Cosmological Origin of the KM3-230213A event and associated GW

Based on arXiv: 2503.22465
Collaboration with Ki-Young Choi (SKKU) & Satyabrata Mahapatra (SKKU)

7TH CUBES: "CHIRALITY IN THE UNIVERSE BEYOND THE ELECTROWEAK SCALE"

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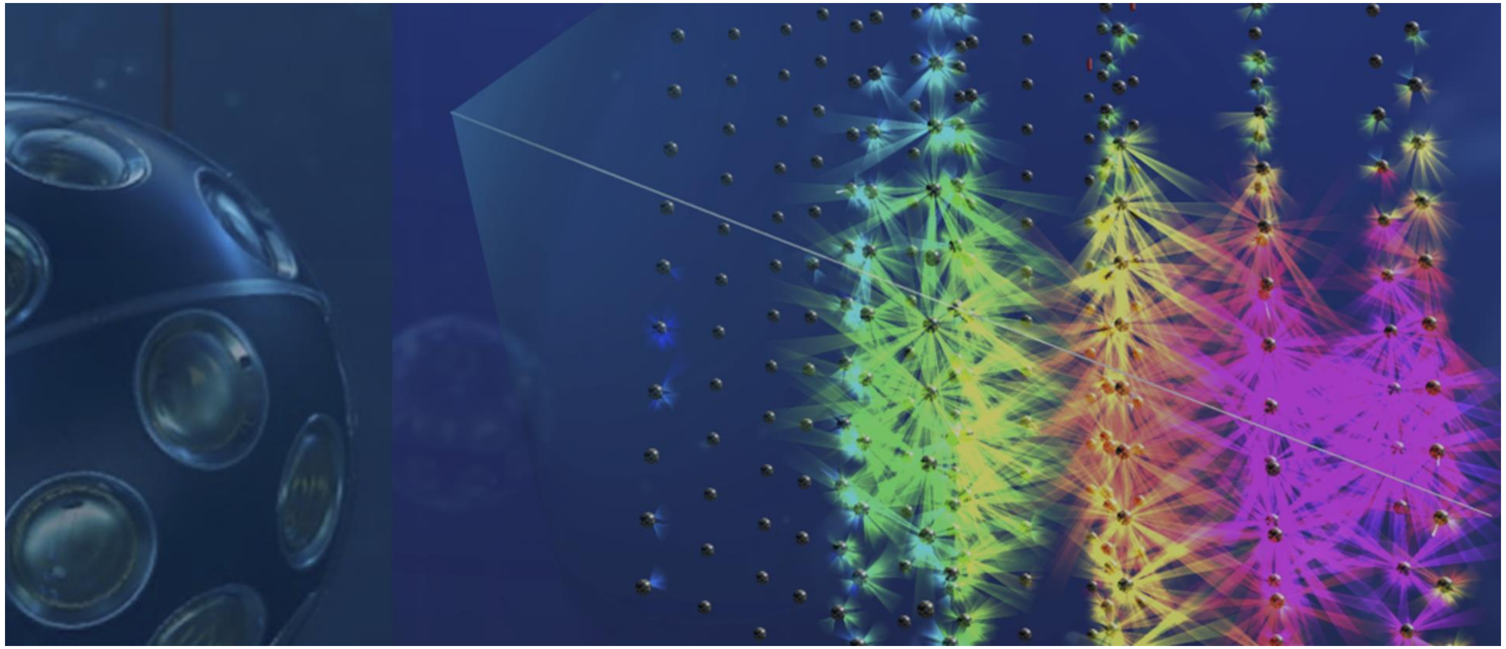
Motivation

Ultra-high energy (UHE) neutrino event KM3-230213A:

- ❖ First ever detection of a neutrino of hundreds of PeV.
- ❖ The detected event was identified as a single muon that crosses the entire detector in the deep sea.
- ❖ UHE cosmogenic neutrinos are expected from the interactions between UHE cosmic rays and CMB photons.



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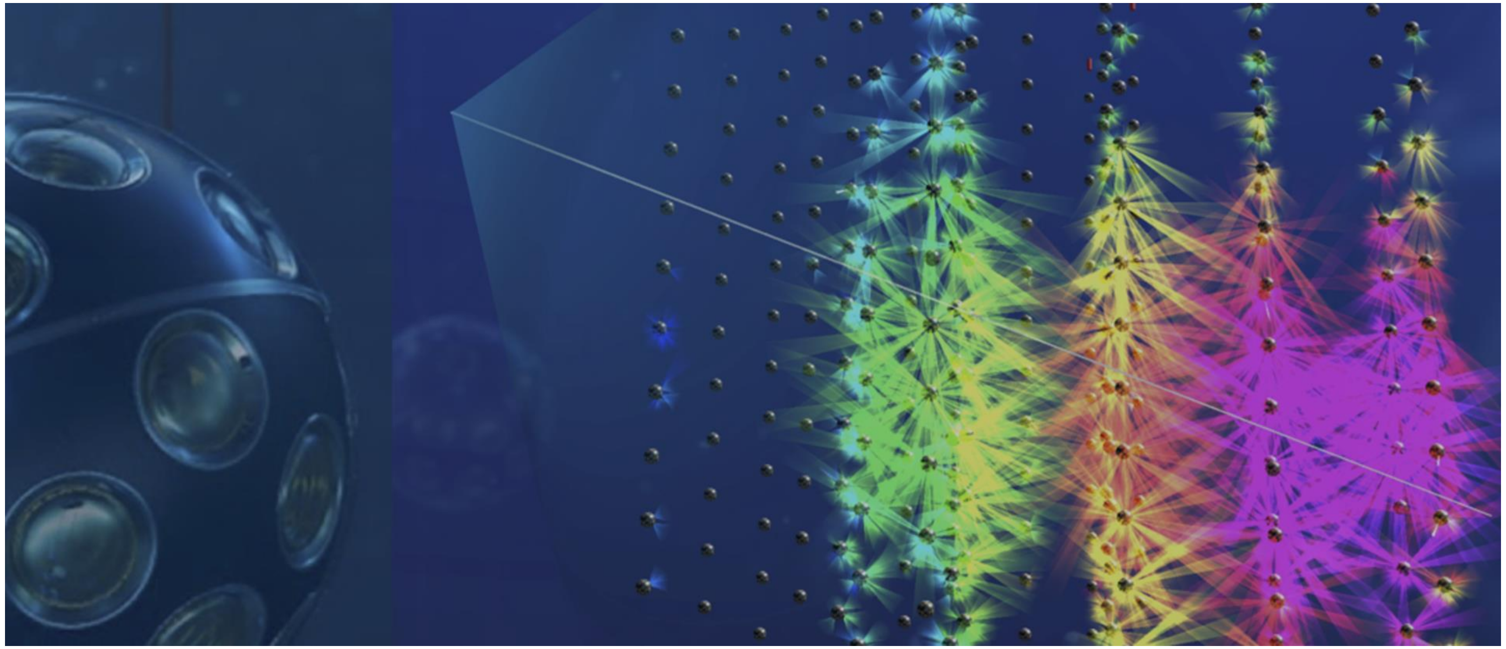

A possible cosmological origin for the KM3-230213A event by considering the decay of a super-heavy particle produced in the early Universe?

