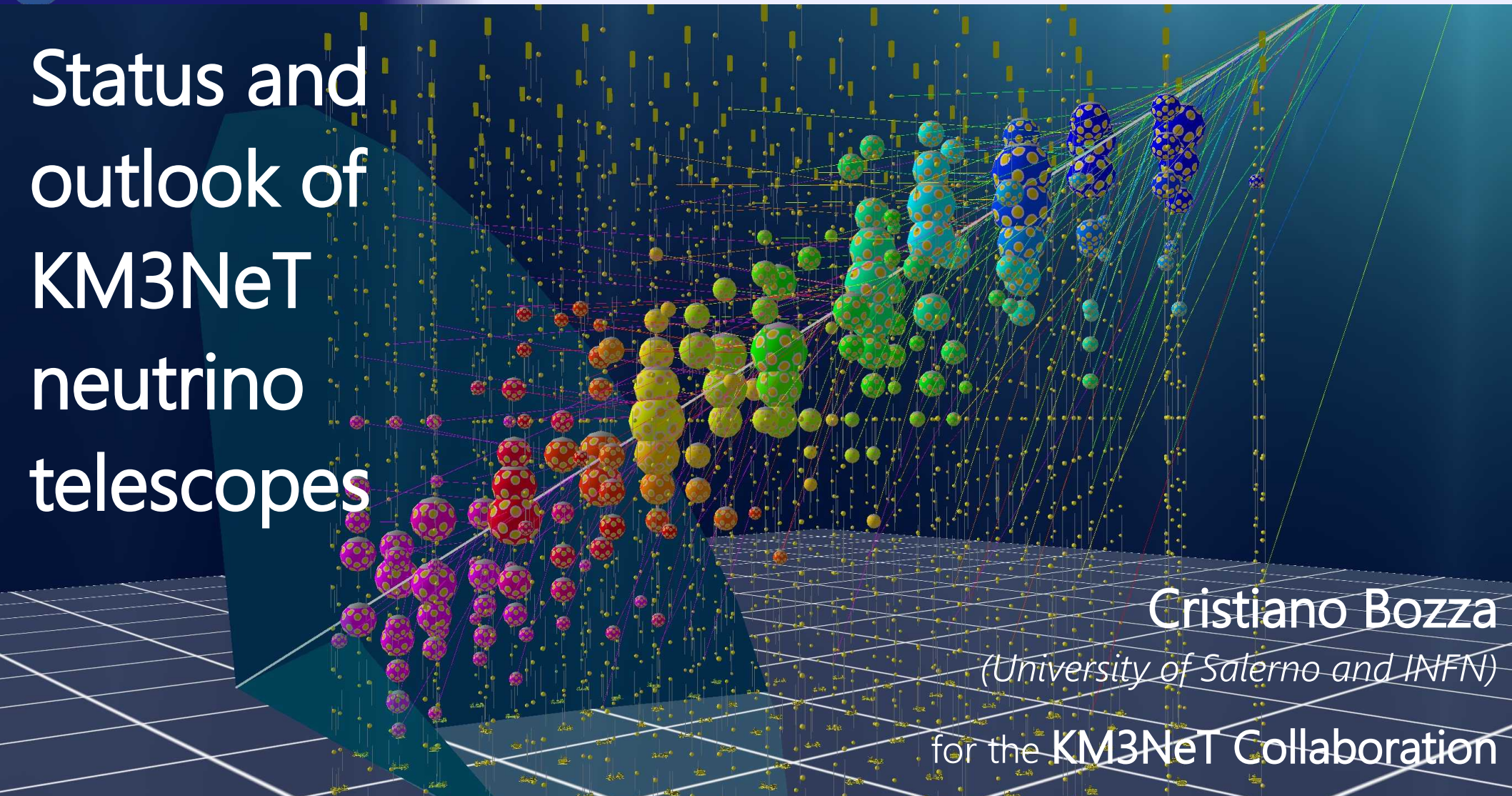
KM3NeT

# Status and outlook of KM3NeT neutrino telescopes



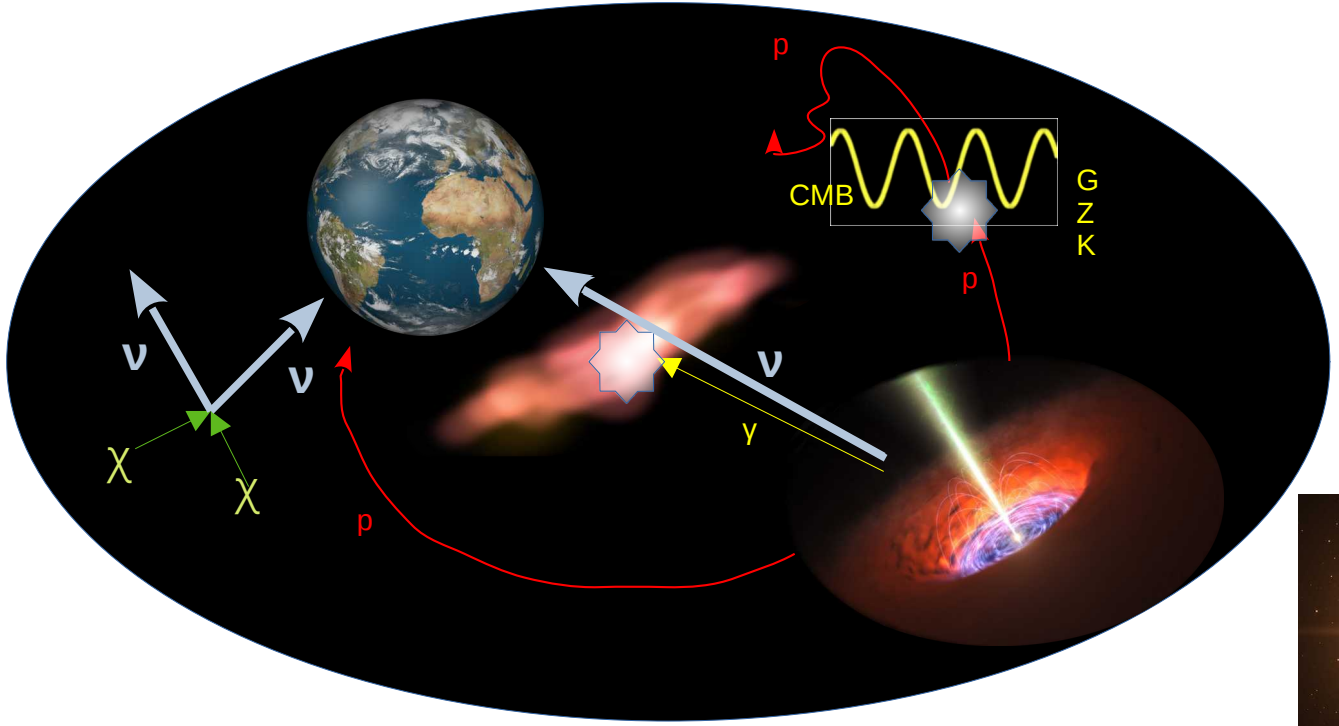
Cristiano Bozza

*(University of Salerno and INFN)*

for the KM3NeT Collaboration

# Overview & Motivation

## Neutrinos from astrophysical sources




Photons can be stopped by interstellar matter

Charged particles can travel long ranges but are affected by magnetic fields and interact with Cosmic Microwave Background

Neutrinos: messengers from deep space

**Neutrino astronomy!**

Neutrino sources:

High-energy neutrino production:

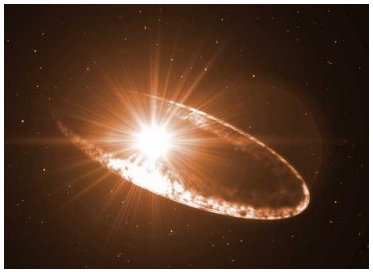
$p+p/\gamma \rightarrow X+\pi^0 \rightarrow \ldots+\gamma\gamma$

$p+p/\gamma \rightarrow X+\pi^{+/-} \rightarrow \ldots+ \mu \rightarrow e + \bar{\nu} + \nu$

**Expect correlation between HE photon and neutrino production**

**Tag for ongoing hadronic processes**

**Galactic**



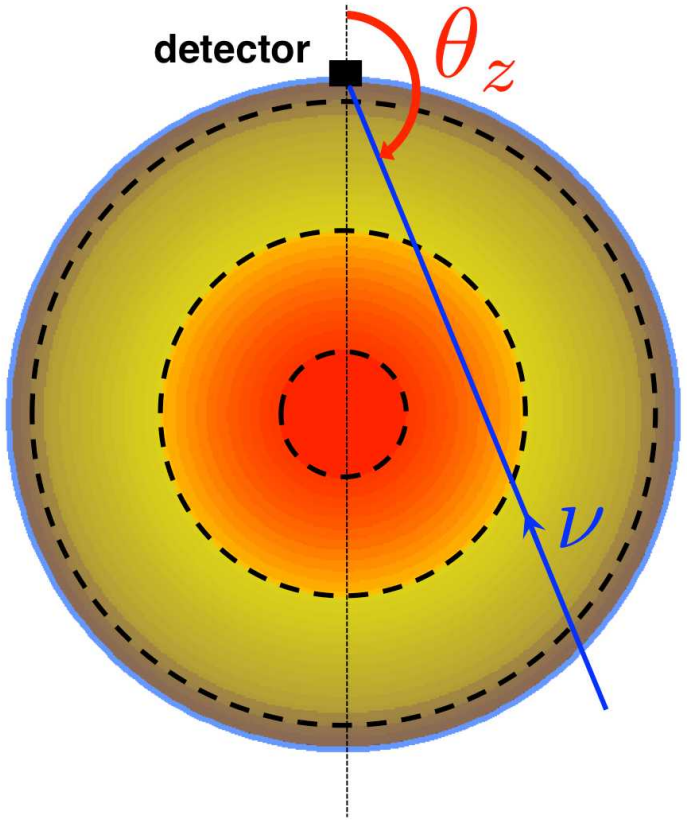
Supernovae, SN relics, Pulsar Wind Nebulae, Dark Matter particle annihilation?

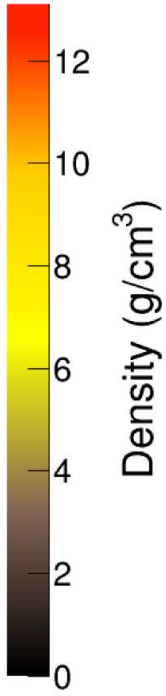
**Extragalactic**

Active Galactic Nuclei, Black hole mergers?

# Overview & Motivation

## Atmospheric neutrino & oscillation




Neutrinos produced by interactions of cosmic rays in atmosphere

$p+N \rightarrow X+K^+,\pi^+ \rightarrow \ldots + \bar{\mu} \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$

$p+N \rightarrow X+K^-,\pi^- \rightarrow \ldots + \mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$

Oscillation + propagation in Earth matter

**Matter-enhanced oscillation**

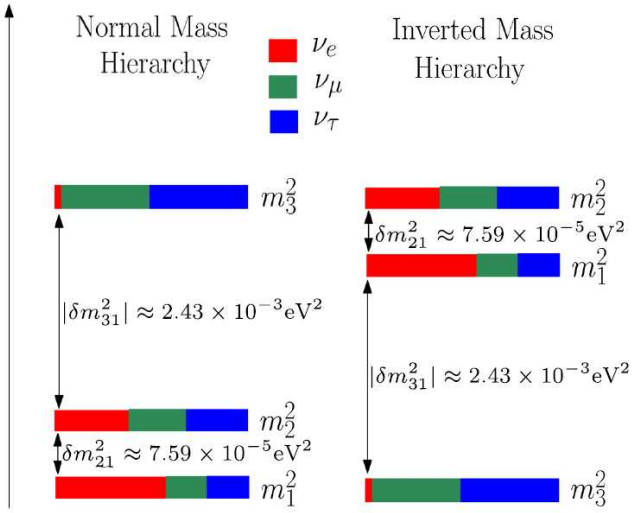
Probing different regions of Length/Energy depending on the inclination (Nadir angle) of the incoming neutrino

Matter effects sensitive to sign of $\Delta m^2_{31}$

Normal Ordering: excess $\nu_e$

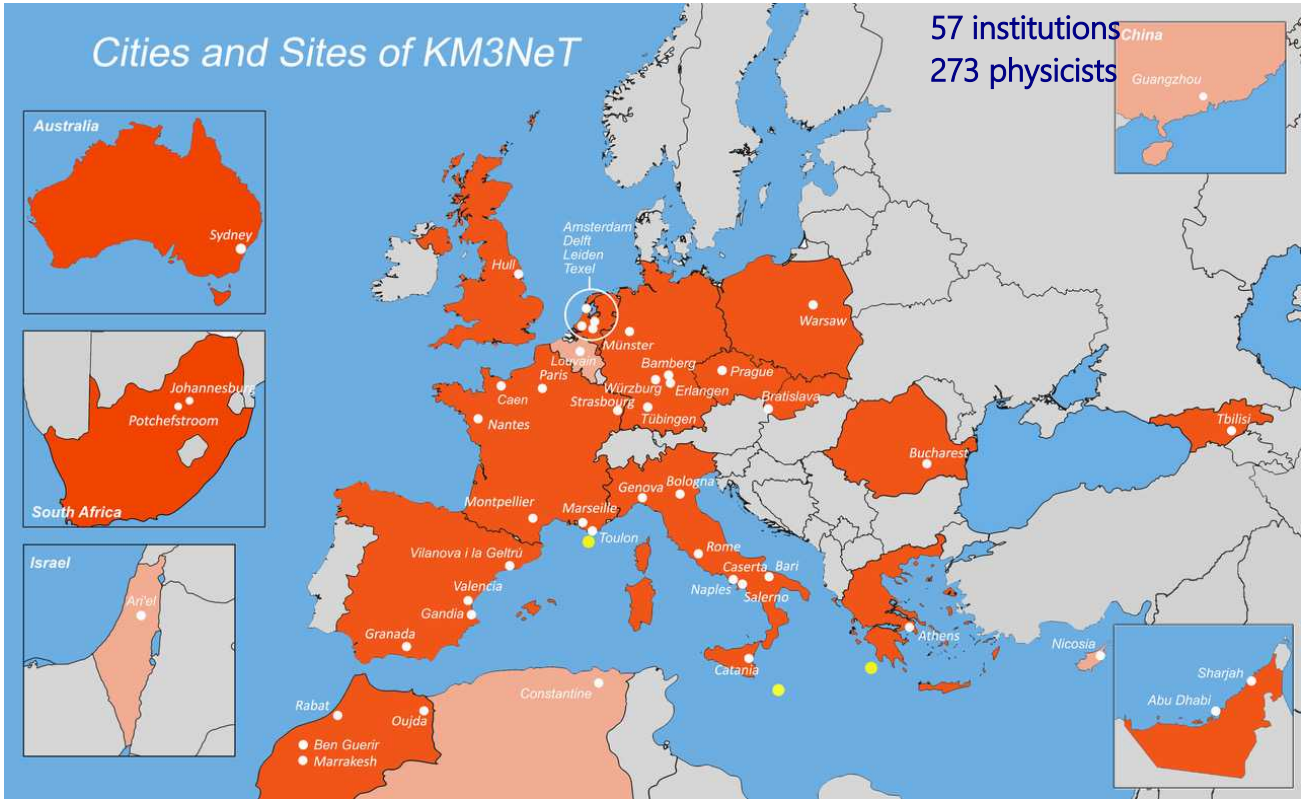
Inverted Ordering: excess $\bar{\nu}_e$

Resonance energy:
7 GeV in Mantle
3 GeV in Core

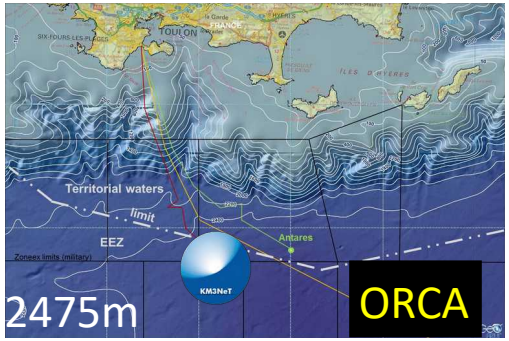


# Collaboration and sites

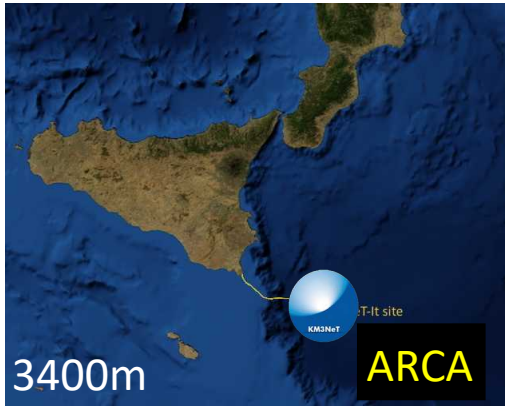
## The Collaboration:




## The Neutrino Telescopes




**O**scillation **R**esearch with **C**osmics In the **A**byss



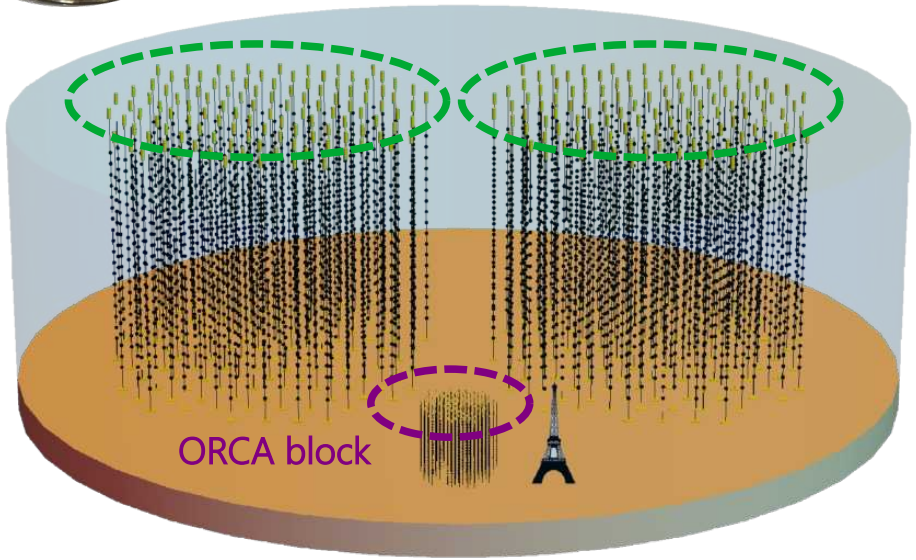

**A**stroparticle **R**esearch with **C**osmics In the **A**byss

# Telescopes

## Neutrino detection technology in KM3NeT

Modular, incremental telescopes
**Detection Unit**: a string of 18 **Digital Optical Modules**
DOM: instrumented sphere hosting 12 upwards-pointing + 19 downward pointing 3" PMTs.

ARCA blocks




| | ARCA | ORCA |
|---|---|---|
| Location | Italy (Sicily) | France (Toulon) |
| Anchor depth | 3450 m | 2450 m |
| Distance from shore | 100 km | 40 km |
| DUs | 115×2 blocks | 115 |
| DU horizontal spacing | 90 m | 20 m |
| DOM vertical spacing | 36 m | 9 m |
| DOMs/DU | 18 | 18 |
| PMTs/DOM | 31 | 31 |
| Instrumented water mass | 1 Gton | 7 Mton |
| | | |
| DUs deployed | 21 | 18 |

# Physics

## Physics programme with ARCA and ORCA

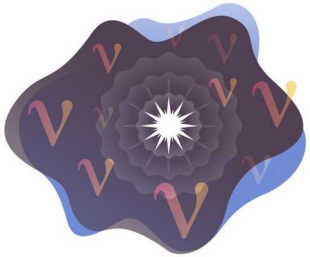
Supernovae

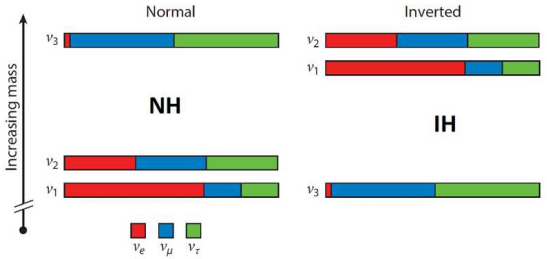
ν oscillations
ν mass ordering

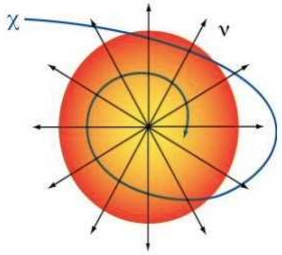
Dark Matter searches
Exotics searches

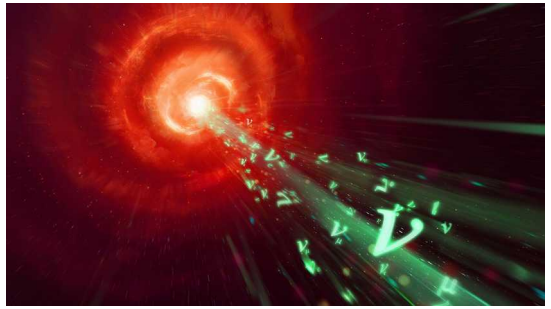
Cosmic neutrinos
Multimessenger Astronomy

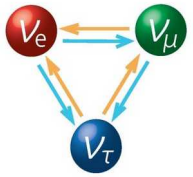
MeV GeV TeV PeV







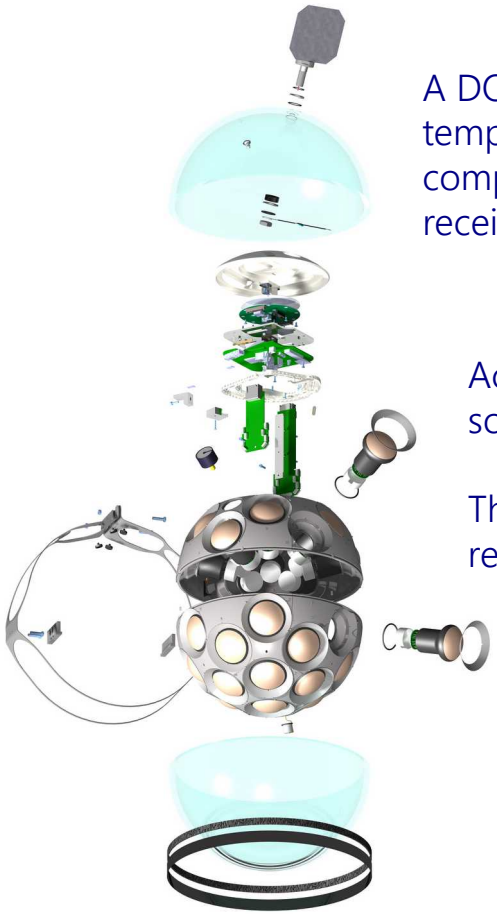

ORCA

ARCA

*Despite the naming, we can also do astronomy with ORCA (GW, AGN, SN, solar flares, GRB follow-up) and particle physics with ARCA (DM, exotics, …)*

# Detection technology

## Neutrino detection technology in KM3NeT

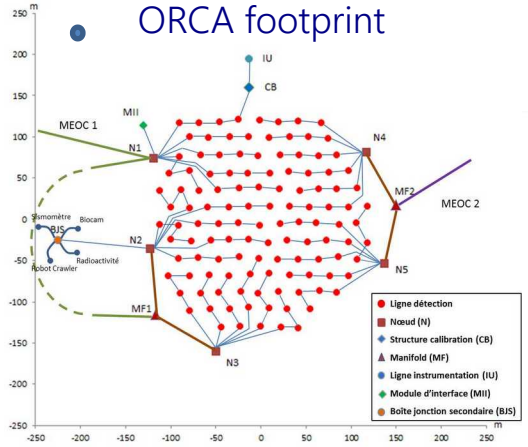


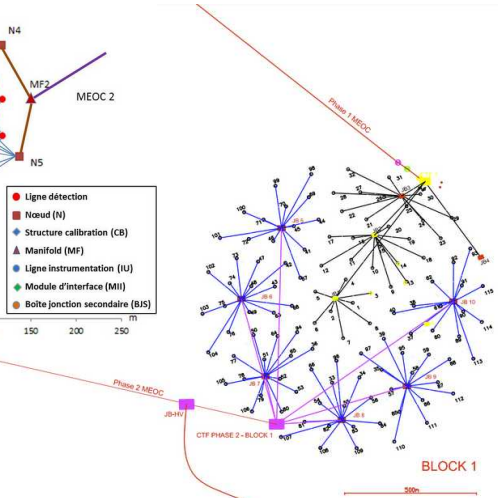
A DOM contains photomultipliers, temperature and humidity sensors, compass + tiltmeter and an acoustic receiver

Acoustic beacons provide reference sounds from known positions

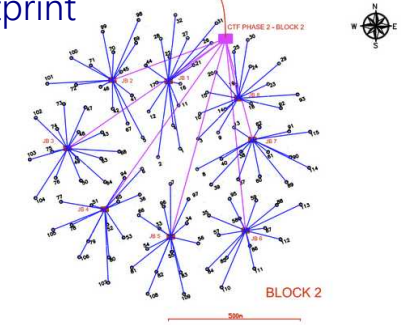
The shape of the telescope is reconstructed using the Times of Arrival

