Online: New open window for dark matter with Memory Burden Effect in evaporating black holes

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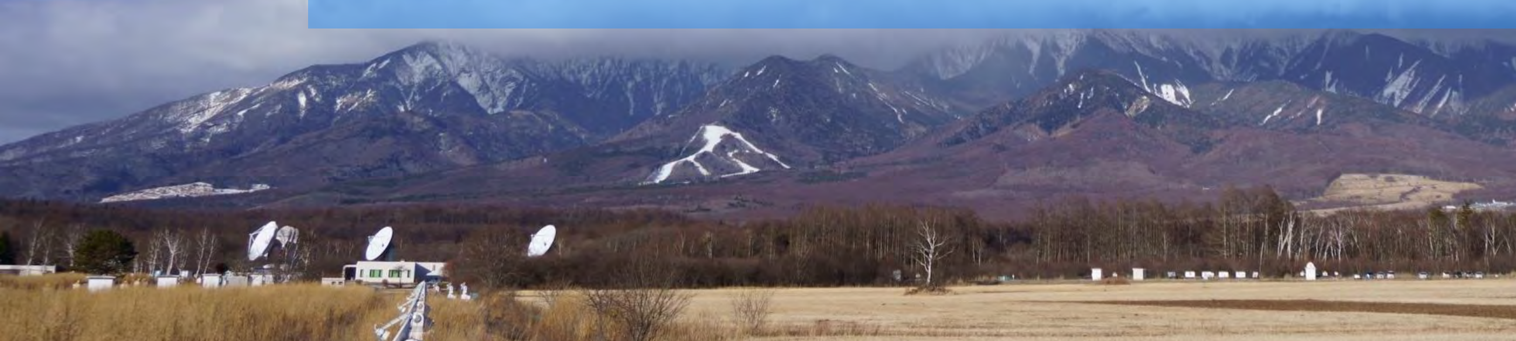
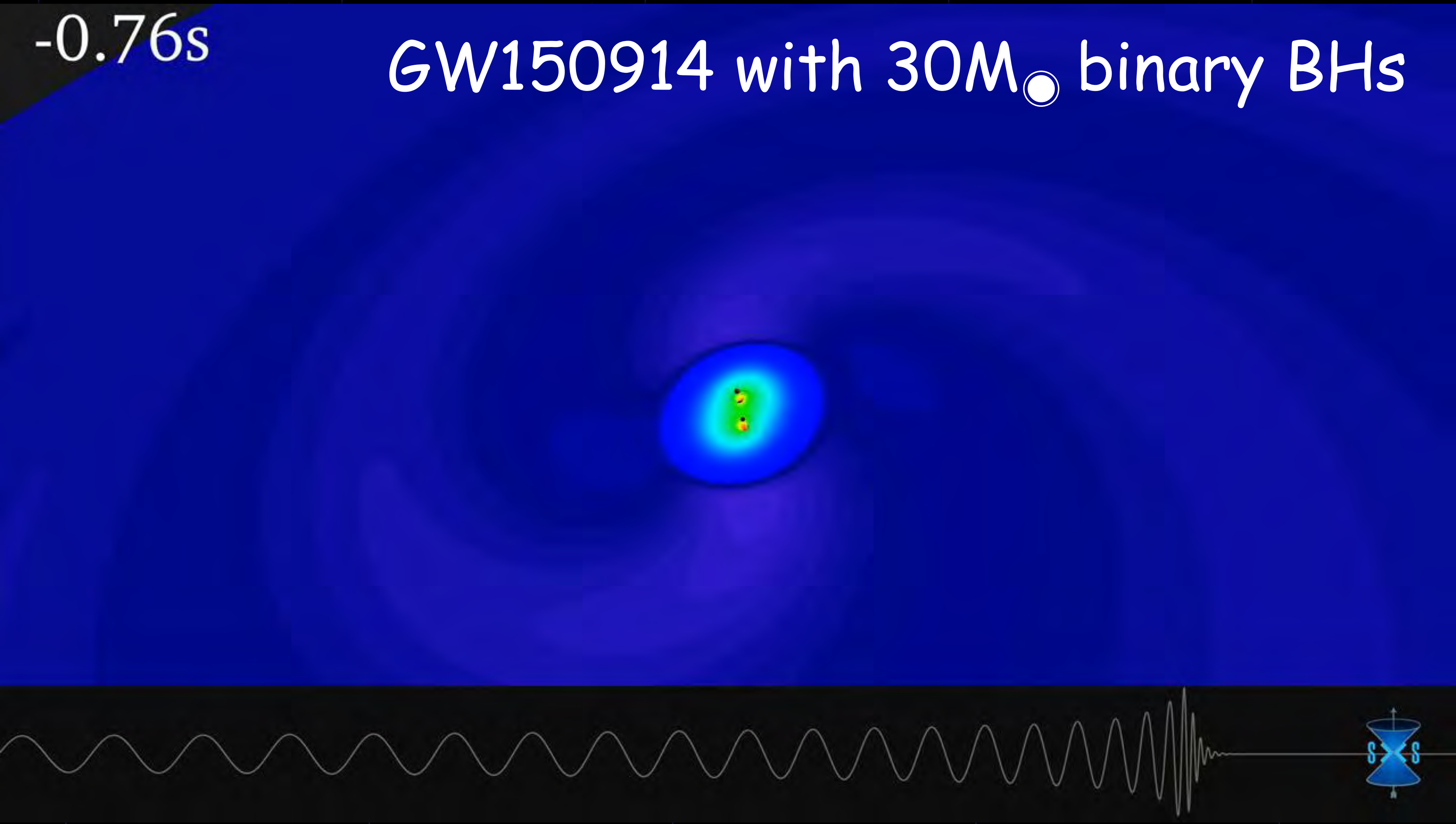


SOKENDAI QUP NAOJ iFPNs KEK 理論センター THEORY CENTER KAVLI IPMU

Detections of GWs from binary PBHs collide?

