Online analysis framework in the KM3NeT neutrino telescope

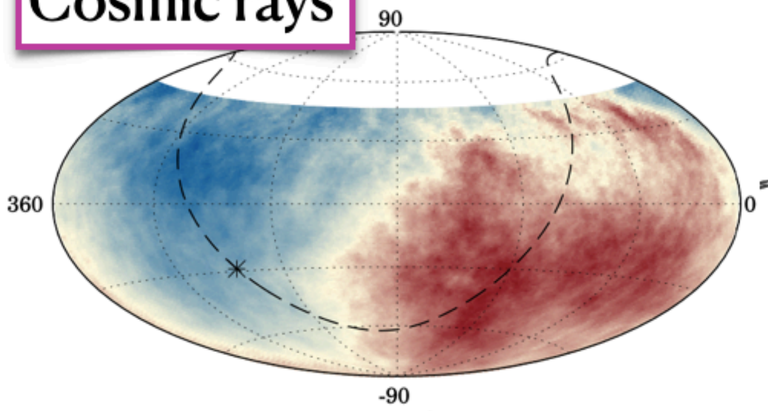
Angela Zegarelli
Sapienza University, Rome

angela.zegarelli@roma1.infn.it
angela.zegarelli@uniroma1.it

On behalf of the KM3NeT Collaboration

Multi-messenger astronomy

Cosmic rays

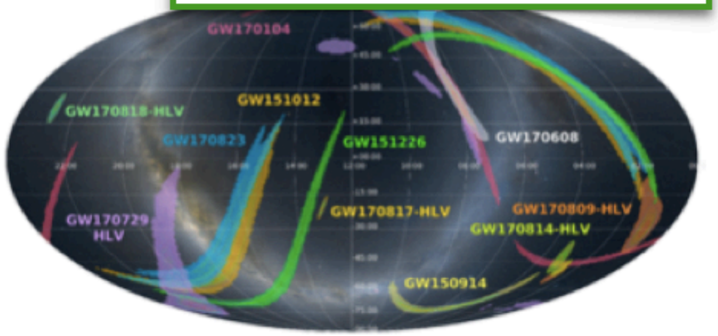


Pierre Auger Observatory

UHECRs

> EeV

Gravitational Waves

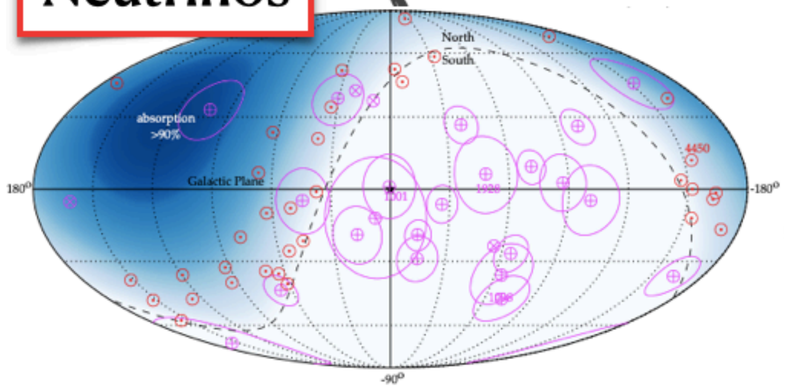


LIGO-Virgo GWs

The sky is full of messengers

Each of these signals carries a message. What can they tell us?

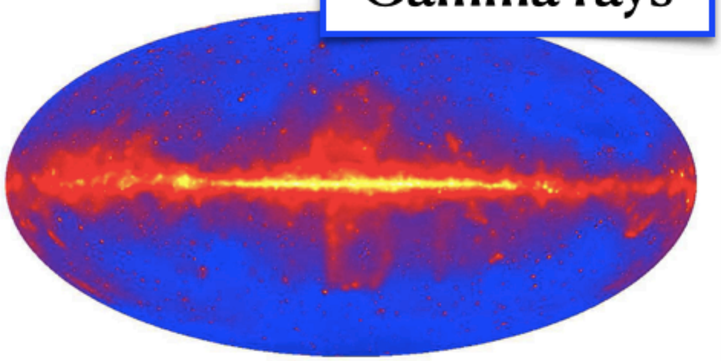
Neutrinos



IceCube astrophysical neutrino events

TeV-PeV

Gamma rays

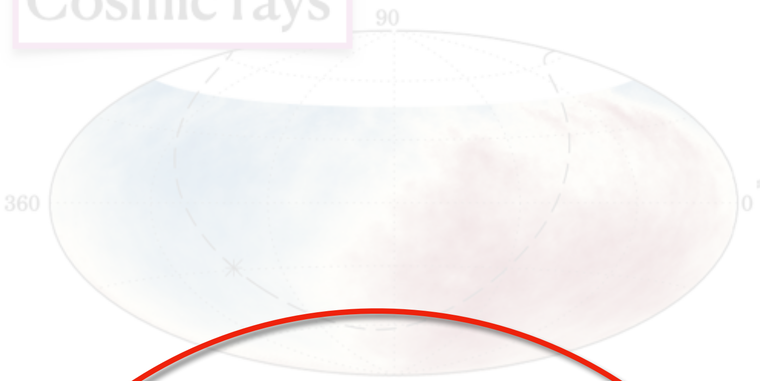


Fermi-LAT map

MeV-GeV

Multi-messenger astronomy

Cosmic rays



Gravitational Waves

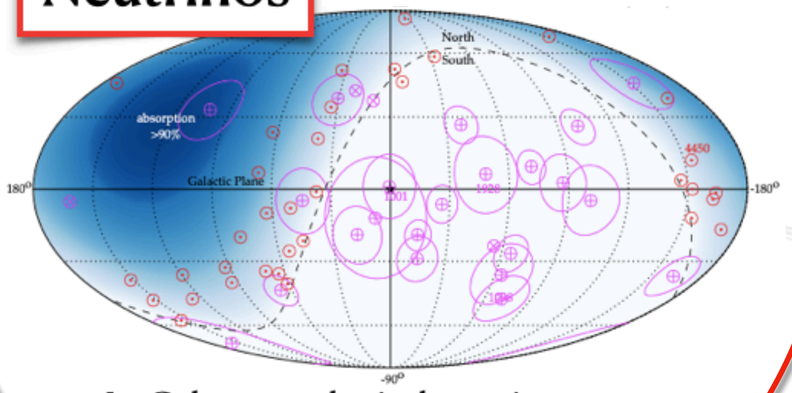
LIGO-Virgo GWs

Gamma rays

Fermi-LAT map
MeV-GeV

<u>This talk is focused on neutrinos</u>

Neutrinos

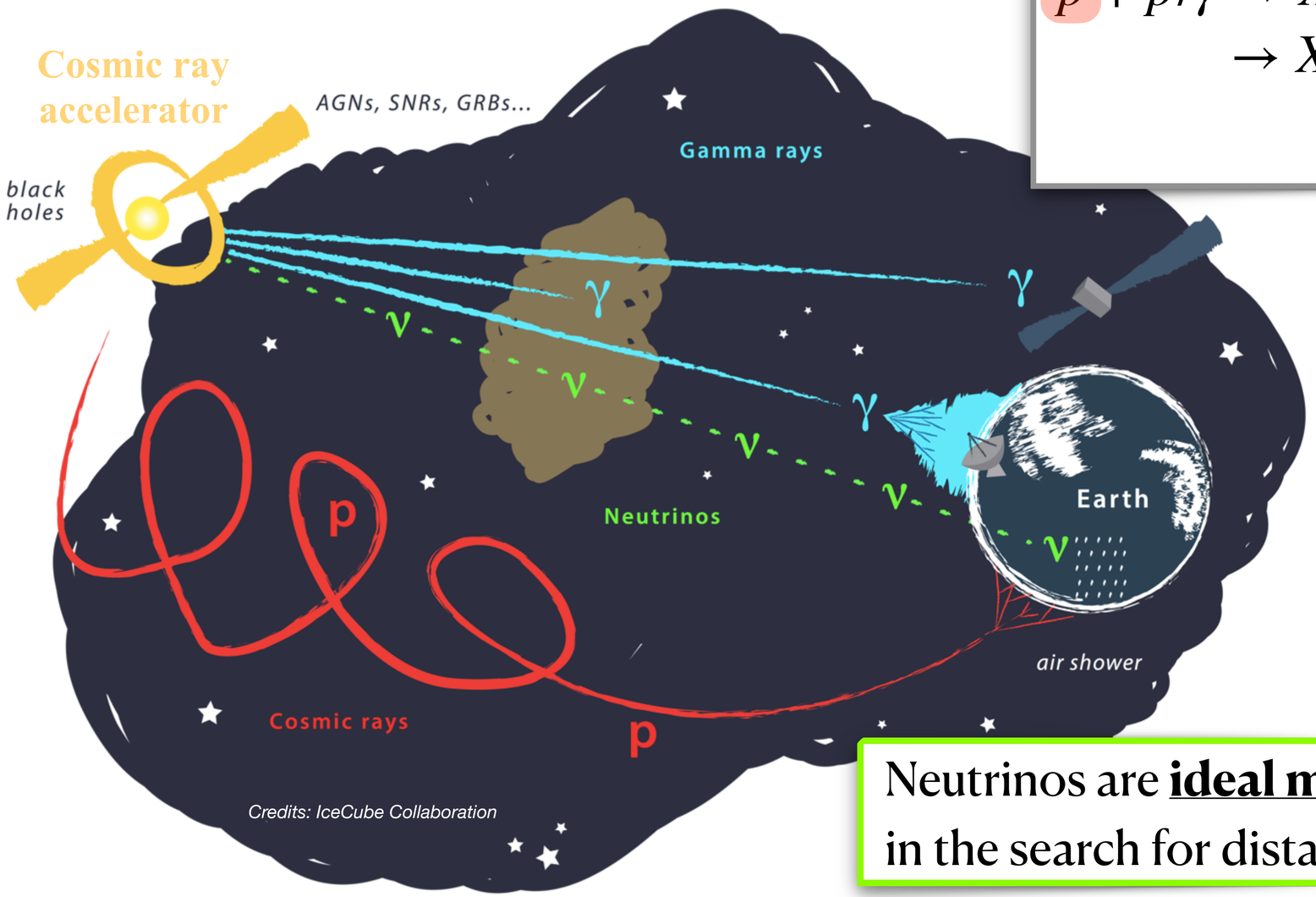


IceCube astrophysical neutrino events
TeV-PeV

Outline

- Why neutrinos are ideal messengers in the MM astronomy field
- Existing high-energy neutrino telescopes and their detection principle
- **KM3NeT neutrino telescope**: description and current status
- **The multi-messenger program of KM3NeT**
    - ✦ Online software architecture
    - ✦ Analysis pipeline for MM follow-ups
    - ✦ Current status and further developments

Neutrinos: ideal messengers



$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow X + \pi^{\pm} \rightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$
$$\mu^{\pm} \rightarrow e^{\pm} + \overset{(-)}{\nu}_{e} + \overset{(-)}{\nu}_{\mu}$$

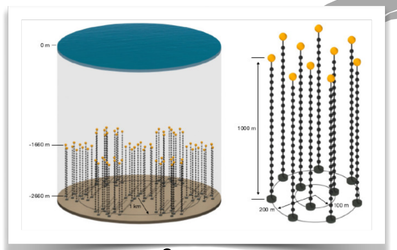
HADRON acceleration

Unique properties of **neutrinos**: electrically neutral, stable, and weakly interacting particles

- ★ **No deflection** in magnetic field (unlike cosmic rays)
- ★ **No absorption** in cosmic backgrounds, as Extragalactic Background Light (unlike gamma-rays)

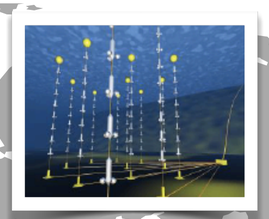
Neutrinos are **ideal messengers** in the search for distant astrophysical objects

High-energy neutrino telescopes: World map



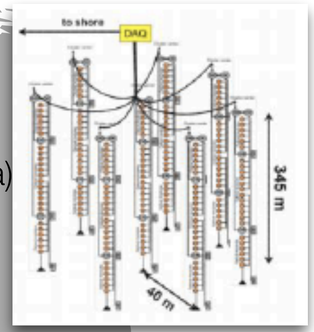
1 km^3, R&D

P-ONE (Canada)



ANTARES, dismantled
>0.01 km^3, 2008-2022

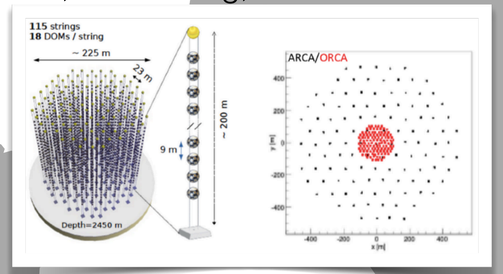
Baikal/GVD (Russia)
1 km^3, in construction



KM3NeT-ORCA (France)

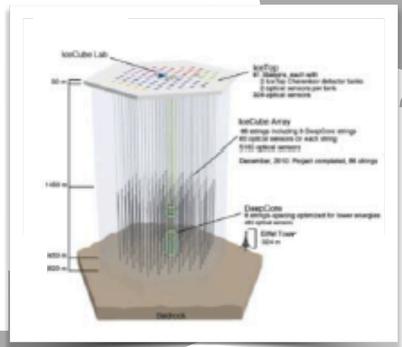
KM3NeT-ARCA (Sicily, Italy)

>1 km^3, data taking, **in construction**



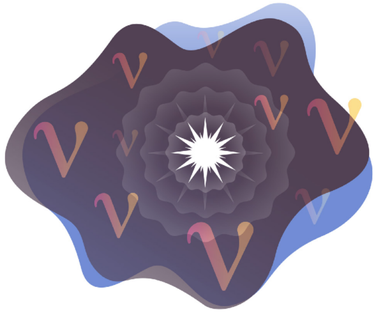
IceCube
(South Pole)
1 km^3, 2011-data taking

IceCube-Gen2
(South Pole)
10 km^3, R&D

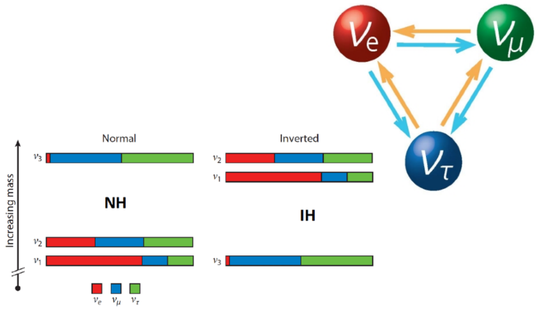


High-energy neutrino telescopes: science

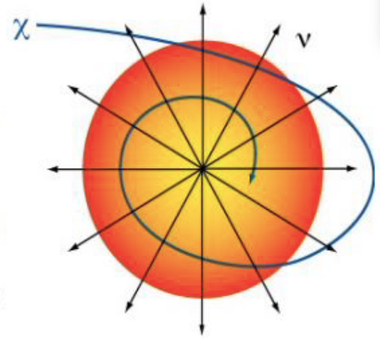
Supernova neutrinos



Neutrino mass hierarchy
Neutrino oscillations



Dark matter



High-energy neutrinos
Neutrino astronomy

Low-energy (MeV scale) — GeV — TeV — High-energy (PeV scale)

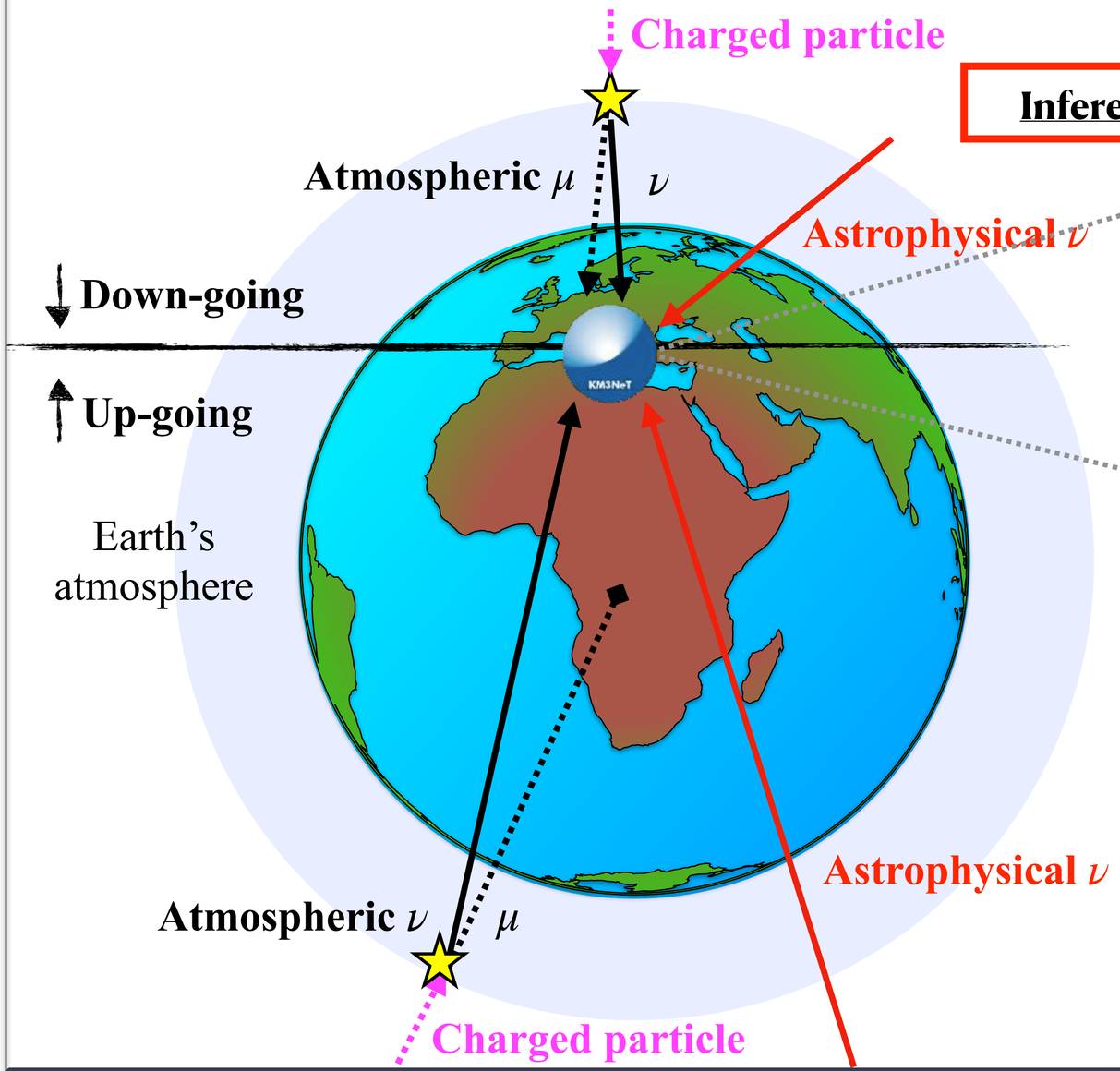
Observation of coincident hits in photomultipliers above the background

KM3NeT/ORCA
DeepCore

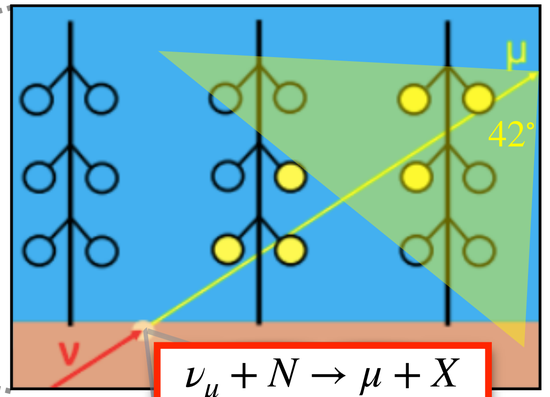
KM3NeT/ARCA
IceCube
Baikal-GVD

ANTARES

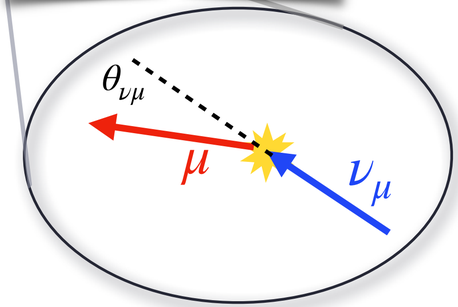
Neutrino telescopes: detection principle



Inference of energy and direction of incoming neutrinos from hits on PMTs



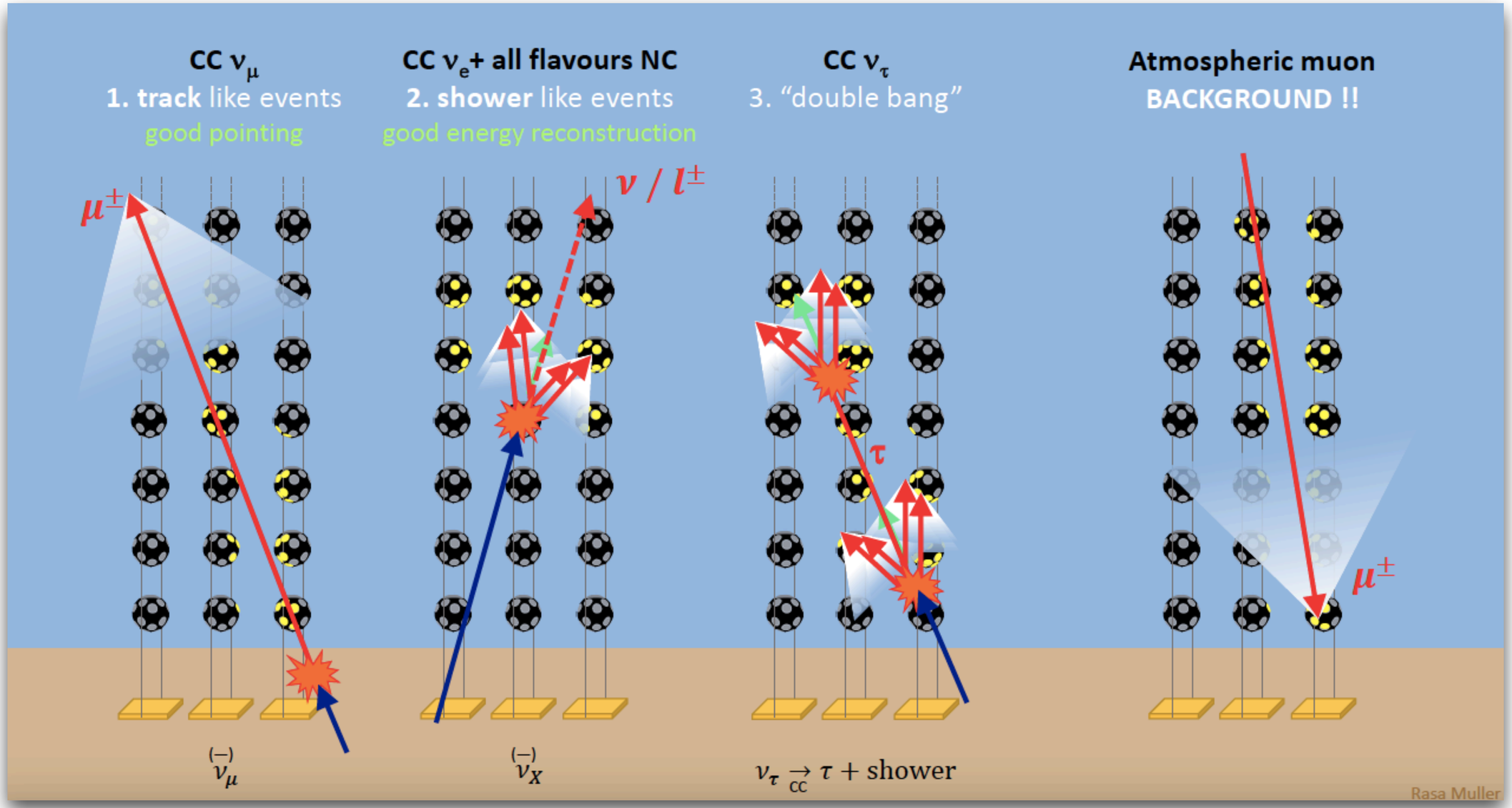
Cone of **Cherenkov light** originated **by secondary particles** produced in the medium as result of neutrino interactions with quarks inside or nearby the detector volume



