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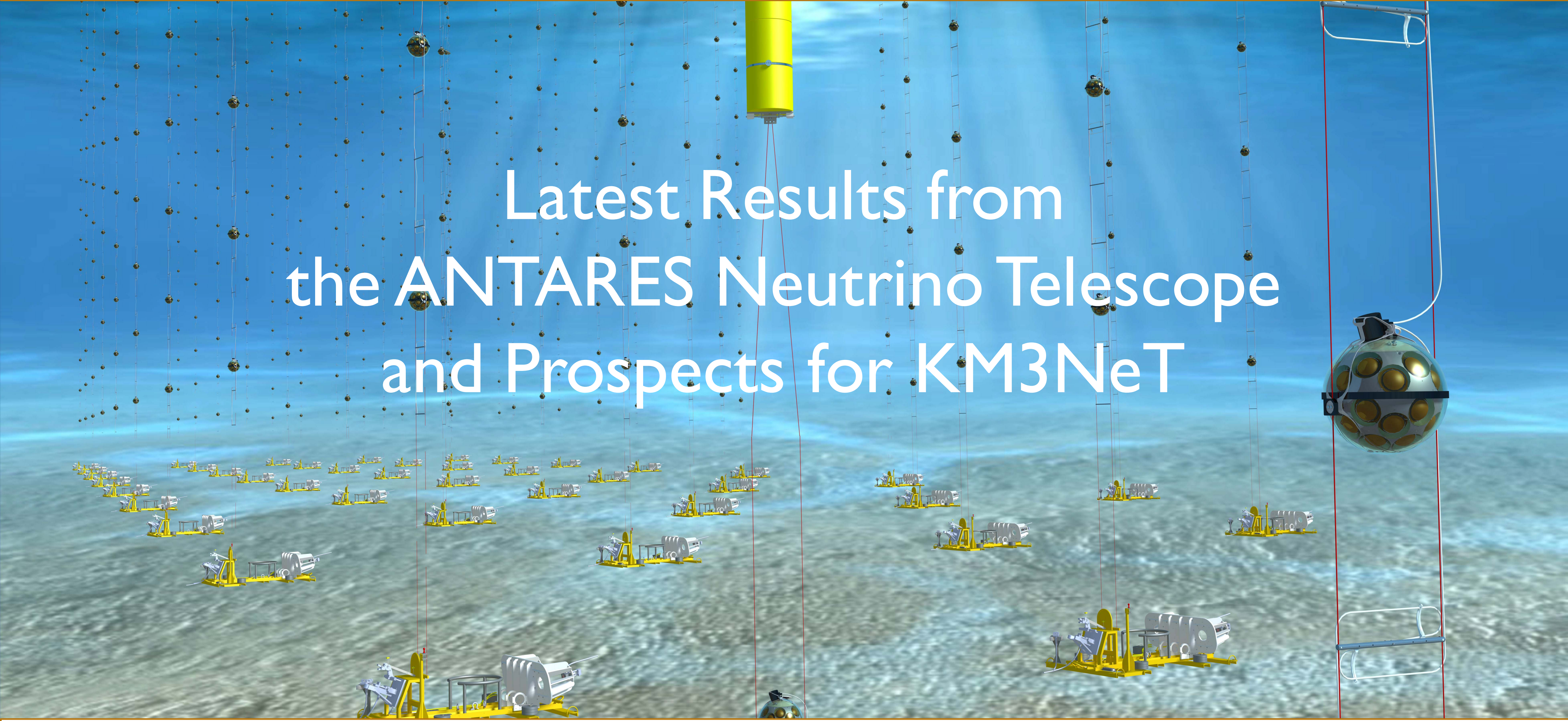
INSTITUT DE FÍSICA CORPUSCULAR

VNIVERSITAT DE VALÈNCIA

ANTARES

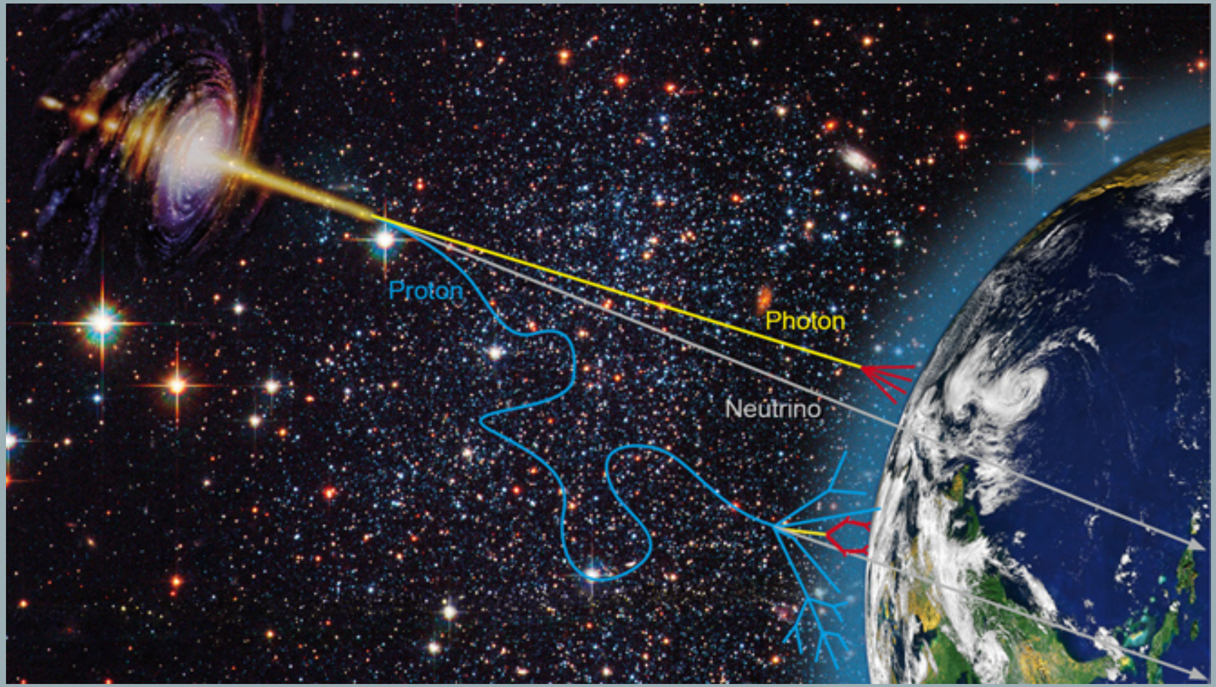
KM3NeT

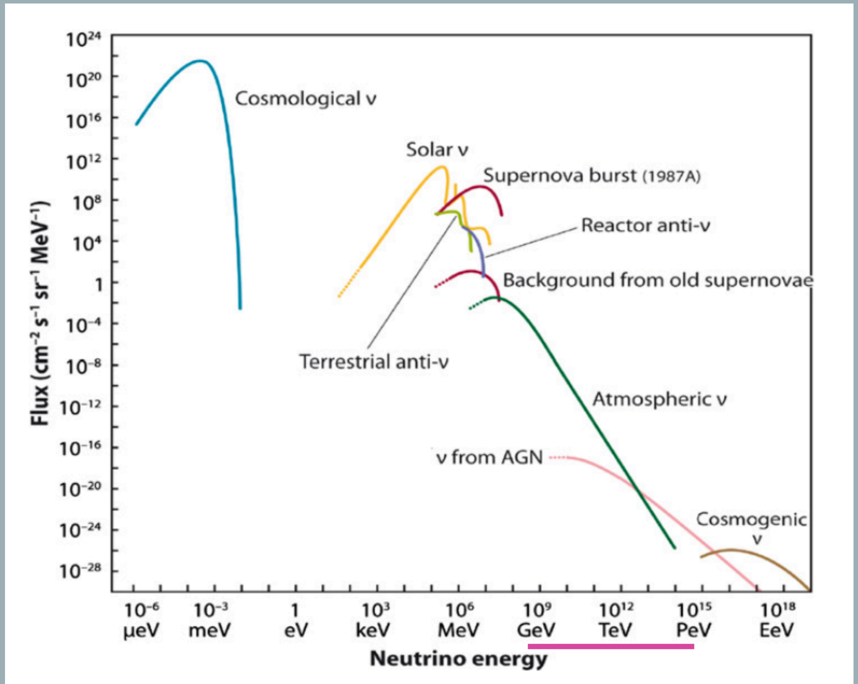


Latest Results from the ANTARES Neutrino Telescope and Prospects for KM3NeT

Giulia Illuminati on behalf of the ANTARES and KM3NeT Collaborations

Neutrino Astronomy





Neutrinos:

- electrically neutral -> trajectory not affected by magnetic fields, point back to the source
- stable -> travel long distances
- weakly interacting -> penetrate regions which are opaque to photons

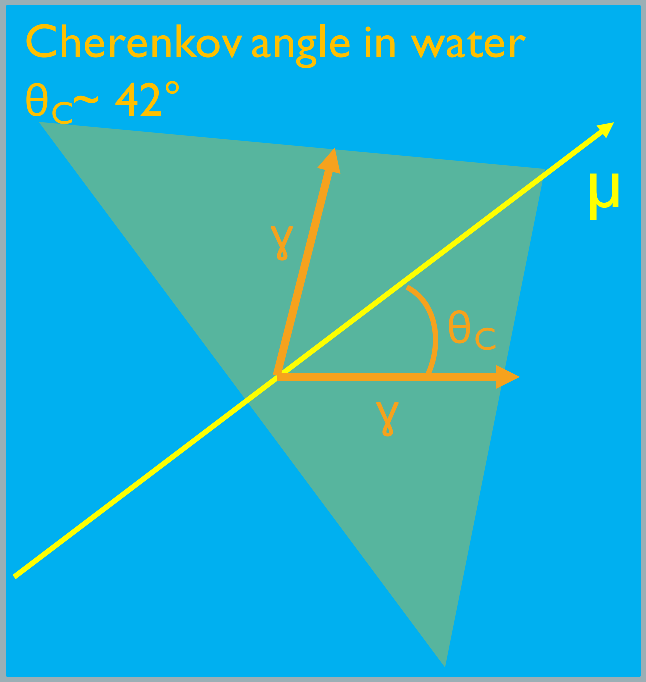
➢ Provide a strong indication of hadronic acceleration in astrophysical sources

$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

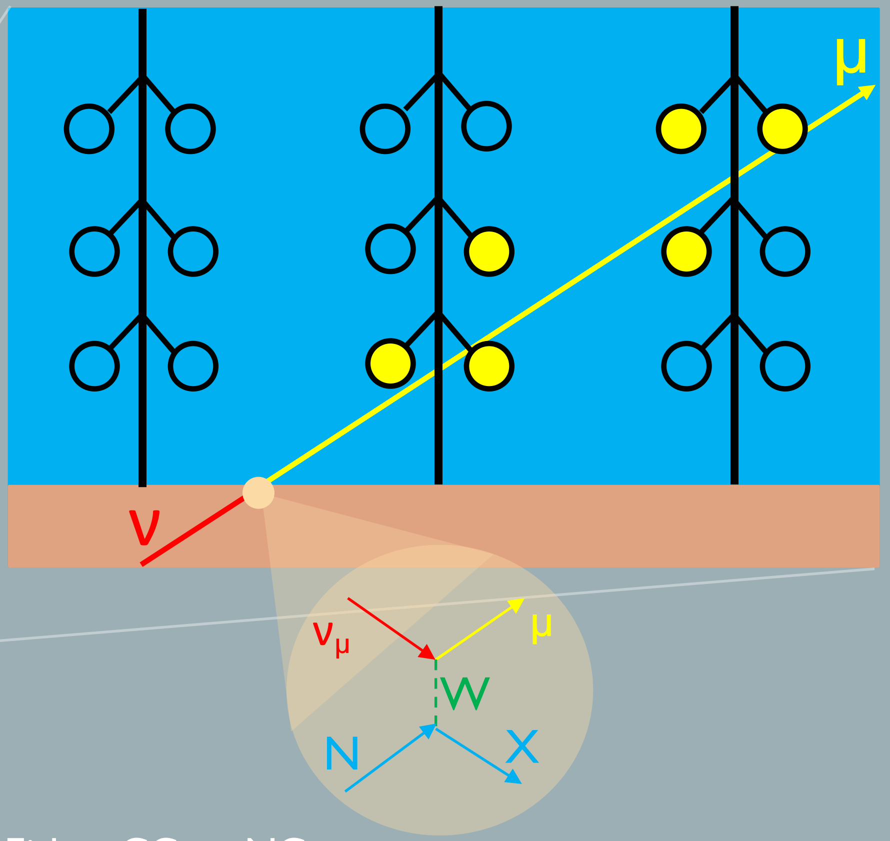
$\nu_e : \nu_\mu : \nu_\tau = 1:2:0$ at the source

$\nu_e : \nu_\mu : \nu_\tau = 1:1:1$ at Earth

Neutrino telescopes:
Detection principle



- Earth used as shield against up-going atmospheric muons
- Detector deployed in deep water/ice to reduce down-going atmospheric muons
- Low ν cross section requires large detector volumes



- Cherenkov radiation detected by arrays of PMTs
- Position, time and charge used to reconstruct direction and energy

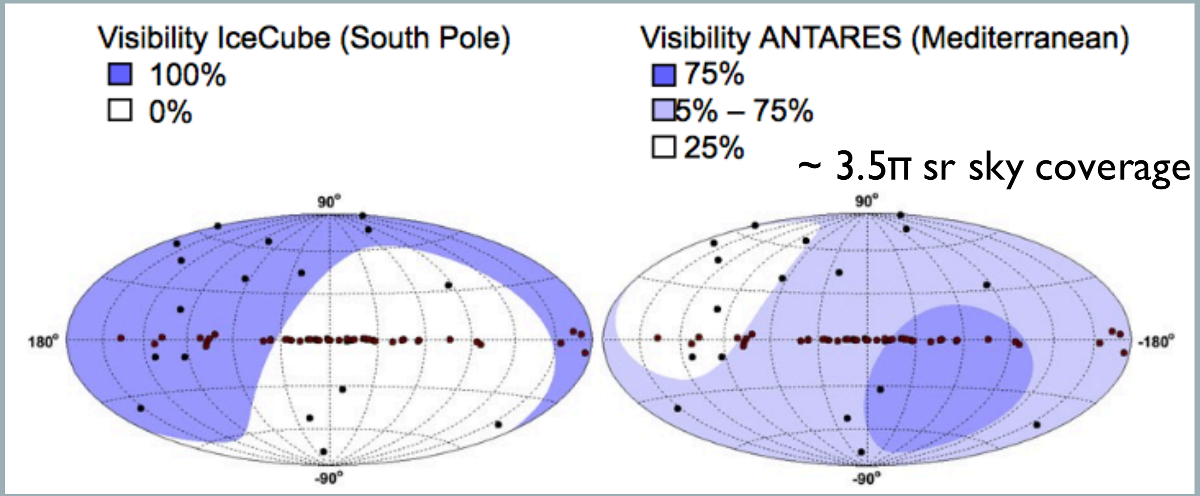
- Either CC or NC interaction with a nucleus inside or nearby the detector volume

key interaction (CC):

$$\nu_\ell + N \rightarrow \ell + X$$

Global Neutrino Network (GNN)

