The memory burden effect with new classes of PBH dark matter and induced high-frequency gravitational waves

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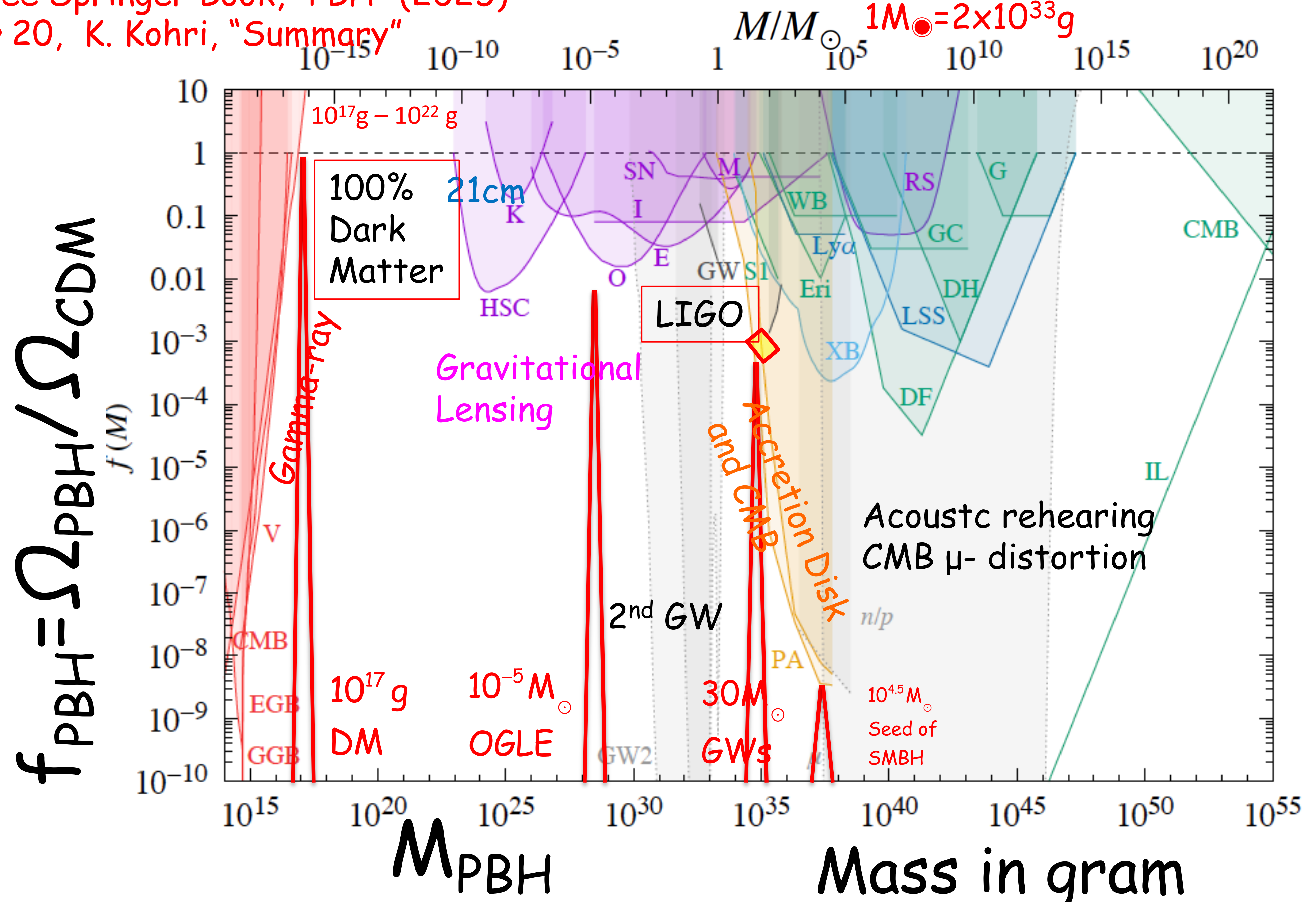
Upper bounds on the fraction to CDM

See Springer Book, "PBH" (2025)
§ 20, K. Kohri, "Summary"

Carr, Kohri, Sendouda, J.Yokoyama (2009)(2020)



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]