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

GW150914 with 30$M_\odot$ binary BHs

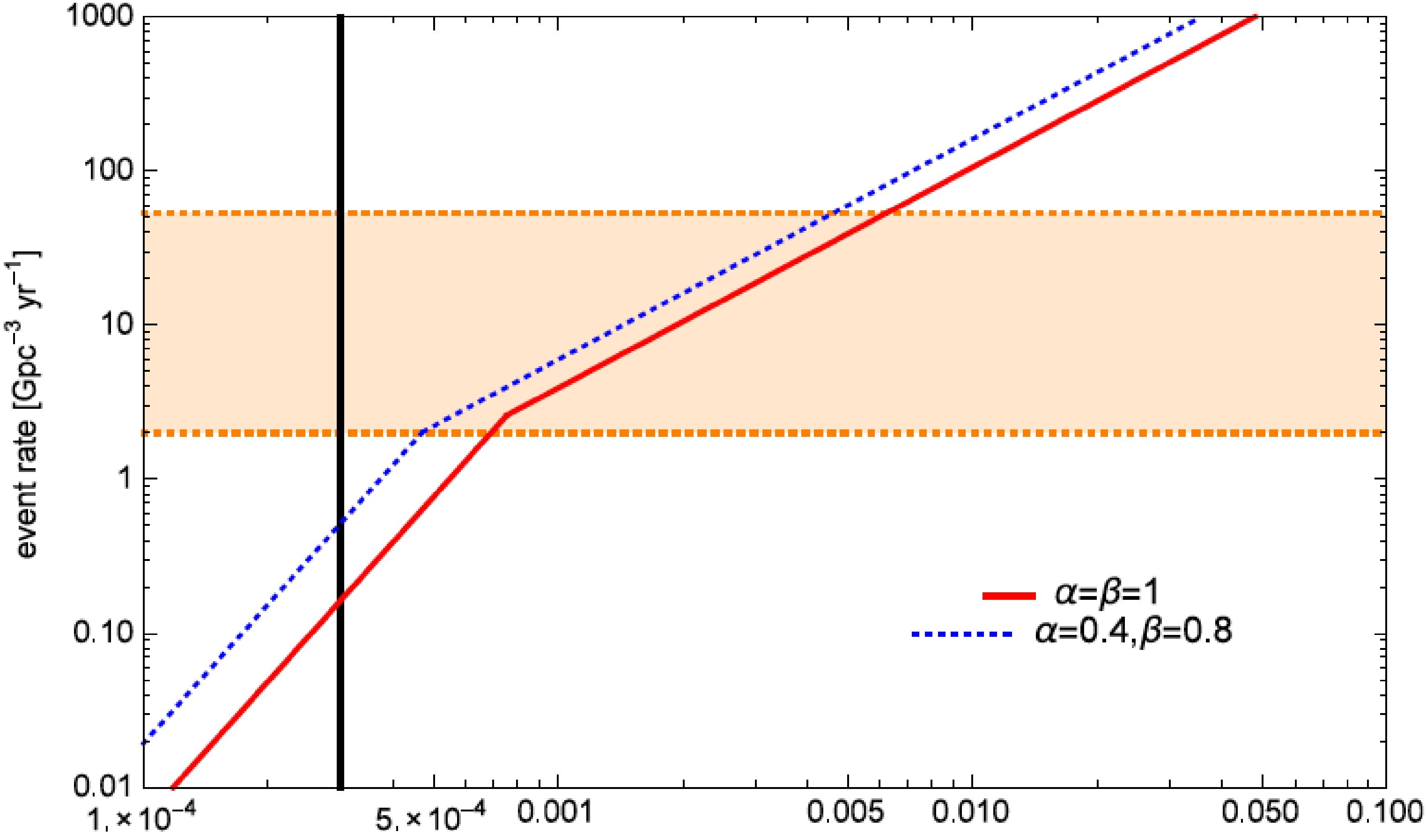


GW150914 and its merger rates for 30 M_{solar} masses BBH

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

A 3-body effect is important for the BBH formations

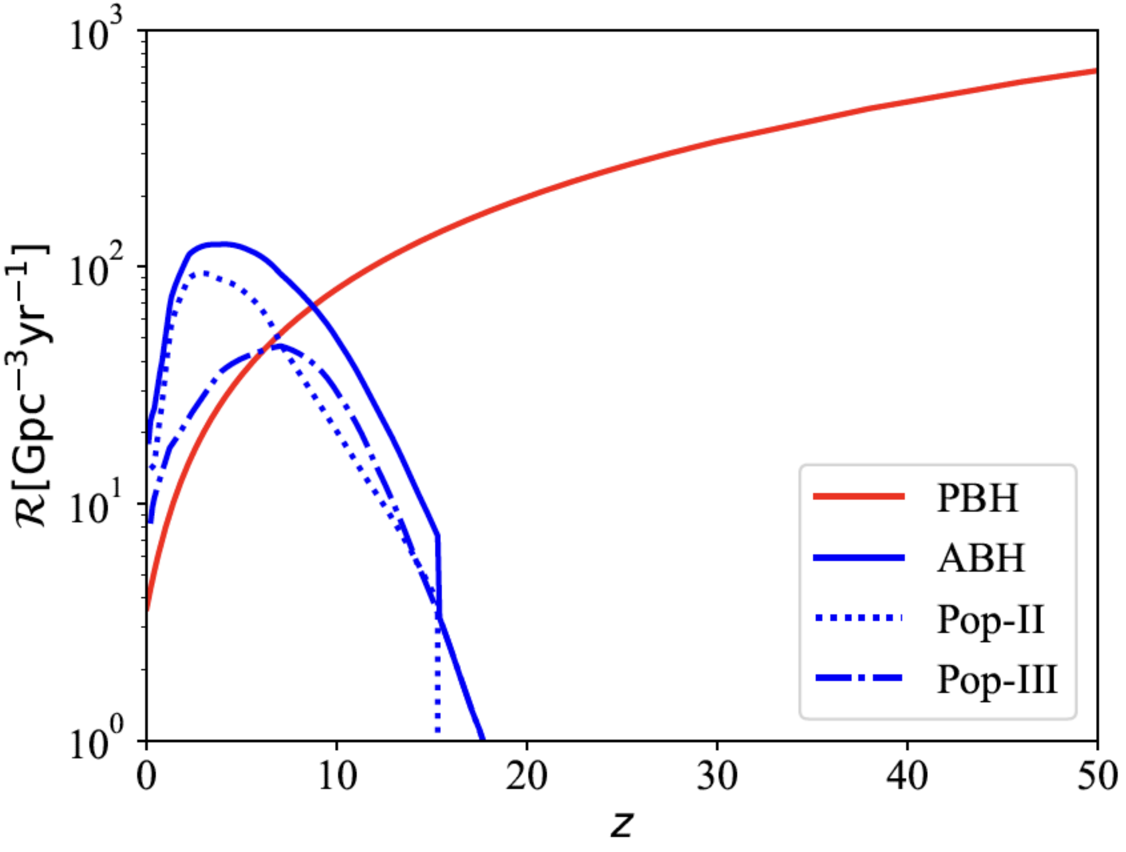
Event rates of Binary BH mergers



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]



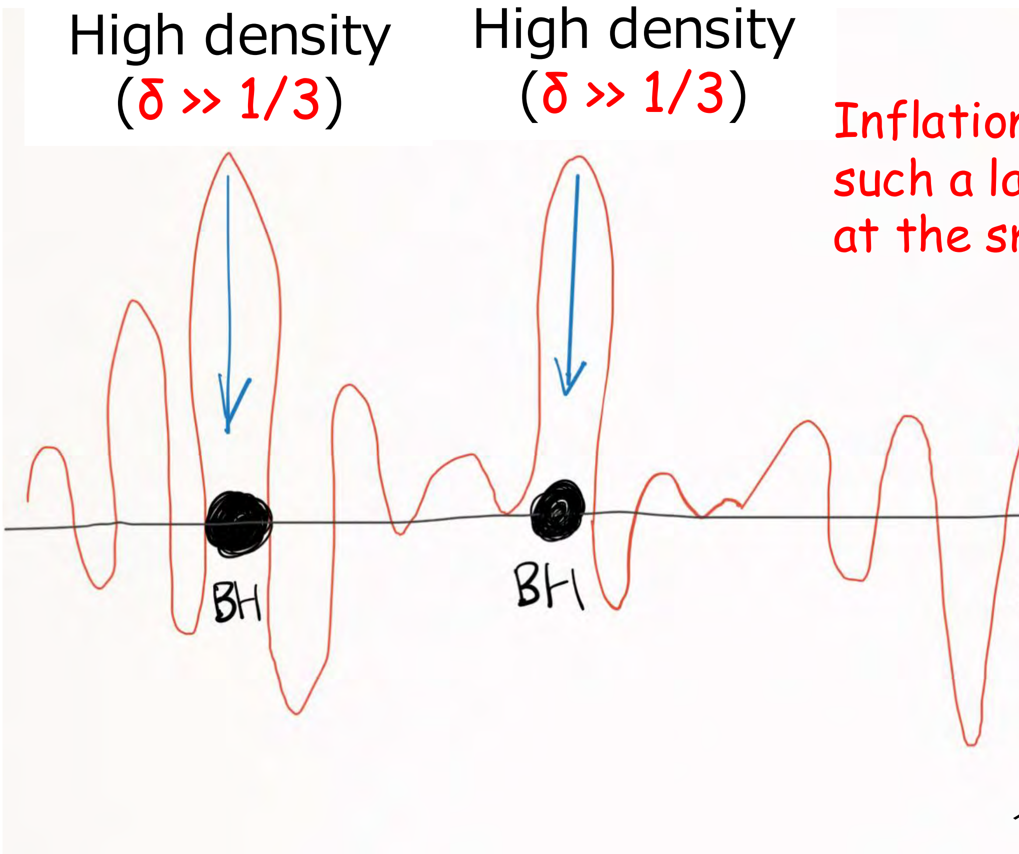
$$1/z \sim \frac{a(t)}{a(t_0)} \sim \left(t/10\mathrm{Gyr}\right)^{2/3}$$

Primordial Black Holes

Bernard J. Carr, Astrophys. J. 201 (1975) 1

- High density perturbation (δ >> 1/3) collapsed to PBHs

$$\delta > \delta_c \sim p / \rho \sim c_s^2 = w = 1/3$$



Inflation could have produced such a large perturbation at the small scales

イメージです
This is a cartoon

Type-III Hilltop inflation models

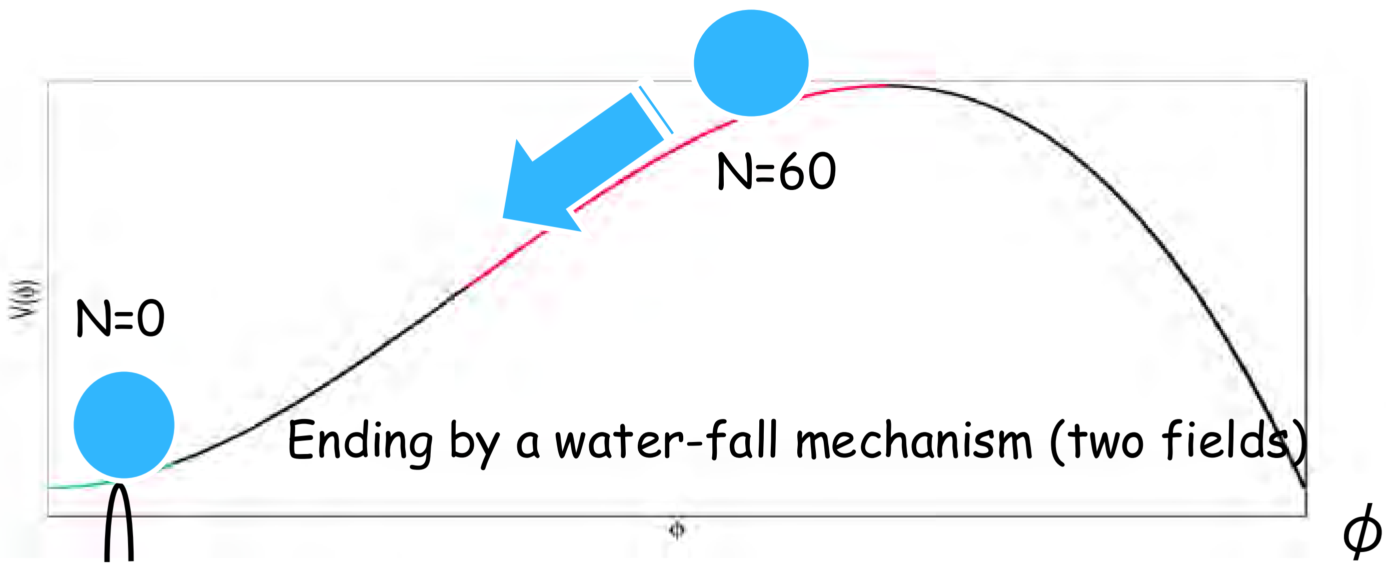
German, Ross, Sarkar (01)
KK, Lin and Lyth (07)

Potential in supergravity, e.g.,

$$V(\phi) = V_0 + \frac{1}{2}m^2\phi^2 - \lambda\frac{\phi^p}{M_P^{p-4}} + \cdots$$

$$W = C\frac{\phi^\rho}{M_{pl}^{p-3}}, \quad \lambda \sim C m_{3/2}/M_{pl}$$ in SUGRA