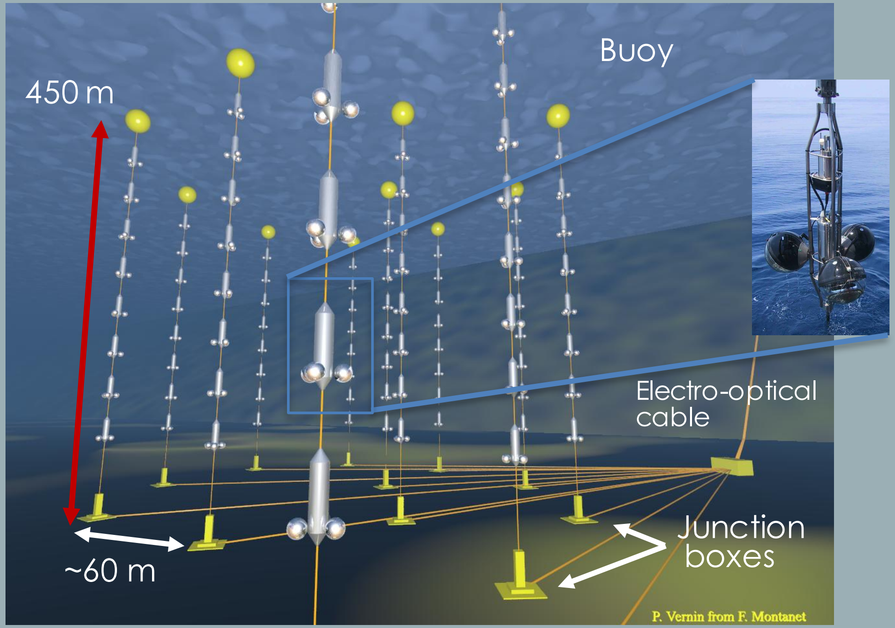
- ANTARES and KM3NeT
  Mediterranean Sea
- IceCube
  Antarctic Ice
- Baikal
  Lake Baikal

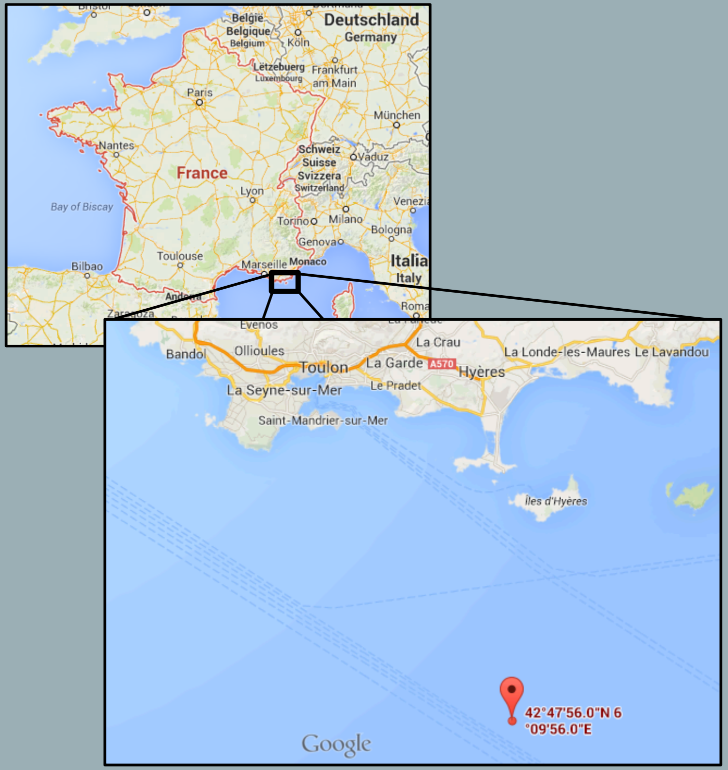


~ 3.5π sr sky coverage

The European neutrino telescopes:
ANTARES

- First detection line installed in early 2006
- Completed in 2008
- 2475 m depth in the Mediterranean Sea
- 40 km offshore from Toulon

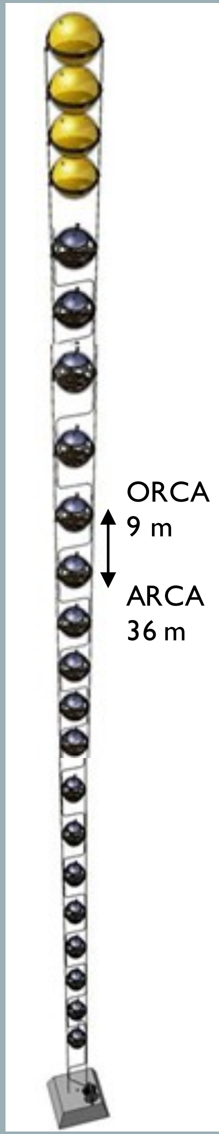




- Three-dimensional array of 885 PMTs
- 12 vertical lines, 25 storeys
- 3 PMTs per storey
- PMT facing 45° downwards

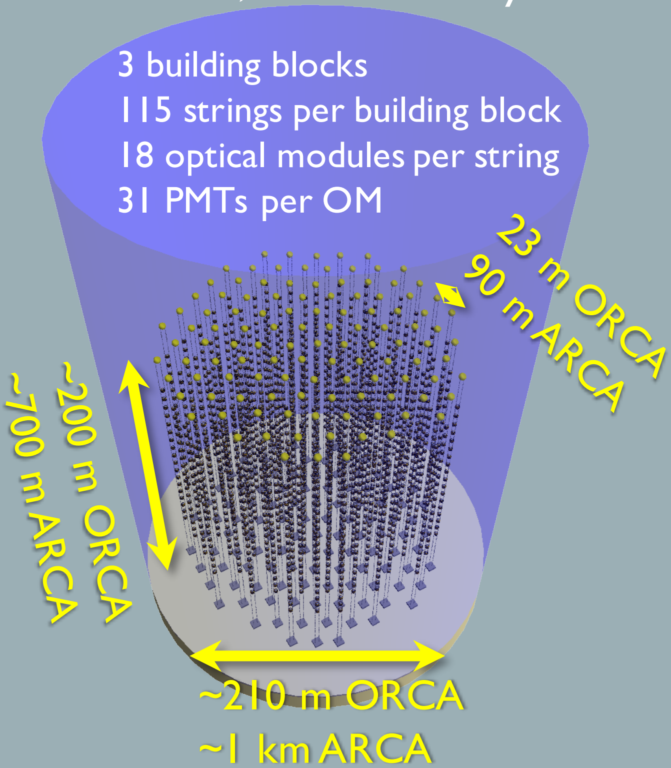
The European neutrino telescopes:

KM3NeT



KM3NeT/ORCA

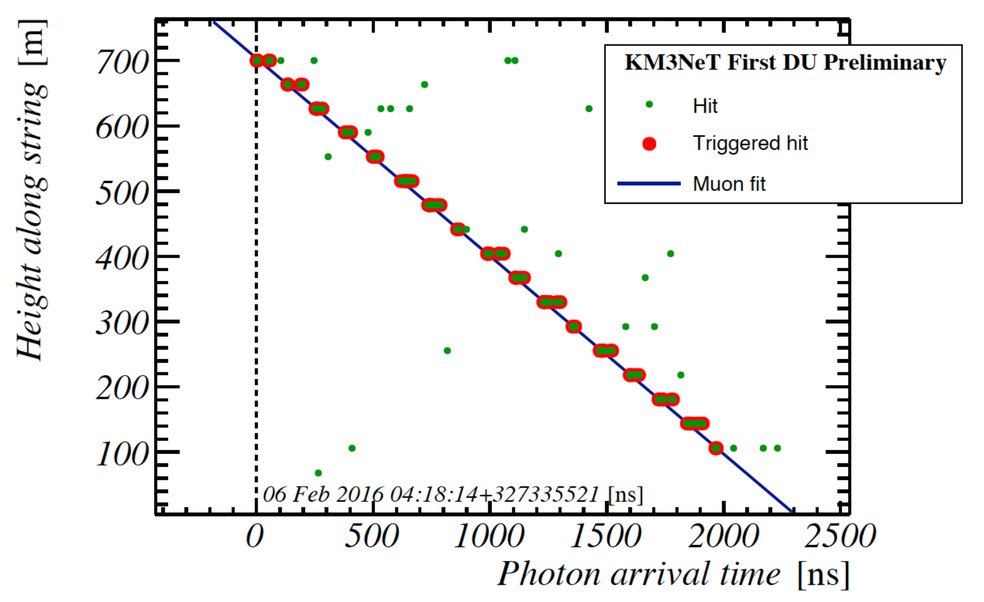
- Under construction
- 2450 m depth in the Mediterranean Sea
- 40 km offshore from Toulon
- 1 dense building block
- GeV energies
- Oscillations, mass hierarchy



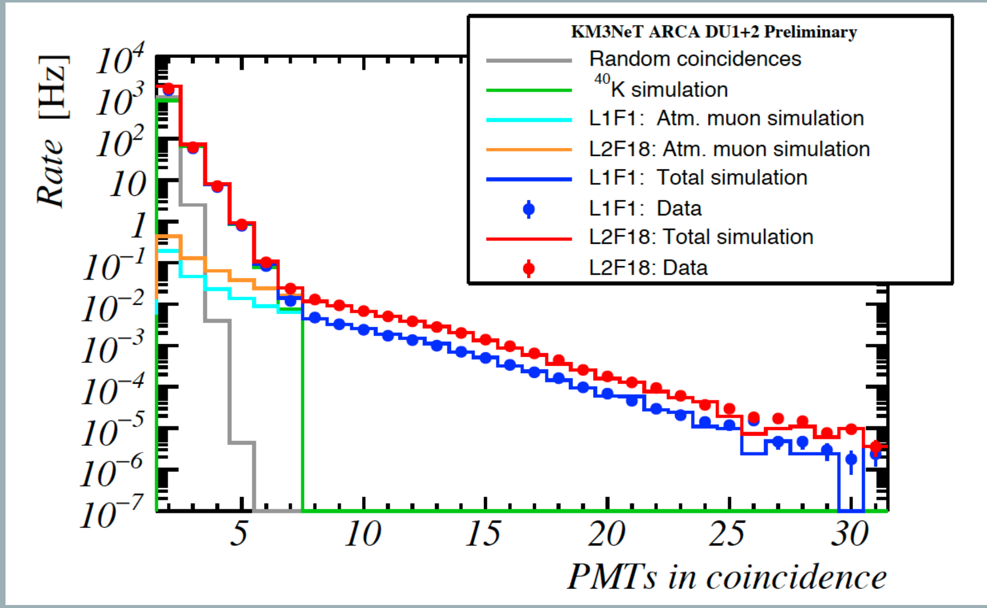
KM3NeT/ARCA

- Under construction
- 3500 m depth in the Mediterranean Sea
- 100 km offshore from Porto Palo di Capo Passero, Sicily
- 2 sparse building blocks
- 1-10 TeV energy threshold
- High-energy neutrino astronomy

KM3NeT: First detection lines

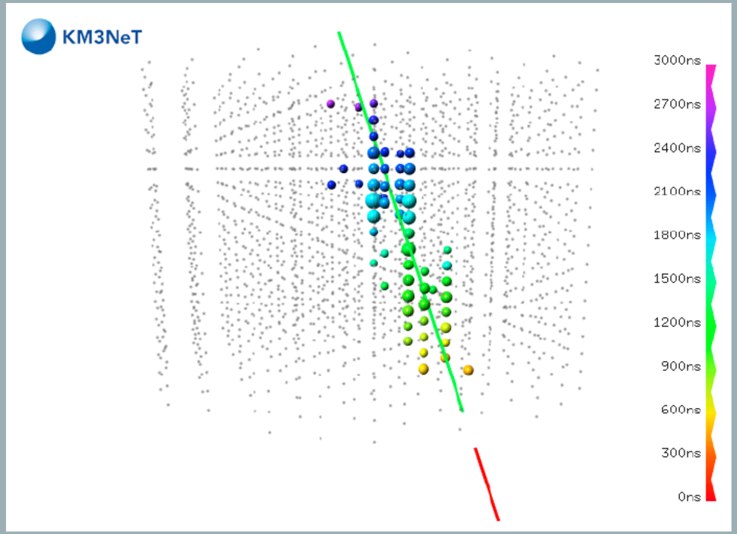


Event display: down-going muon



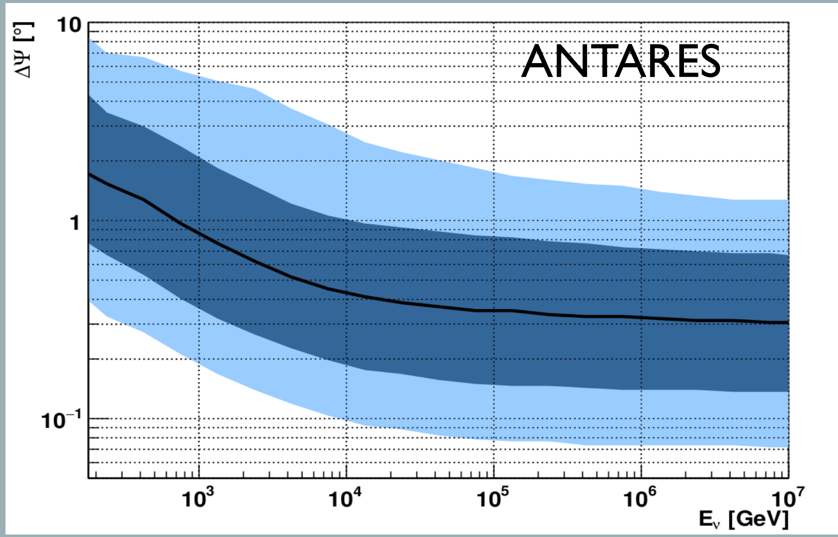
Coincidence rate (clusters of two or more hits on the same DOM within a time window of 25 ns) as a function of the number of hit PMTs

