Recent results from **Antares** and prospects for **KM3NeT/ORCA**

Rencontres de Moriond
Electroweak session
La Thuile, 2018

Ronald Bruijn
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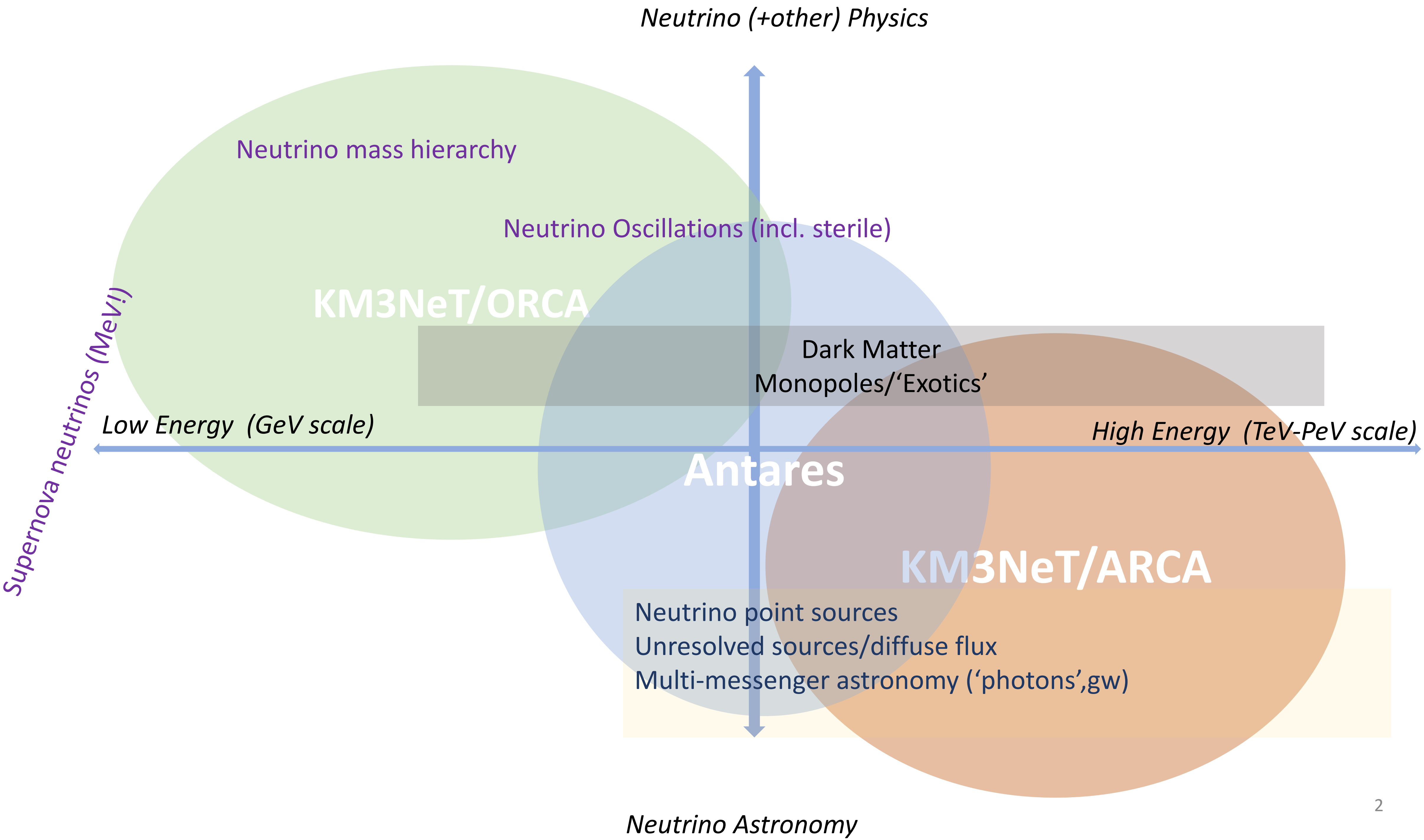
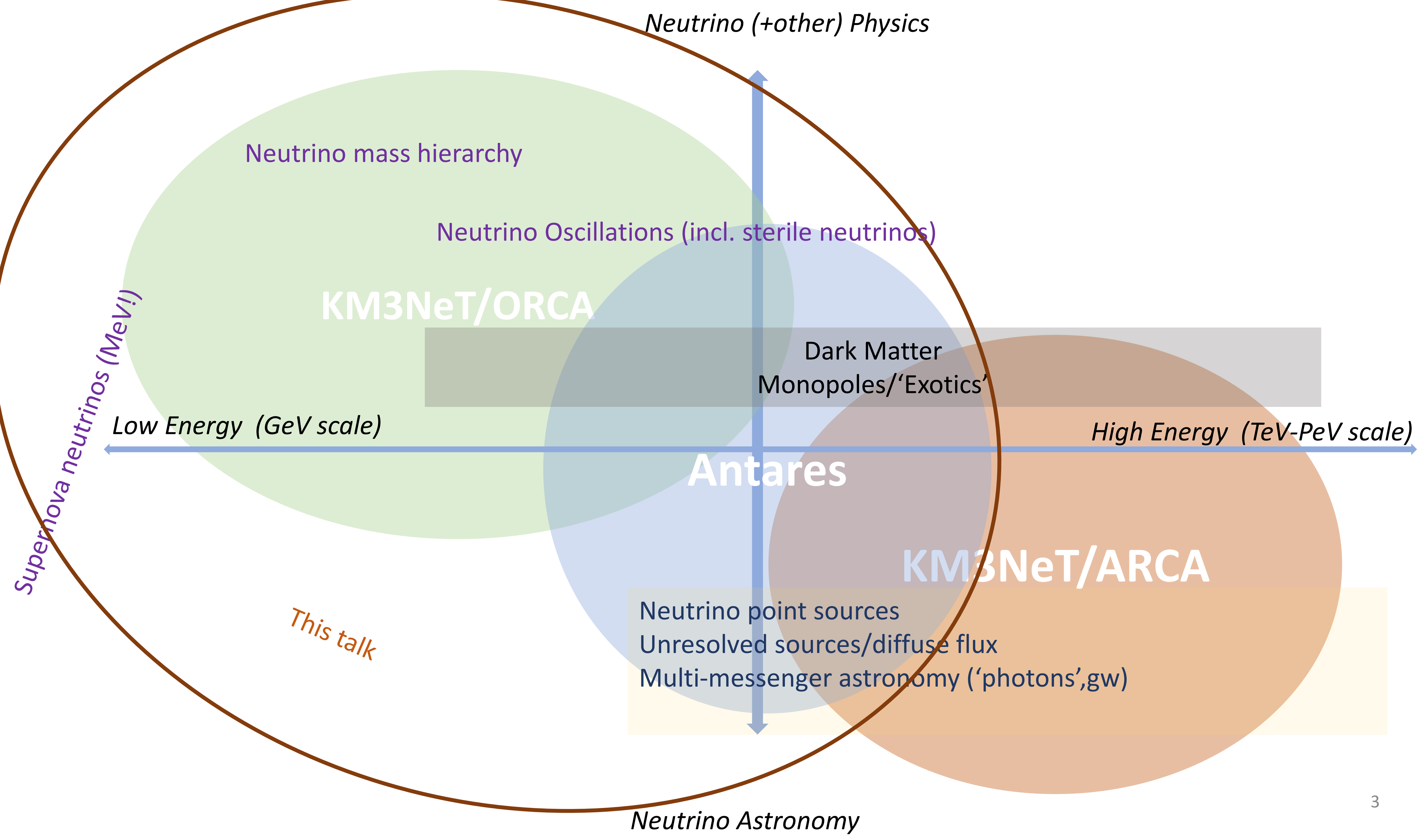
for the Antares & KM3NeT Collaborations


Neutrino (+other) Physics
Neutrino mass hierarchy
Neutrino Oscillations (incl. sterile)
KM3NeT/ORCA
Supernova neutrinos (MeV!)
Dark Matter
Monopoles/'Exotics'
Low Energy (GeV scale)
High Energy (TeV-PeV scale)
Antares
KM3NeT/ARCA
Neutrino point sources
Unresolved sources/diffuse flux
Multi-messenger astronomy ('photons',gw)
Neutrino Astronomy



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This talk
Neutrino Astronomy

Large Volume Neutrino Telescopes

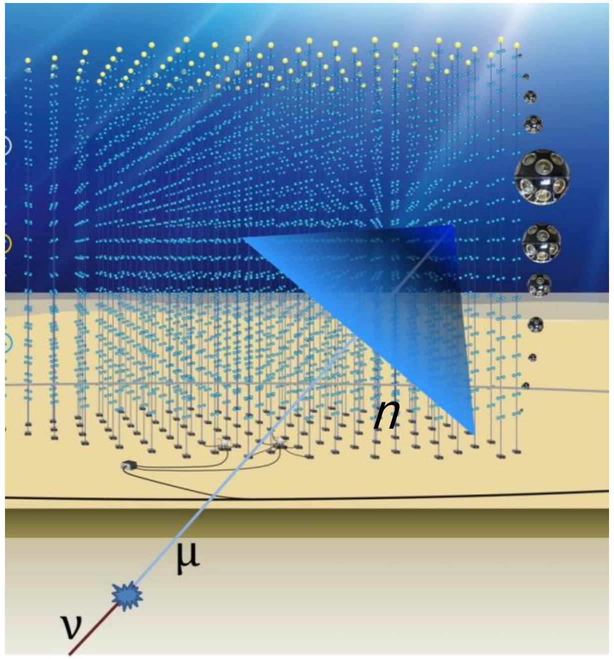
Cherenkov light from the charged products of neutrino interactions in sea-water are detected by a sparse array of photo-multiplier tubes

Two *general* event types:

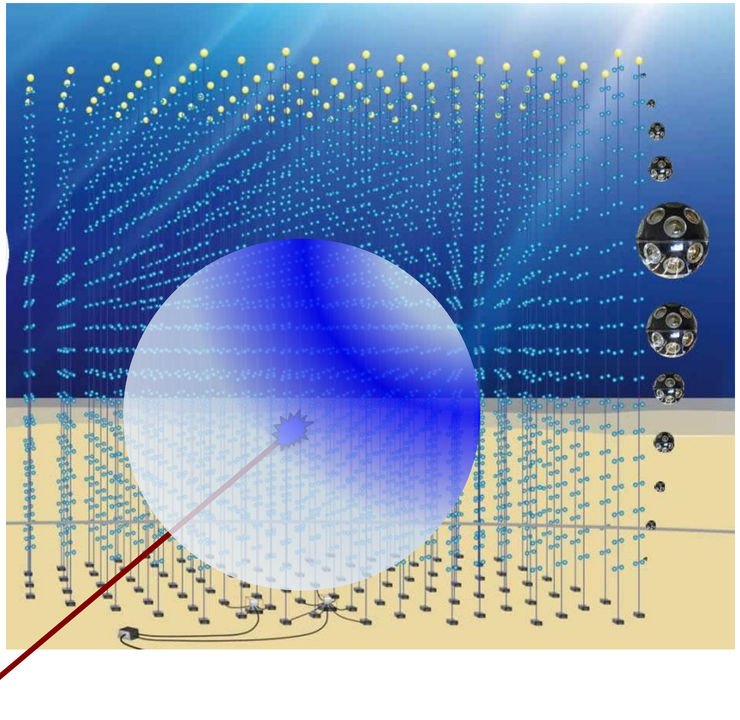
Tracks - Charged current (CC) υ_μ interaction
- Charged current υ_τ interaction

Showers - Neutral current υ interaction
- υ_e CC electromagnetic shower
- Vertex of CC interaction
- τ decay shower

'Track'



'Shower'



Sea-bed: ~2.5 km deep (KM3NeT/ORCA and Antares)

Antares

- Deep-Sea Cherenkov telescope :
  - Detect light from charged products of neutrino interactions
- 2.5 km deep, 40 km off-shore of Toulon, France
- 12 Vertical lines, each is 350 m high
- 25 storeys of 3 10” photomultiplier tubes per line
- 10 Mton instrumented volume
- First line deployed 2006, construction completed 2008

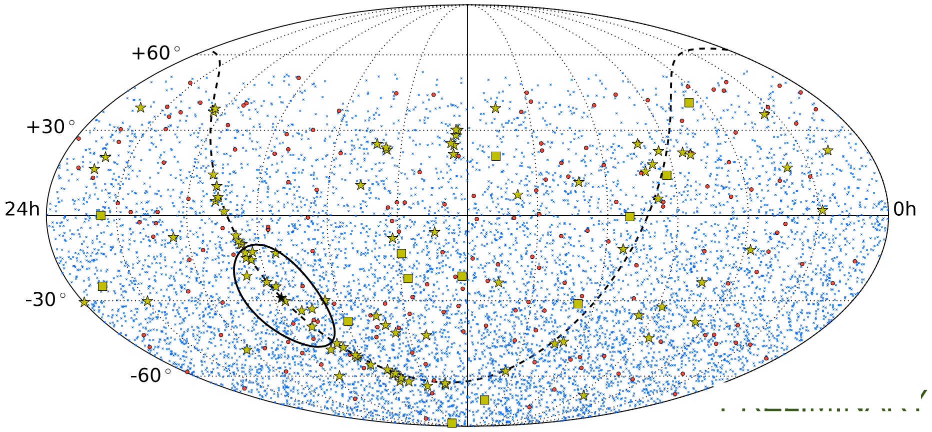
All-flavour neutrino point source search

‘Can we find sources of neutrinos in the sky?’

