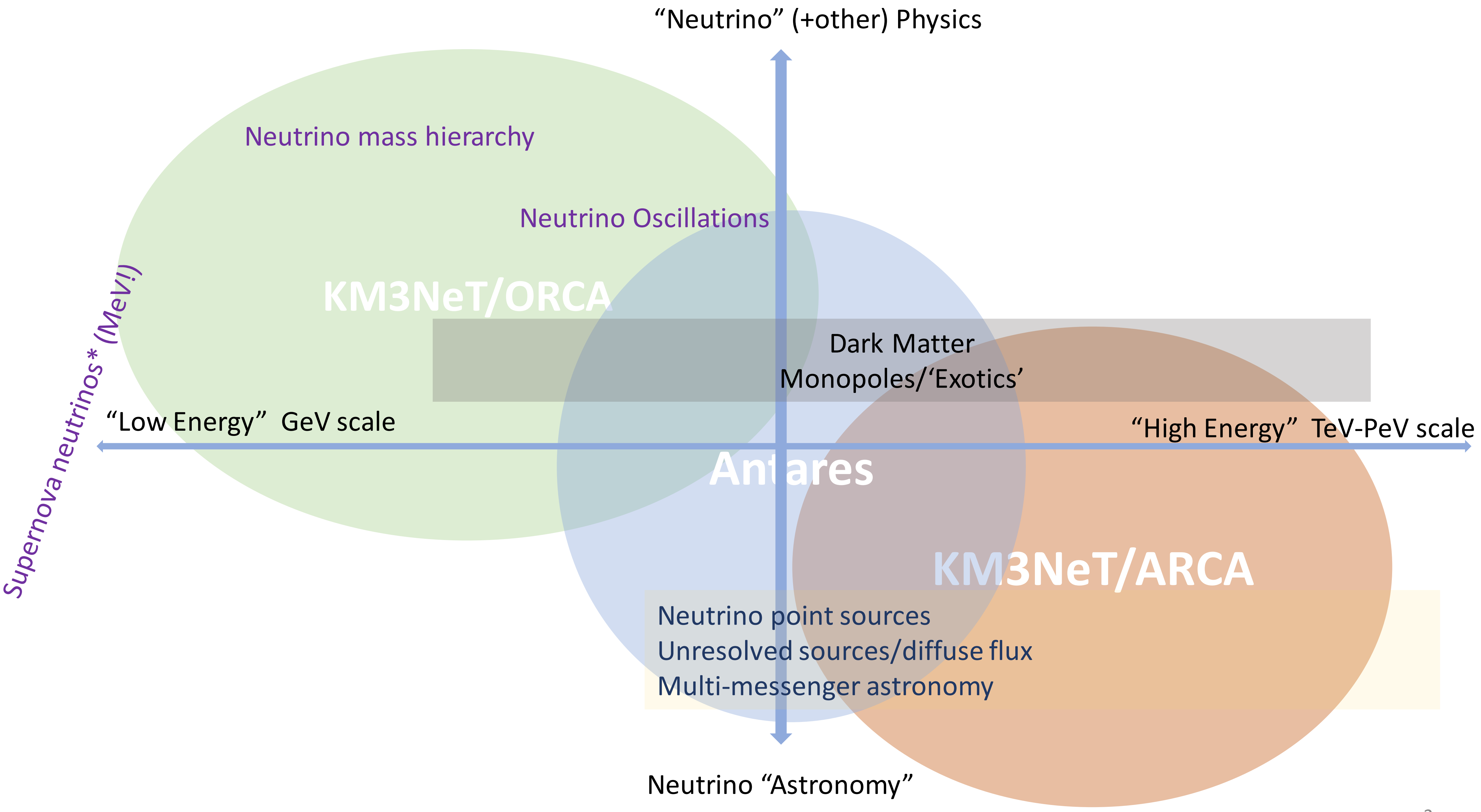
Results and status of the ANTARES and KM3NeT neutrino telescopes

ECRS

Nijmegen, 2022

Ronald Bruijn
Universiteit van Amsterdam & Nikhef
for the Antares & KM3NeT Collaborations



“Neutrino” (+other) Physics
Neutrino mass hierarchy
Neutrino Oscillations
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
Neutrino “Astronomy”

*: ORCA & ARCA

Large Volume Neutrino Telescopes

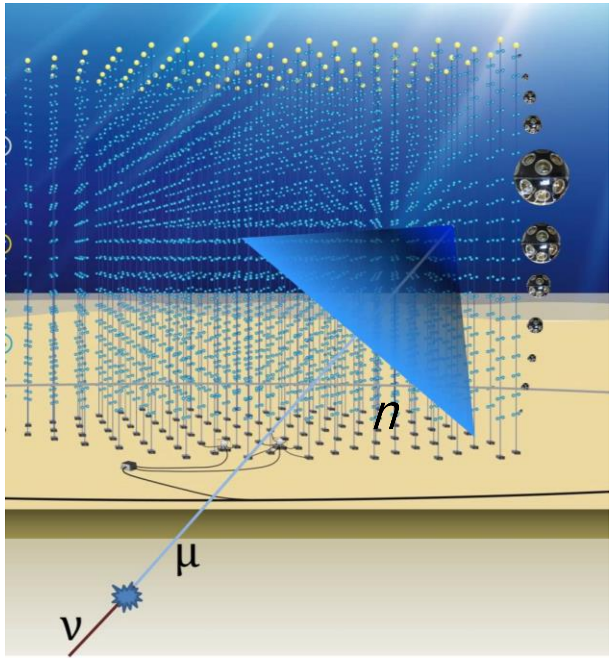
Cherenkov light from the charged products of neutrino interactions in sea-water are detected by a sparse array of photo-multiplier tubes

Two *general* event types:

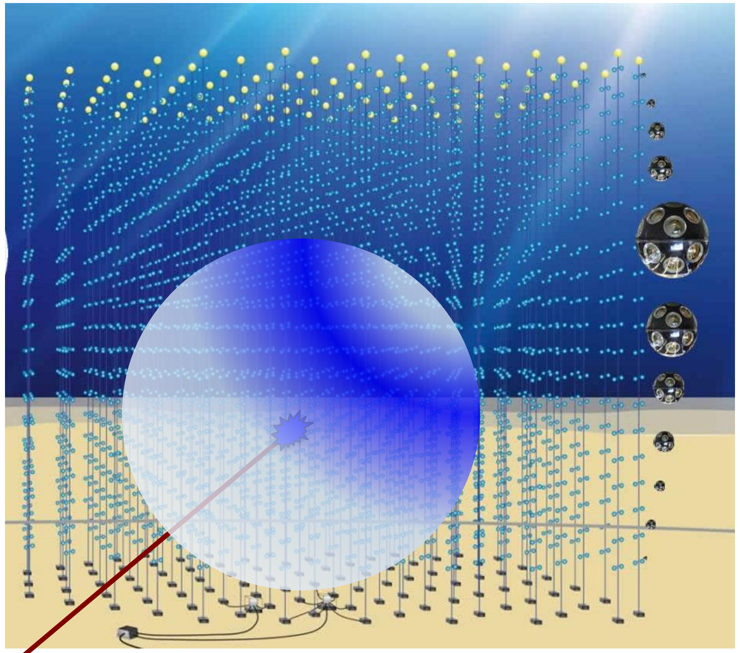
Tracks - Charged current (CC) υ_μ interaction
- Cosmic Ray muons

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

'Track'



'Shower'



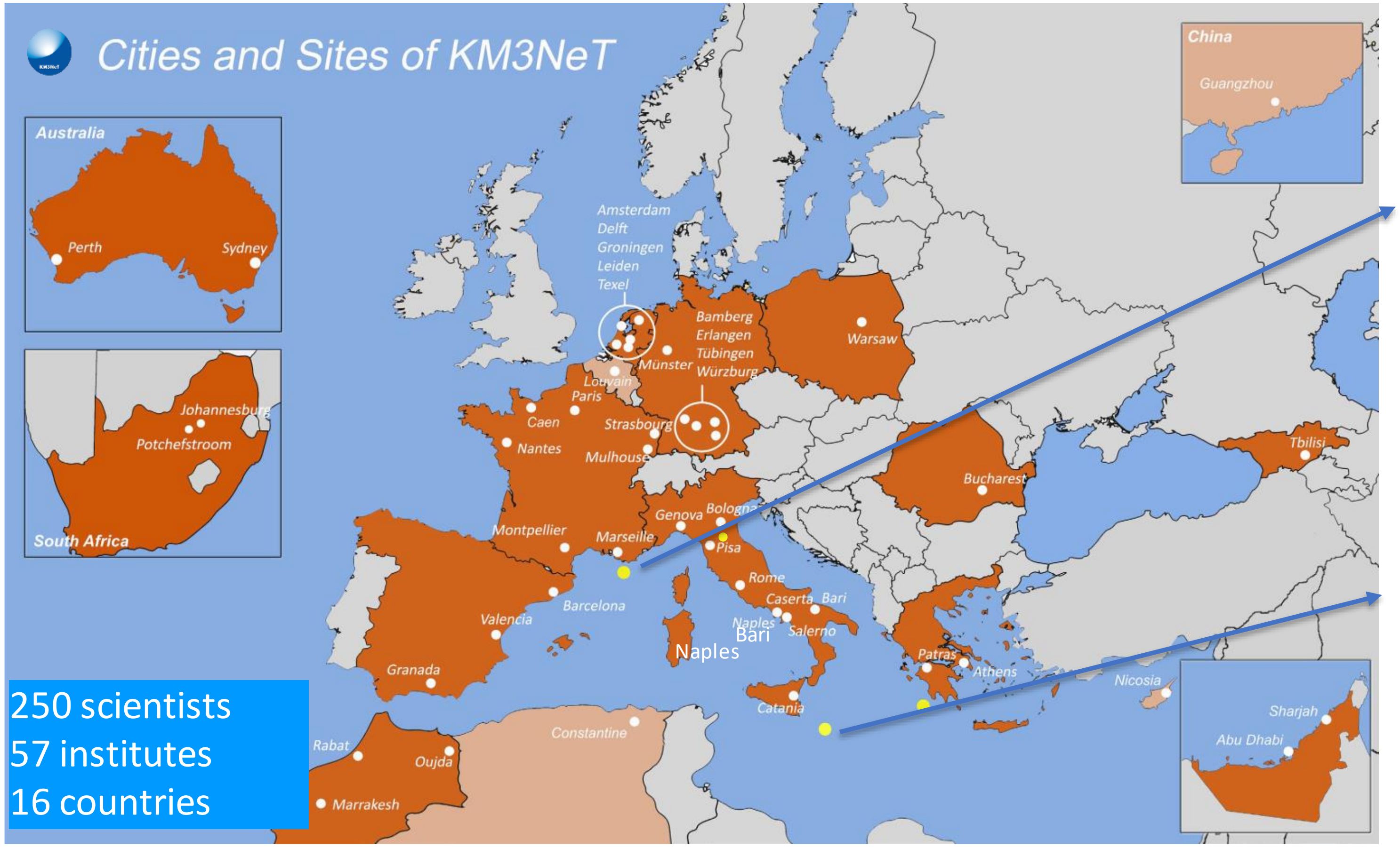
Sea-bed: ~2.5 to 3.5 km deep (Antares & KM3NeT)