Event topologies: TRACKS

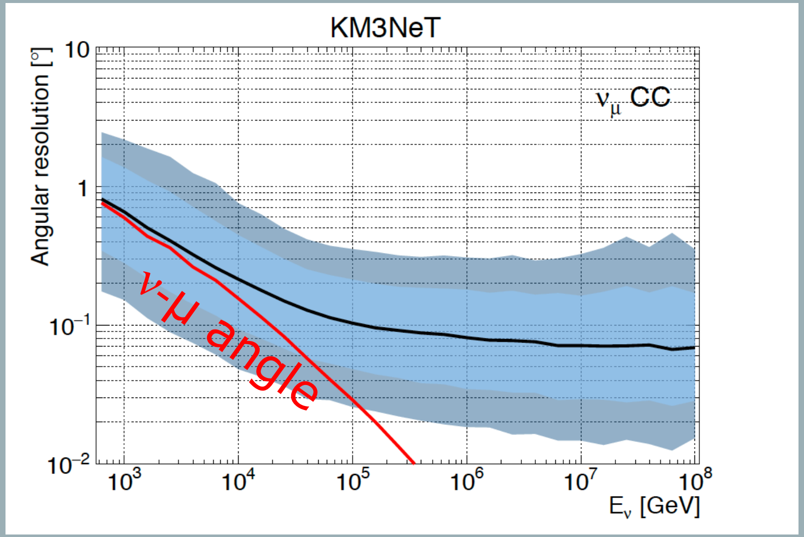


Track-like events:
ν_μ (ν_τ) neutrino
CC interaction near the detector
➔ track

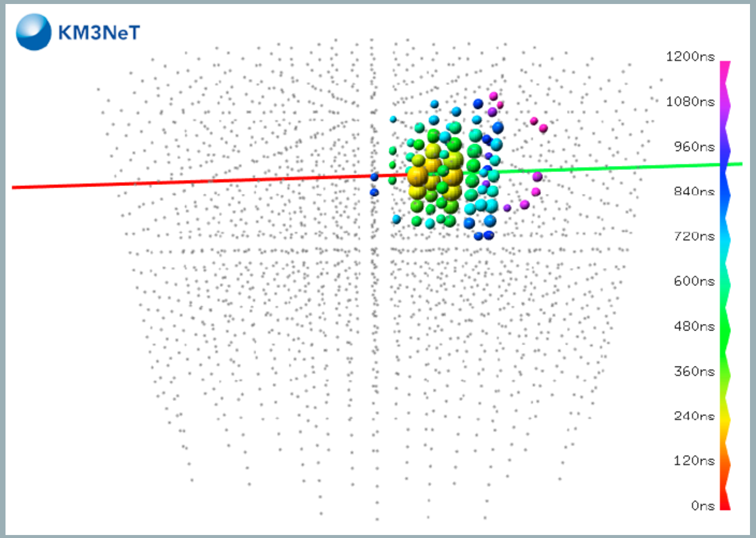
Angular resolution < 0.4° for E_ν > 10 TeV



Angular resolution < 0.1° for E_ν > 100 TeV

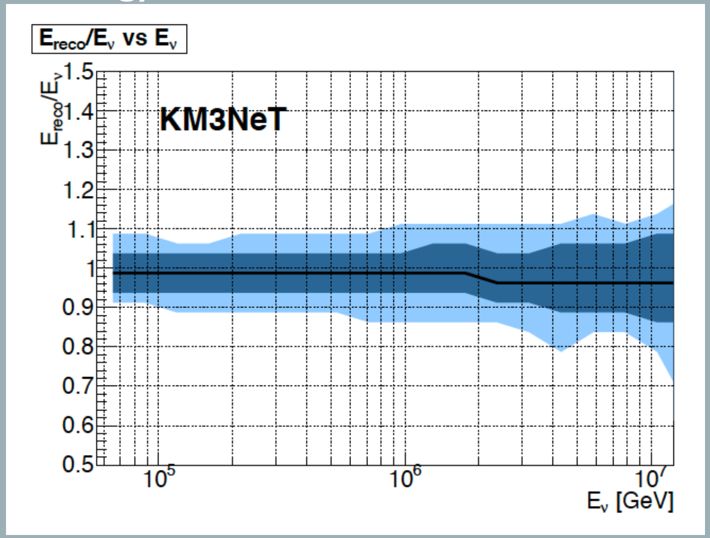


Event topologies: SHOWERS

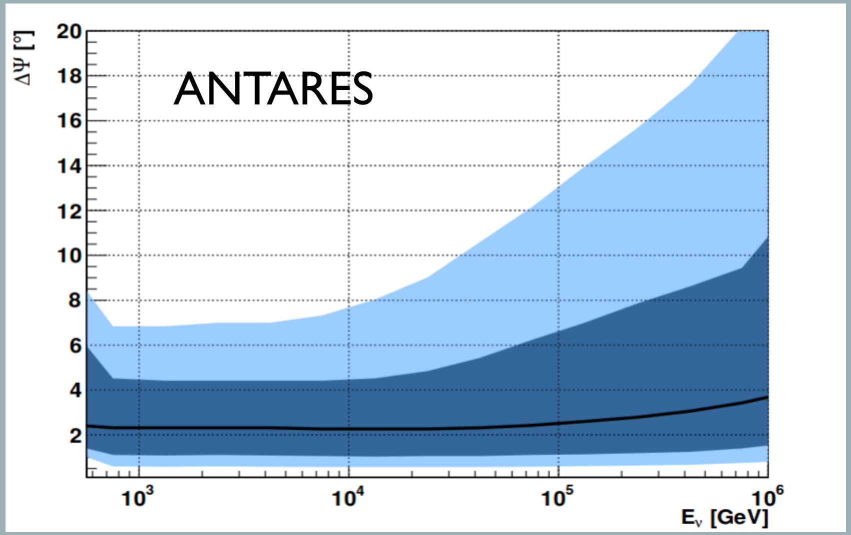


Shower-like events:
all neutrinos NC
ν_e,ν_τ CC interaction inside or very close to the detector ➔ shower

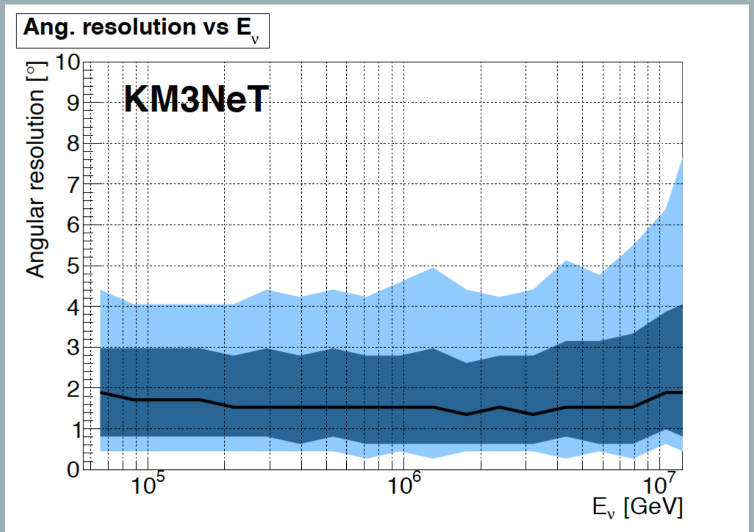
Energy resolution ~ 5%



Angular resolution < 3°



Angular resolution < 2°



Phys. Rev. D **96**, 082001

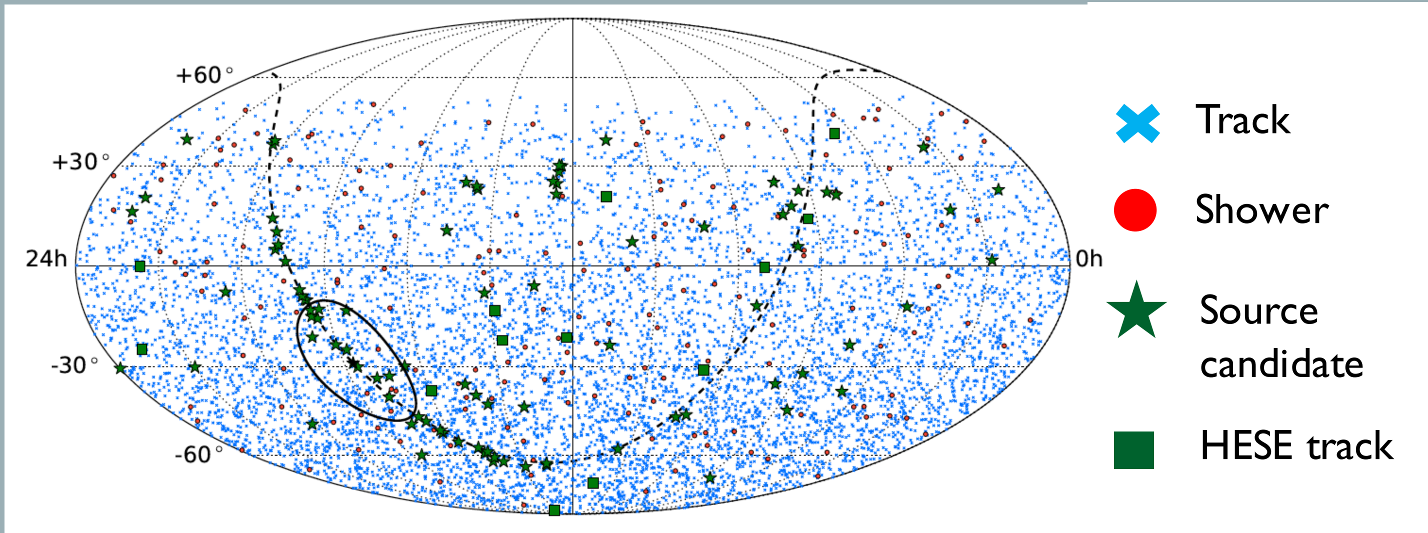
ANTARES – Point Sources

Sample:

- 2007 - 2015
- 2424 days of lifetime
- First all-flavour analysis
- 7622 tracks, 180 showers

- ❑ $\frac{dN_\nu}{dE_\nu} = \Phi_0 E_\nu^{-2}$ neutrino flux assumed
- ❑ Maximum likelihood method used to search for clusters of neutrinos from point sources

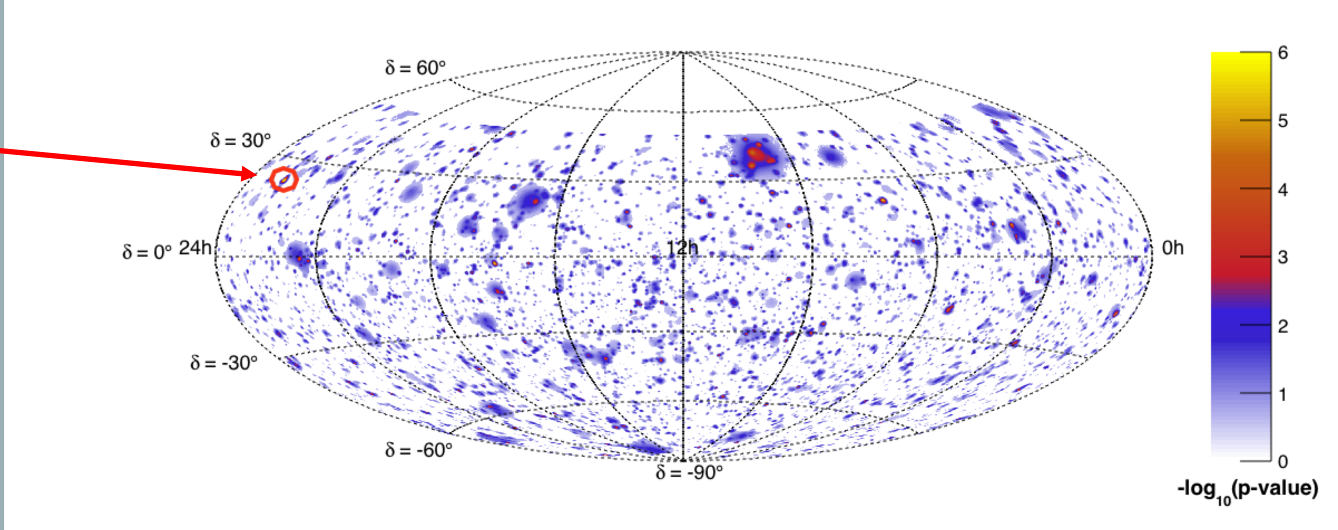
- Full-sky search
  - 1°x1° squares over ANTARES visible sky
- Candidate list searches
  - 106 known astrophysical objects (Pulsars, SNRs, …)
  - 13 IceCube HESE tracks



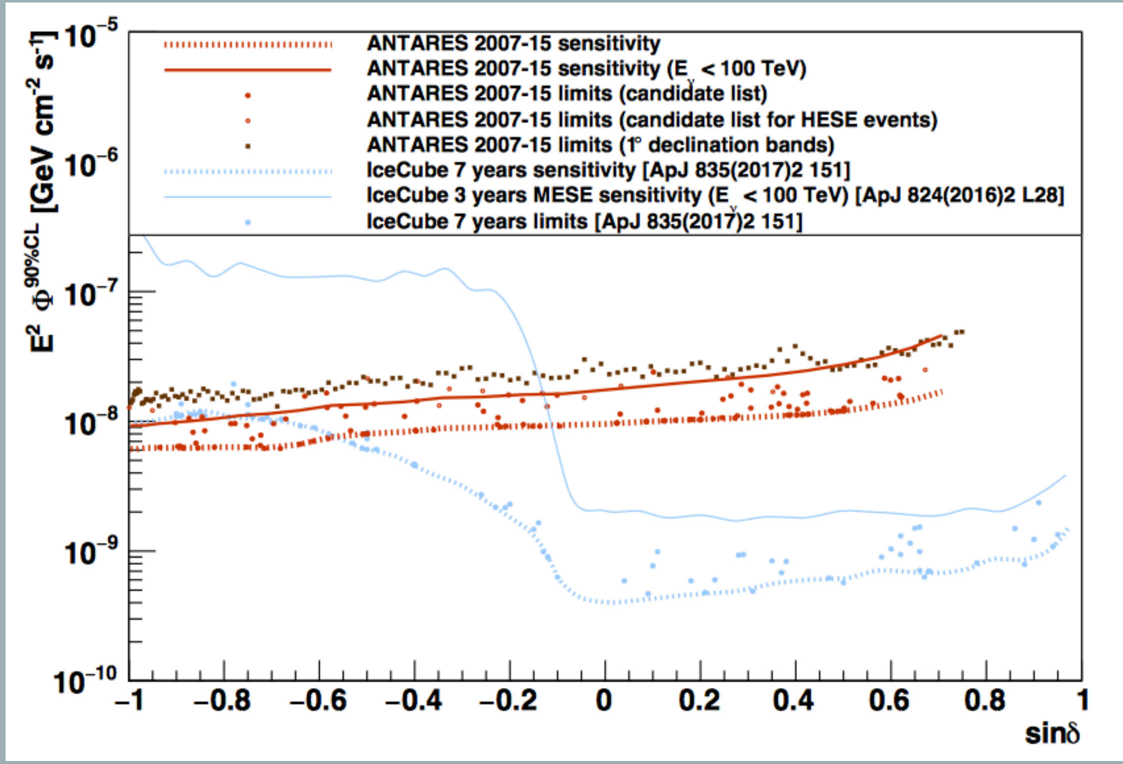
Phys. Rev. D **96**, 082001

ANTARES – Point Sources

Most significant cluster of the full-sky search
$\alpha = 343.8°$ $\delta = 23.5°$
1.9σ significance



