Primordial black hole dark matter

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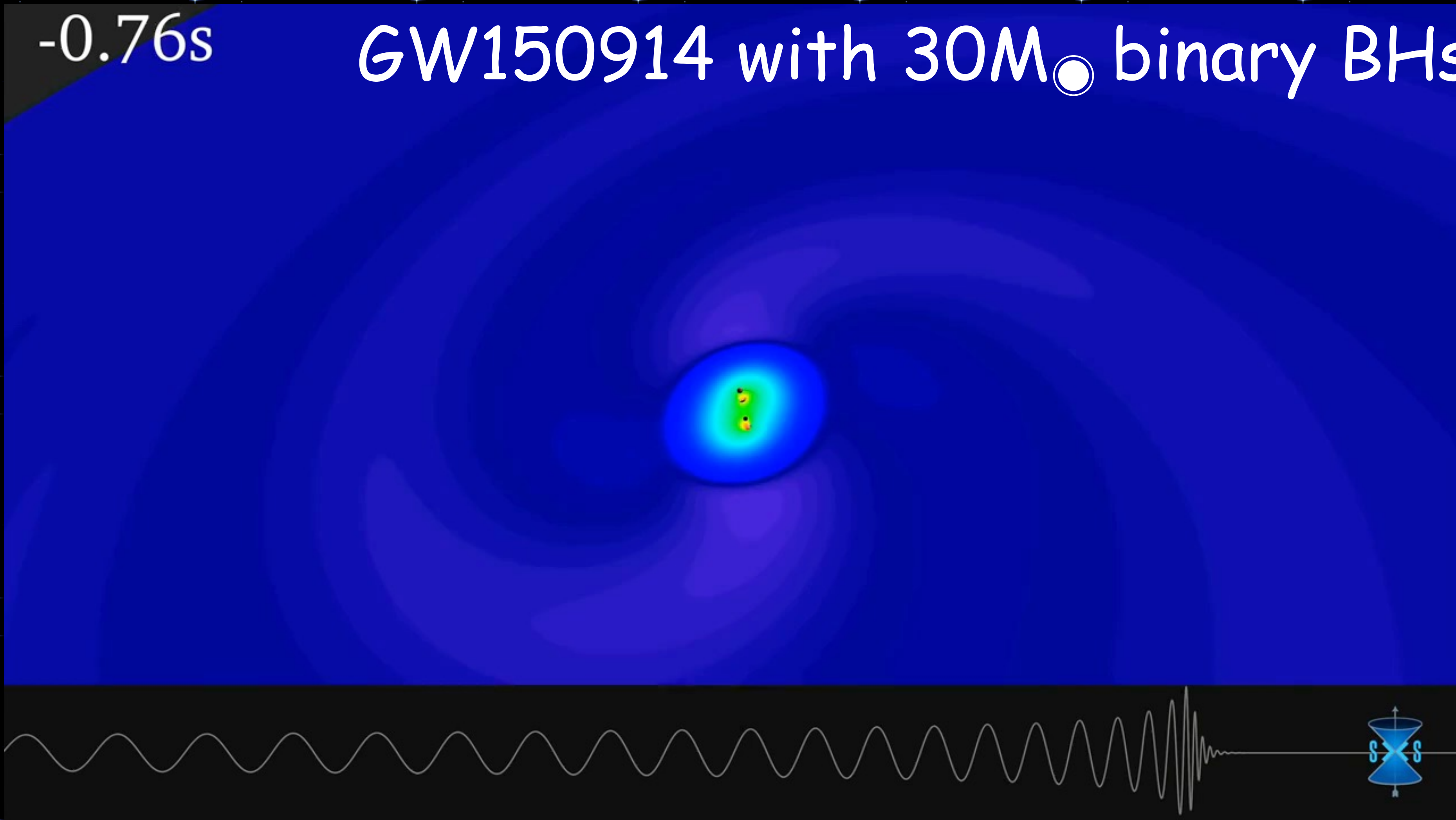
Abstract

- Primordial black holes (PBHs) were formed in the early Universe (e.g, $t \sim 10^{-19}$ -- 10^{-13} sec)
- PBHs with their masses 10^{17} g – 10^{23}g can be dark matter (DM)
- We can test the PBH dark matter by future observations of gravitational wave and/or neutrino

Detections of GWs by LIGO/Virgo/KAGRA from binary PBHs collide?

GW150914 with $30M_\odot$ binary BHs

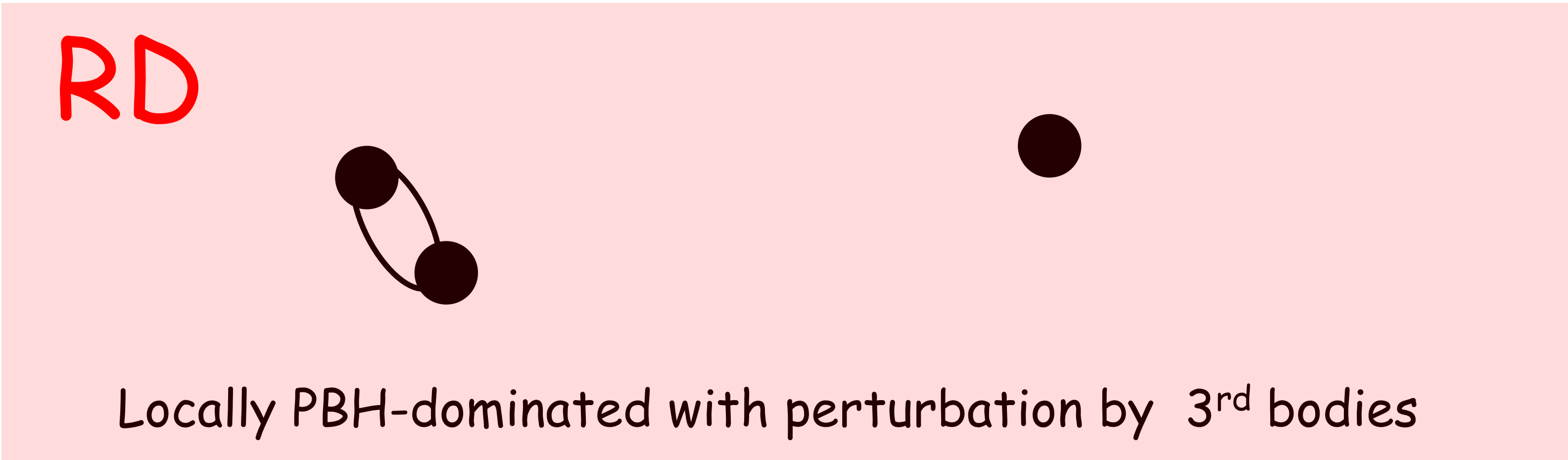


https://www.youtube.com/watch?v=1agm33iEAuo

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

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

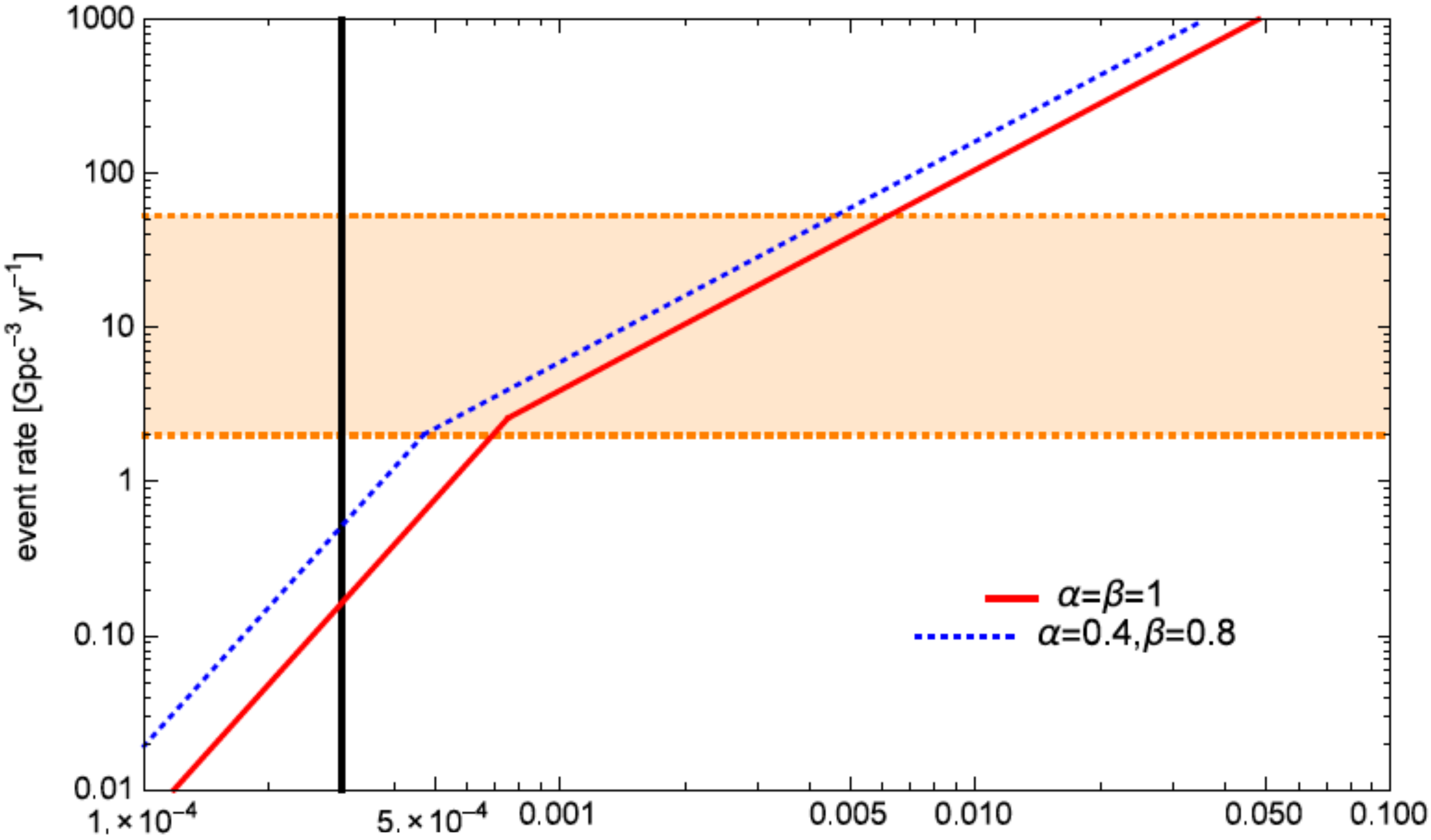
Z.-C. Chen and Q.-G. Huang, Astrophys. J. 864, 61 (2018), 1801.10327

GW150914 and its merger rates for 30 M_{solar} masses BBH

Event rates of Binary BH mergers

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

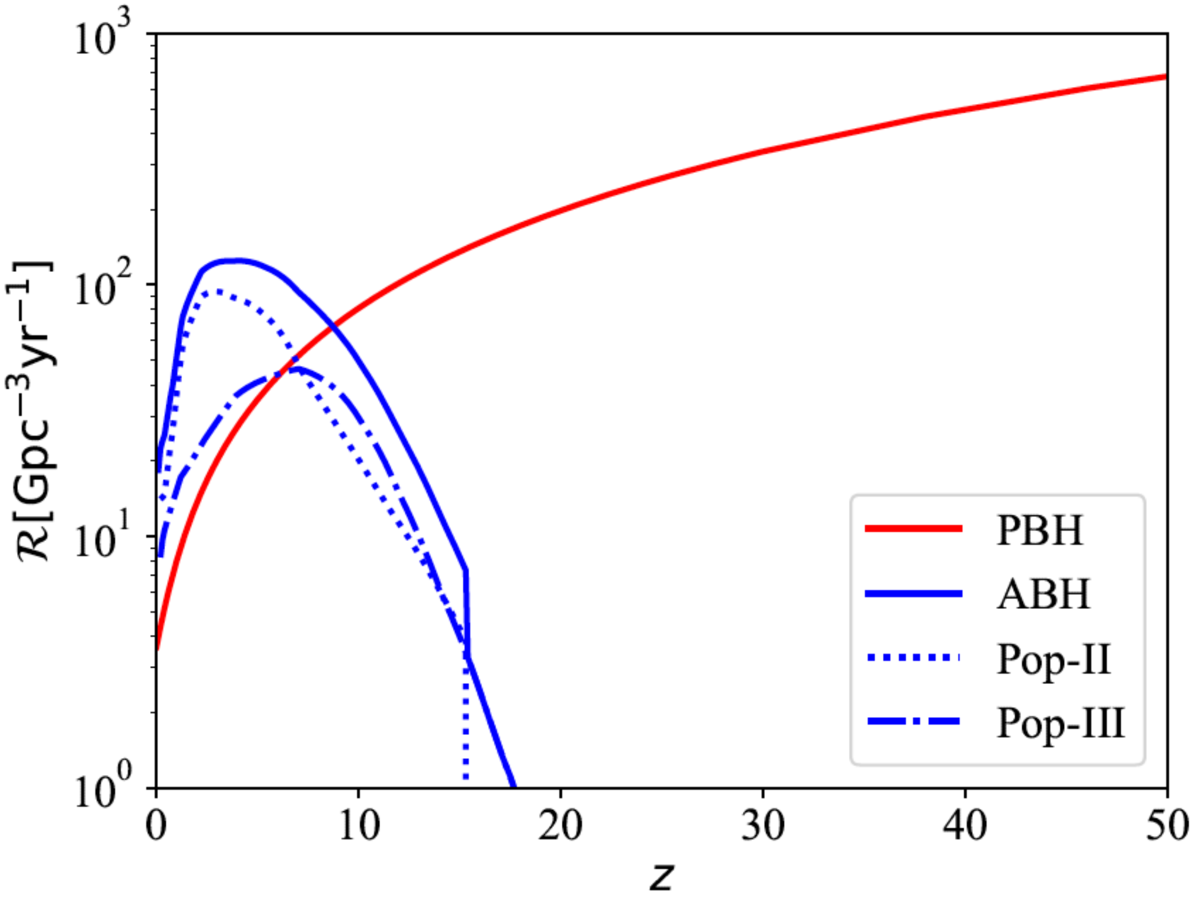
A 3-body effect is important for the BBH formations



Energy fraction of PBHs to CDM (f_{PBH})

DECIGO discriminates BPBHs from the normal BBHs

Sai Wang, Valeri Vardanyan, Kazunori Kohri, arXiv:2107.01935 [gr-qc]

