KM3NeT physics program

Silvia Celli

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on behalf of the KM3NeT Collaboration
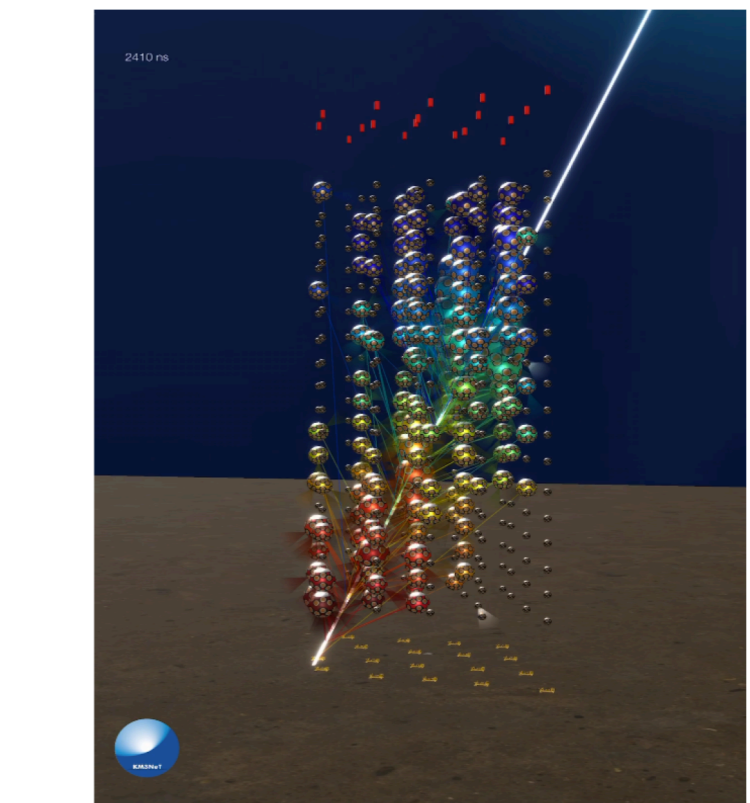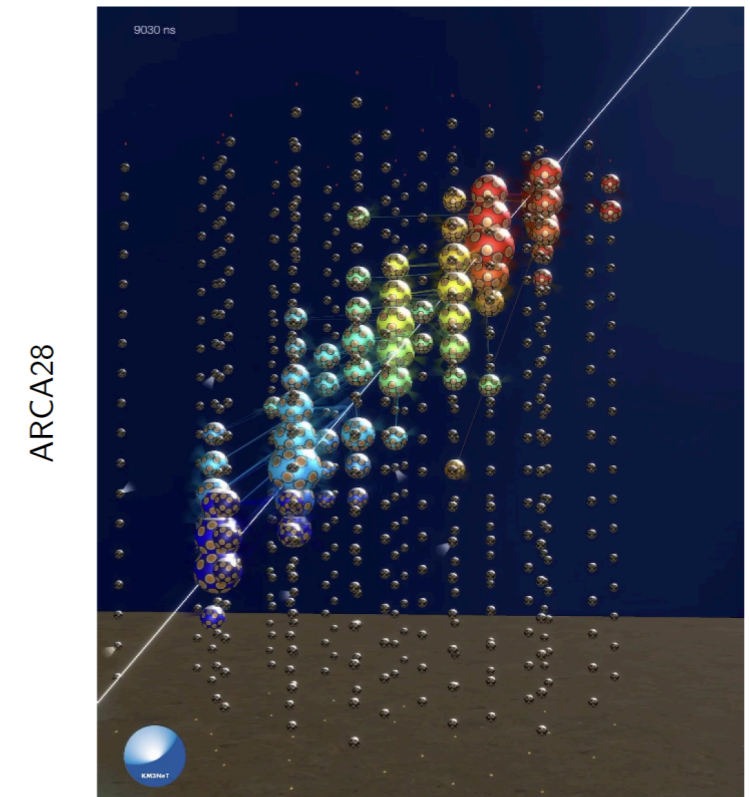
silvia.celli@roma1.infn.it

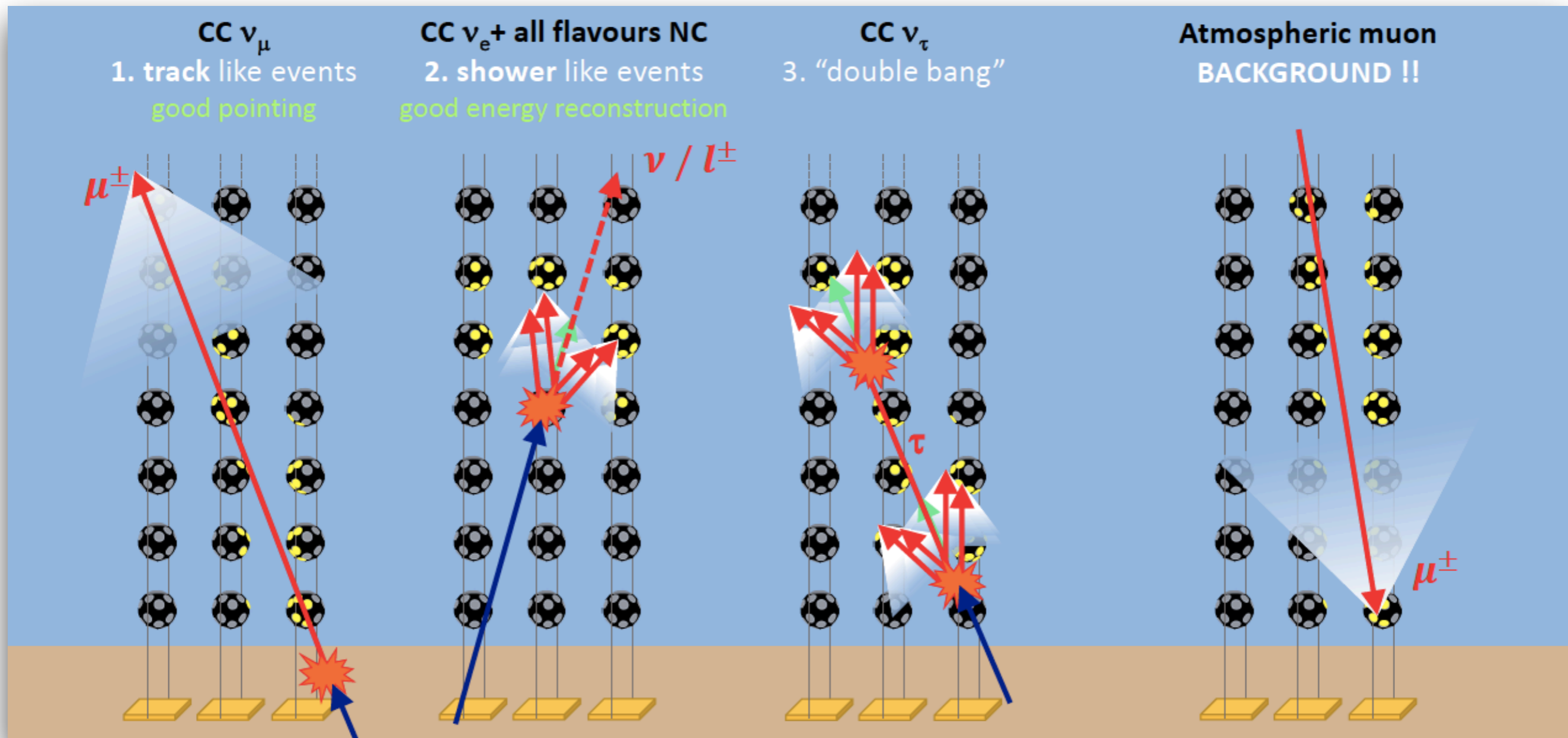**@ Vulcano Workshop 2024 - May 31st, 2024**

Outline of the talk

- The KM3NeT detector(s)

- Neutrino astronomy

- Highlights on recent results

- The multi-messenger program

Neutrino detection principle & event topologies

- Track like events ⟶ golden astronomical channel
- Shower like events ⟶ calorimetric ⟶ diffuse analyses

KM3NeT at a glance
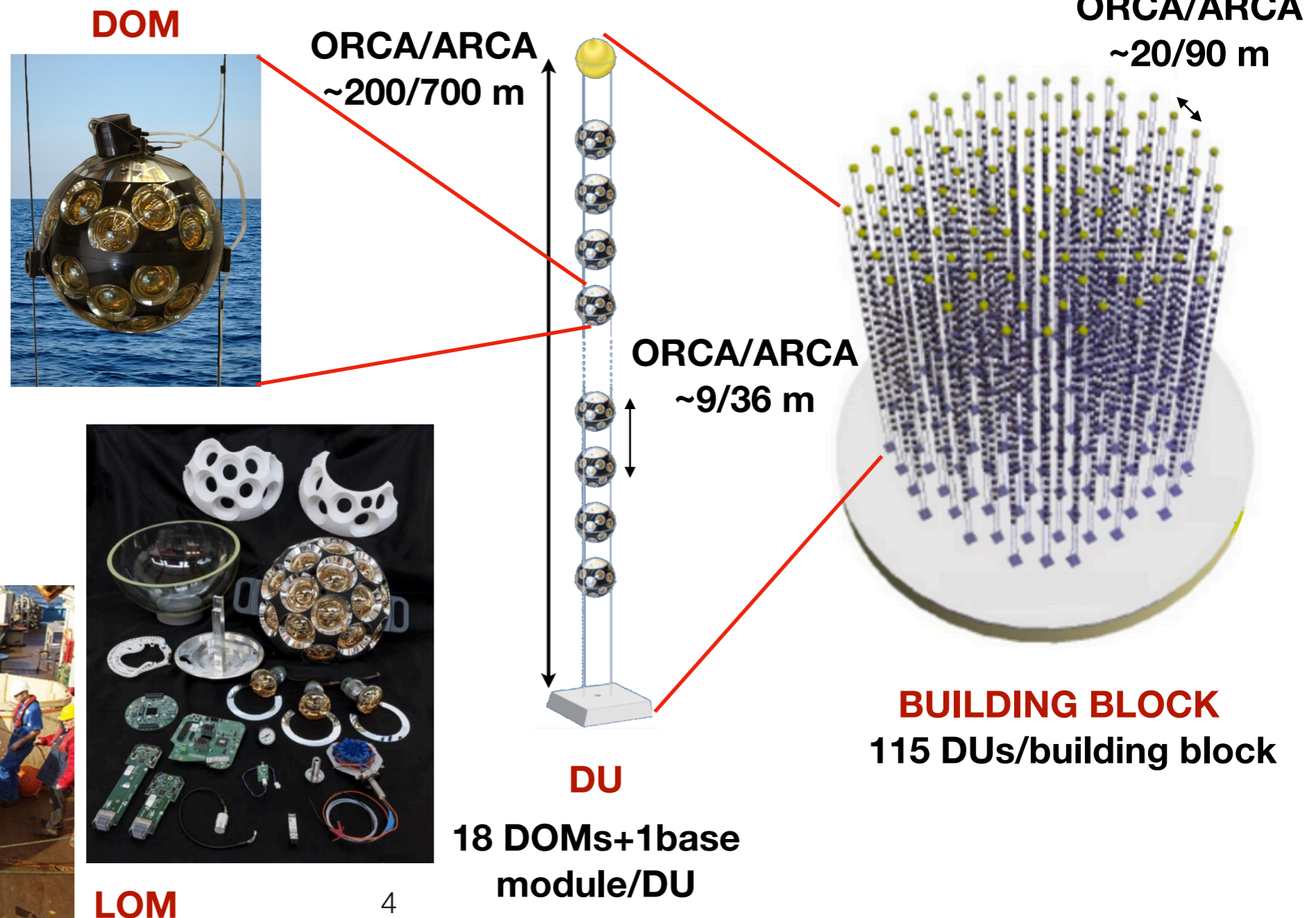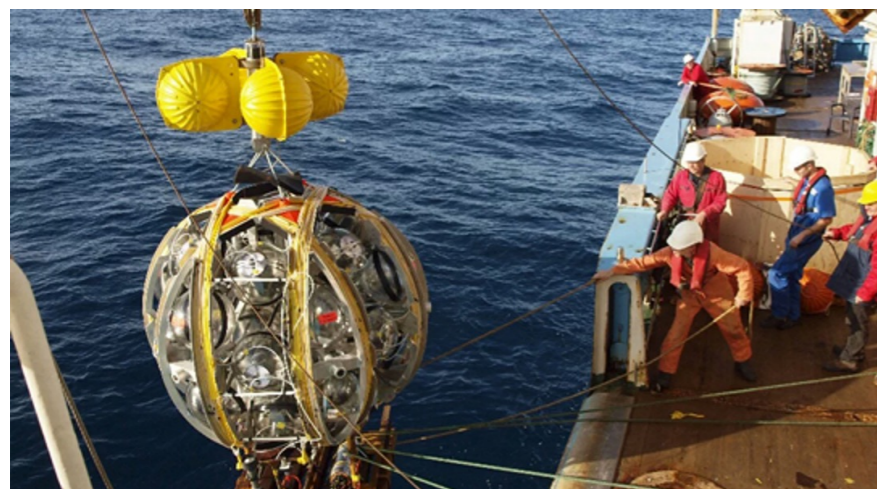
Main detector elements:
- Digital Optical Modules (DOMs)
- Detection Units (DUs)
- Seafloor network: Junction Boxes (JBs) and electro-optical cables

DOM

DOM:
17" glass sphere containing:
31x3" PMTs
LED and Piezo
Front end electronics

- Uniform coverage
- Directional information
- Digital photon counting
- All data to shore

ORCA/ARCA
~200/700 m

ORCA/ARCA
~9/36 m

ORCA/ARCA
~20/90 m

ORCA/ARCA
~20/90 m

BUILDING BLOCK
115 DUs/building block

DU
18 DOMs+1base
module/DU

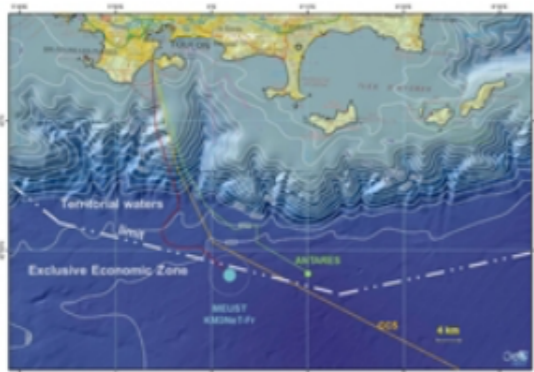**LOM**

KM3NeT: a top view

ARCA (1 GTon)
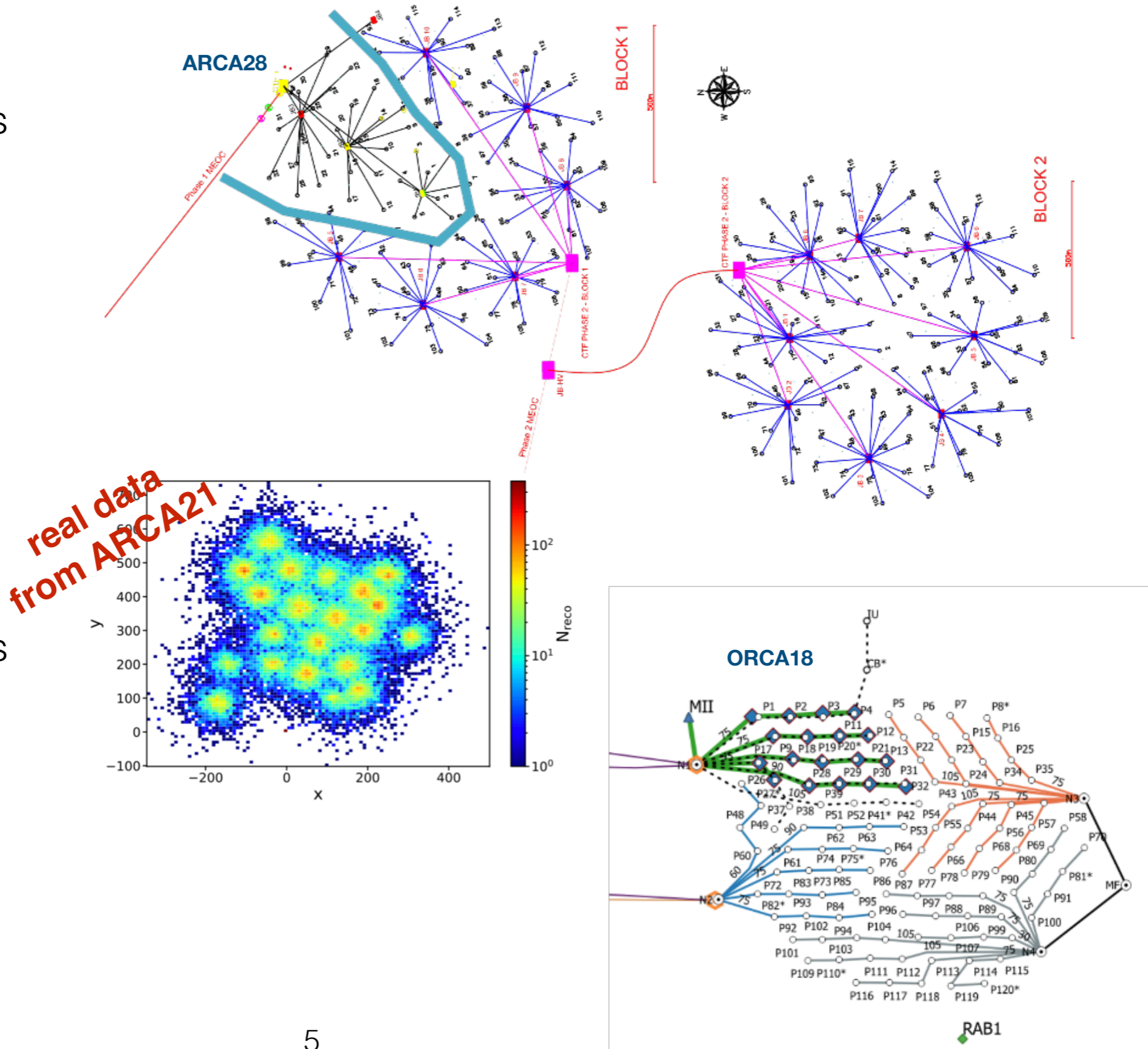Astroparticle Research
with Cosmics in the Abyss