Sky map in equatorial coordinates of pre-trial p-values



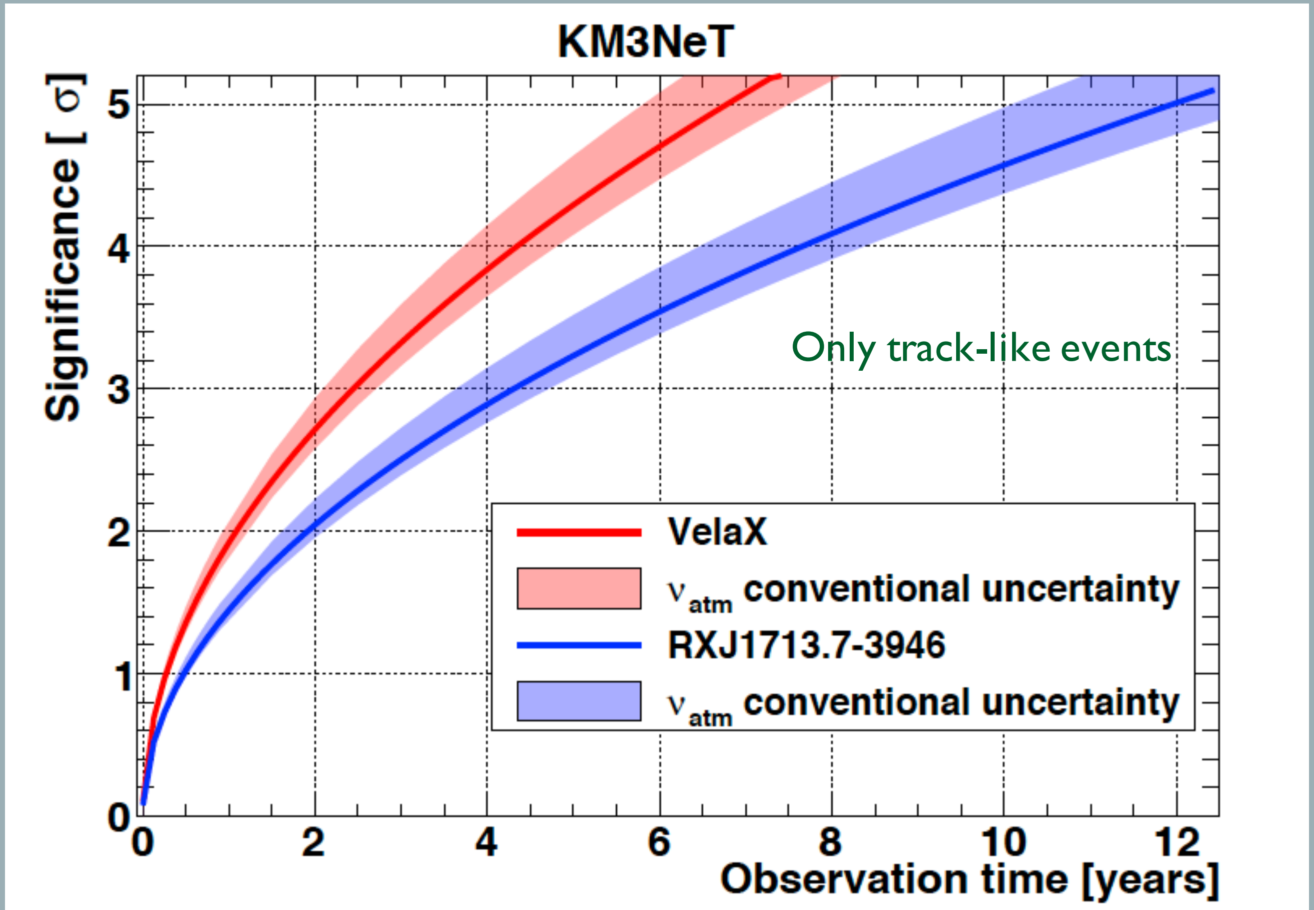
Sensitivities and upper limits at a 90% C.L. on the signal flux from the Full-sky and the Candidate list searches (Neyman method)

Most sensitive limits for a large fraction of the southern sky, especially at neutrino energies below 100 TeV

J.Phys. G43 (2016) no.8, 084001

KM3NeT/ARCA – Point Sources

Galactic Sources

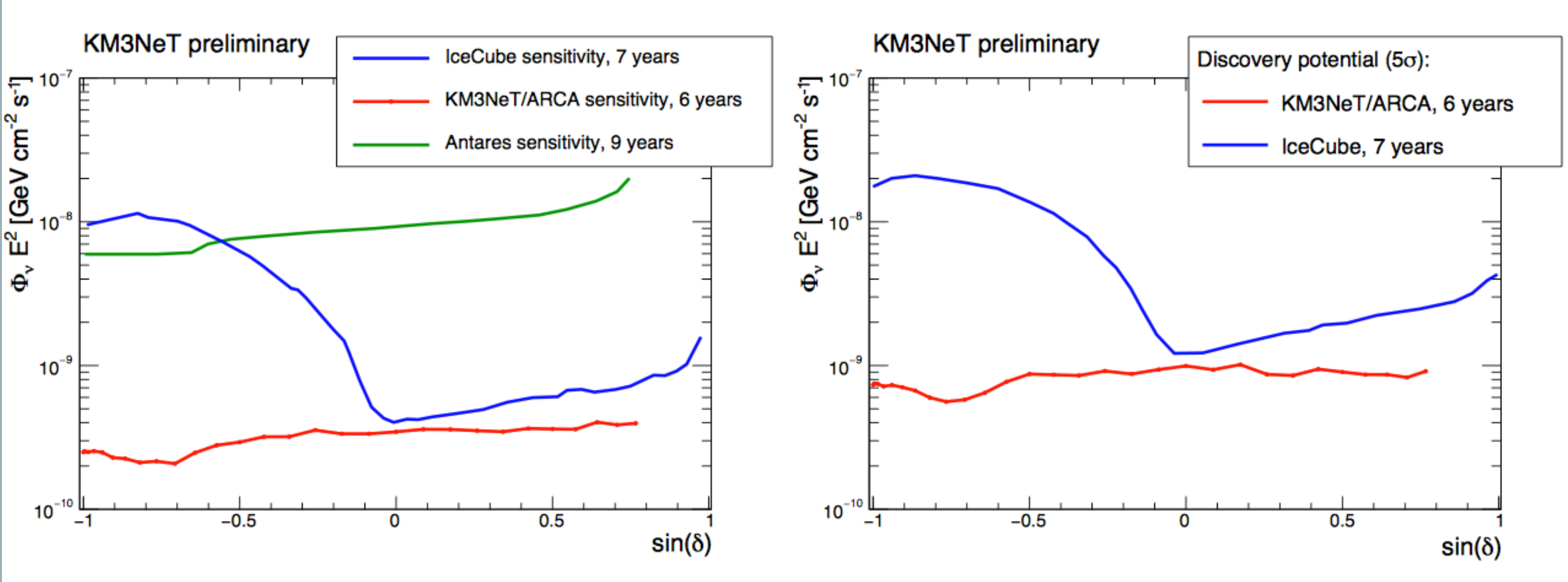


- Adopted neutrino fluxes derived from the measured γ-ray spectrum
- Assumptions:
  - Hadronic scenario for the γ-ray production
  - Transparent sources

3σ median significance in less than
3 years for Vela-X
5 years for RX J173

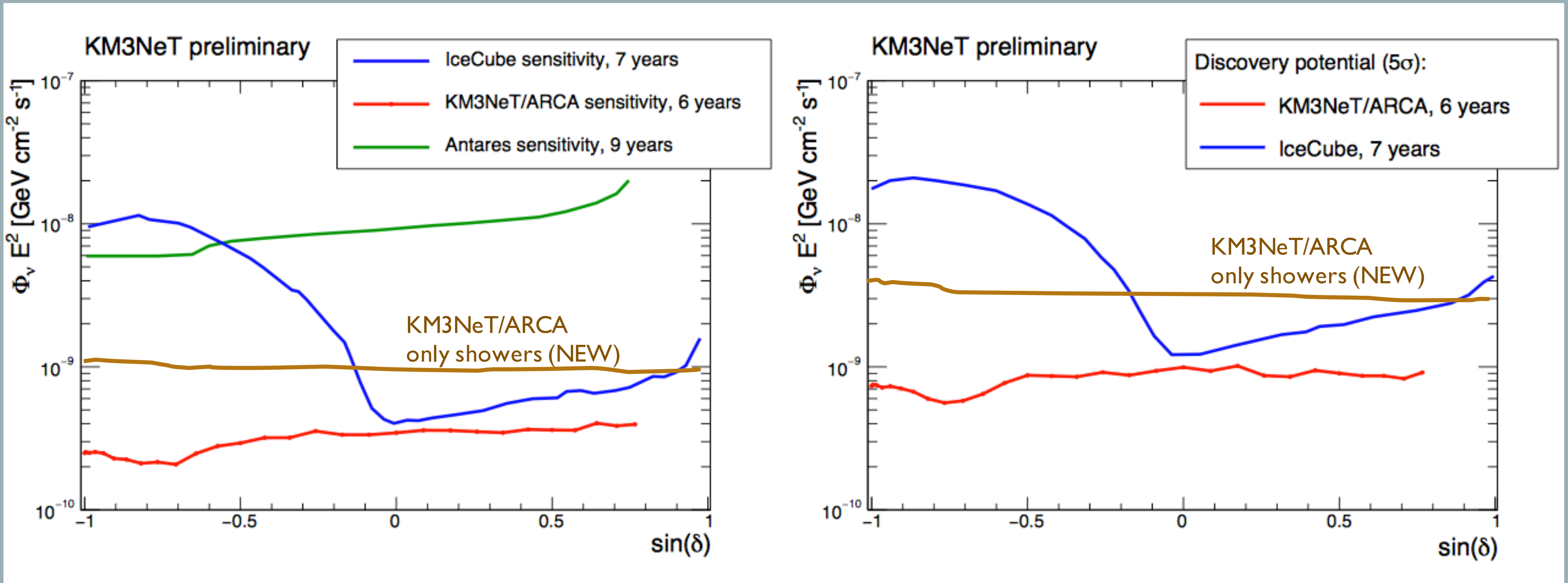
KM3NeT/ARCA – Point Sources

E^{-2} source



KM3NeT/ARCA – Point Sources

E^{-2} source

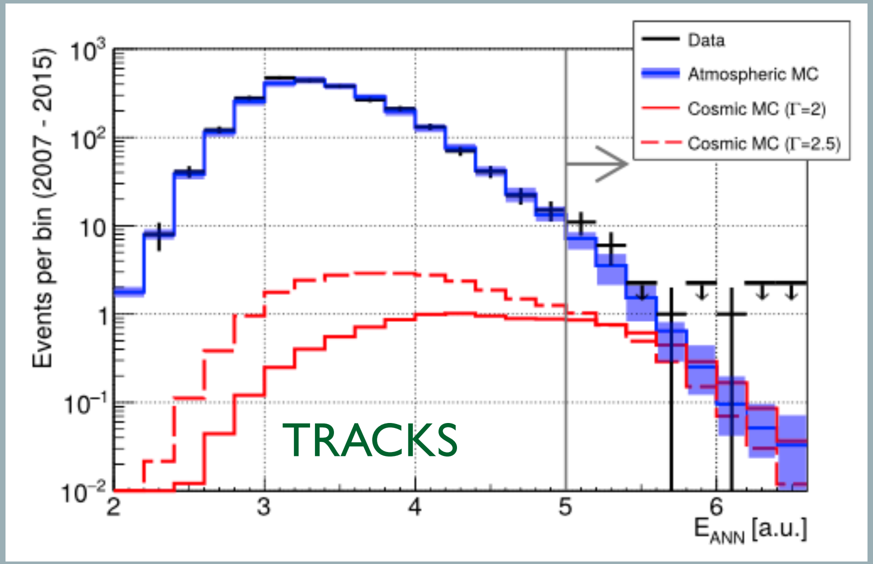


By combining tracks and showers, expected improvement between 15% and 30% depending on the declination!

ApJL 853, L7 (2018)

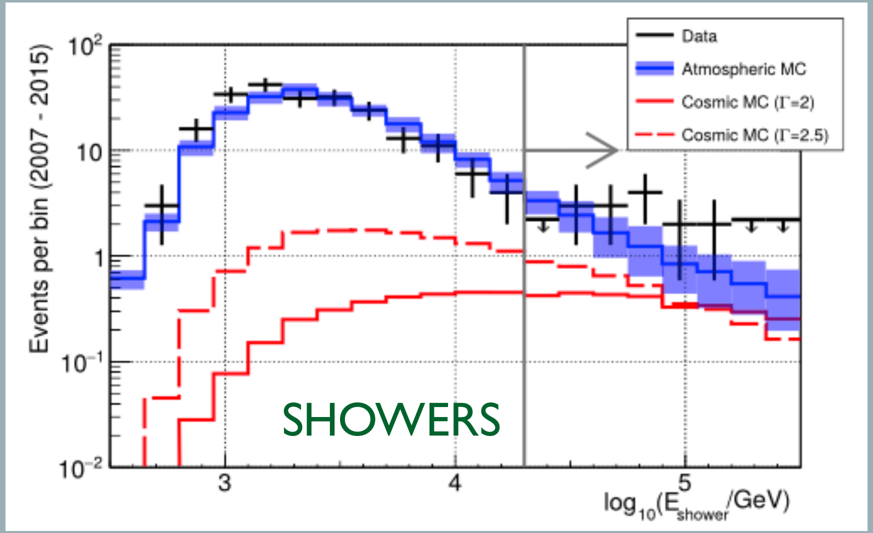
ANTARES – Diffuse flux

Sample:
- 2007 - 2015
- 2450 days of lifetime
- All-flavour analysis



- Event selection chain + energy-related cut applied to
  - obtain a high-purity neutrino sample
  - maximise sensitivity

- $\frac{dN_\nu}{dE_\nu} = \Phi_0 E_\nu^{-\Gamma}$ isotropic neutrino flux assumed
  - $\Gamma = 2,\ \Phi_0^{1f}(100\ \mathrm{TeV}) = 1.0 \cdot 10^{-18} \left(\mathrm{GeV\ cm^2 s\ sr}\right)^{-1}$
  - $\Gamma = 2.5,\ \Phi_0^{1f}(100\ \mathrm{TeV}) = 1.5 \cdot 10^{-18} \left(\mathrm{GeV\ cm^2 s\ sr}\right)^{-1}$



❖ Results:

33 events (19 tracks + 14 showers) in data
24 ± 7 (stat.+syst.) events in background MC

- 1.6σ excess, null cosmic rejected at 85% CL

ApJL 853, L7 (2018)

ANTARES – Diffuse flux

Sensitivity and Unblinded Results from Counting Statistics

	$\Gamma = 2.0$	$\Gamma = 2.5$
$\Phi_0^{1f,90\%\text{Sens.}}$ (100 TeV)	1.2×10^{-18}	2.0×10^{-18}
$\Phi_0^{1f,90\%\text{U.L.}}$(100 TeV)	4.0×10^{-18}	6.8×10^{-18}
$\Phi_0^{1f,68\%\text{C.I.}}$(100 TeV)	$(0.29\text{–}2.9) \times 10^{-18}$	$(0.5\text{–}5.0) \times 10^{-18}$

