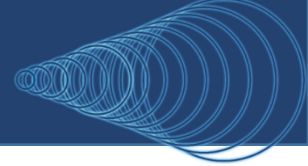


# Αστροσωματιδιακή Φυσική στο ΙΓΣΦ

Χρήστος Μάρκου  
Κατερίνα Τζαμαριουδάκη  
Ευαγγελία Δρακοπούλου

06/06/2024



## Η γέννηση ενός νέου και συναρπαστικού πεδίου έρευνας

Στο πρόσφατο παρελθόν:

- Ανίχνευση νετρίνο από τον ήλιο  
 → αποδεικνύοντας ότι η ενέργεια του Ήλιου παρέχεται από σύντηξη
- Ανίχνευση νετρίνο από supernova (1987)  
 → 20 (Kamionade: 12) supernova νετρίνο – επιβεβαίωση της βασικής θεωρητικής εικόνας του θανάτου ενός άστρου

**Nobel Prize 2002**



Αρχικές πειραματικές μετρήσεις: αριθμός των νετρίνο που φτάνουν στη Γη από τον Ήλιο:  $\sim 1/3$  του αναμενόμενου από τη θεωρία “**solar neutrino puzzle**”

**Ανιχνευτές Super-Kamiokande & SNO:** τα νετρίνο από τον Ήλιο δε χάνονται καθώς ταξιδεύουν προς τη Γη αλλά αλλάζουν ταυτότητα

**Nobel Prize 2015**

“For the greatest benefit to mankind”  
*Alfred Nobel*  
**2015 NOBEL PRIZE IN PHYSICS**  
**Takaaki Kajita**  
**Arthur B. McDonald**

2015 Nobel Prize in Physics  
 The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald “for the discovery of neutrino oscillations, which shows that neutrinos have mass”.

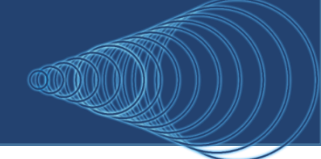
LIVE WEBCAST ON NOW  
 Announcement  
 Nobel Prize in Physics

Watch the 2015 Nobel Prize Announcements Live

Greetings to the 2015 Nobel Laureates  
 “CONGRATULATIONS for this achievement which should truly inspire many more of us to work towards suc...”  
 /Maria Vincent  
 + Post your greetings!

Η αλλαγή της ταυτότητας των νετρίνο μπορεί να γίνει μόνο αν τα νετρίνο έχουν μάζα

Το καθιερωμένο πρότυπο δεν αποτελεί πλήρη θεωρία των θεμελιωδών συστατικών του Σύμπαντος



## νετρίνο

- δεν έχουν ηλεκτρικό φορτίο
- έχουν αμελητέα μάζα
- πρακτικά δεν απορροφώνται
- προϊόντα πυρηνικών διεργασιών

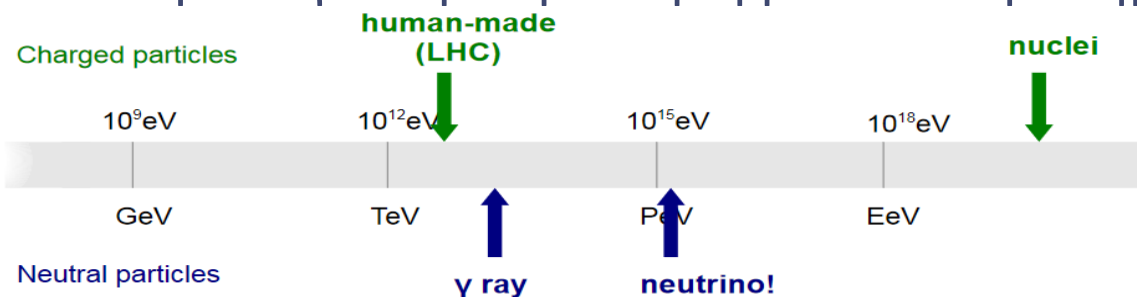
## ❖ ανίχνευση νετρίνο: μια πρόκληση

- Ανίχνευση 2000 νετρίνο από τον Ήλιο σε μια περίοδο 30 ετών!
- Ανίχνευση 12 νετρίνο από τα  $10^{16}$  νετρίνο που πέρασαν μέσα από τον ανιχνευτή Kamiokande!
- ❖ Μια σύγχρονη μαζική εκπομπή νετρίνο παρατηρήθηκε **2-3 ώρες πριν** την άφιξη του φωτός από το SN 1987A στη Γη.

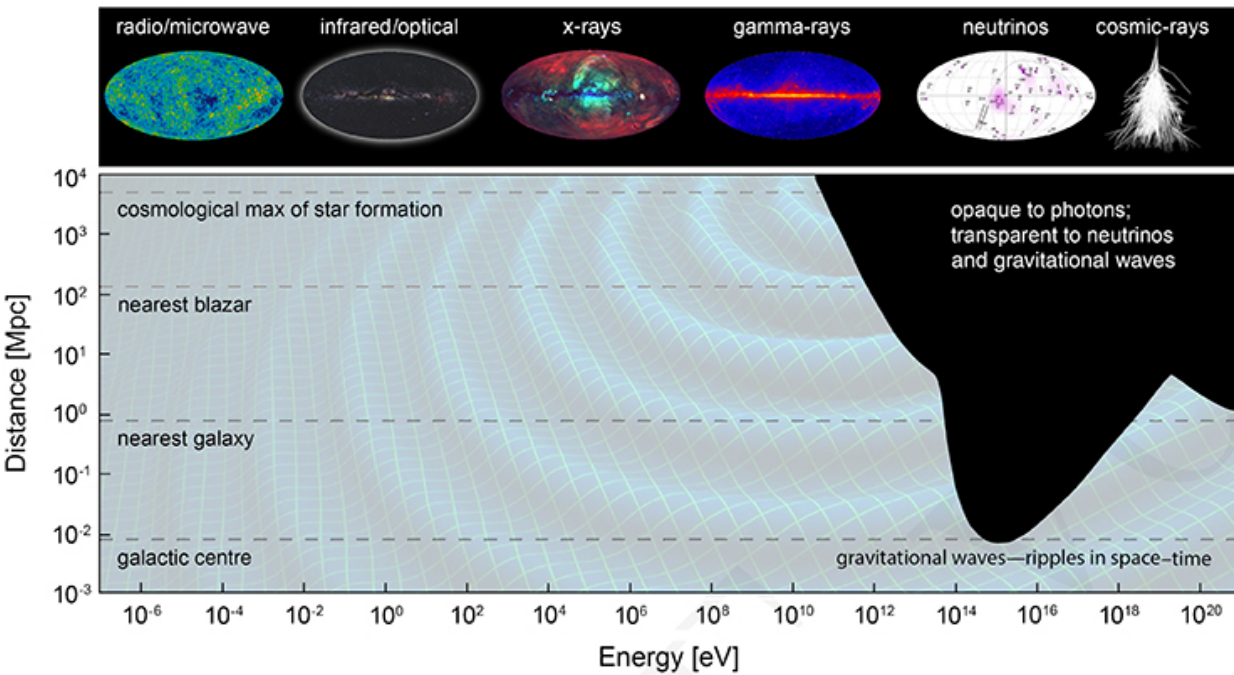
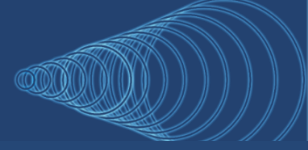
- Ανίχνευση νετρίνο από τον ήλιο ✓
- Ανίχνευση νετρίνο από supernova (1987) ✓

## • Ανίχνευση νετρίνο από γαλαξιακές και εξω-γαλαξιακές πηγές

- νετρίνο ως φορέας πληροφορίας για τα φαινόμενα υψηλής ενέργειας στο Σύμπαν (neutrino: the twitter X of the Universe)
- νετρίνο – δέσμη σωματιδίων από τον ουρανό για τη διερεύνηση βασικών ερωτημάτων της Σωματιδιακής Φυσικής