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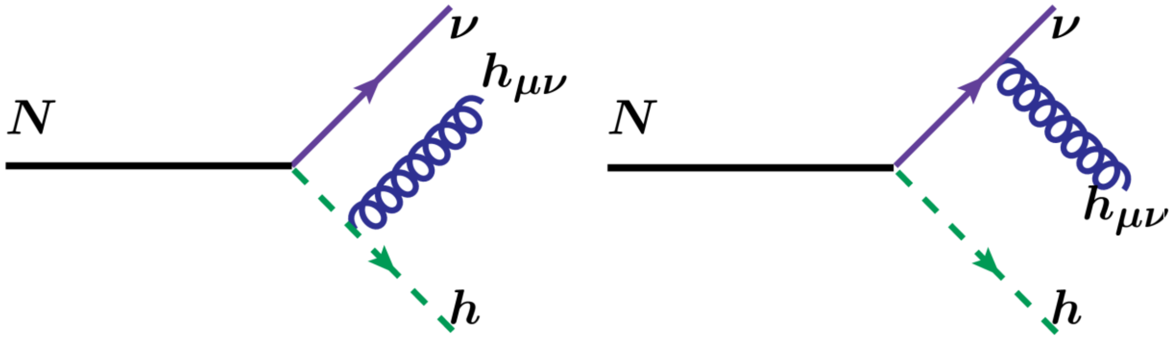
Study for direct graviton emission :

Fermionic particle decay: $Y_D^{\alpha N}\overline{L}_\alpha \tilde{H} N$



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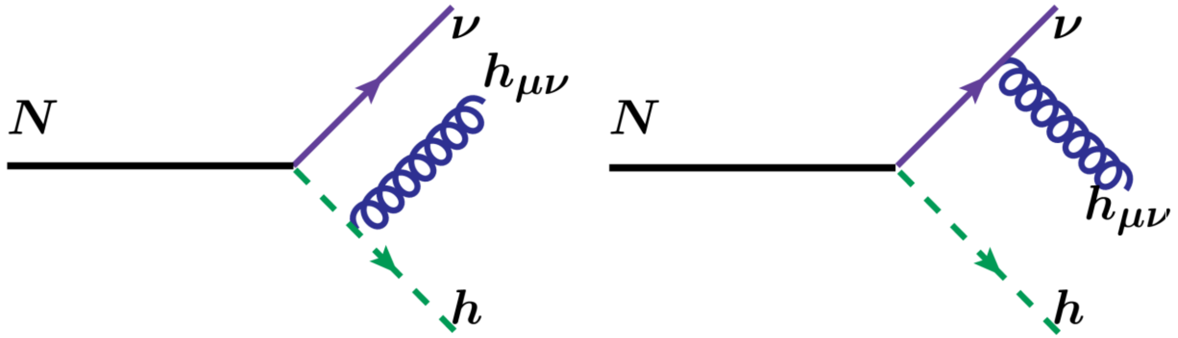

Graviton + Matter interaction

$$\mathcal{L}_{\rm eff} \supset -\frac{1}{M_p} h_{\mu\nu} T^{\mu\nu}$$

Suppression!!

GW sourced through graviton bremsstrahlung would also be suppressed.

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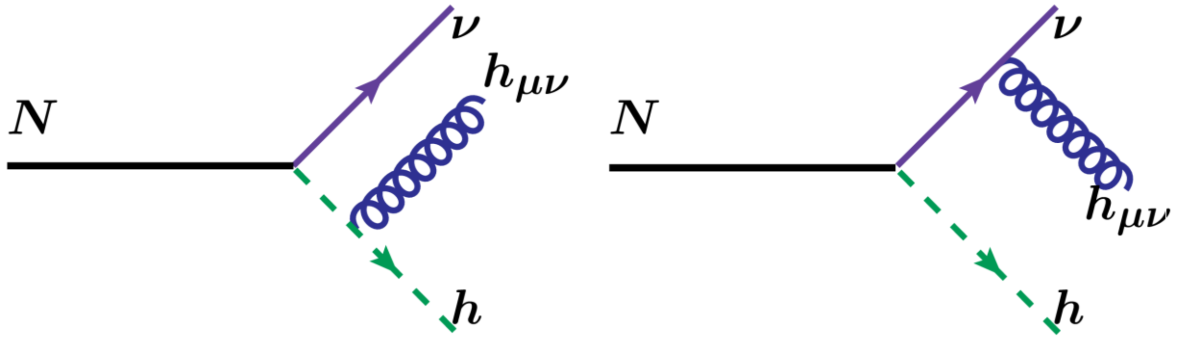

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Compensate suppression :

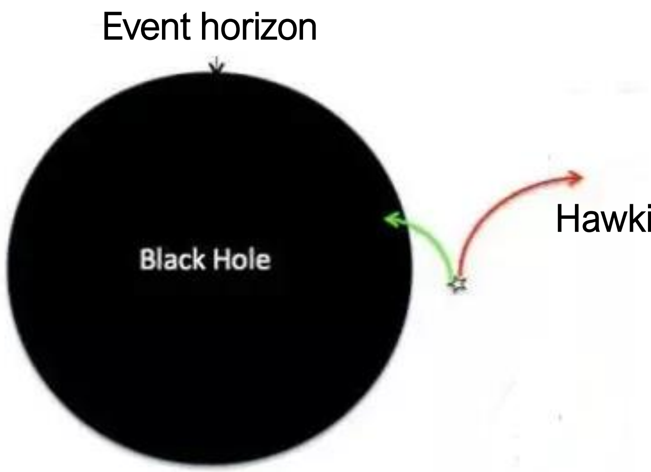
✓ $T^{\mu\nu}$ should be very large (considering inflation model) [N. Bernal et al, 2301.11345; 2311.12694]

✓ Sub-Planckian mass scale particle bremsstrahlung without suppression

How to produce such a massive particle?

Presence of PBH

- PBH could have produced in the early Universe due the collapse of large density perturbations during the radiation dominated era at the end of inflation. [Carr, et al. 2002.12778]



$$R_s = 2GM_{PBH}$$

"Particle Factory"

Hawking radiation → SM, Graviton, Sterile neutrino

Graviton, Sterile neutrino ⟺ SGW

$$m_{\text{particle}} \lesssim T_{\text{BH}} = \frac{M_p^2}{M_{\text{BH}}} \simeq 10^{13}\ \text{GeV}\left(\frac{1\ \text{g}}{\text{M}_{\text{BH}}}\right)$$

Initial mass of the PBH is evaluated as :

$$M_{\text{in}} = \gamma M_{\text{H}} = \gamma M_p^2 t_{\text{in}}$$

- γ: Numerical factor ~ 0.2
- M_{H}: Particle horizon mass
- t_{in}: Formation time

$$M_{\text{in}} = \gamma \frac{4\pi}{3} \frac{\rho(T_{\text{in}})}{H^3(T_{\text{in}})}$$

[Gondolo, et al. 2009.02424
Morrison, et al. 1812.10606
Masina 2004.04730]

PBH evaporation

The energy spectrum of emitted particles with energy by a Schwarzschild BH:

$$\frac{d^2 u_i(E,t)}{dEdt} = \frac{g_i}{2\pi^2} \frac{\sigma_{s_i}(M_{\rm BH}, \mu_i, E_i)}{e^{E_i/T_{\rm BH}} - (-1)^{2s_i}} E_i^3$$

where

$$\sigma_{s_i} = \left(\frac{27}{64\pi} \frac{M_{\rm BH}^2}{M_p^4} \right) \psi_{s_i}(E)$$

[HAWKING1974, HAWKING1975]

The rate of PBH mass loss :

$$\frac{dM_{\rm BH}}{dt} = -\sum_i \int_0^\infty \frac{d^2 u_i(E,t)}{dEdt} dE = -\varepsilon(M_{\rm BH}) \frac{M_p^4}{M_{\rm BH}^2}$$