- Confidence intervals and Upper limits calculated according to the method of Conrad et al. (Phys. Rev. D **67**, 012002)
- Valid in the energy ranges (90% of signal tracks + showers expected):
  - 40 TeV – 7 PeV (Γ = 2.0)
  - 30 TeV – 1.5 PeV (Γ = 2.5)

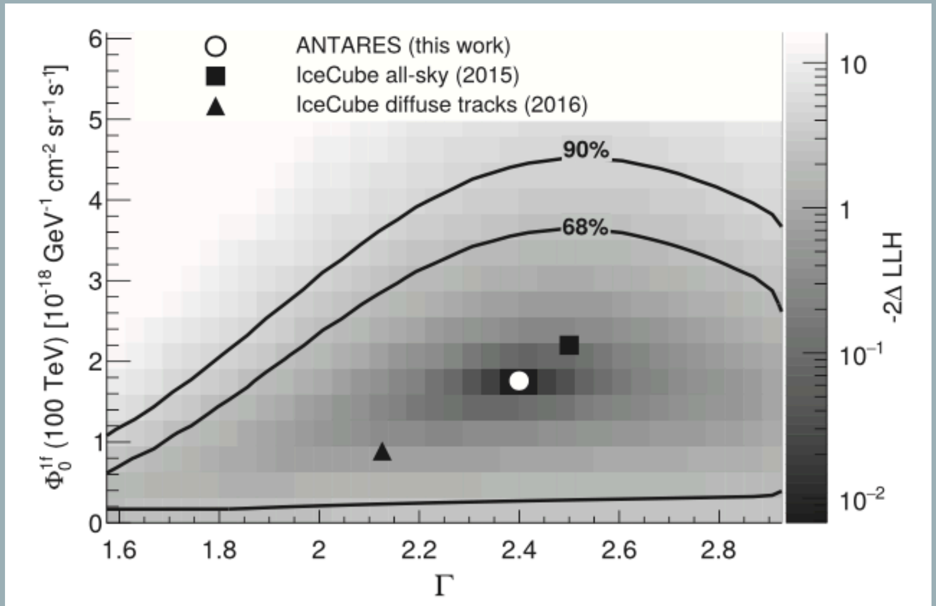
Fitting the data:

- maximum likelihood fitting method applied to provide an estimation of the parameters describing the observed excess (Φ_0, Γ)
- Best-fit cosmic flux:

$$\Gamma = 2.4^{+0.5}_{-0.4}$$

$$\Phi_0^{1f}(100\ \text{TeV}) = (1.7 \pm 1.0) \cdot 10^{-18} \left(\text{GeV cm}^2\text{s sr}\right)^{-1}$$

- Compatible with IceCube signals



2D log-likelihood scan of the diffuse cosmic flux normalization and spectral index

J.Phys. G43 (2016) no.8, 084001
PoS(ICRC2017)998

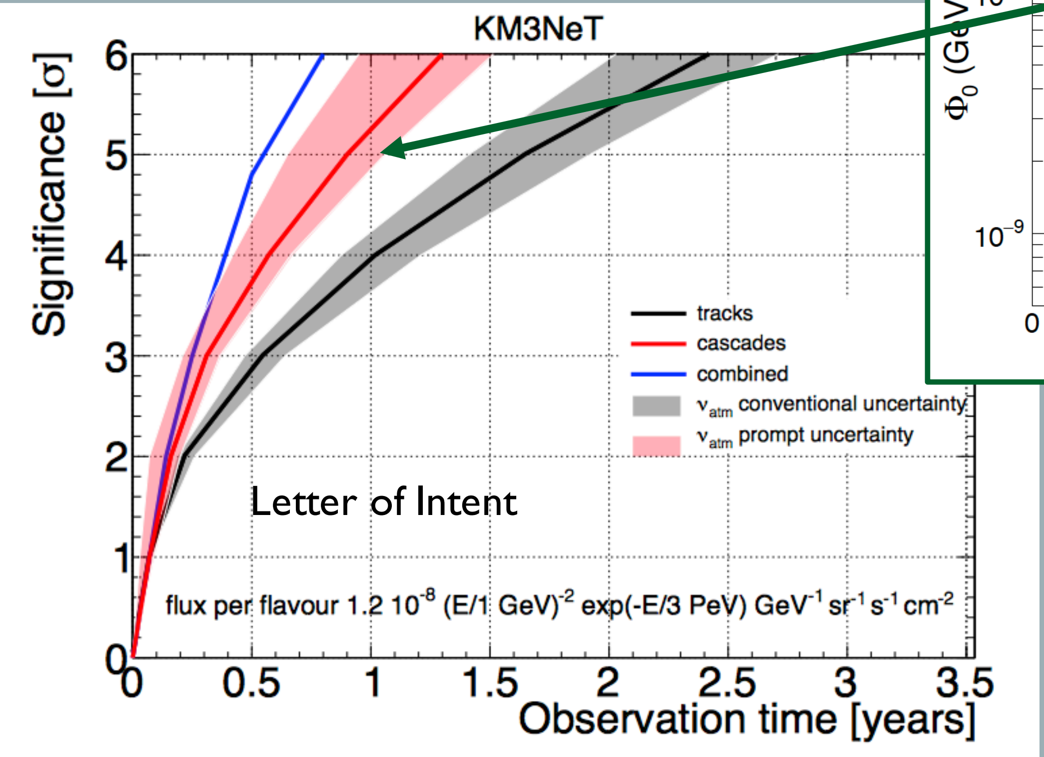
KM3NeT/ARCA – Diffuse flux

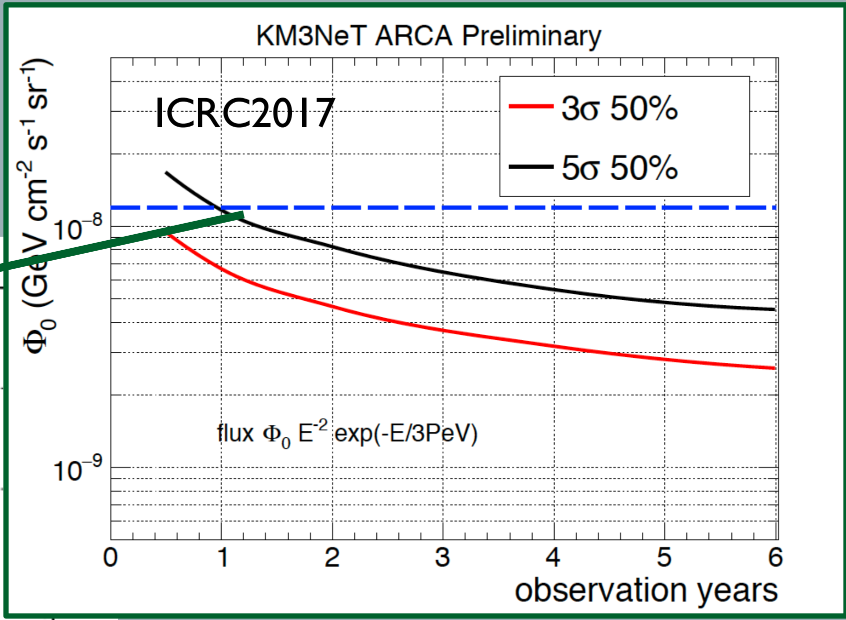
IceCube flux used as benchmark flux:
power law spectrum with a cut-off at a few PeV

Cascade selection cuts:
- Containment
- Energy
- BDT training

Track selection cuts:
- Direction (Up-going)
- Energy
- Quality parameters

Maximum likelihood method for discovery potential calculation





Improved results for tracks from better background discrimination via MVA techniques:

Tracks almost at the level of showers

By combining both samples, the IceCube flux can be seen with 5σ median significance in 6 months!

Phys. Lett. B 759 (2016) 69-74
Phys. Lett. B 769 (2017) 249

ANTARES – Dark Matter

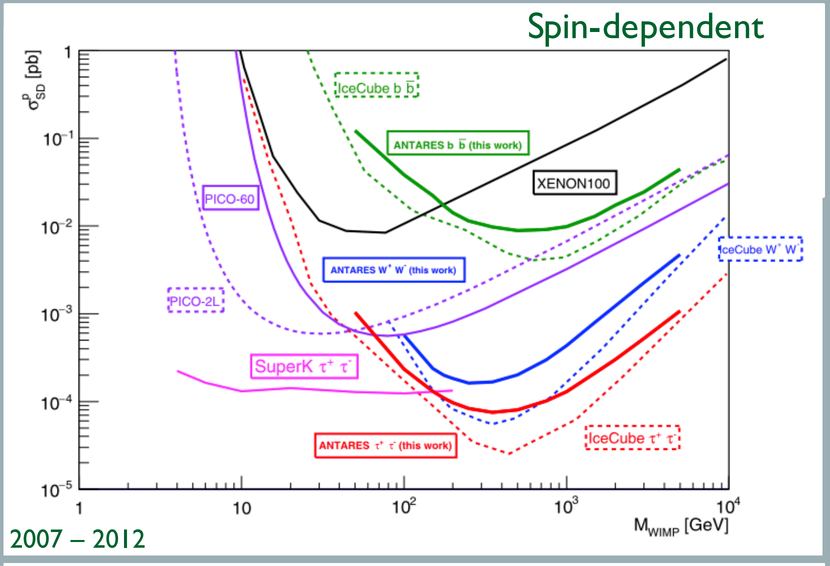
- WIMPs tend to accumulate in massive celestial objects (Sun, Galactic Centre, …)
- Neutrinos could be produced in WIMP-WIMP annihilation
- Clean signal and low expected background

Ingredients:

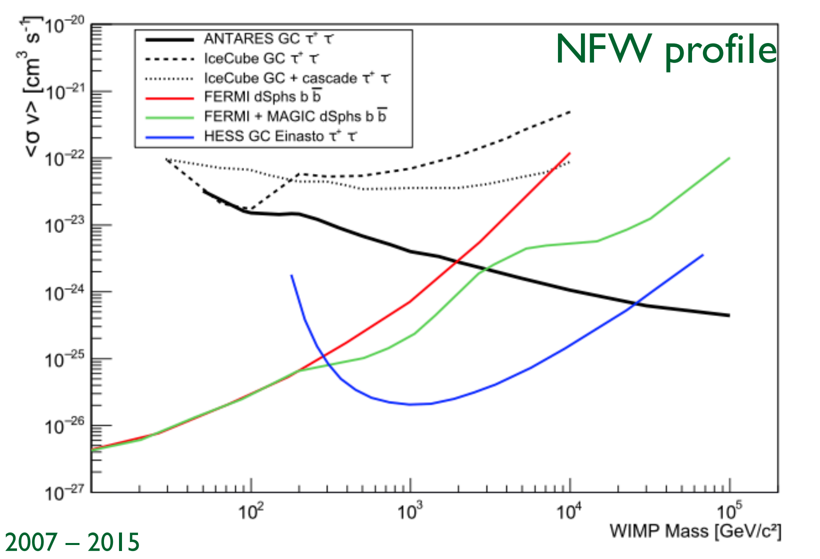
- Signal energy spectra for each considered WIMP mass and annihilation channel:
  $WIMP + WIMP \rightarrow b\bar{b}, W^+W^-, \tau^+\tau^-, \mu^+\mu^-, \nu_\mu\bar{\nu}_\mu$
- Spatial distribution of dark matter in the source:
  - Point-like (Sun)
  - Three halo models used: NFW, Burkert, McMillan (GC)

❖ No significant excess above background observed
❖ Upper limits on
  - spin-(in)dependent WIMP-nucleon scattering cross-section (Sun)
  - thermally averaged annihilation cross-section (GC)

as a function of the WIMP mass



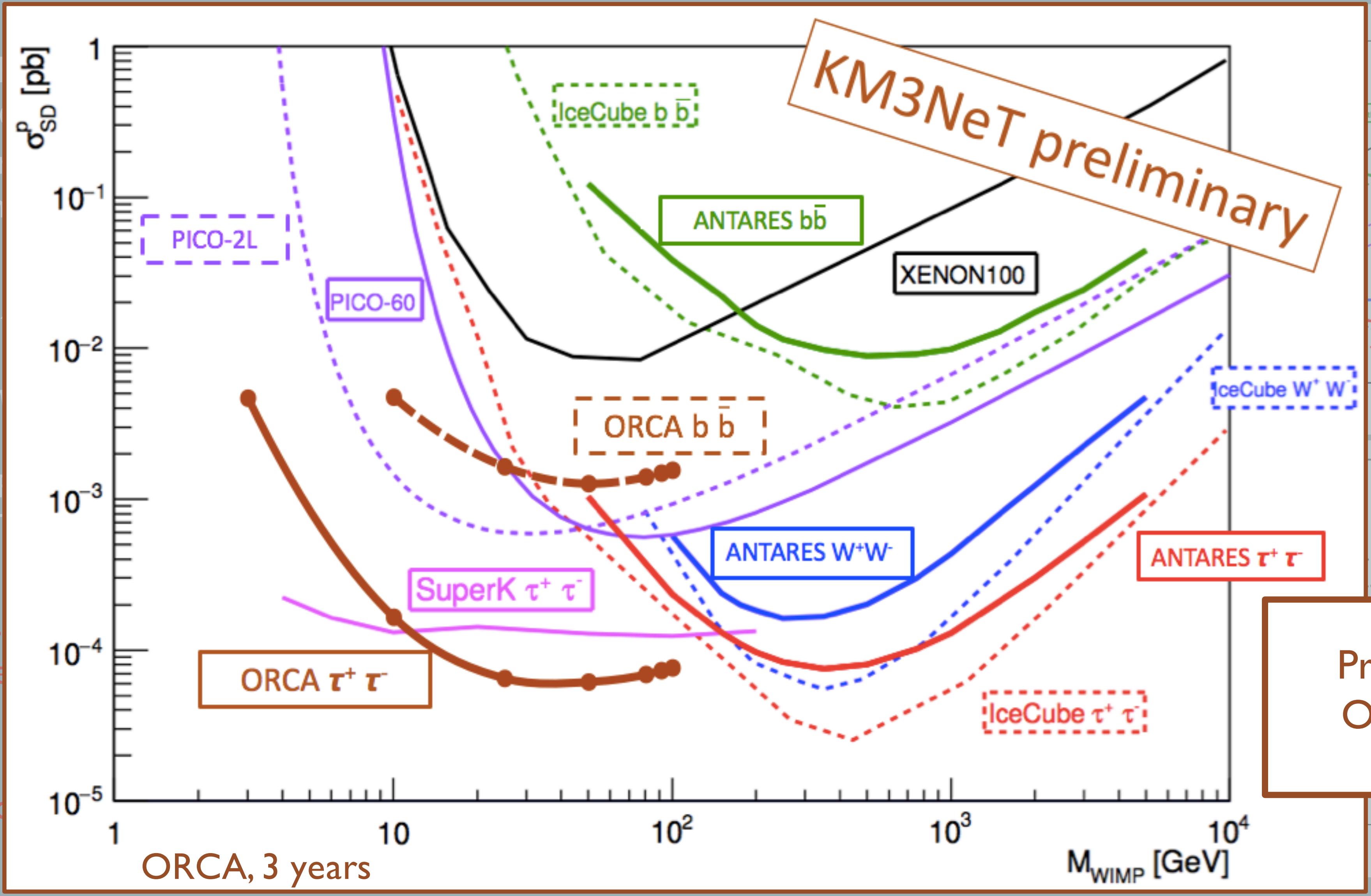
SUN



GC

Nuovo Cim. C40 (2017) no.3, 141

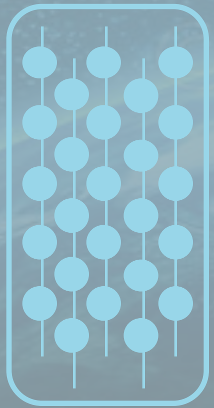
ORCA – Dark Matter

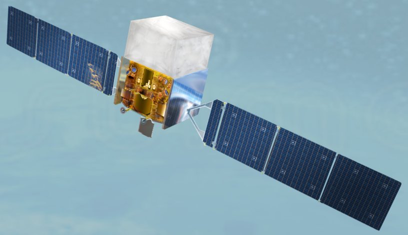


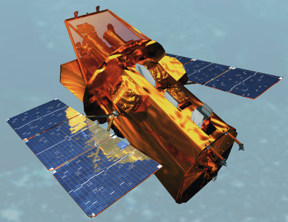
Promising estimated ORCA sensitivities!

