PROBING NEW PHYSICS WITH ULTRA-HIGH-ENERGY COSMIC RAYS

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(working with Lucien Heurtier)

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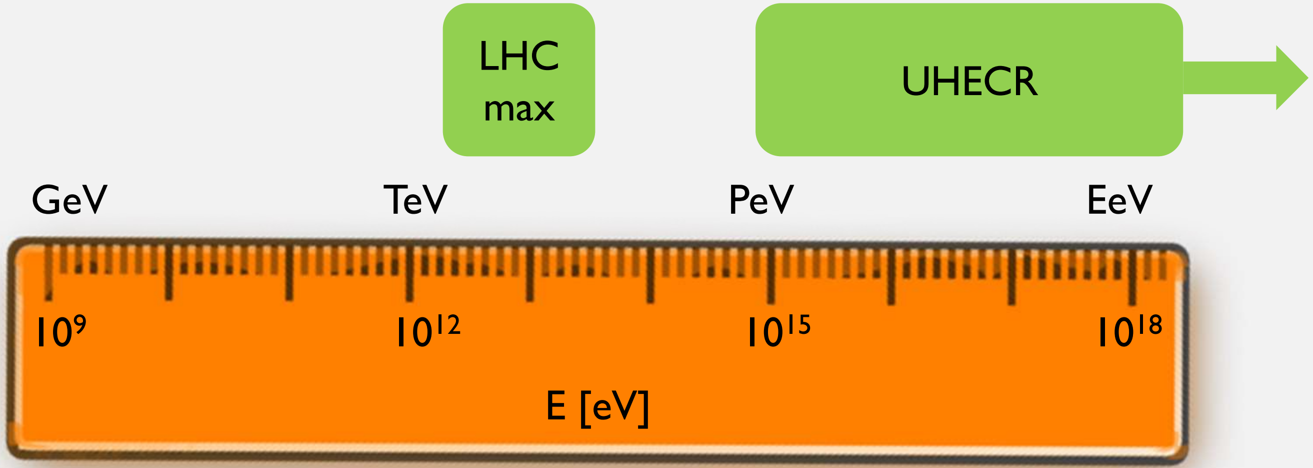
OVERVIEW

- UHECR and cosmogenic neutrinos
- Adding a right-handed Majorana neutrino
- Simulating detector results
- Conclusions

UHE COSMIC RAYS

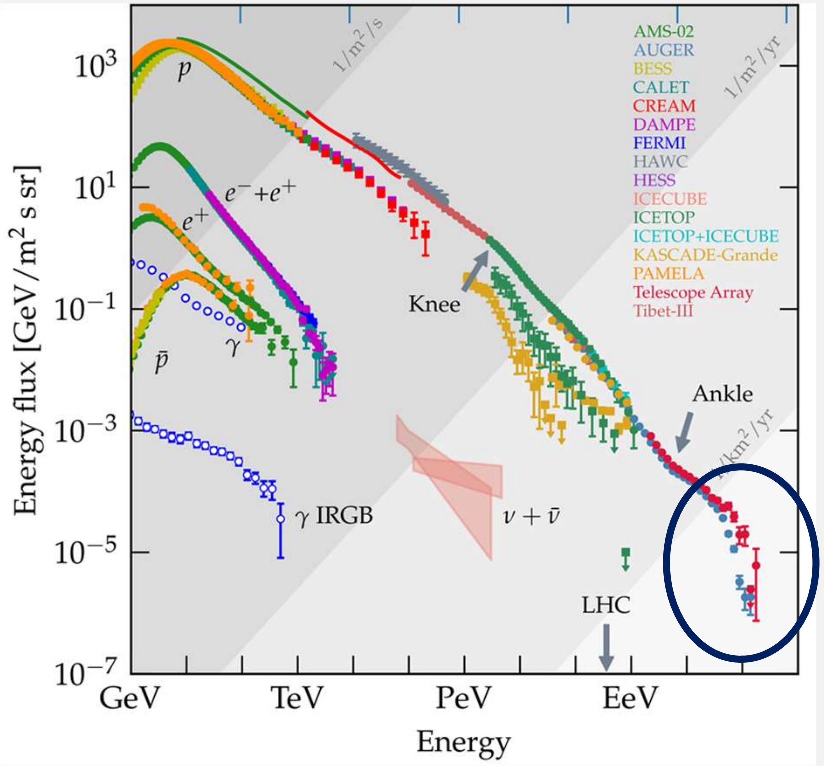
- Cosmic rays: e.g. protons, nuclei
- UHE = ultra-high energy (> PeV)



THE GZK LIMIT

- $E_{\mathrm{GZK}} \approx 50$ EeV
- Protons interact with CMB
- $p + \gamma \longrightarrow \Delta^{+} \longrightarrow n + \pi^{+}$
- Nuclei undergo photodisintegration
- Cutoff of UHECR flux

THE GZK LIMIT



- $p + \gamma \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$
- Pions decay
- ⇒ **Cosmogenic Neutrinos**

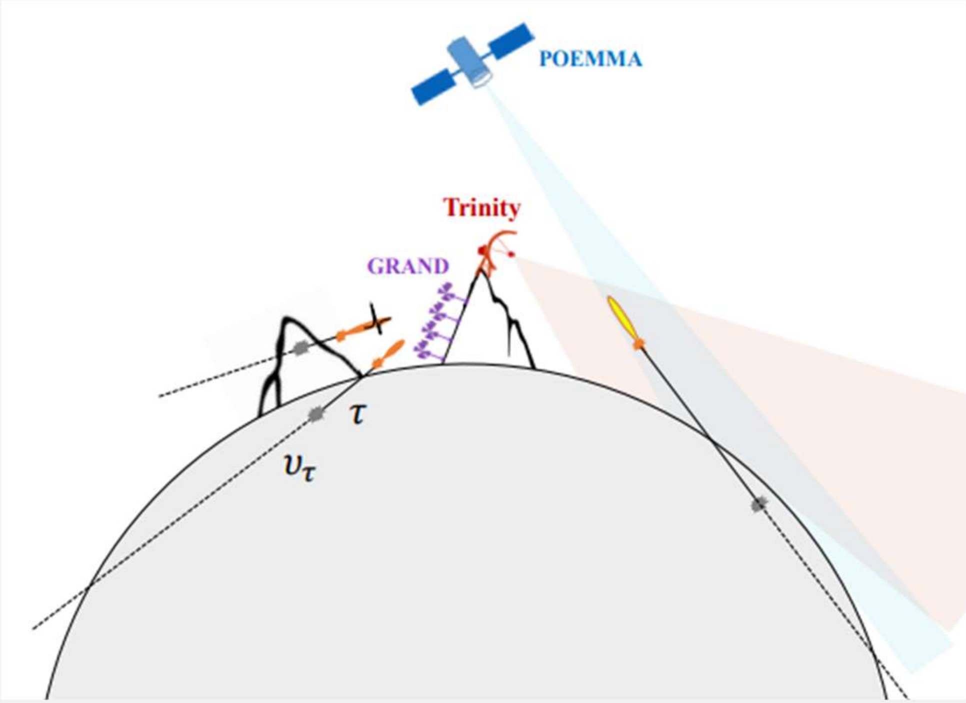
Evoli, Carmelo (2018) The Cosmic-Ray Energy Spectrum. Zenodo https://doi.org/10.5281/zenodo.4309926

