MeV gamma-ray emissions, occasionally PeV emissions with memory burden by evaporating primordial black holes

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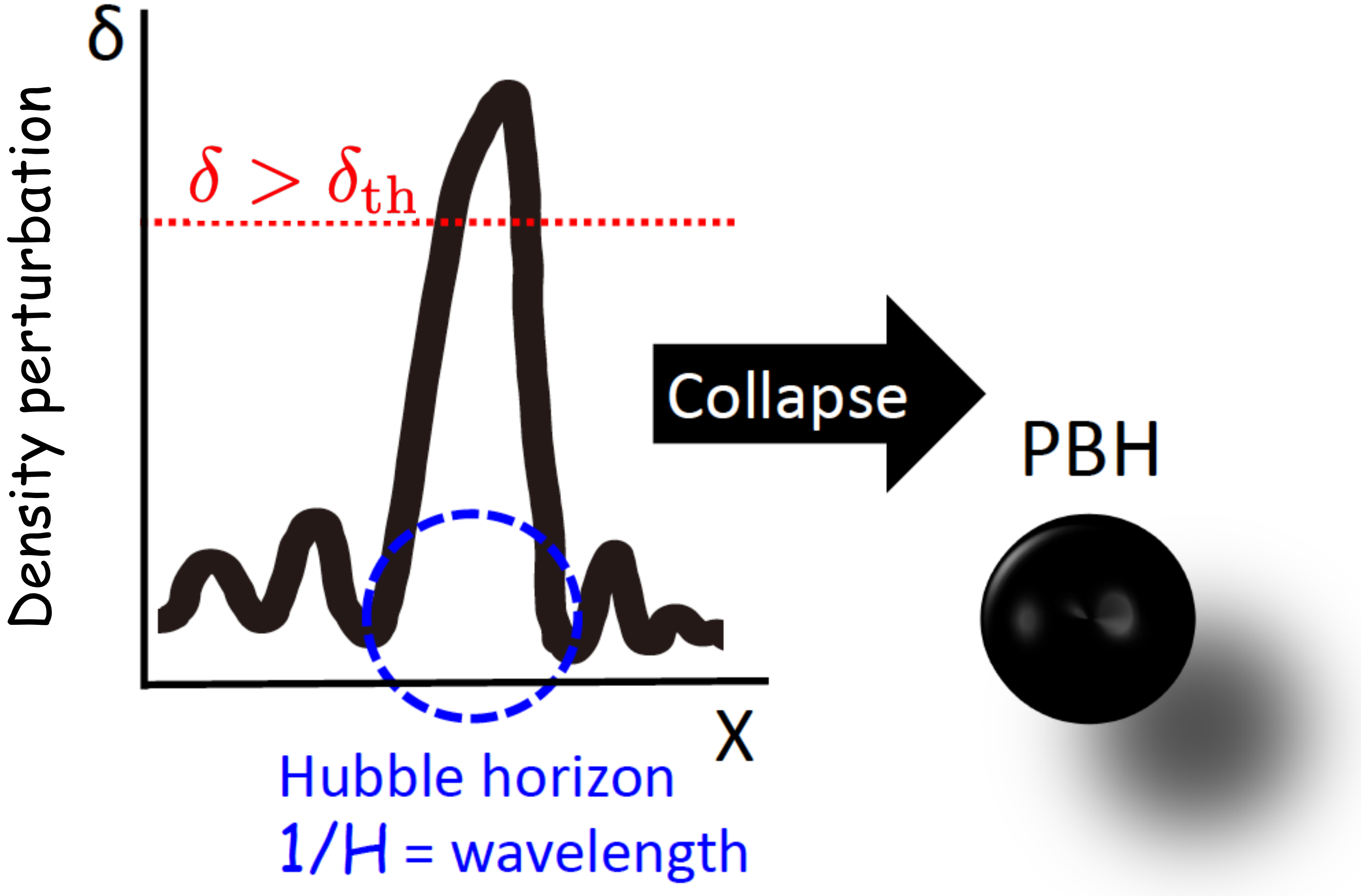
Abstract

- 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

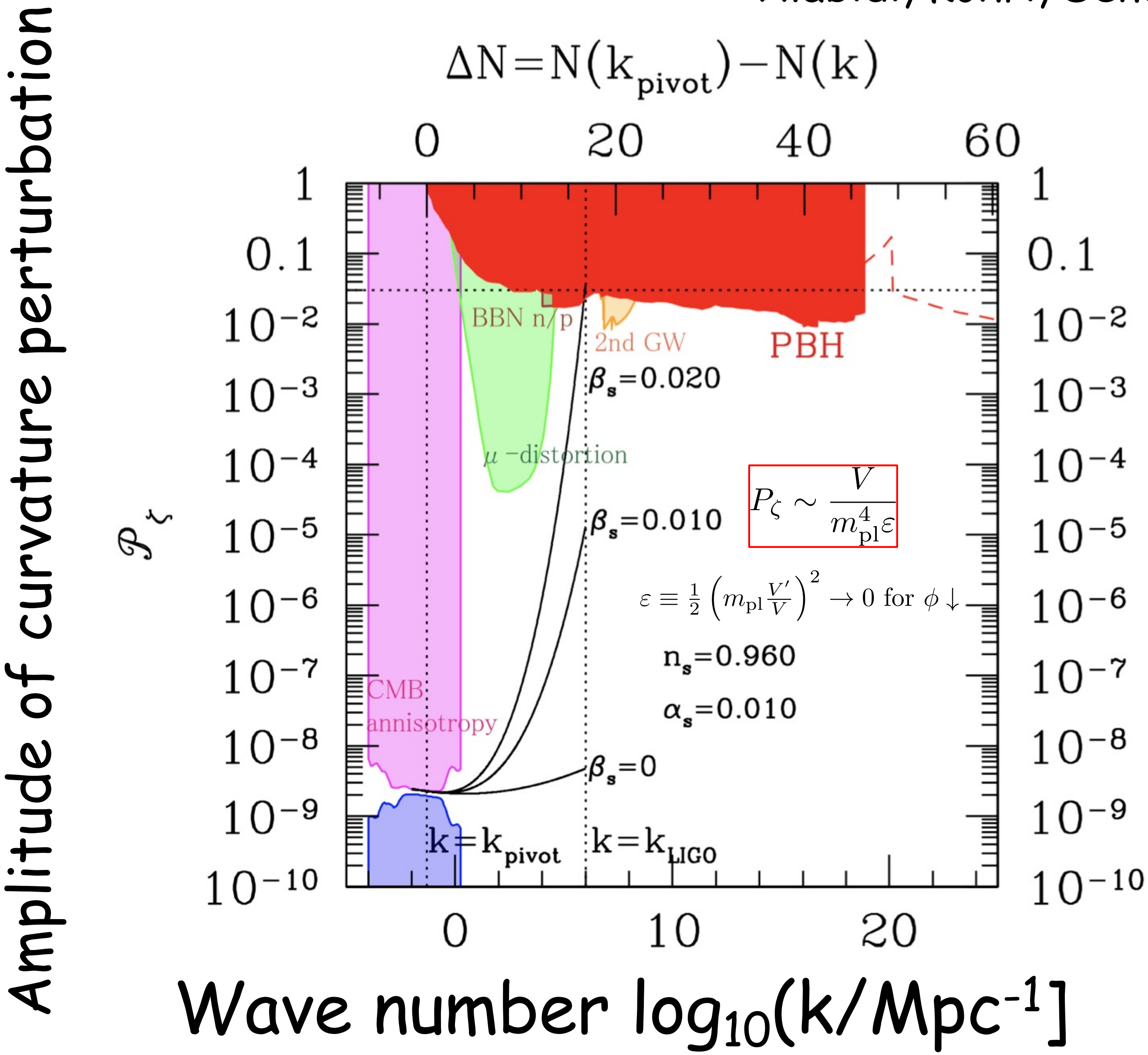
Formation by large density perturbation

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



Curvature perturbation $P_\zeta(k)$

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



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.