3500 m depth,
offshore Sicily

ORCA (6 MTon)
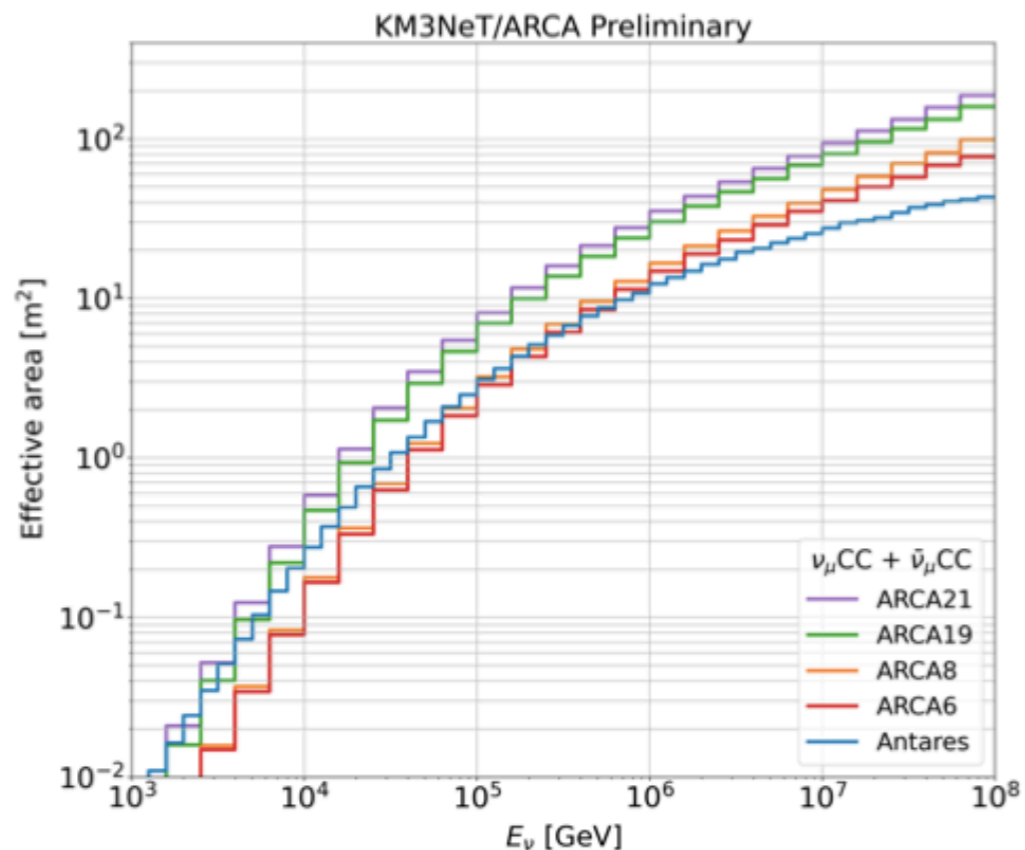Oscillation Research
with Cosmics in the Abyss

2500 m depth,
offshore Toulon

real data
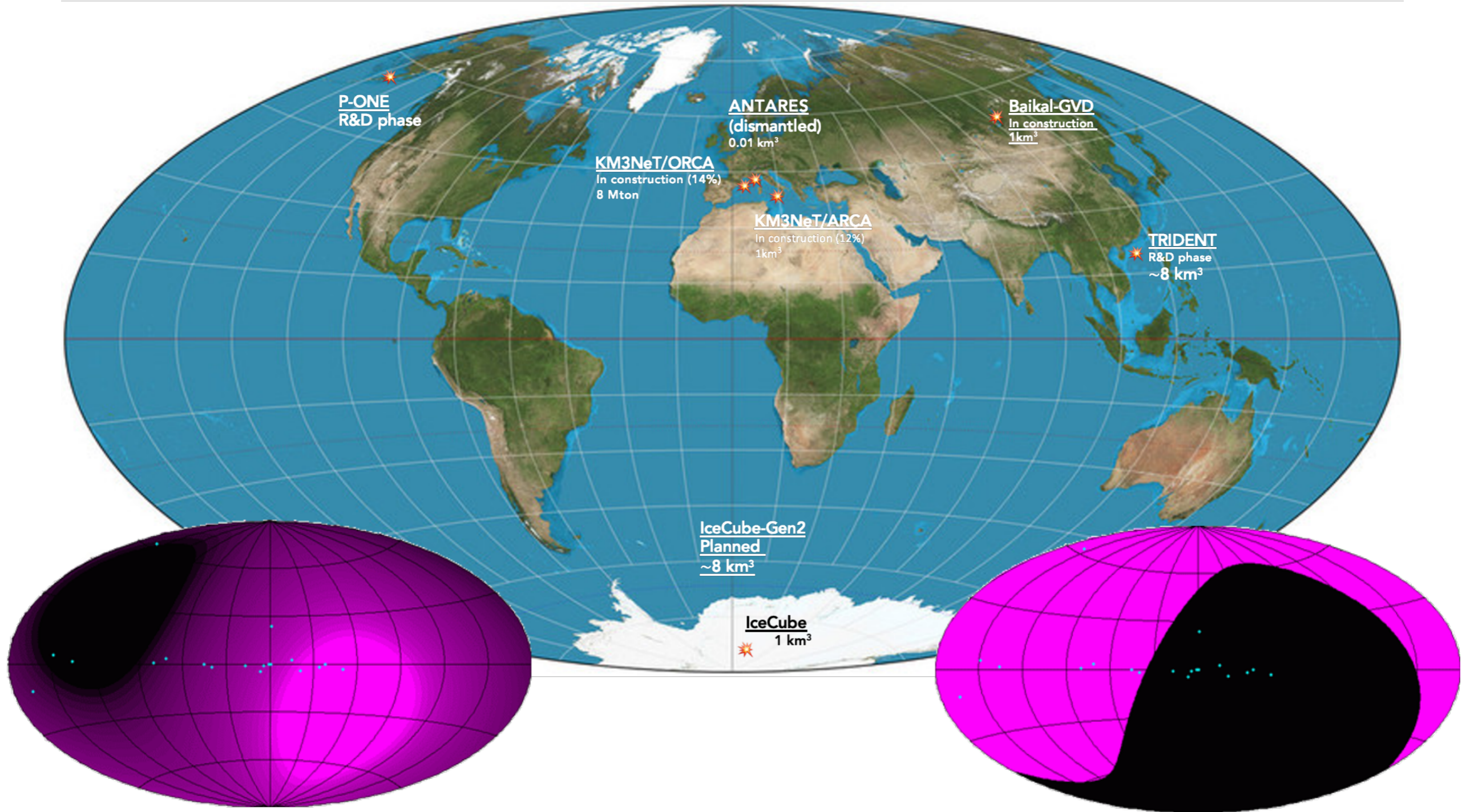from ARCA21

The KM3NeT timeline

ARCA1 ARCA2 ARCA1 ARCA6 ARCA8-9 ARCA19-21 ARCA28

2016 2017 2018 2019 2020 2021 2022 2023 2024

NOW

ORCA1 ORCA4 ORCA6 ORCA10 ORCA18
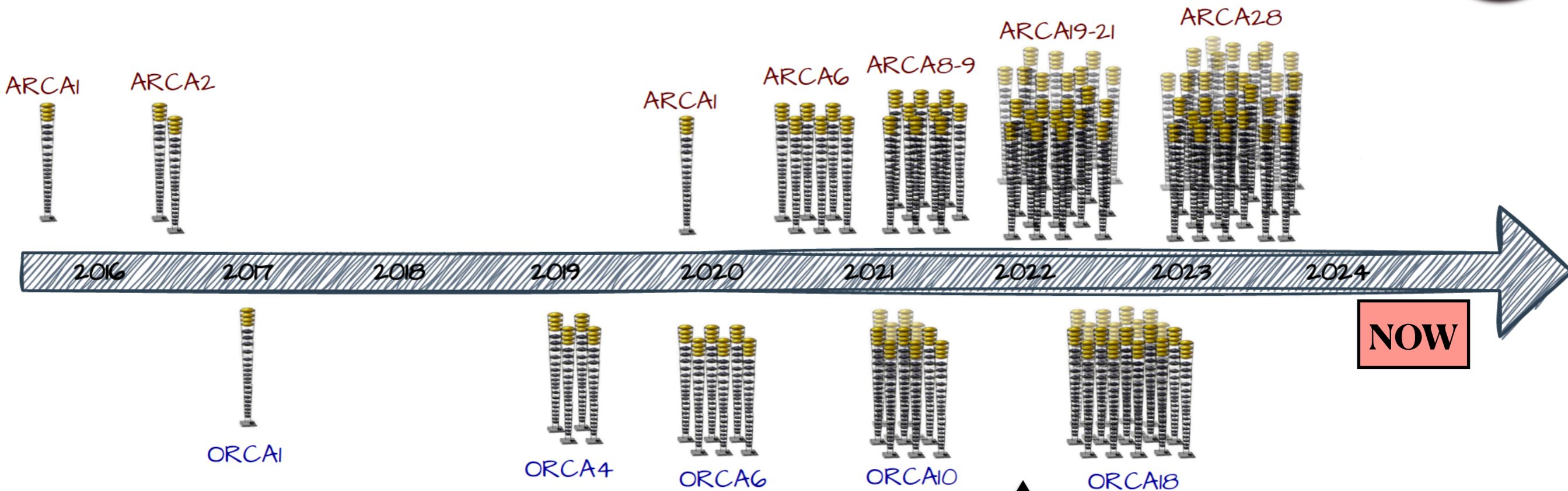
ANTARES dismantling

Additional deployments planned later this year… stay tuned for updates!

KM3NeT/ARCA Preliminary

Effective area [m²]

$\nu_\mu CC + \bar{\nu}_\mu CC$
— ARCA21
— ARCA19
— ARCA8
— ARCA6
— Antares

E_ν [GeV]

6

Large volume neutrino telescopes around the world

P-ONE
R&D phase

ANTARES
(dismantled)
0.01 km³

Baikal-GVD
In construction
1km³

KM3NeT/ORCA
In construction (14%)
8 Mton

KM3NeT/ARCA
In construction (12%)
1km³

TRIDENT
R&D phase
~8 km³
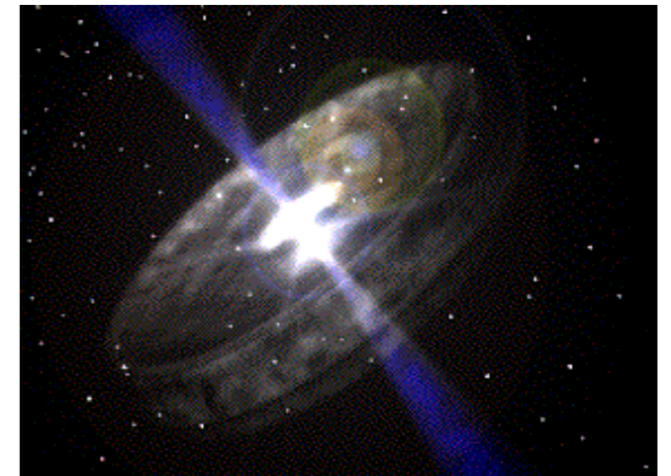
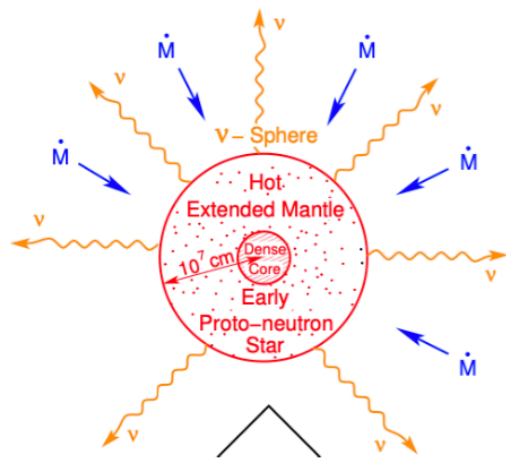IceCube-Gen2
Planned
~8 km³

IceCube
1 km³

Mediterranean

South Pole

Also planned in China:
- HUNT ~30 km³ in Lake Baikal or the South China Sea http://hunt.ihep.ac.cn/
- NEON ~1 km³ in the South China Sea https://pos.sissa.it/444/1017/pdf