THE COSMIC ACCELERATOR

- Cosmogenic neutrino flux at ~EeV scales
- Neutrino-proton interactions with CoM energy ~45 TeV
- A probe of higher energies

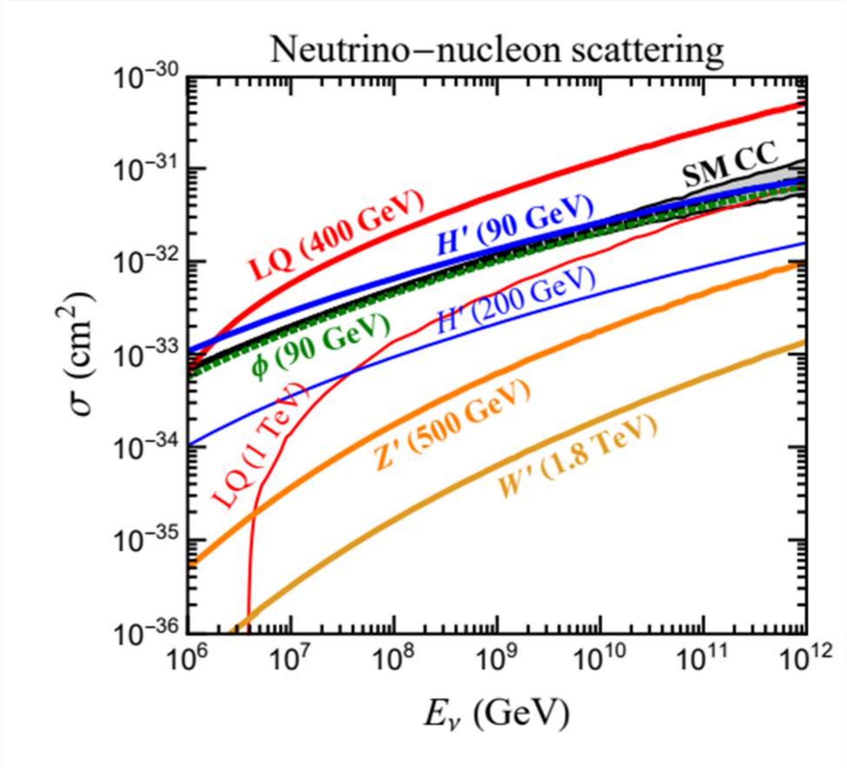
DETECTION

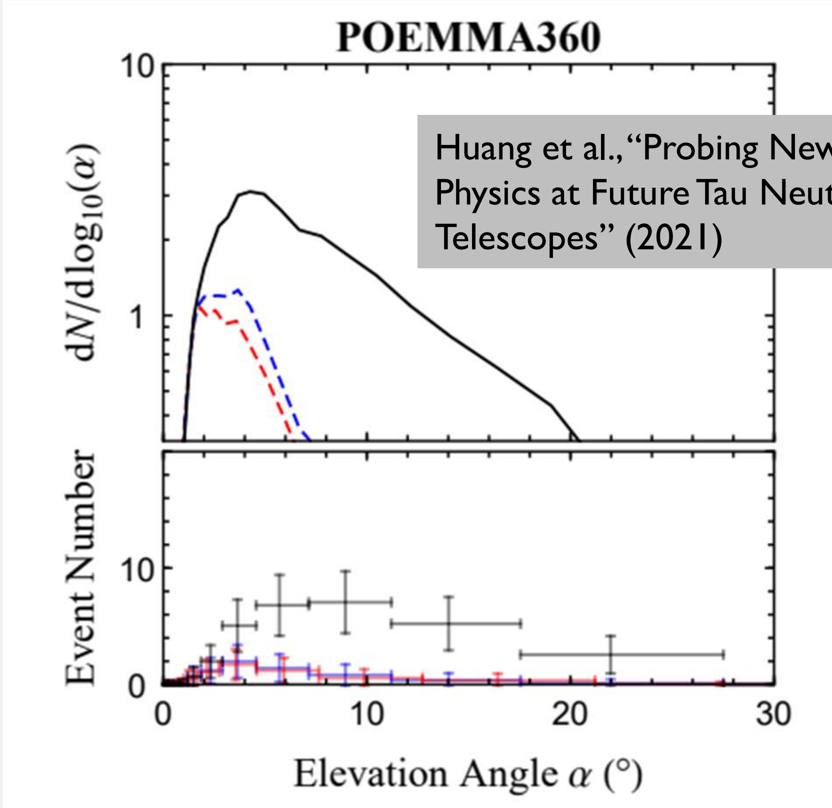
- IceCube, ANITA, Auger
- *in future*: GRAND, POEMMA, Trinity



Huang et al., "Probing New Physics at Future Tau Neutrino Telescopes" (2021)

NEW PHYSICS?