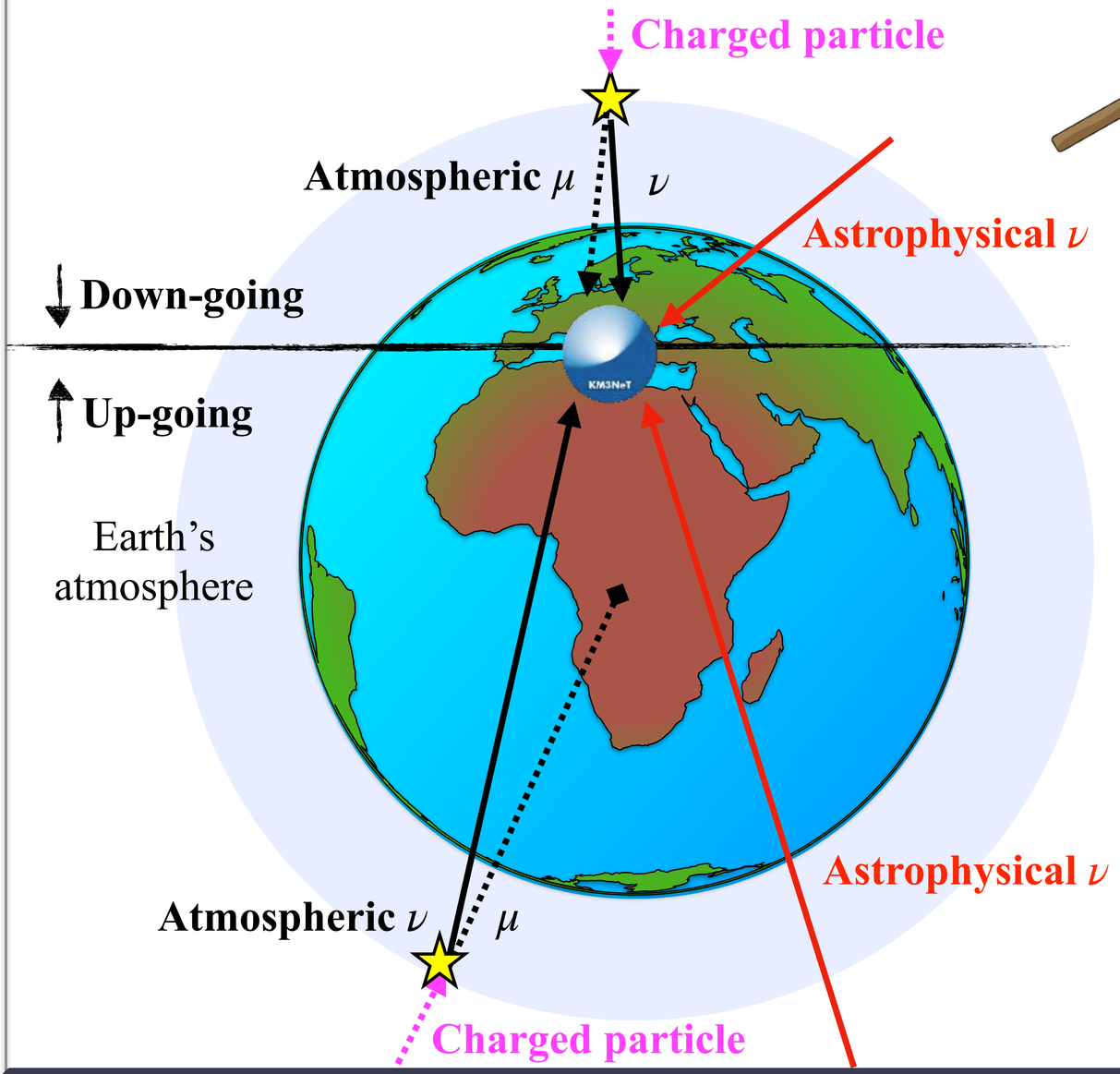
$$\theta_{\nu\mu} \simeq \frac{0.7^\circ}{[E_\nu(\mathrm{TeV})]^{0.7}}$$

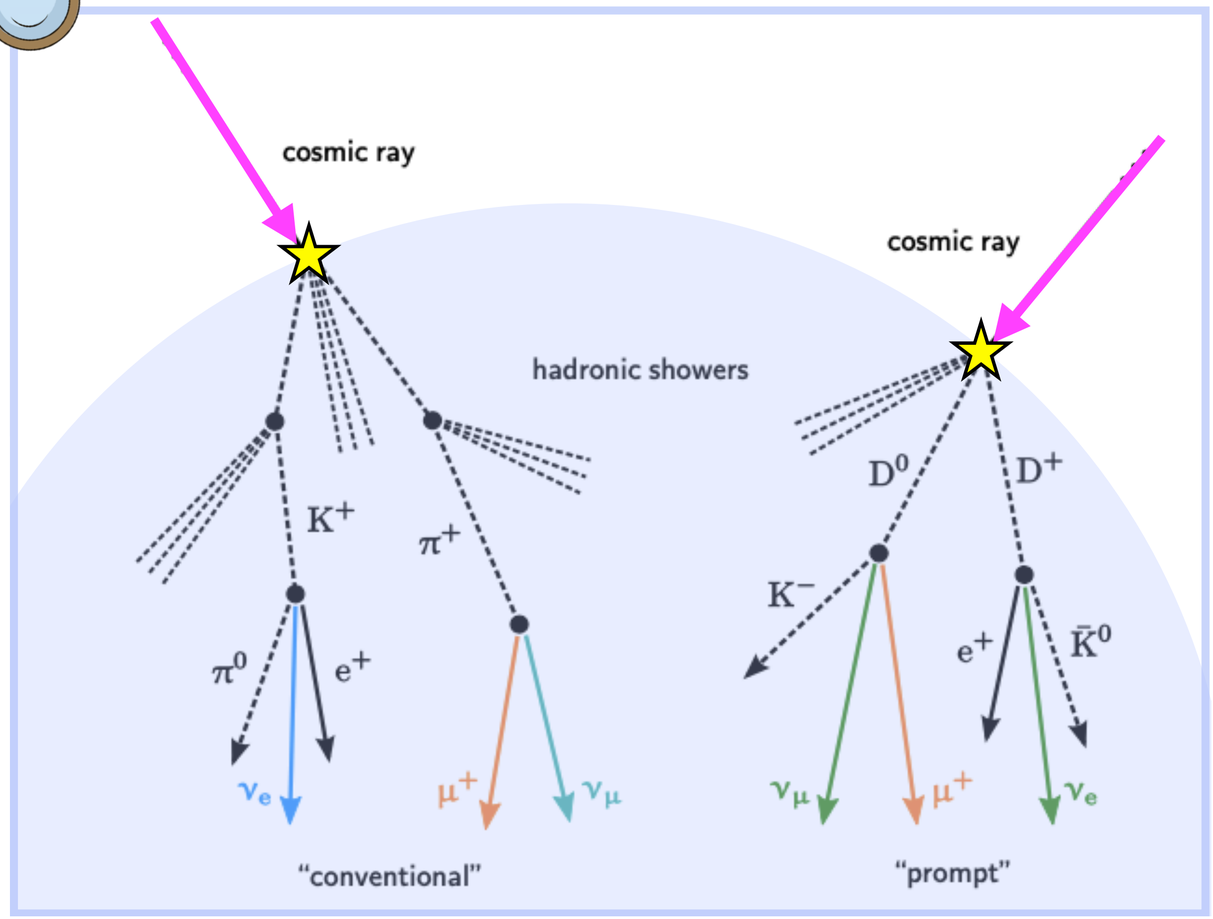
★ Main channel ⟶ charged current ν_μ interactions (**long muon path** inside the detector)

Neutrino telescopes: event topologies



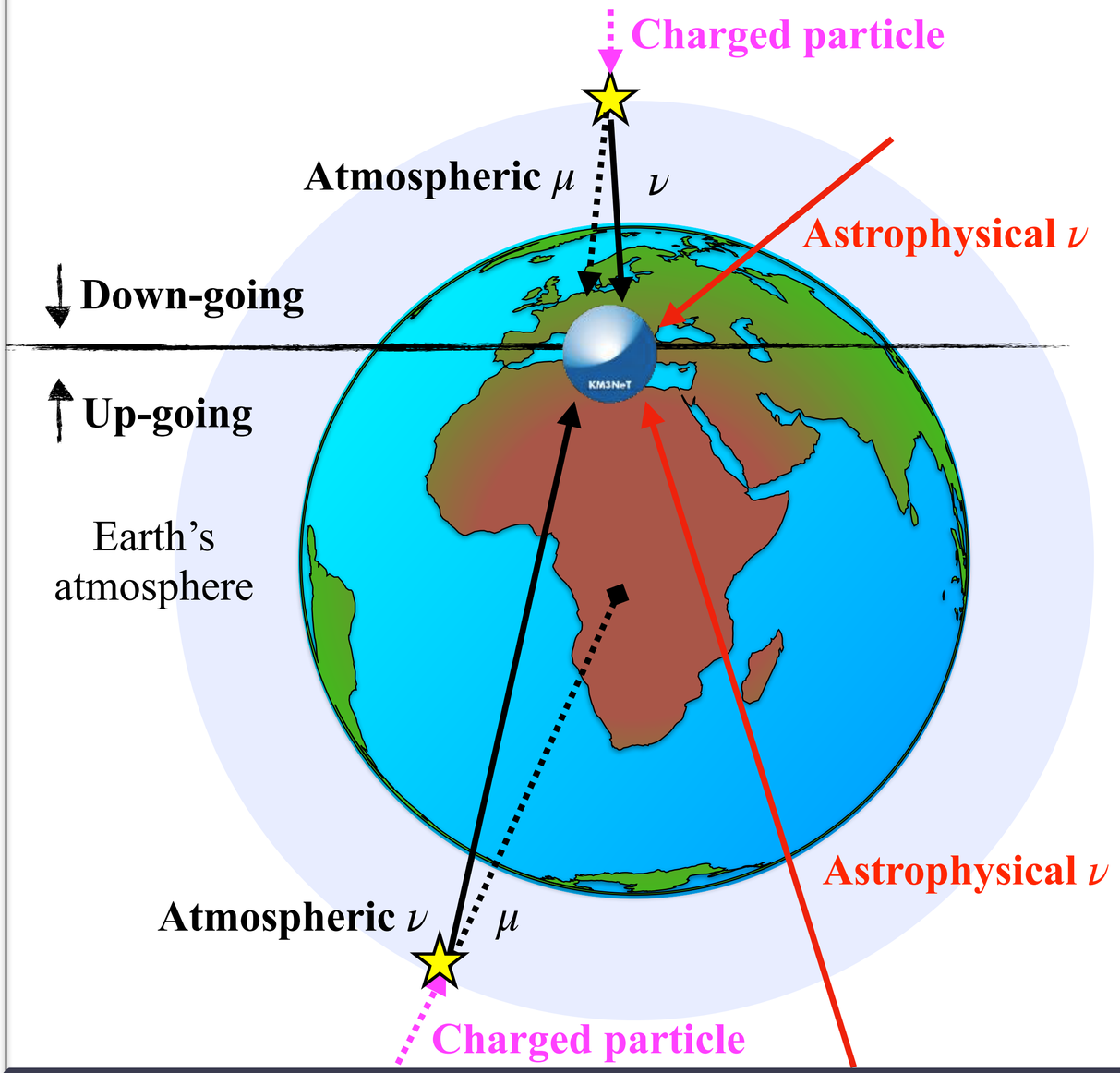
Neutrino telescopes: atmospheric background



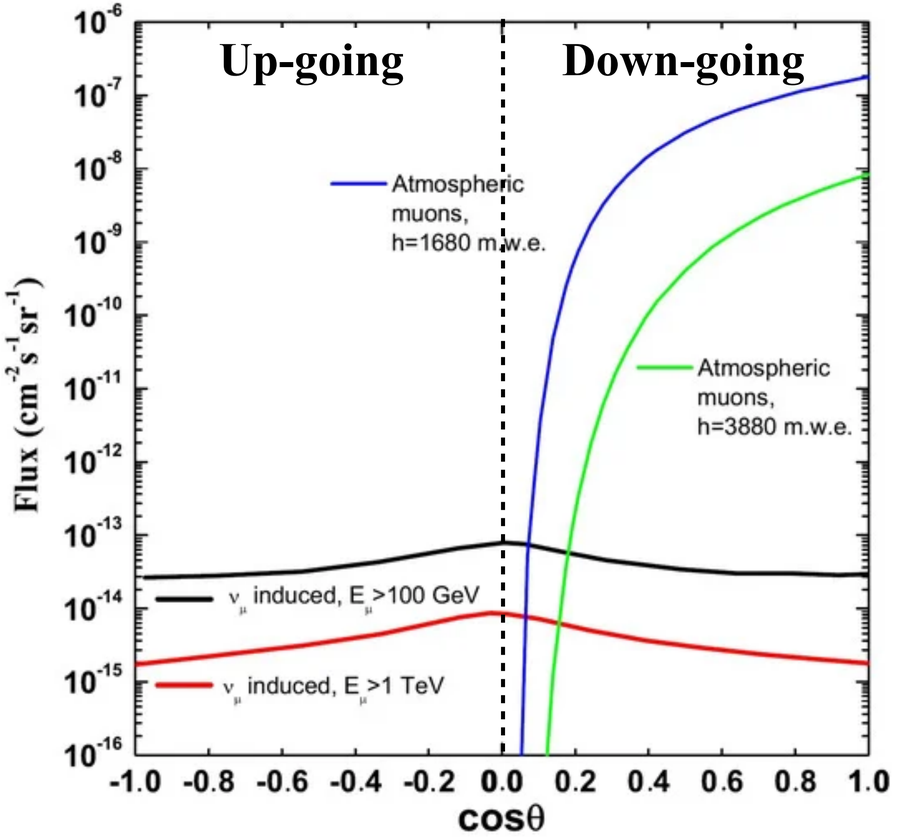


Atmospheric muons and neutrinos can reach neutrino telescopes

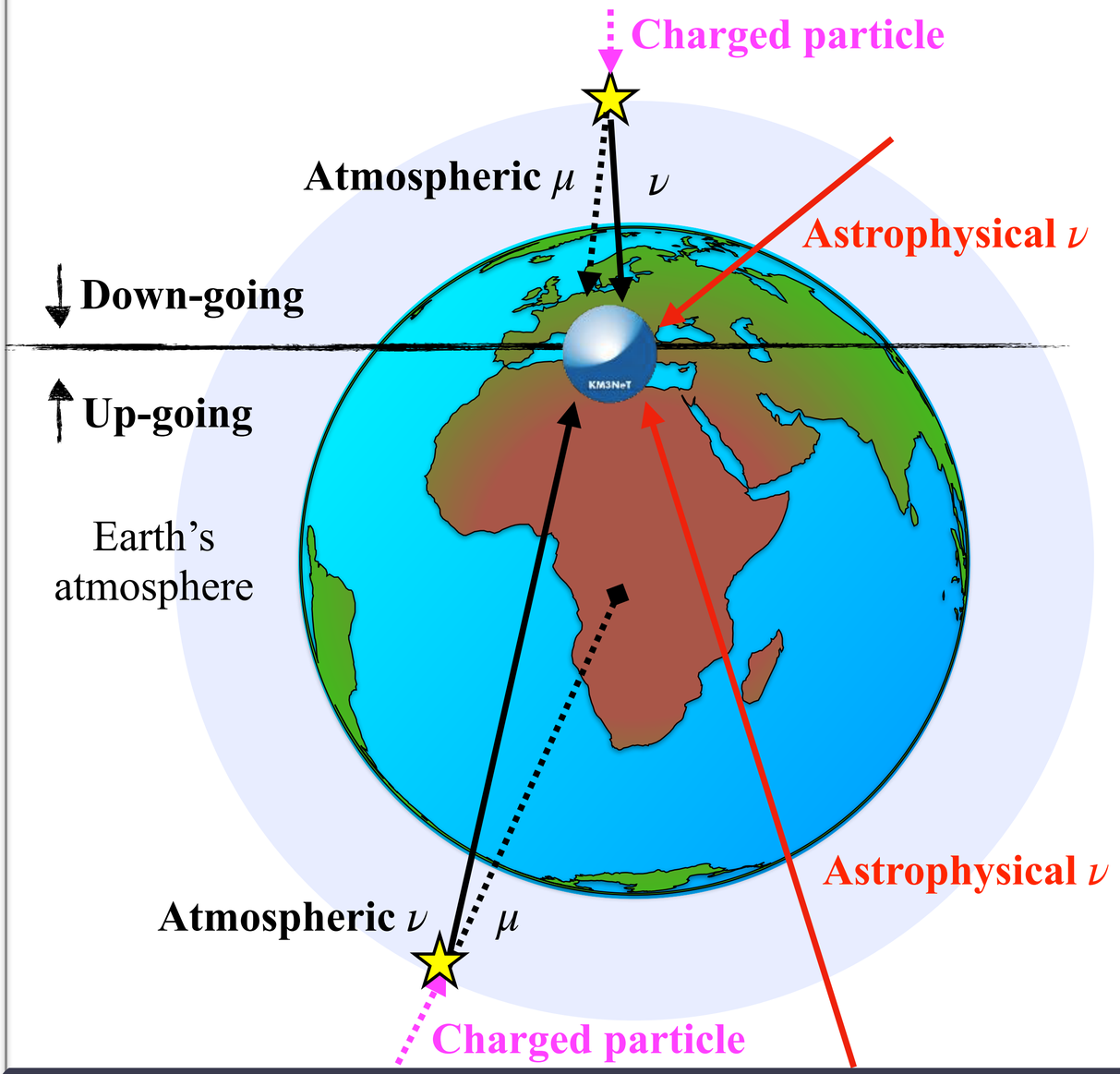
Neutrino telescopes: atmospheric background



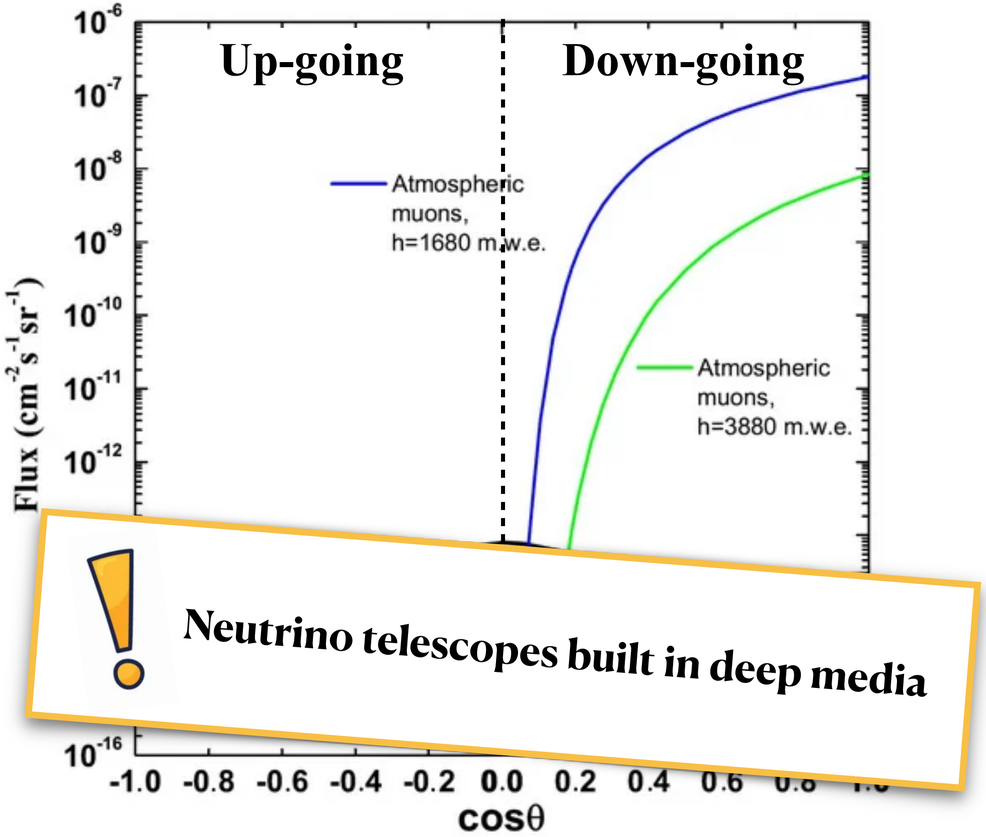
The **Earth** is used as **screening against all particles, except neutrinos** that can traverse the Earth



Neutrino telescopes: atmospheric background



The **Earth** is used as **screening against all particles, except neutrinos** that can traverse the Earth