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

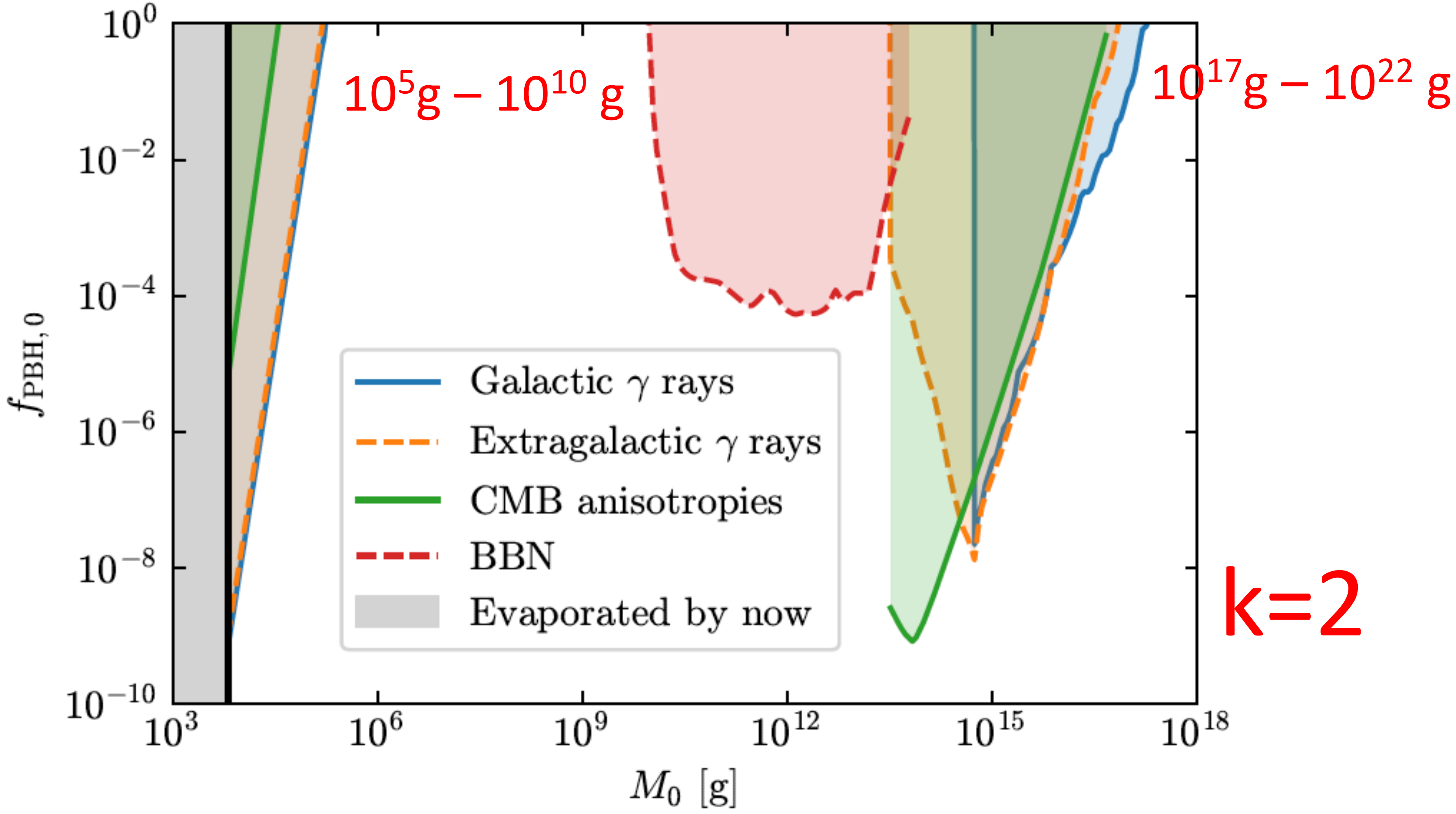
k=2

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

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

Breakdown of Hawking Evaporation opens new Mass Window PBHs as DM

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



Secondary gravitational wave induced from large curvature perturbation (P_ζ >> r) 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
K.Kohri and T.Terada, 2018
R.-G. Cai, S. Pi, and M. Sasaki, 2019

- Power spectrum of the tensor mode

$$\langle h^r_{\boldsymbol{k}}(\eta) h^s_{\boldsymbol{k}'}(\eta)\rangle = \frac{2\pi^2}{k^3}\mathcal{P}_h(k,\eta)\delta(\boldsymbol{k}+\boldsymbol{k}')\delta^{rs}, \qquad h_{ij}(\boldsymbol{x},\eta) = \int \frac{\mathrm{d}^3k}{(2\pi)^{3/2}} e^{i\boldsymbol{k}\cdot\boldsymbol{x}}\left[h^+_{\boldsymbol{k}}(\eta)\mathrm{e}^+_{ij}(\boldsymbol{k}) + h^\times_{\boldsymbol{k}}(\eta)\mathrm{e}^\times_{ij}(\boldsymbol{k})\right]$$

- Omega parameter well inside the horizon

$$\Omega_{\rm GW}(k,\eta) = \frac{1}{3}\left(\frac{k}{\mathcal{H}}\right)^2 \mathcal{P}_h(k,\eta).$$

- Substituting the solution into this

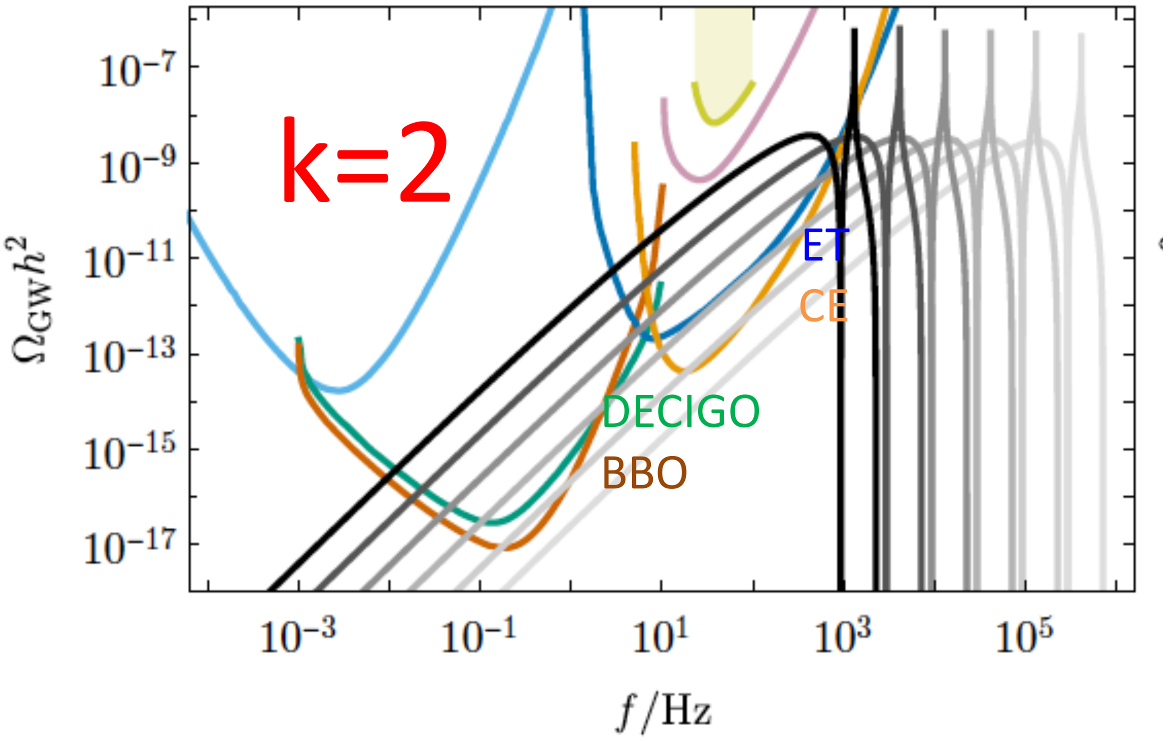
$$\Omega_{\rm GW,c}(f) = \frac{1}{12}\left(\frac{f}{2\pi a H}\right)^2 \int_0^\infty \mathrm{d}t \int_{-1}^{1} \mathrm{d}s \left[\frac{t(t+2)(s^2-1)}{(t+s+1)(t-s+1)}\right]^2 \times \overline{I^2(t,s,k\eta_c)}\,\mathcal{P}_\zeta\left(\frac{(t+s+1)f}{4\pi}\right)\mathcal{P}_\zeta\left(\frac{(t-s+1)f}{4\pi}\right)$$