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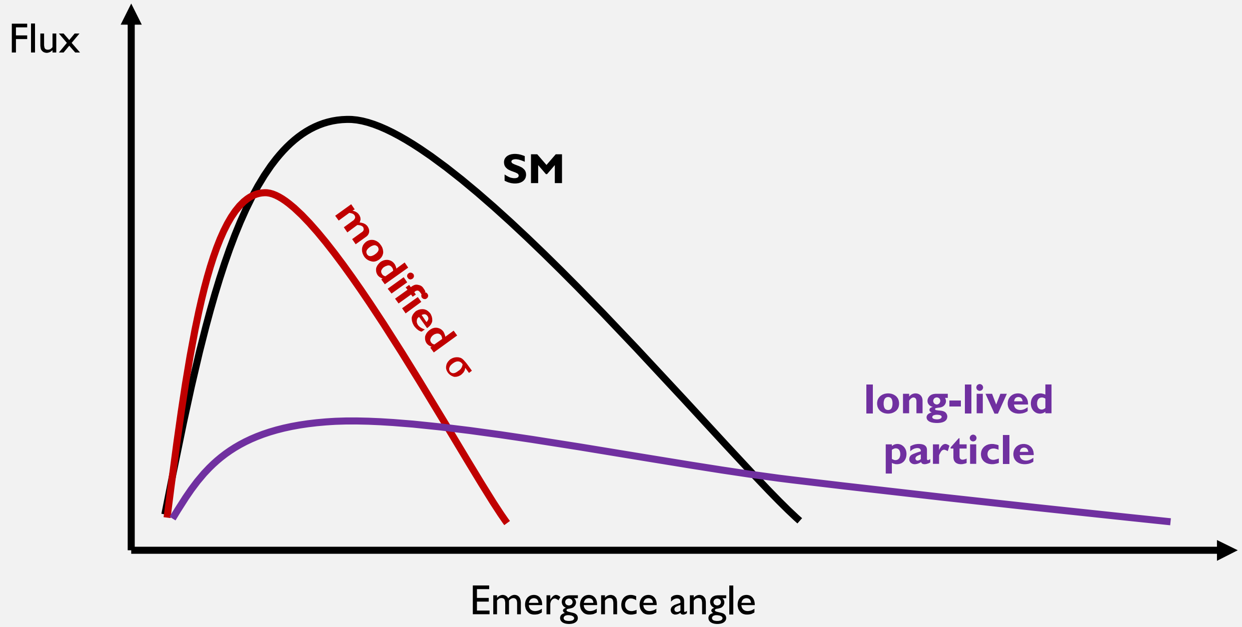
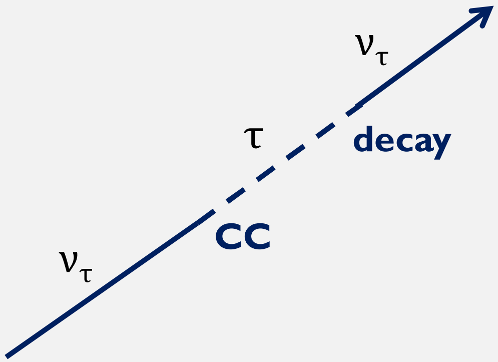
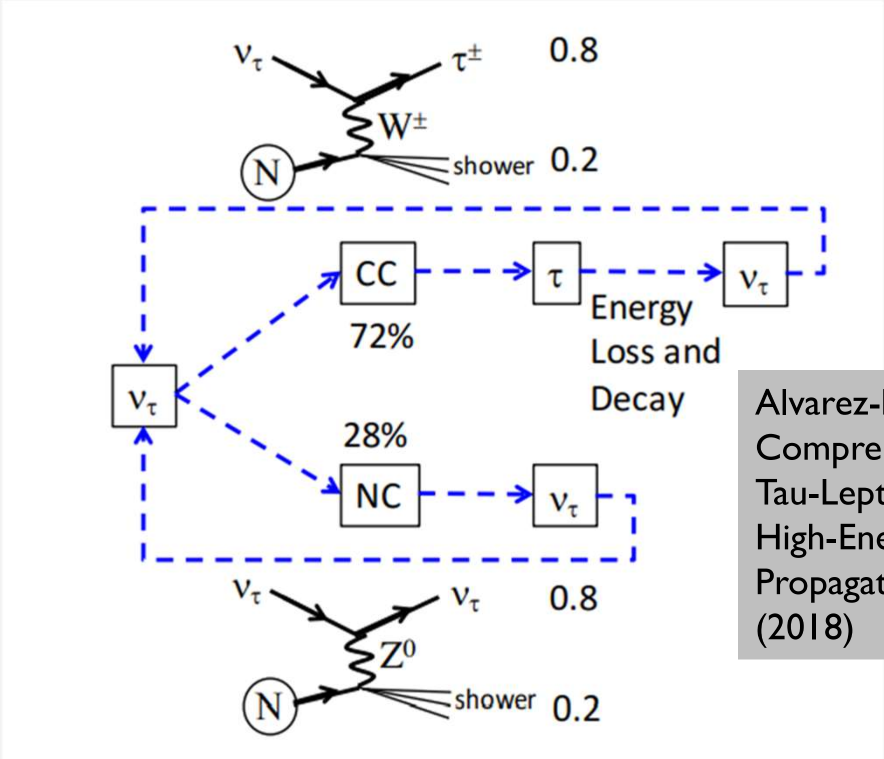
NEW PHYSICS?



