ステライルニュートリノによるKM3-230213Aの起源解明

成田 悠馬
東北大学、東京都立大学

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@京都大学基礎物理学研究所
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共同研究者：殷 文 (東京都立大学)

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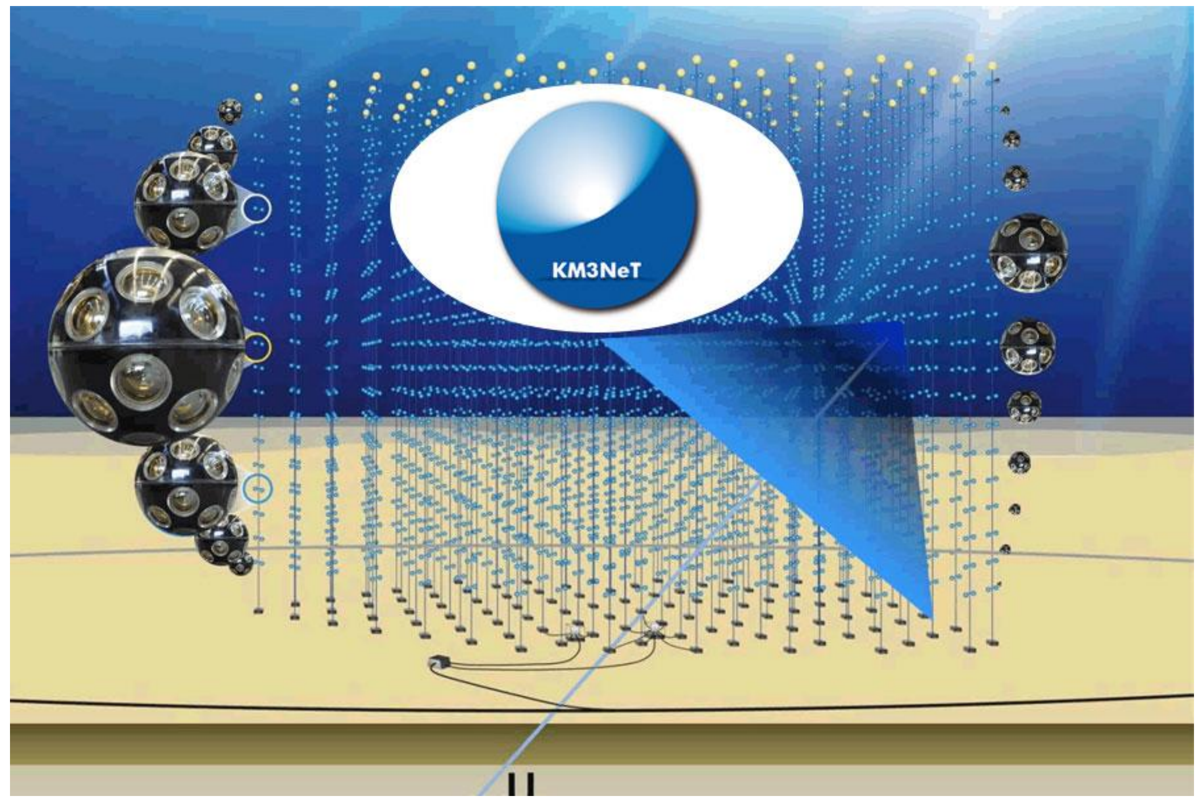
KM3-230213A

Recently, KM3-Net/ARCA detected an ultra-high-energy muon track. The neutrino corresponding flux is

$$E^2\Phi_\nu = 5.8^{+10.1}_{-3.7} \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}},\ E \approx 220\,\mathrm{PeV}.$$

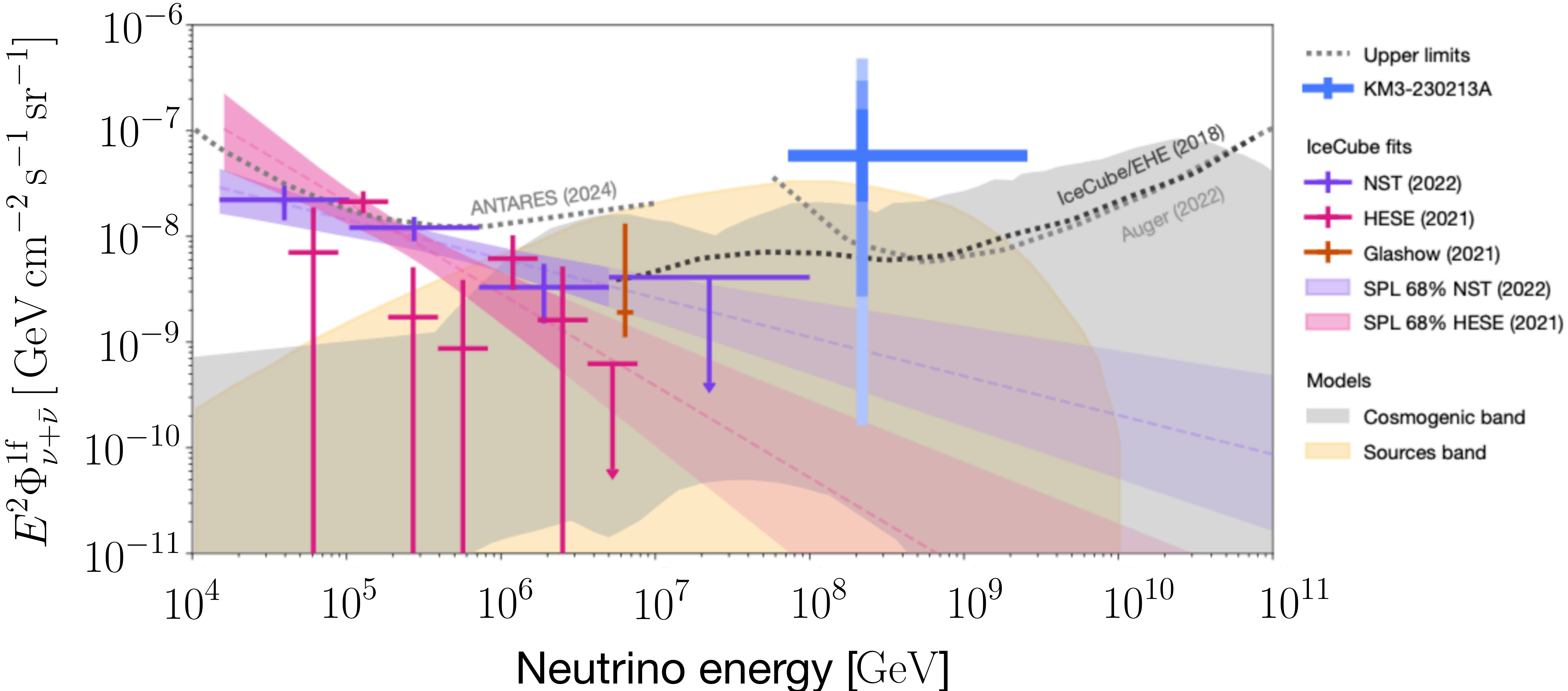


https://www.km3net.org/

KM3-230213A is significantly above the expected spectral decline.

⬇

It suggests a different production origin.



