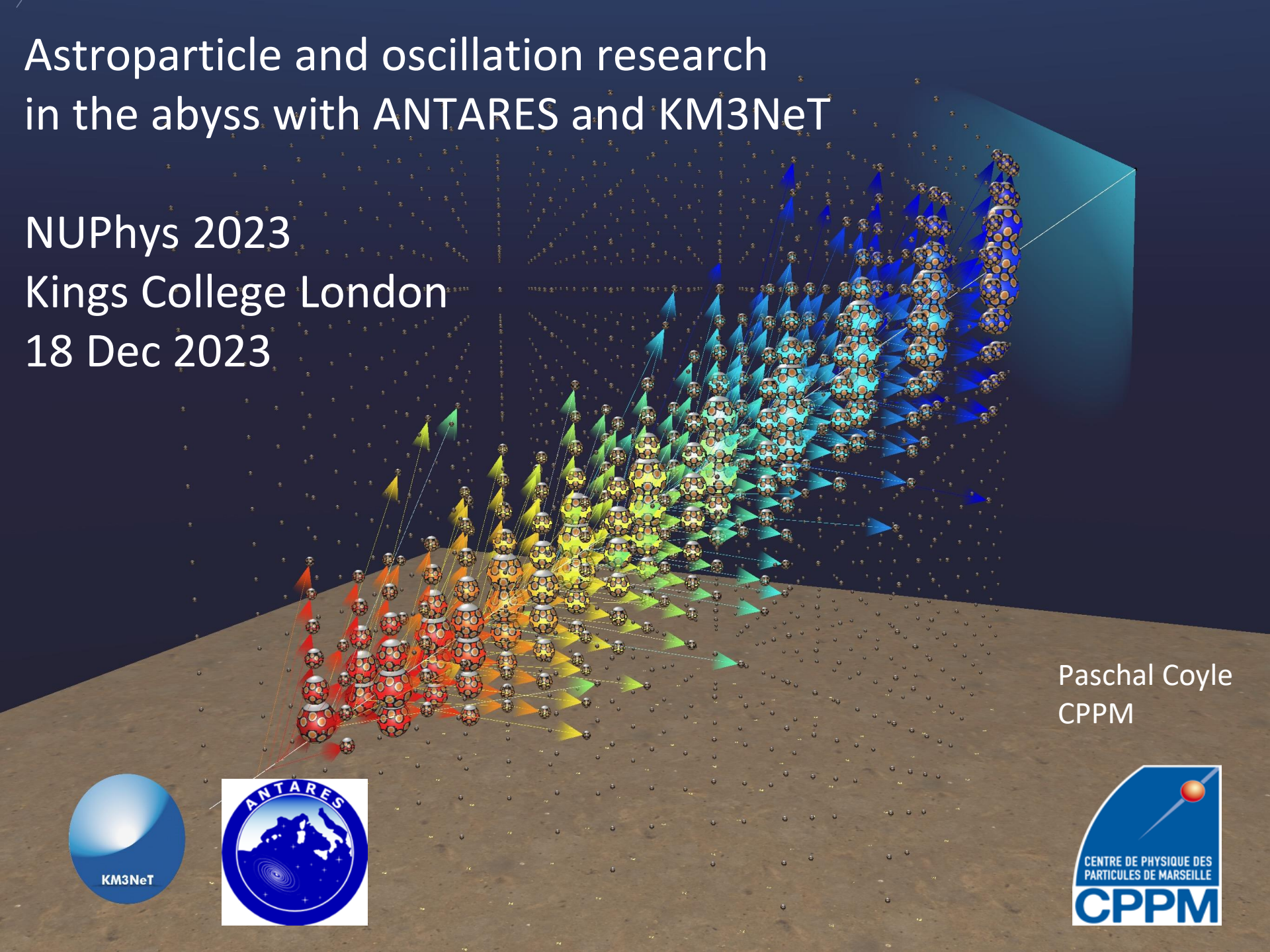
Astroparticle and oscillation research in the abyss with ANTARES and KM3NeT

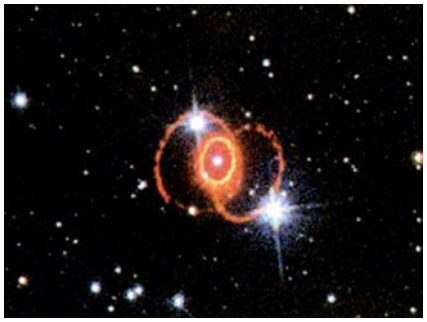
NUPhys 2023
Kings College London
18 Dec 2023

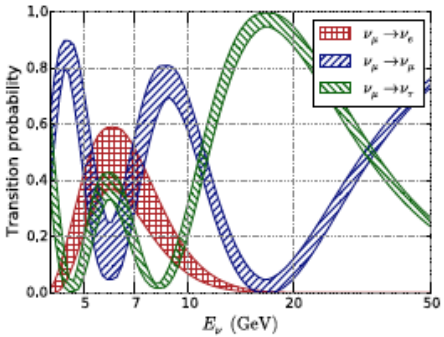


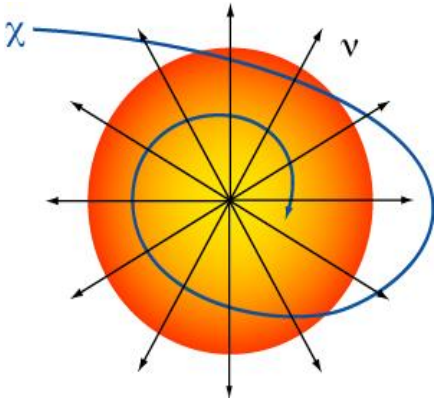
Paschal Coyle
CPPM

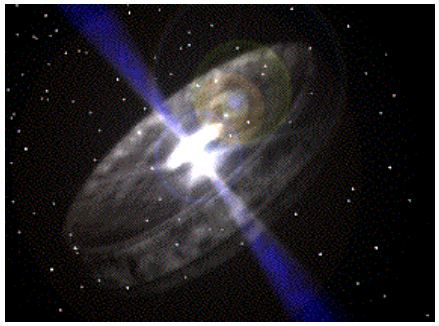
Neutrino telescopes: science

MeV to PeV energies









Supernova
Solar flares

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

Dark matter
Monopoles,
Nuclearites,…

Cosmic neutrinos

Cosmic rays

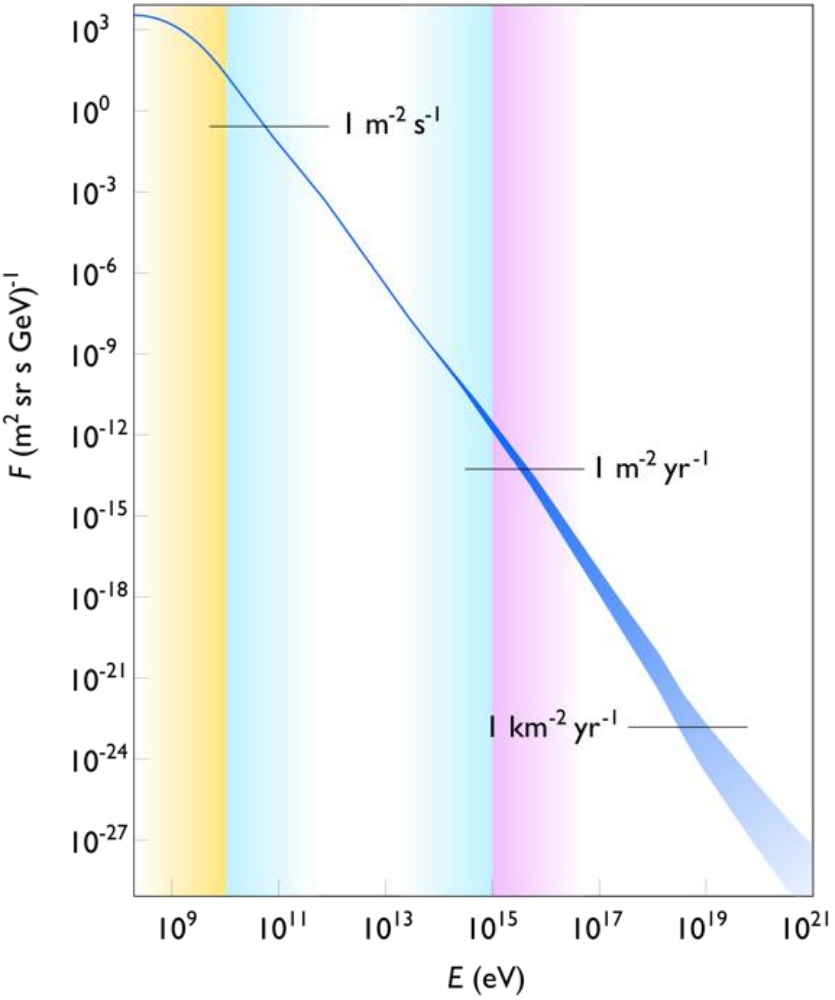
Origin and production mechanism of HE CR

KM3NeT-ORCA ANTARES KM3NeT-ARCA

+ oceanography, biology, bioacoustics, seismology,…

Motivations for neutrino astronomy

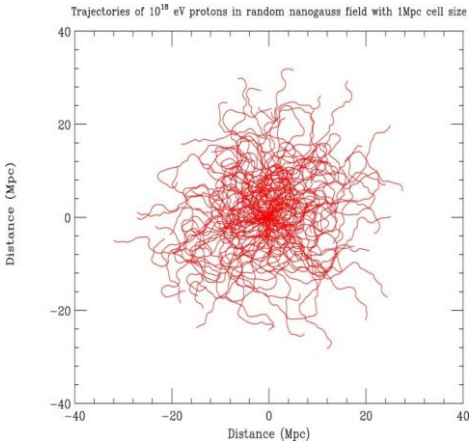
Main question: what is the origin and the role of the cosmic rays in the Universe ?



→ 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

The CR-gamma-neutrino connection

Multi-messenger connection (0th order)

Photo-hadronic interactions of CR

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

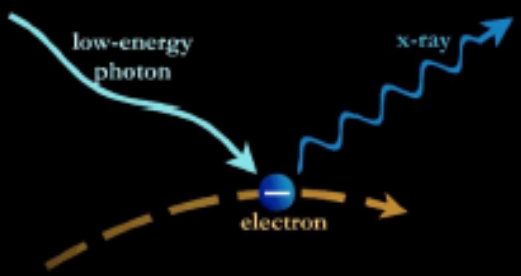
Neutrino emission

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

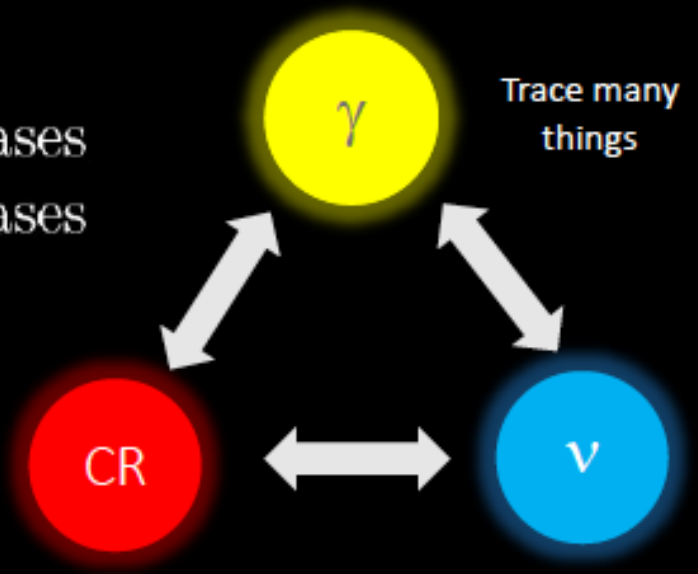
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Photon emission

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

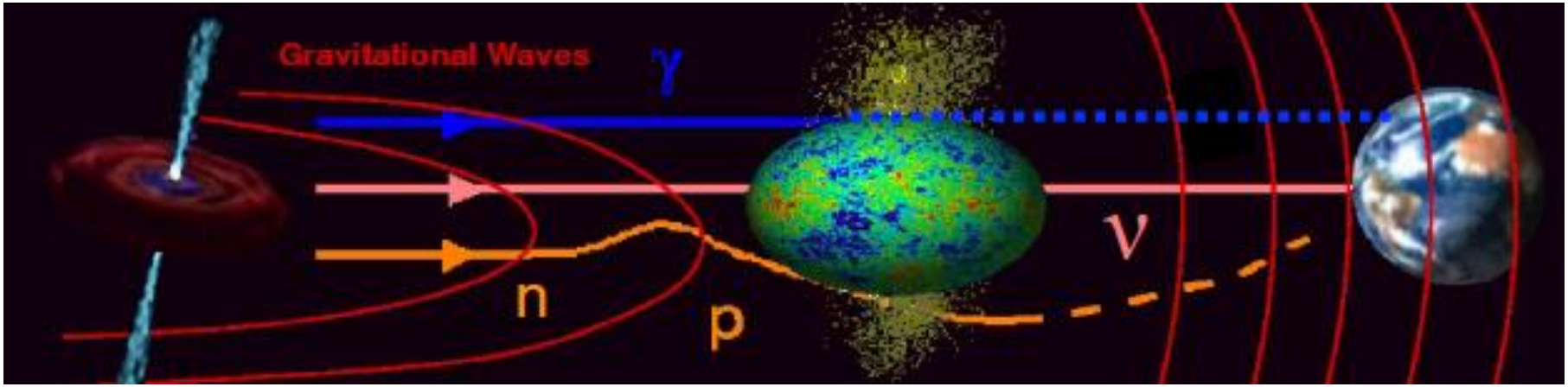


Most of the observed radiation is EM ☹



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

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

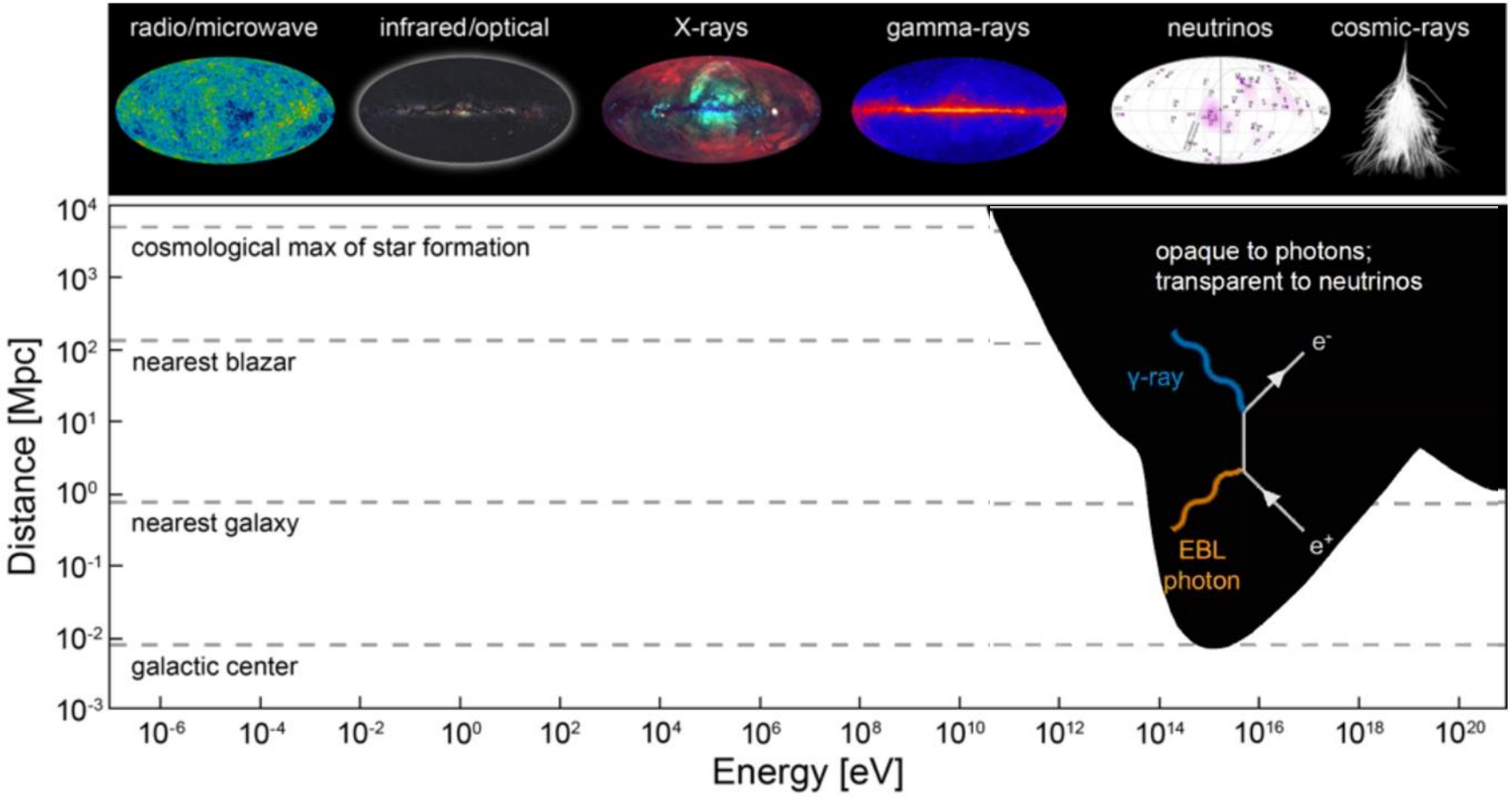
not deviated by magnetic fields ➽astronomy over full energy range

‘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

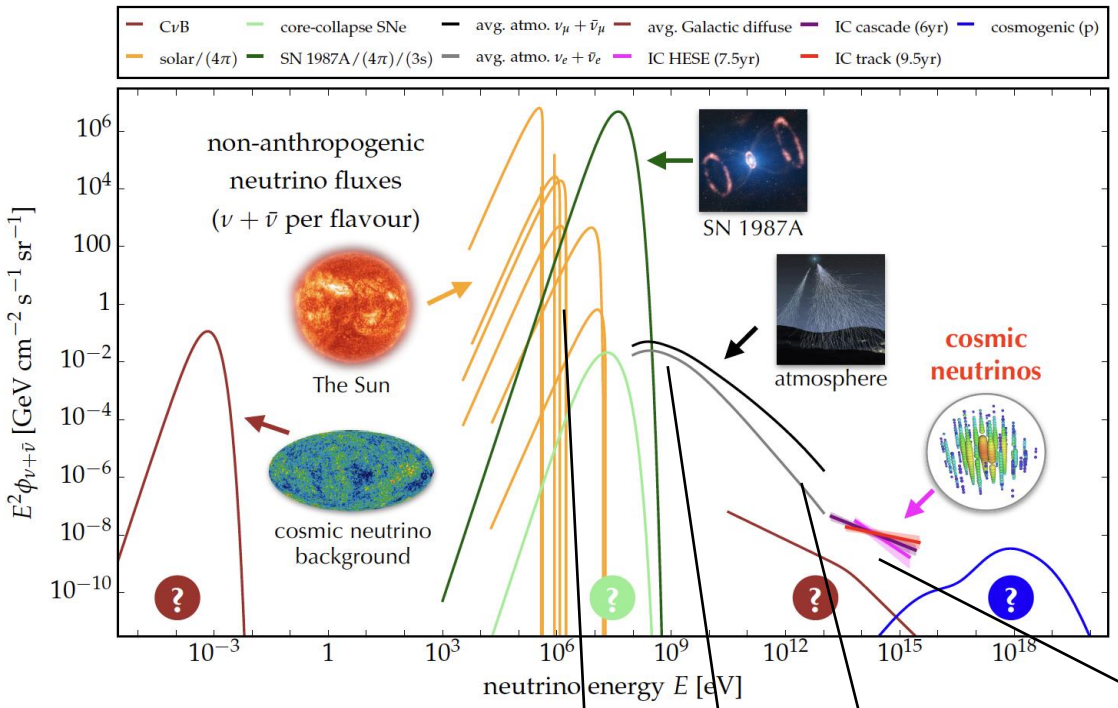


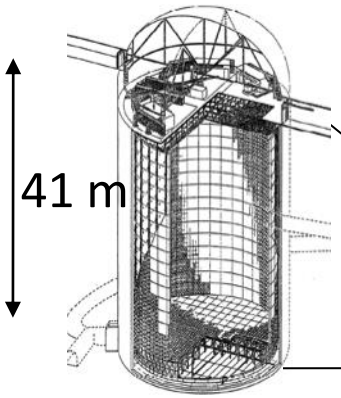
The Universe is opaque to EM radiation above 10-100 TeV, but not to neutrinos