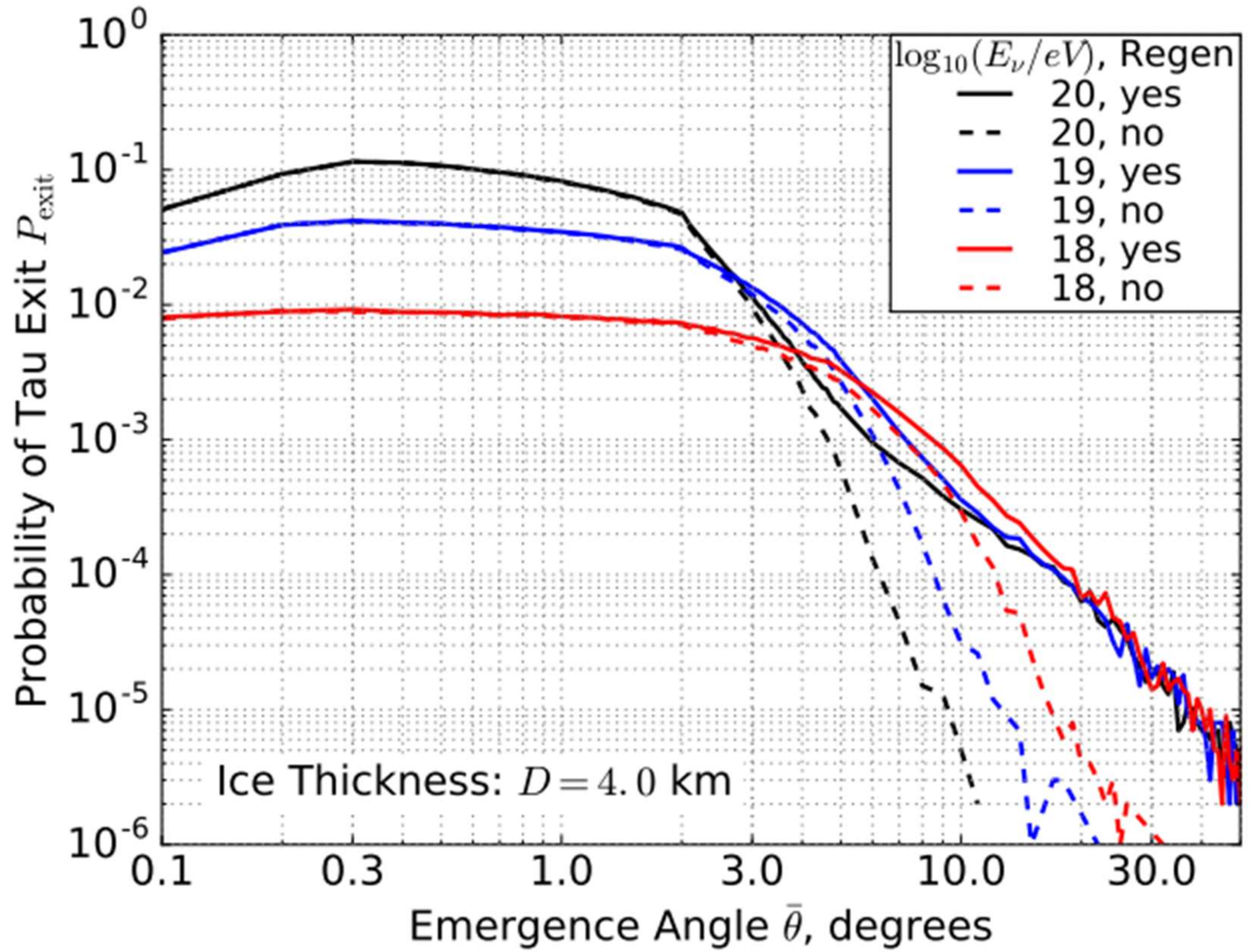
TAU NEUTRINOS IN THE EARTH

- NC and CC interactions
- Tau decay
- Tau regeneration





Alvarez-Muñiz et al., "A Comprehensive Approach to Tau-Lepton Production by High-Energy Tau Neutrinos Propagating Through Earth" (2018)



Alvarez-Muñiz et al., "A Comprehensive Approach to Tau-Lepton Production by High-Energy Tau Neutrinos Propagating Through Earth" (2018)

TAURUNNER

TauRunner: A Public Python Program to Propagate Neutral and Charged Leptons

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Abstract

In the past decade IceCube's observations have revealed a flux of astrophysical neutrinos extending to 10^7 GeV. The forthcoming generation of neutrino observatories promises to grant further insight into the high-energy neutrino sky, with sensitivity reaching energies up to 10^{12} GeV. At such high energies, a new set of effects becomes relevant, which was not accounted for in the last generation of neutrino propagation software. Thus, it is important to develop new simulations which efficiently and accurately model lepton behavior at this scale. We present `TauRunner`, a `PYTHON`-based package that propagates neutral and charged leptons. `TauRunner` supports propagation between 10 GeV and 10^{12} GeV. The package accounts for all relevant secondary neutrinos produced in charged-current tau neutrino interactions. Additionally, tau energy losses of taus produced in neutrino interactions is taken into account, and treated stochastically. Finally, `TauRunner` is broadly adaptable to divers experimental setups, allowing for user-specified trajectories and propagation media, neutrino cross sections, and initial spectra.

Keywords: Ultra-high energy, neutrinos, neutrino telescope, simulation, tau regeneration, open source

- Monte-Carlo approach to propagation of neutrinos and charged leptons
- Accounts for energy loss of tau
- Simulates neutrinos traversing chord of the Earth's interior (all within SM)

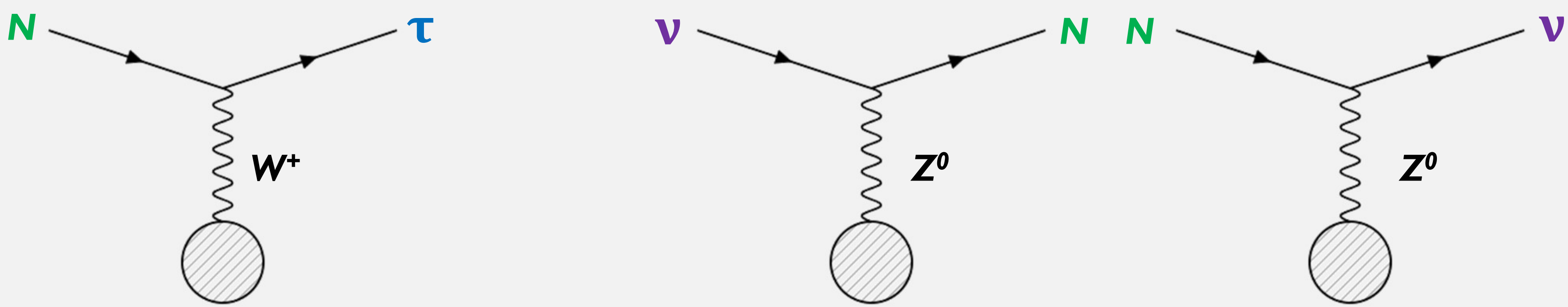
ADDING THE RHN

- Neutrinos in the standard model have left-handed chirality
- Possible BSM physics: right-handed neutrino
- Majorana neutrino coupled via seesaw mechanism

RHN INTERACTIONS

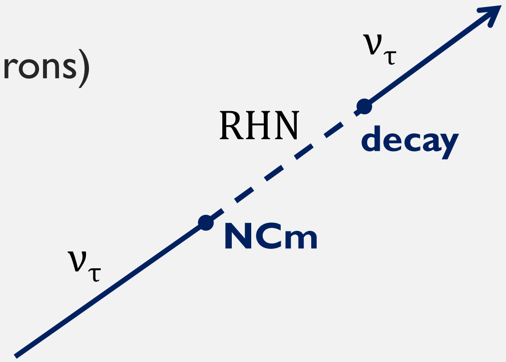
- CC and NC (with mixing)

$$-\mathcal{L} \supset \left(\frac{g}{\sqrt{2}}\right) \sin(\theta_{\mathrm{mix}})\, W_\mu^+ \bar{N}^c \gamma^\mu P_L \tau + \left(\frac{g}{2\cos\theta_w}\right) \sin(\theta_{\mathrm{mix}})\, Z_\mu \bar{N}^c \gamma^\mu P_L \nu_\tau + \mathrm{h.c.}$$



