A Possible Cosmological Origin of the KM3-230213A Event

Based on arXiv: 2503.22465 (accepted by JCAP)
Collaboration with Ki-Young Choi (SKKU) & Satyabrata Mahapatra (IIT Goa)

DESY THEORY WORKSHOP: SYNERGIES TOWARDS THE FUTURE STANDARD MODEL

Erdenebulgan Lkhagvadorj

2025.09.25

Motivation

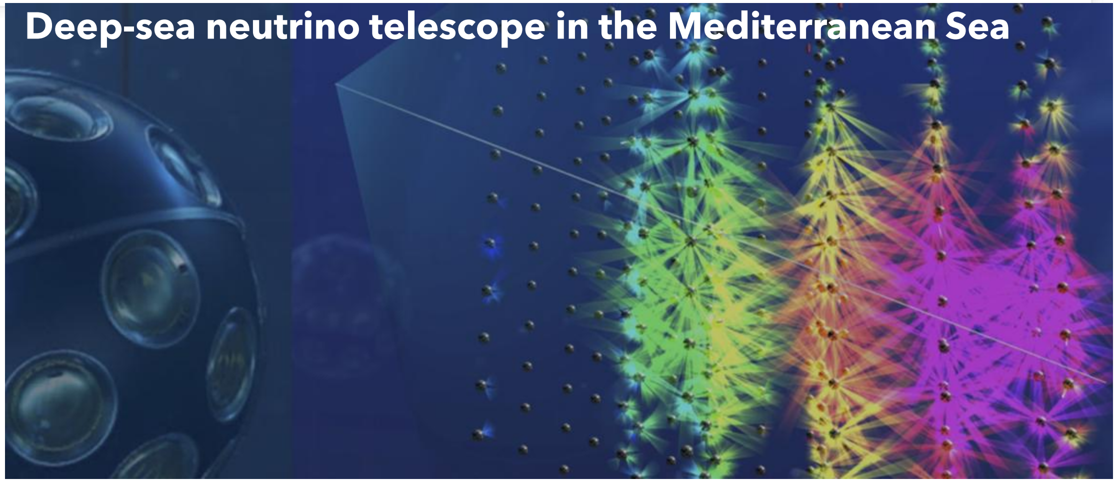
Ultra-high energy (UHE) neutrino event KM3-230213A:

[KM3NeT collab, Nature 638 (2025) 376; KM3NeT collab, 2502.08173]

- The detected event was identified as a single muon with energy of 120 PEV that crosses the entire detector in the deep sea.
- First ever detection of a neutrino of 220 PeV.

$$E_\nu^2 \Phi_\nu(E) = 5.8^{+10.1}_{-3.7} \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

- There is **no astrophysical source** in the KM3NeT analysis.
- Observational **direction is nearly opposite** to the Galactic Center.
- UHE cosmogenic neutrinos are expected from the interactions between UHE cosmic rays and CMB photons.
- Non-observation of similar events by IceCube and the Pierre Auger Observatory introduces a ~3σ tension with the cosmogenic origin hypothesis.

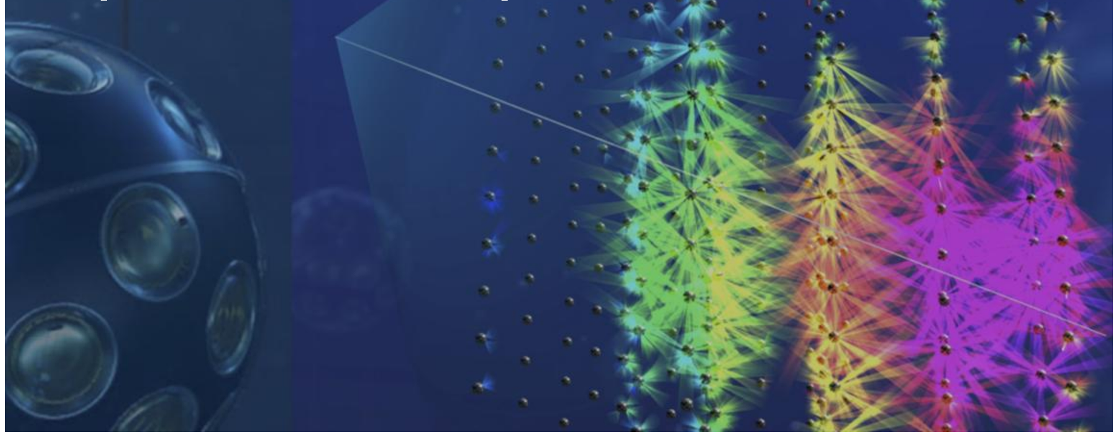


Motivation

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

[KM3NeT collab, Nature 638 (2025) 376; KM3NeT collab, 2502.08173]

Deep-sea neutrino telescope in the Mediterranean Sea



- The detected event was identified as a single muon with energy of 120 PEV that crosses the entire detector in the deep sea.
- First ever detection of a neutrino of 220 PeV.

$$E_\nu^2 \Phi_\nu(E) = 5.8^{+10.1}_{-3.7} \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

- There is **no astrophysical source** in the KM3NeT analysis.
- Observational **direction is nearly opposite** to the Galactic Center.
- UHE cosmogenic neutrinos are expected from the interactions between UHE cosmic rays and CMB photons.
- Non-observation of similar events by IceCube and the Pierre Auger Observatory introduces a ~3σ tension with the cosmogenic origin hypothesis.

Conventional decaying DM models:
Neutrino flux concentrated around the Galactic center
Enhanced neutrino flux due to higher DM energy density

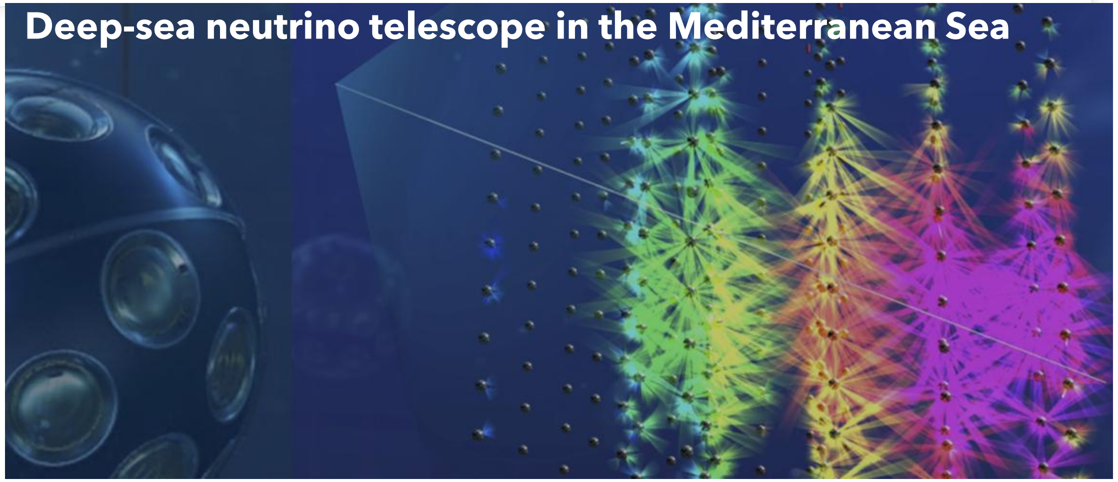
Motivation

Ultra-high energy (UHE) neutrino event KM3-230213A: [KM3NeT collab, Nature 638 (2025) 376; KM3NeT collab, 2502.08173]

- The detected event was identified as a single muon with energy of 120 PEV that crosses the entire detector in the deep sea.
- First ever detection of a neutrino of 220 PeV.

$$E_\nu^2 \Phi_\nu(E) = 5.8^{+10.1}_{-3.7} \times 10^{-8}\, \mathrm{GeV\, cm^{-2}\, s^{-1}\, sr^{-1}}$$

- There is **no astrophysical source** in the KM3NeT analysis.
- Observational **direction is nearly opposite** to the Galactic Center.
- UHE cosmogenic neutrinos are expected from the interactions between UHE cosmic rays and CMB photons.
- Non-observation of similar events by IceCube and the Pierre Auger Observatory introduces a ~3σ tension with the cosmogenic origin hypothesis.



