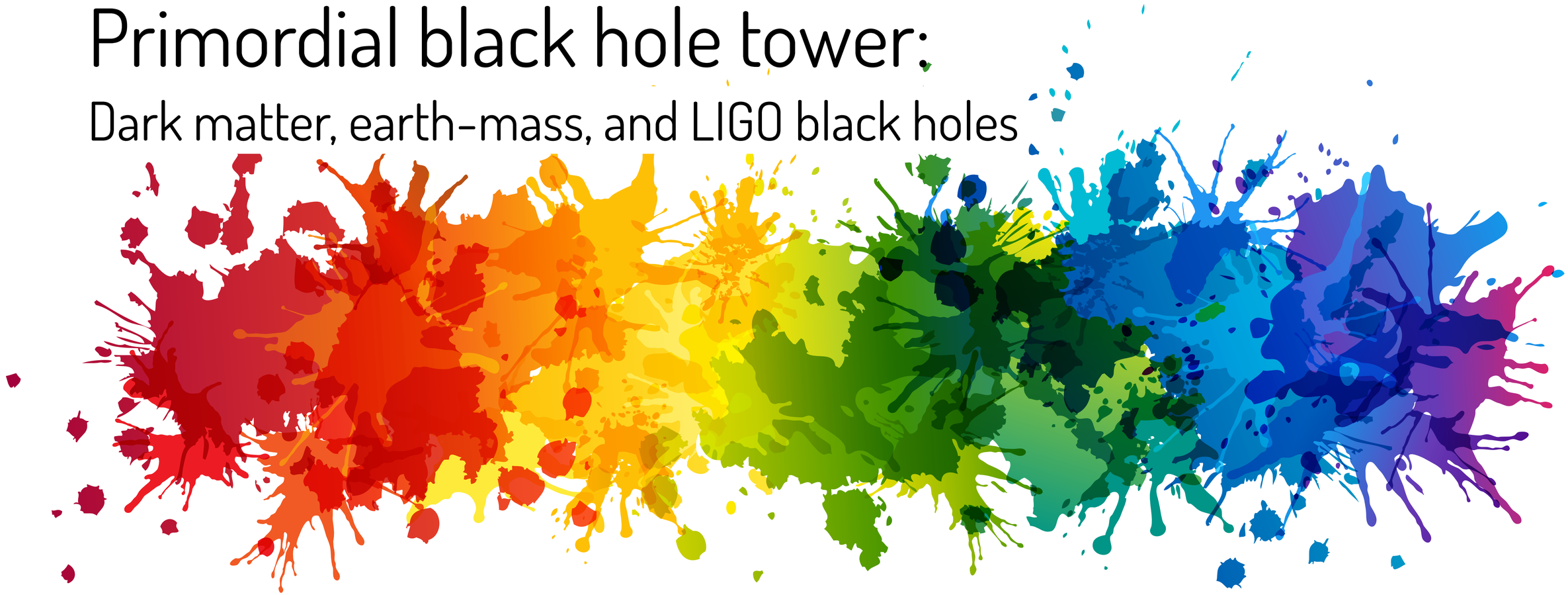
6. Dec. 2019 @ Focus Week on PBH in Kavli IPMU

Primordial black hole tower:

Dark matter, earth-mass, and LIGO black holes



Yuichiro TADA (Nagoya U.)

w/ S. Yokoyama PRD **100**, no. 2, 023537 (2019)

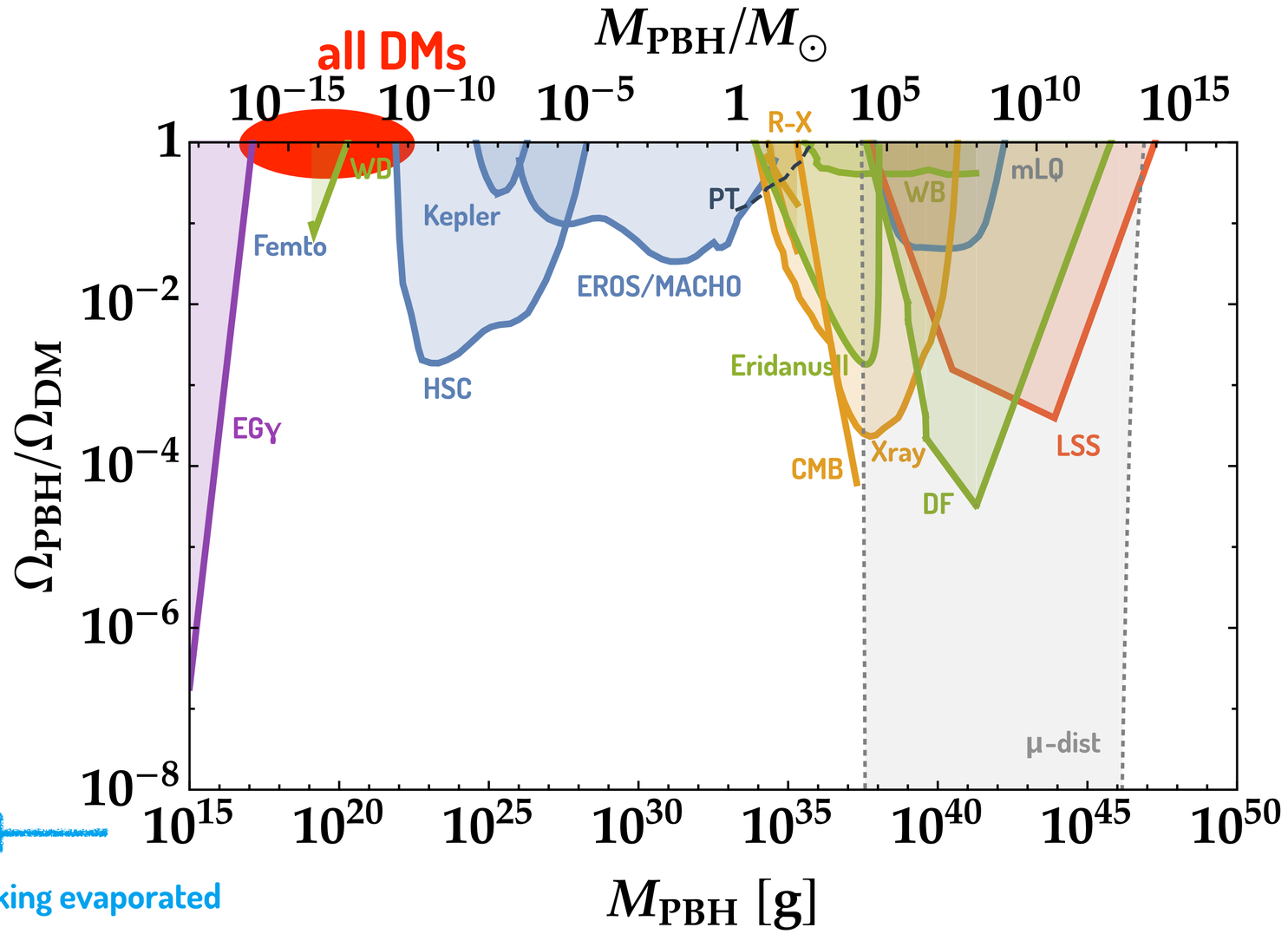
Inomata, Kawasaki, Kusenko, Mukaida, Yanagida 2016,2017

