

*19. Feb. 2019 in IAPS & FAPESP Workshop @ Sao Paulo*

# Aspects of Primordial Black Hole as Dark Matters



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w/ Inomata, Kawasaki, Kusenko, Mukaida, Yanagida  
2016, 2017, 2017, 2017,  
S. Yokoyama in prep.

JSPS-FAPESP Workshop on

dark energy,

dark matter,

and galaxies

PROGRAM

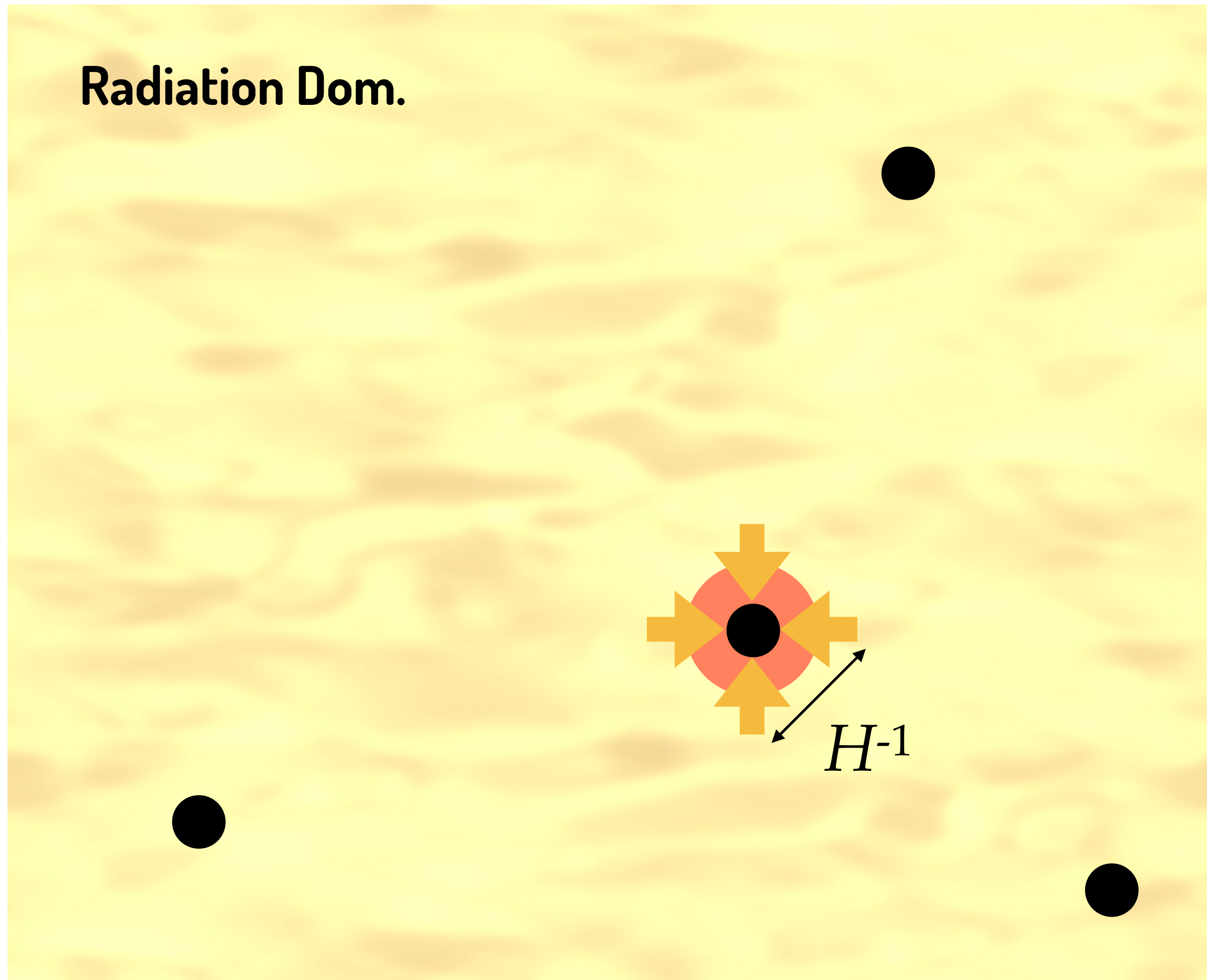
## Dark Matter

- WIMP
- axion
- gravitino
- SIMP
- ⋮
- modified Grav.
- **Black Hole (BH)**



# Primordial Black Hole

Carr & Hawking 1974



## - Overdensity

$$\delta > \delta_{\text{th}} \simeq 0.4$$

Musco, Miller, Rezzolla 2005, ...  
Harada, Yoo, Kohri 2013

$$\left( \text{cf. } \mathcal{R}_{\text{th}} \simeq \frac{9}{4} \delta_{\text{th}} \simeq 1 \right)$$

## - Rarity

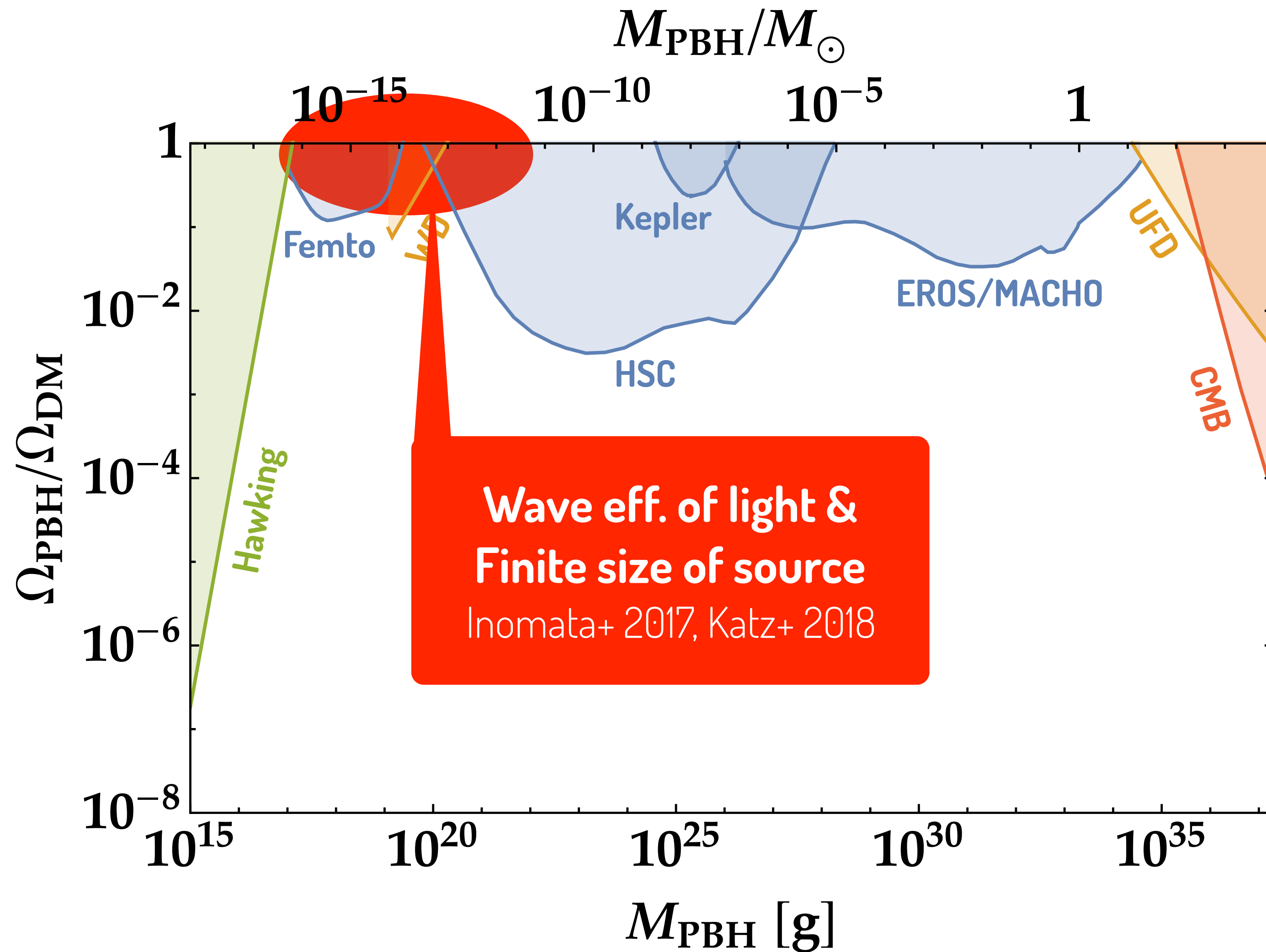
$$\frac{\Omega_{\text{PBH}}}{\Omega_{\text{DM}}} \sim \frac{\rho_{\text{PBH}}/\rho_{\text{R}}|_f}{7 \times 10^{-16}} \left( \frac{M_{\text{PBH}}}{10^{20} \text{ g}} \right)^{-1/2}$$

