THE KM3NET EXPERIMENT AND ITS PROSPECTS FOR MULTI-MESSENGER

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INFN
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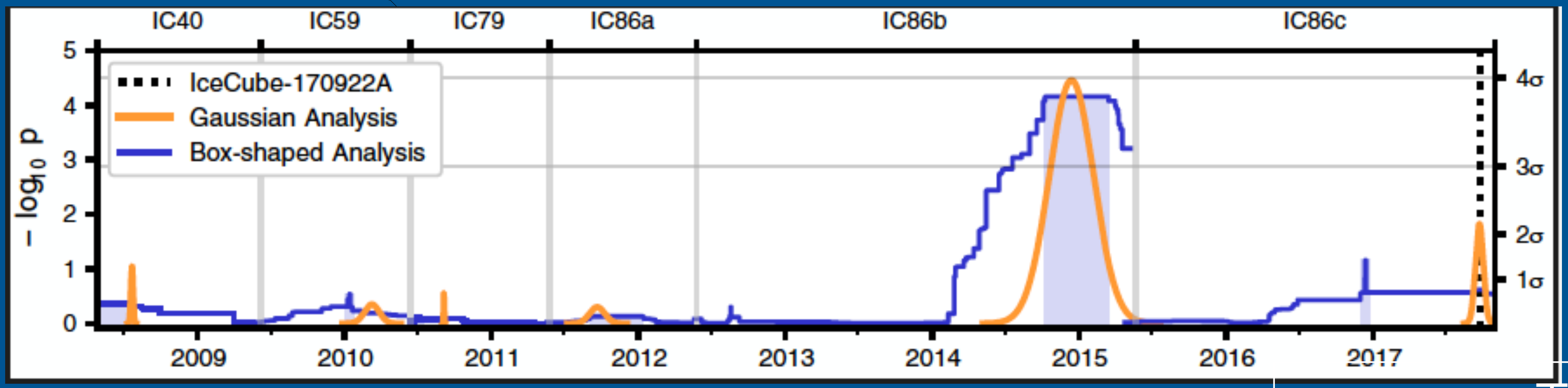
KM3NeT

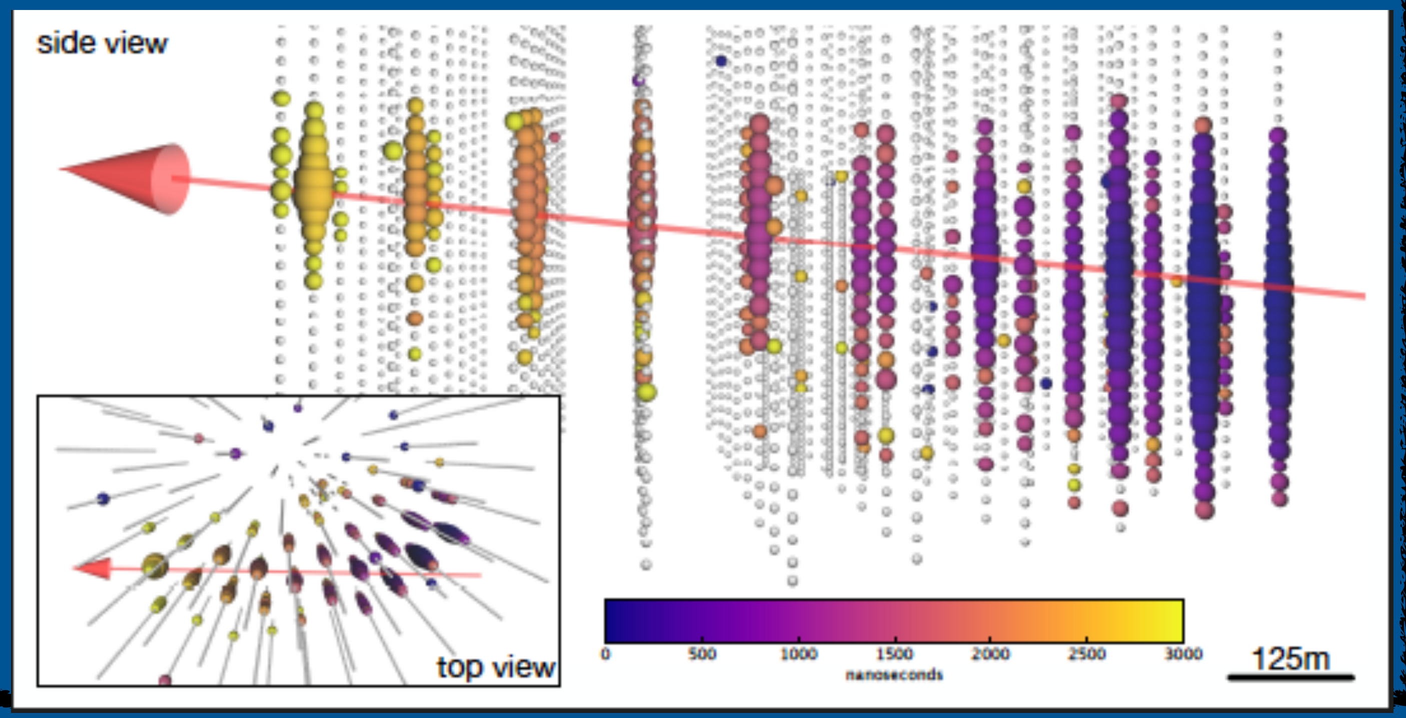
THE BIRTH OF NEUTRINO AND MULTI MESSENGER ASTRONOMY

December 2013 - Observation of the first cosmic neutrinos at ~ 4 σ level

September 2017 - One high energy neutrino event (IC GW170817) detected by IceCube at +5.6° in declination. An increase of the activity in the same direction and time in high-energy gamma-rays, X-rays, optical and radio observed



Track-like event of about 120 TeV traversing all the detector



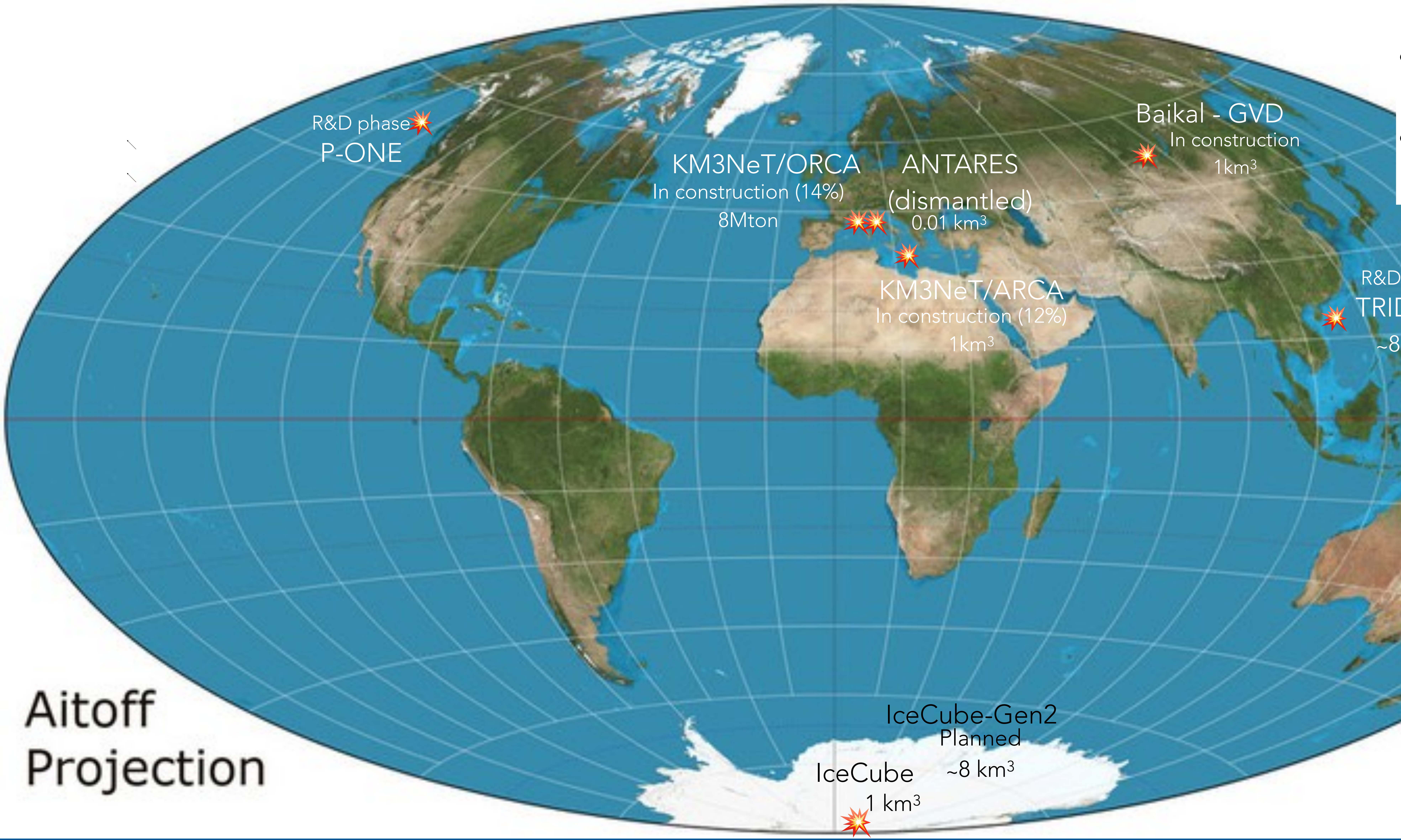
TXS 0506+056
Possible neutrino source identified

August 2017 - Event of Gravitational Waves (GW170817) from a neutron star merger well detected in VIRGO and LIGO - followed 1.7 seconds later by a gamma-rays burst identified by INTEGRAL e FERMI - after hours, days and week X-rays, radio and optical observations NO neutrinos

November 2022 - Analyzed 10 years of IC data with an improved calibration and energy reconstruction 👉 about 80 neutrinos from the active galaxy NGC1068. Significance 4.2σ. 👉 No correlation with high energy gammas

Clear connection between different astrophysical messengers established

THE HIGH ENERGY NEUTRINO DETECTORS

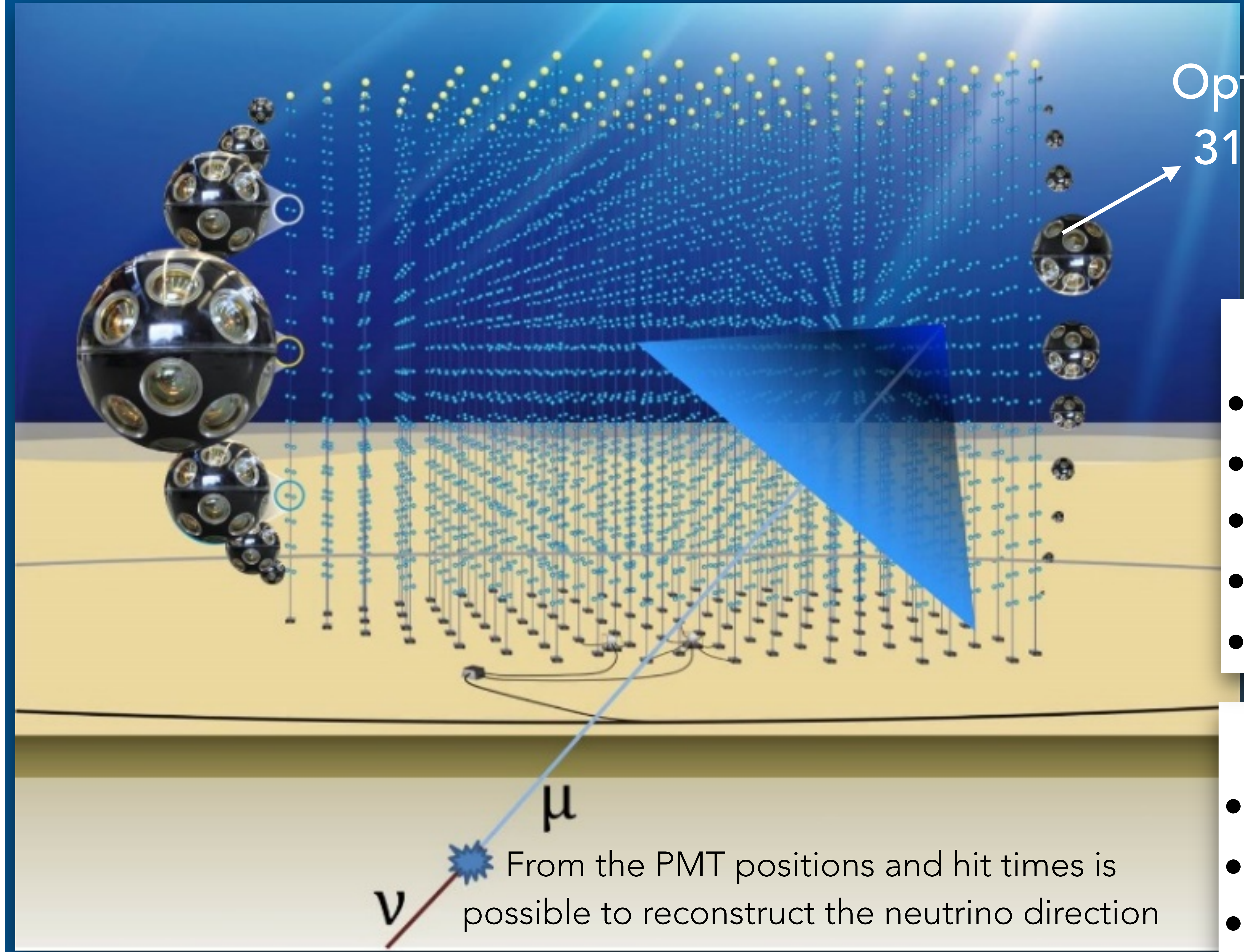


In China also:

- HUNT ~30 km^3 in Lake Baikal or the South China Sea http://hunt.ihep.ac.cn/
- NEON ~1 km^3 in the South China Sea https://pos.sissa.it/444/1017/pdf

THE KM3NET DETECTORS

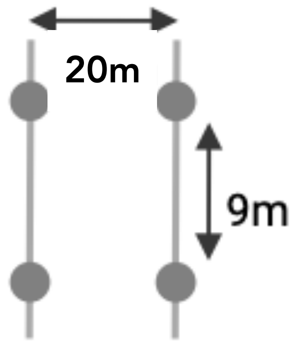
Same technology for the two detectors



Optical sensor (DOM)
31 PMTs of 3 inches

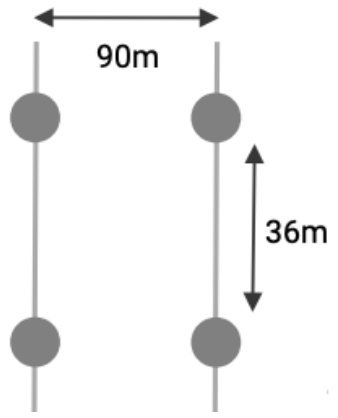
Detection Unit (DU)

ORCA



- Depth ~2500 m
- One block of 115 Detection Units
- Average distance between Detection Units ~20 m
- Average vertical distance between DOMs ~9 m
- **≈8 Mton**

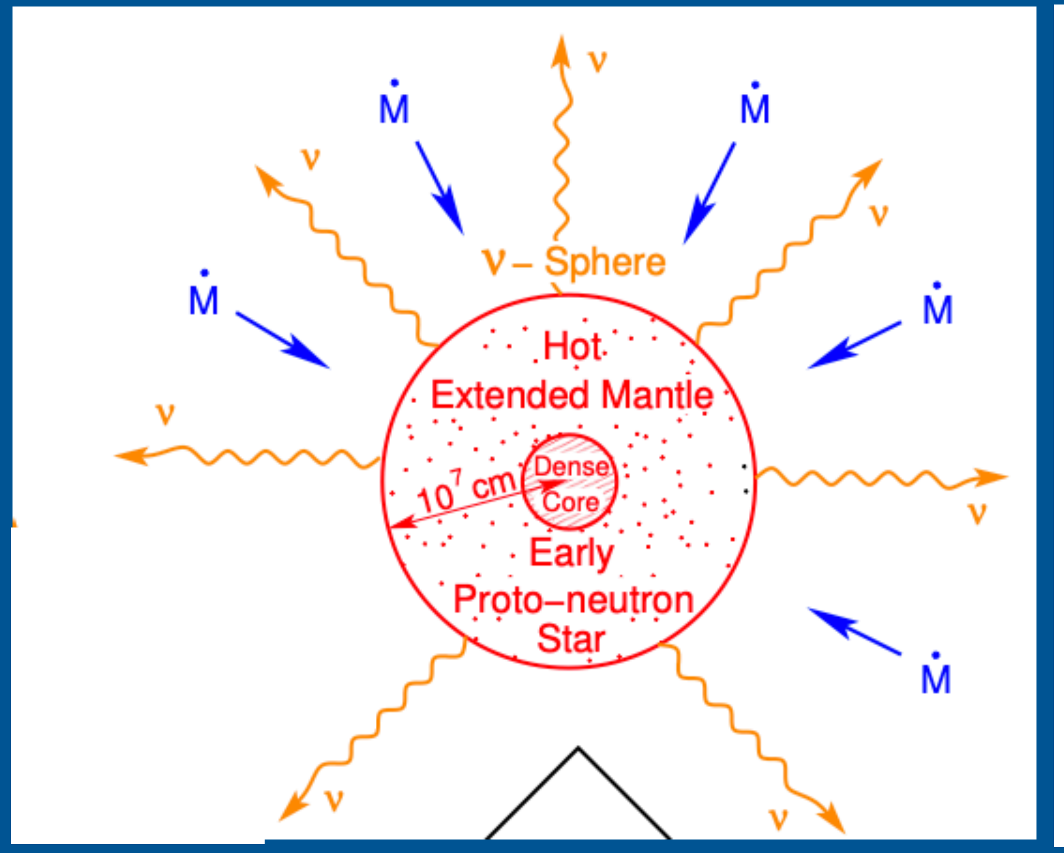
ARCA

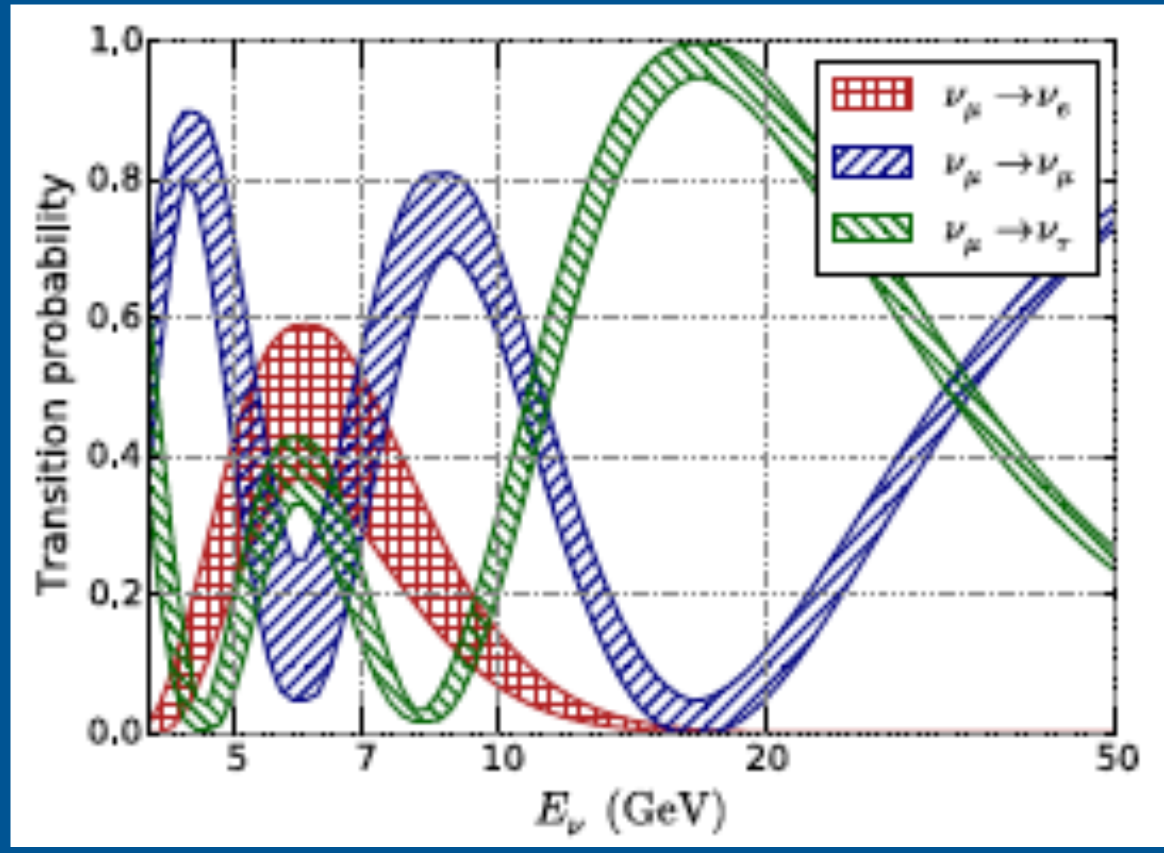


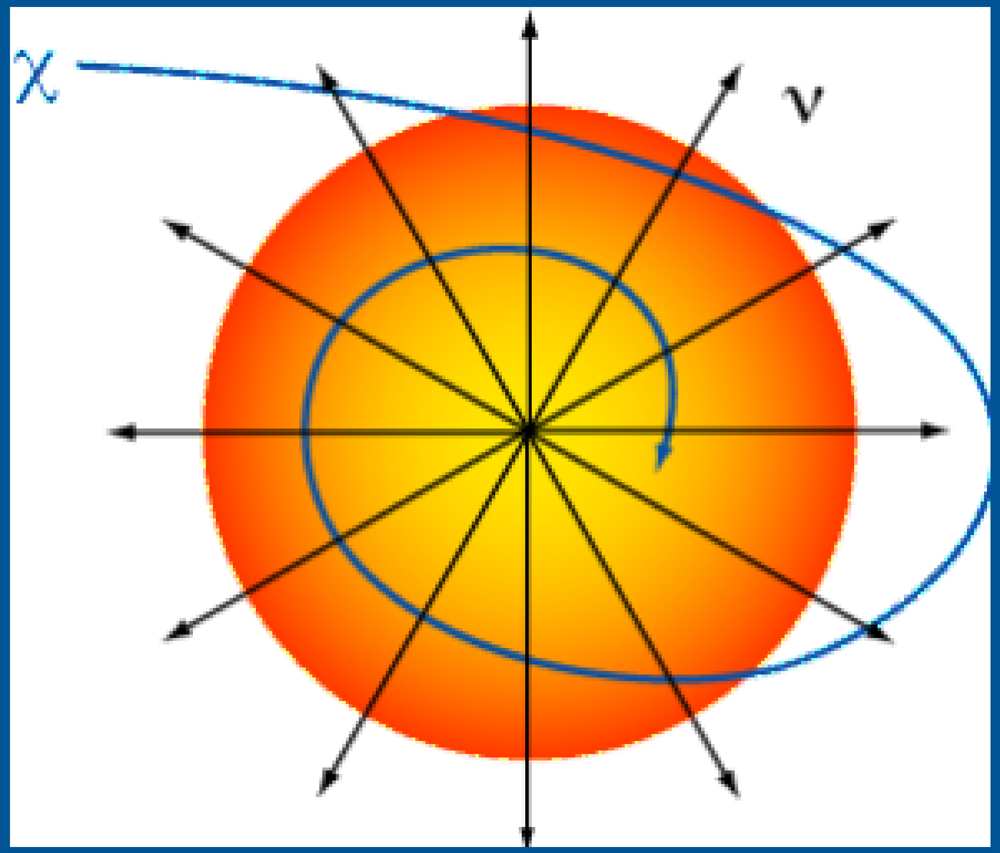
- Depth ~3500 m
- Two blocks of 115 Detection Units each
- Average distance between Detection Units ~90 m
- Vertical distance between DOMs ~36 m
- **Volume (0.5 × 2) km³**

