Neutrino Astronomy and the KM3NeT Experiment: An Introduction

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Overview

- Neutrino Fundamentals
- Neutrino Astronomy
- Neutrino Detectors
- Introduction to the KM3NeT Experiment
- Data Analysis with KM3NeT ARCA
- Future Goals for KM3NeT ARCA

Neutrinos – The elusive ones

- ‘The neutral little ones’, predicted in 1930 by Pauli, first detected only in 1956
- Open up the farthest reaches of the Universe, as well as the deeply shrouded interiors of stars, for investigation
- Yet to be fully understood themselves
- Require very demanding detection techniques
- A very important instrument, in the present era of multi-messenger astronomy

Neutrinos – Quick Overview

- Fundamental Properties:

1. $Q_{EM} = 0$ (neutral)
2. Non-zero mass
3. Weakly interacting (charged & neutral current)
4. Leptons, 3 known flavors (ν_e, ν_μ, ν_τ)
5. Flavor Oscillation
6. Only left-handed observed

Neutrino Oscillations

- The PMNS Matrix – Relates the flavor and mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Can be parametrized - 3 mixing angles (θ_{ij}) and the phase angle δ

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$
$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{bmatrix}.$$

$c_{ij} = \cos_{ij}\theta$
$s_{ij} = \sin_{ij}\theta$

Neutrino Physics - State of the Art

- Open Questions:
  1. Precise measurement of mixing angles
  2. Measuring the CP-violation phase (δ)
  3. Determining neutrino mass hierarchy (normal or inverted)
  4. Determining absolute neutrino masses
  5. Majorana or Dirac??
  6. Sterile neutrinos??

- Other than that, large detectors are exploring the Universe using astrophysical neutrinos

Neutrino Astronomy: Sources

Many astronomical sources believed to be neutrino emitters

Possible sources include galactic (stars, SNRs, galactic centre, diffuse emission), extragalactic (AGNs, GRBs, SN etc.) and cosmological (CNB)

Only two confirmed so far – Sun and a Supernova (1987A)

Apart from the CNB ν-flux, rest of the sources emit neutrinos at higher energies

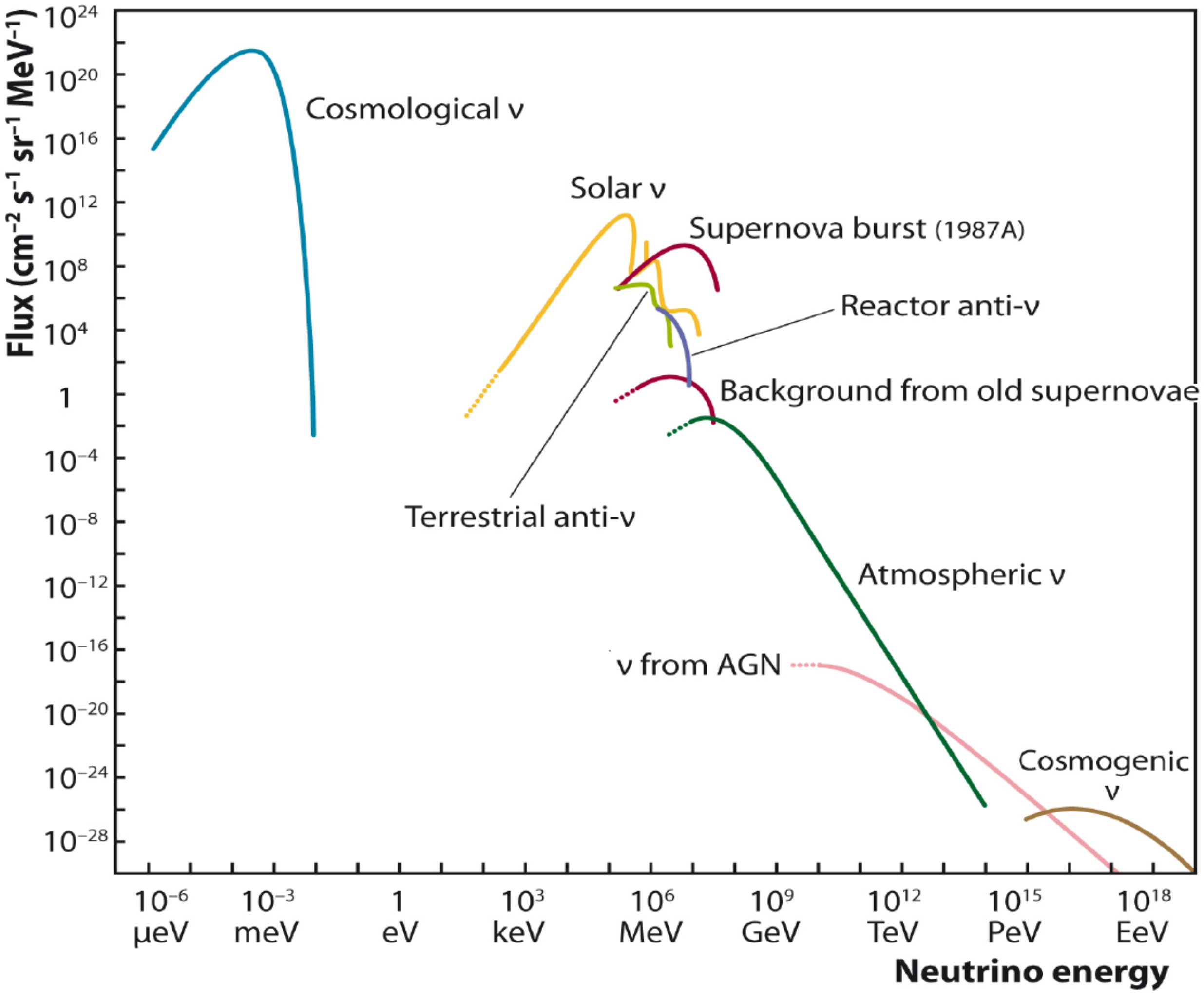


Fig. 1: The neutrino energy spectrum

Neutrino Astronomy - Background

- Major background – Atmospheric neutrinos
- For sea-based experiments: K40 decays, bioluminescence
- For purified water-based experiments: Water impurities
- The overlapping neutrino spectrum means that the signal for one experiment can be the background for another