For inflation models with a big running, see Kohri, Lin Lyth (2008)

k = p x a

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

- Integral of distribution for density-perturbation

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

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

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

Curvature perturbation

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

For Peak Statistics,
e.g., see Yoo, Harada, KK et al (2018)(2020) and so on

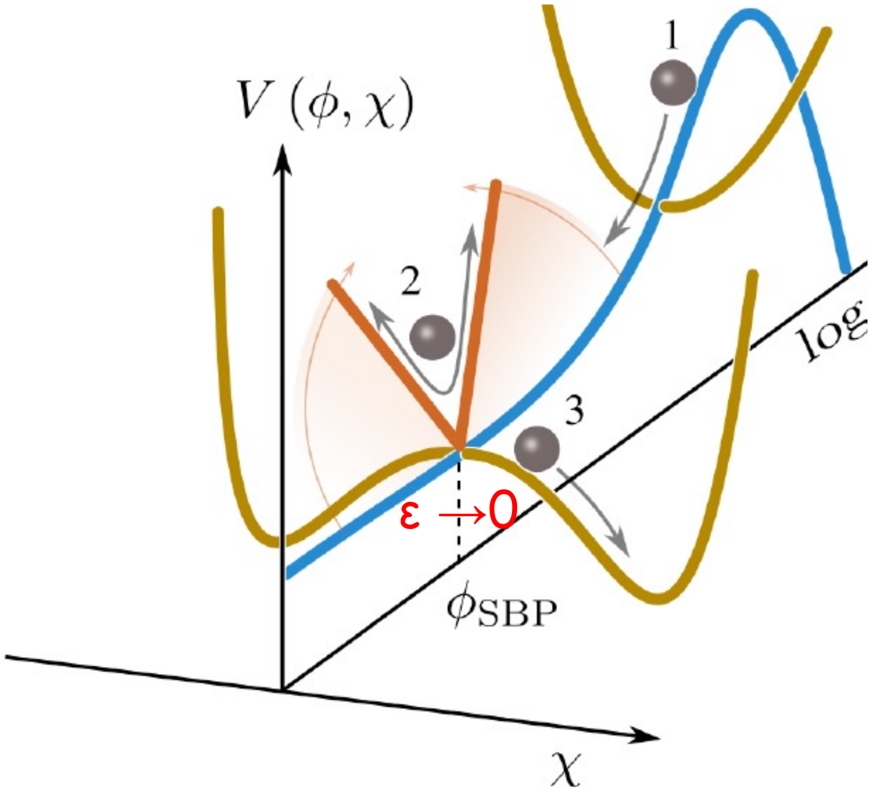
Multi-field inflation models

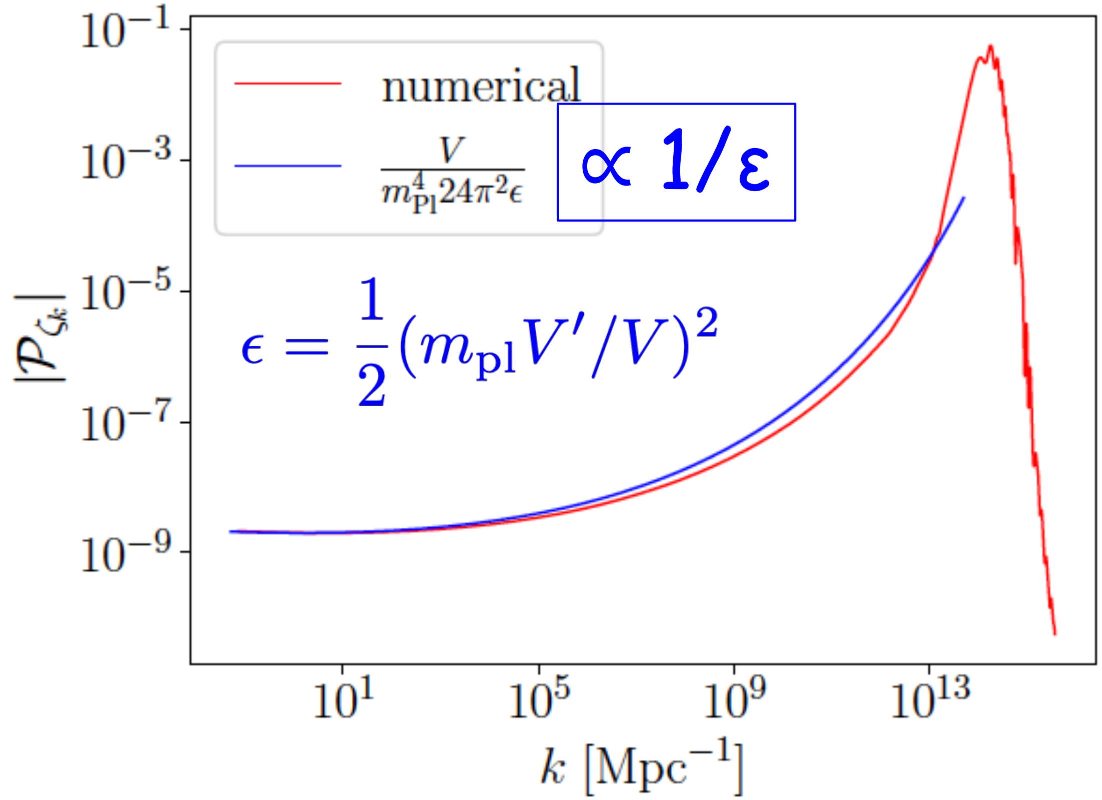
to enhance curvature perturbation at small scales

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

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

narrow peak





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

Multi-field inflation models

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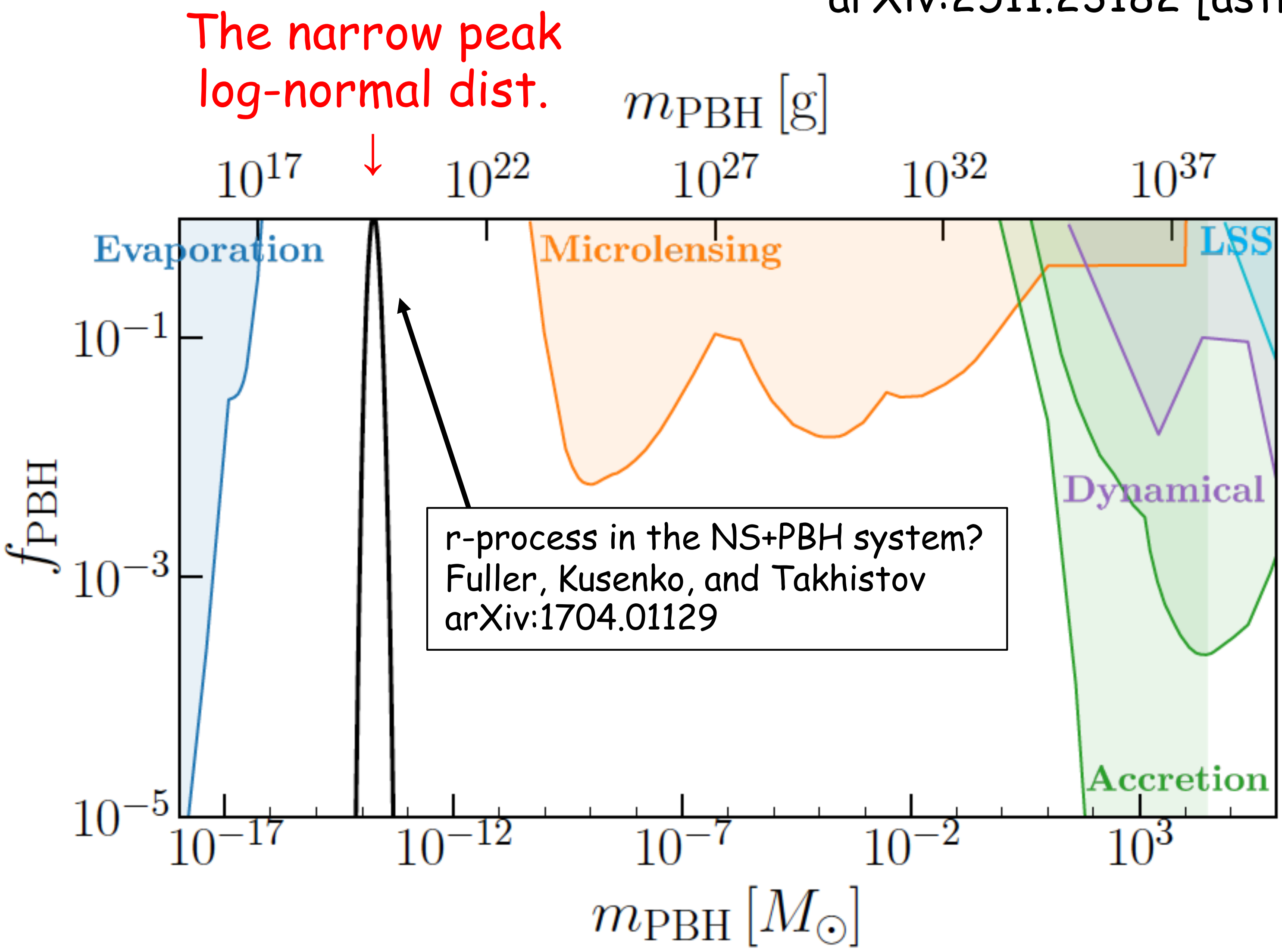