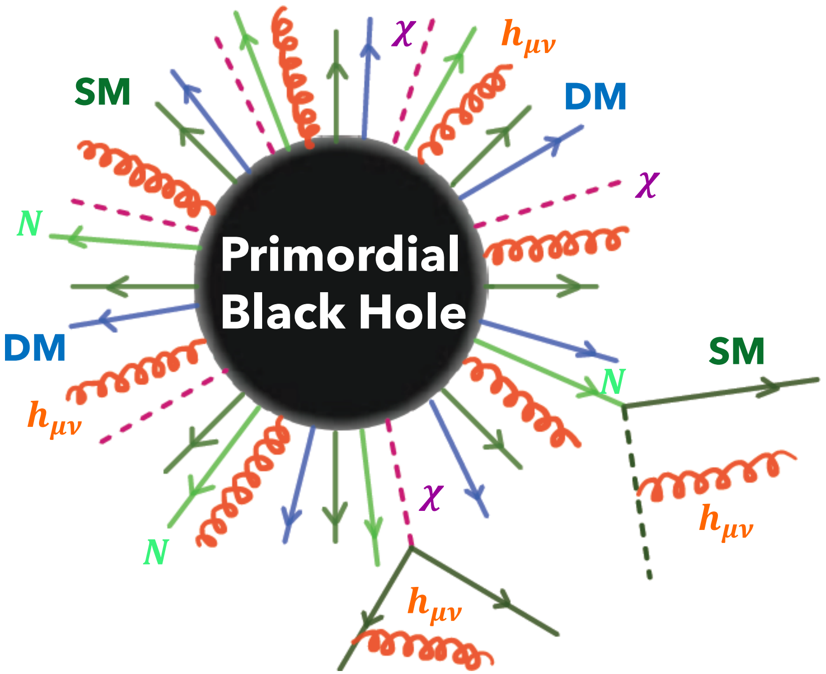
Conventional decaying DM models:
Neutrino flux concentrated around the Galactic center
Enhanced neutrino flux due to higher DM energy density

A possible **cosmological origin** for the KM3-230213A event by considering the **isotropic neutrino flux** originating from decay of super-heavy particle produced in the early Universe?

PBH evaporation during RD
Fermionic particle decay:

$$Y_D^{\alpha N} \overline{L}_\alpha \tilde{H} N$$

Primordial black hole evaporation



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

The energy spectrum of emitted particles with energy by a Schwarzschild BH: [HAWKING1974, HAWKING1975]

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

Absorption cross section

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

The rate of PBH mass loss : [Cheek et al, Phys. Rev. D 105, 015022 Phys. Rev. D 105, 015023]

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

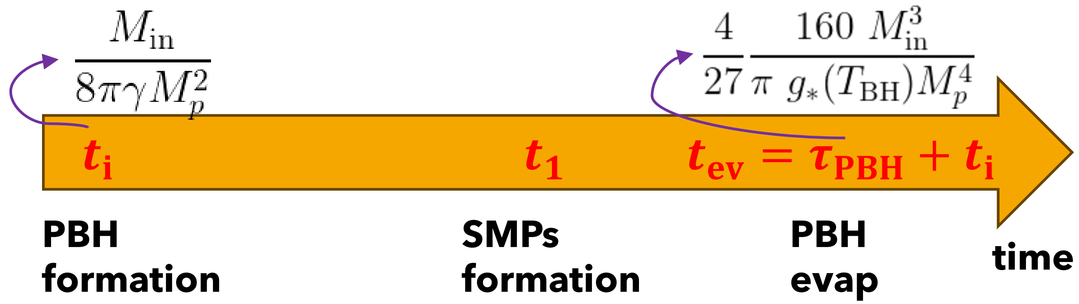
Evaporation function depending on the grey-body factor

Massive particle production

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

Massive particle production

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

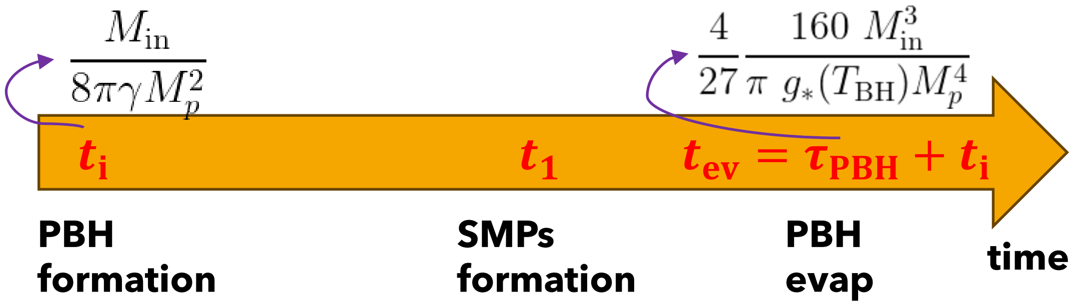


- ✓ **While PBH loses its mass during particle emission, Hawking temperature consequently increases.**

$$t_1 = t_i + \tau\left[1 - \left(\frac{M_p^2}{M_{\text{in}} m_{\text{SMP}}}\right)^3\right] \quad \text{when} \quad \boxed{\text{T}_{\text{BH}} = \text{m}_{\text{SMP}}} \quad \text{or} \quad \text{M}_{\text{BH}}(\text{t}_1) = \text{M}_\text{p}^2/\text{m}_{\text{SMP}}$$

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 ?**



✓ **While PBH loses its mass during particle emission, Hawking temperature consequently increases.**

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

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

$$\tau_{N_1} \simeq 68\ {\rm s}\left(\frac{10^{-21}}{|Y_{\alpha 1}|}\right)^2\left(\frac{0.1 M_p}{m_{N_1}}\right) \qquad \boxed{|Y_{\alpha 1}| < 8.2\times 10^{-21}\left(\frac{0.1 M_p}{m_{N_1}}\right)^{1/2}}$$

