Heavy Neutral Leptons search with KM3NeT-ORCA

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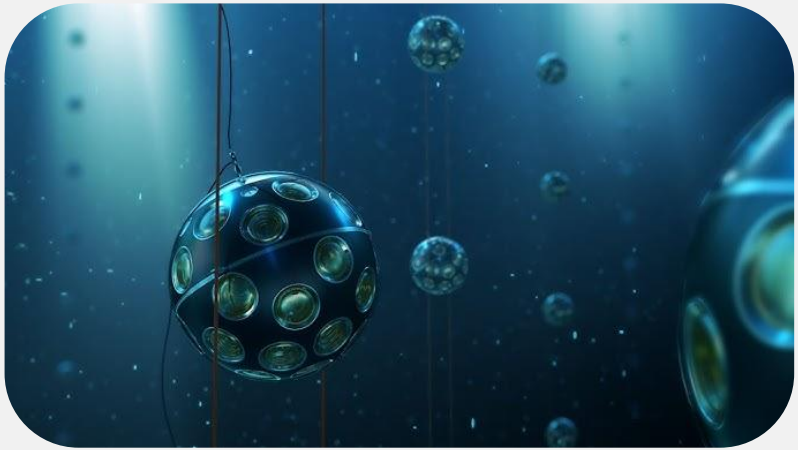
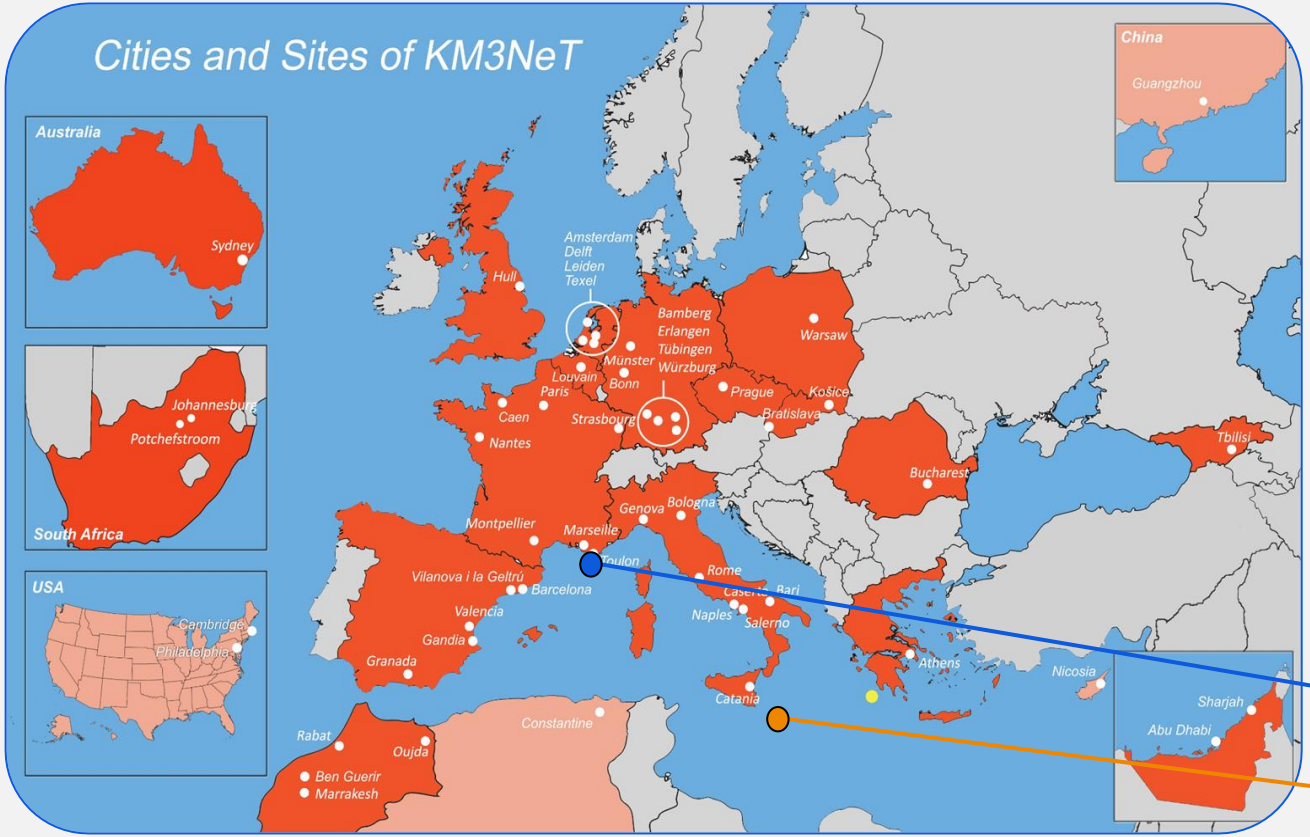
PART I

