VEGA Valencia Experimental Group of Astroparticles

Planes Complementarios AstroHEP
Zaragoza, June 5-7, 2024

KM3NeT

KM3NeT neutrino telescope: first results and prospects

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AccenT l'Associació de Científiques i Científics d'Excel·lència del Pla GenT
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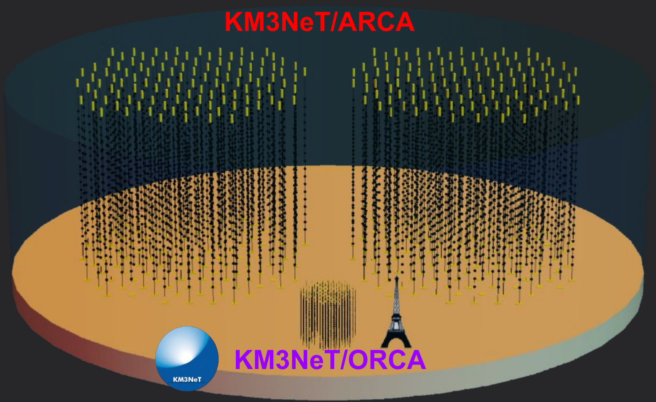
IFIC INSTITUT DE FÍSICA CORPUSCULAR
VNIVERSITAT DE VALÈNCIA
Financiado por la Unión Europea NextGenerationEU
GVANEXT Fondos Next Generation en la Comunitat Valenciana
GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Plan de Recuperación, Transformación y Resiliencia
ASFAE ASTROFÍSICA Y FÍSICA DE ALTAS ENERGÍAS

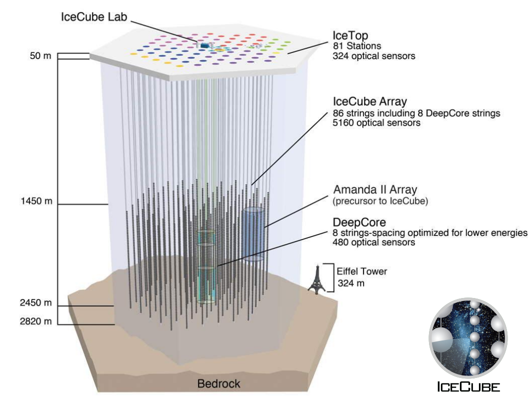
Outline

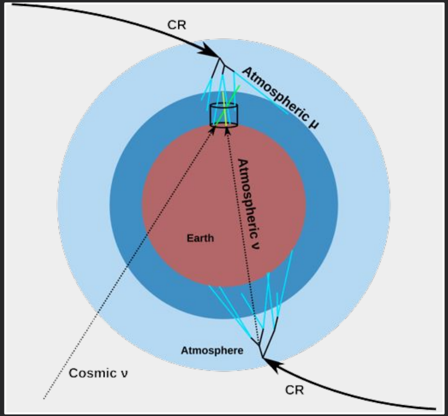
- Introduction to neutrino telescopes
- The KM3NeT detector
- Results highlights & prospects
- Related AstroHEP projects

Neutrino Telescope Concept

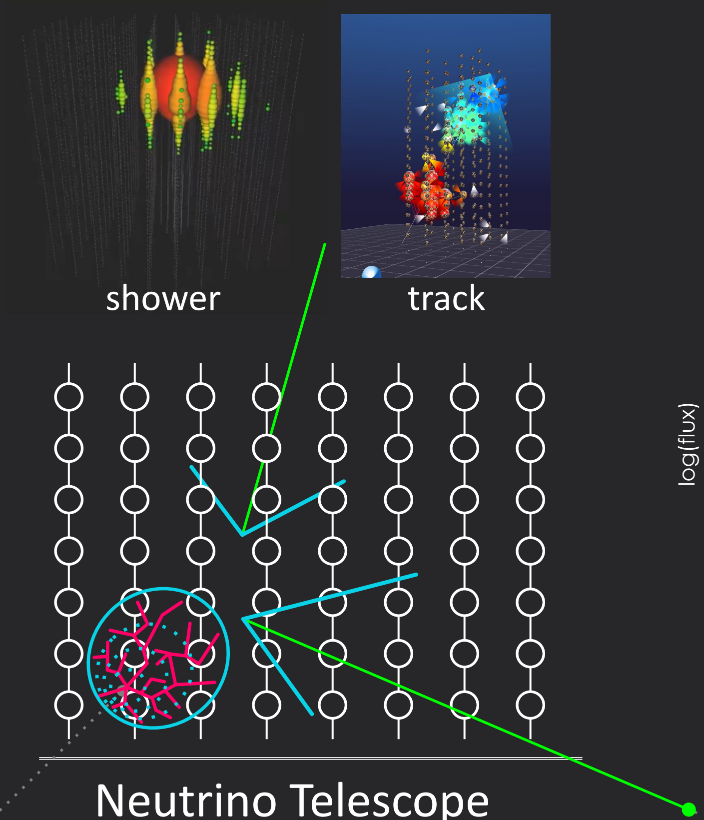
- First proposal by **Markov** at ICHEP conference, **1960**: “We propose setting up apparatus in an underground lake or deep in the ocean in order to separate charged particle directions by Čerenkov radiation”.
- Key ideas:
  - Use large dense transparent volumes (water or ice) to target neutrino interactions
  - Monitor them with light sensors to detect the Cherenkov light emitted by the outgoing particles.
  - **Detecting cosmic neutrino fluxes should require 1 km^3.**





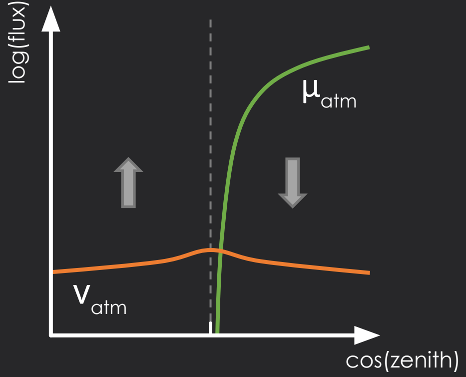


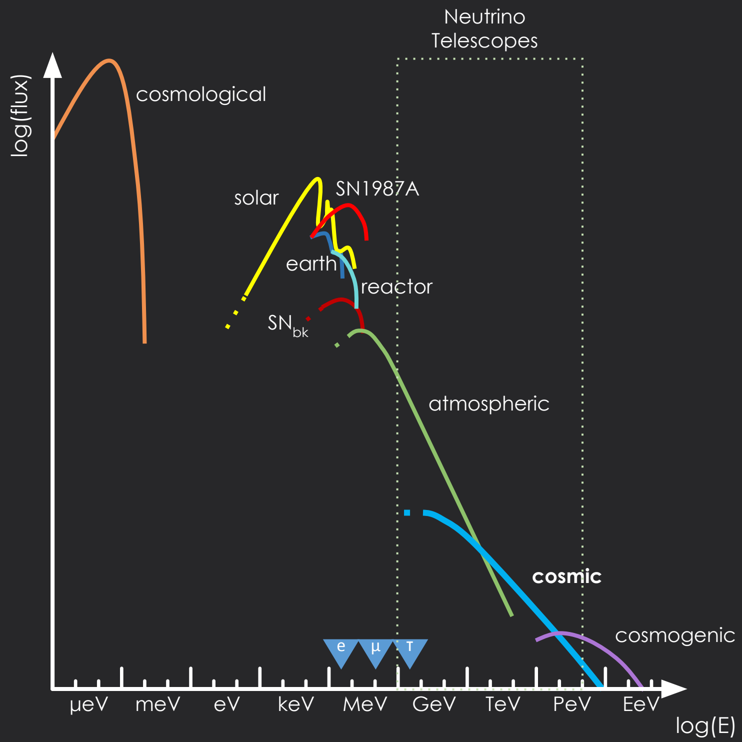
Detection Principle



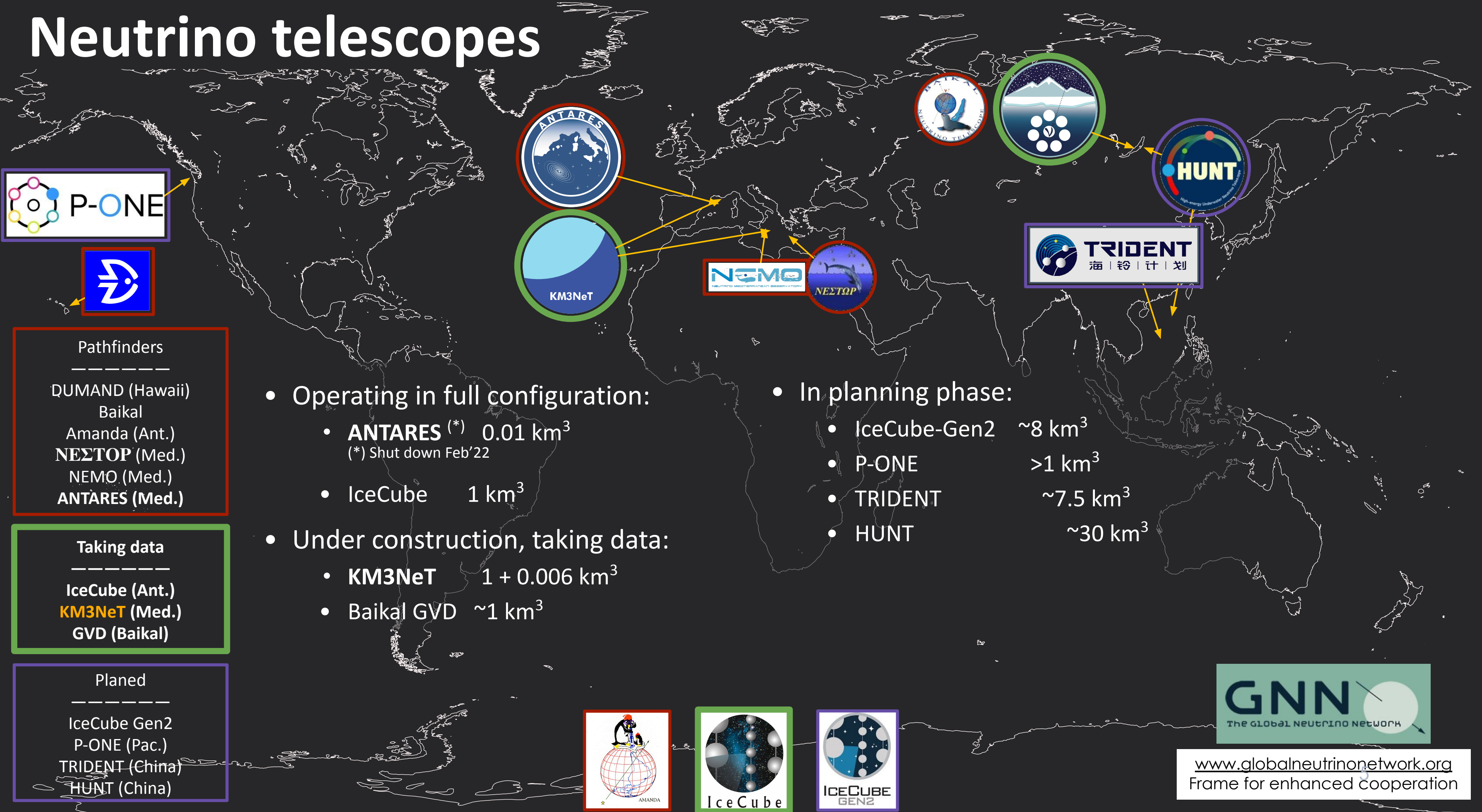
	1 km^3
μ_{atm}	~ 2000 / s (1)
ν_{atm}	~ 400 / day (2)
ν_{cos}	~ 200 / year (2)

(1): depth dependent
(2): analysis dependent





Neutrino telescopes



Pathfinders
———————
DUMAND (Hawaii)
Baikal
Amanda (Ant.)
ΝΕΣΤΩΡ (Med.)
NEMO (Med.)
ANTARES (Med.)