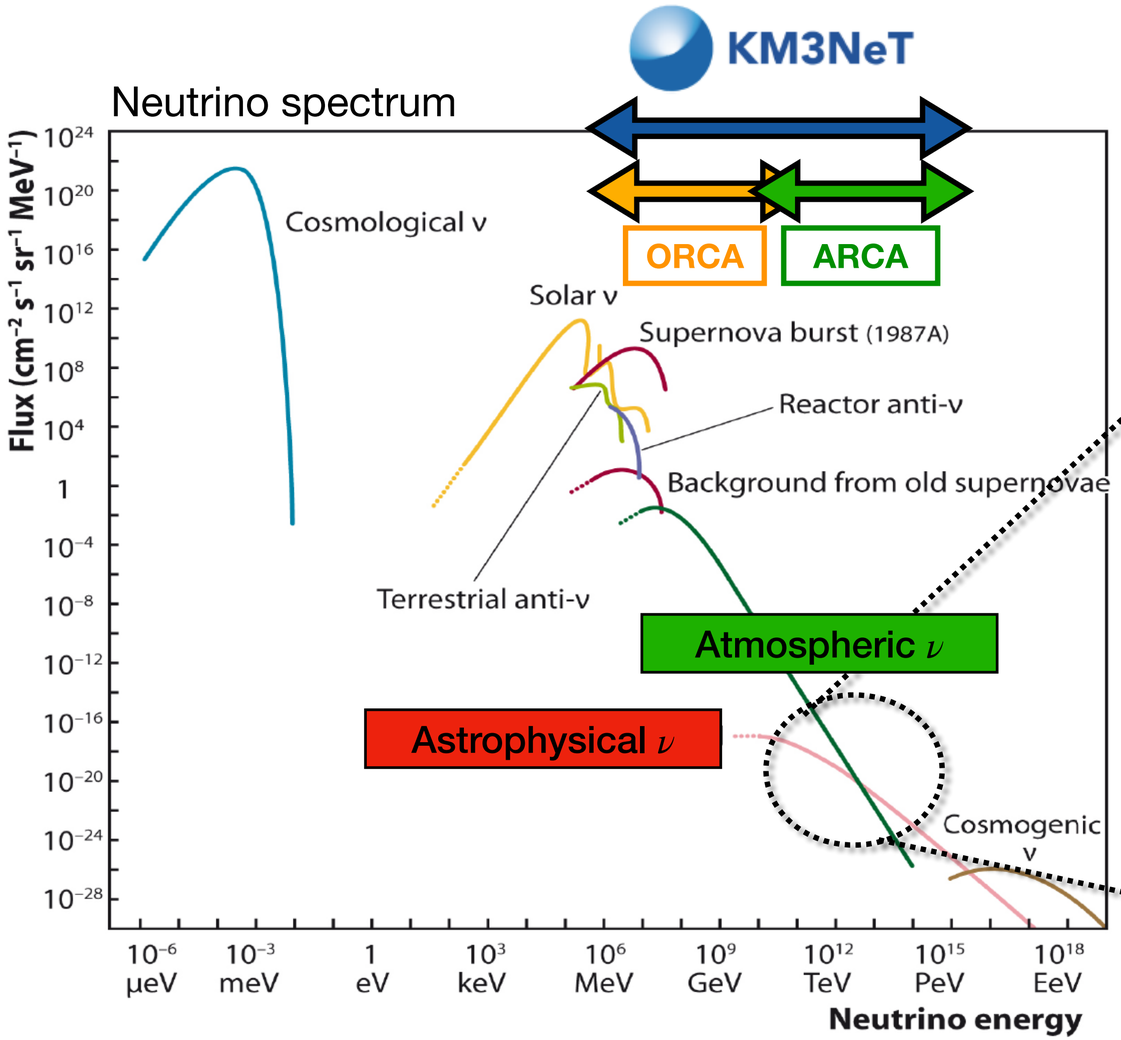


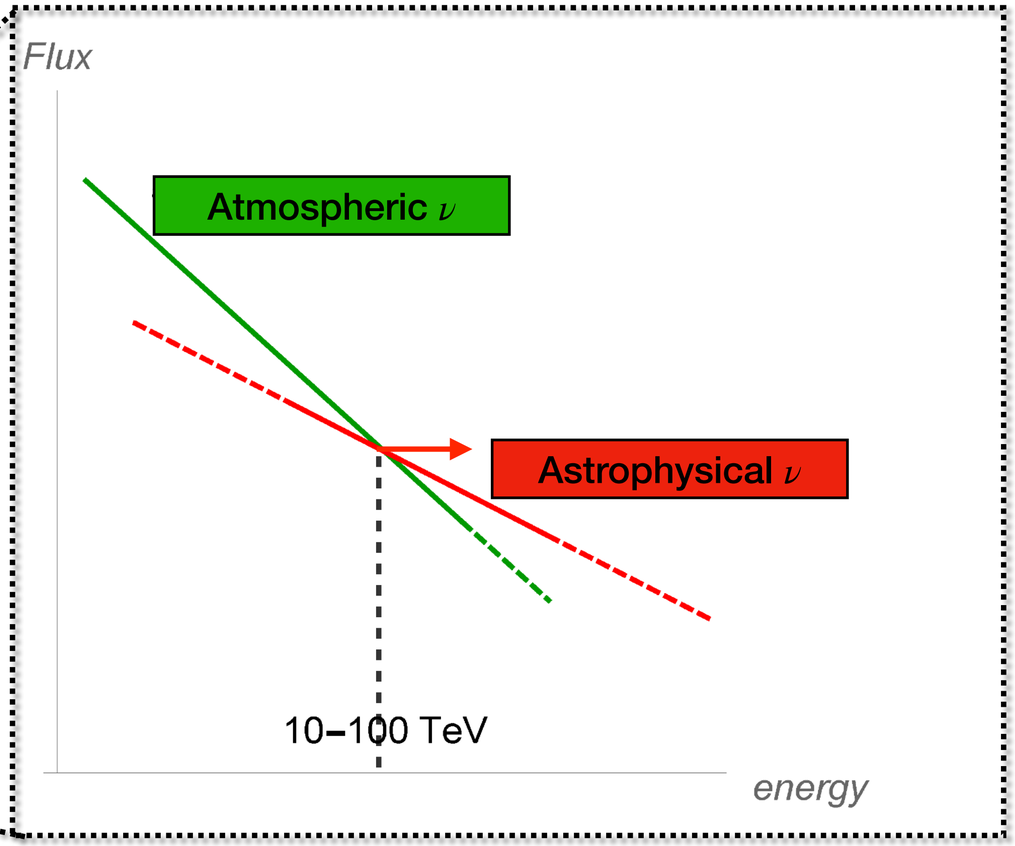
Neutrino telescopes built in deep media

Neutrino telescopes: ν_{astro} vs ν_{atm}

High-energy neutrino telescopes with astrophysical purposes optimized for E > TeV

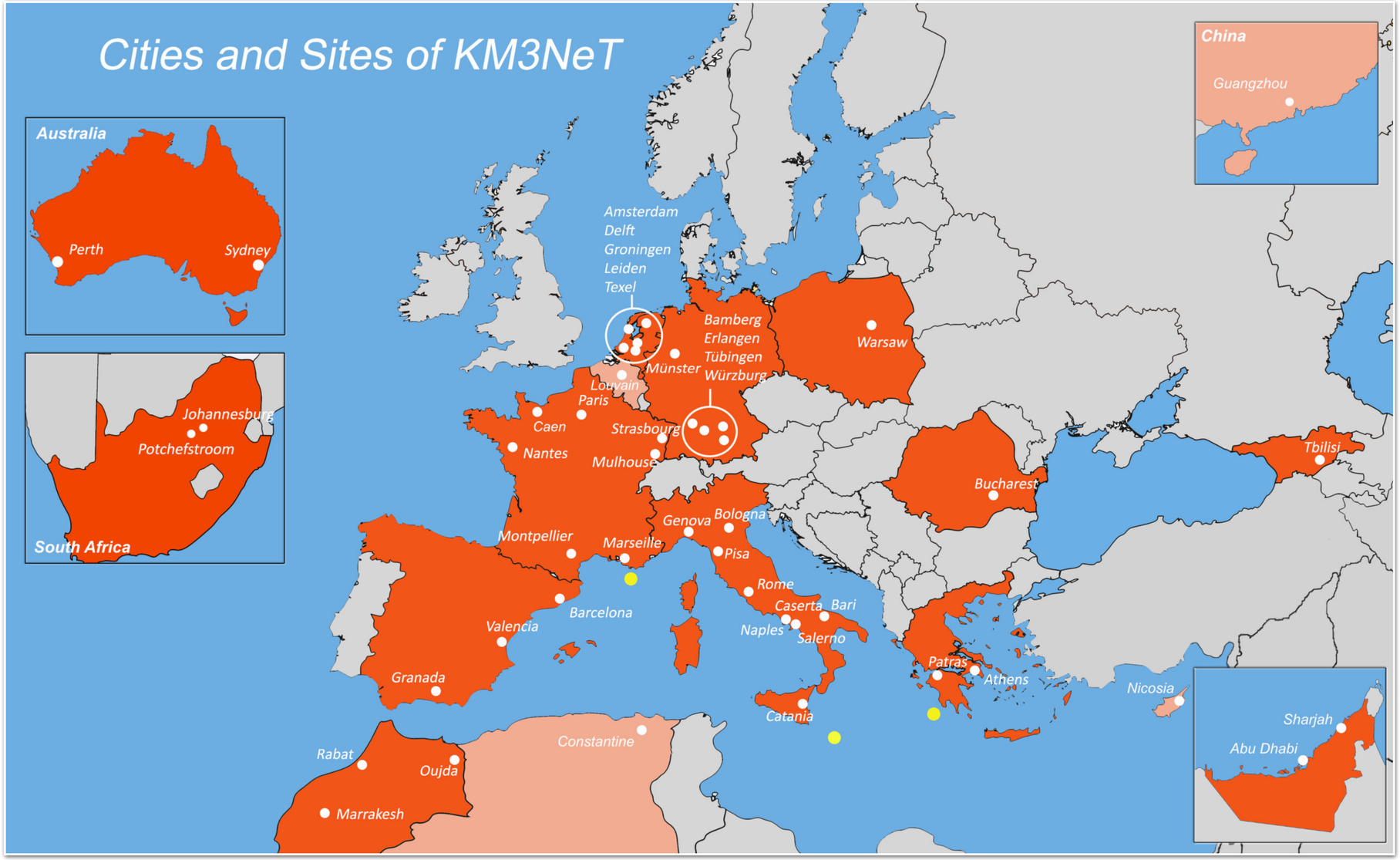
Cosmic neutrinos can stand out over the atmospheric neutrinos at high energies (>10-100 TeV), becoming observable.





The KM3NeT Collaboration

KM3NeT
www.km3net.org

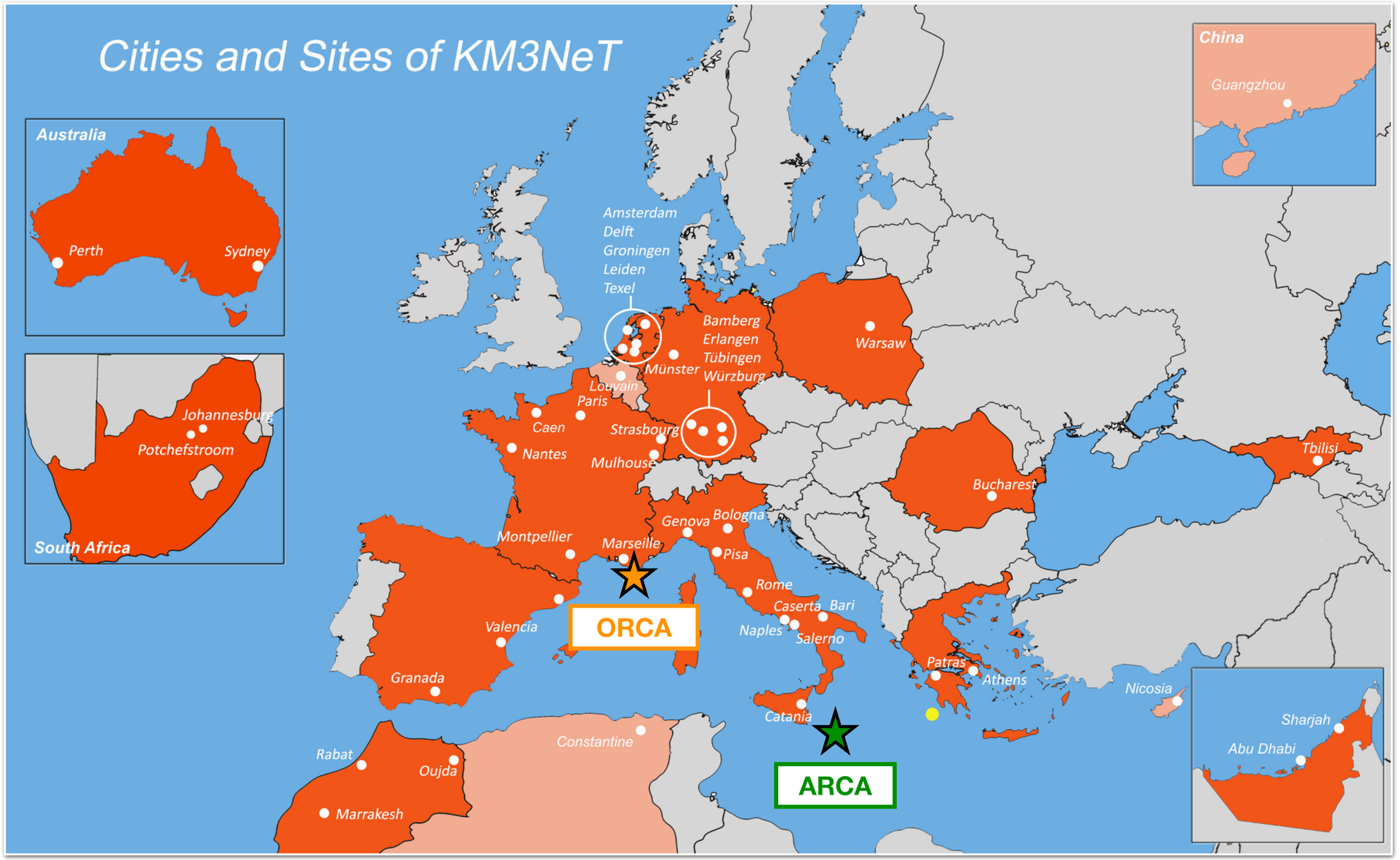


KM3NeT in numbers

- 4 continents
- 16 countries
- 55 groups

The KM3NeT Collaboration

KM3NeT
www.km3net.org



KM3NeT in numbers

- 4 continents
- 16 countries
- 55 groups
- **2 detectors**

~ GeV ⟷ ~10 PeV

Oscillation **R**esearch with **C**osmics in the **A**byss

Designed for **low-E** studies

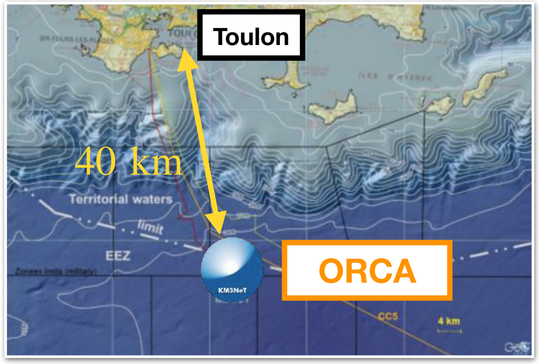
Astroparticle **R**esearch with **C**osmics in the **A**byss

Designed for **high-E** studies

The KM3NeT neutrino telescope

KM3NeT
www.km3net.org

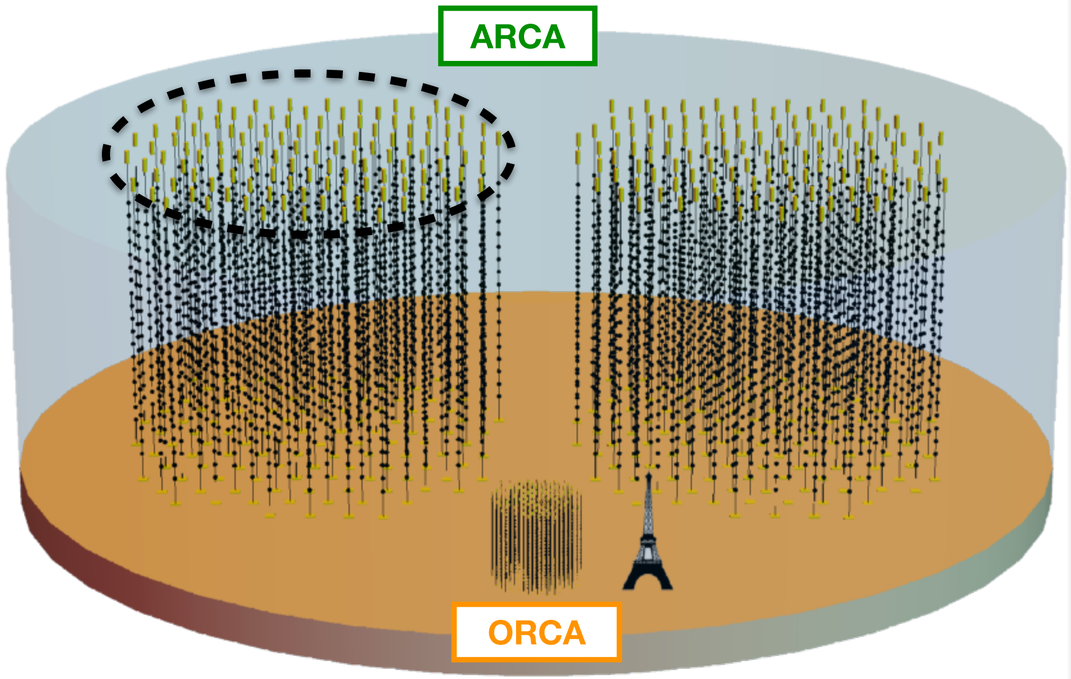
- Deep infrastructure under construction in the Mediterranean Sea
- Two instrument sites: ORCA (France) and ARCA (Italy) ⟶ **Same technology** used for both detectors but **different physics**



	ARCA	ORCA
Location	Italy (Sicilian coast)	France (coast of Toulon)
Depth	3450 m	2450 m
Distance from shore	100 km	40 km
Number of DUs	**115 x 2 (2 BB)**	**115 (1 BB)**
Instrumented volume	~ 1 Gton	~ 7 Mton

> 1 km^3 neutrino telescope

3D array of optical sensors

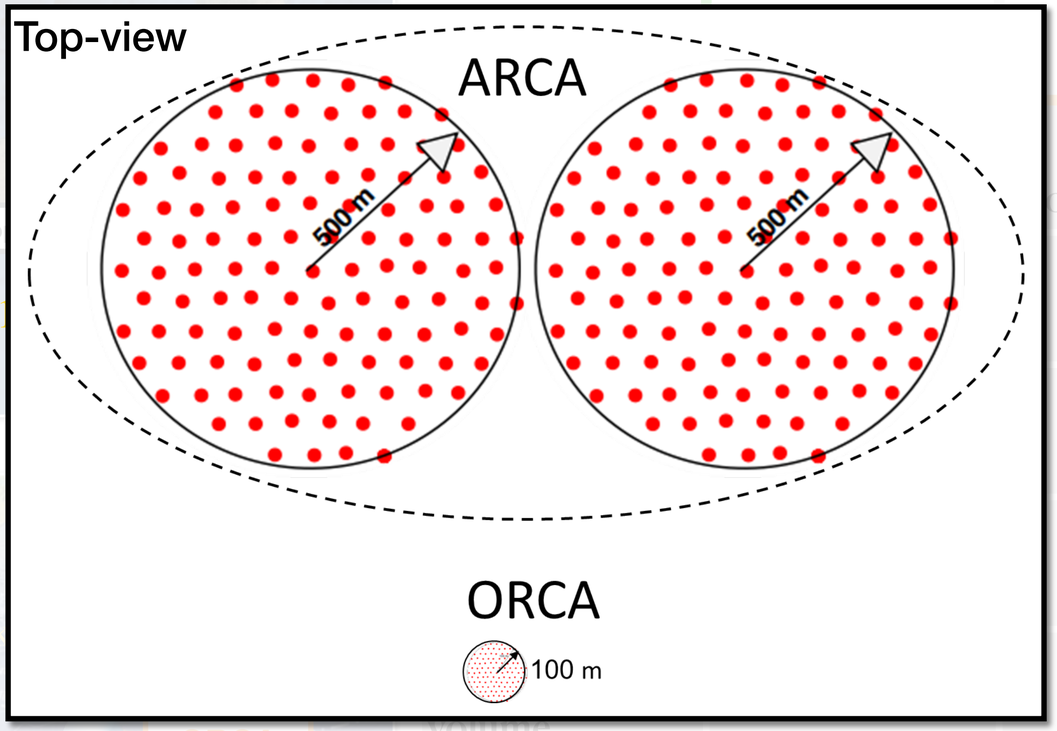


1 Building Block = 115 Detection Units
(1 BB = 115 DUs)

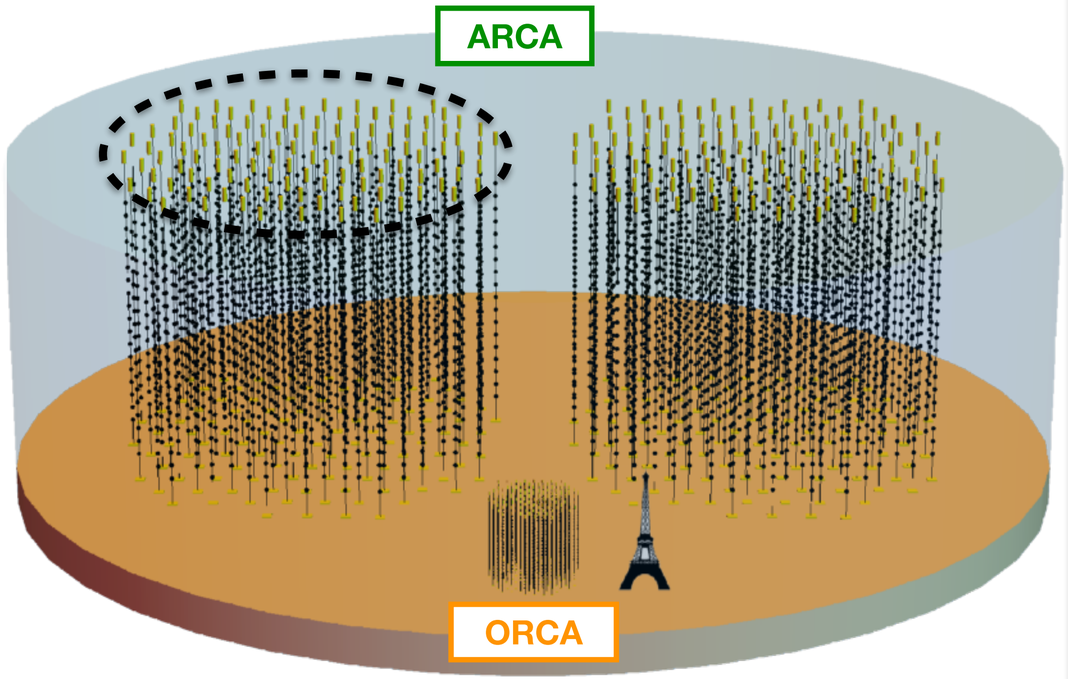
The KM3NeT neutrino telescope

KM3NeT
www.km3net.org

- Deep infrastructure under construction in the Mediterranean Sea
- Two instrument sites: ORCA (France) and ARCA (Italy) ⟶ **Same technology** used for both detectors but **different physics**



3D array of optical sensors



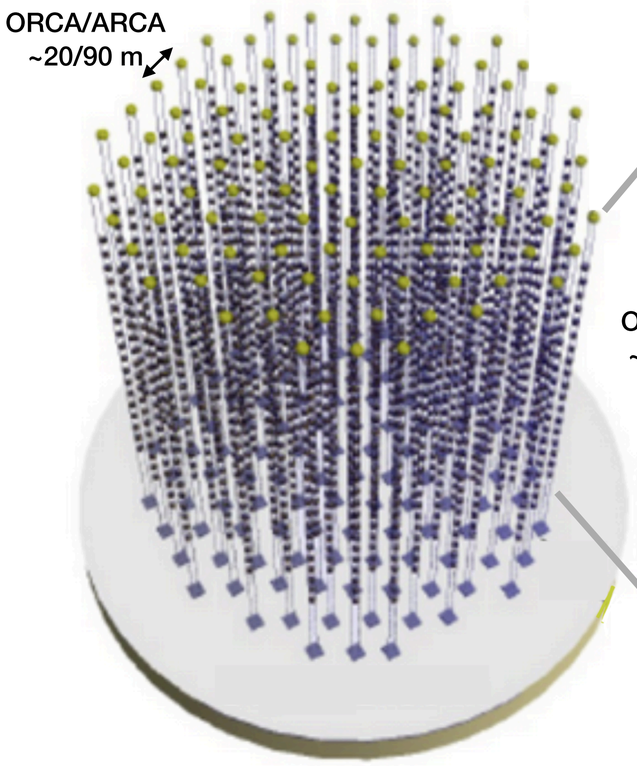
1 Building Block = 115 Detection Units

(1 BB = 115 DUs)