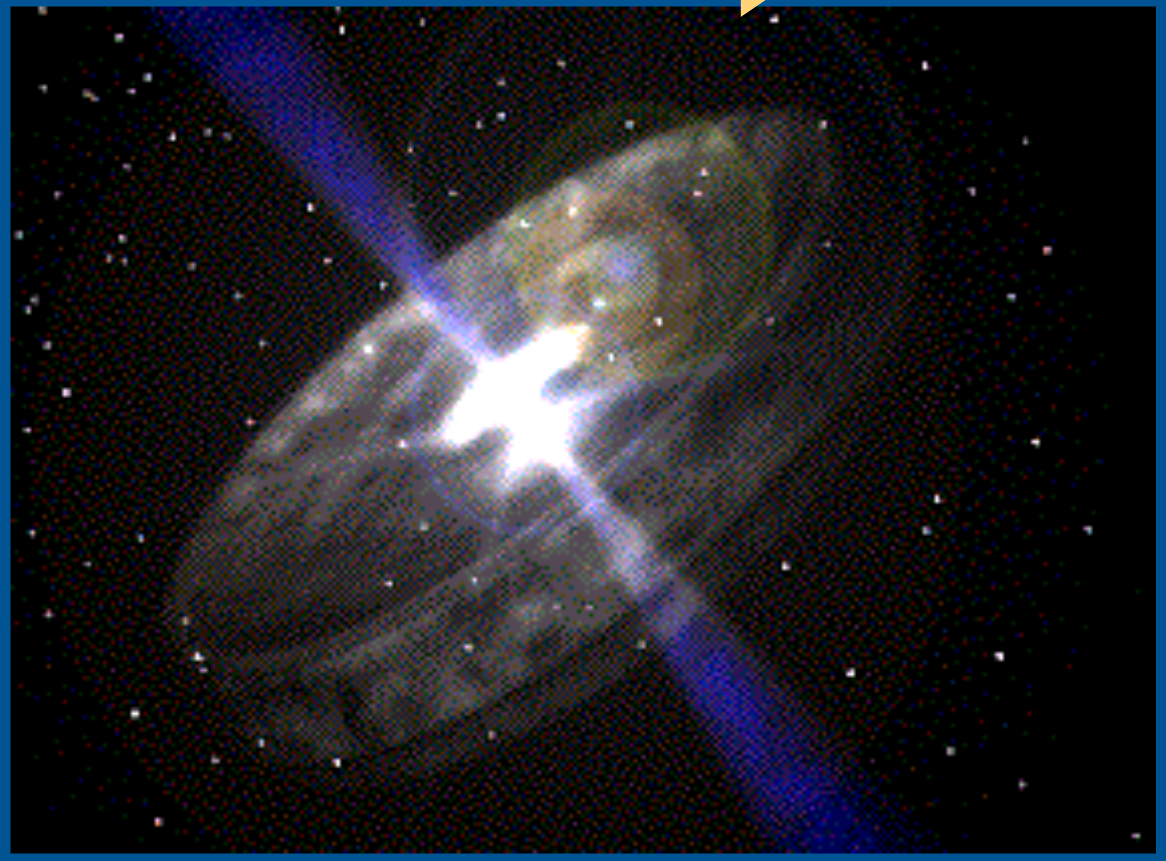
Detectors in construction

Neutrino Energy from MeV to PeV









Supernova explosions
MeV

Neutrino oscillation
GeV

Dark Matter
TeV

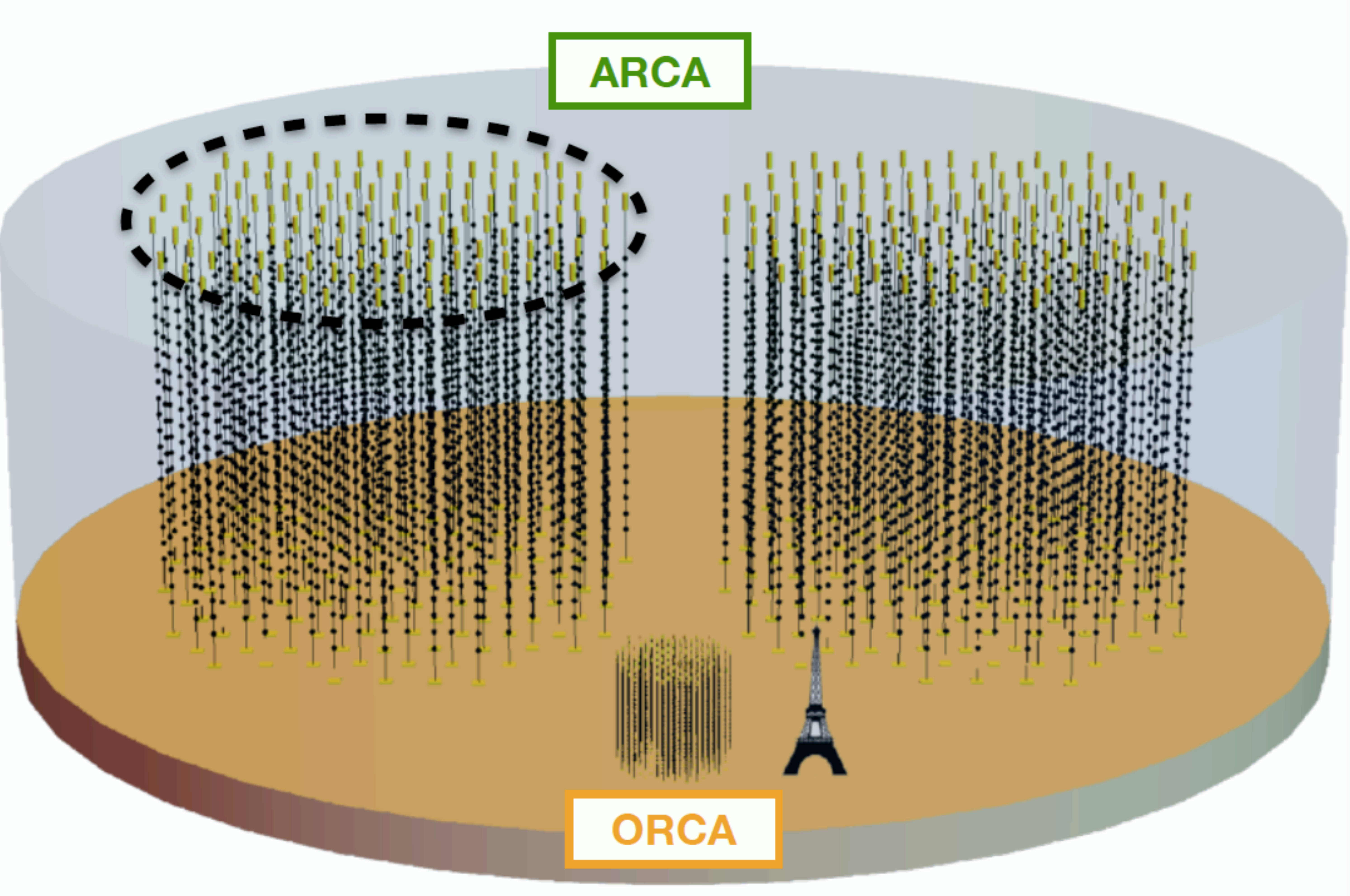
HE neutrinos
Multi-messenger program
PeV

ARCA + ORCA

ORCA

ARCA

THE KM3NET DETECTORS



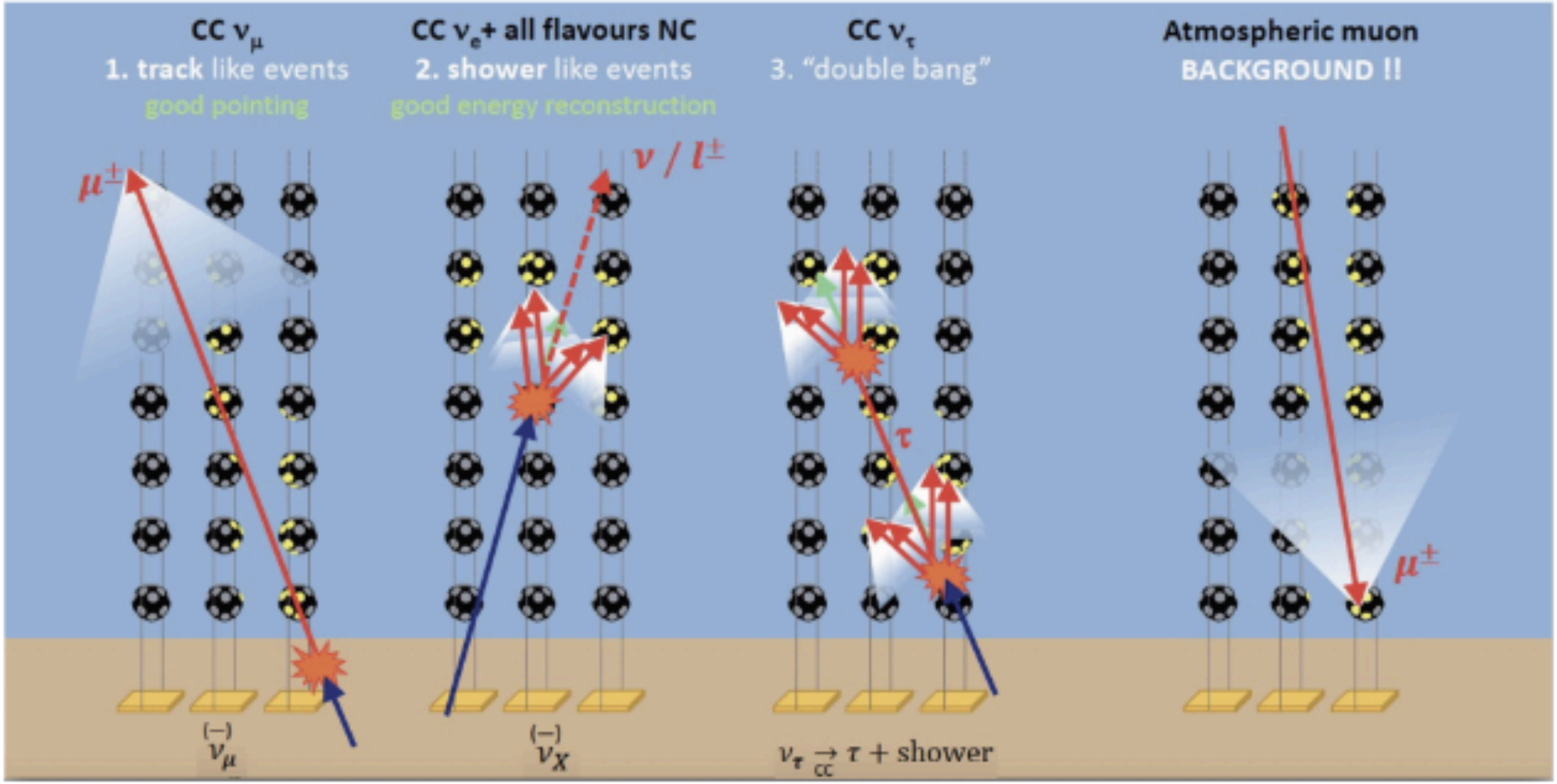
1 Building Block (BB)👉115 Detection Units

ARCA 2 BB

ORCA 1BB

Difference in the spatial distance of optical sensors

DETECTION PRINCIPLE



- Tracks: median ang. res. can drop below 0.1° above 100 TeV, factor 2 energy estimate
- Showers : median angular resolution can reach 1° at 100 TeV, 10% energy resolution

THE TECHNOLOGY

The basic elements:

- Optical sensors 👉 DOMs (Digital Optical Module)
- Strings 👉 DU (Detection Unit)
- Seafloor network 👉 Electro-optical cables and JBs (Junction Boxes)

The Digital Optical Module

DOM

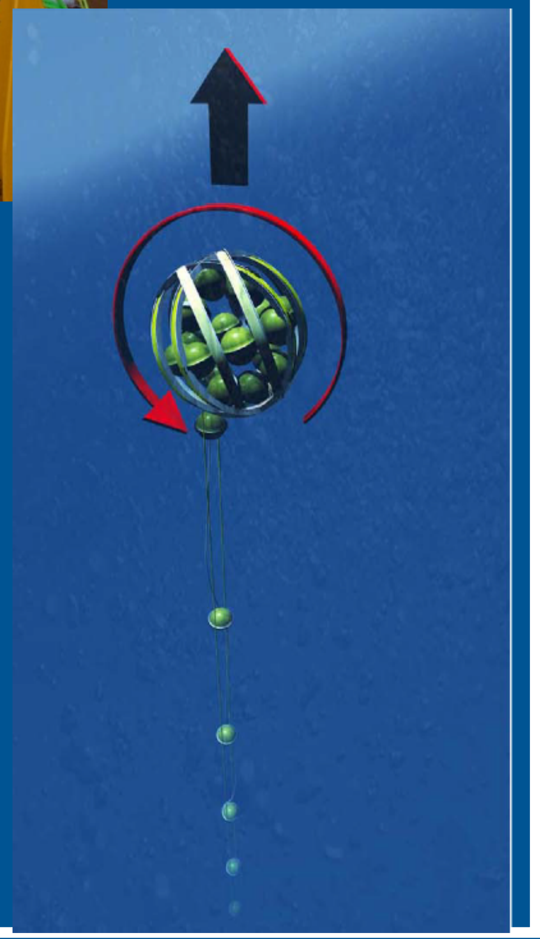
It is a 17” glass sphere containing:

- 31 3” PMTs (photocathode aerea ≃ 3 × 10” PMTs)
- LED and Piezo
- Front-end electronics -> FPGA

