

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

Yongsoo Jho

based on

arXiv:2503.18737 with S. C. Park and C. S. Shin

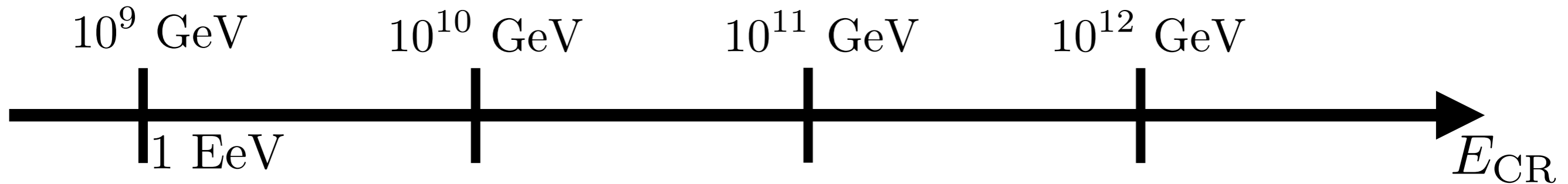
arXiv:2606.xxxxx with S. C. Park and J. H. Park

Jun 17th, 2026

The 16th Particle Physics Phenomenology Workshop, NTHU

Cosmic Particles' Olympic

- Proton & Heavy Nuclei UHE Cosmic Rays



"OMG" particle (1991) / Proton-like / Fly's Eye 320 ± 90 EeV

"Amaterasu" (2021) / Proton-like / Telescope Array 240 ± 30 EeV

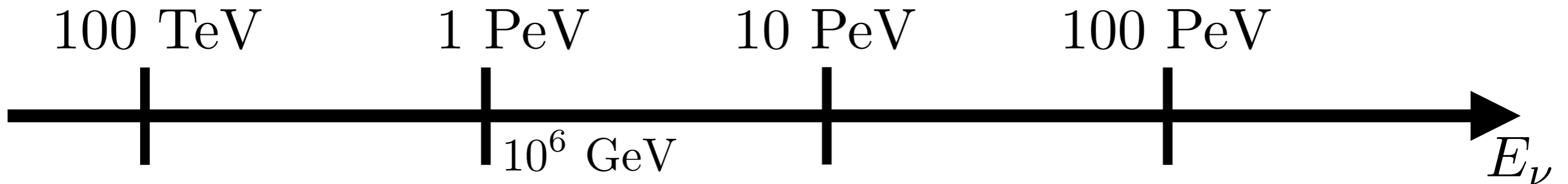
"Super-big" event (1993) / Iron-like / AGASA 200 EeV