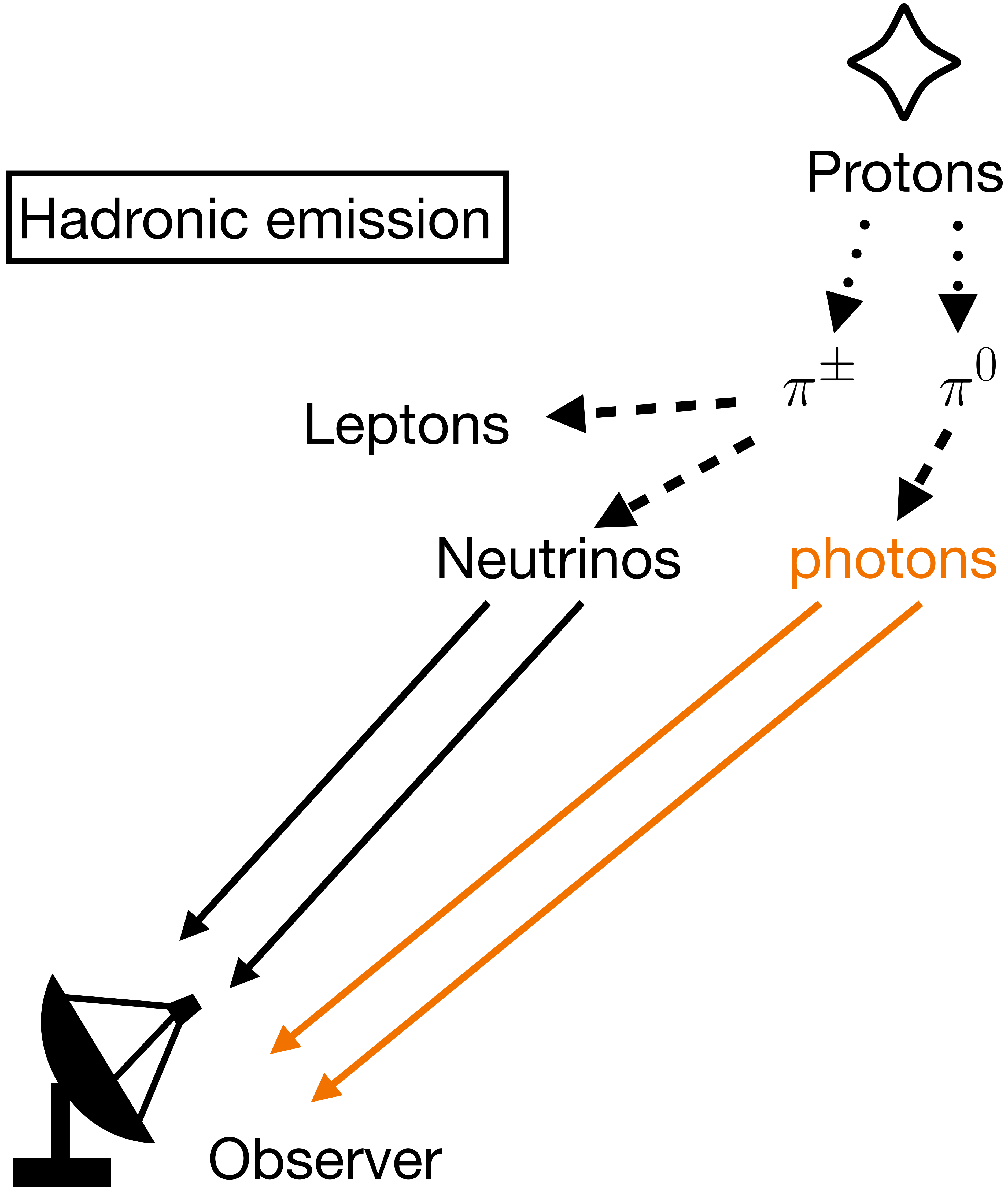
The KM3NeT Collaboration

Challenges in explaining neutrino origin

In conventional astrophysical scenarios, neutrino production is typically accompanied by gamma-ray emission.

However, no corresponding gamma-ray counterpart has been observed.

This makes it difficult to interpret the neutrino signal.



Sterile neutrino

Glashow 1979; Boyarsky, Ruchayskiy et al. 2009;
Abazajian, Acero et al. 2012; Drewes et al. 2017; Abazajian 2017;
Acero, Arguelles et al. 2022

We discuss the possibility that this event originates from an accelerated right-handed neutrino (RHN).

In the broken phase, the mass term is

$$\mathcal{L}_{\rm mass} = -\underset{\text{mixing angle}}{\underline{\underline{\theta}}} m_N \bar{\nu}_R \nu_\alpha - \frac{m_N}{2} \bar{\nu}_R^c \nu_R + \text{h.c.}\,. \qquad (\theta \ll 1)$$

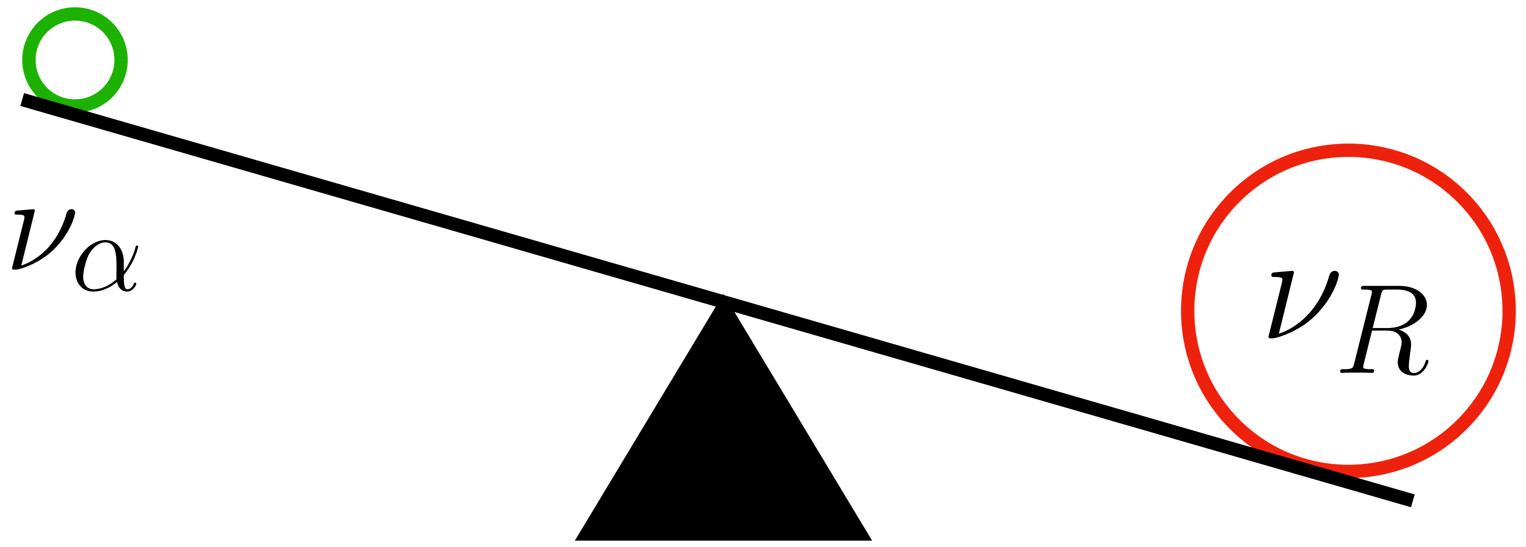
The mass eigenstate with the heavy mass (~ m_N) and the light mass (~ $\theta^2 m_N$) are

Sterile neutrino mass

SM neutrino mass

$$|N\rangle \simeq \theta|\nu_\alpha\rangle + |\nu_R\rangle,$$

$$|\nu\rangle \simeq |\nu_\alpha\rangle - \theta|\nu_R\rangle.$$



The mimicked neutrino flux

In the case of the high energy event, the interaction amplitude involving a single N is given by

$$\langle \text{final}|H_{\text{int}}|N\rangle \approx \theta\,\langle \text{final}|H_{\text{int}}|\nu_\alpha\rangle + \cancel{\langle \text{final}|H_{\text{int}}|\nu_R\rangle}.$$

Then, the cross section is $\sigma_N \simeq \theta^2 \sigma_{\nu_\alpha}$.

The neutrino event can be mimicked by the RHN cosmic ray.

$$\frac{\mathrm{d}N_{\text{event}}}{\mathrm{d}E} = T \times S_{\text{eff}} \times \Phi_\nu(E) = T \times C\theta^2 S_{\text{eff}} \times \Phi_N(E)$$

$$\Downarrow$$

$$\boxed{\Phi_N(E) \simeq C^{-1}\theta^{-2}\Phi_\nu(E)}$$

The KM3NeT Collaboration

To explain KM3-230213A, $E \approx 220\,\text{PeV}$, $E^2\Phi_\nu(E) = 5.8^{+10.1}_{-3.7} \times 10^{-8}\,\text{GeV}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$.