Neutrinos fluxes from MeV to PeV

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

Need very large detectors





SuperK
50 kton

KM3NeT-ORCA
8 Mton

200m

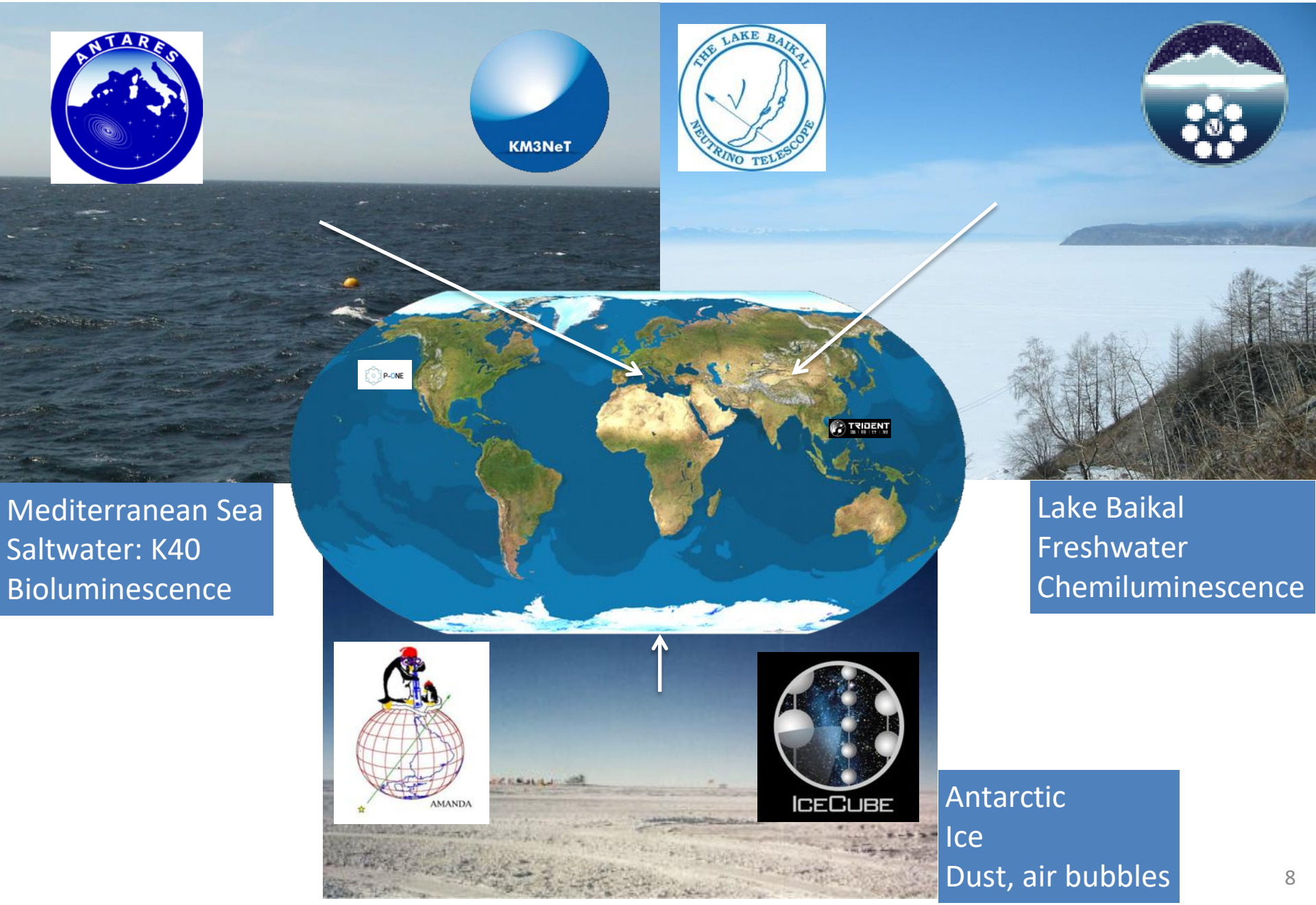
ANTARES
20
Mton

400 m

IceCube
GVD
KM3NeT-ARCA
1 Gton

1000m

Very large volume neutrino telescopes



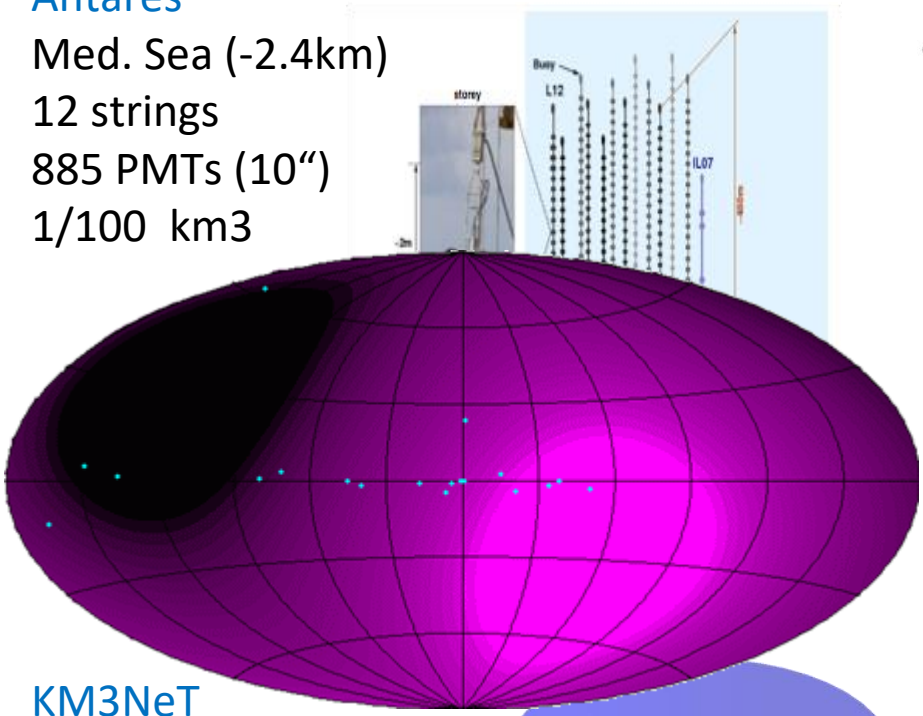
Mediterranean Sea
Saltwater: K40
Bioluminescence

Lake Baikal
Freshwater
Chemiluminescence

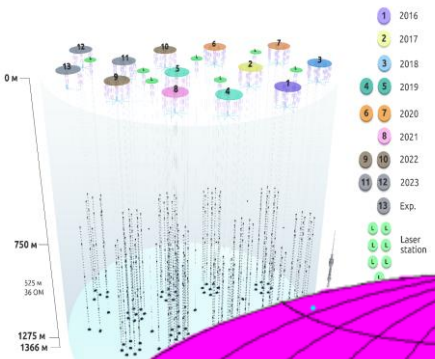
Antarctic
Ice
Dust, air bubbles

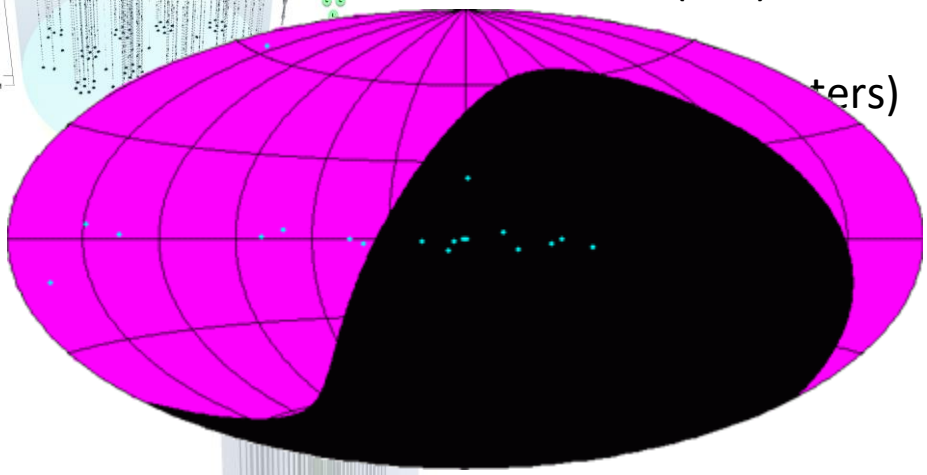
Current H20 (liquid+solid) neutrino telescopes

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



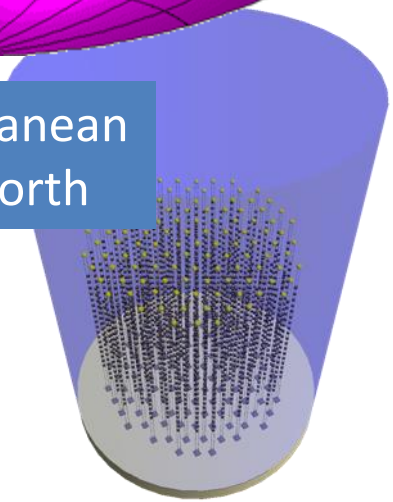
Baikal-GVD
Lake Baikal (-1.3km)
12/18 clusters of 8 strings
0.5 km3
1,728 PMTs (10”)



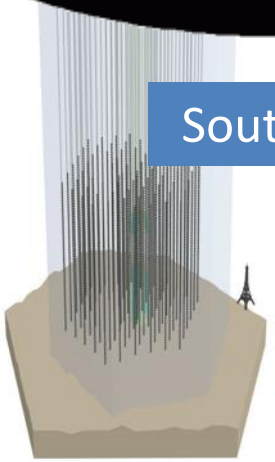


KM3NeT
Med. Sea (-2
3BB (345 stri
6000*31 PM
1.1 km3

Mediterranean
~ 43° North



South Pole

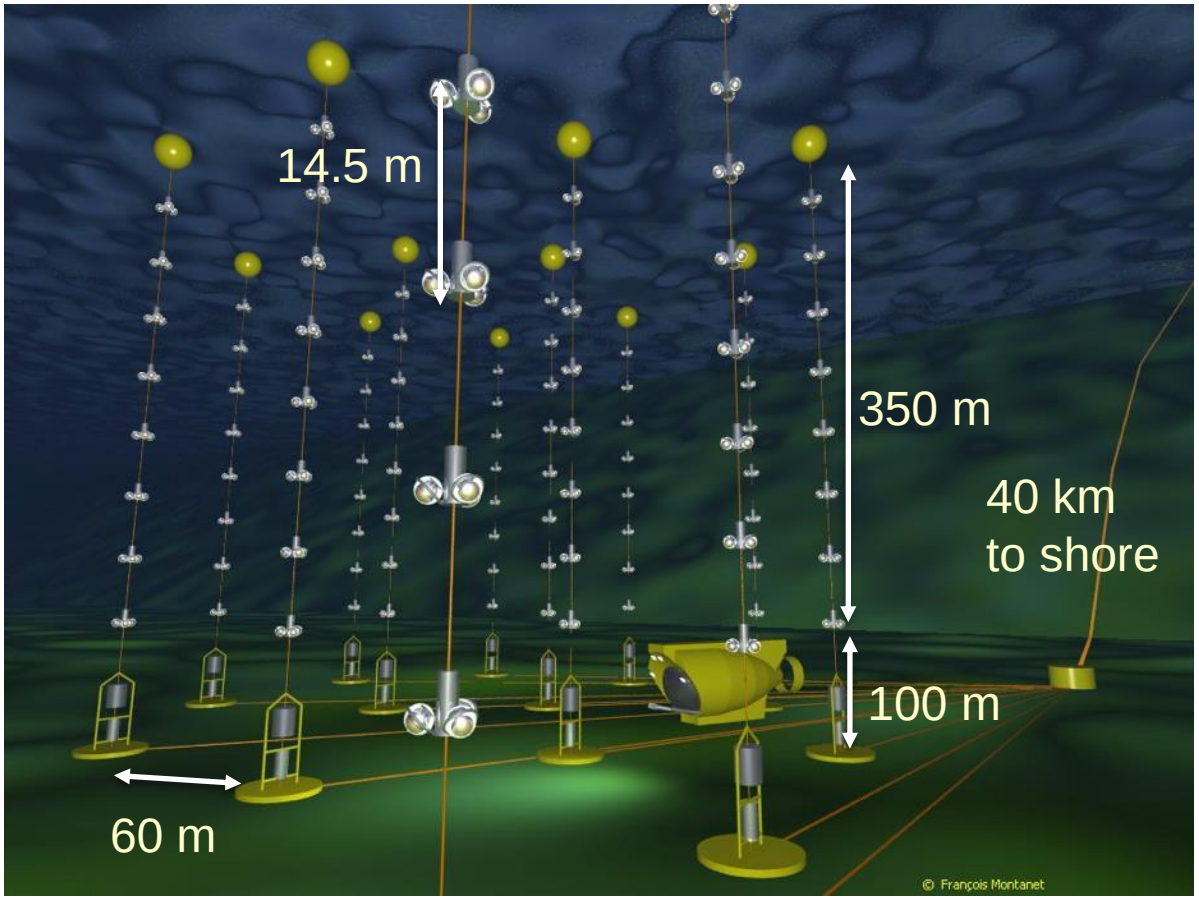


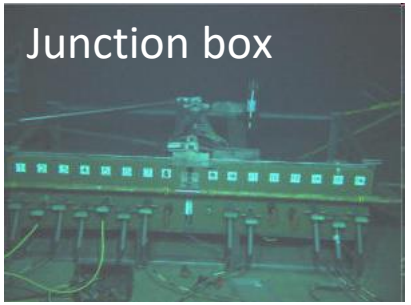
IceCube
th Pole (-2.4km)
86 strings
5160 PMTs (10”)
1 km3

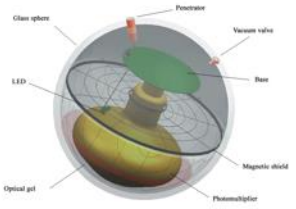
ANTARES Detector

(2008-2022)

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







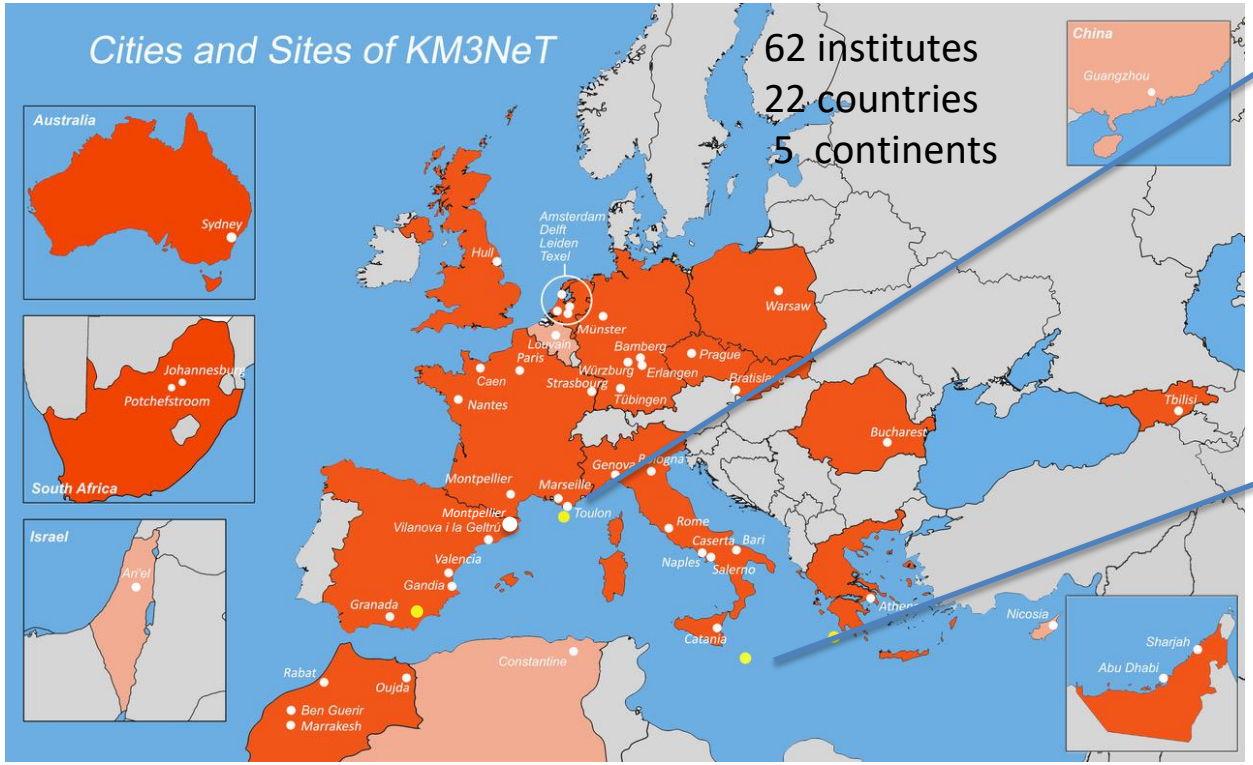
ANTARES Dismantling (feb/June 2022)

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

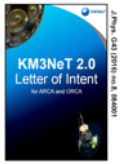
Astroparticle **R**esearch with **C**osmics In the **A**byss