Detectors for Neutrinos

- Scintillators
- Radio-chemical
- Tracking Calorimeters
- Cherenkov

Scintillators

These detectors consist mostly of a liquid scintillator surrounded by PMTs

Preferably investigate the inverse beta decay channel

Examples include the Cowan-Reines (1956), KamLAND and Borexino experiments

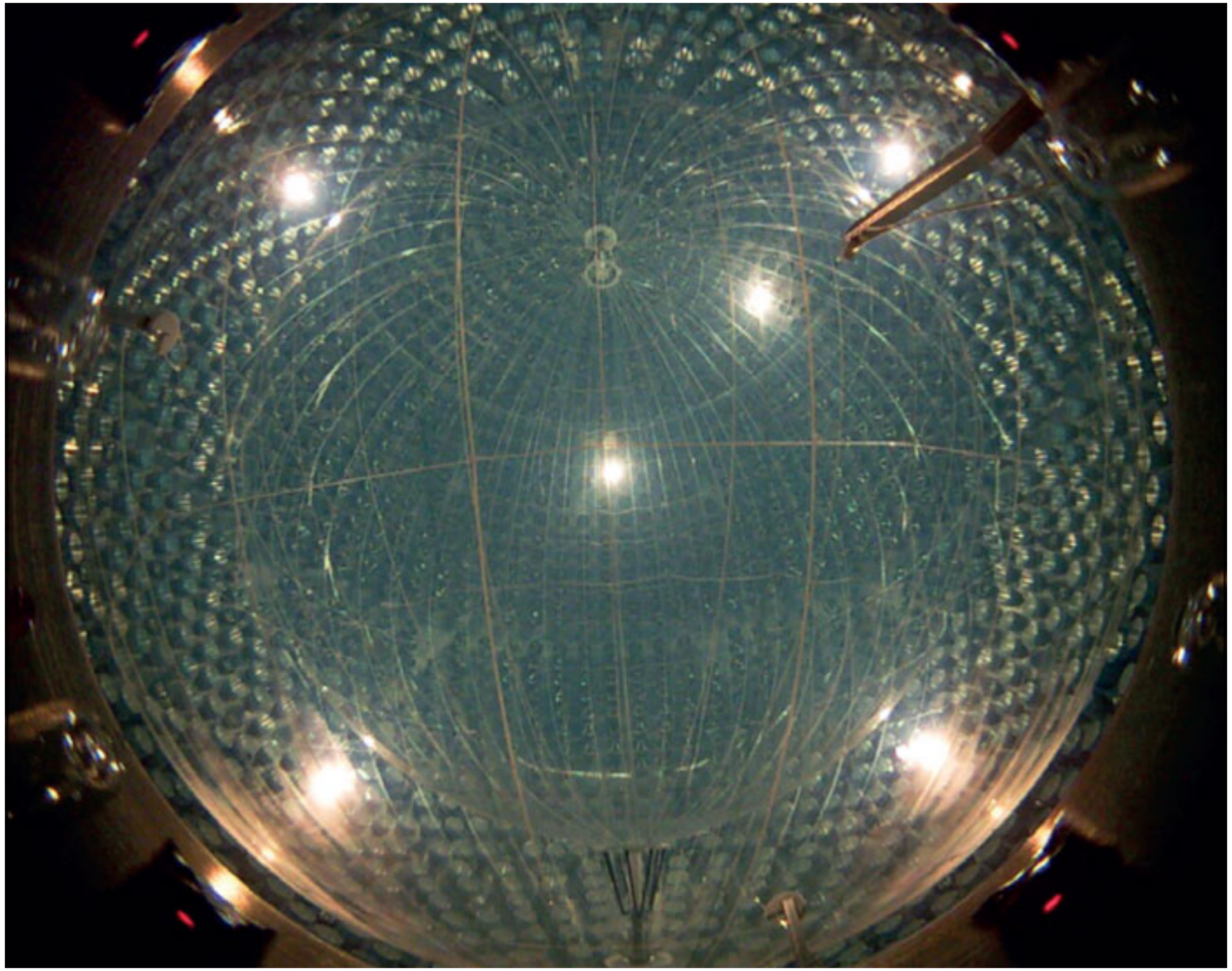


Fig. 2: The Borexino Detector

Radio Chemical Detection

- Involves the conversion of a nucleus to a radioactive isotope upon interaction with a neutrino
- Isotope chemically removed from solution and the conversion rate determined through the radioactive decay of the isotope
- Preferred targets are Chlorine and Gallium
- Examples of experiments include Homestake Mine, GALLEX, SAGE