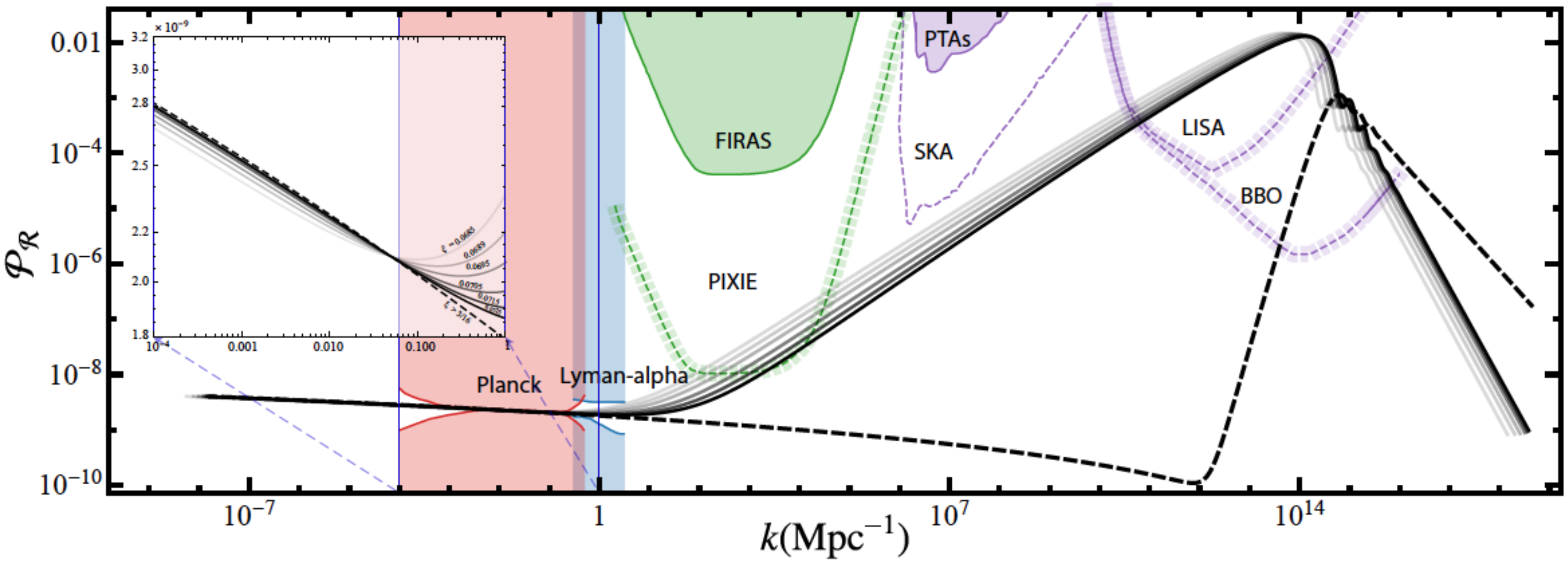
R^2 + Higgs inflation fits ACT spectral index

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

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

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

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

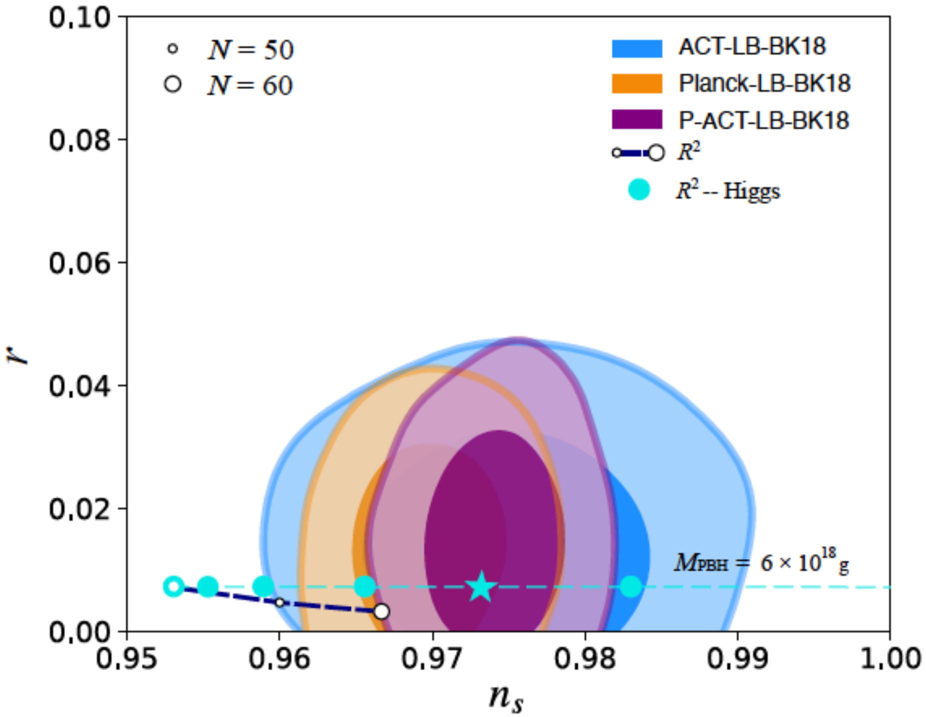


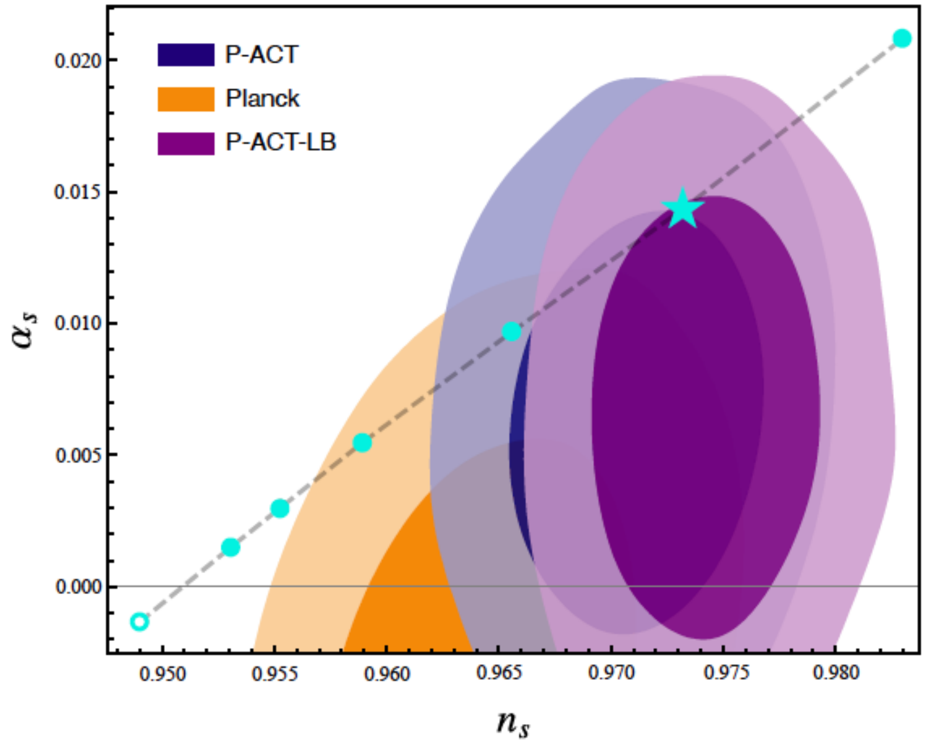
R^2 + Higgs inflation fits ACT spectral index