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

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

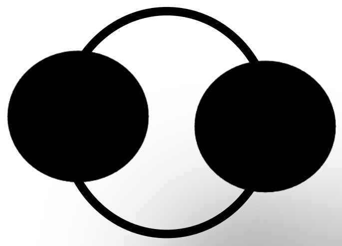
$$\Omega_{\mathrm{GW,c}}(f) = \frac{1}{12}\left(\frac{f}{2\pi a H}\right)^2 \int_0^\infty \mathrm{d}t \int_{-1}^{1} \mathrm{d}s \left[\frac{t(t+2)(s^2-1)}{(t+s+1)(t-s+1)}\right]^2 \times \overline{I^2(t,s,k\eta_c)}\,\mathcal{P}_\zeta\left(\frac{(t+s+1)f}{4\pi}\right)\mathcal{P}_\zeta\left(\frac{(t-s+1)f}{4\pi}\right)$$

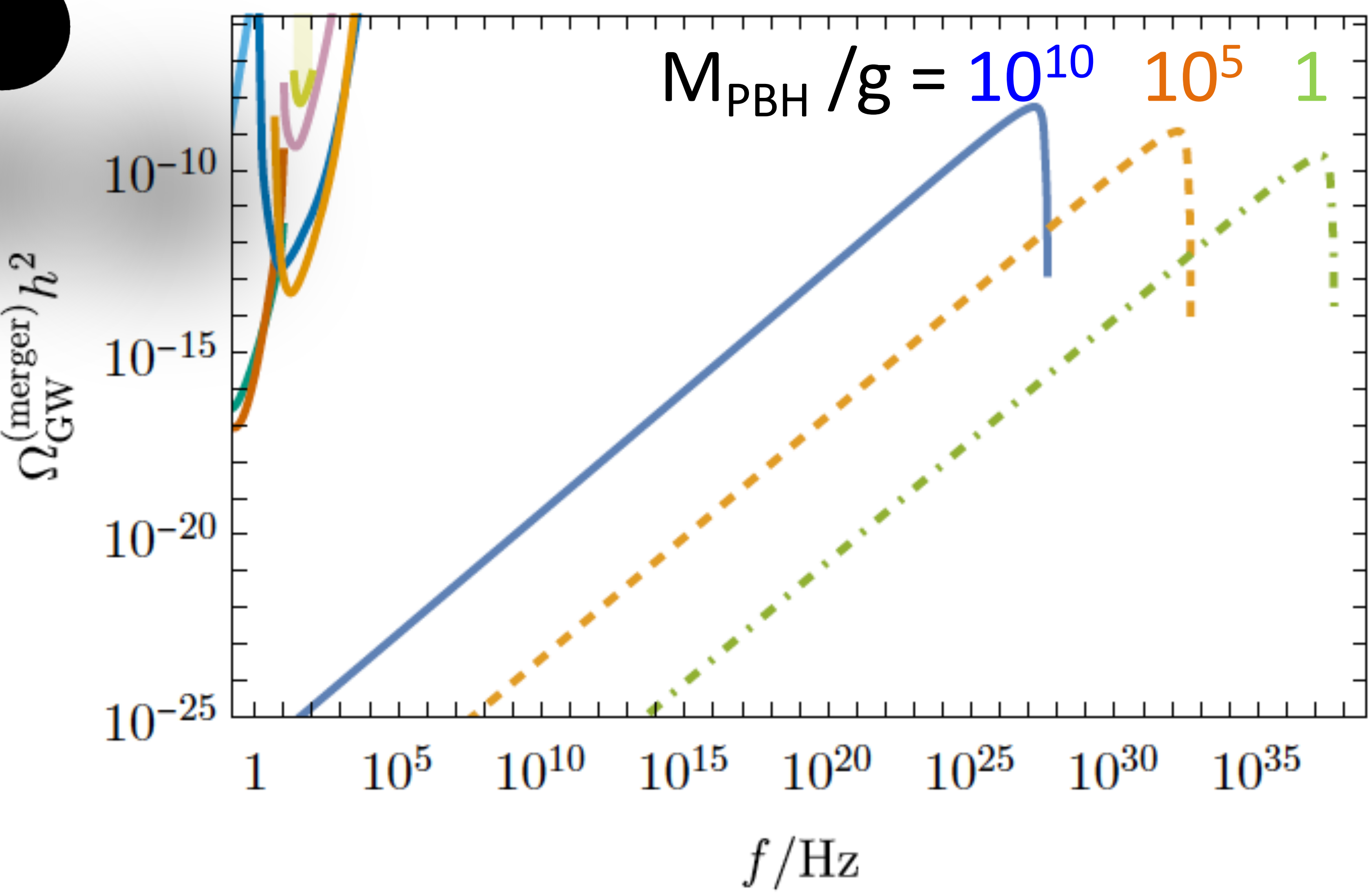
K.Kohri and T.Terada, arXiv:1804.08577



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

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





k=2

Gravitational wave search through electromagnetic telescopes

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

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

$$\begin{cases} \mathcal{A}_\mu(x) = \bar{A}_\mu + A_\mu(x), \\ g_{\mu\nu}(x) = \eta_{\mu\nu} + \dfrac{2}{M_{\rm pl}} h_{\mu\nu}(x). \end{cases}$$