Video of the DOM integration

The Detection Unit

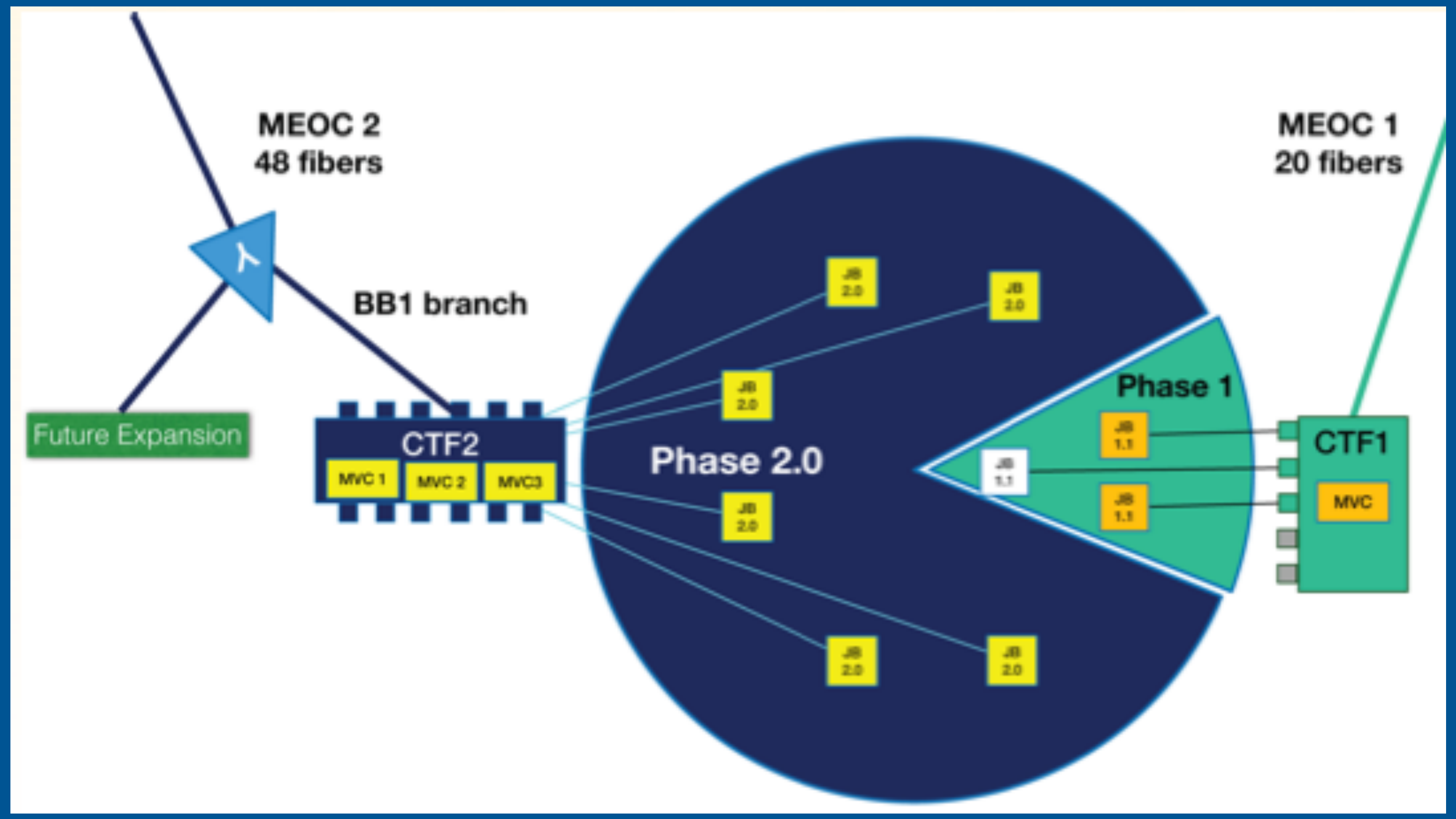
18 DOMs in a DU

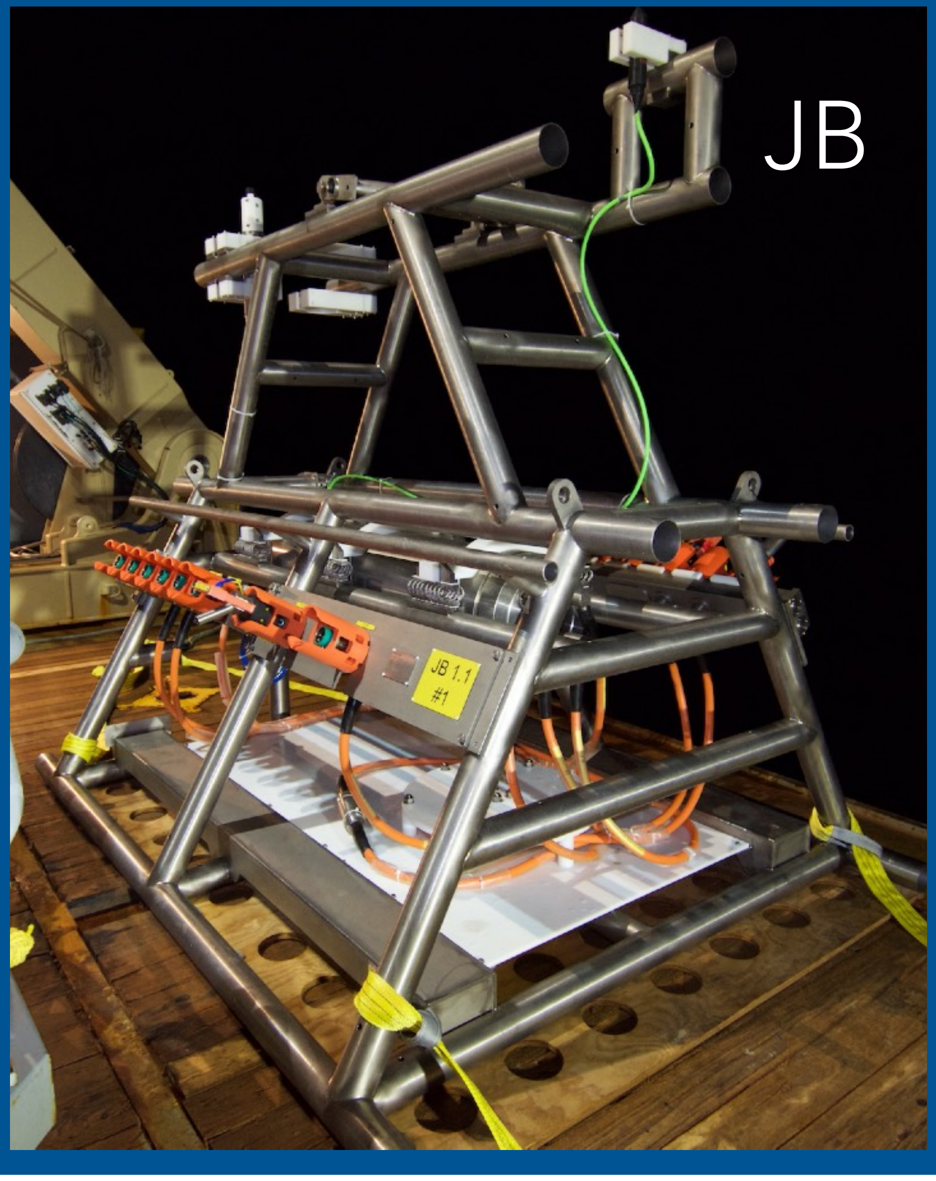


DU

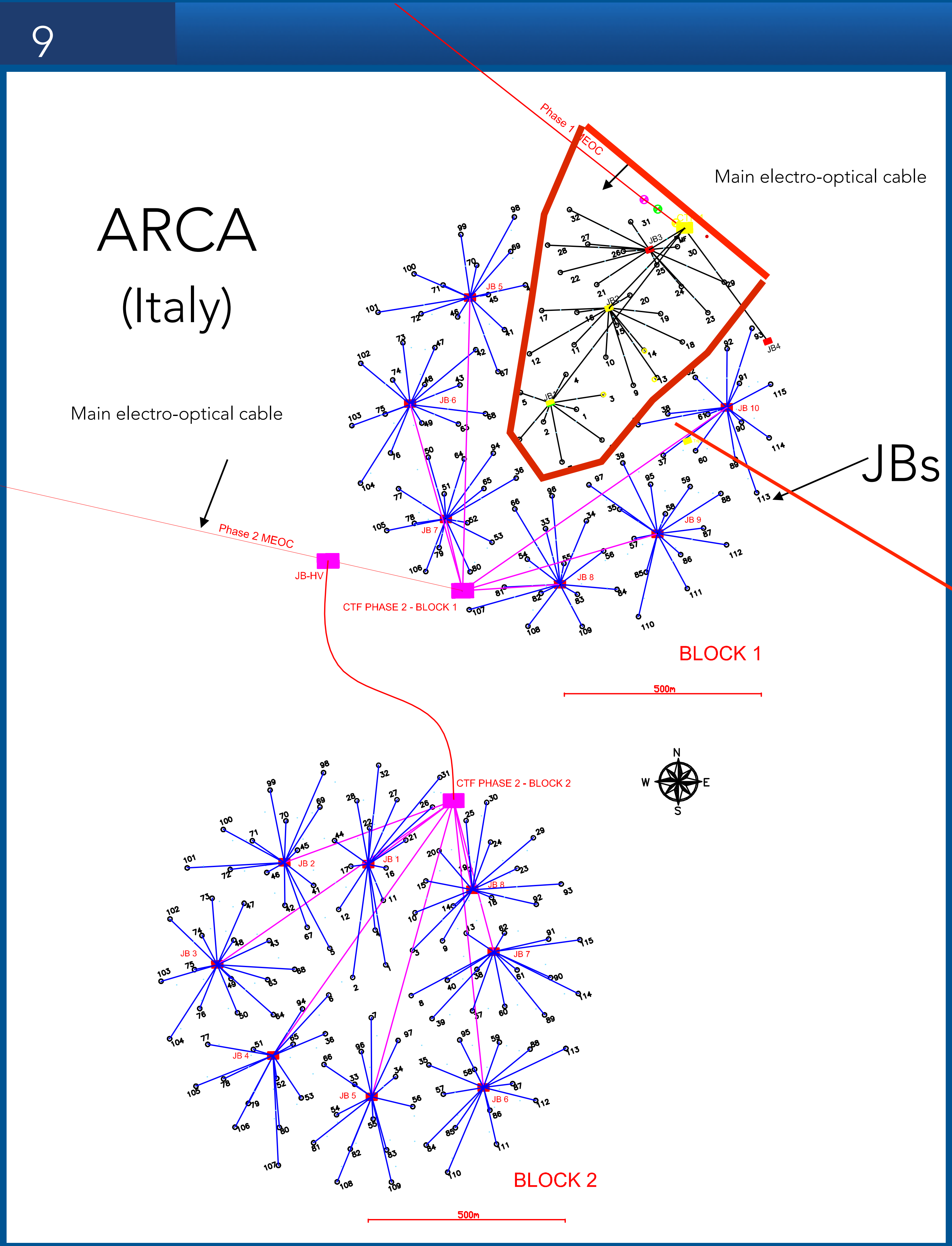
Video of a DU integration

Sea floor network: JB+IL+CTF

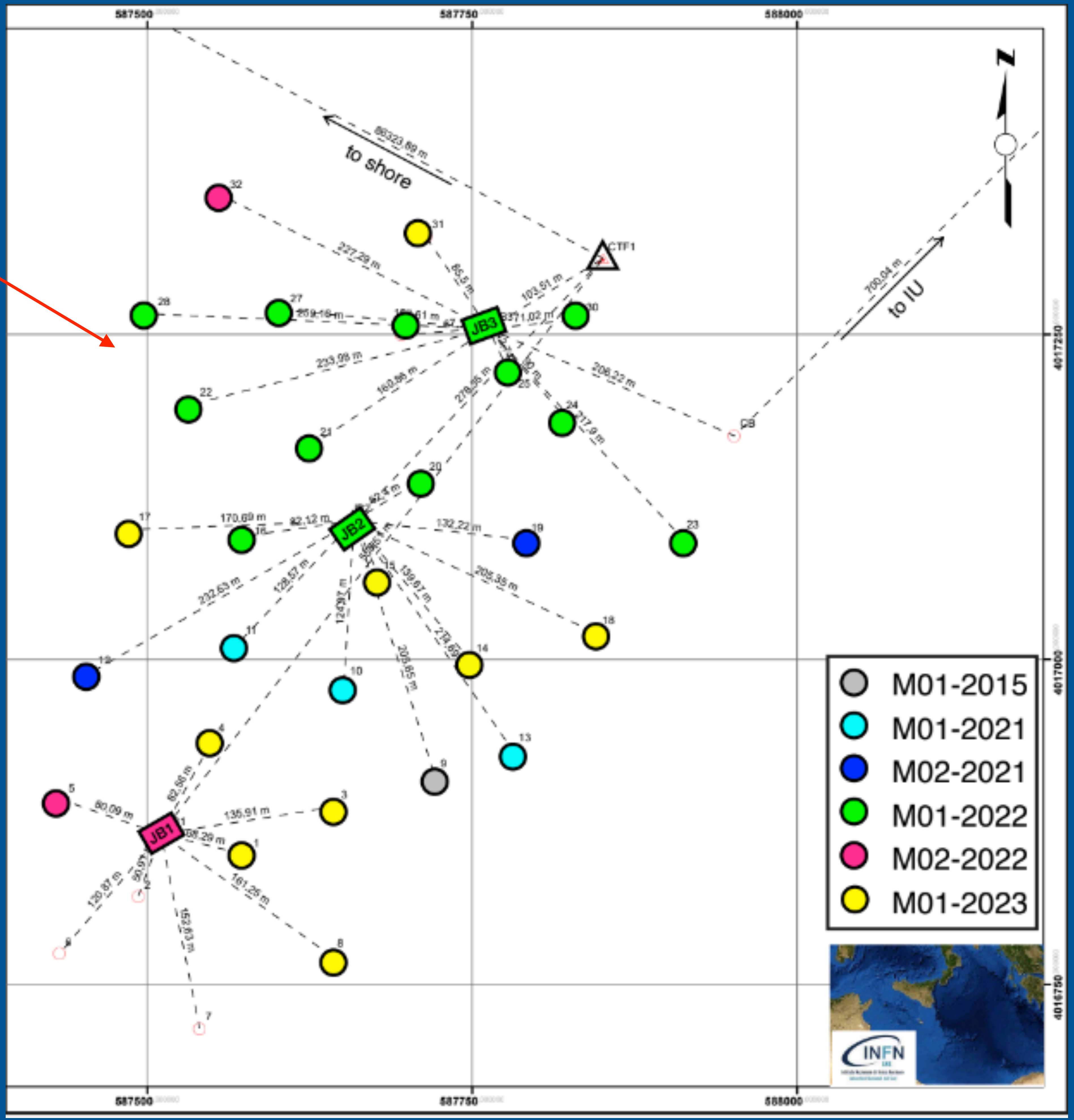




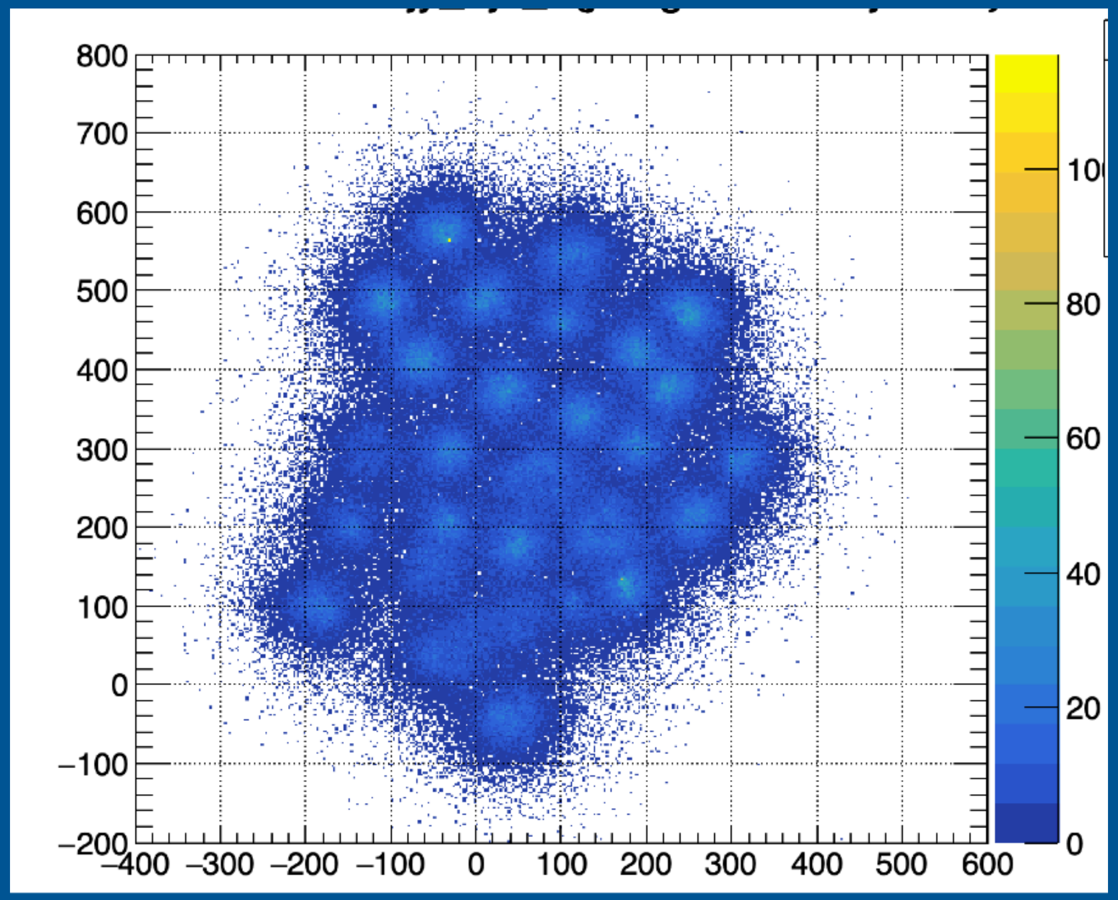
THE KM3NET/ARCA STATUS



Current status 28 DUs deployed
+ 3 JB

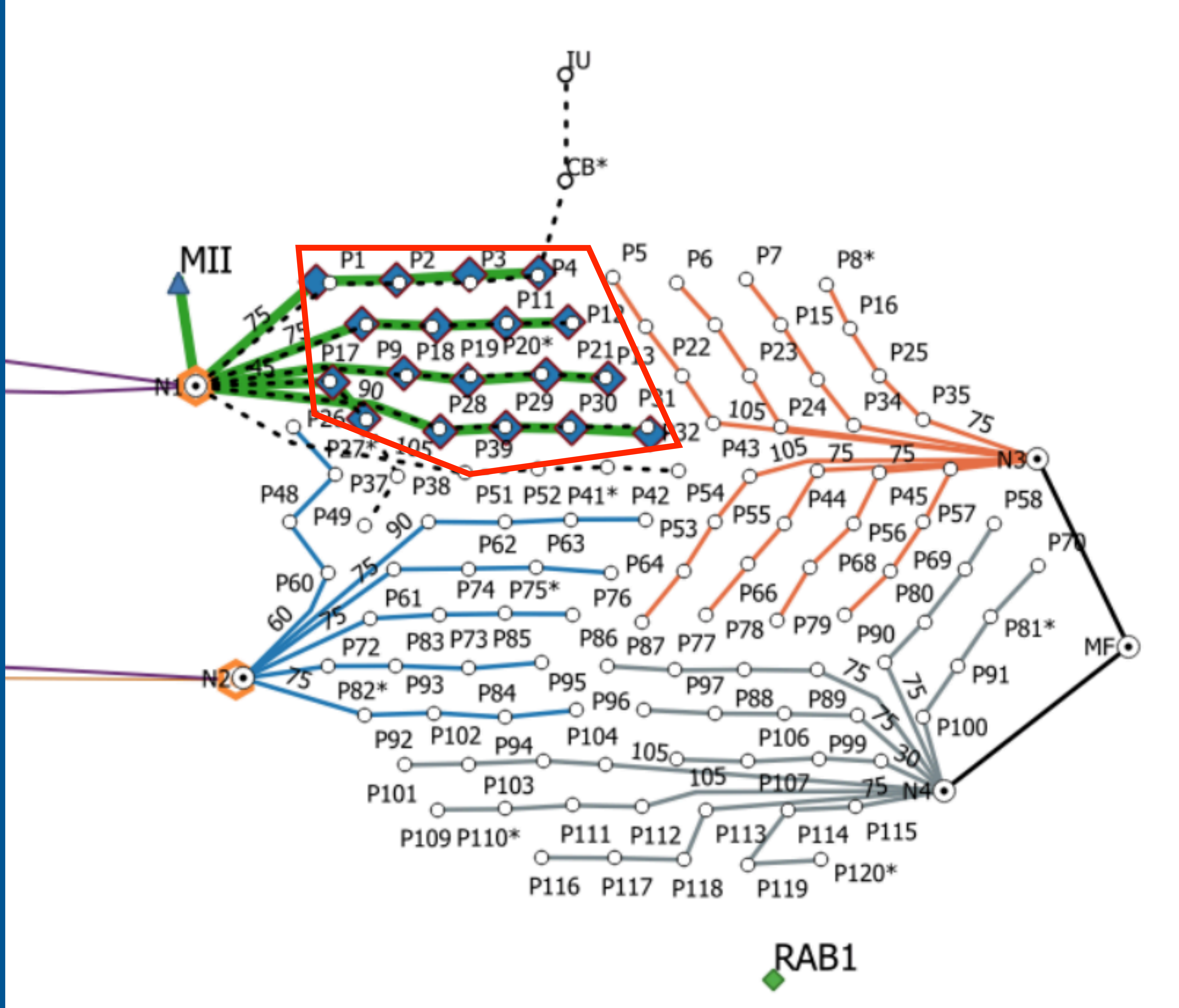


1-2 sea campaigns per year.
The last one in
September 2023 👉 recovered 2 DUs
not working and deployed 9 DUs
Detector commissioning just finished



THE KM3NET/ORCA STATUS

Current status 18 DUs deployed
16 DUs taking data



Many sea campaigns/year

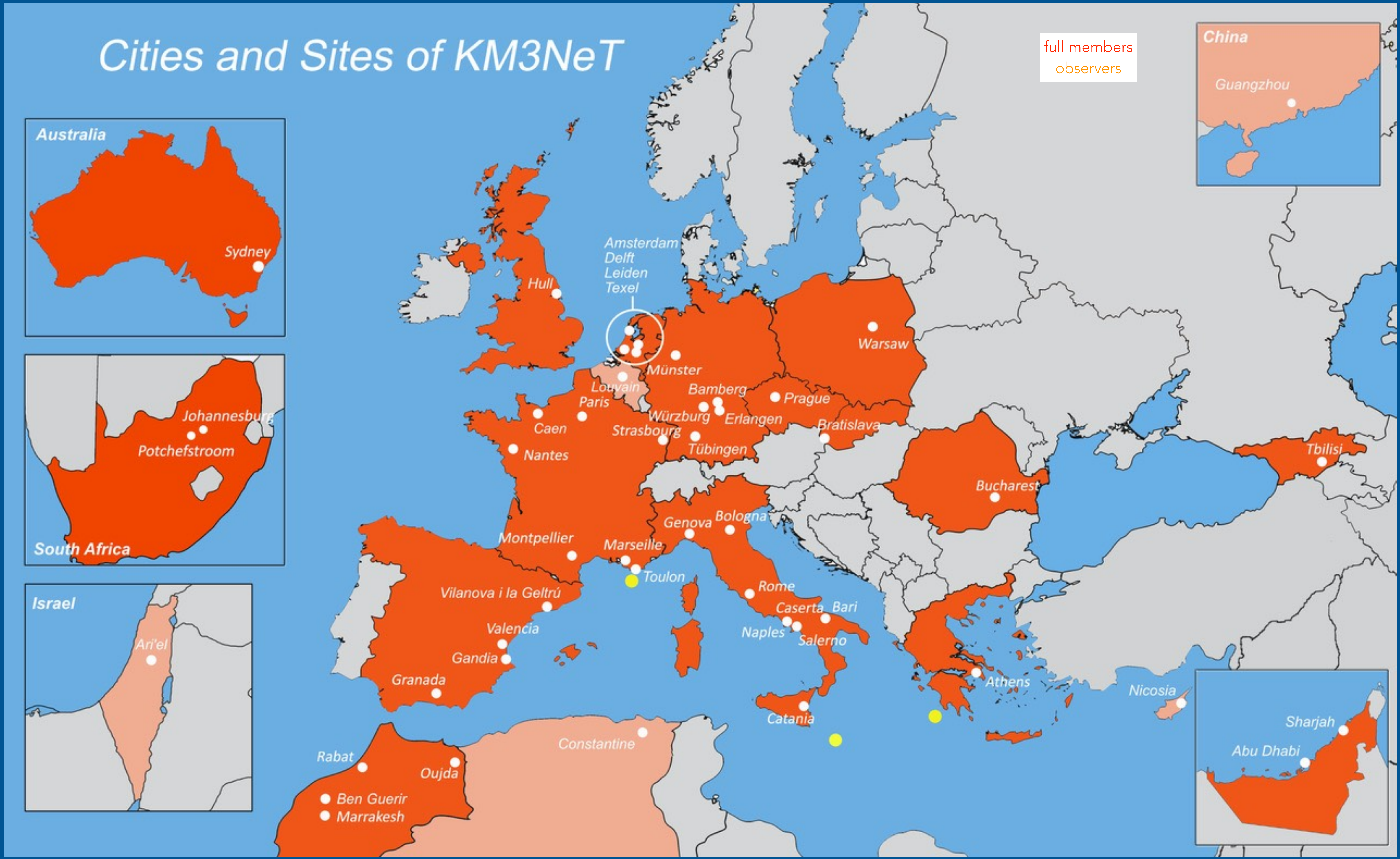
Next campaigns

- November 2023 sea campaign 👉 Replace the two not working DUs and add 4 DUs 👉 22 DUs
- December 2023 sea campaign 👉 + 2 DUs 👉 24 DUs

For the end of 2023 completion of node 1 👉 24 DUs

THE KM3NET COLLABORATION

60 institutes in 20 countries

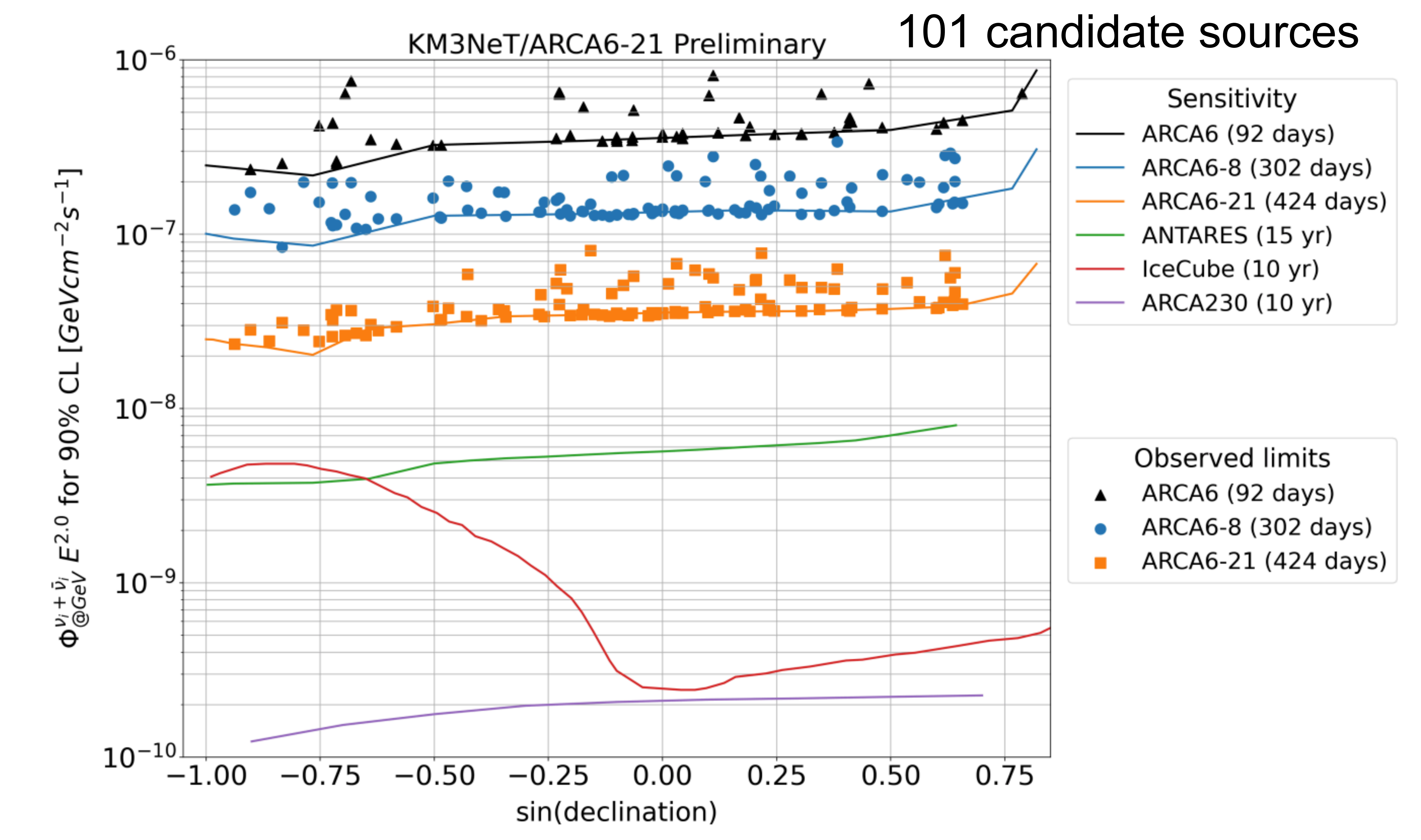


SEARCH FOR POINT-LIKE SOURCES

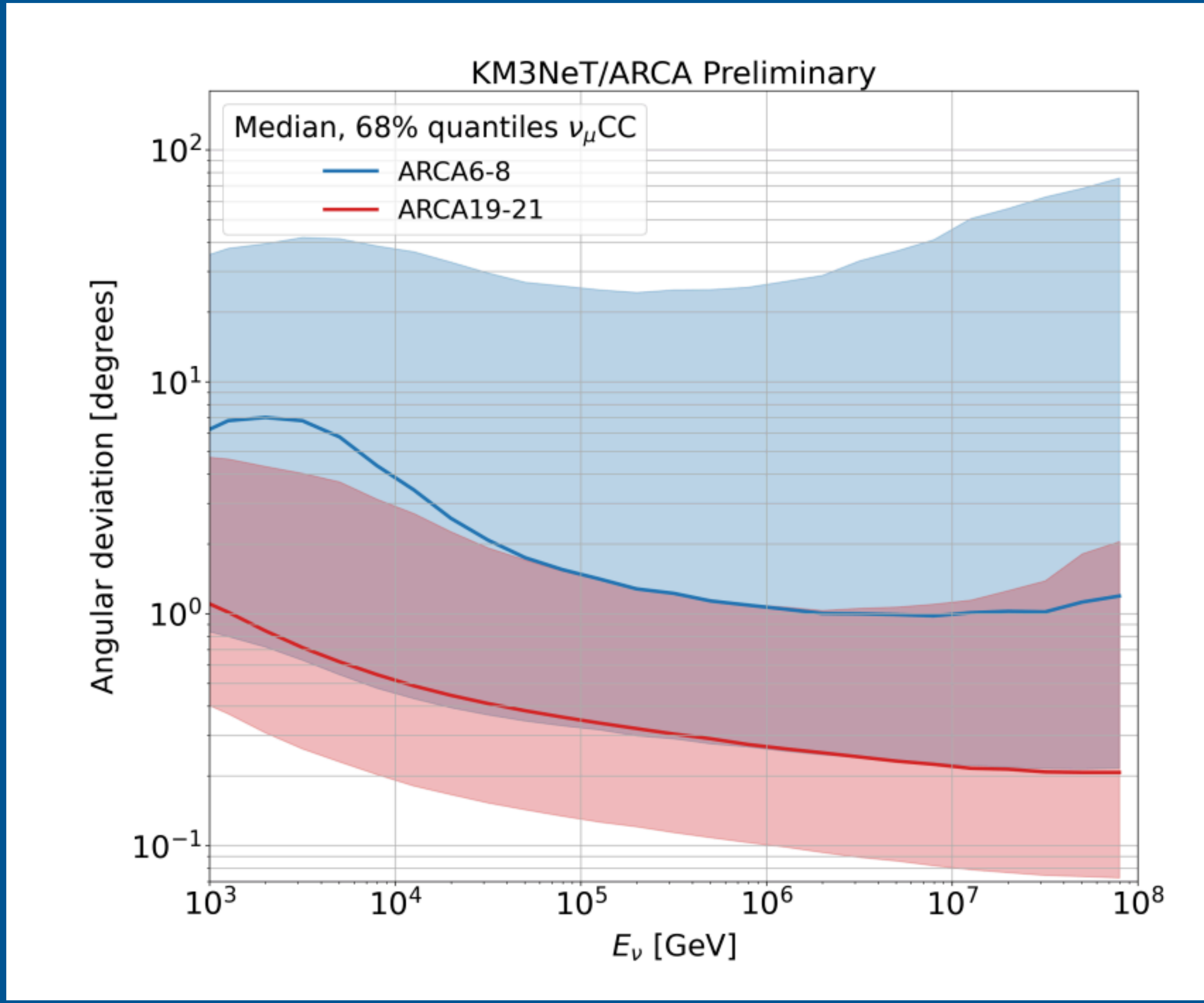
ICRC2023 Pos 1018 https://arxiv.org/abs/2309.05016

ARCA6 & ARCA8 & ARCA19 fully analyzed
ARCA21 partially analyzed (until December 2022)

101 candidate sources



Angular resolution



Large improvement in sensitivity is expected
+ 9 months of unprocessed ARCA21 data
+ extended detector (ARCA28 from sept 2023)

KM3NeT upper limits are quickly reaching the ANTARES 15yr limits

Also big improvements in angular resolution

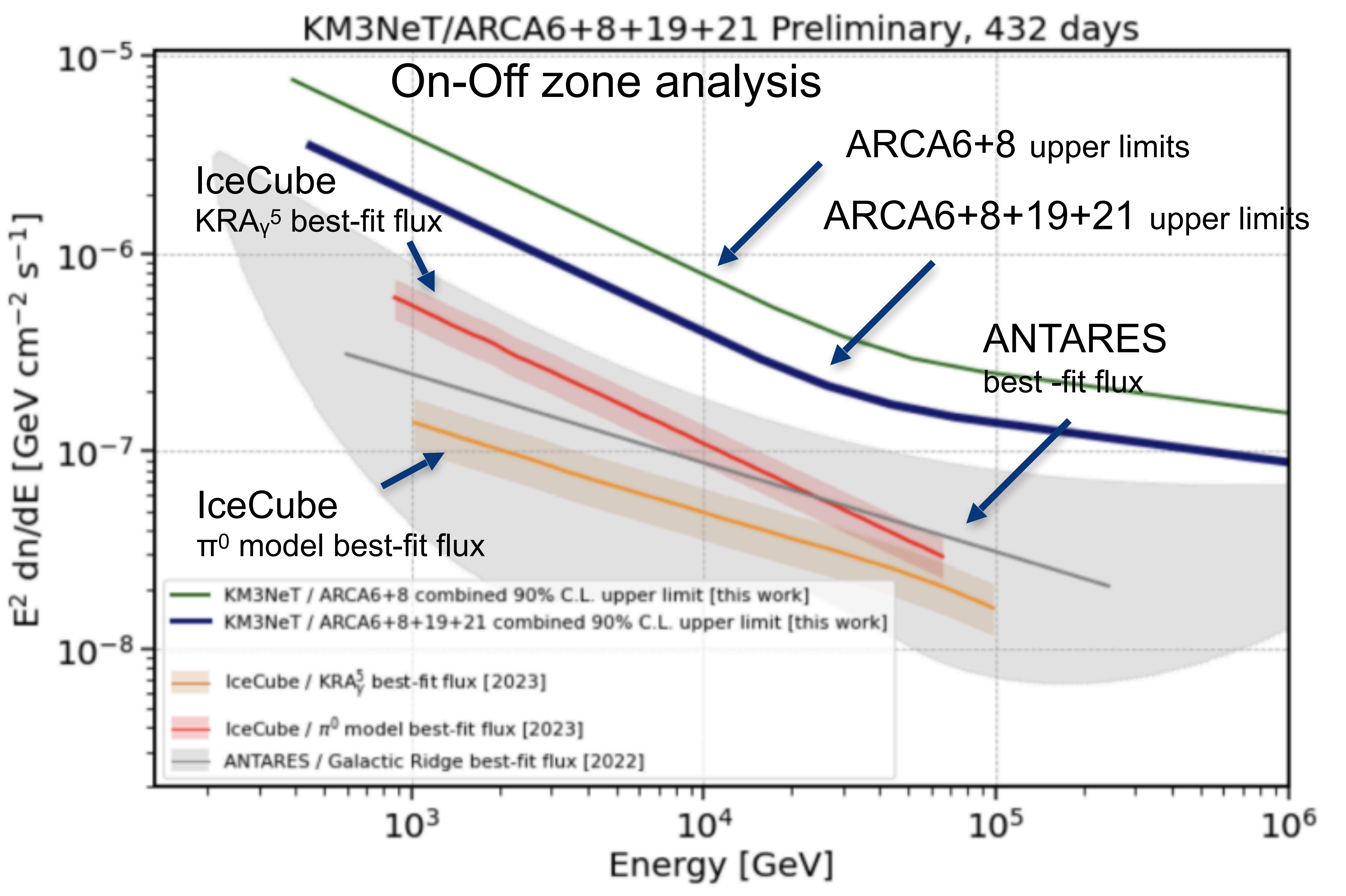
DIFFUSE FROM THE GALACTIC PLANE

ARCA6 & ARCA8 & ARCA19 fully analyzed
ARCA21 partially analyzed (until December 2022)

