

Merger signals of gravitational waves from binary PBHs or SMBHs seeded by PBHs

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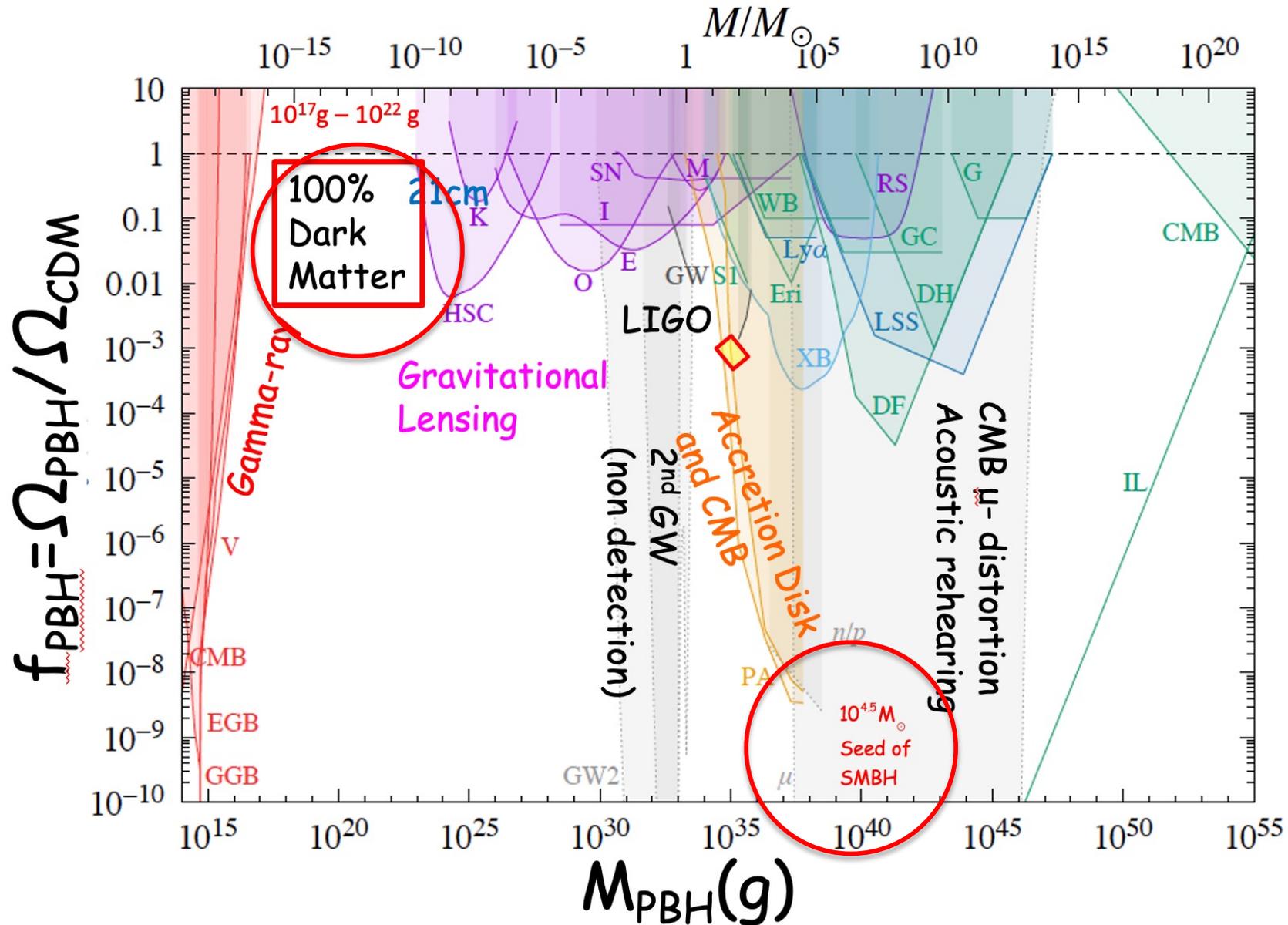


Abstract

- PBHs with their masses $10^{17} \text{ g} - 10^{23} \text{ g}$ can be dark matter (DM)
- PBHs with their masses $10^{15} \text{ g} - 10^{17} \text{ g}$ are now evaporating with emitting the MeV gamma-rays and neutrino
- NANOGrav 15-yr can be fitted by induced GWs or merger GWs by binary SMBHs seeded by $10^2 M_{\odot}$ PBHs
- If we assume the Memory Burden Effect, additionally PBHs with $10^5 \text{ g} - 10^{10} \text{ g}$ can be dark matter, which are now emitting the PeV gamma-rays and neutrinos

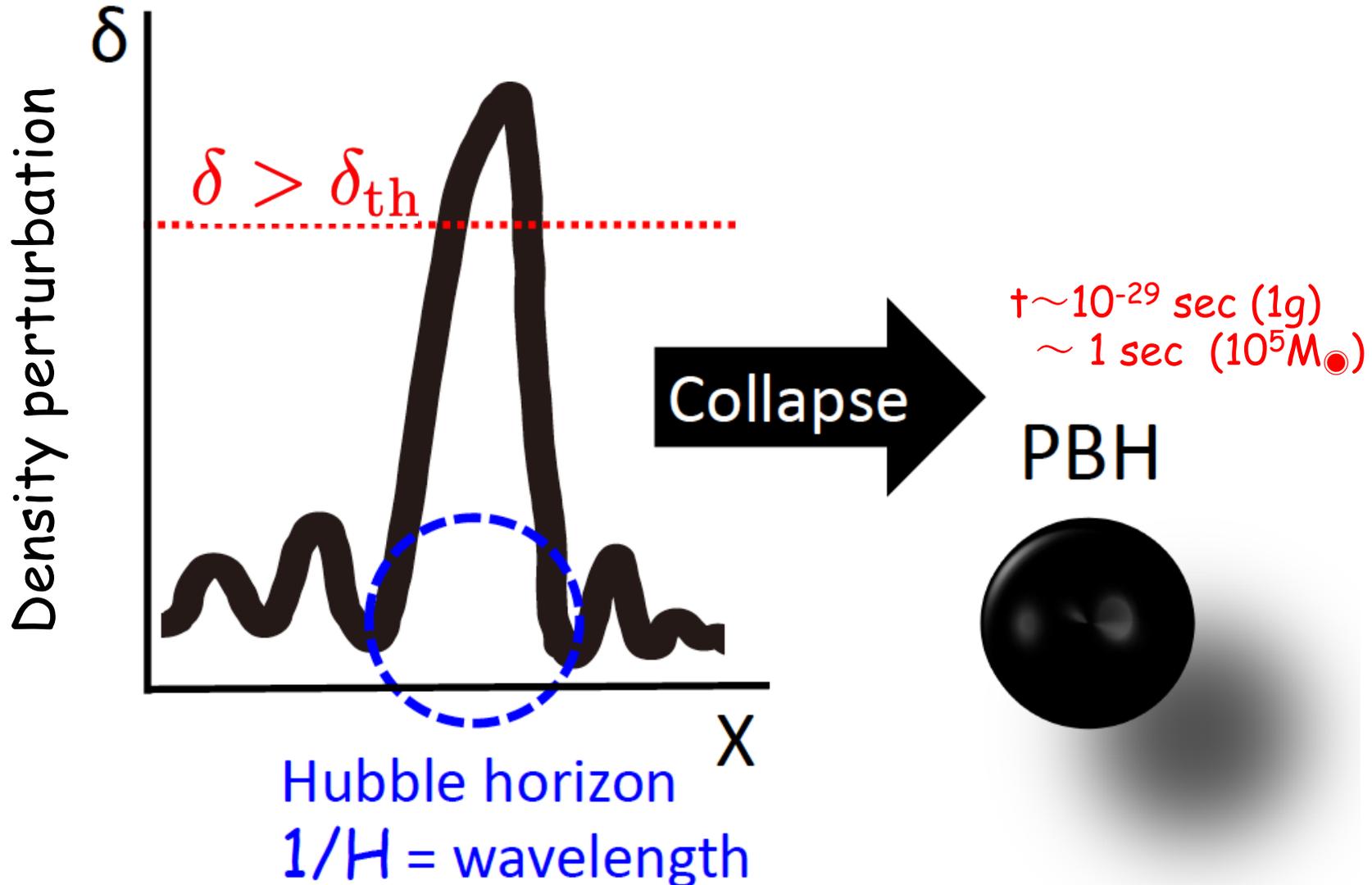
Upper bounds on the fraction to CDM

The original paper, not a review paper
 Carr, Kohri, Sendouda, J. Yokoyama, arXiv:2002.12778



Formation by large density perturbation

$\delta_{\text{th}} = c_s^2 = w = 1/3$, Bernard Carr, ApJ. 201 (1975) 1
 $\delta_{\text{th}} = 0.41$, T. Harada, C.-M. Yoo, K. Kohri, arXiv:1309.4201



Observational constraints

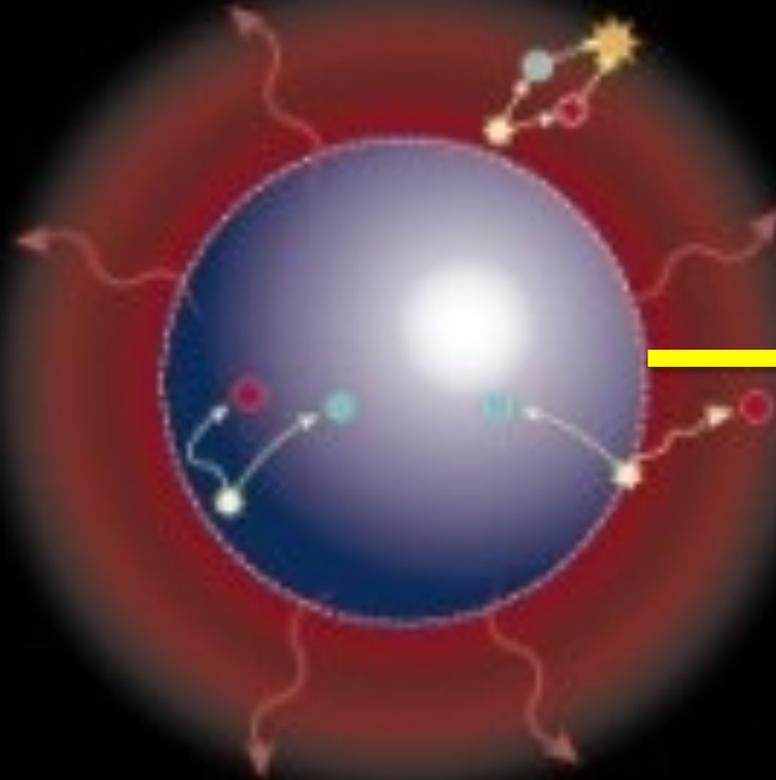
- Gamma-ray observation
- Gravitational Lensing
- Induced Gravitational Wave (future observations)
- Merger Gravitational Wave (future observations)
- Neutrino observation (future observations)
- ...

Hawking evaporation through quantum mechanics

S.W. Hawking, 1974

$$N_{\text{Quantum}} = |\langle \text{vac } 1 | a^\dagger a | \text{vac } 1 \rangle|^2 = |\beta_{\text{Bogoliubov}}|^2$$

$$= \frac{dE}{2\pi} \frac{\Gamma_s}{e^{E/T_{\text{BH}}} - (-1)^{2s}}$$



Blackhole

$|\text{vac}\rangle$ Strong Gravity

Asymptotically flat

$|\text{vac}\rangle$ Minkowski

Typical quantities of PBHs

- Lifetime

$$\tau_{\text{PBH}} \sim \frac{M_{\text{PBH}}^3}{M_{\text{pl}}^4} \sim 13.8 \text{Gyr} \left(\frac{M_{\text{PBH}}}{10^{15} \text{g}} \right)^3 \sim O(10^7) \text{Gyr} \left(\frac{M_{\text{PBH}}}{10^{17} \text{g}} \right)^3$$

$$\sim O(1) \text{sec} \left(\frac{M_{\text{PBH}}}{10^9 \text{g}} \right)^3 \sim O(10^{-12}) \text{sec} \left(\frac{M_{\text{PBH}}}{10^5 \text{g}} \right)^3$$

- Mass (horizon mass = ρH^{-3} at $t=t_{\text{form}}$)

$$M_{\text{PBH}} \sim 10^{15} \text{g} \left(\frac{T_{\text{form}}}{3 \times 10^8 \text{GeV}} \right)^{-2} \sim 10^{17} \text{g} \left(\frac{T_{\text{form}}}{3 \times 10^6 \text{GeV}} \right)^{-2}$$

$(t \sim 10^{-23} \text{sec})$
 $(t \sim 10^{-19} \text{sec})$

- Hawking Temperature

$$T_{\text{PBH}} \sim \frac{M_{\text{pl}}^2}{M_{\text{PBH}}} \sim 10 \text{MeV} \left(\frac{M_{\text{PBH}}}{10^{15} \text{g}} \right)^{-1}$$

