Search of Heavy Neutral Leptons with KM3NeT/ORCA-18

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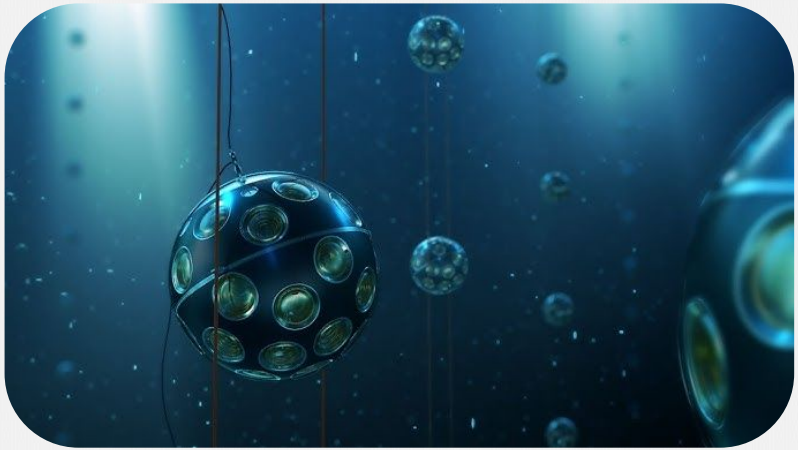
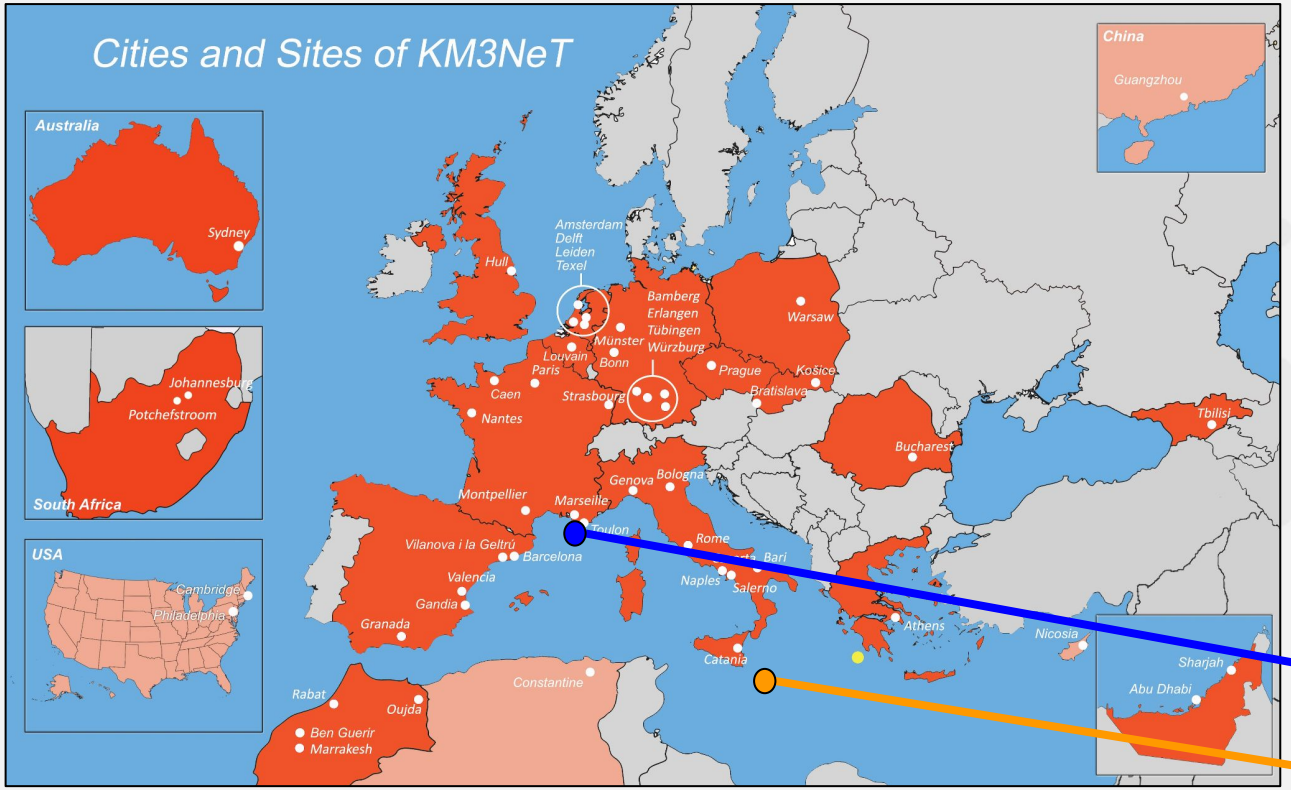
PART I

The KM3NeT Neutrino Telescope



KM3NeT



- **International collaboration with:**
  - ➢ **~250 members.**
  - ➢ **65 partner institutes.**
  - ➢ **Over 22 countries.**
- **Two detectors in different sites: KM3NeT/ORCA and KM3NeT/ARCA:**
  - ➢ **Same technology.**
  - ➢ **Same data processing.**
  - ➢ **Same software and common dataformats.**
  - ➢ **Different size and granularity.**