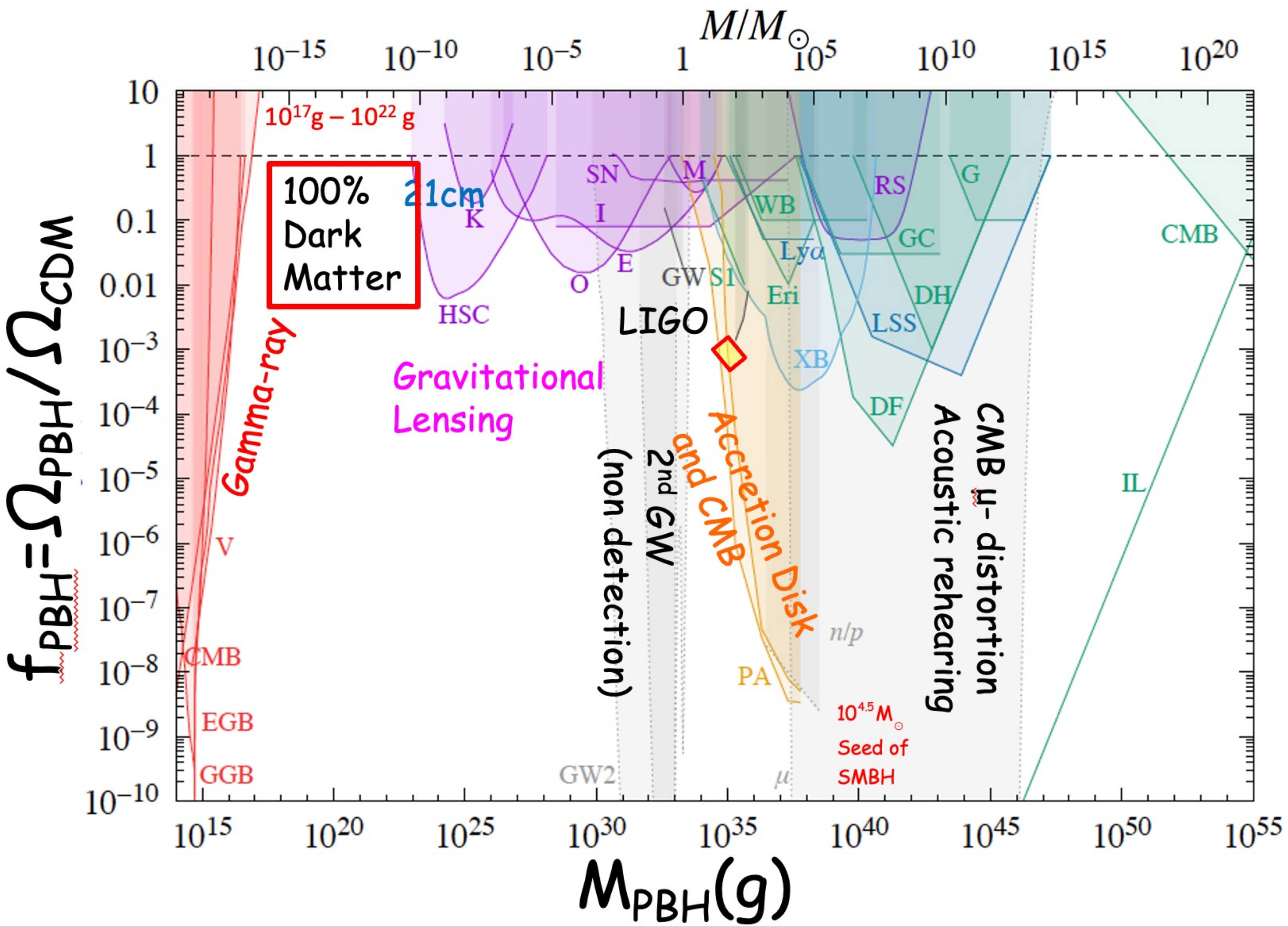


$$1/z \sim \frac{a(t)}{a(t_0)} \sim \left(t/10\mathrm{Gyr}\right)^{2/3}$$

Upper bounds on the fraction to CDM

The original paper, not a review paper

Carr, Kohri, Sendouda, J. Yokoyama, arXiv:2002.12778

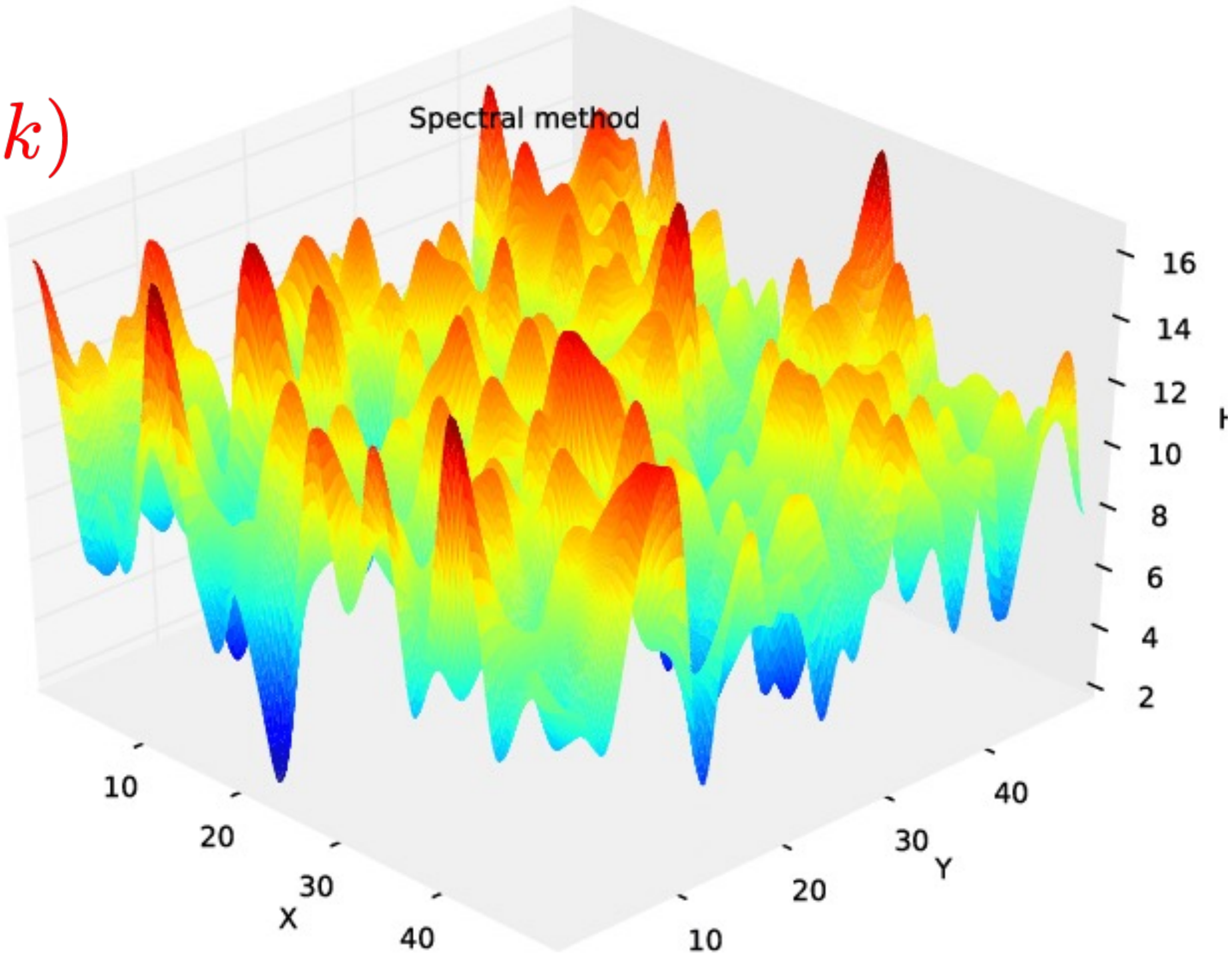


How to produce PBHs?

Spatial density perturbation can be produced by inflation

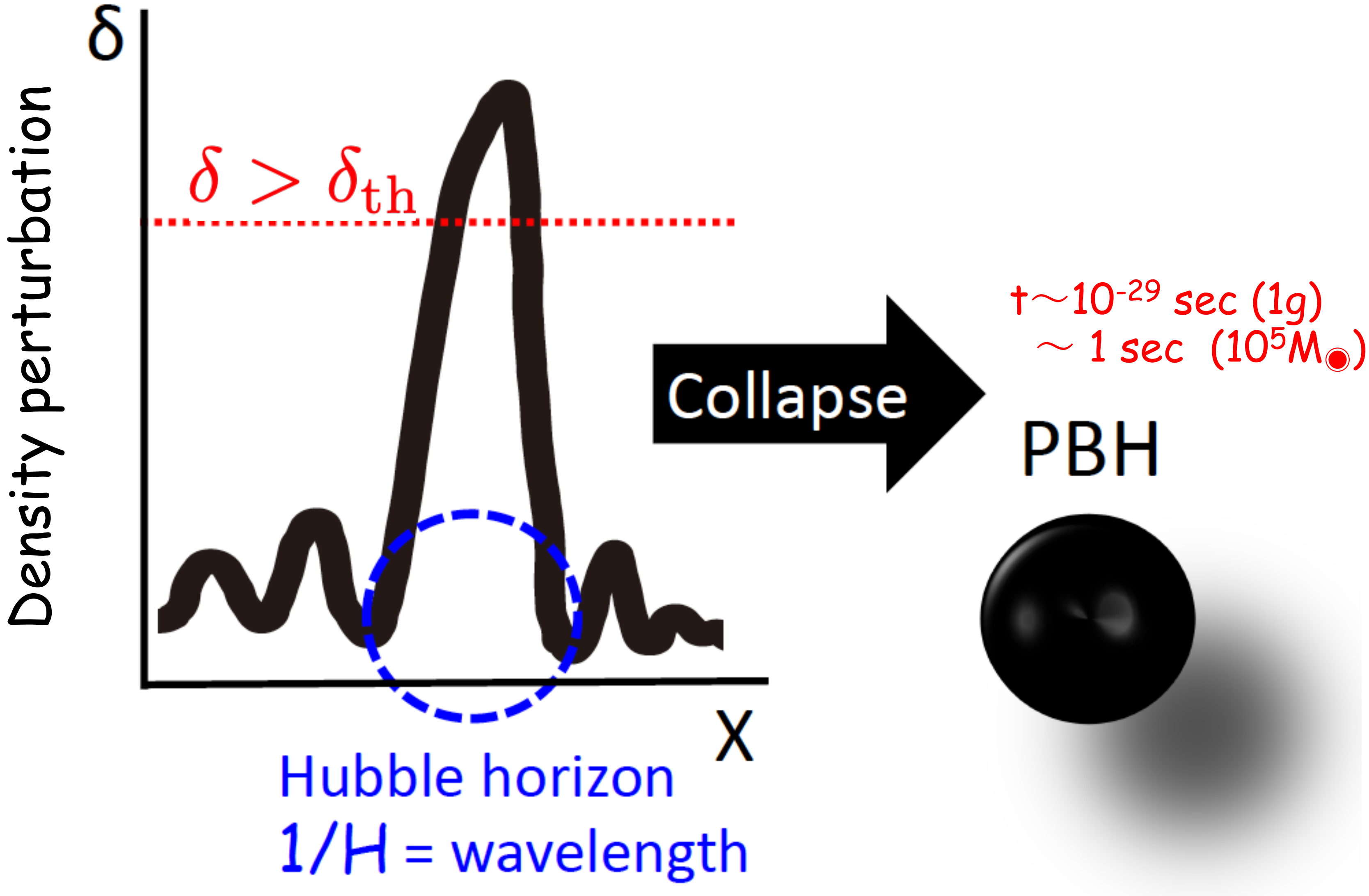
X.H. Dang, B. Sudret, M. Berveiller, 2011

$$\bar{\delta}^2 \sim \mathcal{P}_\zeta(k)$$



Formation by large density perturbation

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



Abundance of PBHs

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

- Gaussian density fluctuation

$$\left.\frac{\rho_{\rm PBH}(M)}{\rho_{\rm tot}}\right|_{\rm form} = \int_{\delta_{\rm th}}^{\infty} d\delta \frac{1}{\sqrt{2\pi\bar{\delta}^2}} \exp\left(-\frac{\delta^2}{2\bar{\delta}^2}\right)$$

$$\simeq \sqrt{\frac{2}{\pi}} \frac{\bar{\delta}}{\delta_{\rm th}} \exp\left(-\frac{\delta_{\rm th}^2}{2\bar{\delta}^2}\right)$$

$$= 1.5 \times 10^{-18} \left(\frac{m_{\rm PBH}}{10^{15} g}\right)^{1/2} \left(\frac{\Omega_{\rm PBH} h^2}{0.1}\right)$$

$$\bar{\delta}^2 \sim \mathcal{P}_\zeta(k)$$

The better one is Peak Statistics, see Yoo, Harada, Garriga, Kohri (2018)

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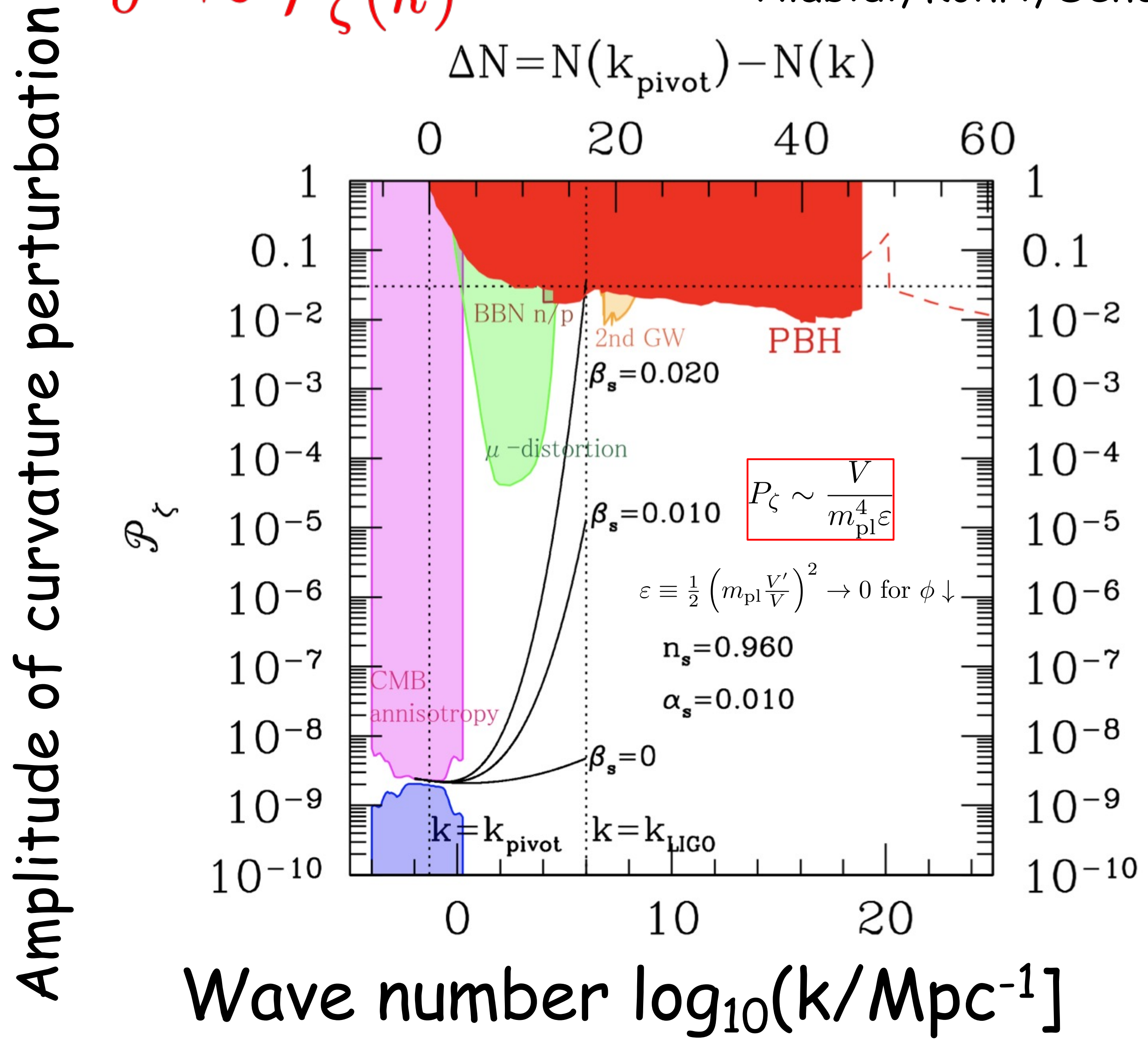
The 2026 (The 31th) Outstanding Paper Award of JPS

Curvature perturbation $P_\zeta(k)$

Kohri and T.Terada, 2018
Alabidi, Kohri, Sendouda, Sasaki, 2013

$\bar{\delta}^2 \sim \mathcal{P}_\zeta(k)$



$P_\zeta \sim \frac{V}{m_{pl}^4 \varepsilon}$

$\varepsilon \equiv \frac{1}{2}\left(m_{pl}\frac{V'}{V}\right)^2 \to 0$ for $\phi \downarrow$

Planck (2018)

$n_s = 0.9586 \pm 0.0056,$

$\alpha_s = 0.009 \pm 0.010,$

$\beta_s = 0.025 \pm 0.013.$

at 68% C.L.

