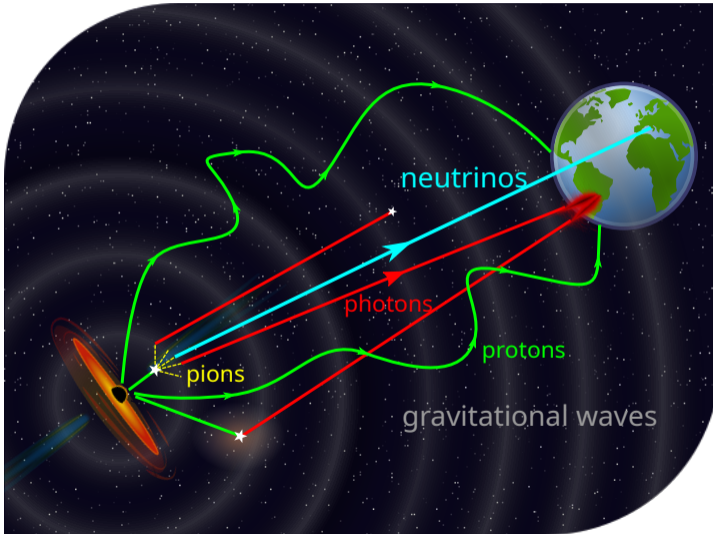


# Neutrino Astronomy with KM3NeT

Lake Louise Winter Institute 2024

**Mathieu Lamoureux (UCLouvain)**  
for the **KM3NeT Collaboration**



- **High-energy gamma-rays**
  - Can be emitted in hadronic or leptonic processes
  - Partially absorbed in interstellar medium or dense sources
- **Cosmic rays (protons&nuclei)**
  - Signature of acceleration sites
  - Deflected by magnetic fields
- **Gravitational waves**
  - Hint of motion, rotation, or merging of compact objects
- **Neutrinos**
  - Can escape dense environment
  - Not absorbed and not deflected
  - Signature of hadronic processes