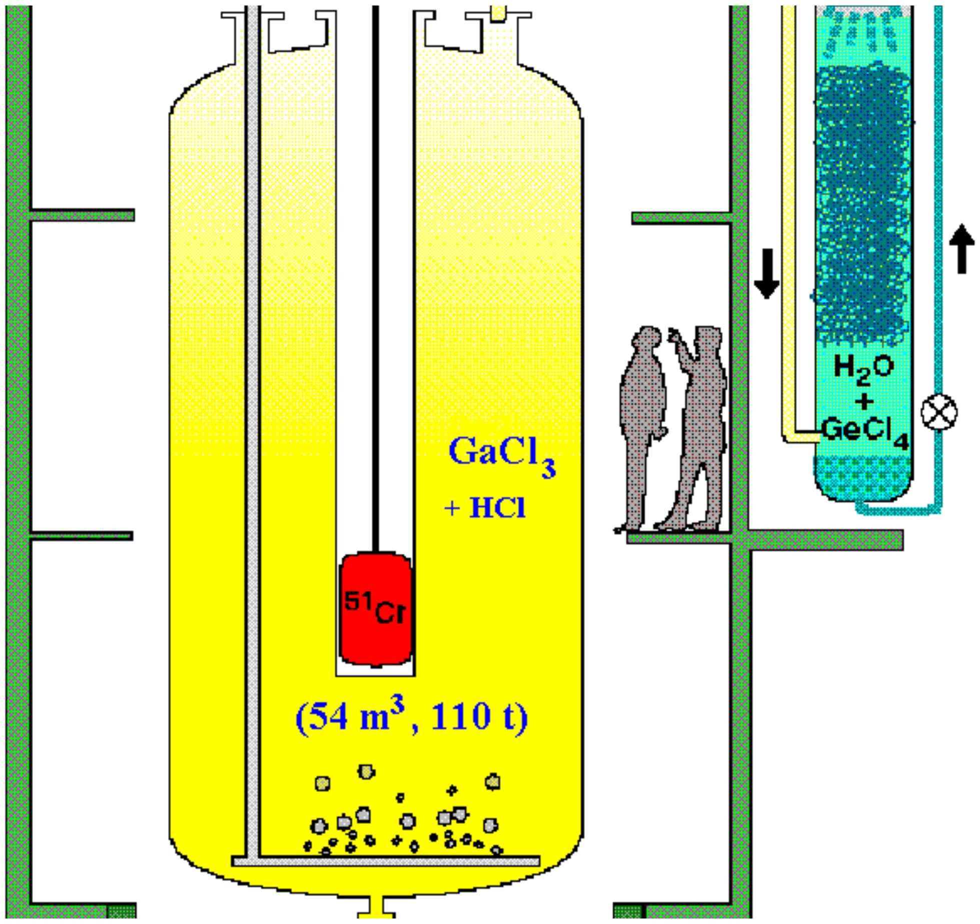


Fig. 3: The GALLEX Detector tank

Tracking Calorimeters

Use large volume active calorimetric detectors or absorber and detector materials in conjunction for detection and tracking

Sensitive to higher energies and essentially both neutral and charged current interactions

Examples include the MINOS and NOvA experiments

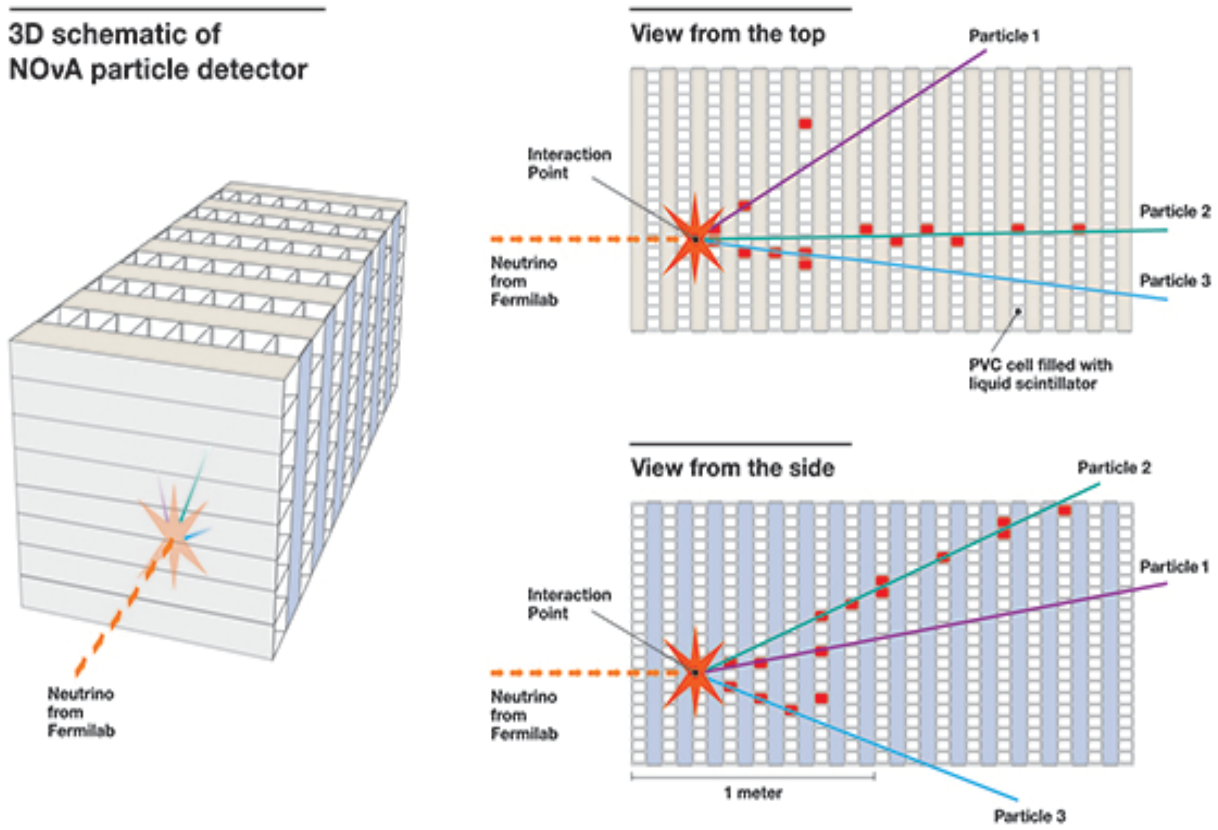


Fig. 4: Schematic of the NOvA Detector

Cherenkov Detectors

- Use a transparent medium (water, ice) as the reaction mass and a vast array of PMTs for detection
- High-energy neutrinos react in the medium to produce their partner lepton, travelling faster than light in the medium
- The resultant Cherenkov radiation is detected by the sensitive PMTs, and a larger volume allows for reconstructing the track
- Examples include Kamiokande, IceCube, ANTARES