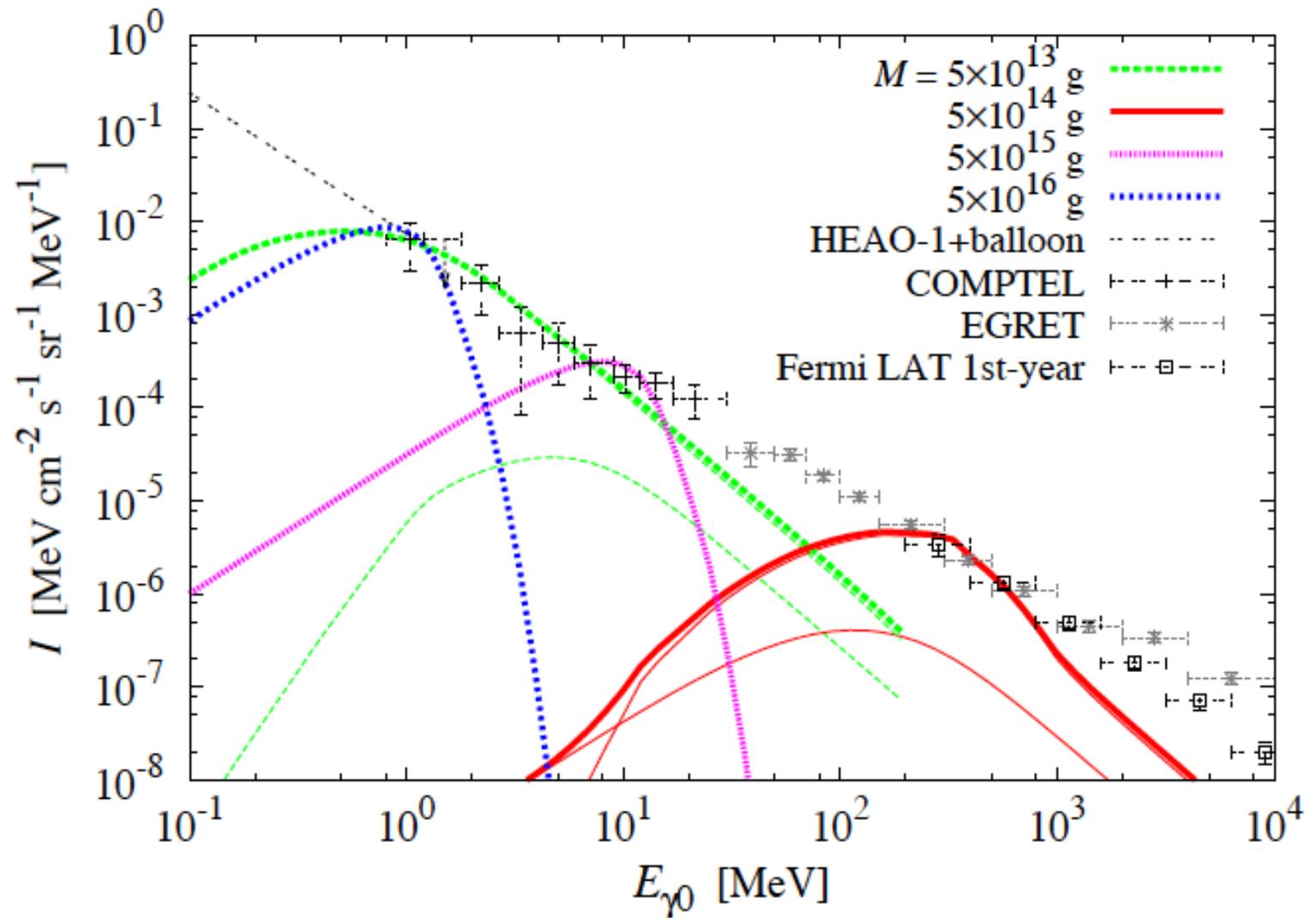
$\sim 0.1 \text{MeV} \left(\frac{M_{\text{PBH}}}{10^{17} \text{g}} \right)^{-1}$

$$\sim 1 \text{TeV} \left(\frac{M_{\text{PBH}}}{10^{10} \text{g}} \right)^{-1}$$

$\sim 100 \text{PeV} \left(\frac{M_{\text{PBH}}}{10^5 \text{g}} \right)^{-1}$

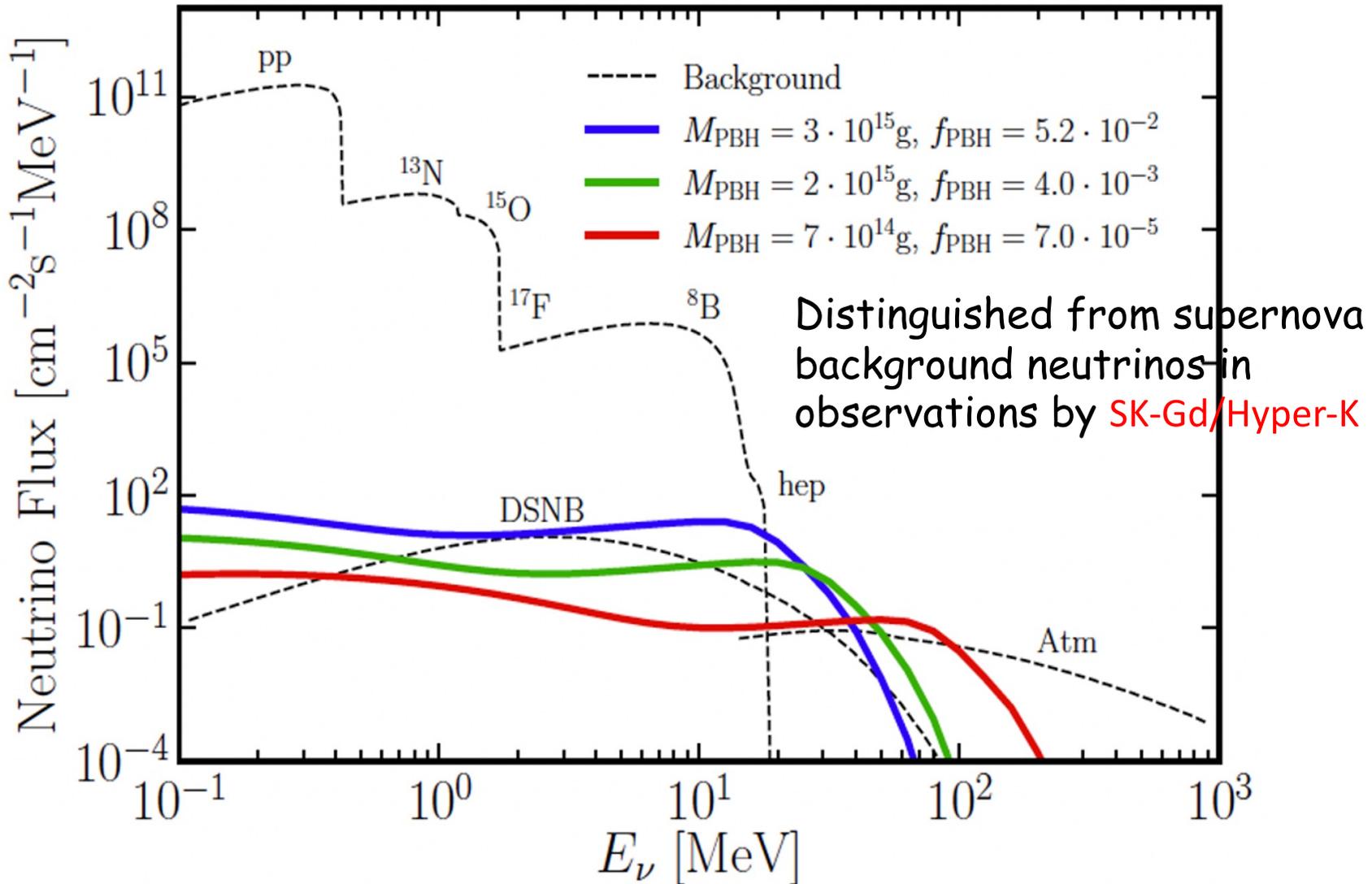
Evaporating PBHs through Hawking Process

The original paper, not a review paper
Carr, Kohri, Sendouda, J.Yokoyama, arXiv:0912.5297



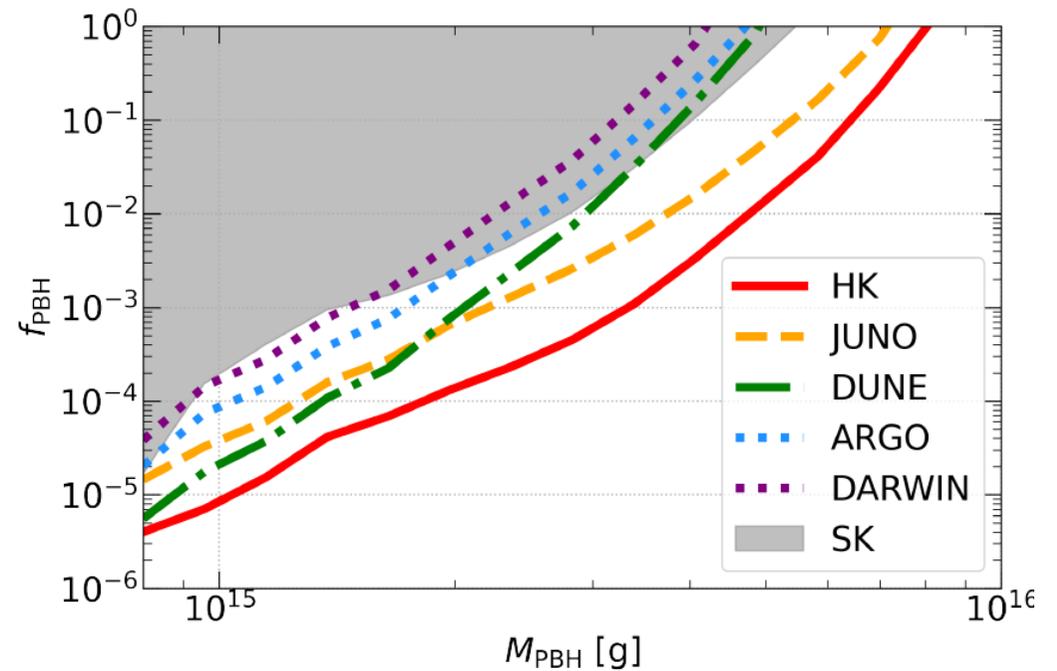
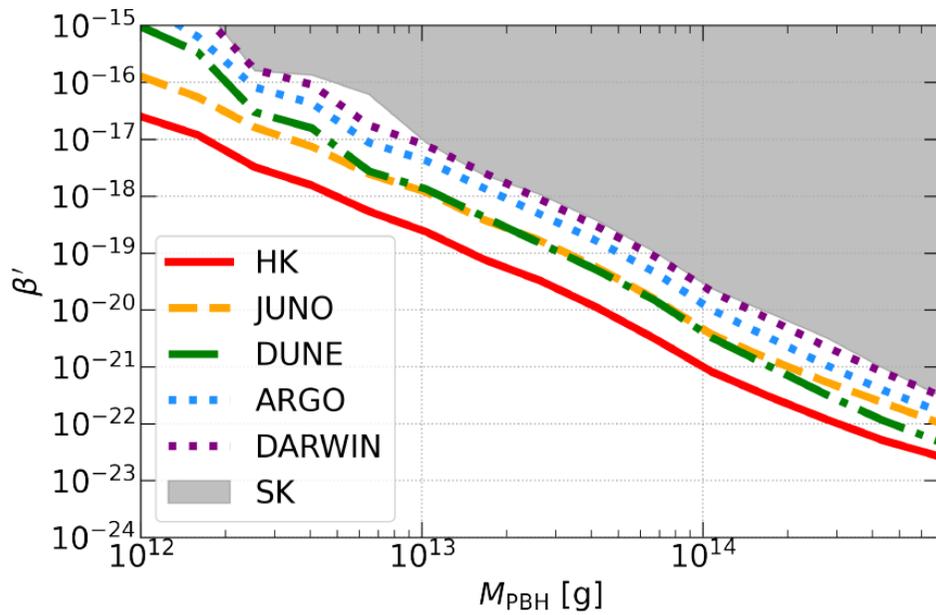
MeV neutrino by evaporating PBHs

R. Calabrese et al, arXiv:2106.02492

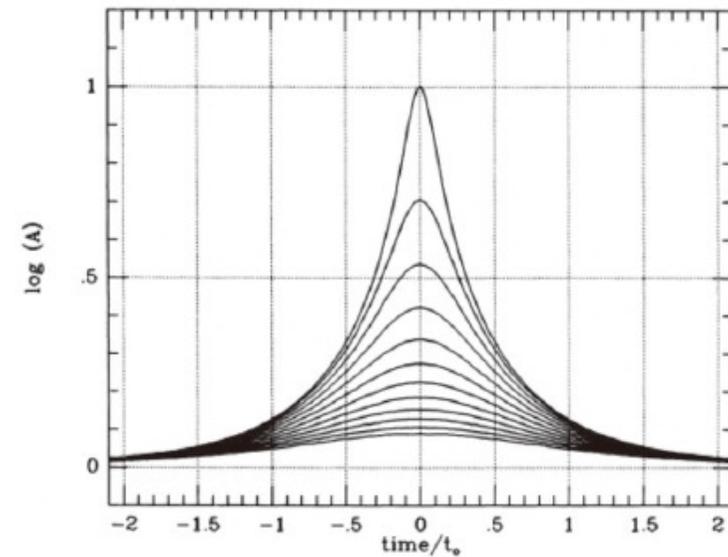
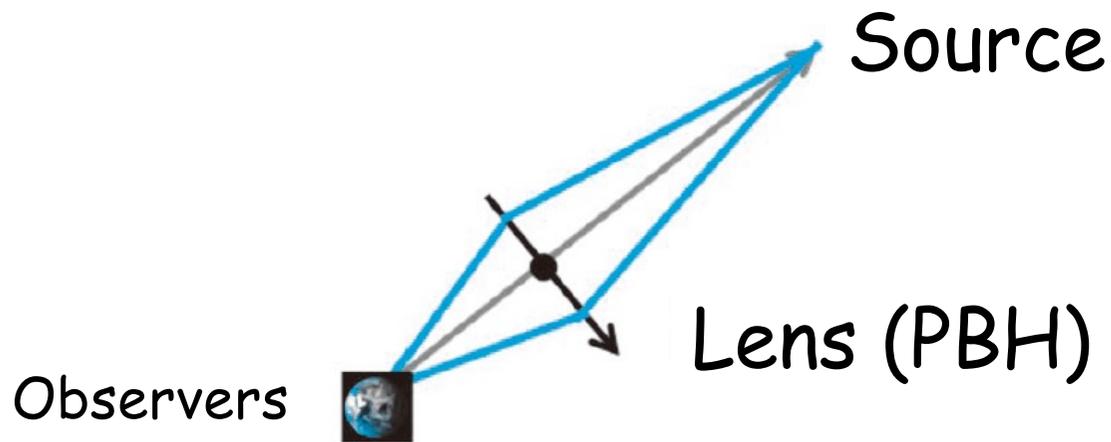