$k = p \times a$

Typical quantities of PBHs

- Lifetime

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

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

- Mass (horizon mass = $\rho H^{-3} = m_{pl}^2 t_{form}$ at $t=t_{form}$)

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

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

- Hawking Temperature

$$T_{\rm PBH} \sim \frac{M_{pl}^2}{M_{\rm PBH}} \sim 10{\rm MeV}\left(\frac{M_{\rm PBH}}{10^{15}{\rm g}}\right)^{-1} \sim 0.1{\rm MeV}\left(\frac{M_{\rm PBH}}{10^{17}{\rm g}}\right)^{-1}$$

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

Multi-field inflation models

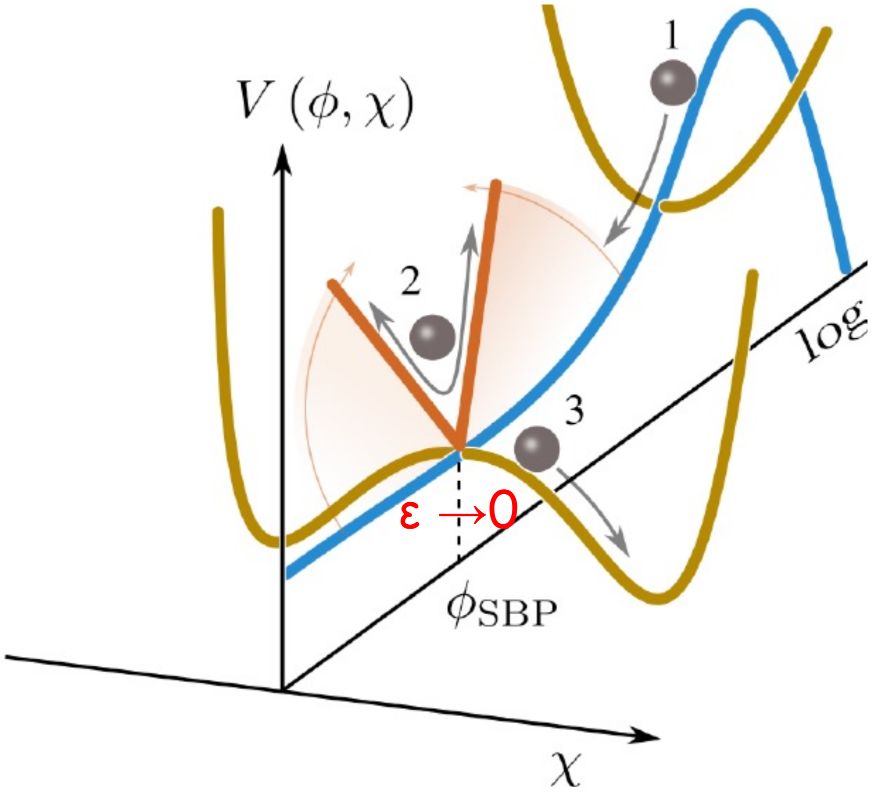
to enhance curvature perturbation at small scales

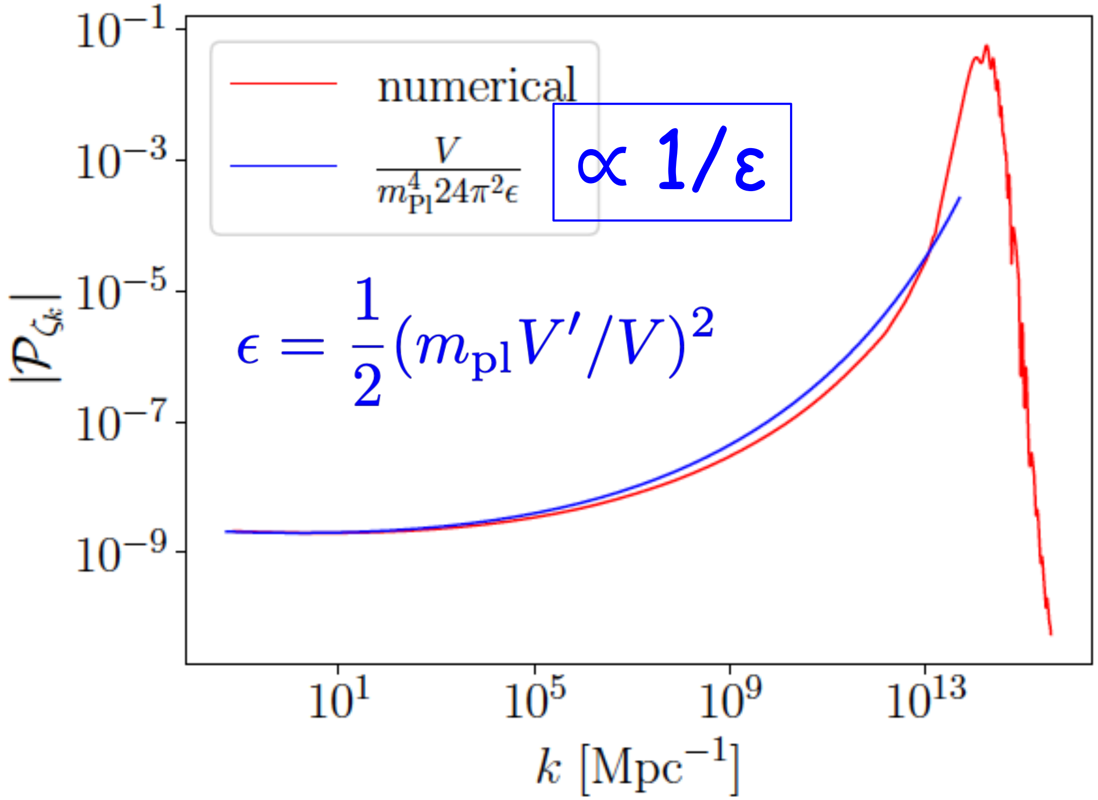
Yuma S. Furuta, Mindaugas Karčiauskas, Kazunori Kohri, Alejandro Sáez,
arXiv:2511.23182 [astro-ph.CO]

$$U(\phi) \equiv -\frac{1}{2}\frac{\phi^2}{m_{\rm Pl}^2}\left(B - \frac{A}{\left(1+\alpha \ln\frac{\phi}{m_{\rm Pl}}\right)^2}\right)$$

$$\bar{\delta}^2 \sim \mathcal{P}_\zeta(k)$$

Shirp peak





$$V(\chi) = -\frac{1}{2}m^2\chi^2 + \lambda\chi^4$$

Multi-field inflation models

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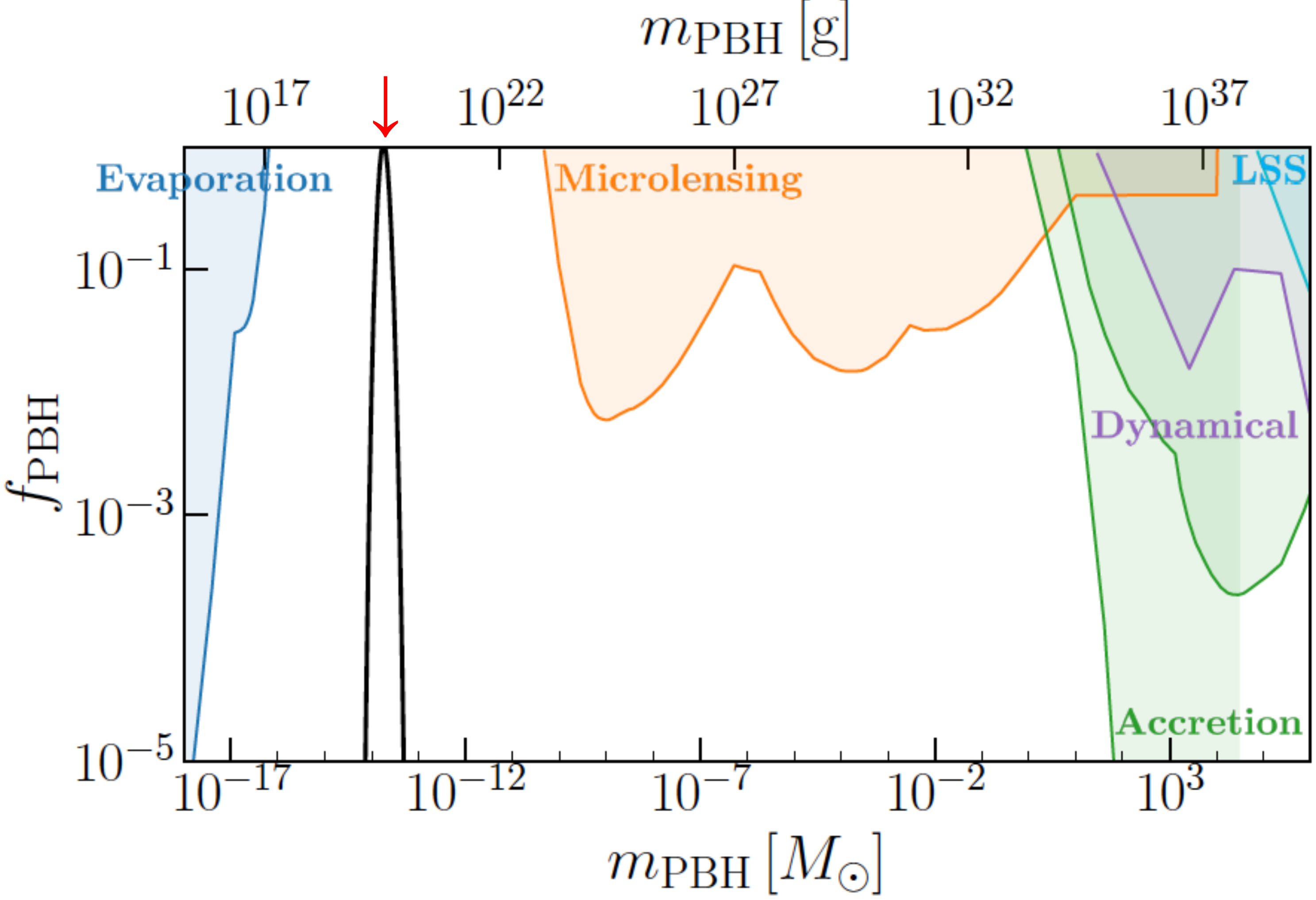
Yuma S. Furuta, Mindaugas Karčiauskas, Kazunori Kohri, Alejandro Sáez,
arXiv:2511.23182 [astro-ph.CO]

The sharp log-normal dist. of $P_\zeta(k)$



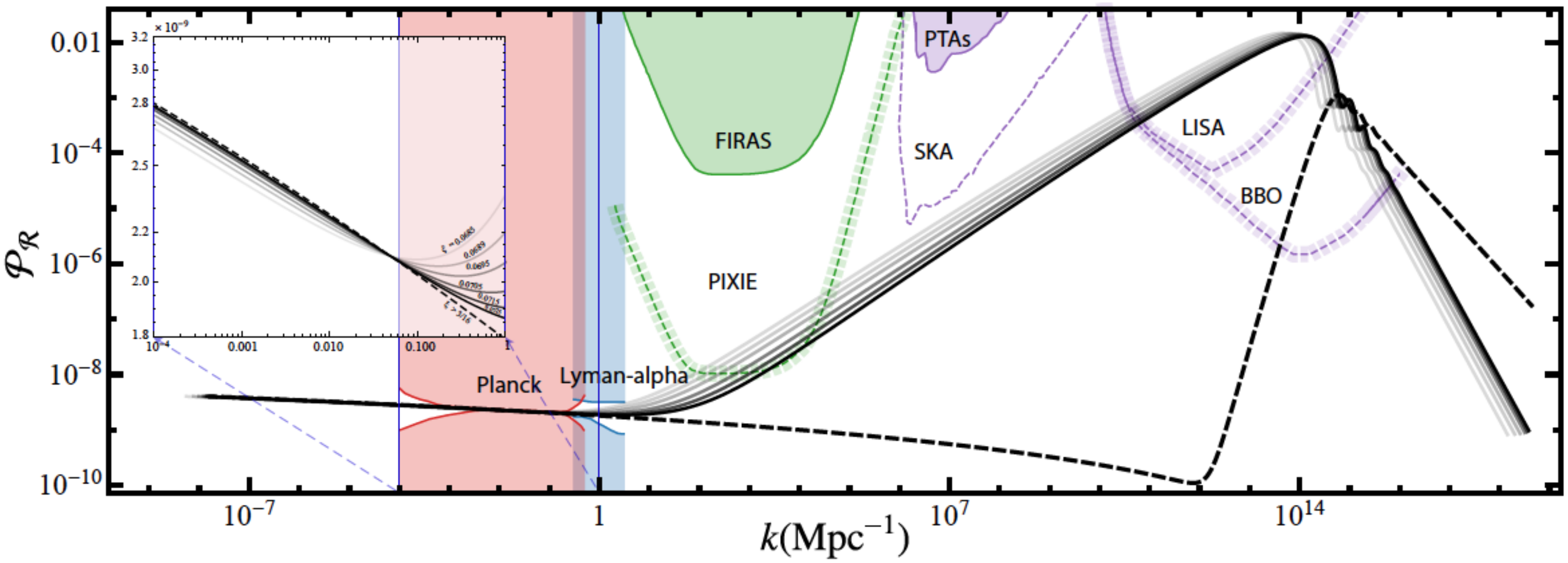
R^2 + Higgs inflation fits ACT spectral index

Kazunori Kohri, Xinpeng Wang, Tsutomu T. Yanagida, arXiv:2506.06797 [astro-ph.CO]

$$S_J = \int d^4x\sqrt{-g}\left[\frac{M_{\rm pl}^2}{2}f(R,\chi) - \frac{1}{2}g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi - V(\chi)\right],$$

$$f(R,\chi) = R + \frac{R^2}{6M^2} - \frac{\xi R}{M_{\rm pl}^2}(\chi-\chi_0)^2,$$

$$V(\chi) = \frac{1}{4}\lambda(\chi^2 - m^2)^2.$$

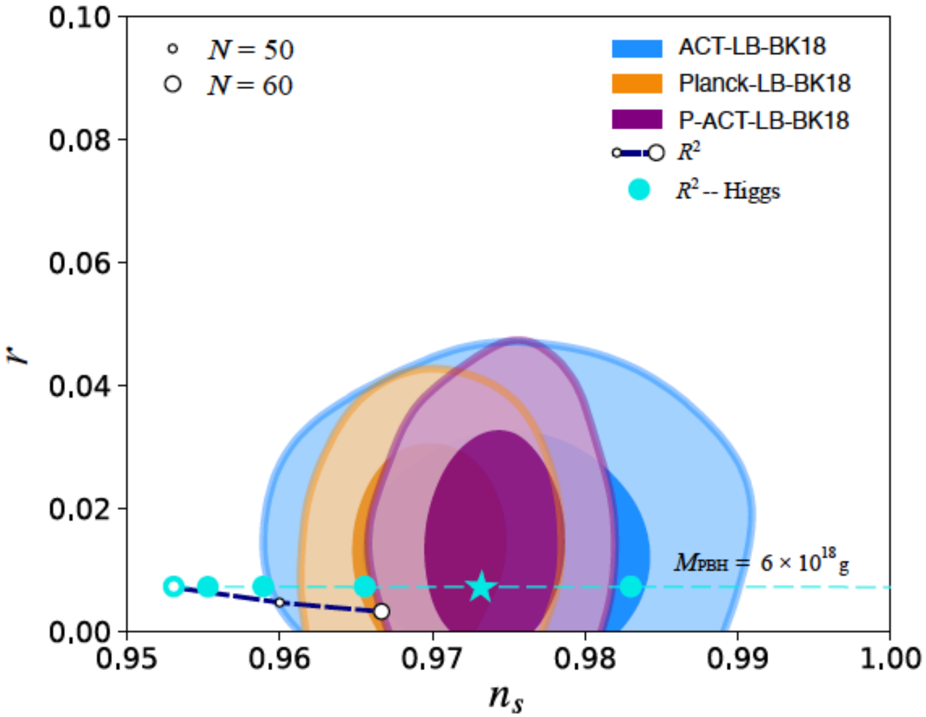


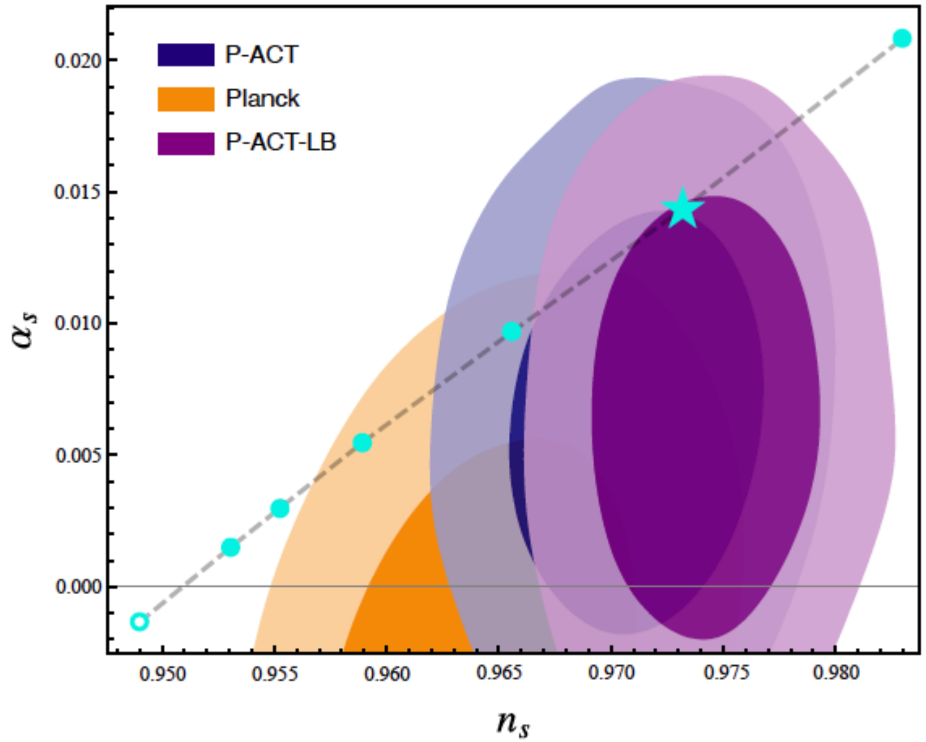
R^2 + Higgs inflation fits ACT spectral index