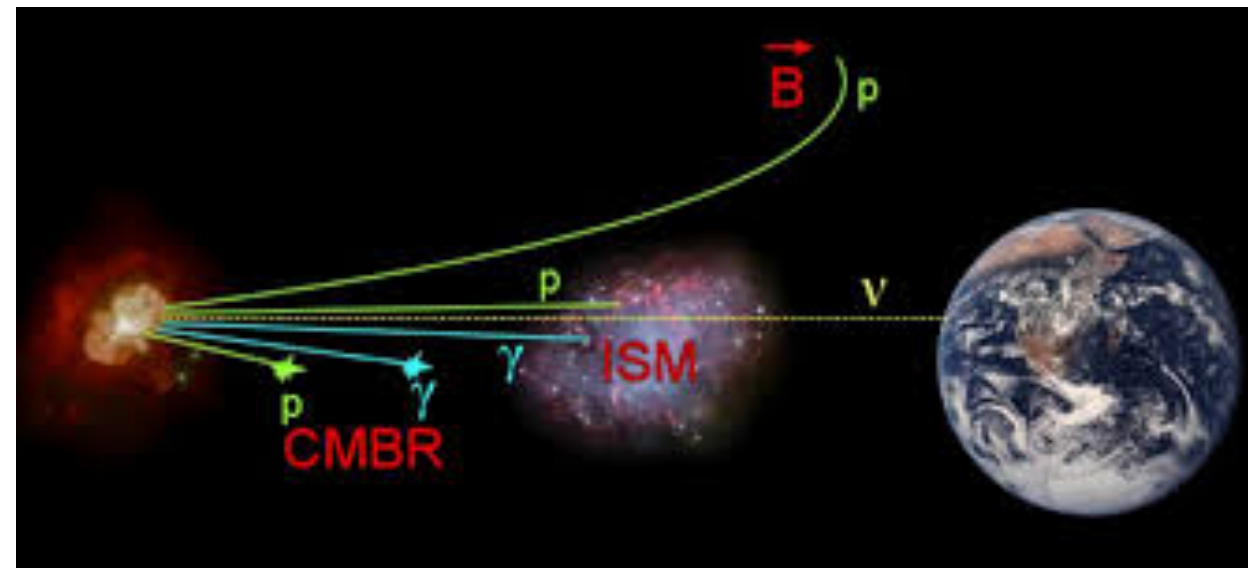
# Φαινόμενα υψηλής ενέργειας στο Σύμπαν: φορείς πληροφορίας



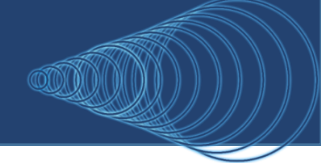
- φωτόνια
- κοσμικές ακτίνες
- νεutrίνο
- βαρυτικά κύματα

$\nu \rightarrow$  Αλληλεπιδρούν μέσω της ασθενούς αλληλεπίδρασης

- Ταξιδεύουν σε ευθύγραμμες τροχιές!
- Πρακτικά, δεν απορροφώνται από την μεσοαστρική ύλη!
- Μπορούν να αποκαλύψουν πληροφορίες σχετικά με τις διεργασίες στις αστροφυσικές πηγές που δεν είναι «προσβάσιμες» μέσω φωτονίων ή κοσμικών ακτίνων

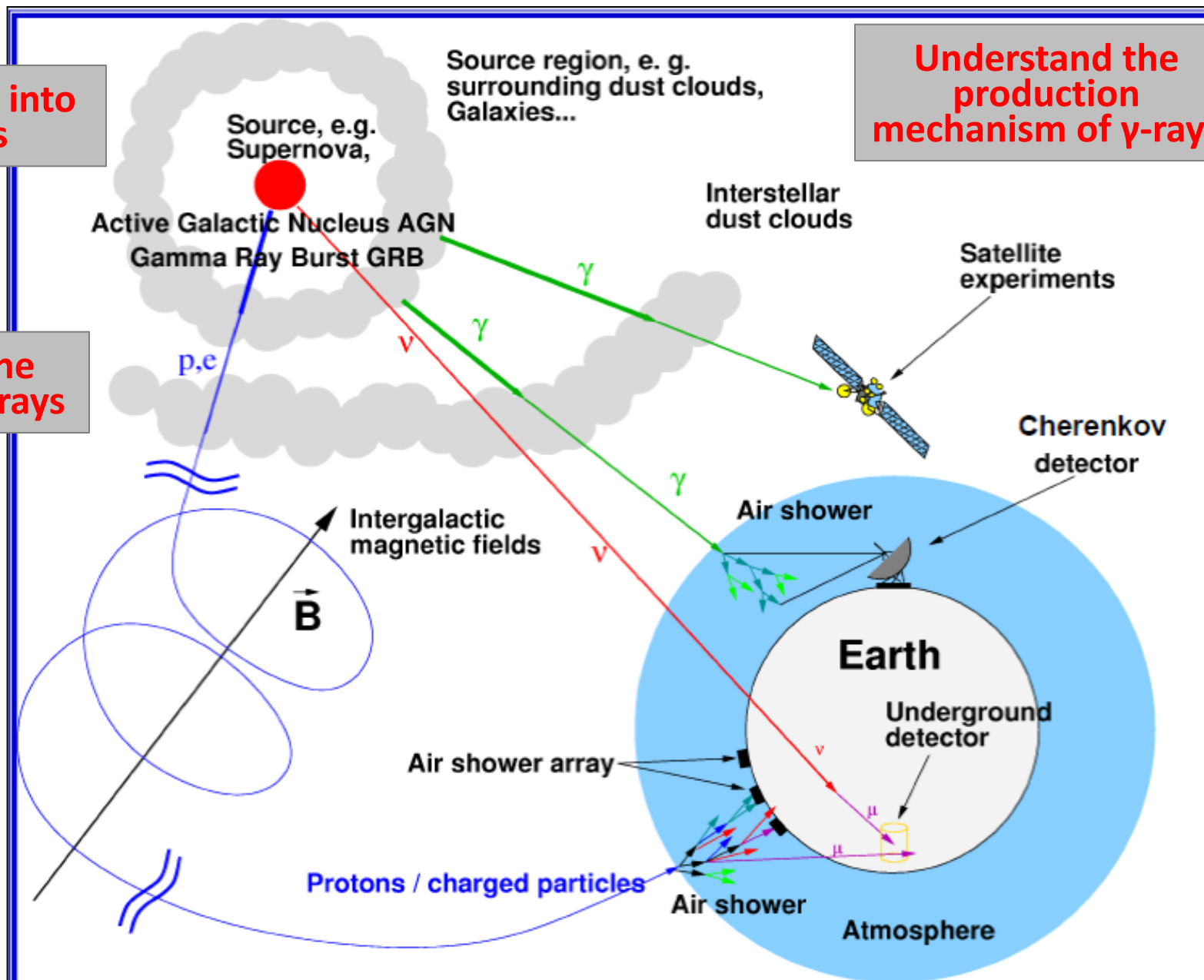


# Αστρονομία Νετρίνων: το όνειρο!



see deeper into sources

learn what is the origin of cosmic rays



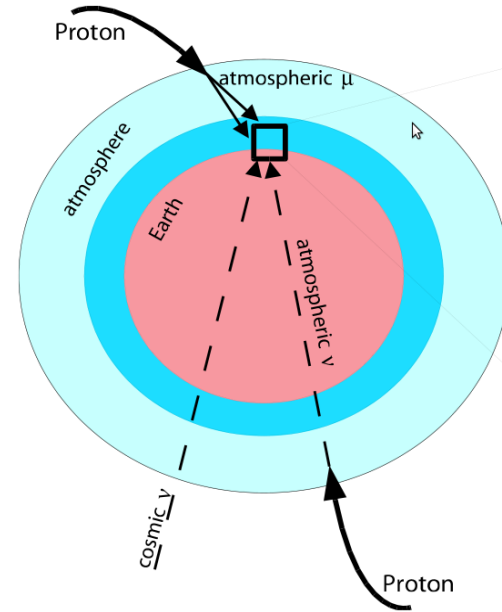
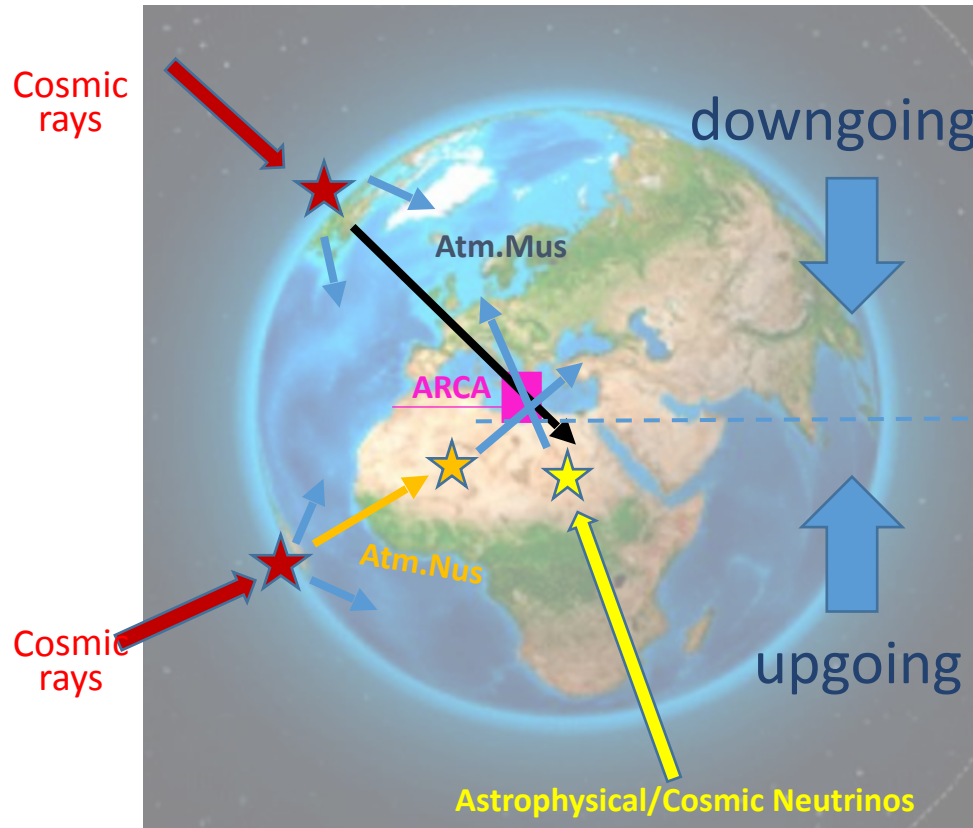
Multi-messenger astronomy