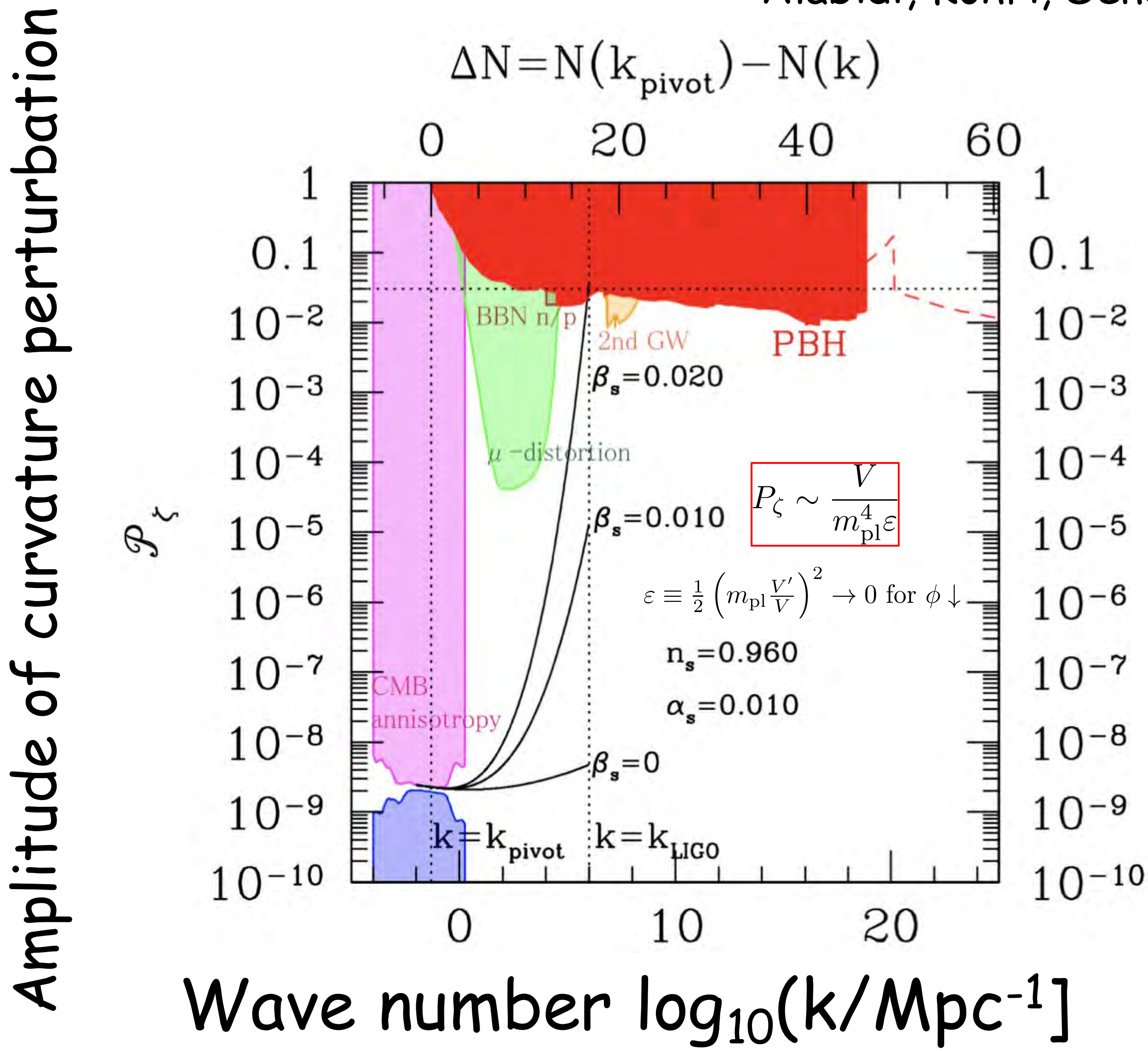
Allahverdi, Kusenko and Mazumdar (06)



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

Higgs-R^2 Inflation

Dhong Yeon Cheong, Kazunori Kohri, Seong Chan Park, arXiv:2205.14813 [hep-ph]

- Action of Higgs and R^2

$$S_J = \int d^4x\sqrt{-g_J}\left[\frac{M_P^2}{2}\left(R_J + \frac{\xi h^2}{M_P^2}R_J + \frac{R_J^2}{6M^2}\right) - \frac{1}{2}g^{\mu\nu}\nabla_\mu h \nabla_\nu h - \frac{\lambda(\mu)}{4}h^4\right]$$

- Conformal transformation

$$\alpha = M_P^2/12M^2$$

$$\sqrt{\frac{2}{3}}\frac{s}{M_P} = \ln\left(1 + \frac{\xi h^2}{M_P^2} + \frac{R_J}{3M^2}\right) \equiv \Omega(s).$$

- Action of scalaron (s) and Higgs (h)

$$S = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R - \frac{1}{2}G_{ab}g^{\mu\nu}\nabla_\mu\phi^a\nabla_\nu\phi^b - U(\phi^a)\right]$$

$$U(\phi^a) \equiv e^{-2\Omega(s)}\left\{\frac{3}{4}M_P^2M^2\left(e^{\Omega(s)} - 1 - \frac{\xi h^2}{M_P^2}\right)^2 + \frac{\lambda(\mu)}{4}h^4\right\}$$

$$g_{\mu\nu} = e^{\Omega(s)}g_{\mu\nu}^J \qquad G_{ab} = \begin{pmatrix}1 & 0\\ 0 & e^{-\Omega(s)}\end{pmatrix}$$

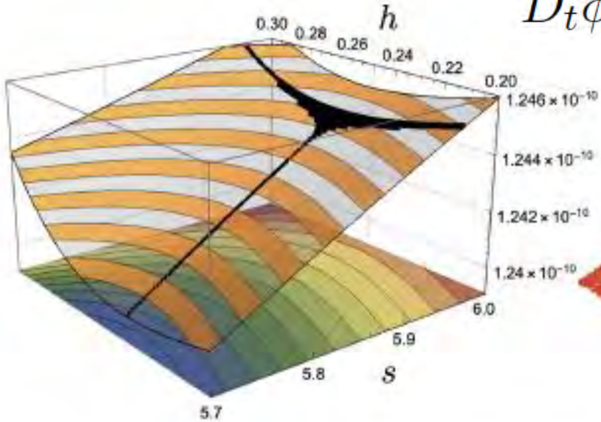
Motions on the potential of the Higgs-scalaron (s) system

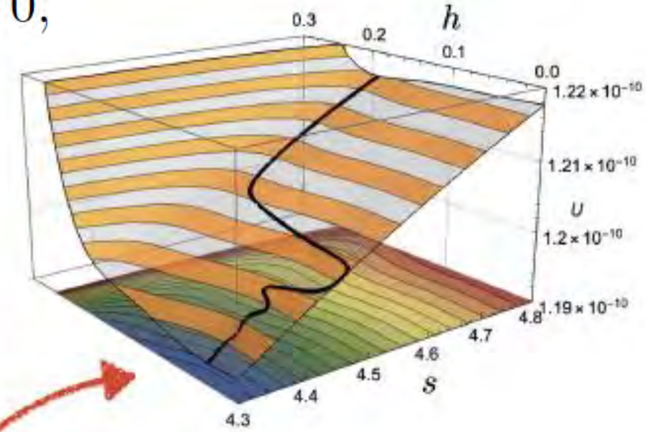
Dhong Yeon Cheong, Kazunori Kohri, Seong Chan Park, arXiv:2205.14813 [hep-ph]

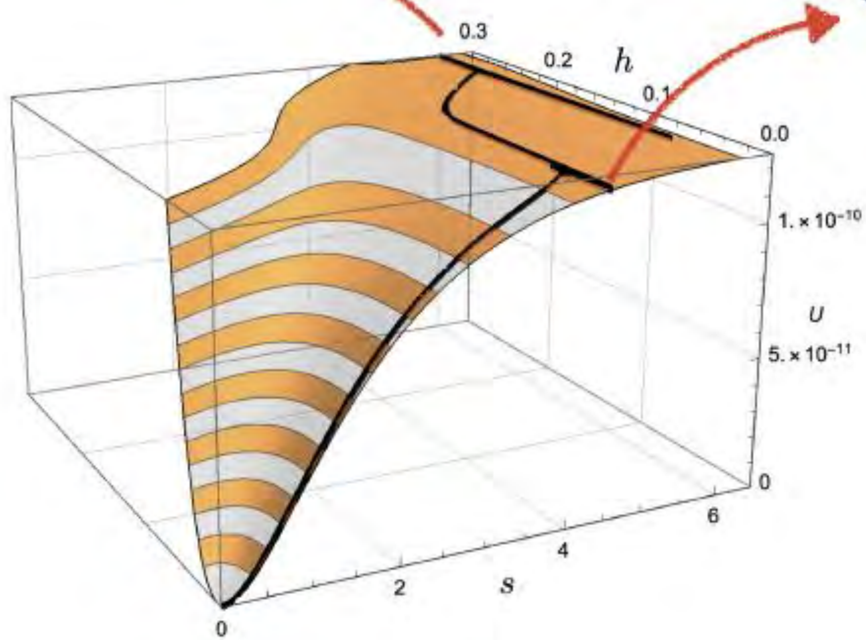
$$D_t\dot{\phi}^a + 3H\dot{\phi}^a + G^{ab}D_bU = 0,$$

$\phi^s = s$

$\phi^h = h$







Tachyonic Instability induced in Higgs-R^2 Inflation

Dhong Yeon Cheong, Kazunori Kohri, Seong Chan Park, arXiv:2205.14813 [hep-ph]

$$\ddot{Q}_N + 3H\dot{Q}_N + \left(\frac{k^2}{a^2} + M_{\rm eff}^2\right) Q_N = 2\dot{\phi}_0 \eta_\perp \dot{\mathcal{R}}$$

$$M_{\rm eff}^2 = U_{NN} + H^2 \epsilon \mathbb{R} - \dot{\theta}^2 \qquad U_{NN} < 0,$$

$$M_{\rm eff}^2 \simeq \frac{1}{\dot{s}^2 + e^{-\sqrt{\frac{2}{3}}s}\dot{h}^2}\left(e^{\sqrt{\frac{2}{3}}s}\dot{s}^2 \frac{\partial^2 U}{\partial h^2}\right) \simeq -3M^2\xi\left(1 - e^{-\sqrt{\frac{2}{3}}s}\right).$$