$h_{\mu\nu}$ has mass dimension one

$$S = \int d^4x \sqrt{-g} \left[\frac{M_{\rm pl}^2}{2} R - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{\alpha^2}{90 m_e^4} \left((F_{\mu\nu}F^{\mu\nu})^2 + \frac{7}{4} (F_{\mu\nu}\tilde{F}^{\mu\nu})^2 \right) \right].$$

Euler-Heisenberg term

Gravitational wave search through electromagnetic telescopes

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

- 2nd-order action

$$\delta S^{(2)} = \int d^4x \Big[-\frac{1}{2}(\partial_\mu h_{ij})^2 - \frac{1}{2}(\partial_\mu A_i)^2 + \frac{2}{M_{\rm pl}}\epsilon_{ijk}\bar{B}^k h^{jl}\partial_i A^l$$

$$+\frac{\alpha^2}{90 m_e^4}\left(16\bar{B}^i\bar{B}^j\left(\delta_{ij}(\partial_k A_l)^2 - (\partial_k A_i)(\partial_k A_j) - (\partial_i A_k)(\partial_j A_k)\right) + 28\left((\partial_0 A_i)\bar{B}_i\right)^2\right)\Big]$$

h + B → γ

$$\left[i\partial_z + \begin{pmatrix} -\frac{1}{2\omega}\frac{\omega^2\omega_{p,(i)}^2}{\omega^2-\omega_{c,(i)}^2} + \frac{1}{2\omega}\frac{16\alpha^2\bar{B}^2\omega^2}{45m_e^4} & i\frac{B}{\sqrt{2}M_{\rm pl}} \\ -i\frac{B}{\sqrt{2}M_{\rm pl}} & 0 \end{pmatrix}\right] \begin{pmatrix} A^+(z) \\ h^+(z) \end{pmatrix} \simeq 0, \quad (13)$$

$$\left[i\partial_z + \begin{pmatrix} -\frac{\omega_{p,(i)}^2}{2\omega} + \frac{1}{2\omega}\frac{28\alpha^2\bar{B}^2\omega^2}{45m_e^4} & i\frac{B}{\sqrt{2}M_{\rm pl}} \\ -i\frac{B}{\sqrt{2}M_{\rm pl}} & 0 \end{pmatrix}\right] \begin{pmatrix} A^\times(z) \\ h^\times(z) \end{pmatrix} \simeq 0. \quad (14)$$

Gravitational wave search through electromagnetic telescopes

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

- Oscillation probability

$$P^{(\times)}_{(i)}(A^\times \leftrightarrow h^\times) = \frac{\frac{8\bar{B}^2\omega^2}{M_{\rm pl}^2}}{\left(\omega^2_{p,(i)} - \frac{28\alpha^2\bar{B}^2\omega^2}{45m_e^4}\right)^2 + \frac{8\bar{B}^2\omega^2}{M_{\rm pl}^2}} \times \sin^2\left(\frac{\sqrt{\left(\omega^2_{p,(i)} - \frac{28\alpha^2\bar{B}^2\omega^2}{45m_e^4}\right)^2 + \frac{8\bar{B}^2\omega^2}{M_{\rm pl}^2}}}{4\omega}\Delta r\right)$$