KM3NeT/ORCA

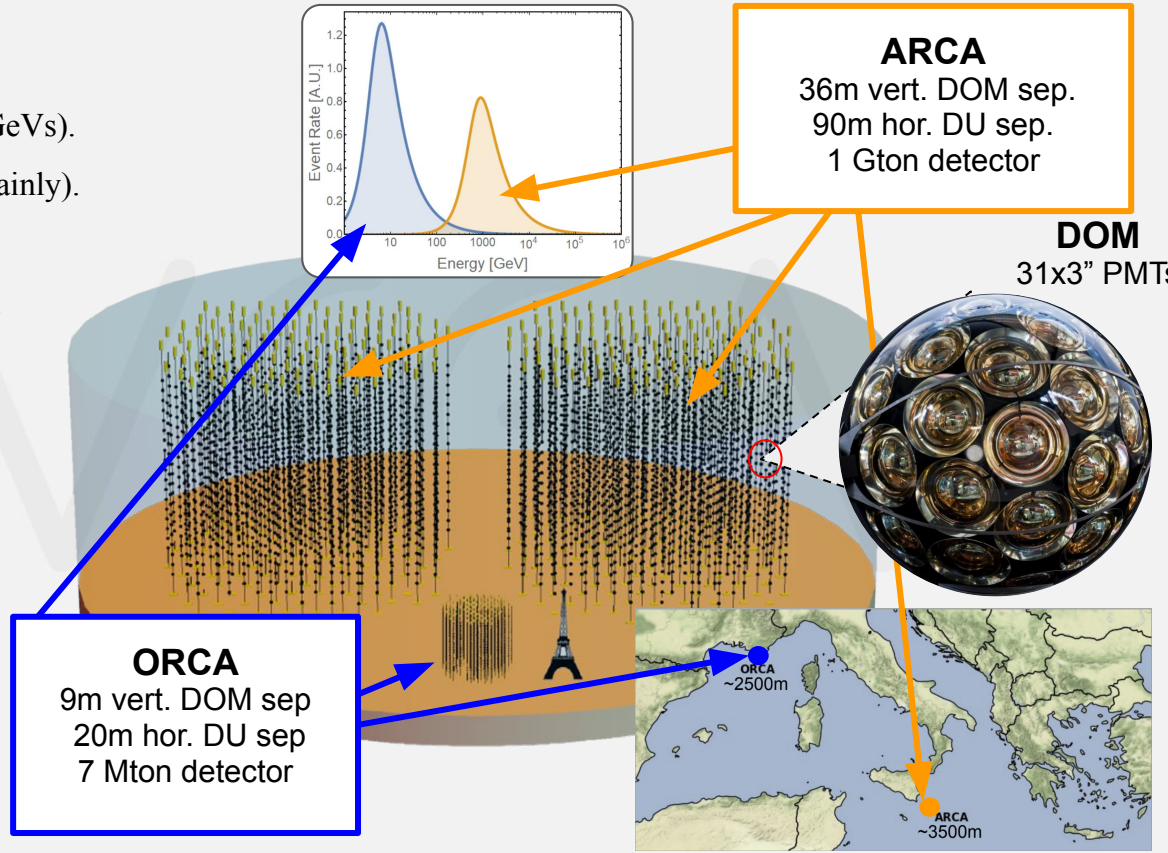
KM3NeT/ARCA

KM3NeT - ARCA and ORCA

- **KM3NeT/ORCA:**
  - Low energies (~few GeV to hundreds of GeVs).
  - Fundamental neutrino property studies (mainly).
  - **Full ORCA:** 115 DUs, 18 DOMs per DU.
  - **Current ORCA:** 33 DUs operating today.
- **KM3NeT/ARCA:**
  - High energies (sub-TeV to few PeV).
  - Astrophysical studies (mainly).
  - **Full ARCA:** 230 DUs, 18 DOMs per DU.
  - **Current ARCA:** 48 DUs operating today.

DU: Detection Unit. String of 18 DOMs.

DOM: Digital Optical Module.



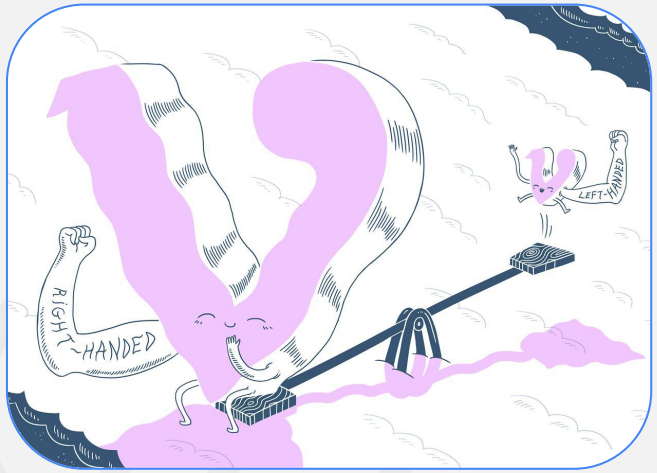
PART II

Heavy Neutral Leptons

Heavy Neutral leptons - Physics motivation

- Neutrino oscillations ➡ Neutrino have masses.
- Addition of a heavy right-handed neutrino to the Standard Model can solve the tiny neutrino masses problem.

$$\mathcal{L}^{\text{mass}}_{\text{see-saw}} = -\frac{1}{2}(\bar{\Phi}_L, \bar{\Phi}_R)\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}\begin{pmatrix} \Phi_L \\ \Phi_R \end{pmatrix}$$



HNLs are/have:

Right-handed neutrino partners	$M >>> eV$	**Feeble interactions with SM neutrinos**

Heavy Neutral Leptons - Portals

There are many proposed portals between HNLs and Standard Model neutrinos:

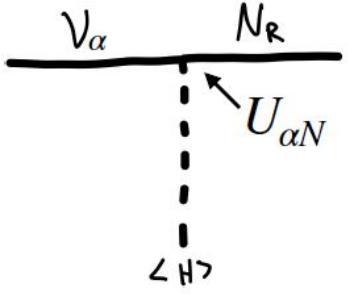
Better know is coupling through mass mixing

Mass-Mixed HNLs

Coupling via mass mixing as in Seesaw Type I

Parameters

- M_N : HNL mass
- $U_{\alpha N}$: mixing matrix elements

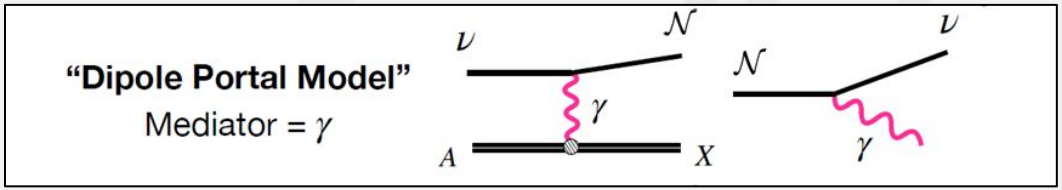


[N. Kamp 2025]

Heavy Neutral Leptons - Portals

There are many proposed portals between HNLs and Standard Model neutrinos:

We will study the **Dipole-Portal HNL model**, focusing on the **coupling to tau-neutrinos**.



