Astroparticle and oscillation research in the abyss with KM3NeT

Paschal Coyle
CPPM

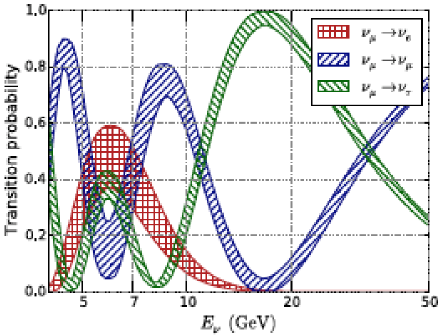
NPB 2024
Hong Kong
19/2/24

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

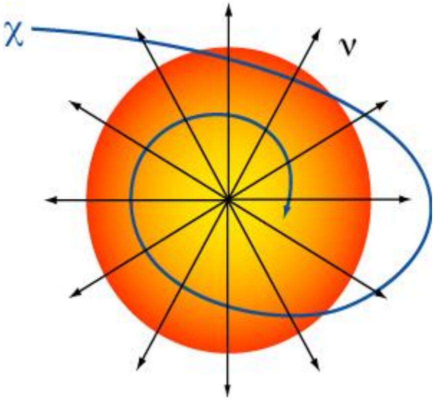
Neutrino telescopes: science

MeV to PeV energies

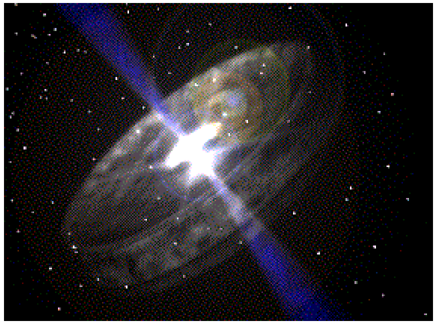
Supernova
Solar flares



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



Dark matter
Monopoles,
Nuclearites,…



Cosmic neutrinos

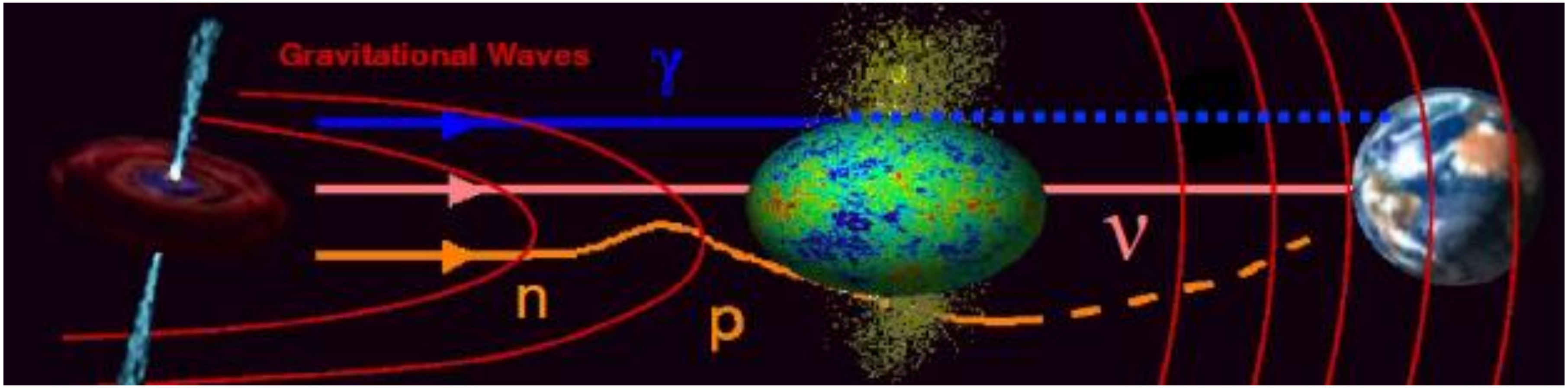
Cosmic rays

Origin and production mechanism of HE CR

KM3NeT-ORCA — ANTARES — KM3NeT-ARCA

+ oceanography, biology, bioacoustics, seismology,…

Neutrinos: cosmic messengers



Neutrinos: neutral, stable, weakly interacting

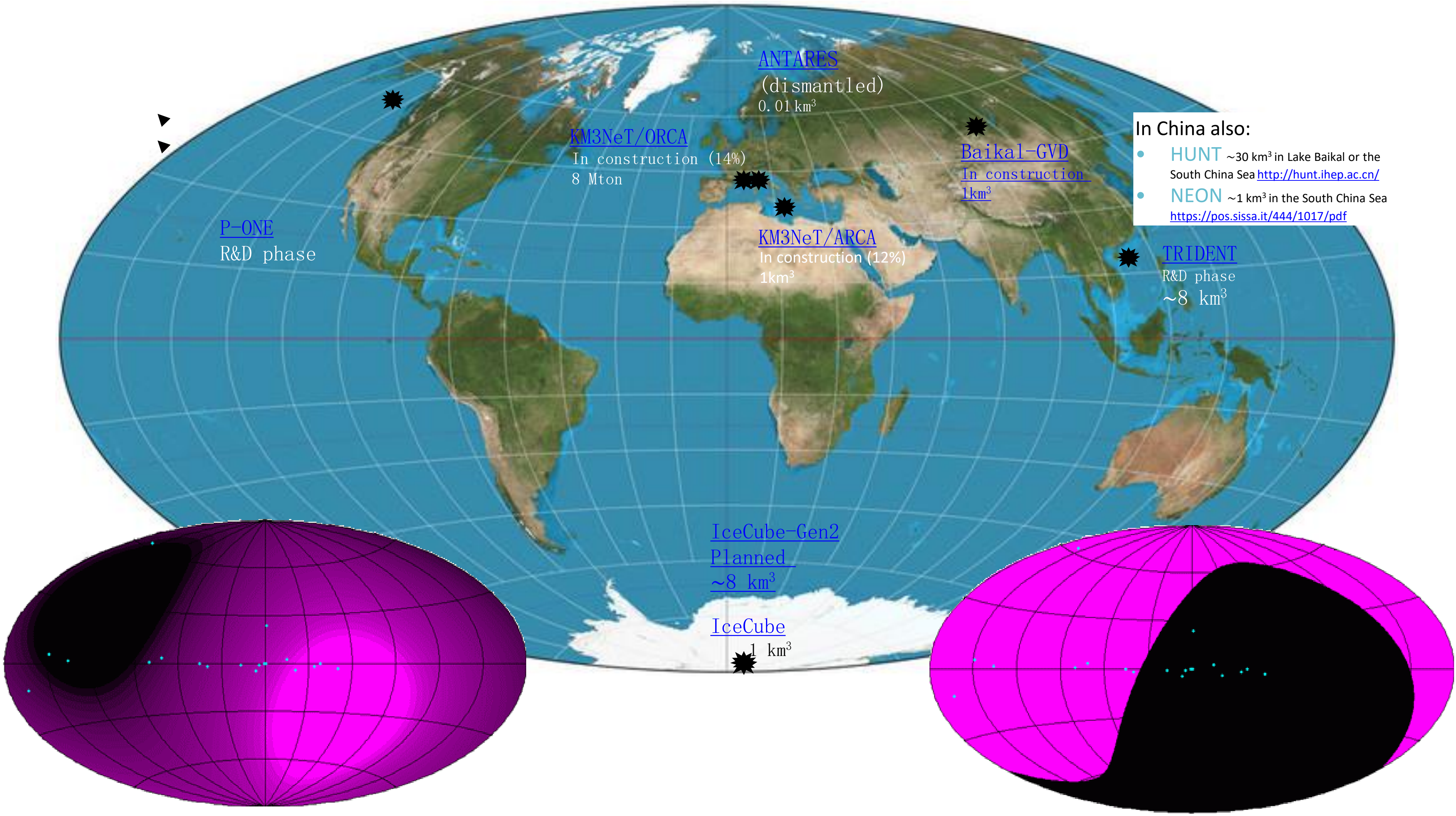
not absorbed by background light/CMB ➒ access to cosmological distances
not absorbed by matter ➒ access to dense environments
not deviated by magnetic fields ➒ astronomy over full energy range

‘Smoking gun’ signature for hadronic processes

Correlated in time/direction with electromagnetic and gravitational waves

New window of observation on the Universe

Very large volume neutrino telescopes



Mediterranean

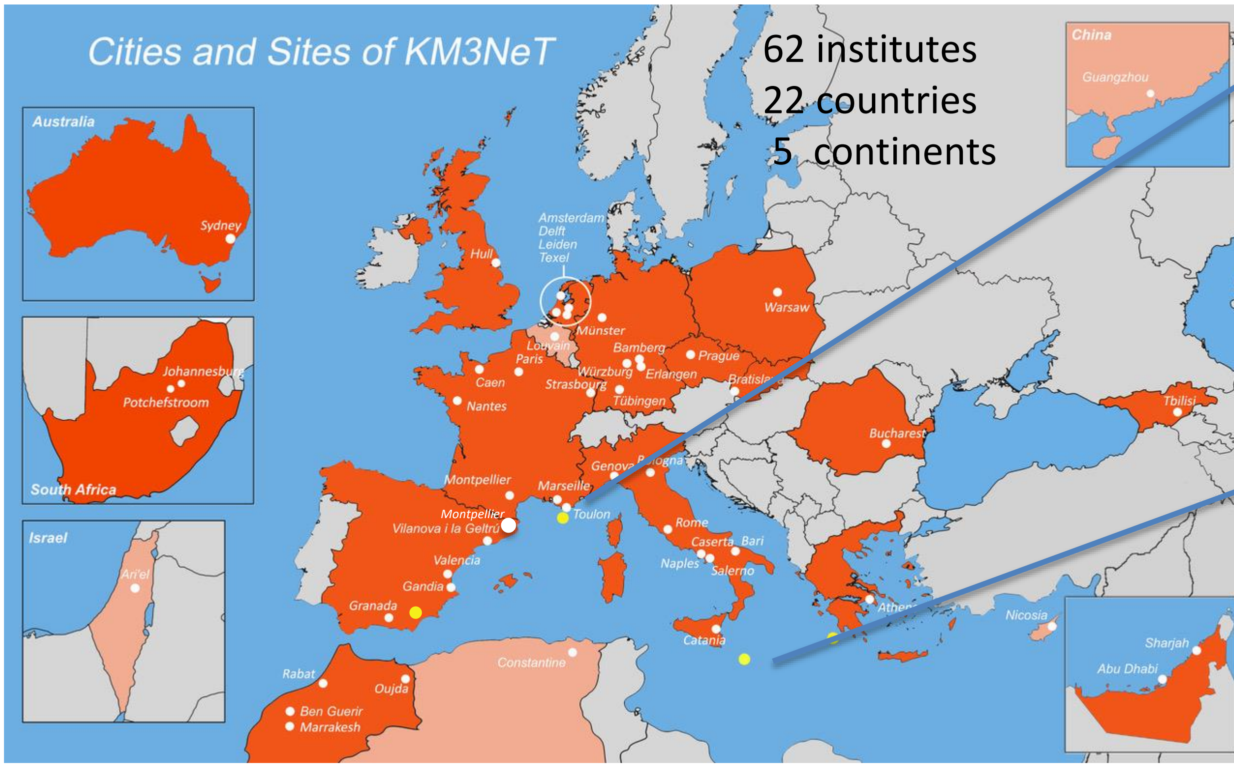
South Pole

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 Univ.
Drexel Univ.

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

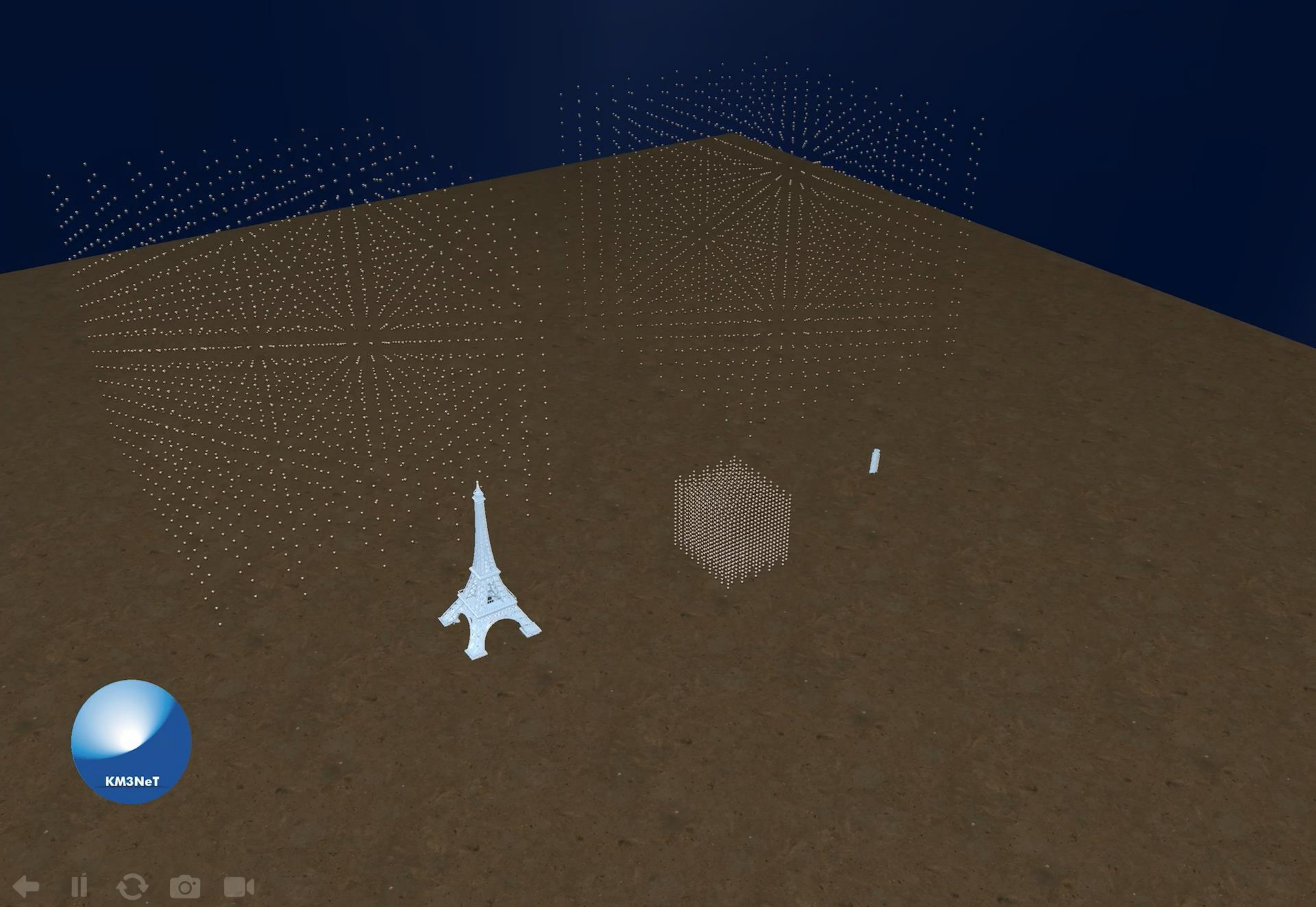
http://dx.doi.org/10.1088/0954-3899/43/8/084001