Taking data
———————
IceCube (Ant.)
KM3NeT (Med.)
GVD (Baikal)

Planed
———————
IceCube Gen2
P-ONE (Pac.)
TRIDENT (China)
HUNT (China)

- Operating in full configuration:
  - **ANTARES** (*) 0.01 km^3
    (*) Shut down Feb'22
  - IceCube 1 km^3
- Under construction, taking data:
  - **KM3NeT** 1 + 0.006 km^3
  - Baikal GVD ~1 km^3

- In planning phase:
  - IceCube-Gen2 ~8 km^3
  - P-ONE >1 km^3
  - TRIDENT ~7.5 km^3
  - HUNT ~30 km^3

GNN
The Global Neutrino Network

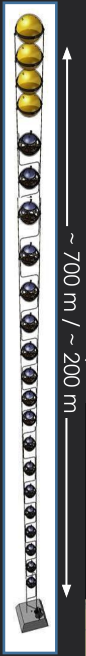
www.globalneutrinonetwork.org
Frame for enhanced cooperation

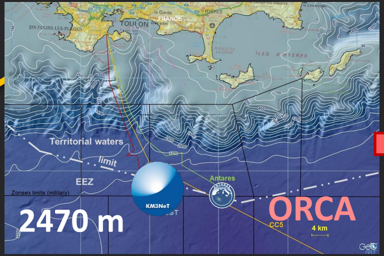
The KM3NeT detectors

Multi-site, deep-sea infrastructure

Single collaboration, Single technology

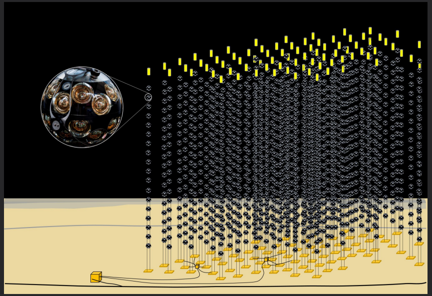
Two outstanding physics cases

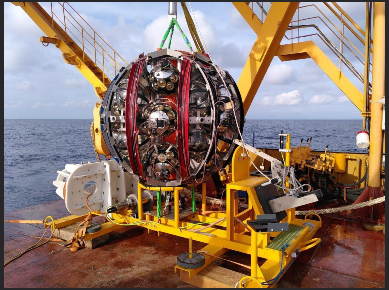


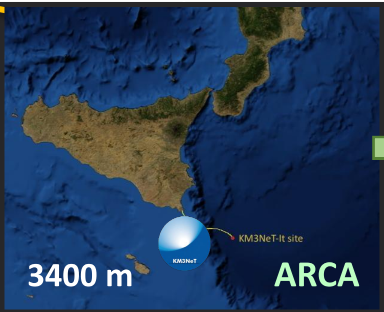


Oscillation **R**esearch with
Cosmics in the **A**byss

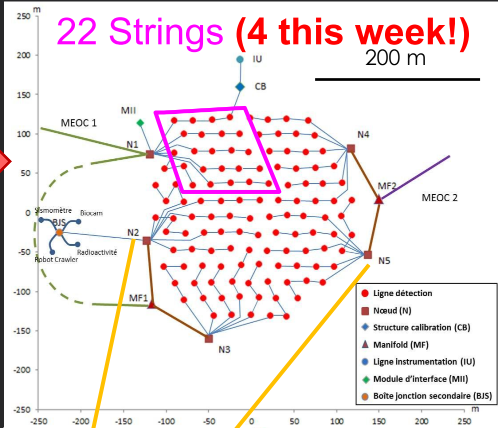
	ORCA	ARCA
Strings	**115**	**115 × 2**
String spacing	20 m	90 m
DOM spacing	9 m	36 m
Instrumented mass	7 Mton	500 × 2 Mton
Energy range	GeV	TeV – PeV

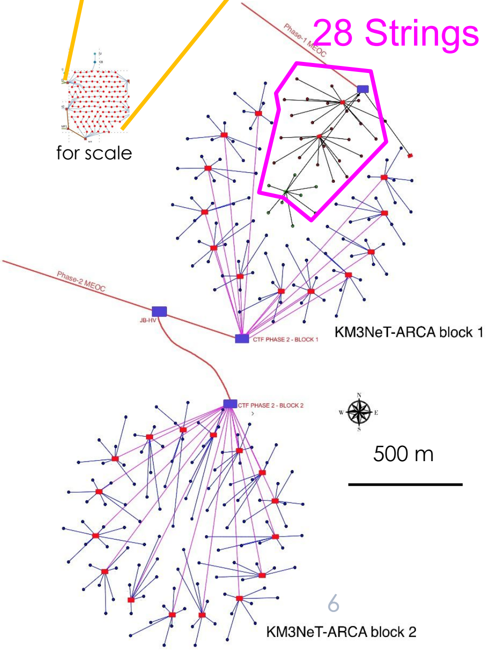






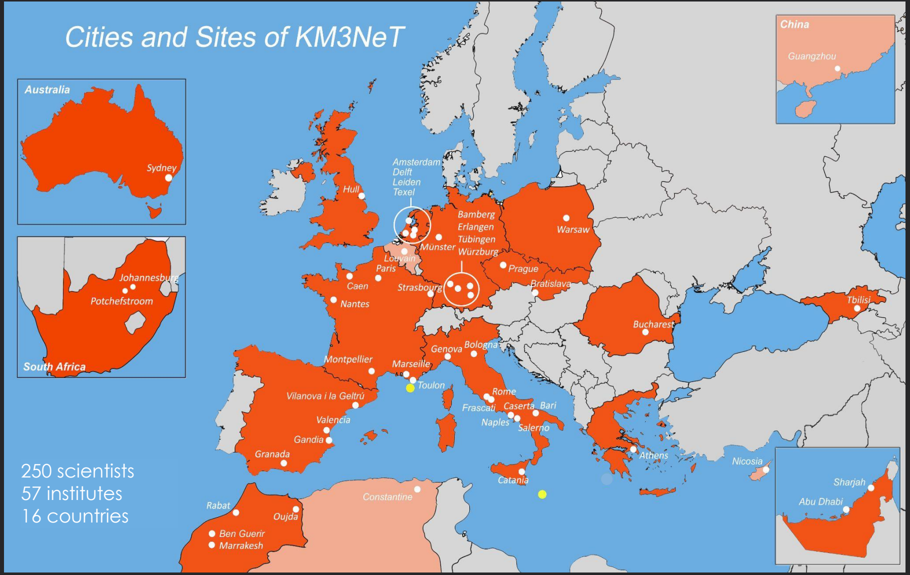
Astroparticle **R**esearch with
Cosmics in the **A**byss





The KM3NeT Collaboration

- The KM3NeT collaboration is **mostly european** based.
- There are **6 groups in Spain** involved (IFIC, UPV, UGR, IEO, UPC, ICM).
- Built upon previous projects in the Mediterranean: NESTOR, NEMO, and mainly **ANTARES**.


Cities and Sites of KM3NeT

250 scientists
57 institutes
16 countries

Paris CM, Oct 2023

Broad Physics Scope

KM3NeT - ARCA

KM3NeT - ARCA

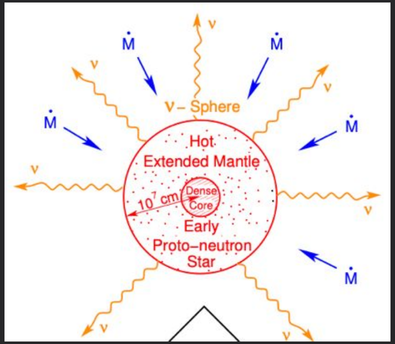
KM3NeT - ORCA

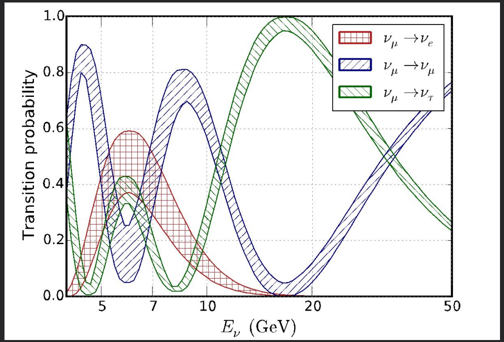
Low Energy
~ MeV

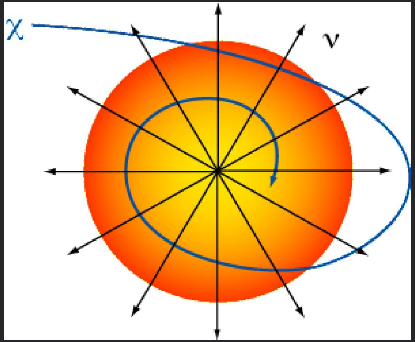
Low Energy
> 10 GeV

Medium Energy
$10\ \text{GeV} < E_\nu < 10\ \text{TeV}$

High Energy
$E_\nu > 1\ \text{TeV}$







E

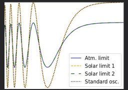
CCSN detection

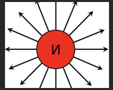
ν oscillations

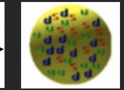
dark matter search

ν from extra-terrestrial sources
origin and production mechanism
of HE CR

…and exotic searches





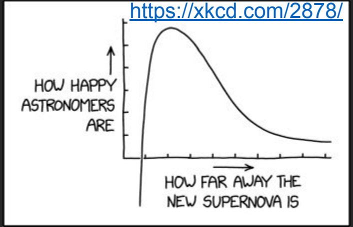


Results Highlights* - from low to high energies

- Supernovae explosions
- Neutrino Properties
- Dark Matter & Exotics searches
- Cosmic neutrinos & Multi-Messenger Astronomy

*new updates to be presented at “Neutrino 2024” conference in 2 weeks

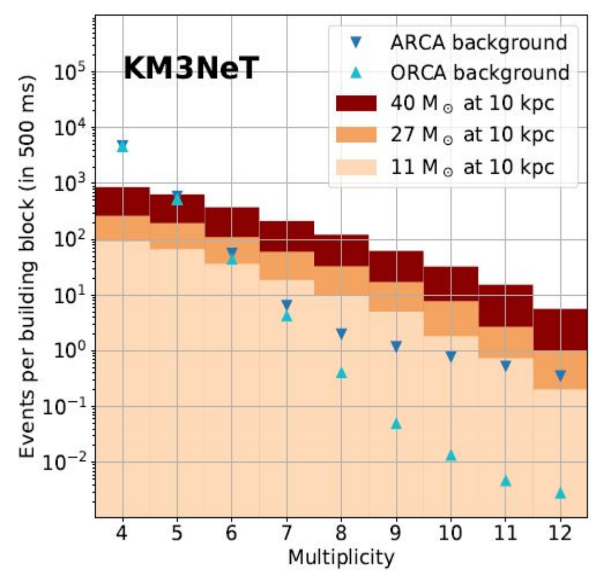
Supernovae Explosions



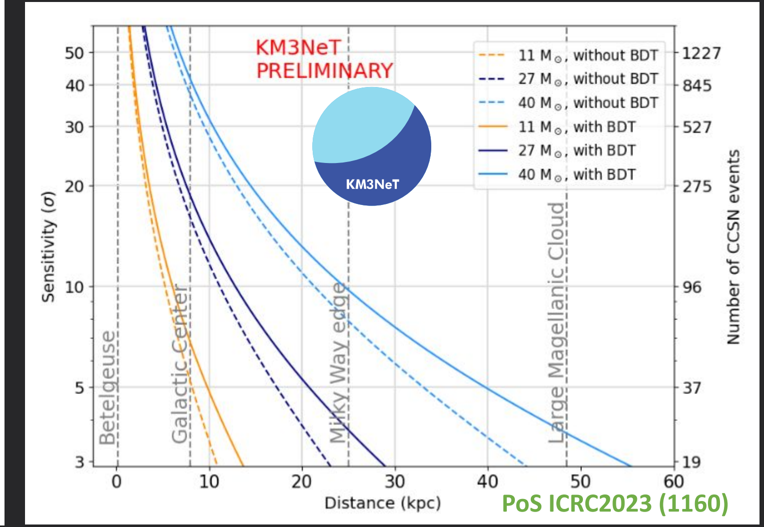
https://xkcd.com/2878/

Each single DOM
can act as a
detector

Aiello, S. et al. Eur. Phys. J. C 81, 445 (2021)



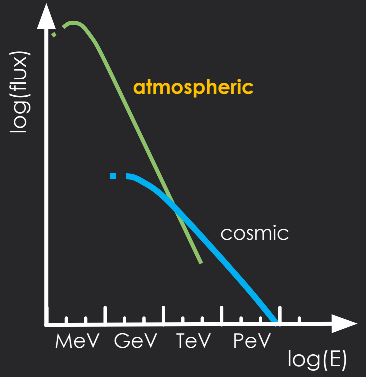
Assumes ARCA29 & ORCA24 configuration



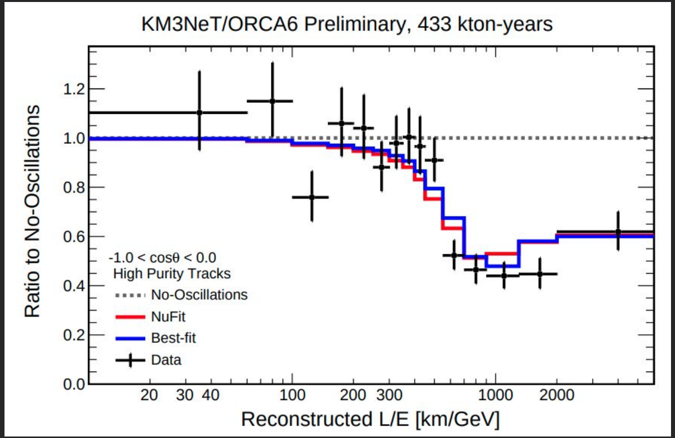
PoS ICRC2023 (1160)