# Αστρονομία Νετρίνων: η πραγματικότητα!

~50.000.000 atm.μ / year

**Πρόκληση!**

~300.000 atm.ν / year



- Σήμα: νεutrino αστροφυσικής προέλευσης
- Υπόβαθρο: νεutrino και μόνια που παράγονται στην ατμόσφαιρα.

~600 ν of astrophysical origin / year

• Numbers refer to ARCA with 2 building blocks of 115 DUs each

•  $10^{-4} \left( \frac{E^{-2}}{GeV} \right) e^{\left( -\frac{E}{3PeV} \right)} GeV^{-1} m^{-2} s^{-1} sr^{-1}$  Applied astrophysical flux: 1.2.

- Σήμα: νεutrino αστροφυσικής προέλευσης
- Υπόβαθρο: νεutrino που παράγονται στην ατμόσφαιρα.  
μύονια που παράγονται στην ατμόσφαιρα.

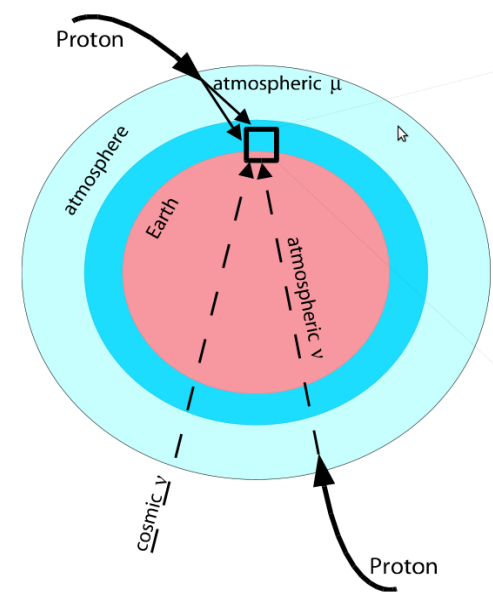
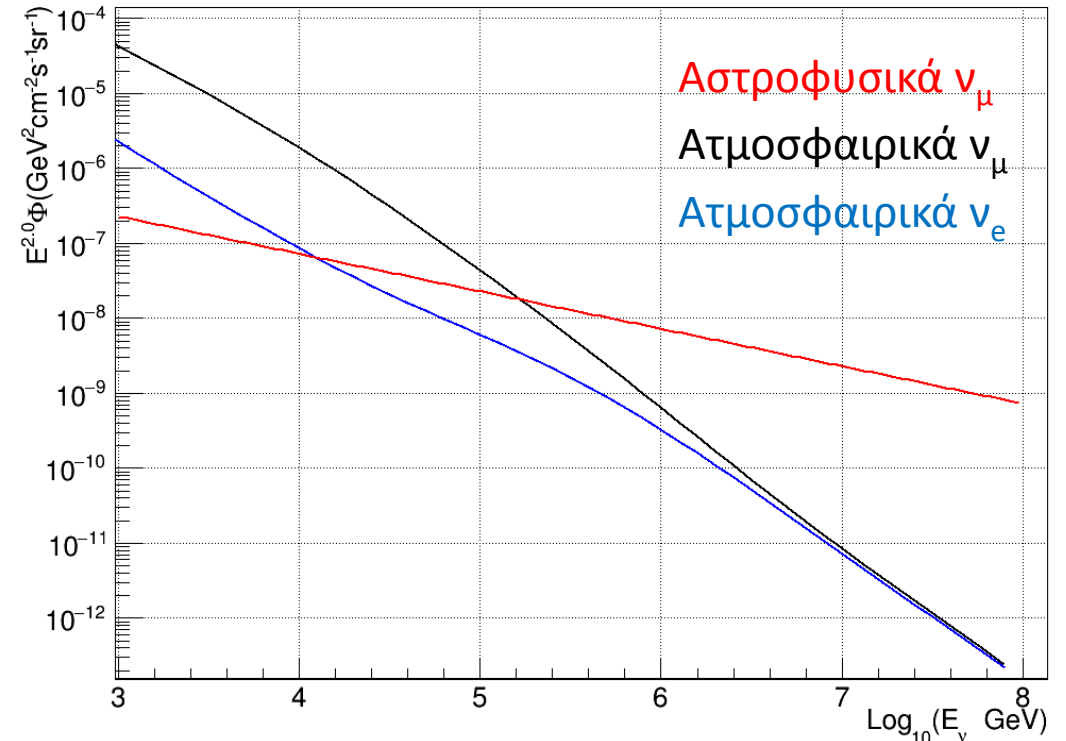
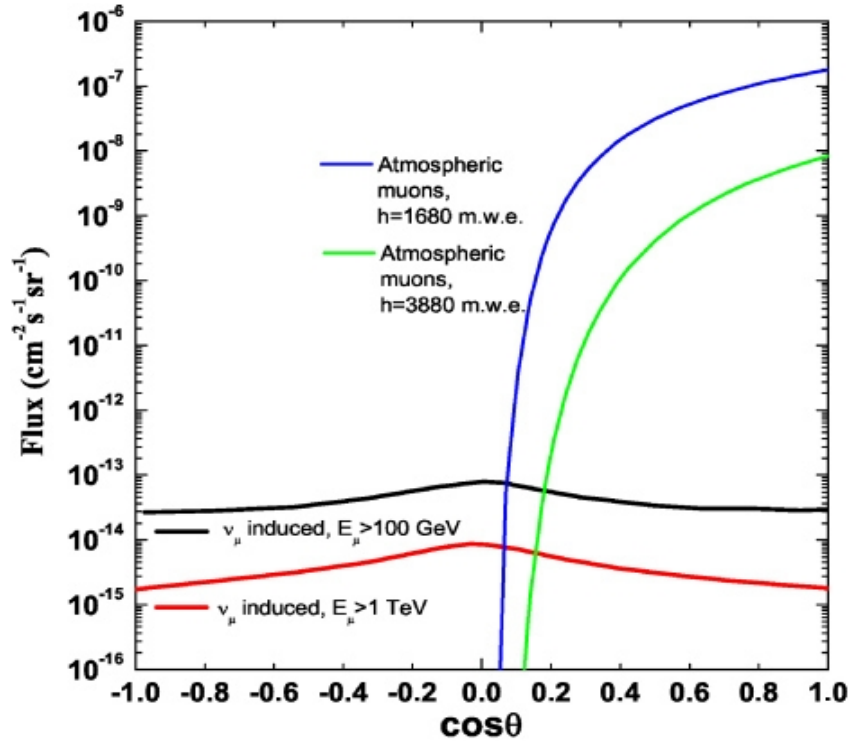
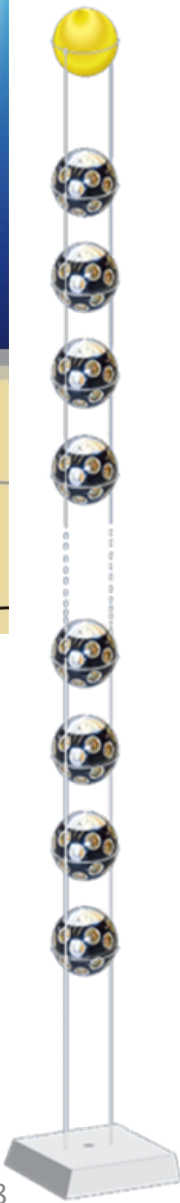
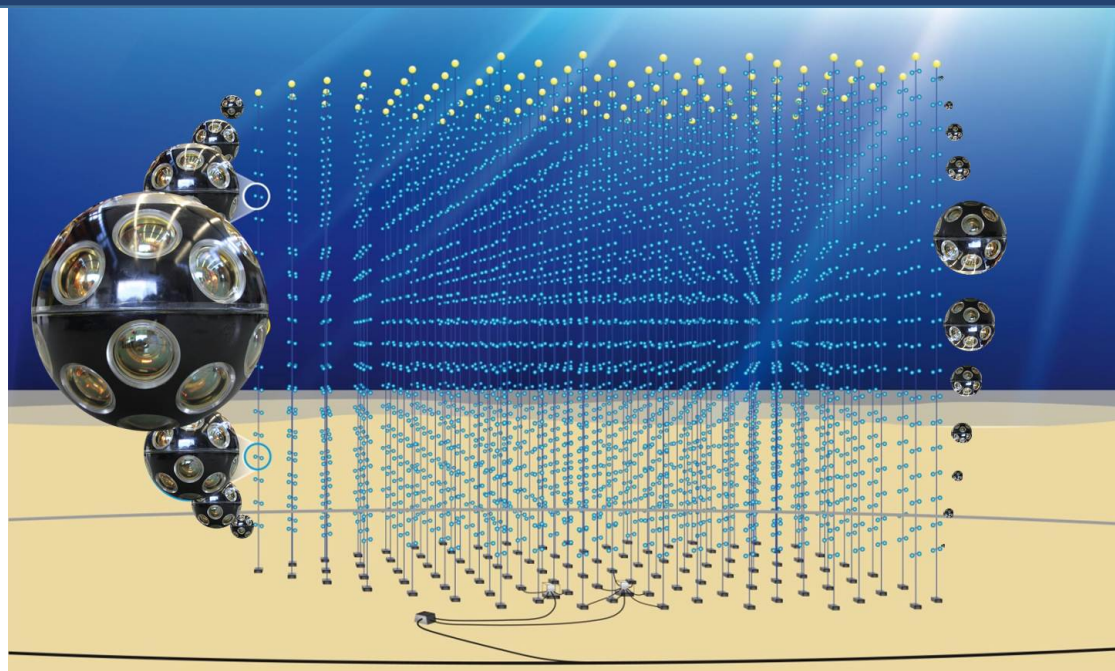
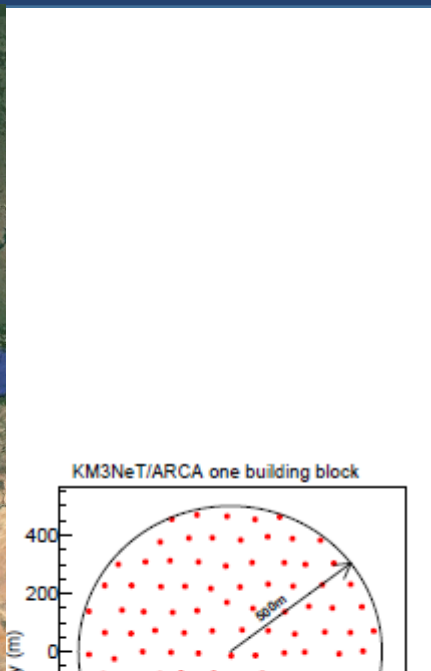