ORCA footprint



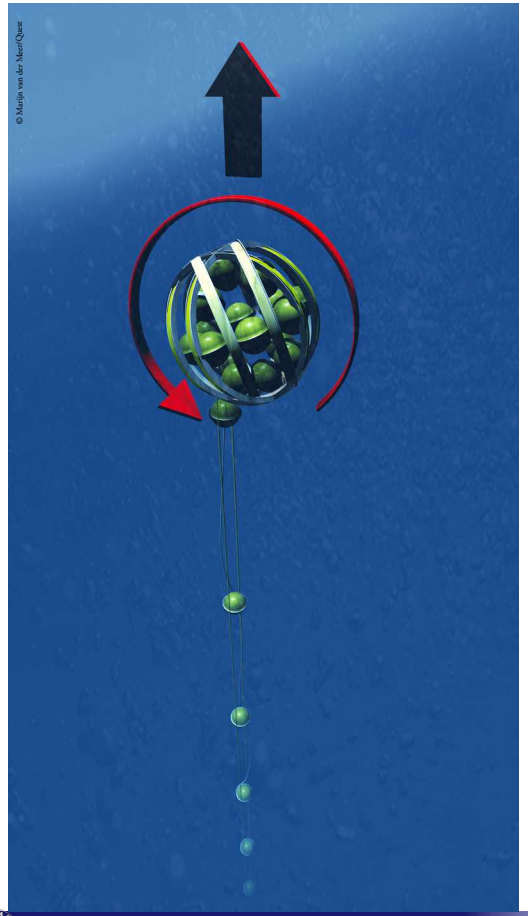




ARCA footprint



# Technology

## Neutrino detection technology in KM3NeT

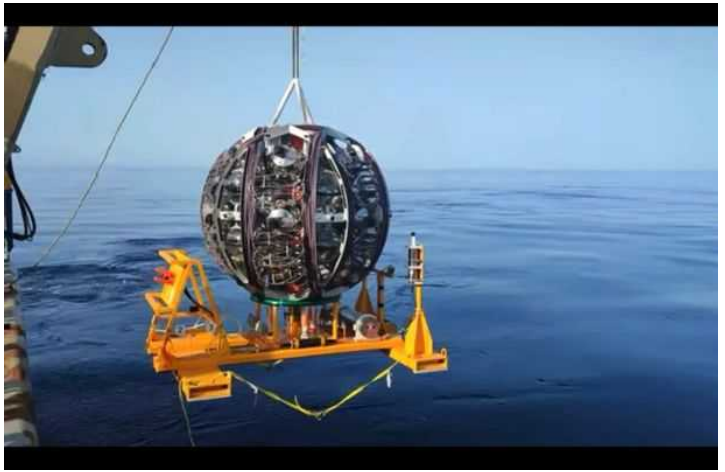


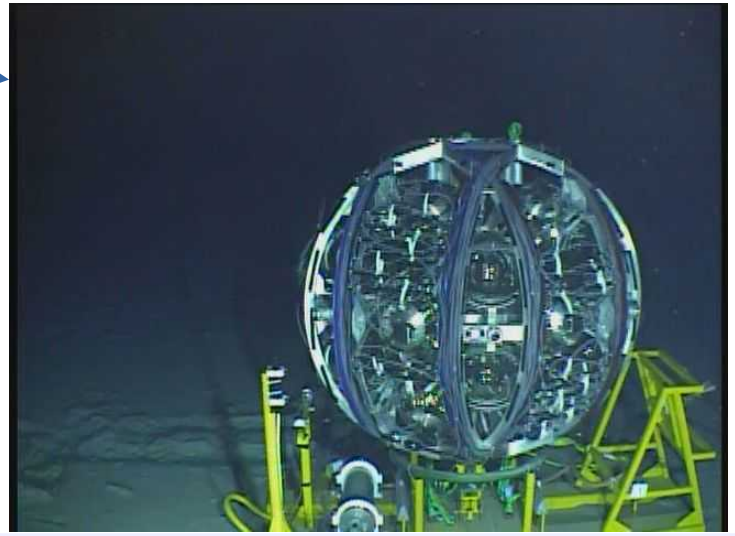
Deployment by a reusable launcher

Connection to power and network cables using a Remotely Operated Vehicle

On the seabed, ready for unfurling

Detection Unit reaching its final configuration after unfurling





# Neutrino detection

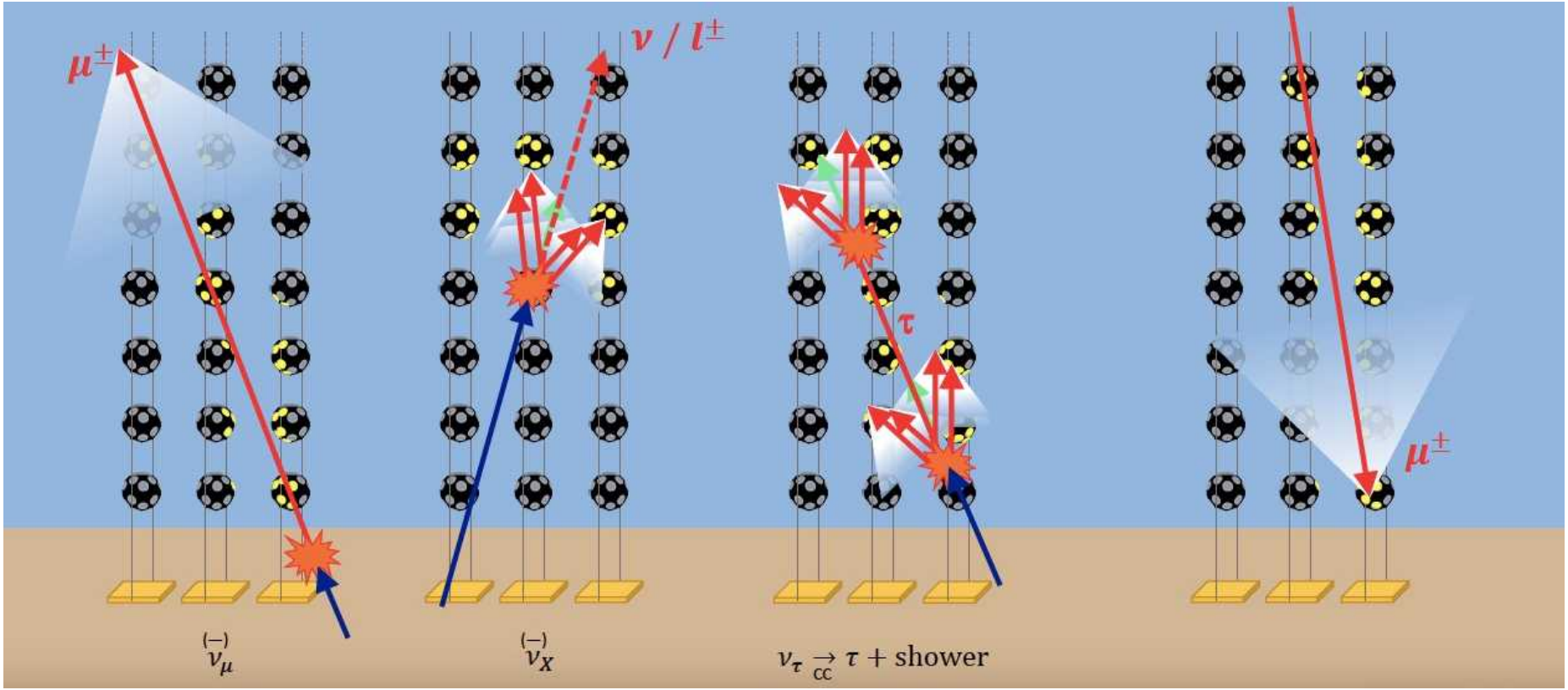
## Neutrino signals in KM3NeT

$\nu_\mu$ CC "track-like"
**good pointing**

$\nu_e$ CC or any $\nu$ NC
"shower-like"
**good energy resolution**

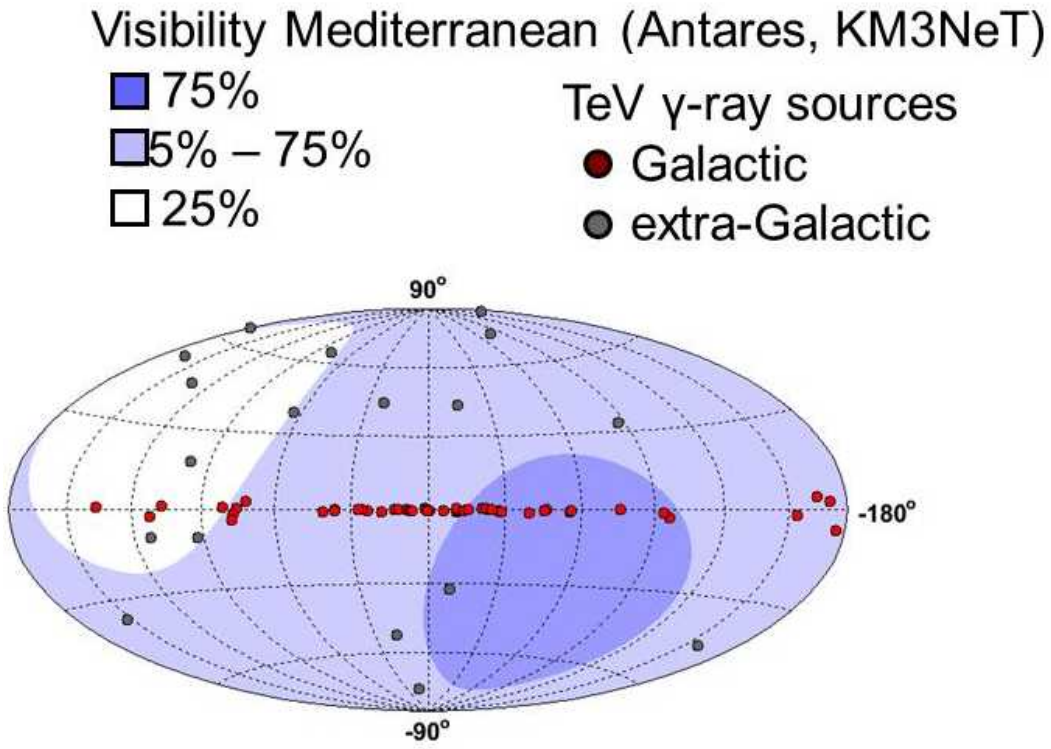
$\nu_\tau$ CC "double-bang"

Atmospheric $\mu$
**background for $\nu$**
**signal for Cosmic Ray studies**



# The Milky Way from KM3NeT's standpoint

## Observing the Galactic centre

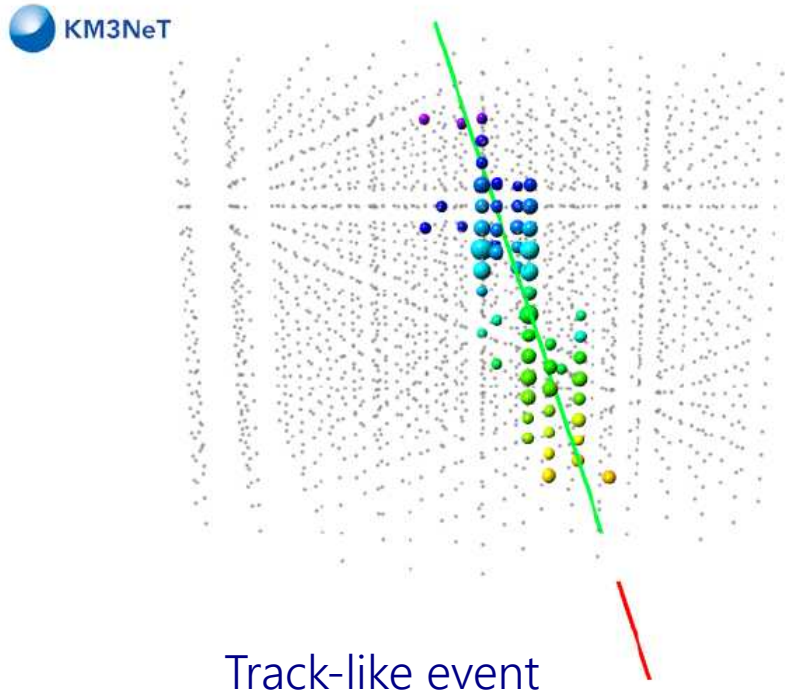



The Mediterranean is almost ideal for observing galactic sources + Logistically comfortable!