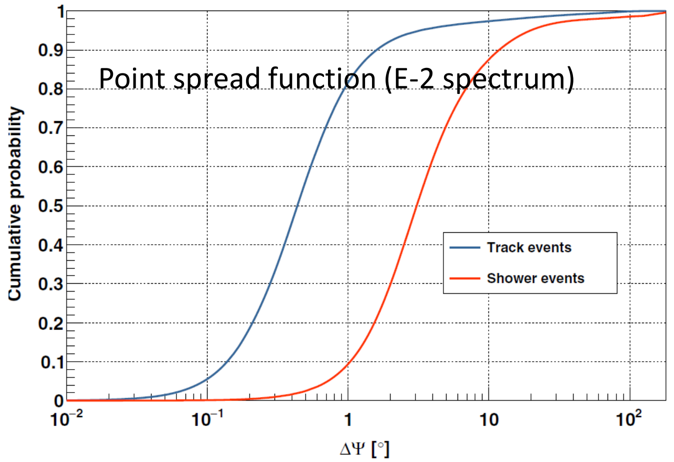
Strategies:
- Grid scan of sky-positions 1x1 degree
- GC region scan
- Sagittarius A* (Extended source: Gaussian profiles)
- Coordinates of interest
  - Candidate list of 106 (pulsars, SNRs)
  - IceCube events (13 HESE)

Ingredients :

Dataset:
o 2007 - 2015
o 2424 days lifetime
o All-flavour analysis:
 7622 tracks
 180 showers



X : track ● : shower

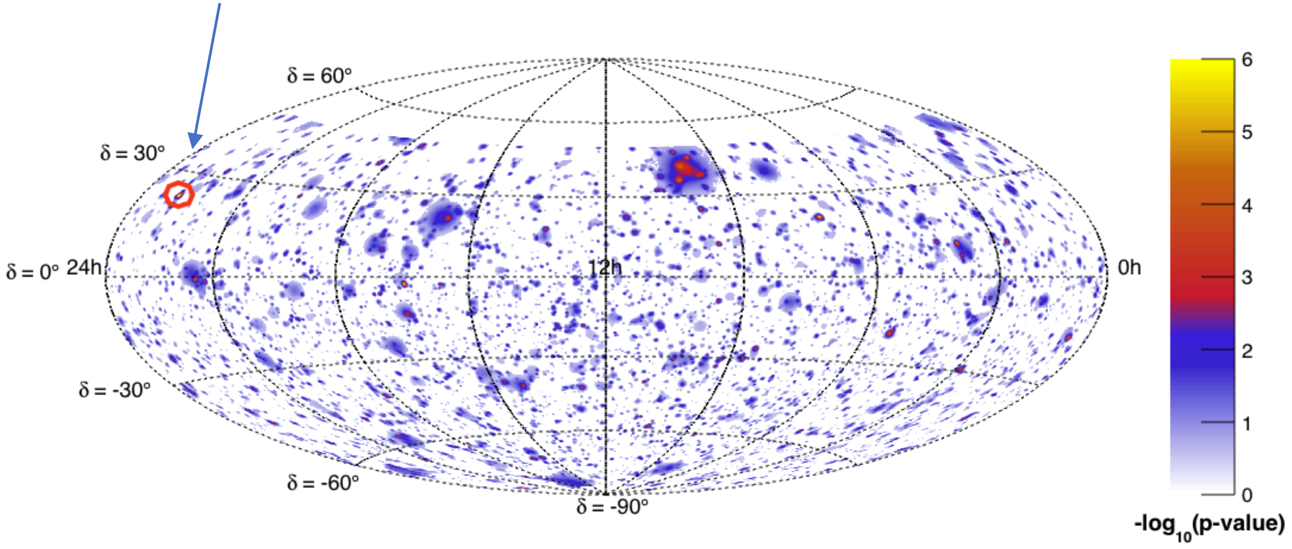


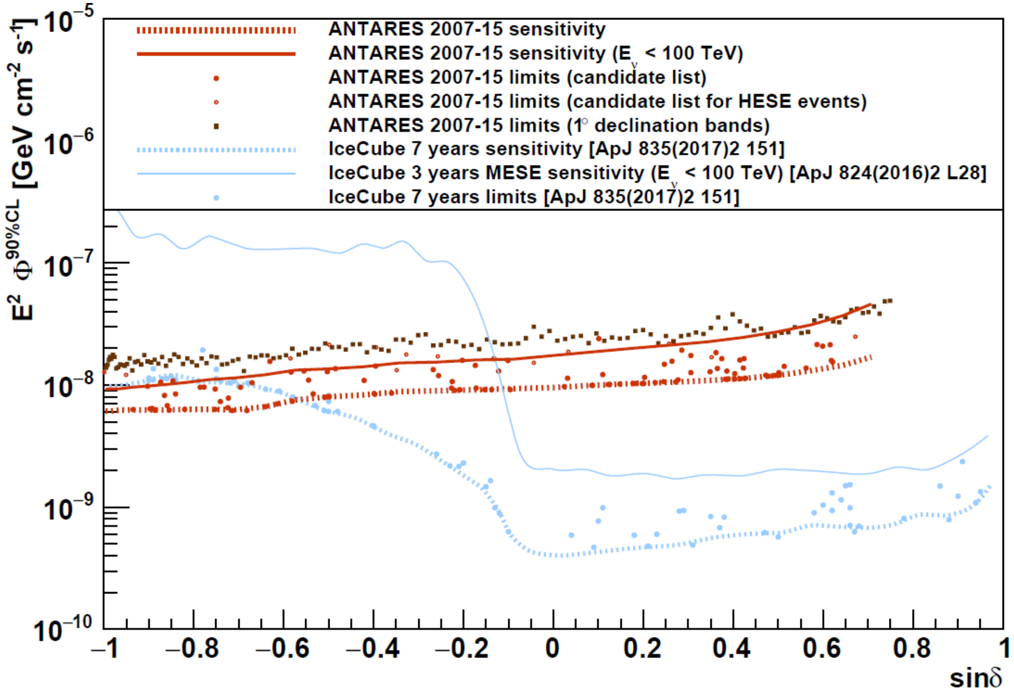
Background Simulation
(Atmospheric Neutrinos and Muons)

Likelihood ratio based test statistic

Point Source Searches

Most significant cluster : 1.9 σ



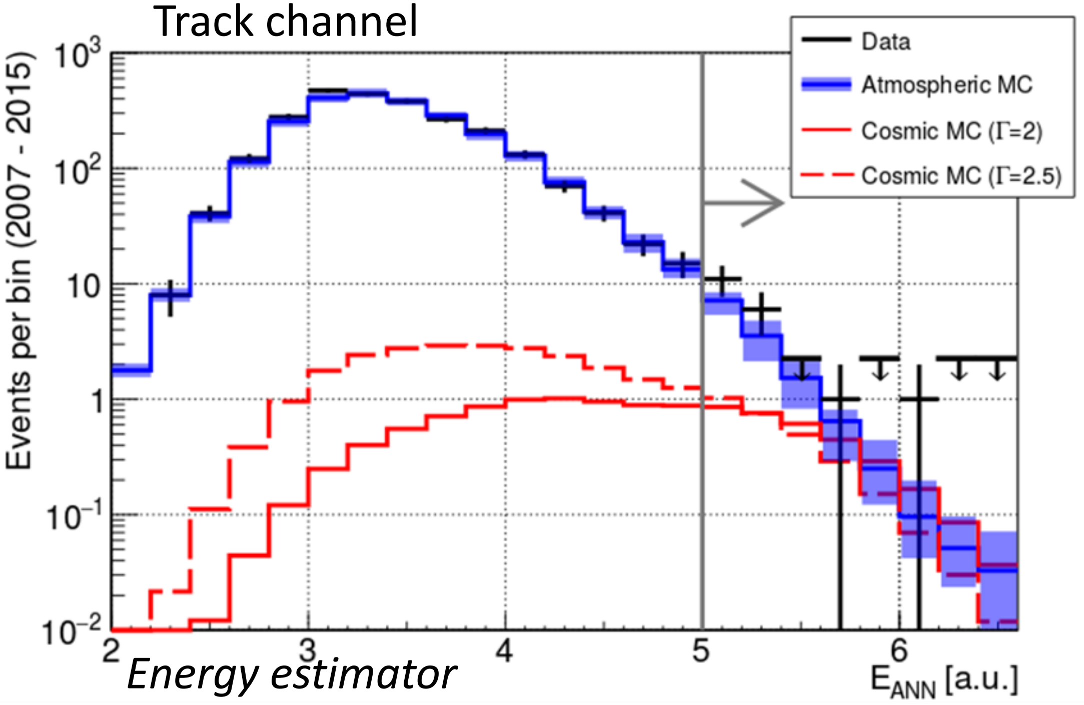


Most sensitive upper limit in fraction of the sky in particular at low energies (< 100 TeV)

Diffuse flux

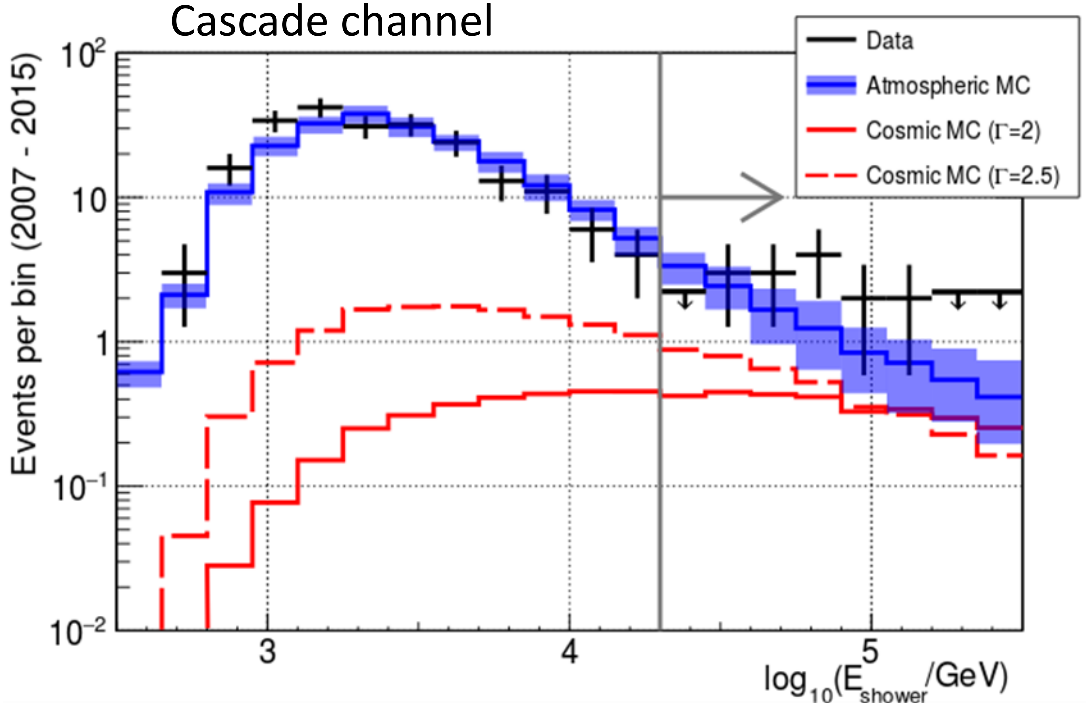
‘Is there a neutrino flux resulting from unresolved sources? (on top of background)’