Neutrino Telescope: KM3NeT



KM3NeT



International collaboration:

- ~250 members
- 65 partner insititutes
- Over 22 countries

Two detectors in two different sites:

- Same technology
- Same data processing
- Shared software and same data formats
- Different size and granularity.

KM3NeT/ORCA

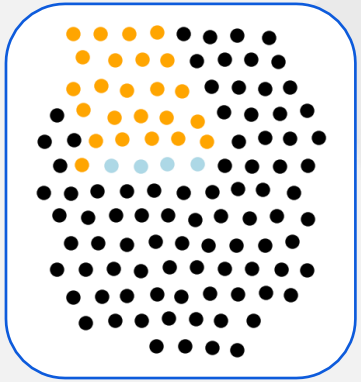
KM3NeT/ARCA

KM3NeT-ARCA and KM3NeT-ORCA

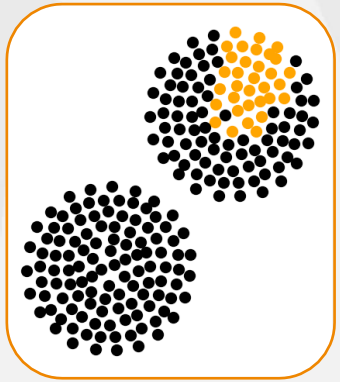
KM3NeT-ORCA:
- Low energy (few to houndreds of GeV)
- Fundamental neutrino properties (mainly).

KM3NeT-ARCA:
- High energy (sub TeV to few PeV)
- Astrophysical studies (mainly).

ORCA has 28 DUs

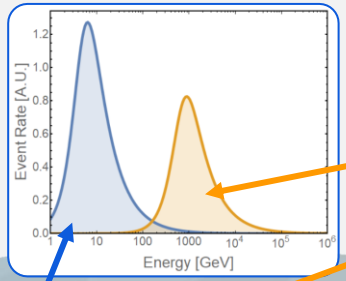


ARCA has 33 DUs



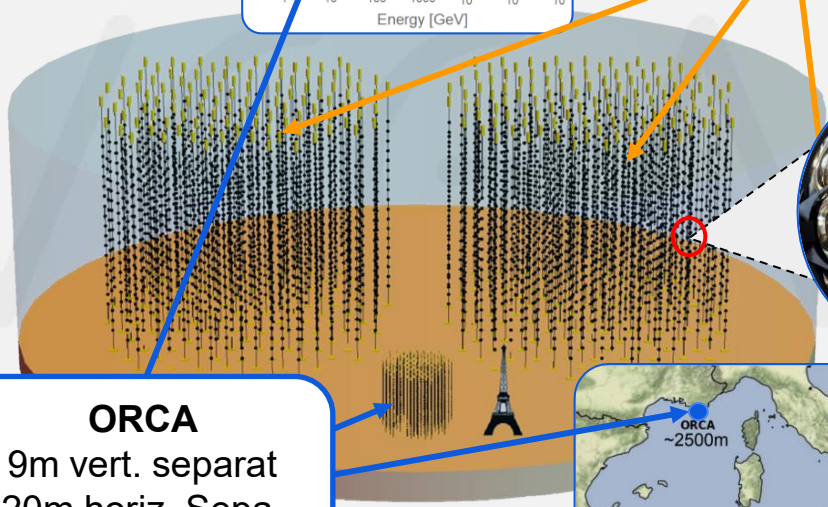
DU: Detection Unit. String of 18 DOMs.

DOM: Digital Optical Module.