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

- Large spectral index n_s ~0.98

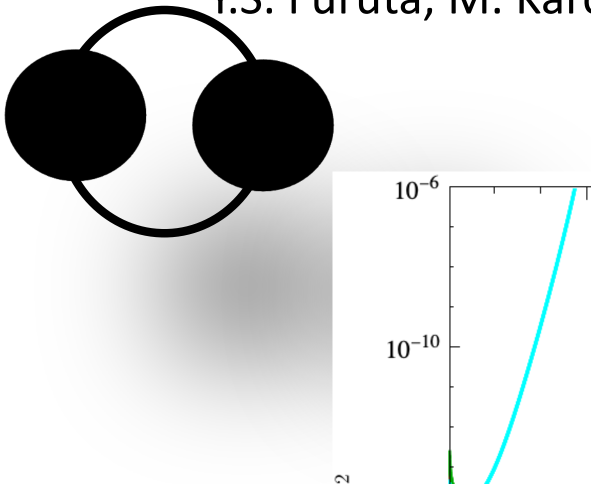
- Positive running α_s ~ O(+0.01)



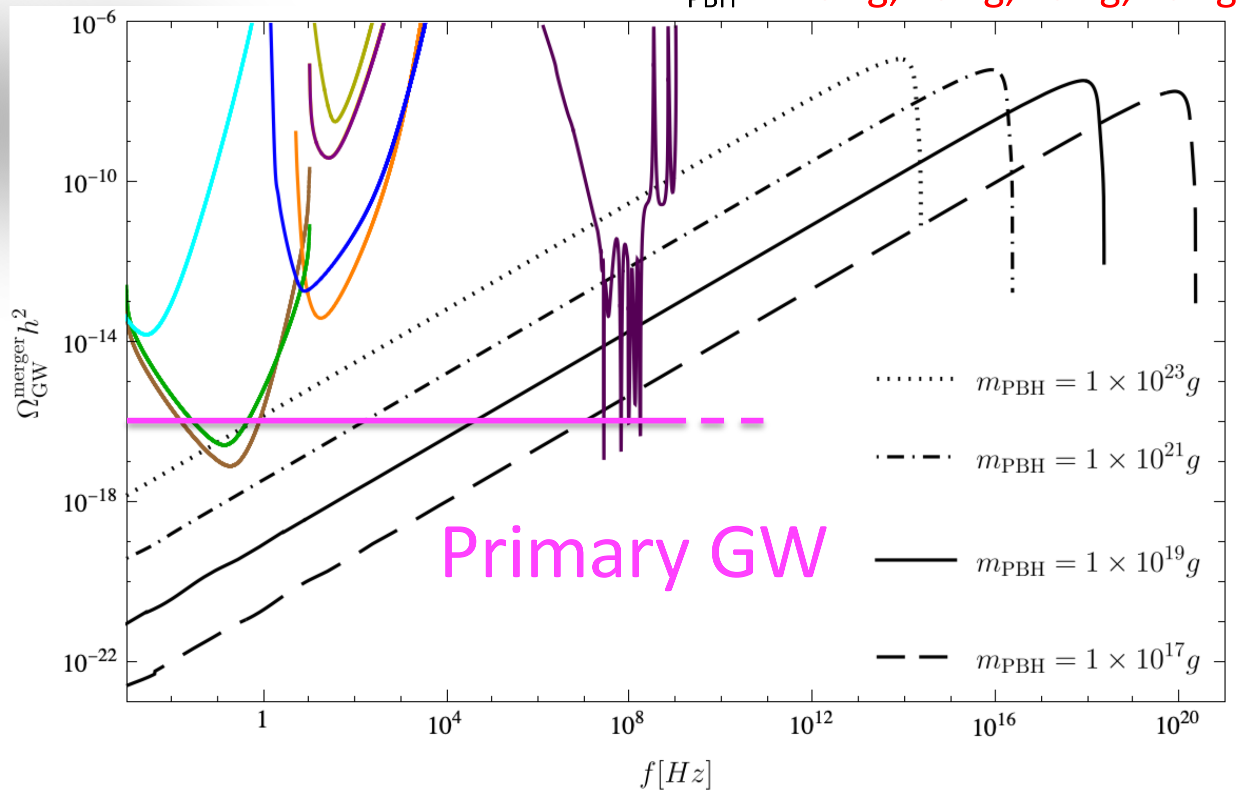


Merger Gravitational Waves probing Primordial Black Hole Dark Matter

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

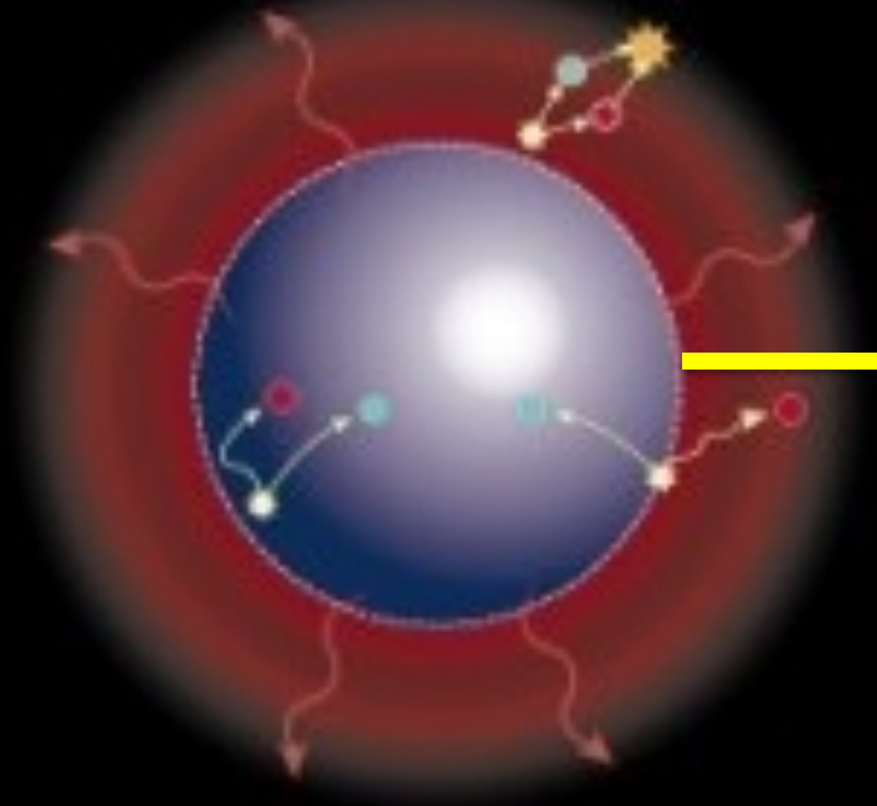


Hawking evaporation through quantum mechanics

S.W. Hawking, 1974

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

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



Blackhole

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

Asymptotically flat

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

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 = ρH^{-3} at $t=t_{\rm form}$)