Science with ν telescopes

NEUTRINO ENERGY FROM MeV TO PeV
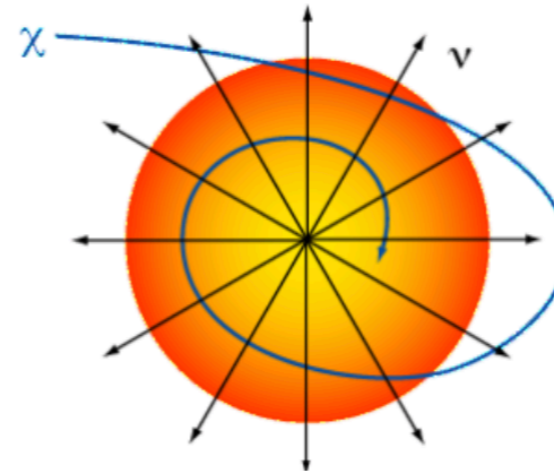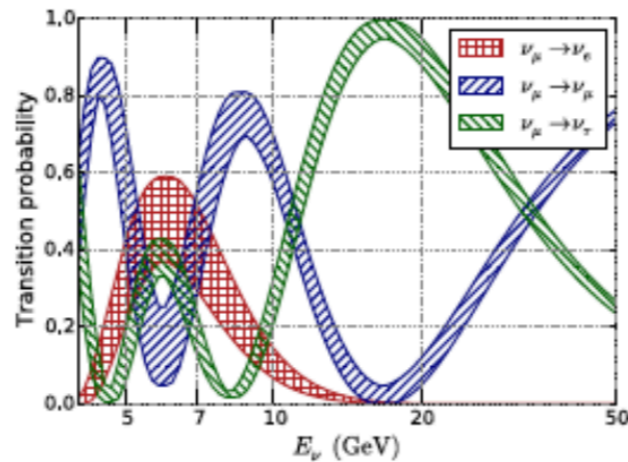
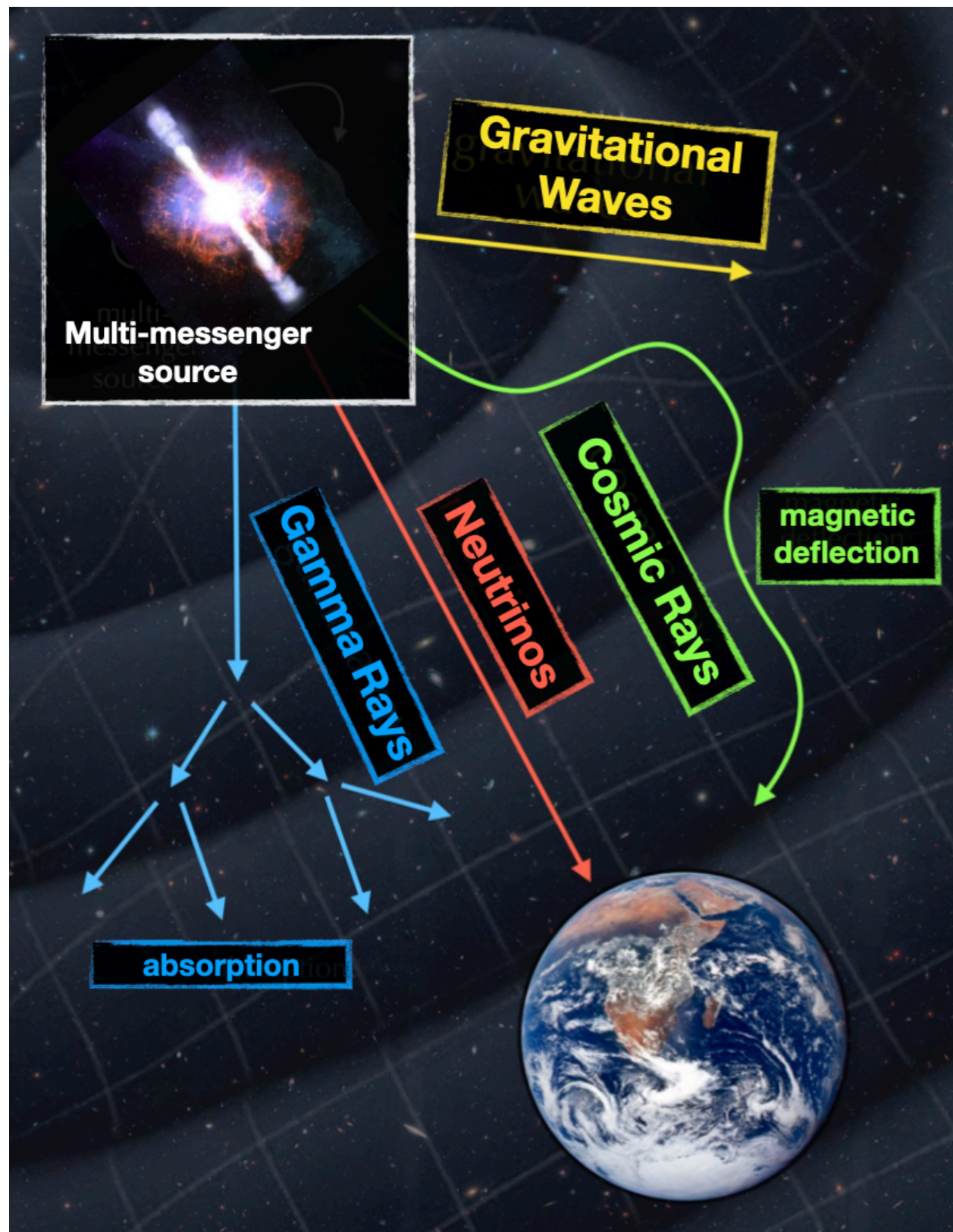| Super Novae explosion MeV	Neutrino oscillation GeV	Dark Matter (*) TeV	HE neutrinos Multi-messenger program PeV

KM3NeT **O R C A**

A R C A   KM3NeT **A R C A**

+ oceanography, biology, bioluminescence, …

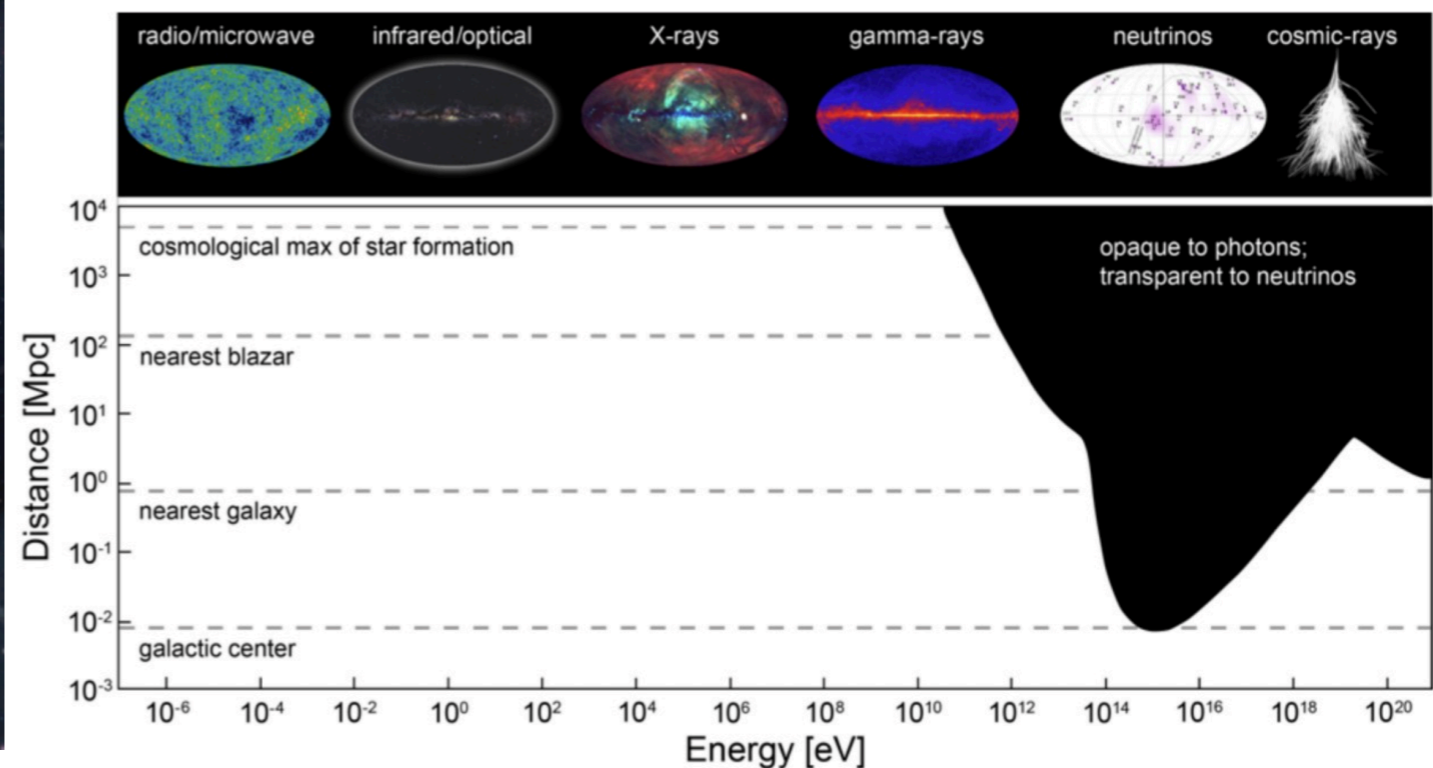# Neutrinos in the multi-messenger framework

WHY NEUTRINOS?
- stable
- electrically neutral
- weakly interacting
- produced **only** at hadronic interactions

PROS:
→ can reach Earth **undeflected** from cosmological distances
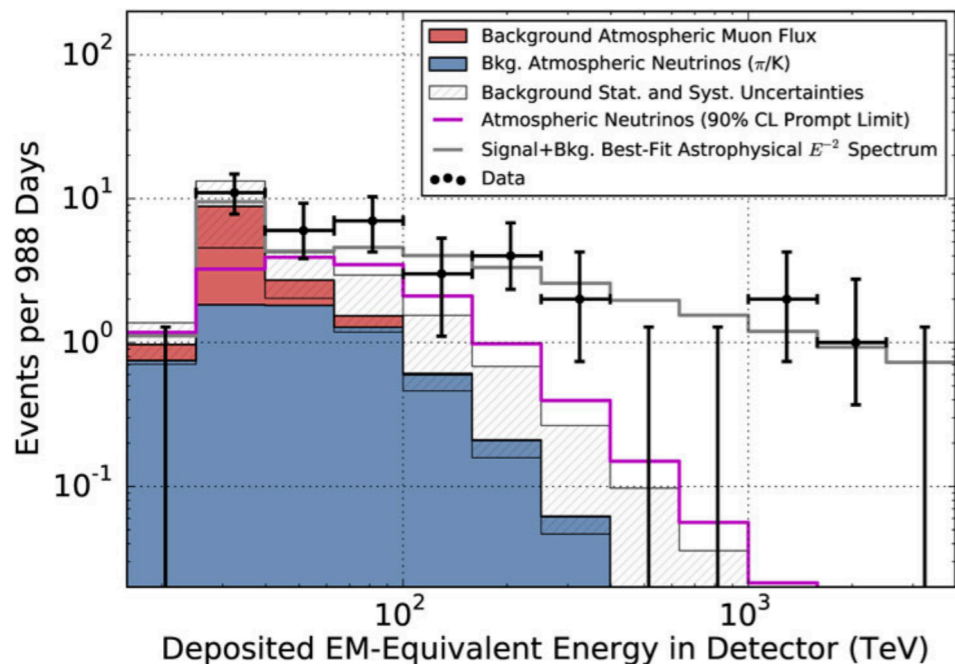→ unambiguous probes of **CR acceleration**

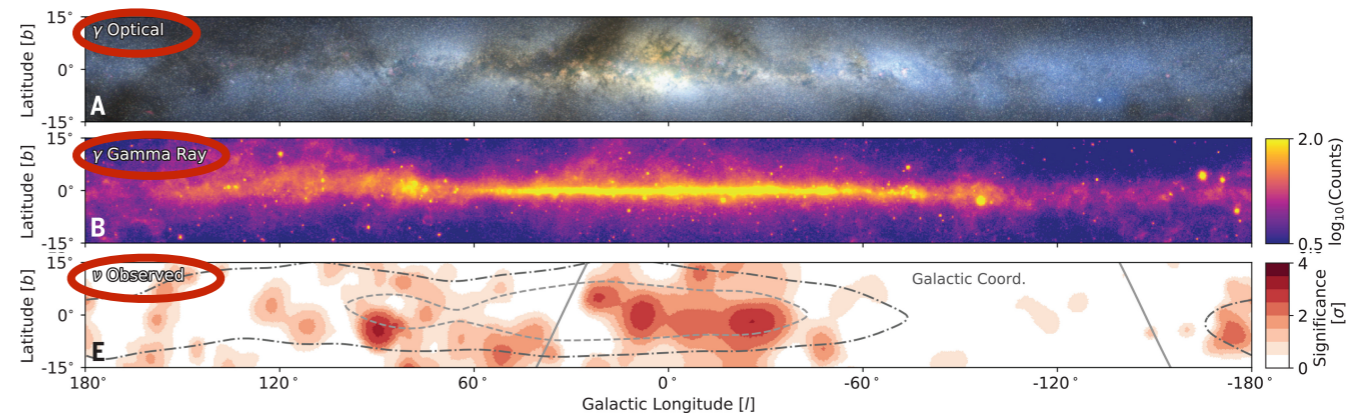**CONS:**
→ low fluxes
→ large background

The cosmic neutrino sky

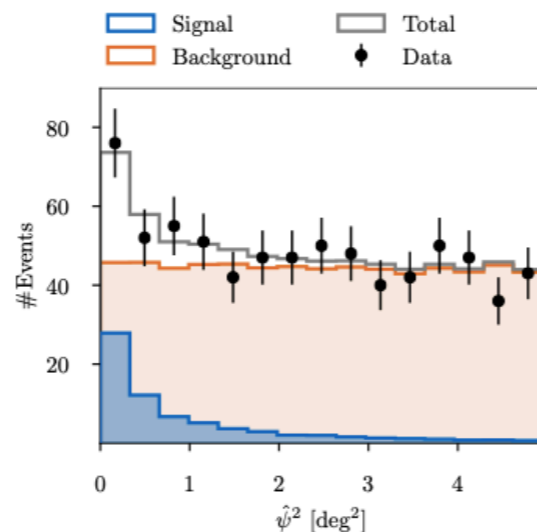## 1. THE ALL-SKY DIFFUSE

Aartsen et al. [IceCube], PRL 113 (2014)

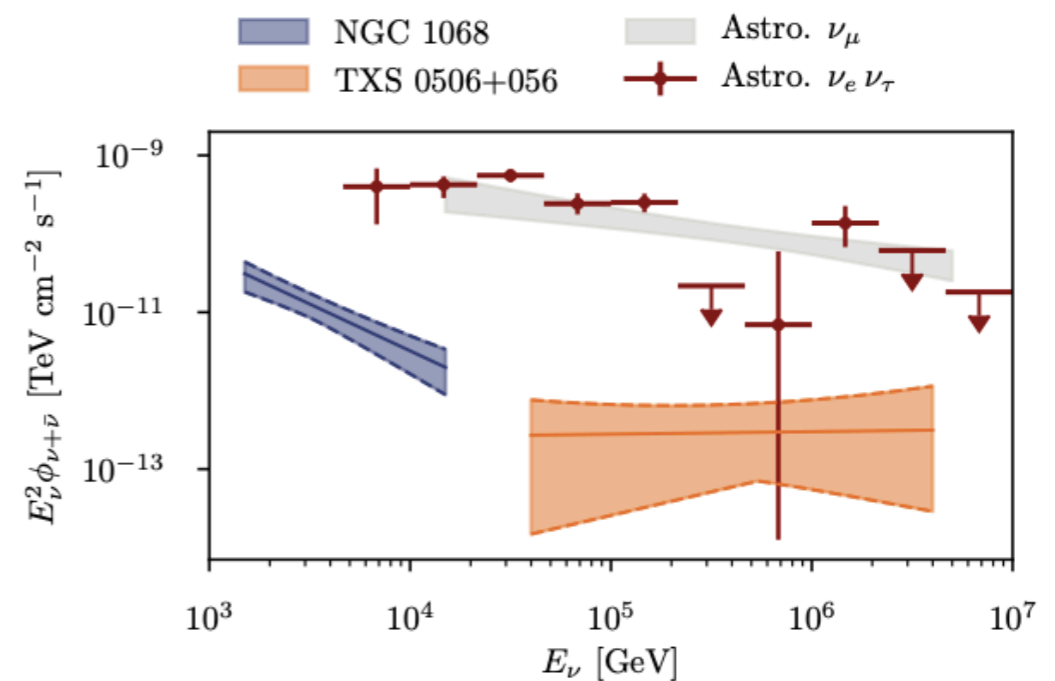## 2. THE MILKY WAY IN MULTI-MESSENGERS

Abbasi et al. [IceCube], Science 380 (2023) 6652
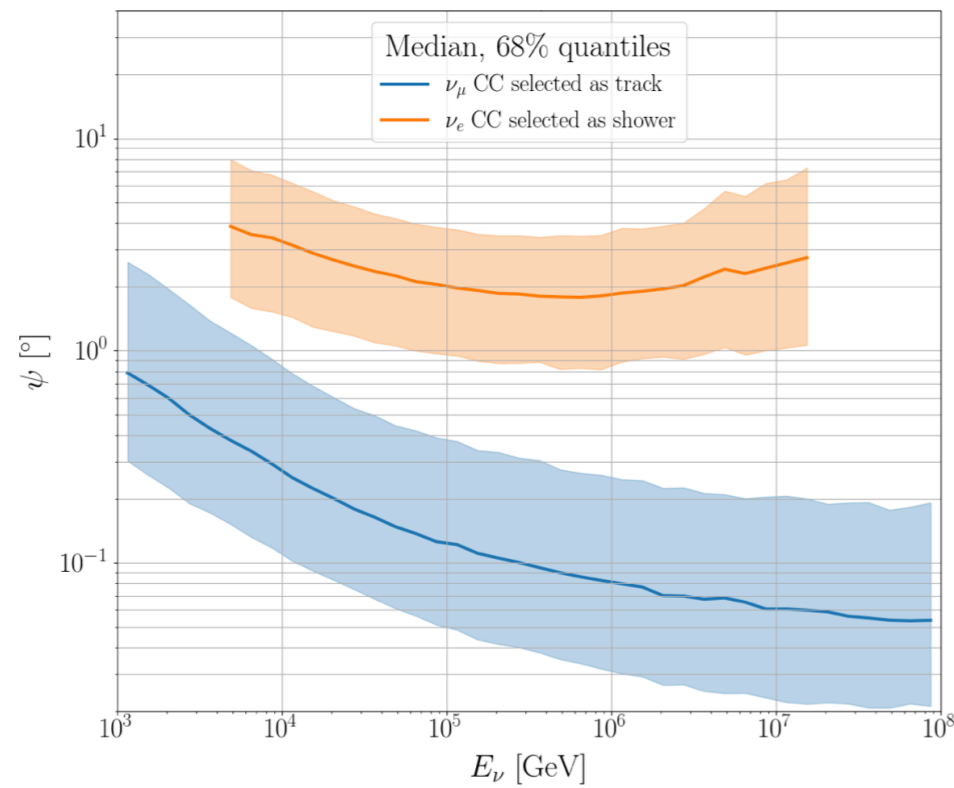
3. NEUTRINO STEADY SOURCES
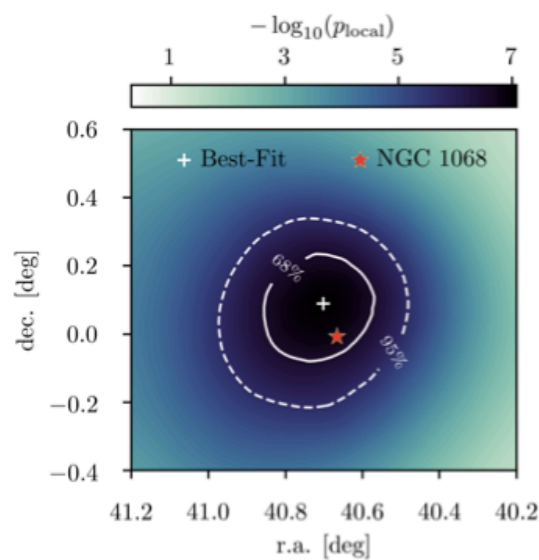
Abbasi et al. [IceCube], Science 378 (2023) 6619