ARCA
36m vert. separat
90m horiz. Sepa.
1 Gton detector

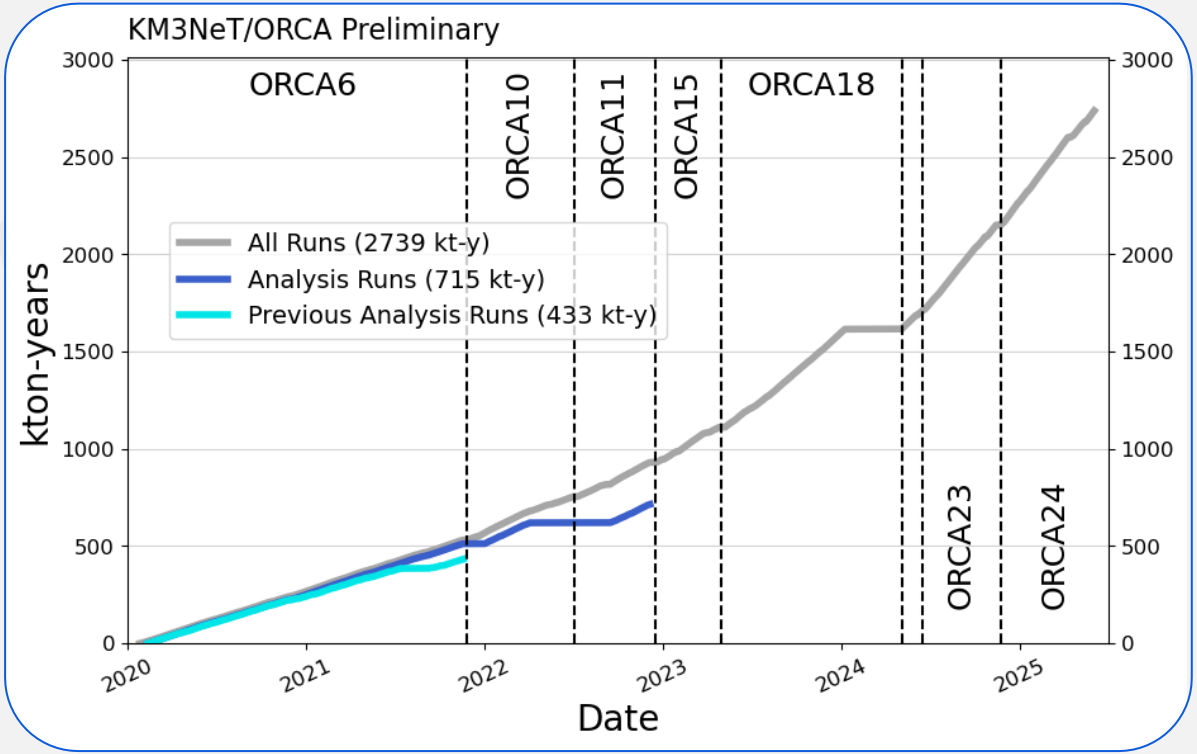
DOM
31x3" PMTs



ORCA
9m vert. separat
20m horiz. Sepa.
7 Mton detector

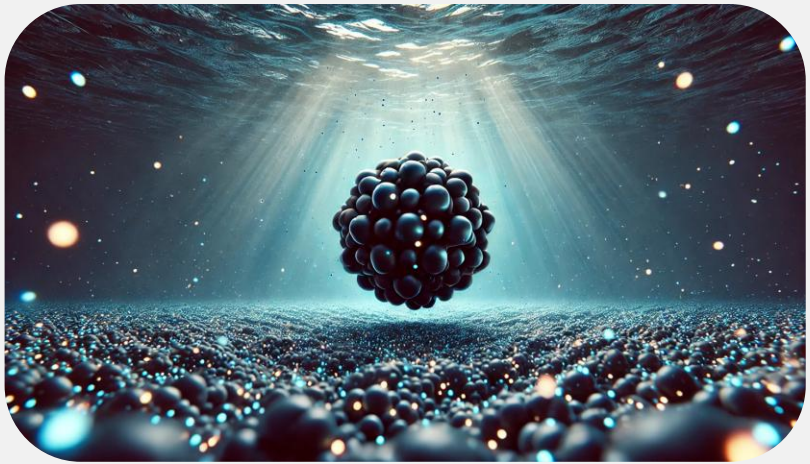
KM3NeT-ORCA

- In this study we will focus on **KM3NeT-ORCA**.
- Already collected **more than 2.7 Mt-y of data**.
- The goal is to study the presence of Heavy Neutral Leptons in ORCA-18.



