16. Aug. 2019 @ Rencontres du Vietnam: Cosmology in Quy Nhon

Primordial black hole tower:

Dark matter, earth-mass, and LIGO black holes

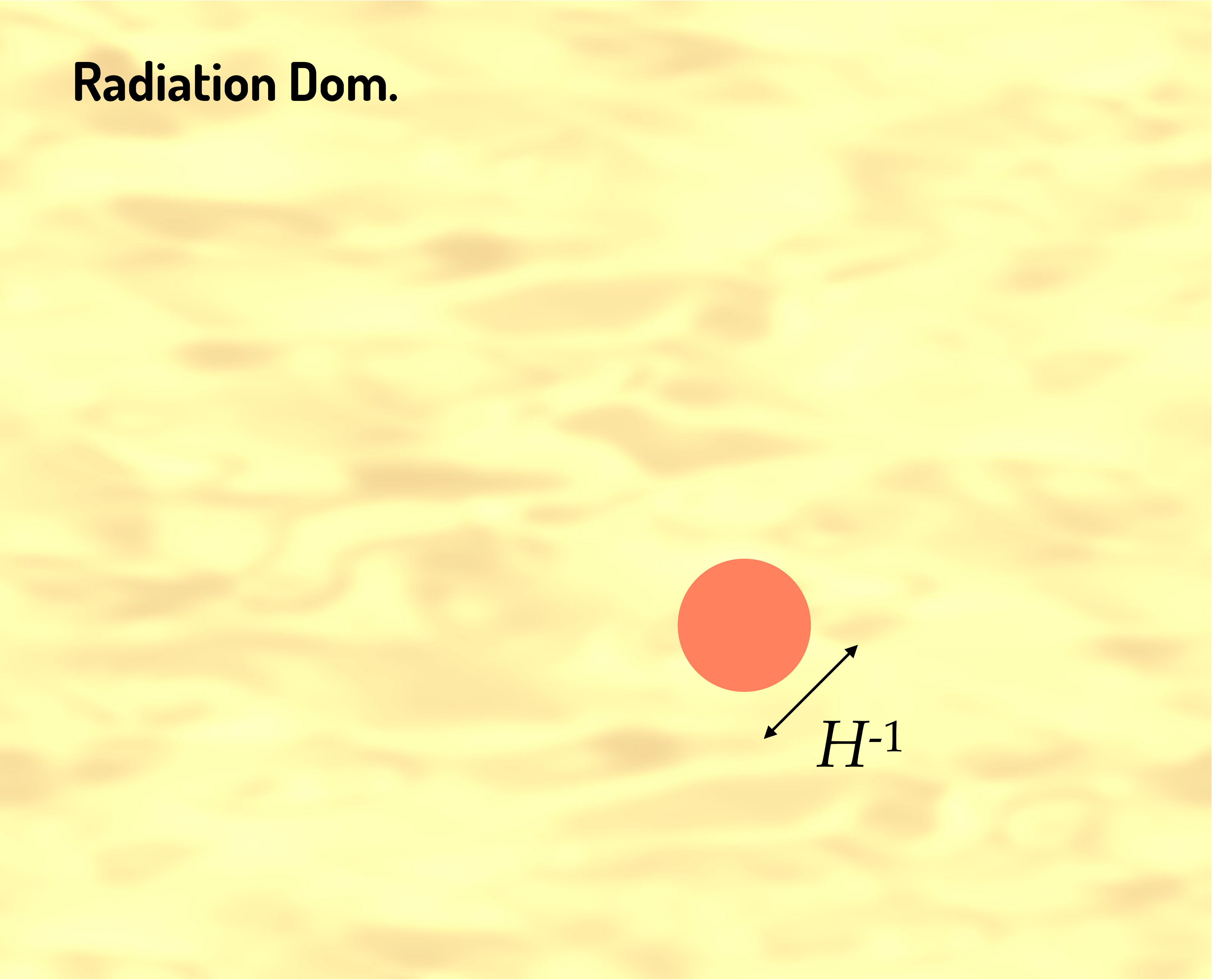
Yuichiro TADA (Nagoya U.)

w/ S. Yokoyama

PRD **100**, no. 2, 023537 (2019)

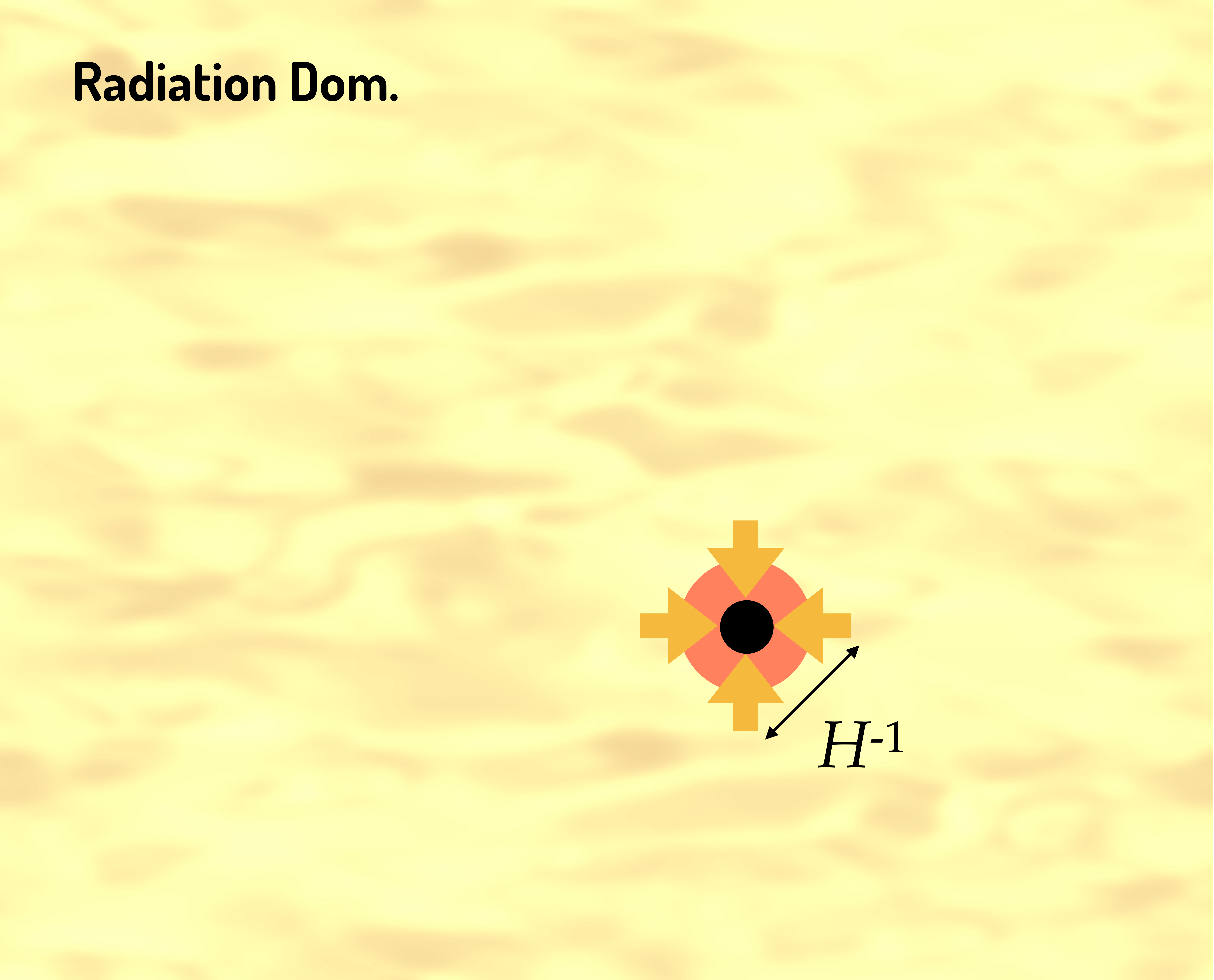
Primordial Black Hole

Carr & Hawking 1974



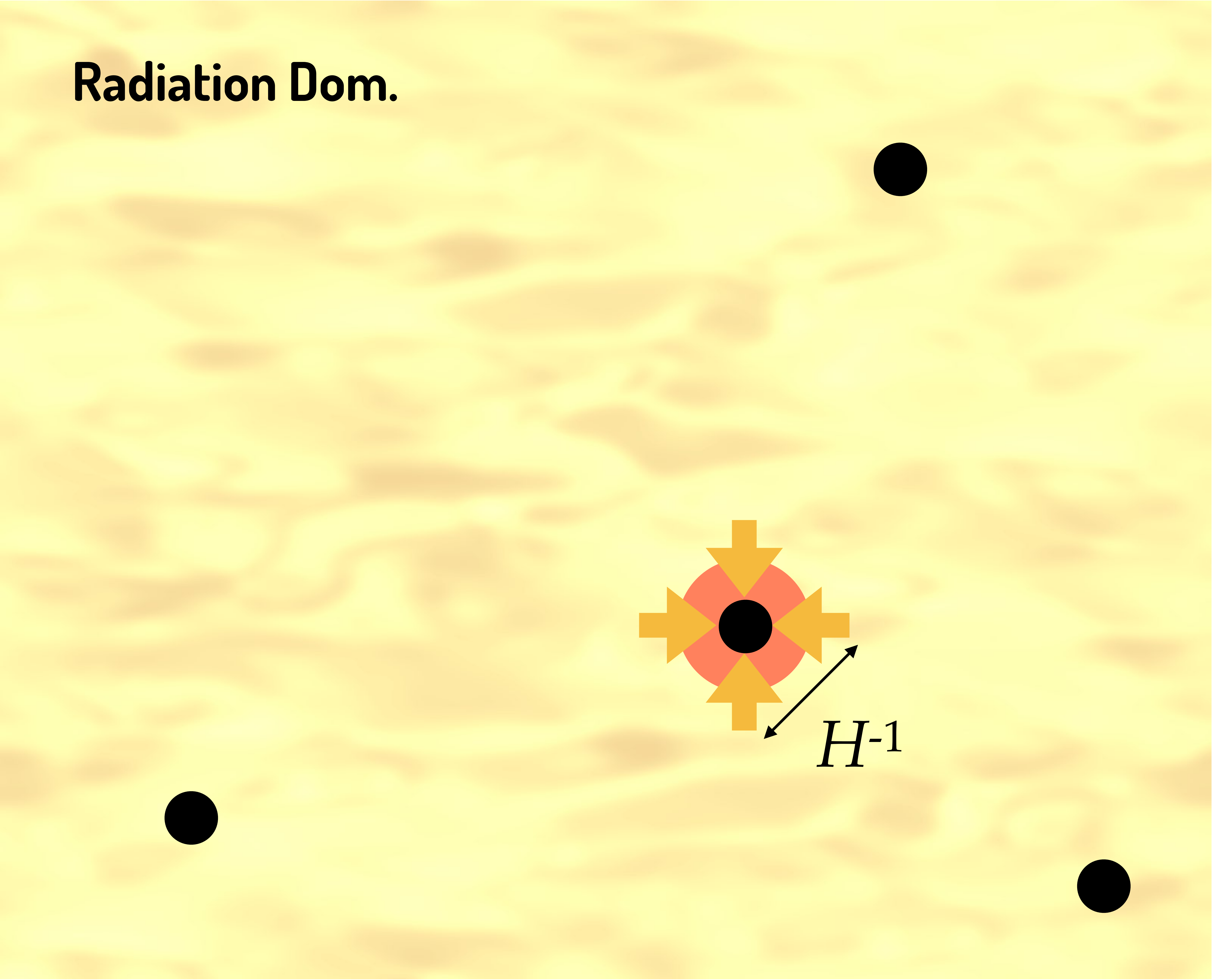
Primordial Black Hole

Carr & Hawking 1974



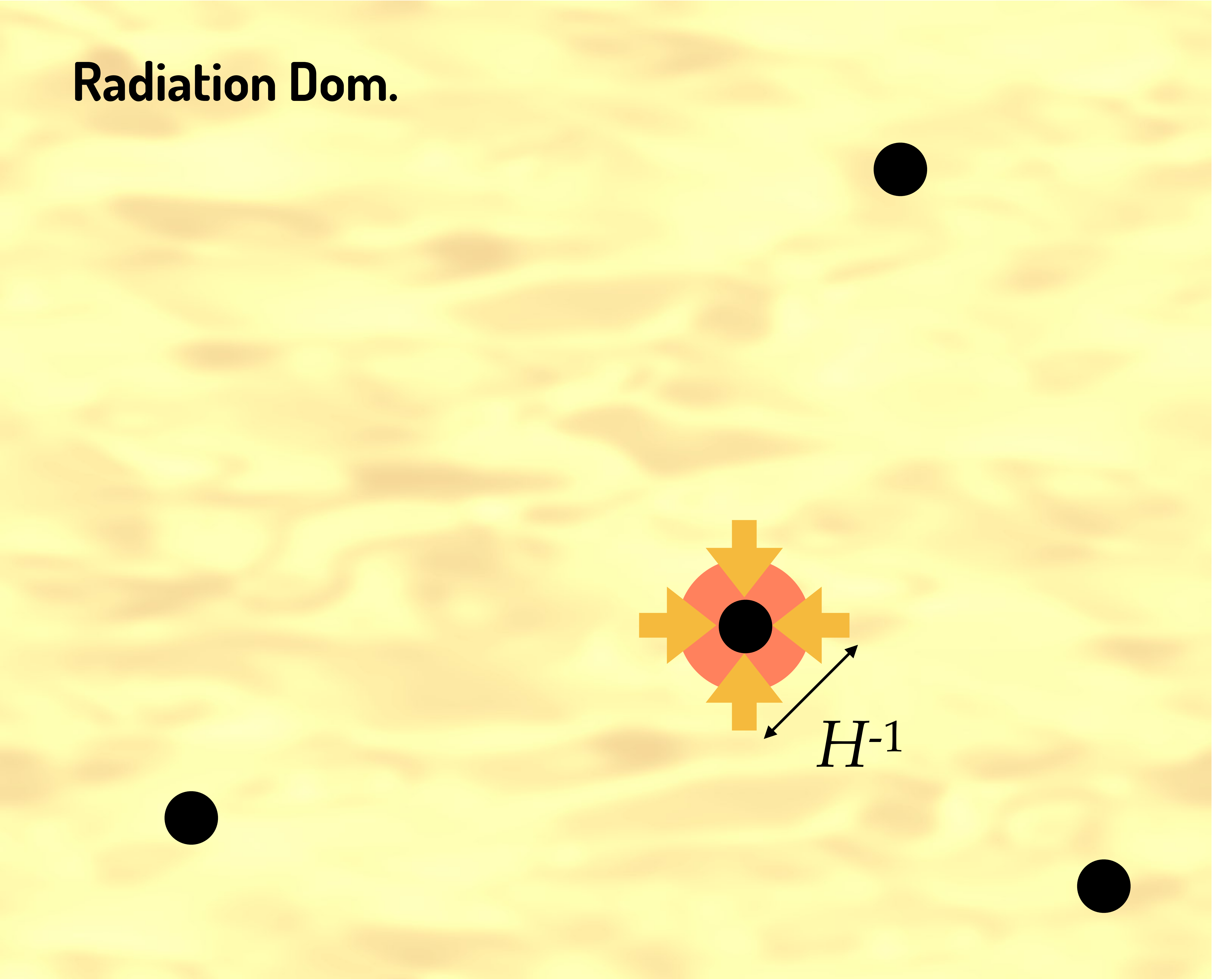
Primordial Black Hole

Carr & Hawking 1974



Primordial Black Hole

Carr & Hawking 1974



- **PBH mass**

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

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

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

Primordial Black Hole

Carr & Hawking 1974

- **PBH mass**

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

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

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

- **Overdensity**

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

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

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

Primordial Black Hole

Carr & Hawking 1974

- **PBH mass**

$$M_{\rm PBH} \sim M_{\rm H} = \frac{4\pi}{3}\rho H^{-3} = \frac{1}{2GH}$$

$$\sim M_\odot \left(\frac{t_{\rm PBH}}{10^{-5}\,{\rm s}}\right) \qquad M_\odot \simeq 2 \times 10^{33}\,{\rm g}$$