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

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

- Hawking Temperature

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

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

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~~

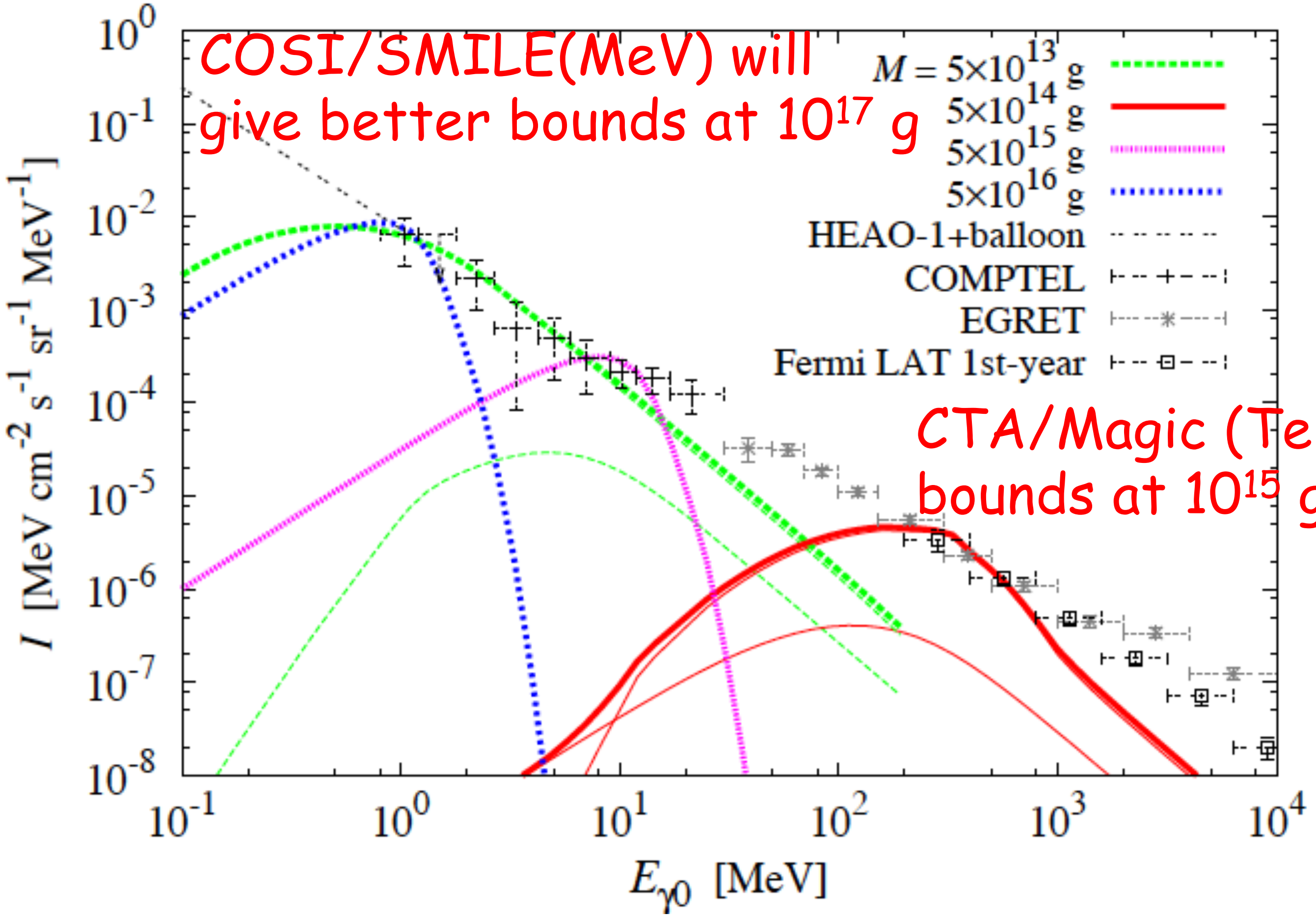
- BBN

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

Evaporating PBHs through Hawking Process

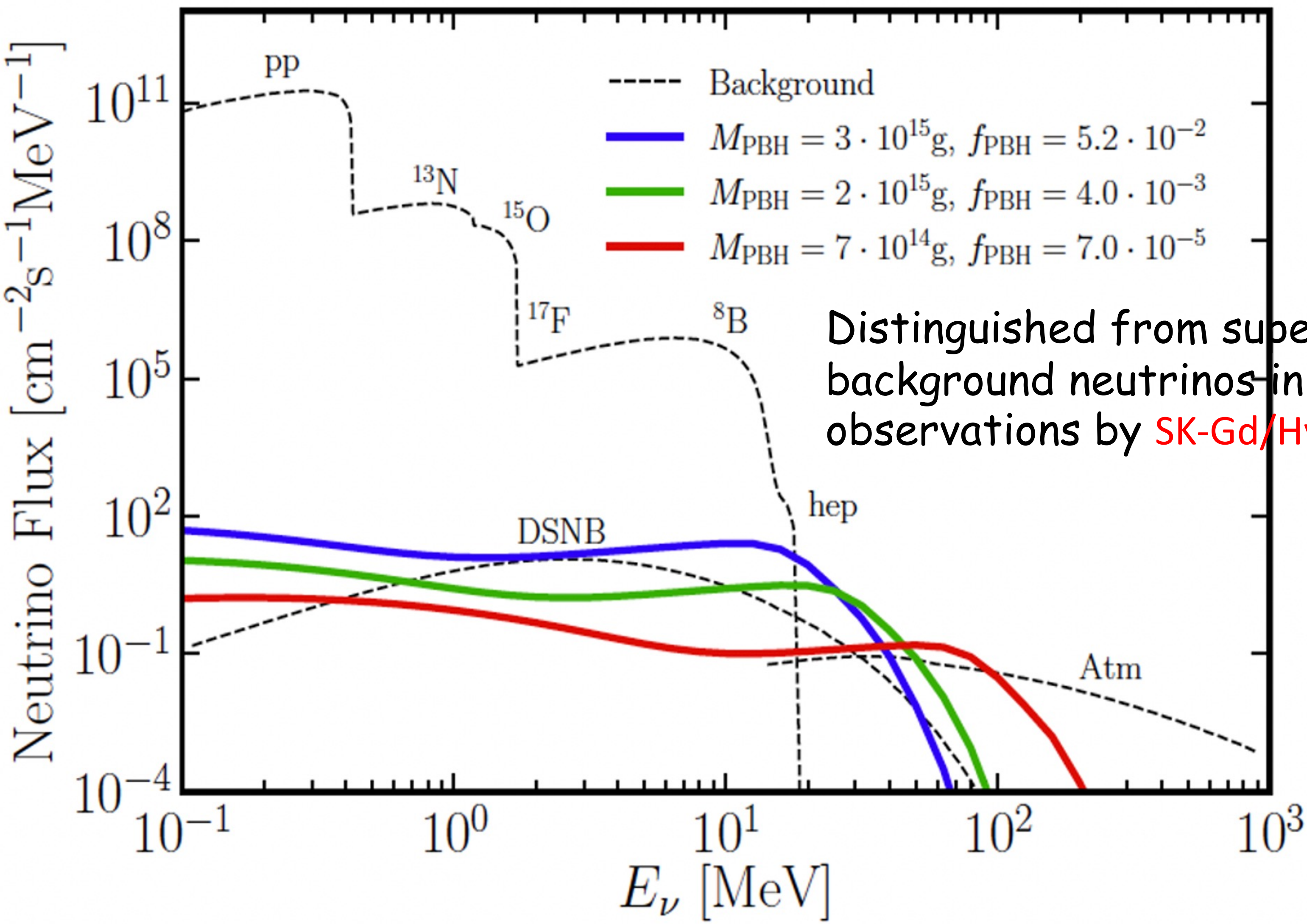
Carr, Kohri, Sendouda and Yokoyama (2010)