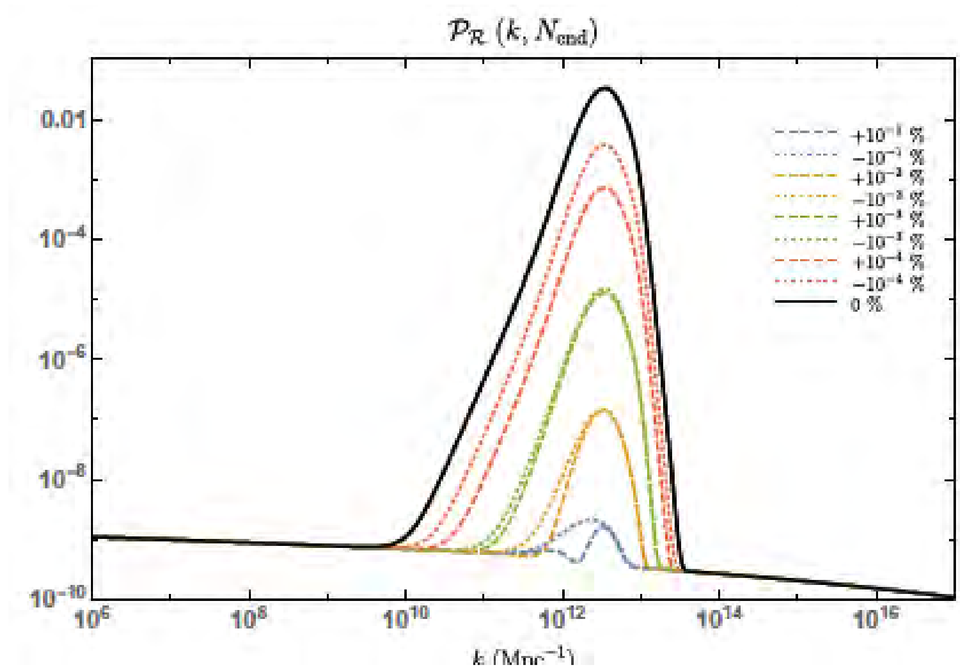
Hence Q_N can exhibit an *exponential* growth due to the tachyonic mass. This growth can be more rapid than cases implementing a USR phase.

$$Q_{N,k}(N_e) = e^{-\frac{3}{2}N_e}\left[d_3\, e^{-\frac{N_e}{2}\sqrt{9-4\frac{M_{\rm eff}^2}{H^2}-4\epsilon_k^2}} + d_4\, e^{\frac{N_e}{2}\sqrt{9-4\frac{M_{\rm eff}^2}{H^2}-4\epsilon_k^2}}\right]$$

$$\xrightarrow[|M_{\rm eff}^2| \gg H^2]{\epsilon_k^2 \ll 1} d_4\, e^{\left(\frac{|M_{\rm eff}|}{H} - \frac{3}{2}\right)N_e}$$

Primordial Black Holes and Second Order Gravitational Waves from Tachyonic Instability induced in Higgs-R^2 Inflation

Dhong Yeon Cheong, Kazunori Kohri, Seong Chan Park, arXiv:2205.14813 [hep-ph]



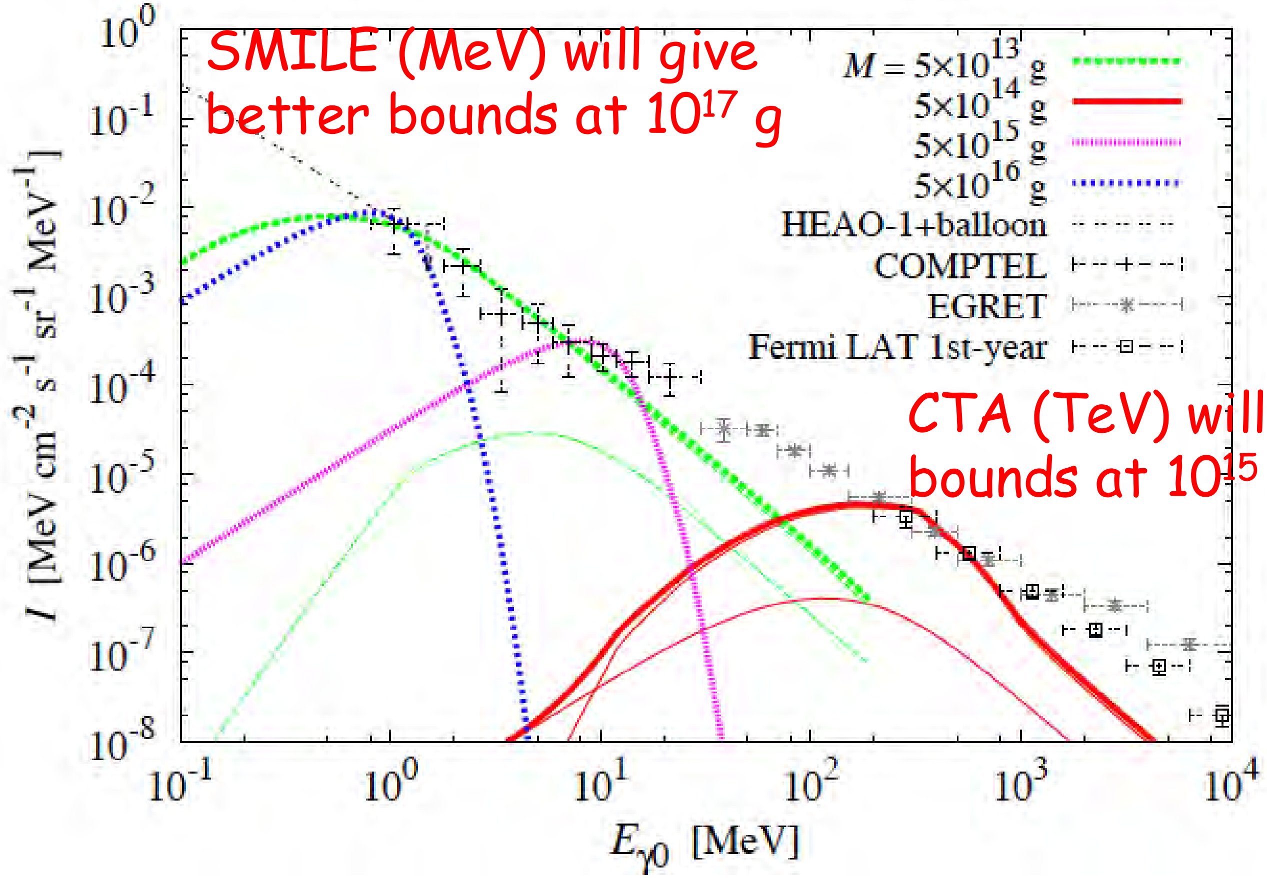
$$\delta\lambda_m/\lambda_m$$

$$\delta\lambda_m/\lambda_m \equiv (\lambda_m^{dev} - \lambda_m)/\lambda_m \sim 10^{-4}\,\%$$

Evaporating PBHs through Hawking Process

Carr, Kohri, Sendouda and Yokoyama (2010)

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



M31 lensing on PBHs modified by size-distribution and finite-size effects on bright star sources

Nolan Smyth, Stefano Profumo, Samuel English, Tesla Jeltema, Kevin McKinnon, Puragra Guhathakurta, arXiv:1910.01285 [astro-ph.CO]

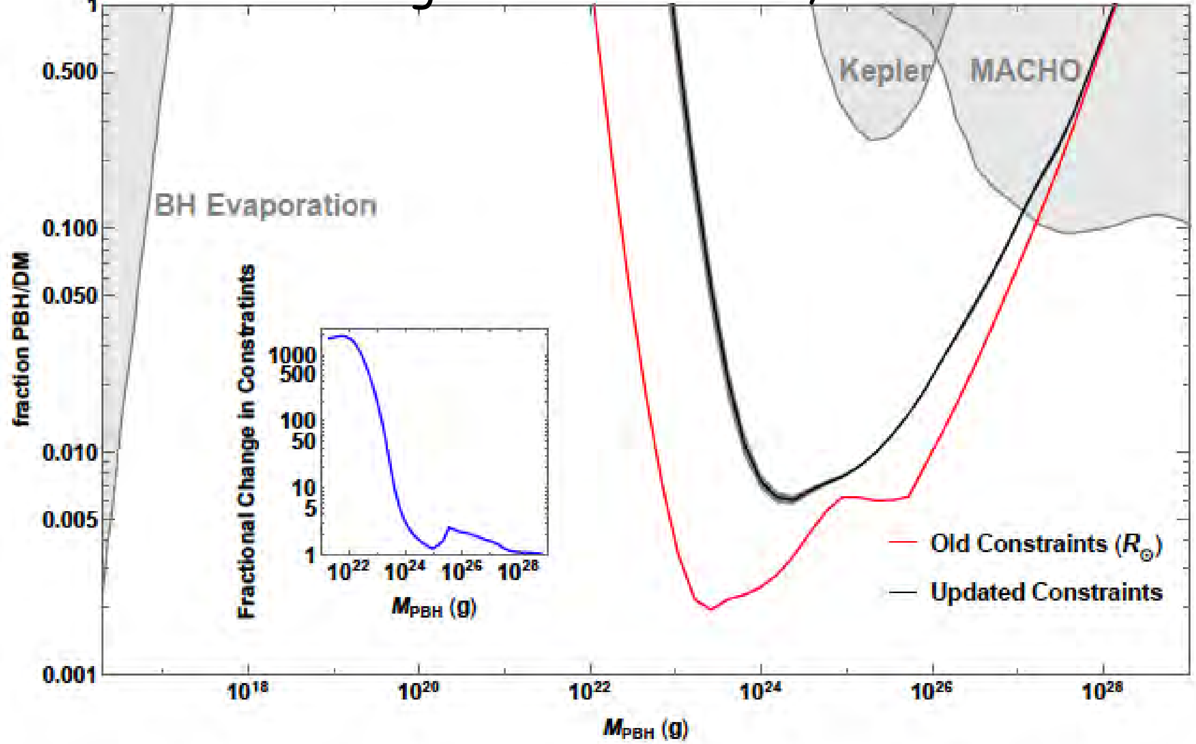
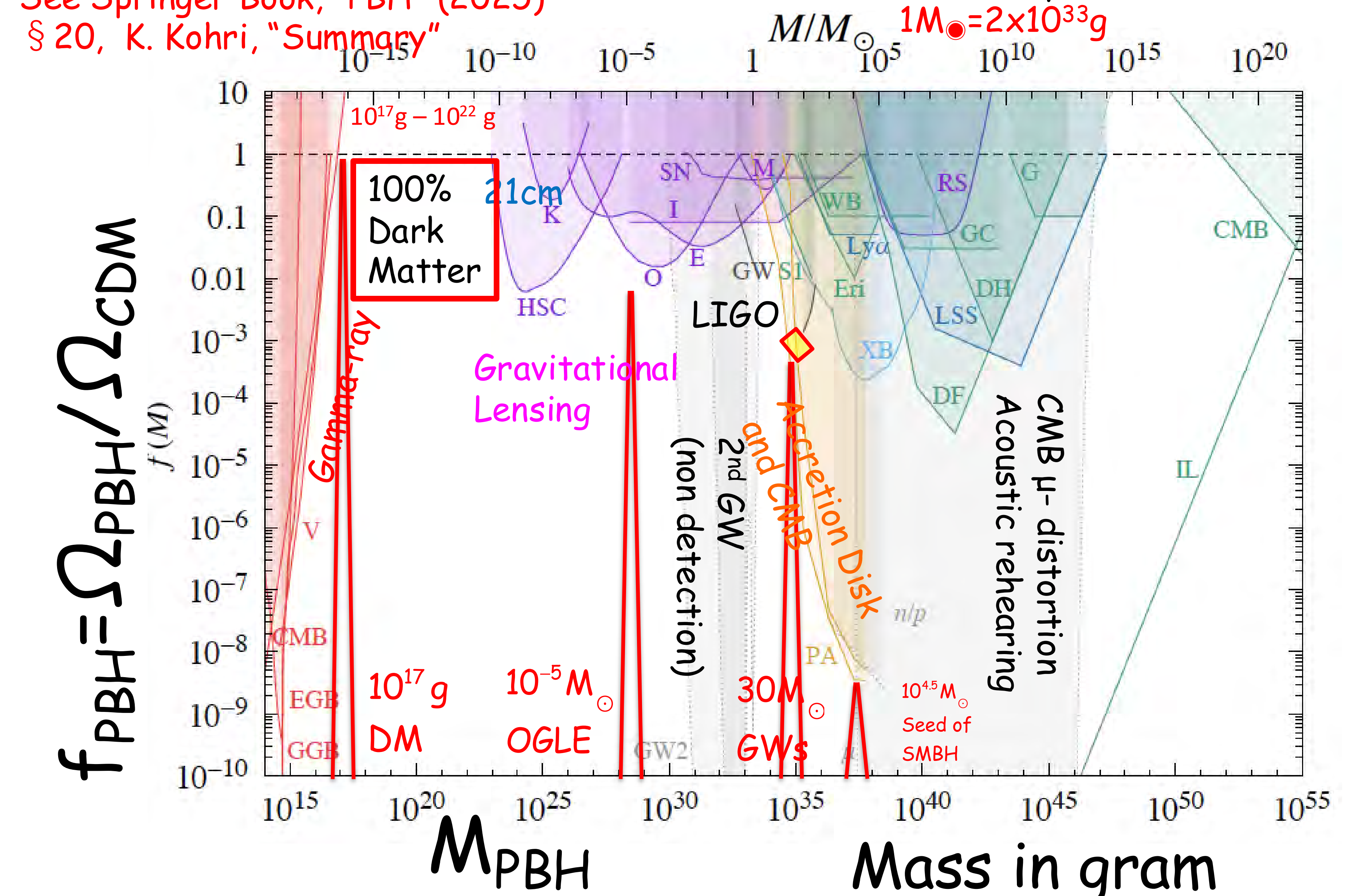