Kazunori Kohri, Xinpeng Wang, Tsutomu T. Yanagida, arXiv:2506.06797 [astro-ph.CO]

- Large spectral index n_s ~0.98

- Positive running α_s ~ O(+0.01)





Observational constraints

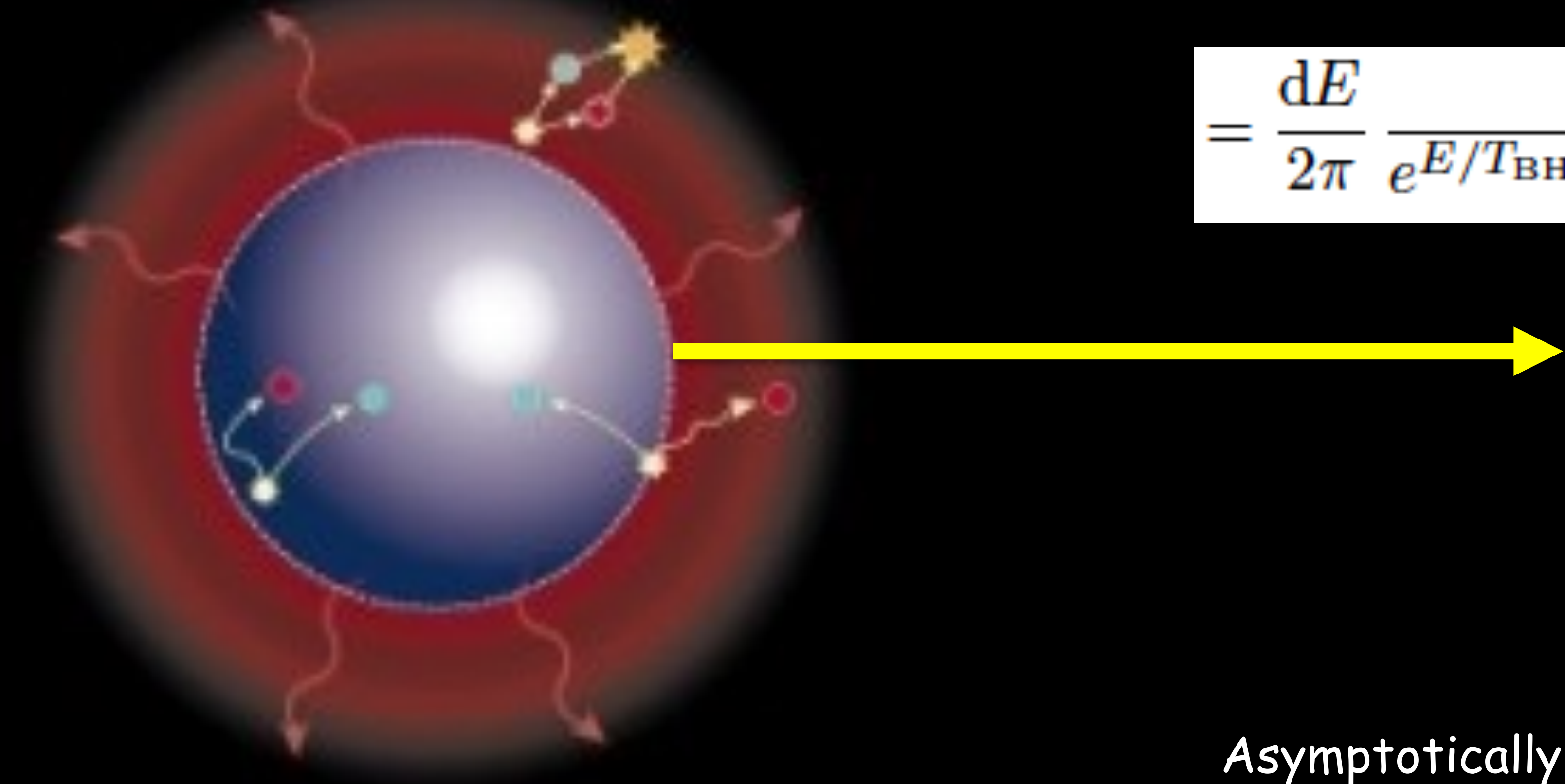
- Gamma-ray observation
- Gravitational Lensing
- Induced Gravitational Wave (future observations)
- Merger Gravitational Wave (future observations)
- Neutrino observation (future observations)
- …

Hawking evaporation through quantum mechanics

S.W. Hawking, 1974

$$\mathrm{N}_{\mathrm{Quantum}} = \left| \langle \mathrm{vac}\, 1 | a^{\dagger} a |\, \mathrm{vac}\, 1 \rangle \right|^2 = \left| \beta_{\mathrm{Bogoliubov}} \right|^2$$

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



Asymptotically flat

Blackhole

$|\mathrm{vac}>_{\mathrm{StrongGravity}}$

$|\mathrm{vac}>_{\mathrm{Minkowski}}$

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

Observational constraints

Observational bounds on Evaporating PBHs through Hawking Process

Carr, Kohri, Sendouda, J.Yokoyama (2010)(2021)

- Extragalactic and galactic gamma-rays/neutrinos

  ~~MeV thermal spectrum with a gray-body factor~~

- CMB

  ~~Heated plasma changes the recombination history~~

- Cosmological 21cm line

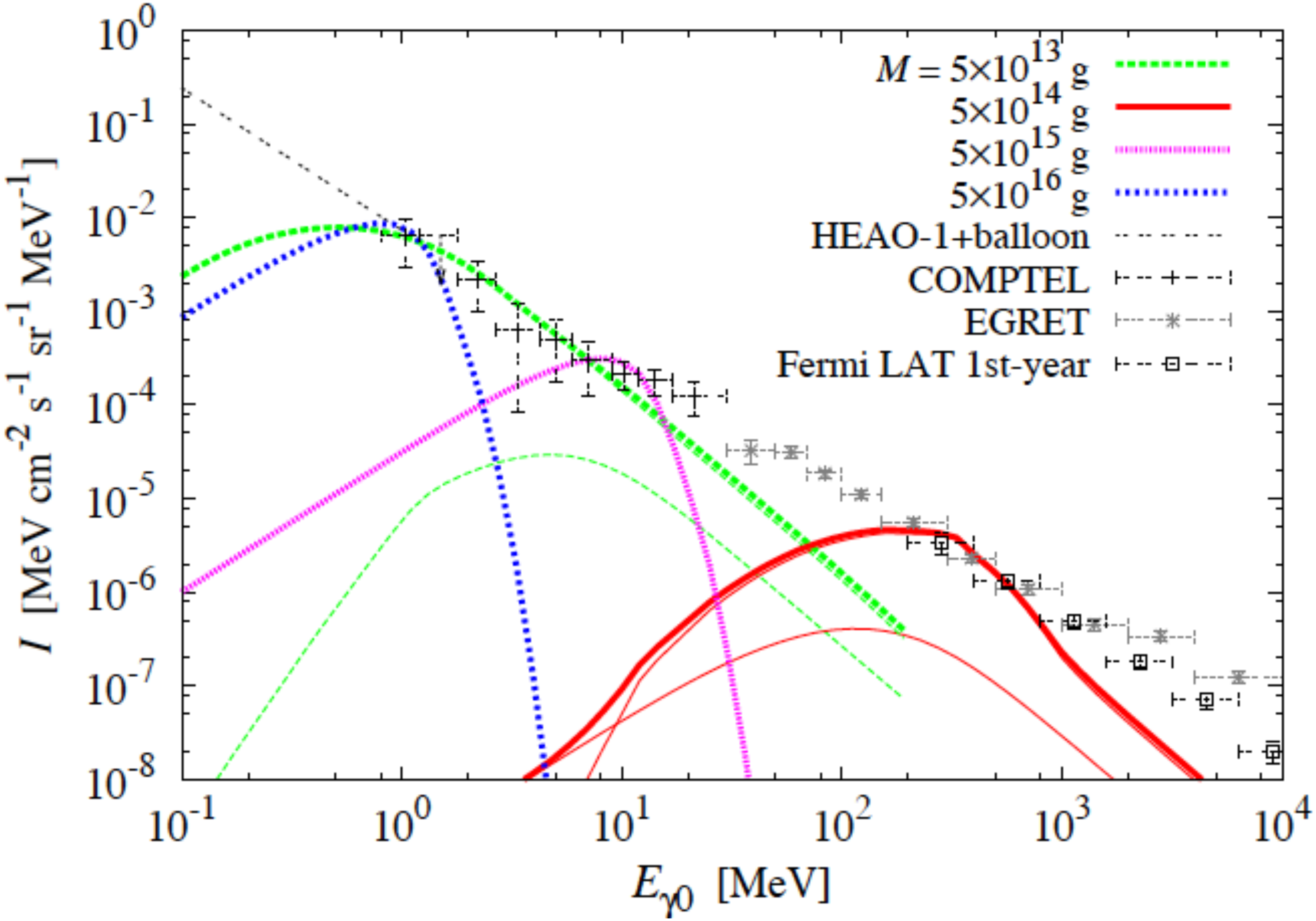
  ~~Heated baryon can emit 21cm line~~

- BBN

  ~~Hadron emission changes n/p and neutrino distribution, and destroy He4 with copiously producing D, He3, …~~

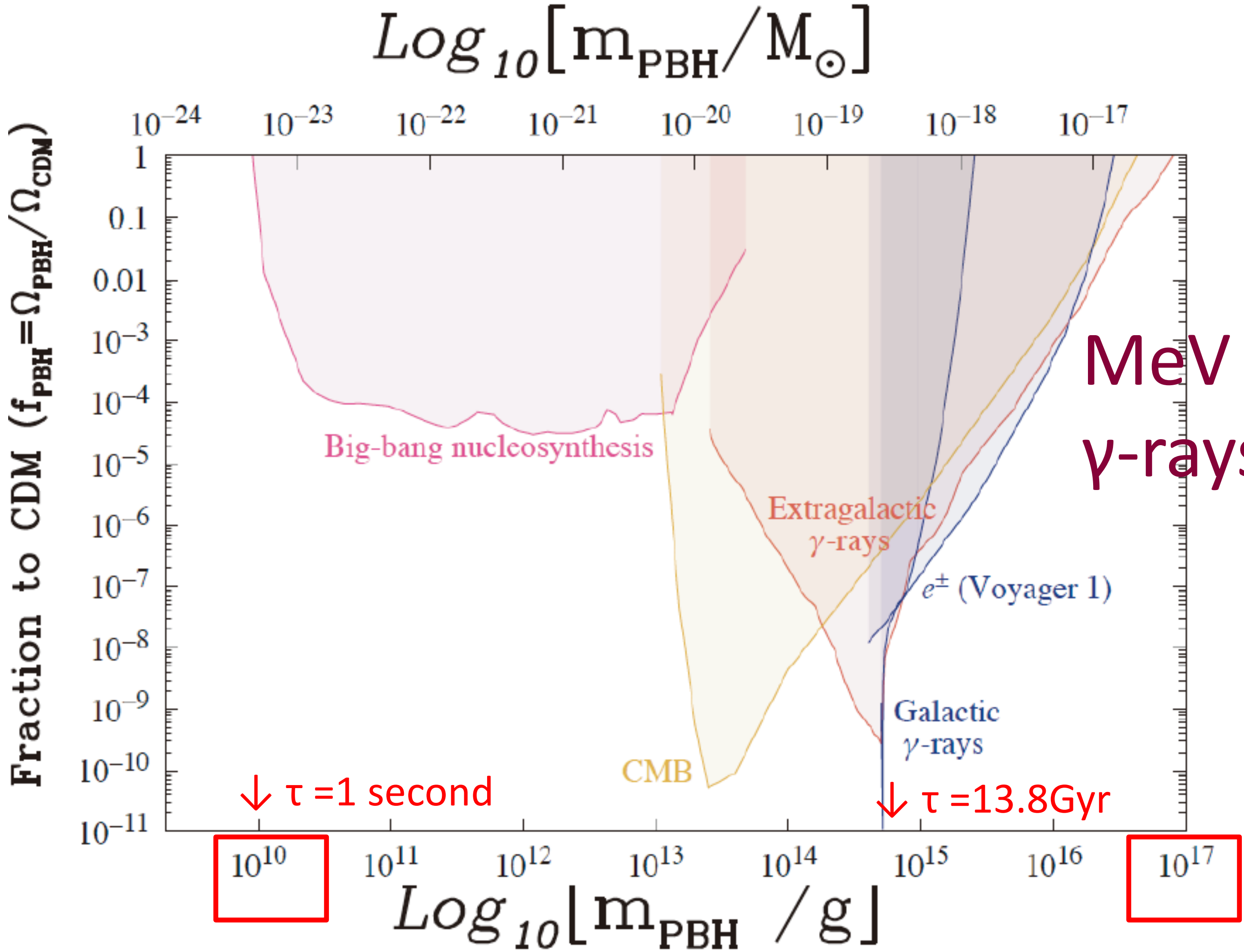
Evaporating PBHs through Hawking Process