Outline

1. Introduction
2. Generic Bounds
3. Right-Handed Neutrino Origin for the KM3Net event
4. Cosmic-Ray Dark Radiation and Reduced γ-Ray Bounds
5. Summary

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Generic Bounds

Cadamuro, Redondo 2012; Jaeckel, Yin 2021

Let us drive generic bounds on the thermally produced sterile neutrino.

We can consider the two main types of constraints.

1. **Galactic RHN contribution** (X/γ-ray searches)

- Relatively heavy RHNs are gravitationally trapped in galaxies.
- Their decay $N \to \nu\gamma$ would produce detectable radiation signals.

2. **Cosmological constraint**

- RHNs would behave as additional radiation component during BBN.
- We carefully consider the impact on $\Delta N_{\rm eff}$ during BBN.

RHN Captured by galaxies

One of the constraints arises from thermally produced RHNs that cluster into our galaxy.

Typical momentum of the thermally produced RHN

$$\overline{p}_N = \frac{7\pi^4}{180\zeta(3)}\left(\frac{4}{11}\right)^3 T_\gamma \sim 2.25 T_\gamma$$

At matter-radiation equality ($T_\gamma \approx 0.75\,\mathrm{eV}$), the typical velocity is given by

$$\overline{v}_N = \frac{\overline{p}_N}{m_N} \sim 10^{-3}\frac{1.7\,\mathrm{keV}}{m_N}.$$

Since the escape velocity is 10^{-3}, RHNs heavier than $1.7\,\mathrm{keV}$ are gravitationally bound to galaxies and clusters.

Bound on photon-emitting decay

To obtain the most conservative photon–emission bound, we consider the case of a low reheating scenario.

Then, the RHN abundance is estimated by

$$\Omega_N h^2 \simeq 0.1 d_\alpha \left(\frac{\sin^2 2\theta}{10^{-3}}\right)\left(\frac{m_N}{1\,\mathrm{keV}}\right)\left(\frac{T_R}{5\,\mathrm{MeV}}\right)^3 .$$

Pal, Wolfenstein 1982;
Boyarsky, Drewes et al. 2019

The (sub MeV) RHN radiative decay rate is given by

$$\Gamma_N^{-1} \approx 2.3 \times 10^{24}\,\mathrm{yr}\frac{10^{-10}}{\sin^2(2\theta)}\left(\frac{\mathrm{keV}}{m_N}\right)^5 .$$

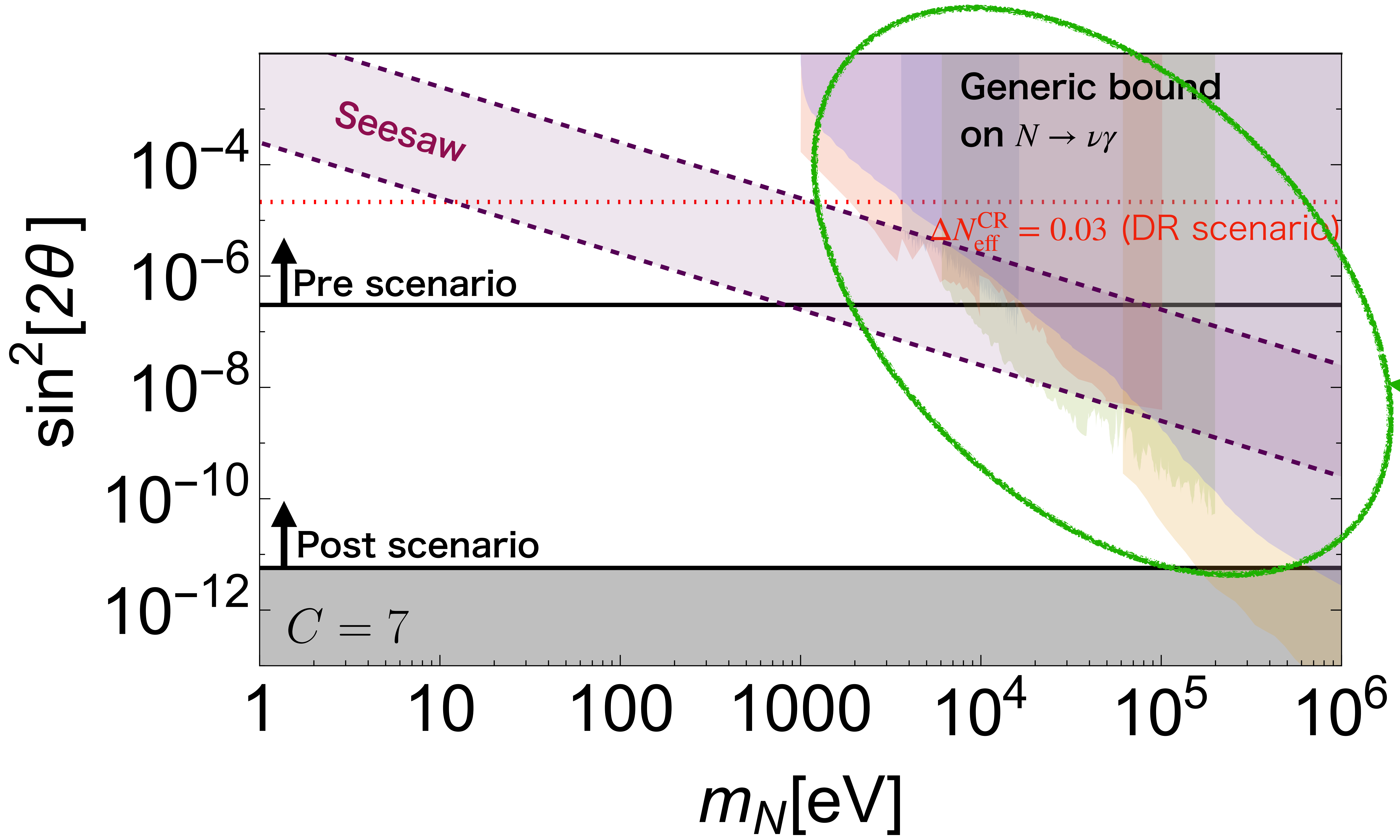
Gelmini, Palomares-Ruiz et al. 2004;
Dodelson, Widrow 1994

Such particles emit photons and are constrained by various astrophysical observations, including INTEGRAL, XRISM, and others.

Calore, Dekker et al. 2022; Yin, Fujita et al. 2025

Allowed region for RHN

YN, Yin 2025



We take $T_R = 1.8\,\mathrm{MeV}$ for the conservative bound.

Hasegawa, Hiroshima et al. 2019

Cosmological constraint

Since the mass is typically small due to photon constraints, RHNs would behave as dark radiation during the BBN era.

The deviation of the effective neutrino number from thermally produced RHN is

$$\Delta N_{\rm eff} = \frac{\rho_N^{\rm th}}{\rho_\nu} \sim \frac{\overline{p}_N^{(0)}(\Omega_N \rho_{\rm crit}/m_N)}{7/4 \times (4/11)^{4/3} \times \rho_\gamma^{(0)}} \sim 0.35 \sin^2 2\theta.$$

We have a constraint of $\Delta N_{\rm eff} \lesssim 0.2$ during BBN. Cyburt, Fields, et al. 2016

Then, this provides an upper limit on the mixing angle, $\sin^2 2\theta \lesssim 0.57$.

It is no longer a significant concern.

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Production scenario

Dark radiation in the form of RHNs can be naturally produced as,

$$\mathcal{L} \supset \phi \overline{N}^c N,$$

where ϕ is a real scalar field.