Figure 2. The constraints on primordial black holes as dark matter. The black line is the benchmark constraint and the primary result of this paper. The gray shading comes from the uncertainty in determining the stellar size distribution. The red line is the previous constraint which includes finite-size effects, but assumes that all stars in M31 have a radius of $R_\odot$.

Upper bounds on the fraction to CDM

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

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



Secondary gravitational wave induced from large curvature perturbation ($P_\zeta >> r$) 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
KK and T.Terada, 2018
R.-G. Cai, S. Pi, and M. Sasaki, 2019

- Power spectrum of the tensor mode

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

- Omega parameter well inside the horizon

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

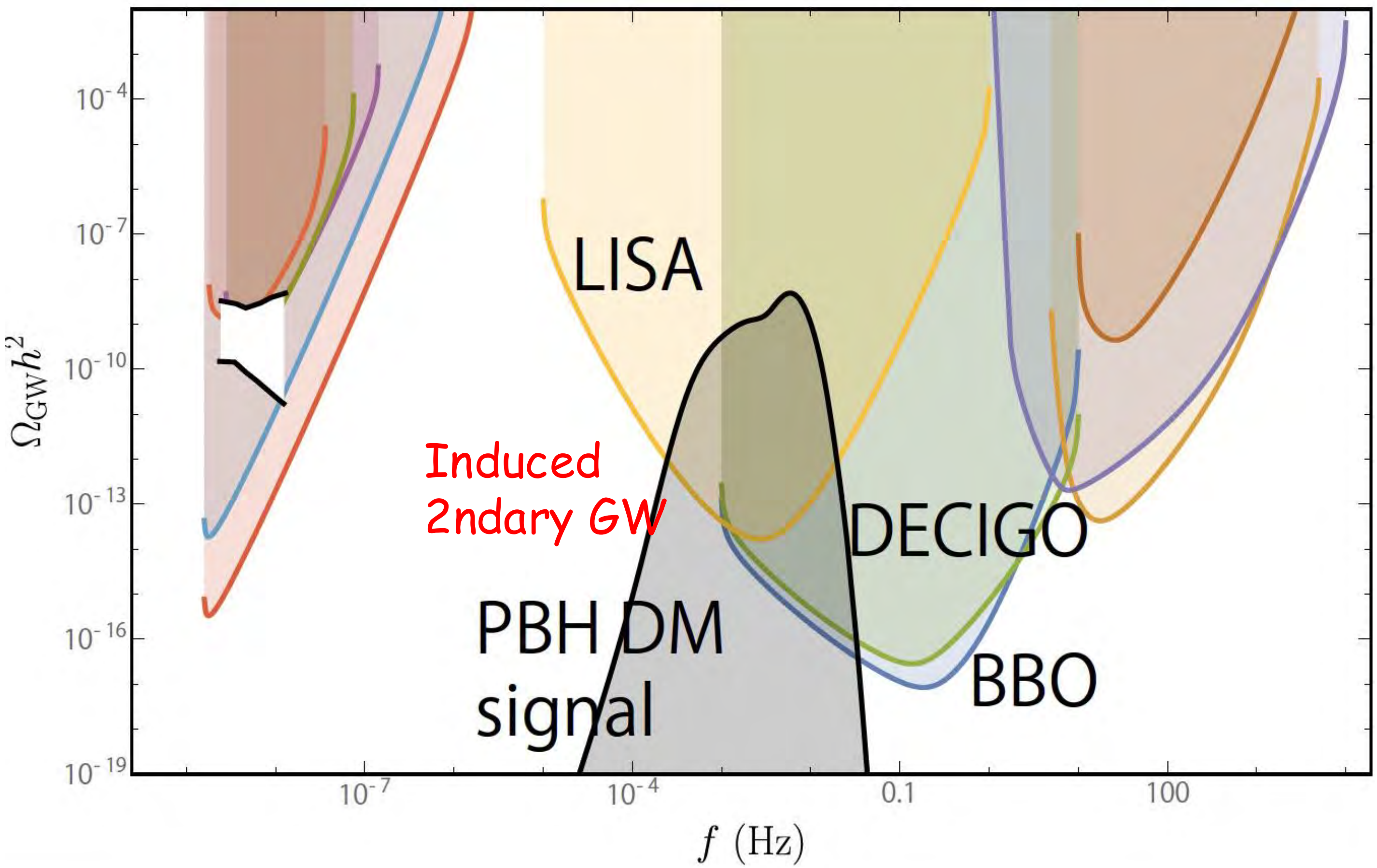
- Substituting the solution into this

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

Primordial Black Holes and Second Order Gravitational Waves from Tachyonic Instability induced in Higgs-R^2 Inflation

Dhong Yeon Cheong, Kazunori Kohri, Seong Chan Park, arXiv:2205.14813 [hep-ph]

See also, K. Kohri and T. Terada, arXiv:2009.11853

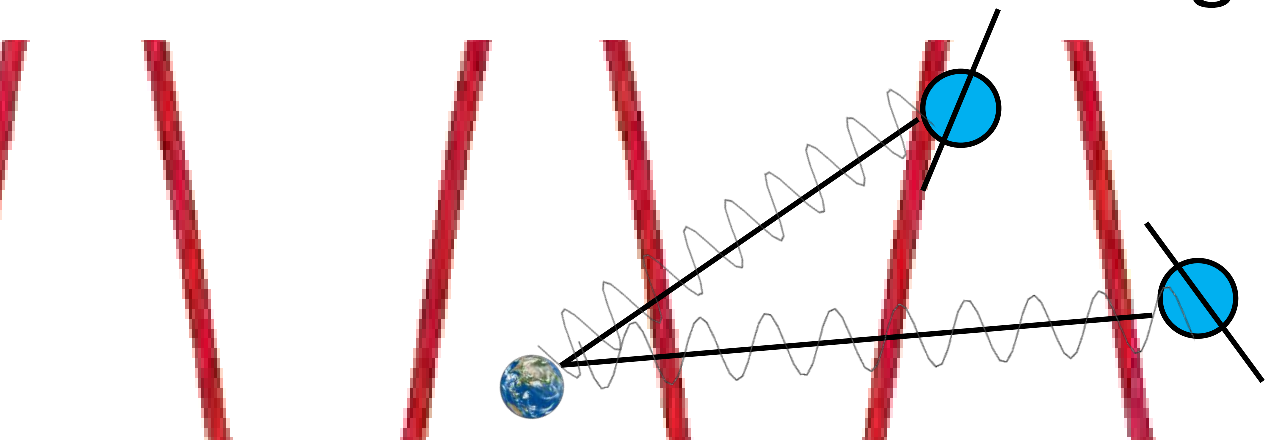


Gabriella Agazie, et al, The NANOGrav15yr collaboration, arXiv:2306.16213 [astro-ph.HE]