$\sim 10\sigma$  rarity

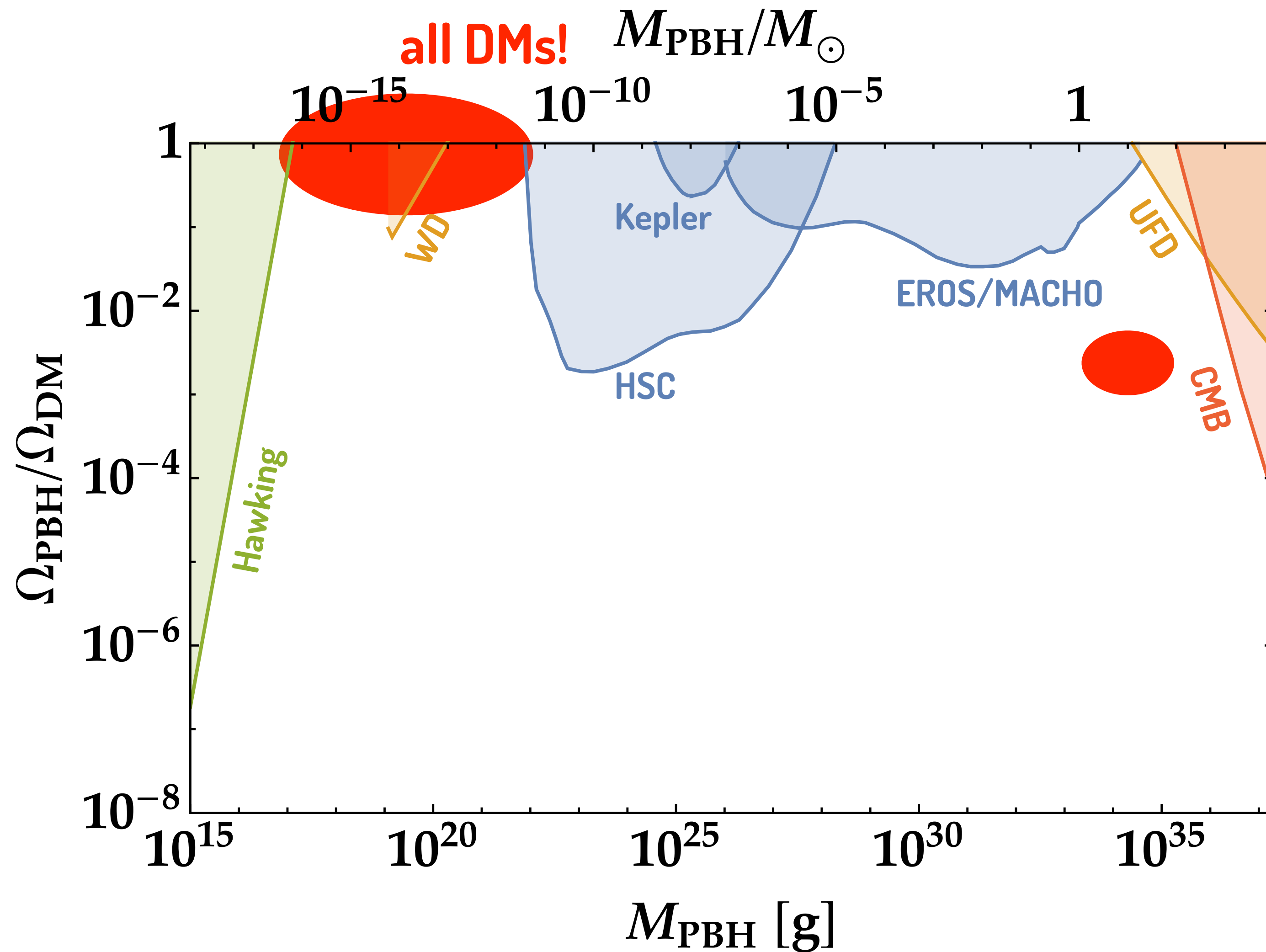
$$\Rightarrow \mathcal{P}_{\mathcal{R}}(k_{\text{PBH}}) \sim \left( \frac{\mathcal{R}_{\text{th}}}{10} \right)^2 \simeq 10^{-2}$$

(cf.  $\mathcal{P}_{\mathcal{R}}(k_{\text{CMB}}) \simeq 2 \times 10^{-9}$ )