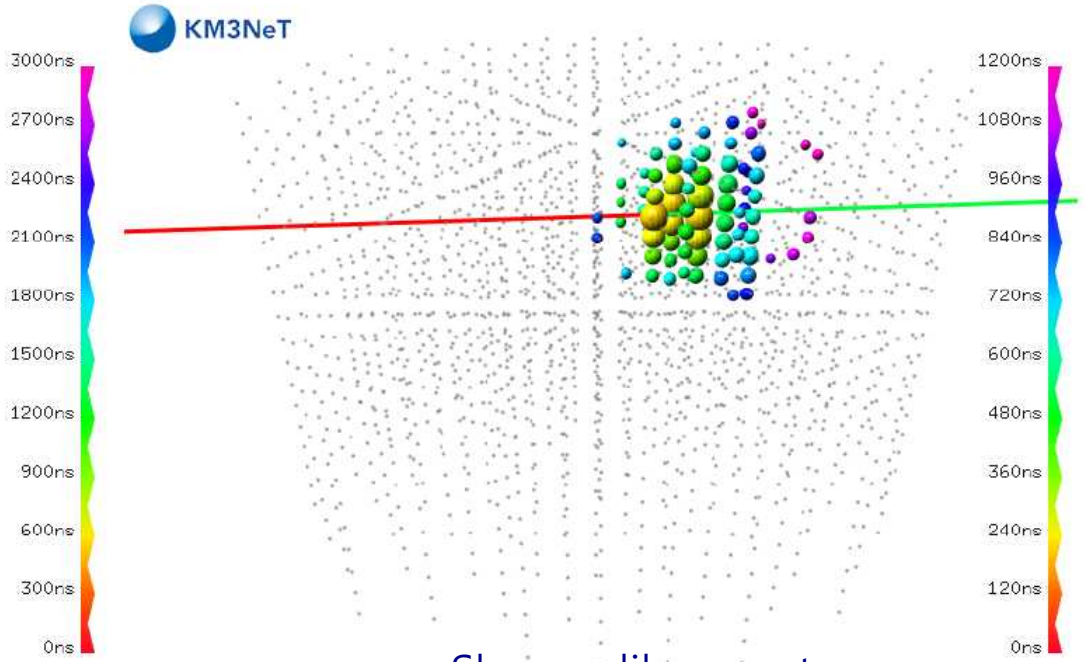
# Example events

## ARCA example events

Timing information encoded in colour: red means earlier, blue/purple means later



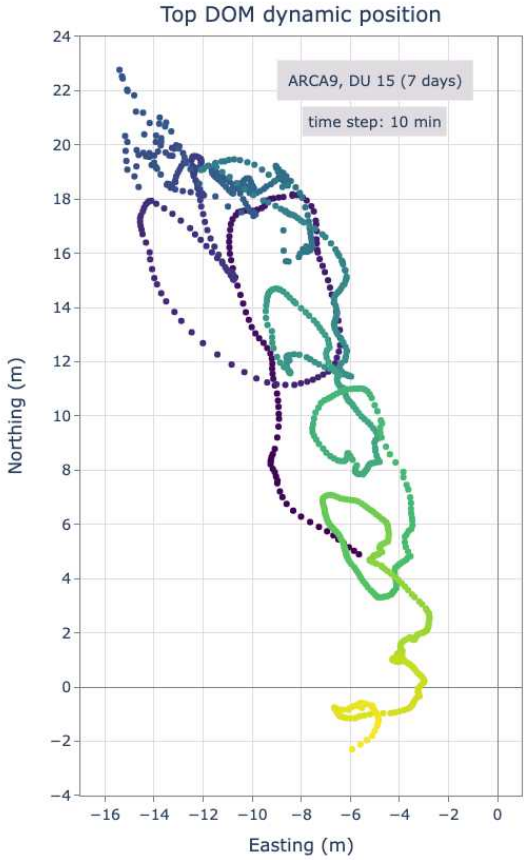

Track-like event

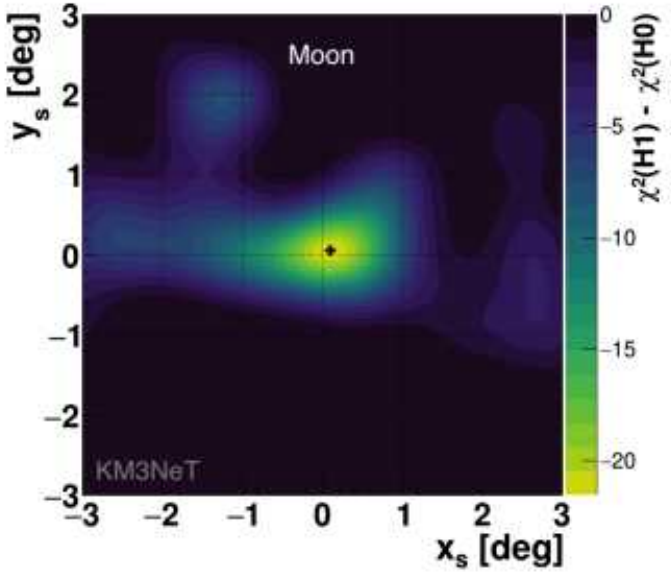


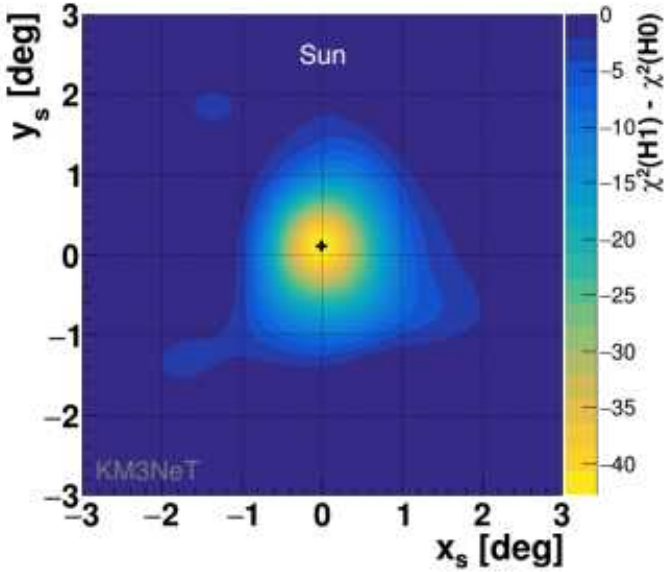

Shower-like event

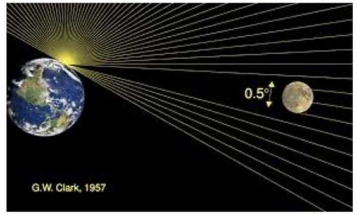
# Basic measurements

## Positioning & timing precision: Sun and Moon shadows



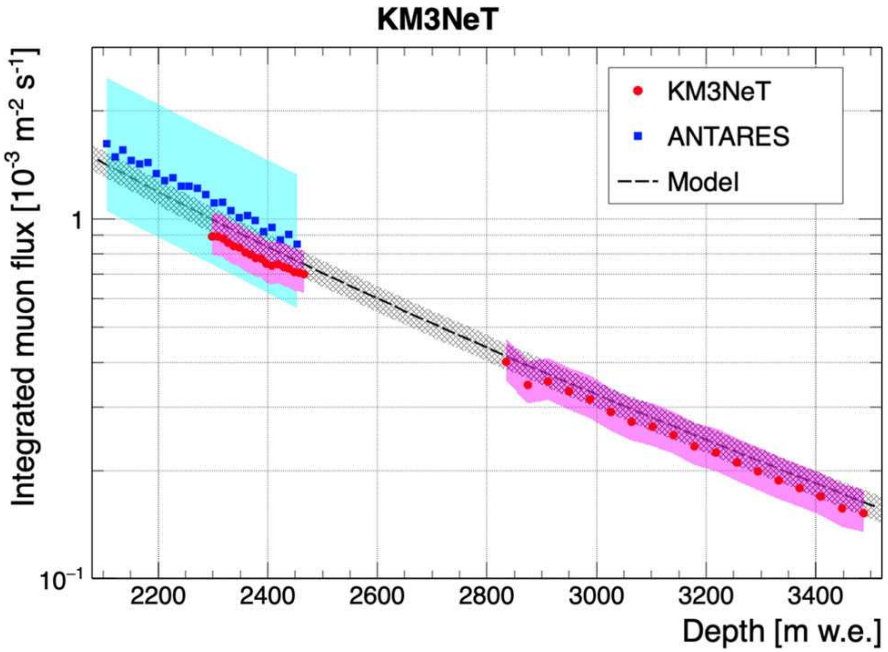



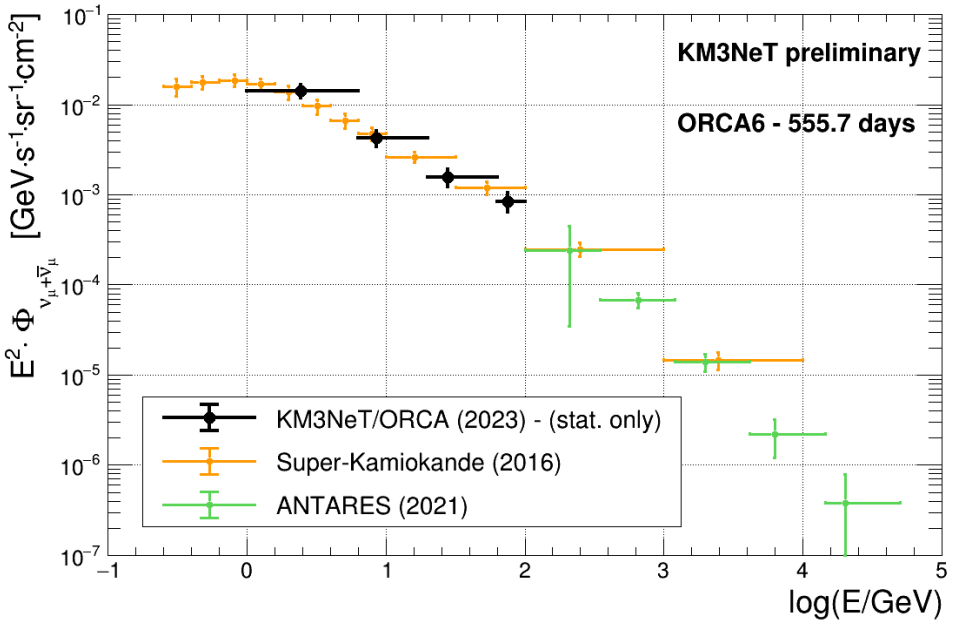

Timing better than 1 ns for inter-DOM calibration (using LED pulsers)
Tilt and heading for each DOM via tiltmeter/compass
Positioning accuracy better than 10 cm using acoustic beacons
Neutrino pointing accuracy ~ 0.1° at high energy (> 100 TeV)