Figure 12 from High-energy neutrino astronomy: detection methods and first achievements B Baret and V Van Elewyck 2011 Rep. Prog. Phys. 74 046902





## ORCA

Ανιχνευτής νετρίνο:  
Σωματιδιακή φυσική  
Ταλαντώσεις νετρίνο  
Ιεραρχία μαζών

2x

## ARCA

Τηλεσκόπιο νετρίνο:  
Ανίχνευση νετρίνο αστροφυσικής  
προέλευσης

18/115 ποντισμένες συστοιχίες

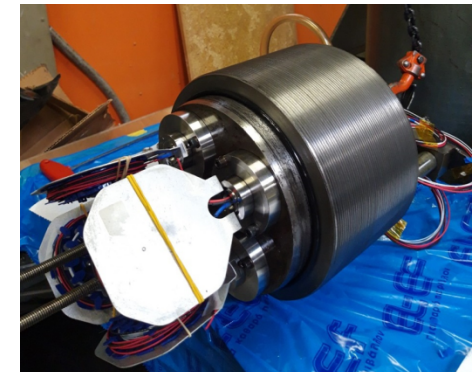
28/115 ποντισμένες συστοιχίες





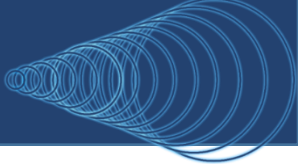
**APP group:** 3 ερευνητές, τεχνικό προσωπικό, 1 φυσικός, 1 PostDoc, 2 Ph.D. Students, 2 MSc students

Undergraduate students - interns

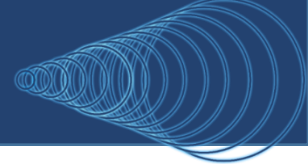


- Κατασκευή και έλεγχος οπτικών στοιχείων του πειράματος KM3NeT
- Συμμετοχή στη βαθμονόμηση και τον έλεγχο συνιστωσών των DOMs
- Έλεγχος της αντοχής των συνιστωσών των DOMs στην πίεση της βαθιάς θάλασσας