ANTARES

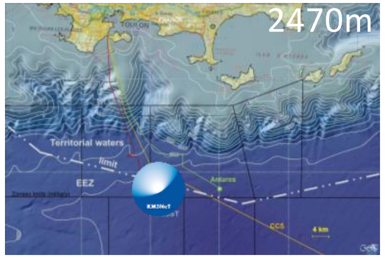
- Deep-Sea Cherenkov telescope :
  - Detect light from charged products of neutrino interactions
- 2.5 km deep, 40 km off-shore of Toulon, France
- 12 Vertical lines, each is 350 m high
- 25 storeys of 3 10” photomultiplier tubes per line
- 10 Mton instrumented volume
- First line deployed 2006, construction completed 2008
- Decommissioned May 2022

KM3NeT

- Multi-site, deep sea neutrino telescope
- Selected by ESFRI roadmap
- Single collaboration
- Single technology



[KM3NeT 2.0: Letter of Intent](#)
J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001



Oscillation **R**esearch
with **C**osmics **I**n the **A**byss

Astro**p**article **R**esearch
with **C**osmics **I**n the **A**byss

Connection nodes of european multidisciplinary seafloor & water column observatory emso

ORCA :
115 Detection Units
7 Mtonne
2.5 km deep,

ARCA:
330 (2x115) Detection Units
1 GTonne
3.5 km deep,

Digital Optical Modules

31 3” PMTs in 17” sphere
+ electronics etc.
- Photon counting
- Directionality
- Cheap(er)

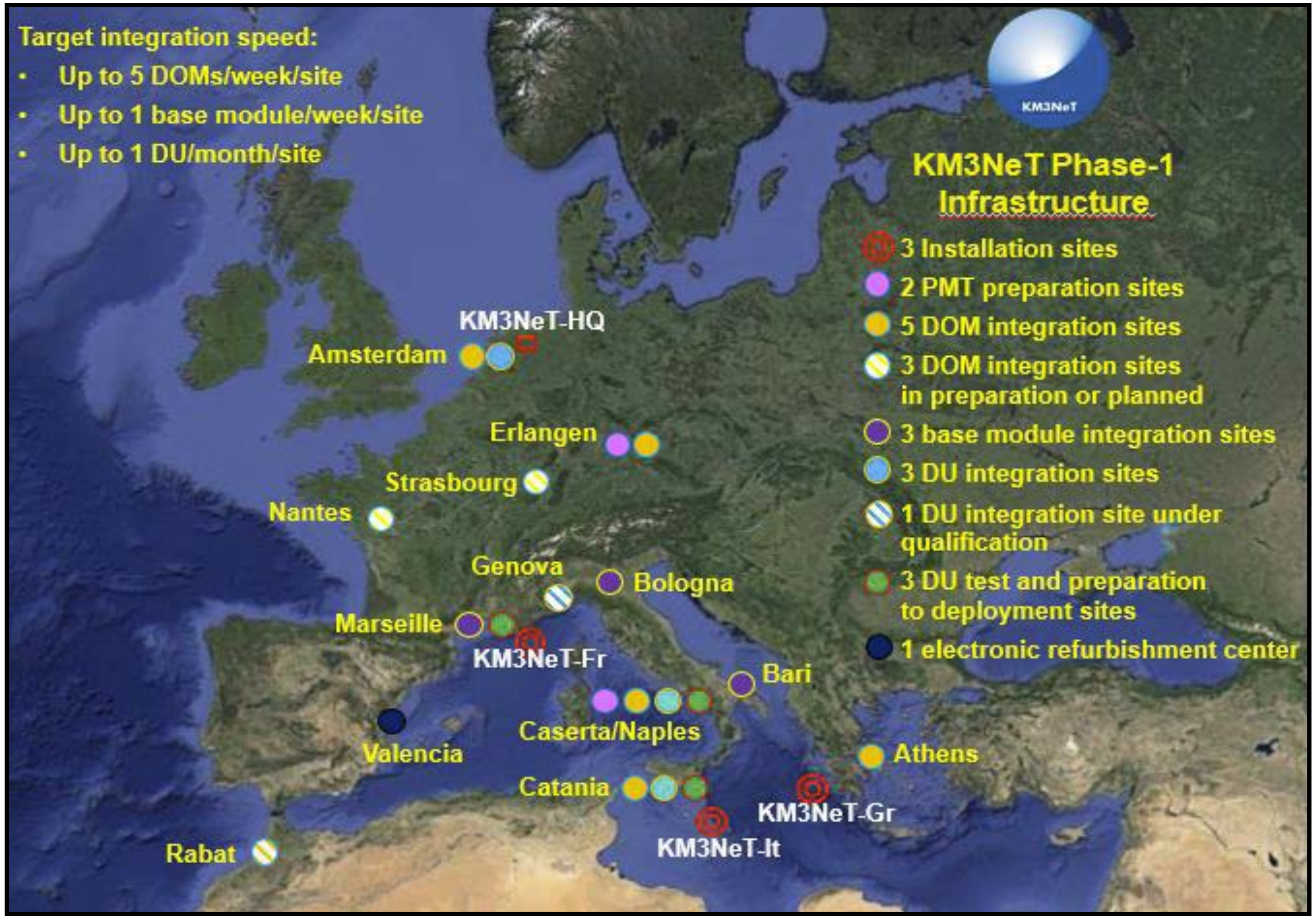
Detection Units:

18 optical modules per detection unit
9m (ORCA)/38m (ARCA) between optical modules

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

Construction & Current Status



Distributed Integration, many institutes participating

ARCA :
Last month 11 DUs were added and currently 19 DUs operational

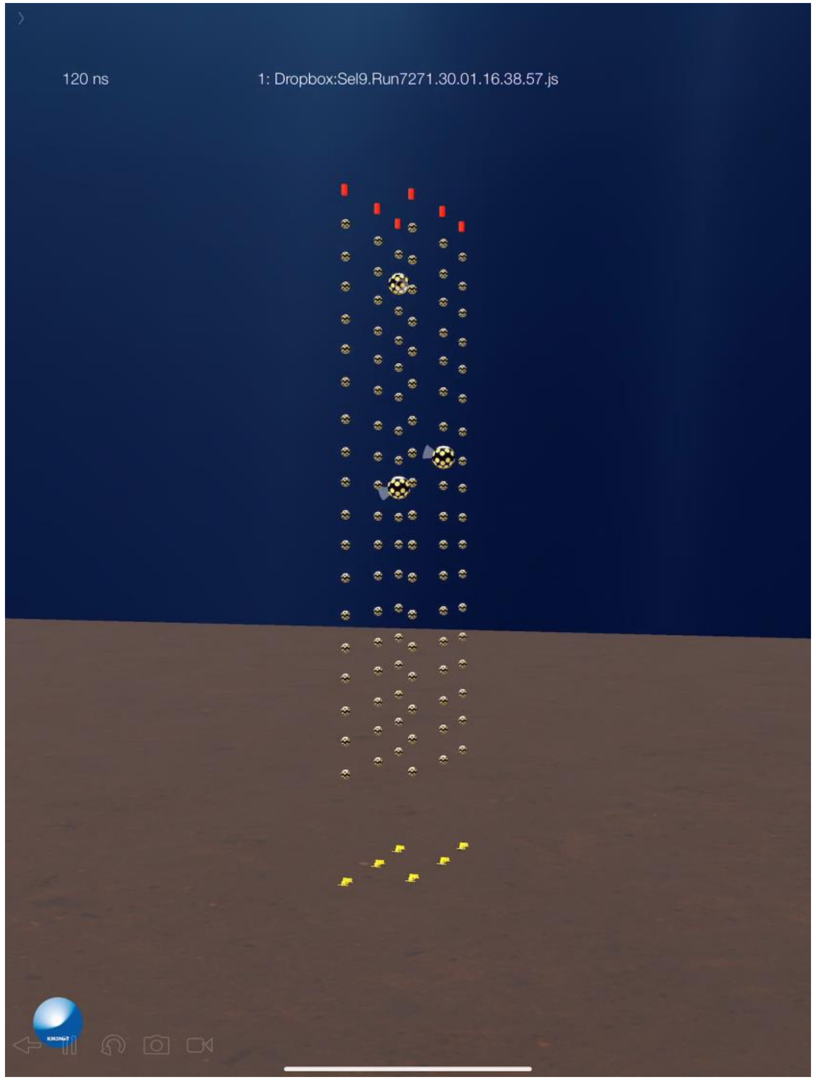
ORCA:
Currently 10 DUs operational

Dynamic recent history (some DU recoveries and deployments)

Next sea-operations in September
ARCA : ~4 DUs + infrastructure
ORCA : 4 DUs + infrastructure

