Superheavy Dark Matter for the origin of KM3NeT Ultra-High Energy signal

Yongsoo Jho

based on arXiv:2503.18737
Collaboration with S. C. Park and C. S. Shin

Aug 21st, 2025
Summer Institute 2025, Yeosu

KM3-230213A: UHE event

- KM3NeT collaboration recently reported an analysis of Ultra-High-Energy event (KM3-230213A)

Article

Observation of an ultra-high-energy cosmic neutrino with KM3NeT

https://doi.org/10.1038/s41586-024-08543-1

Received: 19 August 2024

Accepted: 18 December 2024

Published online: 12 February 2025

Open access

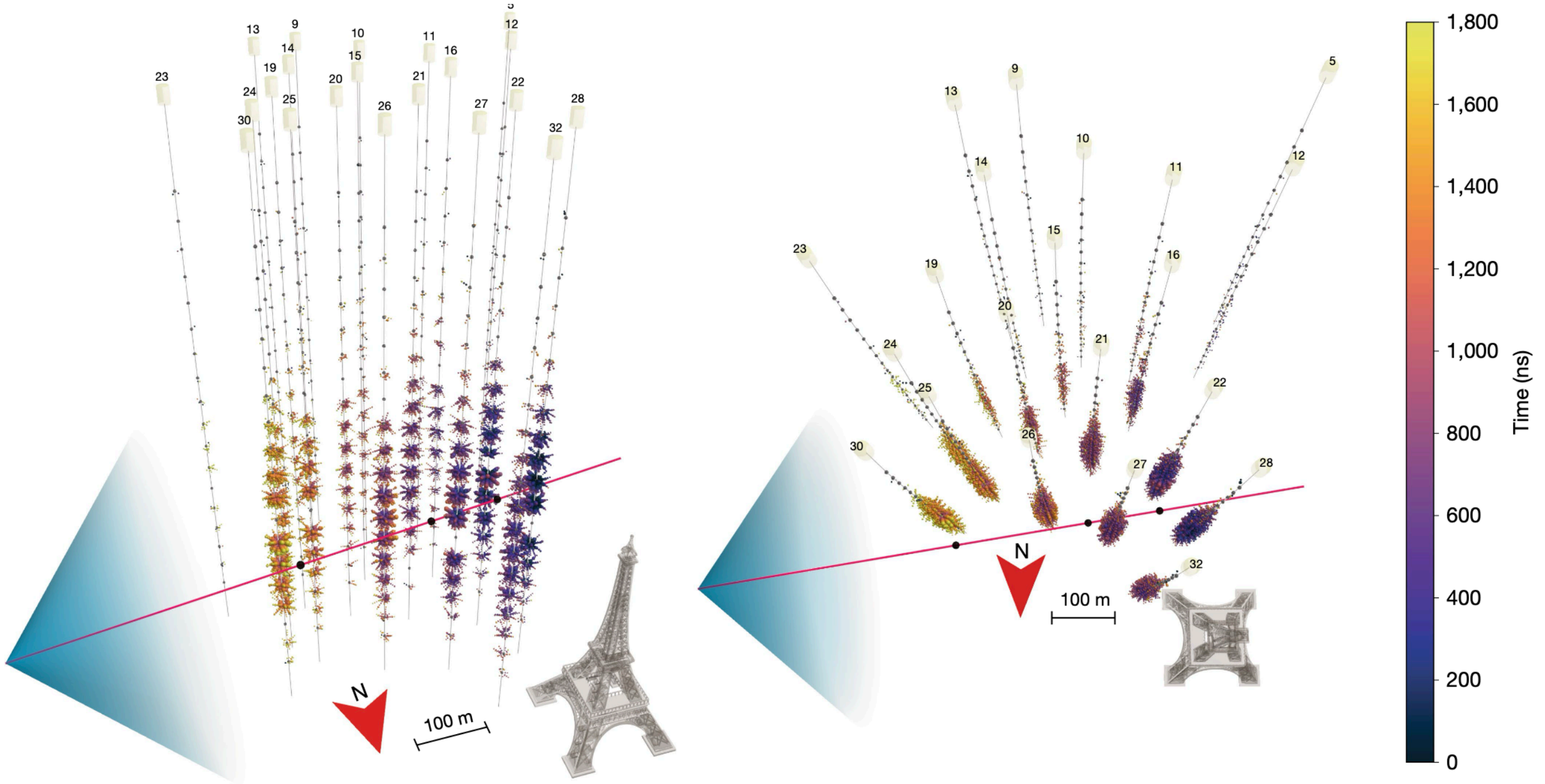
Check for updates

The KM3NeT Collaboration*✉

The detection of cosmic neutrinos with energies above a teraelectronvolt (TeV) offers a unique exploration into astrophysical phenomena[1–3]. Electrically neutral and interacting only by means of the weak interaction, neutrinos are not deflected by magnetic fields and are rarely absorbed by interstellar matter: their direction indicates that their cosmic origin might be from the farthest reaches of the Universe. High-energy neutrinos can be produced when ultra-relativistic cosmic-ray protons or nuclei interact with other matter or photons, and their observation could be a signature of these processes. Here we report an exceptionally high-energy event observed by