ANTARES & KM3NeT – Multi-messenger
Two approaches:

Real-time analysis → Alert triggering







\+ …

Offline analyses

Time correlation and
Multi-messenger searches

ANTARES – Multi-messenger

Real-time analysis

Radio	Optical	X-ray	GeV γ-rays	TeV γ-rays
MWA	TAROT ZADKO MASTER GWAC	Swift INTEGRAL	Fermi	HESS HAWC

Triggers:

- Doublet of neutrinos (~0.04 events/yr)
- Single neutrino with direction close to local galaxies (~1 TeV, ~10 events/ yr)
- Single HE neutrinos:
  - ❖ HE (~5 TeV, 20 events/ yr)
  - ❖ VHE (~30 TeV, ~3-4 events/ yr)

Performances:

- Time to send an alert: ~5 s
- First image of the follow-up: < 20 s
- Median angular resolution:
  - ❖ ~ 0.4° (ANTARES)
  - ❖ Same as in the offline reconstruction expected for KM3NeT!

Statistics of the sent neutrino alerts (07/2009-02/2018)

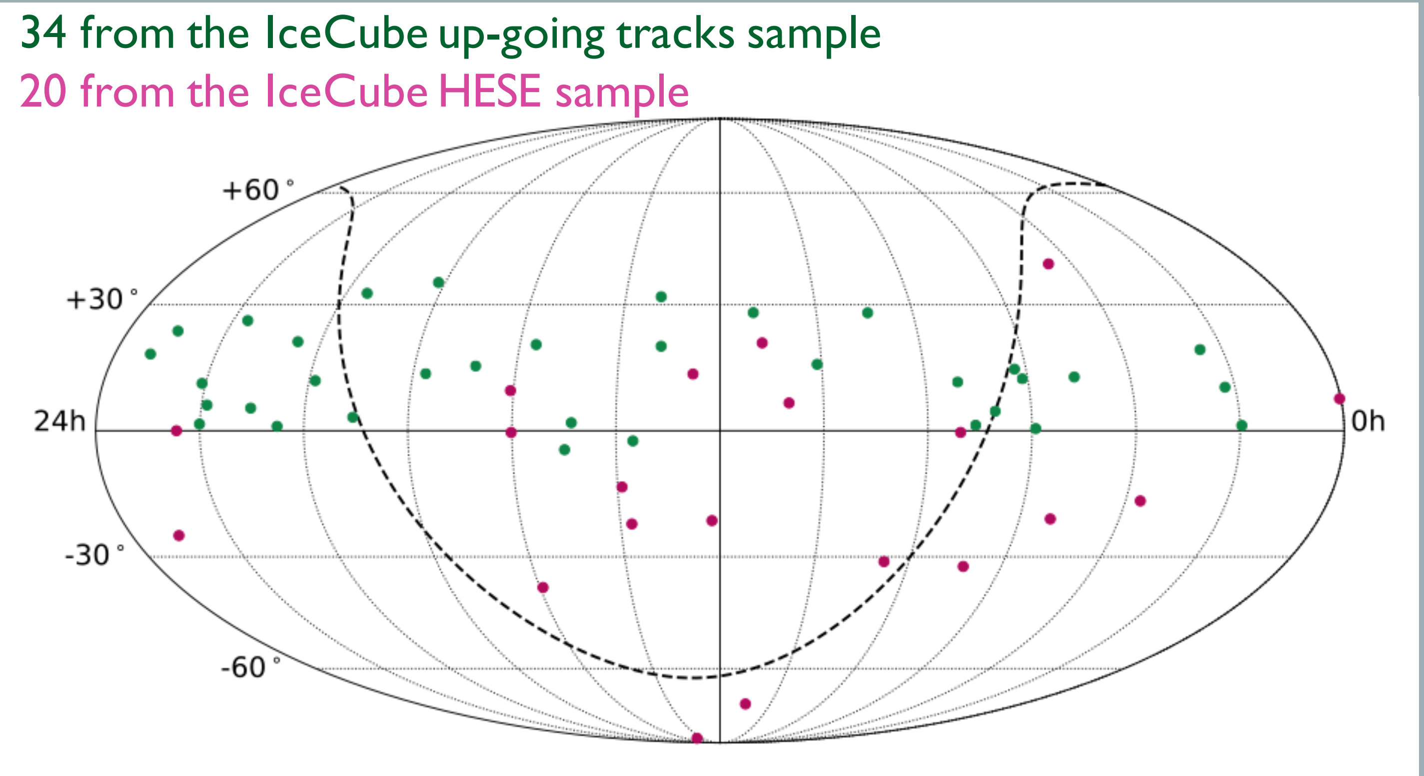
- 272 to robotic telescopes
- 14 to Swift
- 4 to INTEGRAL
- 22 to MWA
- 2 to HESS

ANTARES – Multi-messenger

Offline analyses

Object	Messenger	Telescope
Flaring Blazars	Gamma	FERMI/LAT
Flaring X-ray binaries	X & gamma-ray	Swift, MAXI, RXTE/ASM, Fermi/LAT
Flares from Mrk 421 and Mrk 501	Gamma	HAWC
Gamma Ray Bursts	Gamma	Swift, Fermi, GCN
IceCube Events	**Neutrino**	**IceCube**
UHECR	CR	Auger, TA
Galactic Plane	**CR & gamma-ray**	**Fermi, Milagro**
Fast Radio Bursts	Radio	SUPERB@Parkes
Fermi Bubbles	Gamma	Fermi
Galactic Plane	CR	HAWC
BH/NS mergers	**Gravitational waves**	**Ligo/Virgo (+ IceCube and Pierre Auger Observatory)**

ANTARES – Time correlation with IceCube events



- Search for correlations in time and space between ANTARES data and 54 IceCube neutrino events
- $\frac{dN_\nu}{dE_\nu} = \Phi_0 E_\nu^{-2.5}$ neutrino flux assumed
- Maximum likelihood method used to search for time and spatial clustering
- Gaussian signal time PDF assumed with σ (emission duration) fitted in the likelihood maximization within 0.1 and 120 days

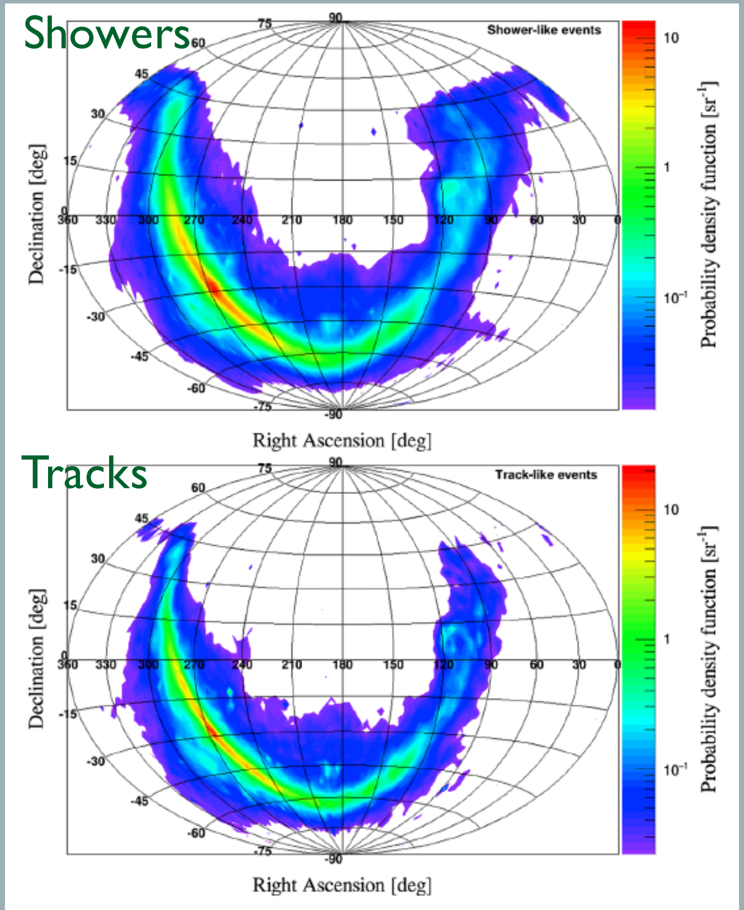
No excess observed
Upper limits on fluence to be provided

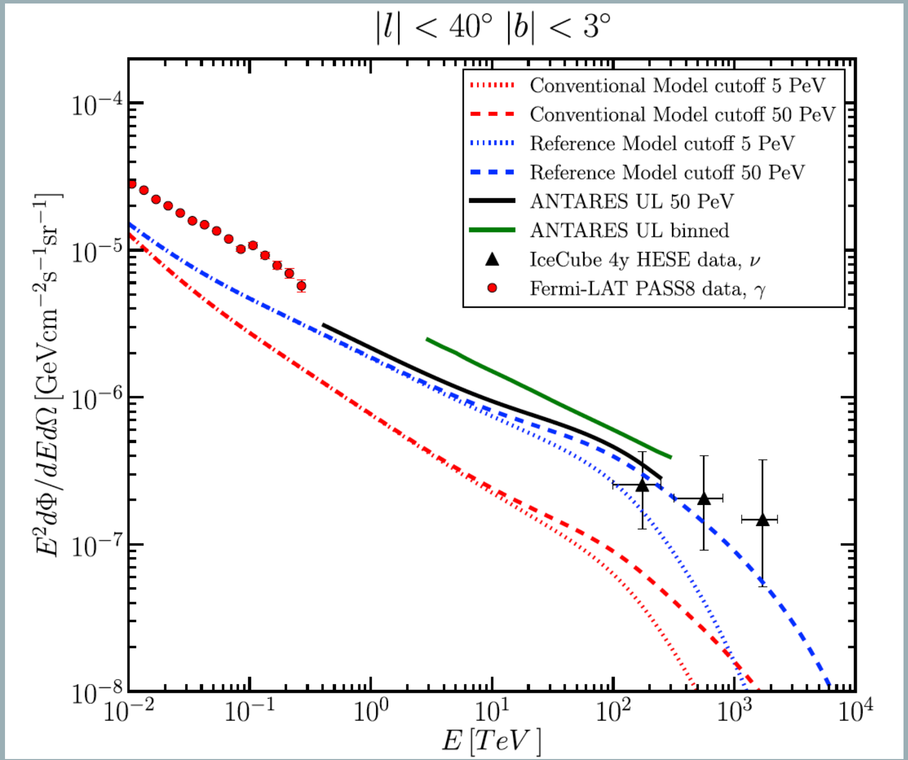
Phys.Rev. D96 (2017) no.6, 062001

ANTARES – Galactic plane

Sample:
- 2007 - 2015
- 2424 days of lifetime
- All-flavour analysis
- 7300 tracks, 208 showers

Search strategy:
- Signal map according to KRA$_\gamma$ modelling
- Two ref models: 5 PeV and 50 PeV cutoffs
- Likelihood ratio test method



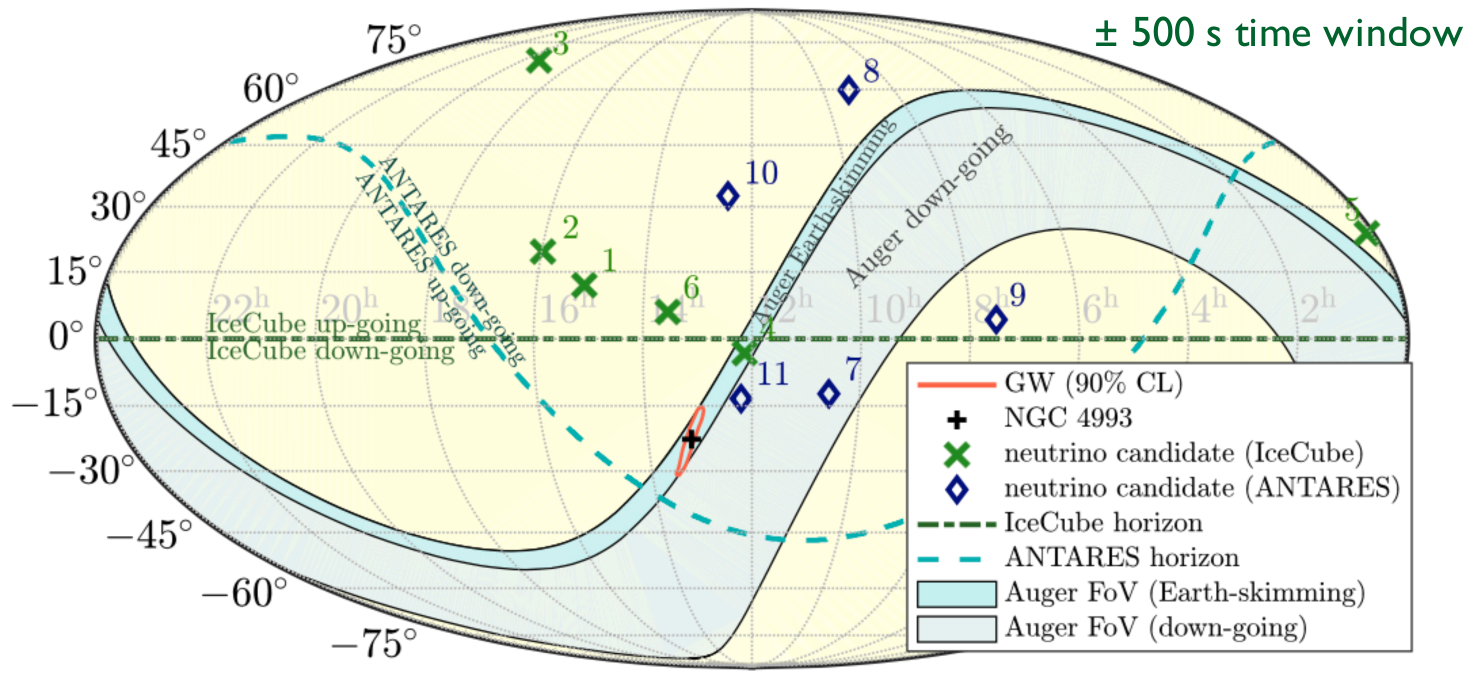


- No excess of events
- 90% flux limits for ref models:
  - < 1.1 ϕ(5 PeV)
  - < 1.2 ϕ(50 PeV)
- Strong constraint on a possible diffuse neutrino emission from the Galactic plane
- Hypothesis of neutrino flux produced by the Galactic CR interaction with gas explaining the IceCube spectral anomaly discarded