Plasma freq. $\omega_p = \sqrt{\frac{4\pi\alpha n_e}{m_e}}$

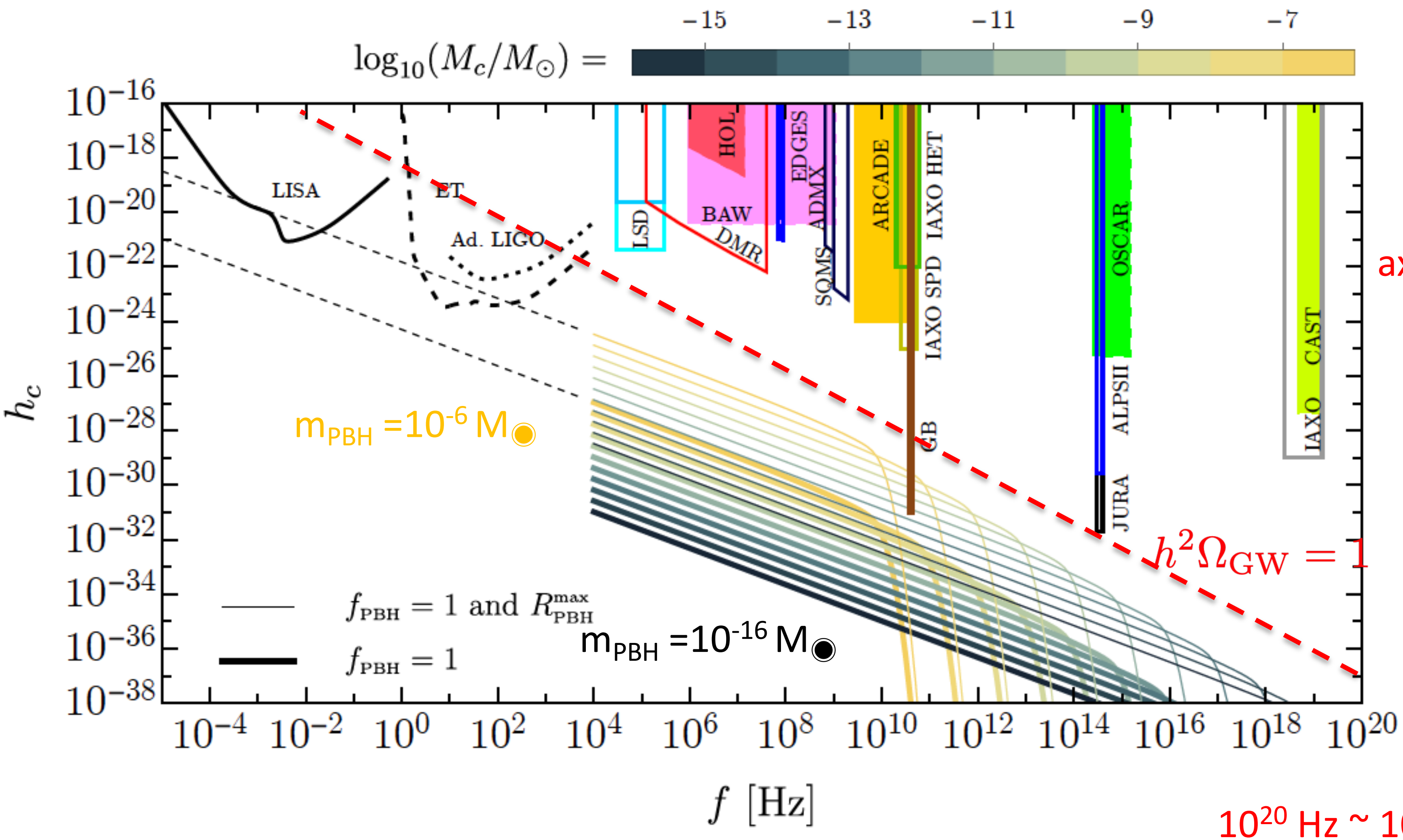
Synchrotron freq. $\omega_{c,(i)} = 1.8 \times 10^{19} \times \left(\frac{511\,\text{keV}}{m_i}\right)\left(\frac{\bar{B}}{10^{12}\,\text{G}}\right)\text{Hz},$

QED mass $\omega_{\rm QED} \equiv \frac{\alpha\bar{B}\omega}{m_e^2} = 3.4 \times 10^{16} \times \left(\frac{\bar{B}}{10^{12}\,\text{G}}\right)\left(\frac{\omega/2\pi}{10^{19}\,\text{Hz}}\right)\text{Hz},$

Mixing $\Omega \equiv \sqrt{\frac{8\bar{B}\omega}{M_{\rm pl}}} = 2.5 \times 10^{9} \times \left(\frac{\bar{B}}{10^{12}\,\text{G}}\right)^{1/2}\left(\frac{\omega/2\pi}{10^{19}\,\text{Hz}}\right)^{1/2}\text{Hz},$

Accumulated merger rates of binary PBHs with subsolar masses

Gabriele Franciolini, Anshuman Maharana, Francesco Muia, arXiv:2205.02153 [astro-ph.CO]