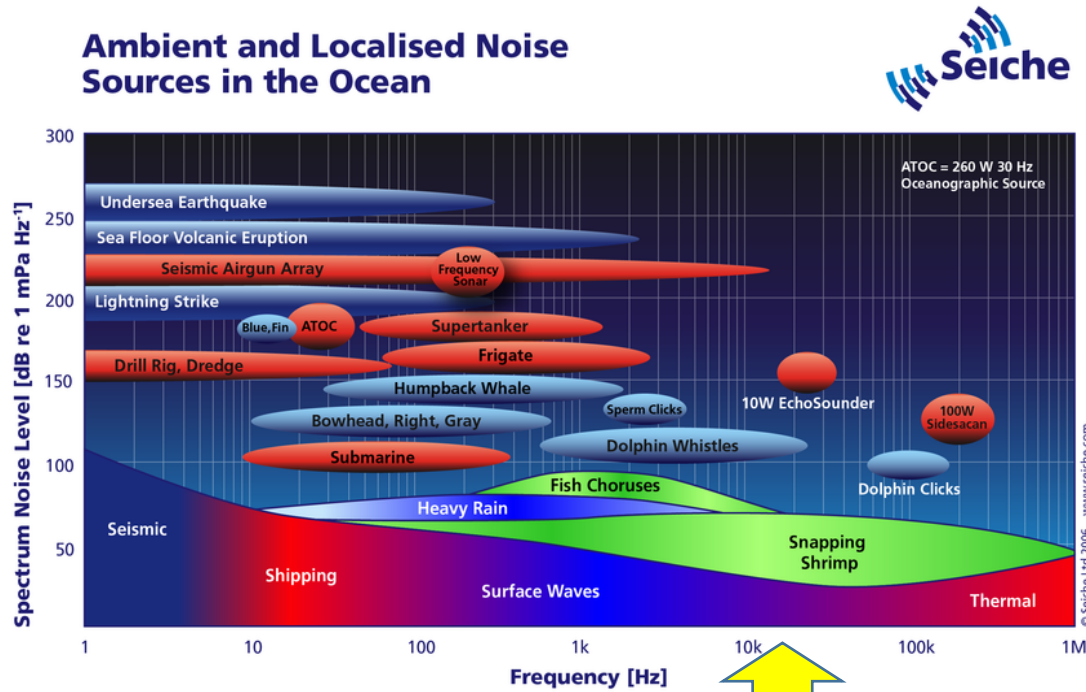
*Hardware Opportunities*



# Ακουστική Ανίχνευση Νετρίνων



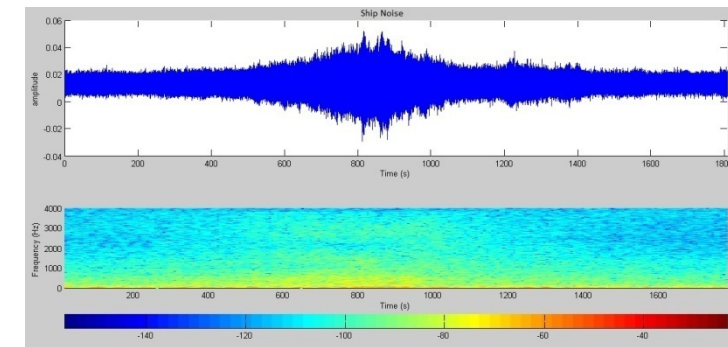
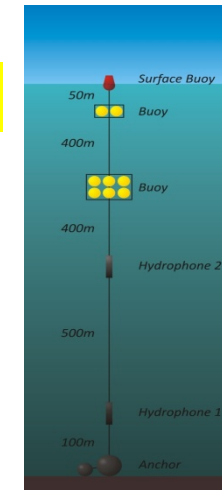
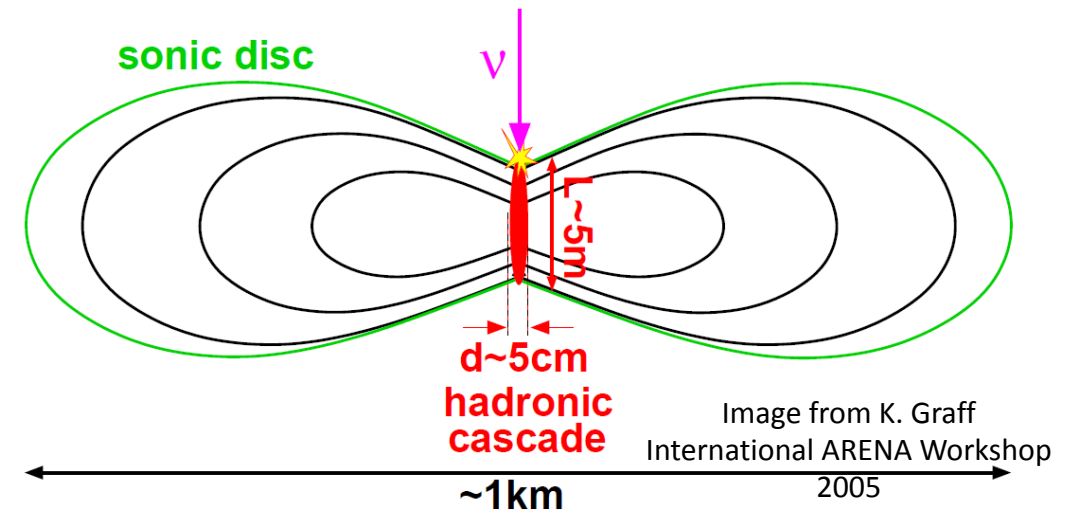
➤ Ίσως ο πλέον υποσχόμενος τρόπος ανίχνευσης νετρίνο εξαιρετικά υψηλών ενεργειών (UHE) : κόστος – δυνατότητες

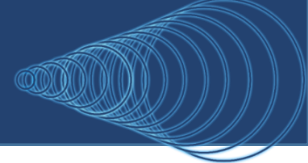


αναμενόμενο σήμα από αλληλεπιδράσεις νετρίνο

## Ανάλυση ακουστικού σήματος και κατηγοριοποίηση:

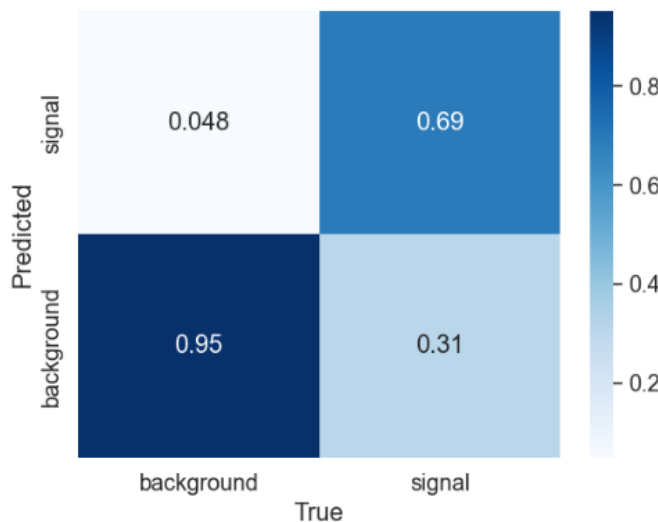
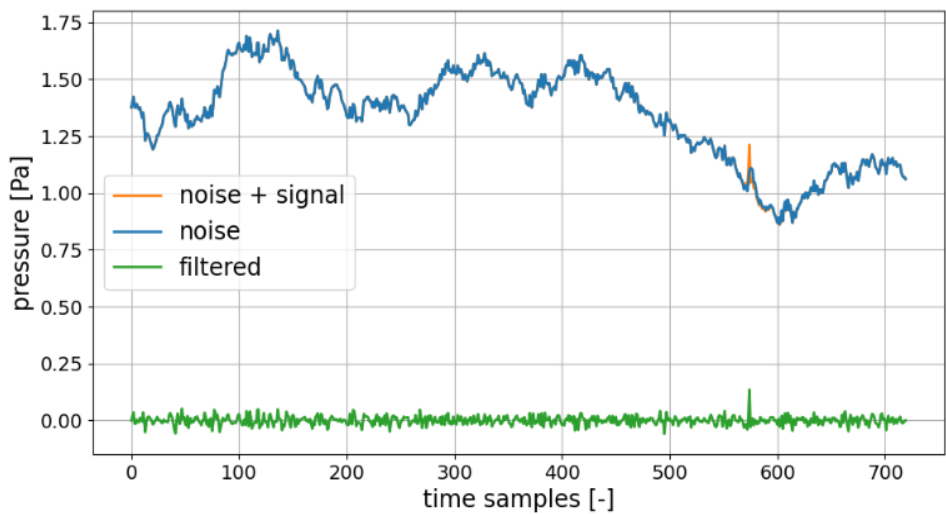
- Αναμενόμενο σήμα από αλληλεπίδραση νετρίνο
- Δεδομένα από την καταγραφή των υδροφώνων (Καλαμάτα 2018) και των ακουστικών αισθητήρων του KM3NeT για την προσομοίωση του υποβάθρου.





**Motivation:** Διερεύνηση της ικανότητας αναγνώρισης ακουστικών παλμών νετρίνων UHE υποθαλάσσια.

Results on the employment of a hydrophone-level trigger were presented at the **38th International Cosmic Ray Conference (ICRC2023)**



- Προσομοίωση ακουστικών παλμών από UHE νεutrino
- Προσθήκη παλμών στα πραγματικά δεδομένα θορύβου
- Εύρεση σήματος χρησιμοποιώντας ανάλυση συχνοτήτων και τεχνικές Μηχανικής και Βαθιάς Μάθησης

**ICRC2023 Identification of Ultra High Energy neutrino induced acoustic pulses**  
 Christos Markou<sup>a\*</sup>, Konstantinos Paschos<sup>b\*</sup>, Dimitris Stavropoulos<sup>c\*</sup>, Vasileios Tsourapis<sup>c\*</sup> and Georgios Zarpas<sup>c\*</sup>

**Acoustic neutrino detection**  
 The instantaneous energy deposition from a particle shower produces a sound wave according to the thermo-acoustic model [1]. The neutrino track and the sound wave directions are perpendicular, resulting in a characteristic disk-like topology. As the flux of cosmic neutrinos is extremely low in the Ultra High Energy (UHE) regime (EeV scale), very large detector configurations have to be built. A hydrophone-array acoustic neutrino detector could be a feasible solution as sound has a much larger attenuation length than light in the seawater. However, the size of continuously recorded acoustic data from such detectors could lead to extremely challenging computational issues. **Can be solved with a trigger condition at the hydrophone level!**

**Data and MC simulation**  
 Underwater acoustic recordings collected at a sea depth of approximately 1600 meters, Southwest of Peloponnese, Greece. A simulation chain was developed in order to calculate UHE acoustic neutrino signals:  
 • Simulation of hadronic showers using CORSIKA-1W [3]  
 • Calculation of the pulse waveform by solving the thermo-acoustic model's wave equation numerically and modeling the sound attenuation in seawater with a method originally developed by ACORNE [4]

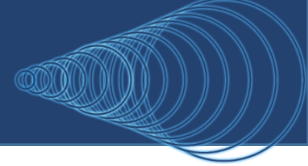
**Dolphin click filtering**  
 Strong presence of cetacean-related sounds in the Mediterranean. Efficiently identified using a band-stop filter.

**Deconvolution using the wavelet transform**  
 The continuous acoustic recordings were separated into 5 ms chunks. Two data sets were created:  
 • Background: chunks with pure noise (top left plot)  
 • Signal: chunks with neutrino acoustic pulse added on the noise (top right plot)  
 Acoustic neutrino pulse added on top of the recorded pressure-time series. High-pass pre-filtering to remove low frequency variations enhancing the neutrino pulse width over the baseline. Matrix with the wavelet transform [5] correlation coefficients. **Strong correlation at the position of the neutrino acoustic pulse!**