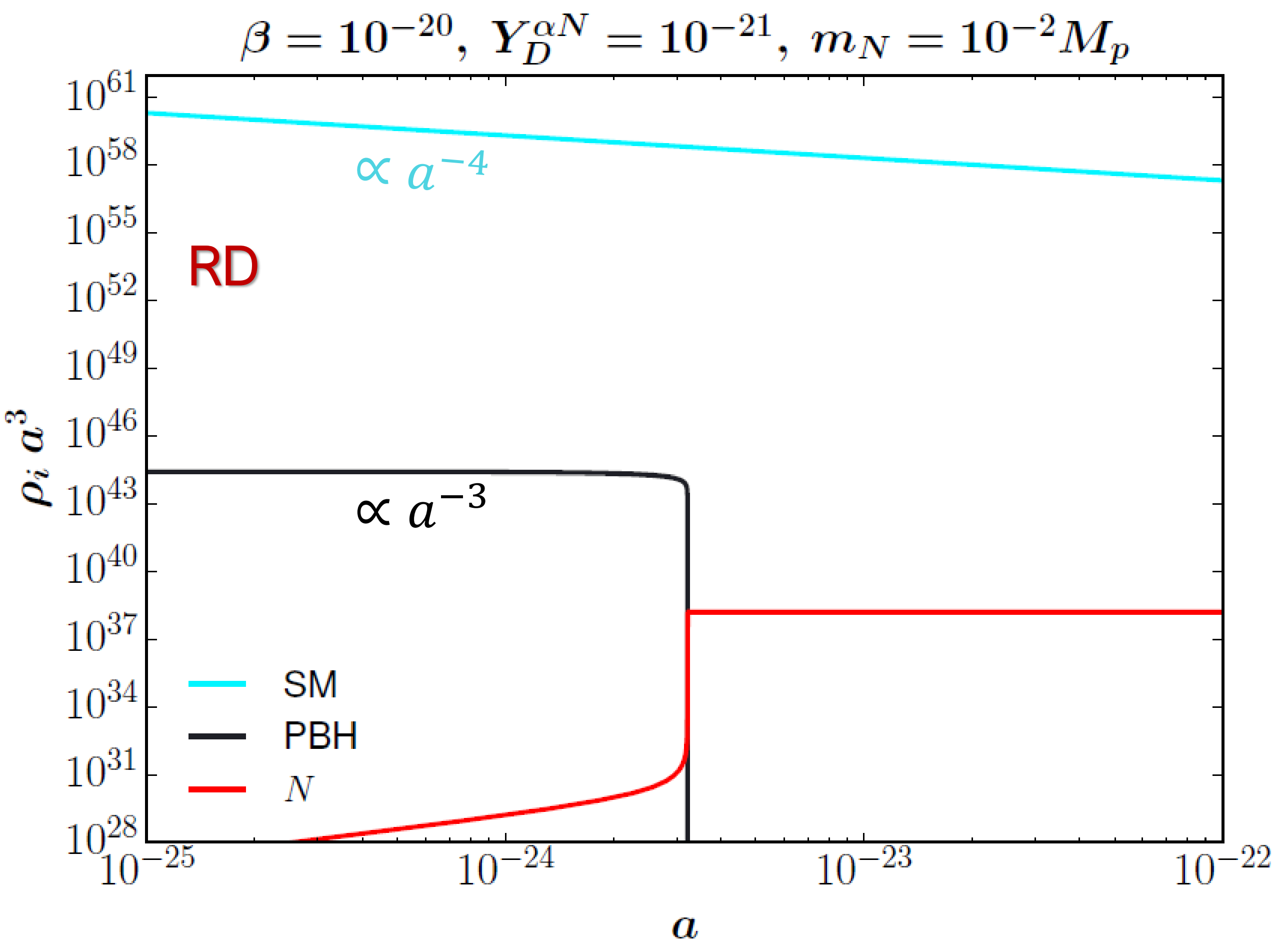
[Cheek et al, Phys. Rev. D 105, 015022
Phys. Rev. D 105, 015023]

Evaporation function depending on the grey-body factor

In Geometric-optic limit: $\psi_{s_i}(E) = 1$

$$M_{\rm BH}(t) = M_{\rm in} \left(1 - \frac{t - t_i}{\tau} \right)^{1/3}$$

Energy density evolution



$$\frac{dM_{\rm BH}}{dt} = -\varepsilon(M_{\rm BH}) \frac{\left(8\pi M_p^2\right)^2}{M_{\rm BH}^2}$$

$$\dot\rho_{\rm BH} + 3H\rho_{\rm BH} = \frac{\rho_{\rm BH}}{M_{\rm BH}} \frac{dM_{\rm BH}}{dt},$$

$$\dot\rho_{\rm r} + 4H\rho_{\rm r} = -\frac{\varepsilon_{\rm SM}(M_{\rm BH})}{\varepsilon(M_{\rm BH})} \frac{\rho_{\rm BH}}{M_{\rm BH}} \frac{dM_{\rm BH}}{dt}$$

The fraction of SM particles from evaporation

$$\beta \lesssim 7 \times 10^{-6} \left(\frac{0.2}{\gamma}\right)^{1/2} \left(\frac{g_*(T_{\rm BH})}{100}\right)^{1/2} \left(\frac{1\ {\rm g}}{M_{\rm in}}\right)$$

[KYC, JK, EL, JCAP 02 (2024) 020]

Massive particle production

$$m_{\rm particle} \lesssim T_{\rm BH} = \frac{M_p^2}{M_{\rm BH}} \simeq 10^{13}\ {\rm GeV} \left(\frac{1\ {\rm g}}{{\rm M_{BH}}}\right)$$ ⟷ Sub-Planckian mass scale ?

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⟺ Sub-Planckian mass scale ?

- ✓ Produced from PBH evaporation at the late stage ($t_1 < \tau$) of its lifetime as a consequence of the increase of Hawking temperature

$$t_1 = t_i + \tau \left[1 - \left(\frac{M_p^2}{M_{\rm in} m_{\rm SMP}}\right)^3\right] \quad \text{when} \quad \boxed{\rm T_{BH} = m_{SMP}} \quad \text{or} \quad \rm M_{BH}(t_1) = M_p^2/m_{SMP}$$

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✓ To obtain large number density of the massive particle we assume that massive particle can be long lived enough to decay after PBH evaporation: $\tau_{\rm SMP} > \tau_{\rm BH}$

✓ The sterile neutrino is long-lived, decaying well after neutrino decoupling: $\tau_N > \tau_{\nu-{\rm decoupling}} \simeq 1{\rm s}$

$$\tau_N \simeq 6.8 \times 10^{-17}\ {\rm s} \left(\frac{10^{-12}}{Y_D^{\alpha N}}\right)^2 \left(\frac{0.1 M_p}{m_N}\right)$$

$$\boxed{Y_D^{\alpha N} < 8.2 \times 10^{-21} \left(\frac{0.1 M_p}{m_N}\right)^{1/2}}$$

Massive particle production

$$\frac{d\tilde{n}_N}{d\ln(a)} = \frac{\tilde{\rho}_{\rm BH}}{M_{\rm BH}}\frac{\Gamma_{{\rm BH}\to N}}{\mathcal{H}} - \frac{\Gamma_N}{\mathcal{H}}\tilde{n}_N$$