NANOGrav 15yr

(North American Nanohertz Observatory for Gravitational Waves)

found stochastic GWs through pulsar timing

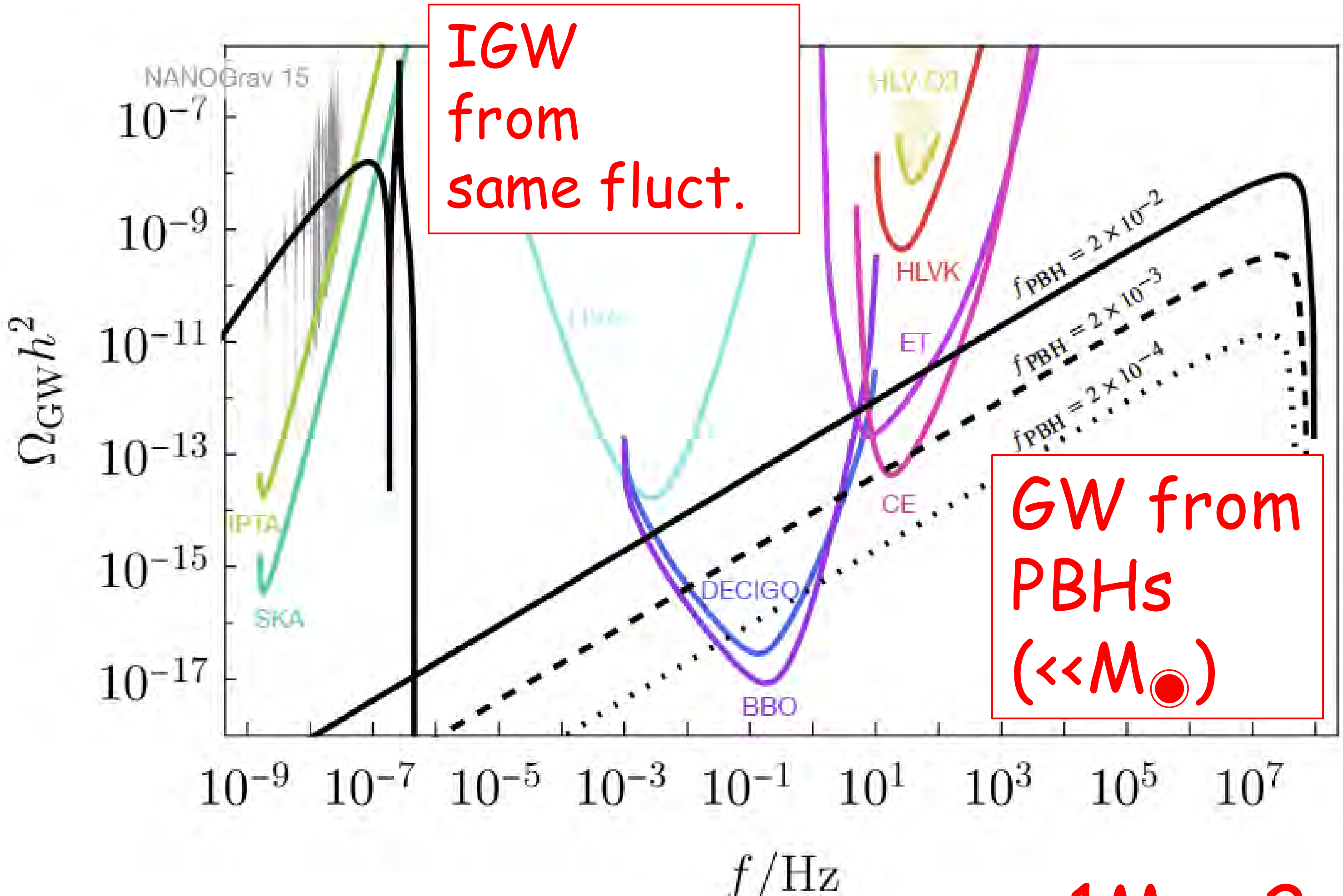


The 305-meter dish of the William E. Gordon Telescope, The Arecibo Obs.

The 100-meter Green Bank Telescope

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

Memory Burden Effects in evaporating BHs

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

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]

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

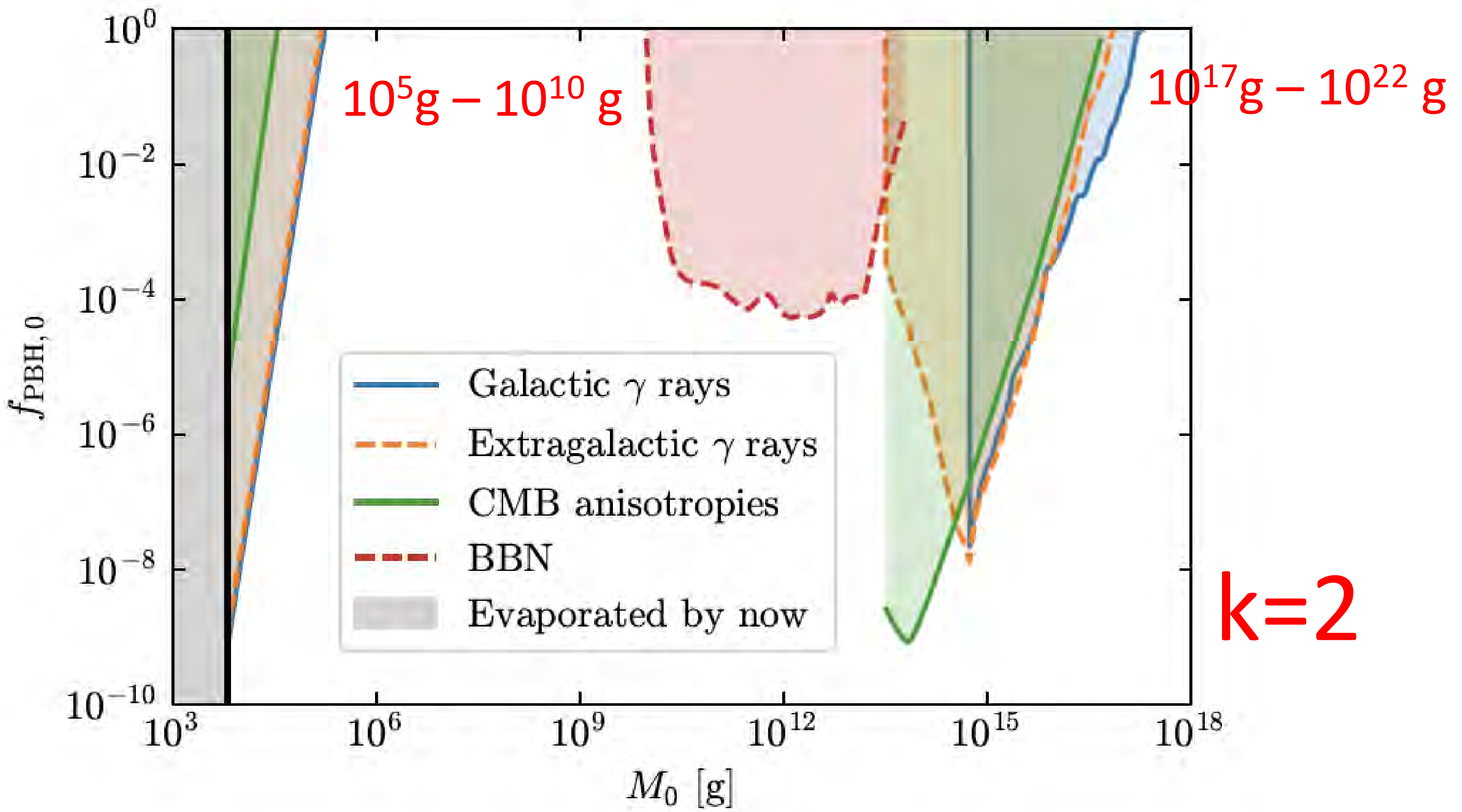
k=2

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

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

Breakdown of Hawking Evaporation opens new Mass Window PBHs as DM

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



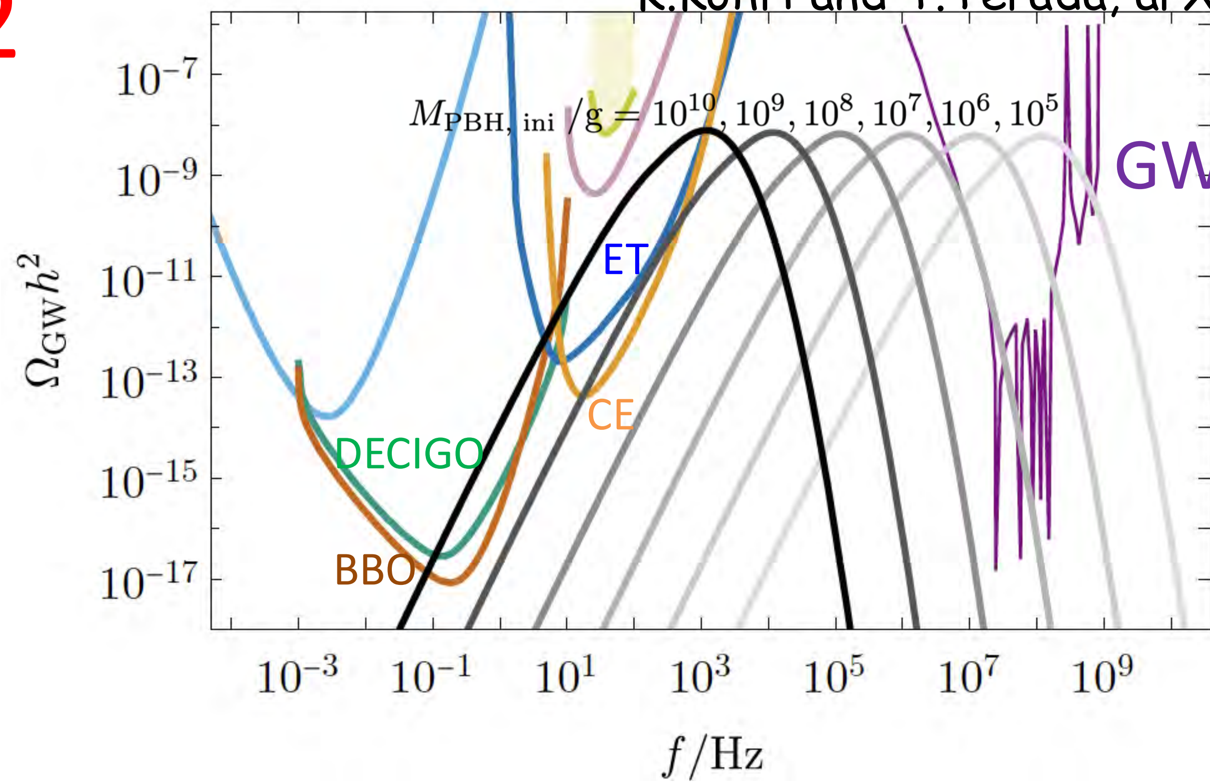
Induced Gravitational Wave probing Primordial Black Hole Dark Matter with Memory Burden