Massive particle production

Long-lived N

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

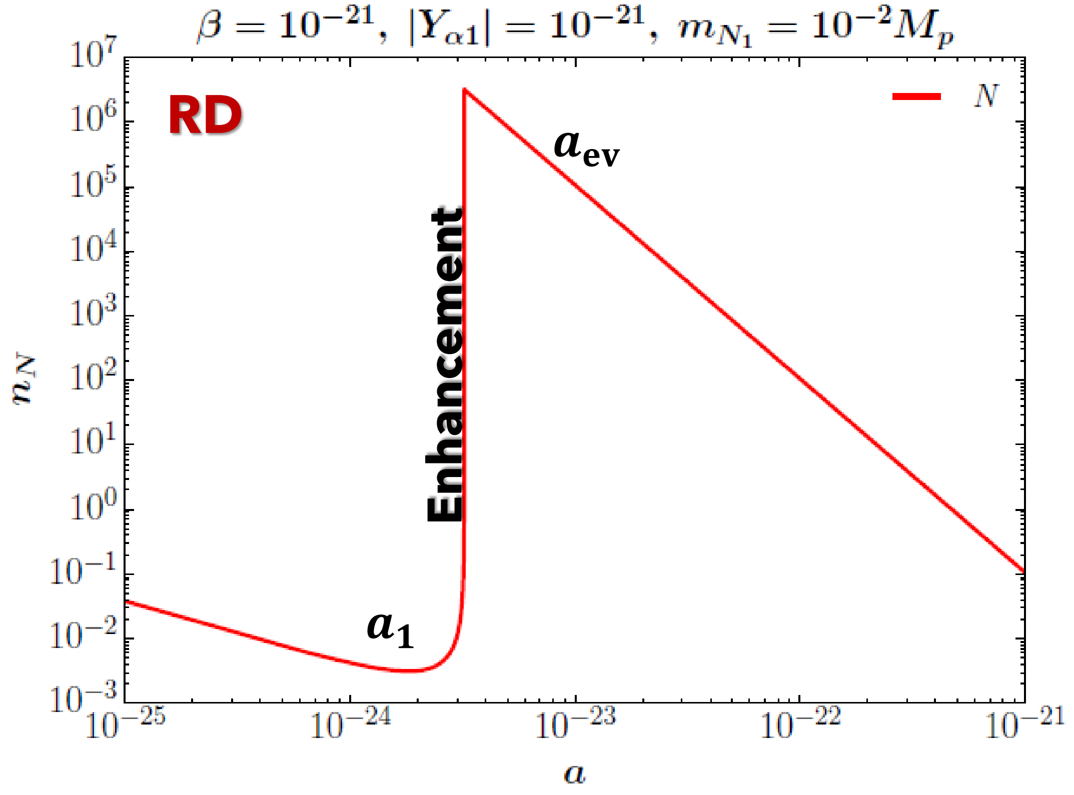
The momentum-integrated emission rate:

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

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

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

The number density of sterile neutrino:



$$n_{N_1}(a_{\rm ev}) \simeq 4 \times 10^3 \ {\rm GeV}^3 \left(\frac{\beta}{10^{-21}}\right) \left(\frac{1\ {\rm g}}{M_{\rm in}}\right)^6 \left(\frac{0.1 M_p}{m_{N_1}}\right)^2$$

Neutrino flux from sterile neutrino decay

- **The sterile neutrinos, produced non-thermally via Hawking radiation, decay into active neutrinos after neutrino decoupling.**

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

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

Non-relativistic limit:

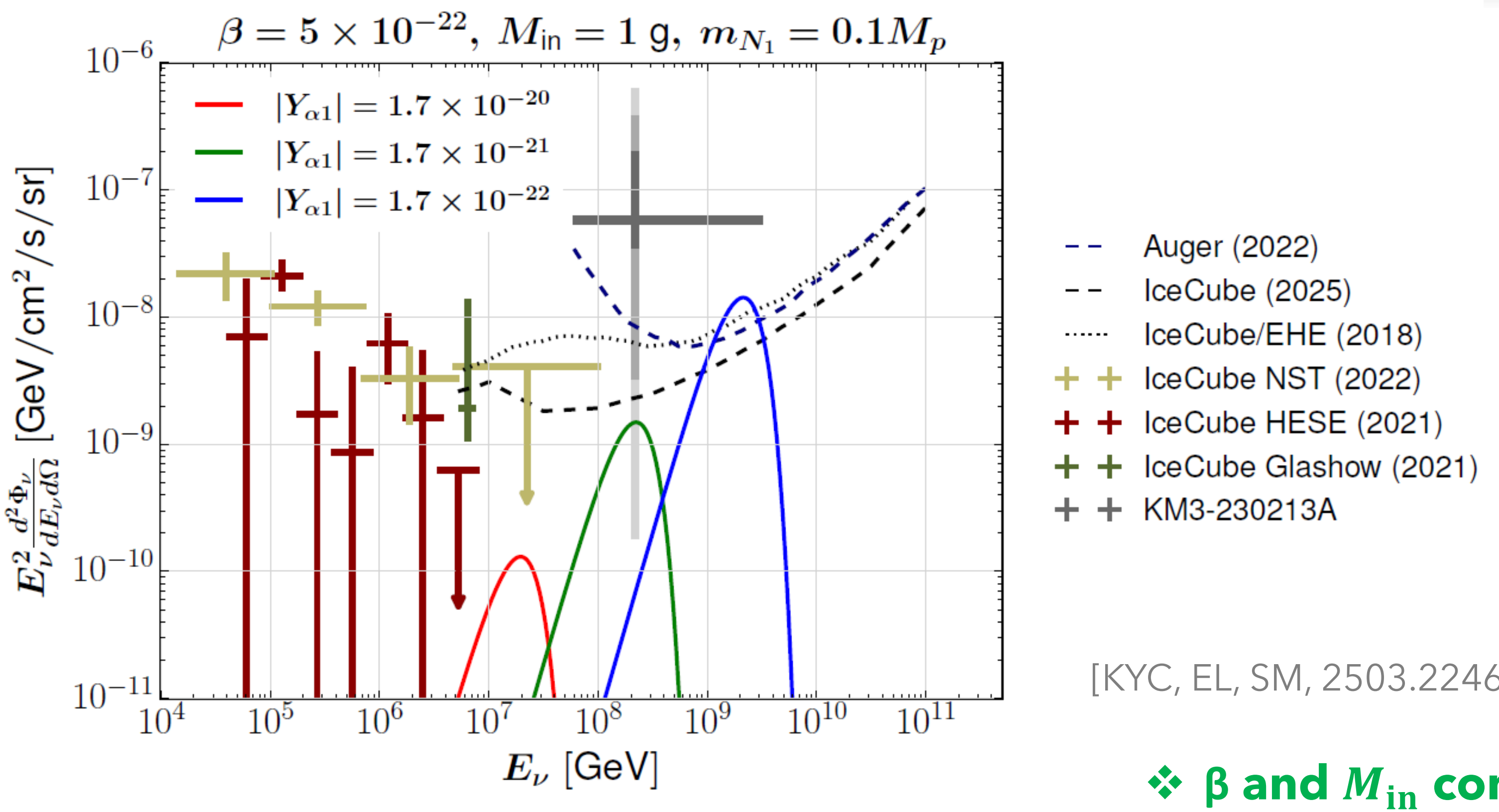
$$\Gamma_{\rm prod}^{(f_\nu)} \simeq \frac{\pi|\mathcal{M}|^2}{2m_N^3} n_N \delta(E_\nu - \frac{m_N}{2})$$

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

$$\frac{a_{N_1}}{a_0} \simeq \frac{T_0}{T_{N_1}} \left(\frac{g_{*,s}(T_0)}{g_{*,s}(T_{N_1})}\right)^{1/3} \simeq 1.7\times 10^{-9} \left(\frac{10^{-21}}{|Y_{\alpha 1}|}\right) \left(\frac{0.1 M_p}{m_{N_1}}\right)^{1/2}$$

Neutrino flux from sterile neutrino decay

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



[KYC, EL, SM, 2503.22465]