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

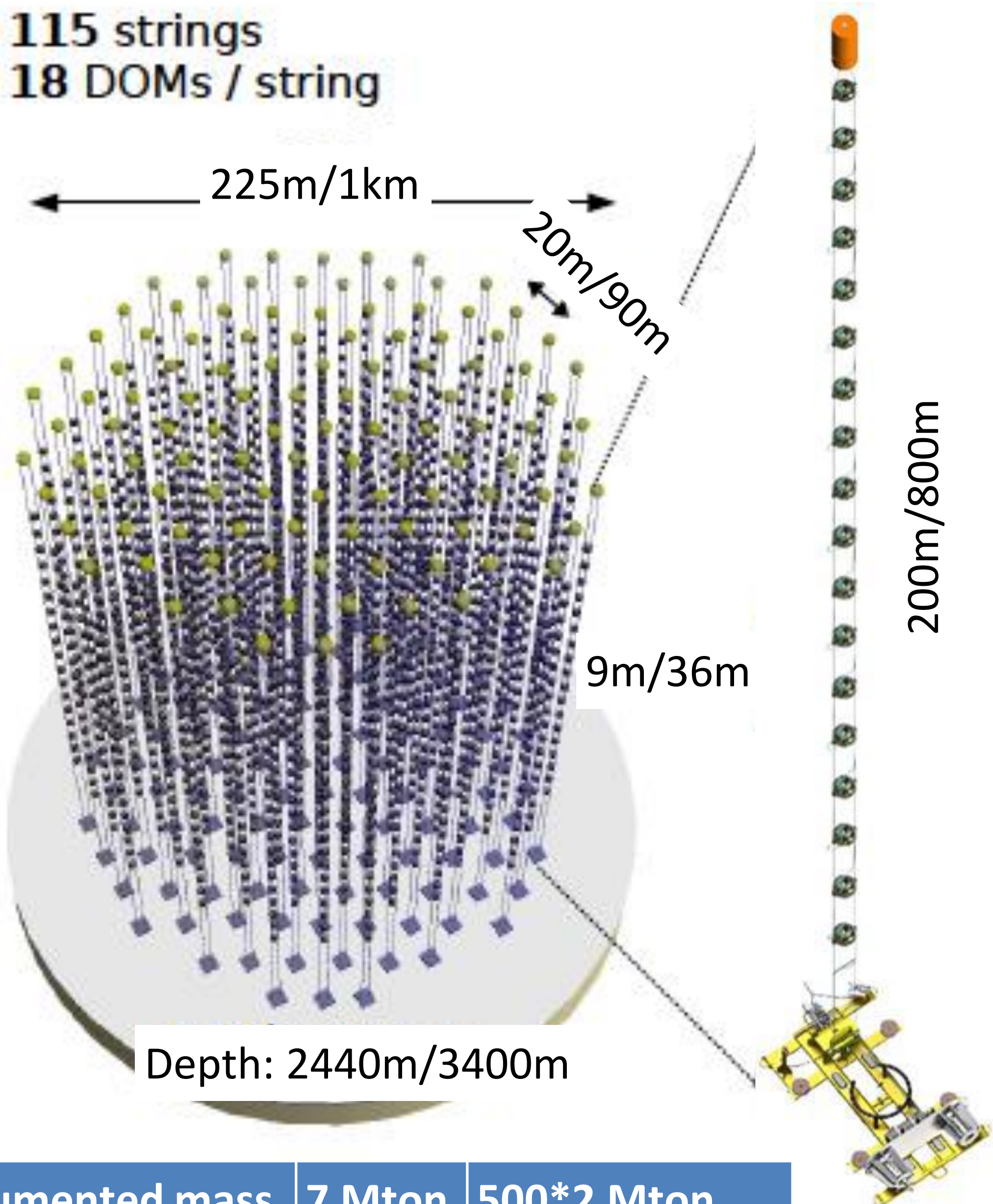
Connection nodes of

european multidisciplinary seafloor & water column observatory emso

KM3NeT: ARCA and ORCA



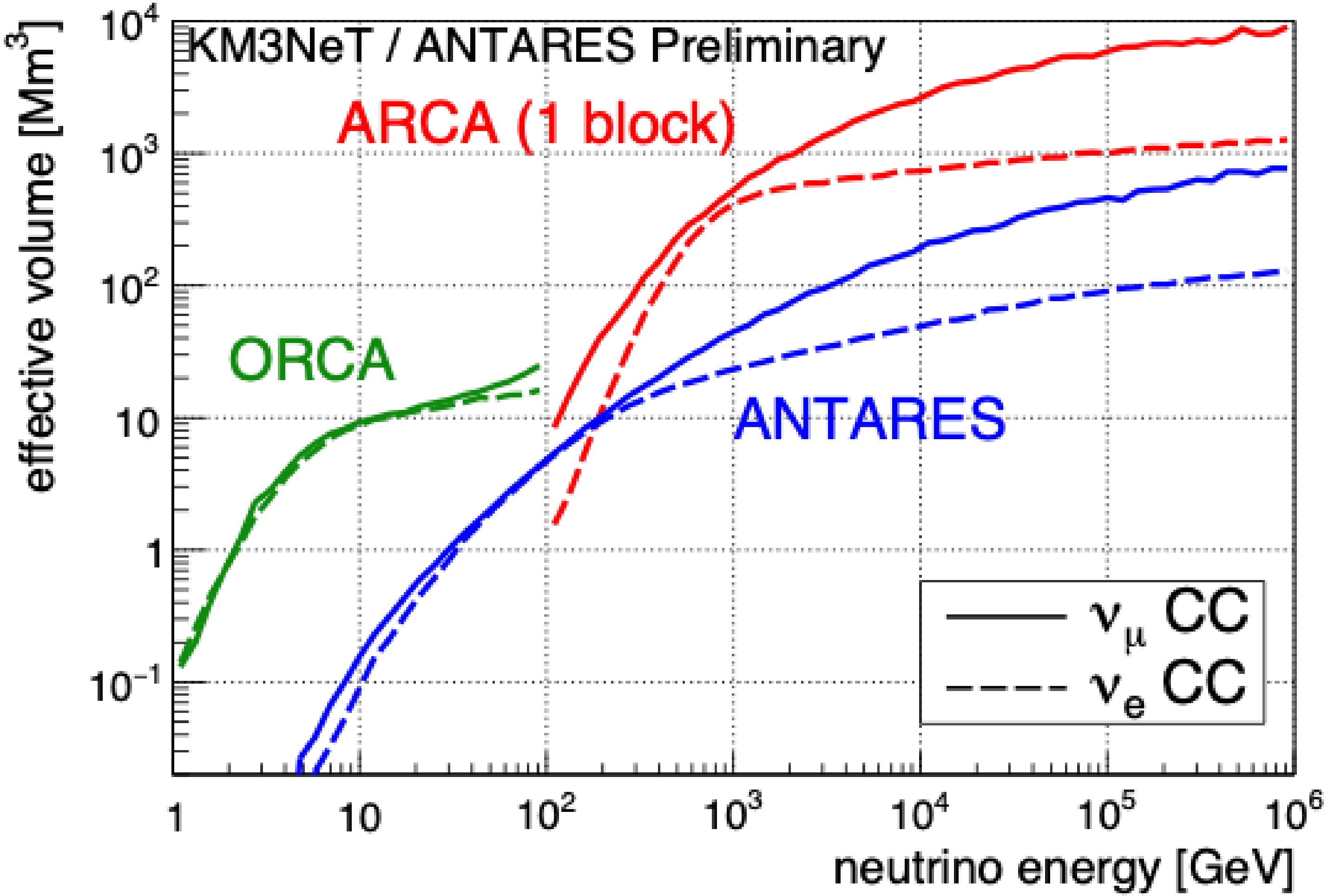
KM3NeT building block



- 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

Erlangen

Genova

Nantes

Athens

Catania

Caen

Montpellier

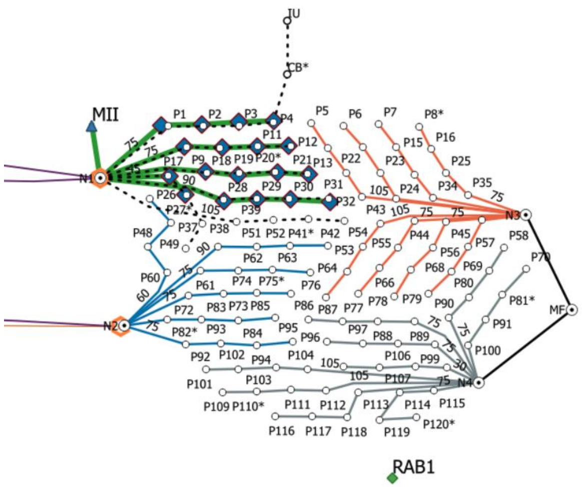
Marseille

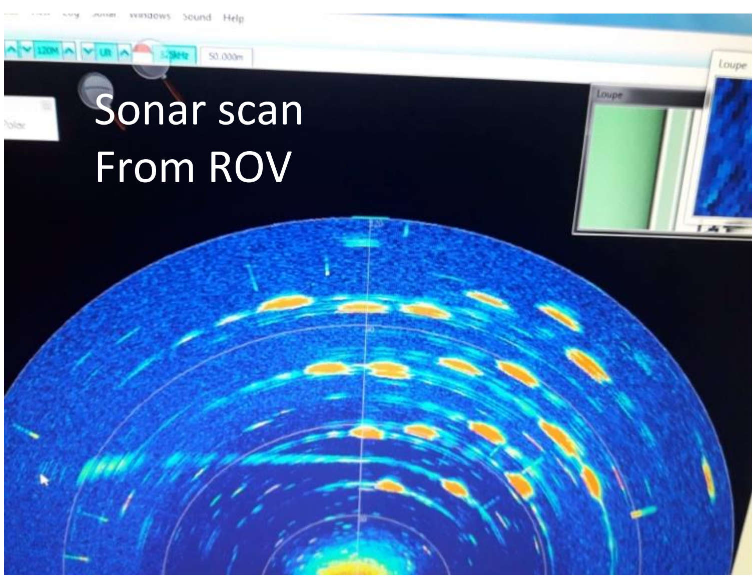
Caserta

KM3NeT Detector Unit deployment

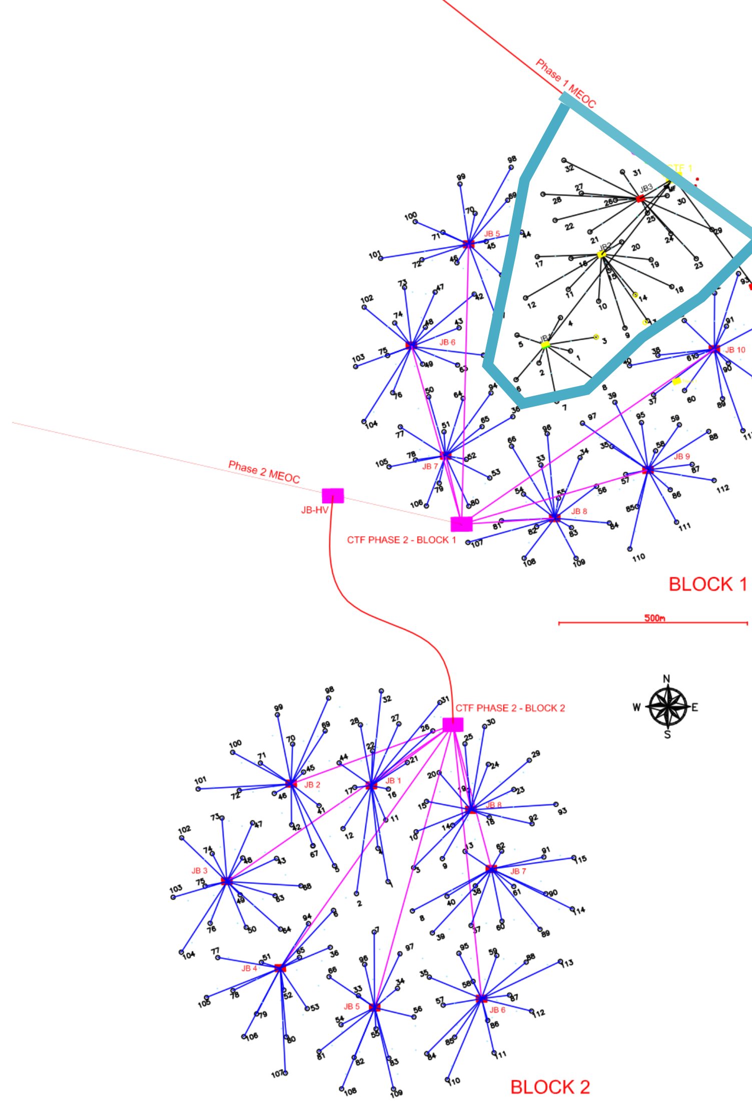
Current Status: 46 DUs deployed

ORCA18



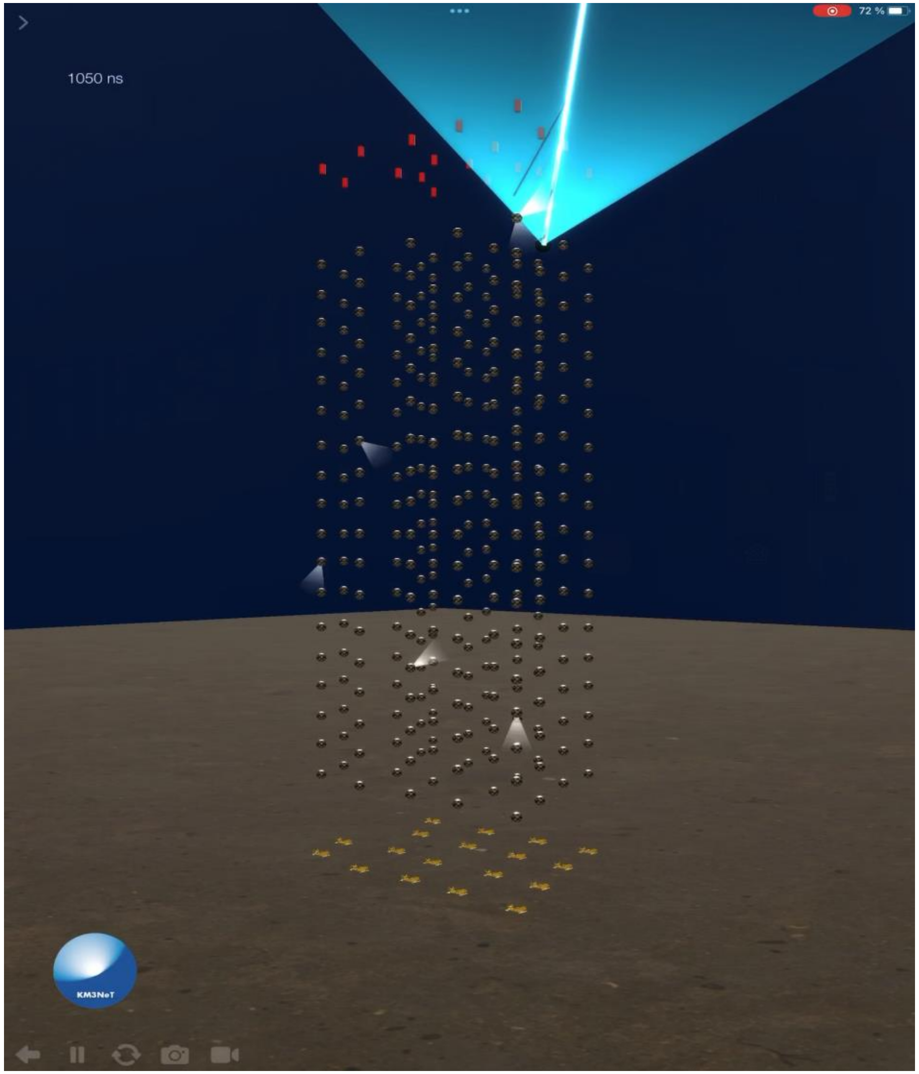


ARCA28