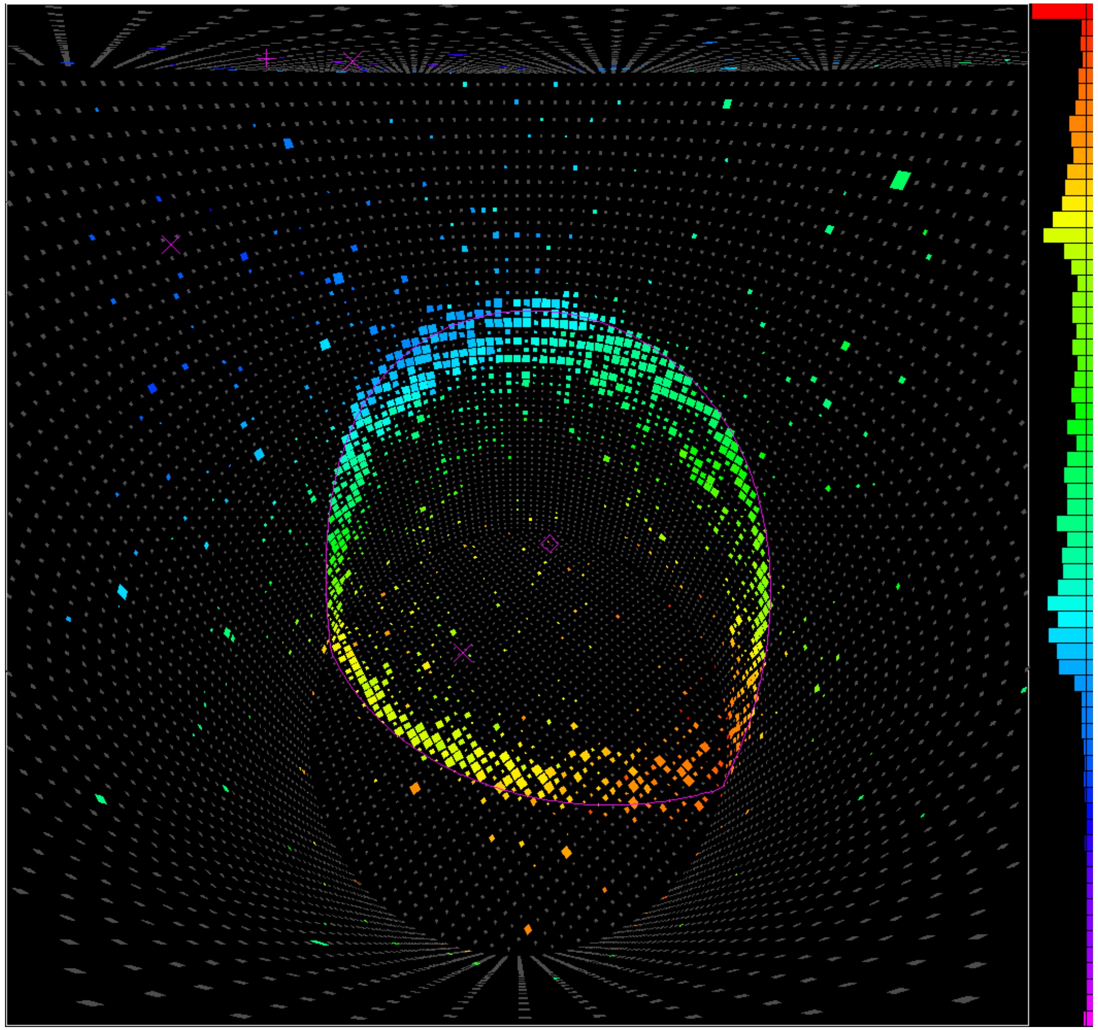


Fig. 5: A muon event in the Super-K detector

The KM3NeT Experiment

- Next-gen Cherenkov neutrino telescope, to be built in Mediterranean Sea
- Multiple detector blocks, to be located off the coast of France (KM3NeT-Fr), Italy (KM3NeT-It) and Greece (KM3NeT-Gr)
- Objectives:
  - Astroparticle Research with ARCA
  - ν-oscillations and particle physics with ORCA
  - Marine Biology research, Oceanography and Geophysics
- Together with IceCube, will form a global neutrino observatory

KM3NeT Detector

- Digital Optical Modules (DOMs) as the basic detector block
- Each DOM consisting of 31, 3-inch PMTs, looking at all directions
- Sensitive to all three flavors
- Energy sensitivity: Ev > 0.1 GeV
- Angular Resolution: upto 0.1^o
- Depth in Sea: 2.5 – 3 km
- Total detector volume upon completion: ~ 5 km3
- ARCA: Astroparticle Research with Cosmics in the Abyss
- ORCA: Oscillation Research with Cosmics in the Abyss