KM3NeT: detector design

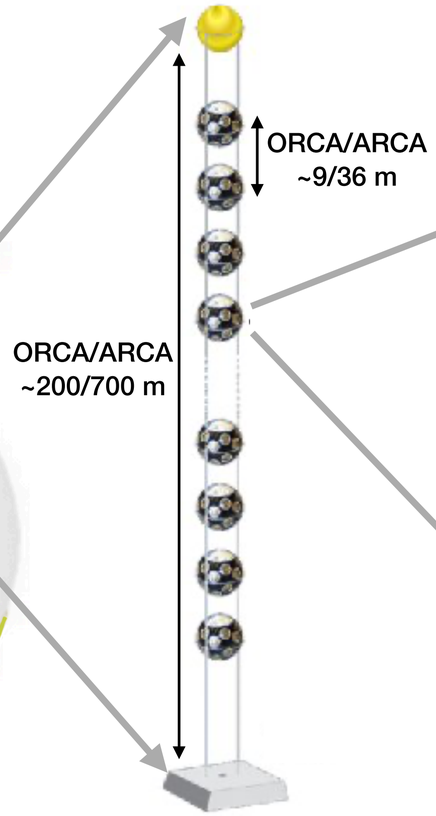
KM3NeT
www.km3net.org

Building Block



1 BB = 115 DUs

Detection Unit



1 DU = 18 DOMs

+ Base Module

Digital Optical Module

17" glass sphere containing:

- 31x3" PMTs
- LED and Piezo
- Front and electronics

1 DOM = 31 PMTs

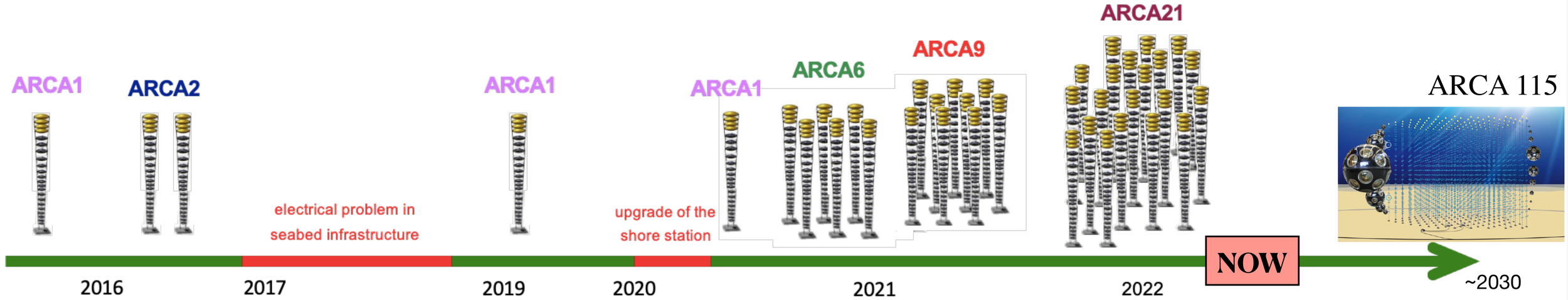
71 unique components
(in solid or liquid phase)

Technical publications

KM3NeT: current status

KM3NeT
www.km3net.org

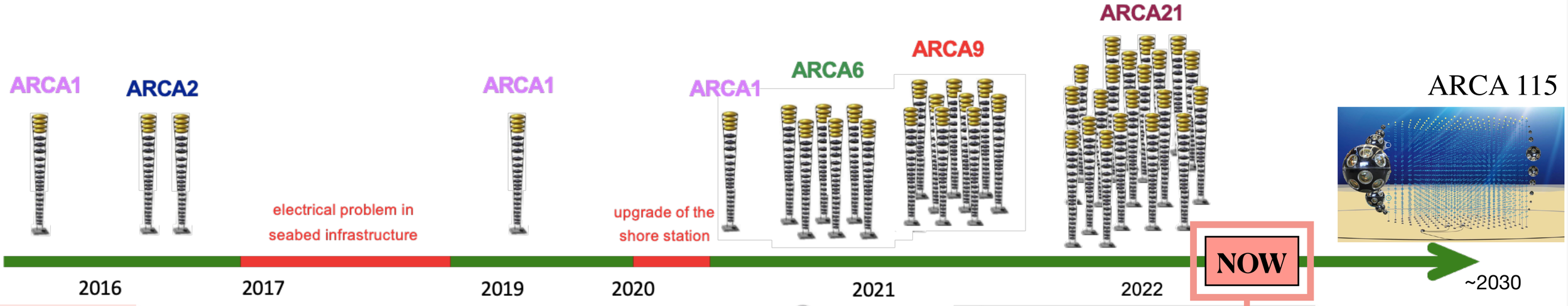
We are now in the construction phase

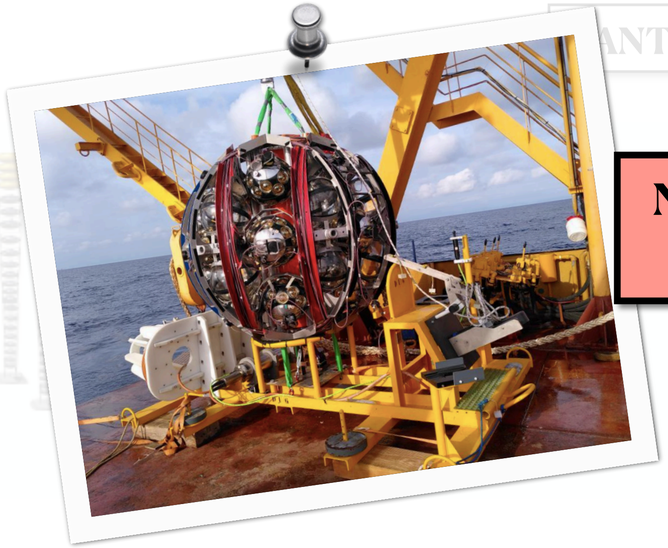


KM3NeT: current status

KM3NeT
www.km3net.org

We are now in the construction phase

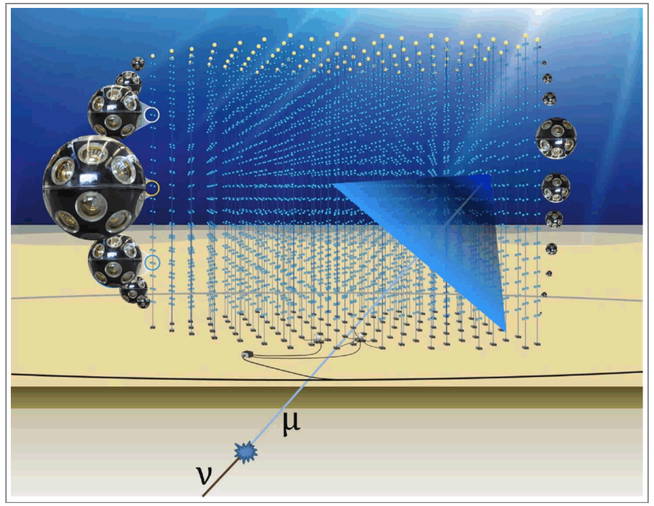




New ARCA deloyment in these days.
More strings taking data soon!

KM3NeT: the multimessenger program

Data AcQuisition (DAQ) level



KM3NeT ORCA and ARCA

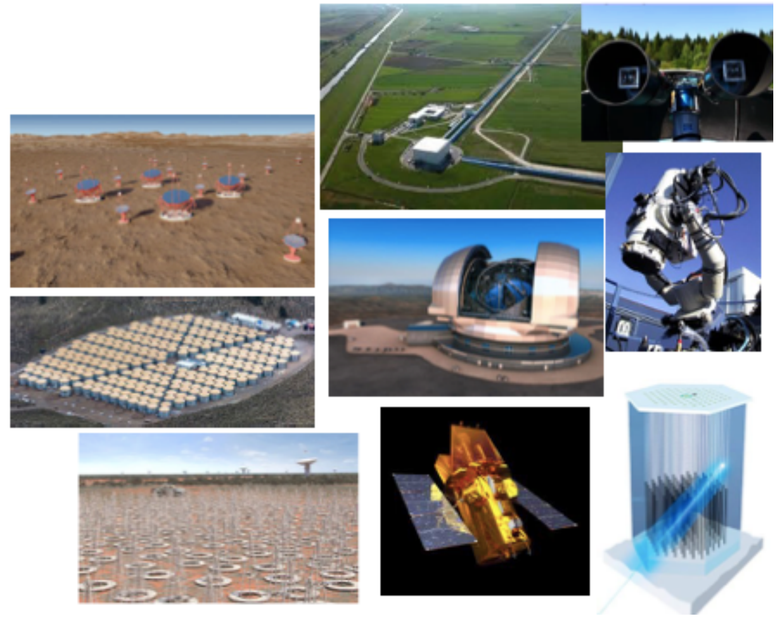
SENDING ALERTS

Send neutrino alerts to external communities for subsequent follow-ups

- Follow-up of EM/GW alerts
- Offline time/space correlation search with catalogues (GRB, AGN, SN, etc.)

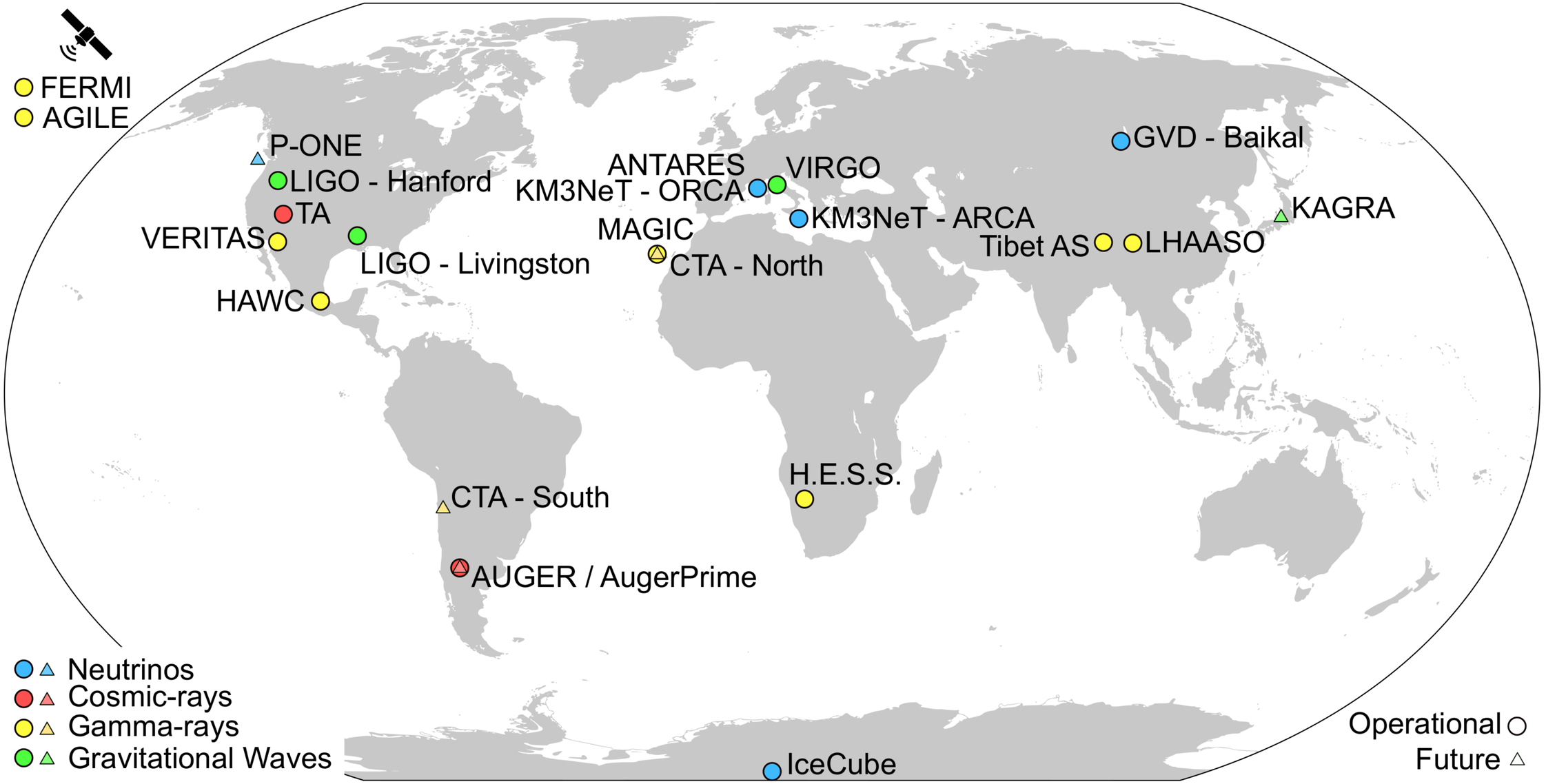
RECEIVING ALERTS

EM/MM external communities

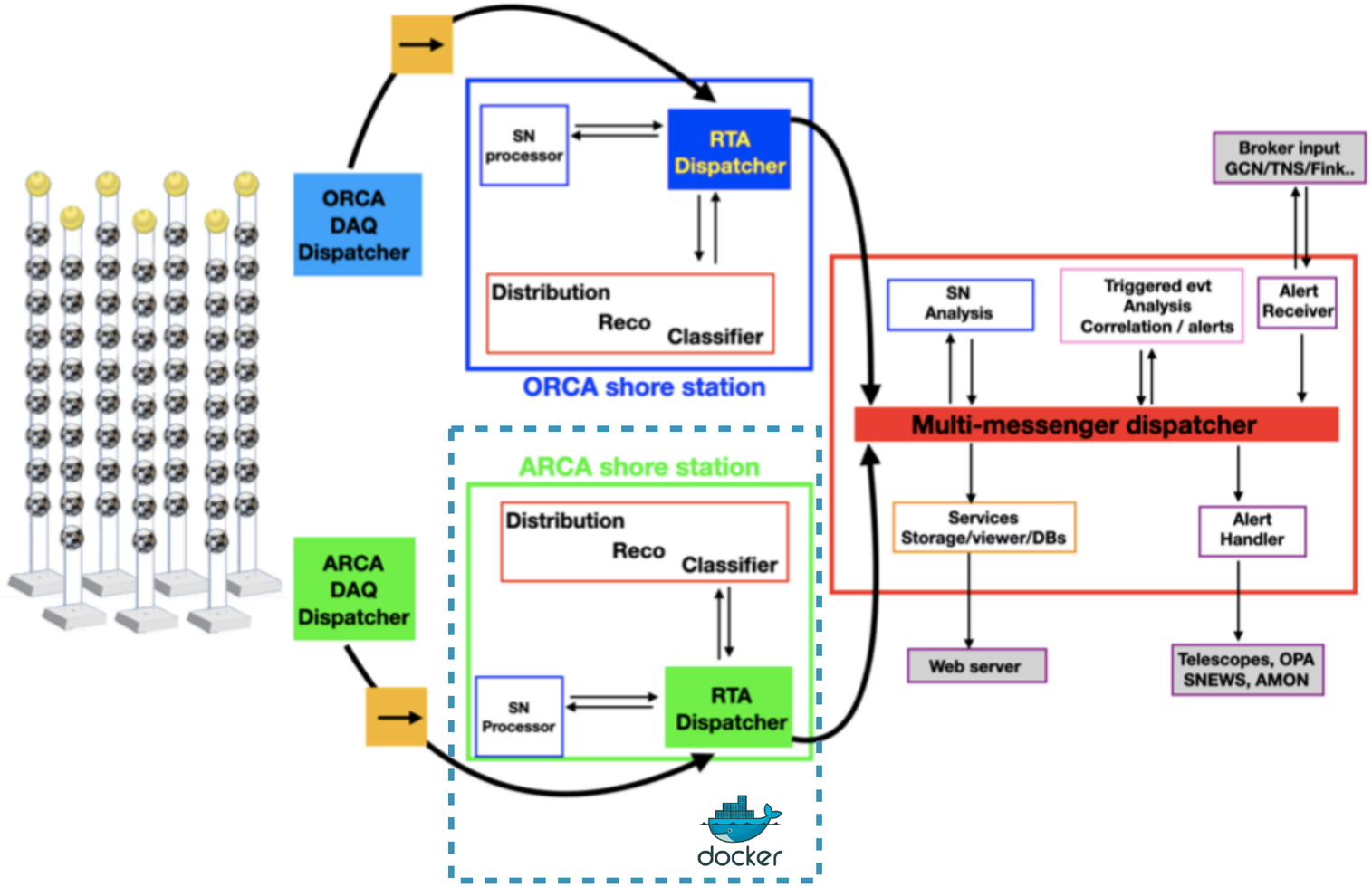


PoS (ICRC2023) 1125

Synergy between different observatories



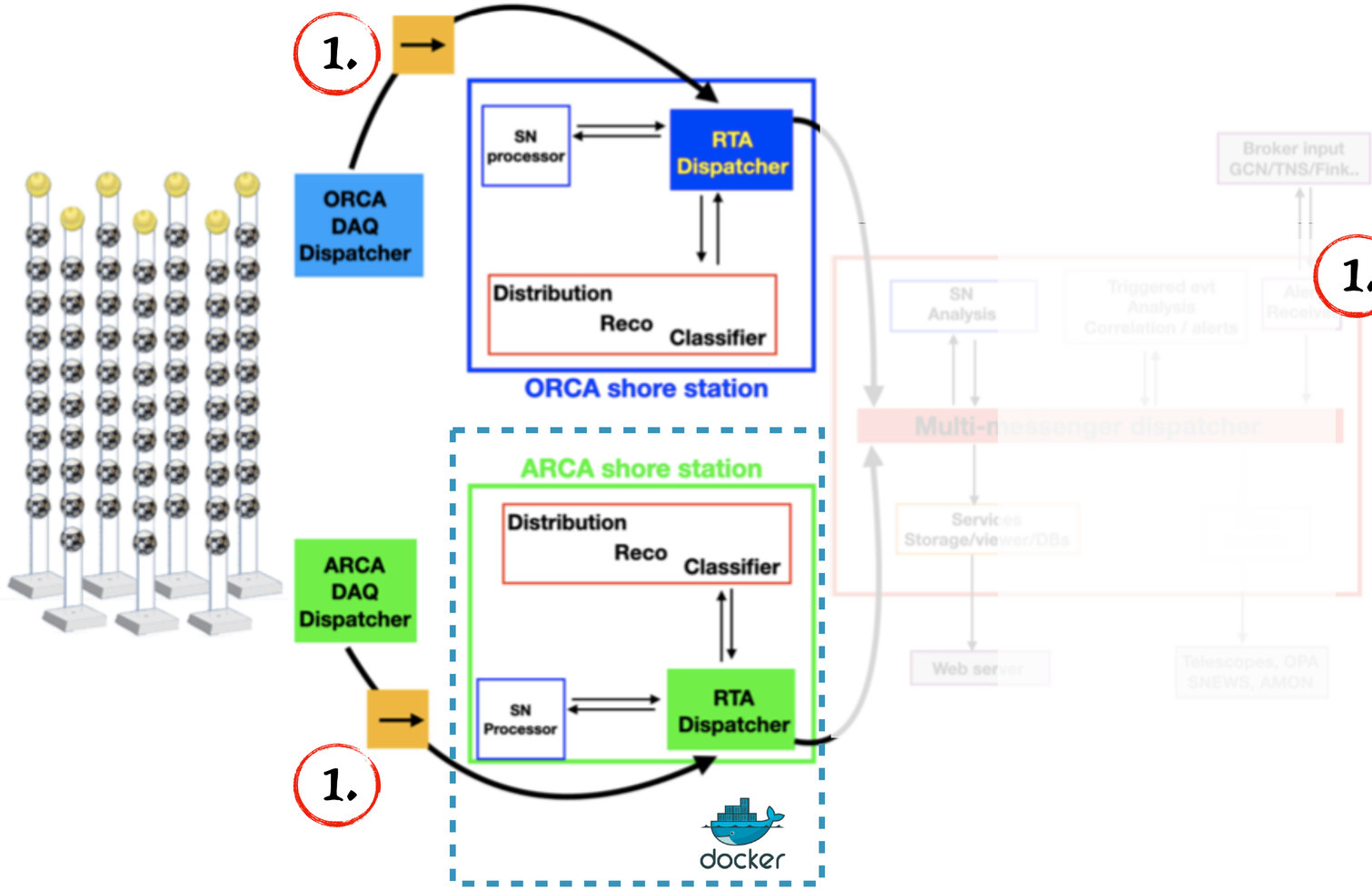
Online software architecture



- **Event processing done separately for ORCA and ARCA at each store station**
- **Same processing structure** but different software architecture (in ARCA the docker software infrastructure is implemented)
- Data from each detector are transferred to a **common dispatcher (MM dispatcher)**, where analysis pipelines are also activated