Long-lived ***N***

The momentum-integrated emission rate

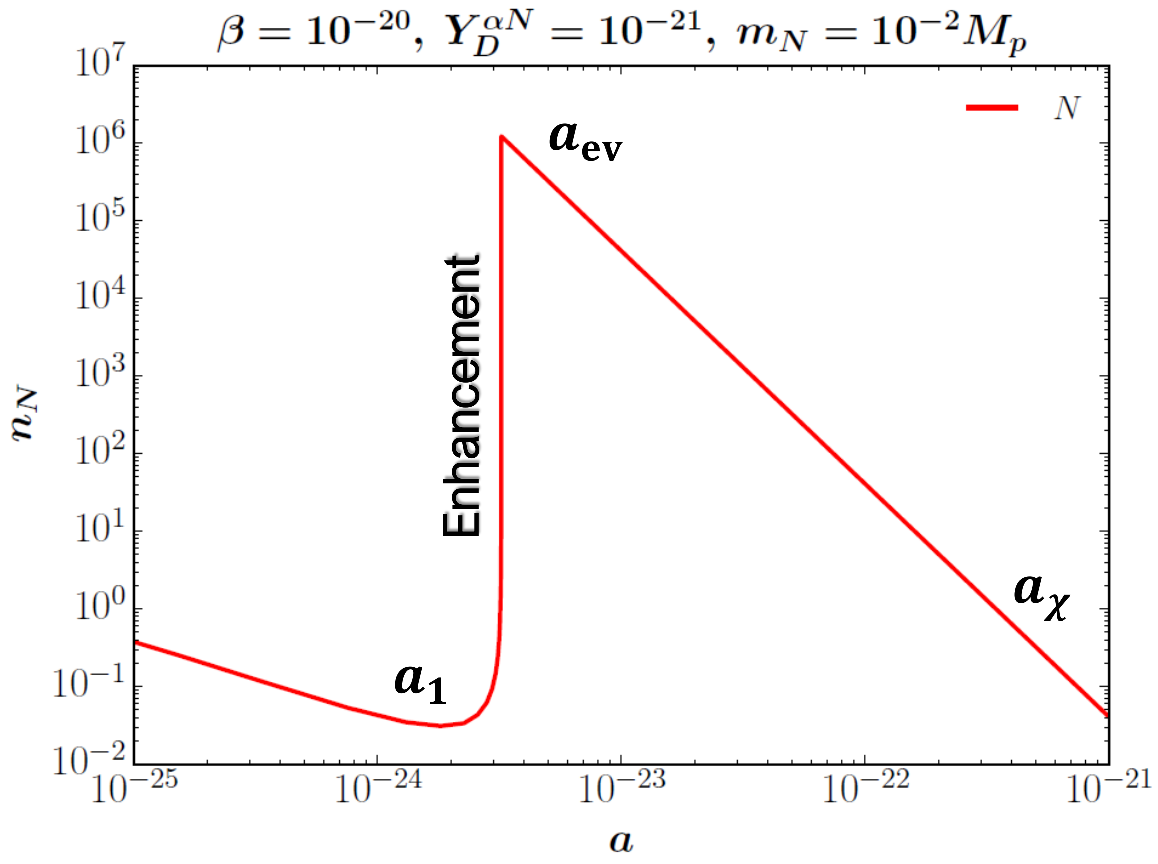
$$H^2 = \frac{8\pi}{3M_{\rm pl}^2}(\rho_r + \rho_{\rm BH})$$

$$\Gamma_{{\rm BH}\to N}(t) = \frac{27 g_N}{64\pi^3}\frac{M_p^2}{M_{\rm in}}\left(1 - \frac{t-t_i}{\tau}\right)^{-1/3}\mathcal{F}(z)$$

$$\mathcal{F}(z) = [z{\rm Li}_2(e^{-z}) + {\rm Li}_3(e^{-z})]$$

$$\Gamma_N = \frac{|Y_D^{\alpha N}|^2 m_N}{8\pi^2}$$

The number density of sterile neutrino:



$$n_N(a_{\rm ev}) \simeq 4\times 10^6 \left(\frac{\beta}{10^{-20}}\right)\left(\frac{1\,{\rm g}}{M_{\rm in}}\right)^4\left(\frac{10^{-2}M_p}{m_N}\right)^2$$

Neutrino flux from sterile neutrino decay

- The sterile neutrinos, produced non-thermally via Hawking radiation, decay into active neutrinos after neutrino decoupling.
- The resulting neutrino flux is determined by cosmological redshift and the decay kinematics.

$$\left[\frac{\partial}{\partial t} - \mathcal{H} p \partial_p\right] f(t,p) = (1-f)\Gamma_{\text{prod}} - f\Gamma_{\text{abs}}$$

$$f \ll 1; \quad f(t,p) = \int_0^a \frac{\Gamma_{\text{prod}}(a',p')}{\mathcal{H}(a')a'} da', \quad \text{where } p' \equiv p\frac{a}{a'}$$

$$\Gamma_{\text{prod}}^{(f_\nu)} \simeq \frac{\pi|\mathcal{M}|^2}{2m_N^3} n_N \delta(E_\nu - \frac{m_N}{2})$$

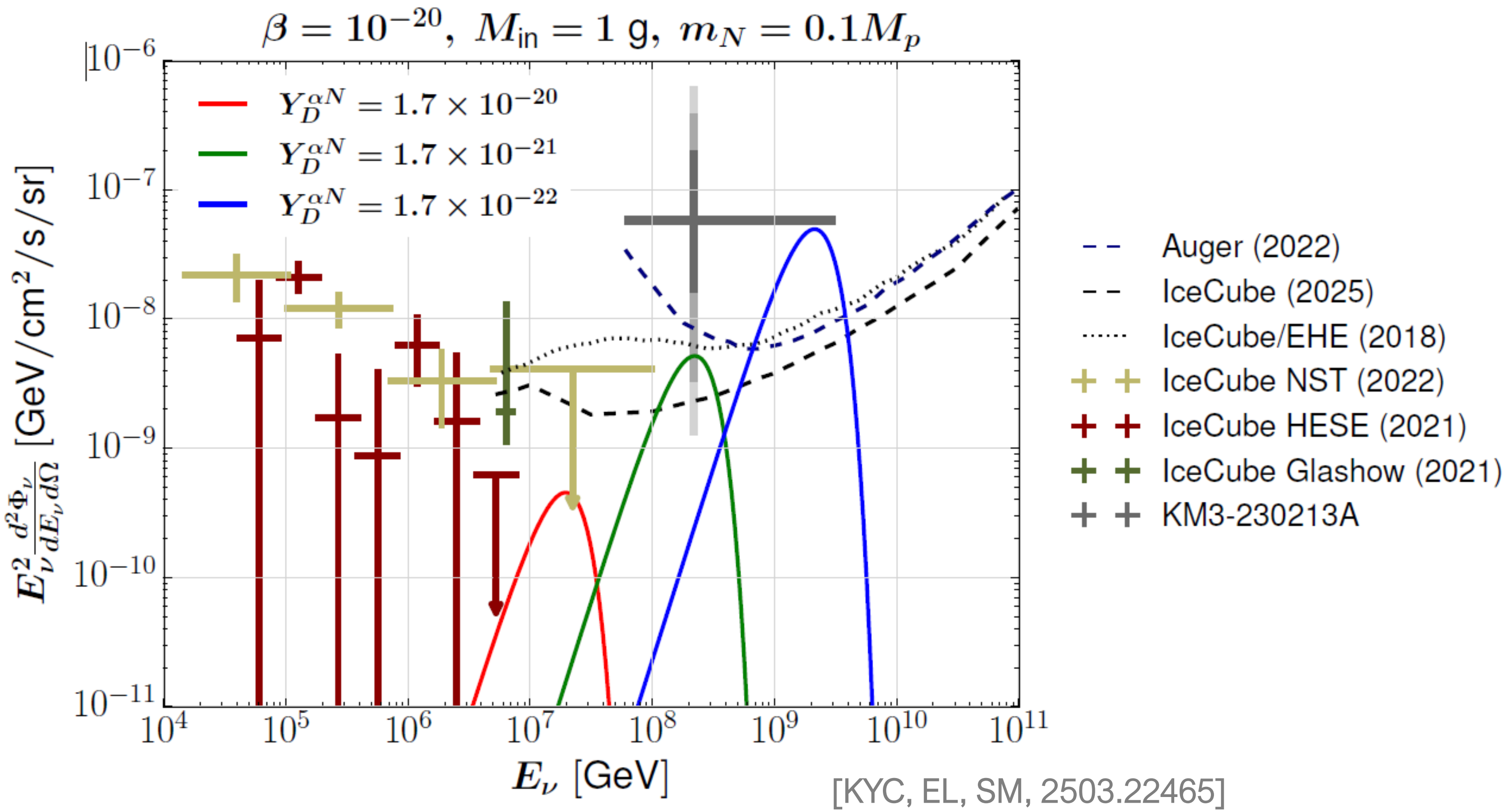
$$f_\nu(E_\nu)|_{t\to t_0} \simeq 16\pi^2 n_N(a_{\text{ev}}) a_{\text{ev}}^3 \left(\frac{2E_\nu}{m_N}\frac{a_0}{a_N}\right)^2 \left(\frac{1}{2E_\nu a_0}\right)^3 \exp\left\{-\frac{1}{2}\left[\left(\frac{2E_\nu a_0}{m_N a_N}\right)^2 - 1\right]\right\}$$