+ 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



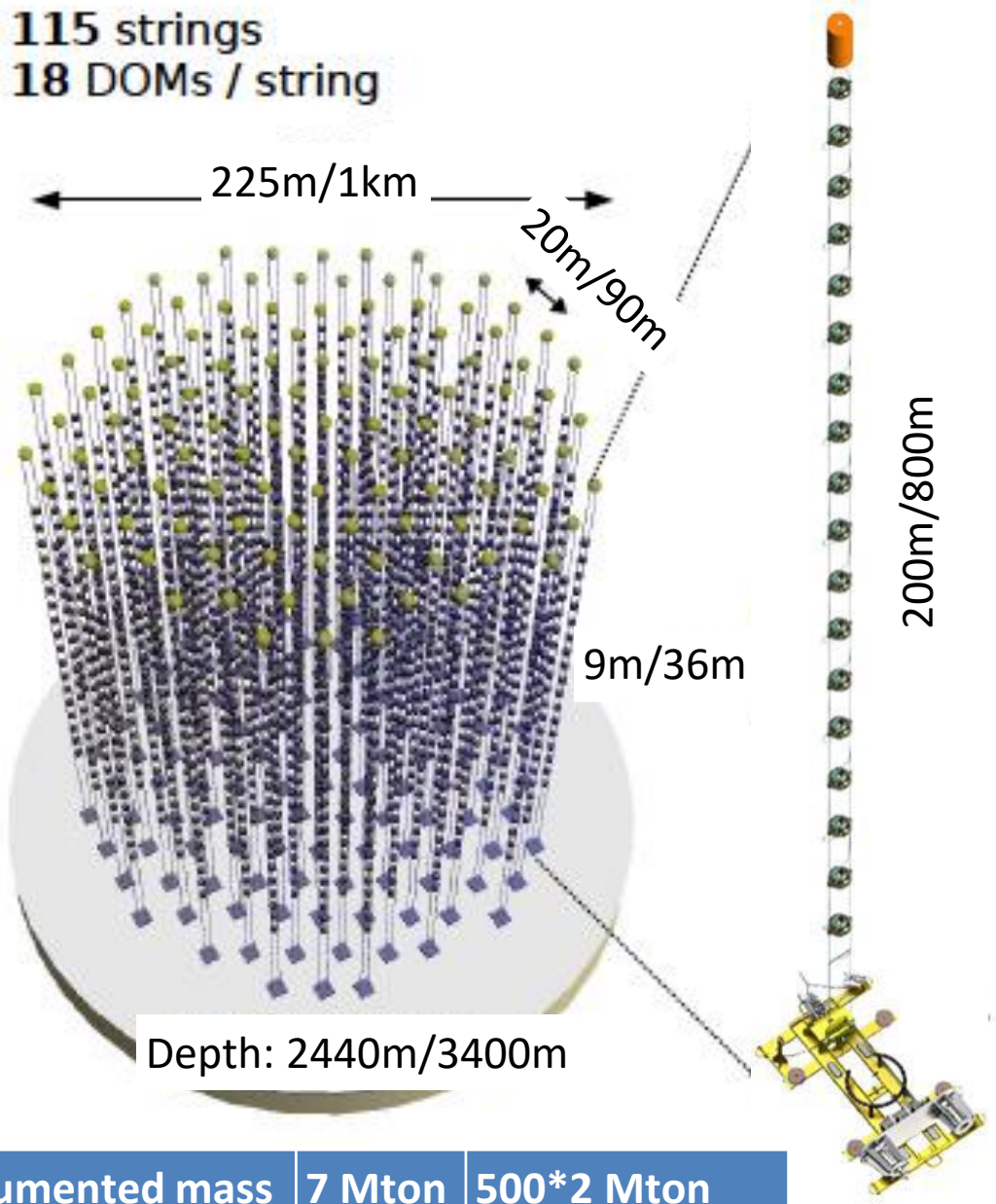
Connection nodes of

european multidisciplinary seafloor & water column observatory

emso

KM3NeT: ARCA and ORCA

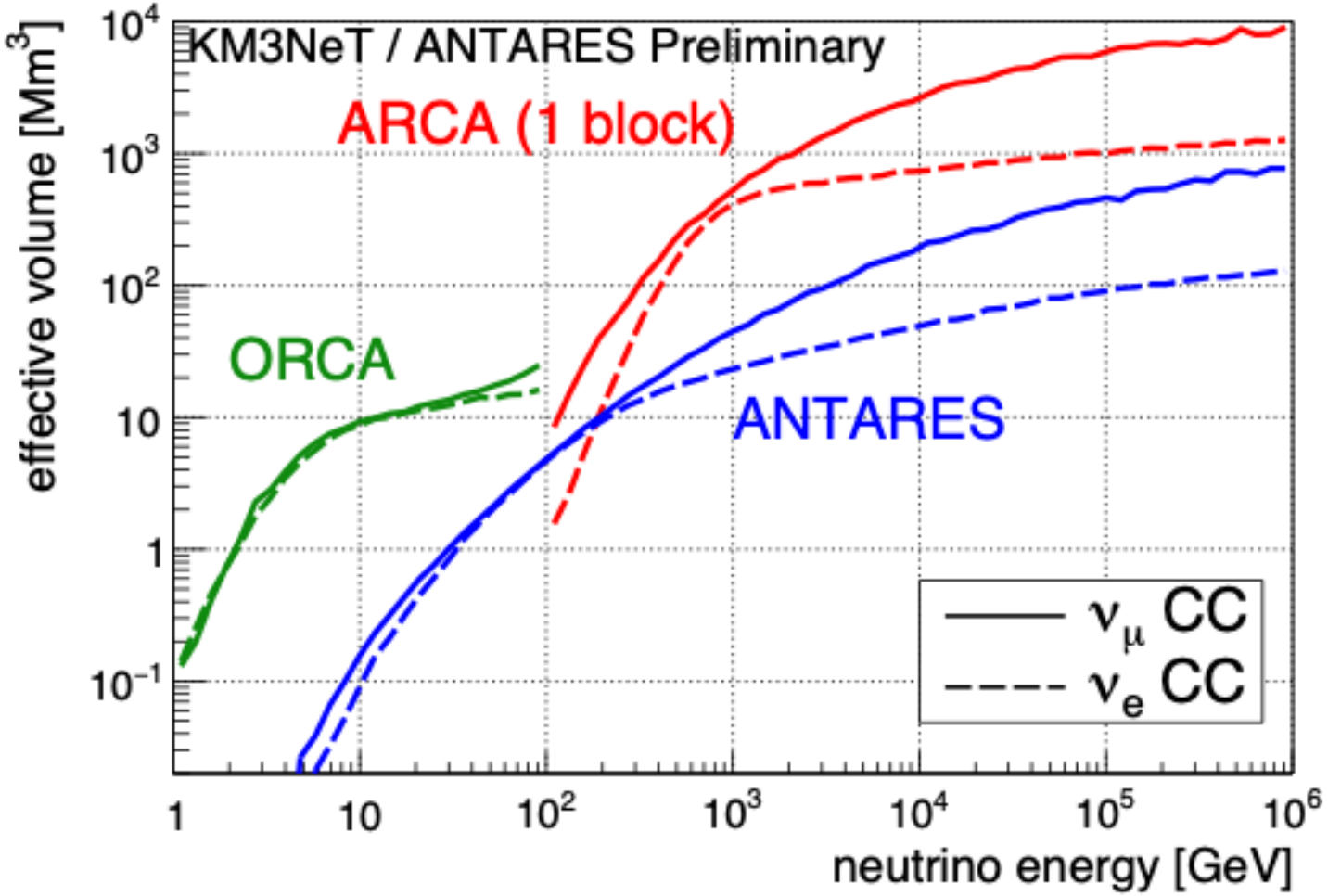
KM3NeT building block



- 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**

Effective areas: KM3NeT vs ANTARES



Detector Construction

Amsterdam

Strasbourg

Bologna

Genova

Nantes

Erlangen

Athens

Catania

Caen

Marseille

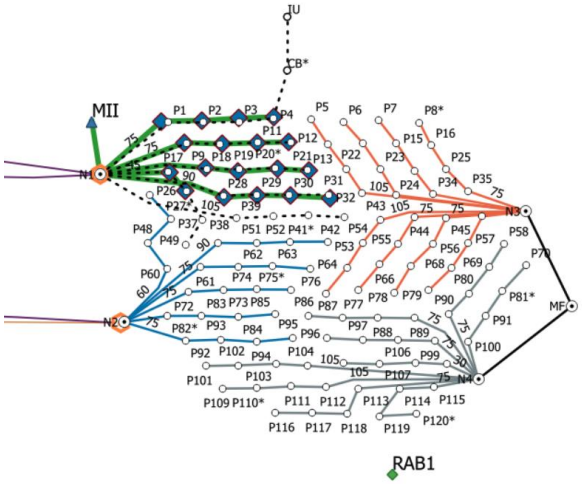
Caserta

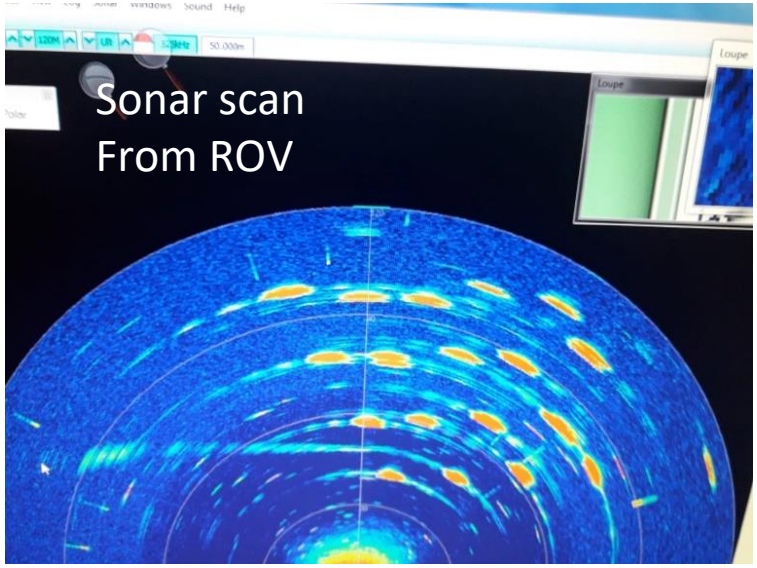
Montpellier

KM3NeT Detector Unit deployment

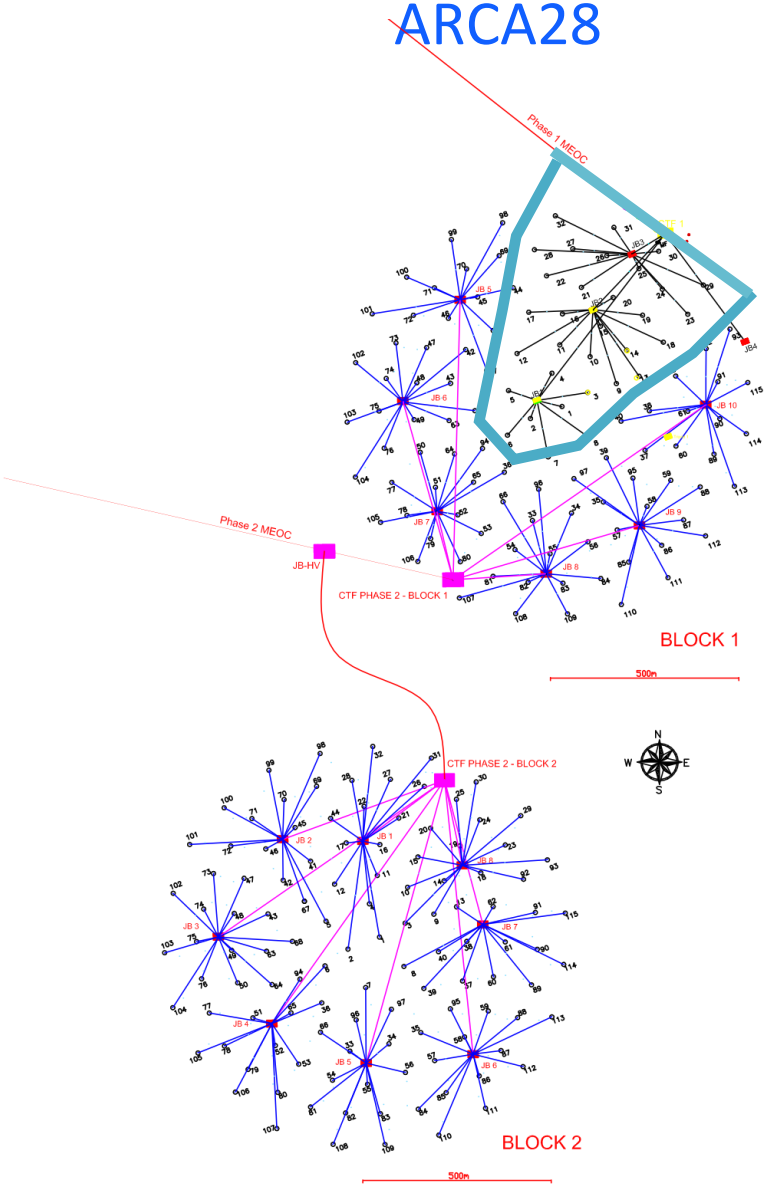
Current Status: 46 DUs deployed

ORCA18



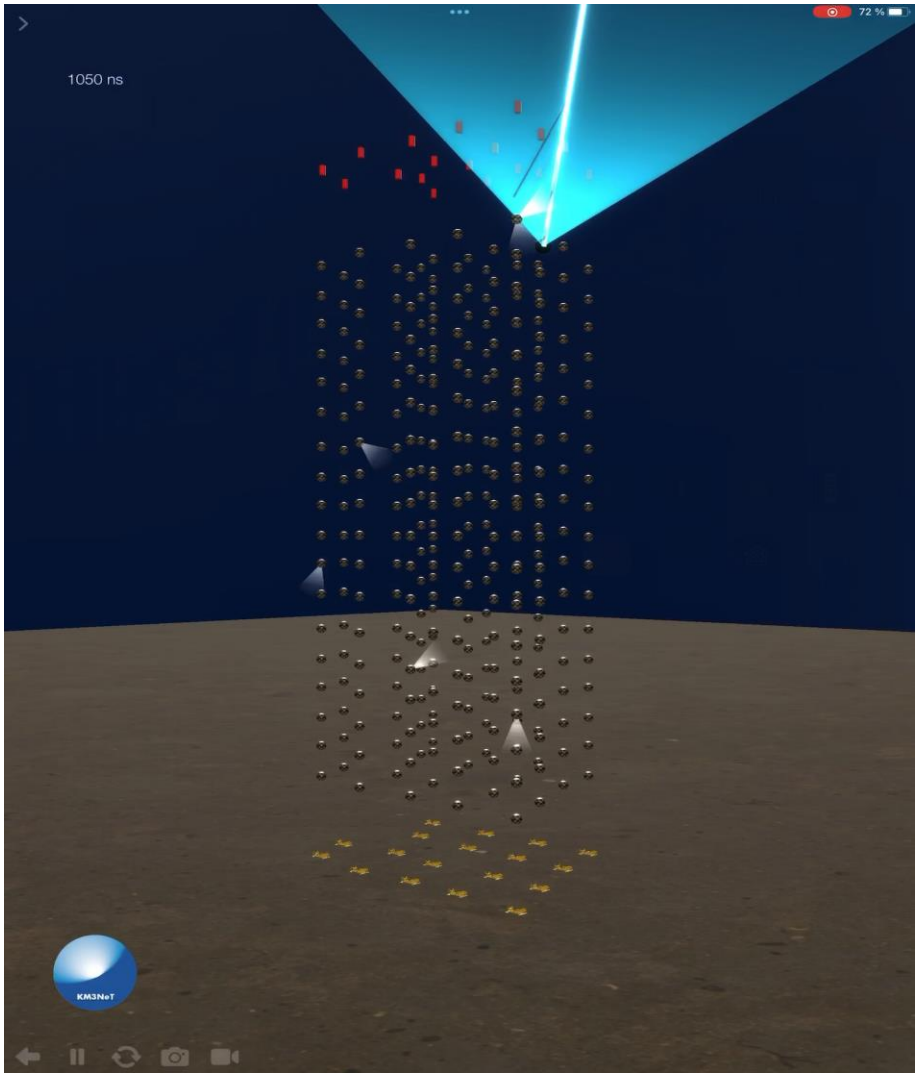


ARCA28

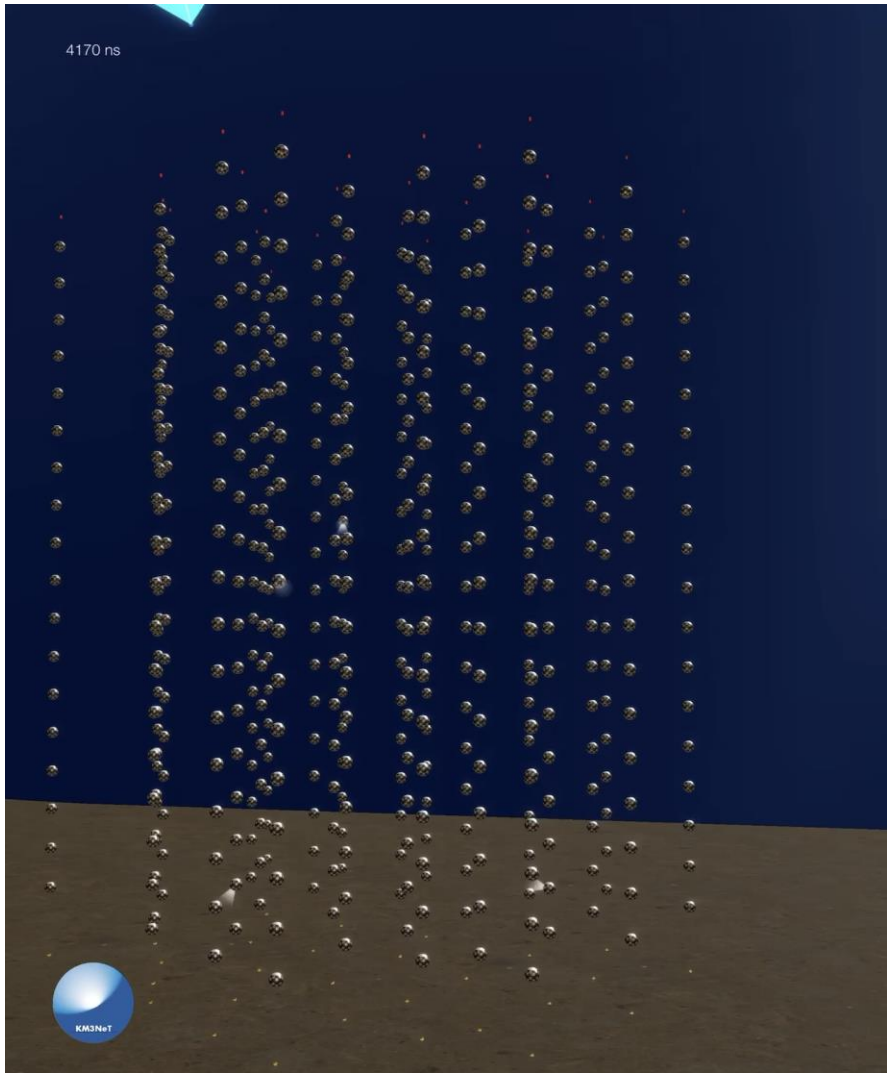


KM3NeT Event display

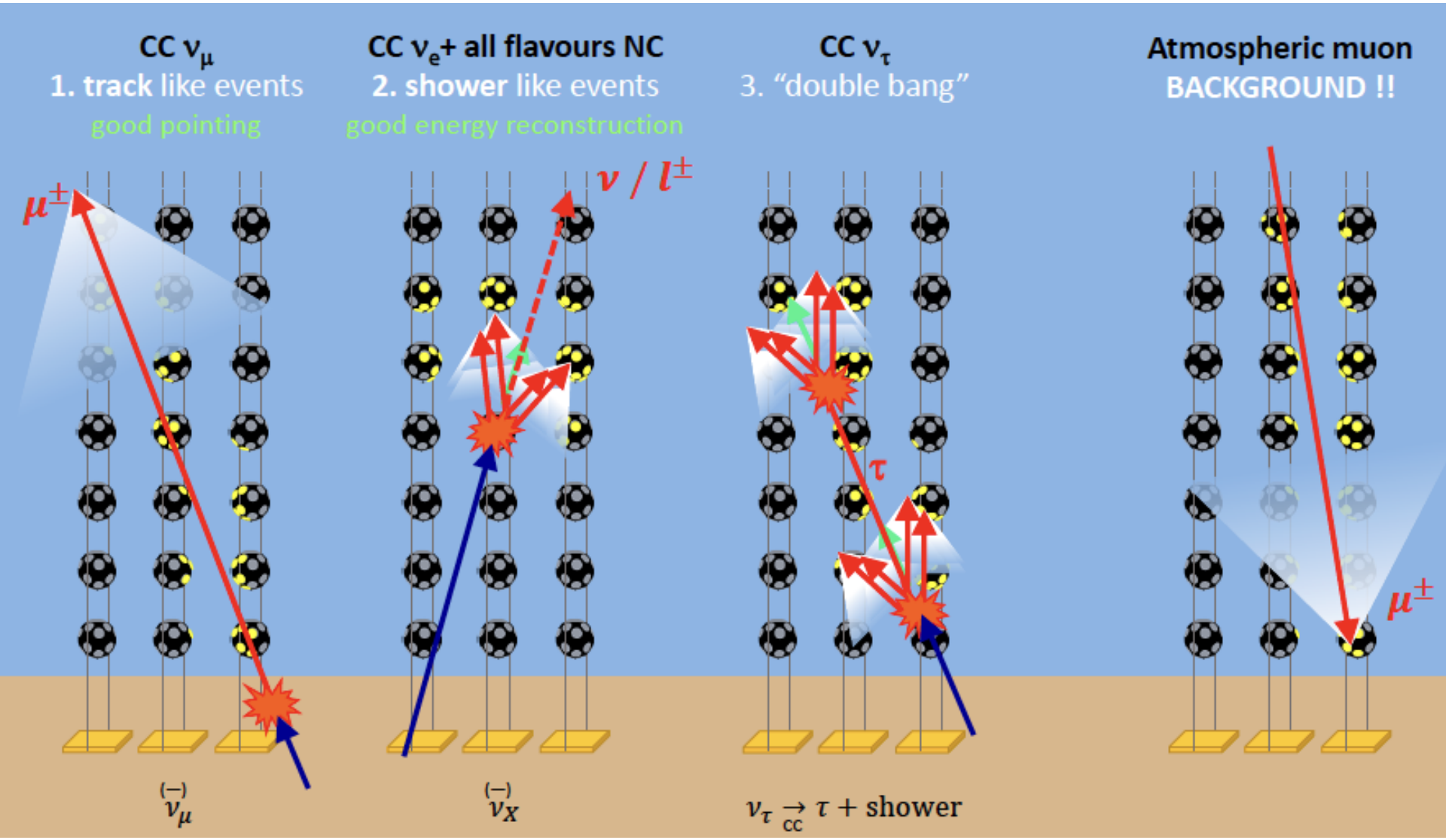
ORCA18



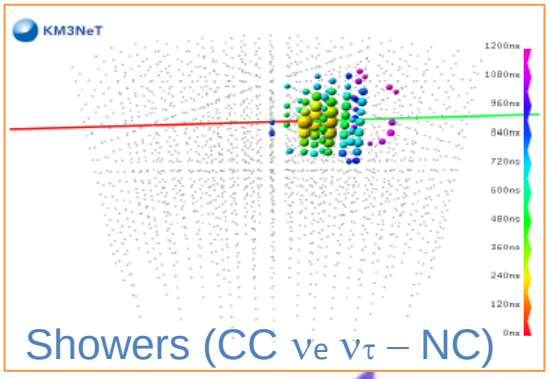
ARCA28

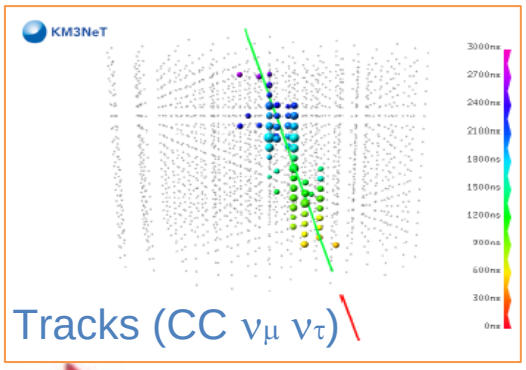


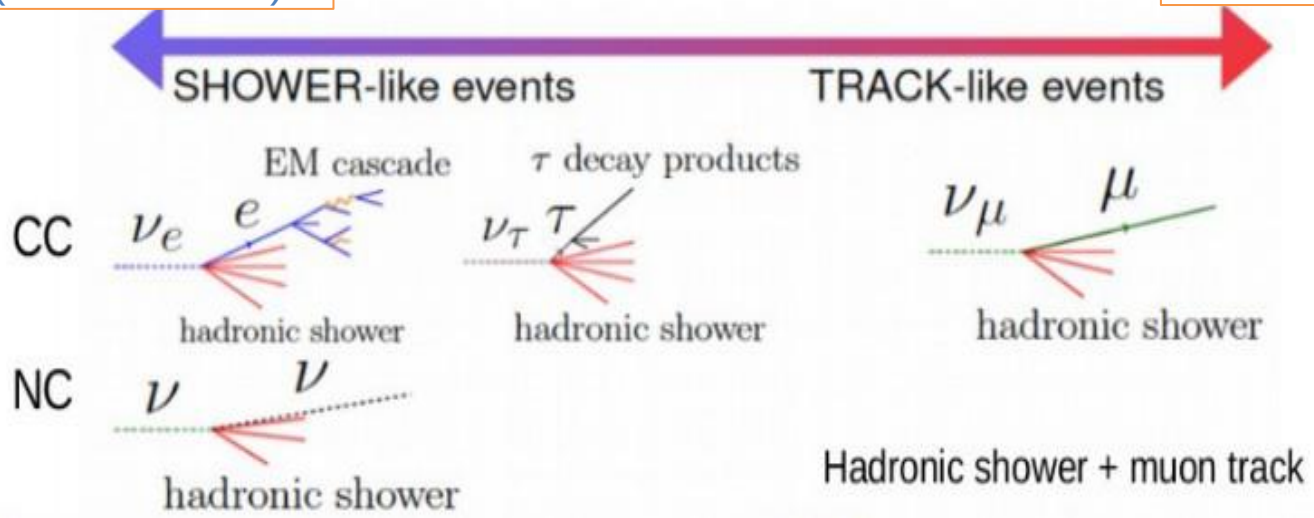
Event Topologies



Resolutions







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

Energy resolution ~ 5%

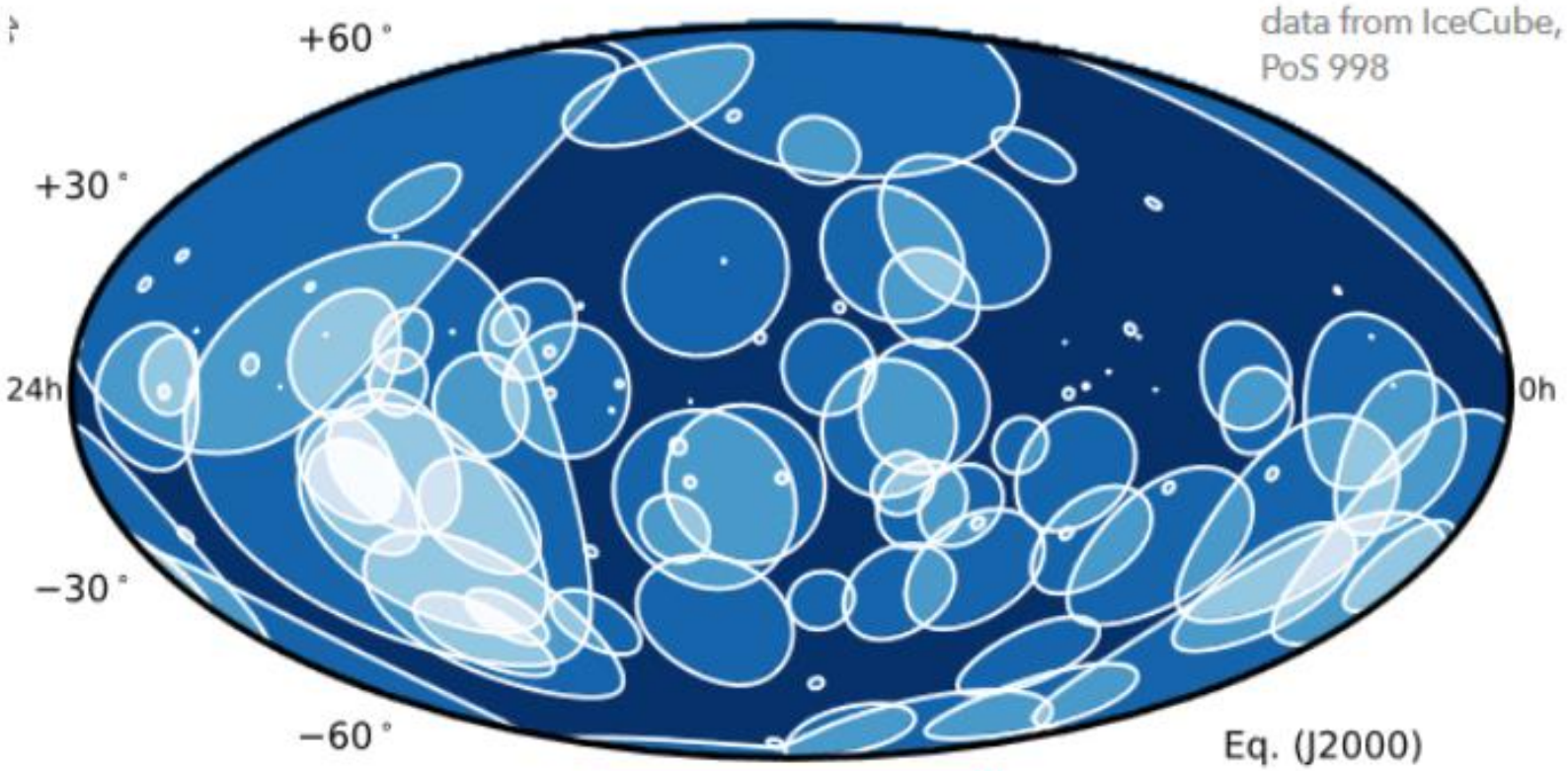
Angular resolution 0.5°/0.1°
at 100 TeV for Ice/water

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

Precision multi-flavour astronomy with water based telescopes