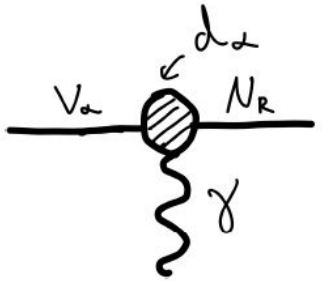
[N. Kamp 2025]

Dipole-Portal HNLs

Coupling via an effective transition magnetic moment

Parameters

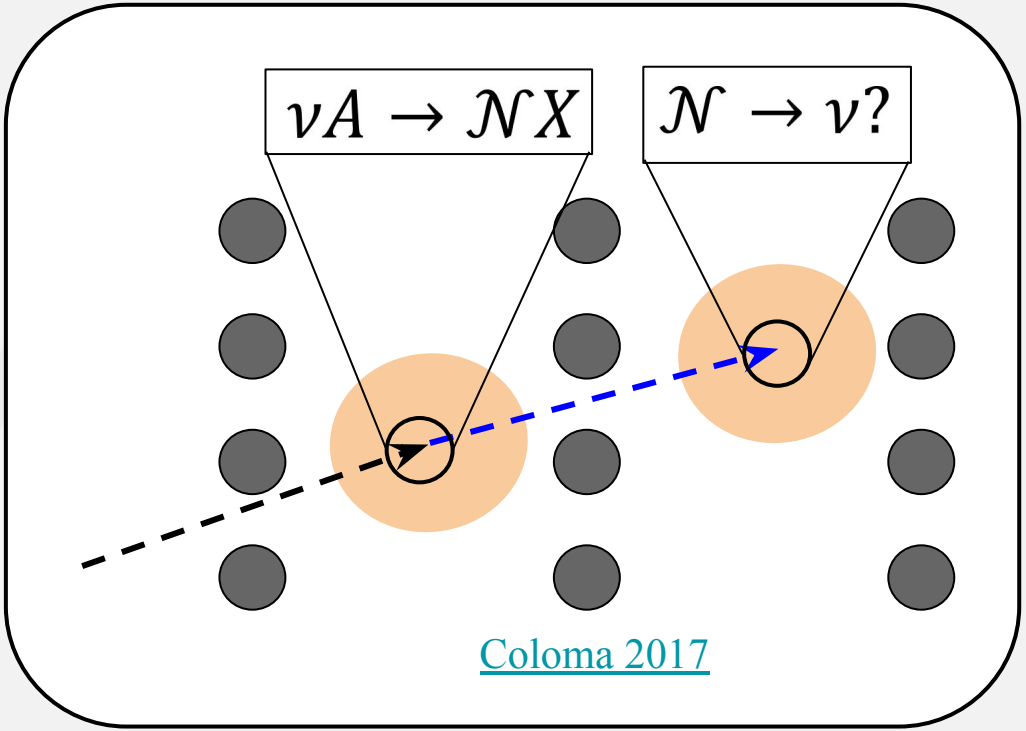
- M_N : HNL mass
- $d_{\alpha N}$: effective dipole moment



Heavy Neutral Leptons - Signal in ORCA

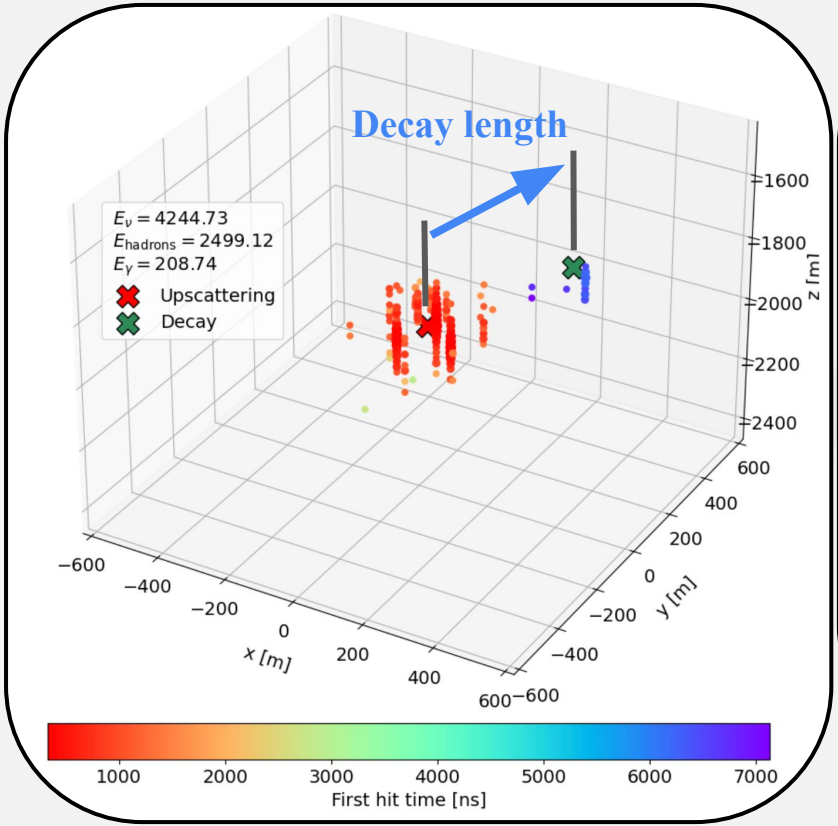
The presence of HNLs could leave a signal in KM3NeT/ORCA!