$$\frac{a_N}{a_0} \simeq \frac{T_0}{T_N}\left(\frac{g_{*,s}(T_0)}{g_{*,s}(T_N)}\right)^{1/3} \simeq 10^{-10}\left(\frac{1.5\times 10^{-20}}{Y_D^{\alpha N}}\right)\left(\frac{0.1 M_p}{m_N}\right)^{1/2}$$

Neutrino flux from sterile neutrino decay

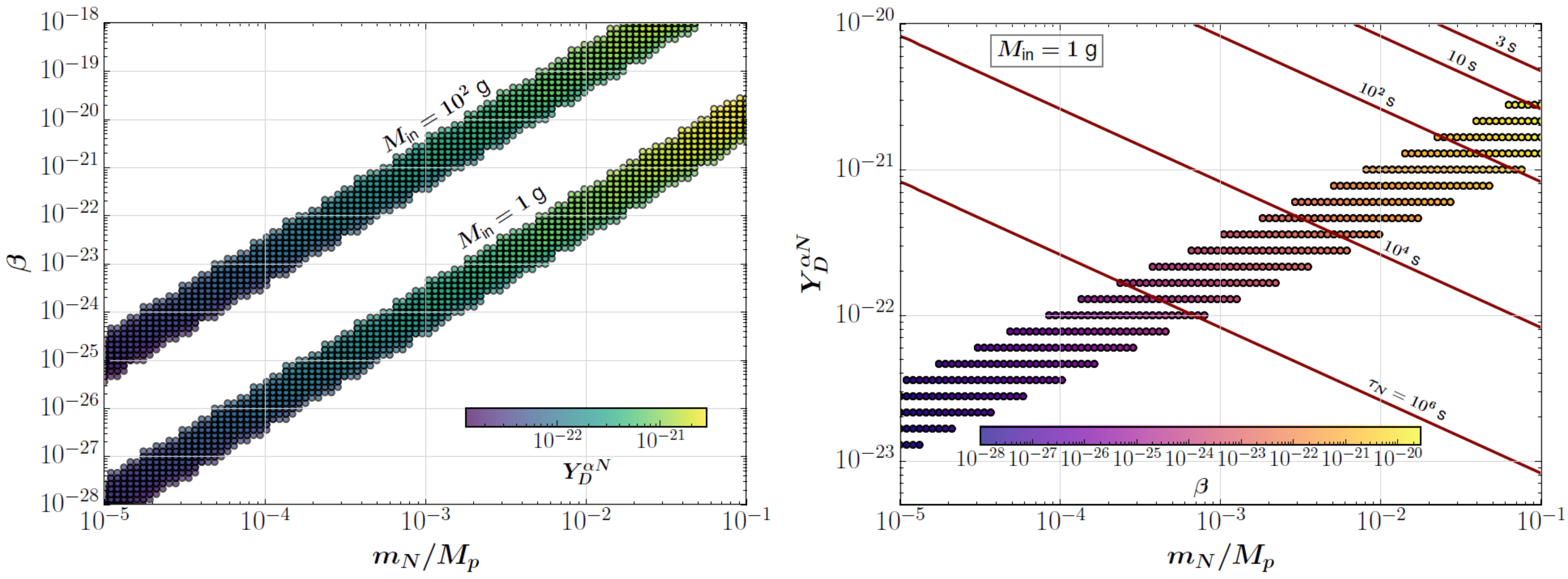
The present day total differential flux of neutrinos per unit solid angle for a single flavour.

$$\frac{d^2\Phi_\nu}{dE_\nu d\Omega} = \frac{\mathrm{BR}_{N\to\nu}}{3}\frac{1}{4\pi}\frac{E_\nu^2}{2\pi^2}f_\nu(E_\nu)|_{t\to t_0}$$



[KYC, EL, SM, 2503.22465]

Neutrino flux from sterile neutrino decay



❖ Yukawa couplings and sterile neutrino mass control the peak position of spectrum
❖ β and the initial mass of PBH control the peak flux of spectrum
❖ As PBH mass increases, the initial number density of PBH decreases, which in turn lowers the sterile neutrino number density

GW production from direct PBH evaporation

The rate of graviton emission for a collective population of evaporating PBHs :

$$\frac{d\rho_{\rm GW}}{dt dE} \simeq n_{\rm BH}(t) \frac{d^2 u_{\rm GW}}{dt dE} \quad \text{where} \quad n_{\rm BH}(t) = n_{{\rm BH},i} \left(\frac{a_i}{a}\right)^3$$

- ❖ Comoving PBH number density remain conserved

Redshifting at the time of the complete evaporation of PBH :

$$\rho_{\rm GW} = \rho_{\rm GW,ev} \left(\frac{a_{\rm ev}}{a}\right)^4 , \quad \omega = \omega_{\rm ev} \left(\frac{a_{\rm ev}}{a}\right)$$

$$\frac{d\rho_{\rm GW,ev}}{d\ln \omega_{\rm ev}} = \frac{27}{64\pi^3} \frac{M_{\rm in}^2}{M_p^4} n_{\rm BH}(t_i) \omega_{\rm ev}^4 \underbrace{\int_{t_i}^{t_{\rm ev}=t_i+\tau} dt \left(1 - \frac{t-t_i}{\tau}\right)^{2/3} \frac{(a_i/a)^3}{e^{\omega_{\rm ev} a_{\rm ev}/a T_{\rm BH}} - 1}}_{I(\omega_{\rm ev})}$$

$$\text{where} \quad n_{\rm BH}(t_i) = \beta \frac{\rho_{\rm r}(t_i)}{M_{\rm in}} = \beta \frac{48\pi^2\gamma^2 M_p^6}{M_{\rm in}^3}$$

GW production from direct PBH evaporation

The final relic abundance for GW at present:

$$h^2\Omega_{\rm GW} = \frac{1}{\rho_{\rm cr,0}h^{-2}}\frac{d\rho_{\rm GW,0}}{d\ln\omega_0} \quad \text{where} \quad \frac{d\rho_{\rm GW,0}}{d\ln\omega_0} = \frac{d\rho_{\rm GW,ev}}{d\ln\omega_{\rm ev}}\left(\frac{a_{\rm ev}}{a_0}\right)^4$$