# Obs. const. on PBH



# Obs. const. on PBH



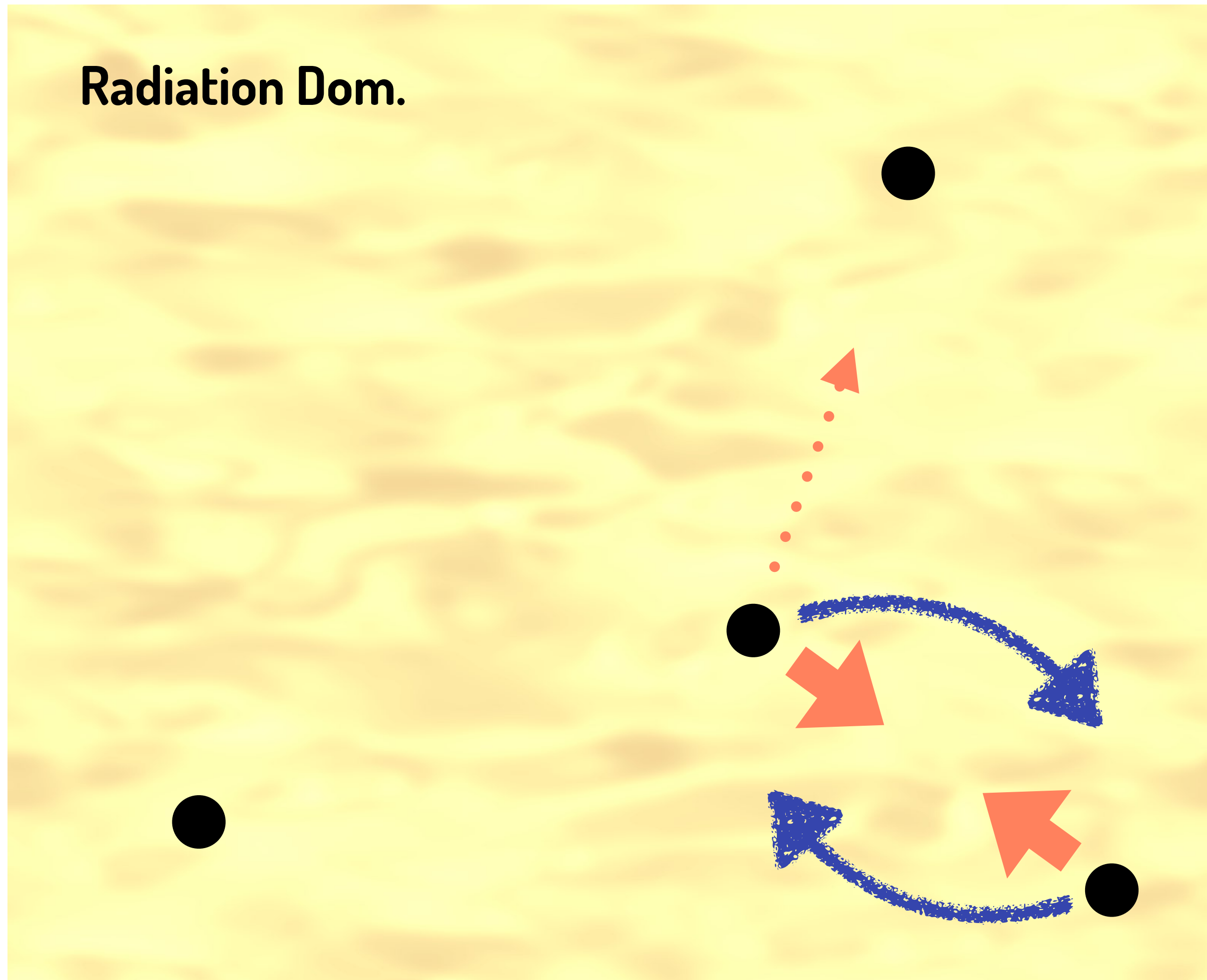
Massive than stellar BHs found

small spin

Event	$m_1/M_{\odot}$	$m_2/M_{\odot}$	$M/M_{\odot}$	$\chi_{\text{eff}}$
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	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$0.08^{+0.20}_{-0.22}$

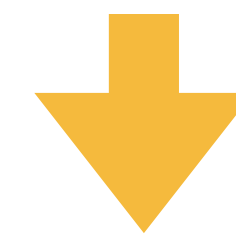
LIGO/Virgo 2018

# Binary PBH



Sasaki+ 2016

$$\text{if } \frac{\Omega_{\text{PBH}}}{\Omega_{\text{DM}}} \sim 10^{-3} - 10^{-2}$$

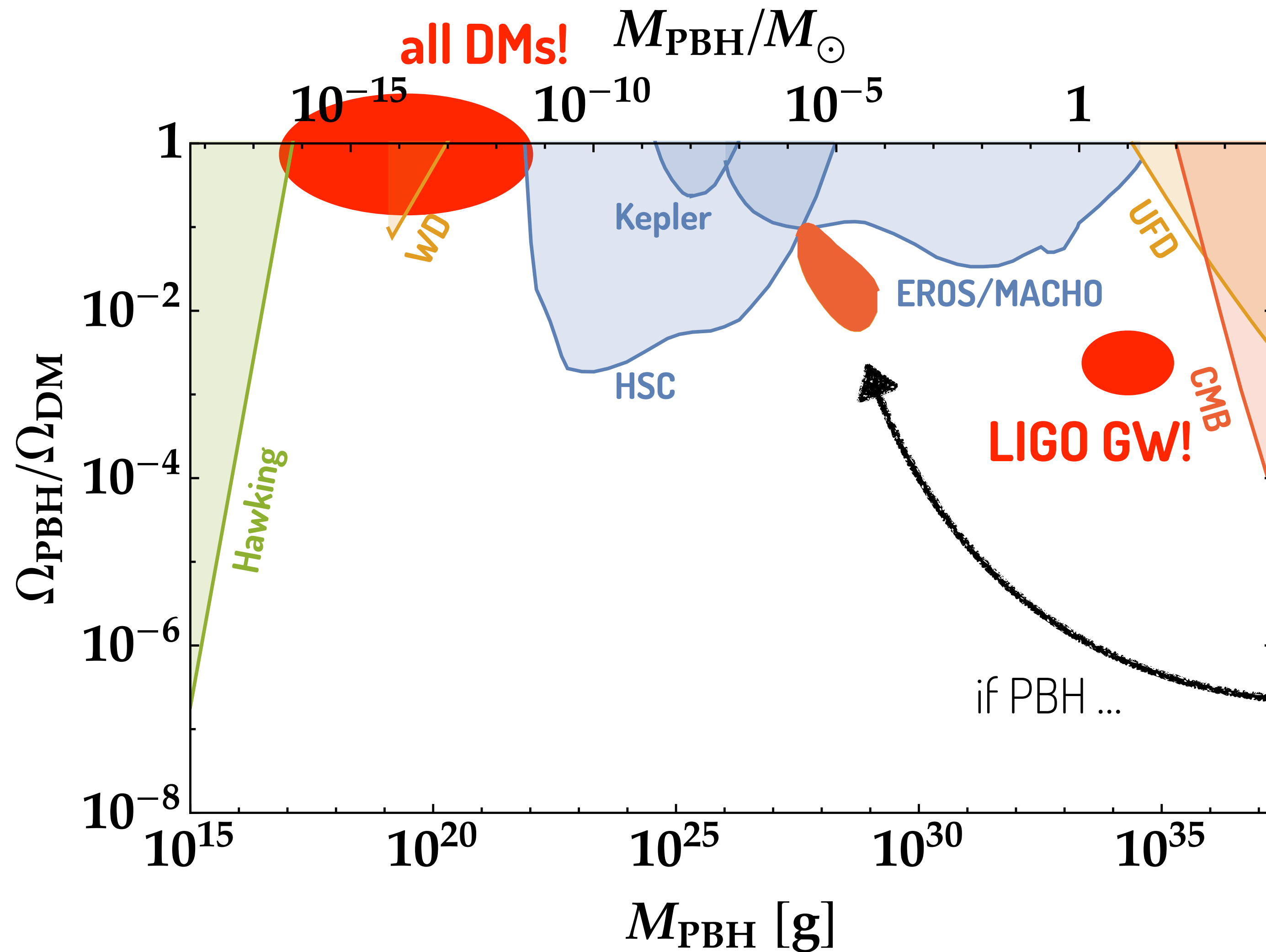


$$[\text{merger rate}] \simeq 52.9^{+55.6}_{-27.0} \text{ Gpc}^{-3} \text{ yr}^{-1}$$