$$\sim M_\odot \left(\frac{k_{\rm PBH}}{4\,{\rm pc}^{-1}}\right)^{-2}$$

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

- **Overdensity**

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

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

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

- **Rarity**

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

Primordial Black Hole

Carr & Hawking 1974

- **PBH mass**

$$M_{\rm PBH} \sim M_{\rm H} = \frac{4\pi}{3}\rho H^{-3} = \frac{1}{2GH}$$

$$\sim M_\odot \left(\frac{t_{\rm PBH}}{10^{-5}\,{\rm s}}\right) \qquad M_\odot \simeq 2\times 10^{33}\,{\rm g}$$

$$\sim M_\odot \left(\frac{k_{\rm PBH}}{4\,{\rm pc}^{-1}}\right)^{-2}$$

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

- **Overdensity**

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

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

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

- **Rarity**

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

~ 10σ rarity

Primordial Black Hole

Carr & Hawking 1974

- **PBH mass**

$$M_{\rm PBH} \sim M_{\rm H} = \frac{4\pi}{3}\rho H^{-3} = \frac{1}{2GH}$$

$$\sim M_\odot \left(\frac{t_{\rm PBH}}{10^{-5}\,{\rm s}}\right) \qquad M_\odot \simeq 2\times 10^{33}\,{\rm g}$$

$$\sim M_\odot \left(\frac{k_{\rm PBH}}{4\,{\rm pc}^{-1}}\right)^{-2}$$

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

- **Overdensity**

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

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

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

- **Rarity**

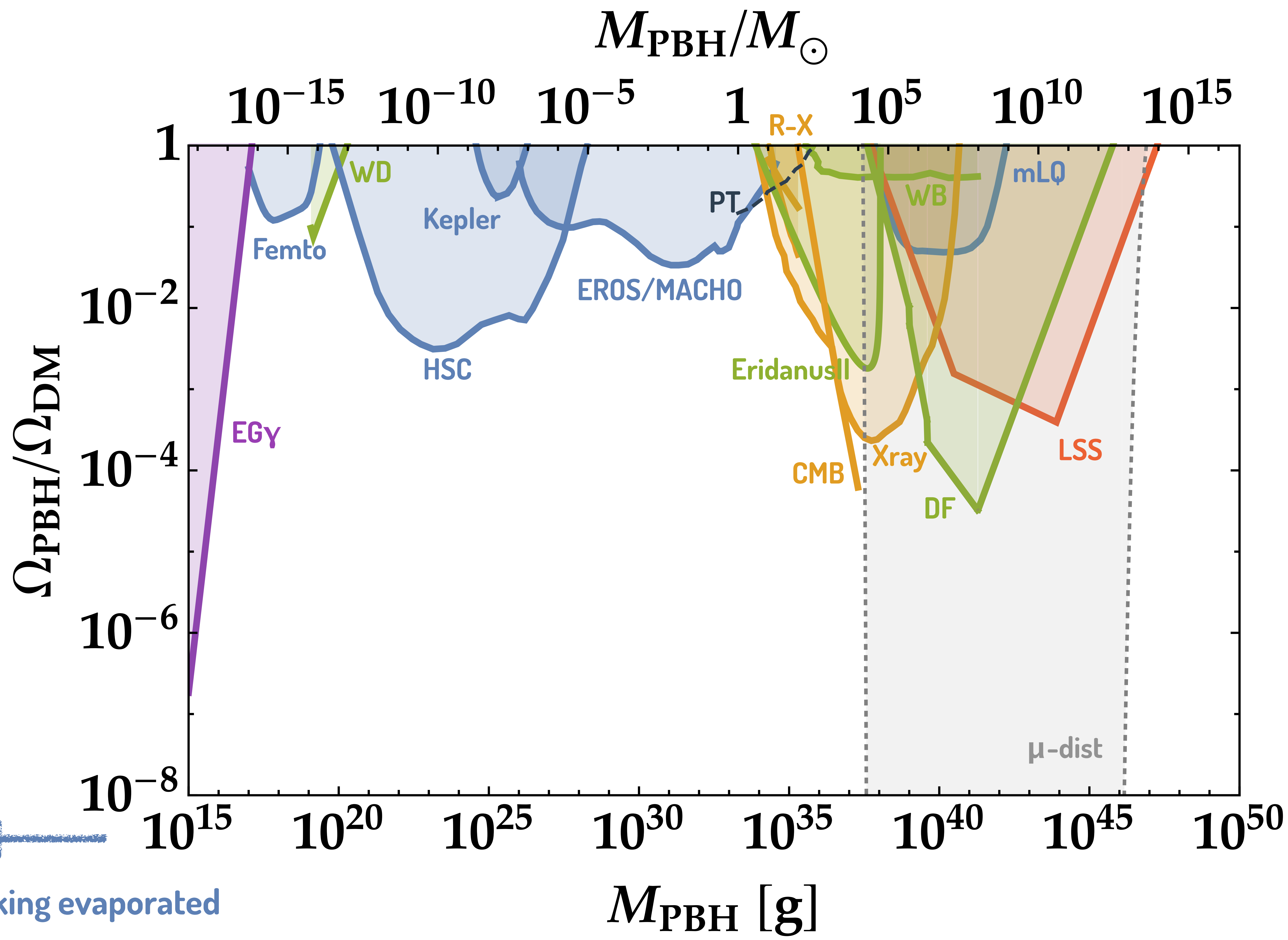
$$\frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} \sim \frac{\rho_{\rm PBH}/\rho_{\rm R}\,|_{\rm f}}{7\times 10^{-16}} \left(\frac{M_{\rm PBH}}{10^{20}\,{\rm g}}\right)^{-1/2}$$

∼ 10σ rarity

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

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

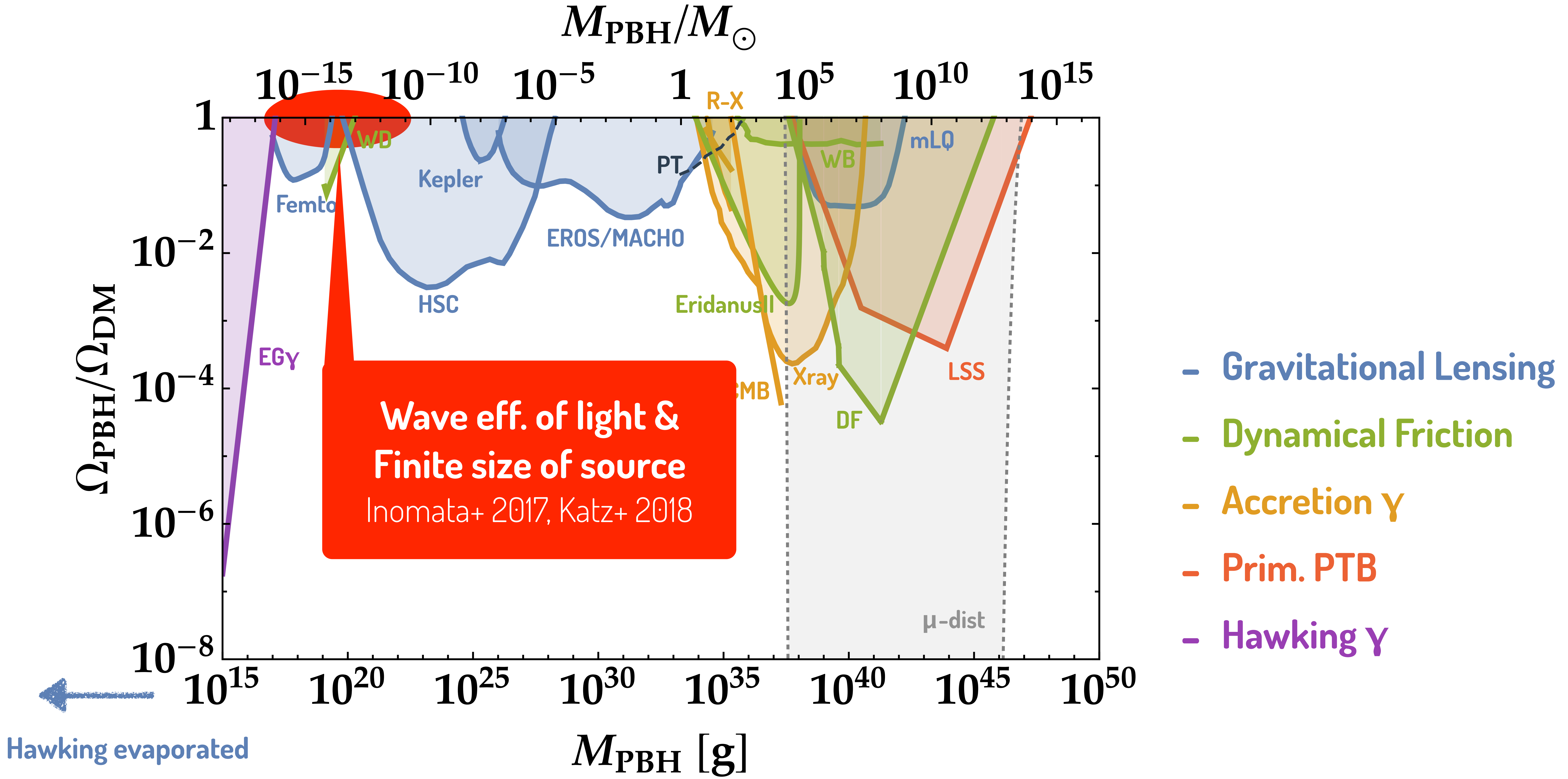
Obs. const. on PBH



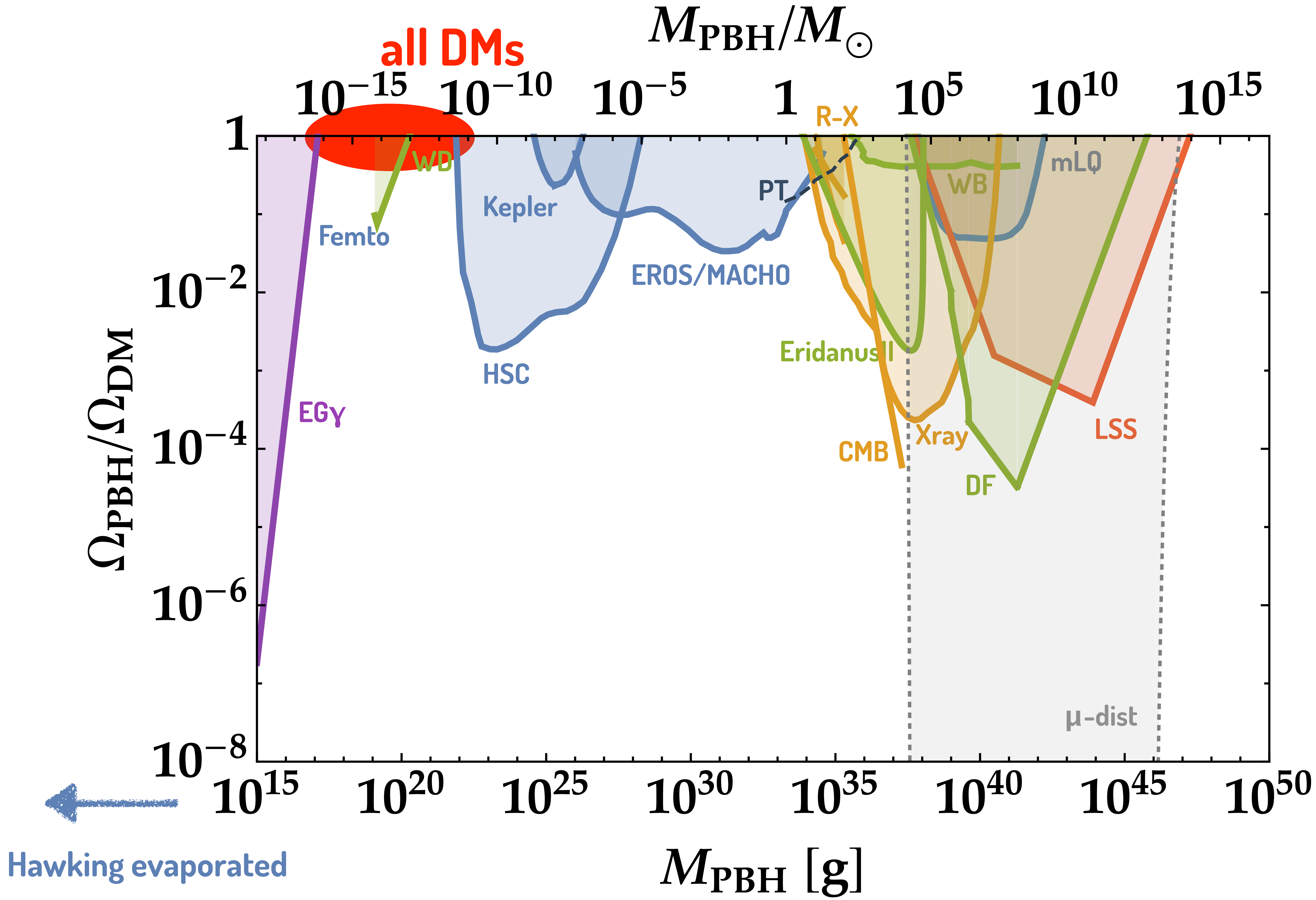
- Gravitational Lensing
- Dynamical Friction
- Accretion γ
- Prim. PTB
- Hawking γ