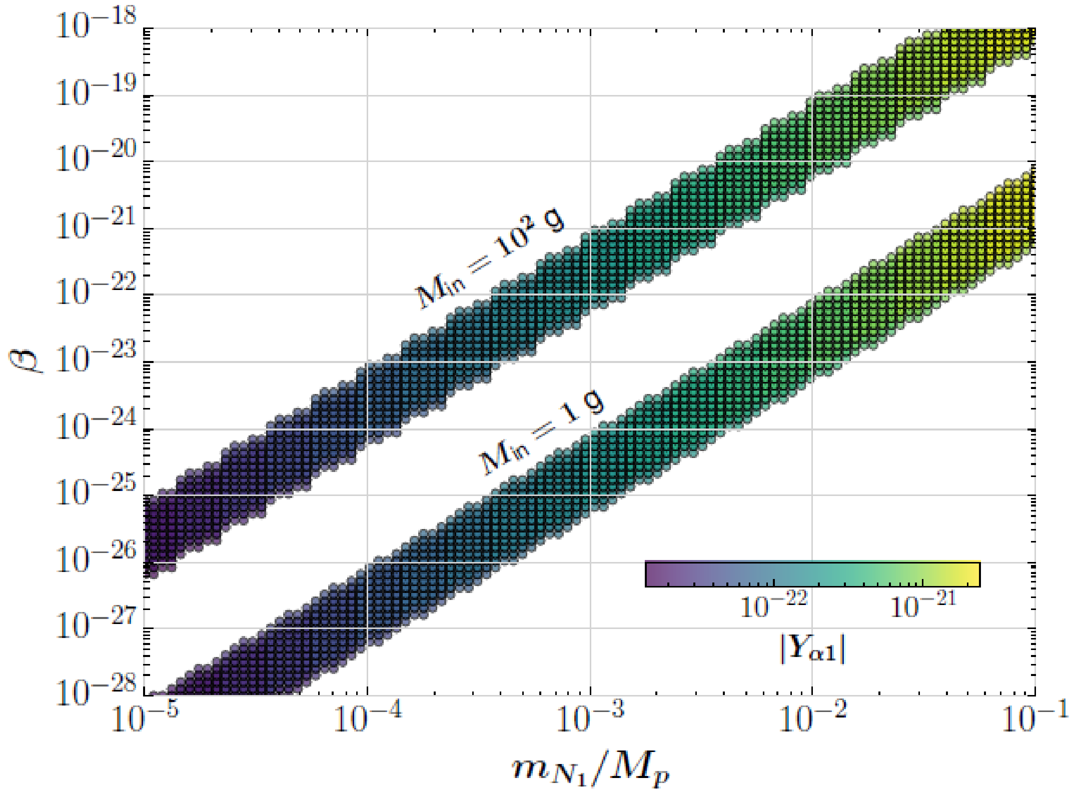
$$\frac{d^2\Phi_\nu}{dE_\nu d\Omega} = \frac{\mathrm{BR}_{N\to\nu}}{3}\frac{1}{4\pi}\frac{E_\nu^2}{2\pi^2} f_\nu(E_\nu)|_{t\to t_0}$$

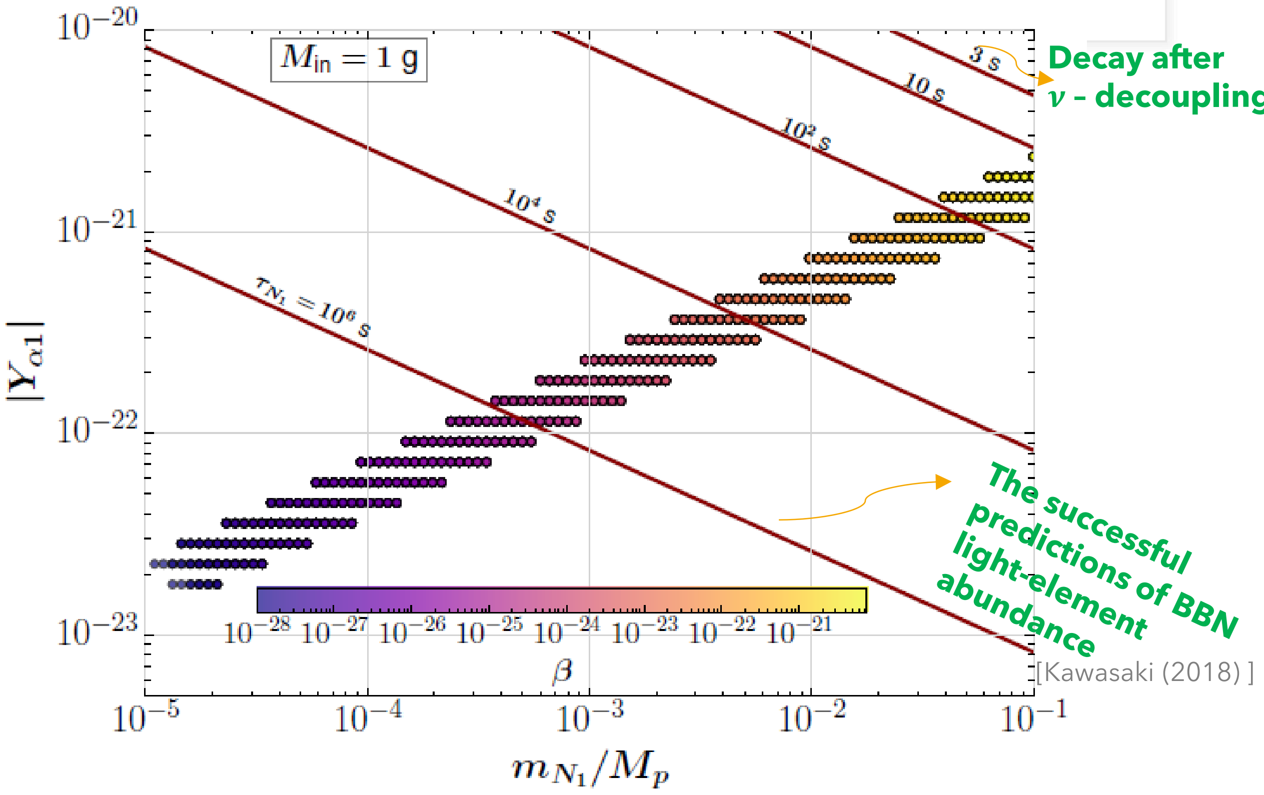
- The resulting neutrino flux is determined by cosmological redshift and the decay kinematics.
- The predicted flux not only explains the cosmological origin of KM3NeT event but also respects the existing constraints from IceCube and Auger.

- **β and $M_{\rm in}$ control the flux amplitude.**
- **Yukawa couplings and m_N control the peak position of spectrum.**

Neutrino flux from sterile neutrino decay

The allowed parameter space generating the required flux to explain the KM3NeT event:





❖ As PBH mass increases, the initial number density of PBH decreases, which in turn lowers the sterile neutrino number density.

Neutrino mass & Leptogenesis

Type-I seesaw mechanism: $\mathcal{L} \supset -Y_{\alpha k}\overline{L}_\alpha \tilde{H} N_k - \frac{1}{2}(\bar{N}_k^c M_{N_k} N_k) + \text{h.c.}$

Active neutrino mass: $(m_\nu)_{\alpha\beta} = -M_D M_R^{-1} M_D^T \equiv -\frac{1}{2} Y_{\alpha k} M_{N_k}^{-1} Y_{k\beta} v^2, \quad Y = \frac{i\sqrt{2}}{v} U^* D_{\sqrt{m_\nu}} R^T D_{\sqrt{M_R}}$

$$M_R = \text{Diag}\{m_{N_1}, m_{N_2}, m_{N_3}\} = \text{Diag}\{0.1M_p,\ 2.5\times10^{-5}M_p,\ 2.5\times10^{-4}M_p\}.$$

- Perturbativity of Yukawa coupling
- Higgs vacuum metastability [Seyda Ipek et al, JHEP 1812 (2018) 111; Garv Chauhan et al, JHEP 09 (2023) 151]