ANTARES – Gravitational Waves

Phys.Rev. D93 (2016) no.12, 122010
Phys.Rev. D96 (2017) no.2, 022005
Eur.Phys.J. C77 (2017) no.12, 911
Astrophys.J. 850 (2017) no.2, L35
Astrophys.J. 848 (2017) no.2, L12

- High-energy neutrino follow-up on several GW events/candidates:
  - GW150914 (BBH merger)
  - GW151226 (BBH merger)
  - LVT151012 (candidate)
  - GW170104 (BBH merger)
  - GW170817 (BNS merger)
- Joint searches with other neutrino telescopes (IceCube, Pierre Auger Observatory) members of the multi-messenger Virgo/LIGO follow-up effort
- Neutrinos would reveal the hadronic content and dissipation mechanism in relativistic outflows
- Could significantly constrain the location of the source
- Both prompt on-line search for a neutrino counterpart and analysis of offline-reconstructed data set performed
- Search for neutrinos in a ±500 s window around the GW transient



No neutrino candidates temporally & directionally coincident with the GW signals at the 90% credible level

Non-detection used to constrain the neutrino spectral fluence

Conclusions

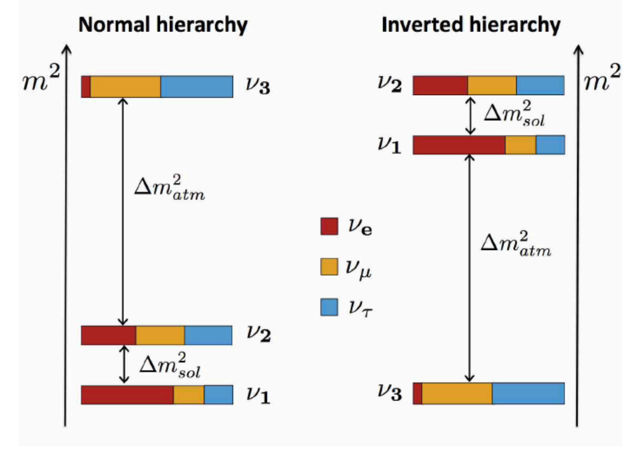
- ❑ ANTARES
  - 10 years of continuous data taking
  - Solid results from various searches of neutrino emission (point-like, diffuse, dark matter, …)
  - Active multi-messenger program
  - Combined analyses with IceCube (point sources, galactic plane, dark matter)

- ❑ KM3NeT
  - Under construction
  - ARCA: median 3σ significance for galactic sources (hadronic scenario) within 3-5 years of operation
  - ARCA: Observation of HE neutrino flux discovered by IceCube expected in less than 1 year of operation

Neutrino Mass Hierarchy and Oscillations

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} \qquad U = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

$c_{ij} = cos\theta_{ij}$
$s_{ij} = sin\theta_{ij}$
δ=CP violating phase

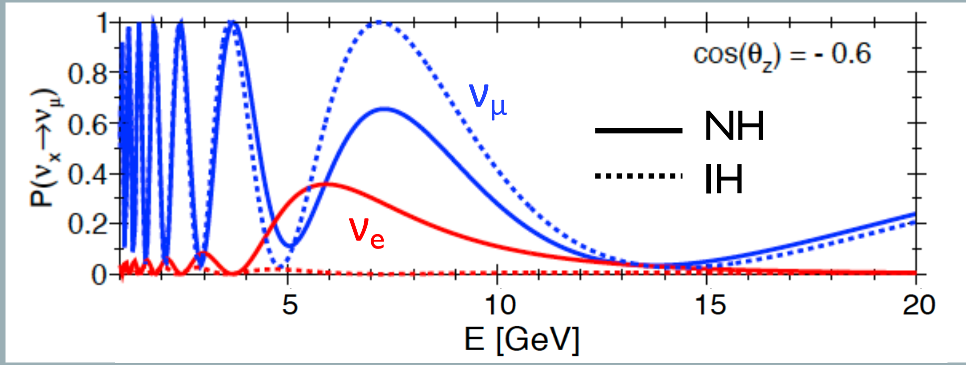


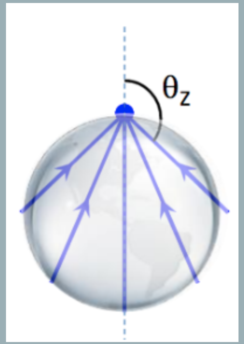
Remaining major unknowns:
Mass hierarchy
Octant of θ_{23}
CP phase

- Constrain theory models
- Help measuring the CP phase
- Absolute mass scale
- Nature (Dirac vs Majorana)
- Origin of neutrino mass and flavor
- Core-Collapse Supernovae Physics
- Precise determination of the PMNS matrix parameters

Approach:
Measure E_ν and θ_ν of few-GeV atmospheric neutrinos traversing the Earth, identify and count ν_μ and ν_e events

Oscillation pattern distorted by Earth matter effects: IH/NH difference



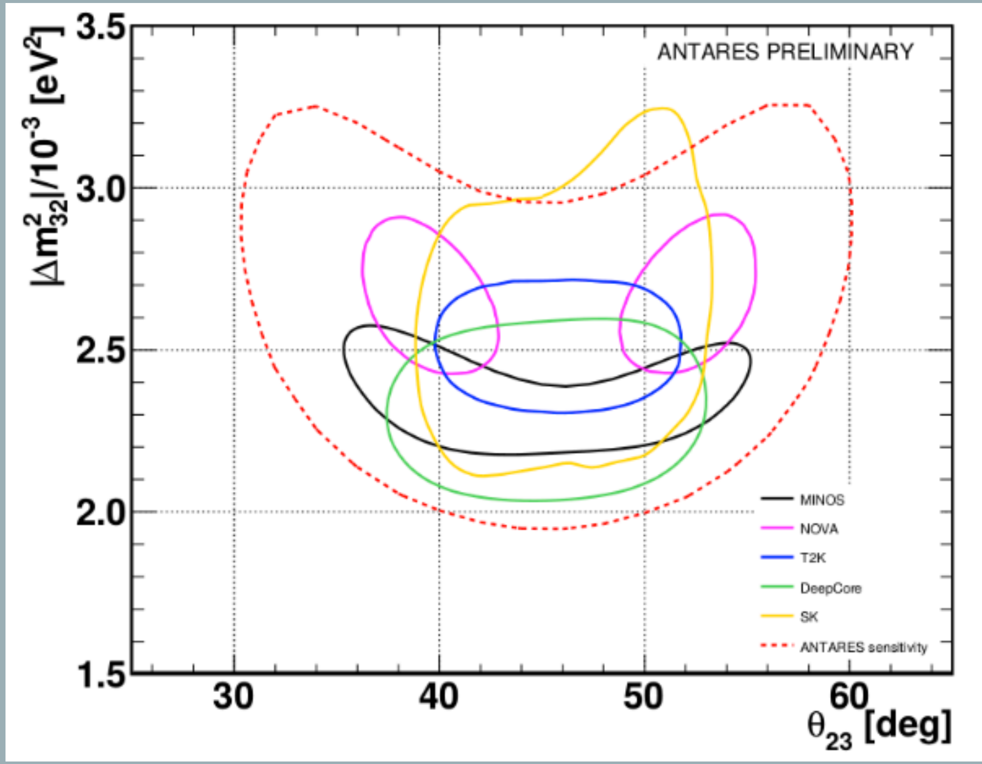


To resolve Mass Hierarchy,
Good energy and angular resolution in 5-10 GeV range are needed

ANTARES – Oscillations

Sensitivity estimate

- 3-flavour description of the oscillation probability
- matter effects in the Earth included



Still room for improvement: Treatment of different sources of systematic effects and refinement of the quality cuts for selecting events before *unblinding*

Red-dashed curve: allowed parameter region at 90% C.L.

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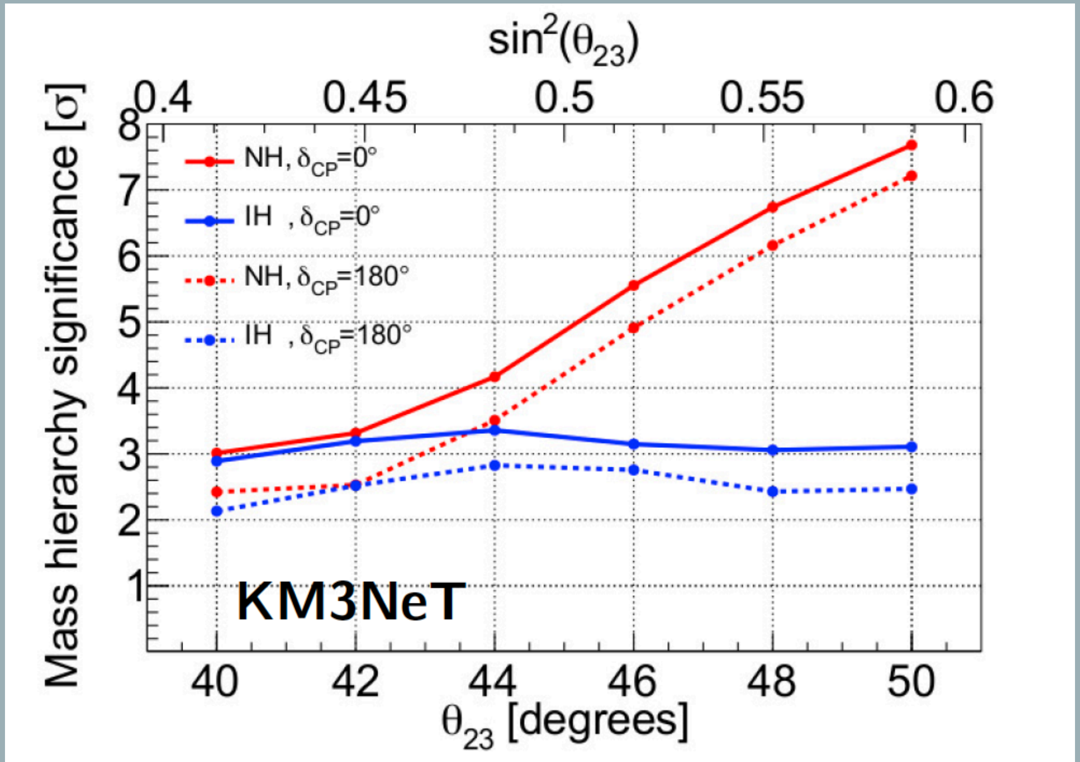
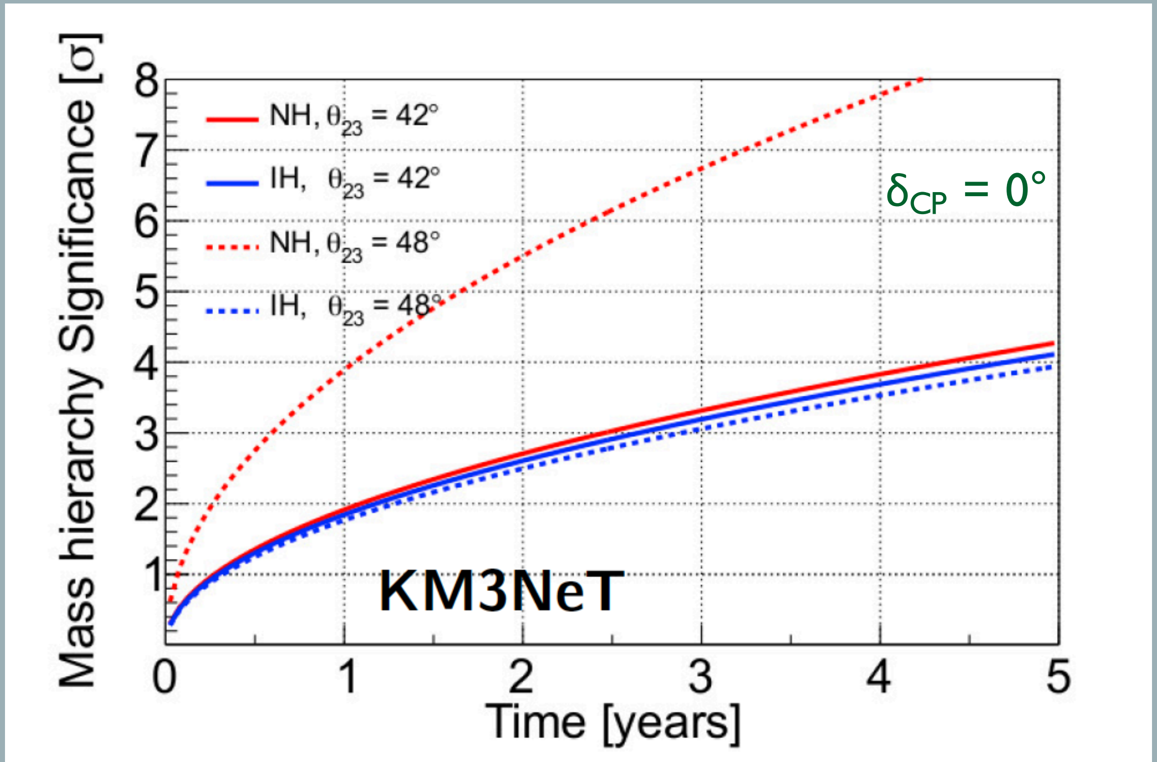
KM3NeT/ORCA – NMH and Oscillations





- ~3σ NMH median significance in 3-4 years of a complete KM3NeT/ORCA in most cases
- If NH and θ_{23} in the second octant, significant improvement of sensitivity (>5σ!)
- Best case scenario: 5σ in 1.5 years of complete ORCA!
- MH sensitivity comes from both track-like and shower-like events