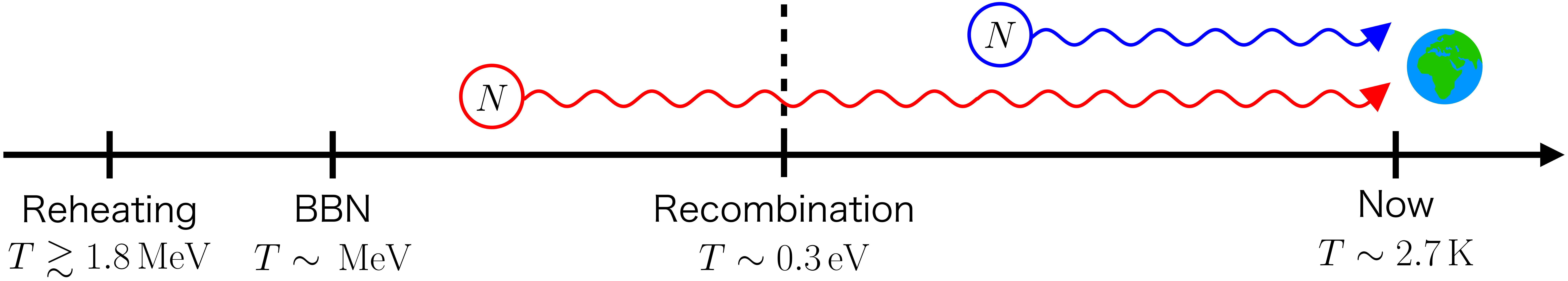
We consider two scenarios depending on the origin of the RHN.

Pre-recombination scenario

- RHNs affect CMB and ΔN_{eff}.

Post-recombination scenario

- Bound is weak from small redshift.



Pre-recombination scenario

We assume that the decay into RHNs completes before the recombination.

The dark radiation component is parameterized by $\Delta N_{\rm eff}$ for this primordial cosmic-ray.

The boosted RHN energy density after production ceases is given by

$$\rho_N^{\rm CR} = \Delta N_{\rm eff}^{\rm CR} \left(\frac{4}{11}\right)^{4/3} \frac{7}{8} \times \rho_\gamma .$$

This leads to an energy flux of boosted RHNs satisfying

$$E^2 \Phi_N(E) \sim \int {\rm d}E \, E \Phi_N(E) \approx \frac{\rho_N^{\rm CR(0)}}{4\pi} \sim 0.14 \, \Delta N_{\rm eff}^{\rm CR} \; {\rm GeV \, cm^{-2} \, s^{-1} \, sr^{-1}} .$$

Pre-recombination scenario

The neutrino event is mimicked by the RHN cosmic ray,

$$E^2\Phi_N(E) = C^{-1}\theta^{-2}\underline{\underline{E^2\Phi_\nu(E)}}.$$

The KM3NeT Collaboration

$$= 5.8^{+10.1}_{-3.7} \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

form the KM3-230213A.

Then, we obtain $\Delta N_{\rm eff}^{\rm CR}$ to explain the KM3-230213A event,

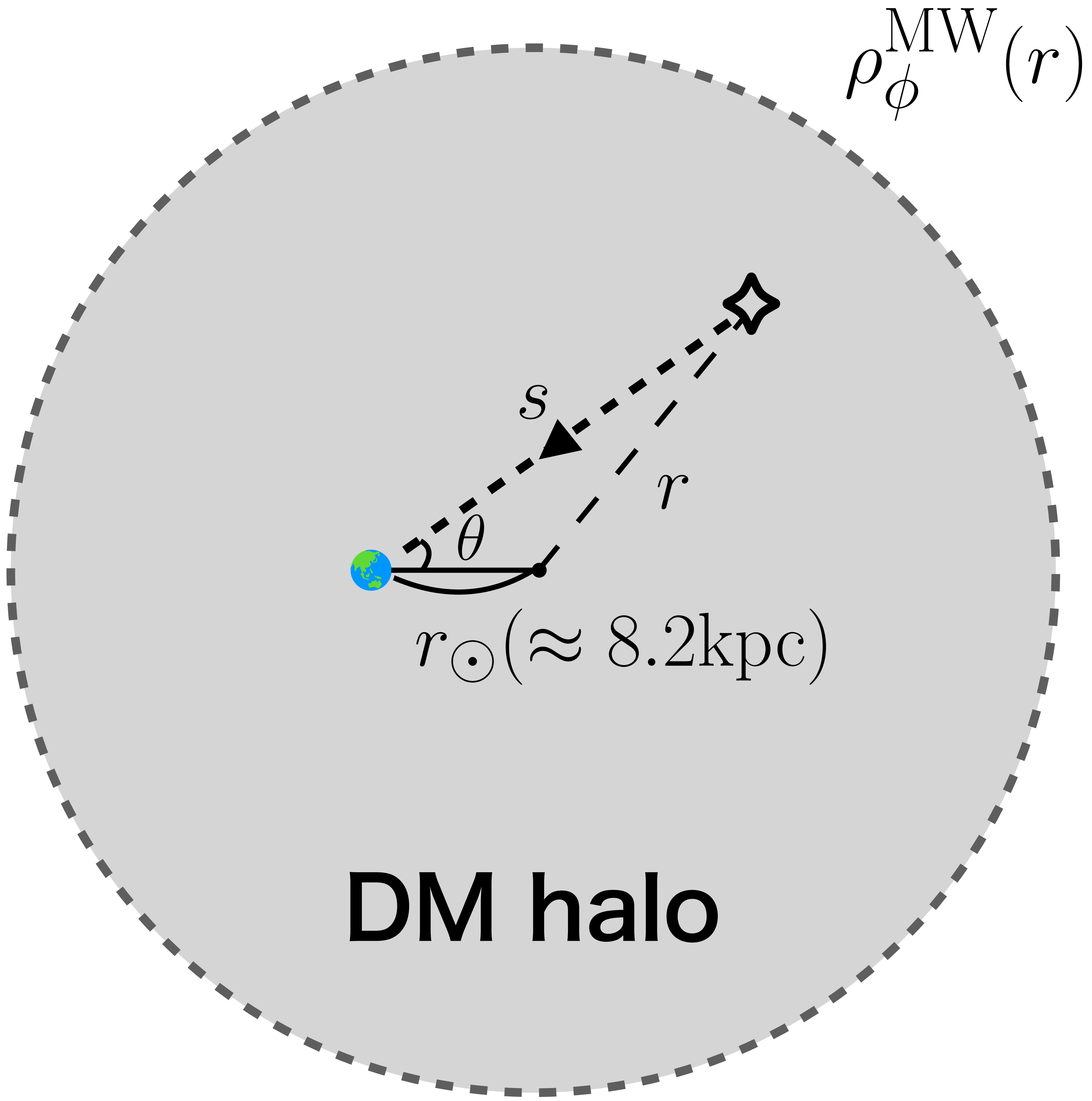
$$\Delta N_{\rm eff}^{\rm CR} \sim 4.2 \times 10^{-7} C^{-1}\theta^{-2}\frac{E^2\Phi_\nu(E)}{5.8\times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}}.$$

We get a lower bound on the mixing angle from the Planck constraint,

$\Delta N_{\rm eff} \lesssim 0.28$ (2σ limit), The Planck Collaboration

$$\boxed{\theta^2 \gtrsim 5.4 \times 10^{-7} C^{-1}.}$$

Post-recombination scenario



Let us consider that ϕ becomes DM to get the conservative bound.