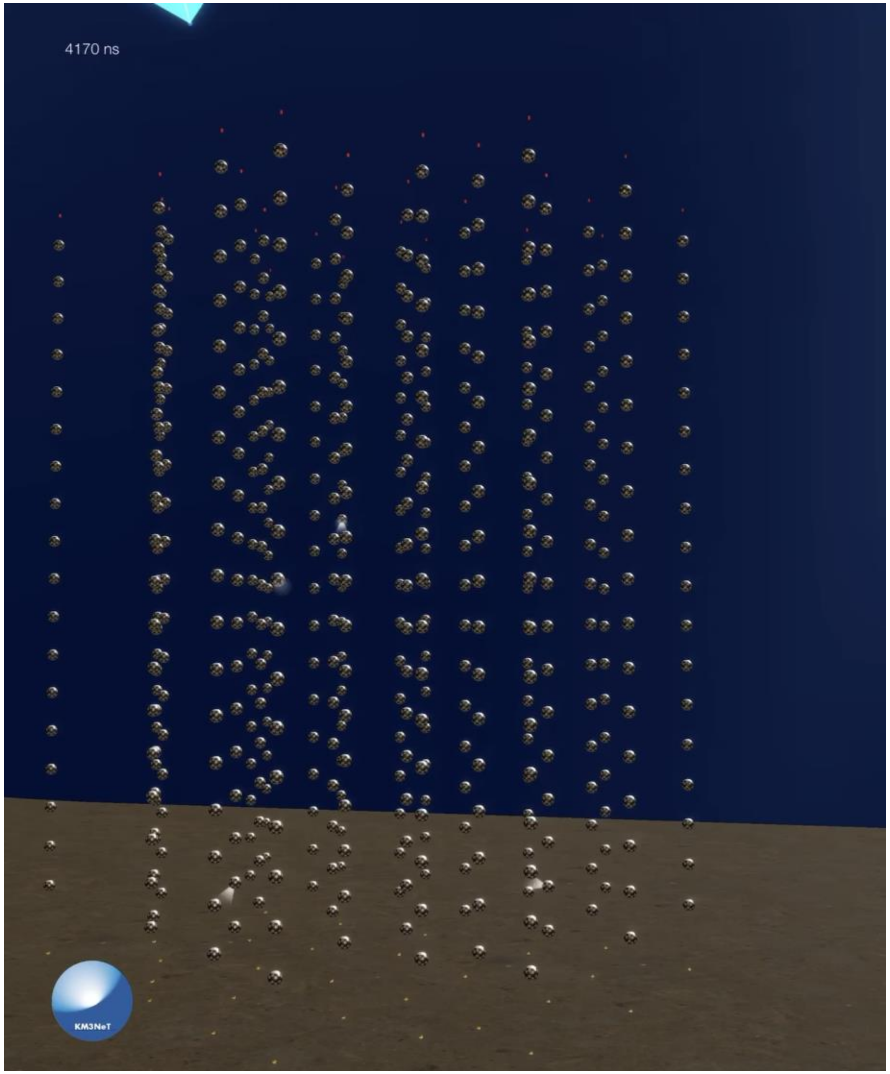


KM3NeT Event display

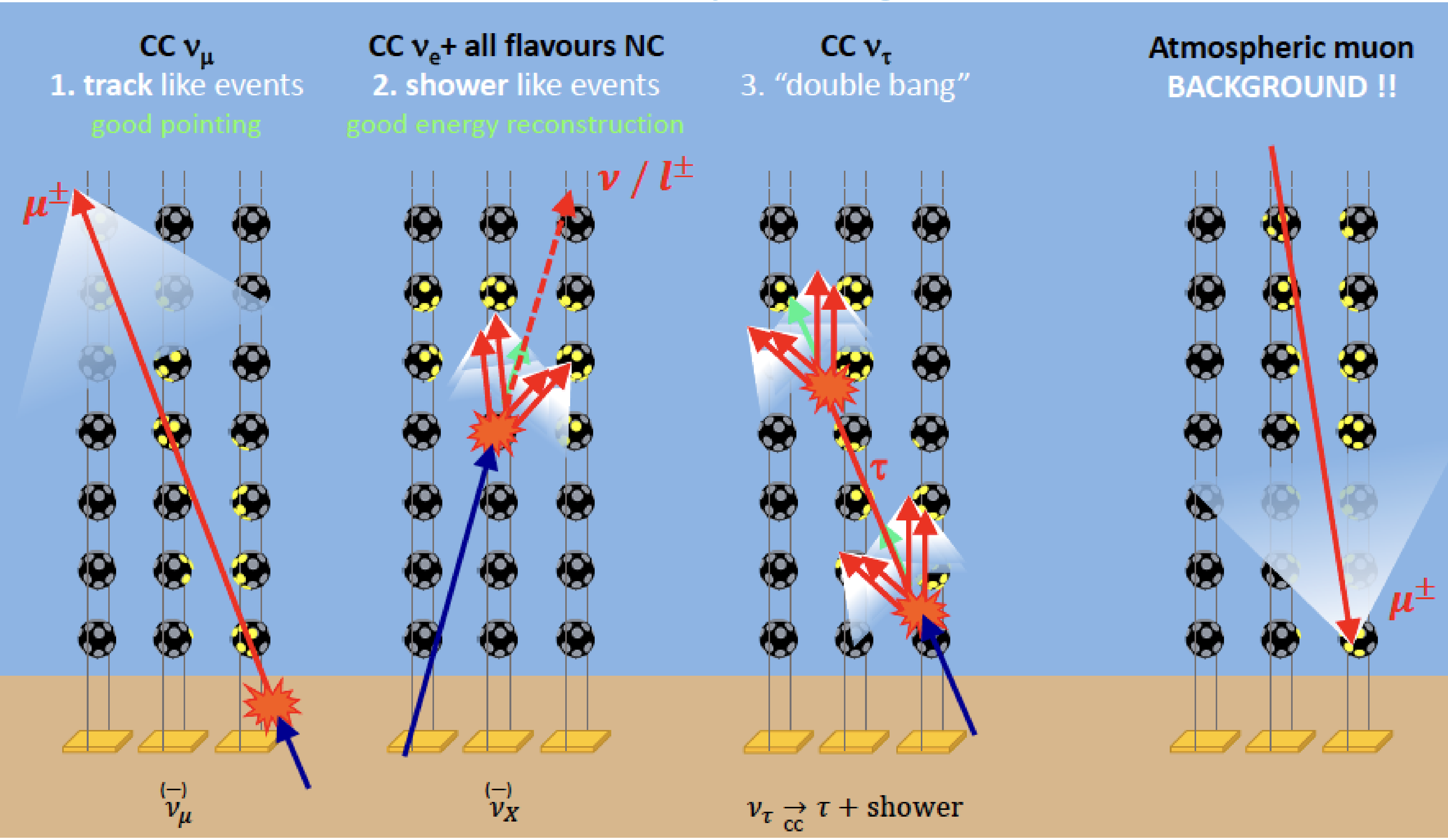
ORCA18



ARCA28



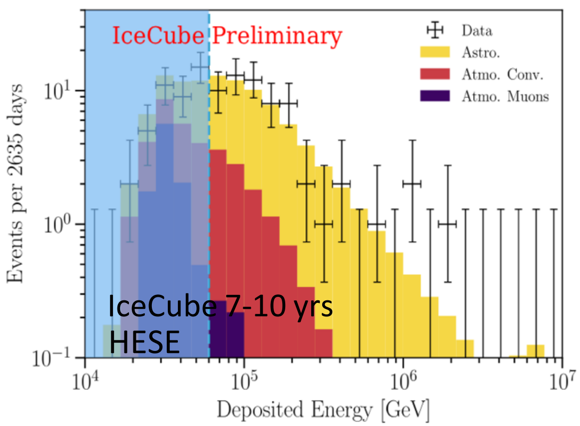
Event Topologies

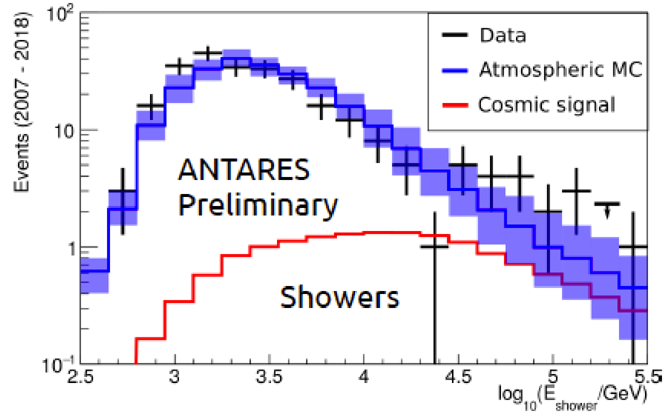


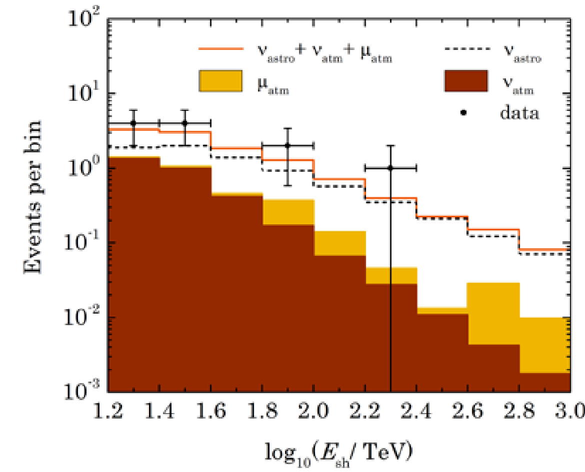
Tracks @E_ν>100 TeV Ang. res. below 0.1° - Energy res. ~ factor 2

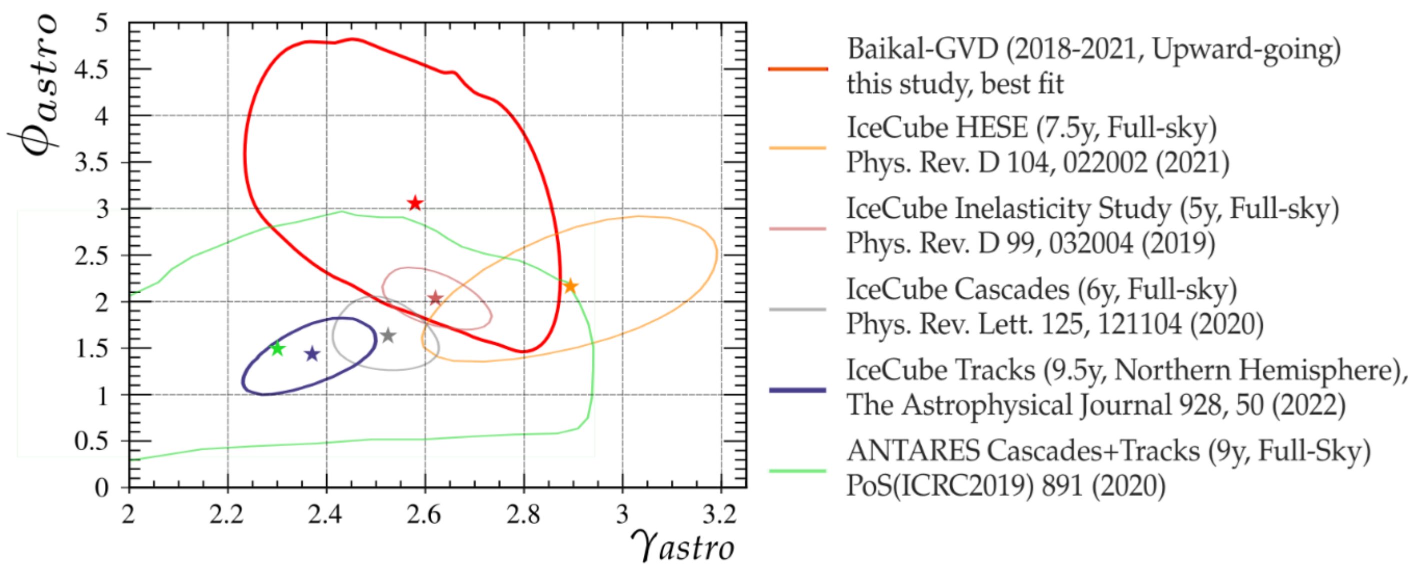
Shower @E_ν>100 TeV Ang. res. below 2° - Energy res. ~6%

Measurements of the diffuse neutrino flux ν_e





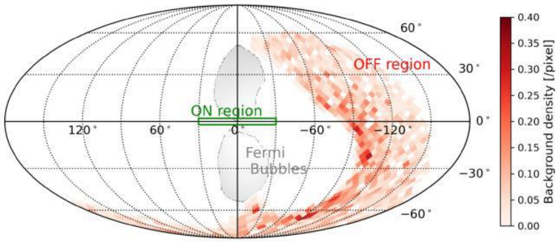




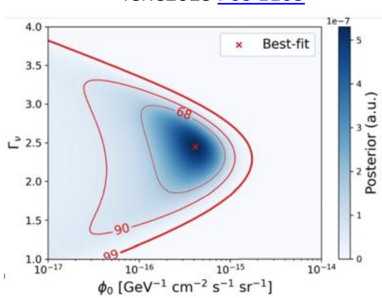
Diffuse from Galactic Plane

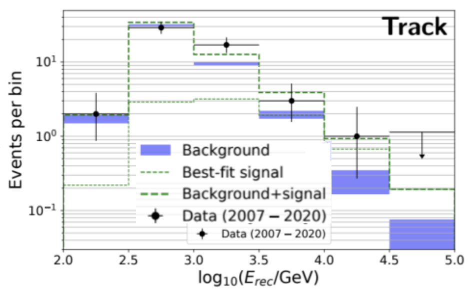
ANTARES 2007-2020 data Phys. Lett. B 841 (2023), p. 137951