## Cherenkov light detection with optical sensors:

DOMs (Digital Optical Modules)  
with  $31 \times 3''$  PMTs



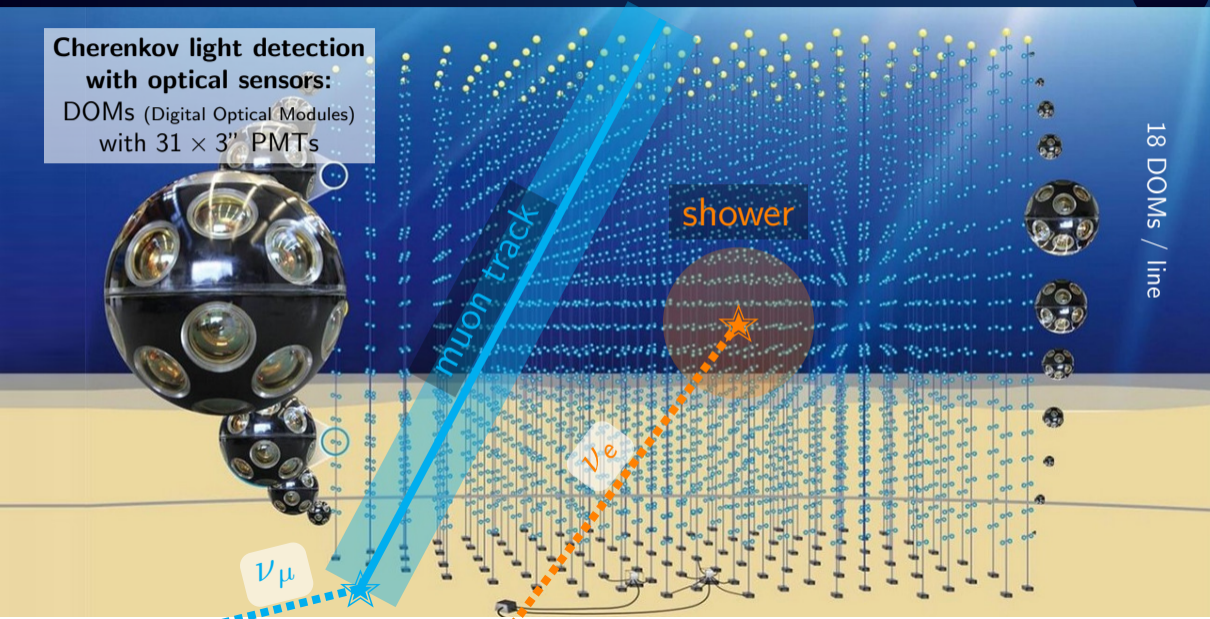
$\nu_{\mu}$

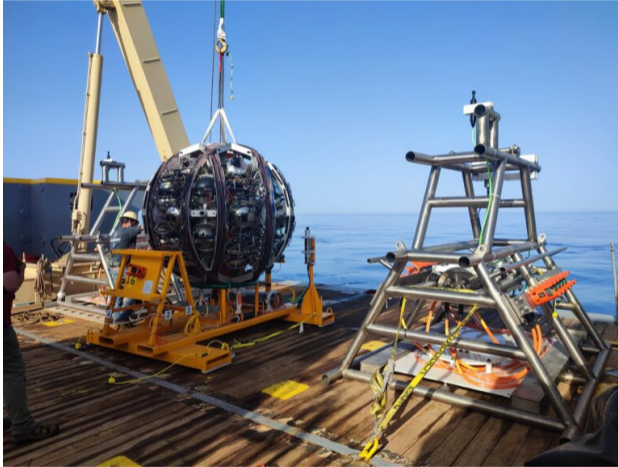
muon track

$\nu_e$

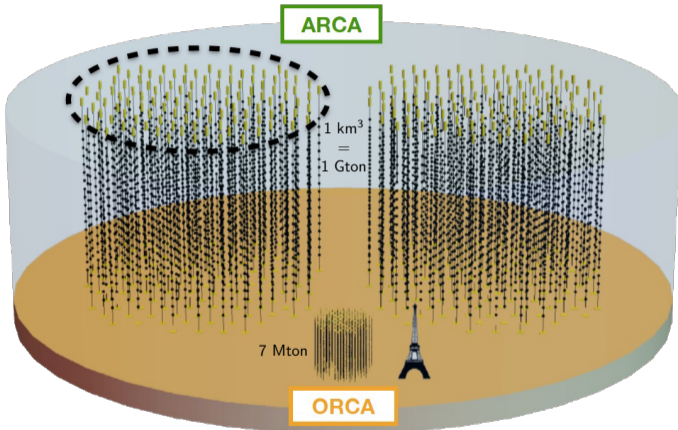
shower

18 DOMs / line

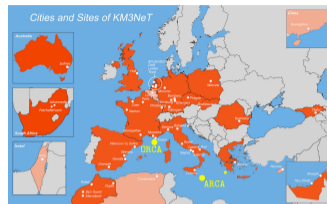




## Astroparticle Research with Cosmics in the Abyss



## Oscillation Research with Cosmics in the Abyss

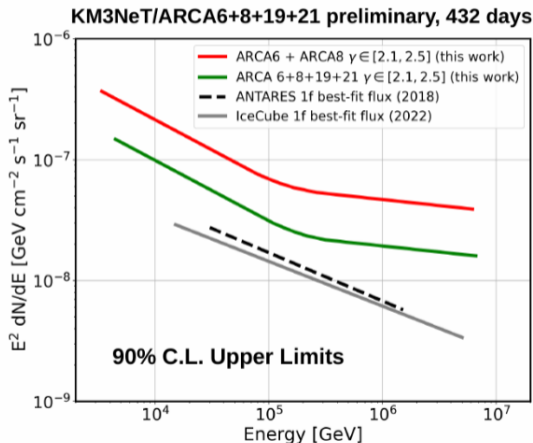
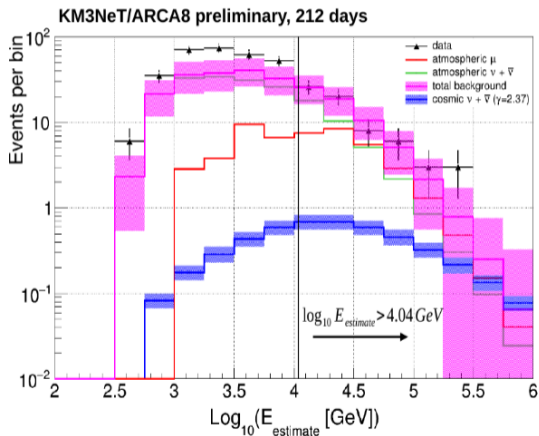


- 1 Building Block = 115 lines
- **ARCA** = 2 Building Blocks
  - 90 m between lines
  - 36 m between DOMs
  - energy range: TeV–PeV
- **ORCA** = 1 Building Block
  - 20 m between lines
  - 9 m between DOMs
  - energy range: GeV–TeV

28 lines deployed at **ARCA** site and 18 lines at **ORCA** → all taking physics data.

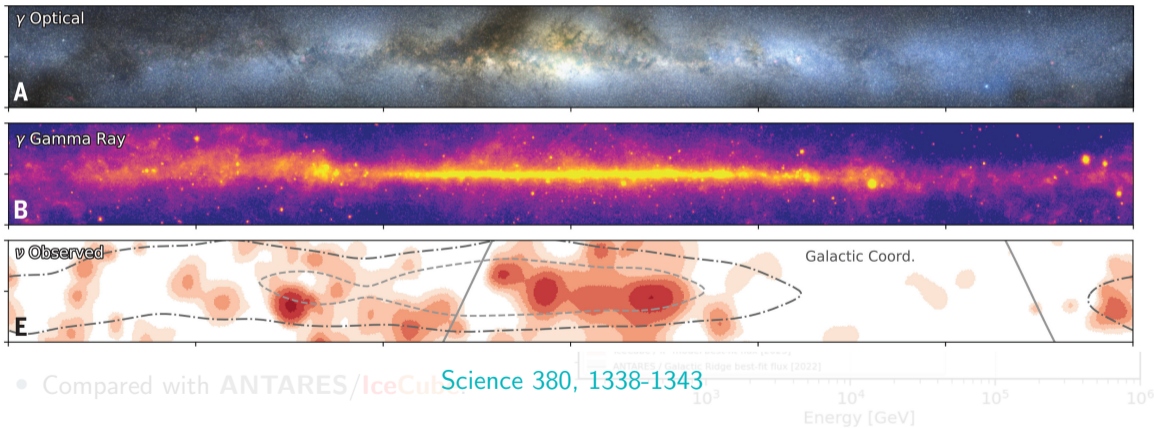


ARCA 6+8+19+21, 14 months of data, upgoing track selection ( $\nu_\mu/\bar{\nu}_\mu$  signal).



Limits  $\approx$  IceCube/ANTARES best-fit flux  $\Rightarrow$  will soon be sensitive to it (bigger detector + more data).