# Basic measurements

## Muon-depth dependency and atmospheric muon neutrinos



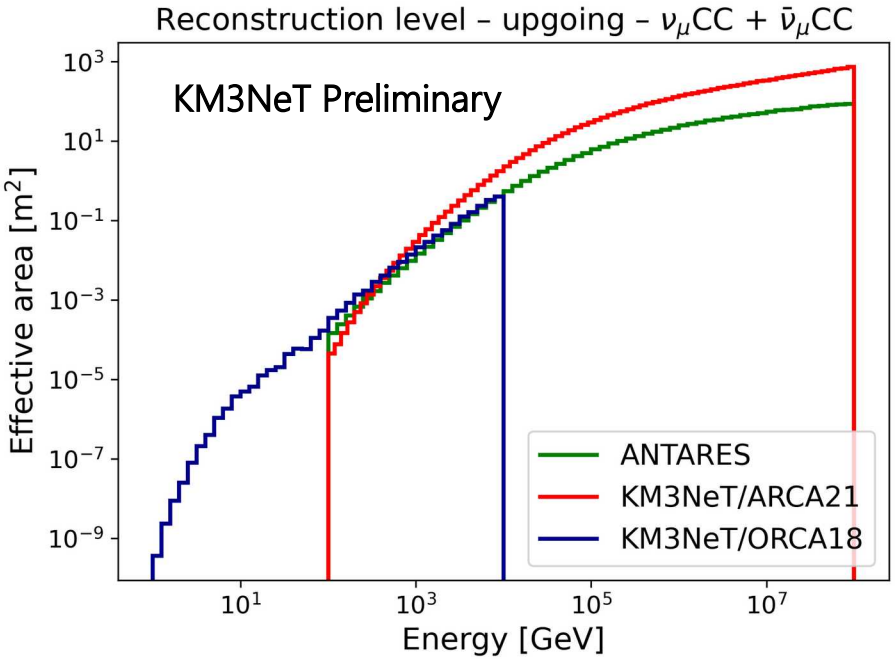

Muon-depth dependency from data



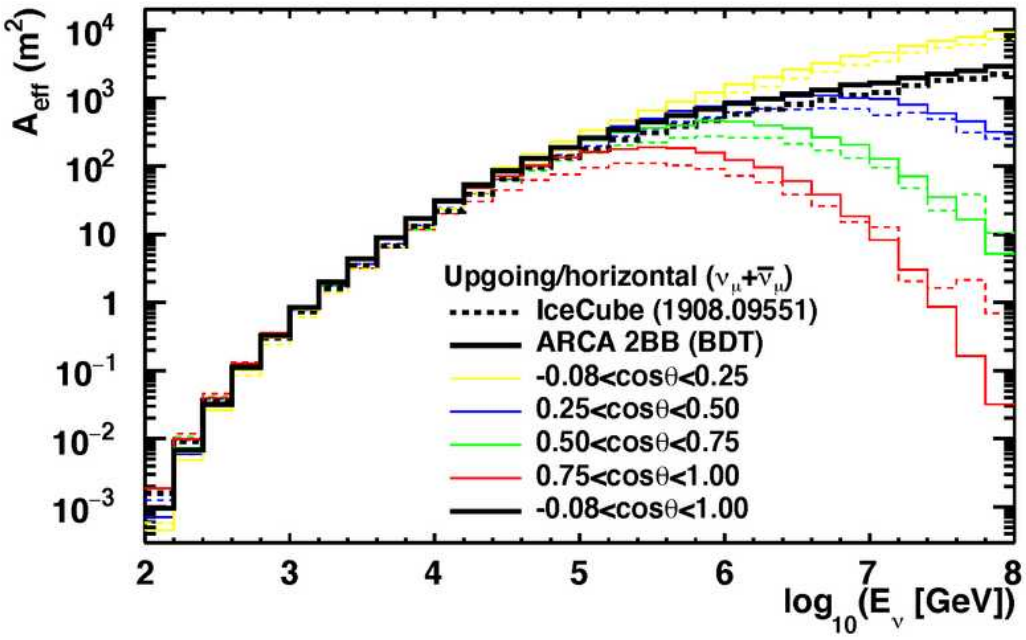

Atmospheric muon neutrino flux: data

# Detection capabilities

## Performance: now and future

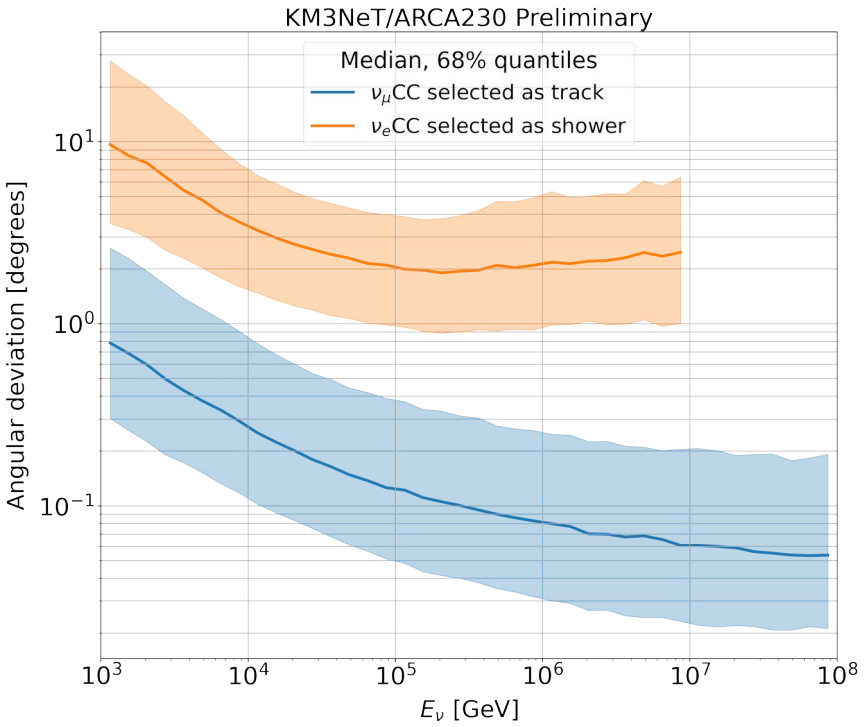



Effective area compared to ANTARES

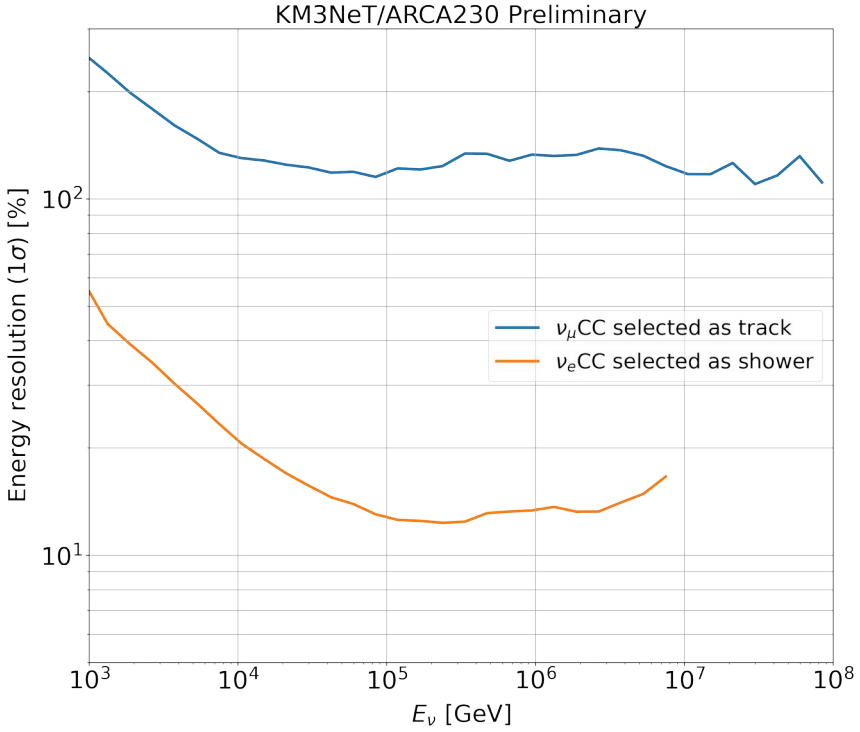



Effective area for full ARCA configuration

## Performances for full ARCA



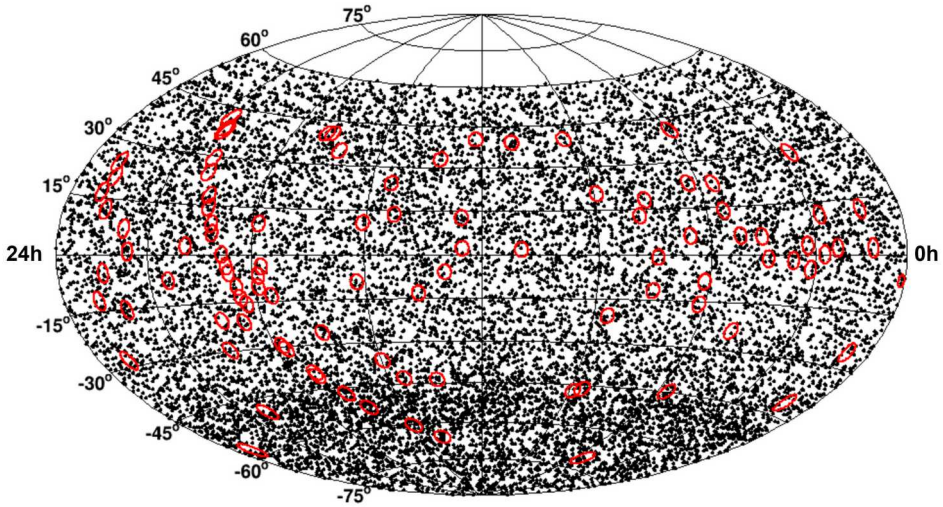

Aiming accuracy



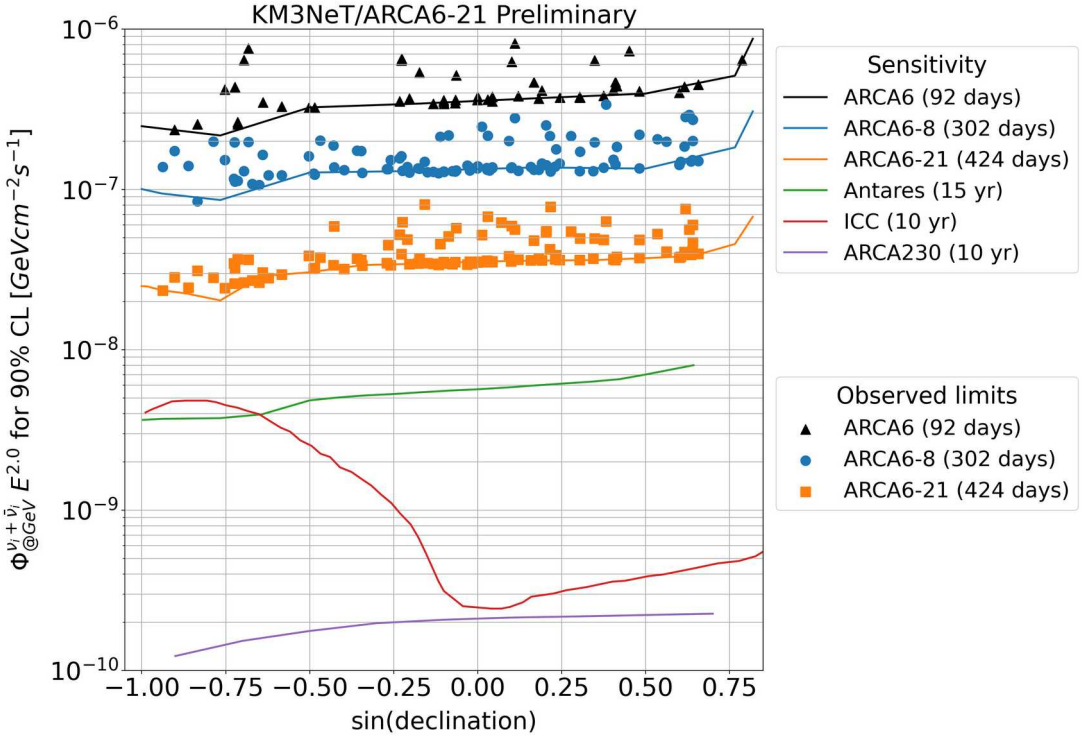

Energy resolution

# ARCA

## Status: Point source searches




Source from catalogue, 2.5° circle

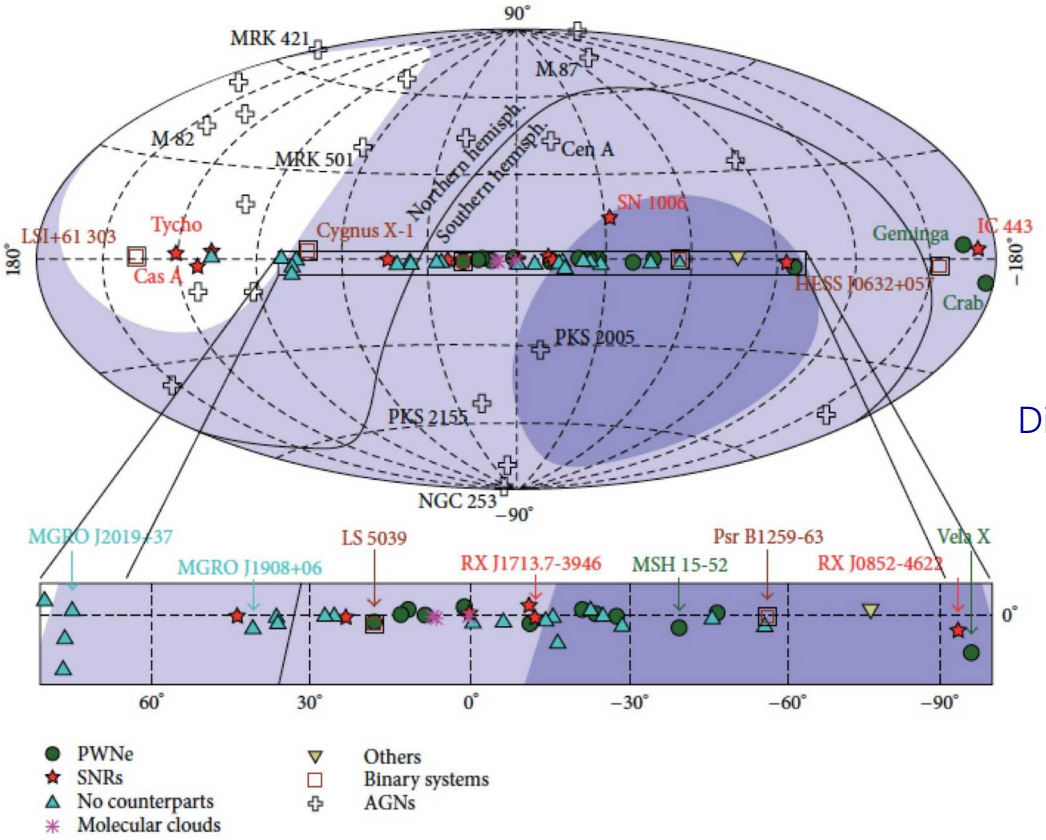


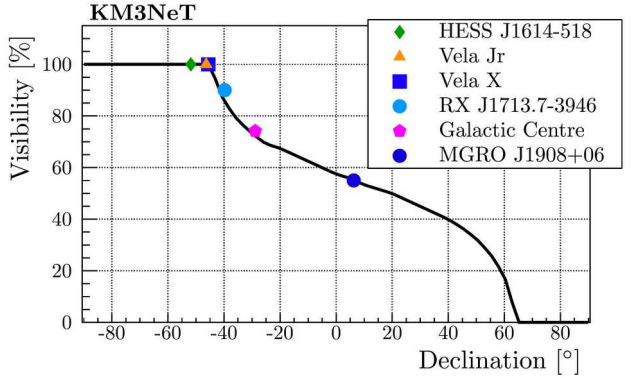

Time integrated point-like search for ν excess ($E^{-2}$)
100 sources selected: ANTARES + IC searches/alerts
Galactic (TeVCat - γ) + AGN (Active Galactic Nuclei)
Track channel, binned likelihood search

No source exceeding background yet

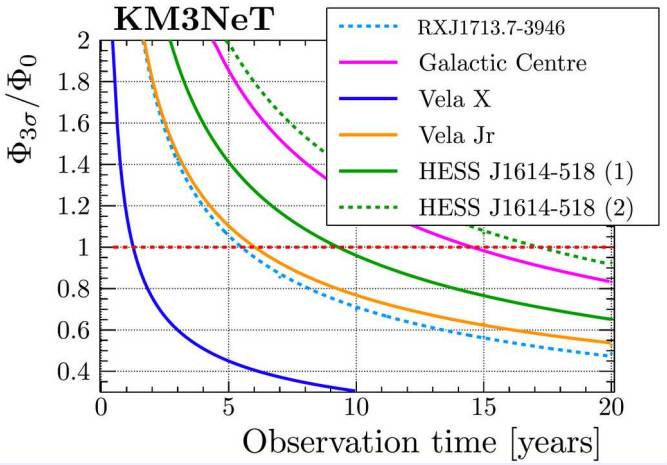
Background dominated by misreconstructed atmospheric μ

## Outlook: Point source searches



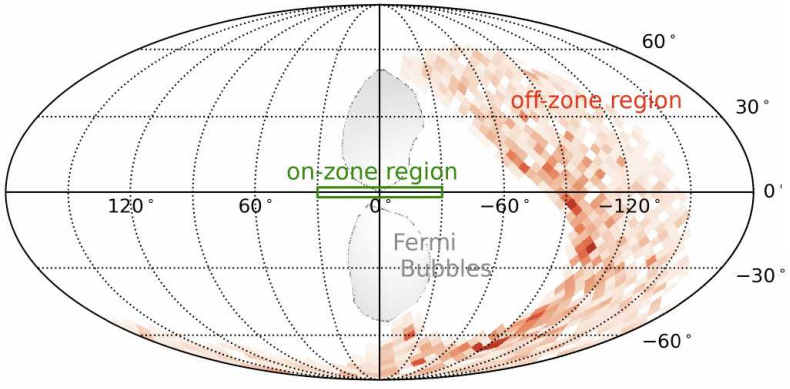

Discovery potential – $E^{-2.4}$ spectrum, hadronic scenario

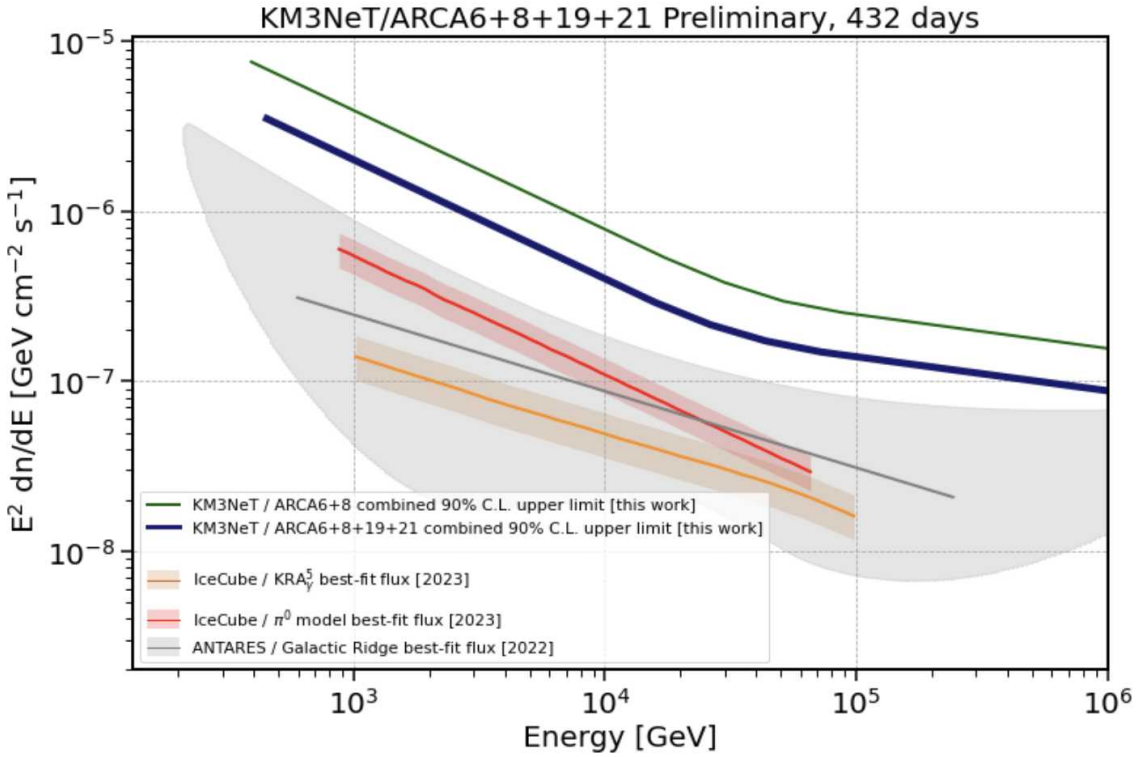


## Galactic Ridge: Status

Multiple sources of high-energy CR (Cosmic Rays) in the plane of the Milky Way
High-energy neutrinos should be produced via interaction of CR with the interstellar medium

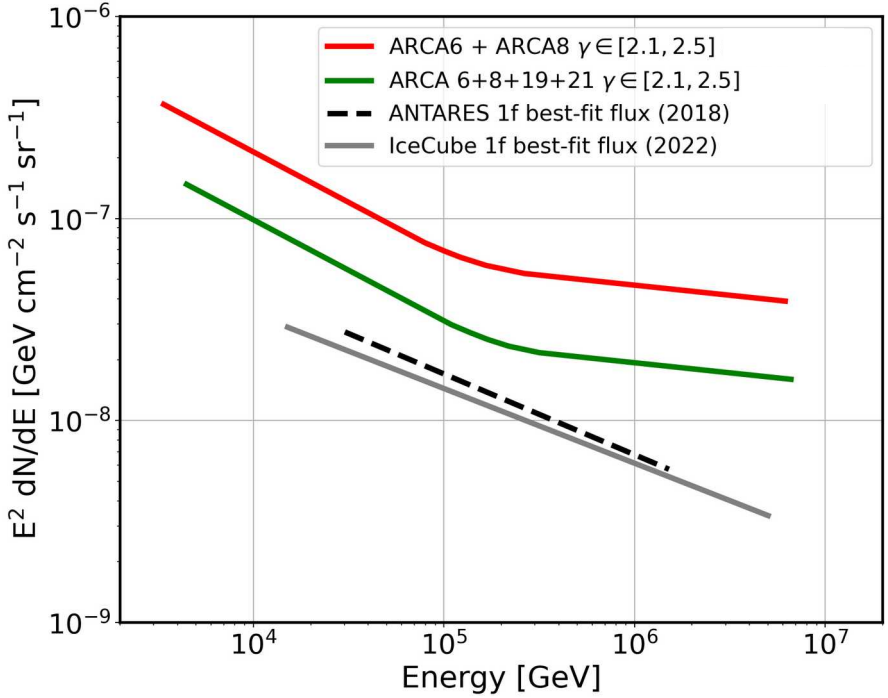
$p+N \rightarrow X+K^+,\pi^+ \rightarrow \ldots + \bar{\mu} \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$
$p+N \rightarrow X+K^-,\pi^- \rightarrow \ldots + \mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$



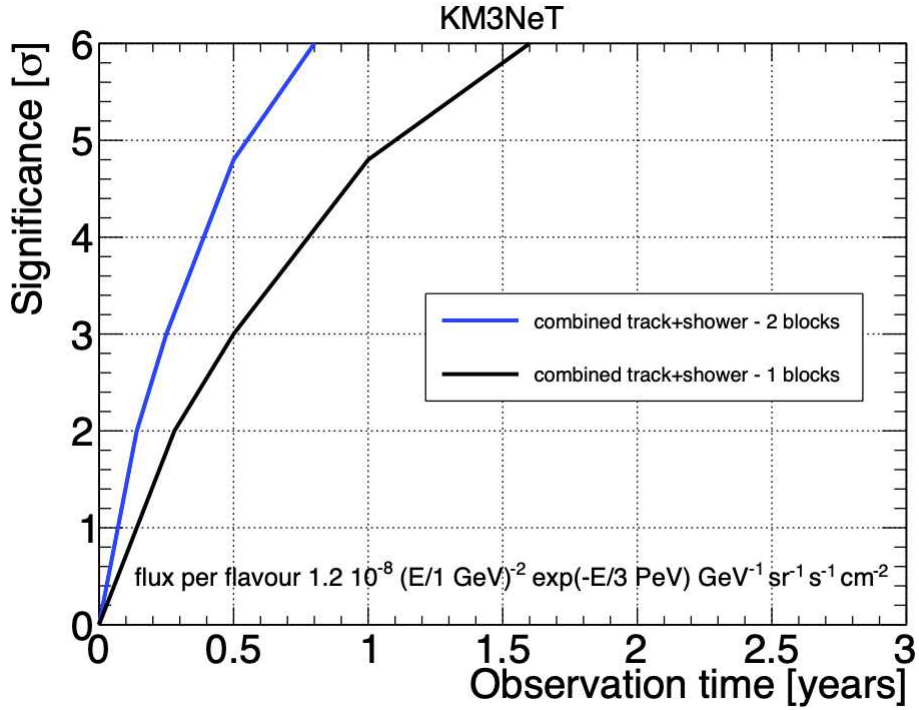




- ARCA6+ARCA8+ARCA19+ARCA21 data
- ON region: the Galactic ridge |Lgal|<30°, |Bgal|< 2°
- OFF region obtained by shifting the ON region and avoiding the Fermi Bubbles