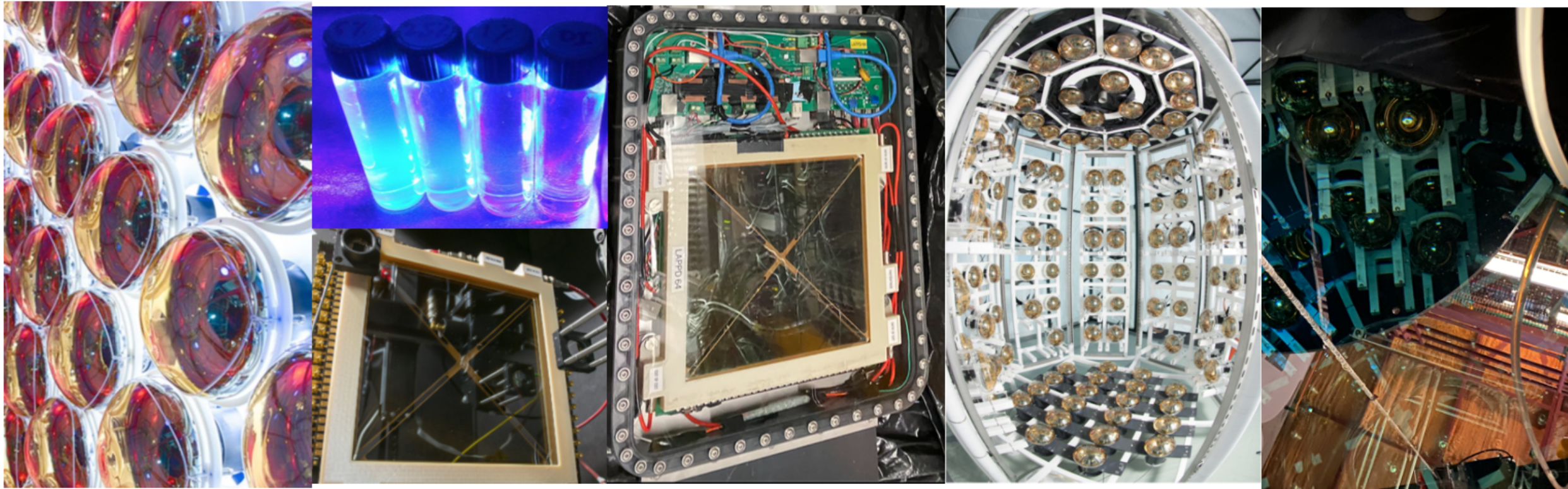
**Acoustic neutrino pulse identification**  
 A Boosted Decision Tree algorithm used for classifying chunks containing acoustic neutrino pulses over background, with features extracted from the wavelet correlation matrix. Signal efficiency of ~69% achieved with a ~95% background rejection!  
 Preliminary results with a state-of-the-art Convolutional Neural Networks implemented as an alternative approach, using high-pass pre-filtered pressure time-series, show a signal efficiency of ~76% achieved with a ~93% background rejection!

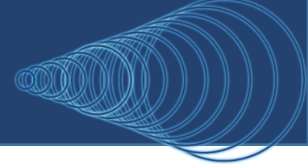
**Conclusions**  
 Promising first results for neutrino acoustic pulse identification at the hydrophone level are presented. Full simulation chain and state-of-the-art techniques for signal classification have been developed. **Our methodology could lead to a feasible data acquisition system for a future acoustic neutrino detector.**

**References**  
 1: J. G. Learned, Phys. Rev. D19 (1979) 3293.  
 2: C. Richter et al., Astrophysical Journal 21 (2009) 19-23.  
 3: https://web.lap.kit.edu/corsika/downloads/010/v050/, access provided by developers.  
 4: S. Bevan et al. Astrophysical Journal 20 (2007) 360-379.  
 5: J. Daubechies, IEEE Transactions on Information Theory, vol. 30, no. 3, pp. 901-1003, (1980).

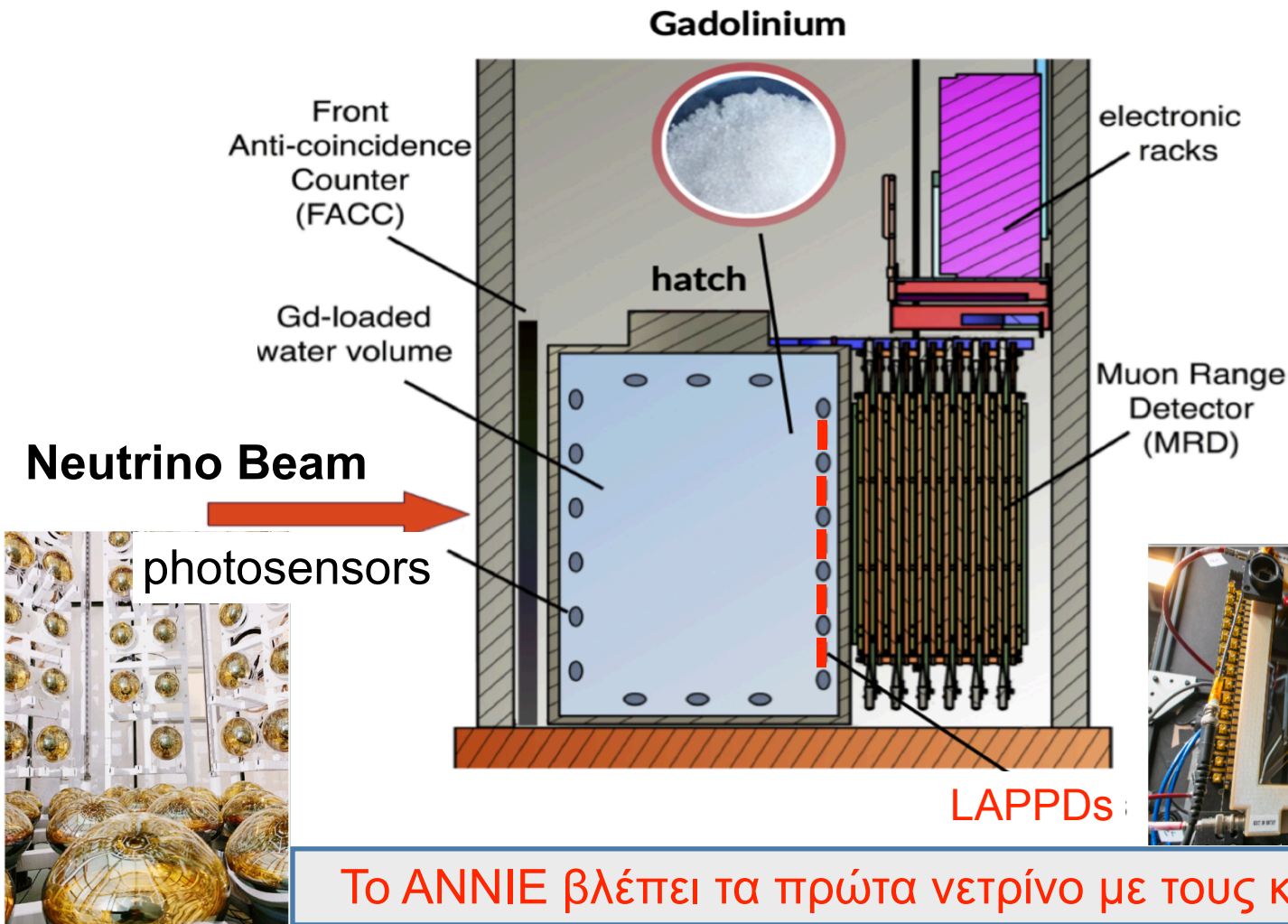


# ANNIE



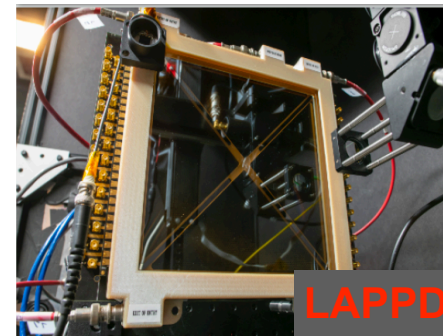


- Accelerator Neutrino Neutron Interaction Experiment (ANNIE): ένας Gd-doped water Cherenkov ανιχνευτής 26 τόνων στη δέσμη νετρίνων του Fermilab ( $E \sim 600$  MeV).
- Συμμετέχουμε στο ANNIE από το 2021.

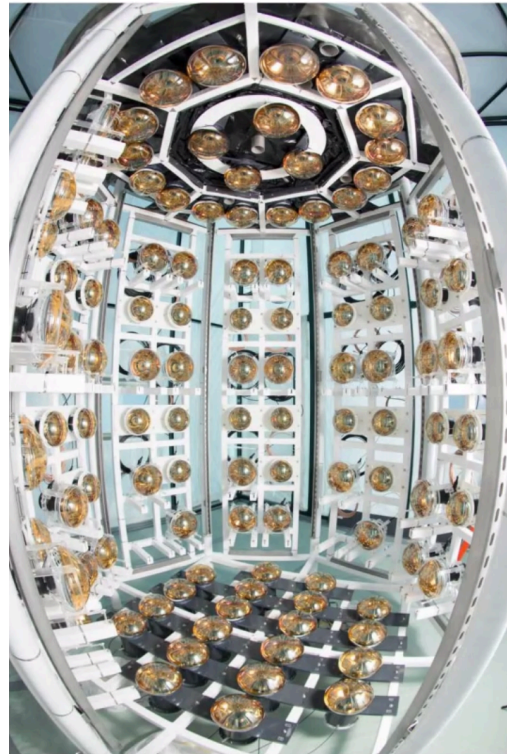
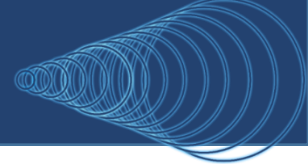


**Ανιχνευτικό Μέσο:** Τώρα: Gadolinium-loaded water, 2022: Water-based Liquid Scintillator.

- Το ANNIE είναι το πρώτο πείραμα που χρησιμοποιεί φωτοανιχνευτές ταχείας απόκρισης ( $\sim 60$  psec time resolution) **Large Area Picosecond PhotoDetectors (LAPPDs)** για ανακατασκευή γεγονότων νετρίνων.