The predicted of RHNs is

$$\Phi_N(E) = \frac{1}{4\pi}\int s^2 {\rm d}s{\rm d}\Omega \frac{1}{4\pi s^2}\Gamma_\phi \frac{{\rm d}N_\phi}{{\rm d}E}\frac{\rho_\phi^{\rm MW}(r)}{m_\phi}.$$

Simply, we have ${\rm d}N_\phi/{\rm d}E = 2\delta(E - m_\phi/2)$,

$$\int {\rm d}E\,\Phi_N(E) \approx \frac{\Gamma_\phi}{8\pi^2 m_\phi}\int {\rm d}\Omega{\rm d}s\,\rho_\phi^{\rm MW}.$$

Here, we adapt NFW profile : $\rho_\phi^{\rm MW} = r_s r^{-1}\rho_0(1 + r/r_s)^{-2}$. Navarro, Frenk et al. 1997

Post-recombination scenario

As a rough approximation,

$$E^2\Phi_N(E) \approx \frac{m_\phi}{2}\int \mathrm{d}E\,\Phi_N(E) \approx \frac{\Gamma_\phi}{16\pi^2}\int \mathrm{d}\Omega\mathrm{d}s\,\rho_\phi^{\mathrm{MW}}.$$

Similar to the pre-recombination scenario, we can get the constraint

$$\Gamma_\phi^{-1} \sim C\theta^2 \times 9.2\times 10^{12}\,\mathrm{Gyr}\,\frac{5.8\times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}}{E^2\Phi_\nu(E)}.$$

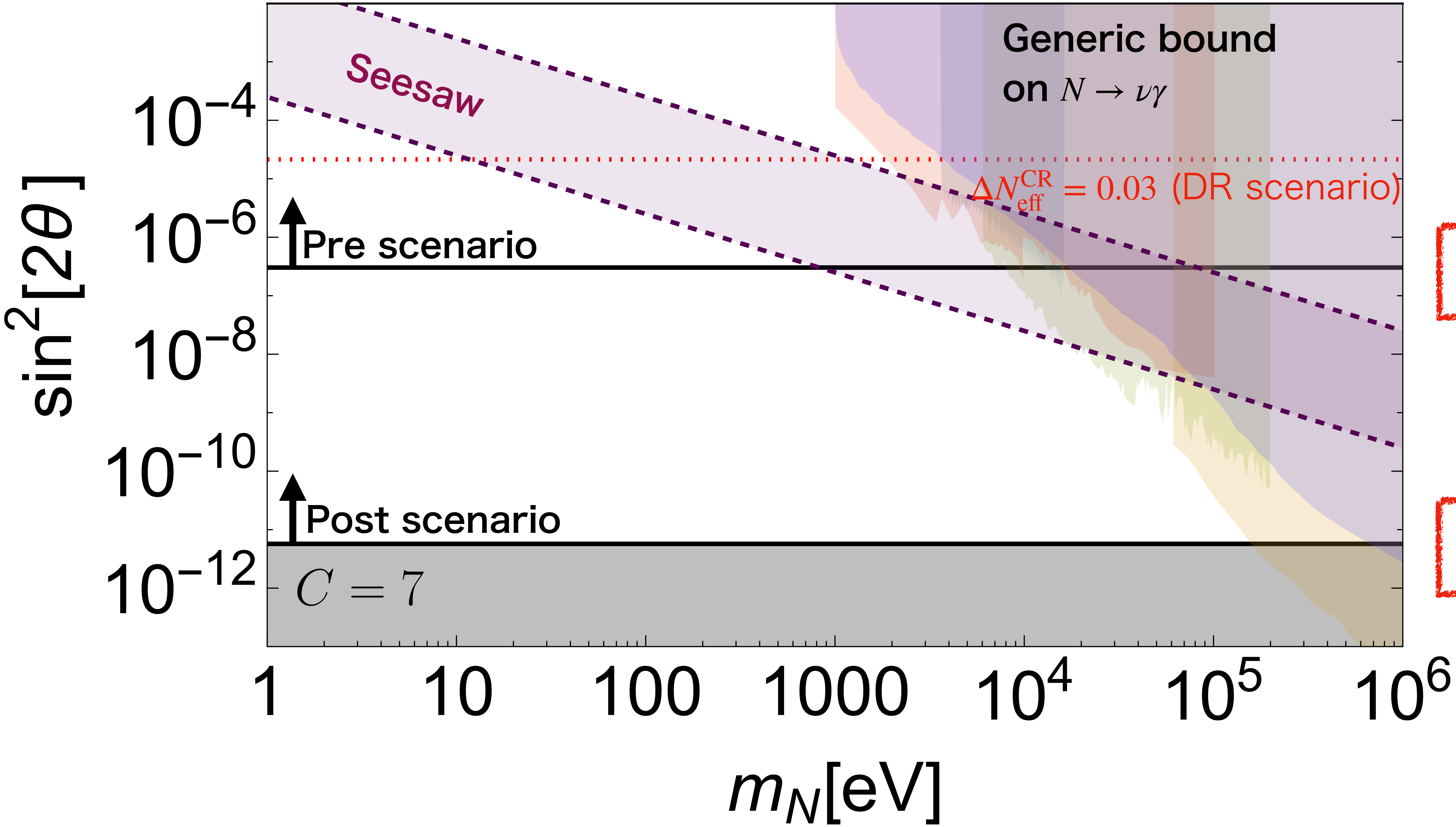
Since the decay into dark particles is constrained $\Gamma_\phi < (246\mathrm{Gyr})^{-1}$, we obtain a lower bound on the mixing,