4. NEUTRINO TRANSIENT SOURCES

The KM3NeT/ARCA astronomical potential

Angular resolution

ARCA energy resolution

NGC1068

Science 378, 6619, 538-543 (2022)

Diffuse tracks

IceCube measured flux
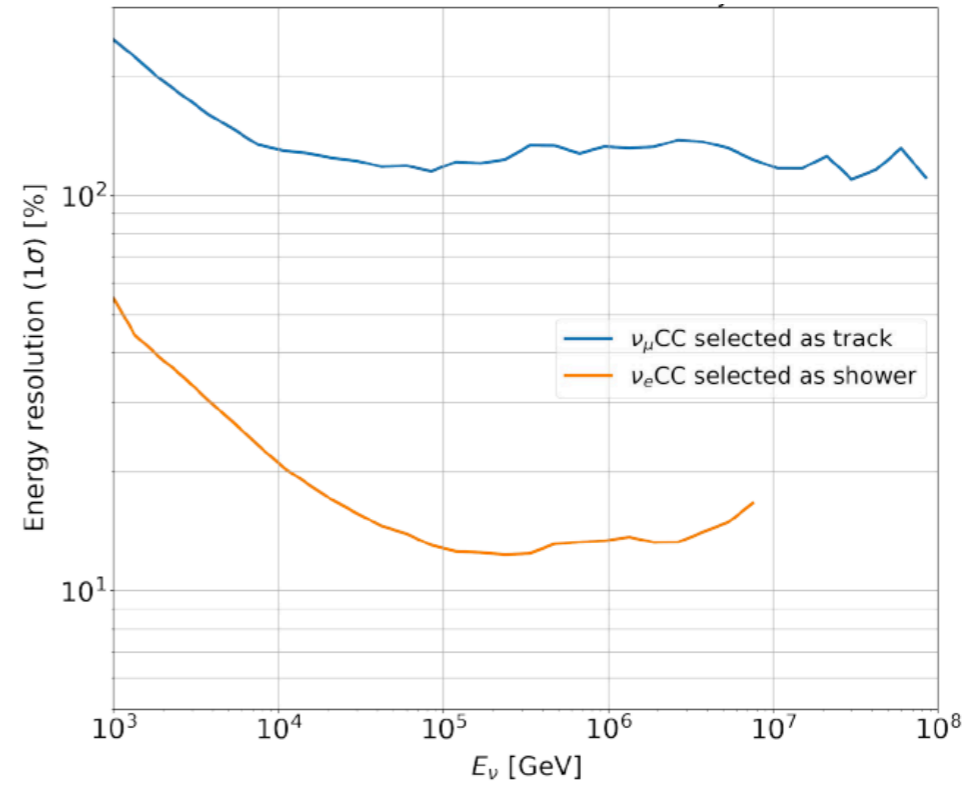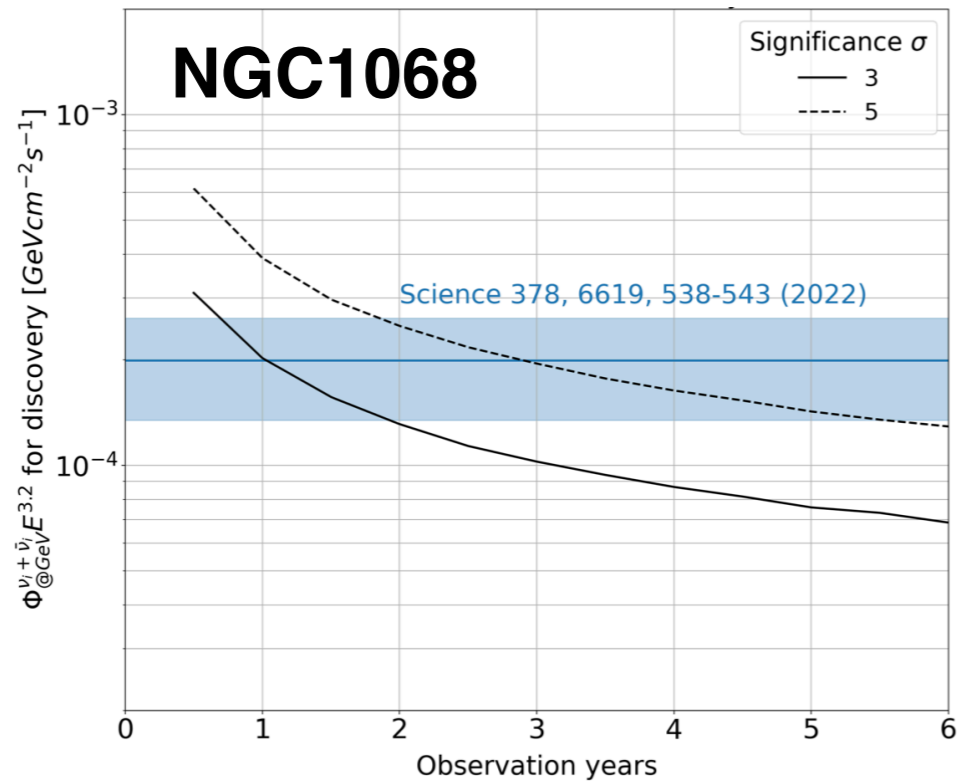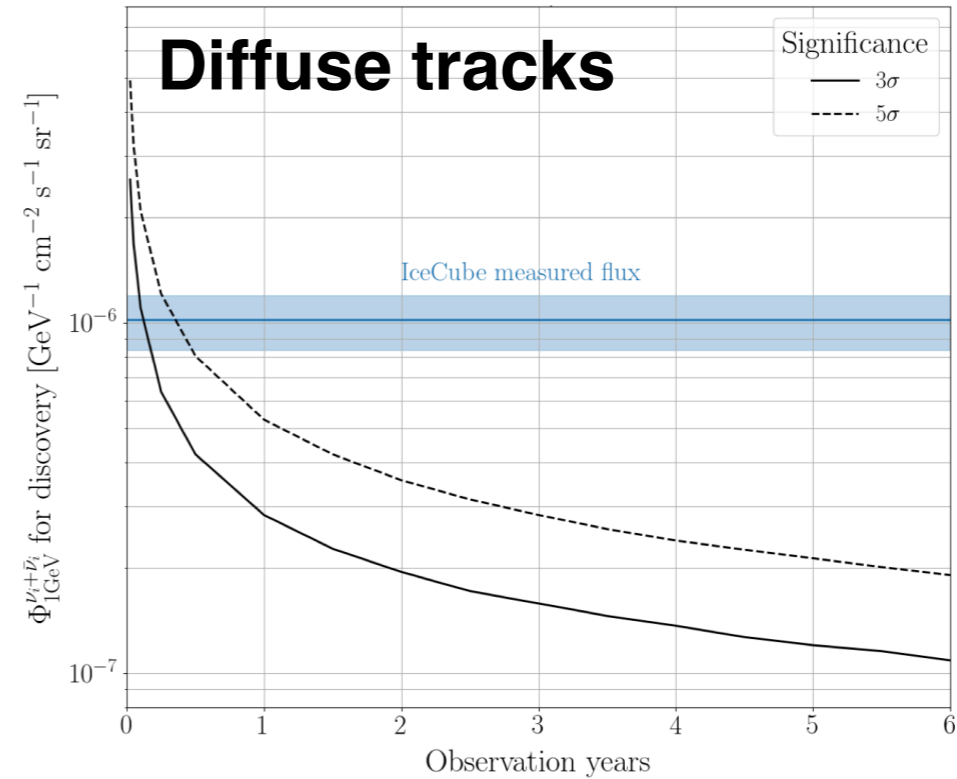
ARCA Galactic Ridge analysis

First KM3NeT/ARCA search limited to Galactic Ridge (|l|<30°, |b|<2°):

- data from ARCA6+8+19+21
- upgoing track selection
- background estimation from off-zone regions in data
- optimized event selection for signal flux with 2.4 spectral slope
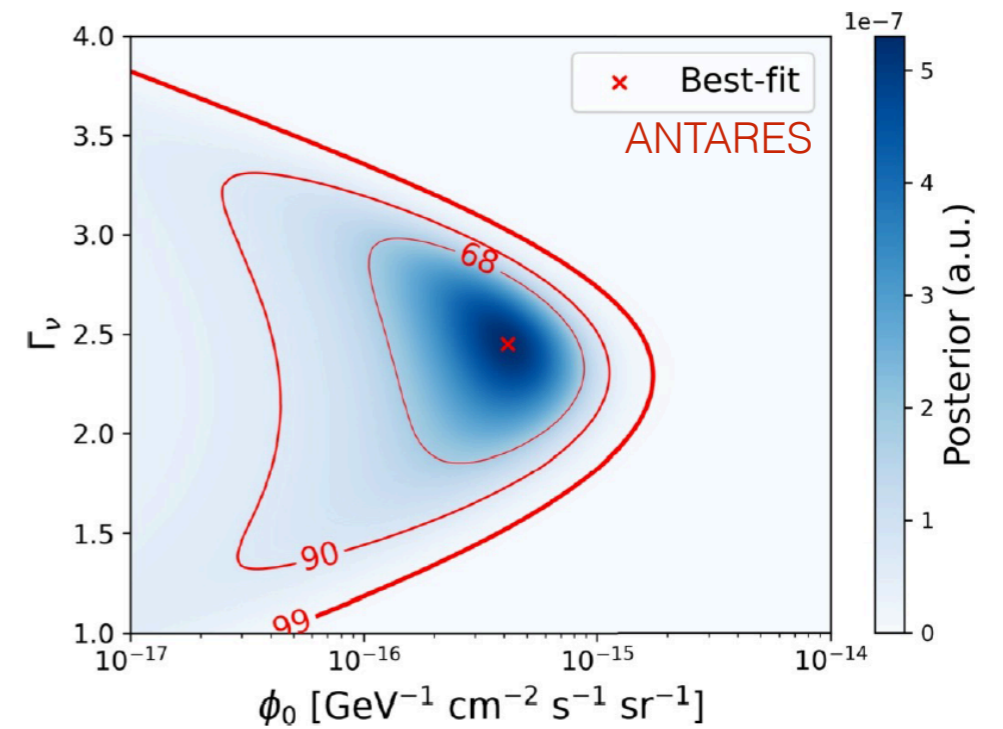
Albert et al. [ANTARES Coll.], Phys. Lett. B 841 (2023)
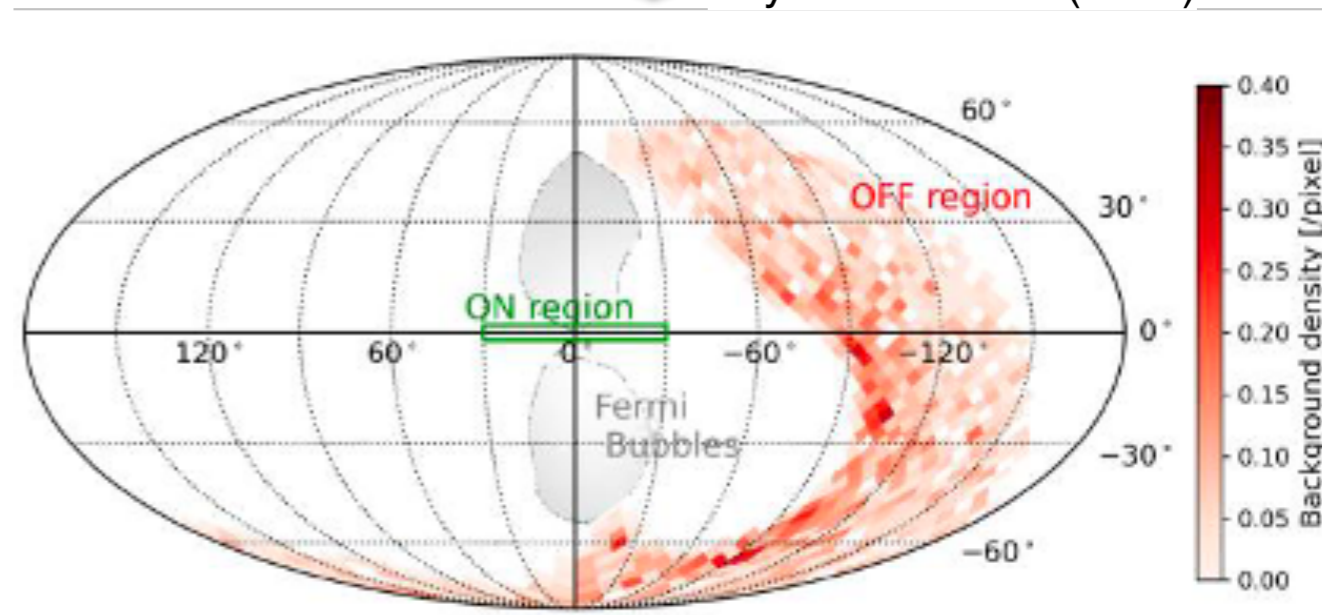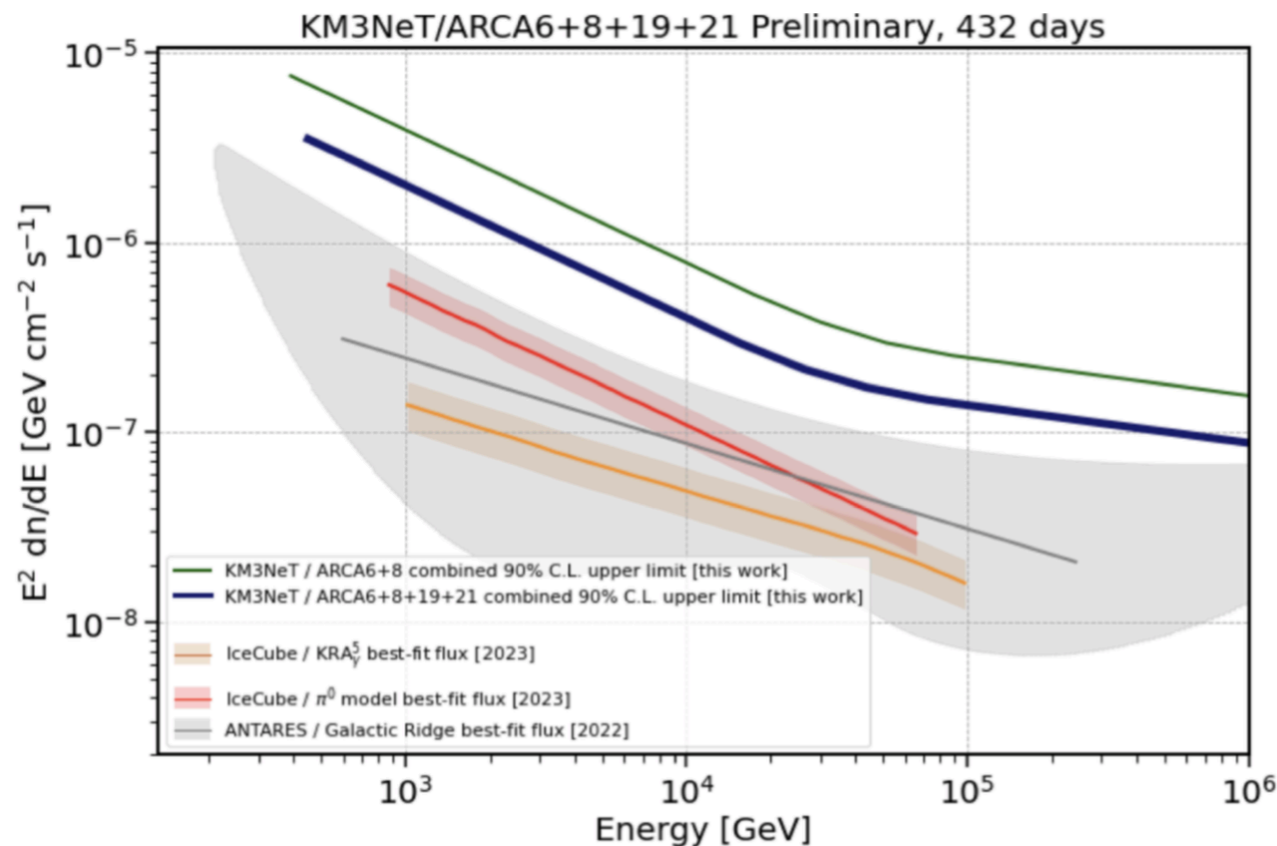
F. Filippini et al. [KM3NeT Coll.], PoS (ICRC2023) 1190