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



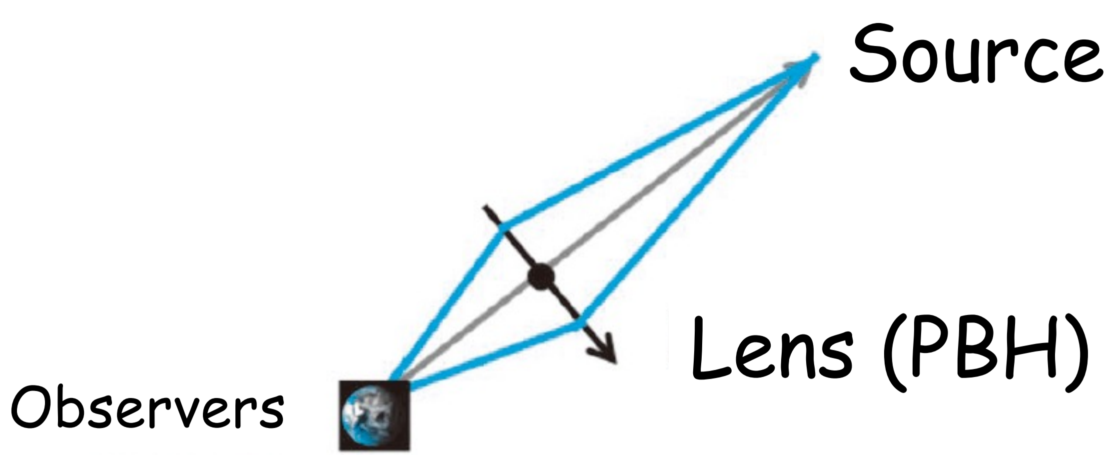
BBN, CMB, γ-ray bounds on PBHs

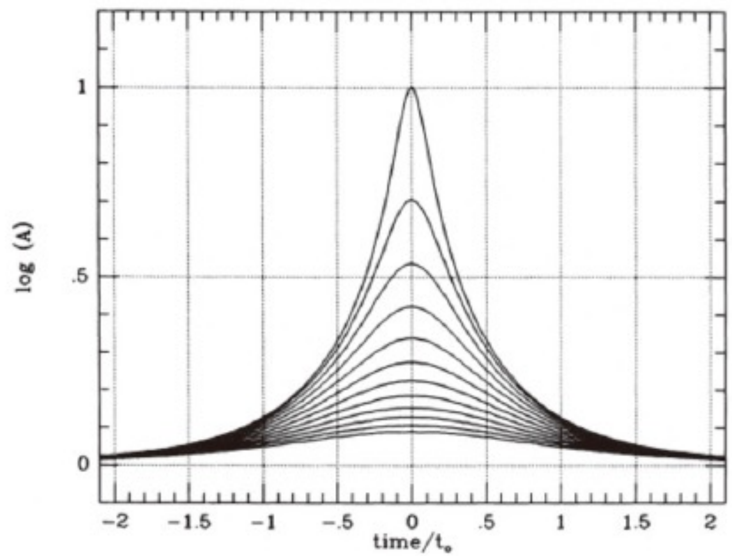
The original, not a review, Carr, Kohri, Sendouda, J.Yokoyama, arXiv:2002.12778



MeV galactic γ-rays

Gravitational Lensing

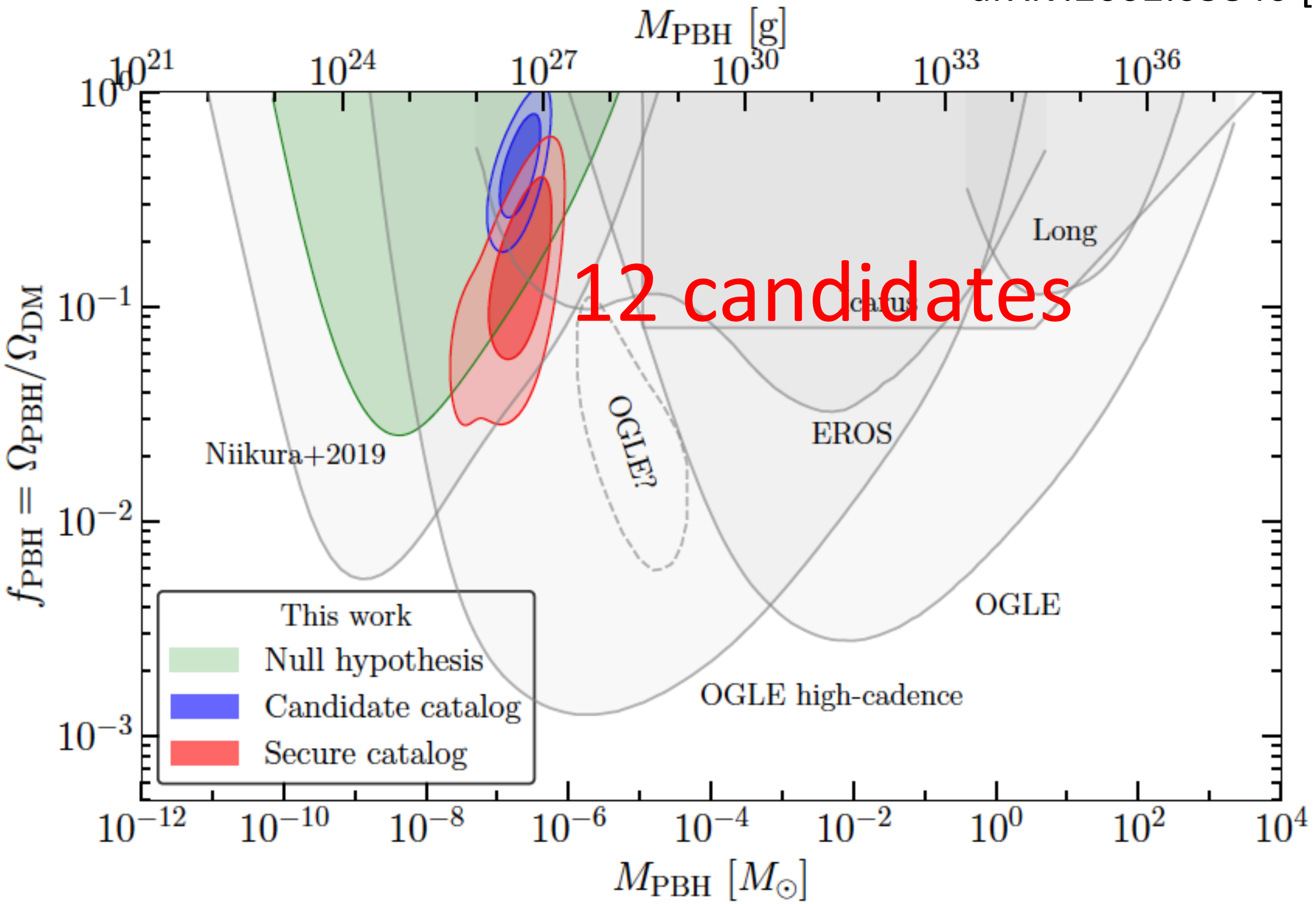




Hiroko Niikura, https://stg.asj.or.jp/jp/activities/geppou/item/113-1_6.pdf

Gravitational Lensing bounds on PBH towards Andromeda M31

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



Future observational tests

Induced gravitational wave

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 x Scalar → Tensor

- Induced gravitational wave by perturbation

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

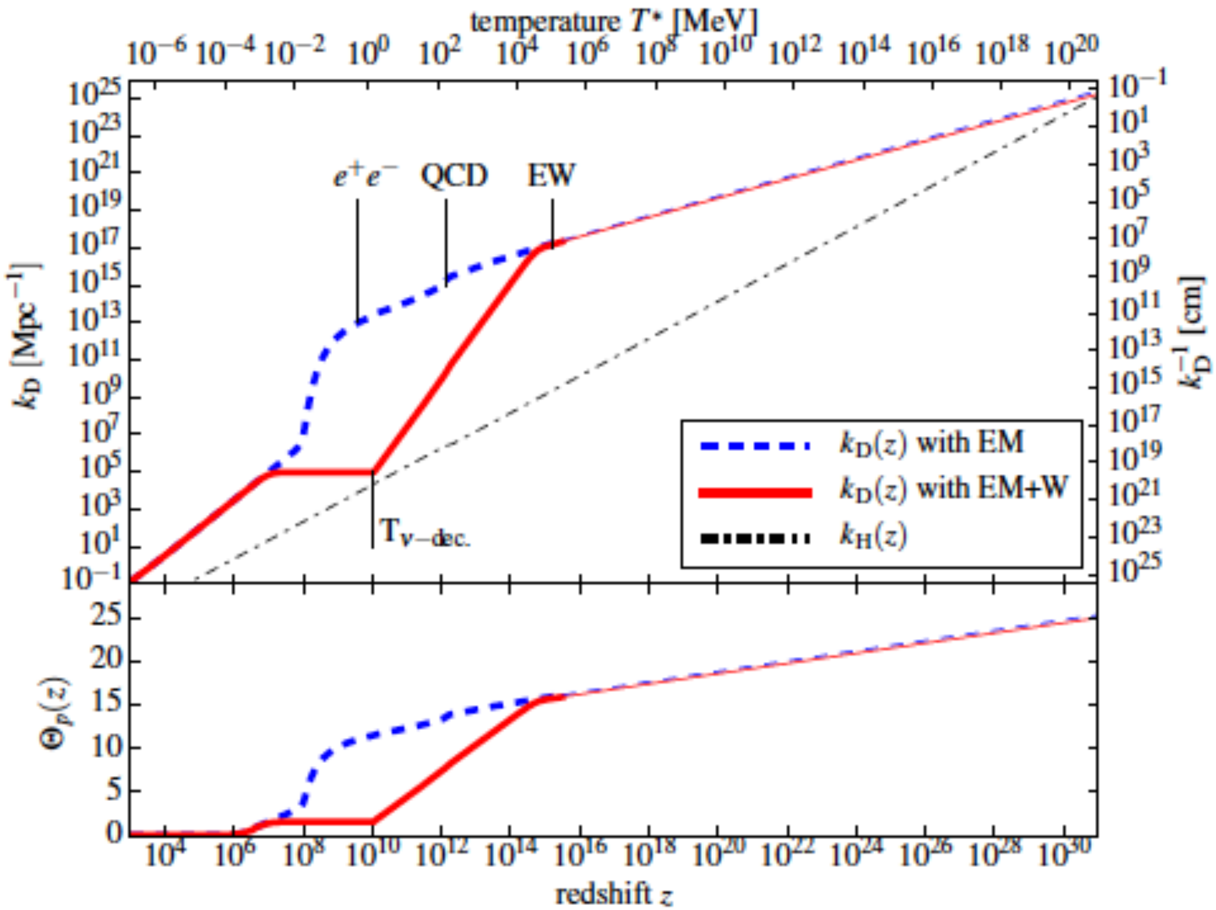
$\delta^2 \quad \times \quad \delta^2$

Acoustic reheating and dissipation

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

Jeong,Kamionkowksi, Chluba and Pradler (2014)
Nakama, Suyama, Yokoyama (2014)
Inomata, Tada, Kawasaki (2016)

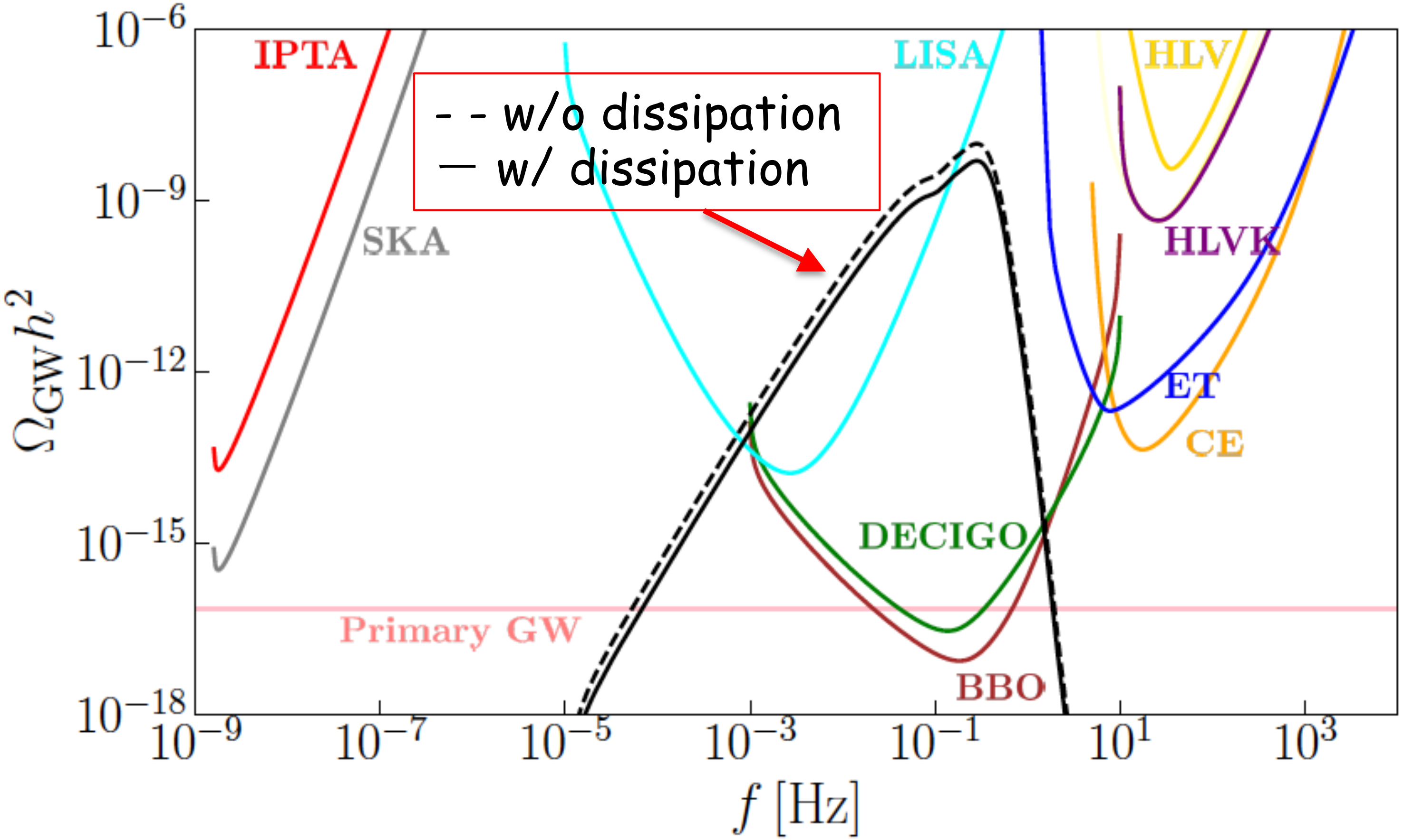
Diffusion scale



Induced GWs with dissipation to test dark matter PBHs with 10^{17}g – 10^{23}g

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

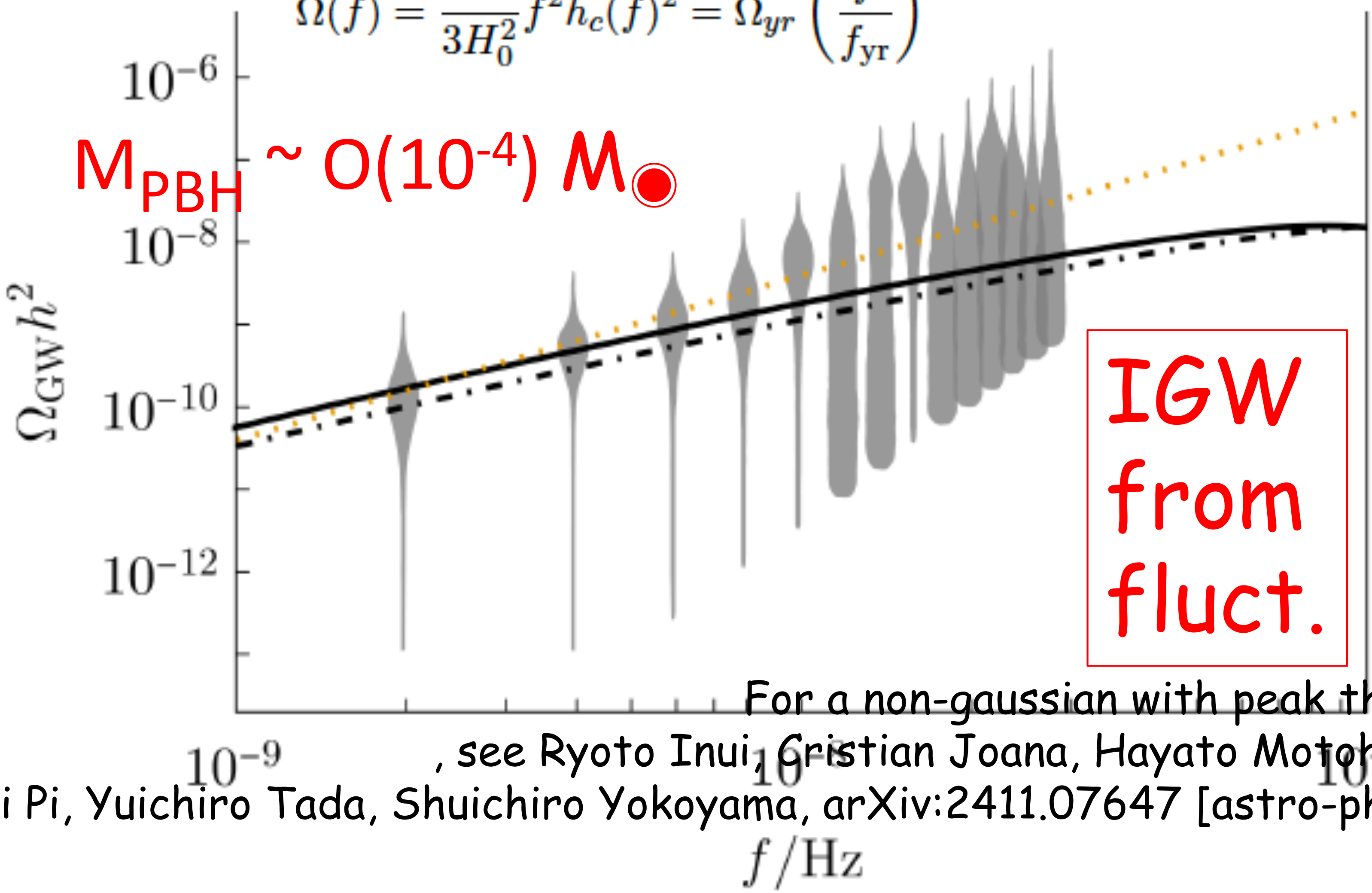
Y.S. Furuta, M. Karciauskas, K. Kohri and A. Saez, 2025, arXiv:2512.XXXXX to appear



NANOGrav15yr by Induced GW and sub-solar PBHs

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

$$\Omega(f) = \frac{2\pi}{3H_0^2} f^2 h_c(f)^2 = \Omega_{yr} \left(\frac{f}{f_{yr}}\right)^{\beta}$$



M_{PBH} ~ $O(10^{-4})$ $M_{\odot}$

β=2 (γ=3) for

P_ζ~δ-func (→β~2)

A braod P_ζ (→β~3) .