RHN DECAY

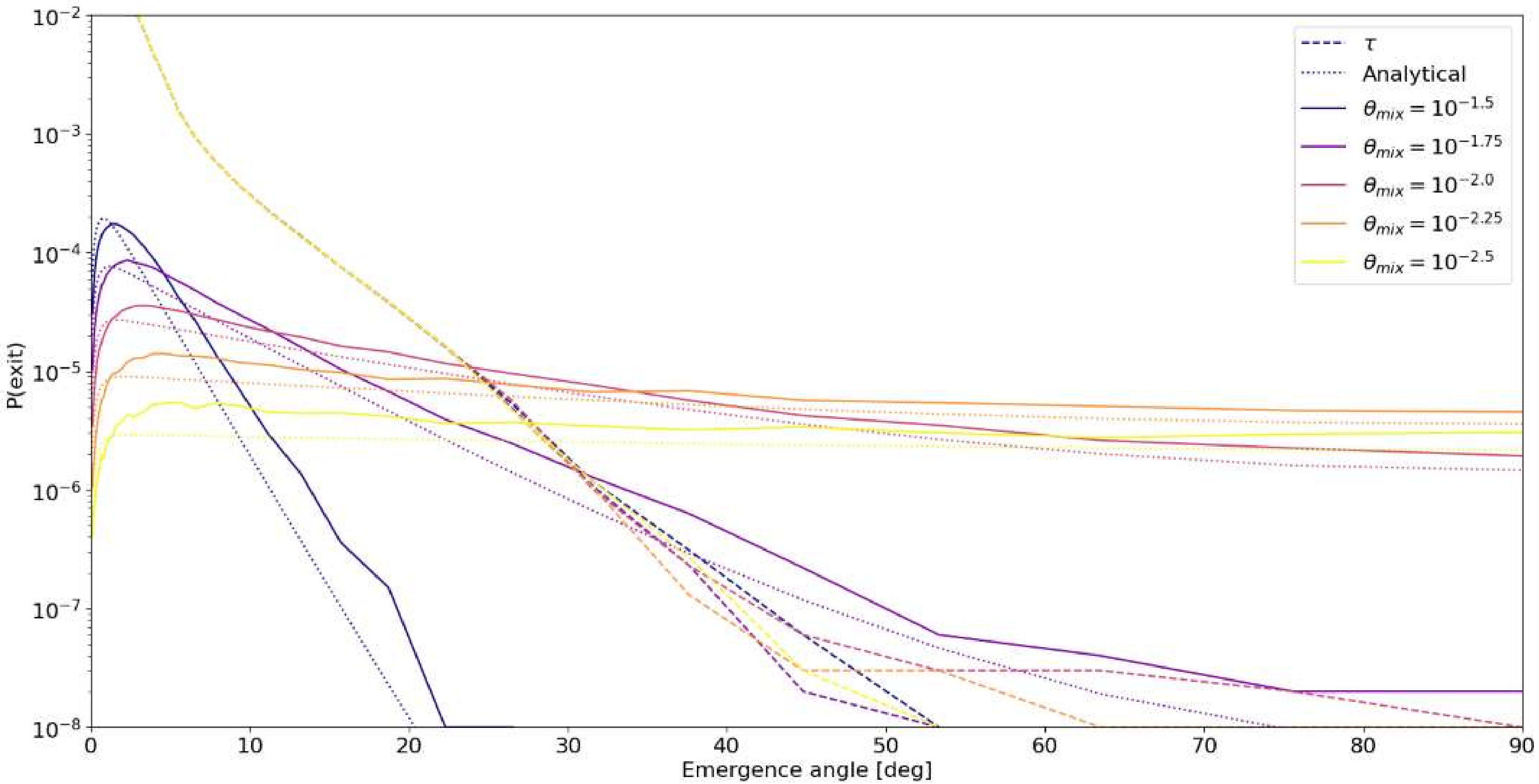
- Various decay modes (lighter charged leptons, neutrinos, hadrons)
- Strongly mass-dependent
- Regeneration



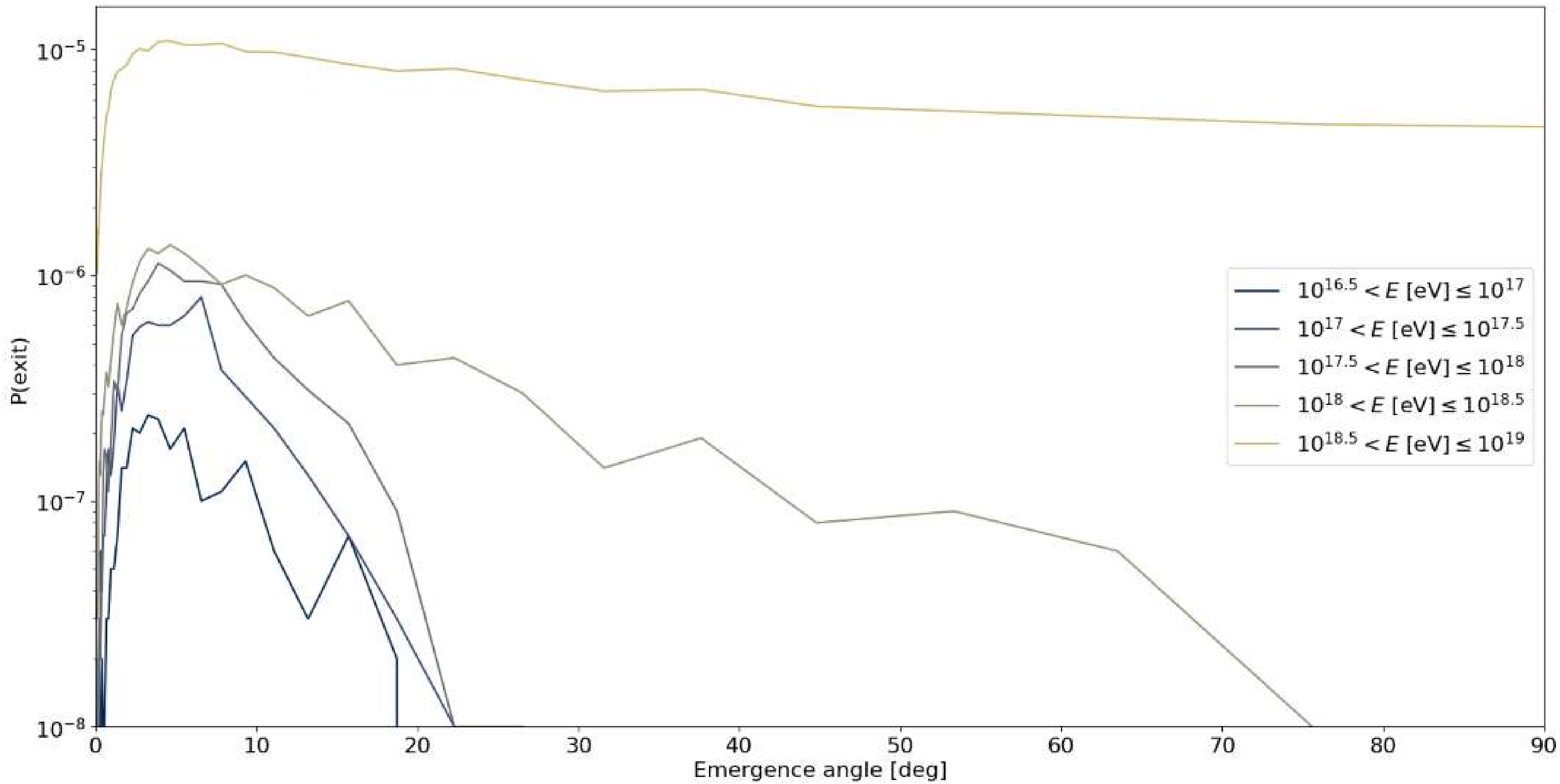
- Additional detectable air showers (analogous to taus)