KM3NeT, the deep-sea neutrino telescope in the Mediterranean Sea[4], which we associate with a cosmic neutrino detection. We detect a muon with an estimated energy of 120^{+110}_{-60} petaelectronvolts (PeV). In light of its enormous energy and near-horizontal direction, the muon most probably originated from the interaction of a neutrino of even higher energy in the vicinity of the detector. The cosmic neutrino energy spectrum measured up to now[5–7] falls steeply with energy. However, the energy of this event is much larger than that of any neutrino detected so far. This suggests that the neutrino may have originated in a different cosmic accelerator than the lower-energy neutrinos, or this may be the first detection of a cosmogenic neutrino[8], resulting from the interactions of ultra-high-energy cosmic rays with background photons in the Universe.

KM3-230213A: UHE event

- KM3NeT collaboration recently reported an analysis of Ultra-High-Energy event (KM3-230213A)



KM3-230213A: UHE event

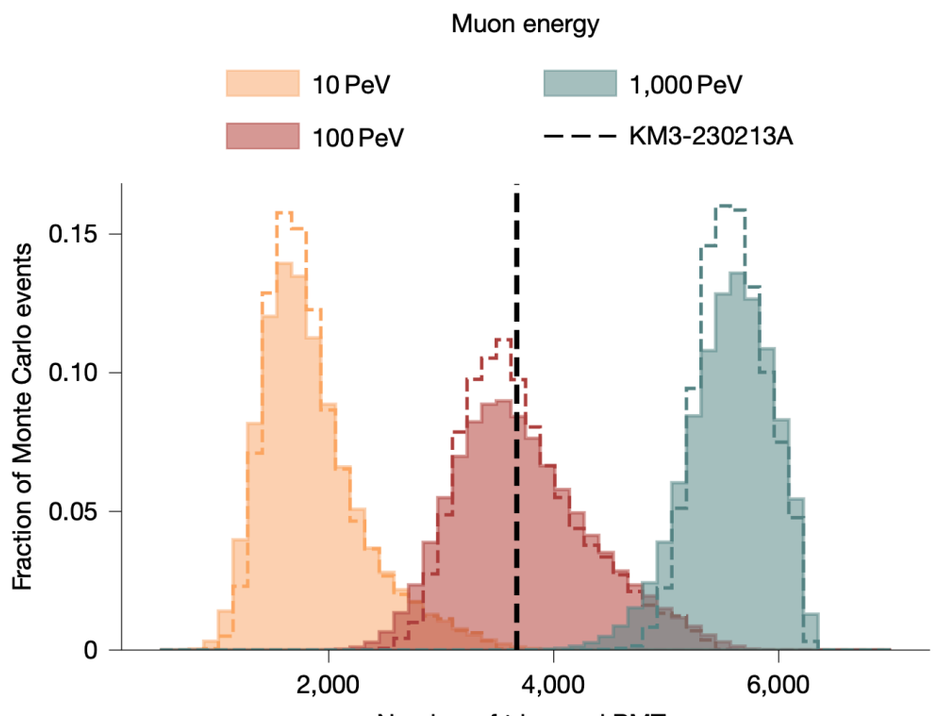
- KM3NeT collaboration recently reported an analysis of Ultra-High-Energy event (KM3-230213A) with

  - 3,672 triggered PMTs in the detector region

  - The reconstructed energy of the muon track ~ 120 PeV
    -> The median neutrino energy ~ 220 PeV