ICRC2023 Pos 1190
https://arxiv.org/abs/2309.05016

KM3NeT

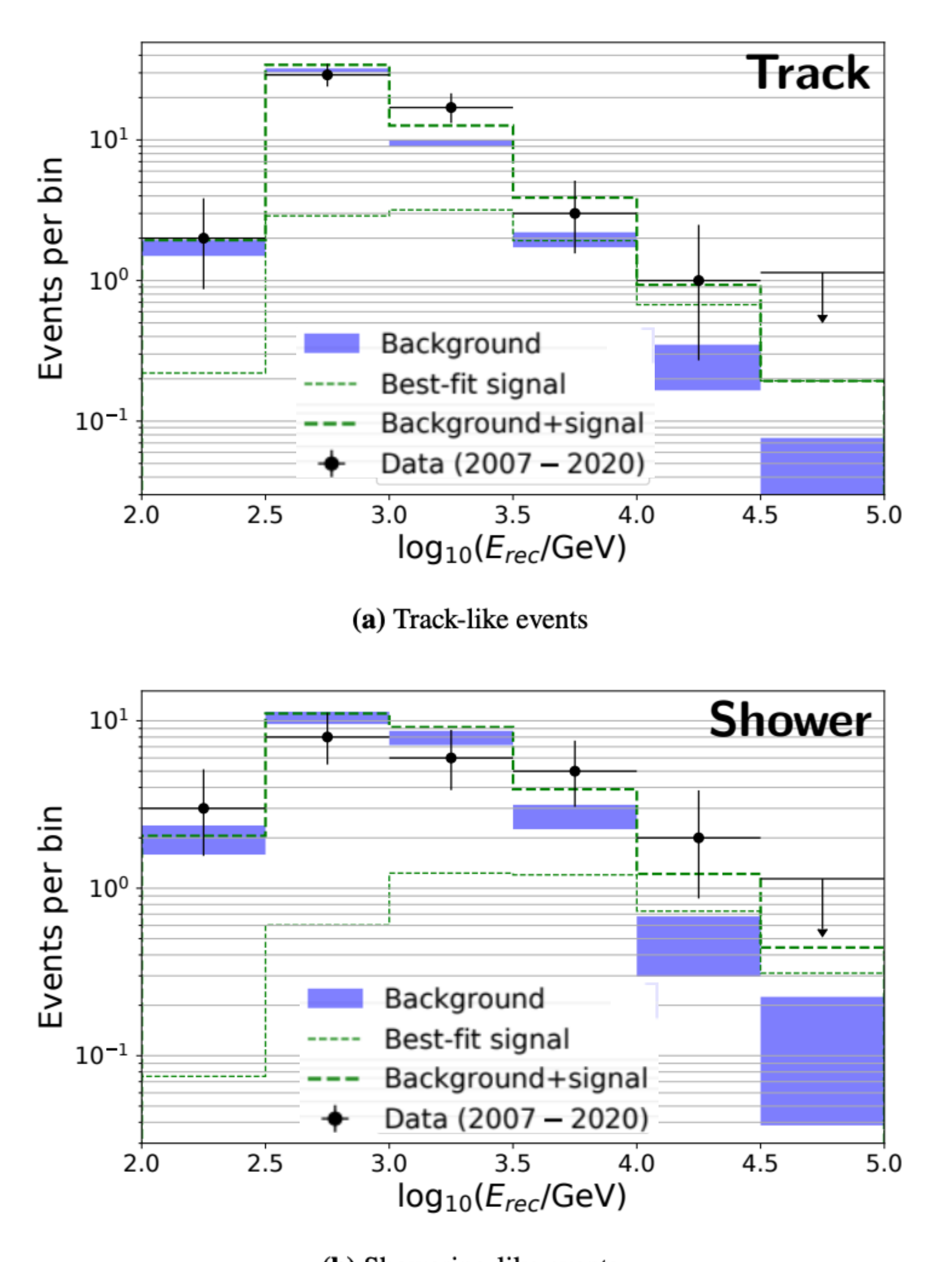
|l| < 31° and |b| < 5° for KM3NeT/ARCA6-8 and
|l| < 31° and |b| < 4° for KM3NeT/ARCA19-21



ANTARES 2007-2020 data

Phys. Lett. B 841 (2023), p. 137951

2σ excess in tracks and showers → hint for Galactic signal



(a) Track-like events

(b) Showering-like events

For E_{ν}>1 TeV

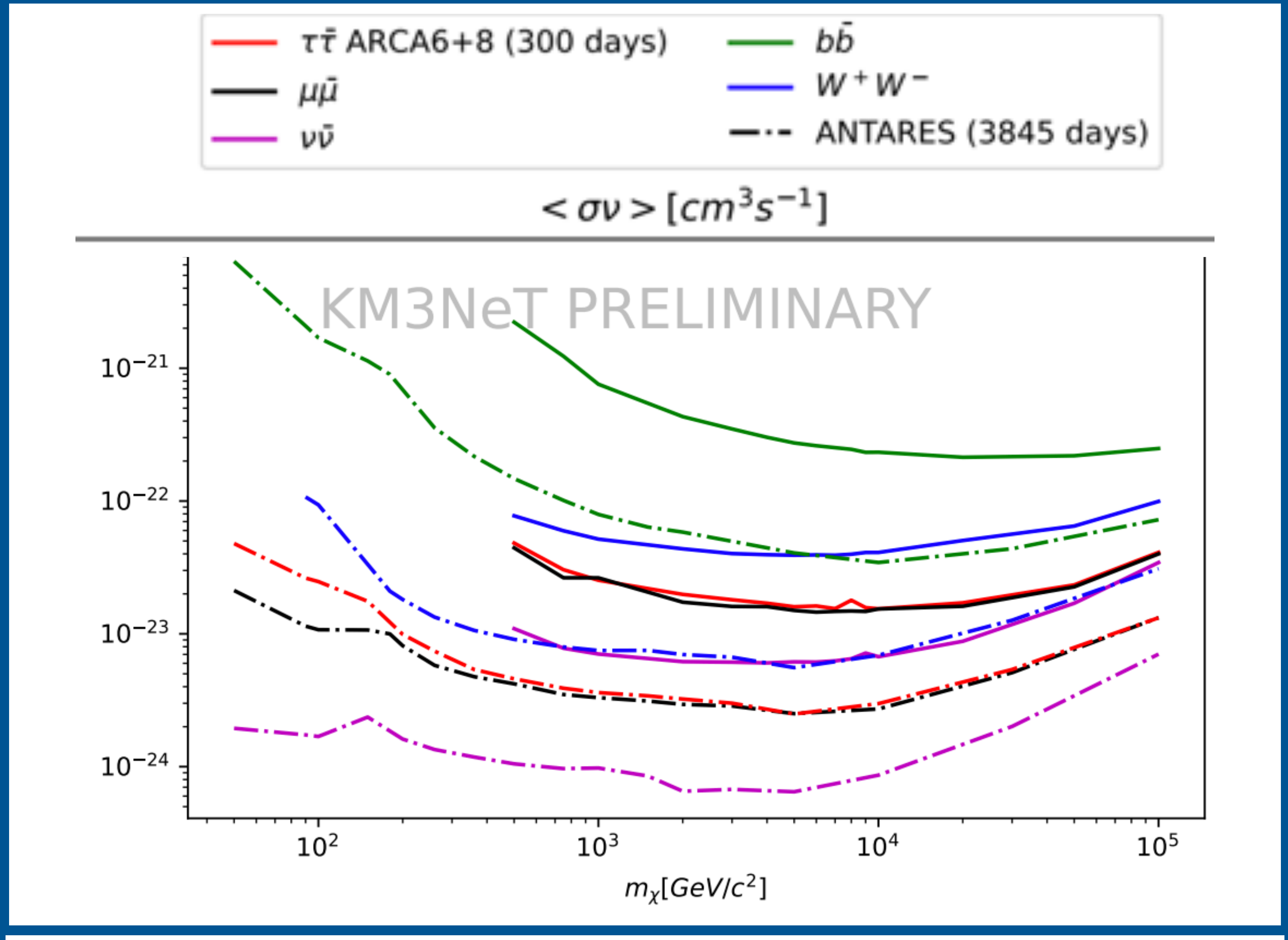
21 track events observed -> 11.7±0.6 back. expected

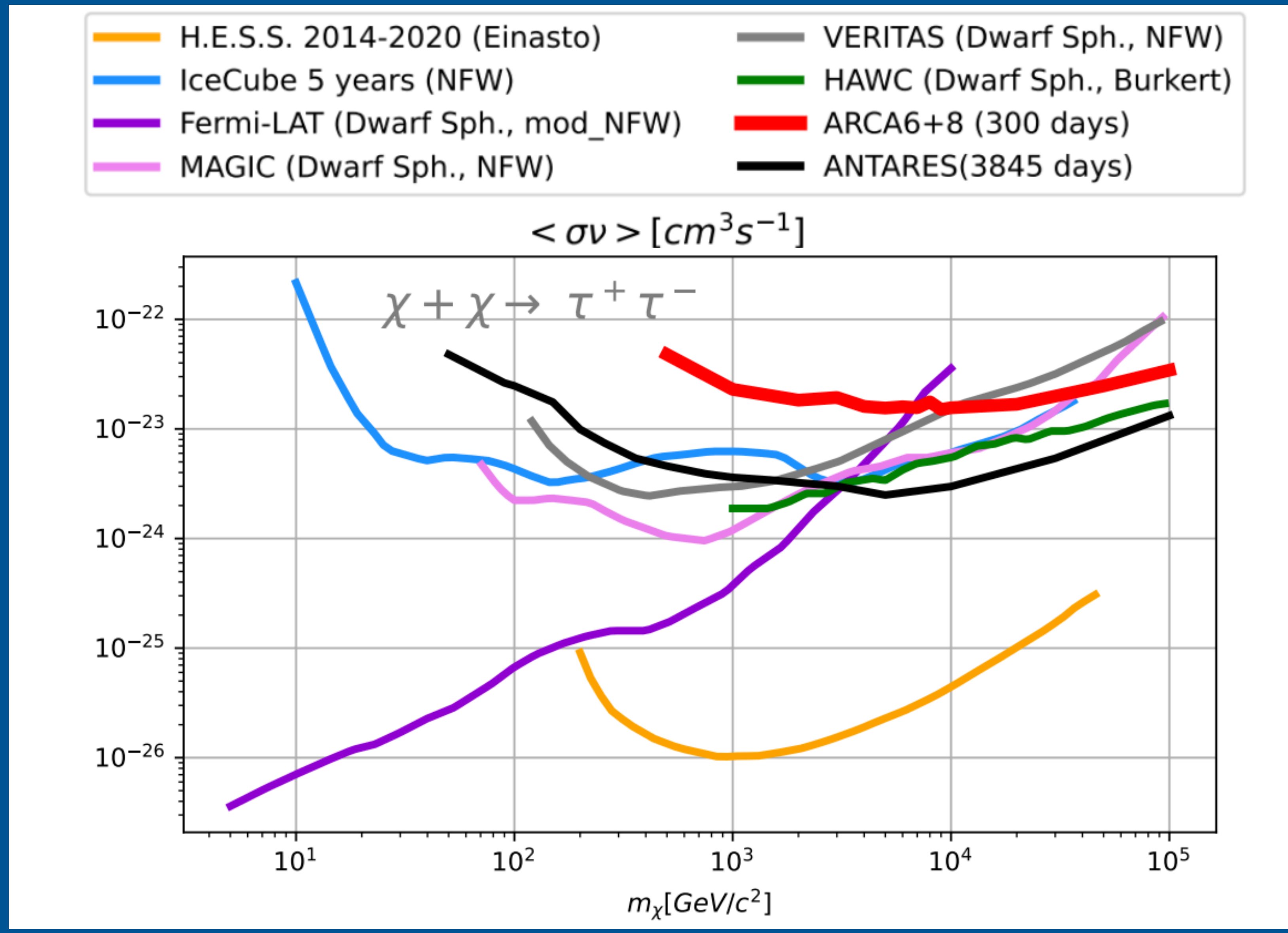
13 shower events observed -> (11.2±0.9 back. expected

DARK MATTER

From the Galactic Center

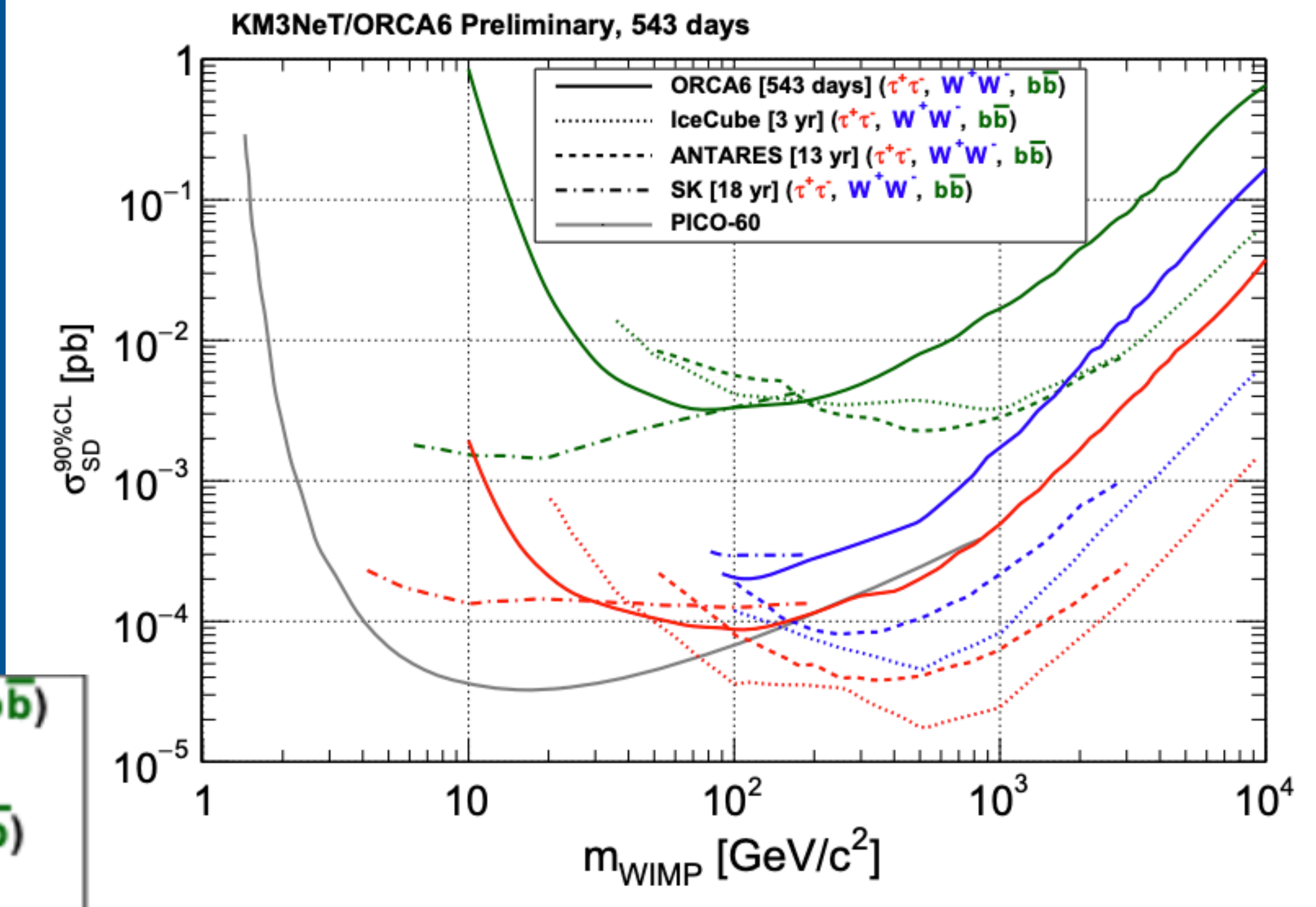
ARCA6 & ARCA8 analyzed ICRC2023 Pos 1377