Primordial Black Hole : well-known to you

- PBH formation in RD

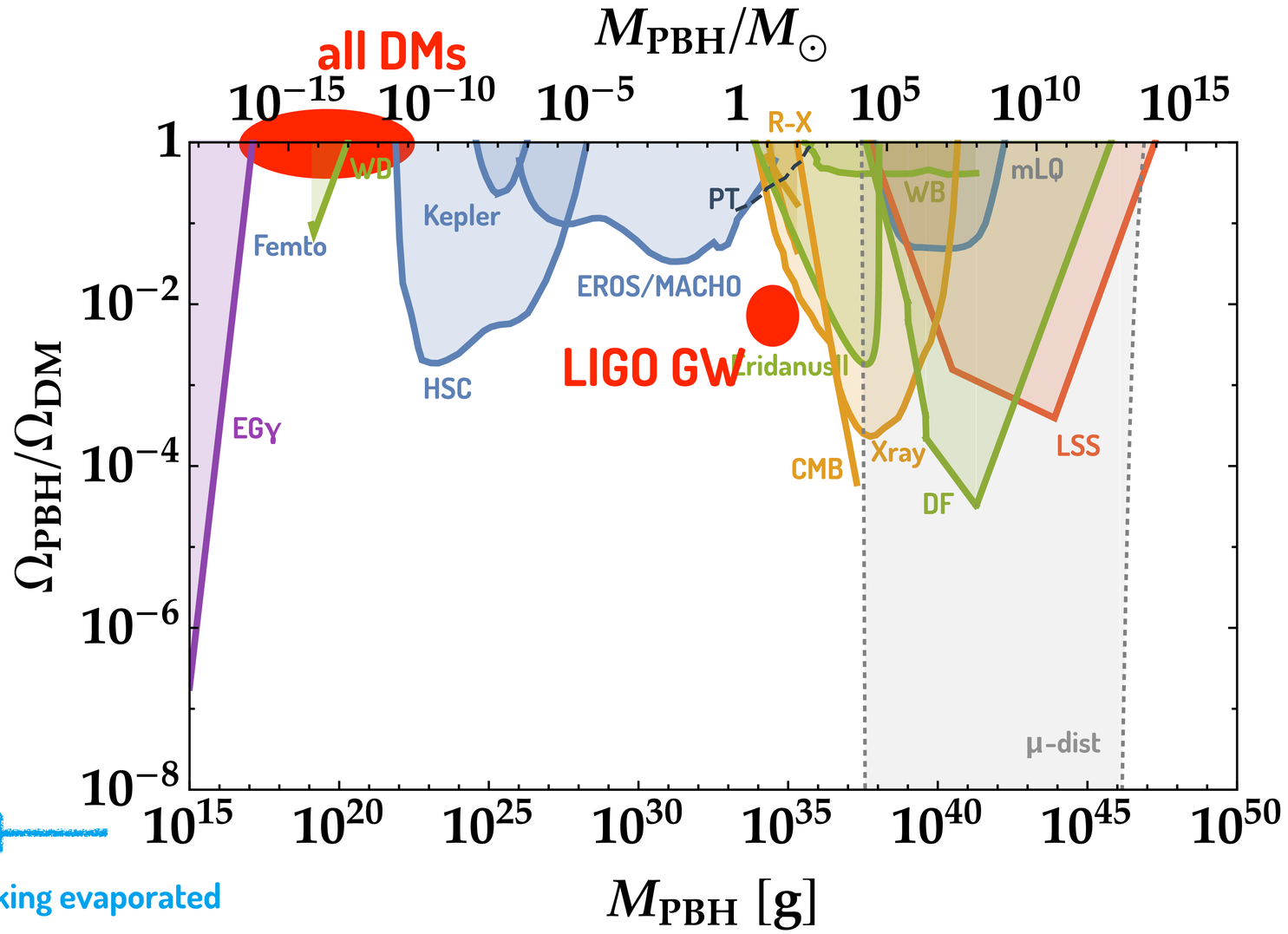
$$\zeta_{\rm th} \sim 1 \quad \Rightarrow \quad \mathcal{P}_\zeta(k_{\rm PBH}) \sim 10^{-2}$$

Motivations of PBH



- Gravitational Lensing
- Dynamical Friction
- Accretion γ
- Prim. PTB
- Hawking γ

Motivations of PBH



Hawking evaporated

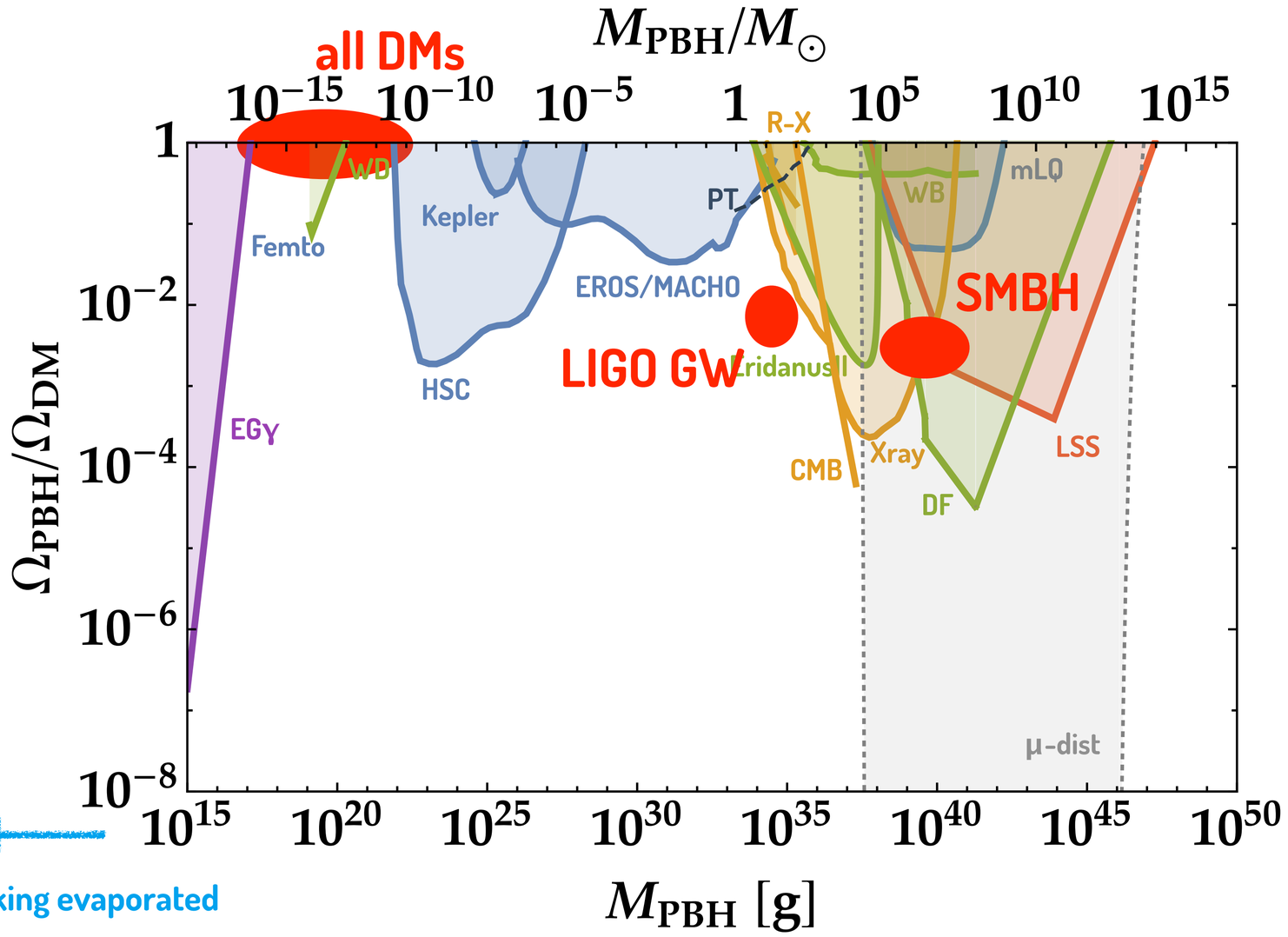
Massive than stellar BHs found

small spin

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	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$0.08^{+0.20}_{-0.22}$