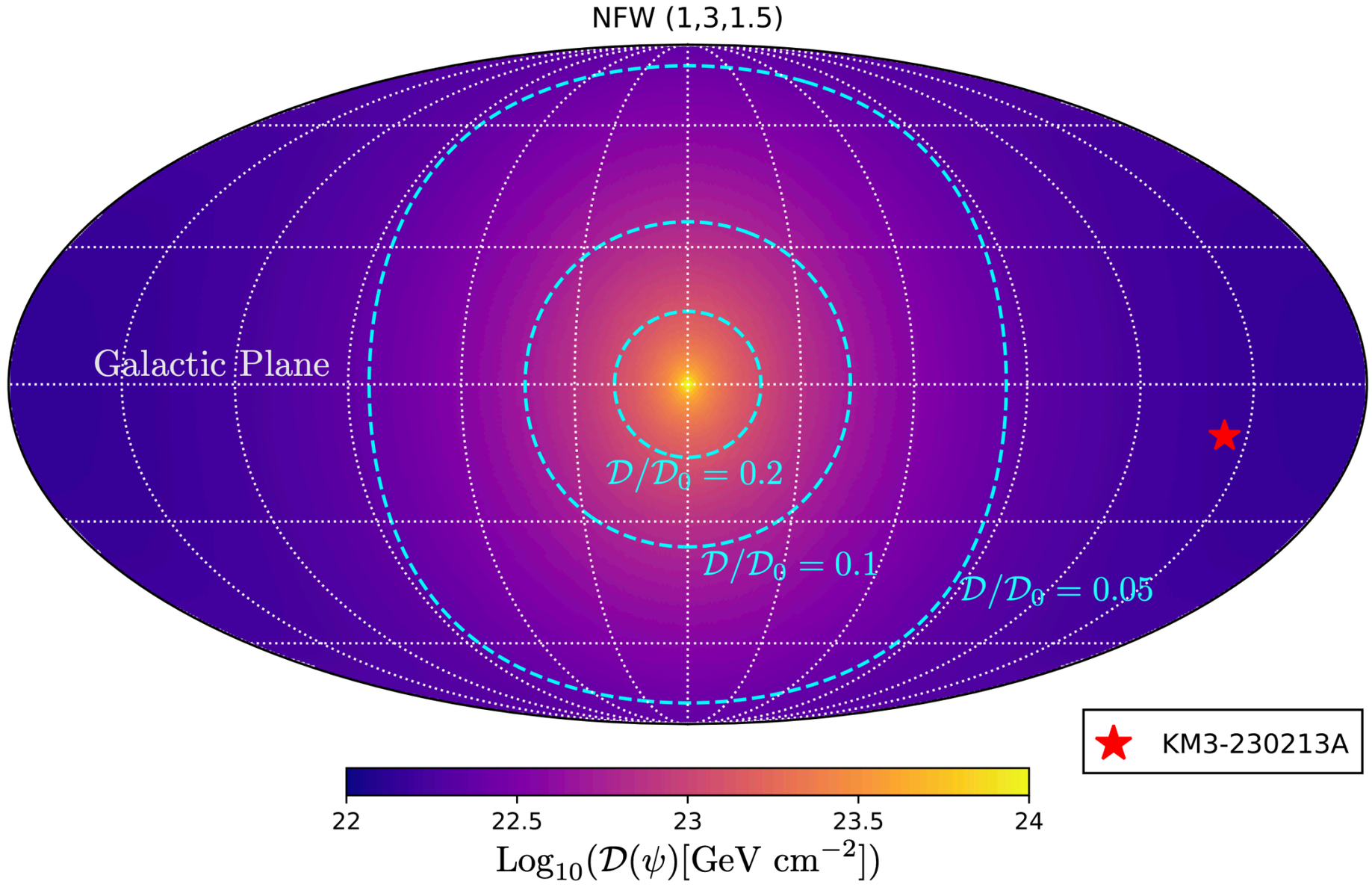
$$E_\nu \subset [72\ \mathrm{PeV},\ 2.6\ \mathrm{EeV}]\ @\ 90\%\ \mathrm{C.\ L.}$$

- The most energetic neutrino event ever measured.
- The only neutrino event candidate with >O(10) PeV so far.



KM3-230213A: UHE event

- RA (Right Ascension): +94.3°
- Dec (Declination): -7.8°
- 68% C.L. angular uncertainty $\delta \sim 1.5°$
- Altitude 0.6°



KM3-230213A: UHE event

- The source of the neutrino is not clearly identified.
- Many intriguing interpretations have been investigated so far:

  - Transient astrophy. high-E sources (GRB, Blazar, AGN, etc.)

  [P. Machado, S.W.Li, D. Narero-Tuero, T. Schwemberger],
  [S. Palmisano, D. Redigolo, M. Tammaro, A. Tesi],
  ...+more

  - Cosmogenic (GZK) neutrinos from UHECRs

  - Neutrinos from decaying heavy DM

  [S. Khan, J. Kim, P. Ko], [D. Borah, N. Das, N. Okada, P. Sarmah],
  [K. Kohri, P. K. Paul, N. Sahu], [This talk, YJ, S.C.Park, C.S.Shin], ...+more

  - Sterile/Heavy Neutrinos and its oscillation and decays

  [V. Brdar, D.S.Chattopadhyay], [K. Murase, Y. Narita, W. Yin],...+more

  - Primordial Black Hole burst/steady evaporation signals

  [K.-Y.Choi, E. Lkhagvadorj, S. Mahapatra],
  [J.H.Park, M.G.Park,S.Park,S.C.Park, YJ, in progress], ...+more

- None of them are certainly confirmed yet.

Superheavy Dark Matter for KM3-230213A?

- The origin of UHE event seems to be Extragalactic, and there is no similar signature near the Galactic Center.
- The energy O(100-1000) PeV of the neutrino is even extremely high for various astrophysical transient processes.
- The origin of UHE neutrino and the structure of the Flux is still very mysterious.
- We have only a single event at ~ O(100-1000) PeV for now.
- DM interpretation could be attractive and naturally realize Ultra-High-Energy in signals.

Decaying superheavy DM for KM3-230213A

Q: Decaying DM signatures can be Extragalactic-dominated?