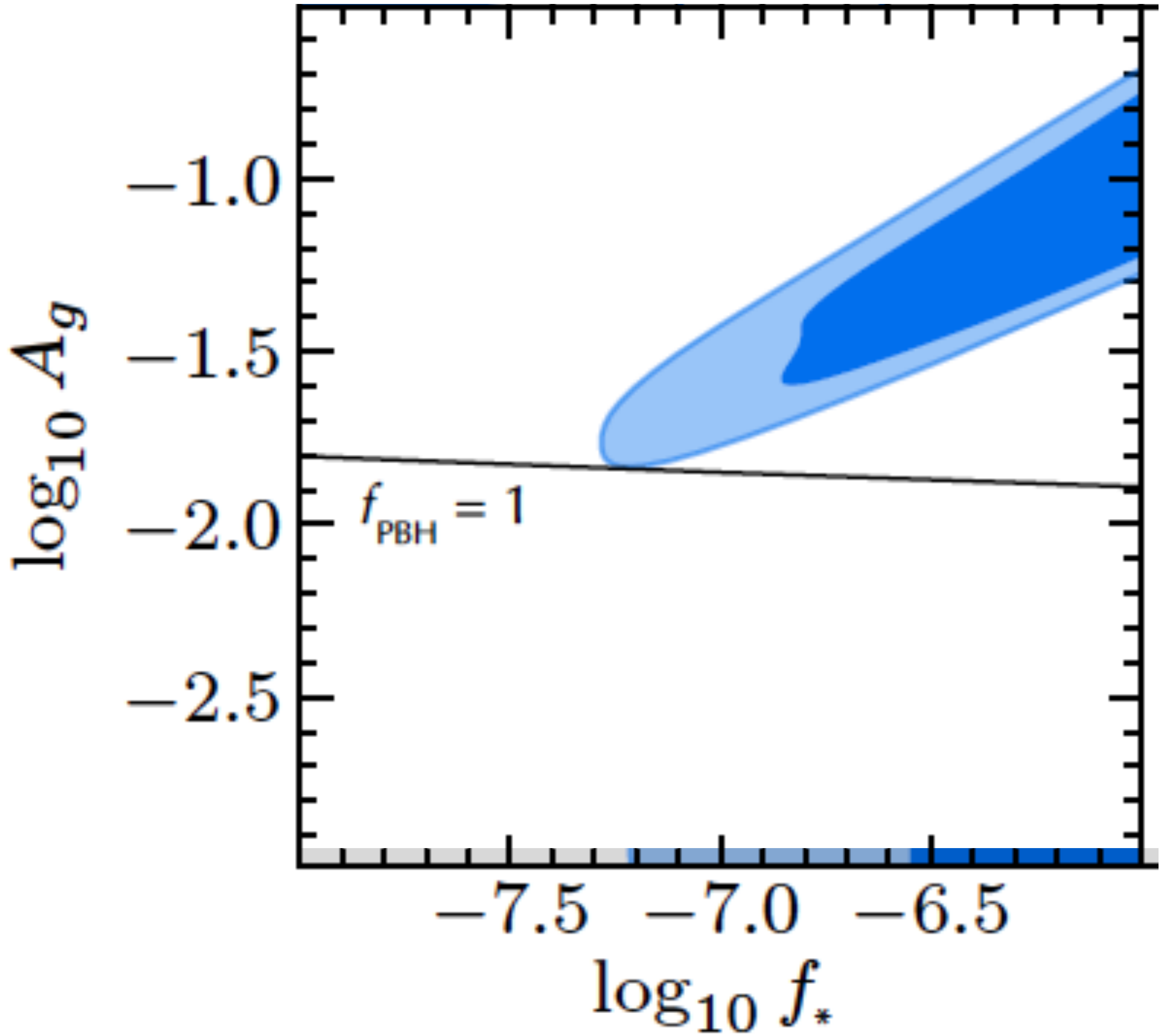
Gaussian ζ

IGW from fluct.

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

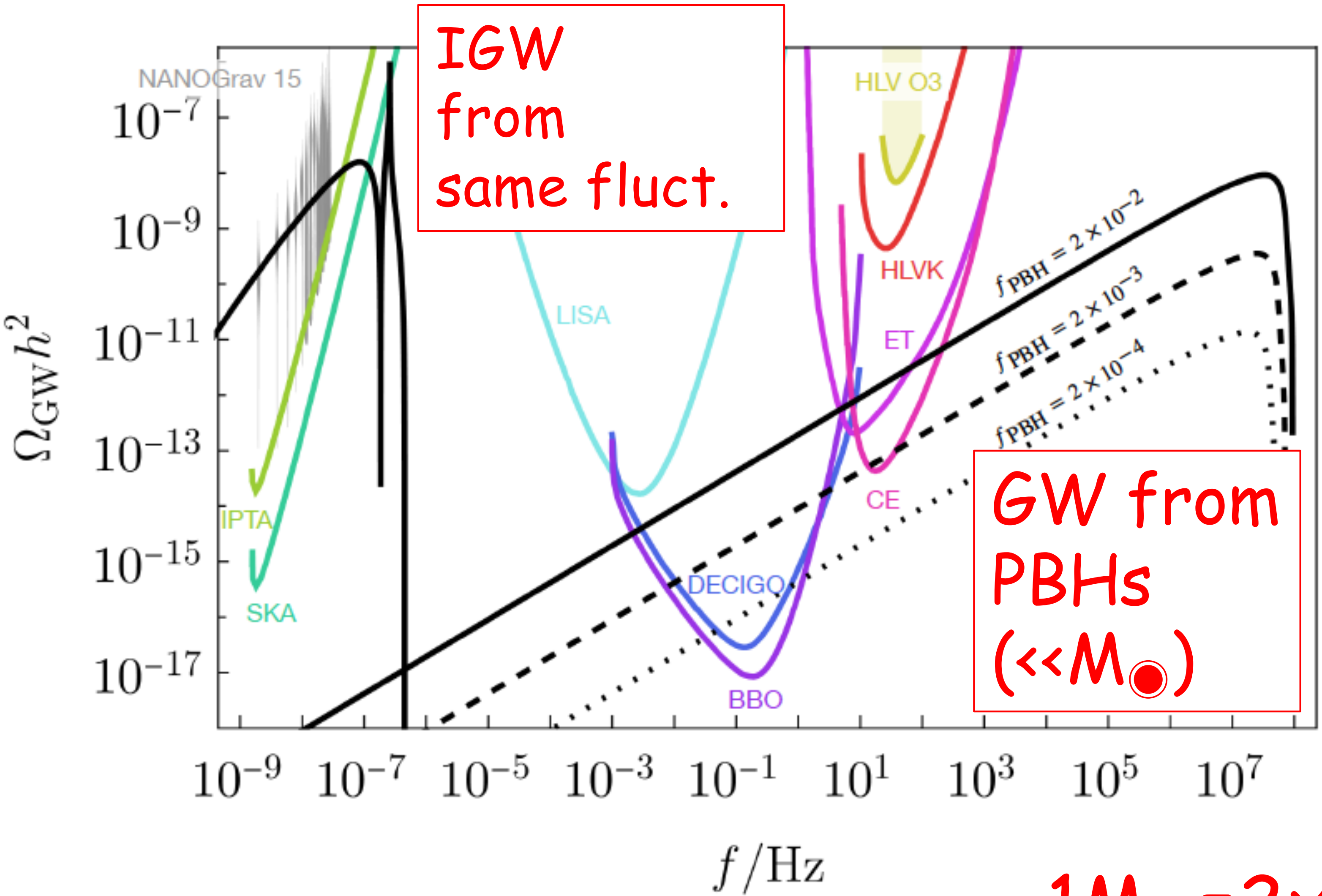
Peak theory + non-gaussianity?

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]



NANOGrav15yr by Induced GW and sub-solar PBHs

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



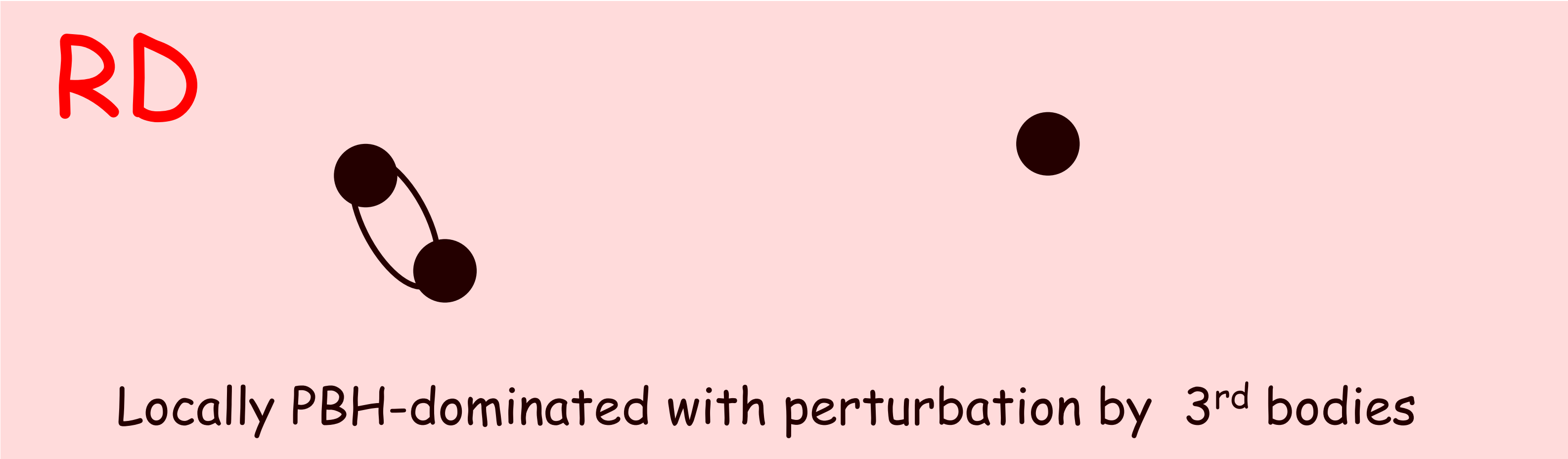
$1M_\odot = 2\times10^{33}$g

Merger gravitational wave

Binary formations of PBHs in the radiation dominated epoch

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

- Three body effects are important



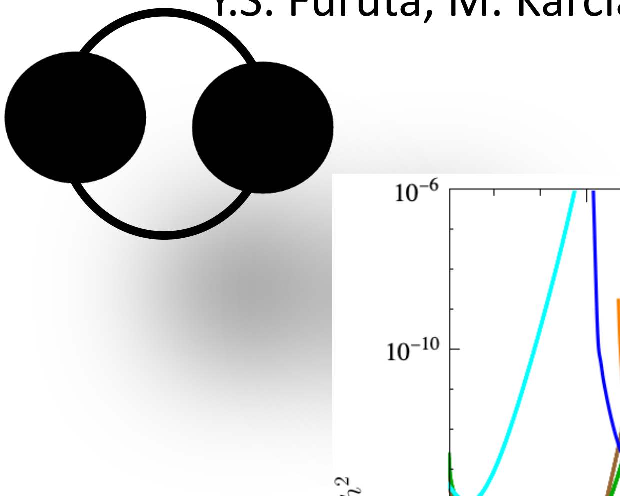
- Formation rate

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

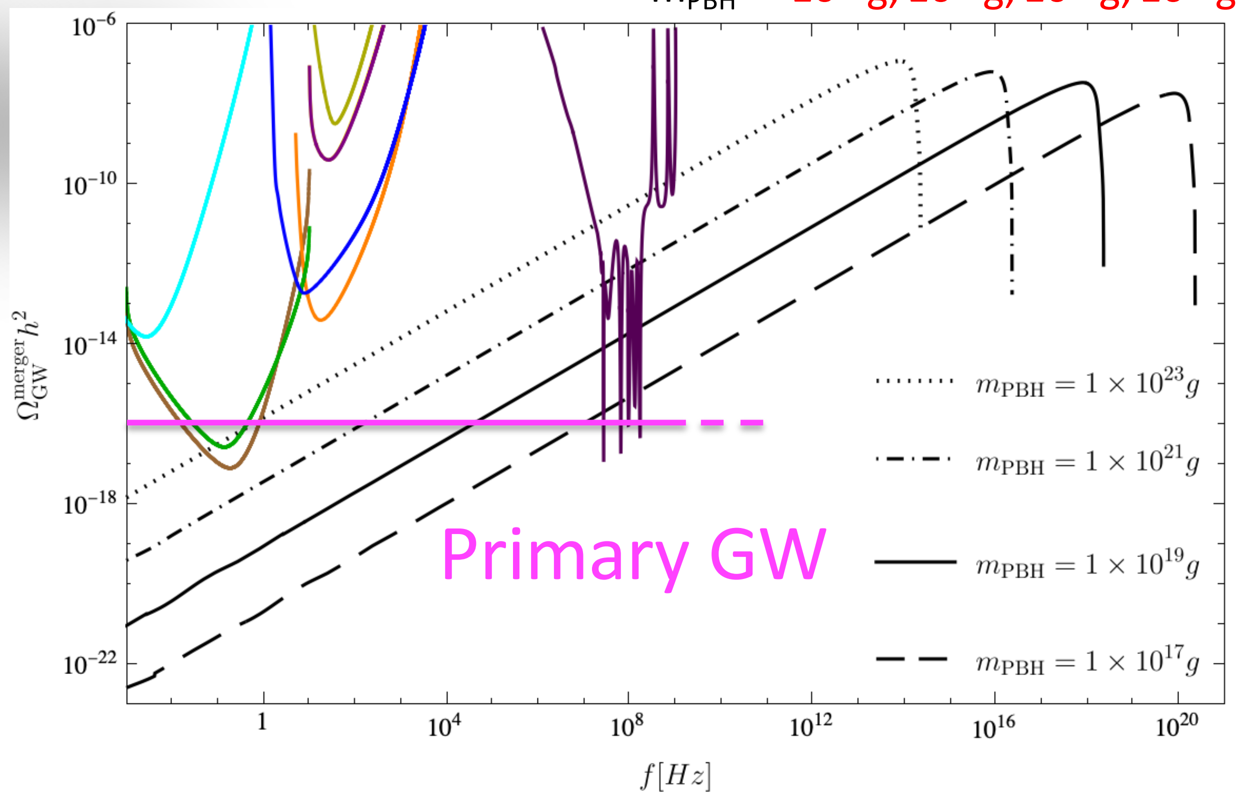
Z.-C. Chen and Q.-G. Huang, Astrophys. J. 864, 61 (2018), 1801.10327