$$d\dot{N}_s = \frac{dE}{2\pi} \frac{\Gamma_s}{e^{E/T_{\rm BH}} - (-1)^{2s}}$$



MeV neutrino by evaporating PBHs

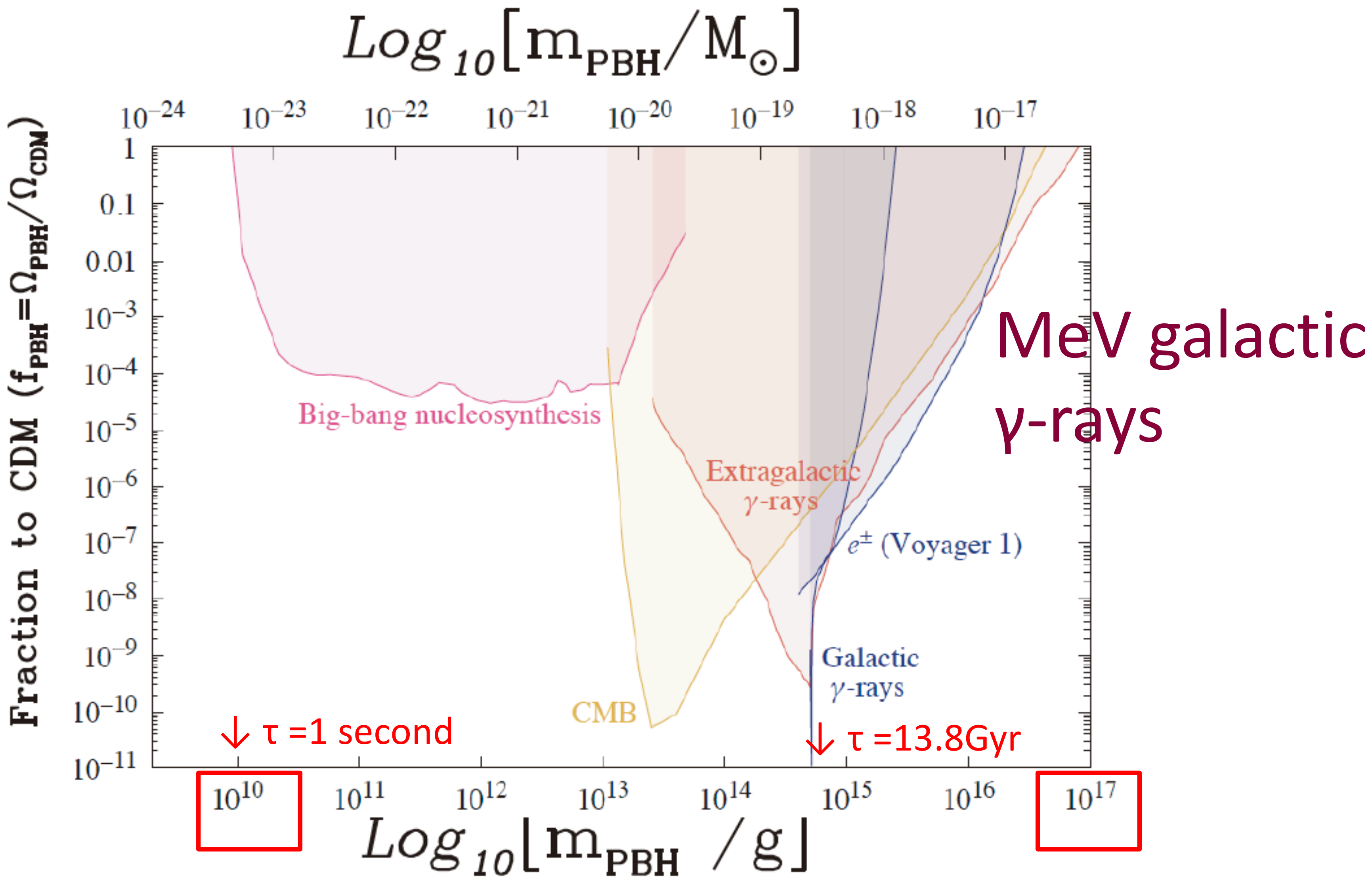
R. Calabrese et al, arXiv:2106.02492



Distinguished from supernova background neutrinos in observations by SK-Gd/Hyper-K

BBN, CMB, γ-ray bounds on PBHs

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



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

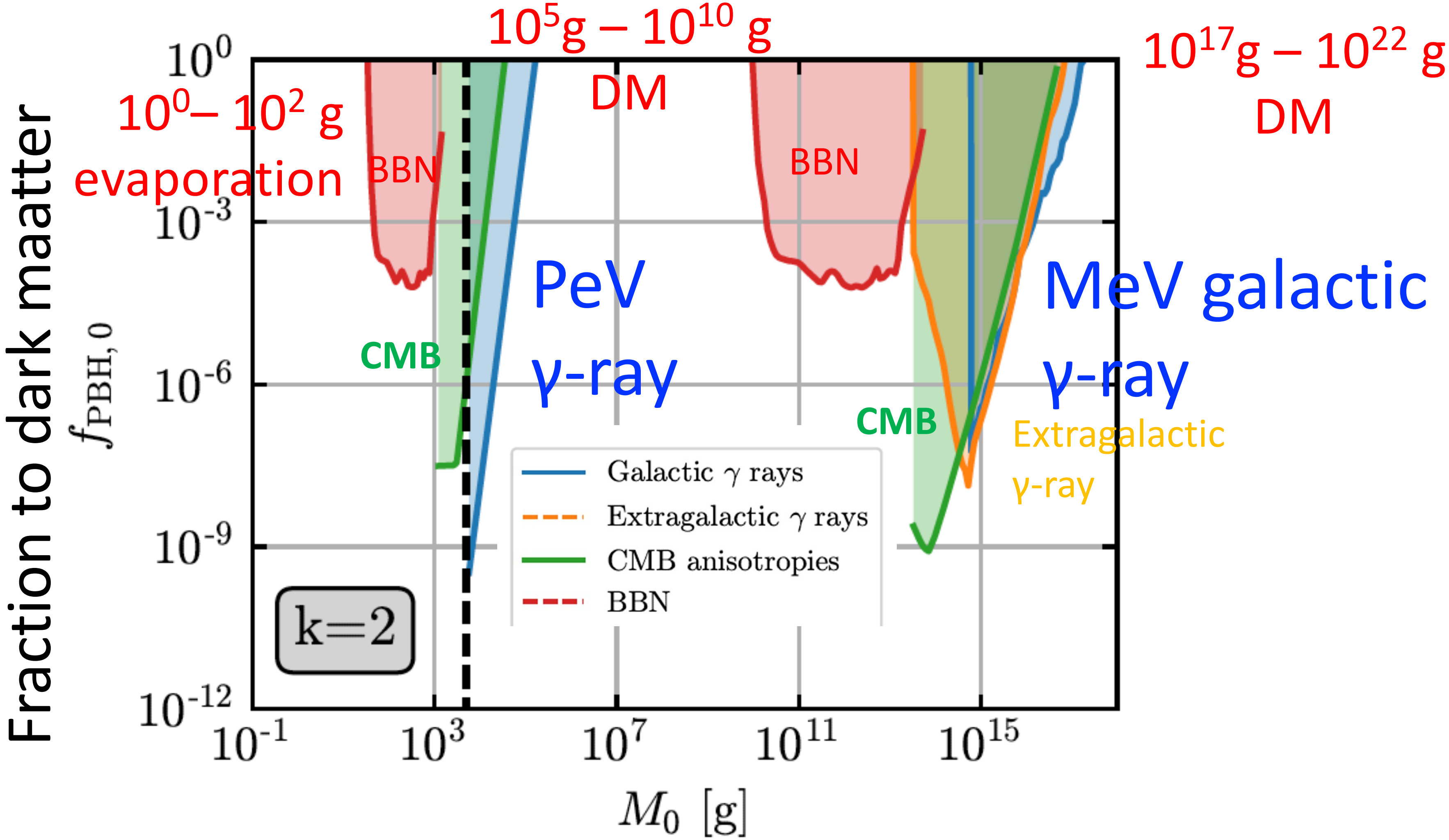
$$S = \frac{4\pi M^2 G}{\hbar c} \approx 2.6 \times 10^{10} \left(\frac{M}{1\,\mathrm{g}}\right)^2$$

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

q=1/2

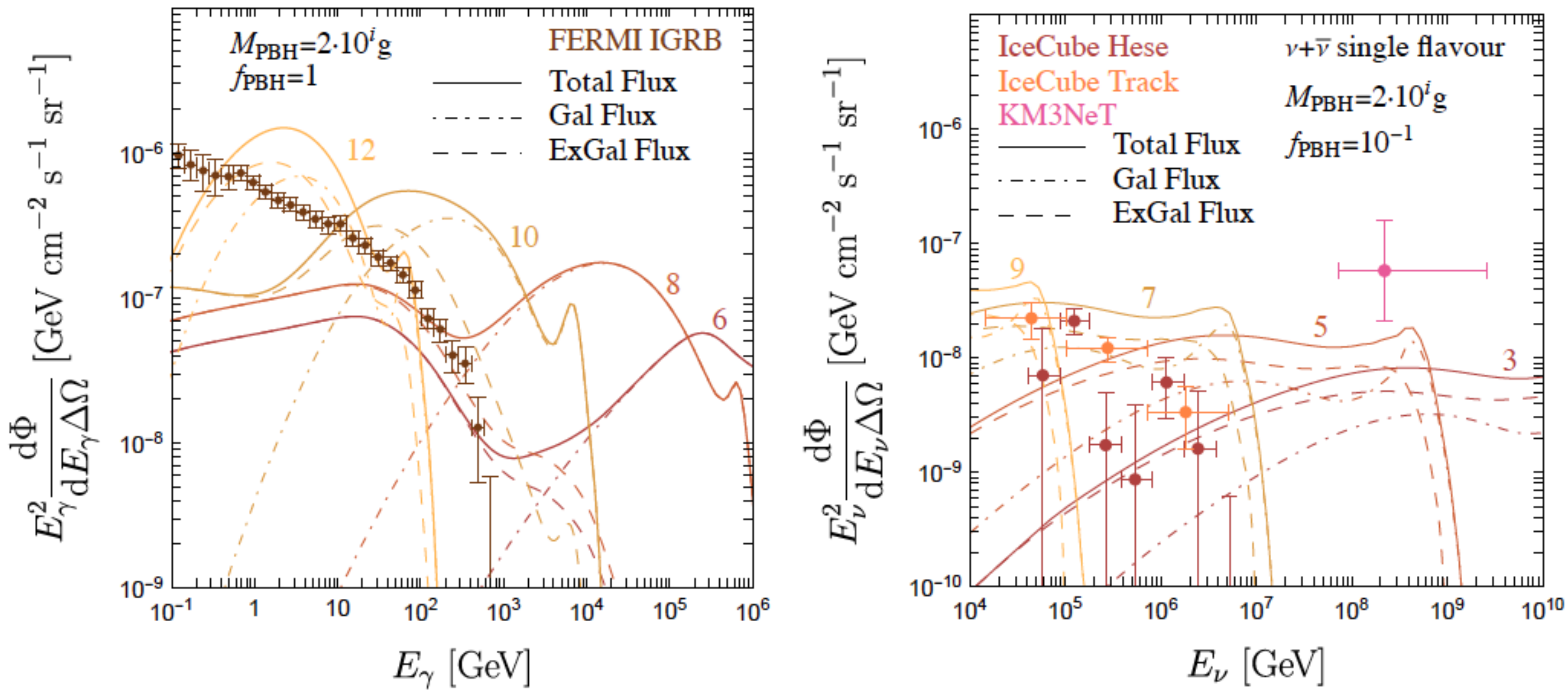
Breakdown of Hawking Evaporation opens new Mass Window PBHs as DM