Our Answer:
It's in general possible with

- a O(1-10) Gyr lifetime for Heavy-to-Light decays between DM components

- Nearly degenerated spectrum in Dark Matter sector.

Outline on our analysis

- Nearly degenerate heavy DM scenario
- Decay channels relevant for UHE neutrinos
- Expected signal in a landscape of nu/gamma observations
- Prospects & Conclusion

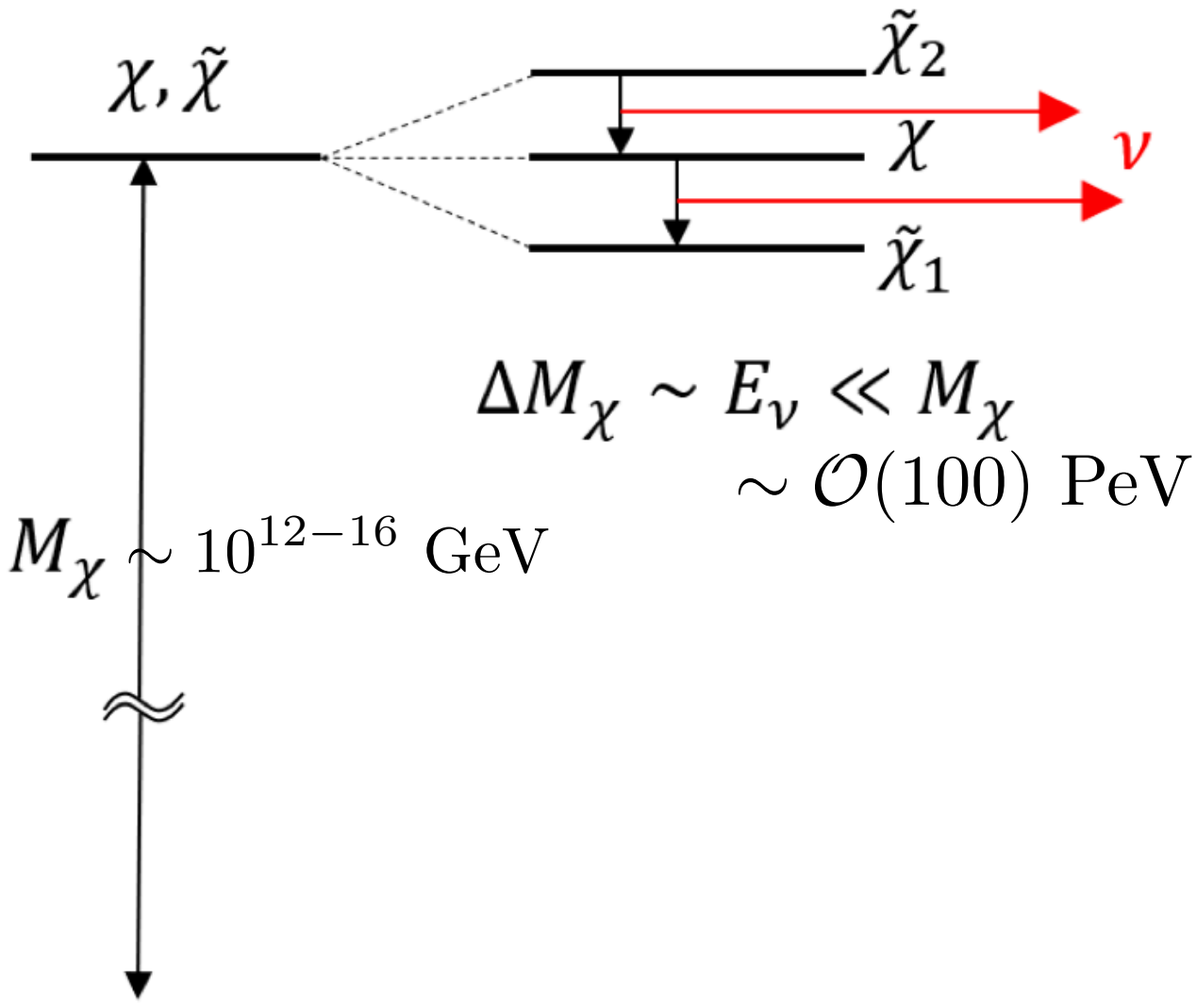
DM Scenario

DM candidates are given as a chiral multiplet:

$$X = \tilde{\chi} + \sqrt{2}\theta\chi + \theta^2 F_\chi$$

SUSY breaking scale is characterized by a spurion as

$$W = \frac{1}{2}\mathcal{M}X^2 \qquad \mathcal{M} = M + \theta^2 F$$



$$V = \frac{1}{2}M(\chi\chi + h.c.) + M^2|\tilde{\chi}|^2 + \frac{1}{2}F(\tilde{\chi}^2 + h.c.).$$

$$M_{\tilde{\chi}_{1,2}} = M \pm \frac{F}{M}, \quad M_\chi = M.$$

$$\frac{\Delta M_\chi}{M_\chi} \equiv \frac{M_\chi - M_{\tilde{\chi}_1}}{M_\chi} = \frac{M_{\tilde{\chi}_2} - M_\chi}{M_\chi} = \frac{F}{M^2} \ll 1.$$