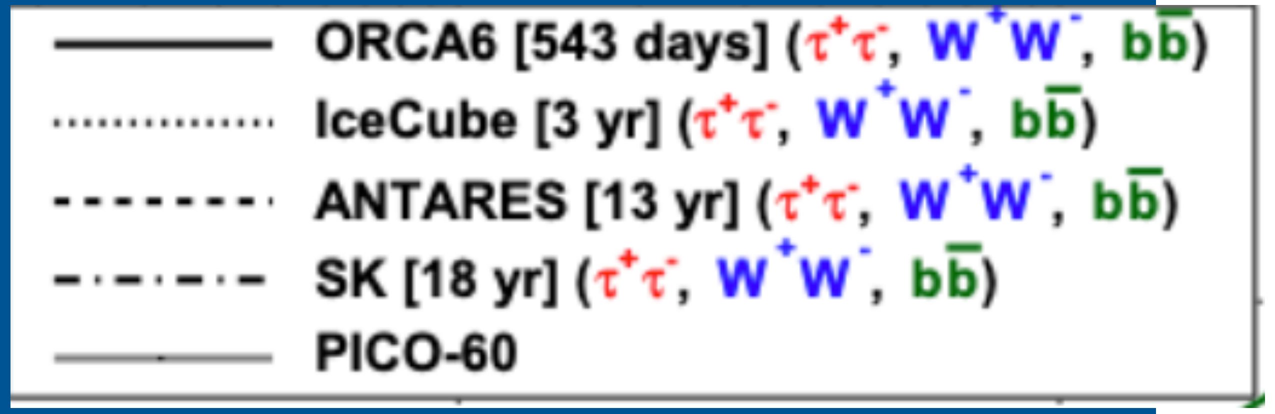




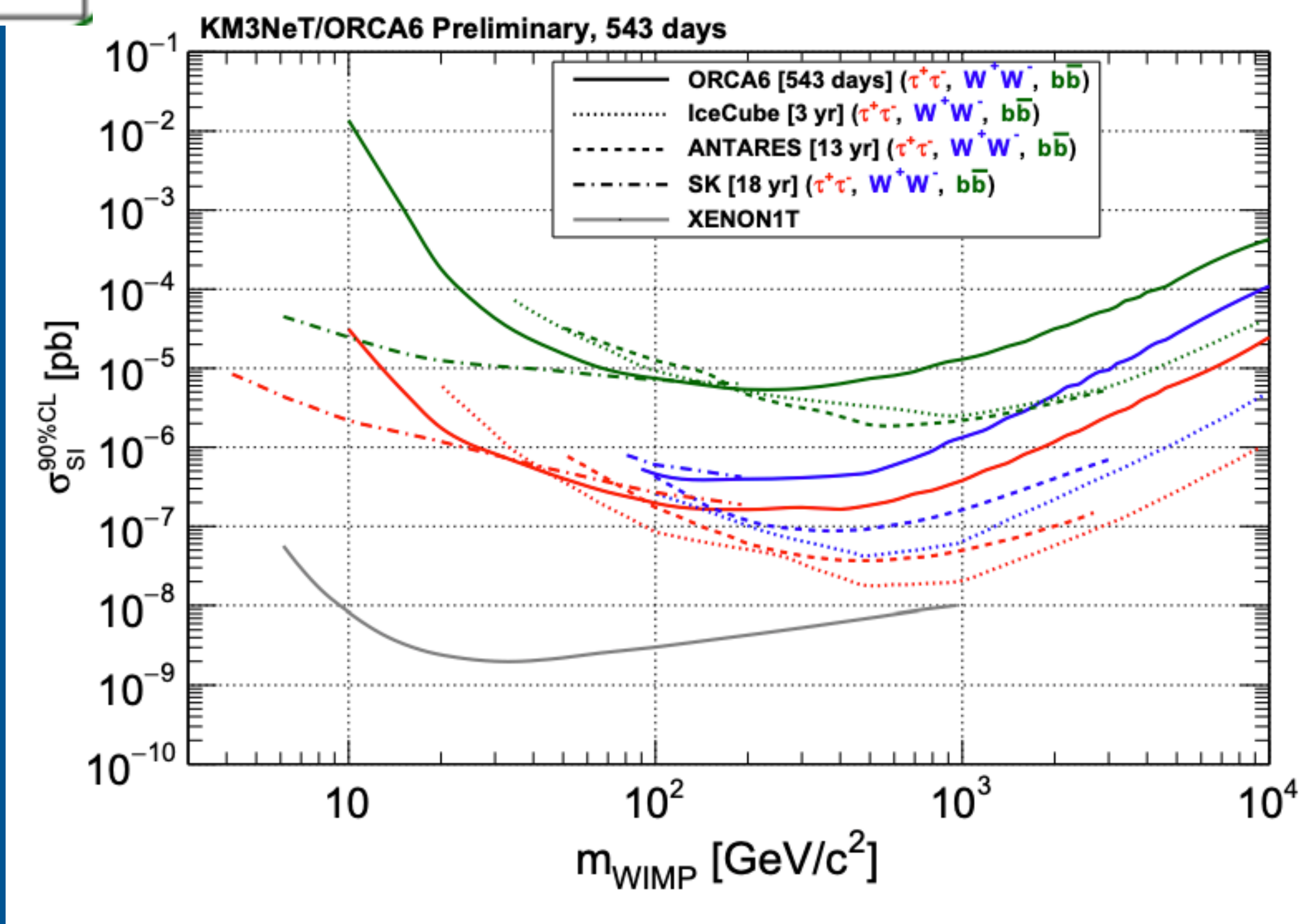
From the sun

ORCA6 analyzed ICRC2023 Pos 1406



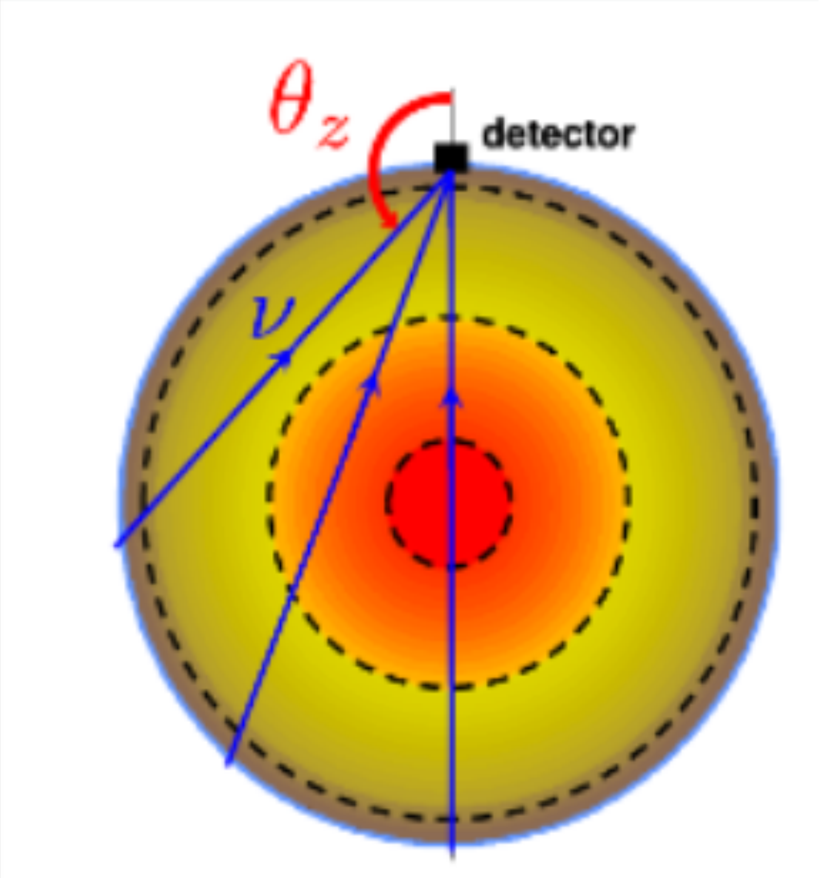


KM3NeT quickly reaching the ANTARES limits



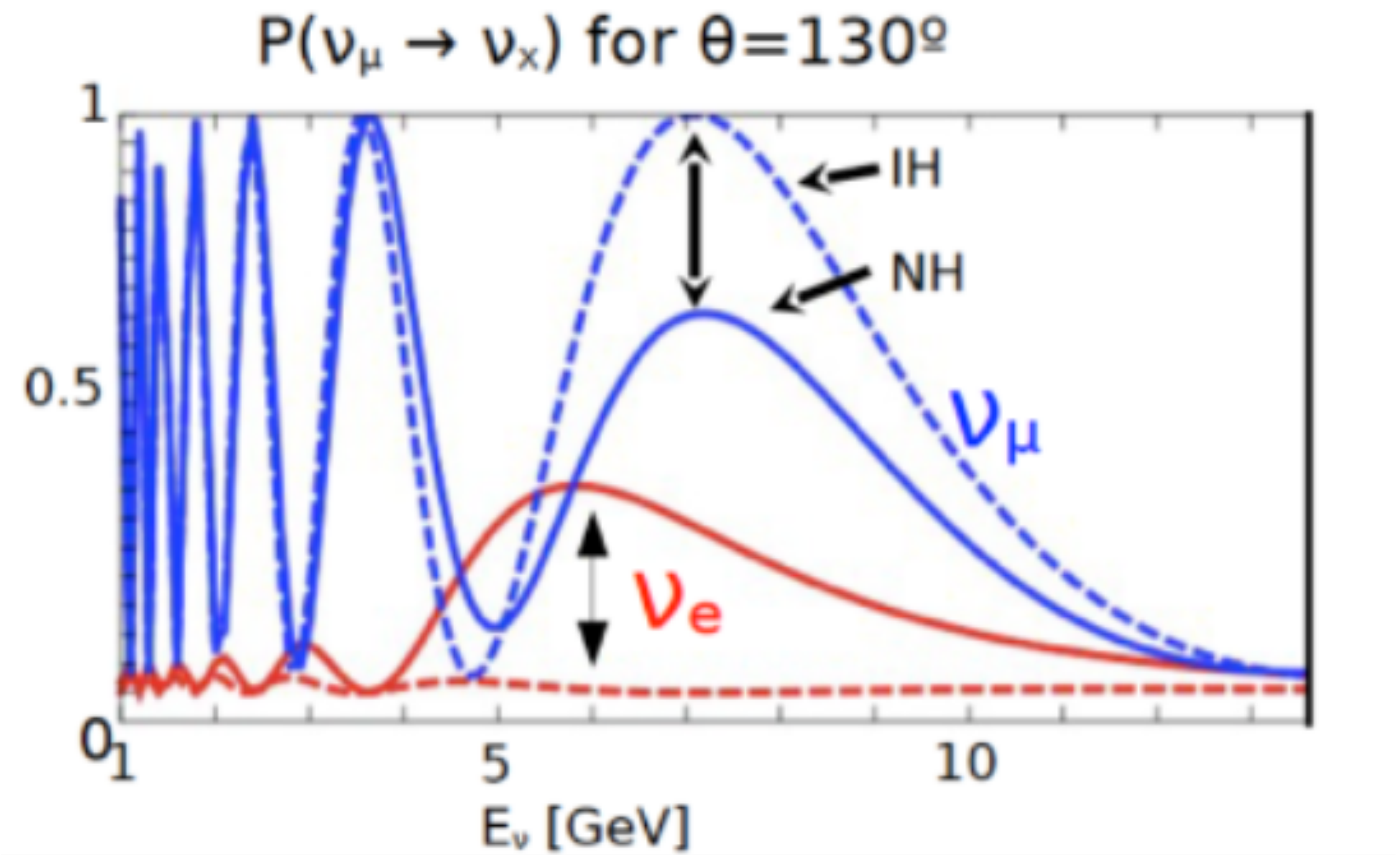
NEUTRINO OSCILLATION WITH KM3NET/ORCA

Baseline from 50 to 12800 km

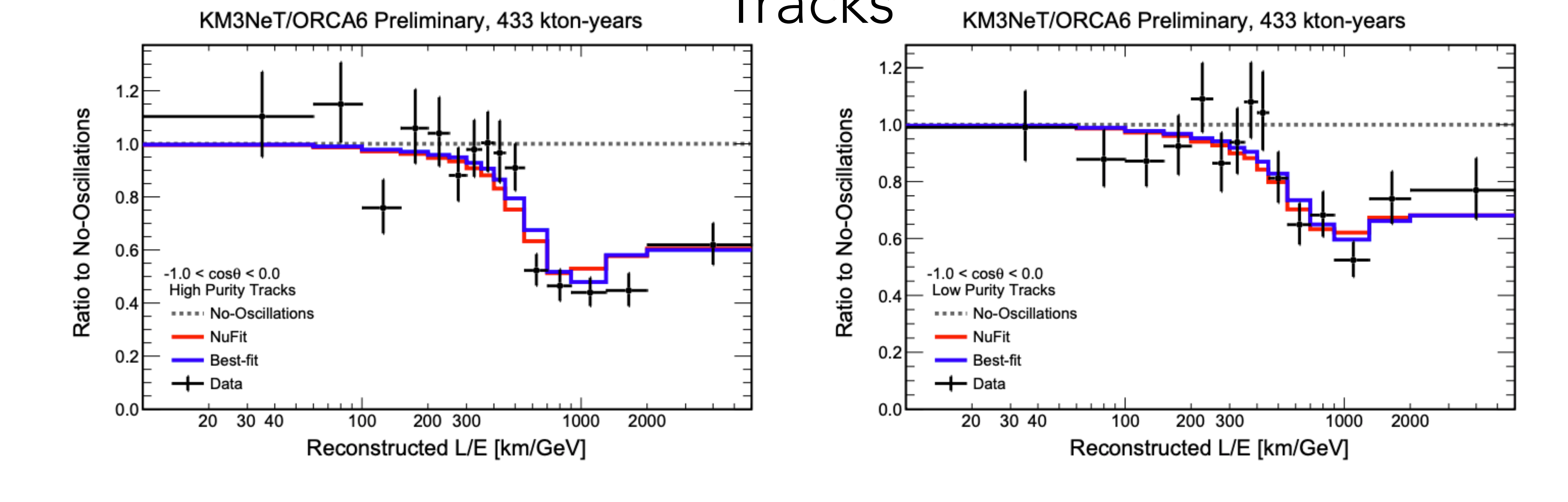


Neutrino Mass Ordering measuring atmospheric neutrinos crossing the Earth

Energy range of interest 5-15 MeV

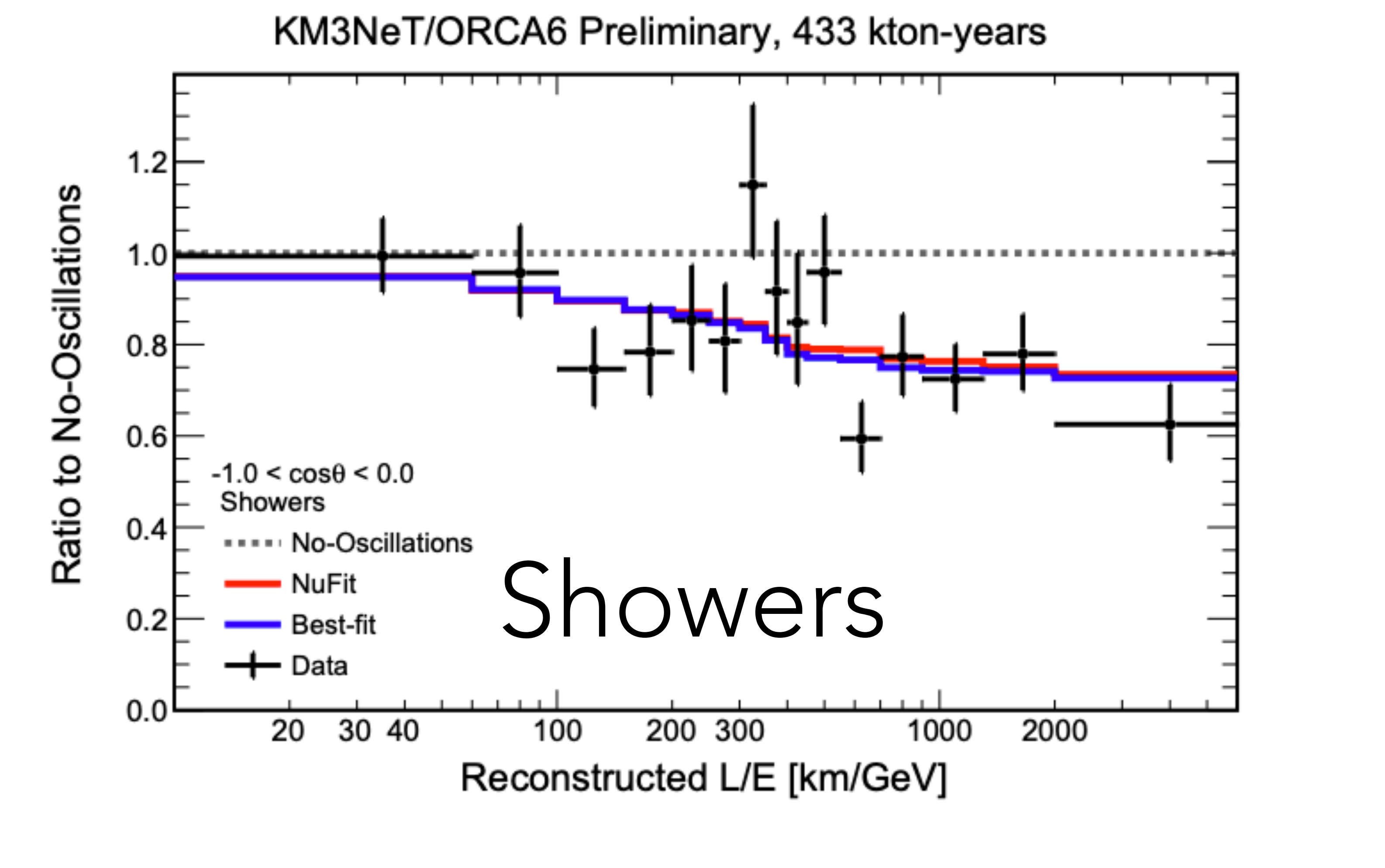


Tracks



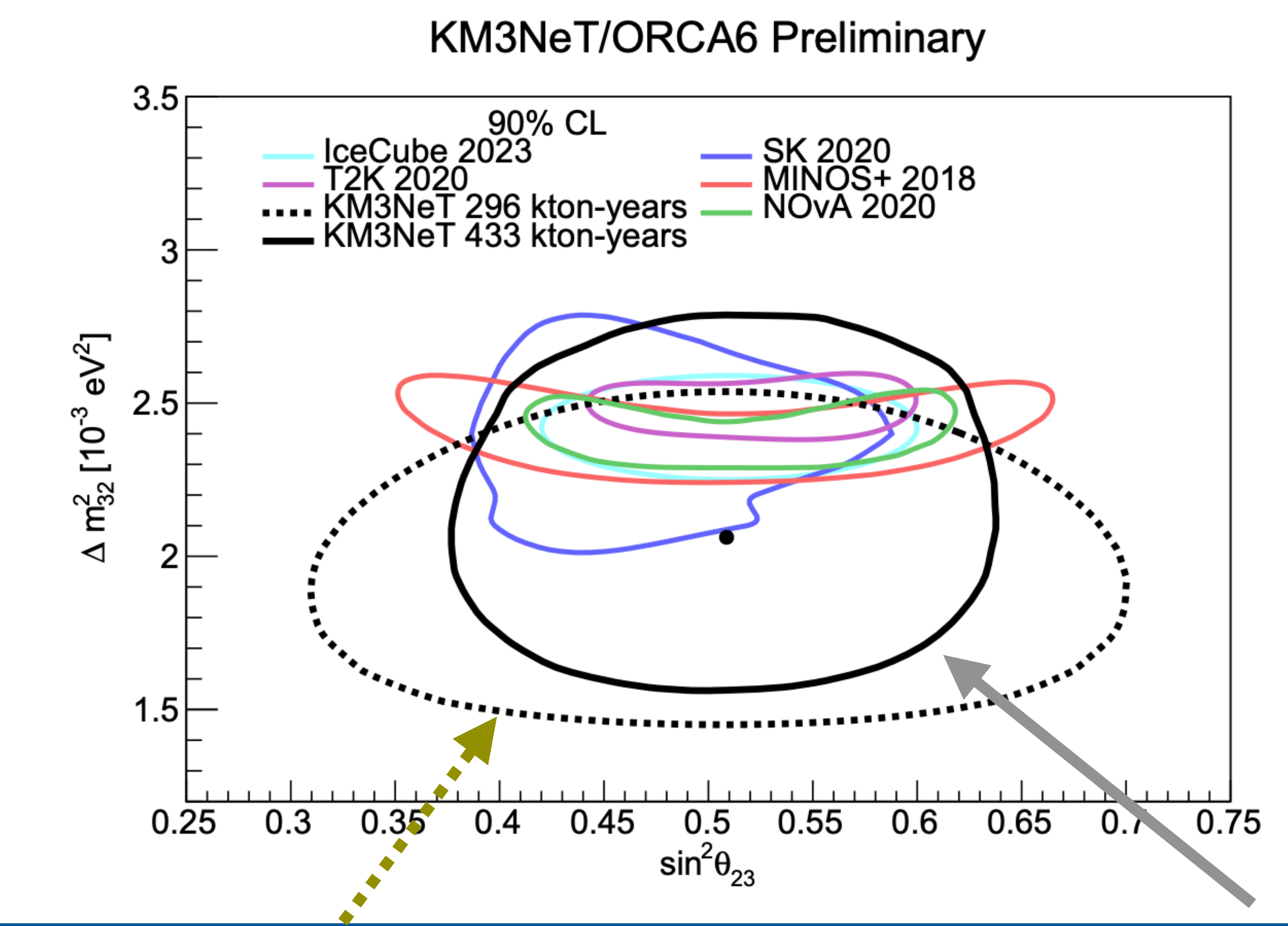
ORCA6 data

Oscillation clearly seen both in tracks and showers



NEUTRINO OSCILLATION WITH KM3NET/ORCA

• ICRC2023 Pos 996



ORCA6 DUs 354days

ORCA 6 DUs 510days

Increased event sample of a factor 5:

- Better selection track/shower 👉 ICRC2023 Pos 1191
- Added showers
- Livetime + 40%

Also competitive results in:

- Tau appearance 👉 ICRC2023 Pos 1107
- Non standard interactions 👉 ICRC2023 Pos 998
- Neutrino decay 👉 ICRC2023 Pos 997
- Lorents invariance violation 👉 ICRC2023 Pos 1086

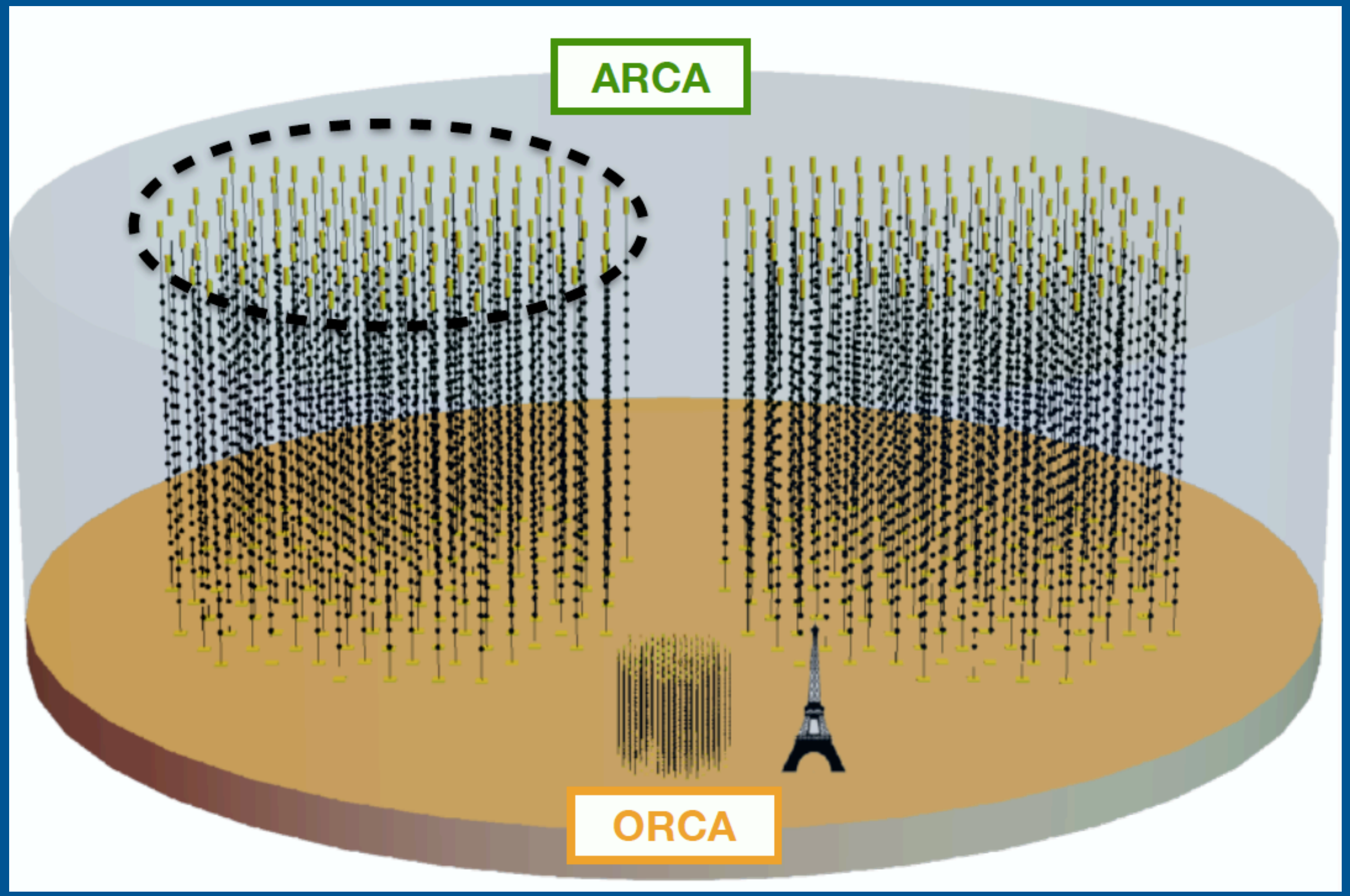
KM3NeT/ORCA competitive

MULTI-MESSENGER PROGRAM

A dedicated software is installed at the shore stations for Real-Time Analysis (RTA)

ICRC2023 Pos 1125
ICRC2023 Pos 1521

https://arxiv.org/abs/2309.05016



Sending alerts

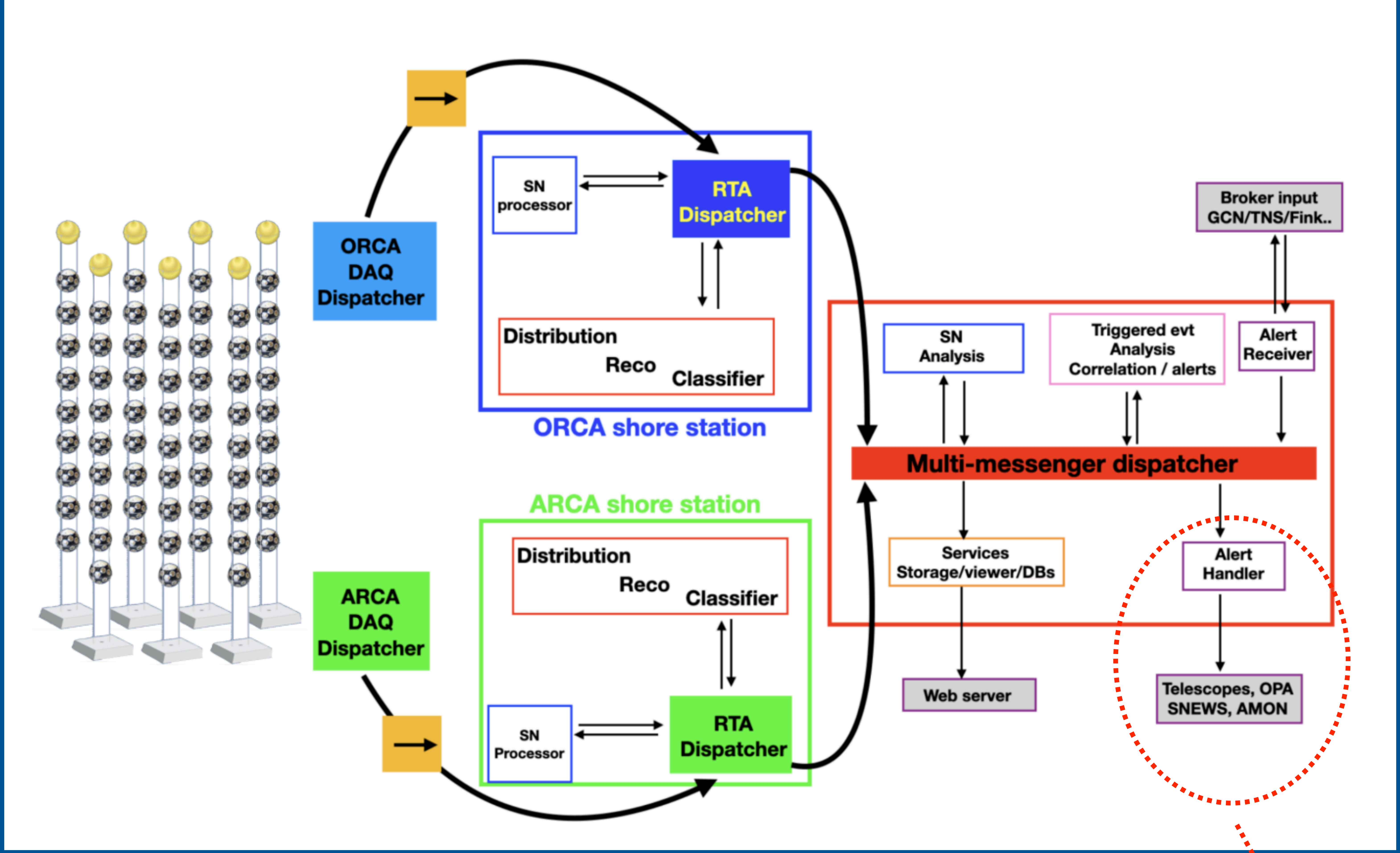
Send neutrino alert to external communities

Receiving alerts

Receive alert from external communities - on-line analysis and follows ups

RTA platform already active from November 2022 in ARCA and in ORCA detectors

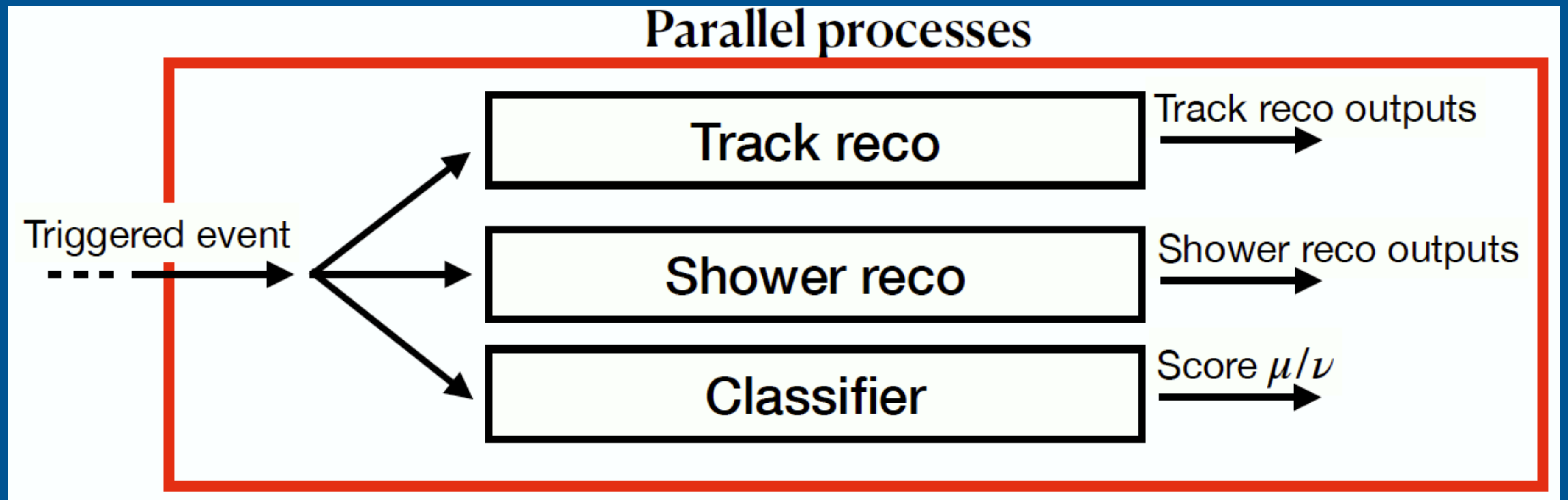
MULTI-MESSENGER: ONLINE SOFTWARE ARCHITECTURE

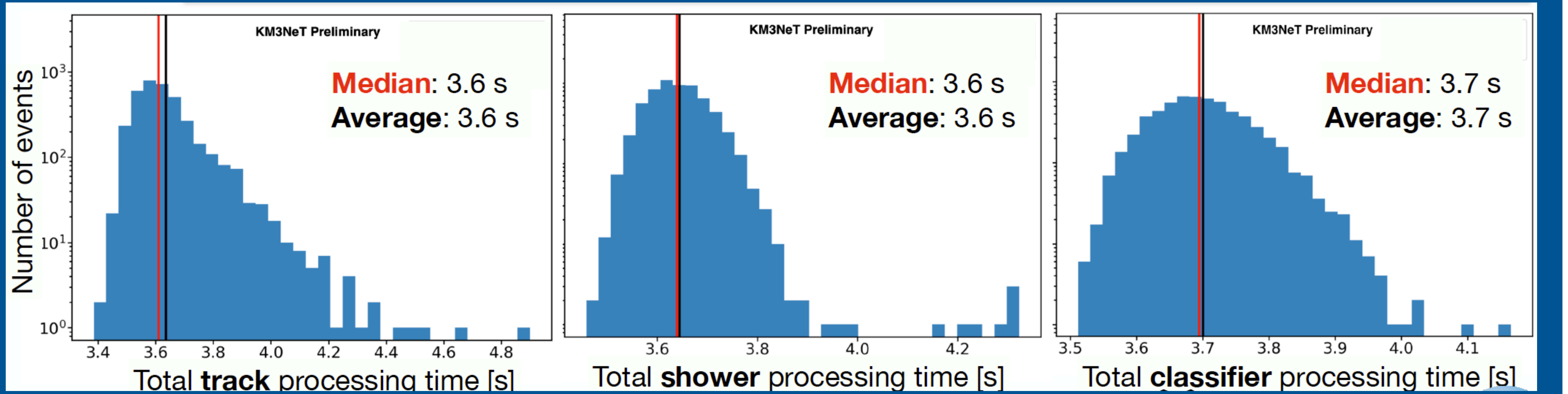


- Event processing done separately for ORCA and ARCA at each shore station
- Data from each detector are transferred to a common dispatcher (MM dispatcher), where analysis pipelines are also activated
- Events reconstructed in real-time (both as track and shower) and classified (μ/ν) via machine learning algorithms