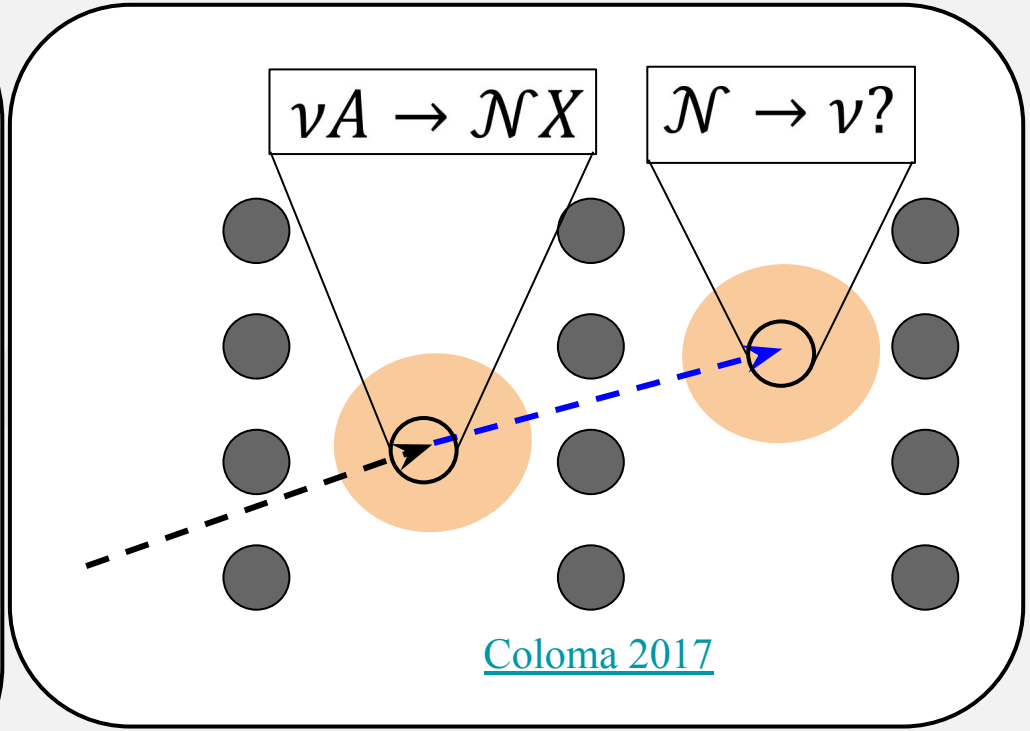
- The signature of this events in ORCA would be the one of **two showers separated a certain distance** at low energy.
- Very unique signal as tau-neutrinos double bang at GeV energies generate showers ~micrometers apart from each other.



Coloma 2017

Heavy Neutral Leptons - Signal in ORCA

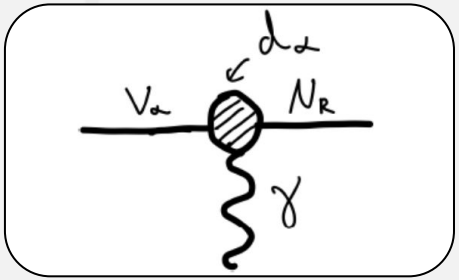




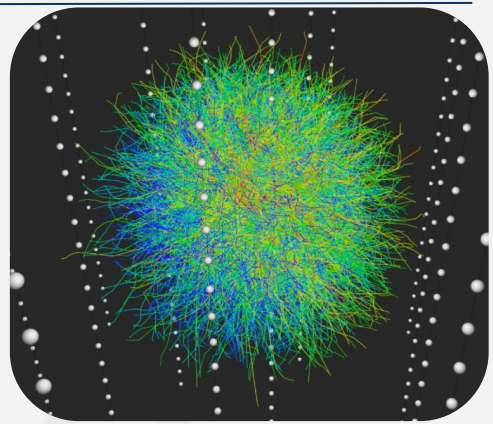
Coloma 2017

Why Dipole Portal Model KM3NeT/ORCA-18?

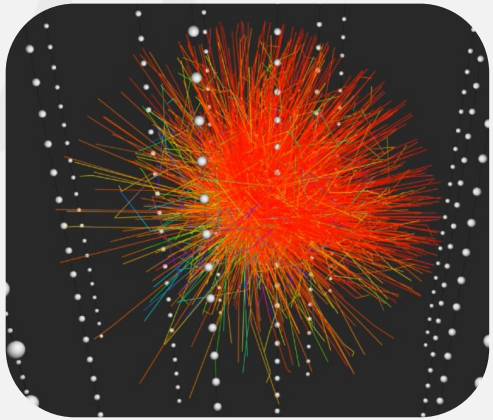
- KM3NeT, placed in water and not in ice, might have **better capabilities to reconstruct the signal of the two showers**.
- KM3NeT has a **natural beam of tau neutrinos** of those oscillating as they transverse the Earth.
- The dipole portal channel is mediated via a **photon which might be difficult to identify in other experiments** designed to look for LLPs.



10 TeV in ice

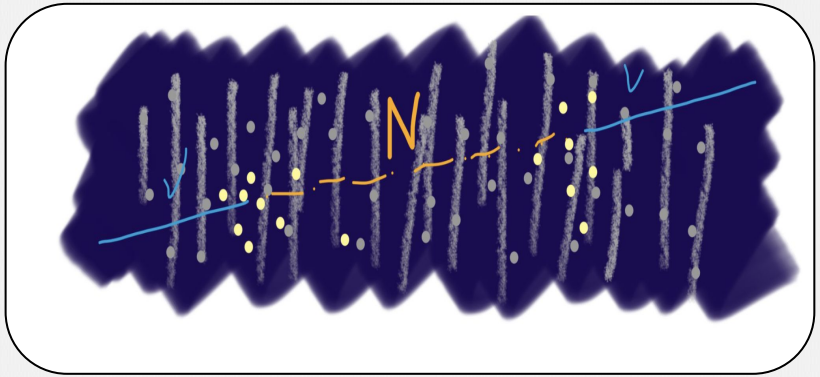


10 TeV in water



PART III

Methodology and results



Methodology - Simulation with SIREN

- The “HNL-driven double bang” signal **simulated with SIREN** (Sampling and Injection for Rare EveNts) [GITHUB, 2406.01745].
- Designed for efficient injection and re-weighting of rare neutrino interactions in detailed detector geometry descriptions.
- Significant extension from the IceCube’s LeptonInjector and LeptonWeighter software packages.