axion + B → γ

⬇

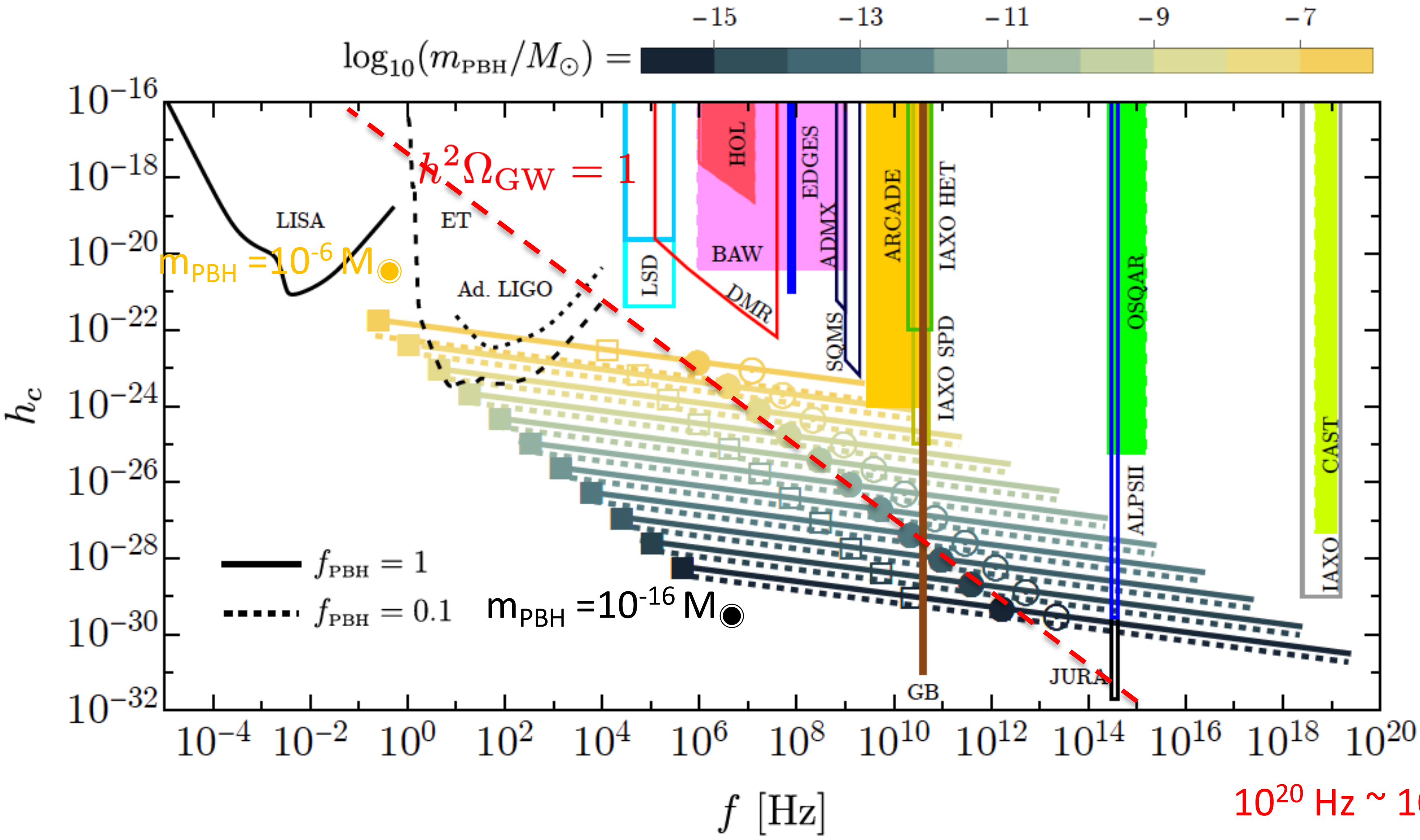
h + B → γ

10^{20} Hz ~ 100 keV

Rates for transient mergers of binary PBHs with subsolar masses

Gabriele Franciolini, Anshuman Maharana, Francesco Muia, arXiv:2205.02153 [astro-ph.CO]

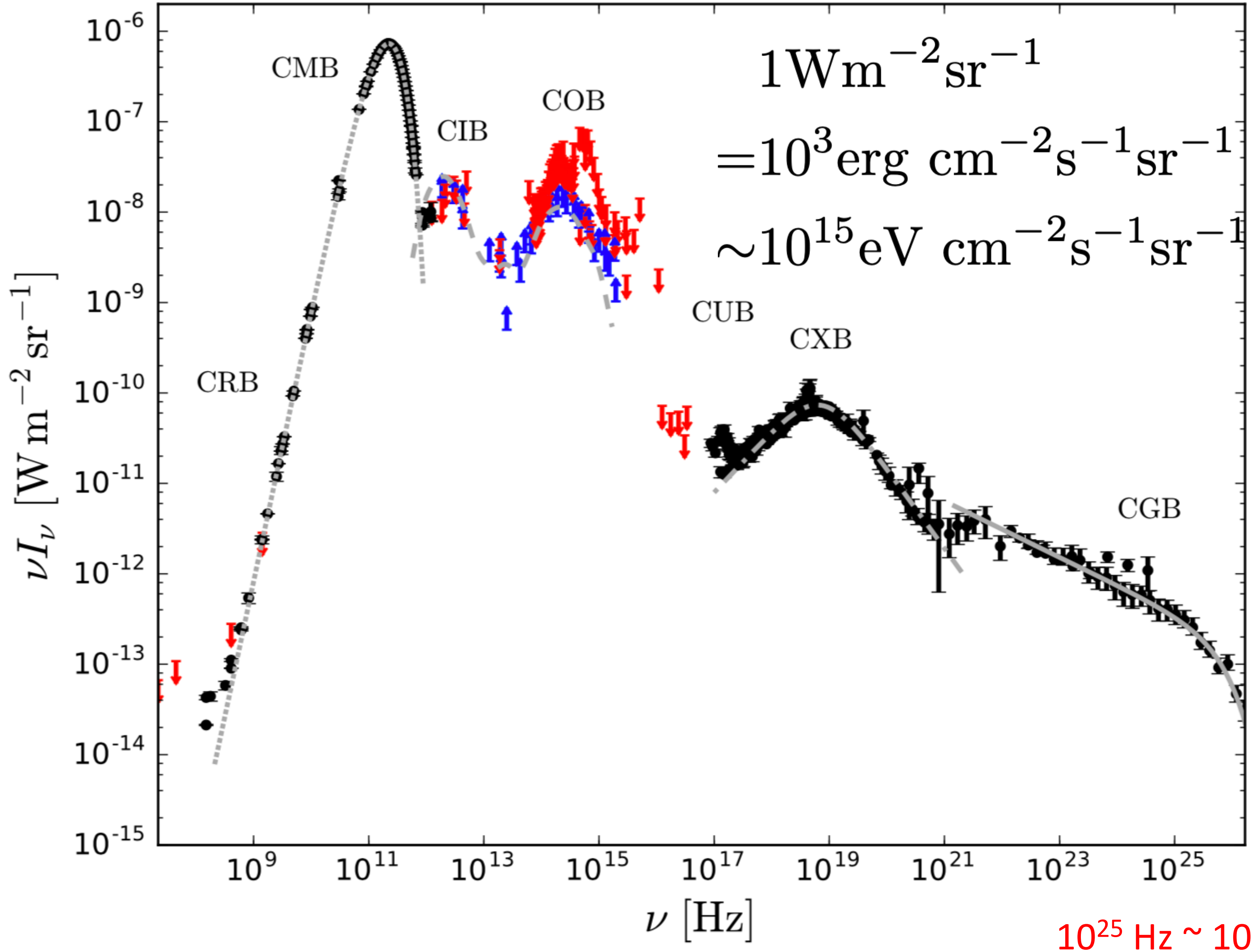
$$|h_c(f)| \simeq 4.54 \times 10^{-28} \left(\frac{m_{\rm PBH}}{10^{-12} M_\odot}\right)^{5/6} \left(\frac{d_{\rm L}}{\rm kpc}\right)^{-1} \left(\frac{f}{\rm GHz}\right)^{-1/6}$$