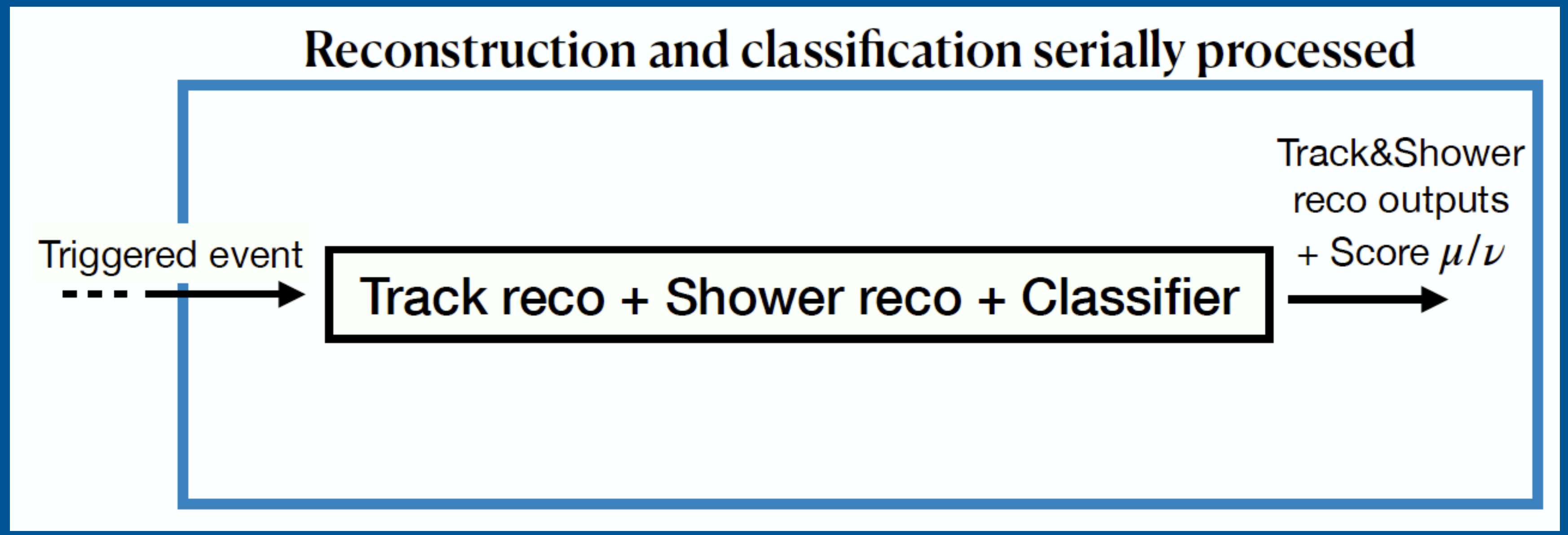
Not yet implemented
Work on-going

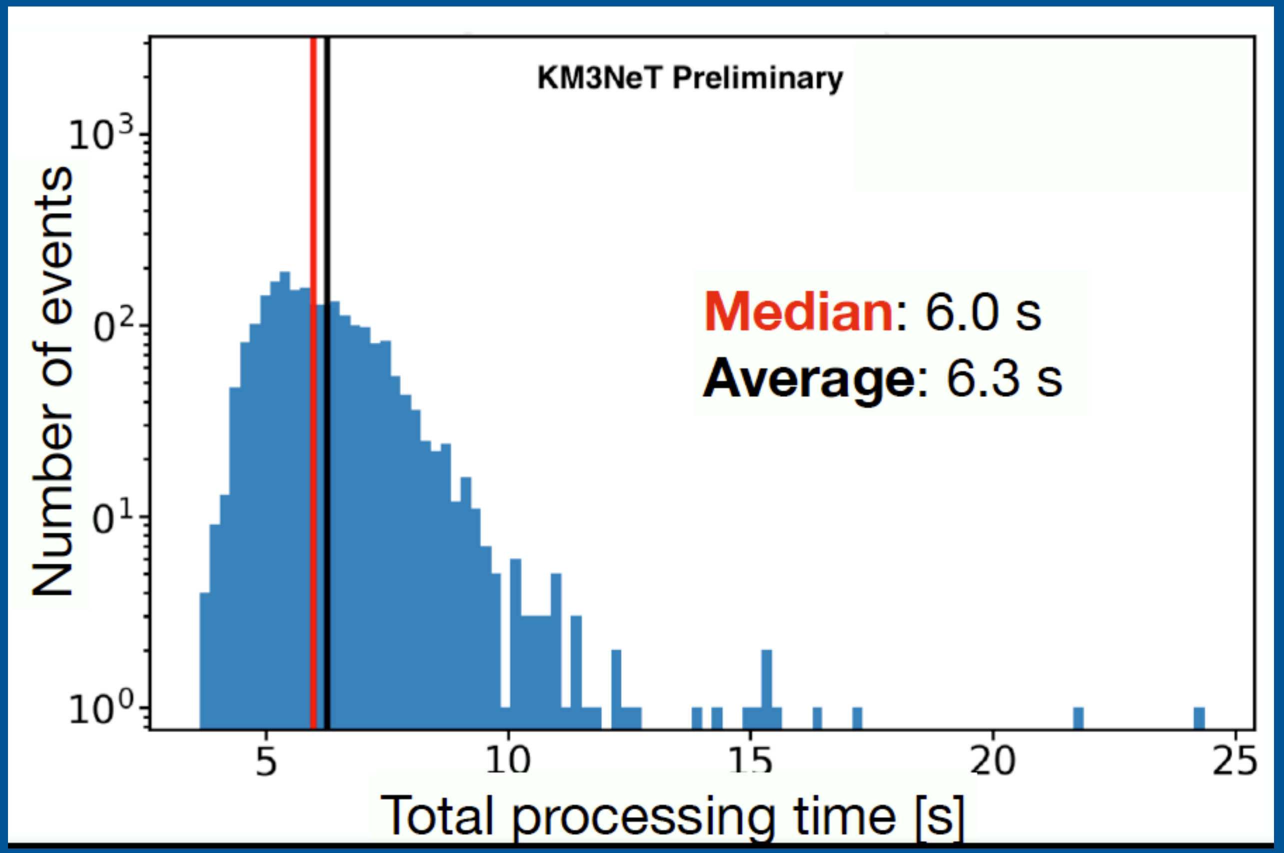
MULTI-MESSENGER: ONLINE PROCESSING TIME





On average ~4 seconds to reconstruct and classify ARCA events





On average ~6 seconds to reconstruct and classify ORCA events

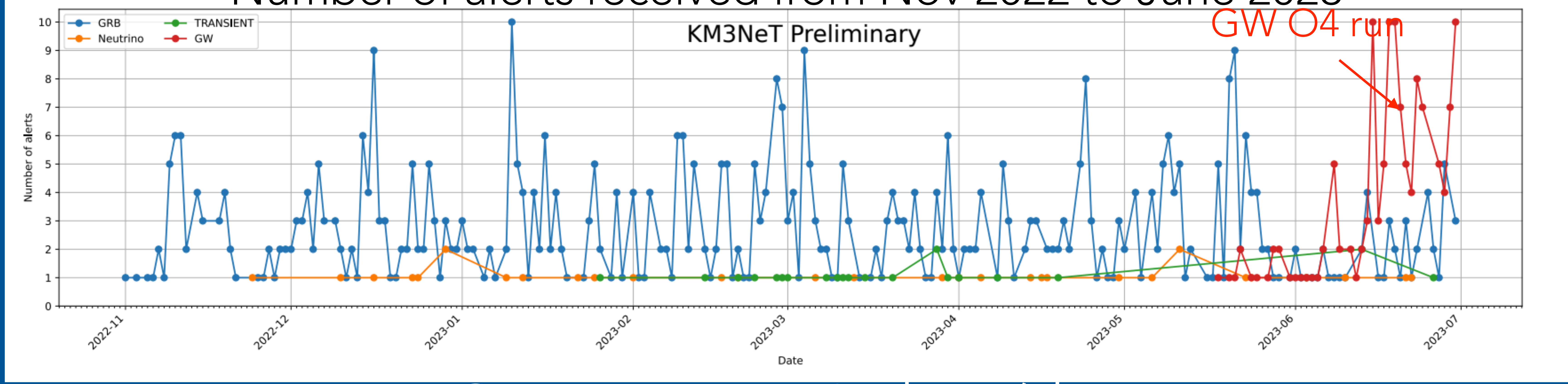
oS(ICRC2023)1125

MULTI-MESSENGER: REAL TIME FOLLOW UPS

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

Each received alert is tagged 👉GRBs, GW extended region, Neutrinos identified by IceCube, Transient events (e.g., flaring/variable objects).

Number of alerts received from Nov 2022 to June 2023



On average ~2 alert /day

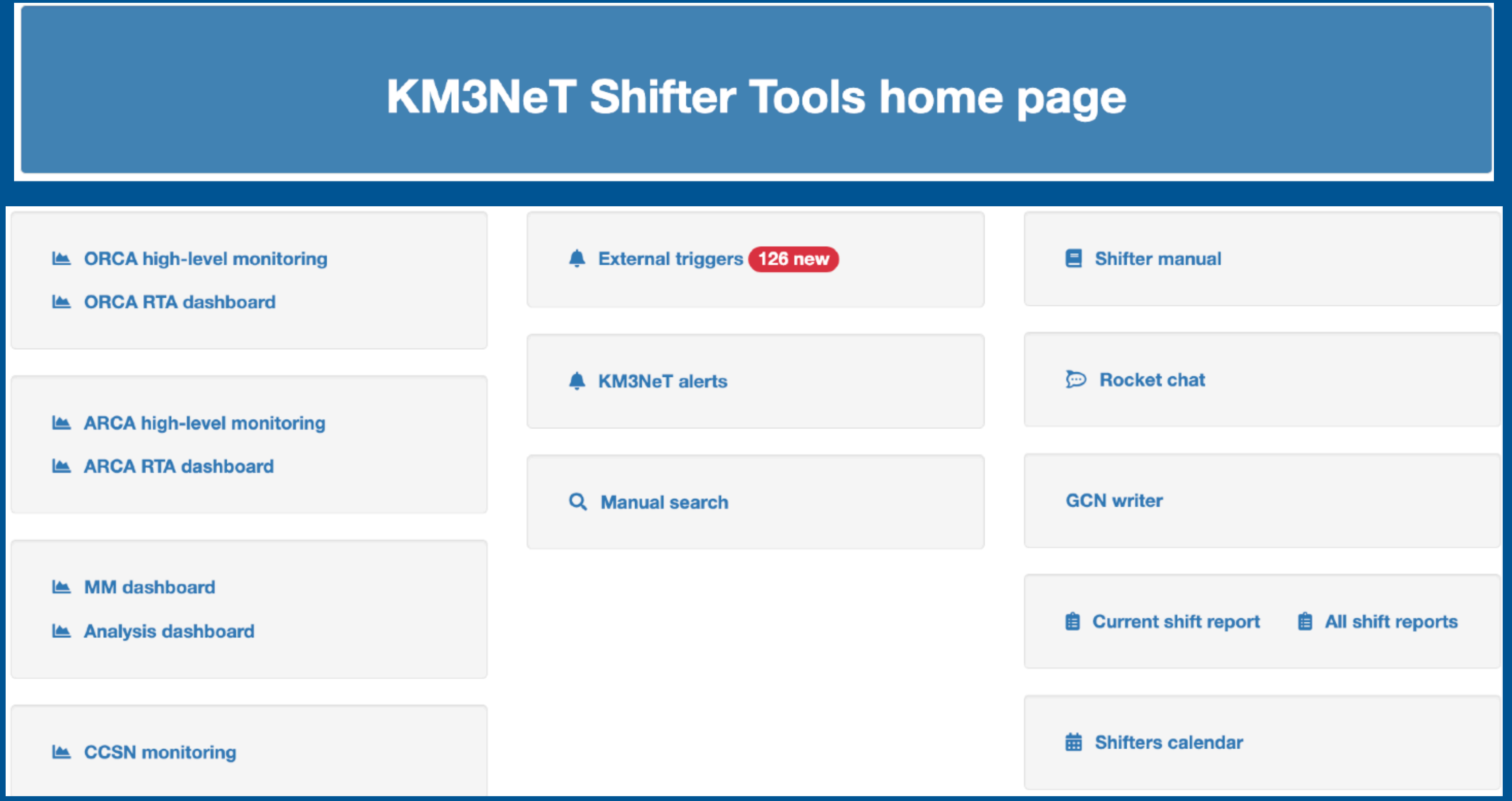
- External alerts trigger the RTA system 👉 only events satisfying the following criteria are selected:
  - temporal and spatial coincidences
  - visibility in KM3NeT for up-going tracks
  - reported false alarm rate

Only track events are considered (better angular resolution)
Inclusion of shower events on-going

No significant excess has been found so far

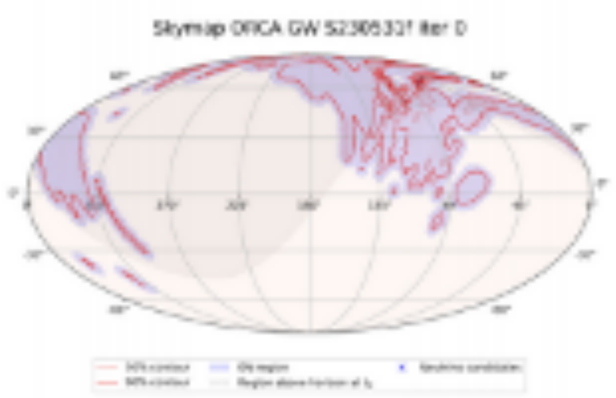
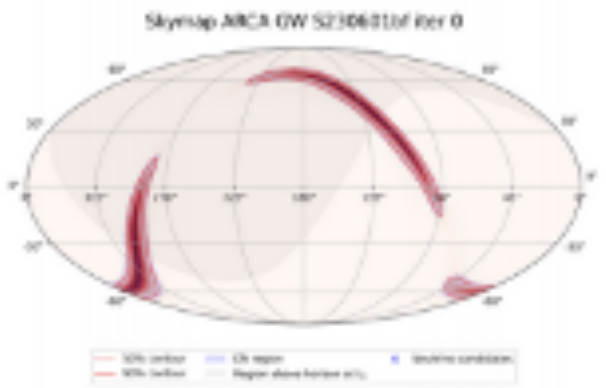
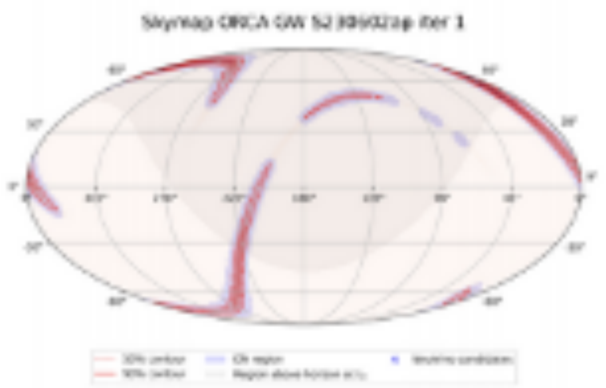
MULTI-MESSENGER: ON LINE SYSTEM

Online system set for shifters



new 709944284	GRB	2023-07-01 22:44:39	Selected	115.74	43.02	GCN_n	Details	Analysis
new 709864601	GRB	2023-07-01 00:36:36	Selected	254.8	72.91	GCN_n	Details	Analysis
S230630bq	GW	2023-06-30 23:45:32	Selected	-	-	GCN_n Link	Details	Analysis
new S230630am	GW	2023-06-30 12:58:06	Selected	-	-	GCN_n Link	Details	Analysis
new S230628ax	GW	2023-06-28 23:12:00	Selected	-	-	GCN_n Link	Details	Analysis
new 1177054	GRB	2023-06-28 22:29:56	Selected	171.8486	-11.464	GCN_n	Details	Analysis
new 709676556	GRB	2023-06-28 20:22:31	Selected	175.02	12.29	GCN_n	Details	Analysis
new 709666599	GRB	2023-06-28 17:36:34	Selected	300.97	35.6	GCN_n	Details	Analysis
new 709623341	GRB	2023-06-28 05:35:36	Selected	131.19	-12.54	GCN_n	Details	Analysis
new 709608965	GRB	2023-06-28 01:36:00	Selected	351.77	-43.8499	GCN_n	Details	Analysis
new S230627c	GW	2023-06-27 01:53:37	Selected	-	-	GCN_n Link	Details	Analysis
new 709482627	GRB	2023-06-26 14:30:22	Selected	146.38	0.09	GCN_n	Details	Analysis
new 709410255	GRB	2023-06-25 18:24:10	Selected	321.2	-18.66	GCN_n	Details	Analysis
new S230624ax	GW	2023-06-24 12:14:46	Selected	-	-	GCN_n Link	Details	Analysis
new S230624av	GW	2023-06-24 11:31:03	Selected	-	-	GCN_n Link	Details	Analysis

Examples of GW follow ups

Alert	Analysis	Results	Plot
S230531f Burst FAR=1/13.6d	MeV [0, 2s]	z-score=0.56	
	ORCA ±500 s	N_{ON}=0, N_{BKG}=4.23e-3	
	ARCA ±500 s	N_{ON}=0, N_{BKG}=2.78e-3	
	ORCA [-500s, +6h]	N_{ON}=0, N_{BKG}=9.22e-2	
	ARCA [-500s, +6h]	N_{ON}=0, N_{BKG}=6.11e-2	
S230601bf BBH (>99%) FAR=1.7e-15 Hz	MeV [0, 2s]	z-score=1.47	
	ORCA ±500 s	N_{ON}=0, N_{BKG}=2.38e-3	
	ARCA ±500 s	N_{ON}=0, N_{BKG}=2.51e-3	
	ORCA [-500s, +6h]	N_{ON}=0, N_{BKG}=3.51e-2	
	ARCA [-500s, +6h]	N_{ON}=0, N_{BKG}=2.22e-2	
S230602ap Burst FAR=1.48e-6 Hz	MeV [0, 2s]	z-score=0.49	
	ORCA ±500 s	N_{ON}=0, N_{BKG}=2.33e-3	
	ARCA ±500 s	N_{ON}=0, N_{BKG}=2.48e-3	
	ORCA [-500s, +6h]	N_{ON}=0, N_{BKG}=3.43e-2	
	ARCA [-500s, +6h]	N_{ON}=0, N_{BKG}=1.82e-2	

More than 100 GW alerts have been followed up so far

On-line system for the detection of SN explosions also in place

MULTI-MESSENGER: GRB221009A FOLLOW UPS

oS(ICRC2023)1125

ICRC2023 Pos 1503 https://arxiv.org/abs/2309.05016

GRB 221009A

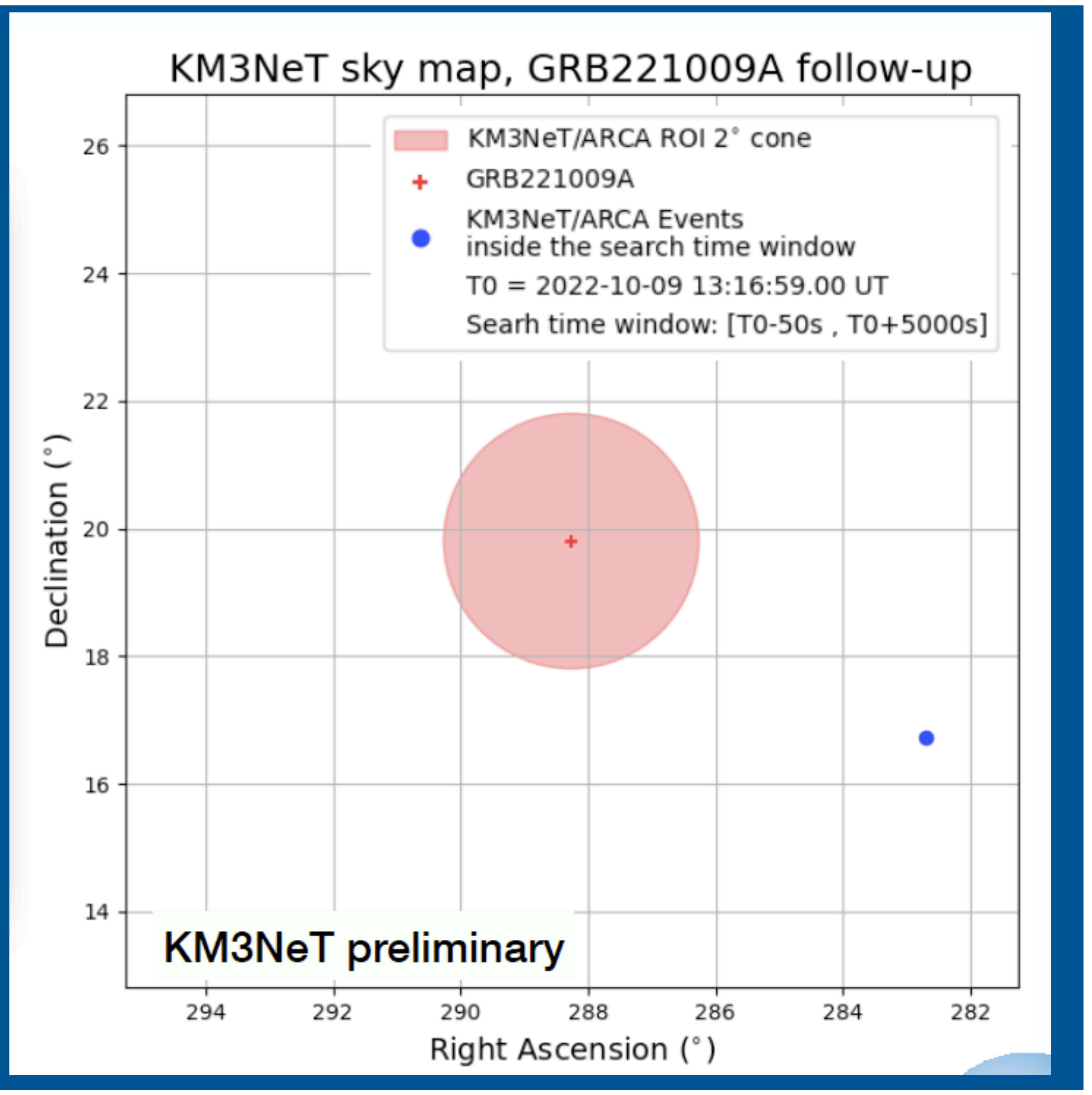
On 9 October 2022 the brightest long GRB ever detected was observed relatively close to us ($z \sim 0.15$) at RA=288.263° and DEC= +19.803°

- the most energetic GRB photon ever seen by Fermi LAT (99GeV) 👉 ATel #15656
- LHAASO 2000 sec after the GRB trigger detected photons up to 18 TeV 👉 GCN #32677
- Observations also at different wavelength 👉 MAXI/GSC, INTEGRAL SPI/ACS or HAWC ,….
- IceCube did not detect neutrinos (search in -1 hour/+2 hours) 👉 GCN #32665

KM3NeT and GRB 221009A

GRB 221009A was in the downgoing sky of the KM3NeT (ARCA21 and ORCA10) detectors at the time of the event

- Online follow up done by KM3NeT [T0-50s, T0+5000s] (GCN #32741) 👉 NO event found
- More refined offline follow up done during the [T0-50s, T0+5000s] and T0 ± 1 day 👉 NO event found 👉 upper limits have been set



SUMMARY

KM3NeT under construction 👉 present status: ARCA 28 DUs and ORCA 18DUs

First results presented at ICRC2023 👉 more than 40 contributions (https://arxiv.org/abs/2309.05016)
KM3NeT upper limits are quickly reaching the ANTARES limits

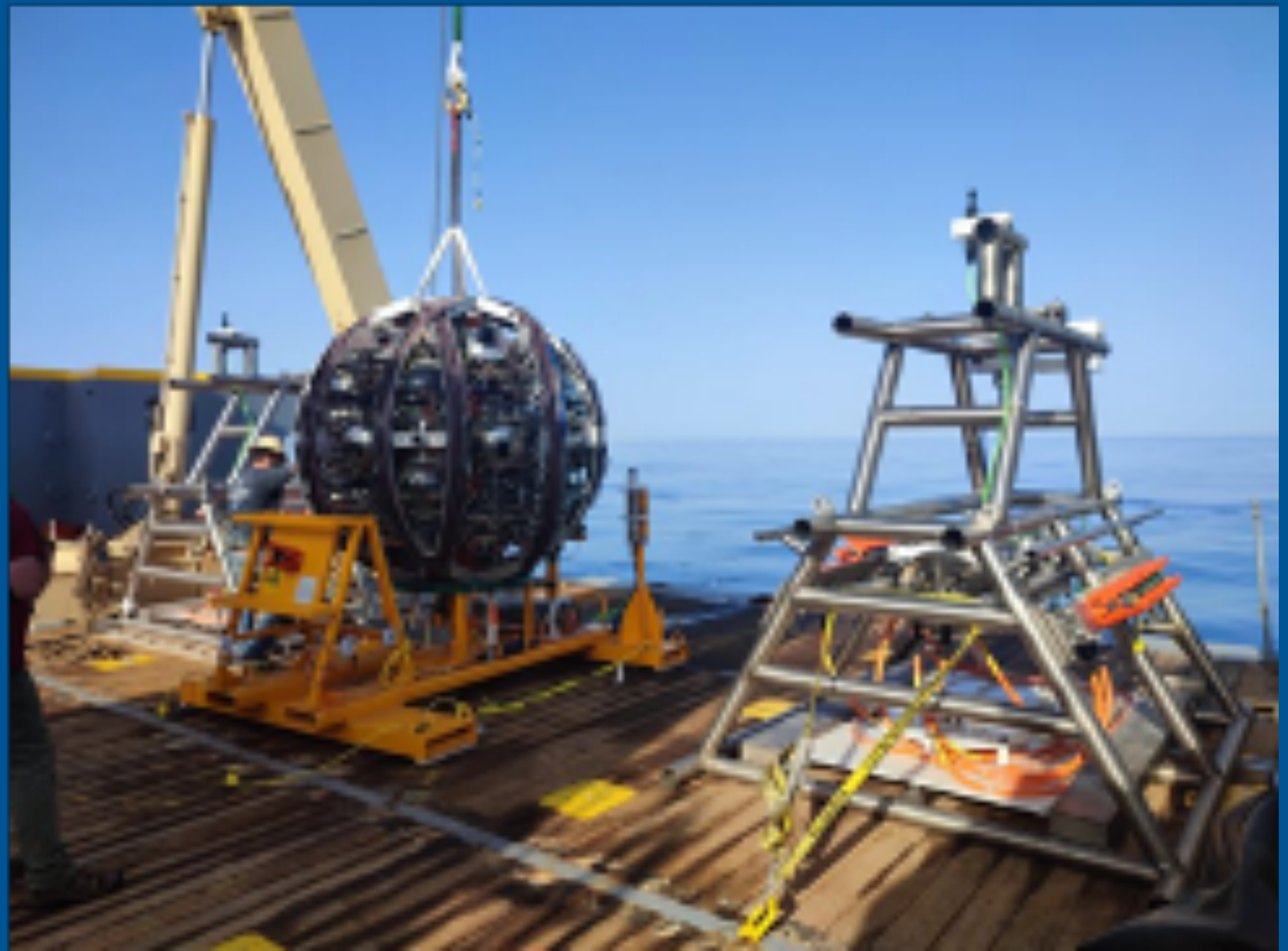
Online multi-messenger analysis framework for KM3NeT in progress and already operative 👉
Online analyses in place to look for temporal and spatial coincidences among the KM3NeT reconstructed events and GRBs, GW extended regions, neutrinos identified by IceCube, transient events