Harvard-Neutrino / SIREN

SIREN: An Open Source Neutrino Injection Toolkit

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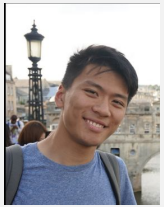
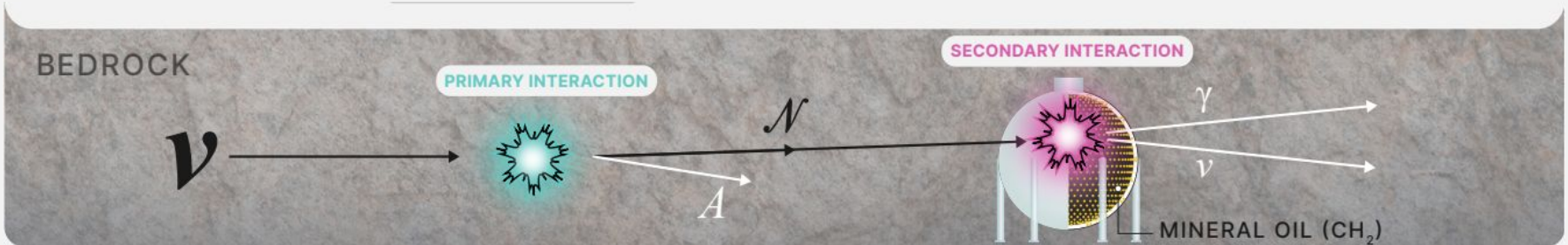
[b]Massachusetts Institute of Technology, Cambridge , MA, United States
[c]Department of Physics & Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge 02138, MA, United States

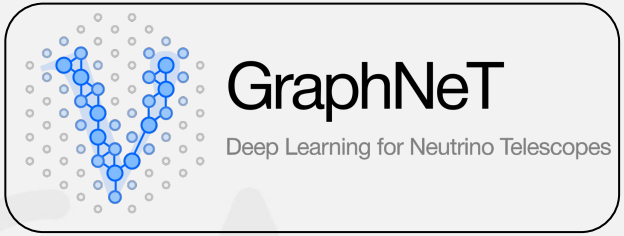


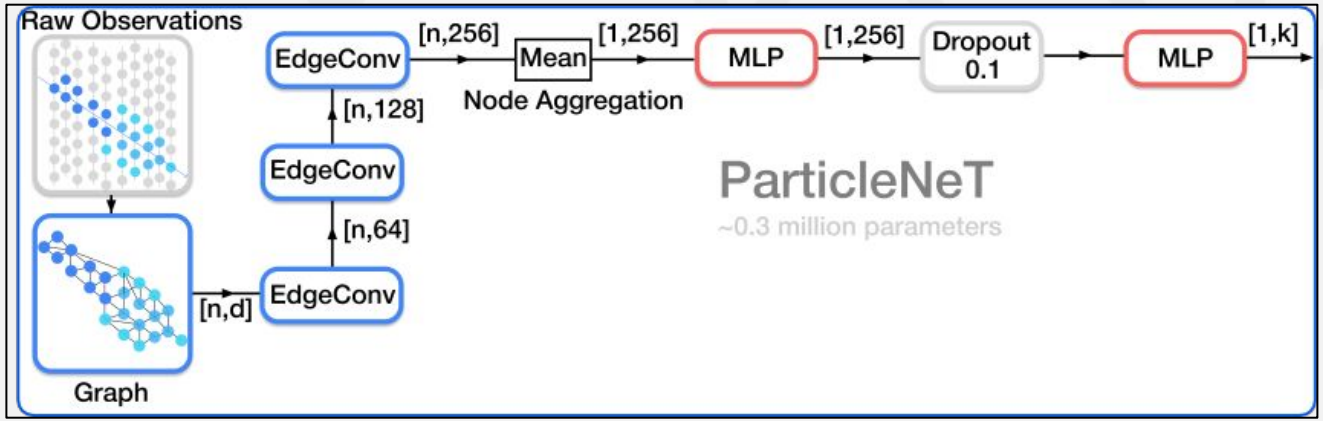


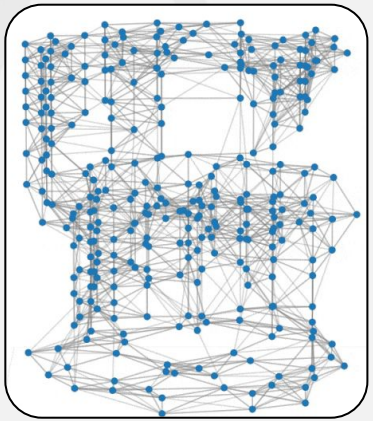


Methodology - Reconstruction

- "*It is preferable not to shape the problem to the tool, but the tool to the problem" [Rasmus Orsoe on a ML lecture].*
- Given the importance of capture shape of the event in the reconstruction Graph Neural Networks (GNNs) are a good tool to try and reconstruct these events.
- Attempts to use a slightly-tuned **ParticleNeT** model to reconstruct these signals.(see GraphNeT)