RESULTS

- Using mass 5 GeV
- Varying mixing angle
- Incoming energy 10 EeV
- Define *P(exit)* as number of RHNs exiting with energy > 30 PeV per incoming neutrino
- Compare to analytical result for one interaction (dotted line)

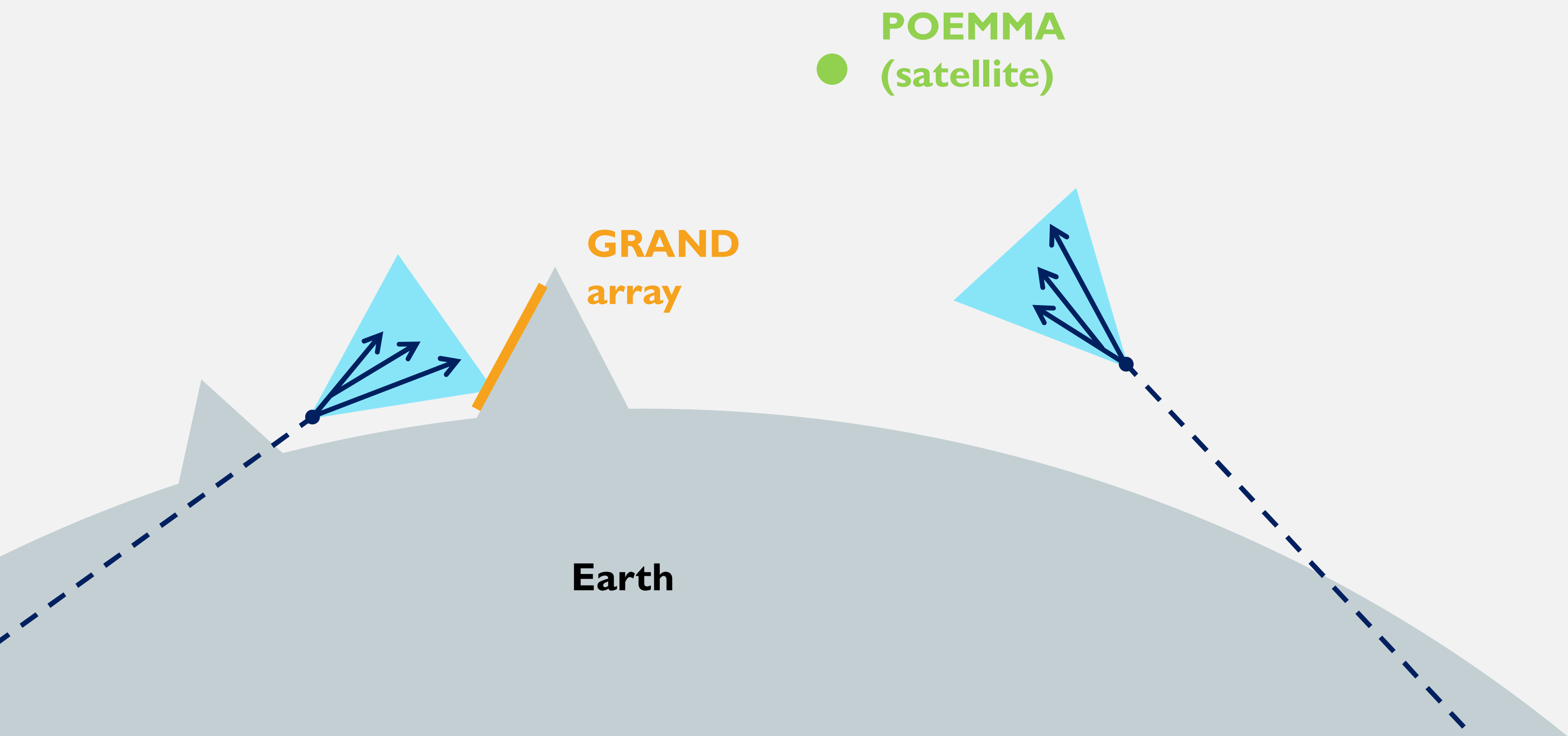


τ
Analytical
$\theta_{mix} = 10^{-1.5}$
$\theta_{mix} = 10^{-1.75}$
$\theta_{mix} = 10^{-2.0}$
$\theta_{mix} = 10^{-2.25}$
$\theta_{mix} = 10^{-2.5}$
P(exit)
Emergence angle [deg]