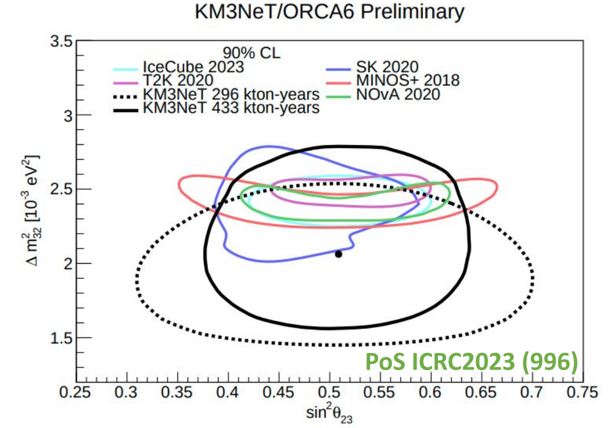
- Increase of the DOM rates due to many **MeV neutrinos** from the star collapse
- Alert system already operational!
- Integrated in the Supernova Early Warning System (SNEWS) network
- With the detector final configuration KM3NeT **will be sensitive to 96% of Galactic CCSNe**

Neutrino Physics - oscillations

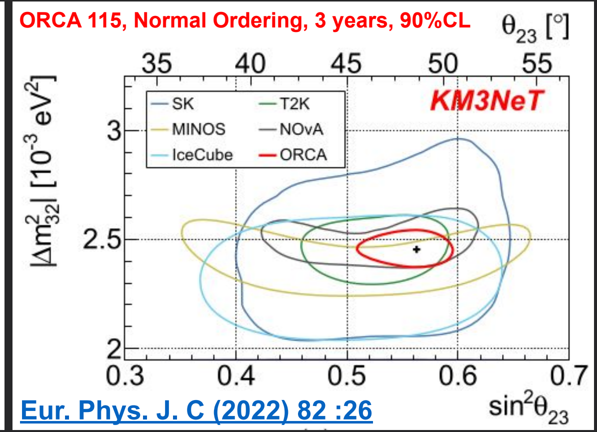


- In the ORCA energy range, once the overwhelming majority of atmospheric muons are filtered out, the dominant flux comes from **atmospherics neutrinos**.
- We can use them to study the neutrino properties, for instance: **neutrino oscillations**, neutrino mass ordering, and other exotic searches.
- With just a small fraction of ORCA (6 DUs) the first oscillation measurements have been already done. The results are compatible with other experiments.
- With the full ORCA detector we will do **world-class measurements** of oscillation parameters (Δm^2_{32}, θ_{23}).





PoS ICRC2023 (996)

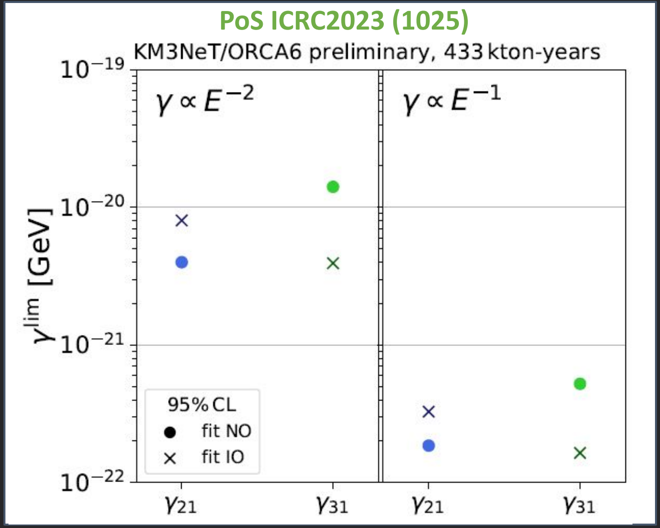


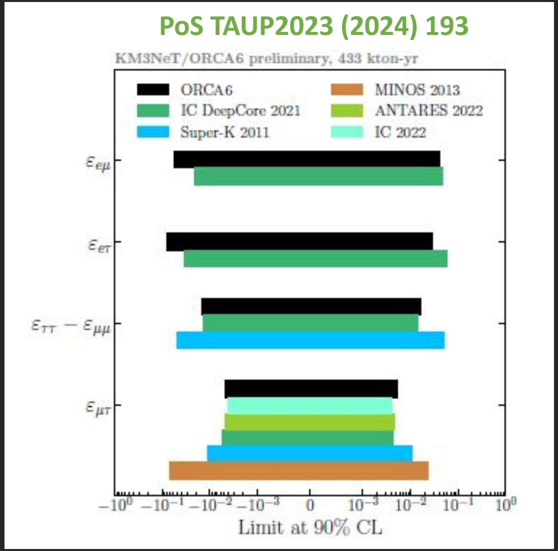
ORCA 115, Normal Ordering, 3 years, 90%CL

Eur. Phys. J. C (2022) 82 :26

Neutrino Physics - search for new physics

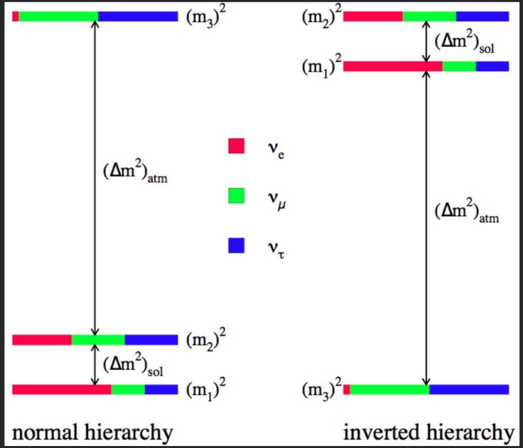
- Atmospheric neutrinos cover a **wide range of baselines and energies**: $10^{-4} < L/E_\nu < 10^{6}$ km/GeV, what makes them an excellent laboratory to test beyond the SM models.
- Among the new phenomena that can be searched for we can mention: **non-standard interactions, quantum decoherence,** sterile neutrinos/neutral heavy leptons, long live particles, Lorentz invariance violation, etc.
- The results obtained with 1.5 years of ORCA 6 data provide already **results.**

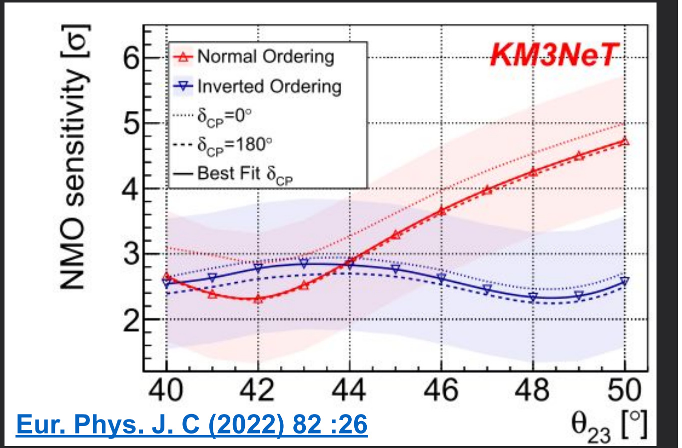

PoS ICRC2023 (1025)


PoS TAUP2023 (2024) 193

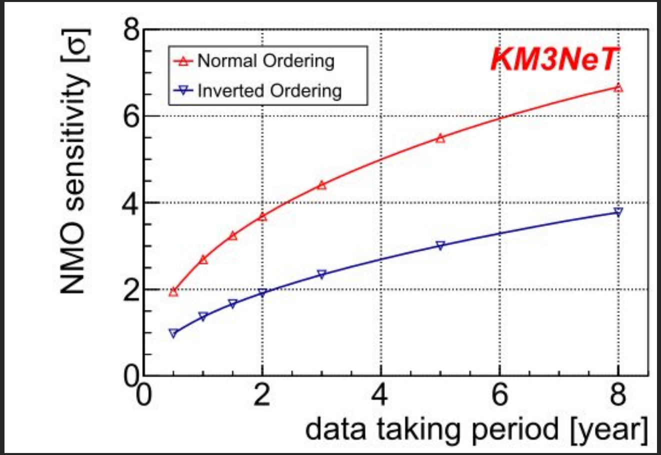
Neutrino Physics - neutrino mass ordering

- **Neutrino mass hierarchy** (normal or inverted) can be studied with high precision with ORCA.
- Even if we cannot distinguish between ν and anti-ν, on an event by event basis, we can determine the mass hierarchy by observing net differences in the event rates.
- During the lifetime of the experiment we should be **able to answer this fundamental question**.
- Synergies with reactor experiments (e.g. JUNO) should speed up the answer.





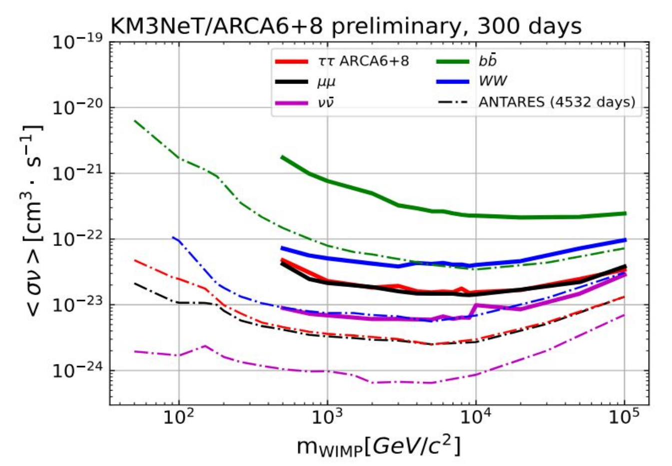
Eur. Phys. J. C (2022) 82 :26



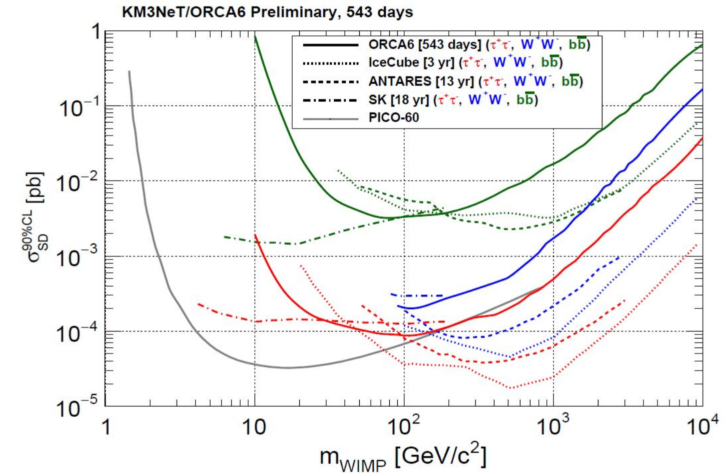
Dark Matter & Exotic searches

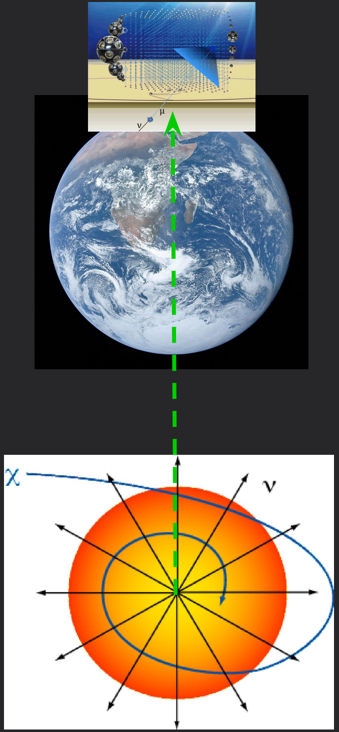
- Dark Matter candidates are expected to be trapped in massive objects, then decay or annihilate producing neutrinos that could be observed (indirect detection) by neutrino telescopes.
- First results with ARCA6-8 for both Galactic Center [**PoS ICRC2023 (1406)**] and Sun as targets [**PoS ICRC2023 (1377)**].
- Other exotic searches: monopoles or nuclearites are also possible.