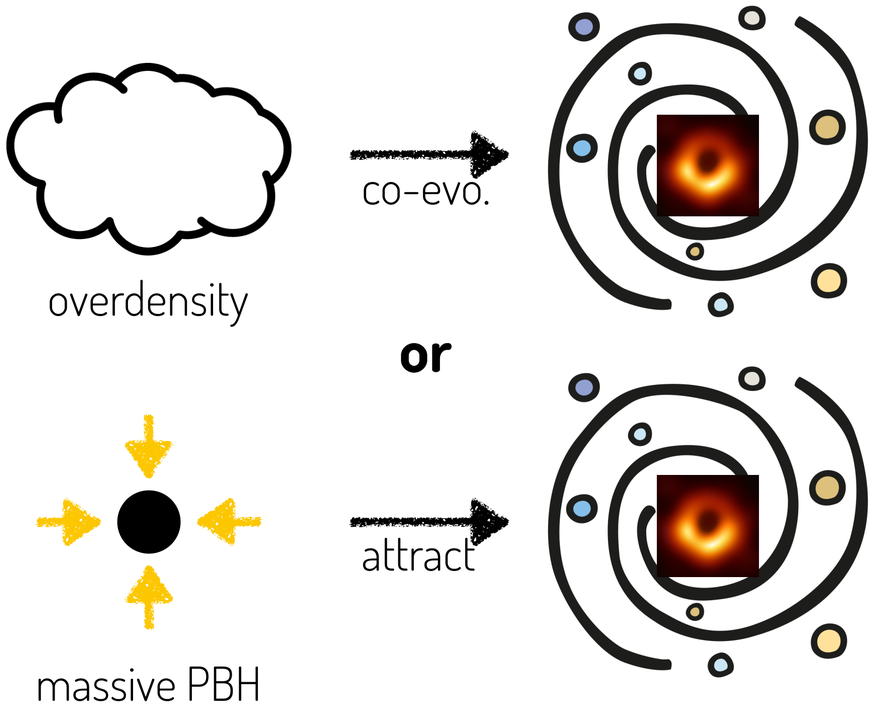
LIGO/Virgo 2018

Motivations of PBH



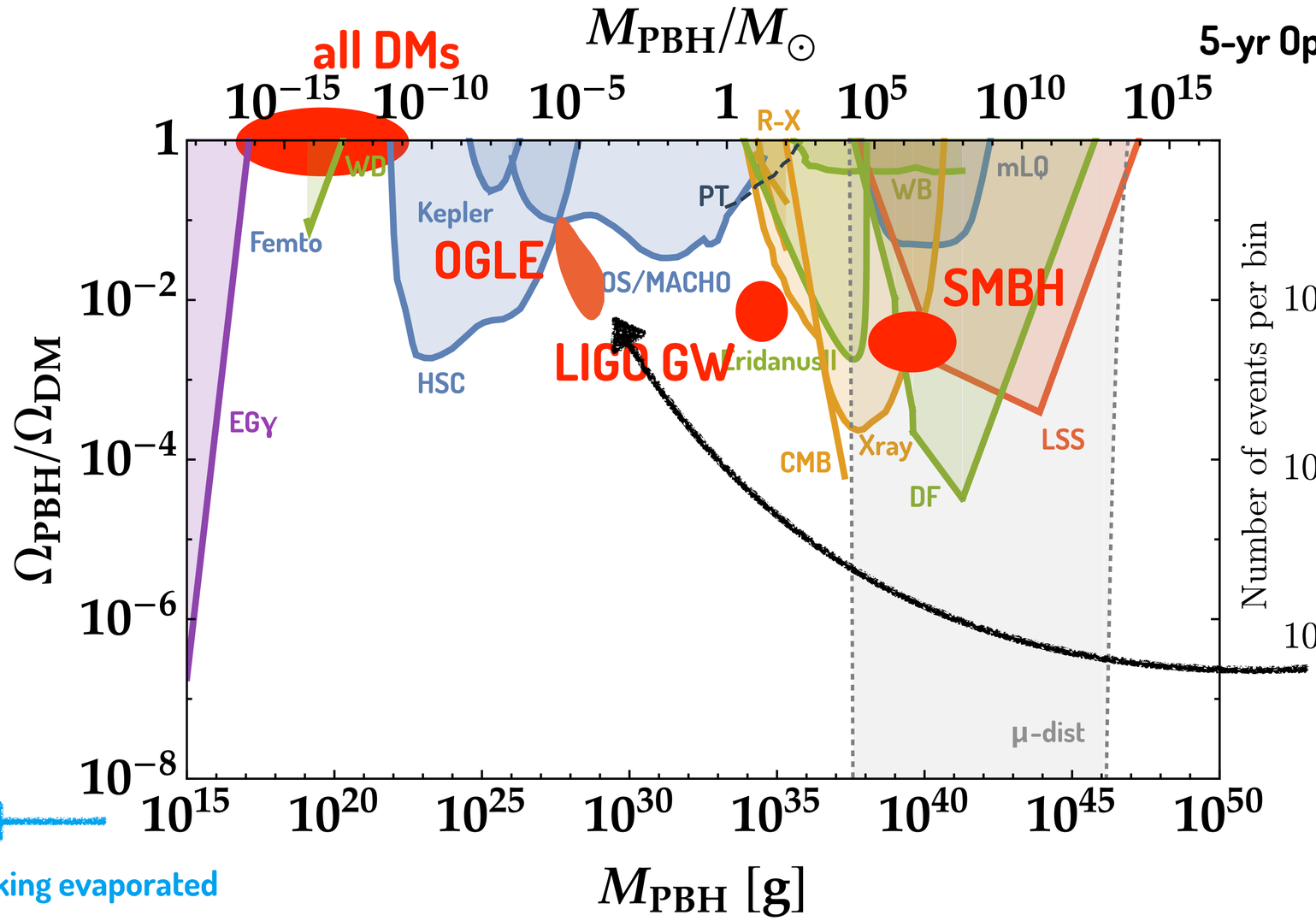
Supermassive Black Hole

~ 10^{5-10} $M_\odot$ SMBH in each galaxy



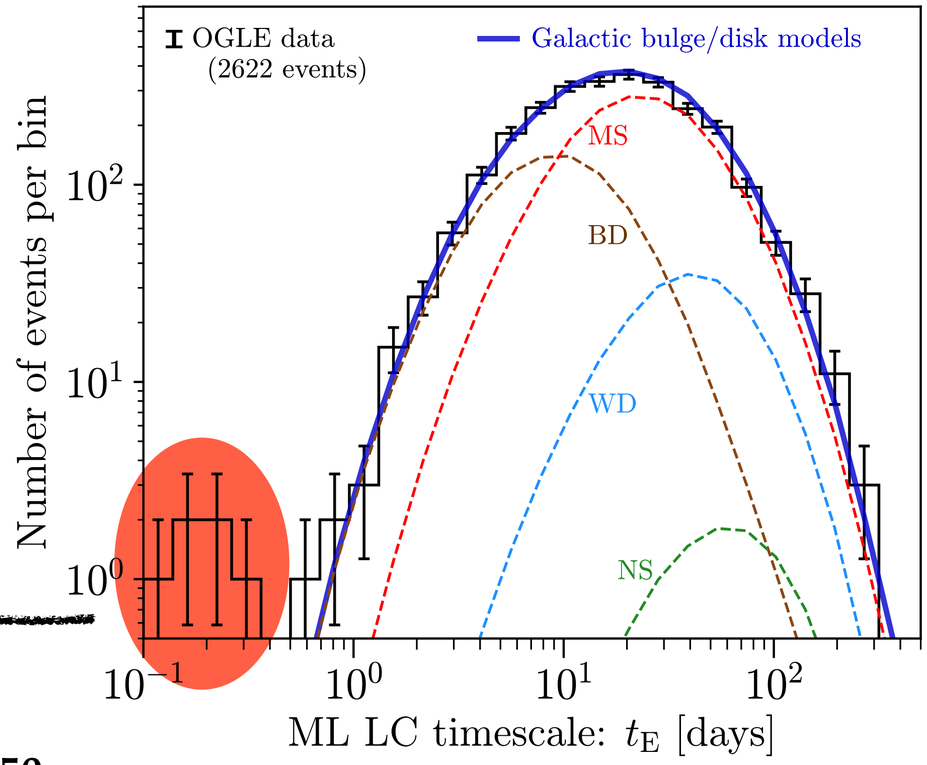
Bean & Magueijo 2002
Carr & Silk 2018

Motivations of PBH

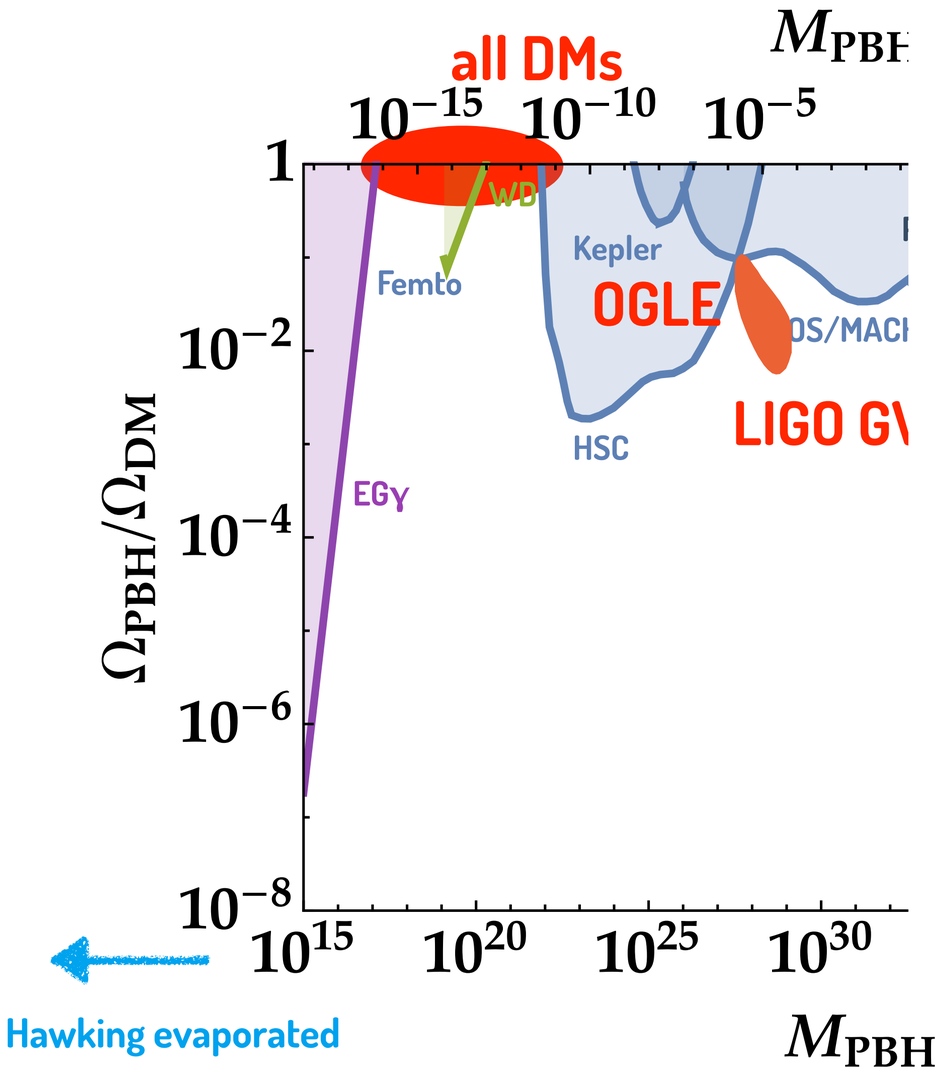


5-yr Optical Gravitational Lensing Experiment (OGLE)

Niikura+ 2019



Motivations of PBH



arXiv: 1909.11090

What if Planet 9 is a Primordial Black Hole?

Jakub Scholtz[1] and James Unwin[2]

[1] *Institute for Particle Physics Phenomenology, Durham University, Durham, DH1 3LE, United Kingdom*
[2] *Department of Physics, University of Illinois at Chicago, Chicago, IL 60607, USA;*
& Department of Physics, University of California, Berkeley & Theoretical Physics Group, LBNL & Mathematics Sciences Research Institute, Berkeley, CA 94720, USA

1. Introduction. As of this year, two gravitational anomalies of similar mass but very different origins remain to be explained. First, there is a growing body of observational anomalies connected to the orbits of trans-Neptunian Objects (TNOs) [1–3]. These observations have been taken as evidence of