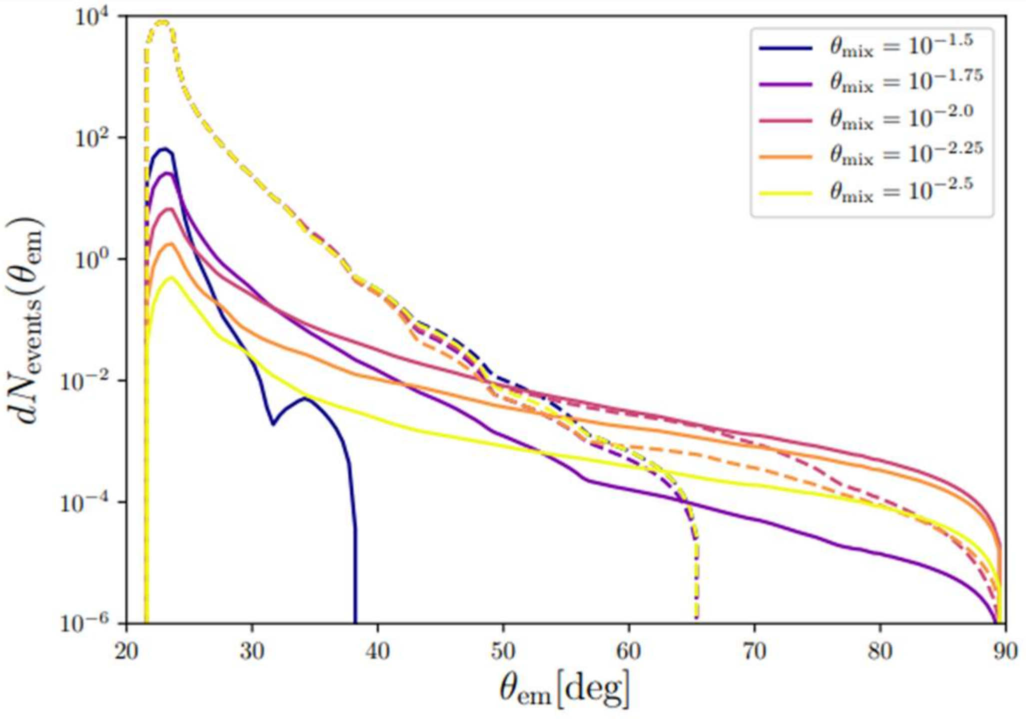
P(exit)
Emergence angle [deg]
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0 10 20 30 40 50 60 70 80 90
$10^{16.5} < E$ [eV] $\leq 10^{17}$
$10^{17} < E$ [eV] $\leq 10^{17.5}$
$10^{17.5} < E$ [eV] $\leq 10^{18}$
$10^{18} < E$ [eV] $\leq 10^{18.5}$
$10^{18.5} < E$ [eV] $\leq 10^{19}$

DETECTOR SIMULATIONS

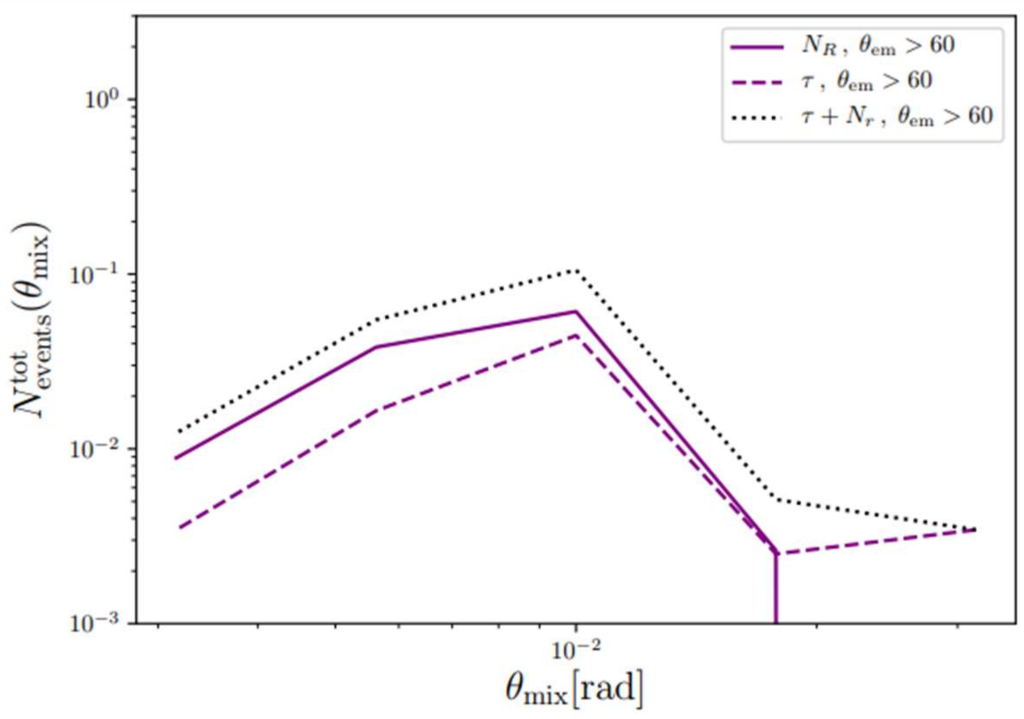


PRELIMINARY DETECTOR PREDICTIONS

- Simplified simulation of POEMMA
- (similar code for GRAND in progress)
- Modelling with optimistic cosmogenic neutrino flux within IceCube and Auger constraints
- Event number (of RHNs and taus) over 5-year run



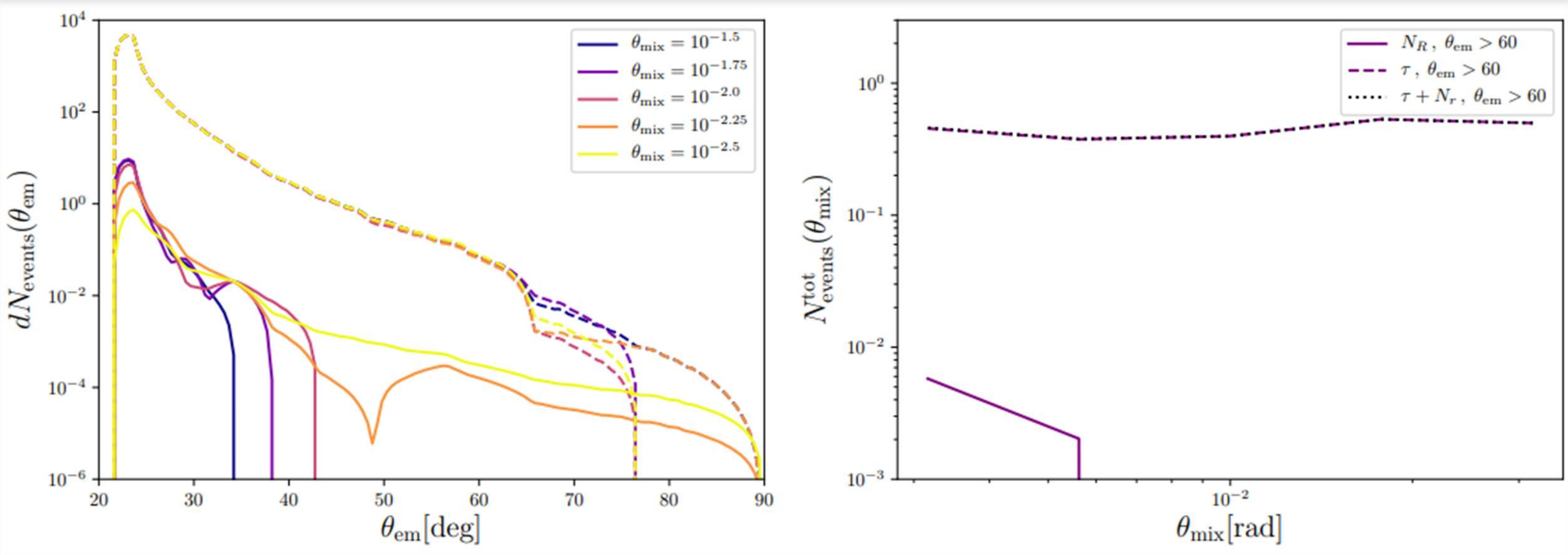
$\theta_{\rm mix} = 10^{-1.5}$
$\theta_{\rm mix} = 10^{-1.75}$
$\theta_{\rm mix} = 10^{-2.0}$
$\theta_{\rm mix} = 10^{-2.25}$
$\theta_{\rm mix} = 10^{-2.5}$
$dN_{\rm events}(\theta_{\rm em})$
$\theta_{\rm em}[\rm deg]$