UHE neutrinos from DM decays

- Estimation of the Flux from DM decays

[YJ, S.C.Park, C.S.Shin, '25]

$$E_\nu^2 \frac{d\Phi_\nu}{dE_\nu} \sim \frac{\mathrm{Br}_\nu f_\chi}{4\pi M_\chi} \frac{\Delta M_\chi}{(1+z_\chi)} \rho_{\mathrm{DM}} c$$

$$= 2.5 \times 10^{-8} \left(\frac{\mathrm{GeV}}{\mathrm{cm}^2\,\mathrm{sec}\,\mathrm{sr}} \right) \times \left(\frac{\mathrm{Br}_\nu f_\chi}{10^{-3}} \right) \left(\frac{\Delta M_\chi}{10^{-7} M_\chi} \right) \left(\frac{10}{1+z_\chi} \right)$$

UHE neutrinos from DM decays

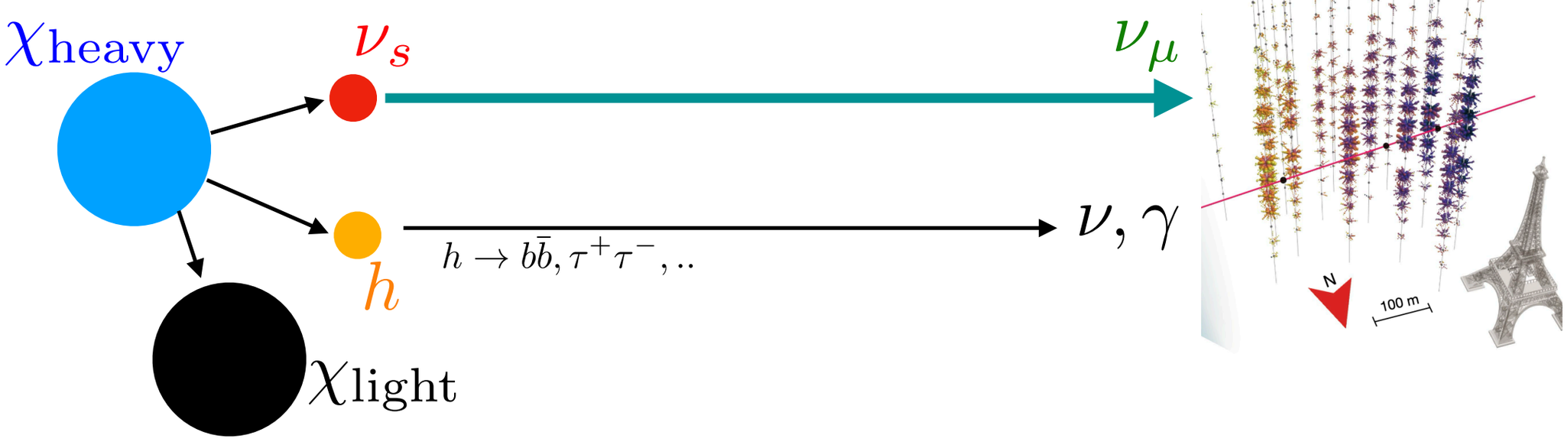
- Relevant scenarios for DM decays

[YJ, S.C.Park, C.S.Shin, '25]

- Scenario I : 3-body decay case with a heavy RH neutrino.

$$\Delta W_{\rm I} = \frac{L H_u X^2}{2\Lambda} \to \mathcal{L}_{int.} \supset \frac{\nu h \tilde{\chi} \chi}{\Lambda} + h.c.$$

$$\Gamma_{\tilde{\chi}_2 \to \chi \nu h} \simeq \Gamma_{\chi \to \tilde{\chi}_1 \nu h} \simeq \frac{M_\chi^3}{24\pi^3 \Lambda^2} \left(\frac{\Delta M_\chi}{M_\chi} \right)^4$$



UHE neutrinos from DM decays

- Relevant scenarios for DM decays

[P. Bandyopadhyay, E. J. Chun, and R. Mandal, '20]
[YJ, S.C.Park, C.S.Shin, '25]

- Scenario II : 2-body decay case with a light sterile neutrino.

$$S = \tilde{\nu}_s + \sqrt{2}\theta\nu_s + \theta^2 F_s$$

$$W_D = \frac{1}{2}\lambda_s S X^2 \;\; \rightarrow \mathcal{L}_{\text{int.}} \supset \lambda_s \tilde{\chi}\chi\nu_s + \ldots$$

$$\Gamma_{\tilde{\chi}_2 \to \chi\nu_s} \simeq \Gamma_{\chi \to \tilde{\chi}_1 \nu_s} \simeq \frac{\lambda_s^2 M_\chi}{8\pi}\left(\frac{\Delta M_\chi}{M_\chi}\right)^2$$