Enqvist, Nadathur et al. 2020;
Alvi, Brinckmann et al. 2022

$$\boxed{\theta^2 \gtrsim 1.0\times 10^{-11}C^{-1}.}$$

Allowed region for RHN

YN, Yin 2025



$$\boxed{\theta^2 \gtrsim 2.1 \times 10^{-6} C^{-1}.}$$

$$\boxed{\theta^2 \gtrsim 1.0 \times 10^{-11} C^{-1}.}$$

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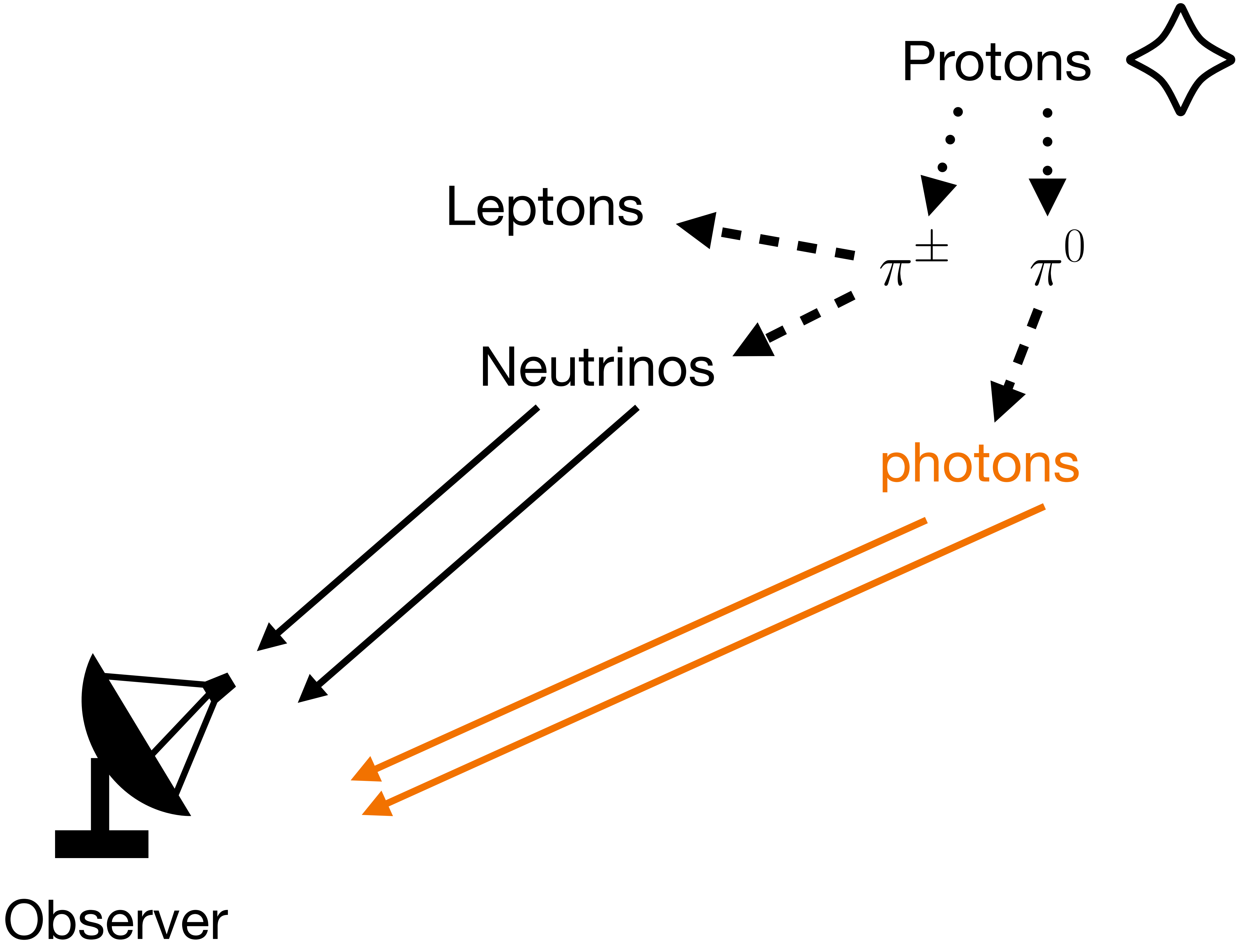
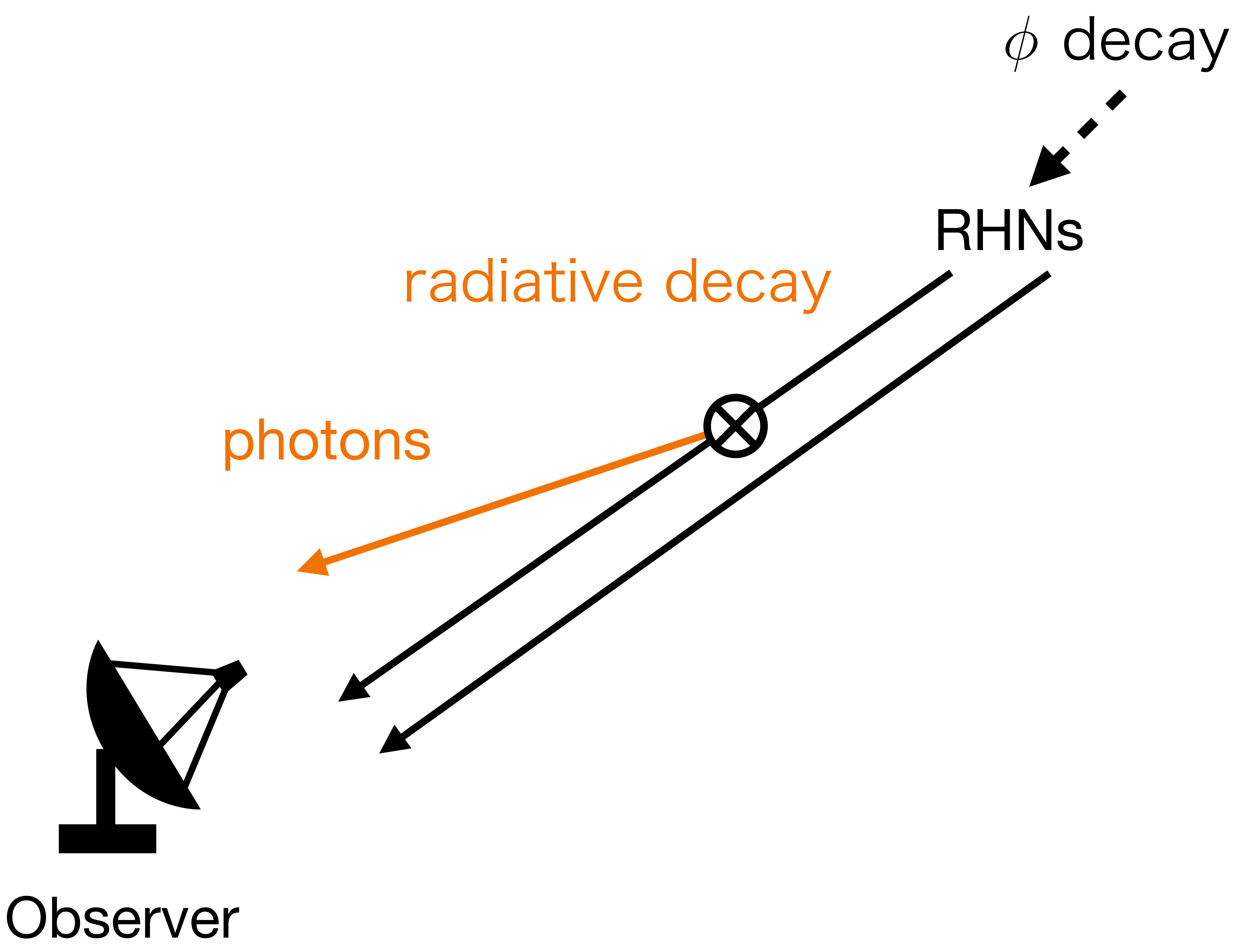
Photon emission



Hadronic emission



Production of RHNs

RHNs emit fewer photons because of the secondary production.

Estimation of the photon flux

The emitted photon energy density can be estimated as

$$\rho_\gamma^{(0)} \approx \int \frac{dz}{(1+z)^2} \frac{\Gamma_N m_N}{E_N^{(0)} H} \rho_N^{(0)} \approx 0.52 \frac{\Gamma_N m_N}{E_N^{(0)} H^{(0)}} \rho_N^{(0)} .$$

Thus, the expected photon flux associated with KM3-230213A is given by

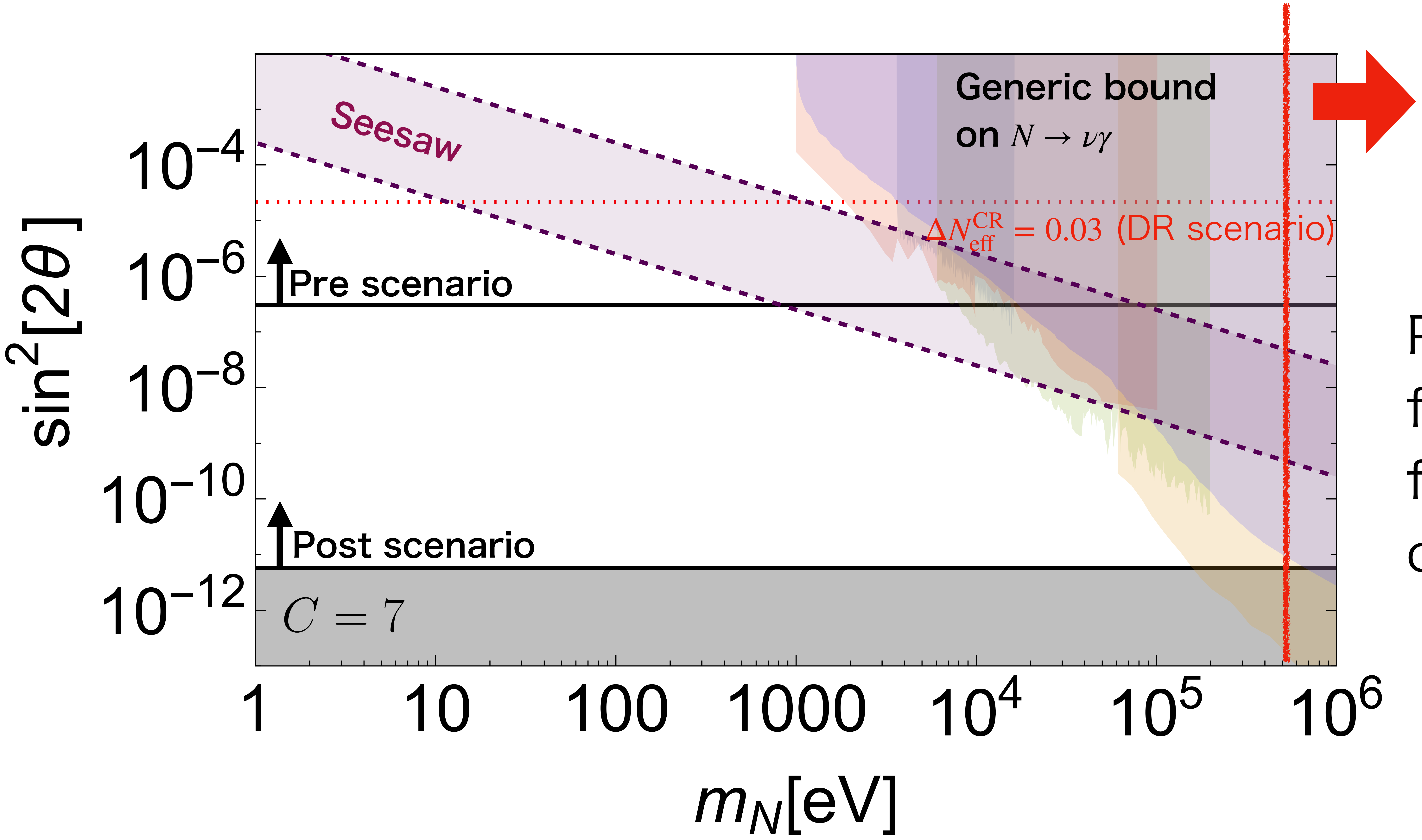
$$E^2 \Phi_\gamma \approx 3.5 \times 10^{-8} \left(\frac{m_N}{\mathrm{MeV}} \right)^6 C^{-1} \, \mathrm{GeV cm^{-2} s^{-1} sr^{-1}}.$$

