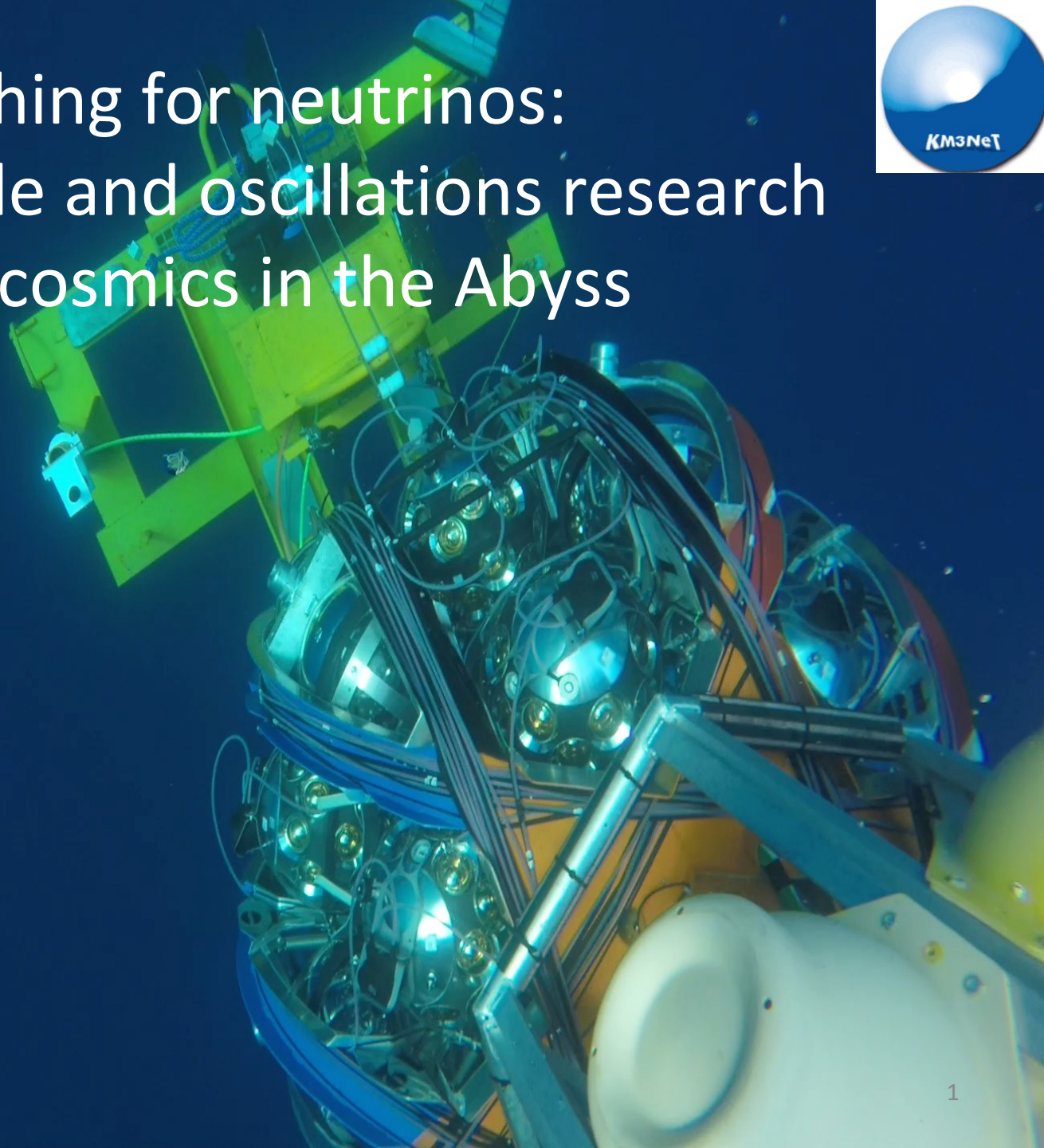
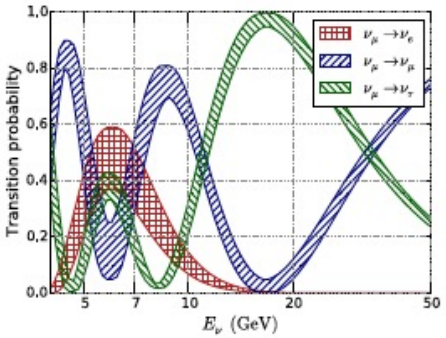
Fishing for neutrinos: Astroparticle and oscillations research with cosmics in the Abyss

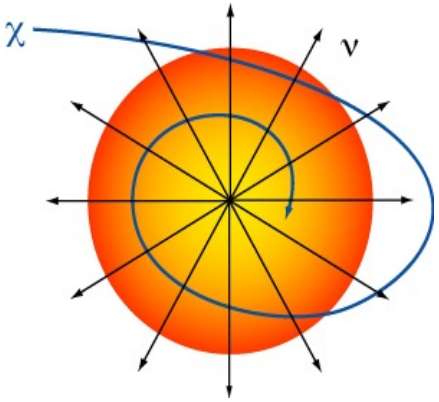


Warwick University Seminar
Paschal COYLE, CPPM
28/4/22

Neutrino telescopes: science

MeV to PeV energies





Supernova
Solar flares

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

Dark matter
Monopoles,
Nuclearites,…

Cosmic neutrinos

Cosmic rays

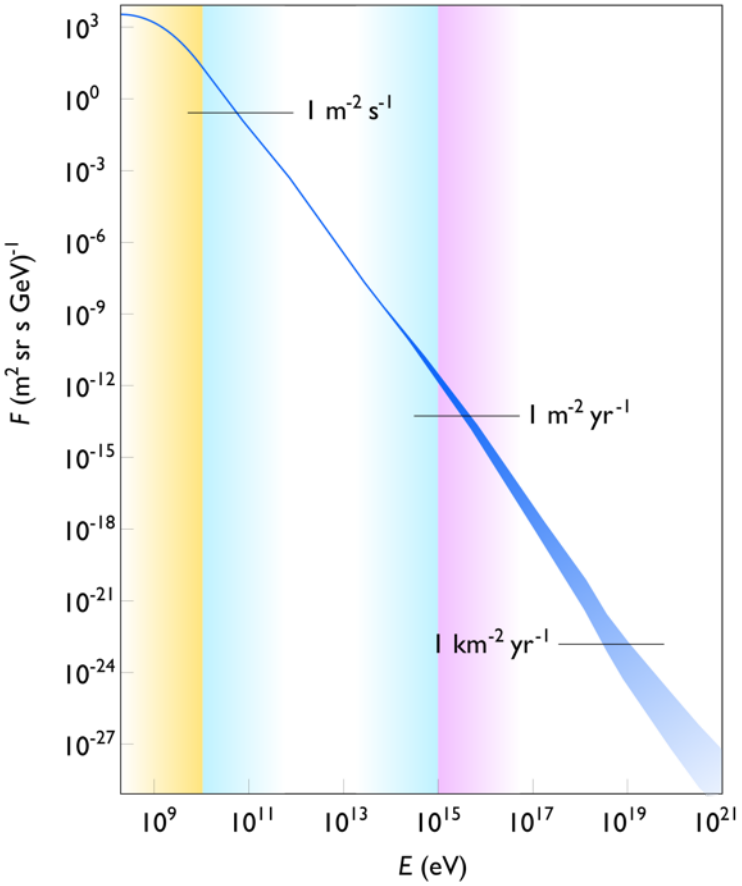
Origin and production mechanism of HE CR

KM3NeT-ORCA ANTARES KM3NeT-ARCA

+ oceanography, biology, bioacoustics, seismology,…

Motivations for neutrino astronomy

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

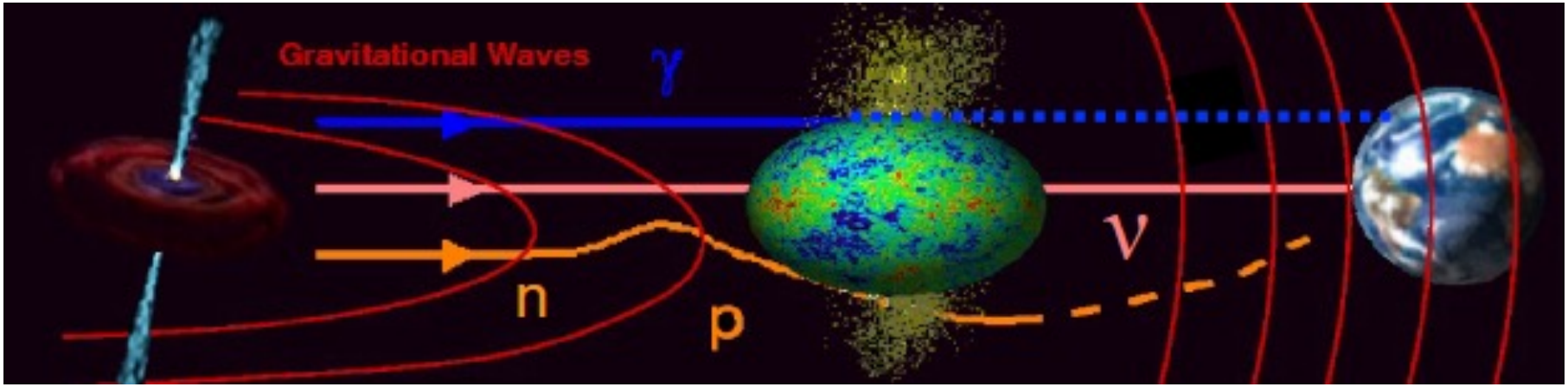


→ Discover ~100 years ago but still unknown origin
→ Spectrum over 32 orders of magnitude

→ 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 ➔ access to cosmological distances
not absorbed by matter ➔ access to dense environments
not deviated by magnetic fields ➔ 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

THE CR-GAMMA-NEUTRINO CONNECTION

Multi-messenger connection (0th order)

Photo-hadronic interactions of CR

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ & 1/3 \text{ of all cases} \\ p + \pi^0 & 2/3 \text{ of all cases} \end{cases}$$

Neutrino emission

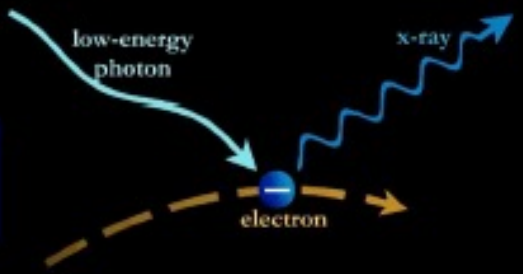
$$\pi^+ \rightarrow \mu^+ + \nu_\mu\,,$$

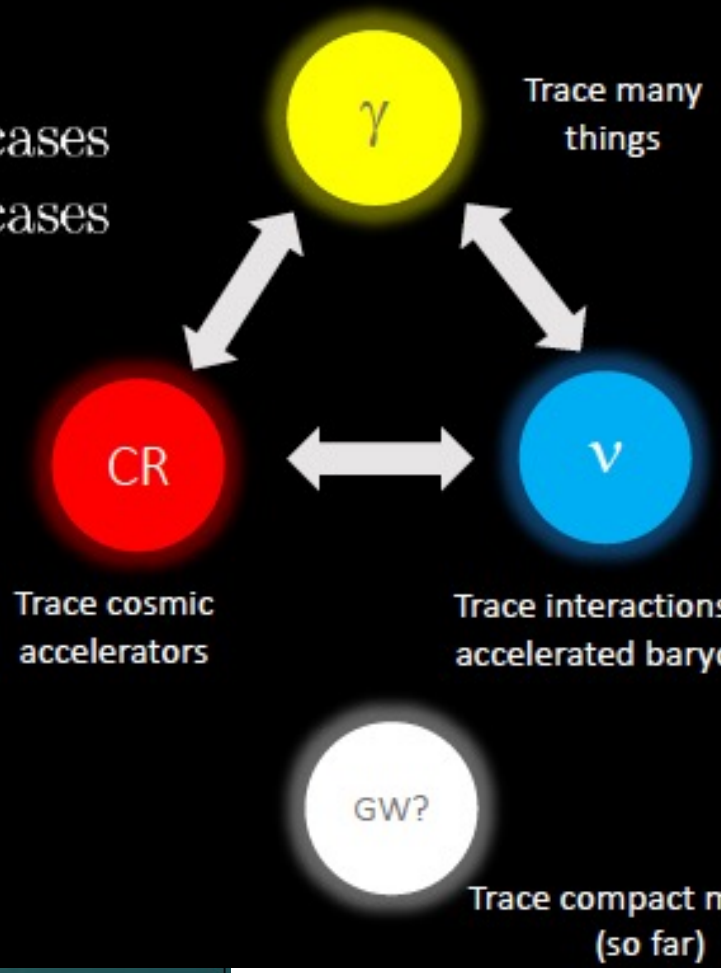
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Photon emission

$$\pi^0 \rightarrow \gamma + \gamma$$

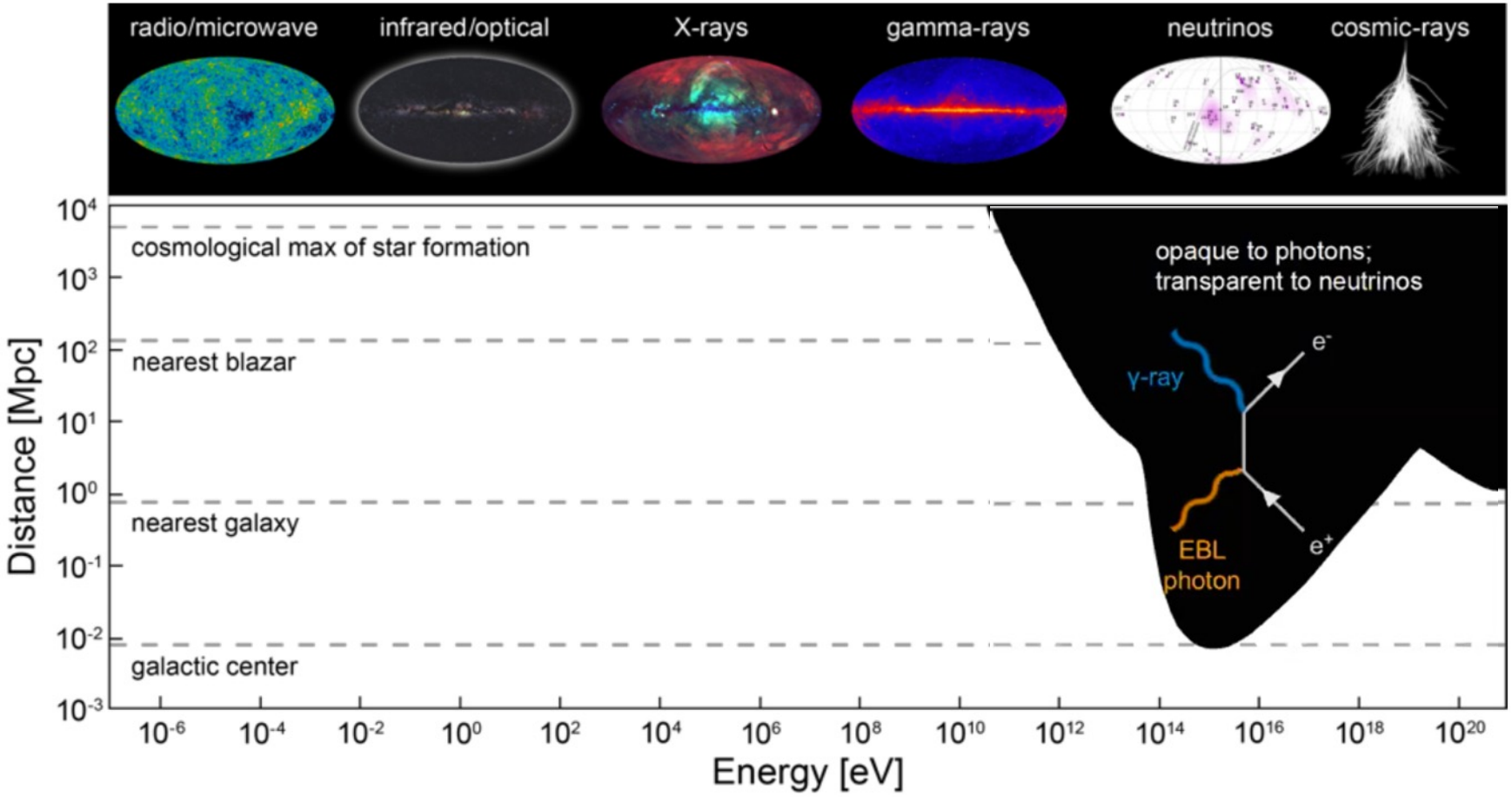
Most of the observed radiation is EM ☹





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

A new window on the Universe

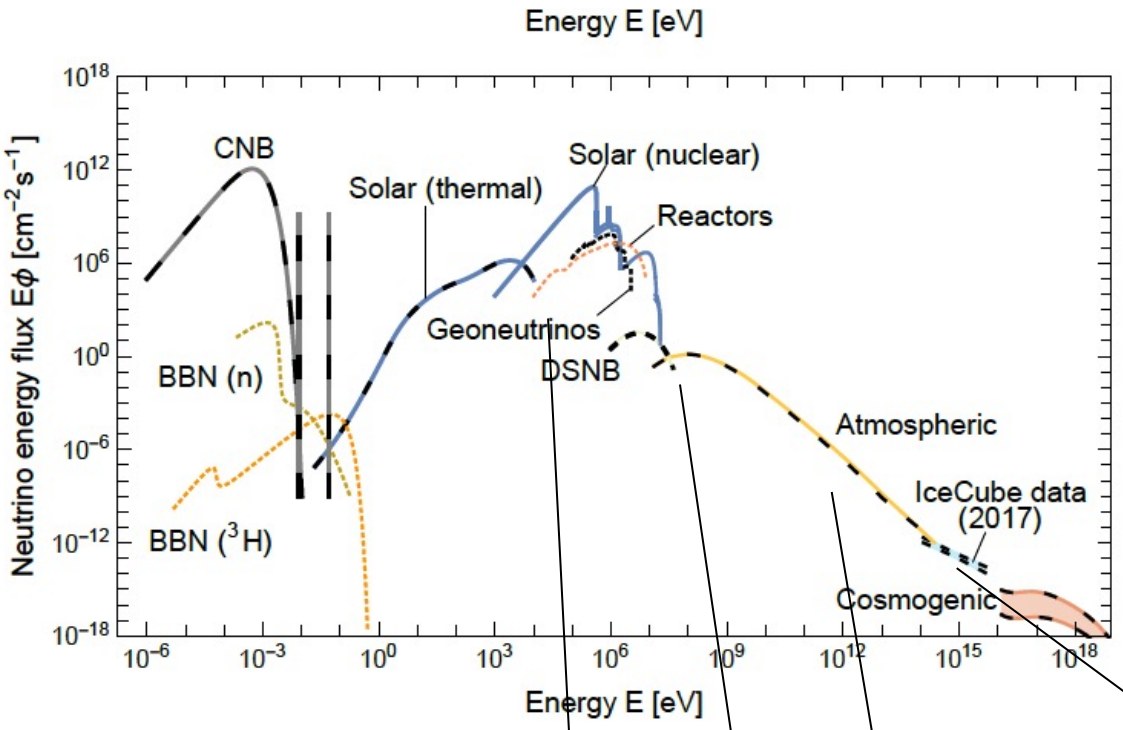


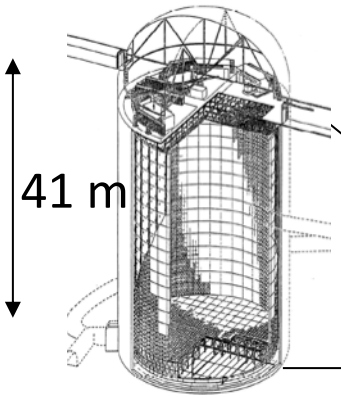
The Universe is opaque to EM radiation above 10-100 TeV, but not to neutrinos

Neutrinos fluxes from MeV to PeV

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

Need very large detectors





SuperK
50 kton

KM3NeT-ORCA
8 Mton

200m

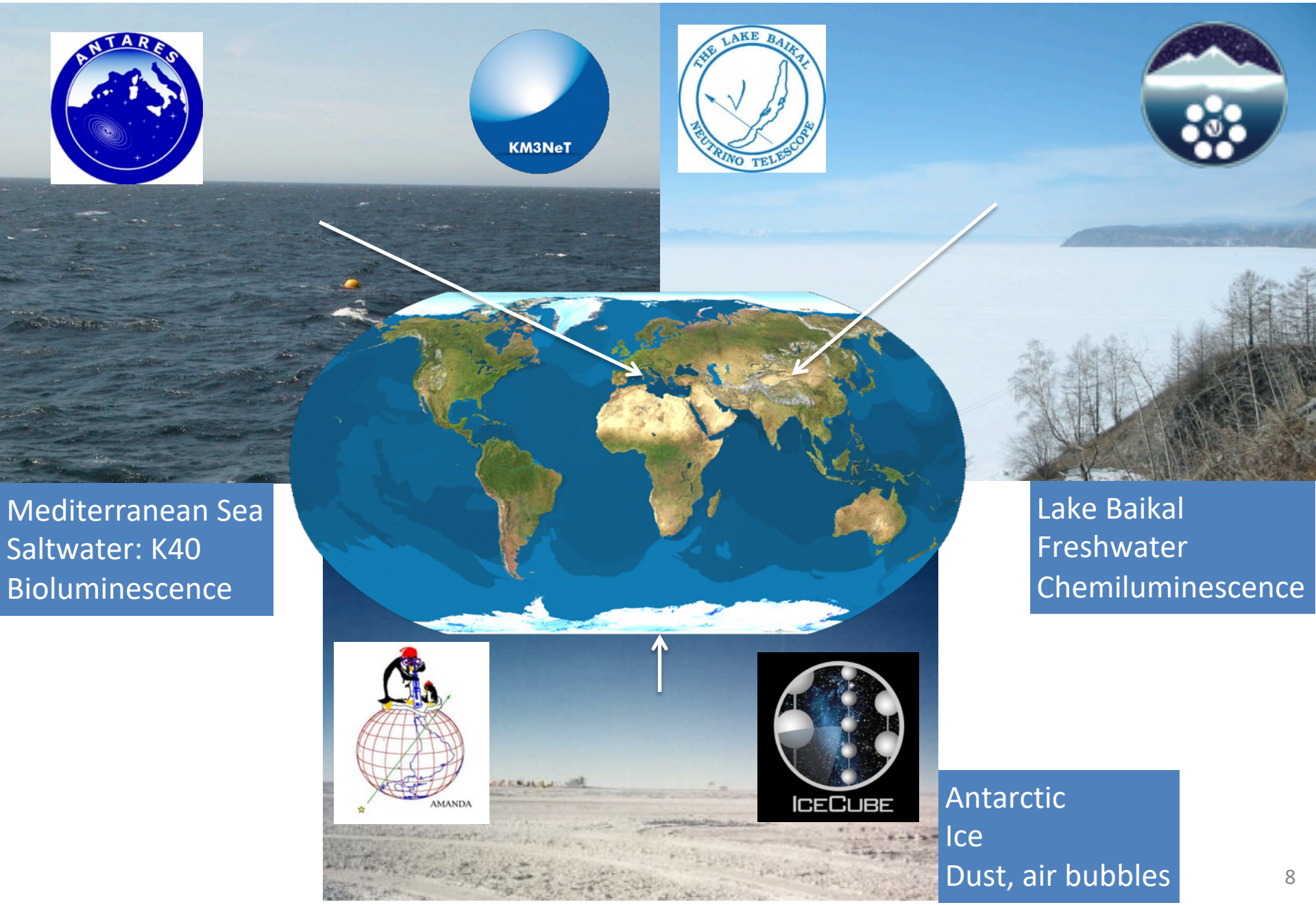
ANTARES
20
Mton

400 m

IceCube
GVD
KM3NeT-ARCA
1 Gton

1000m

Very large volume neutrino telescopes



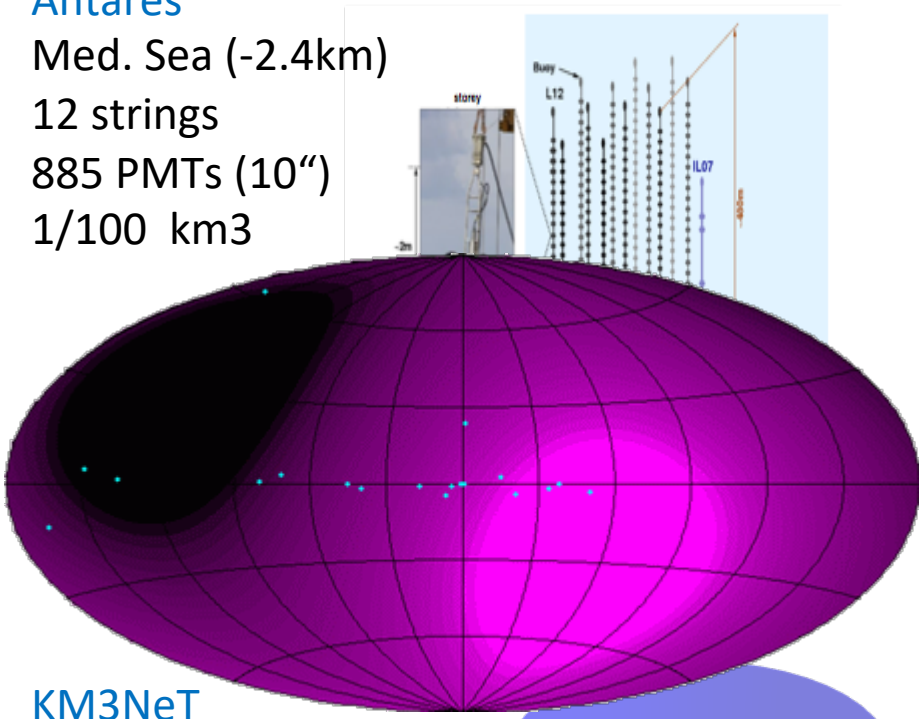
Mediterranean Sea
Saltwater: K40
Bioluminescence

Lake Baikal
Freshwater
Chemiluminescence

Antarctic
Ice
Dust, air bubbles

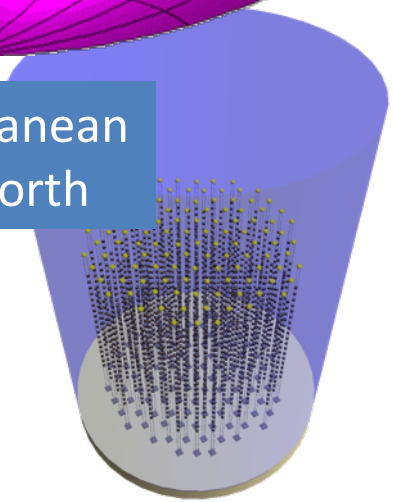
Current H20 (liquid+solid) neutrino telescopes

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

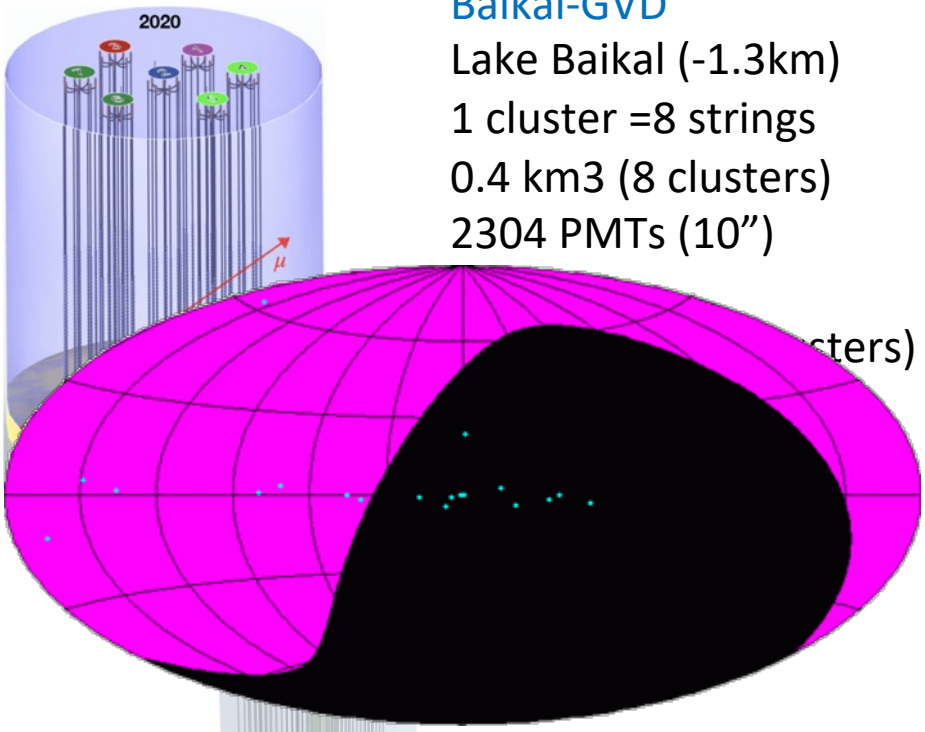


KM3NeT
Med. Sea (-2
3BB (345 stri
6000*31 PM
1.1 km3

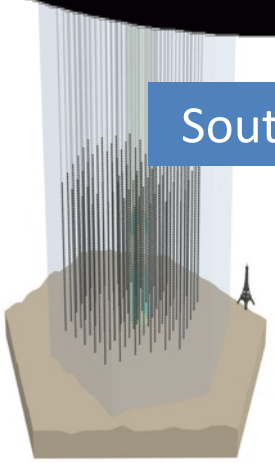
Mediterranean
~ 43° North



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

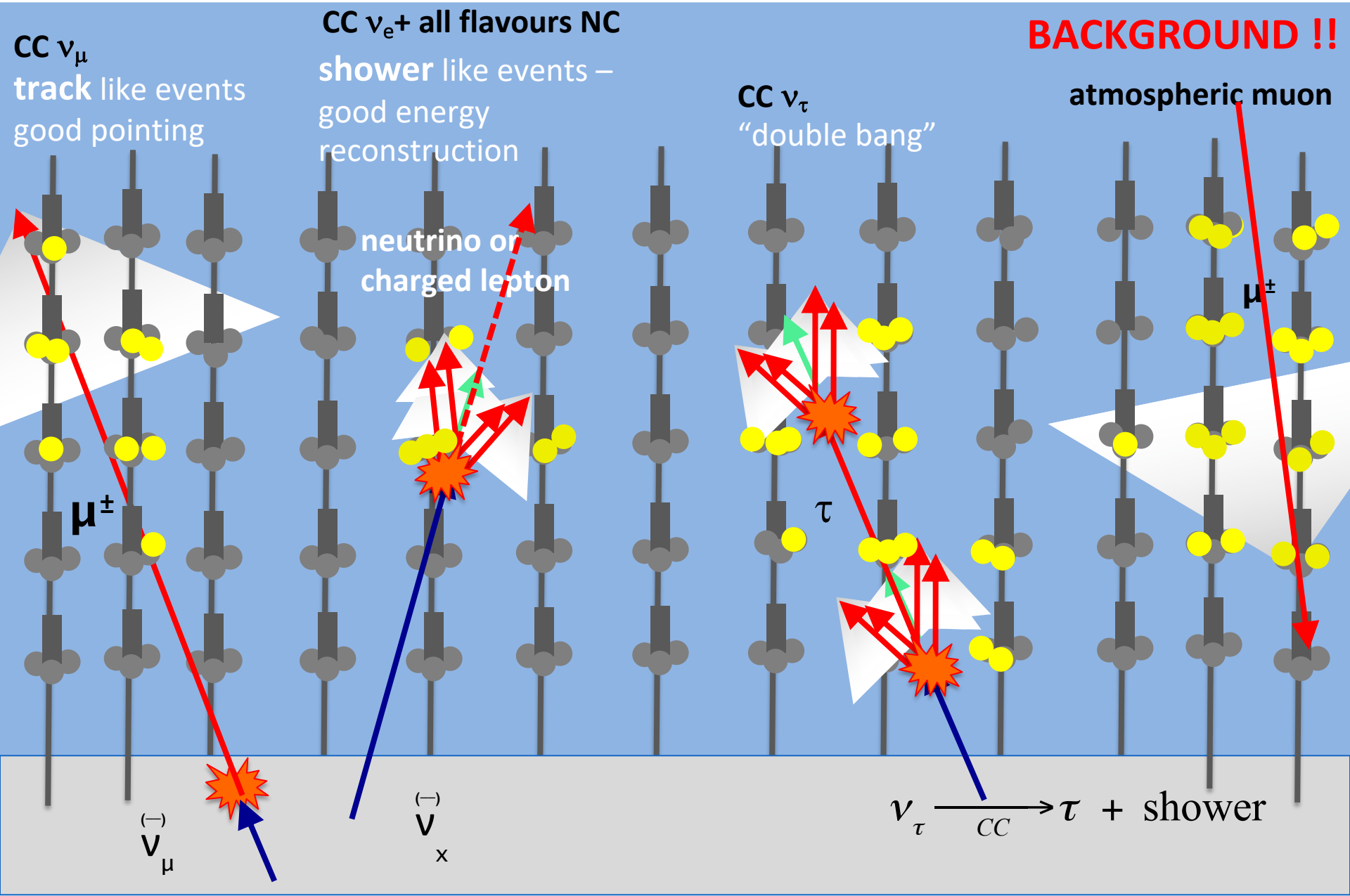


South Pole

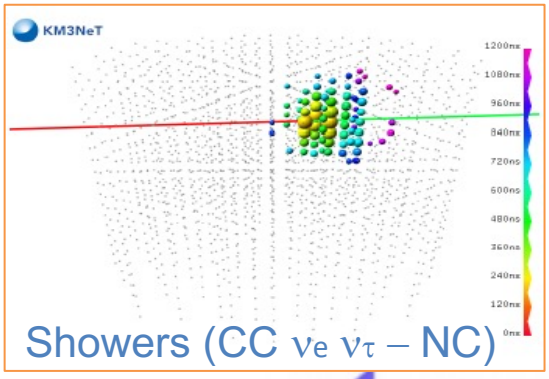


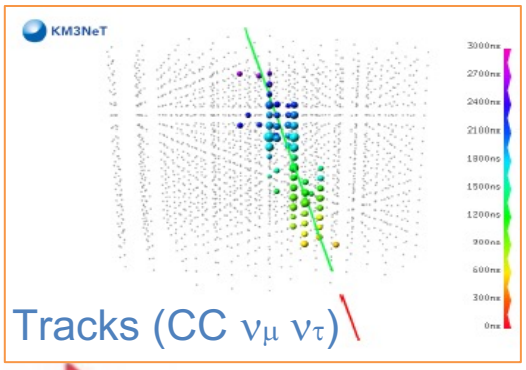
IceCube
th Pole (-2.4km)
86 strings
5160 PMTs (10”)
1 km3

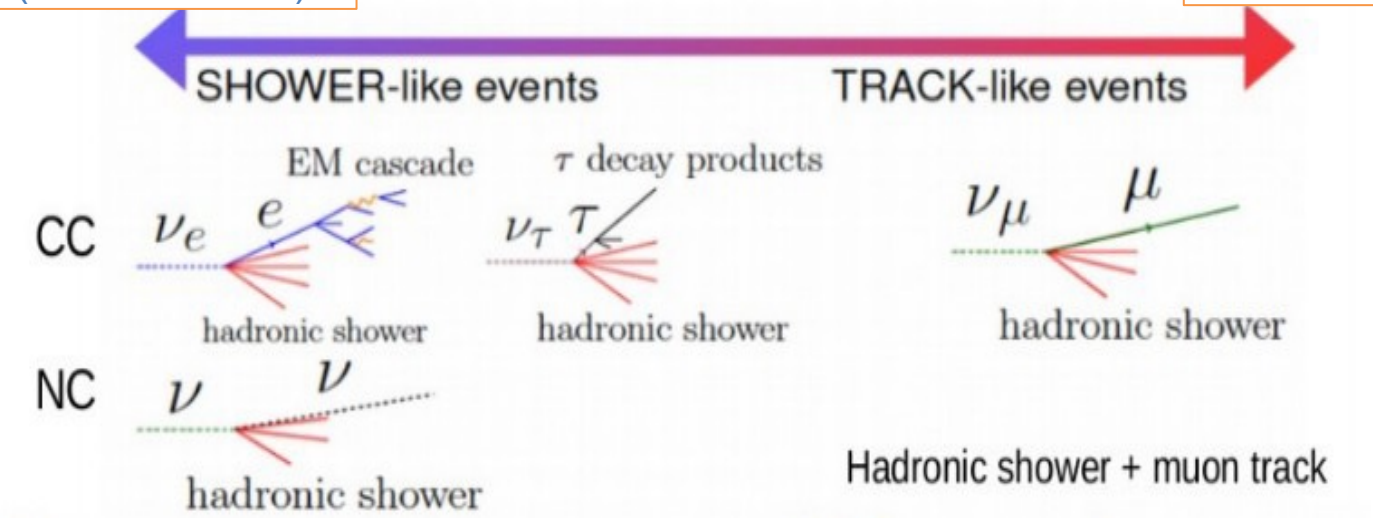
Event Topologies



Resolutions







Angular resolution 10°/1°
at 100 TeV for Ice/water

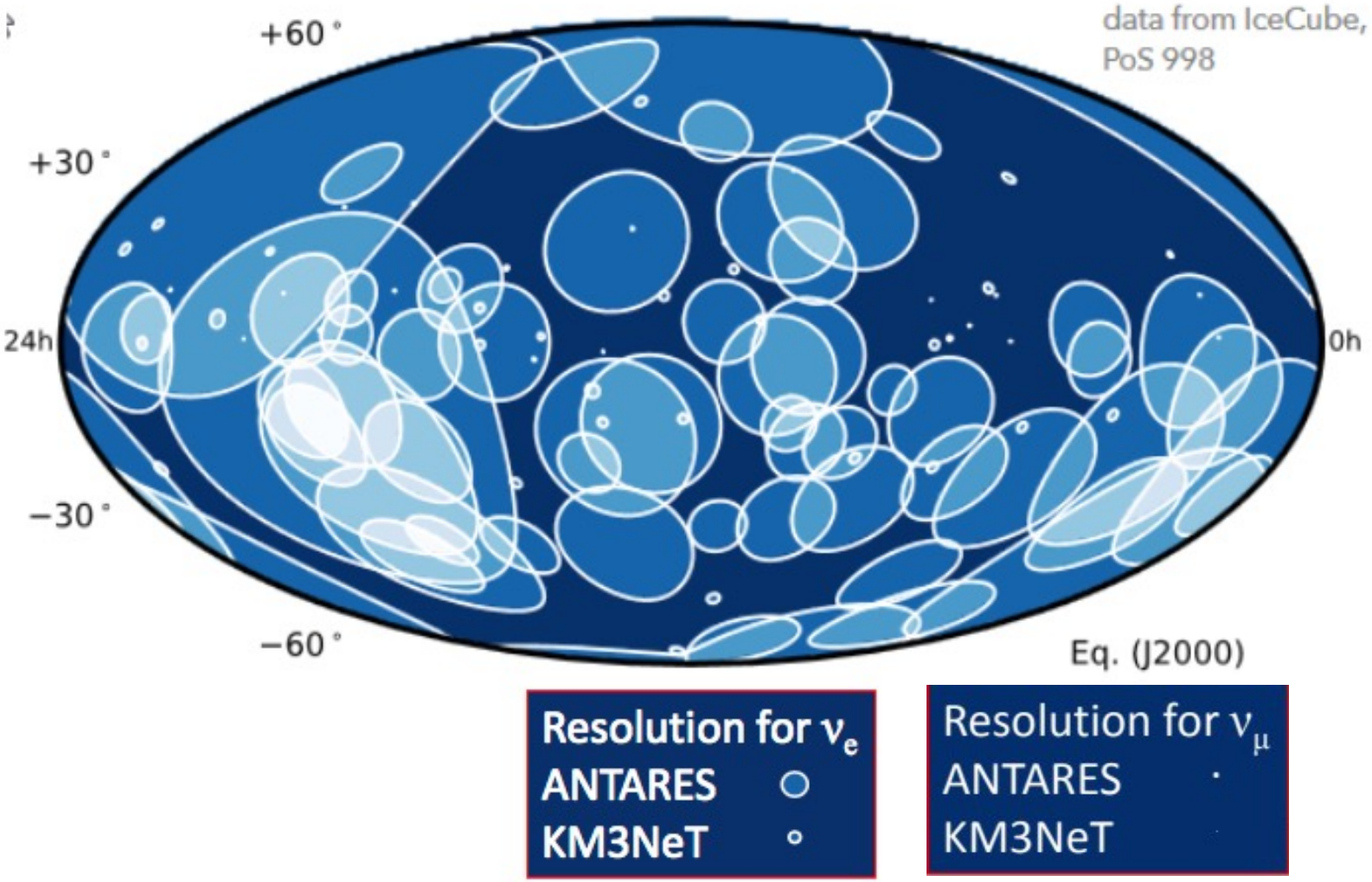
Energy resolution ~ 5%

Angular resolution 0.5°/0.1°
at 100 TeV for Ice/water

Energy resolution ~ 200-300%
(if contained: 25%)

Precision multi-flavour astronomy with water based telescopes

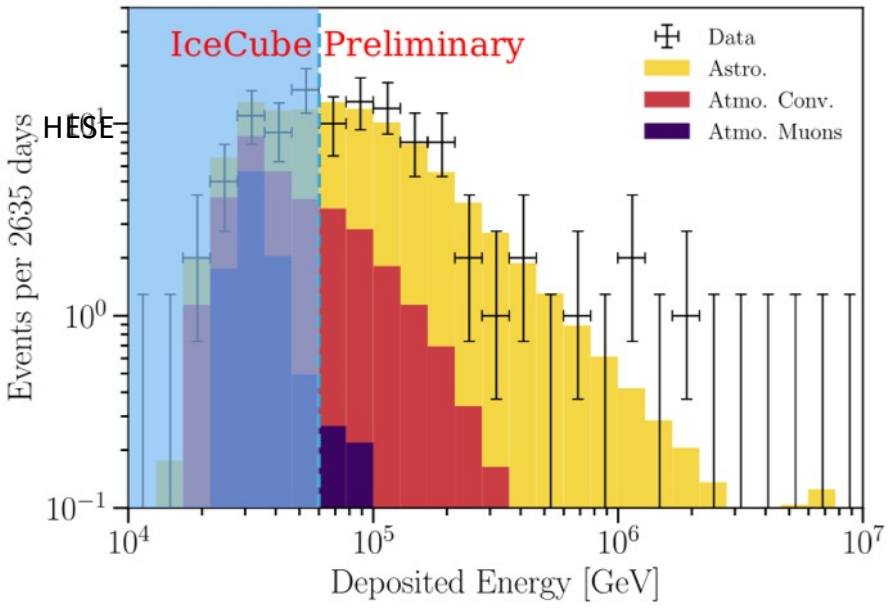
IceCube- SkyMap



Diffuse flux observed by IceCube

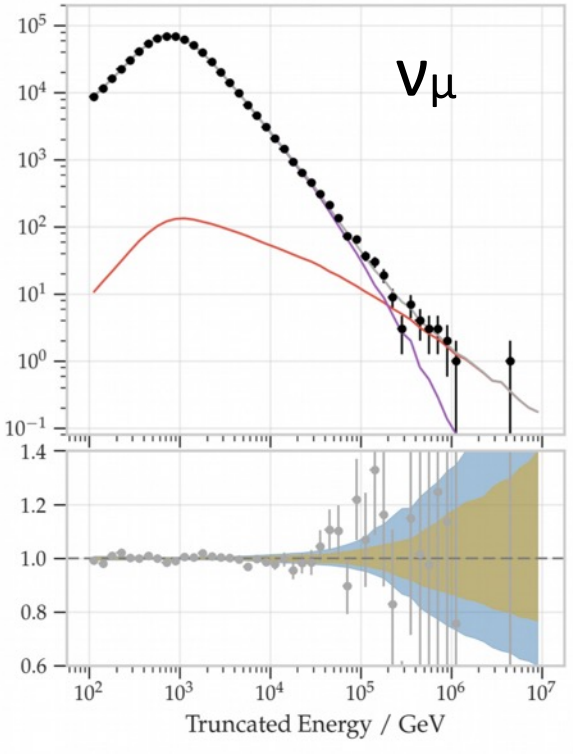
νe

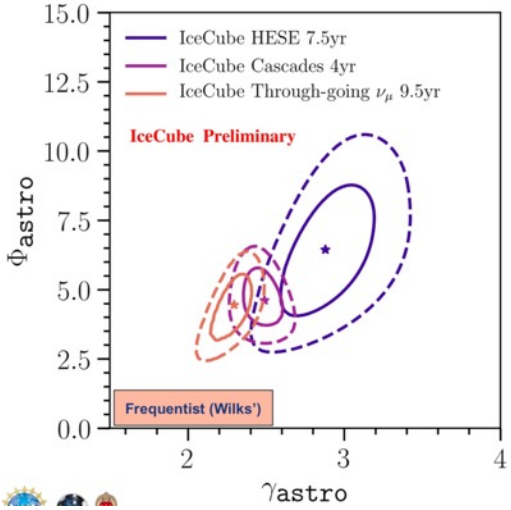
HESE



IceCube 7-10 yrs

νμ





Name	Approx. Neutrino Energy	Direction	Dominant Flavor	Unbroken Spectral Index
HESE	50 TeV - 5 PeV	All-sky	e, μ, τ	2.89
Cascades	5 TeV - 5 Pev	All-sky	e, τ	2.48
NuMu	50 TeV - 10 PeV	Northern sky	μ	2.28

Site ANTARES/KM3NeT

Toulon

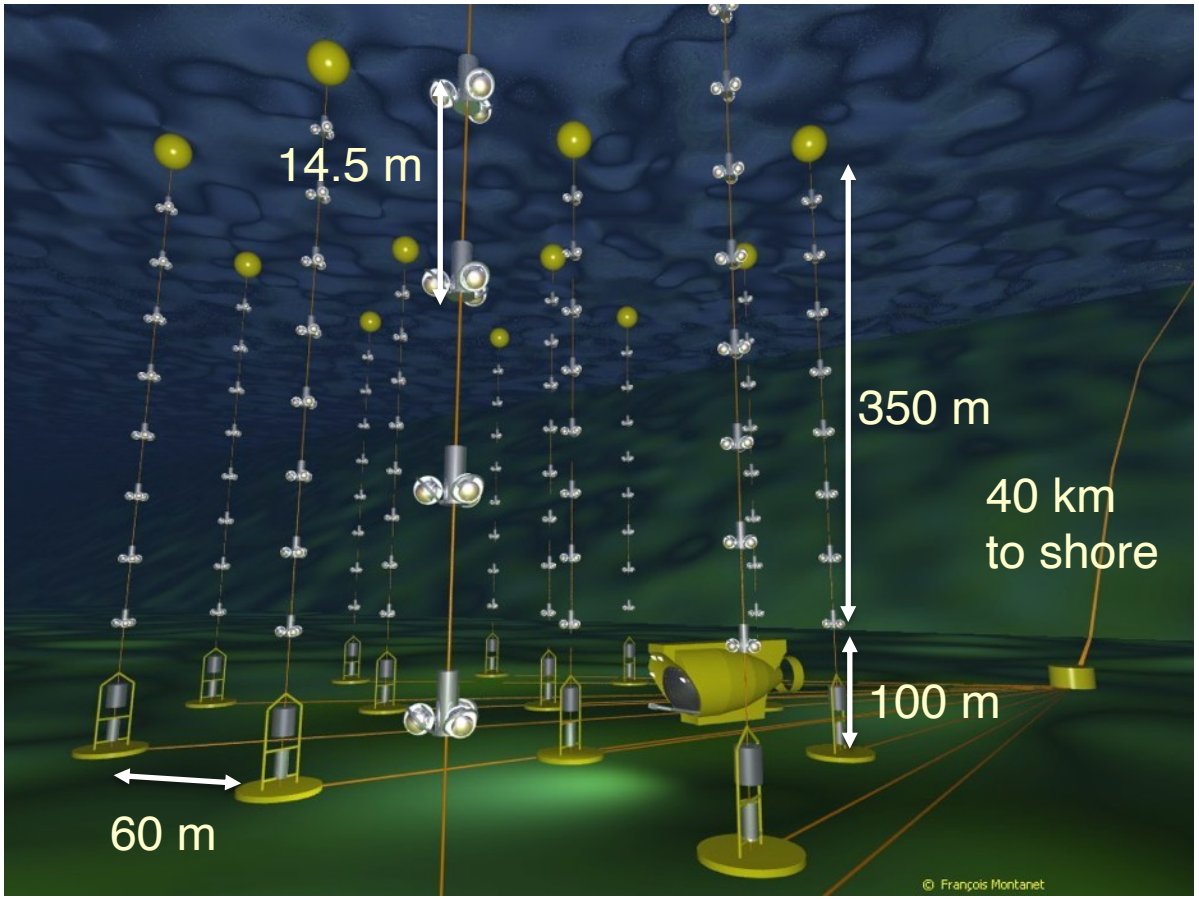
Insitut M.Pacha

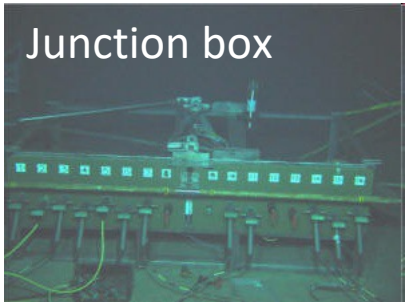
câble
sous-marin
de 40 km

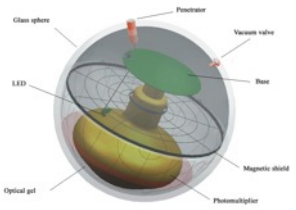
Site ANTARES
42 50'N, 6 10'E

ANTARES Detector

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

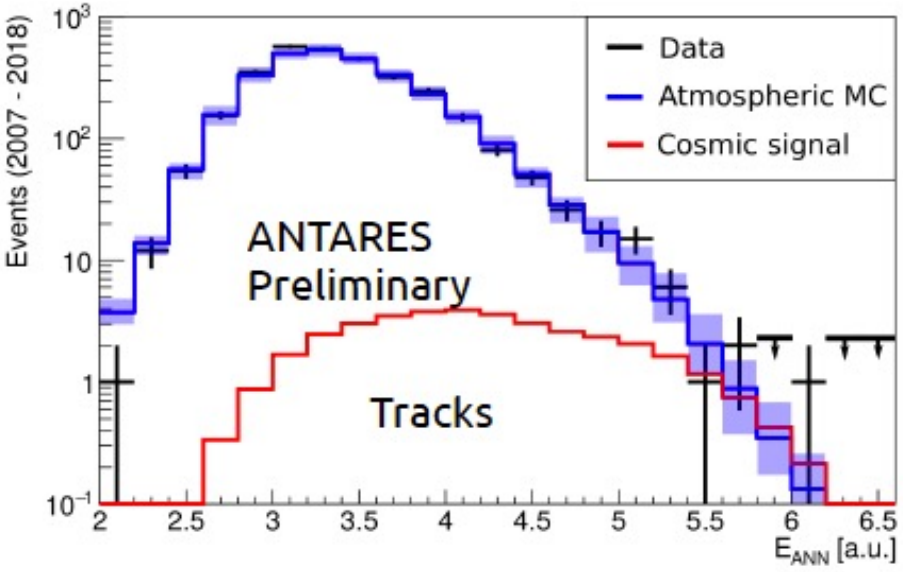


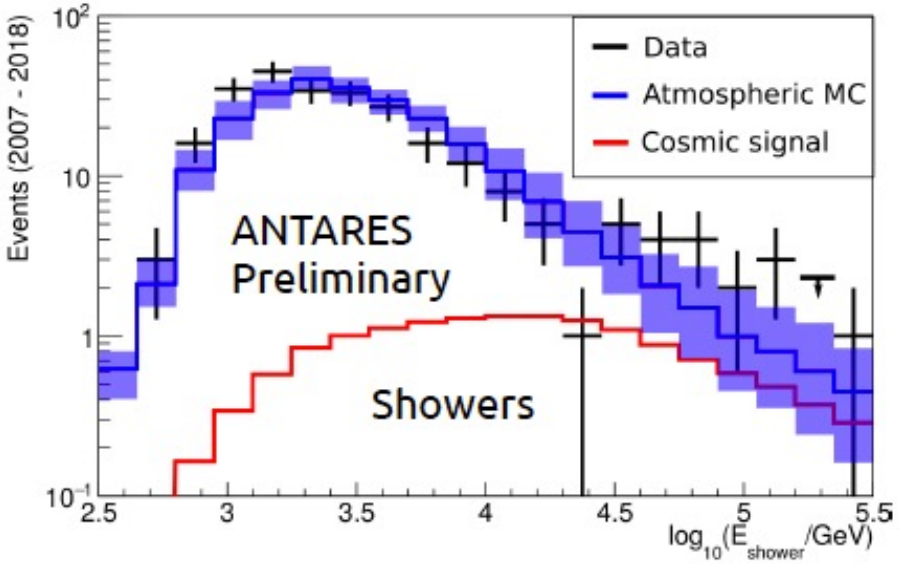




Diffuse cosmic flux I

ANTARES 2007-2018 (3330 days)





Data: 50 events (27 tracks + 23 showers)

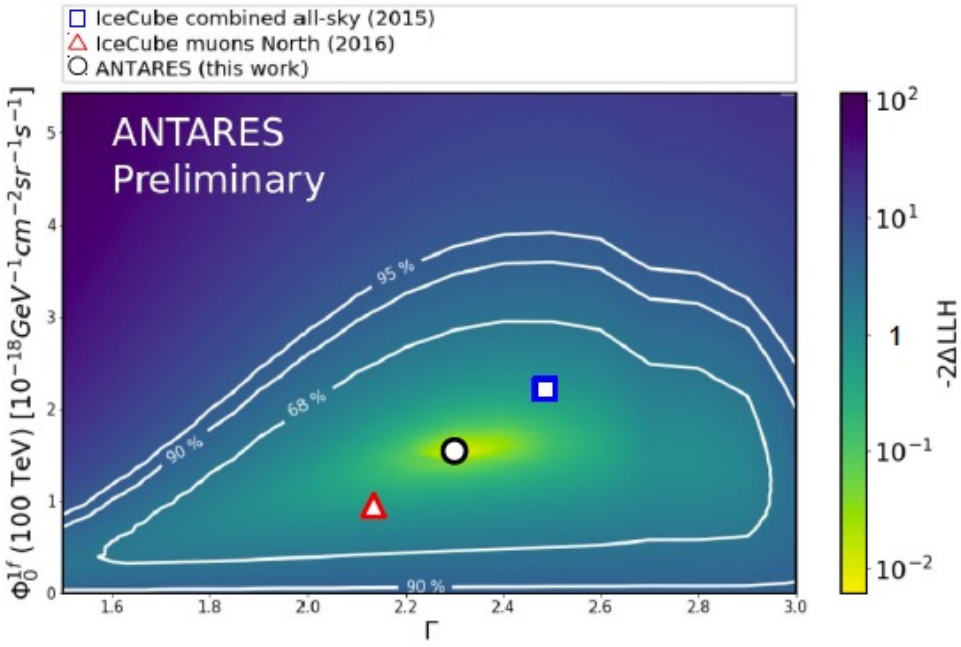
Background expectation (atm. flux, HONDA + Enberg, scaled x ~1.25) :
36.1 ± 8.7 (19.9 tracks and 16.2 showers) – stat. + syst.

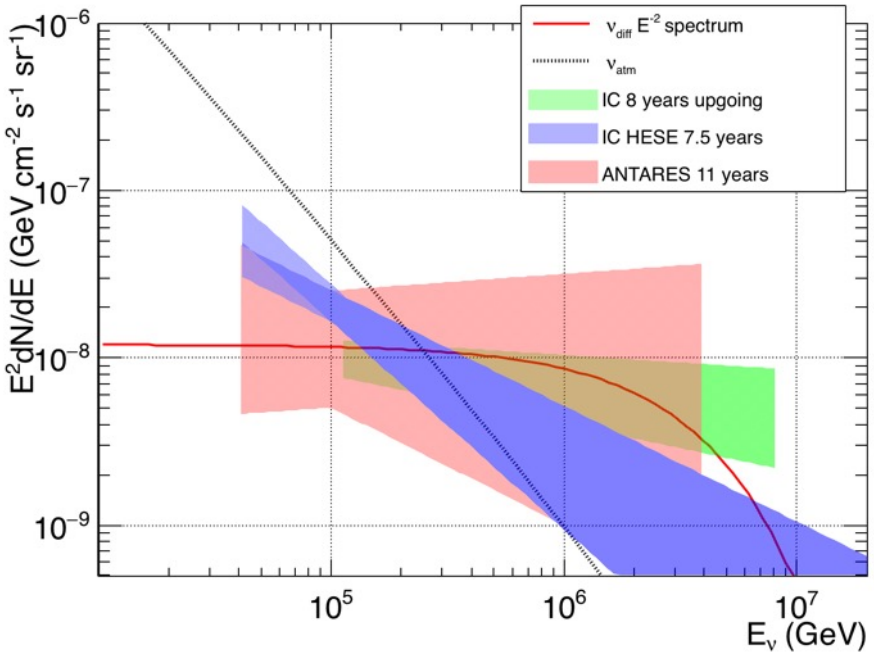
Results not really constraining… but fully compatible with IceCube

Updated and improved analysis coming soon

Diffuse cosmic flux II

Combined tracks & showers likelihood fitting:



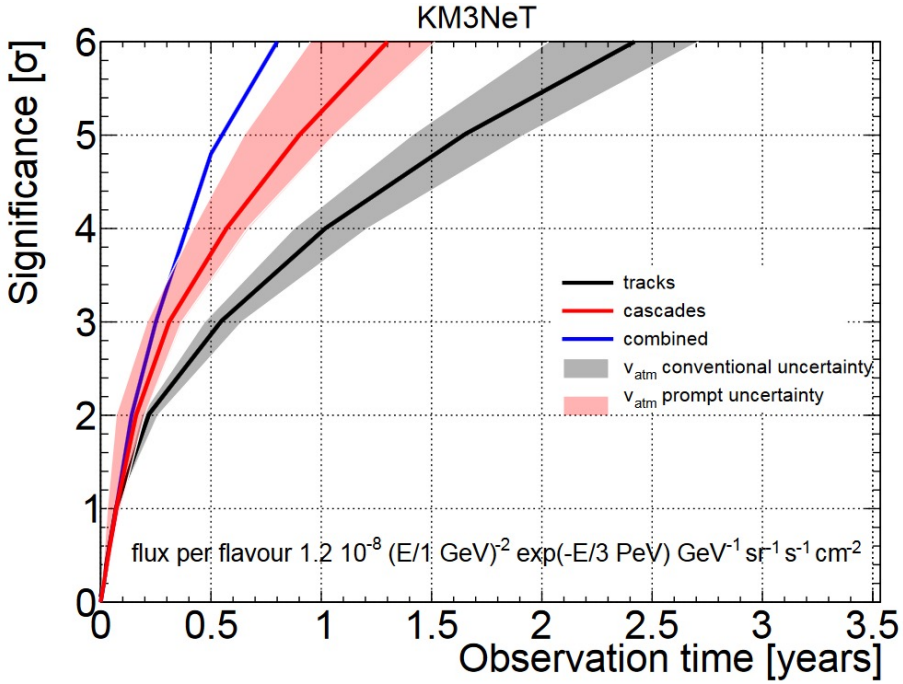


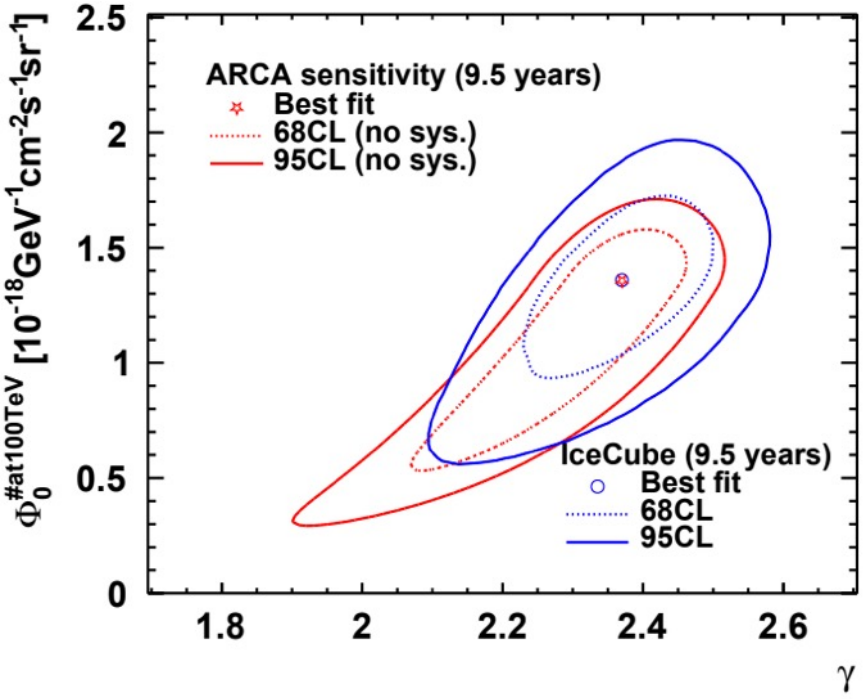
Cosmic flux:

$$\Phi_{100\ \mathrm{TeV}} = (1.5 \pm 1.0) \times 10^{-18}\ \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$

$$\Gamma = 2.3 \pm 0.4$$

KM3NeT diffuse cosmic flux

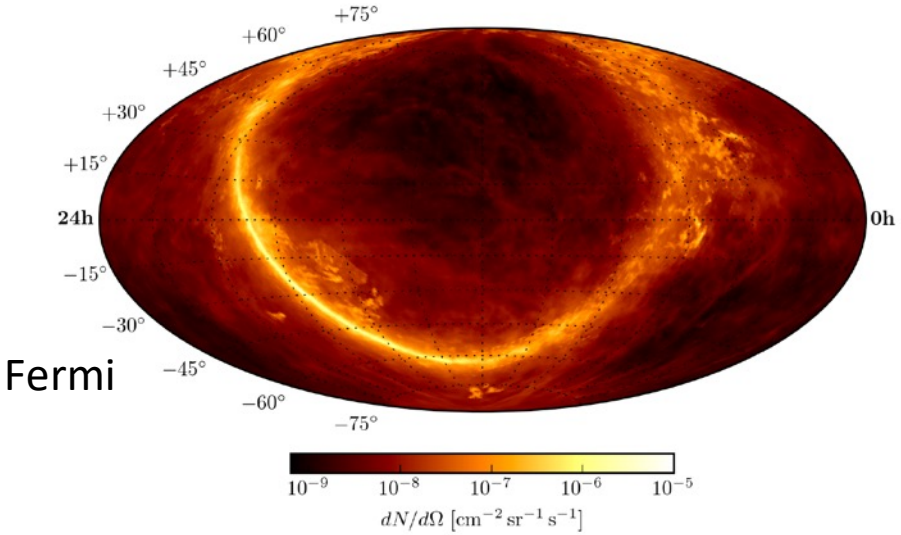




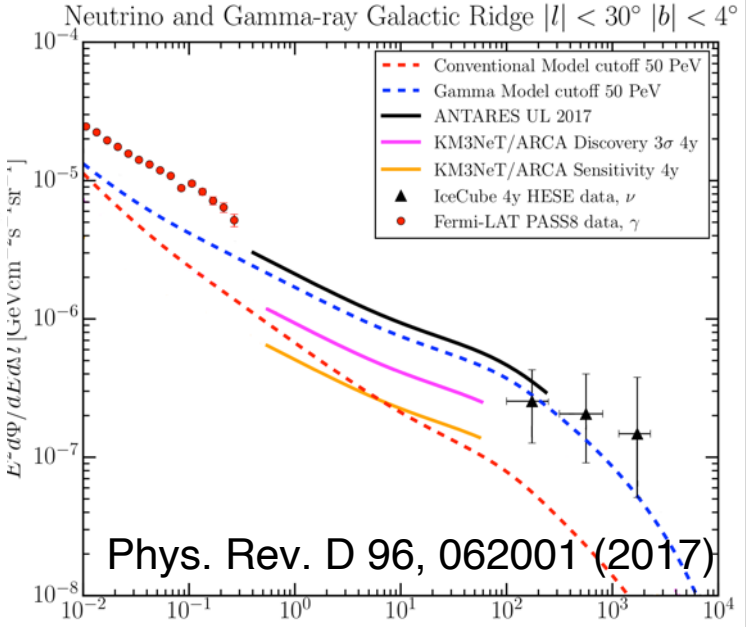
5σ in ~ 0.5 year for the full detector (230 DUs)

5σ ~ 1 year for one block detector (115 DUs)

Galactic plane



Fermi



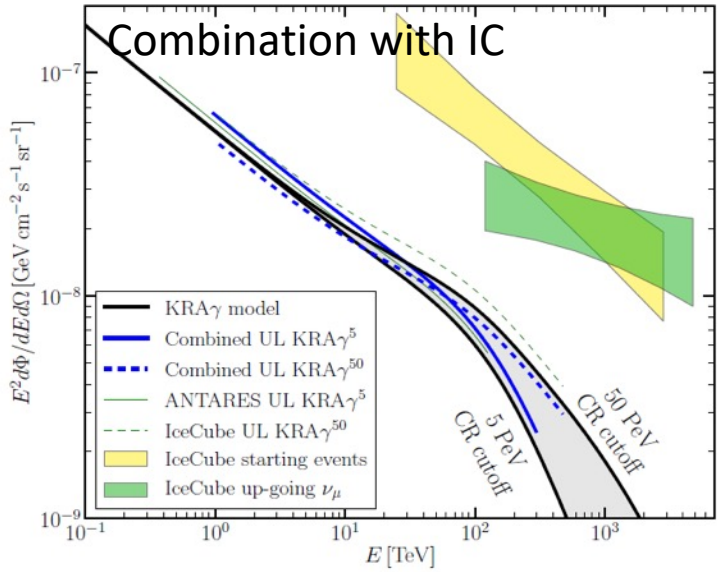
Guaranteed galactic neutrinos from CR interactions with matter

Analysis uses full model morphology & spectrum – tracks and cascades

ANTARES Limit is a factor 1.2 above the 'KRAγ' model.

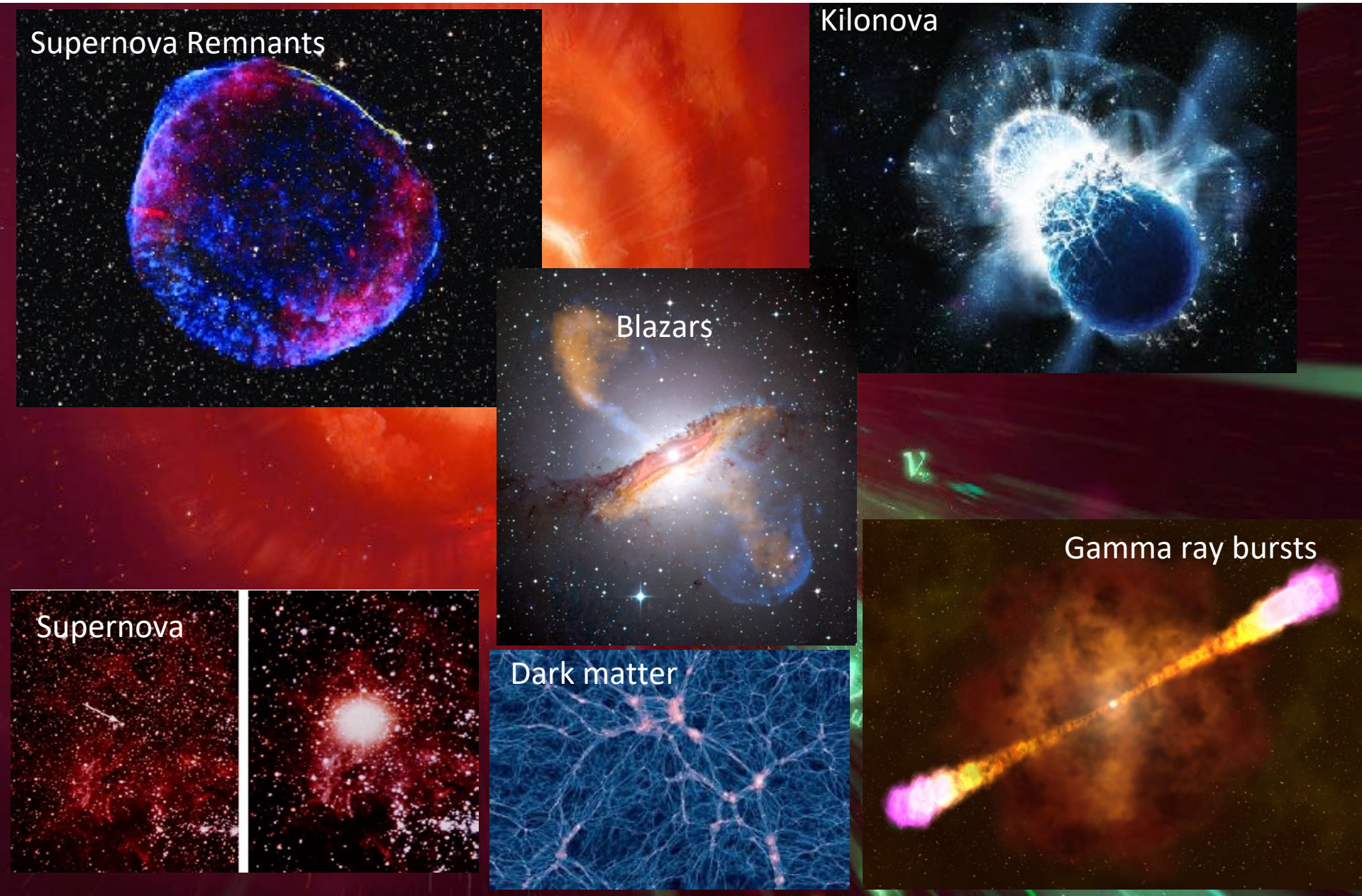
ANTARES updated analysis soon

KM3NeT sensitivity very promising



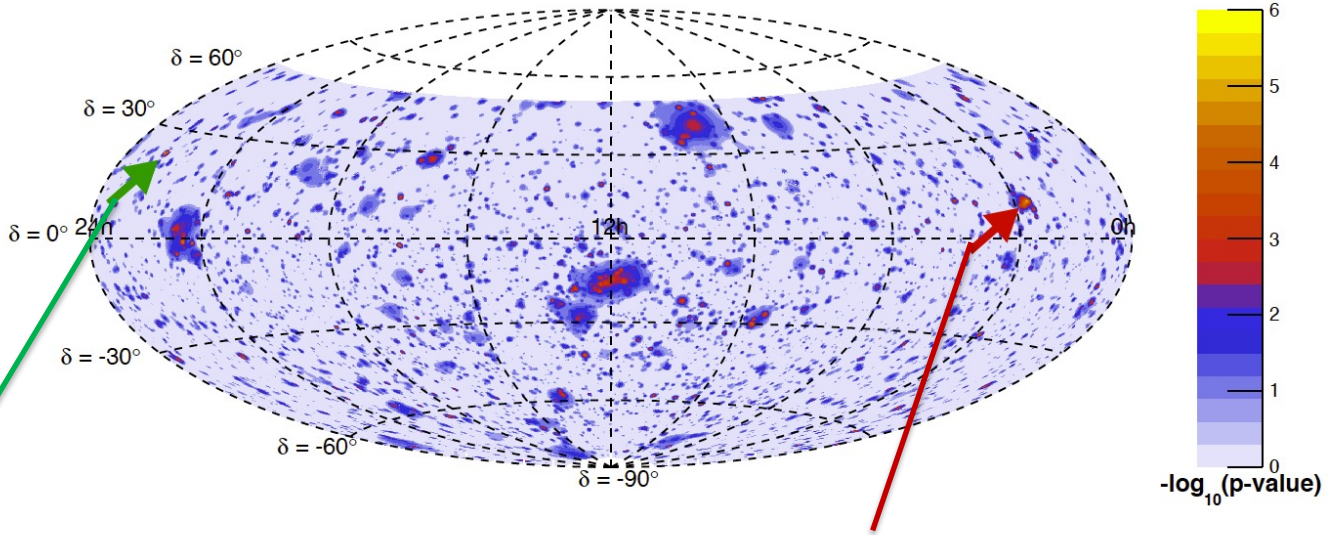
ApJL 868, L20 (2018)

Neutrino Sources?

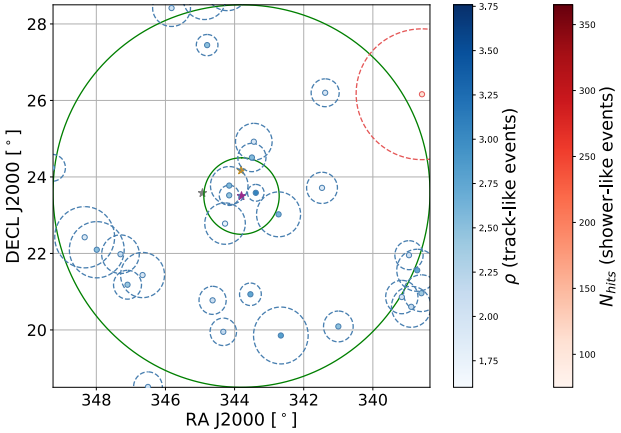


Point source searches

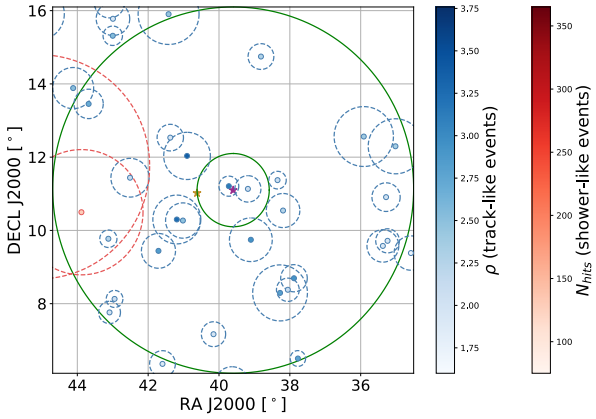
Updated: ANTARES 13 years (3845 days of live time): 10162 tracks and 225 showers



2nd most significant cluster:
RA=343.8° δ=+23.5°
pre trial: 4.2 σ
Close to blazar MG3 J225517+2409 (orange star)

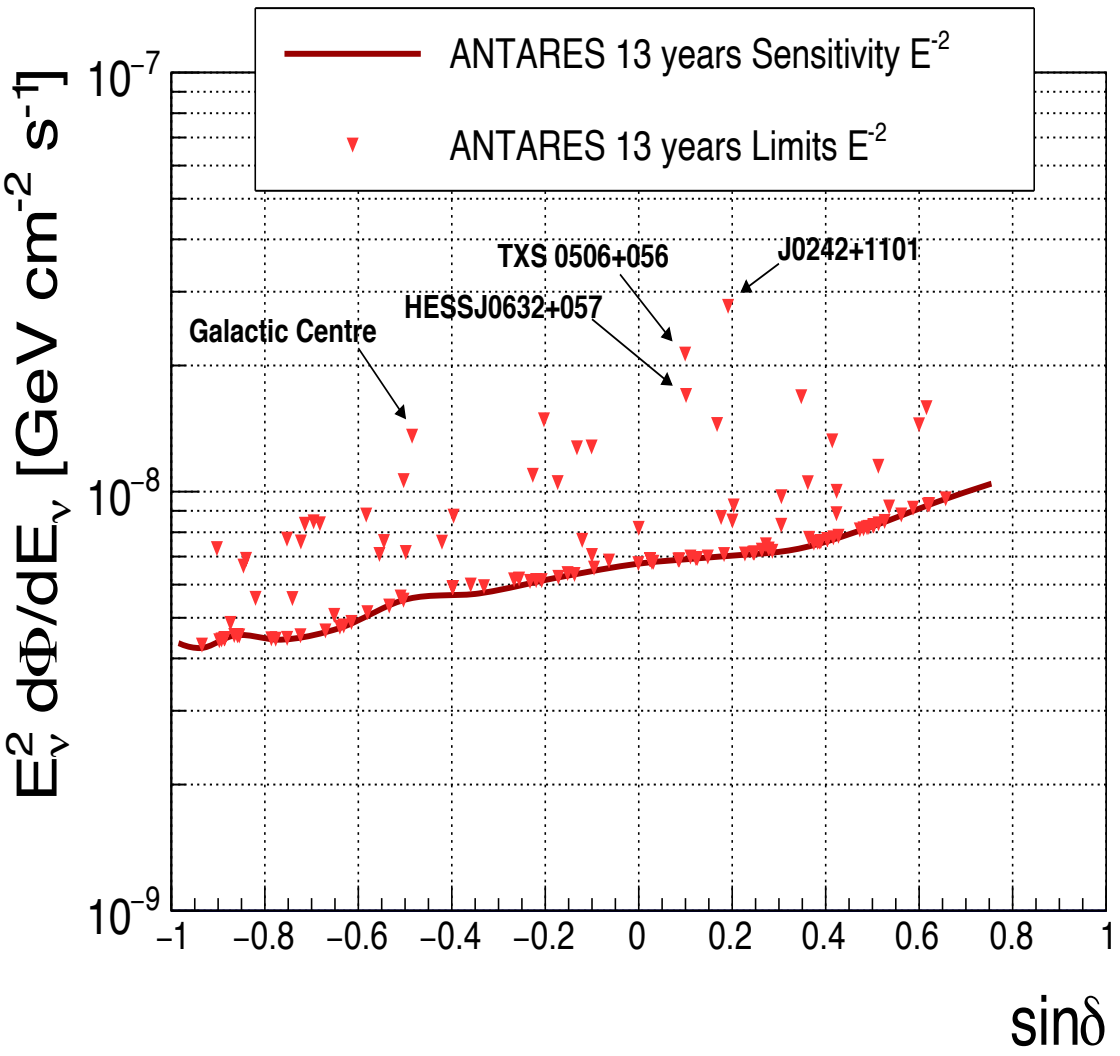


The most significant cluster:
RA=39.6° δ=+11.1°
pre trial: 4.3 σ (48% post)
Within 1 degree of J0242+1101 (orange star)

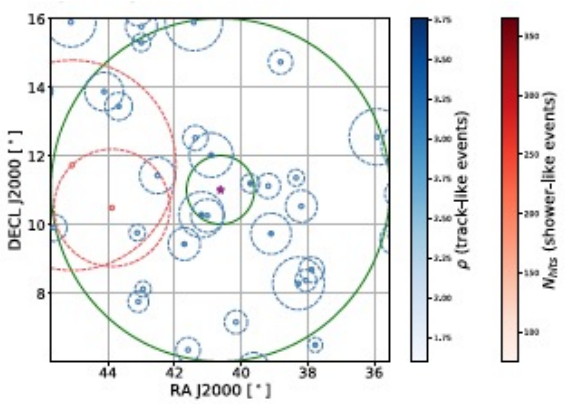


Candidate list

121 sources investigated

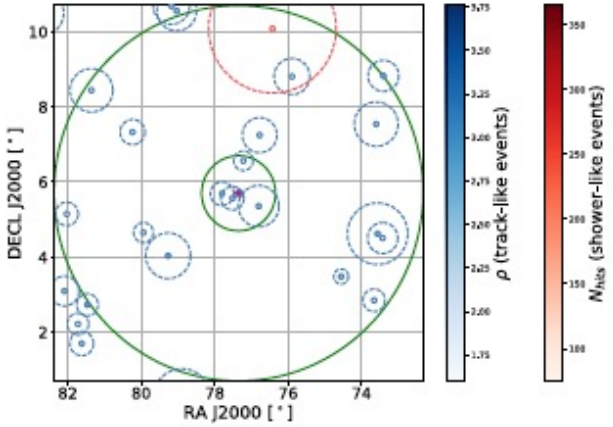


1st: J0242+1101



Pre (post) trial: 3.8σ (2.4σ)

2nd: TXS 0506+056

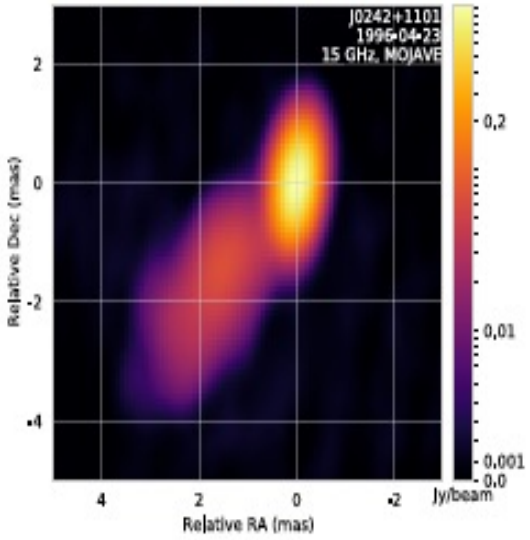


Pre (post) trial: 3.1σ (2.6σ)

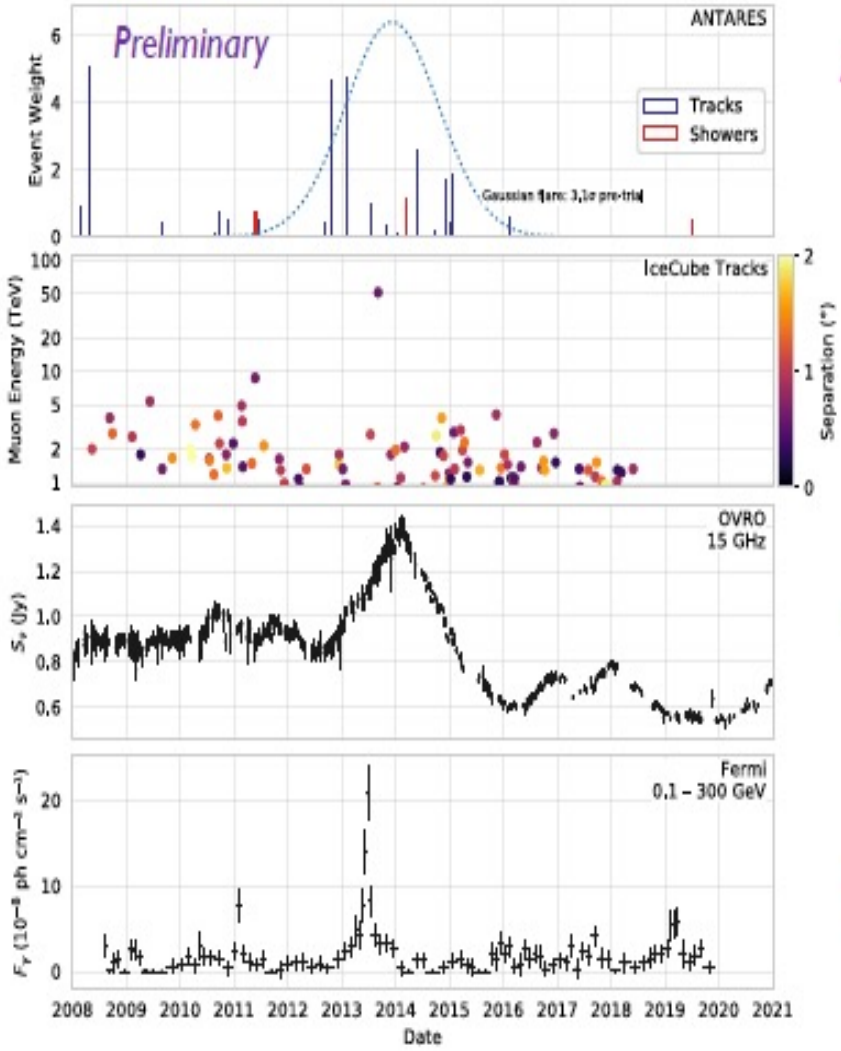
4 muon events within 1°

J0242+1101: potential radio-γ-ν association

VLBI image at 15 GHz



Chance probability of the multi-messenger association under study



ANTARES best-fit flare for this source

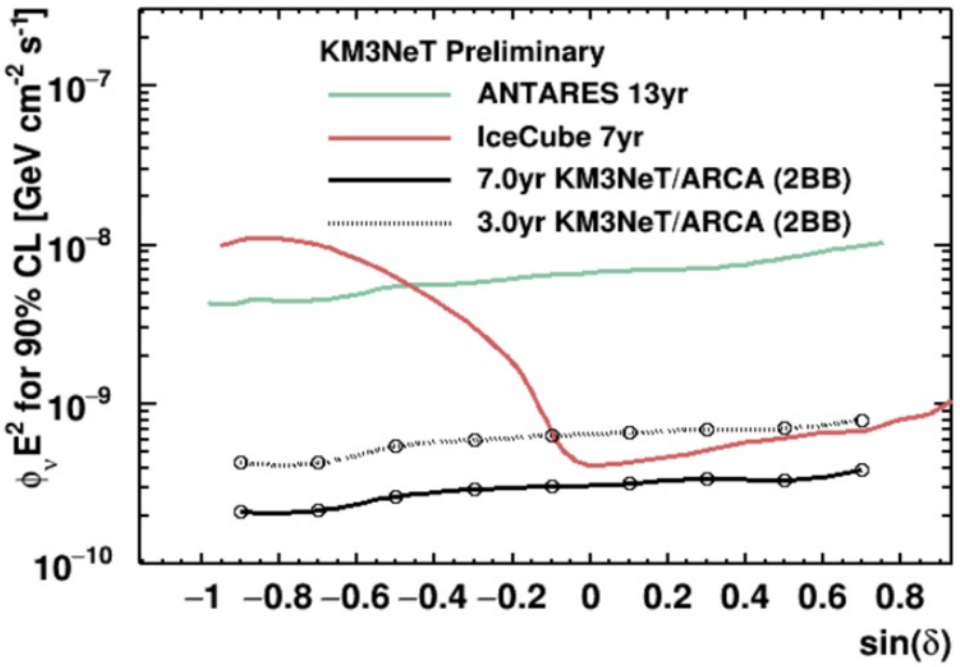
IceCube tracks from 10-years point-source sample
- Tracks within 90% angular error from source
- angular error < 10deg^2

OVRO radio light-curve

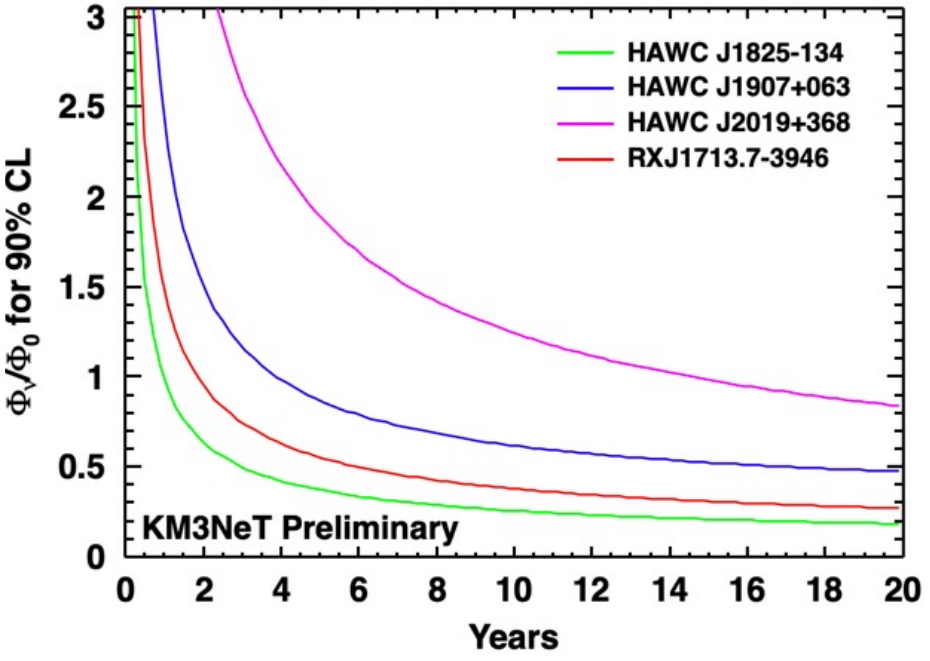
Adaptive binned gamma-ray light-curve obtained from Fermi LAT data

KM3NeT: sources

Point sources

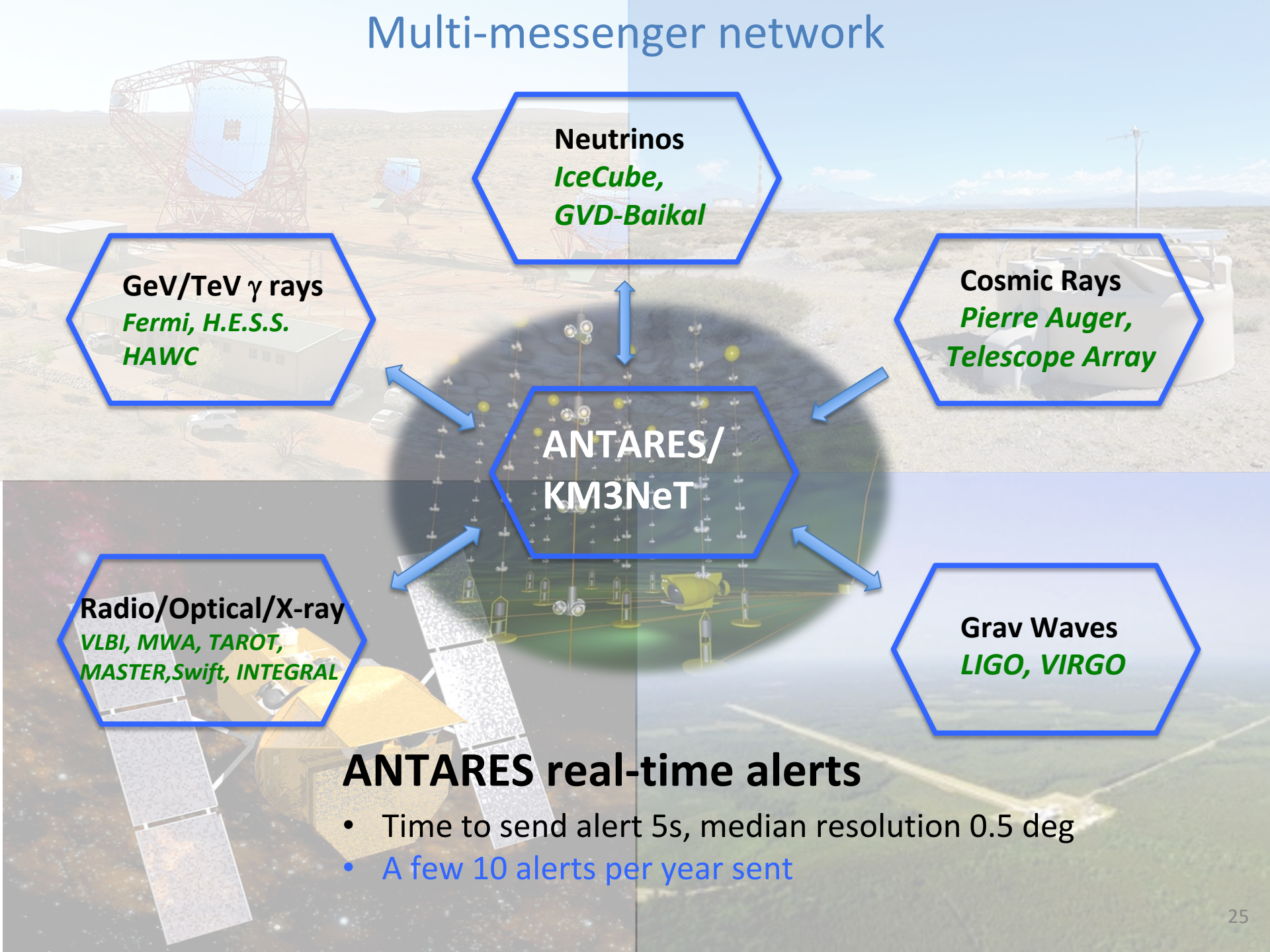


Extended sources



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)

Multi-messenger network

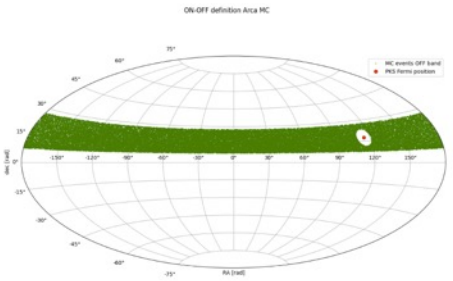


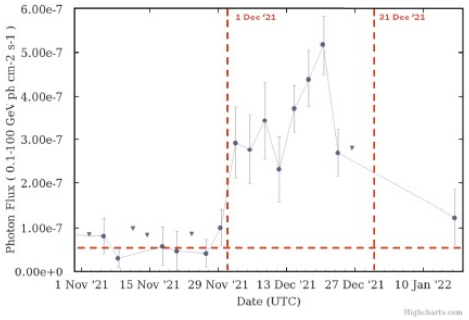
ANTARES real-time alerts

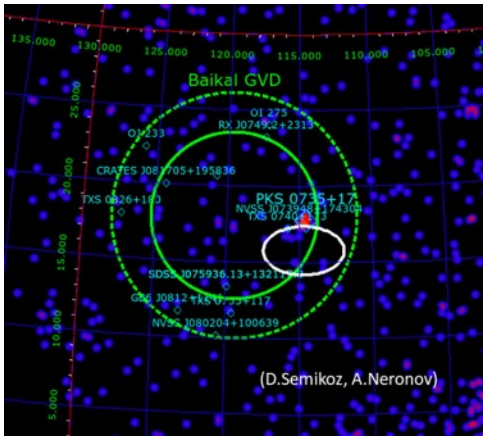
- Time to send alert 5s, median resolution 0.5 deg
- A few 10 alerts per year sent

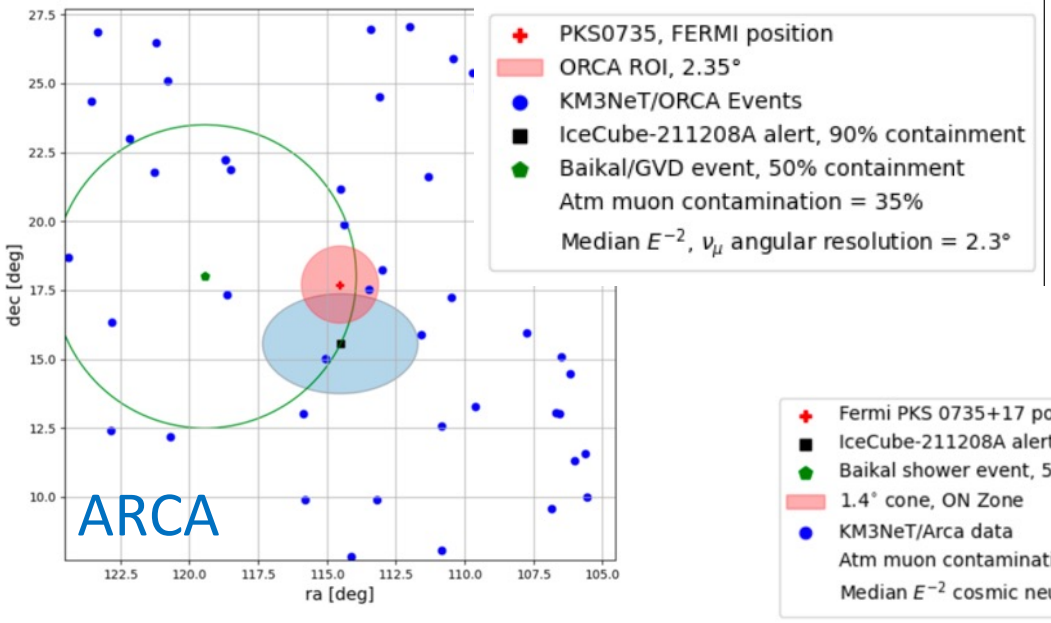
1st KM3NeT treatment of external alert: PKS 0735+17

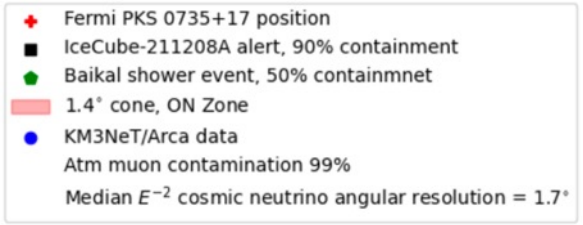
- Dec ‘21 : high energy IceCube neutrino alert.
  Flaring blazar just outside error Box
- Followed up with ARCA and ORCA

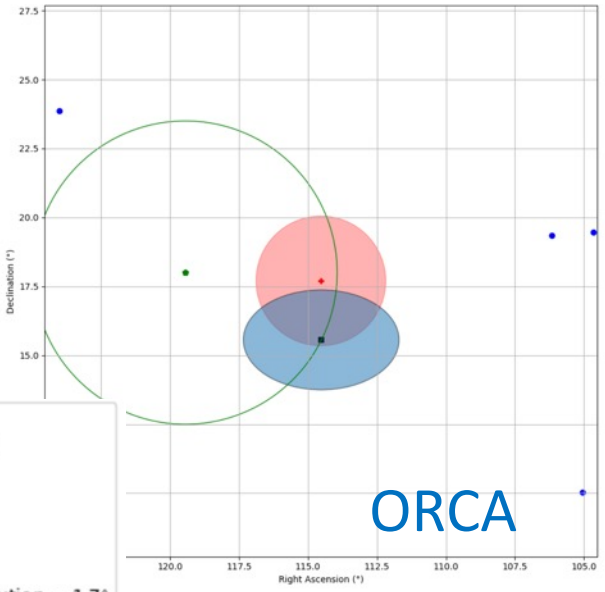












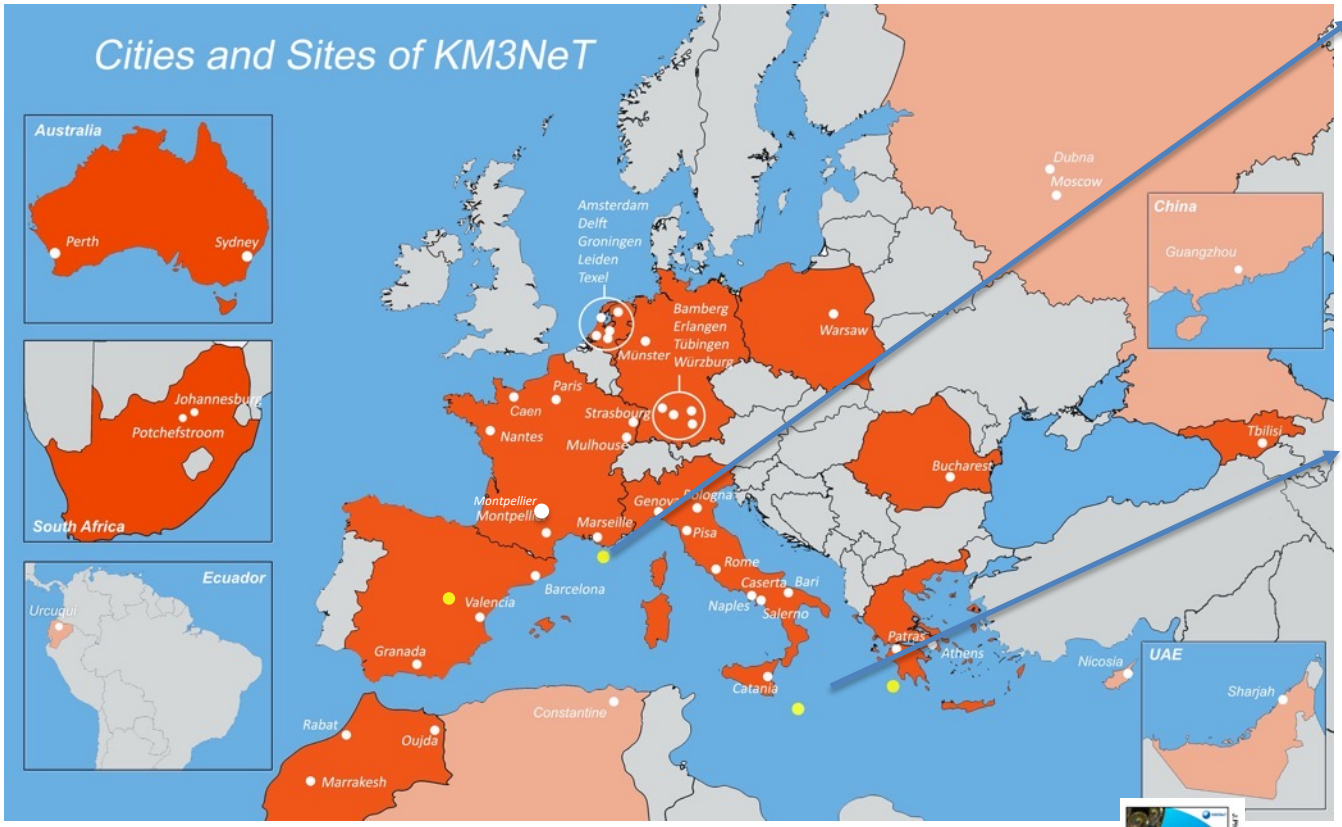
https://www.astronomerstelegram.org/?read=15290

KM3NeT

Multi-site, deep-sea infrastructure

Selected for ESFRI roadmap

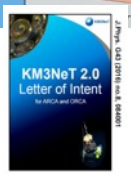
Single collaboration, Single technology



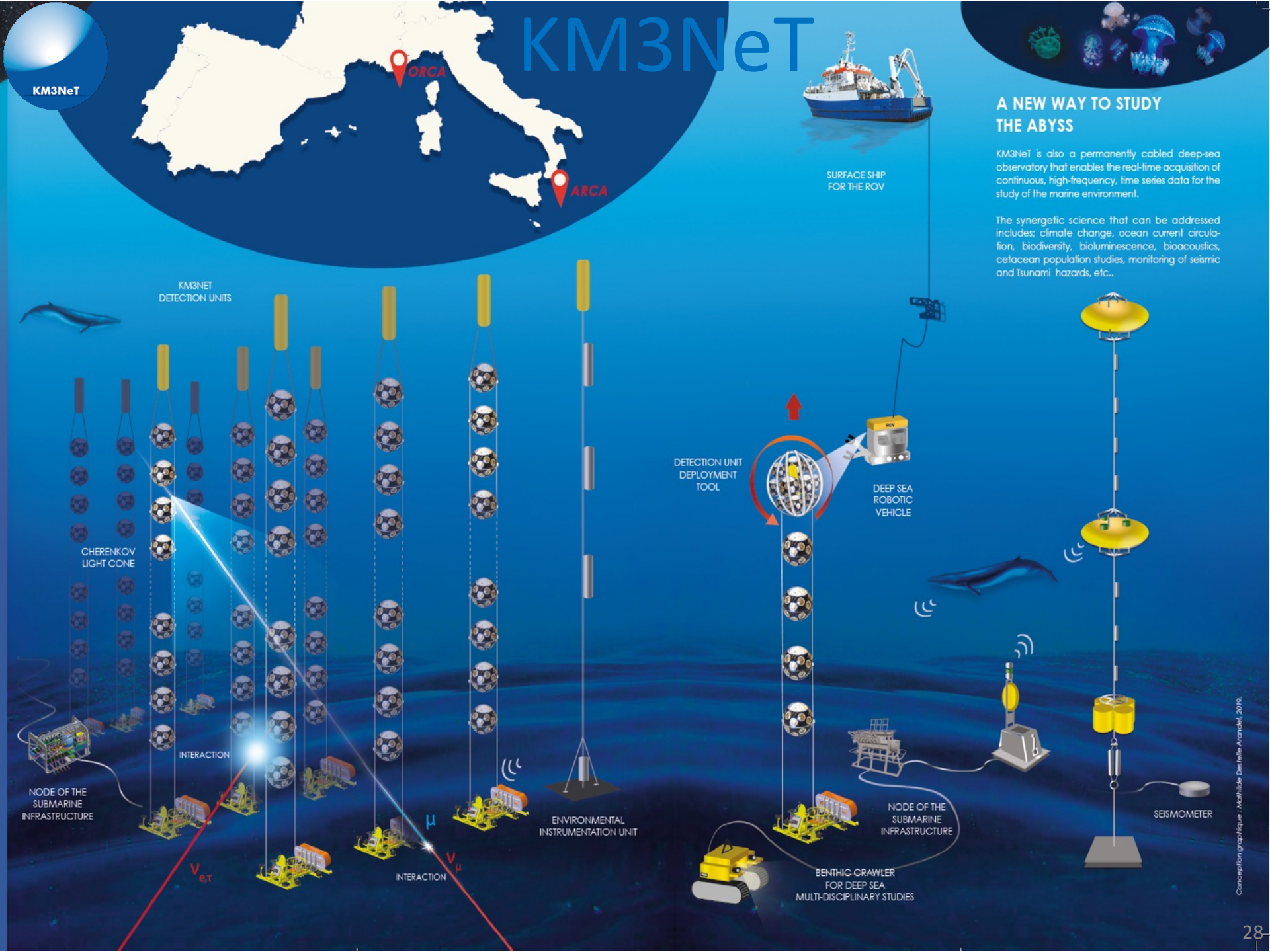
Oscillation **R**esearch with **C**osmics In the **A**byss

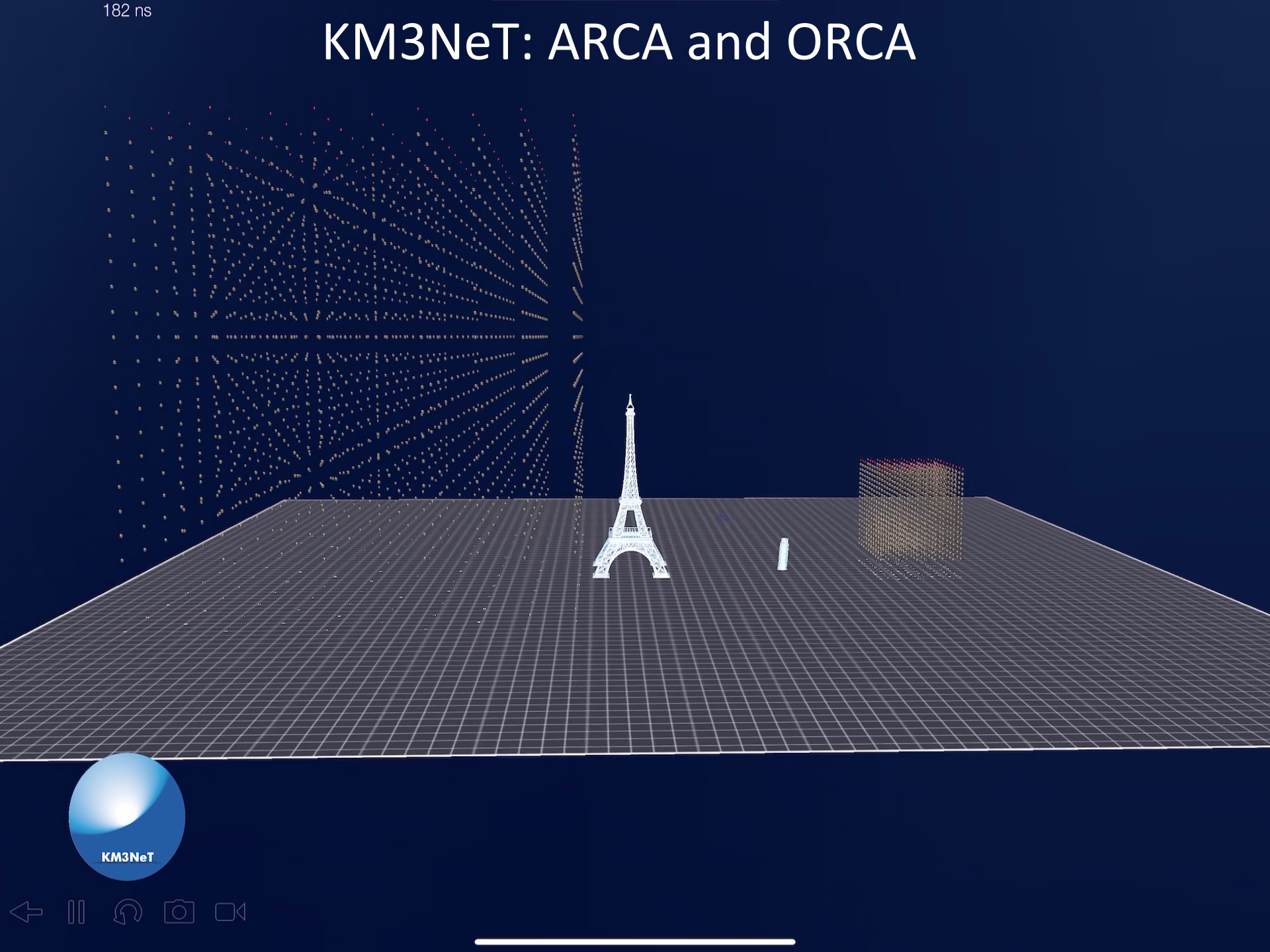
Astroparticle **R**esearch with **C**osmics In the **A**byss

KM3NeT 2.0: Letter of Intent
http://dx.doi.org/10.1088/0954-3899/43/8/084001
J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001

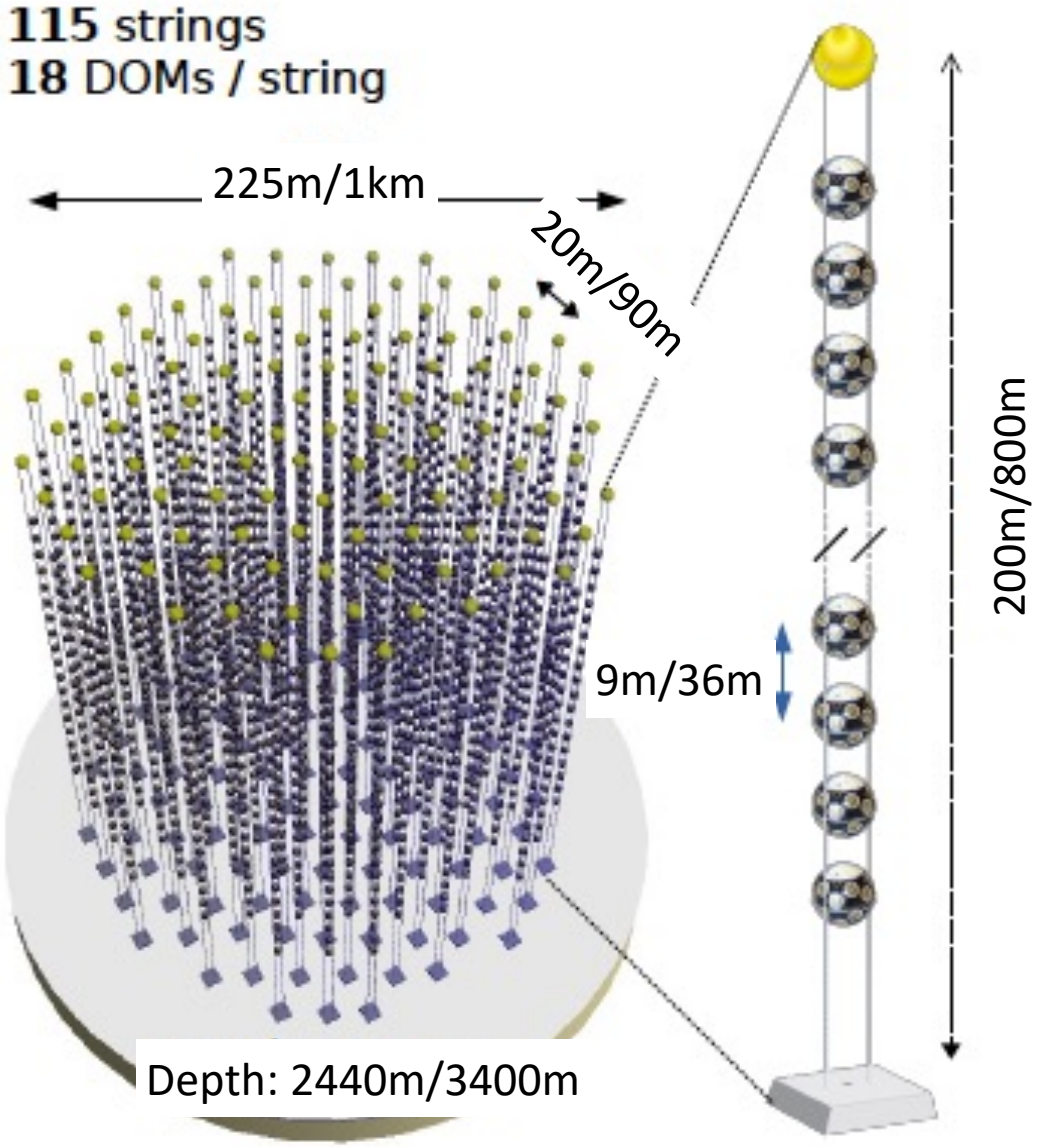


Connection nodes of
european multidisciplinary seafloor & water column observatory
emso


KM3NeT
ORCA
ARCA
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 DETECTION UNITS
CHERENKOV LIGHT CONE
INTERACTION
NODE OF THE SUBMARINE INFRASTRUCTURE
ENVIRONMENTAL INSTRUMENTATION UNIT
INTERACTION
DETECTION UNIT DEPLOYMENT TOOL
DEEP SEA ROBOTIC VEHICLE
NODE OF THE SUBMARINE INFRASTRUCTURE
BENTHIC CRAWLER FOR DEEP SEA MULTI-DISCIPLINARY STUDIES
SEISMOMETER
Conception graphique : Mathilde Destelle Arandel, 2019.


182 ns
KM3NeT: ARCA and ORCA
KM3NeT

KM3NeT building block



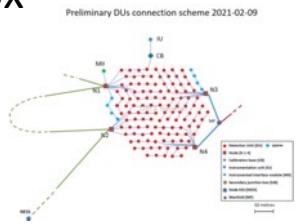
- 31 x 3” PMTs
- All data to shore: Gbit/s optical fibre
- White Rabbit time synchronisation
- LED flasher & acoustic piezo
- Tiltmeter/compass
- Low drag

Instrumented mass	**7 Mton**	**500*2 Mton**

Seafloor infrastructures

ORCA
2nd junction box
Oct 2020

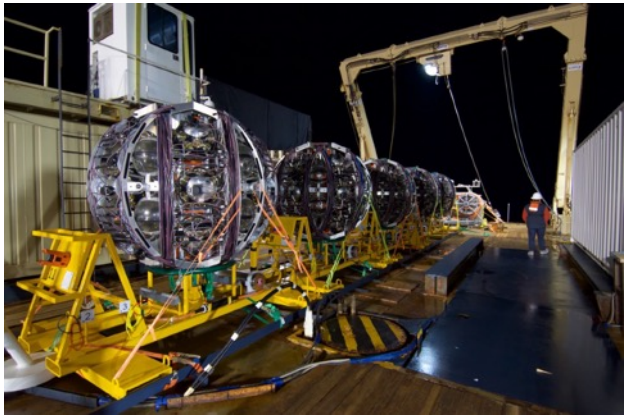
ORCA
(France)



200 m

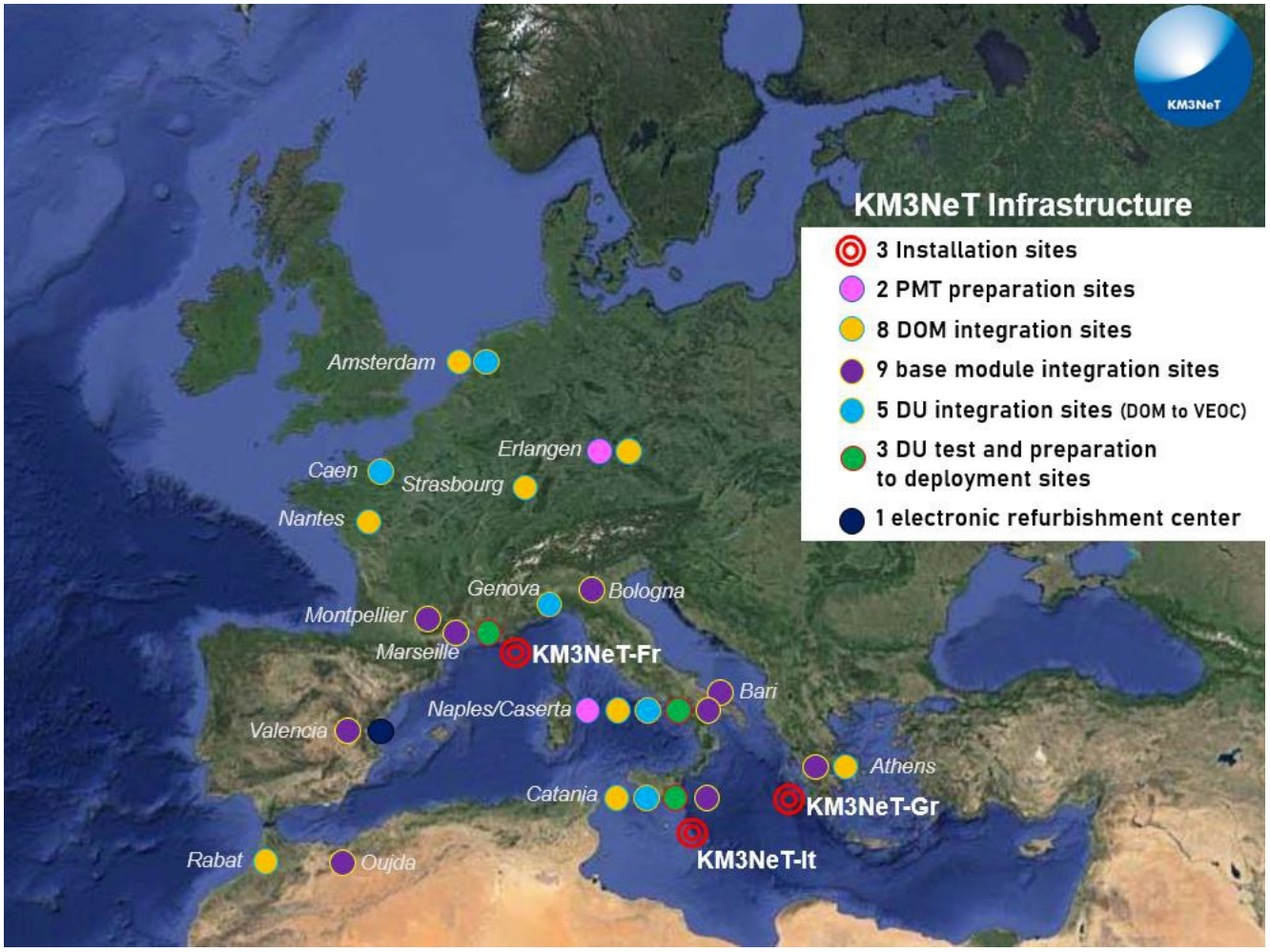
ARCA
(Italy)

ARCA
2nd Cable
Nov 2020



ARCA
junction box
+5 detection units
April 2021

Detector construction all around Europe



DOMs
- 8 integration sites
- 860 produced
- 105 currently on bench

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

Detection Units
- 6 integration sites
- 33 DUs produced
- 8 currently on bench
- 19 deployed

Despite pandemic big efforts are on going in the detector construction

Production ongoing around europe

Athens

Amsterdam

Erlangen

Genova

Nantes

Bologna

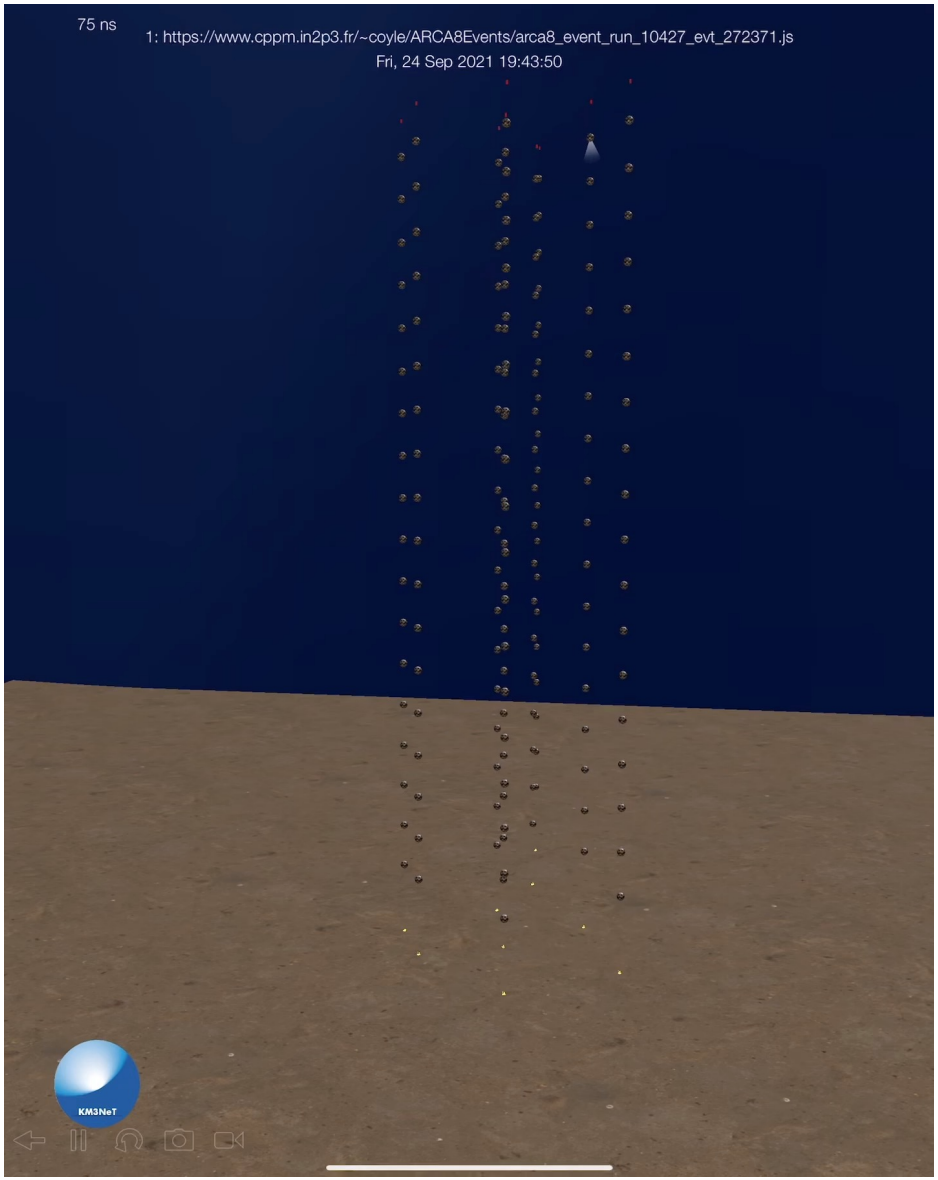
Catania

Marseille

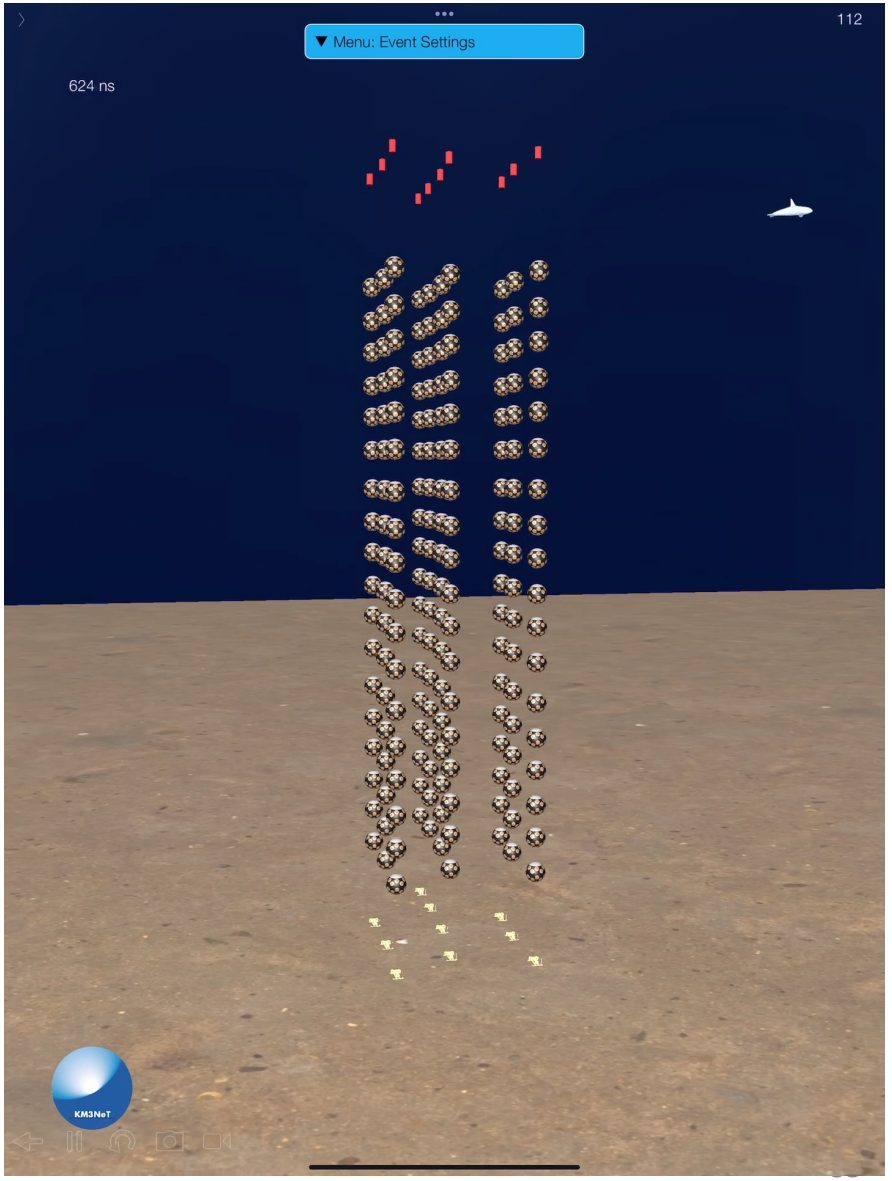
KM3NeT DU deployment

18 KM3NeT detection units operational

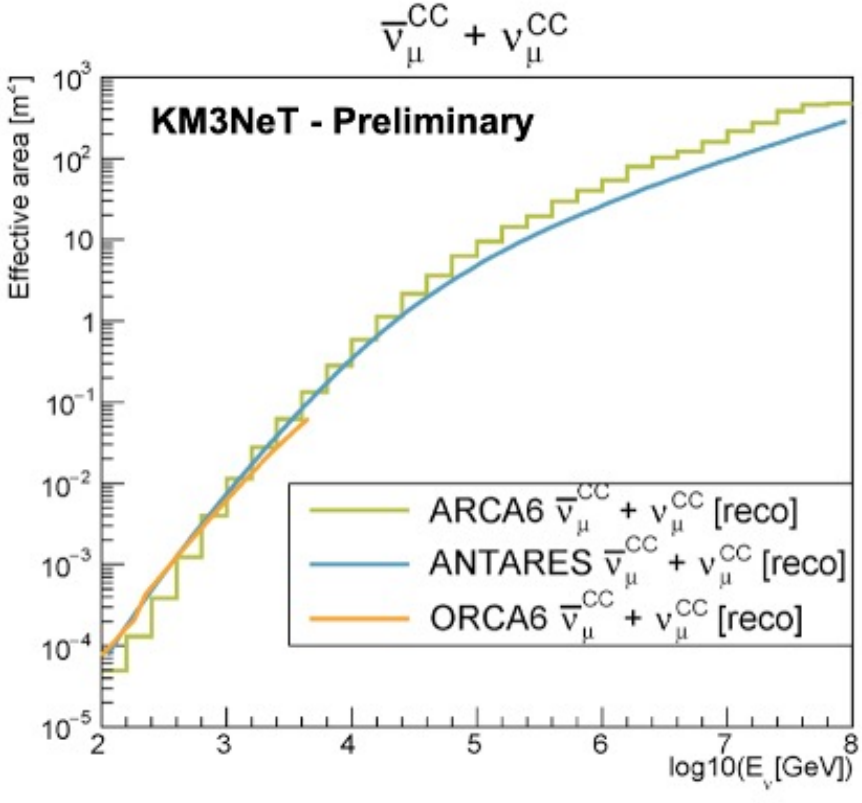
ARCA8

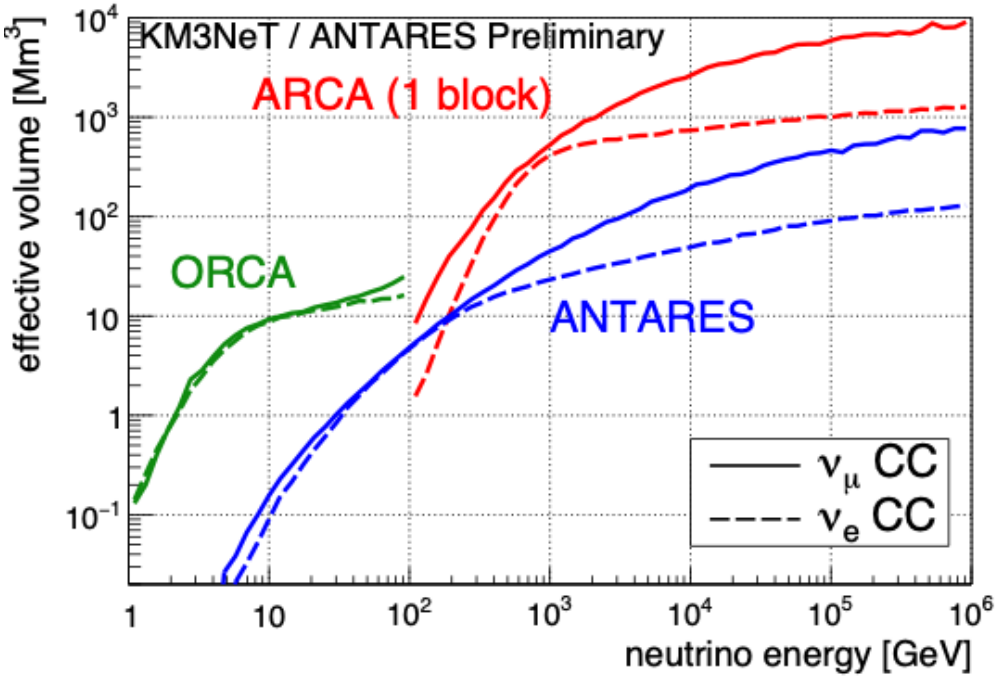


ORCA10



Effective areas: KM3NeT vs ANTARES

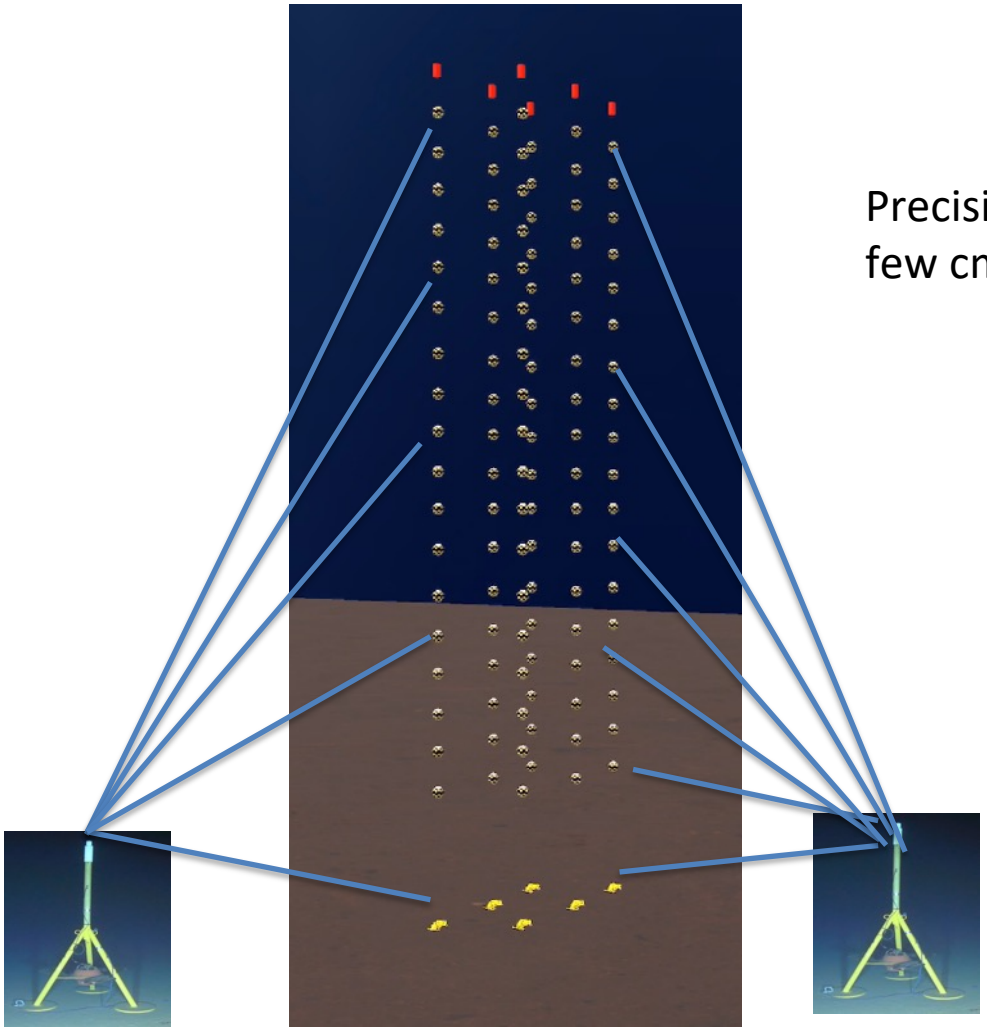




ARCA6+ORCA6 bit better than ANTARES

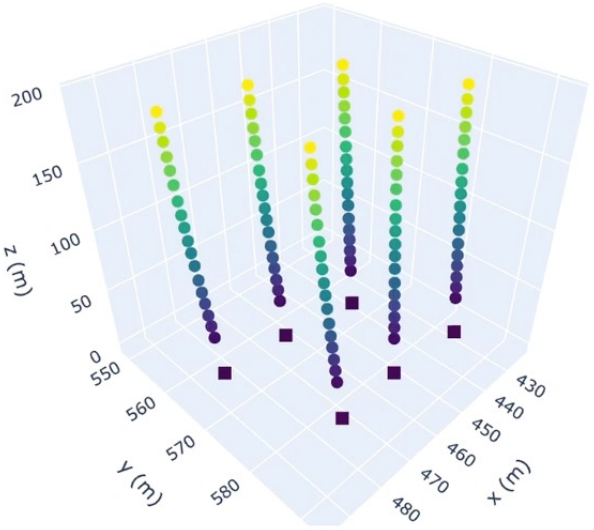
If completely funded:
Completion of ORCA115 array in 2026
and ARCA230 in 2027

Acoustic position calibration in KM3NeT

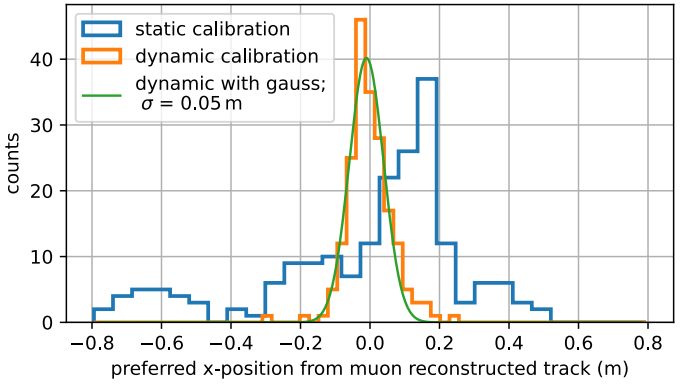


Precision
few cm

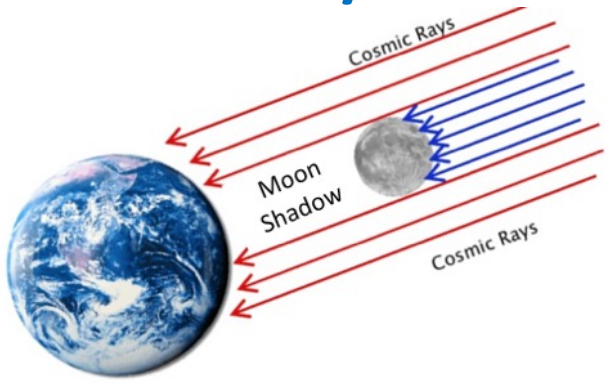
Animation of DU movement

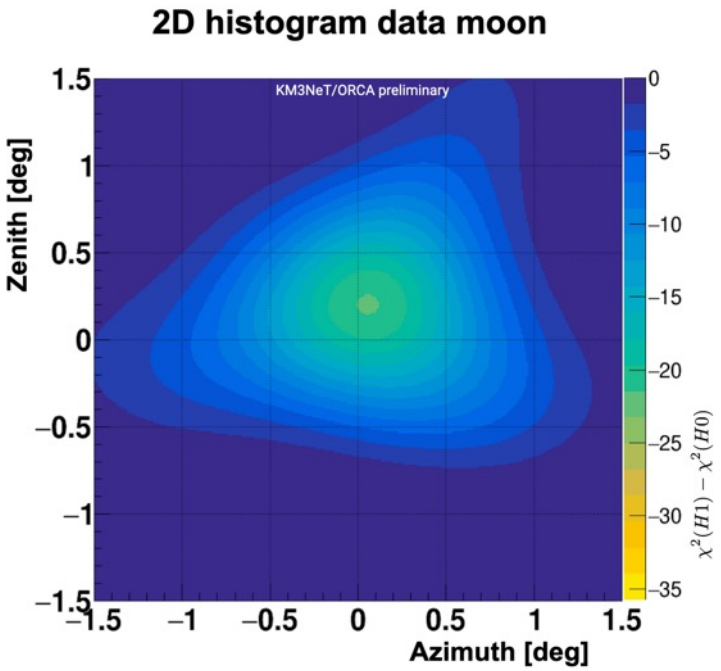


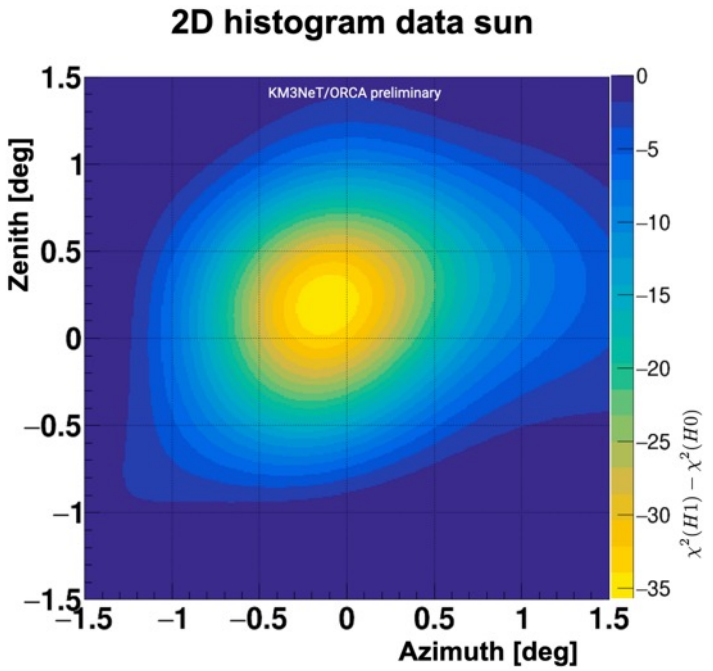
Use of dynamic positions,
verified by muon calibration



ORCA6: Moon/Sun Shadow





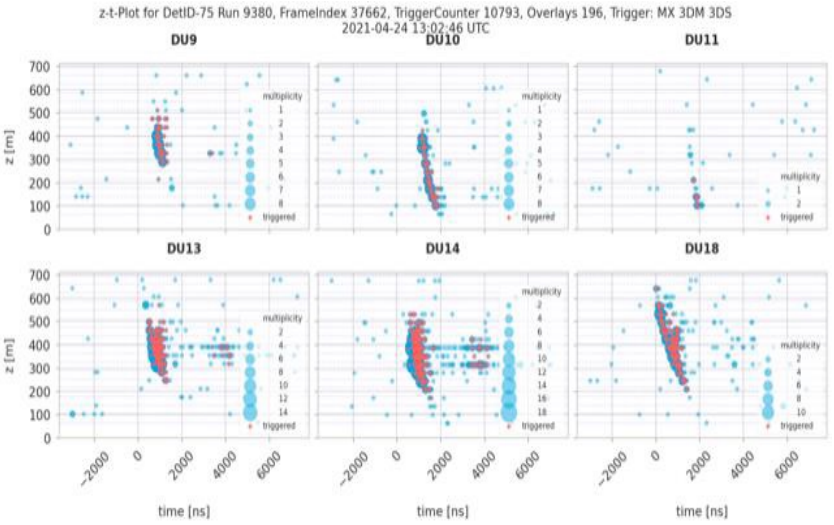


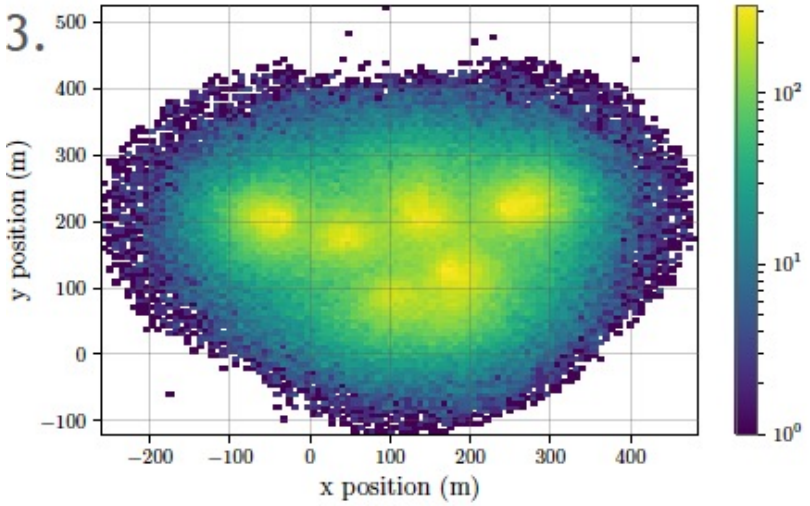
KM3NeT
ORCA
13 months
data taking

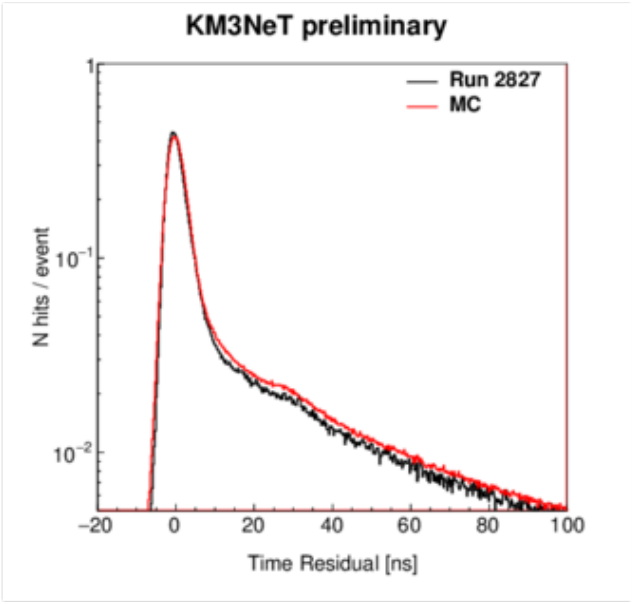
Significance = 4.4 σ
Angular resolution = 0.54°+/-0.13°

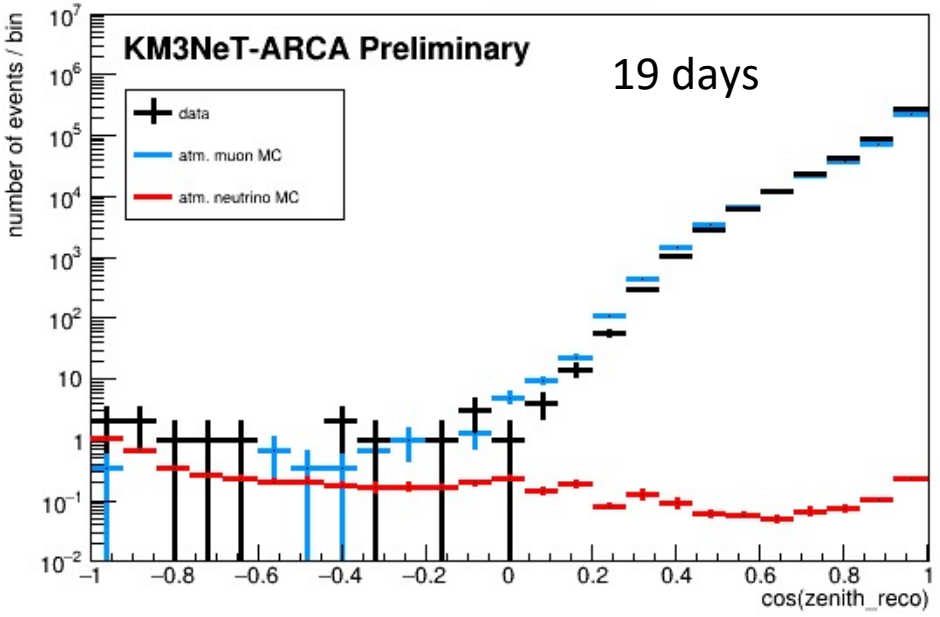
Significance = 5.7 σ
Angular resolution = 0.59°+/-0.10°

ARCA6 data

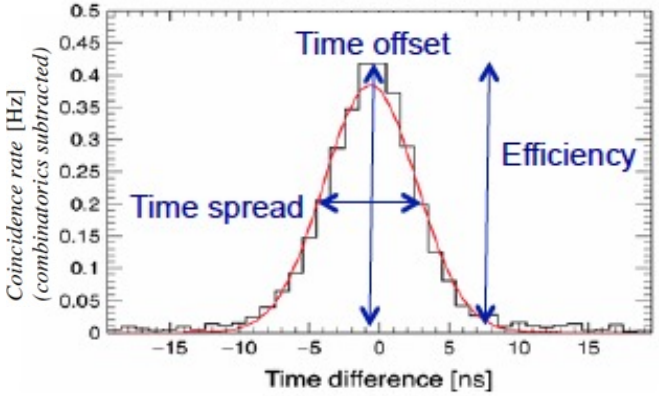

z-t-Plot for DetID-75 Run 9380, FrameIndex 37662, TriggerCounter 10793, Overlays 196, Trigger: MX 3DM 3DS
2021-04-24 13:02:46 UTC
DU9
DU10
DU11
DU13
DU14
DU18
z [m]
time [ns]
multiplicity
triggered

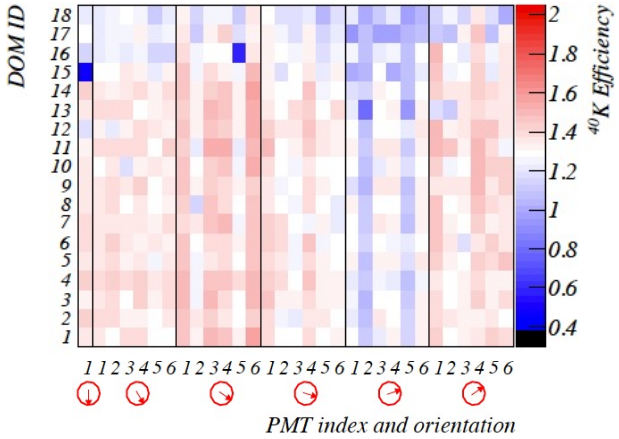

3.
y position (m)
x position (m)


KM3NeT preliminary
Run 2827
MC
N hits / event
Time Residual [ns]


KM3NeT-ARCA Preliminary
19 days
data
atm. muon MC
atm. neutrino MC
number of events / bin
cos(zenith_reco)

PMT efficiencies: ^{40}K

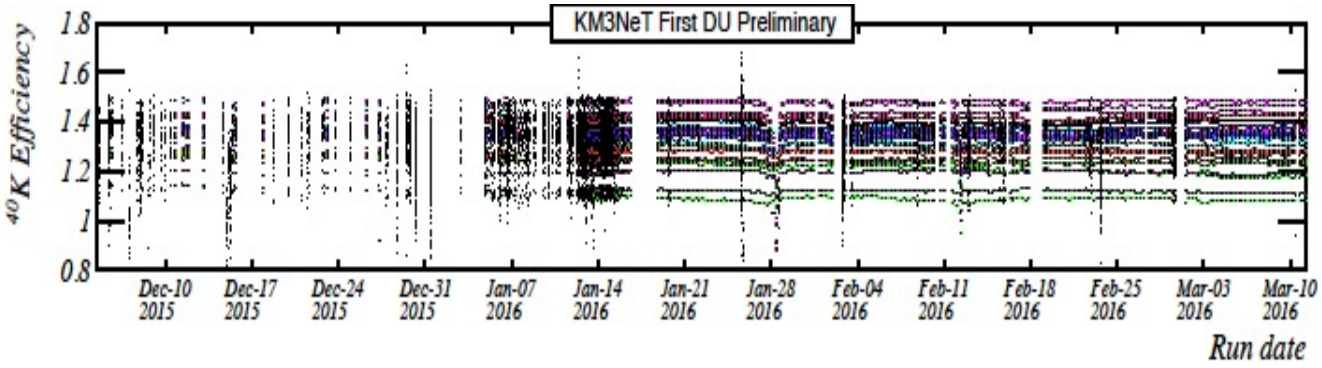




^{40}K → e$^-$ (β decay)

^{40}Ca

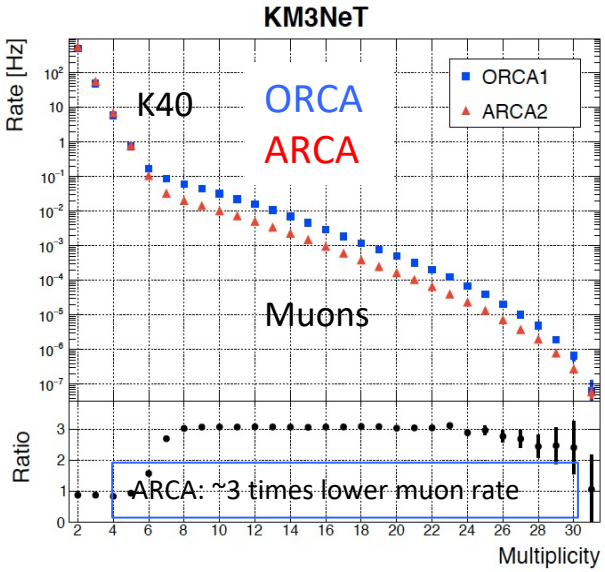
Up to 150 Cherenkov photons per decay; stable ^{40}K concentration

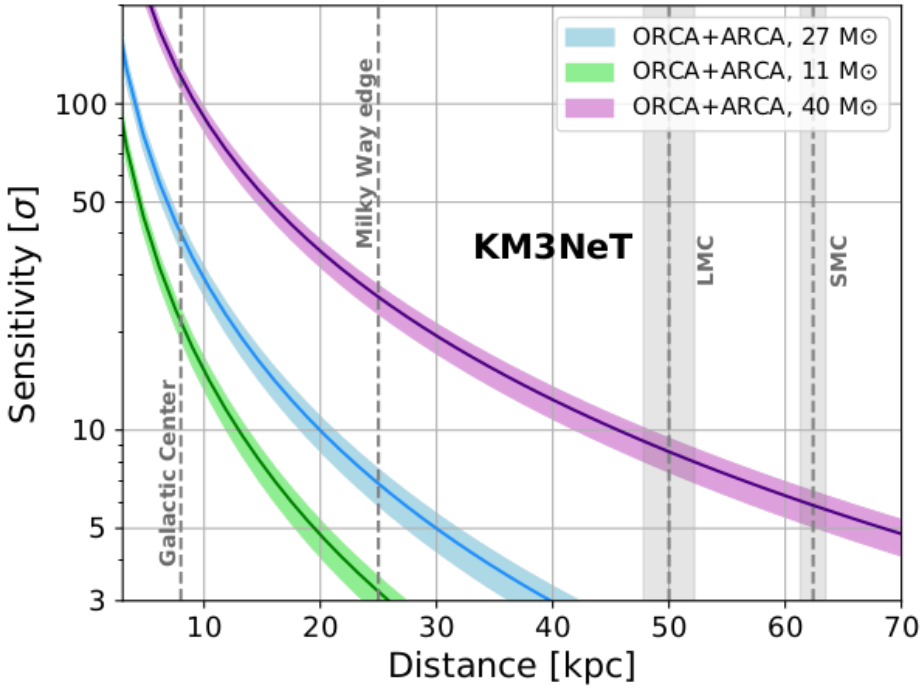


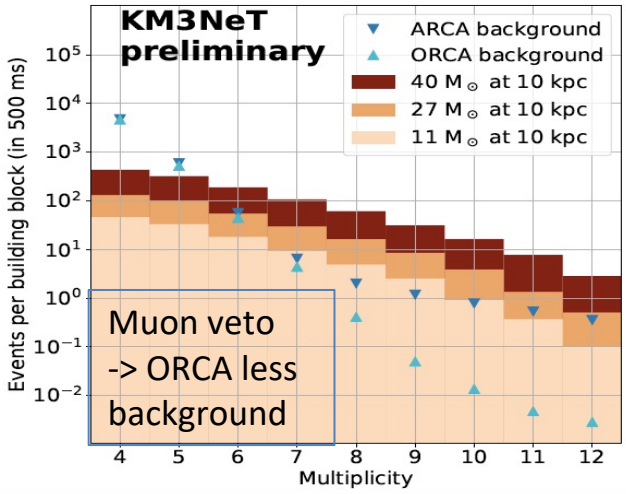
Supernova monitoring in KM3NeT

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

Eur. Phys. J. C81 (2021) 445







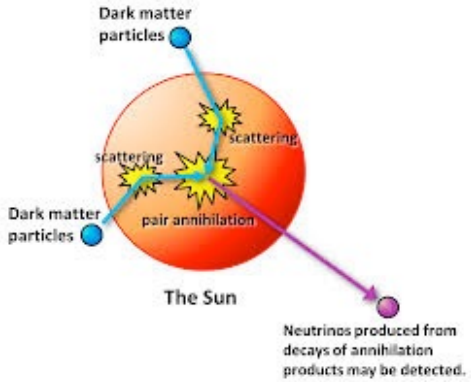
Discovery potential for 95% of Galactic CCSNe

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

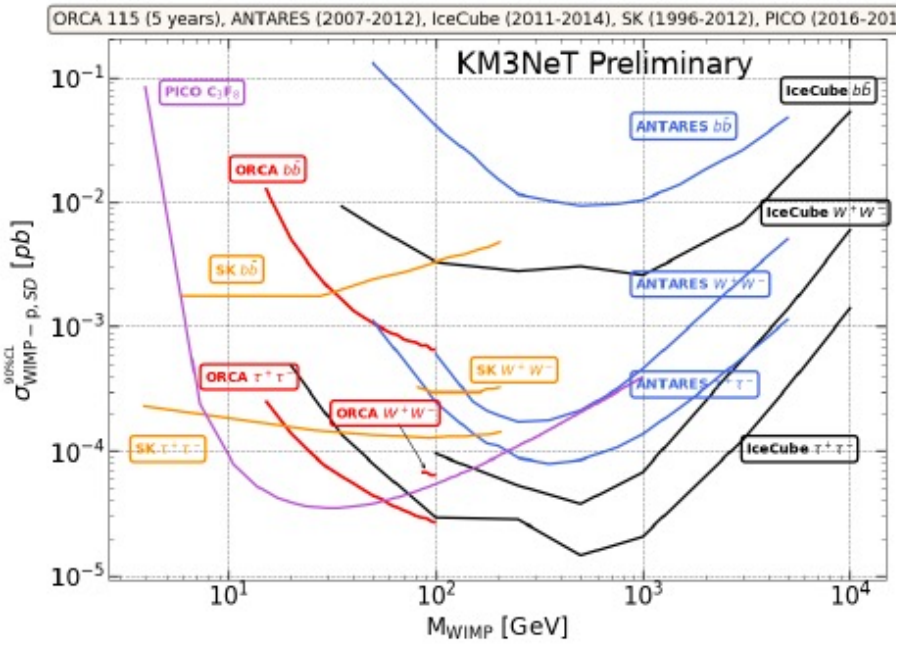
Joint real time trigger operational for SNEWS since early 2019

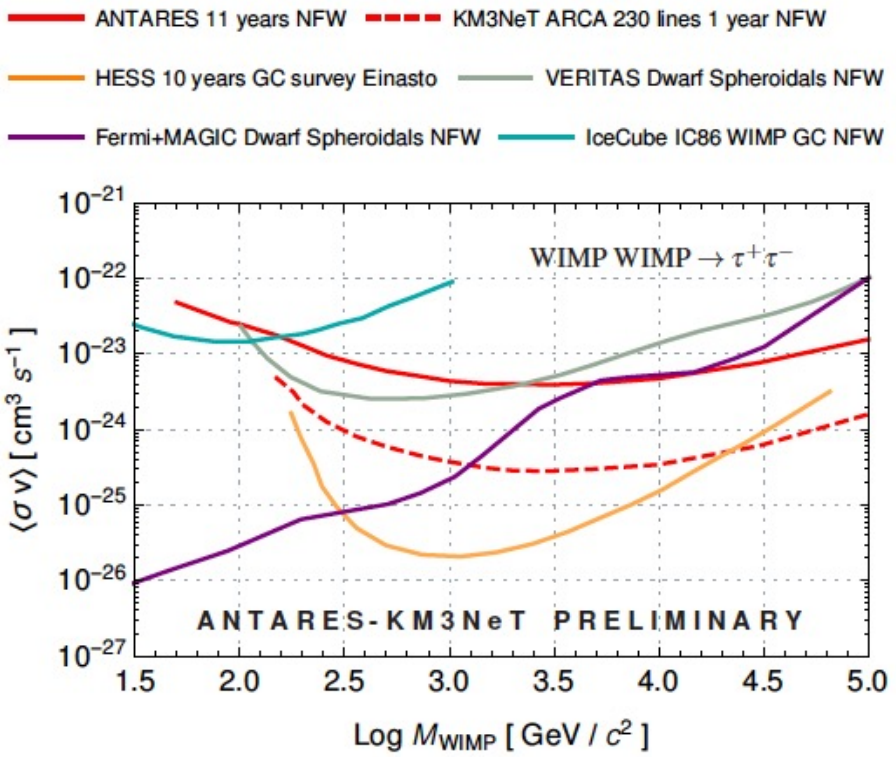
Dark matter-indirect detection

Sun



Galactic Centre

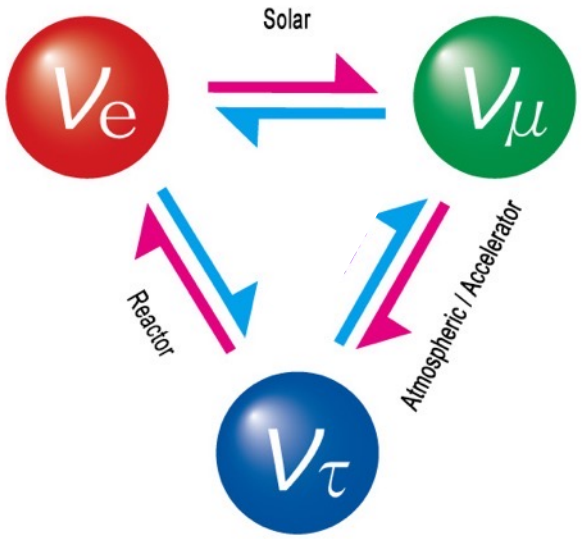


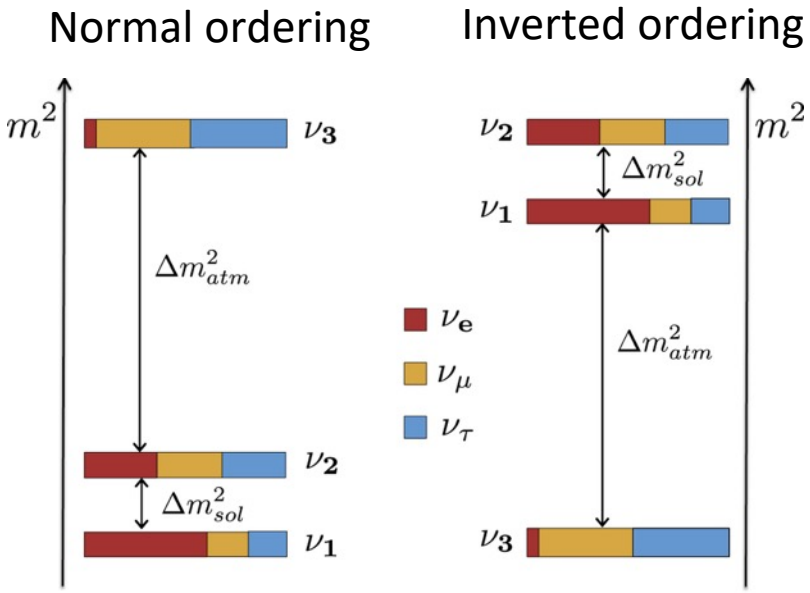


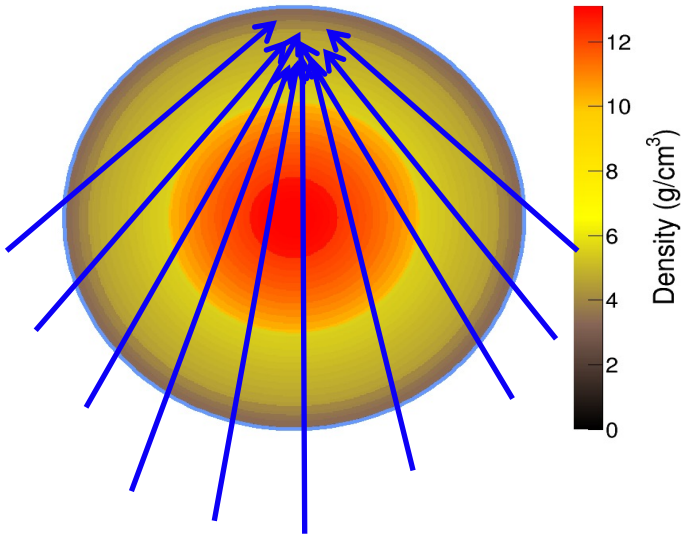
Phys.Lett. B759 2016

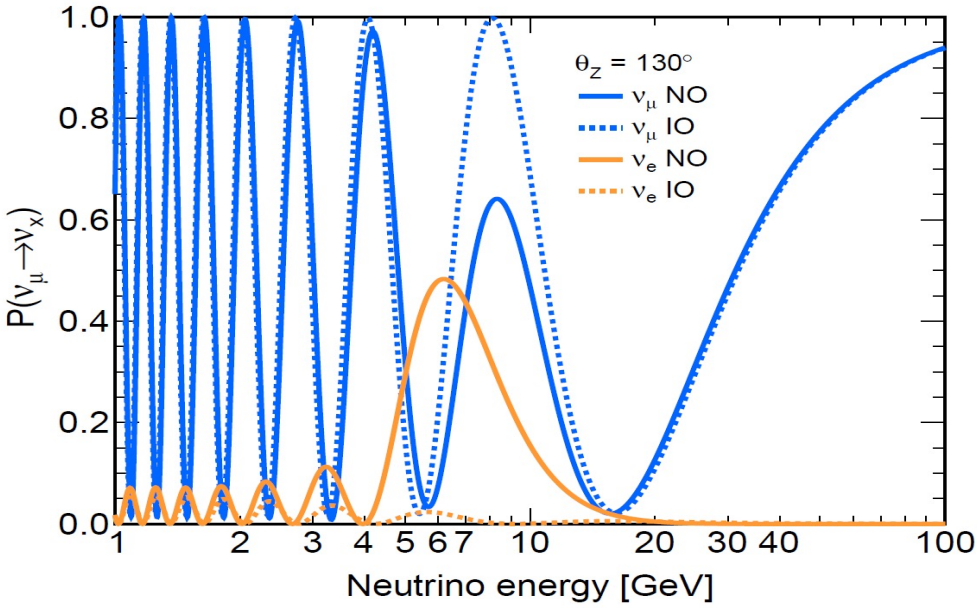
Phys. Lett. B 805 135439 (2020)

neutrino oscillations with atmospheric neutrinos

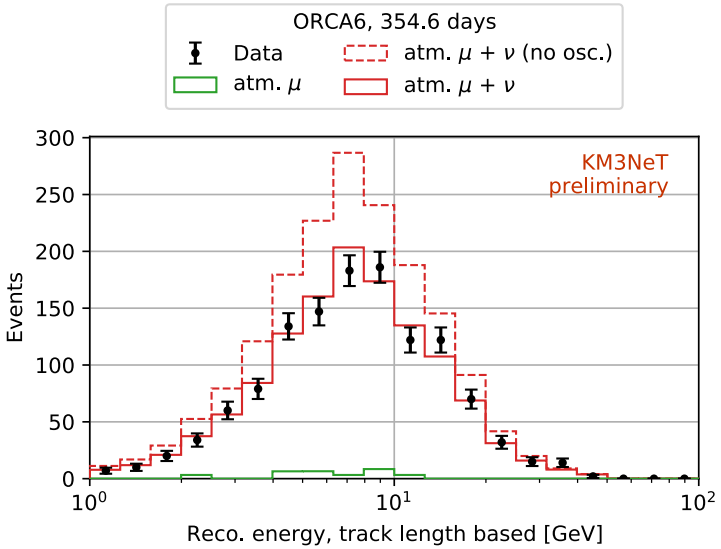


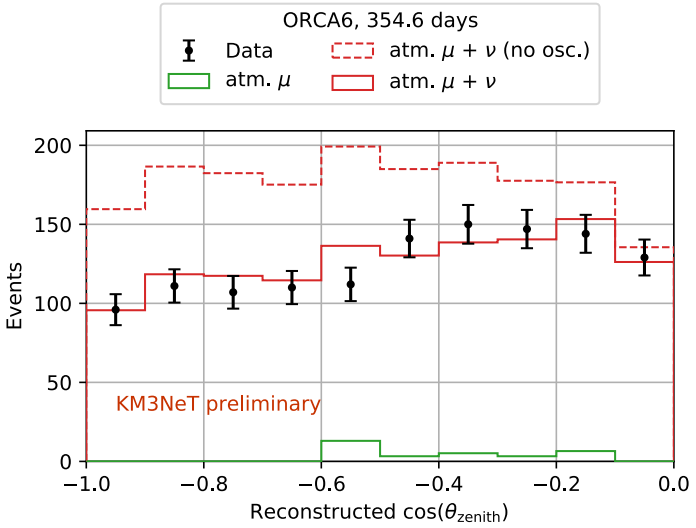


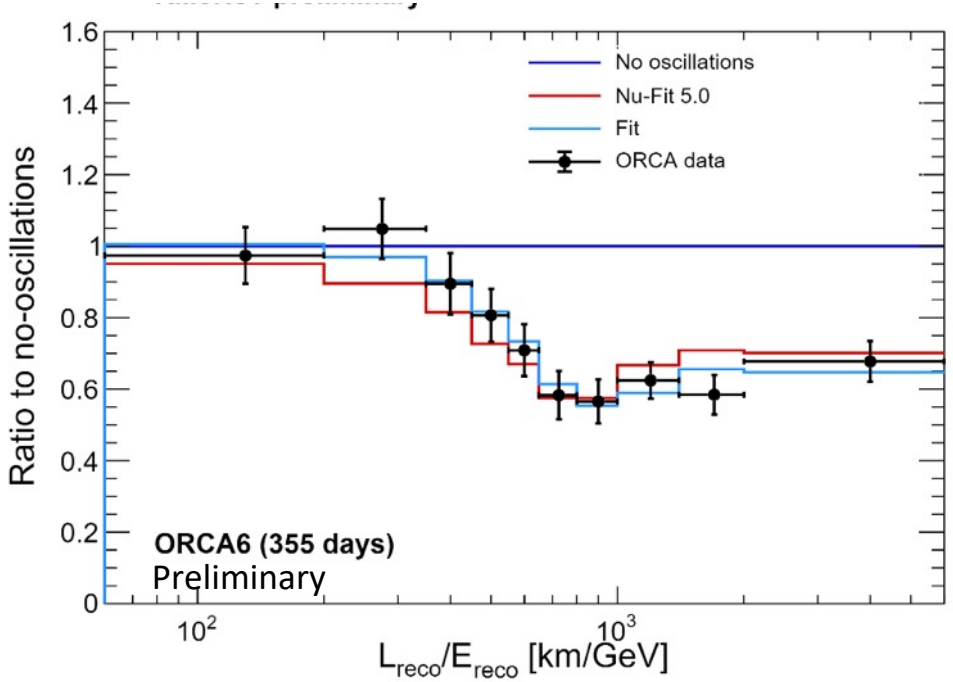




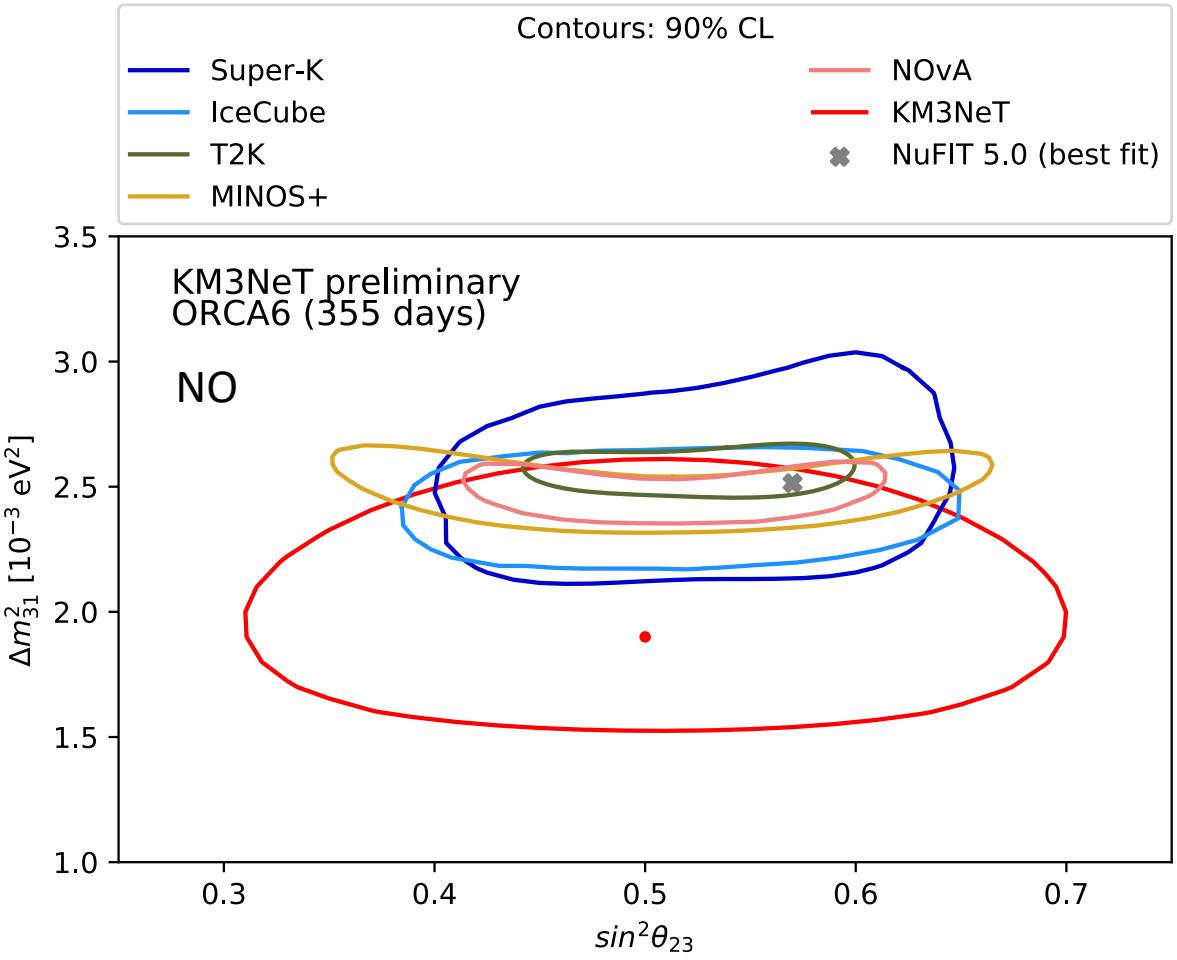
ORCA6 neutrino oscillations (tracks)

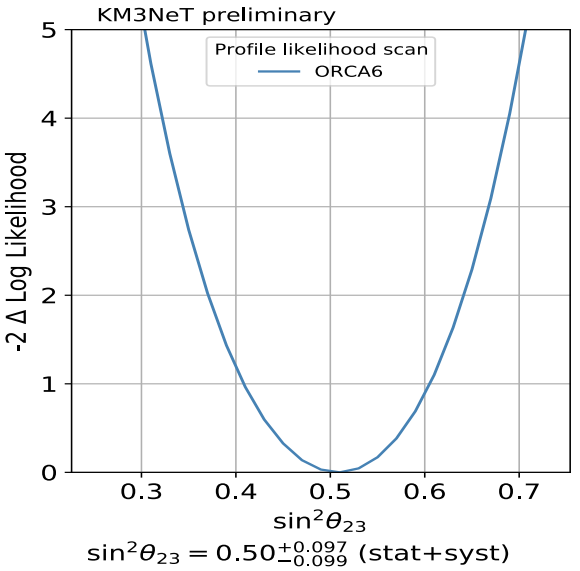


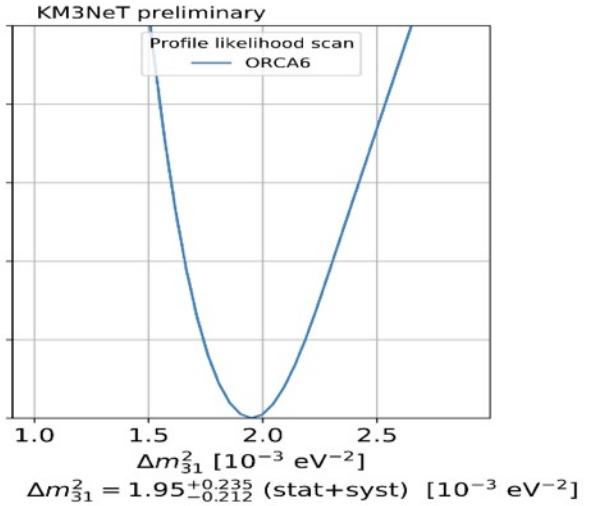




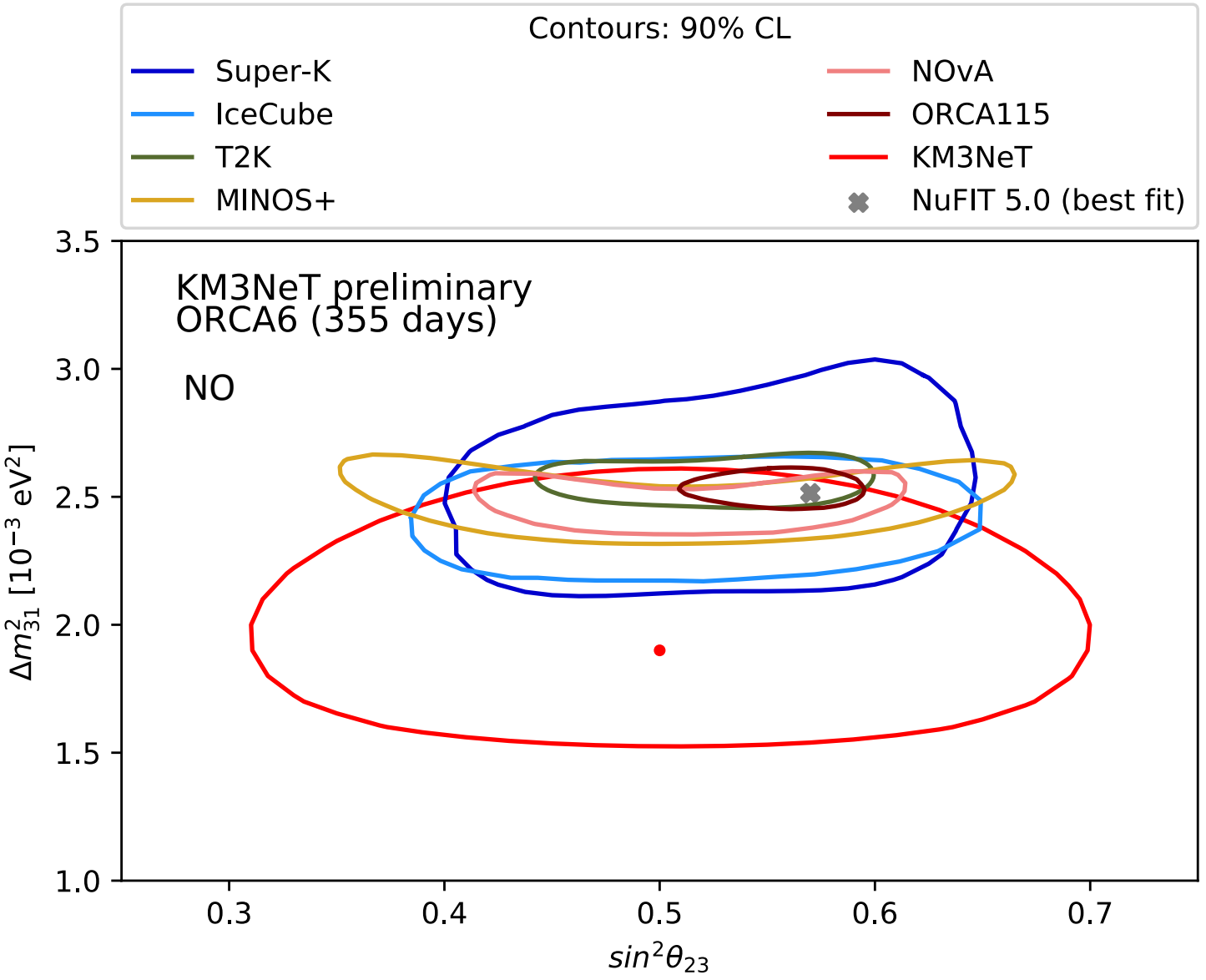
ORCA6: measurement of oscillation parameters







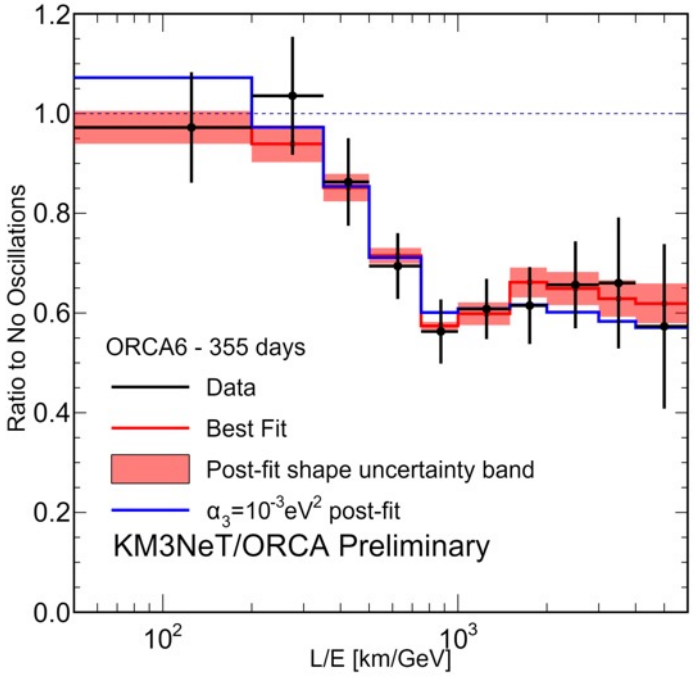
ORCA115: neutrino oscillations sensitivity (3 years)



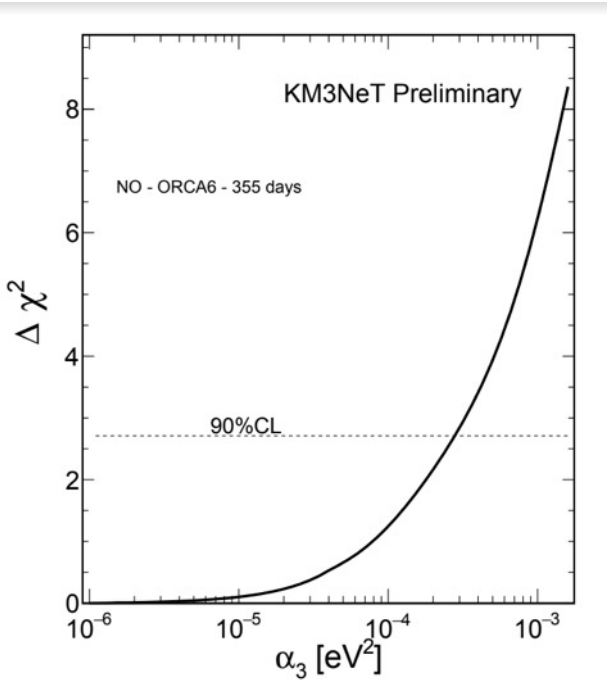
ORCA6: neutrino decay

ORCA6 353 kton-year sample:

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



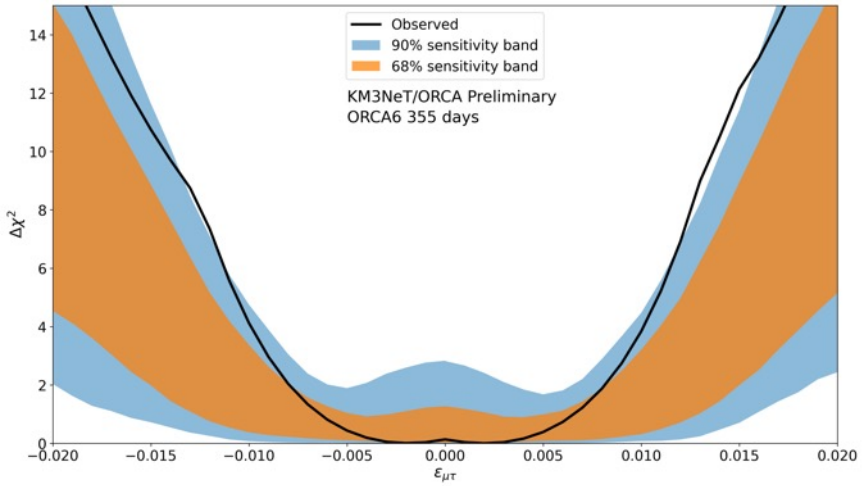
(comparable to LBL limits)

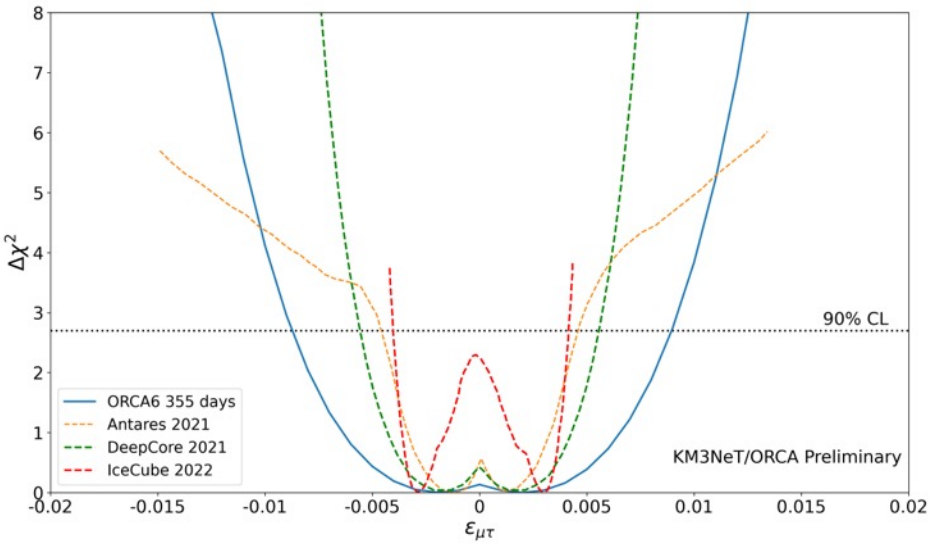


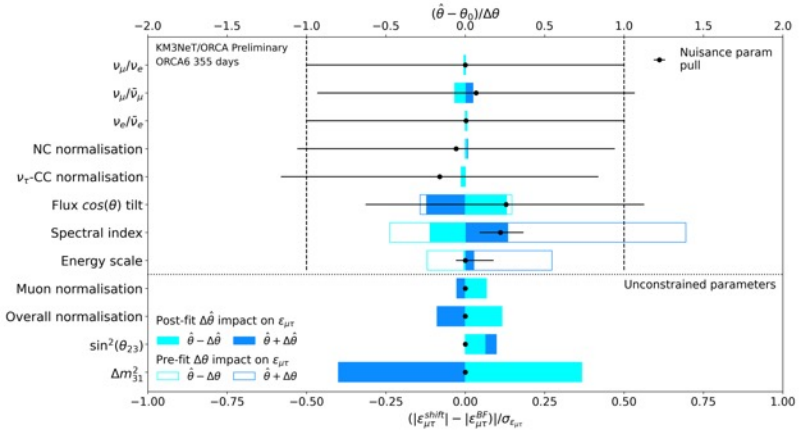
ORCA6: non-standard interactions

ORCA6 353 kton-year sample:

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

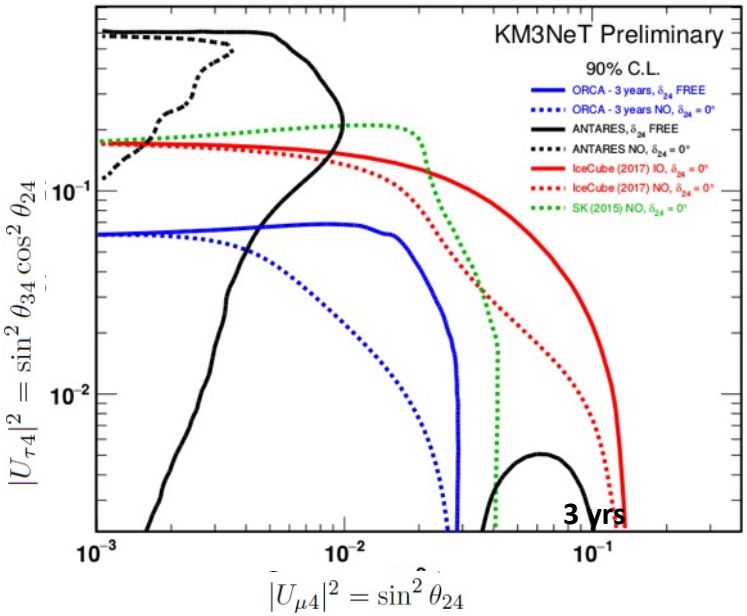






ORCA115: sterile neutrinos

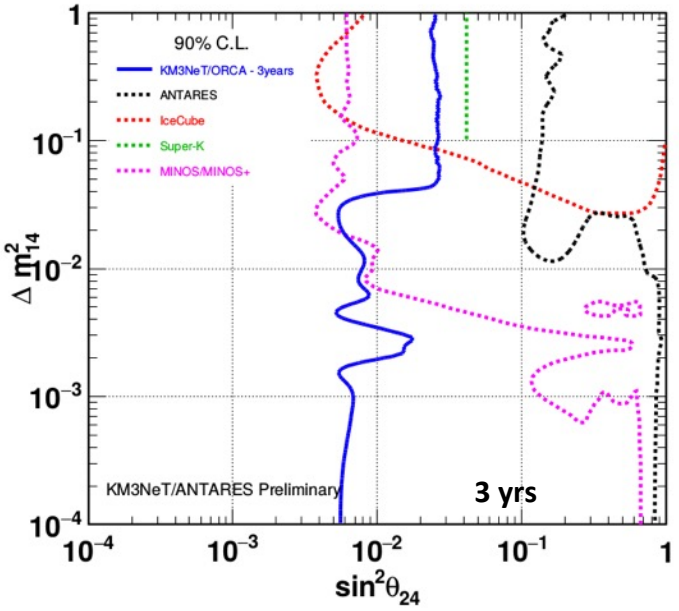
$\Delta m_{41}^2 > 0.1$ eV^2



Dependence on δ_{24}

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

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



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

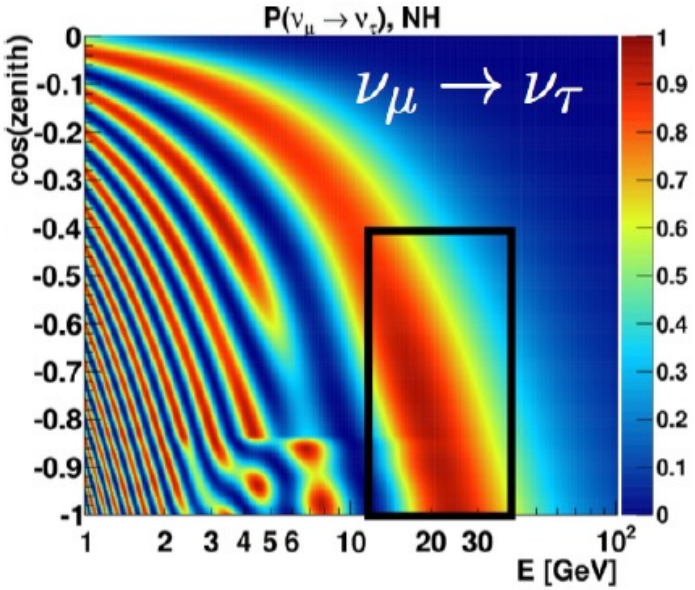
Tau appearance

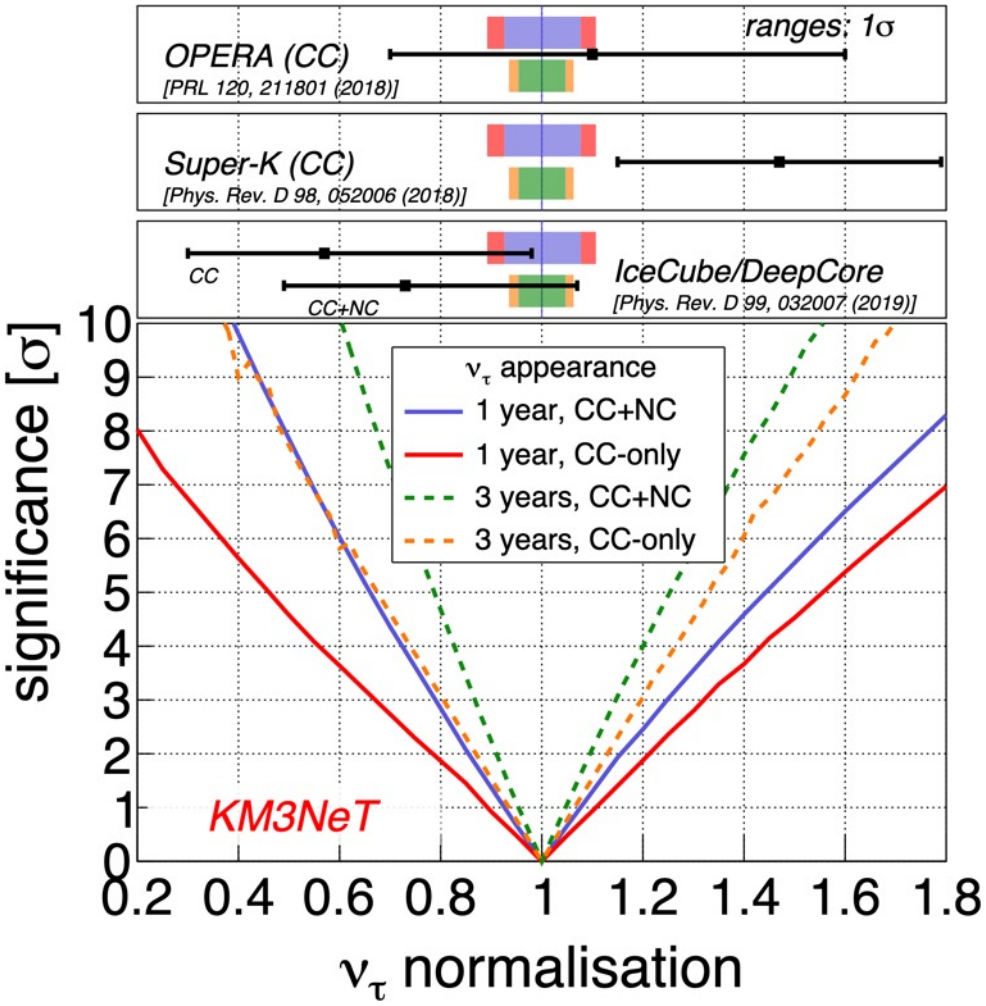
The muon neutrinos mainly oscillate to tau neutrinos.

They appear as showers events.

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

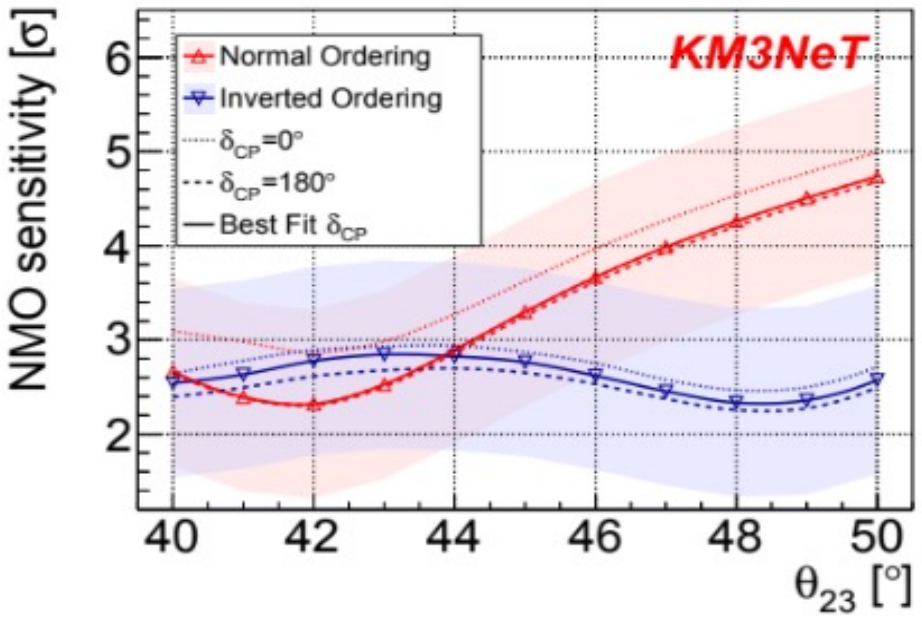
≈3k ν_τ CC events/year with full ORCA





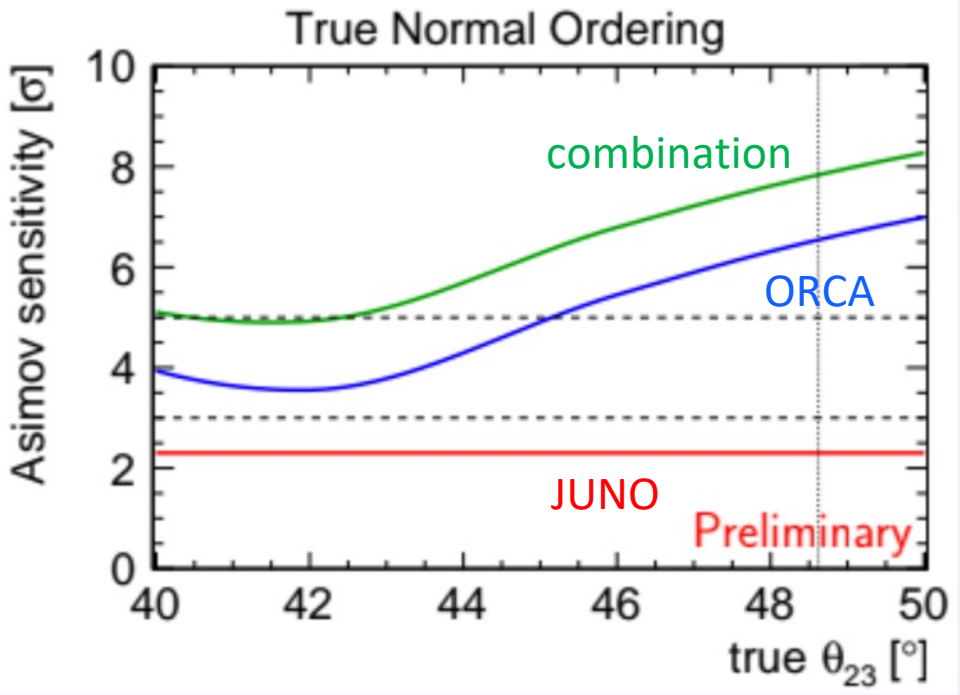
ORCA115: neutrino mass ordering

3 years



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

6 yrs & combination with JUNO



Combination power relies on tension between best-fit of Δm^2_{31} in "wrong ordering" between JUNO and ORCA

ORCA115: NMO compared with the world

Draft SNOWMASS White paper, Denton et al., 2022

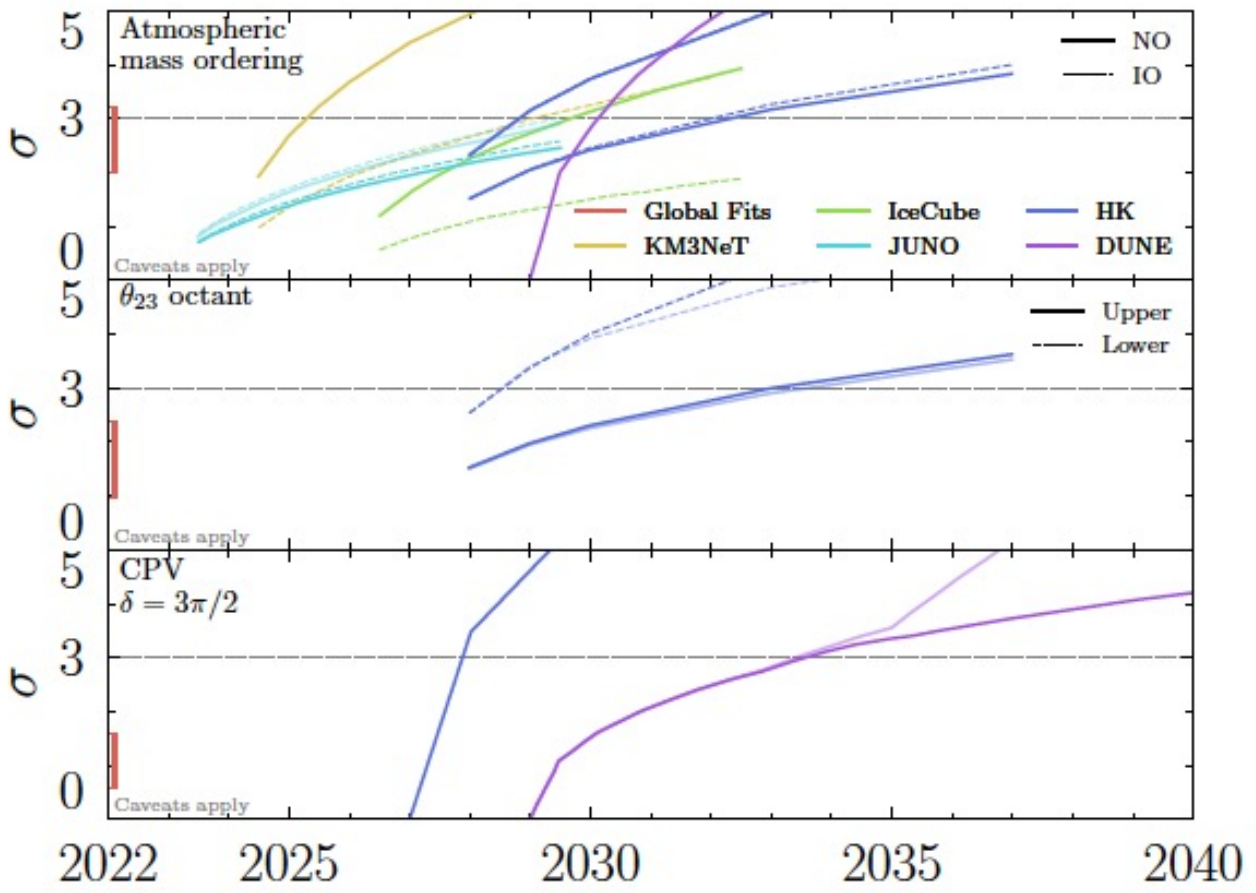
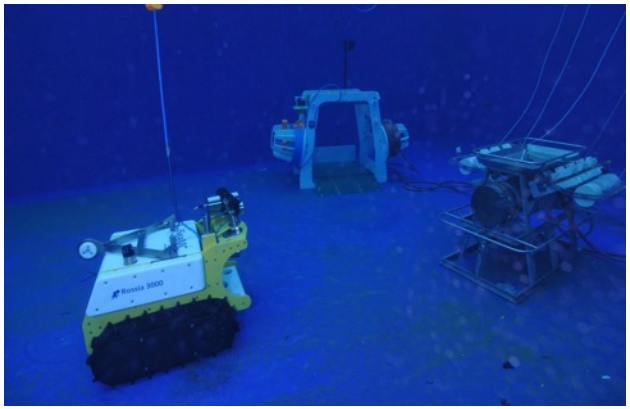
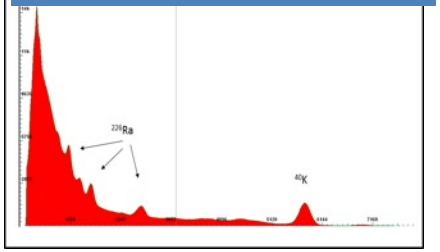


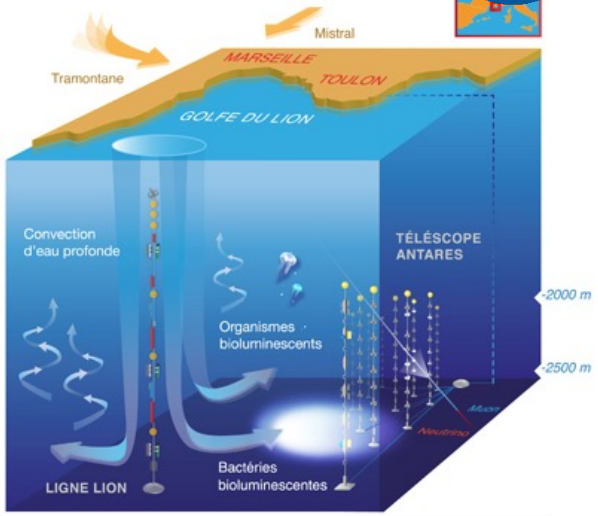
Figure 26: The estimated sensitivities to the three remaining oscillation unknowns based on the latest estimates of sensitivities and starting dates. Many caveats are required, see the text for details. *[Note: DUNE has sensitivity to the octant; future versions will include this curve.]*

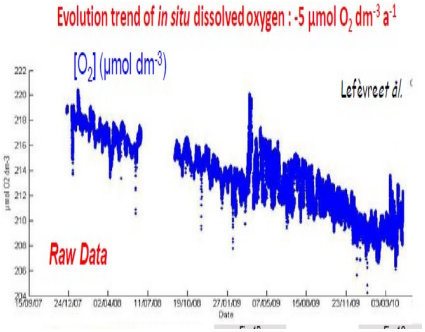
Earth and sea sciences

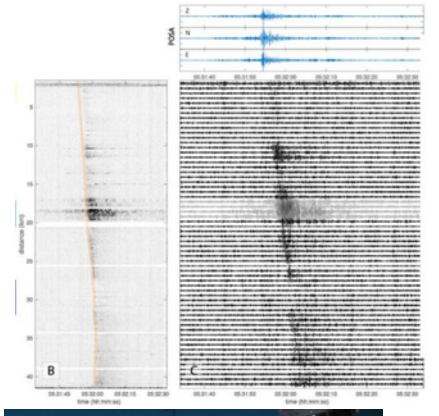


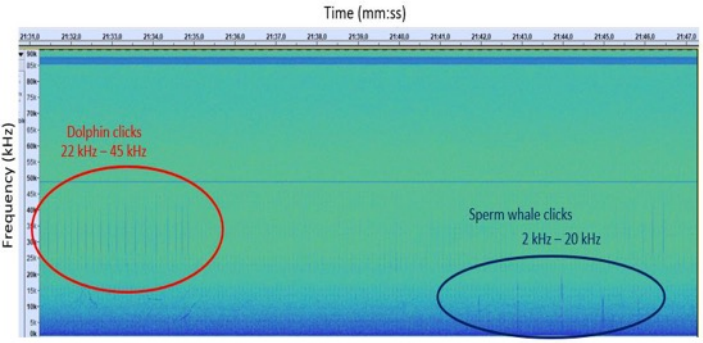
Gamma detector

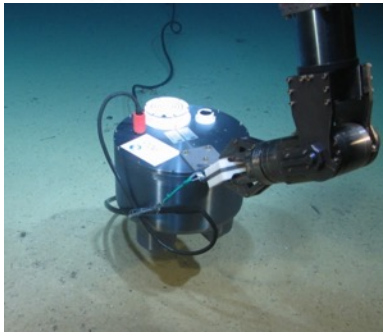




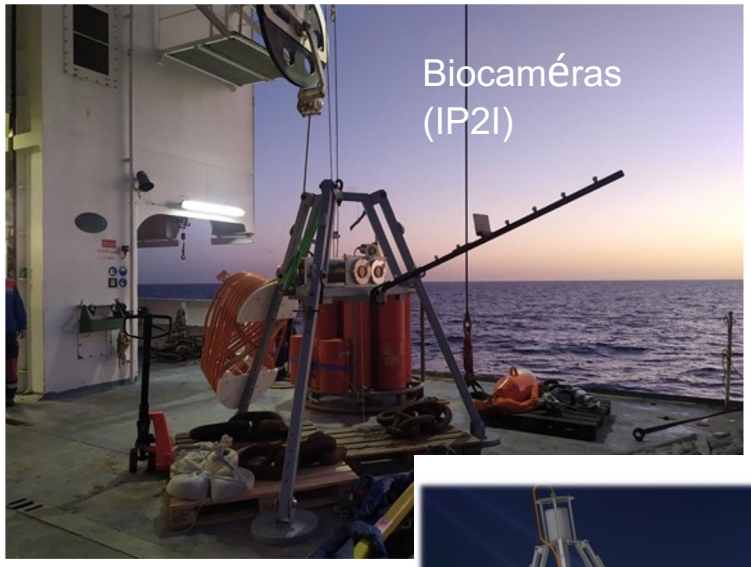


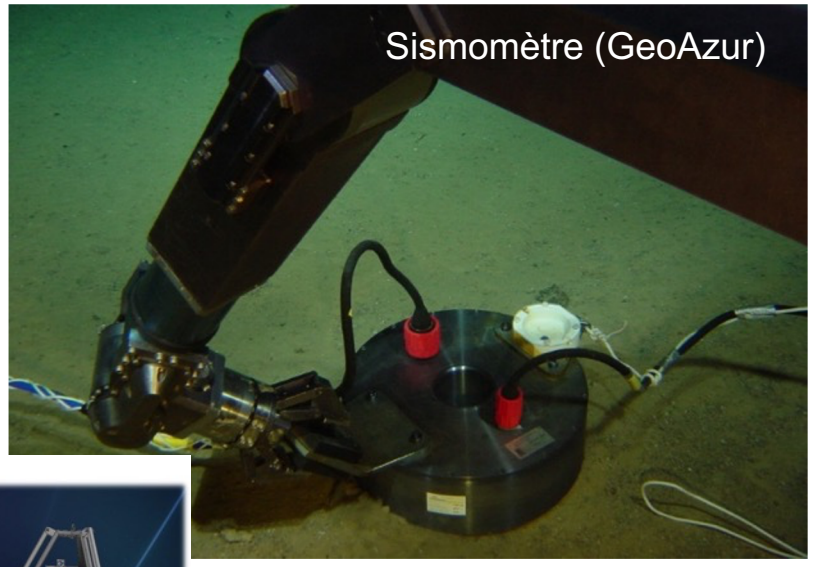


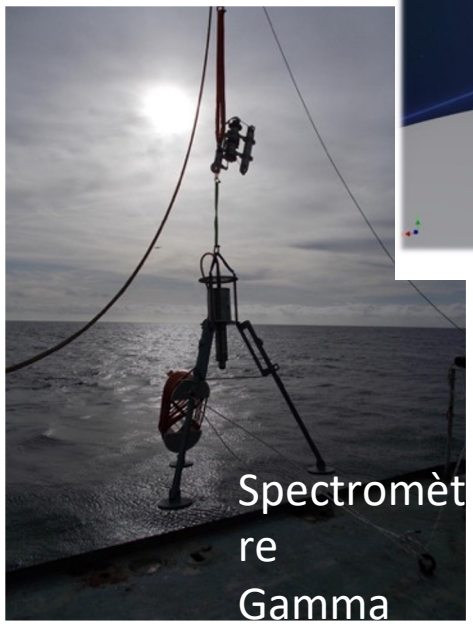




Opération Nautile: Déploiement instrumentation



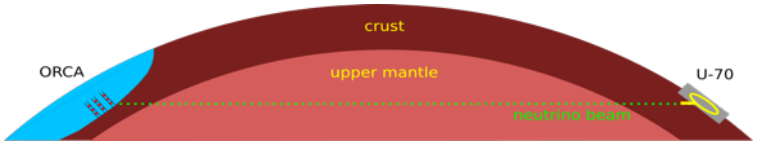




https://www.mio.osupytheas.fr/fr/mers-et-oceans-changement-global/emso-lo-bathycruise

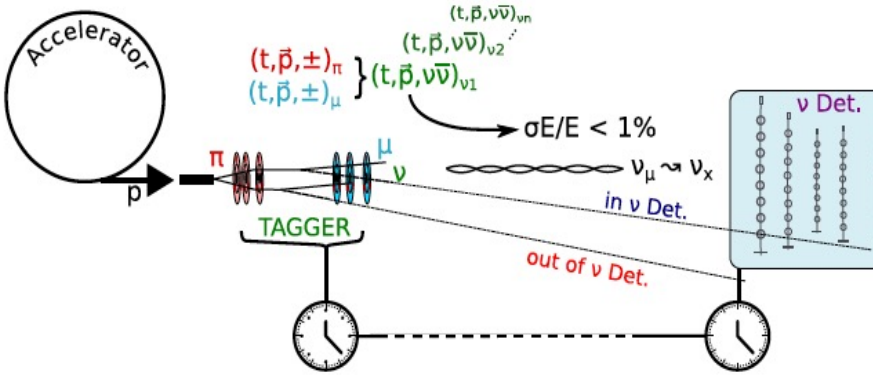
New idea: Tagged Protvino to ORCA

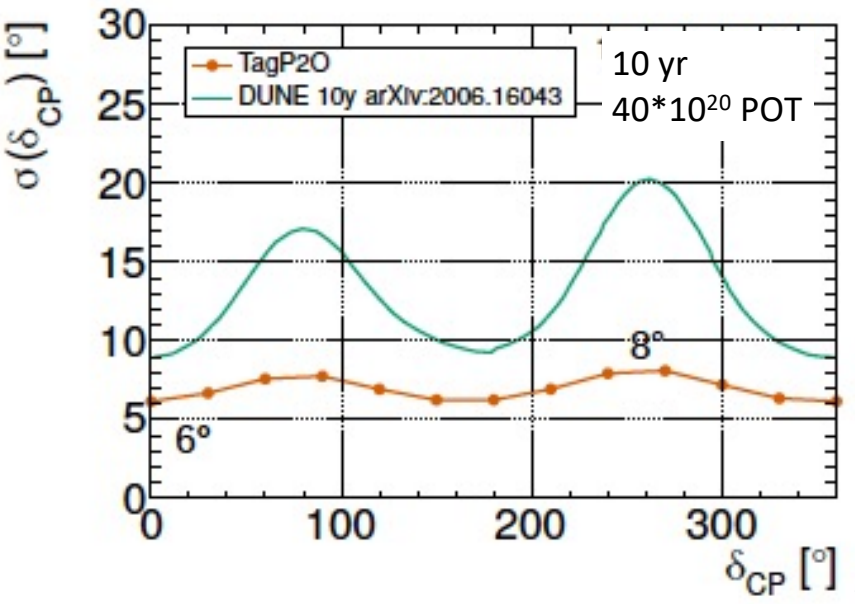
A. V. Akindinov et al.,
"Letter of Interest for a Neutrino Beam from Protvino to KM3NeT/ORCA"
https://arxiv.org/abs/1902.06083



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

M. Perrin-Terrin
https://arxiv.org/abs/2112.12848





Summary

Water based nu telescopes:

- angular resolution, multi-flavour astronomy, galactic sources

Intriguing indications of cosmic neutrino sources from ICECUBE/ANTARES associated with radio loud and/or gamma blazar flares

- J0242+1101
- MG3 J225517+2409
- TXS 0506+056

KM3NeT taking data and growing rapidly

-First measurement of neutrino oscillation parameters by ORCA6

-First ATELs reacting to external alerts

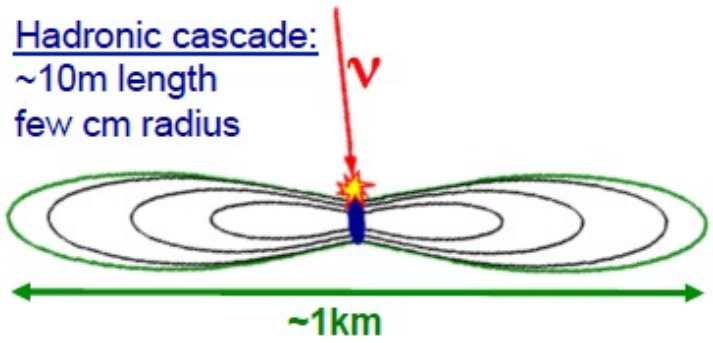
New ideas in gestation

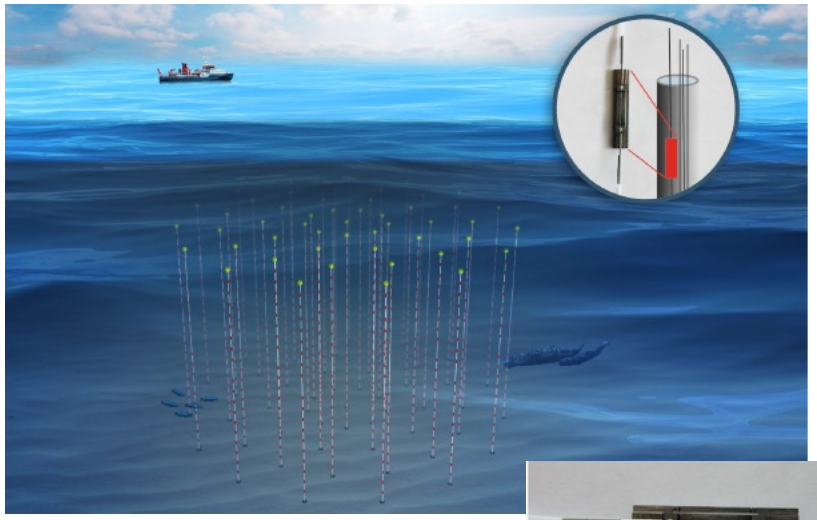
- Protvino to ORCA (P2O)
- Acoustic detection of UHE neutrinos

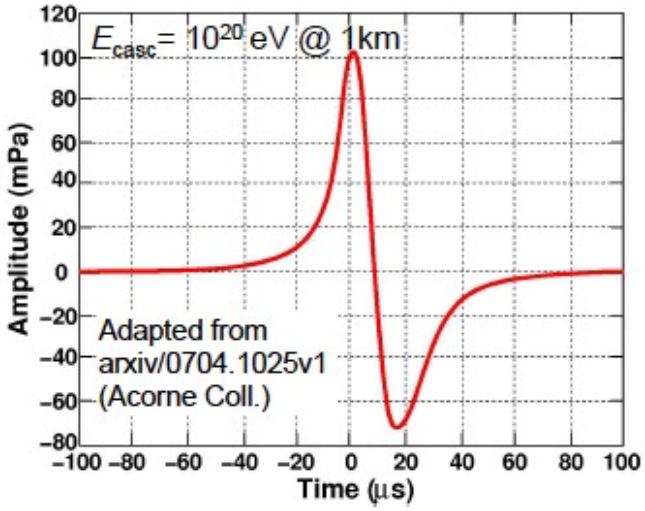
Come and join the adventure!

BACK UP

Old idea/New technology: Acoustic detection of UHE neutrino







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