Neutrino & Gamma-ray signals

- Neutrino Flux

[YJ, S.C.Park, C.S.Shin, '25]

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{\mathrm{Br}_\nu \Gamma_\chi}{4\pi M_\chi} \frac{f_\chi \rho_{\mathrm{DM}} c}{H_0} \times \int_0^{z_{\max}} \frac{dz}{1+z} \frac{e^{-\Gamma_\chi t(z)}}{\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}} \frac{dN_\nu}{dE'_\nu}$$

Only Redshifted

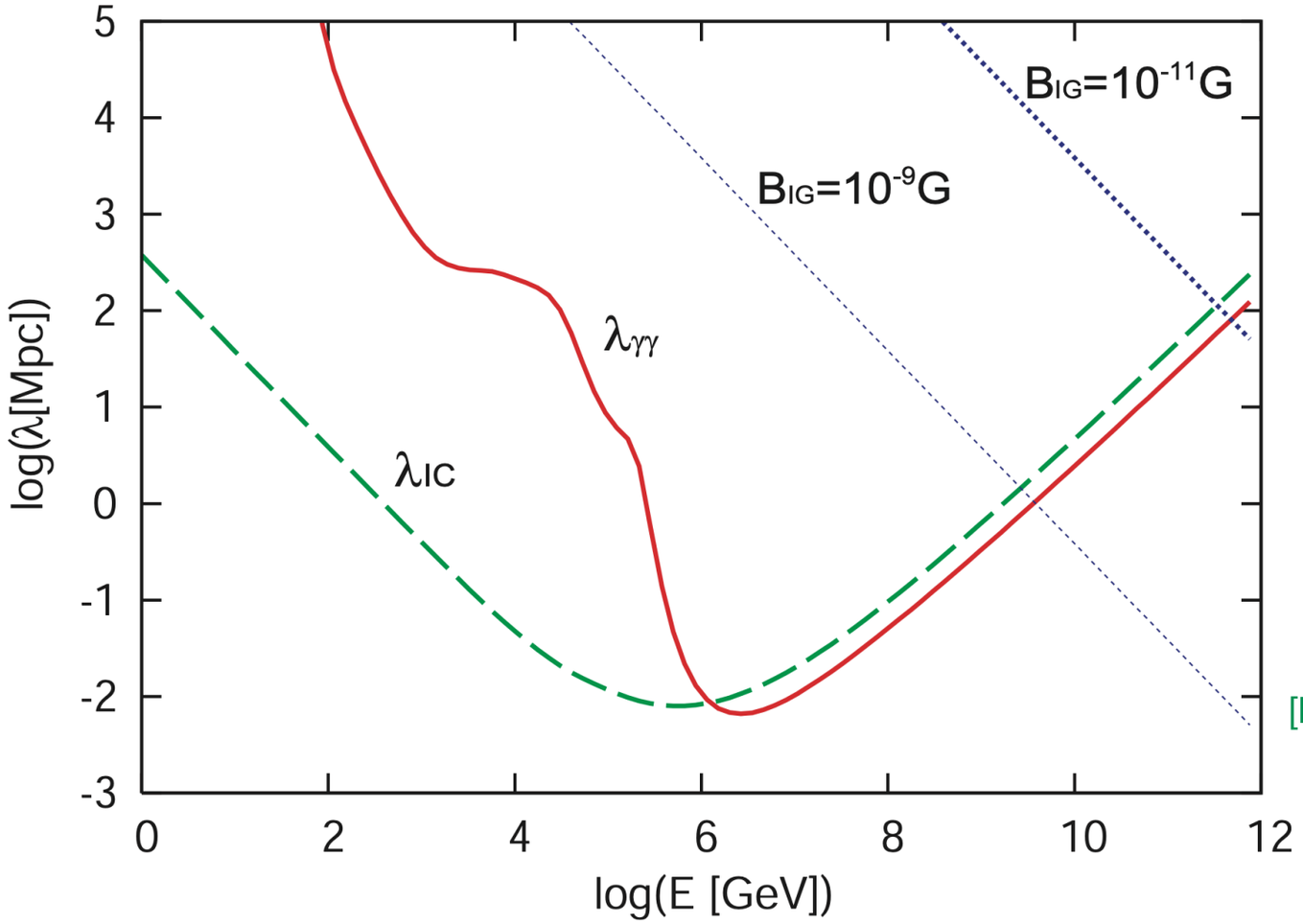
$$E'_\nu \equiv (1+z) E_\nu$$

Neutrino & Gamma-ray signals

- Gamma-ray Flux

$$\frac{d\Phi_\gamma^{\rm EG}}{dE_\gamma} = \frac{\Gamma_\chi(\gamma)}{4\pi M_\chi}\frac{f_\chi \rho_{\rm DM} c}{H_0} \times \int_0^{z_{\rm max}} \frac{dz}{1+z}\frac{e^{-\Gamma_\chi t(z)}}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}} P\left(z, \frac{dN_\gamma^{\rm inj}}{dE_\gamma}\right)$$