10^{20} Hz ~ 100 keV

Cosmic photon background

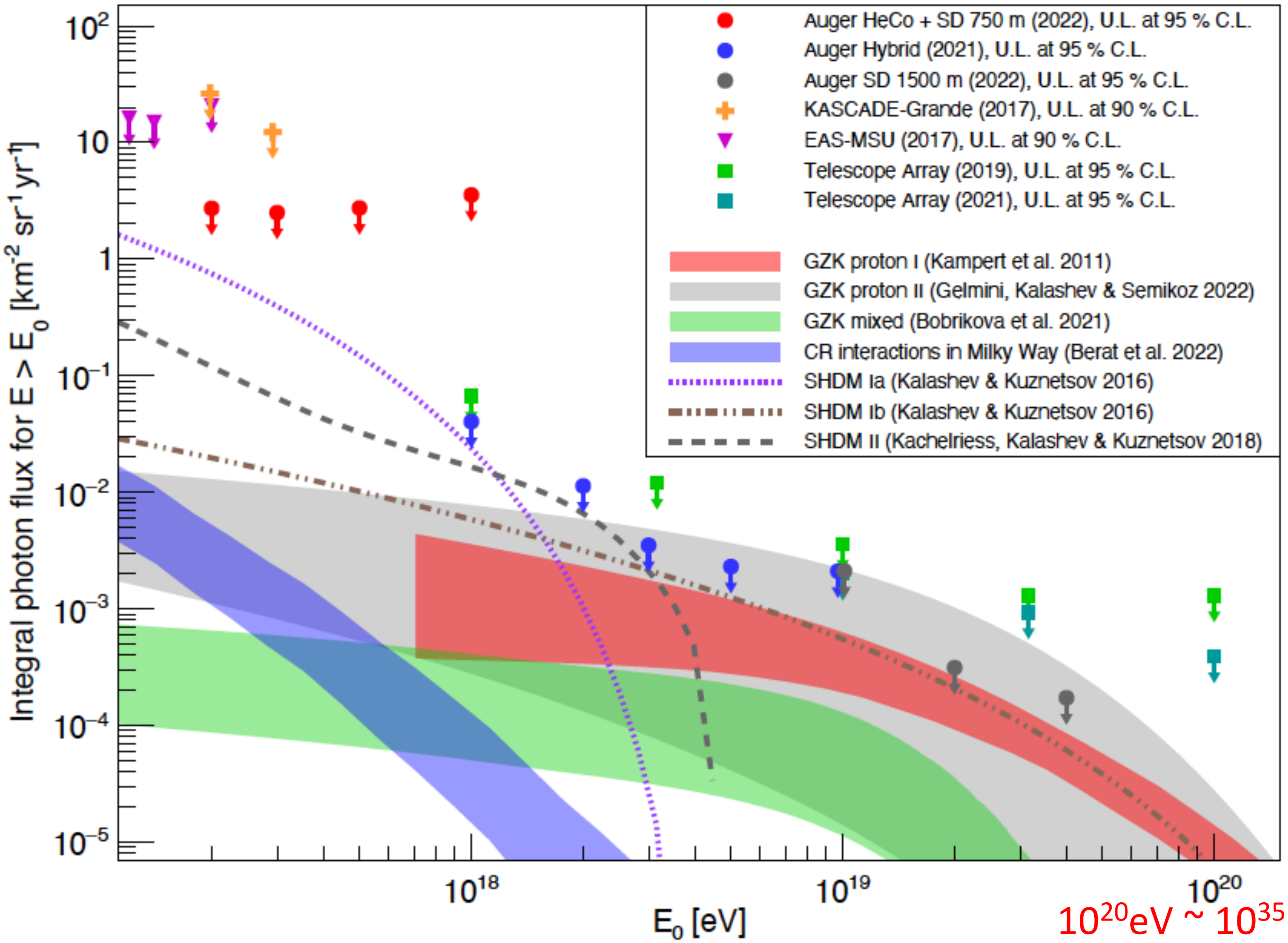
Ryley Hill, Kiyoshi W. Masui, Douglas Scott, arXiv:1802.03694 [astro-ph.CO]



10^{25} Hz ~ 10 GeV

Searches for Ultra-High-Energy Photons at the Pierre Auger Observatory

The Pierre Auger Collaboration: P. Abreu, et al., arXiv:2210.12959 [astro-ph.HE]