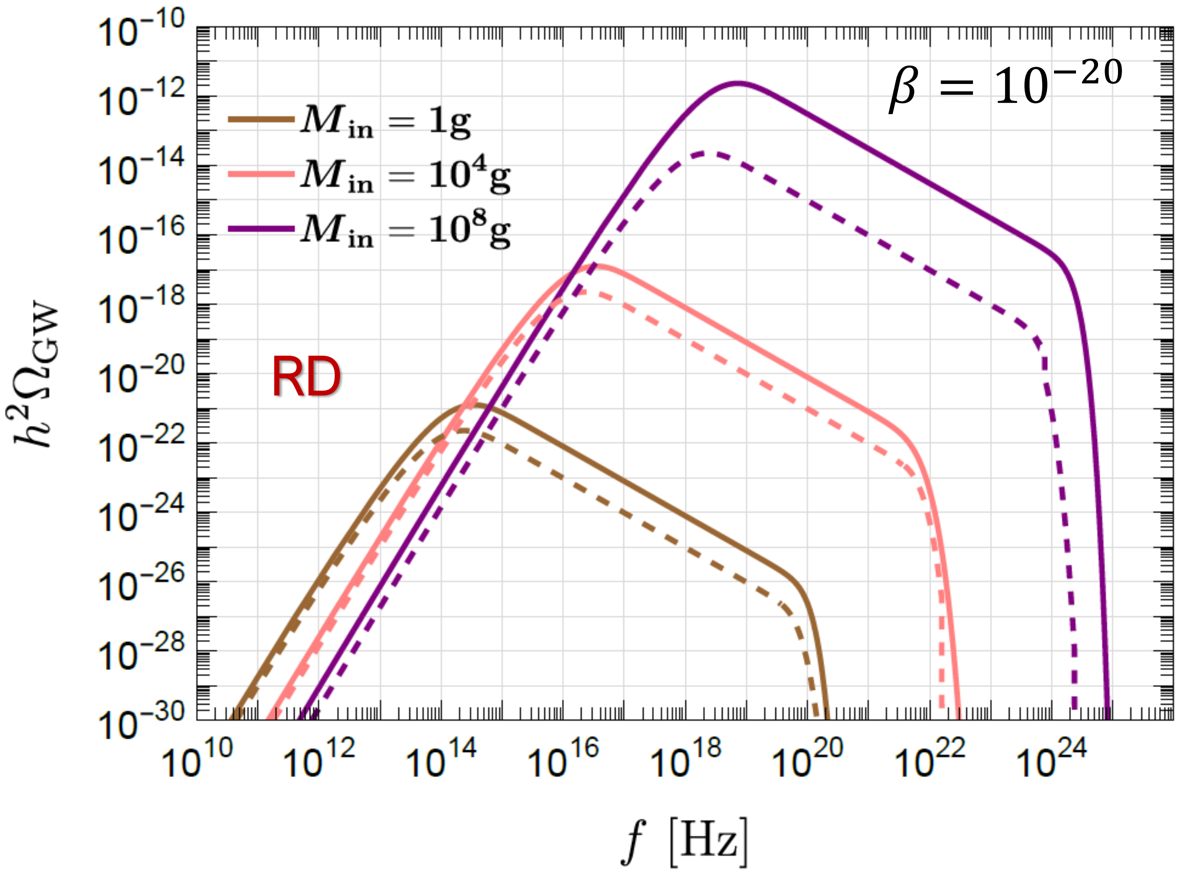
$$\frac{a_{\rm ev}}{a_0} \simeq \frac{T_0}{T_{\rm ev}}\left(\frac{g_{*,s}(T_0)}{g_{*,s}(T_{\rm ev})}\right)^{1/3} \simeq 2.3\times 10^{-24}\left(\frac{M_{\rm in}}{1\ {\rm g}}\right)^{3/2}$$

$$I(\omega_0) = A^{-3}\int_{t_i}^{t_{\rm ev}} dt\left(1-\frac{t-t_i}{\tau}\right)^{2/3}\frac{t^{-2}}{\exp\left[\frac{\omega_0 M_{\rm in}}{AM_p^2}\,t^{-2/3}\left(1-\frac{t-t_i}{\tau}\right)^{1/3}\right]-1}$$

where $A = a_{\rm ev}/a_0(1/\tau)^r$ $\quad \begin{cases} r = 2/3 & \text{for MD} \\ r = 1/2 & \text{for RD} \end{cases}$

GW production from direct PBH evaporation

GW spectrum from direct evaporation of PBH:



- ❖ As the PBH mass increases, the peak frequency of the GW spectrum increases, consequently shifting the spectrum towards higher frequencies.
- ❖ The GW spectrum behavior is due to heavier PBHs form at late times as well as evaporate for a long time, resulting in a reduced cosmological redshifting.

$$f_{\rm peak} \simeq 1.6 \times 10^{13}\ {\rm Hz} \left(\frac{M_{\rm in}}{1\ {\rm g}}\right)^{1/2} .$$

GW production from massive particles

Boltzmann equation for the evolution of the energy density of gravitons produced in the bremsstrahlung of heavy particles:

$$\frac{d}{da}\left(a^4 \frac{d\rho_{\rm GW}}{d\ln E_{\rm GW}}\right) = \frac{n_{\rm SMP}(a_{\rm ev})a_{\rm ev}^3}{H}\boxed{\frac{d\Gamma_{\rm SMP\to GW}}{dE_{\rm GW}}}E_{\rm GW}^2$$

→The differential decay rate of massive particle

[S.Kanemura, et al. 2310.12023]

The generation of GW can occur from $\boldsymbol{a_{\rm ev}}$ to $\boldsymbol{a_N}$:

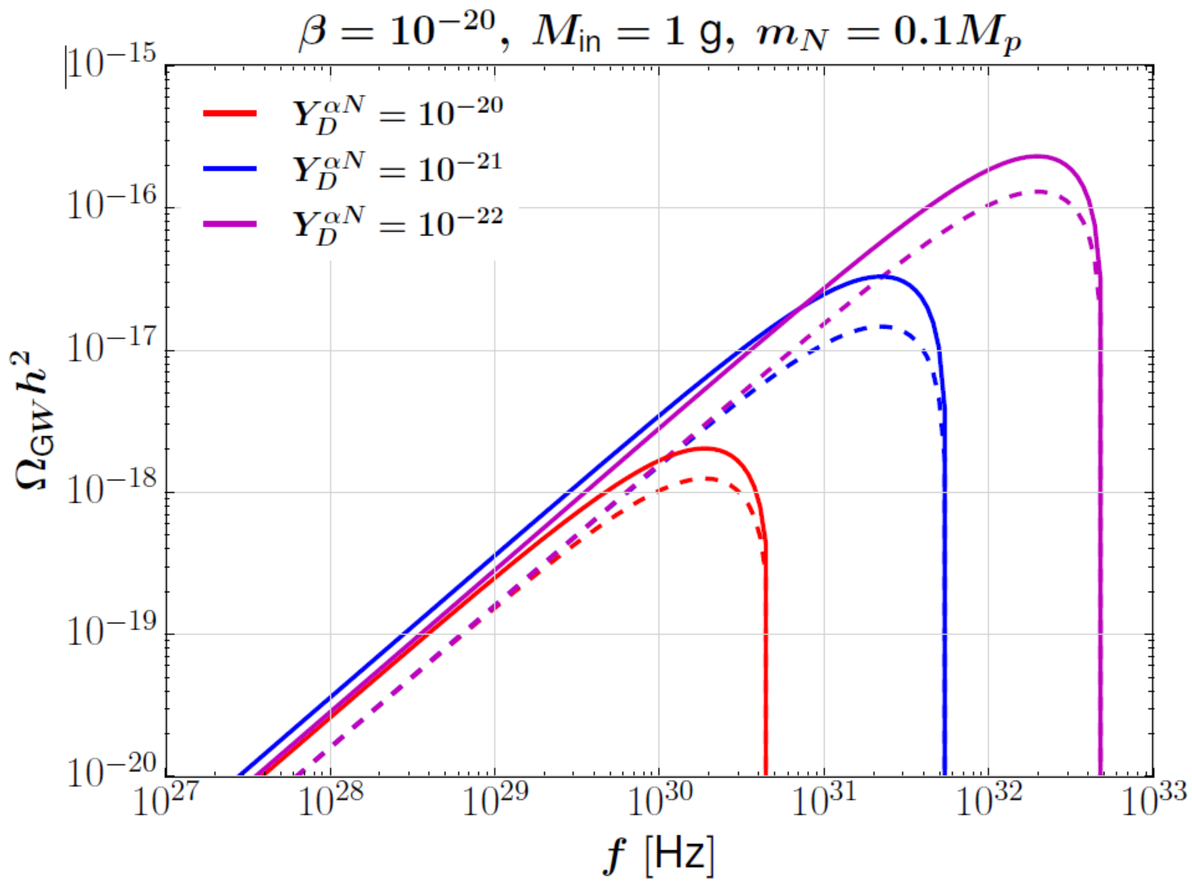
$$\frac{d\rho_{\rm GW}(a_N)}{d\ln E_{\rm GW}} \simeq 5\times 10^{-6}\beta (Y_D^{\alpha N})^2 \frac{m_N M_p^5}{M_{\rm in}^3} E_{\rm GW}\mathcal{G}(E_{\rm GW}/m_N)\frac{a_{\rm ev}}{a_N}\left[1-\left(\frac{a_{\rm ev}}{a_N}\right)^3\right]$$