Point source searches with ARCA

Search for neutrinos from 101 candidate cosmic sources:

- 14 months of ARCA6+8+19+21
- upgoing track selection
- most significant p-value = 1%
- data from ARCA28 to be included
- ANTARES limits to be reached soon

Muller et al., PoS 1018 (ICRC 2023)
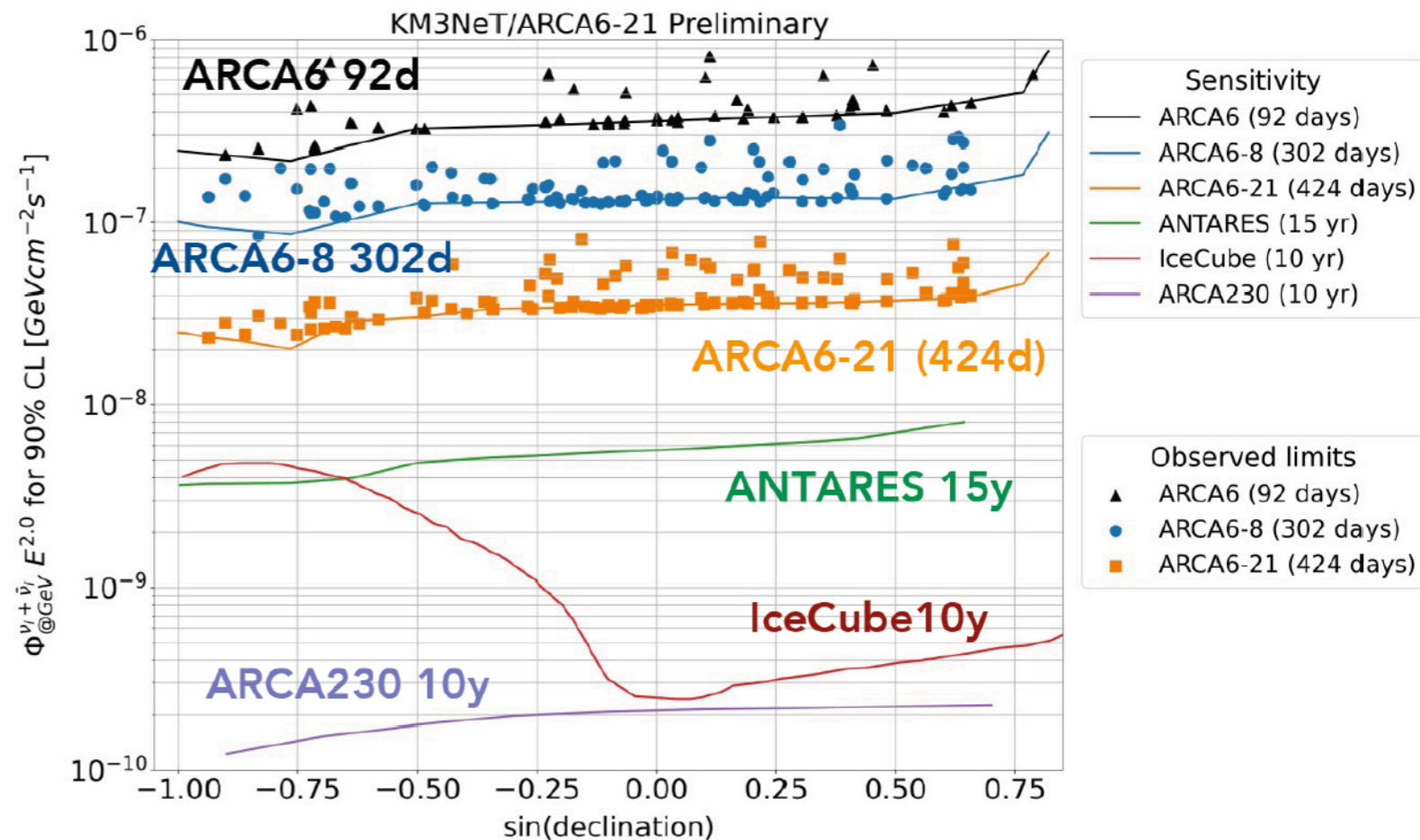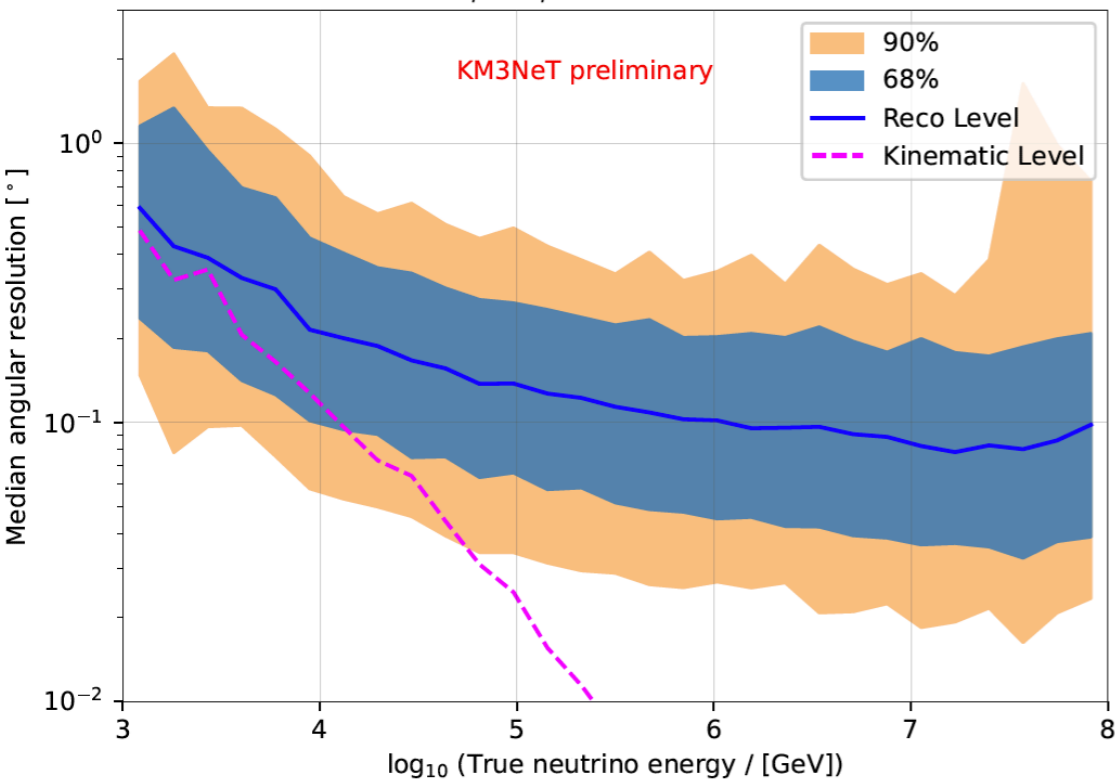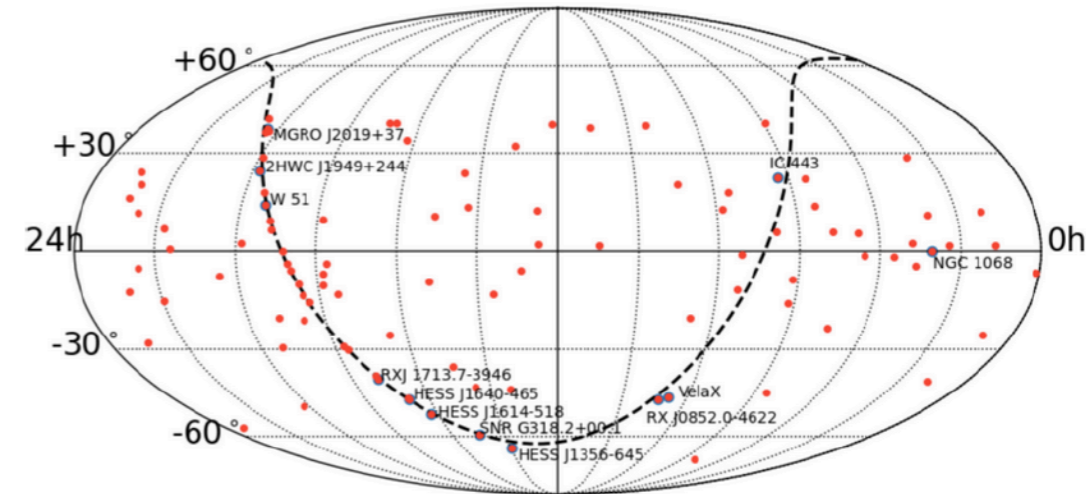
ARCA all-sky diffuse flux analysis

- ARCA 6+8+19+21
- Upgoing track selection
- Boosted decision tree to separate neutrinos from muons

V. Tsourapis et al. [KM3NeT Coll.],
PoS (ICRC2023) 1195

TXS 0506+056: a flaring blazar

side view

top view

Sep 29, 2017

Fermi-LAT   0.1 - 300 GeV

original GCN Notice Fri 22 Sep 17 20:55:13 UT
refined best-fit direction IC170922A
IC170922A 50% - area: 0.15 square degrees
IC170922A 90% - area: 0.97 square degrees

TXS 0506+056

PKS 0502+049

Fermi-LAT Counts/Pixel

Declination

Right Ascension

Upgoing

60°   60°

30°   30°

0°   0°

-30°   -30°

-60°   -60°

IC-170922A

Galactic
Center

Down-going   **Equ. coordinates**

● Extremely-high energy (EHE)   ▲ Bronze   ✚ Neutrino + EM

✕ High-energy starting event (HESE)   ▣ Gold   ★ Cascades

Chasing the ammonia economy *p. 120*   Time invested matters for mice, rats, and humans *pp. 124 & 178*   Two spindles are better than one *pp. 138 & 189*

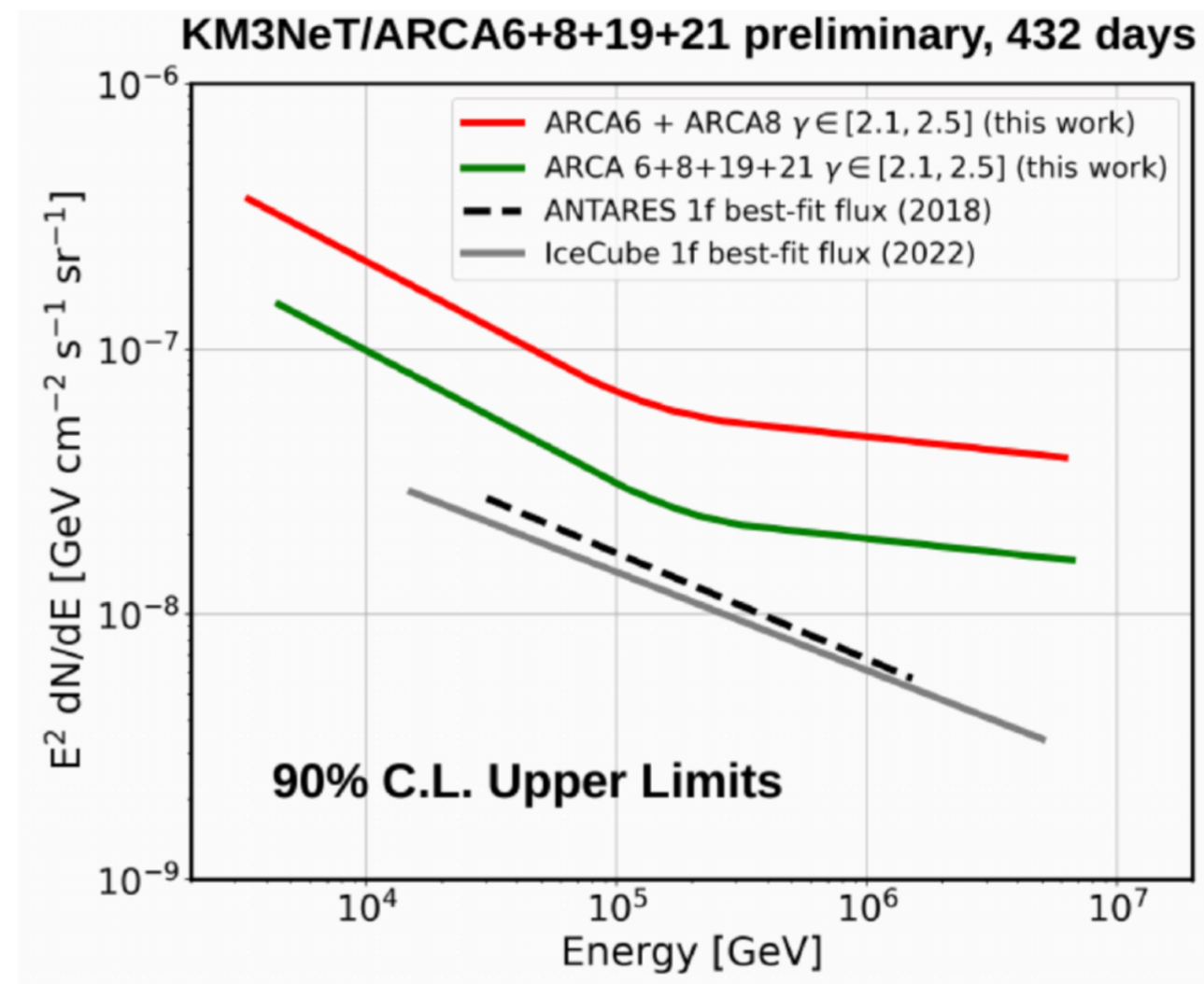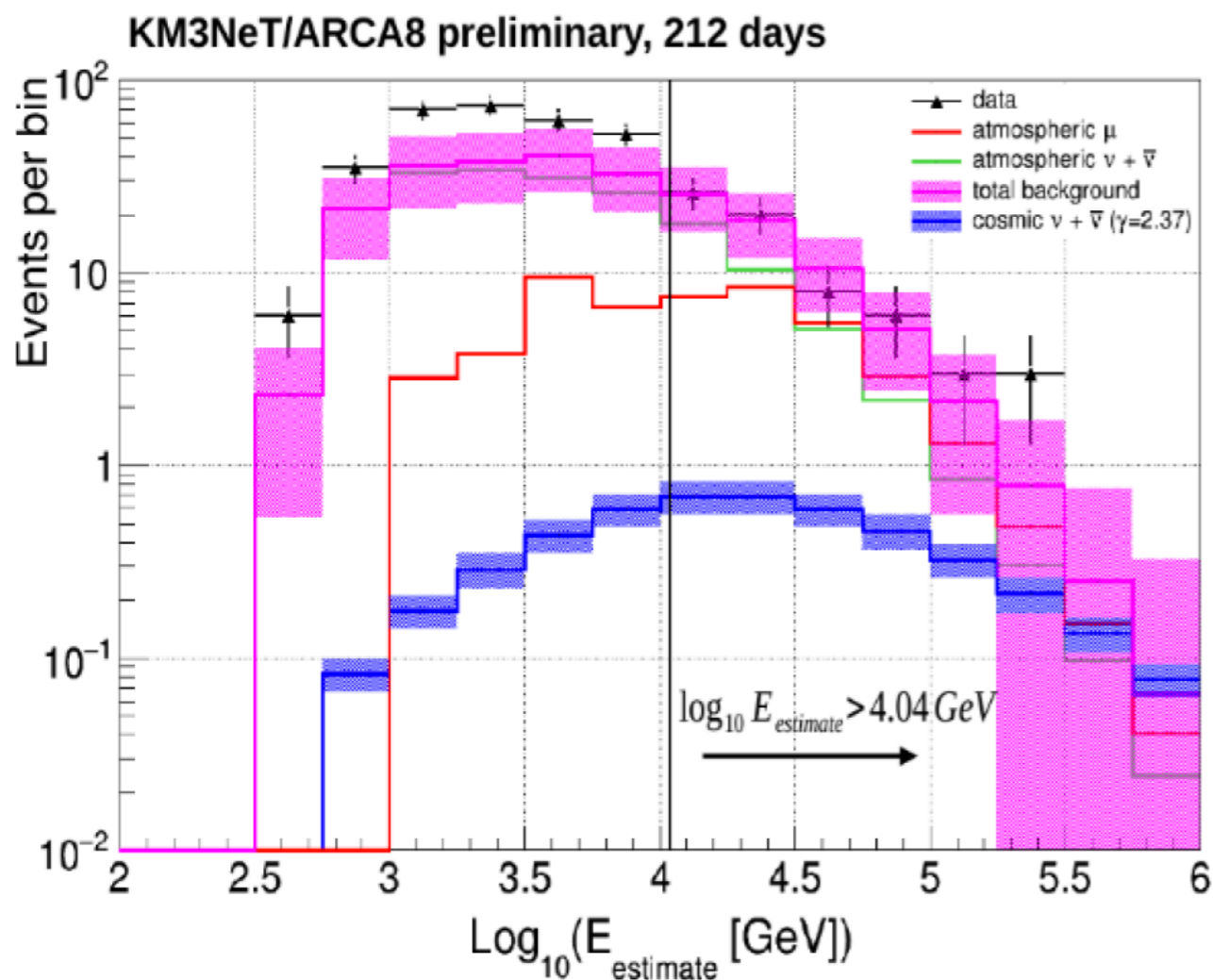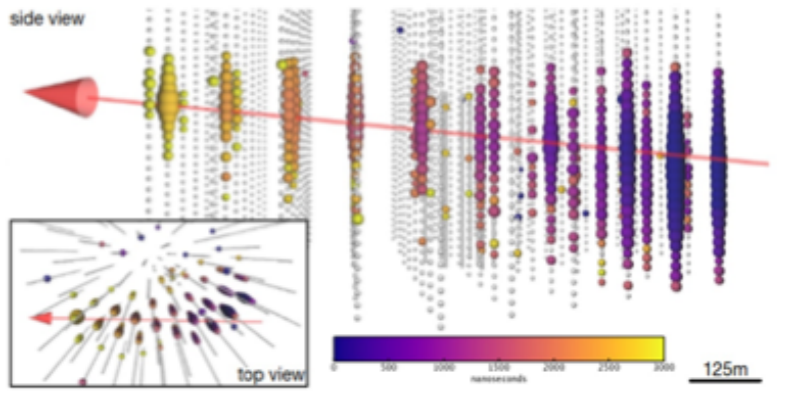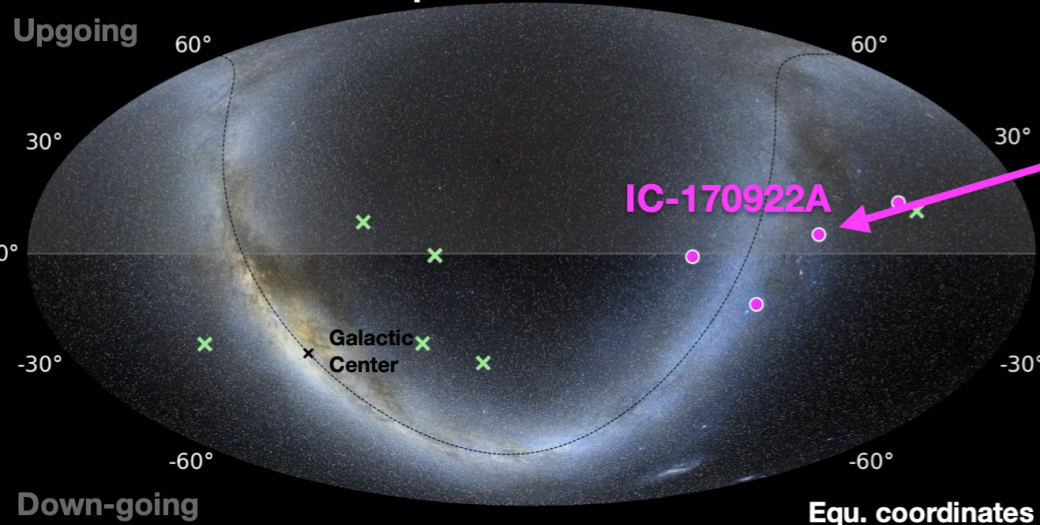# Science