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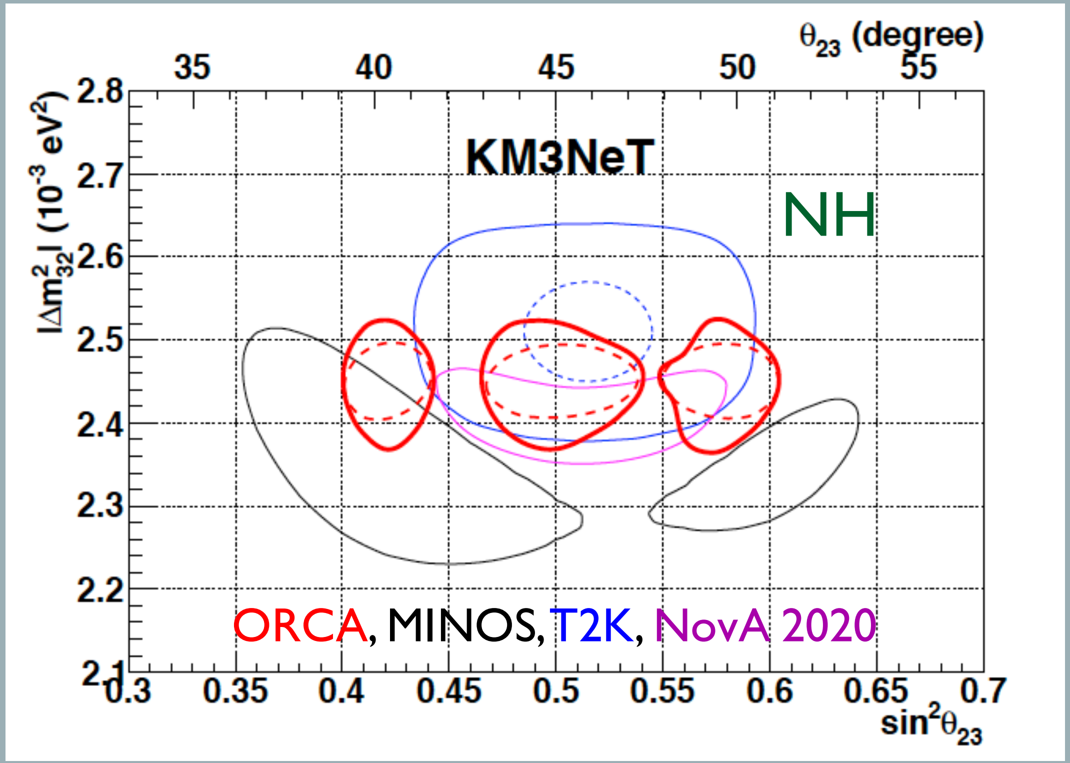
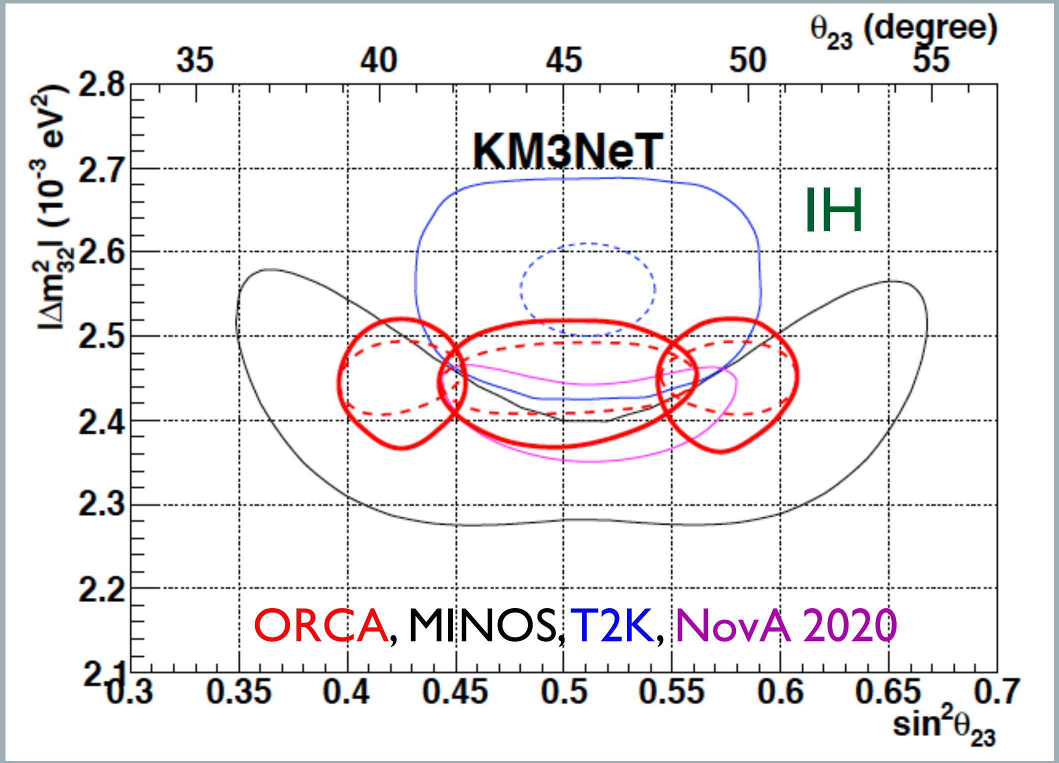
KM3NeT/ORCA – NMH and Oscillations



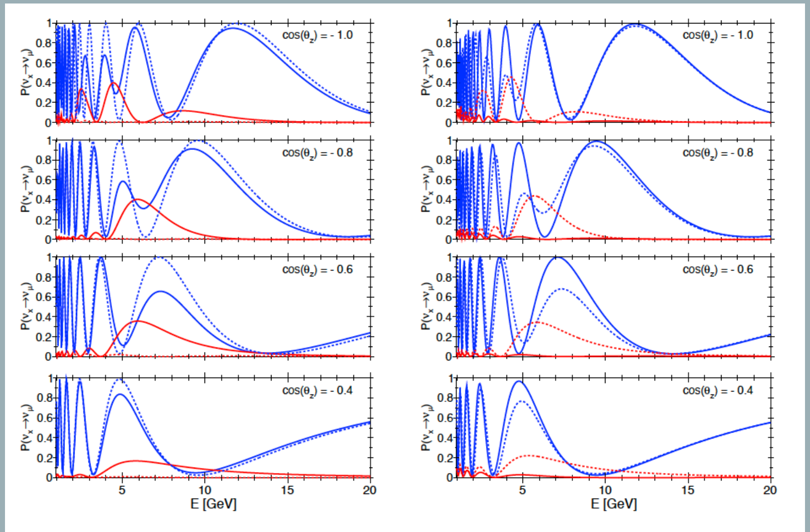


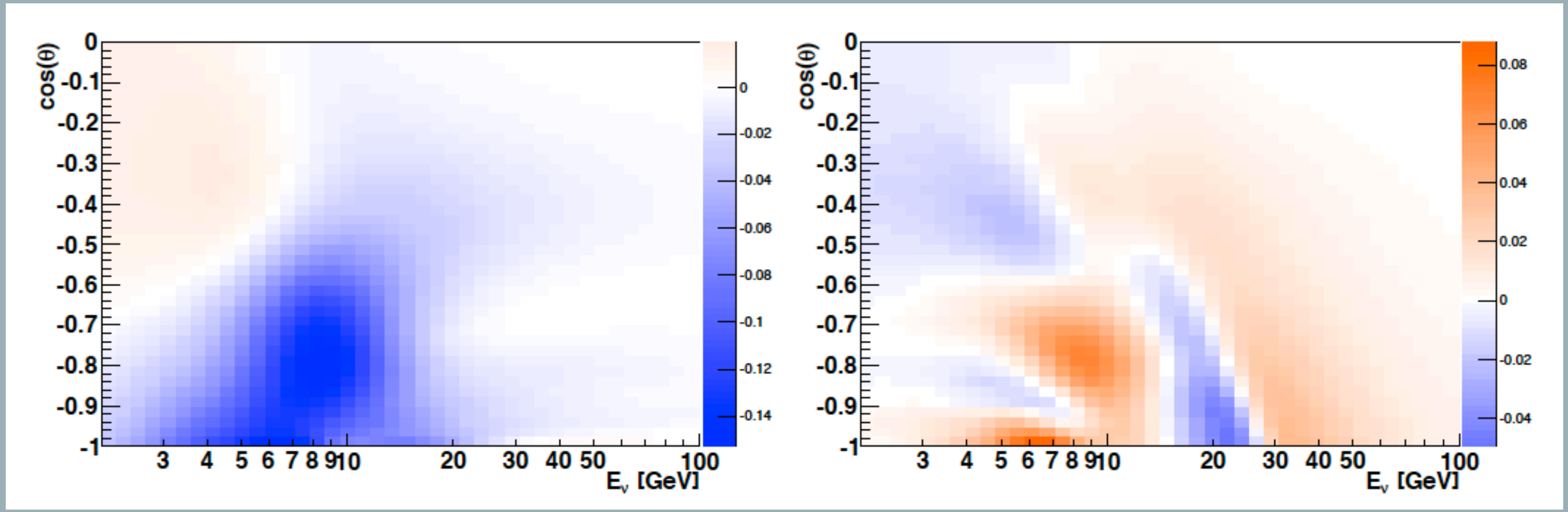
1σ contour sensitivity to the atmospheric parameters after 3 years of data taking
ORCA: red ellipses (solid/dashed = with/wo additional E scale)

ORCA sensitivities are expected to improve with the on-going studies of the trigger scheme and the reconstruction algorithms

In addition to the standard 3-flavour oscillation studies, ORCA can also constrain sterile neutrinos and the NSI parameters

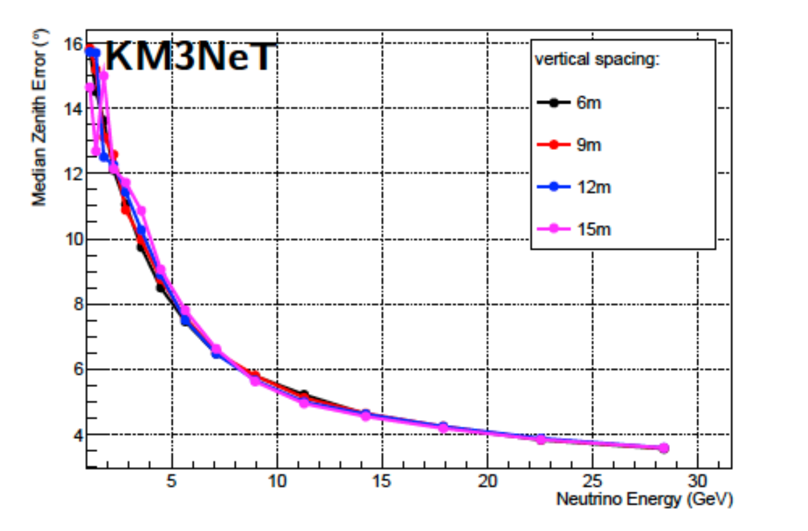
KM3NeT/ORCA – NMH and Oscillations

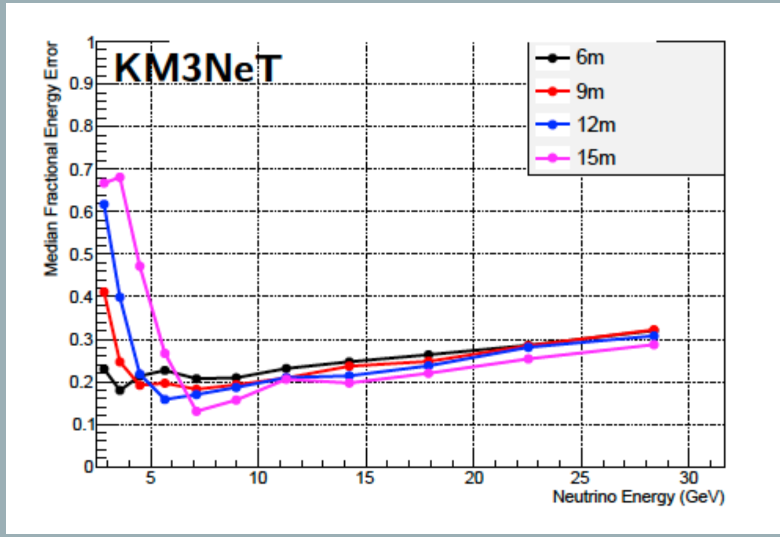


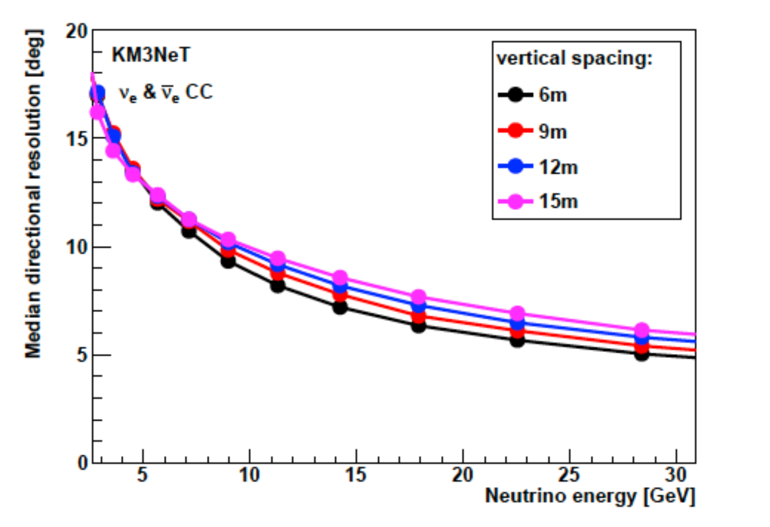


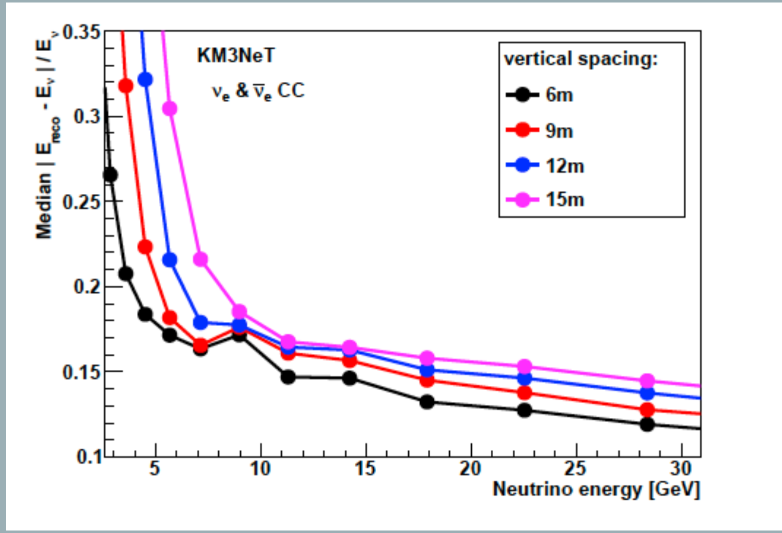
$$\mathcal{A}' = \frac{N_{IH} - N_{NH}}{N_{NH}}$$

KM3NeT/ORCA – NMH and Oscillations









KM3NeT/ORCA – NMH and Oscillations