Hawking evaporated

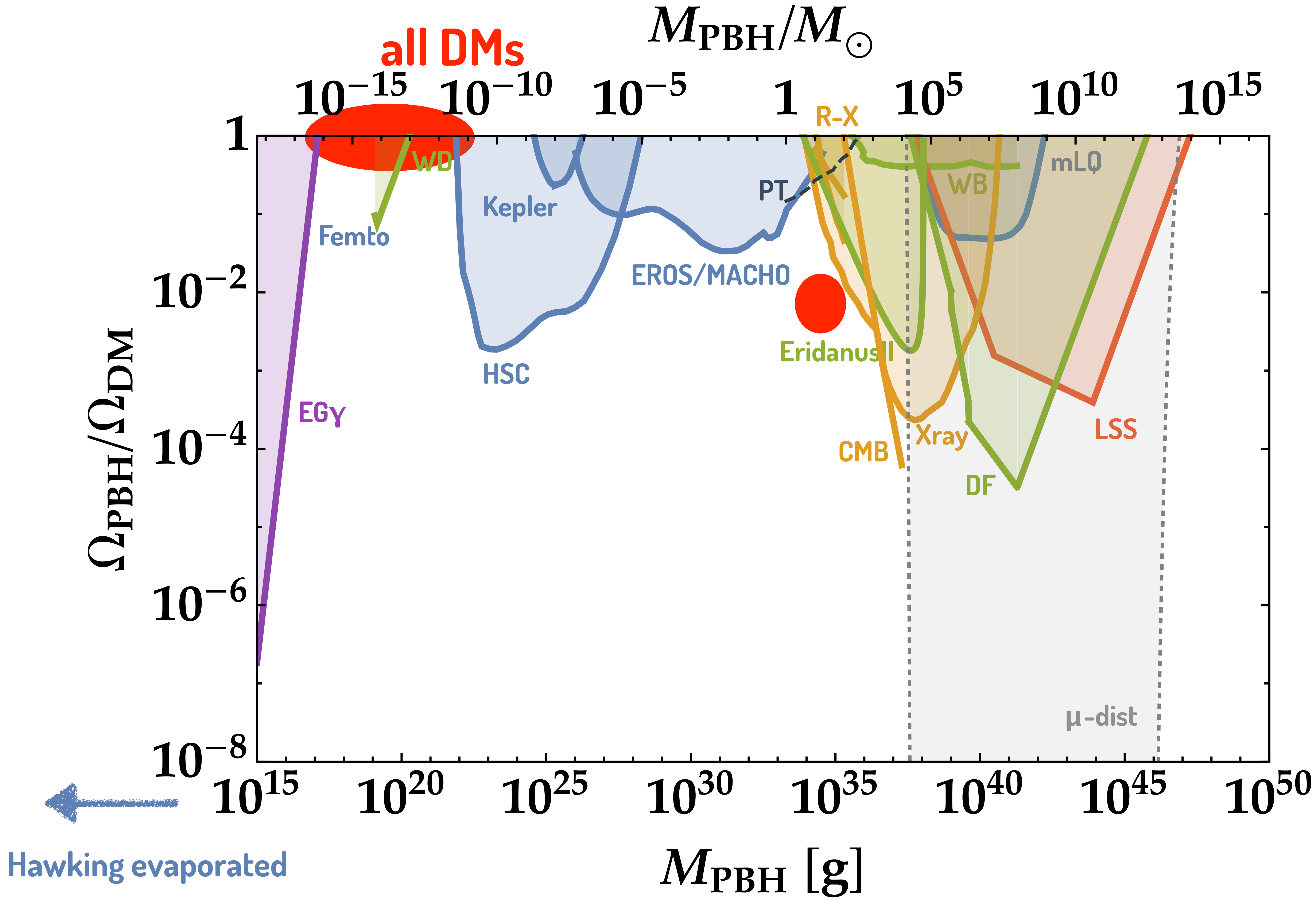
Obs. const. on PBH



Obs. const. on PBH



Obs. const. on PBH



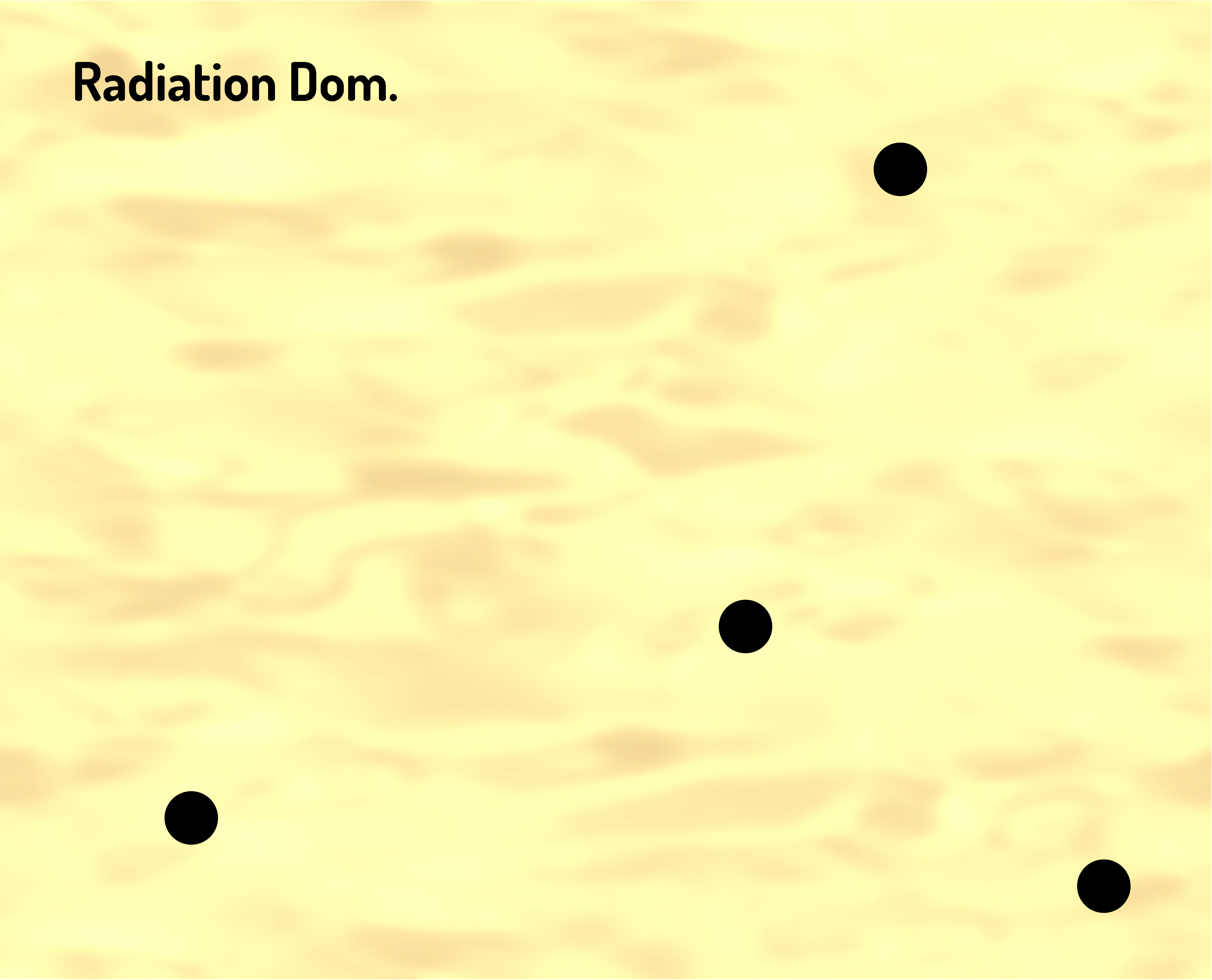
Massive than stellar BHs found

small spin

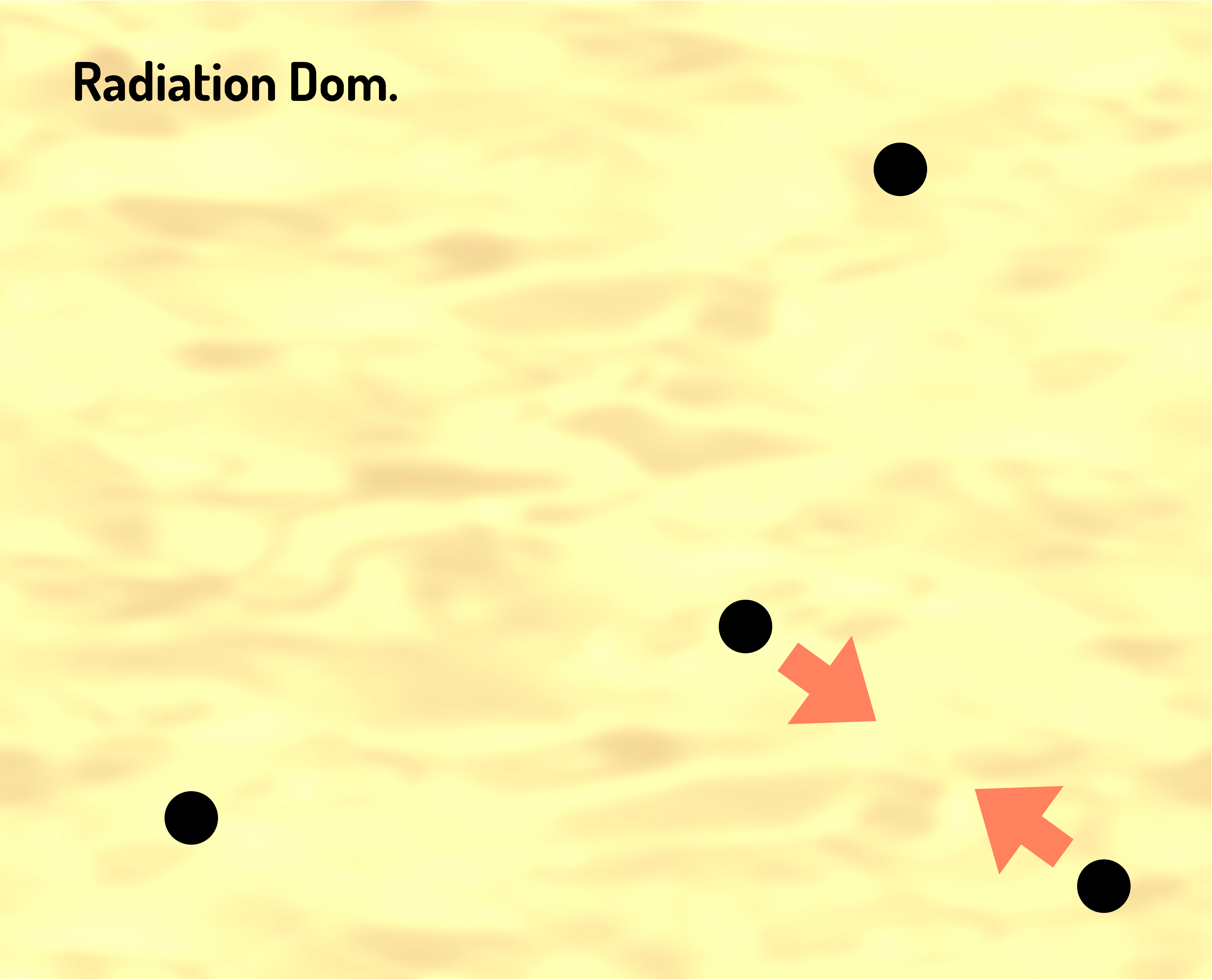
Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	$\chi_{\rm eff}$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.1}$	$0.04^{+0.28}_{-0.19}$
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$
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