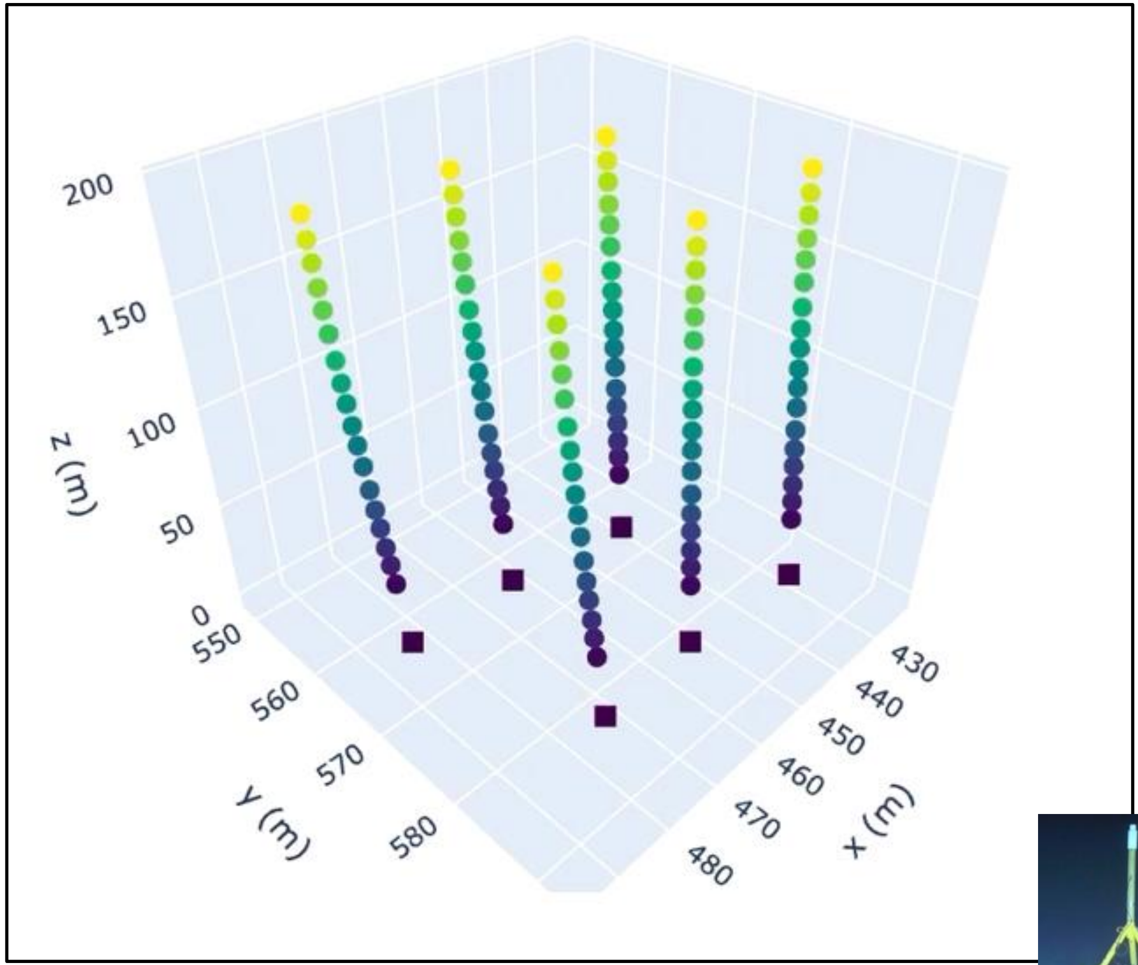
Note: e.g. ‘ORCA 6’ indicates a configuration of ORCA with 6 DUs

ARCA 6 downgoing event

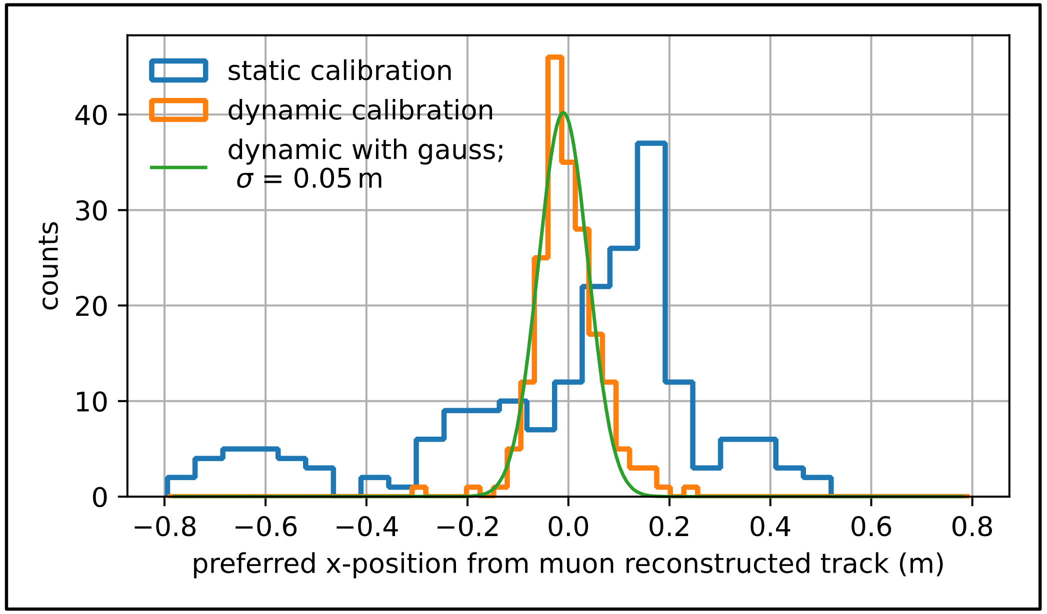


ORCA 6 upgoing event

Calibration / Alignment



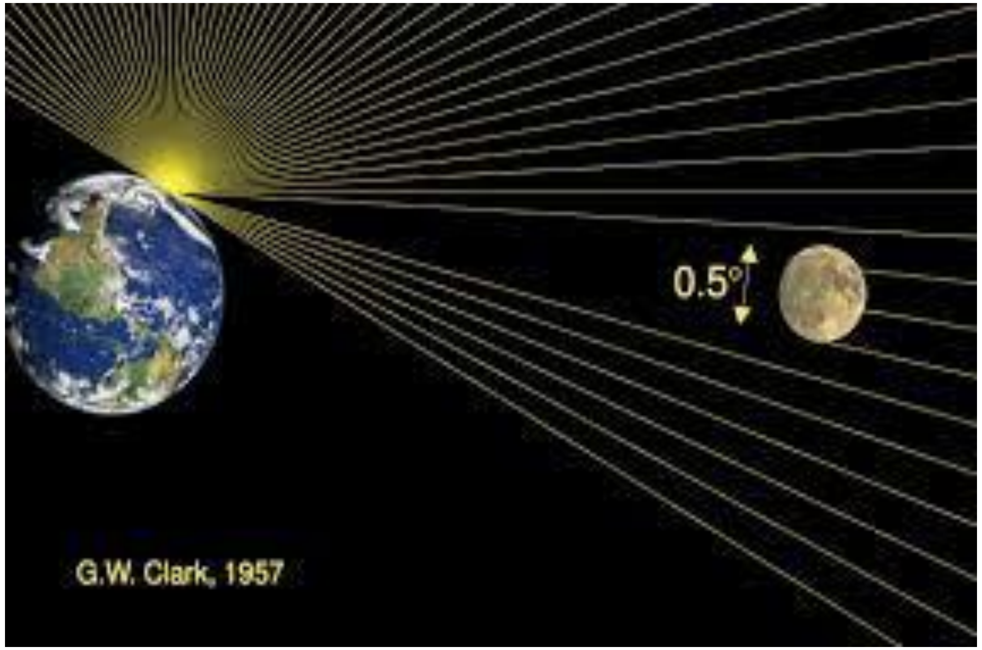
- Acoustic system for dynamic alignment
- Precision O(10 **cm)**
- Checked with muons