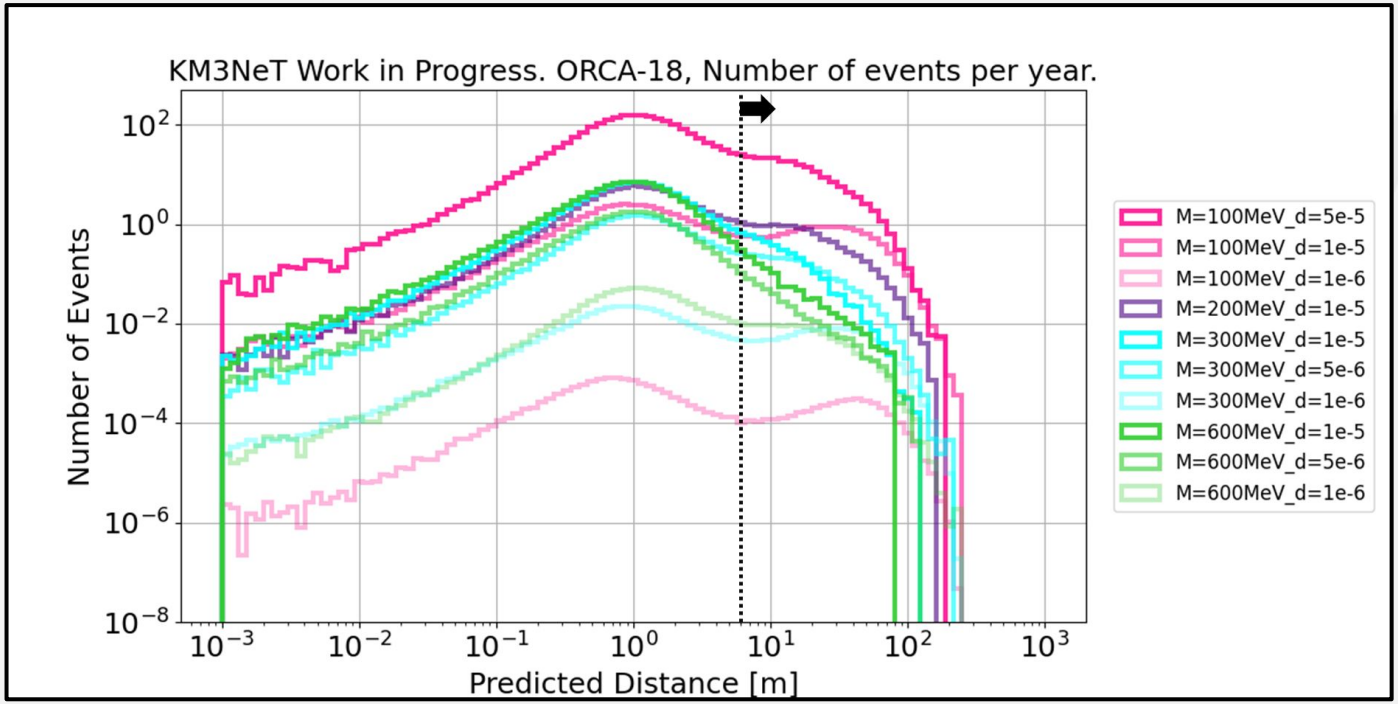






Results - Reconstructed distance

- Reconstruct the **distance between the two showers** with ParticleNeT and constrain **d>5m**