PoS (ICRC2023) 1125

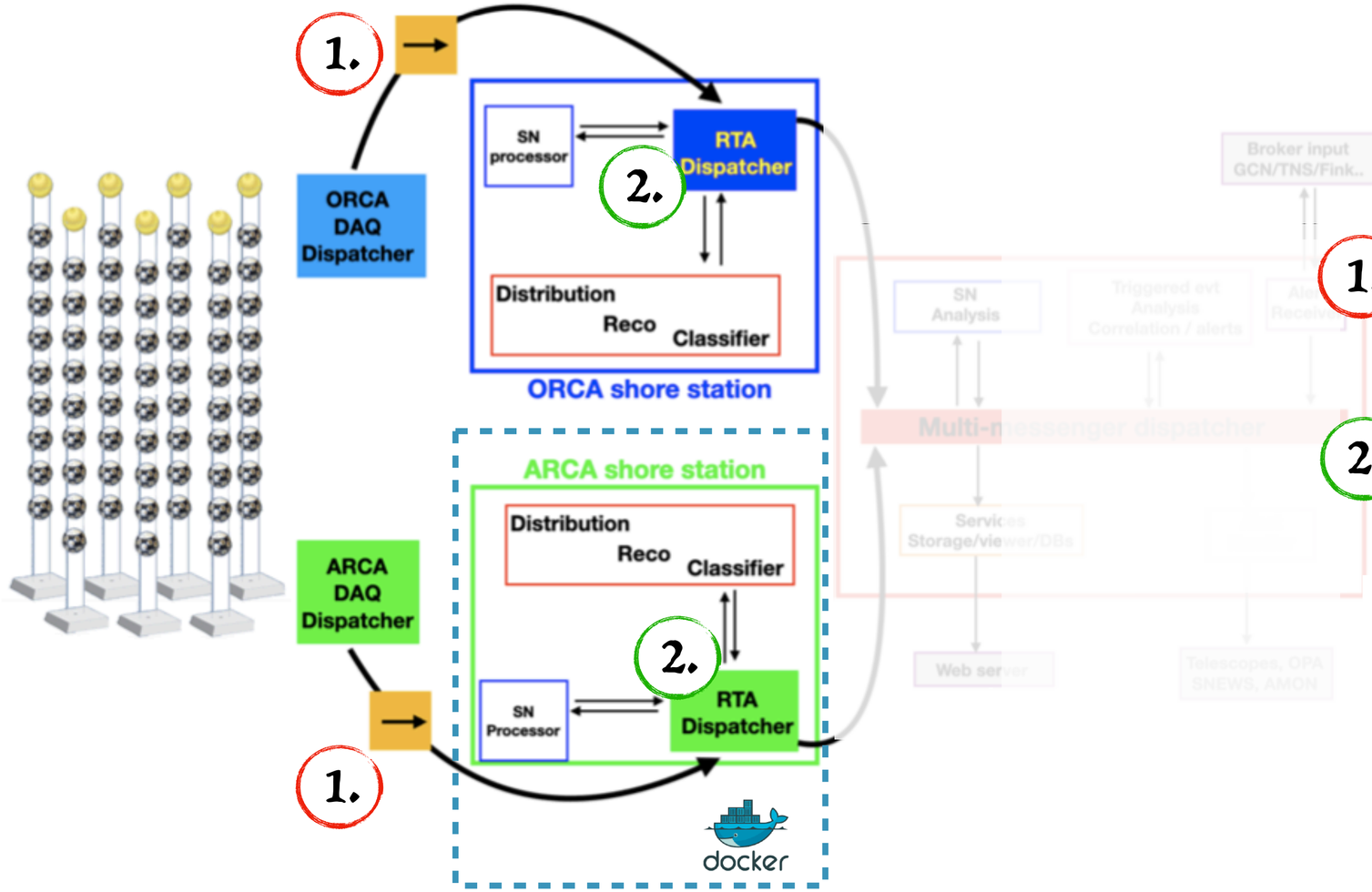
Online software architecture



1. Mirroring of data from DAQ to Real Time Analysis (RTA) dispatcher (local dispatcher)

PoS (ICRC2023) 1125

Online software architecture

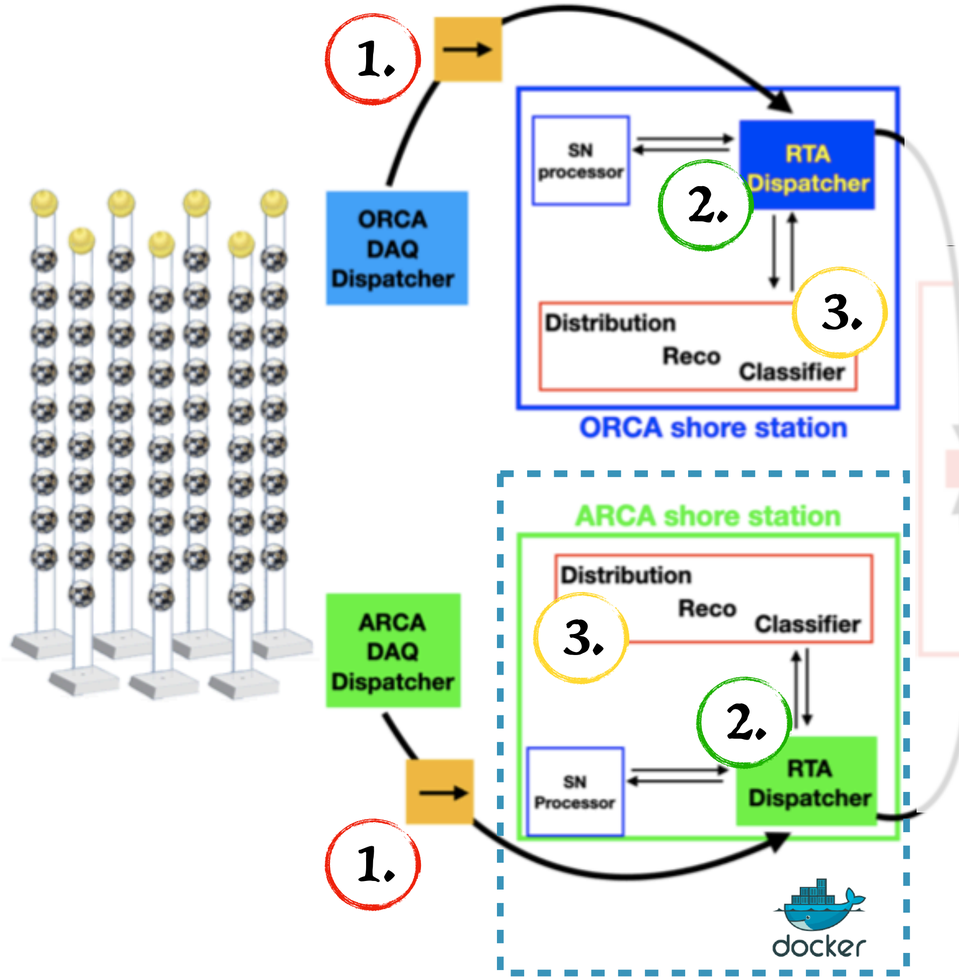


1. Mirroring of data from DAQ to Real Time Analysis (RTA) dispatcher (local dispatcher)

2. Event distribution via the open-source multi-protocol messaging broker Rabbit-MQ

PoS (ICRC2023) 1125

Online software architecture



1. Mirroring of data from DAQ to Real Time Analysis (RTA) dispatcher (local dispatcher)
2. Event distribution via the open-source multi-protocol messaging broker Rabbit-MQ
3. Multi-core processing in place

- **Events reconstructed in real-time (both as track and shower) and classified (μ/ν) via machine learning algorithms**

PoS (ICRC2023) 1125

Multi-core online data processing

ARCA21

All data to shore

SHORE STATION

Portopalo di Capo Passero (Sicily)

Parallel processes

Triggered event

- Track reco → Track reco outputs
- Shower reco → Shower reco outputs
- Classifier → Score μ/ν

ORCA18

All data to shore

SHORE STATION

Institut Michel Pacha, La Seyne-sur-Mer (France)

Reconstruction and classification serially processed

Triggered event → Track reco + Shower reco + Classifier → Track&Shower reco outputs + Score μ/ν

PoS (ICRC2023) 1125

Online processing times

After ~**4 seconds** each event triggered by the **ARCA detector** has been reconstructed and classified

ARCA21

All data to shore

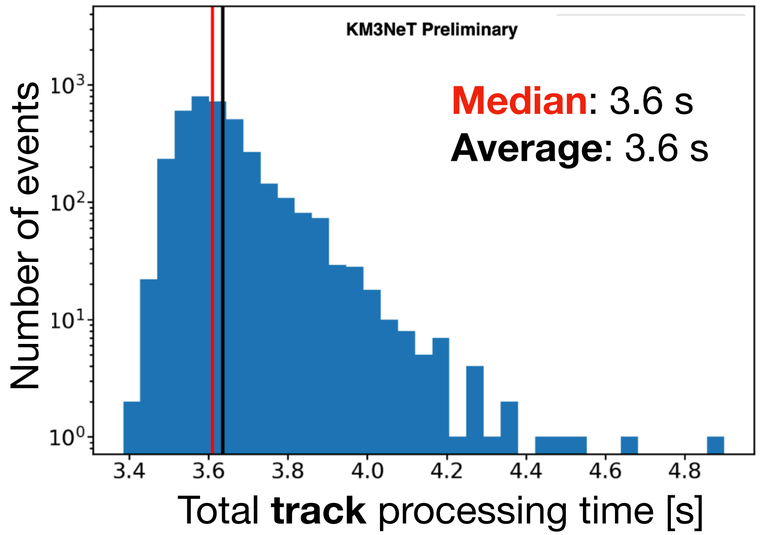
SHORE STATION

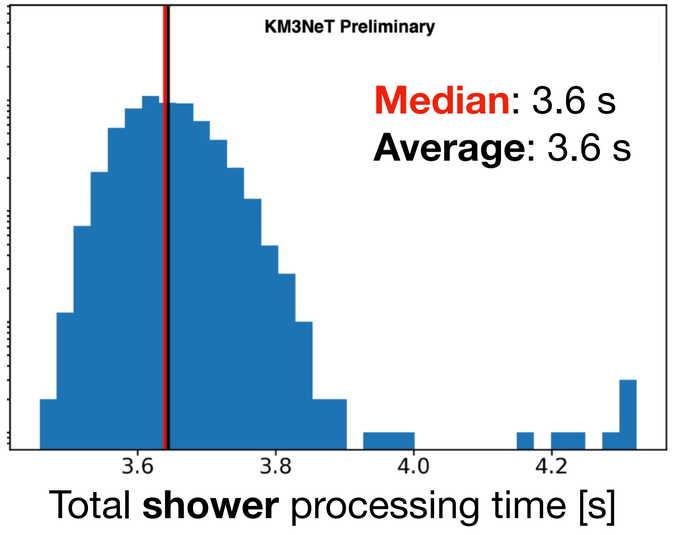
Portopalo di Capo Passero (Sicily)

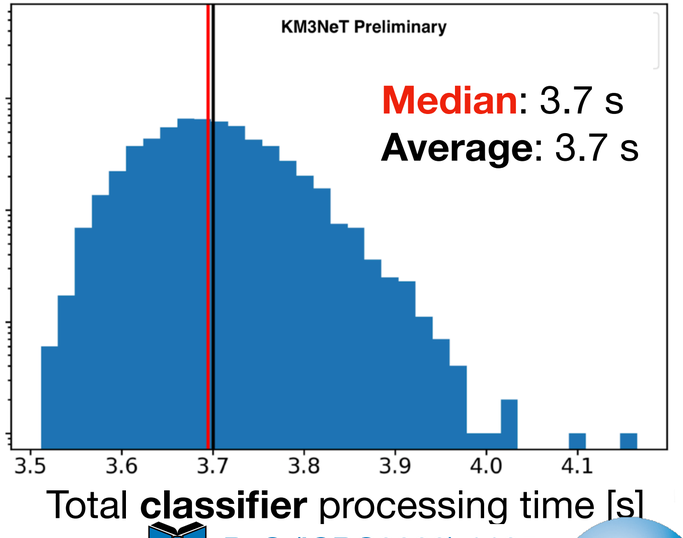
Parallel processes

Triggered event

- **Track reco** → Track reco outputs
- **Shower reco** → Shower reco outputs
- **Classifier** → Score μ/ν



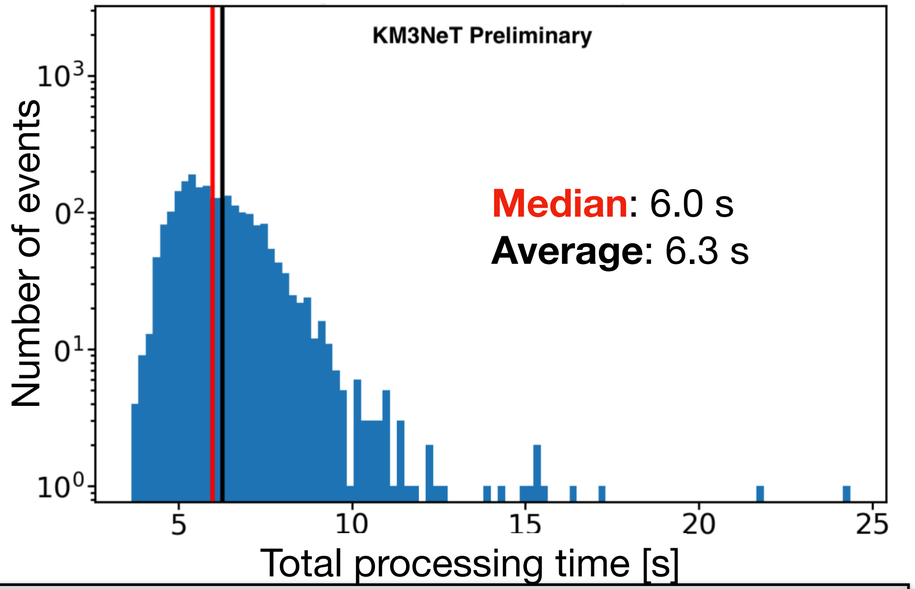




PoS (ICRC2023) 1125

Online processing times

After **~6 seconds** each event triggered by the **ORCA detector** has been reconstructed and classified



ORCA18

All data to shore

SHORE STATION

Institut Michel Pacha, La Seyne-sur-Mer (France)

Reconstruction and classification serially processed

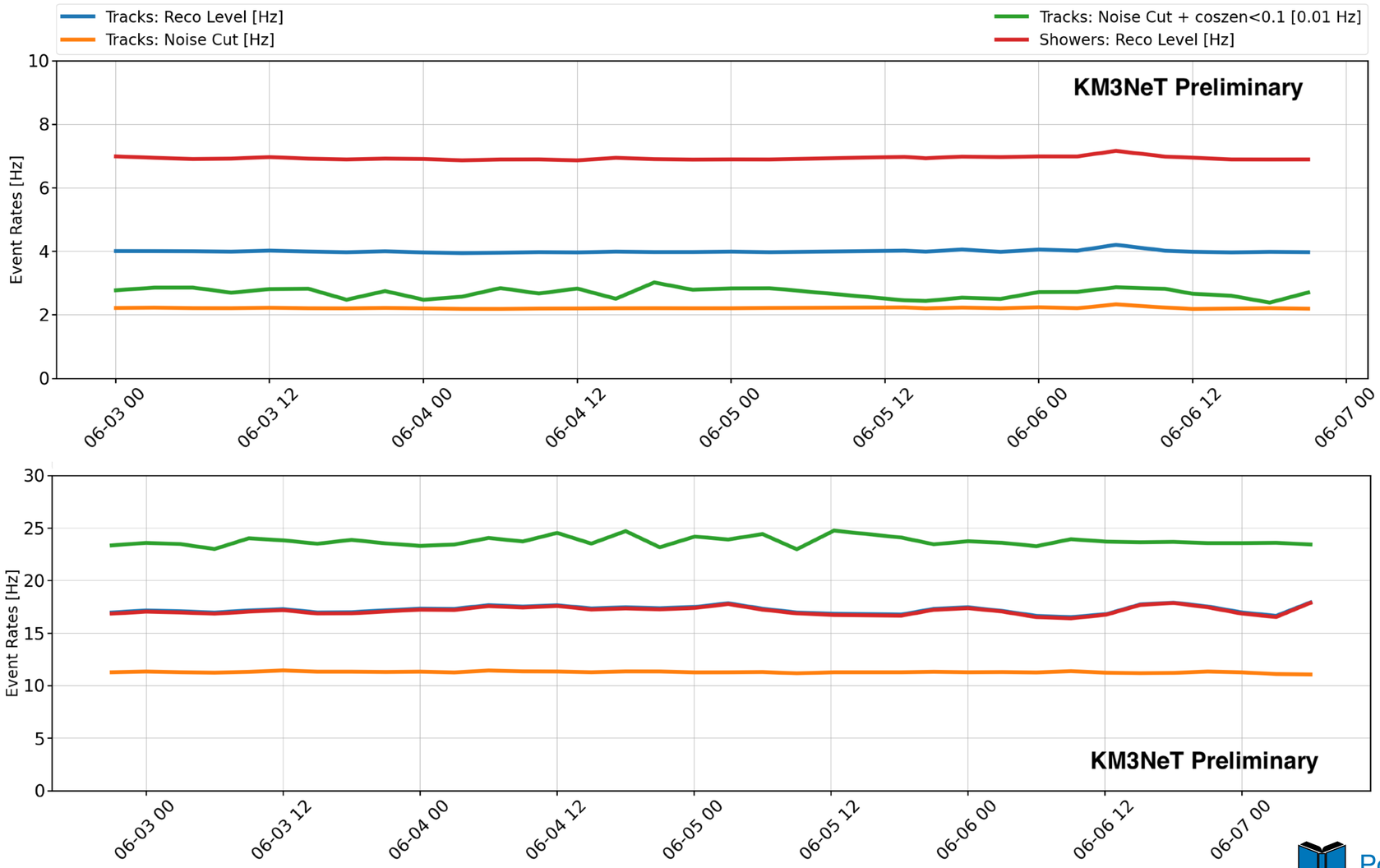
Triggered event → Track reco + Shower reco + Classifier → Track&Shower reco outputs + Score μ/ν

PoS (ICRC2023) 1125

Online event rates

ARCA21

ORCA18

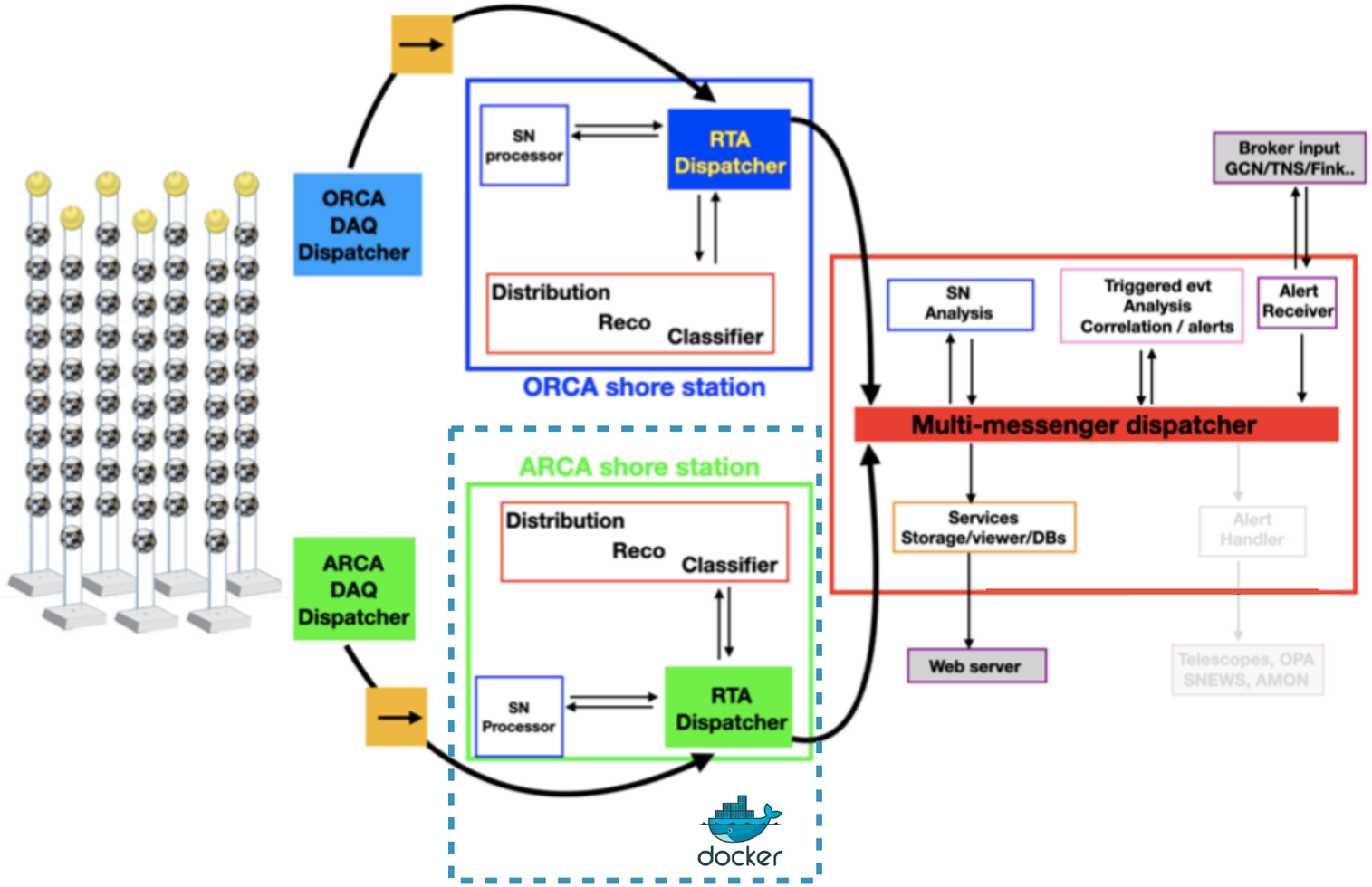


Events with poor quality of reconstruction are discarder after being processed

PoS (ICRC2023) 1125

Online software architecture

KM3NeT
www.km3net.org



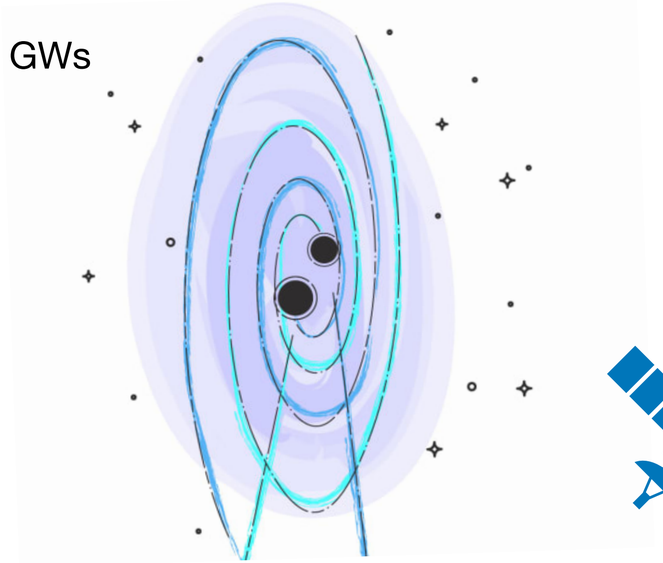
- Reception of external alerts and automatic follow-up of EM/GW alerts currently active

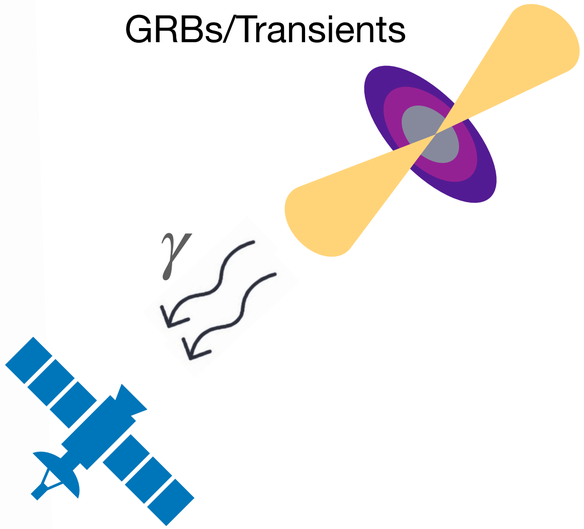
Events reconstructed online are used to perform real-time analyses

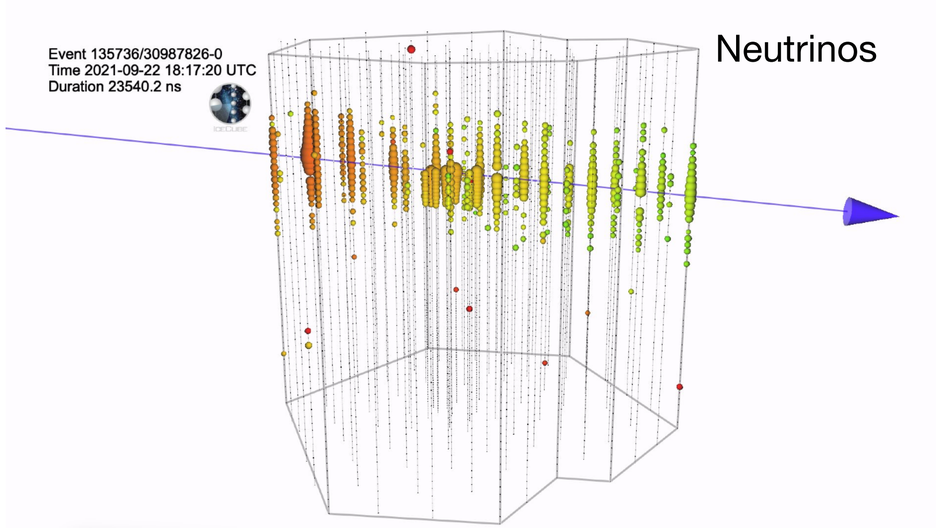
- Events reconstructed in real-time (both as track and shower) and classified (μ/ν) via machine learning algorithms

PoS (ICRC2023) 1125

Analysis pipeline for MM alert follow-ups







Four kinds of **online analyses** are in place to look for temporal and spatial coincidences among the KM3NeT reconstructed events and either:

- GRBs;
- GW extended region;
- Neutrinos identified by IceCube;
- Transient events (e.g., flaring/variable objects).