Resolutions: IceCube vs KM3NeT

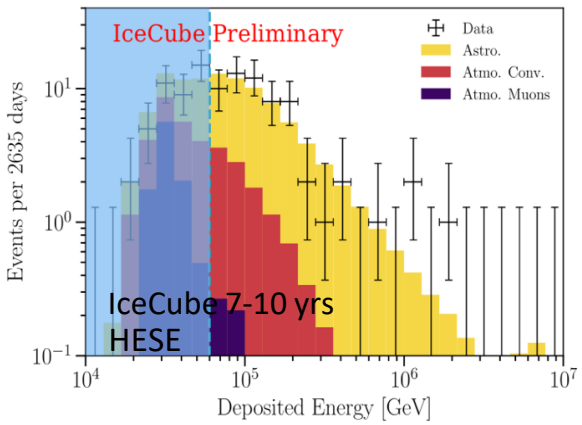
Old IceCube skymap

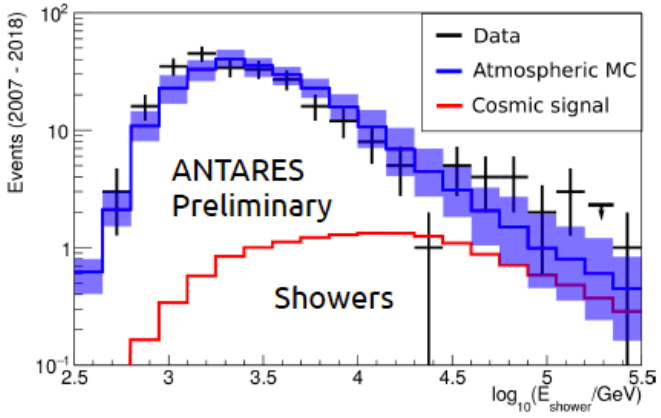


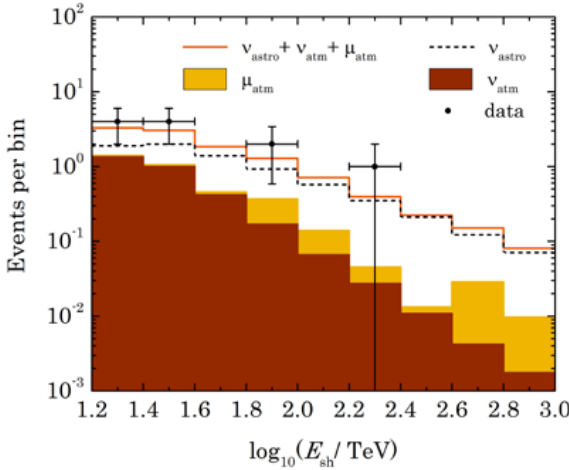
Resolution for ν_e
ANTARES ○
KM3NeT ○

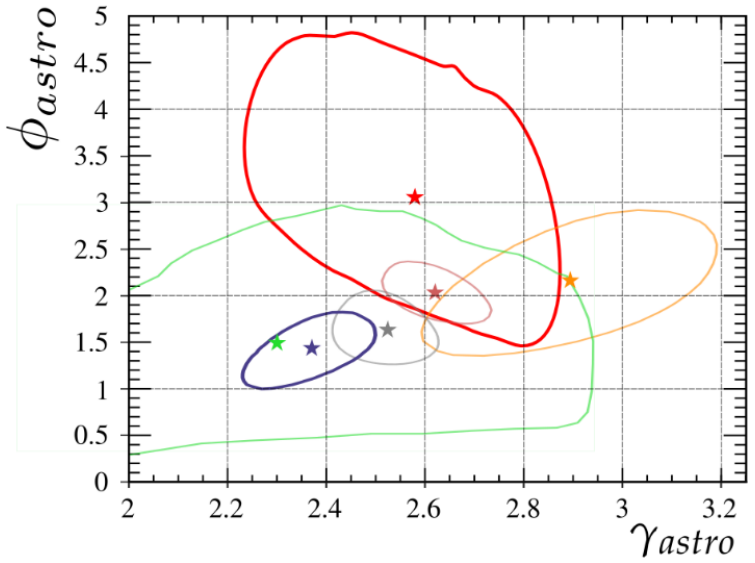
Resolution for ν_μ
ANTARES ·
KM3NeT ·

Measurements of the diffuse neutrino flux ν_e









Baikal-GVD (2018-2021, Upward-going)
this study, best fit

IceCube HESE (7.5y, Full-sky)
Phys. Rev. D 104, 022002 (2021)

IceCube Inelasticity Study (5y, Full-sky)
Phys. Rev. D 99, 032004 (2019)

IceCube Cascades (6y, Full-sky)
Phys. Rev. Lett. 125, 121104 (2020)

IceCube Tracks (9.5y, Northern Hemisphere),
The Astrophysical Journal 928, 50 (2022)

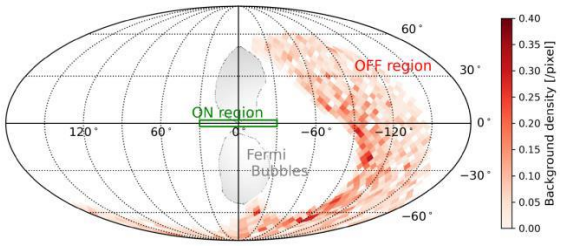
ANTARES Cascades+Tracks (9y, Full-Sky)
PoS(ICRC2019) 891 (2020)

Diffuse from Galactic Plane

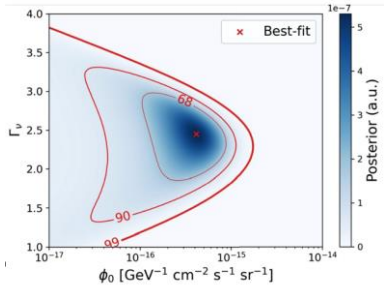
ANTARES 2007-2020 data

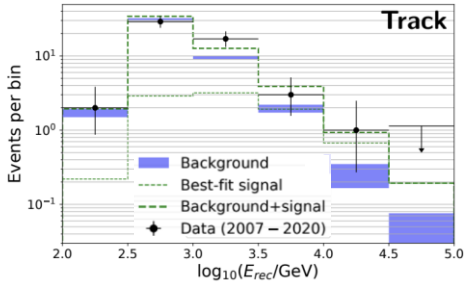
Phys. Lett. B 841 (2023), p. 137951

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

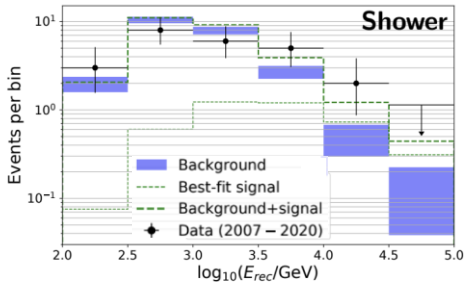


ICRC2023 PoS 1103





(a) Track-like events



(b) Showering-like events

For E_ν>1 TeV

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

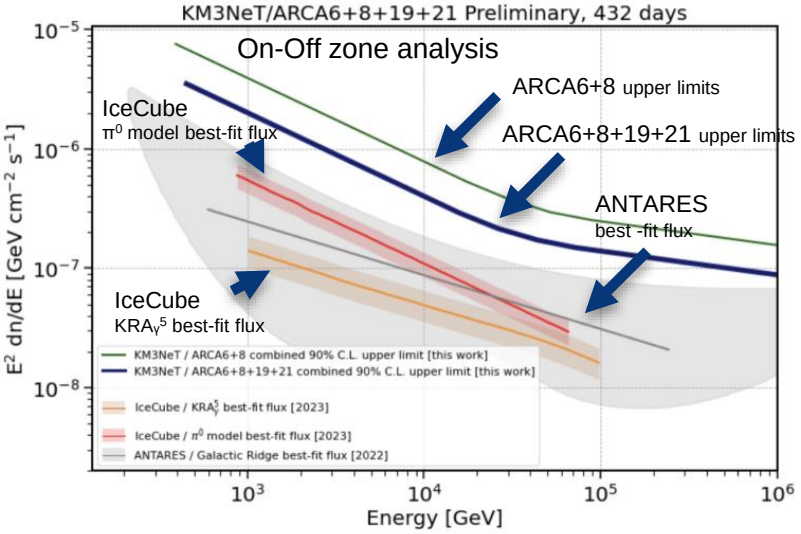
13 shower events observed -> (11.2±0.9 back. expected