By requiring the photon flux constraint $E^2\Phi_\gamma \lesssim 10^{-9}\,\mathrm{GeV cm^{-2} s^{-1} sr^{-1}}$, we obtain the bound $m_N \lesssim 0.55\, C^{1/6}\, \mathrm{MeV}$.

KASCADE Grande, 2017; Pierre Auger, 2021, 2022, 2023

Allowed region for RHN

YN, Yin 2025

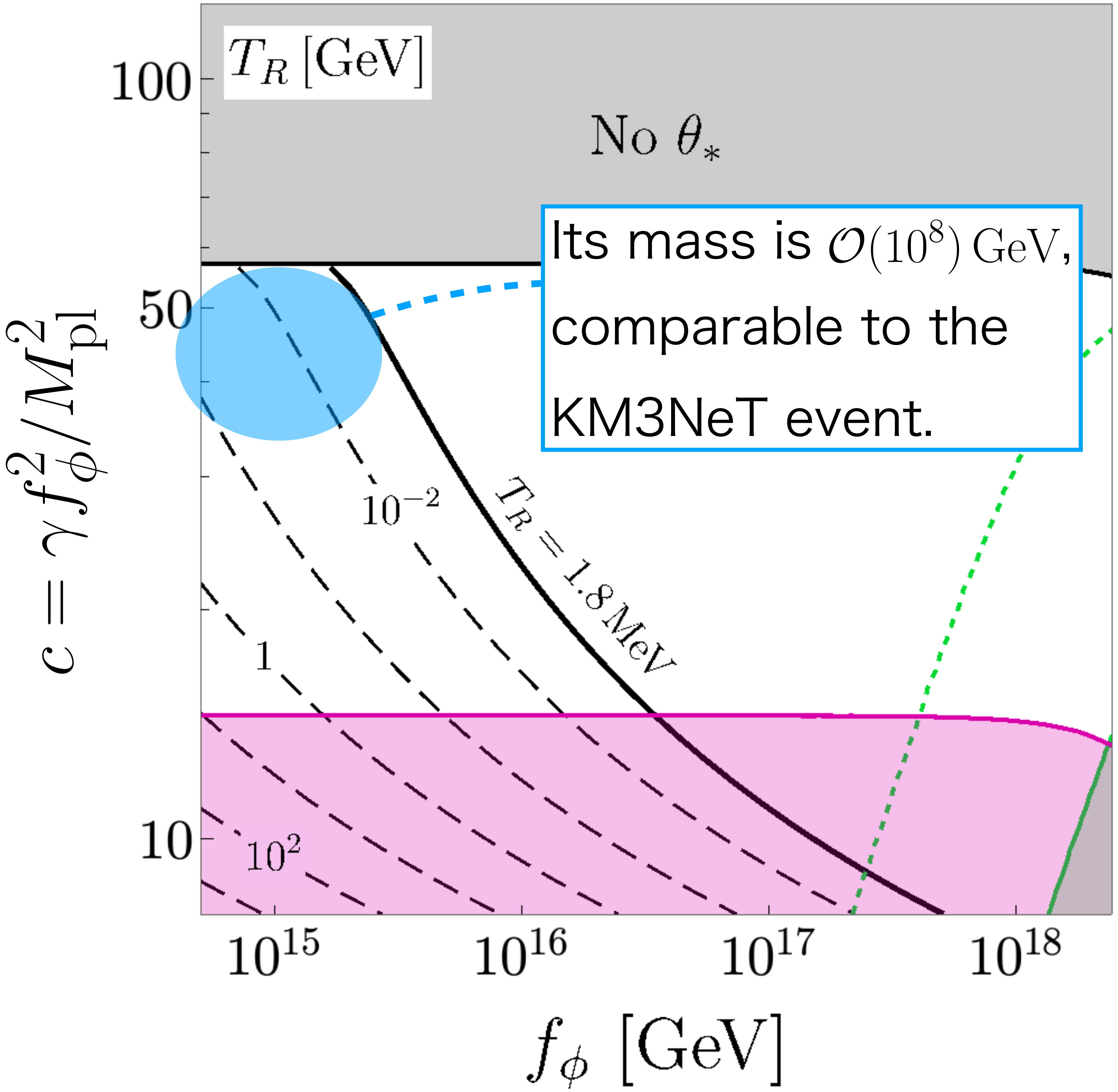


Excluded

Photon emission from thermal RHNs faces stronger observational limits.

Possible Origins of Boosted RHNs

Murase, YN, Yin 2025



Its mass is $\mathcal{O}(10^8)$ GeV, comparable to the KM3NeT event.

It is possible from RHNs to originate from the inflaton of hybrid natural inflation, if it survives as DM.

Potential during inflation

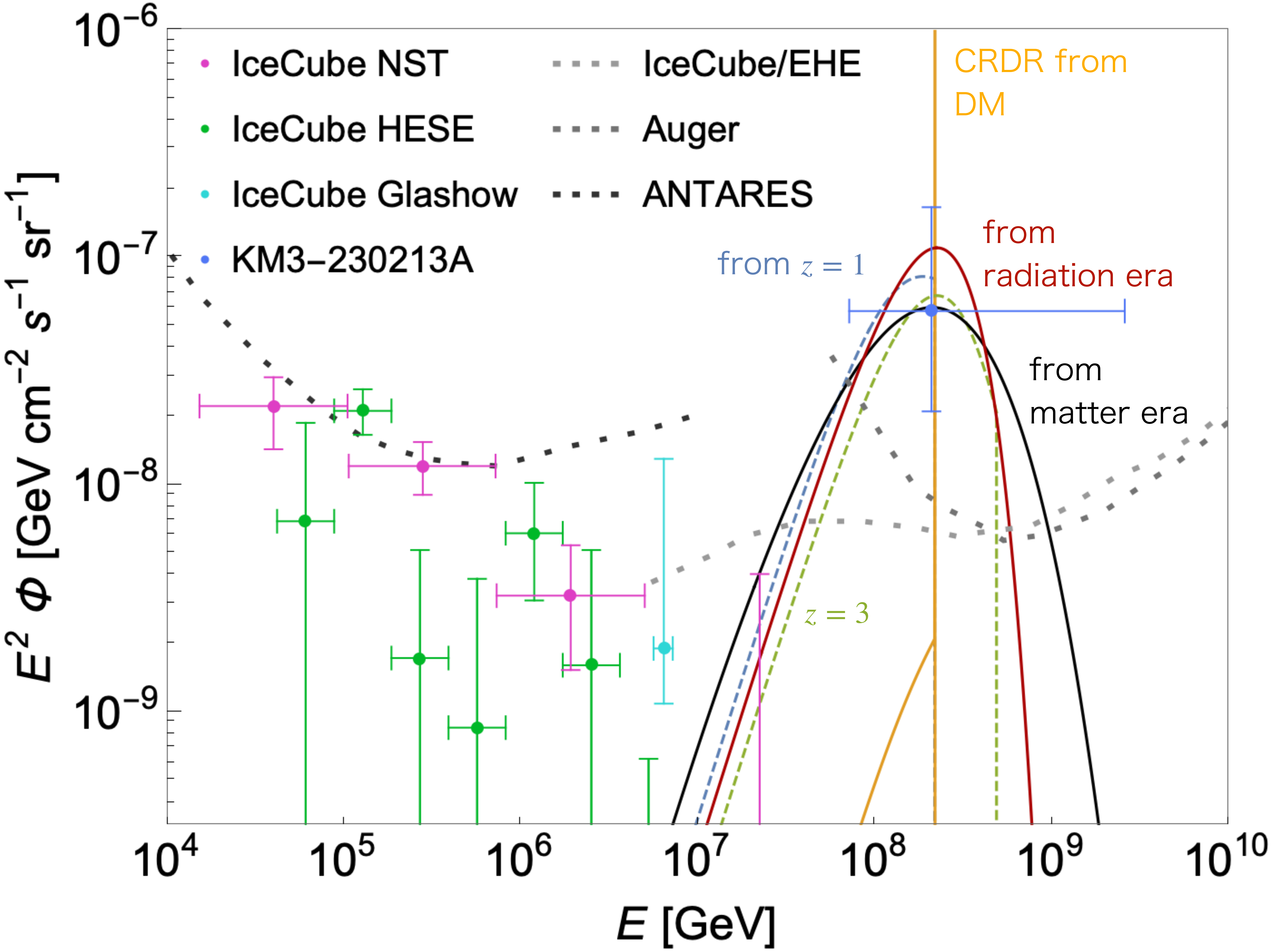
$$V(\phi) = \Lambda^4 \left(\gamma + 1 - \cos(\phi/f_\phi)\right)$$