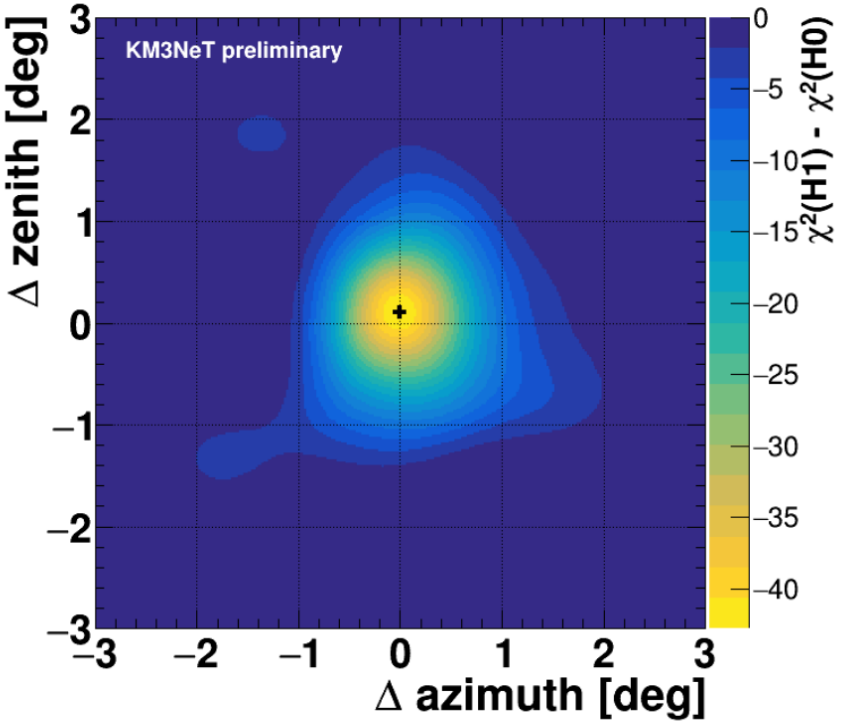


Acoustic beacon

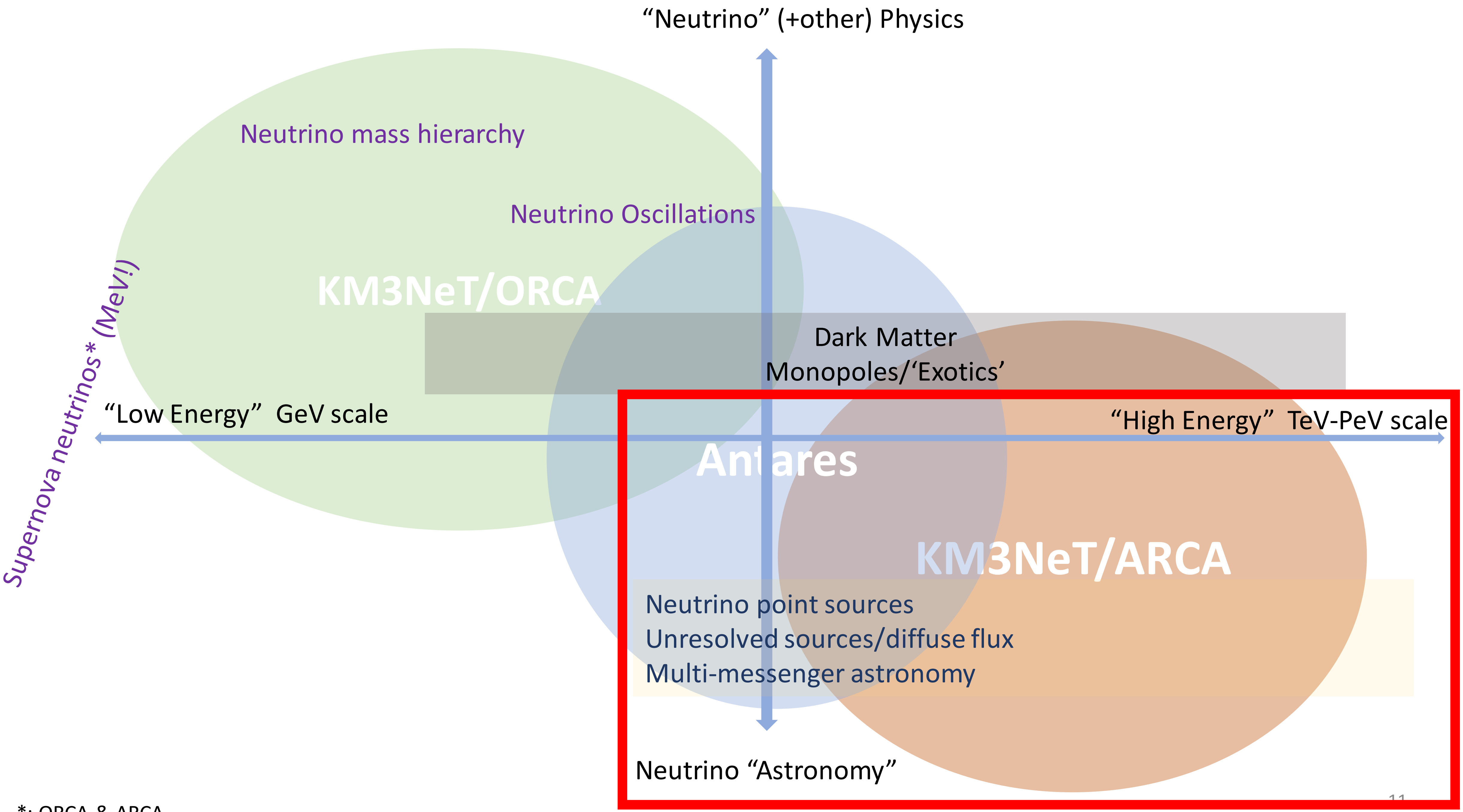
Checking resolution / alignment

- No standard candle source
- Cosmic rays to the rescue





	Sun	Moon
Significance	6.2 σ	4.2 σ
Amplitude	1.31±0.34,	0.71 ± 0.27
Resolution	0.65° ± 0.13°	0.49° ± 0.15°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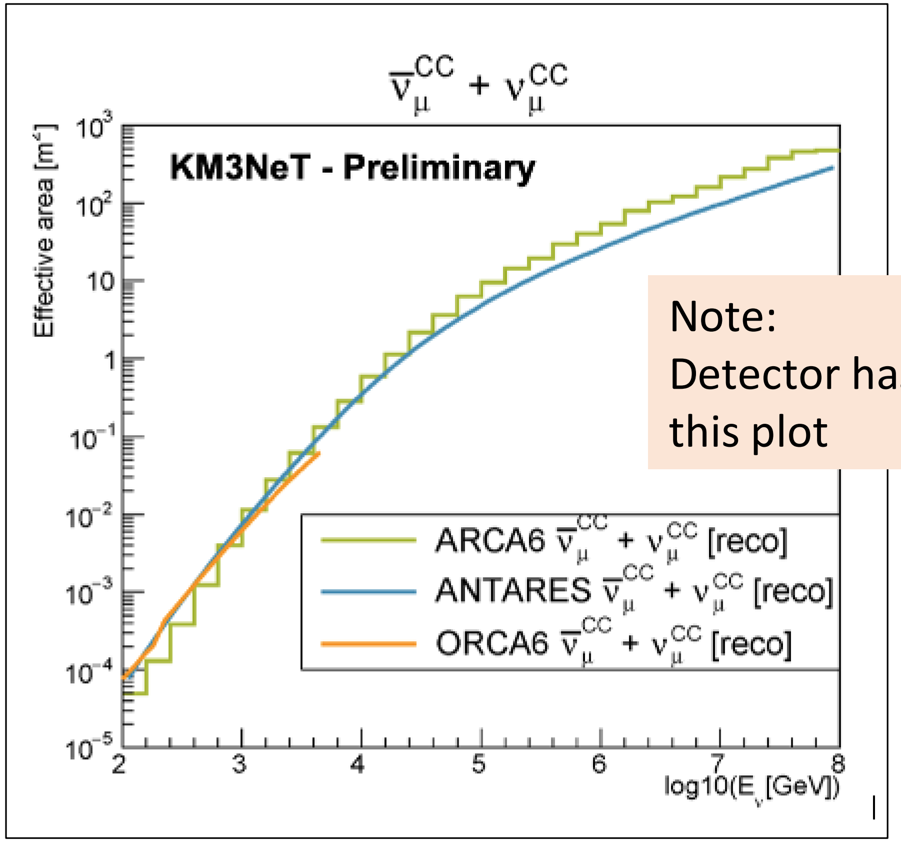
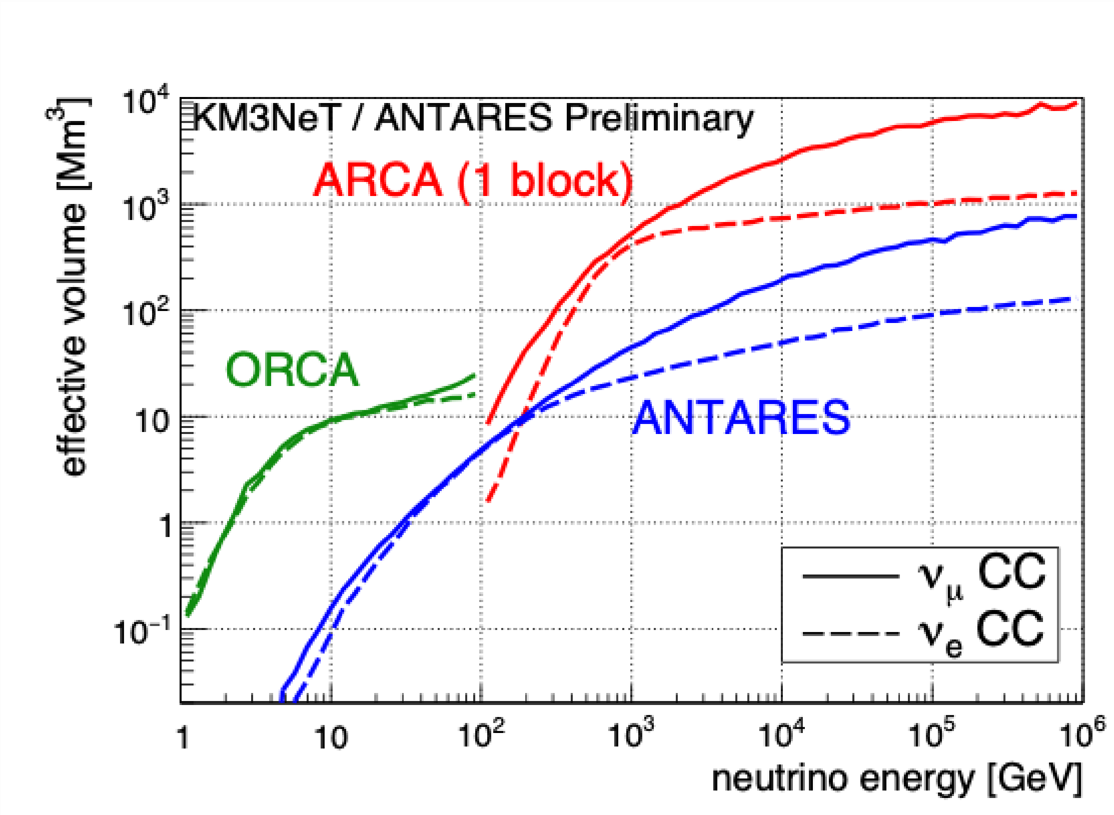
Neutrino Astronomy

KM3NeT has currently about the same acceptance as Antares

…. but Antares has about 40 times the livetime at the moment



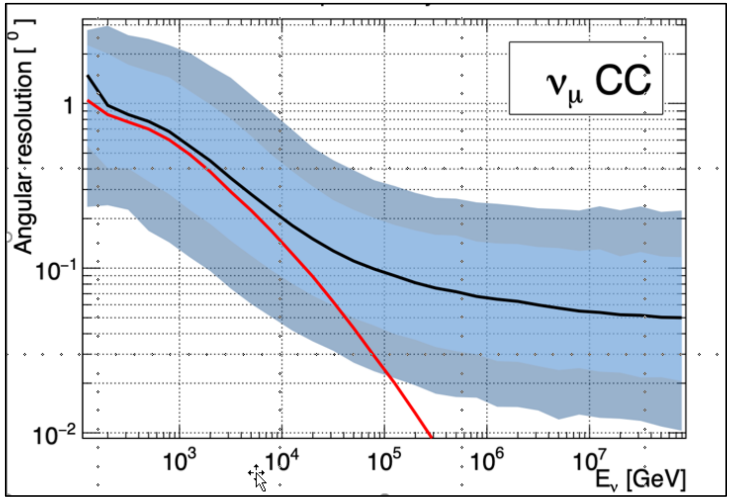
Note:
Detector has grown since this plot



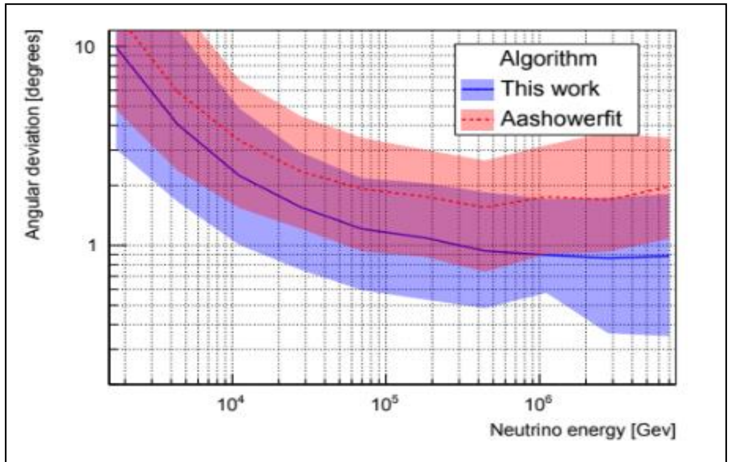
Effective volumes for complete detectors