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

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

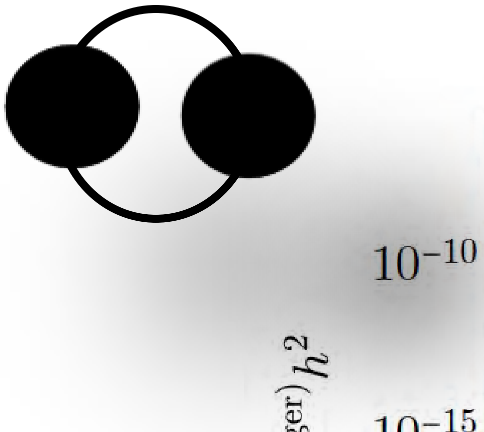
K.Kohri and T.Terada, arXiv:1804.08577

k=2

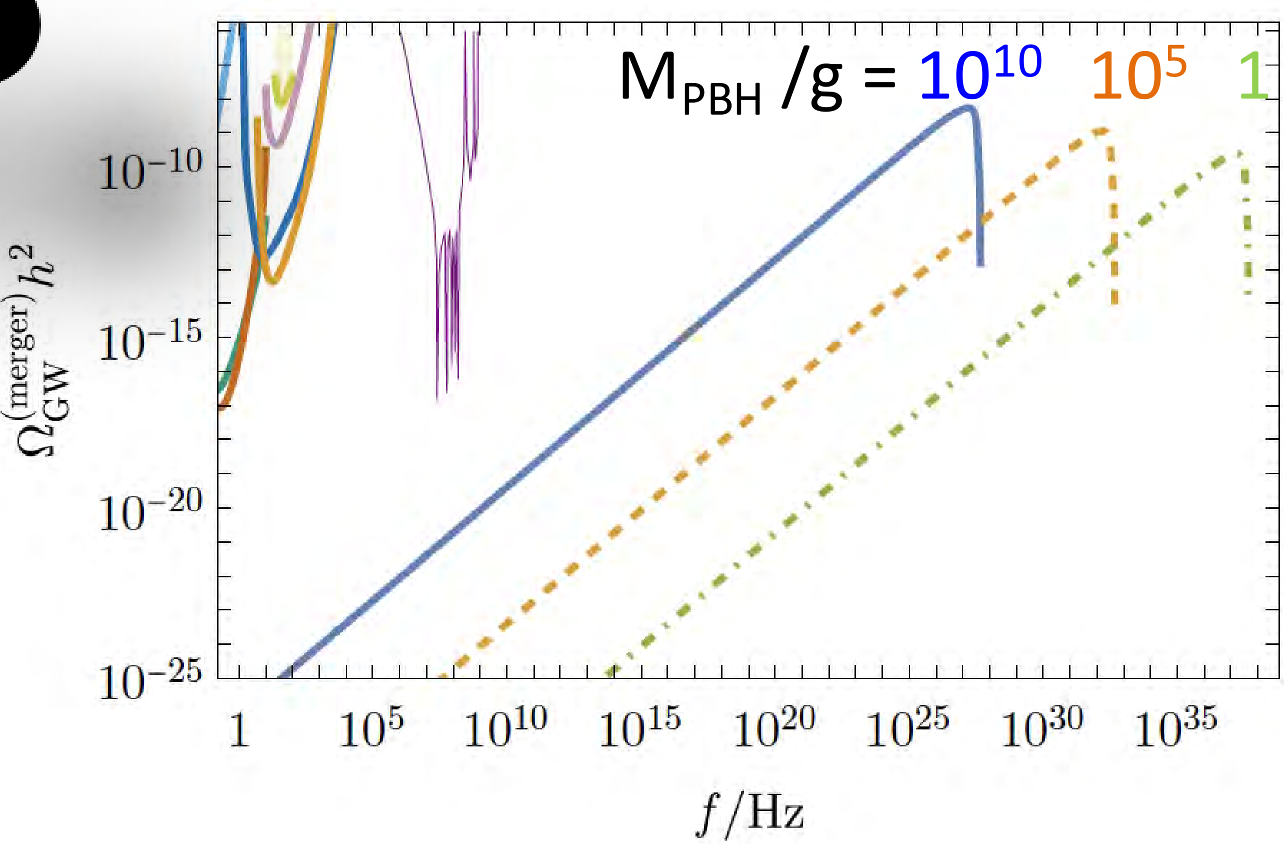


Induced Gravitational Waves probing Primordial Black Hole Dark Matter with Memory Burden

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



GW + B → γ



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]