$15
13 JULY 2018
sciencemag.org

AAAS

**NEUTRINOS
FROM A BLAZAR**
Multimessenger observations
of an astrophysical neutrino
source *pp. 115, 146, & 147*

IC40   IC59   IC79   IC86a   IC86b   IC86c

IceCube-170922A
Gaussian Analysis
Box-shaped Analysis

$-\log_{10} p$

4σ
3σ
2σ
1σ

2009 2010 2011 2012 2013 2014 2015 2016 2017
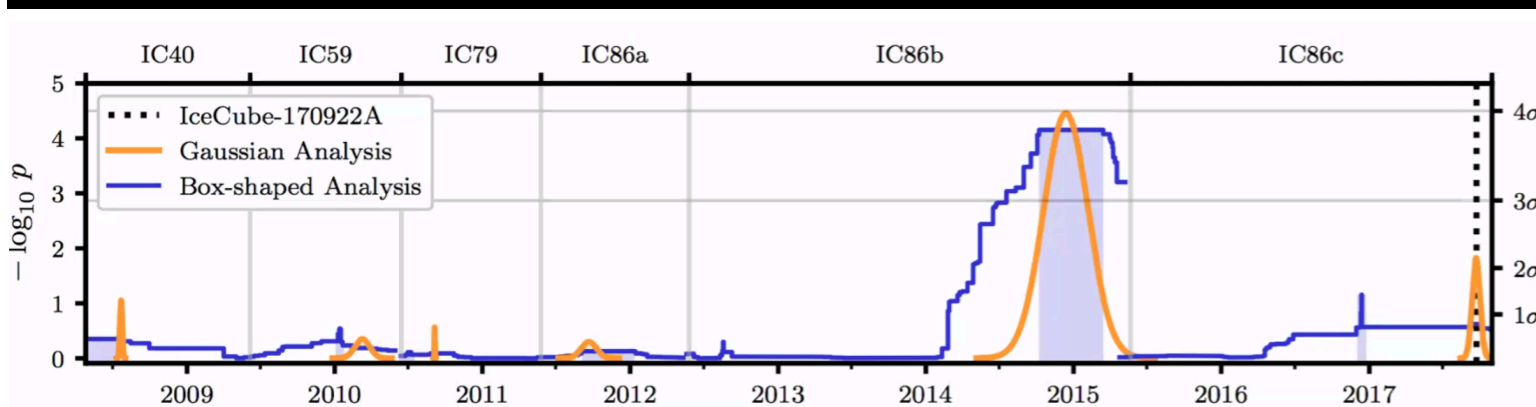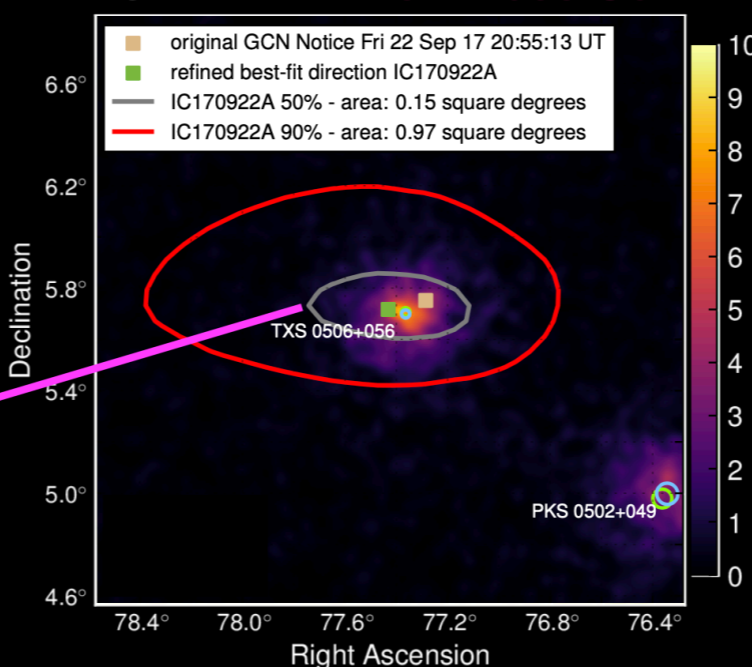
Archival search in IceCube data has lead to the
identification of additional **19** neutrino-induced events
(5 bkg expected) in 110 days (2014-2015), in the
energy range (68%) **32 TeV - 3.6 PeV** (post-trial
coincidence probability ~**3.5σ**).

MASTER robotic telescope: after 73 seconds

Follow-up detections of IC170922 based on public telegrams

IceCube
September 22

Swift
September 26

Fermi, ASAS-SN
September 28

SALT, Kapteyn
October 7

MAGIC
October 4

Liverpool, AGILE
September 29

Kanata, NuSTAR
October 12

VLA
October 17

Subaru
October 25

15
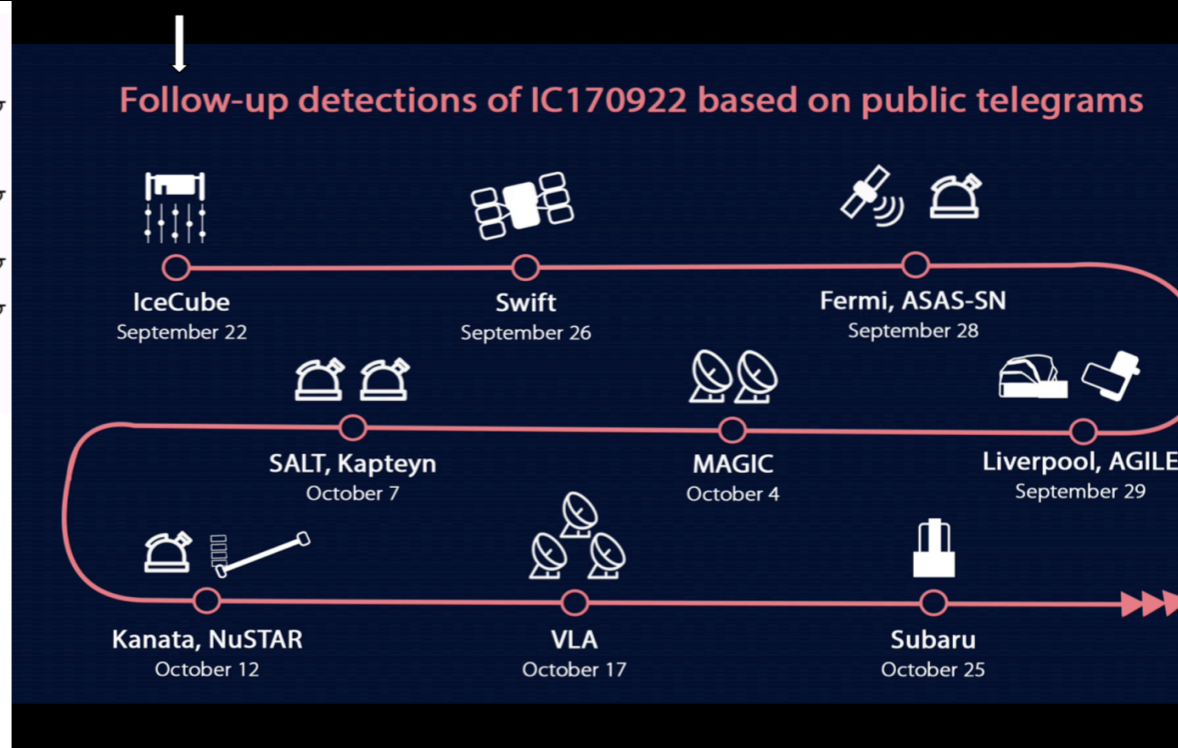
KM3NeT real time analysis system

In the view of searching for correlation among ν and MM signals (EM, GW), it is increasingly crucial to be able to identify (**reconstruct, classify & select)** cosmic neutrinos in real-time as to allow **fast follow up** for counterpart identification.

The **Real-Time Analysis (RTA)** program includes:
1) Neutrino **alert sending** (HE, multiplets, …)
2) External trigger **follow-up** (GW, IC, gamma) with high-energy neutrino data
3) Continuos **SN monitoring** (MeV)

KM3NeT real time analysis system

ARCA SHORE STATION
Portopalo di Capo Passero (Sicily)

Similarly for ORCA

All data to shore

Triggered event

Parallel processes

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

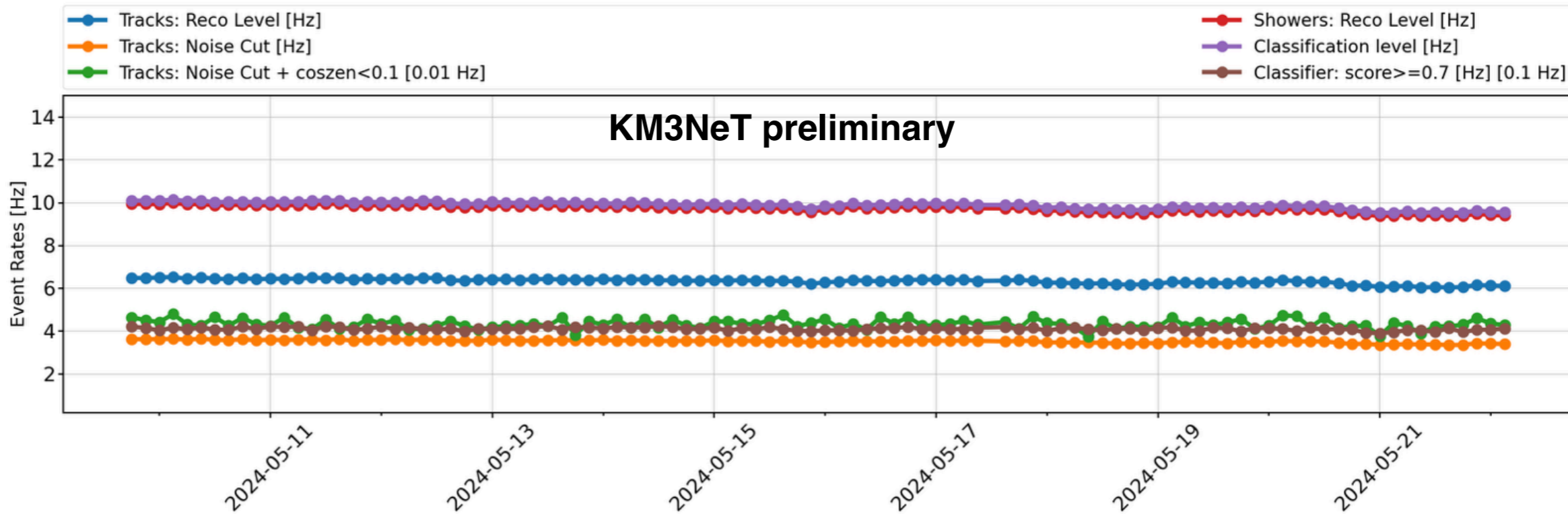ORCA shore station
Supernova
ORCA DAQ → Dispatcher
Reco Tracks+Showers, Classifier

ARCA shore station
Supernova.
ARCA DAQ → Dispatcher
Reco Tracks+Showers, Classifier

Event writer → Events DB ← sql query
Neutrino alerts

Multi-messenger dispatcher → Online analysis pipeline

GCN alert handler

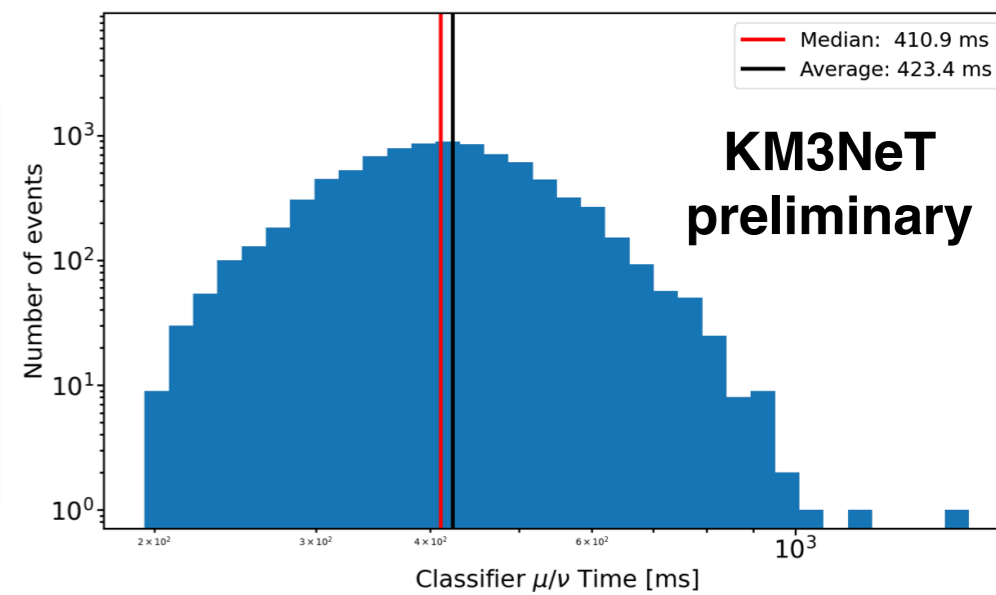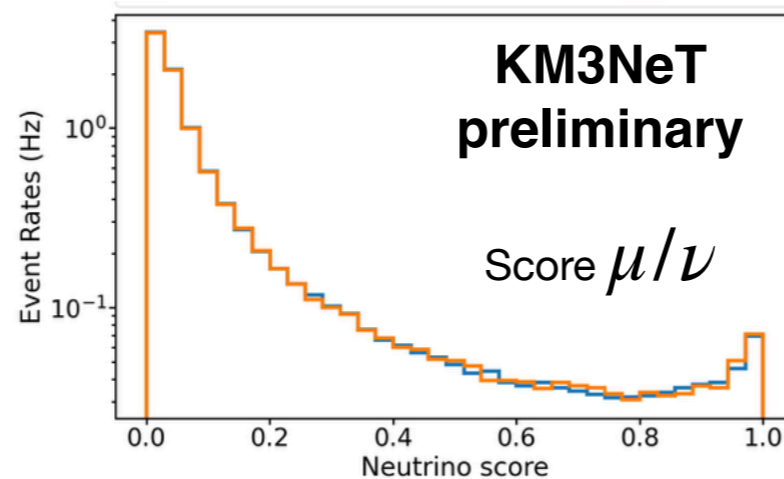Alerts DB ← sql query