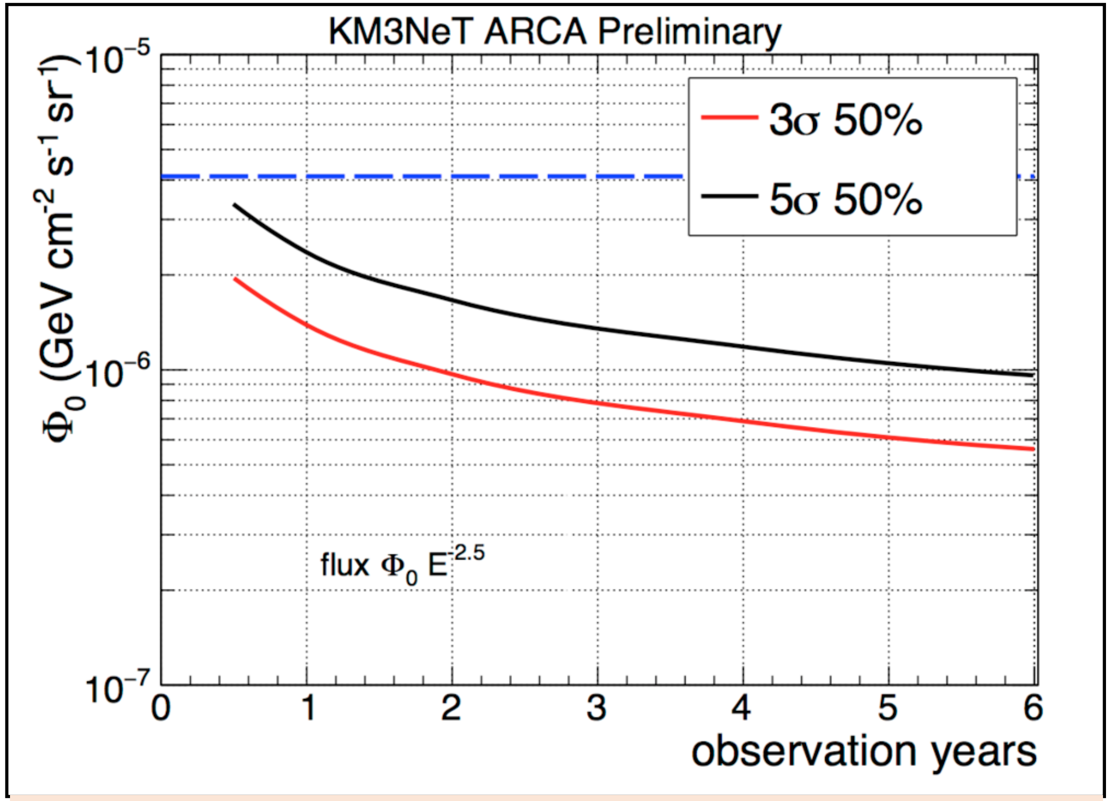
Neutrino Astronomy

Track angular resolution



Cascade angular resolution



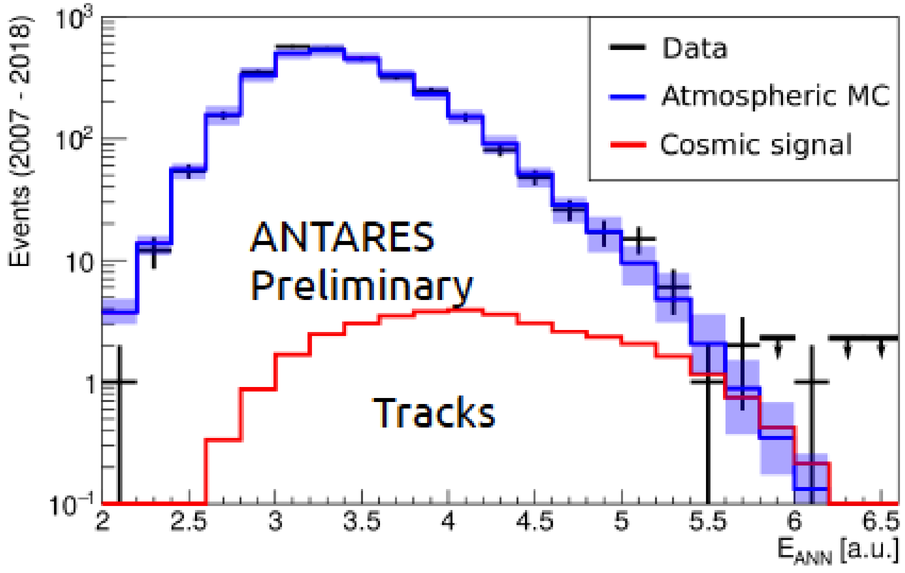


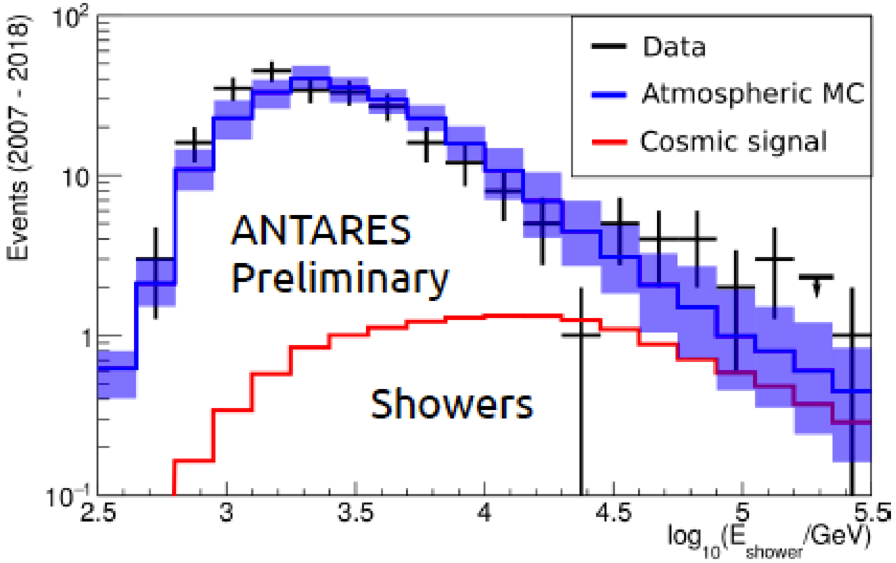
ARCA can confirm IceCube flux within 1 year of data

Diffuse (Cosmic) flux

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

ANTARES 2007-2018 (3330 days)





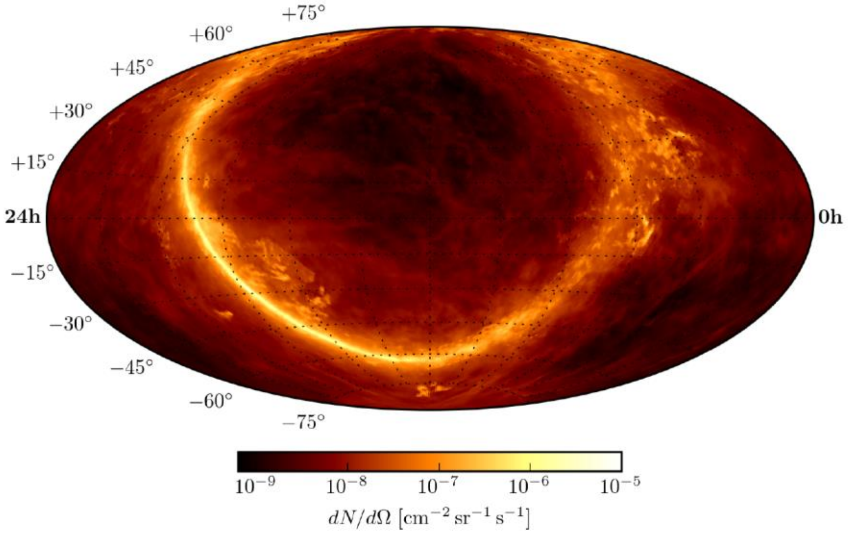
Data: 50 events (27 tracks + 23 showers)

Background expectation : 36.1 ± 8.7 (19.9 tracks and 16.2 showers) – stat. + syst.

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

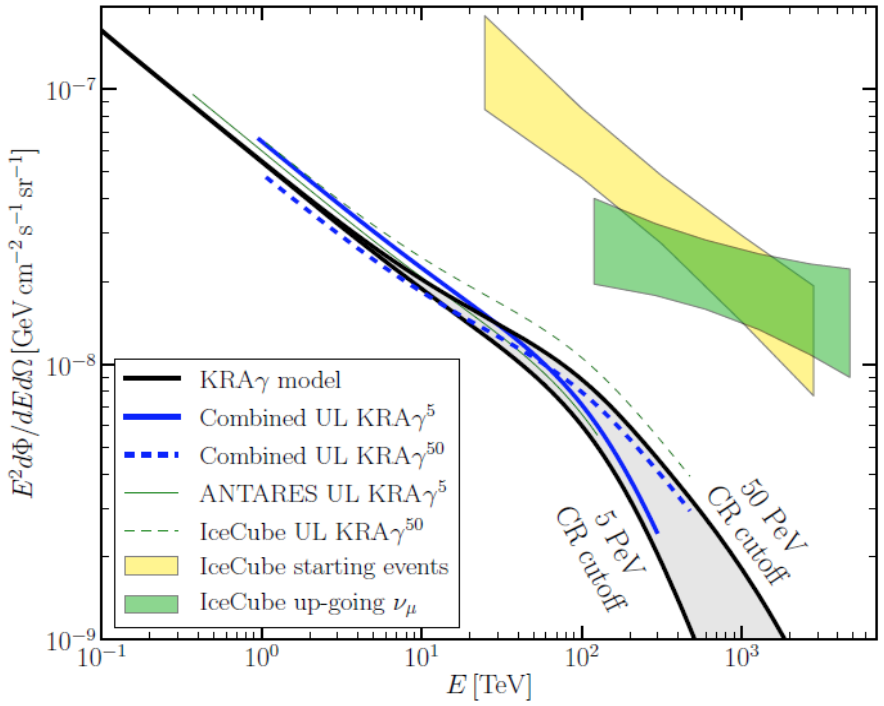
Galactic Plane

Neutrinos from interactions of cosmic rays with galactic matter



Analysis uses full model morphology & spectrum – tracks and cascades

ANTARES Limit is a factor 1.2 above the 'KRAγ' model.