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

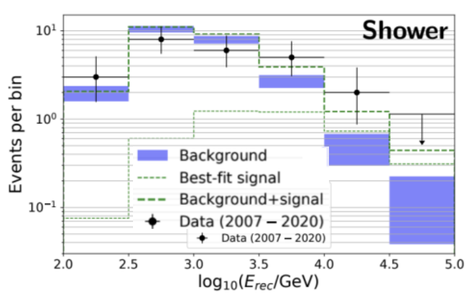


ICRC2023 PoS 1103





(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

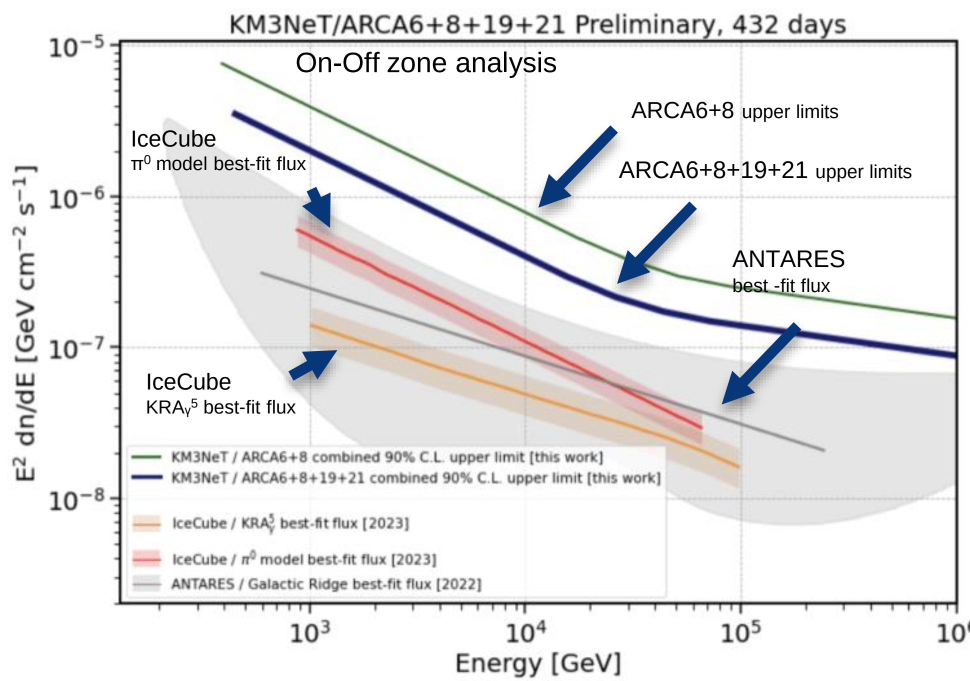
KM3NeT **ICRC2023** **PoS 1190**

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

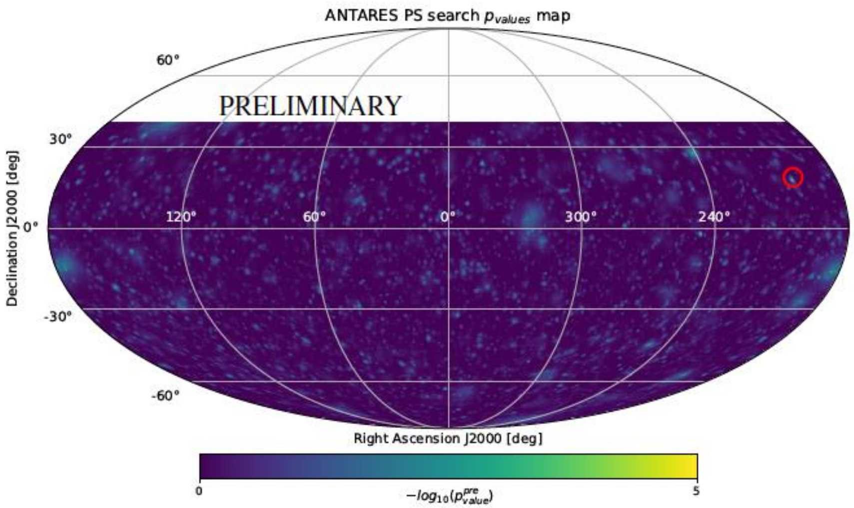
|l| < 31° and |b| < 4° for KM3NeT/ARCA19-21

ARCA6 & ARCA8 & ARCA19 fully analyzed

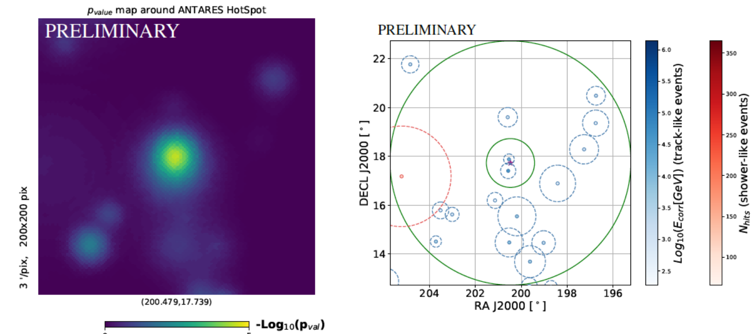
ARCA21 partially analyzed (until December 2022)

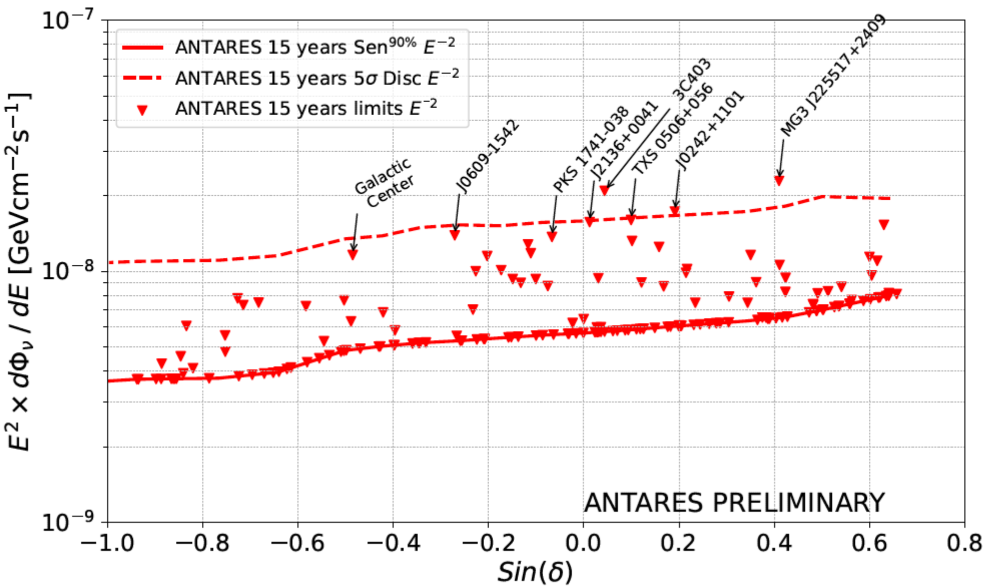


ANTARES point source searches (15 years)



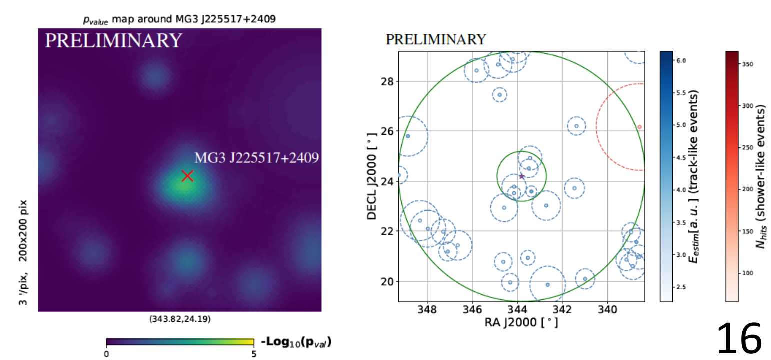
Hotspot (α, δ)=(200.46, 17.74)



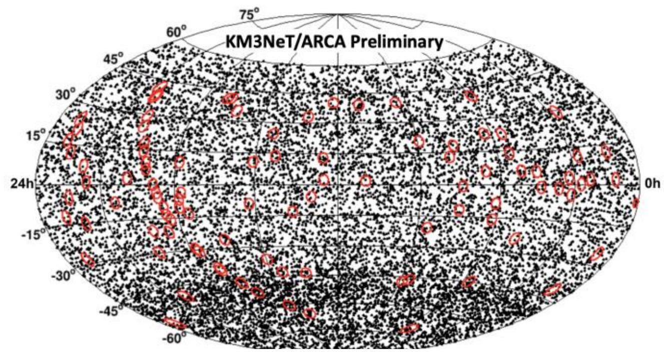


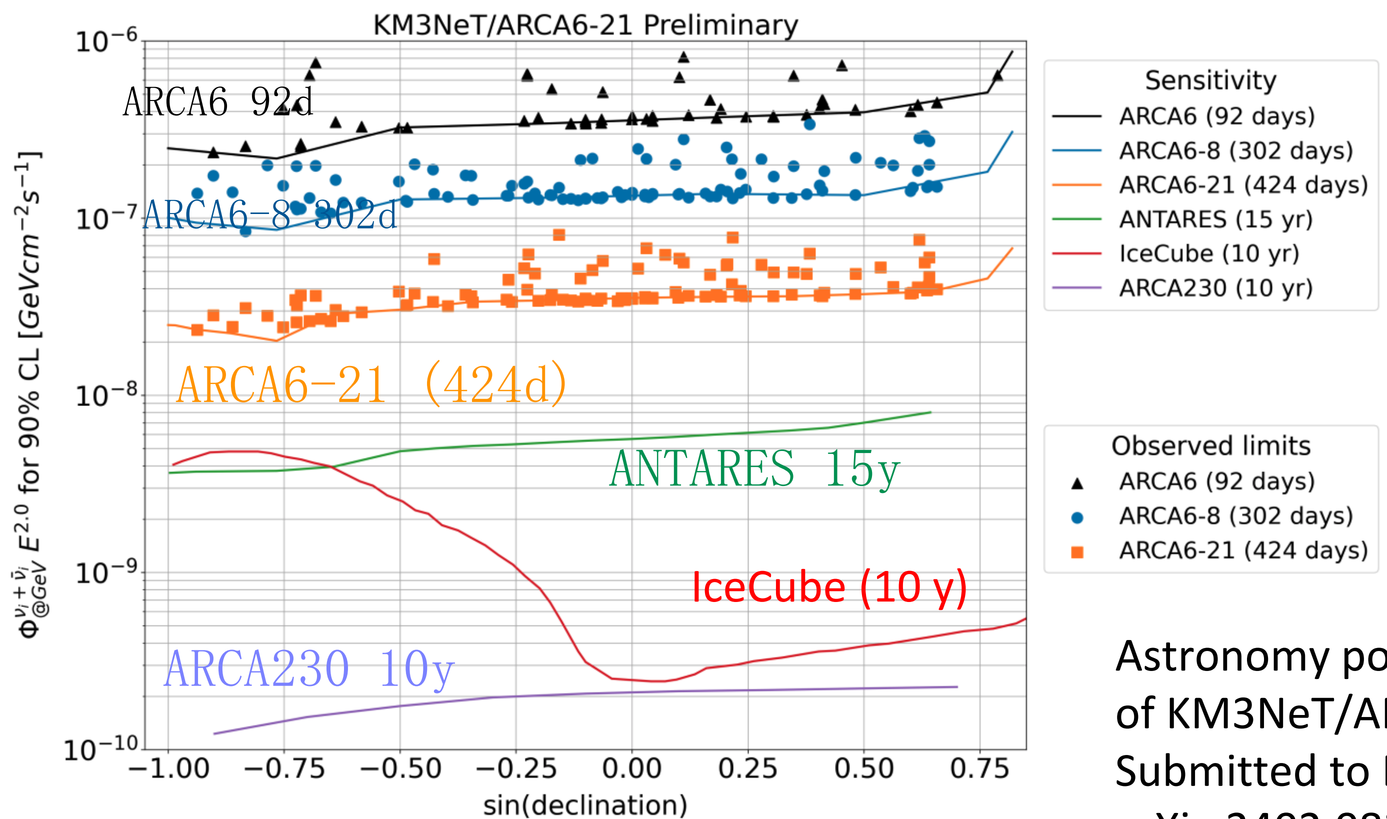
MG3 J225517+2409 (3.4 σ pre-trial)
3C403 (3.4 σ pre-trial)
J0242+1101 (2.6 σ pre-trial)
J2136+0041 (2.4 σ pre-trial)
TXS 0506+056 (2.4 σ pre-trial)

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



KM3NeT point source searches

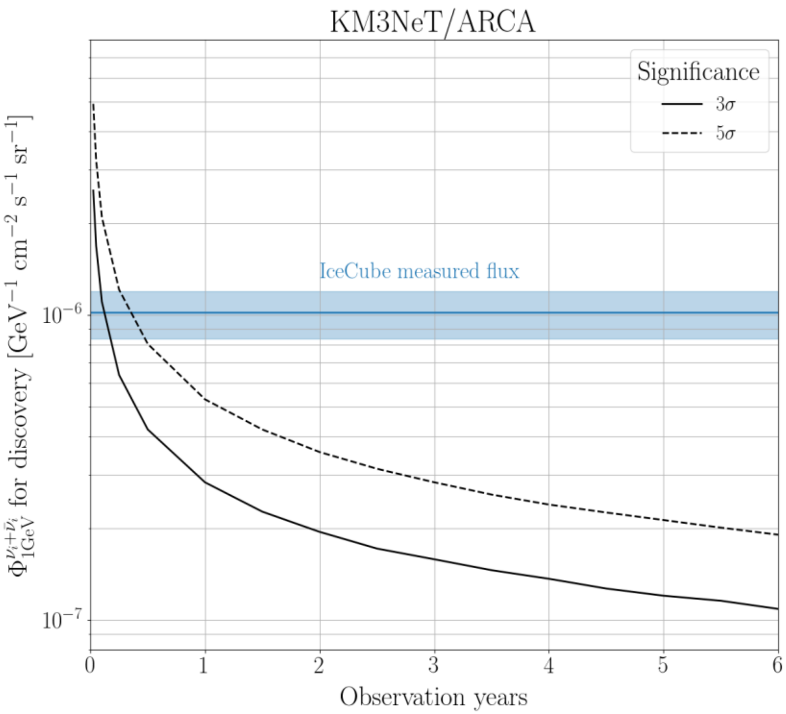




Astronomy potential of KM3NeT/ARCA. Submitted to EPJC, arXiv:2402.08363.