KM3NeT

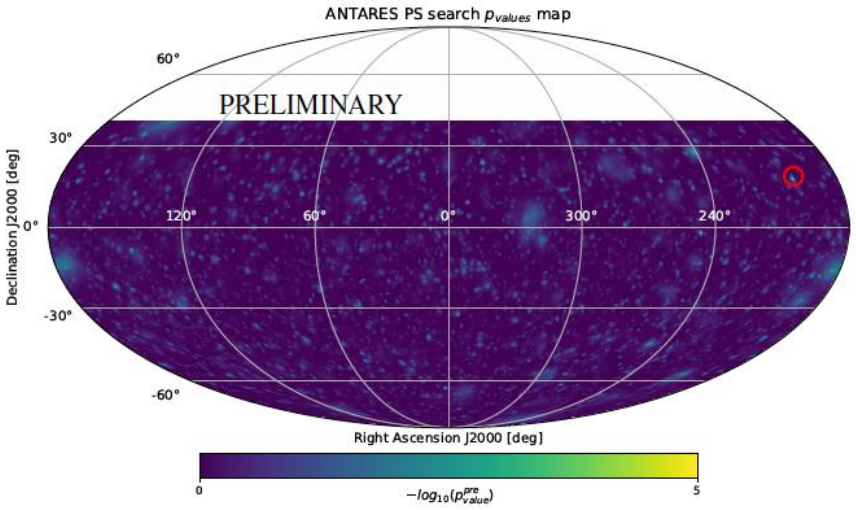
ICRC2023 PoS 1190

|l| < 31° and |b| < 5° for KM3NeT/ARCA6-8 and
|l| < 31° and |b| < 4° for KM3NeT/ARCA19-21

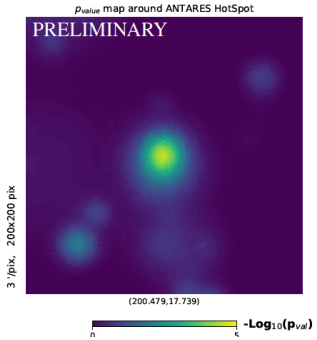
ARCA6 & ARCA8 & ARCA19 fully analyzed
ARCA21 partially analyzed (until December 2022)

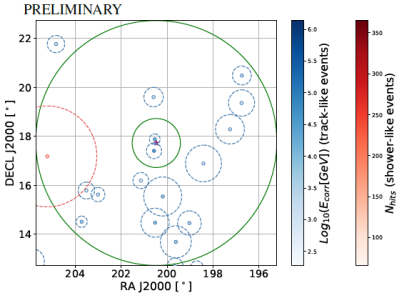


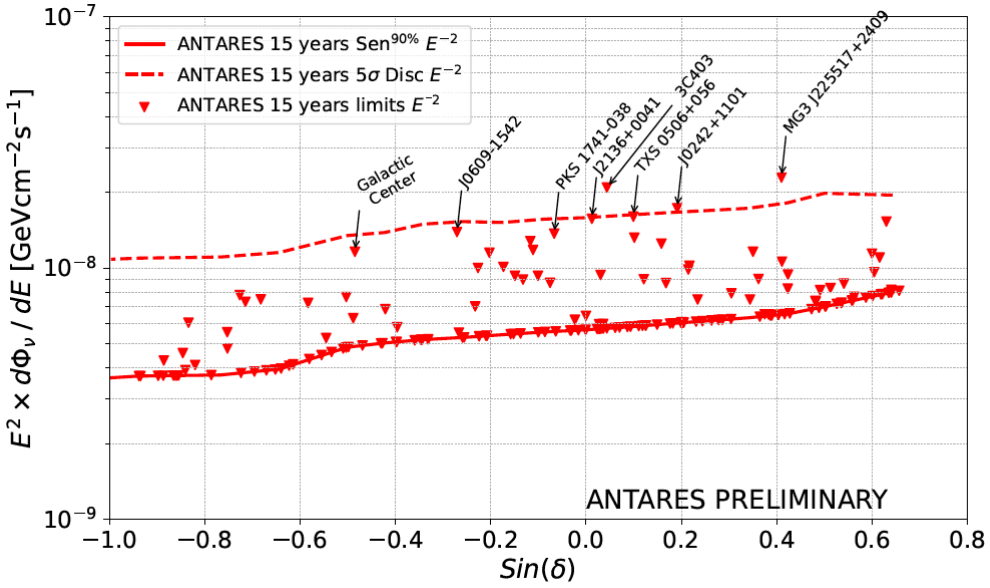
ANTARES point source searches (15 years)



Hotspot (α, δ)=(200.46, 17.74)

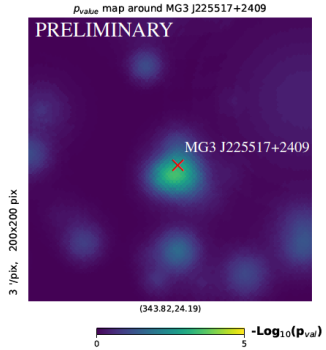


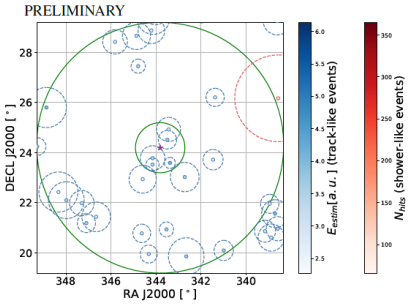




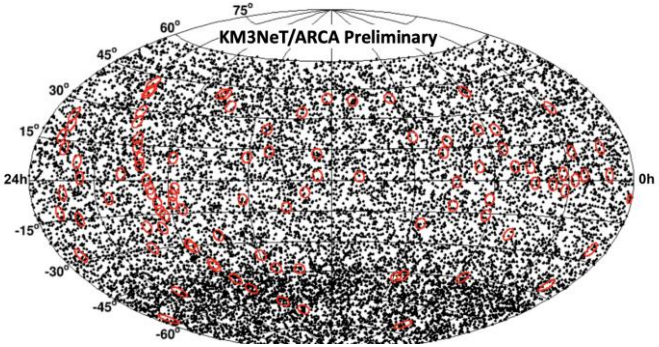
MG3 J225517+2409 (3.4 σ pre-trial)
3C403 (3.4 σ pre-trial)
J0242+1101 (2.6 σ pre-trial)
J2136+0041 (2.4 σ pre-trial)
TXS 0506+056 (2.4 σ pre-trial)

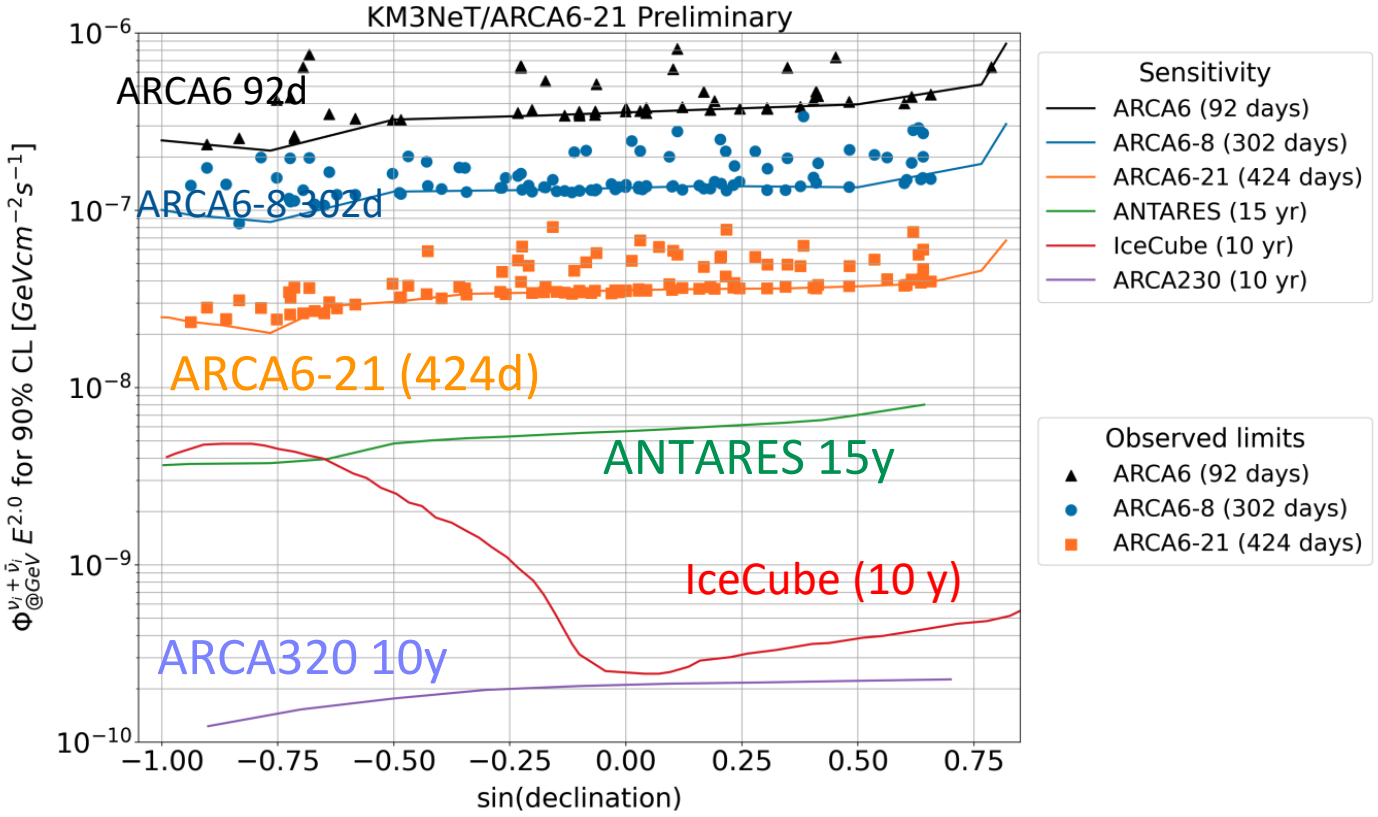
MG3 J225517+2409 (3.4 σ pre-trial) BL Lac





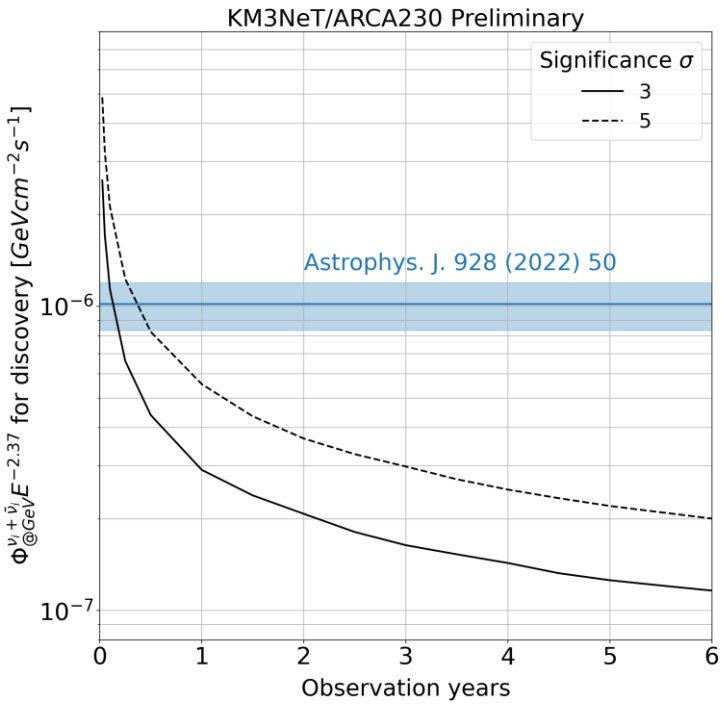
KM3NeT point source searches





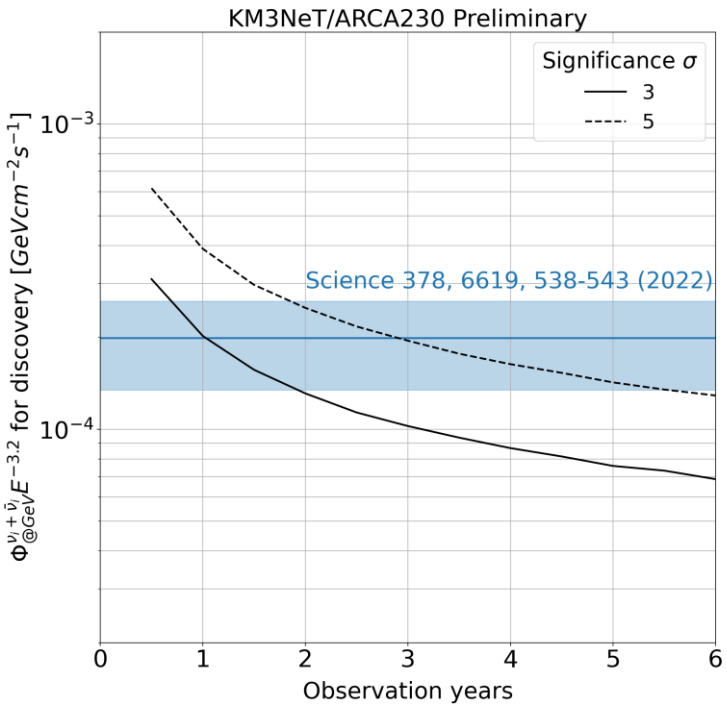
KM3NeT expected sensitivities

Diffuse flux



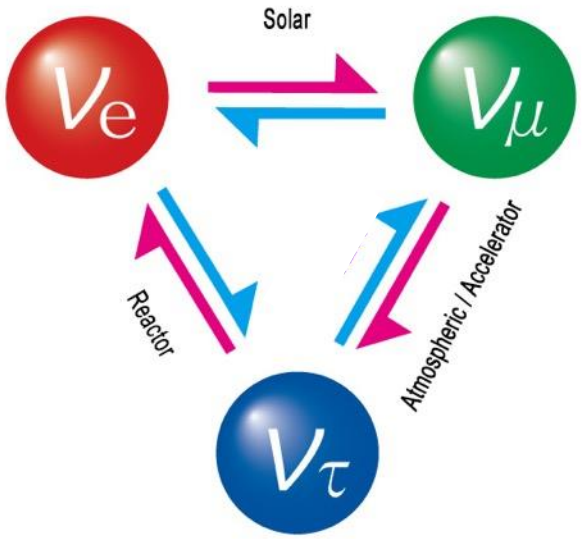
5σ in ~ 0.5 year for the full detector (230 DUs)