Galactic Center

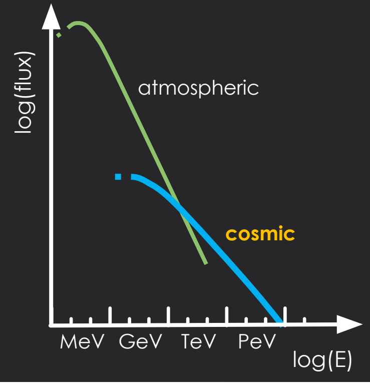


Sun

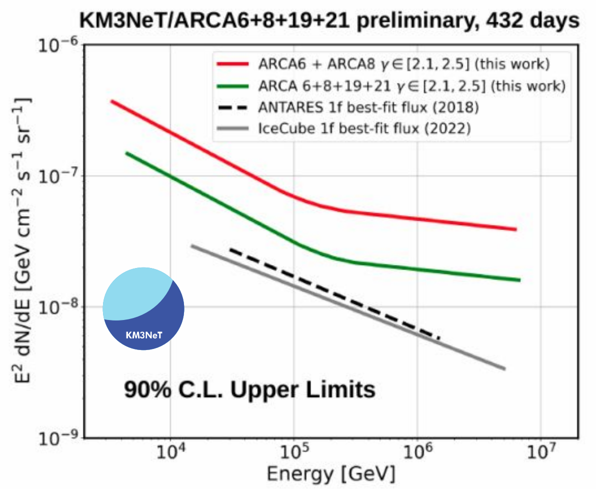


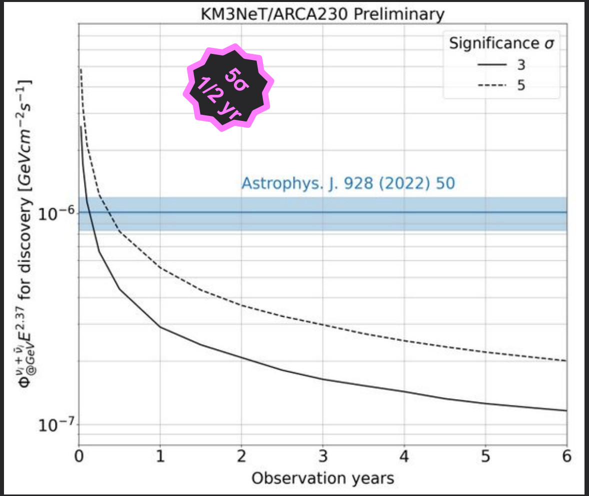


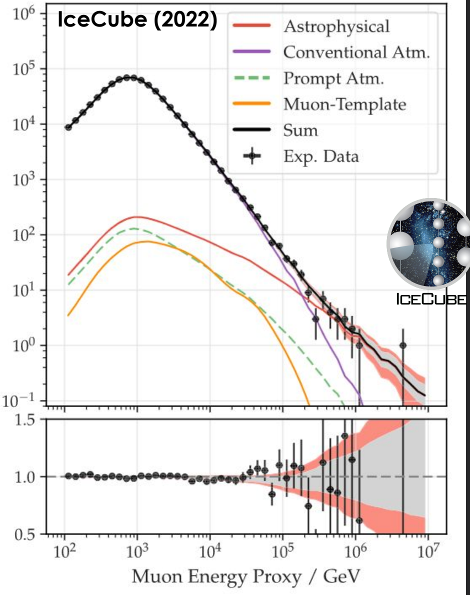
Cosmic Diffuse Neutrino Emission



- Probably the main goal of a Neutrino Telescope is to do **astronomy.**
- High-energy **cosmic neutrinos observed** by the IceCube collaboration in 2013.
- ANTARES: mild 1.8 σ excess with ~9 years of data: 50 events (27 tr + 23 sh) observed while 36.1 ± 8.7 (19.9 tr + 16.2 sh) expected from background.
- KM3NeT/ARCA6+8+18+21: 432 days, no excess, **PoS(IRC2023)1195.**

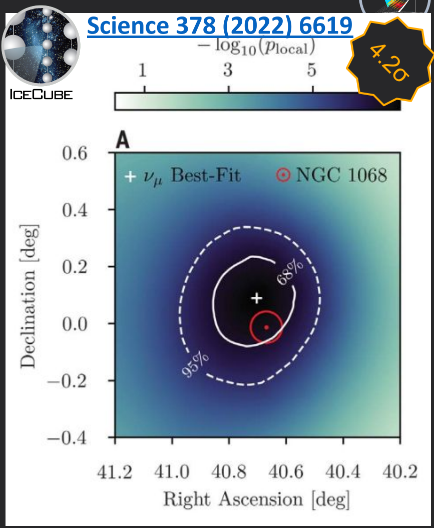




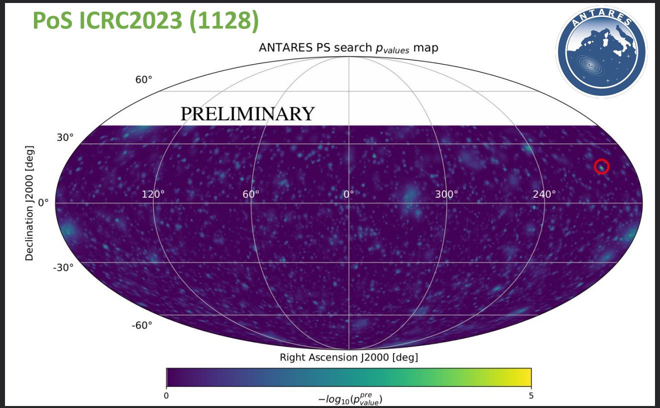


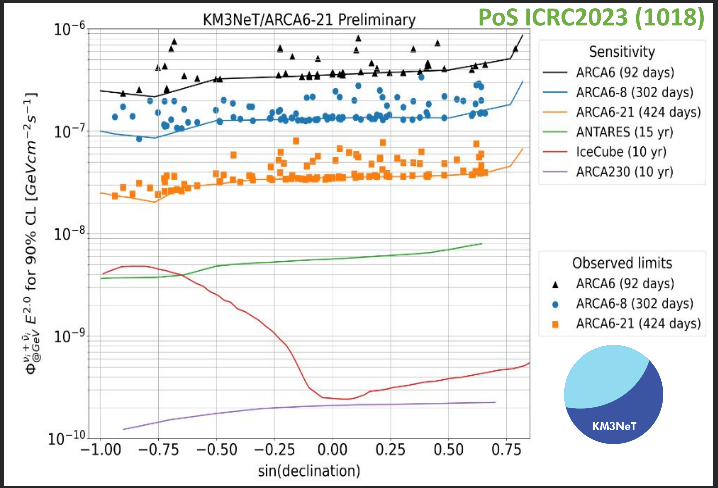
Search for Cosmic Neutrino Sources

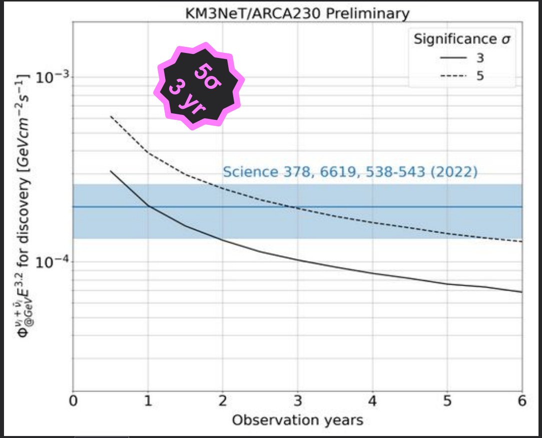
- Different type of searches: time-dependent, time-integrated, all-sky search, candidate list search, catalog-stacked, etc.
- **ANTARES** all-sky time-integrated search: most significant spot 1.2σ (post-trial), no evident association. No significant excess from the 163 candidates, best 1.7σ. Known IceCube source **TXS0506+056 in top 5**.
- **KM3NeT** alone, no significant excess. Combined searches (ANTARES & KM3NeT) ongoing.
- **IceCube**: NGC1068 **4.2σ** other Seyfert Galaxies 2.7σ global significance [**PoS(ICRC2023)1052**].


Science 378 (2022) 6619

4.2σ

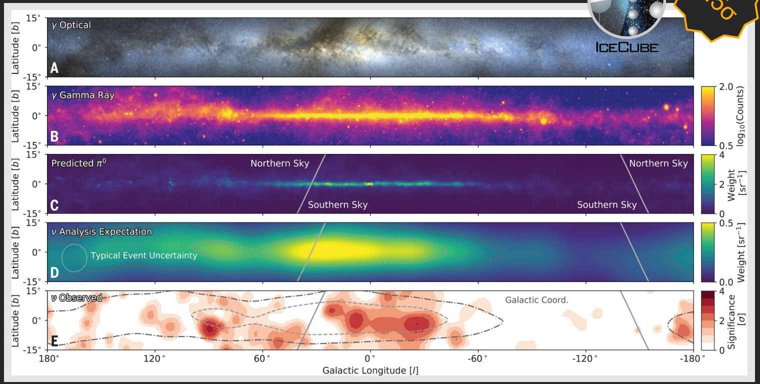

PoS ICRC2023 (1128)

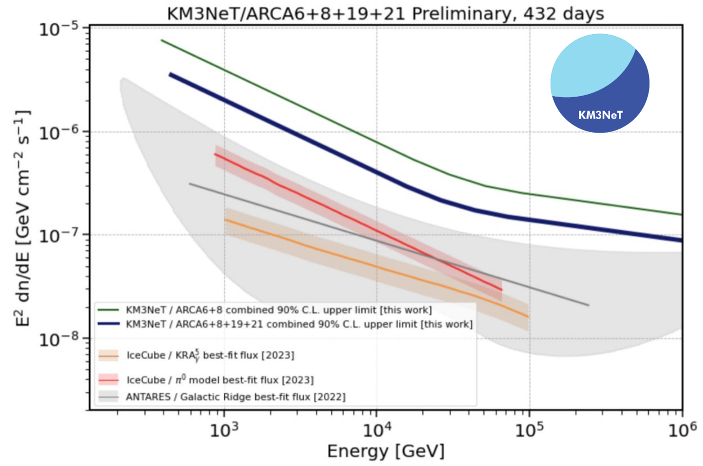

PoS ICRC2023 (1018)

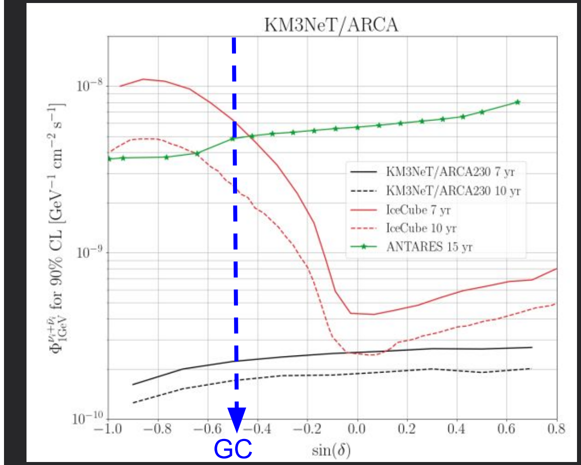

5σ 3 yr

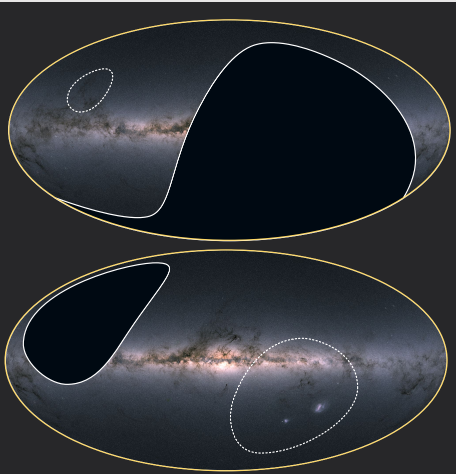
Galactic Neutrino Diffuse Emission

- A Galactic component contributing to the cosmic neutrino diffuse flux announced **last year** by ANTARES (**2 σ**) and IceCube (**4.5 σ**).
- ANTARES ON/OFF analysis at E>1 TeV detects 21 (13) track (shower) events while ~12 tracks (~11 showers) events are expected, 2.2 (0.2) σ excess. ANTARES template analysis, comparing with models, shows a 1.5-1.8 σ excess.
- KM3NeT/ARCA6+8+18+21: short lifetime (432 days), so far no excess, **PoS(IRC2023)1190**.