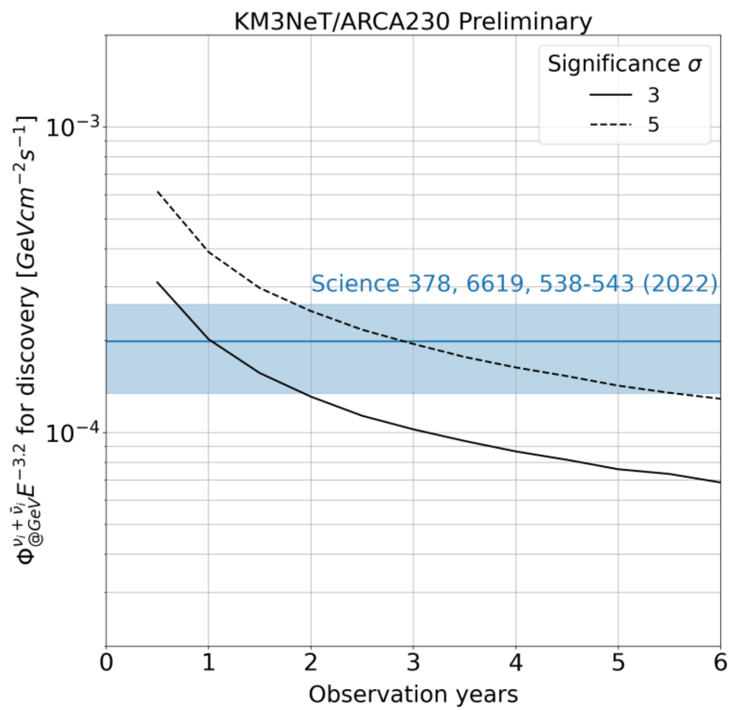
KM3NeT expected sensitivities

Diffuse flux



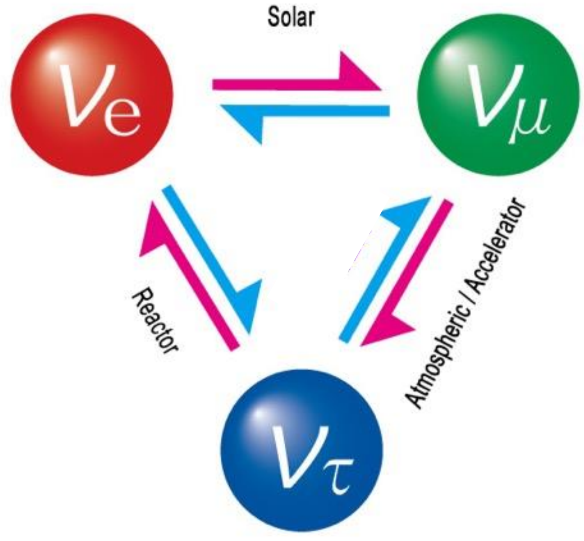
5σ in ~ 0.5 year for the full detector (230 DUs)

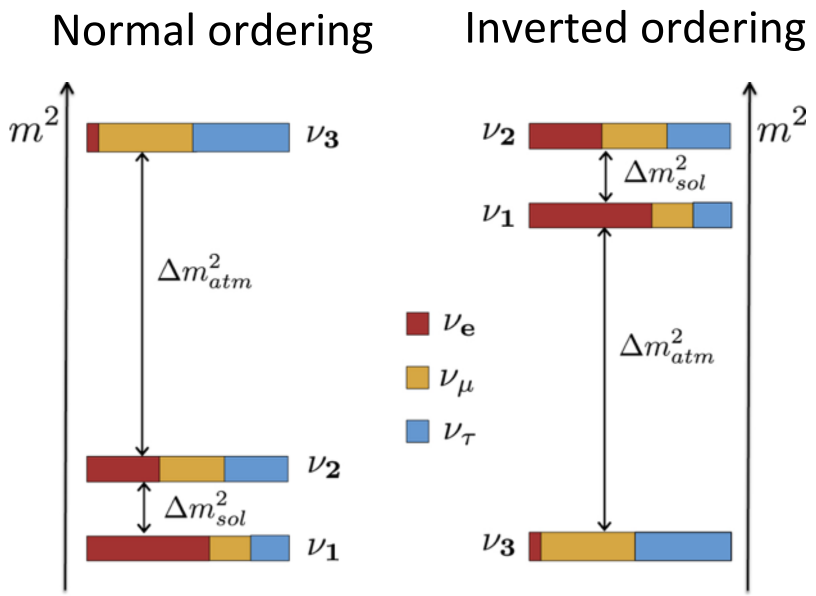
NGC1068

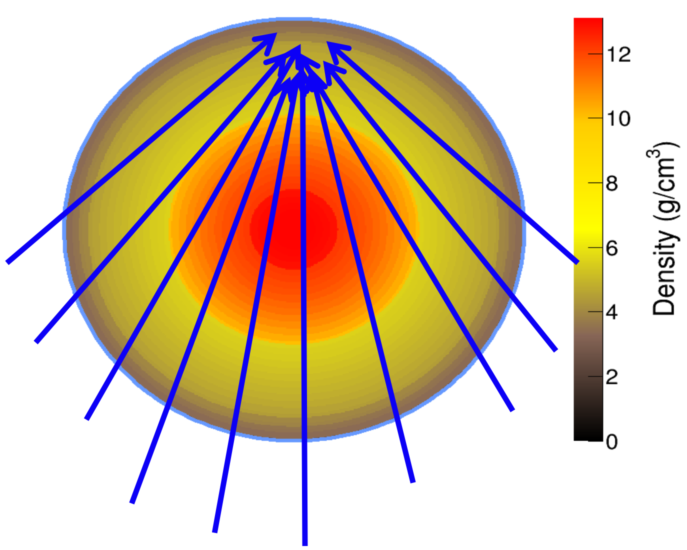


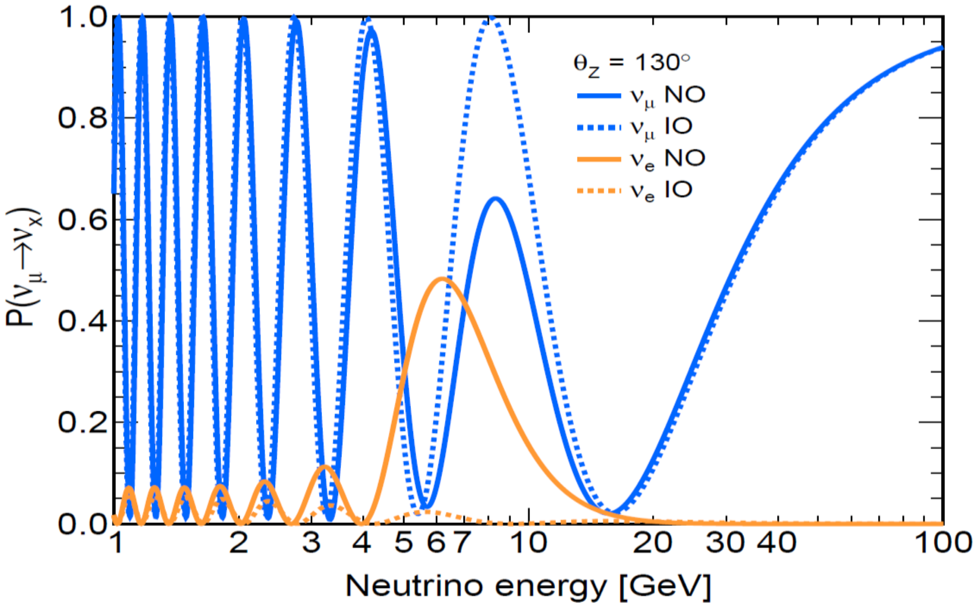
3σ in one year

Neutrino oscillations with atmospheric neutrinos

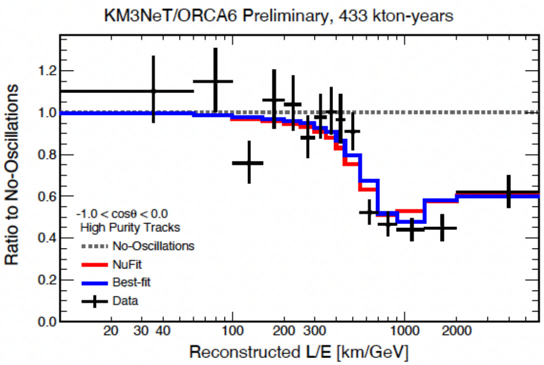




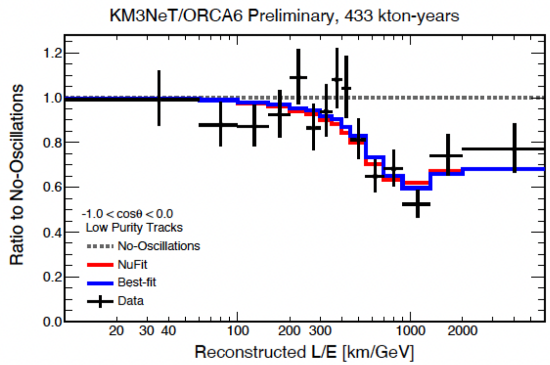




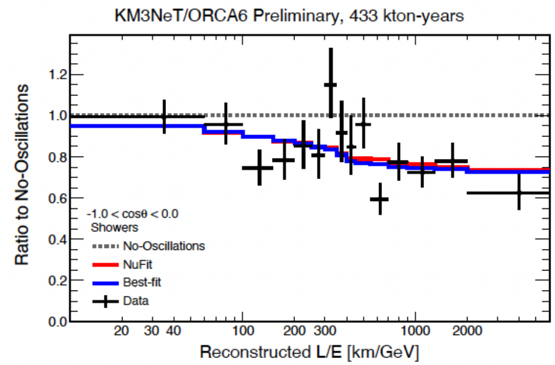
Oscillation results with ORCA6



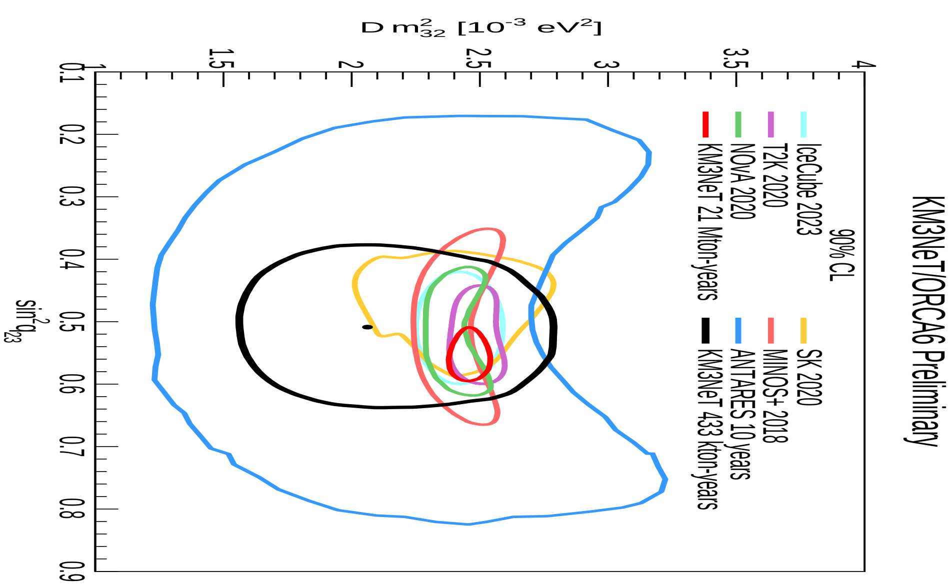
High Purity Tracks



Low Purity Tracks



Showers



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

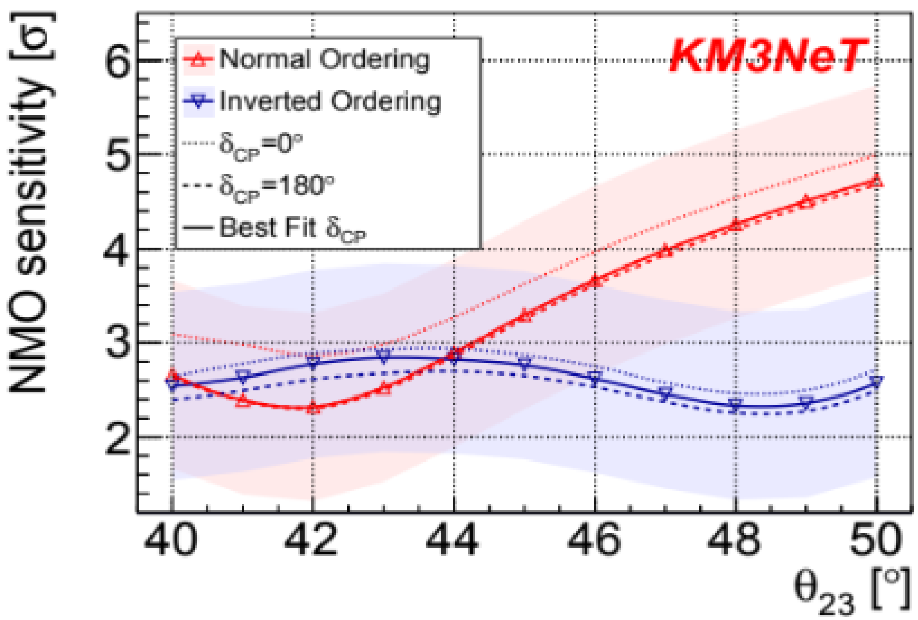
and $\Delta m^2_{31} = 2.14^{+0.36}_{-0.25} \cdot 10^{-3}\mathrm{eV}^2$.

Normal Ordering favoured at delta_chi2=0.9

ICRC2023 PoS 996

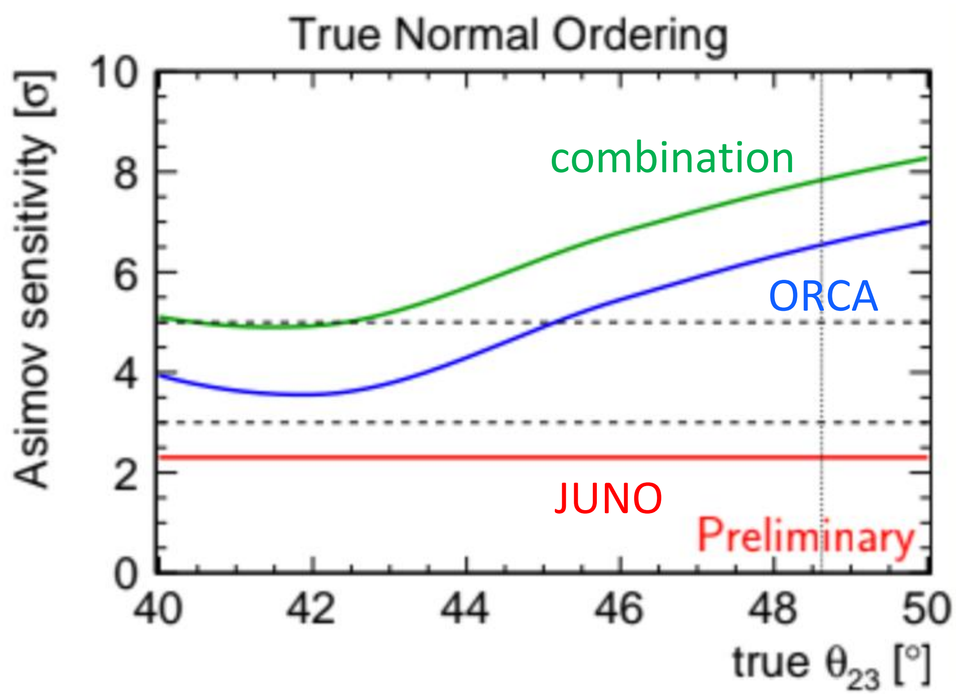
ORCA115: neutrino mass ordering

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

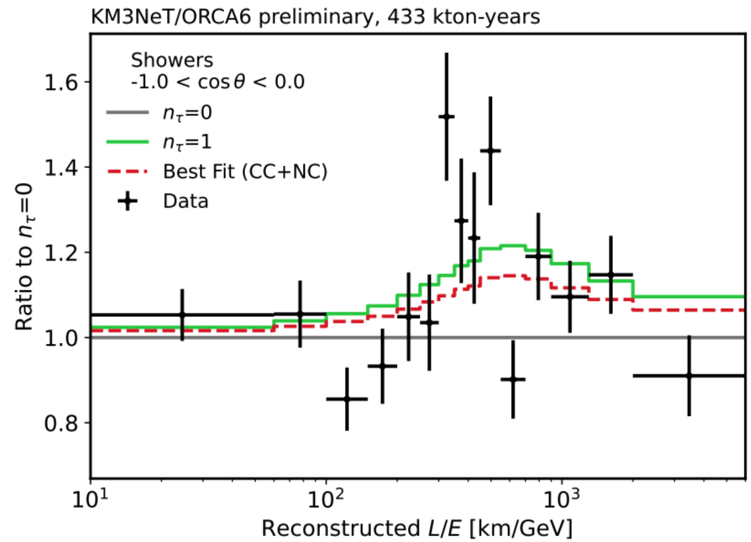
Tau appearance

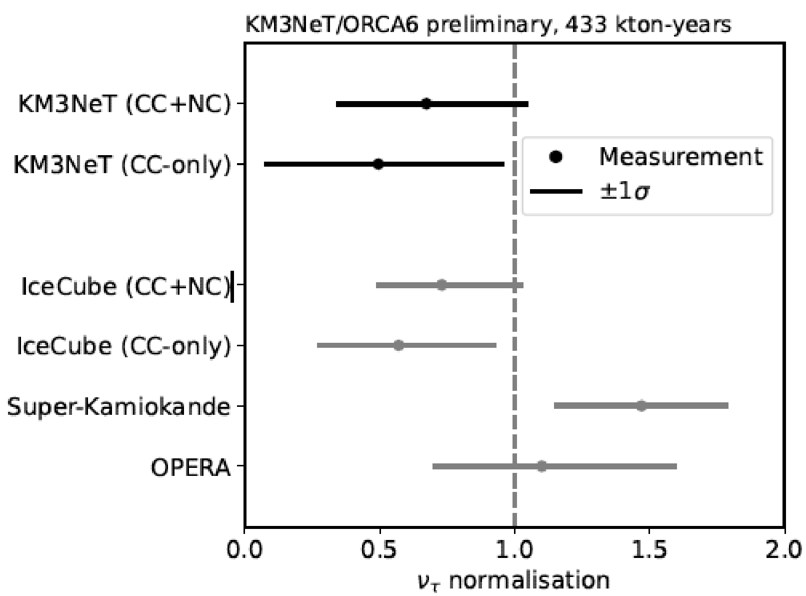
The muon neutrinos mainly oscillate to tau neutrinos.