PAO070114 (2007) / Iron-like / Auger 165 ± 15 EeV

Volcano Ranch (1962) / Proton-like 100 EeV

Cosmic Particles' Olympic

- High & Ultra-High energy Neutrinos



KM3-230213A / muon-track / KM3NeT

220 PeV

Glashow Res. Candidate / cascade / IceCube

6.3 PeV $\bar{\nu}_e e^- \rightarrow W^- \rightarrow had.$

IC-200208A / muon-track / IceCube

6 PeV

"Big Bird" (2012) / casc. / IC

2.6 PeV

"Ernie" (2011) / casc./ IC

1.14 PeV

"Bert" (2010) / casc. / IC

1.04 PeV



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>

The KM3NeT Collaboration*

Received: 19 August 2024

Accepted: 18 December 2024

Published online: 12 February 2025

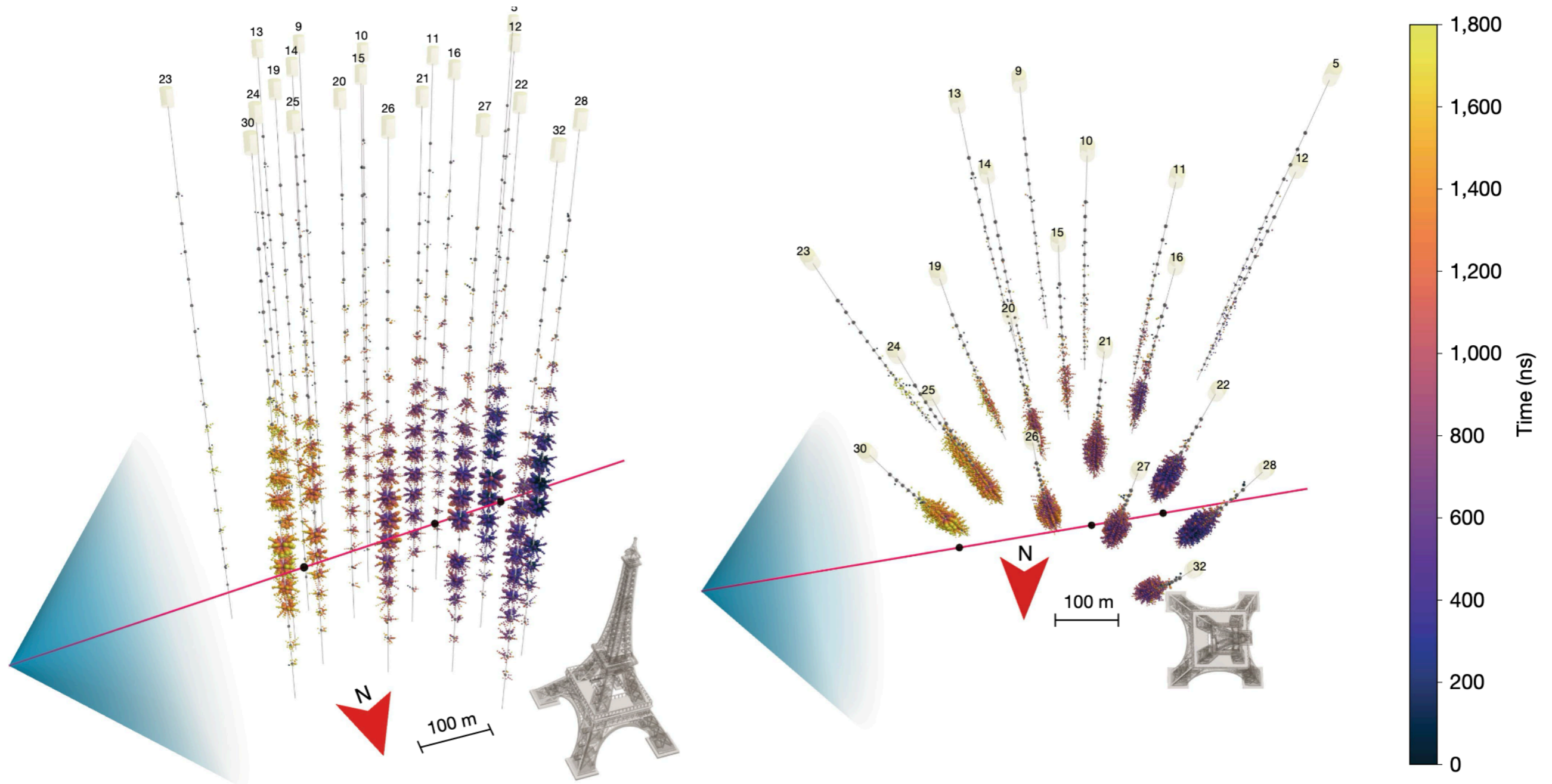
Open access

 Check for updates

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 Sea⁴, which we associate with a cosmic neutrino detection. We detect a muon with an estimated energy of 120_{-60}^{+110} 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 neutrino⁸, 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

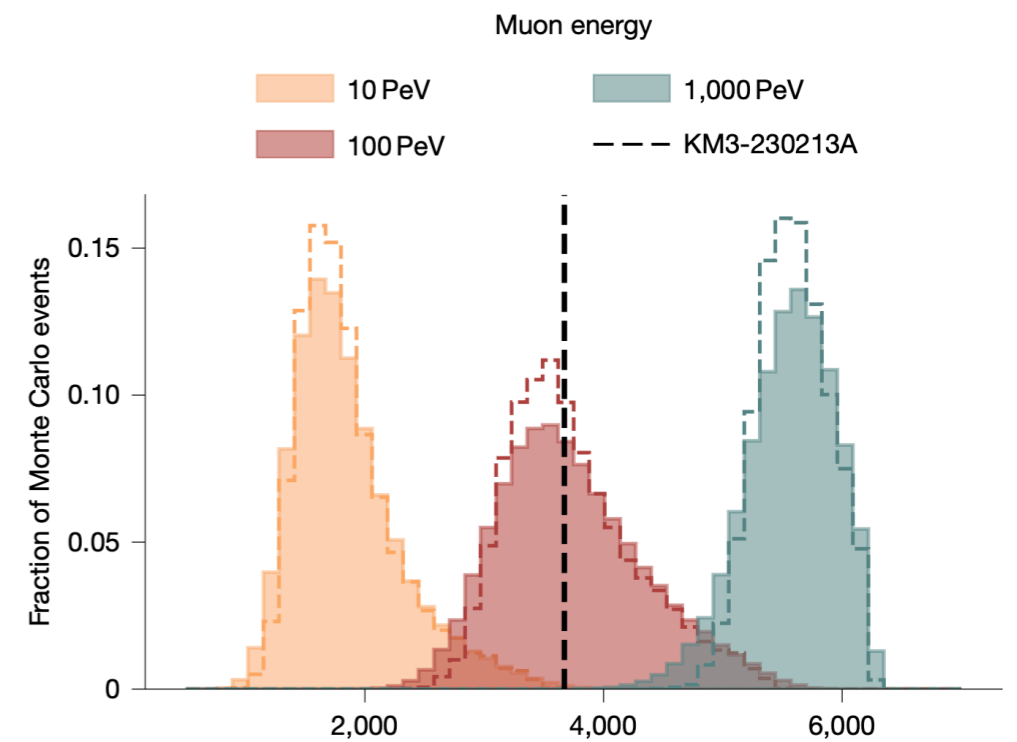
- The reconstructed energy of the muon track ~ 120 PeV