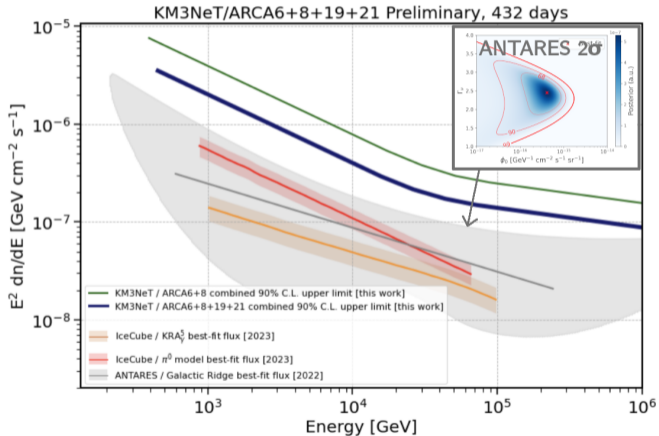
## Search for $4.5\sigma$ observation in IceCube and $2\sigma$ excess in ANTARES





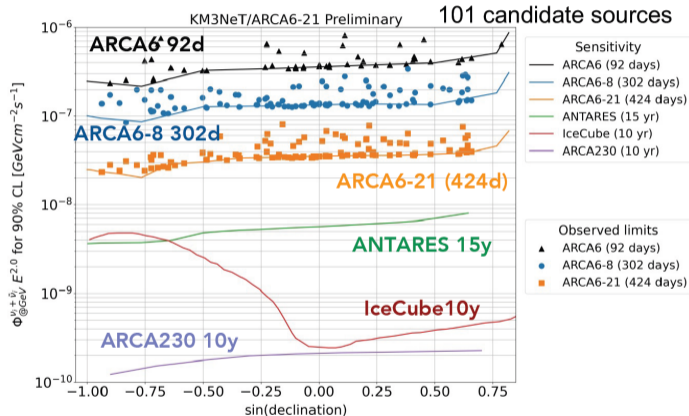
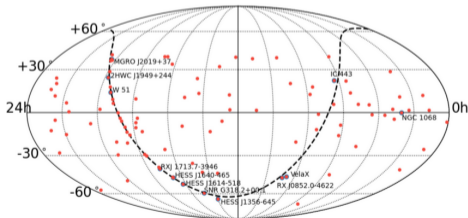
Search limited to Galactic Ridge ( $|l| < 30^\circ$ ,  $|b| < 2^\circ$ ) and muon neutrinos.

- 14 months of ARCA 6+8+19+21.
- Selection of track events in Galactic Ridge direction.
- Background estimated using off-zone regions in data.
- Fit of spectrum with background +  $dN/dE = \phi \cdot E^{-\Gamma}$  signal.
- Compared with **ANTARES**/**IceCube**.



Search for neutrinos in the direction of 101 candidate astrophysical sources

- Upgoing track selection ( $\nu_\mu$ )
- 14 months of ARCA6+8+19+21
- Pointing resolution from 1 to  $0.2^\circ$
- Most significant p-value = 1%



- Soon to be updated with 9 months of ARCA21 and ARCA28+ data.
- KM3NeT will soon reach ANTARES sensitivity.

Search for prompt neutrino emission from transient sources detected by other messengers.

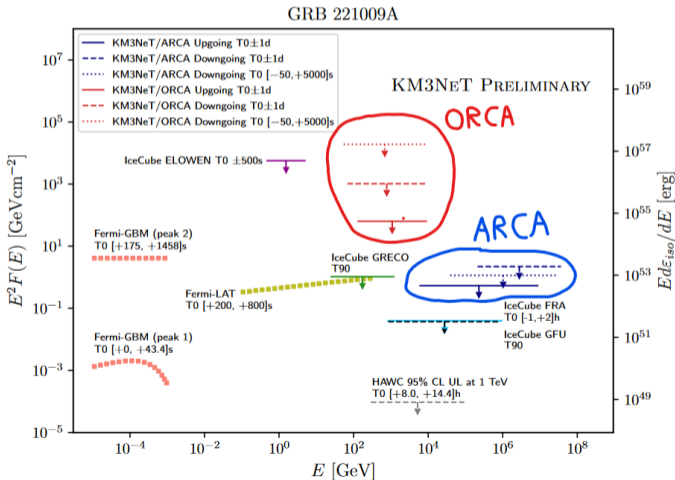
## Follow-up of GW events during O3

- Upgoing tracks and MeV  $\nu$  searches in ORCA 4/6
- Search time windows:
  - tracks:  $\pm 500$  s
  - MeV  $\nu$ :  $[0, 2]$  s

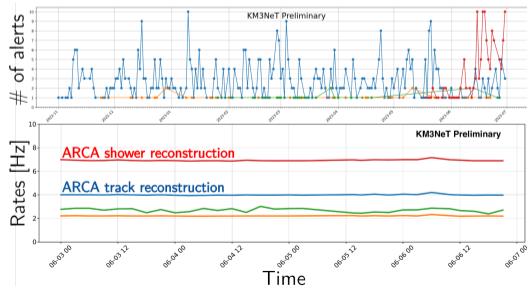
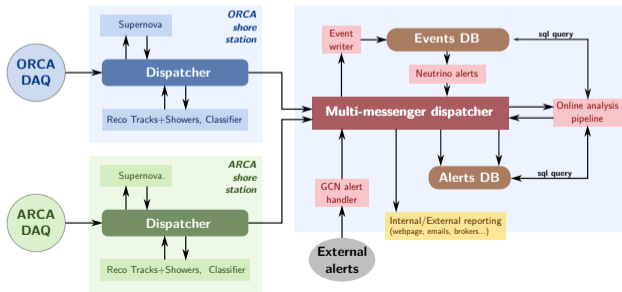
## GRB 221009A (Brightest Of All Time)