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



m_{PBH} = 10^{23}g, 10^{21}g, 10^{19}g, 10^{17}g



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

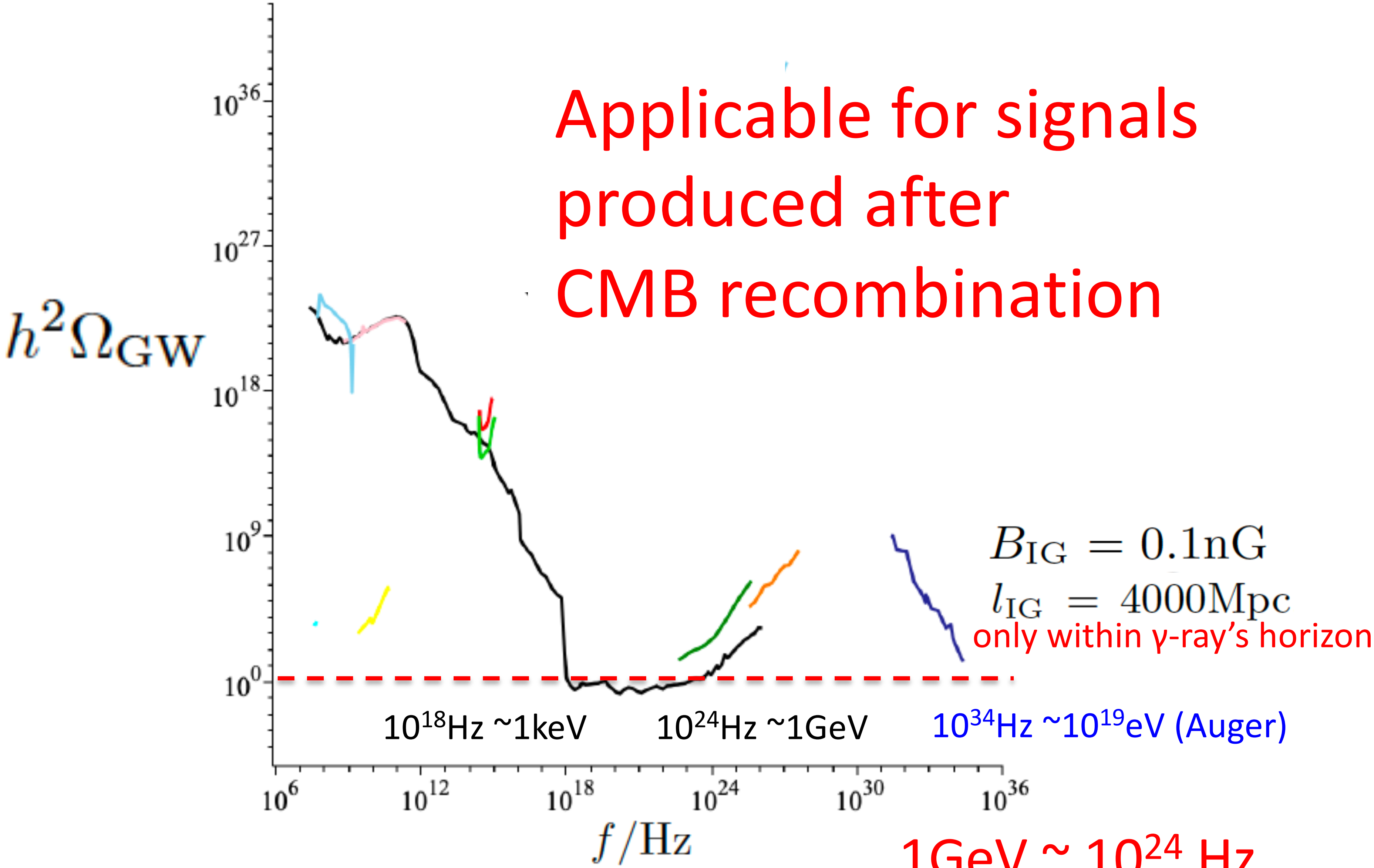
$$S = \int d^4x \sqrt{-g}\left[\frac{M_{\rm pl}^2}{2}R - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}\right]$$

GW + B → γ

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

Gravitational wave search through electromagnetic telescopes

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

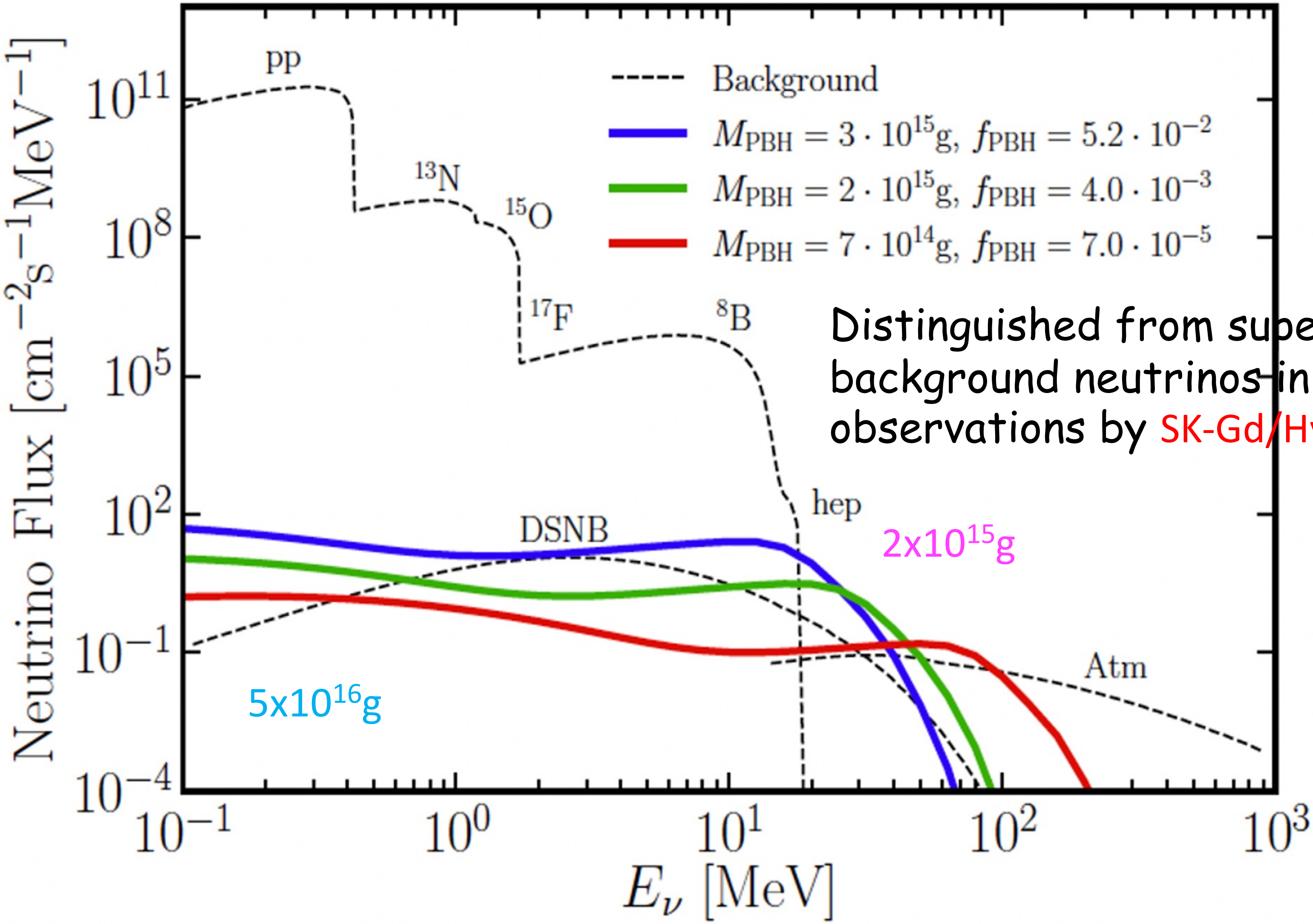


1GeV ~ 10^{24} Hz

MeV neutrinos by Hyper-Kamiokande

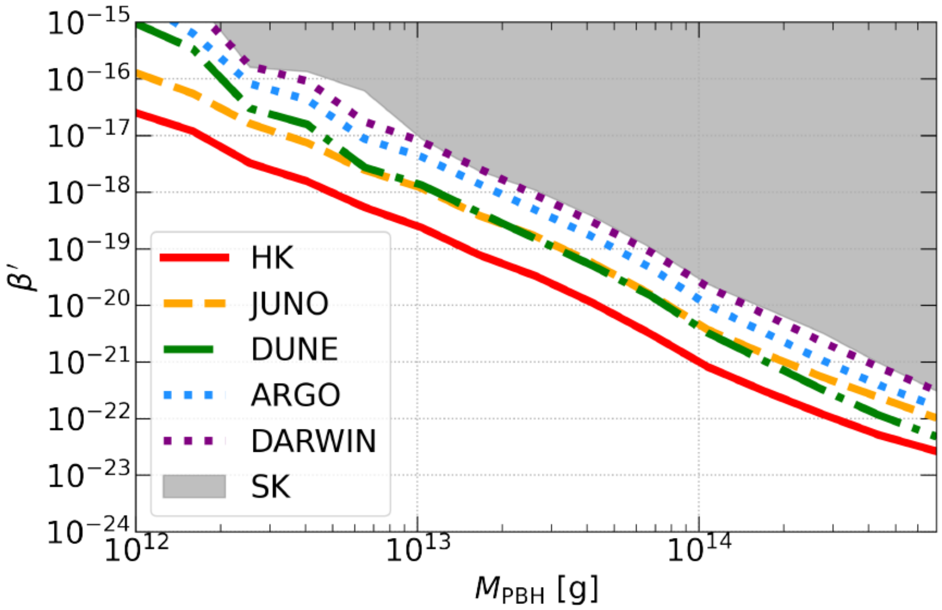
MeV neutrino by evaporating PBHs

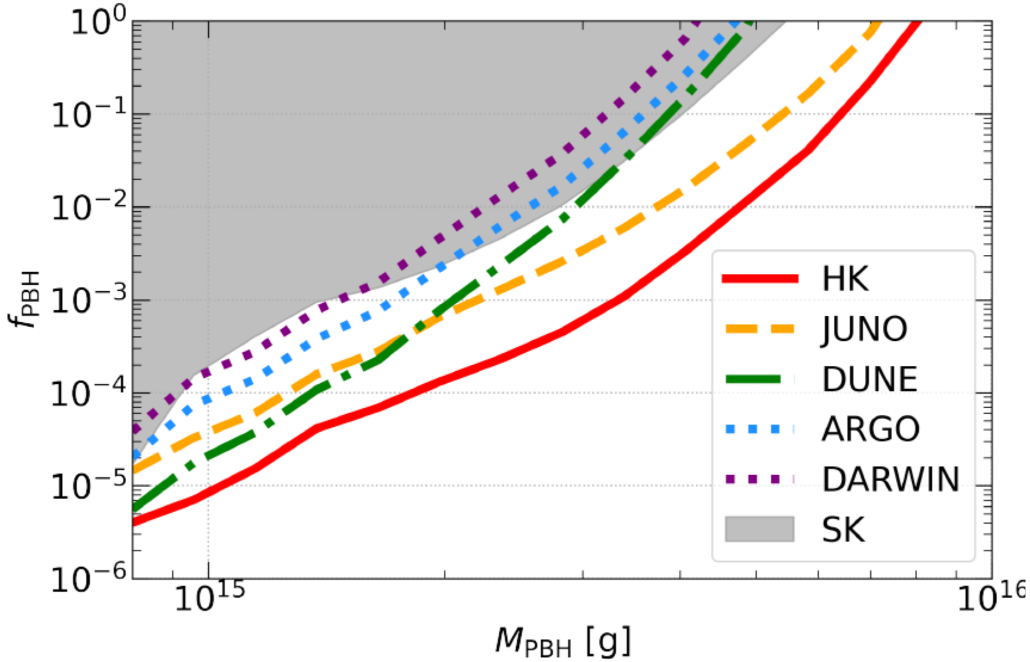
R. Calabrese et al, arXiv:2106.02492



Future bounds on evaporating PBHs through neutrino emissions

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





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]

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

k=2

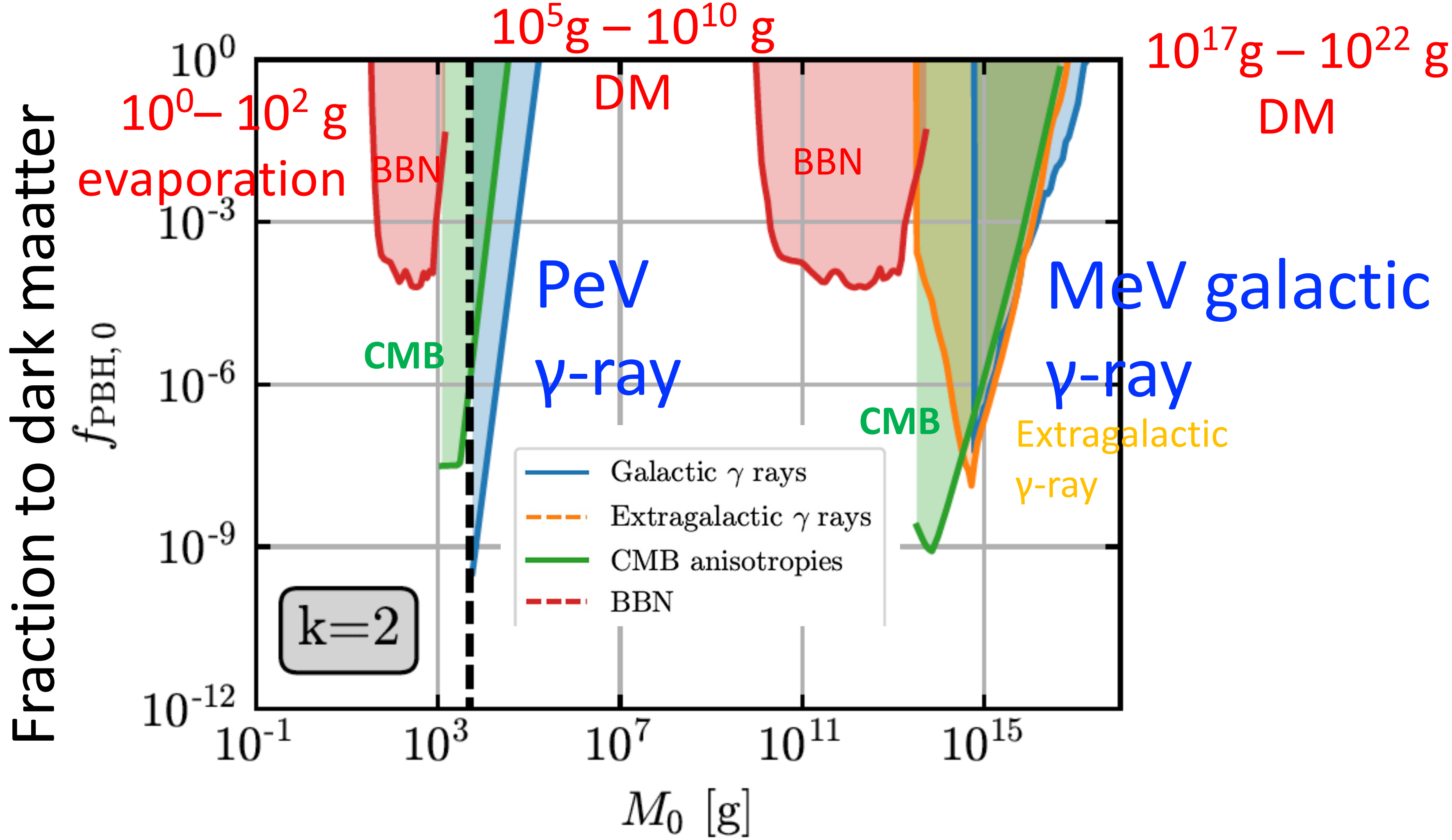
$$S = \frac{4\pi M^2 G}{\hbar c} \approx 2.6 \times 10^{10} \left(\frac{M}{1\,\mathrm{g}}\right)^2$$

$$\dot{M}_{\mathrm{PBH}} \sim \begin{cases} -\dfrac{M_{\mathrm{pl}}^4}{M_{\mathrm{PBH}}^2} & \left(M_{\mathrm{PBH}} \geq \boxed{\tfrac{1}{2}} M_{\mathrm{PBH,ini}}\right) \\ -\boxed{\dfrac{1}{S^k}} \dfrac{M_{\mathrm{pl}}^4}{M_{\mathrm{PBH}}^2} & \left(M_{\mathrm{PBH}} < \boxed{\tfrac{1}{2}} M_{\mathrm{PBH,ini}}\right) \end{cases}$$