PoS (ICRC2023) 1125, PoS (ICRC2023) 1521

- Current analyses consider **only track-like events (best angular resolution)**. Work is ongoing to include shower-like events as well.
- The **event selection** is mainly focused on **up-going events**. Progress is being made for including also downgoing events, to ensure a full sky coverage

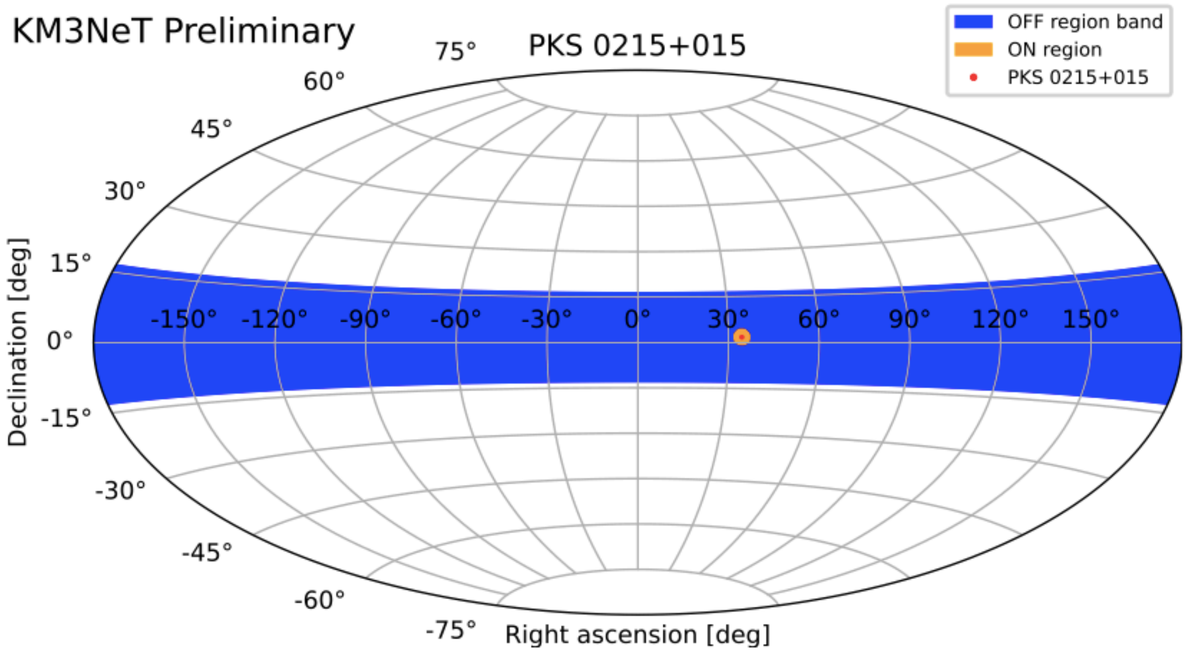
In addition, a **pipeline for MeV neutrinos in coincidence with GWs** is also in place, that counts the **number of coincidences within single DOMs in a sliding window of 0.5 s.** PoS (ICRC2023) 1223

Analysis pipeline for MM alert follow-ups: ON/OFF technique

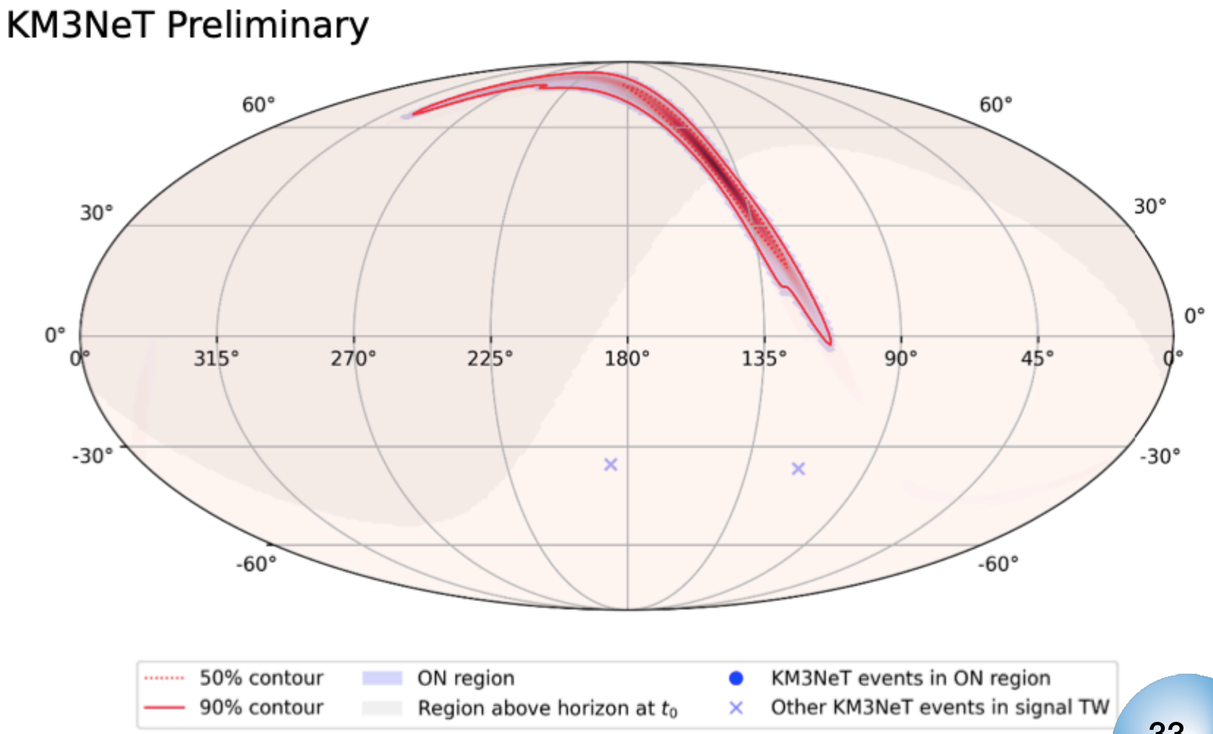
- **Event selection optimised for each alert** reducing the expected background to the minimum possible taking into account the shape of the Region of Interest (RoI). **Basic cuts (on number of triggered hits, reco quality, energy, and track length) applied to reduce the background.**
- **Expected background** is computed from an **OFF region** defined for each alert, using various days before the alert trigger time in a region with similar coverage in local coordinates as the **ON region, where the signal is expected.**
- **Checks on the stability conditions during the ON and the OFF period ensure a stable data-taking flow**

PoS (ICRC2023) 1521

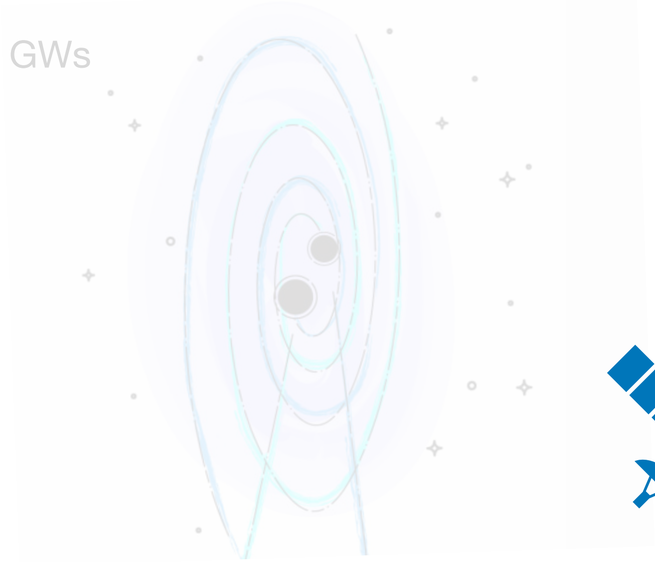
PKS 0215+015
(Potentially correlated with IC-220225A)



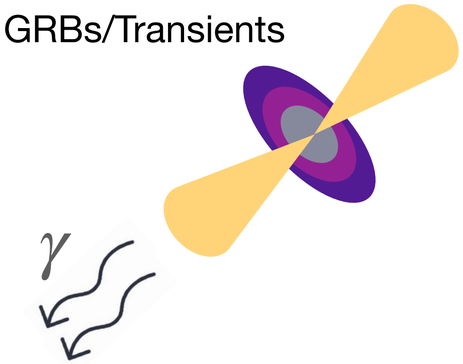
GW S230628ax



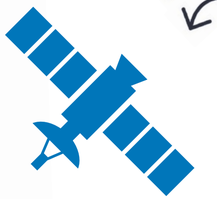
Analysis pipeline for MM alert follow-ups: temporal windows



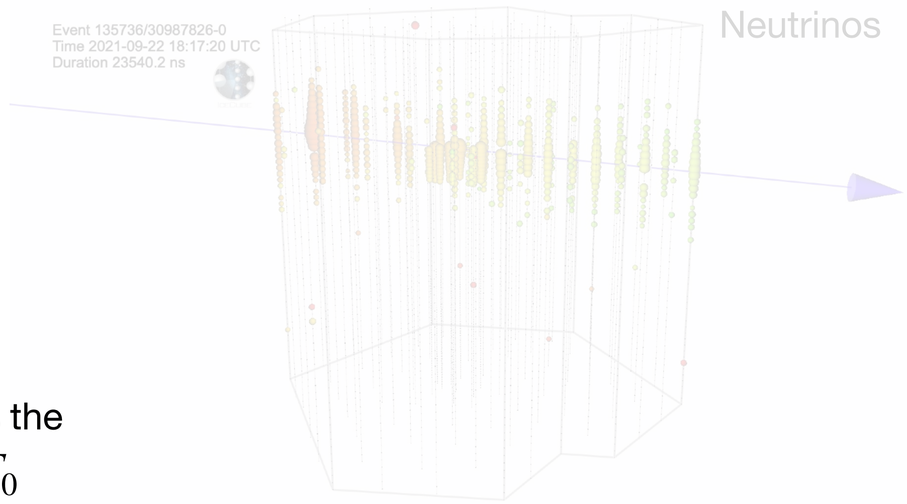
GRBs/Transients



γ



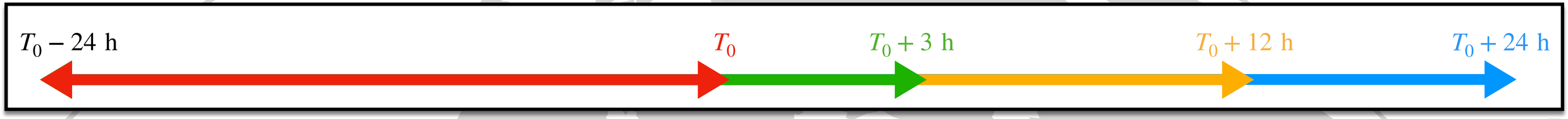
A γ-ray satellite triggers the GRB/transient at time T_0



GCN Alert published to the **G**amma-ray **C**oordinates **N**etwork (GCN)

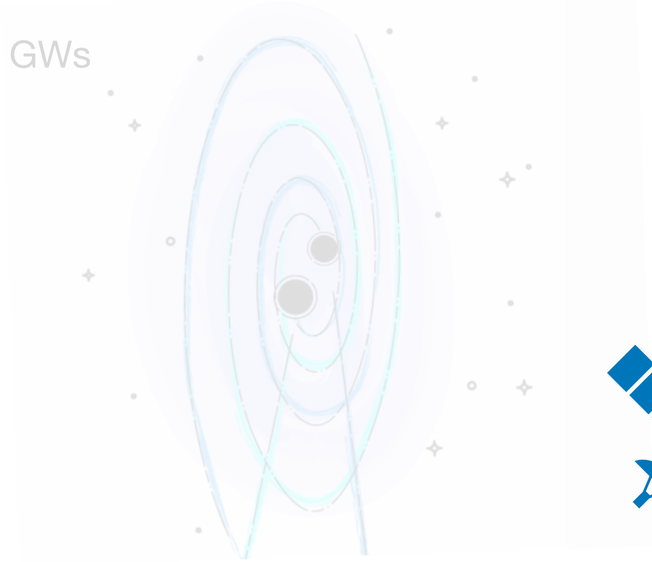
KM3NeT receive the external trigger (connection with the GCN broker)

Automatic analysis pipeline runs with multiple iterations … for different time windows

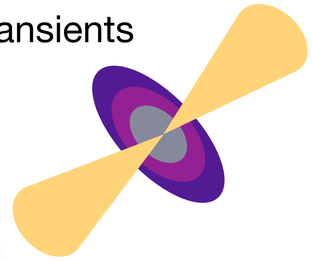


PoS (ICRC2023) 1125, PoS (ICRC2023) 1521

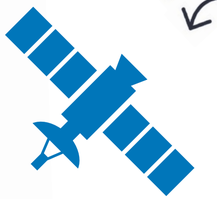
Analysis pipeline for MM alert follow-ups: temporal windows



GRBs/Transients



γ



A γ-ray satellite triggers the GRB/transient at time T_0

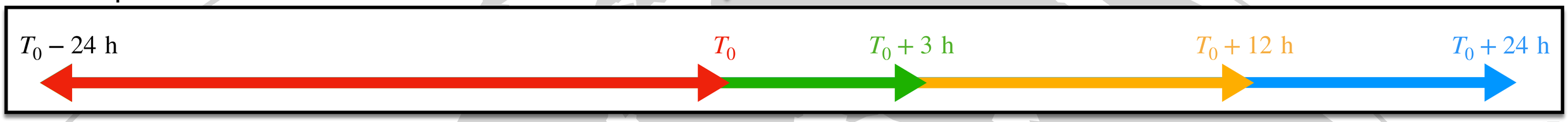
For GRBs will be activated soon dedicated time windows, i.e. [-250 s,+750 s] and [-1 h, +1 day]

GCN Alert published to the **G**amma-ray **C**oordinates **N**etwork (GCN)

KM3NeT receive the external trigger (connection with the GCN broker)

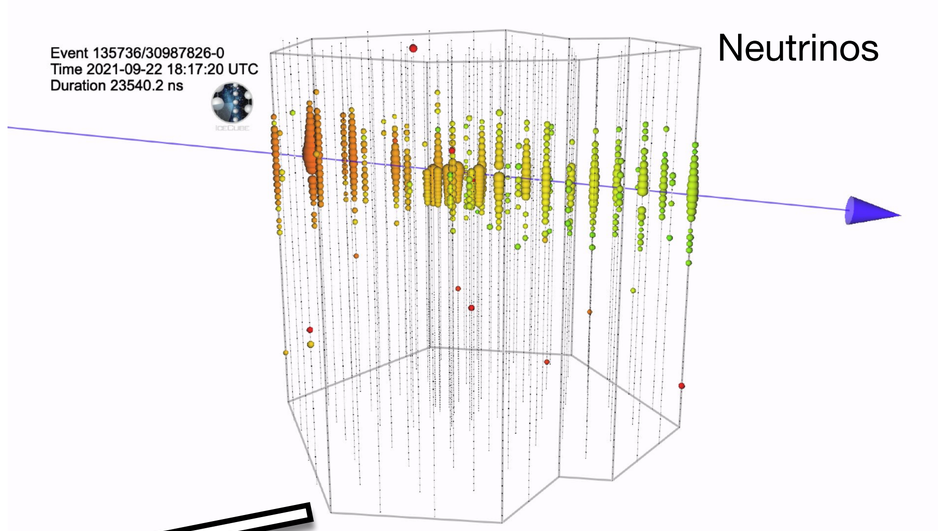
Automatic analysis pipeline runs with multiple iterations

… for different time windows



PoS (ICRC2023) 1125, PoS (ICRC2023) 1521

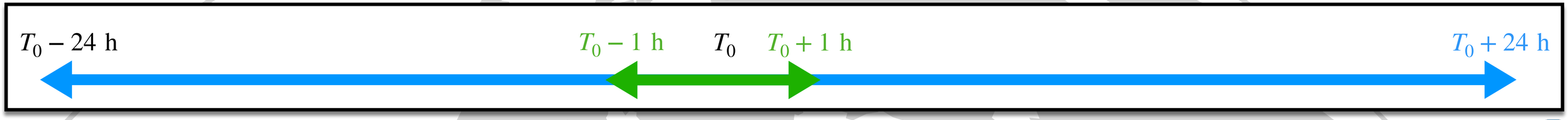
Analysis pipeline for MM alert follow-ups: temporal windows



GCN Alert published to the **G**amma-ray **C**oordinates **N**etwork (GCN)

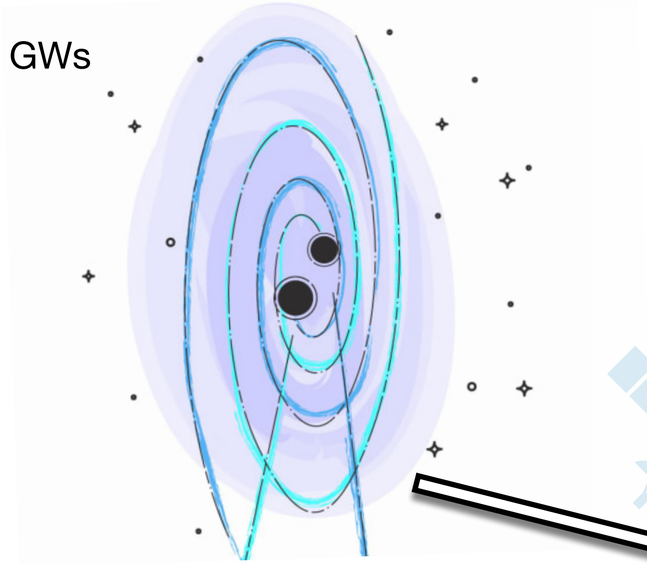
KM3NeT receive the external trigger
(connection with the GCN broker)

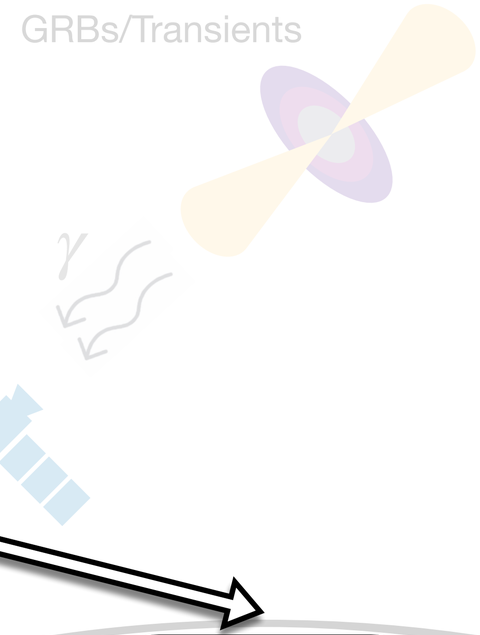
Automatic analysis pipeline runs with multiple iterations … for different time windows



PoS (ICRC2023) 1125, PoS (ICRC2023) 1521

Analysis pipeline for MM alert follow-ups: temporal windows



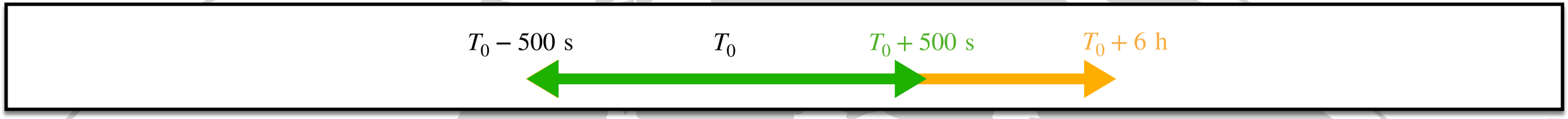


GCN Alert published to the **G**amma-ray **C**oordinates **N**etwork (GCN)

KM3NeT receive the external trigger
(connection with the GCN broker)

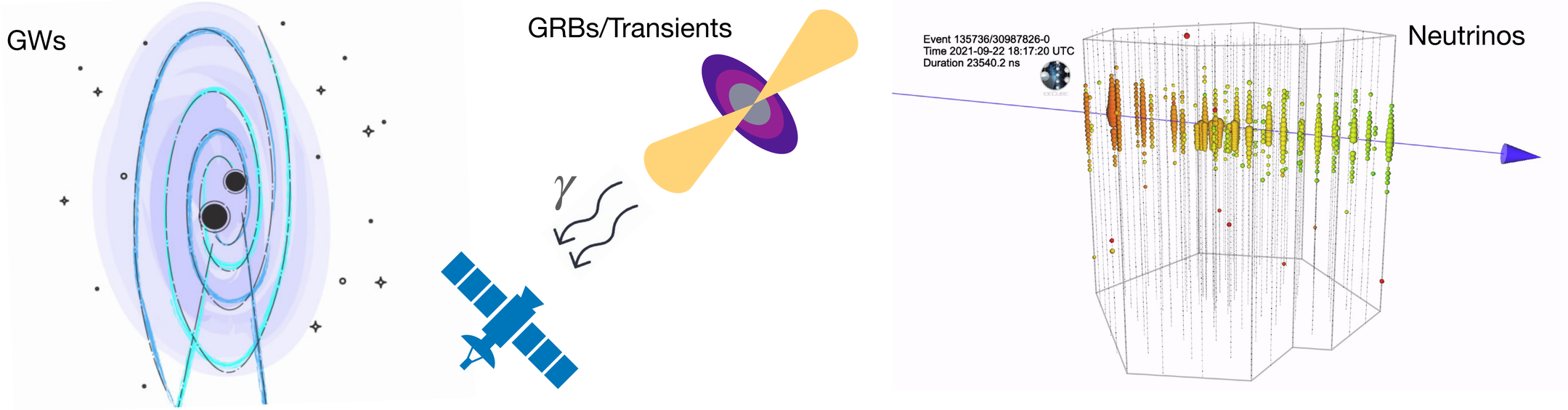
<u>Automatic analysis pipeline</u> runs
with multiple iterations

… for different time windows



PoS (ICRC2023) 1125, PoS (ICRC2023) 1521

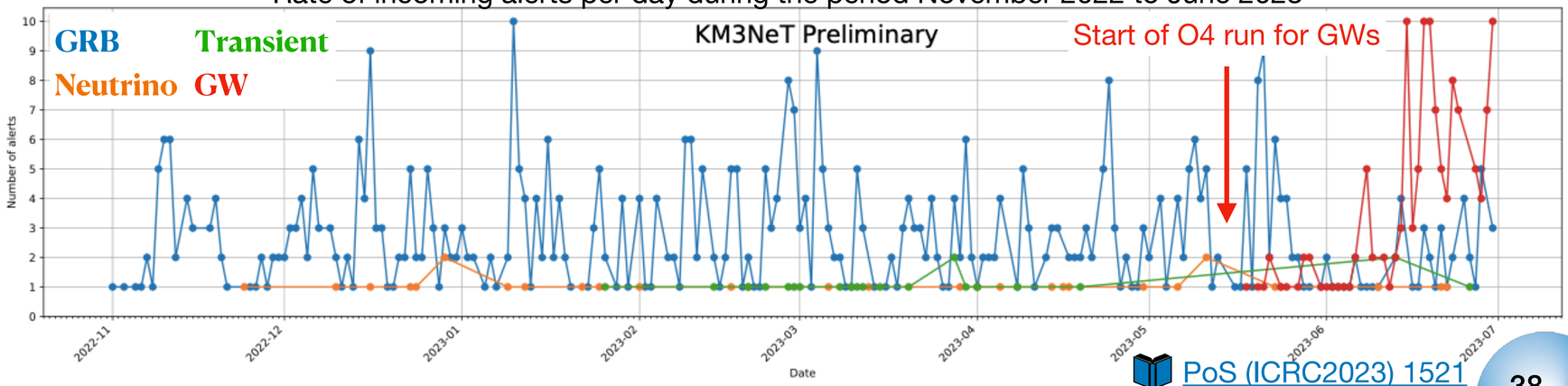
Analysis pipeline for MM alert follow-ups: temporal windows



From November 2022 to June 2023, ~300 alerts from the up-going sky have been processed: 153 GRBs, 106 in coincidence with GW candidates, 16 with neutrinos and 6 with other transients

No significant excess has been found in any of the analyses performed!