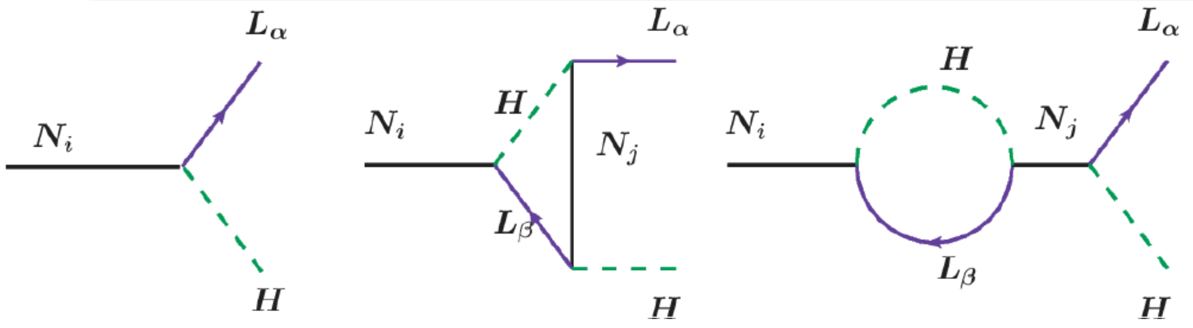
❖ The N_1 coupling of order $\vartheta(10^{-21})$ can be made dependent on the lightest active neutrino (a vanishingly small value).

❖ N_2 and N_3 couplings of order $\vartheta(10^2)$ or larger are dominant to explain the neutrino oscillation data.

$$Y = \begin{pmatrix} 0. + 2.32488\times10^{-21}i & 0.0100373 - 0.0604792i & -0.0003079 - 0.18223i \\ 7.7151\times10^{-23} - 7.62991\times10^{-22}i & 0.0504647 + 0.123094i & 0.085298 - 0.706361i \\ 6.68303\times10^{-23} + 1.39073\times10^{-21}i & -0.0494323 + 0.0387449i & 0.0253041 + 0.695677i \end{pmatrix}$$

Neutrino mass & Leptogenesis

The leptogenesis is dynamically produced from the CP-violating decays of the heavy Majorana neutrinos.



$$\varepsilon_i = \frac{\Gamma(N_i \to LH) - \Gamma(N_i \to \bar{L}\bar{H})}{\Gamma(N_i \to LH) + \Gamma(N_i \to \bar{L}\bar{H})}$$

N_1 decay: $\varepsilon_1 \lesssim 10^{-30}$

$$\frac{dN_{N_2}}{dz} = -(D_2 + S_2)(N_{N_2} - N_{N_2}^{\rm eq}),$$

Decay process

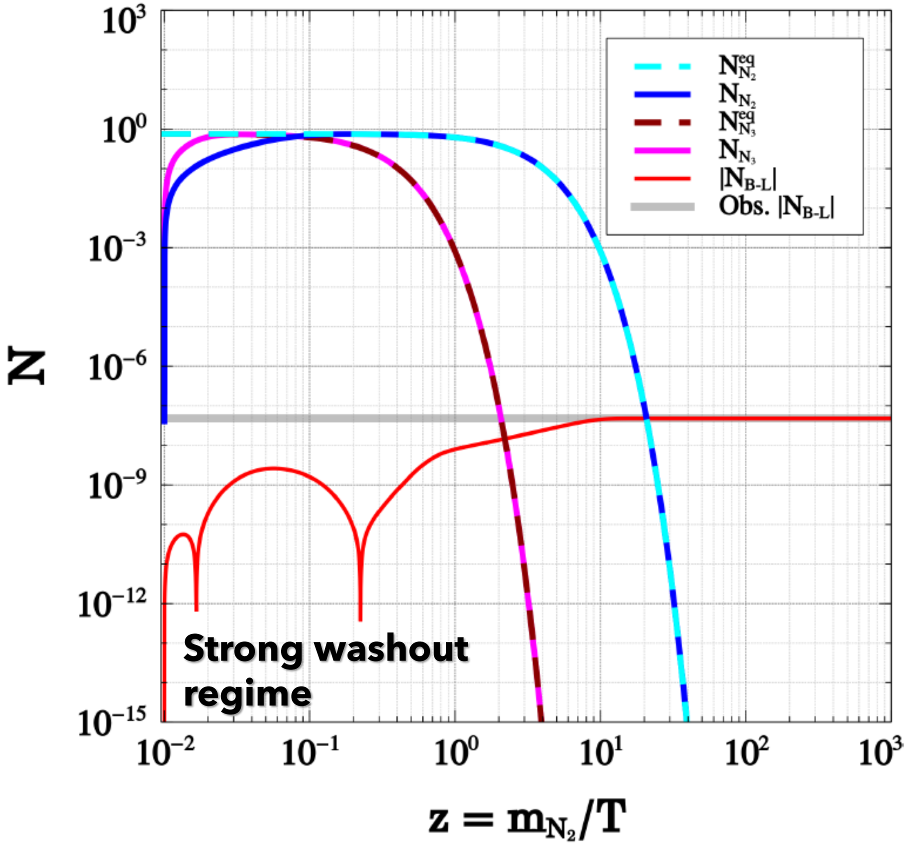
$$\frac{dN_{N_3}}{dz} = -(D_3 + S_3)(N_{N_3} - N_{N_3}^{\rm eq}),$$

Scattering process

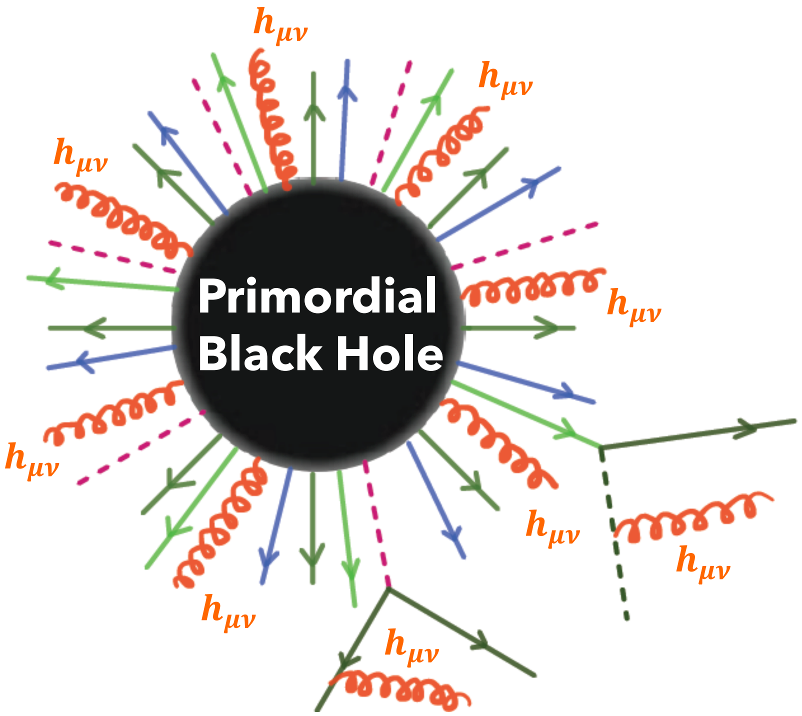
$$\frac{dN_{\rm B-L}}{dz} = -\sum_{i=2}^{3}[\varepsilon_i D_i(z)(N_{N_i} - N_{N_i}^{\rm eq}) + W_i(z)N_{\rm B-L}(z)],$$