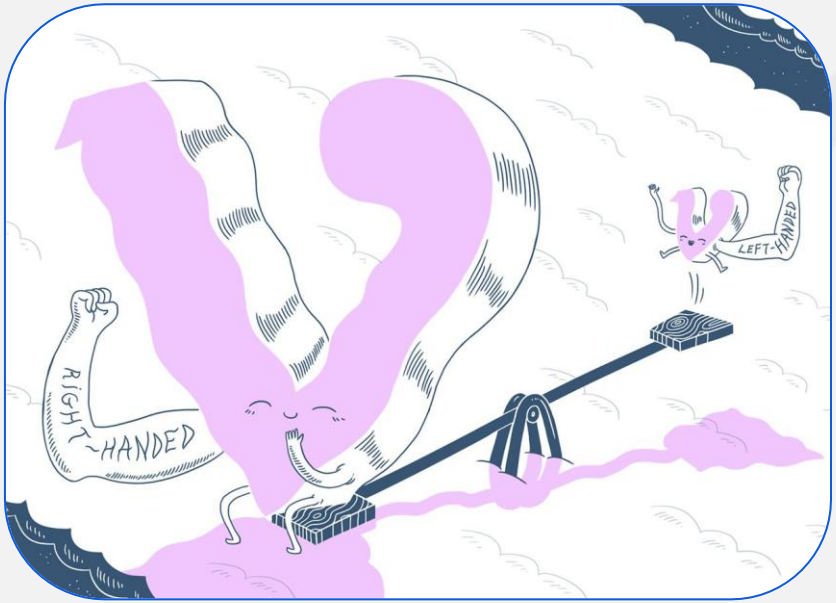
PART II

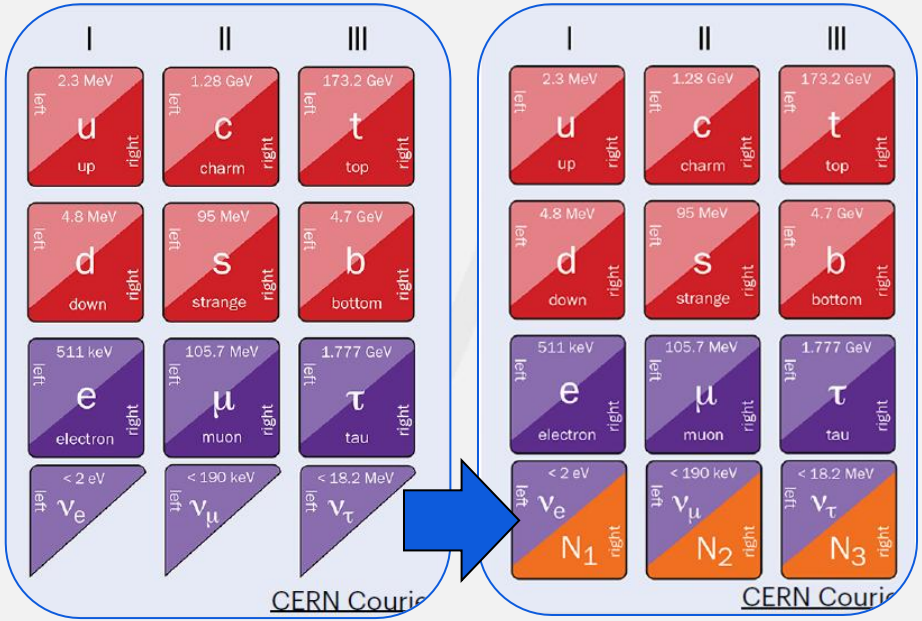
Heavy Neutral Leptons



Physics motivation

- Neutrino oscillations -> Neutrino have masses.
- No right-handed neutrinos in the standard model means no neutrino mass. **Let's add them!**





Heavy Neutral Leptons – A bit of theory

- Heavy Neutral Leptons famously appear in See-saw type-I mechanism to explain the tiny neutrino masses.