Rate of incoming alerts per day during the period November 2022 to June 2023



PoS (ICRC2023) 1521

The online follow-up of GRB 221009A

- Almost one year ago, the **brightest long GRB** ever detected was observed, relatively close to us ($z \sim 0.15$, corresponding to 2.4 billion light-years away), at 13:16.59 UT
- This event produced the **most energetic GRB photon ever seen by Fermi LAT** (ATel #15656), that of **99 GeV**
- LHAASO during 2000 sec after the GRB trigger detected **photons up to 18 TeV, highest energies ever detected from a GRB** (GCN #32677)

KM3NeT GCN Circular 32741

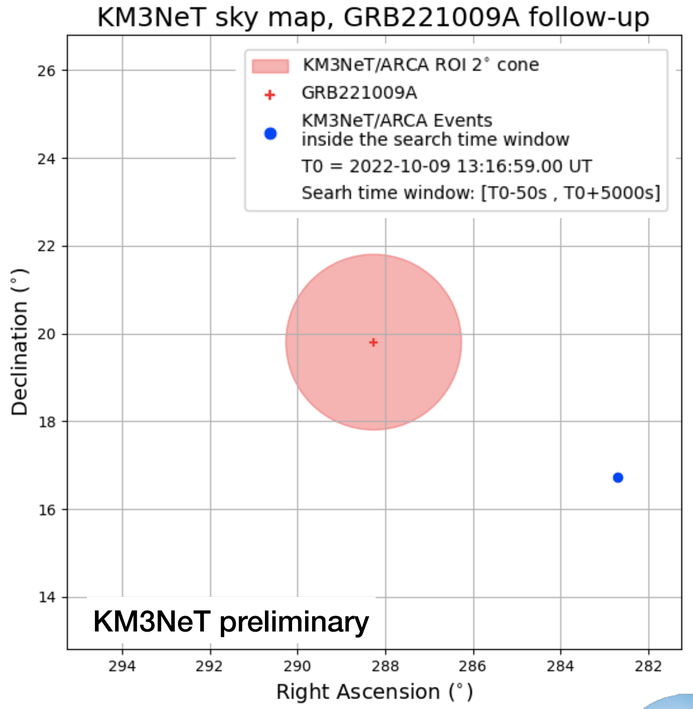
TITLE: GCN CIRCULAR
NUMBER: 32741
SUBJECT: GRB 221009A: search for neutrinos with KM3NeT
DATE: 22/10/13 18:57:37 GMT
FROM: Damien Dornic at CPPM,France <dornic@cppm.in2p3.fr>

The KM3NeT Collaboration (https://www.km3net.org/) reports:

Using the data from the online fast processing chain, the KM3NeT Collaboration has performed a dedicated search for track-like muon neutrino events arriving from the direction of GRB 221009A (Dichiara et al. GCN 32632 (Swift); Veres et al. GCN 32636 (Fermi-GBM)). The search covers the time range of [T0-50s, T0+5000s], with T0 being the trigger time reported by Fermi-GBM (T0=2022-10-09 13:16:59.00 UTC), during which both KM3NeT detectors were collecting good quality data. However, the GRB location was above the KM3NeT horizon (mean elevation of about ~40deg) during the search time window, significantly reducing the point-like source sensitivity. In both detectors, zero events were observed in the search window, while o(0.1) were expected from the background. The online fast processing uses preliminary calibrations and detector alignment, which will be superseded in a future elaborated analysis.

A parallel search has been performed in the MeV range (Eur.Phys.J.C 82 (2022) 4, 317) without any significant neutrino coincidence.

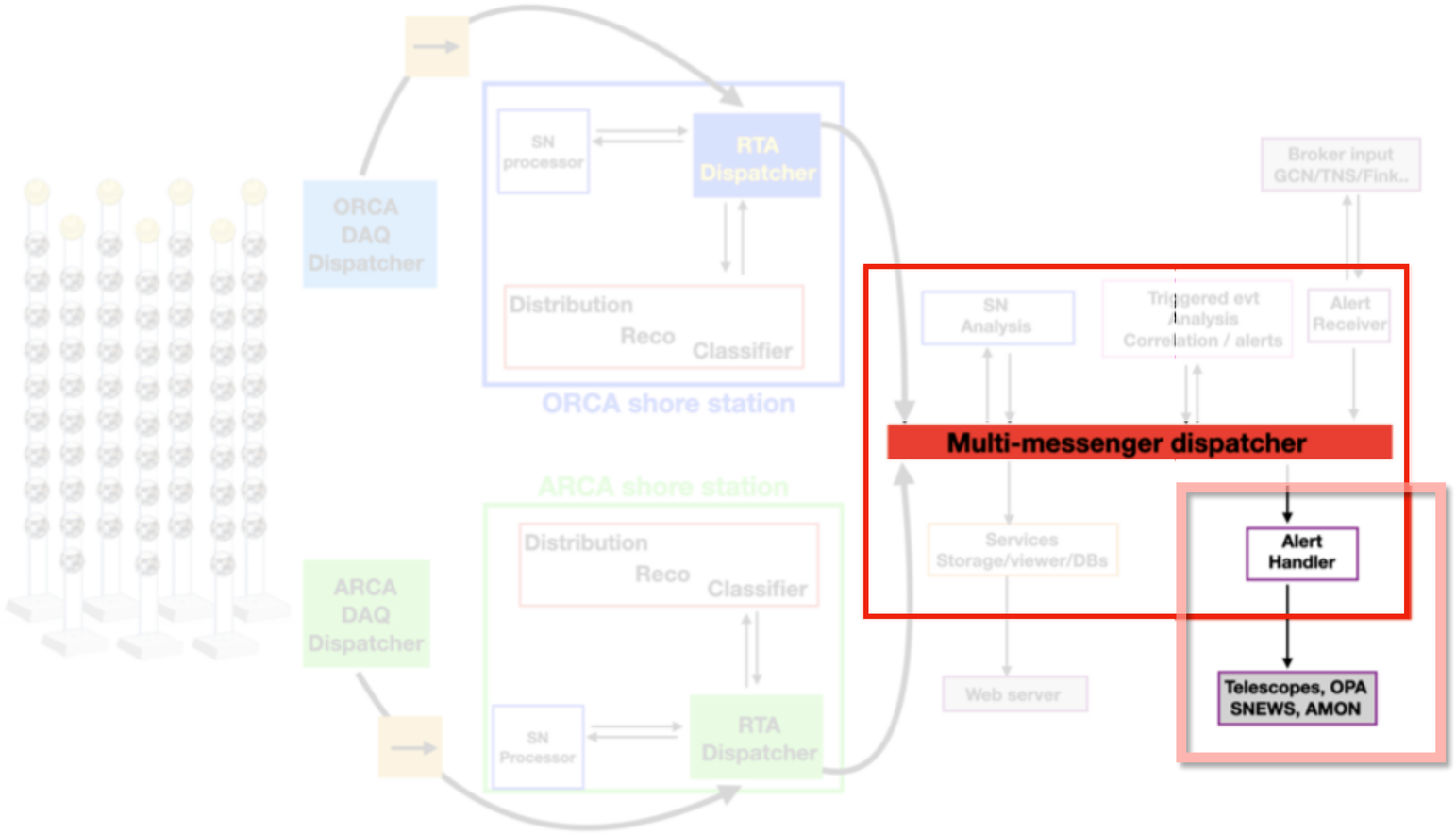
KM3NeT is a large undersea (Mediterranean Sea) infrastructure hosting two neutrino detectors, sensitive to burst of supernova neutrinos in the MeV range and to astrophysical neutrinos in the GeV-PeV energy range: ARCA at high energy and ORCA at low energy. A total of 21 and 11 detection lines are currently in operation in ARCA and ORCA, respectively.



No events found in the signal region!

For refined follow-up of GRB 221009A with KM3NeT ARCA and ORCA (offline analysis), see PoS (ICRC2023) 1503

Online software architecture



Still in progress:
- Implementation of the neutrino selection for the alert sending
- Alert sending program

PoS (ICRC2023) 1125

Summary

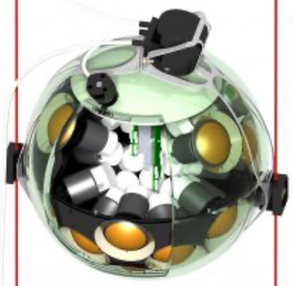
- The next generation neutrino telescope **KM3NeT** (ORCA + ARCA) is **under construction in the Mediterranean Sea**
- **KM3NeT/ARCA** (in Sicily, Italy) is designed for the detection of **high-energy neutrinos (from ~100 GeV to PeV)** , thus is optimized for **neutrino astronomy & multimessenger studies**
- **First string** is operating since **more than 6 years**
- **ARCA** and **ORCA** are taking data now with **21** and **18 strings**, respectively
- **Online multimessenger analysis framework** for KM3NeT **in progress** and **already operative**
- **Automatic online analyses in place** to look for temporal and spatial coincidences among the KM3NeT reconstructed events and GRBs, GW extended regions, neutrinos identified by IceCube, transient events
- A pipeline for MeV neutrinos in coincidence with GWs is also in place, that counts the number of coincidences within single DOMs in a sliding window of 0.5 s
- More than 300 online analyses performed so far (mainly after GRB external triggers); no significant excess has been found in any of the analyses performed.

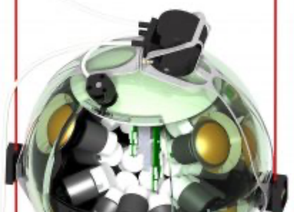
Summary

- The next generation neutrino telescope KM3NeT (ORCA + ARCA) is under construction in the Mediterranean Sea
- KM3NeT/ARCA (in Sicily, Italy) is designed for the detection of high-energy neutrinos (from ~100 GeV to PeV) , thus is optimized for neutrino astronomy & multimessenger studies
- First string is operating since more than 6 years
- ARCA and ORCA
- Online multime already operative
- Automatic onlin alyses in place to look for temporal and spatial coincidences among the KM3NeT reconstructed events and GRBs, GW extended regions, neutrinos identified by IceCube, ANTARES events
- A pipeline for MeV neutrinos in coincidence with GWs is also in place, that counts the number of coincidences within single DOMs in a sliding window of 0.5 s
- More than 300 online analyses performed so far (mainly after GRB external triggers); no significant excess has been found in any of the analyses performed.

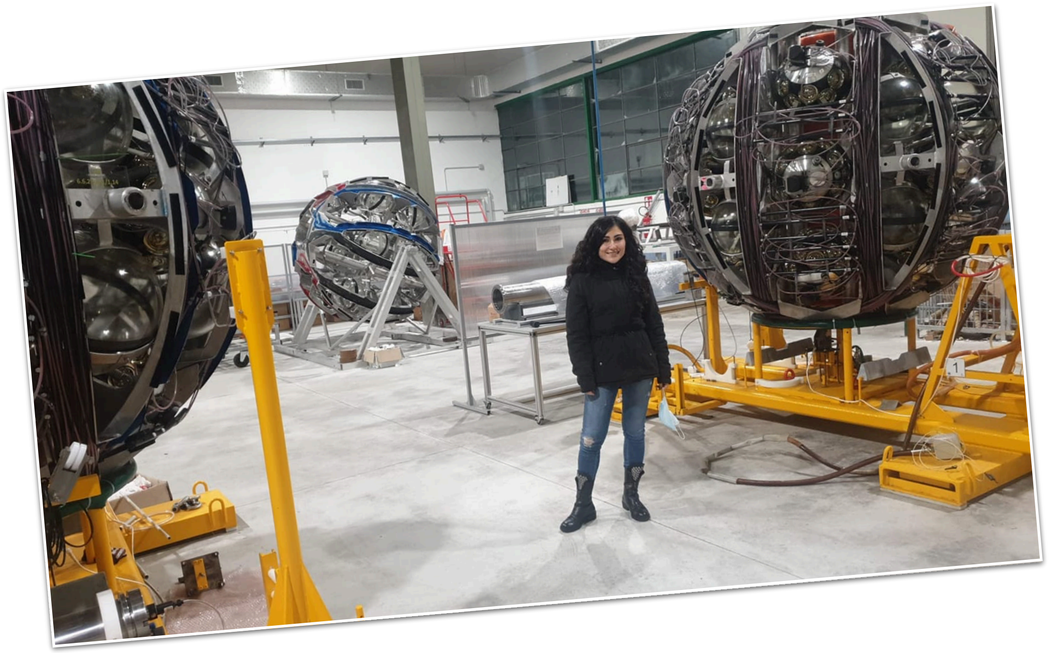
KM3NeT has started to play his role in the field of the real-time multimessenger astronomy!

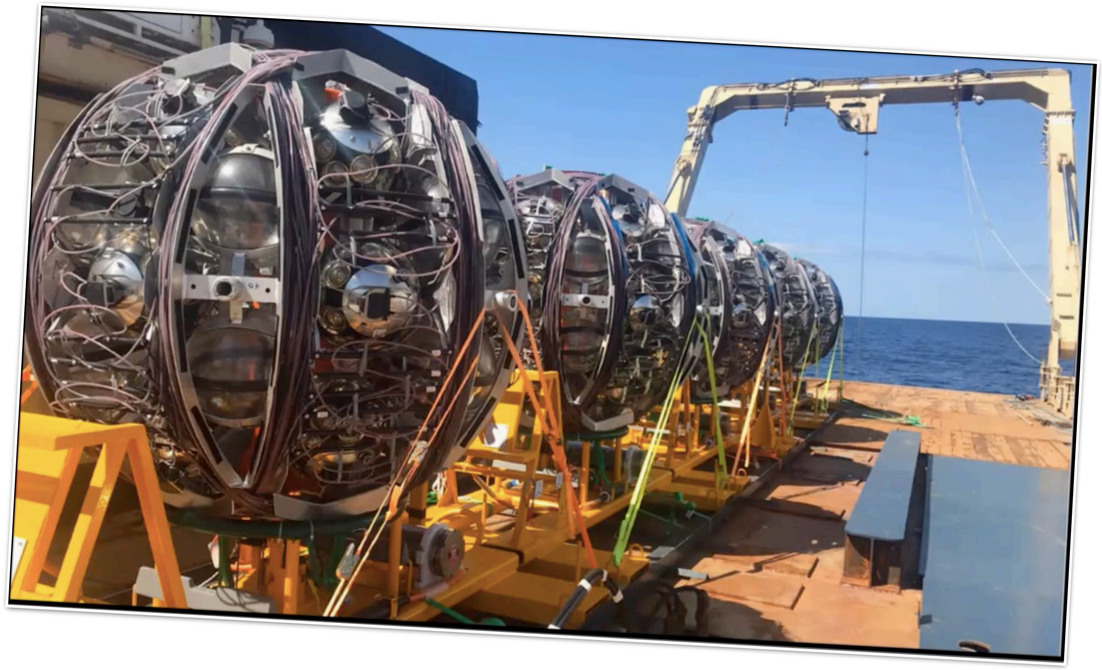
Stay tuned ...



Thank you for your attention!

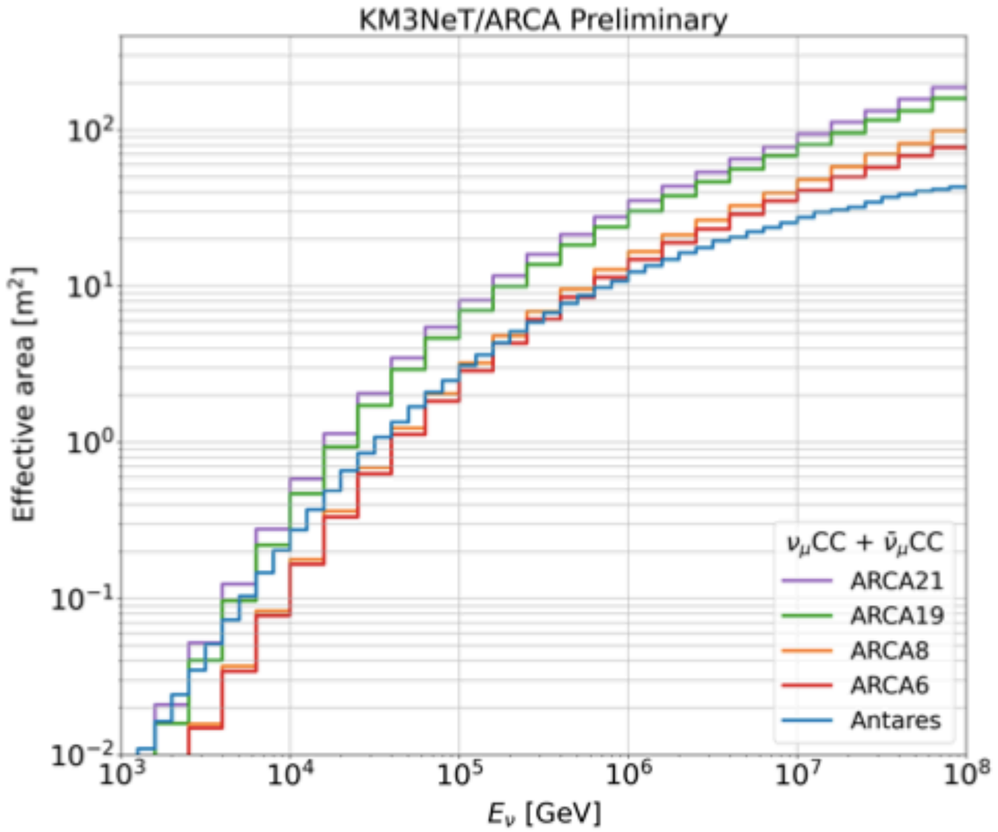


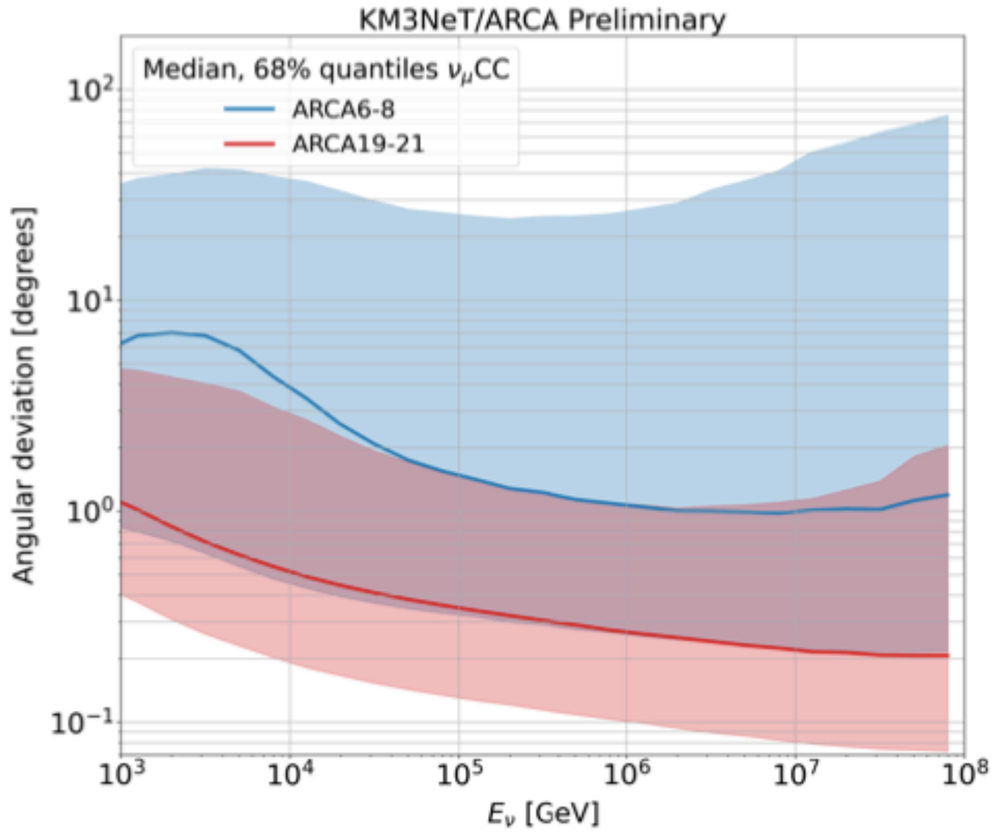


Backup

KM3NeT/ARCA performances

KM3NeT
www.km3net.org



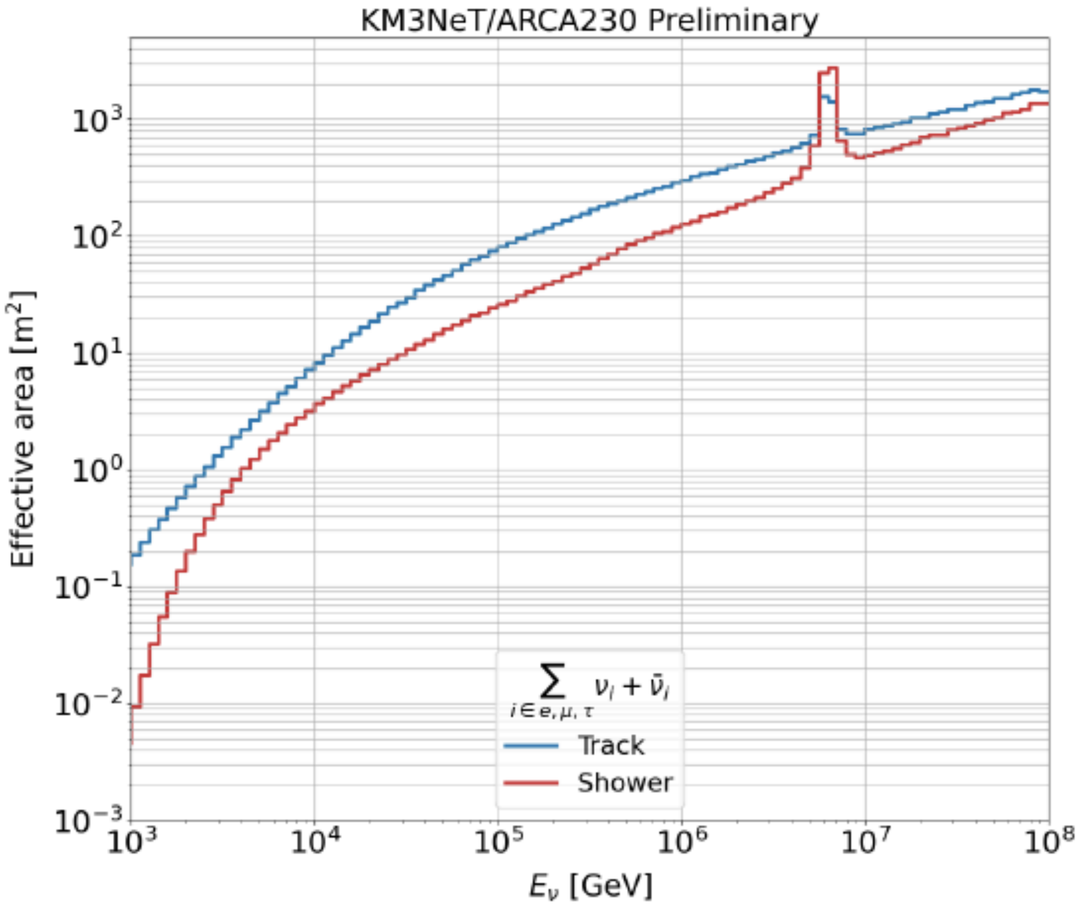


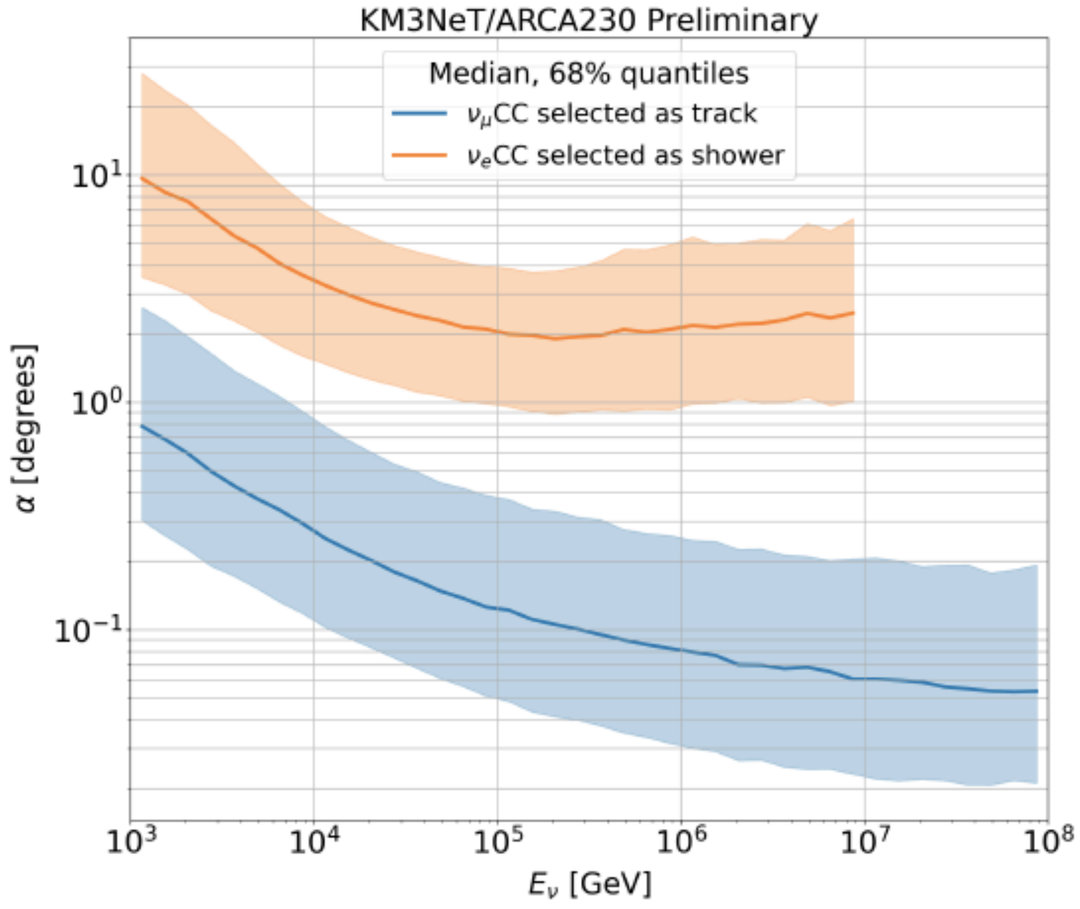
The ARCA6-8 period reaches an angular deviation of $\sim 1^\circ$ at 100 PeV while the ARCA19-21 period already reaches $\sim 0.2^\circ$. For the full detector this is expected to improve towards $\sim 0.06^\circ$.