In a low-reheating framework, this scenario can explain DM, the KM3NeT event, and the seesaw mechanism.

Summary

- KM3-230213A can be explained by sterile (right-handed) neutrinos mimicking active neutrino events.
- This scenario avoids gamma-ray constraints that challenge standard explanations.
- If this event really come from a RHN, it would represent a valuable messenger of the early Universe.
- This model predicts observable signals in future CMB and neutrino experiments, including LiteBIRD and IceCube-Gen2.

Fake neutrino flux



The value of C

Optical depth for active neutrinos

$$\tau_\nu \approx N_A \rho_{\mathrm{Earth}} L \sigma_\nu \sim 10^2$$

Then, if $\theta^2 \lesssim 10^{-2}$, the optical depth for RHNs is less than 1. → RHNs can traverse the Earth.

The effective zenith angle range is

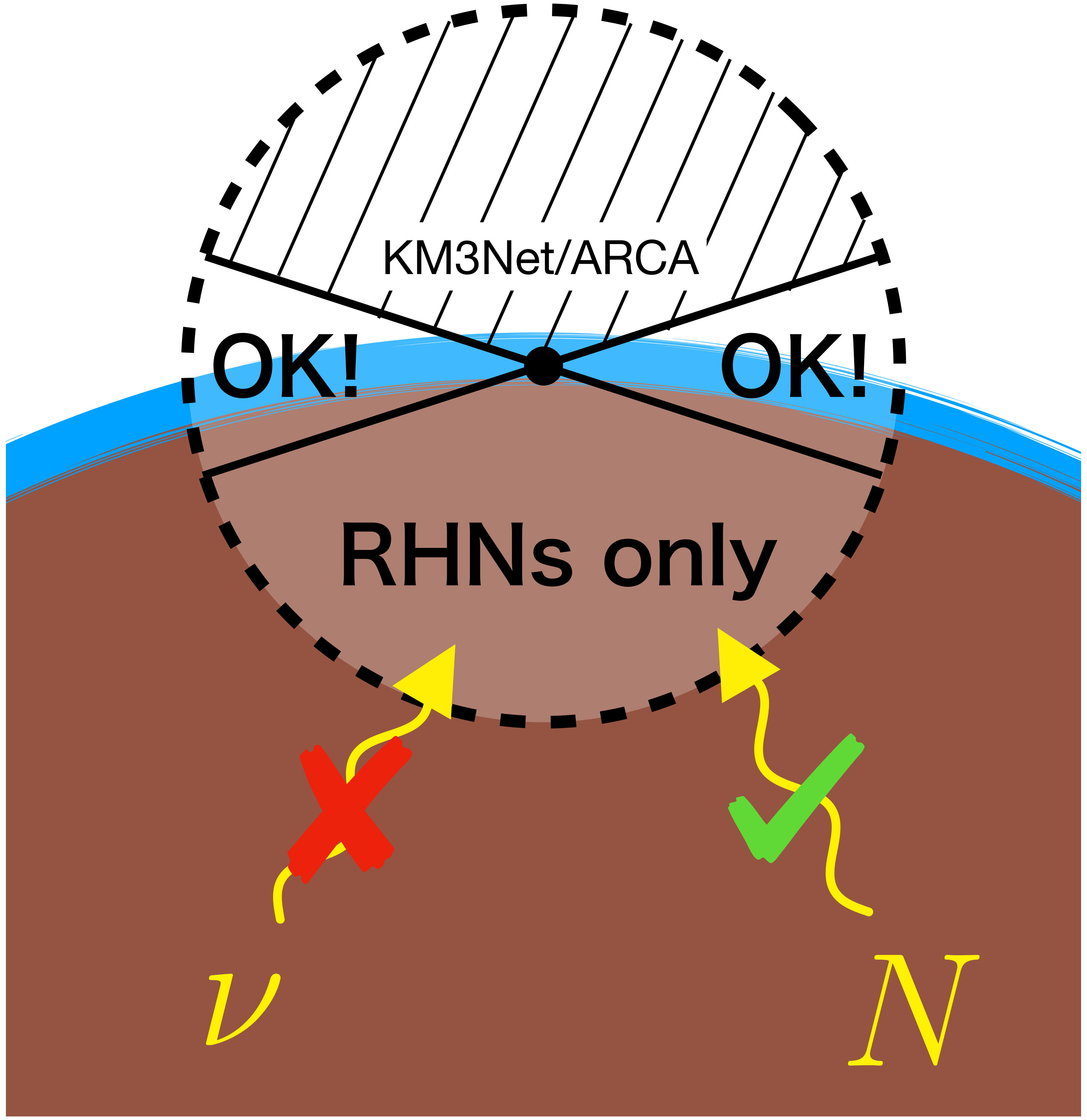
$$-0.1 \lesssim \cos\Theta \lesssim 0.08.$$

S. Aiello et al. (KM3NeT) 2024; M. G. Aartsen et al. (IceCube) 2017

So,

$$C \sim \frac{2\pi \int_{-1}^{0.08} \mathrm{d}\cos\Theta}{2\pi \int_{-0.1}^{0.08} \mathrm{d}\cos\Theta} \approx 7.$$

Hidden by atmospheric neutrino background



Estimate in post-recombination scenario

We consider the same decay process, $\phi \to NN$, $N \to \nu\gamma$.

The radiation decay is strongly suppressed within the galaxy due to its long lifetime.

Cf. $\Gamma_N^{-1} \approx 2.3 \times 10^{24}\,\mathrm{yr}\frac{10^{-10}}{\sin^2(2\theta)}\left(\frac{\mathrm{keV}}{m_N}\right)^5$

➡ It dominated by the extragalactic part.

Using the formula in Ho, Takahashi, Yin (2019), the extra-galactic flux is estimated as:

$$E_N^2\Phi_N^{\mathrm{ext}}(E_N)|_{E_N \approx m_\phi/2} \approx C^{-1}\theta^{-2}2.1 \times 10^{-9}\,\mathrm{GeV cm^{-2} s^{-1} sr^{-1}}.$$

Applying the same procedure as before gives: $m_N \lesssim \mathcal{O}(0.1)\,\mathrm{MeV} \times C^{1/6}$.