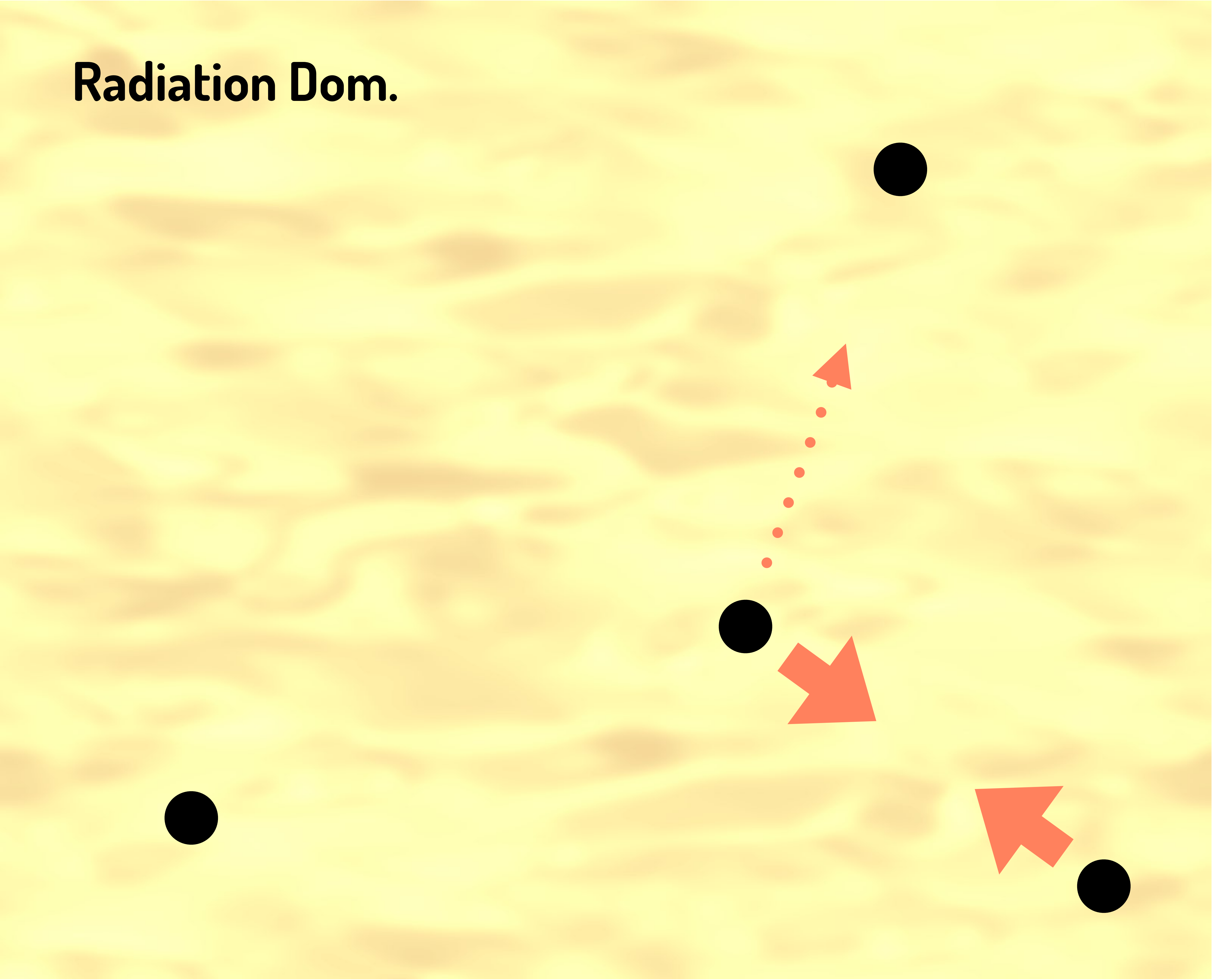
Binary PBH



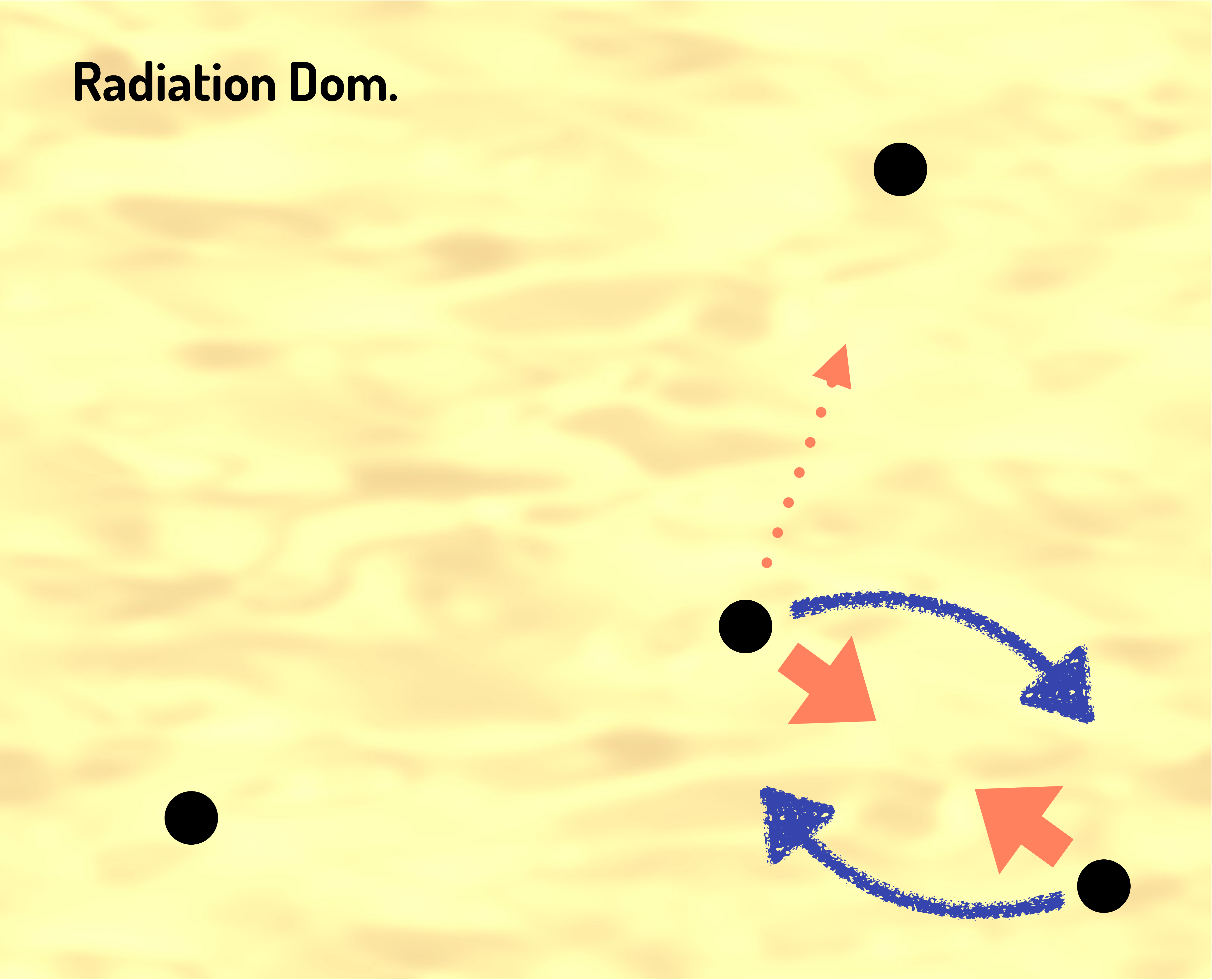
Binary PBH



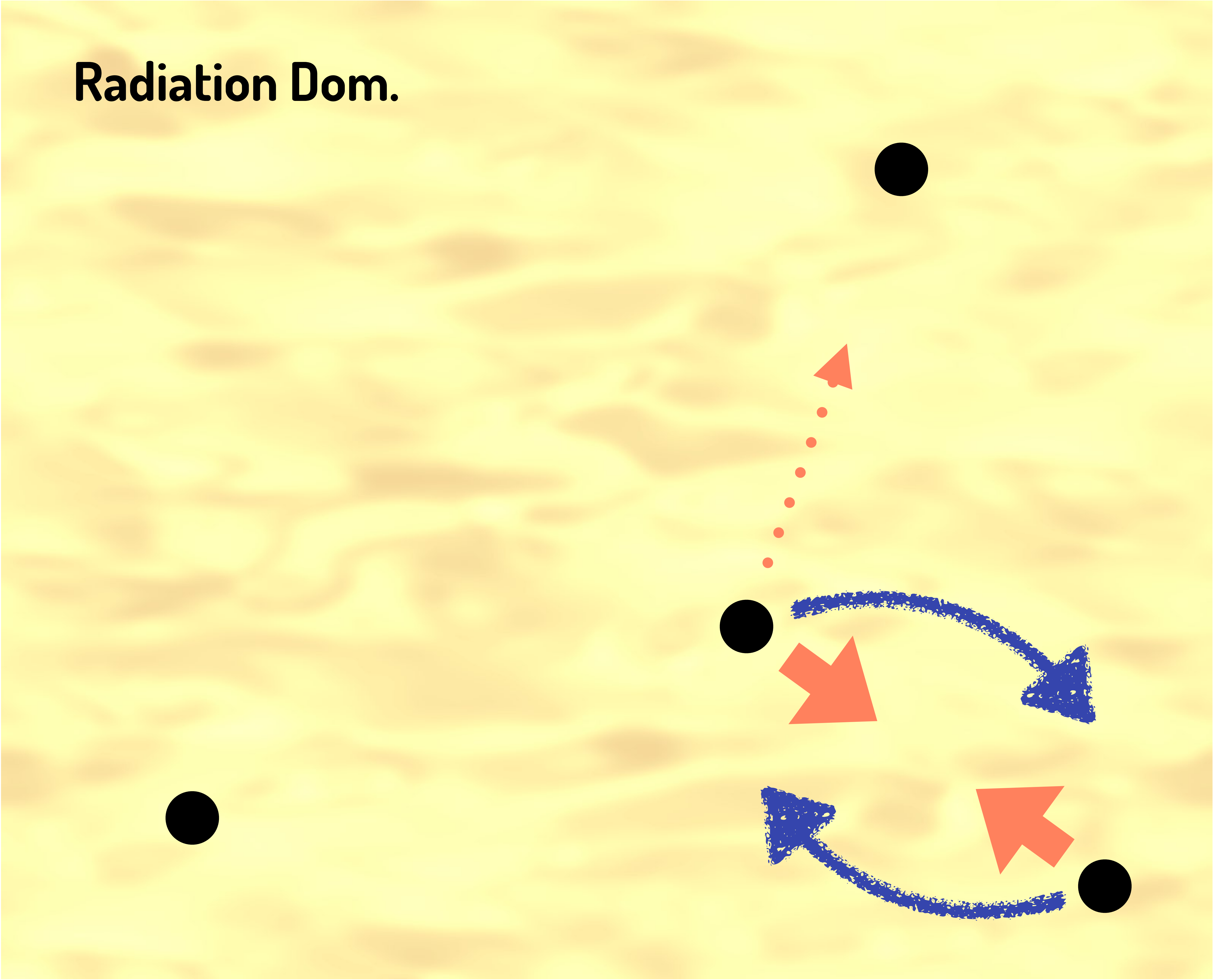
Binary PBH



Binary PBH



Binary PBH



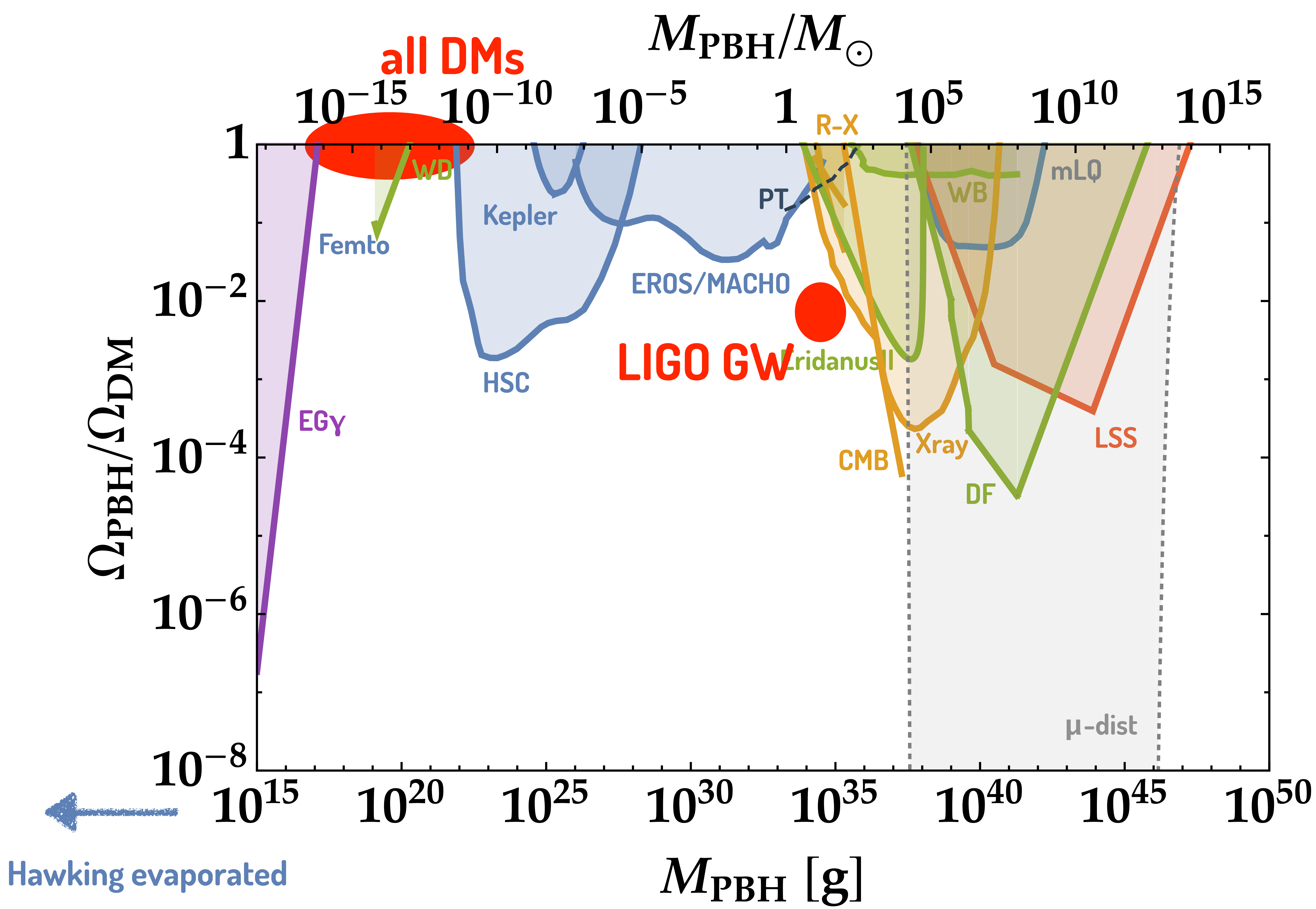
Sasaki+ 2016

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

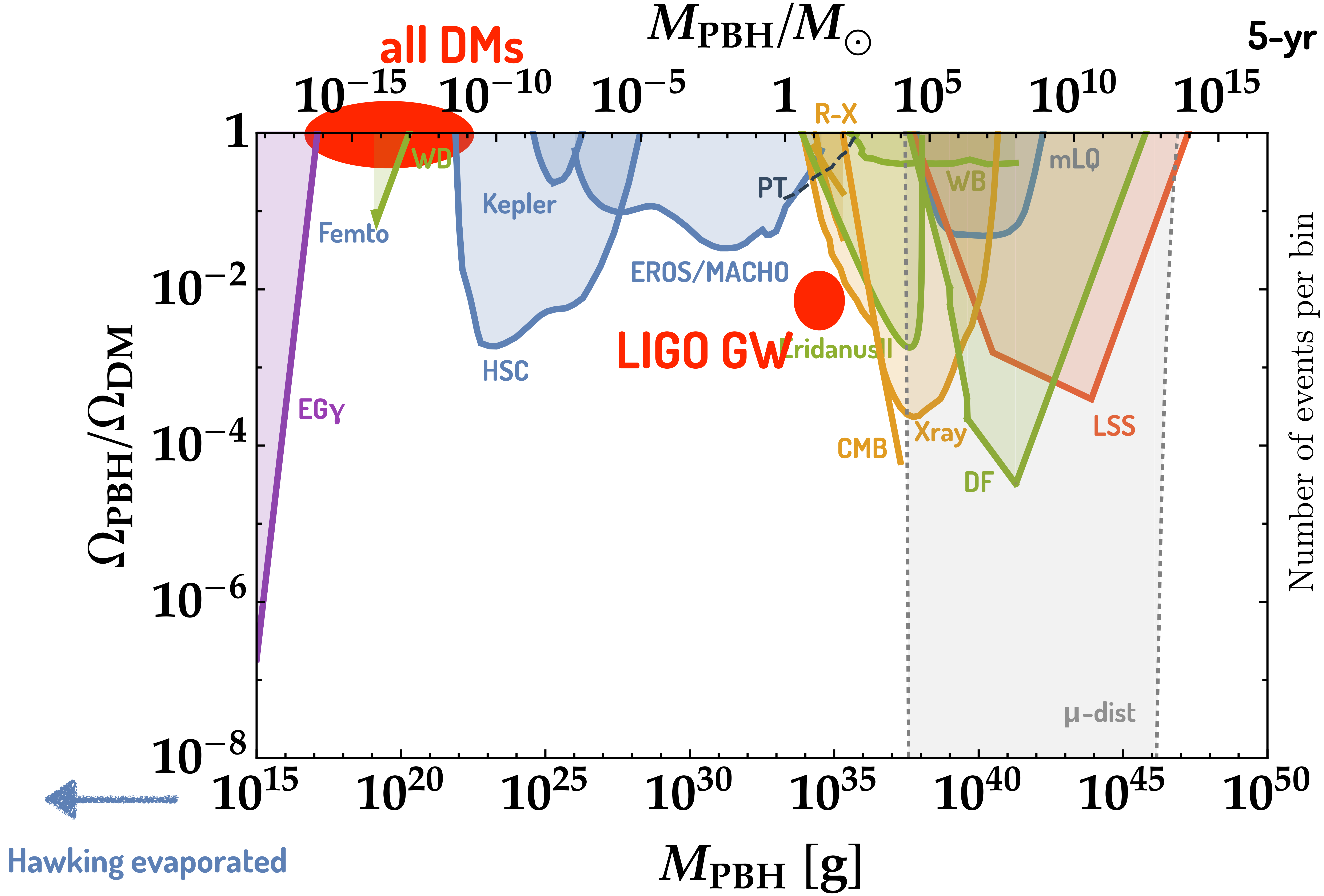
$$\text{(merger rate)} \simeq 52.9^{+55.6}_{-27.0}\,{\rm Gpc^{-3}\,yr^{-1}}$$