Results - Reconstructed distance

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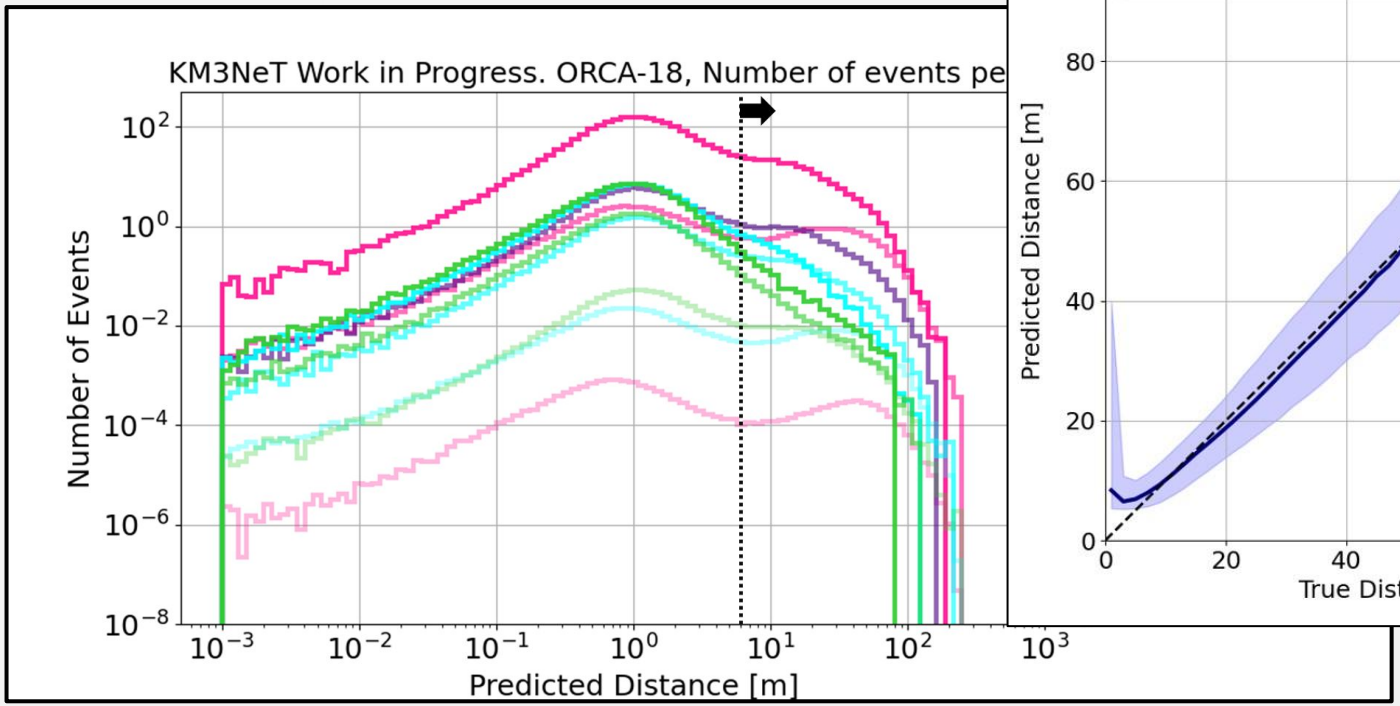
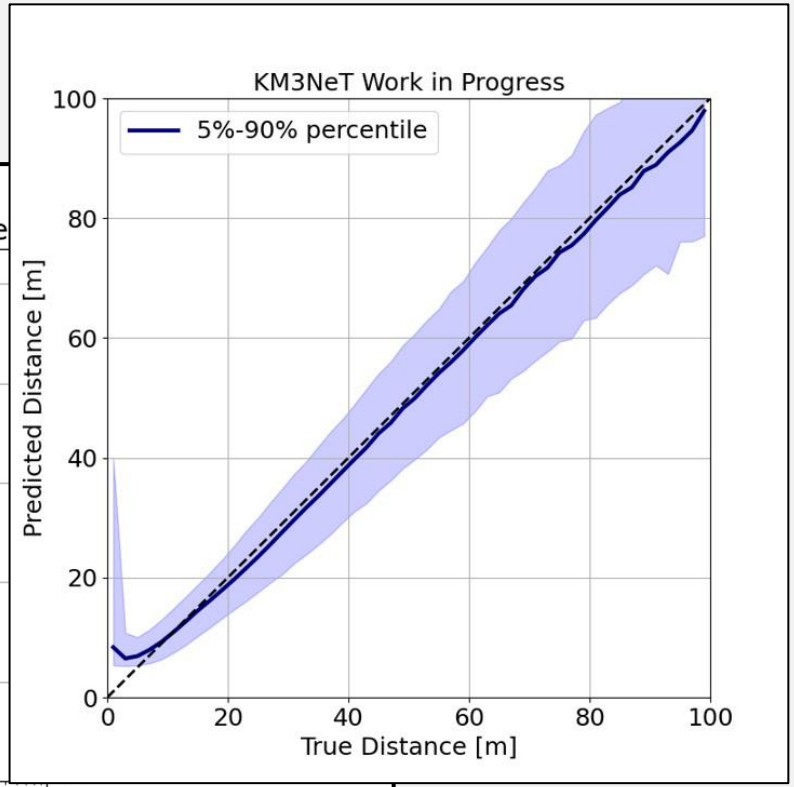
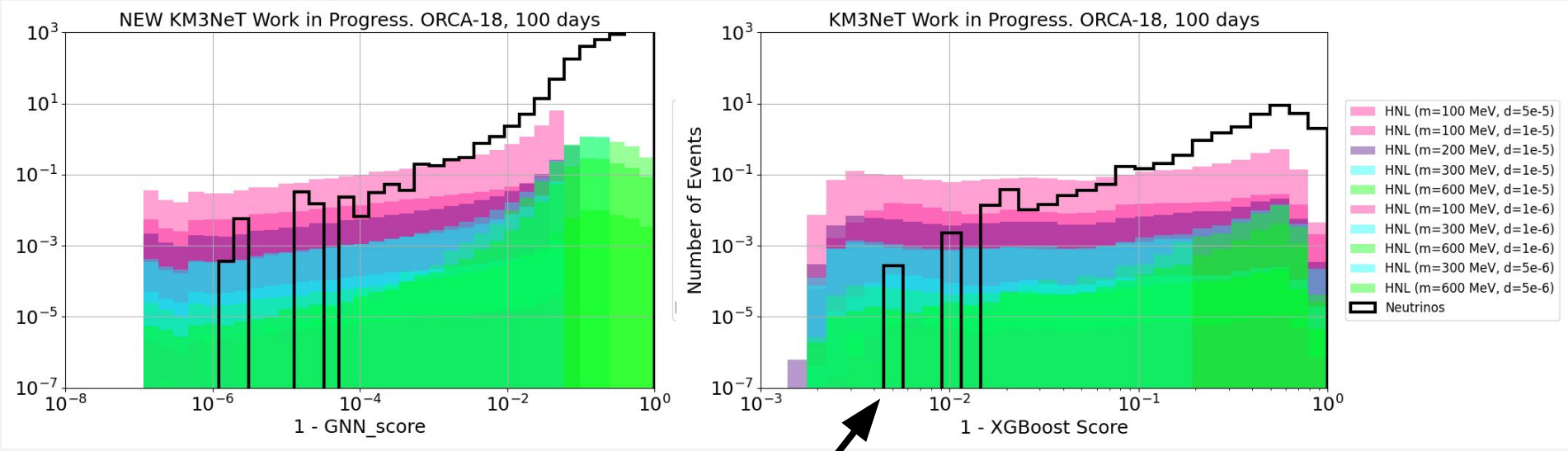




Results - Classifiers

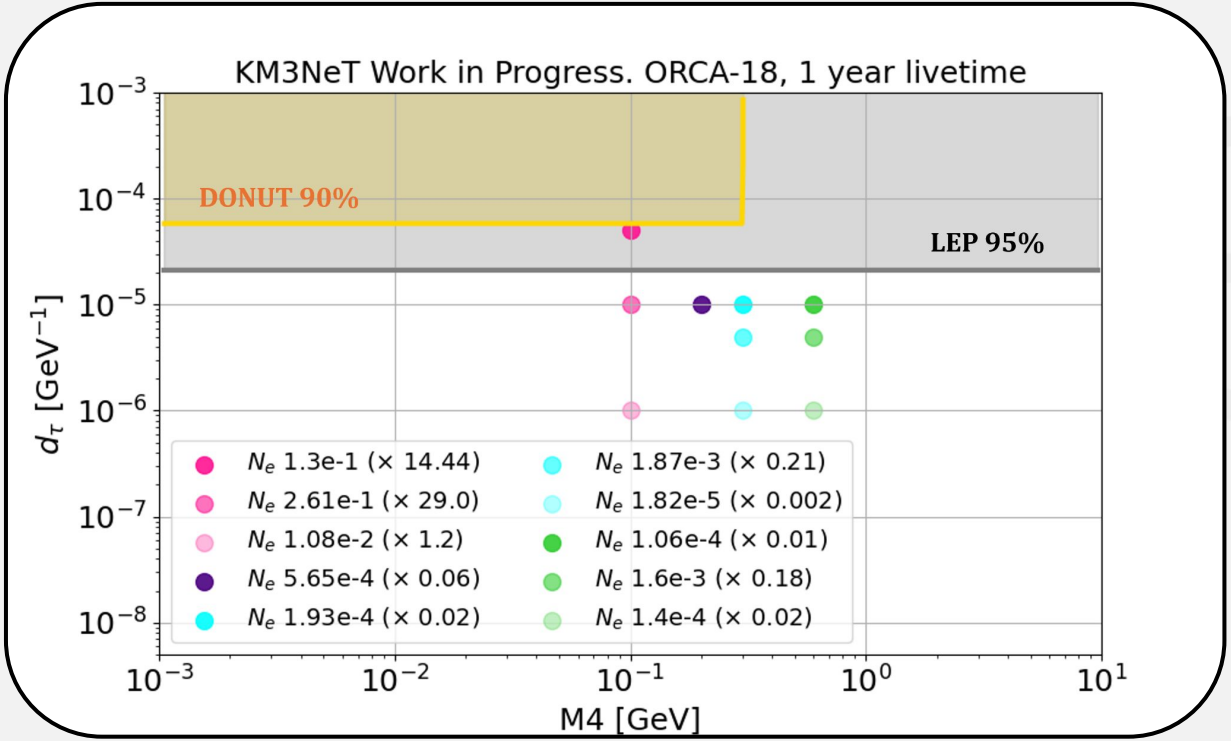
- Train **ParticleNeT** to **classify neutrinos and HNL**. Train a **BDT** to reject the difficult events. Combine the scores of both to reject neutrinos.