Track channel



Energy estimator

Cascade channel



MC uncertainty bands include
Honda +- 25 %
Enberg high/low
Detector systematics

Diffuse Flux : upper limits and best fit

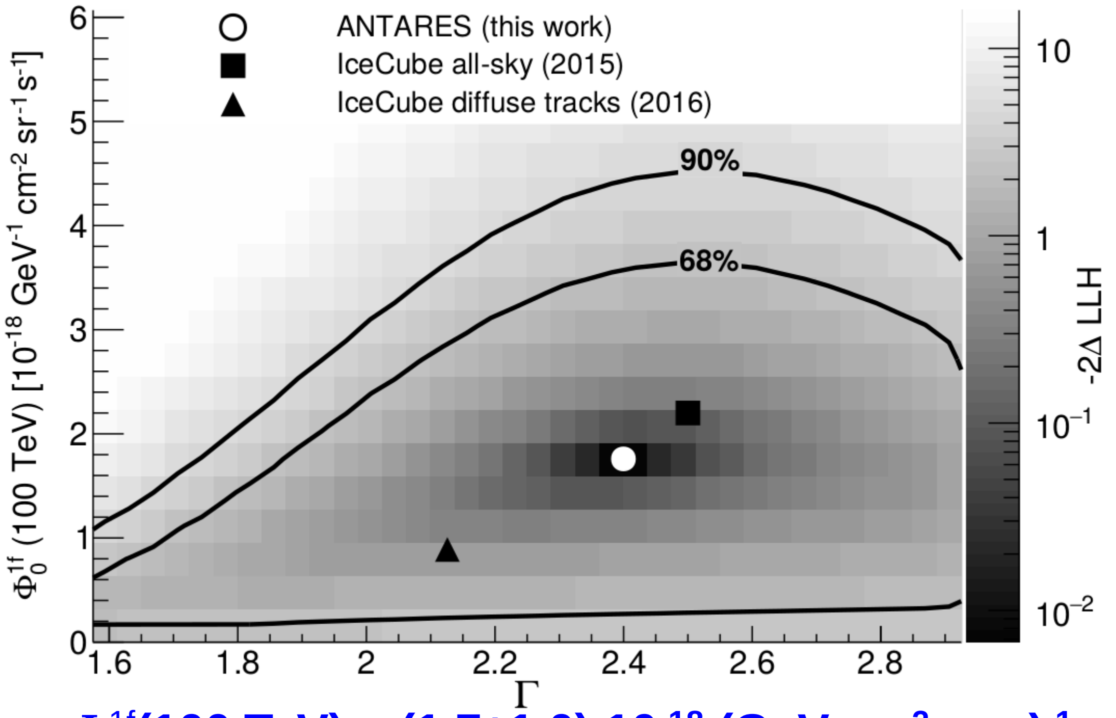
Results :

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

1.6σ excess, null cosmic rejected at 85% CL

Limits on 1-flavour flux normalization (100 TeV)

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

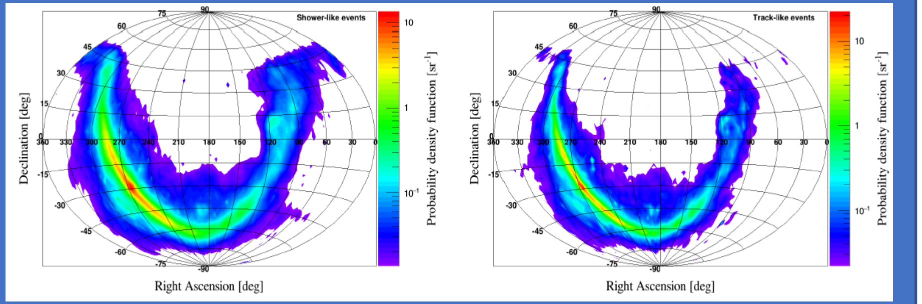


Φ^{1f}(100 TeV) ~ (1.7±1.0) 10^{-18} (GeV cm^2 s sr)$^{-1}$
$\Gamma \sim 2.4^{+0.5}_{-0.4}$

Galactic plane

Neutrinos from interactions of cosmic rays with galactic matter

Cosmic Ray diffusion model : KRAγ
5 & 50 PeV CR cutoffs
(predicts photon+neutrino flux)



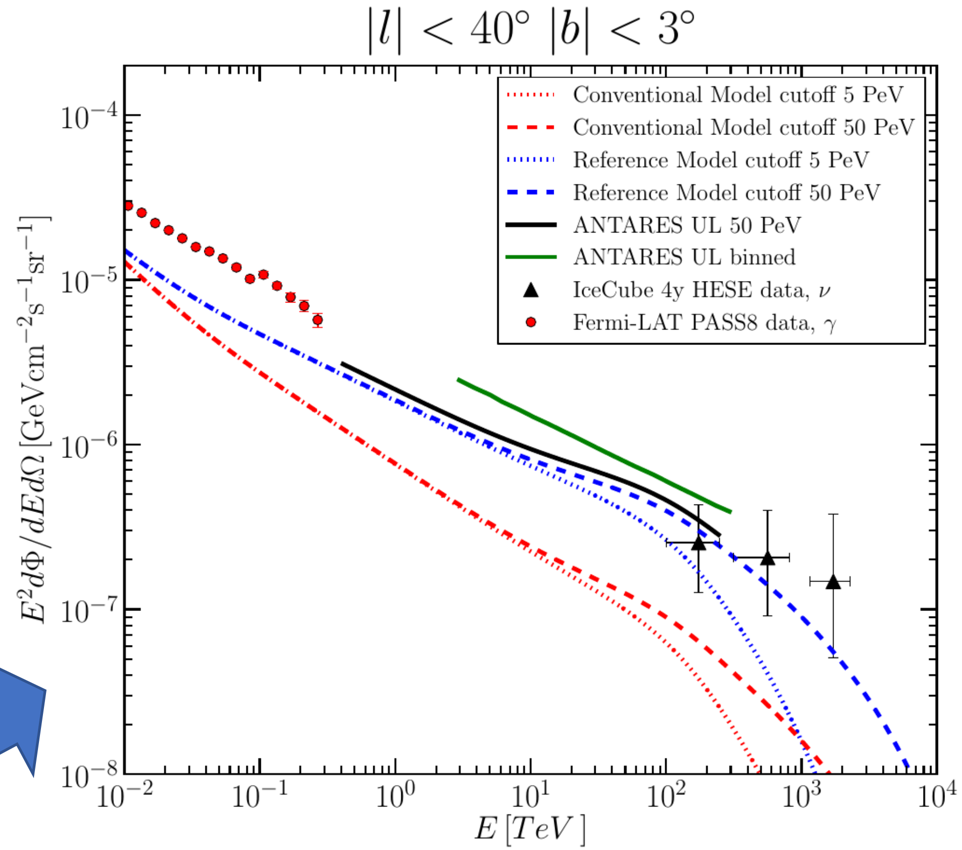
Probability density for signal (plots)

+ background probability density

Evaluate Likelihood ratio distribution using pseudo experiments for different signal strengths

Get data Likelihood ratio

2007-2015
7300 tracks, 208 showers



(model dependent) upper limit

Multi-messenger program

Bi-directional real-time:
- Provide triggers (order 1/day over all programs)
  - Coincidence & High energy triggers
  - 5 s first response, 0.4 degree resolution
- Receive triggers, e.g. :
  - Supernovae
  - FRBs, AGNs
  - Flaring objects
  - Gravitational waves

On- and offline Analyses, e.g
- Time and location coincidences
  - IceCube HESE events
  - Auger/TA cosmic ray events
  - AGN flares from HAWC

Radio/Visible/X-rays
MWA, TAROT, ZADKO,MASTER,SWIFT, SUPERB

Gamma rays:
Fermi, Hess, Magic

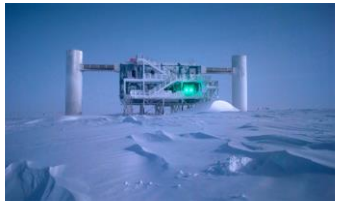
Neutrinos
IceCube

UHE Cosmic Rays
Auger, TA

Gravitational Waves
Ligo/Virgo



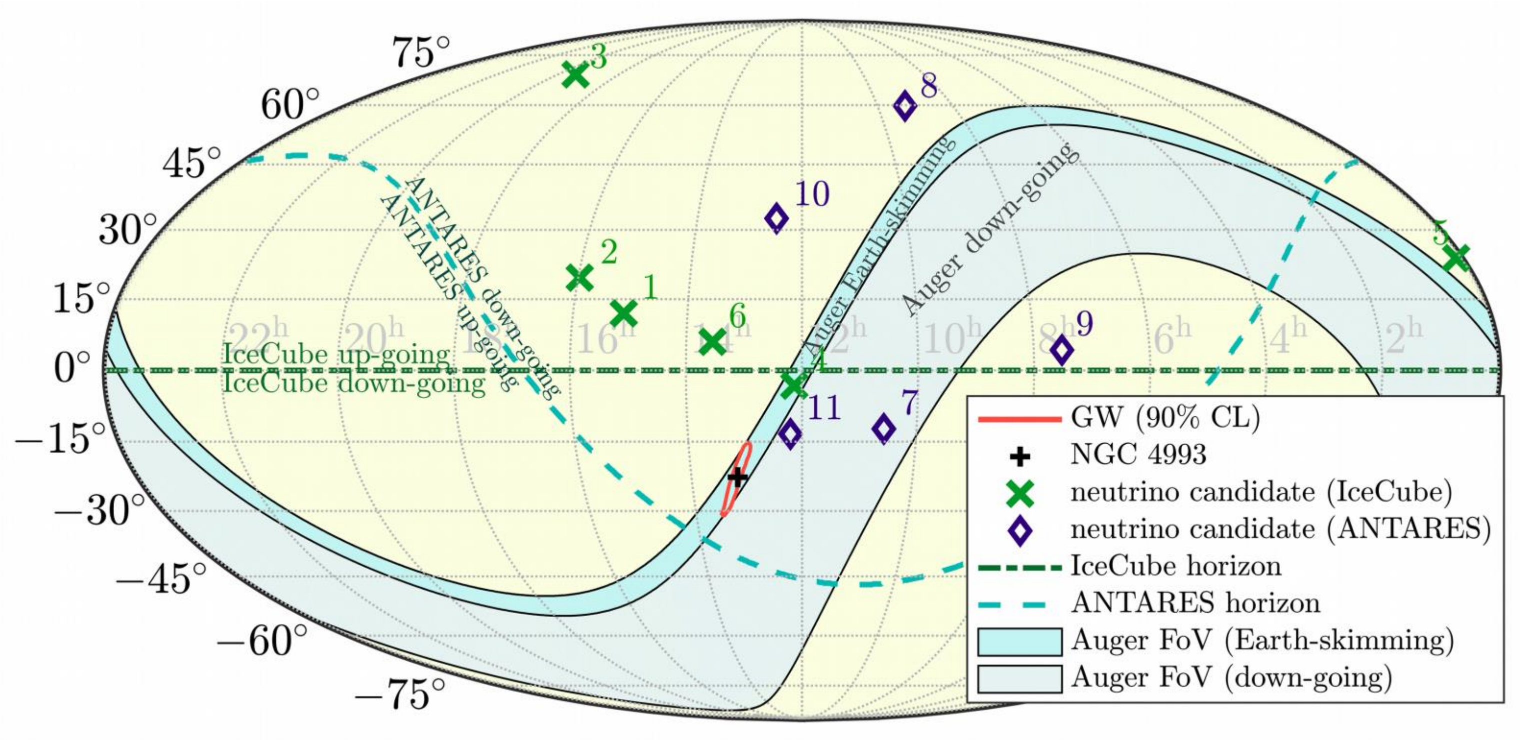




Gravitational Wave follow-up

Follow-up of several GW events

GW150914 (BBH merger)
GW151226 (BBH merger)
LVT151012 (candidate)
GW170104 (BBH merger)
GW170817 (BNS merger)



Features

- Optimized reconstruction
- +-500 s search window
- Combined IceCube/Antares searches

No coincidences found

Search for coincidences of Antares/IceCube events with sub-threshold GW events ongoing

KM3NeT/ORCA

(Oscillations Research with Cosmics in the Abyss)

115 Detection Units
5 Mton
2.5 km deep, 40 km off-shore of Toulon

‘compact version of ARCA’

Digital Optical Modules

31 3” PMTs in 17” sphere
+ electronics etc.