More than 300 online analyses performed so far (mainly after GRB external triggers); no significant excess has been found

SPARE

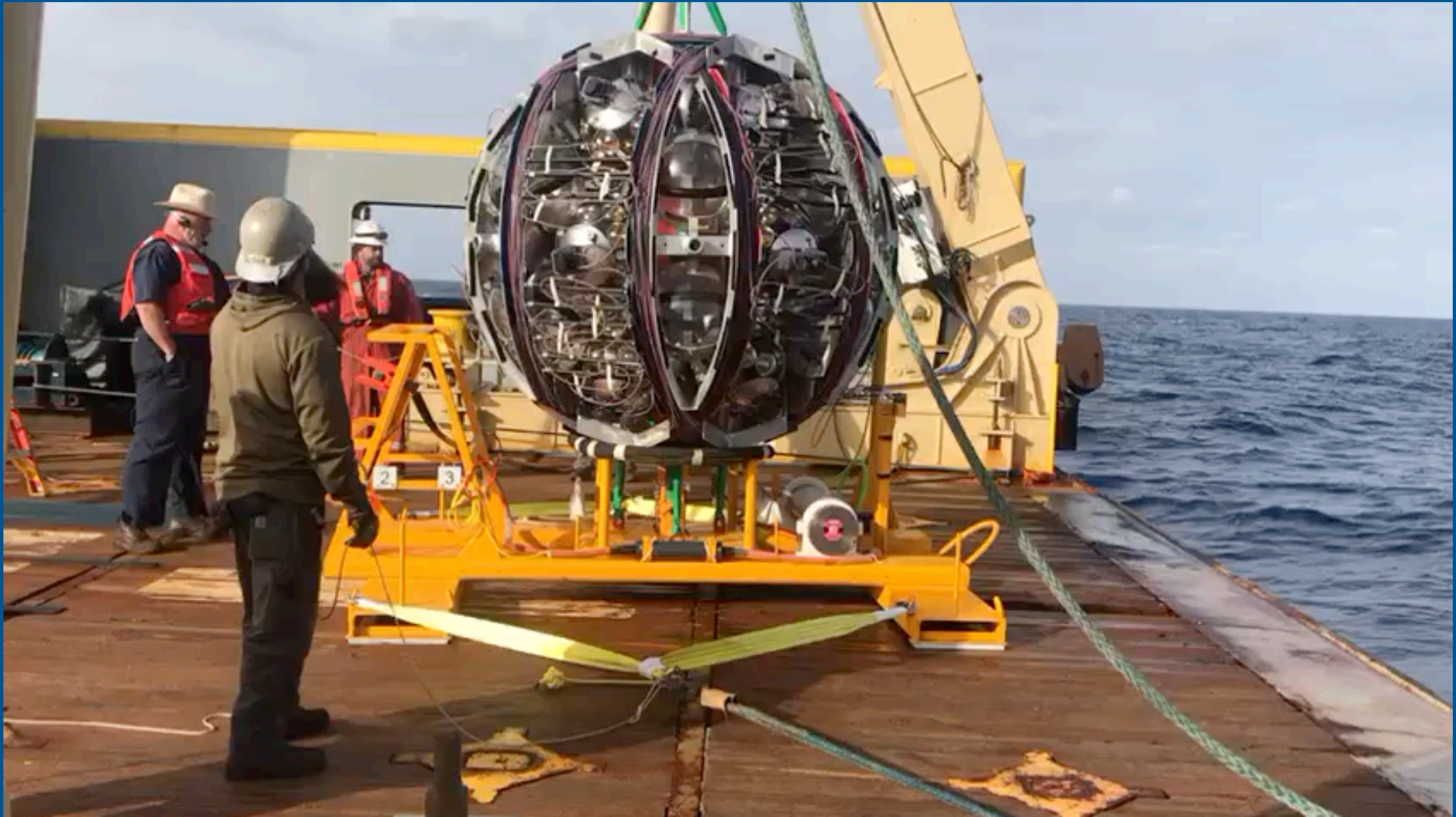
DU DEPLOYMENT

June 2022 sea campign:
11 DUs and 2 JBs + recovery of TJB

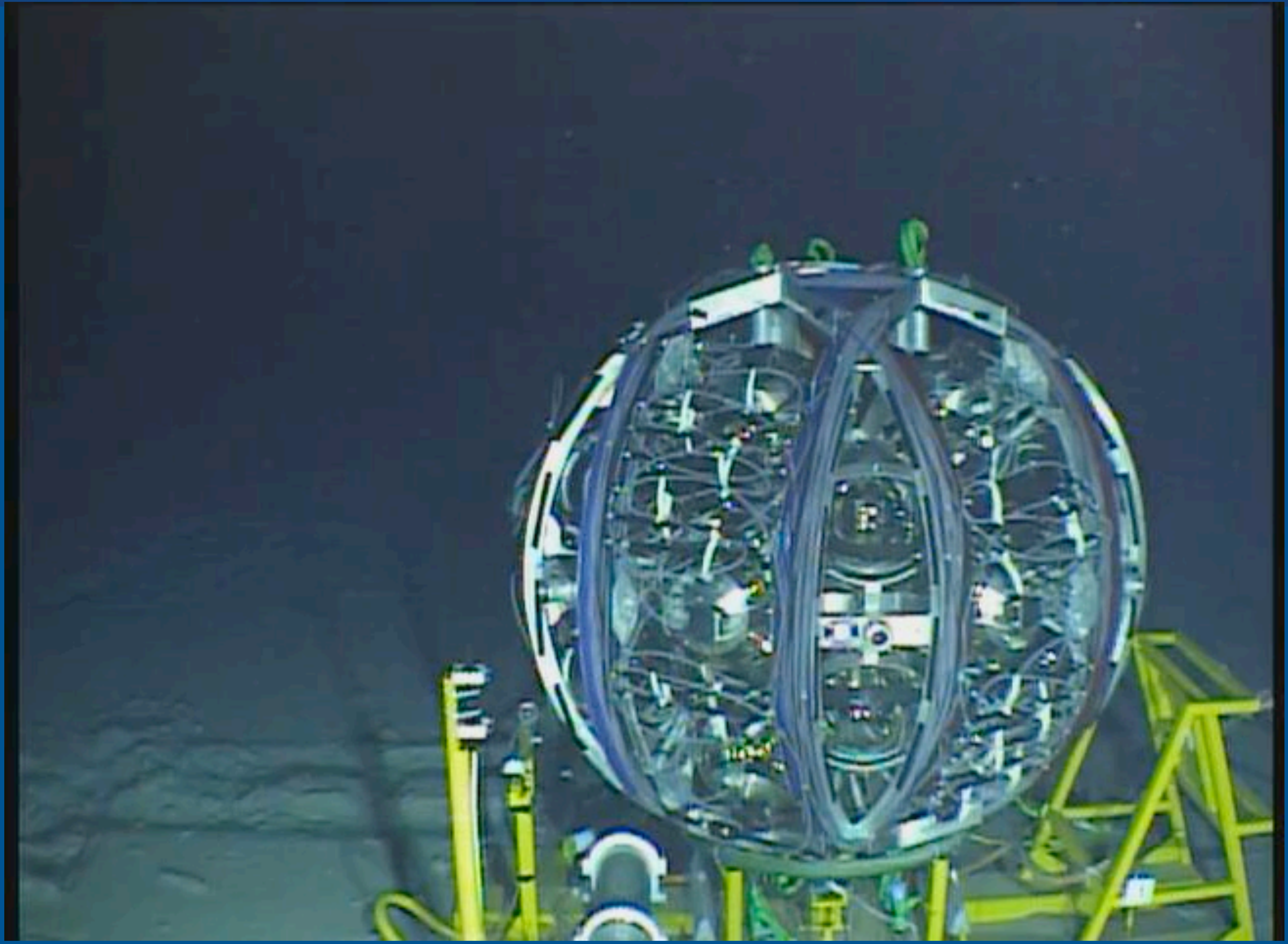


MOVIE: DU DEPLOYMENT

Deployment DU



MOVIE: THE UNROLLING



MOVIE: LOM AT SEA SURFACE

THE INTEGRATION

DOM integration

Base Module integration

THE INTEGRATION

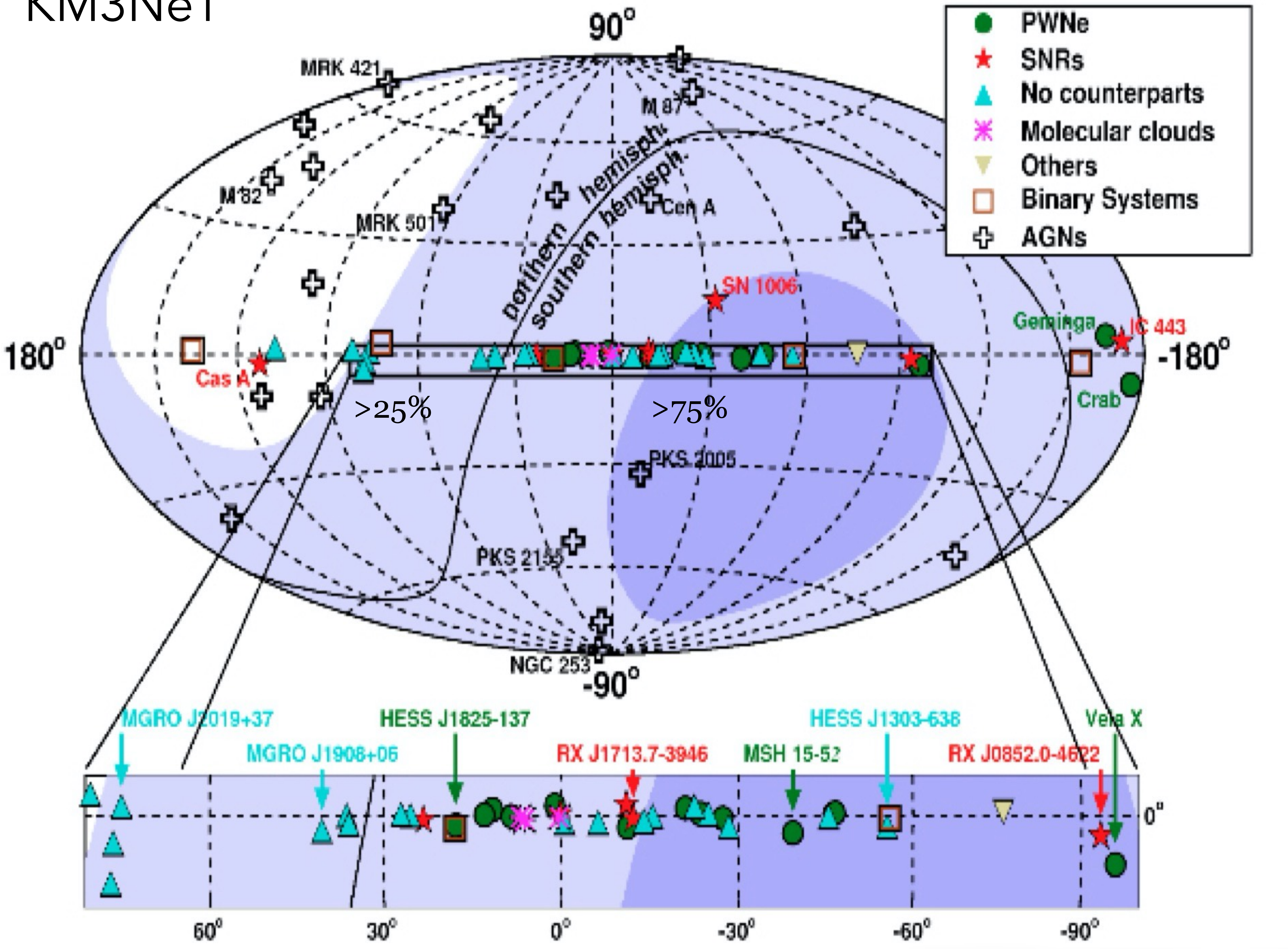
[redacted]

WHY TWO LARGE DETECTORS

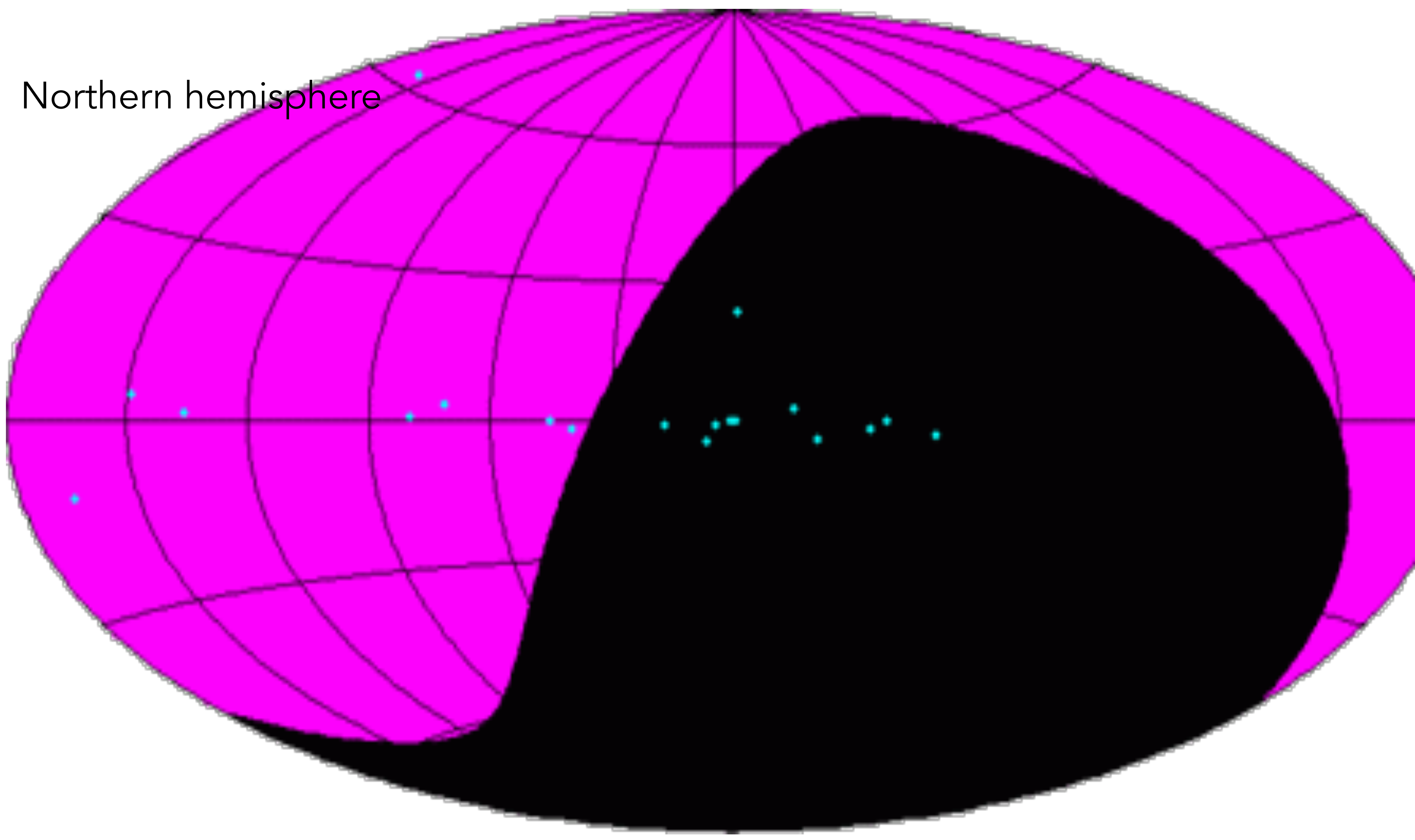
Visibility for up-going tracks

Galactic coordinates

KM3NeT



IceCube



Complementary detectors

EVENT TYPE AND ANGULAR RESOLUTION

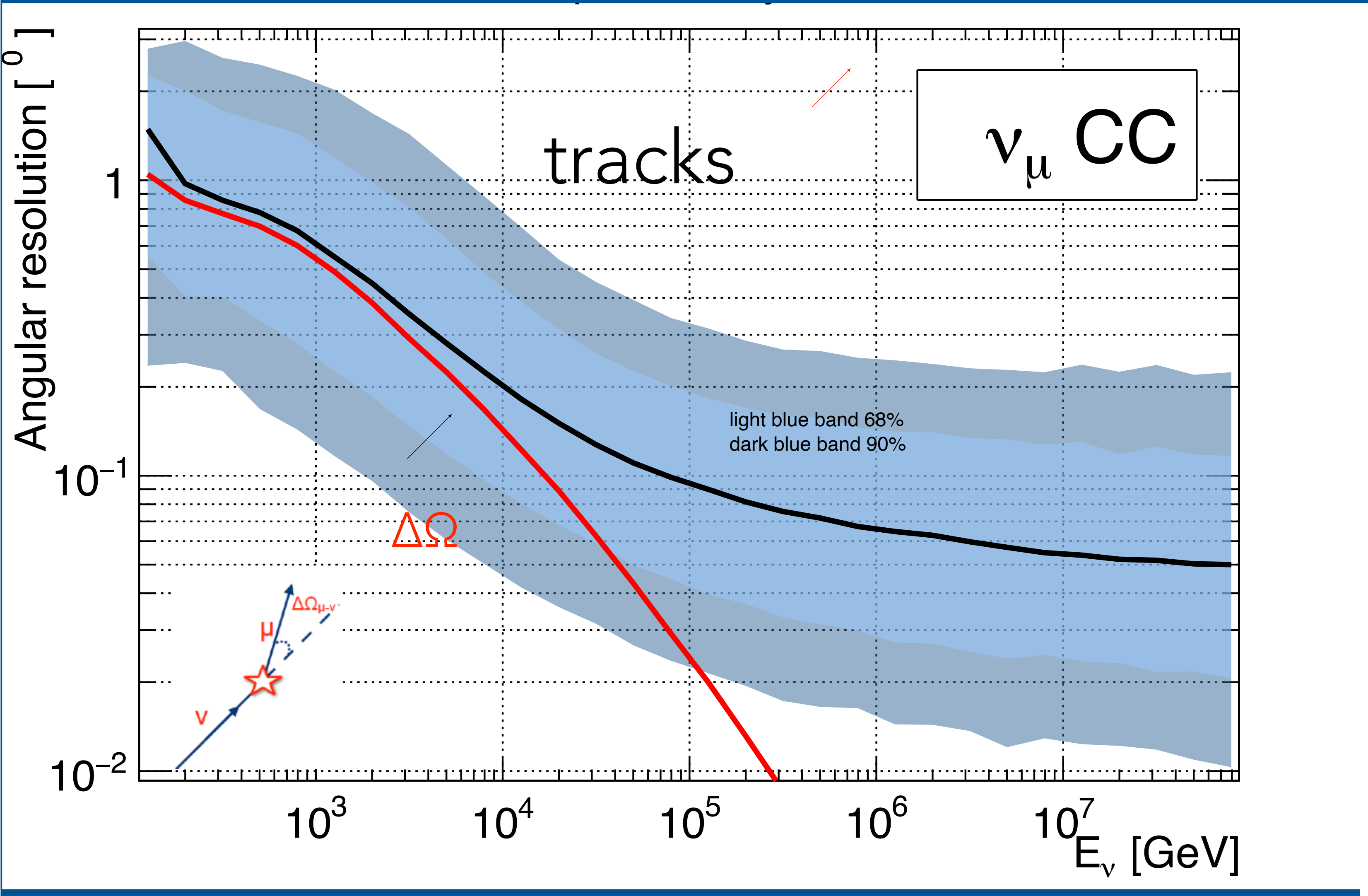
	TRACK*	CASCADE*
ANTARES	0.3°	3°
KM3NET	0.1°	1.5°
ICECUBE	0.3°	7°-8°
BAIKAL -GVD	0.25°	3° - 3.5°

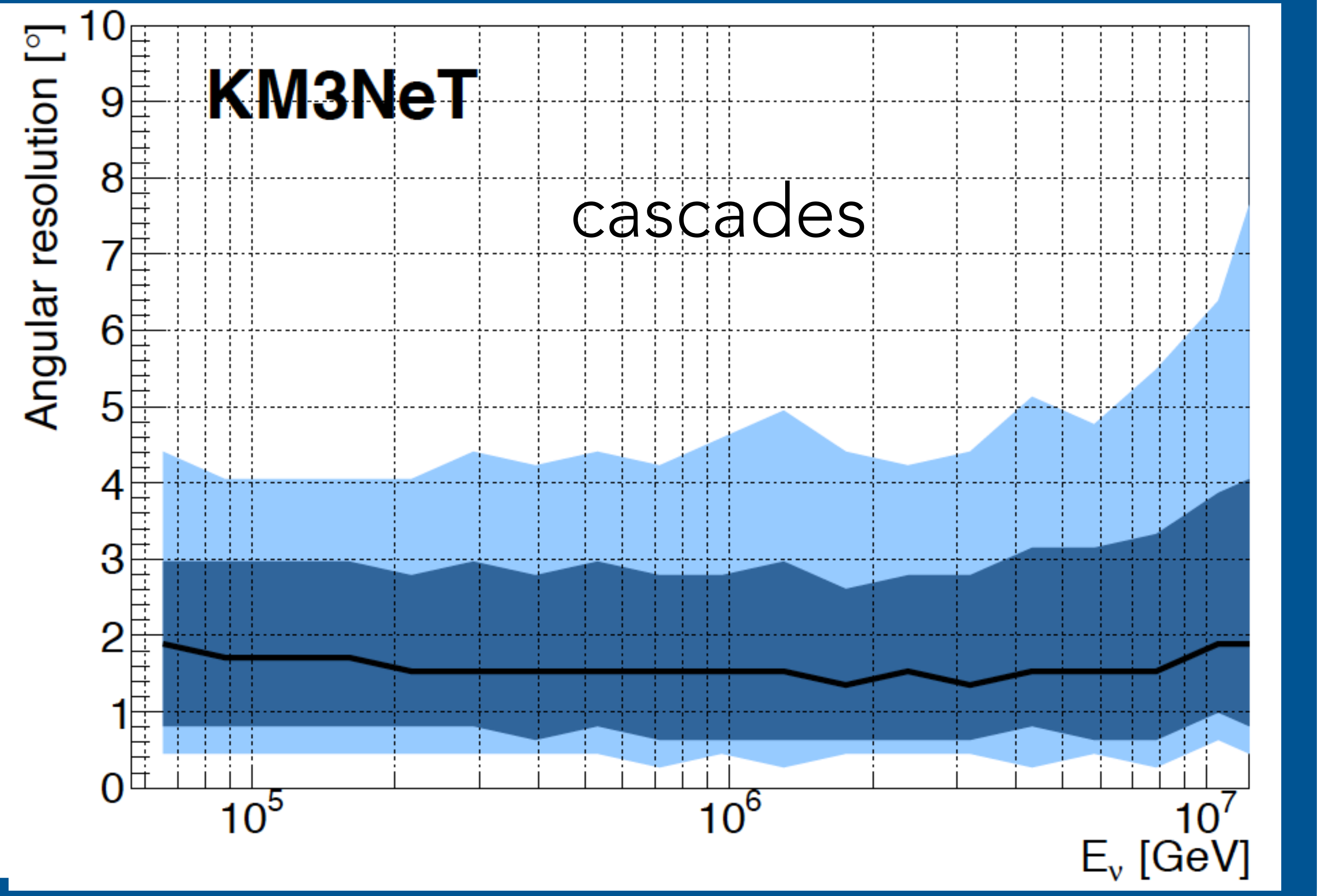
*Resolution at 100 TeV

Tracks: very long path (Eμ>1TeV several km)
Big lever arm
- Good angular resolution