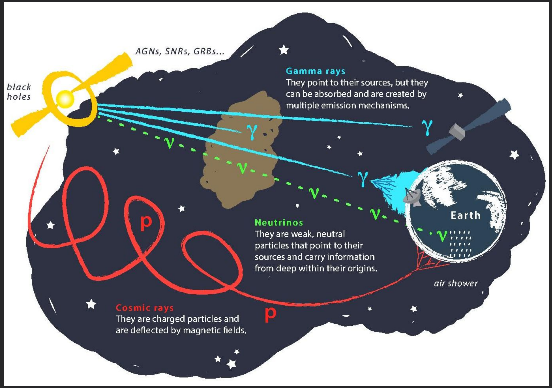


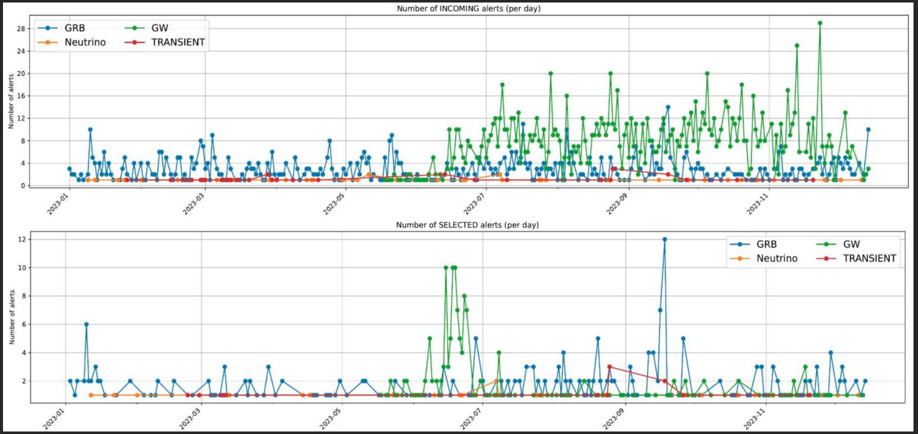


Real Time Multi-Messenger Program

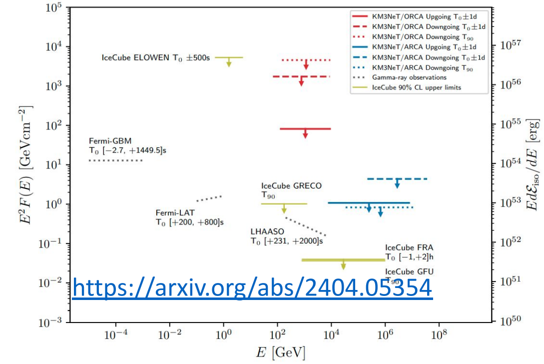
- **Different messengers** are expected to be **produced** and accelerated at cosmic sources.
- **Multi-Messenger astronomy** is the combination of observations: background reduction, enhance detection chances, allows comprehensive study of astrophysical phenomena.
- Famous MM events: **TXS0506+056** (1^{st} HE neutrino source), **GW170817** (kilonova observation).
- KM3NeT has prepared a system (online & offline) for both following-up and sending alerts.
- **Best neutrino telescope angular resolution**, once completed: <0.1° (HE tracks), <2° (showers).

Reminder: Neutrino telescopes cover mainly ½ sky at any time and are not pointing instruments.

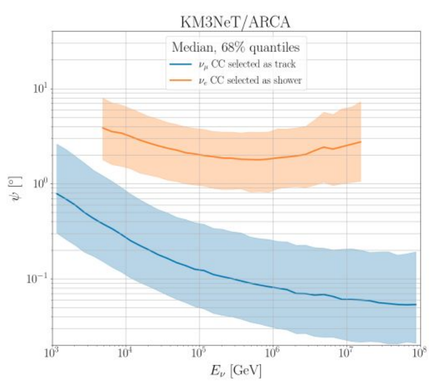




GRB 221009A

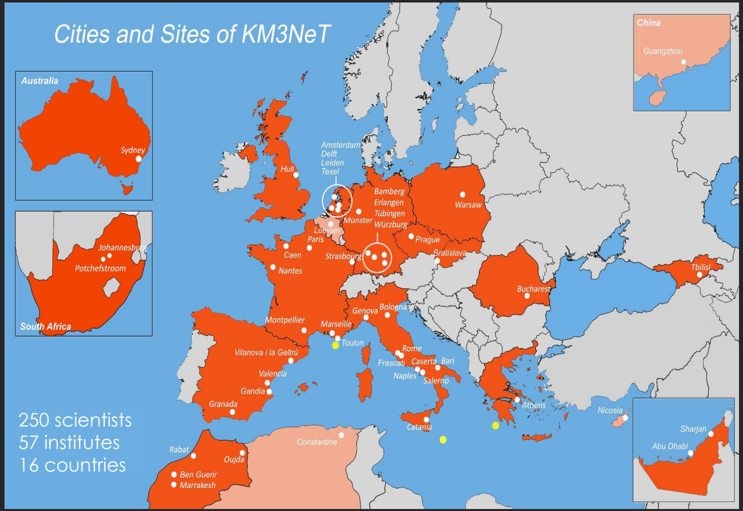


https://arxiv.org/abs/2404.05354



Spanish groups in KM3NeT

- There are 6 Spanish groups in KM3NeT:
    - **IFIC** (Institut de Física Corpuscular - CSIC):
    19 members, astroparticle, dark matter & exotics, neutrino properties, electronics.
    - **UPV** (Universitat Politècnica de València):
    4 members, dark matter, acoustics.
    - **UGR** (Universidad de Granada):
    5 members, astroparticle, dark matter, electronics.
    - **IEO** (Instituto Español de Oceanografía - CSIC):
    1 member, acoustics.
    - **UPC** (Universitat Politècnica de Catalunya):
    1 member, acoustics (Earth sciences).
    - **ICM** (Institut de Ciències el Mar - CSIC):
    2 members, acoustics (Earth sciences).

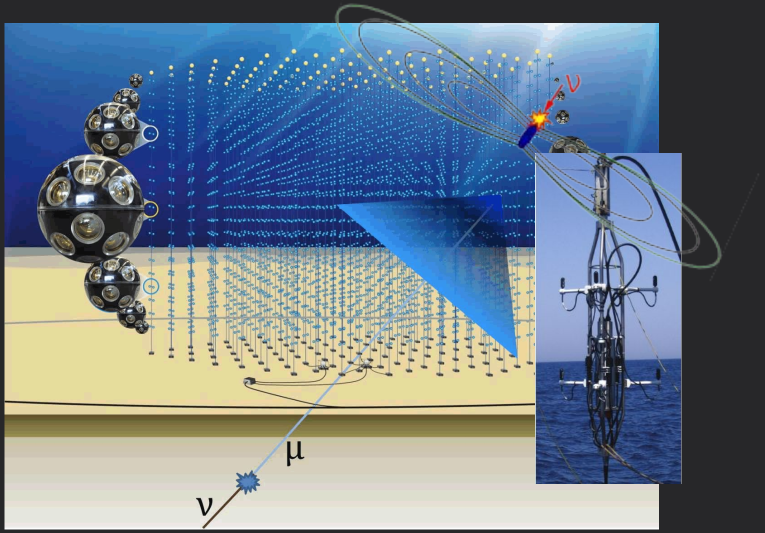


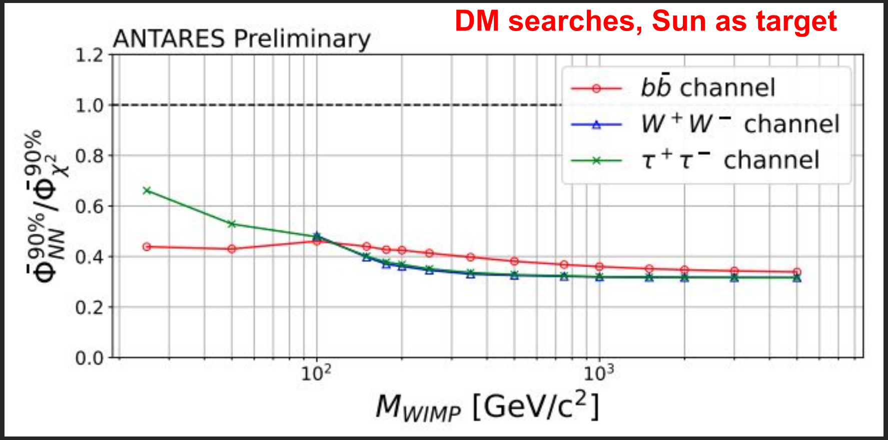
Two types of membership:

- **Full member**
- **Observer**

“Planes Complementarios AstroHEP” projects

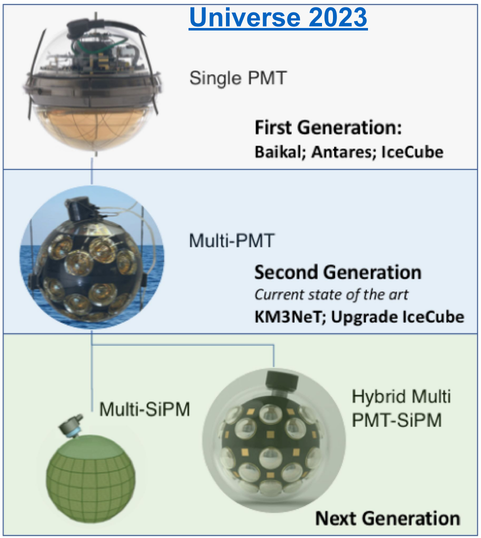
- ASFAE/2022/014: “Telescopios submarinos de neutrinos: nuevas perspectivas” (**UPV**)
  - Towards a hybrid optical-acoustic neutrino telescope: Extending detection to the ultra-energetic range (>10 PeV). Developing an acoustic antenna to enable the detection of neutrinos based on knowledge gained from the existing acoustic monitoring system for positioning.
  - Machine learning algorithms for ANTARES/KM3NeT: improvement at low energies (~GeV).

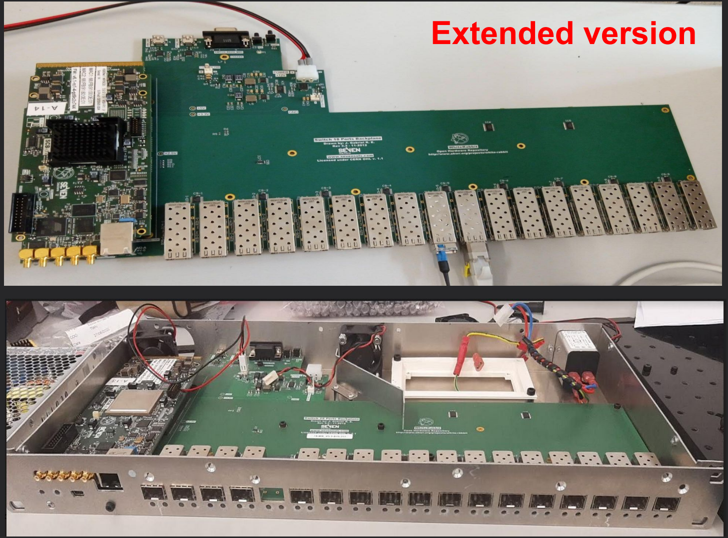



DM searches, Sun as target

“Planes Complementarios AstroHEP” projects

- ASFAE/2022/023: “ASTROSYNC: Advanced acquisition and synchronization for Astrophysics” (**IFIC**)
  - Developing an advanced acquisition system capable of operating in a distributed manner with sub-nanosecond time synchronization (Electronics 2023), taking as a starting point the KM3NeT White Rabbit (WR) Switching Core Board.
  - Readout from PMTs (and SiPMs) with TDCs and ADCs using low resources (TechRxiv 2024 & Sensors 2024).