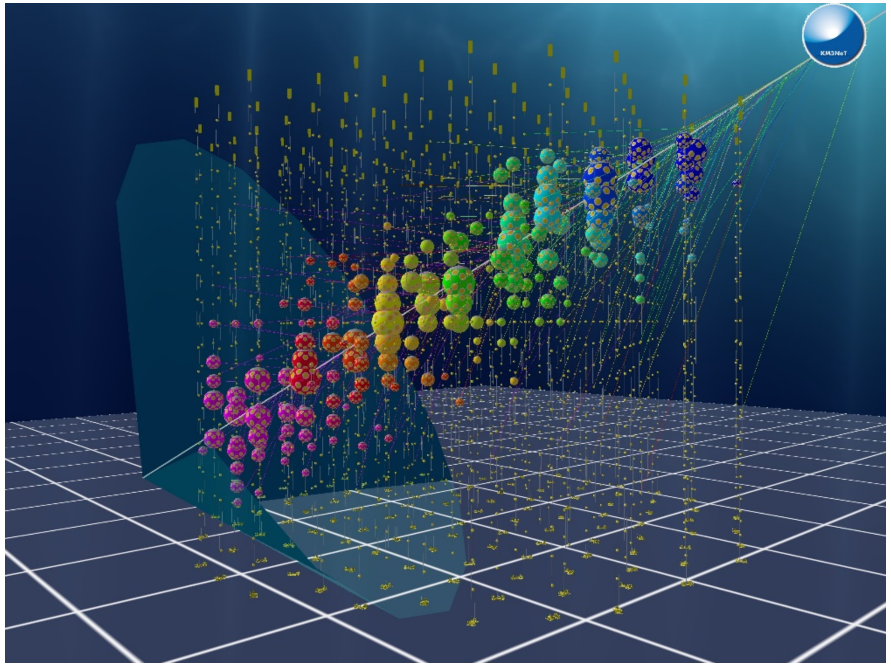


Fig. 6: Simulated event in the KM3NeT detector

Fig. 7: A DOM in KM3NeT

Present Status

- KM3NeT-It :
  - ARCA operational in 2-string configuration since 2016
  - Detector currently not taking data due to faulty junction box
  - More strings to be deployed by the end of the year

- KM3NeT-Fr: ORCA will see its first 2 strings deployed within the week

- KM3NeT-Gr: A 8-DOM test configuration with 13” PMTs took data for 18 months before being removed from the sea earlier this year

KM3NeT ARCA – Data Analysis

- Data from the two strings available for analysis.
- Physics runs usually of 6 hours duration each.
- Official MC also available for a part of the data.
- Suitable triggers available; L1 data majorly used for analyses

L1 hit $\longrightarrow$ Min. two hits within t < 25 ns

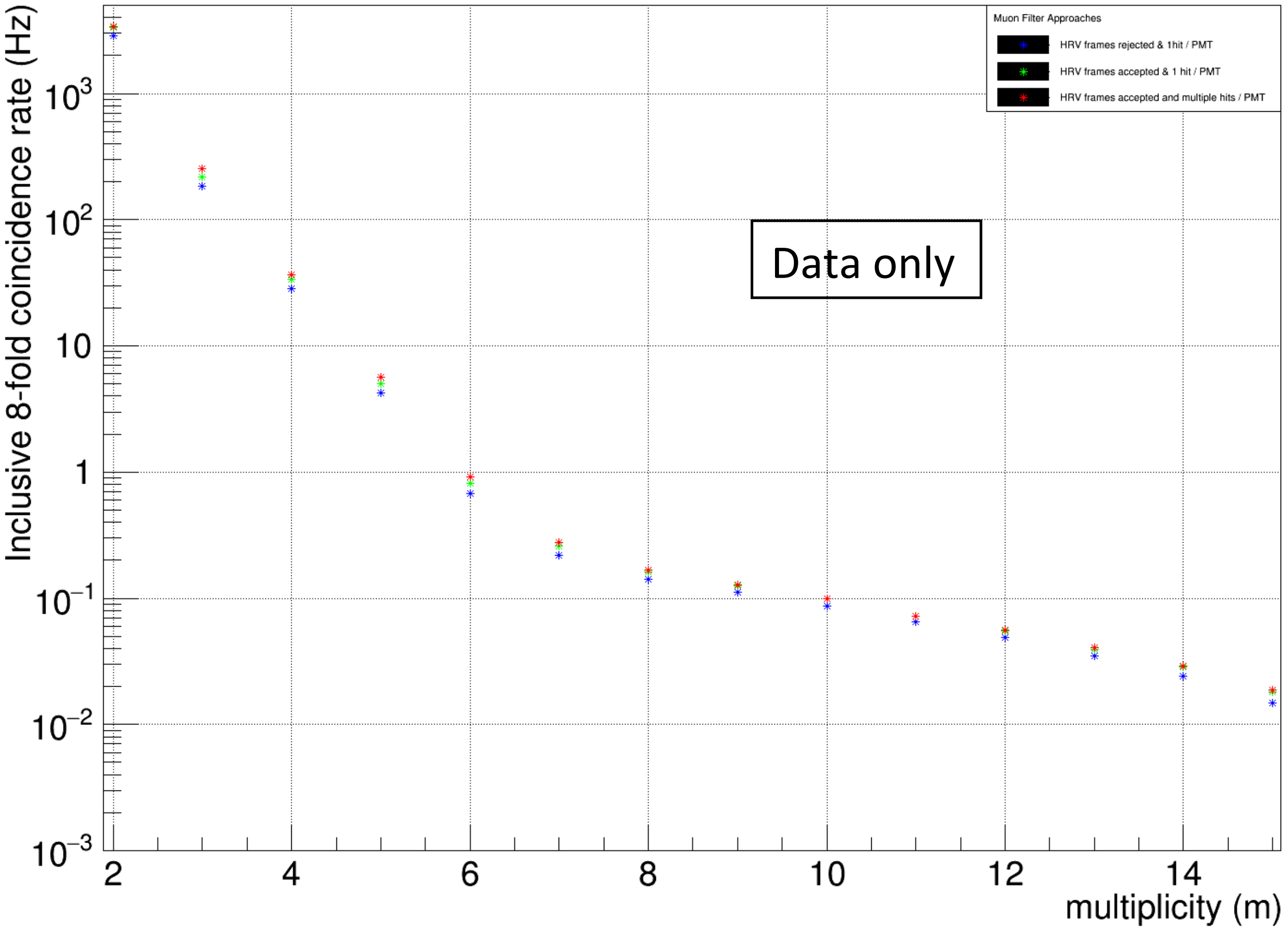
- Data validation activity ongoing
- Some official plots available after preliminary investigations