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

Diagonalizing mass matrix: $m_{\text{light}} \simeq \frac{m_D^2}{M}$, $m_{heavy} \simeq M$

- Models with M~KeV are good dark matter candidates and models with M~GeV can successfully generate matter-antimatter asymmetry.

HNLs are/have:

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

Portals to Heavy Neutral Leptons

There are many proposed portals between HNLs and SM-neutrinos:

In this study only the **Dipole-Portal model** will be explored

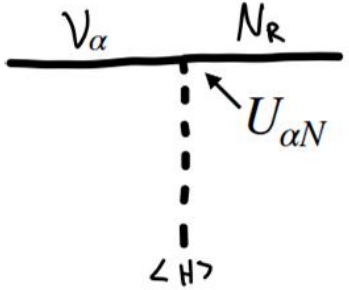
[See N.Kamp+ (2025)]

Mass-Mixed HNLs

Coupling via mass mixing as in Seesaw Type I

Parameters

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

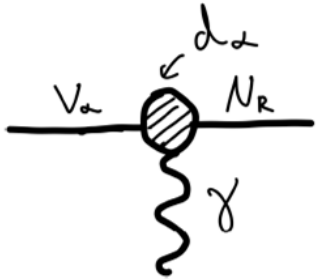


Dipole-Portal HNLs

Coupling via an effective transition magnetic moment

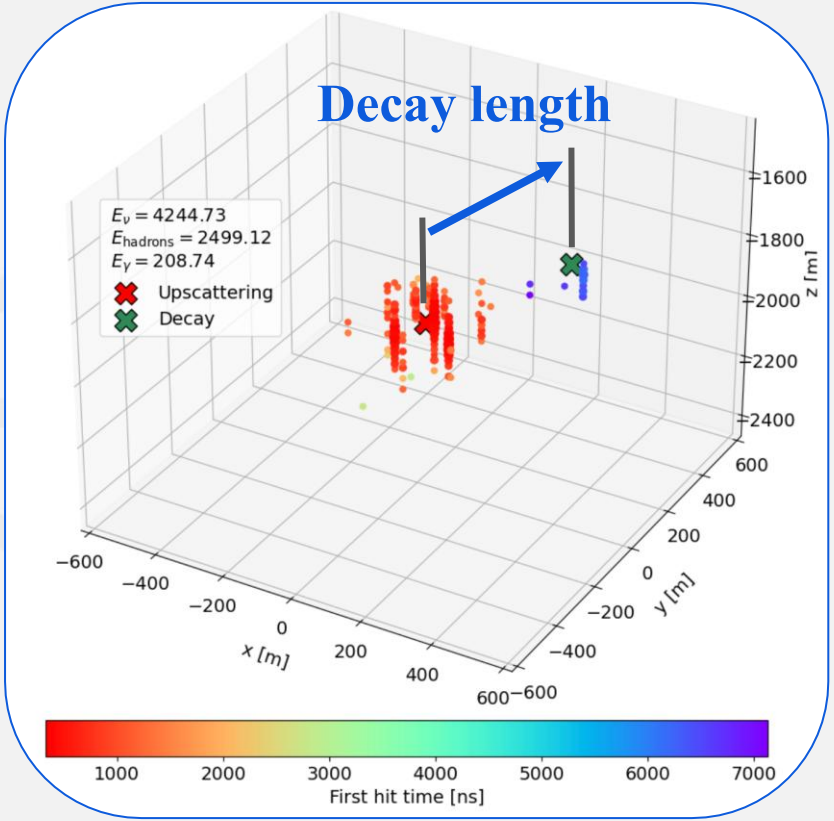
Parameters

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



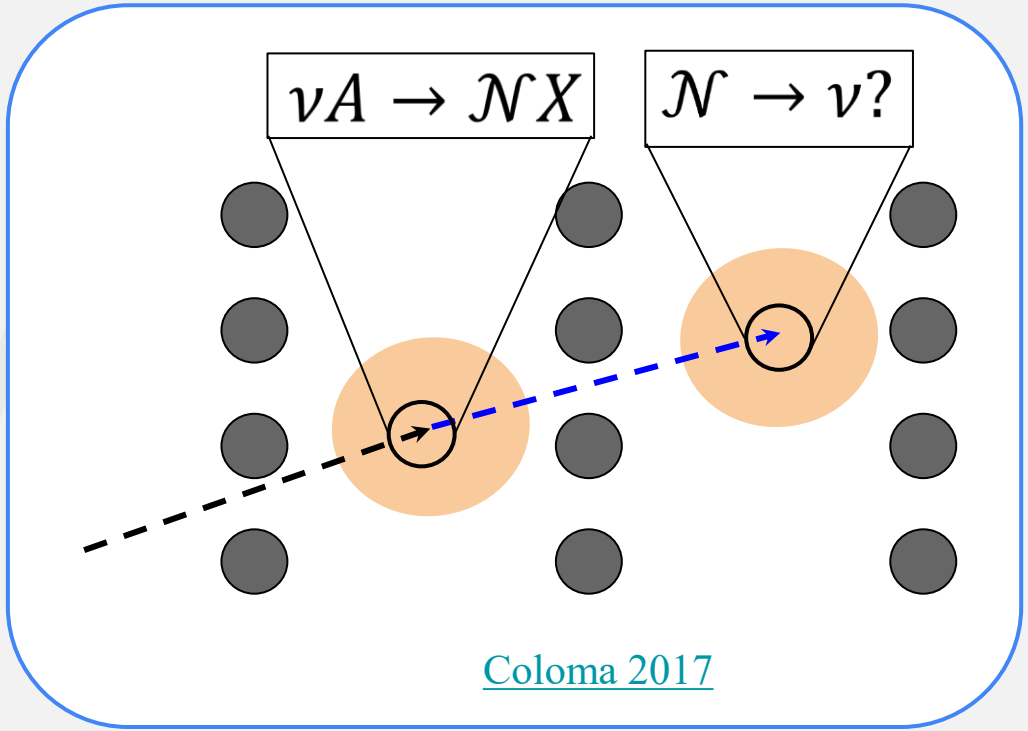
Heavy Neutral Leptons

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



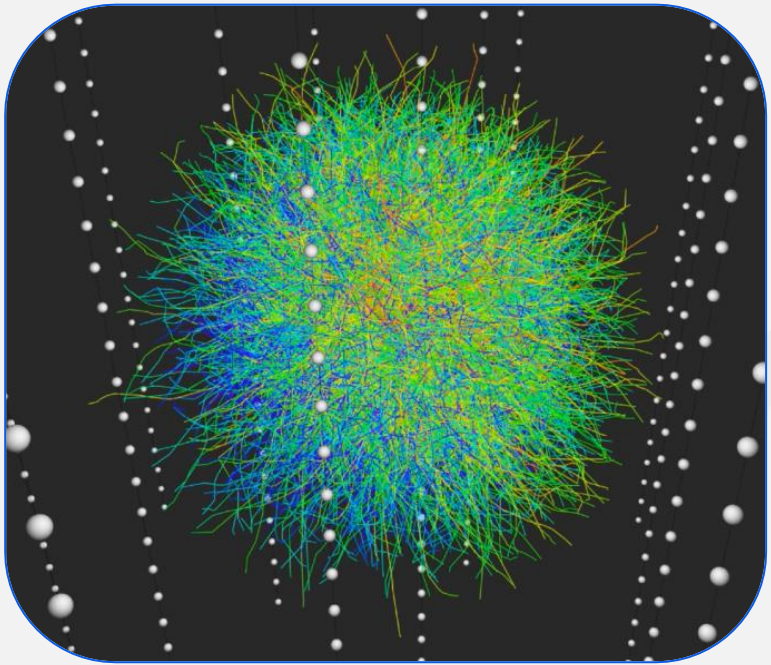
Heavy Neutral Leptons

- 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.