ApJL 868, L20 (2018)

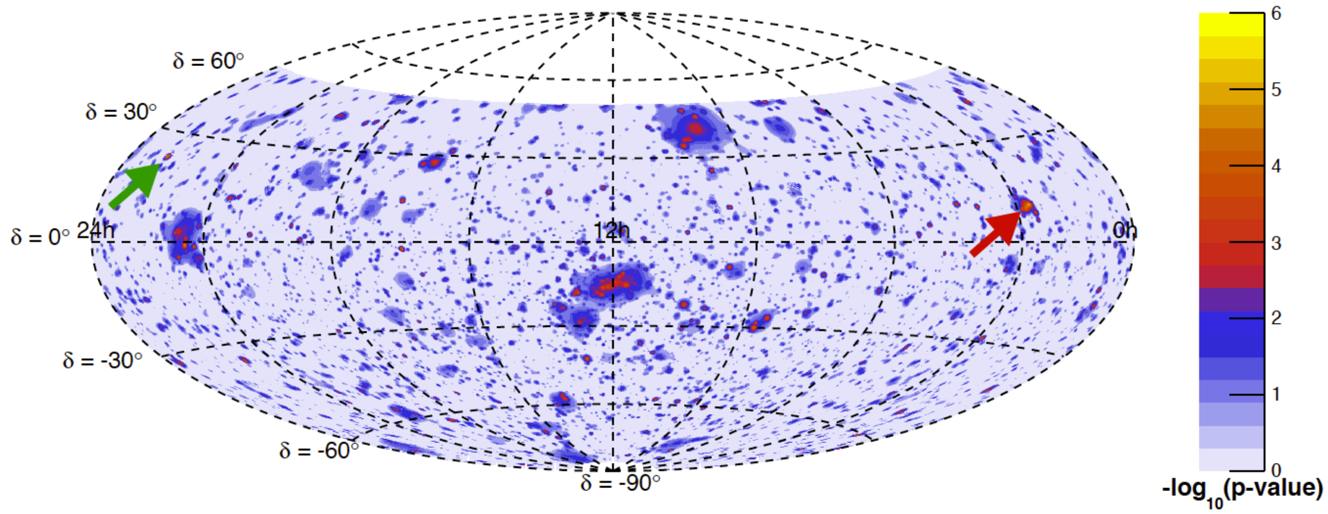
KM3NeT/ARCA :
100 days of ARCA 6 no significant signal (as expected)

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

Point Source Searches

ANTARES 13 years (3845 days of live time): 10162 tracks and 225 showers

Full sky search

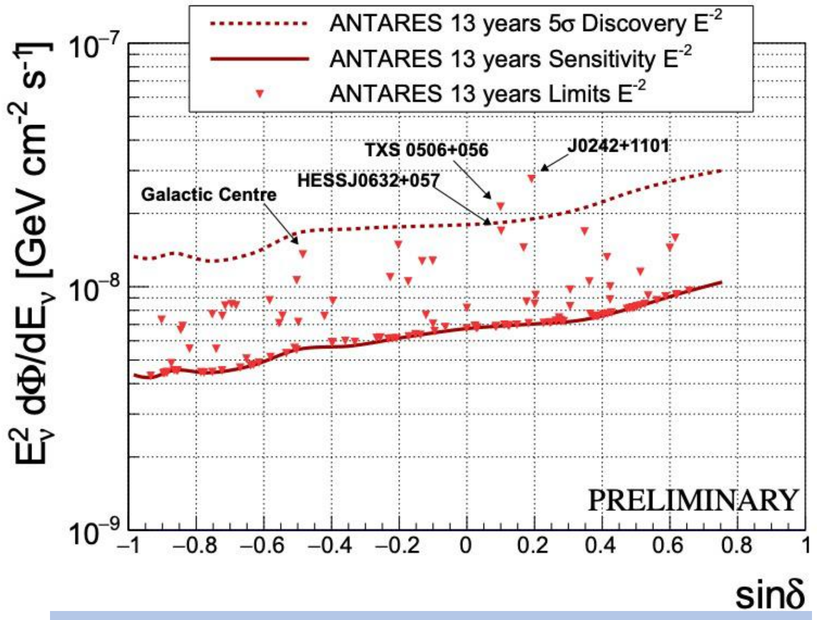


The most significant cluster:
RA=39.6° δ=+11.1°
pre trial: 4.3 σ (48% post)
Within 1 degree of J0242+1101

2nd most significant cluster:
RA=343.8° δ=+23.5°
pre trial: 4.2 σ
Close to blazar MG3 J225517+2409

Both are close to IceCube HE tracks

Catalog search : 121 candidates



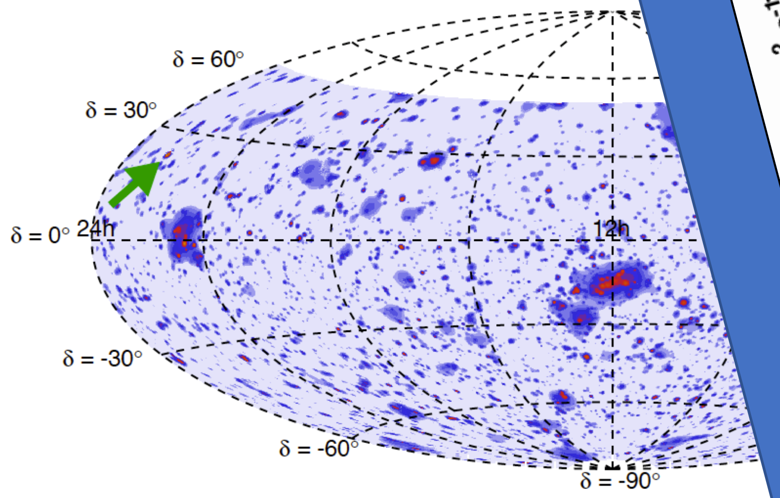
Most significant source
Radio-bright blazar J0242+1101
Pre-trial: 3.8σ
Post-trial: 2.4σ

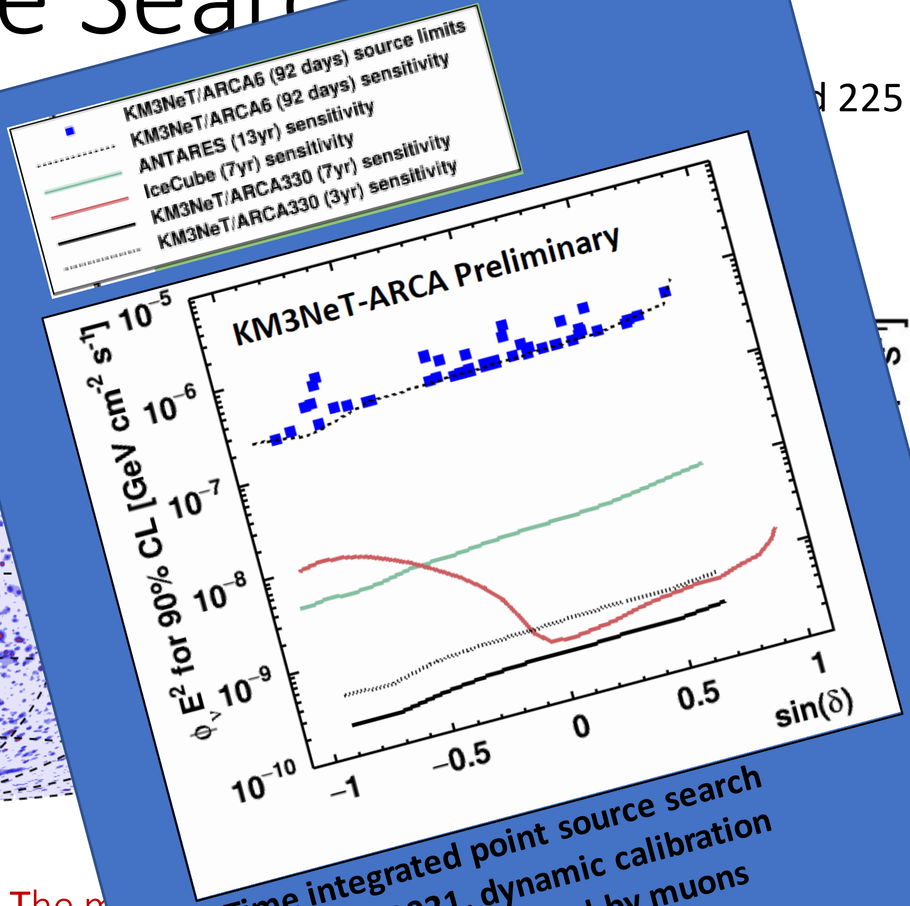
Point Source Searc

ANTARES 13 ... d 225 showers

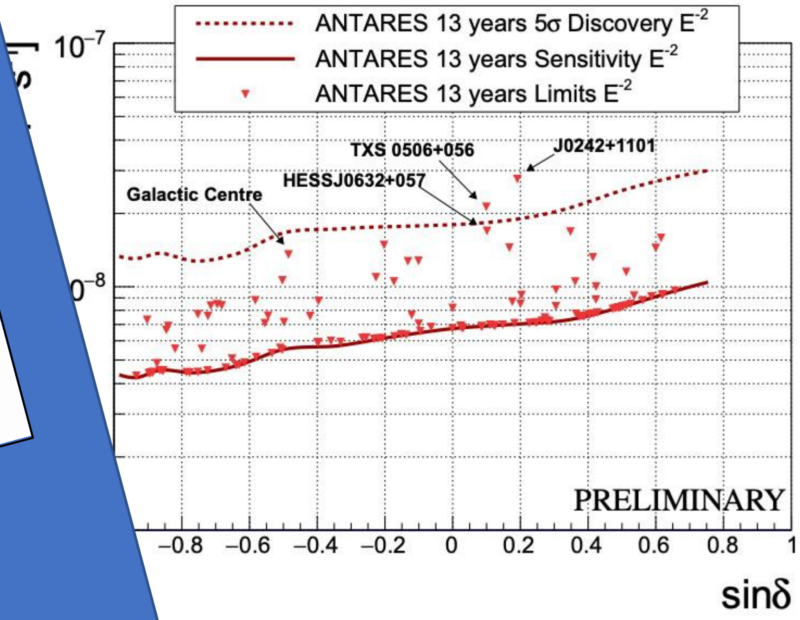
Full sky sear

Catalog search : 121 candidates





- Time integrated point source search
- May-Sept 2021, dynamic calibration
- Background dominated by muons
- Resolution ~1.3 degree for E^{-2}
- No significant excess observed
- Limits not yet competitive, as expected