## All-sky diffuse emission searches: Status & Outlook

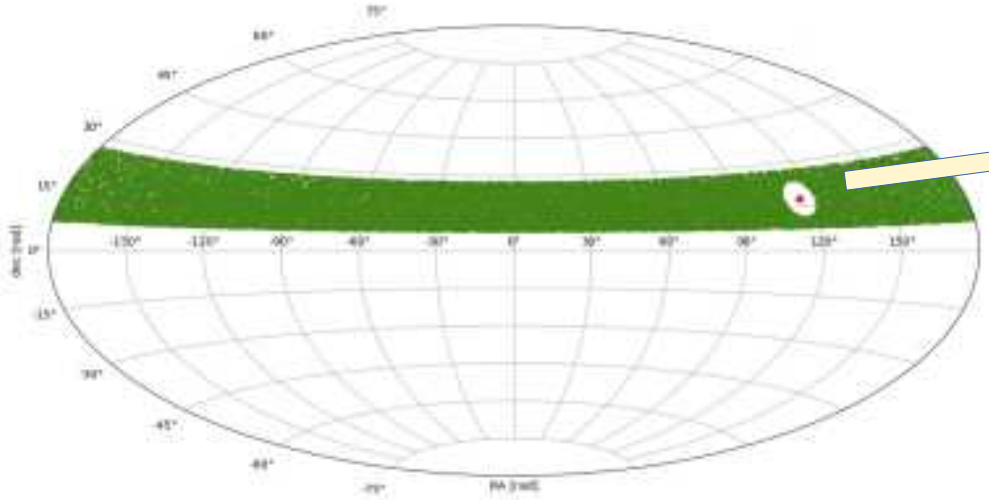


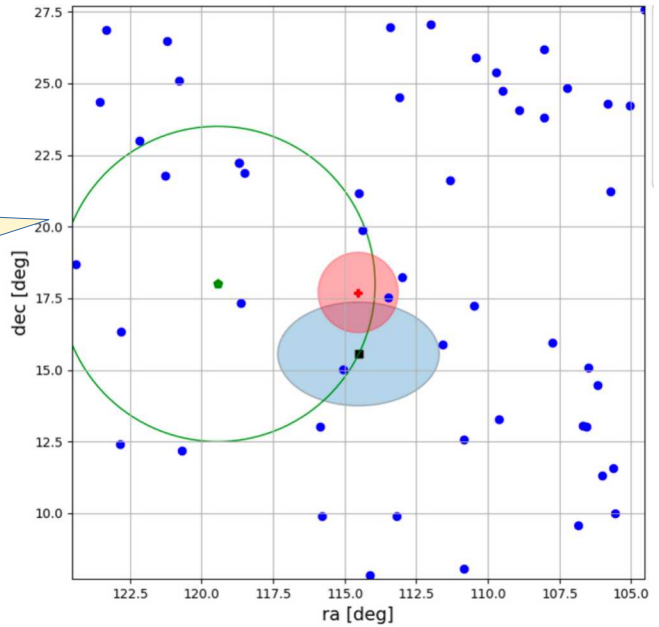

Simulated flux of $\nu_\mu = 1.44\times10^{-18}\ (E/100\text{TeV})^{-2.37}$ [GeV$^{-1}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$] (IceCube 10 yr spectrum)




5σ detection in ~ 1 year for 1 block
or in ~0.6 year for 2 blocks

## Status: Combined searches / alert follow-ups



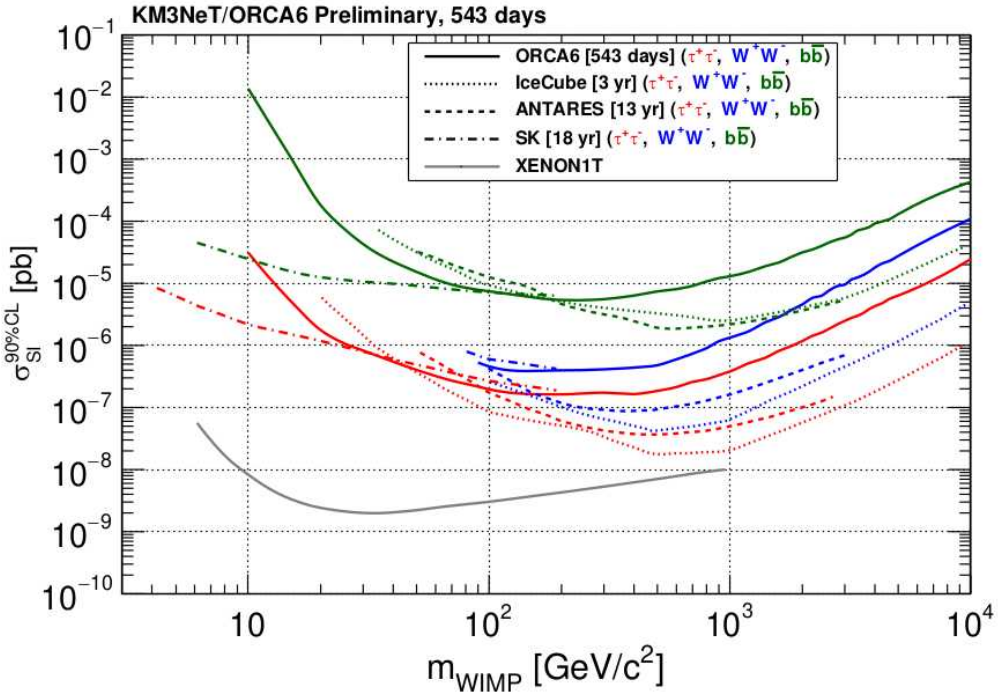



Actively following up alerts of Blazars and AGNs (includes also ORCA)

No confirmation found yet

Fermi PKS 0735+17 position
IceCube-211208A alert, 90% containment
Baikal shower event, 50% containmnet
1.4° cone, ON Zone
KM3NeT/Arca data
Atm muon contamination 99%
Median $E^{-2}$ cosmic neutrino angular resolution = 1.7°

# Dark Matter searches: Status

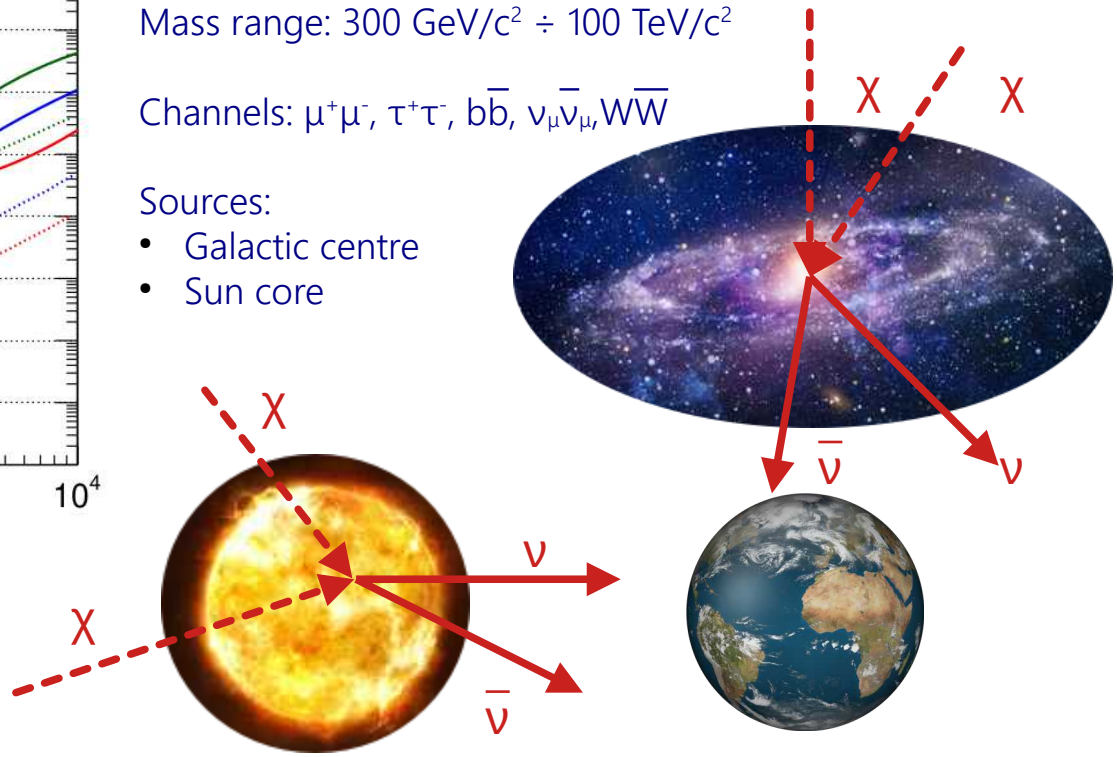



Search for WIMPs annihilating

Mass range: 300 GeV/$c^2$ ÷ 100 TeV/$c^2$

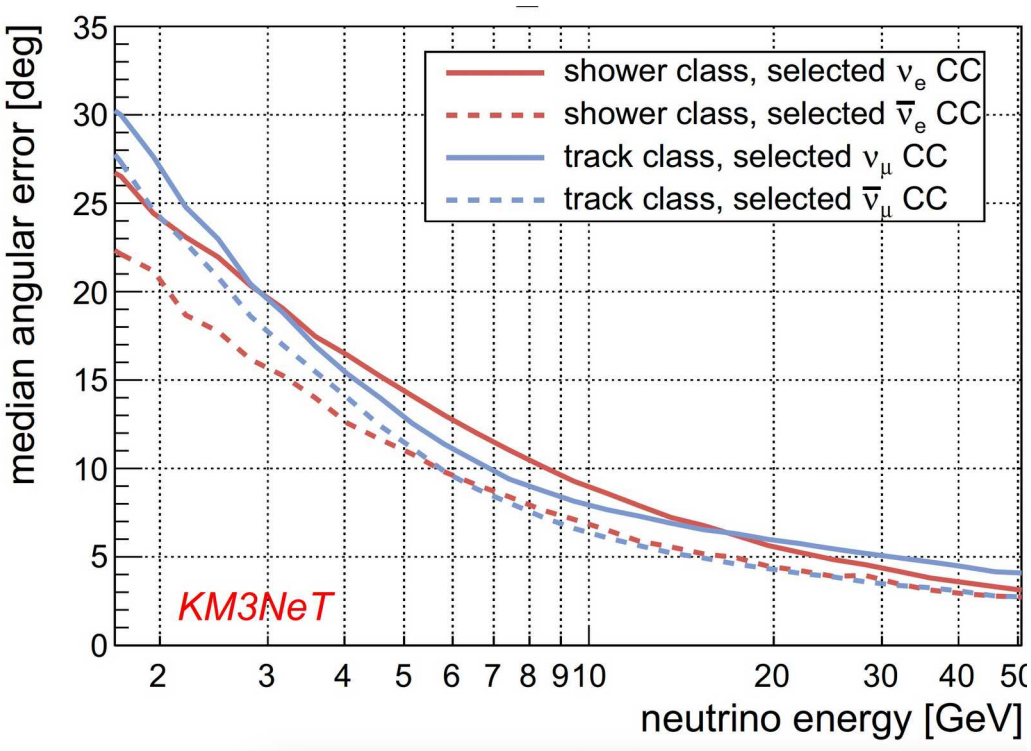
Channels: $\mu^+\mu^-$, $\tau^+\tau^-$, $b\bar{b}$, $\nu_\mu\bar{\nu}_\mu$, $W\overline{W}$

Sources:
- Galactic centre
- Sun core

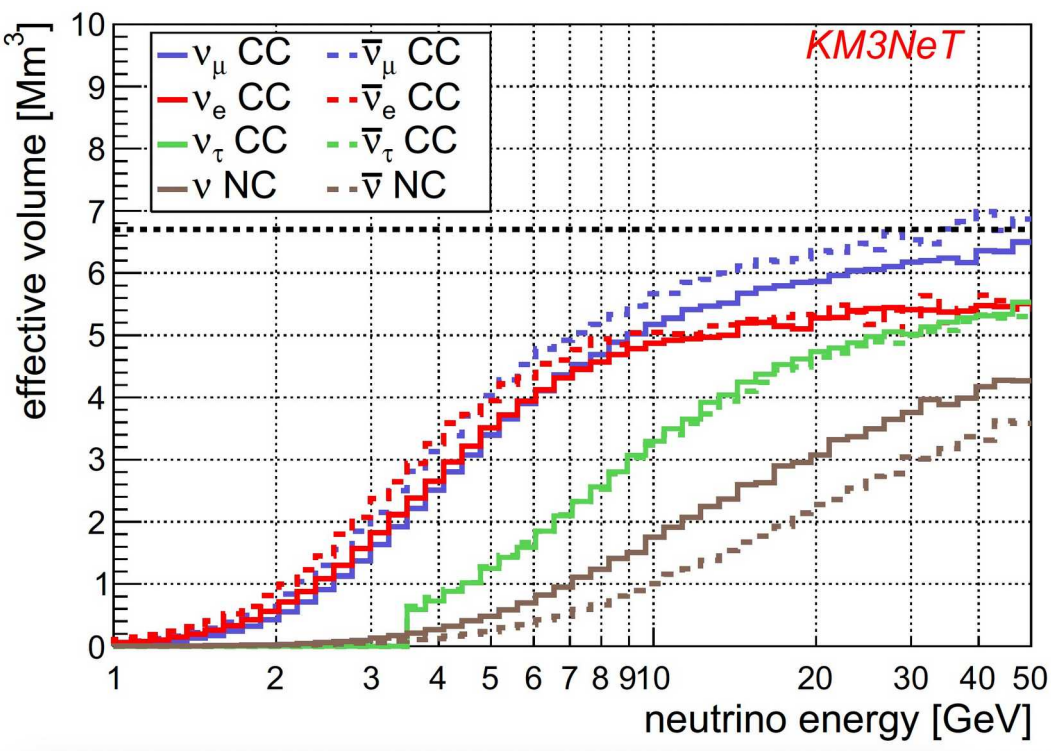


# ORCA measurements

## Performances



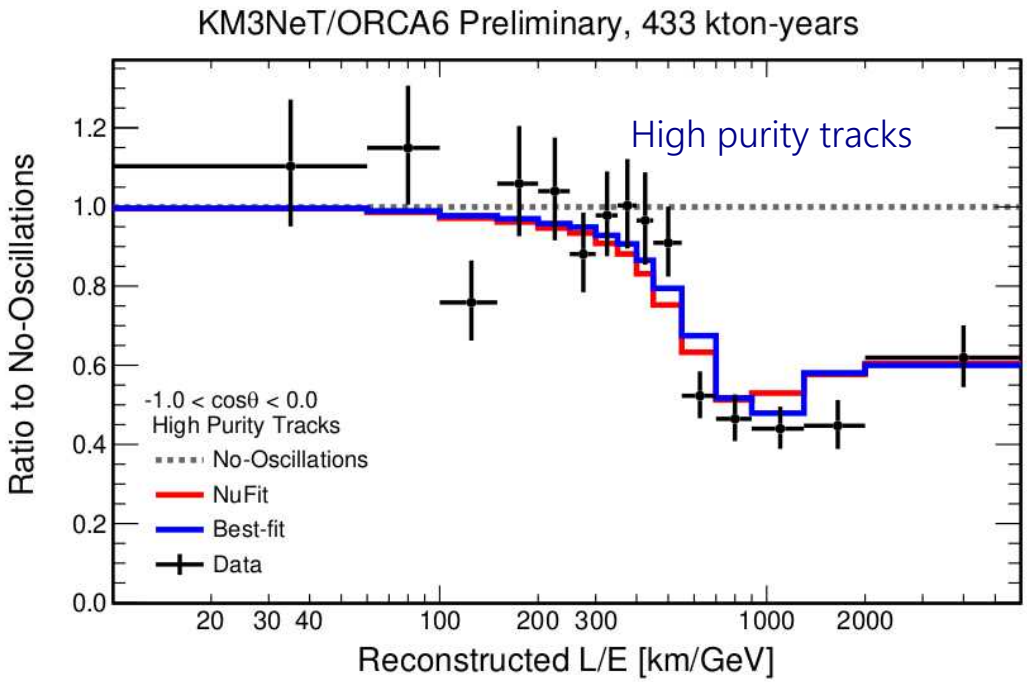

Aiming accuracy: dominated by neutrino scattering kinematics

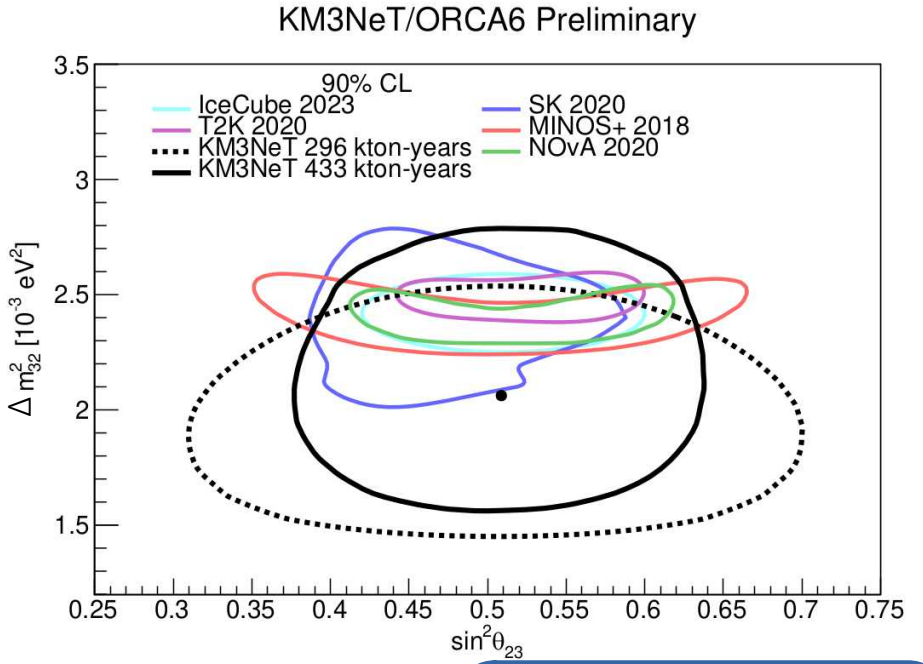



Effective volume as a function of neutrino energy

# ORCA measurements

## Neutrino oscillations, 1 year: Status




KM3NeT/ORCA already able to measure neutrino oscillations

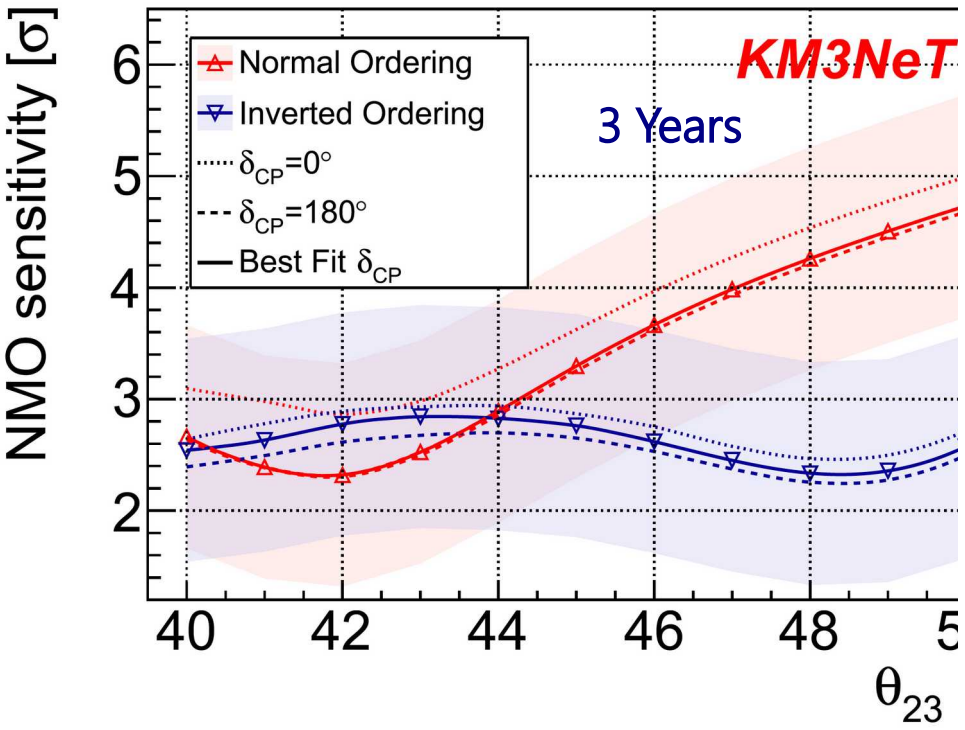
Oscillation preferred with 5.9σ CL over the hypothesis of no oscillations

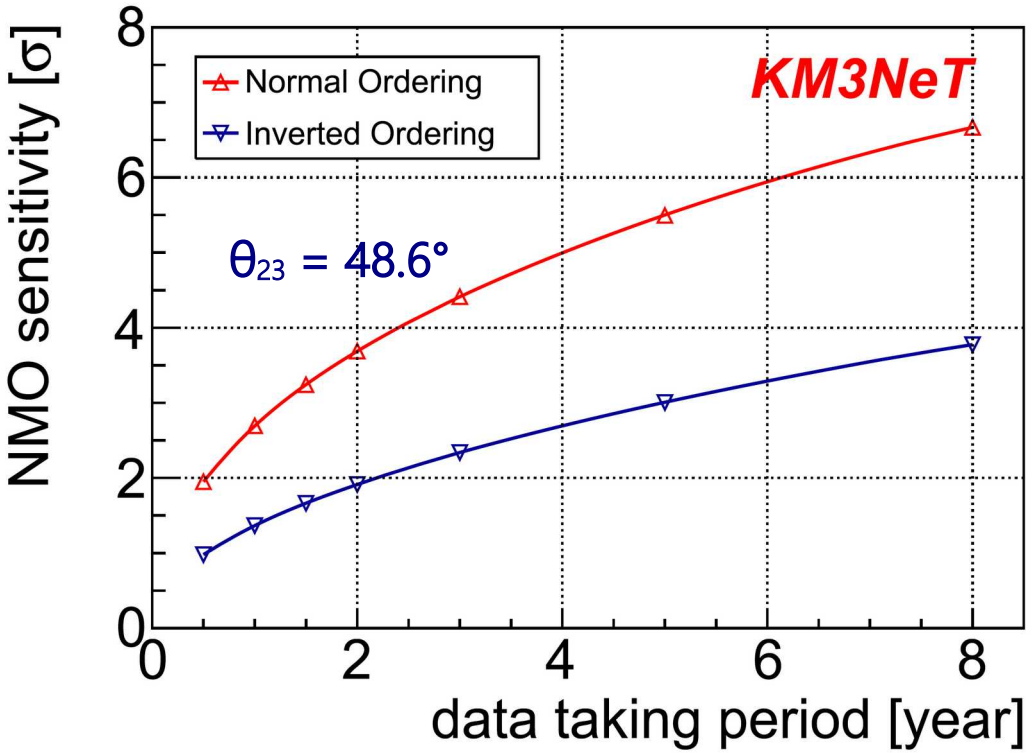
Normal mass ordering preferred

$$\sin^2\theta_{23} = 0.51^{+0.06}_{-0.07}$$
$$\Delta m^2_{31} = 2.14^{+0.36}_{-0.25} \times 10^{-3}\, eV^2$$
$$2\log\left(\frac{L_{NO}}{L_{IO}}\right) = 0.9$$

# ORCA outlook

## Neutrino mass ordering: Outlook



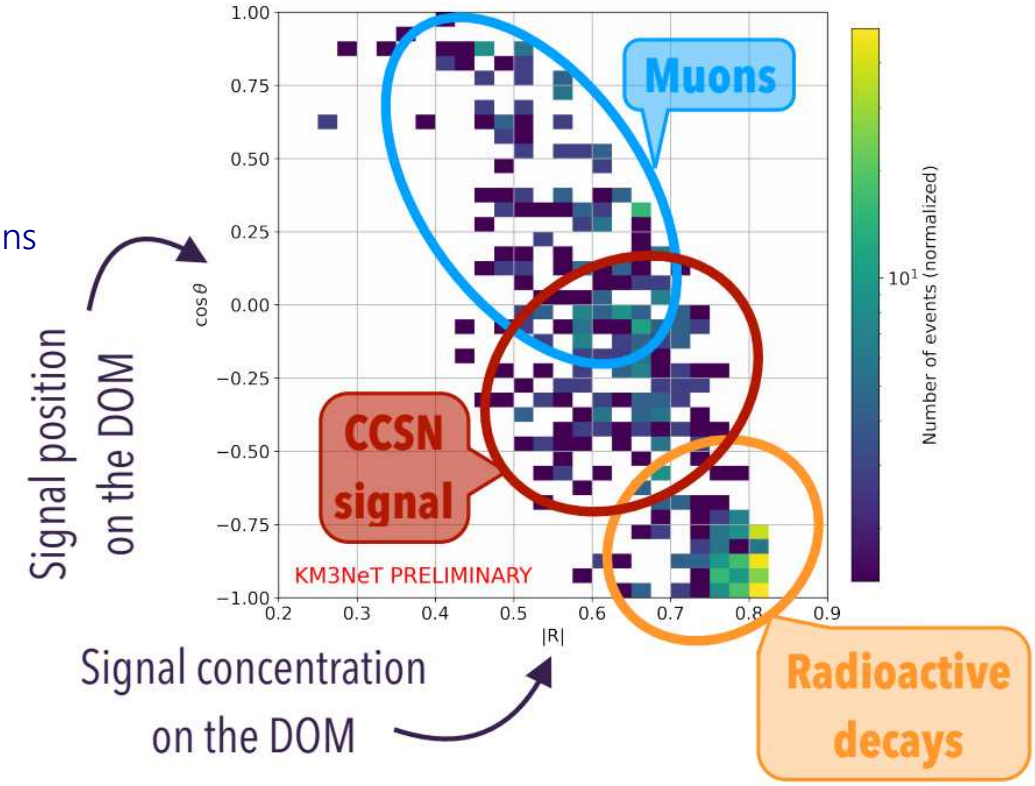

Expected performances with **full detector**

# ARCA+ORCA outlook

## Supernova neutrinos: Status

Neutrinos from core-collapse Supernovae:

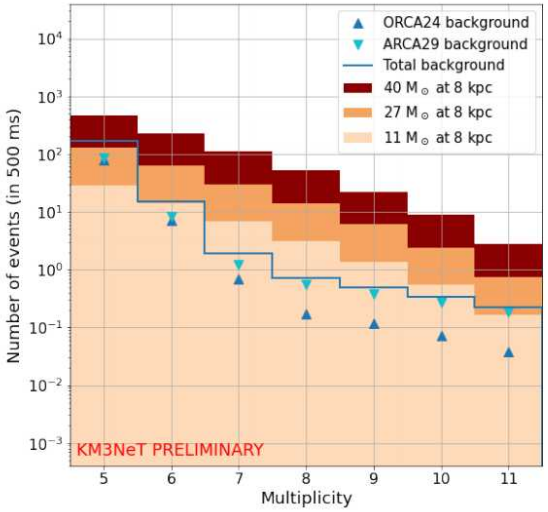
Low energy neutrinos
Multiple signals in a single DOM
Competition with $^{40}$K in seawater, atmospheric muons
muons from neutrino interactions



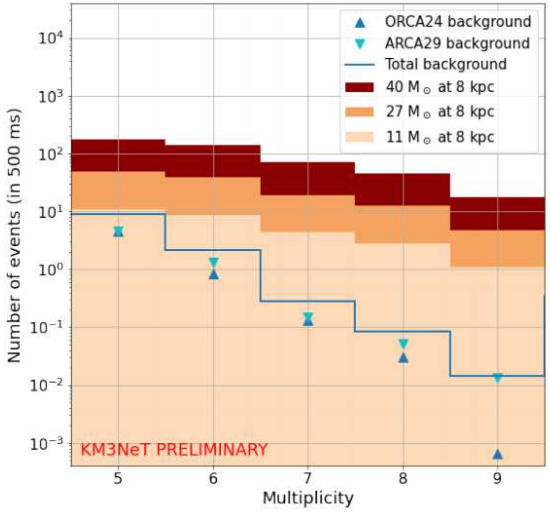
# ARCA+ORCA outlook

## Supernova neutrinos: Status & Outlook

### Enhancement of detection using Boosted Decision Trees

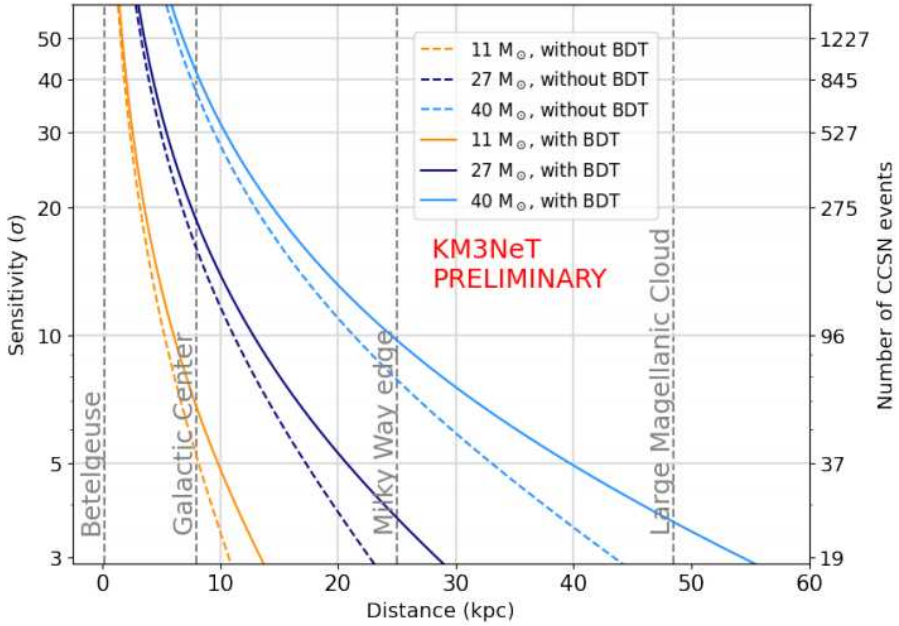



Without BDT cuts




With BDT cuts

Discrimination using average direction, signal concentration, multiplicity and Time-over-Threshold (signal intensity)




Expected observational capabilities combining ARCA**29**+ORCA**24**

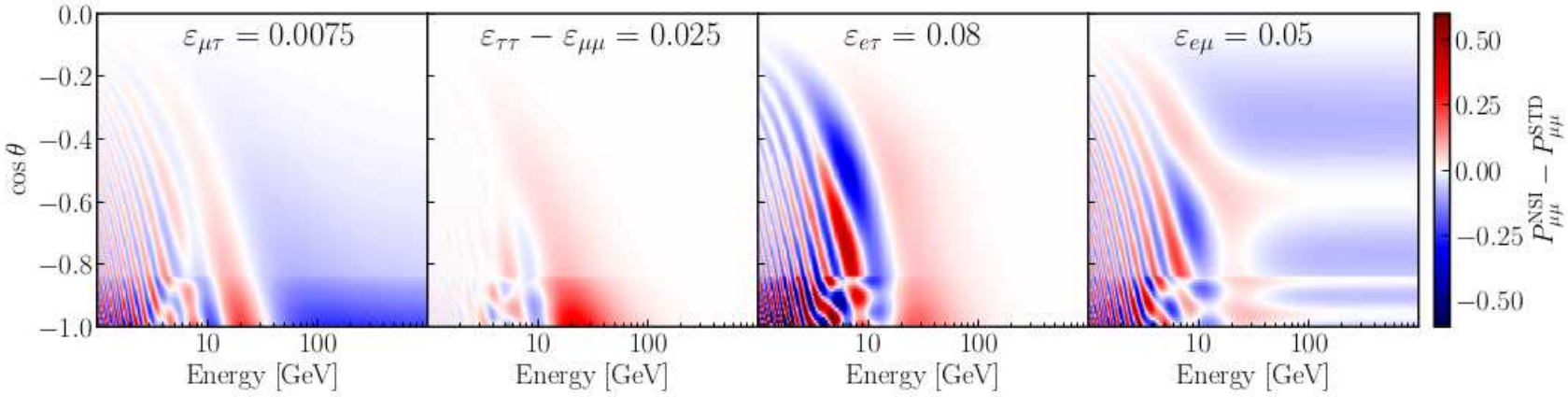
# Non Standard Interactions

Effective Hamiltonian of
4-fermion interaction model

$$\mathcal{H}_{\text{eff}} = \frac{1}{2E}\mathcal{U}\begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{bmatrix}\mathcal{U}^{+} + A(x)\begin{bmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{bmatrix}$$

Usual interaction potential term

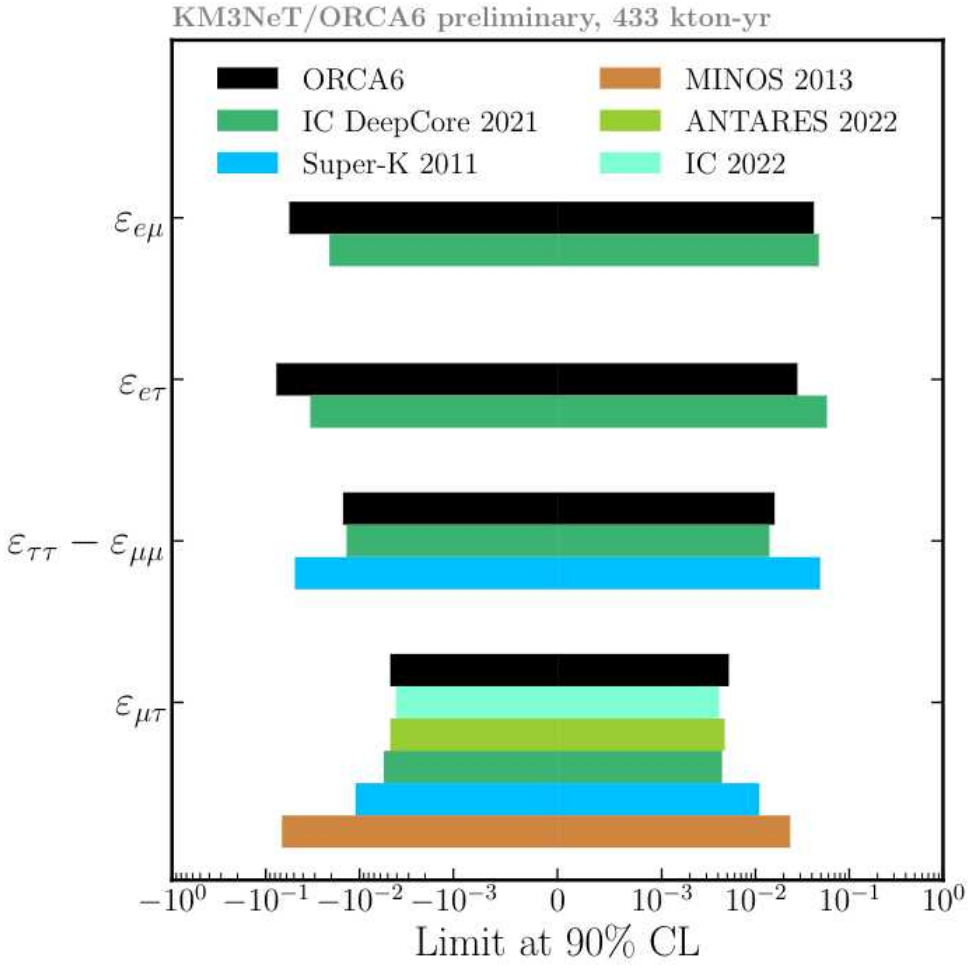
$$A(x) = \sqrt{2} G_F n_e(x)$$




Difference in $\nu_\mu$ survival probability (NSI-Standard)

## Non Standard Interactions

ORCA is already able to effectively constrain parameters for Non Standard Interactions



# Conclusions…?

KM3NeT is in an exciting stage

Construction

Data-taking

Point searches

Neutrino mass hierarchy

KM3NeT detectors are steadily growing!

Data quality assessment

Expect frequent updates!

Neutrino Oscillation

Machine Learning

All-sky

Dark Matter

Massive data processing

"Stay tuned!"

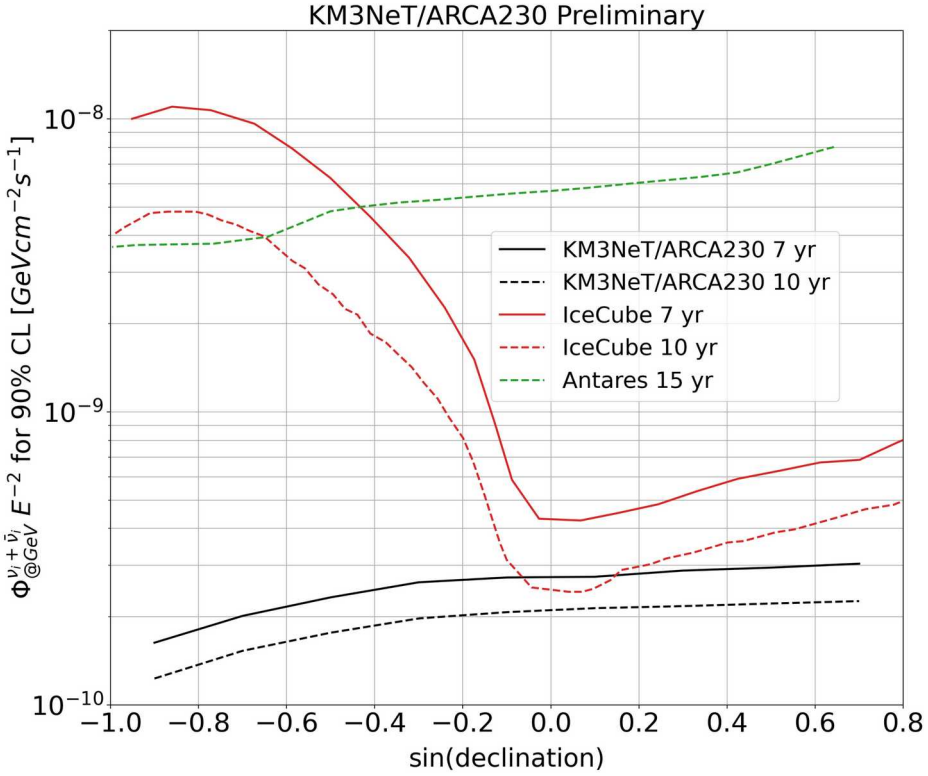
"Thanks for your attention!"

# Backup

BACKUP

# ARCA

## Point source sensitivitv

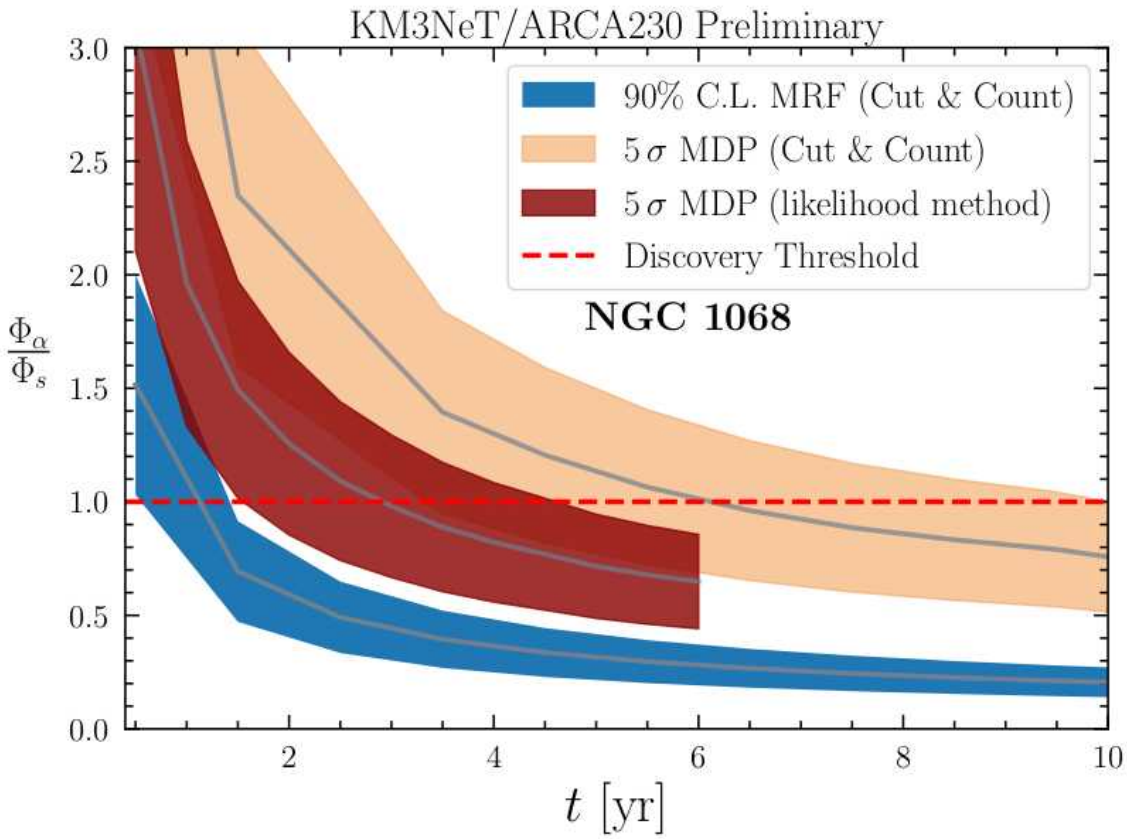



## Spectral index 2.0

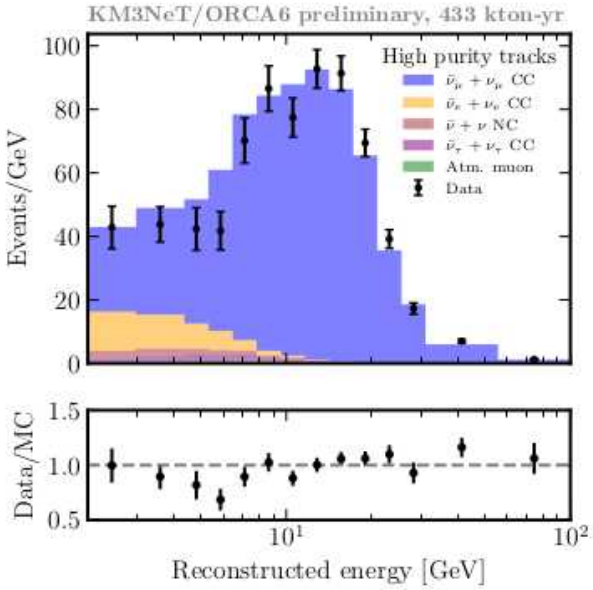
## Point source sensitivity

MRF: model rejection factor

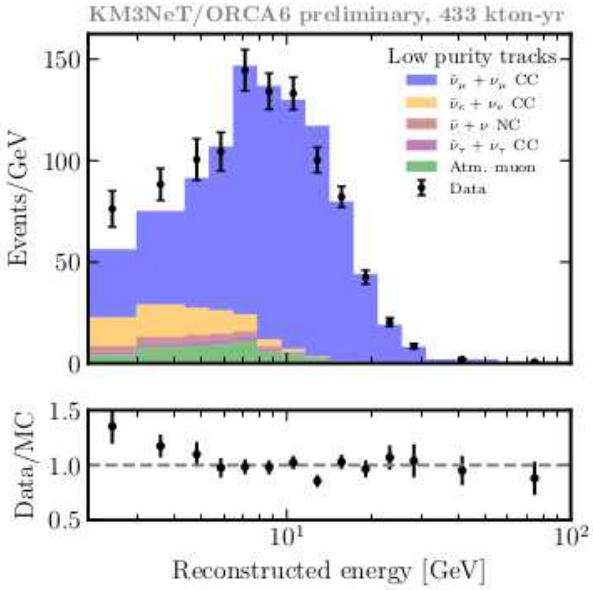
MDP: model discovery potential



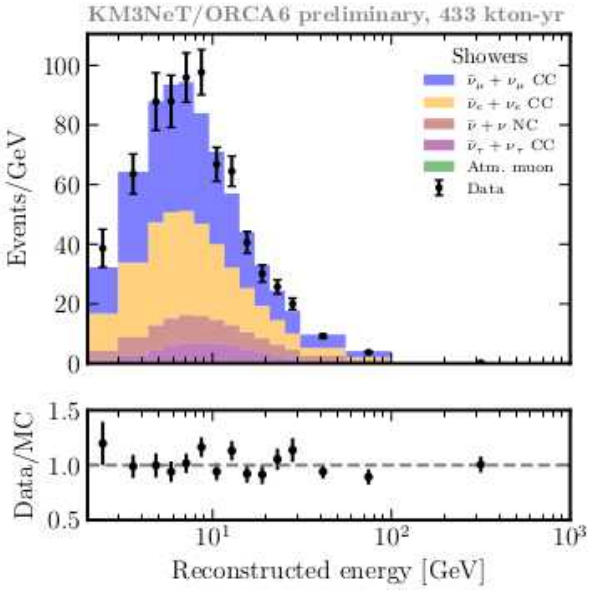
## ORCA events




High purity tracks




Low purity tracks




Showers

## Atmospheric temperature – muon flux

Higher temperature →
lower density →
higher muon yield from
pion and kaon decays