Redshift
+Attenuation
+Cascade



$$\gamma + \gamma_{\rm bkd.} \to e^+ + e^-$$

$$e^\pm + \gamma_{\rm bkd.} \to \gamma + e^\pm$$

[K. Murase, J. Beacom, '10, '12]

Neutrino/Gamma-ray signals

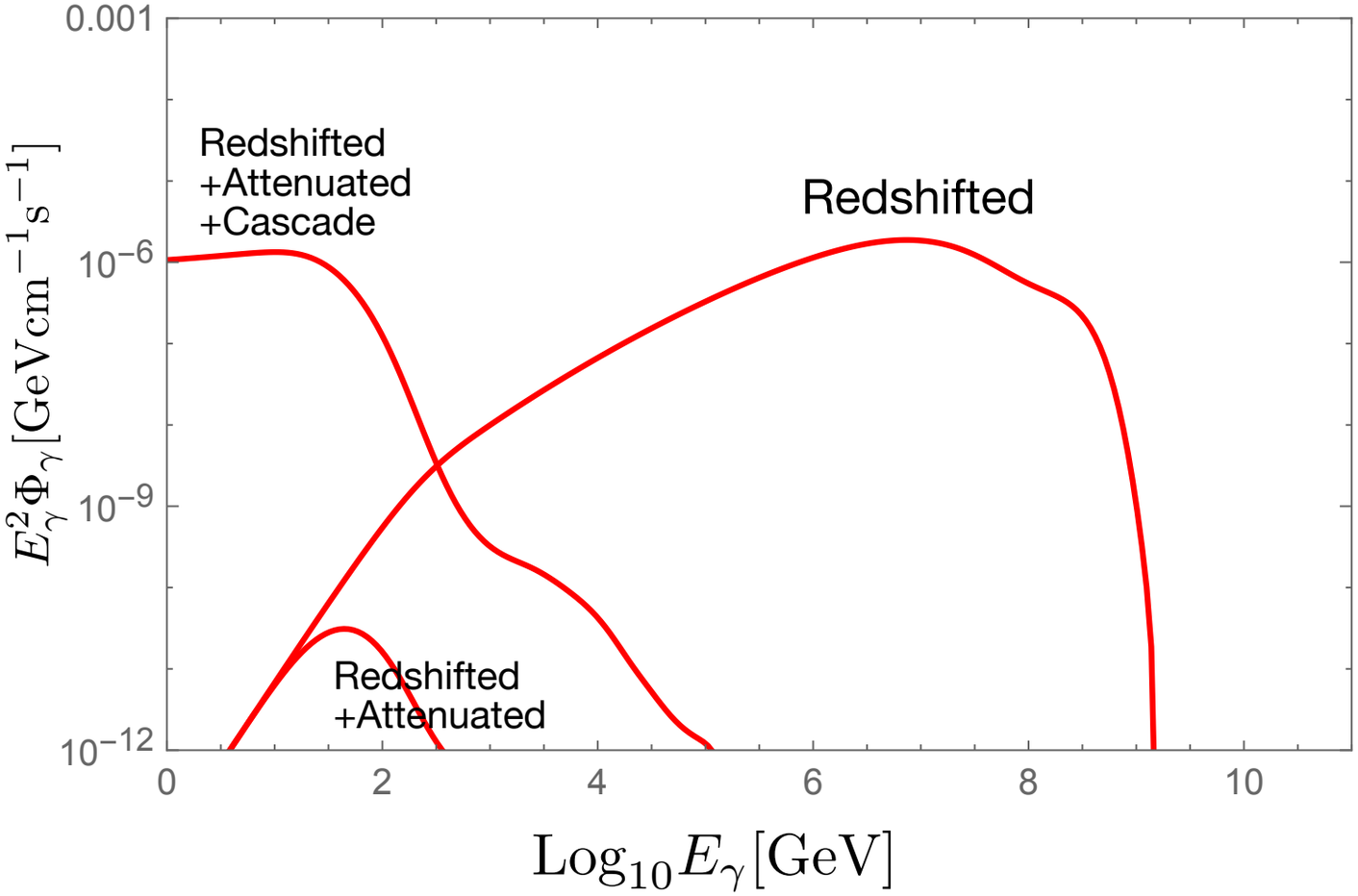
- Gamma-ray Flux

$$\frac{d\Phi_\gamma^{\rm EG}}{dE_\gamma} = \frac{\Gamma_\chi(\gamma)}{4\pi M_\chi}\frac{f_\chi \rho_{\rm DM} c}{H_0} \times \int_0^{z_{\rm max}} \frac{dz}{1+z}\frac{e^{-\Gamma_\chi t(z)}}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}} P\left(z, \frac{dN_\gamma^{\rm inj}}{dE_\gamma}\right)$$