- Track selection in ARCA & ORCA.
- Search time windows:
  - $[-50, +5000]$  s
  - $\pm 1$  day

**Both:** no excess  $\Rightarrow$  upper limits

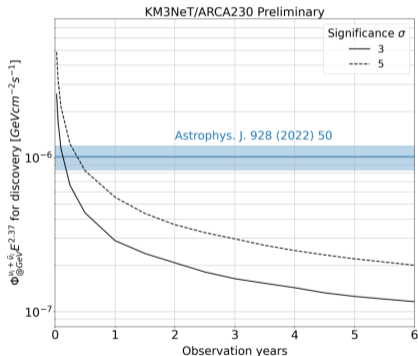


- From data collection to reconstruction takes about 4 s.
- Performing **follow-ups of external triggers** (GW,  $\gamma$ , IC  $\nu$ ) with KM3NeT  
⇒ for now internal, soon to be circulated publicly promptly
- **Sending KM3NeT high-energy neutrino alerts** in preparation.
- KM3NeT also sensitive to MeV neutrinos from **Core-Collapse Supernova**  
⇒ system already in place to send alerts



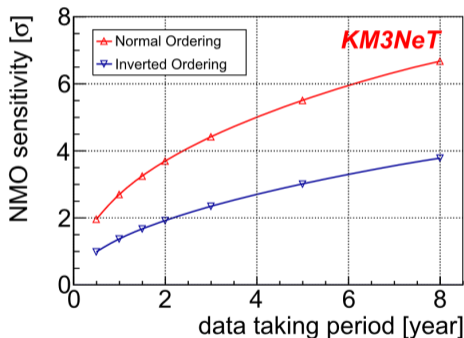
This spring:  $\sim 15$  more lines on ARCA and  $\sim 10$  more lines on ORCA site.

## All-flavour astrophysical diffuse flux



Full ARCA will measure diffuse flux at  $5\sigma$  in 6 months.

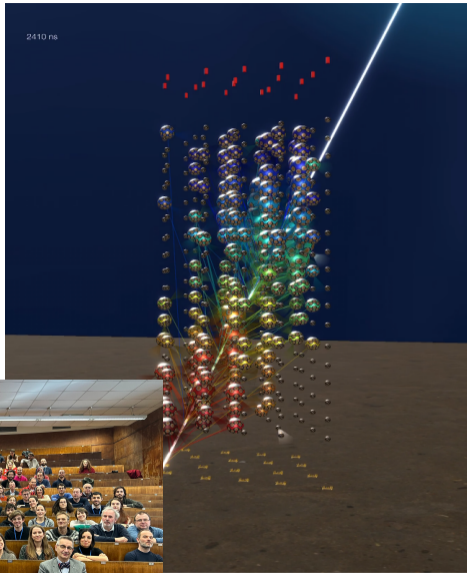
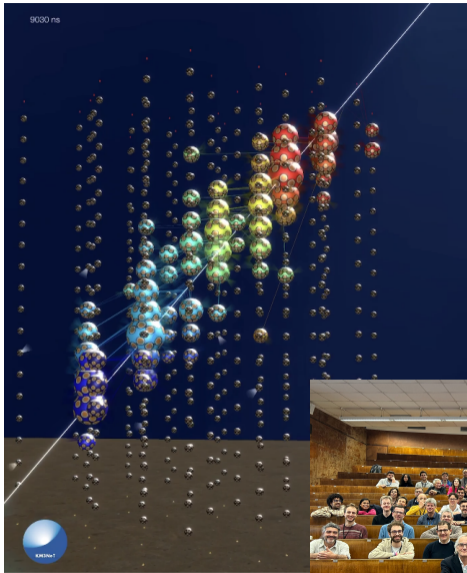
## Neutrino Mass Ordering



With ORCA,  $4.4\sigma$  ( $2.3\sigma$ ) determination in 3 years if Ordering=Normal (Inverted).

- KM3NeT telescope is currently **under construction**. . . COMPLETION IN 2027–2028
- . . . but already **taking data with partial configurations**. ARCA: 28 LINES, ORCA: 18 LINES
- Two sites with **complementary energy coverages**:
  - **ORCA** from 5 GeV to TeV → optimized for neutrino oscillations
  - **ARCA** from TeV to 100 PeV → optimized for high-energy astrophysical neutrinos  
⇒  $< 0.1^\circ$  ( $< 1.5^\circ$ ) for tracks (showers) for  $E_\nu > 100$  TeV
- **First results**:
  - *Diffuse emission and point-source searches*: getting close to ANTARES sensitivities.
  - *Transient follow-ups*: upper limits for GRB 221009A, blazar alerts and GWs.
  - *Multimessenger online program*: started. SOON: SENDING FOLLOW-UPS AND  $\nu$  ALERTS
- **Topics not covered**: study of neutrino oscillations, cosmic ray physics, dark matter and other exotic searches, multidisciplinary science. . . (see [compilation of ICRC proceedings](#))
- **Stay tuned for new results!**