LIGO/Virgo 2018

Obs. const. on PBH

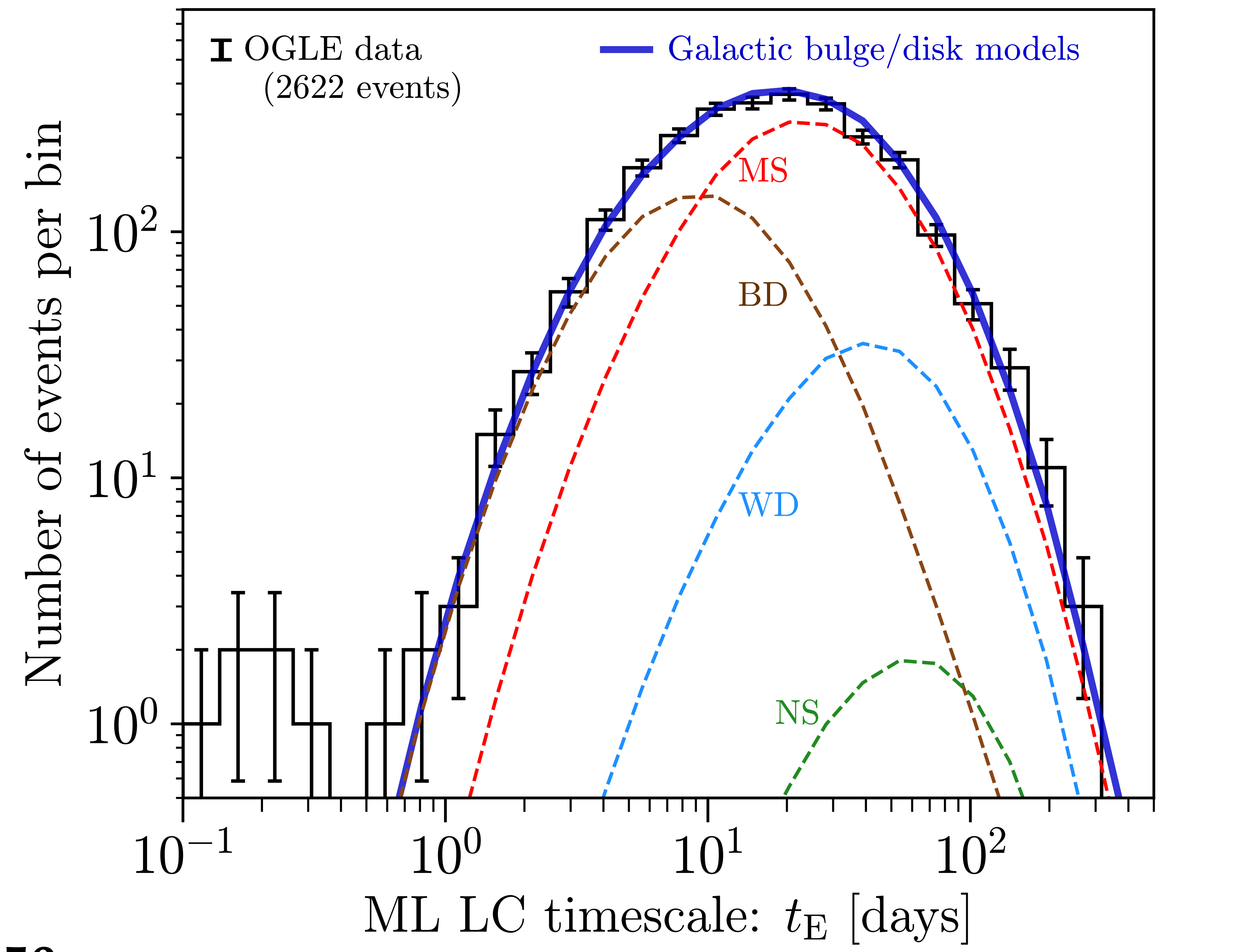


Obs. const. on PBH

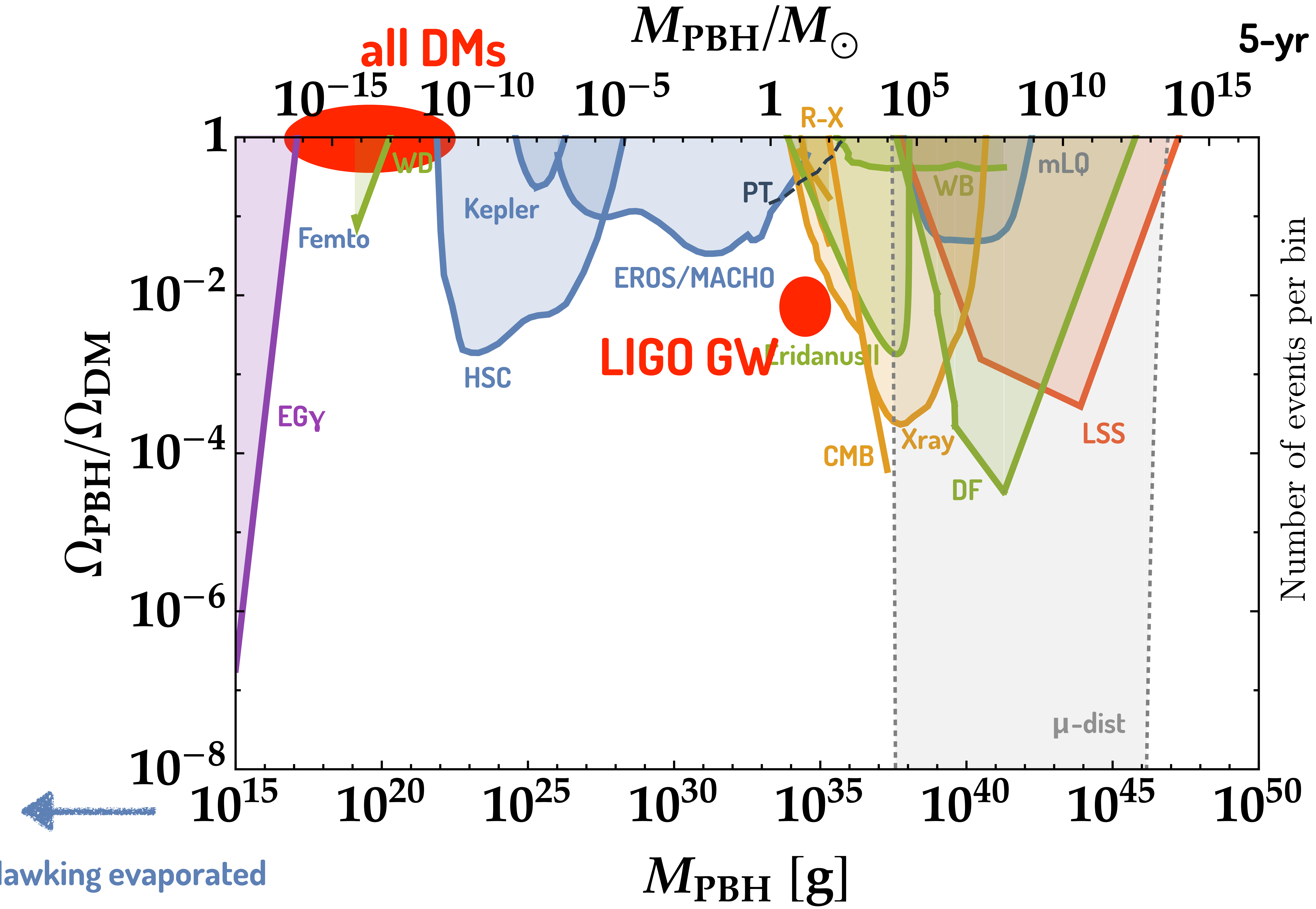


5-yr Optical Gravitational Lensing Experiment (OGLE)

Niikura+ 2019

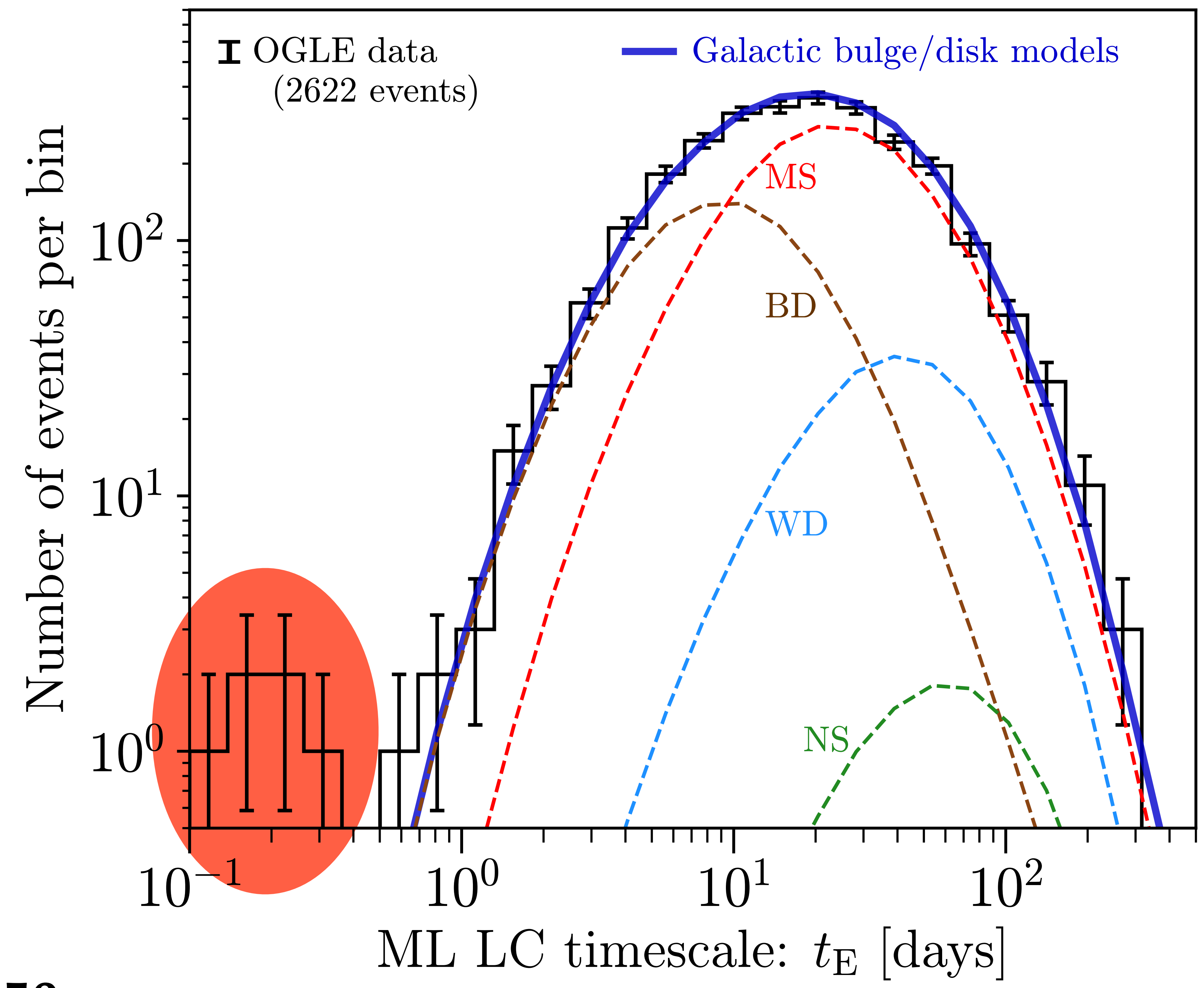


Obs. const. on PBH



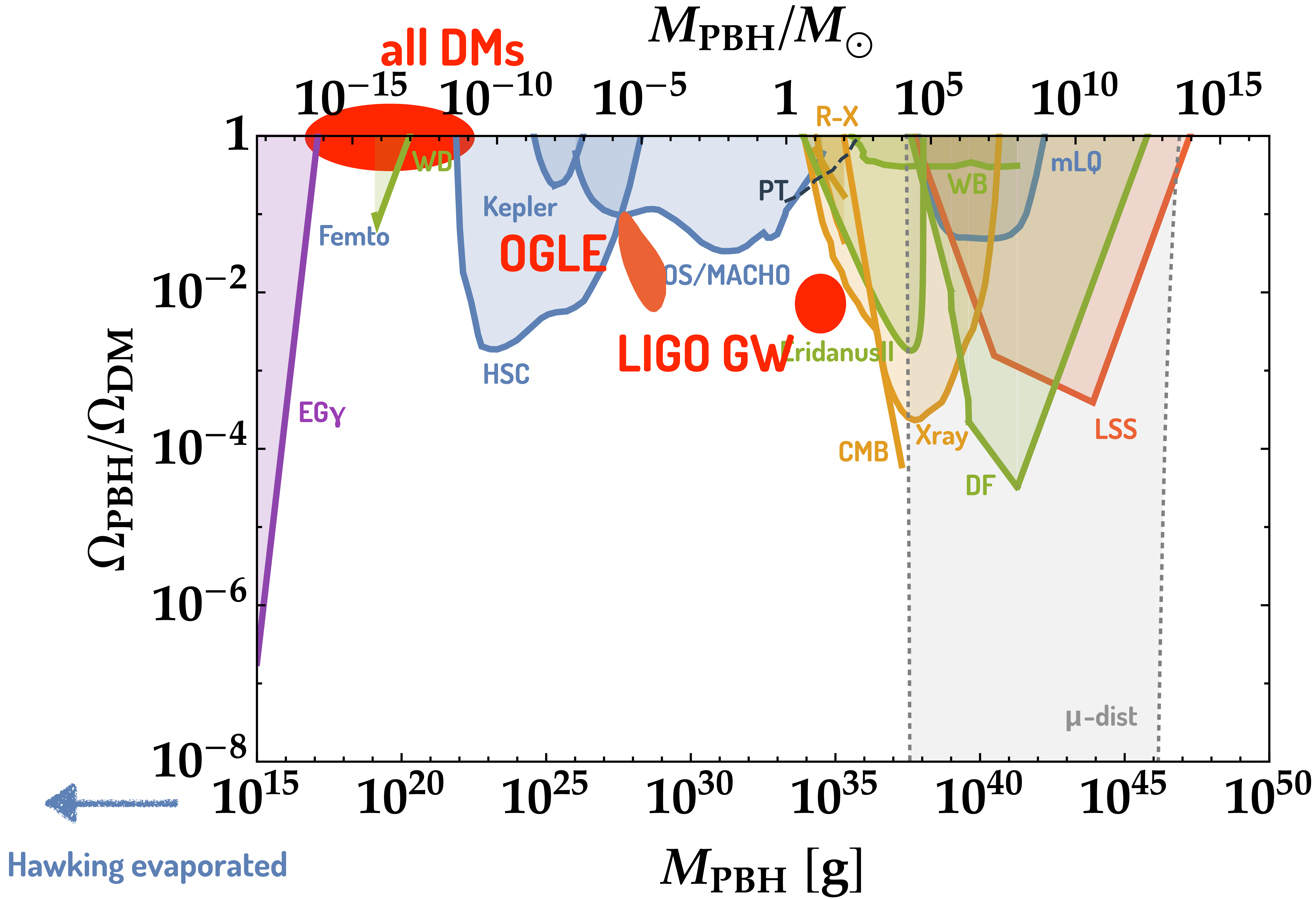
5-yr Optical Gravitational Lensing Experiment (OGLE)