Future bounds on evaporating PBHs through neutrino emissions

Nicolás Bernal, Víctor Muñoz-Albornoz, Sergio Palomares-Ruiz, Pablo Villanueva-Domingo, arXiv:2203.14979 [hep-ph]



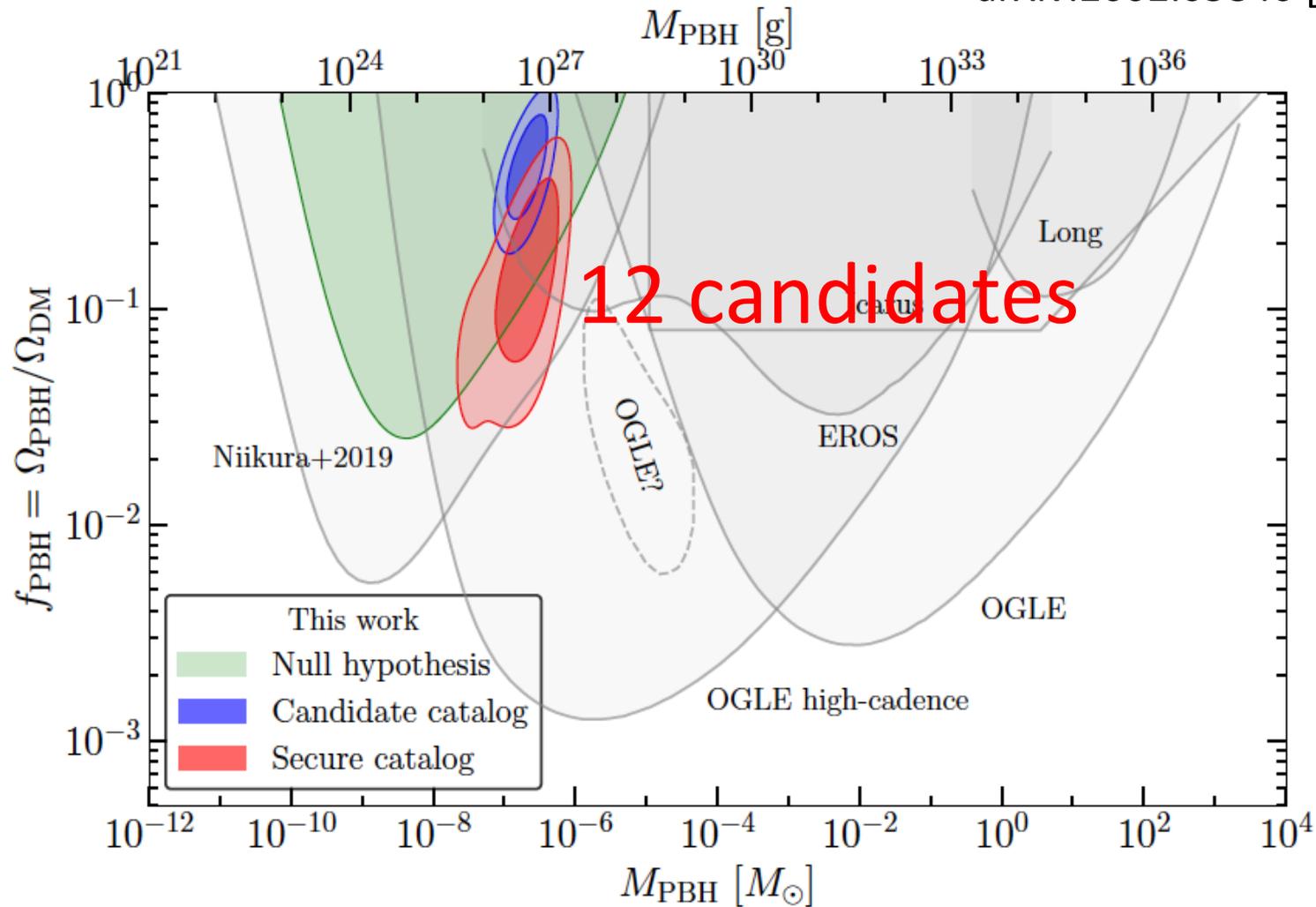
Gravitational Lensing



Hiroko Niikura, https://stg.asj.or.jp/jp/activities/geppou/item/113-1_6.pdf

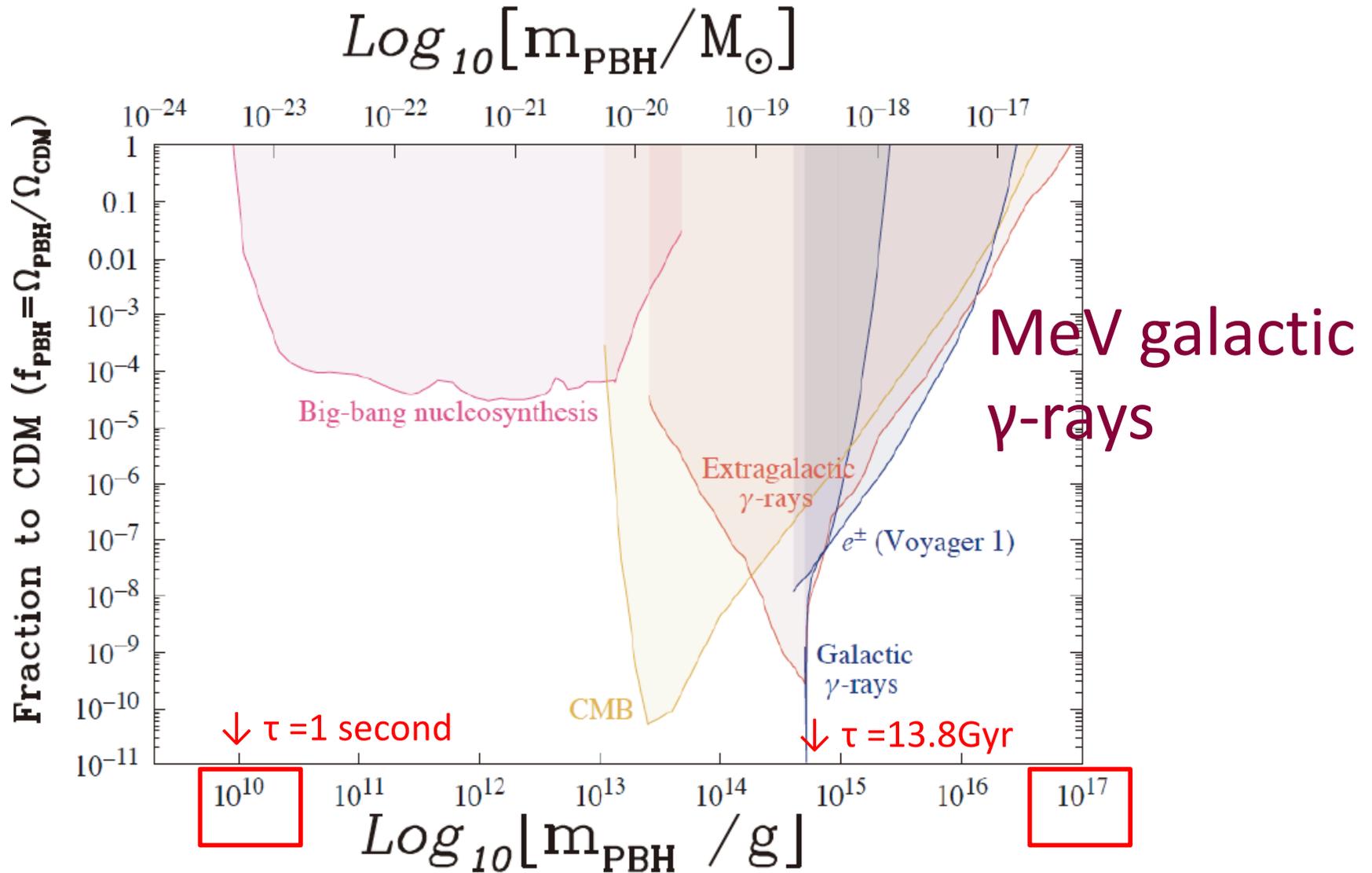
Gravitational Lensing bounds on PBH towards Andromeda M31

Sunao Sugiyama, Masahiro Takada, Naoki Yasuda, Nozomu Tominaga,
arXiv:2602.05840 [astro-ph.CO]



BBN, CMB, γ -ray bounds on PBHs

The original, not a review, Carr, Kohri, Sendouda, J.Yokoyama, arXiv:2002.12778



Secondary gravitational wave induced from large δ^2 at small scales

K. N. Ananda, C. Clarkson, and D. Wands, 2006

D. Baumann, P. J. Steinhardt, K. Takahashi and K. Ichiki, 2007

R. Saito and J. Yokoyama, 2008

Kohri and T. Terada, 2018

R.-G. Cai, S. Pi, and M. Sasaki, 2019

Scalar \times Scalar \rightarrow Tensor

- Induced gravitational wave by perturbation

$$\Omega_{\text{GW},c}(f) = \frac{1}{12} \left(\frac{f}{2\pi aH} \right)^2 \int_0^\infty dt \int_{-1}^1 ds \left[\frac{t(t+2)(s^2-1)}{(t+s+1)(t-s+1)} \right]^2$$
$$\times \overline{I^2(t, s, k\eta)} \mathcal{P}_\zeta \left(\frac{(t+s+1)f}{4\pi} \right) \mathcal{P}_\zeta \left(\frac{(t-s+1)f}{4\pi} \right)$$

$\delta^2 \quad \times \quad \delta^2$

Acoustic reheating and dissipation

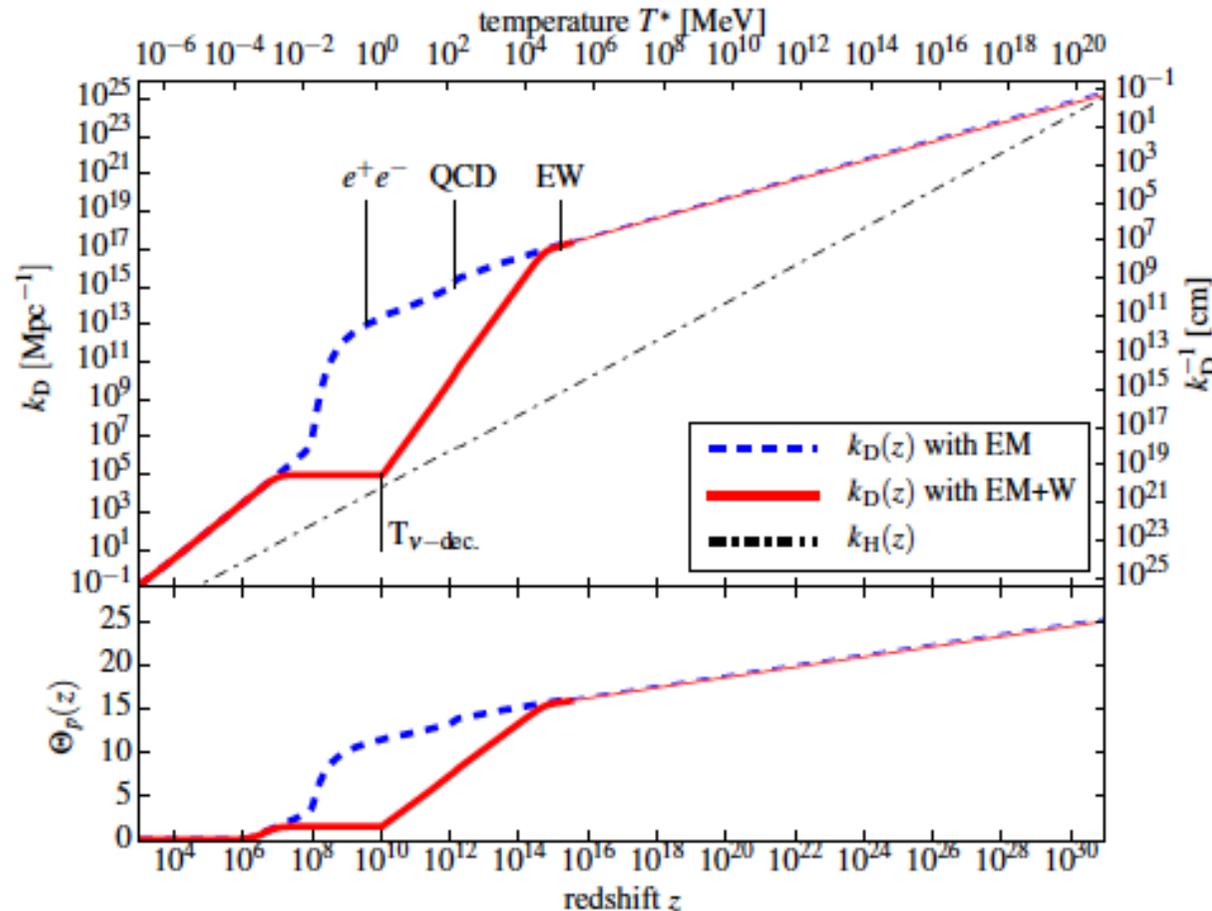
- Nonthermal heating by Silk dumping which can be constrained by BBN and CMB

Jeong, Kamionkowski, Chluba and Pradler (2014)

Nakama, Suyama, Yokoyama (2014)

Inomata, Tada, Kawasaki (2016)