10^{20}eV ~ 10^{35} Hz

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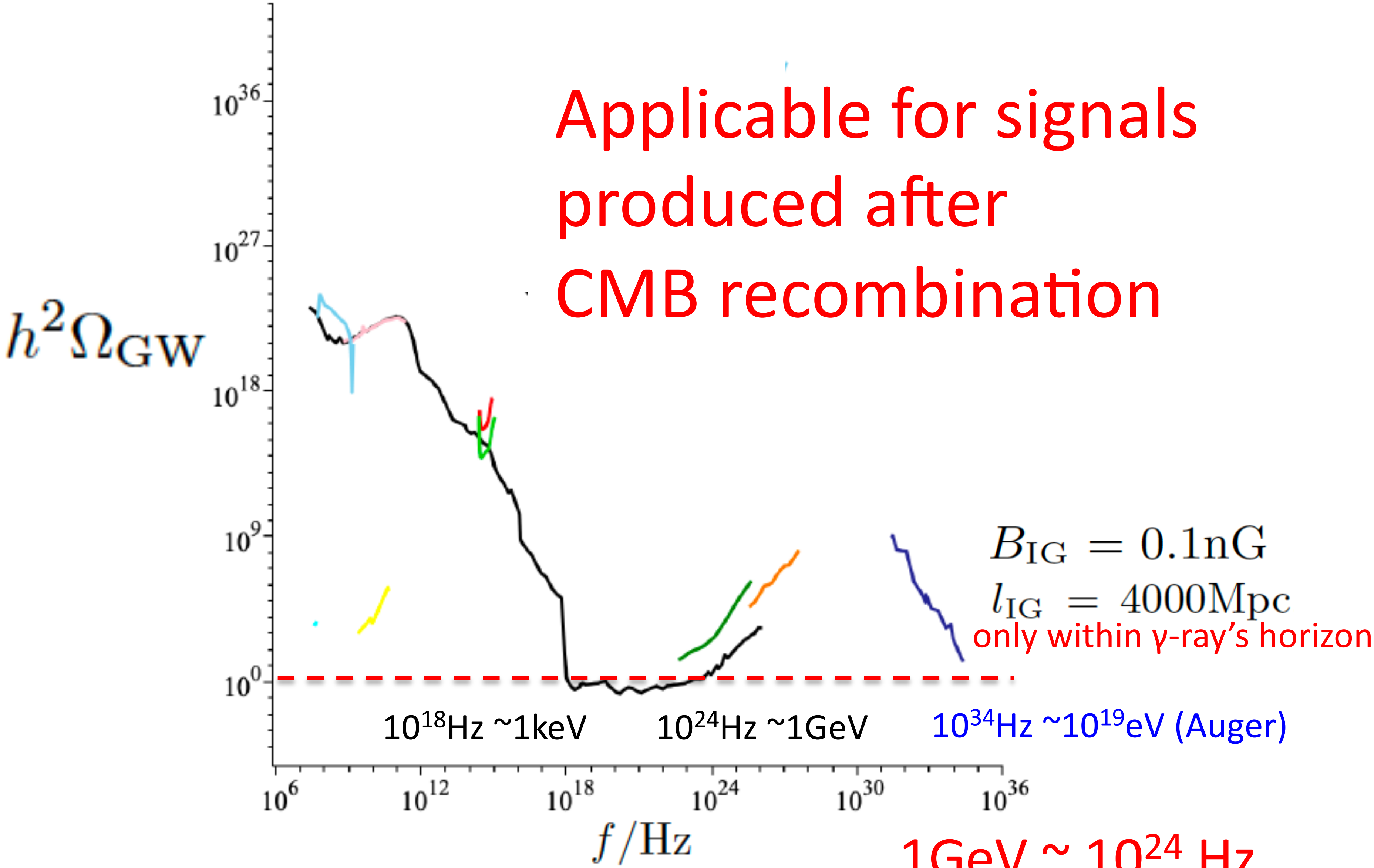
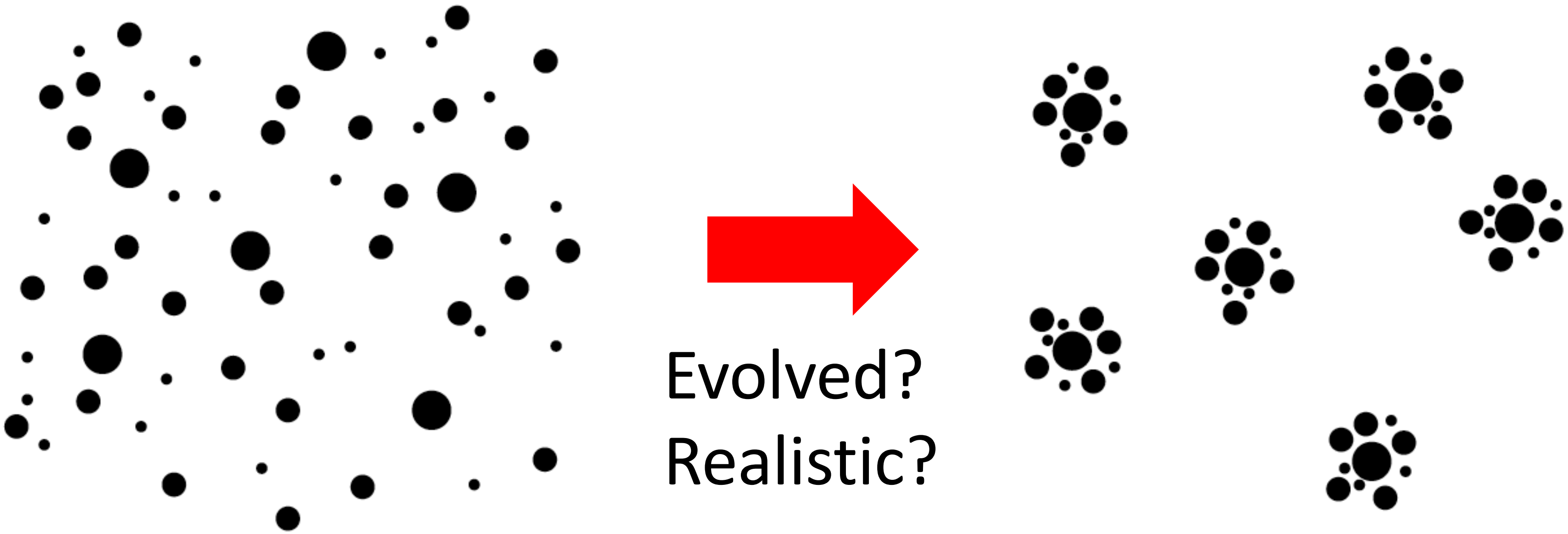


1GeV ~ 10^{24} Hz

Confusion of Words

Clustering or Clusters of PBHs?

Yacine Ali-Haïmoud, arXiv:1805.05912 [astro-ph.CO]



Initial Clustering of PBHs

Clusters of PBHs

$P_{\text{PBH-PBH}}$ → bound objects?

V. Desjacques and A. Riotto, arXiv:1806.10414
T. Suyama and S. Yokoyama,arXiv:1906.04958
T.Matsubara, T.Terada, K.Kohri, S.Yokoyama, arXiv:1909.04053

J. R. Chisholm, astro-ph/0509141.

Conclusion

- The search for high-frequency GWs is a new direction for investigating phenomena in the early Universe.
- The targets are so many:

  1. GWs from merging binary (ultra-)light PBHs
  2. etc.

- We can test high-frequency GWs by observing the electromagnetic wave converted from them.