Niikura+ 2019



Obs. const. on PBH

Obs. const. on PBH



Rosa & Kephart 2018

spinning PBH ~ 10^{27} g

↓

superradiant on QCD axion

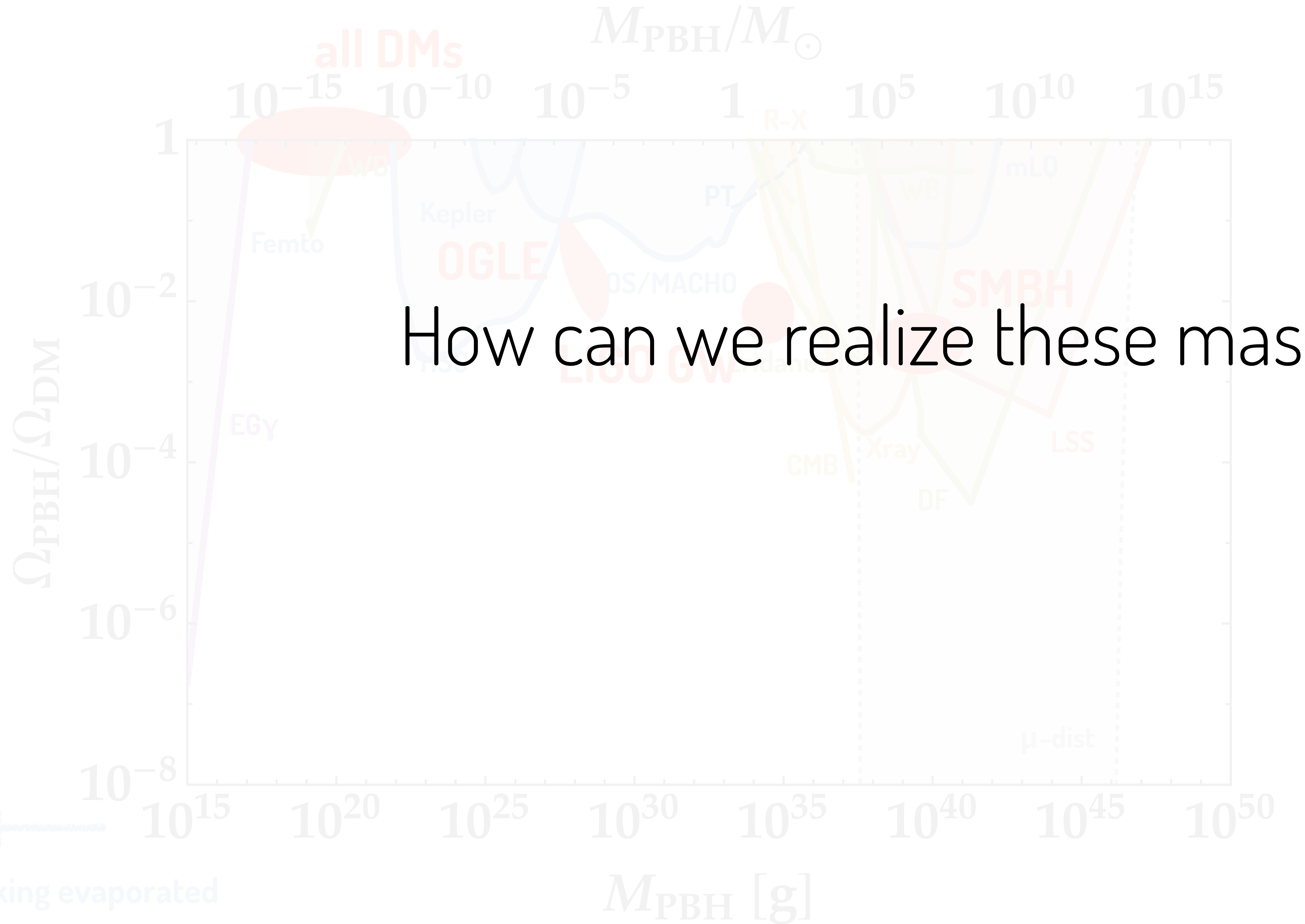
↓

stimulated decay of axion

↓

Fast Radio Burst

Obs. const. on PBH



Hawking evaporated

Rosa & Kephart 2018

spinning PBH ~ 10^{27} g

↓

superradiant on QCD axion

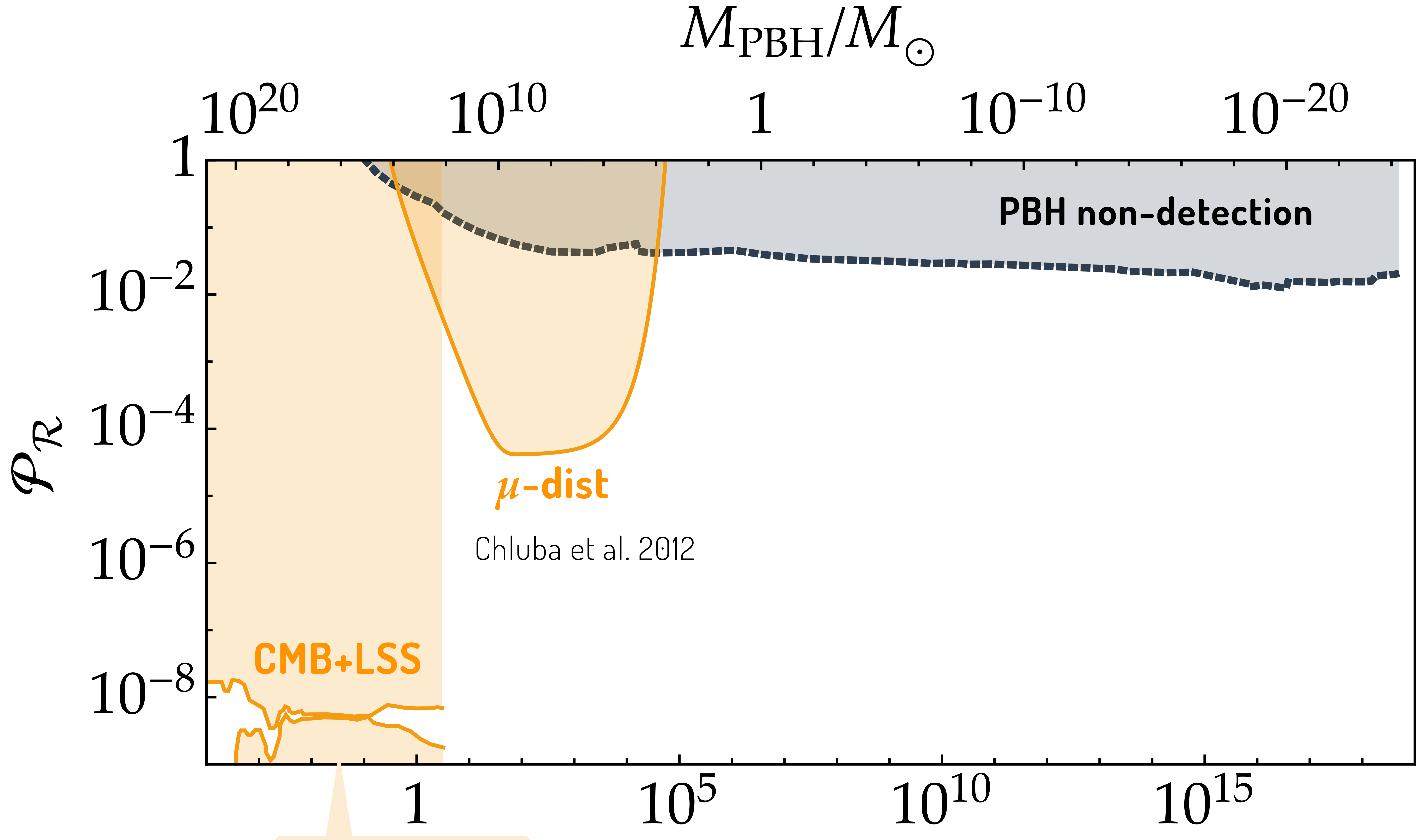
↓

stimulated decay of axion

↓

Fast Radio Burst

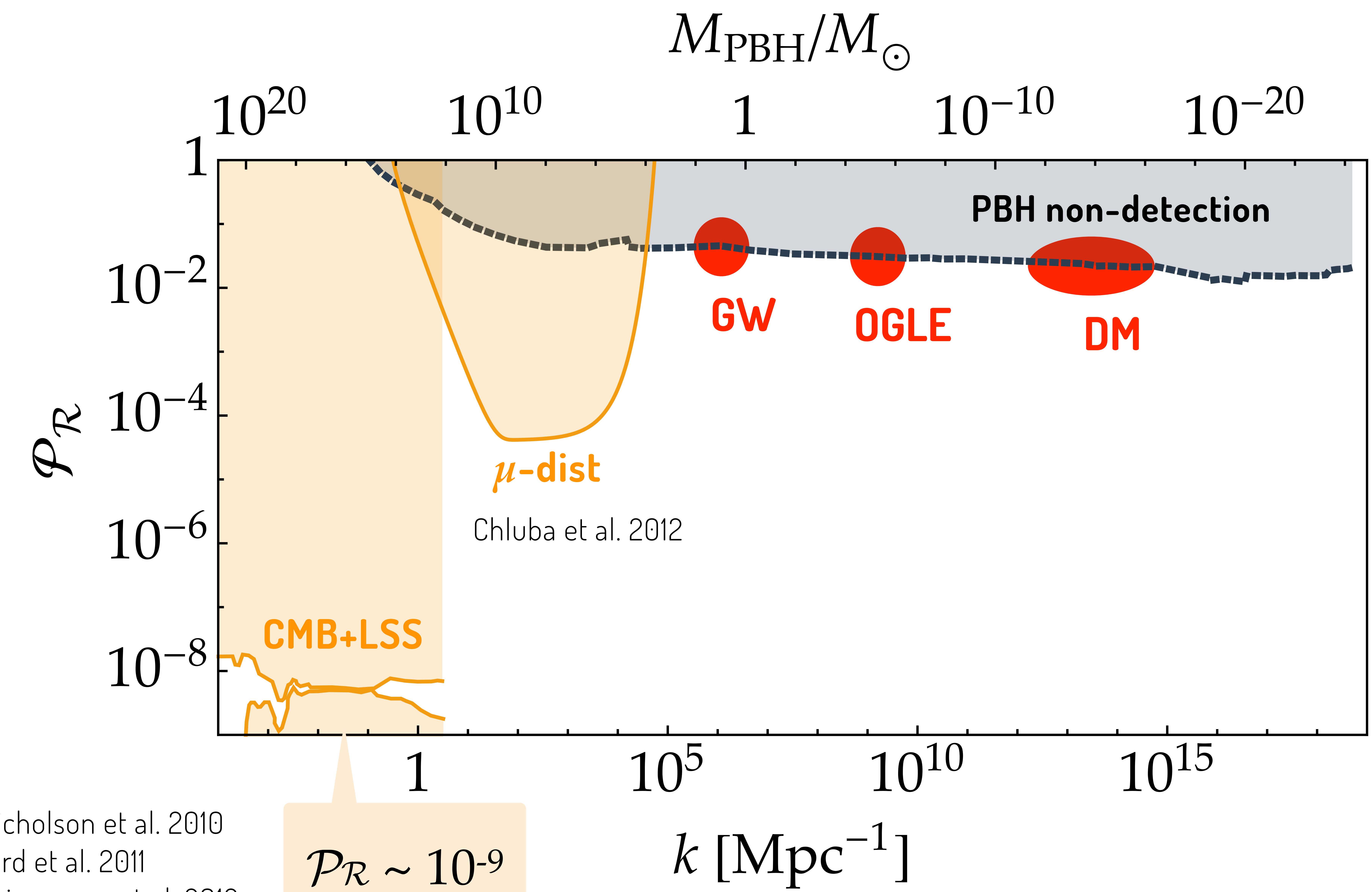
How can we realize these mass spectra?



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

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

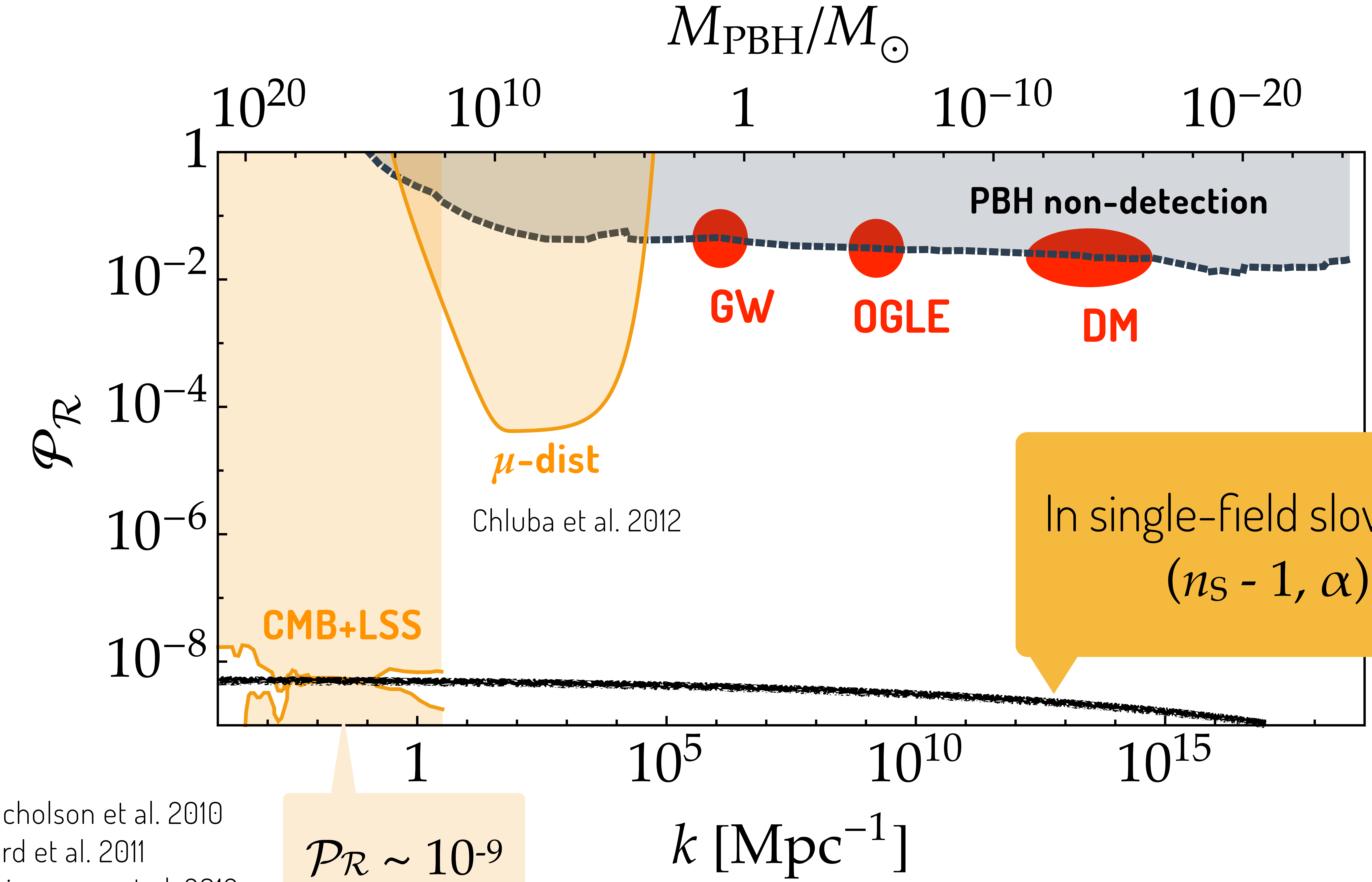
Nicholson et al. 2010
Bird et al. 2011
Bringmann et al. 2012



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

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

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

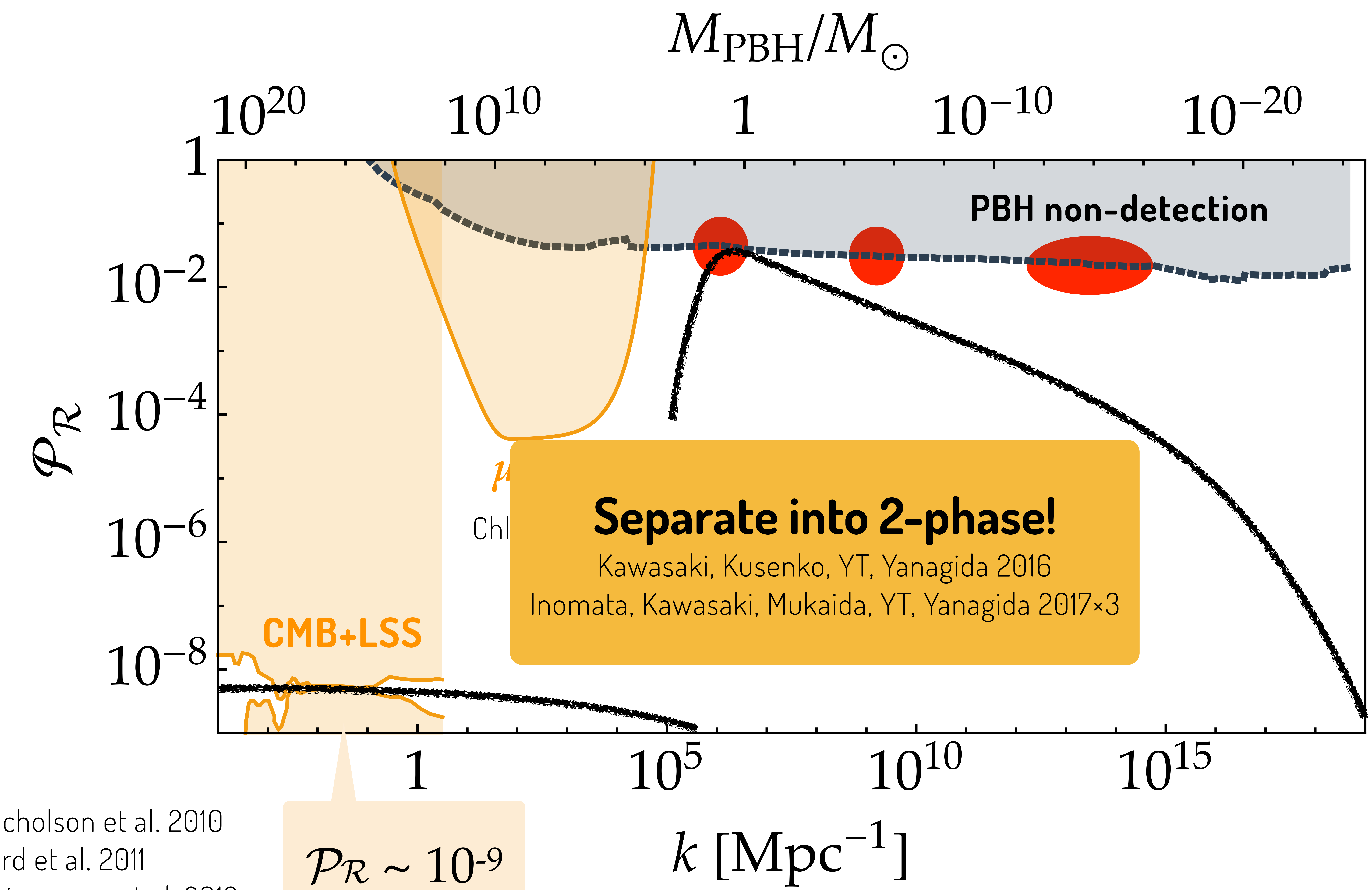


$\mathcal{P}_{\mathcal{R}} \sim 10^{-2}$

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

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



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

Separate into 2-phase!