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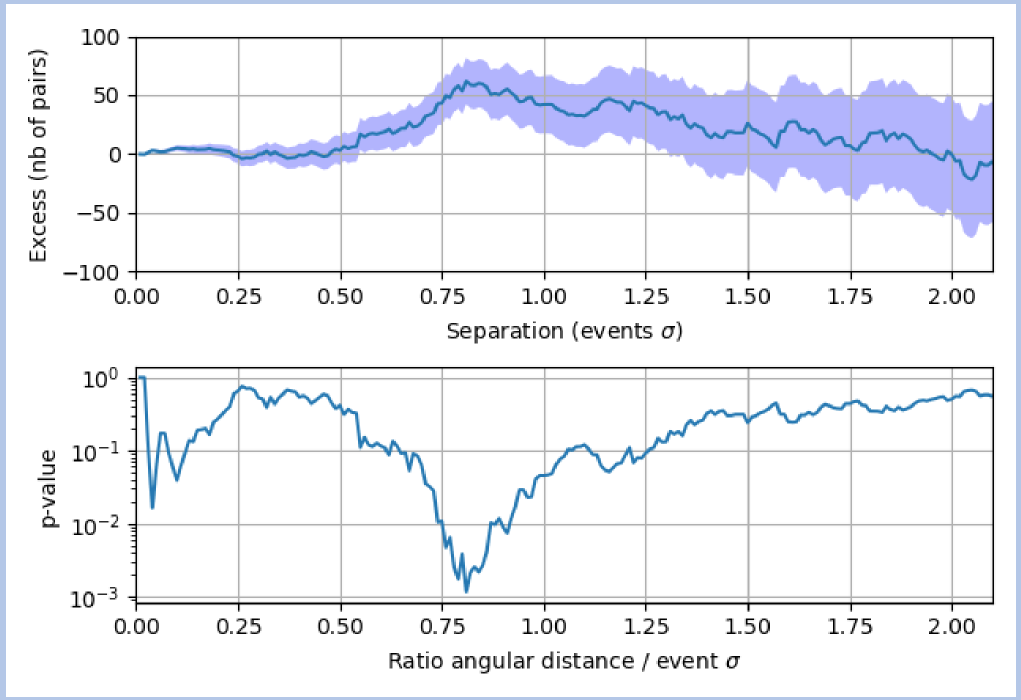
The m
RA=39
pre tria
Within 1

...significant source
Radio-bright blazar J0242+1101
Pre-trial: 3.8σ
Post-trial: 2.4σ

Both

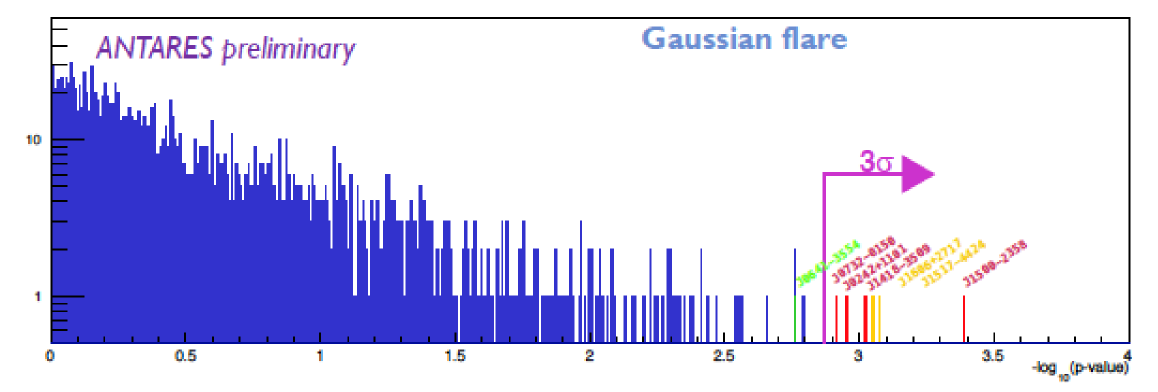
Blazars

Search for correlation between neutrino candidates and radio blazars in VLBI data (2774 objects), inspired by A. V. Plavin et al, 2021 ApJ 908 157



Antares point-source sample (2007-2020/10162 tracks)
Pair counting shows indication of neutrino-blazar excess at sub-degree angular scale

Time-dependent un-binned likelihood search results in a few with >3 sigma pre-trial



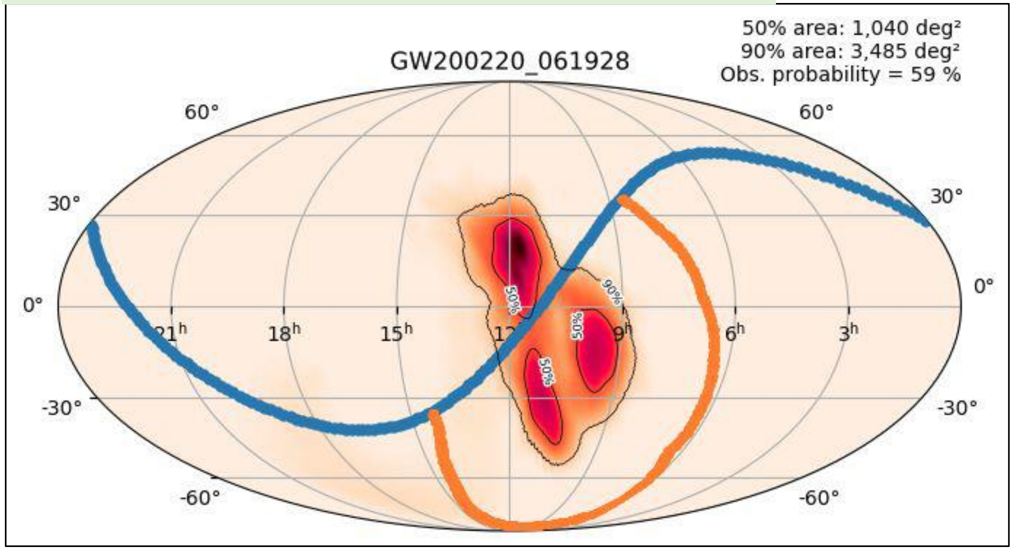
J1500-2358 (overlapping radio, gamma flaring)
J1517-4424
J1606+2717
J1418-3509
J0242+1101 (most significant in catalog search)
J0732-0150
J0641-3554

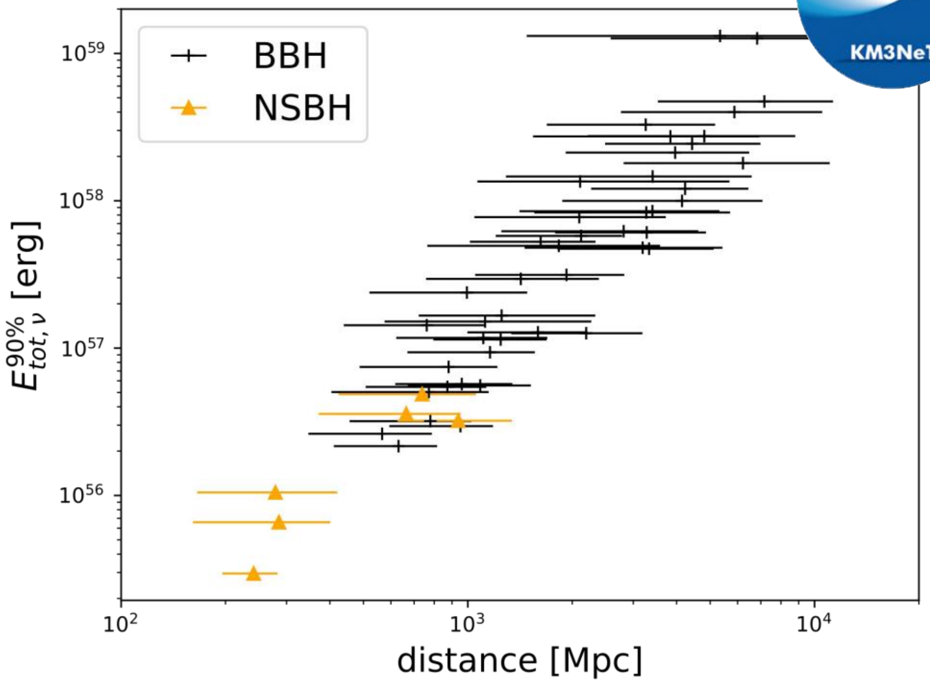
Gravitational Wave follow-up

Search for spatial and temporal coincidences with GW events (O3)

Antares and ORCA analyses (no neutrino counterpart found)

ORCA4/6 :
+- 500 s around events
90% confidence region + 30 degrees
ON/OFF method





Limits on $\phi = E^2 dn/dE$		
(all-flavour, *E^{-2} spectrum)*	**ORCA4**	**ORCA6**
Limits [GeV/cm²]	100-500	50-200
5-95% neutrino energy range	70 GeV - 5 TeV	40 GeV - 5 TeV

Flux upper limits for 55 events set with ORCA4 and 6 data

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

First KM3NeT ATEL follow up (#15920)

Search for neutrino counterpart to the blazar PKS0735+178 potentially associated with IceCube-211208A and Baikal-GVD-211208A with the KM3NeT neutrino detectors.