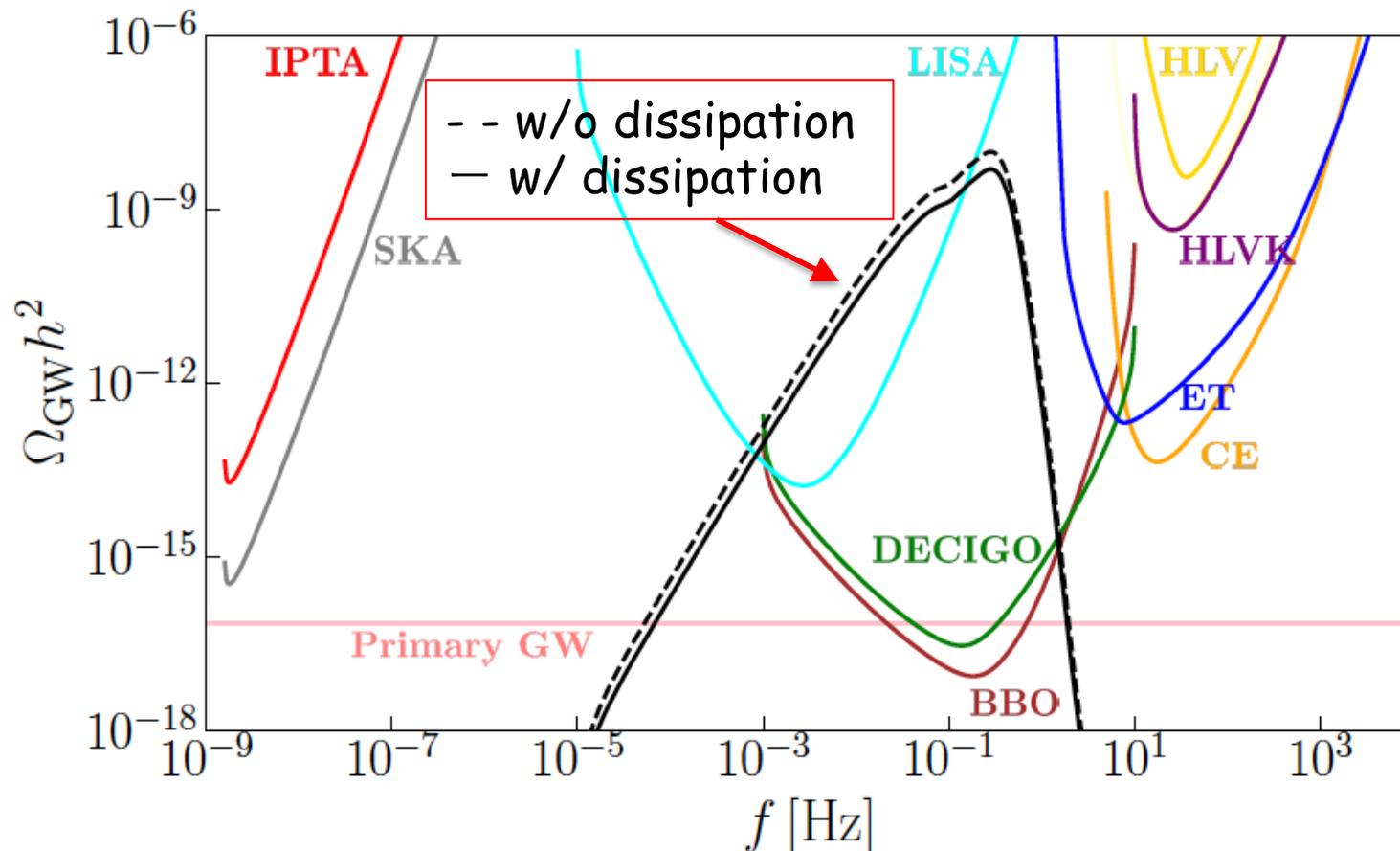
Diffusion scale



Induced GWs with dissipation to test dark matter PBHs with $10^{17}\text{g} - 10^{23}\text{g}$

Guillem Domènech, Jens Chluba, arXiv:2503.13670 [gr-qc]

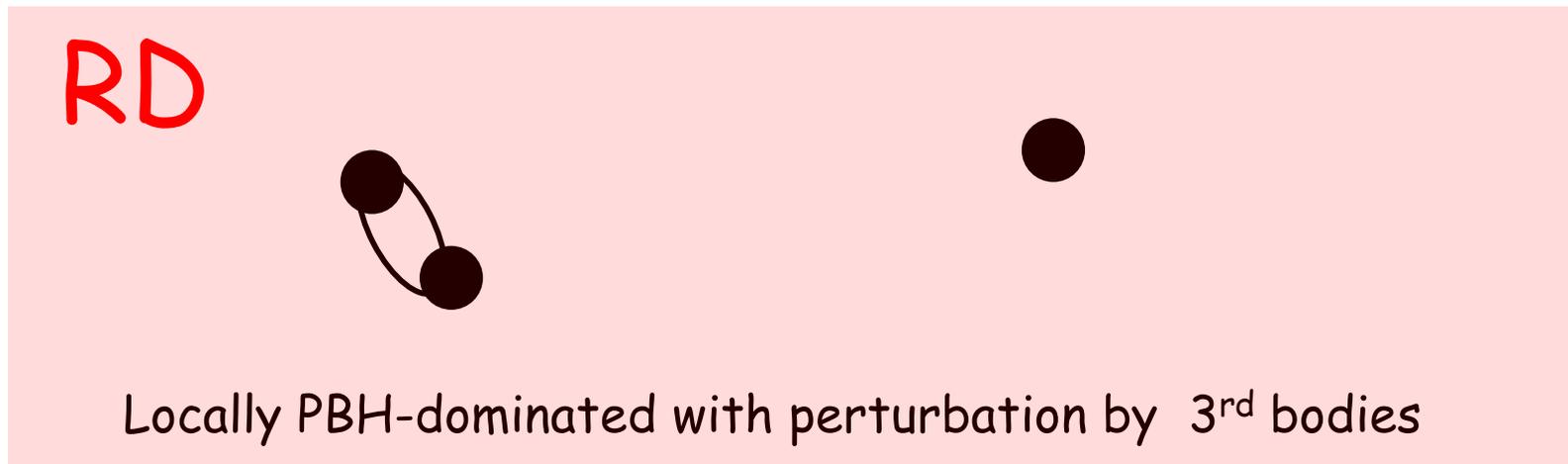
Y.S. Furuta, M. Karciauskas, K. Kohri and A. Saez, 2025, arXiv:2512.XXXXX to appear



Binary formations of PBHs in the radiation dominated epoch

M. Sasaki, T. Suyama, T. Tanaka and S. Yokoyama (2016)

- Three body effects are important



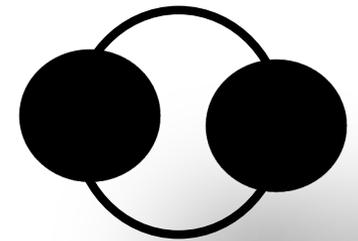
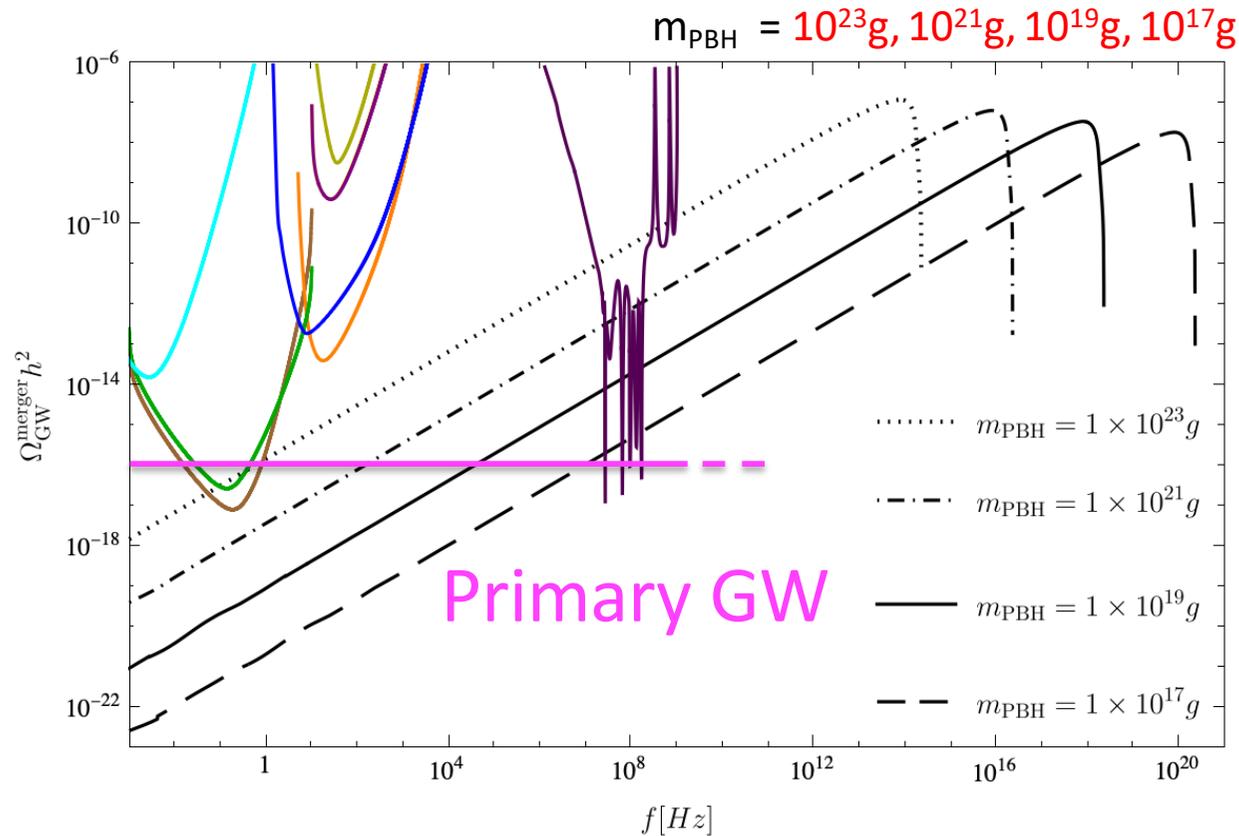
- Formation rate

$$\mathcal{R}_{\text{PBH}}(z) = A_{\text{PBH}} \left(\frac{t(z)}{\tau} \right)^{-\frac{34}{37}}$$

Z.-C. Chen and Q.-G. Huang, *Astrophys. J.* 864, 61 (2018), 1801.10327

Merger Gravitational Waves probing Primordial Black Hole **Dark Matter**

Y.S. Furuta, M. Karciauskas, K. Kohri and A. Saez, 2025, arXiv:2512.XXXXX to appear



Gravitational wave search through Gertsenshtein Effect

M.E.Gertsenshtein, JETP15 (1962) 84.

A. Ito, K. Kohri, K. Nakayama, arXiv:2309.14765 [gr-qc]

See also, M. E. Gertsenshtein, Sov. Phys. JETP 14 (1962) 84.

V. Domcke, C. Garcia-Cely, arXiv:2006.01161 [astro-ph.CO]

T. Fujita, K. Kamada, Y. Nakai, arXiv:2002.07548 [astro-ph.CO]

- Action of EM + gravity

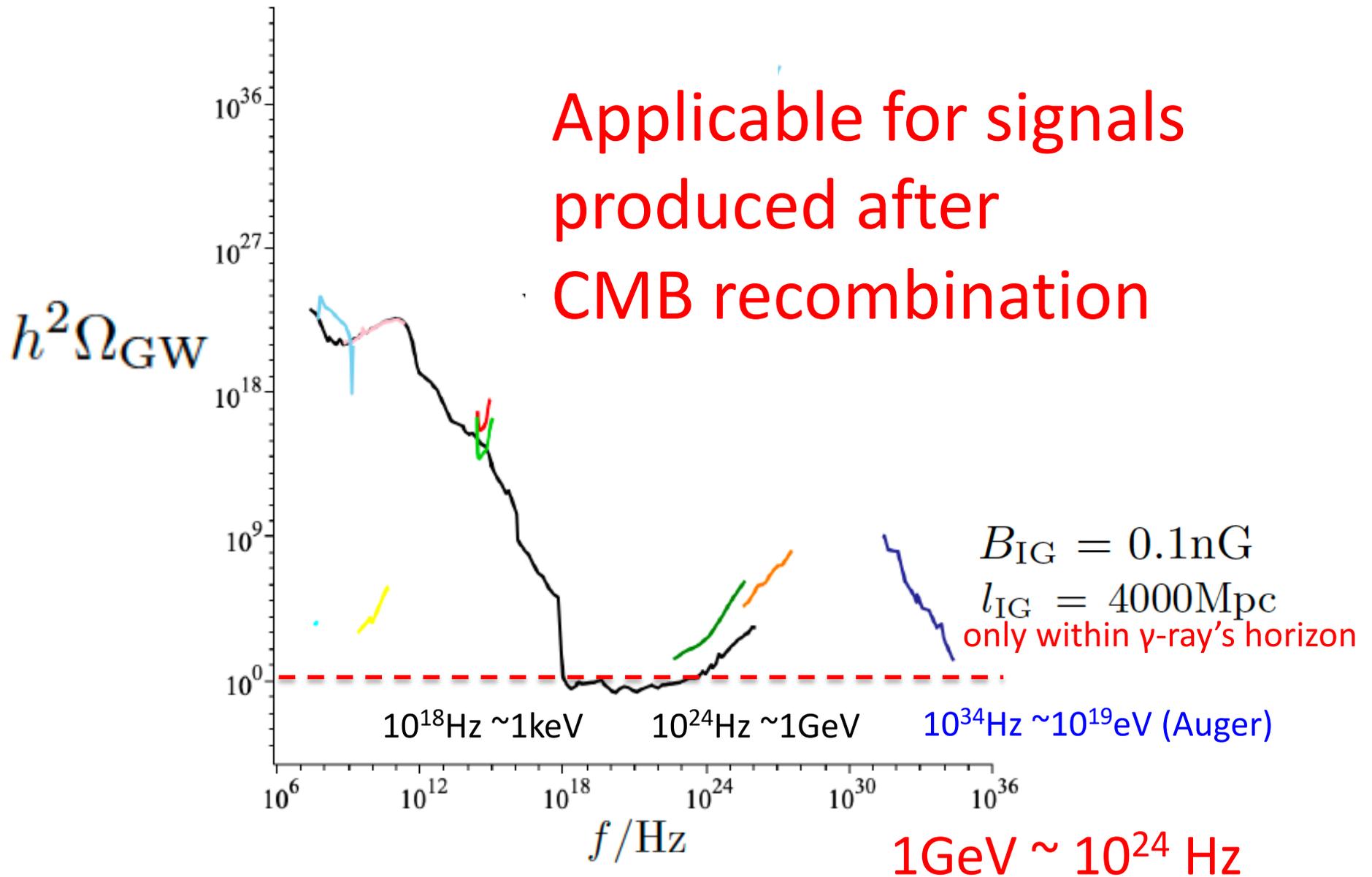
$$S = \int d^4x \sqrt{-g} \left[\frac{M_{\text{pl}}^2}{2} R - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \right]$$