ARCA28



ORCA18

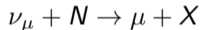


Backups



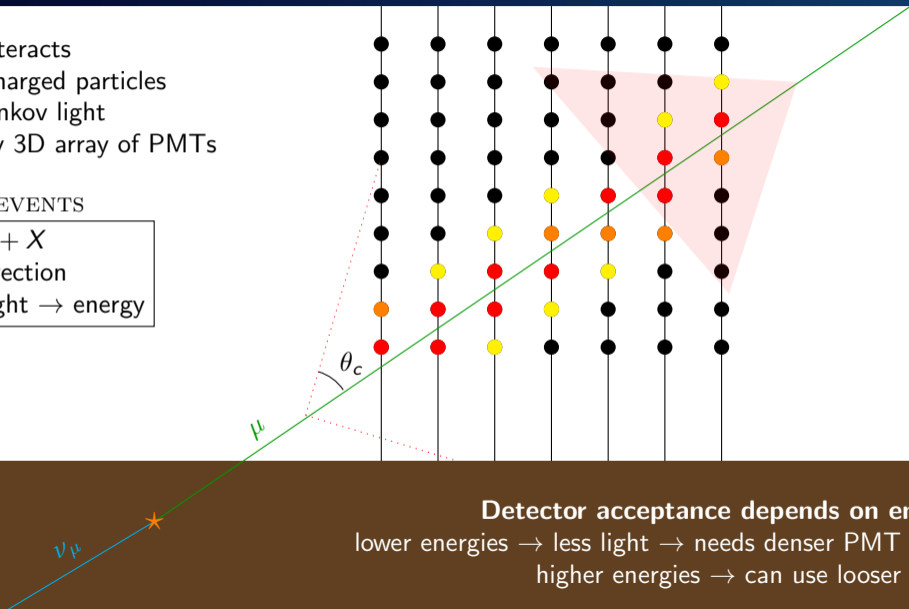
1. Neutrino interacts
2. Produces charged particles
3. Emit Cherenkov light
4. Detected by 3D array of PMTs

## TRACK EVENTS



- fit line  $\rightarrow$  direction

- amount of light  $\rightarrow$  energy



**Detector acceptance depends on energy:**

lower energies  $\rightarrow$  less light  $\rightarrow$  needs denser PMT layout

higher energies  $\rightarrow$  can use looser layout

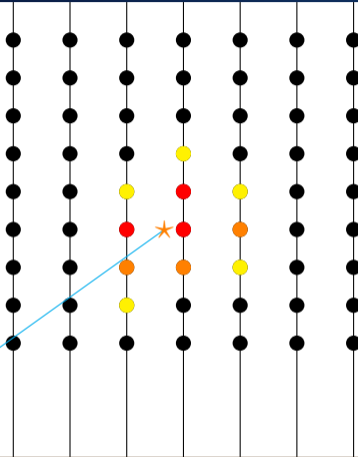
1. Neutrino interacts
2. Produces charged particles
3. Emit Cherenkov light
4. Detected by 3D array of PMTs

## SHOWER EVENTS

$\nu_e + \nu_\tau$  charged current interactions

$\nu_e + \nu_\mu + \nu_\tau$  neutral current interactions

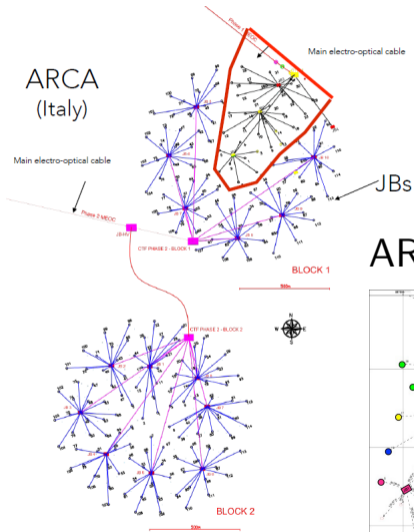
$\nu_e$



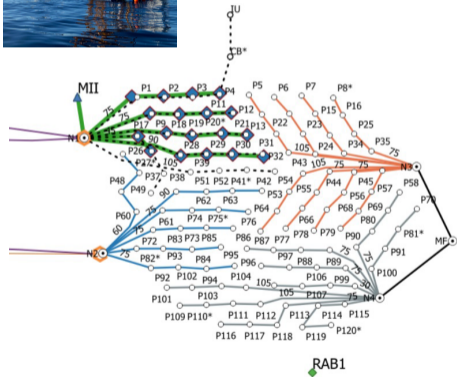
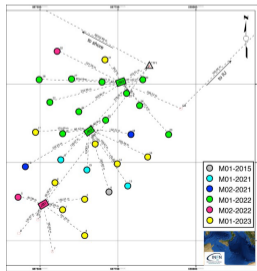
**Detector acceptance depends on energy:**

lower energies  $\rightarrow$  less light  $\rightarrow$  needs denser PMT layout

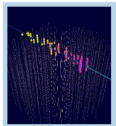
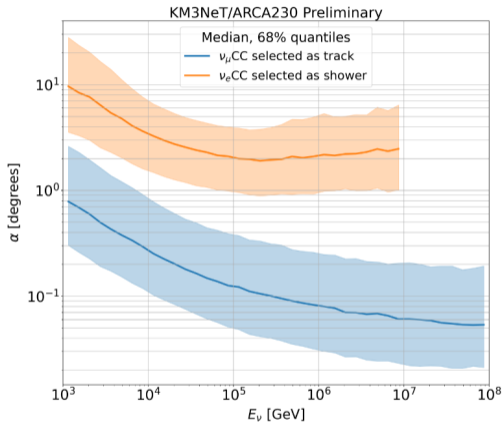
higher energies  $\rightarrow$  can use looser layout



ARCA: 28 lines

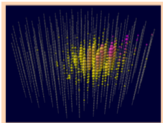


ORCA: 18 lines



Tracks

Showers



## Calibration

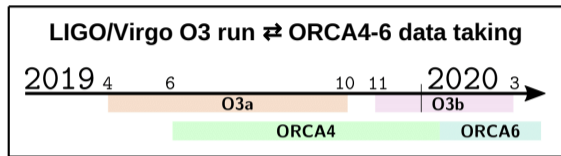
- Time offset corrected using  $^{40}\text{K}$  (intra-DOM), LED beacon (inter-DOM), laser beacon (inter-line).
- Acoustic positioning system + compass for position/orientation.