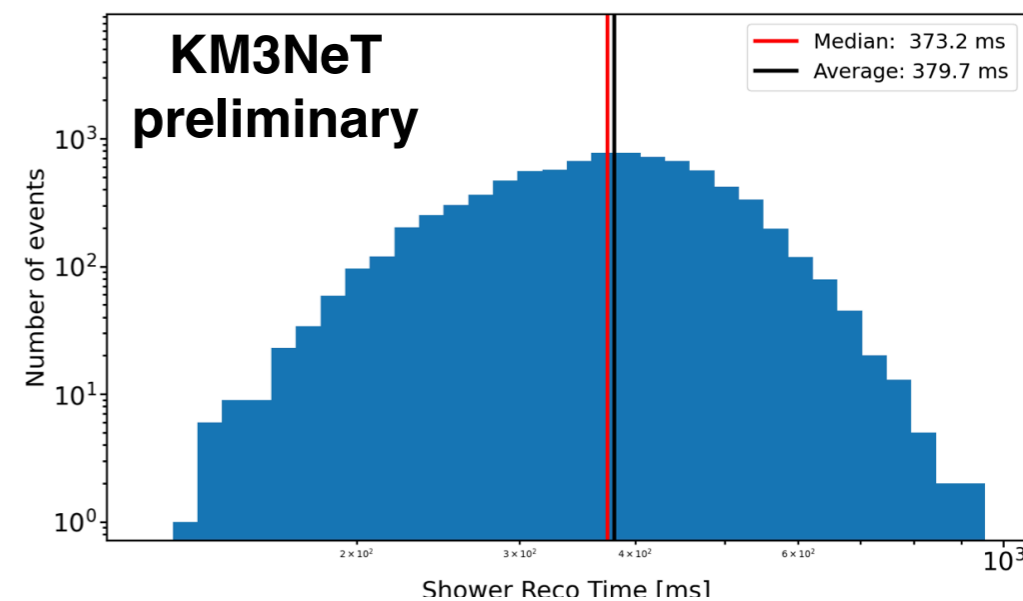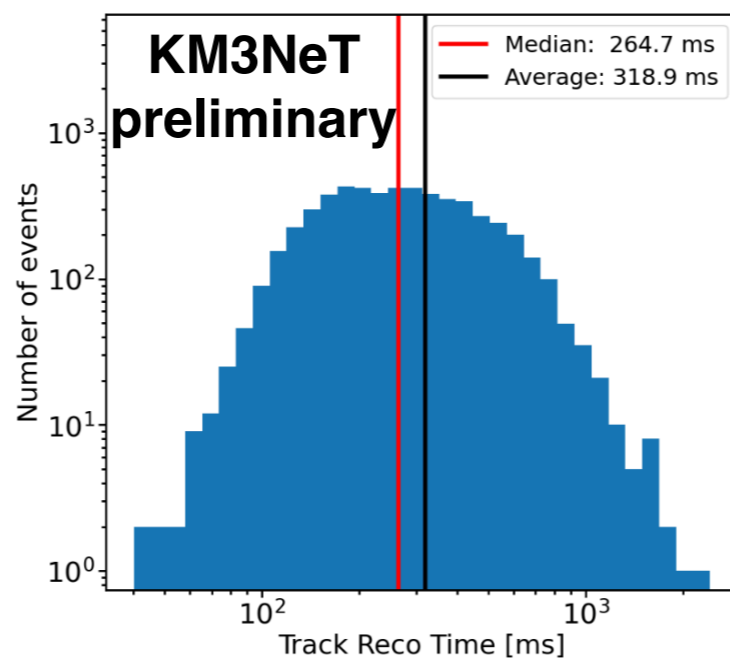Internal/External reporting (webpage, emails, brokers...)

External alerts

ARCA28

Current status of the detector

S. Celli et al. [KM3NeT], PoS 444 (ICRC2023) 1125

KM3NeT real time analysis system

All data to shore

ARCA SHORE STATION
Portopalo di Capo Passero (Sicily)

Similarly for ORCA

Parallel processes

Triggered event

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

ORCA shore station

Supernova

ORCA DAQ → Dispatcher

Reco Tracks+Showers, Classifier

ARCA shore station

Supernova.

ARCA DAQ → Dispatcher

Reco Tracks+Showers, Classifier

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External alerts

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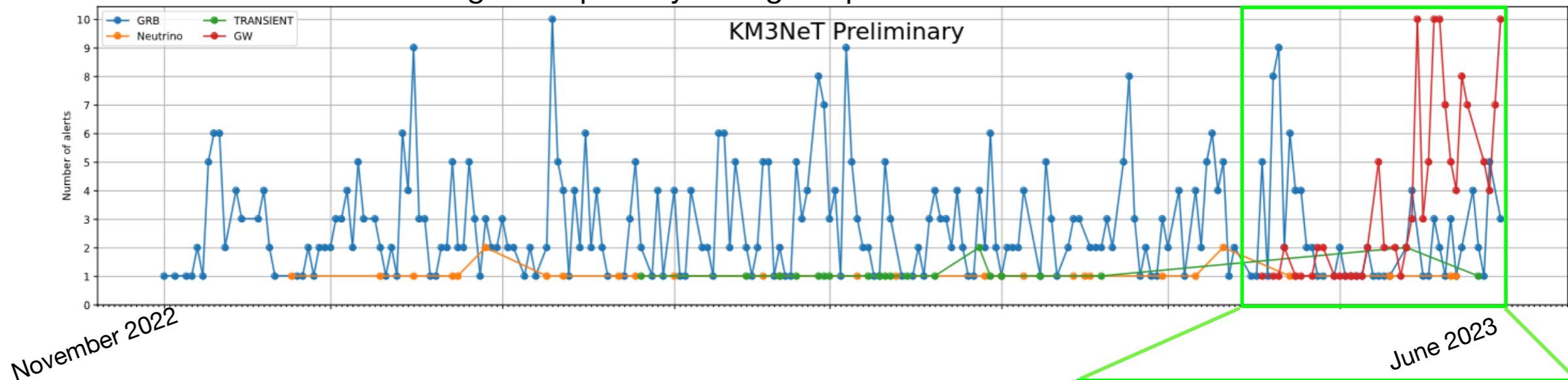
Online follow-ups with KM3NeT

Four automated pipelines are in place to regularly process alerts received from external partners:
i) GRBs, ii) IceCube neutrinos, iii) GWs and iv) other transients (opt/X)
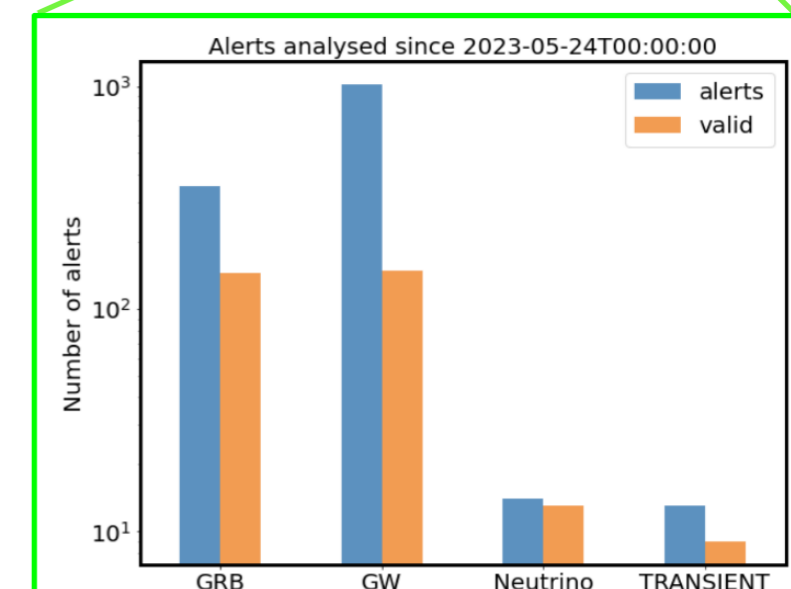+ MeV pipeline to monitor CC SNe

Start of the O4 run for GWs

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

Total number of follow ups (from May 2021 to May 2024)

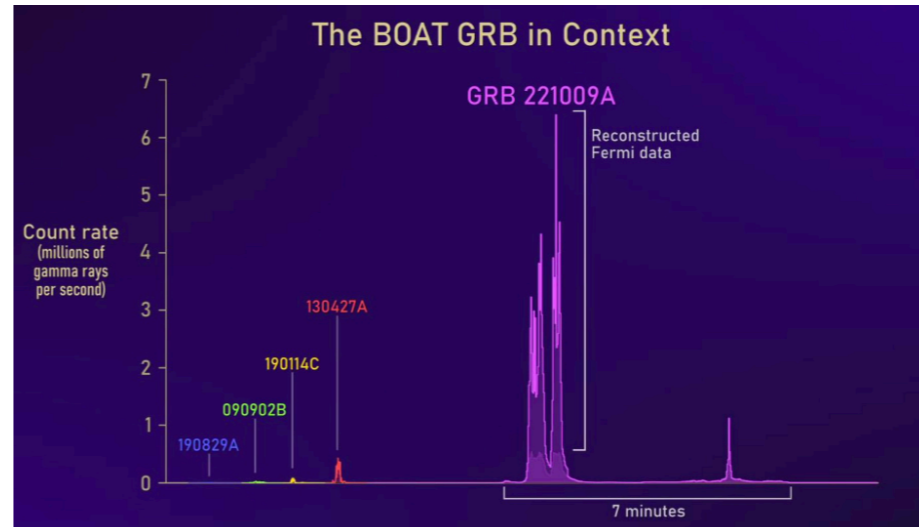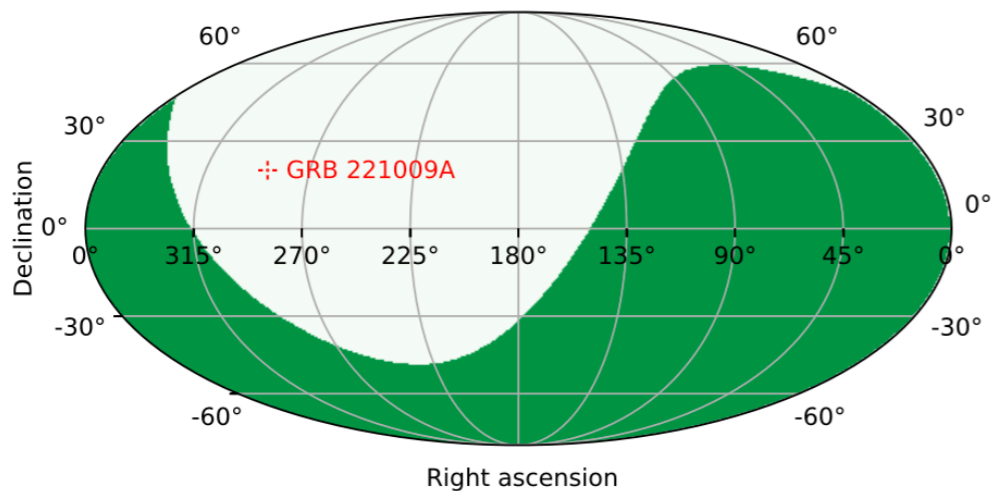|	
GRB	522 out of 2234
IC neutrino	77 out of 116
GW	199 out of 2173
Transient	47 out of 60

The BOAT GRB: offline search for neutrinos in KM3NeT data

★ Highest fluence;
★ Nearby: z=0.152;
★ Highest $E_{iso} \sim 1 \times 10^{55}$ erg;
★ Once in a 1000/10000 yr event.

Burns et al., ApJL 946 (2023) 31B

The BOAT GRB in Context

GRB 221009A
Reconstructed Fermi data
130427A
190114C
090902B
190829A
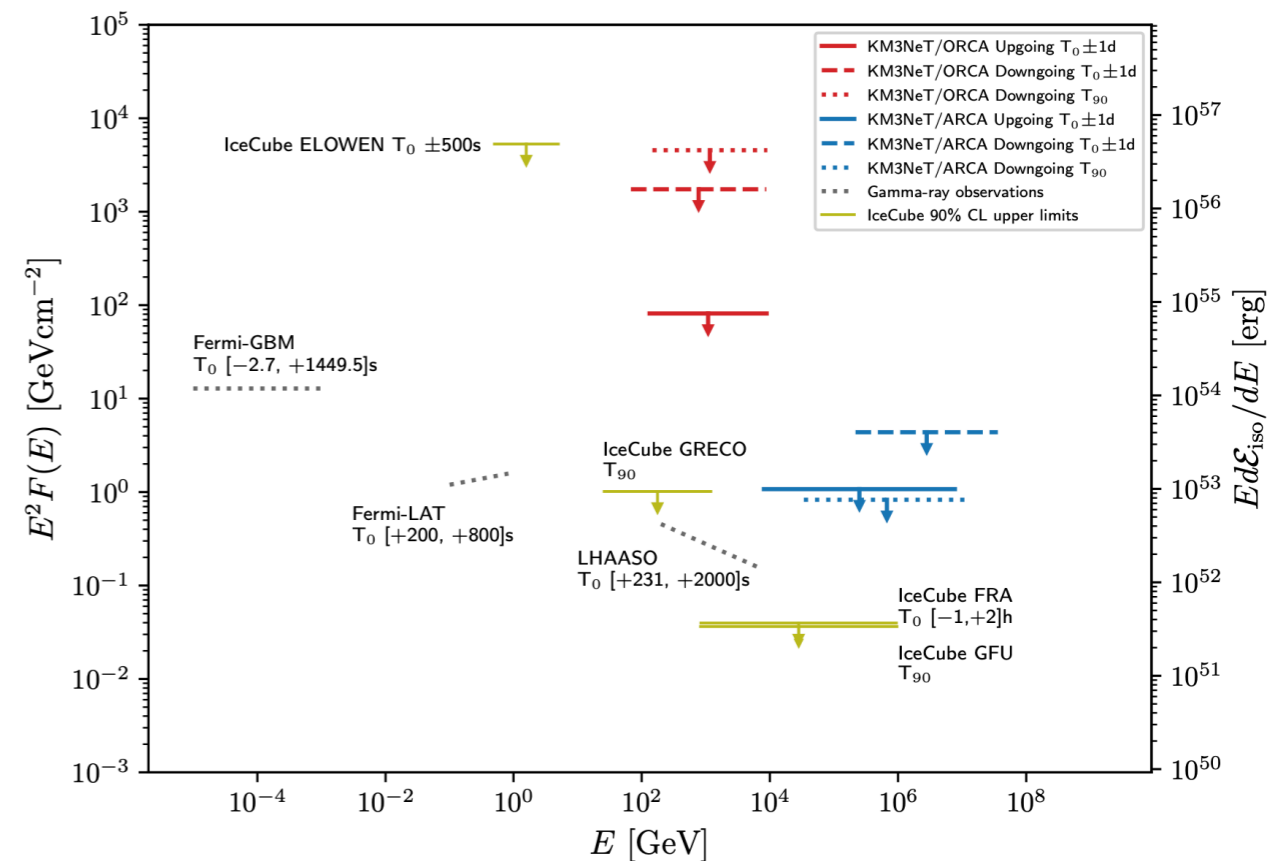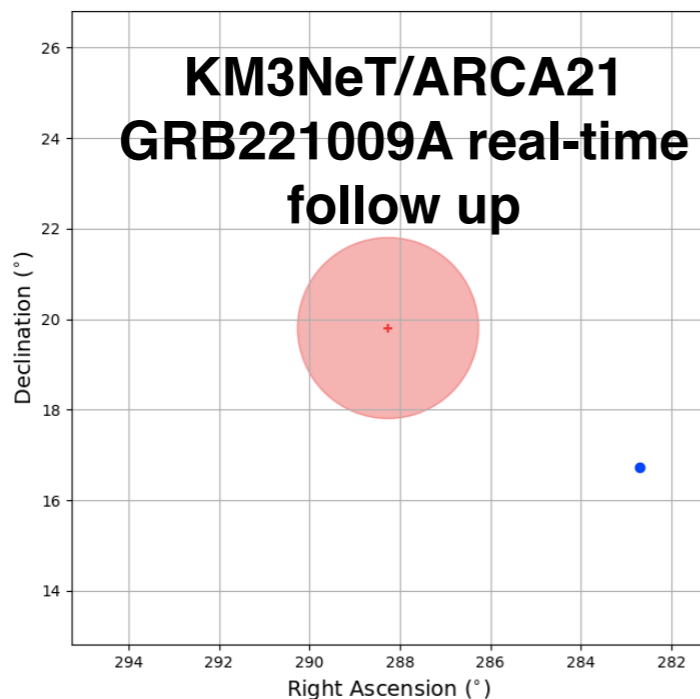7 minutes