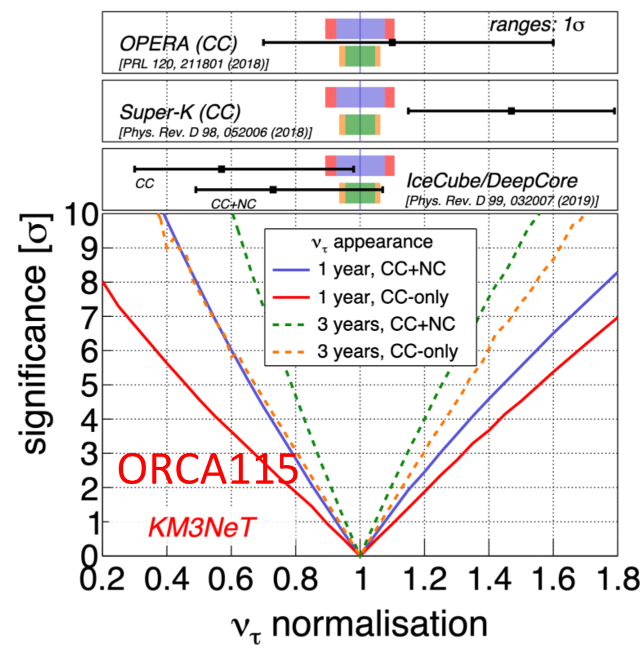
They appear as showers events.

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

≈3k ν_τ CC events/year with full ORCA



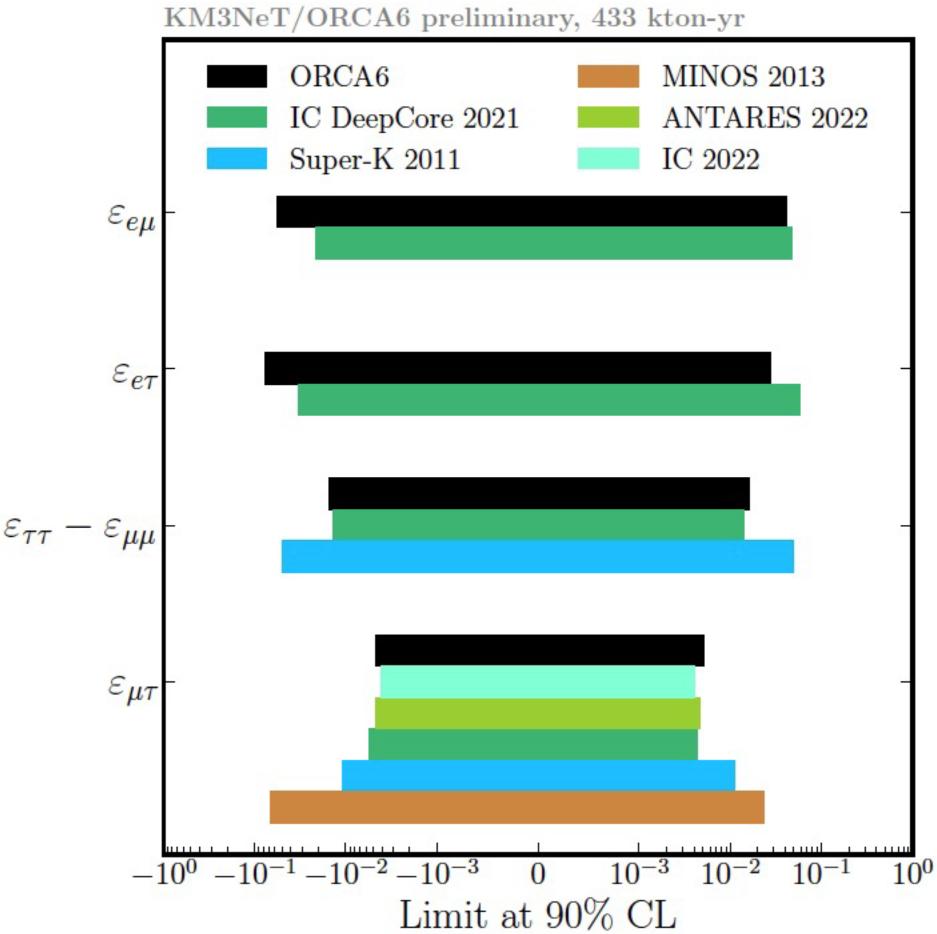




Beyond Standard Model

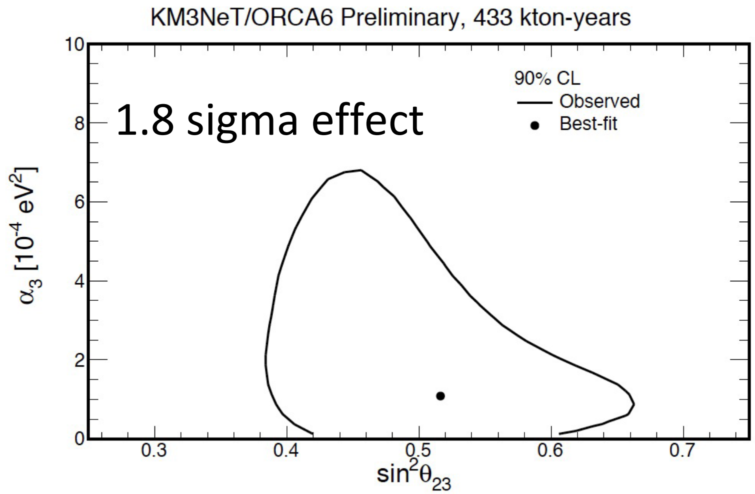
Non Standard Interactions

☞ ICRC2023 PoS 998



Neutrino decay

ICRC2023 PoS 997

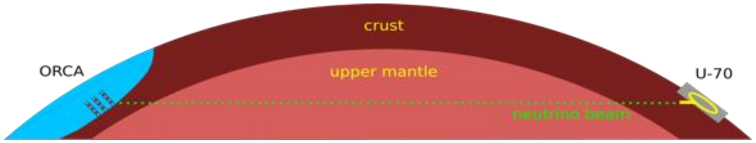


Quantum decoherence

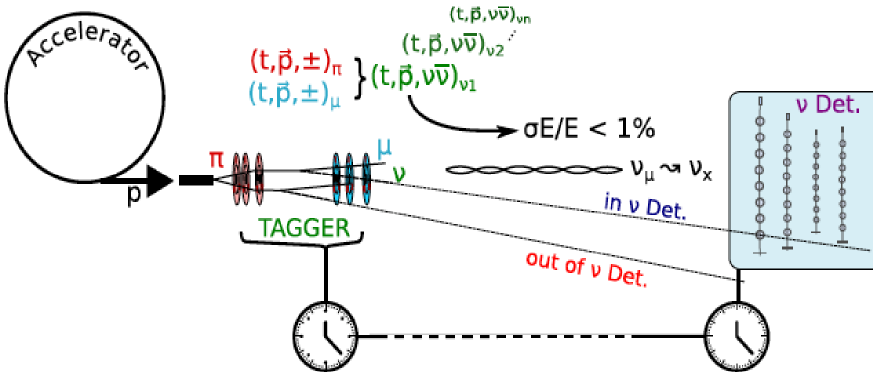
	$\gamma \propto E^{-2}$	$\gamma \propto E^{-1}$
ORCA6		
γ_{21} [GeV]	7.7×10^{-21}	3.1×10^{-22}
γ_{31} [GeV]	1.4×10^{-20}	5.0×10^{-22}
$\gamma_{21} = \gamma_{31}$ [GeV]	3.0×10^{-21}	1.1×10^{-22}
DeepCore		
$\gamma_{21} = \gamma_{32}$ [GeV]	7.5×10^{-20}	3.5×10^{-22}
$\gamma_{31} = \gamma_{32}$ [GeV]	4.3×10^{-20}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

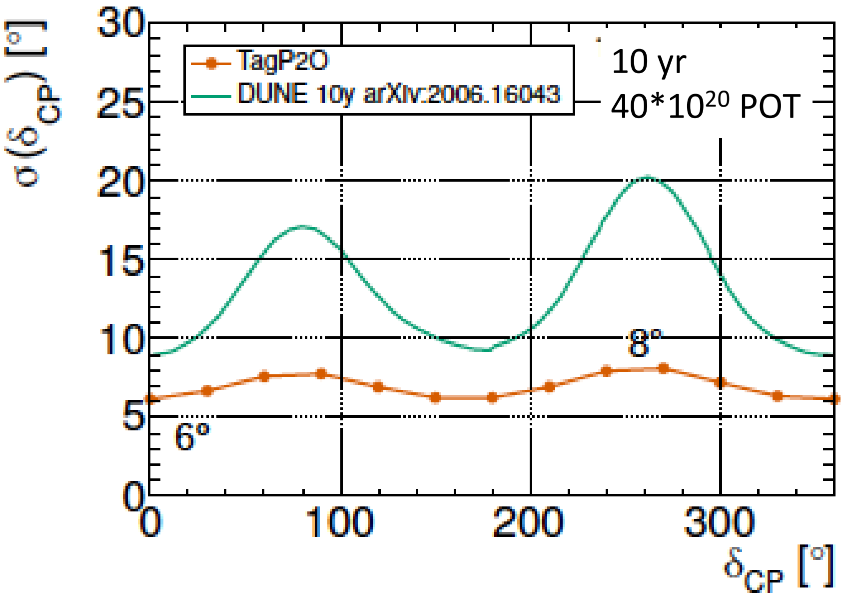
New idea: Tagged neutrino beam to KM3NeT

- 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

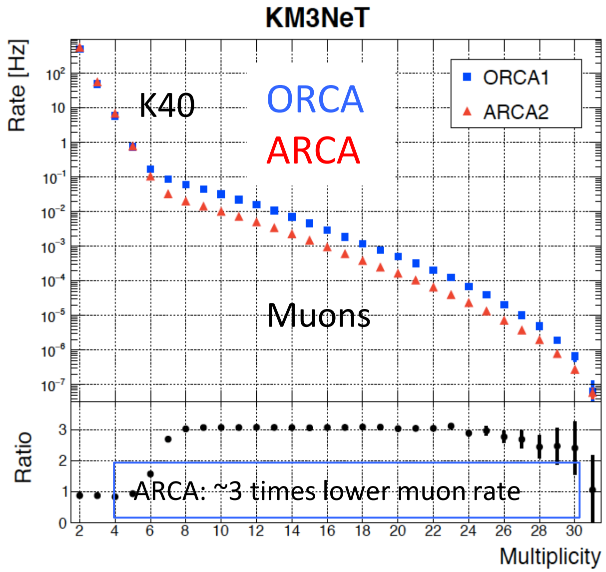
New collaborators very welcome
Come and join the adventure!

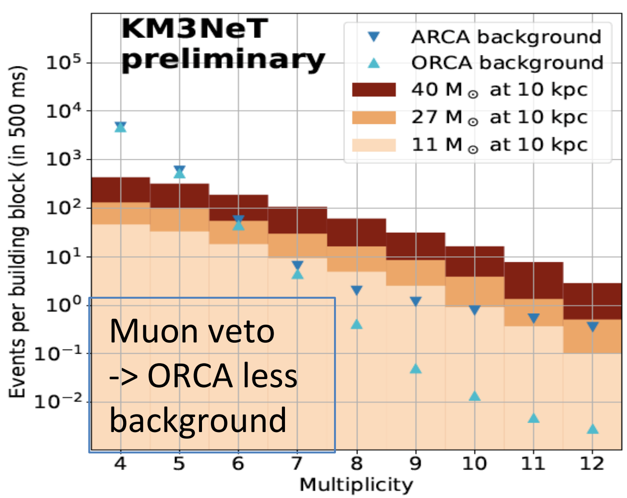
BACK UP

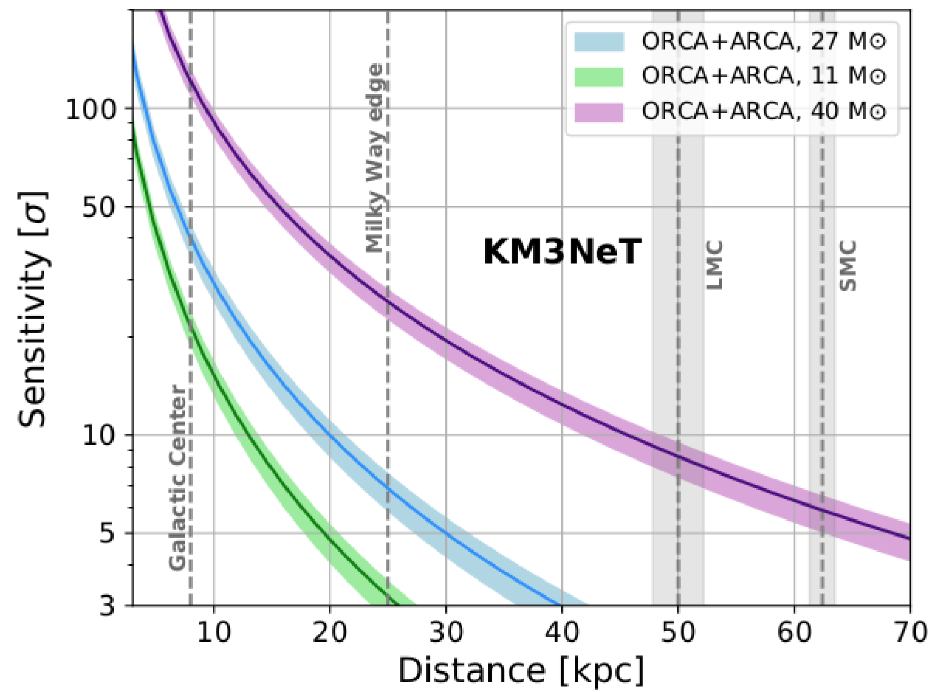
Supernova monitoring in KM3NeT

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

Eur. Phys. J. C81 (2021) 445







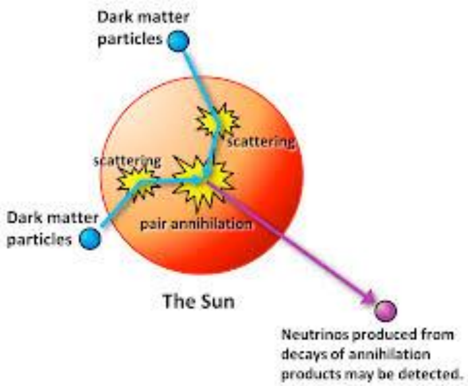
Discovery potential for 95% of Galactic CCSNe