Το ANNIE βλέπει τα πρώτα νετρίνο με τους καινοτόμους ανιχνευτές φωτός LAPPDs.



2016

2018

2024

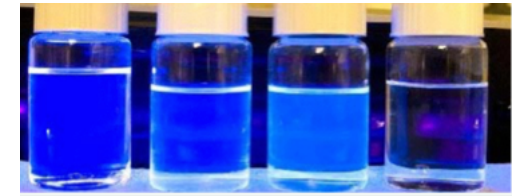
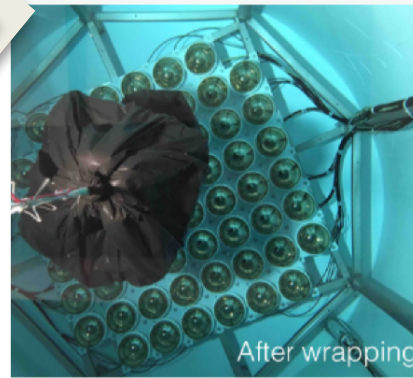
Past:  
ANNIE – Phase I

Present:  
ANNIE – Phase II

Future:  
ANNIE – Phase III

Completed

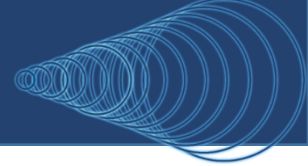
NOW



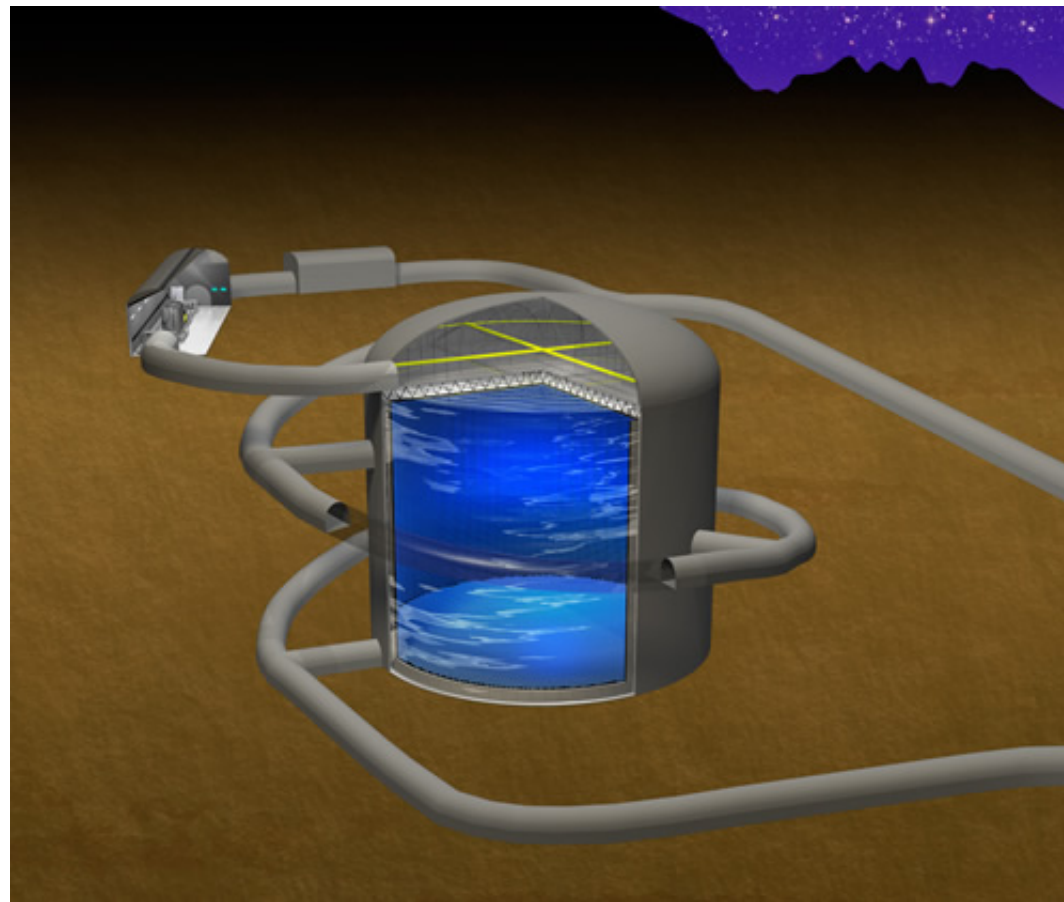
- Μέτρηση του υποβάθρου του ανιχνευτή
- Επιτυχής λειτουργία του ανιχνευτή

- Μέτρηση της πολλαπλότητας νετρονίων από CCQE γεγονότα
- Πρώτη πόντιση και λειτουργία των LAPPDs

- Περισσότερα LAPPDs: βελτιωμένη ανακατασκευή
- Water-based Liquid Scintillator (WbLS)

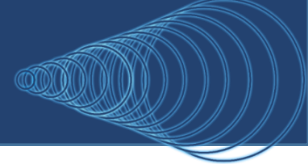


# Hyper-Kamiokande (Hyper-K)

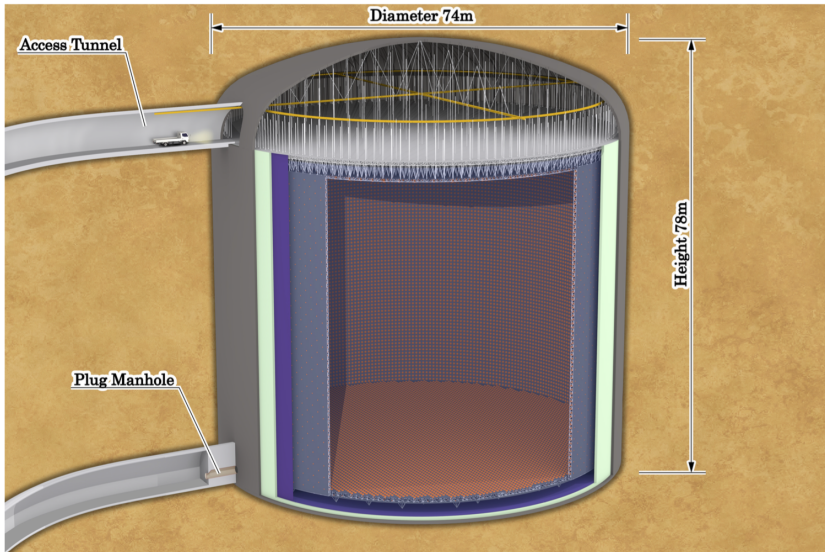




# Hyper-Kamiokande (Hyper-K)



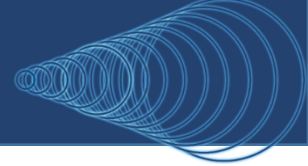
**Hyper Kamiokande (Hyper-K) detector**



start operation in 2027

**Upgrade of J-PARC neutrino beam to 1.3 MW beam power**





## Physics beyond the SM:

- Search for CP violation in the lepton sector
- Determination of neutrino mass hierarchy with beam and atmospheric  $\nu$
- $\theta_{23}$  octant determination
- Search for nucleon decay

## Neutrino astrophysics:

- Precision measurements with solar  $\nu$
- High statistics measurements with  $\nu$  from supernova bursts
- Supernova relic  $\nu$  detection

### Physics Goals of Hyper-K

**Supernova neutrinos**

**Solar neutrinos**  
The Sun in Neutrinos  
Super-K, 1500 days

**Atmospheric neutrinos**

**Nucleon decay**

$e^+$ ,  $p$ ,  $\pi^0$ ,  $\gamma$ ,  $\gamma$

**J-PARC neutrino beam**

1 talk and 3 posters at ICRC2023!  
3 contributions accepted for NEUTRINO2024!  
& talks and posters in other conferences.