Cao et al. [LHAASO Coll.], Science 380 (2023) 1390

GCN 32677

- KM3NeT real-time follow-up in [-50;5000]s time window
- KM3NeT offline analysis

GCN 32741

Aiello et al. [KM3NeT] arXiv:2404.05354

KM3NeT/ARCA21 GRB221009A real-time follow up

21

Search for MeV neutrinos from CCSNe

- Neutrinos <100 MeV expected at massive stellar collapse
- Main interaction channels in water are IBD of electron antineutrinos with protons, ES on electrons and CC interaction with O nuclei
- Cherenkov signature detected as a population of coincidences in single DOMs = overall excess in whole detector
- K40, bioluminescence and atmospheric muons are main backgrounds
- Alert sent in realtime through SNEWS

Aiello et al. [KM3NeT], EPJC 81 (2021) 445   Goos et al. PoS (ICRC2023) 1160
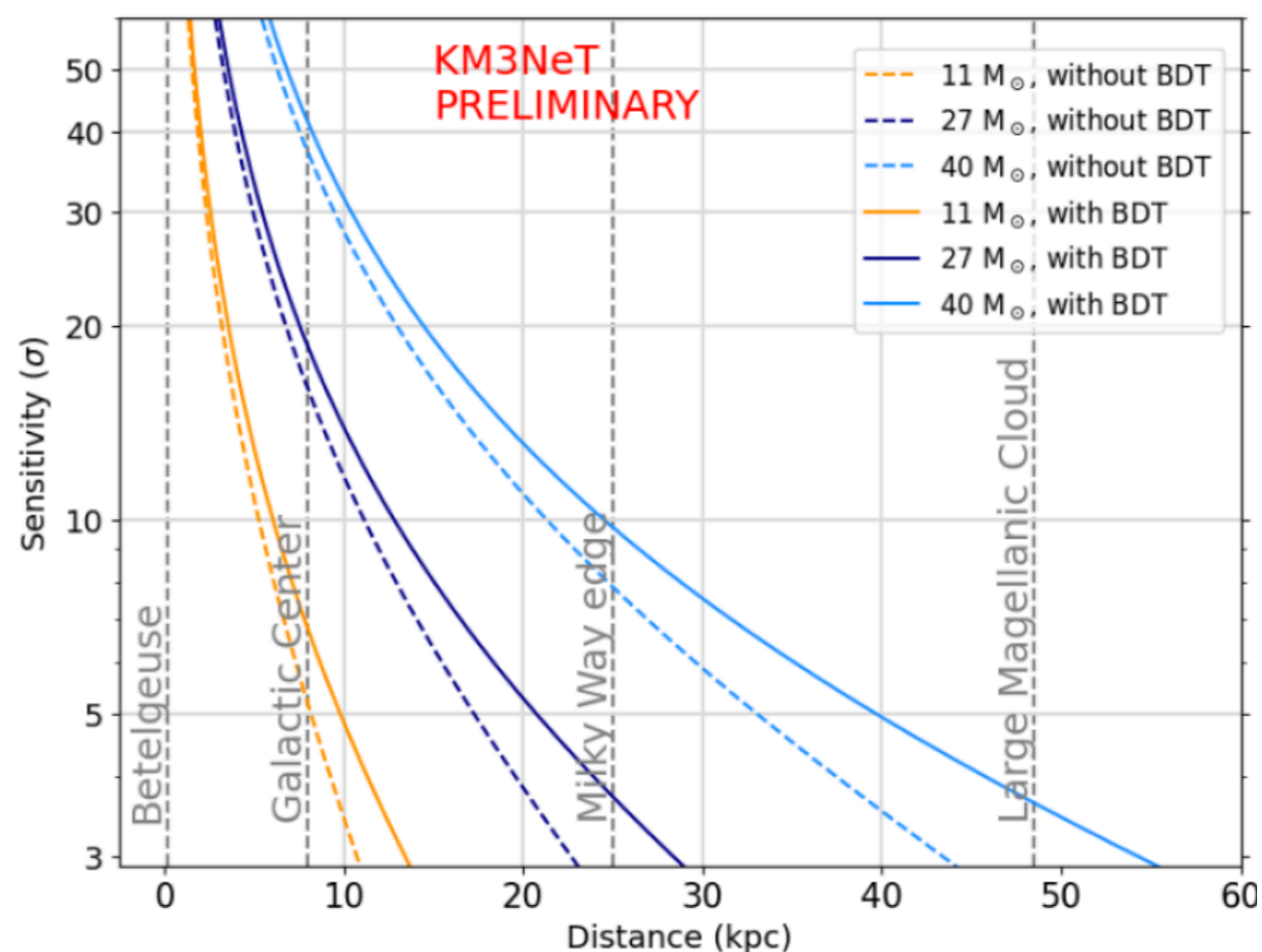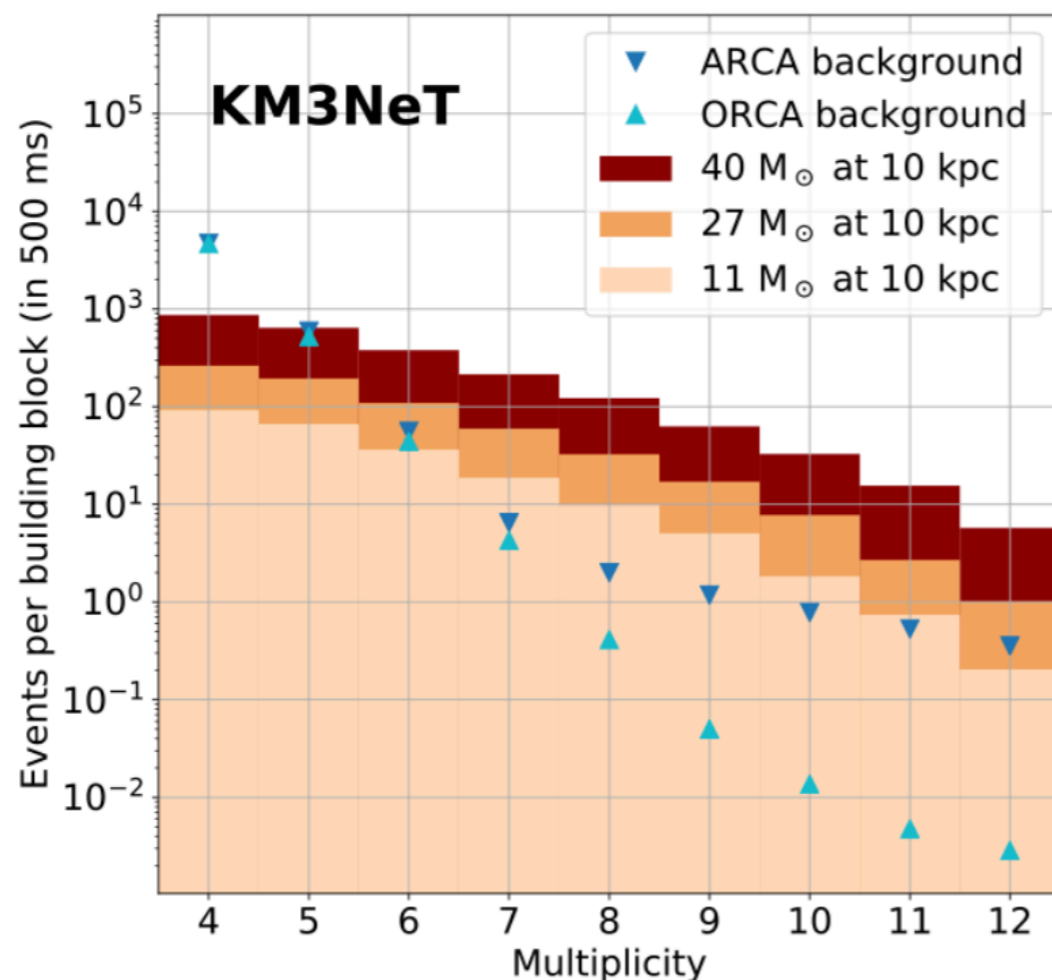
Offline GW follow-ups with KM3NeT

50+ follow ups performed with high-energy & MeV neutrinos during LIGO-VIRGO RUN O3

- Upgoing and horizontal track-like selection
- Time window for correlation set to [t_{GW}-500s; t_{GW}+500s]
- No significant detection in KM3NeT data
- Limits on flux and total energy emitted by individual mergers
- Also stacking limits to merger populations of BBH and NSBH (6)

23
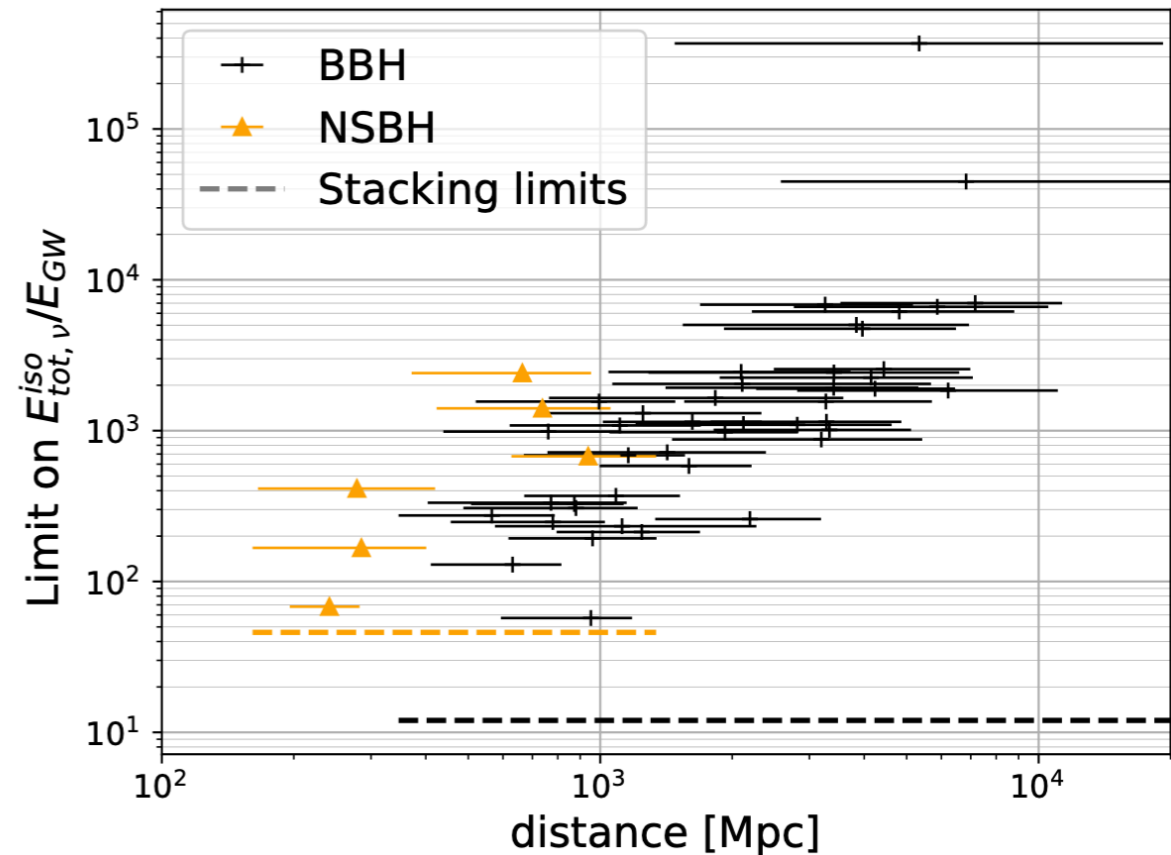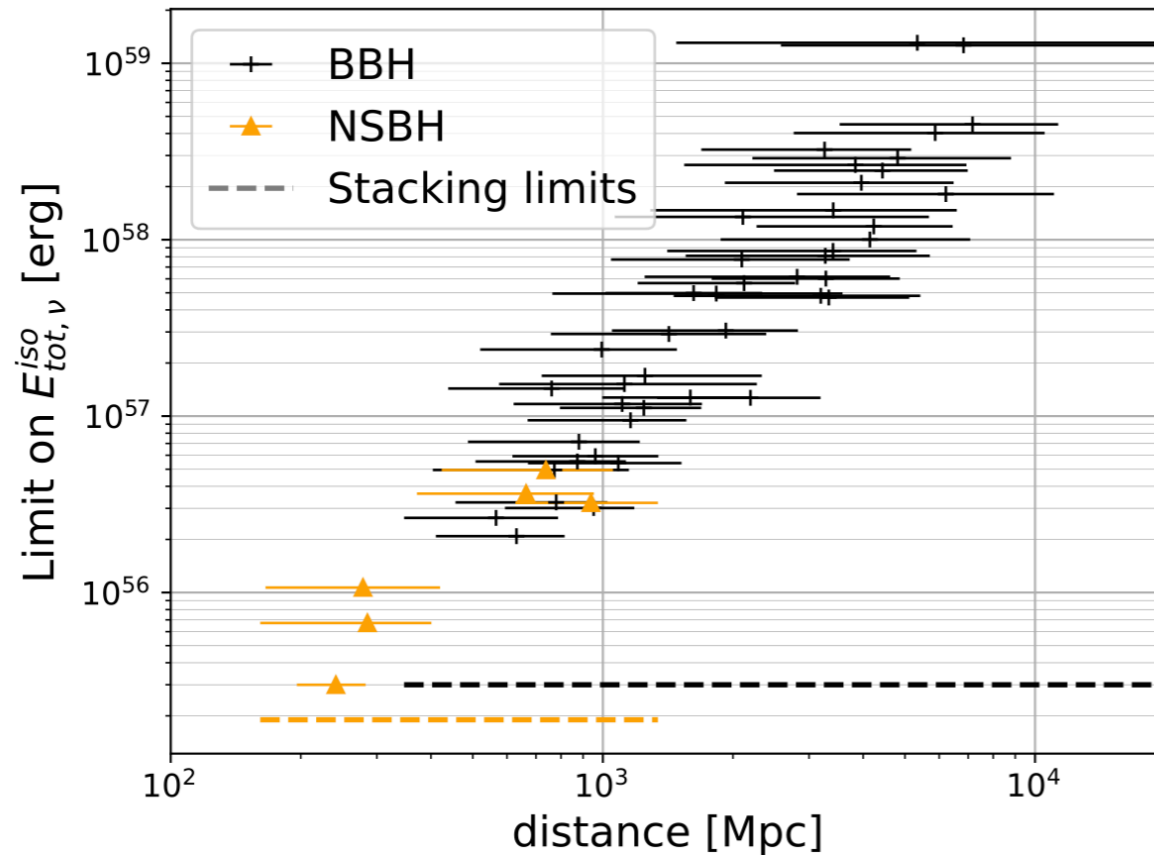
Conclusions

Water-based Cherenkov neutrino telescopes:
- **angular resolution** $\longrightarrow$ precision multi-flavor astronomy;
- location $\longrightarrow$ **privileged visibility of the Galaxy**;
- ARCA & ORCA $\longrightarrow$ **broad energy coverage**;
- marine observatory for environmental sciences.

KM3NeT is taking data and growing rapidly:
- First limits of **point-like sources**;
- First ATEL and GCN for **follow-up of external alerts.**

Many more topics not covered here:
- First measurements of neutrino oscillation parameters;
- Dark matter searches;
- BSM physics.

THANKS FOR YOUR KIND ATTENTION