N_R , $\theta_{\rm em} > 60$
τ , $\theta_{\rm em} > 60$
$\tau + N_r$, $\theta_{\rm em} > 60$
$N^{\rm tot}_{\rm events}(\theta_{\rm mix})$
$\theta_{\rm mix}[\rm rad]$

VARYING INITIAL ENERGY

- Used 10 EeV
- Expected cosmogenic neutrino flux spread over EeV scales
- Simulate with lower energy



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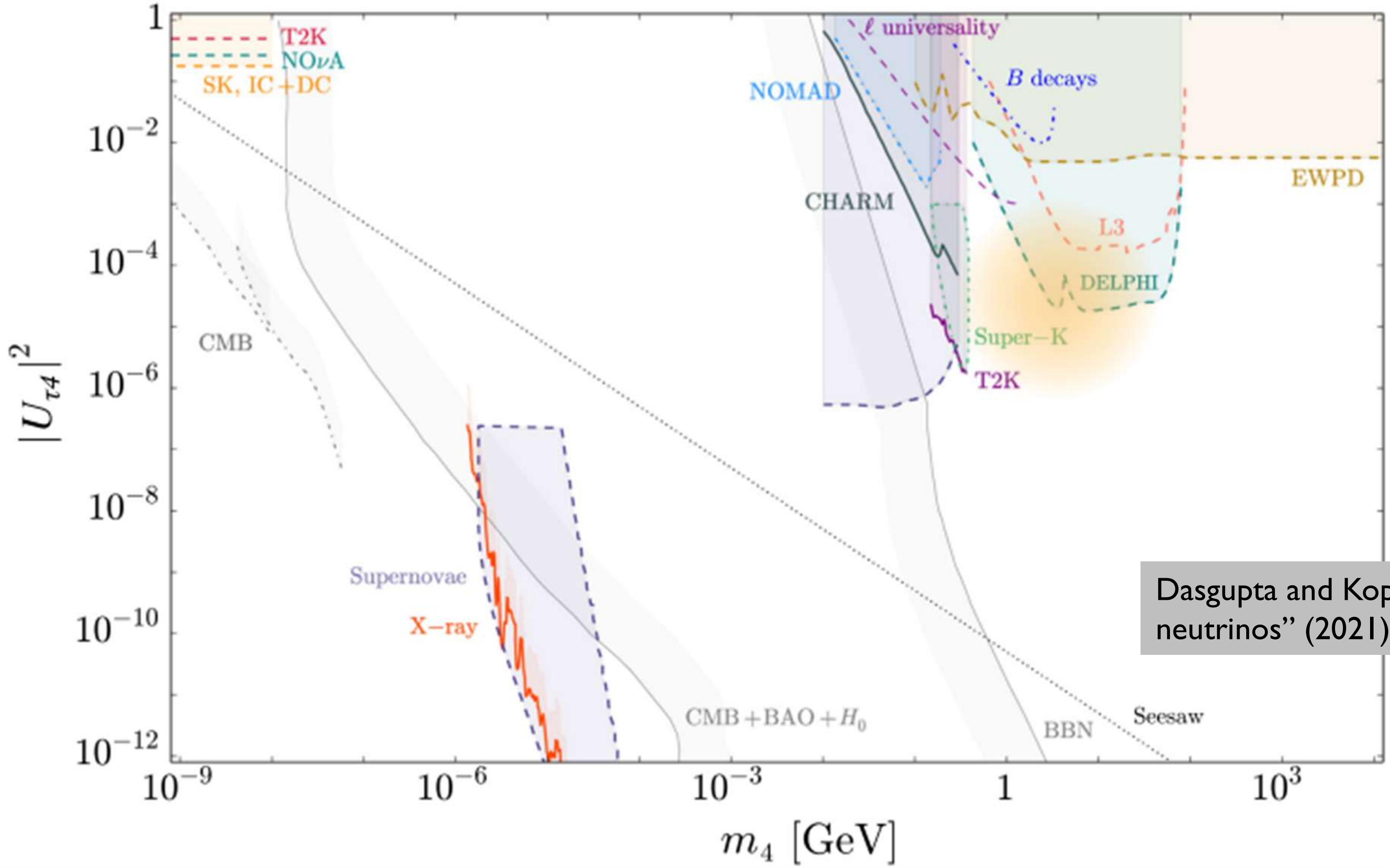
$\theta_{\rm mix} = 10^{-2.25}$
$\theta_{\rm mix} = 10^{-2.5}$
$dN_{\rm events}(\theta_{\rm em})$
$\theta_{\rm em}[\rm deg]$
$N_R\,,\ \theta_{\rm em} > 60$
$\tau\,,\ \theta_{\rm em} > 60$
$\tau + N_r\,,\ \theta_{\rm em} > 60$
$N^{\rm tot}_{\rm events}(\theta_{\rm mix})$
$\theta_{\rm mix}[\rm rad]$

DISCUSSION

- Necessity for high energies motivates methodology
- Observable effects
- Can be used to constrain parameters

FURTHER STUDY

- Improve statistics
- Test other masses
- Predict constraints
- Play with further BSM models (e.g. Majoron?)



Dasgupta and Kopp, "Sterile neutrinos" (2021)

CONCLUSIONS

- BSM physics, such as a right-handed Majorana neutrino model, would affect the phenomenology of Earth-traversing UHE neutrinos, modifying results at observatories such as POEMMA.
- Future experimental results may allow us to constrain model parameters.
- The necessity of vast energies, even for exploring physics at smaller scales, motivates UHECRs as an avenue for testing BSM physics.

QUESTIONS?