LIGO/Virgo 2018

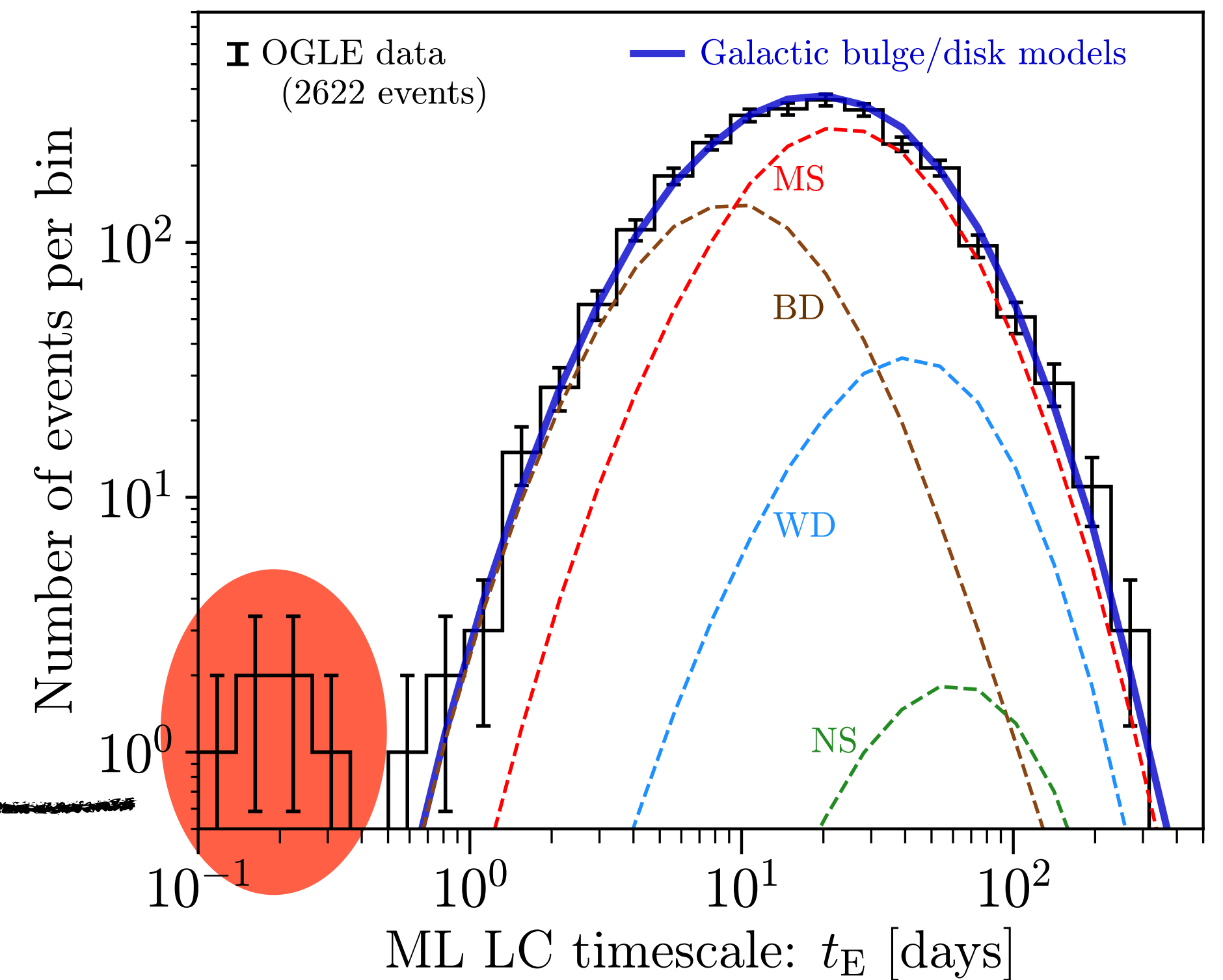


# Obs. const. on PBH



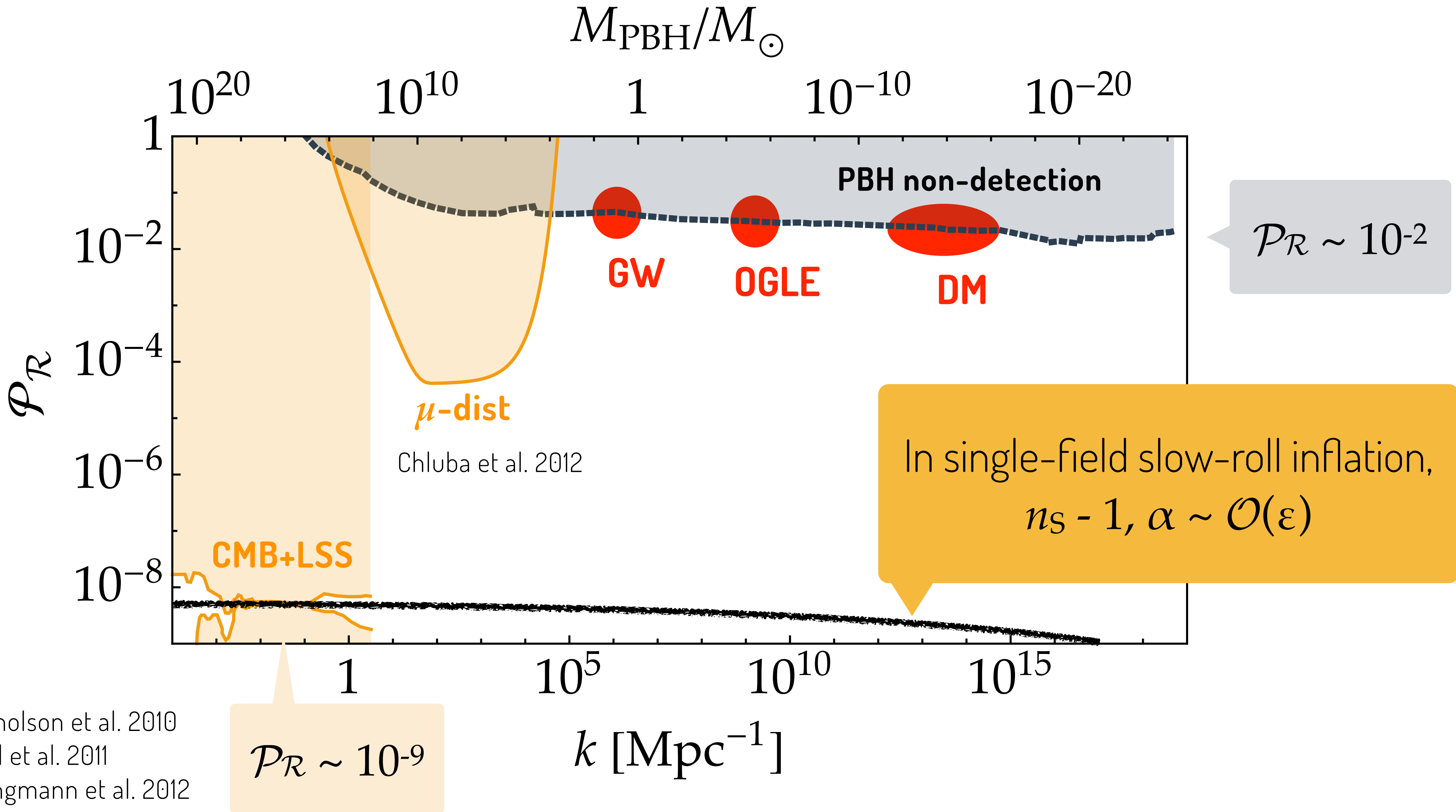
## 5-yr Optical Gravitational Lensing Experiment (OGLE)