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]
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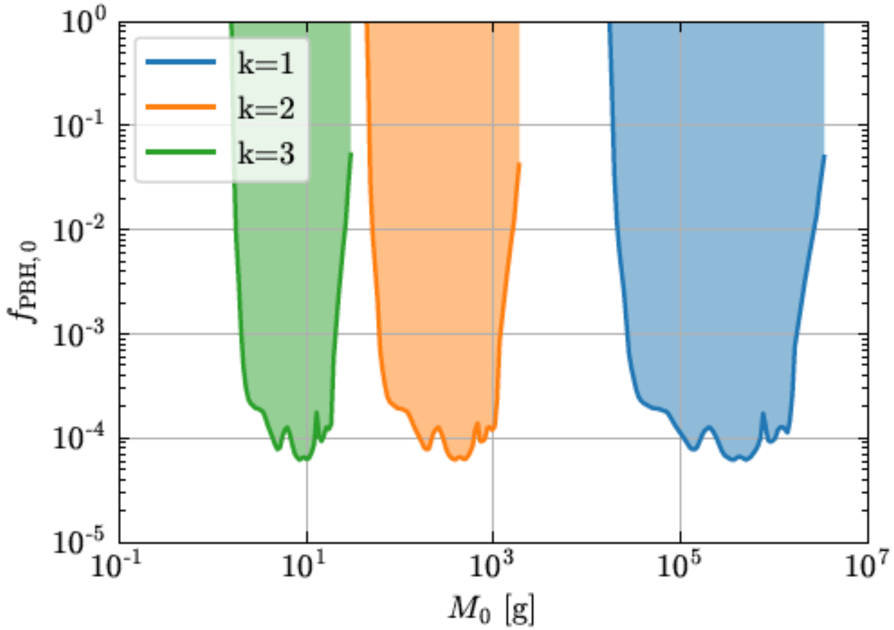
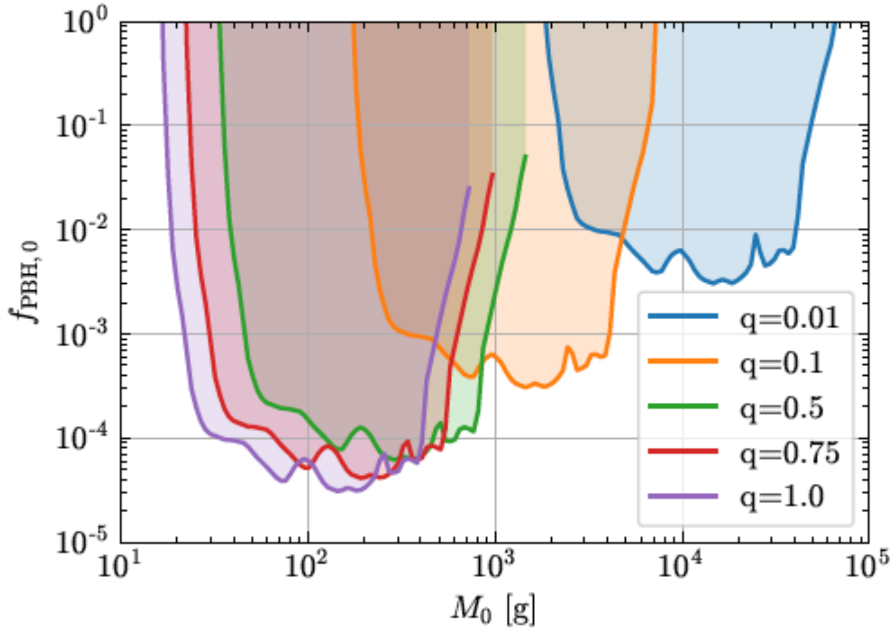
q=1/2



k=2



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

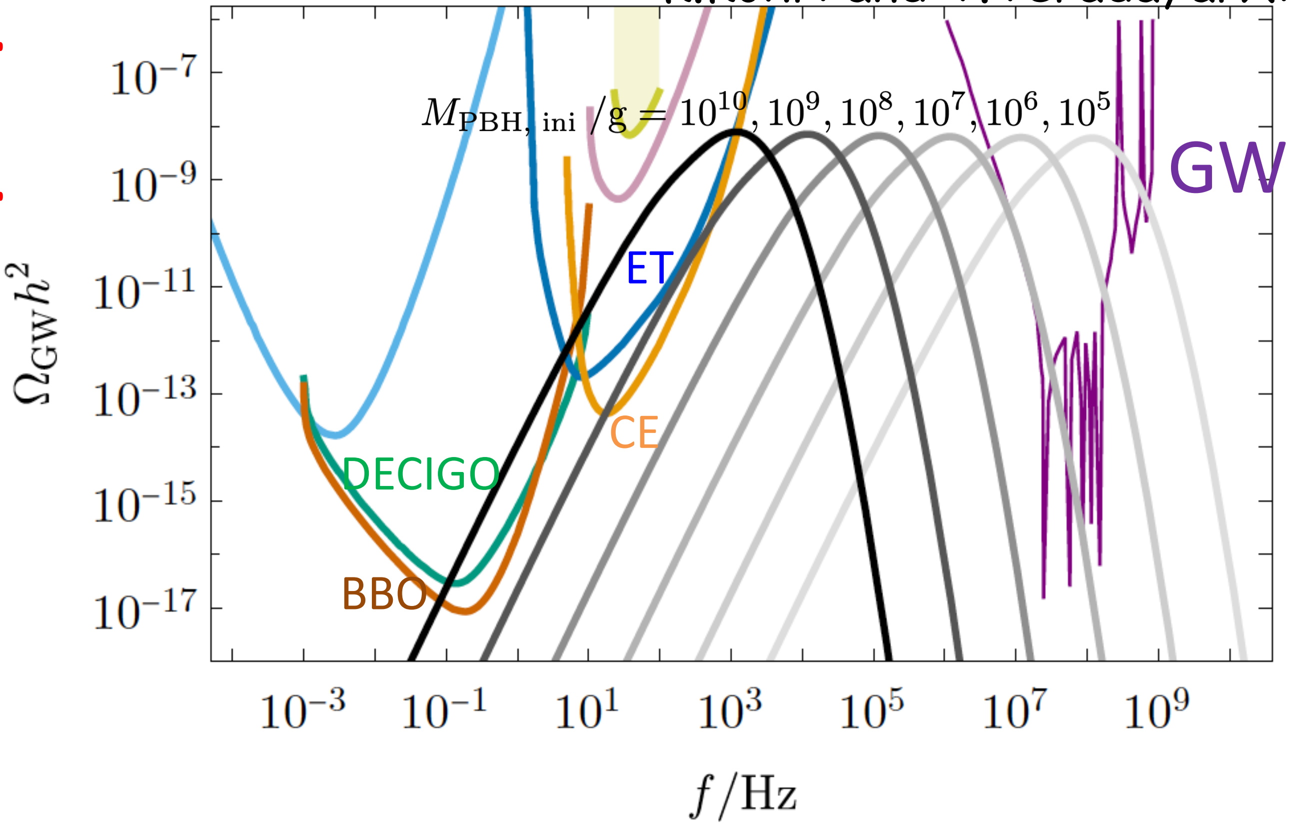
K. Kohri. T. Terada. T. Yanagida. arXiv:2409.06365

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

K.Kohri and T.Terada, arXiv:1804.08577

k=2

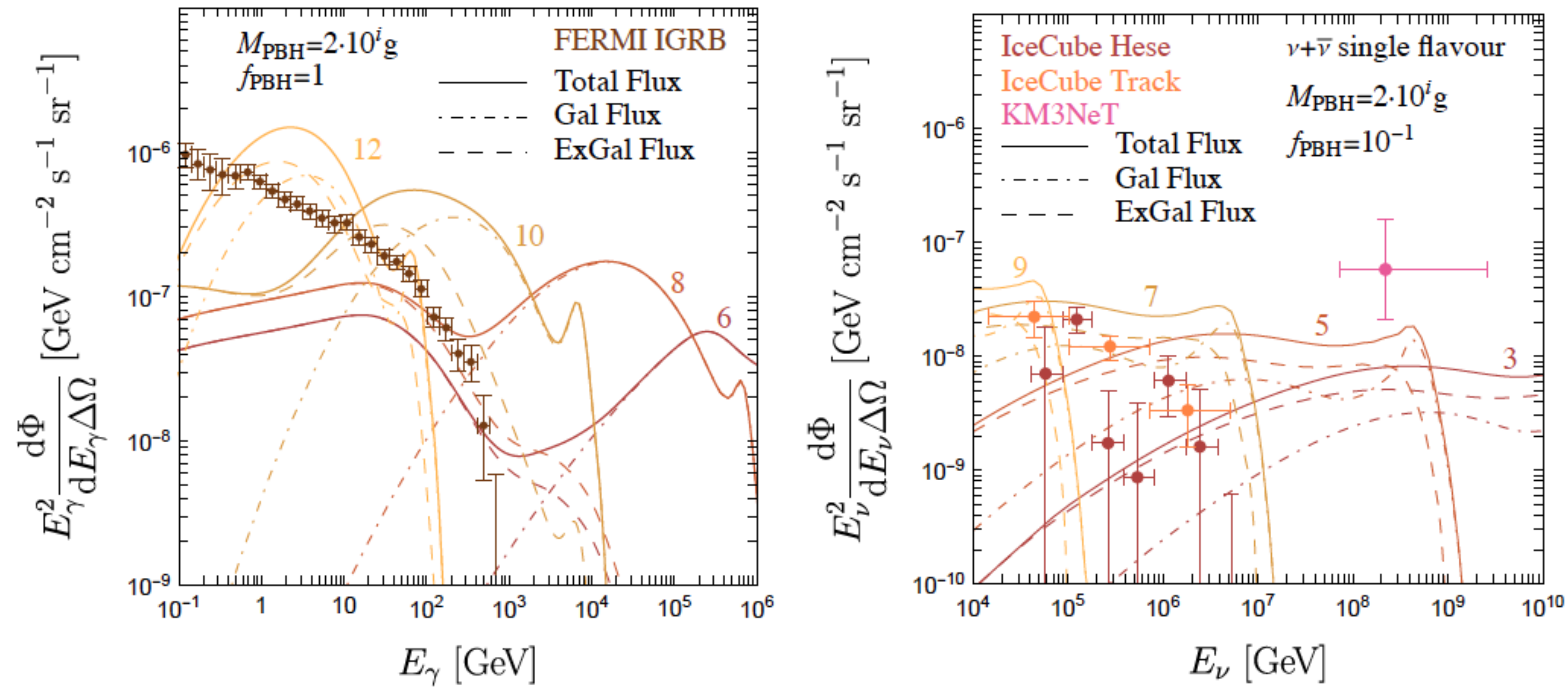
q=1/2



GW + B → γ

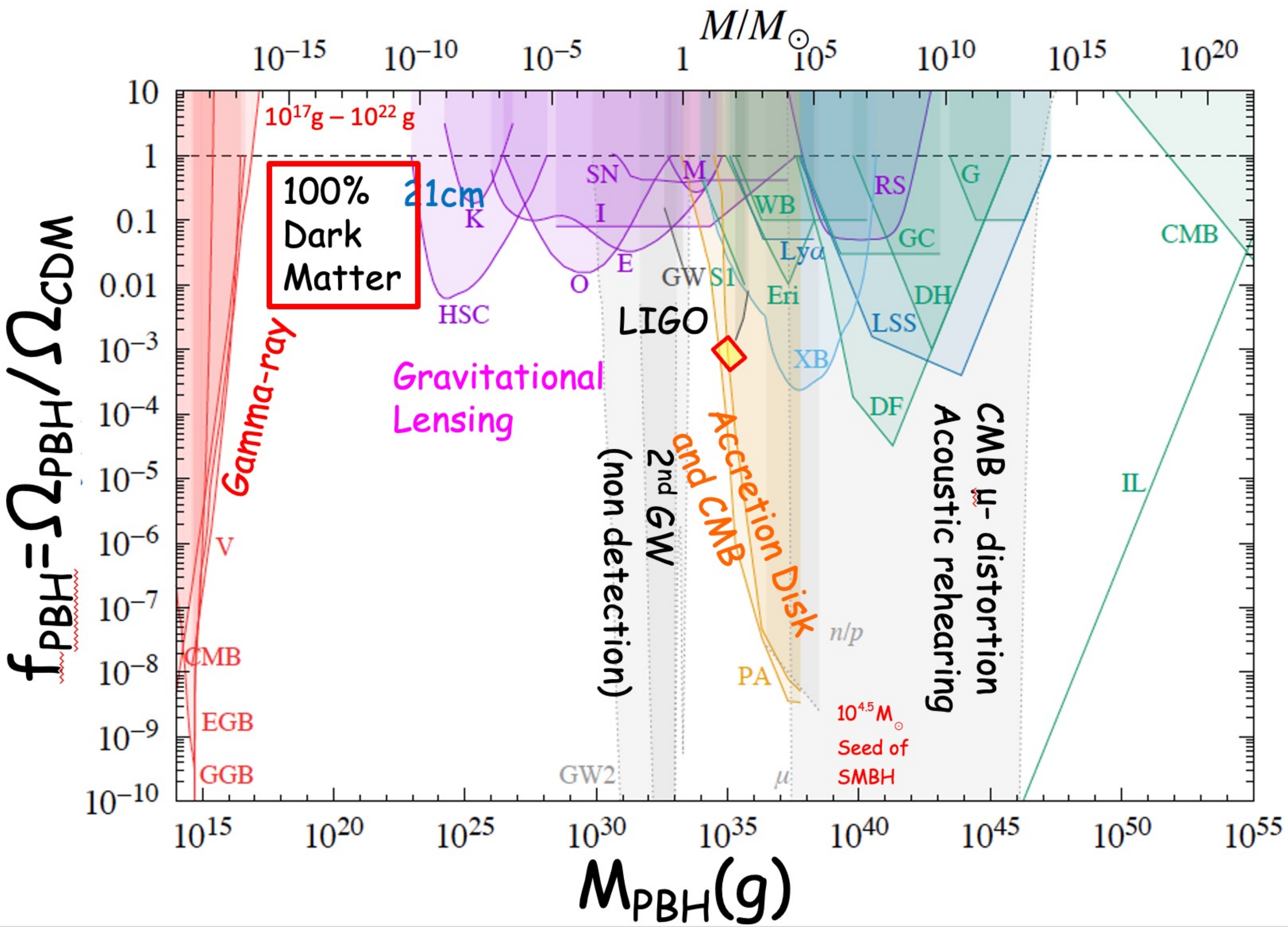
Fermi and KM3NeT bounds on newly-produced merging PBHs with memory burden effects

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



Upper bounds on the fraction to CDM

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



Conclusion

- Primordial black holes (PBHs) are black holes formed in the early Universe ($t \sim 10^{-19}$ sec)
- PBHs with their masses 10^{17} g – 10^{23}g can be dark matter (DM)
- PBHs with their masses 10^{15} g – 10^{17}g are now evaporating with emitting the MeV gamma-rays and neutrino
- If we assume the Memory Burden Effect, additionally PBHs with 10^{5} g – 10^{10}g can be dark matter, which are now emitting the PeV gamma-rays and neutrinos