KM3NeT ARCA – PMT & DOM Rates

- Rates of the DOMs calculated for atmospheric muons using various filter strategies
- MC statistics worth ~ 10 days of data
- Multiplicity defined as the number of hits in an L1 time window
- At the 8-fold coincidence level and beyond, muon MC and data can be safely assumed to be in agreement, signalling a threshold for filtering atmospheric muons

DOM Rates – Various strategies

Fig. 8: Inclusive m-fold DOM rate vs. multiplicity (S1F1)



ARCA – Data vs. MC

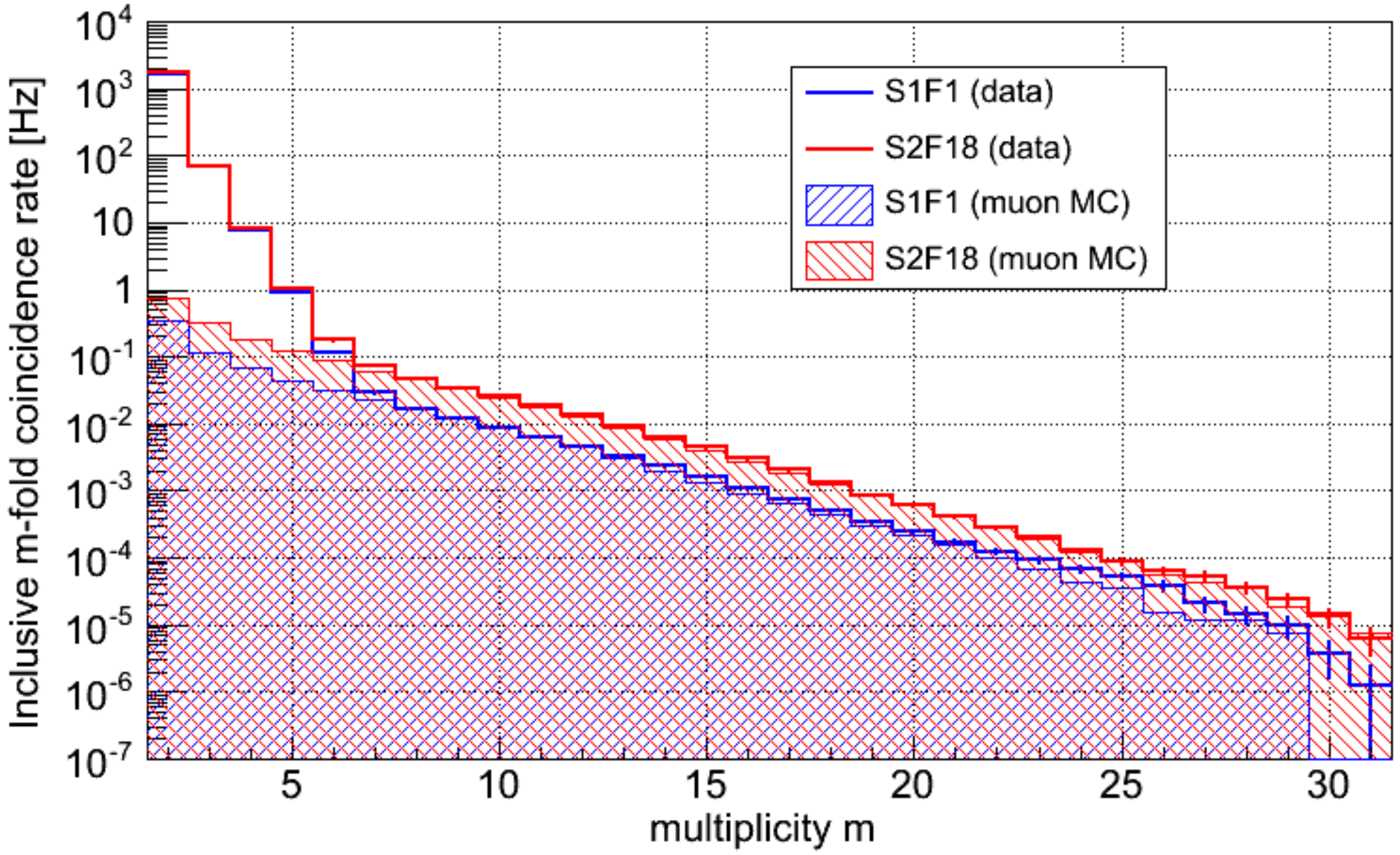


Fig. 9: Inclusive m-fold coincidence rate vs. multiplicity for DOM S1F1 and S2F18