Washout process

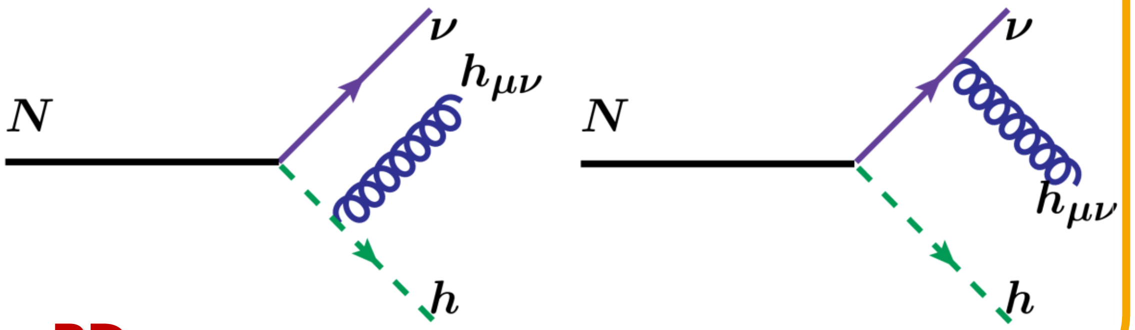
$$\eta_B = \frac{C_{B\to L}}{d} N_{\rm B-L}^{\rm f} = 1.23 \times 10^{-2} N_{\rm B-L}^{\rm f}$$



The generation of SGWBs



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



RD

Graviton + Matter interaction

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

Suppression!!

Compensate suppression :

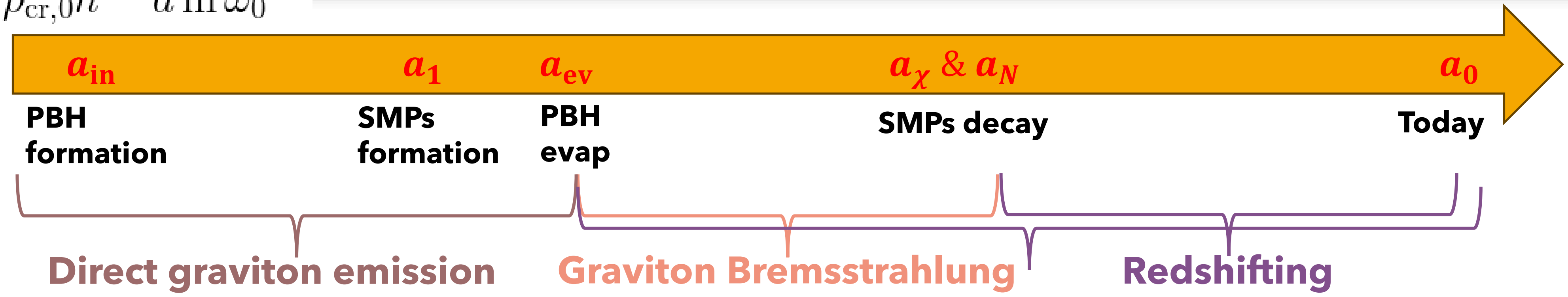
- ✓ **$T^{\mu\nu}$ should be very large (considering inflation model)**

[N. Bernal et al, 2301.11345; 2311.12694]

- ✓ **Sub-Planckian mass scale particle bremsstrahlung without suppression**

The generation of SGWBs

$$h^2\Omega_{\rm GW} = \frac{1}{\rho_{{\rm cr},0}h^{-2}}\frac{d\rho_{{\rm GW},0}}{d\ln\omega_0}$$



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

$$\frac{d}{da}\left(a^4\frac{d\rho_{\rm GW}}{d\ln E_{\rm GW}}\right) = \frac{n_{N_1}(a_{\rm ev})a_{\rm ev}^3}{\mathcal{H}}\frac{d\Gamma_{N_1\to{\rm GW}}}{dE_{\rm GW}}E_{\rm GW}^2$$

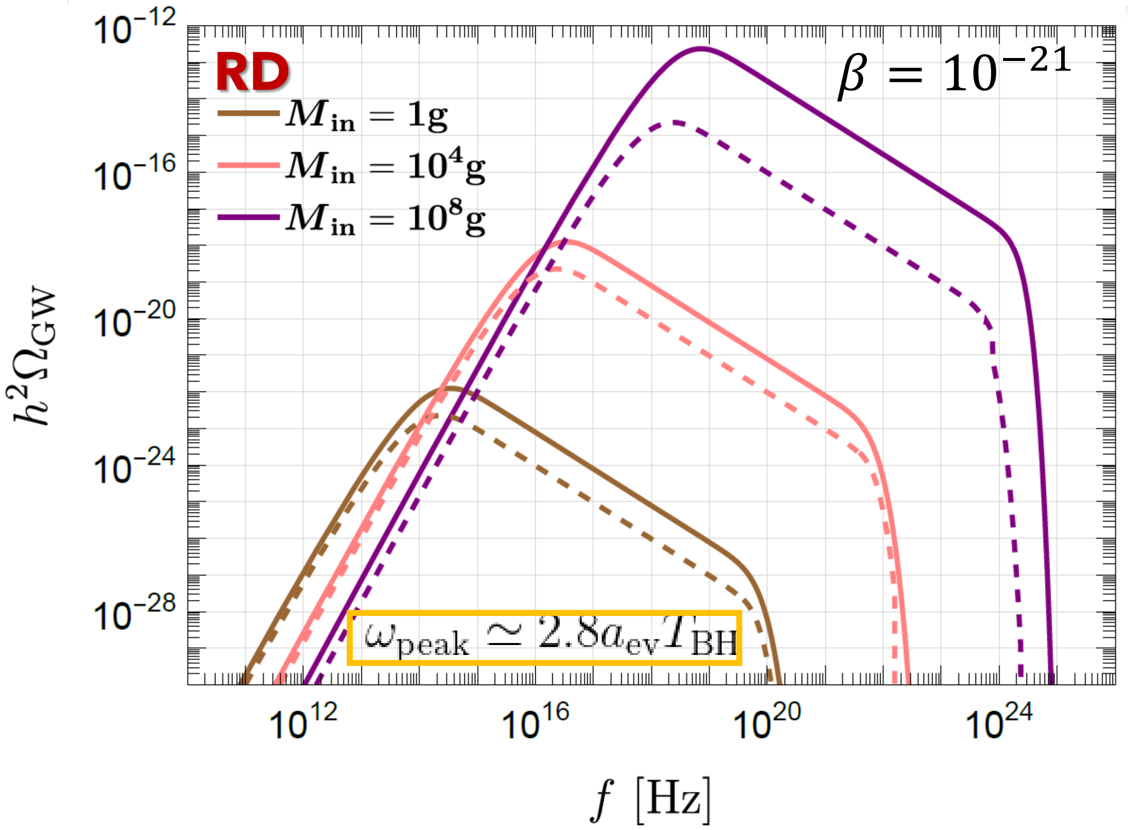
[Choi, et al. 2403.15269]

$$\frac{a_{\rm ev}}{a_0} \simeq 2.3\times10^{-24}\left(\frac{M_{\rm in}}{1\,{\rm g}}\right)^{3/2}$$