GW + B \rightarrow γ

$$\delta S^{(2)} = \int d^4x \left[-\frac{1}{2} (\partial_\mu h_{ij})^2 - \frac{1}{2} (\partial_\mu A_i)^2 + \frac{2}{M_{\text{pl}}} \epsilon_{ijk} \bar{B}^k h^{jl} \partial_i A^l \right. \\ \left. + \frac{\alpha^2}{90 m_e^4} \left(16 \bar{B}^i \bar{B}^j \left(\delta_{ij} (\partial_k A_l)^2 - (\partial_k A_i) (\partial_k A_j) - (\partial_i A_k) (\partial_j A_k) \right) + 28 \left((\partial_0 A_i) \bar{B}_i \right)^2 \right) \right].$$

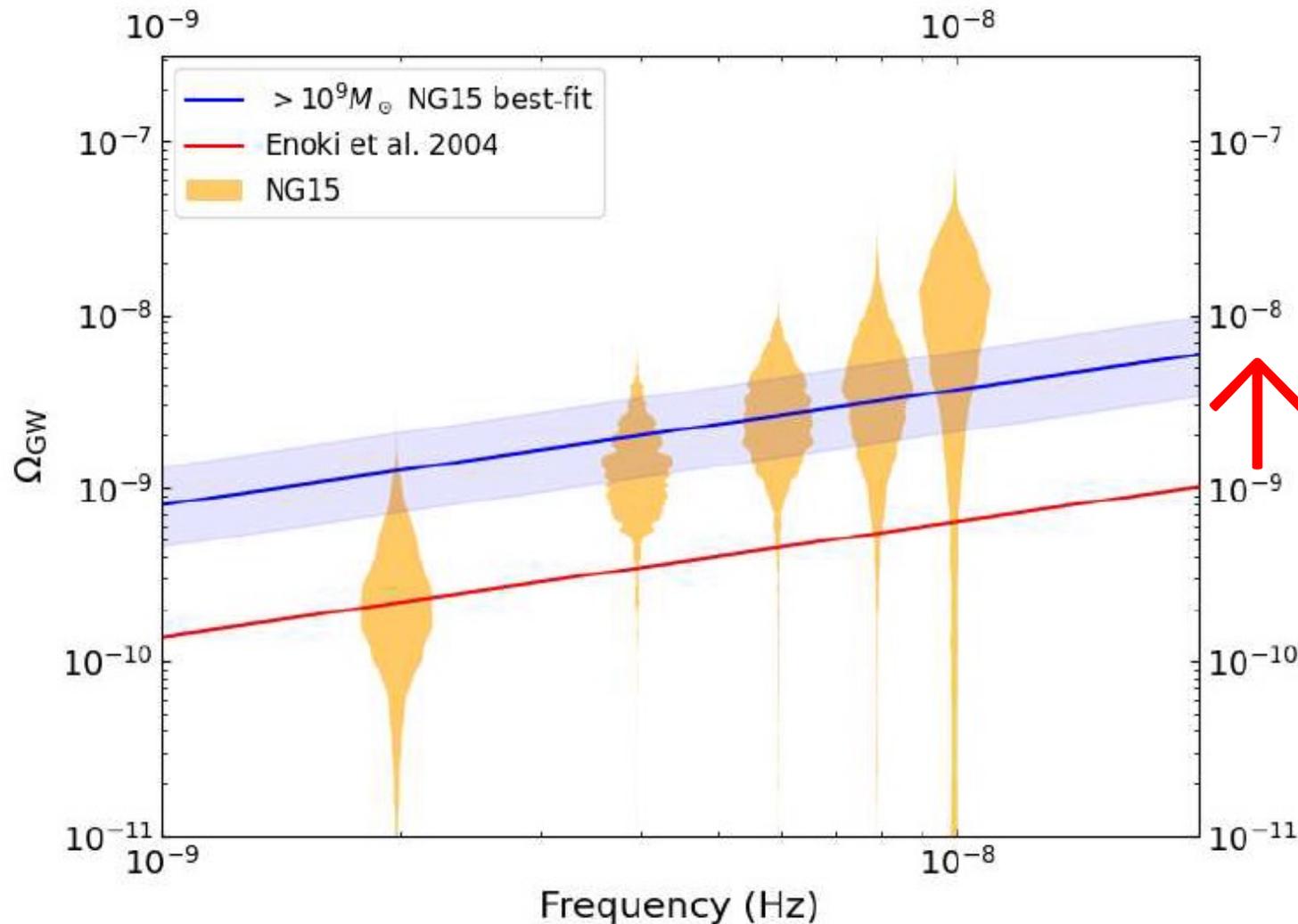
Gravitational wave search through electromagnetic telescopes

Asuka Ito, Kazunori Kohri, Kazunori Nakayama, arXiv:2309.14765 [gr-qc]

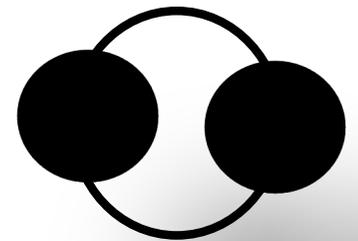


NANOGrav 15-yr GW from merging binary SMBHs seeded by PBHs

Mikage U. Kobayashi and Kazunori Kohri, arXiv:2511.04210 [astro-ph.CO]

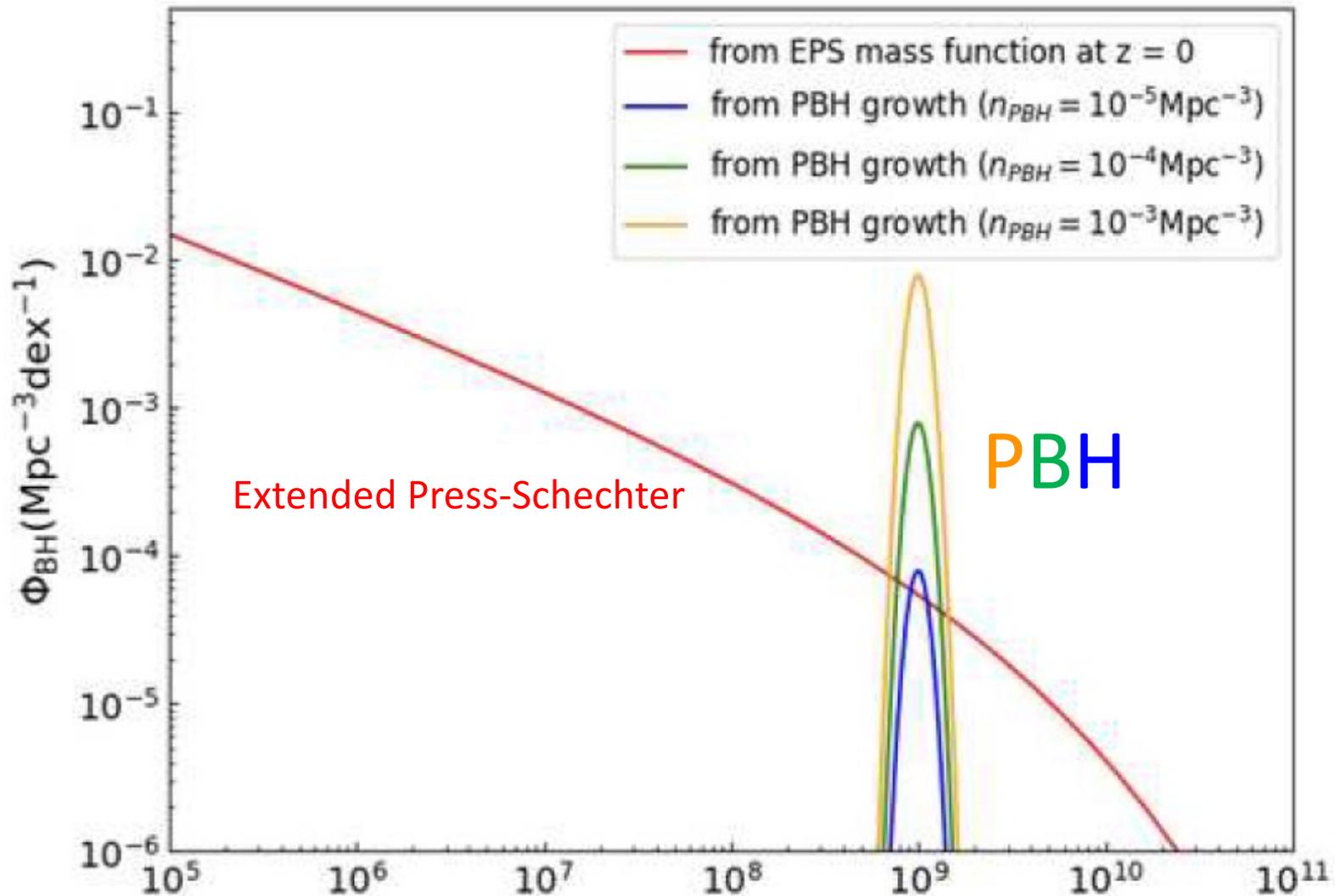


↑ PBHs?



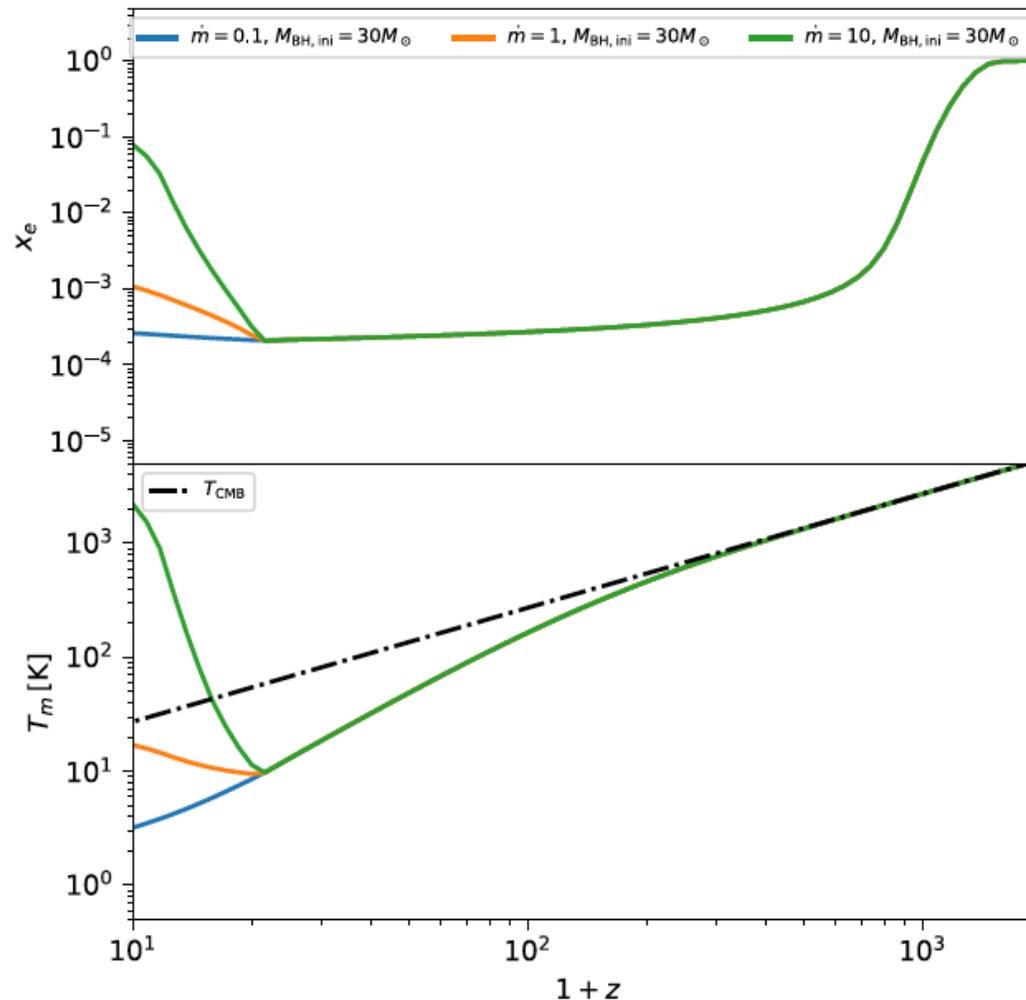
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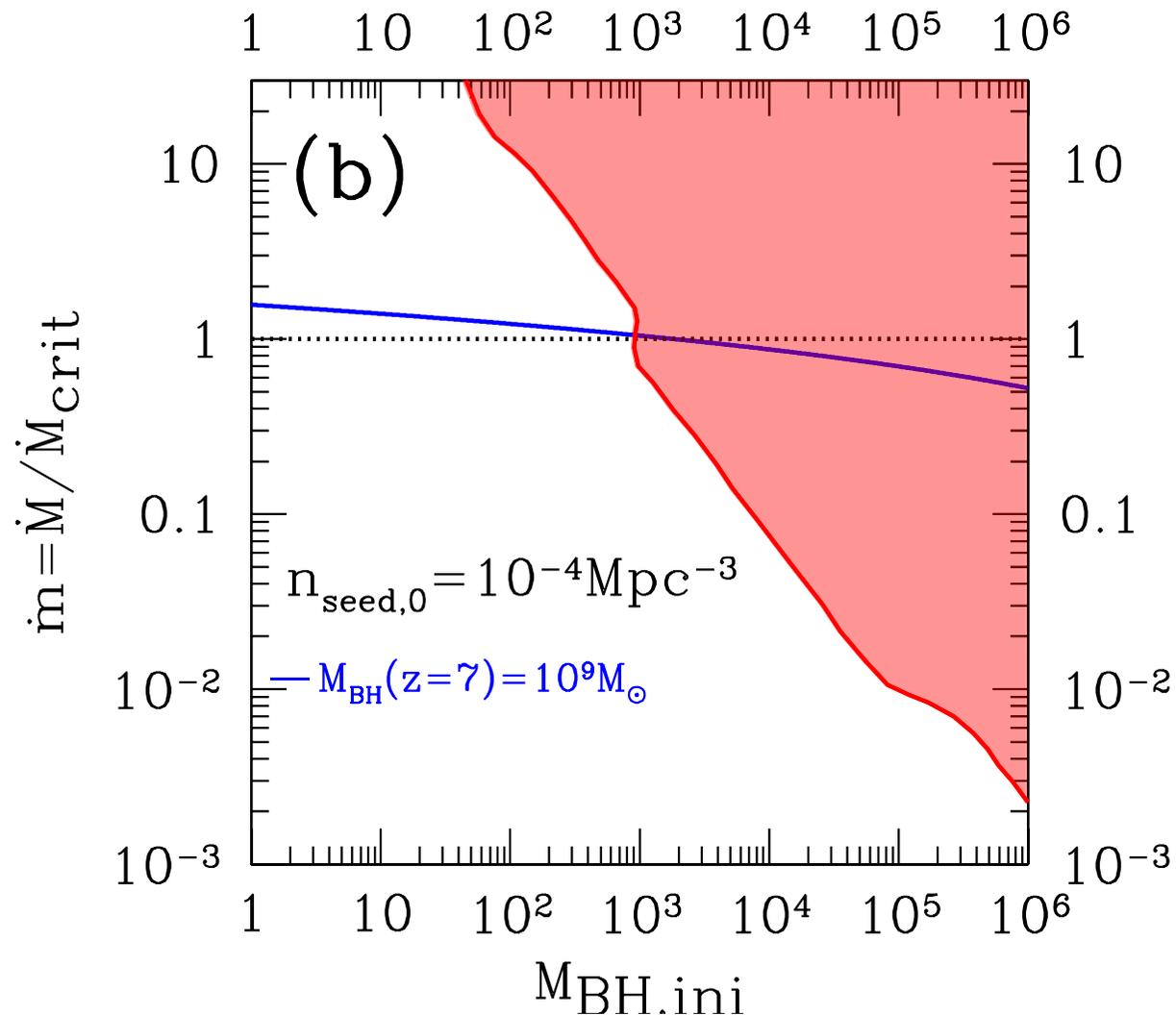
Accretion can heat the plasma, which changes the reionization history