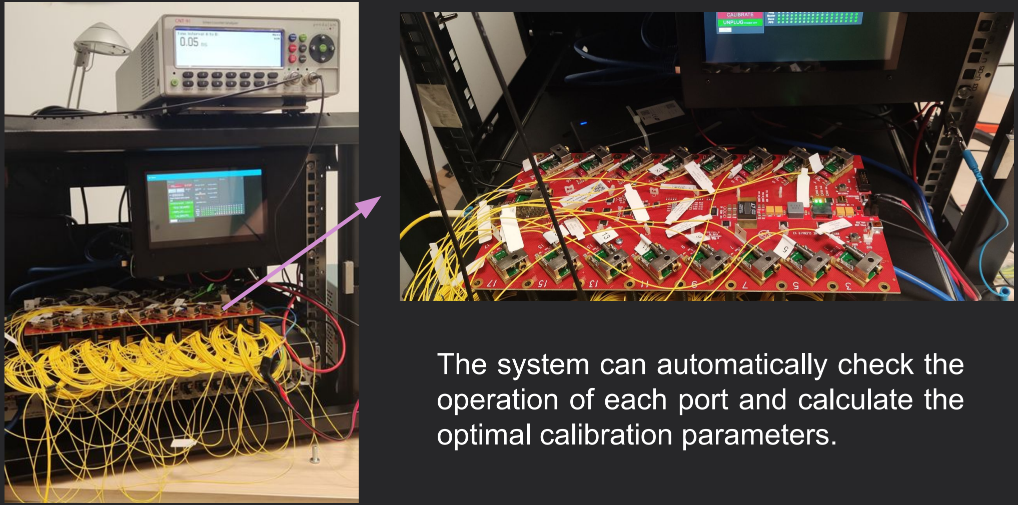




“Planes Complementarios AstroHEP” projects

UNIVERSIDAD DE GRANADA

- AST22.6.2: “Instrumentación para telescopios de neutrinos” (**UGR**)
  - Develop a system for the characterization and analysis of WR-based synchronization and acquisition networks.
  - Guarantee sub-nanosecond synchronizations and support a high data rate based on switches and slave nodes.
  - Develop a system able to send test signals, monitor for lost data packets, keep network synchronization, check the quality at different points.



The system can automatically check the operation of each port and calculate the optimal calibration parameters.

Summary

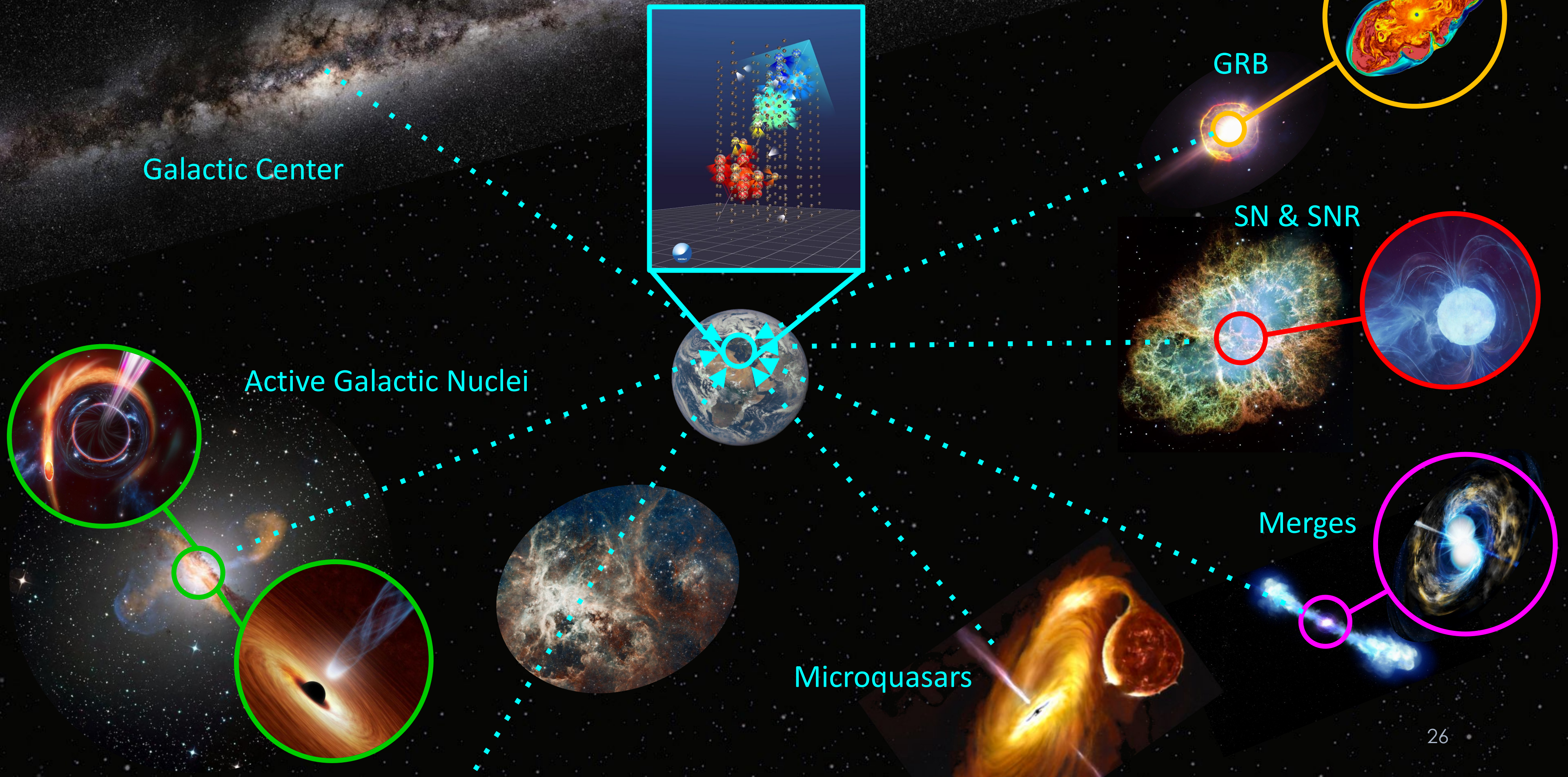
- Neutrino telescopes are powerful instruments covering a wide E range with a broad scientific scope.
- A fraction of KM3NeT is already operational and is providing relevant results in both neutrino and astroparticle physics.
- KM3NeT is progressively growing, aiming to reach its final configuration around 2028.
- The work through the AstroHEP projects aims to enhance the performance of current and next-generation experiments.

Thanks for your attention

VEGA
Valencia
Experimental
Group of
Astroparticles

Bonus slides

Cosmic Neutrinos



Galactic Center

GRB

SN & SNR

Active Galactic Nuclei

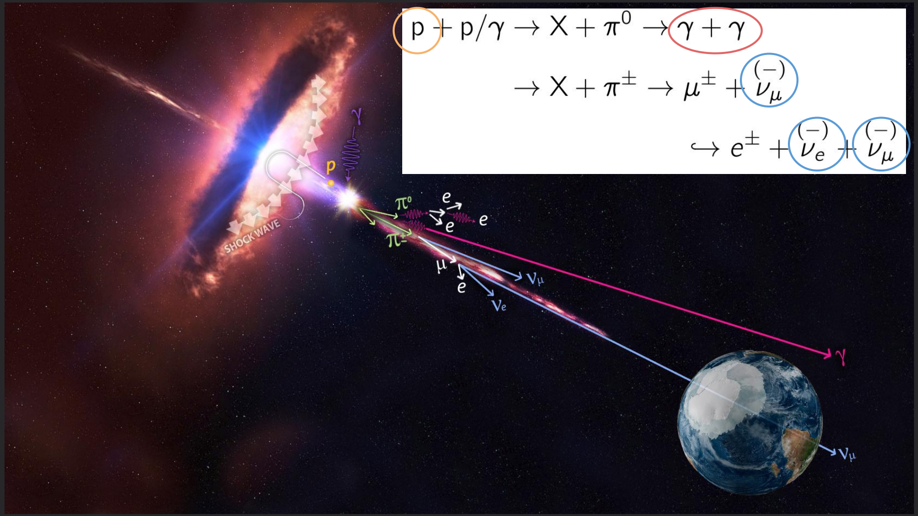
Merges

Microquasars

The Multi-Messenger Connection

- Cosmic accelerators can produce different *messengers*: **CRs**, **gamma rays**, **neutrinos**, and **gravitational waves**.
- **Common origin**: **CR** accelerators produce both γ and ν through hadronic processes: **pγ** and **pp** interactions.
- **Gamma rays** can also be produced in leptonic processes: synchrotron, inverse Compton.
- **Neutrinos can unambiguously reveal the CR sources.**

- They all have **pros and cons** when doing astronomy:
  - **Cosmic rays**: can reach UHE (>EeV) but deflected by the magnetic fields.
  - **Gamma rays**: very abundant, but absorbed at VHE (>TeV).
  - **Neutrinos**: neutral and unabsorbed can probe long distances, but small cross-section require huge detectors.
  - **Gravitational waves**: come from long distances and point back to the source, but poor localization and for now only few types of mergers (BH, NS).



$$
\begin{aligned}
p + p/\gamma &\rightarrow X + \pi^0 \rightarrow \gamma + \gamma \\
&\rightarrow X + \pi^\pm \rightarrow \mu^\pm + \overset{(-)}{\nu}_\mu \\
&\qquad\qquad \hookrightarrow e^\pm + \overset{(-)}{\nu}_e + \overset{(-)}{\nu}_\mu
\end{aligned}
$$

Multi-messenger astronomy concept: Combination of two or more messengers in spatial and/or temporal coincidence enhancing the discovery potential of a source.

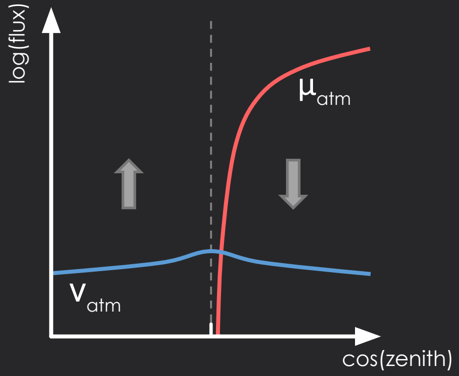
nu+γ/radio GW **nu** follow-ups

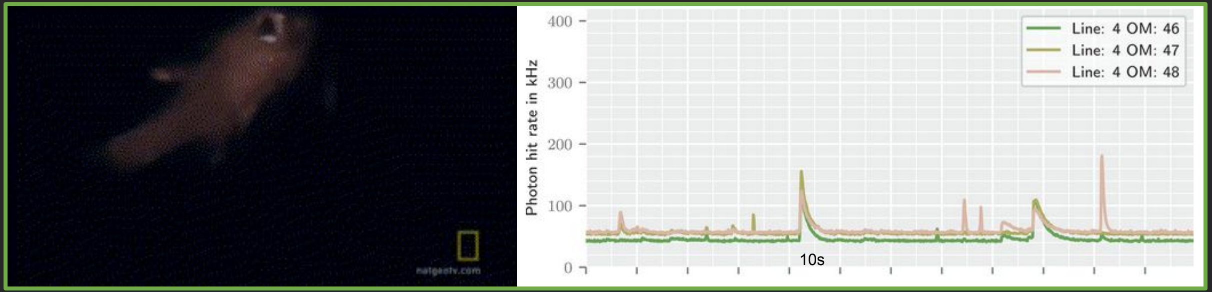
nu+nu **nu-CR**

Backgrounds

- **Atmospheric Muons**: downgoing muon tracks, from CR, depth dependent.
- **Atmospheric Neutrinos**: isotropic, soft energy spectrum neutrinos, from CR.

- **Light backgrounds in water:**
  - **^{40}K**: β decay (~1.3 MeV vs water $\check{C}_{th}$ ~0.8 MeV) of ^{40}K (120 ppm K) from **K Cl**, 2,5% in seawater salt.
  - **Bioluminescence**: long light events (seconds), seasonal component.