### ICRC2023 Identification of Ultra High Energy neutrino induced acoustic pulses

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<sup>a</sup> NCSR Demokritos, Institute of Nuclear and Particle Physics, Ag. Paraskevi Attika, Athens, 15110 Greece  
<sup>b</sup> National Technical University of Athens, School of Mechanical Engineering, Zografou Campus, 9, Iroon Polytechniou str., 15701 Zografou, Athens, Greece  
<sup>c</sup> National Technical University of Athens, School of Applied Mathematical and Physical Sciences, Zografou Campus, 9, Iroon Polytechniou str., 15701 Zografou, Athens, Greece

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Underwater acoustic recordings collected at a sea depth of approximately 1600 meters, Southwest of Patagonia, Greece. A simulation chain was developed in order to calculate UHE acoustic neutrino signals.

- Simulation of hadronic showers using CORSIKA-1W [3]
- Calculation of the pulse waveform by solving the thermo-acoustic model's wave equation numerically and modeling the sound attenuation in seawater with a method originally developed by ACORNE [4]

Acoustic neutrino pulses were simulated in the range 10-100 EeV for an E<sup>2</sup> spectrum

#### Dolphin click filtering

### Measurement of the atmospheric muon neutrino flux with KM3NeT/ORCA6

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#### The KM3NeT/ORCA detector

The KM3NeT/ORCA detector [1] is an array of Digital Optical Modules, spheres that host 31 photomultiplier tubes, which is being constructed at a sea depth of ~2450 m, offshore Toulon, France. Such an array configuration can detect neutrino events from the Cherenkov radiation emitted by the secondary particles of neutrino interactions in the abyssal depths of the Mediterranean Sea. The determination of the Neutrino Mass Ordering is the main physics goal of the detector.

#### Deconvolution using

The continuous acoustic recordings were separated into 5 ms chunks. Two data sets were created:

- Background: chunks with pure noise (top left plot)
- Signal: chunks with neutrino acoustic pulse added on the noise (top right plot)

The Digital Optical Module of KM3NeT

Artist view of the completed ORCA detector

#### Neutrino event selection with high purity

Data corresponding to 555.7 days, collected with a 6-Detection Unit configuration (ORCA6) have been used for this measurement. Sophisticated event variables have been developed and used as features in a BDT classifier (TMVA) to discriminate reconstructed as genuine atmospheric neutrinos from the misreconstructed atmospheric muon background. A BDT score cut at 0.56 results in 4197 data events, 4196.1 atm. neutrino MC events and just 28.1 atm. muon MC events, with a good agreement between data and simulation.

#### Acoustic neutrino

A Boosted Decision Tree algorithm used for classifying chunks containing acoustic neutrino pulses over background, with features extracted from the wavelet correlation matrix. Signal efficiency of ~69% achieved with a ~95% background rejection!

Promising first for neutrino ac pulse identify the hydrophone and present

#### Unfolding the $\nu_{\mu} + \bar{\nu}_{\mu}$ CC energy spectrum

An unfolding scheme (TMVA) is used in order to deconvolute the muon neutrino CC energy distribution from the experimentally measured one (left). The binning schemes for the true and reconstructed phases spaces have been defined according to the bin purity, the consistency and the robustness of the procedure have been tested using toy MC experiments. After defining and testing the procedure in MC, the energy distribution measured in data is unfolded (right).

#### Flux measurement

The unfolded numbers of events per bin are converted to flux values using the HKKM14 conventional flux model [2] and the NuFIT v5.2 oscillation probabilities [3].

$M(E_{\nu}, \theta_{12})$	$\log(E_{\nu}/\text{GeV})$	$E_{\nu}^2 \Phi_{\nu} [\text{GeV}^{-2} \text{sr}^{-1} \text{cm}^{-2}]$	stat.
0.0-0.8	0.37	$1.43 \cdot 10^{-3}$	+31%
0.8-1.3	0.93	$4.25 \cdot 10^{-3}$	+21%
1.3-1.8	1.45	$1.57 \cdot 10^{-3}$	+21%
1.8-2.0	1.88	$8.46 \cdot 10^{-4}$	+24%

## Search for a diffuse astrophysical neutrino flux with KM3NeT/ORCA using data of 2021-2022

Vasileios Tsourapis<sup>\*</sup>, E. Drakopoulou, C. Markou, A. Sinopoulou and E. Tzamariudaki on behalf of the KM3NeT collaboration

Nagoya, Japan, 26.7.2023

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2 scientific papers under preparation!!

## Data reconstruction and classification with graph neural networks in KM3NeT/ORCA6-8

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#### Abstract

KM3NeT is a research infrastructure hosting two large-volume Cherenkov neutrino detectors which are currently under construction in the Mediterranean Sea. The KM3NeT/ORCA6-8 detector is optimized for the detection of high-energy neutrinos from astrophysical sources in the TeV-PeV energy range. Once completed, the detector will consist of 230 detection units. Here, we present a Deep Learning method using graph neural networks (GNNs) that is trained and applied to detect neutrino events with 6 and 8 active detection units of KM3NeT/ORCA. GNNs have been trained for classification and regression tasks, showing very promising performances in a range of different tasks like neutrino-background identification, neutrino event topology classification, energy and direction reconstruction, and also in the study of properties of muon bundles.

#### KM3NeT detectors

- Network of Cherenkov detectors [1]
- KM3NeT/ORCA optimized for high-energy (TeV-PeV) astrophysical [2]
- KM3NeT/ORCA optimized for low-QGV atmospheric [3]
- 30 array of photoselectors capable to detect the Cherenkov light induced by particles emerging from  $\nu$  interactions
- 21 x 3 PMTs needed in pressure resistant glass sphere: Digital Optical Module (DOM)
- 18 DOMs anchored to the seafloor with buoyancy at the top form a detection unit (DU)
- 115 DUs evenly spaced form a building block.

#### Graph Neural Networks

High dimensionality and sparse signal of KM3NeT detectors are perfectly encoded into graph structure (other studies of the KM3NeT Collaboration available [2]). Not limited by position and time resolution as in image based methods, DOMs are also moving under the effect of sea-current.

Node  $\rightarrow$  every photon hit of an event. 7D feature space: 3 spatial coordinates, 3 PMT directions, time.

Edges  $\rightarrow$  distance between nodes computed with Euclidean metric.

For memory optimization and for keeping the number of connections under control, each node is connected to its k-nearest neighbors. ParticleNet architecture was employed [3].

#### Signal / Background classification

To distinguish neutrino induced events with respect to the overwhelming background represented by atmospheric muons, GNNs have been trained in order to classify between signal and background events.

Training sample: balanced dataset (50% muons and 50% neutrinos), k-nearest neighbors k=16, Adam optimizer, output activation function: softmax. Validation set: 10%.

A peak of events with very high neutrino score in the data is visible, fully compatible with an excess of atmospheric neutrinos.

#### Regression

##### Neutrino energy regression

Training sample: evenly composed by track-like ( $\nu_{\mu}$  CC interaction) and by shower-like ( $\nu_{\mu}$  NC,  $\nu_{\tau}$  CC,  $\nu_{\tau}$  NC interactions) events; k-nearest neighbors k=16; linear output activation function. The better containment of shower like events inside the detector produces better results respect to track like events in the inference of neutrino energy.

##### Neutrino direction regression

Training sample: same as the one used for energy regression. Three fully connected layers, with custom cosine activation function: one for each component of the neutrino direction. For this task instead the outgoing muon produced in track-like events allow to better predict the zenith direction respect to shower-like events.

#### Conclusions:

Graph Neural Networks has shown very interesting capabilities in classification and reconstruction tasks, even with a small number of detection units. With the planned KM3NeT detector expansion in the near future, more photon hits will be collected by the larger number of DOMs, increasing the complexity of the event signatures registered inside the detector, but gathering overall more information that can be fully exploited by Deep Learning methods like GNNs, producing even more accurate results in classification and regression tasks.

#### Acknowledgments

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## Neutrino experiments are expecting lots of new data!!

- ❑ **ARCA & ORCA data:** atmospheric neutrino candidates (atmospheric muon background suppression)
  - ARCA: Ανίχνευση νετρίνων αστροφυσικής προέλευσης με τον ανιχνευτή ARCA28
  - ARCA & ORCA: Μέτρηση της ροής ατμοσφαιρικών νετρίνων και σύγκριση με τα υπάρχοντα μοντέλα
  - Ανάπτυξη μοντέλων βαθιάς μάθησης για την ανακατασκευή γεγονότων και τον διαχωρισμό σήματος υποβάθρου
- ❑ **Simulation studies:** Μελέτες ατμοσφαιρικών μιονίων και σύγκριση MC προσομοιώσεων με data
- ❑ **Acoustic Neutrino Detection:** Ανάπτυξη μεθόδων για την αναγνώριση, το χαρακτηρισμό και την κατηγοριοποίηση ηχητικών σημάτων χρησιμοποιώντας τεχνικές μηχανικής μάθησης
- ❑ **ANNIE:** Ανάπτυξη μεθόδων βαθιάς μάθησης για την ανακατασκευή γεγονότων και ανάλυση data
- ❑ **Hyper-K:** πιθανά θέματα υπό συζήτηση



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