a new ninth planet in our solar system, called Planet 9 (P9), with mass $M_9 \sim 5 - 15 M_\oplus$ and orbiting around the Sun at a distance of 300−1000 AU [4]. Second, there is set of gravitational anomalies recently observed by the Optical Gravitational Lensing Experiment (OGLE). OGLE reported an excess of six ultrashort microlensing events with crossing times of $0.1 - 0.3$ days [5]. The lensing objects are located towards the galactic bulge, roughly 8kpc away. These events correspond to lensing by objects of mass $M \sim 0.5 M_\oplus - 20 M_\oplus$ [6] and could be interpreted as an unexpected population of free floating planets (FFPs) or as Primordial Black Holes (PBHs).

SUPPLEMENTARY MATERIAL

A. SIZE OF THE PBH

The Schwarzschild radius of a black hole is given by

$$r_{\rm BH} = \frac{2GM_{\rm BH}}{c^2} \simeq 4.5{\rm cm}\left(\frac{M_{\rm BH}}{5M_\oplus}\right) . \quad (15)$$

In Figure 1 we provide an exact scale image of a $5M_\oplus$ PBH. The associated DM halo however extends to the stripping radius $r_{t,\odot} \sim 8$AU, this would imply a DM halo which extends roughly the distance from Earth to Saturn (both in real life and relative to the image).