- > The median neutrino energy ~ 220 PeV

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

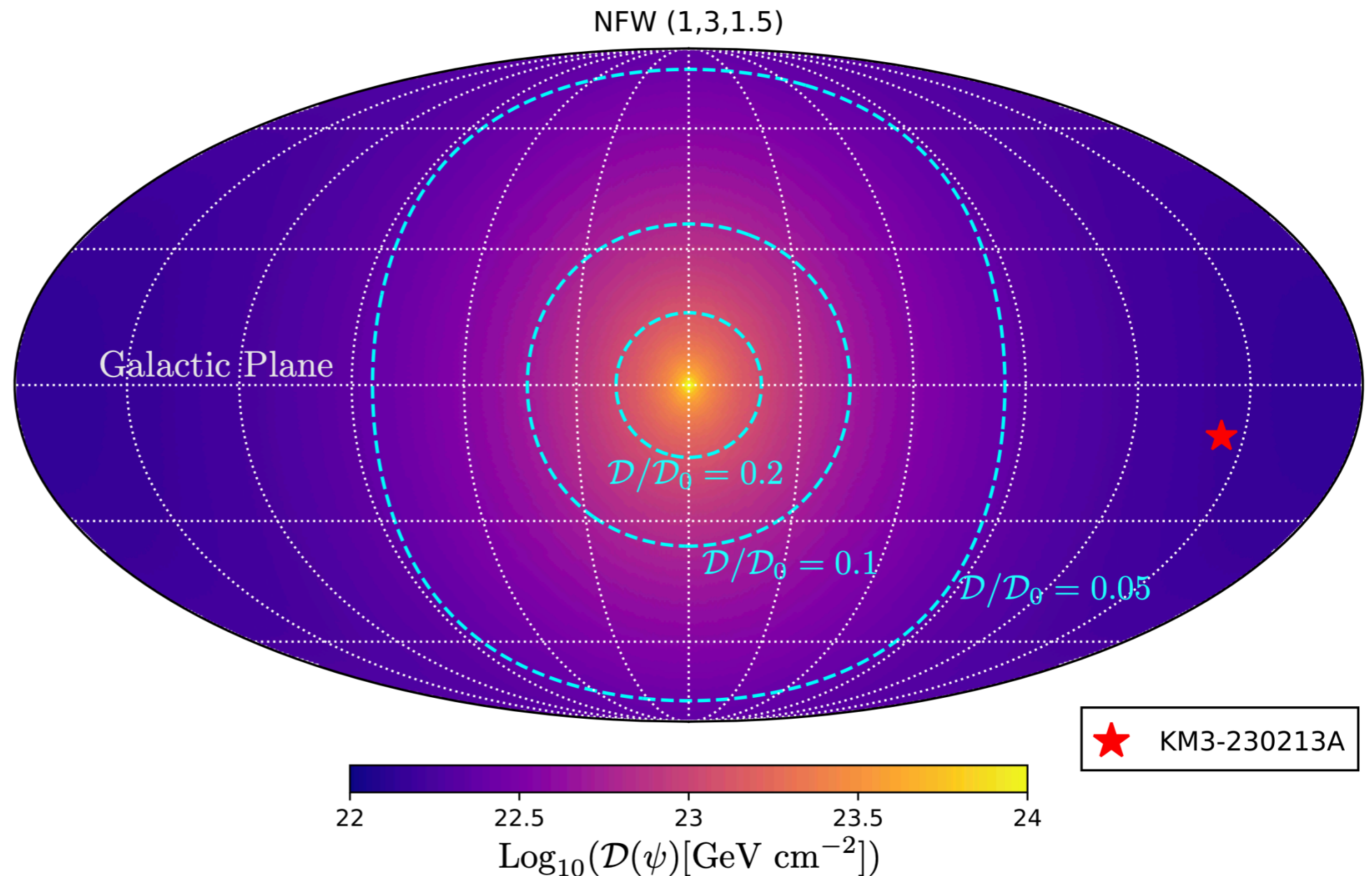
- The most energetic neutrino event ever measured.

- The only neutrino event candidate with $>O(10)$ PeV so far.



KM3-230213A: UHE event

- RA (Right Ascension): $+94.3^\circ$
- Dec (Declination): -7.8°
- 68% C.L. angular uncertainty $\delta \sim 1.5^\circ$
- 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 astrophysics. high-E phenomena (GRB, Blazar, AGN, etc.)
 - Cosmogenic (GZK) neutrinos from UHECRs
 - Neutrinos from decaying heavy DM
 - Sterile/Heavy Neutrinos and its oscillation and decays
 - Primordial Black Hole burst/steady evaporation signals
- None of them are 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 spectral structure of the flux is still very mysterious.
- We have only a single event at $\sim O(100-1000)$ 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:

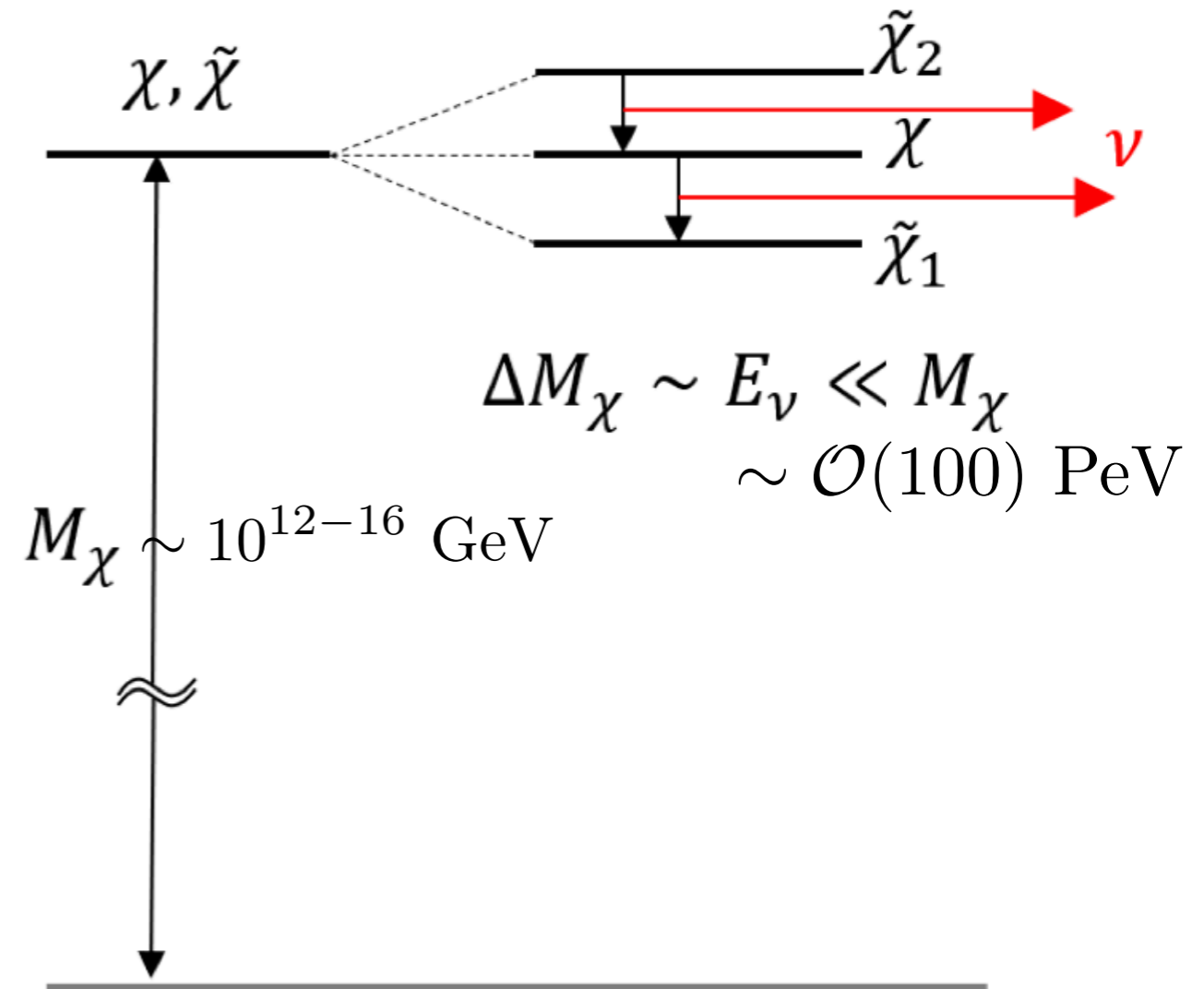
$$X = \tilde{\chi} + \sqrt{2}\theta\chi + \theta^2 F_\chi$$