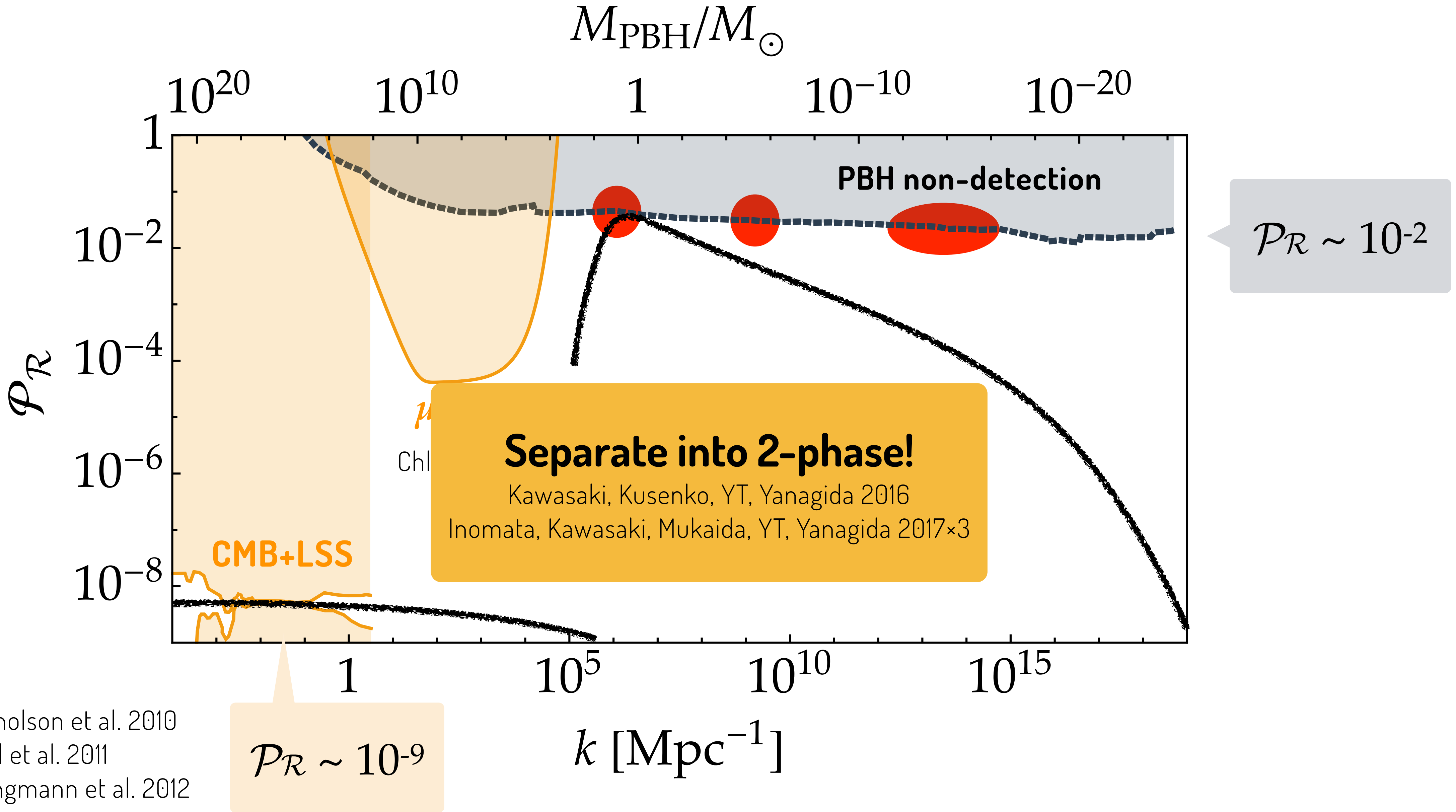
Niikura+ 2019



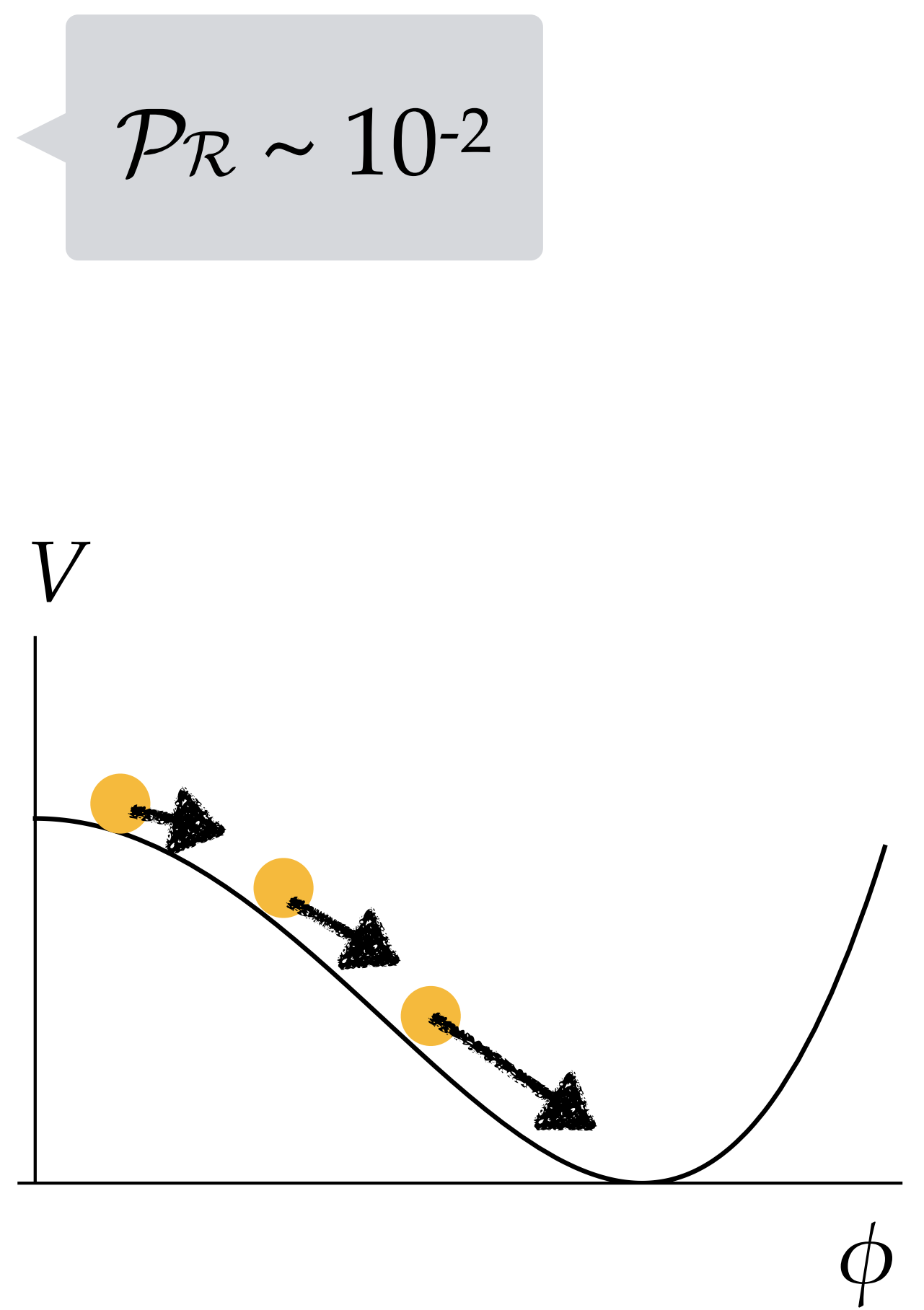