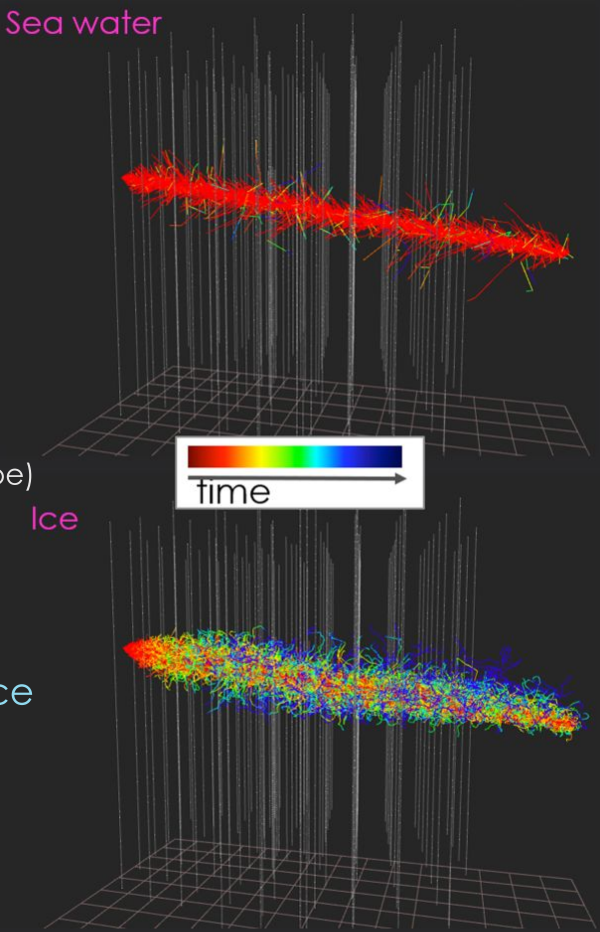


Event reconstruction

- Event topology fits over all detected photons (hits)
- Impact from optical properties:
  - Absorption length:
    - water, blue(UV): 60(26) m (ANTARES)
    - ice, top[dust](bottom): 40[20]300 m (IceCube)
  - Scattering length:
    - water, blue(UV): 265(122) m (ANTARES)
    - ice: 5-50 m, depth dep., anisotropies,... complex → ice model (IceCube)

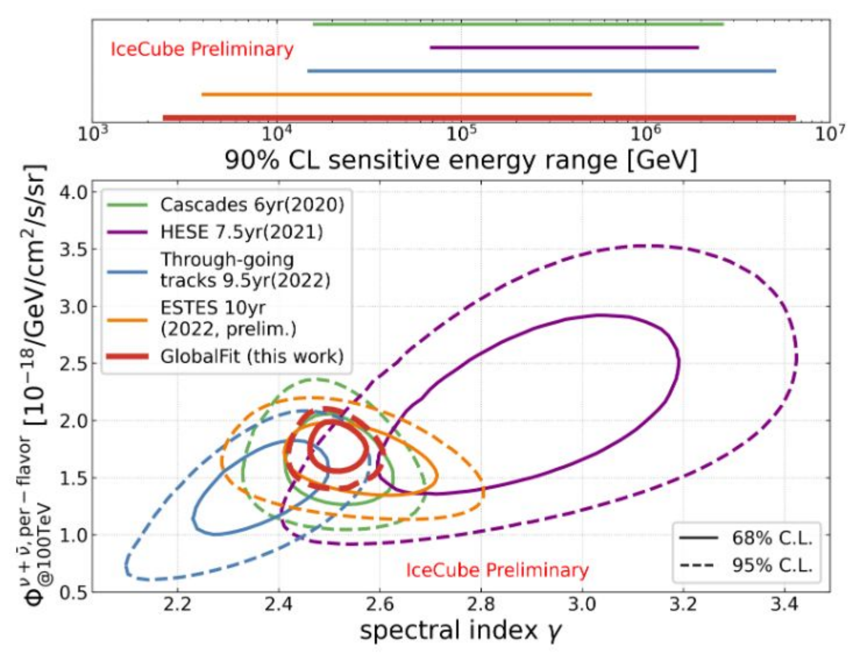
water → optimal pointing accuracy | ice → better calorimeter

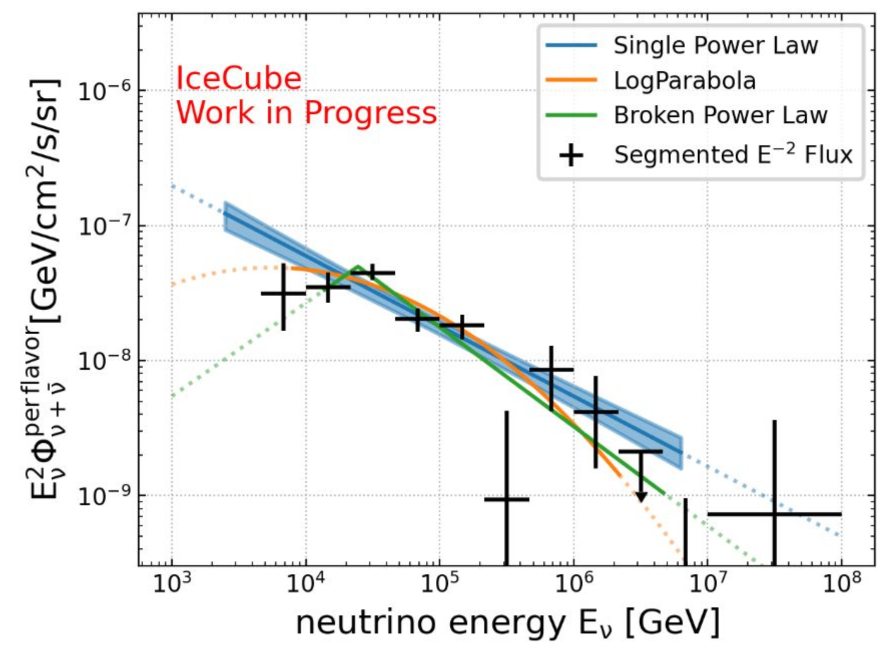
- Light speed events: positioning + time relative calibrations critical
  - Time: ~1 ns; beacons, muons, electronics (e.g. WhiteRabbit)
  - Positioning: ~10 cm; real time for water (acoustic), fixed for ice
- Energy resolution: energy scale calibration
- ML revolution: improving reconstruction, direction and energy
- Challenging!



Cosmic Diffuse Emission

IceCube fit to the astrophysical neutrino flux





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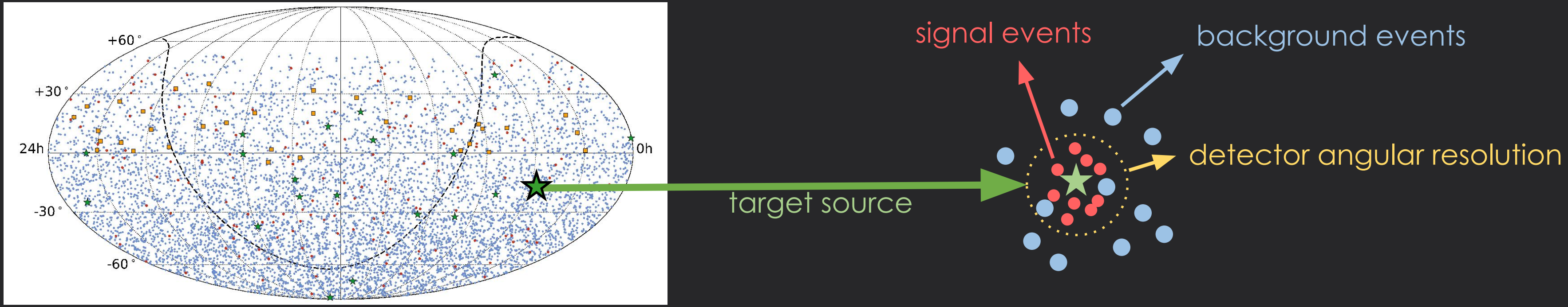
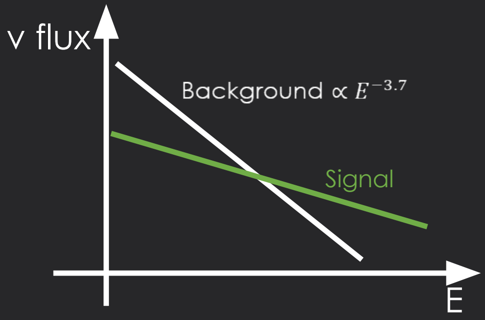
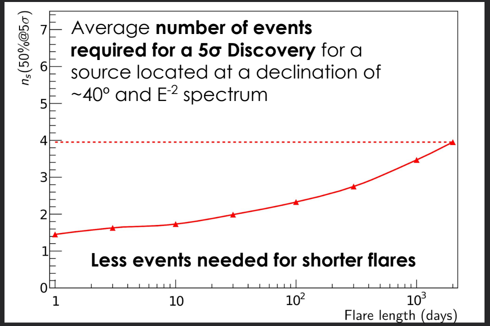
Statistical analyses on Direction-Energy-Time

- **Spatial** distribution: compatible with point-like/extended sources?

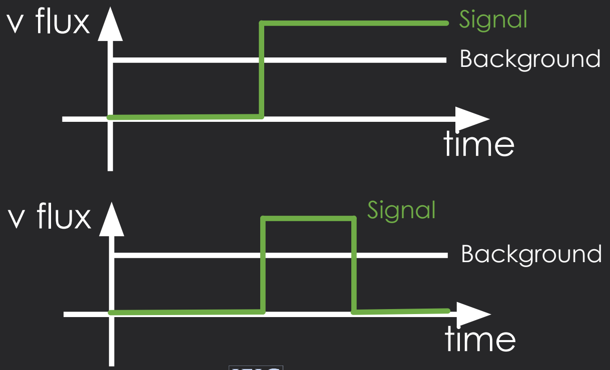


- **Energy** spectrum: compatible with signal expectation?





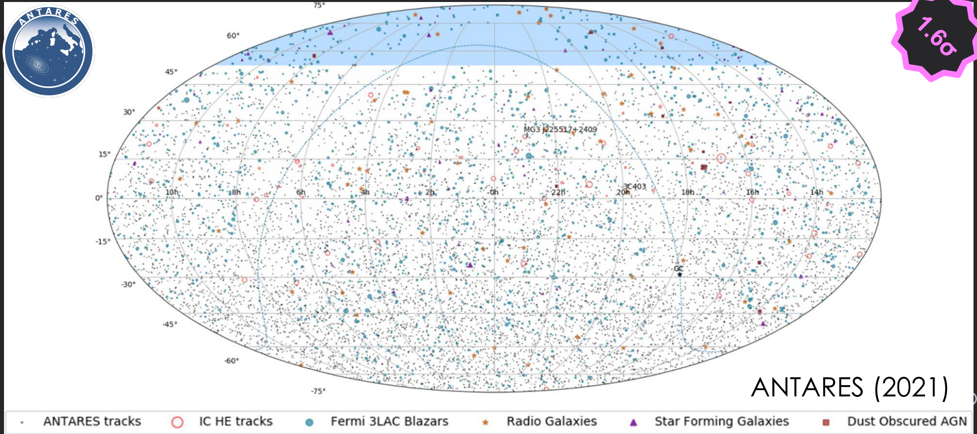
- Arrival **time**: limited to a transient signal hypothesis?



Catalogue Searches

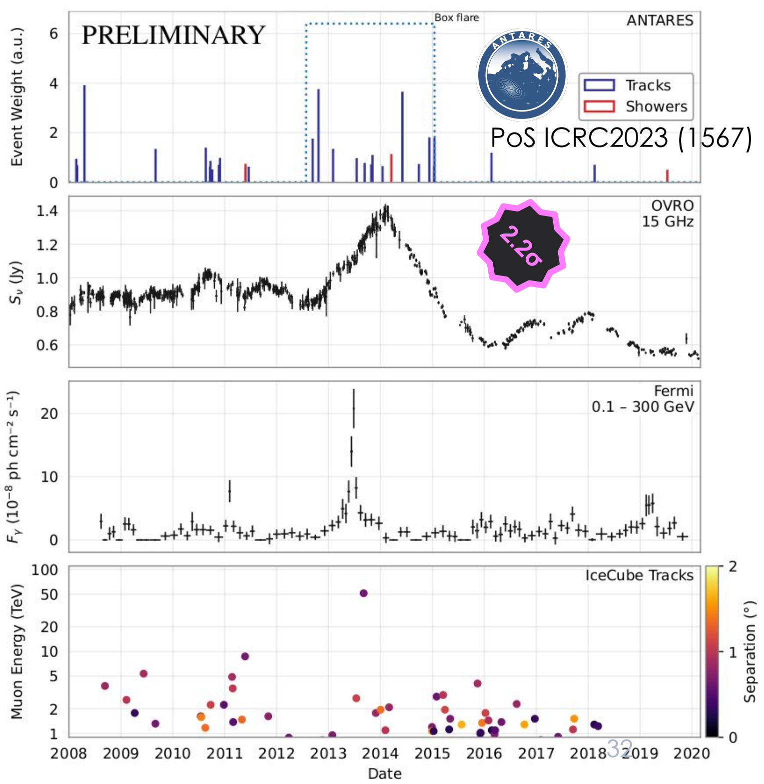
- Different catalogues tested in ANTARES (11 years). The most significant: Radio Galaxies pre(post)-trial **2.8 (1.6) σ** excess.
- New analysis: updated radio-bright (VLBI) blazars catalog +2 yr data. Counting and likelihood analyses consistent (**2.2 σ**).
- Additional search for neutrino flares (untriggered) show 18 sources (out of 2744 tested) with pre-trial significance **>3 σ** pre-trial (background probability of this 1.4%, **2.5 σ**).
- **Both time-integrated and time-dependent analyses hint that some blazars might emit neutrinos.**
- Interesting case of J0242+1101, showing temporal coincidence with gamma and radio flares and also coincident with a high-energy IceCube track. Chance coincidence probability 0.5% (caveat: coincidence found a posteriori, assumptions made in this estimation).