SUSY breaking scale is characterized by a spurion M as

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

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

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



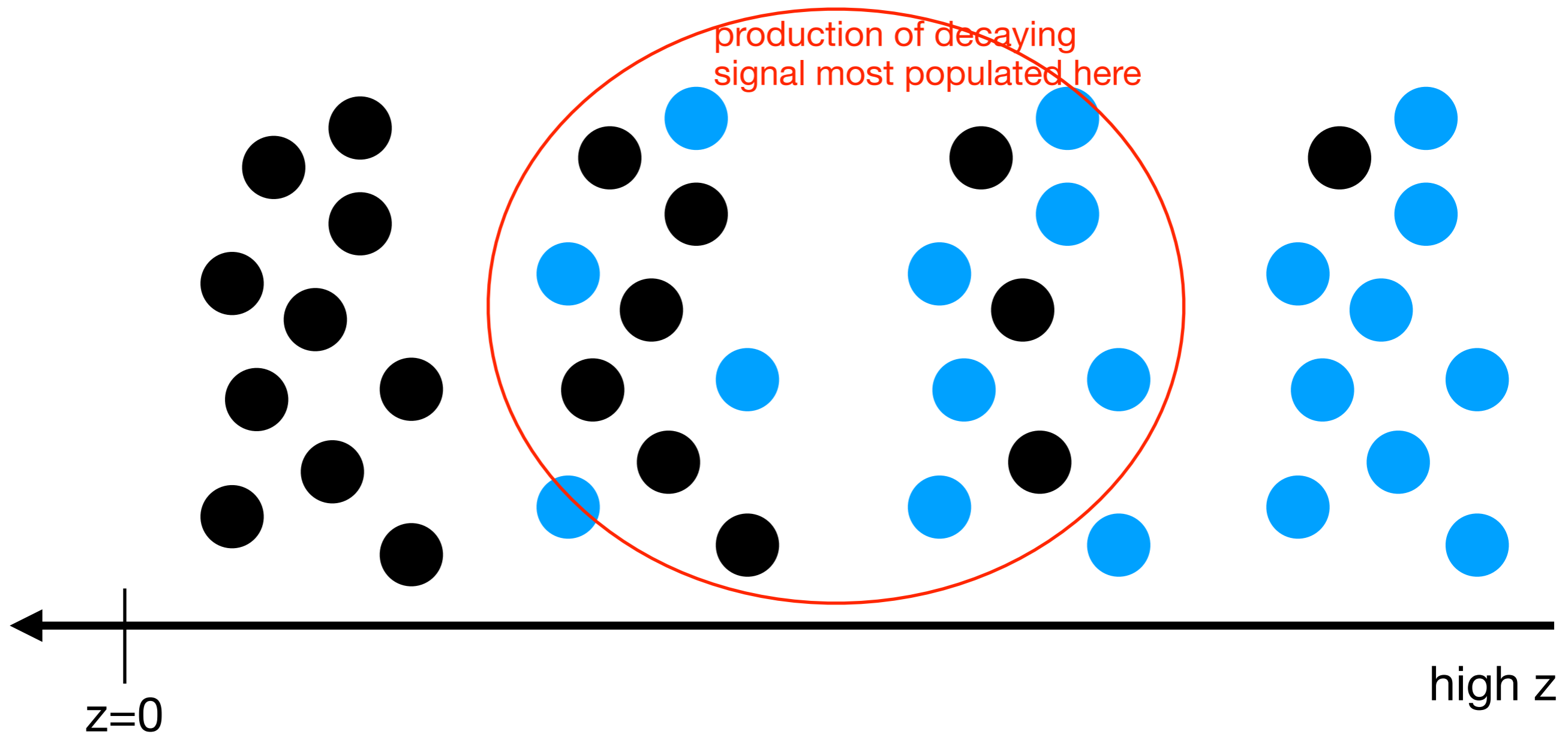
$$\frac{\Delta M_\chi}{M_\chi} \equiv \frac{M_\chi - M_{\tilde{\chi}_1}}{M_\chi} = \frac{M_{\tilde{\chi}_2} - M_\chi}{M_\chi} = \frac{F}{M^2} \ll 1.$$

UHE neutrinos from DM decays

- Estimation of the Flux from DM decays

$$\begin{aligned} E_\nu^2 \frac{d\Phi_\nu}{dE_\nu} &\sim \frac{\text{Br}_\nu f_\chi}{4\pi M_\chi (1+z_\chi)} \Delta M_\chi \rho_{\text{DM}} c \\ &= 2.5 \times 10^{-8} \left(\frac{\text{GeV}}{\text{cm}^2 \text{ sec sr}} \right) \\ &\quad \times \left(\frac{\text{Br}_\nu f_\chi}{10^{-3}} \right) \left(\frac{\Delta M_\chi}{10^{-7} M_\chi} \right) \left(\frac{10}{1+z_\chi} \right) \end{aligned}$$

Multi-component Dark sector and extragalactic-dominated signatures

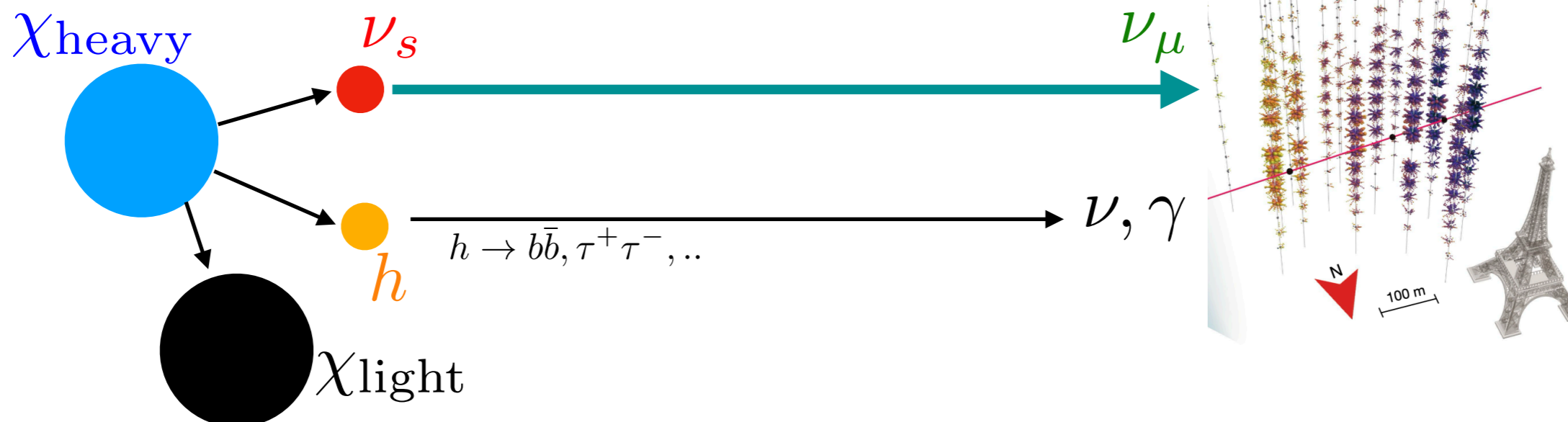


UHE neutrinos from DM decays

- Relevant scenarios for DM decays
- Scenario I : 3-body decay case with a heavy RH neutrino.