- Photon counting
- Directionality
- Cheap(er)

Detection Units:

18 optical modules per detection unit
9m between optical modules
153 m instrumented

KM3NeT Collaboration

51 institutes in 15 countries (mainly European)
2 current deployment sites (Fr, It), one future (Gr)

Infrastructure:

Sea-bed infrastructure
(facility for long term high-bandwidth connection for sea-science, biology etc.)
Optical data transmission
All-data-to-shore
Filtering/Trigger on-shore in computer farm

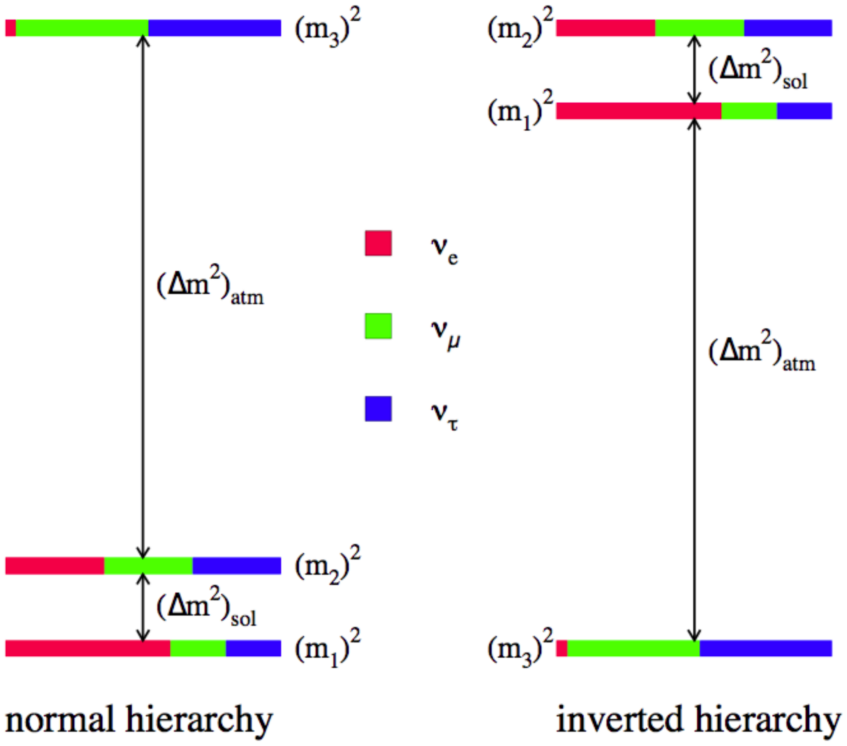
KM3NeT/ORCA Goal: Neutrino Mass Hierachy

Neutrinos can change flavour during propagation as the mass eigenstates are not their flavour eigenstates

Neutrino flavour oscillations are described by the PMNS matrix:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

and two mass squared differences



Only the size (not the sign) of the large mass squared difference ΔM^2 is known. This allows for two orderings of the neutrino mass eigenstates

Neutrino Mass Hierarchy (NMH)

Also: CP violating phase δ_{CP} unknown and octant of θ_{23}

Determining the NMH with atmospheric υ´s

In vacuum, neutrino oscillations are unaffected by the mass ordering. E.g:

$$P_{3\nu}(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\,\sin^2 2\theta_{13}\,\sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right)$$

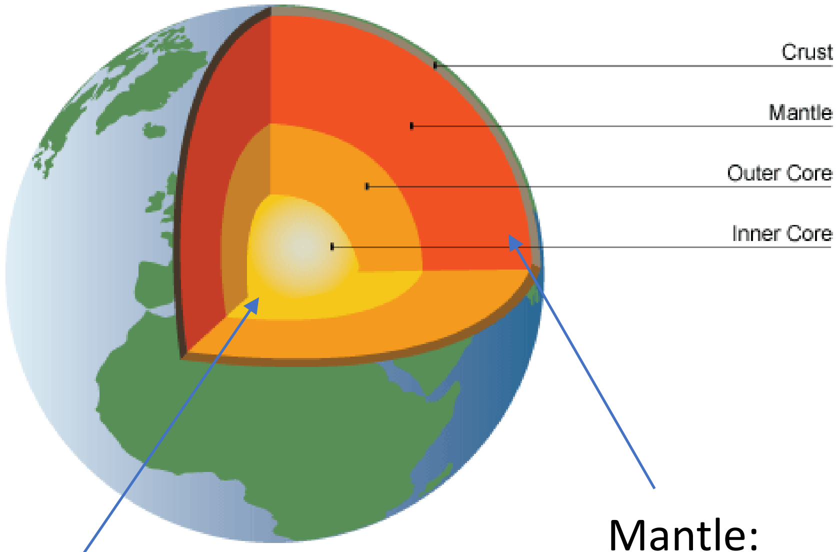
$$P_{3\nu}(\nu_\mu \to \nu_\mu) \approx 1 - 4\cos^2\theta_{13}\,\sin^2\theta_{23}\,(1-\cos^2\theta_{13}\,\sin^2\theta_{23})\,\sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right)$$

In matter $\nu_e(\,\overline{\nu_e})$acquires effective potential $A = \pm\sqrt{2}G_f N_e$ through charged current elastic interactions with electrons. And oscillations probabilities are modified.

This affects phase and amplitude of oscillations and is strongest at resonance energy:

$$E_{res} \equiv \frac{\Delta m^2_{31}\,\cos 2\theta_{13}}{2\sqrt{2}\,G_F\,N_e} \simeq 7\,\mathrm{GeV}\left(\frac{4.5\,\mathrm{g/cm^3}}{\rho}\right)\left(\frac{\Delta m^2_{31}}{2.4\times10^{-3}\,\mathrm{eV^2}}\right)\cos 2\theta_{13}$$

Density profile of the path through the Earth depends on zenith angle



Core: $E_{res} \approx 3GeV$

Mantle: $E_{res} \approx 7GeV$

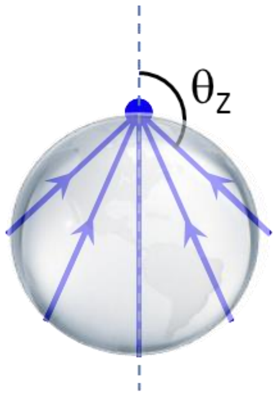
See: Akhmedov, E.K., Razzaque, S. & Smirnov, A.Y. J. High Energ. Phys. (2013) 2013: 82.

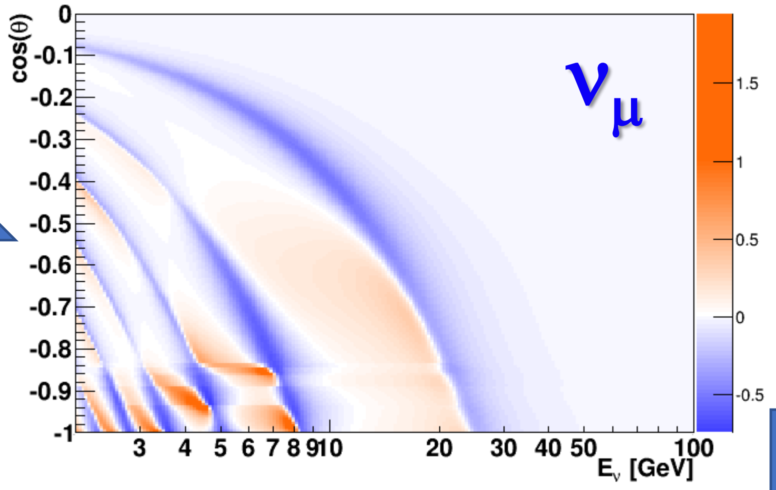
Measure atmospheric neutrino flux as function of energy and zenith angle!

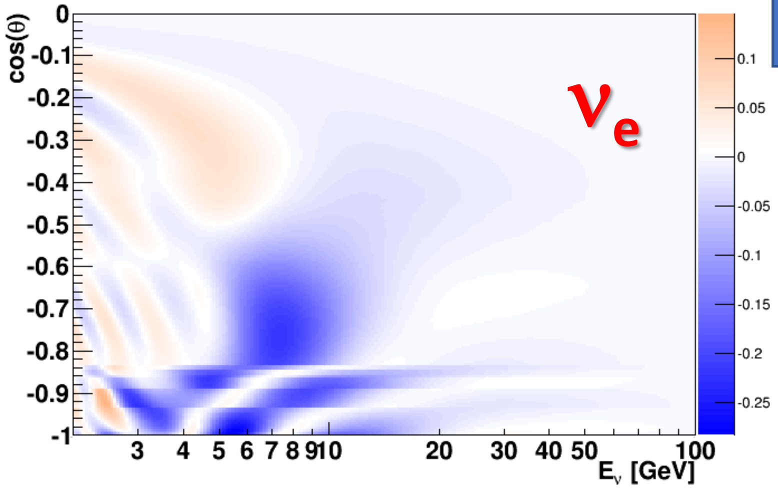
Determining the NMH with atmospheric υ´s

Relative difference in event numbers between normal and inverted hierarchy $(N_{IH}-N_{NH})/N_{NH}$

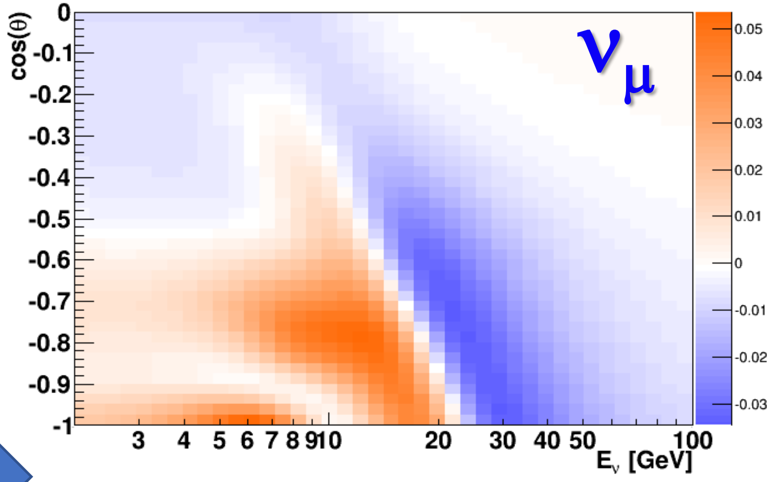
Zenith angle
corresponds with different distance and density profile !