PoS (ICRC2023) 1018

KM3NeT/ARCA performances

KM3NeT
www.km3net.org

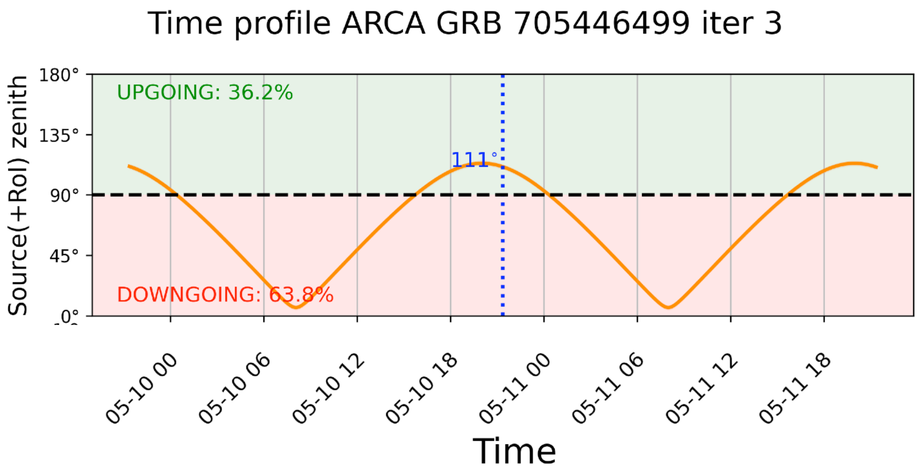


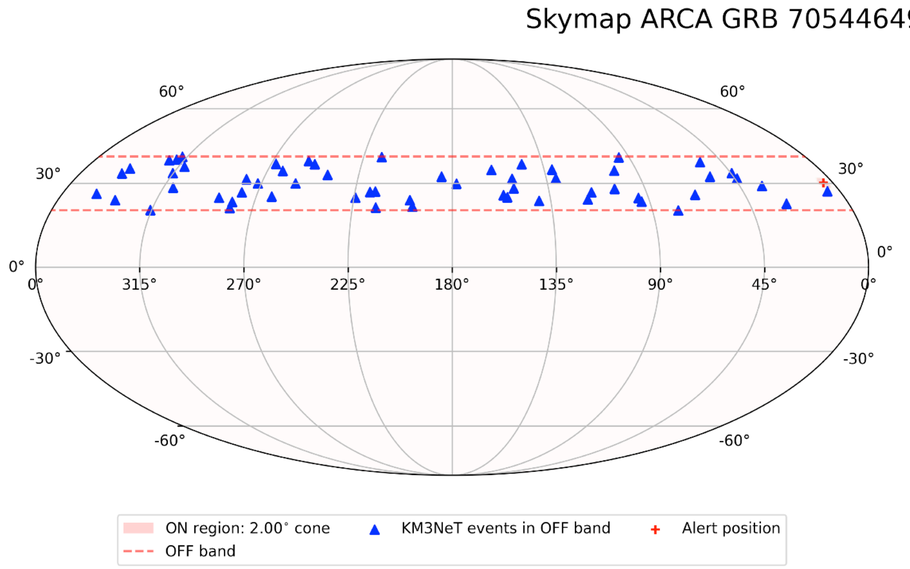


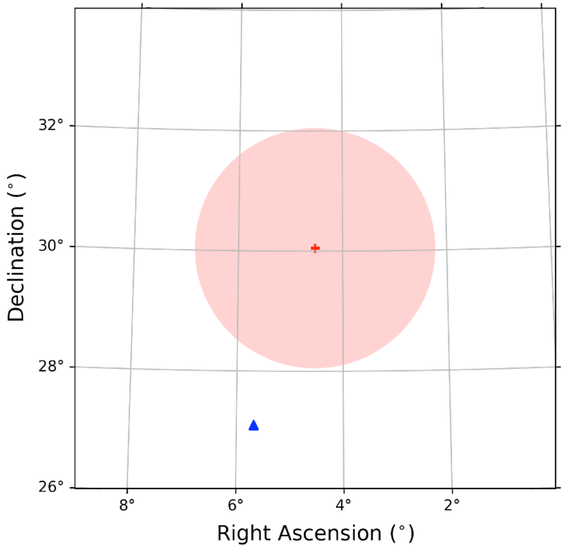
PoS (ICRC2023) 1075

Monitoring of the GRB real-time analysis

Date Event: 2023-05-10 21:21:34.01
https://gcn.gsfc.nasa.gov/other/705446499.fermi

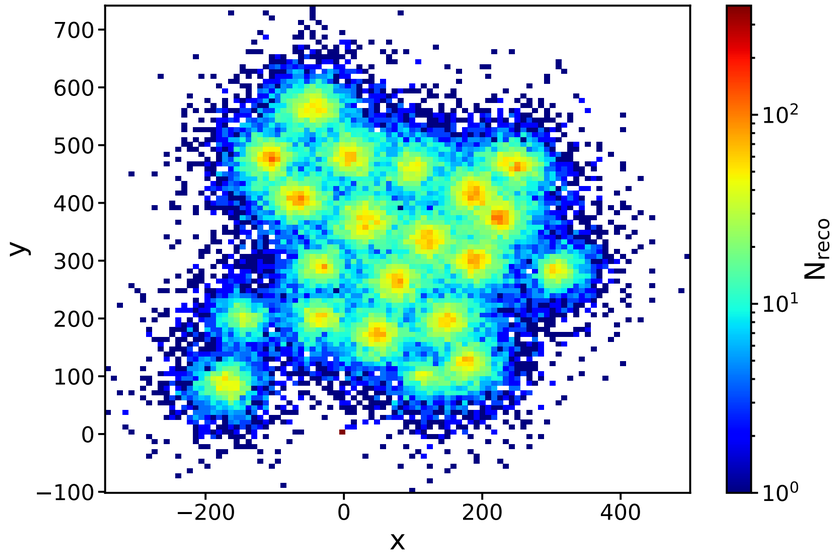


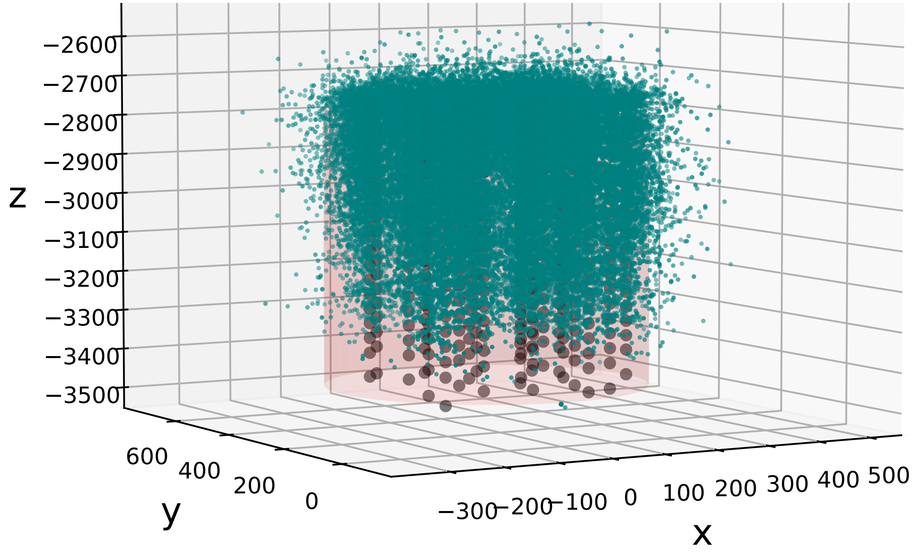


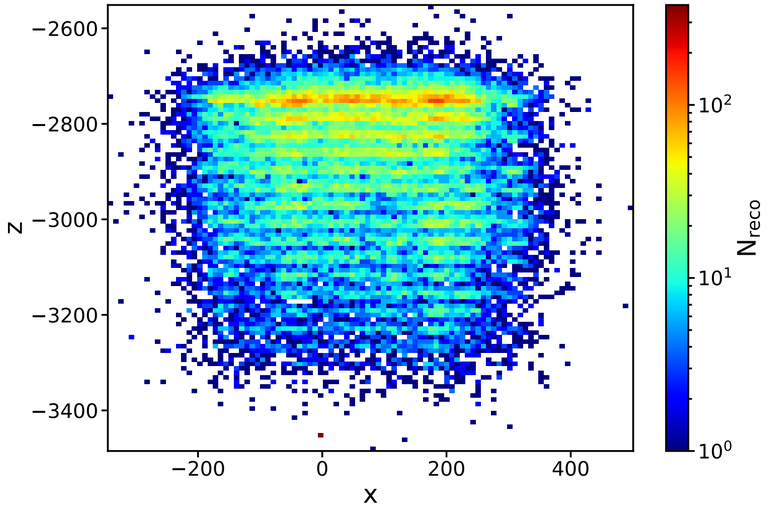


Events reconstructed in real-time

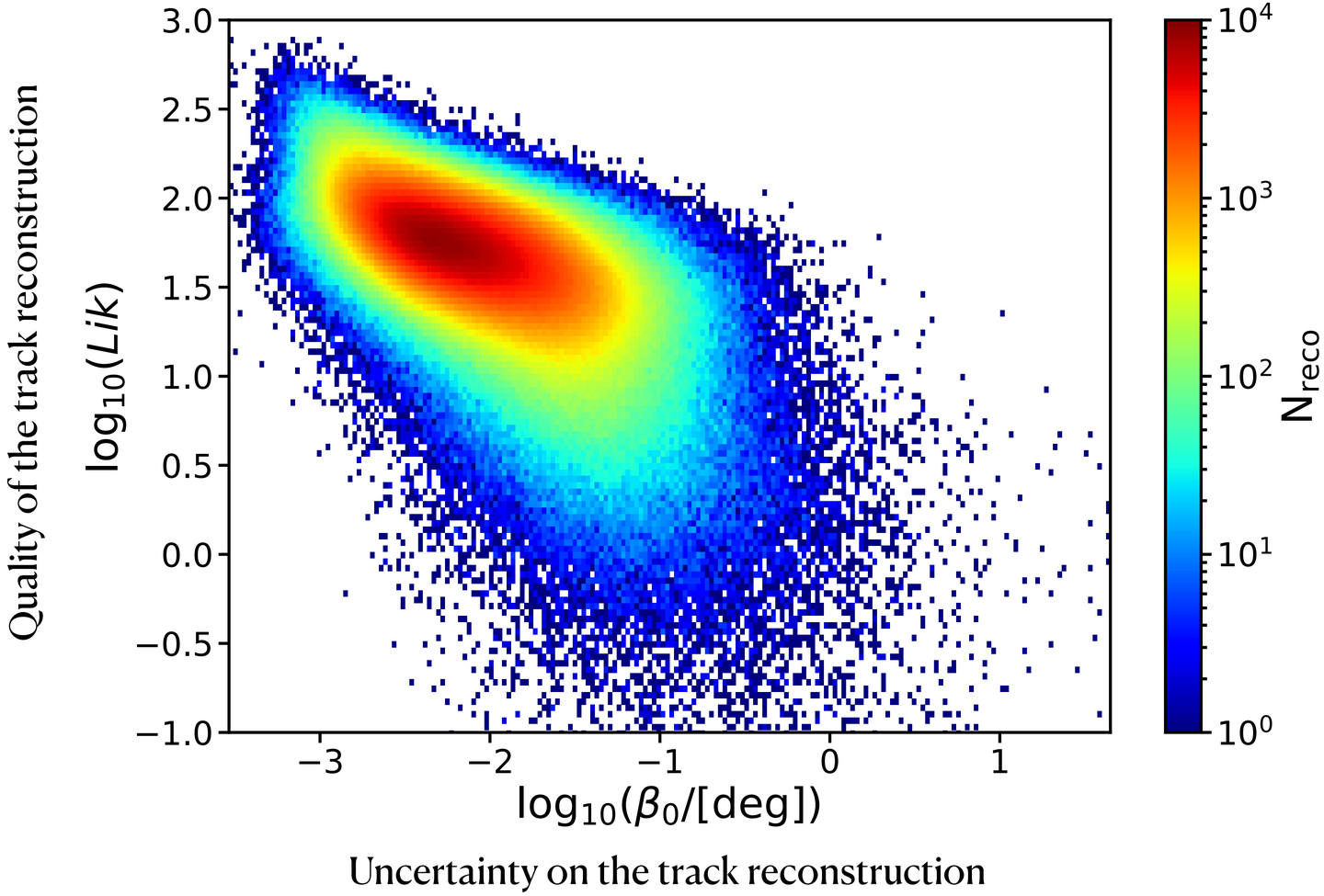
Reconstructed verteces







Events reconstructed in real-time



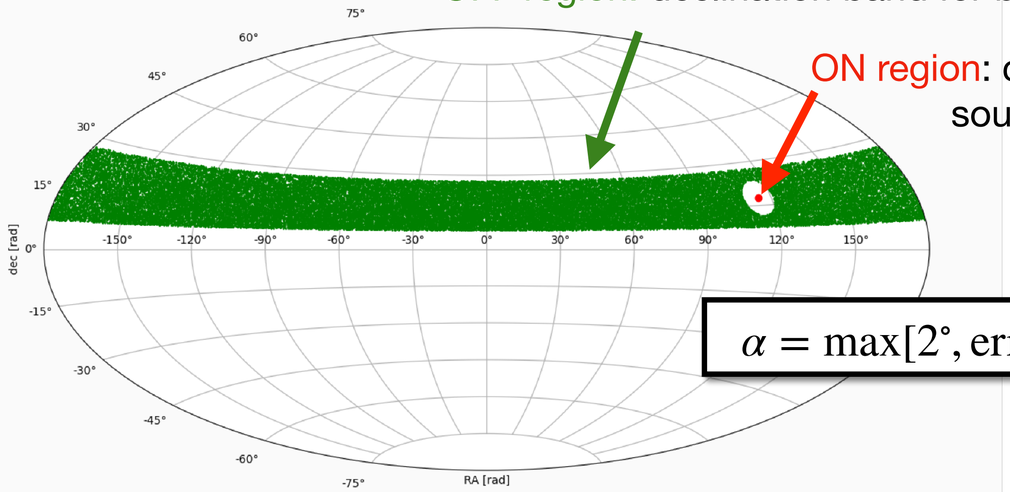
GRB real-time analysis in KM3NeT

Basic cuts (on number of triggered hits, reco quality, energy, and track length) applied to reduce the background

ON/OFF technique

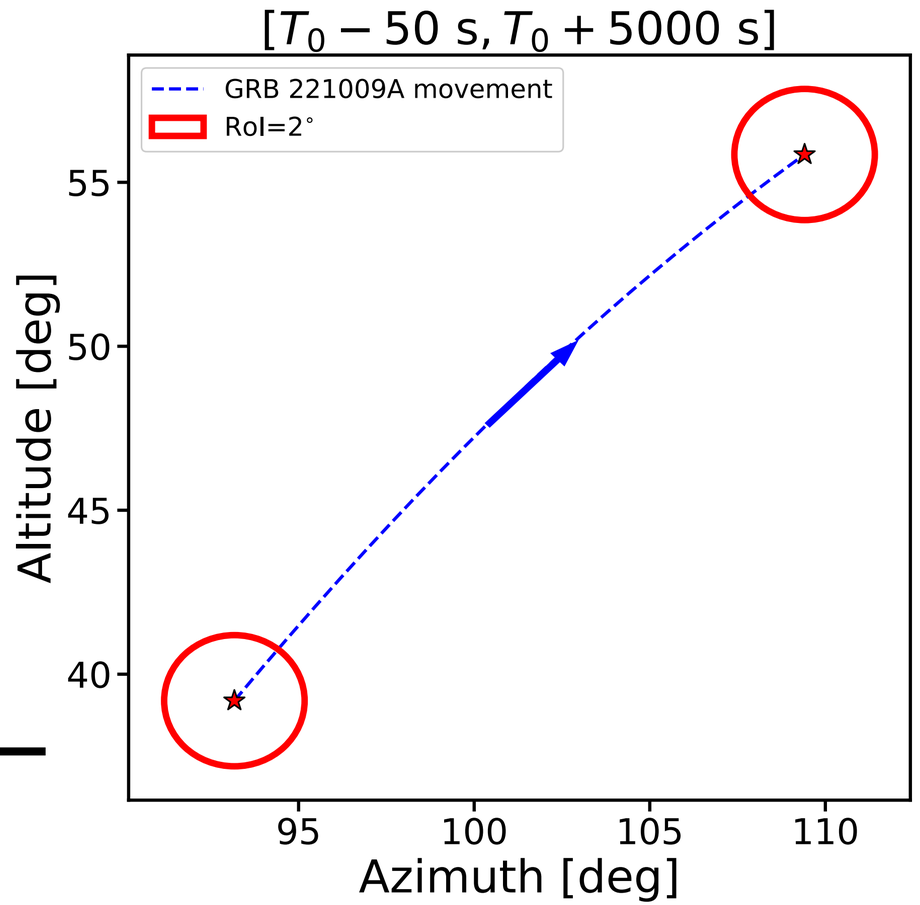
OFF region: declination band for background

ON region: cone centered at the source position



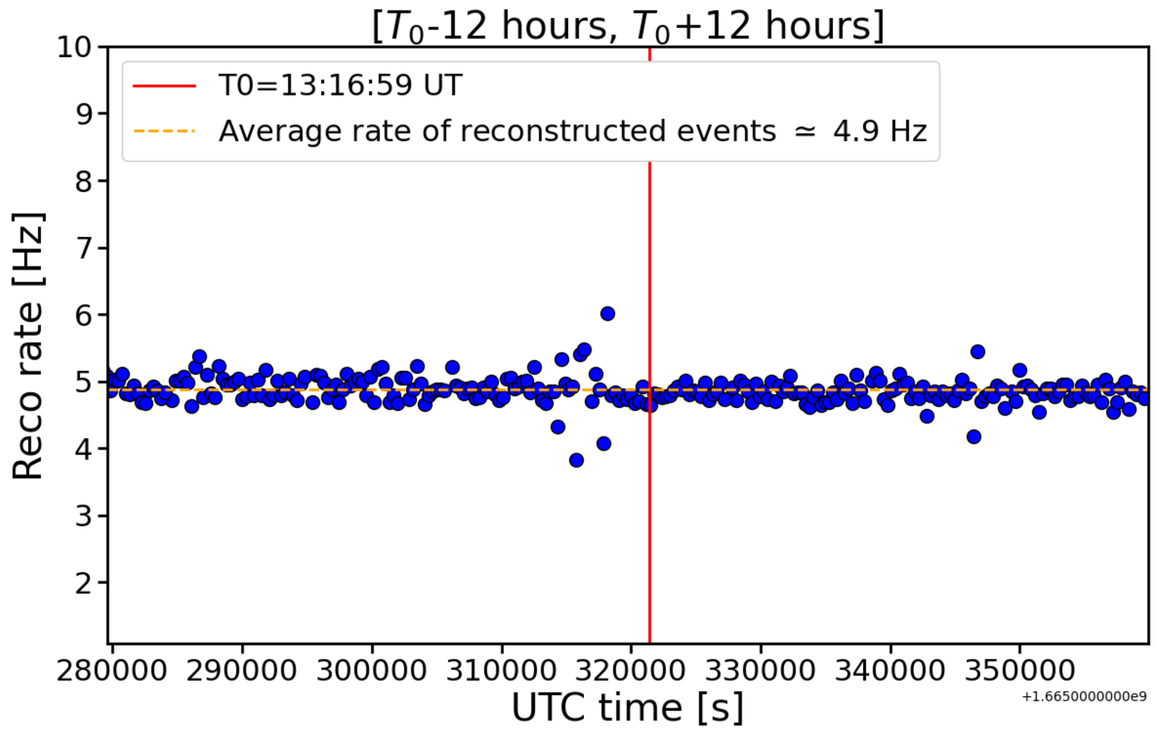
$$\alpha = \max[2^{\circ}, \text{error position GRB}]$$

Signal and background estimated following the movement of the source during the search time window



Search of ν_μ from GRB 221009A using online reconstructed data

Check of the stability of real-time reconstruction data



Check of the stability of real-time reconstruction data after analysis cuts (to reduce background)