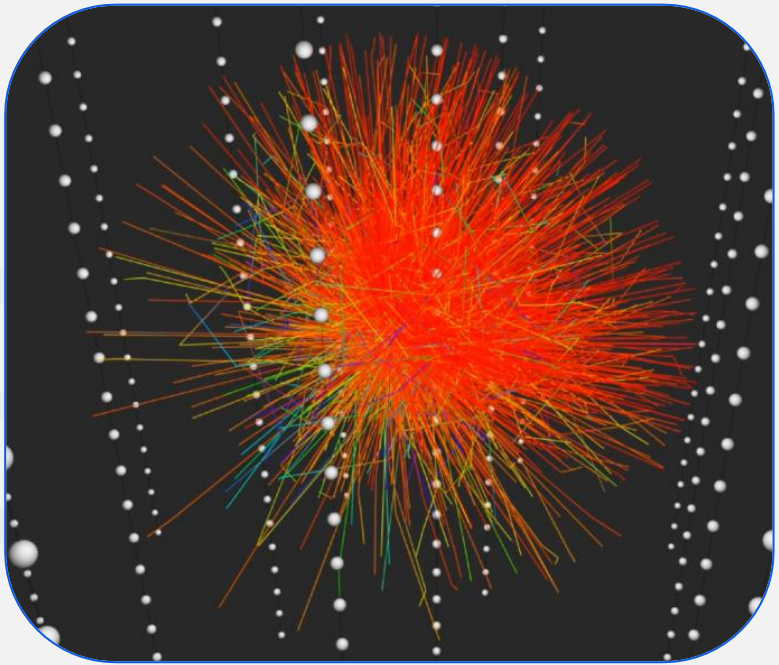


Coloma 2017

Why in KM3NeT-ORCA-18?



10 TeV cascade ice

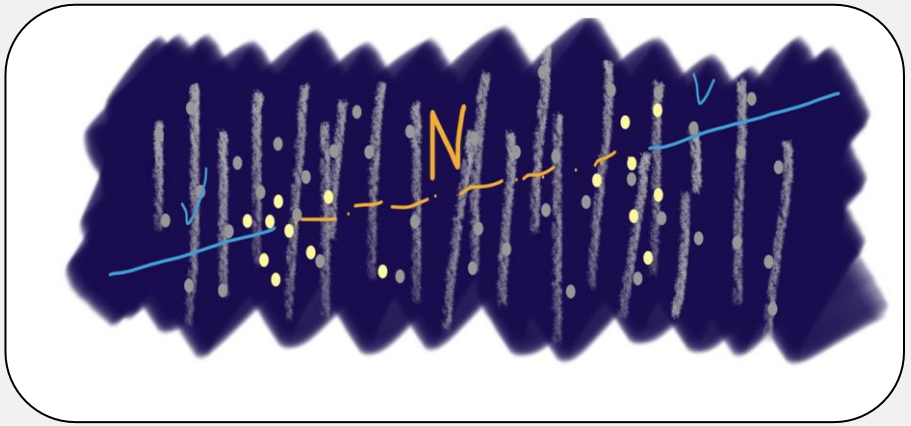


10 TeV in water

Water detectors are expected to have better particle identification capability

PART III

Some preliminary results



Software

- HNL-Events simulated with **SIREN** (Sampling and Injection for Rare EveNts) [GITHUB, 2406.01745]

SIREN: An Open Source Neutrino Injection Toolkit

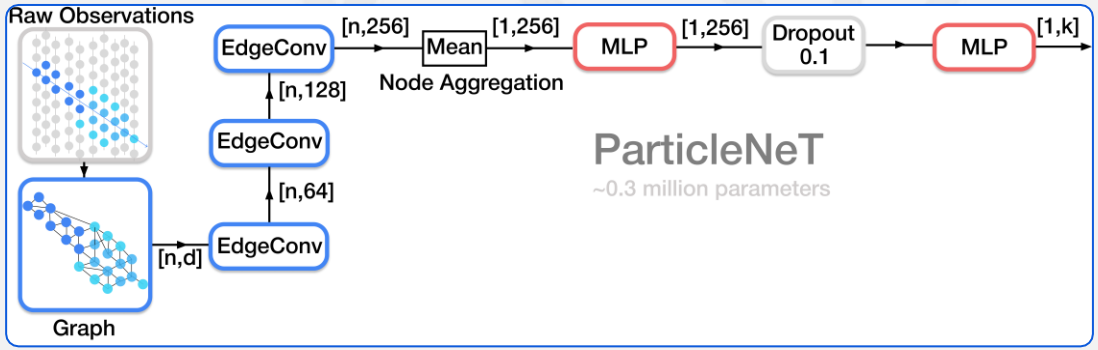
Austin Schneider[a,b,*], Nicholas W. Kamp[c,*] and Alex Y. Wen[c]

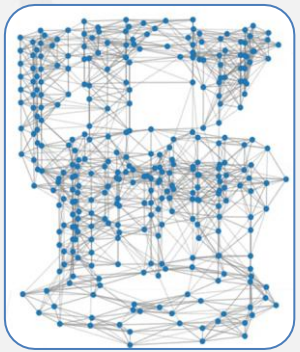
[a]Los Alamos National Laboratory, Los Alamos , NM, United States
[b]Massachusetts Institute of Technology, Cambridge , MA, United States
[c]Department of Physics & Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge 02138, MA, United States



- A slight modification of **ParticleNeT** model (GNN) used to reconstruct this events.