$$\Delta W_I = \frac{LH_u X^2}{2\Lambda} \rightarrow \mathcal{L}_{int.} \supset \frac{\nu h \tilde{\chi} \chi}{\Lambda} + h.c.$$

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



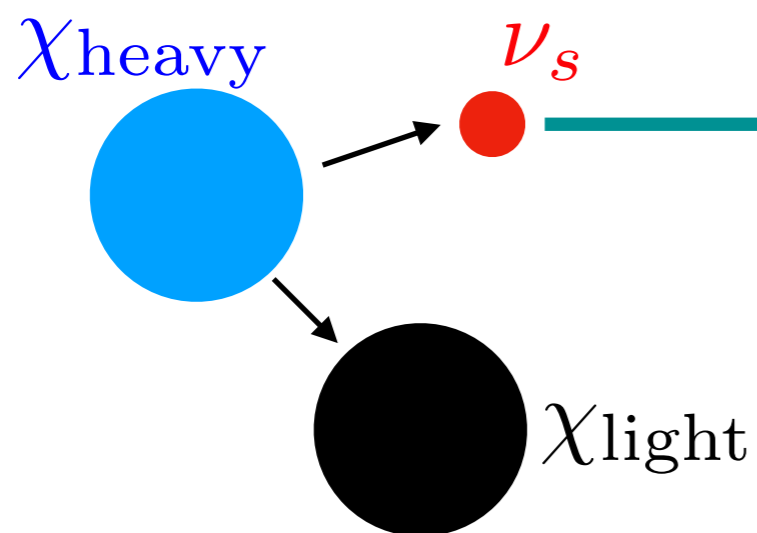
UHE neutrinos from DM decays

- Relevant scenarios for DM decays
- Scenario II : 2-body decay case with a light sterile neutrino.

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

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

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



Neutrino & Gamma-ray signals

- Neutrino Flux

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

Only Redshifted

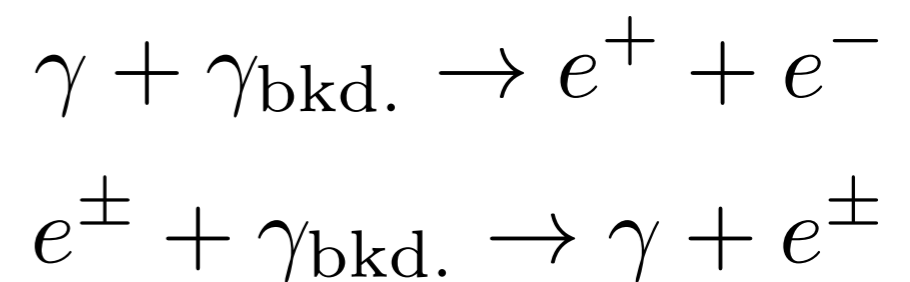
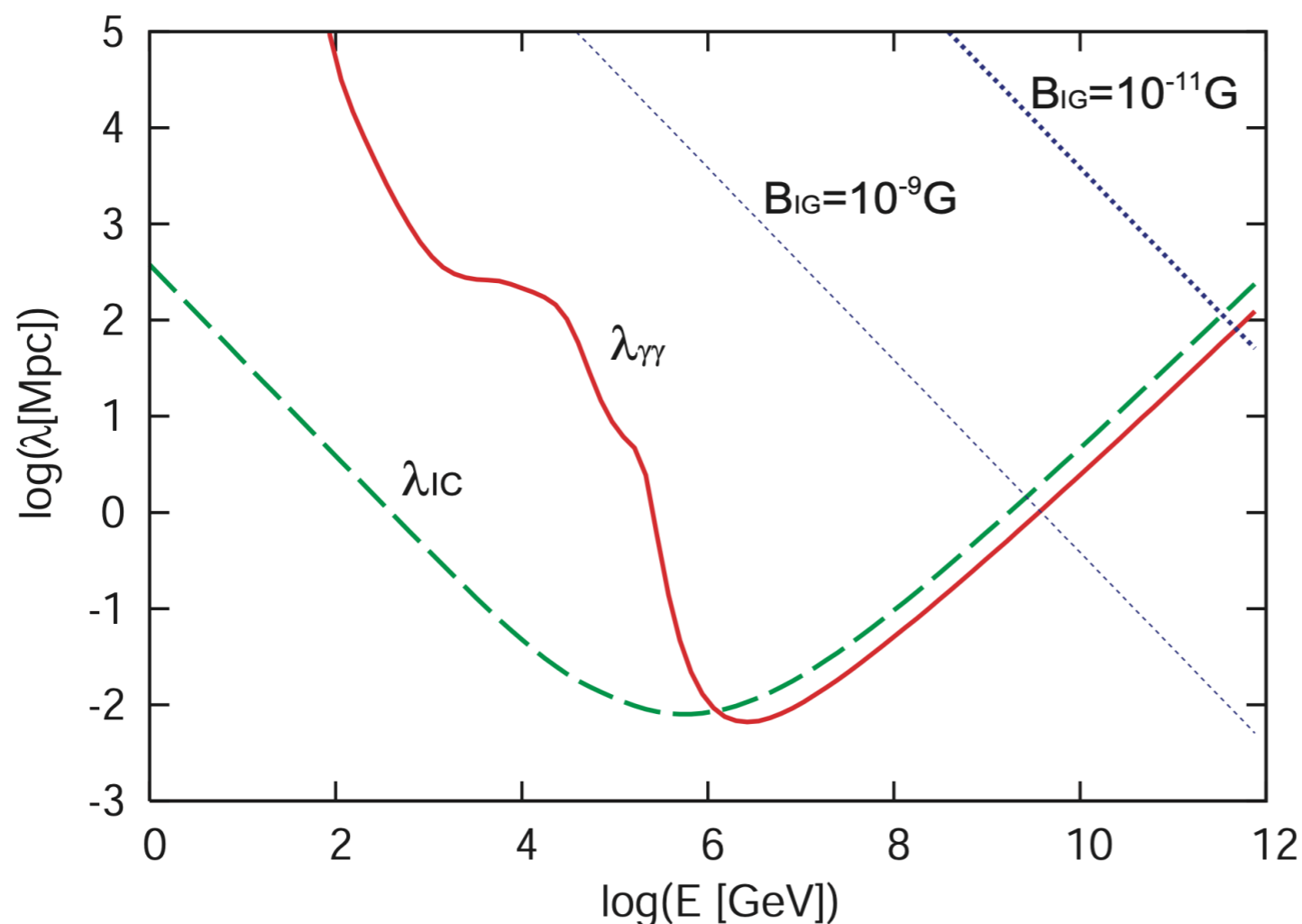
$$E'_\nu \equiv (1+z)E_\nu$$