## Reconstruction

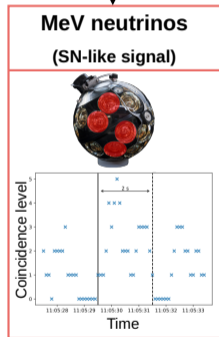
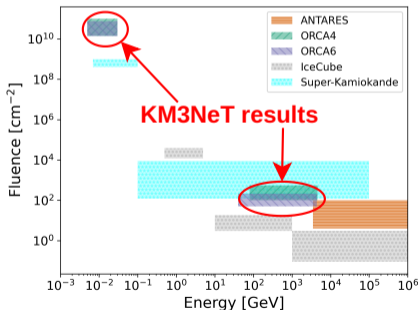
With standard likelihood methods or Graph Neural Network (GNN) approach.

Resolution @ 100 TeV	Tracks	Cascade
ANTARES	$0.3^\circ$	$3^\circ$
KM3NeT	$0.1^\circ$	$1.5^\circ$
IceCube	$0.3^\circ$	$7^\circ$

- Neutrino emission from binary mergers (neutron star, black hole) **expected** but **not yet observed**.

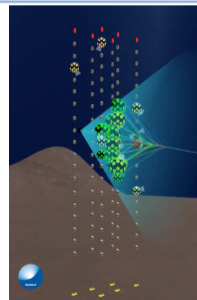


Limits on the total energy emitted in  $\nu$  for each source  
+  
Population studies  
 $\rightarrow$  constraints on typical emission in subpopulations



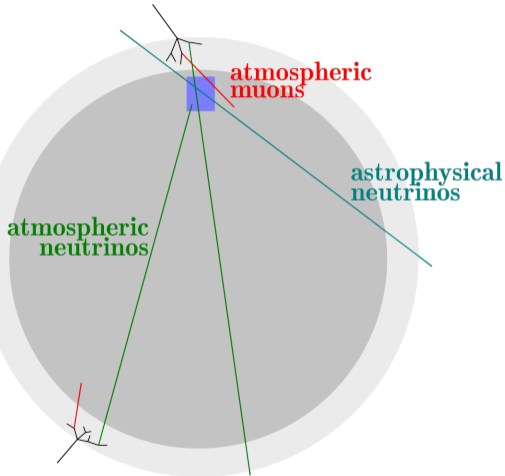
Multiple single DOM coincidences in  $[t_{\text{GW}}, t_{\text{GW}}+2\text{s}]$

**High-energy  $\nu$  emission (upgoing tracks)**



Excess of tracks with respect to expectation in  $[t_{\text{GW}}-500\text{s}, t_{\text{GW}}+500\text{s}]$

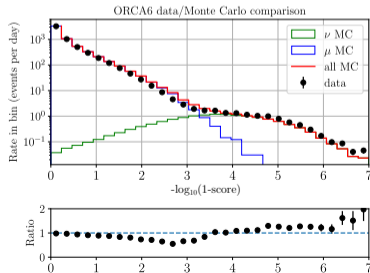
No excess observed  $\rightarrow$  upper limits on neutrino emission



- Downgoing = dominated by atmospheric  $\mu$
- Upgoing = atmospheric+astro  $\nu$

## ORCA analysis

- Focus on upgoing track events = sensitive to  $\nu_\mu(\bar{\nu}_\mu)$ -CC from sky below horizon.
- Boosted Decision Tree (BDT) to separate  $\nu$  from misreconstructed muons.
- Selection of events in GW direction.
- Cut on BDT score optimized for each event to optimize analysis sensitivity.



- **ON/OFF approach:**

- measurement in OFF region (off time)  $N_{\text{OFF}}$
- measurement in ON region (search window)  $N_{\text{ON}}$
- ratio between sizes  $\alpha$

- **Signal assumption:**

$$\frac{dN}{dE} = \phi \cdot (E/\text{GeV})^{-2}$$

- **Bayesian analysis:**

- Likelihood:  $\mathcal{L}(N_{\text{ON}}|b, \phi, A(\Omega)) = \text{Poisson}(N_{\text{ON}}, b + A(\Omega) \cdot \phi)$
- Priors:

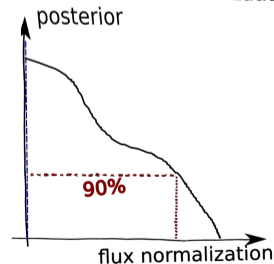
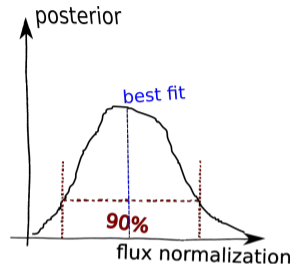
- Background estimation:  $\pi(b) = \text{Poisson}(N_{\text{OFF}}, b/\alpha)$
- Systematics on acceptance:  $\pi(a) = \text{Normal}(\sigma = 10\%)$
- Gravitational wave localization:  $\pi(\Omega) = \text{skymap}$
- Signal parameter:  $\pi(\phi)$  flat prior on normalization