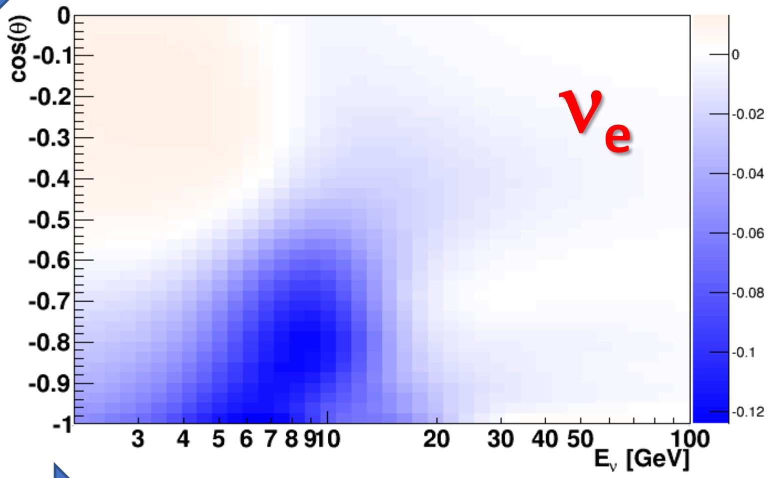






Resolutions





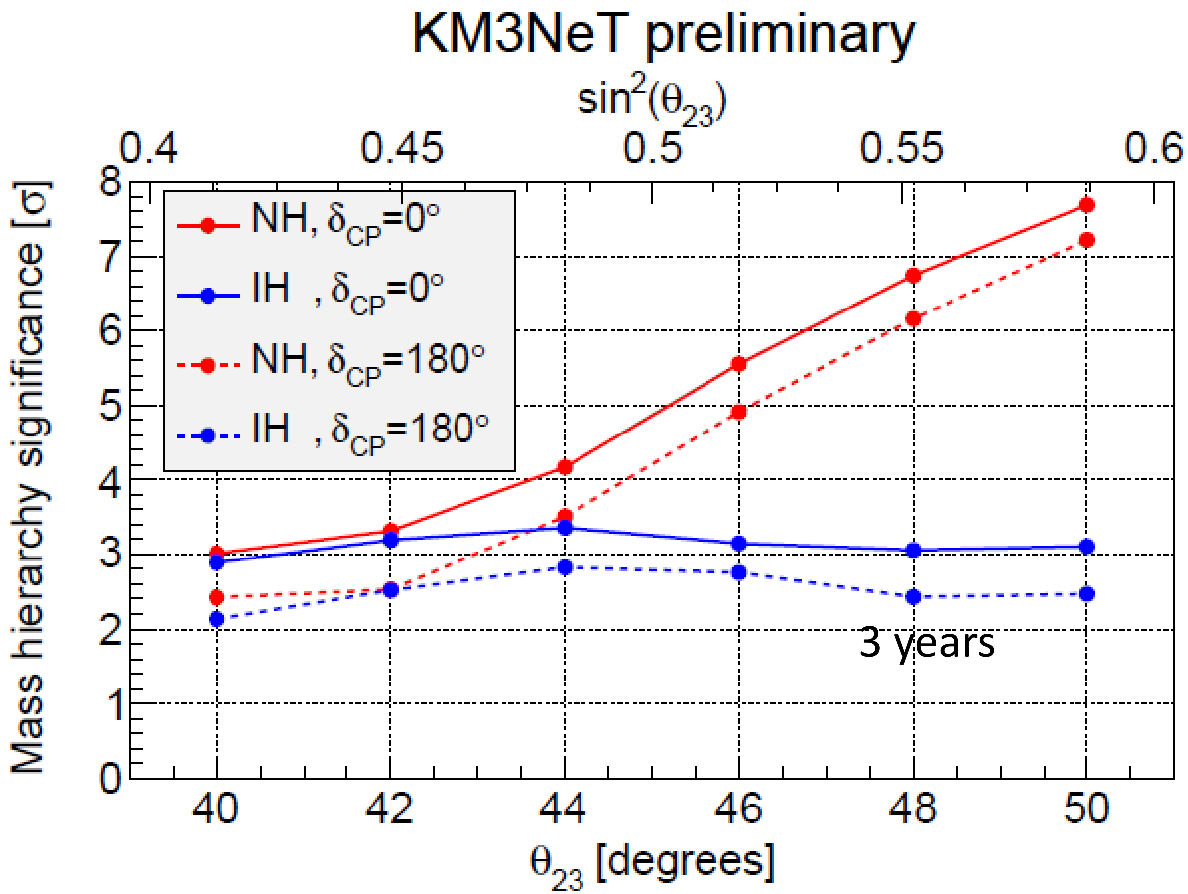
Neutrino Energy

Sensitivity for Neutrino mass ordering

Sensitivity to distinguish between normal and inverted hierarchy:

3 σ in 3 years (median sensitivity)

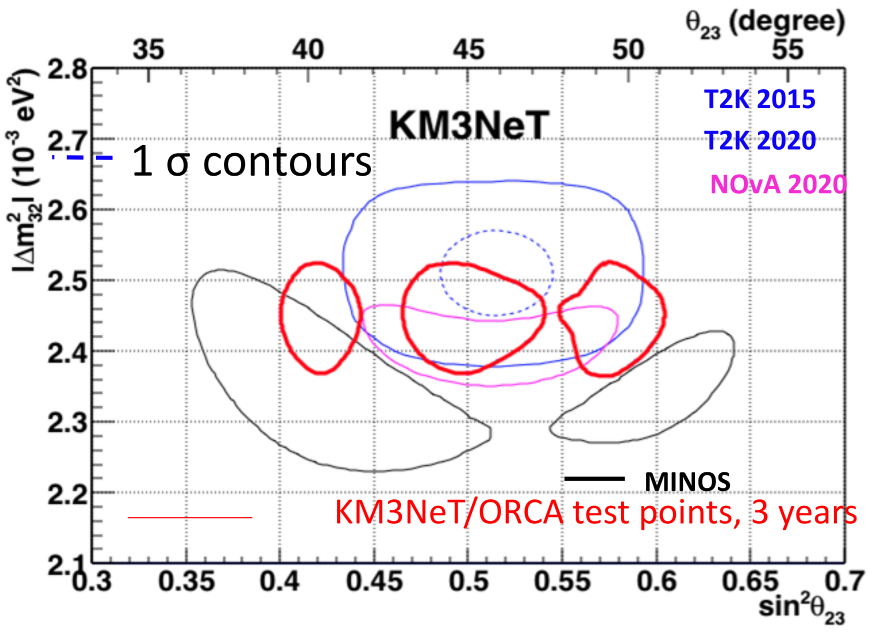
Normal hierarchy + upper octant θ_{23} gives more sensitivity (5 σ in 3 years)



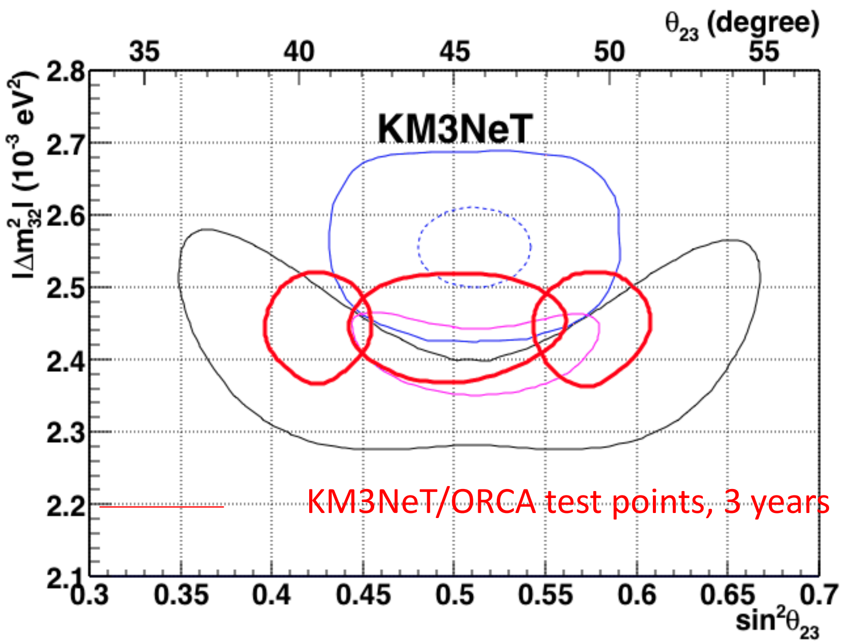
New (improved!) results underway !!

Δm^2_{32} and $sin^2\theta_{23}$

Normal Hierarchy

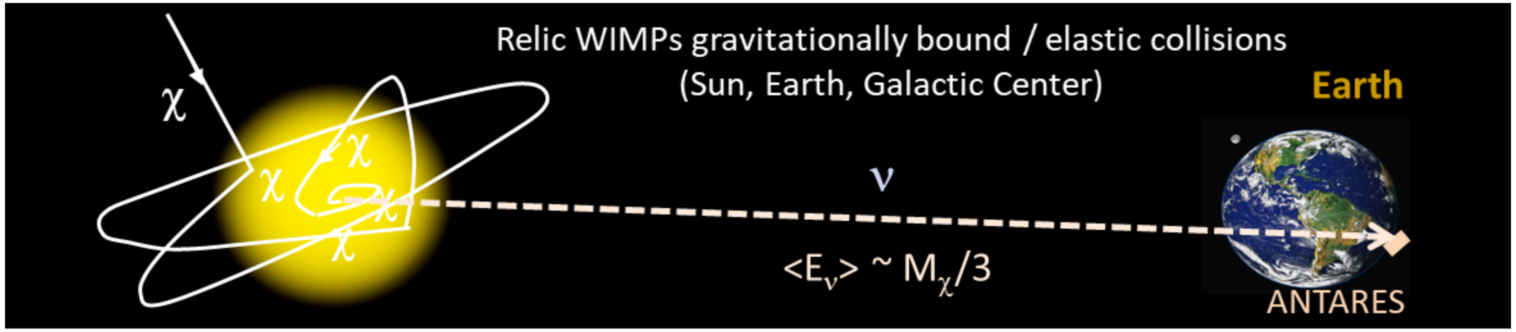


Inverted Hierarchy

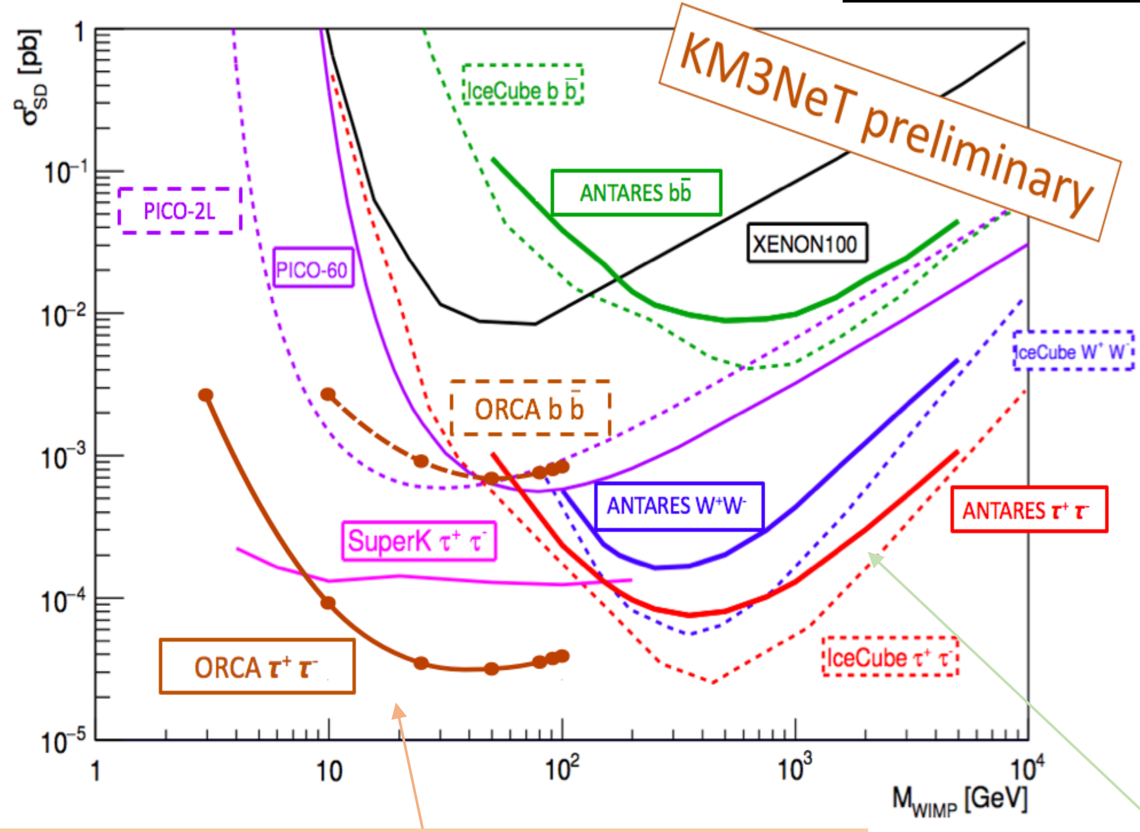


Competitive measurements of Δm^2_{32} (2-3%) and $sin^2\theta_{23}$ (4-10 %)

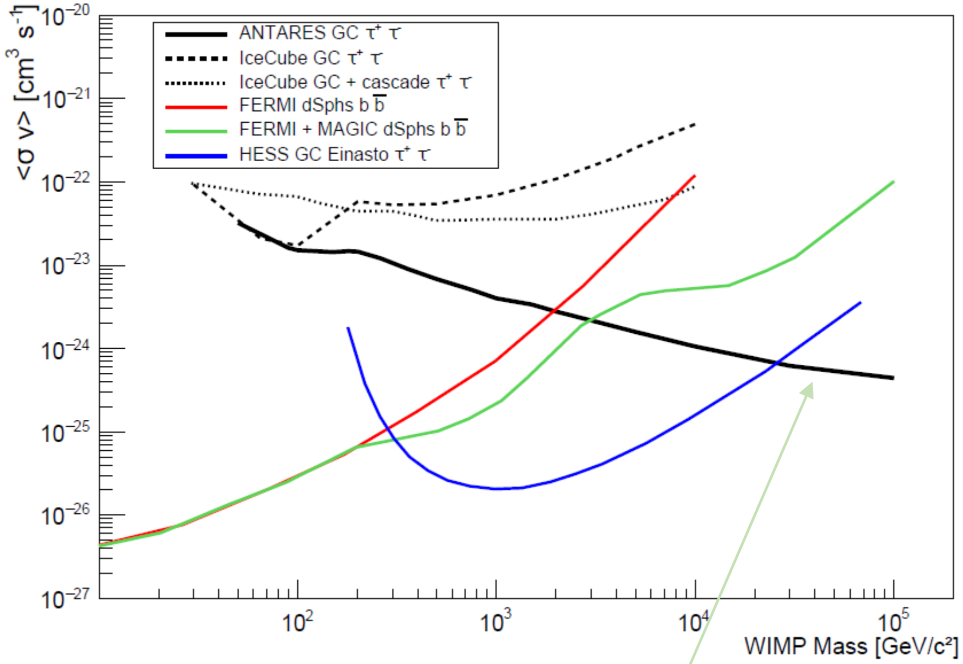
Dark Matter



Spin-dependent scattering cross-section (Sun)



Thermally averaged annihilation cross-section (GC)



KM3NeT/ORCA senstivity (3 years, tracks and showers)

Antares limits
Competitive due to low energy threshold and good angular resolution

Other KM3NeT/ORCA Physics Topics

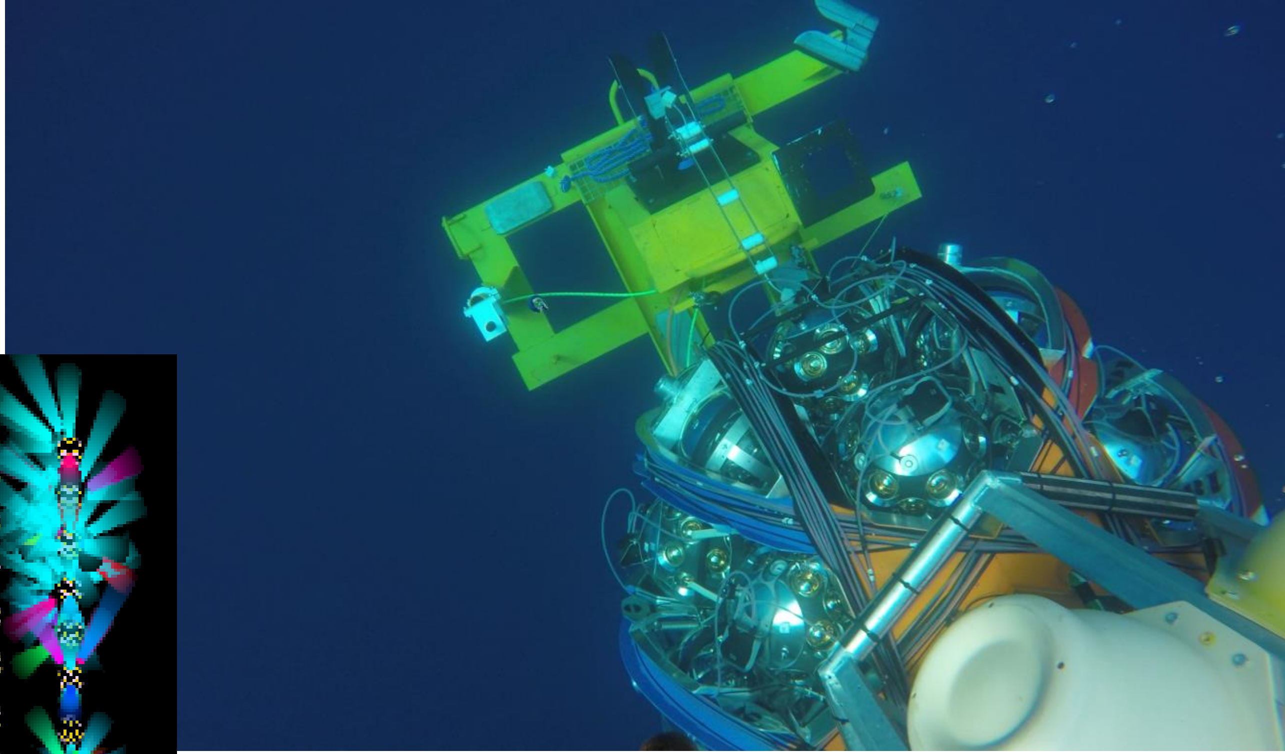
- Supernova detection
- Tau-neutrino appearance
- Non-Standard interactions and Sterile Neutrinos
- Neutrino Beam from Protvino to KM3NeT/ORCA
  - CP & NMH
- Low Energy Neutrino Astrophysics
- Earth Tomography and Composition
- Earth and Sea Sciences

KM3NeT/ORCA Status

First DU deployed September last year

DU behaved splendidly

Fault in commercial undersea cable
(Will be repaired)



Construction of phase-1 DOMs and DUs ongoing

DUs to be deployed end of this year

Phase-2 partially funded, starting tenders for components

Summary

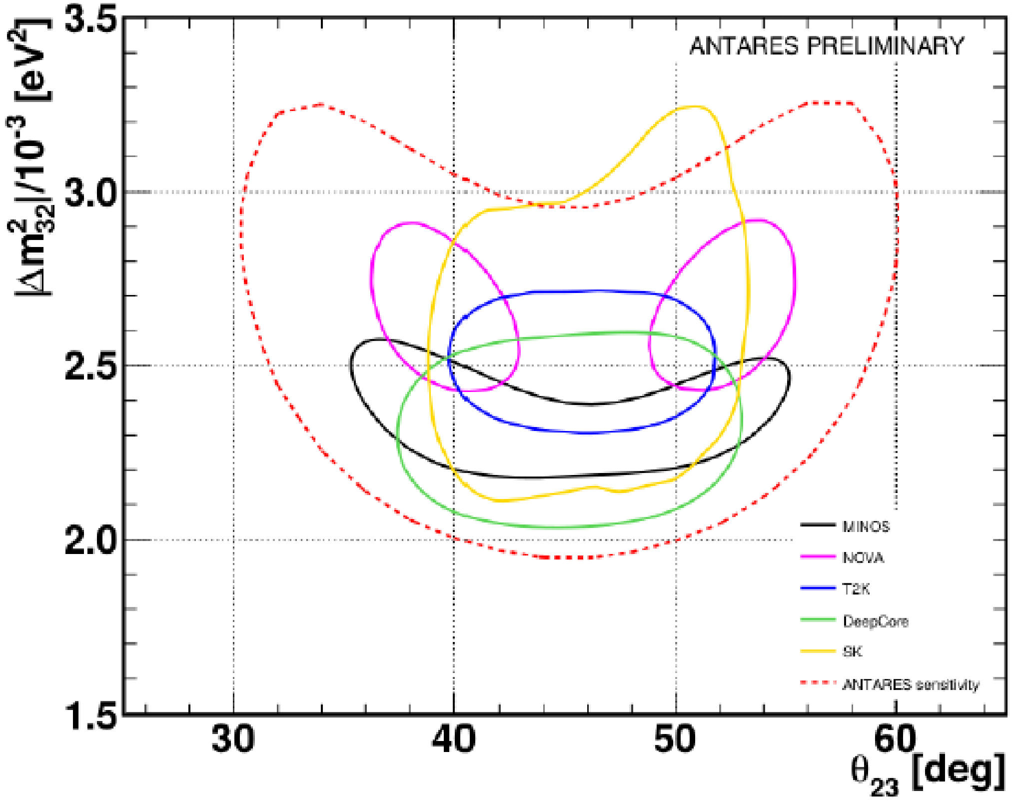
- Antares
  - 10 years operational and running
  - Large variety in physics results
  - Combined analyses
  - Multi-messenger astronomy

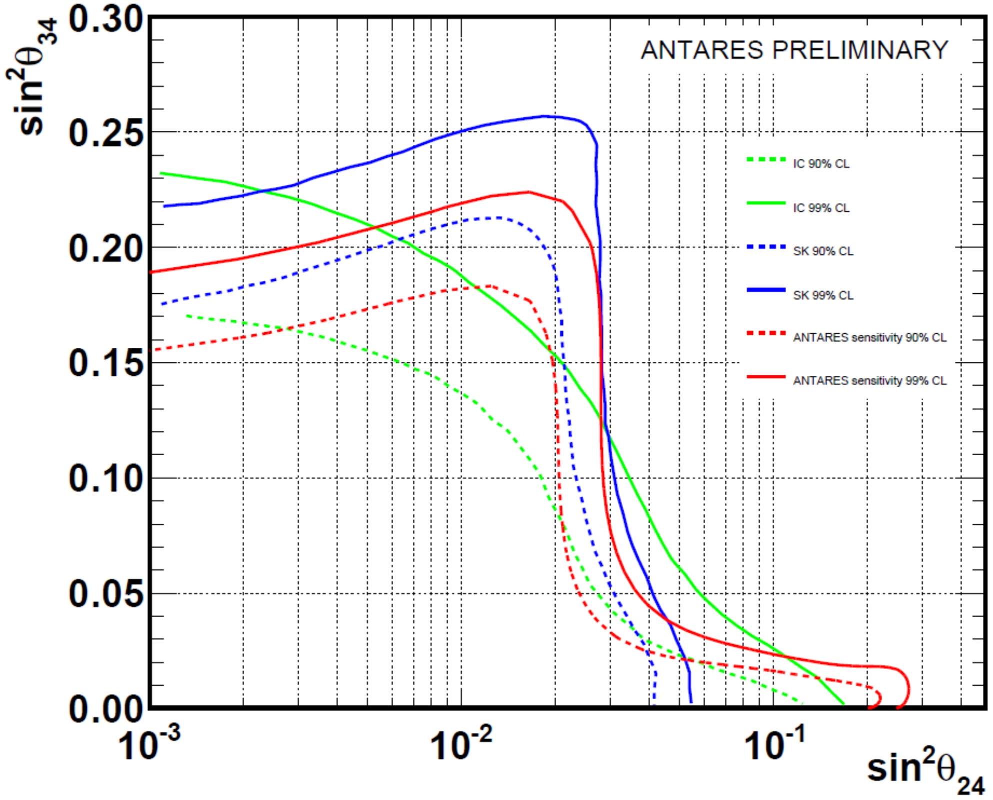
- KM3NeT/ORCA
  - Neutrino mass hierarchy
    - Strong potential to make the first measurement
    - ‘3 sigma in 3 years’
  - Broad physics program
  - Under construction

Backup

Oscillation parameters and sterile neutrinos

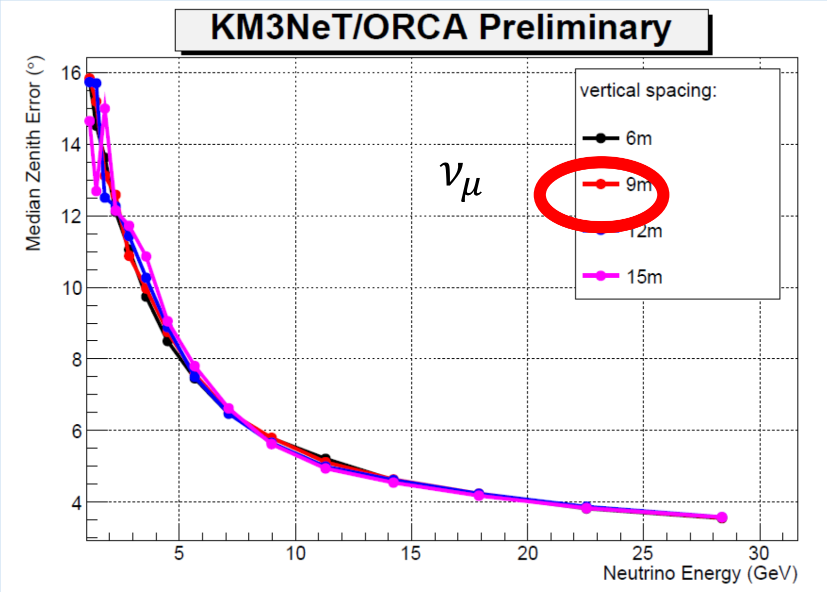
Evaluation of the sensitivity of Antares to oscillation parameters and sterile neutrinos work in progress



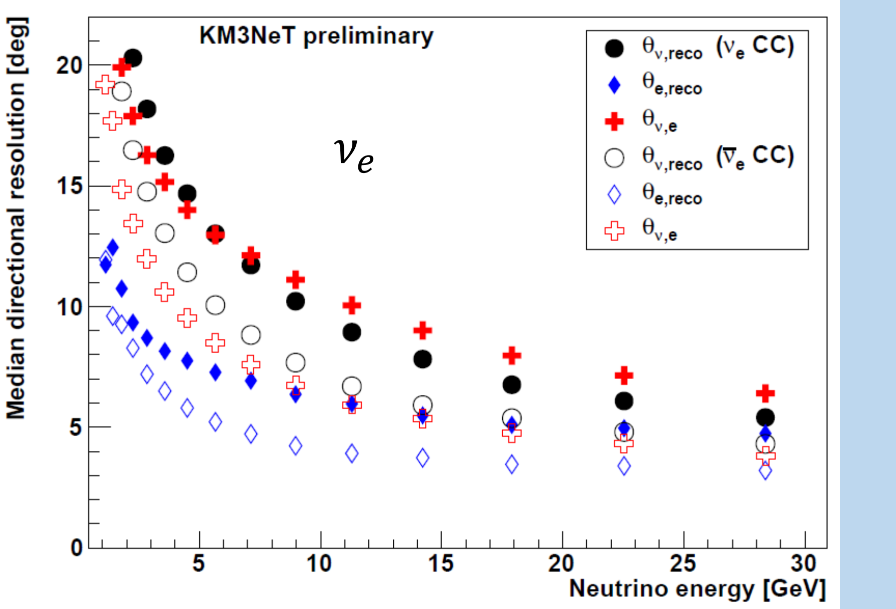


Resolutions

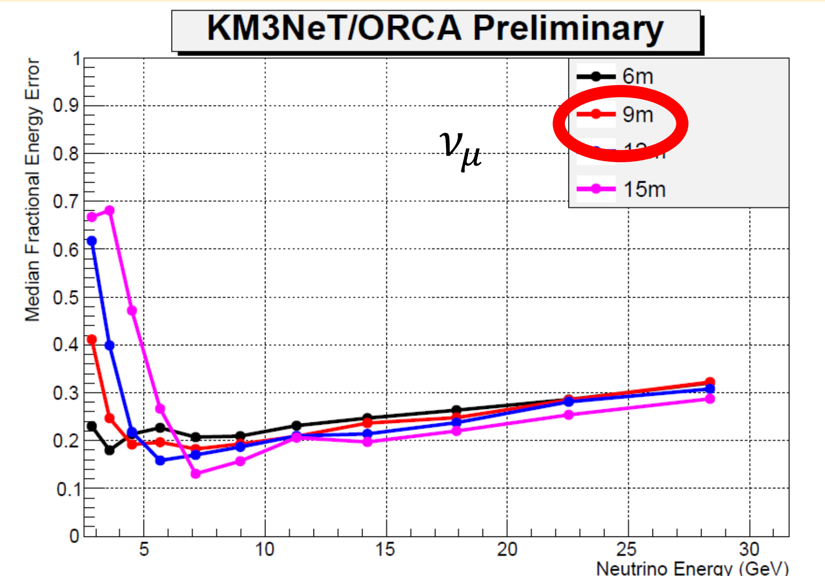
Direction

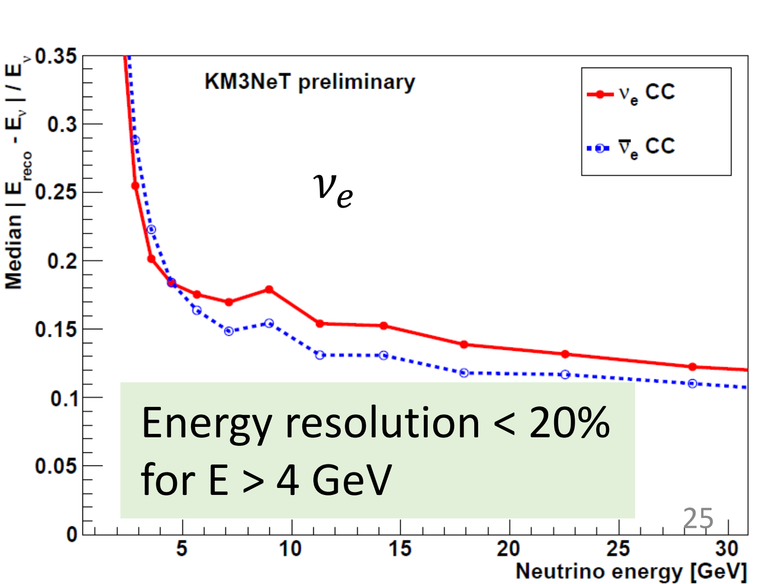


At relevant energies, neutrino/lepton scattering angle dominates



Energy





Energy resolution < 20% for E > 4 GeV

Supernova detection

~10 MeV supernova neutrinos can not be resolved individually

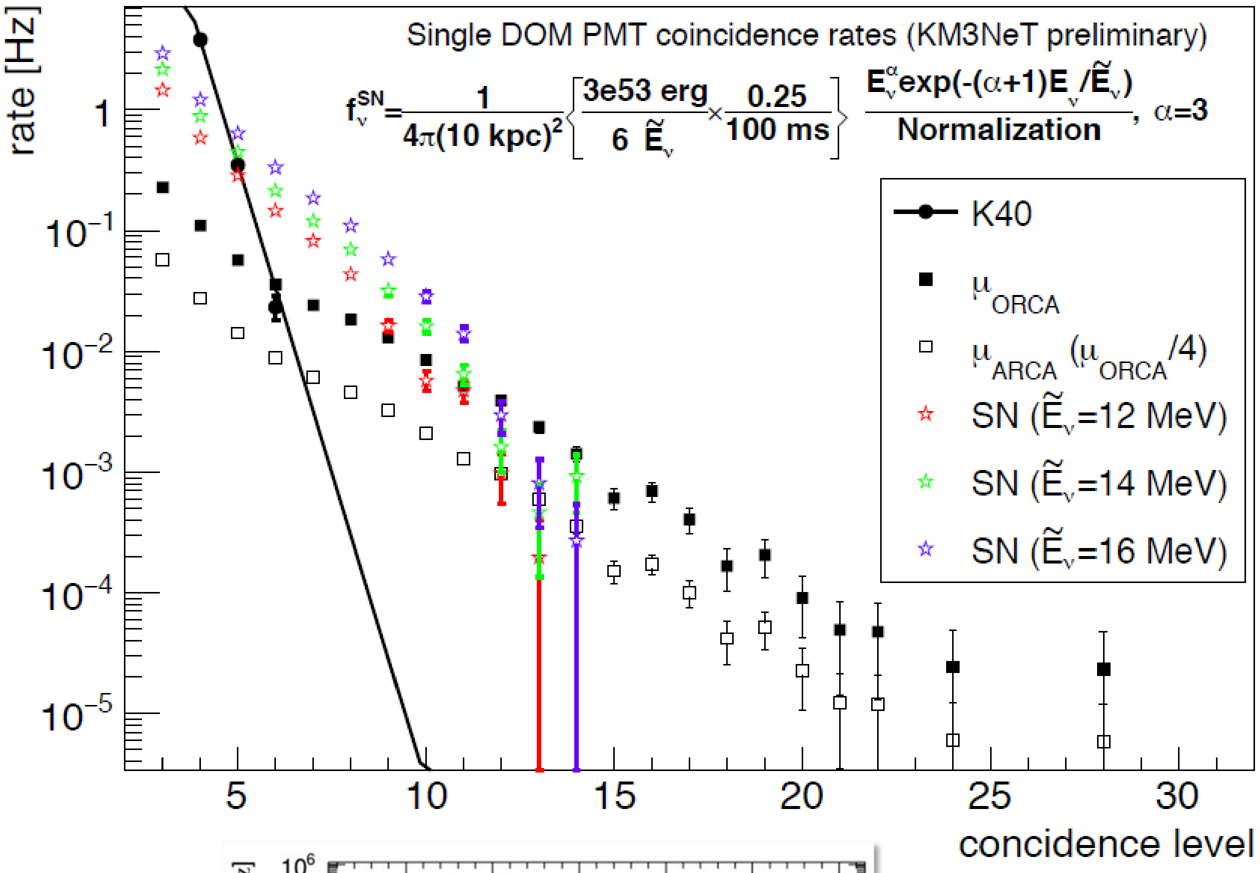
Detection of Galactic supernovae by enhanced collective coincidence rates between PMTs in DOMs

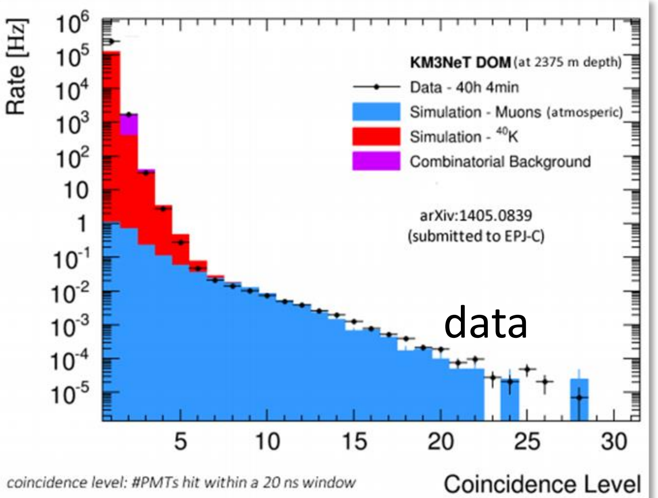
SN1987A - like supernova at 10 kpc, $3 \cdot 10^{53}$ erg, $\bar{\nu}_e$ component (1/6) with 25% in first 100 ms

At >= 6 coincidences per DOM, SN signal exceeds background.

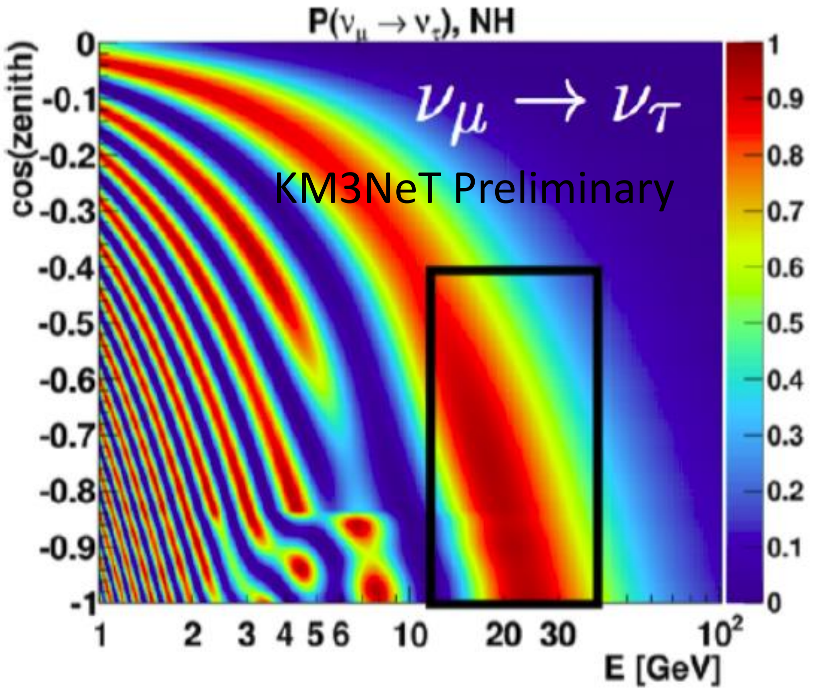
KM3NeT/ORCA: 5 σ discovery distance 16 (24) kpc at $\langle E_\nu \rangle$ = 12 (16) MeV (KM3NeT/ARCA: up to 37 kpc)

(Note: neutrino fluxes from SN are influenced by mass-hierarchy!)





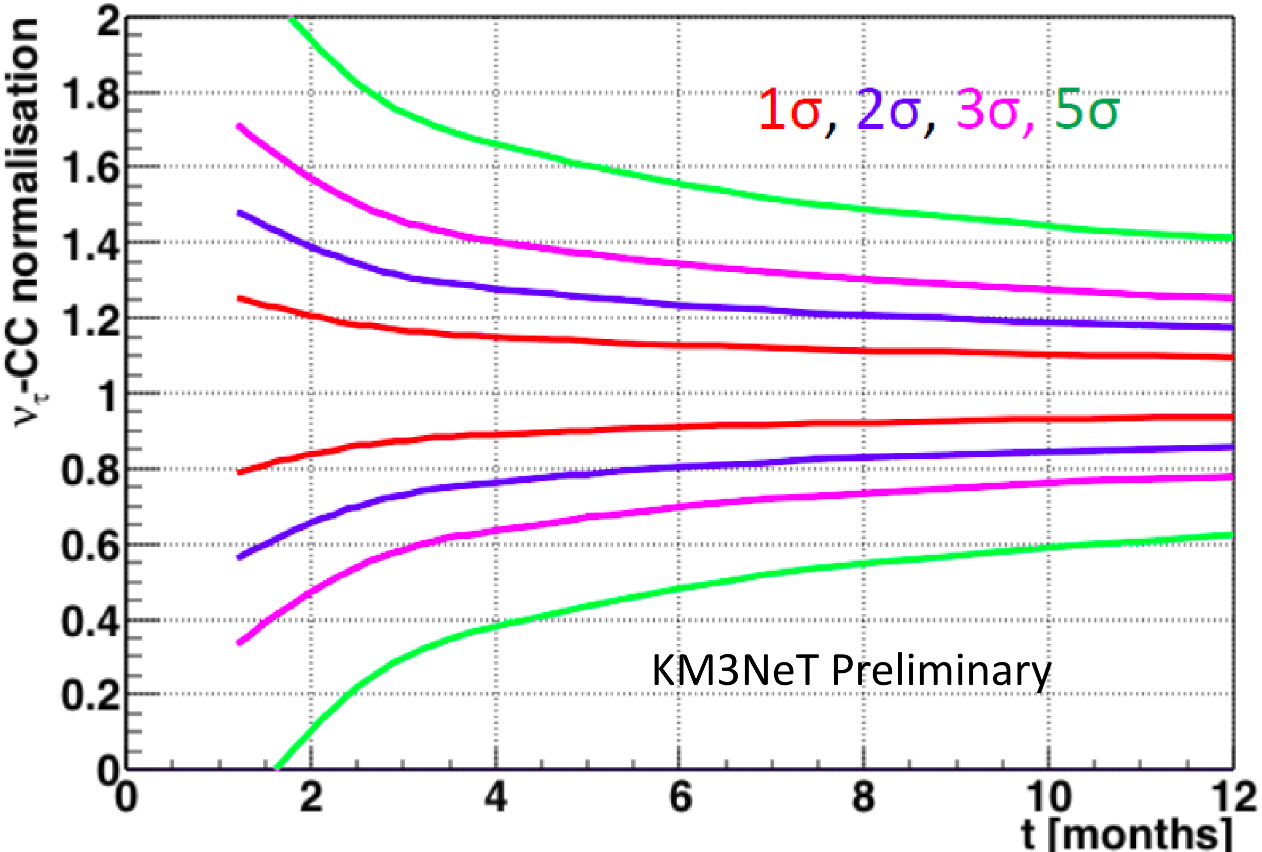
τ appearance

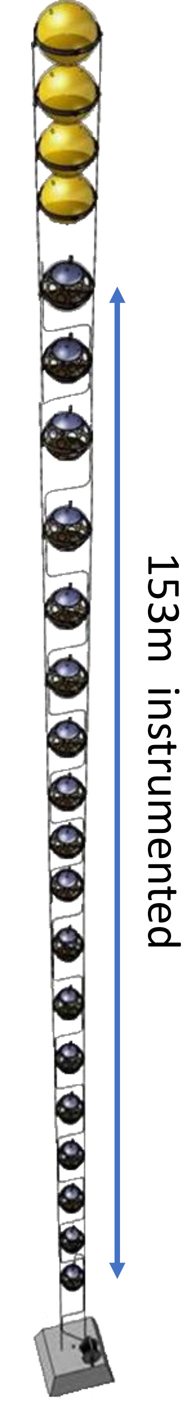


Early physics result

3k tau events/year

Rate constrained to 10% in one year





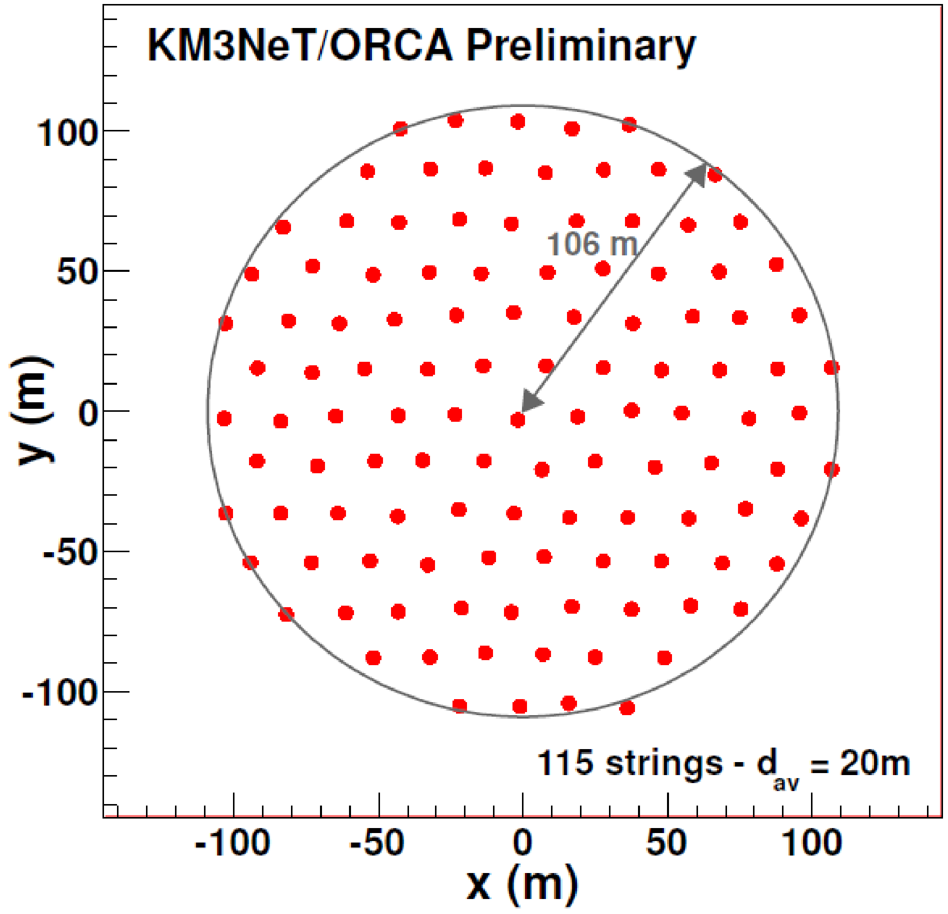
KM3NeT Design (ORCA)

Detection Units:

18 optical modules per detection unit
9m between optical modules
Lowest optical module 40m above seabed
Two Dyneema® ropes
Backbone: 2 copper conductors; 18 fibres (+spares)
Break out of cable at each optical module
Base module with DWDM at anchor
Cable for connection to seafloor network
Cost saving design

Infrastructure:

Building block of 115 strings
Sea-bed infrastructure
(facility for long term high-bandwidth connection for sea-science, biology etc.)
Optical data transmission
All-data-to-shore
Filtering/Trigger on-shore in computer farm

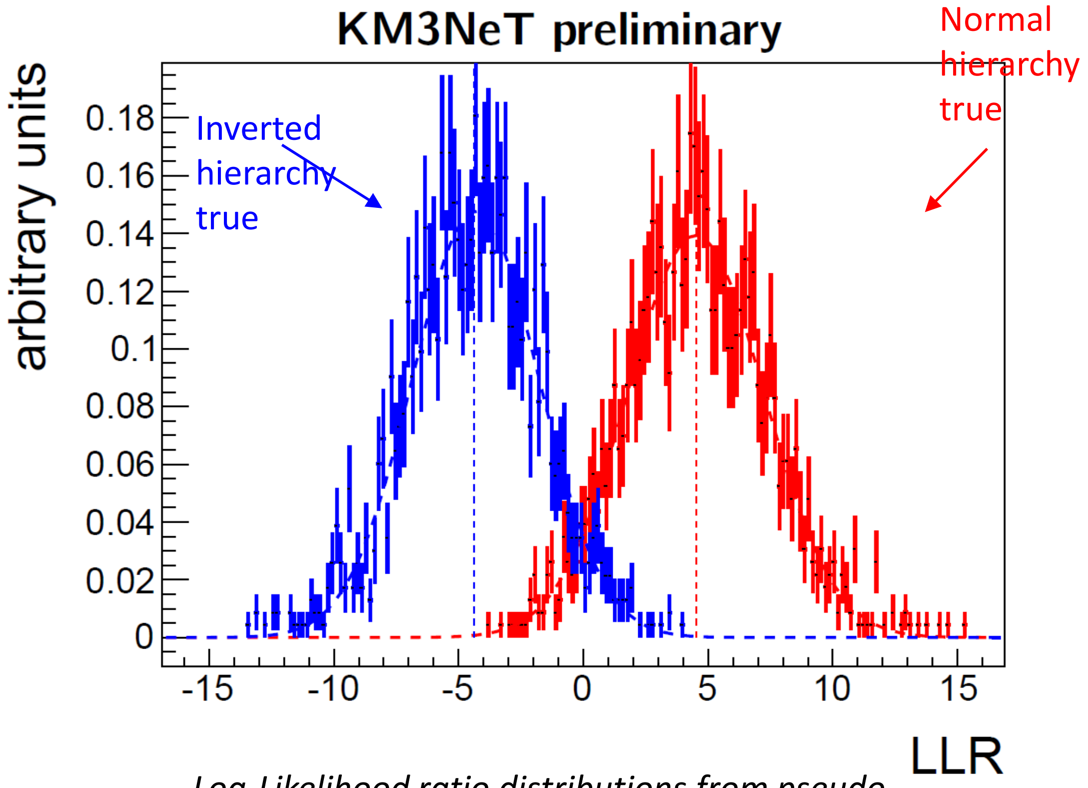


(´ORCA´ layout)

Sensitivity study

- Generate many pseudo-experiments
  - A set of ´true´ values for oscillation parameters and systematics
  - Both normal and inverted hierarchy
  - Calculate oscillation probabilites
  - Apply resolutions, particle ID etc. (determined from simulations)
- Determine likelihood for both NH and IH cases
  - Maximize w.r.t. free parameters
- Calculate log-likelihood ratio L_{IH}/L_{NH}
- Calculate median sensitivity for hypothesis and time

A simpler approach based on Asimov-sets yields similar results



Log-Likelihood ratio distributions from pseudo-experiments

parameter	*true value distr.*	*initial value distr.*	*treatment*	*prior*
θ_{23} [°]	$\{40, 42, \ldots, 50\}$	uniform over [35, 55] †	fitted	no
θ_{13} [°]	8.42	$\mu = 8.42$, $\sigma = 0.26$	fitted	yes
θ_{12} [°]	34	$\mu = 34$, $\sigma = 1$	nuisance	N/A
ΔM^2 [10^{-3} eV^2]	$\mu = 2.4$, $\sigma = 0.05$	$\mu = 2.4$, $\sigma = 0.05$	fitted	no
Δm^2 [10^{-5} eV^2]	7.6	$\mu = 7.6$, $\sigma = 0.2$	nuisance	N/A
δ_{CP} [°]	0	uniform over [0, 360]	fitted	no
overall flux factor	1	$\mu = 1$, $\sigma = 0.1$	fitted	yes
NC scaling	1	$\mu = 1$, $\sigma = 0.05$	fitted	yes
$\nu/\bar{\nu}$ skew	0	$\mu = 0$, $\sigma = 0.03$	fitted	yes
μ/e skew	0	$\mu = 0$, $\sigma = 0.05$	fitted	yes
energy slope	0	$\mu = 0$, $\sigma = 0.05$	fitted	yes