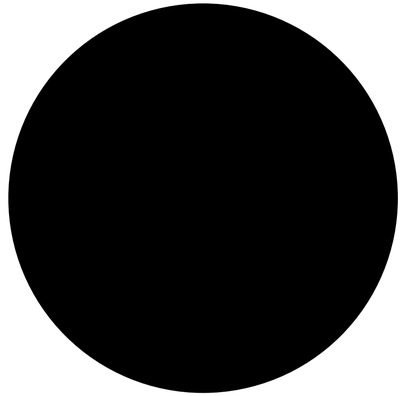
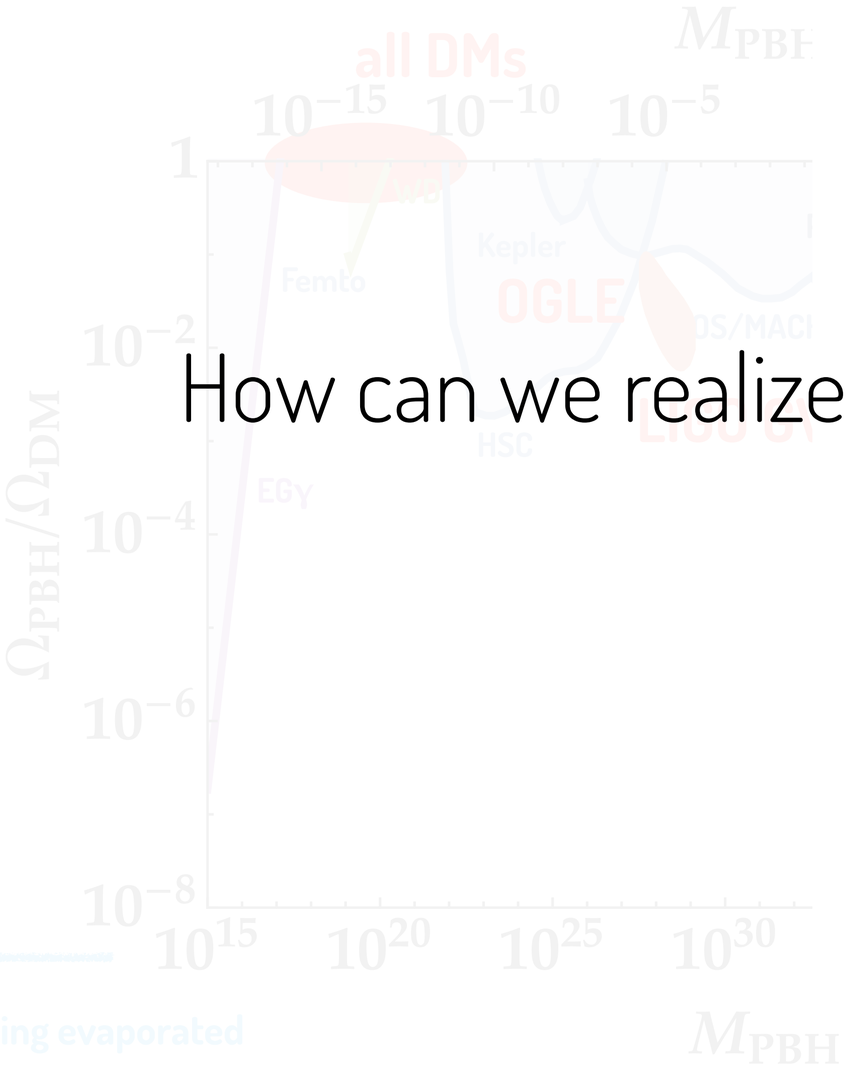
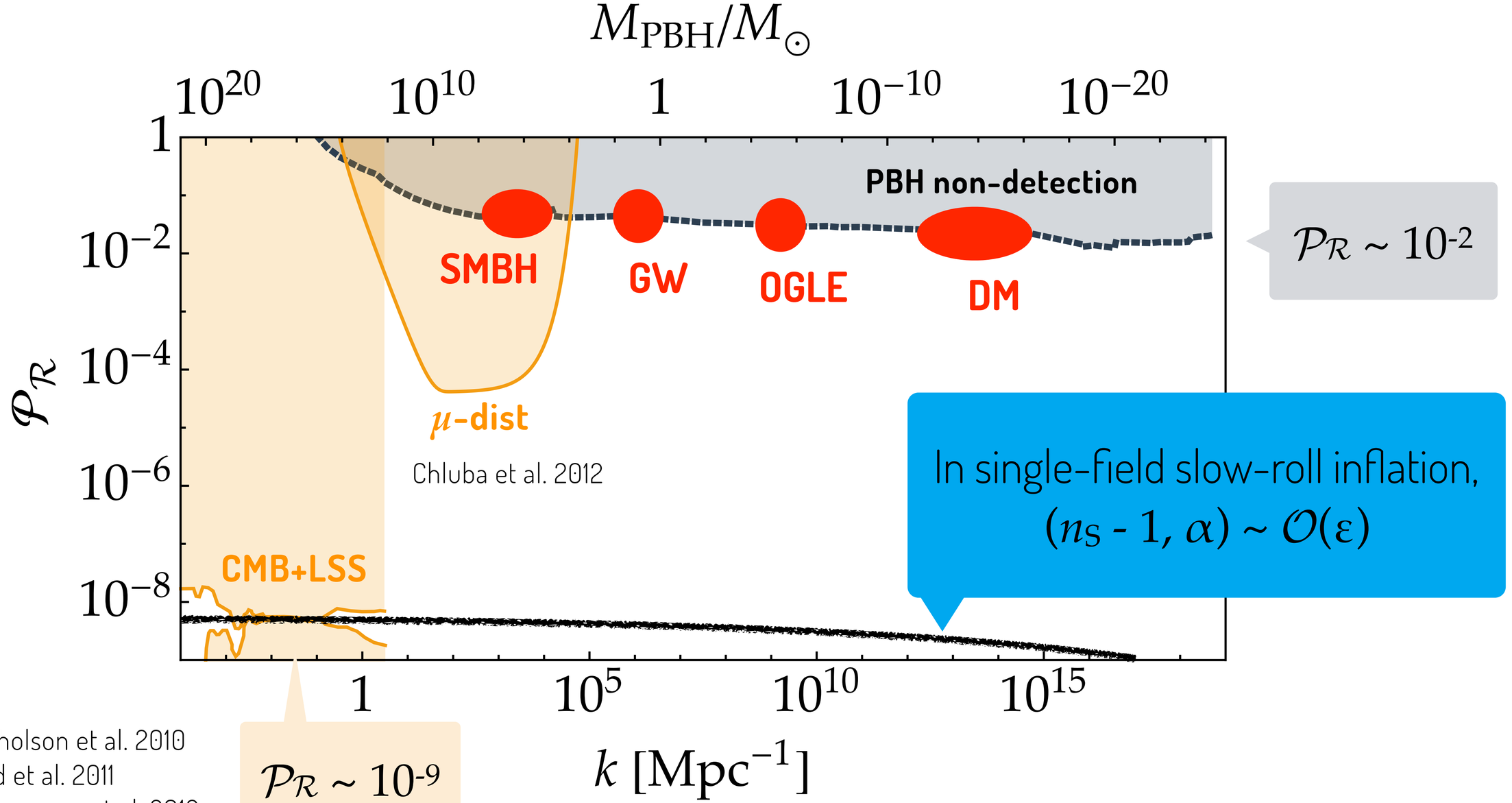


FIG. 1. Exact scale (1:1) illustration of a $5M_\oplus$ PBH. Note that a $10M_\oplus$ PBH is roughly the size of a ten pin bowling ball.