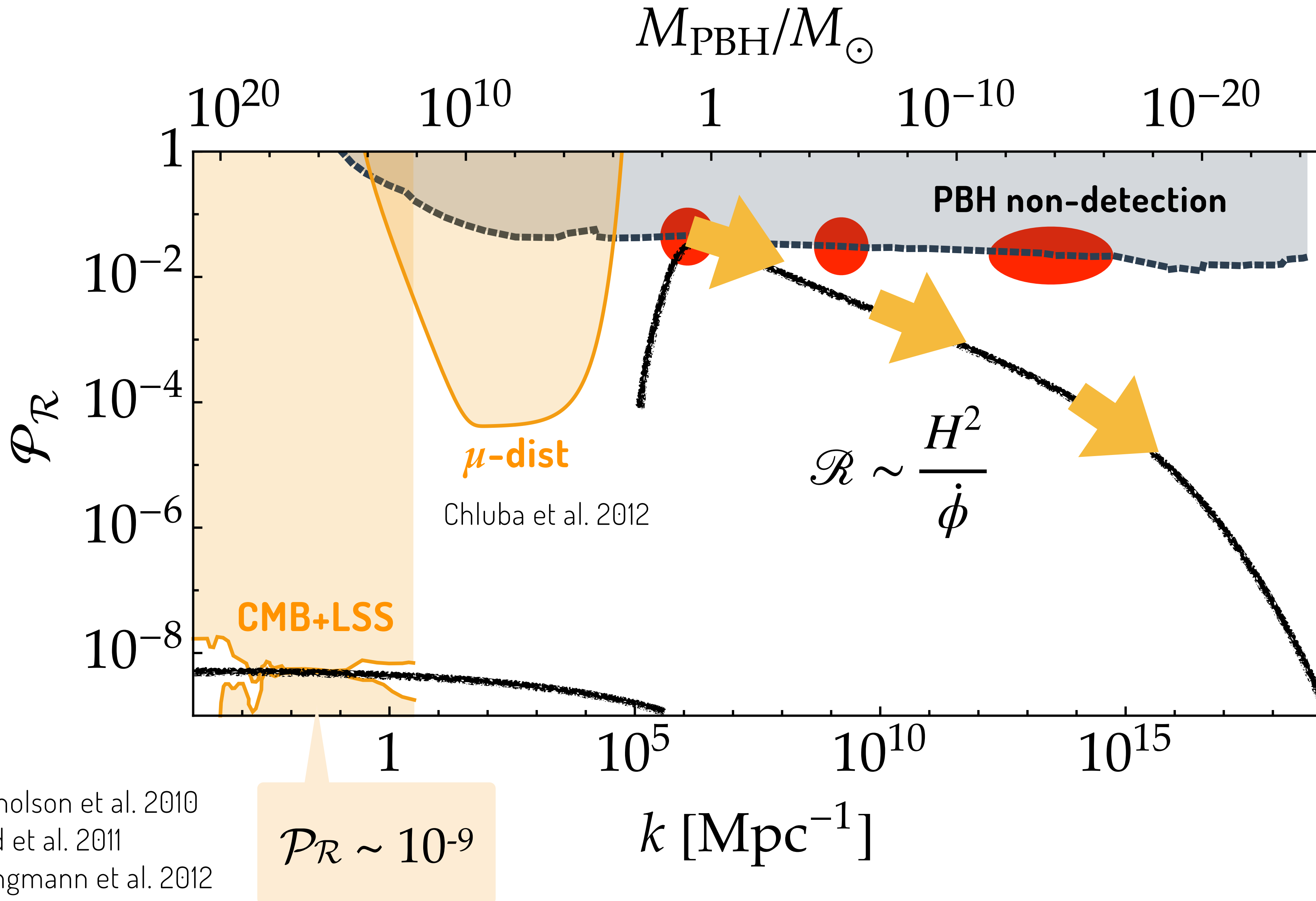
*Inflationary sector ...*