Kawasaki, Kusenko, YT, Yanagida 2016

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

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

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

Double Inflation

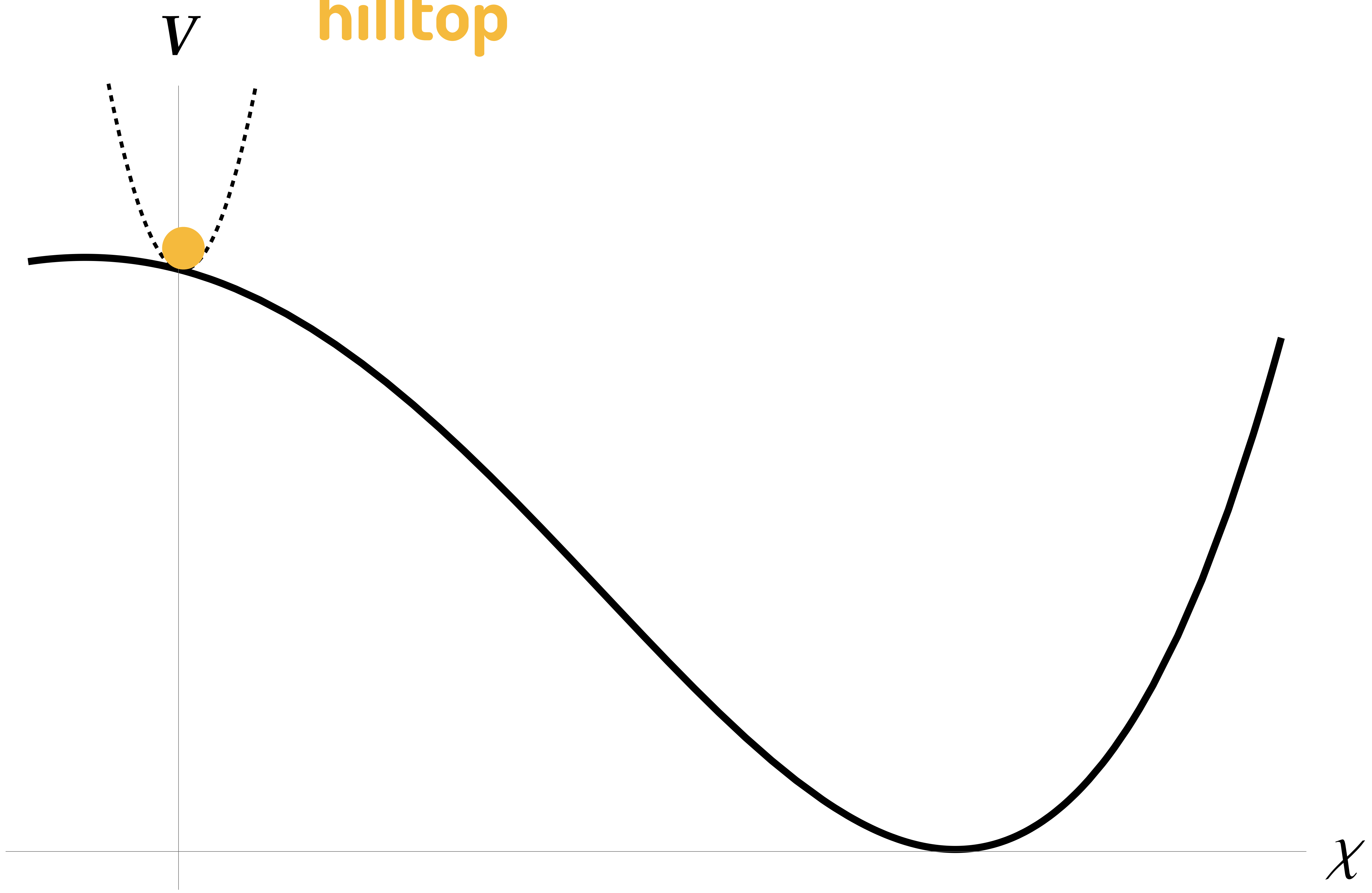
Kumekawa, Moroi, Yanagida 1994
Izawa, Kawasaki, Yanagida 1997
Kawasaki, Sugiyama, Yanagida 1998

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

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

hilltop

stabilizer



Double Inflation

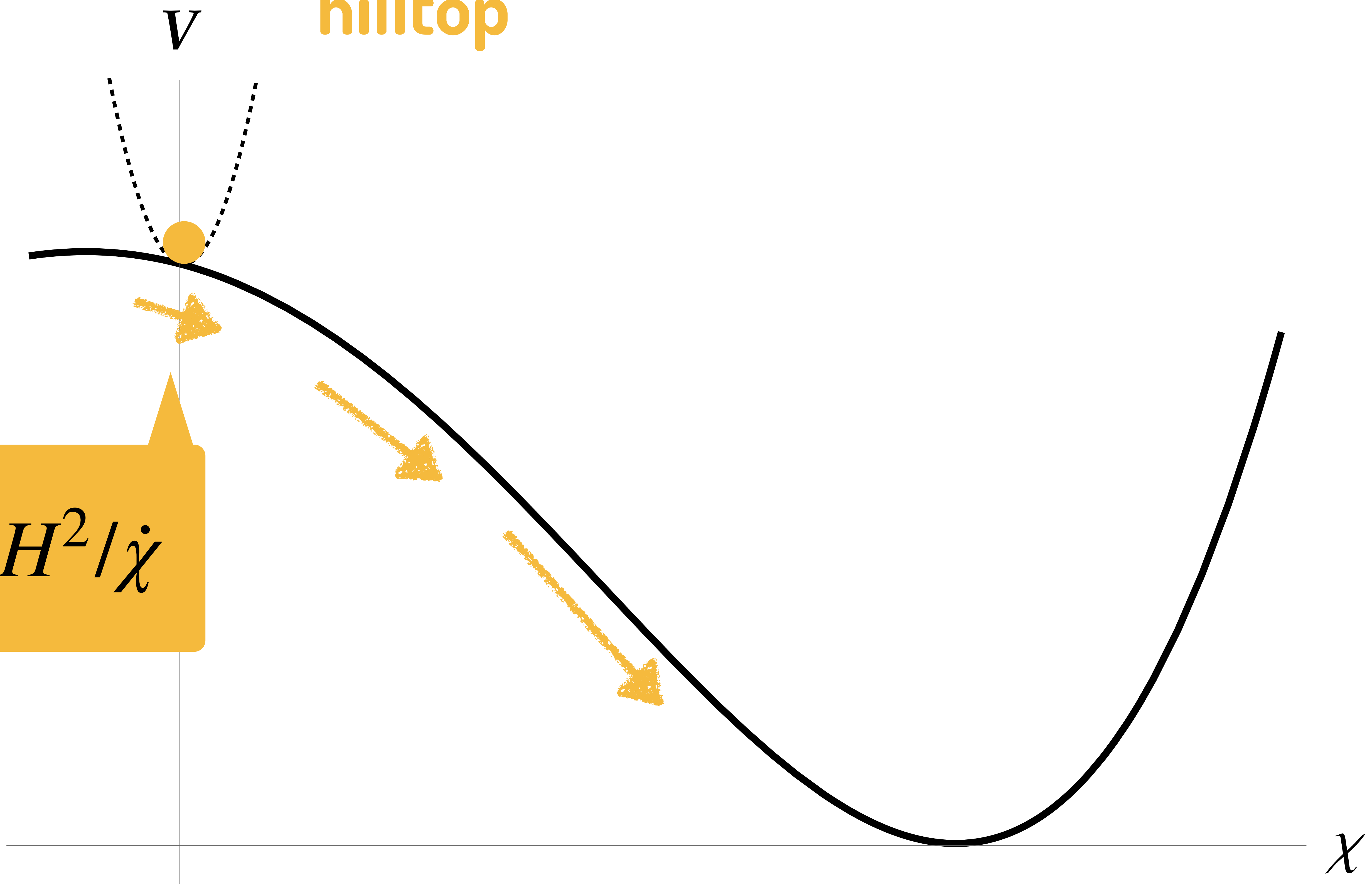
Kumekawa, Moroi, Yanagida 1994
Izawa, Kawasaki, Yanagida 1997
Kawasaki, Sugiyama, Yanagida 1998

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

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

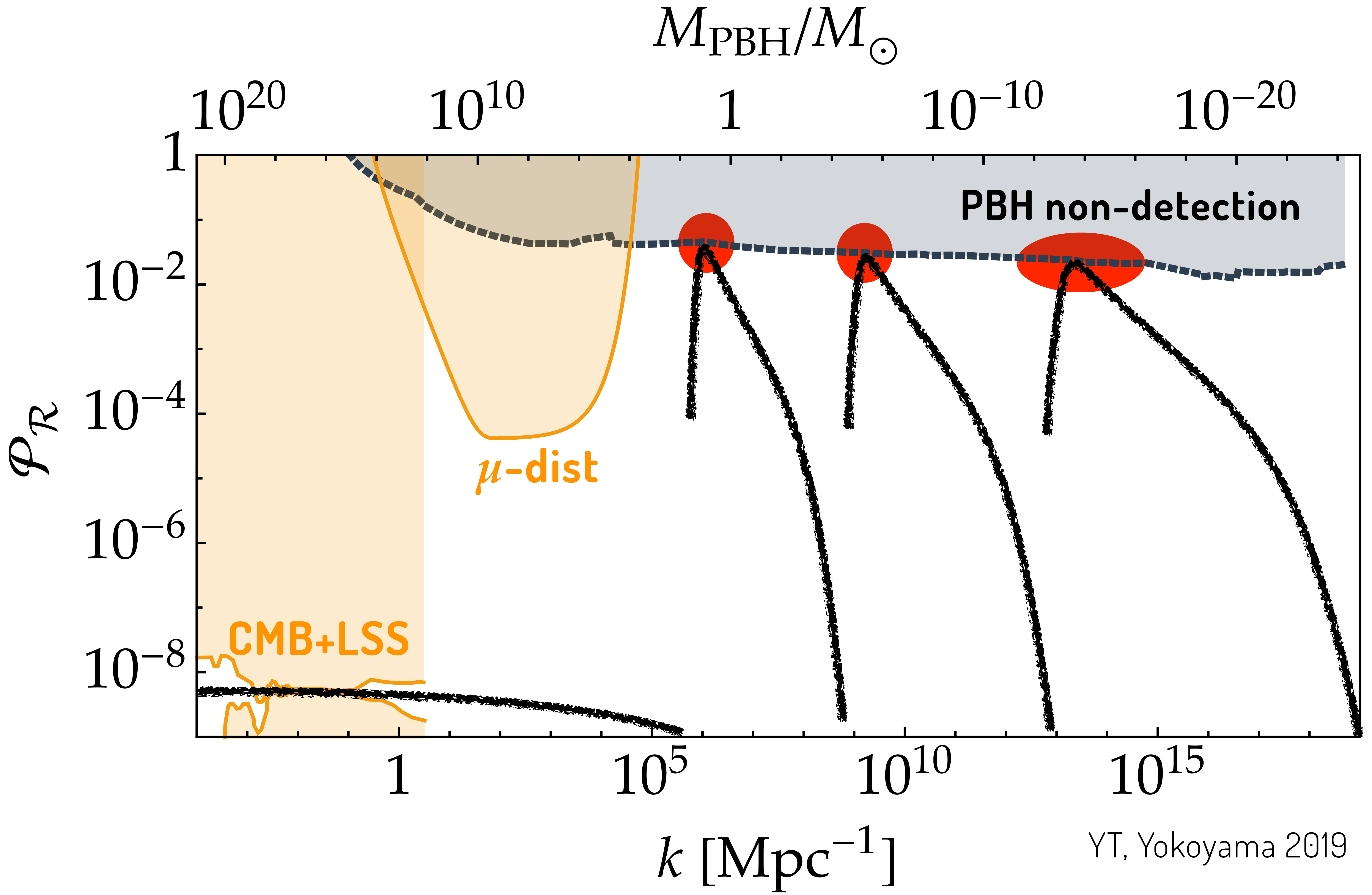
hilltop

stabilizer



$\zeta_{\rm max} \sim H^2/\dot{\chi}$

Extreme Case



- **4-hilltop**

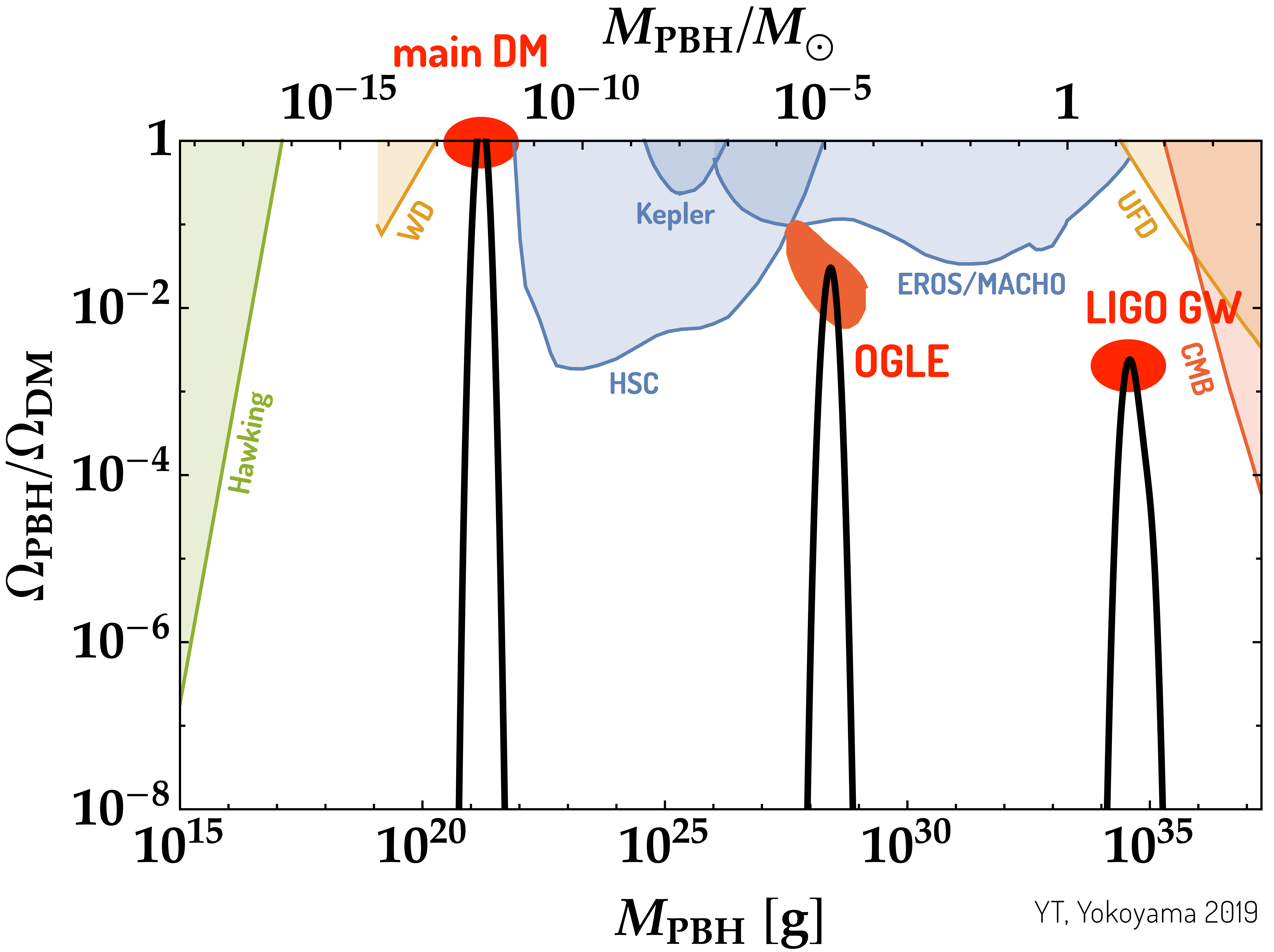
$$V_{\rm hill} = \sum_{i=1}^{4} V_{{\rm hill},i}$$

$$+$$

- **Stabilization**

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

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



main DM
$M_{\rm PBH}/M_\odot$
10^{-15}
10^{-10}
10^{-5}
1
Kepler
WD
UFD
EROS/MACHO
LIGO GW
OGLE
HSC
CMB
Hawking
$\Omega_{\rm PBH}/\Omega_{\rm DM}$
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{15}
10^{20}
10^{25}
10^{30}
10^{35}
$M_{\rm PBH}$ [g]
YT, Yokoyama 2019