ARCA – Depth Dependence Analysis

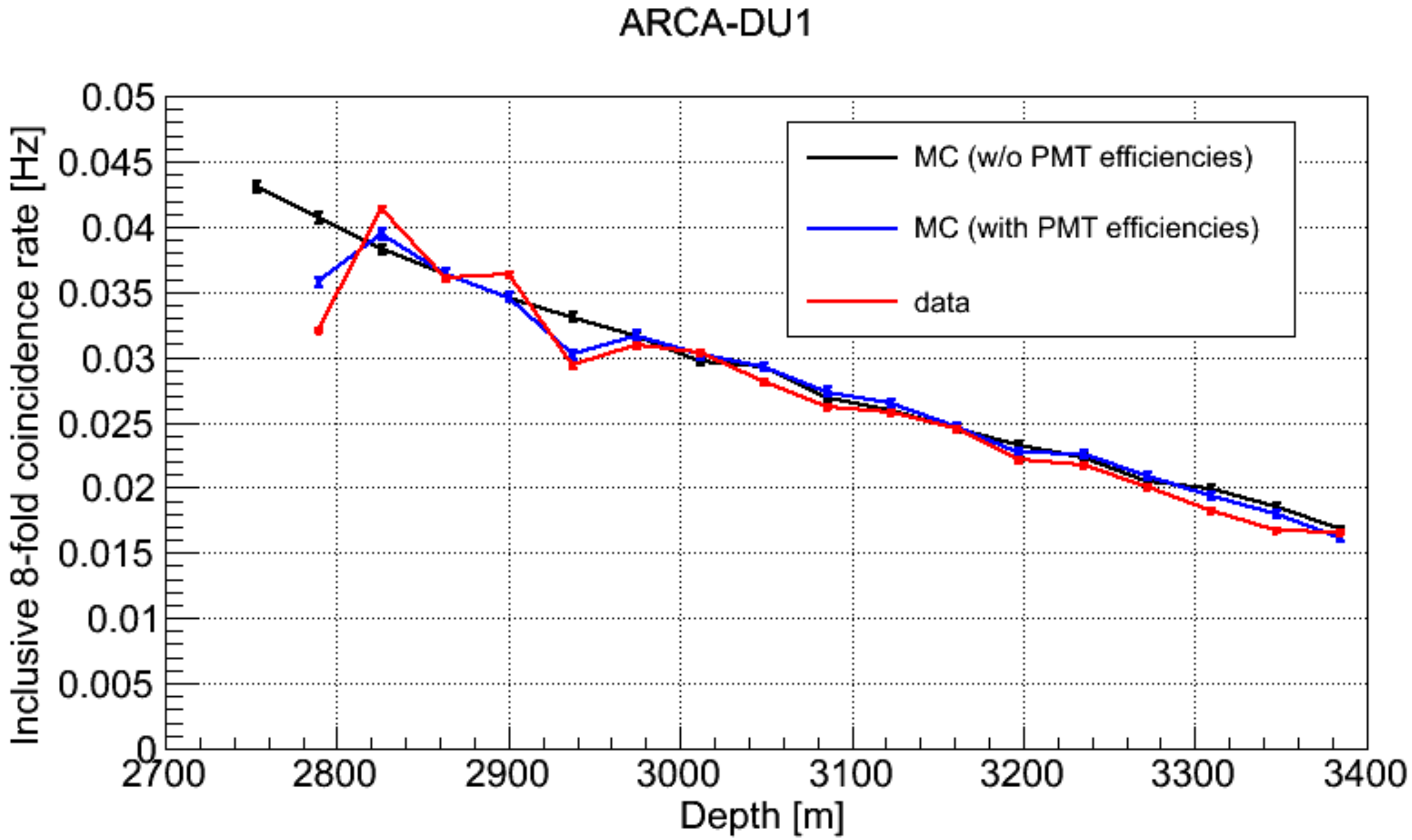
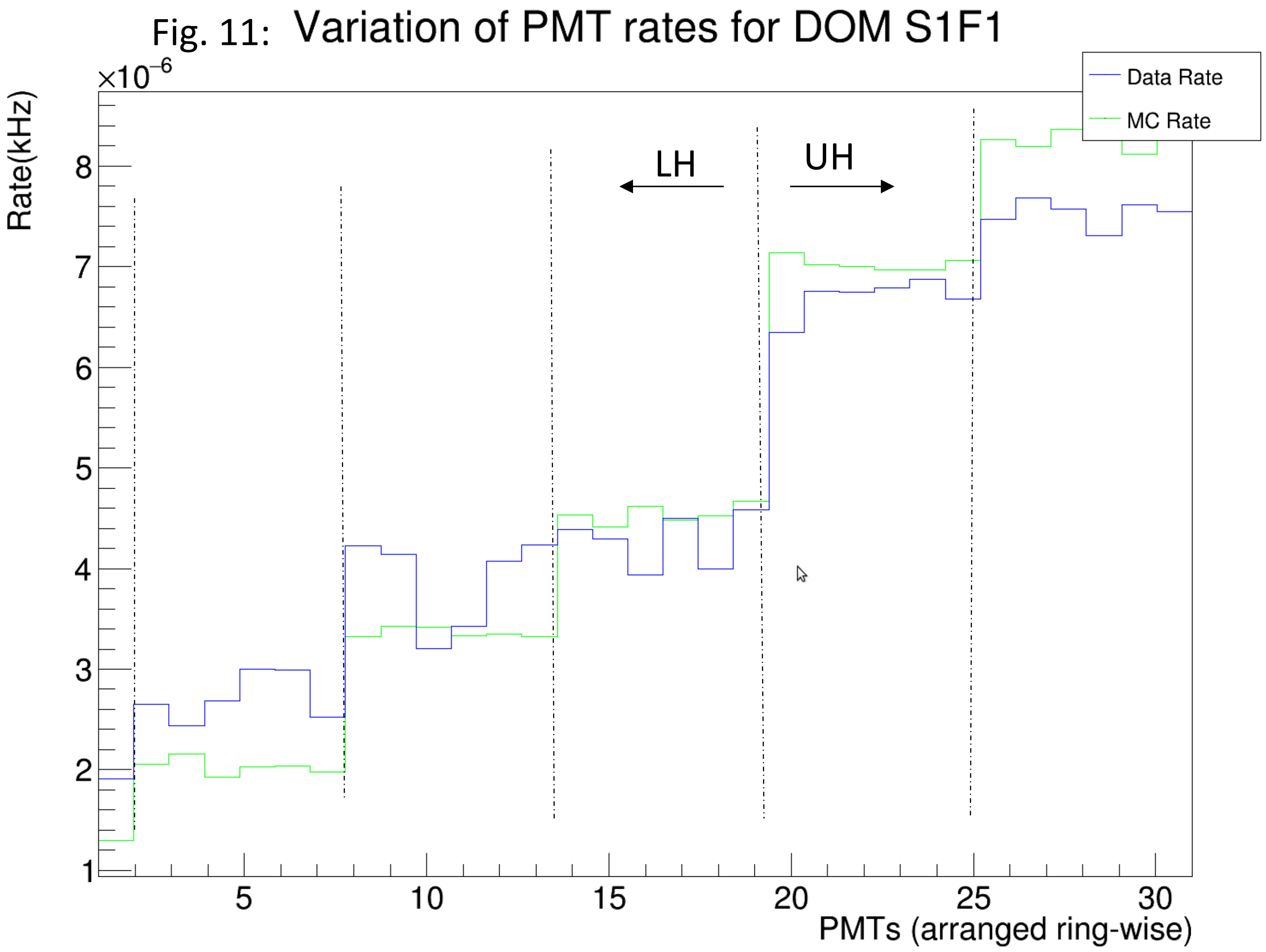