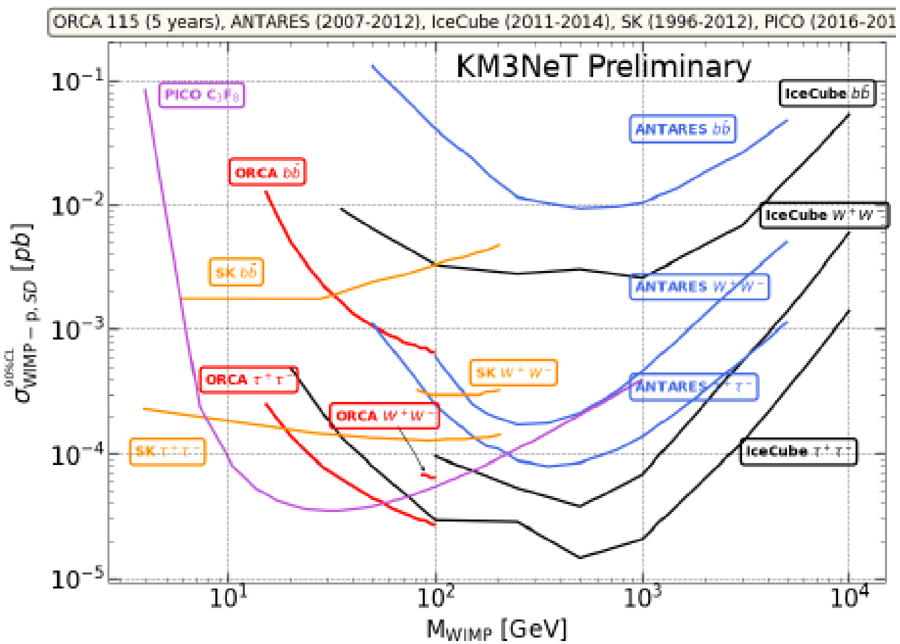
ARCA6+ORCA6 already sensitive to 60% of Galactic CCSNe (<11 kpc)

Joint real time trigger operational for SNEWS since early 2019

Dark matter-indirect detection

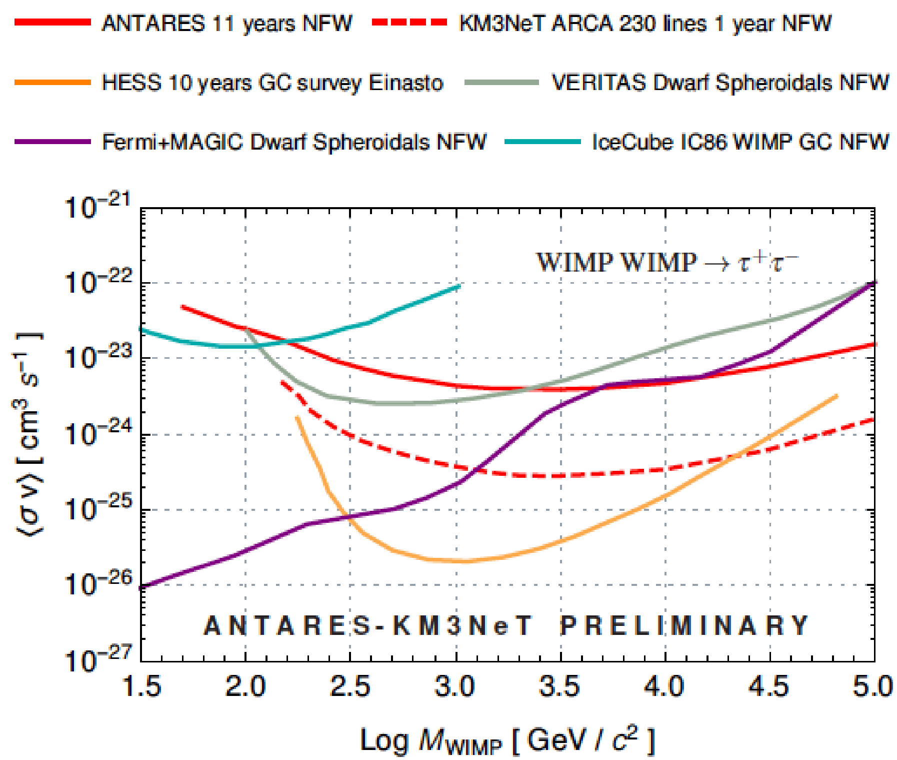
Sun





Phys.Lett. B759 2016

Galactic Centre

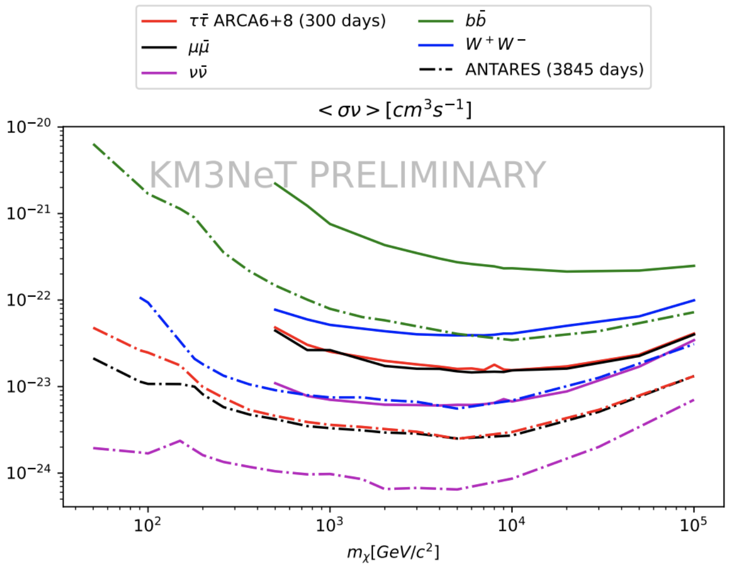


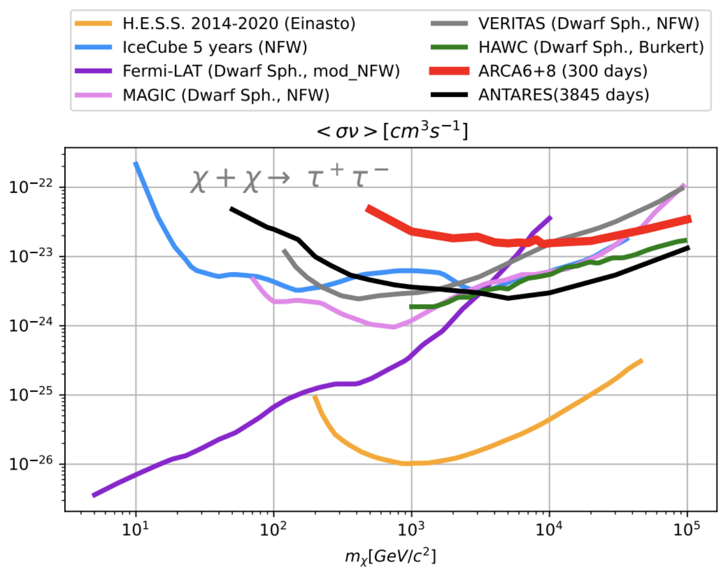
Phys. Lett. B 805 135439 (2020)

Dark Matter

Galactic Centre

ARCA6 + ARCA8 ICRC2023 [PoS 1377]

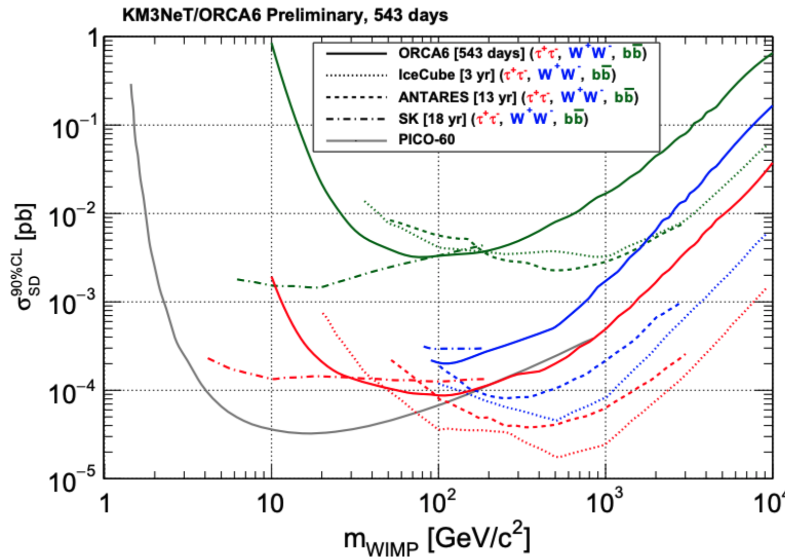


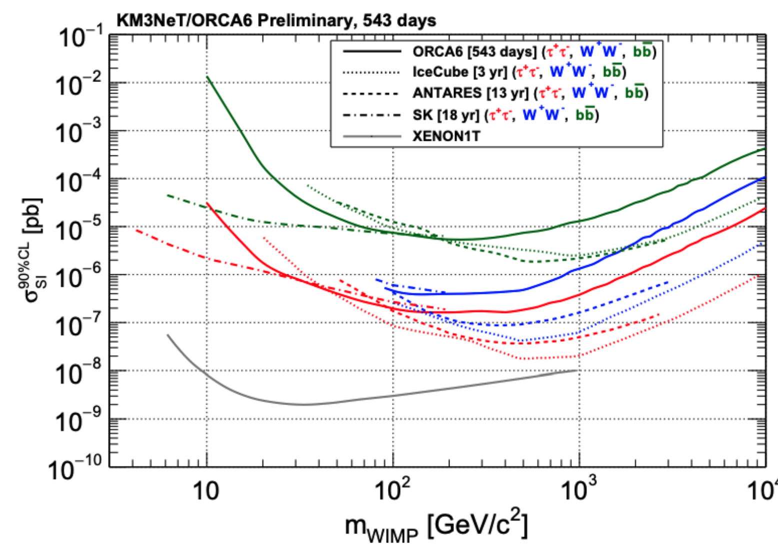


KM3NeT quickly reaching the ANTARES limits

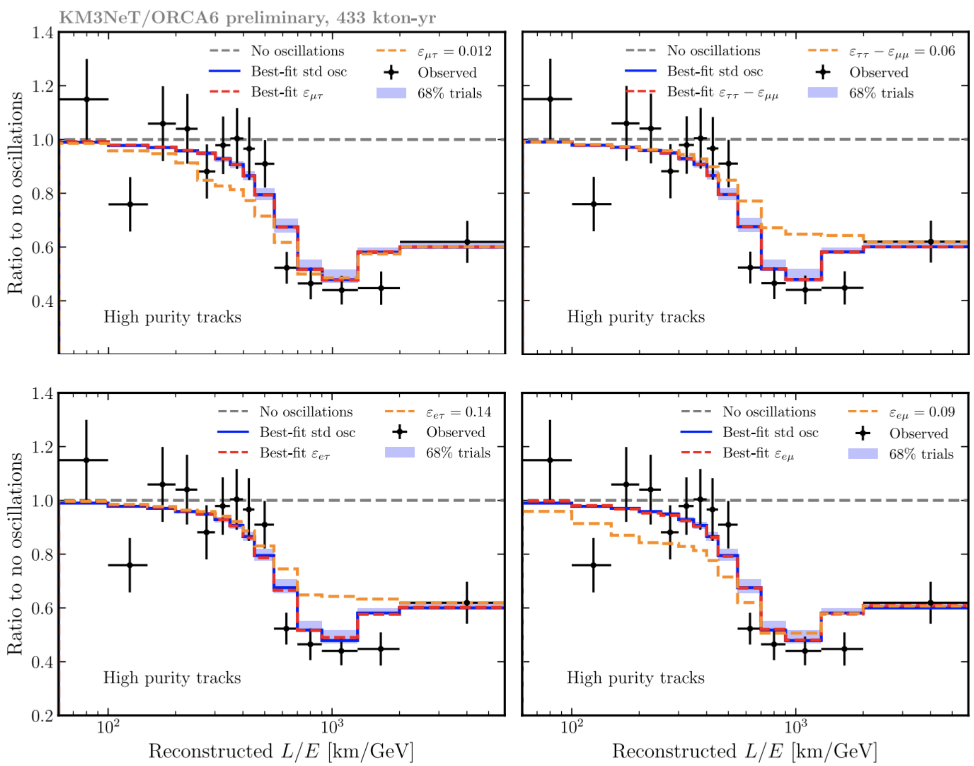
The Sun

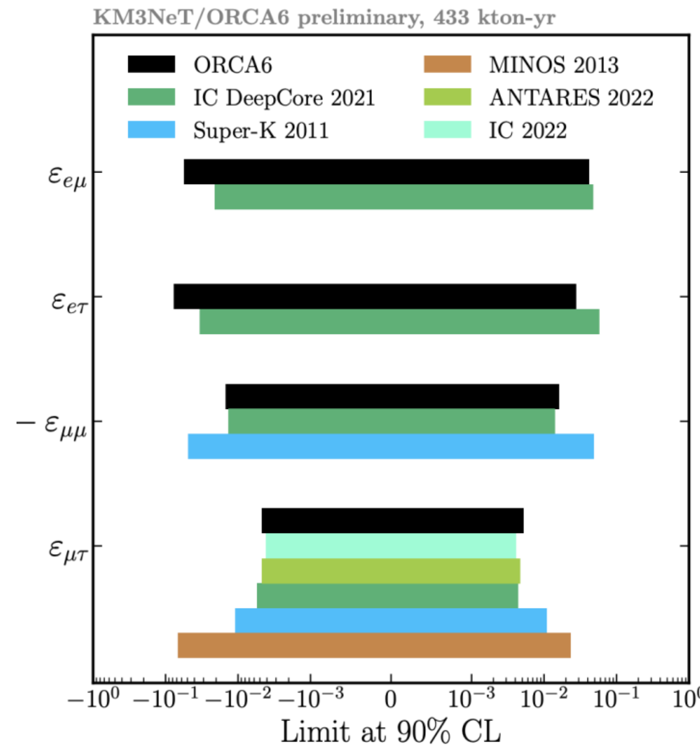
ORCA6 ICRC2023 [PoS 1406]