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



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]



Breakdown of Hawking Evaporation opens new Mass Window PBHs as DM

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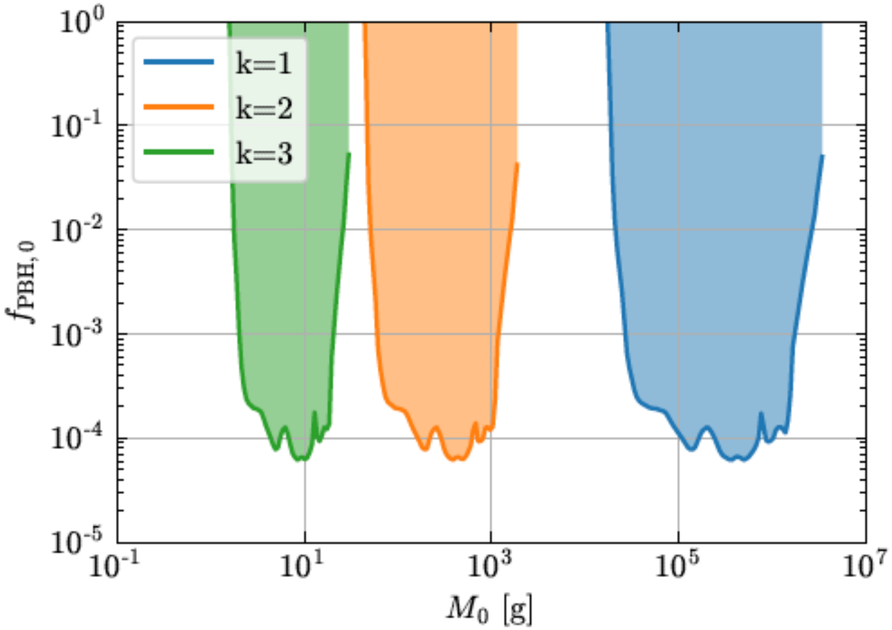
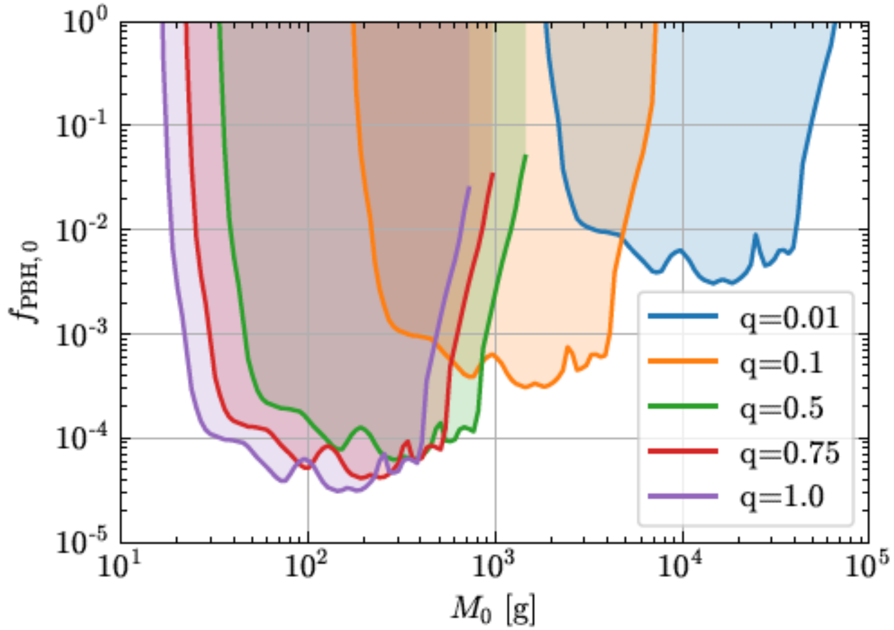
q=1/2



k=2



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

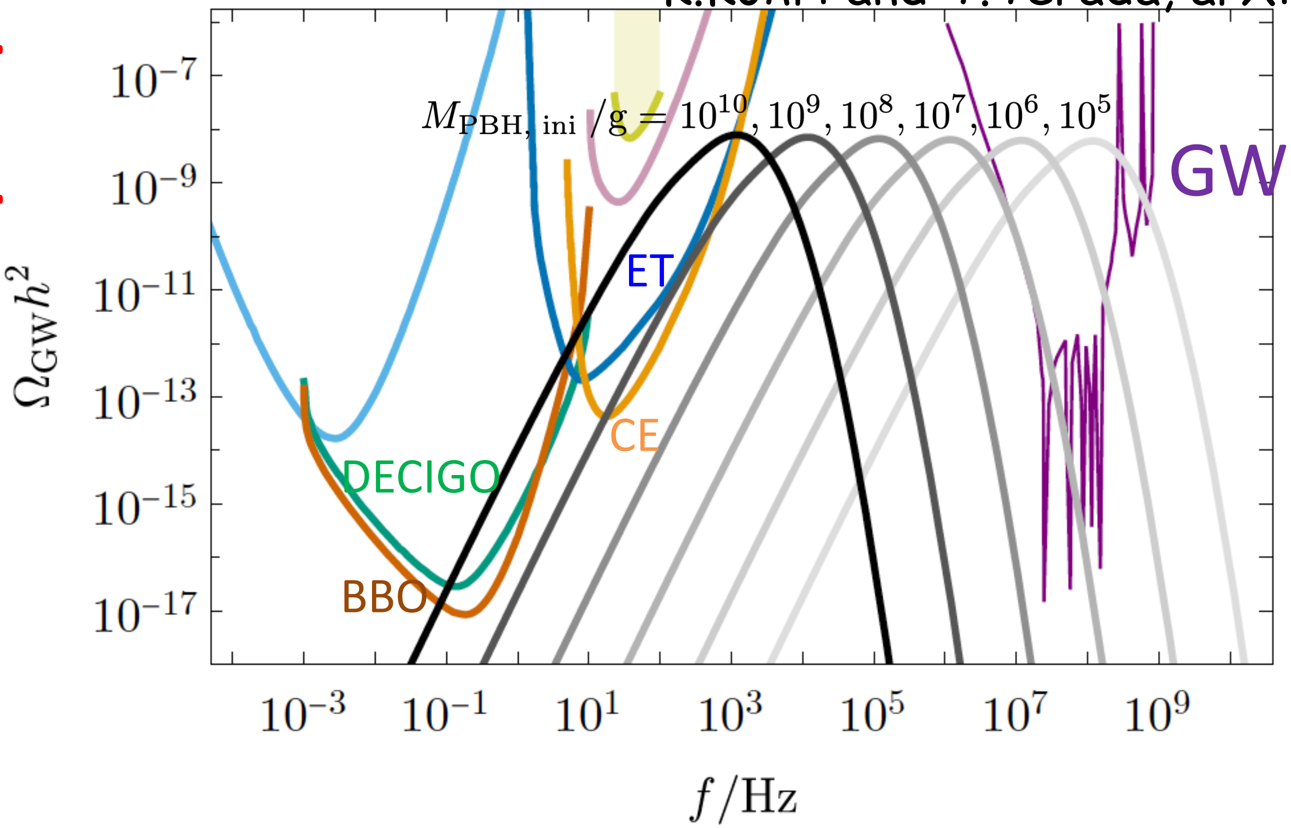
K. Kohri. T. Terada. T. Yanagida. arXiv:2409.06365