Redshift

+Attenuation

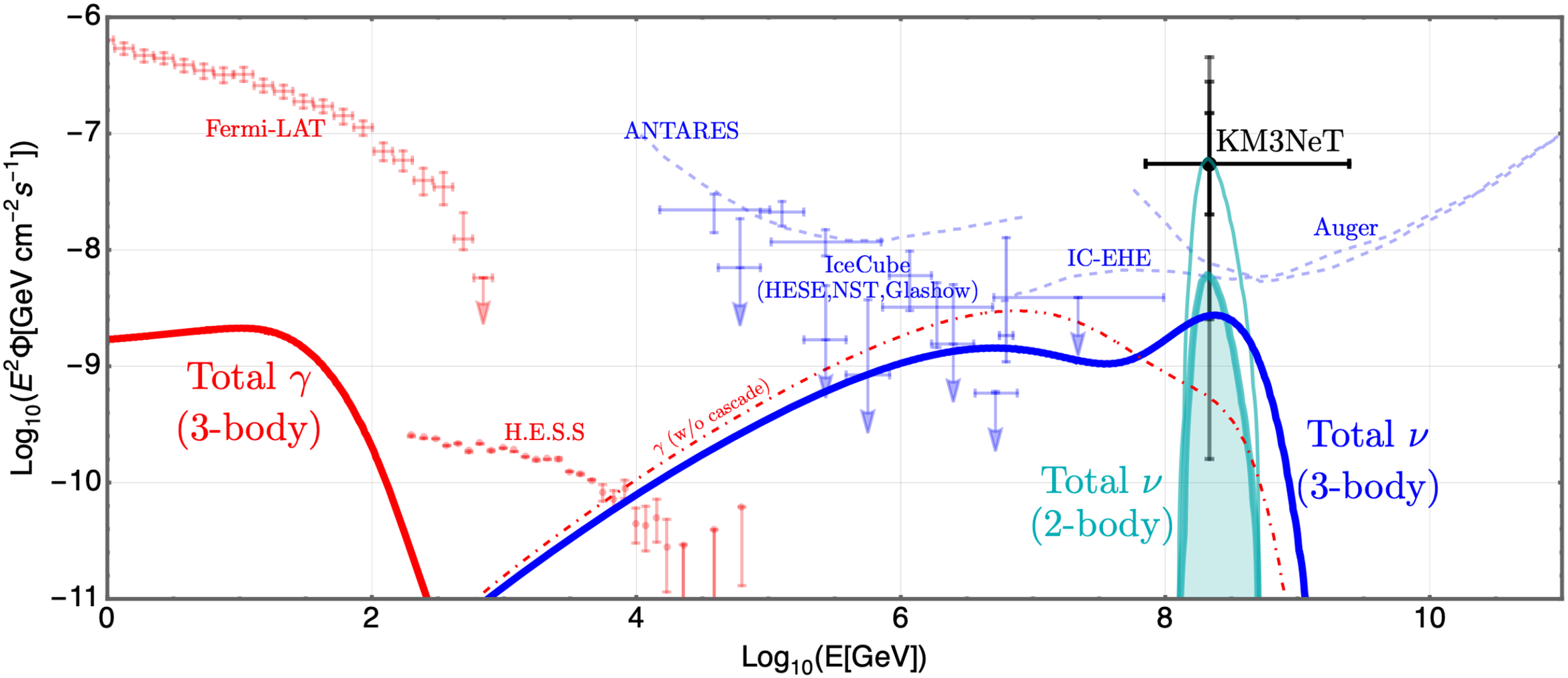
+Cascade



$$\gamma + \gamma_{\rm bkd.} \to e^+ + e^-$$

$$e^\pm + \gamma_{\rm bkd.} \to \gamma + e^\pm$$

illustrative parameter examples



- Scenario I ($\chi_h \to \chi_l + \nu + h$)

$$
\begin{aligned}
M_\chi &= 10^{16}\ \text{GeV}, \\
\Delta M_\chi &= 3 \times 10^{9}\ \text{GeV}, \\
\Lambda &= 1.44 \times 10^{31}\ \text{GeV}
\end{aligned}
$$

- Scenario II ($\chi_h \to \chi_l + \nu_s$)

$$
\begin{aligned}
M_\chi &= 6 \times 10^{12}\ \text{GeV}, \\
\Delta M_\chi &= 5 \times 10^{8}\ \text{GeV}, \\
\lambda_s &= (1.12 - 3.55) \times 10^{-24}
\end{aligned}
$$

Conclusion

- Neutrino astronomy above O(10) PeV is very interesting and still mysterious for UHE neutrinos.
- Various astrophysical and cosmological scenarios for the production of UHE neutrinos (and BSM particles) are going to be investigated.
- Recently, KM3NeT collaboration reported analysis on UHE event KM3-230213A.
- In decaying heavy DM scenarios, relatively short lifetime and nearly degenerated spectrum in Dark Matter sector make the signature robustly compatible with the observation of KM3-230213A.
- Next-generation UHE neutrino and cosmic ray observatories will reveal the detailed features of UHE neutrino physics.