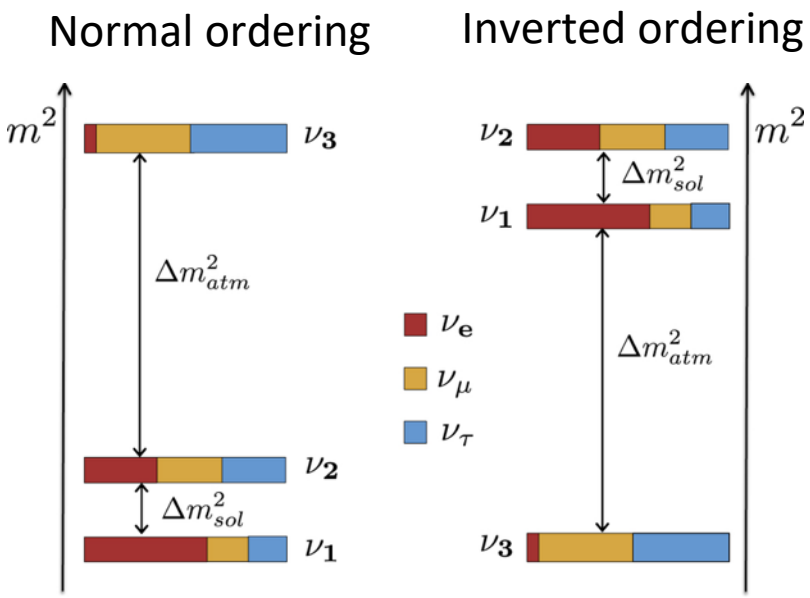
NGC1068

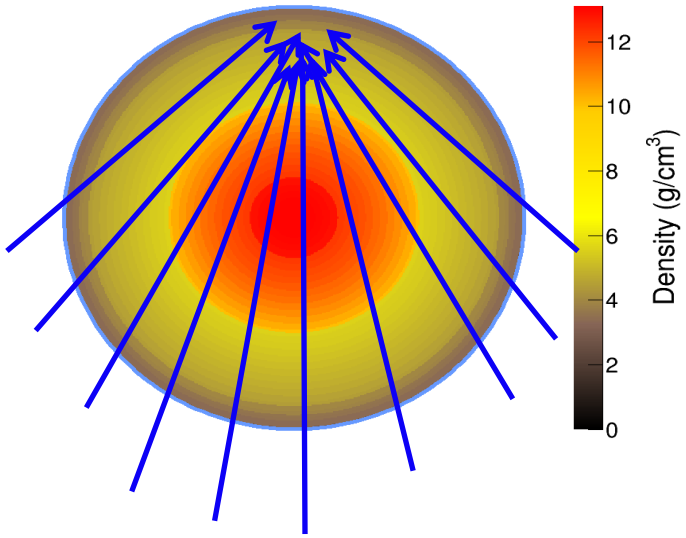


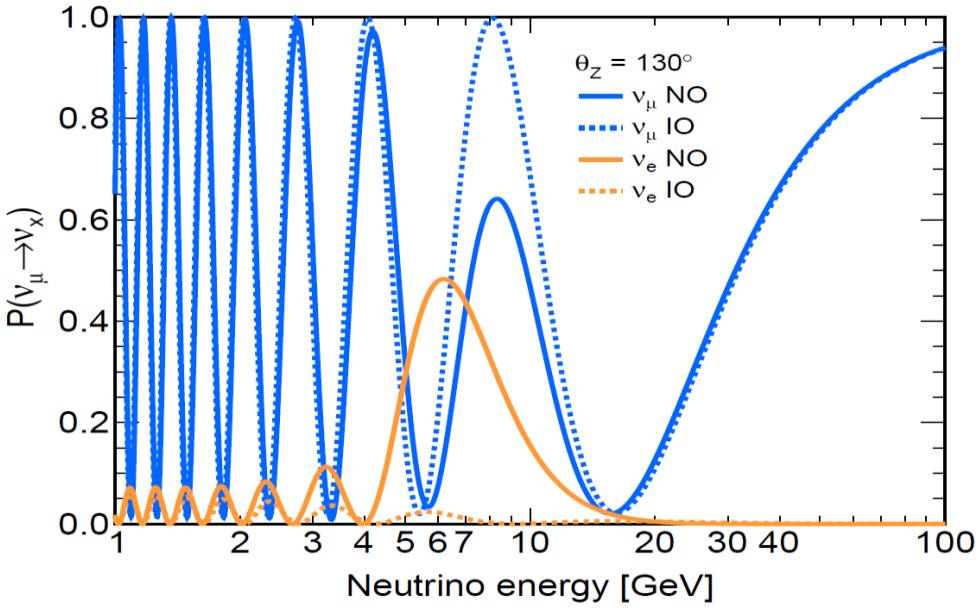
3σ in one year

Neutrino oscillations with atmospheric neutrinos

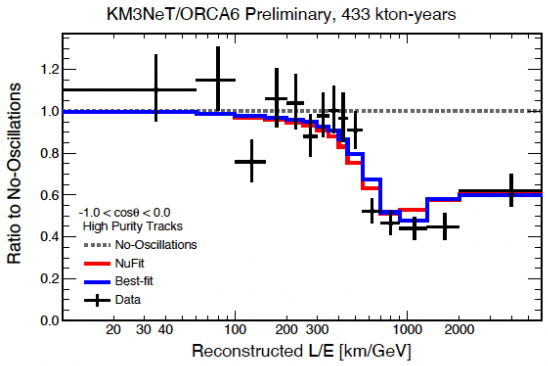




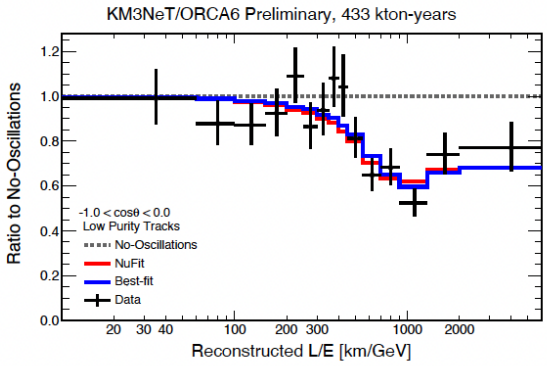




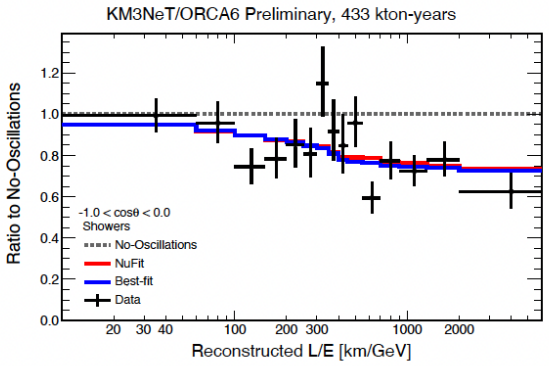
New oscillation results with ORCA6



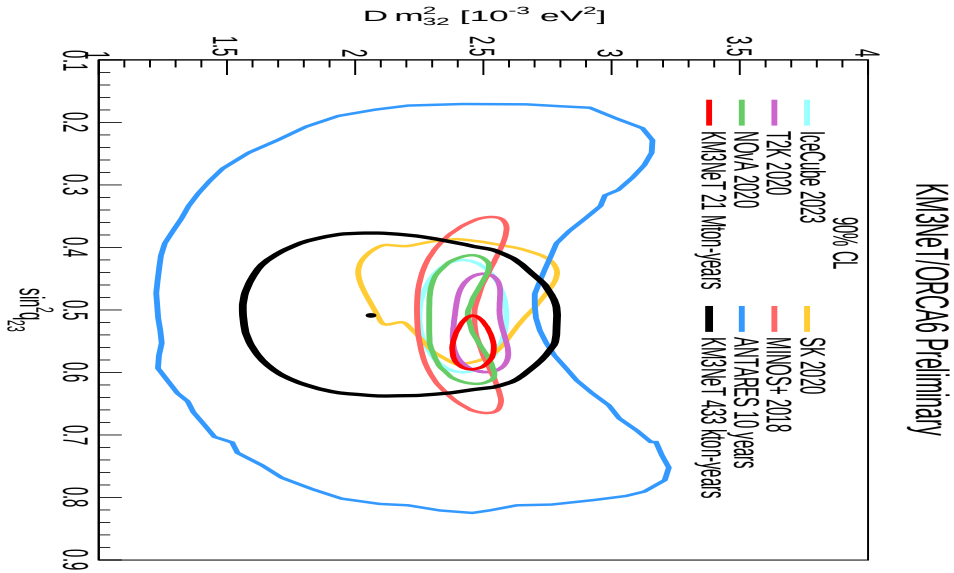
High Purity Tracks



Low Purity Tracks



Showers



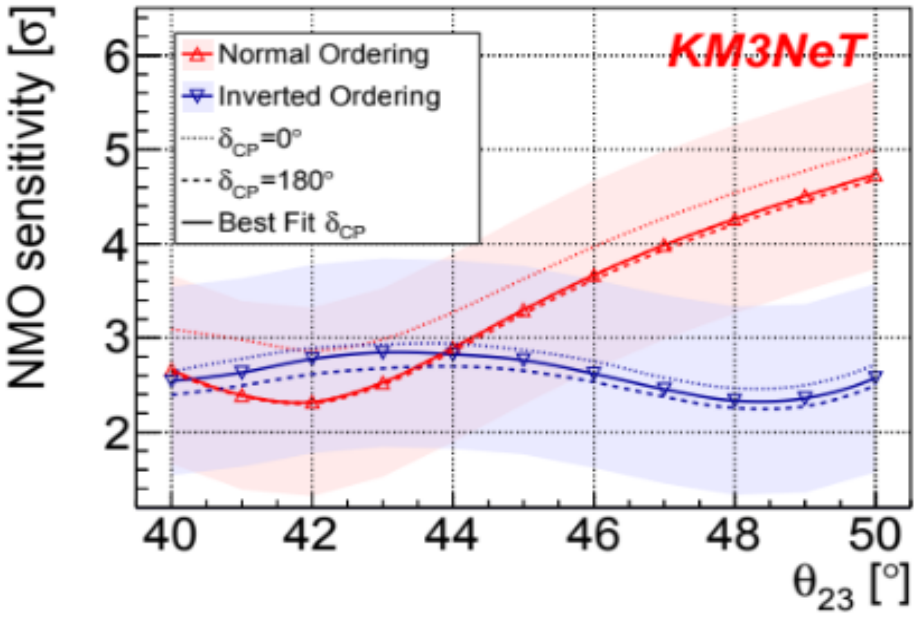
- Best-fit: $\sin^2\theta_{23} = 0.51^{+0.06}_{-0.07}$

and $\Delta m^2_{31} = 2.14^{+0.36}_{-0.25} \cdot 10^{-3}\text{eV}^2$.

Normal Ordering favoured at delta_chi2=0.9

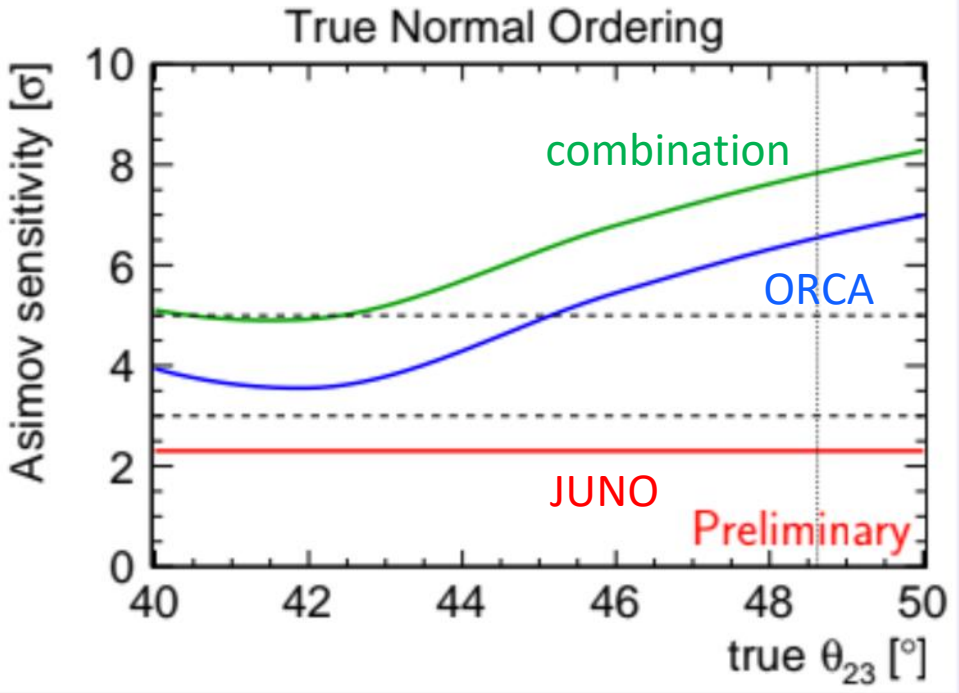
ORCA115: neutrino mass ordering

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

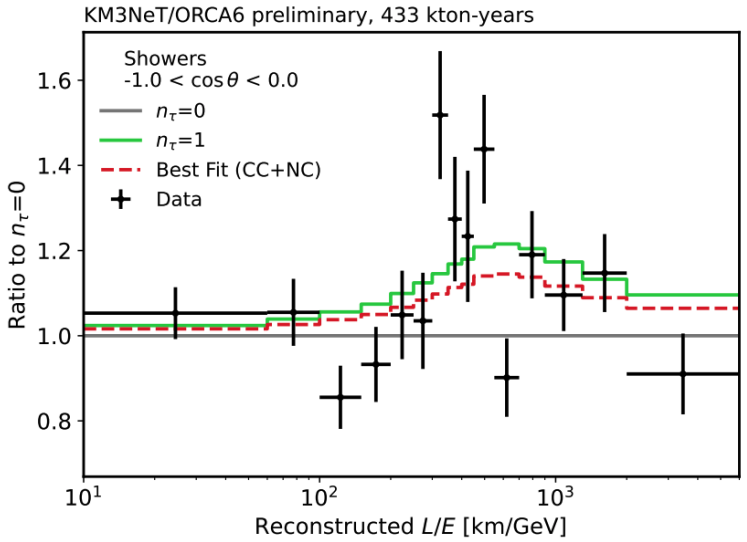
Tau appearance

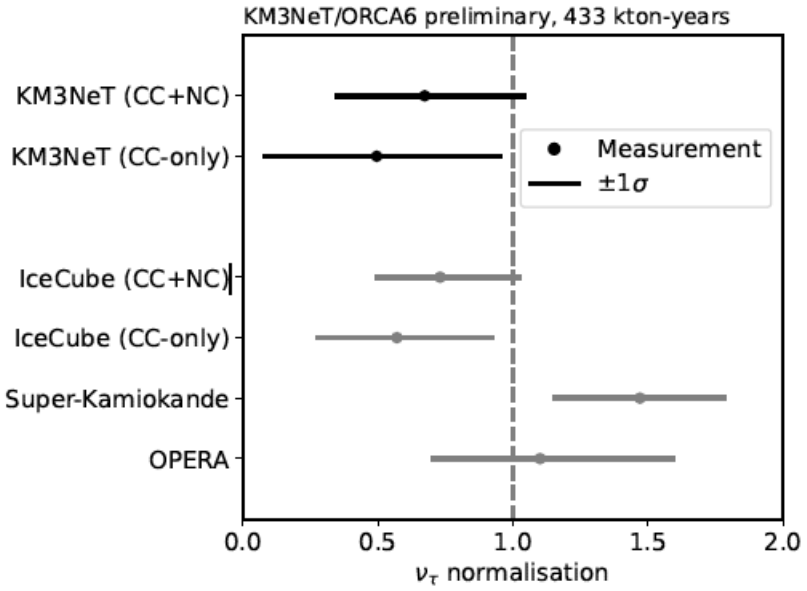
The muon neutrinos mainly oscillate to tau neutrinos.

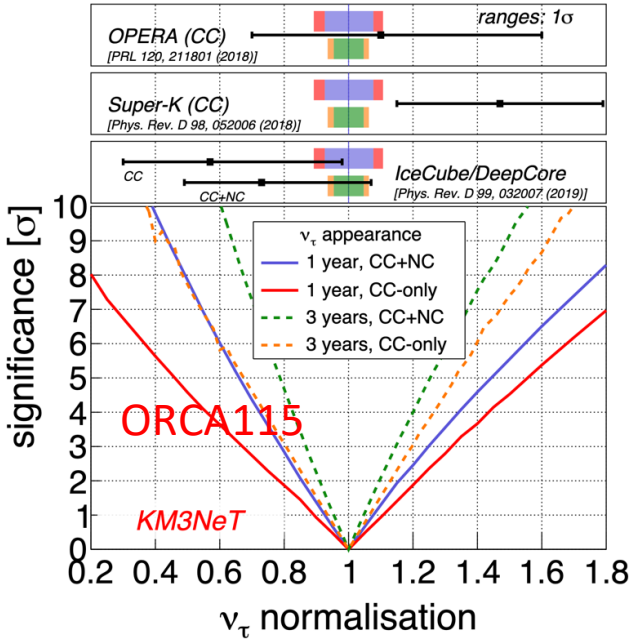
They appear as showers events.

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

≈3k ν_τ CC events/year with full ORCA



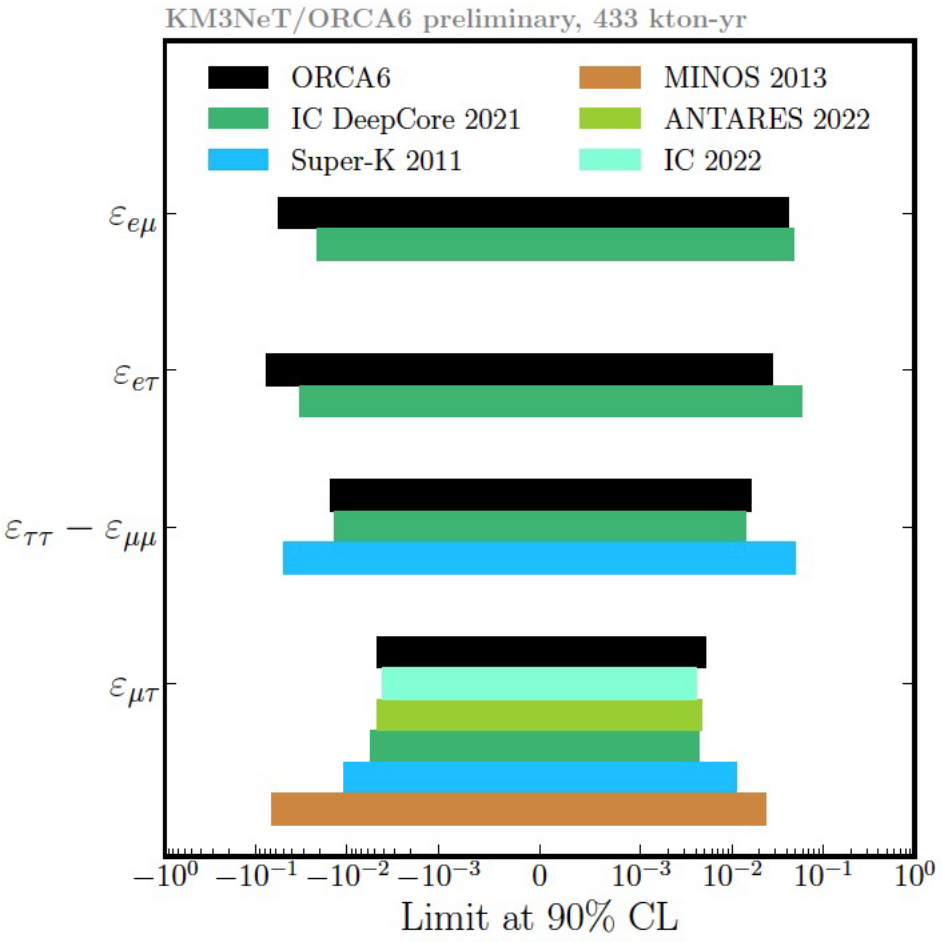




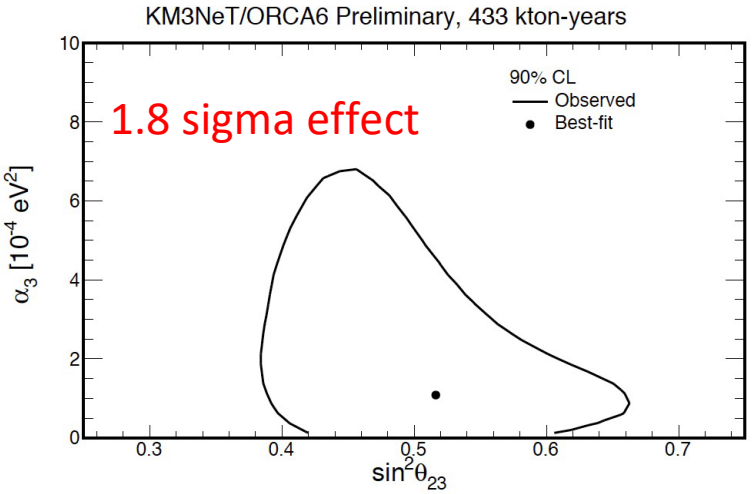
Also NSI, decoherence, LIV, sterile,…

Beyond Standard Model

Non Standard Interactions



Neutrino decay

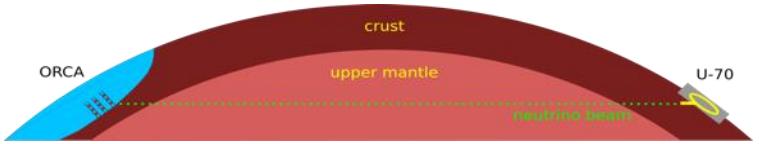


Quantum decoherence

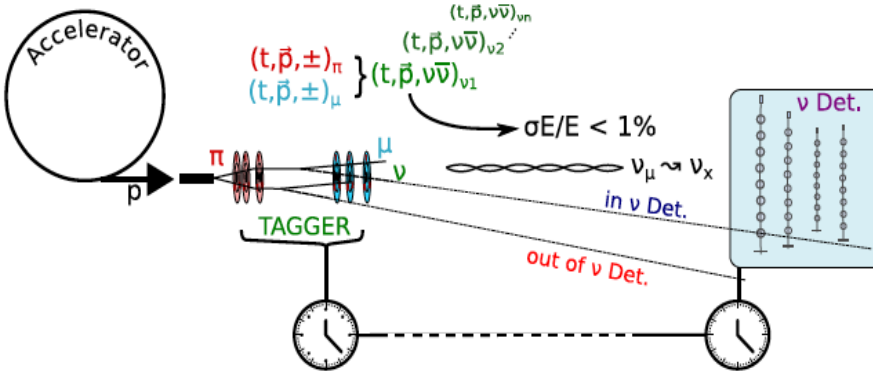
	$\gamma \propto E^{-2}$	$\gamma \propto E^{-1}$
ORCA6		
γ_{21} [GeV]	7.7×10^{-21}	3.1×10^{-22}
γ_{31} [GeV]	1.4×10^{-20}	5.0×10^{-22}
$\gamma_{21} = \gamma_{31}$ [GeV]	3.0×10^{-21}	1.1×10^{-22}
DeepCore		
$\gamma_{21} = \gamma_{32}$ [GeV]	7.5×10^{-20}	3.5×10^{-22}
$\gamma_{31} = \gamma_{32}$ [GeV]	4.3×10^{-20}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

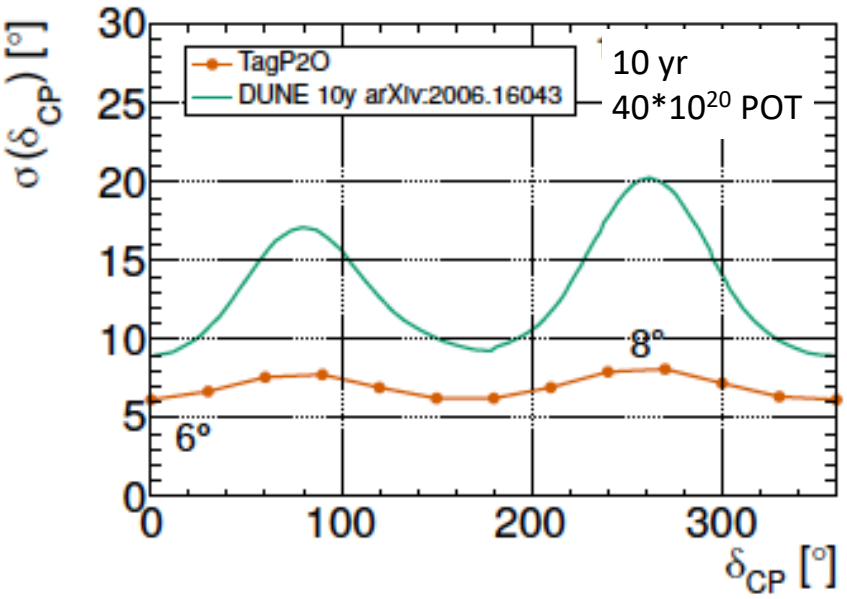
New idea: Tagged Protvino to ORCA

- 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





Summary

Water based neutrino telescopes:

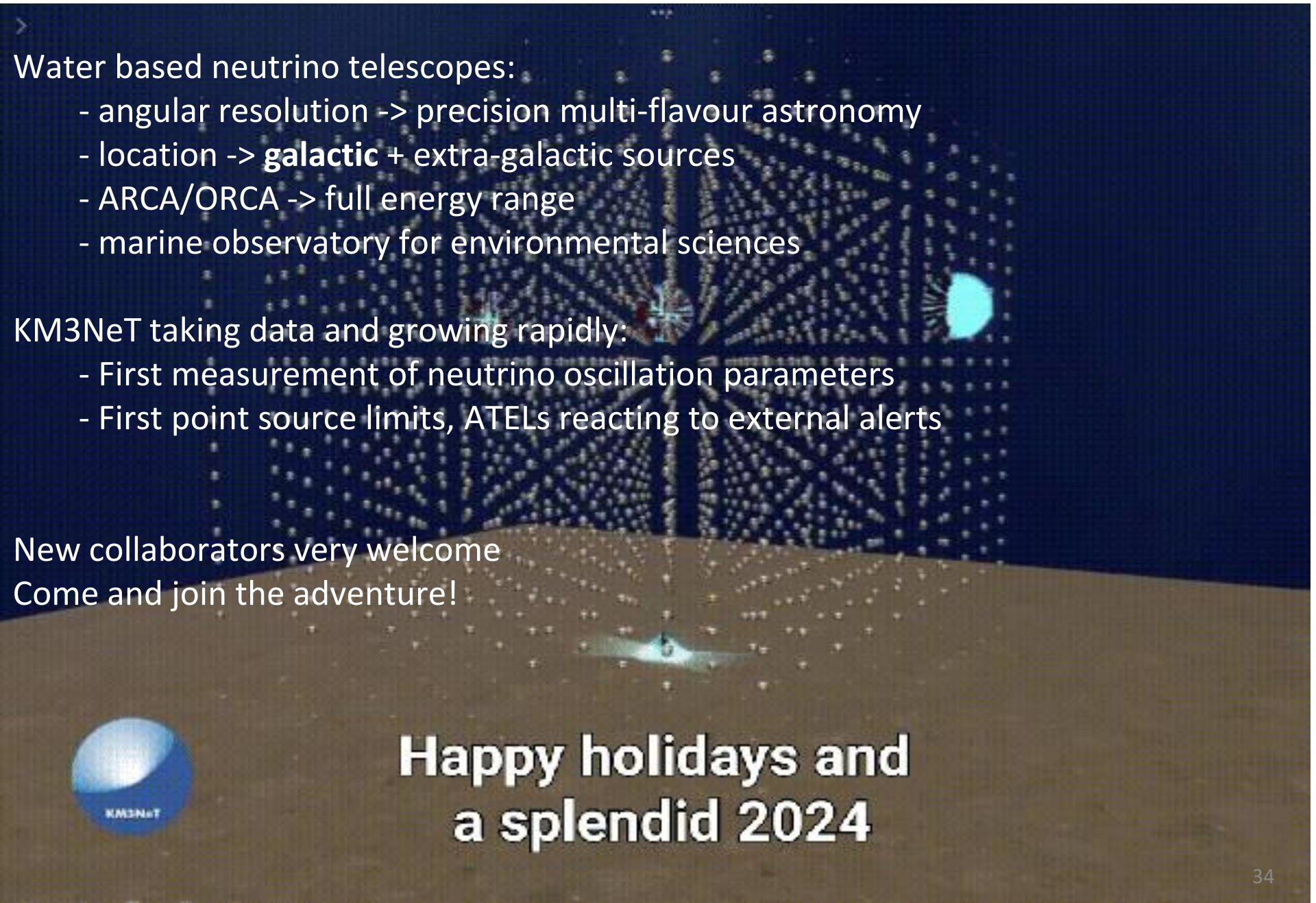
- angular resolution -> precision multi-flavour astronomy
- location -> **galactic** + extra-galactic sources
- ARCA/ORCA -> full energy range
- marine observatory for environmental sciences

KM3NeT taking data and growing rapidly:

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

New collaborators very welcome

Come and join the adventure!

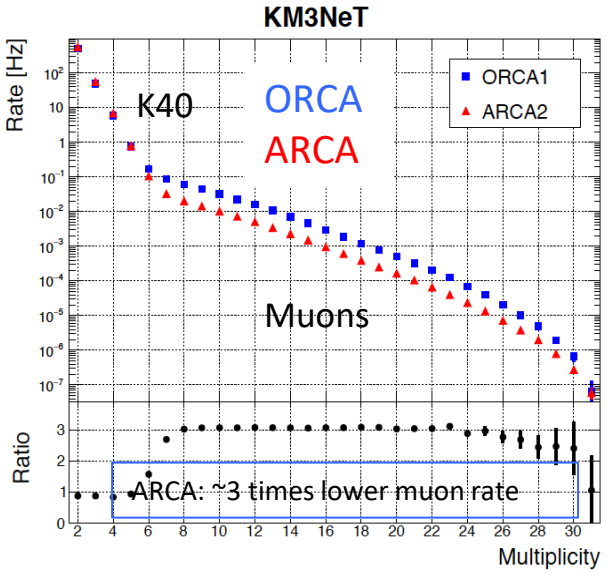


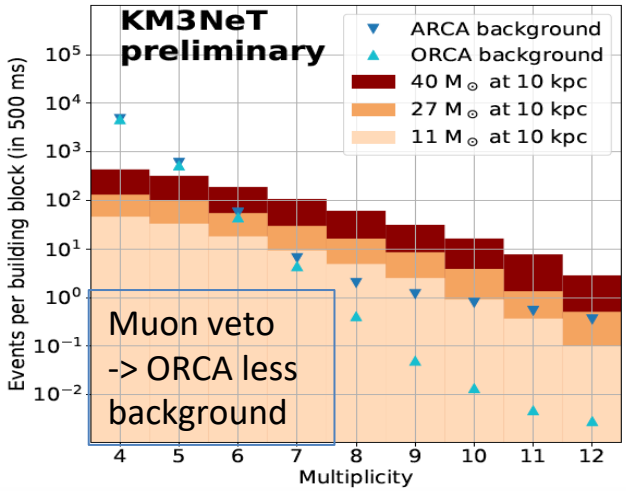
BACK UP

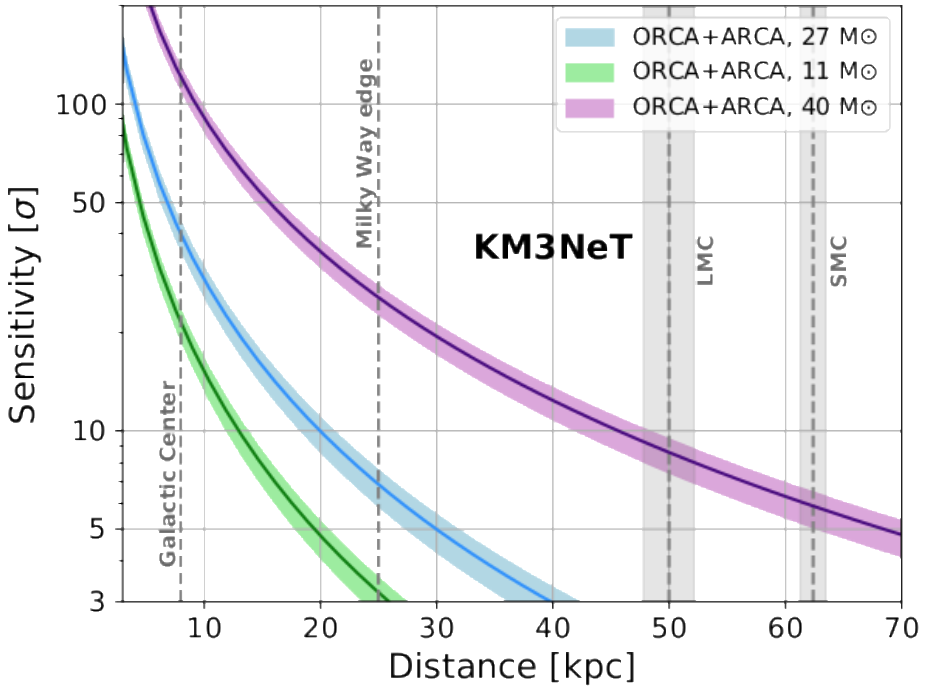
Supernova monitoring in KM3NeT

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

Eur. Phys. J. C81 (2021) 445







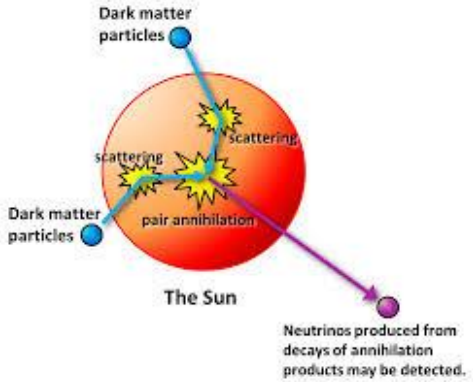
Discovery potential for 95% of Galactic CCSNe

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

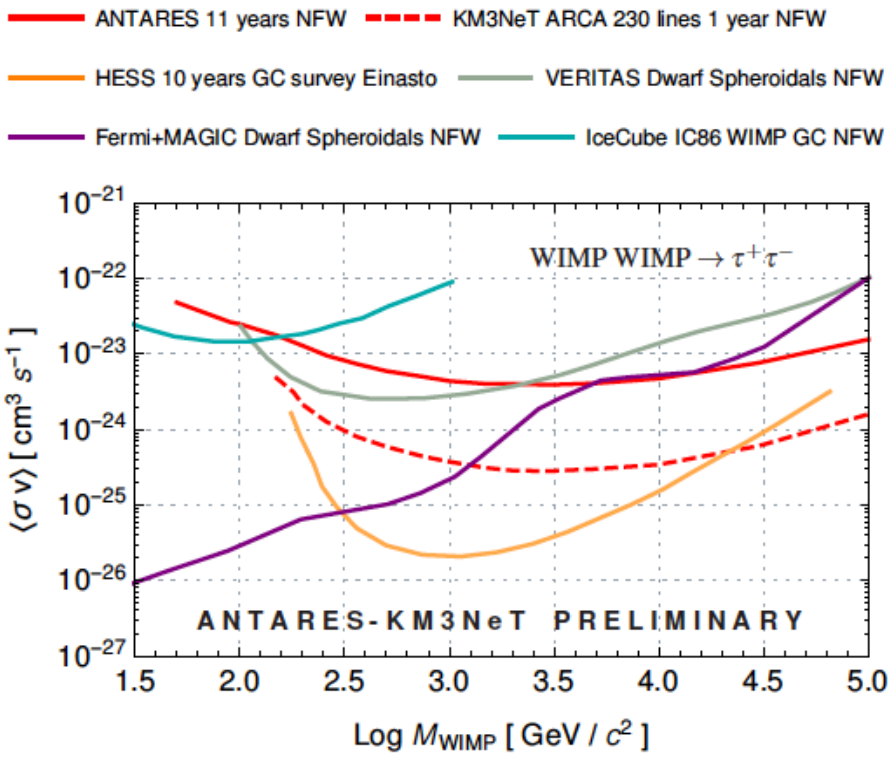
Joint real time trigger operational for SNEWS since early 2019

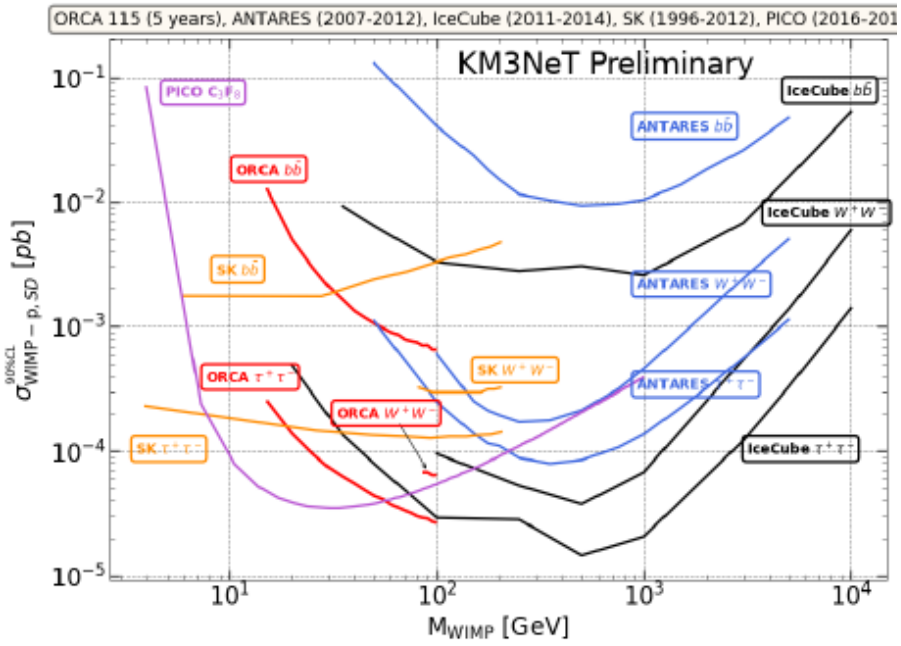
Dark matter-indirect detection

Sun



Galactic Centre





Phys.Lett. B759 2016

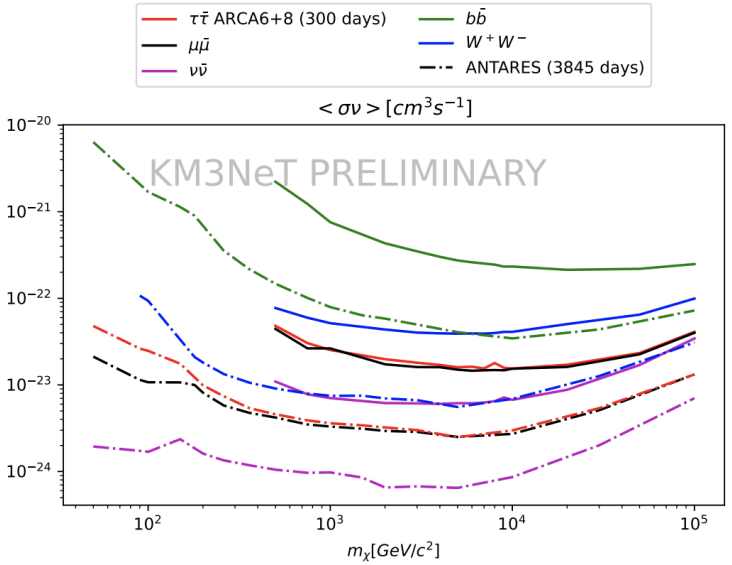
Phys. Lett. B 805 135439 (2020)