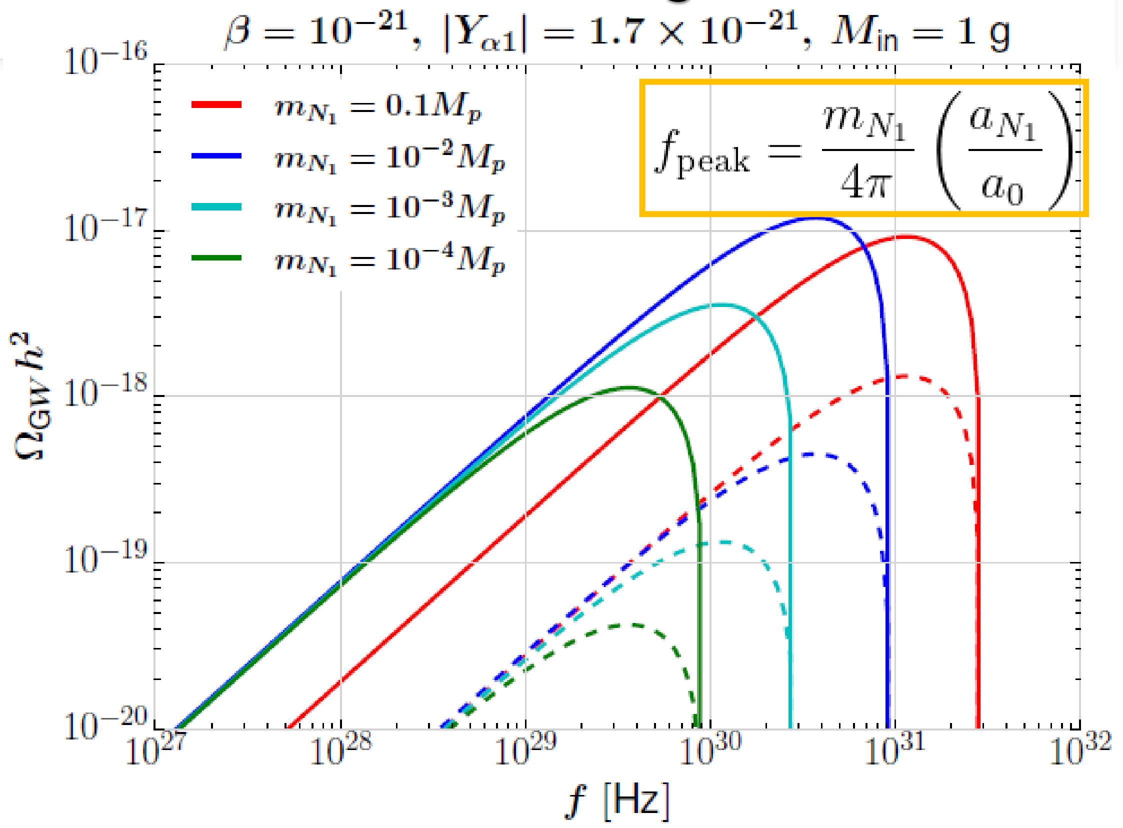
$$\frac{a_{N_1}}{a_0} \simeq 1.7\times10^{-9}\left(\frac{10^{-21}}{|Y_{\alpha1}|}\right)\left(\frac{0.1M_p}{m_{N_1}}\right)^{1/2}$$

SGWB signatures

Direct graviton emission contribution:



Graviton Bremsstrahlung contribution:

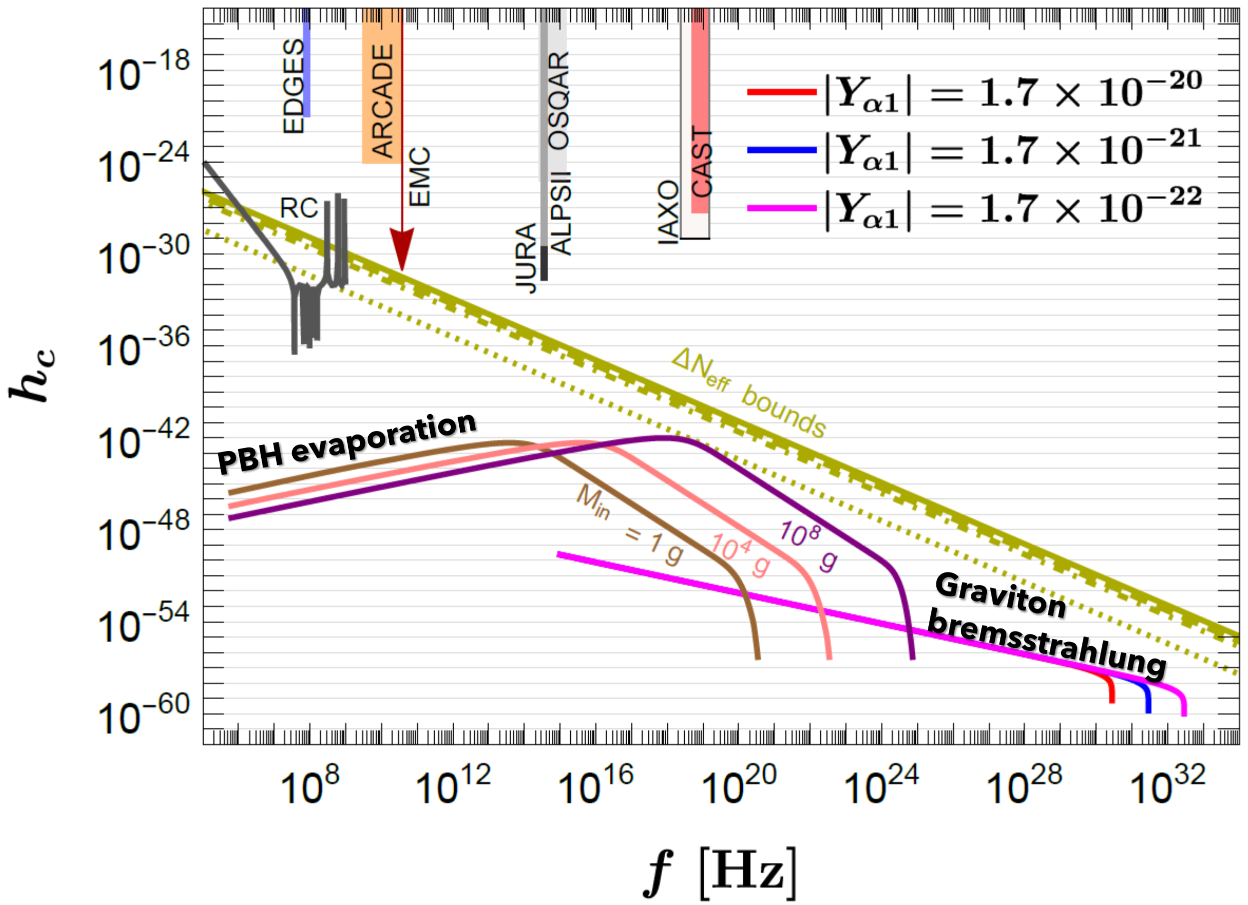


- ❖ As the PBH mass increases, both the peak frequency and amplitude of the GW spectrum increase.
- ❖ Either decreasing Yukawa couplings or increasing the mass of SMPs shifts the corresponding peak frequency to a higher value.