- Posterior:

$$P(\phi) = C \iiint \mathcal{L}(N_{\text{ON}}|b, \phi, A(\Omega)) \times \pi(b) \pi(a) \pi(\Omega) \pi(\phi) db da d\Omega$$

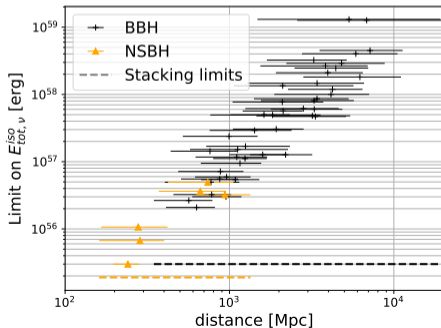
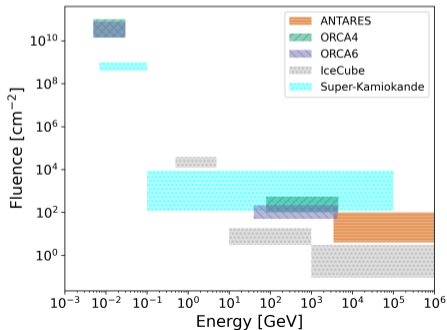
- 90% upper limits:

$$\int_0^{\phi^{90\%}} P(\phi) d\phi = 0.90$$



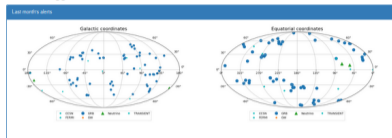
50 (55) follow-ups performed with high-energy (MeV) neutrinos → no excess → upper limits

- Limits on flux and total energy emitted in neutrinos by individual mergers:
  - High-energy neutrinos ( $E^{-2}$  spectrum):  $E_{\text{tot},\nu}^{\text{iso}} < 10^{55} - 10^{59}$  erg
  - MeV neutrinos (quasi-thermal spectrum):  $E_{\text{tot},\nu}^{\text{iso}} < 10^{60} - 10^{63}$  erg
- Stacking limits:
  - Considering all **BBH** (**NSBH**) events, constraints on the typical  $E_{\text{tot},\nu}^{\text{iso}}$  or ratio  $E_{\text{tot},\nu}^{\text{iso}}/E_{\text{GW}}$





## External triggers



Filter

Name TagID:  Status: All Event type: All

RA:  DEC:  Radius:

Between: dd/mm/yyyy And: dd/mm/yyyy

Filter Reset

Alerts

Showing alerts 1 to 198 of 4142 in total

Entries per page: 10 20 50 100

1 2 3 4 5 ... 41 42

Event ID	Type	Event date (UTC)	Validity	RA (deg)	Dec (deg)	Links
S240116ac	GW	2024-01-16 06:18:20	Excluded	-	-	GCM, Link, Details
S240116aa	GW	2024-01-16 07:01:41	Excluded	-	-	GCM, Link, Details
S240116c	GW	2024-01-16 07:01:14	Excluded	-	-	GCM, Link, Details
S240116g	GW	2024-01-16 04:22:14	Excluded	-	-	GCM, Link, Details
S240116e	GW	2024-01-16 04:22:01	Excluded	-	-	GCM, Link, Details
S240116f	GW	2024-01-16 02:15:07	Excluded	-	-	GCM, Link, Details
S240115aa	GW	2024-01-15 21:08:02	Excluded	-	-	GCM, Link, Details
S240115ak	GW	2024-01-15 20:08:03	Excluded	-	-	GCM, Link, Details
102-0439399	TRANSIENT	2024-01-15 20:00:27	Excluded	267.4919	-33.204	GCM, Link, Details
78008	GRB	2024-01-15 16:46:05	Selected	191.8481	-35.5205	GCM, Link, Details, Analysis
19472	GRB	2024-01-15 16:45:05	Selected	191.8174	-35.5992	GCM, Link, Details, Analysis
727529342	GRB	2024-01-15 16:45:37	Selected	198.5	-34.79	GCM, Link, Details, Analysis
S240117a	GW	2024-01-15 14:21:01	Excluded	-	-	GCM, Link, Details
S240117b	GW	2024-01-15 11:29:17	Excluded	-	-	GCM, Link, Details
727509399	GRB	2024-01-15 11:03:14	Selected	16.29	24.97	GCM, Link, Details, Analysis

## Internal tools:

- Monitoring of ARCA and ORCA status (event rates, processing times. . .).
- Status of online systems.
- List of received alerts ( $\nu$ , GW, GRB, others).
- Results of performed follow-ups.

Analysis ARCA - v1

TAG: RES\_ALERT

Notice\_Name: LVC\_PREAM

ID\_Event: S230621ad

Date\_Event: 2023-06-21T10:22:23.000

Detector: ARCA

Pipeline: ARCA\_GW

Iteration: 1

Date\_Analysis: 2023-06-21T12:25:46.827

Code\_Version: 0.3.0

Search time window: 1\_alert-0:0 second TO 1\_alert-4 hour

Livetime(sic) (seconds): 21100.0

Livetime(bkg) (days): 9.195

Remaining fraction after rate cuts (%) : 77.229

nON: 0

nOFF: 2,2,2,2,2,2,2

Expected Background: 0.03871

Cuts on RecoQuality: 1.42571200e+02, 1.25639012e+02, 1.43064194e+02, 2.09849172e+02, 1.82951536e+02, 3.80623191e+02, 4.89519479e+02, 8.00980209e+02