Kazunori Kohri, Toyokazu Sekiguchi, Sai Wang, arXiv:2201.05300 [astro-ph.CO]



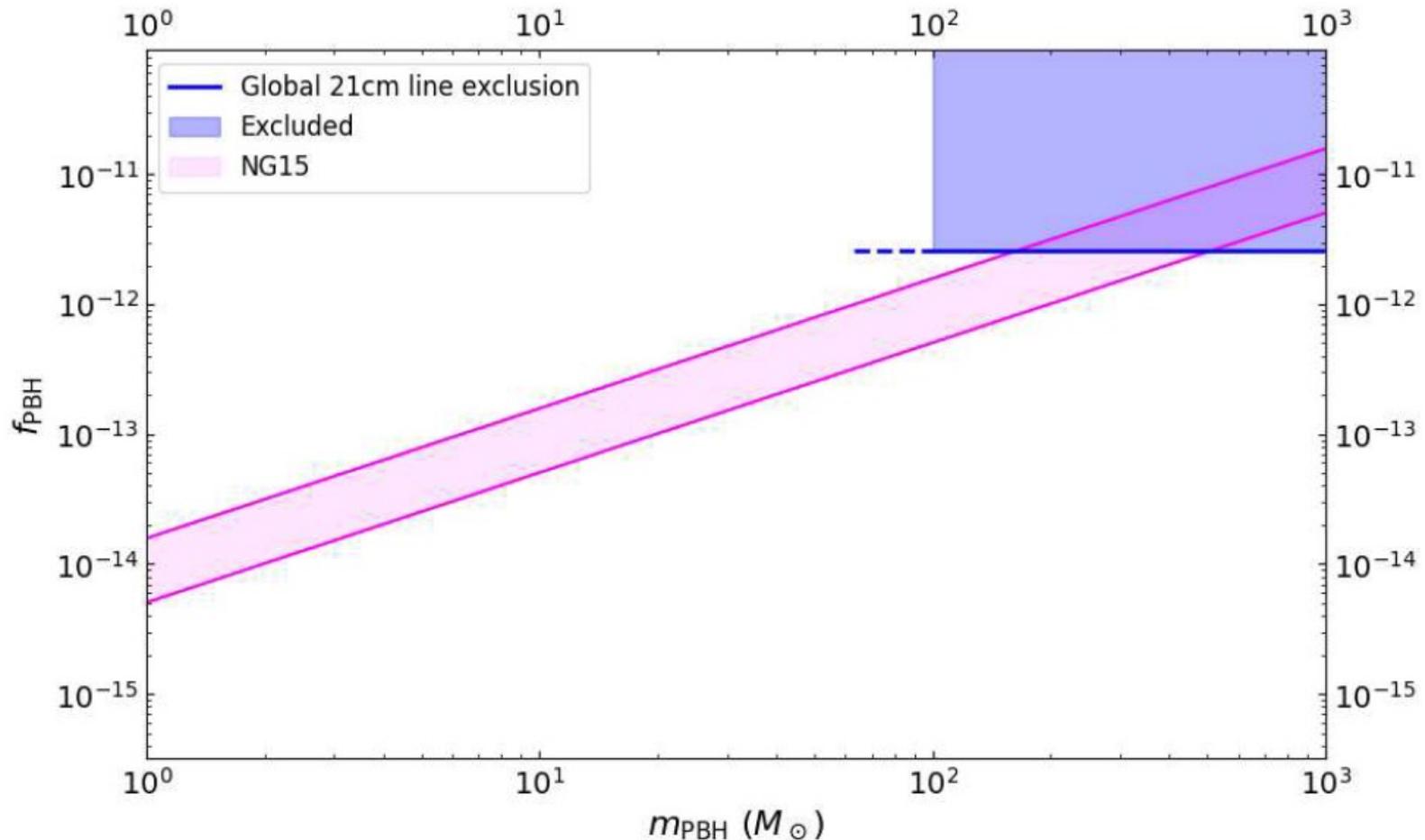
21cm global spectrum gives the upper bounds on accretion rates on seed BHs at $z=17$ evolved to SMBHs until $z=7$

Kazunori Kohri, Toyokazu Sekiguchi, Sai Wang, arXiv:2201.05300 [astro-ph.CO]



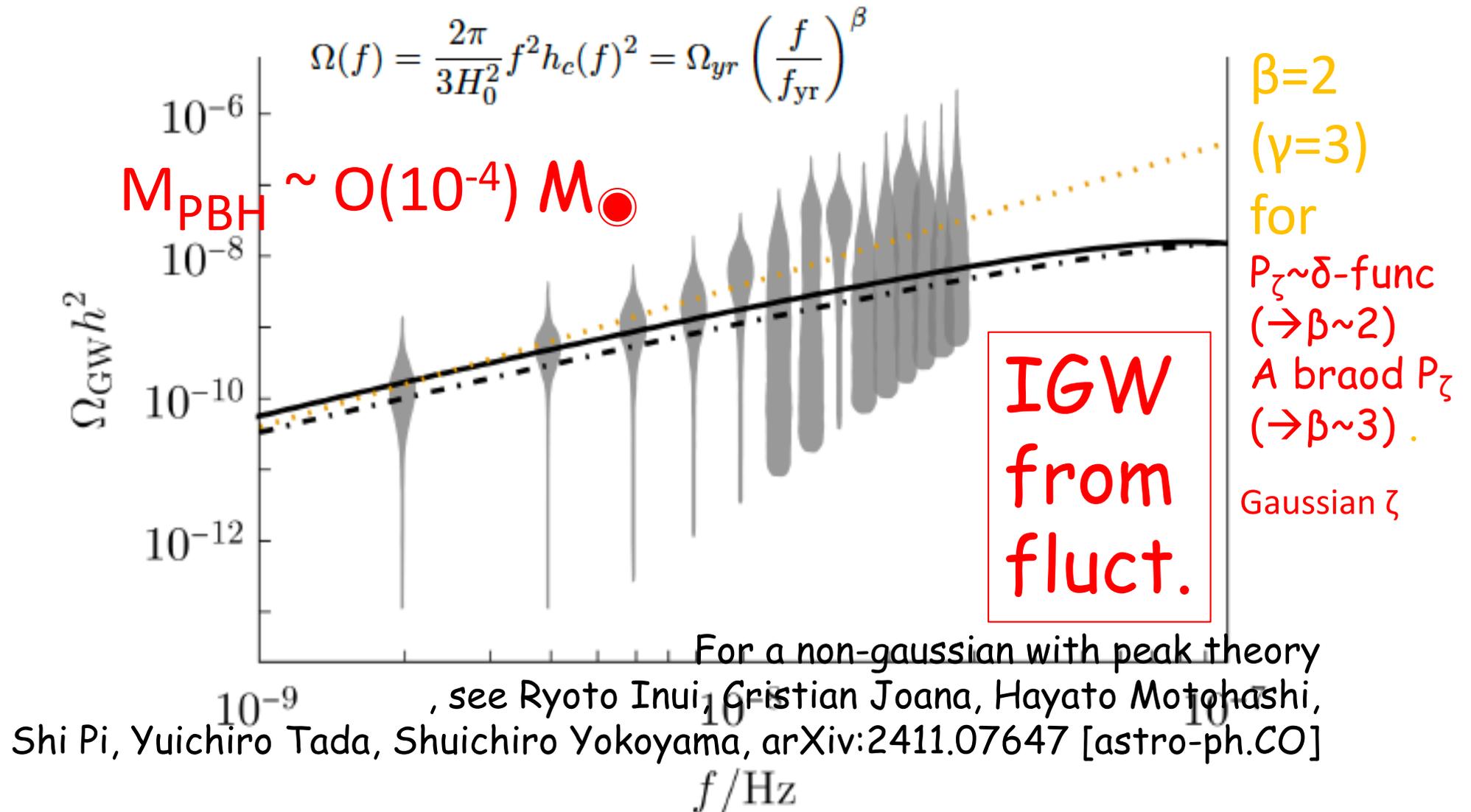
NANOGrav 15-yr GW from merging binary SMBHs seeded by PBHs

Mikage U. Kobayashi and Kazunori Kohri, arXiv:2511.04210 [astro-ph.CO]



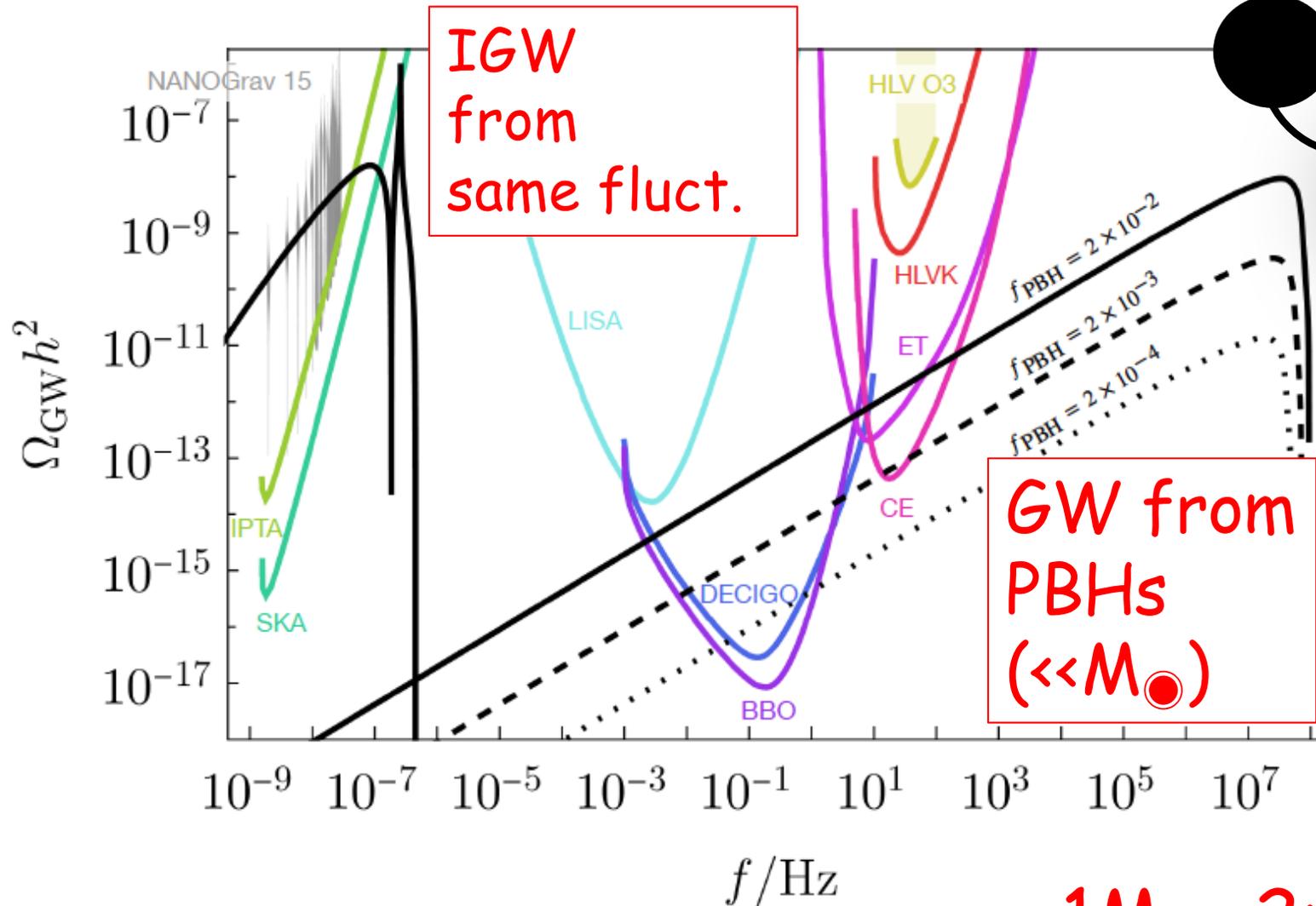
NANOGrav15yr by Induced GW and sub-solar PBHs

Keisuke Inomata, Kazunori Kohri, Takahiro Terada, arXiv:2306.17834 [astro-ph.CO]