Motivations of PBH



How can we realize these HIERARCHICAL mass spectra?

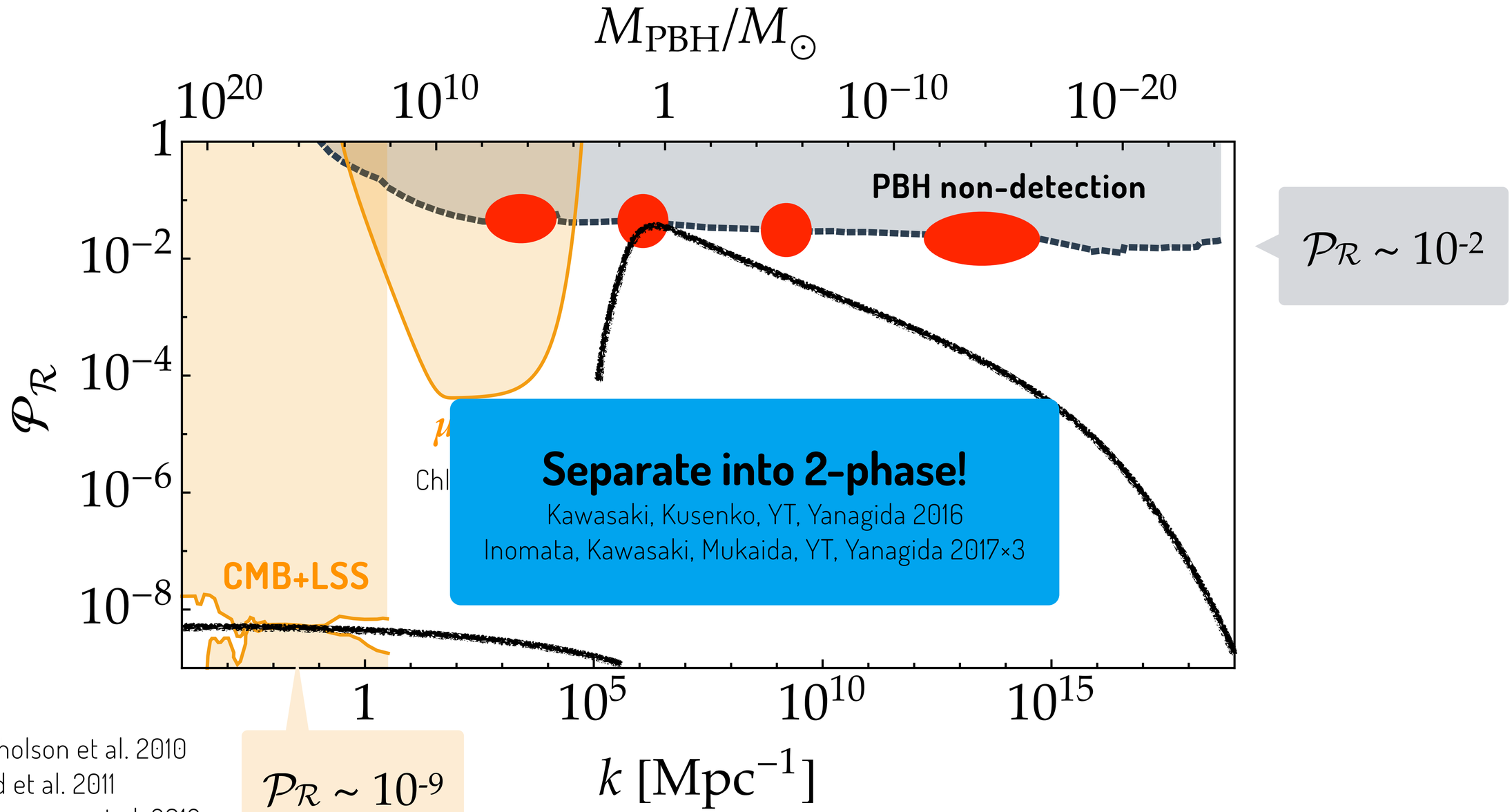


$\mathcal{P}_\mathcal{R} \sim 10^{-2}$

In single-field slow-roll inflation,
$(n_S - 1, \alpha) \sim \mathcal{O}(\varepsilon)$

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

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



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

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

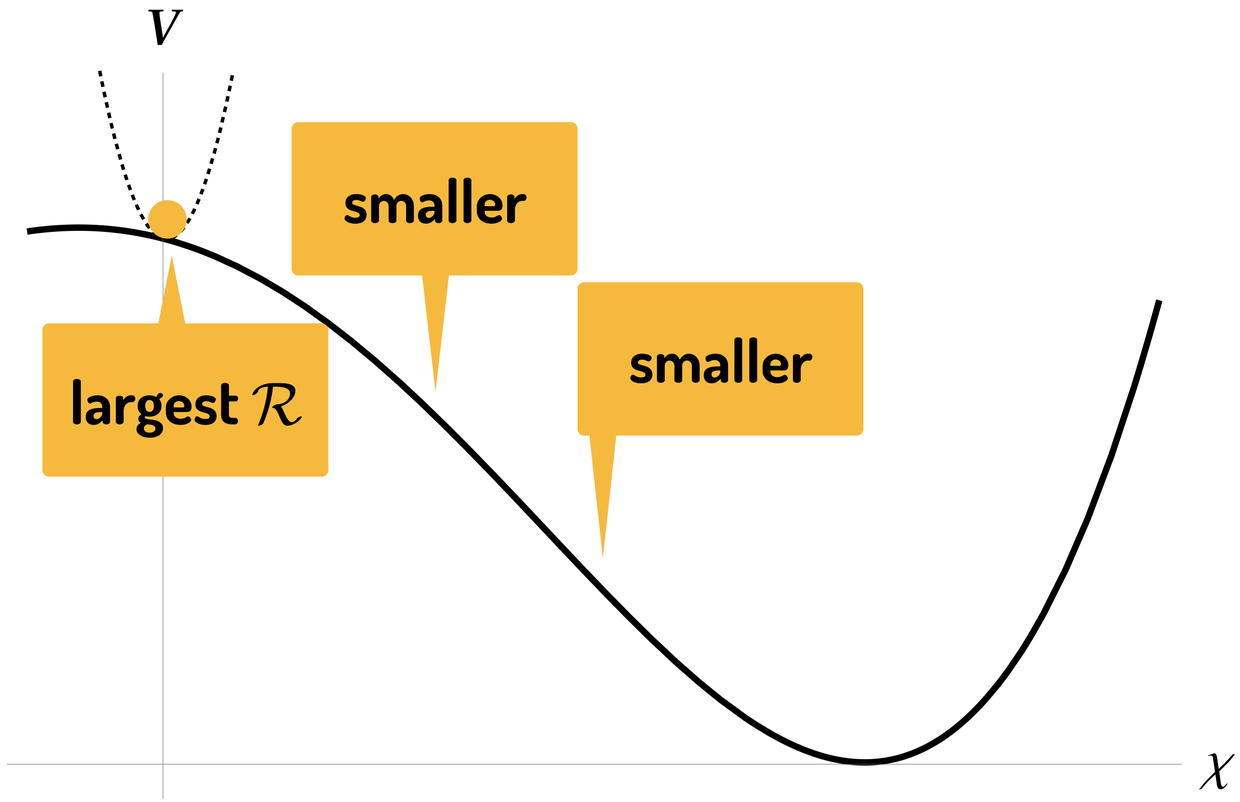
Nicholson et al. 2010
Bird et al. 2011
Bringmann et al. 2012