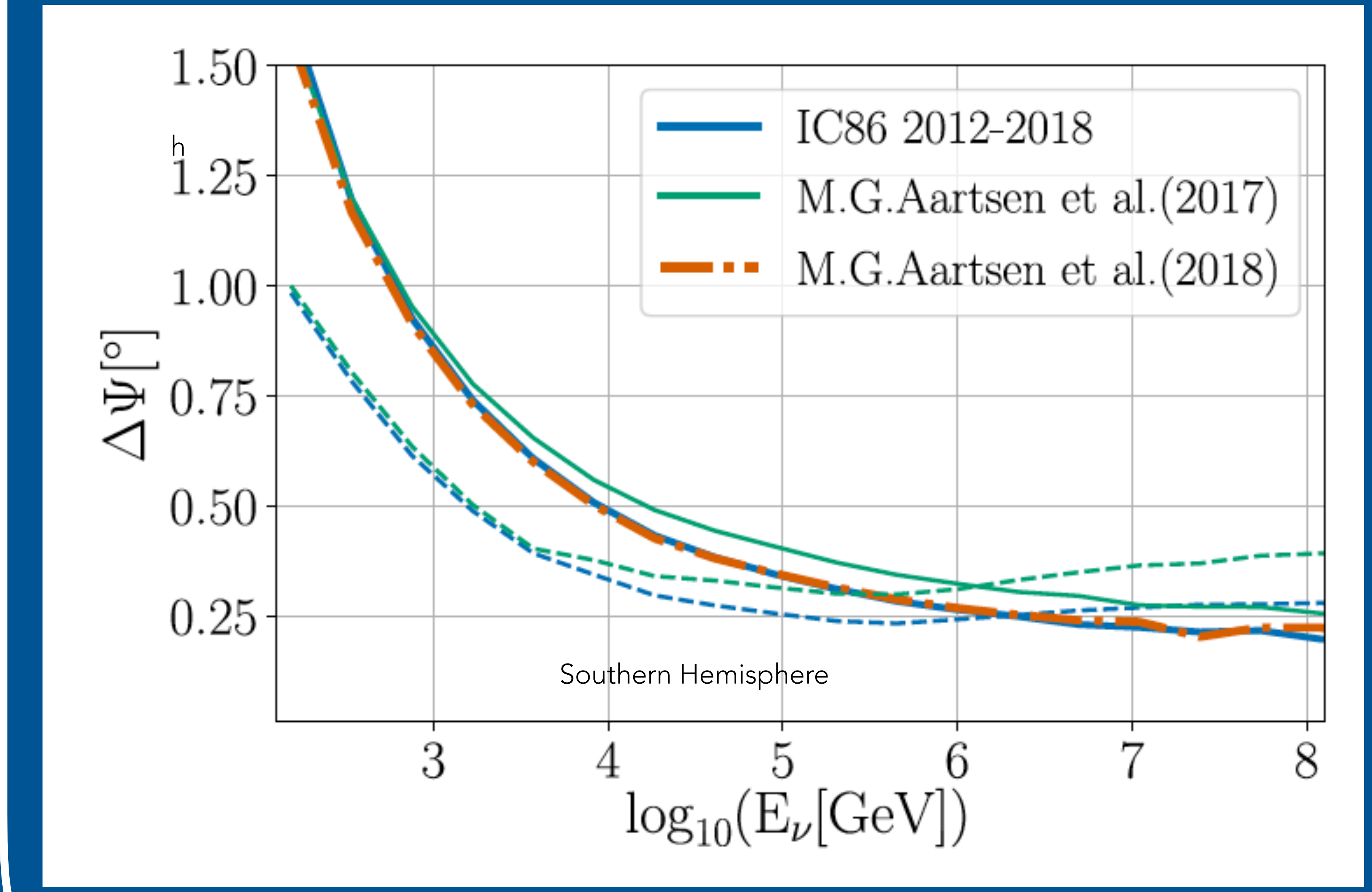
Cascades: small path (Ecasc >1TeV some tens of meters)
- Modest angular resolution

KM3NeT





IC resolution for tracks
from arXiv:1910.08488, 15 October 2019



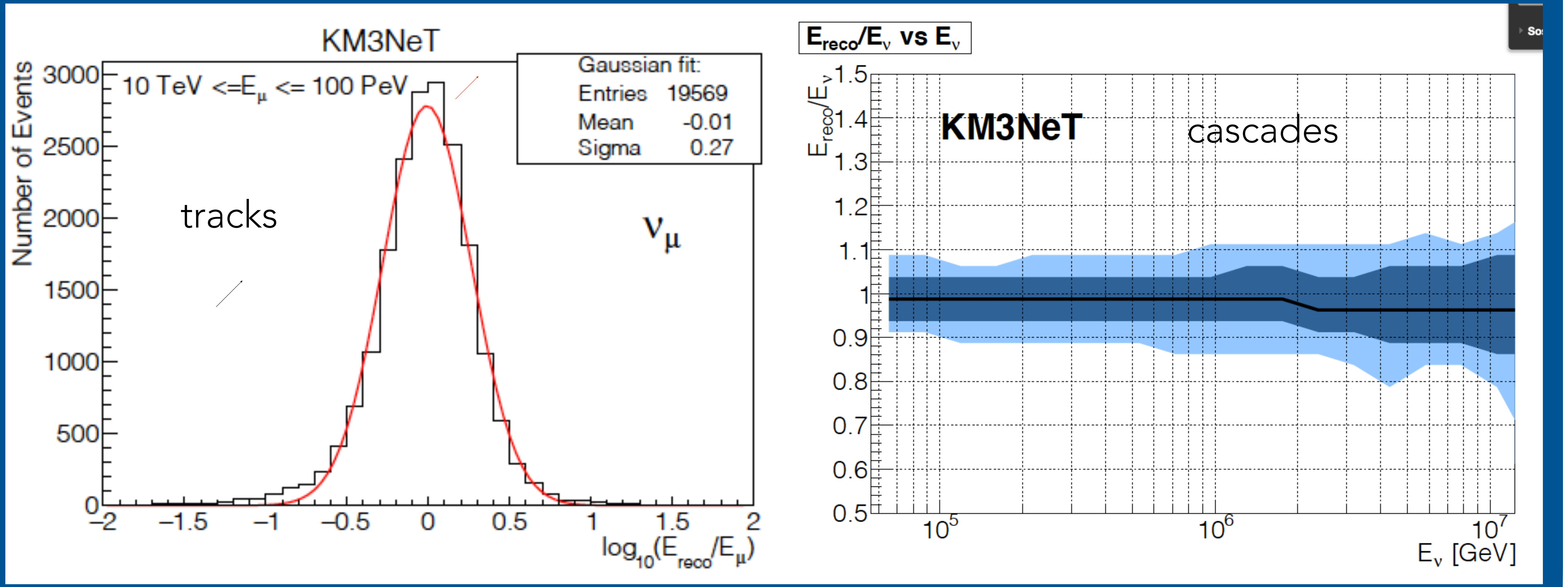
EVENT TYPE AND ENERGY RESOLUTION

Tracks: very long path (Eμ>1TeV several km)
Neutrino interaction vertex far from the detector
- Modest energy resolution

Cascades: small path (E_{casc} >1TeV some tens of meters)
All the energy released inside the detector
- Good energy resolution

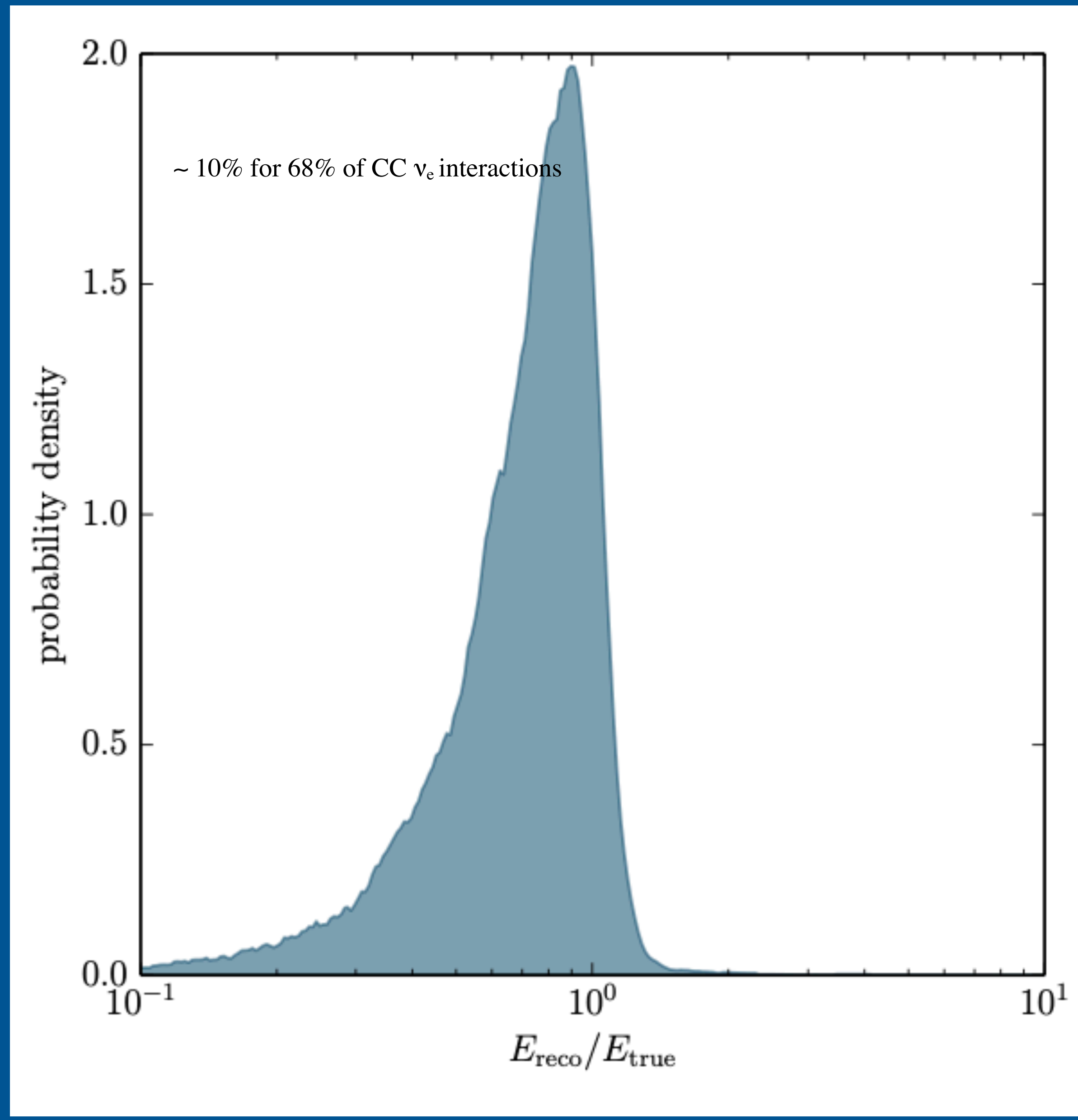
	TRACK IN LOG(E)	CASCADE
ANTARES	35%	5%
KM3NET	27%	5%
ICECUBE	~ 30%	10%
BAIKAL -GVD		

KM3NeT



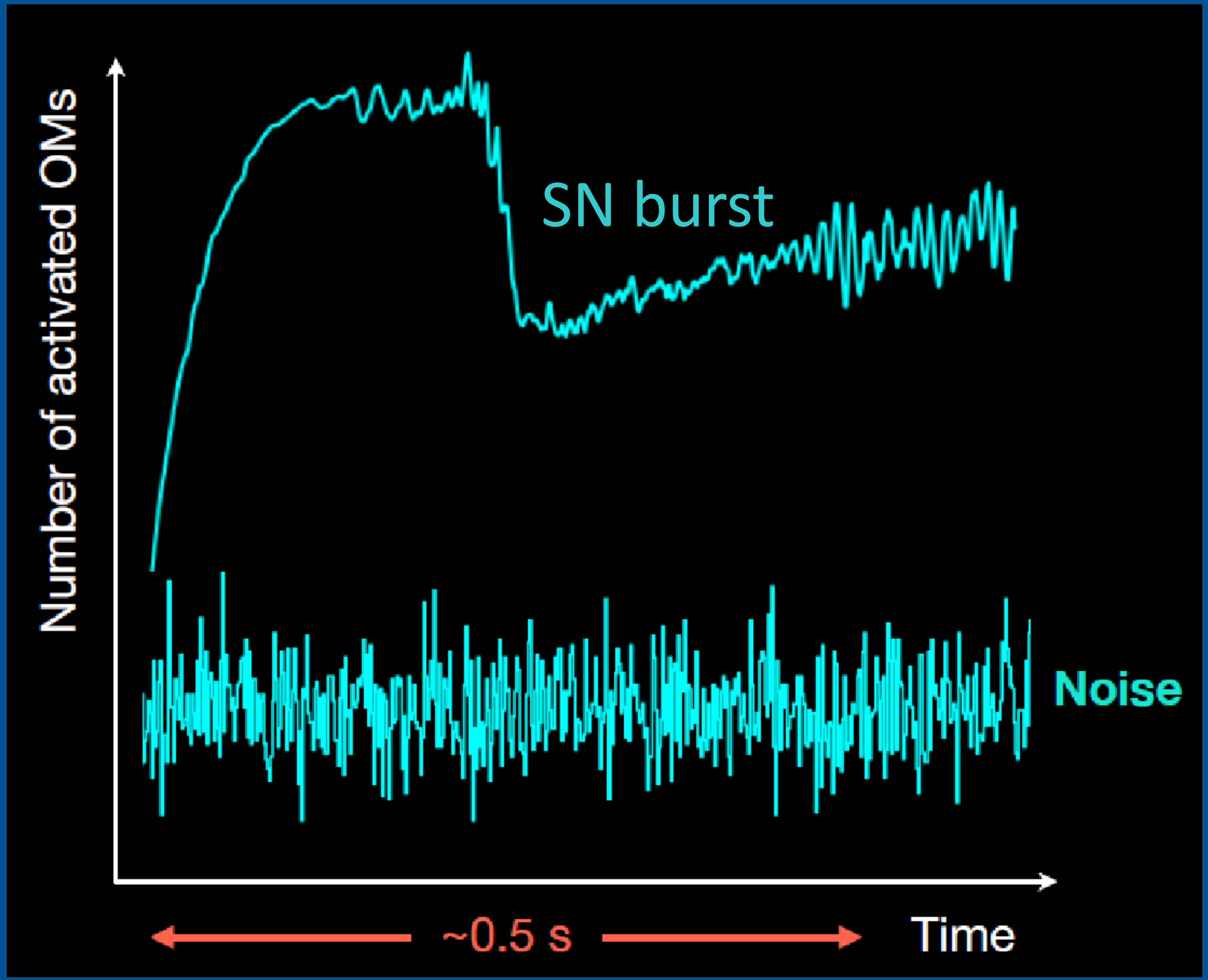
IC energy resolution for cascades

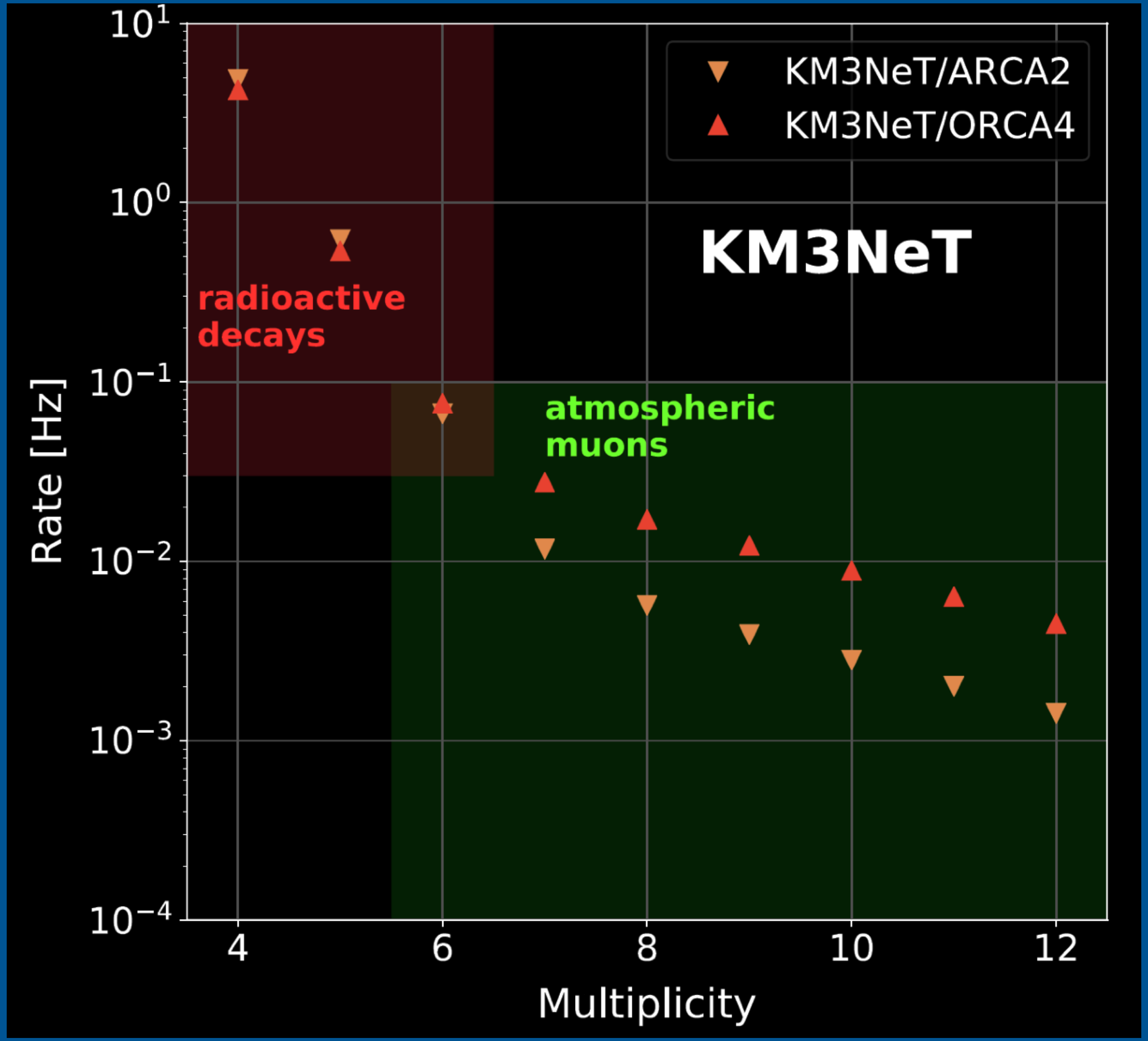
ArXiv:1705.02383



NEUTRINOS FROM CORE-COLLAPSE SUPERNOVAE

- 2070 DOMs in one detector building block
- Each DOM is a detector





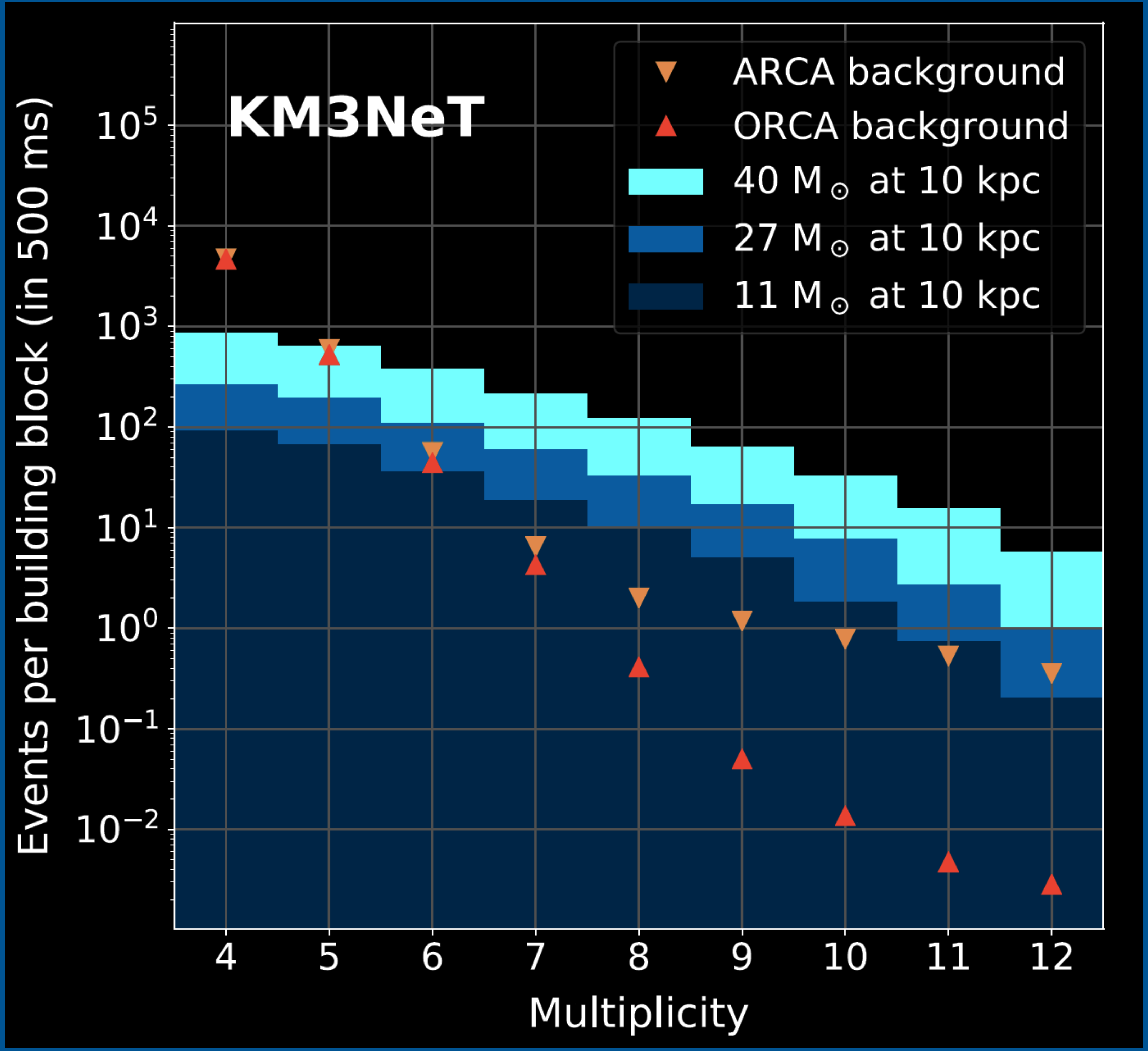
SN burst

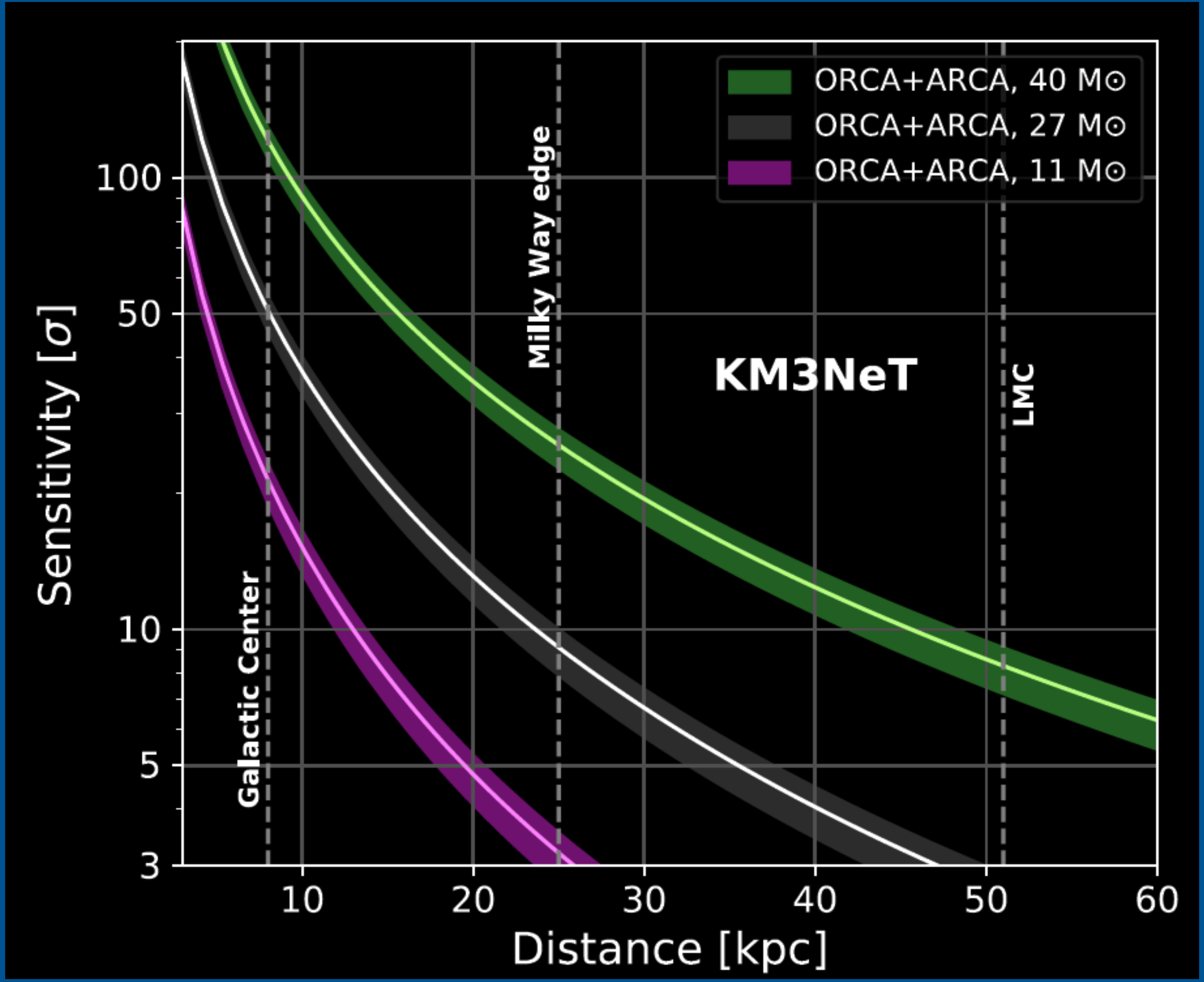
MeV radioactivity: 1-2 PMTs in 20 ns

10 MeV electron: > 4 PMTs in 20 ns

Muons: > 4 PMTs in many DOMSs but within few µs

NEUTRINOS FROM CORE-COLLAPSE SUPERNOVAE





Eur. Phys. J. C (2021) 81:445