NANOGrav15yr by Induced GW and sub-solar PBHs

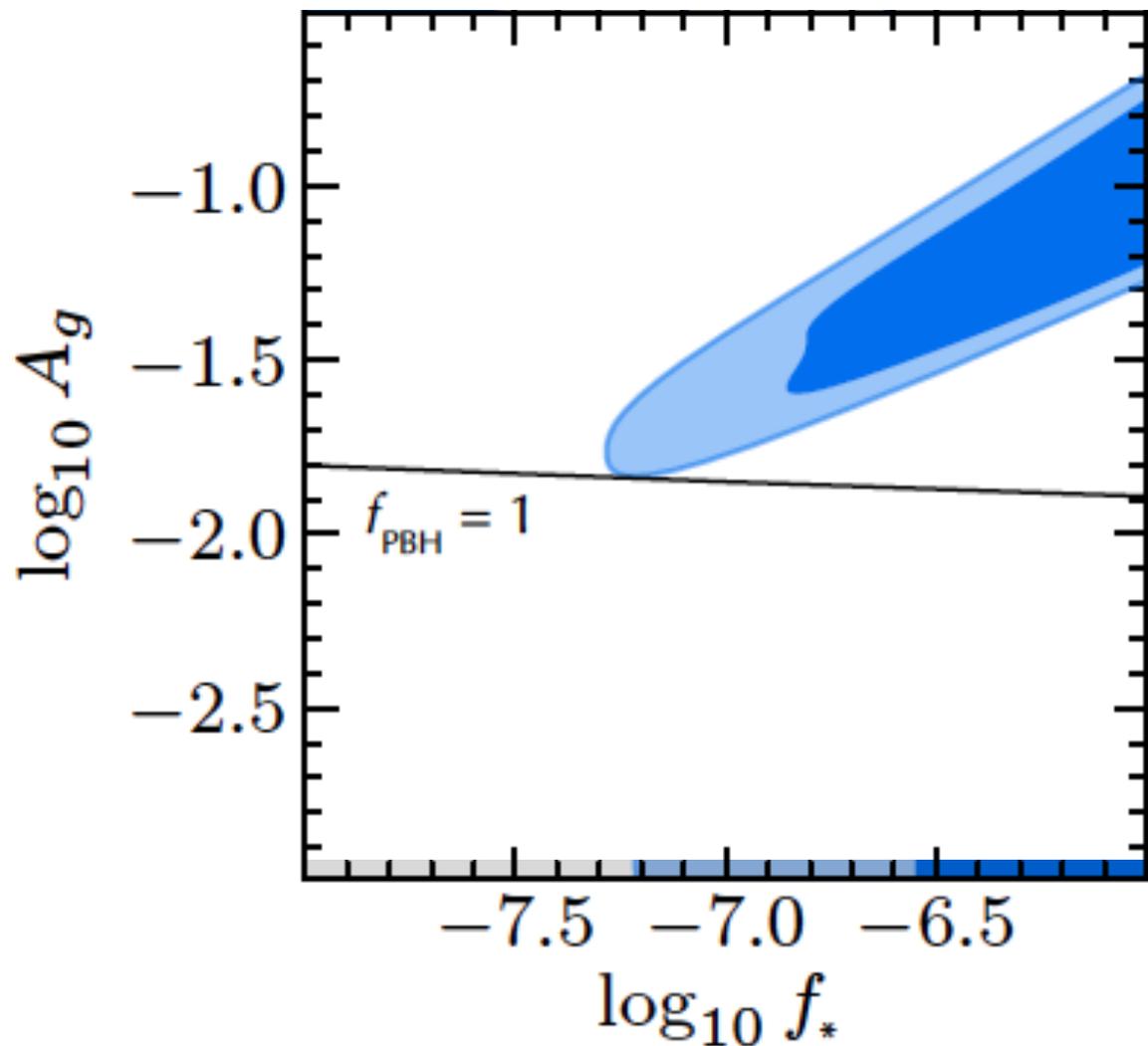
Keisuke Inomata, Kazunori Kohri, Takahiro Terada, arXiv:2306.17834 [astro-ph.CO]



$$1M_{\odot} = 2 \times 10^{33} \text{g}$$

Peak theory + non-gaussianity?

For a non-gaussianity with peak theory,
see also Ryoto Inui, Cristian Joana, Hayato Motohashi,
Shi Pi, Yuichiro Tada, Shuichiro Yokoyama, arXiv:2411.07647 [astro-ph.CO]



Memory Burden in evaporating BHs

Gia Dvali, Lukas Eisemann, Marco Michel, Sebastian Zell, arXiv:2006.00011 [hep-th]

Valentin Thoss, Andreas Burkert, Kazunori Kohri, arXiv:2402.17823 [astro-ph.CO]

$$\frac{d^2 N_{i,MB}}{dE dt}(E, M, s_i) = \frac{1}{S(M)^k} \frac{d^2 N_{i,SC}}{dE dt}(E, M, s_i)$$

$$k=2$$

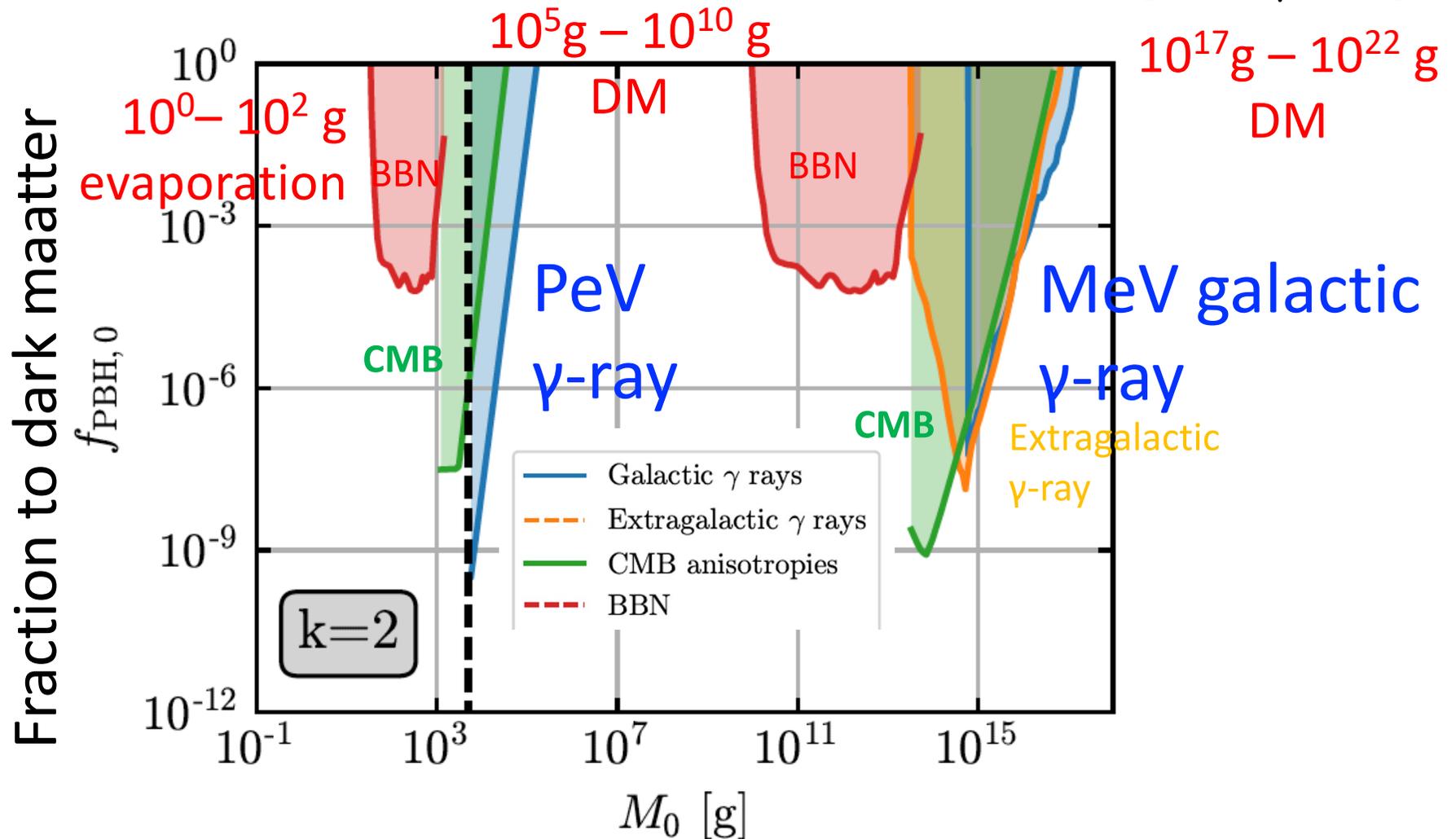
$$S = \frac{4\pi M^2 G}{\hbar c} \approx 2.6 \times 10^{10} \left(\frac{M}{1 \text{ g}}\right)^2$$

$$\dot{M}_{\text{PBH}} \sim \begin{cases} -\frac{M_{\text{pl}}^4}{M_{\text{PBH}}^2} & (M_{\text{PBH}} \geq \frac{1}{2} M_{\text{PBH,ini}}) \\ -\frac{1}{S^k} \frac{M_{\text{pl}}^4}{M_{\text{PBH}}^2} & (M_{\text{PBH}} < \frac{1}{2} M_{\text{PBH,ini}}) \end{cases}$$

$$q=1/2$$

Breakdown of Hawking Evaporation opens new Mass Window PBHs as DM

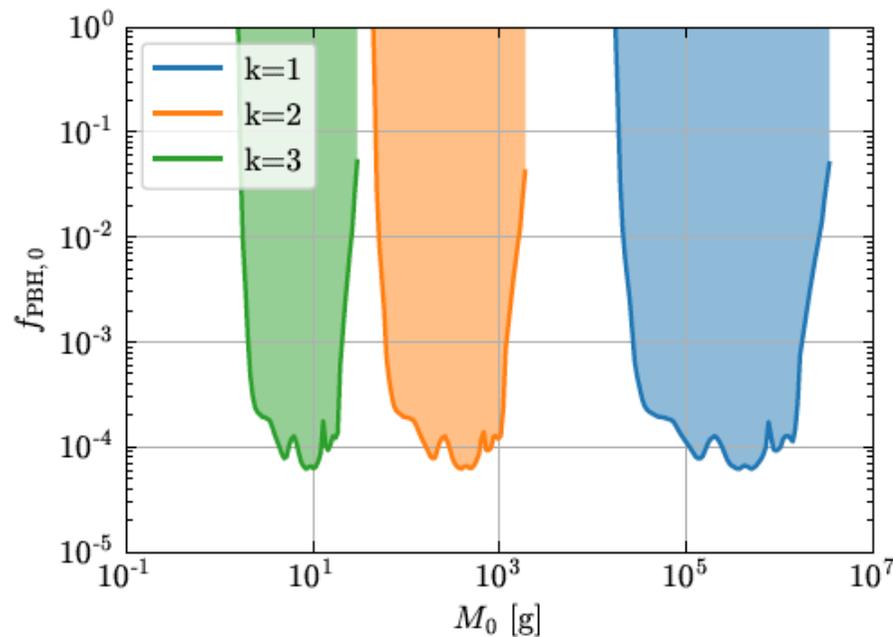
Valentin Thoss, Andreas Burkert, Kazunori Kohri, arXiv:2402.17823 [astro-ph.CO]
 Aarnab Chaudhuri, Kazunori Kohri, Valentin Thoss, 2506.20717 [astro-ph.CO]



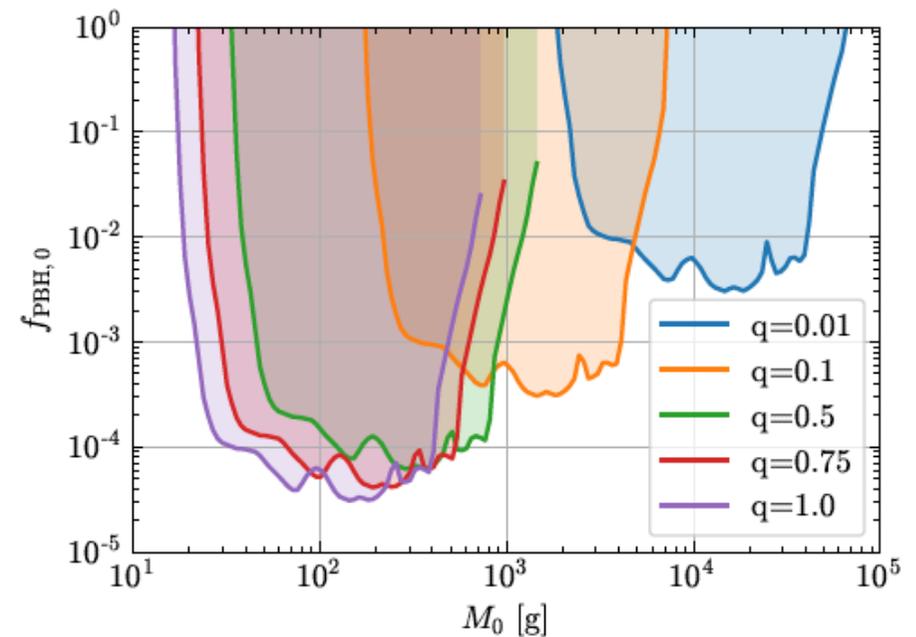
Breakdown of Hawking Evaporation opens new Mass Window PBHs as DM

Valentin Thoss, Andreas Burkert, Kazunori Kohri, arXiv:2402.17823 [astro-ph.CO]
Aarnab Chaudhuri, Kazunori Kohri, Valentin Thoss, 2506.20717 [astro-ph.CO]