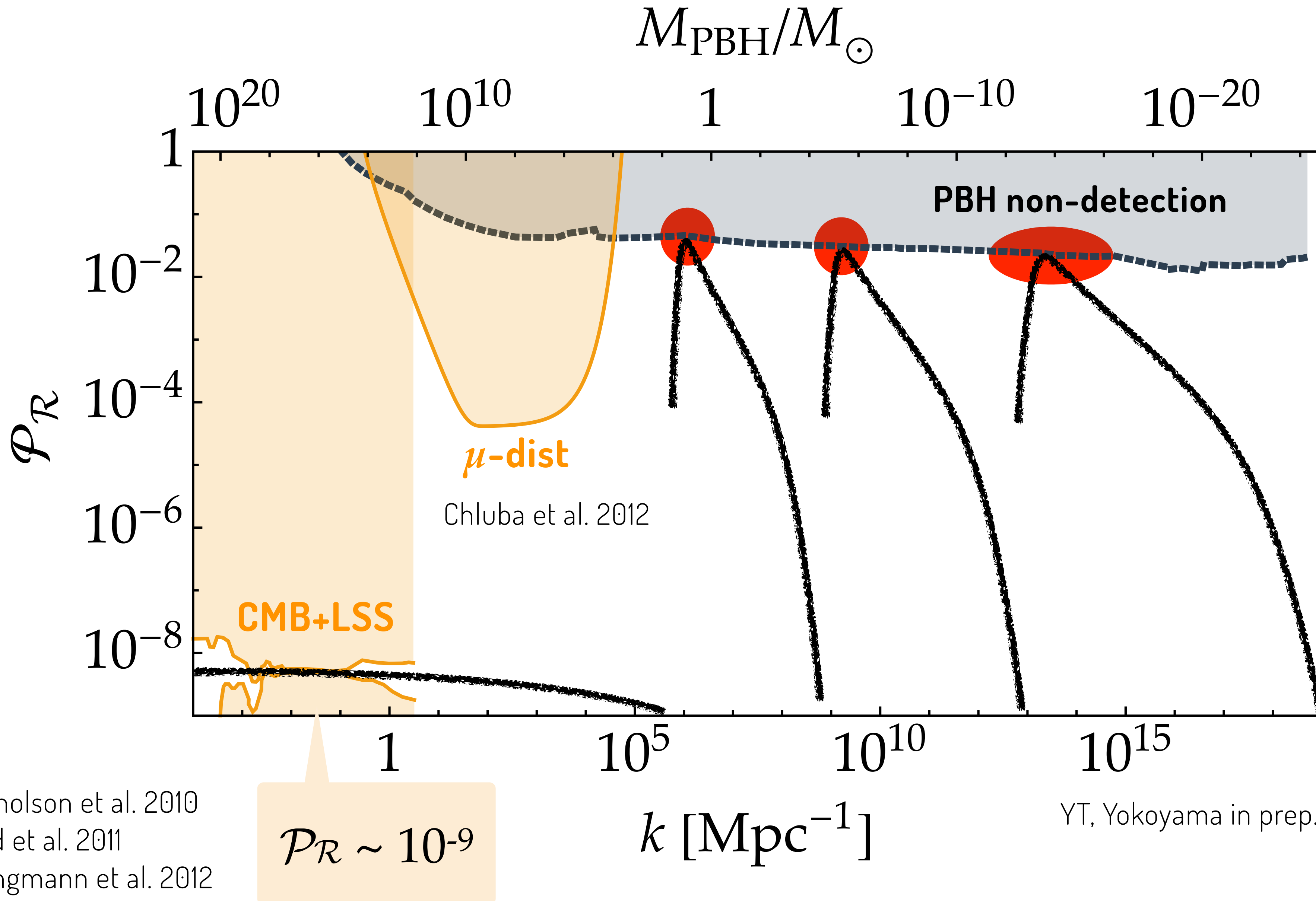




Nicholson et al. 2010  
 Bird et al. 2011  
 Bringmann et al. 2012



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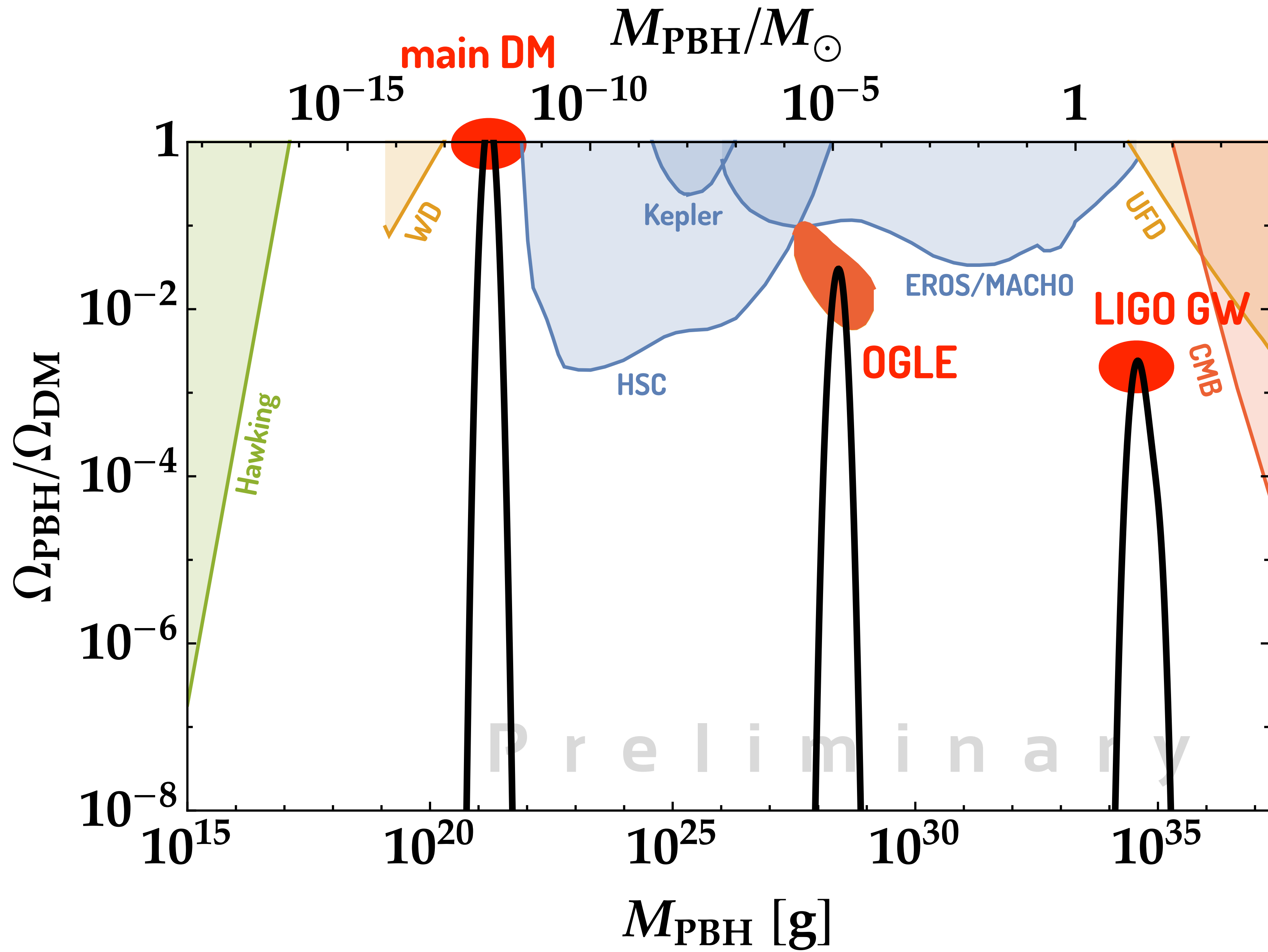


**- Stabilization**

$$V_{\text{stab}} = \frac{1}{2} V_{\text{pre}} \frac{\phi^2}{M_{\text{Pl}}^2}$$

- during pre-phase: stabilize  $\phi$
- after  $V_{\text{pre}}$  decays: start next phase