Implication to String Theory

dS swampland conjecture   Ooguri & Vafa+ 2018

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

$$\frac{|\nabla V|}{V} \gtrsim \mathcal{O}(1), \quad \text{or} \quad \frac{\min(\nabla_i \nabla_j V)}{V} \lesssim -\mathcal{O}(1)$$

each inflationary phase cannot continue long ➡ multi-phase inflation

c.f. YT & Yokoyama 2019

$$-\frac{\min(\nabla_i \nabla_j V)}{V} \simeq \kappa \simeq 5$$

Testability

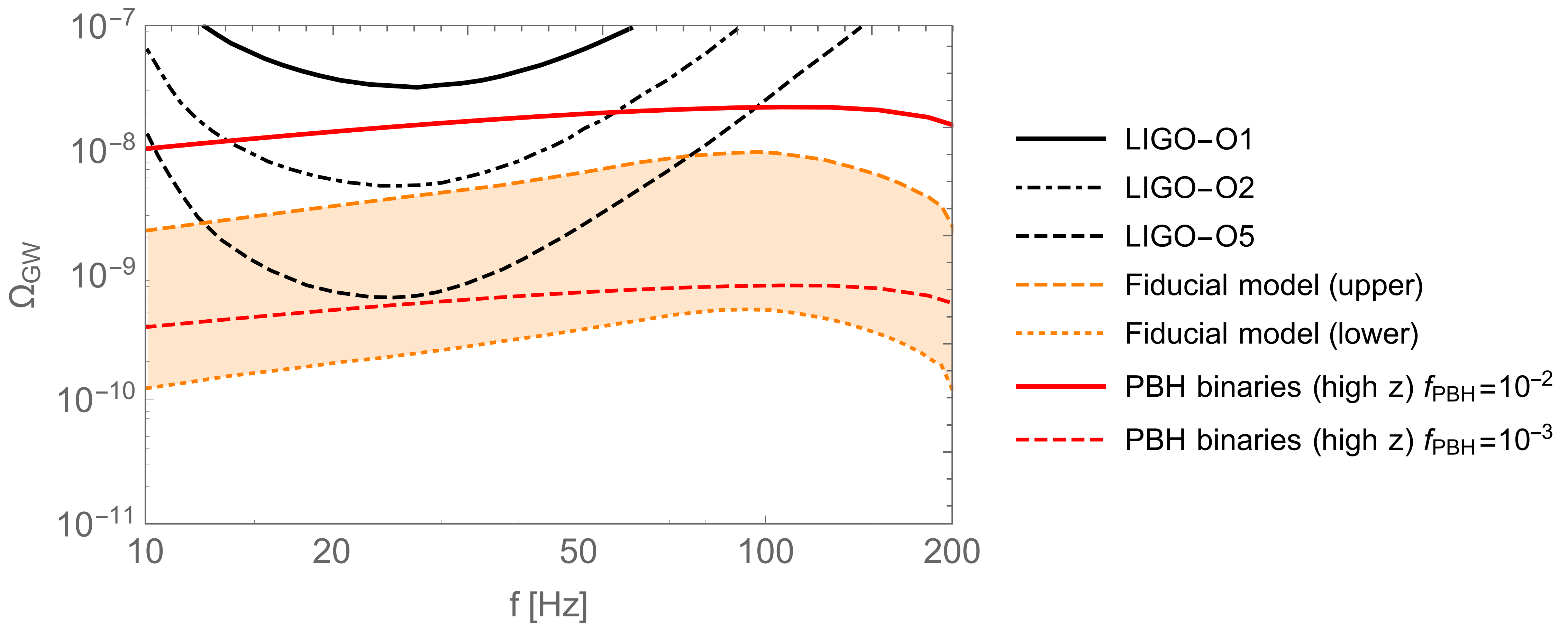
– LIGO/Virgo PBH

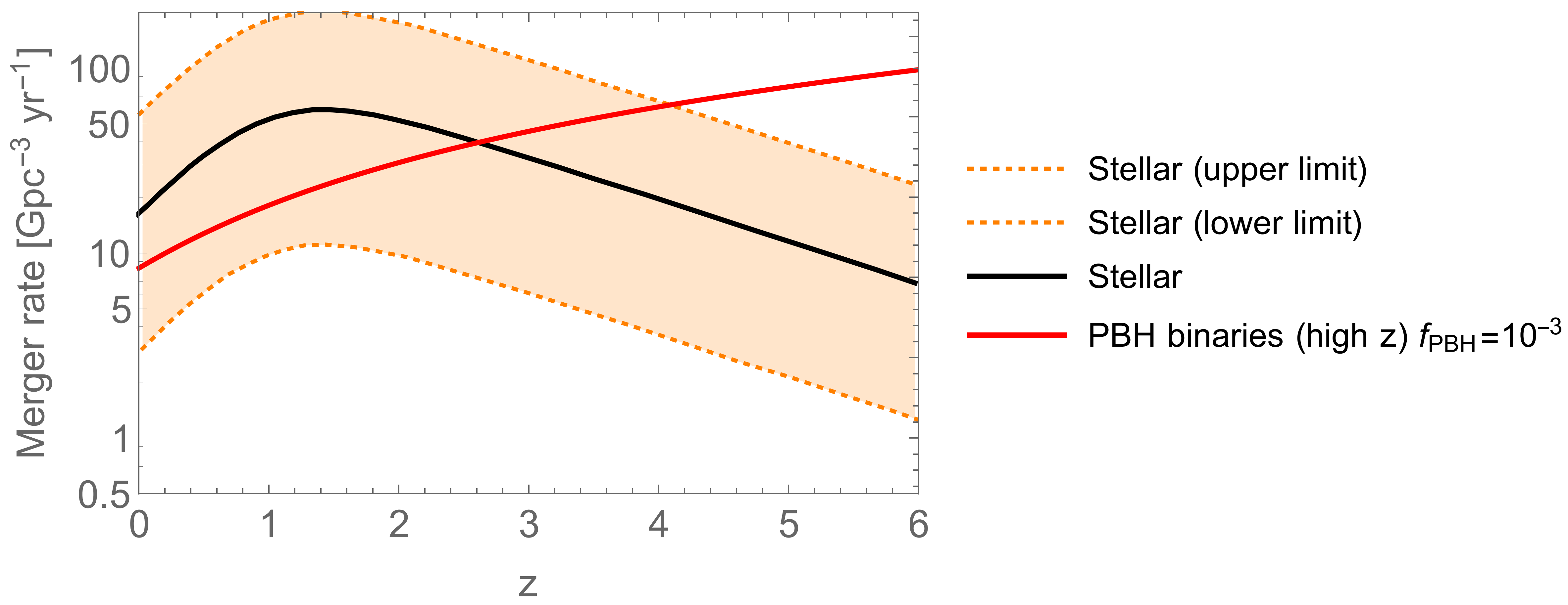
PBH tends to be spinless
Chiba & Yokoyama 2017

Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	$\chi_{\rm eff}$
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

Sasaki+ 2018





Testability

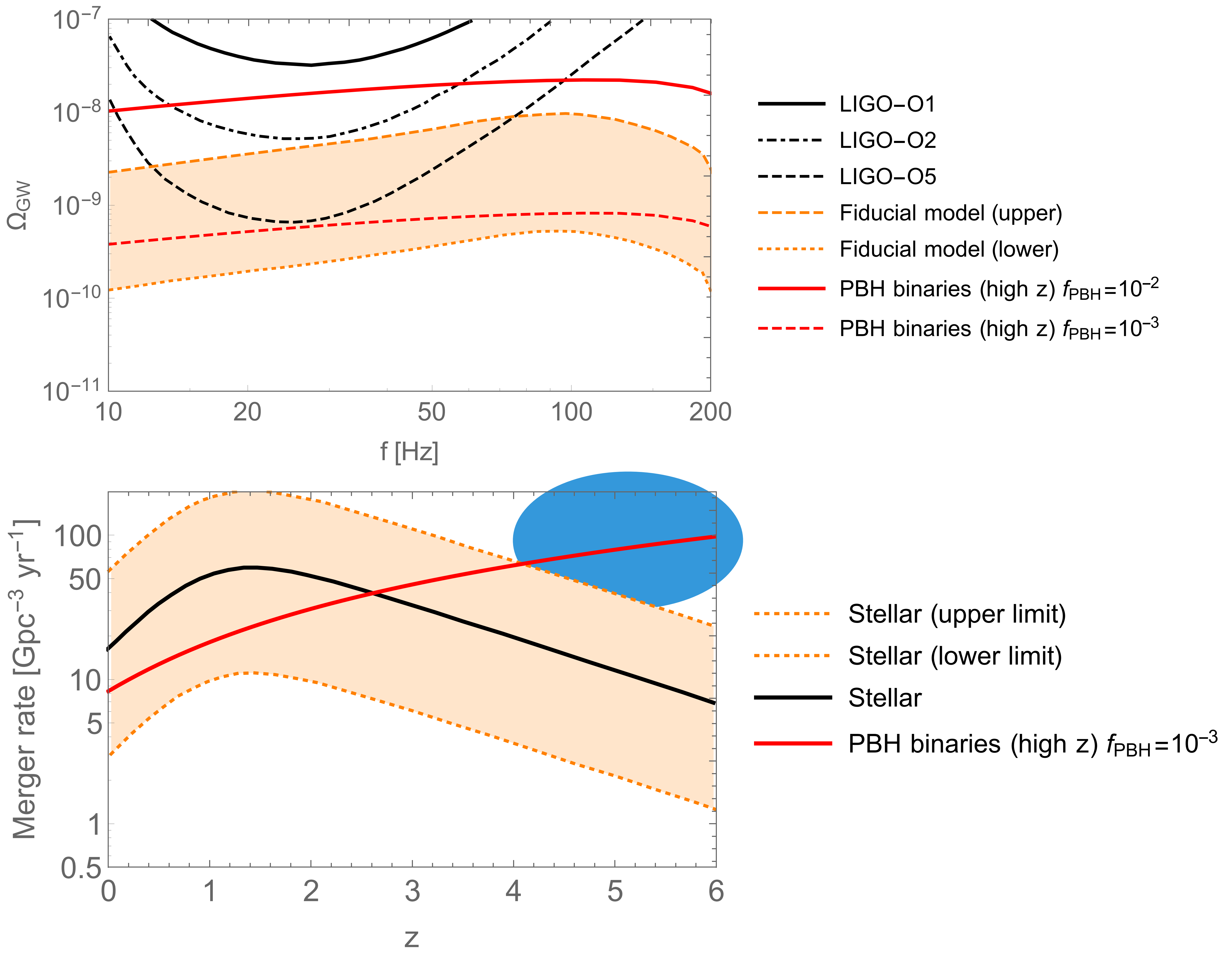
- LIGO/Virgo PBH

PBH tends to be spinless
Chiba & Yokoyama 2017

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

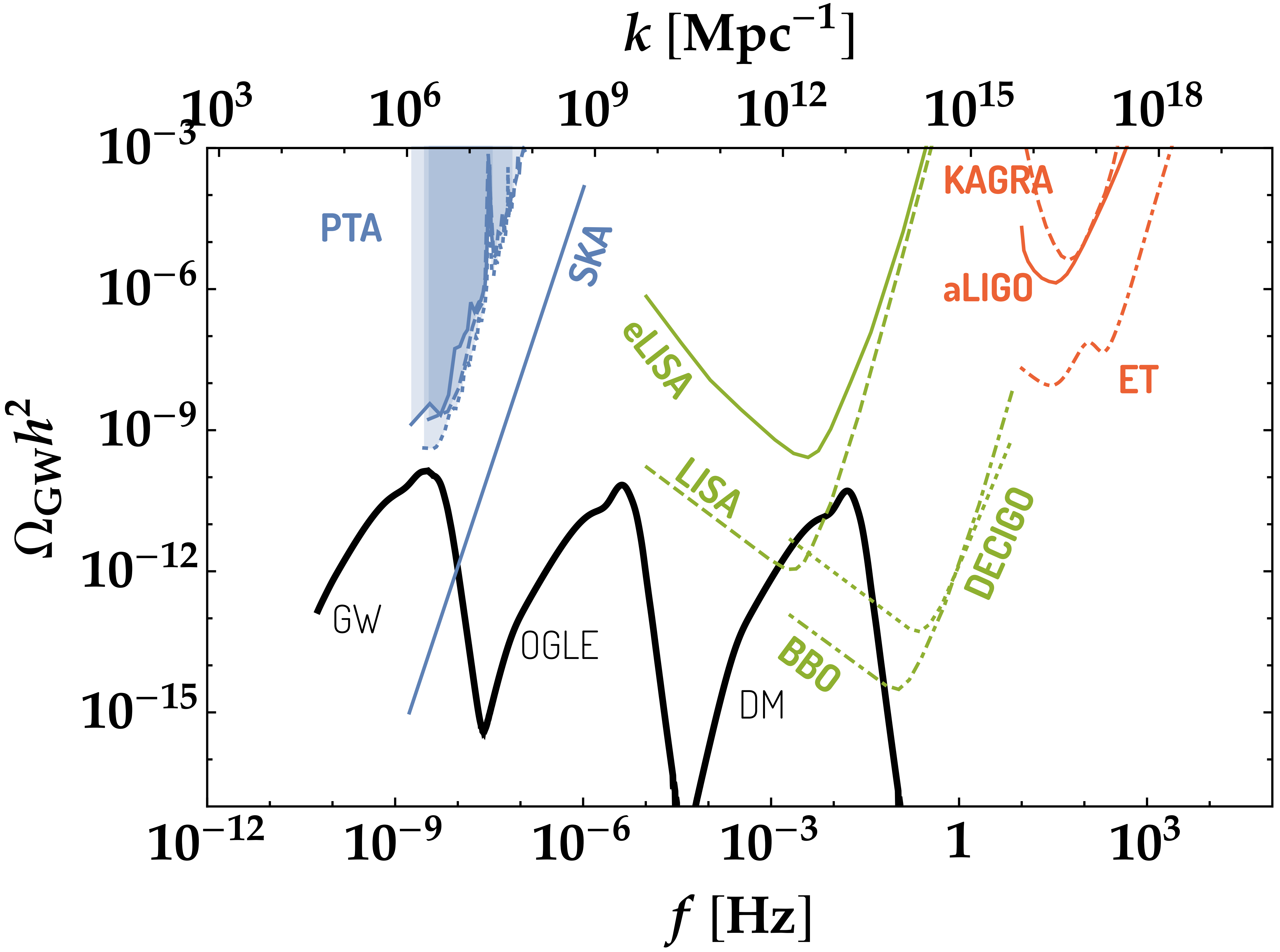
LIGO/Virgo 2018

Sasaki+ 2018



Testability

large scalar ptb. → secondary tensor ptb. (stochastic GW) : $\Omega_{\mathrm{GW}}h^2 \sim 10^{-9}\left(\frac{\mathcal{P}_{\mathcal{R}}}{10^{-2}}\right)^2$



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