$q=1/2$



$k=2$



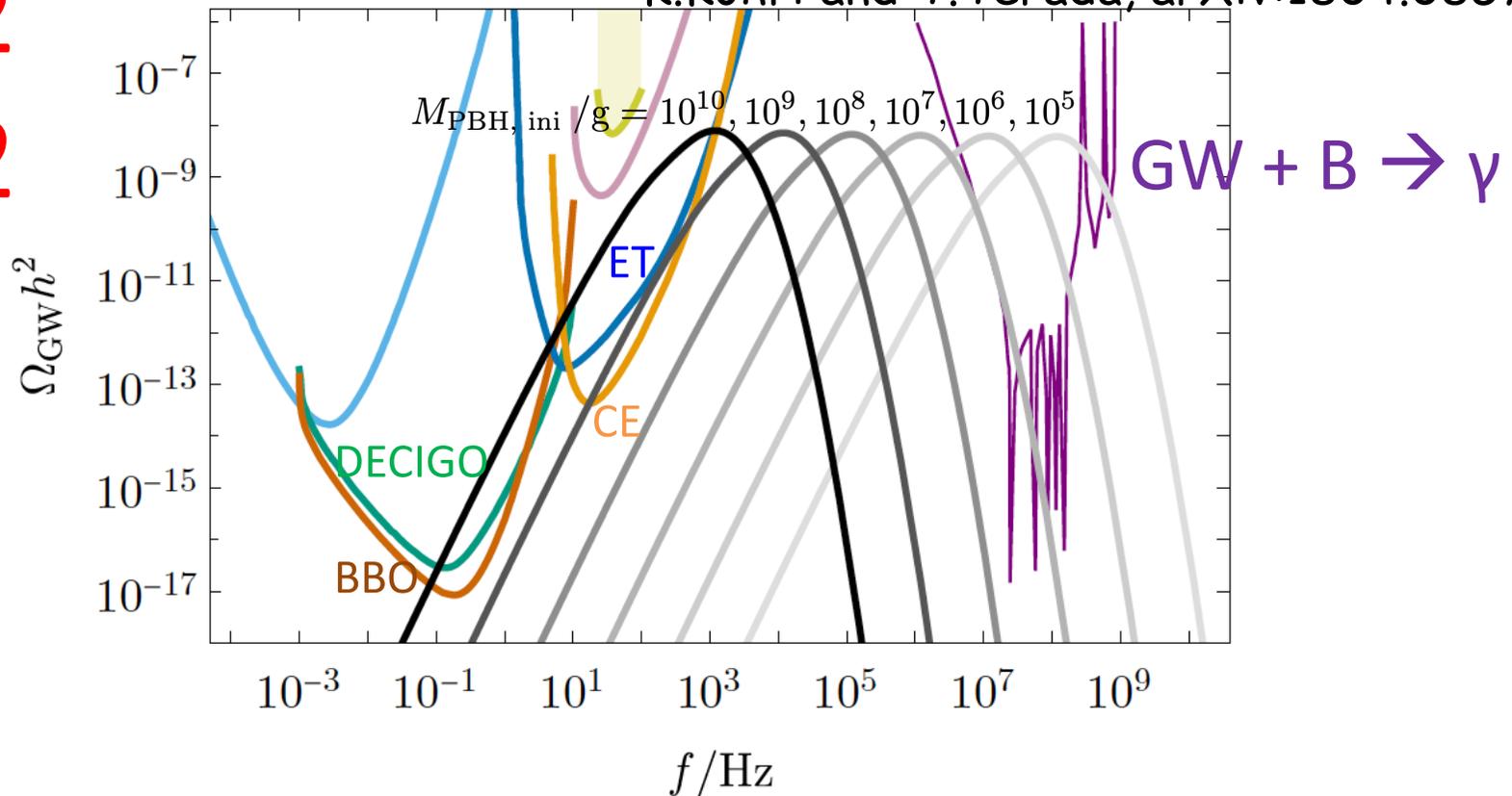
Induced Gravitational Wave probing Primordial Black Hole **Dark Matter** with Memory Burden

K. Kohri. T. Terada. T. Yanagida. arXiv:2409.06365

$$\Omega_{\text{GW},c}(f) = \frac{1}{12} \left(\frac{f}{2\pi aH} \right)^2 \int_0^\infty dt \int_{-1}^1 ds \left[\frac{t(t+2)(s^2-1)}{(t+s+1)(t-s+1)} \right]^2 \times \overline{I^2(t, s, k\eta_c)} \mathcal{P}_\zeta \left(\frac{(t+s+1)f}{4\pi} \right) \mathcal{P}_\zeta \left(\frac{(t-s+1)f}{4\pi} \right)$$

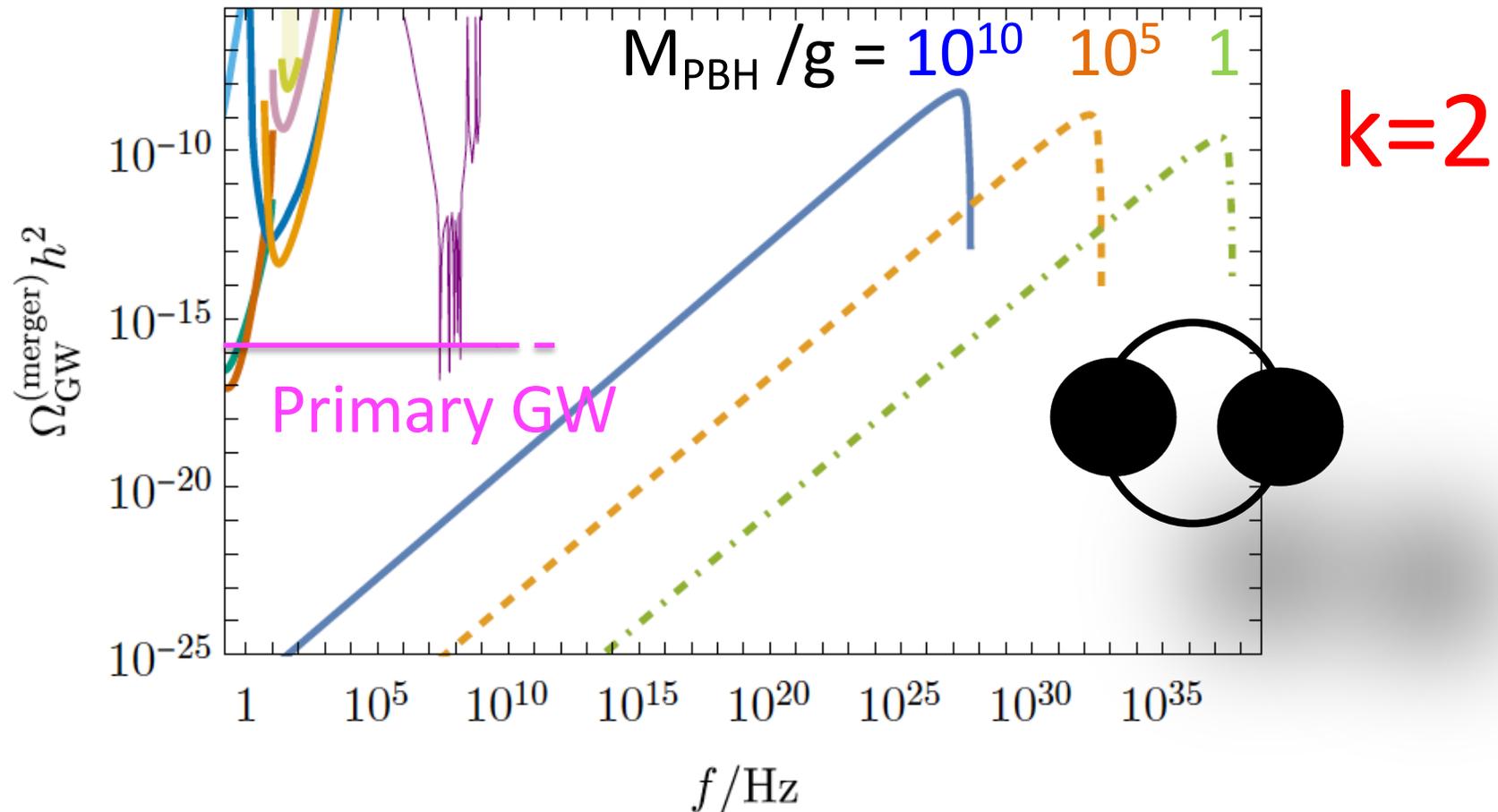
k=2
q=1/2

K. Kohri and T. Terada, arXiv:1804.08577



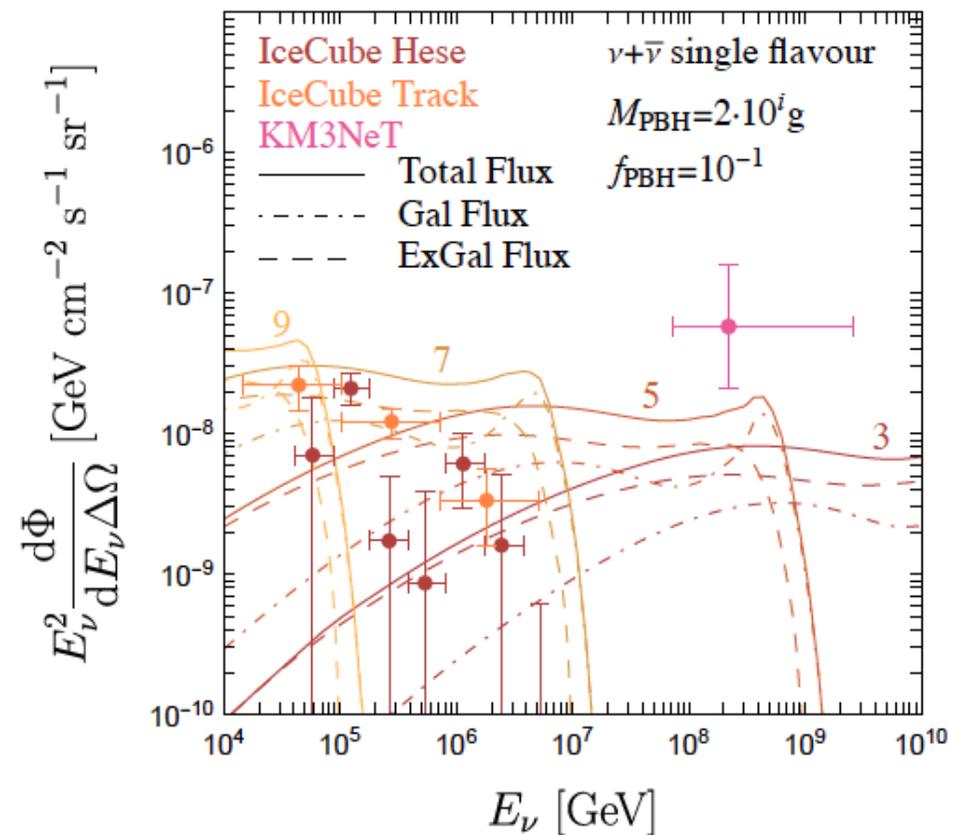
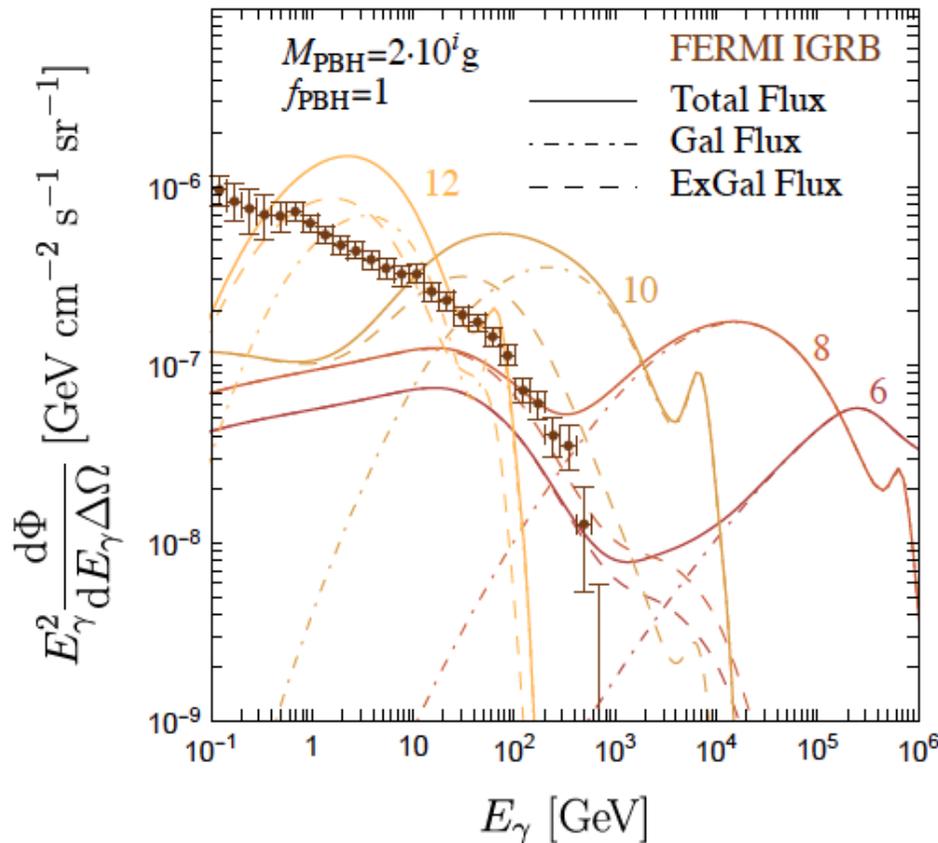
Merger Gravitational Waves probing Primordial Black Hole **Dark Matter** with Memory Burden

K. Kohri, T. Terada, T. Yanagida, arXiv:2409.06365



Fermi and KM3NeT bounds on newly-produced merging PBHs with memory burden effects

Alessandro Dondarini, Giulio Marino, Paolo Panci, Michael Zantedeschi, arXiv:2506.13861 [hep-ph]



Conclusion

- PBHs with their masses $10^{17} \text{ g} - 10^{23} \text{ g}$ can be dark matter (DM)
- PBHs with their masses $10^{15} \text{ g} - 10^{17} \text{ g}$ are now evaporating with emitting the MeV gamma-rays and neutrino
- NANOGrav 15-yr can be fitted by induced GWs or merger GWs by binary SMBHs seeded by $10^2 M_{\odot}$ PBHs
- If we assume the Memory Burden Effect, additionally PBHs with $10^5 \text{ g} - 10^{10} \text{ g}$ can be dark matter, which are now emitting the PeV gamma-rays and neutrinos