2.5σ



ANTARES (2021)

1.6σ



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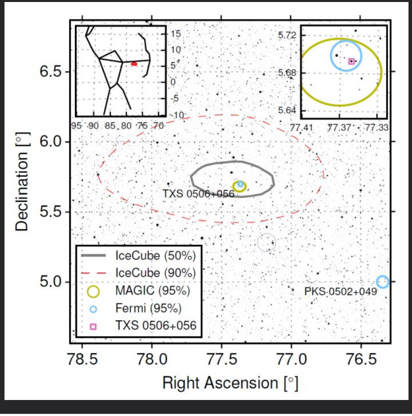
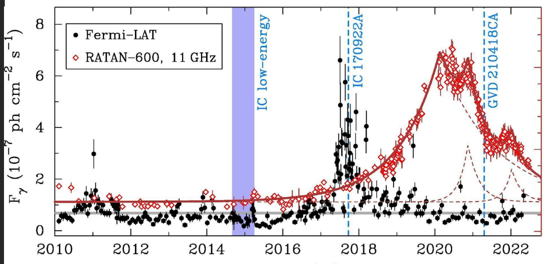
2.2σ

TXS 0506+056

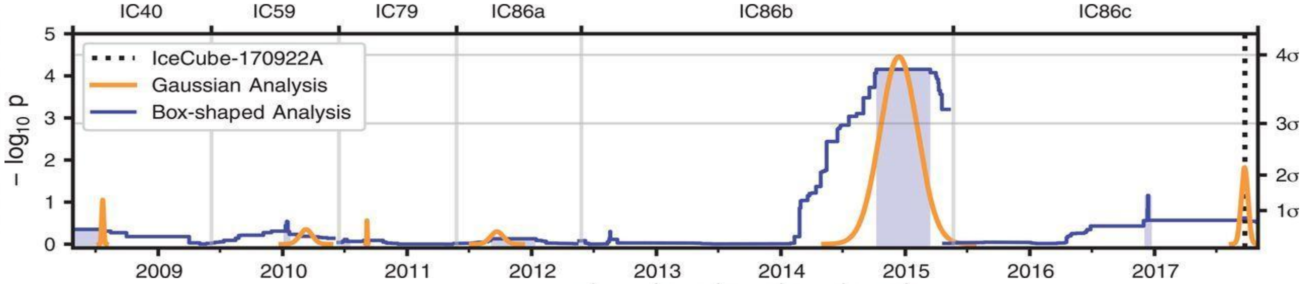
- On Sep 22nd 2017 an IceCube **neutrino** event (IC170922A) was detected in coincidence with **gamma rays** (Fermi & MAGIC) from the blazar TXS 0506+056 in a flaring state (3σ)
- Archival data revealed a previous neutrino emission from the same blazar (3.5σ, independent)
- Second best source in ANTARES 13yr search (2.8σ pre-trial, later 2.2σ pre-trial)

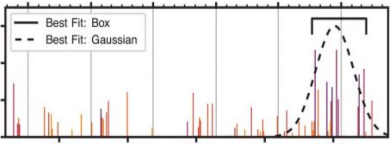
Science 361, 147-151 (2018)

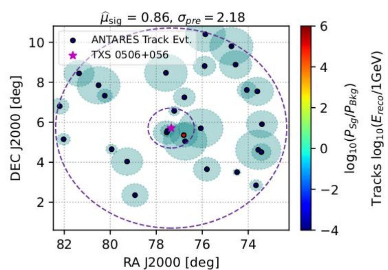


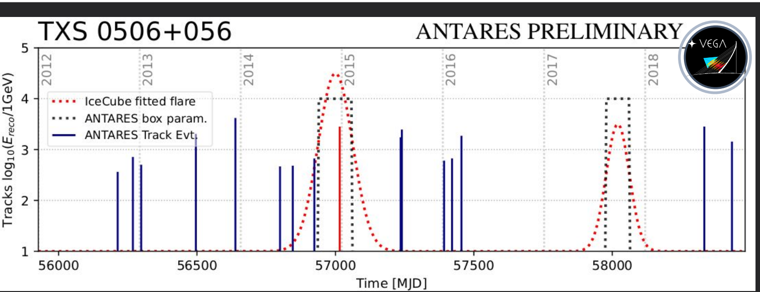


MNRAS 527, 3 (2023)









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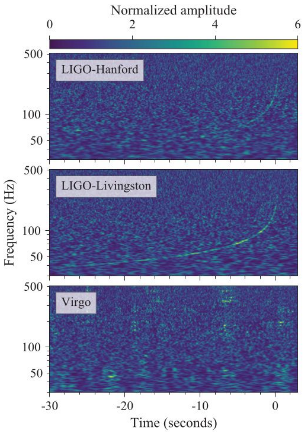
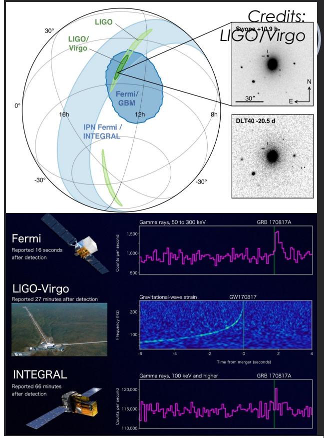
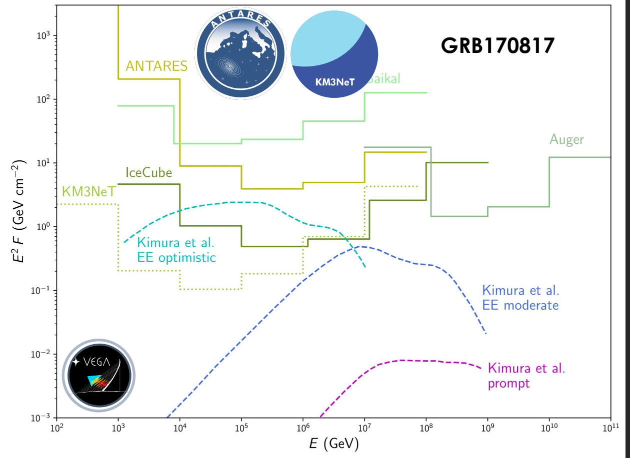
GW+nu

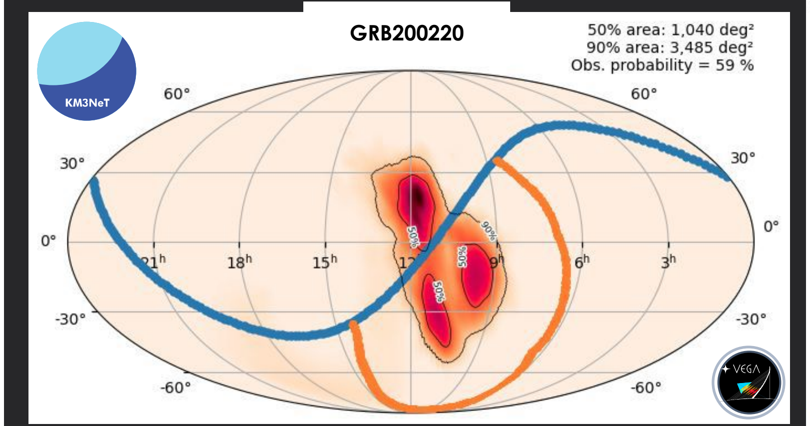
On Aug 17th 2017 a gravitational wave (**GW170817**) was detected by LIGO-Virgo and less than 2 seconds after, a Gamma-ray Burst (**GRB170817A**) was detected by Fermi and INTEGRAL. The GW was caused by two neutron stars merging. That single event confirmed what is called Kilonova, a type of short gamma ray bursts.







Estimation of the sensitivity of the complete KM3NeT detector to constrain models



Follow-up of Gravitational Wave events (run 03) with ORCA

- Search for 1000s in 30 degree area around the GW confidence region.
- Limits on neutrino flux of 55 GW events in MeV and GeV-TeV ranges.

KM3NeT Preliminary

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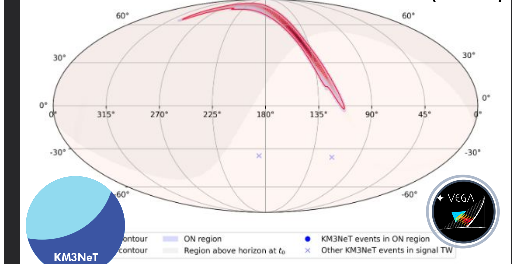
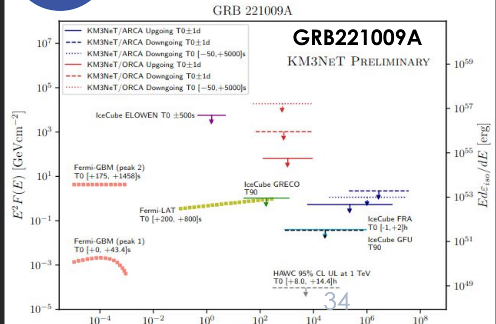




PoS ICRC2023 (1503)

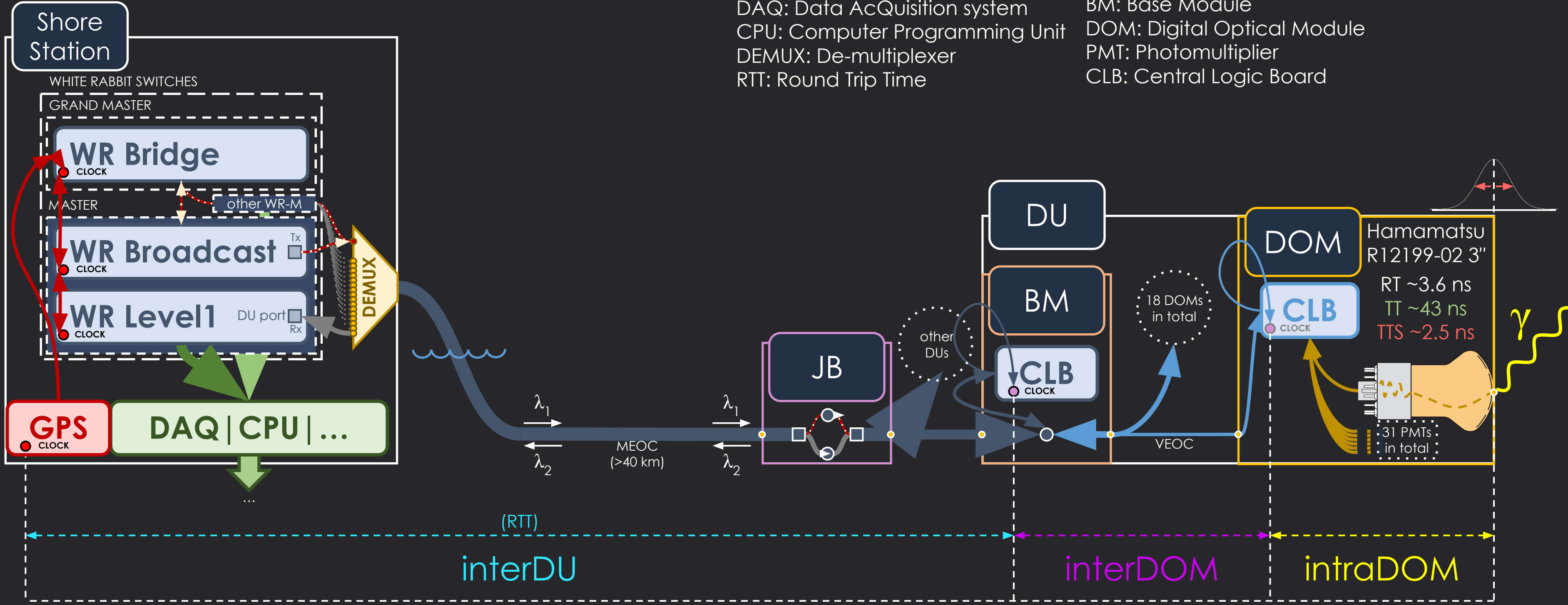
DON'T PANIC

Sea SC/DC paths (†)

SOME ACRONYMS

SC: Slow Control
DC: Detector Control
WR: White Rabbit
GPS: Global Positioning System
DAQ: Data AcQuisition system
CPU: Computer Programming Unit
DEMUX: De-multiplexer
RTT: Round Trip Time

MEOC: Main Electro-Optical Cabel
VEOC: Vertical Electro-Optical Cable
JB: Junction Box
DU: Detector Unit
BM: Base Module
DOM: Digital Optical Module
PMT: Photomultiplier
CLB: Central Logic Board



(†): All specifications subject to change without notice.

The End