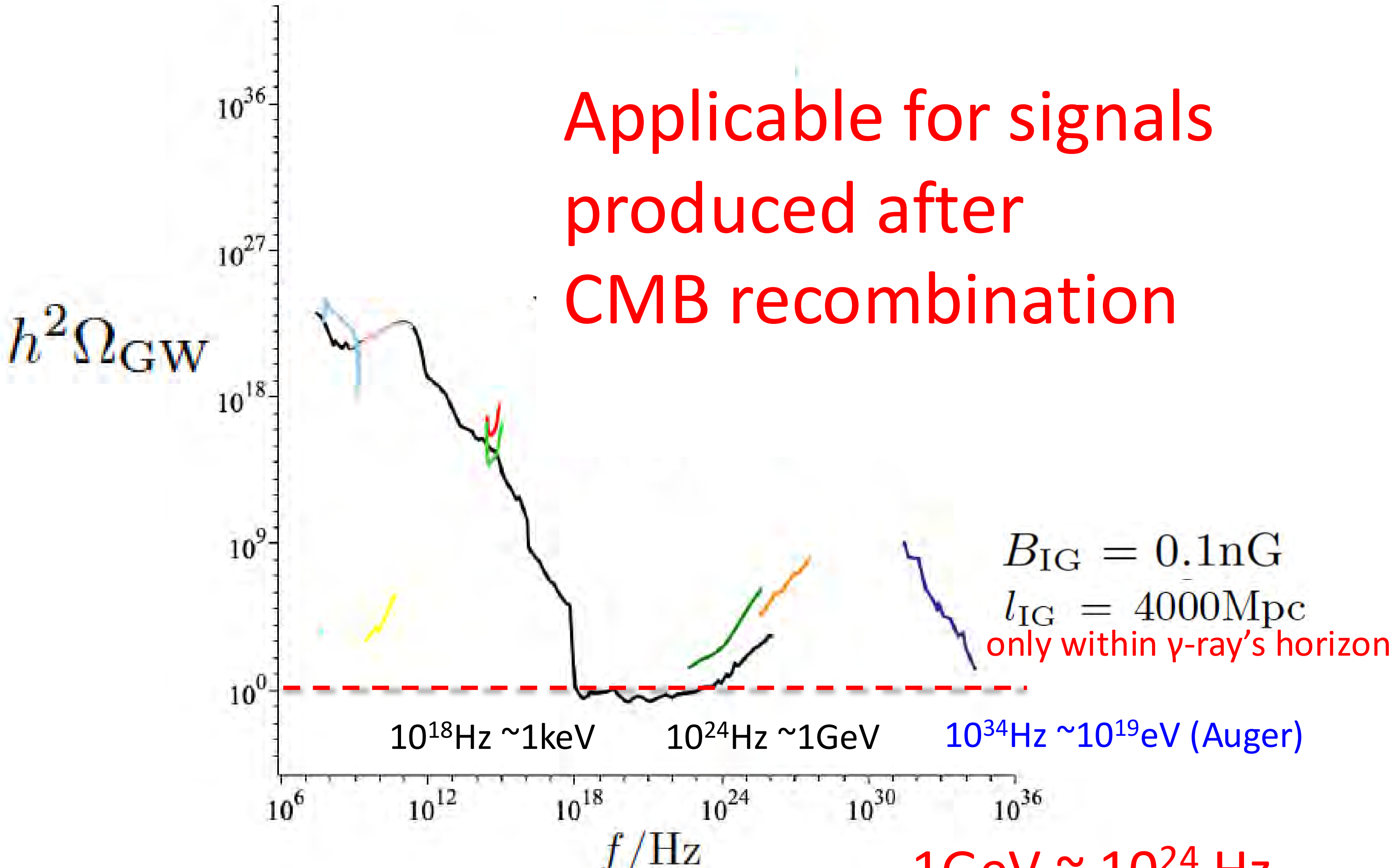
- Action of EM + gravity

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

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

Gravitational wave search through electromagnetic telescopes

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



1GeV ~ 10^{24} Hz

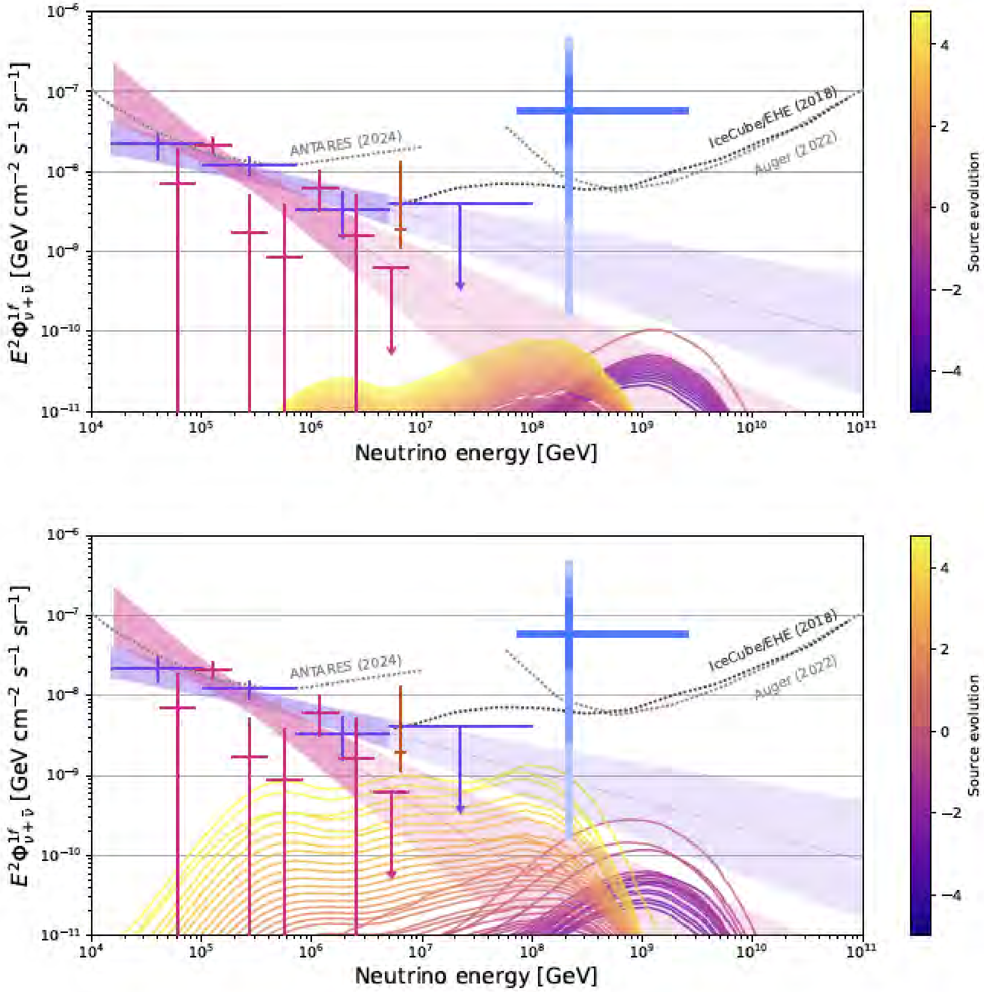
Conclusion

- The Memory Burden (MB) effect completely change the mass ranges for PBHs to be dark matter (10^5g-10^{10}g)
- The search for high-frequency GWs is a new direction for investigating phenomena in the early Universe.
- The targets are so many:
  1. Induced GW to produce dark matter PBHs with MB
  2. GWs from merging binary PBHs with subsolar mass
  3. Thermal/nonthermal graviton just after inflation,
  4. 1st-order phase transition at E >> weak scale
  5. …
- We can test high-frequency GWs by observing the electromagnetic wave converted from the GWs (Ito, Kohri, Nakayama, 2023;2024)

Another topics

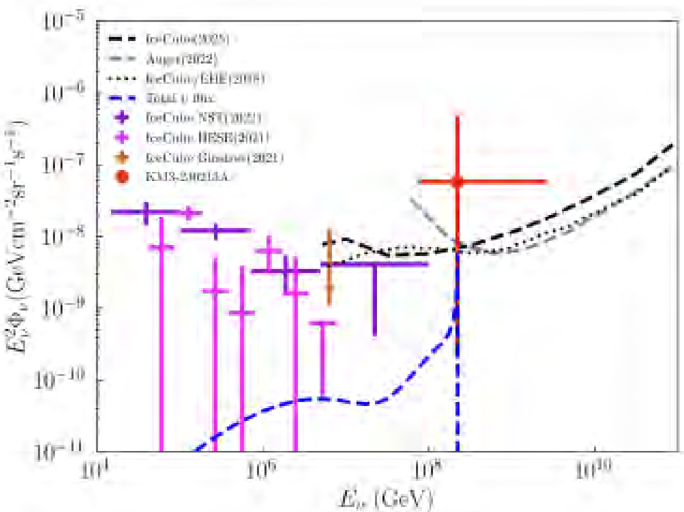
On the potential cosmogenic origin of the ultra-high-energy event KM3-230213A

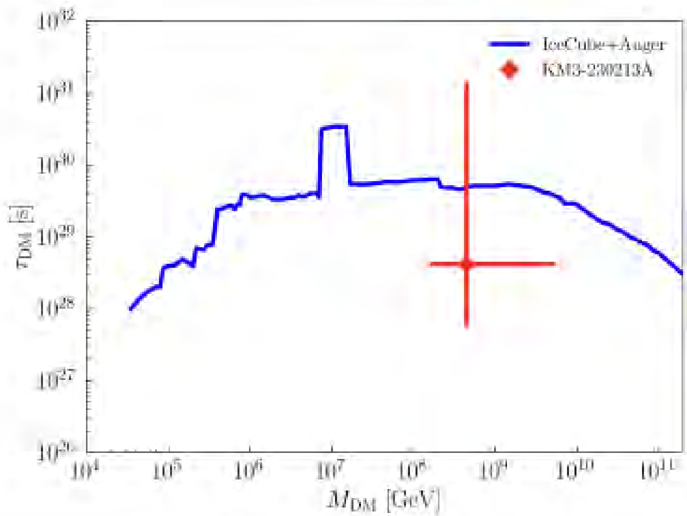
O. Adriani et al, The KM3NeT collaboration, arXiv:2502.08508 [astro-ph.HE]

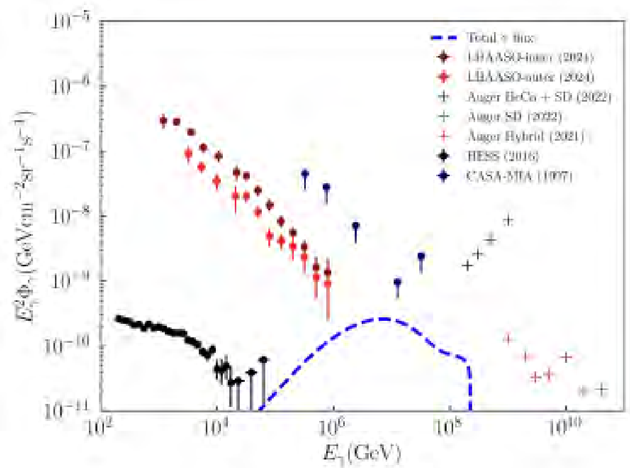


KM3-230213A
and dark matter decay

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

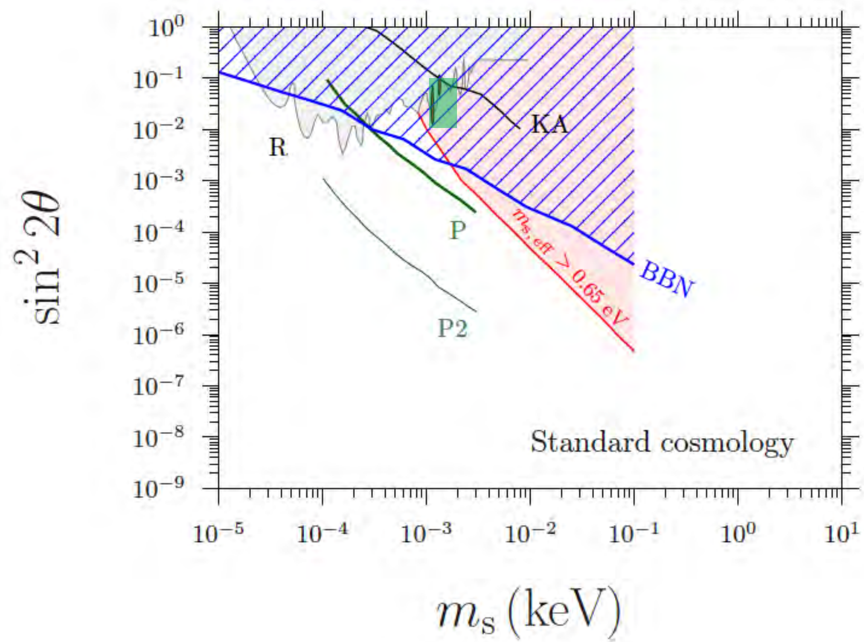




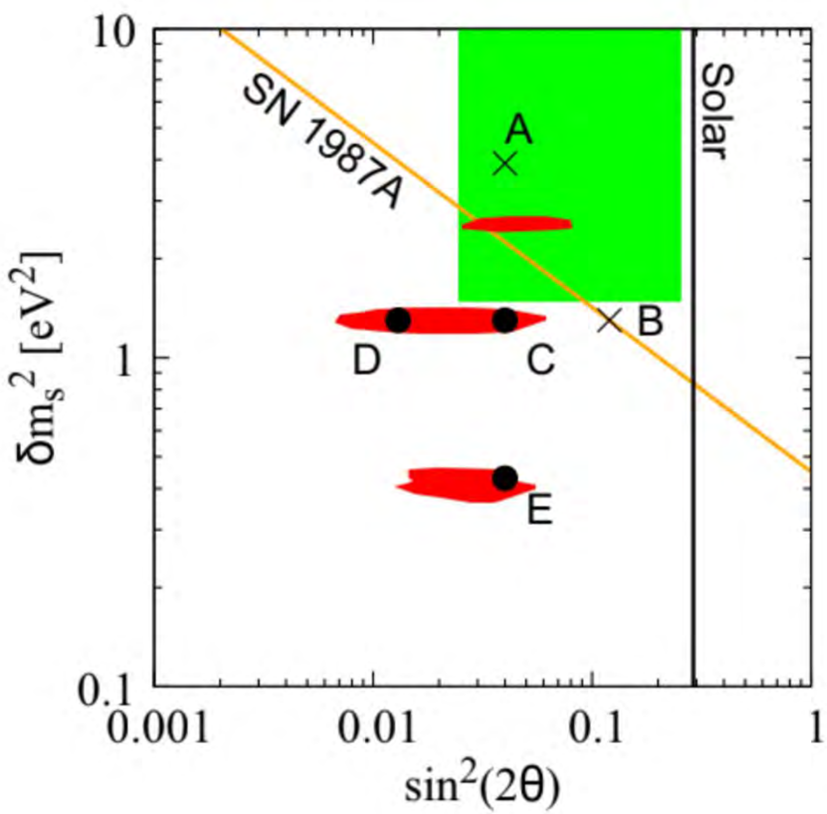


Core-collapse supernova explosions hindered by eV-mass sterile neutrinos

Kanji Mori, Tomoya Takiwaki, Kazunori Kohri, Hiroki Nagakura, arXiv:2503.14027 [astro-ph.HE]



T. Hasegawa, Hiroshima, Kohri, et al,
arXiv:2003.13302 [hep-ph]



Time dependent H_0?

Maria Giovanna Dainotti, Biagio De Simone, Anargha Mondal, Kazunori Kohri, et al, arXiv:2501.11772 [astro-ph.CO]