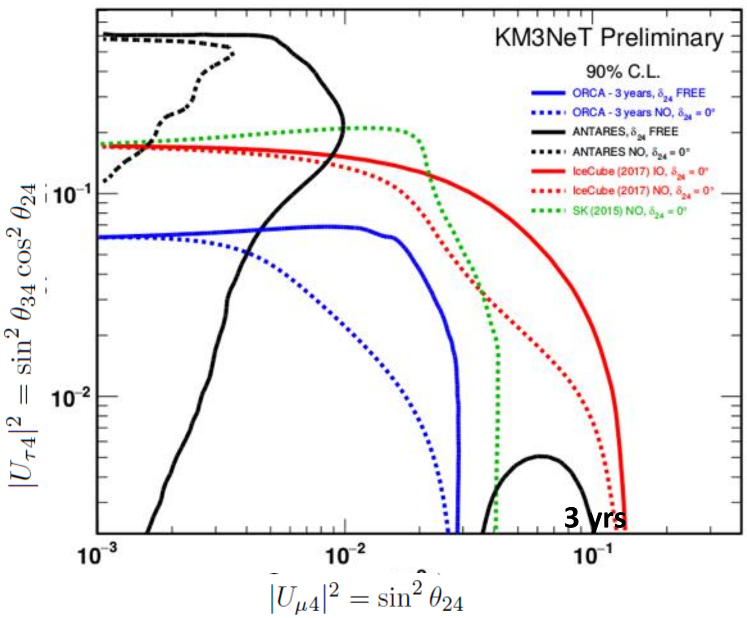
Non-Standard Interactions





ORCA115: sterile neutrinos

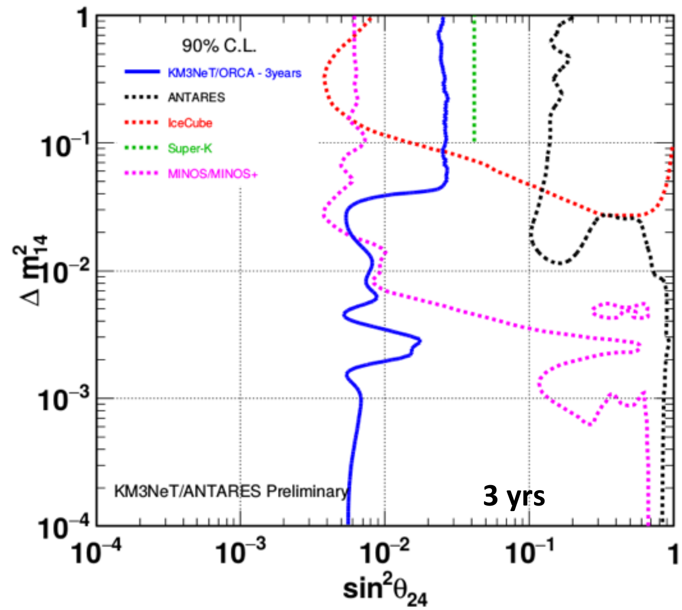
$\Delta m_{41}^2 > 0.1$ eV^2



Dependence on δ_{24}

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

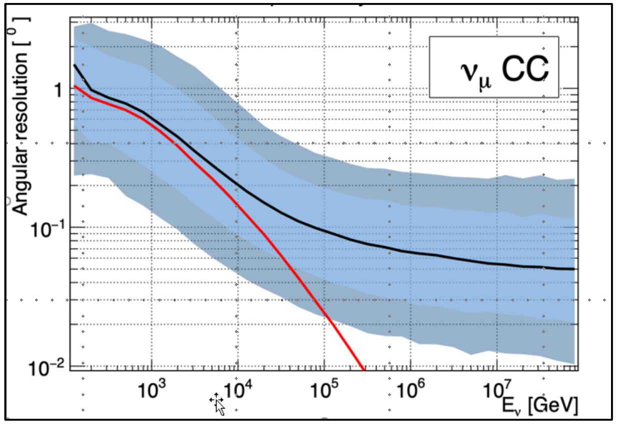
$\Delta m_{41}^2 < 0.1$ eV^2



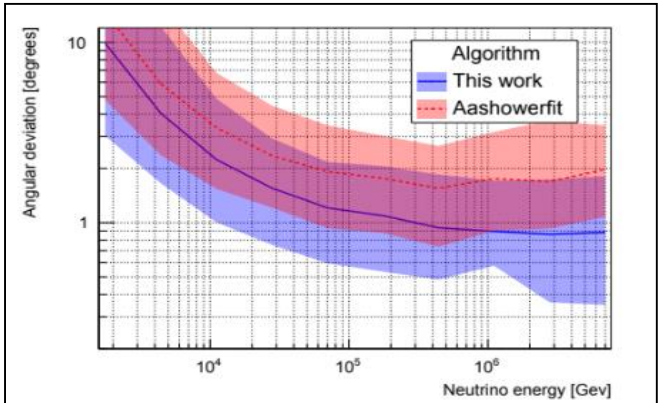
Due to longer & multiple baselines improve on MINOS/MINOS+ limits by 2 orders of magnitude

Angular Resolutions

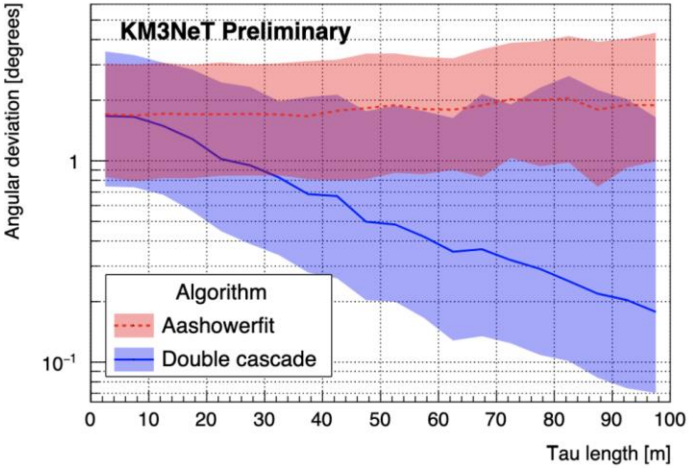
Better than 0.1° > 20 TeV



Better than 1° > 30 TeV



Better than 1° for tau track length > 22 m



EVENT TYPE AND ANGULAR RESOLUTION

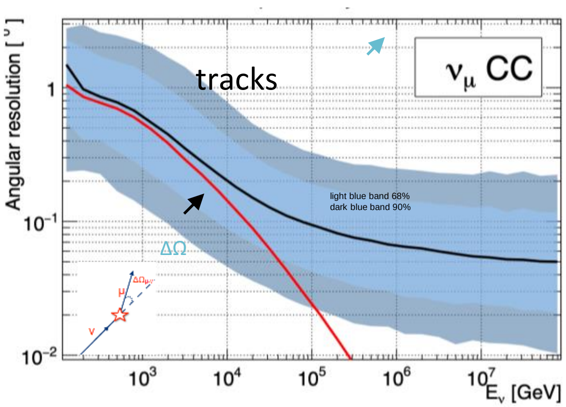
	TRACK*	CASCADE*
ANTARES	0.3°	3°
KM3NET	0.1°	1.5°
ICECUBE	0.3°	7° -8°
BAIKAL - GVD	0.25°	3° - 3.5°

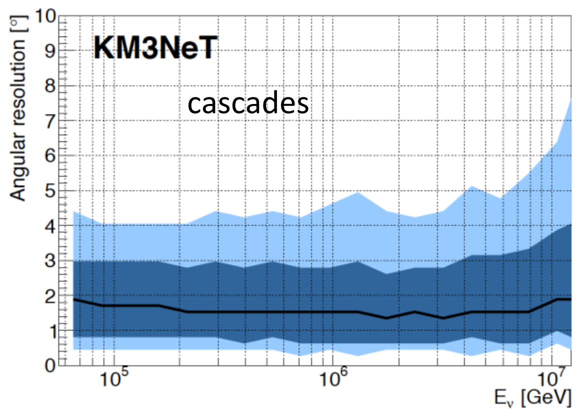
Tracks: very long path (Eμ>1TeV several km)
Big lever arm
- Good angular resolution

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

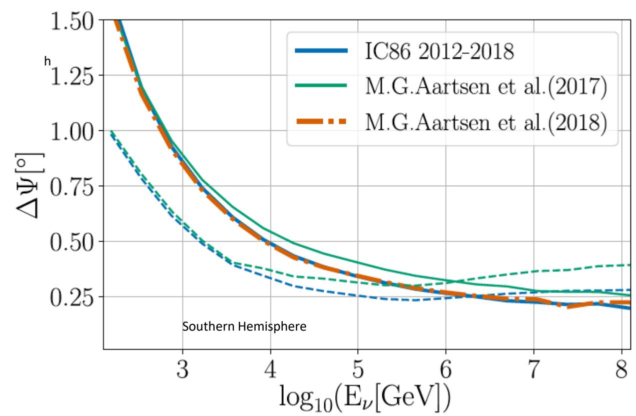
*Resolution at 100 TeV

KM3NeT





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



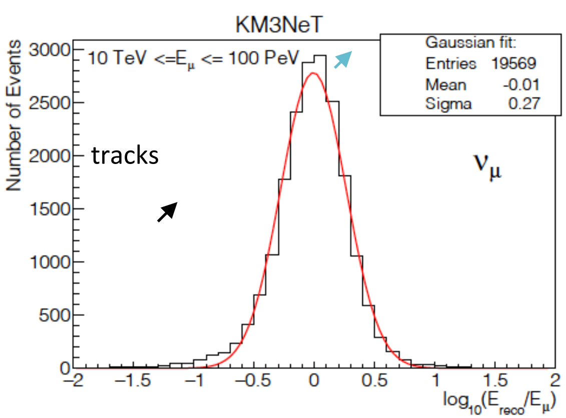
EVENT TYPE AND ENERGY RESOLUTION

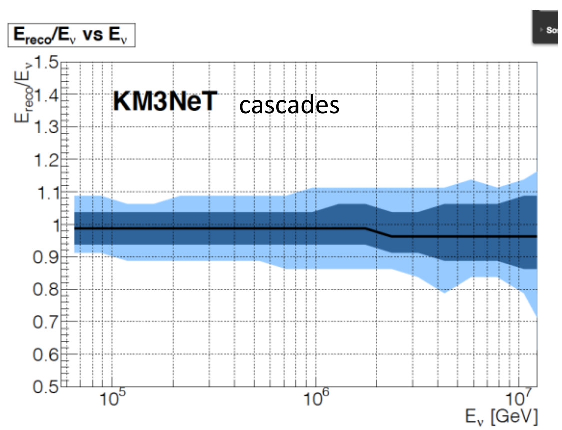
Tracks: very long path (E_μ>1TeV several km)
Neutrino interaction vertex far from the detector
- Modest energy resolution

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

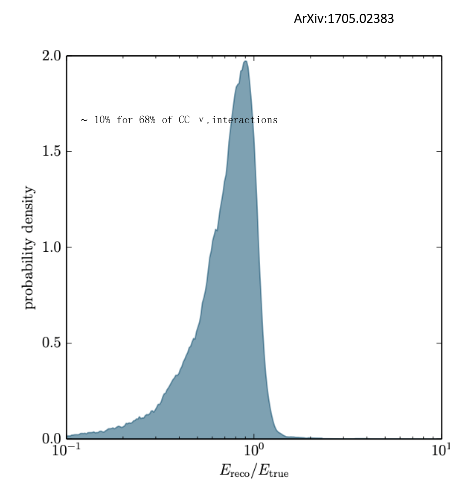
	TRACK IN LOG(E)	CASCADE
ANTARES	35%	5%
KM3NET	27%	5%
ICECUBE	~30%	10%
BAIKAL -GVD		

KM3NeT



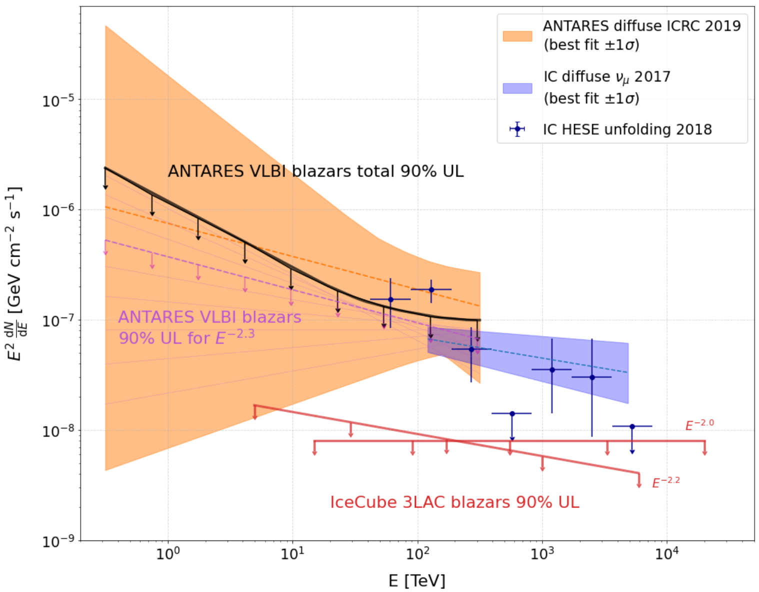


IIC energy resolution for cascades



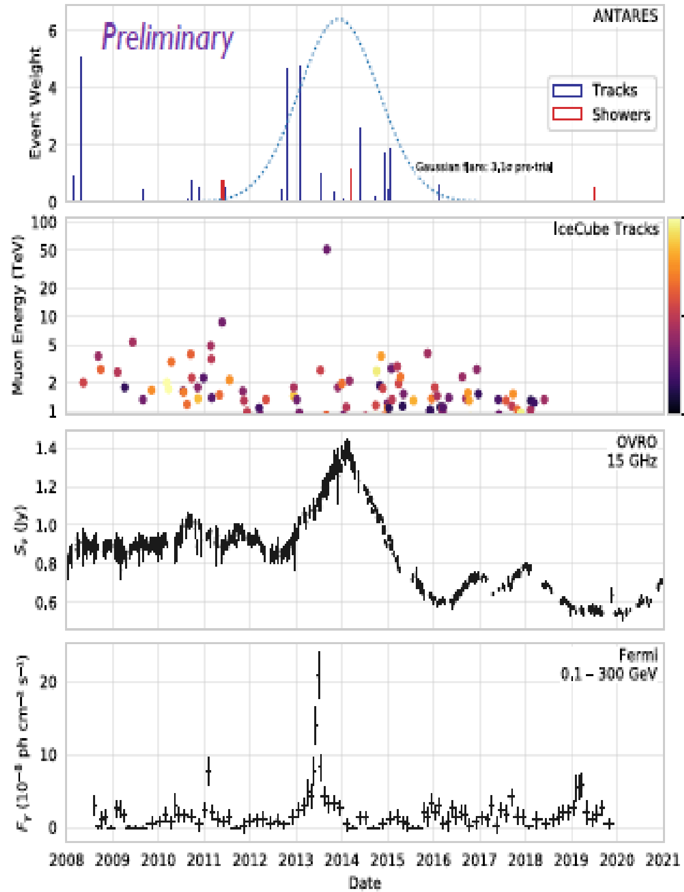
Neutrinos from radio-loud blazars?

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 < 10deg²

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%