Neutrino & Gamma-ray signals

- Gamma-ray Flux

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

Redshift
+Attenuation
+Cascade

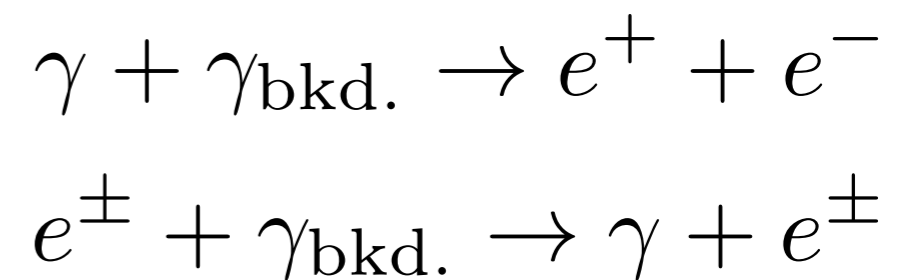
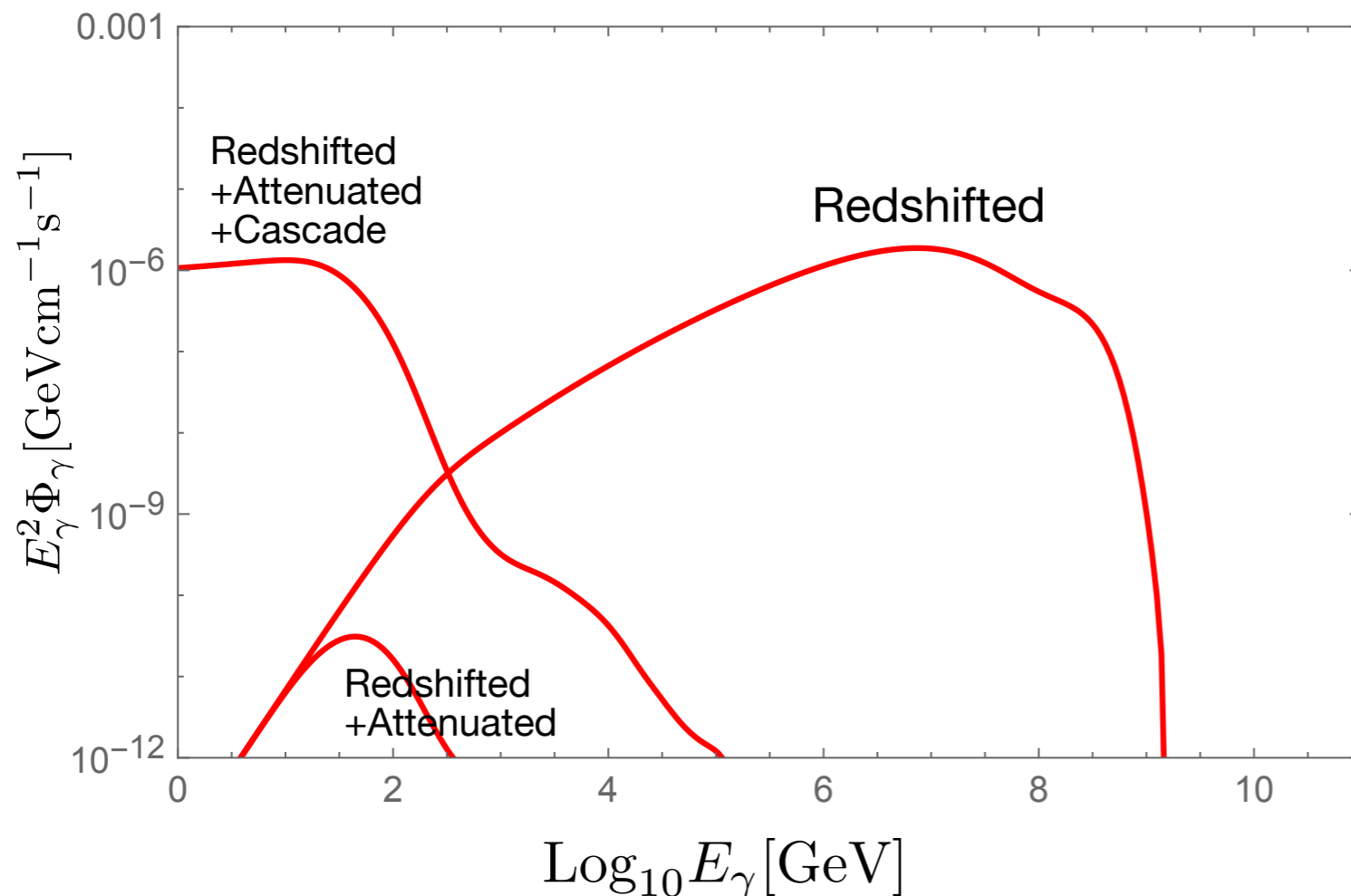