After removing events with (d>5m) and (GNN_score>0.8)

Results

Reco. as Upgoing	Distance > 5m	GNN-Score>0.8	BDT-Score>0.993



Already expecting more HNL events for some masses and coupling than background.

Chances not only to set **world leading constraints** but also we have **discovery potential** on some unexplored regions of the parameter space!

Summary and conclusions

- KM3NeT/ORCA seems to be a **very suitable experiment to search for HNL signal.**

- Capability to set **competent limits on the tau coupling through dipole portal model** as other experiments lack a tau beam, or the capability to detect and identify the mediator photon.

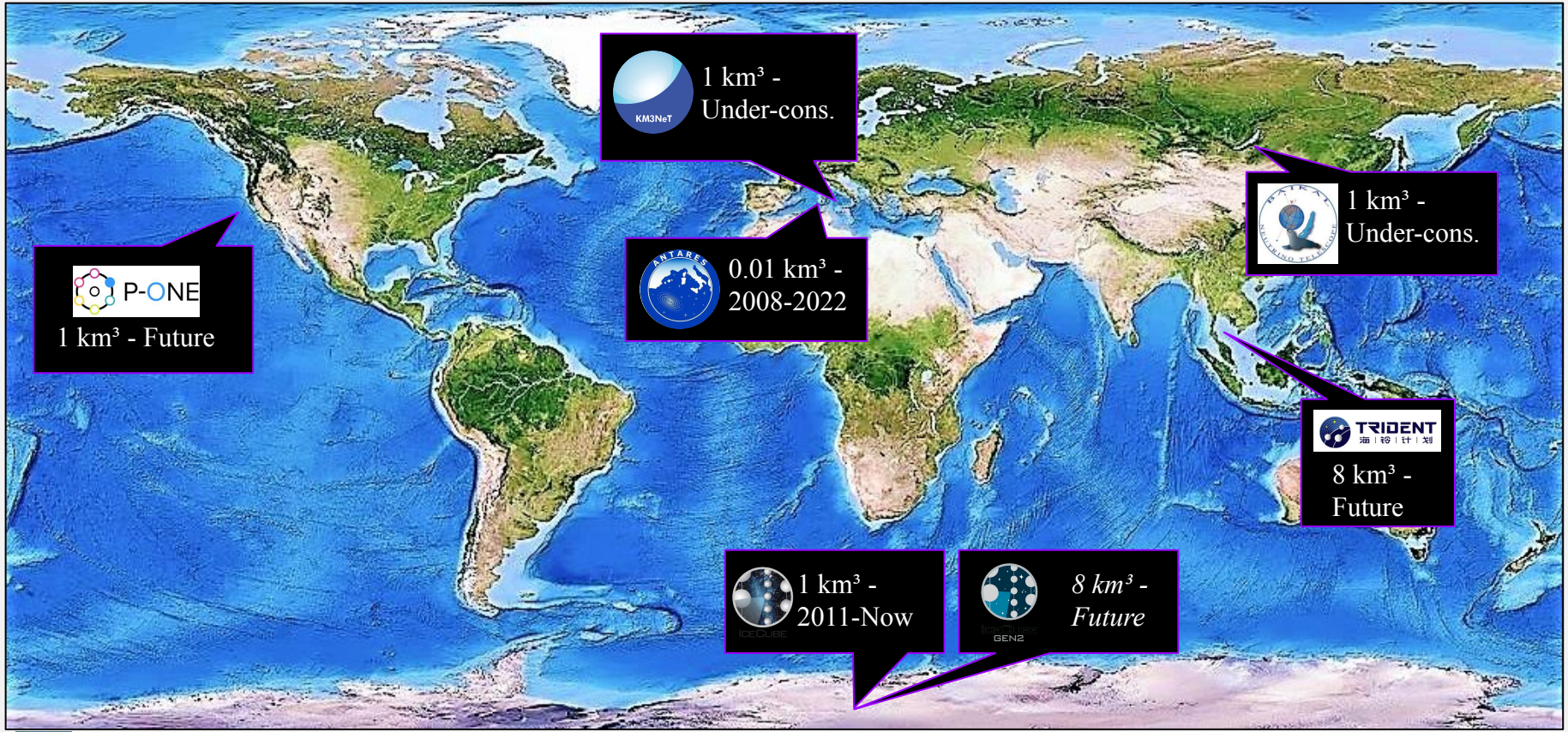
- This study is still work in progress, with further studies covering larger parts of the parameter space to be done.

- Given the nice results, exploring the possibility of searching for other portal or model where to expand this search.

Thank you!

Models trained in:

Neutrino telescopes



Muon sector studies