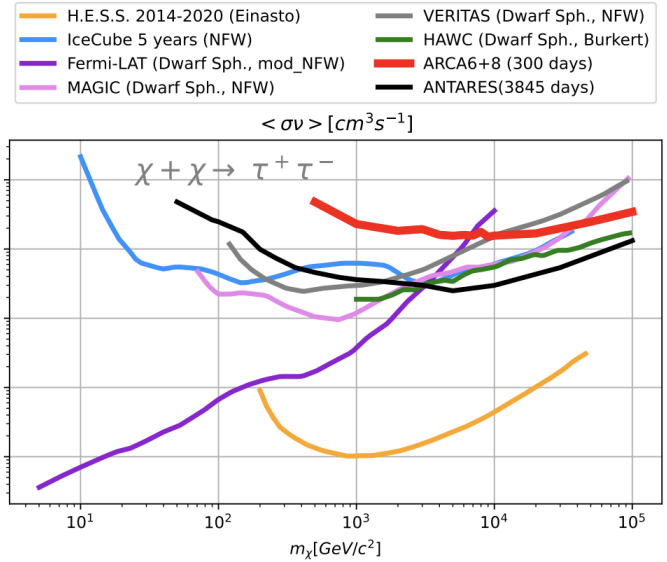
Dark Matter

Galactic Centre

ARCA6 + ARCA8

ICRC2023 PoS 1377

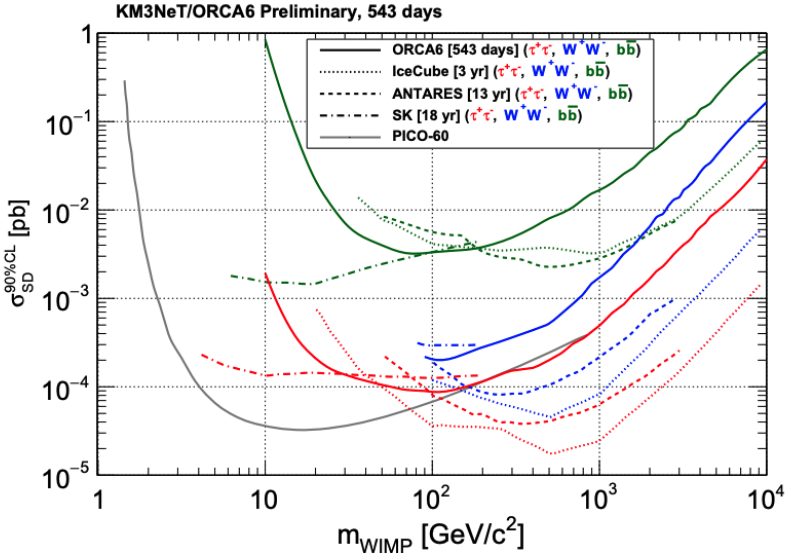


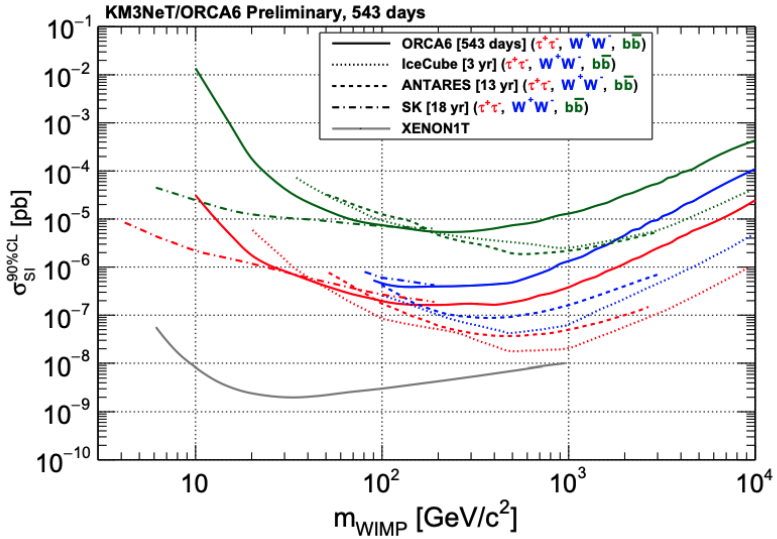


The Sun

ORCA6

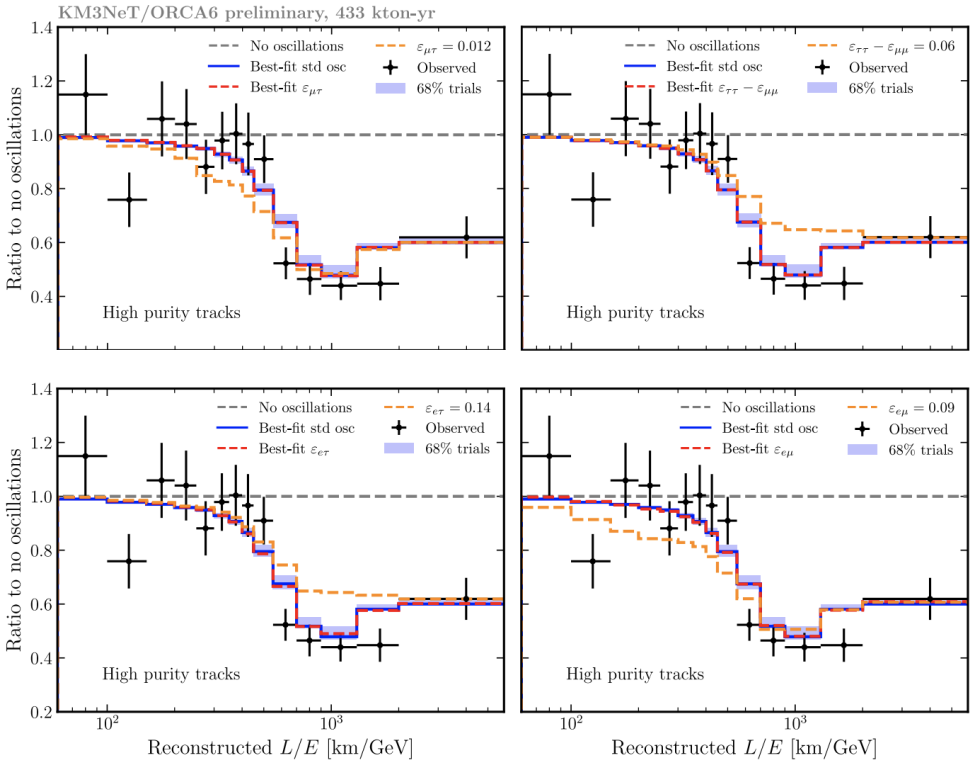
ICRC2023 PoS 1406

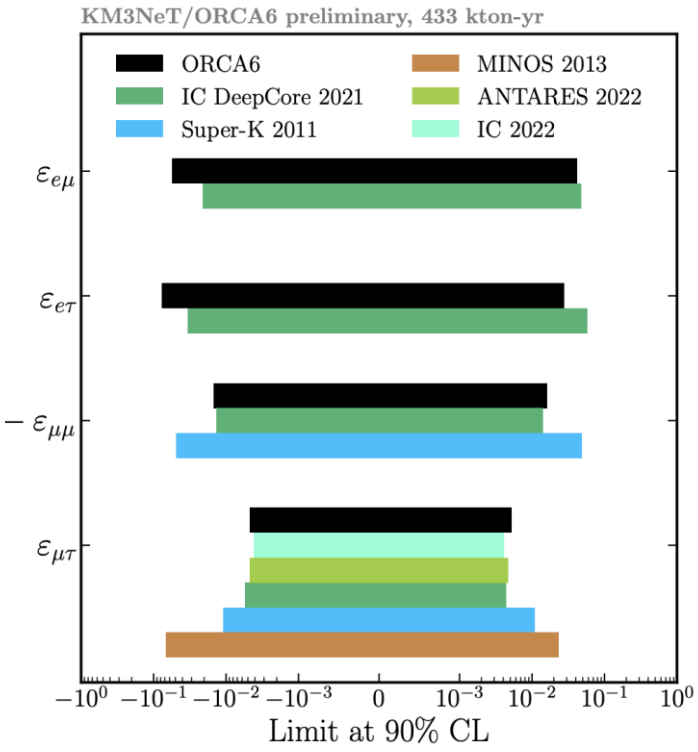




KM3NeT quickly reaching the ANTARES limits

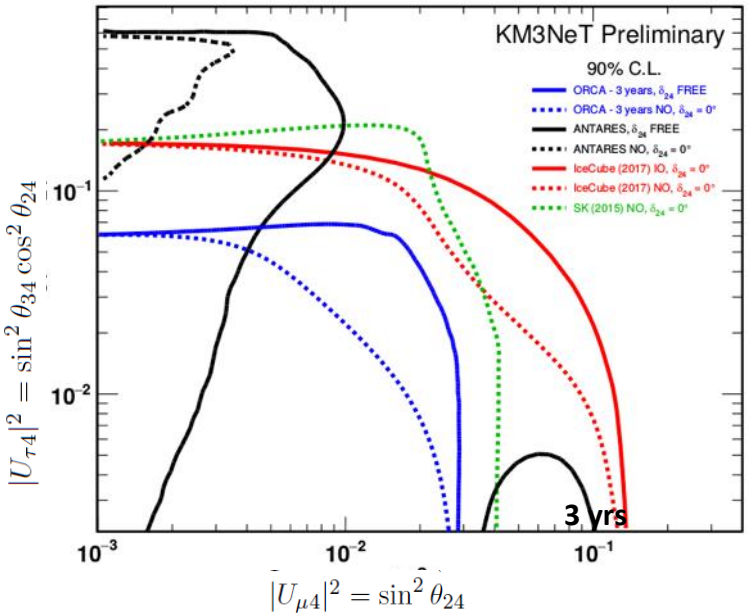
Non-Standard Interactions





ORCA115: sterile neutrinos

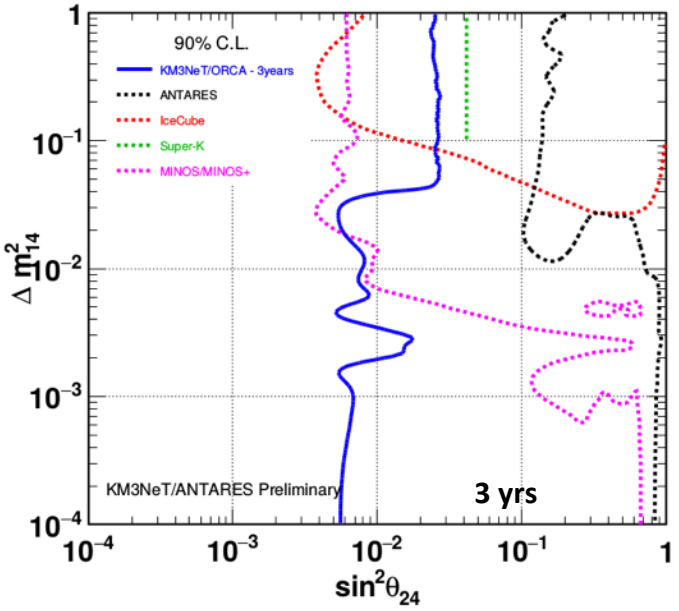
$\Delta m_{41}^2 > 0.1$ eV^2



Dependence on δ_{24}

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

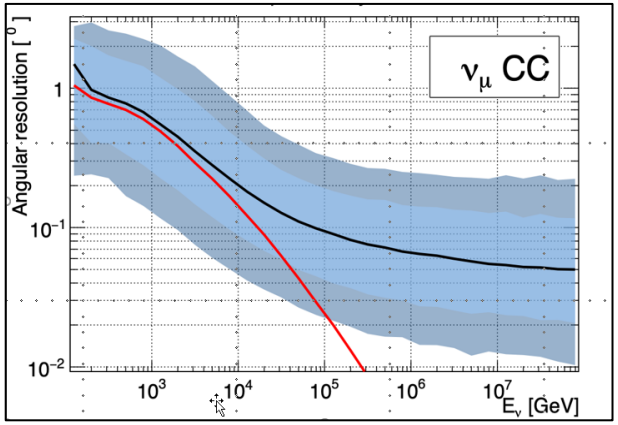
$\Delta m_{41}^2 < 0.1$ eV^2



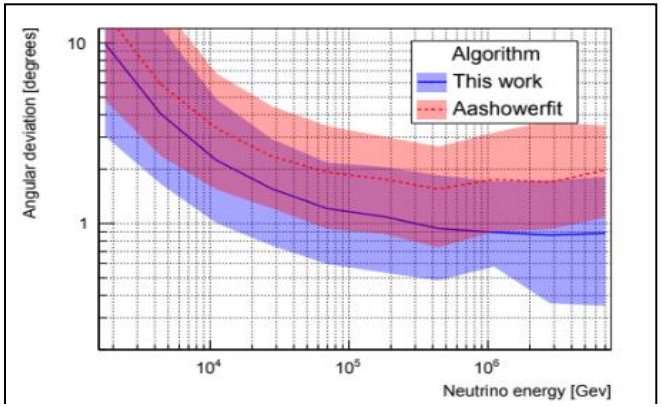
Due to longer & multiple baselines improve on MINOS/MINOS+ limits by 2 orders of magnitude

Angular Resolutions

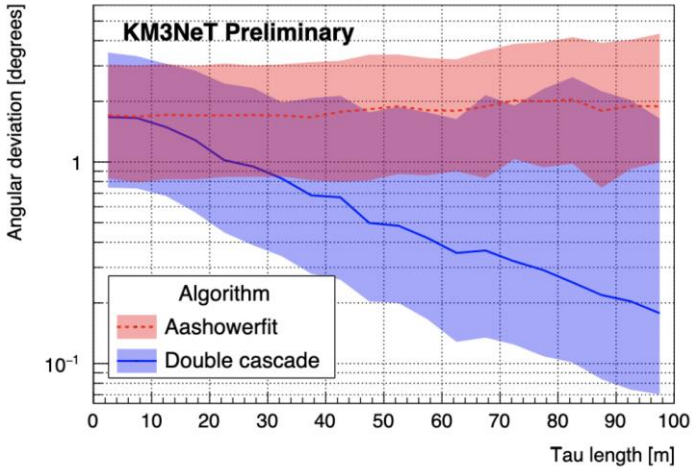
Better than 0.1° > 20 TeV



Better than 1° > 30 TeV



Better than 1° for tau track length > 22 m



EVENT TYPE AND ANGULAR RESOLUTION

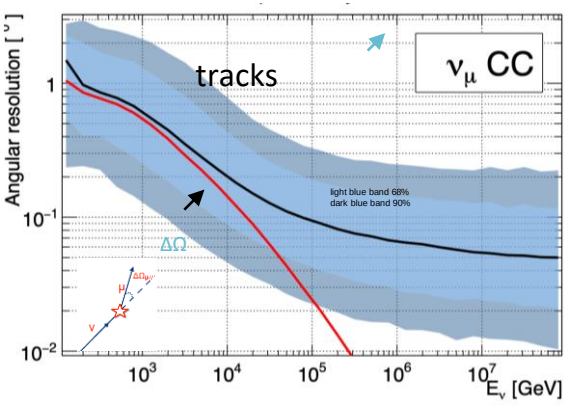
	TRACK*	CASCADE*
ANTARES	0.3°	3°
KM3NET	0.1°	1.5°
ICECUBE	0.3°	7° - 8°
BAIKAL - GVD	0.25°	3° - 3.5°

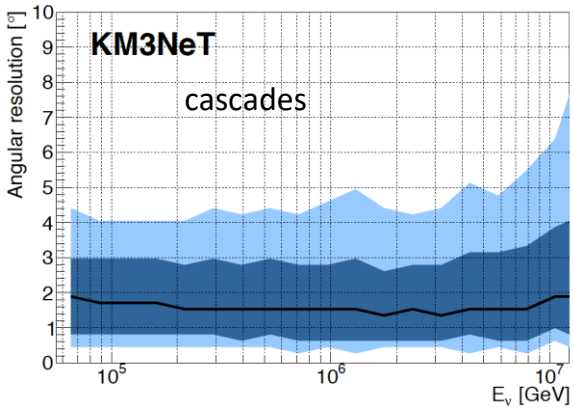
Tracks: very long path (Eμ>1TeV several km)
Big lever arm
- Good angular resolution

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

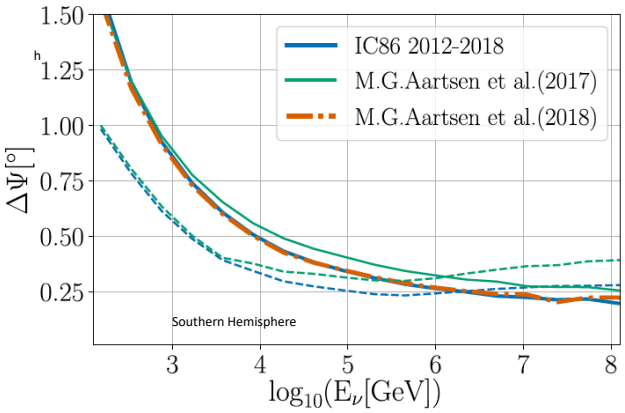
*Resolution at 100 TeV

KM3NeT





IC resolution for tracks
from arXiv:1910.08488, 15 October 2019



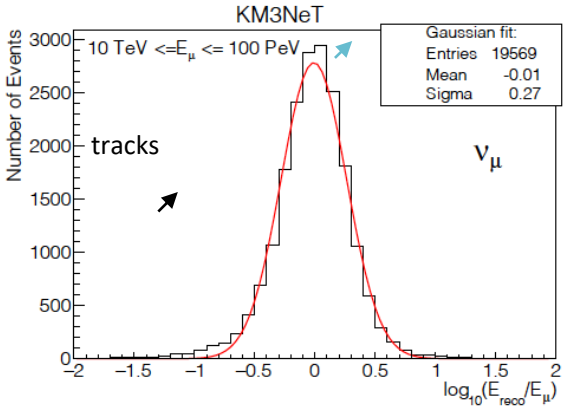
EVENT TYPE AND ENERGY RESOLUTION

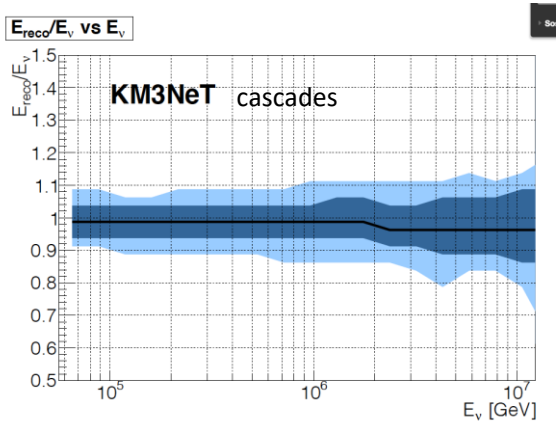
Tracks: very long path (Eμ>1TeV several km)
Neutrino interaction vertex far from the detector
• Modest energy resolution

Cascades: small path (E_{casc} >1TeV some tens of meters)
All the energy released inside the detector
• Good energy resolution

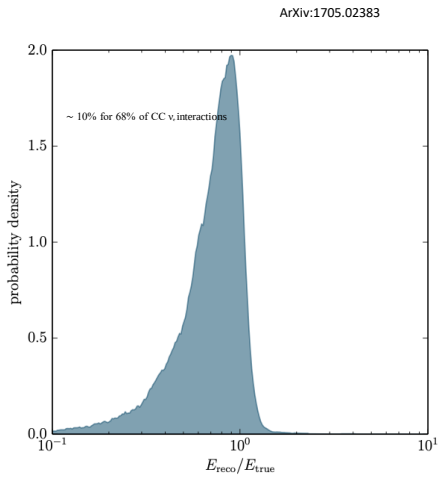
	TRACK IN LOG(E)	CASCADE
ANTARES	35 %	5 %
KM3NET	27 %	5 %
ICECUBE	~ 30 %	10 %
BAIKAL -GVD		

KM3NeT



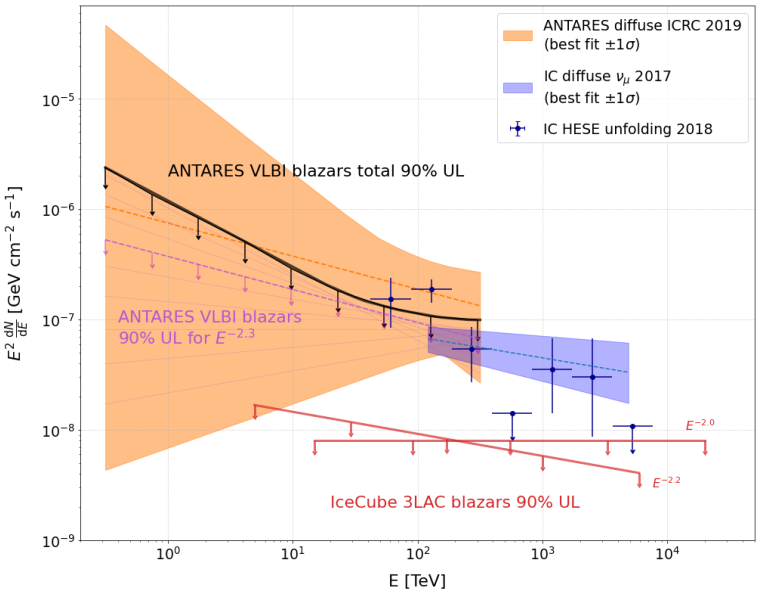


IIC energy resolution for cascades



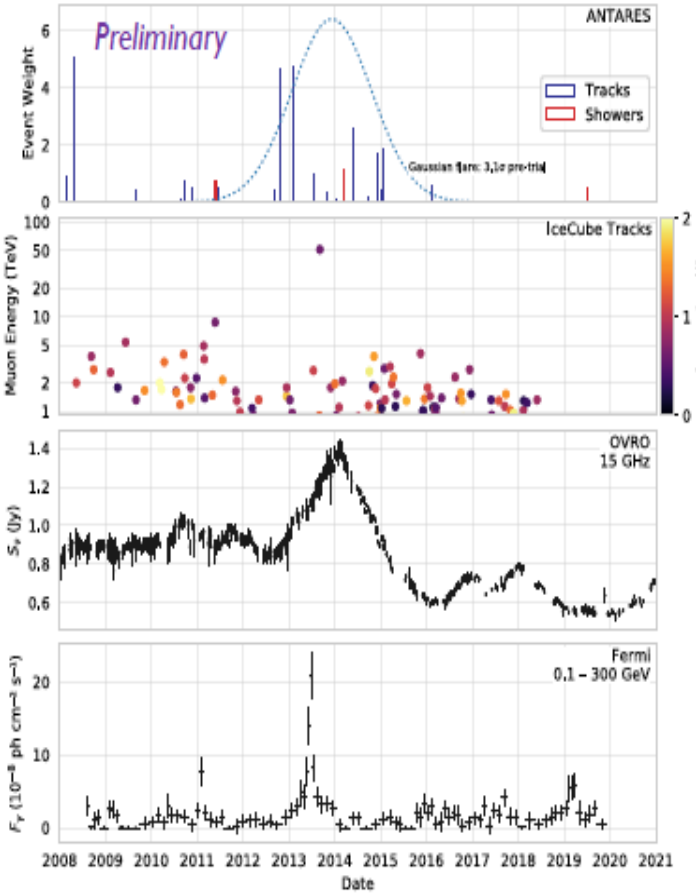
Neutrinos from radio-loud blazars?

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%

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%
$\nu_{\text{up}}/\nu_{\text{hor}}$ skew	0	2%
Spectral index	0	0.3
Energy scale	1	9%