Gravitational wave characteristic strain with both contributions

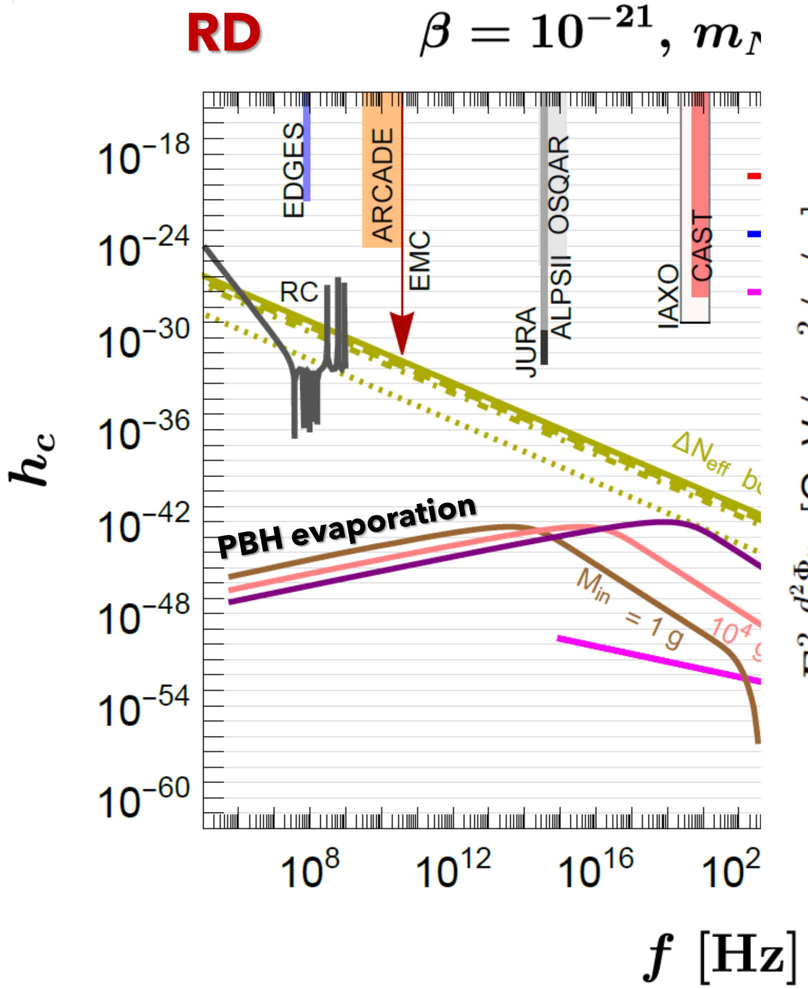
$$h_c = f^{-1}\sqrt{\frac{3H_0^2}{4\pi^2}\Omega_{\rm GW}} \simeq 8.93\times10^{-19}\sqrt{\Omega_{\rm GW}h^2}\left(\frac{\rm Hz}{f}\right)$$

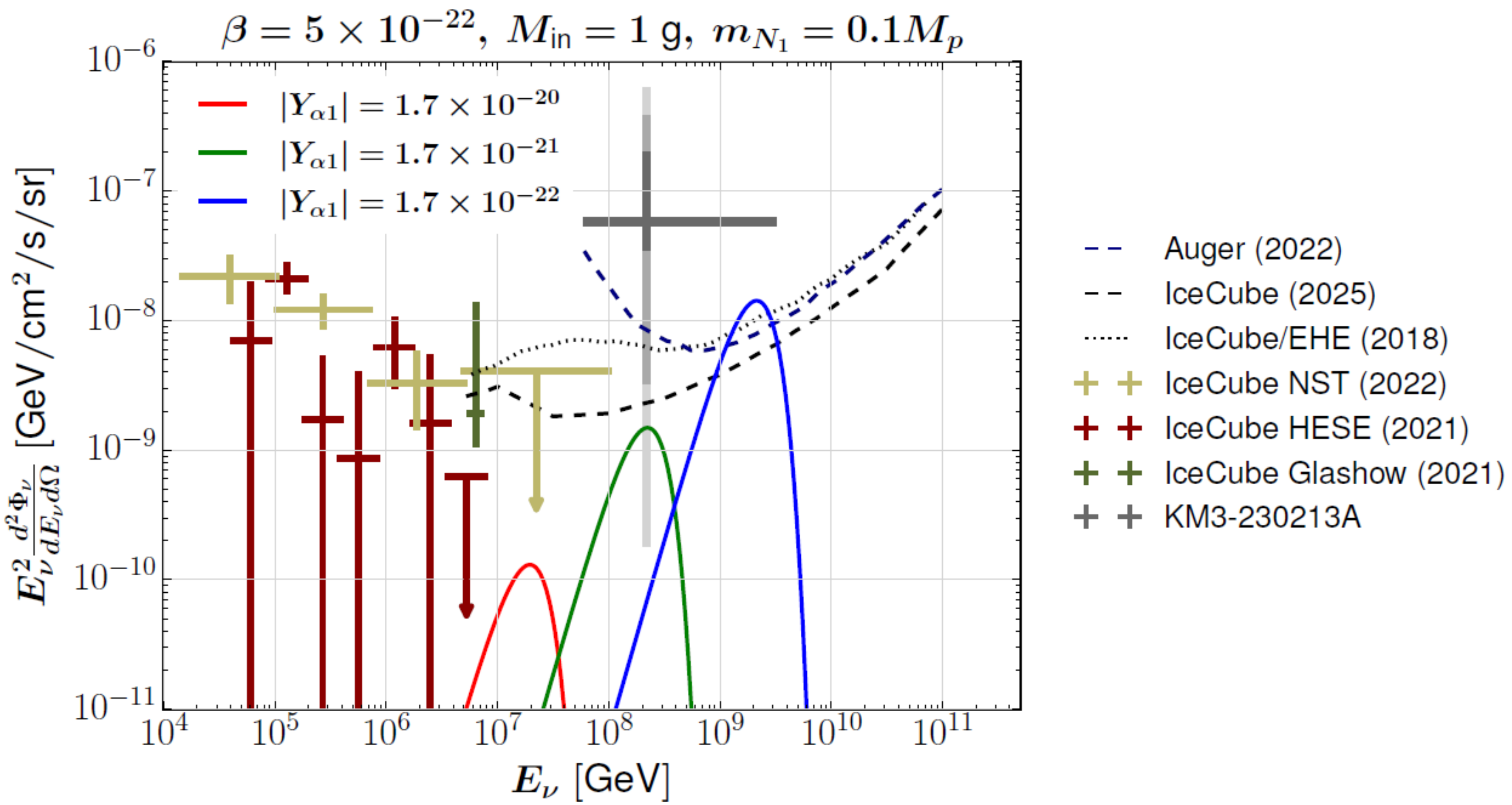
RD $\beta = 10^{-21},\ m_{N_1} = 0.1M_p$



Gravitational wave characteristic strain with both contributions

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





Conclusion

We explore the consequences of primordial black hole evaporation in the early universe and its implications for the ultra-high-energy event KM3-230213A and the ultra-high-frequency GWs.

1. Sterile neutrinos generated from PBH via Hawking radiation subsequently decay into ultra-high-energy active neutrinos.
   - ❖ The resulting flux, after cosmological redshift, aligns with the energy and isotropic origin of KM3-230213A event while respecting constraints from IceCube and the Pierre Auger Observatory.
   - ❖ The model employs a type-I seesaw mechanism, while a third, feebly coupled sterile neutrino with a Planck-scale mass decays to produce the observed ultra-high-energy neutrinos.
   - ❖ The sterile neutrinos with significant coupling so as to generate the neutrino masses consistent with oscillation data can also be leveraged to produce the matter-antimatter asymmetry of the Universe via the baryo-lepto-genesis route.
2. We have explored the production of SGW not only through the direct evaporation of PBHs but also via the bremsstrahlung process during the decay of the super-massive particles.
   - ❖ Both contributions give two distinct spectral signatures; these GW signals are intrinsically tied to the parameters governing the neutrino flux i.e. PBH mass, PBH energy density relative to radiation at its formation time , sterile neutrino mass and the Yukawa coupling, offering a multi-messenger probe of the mechanism.
   - ❖ Even though the high-frequency SGW spectra during RD remain below the sensitivity of the future experiments, parameters of our model scenario, rooted in PBH evaporation, can be tested by the high-energy neutrino experiments.

Thank You!

Backup slides: GW contribution to dark radiation

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

Gravitational Wave contribution to ΔN_{eff}:

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

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]

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

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