# Testability

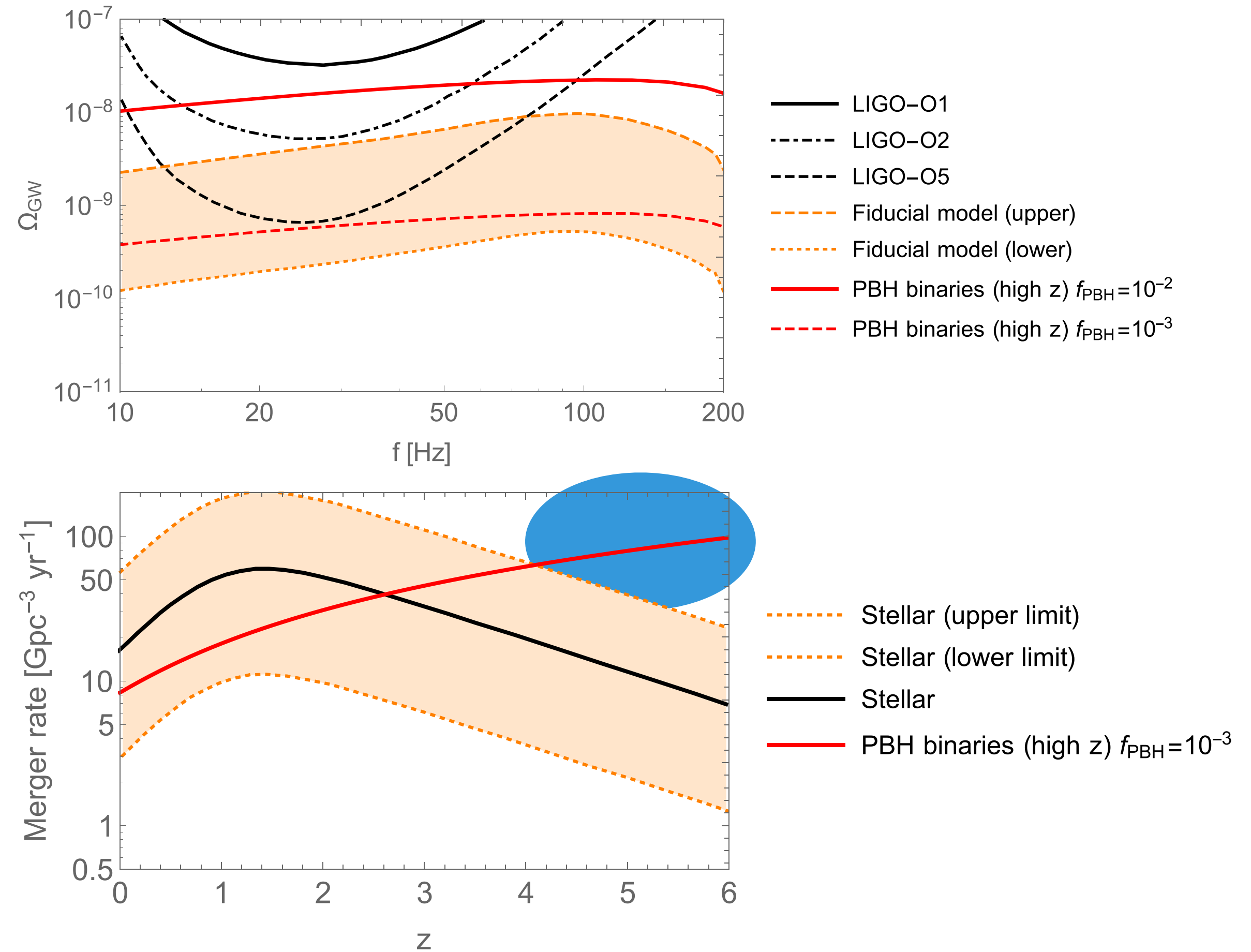
- LIGO/Virgo PBH

**PBH tends to be spinless**  
Chiba & Yokoyama 2017

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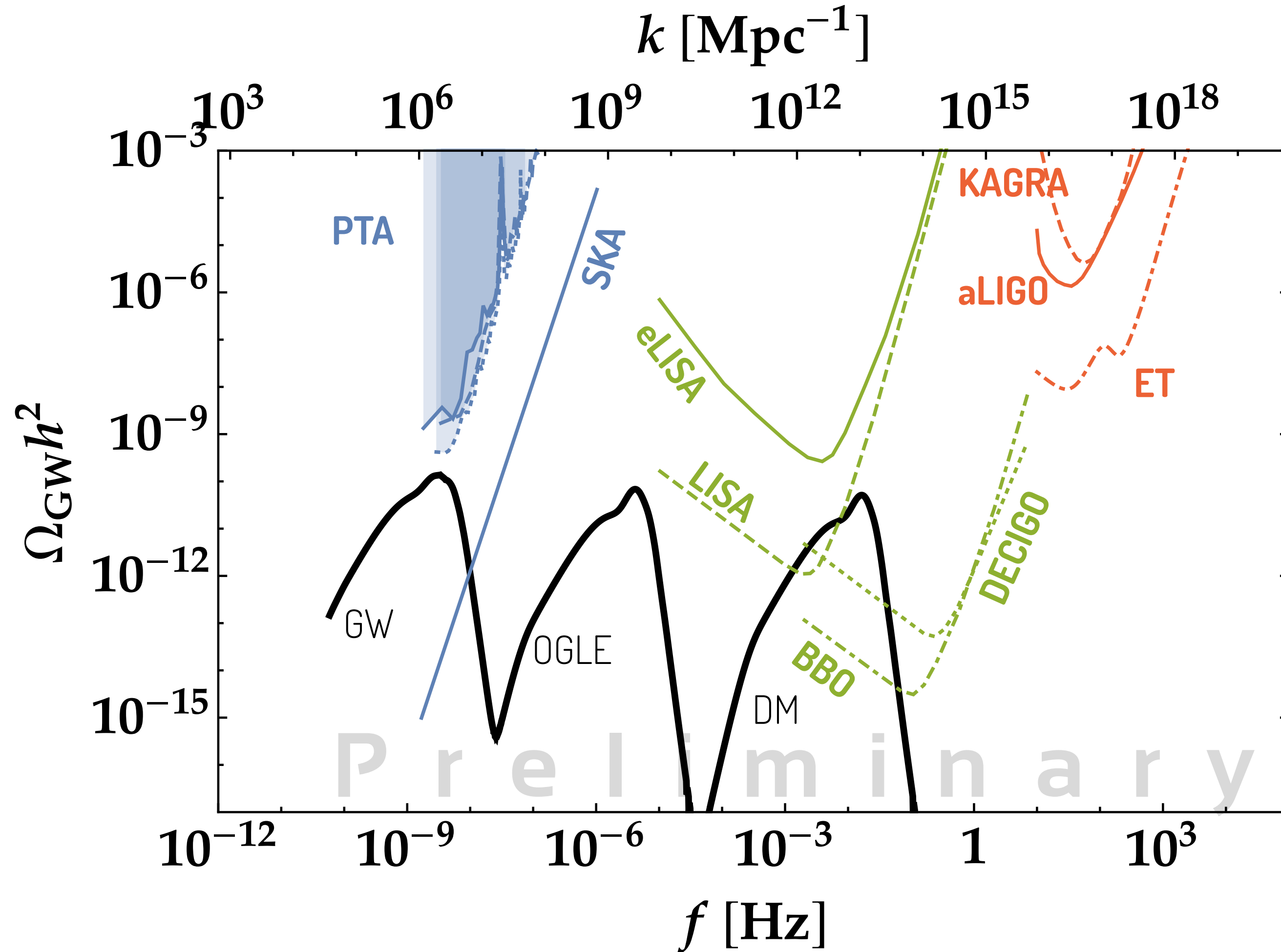
LIGO/Virgo 2018

Sasaki+ 2018



# Testability

large scalar ptb.  $\rightarrow$  secondary tensor ptb. (stochastic GW):  $\Omega_{\text{GW}} h^2 \sim 10^{-8} \left( \frac{\mathcal{P}_{\mathcal{R}}}{10^{-2}} \right)^2$



# Conclusions

- 3 interesting mass region for PBH
  - $10 M_{\odot}$  : LIGO/Virgo GW
  - $10^{-5} M_{\odot}$  : OGLE lensing
  - $10^{-12} M_{\odot}$  : main component of DMs
- multi-phase inflation can realize them simultaneously
  - cf. string swampland conjecture Ooguri & Vafa+ 2018
    - “dS vacua will be unstable in UV-complete theories”*
- testable by GW