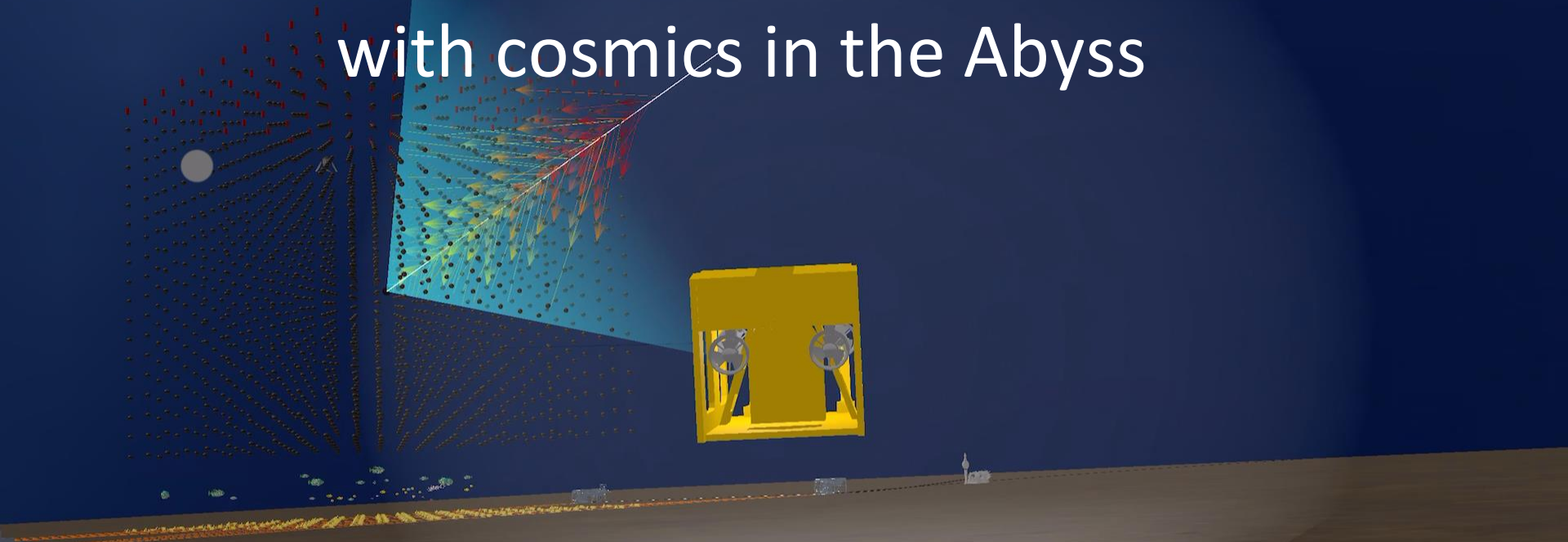


637 ns

Menu: Scene Settings



KM3NeT: Astroparticle and oscillations research with cosmics in the Abyss

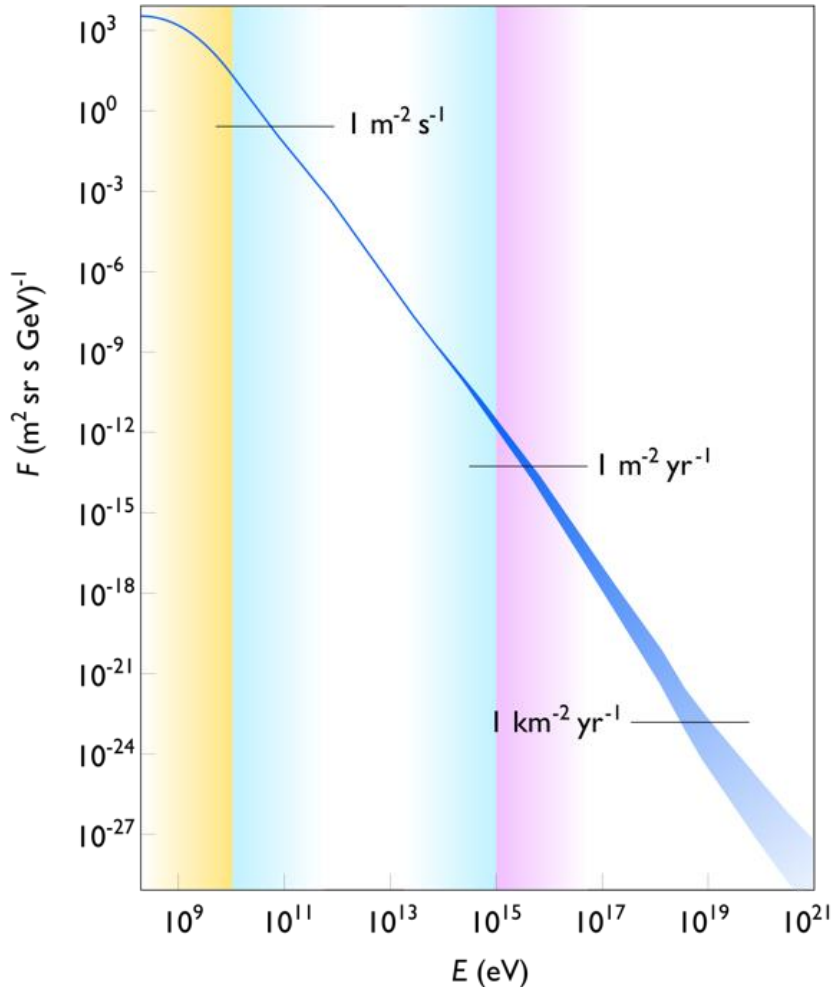


KM3NeT Town Hall Meeting
Catania, 20/9/22
Paschal COYLE, CPPM



Motivations for neutrino astronomy

Main question: what is the origin and the role of the cosmic rays in the Universe ?

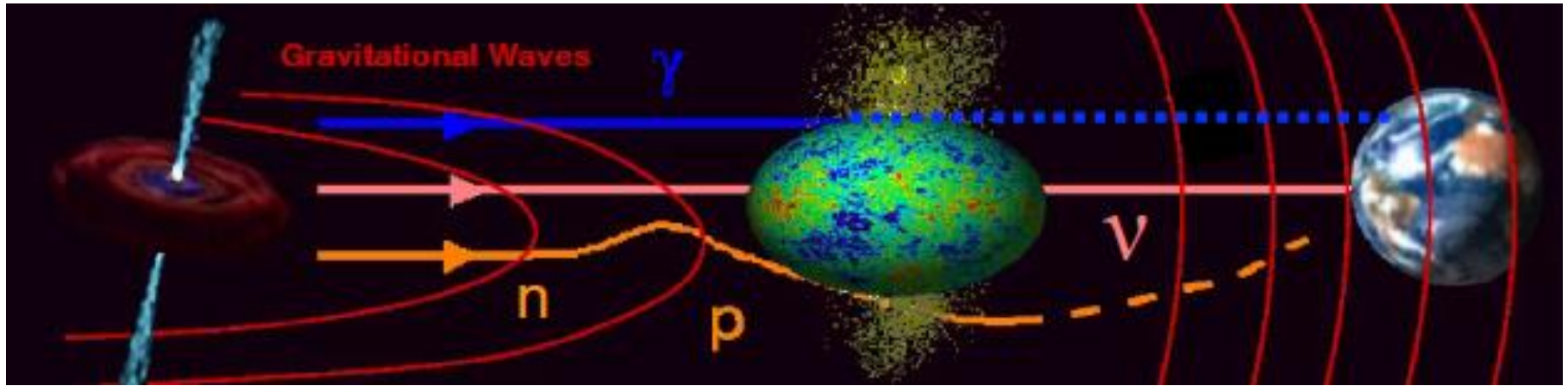


→ Discover ~100 years ago but still unknown origin
→ Spectrum over 32 orders of magnitude

→ Mysteries at the ultra high energies $> 10^{20}$ eV,
which acceleration mechanism ?
Which sources ?
Which cosmic evolution ?

→ Connection to the other messengers (ν , γ , GW)
→ At the heart of the non-thermal astronomy

Neutrinos: cosmic messengers



Neutrinos: neutral, stable, weakly interacting

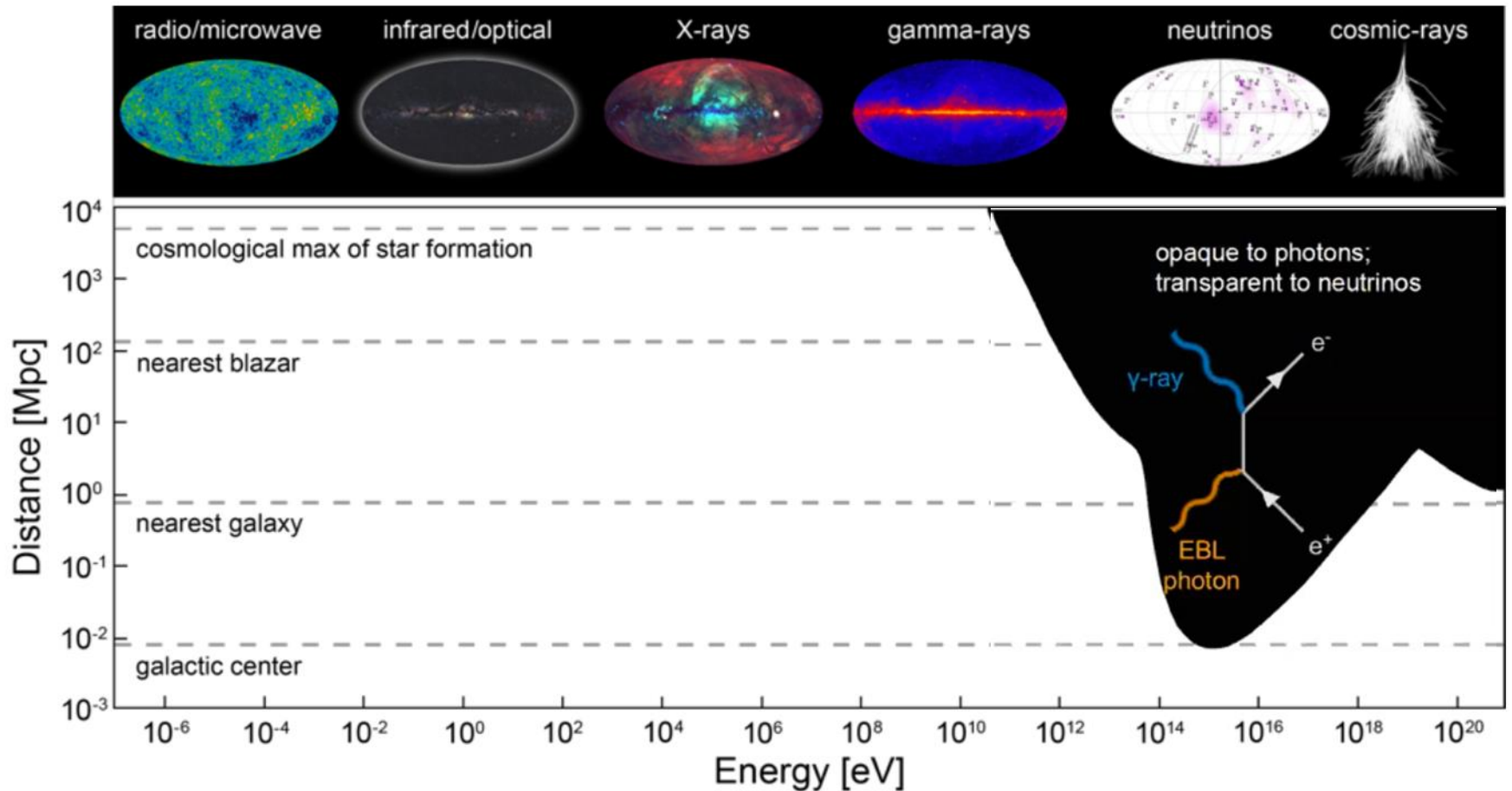
- not absorbed by background light/CMB
- not absorbed by matter
- not deviated by magnetic fields
- ☉ access to cosmological distances
- ☉ access to dense environments
- ☉ astronomy over full energy range

‘Smoking gun’ signature for hadronic processes

Correlated in time/direction with electromagnetic and gravitational waves

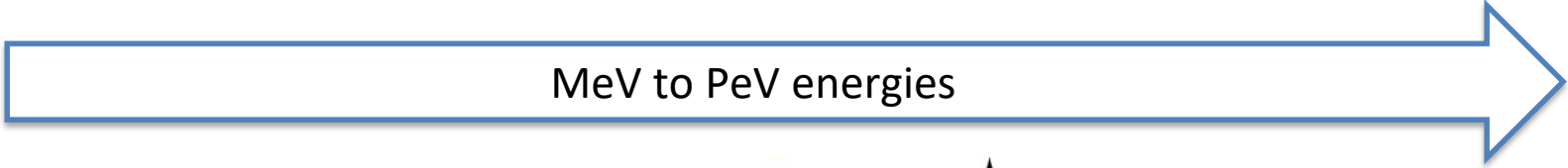
New window of observation on the Universe

A new window on the Universe

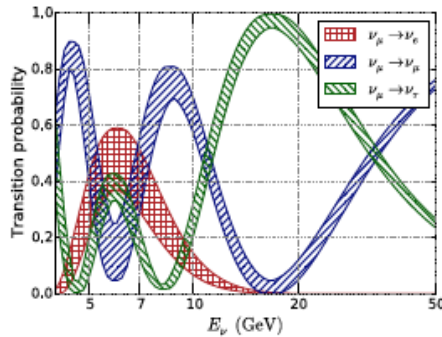


The Universe is opaque to EM radiation above 10-100 TeV,
but not to neutrinos

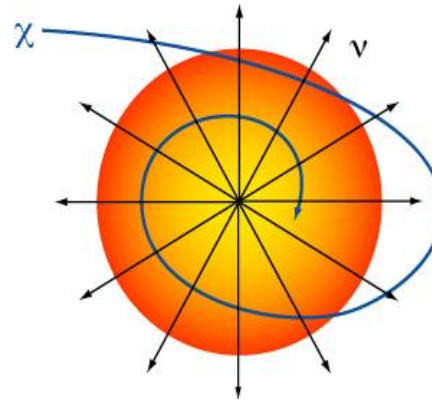
Neutrino telescopes: science



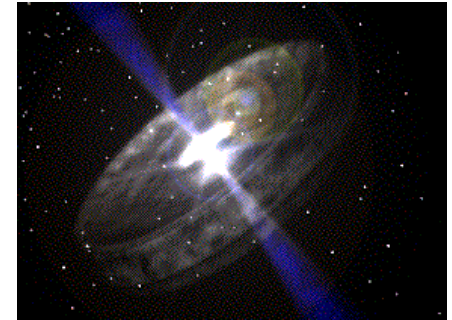
Supernova
Solar flares



Atmos neutrinos
 ν oscillations
 ν mass ordering
Sterile, NSI, ...



Dark matter
Monopoles,
Nuclearites,...



Cosmic neutrinos
Cosmic rays
Origin and production
mechanism of HE CR



+ oceanography, biology, bioacoustics, seismology,...

Neutrino Sources?

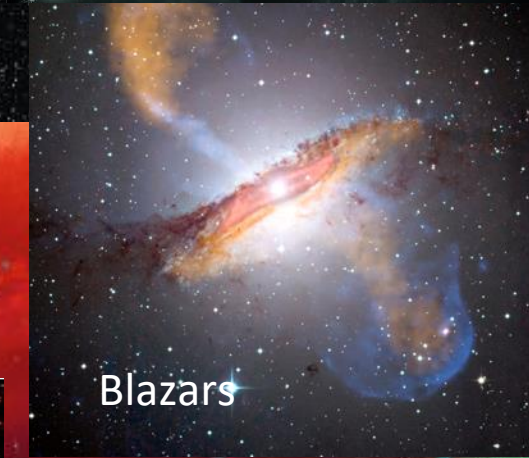
Supernova Remnants



Kilonova



Blazars



Supernova



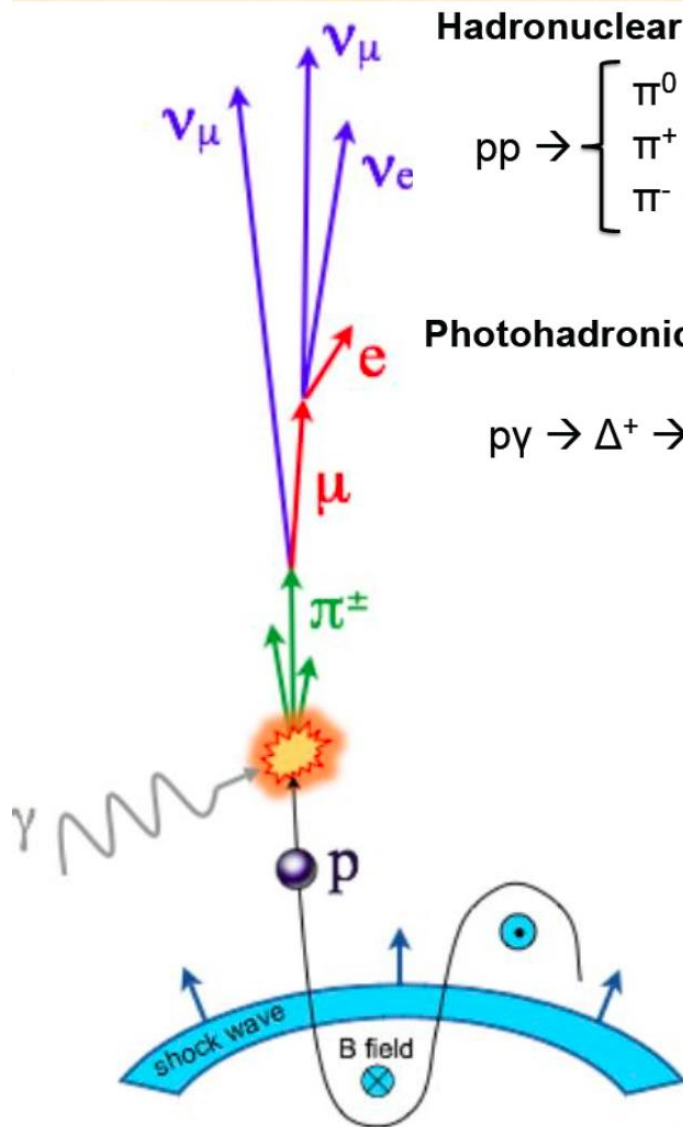
Dark matter



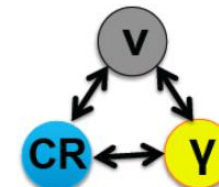
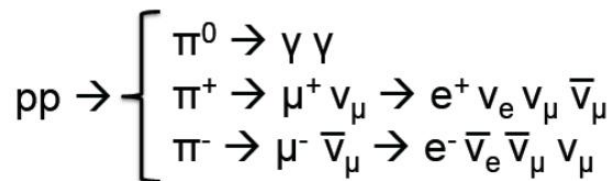
Gamma ray bursts



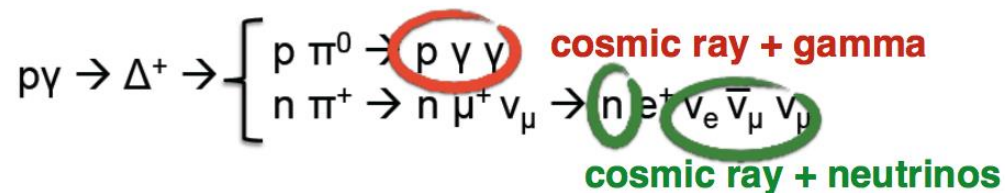
THE CR-GAMMA-NEUTRINO CONNECTION



Hadronuclear (e.g. star burst galaxies and galaxy clusters)



Photohadronic (e.g. gamma-ray bursts, active galactic nuclei)



Neutrino flavour ratio at source:

pion-muon decay

$$\nu_e : \nu_\mu : \nu_\tau \sim 1 : 2 : 0$$

Oscillations average out over cosmic baselines

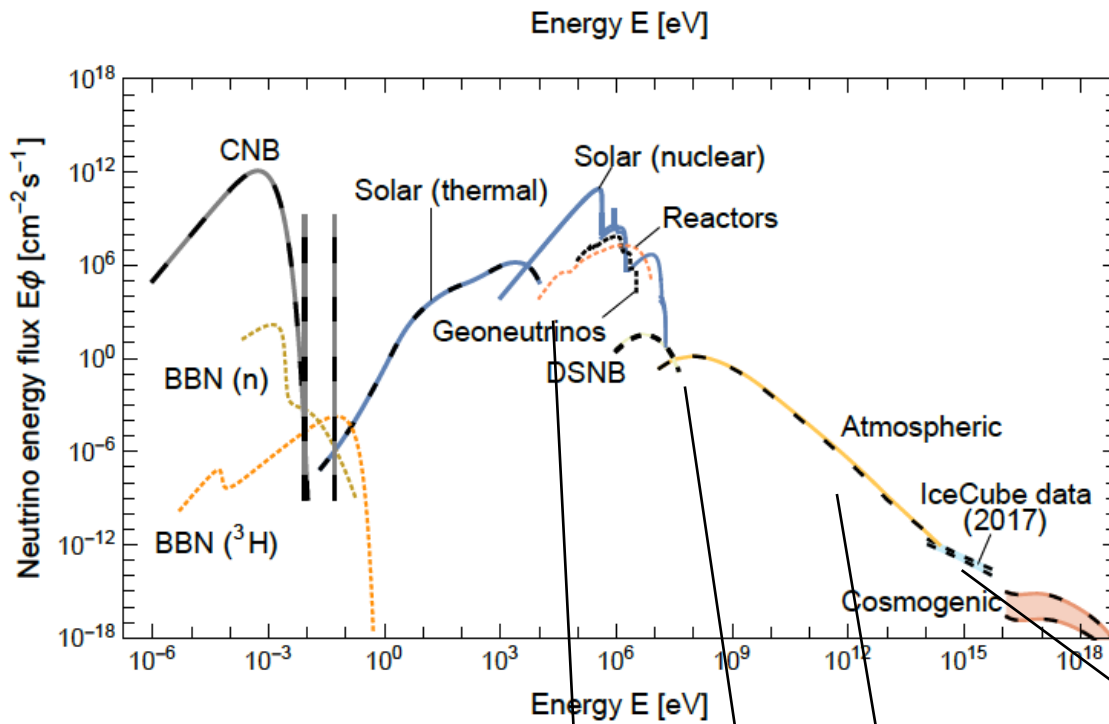
$$\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$$

$$E_\nu \approx \frac{1}{20} E_p \approx \frac{1}{2} E_\gamma$$

Multi-messenger network

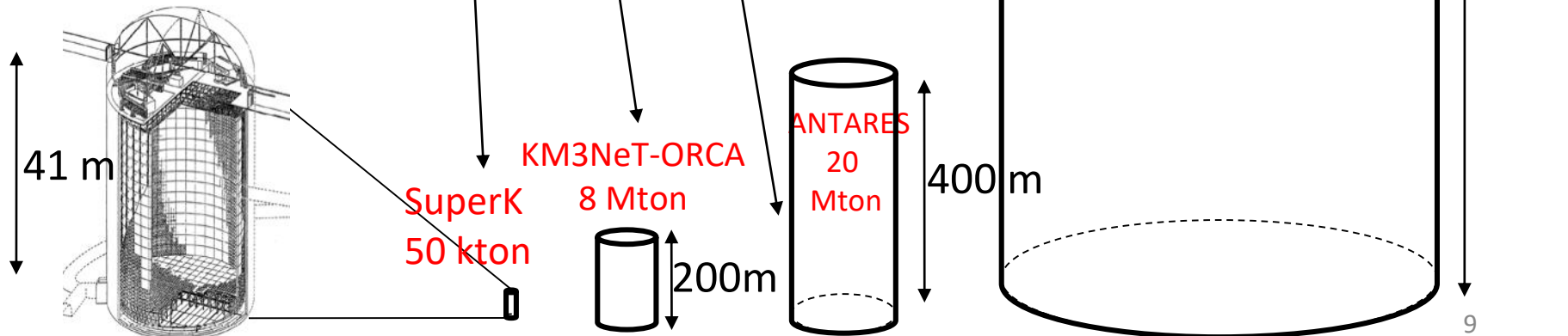


Neutrinos fluxes from MeV to PeV



$$\sigma(\nu p)/\sigma(\gamma p) = 10^{-7} \text{ at } 1 \text{ TeV}$$

Need very large detectors

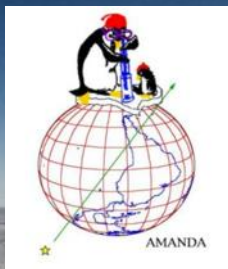


Very large volume neutrino telescopes



Mediterranean Sea
Saltwater: K40
Bioluminescence

Lake Baikal
Freshwater
Chemiluminescence

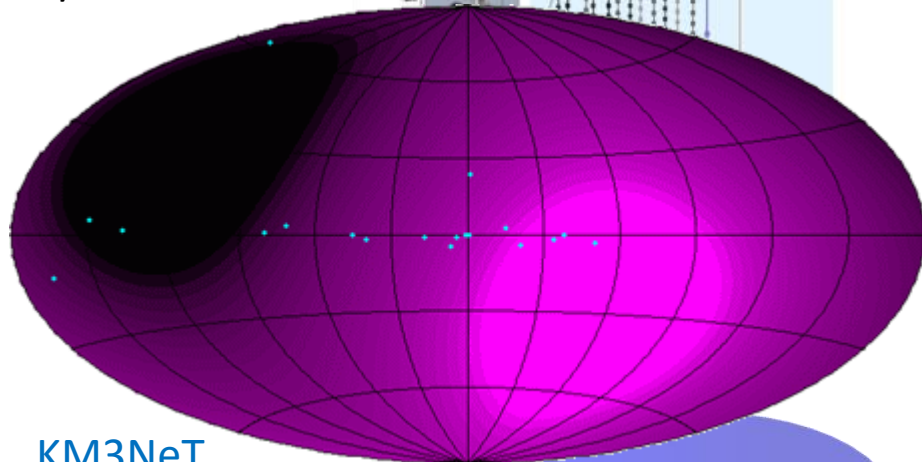
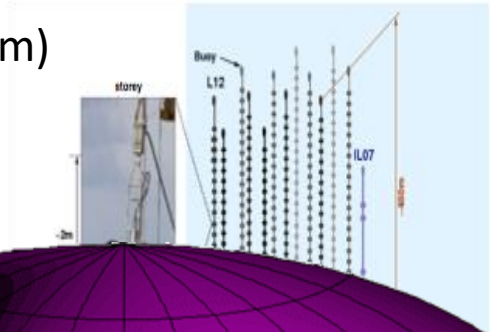


Antarctic
Ice
Dust, air bubbles

Current H2O (liquid+solid) neutrino telescopes

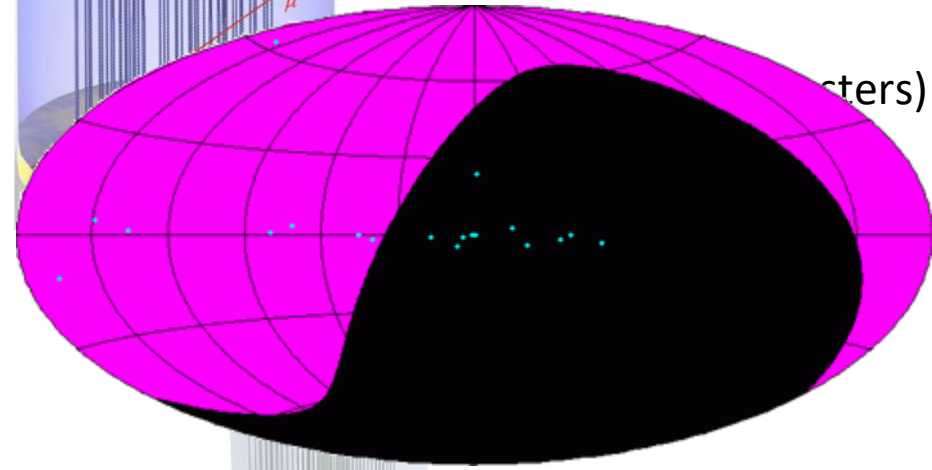
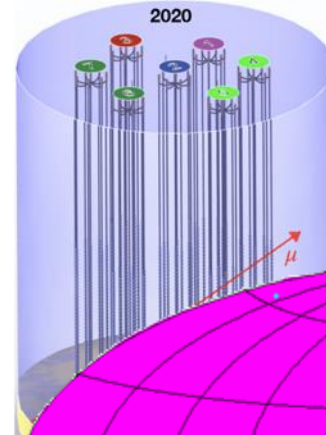
Antares

Med. Sea (-2.4km)
 12 strings
 885 PMTs (10")
 1/100 km³



Baikal-GVD

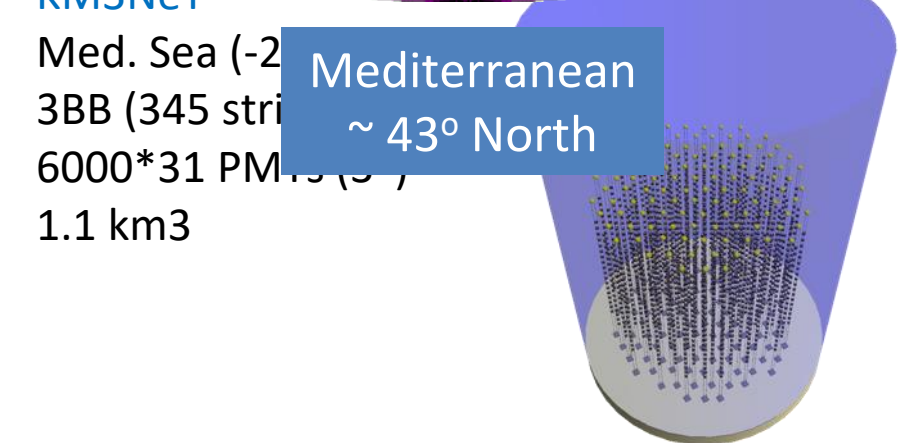
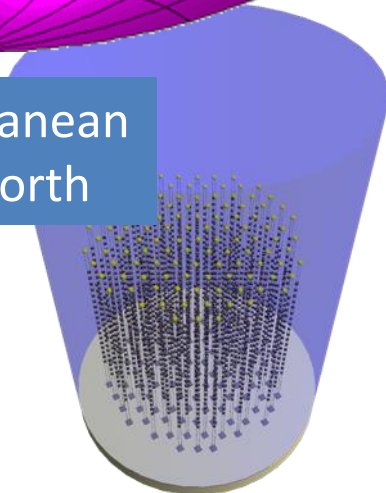
Lake Baikal (-1.3km)
 1 cluster = 8 strings
 0.4 km³ (8 clusters)
 2304 PMTs (10")



KM3NeT

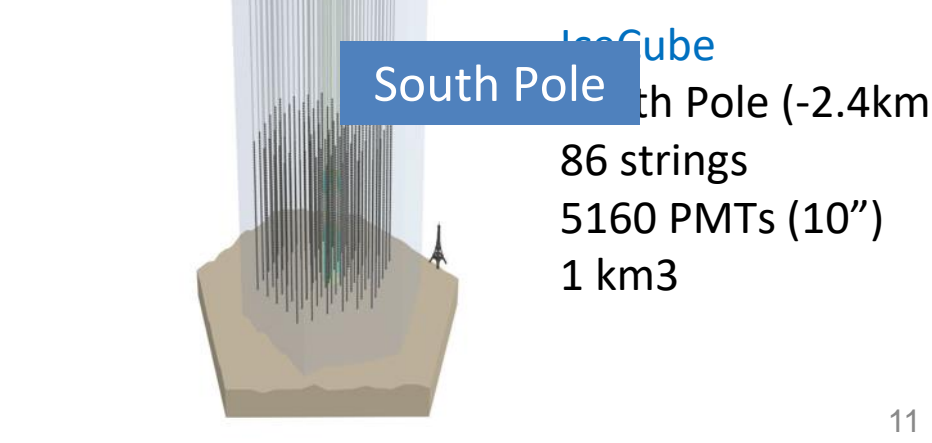
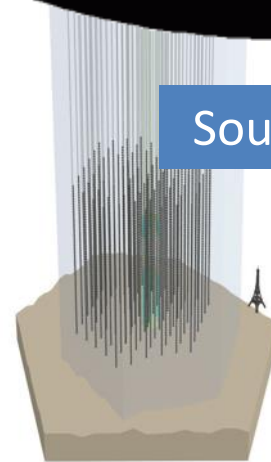
Med. Sea (-2.4km)
 3BB (345 strings)
 6000*31 PMTs (10")
 1.1 km³

Mediterranean
 ~ 43° North



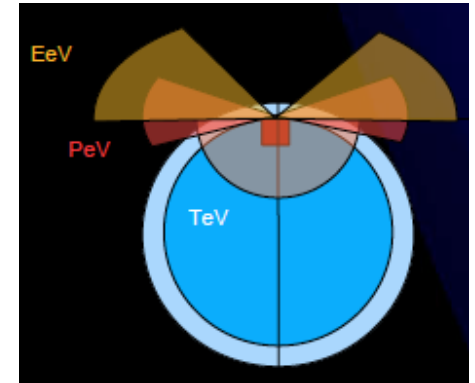
IceCube

South Pole (-2.4km)
 86 strings
 5160 PMTs (10")
 1 km³

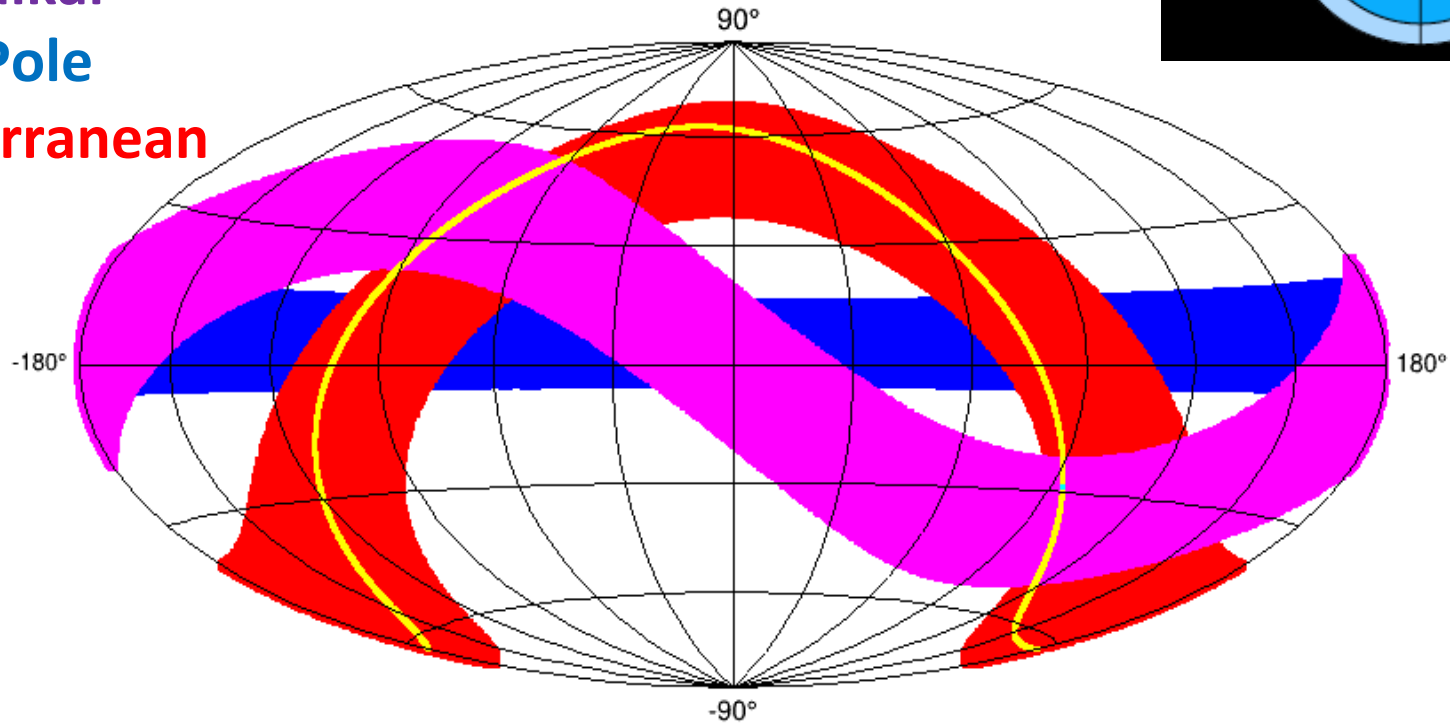


Instantaneous PeV fields of view

At highest energies, neutrinos don't make it through the Earth: horizontal tracks are golden channel



Lake Baikal
South Pole
Mediterranean



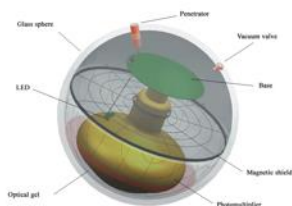
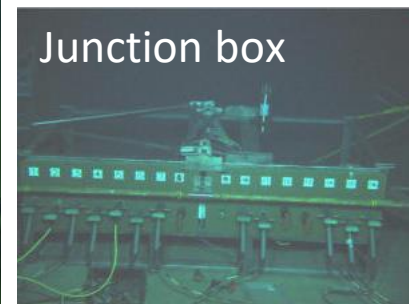
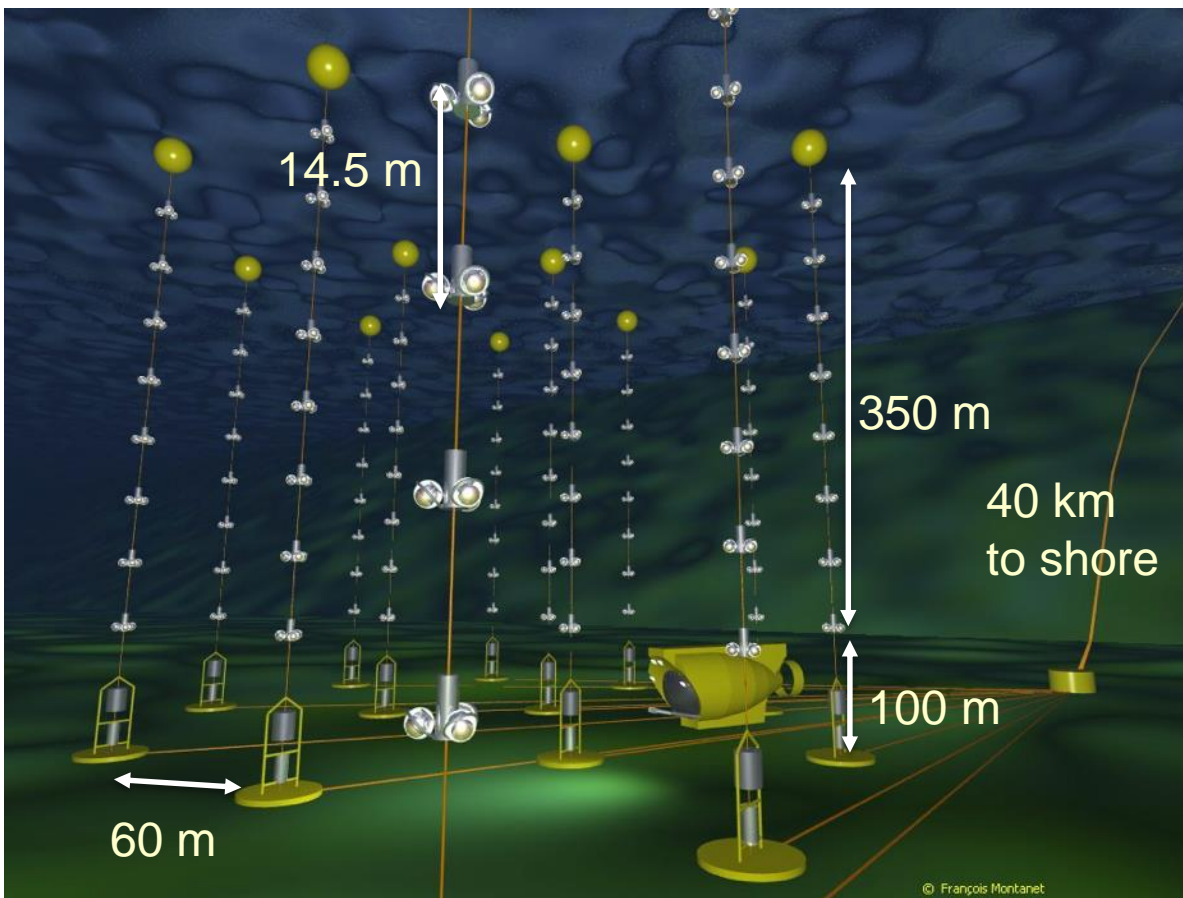
Instantaneous field of view with horizontal tracks



ANTARES Detector

(2008-2022)

12 lines (885 PMTs)
25 storeys / line
3 PMTs / storey
5-line setup in 2007
Completed in 2008
Dismantle 2022





ANTARES Dismantling (feb/June 2022)



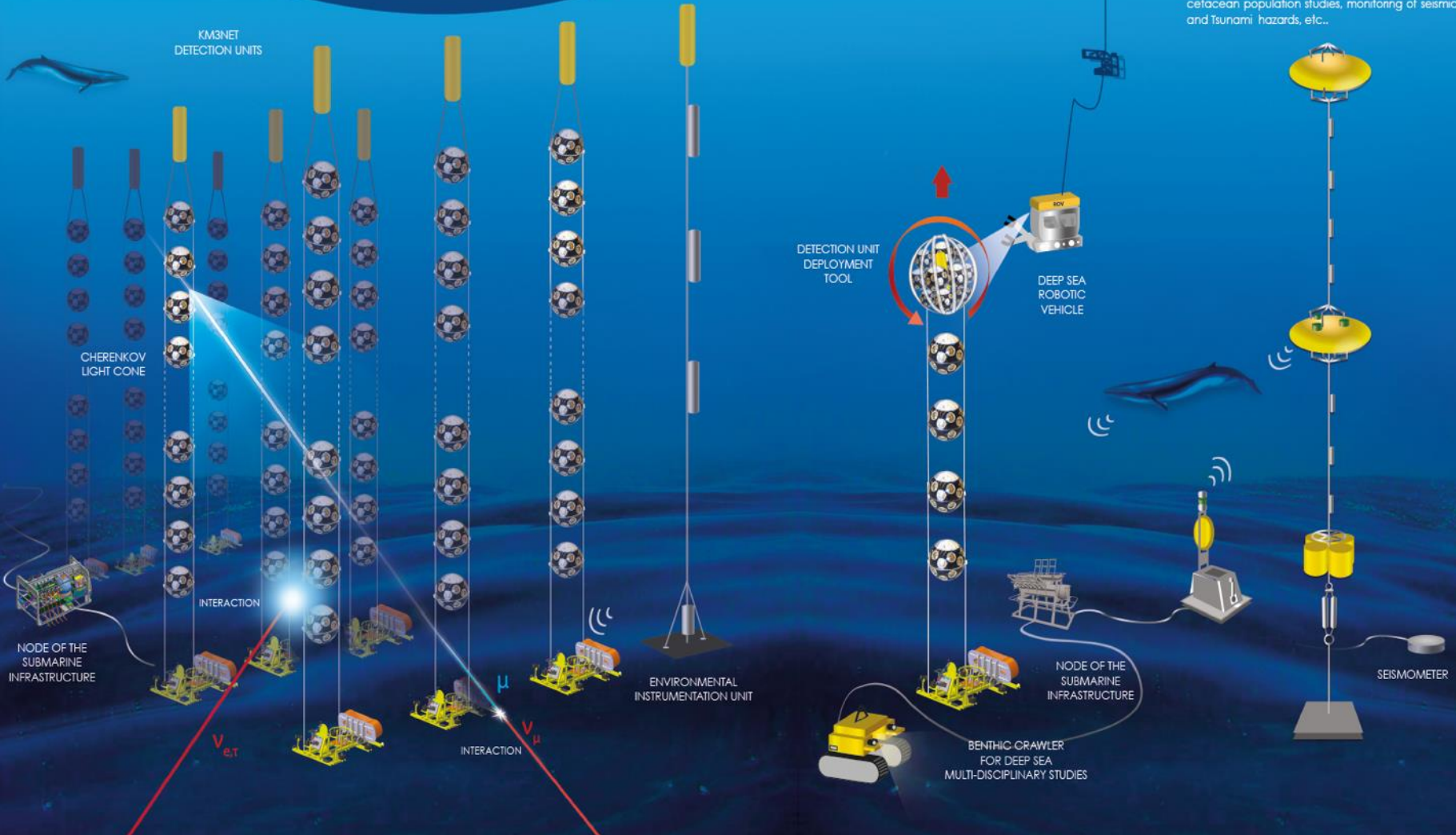


SURFACE SHIP FOR THE ROV

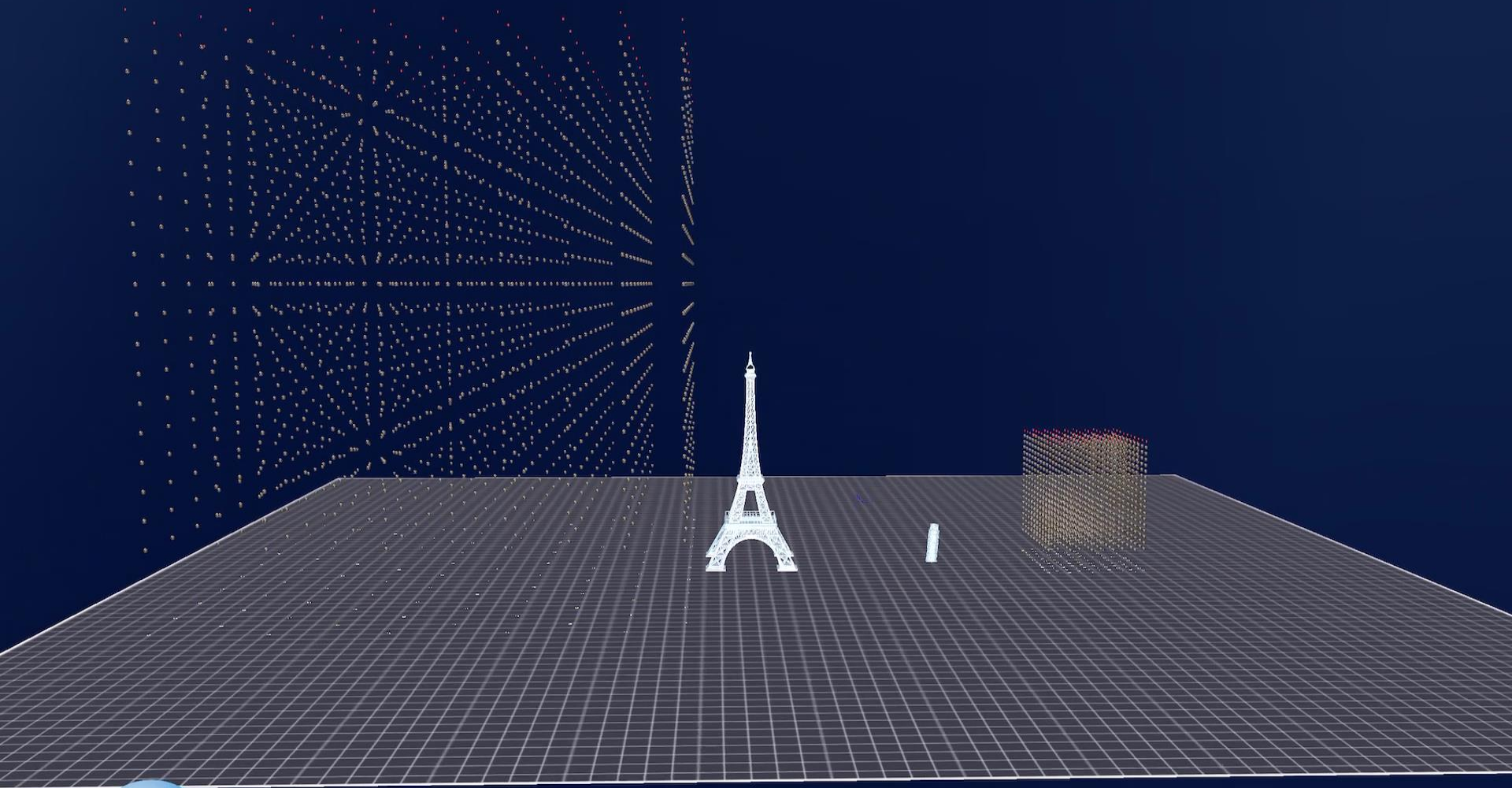
A NEW WAY TO STUDY THE ABYSS

KM3NeT is also a permanently cabled deep-sea observatory that enables the real-time acquisition of continuous, high-frequency, time series data for the study of the marine environment.

The synergetic science that can be addressed includes; climate change, ocean current circulation, biodiversity, bioluminescence, bioacoustics, cetacean population studies, monitoring of seismic and Tsunami hazards, etc..



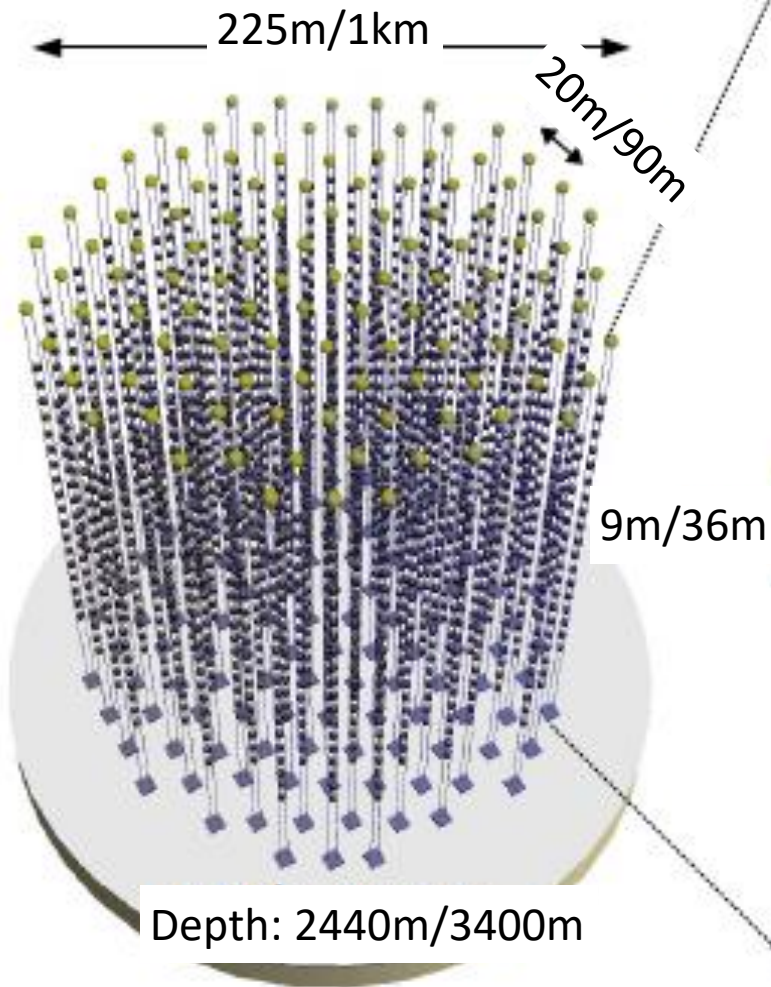
KM3NeT: ARCA and ORCA





KM3NeT building block

115 strings
18 DOMs / string



- 31 x 3" PMTs
- All data to shore: Gbit/s optical fibre
- White Rabbit time synchronisation
- LED flasher & acoustic piezo
- Tiltmeter/compass
- Low drag

Instrumented mass	7 Mton	500*2 Mton
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Seafloor infrastructures



ORCA
2nd junction box
Oct 2020

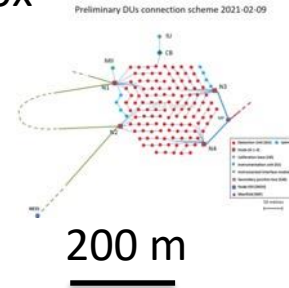


ARCA
2nd Cable
Nov 2020

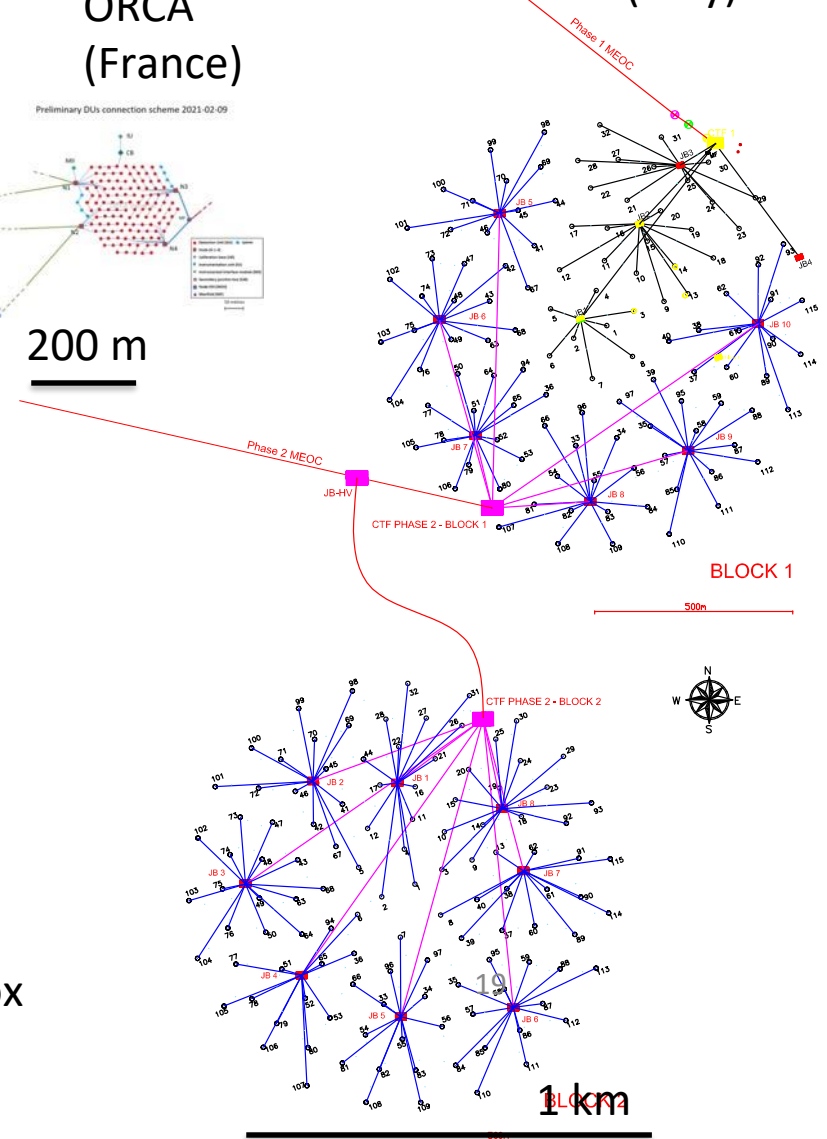


ARCA
3rd junction box
Sept 2022

ORCA
(France)



ARCA
(Italy)



Detection Construction

Amsterdam



Nantes

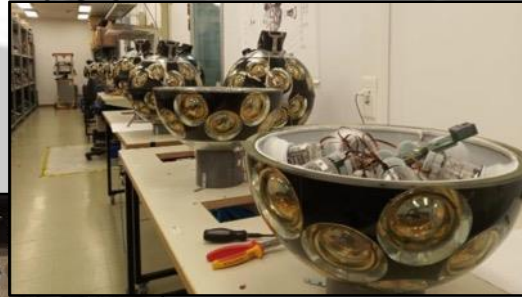


Erlangen



Bologna

Athens



Genova



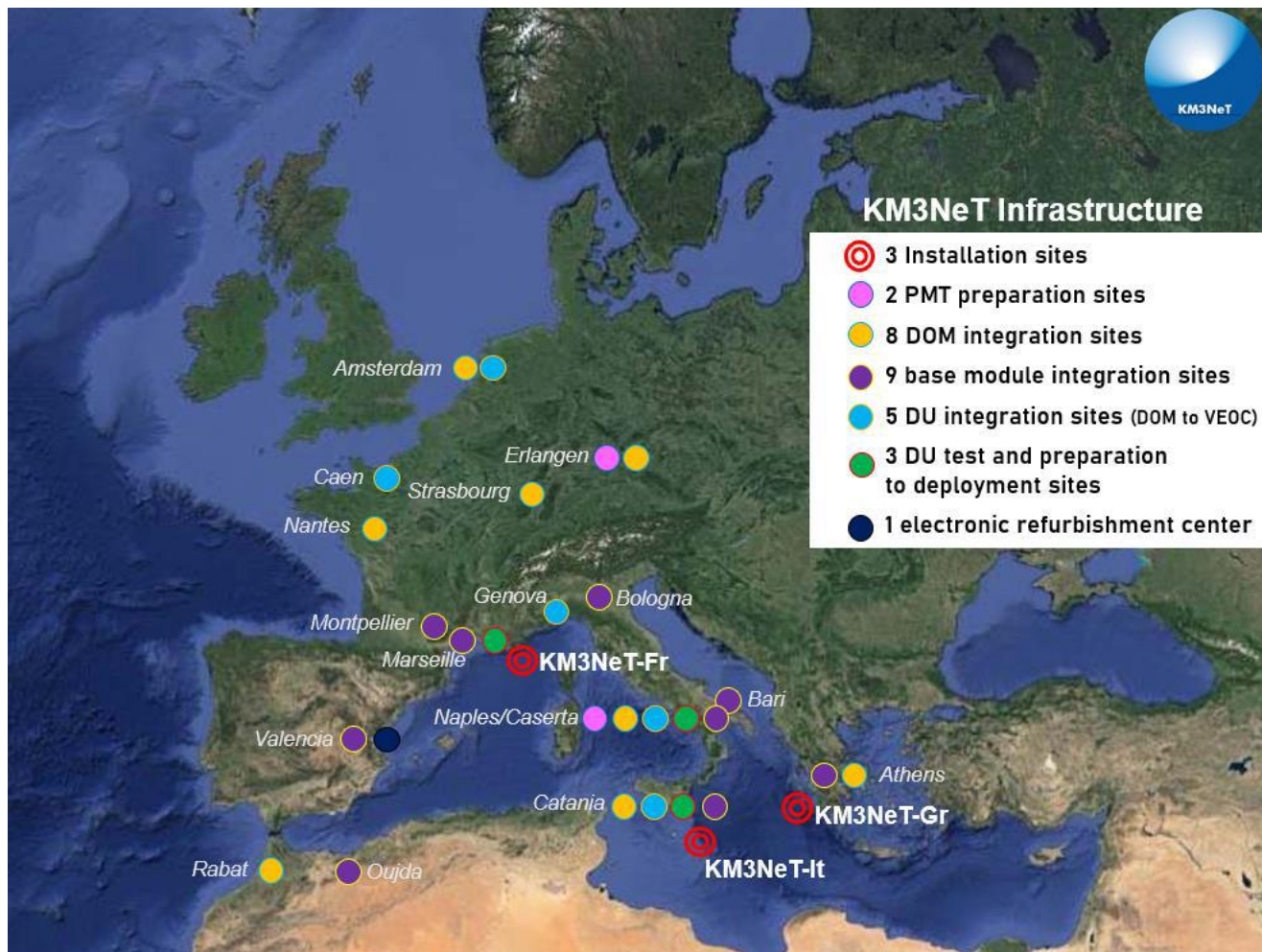
Catania



Marseille



Detector construction: status



DOMs

- 8 integration sites
- 946 produced (52 Dus)
- 36 currently on bench

Base Modules

- 9 integration sites
- 45 BM produced
- 5 currently on bench

Detection Units

- 6 integration sites
- 37 DUs produced
- 7 currently on bench
- 32 operating

Despite pandemic big efforts are on going in the detector construction



KM3NeT DU deployment



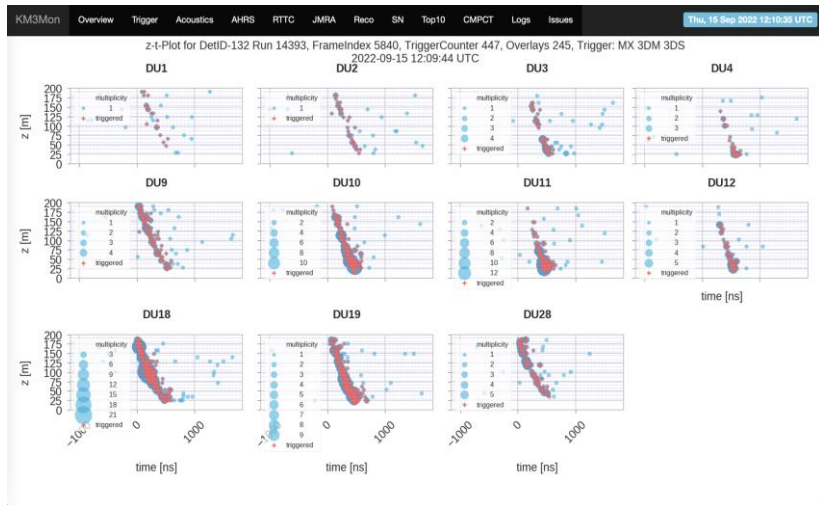


Current Status: 32 DUs operating

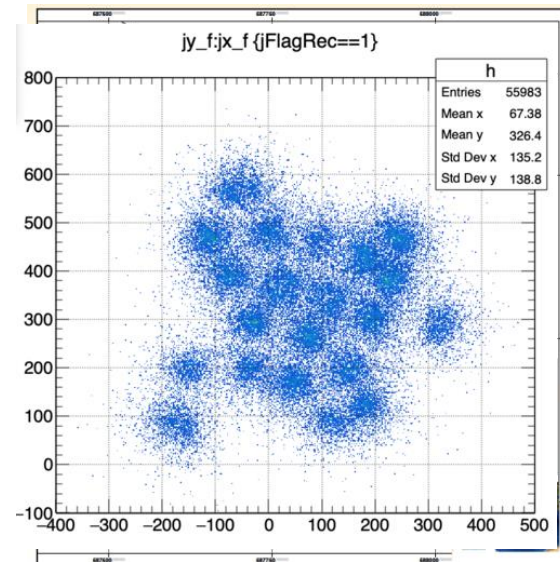
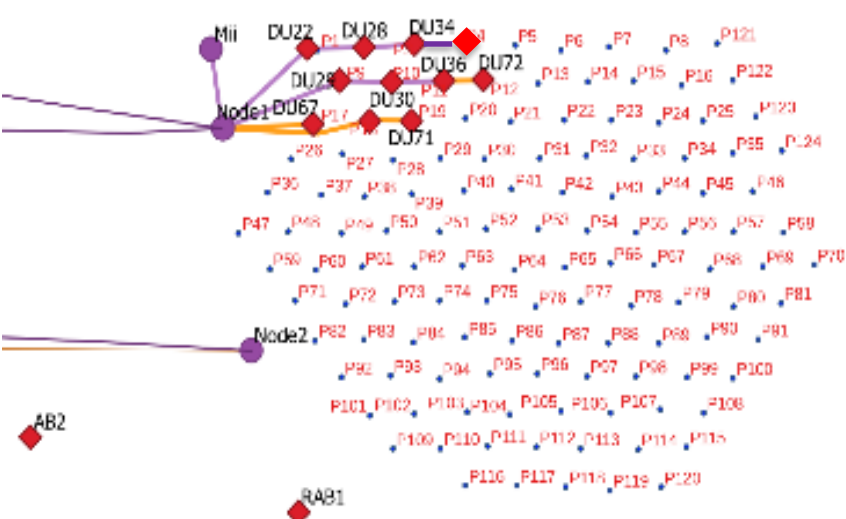
ORCA11

Online Zt plots

ARCA21



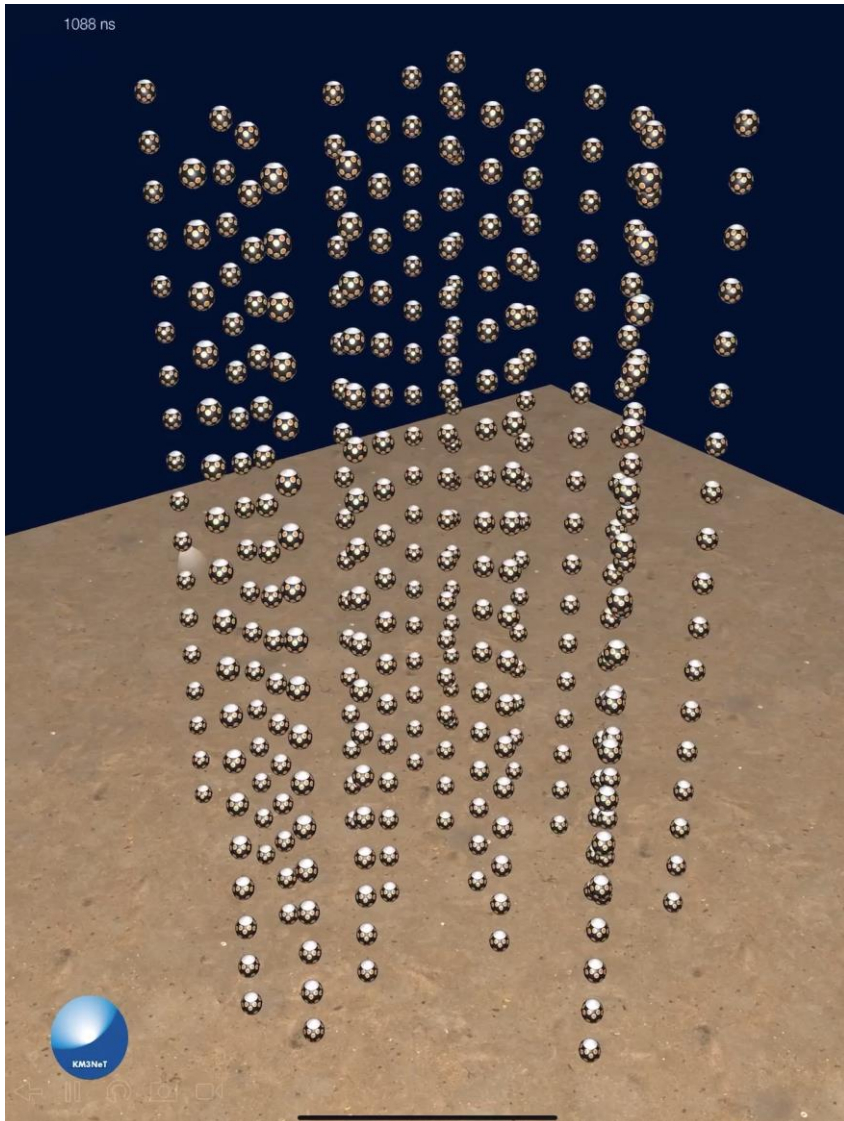
z-t-Plot for DetID-133 Run 13243, FrameIndex 50722, TriggerCounter 1476, Overlays 117, Trigger: MX 3DM 3DS
2022-09-17 07:24:32 UTC



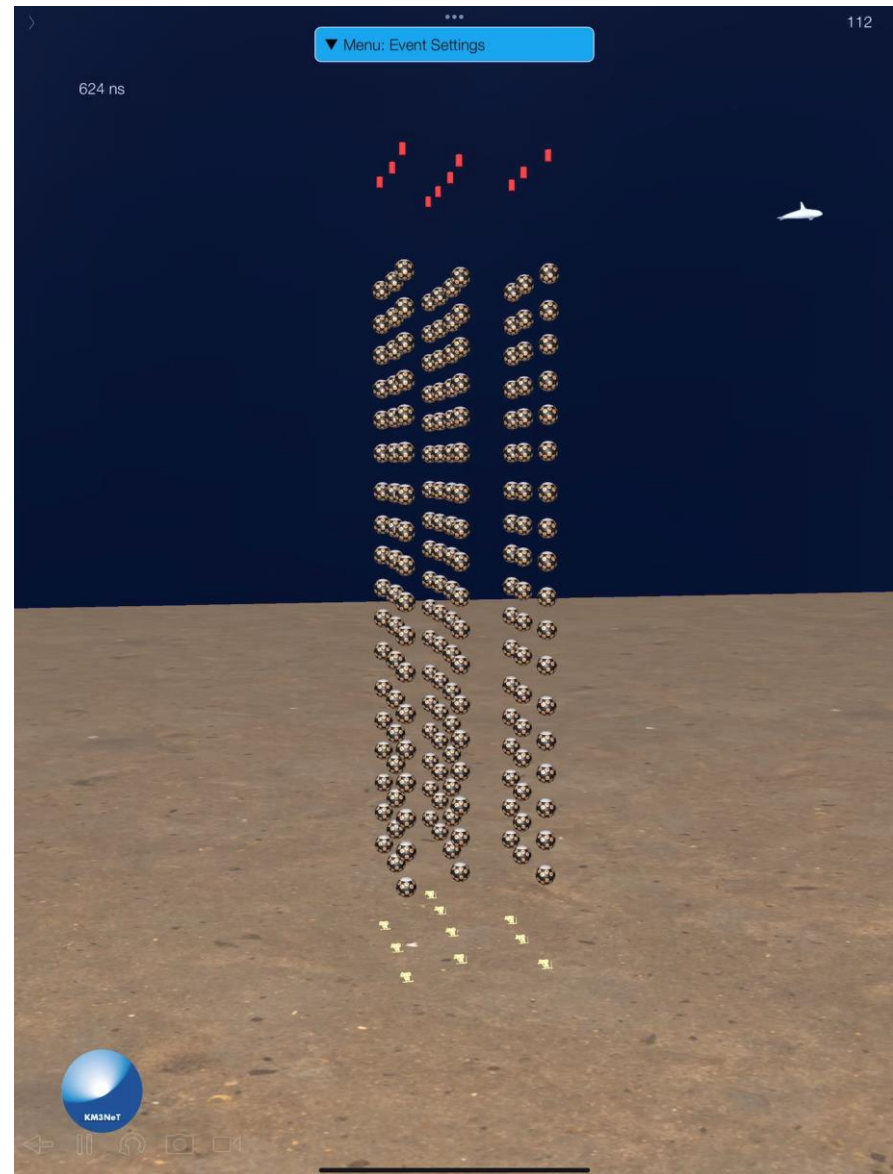


KM3NeT Event Displays

ARCA19

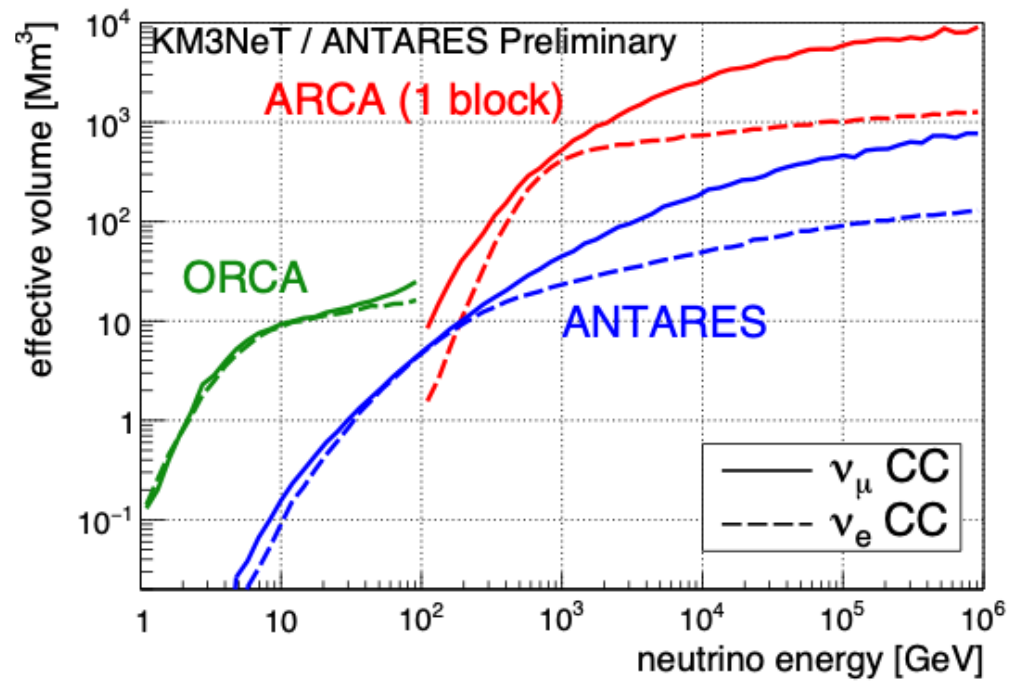
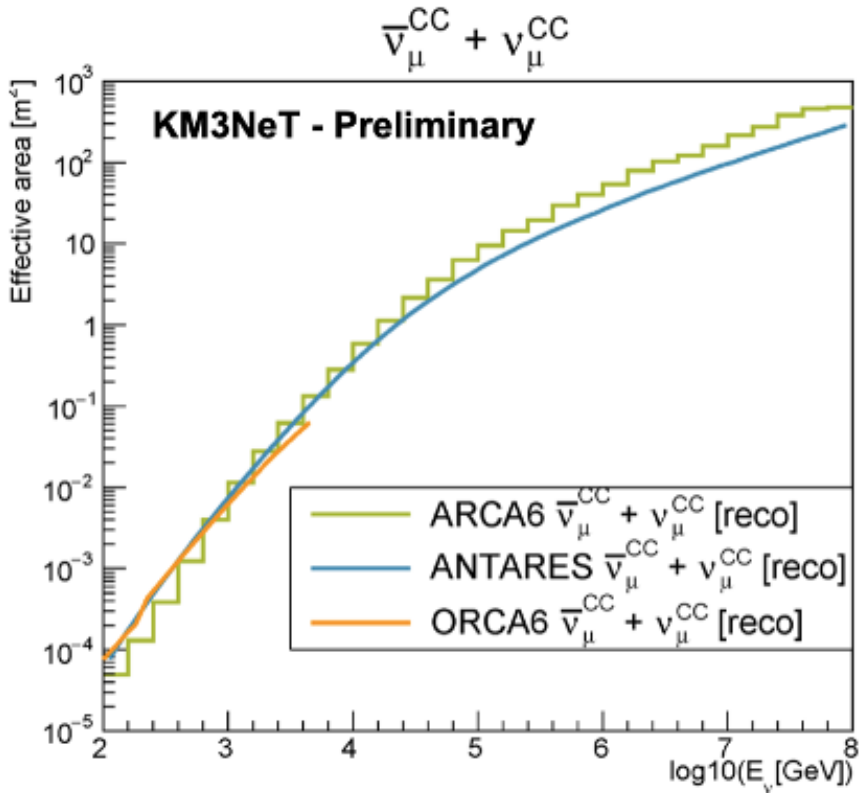


ORCA10





Effective areas: KM3NeT vs ANTARES

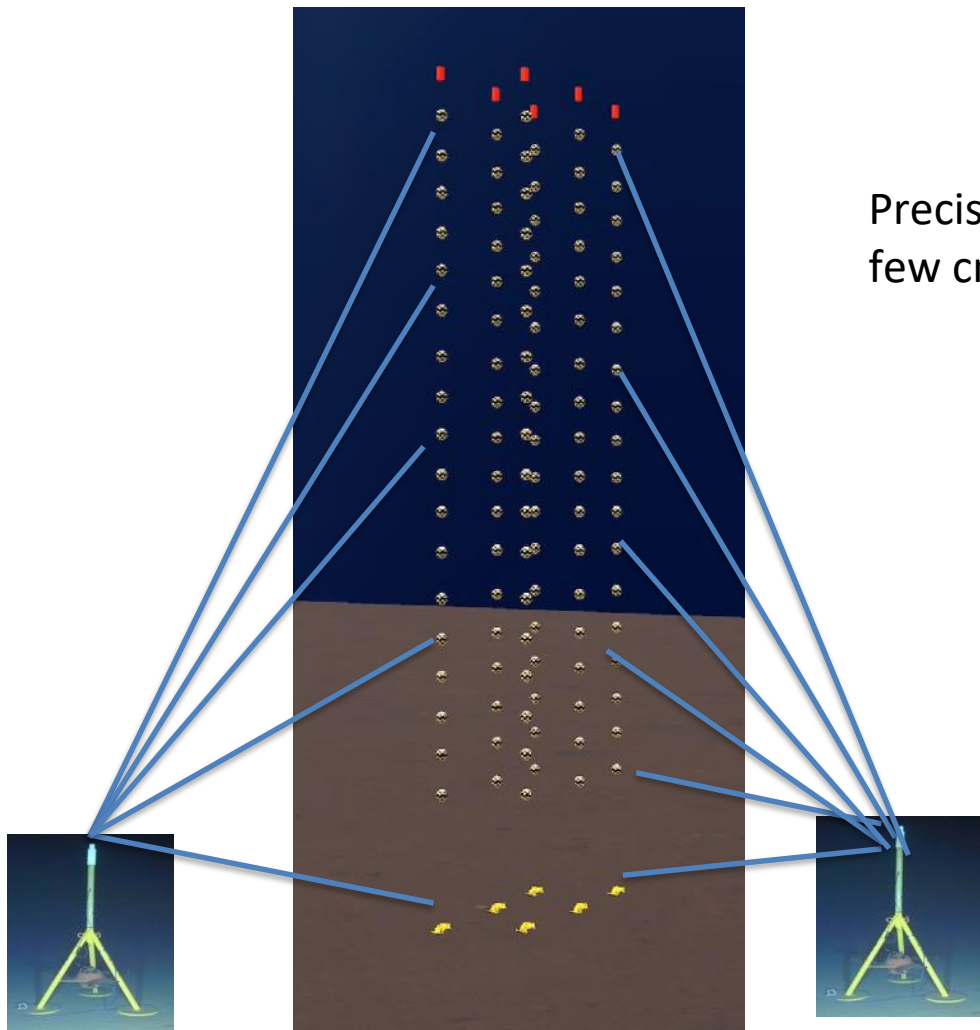


ARCA6+ORCA6 bit better than ANTARES

-> ok to dismantle ANTARES

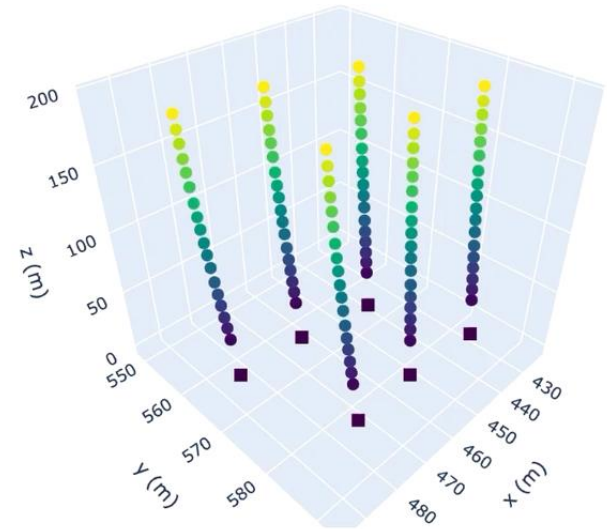


Acoustic position calibration in KM3NeT

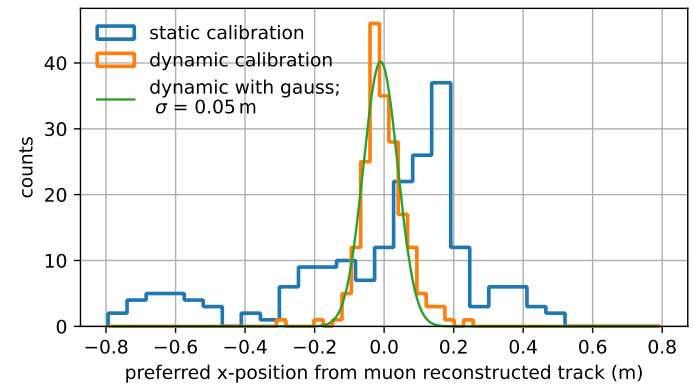


Precision
few cm

Animation of DU movement



Use of dynamic positions,
verified by muon calibration

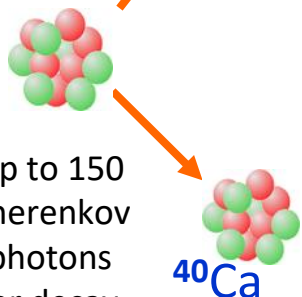




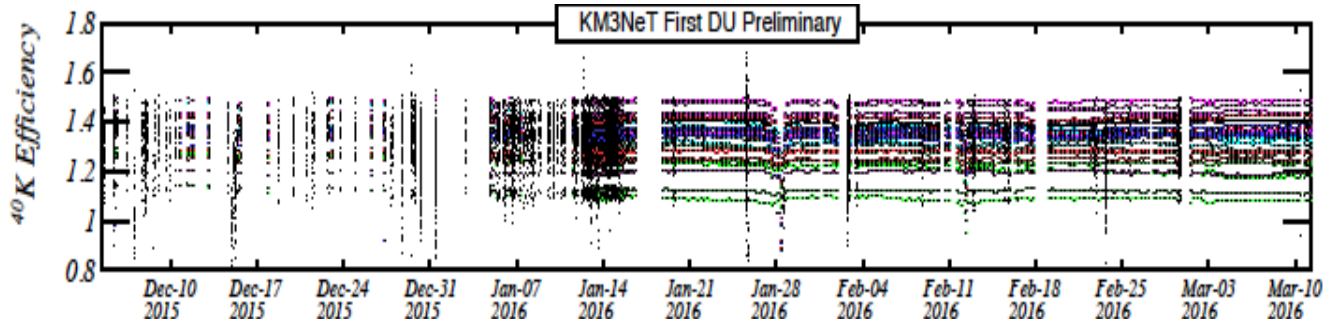
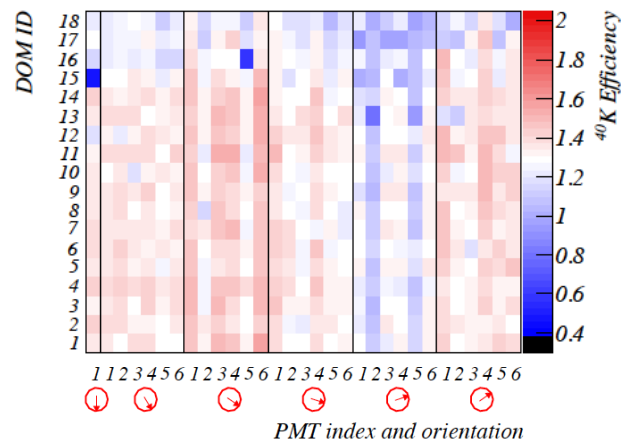
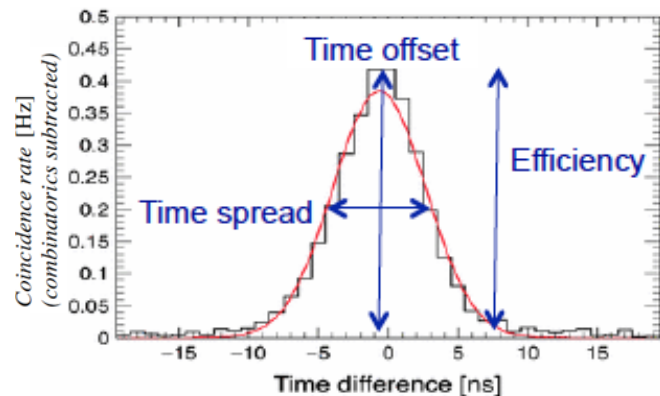
PMT efficiencies: ^{40}K



^{40}K e^- (β decay)



Up to 150 Cherenkov photons per decay; stable ^{40}K concentration

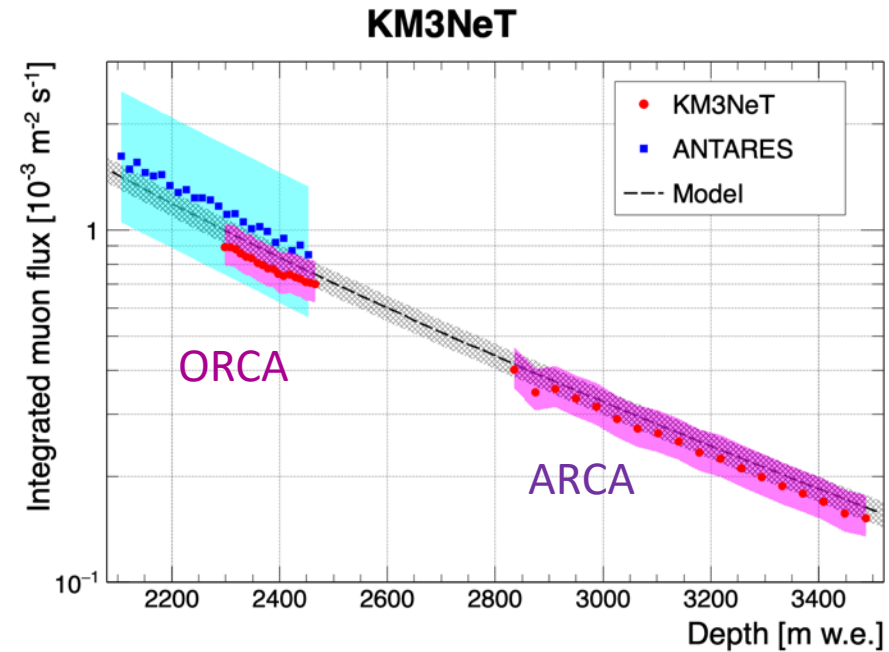
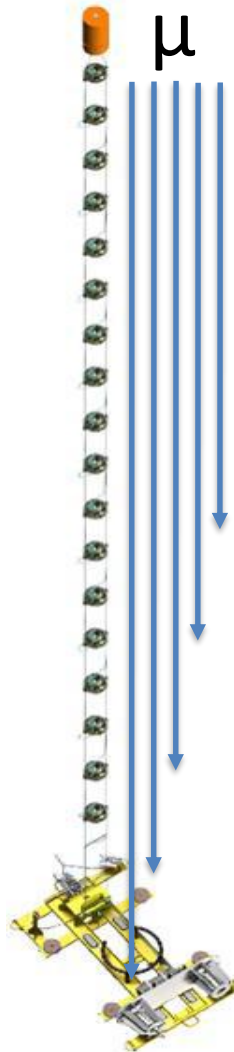
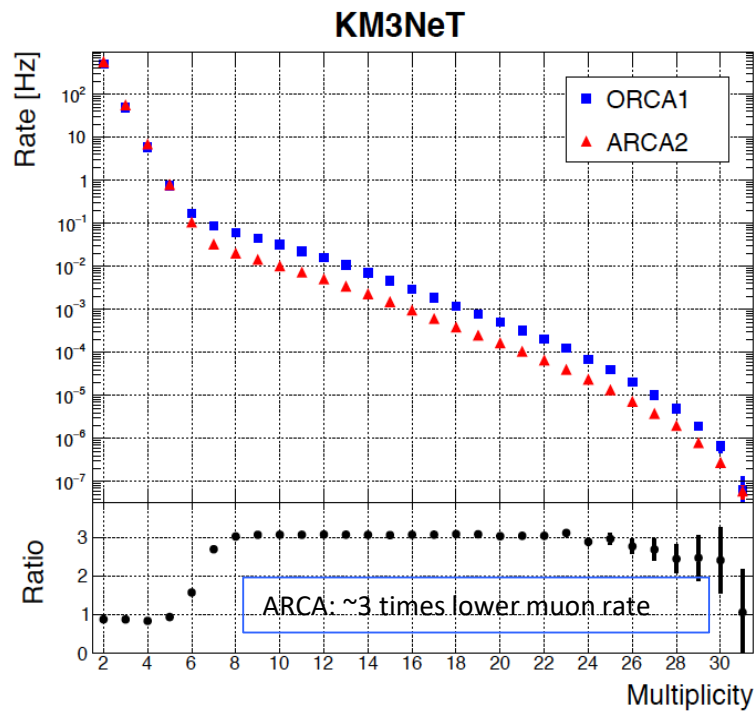




Muon depth dependence

2 DUs of ARCA (23/12/2016-2/3/2017) &
1 DU of ORCA (9/11/2017-13/12/2017)

Muon flux as function of depth compared
to Bugaev model (Bugaev et al, Phys. Rev. D 58 1998 054001)

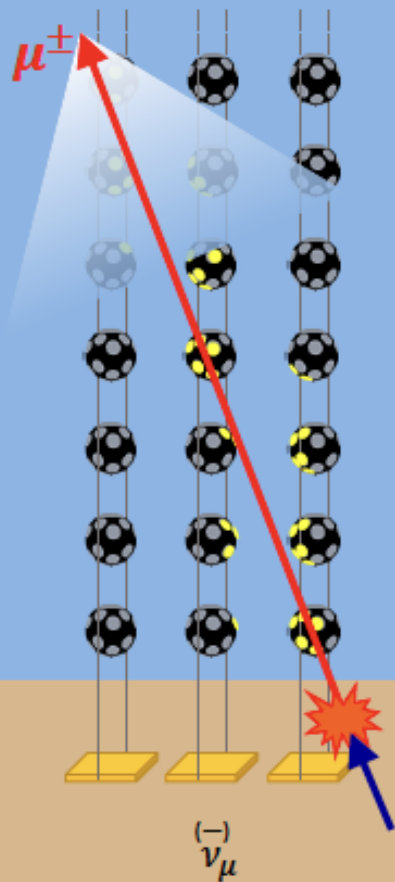


<https://arxiv.org/pdf/1906.02704.pdf>

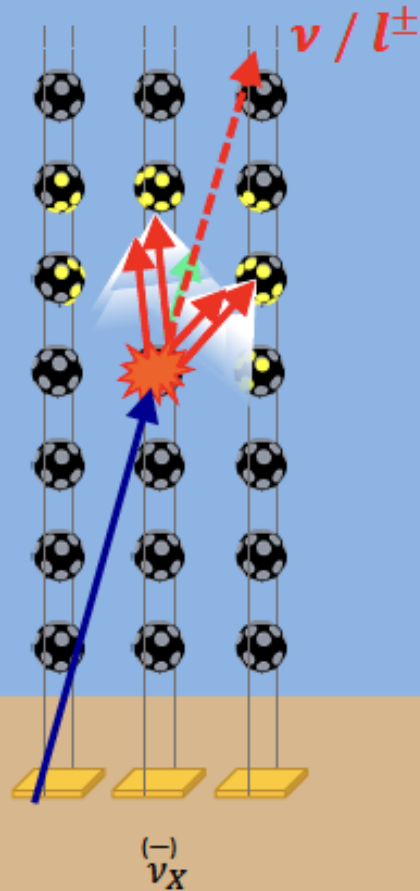
PMT detection efficiency calibration verified

Event Topologies

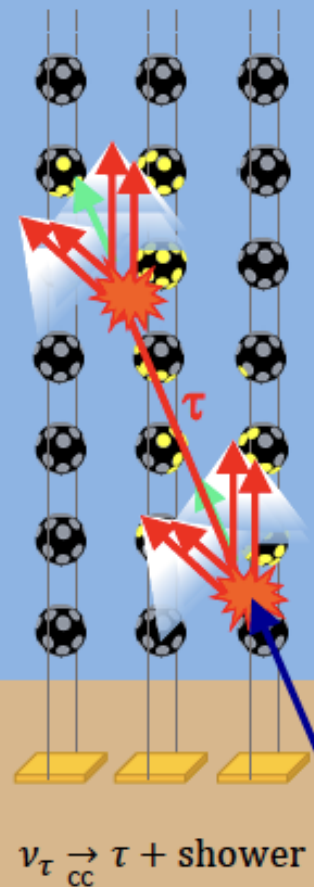
CC ν_μ
1. track like events
good pointing



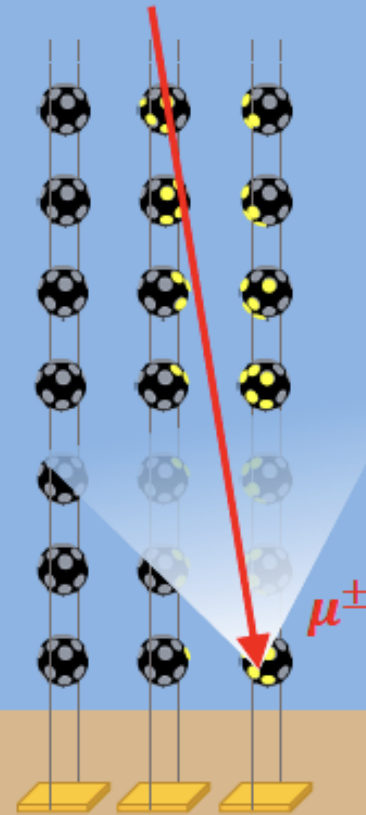
CC ν_e + all flavours NC
2. shower like events
good energy reconstruction



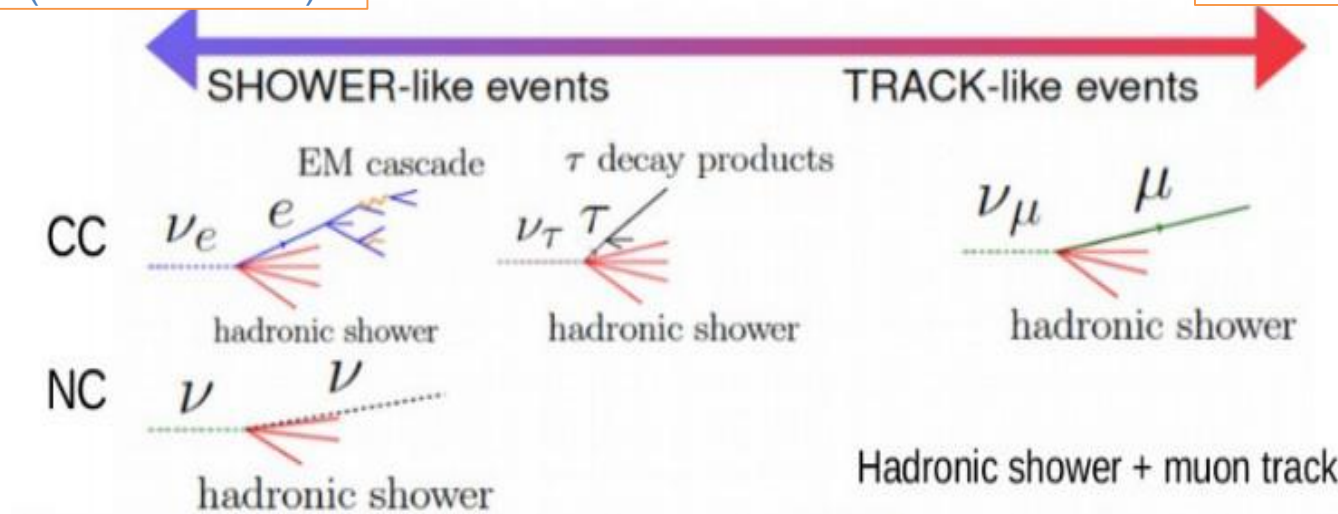
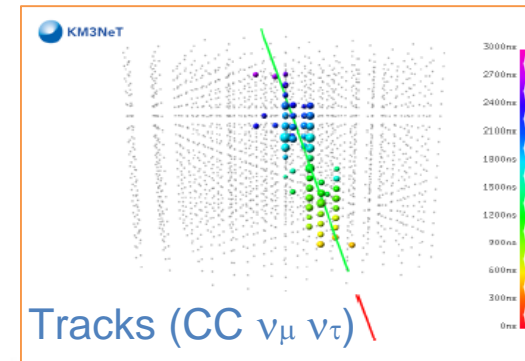
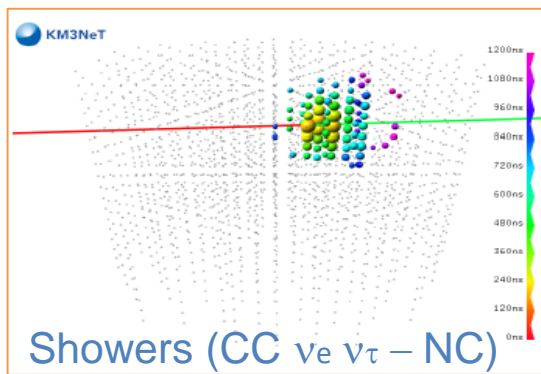
CC ν_τ
3. "double bang"



Atmospheric muon
BACKGROUND !!



Resolutions



Angular resolution $10^\circ/1^\circ$
at 100 TeV for Ice/water

Energy resolution $\sim 5\%$

Angular resolution $0.5^\circ/0.1^\circ$
at 100 TeV for Ice/water

Energy resolution $\sim 200-300\%$
(if contained: 25%)

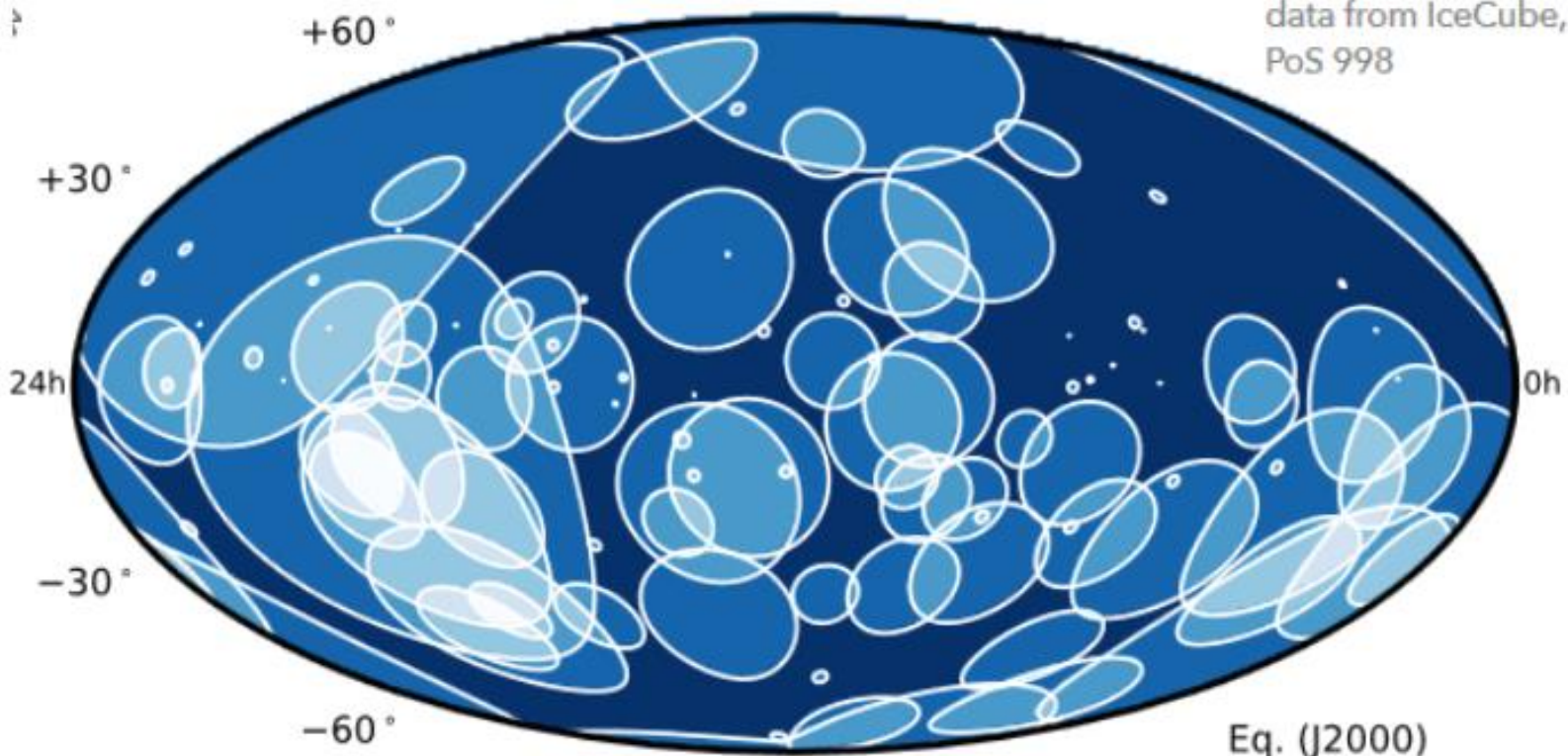
Precision multi-flavour astronomy with water based telescopes



Resolutions: IceCube vs KM3NeT

Old IceCube skymap

data from IceCube,
PoS 998



Resolution for ν_e

ANTARES ○

KM3NeT ◦

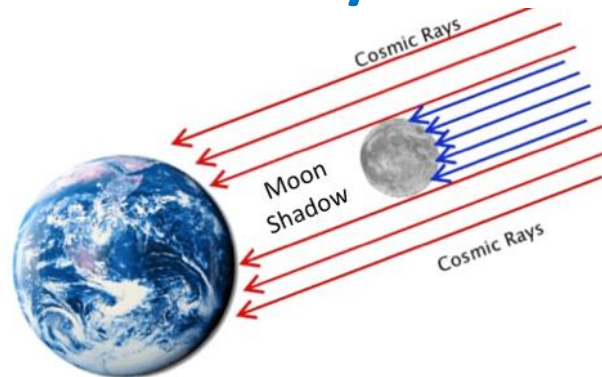
Resolution for ν_μ

ANTARES ·

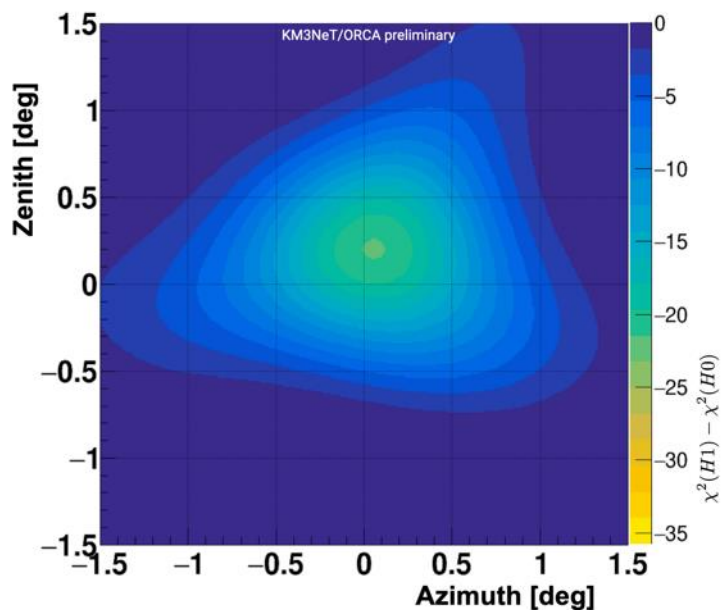
KM3NeT ·



ORCA6: Moon/Sun Shadow

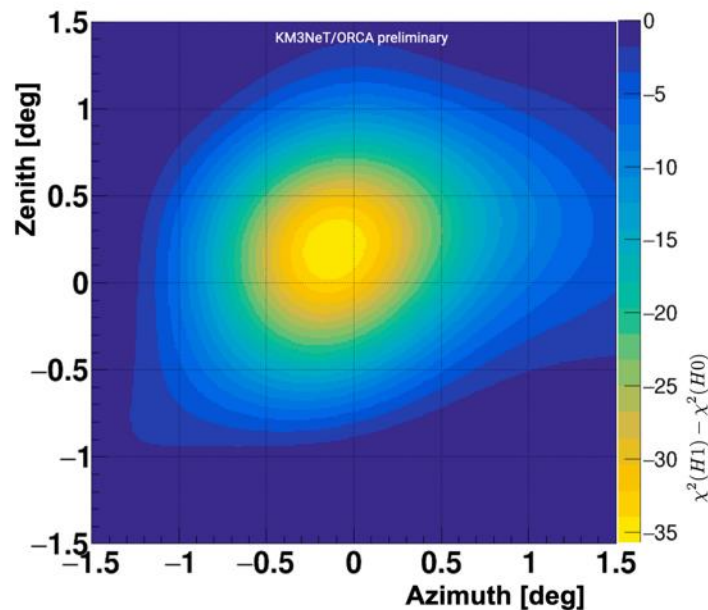


2D histogram data moon



Significance = 4.2σ
Angular resolution = $0.49^\circ \pm 0.15^\circ$

2D histogram data sun



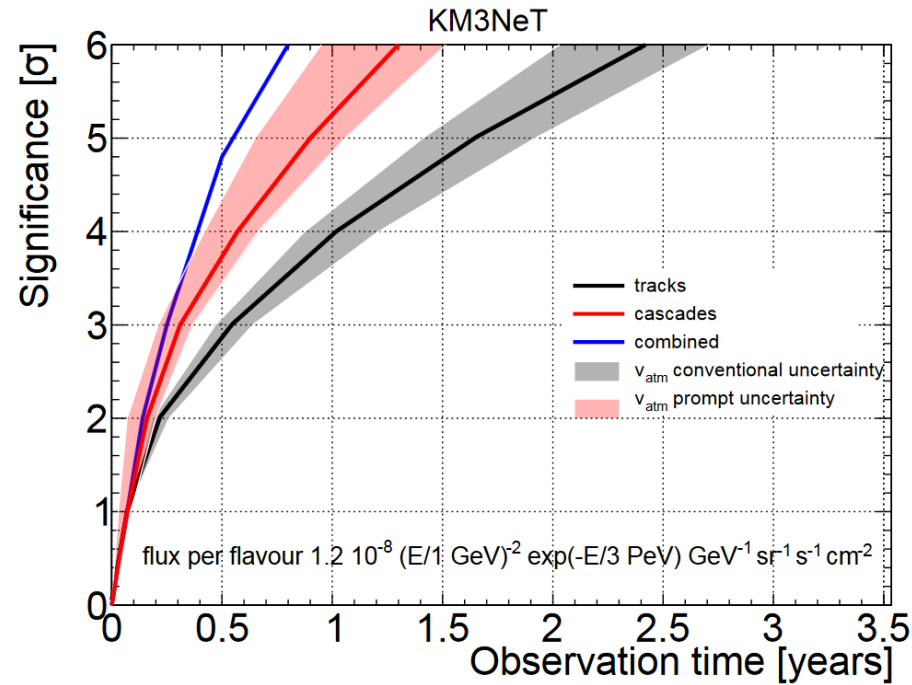
Significance $> 6 \sigma$
Angular resolution = $0.8^\circ \pm 0.14^\circ$

KM3NeT
ORCA6
13 months
data taking

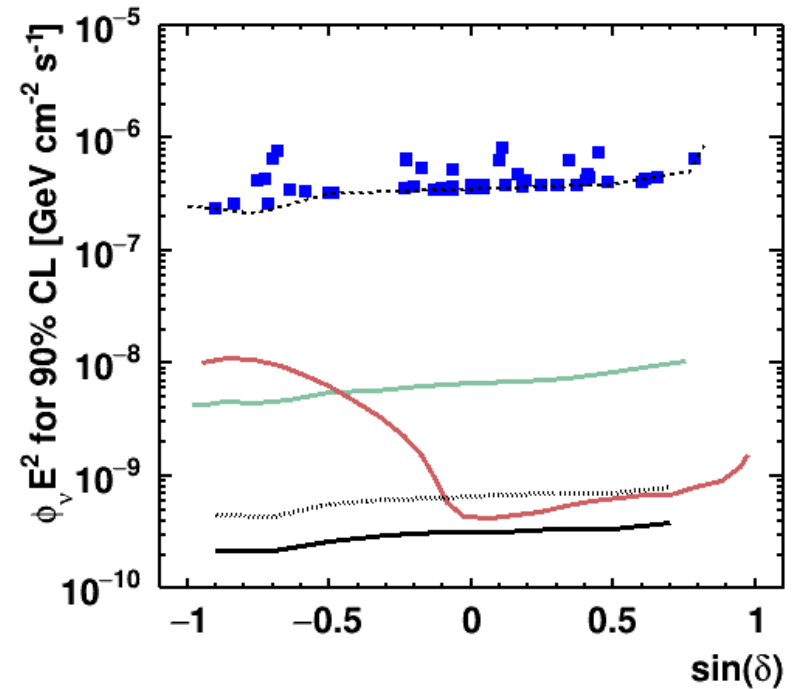


KM3NeT Sensitivities

Diffuse flux



Point sources

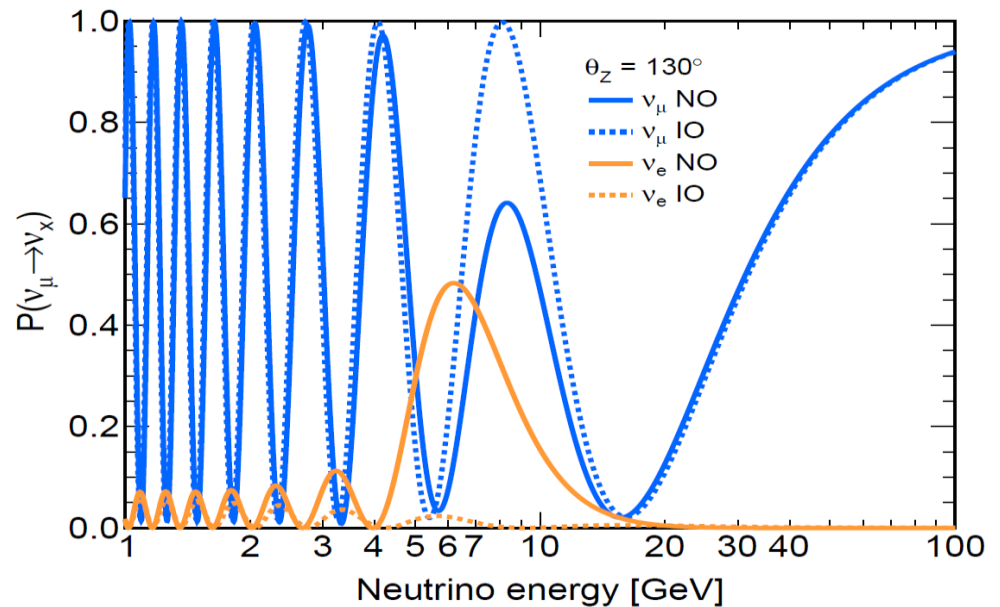
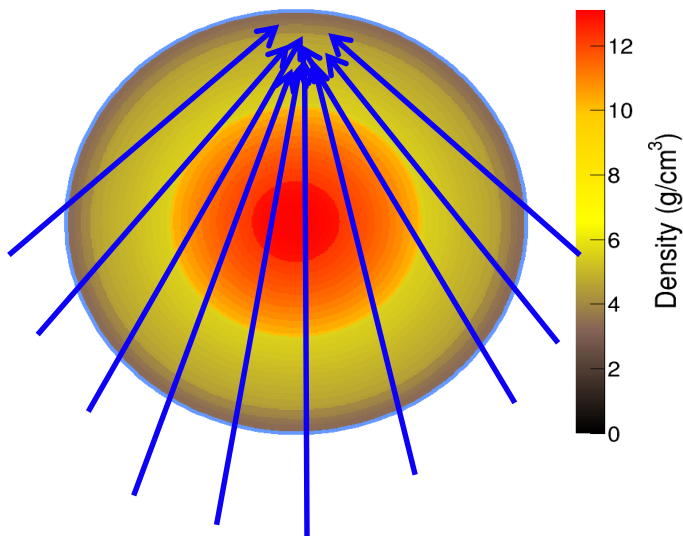
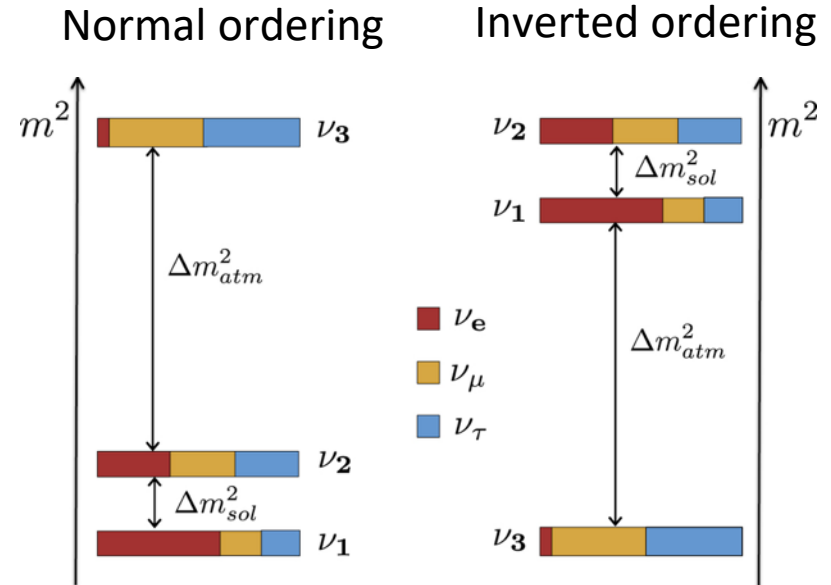
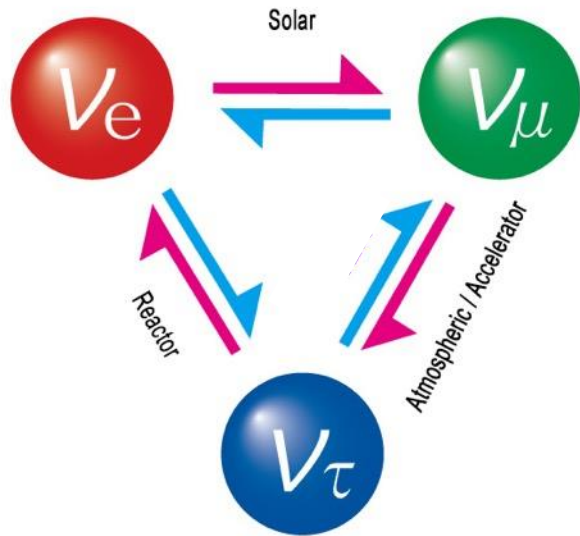


KM3NeT Preliminary

- KM3NeT/ARCA6 (92 days) source limits
- ⋯ KM3NeT/ARCA6 (92 days) sensitivity
- ANTARES (13yr) sensitivity
- IceCube (7yr) sensitivity
- KM3NeT/ARCA230 (7yr) sensitivity
- ⋯ KM3NeT/ARCA230 (3yr) sensitivity

5σ in ~ 0.5 year for the full detector (230 DUs)
 $5\sigma \sim 1$ year for one block detector (115 DUs)

neutrino oscillations with atmospheric neutrinos

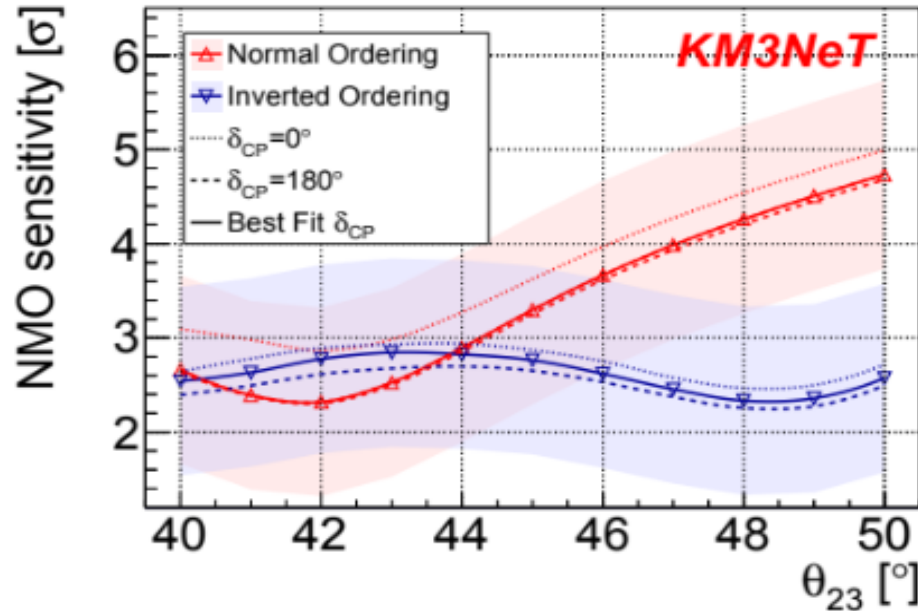




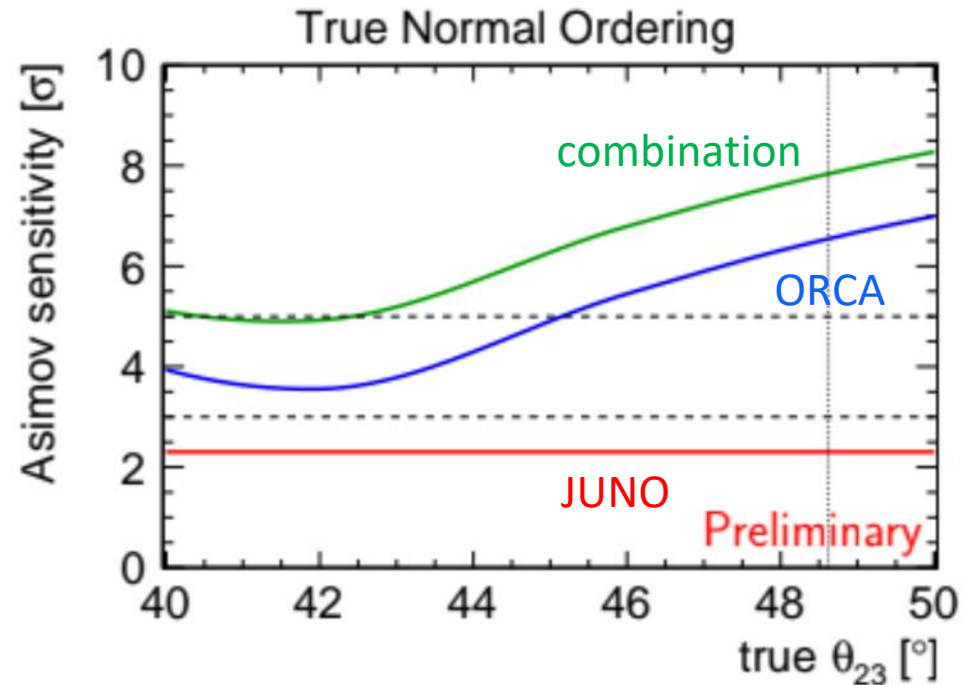
ORCA115: neutrino mass ordering

3 years

6 yrs & combination with JUNO



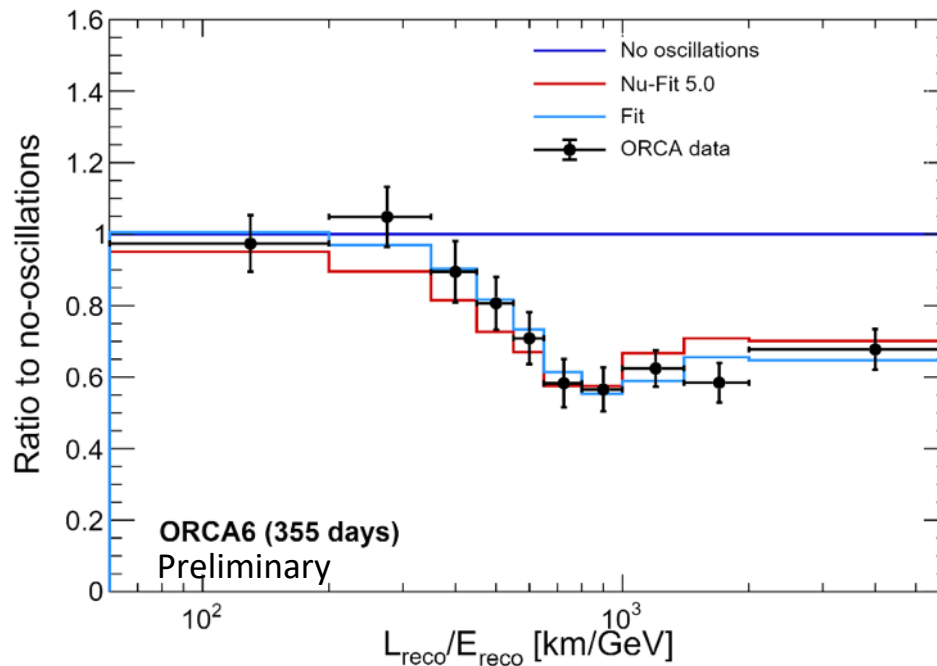
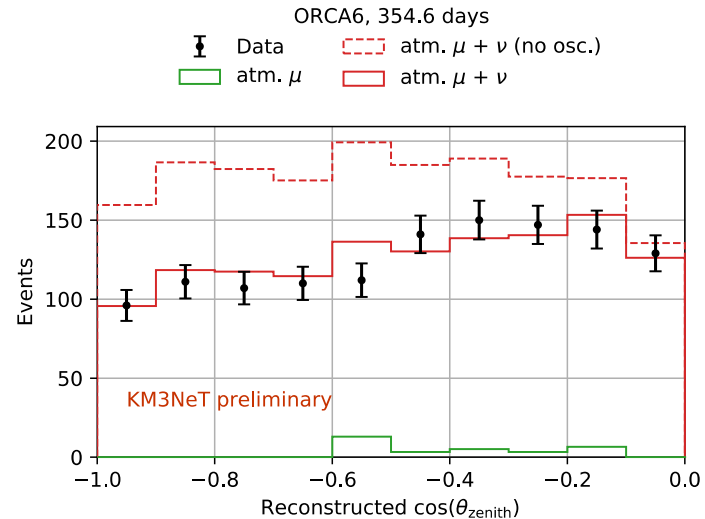
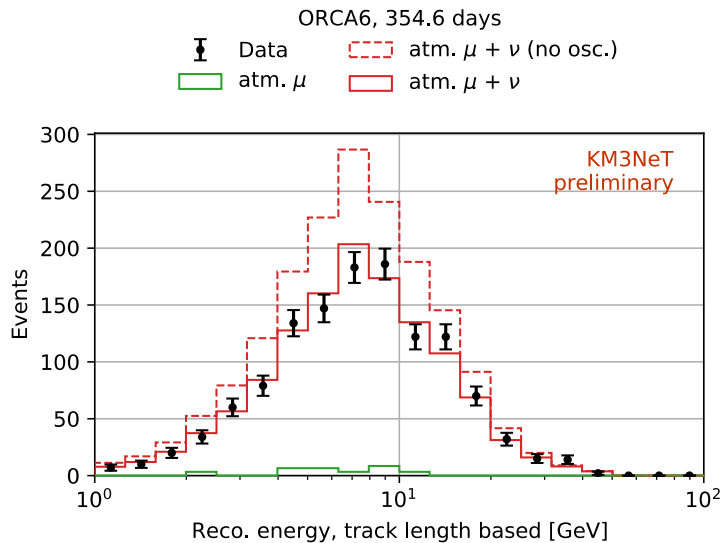
2.5-5 σ determination of Neutrino Mass Ordering possible in 3 years



Combination power relies on tension between best-fit of Δm_{31}^2 in “wrong ordering” between JUNO and ORCA

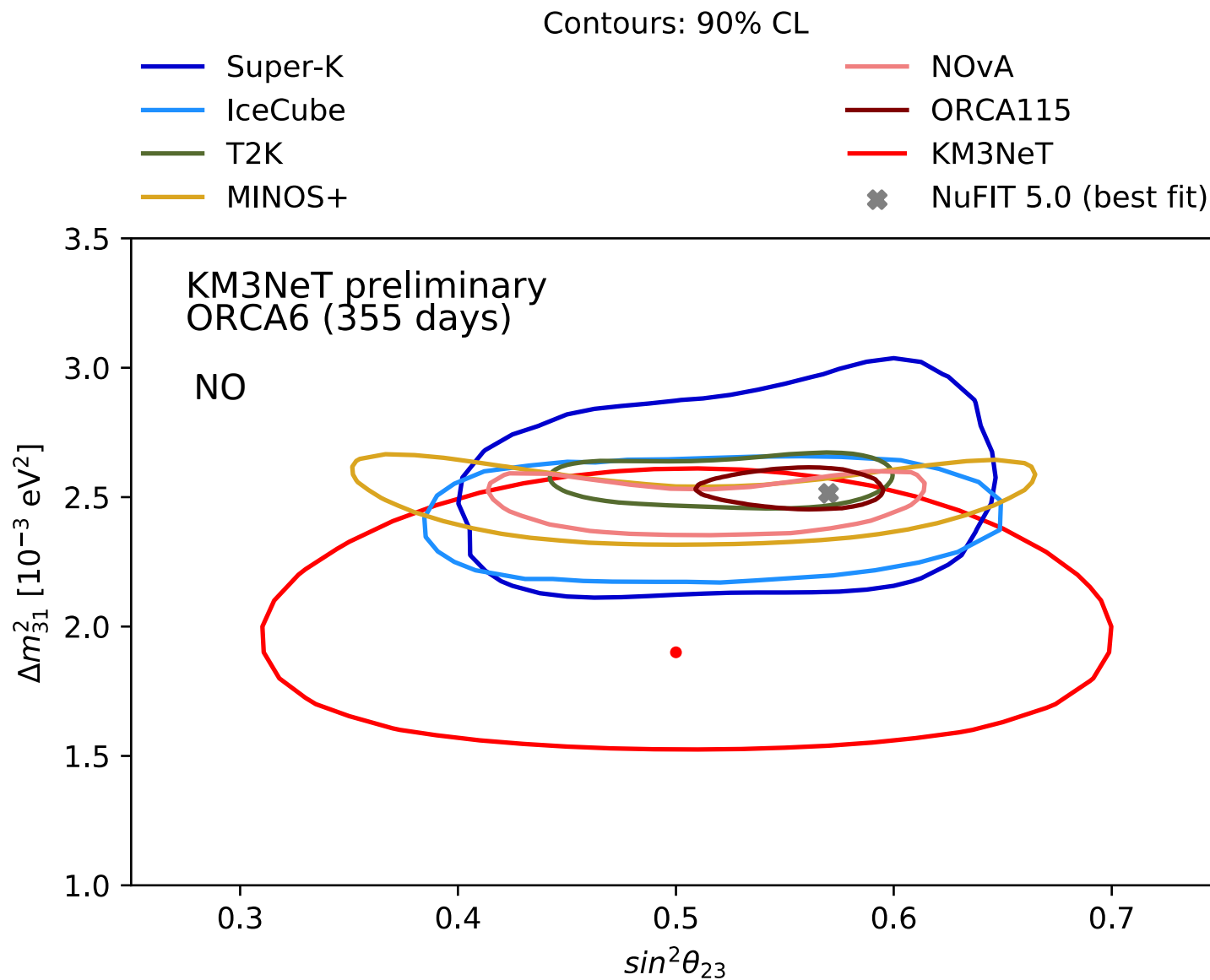


ORCA6 neutrino oscillations (tracks)





ORCA115: neutrino oscillations sensitivity (3 years)

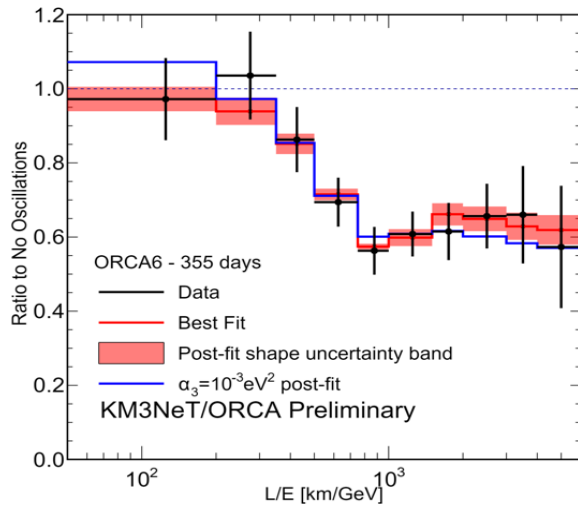




ORCA6: Other neutrino physics

ORCA6 353 kton-year sample:

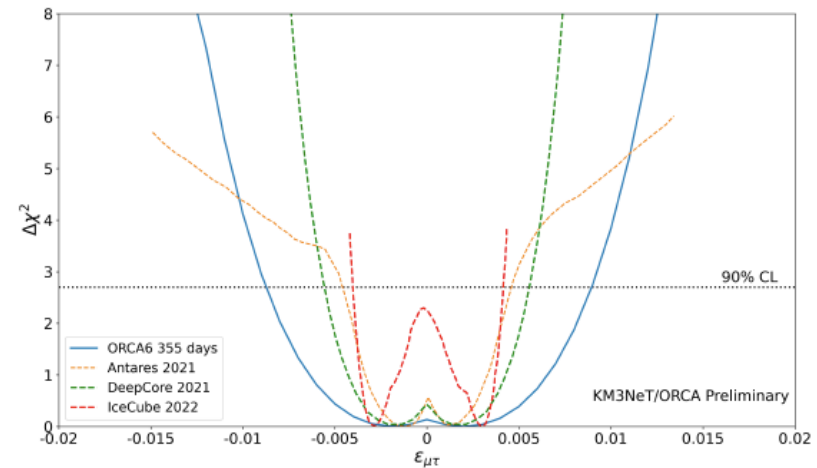
Neutrino decay



$$\frac{1}{\alpha_3} \equiv \frac{\tau_3}{m_3} > 2.4 \text{ ps/eV}$$

Experiment	L.L.(90%CL) (ps/eV)
ORCA6	2.4
ORCA115 (10y)	180
T2K, NOvA	2.3
T2K, MINOS	2.8
K2K, MINOS, SK I+II	290

Non-standard interactions (NSI)

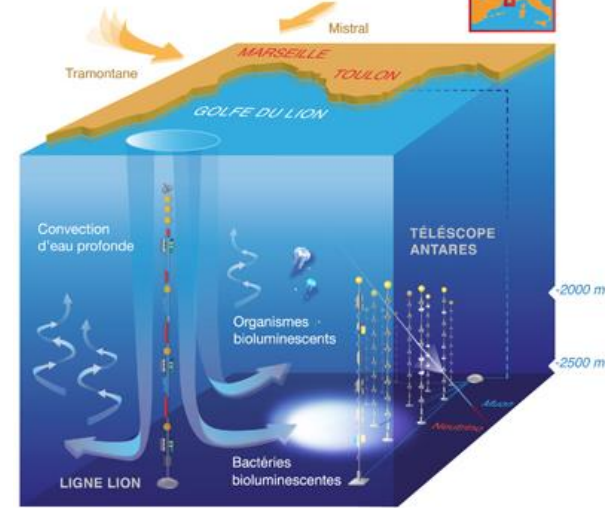
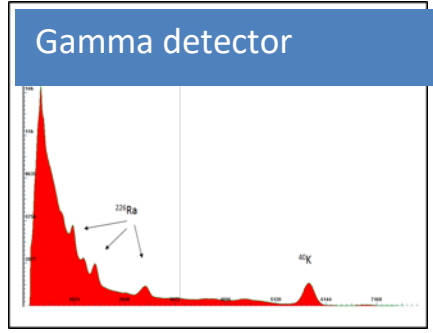
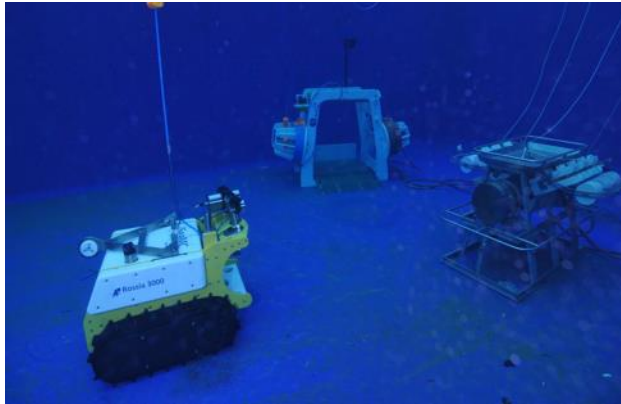


KM3NeT/ORCA6 limit: $-8.7 \times 10^{-3} < \epsilon_{\mu\tau} < 9.0 \times 10^{-3}$
 KM3NeT/ORCA115 3-year sensitivity: $-1.7 \times 10^{-3} < \epsilon_{\mu\tau} < 1.7 \times 10^{-3}$ (TBU)

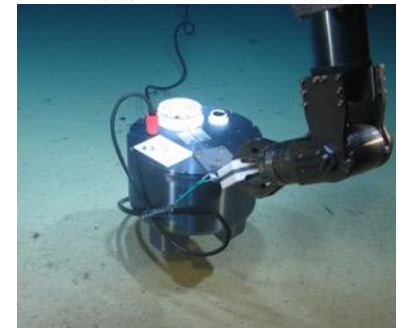
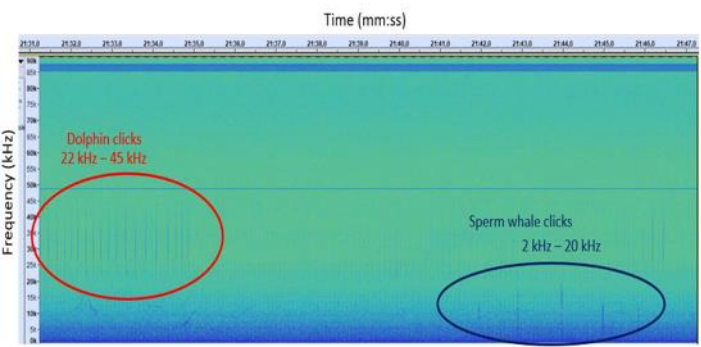
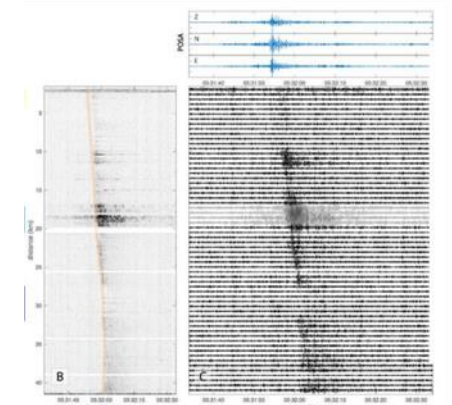
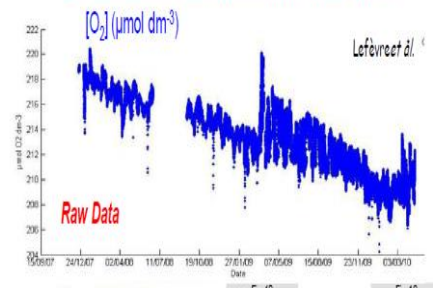
Other physics

Tau appearance
 Sterile neutrinos
 Quantum decoherence

...

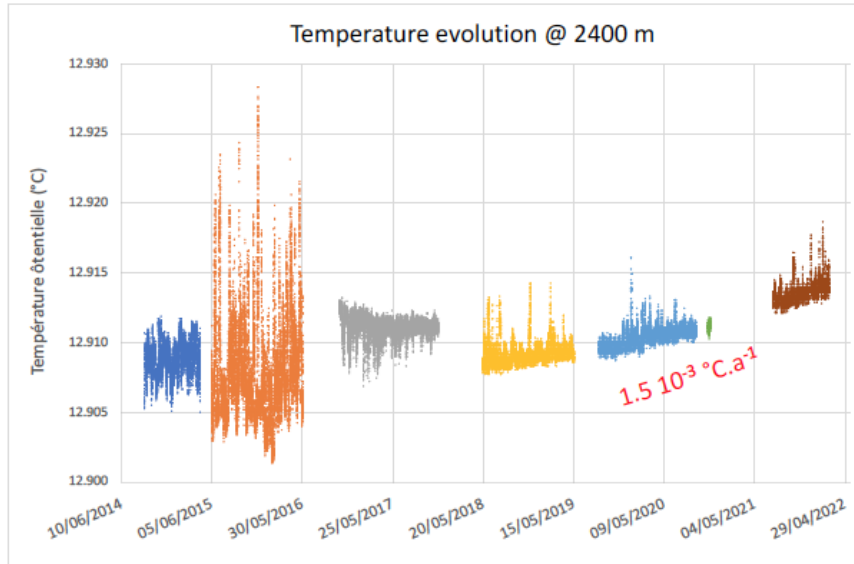


Evolution trend of *in situ* dissolved oxygen : $-5 \mu\text{mol O}_2 \text{ dm}^{-3} \text{ a}^{-1}$

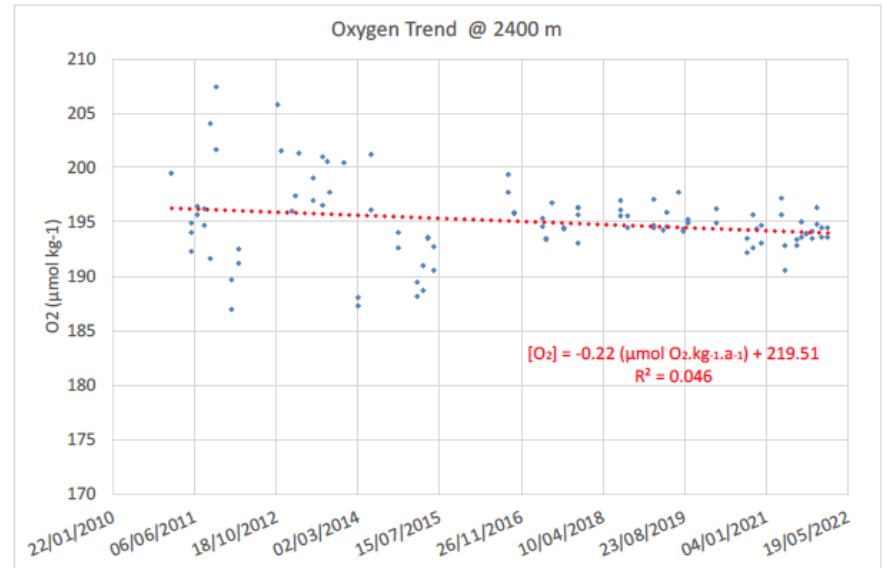


Climate change

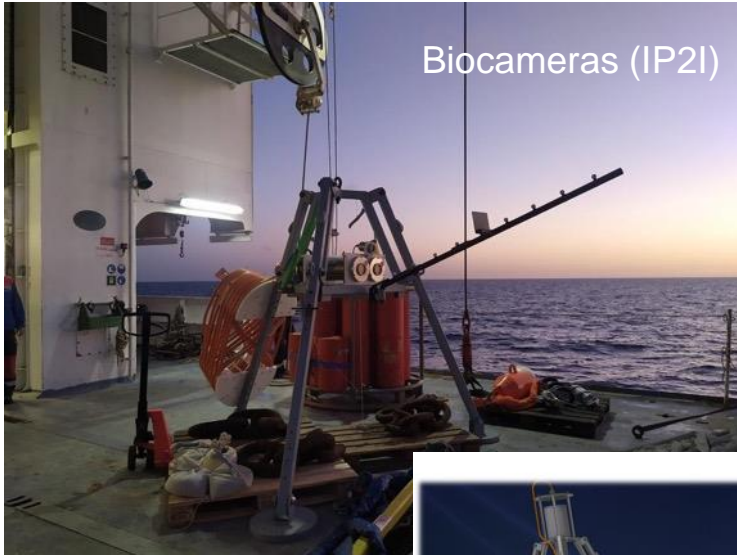
Temperature



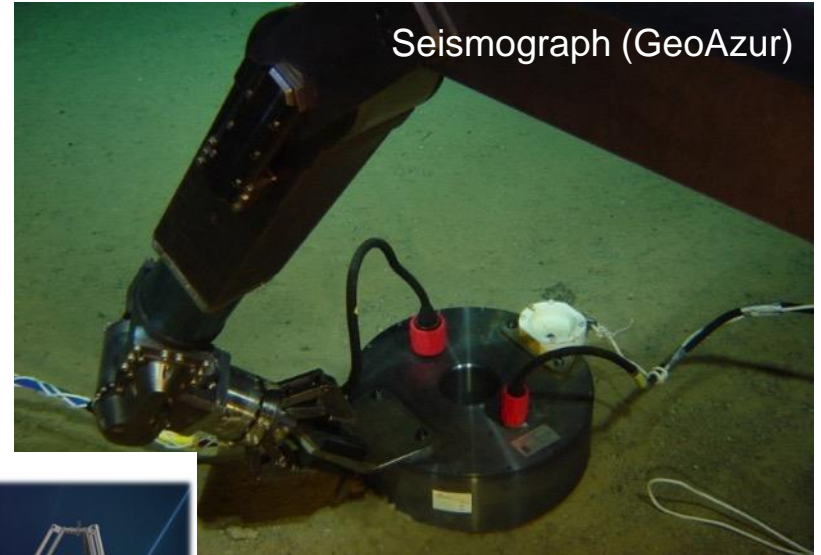
Oxygen



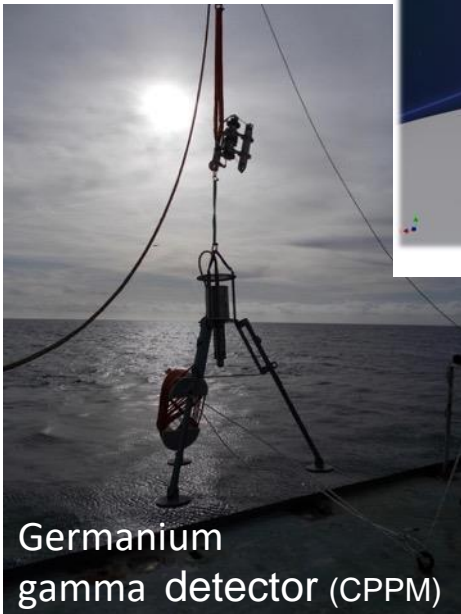
Deployment with Nautille



Biocameras (IP21)



Seismograph (GeoAzur)



Germanium
gamma detector (CPPM)



BathyBot (MIO, DT-INSU)

Summary

Water based neutrino telescopes:

- angular resolution -> precision multi-flavour astronomy
- location -> galactic sources
- ARCA/ORCA -> full energy range

KM3NeT taking data and growing rapidly

- First measurement of neutrino oscillation parameters
- First point source limits, ATELs reacting to external alerts

ORCA currently taking data with 11 lines.

Funding assured, and procurement and construction in progress, for ~50 lines.

End of 2023: ~32 lines

ARCA currently taking data with 21 lines.

Funding assured, and procurement and construction in progress, for ~130 lines.

End of 2023: ~38 lines

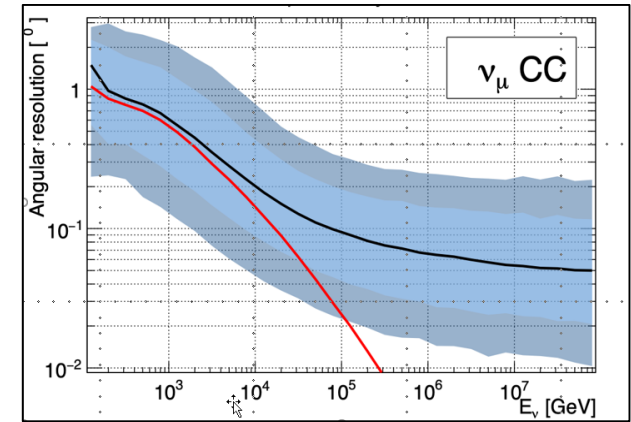
New collaborators very welcome

Come and join the adventure!

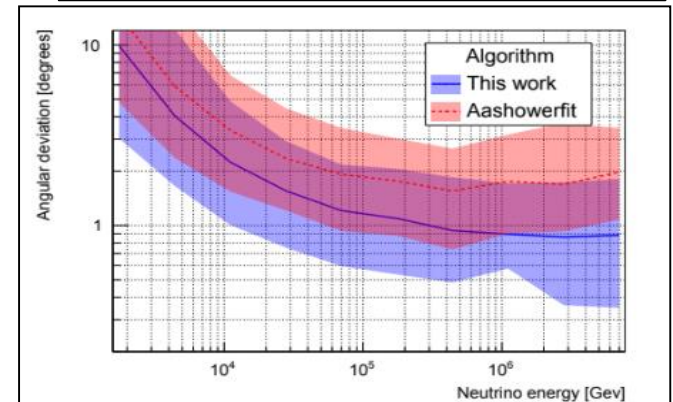
BACK UP

Angular Resolutions

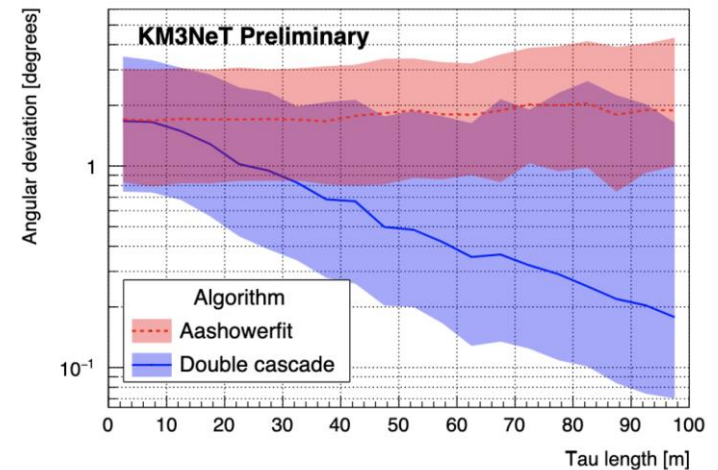
Better than $0.1^\circ > 20 \text{ TeV}$



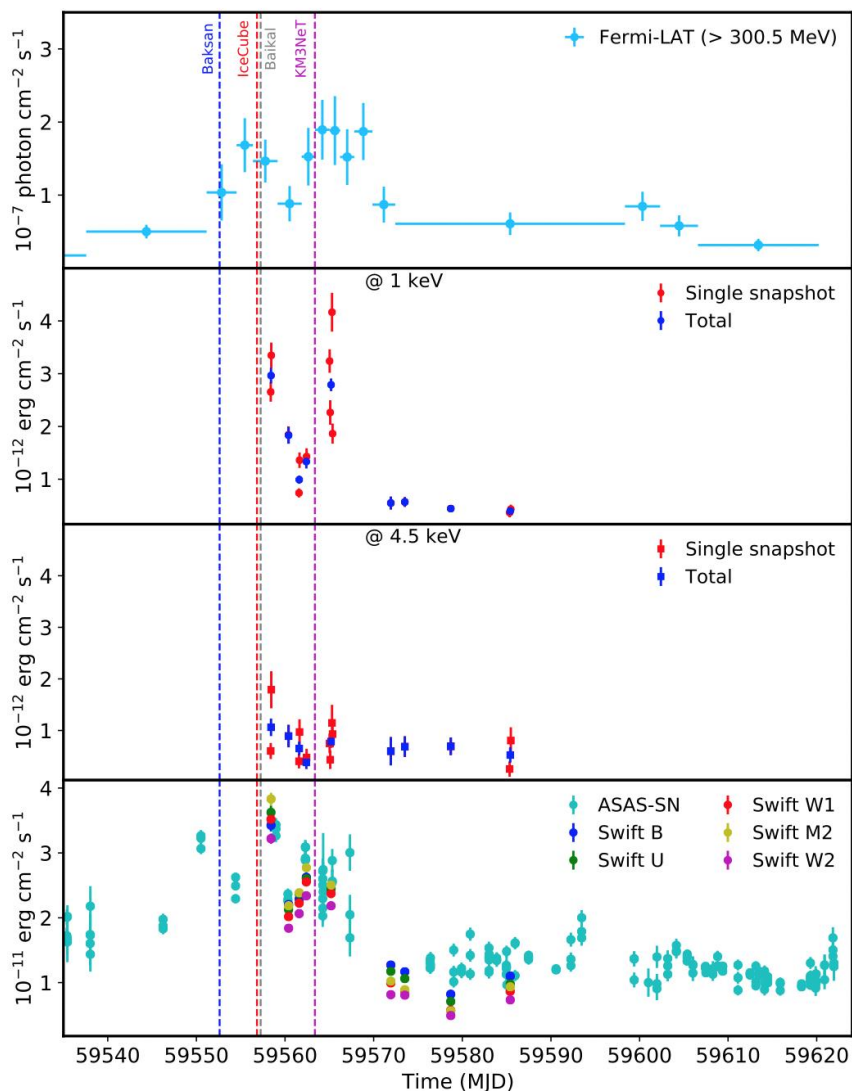
Better than $1^\circ > 30 \text{ TeV}$



Better than 1° for tau track length $> 22 \text{ m}$



Intriguing association with PKS 0735+17



IceCube: 1 bronze alert (~ 172 TeV) [[GCN #31191](#)]

ANTARES: no coincidence [[ATel #15106](#)]

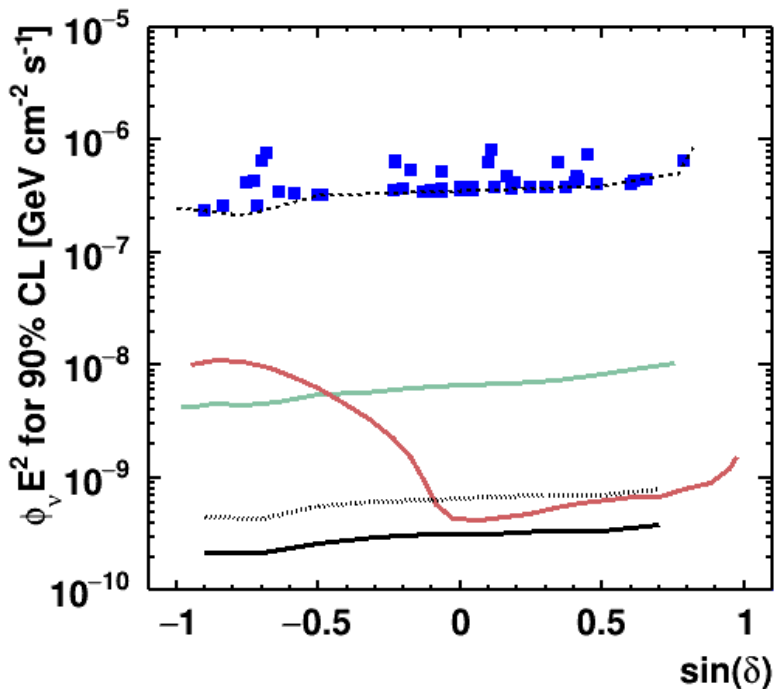
GVD-Baikal: 1 cascade event (~ 43 TeV), ~ 4 h after the IC neutrino, ~ 5 deg from the blazar direction (2.85σ) [[ATel #15112](#)]

KM3NeT: 1 track neutrino candidate (~ 18 TeV) in ARCA, 1.8 deg from the blazar ($p=0.14$). No coincidence in ORCA [[ATel #15290](#)]

Baksan: 1 track neutrino (1 GeV), 2.2 deg from the blazar ($\sim 3 \sigma$) [[ATel #15143](#)]

The blazar was found to experience a strong flare in gamma rays (ATel #15099, ATel #15129), X-rays (ATel #15102, ATel #15108, ATel #15109, ATel #15113, ATel #15130), optical (ATel #15098, ATel #15100, ATel #15132, ATel #15136, ATel #15148) and radio (ATel #15105) bands.

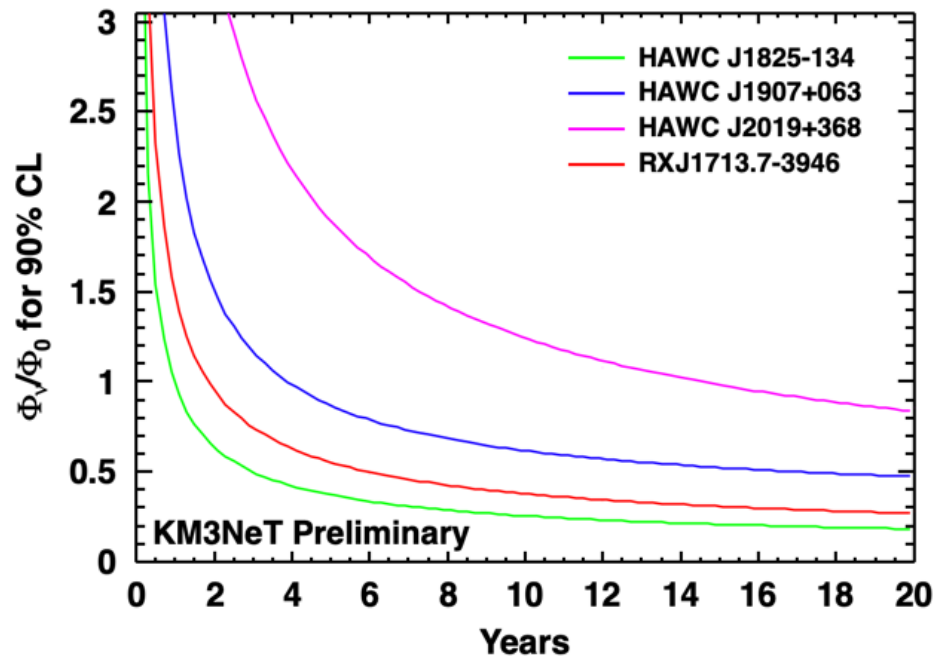
Point sources



KM3NeT Preliminary

- KM3NeT/ARCA6 (92 days) source limits
- KM3NeT/ARCA6 (92 days) sensitivity
- ANTARES (13yr) sensitivity
- IceCube (7yr) sensitivity
- KM3NeT/ARCA230 (7yr) sensitivity
- KM3NeT/ARCA230 (3yr) sensitivity

Extended sources



Source	Decl, RA [°]	Ext [°]
RXJ 713.7-3946	-39.77, 258.8	0.6 (disk)
HAWC J1825-134	-13.37, 276.4	0.53 (Gauss)
HAWC J2019+368	36.76, 304.92	0.356 (Gauss)
HAWC J1907+063	6.32, 286.91	0.67 (Gauss)

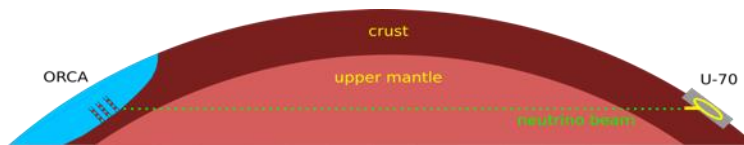


New idea: Tagged Protvino to ORCA

A. V. Akindinov et al.,
"Letter of Interest for a Neutrino Beam from Protvino to KM3NeT/ORCA"

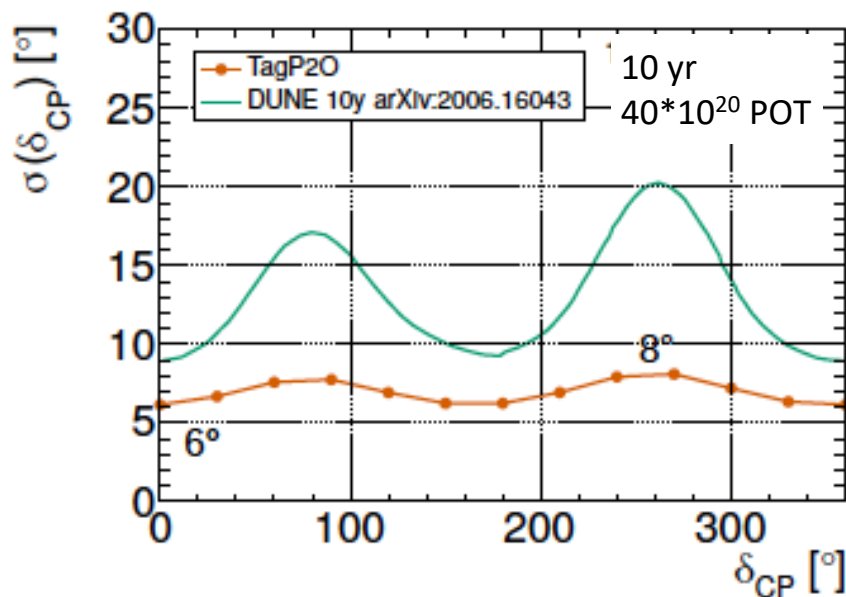
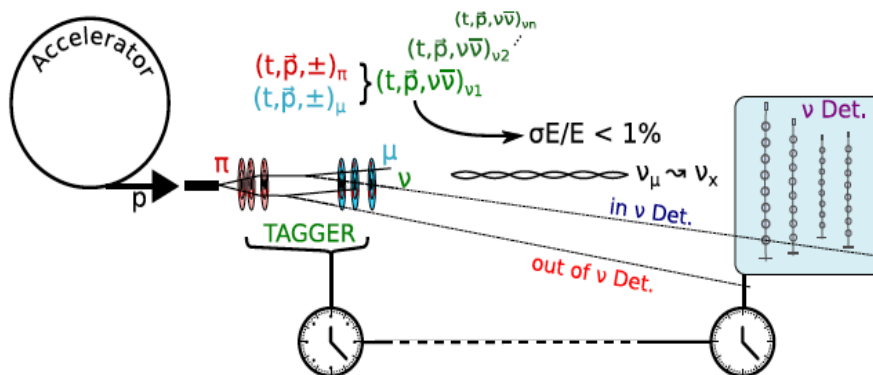
<https://arxiv.org/abs/1902.06083>

- Neutrino Beam from Protvino to ORCA
- Baseline 2590 km
- First oscillation maximum 5.1 GeV
- Sensitivity to mass hierarchy and CPV
- Lol published: arXiv:1902.06083
- Huge detector -> relax beam power
- **New idea - ν tagging at source:**

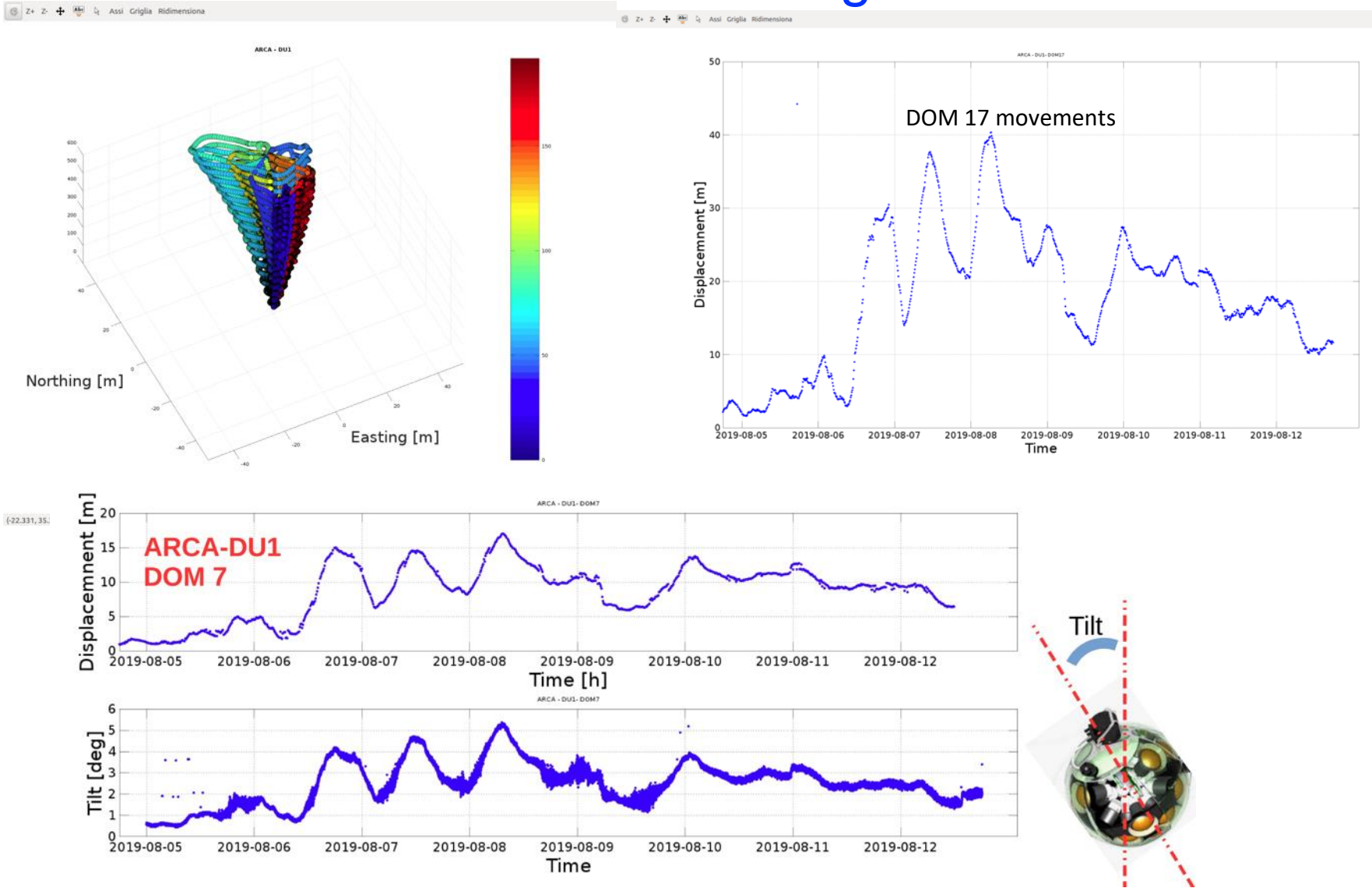


[M. Perrin-Terrin](https://arxiv.org/abs/2112.12848)

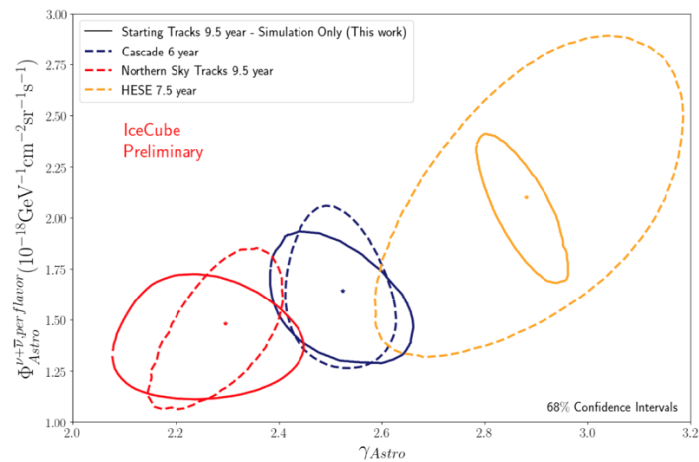
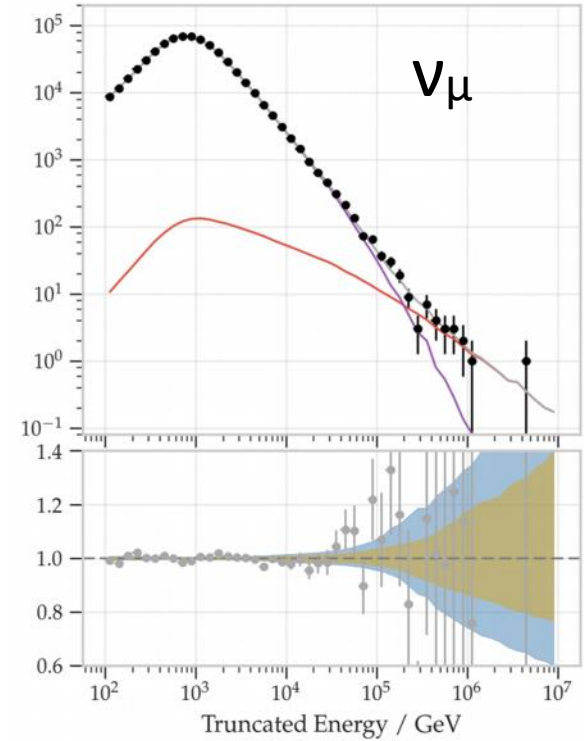
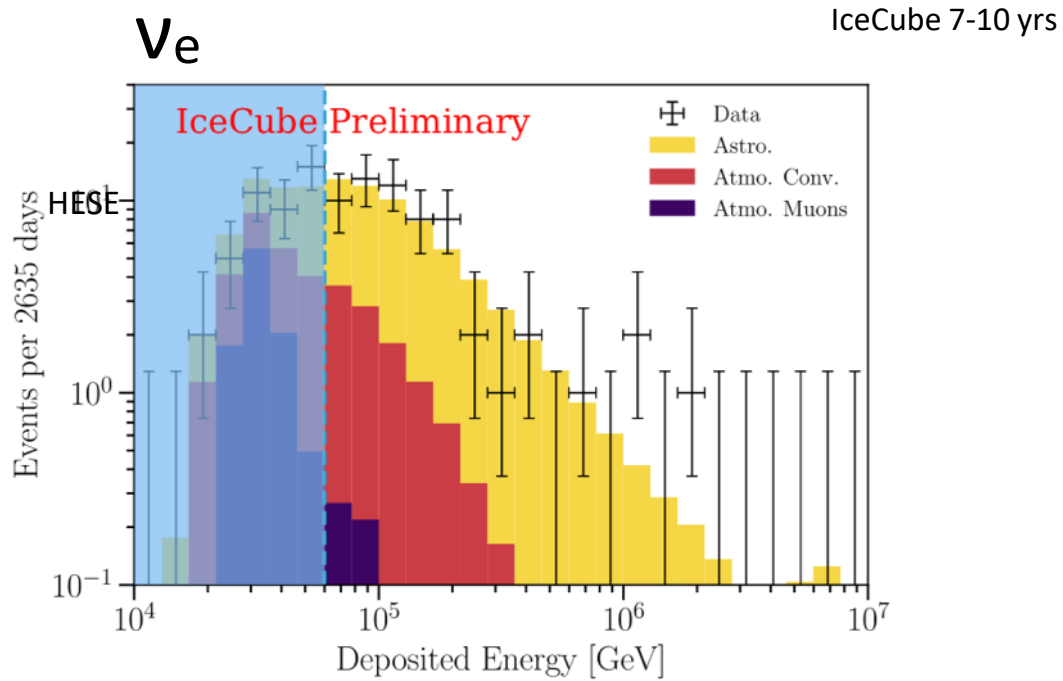
<https://arxiv.org/abs/2112.12848>



Acoustic Positioning: ARCA movement-strong currents



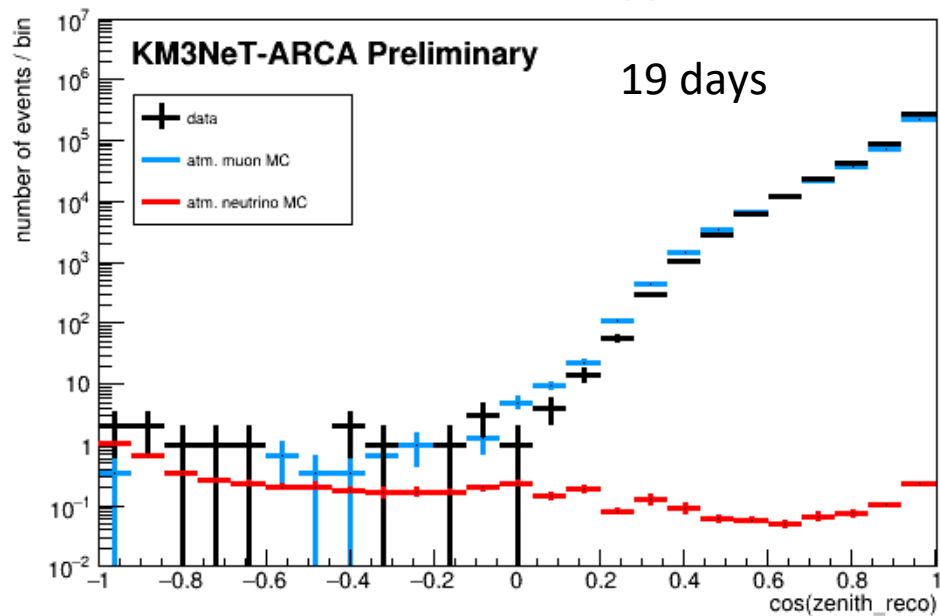
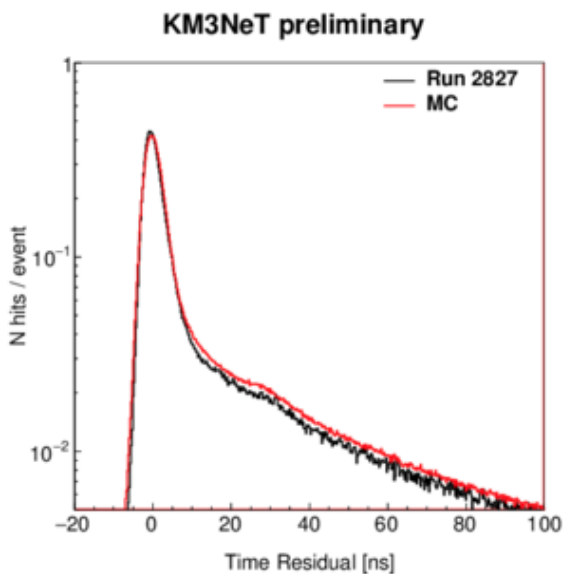
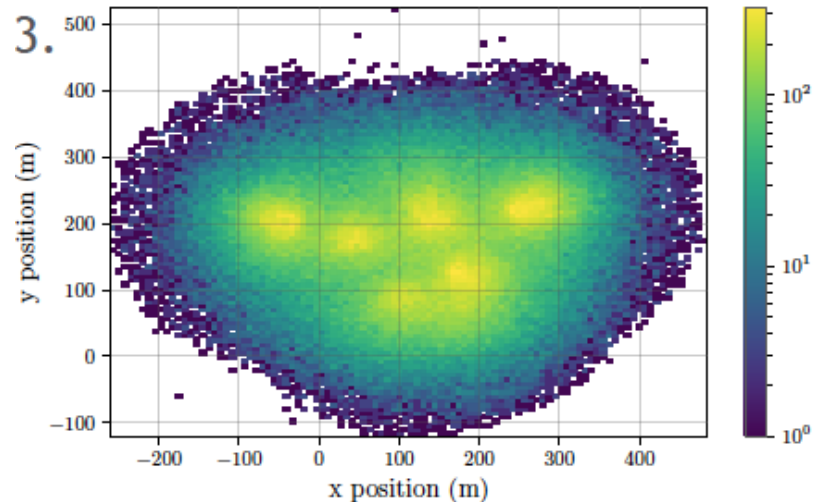
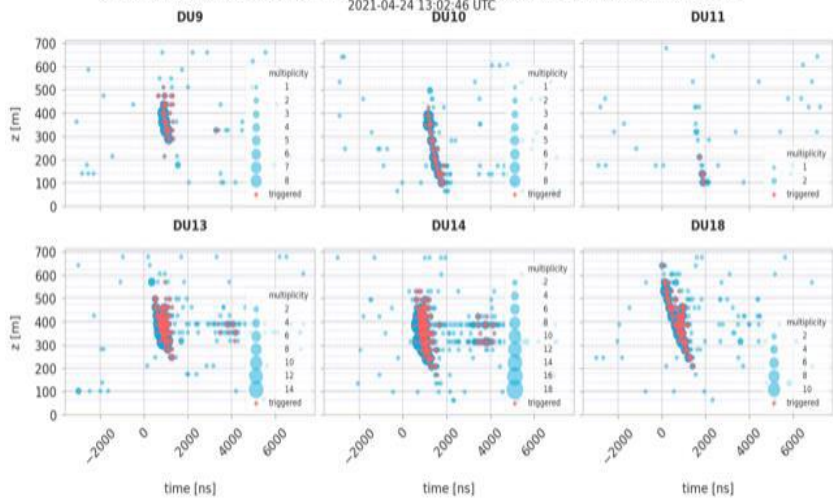
Diffuse flux observed by IceCube





ARCA6 data

z-t-Plot for DetID:75 Run 9380, FrameIndex 37662, TriggerCounter 10793, Overlays 196, Trigger: MX 3DM 3DS
2021-04-24 13:02:46 UTC

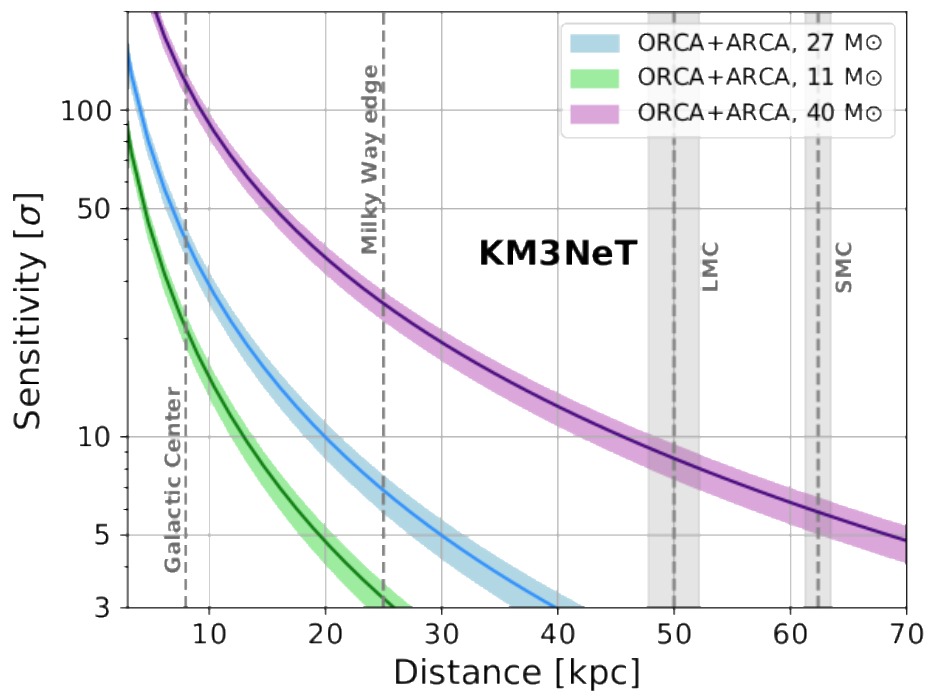
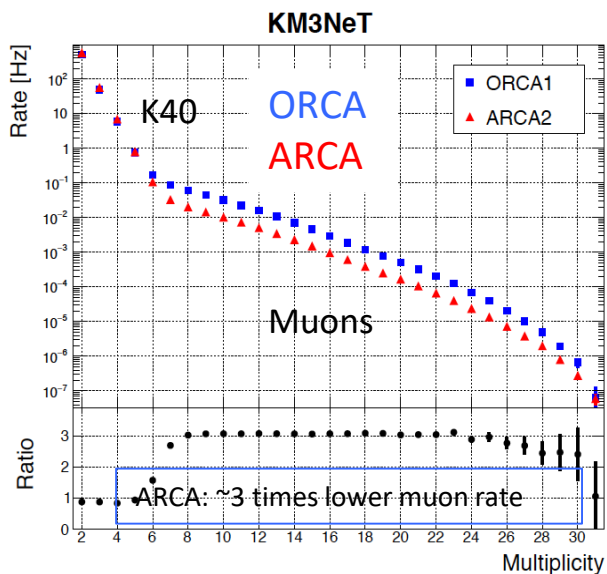




Supernova monitoring in KM3NeT

SN MeV neutrinos => collective excess of multi-fold coincidences on all DOMs

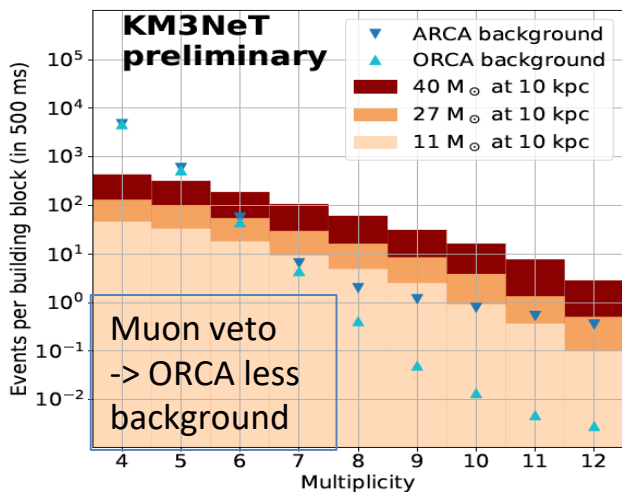
Eur. Phys. J. C81 (2021) 445



Discovery potential for 95% of Galactic CCSNe

ARCA6+ORCA6 already sensitive to 60% of Galactic CCSNe (<11 kpc)

Joint real time trigger operational for SNEWS since early 2019

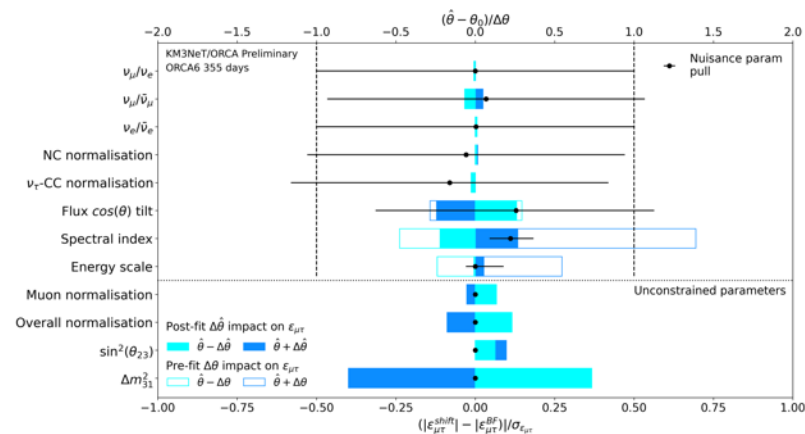
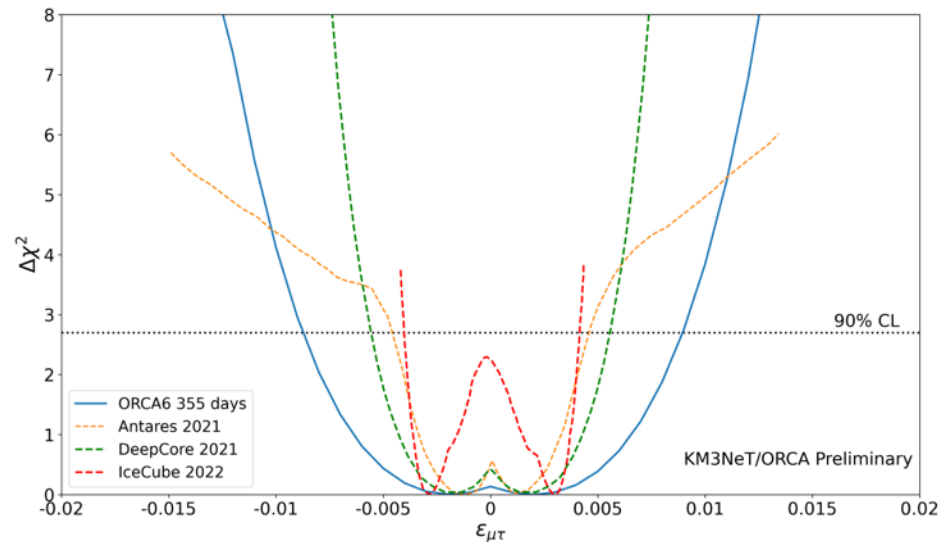
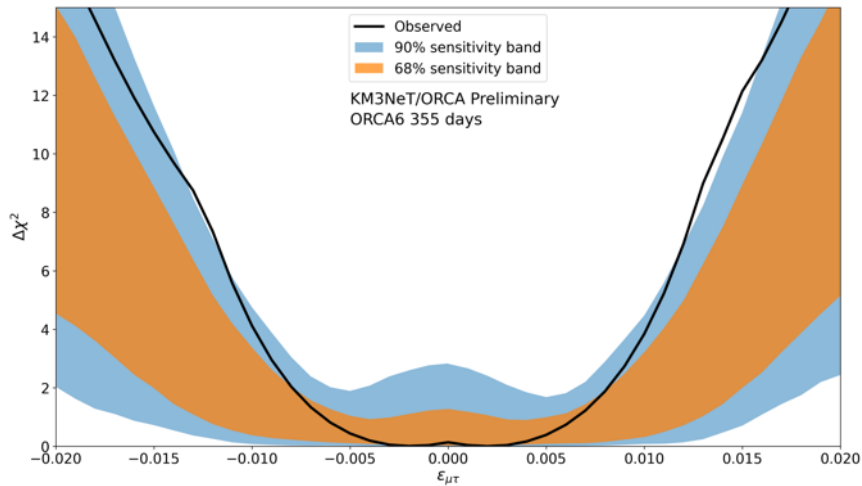




ORCA6: non-standard interactions

ORCA6 353 kton-year sample:

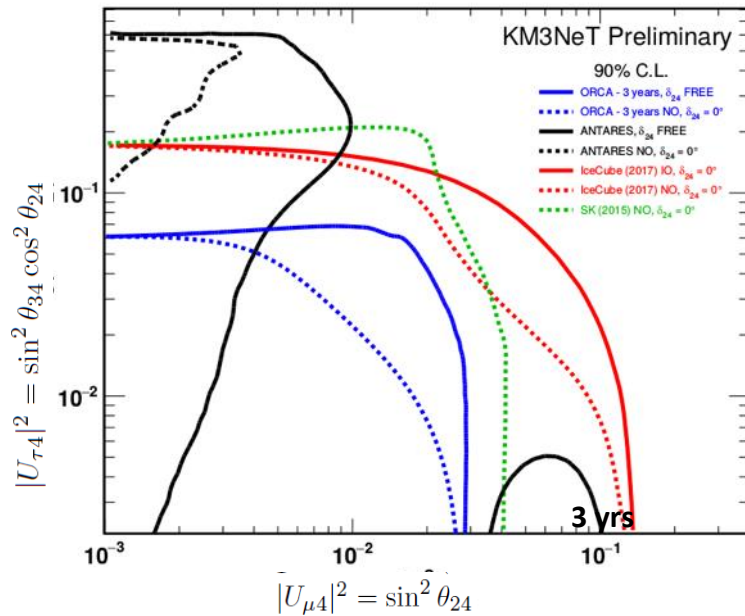
NSI parameter $|\varepsilon_{\mu\tau}| < 0.009$ (comparable to world best limits)





ORCA115: sterile neutrinos

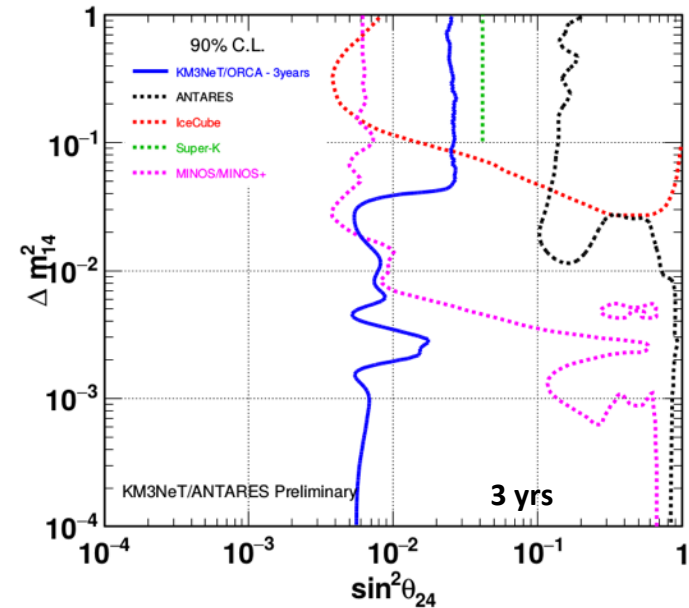
$$\Delta m_{41}^2 > 0.1 \text{ eV}^2$$



Dependence on δ_{24}

Factor of two better sensitivity on $U_{\tau 4}$ than current limits from SK and IC

$$\Delta m_{41}^2 < 0.1 \text{ eV}^2$$



Due to longer & multiple baselines improve on MINOS/MINOS+ limits by 2 orders of magnitude

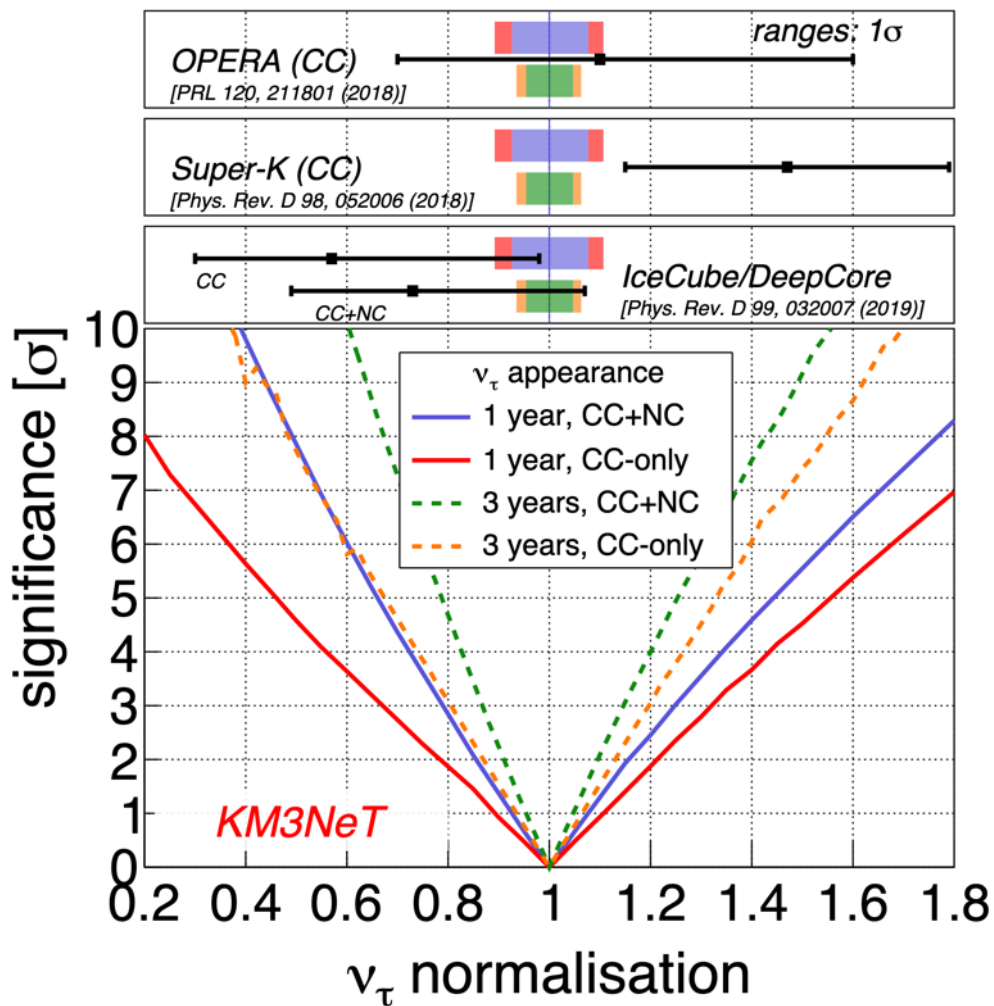
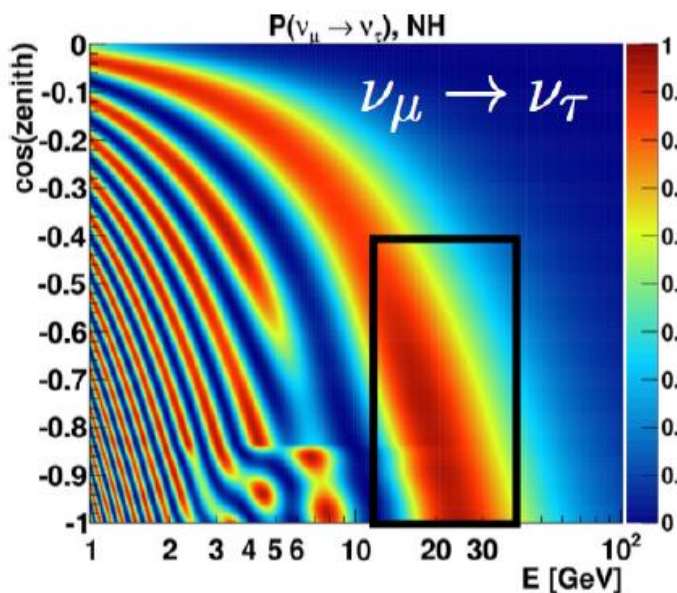
Tau appearance

The muon neutrinos mainly oscillate to tau neutrinos.

They appear as showers events.

Counting shower events is the sum of the tau and electron neutrinos

$\approx 3k \nu_\tau$ CC events/year with full ORCA



Water versus Ice

Long (homogeneous) scattering length

Good pointing accuracy

Deep sites: 2500→5000m

Shielding from downgoing muons

Logistically attractive

Close to shore (deployment / repair)

Complementarity to IceCube South Pole

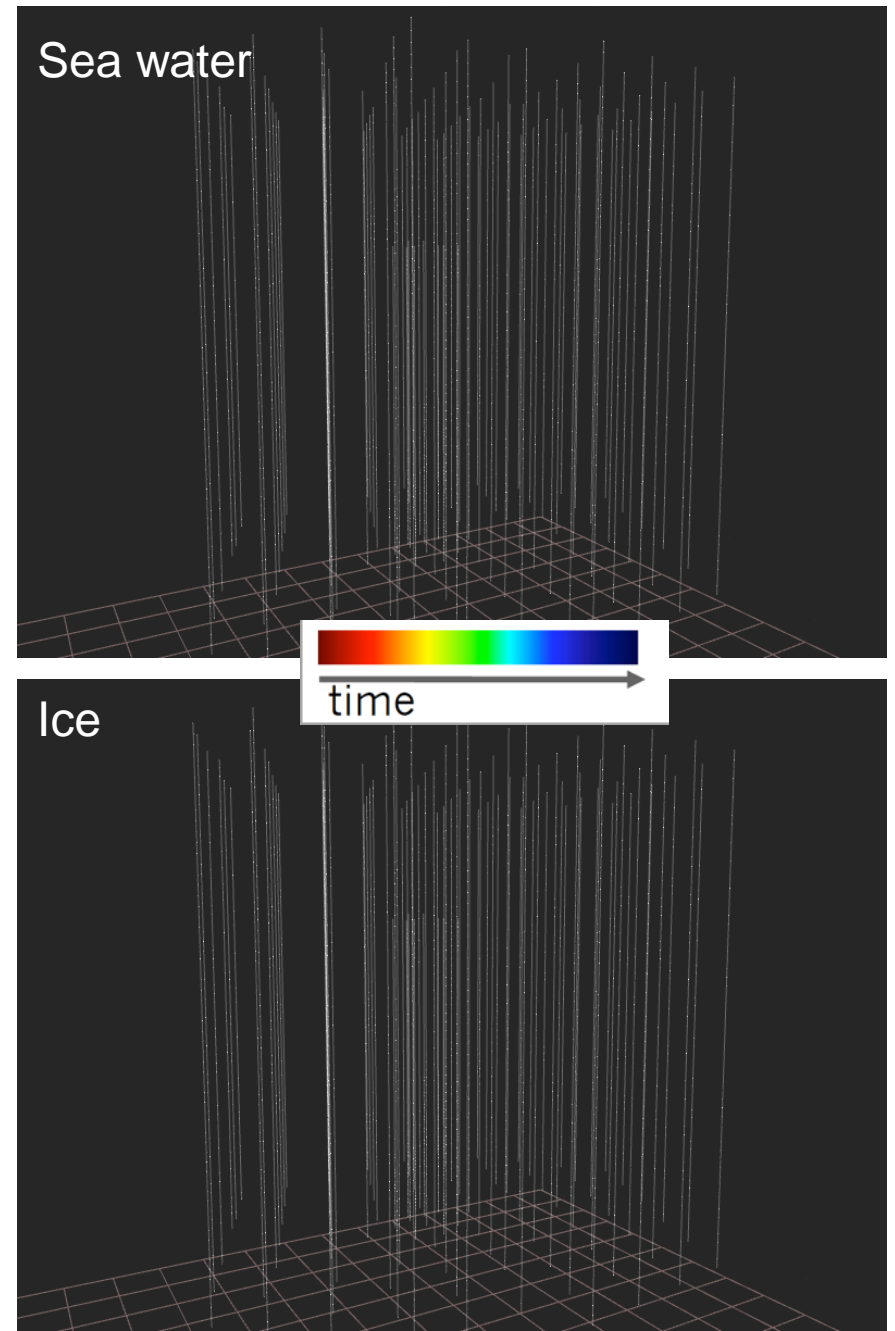
Excellent view of Galaxy

Mild Latitude

On/off studies ! Background control

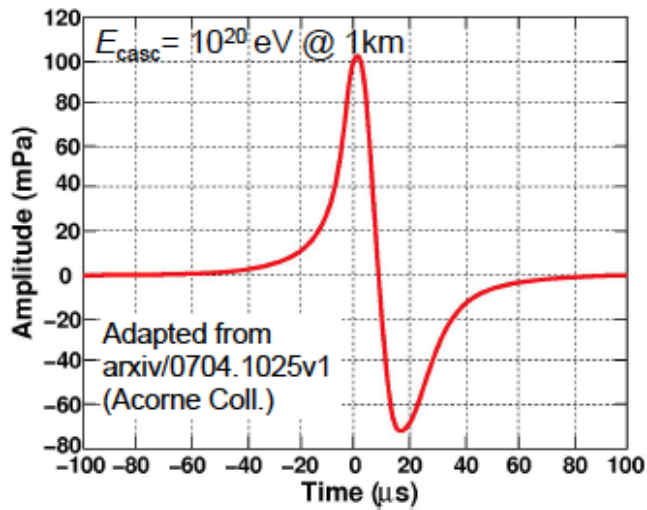
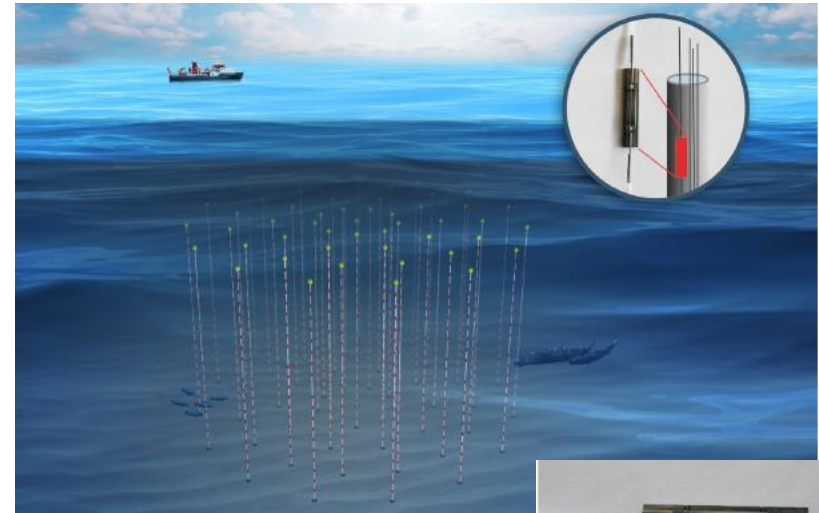
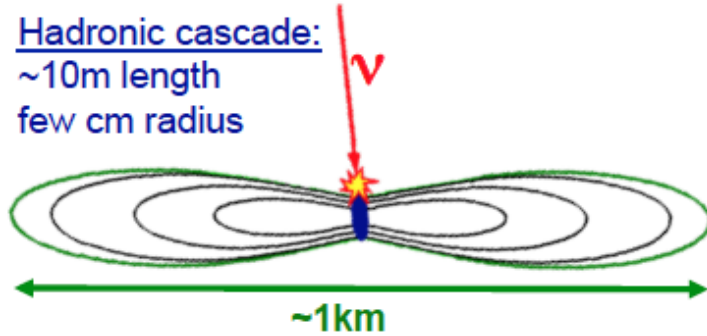
K40 optical background

Useful calibration, but requires causality filters

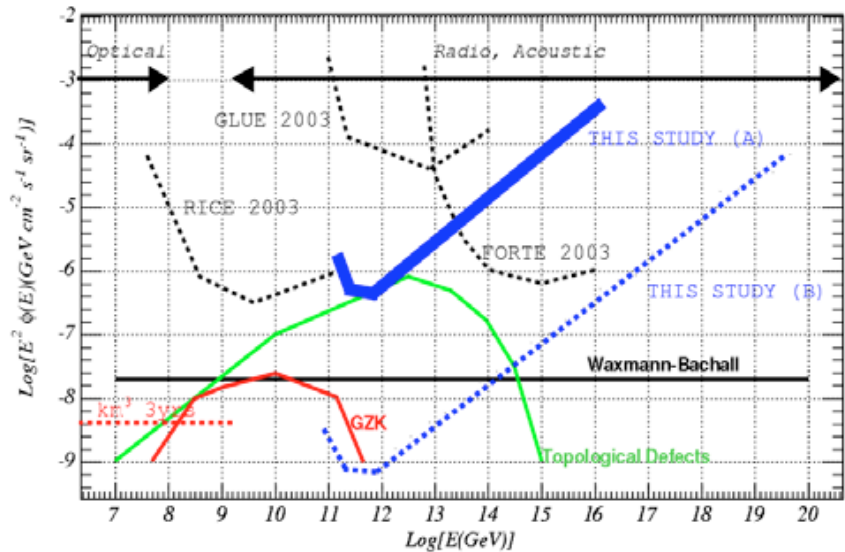


Old idea/New technology: Acoustic detection of UHE neutrino

Hadronic cascade:
 ~10m length
 few cm radius



$$P(r = 200 \text{ m}) \approx 10 \times \frac{E_{\text{casc}}}{1 \text{ EeV}} \text{ mPa}$$



Opération Nautille (31/1/22-14/2/22): Déploiement BJS

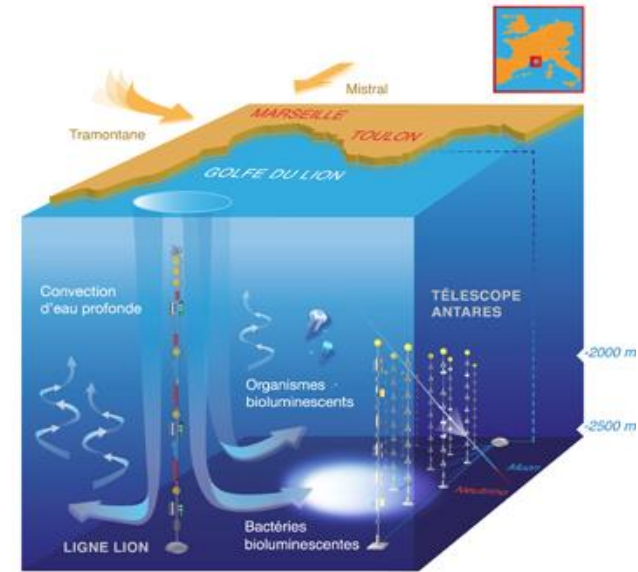
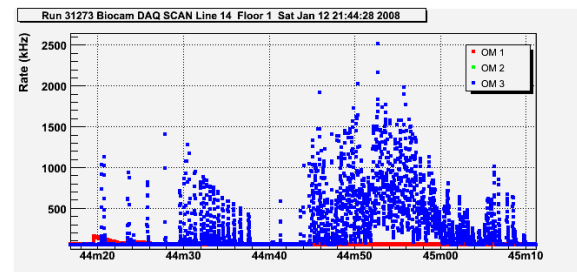
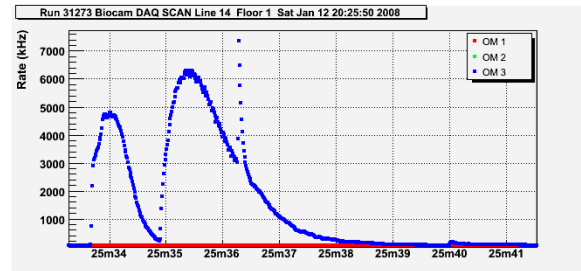
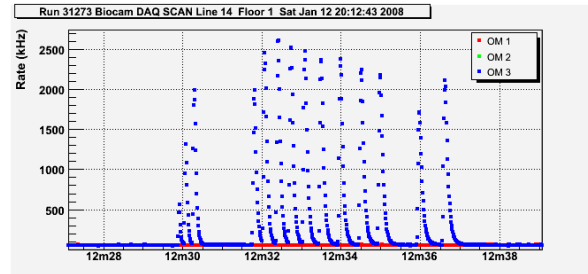


Bioluminescence



90% of deep sea organisms:

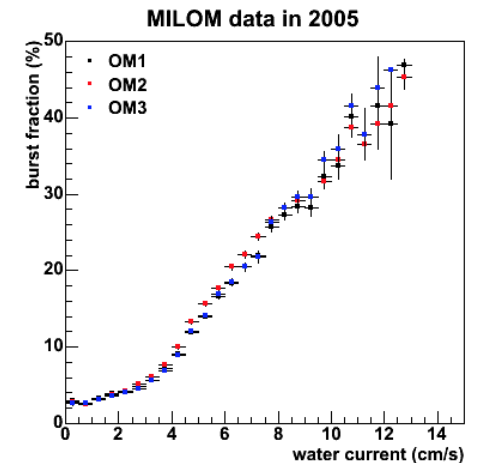
- Communication
- Attract prey
- Repel predators



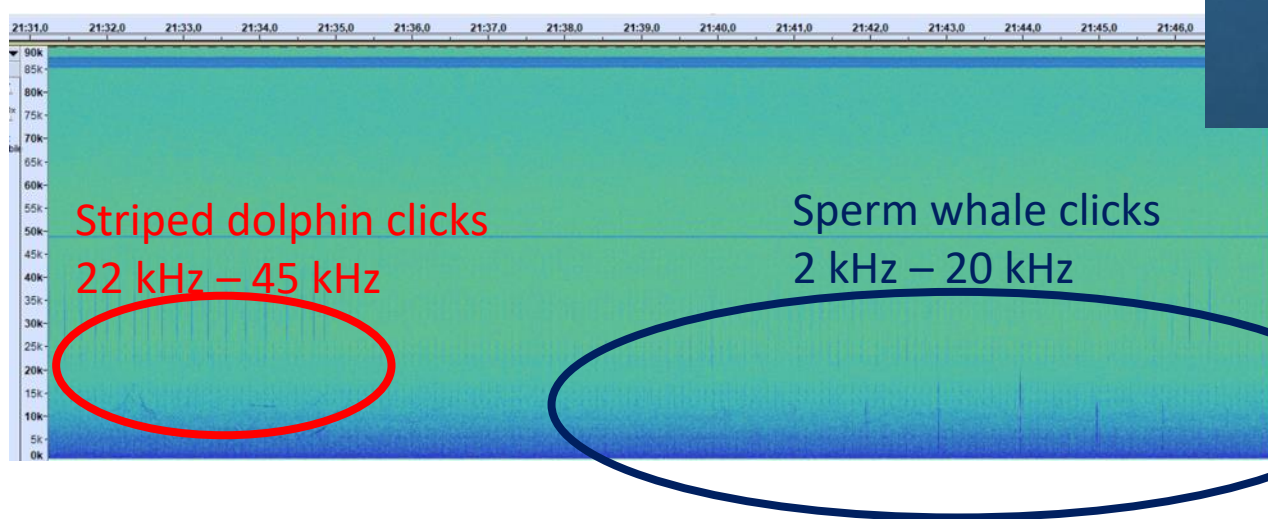
ANTARES: "La Recherche Prize"

📖 PLoS ONE 8(7) 2013

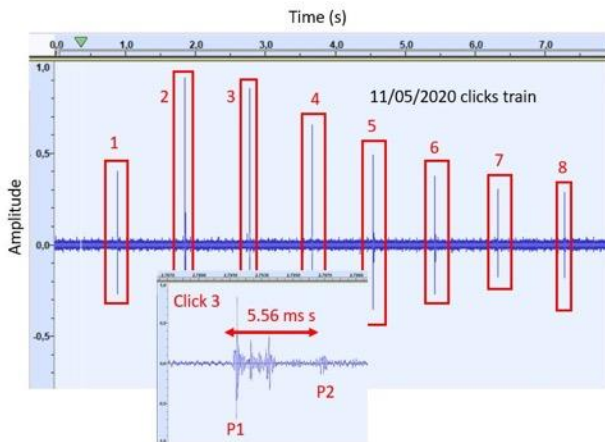
Deep-sea bioluminescence blooms after dense water formation at the ocean surface



Bioacoustics



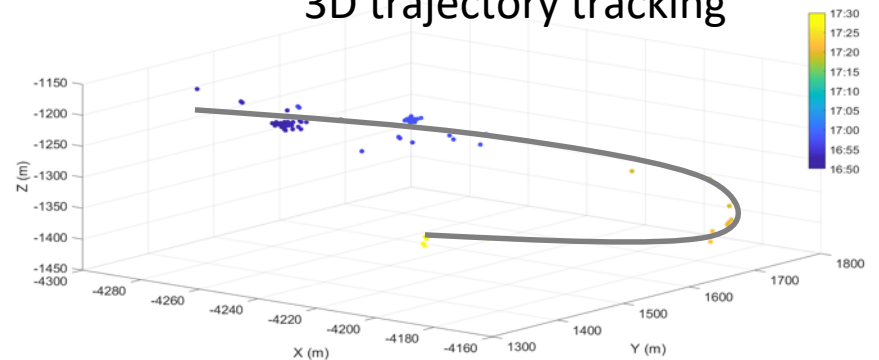
size of whales



Click	IPI	Size
1	5.33 ms	12.58 m
2	5.45 ms	12.64 m
3	5.56 ms	12.71 m
4	5.42 ms	12.63 m
5	5.31 ms	12.57 m
6	5.33 ms	12.58 m
7	5.30 ms	12.57 m
8	5.45 ms	12.64 m

Mean value: $(12.62 \pm 0.04) m$

3D trajectory tracking



BathyBot & LSPM/KM3NeT dans la presse

Parisien (29/1/22)

BathyBot, le rover des fonds marins

VAR
Toulon Mer Méditerranée
 ≈40 km
 Zone de mission

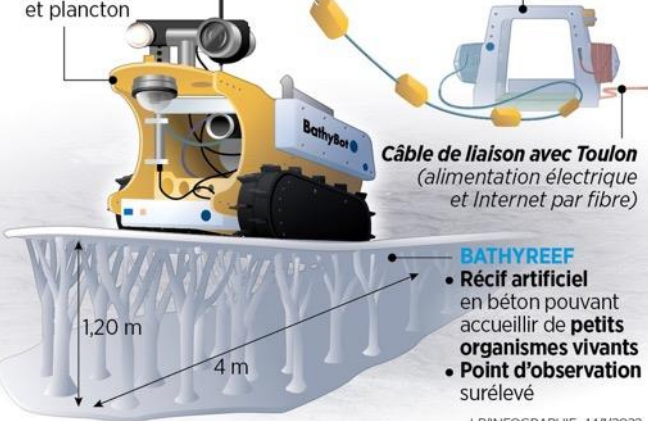
Mission : observation sous-marine
Localisation : au large de **Toulon (Var)**
Profondeur : 2 500 m
Durée : au moins **dix ans**

BATHYBOT

- Rayon d'action : **50 m**
- **Piloté à distance**
- Capteurs : température, salinité, oxygénation de l'eau, système d'imagerie détectant particules et plancton

BATHYDOCK

- **Point d'ancrage** du BathyBot et **boîtier de liaison**
- Permet la **descente** du BathyBot depuis un bateau



BATHYREEF

- **Récif artificiel** en béton pouvant accueillir de **petits organismes vivants**
- **Point d'observation** surélevé

LP/INFGROPHIE, 14/1/2022

Le Figaro (29/1/22)



Le Figaro (3/2/22)





ORCA6: neutrino fit systematics uncertainties

Parameter	Treatment	Fit value
Δm_{31}^2 [10^{-3} eV ²]	Free	$1.95^{+0.24}_{-0.21}$
θ_{23} [deg]	Free	$45.4^{+5.6}_{-5.7}$
Norm	Free	$0.88^{+0.03}_{-0.11}$
Flux: spectral index	$\mathcal{N}(0, 0.3)$	$0.052^{+0.053}_{-0.010}$
Flux: zenith angle bias	$\mathcal{N}(0, 0.07)$	$0.035^{+0.059}_{-0.060}$
Skew $\mu\bar{\mu}$	$\mathcal{N}(0, 0.1)$	$0.00^{+0.10}_{-0.10}$
Skew e/\bar{e}	$\mathcal{N}(0, 0.1)$	$0.00^{+0.10}_{-0.10}$
Skew μe	$\mathcal{N}(0, 0.03)$	$0.00^{+0.03}_{-0.03}$
NC normalization	$\mathcal{N}(1, 0.1)$	$0.99^{+0.10}_{-0.10}$
τ normalization	$\mathcal{N}(1, 0.2)$	$0.97^{+0.20}_{-0.20}$
Energy scale	$\mathcal{N}(0, 0.1)$	$0.00^{+0.03}_{-0.01}$