p-value: 1.0

KOSMORE\_Stress: 0

Analysis skymap

Click to enlarge

Skymap ARCA GW S230621ad iter 1

Stability

Click to enlarge

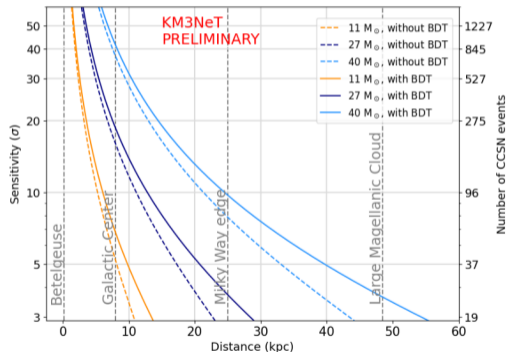
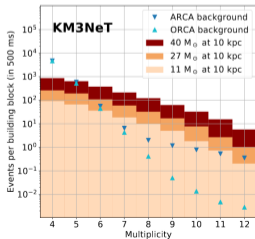
Time profile

Click to enlarge

Time profile ARCA GW S230621ad iter 1

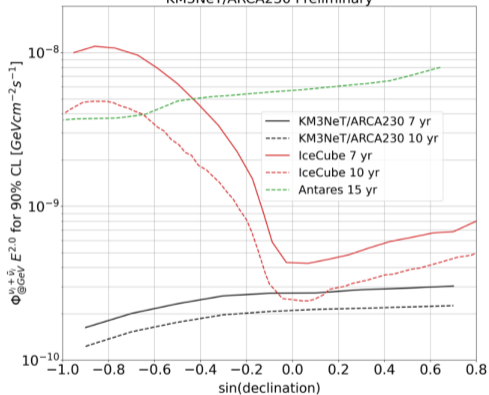
Detection of Core-Collapse Supernovae (CCSN) through  $\bar{\nu}_e$  inverse beta decays in ORCA+ARCA.

- Looking for overall excess of coincidences over the whole detector.
- Background for  $^{40}\text{K}$ , bioluminescence and atmospheric muons.
- Alerts sent in realtime through SNEWS network.
- Horizon extending already beyond the Galactic Center.



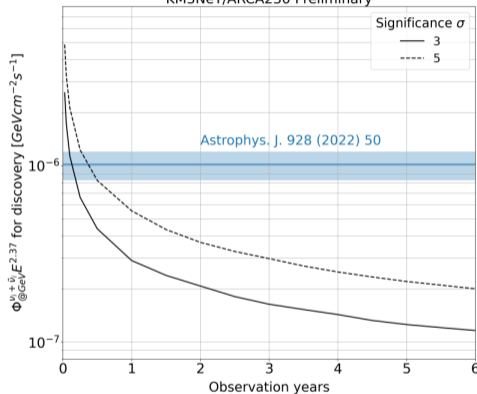
## Point-source searches

KM3NeT/ARCA230 Preliminary



## Discovery of diffuse flux

KM3NeT/ARCA230 Preliminary



### Expected yearly rates

Atmospheric muons

Atmospheric neutrinos

Astrophysical neutrinos

Track selection

700

85000

200

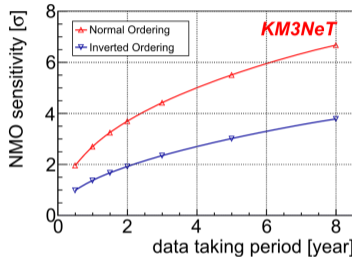
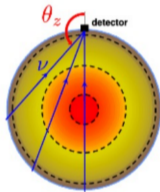
Shower selection

1500

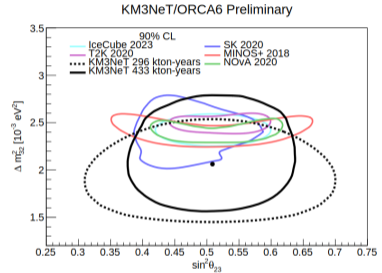
2300

100

ORCA site is optimized for the study of atmospheric neutrino oscillations.



4.4 $\sigma$  (2.3 $\sigma$ ) determination of Neutrino Mass Ordering in 3 years if Normal (Inverted)



Precision measurements of  $\Delta m^2_{32}$  and  $\theta_{23}$ .

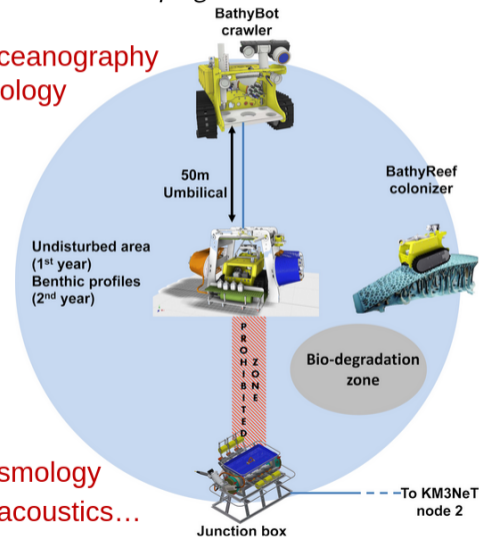
## Other measurements:

- Tau neutrino appearance
- Composition of Earth core
- Various BSM physics (NSI,  $\nu$  decay, LIV...)

- PMT data (light)  
⇒ study of bioluminescence activity
- Hydrophone data (sound)  
⇒ monitoring of anthropogenic noise, presence of Cetaceans, geophysical noise
- Complementary instruments  
⇒ sea current, seismic activity, O<sub>2</sub> levels. . .

*Dedicated program at ORCA site*

Oceanography  
Biology



Seismology  
Bioacoustics...

---To KM3NeT  
node 2