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

K.Kohri and T.Terada, arXiv:1804.08577

k=2

q=1/2

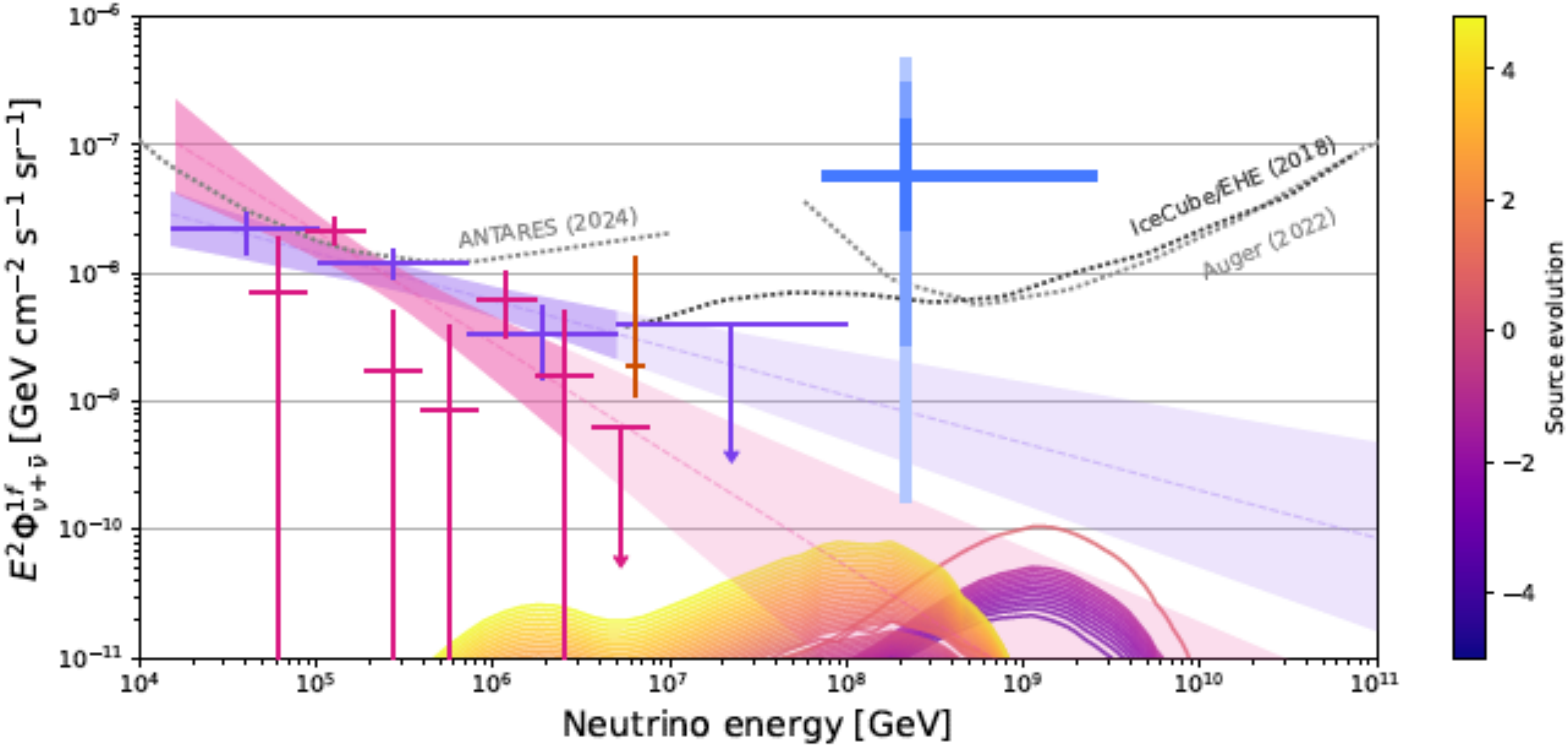


GW + B → γ

On the potential cosmogenic origin of the ultra-high-energy event KM3-230213A

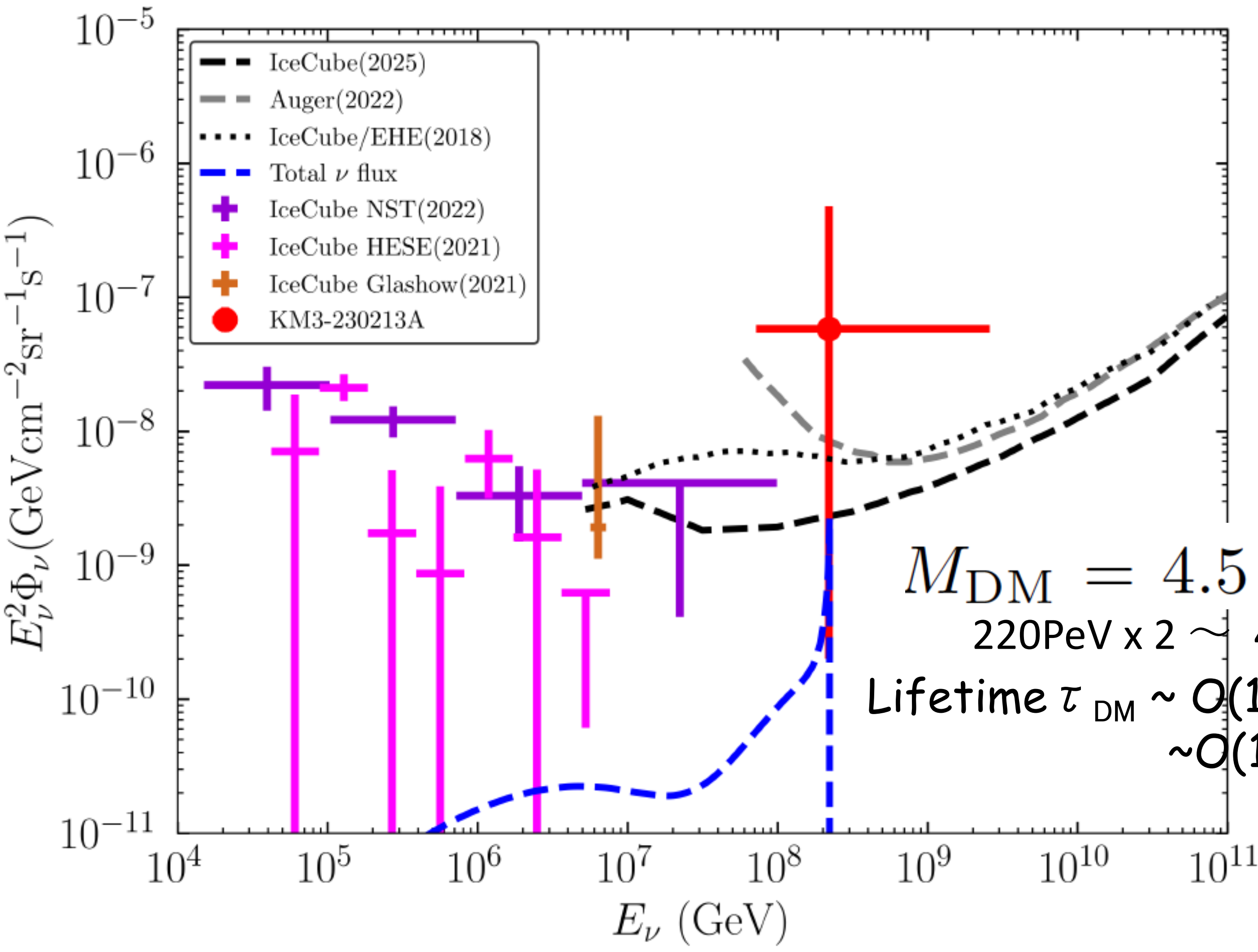
O. Adriani et al, The KM3NeT collaboration, arXiv:2502.08508 [astro-ph.HE]

$$220^{+570}_{-100}\ \mathrm{PeV}$$



KM3-230213A and dark matter decay (DM → ν + Higgs)

Kazunori Kohri, Partha Kumar Paul, Narendra Sahu, arXiv:2503.04464 [hep-ph]



$$M_{\mathrm{DM}} = 4.5 \times 10^{8}\ \mathrm{GeV}$$

220PeV x 2 $\sim$ 450PeV

Lifetime $\tau_{\mathrm{DM}} \sim O(10^{30})$ sec

$\sim O(10^{12}) \times 13.8$Gyr

Conclusion

- Primordial black holes (PBHs) are black holes formed in the early Universe
- 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
- 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