Fig. 10: Depth dependence of muon rates for 8-fold multiplicity in ARCA-DU1

ARCA: PMTs in a ring (8-fold)



ToT Analysis

- ToT (Time over Threshold) is a measure of the charge deposited in the PMT
- Can be used to deduce the energy of the incident photon
- A threshold value of 0.3 p.e. used in KM3NeT ARCA
- ToT for the first p.e. peaks at around 26 ns
- A tail is seen in the ToT signal for PMTs; not yet understood if due to the 2nd p.e. strike

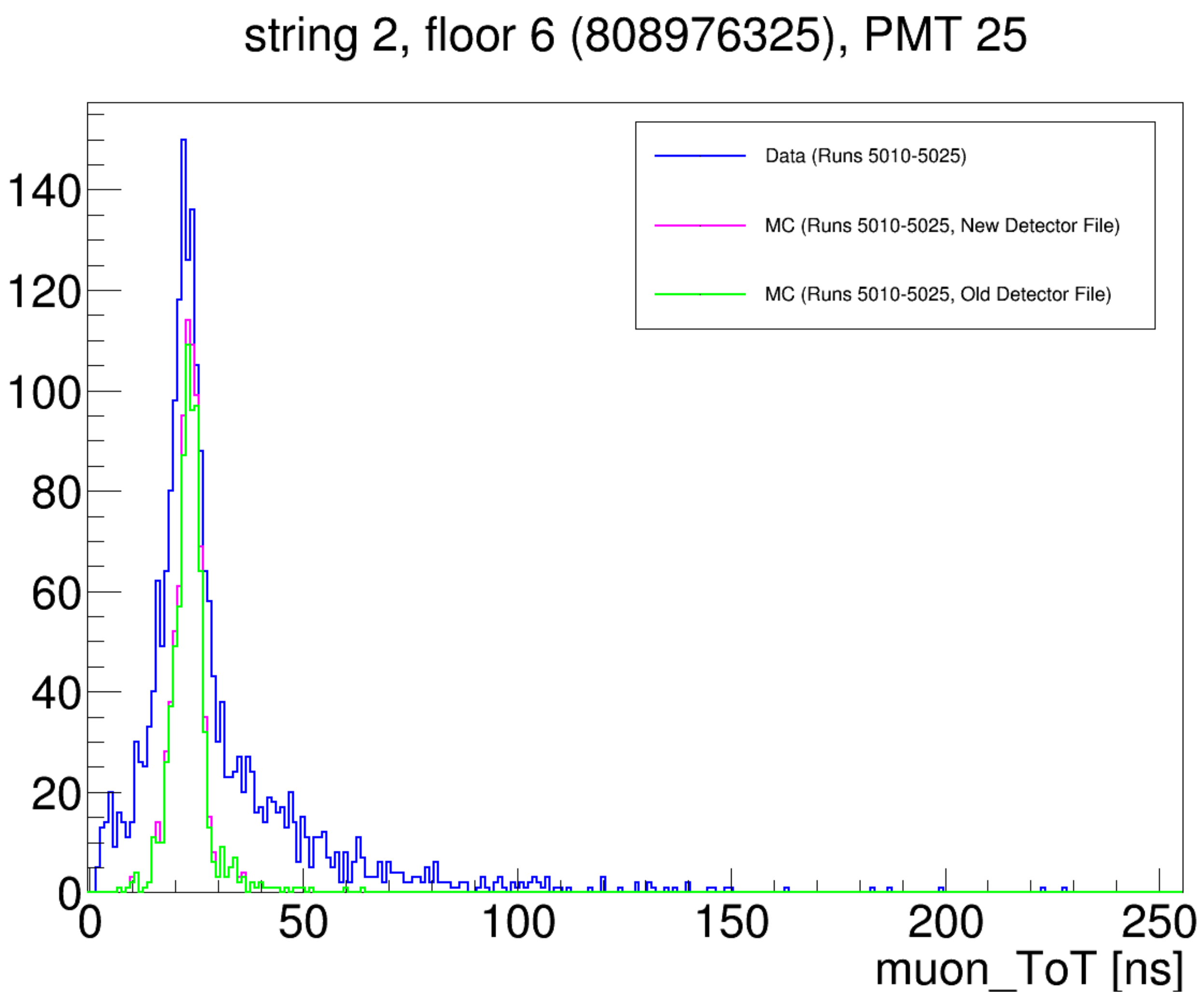


Fig. 12: Data and MC ToT signal for S2F6, PMT 25

Future Goals with KM3NeT ARCA

- Many calibration and data validation studies ongoing
- The completed detector, along with IceCube, can cover the whole sky and form a global network of neutrino telescopes
- With its high angular precision, can be used to more precisely map the neutrino sources in the sky, especially point-like
- Can be used to set strong limits on the emission from AGNs and GRBs
- As a specific goal, useful for estimating the hadronic emission from BL-Lac objects
- Along with gamma-ray and G-wave observatories, form an important pillar of multi-messenger astronomy in the Northern hemisphere

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THANK YOU