GraphNeT
Deep Learning for Neutrino Telescopes

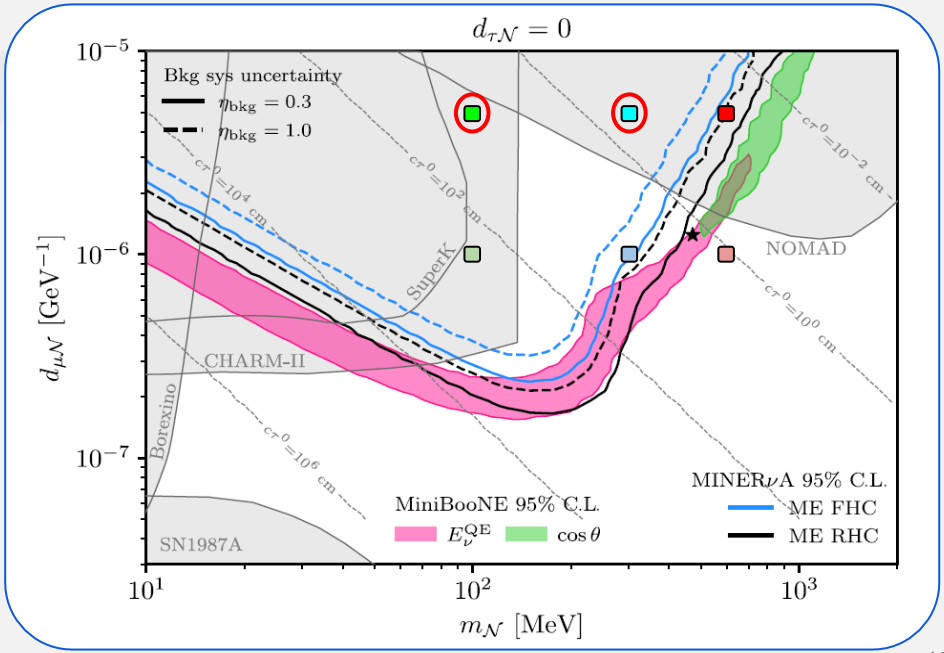




Test

- Test on a SIREN driven simulation on **ORCA-15**.
- Using models with $M_N = 100$, 300 and 600 MeV and $d_{\mu N} = 10^{-6}$, 5×10^{-6}

	Total Events (per year)	Total Events with d>10m (per year)
m=0.1, d=1e-6	0.12	0.11
m=0.1, d=5e-6	35.3	33.7
m=0.3, d=1e-6	2.27	1.82
m=0.3, d=5e-6	80	14.8
m=0.6, d=1e-6	3.0	0.81
m=0.6, d=5e-6	78.5	0.27



Event selection

Steps to get a pure HNL sample.

- **L0 – Cut on variables:** Upgoing events with more than six hits in total.
- **L1 – Antonoise BDT:** Cut on score so that all noise is rejected.
- **L2 – Antimuon BDT:** Cut on score so that all the muons are rejected.
- **L3 - Antineutrino cut:** Cut on the reconstructed distance between vertices and a classifier both predicted by ParticleNeT.

Event selections

The BDTs are quite efficient rejecting muons and noise.

KM3NeT-Work in Progress

KM3NeT-Work in Progress

Event selections

KM3NeT-Work in Progress

KM3NeT-Work in Progress

Event selections

KM3NeT-Work in Progress

In this first study we were capable of **isolating an HNL sample with no** noise, muons or neutrino **contamination**.

Very pure sample with ~XX events per year!

KM3NeT-Work in Progress

Conclusions

- First studies showing **very promising results**, even if the study is very preliminary.

- Already working with the ORCA-18 simulation. Exciting results son!

Thank you!

Models trained in: