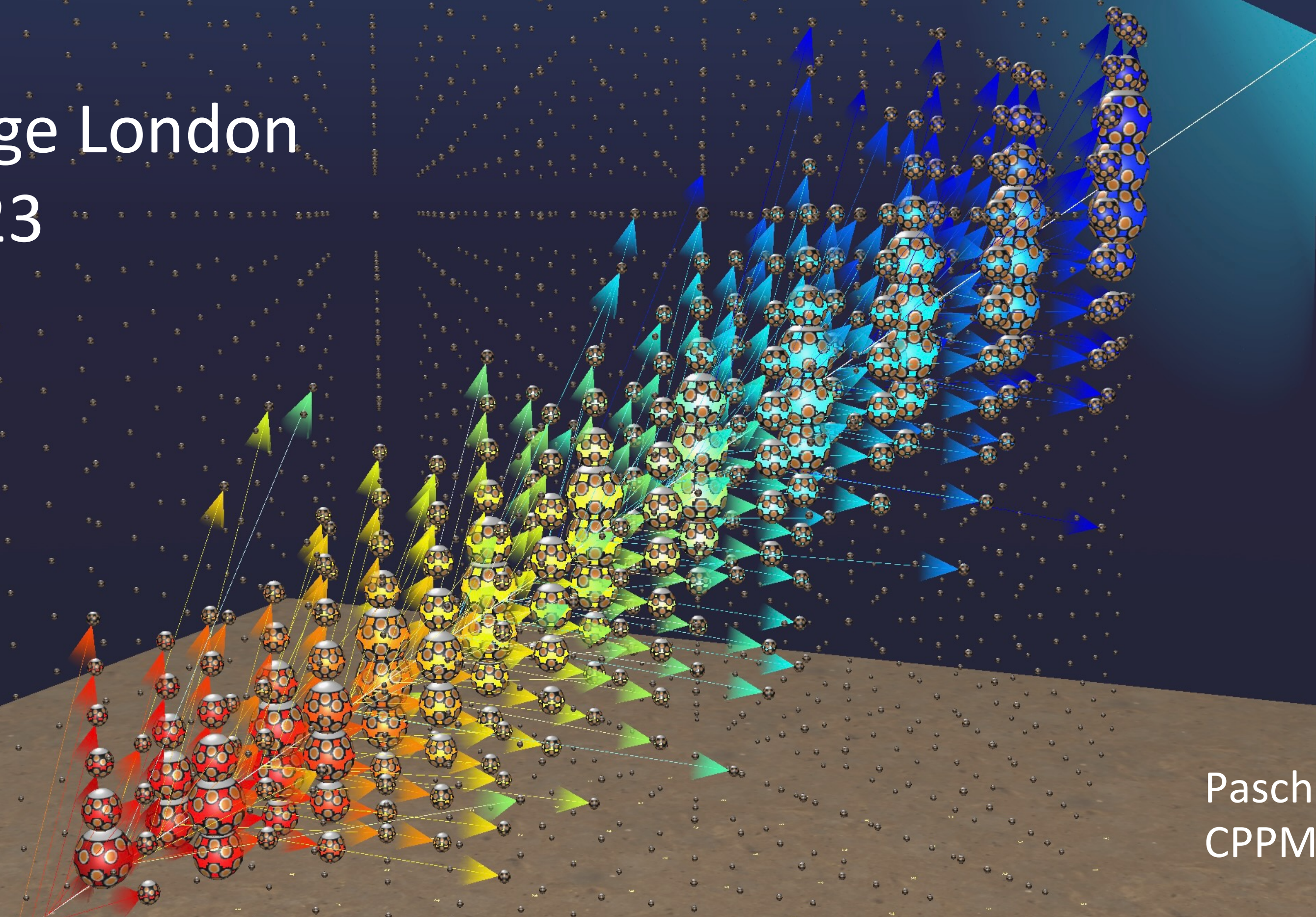
Fishing for neutrinos with KM3NeT: Astroparticle and oscillation research in the abyss

Kings College London
16 Nov 2023



Paschal Coyle
CPPM

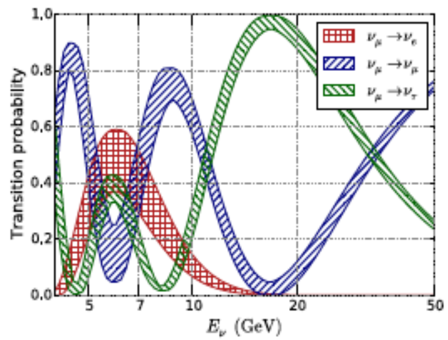
KM3NeT

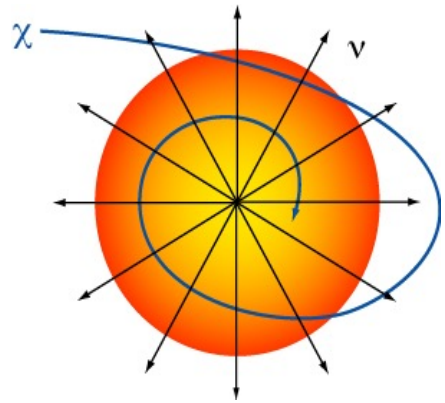
ANTARES

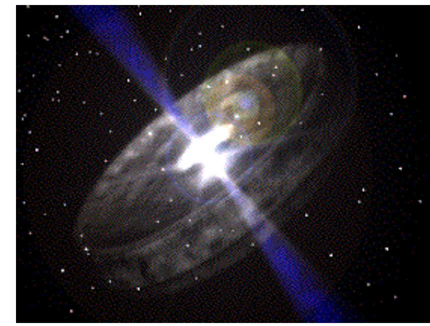
CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

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

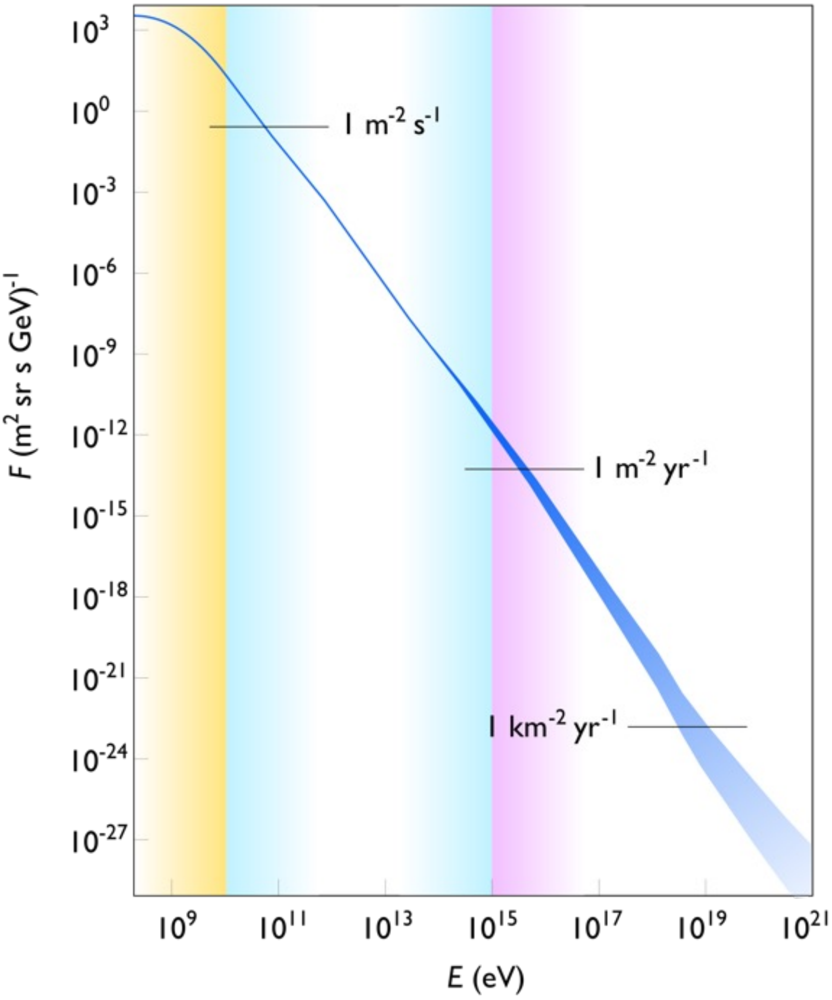
Origin and production mechanism of HE CR

KM3NeT-ORCA ANTARES KM3NeT-ARCA

+ oceanography, biology, bioacoustics, seismology,…

Motivations for neutrino astronomy

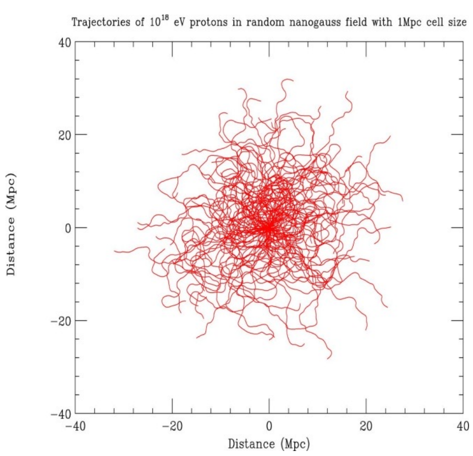
Main question: what is the origin and the role of the cosmic rays in the Universe ?



→ 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 ?

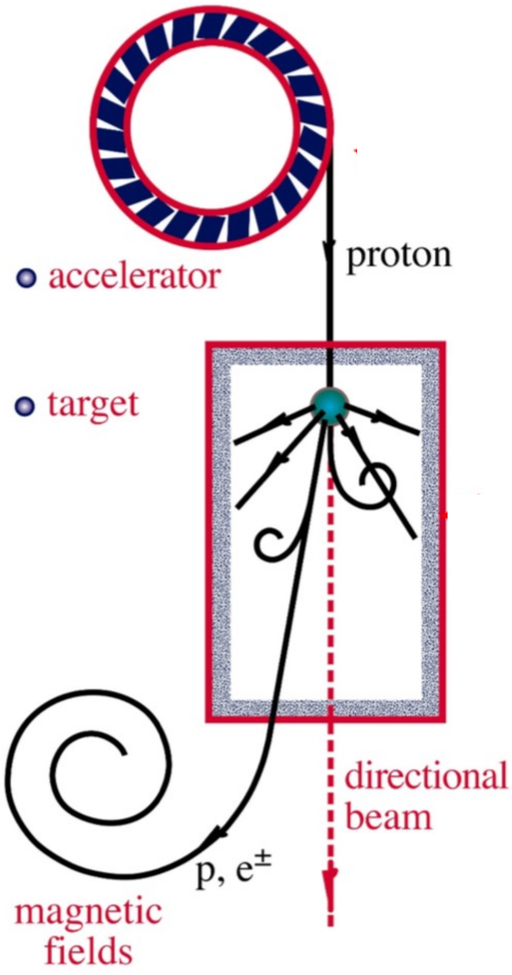
→ Connection to the other messengers (ν, γ, GW)
→ At the heart of the non-thermal astronomy

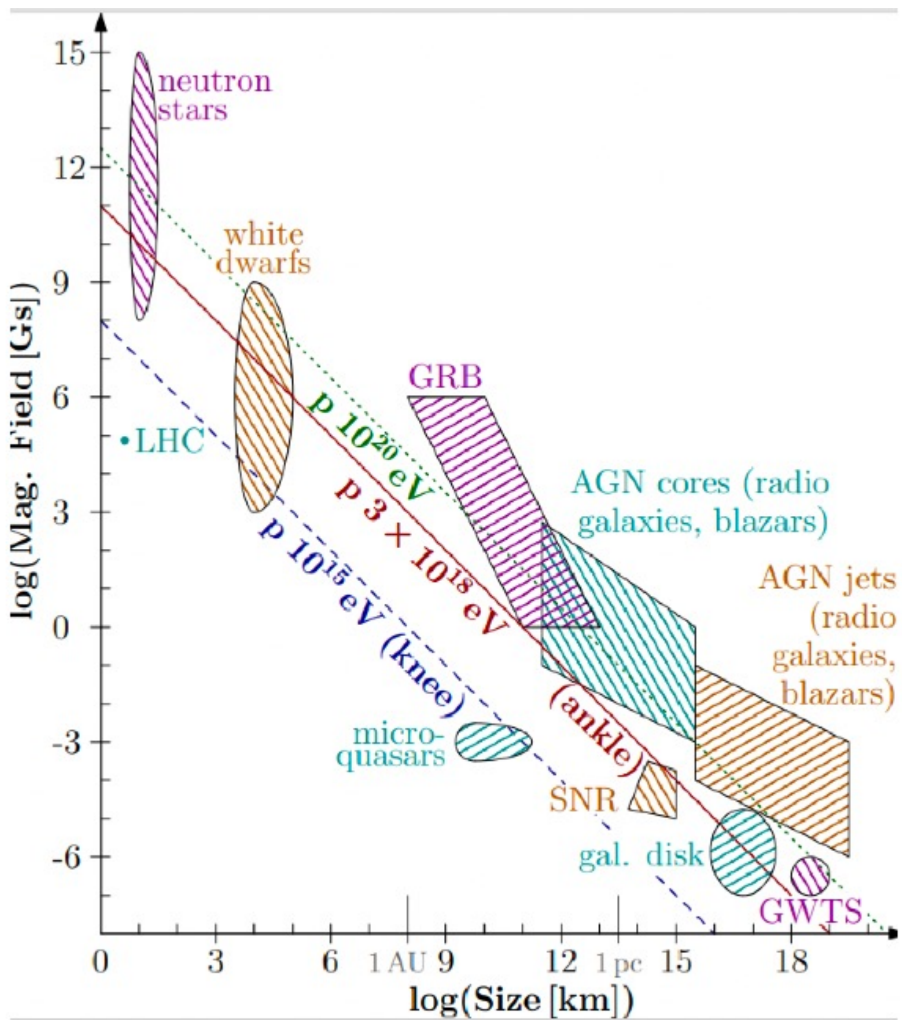


Charged protons scrambled due to magnetic fields

How to produce CRs and neutrinos

To produce neutrino ⟹ CR accelerator & target





The CR-gamma-neutrino connection

Multi-messenger connection (0th order)

Photo-hadronic interactions of CR

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

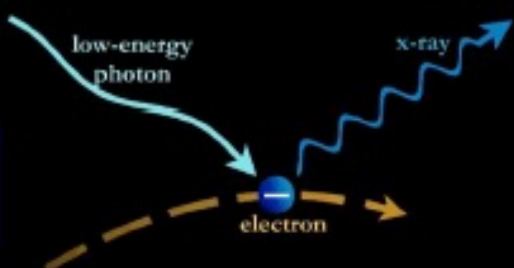
Neutrino emission

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

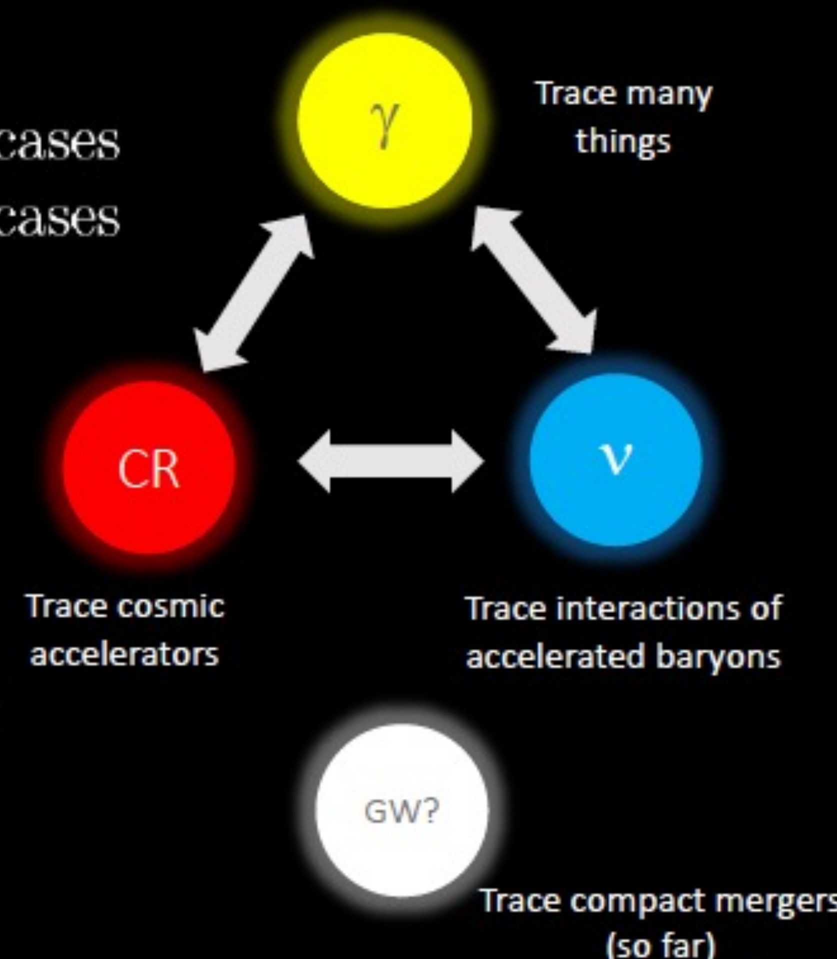
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Photon emission

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

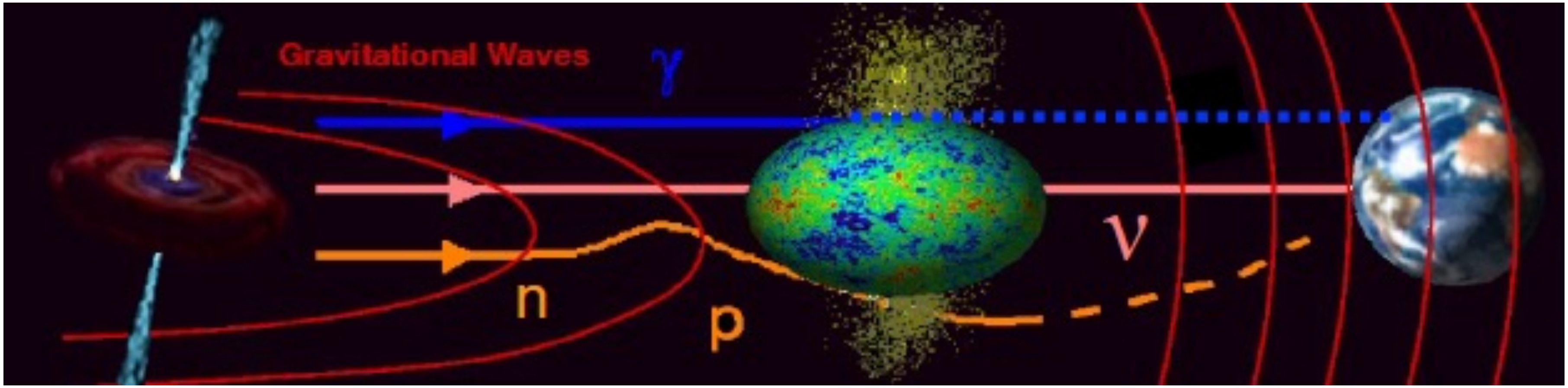


Most of the observed radiation is EM ☹



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

Neutrinos: cosmic messengers



Neutrinos: neutral, stable, weakly interacting

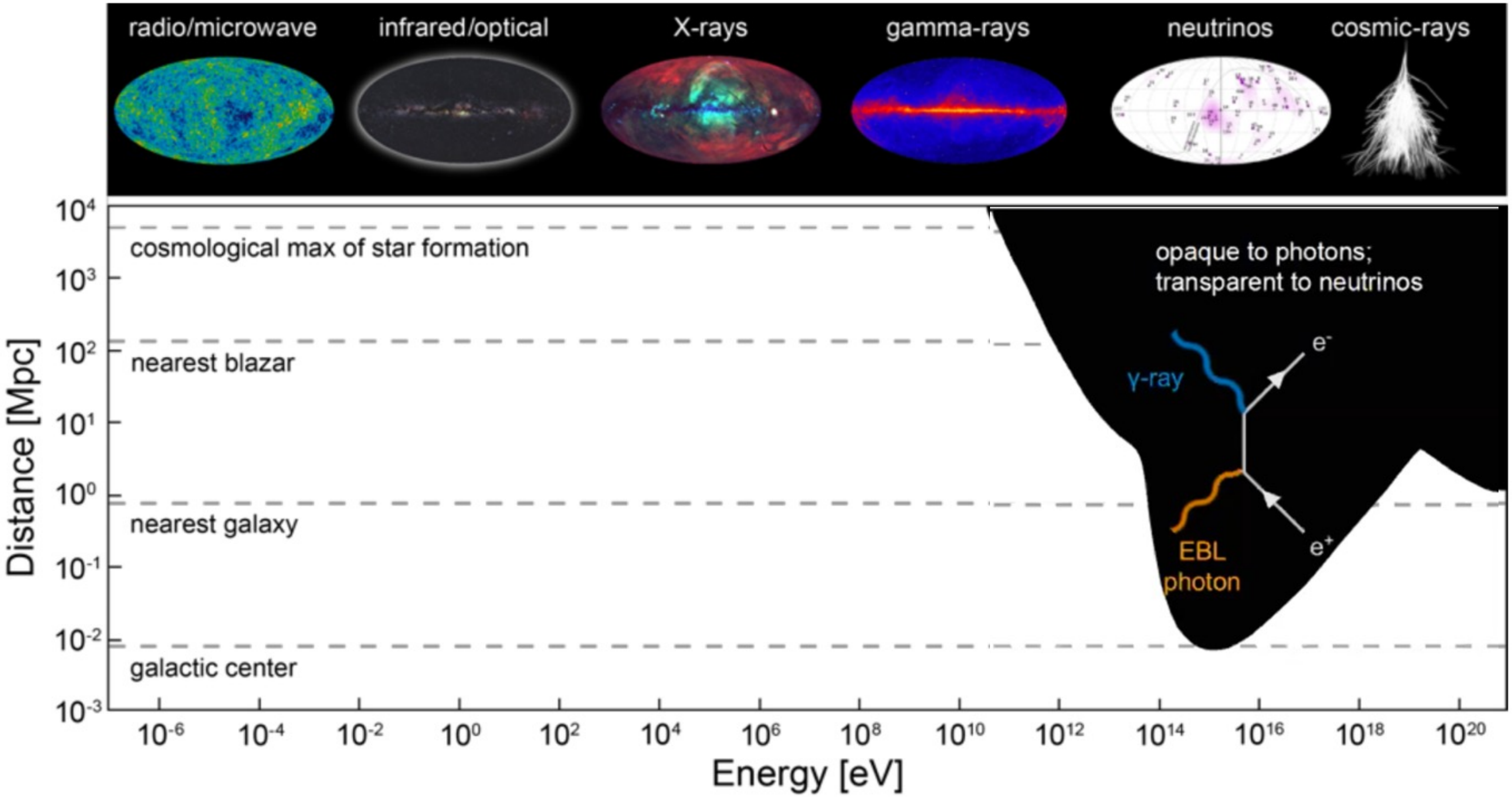
- not absorbed by background light/CMB ➔ access to cosmological distances
- not absorbed by matter ➔ access to dense environments
- not deviated by magnetic fields ➔ astronomy over full energy range

'Smoking gun' signature for hadronic processes

Correlated in time/direction with electromagnetic and gravitational waves

New window of observation on the Universe

A new window on the Universe

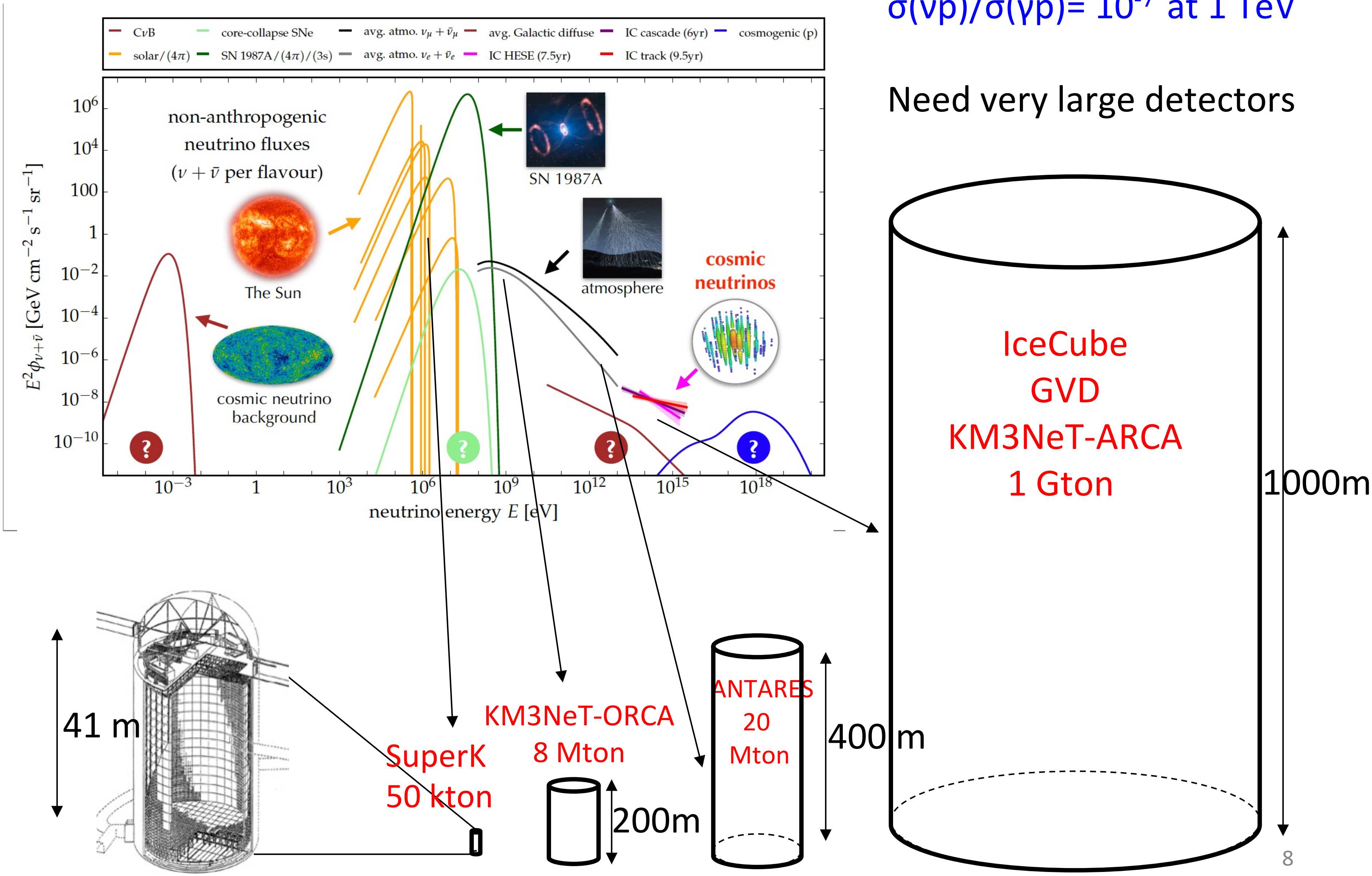


The Universe is opaque to EM radiation above 10-100 TeV, but not to neutrinos

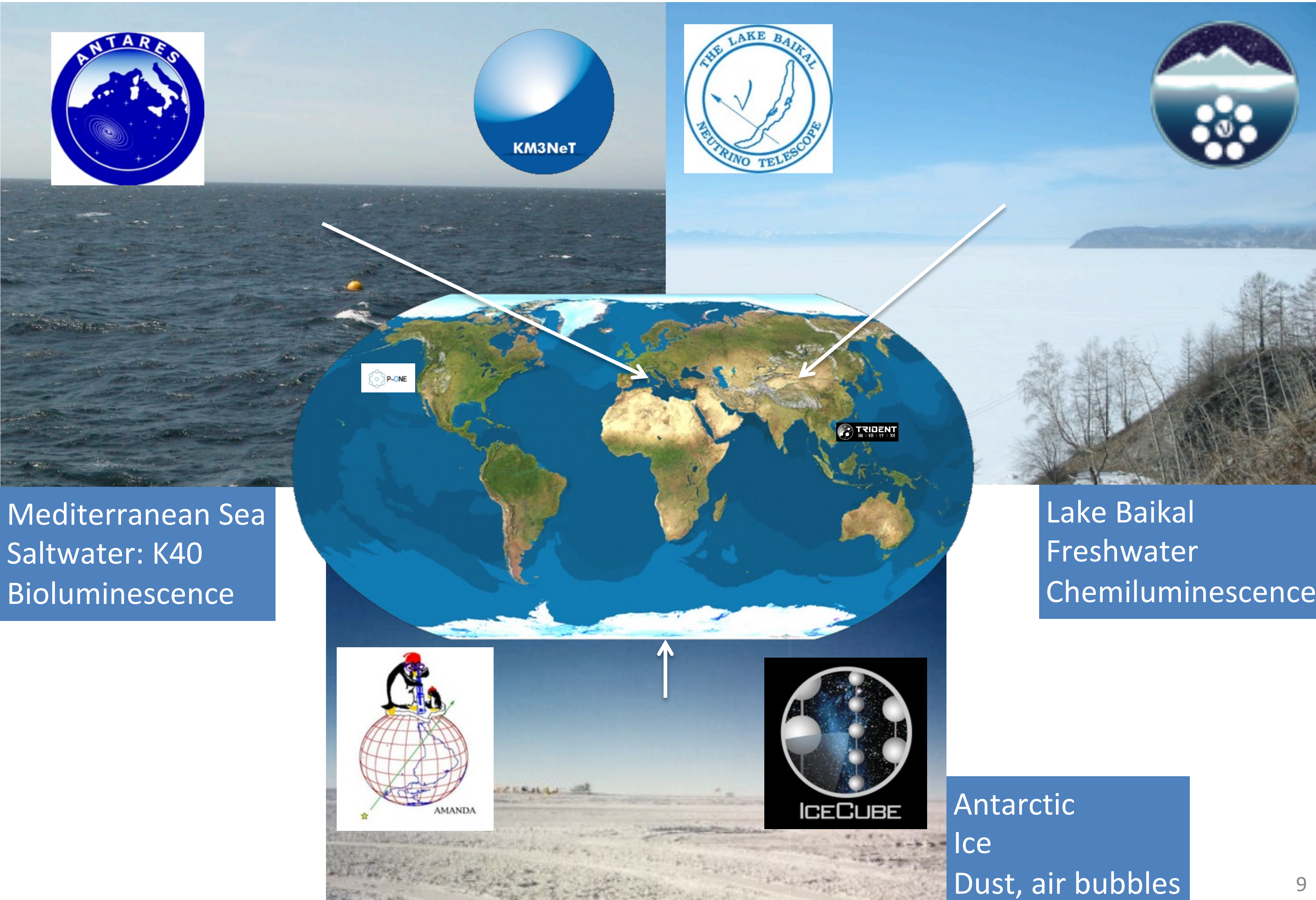
Neutrinos fluxes from MeV to PeV

σ(νp)/σ(γp)= 10^{-7} at 1 TeV

Need very large detectors



Very large volume neutrino telescopes



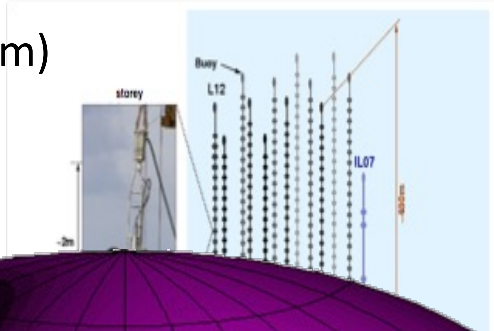
Mediterranean Sea
Saltwater: K40
Bioluminescence

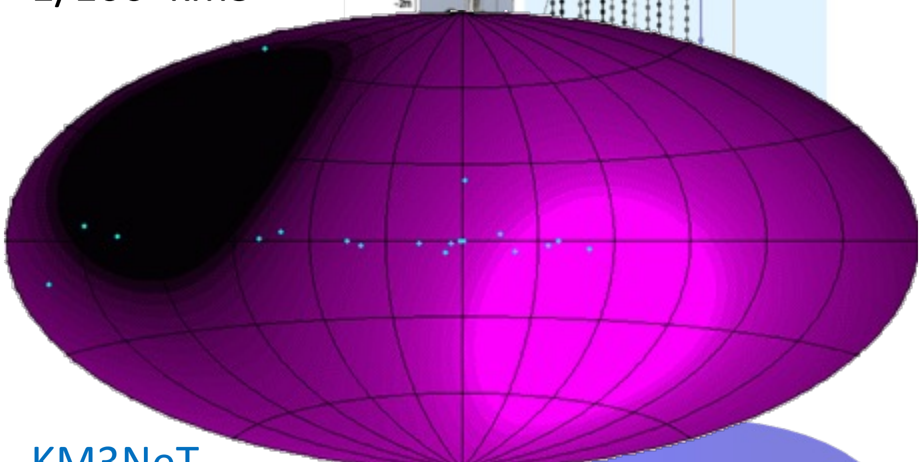
Lake Baikal
Freshwater
Chemiluminescence

Antarctic
Ice
Dust, air bubbles

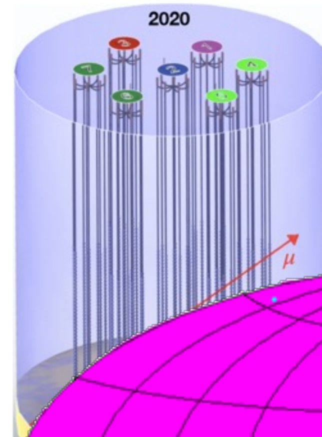
Current H20 (liquid+solid) neutrino telescopes

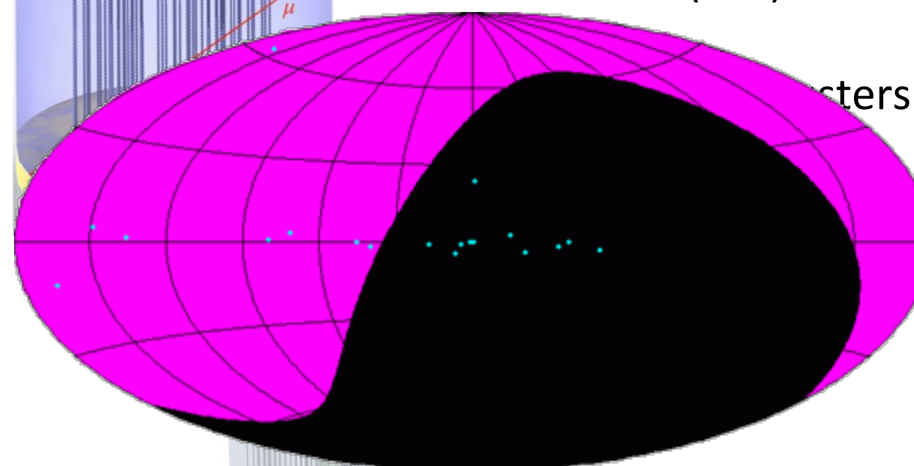
Antares
Med. Sea (-2.4km)
12 strings
885 PMTs (10“)
1/100 km3



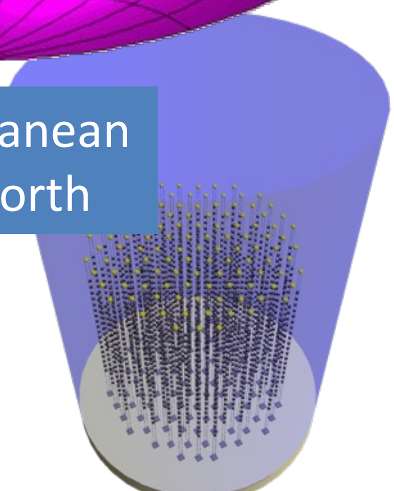


Baikal-GVD
Lake Baikal (-1.3km)
1 cluster =8 strings
0.5 km3 (14 clusters)
3168 PMTs (10”)
cters)



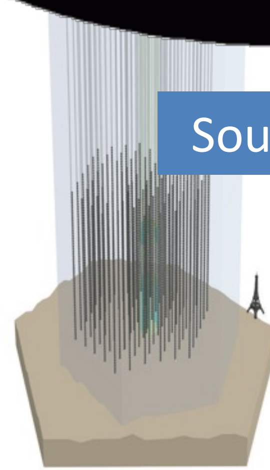


KM3NeT
Med. Sea (-2
3BB (345 stri
6000*31 PM
1.1 km3



Mediterranean
~ 43° North

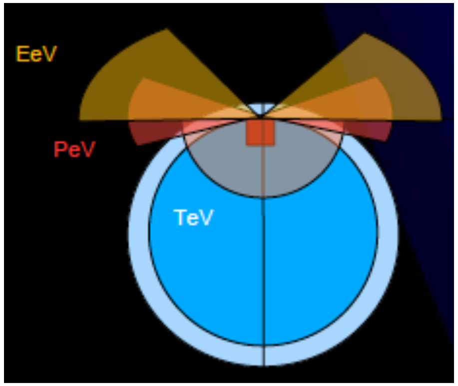
IceCube
th Pole (-2.4km)
86 strings
5160 PMTs (10”)
1 km3



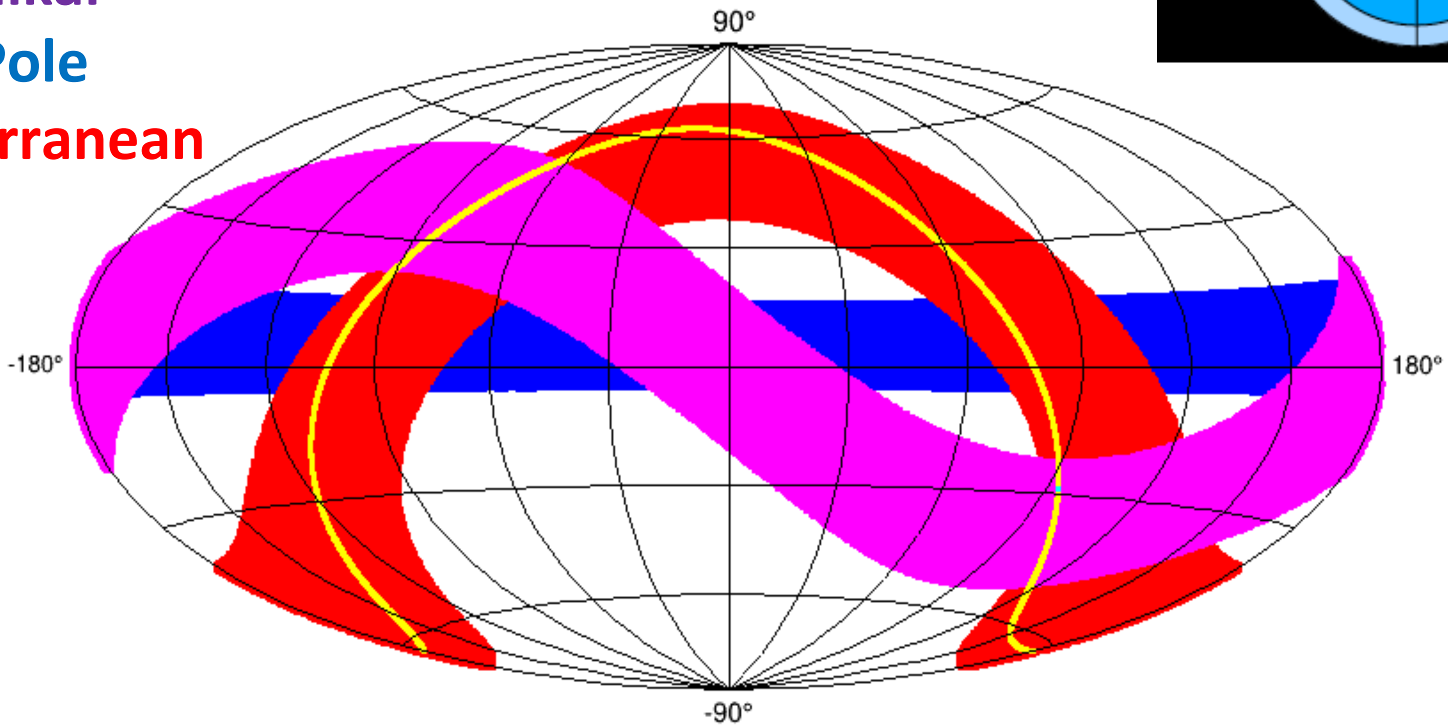
South Pole

Instantaneous PeV fields of view

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



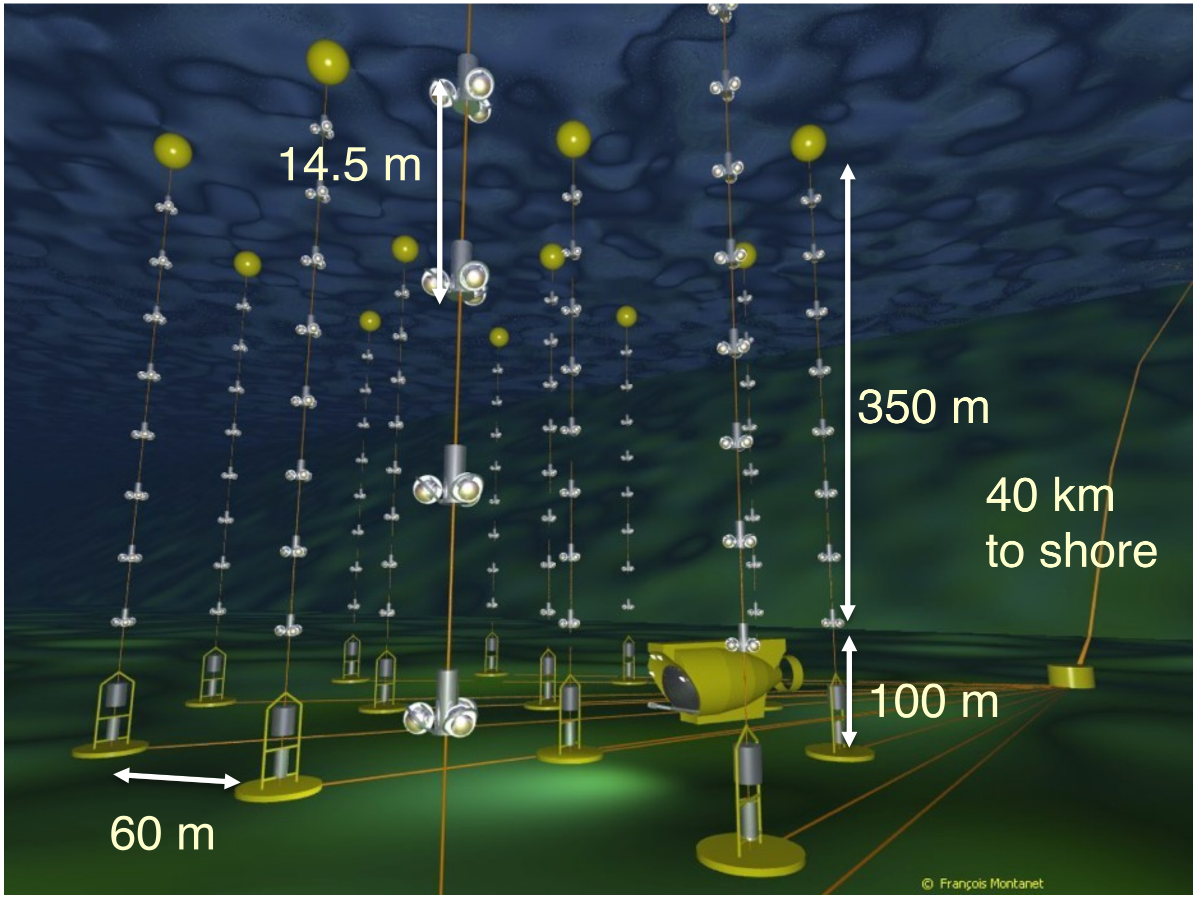
Lake Baikal
South Pole
Mediterranean



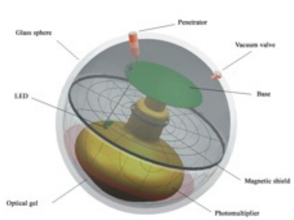
Instantaneous field of view with horizontal tracks

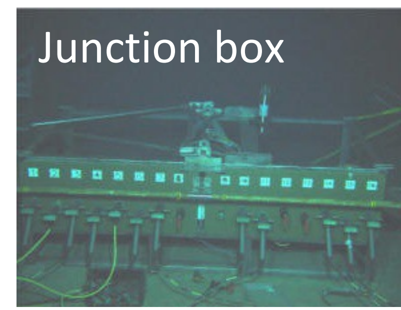
ANTARES Detector

(2008-2022)



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





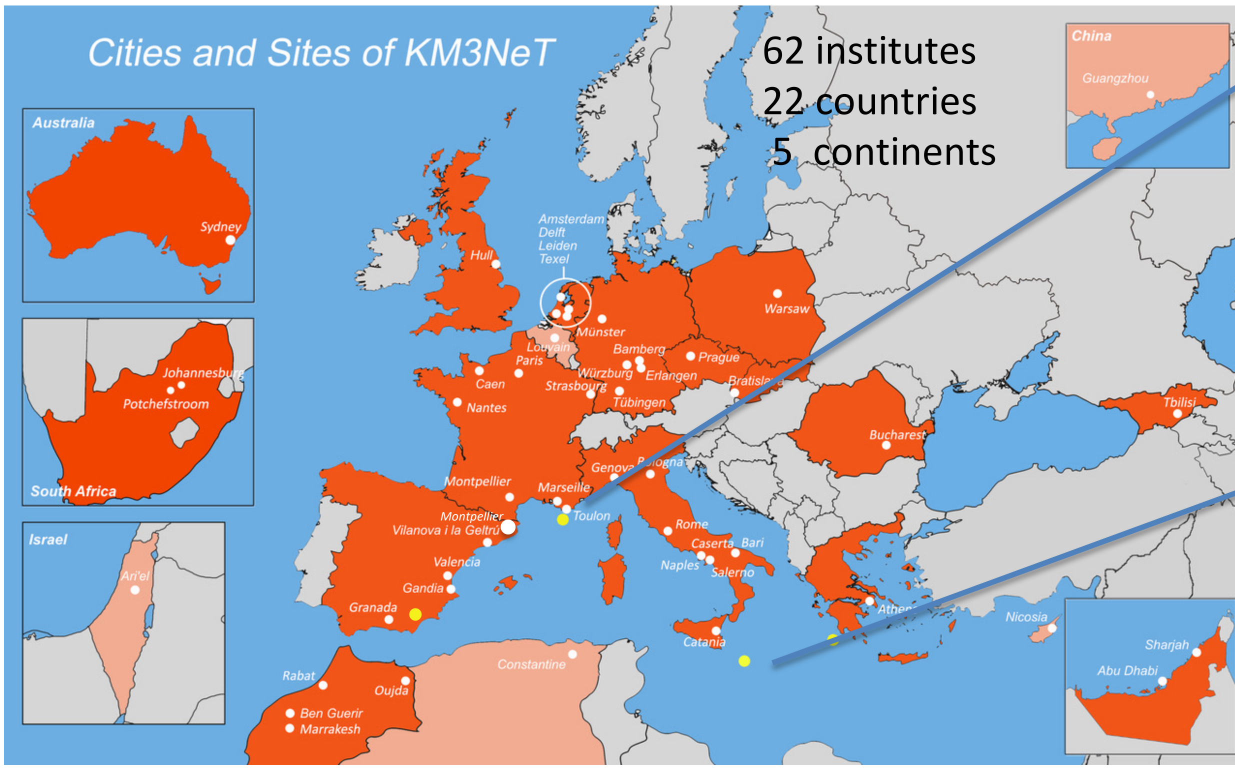
ANTARES Dismantling (feb/June 2022)

KM3NeT

Multi-site, deep-sea infrastructure

Single collaboration, single technology

Selected for ESFRI roadmap 2016



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

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

+ Harvard

[KM3NeT 2.0: Letter of Intent](http://dx.doi.org/10.1088/0954-3899/43/8/084001)

http://dx.doi.org/10.1088/0954-3899/43/8/084001

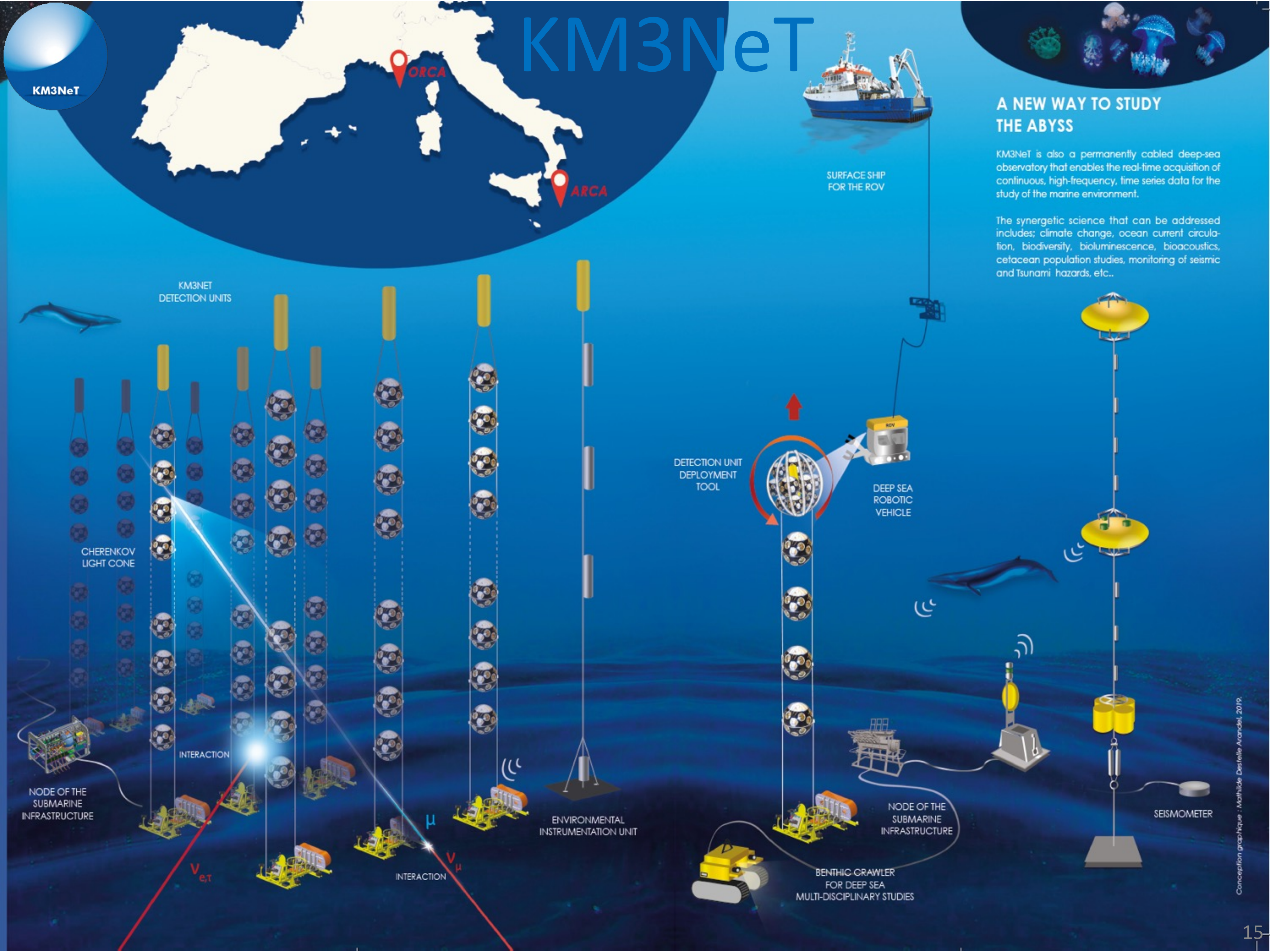
J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001

Connection nodes of

european multidisciplinary seafloor & water column observatory

emso

KM3NeT

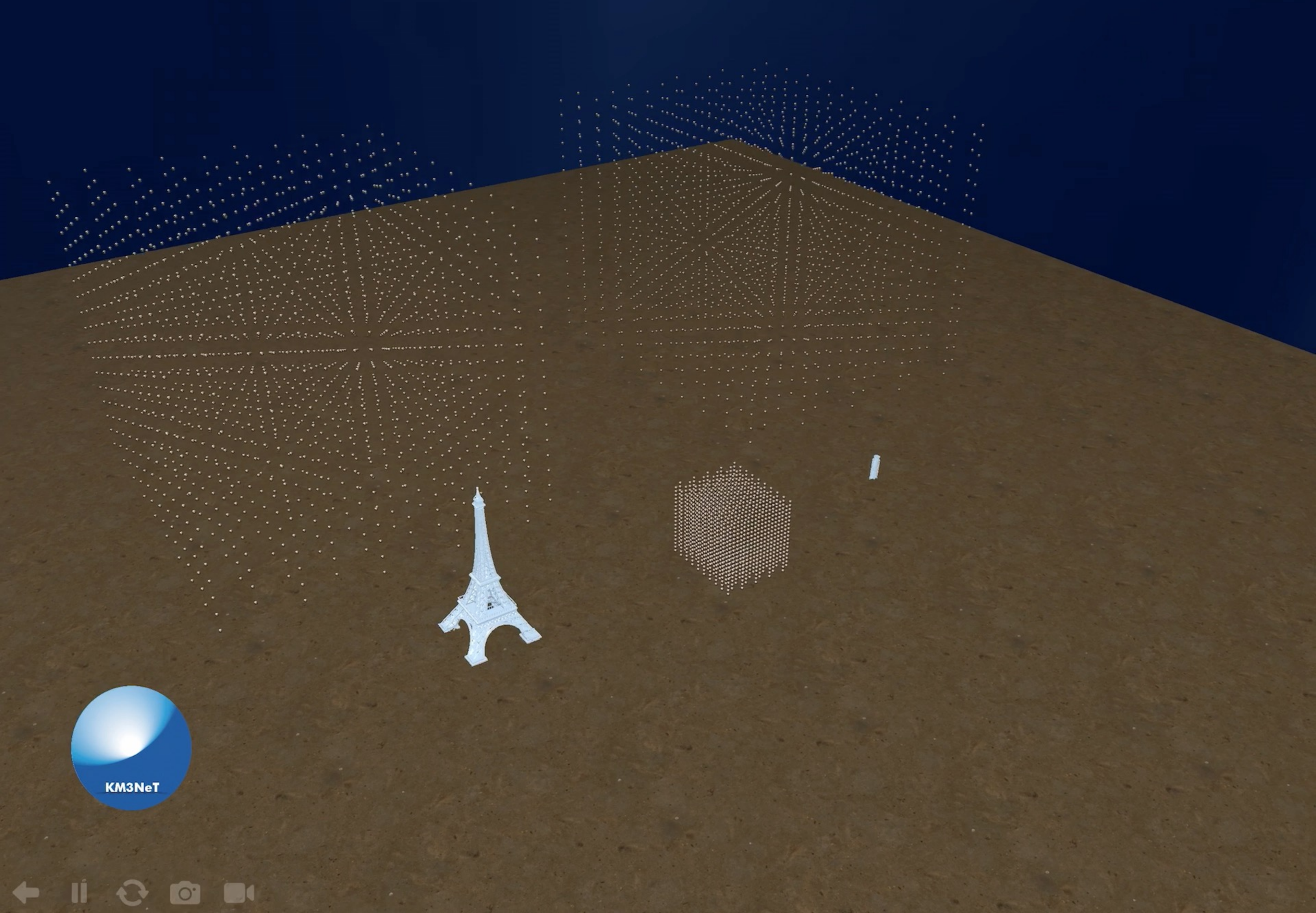


A NEW WAY TO STUDY THE ABYSS

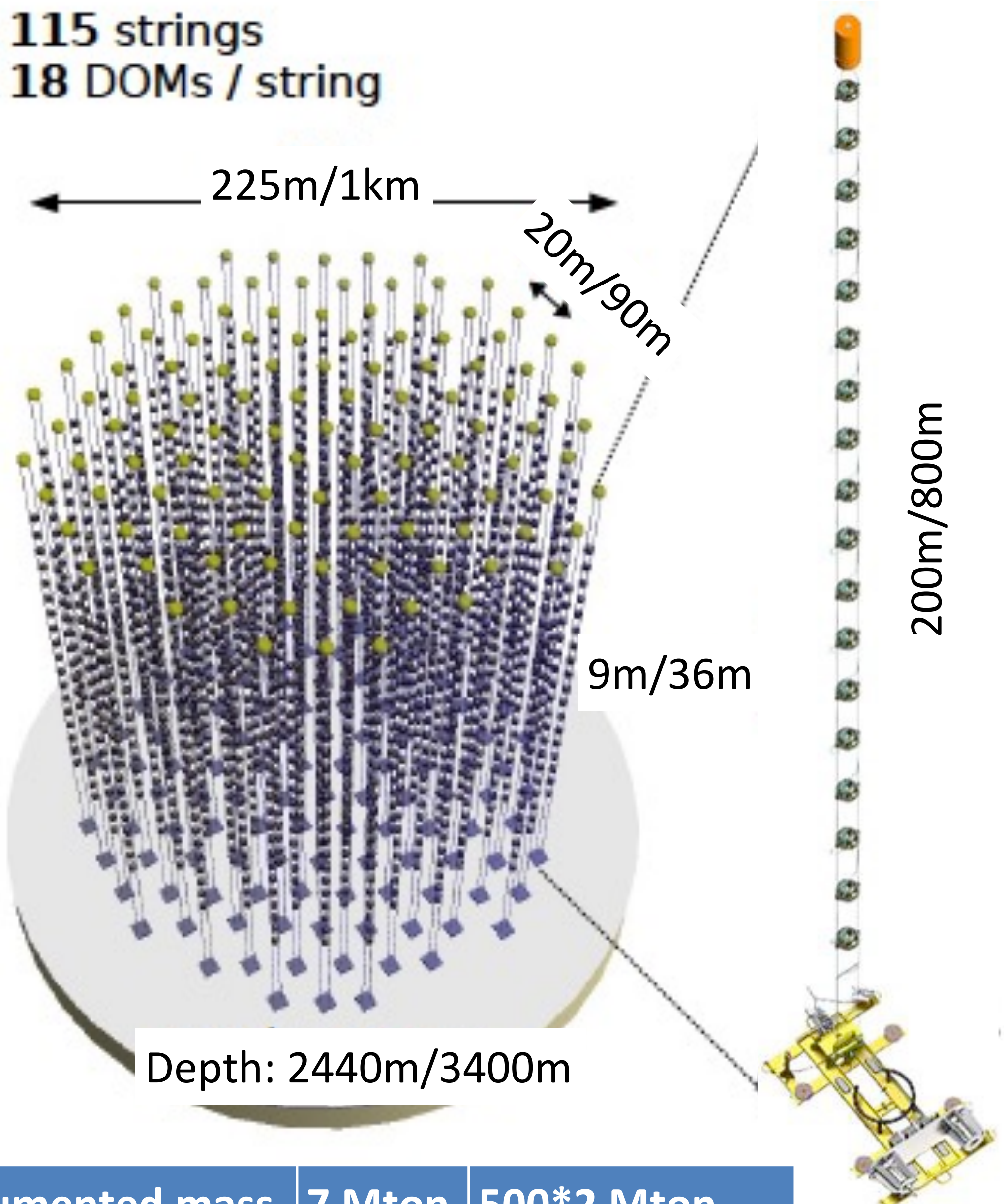
KM3NeT is also a permanently cabled deep-sea observatory that enables the real-time acquisition of continuous, high-frequency, time series data for the study of the marine environment.

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



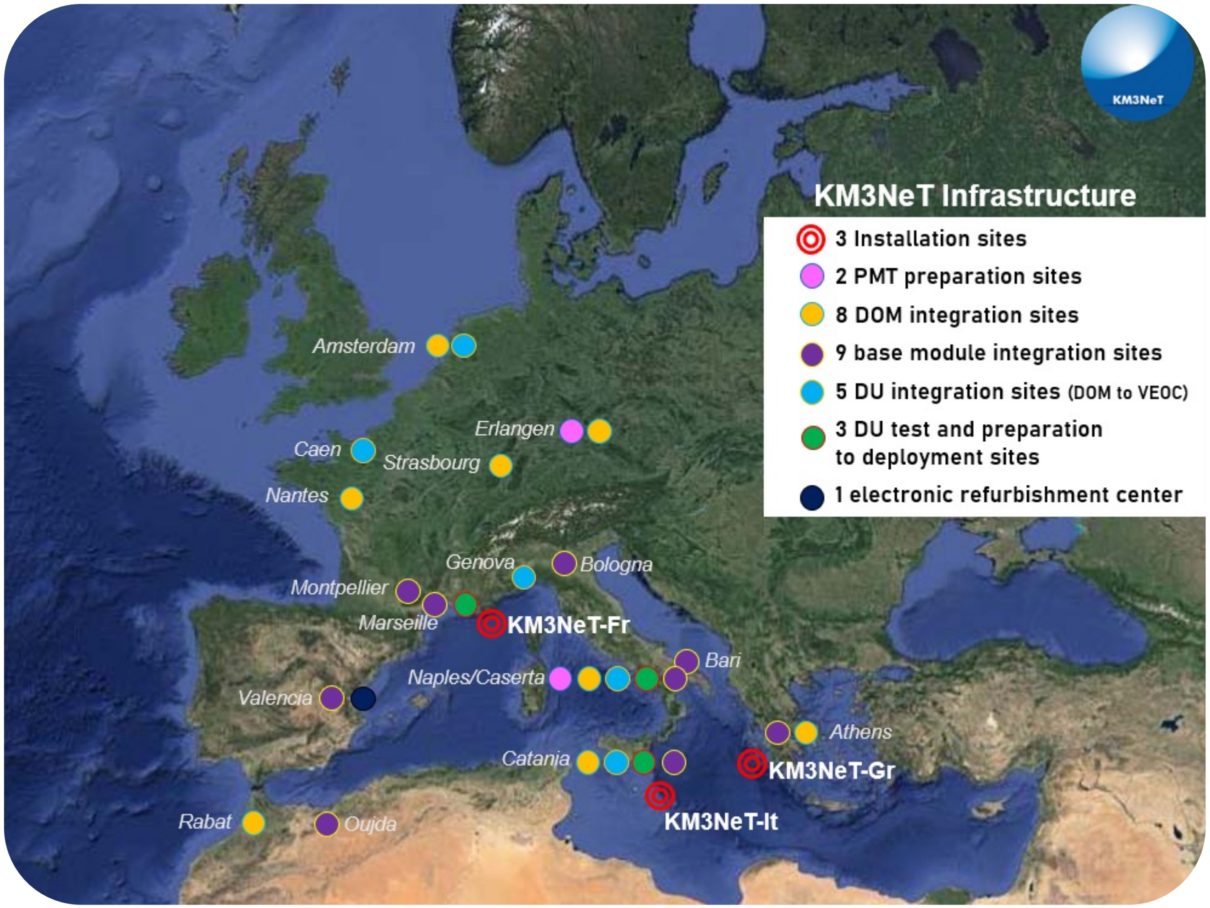
KM3NeT building block



- 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

Status of detector integration



DOMs

- 8 integration sites
- 1234 DOMs integrated
- 80 currently on bench

BMs

- 9 integration sites
- 66 BMs integrated
- 4 currently on bench

DUs

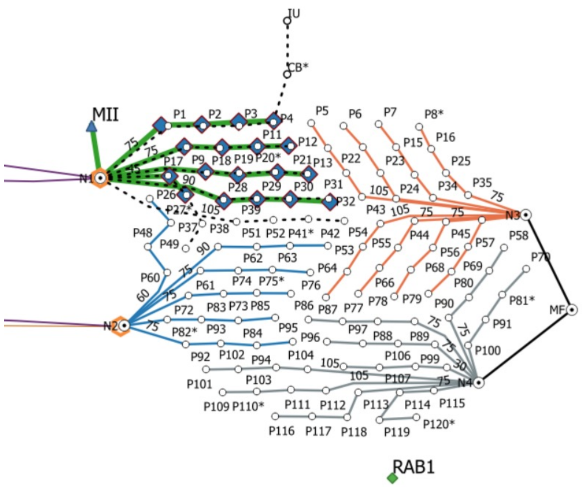
- 6 integration sites
- 56 DUs integrated
- 46 deployed

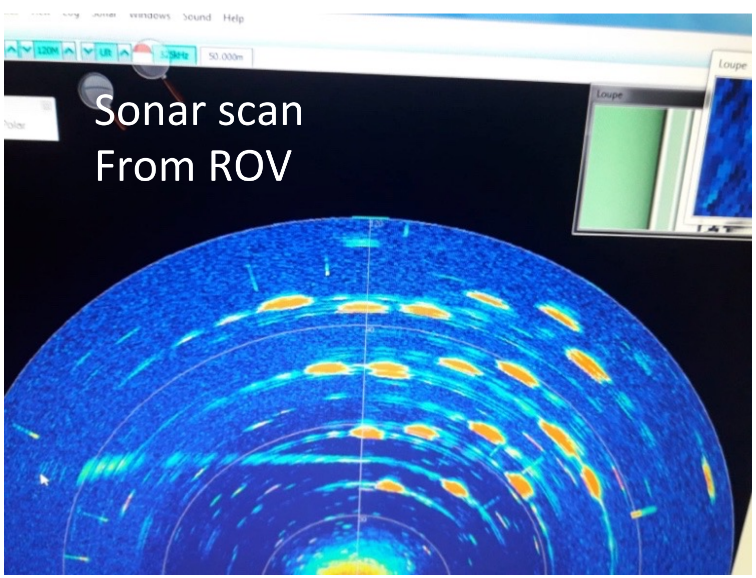
Detector Construction

KM3NeT Detector Unit deployment

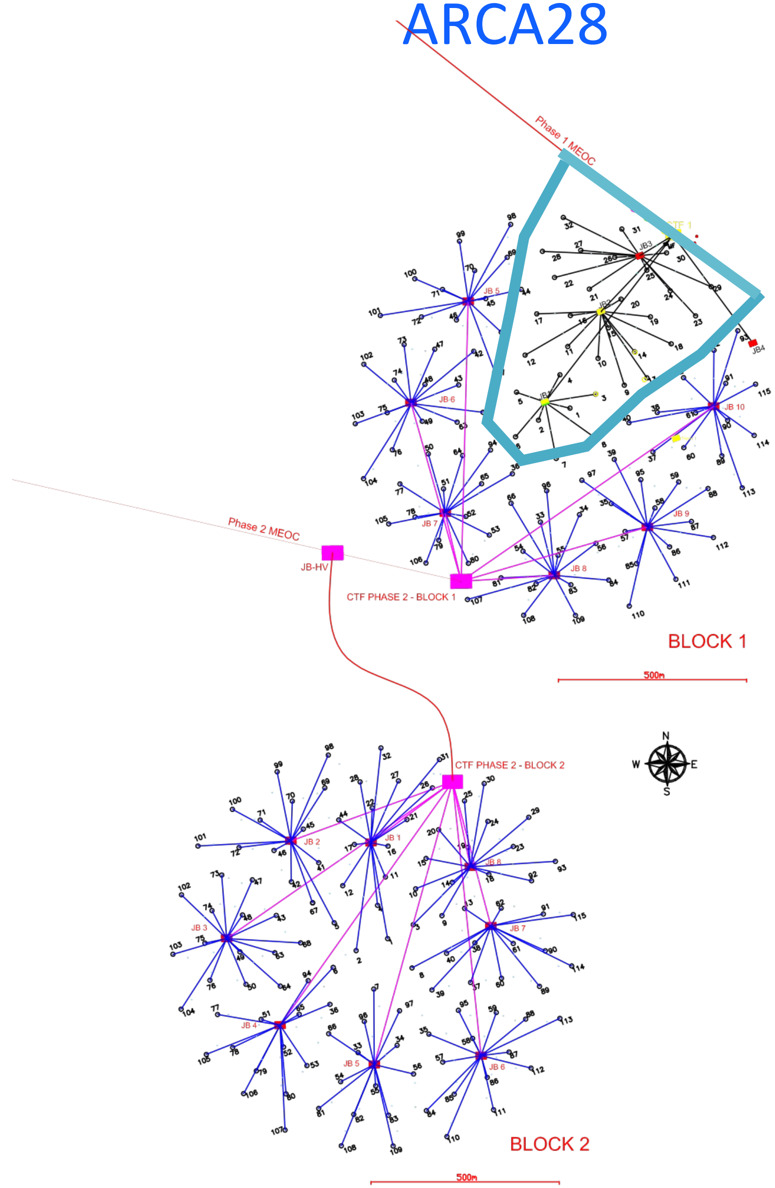
Current Status: 46 DUs deployed

ORCA18



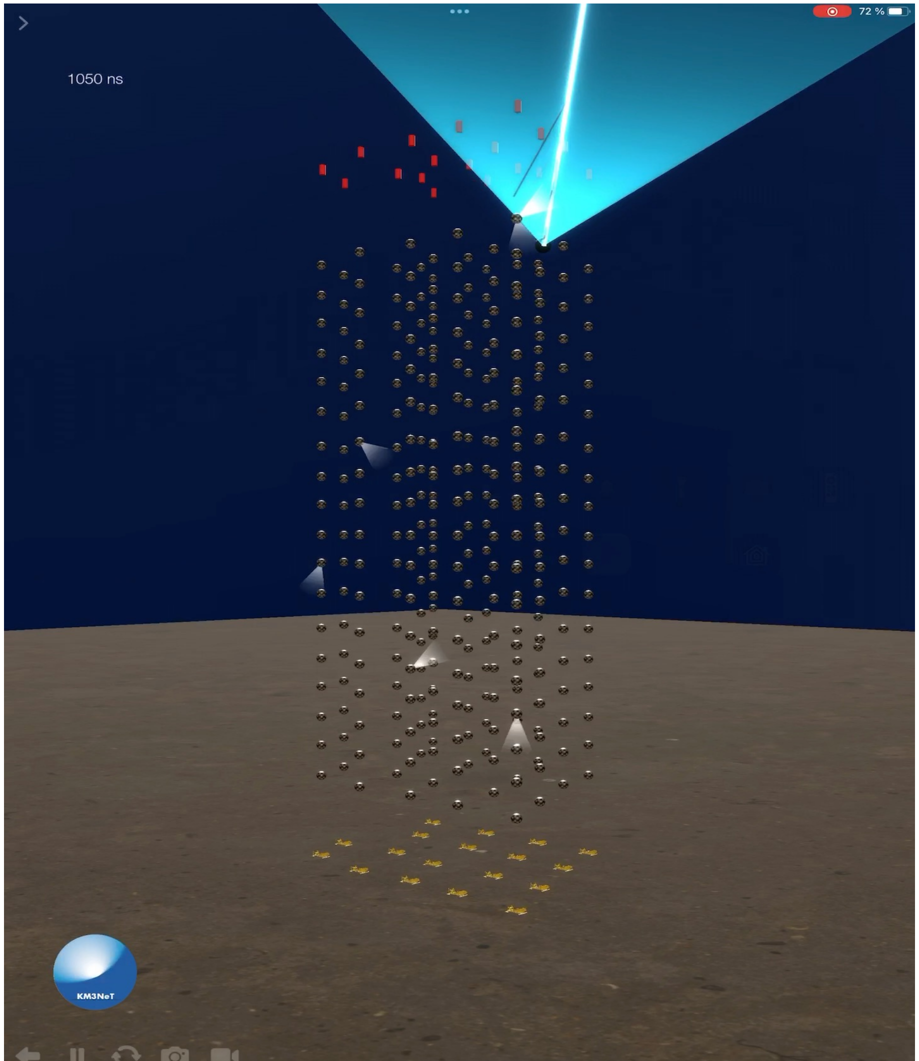


ARCA28

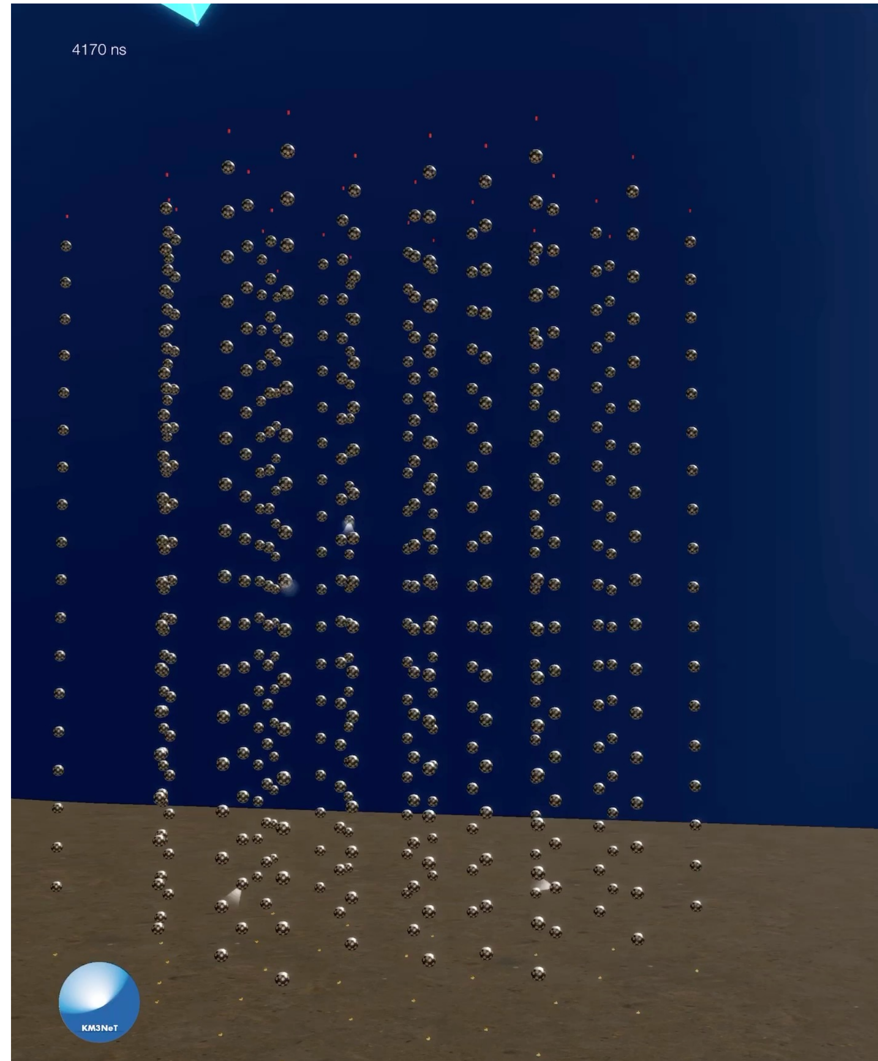


KM3NeT Event display

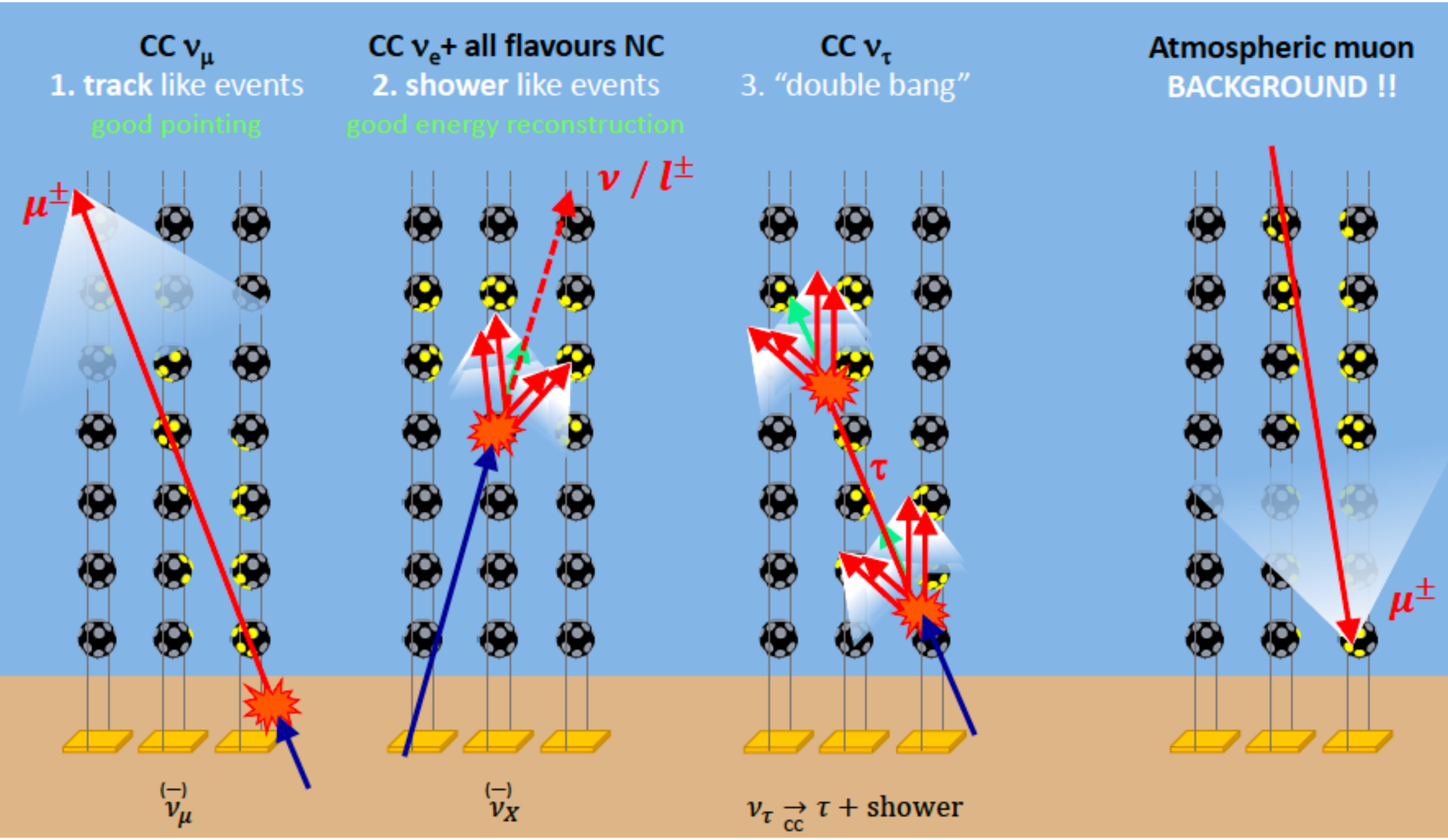
ORCA18



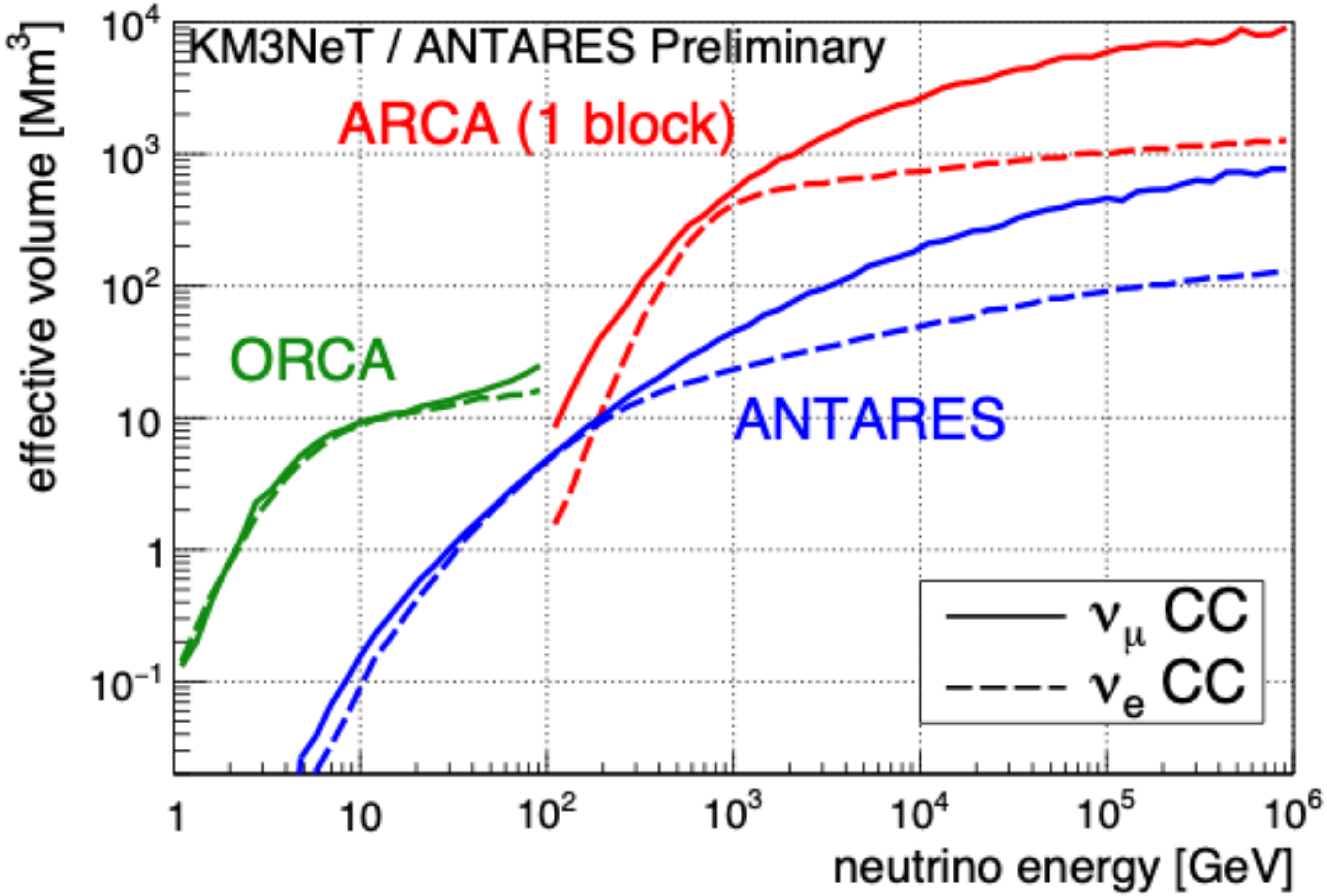
ARCA28



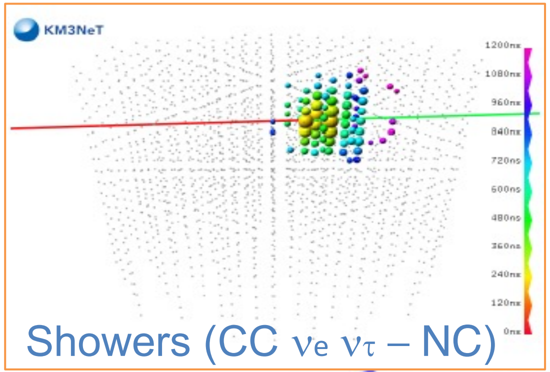
Event Topologies

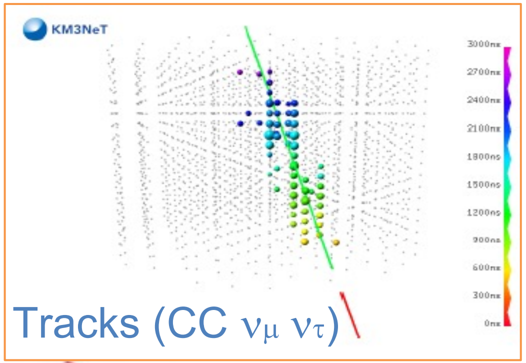


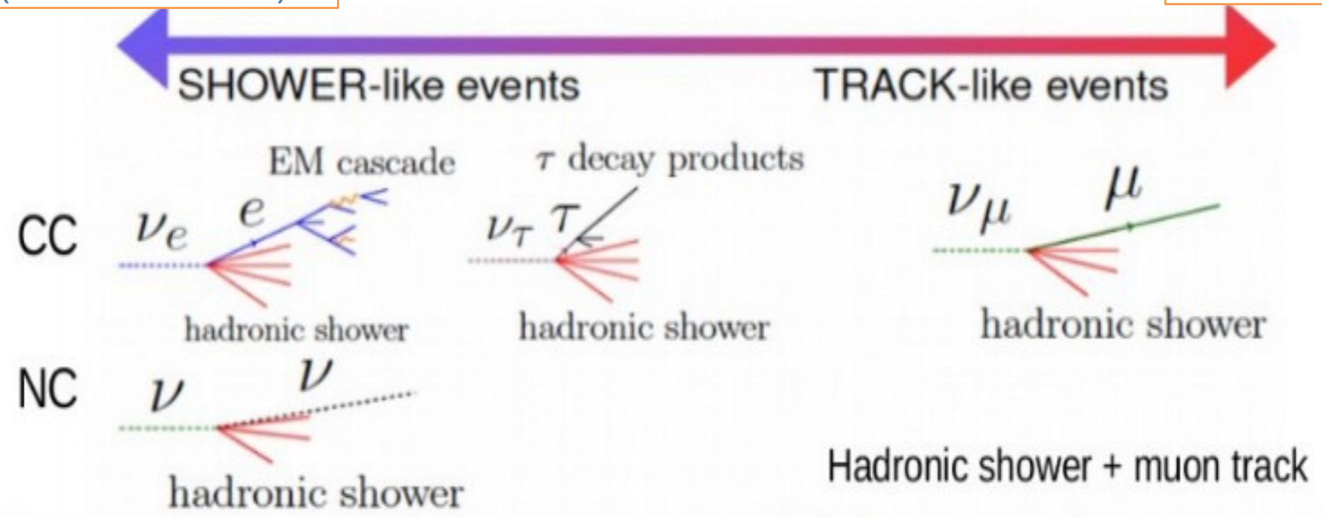
Effective areas: KM3NeT vs ANTARES



Resolutions







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

Energy resolution ~ 5%

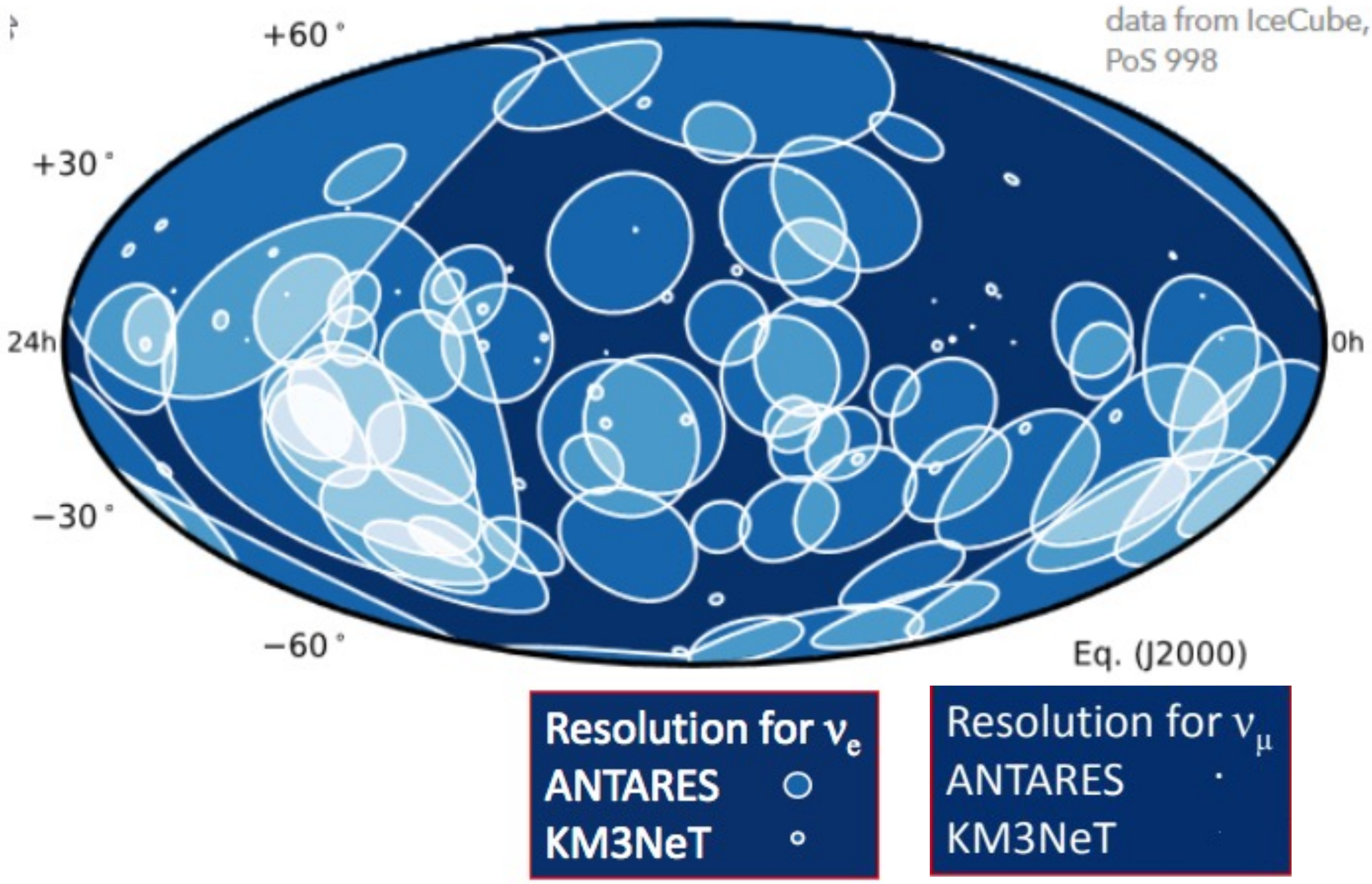
Angular resolution 0.5°/0.1° at 100 TeV for Ice/water

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

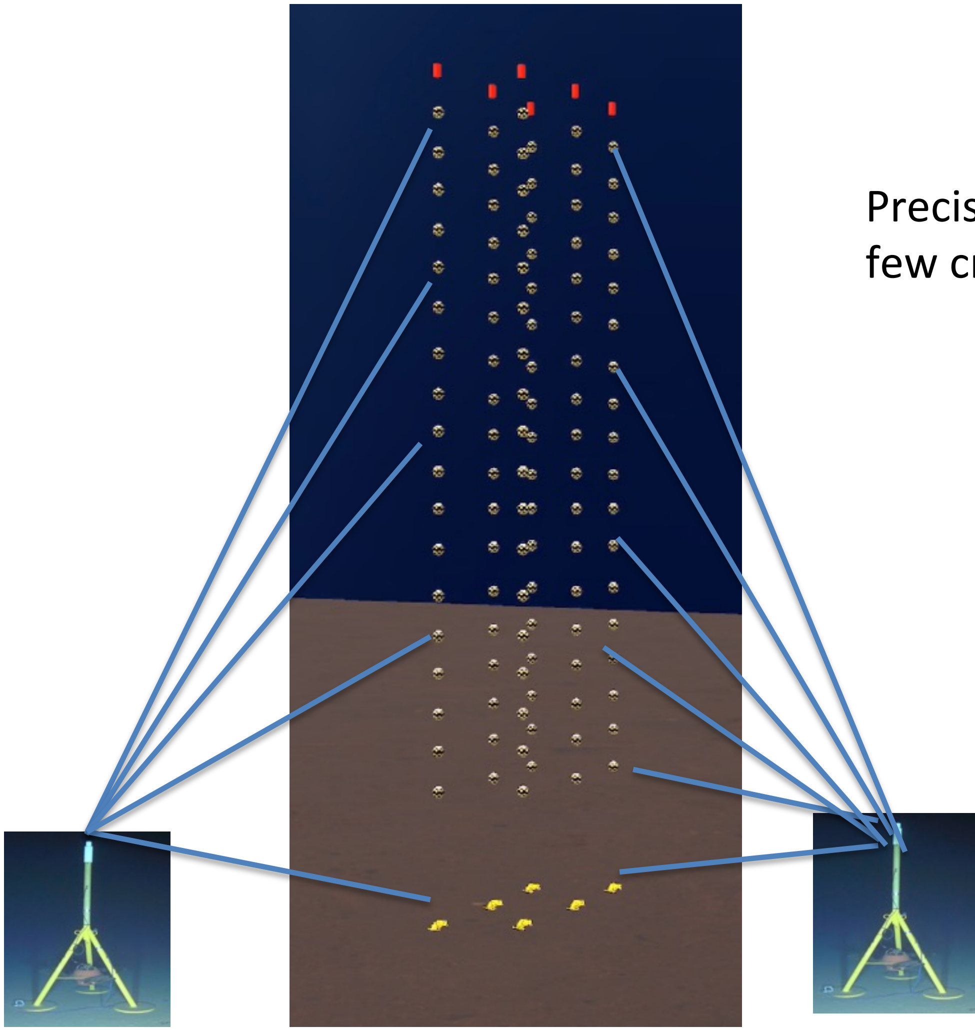
Precision multi-flavour astronomy with water based telescopes

Resolutions: IceCube vs KM3NeT

Old IceCube skymap

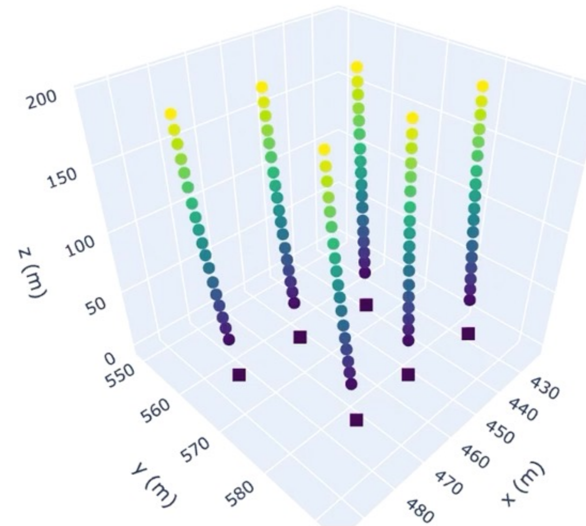


Acoustic position calibration in KM3NeT

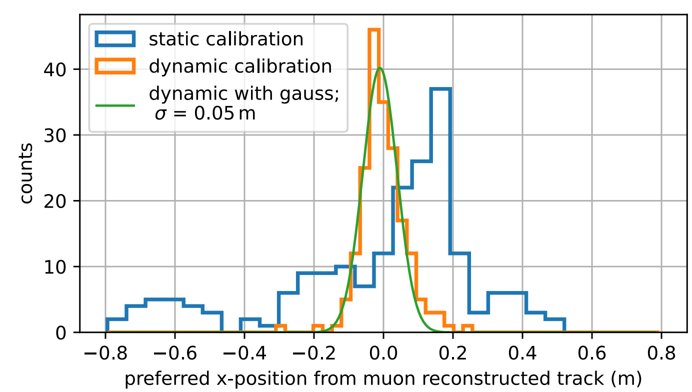


Precision
few cm

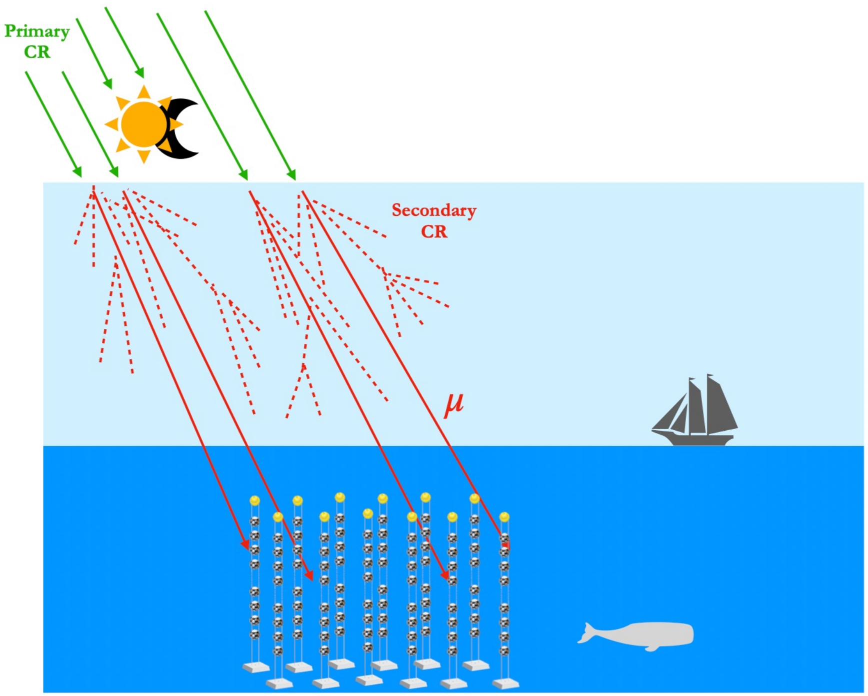
Animation of DU movement

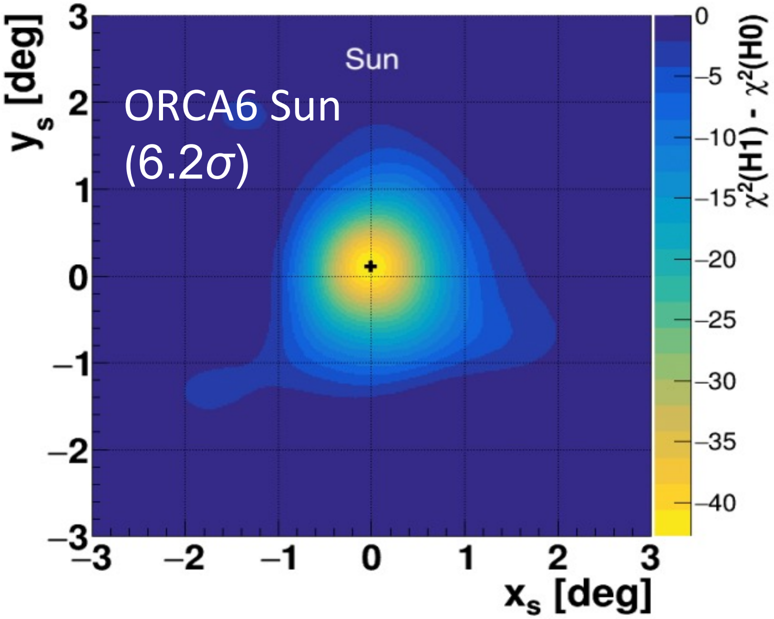


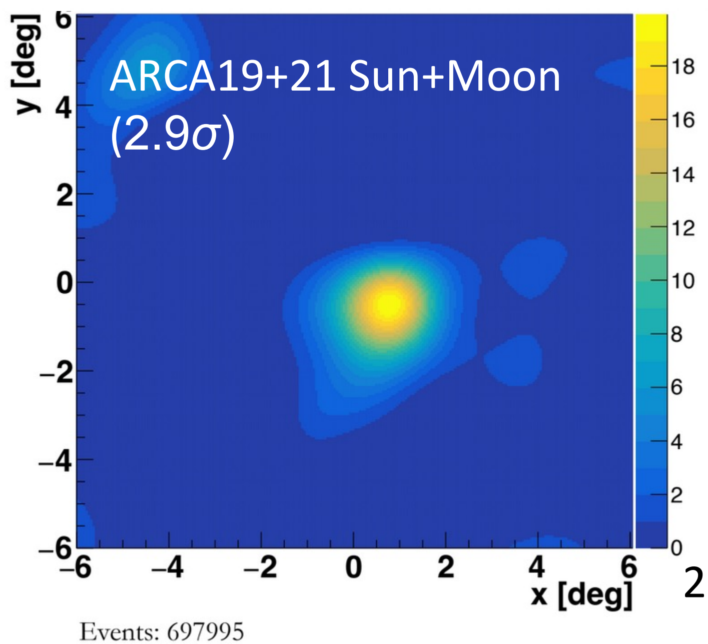
Use of dynamic positions, verified by muon calibration



Absolute pointing calibration with Moon/Sun Shadow







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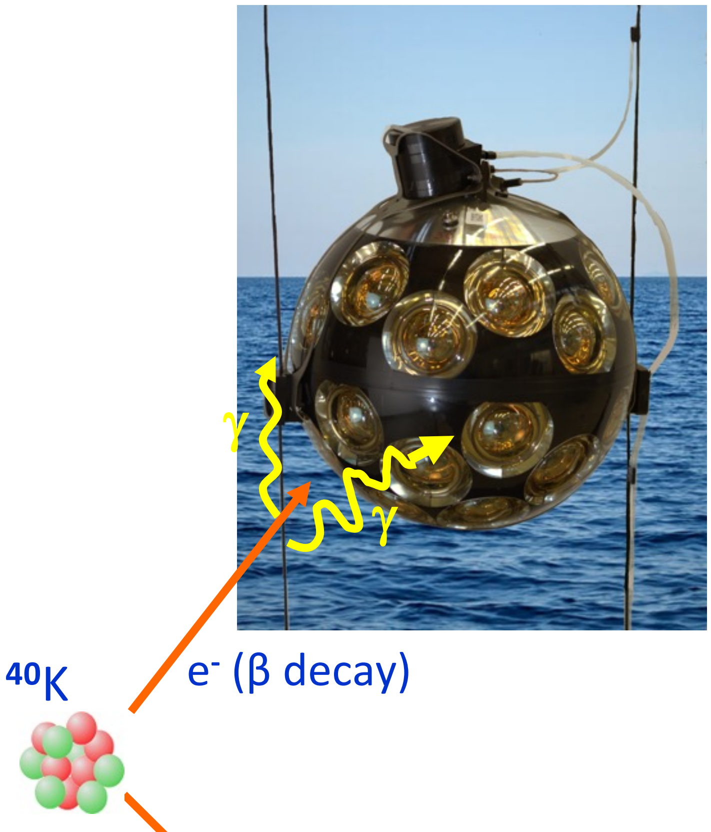
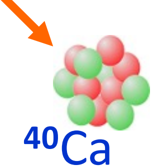
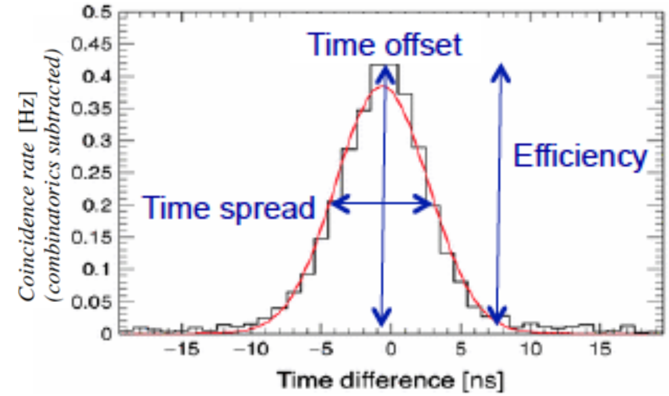
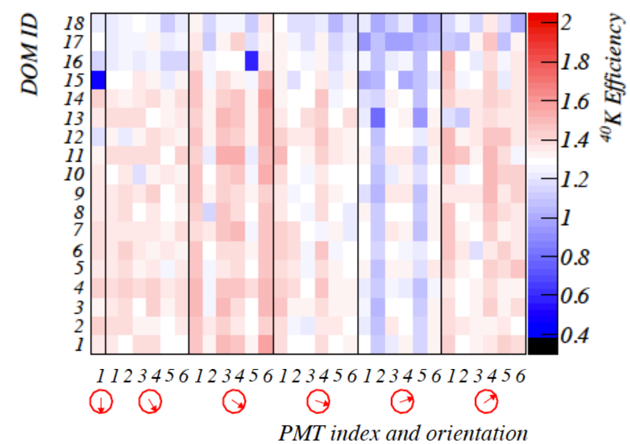
PMT efficiencies: ^{40}K

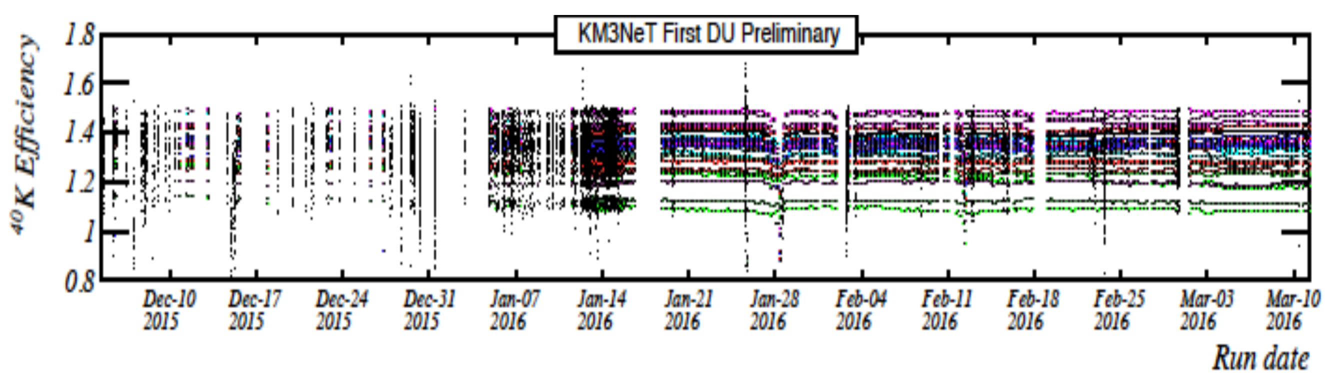




Up to 150 Cherenkov photons per decay; stable ^{40}K concentration



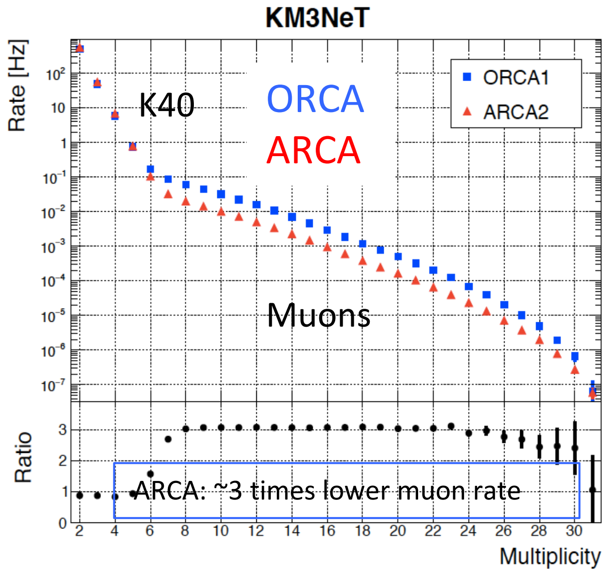


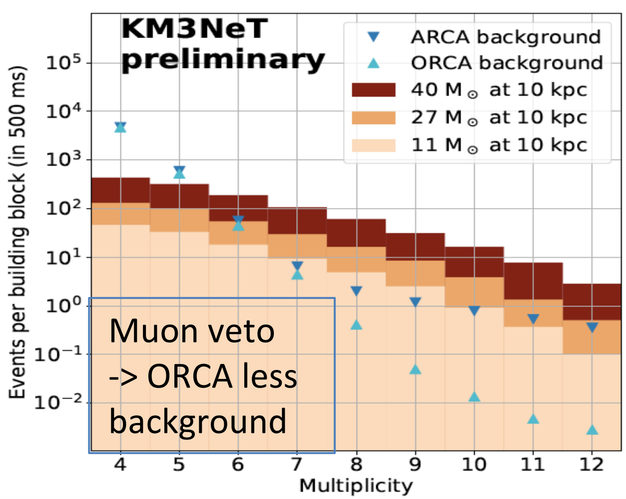


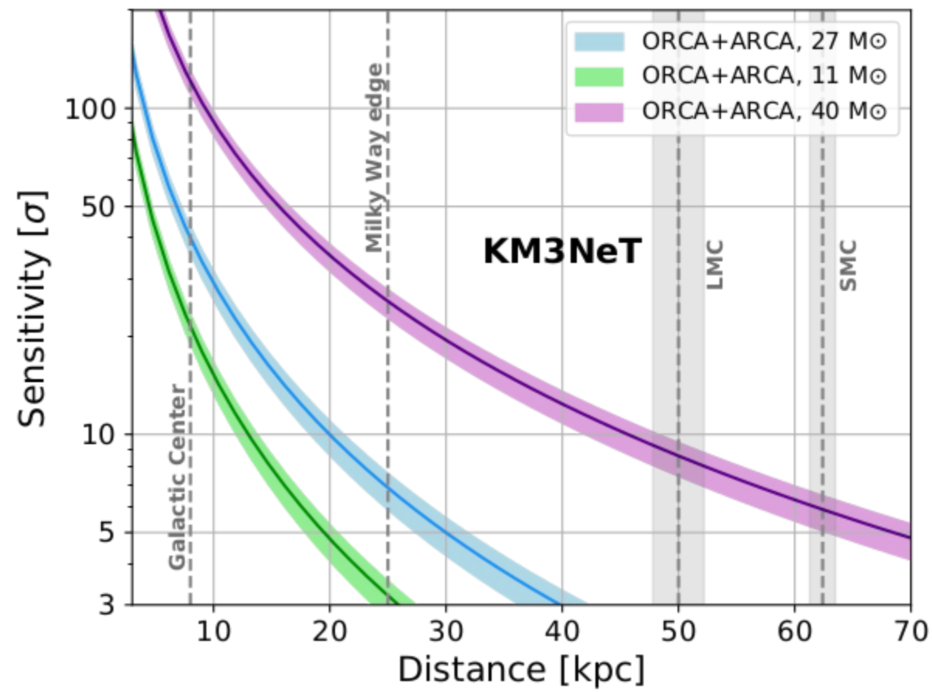
Supernova monitoring in KM3NeT

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

Eur. Phys. J. C81 (2021) 445





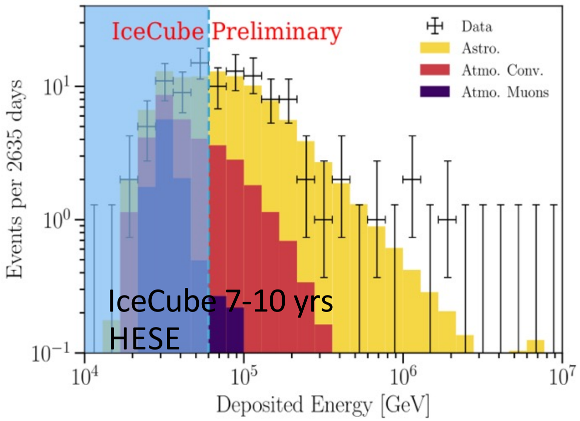


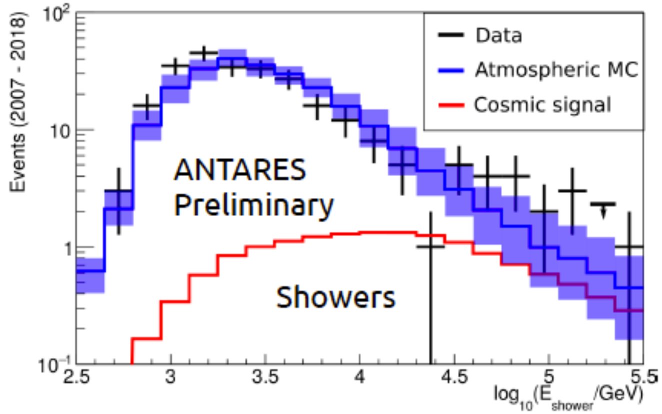
Discovery potential for 95% of Galactic CCSNe

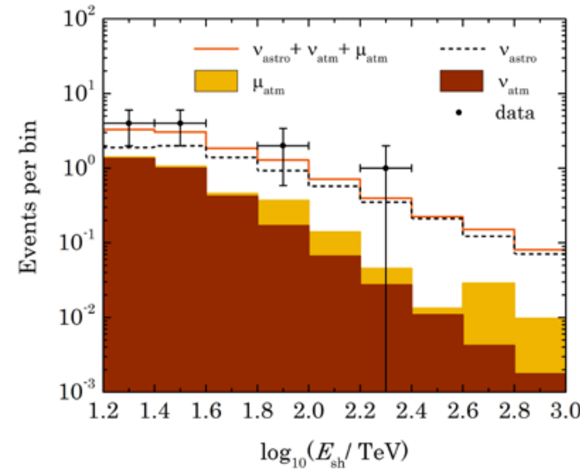
ARCA6+ORCA6 already sensitive to 60% of Galactic CCSNe (<11 kpc)

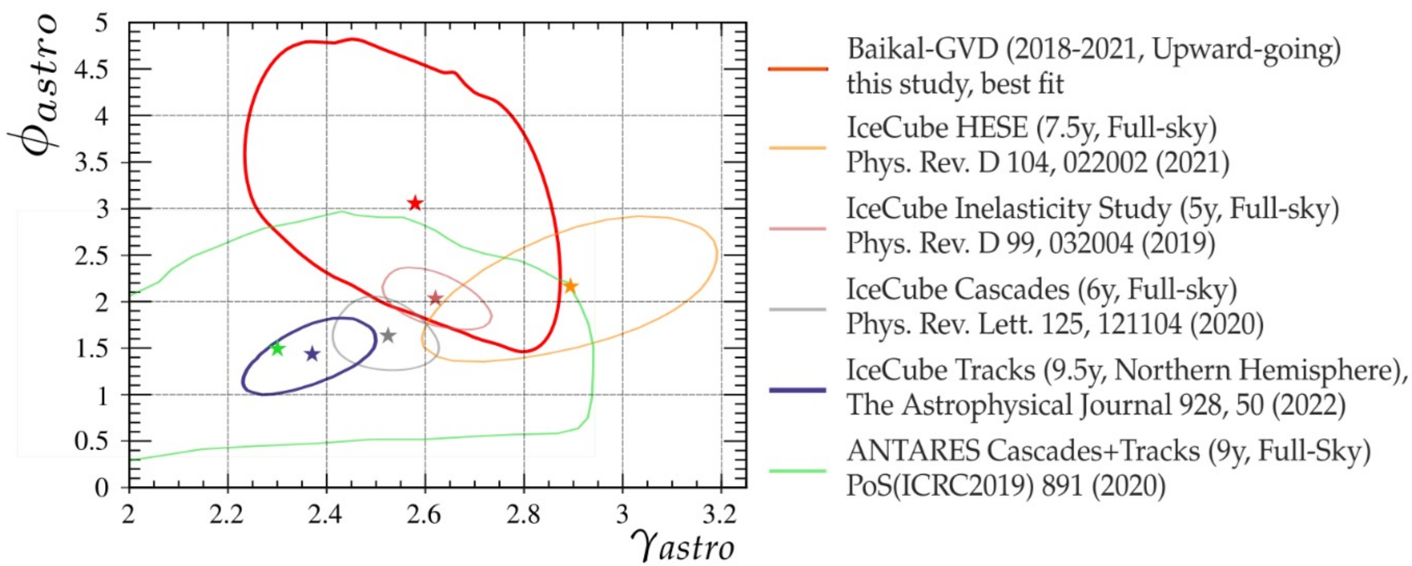
Joint real time trigger operational for SNEWS since early 2019

Measurements of the diffuse neutrino flux ν_e





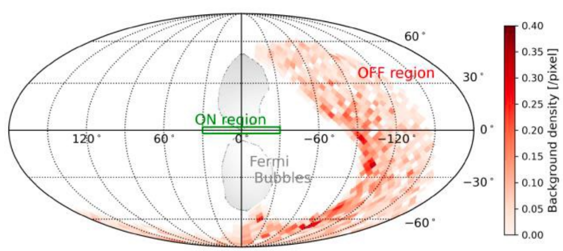




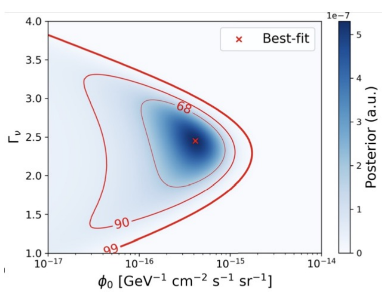
Diffuse from Galactic Plane

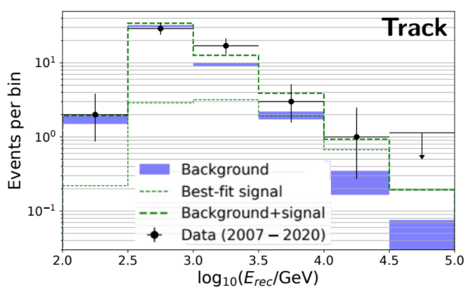
ANTARES 2007-2020 data Phys. Lett. B 841 (2023), p. 137951

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

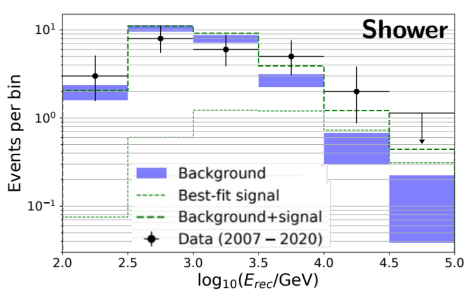


ICRC2023 PoS 1103





(a) Track-like events



(b) Showering-like events

For E_ν>1 TeV

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

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

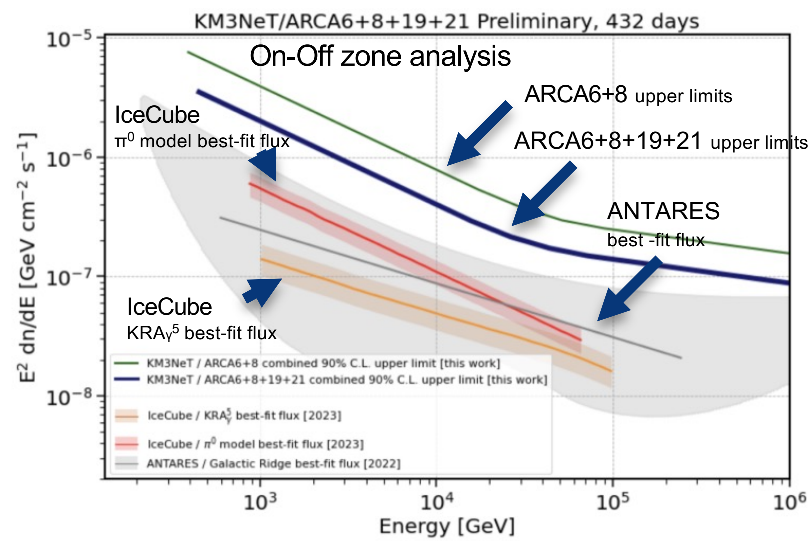
KM3NeT ICRC2023 PoS 1190

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

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

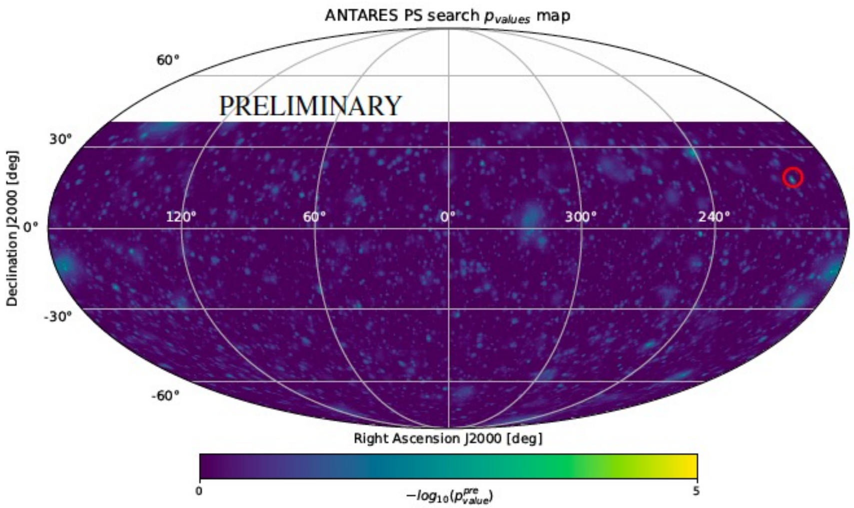
ARCA6 & ARCA8 & ARCA19 fully analyzed

ARCA21 partially analyzed (until December 2022)

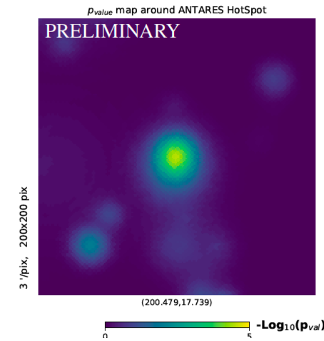


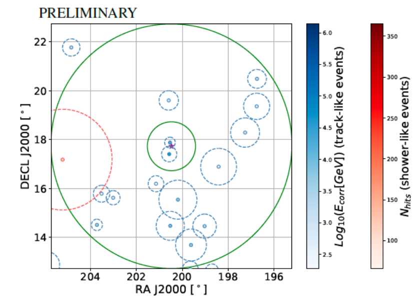
Neutrino Sources?

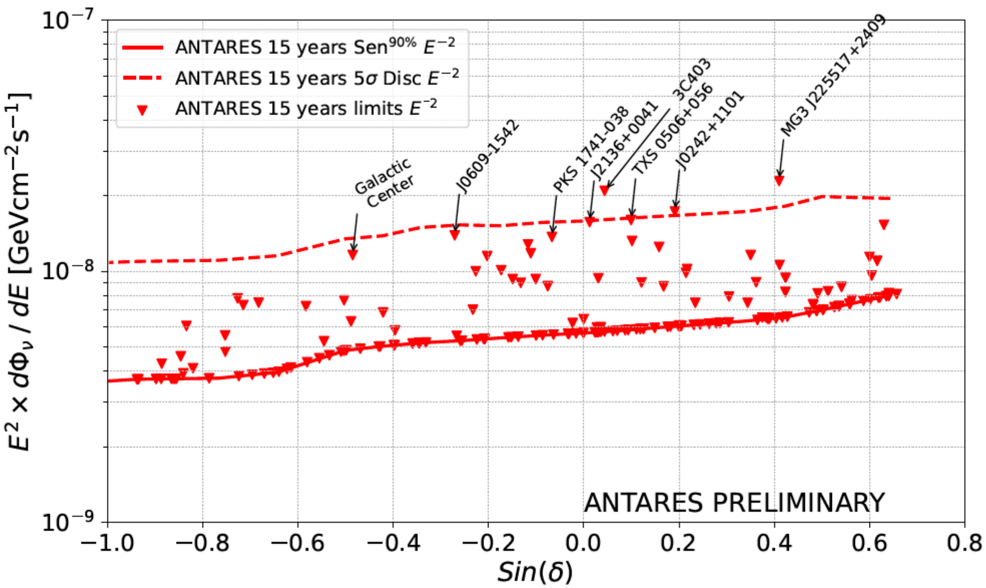
ANTARES point source searches (15 years)



Hotspot (α, δ)=(200.46, 17.74)

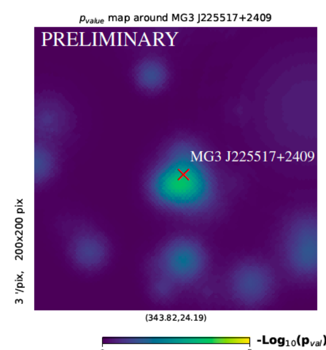


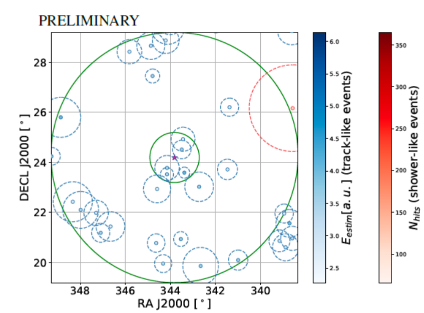




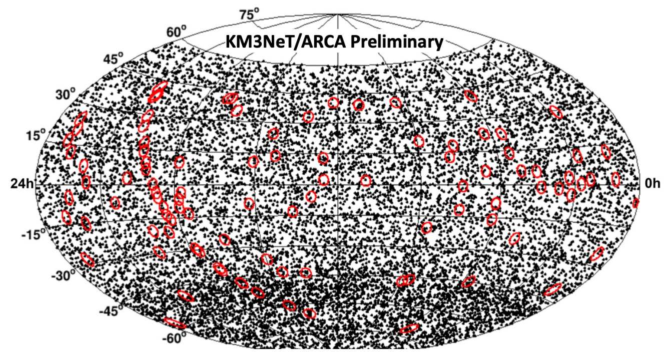
MG3 J225517+2409 (3.4 σ pre-trial)
3C403 (3.4 σ pre-trial)
J0242+1101 (2.6 σ pre-trial)
J2136+0041 (2.4 σ pre-trial)
TXS 0506+056 (2.4 σ pre-trial)

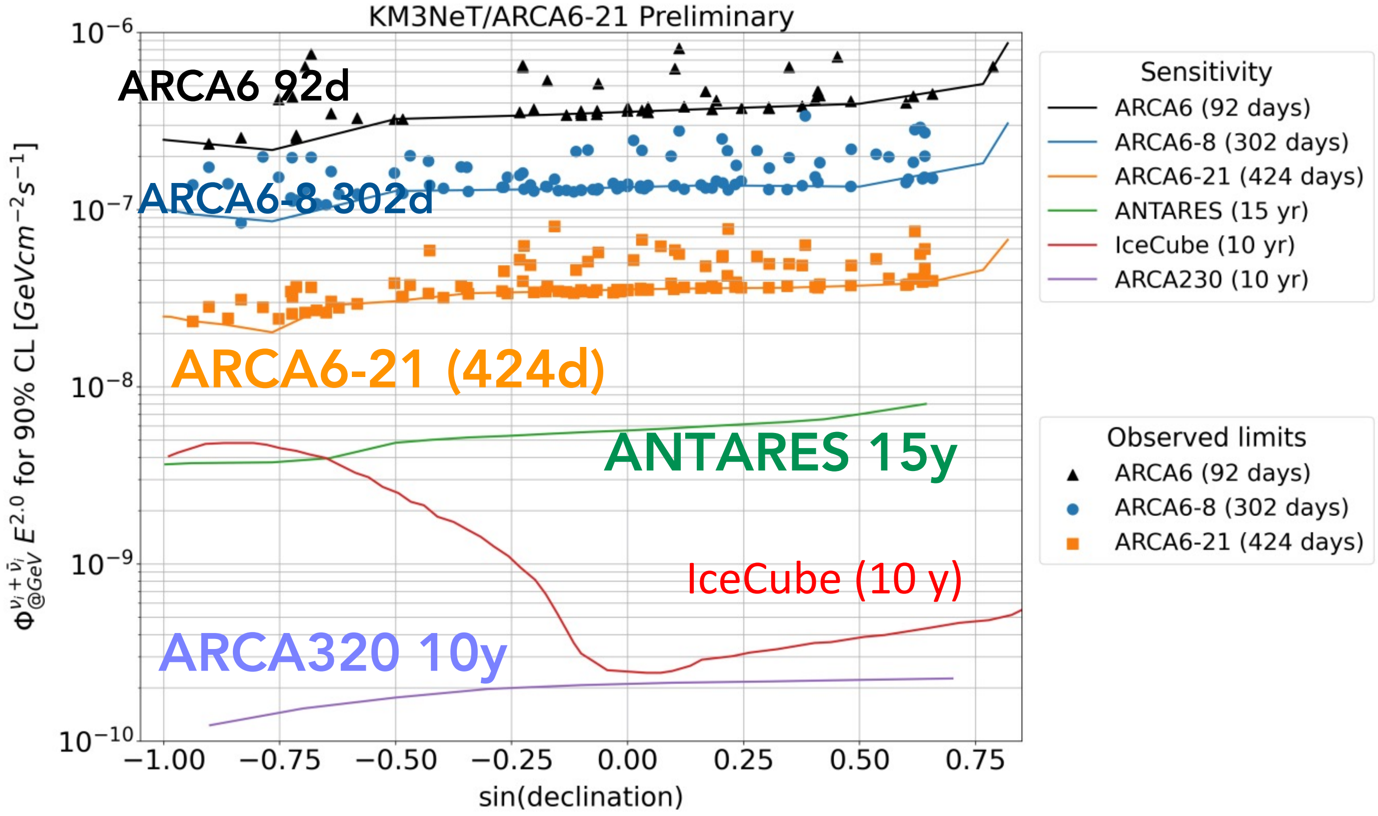
MG3 J225517+2409 (3.4 sigma)





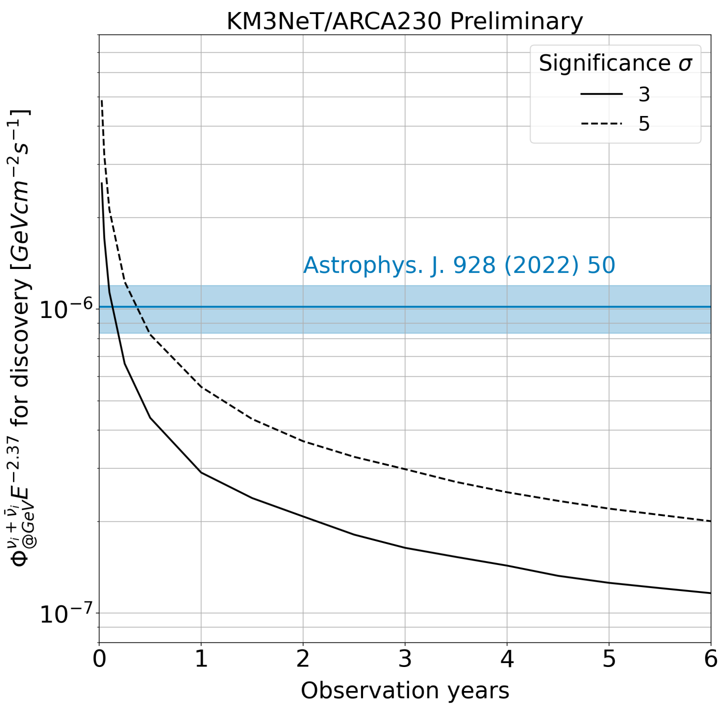
KM3NeT point source searches





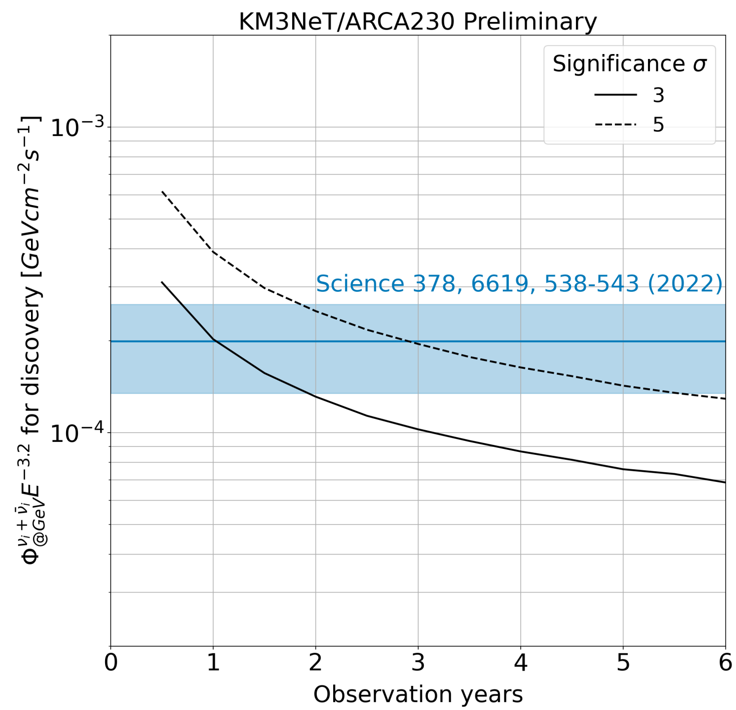
KM3NeT expected sensitivities

Diffuse flux



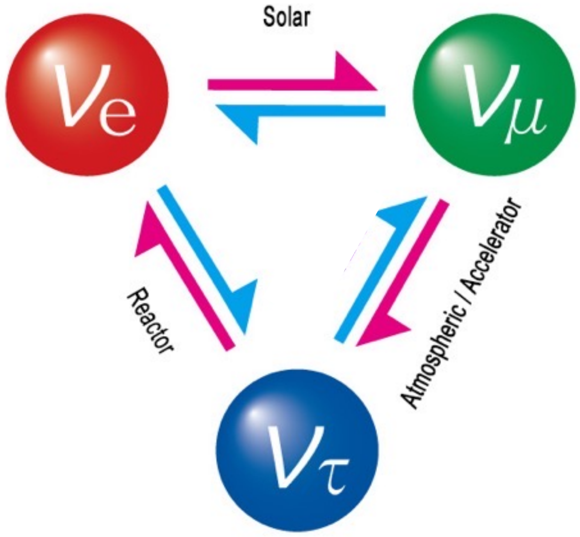
5σ in ∼ 0.5 year for the full detector (230 DUs)

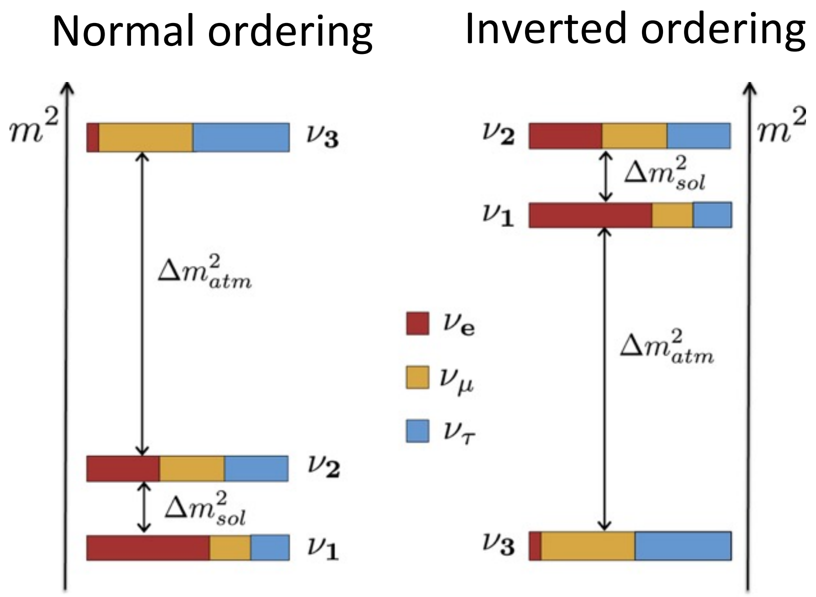
NGC1068

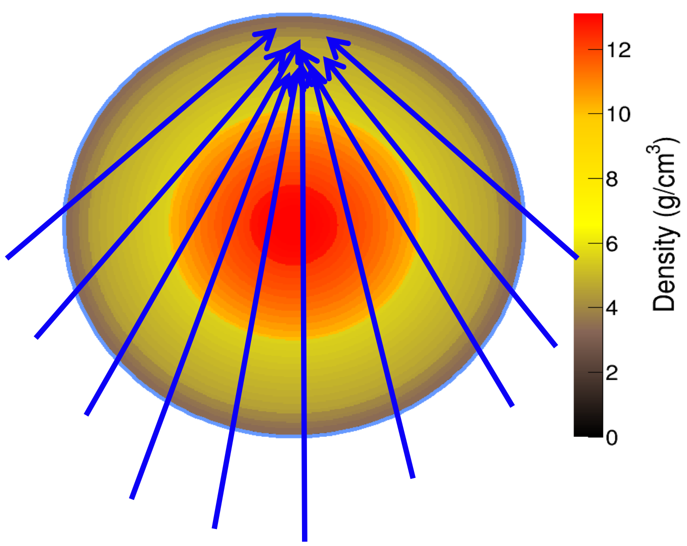


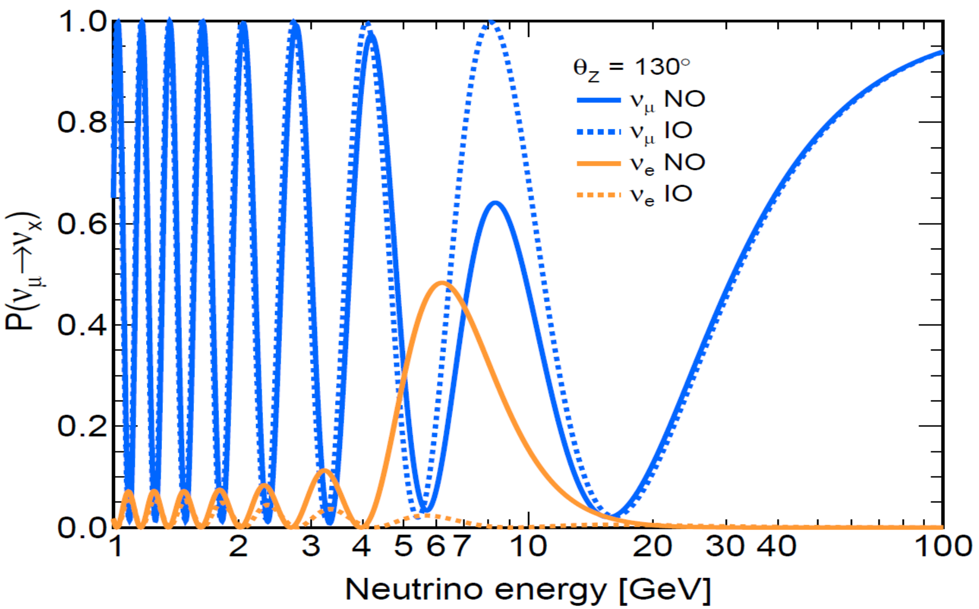
3σ in one year

Neutrino oscillations with atmospheric neutrinos







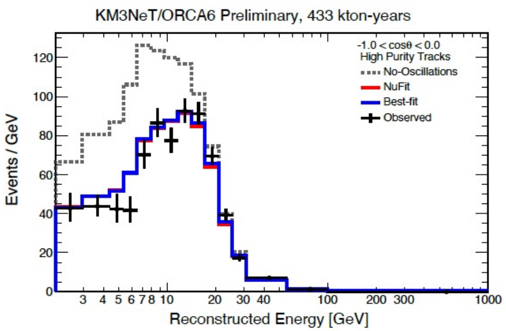


New neutrino oscillations with ORCA6

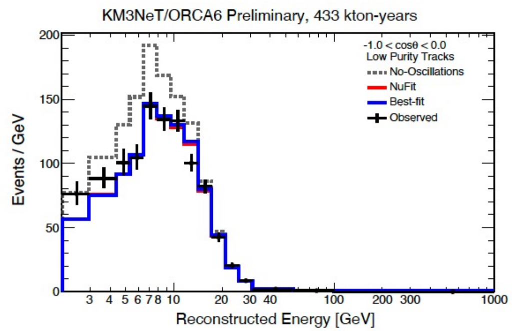
- Increased event sample by factor of 5:
  better selection, add showers, livetime +40%

  510 days, 433 kton-years

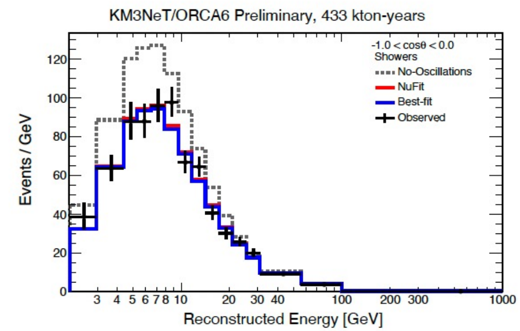
- First time we see oscillations in showers



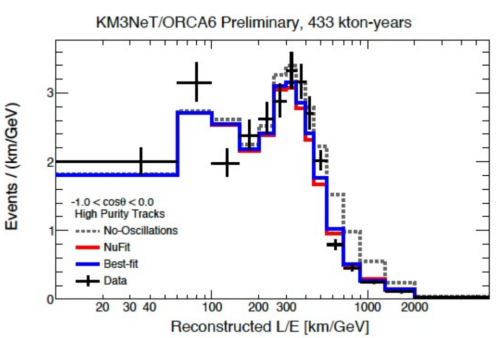
High Purity Tracks



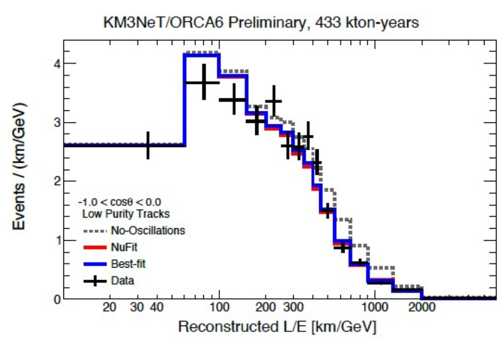
Low Purity Tracks



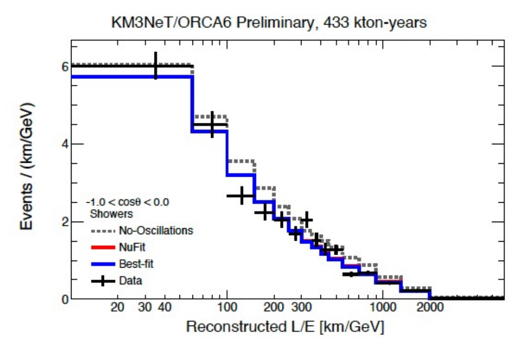
Showers



High Purity Tracks

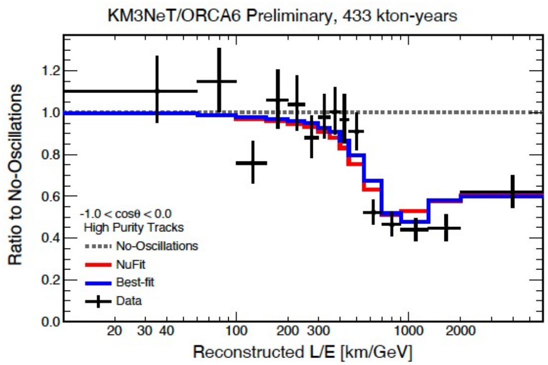


Low Purity Tracks

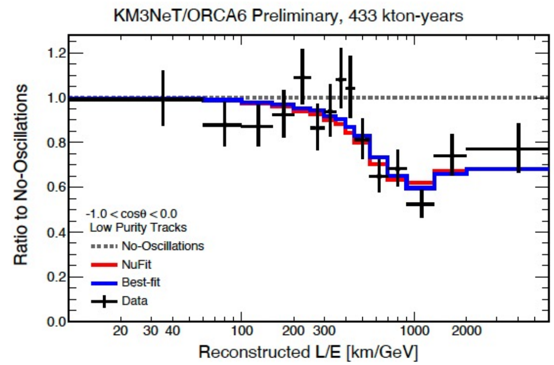


Showers

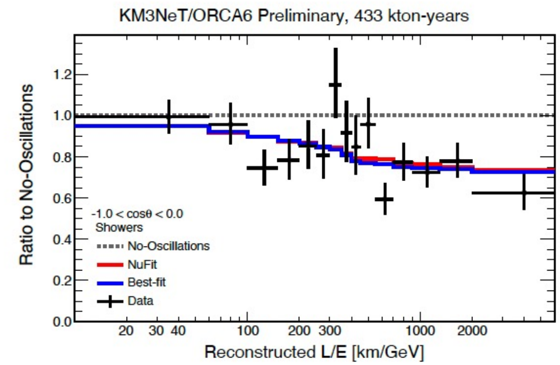
New oscillation results with ORCA6



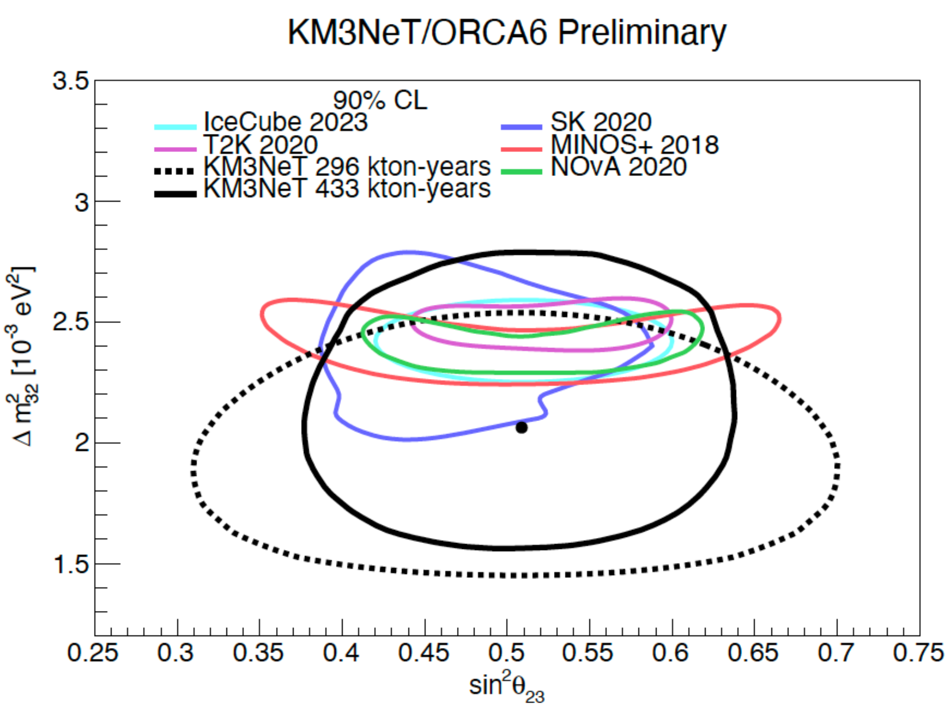
High Purity Tracks



Low Purity Tracks



Showers

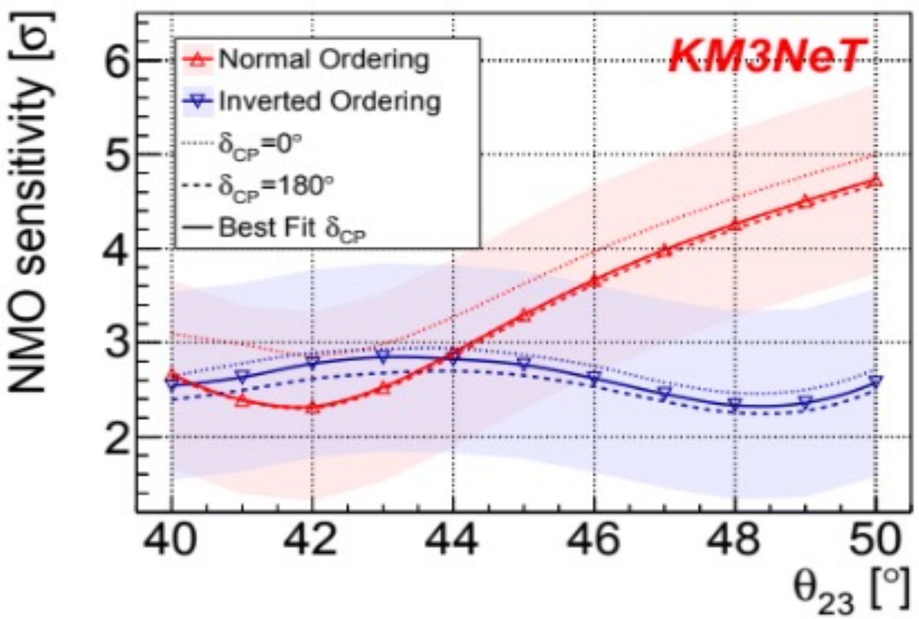


- Best-fit: $\sin^2\theta_{23} = 0.51^{+0.06}_{-0.07}$ and $\Delta m^2_{31} = 2.14^{+0.36}_{-0.25} \cdot 10^{-3}\mathrm{eV}^2$.

Normal Ordering favoured at 0.9 sigma

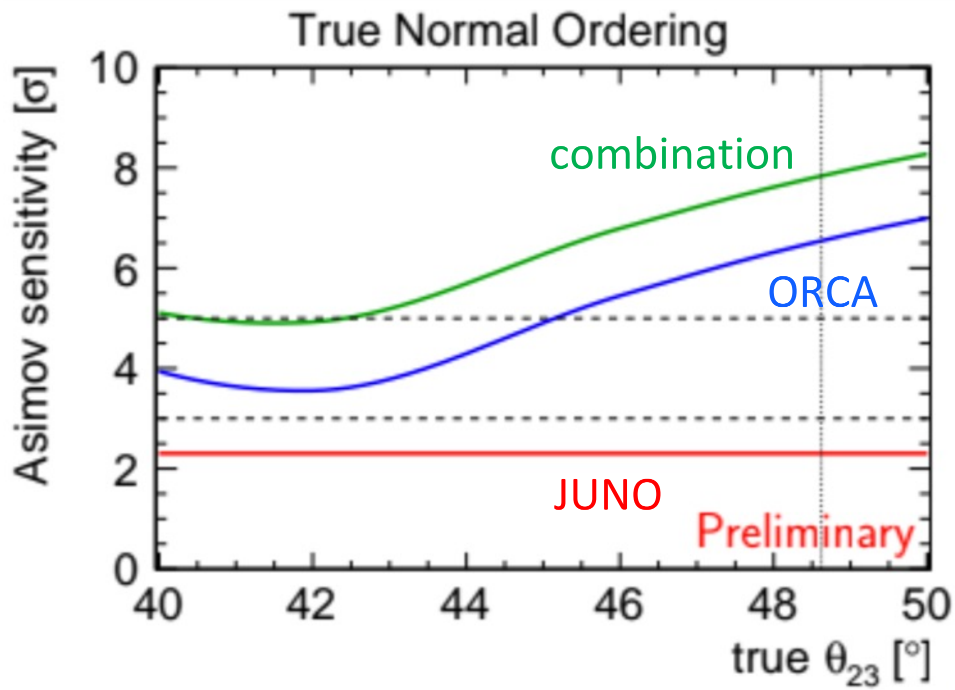
ORCA115: neutrino mass ordering

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

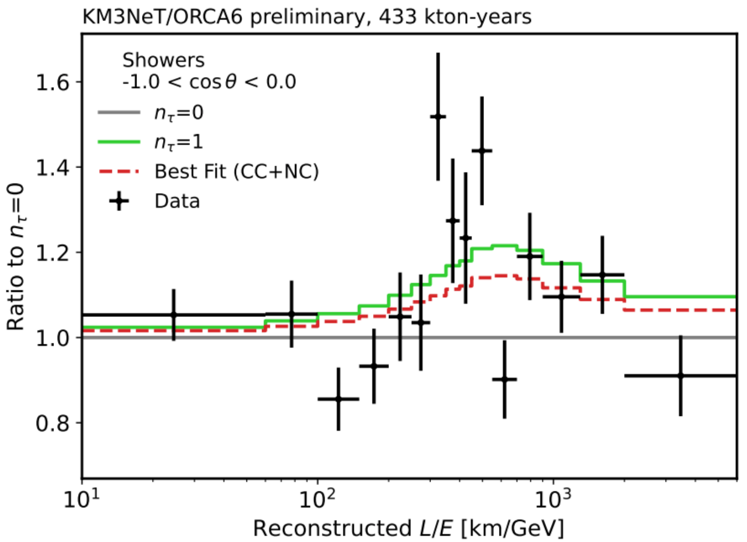
Tau appearance

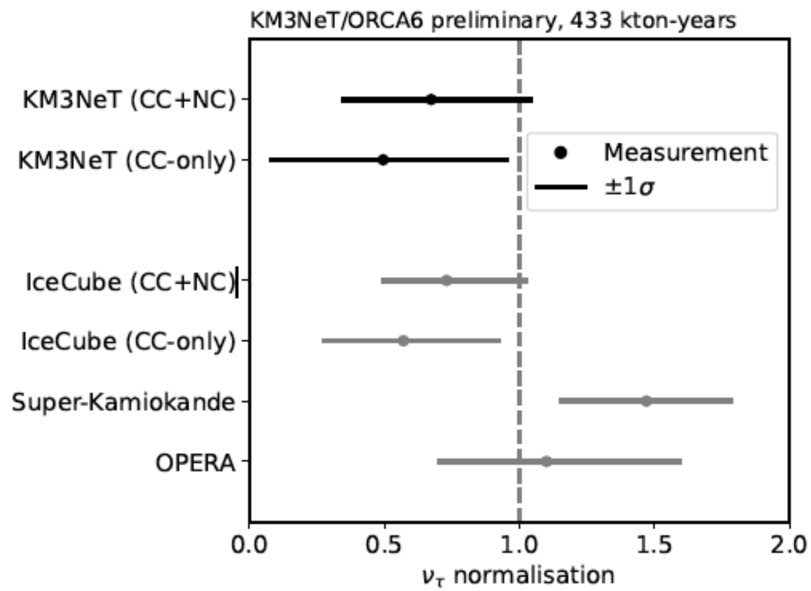
The muon neutrinos mainly oscillate to tau neutrinos.

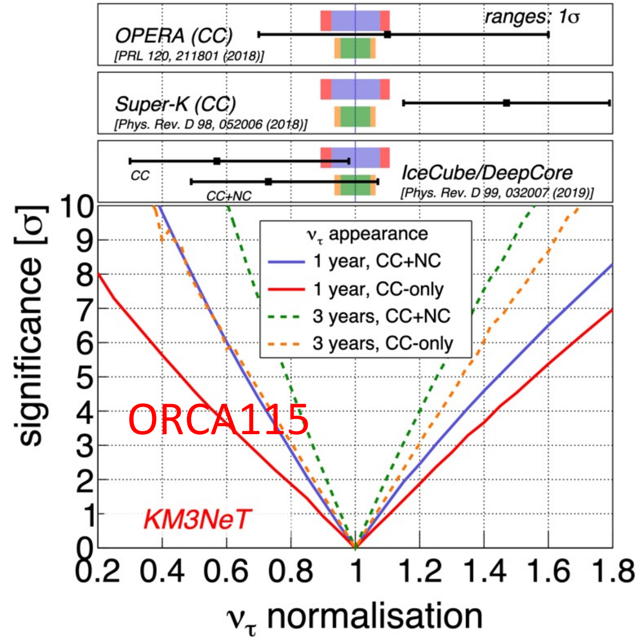
They appear as showers events.

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

≈3k ν_τ CC events/year with full ORCA



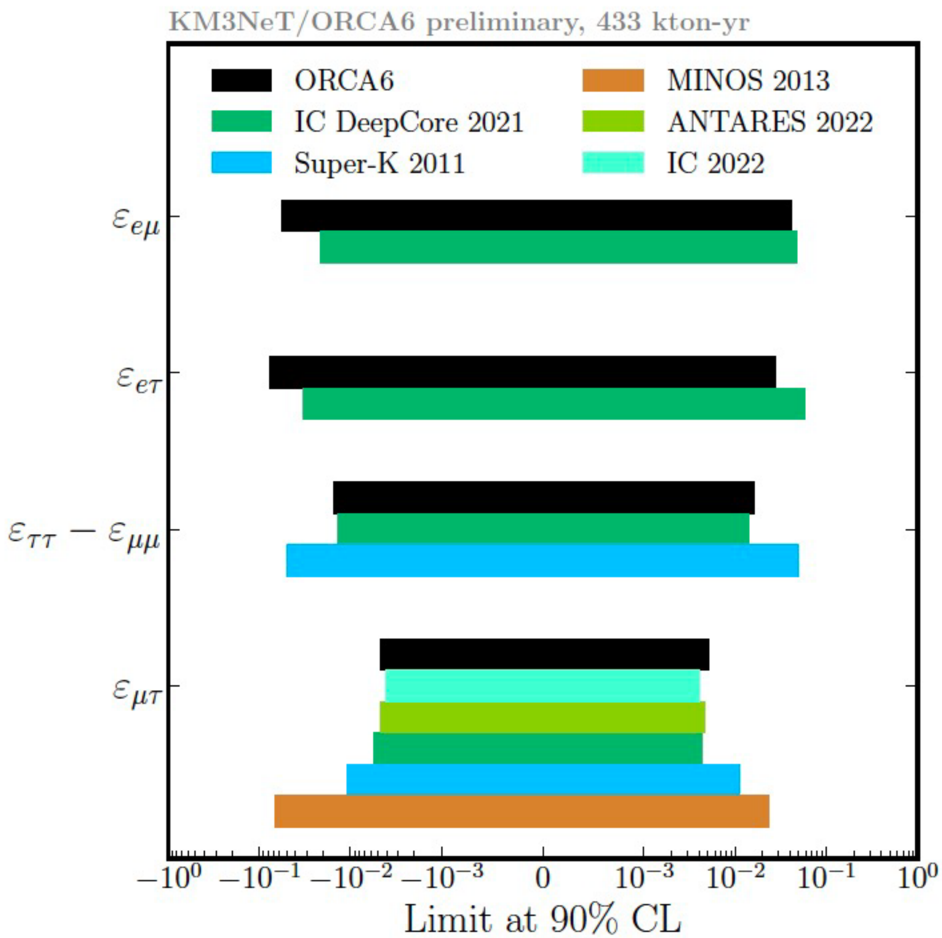




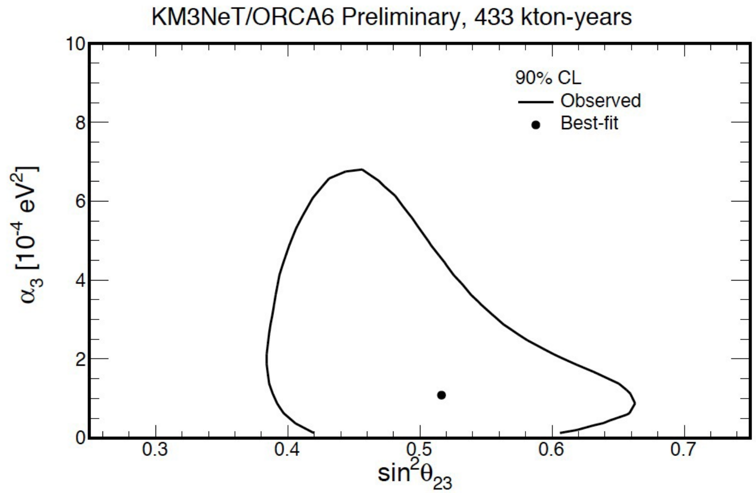
Also NSI, decoherence, LIV, sterile,…

Beyond Standard Model

NSI



Neutrino decay

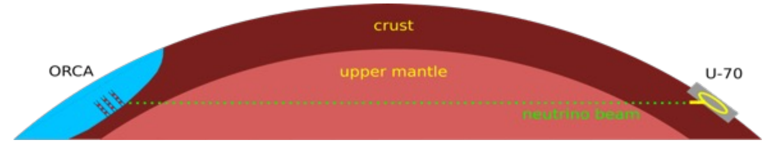


Quantum decoherence

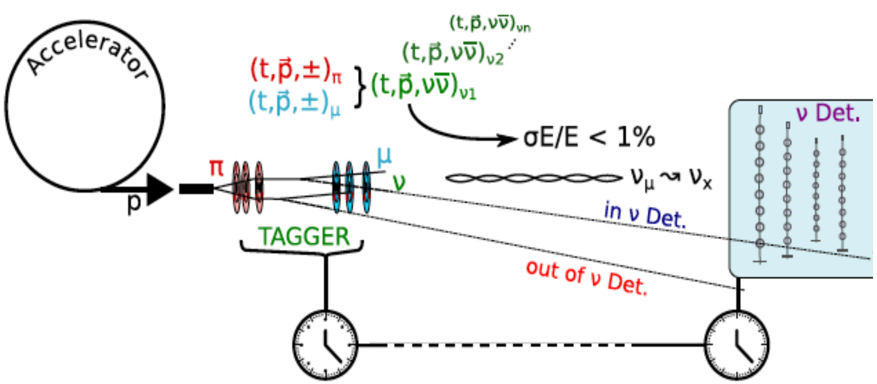
	$\gamma \propto E^{-2}$	$\gamma \propto E^{-1}$
ORCA6		
γ_{21} [GeV]	7.7×10^{-21}	3.1×10^{-22}
γ_{31} [GeV]	1.4×10^{-20}	5.0×10^{-22}
$\gamma_{21} = \gamma_{31}$ [GeV]	3.0×10^{-21}	1.1×10^{-22}
DeepCore		
$\gamma_{21} = \gamma_{32}$ [GeV]	7.5×10^{-20}	3.5×10^{-22}
$\gamma_{31} = \gamma_{32}$ [GeV]	4.3×10^{-20}	2.0×10^{-21}
$\gamma_{21} = \gamma_{31}$ [GeV]	1.2×10^{-20}	5.4×10^{-22}

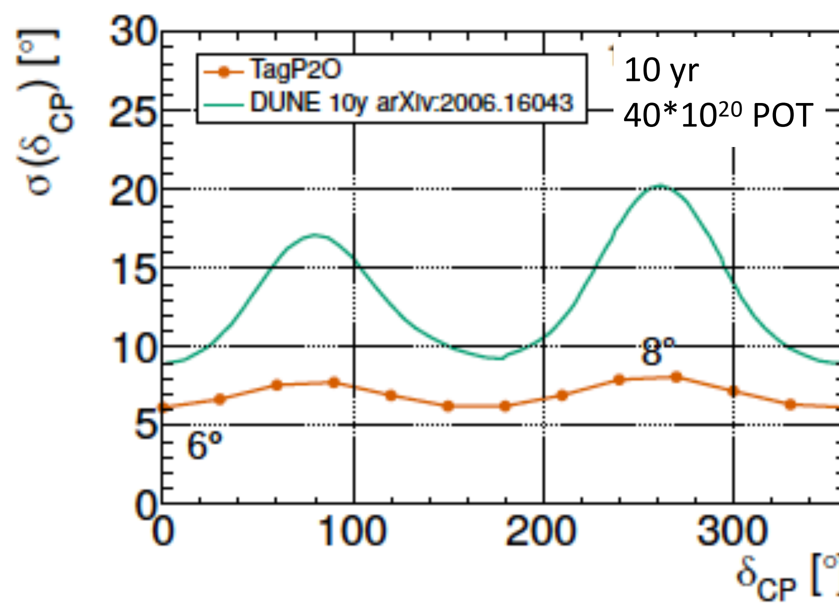
New idea: Tagged Protvino to ORCA

- Neutrino Beam from Protvino to ORCA
- Baseline 2590 km
- First oscillation maximum 5.1 GeV
- Sensitivity to mass hierarchy and CPV
- LoI published:
  A. V. Akindinov et al.,
  "Letter of Interest for a Neutrino Beam from Protvino to KM3NeT/ORCA"
  https://arxiv.org/abs/1902.06083
- Huge detector -> relax beam power
- New idea - ν tagging at source:

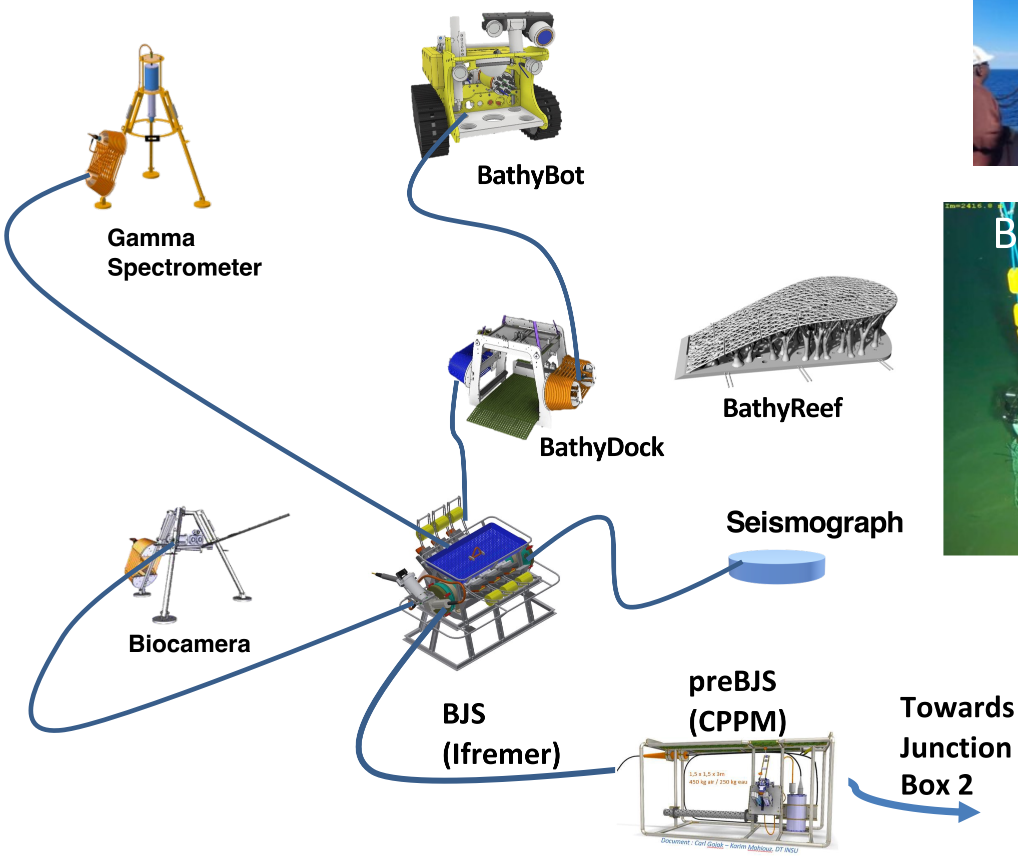


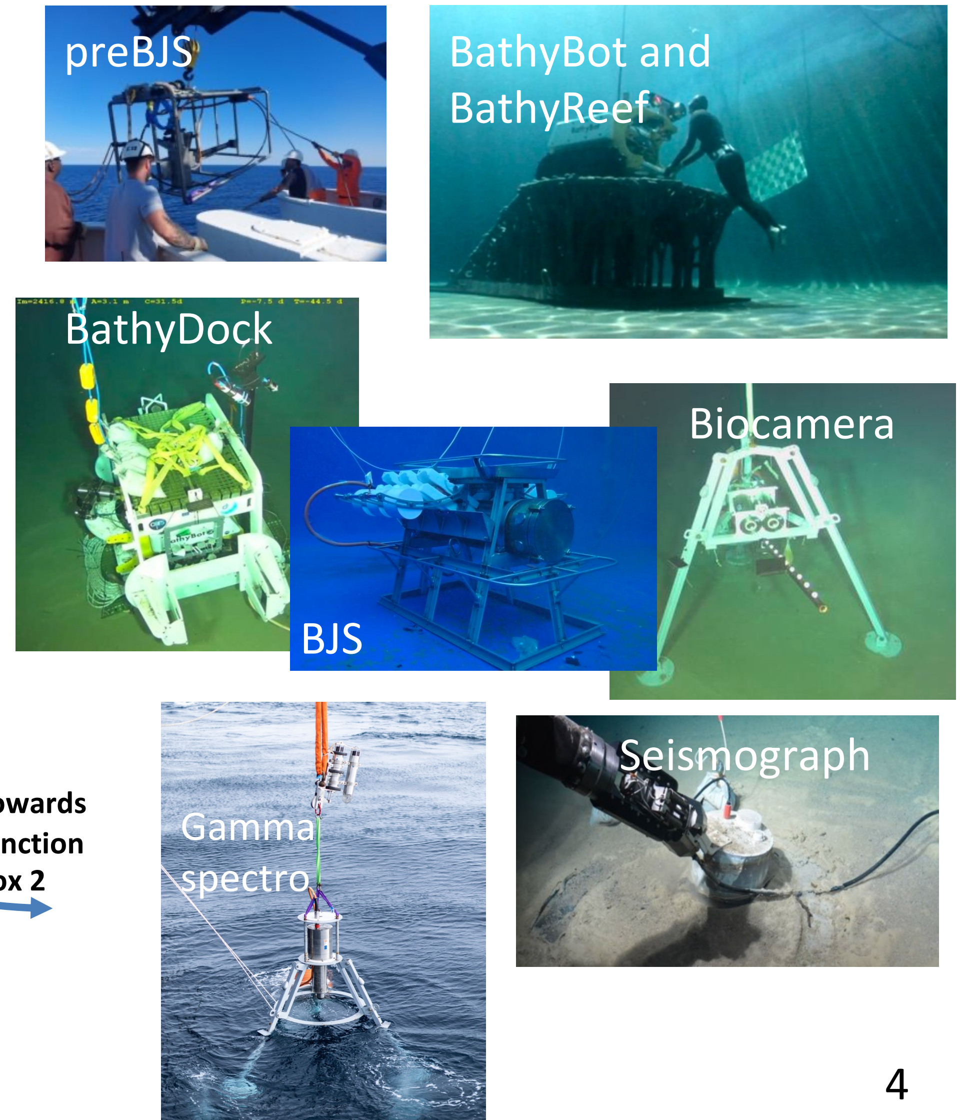
M. Perrin-Terrin
https://arxiv.org/abs/2112.12848



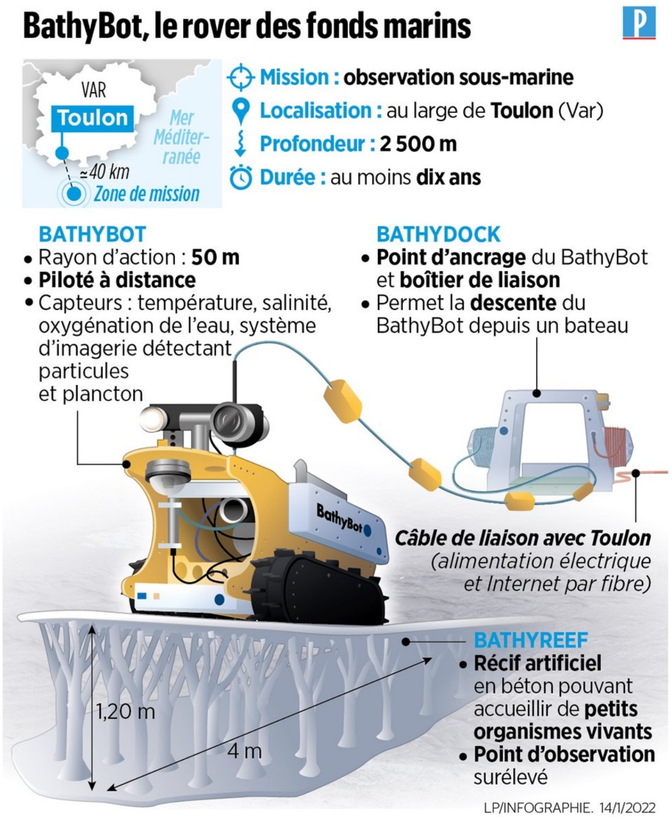


Instrumentation for marine sciences



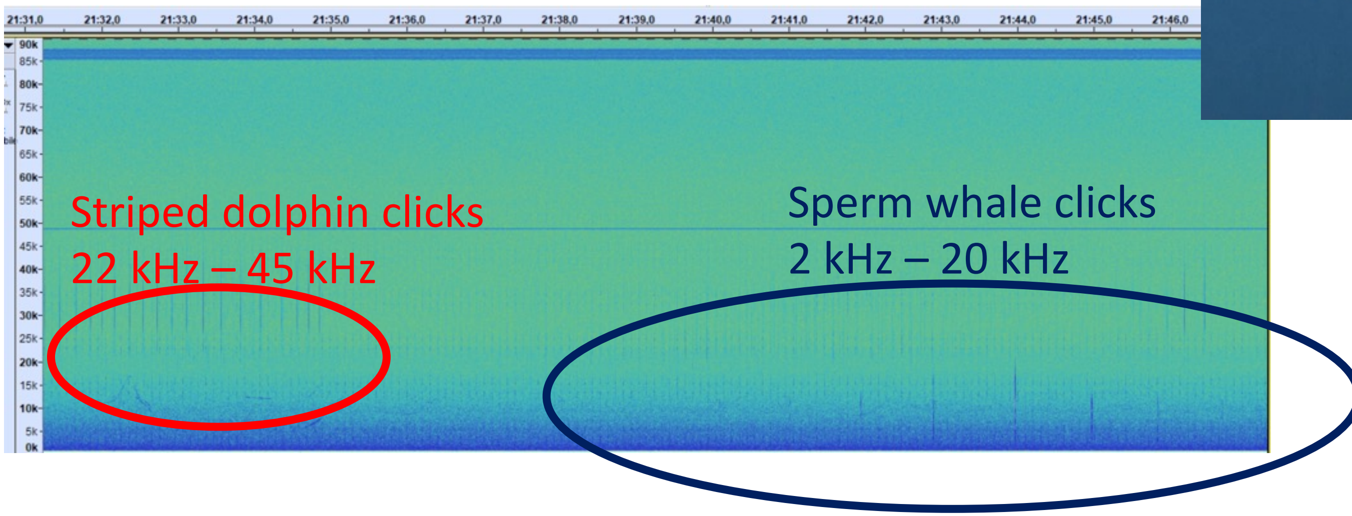


BathyBot

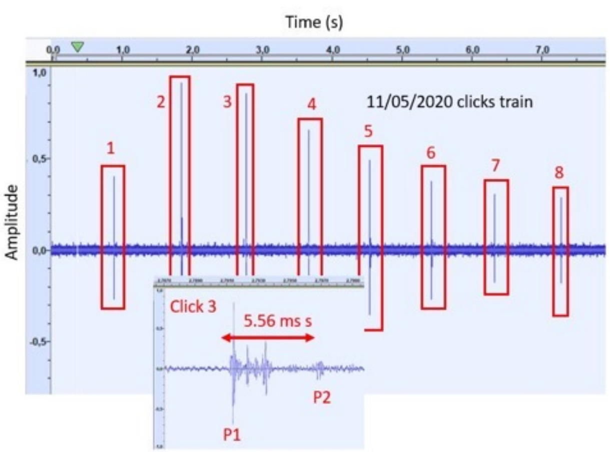


Cameras, lights, sensors – ok
Movement – not ok

Bioacoustics



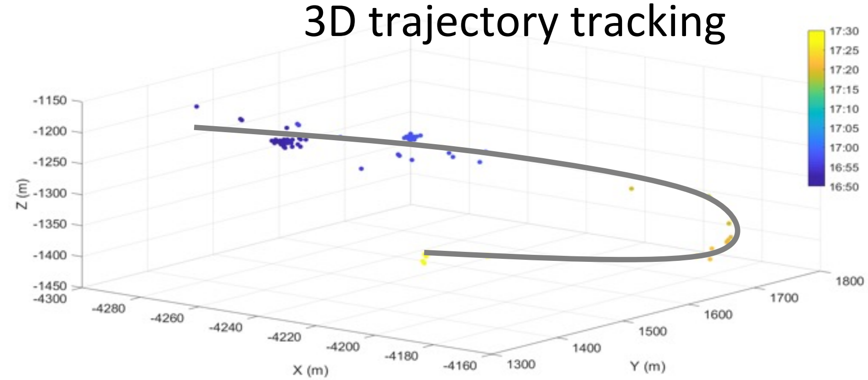
sIze of whales



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

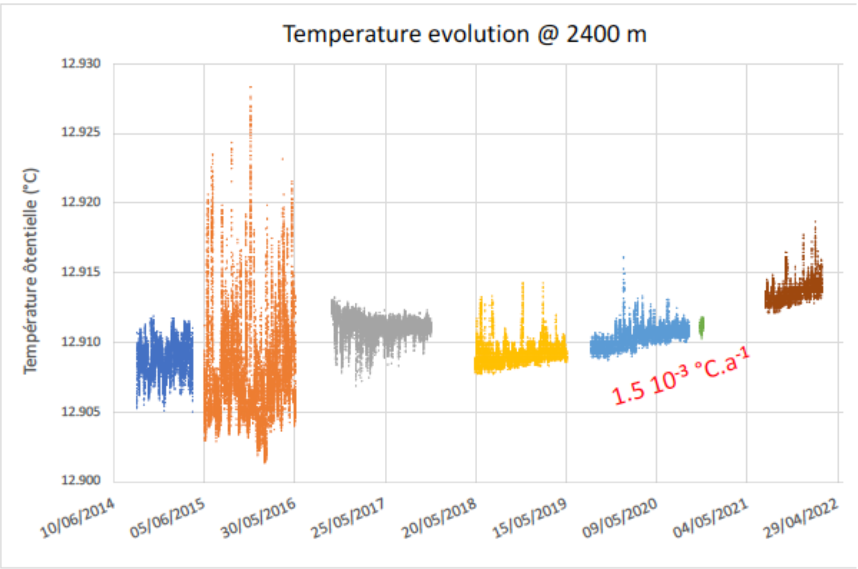
Mean value: $(12.62 \pm 0.04)\ m$

3D trajectory tracking

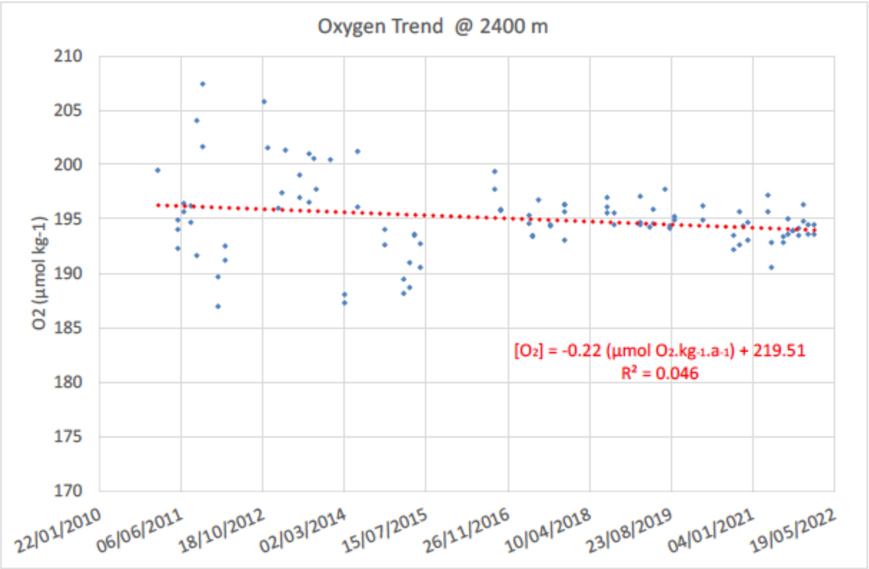


Climate change

Temperature



Oxygen



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 18 lines
End of 2023: ~24 lines

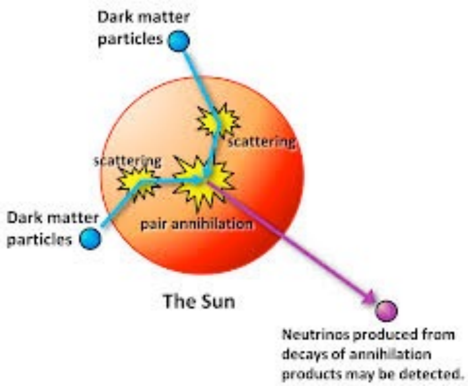
ARCA currently taking data with 28 lines

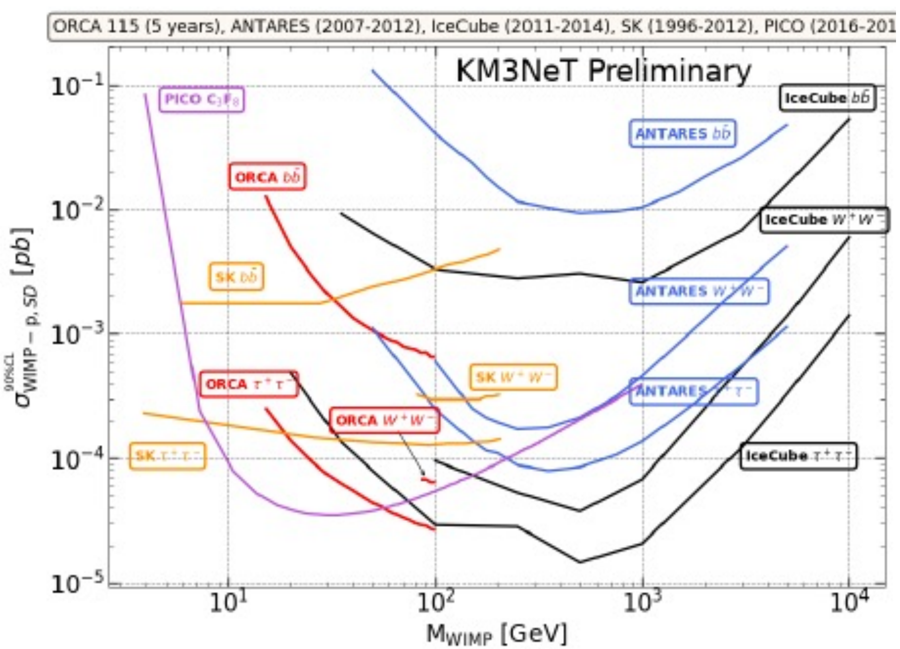
New collaborators very welcome
Come and join the adventure!

BACK UP

Dark matter-indirect detection

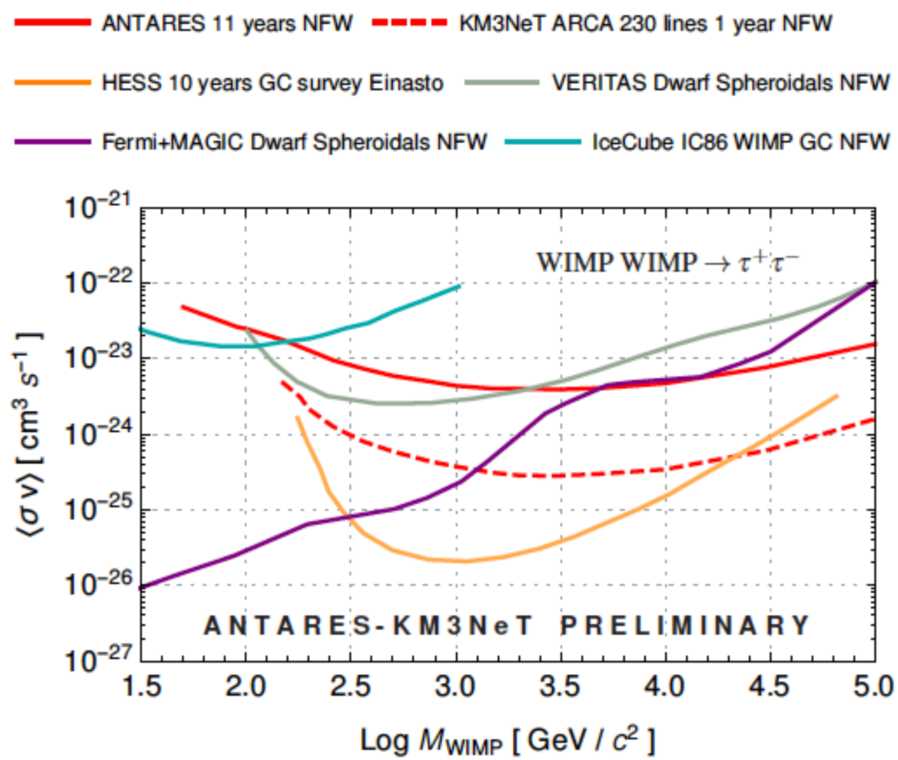
Sun





Phys.Lett. B759 2016

Galactic Centre

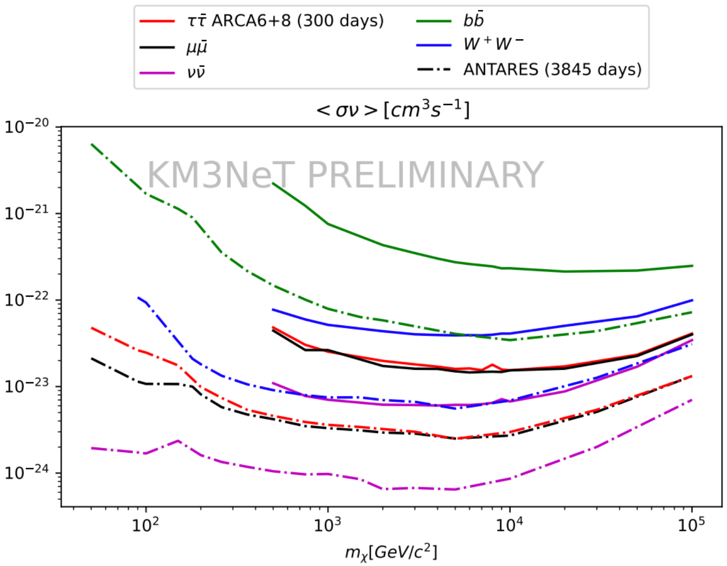


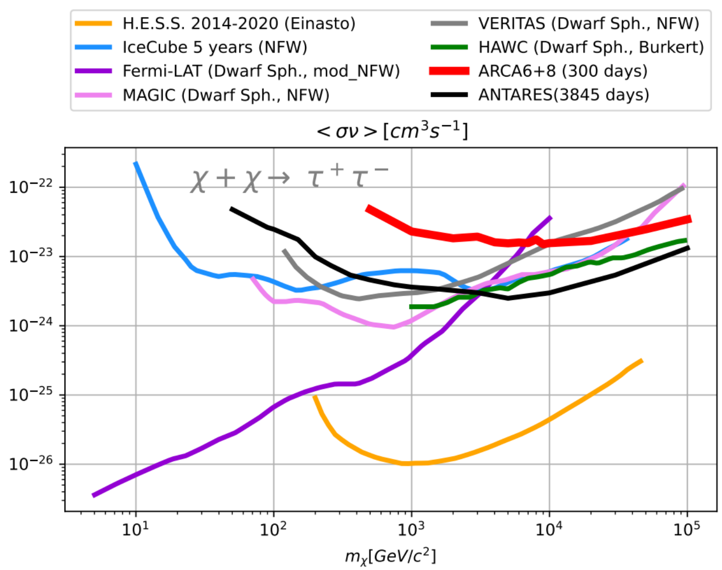
Phys. Lett. B 805 135439 (2020)

DARK MATTER

Galactic Centre

ARCA6 + ARCA8 ICRC2023 PoS 1377

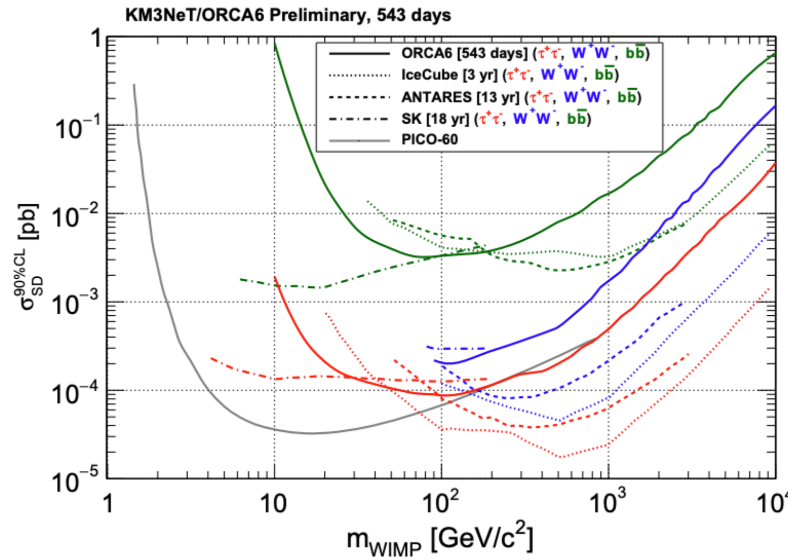


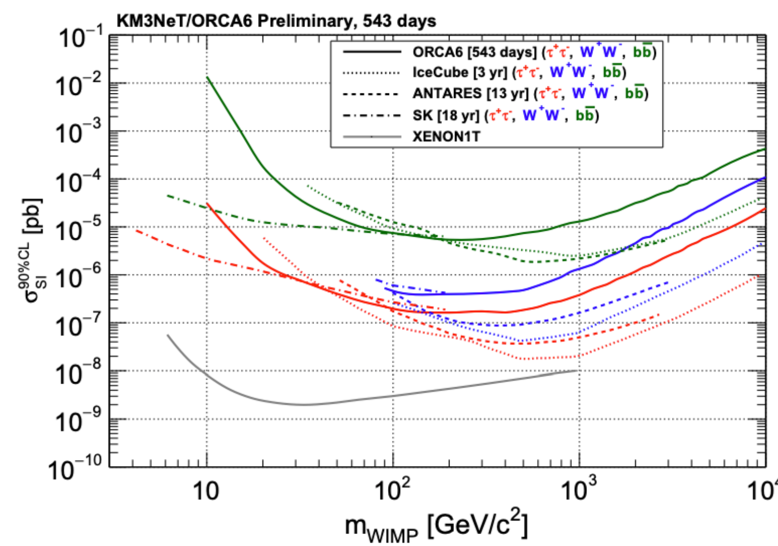


KM3NeT quickly reaching the ANTARES limits

The Sun

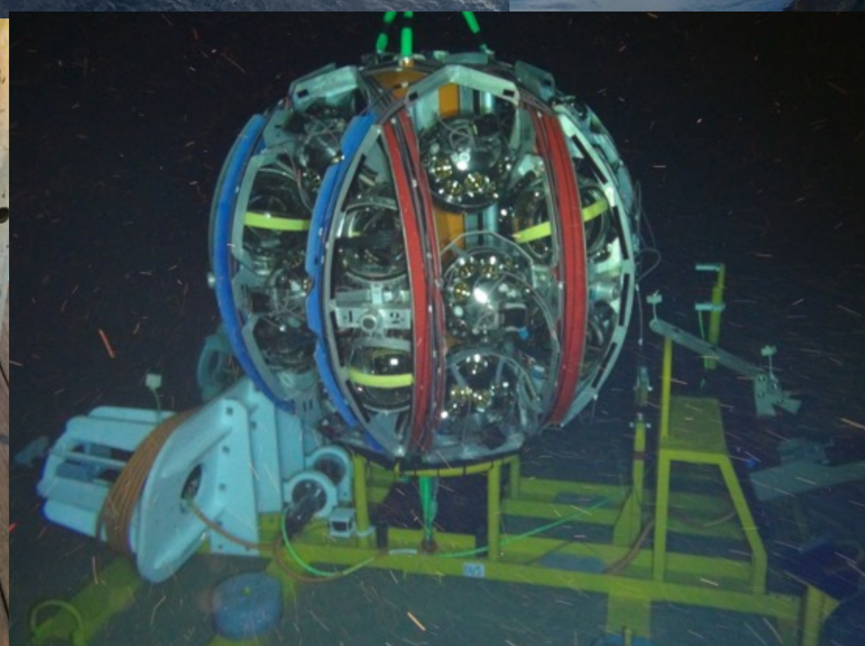
ORCA6 ICRC2023 PoS 1406





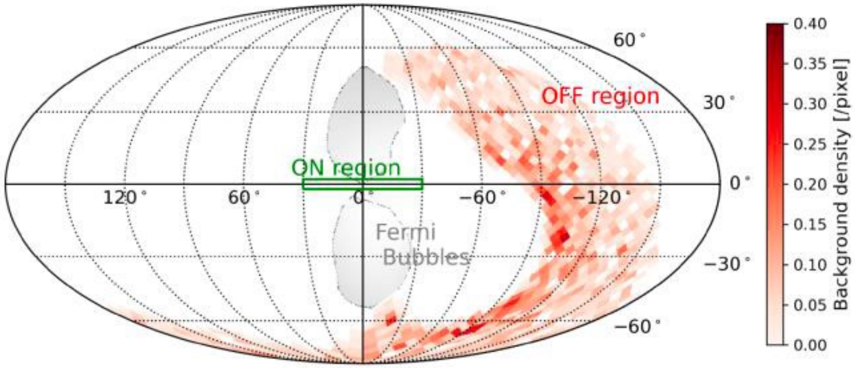
Deployment of neutrino detection lines

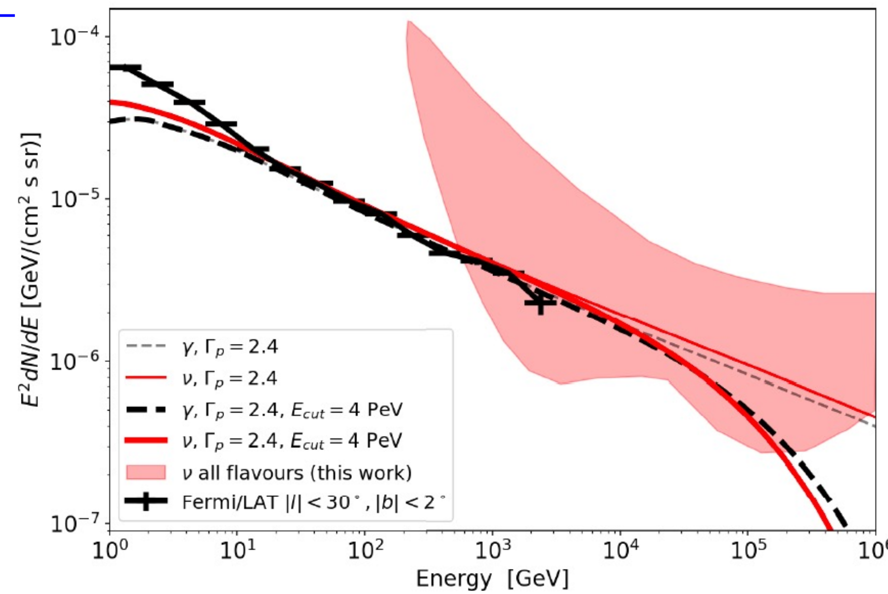
LeMonde/CNRS: https://www.in2p3.cnrs.fr/en/node/1575

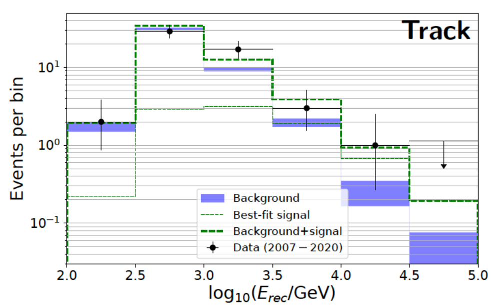


Hint for a TeV neutrino emission from the Galactic Ridge with ANTARES

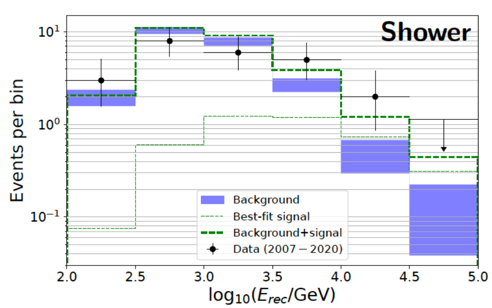
[2212.11876.pdf (arxiv.org)](2212.11876.pdf)

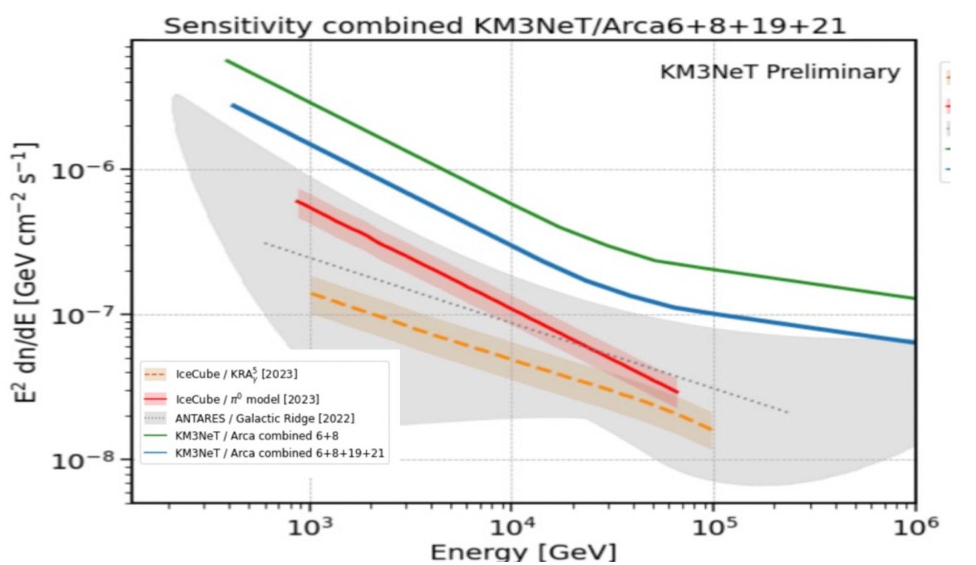






(a) Track-like events





2.2 sigma effect

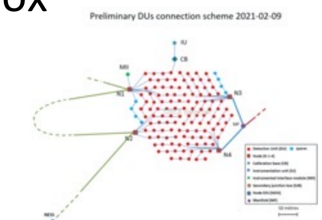
Seafloor infrastructures

ORCA
2nd junction box
Oct 2020

ARCA
2nd Cable
Nov 2020

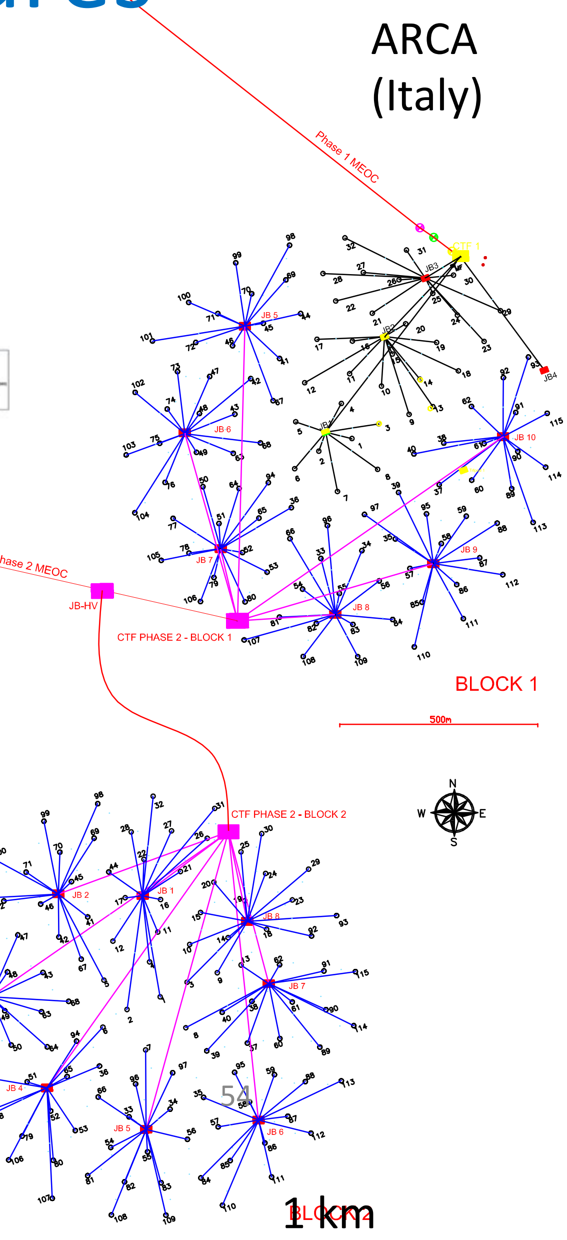
ARCA
3rd junction box
Sept 2022

ORCA
(France)



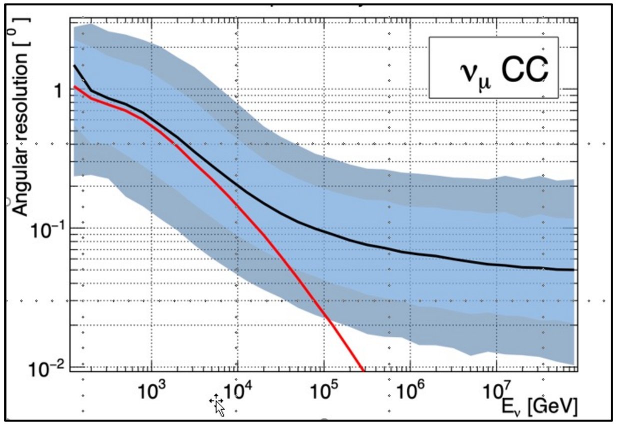
200 m

ARCA
(Italy)

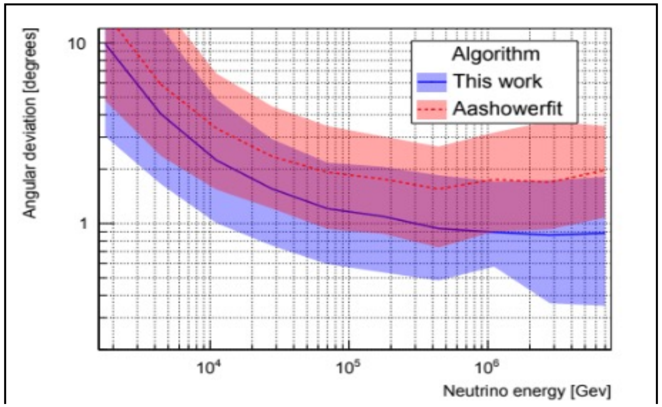


Angular Resolutions

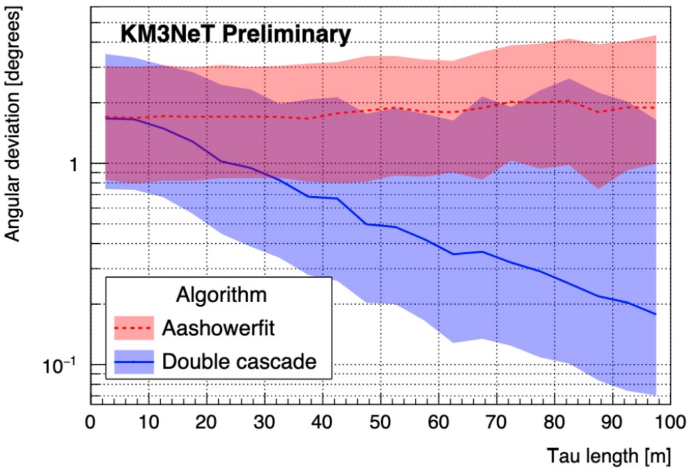
Better than 0.1° > 20 TeV



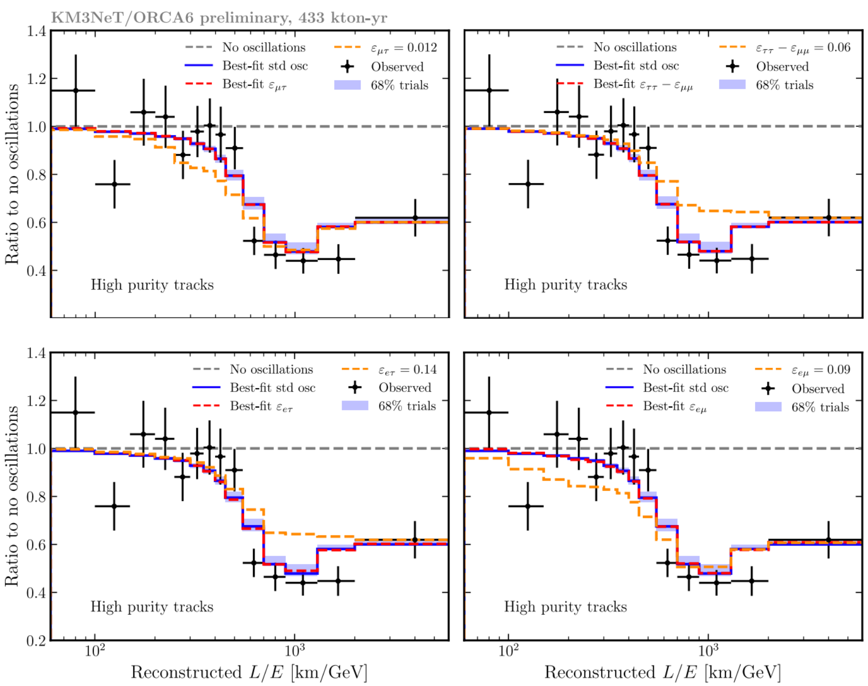
Better than 1° > 30 TeV

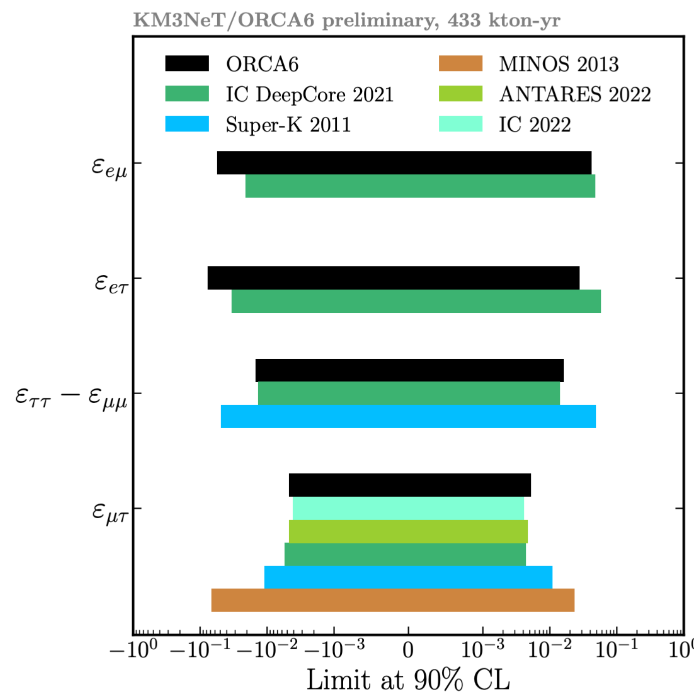


Better than 1°for tau track length > 22 m



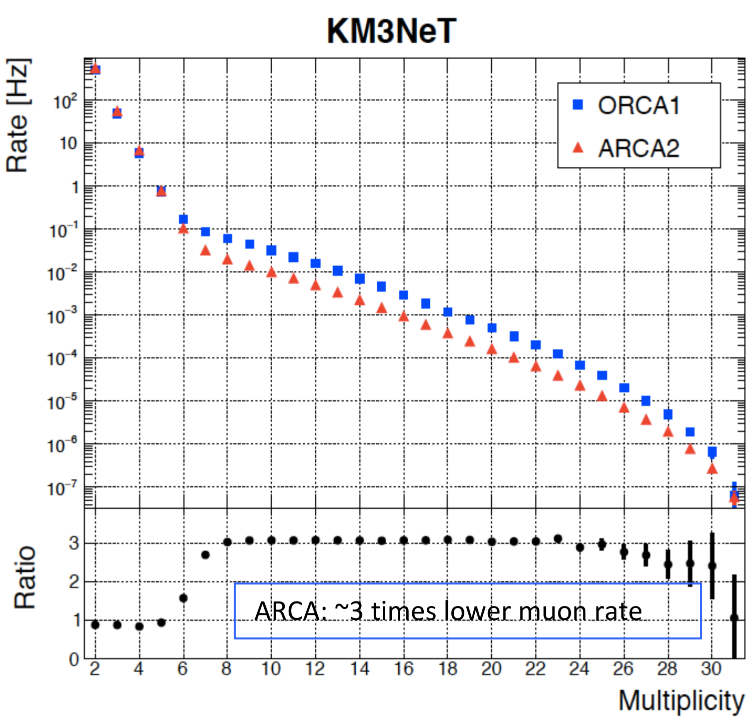
Non-Standard Interactions

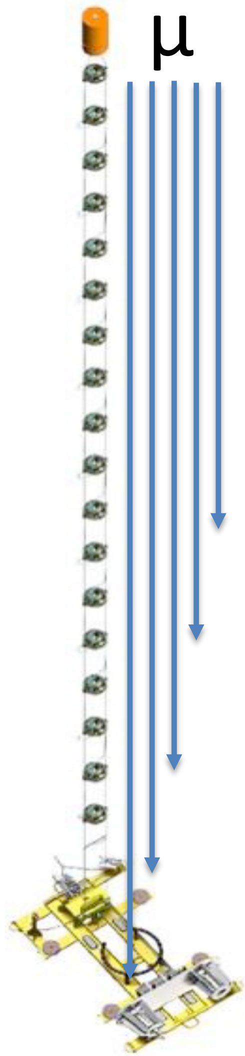




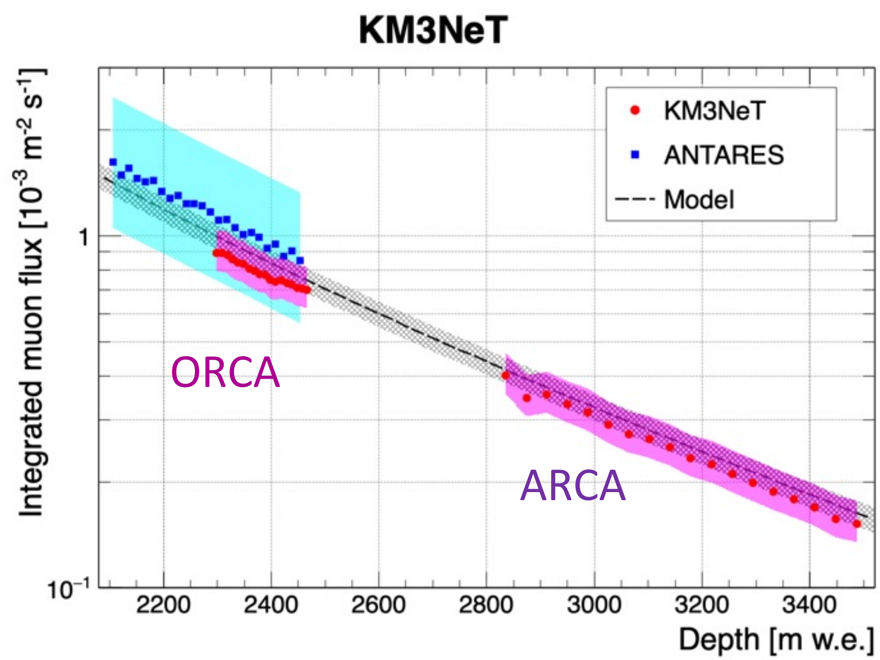
Muon depth dependence

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 TYPE AND ANGULAR RESOLUTION

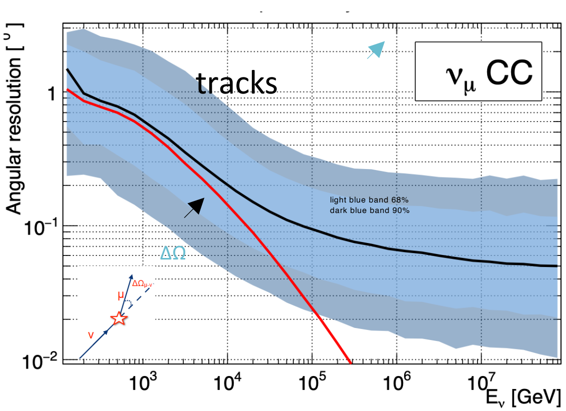
	TRACK*	CASCADE*
ANTARES	0.3°	3°
KM3NET	0.1°	1.5°
ICECUBE	0.3°	7°-8°
BAIKAL-GVD	0.25°	3° - 3.5°

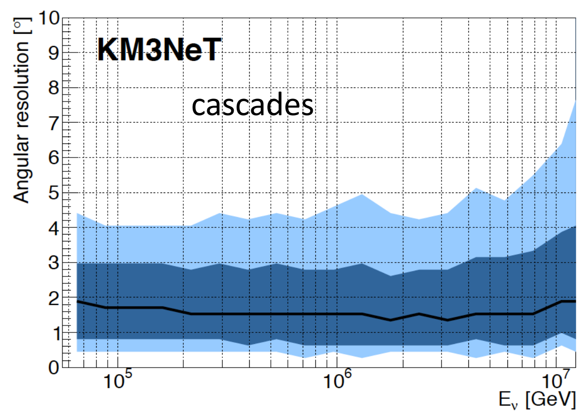
*Resolution at 100 TeV

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

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

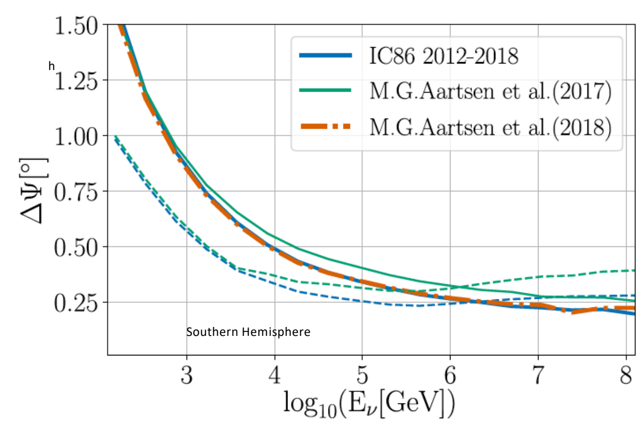
KM3NeT





IC resolution for tracks

from arXiv:1910.08488, 15 October 2019



EVENT TYPE AND ENERGY RESOLUTION

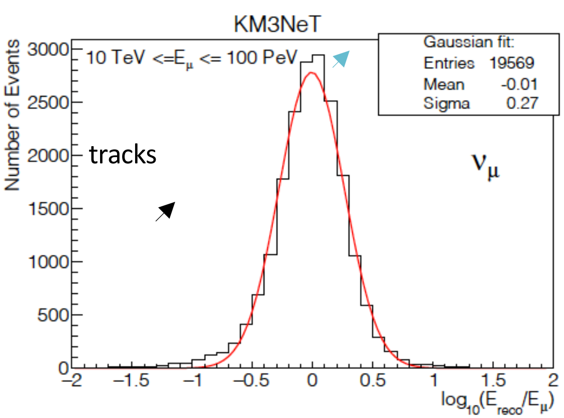
Tracks: very long path (Eμ>1TeV several km)
Neutrino interaction vertex far from the detector
- Modest energy resolution

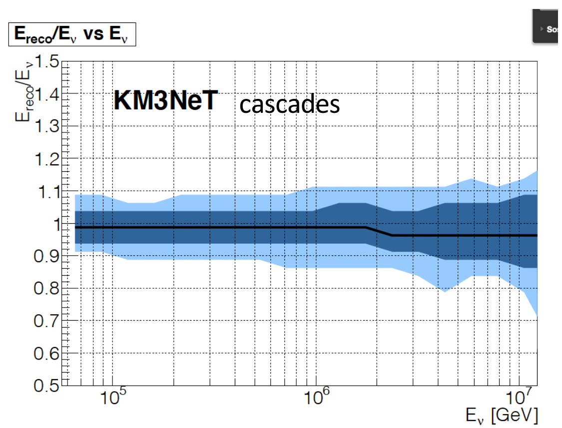
Cascades: small path (Ecasc >1TeV some tens of meters)
All the energy released inside the detector
- Good energy resolution

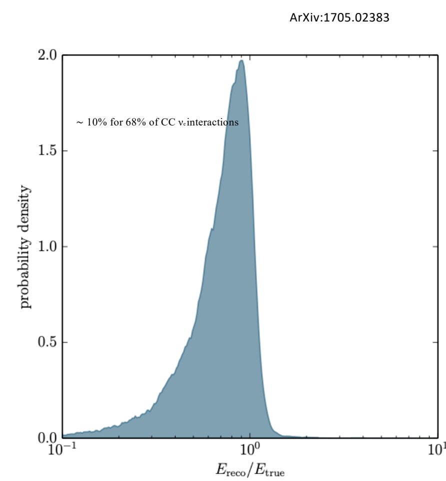
	TRACK IN LOG(E)	CASCADE
ANTARES	35%	5%
KM3NET	27%	5%
ICECUBE	~ 30%	10%
BAIKAL - GVD		

KM3NeT

C energy resolution for cascades







NGC1068

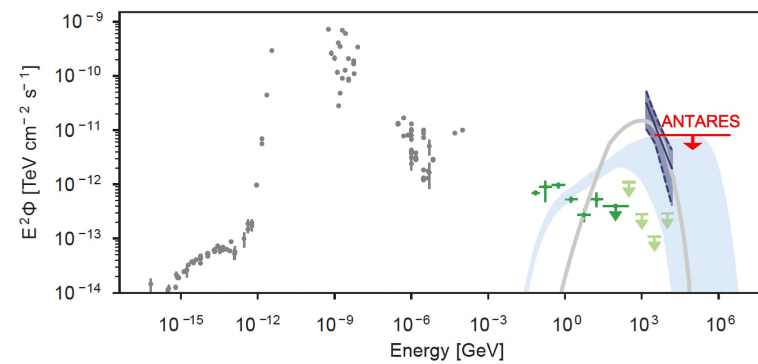
4 Nov (Science) : IceCube AGN IC at 4.2 sigma (steady state)

https://www.science.org/doi/10.1126/science.abg3395

https://icecube.wisc.edu/news/press-releases/2022/11/icecube-neutrinos-give-us-first-glimpse-into-the-inner-depths-of-an-active-galaxy/

Analyses ANTARES et KM3NeT -> nothing

More precise analyses -> ongoing



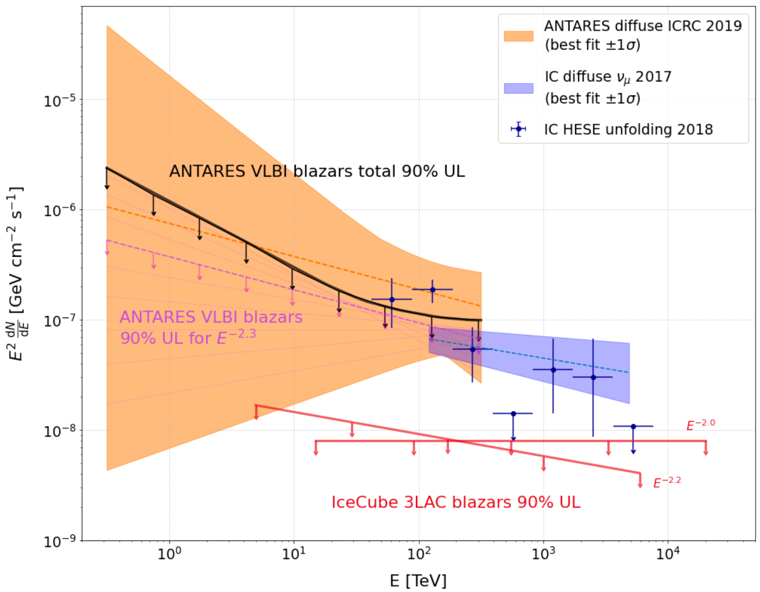
"Recent models of the black hole environments in these objects suggest that gas, dust, and radiation should block the gamma rays that would otherwise accompany the neutrinos," says Hans Niederhausen

"It is great news for the future of our field," says Marek Kowalski,
"It means that with a new generation of more sensitive detectors there will be much to discover".

"The unveiling of the obscured universe has just started, and neutrinos are set to lead a new era of discovery in astronomy," says Elisa Resconi

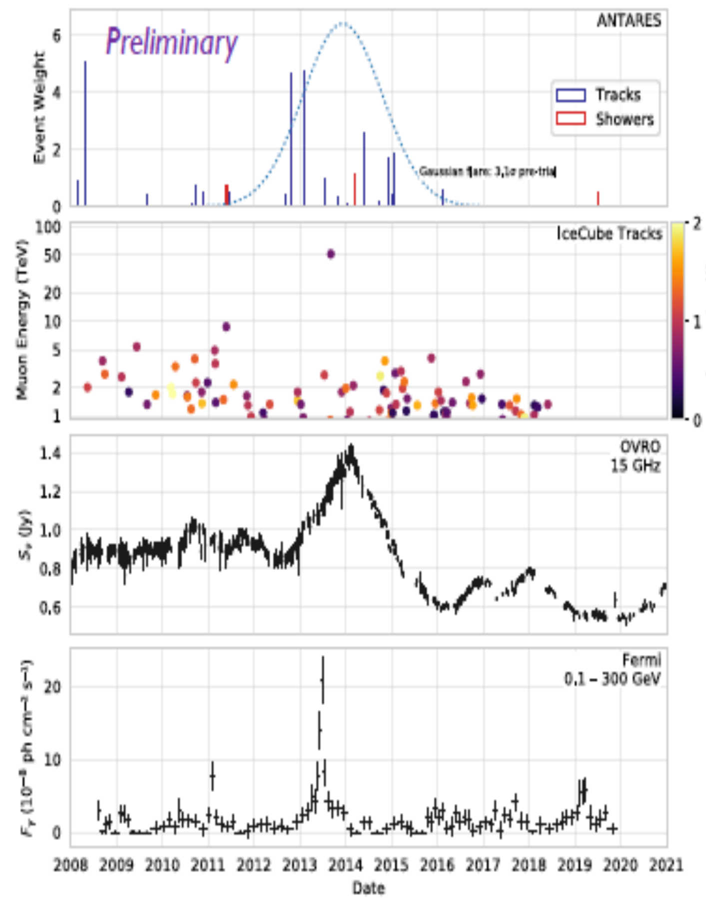
Neutrinos from radio-loud blazars?

VLBI catalog: 3411 sources



18 sources have pre-trial above 3 σ : chance probability 2.5 σ

J0242+1101: radio-γ-ν association?



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

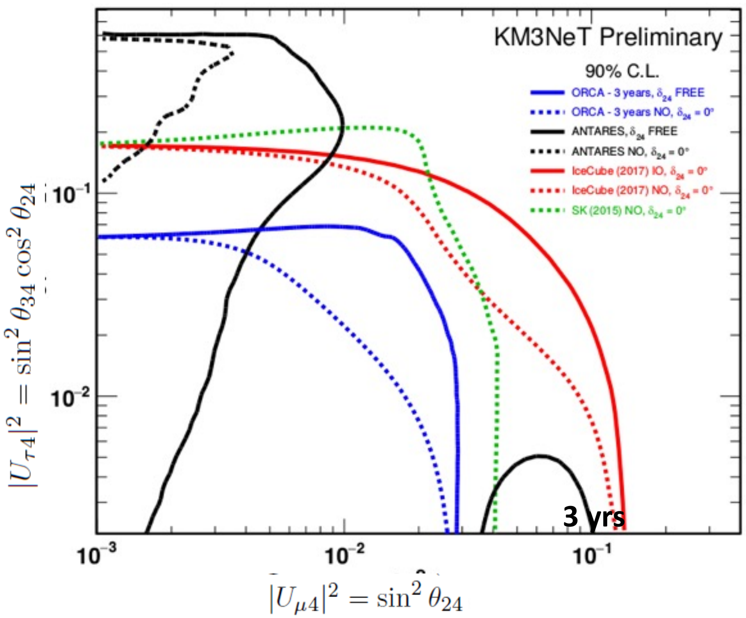
OVRO radio light-curve

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

Chance probability 0.5%

ORCA115: sterile neutrinos

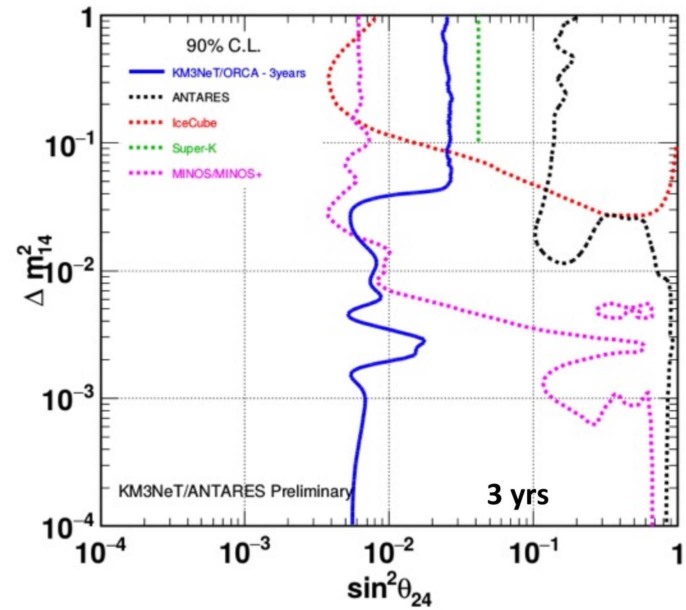
$\Delta m_{41}^2 > 0.1\ eV^2$



Dependence on δ_{24}

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

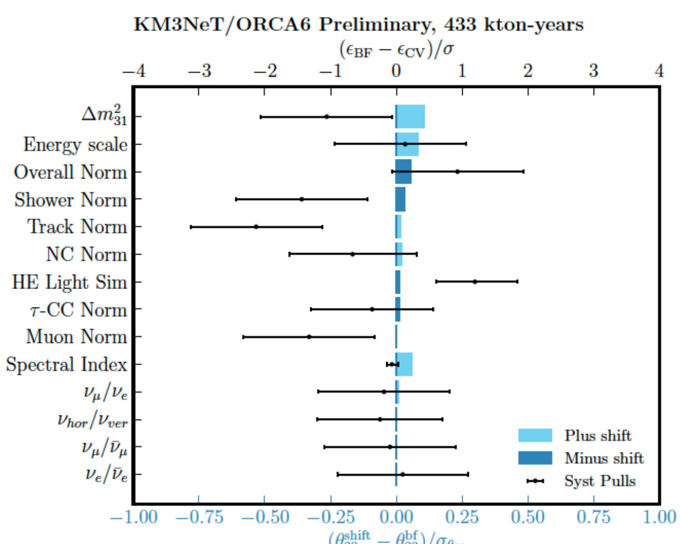
$\Delta m_{41}^2 < 0.1\ eV^2$

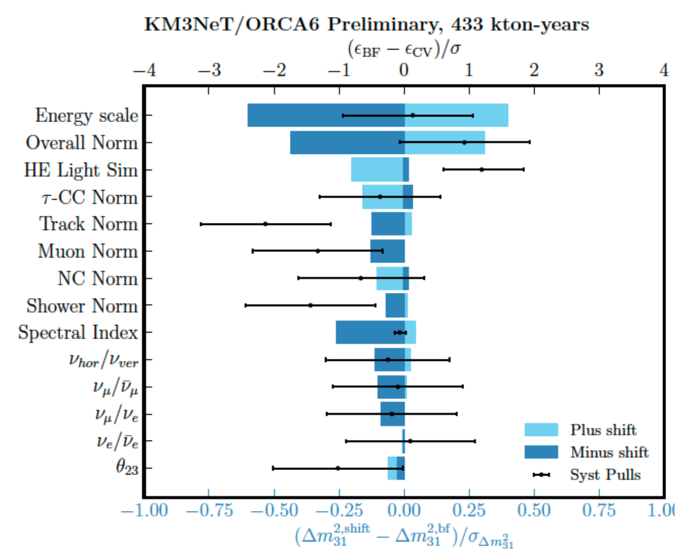


Due to longer & multiple baselines improve on MINOS/MINOS+ limits by 2 orders of magnitude

ORCA6: neutrino fit systematics uncertainties

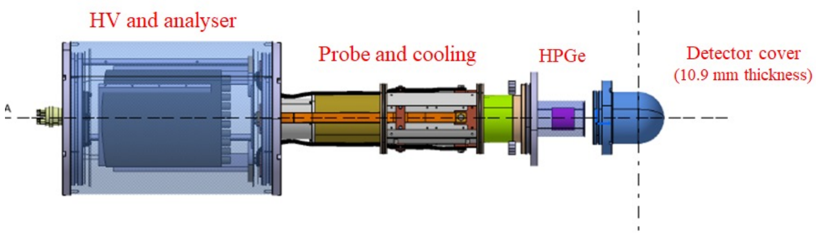
Systematic	Expectation, $\langle\epsilon_k\rangle$	Std deviation, σ_k
Overall normalisation	1	No prior
Track normalisation	1	No prior
Shower normalisation	1	No prior
NC normalisation	1	20%
τ-CC normalisation	1	20%
High Energy Light Sim.	1	No prior
Atm. muon normalisation	1	No prior
$\nu_\mu/\bar{\nu}_\mu$ skew	0	5%
$\nu_e/\bar{\nu}_e$ skew	0	7%
ν_μ/ν_e skew	0	2%
$\nu_{\mathrm{up}}/\nu_{\mathrm{hor}}$ skew	0	2%
Spectral index	0	0.3
Energy scale	1	9%

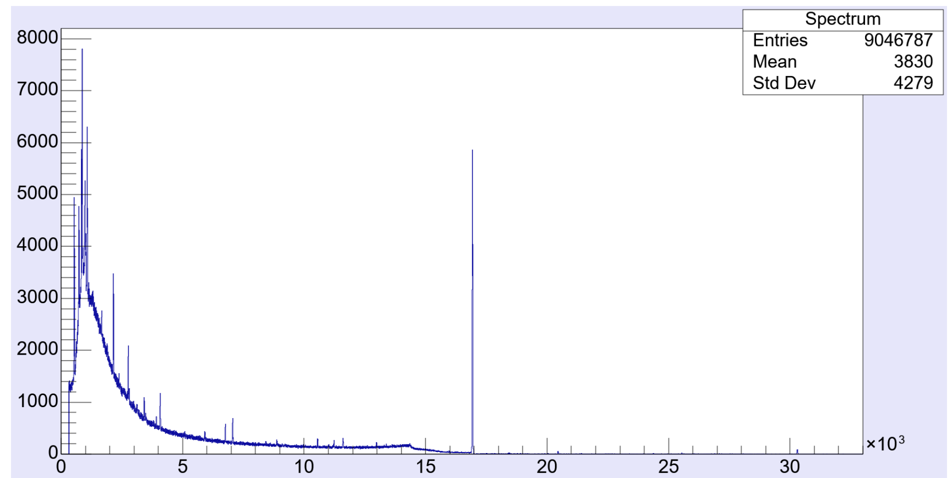




Gamma Spectrometer (Ge)

Jose Busto, Mathieu PT, Alain Cosquer





Concentrations of Natural Radionuclides in the sea

	Radionuclide	Half – life	Activity (dpm / l)
Single Long Lived	**^{40}K**	**1.25 10^9 yr**	**670**
	^{87}Rb	**4.7 10^{10} yr**	**64**
	^{129}I	**1.7 10^7 yr**	**0.06**
U and Th Chains	**^{238}U**	**4.9 10^9 yr**	**~3 – 0.2**
	… ,^{226}Ra, ^{214}Bi, ^{210}Pb … ^{206}Pb		
	^{232}Th	**1.4 10^{10}yr**	**0.005 - 0.05**
	…, ^{228}Ac, ^{212}Pb, ^{208}Tl … ^{208}Pb		
Cosmogenic	**^{3}H**	**12.26 yr**	**0.036**
	^{7}Be	**53 d**	**0.05**
	^{14}C	**5570 yr**	**0.2 - 0.3**

Anthropogenic Radionuclides

^{137}Cs, ^{60}Co, ^{90} Sr, ^{3}H, ….

First real time measurement in the deep sea
Mesurement of K40 concentrations
Identification of water masses as fn of time
Sediment transport
Geological cartography
Discharge of radioactive waste