$$h^2\Omega_{\rm GW} = \frac{1}{\rho_{\rm cr,0}h^{-2}}\frac{d\rho_{\rm GW}(a_{\rm SMP})}{d\ln E_{\rm GW}}\boxed{\left(\frac{a_{\rm SMP}}{a_0}\right)^4}, \quad \text{where} \quad \mathrm{E_{GW}} = 2\pi \mathrm{f}(\mathrm{a_0}/\mathrm{a_{SMP}})$$

Redshifting effect

GW production from massive sterile neutrino

Gravitational wave spectrums for graviton bremsstrahlung from decay of sterile neutrino



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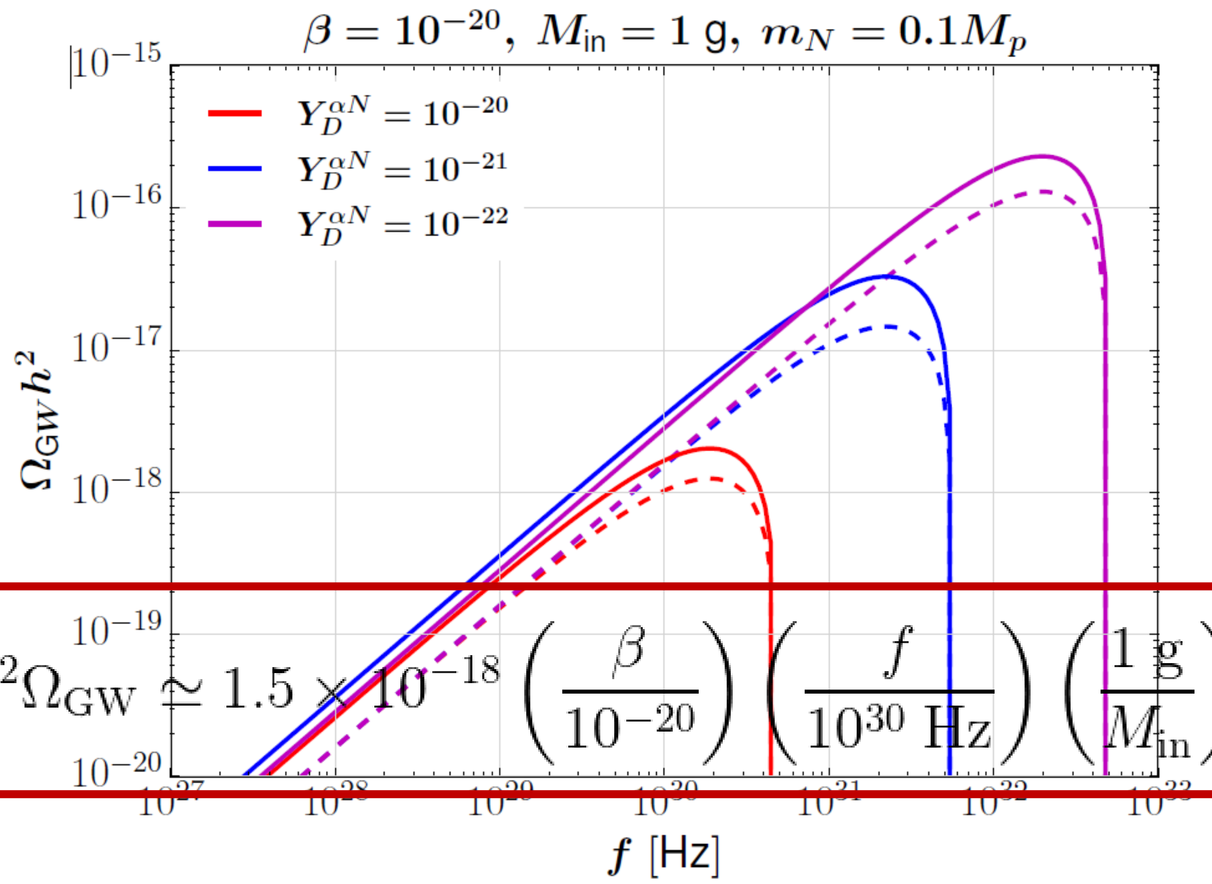

$$h^2\Omega_{\text{GW}} \simeq 1.5\times 10^{-18}\left(\frac{\beta}{10^{-20}}\right)\left(\frac{f}{10^{30}\text{ Hz}}\right)\left(\frac{1\text{ g}}{M_{\text{in}}}\right)^{3/2}$$

$$f_{\text{peak}} = \frac{m_N}{4\pi}\left(\frac{a_N}{a_0}\right) \simeq 4.3\times 10^{30}\text{ Hz}\left(\frac{10^{-20}}{Y_D^{\alpha N}}\right)\left(\frac{m_N}{0.1M_p}\right)^{1/2}$$

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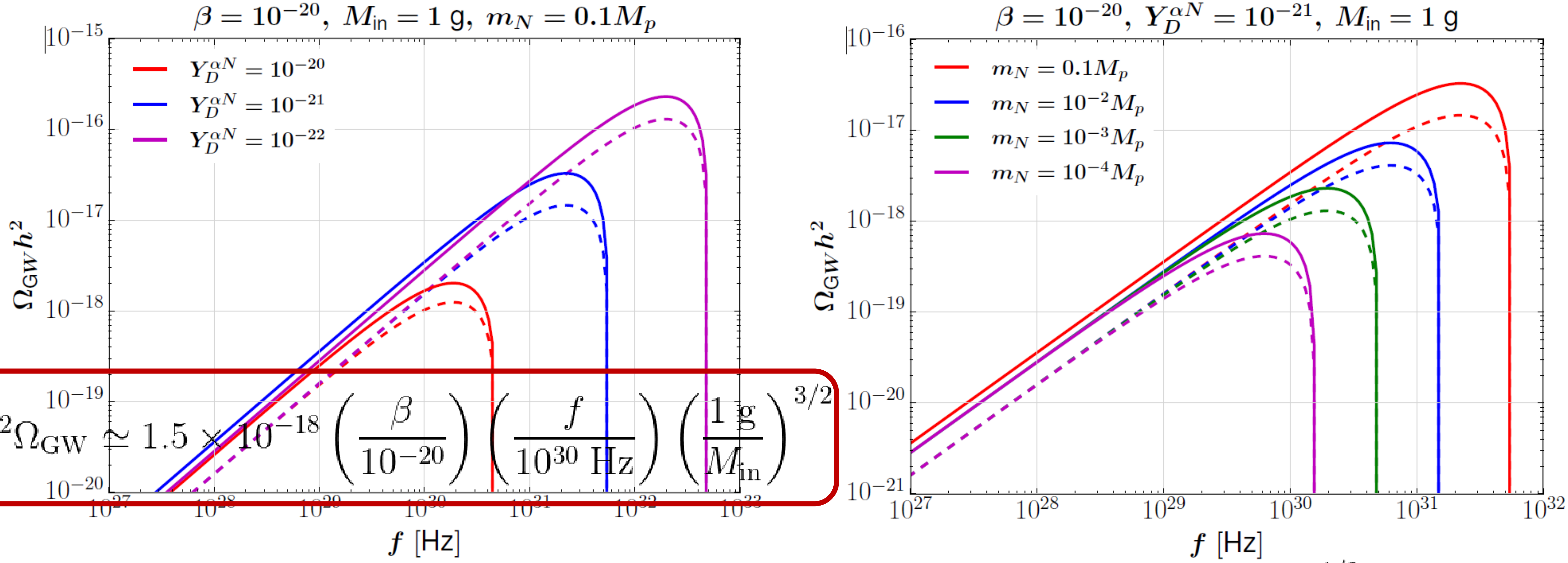

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GW contribution to dark radiation

$$\rho_{\rm rad} = \rho_\gamma \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} (N_{\rm eff}^{\rm SM} + \boxed{\Delta N_{\rm eff}})\right]; \qquad \text{since } \rho_{\rm GW} \propto a^{-4}$$

Gravitational Wave contribution to $\Delta \boldsymbol{N_{eff}}$:

$$\Delta N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3} \frac{\rho_{\rm GW}}{\rho_\gamma} = \int df\, f^{-1}\Omega_{\rm GW}(f) = \frac{120}{7\pi^2}\left(\frac{11}{4}\right)^{4/3} \frac{\rho_{\rm cr,0}}{T_0^4}\Omega_{\rm GW}^{\rm max}$$

$$\boxed{h^2\Omega_{\rm GW}^{\rm max} \lesssim 5.6269 \times 10^{-6}\Delta N_{\rm eff}}$$

Indirect probe of GW spectrum:

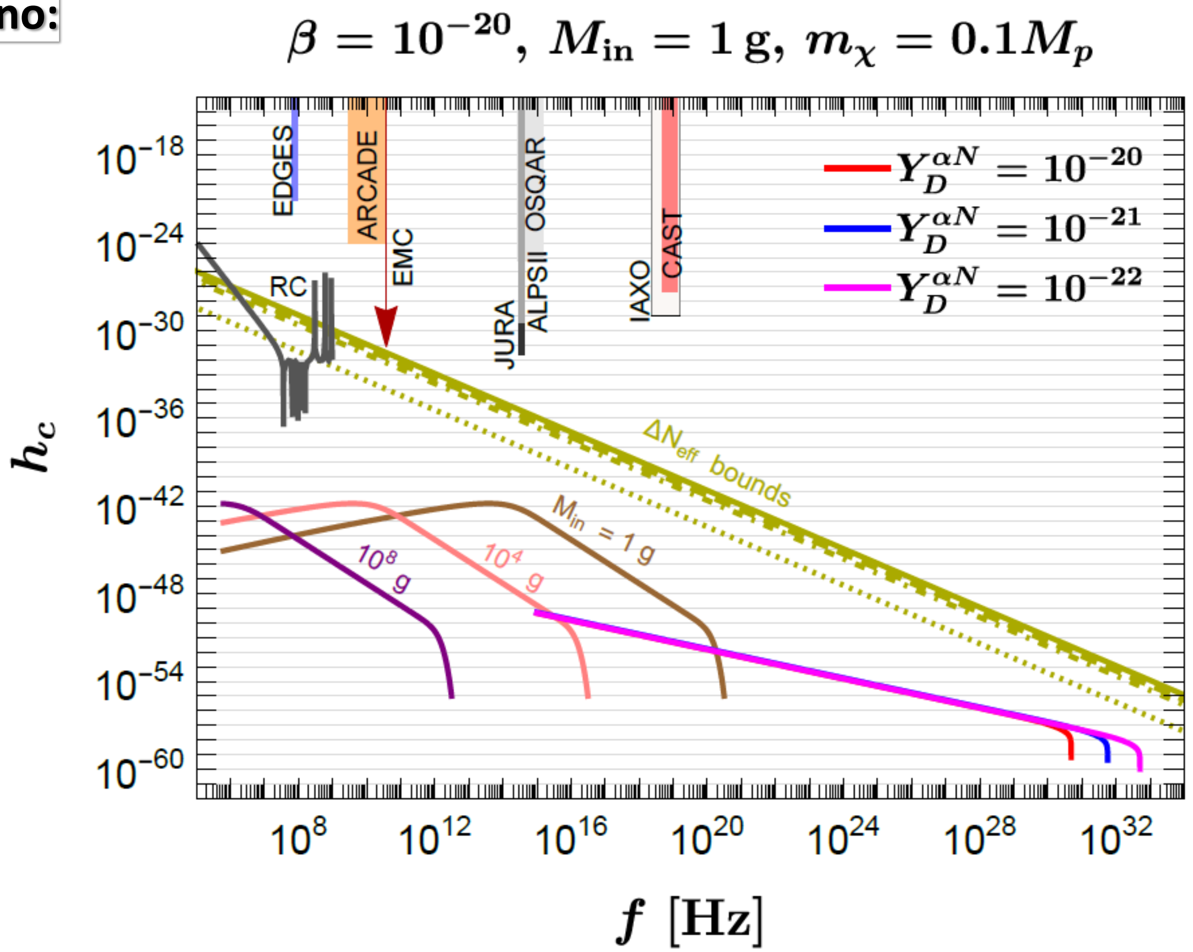
- Planck: $\Delta N_{\rm eff} < 0.30$ [1807.06209]
- CMB-S4: $\Delta N_{\rm eff} \lesssim 0.06$ [1610.02743]
- EUCLID: $\Delta N_{\rm eff} \lesssim 0.013$ [1110.3193]
- CMB-CVL: $\Delta N_{\rm eff} \lesssim 3.1 \times 10^{-6}$ [1903.11843]

Fisher matrix analysis of cosmic variance limited (CVL) CMB polarization measurement

Gravitational wave characteristic strain with both contributions

$$h_c = f^{-1}\sqrt{\frac{3H_0^2}{4\pi^2}\Omega_{\rm GW}} \simeq 8.93\times 10^{-19}\sqrt{\Omega_{\rm GW}h^2}\left(\frac{\rm Hz}{f}\right)$$

Sterile neutrino:



Conclusion

- We propose a novel cosmological scenario that PBHs formed in the early Universe emit sterile neutrinos via Hawking radiation, which subsequently decay into active neutrinos.
- The resulting flux, after cosmological redshift, aligns with the energy and isotropic origin of KM3-230213A event.
- We have explored the production of stochastic gravitational waves not only through the direct evaporation of PBHs but also via the bremsstrahlung process during the decay of the sterile neutrino.
- Even though both contributions give two distinct spectral signatures, the high-frequency SGW spectra remains below the sensitivity of the future experiments.
- Our parameters of model scenario, is rooted by PBH evaporation, can tested by the high-energy neutrino experiments.

Thank You!