Neutrino/Gamma-ray signals

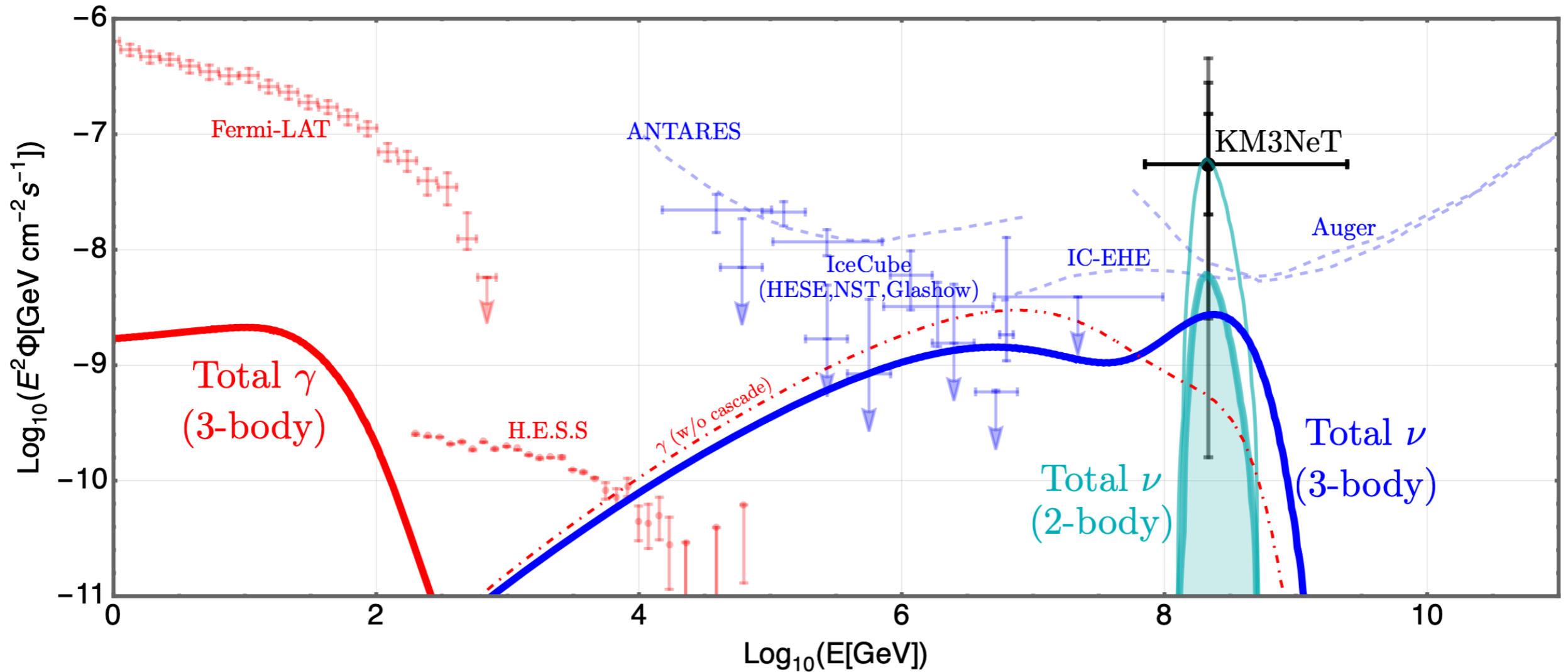
- Gamma-ray Flux

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

Redshift
+Attenuation
+Cascade



illustrative parameter examples



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

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

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

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

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 DM spectrum 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.

Thank you