Double Inflation

Kumekawa, Moroi, Yanagida 1994
Izawa, Kawasaki, Yanagida 1997
Kawasaki, Sugiyama, Yanagida 1998

$$V(\phi,\chi) = V_{\rm CMB}(\phi) + \left(v^2 - g\frac{\chi^n}{M_{\rm Pl}^{n-2}}\right)^2 - \epsilon v^4 \frac{\chi}{M_{\rm Pl}} - \frac{1}{2}\kappa v^4 \frac{\chi^2}{M_{\rm Pl}^2} + \frac{c}{2} V_{\rm CMB}(\phi)\frac{\chi^2}{M_{\rm Pl}^2}$$

$$V_{\rm CMB} \gg v^4$$

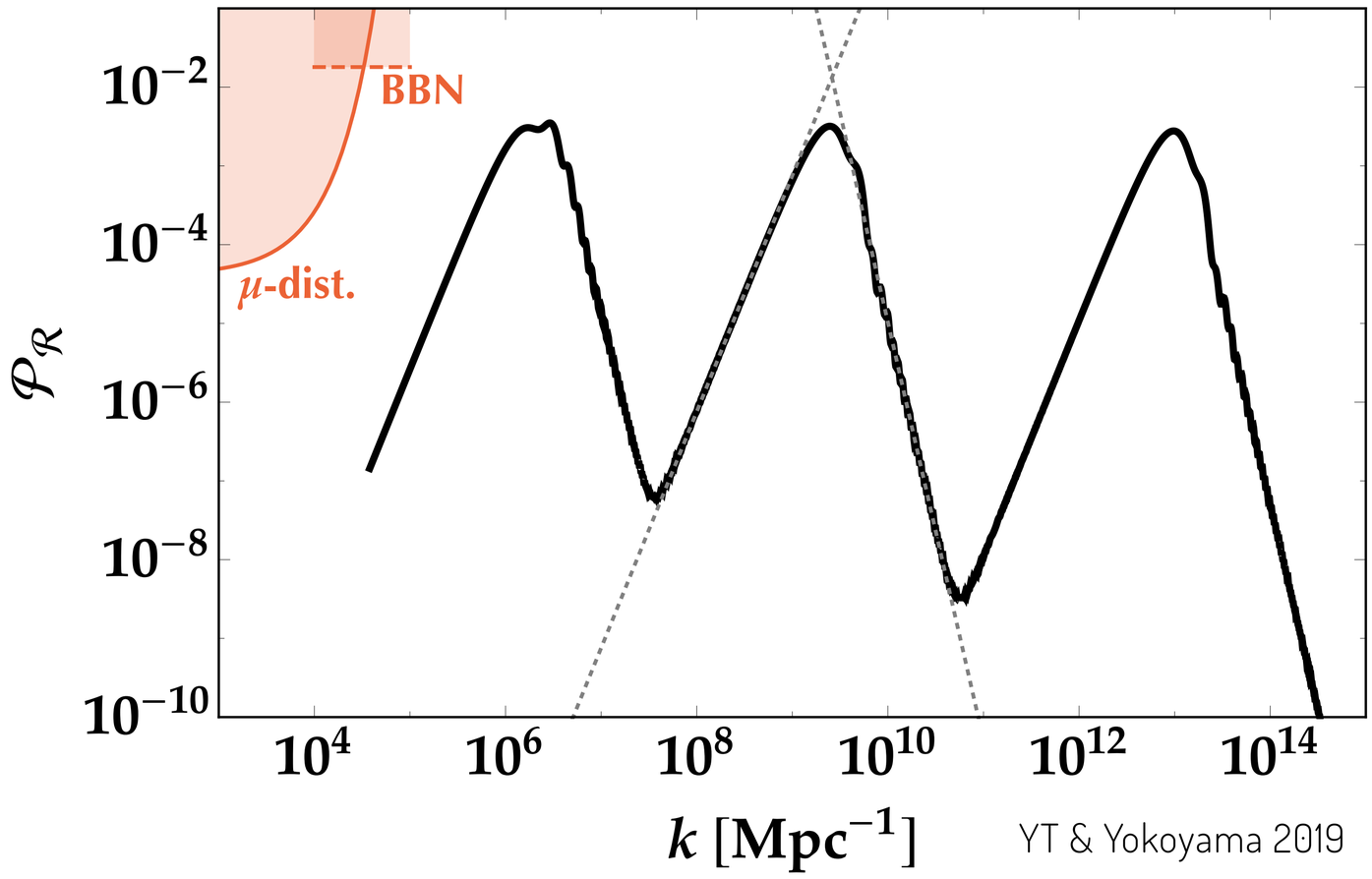


not short inflation

↕

large PTB at the onset

Extreme Case



YT & Yokoyama 2019

- 4 hilltop inflation

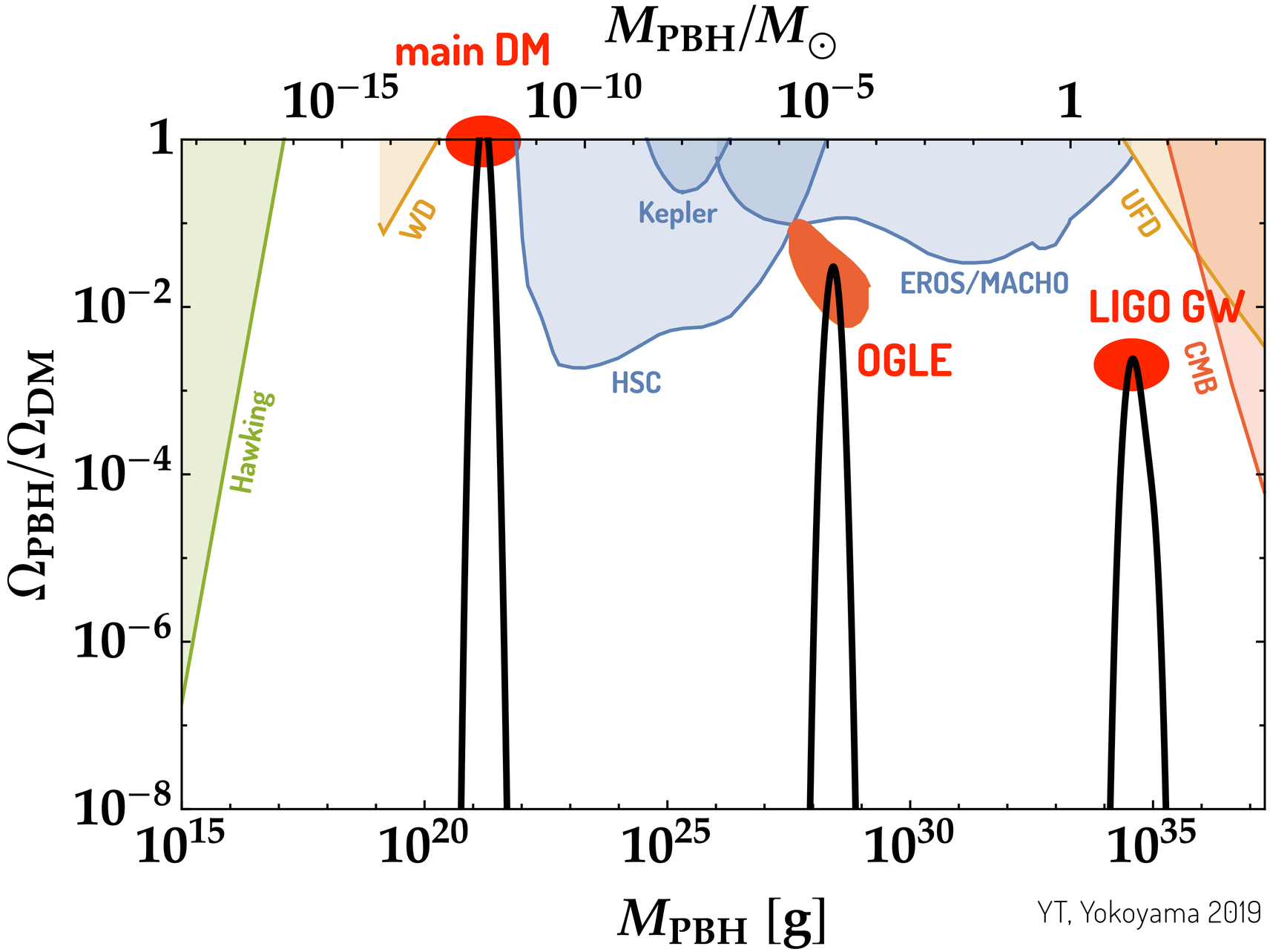
$$V_{\rm hill} = \sum_{i=1}^{4} V_{{\rm hill},i}$$

$$+$$

- Stabilizer

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

  - during phase-i:
    stabilize ϕ_{i+1}
  - after $V_{{\rm hill},i}$ decays:
    start phase-$(i+1)$



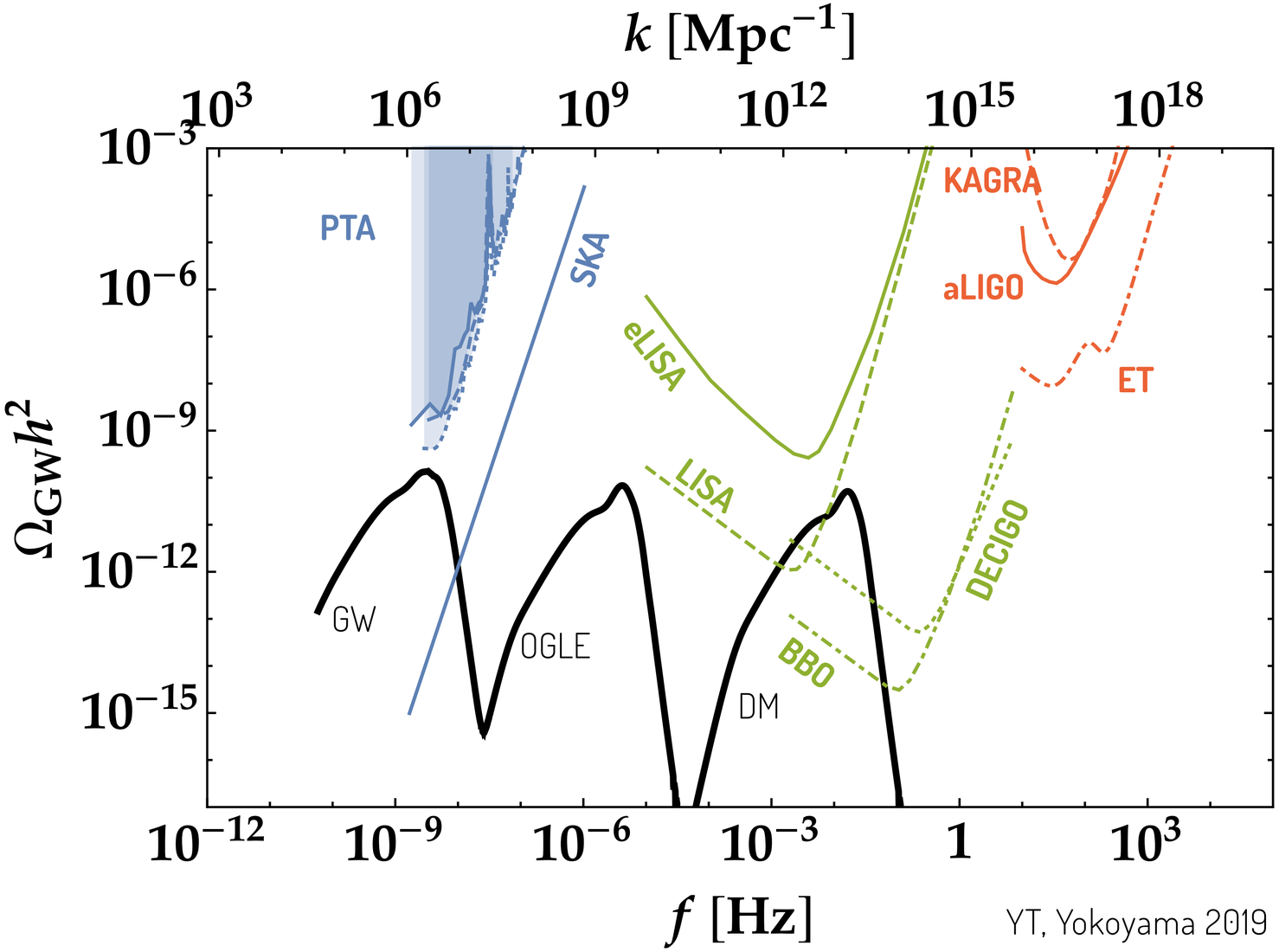
YT, Yokoyama 2019

Testability

large scalar PTB.

2ndary tensor PTB.
(stochastic GWs)

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



YT, Yokoyama 2019

Implication to String Theory?

dS swampland conjecture Ooguri & Vafa+ 2018

"dS vacua will be unstable in UV-complete theories"

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

each infl. phase CANNOT continue long → 60 e-folds in total by multi-phase

- CMB scale?

  PTB by inflaton

$$-0.035 \times \frac{{\rm d}\log \mathcal{P}_\zeta}{{\rm d}\log k}(k_{\rm CMB}) = n_{\rm s} - 1 \simeq -6\epsilon_V + 2\eta_V \sim \mathcal{O}(1)$$

Planck 2018

Implication to String Theory?

dS swampland conjecture Ooguri & Vafa+ 2018

"dS vacua will be unstable in UV-complete theories"

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

each infl. phase CANNOT continue long → 60 e-folds in total by multi-phase

- CMB scale?

  PTB by curvaton Kogai, YT in prep.

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

Planck 2018

Conclusions

- interesting mass regions for PBH are hierarchical
- multi-phase inflation can realize them simultaneously

    cf. dS swampland conjecture may support multi-phase inflation

- testable by GW