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

Gamma rays:
Fermi, Hess, Magic

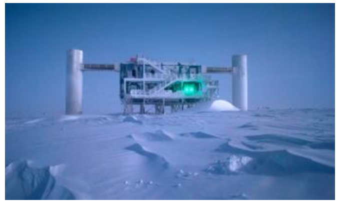
Neutrinos
IceCube

UHE Cosmic Rays
Auger, TA

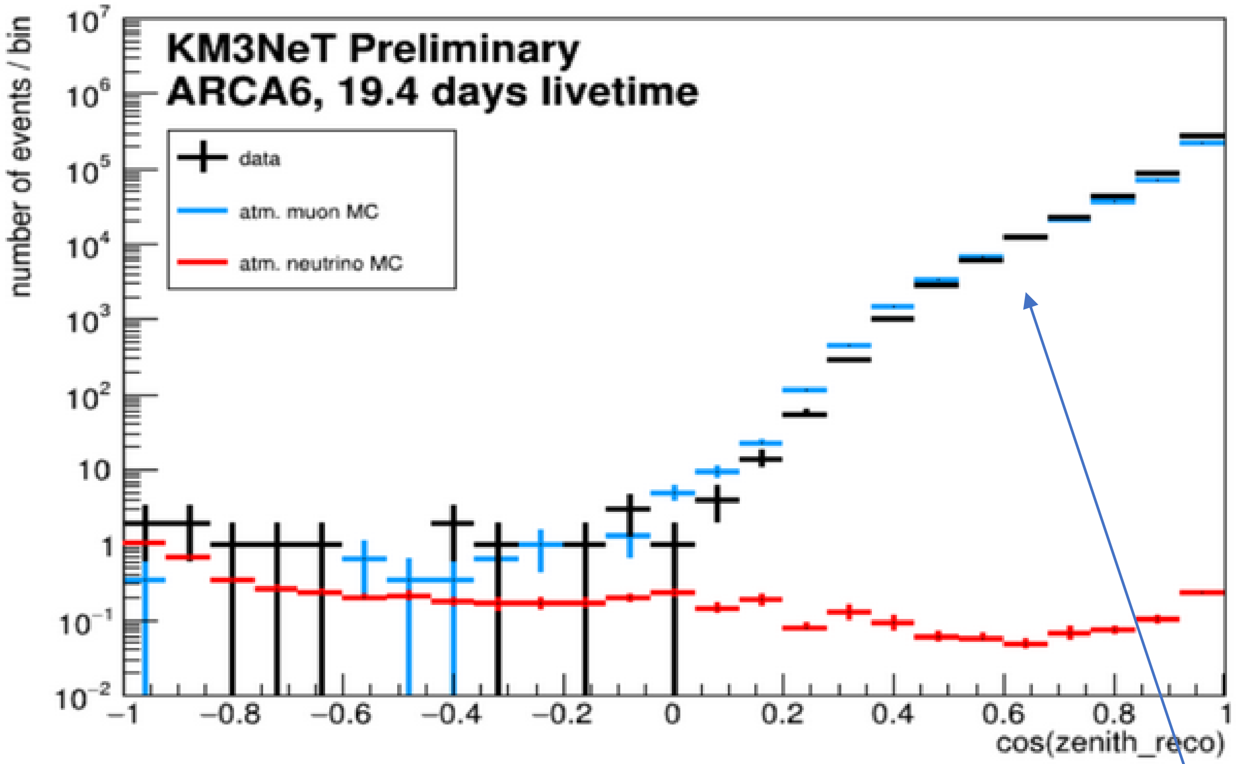
Gravitational Waves
Ligo/Virgo

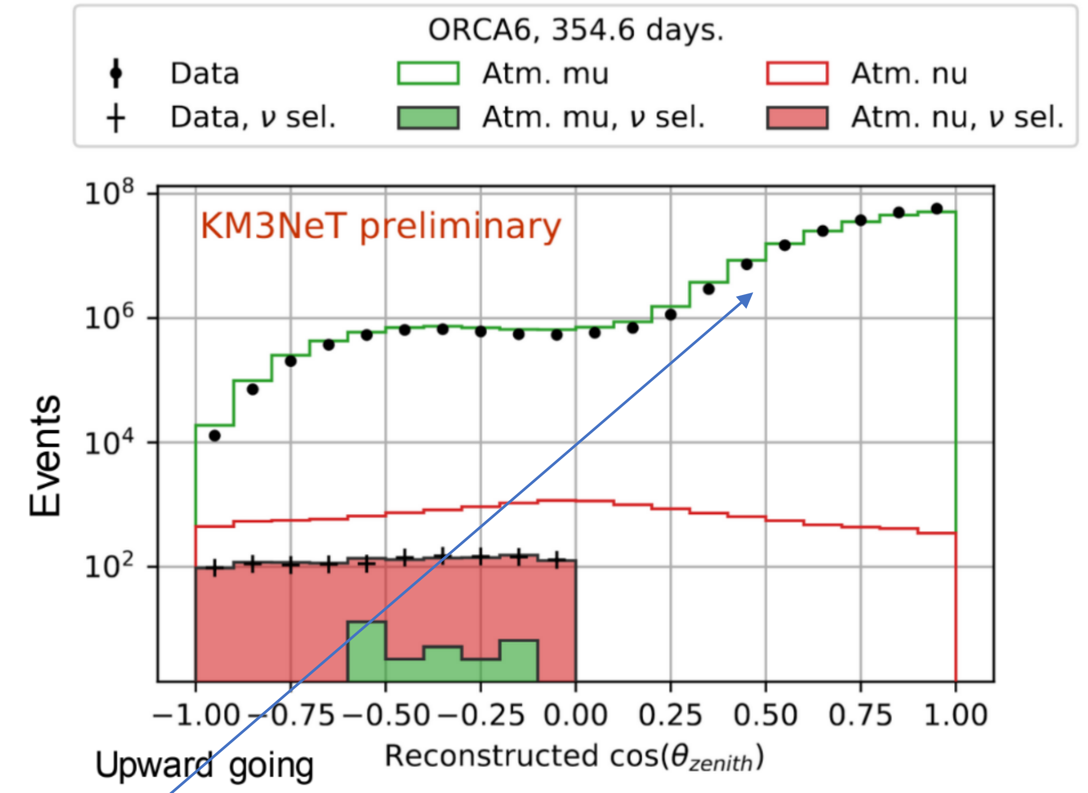






Cosmic Ray Physics

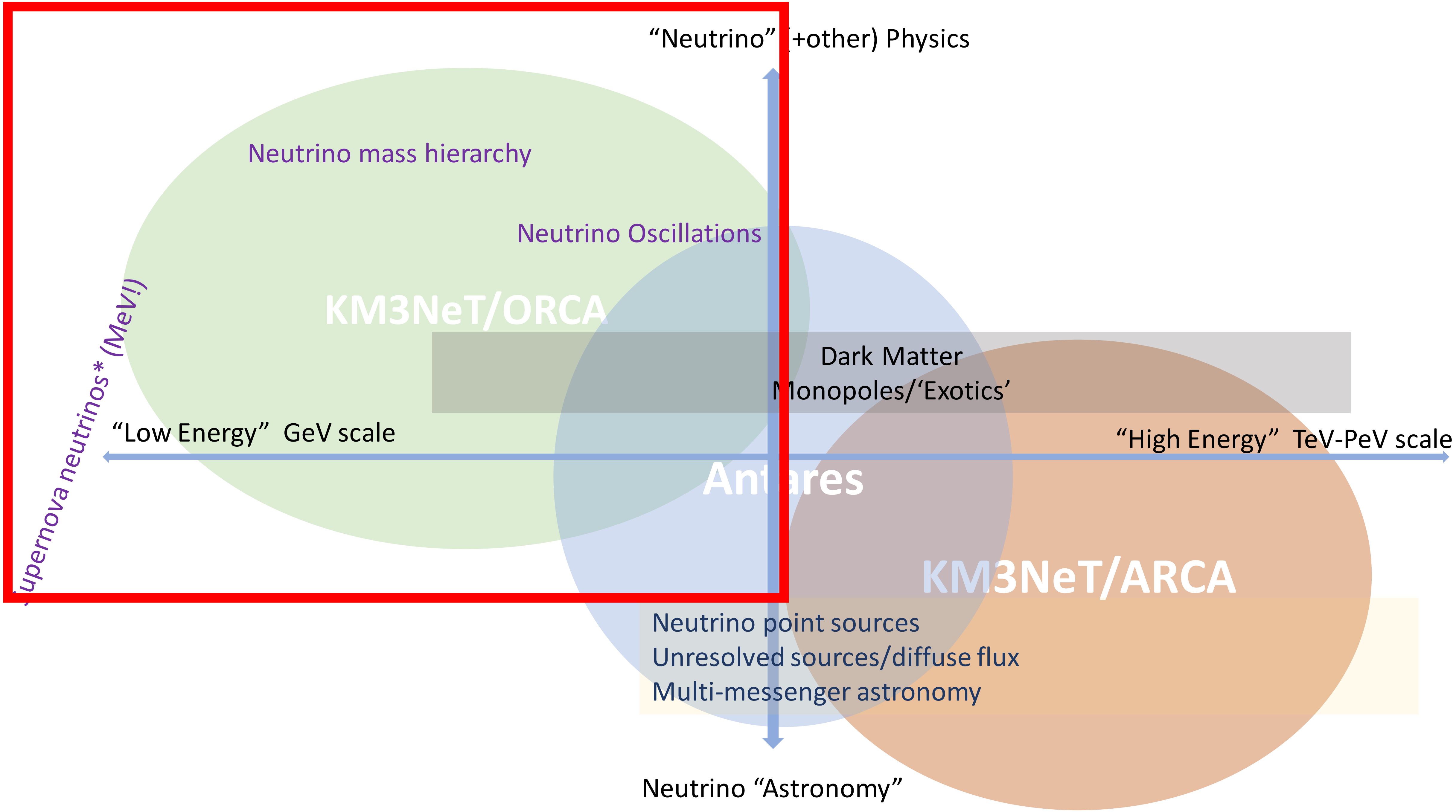




Data/MC differences -> Cosmic Ray Physics!!

Many more topics ….

- Dark matter, sensitivity
- Gamma-ray bursts
    - e.g. see A. Zegarelli last Monday
- Starburst Galaxies
- Monopoles, Nuclearites
- Combination with gamma-ray observatories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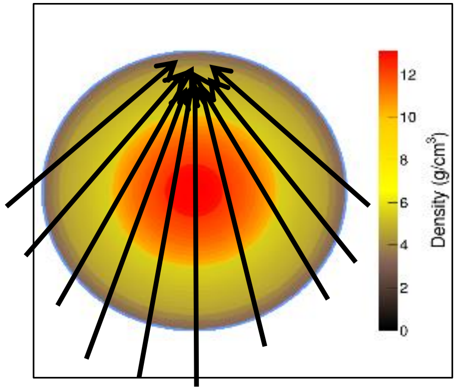
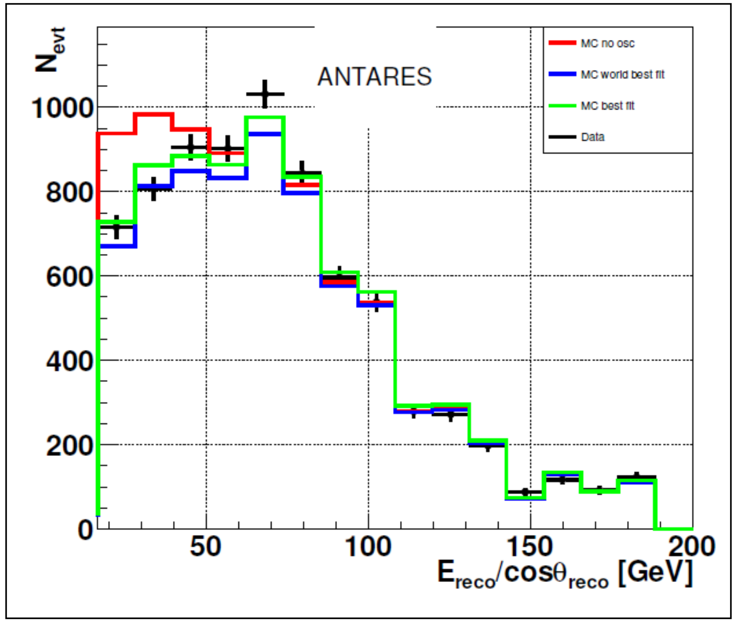
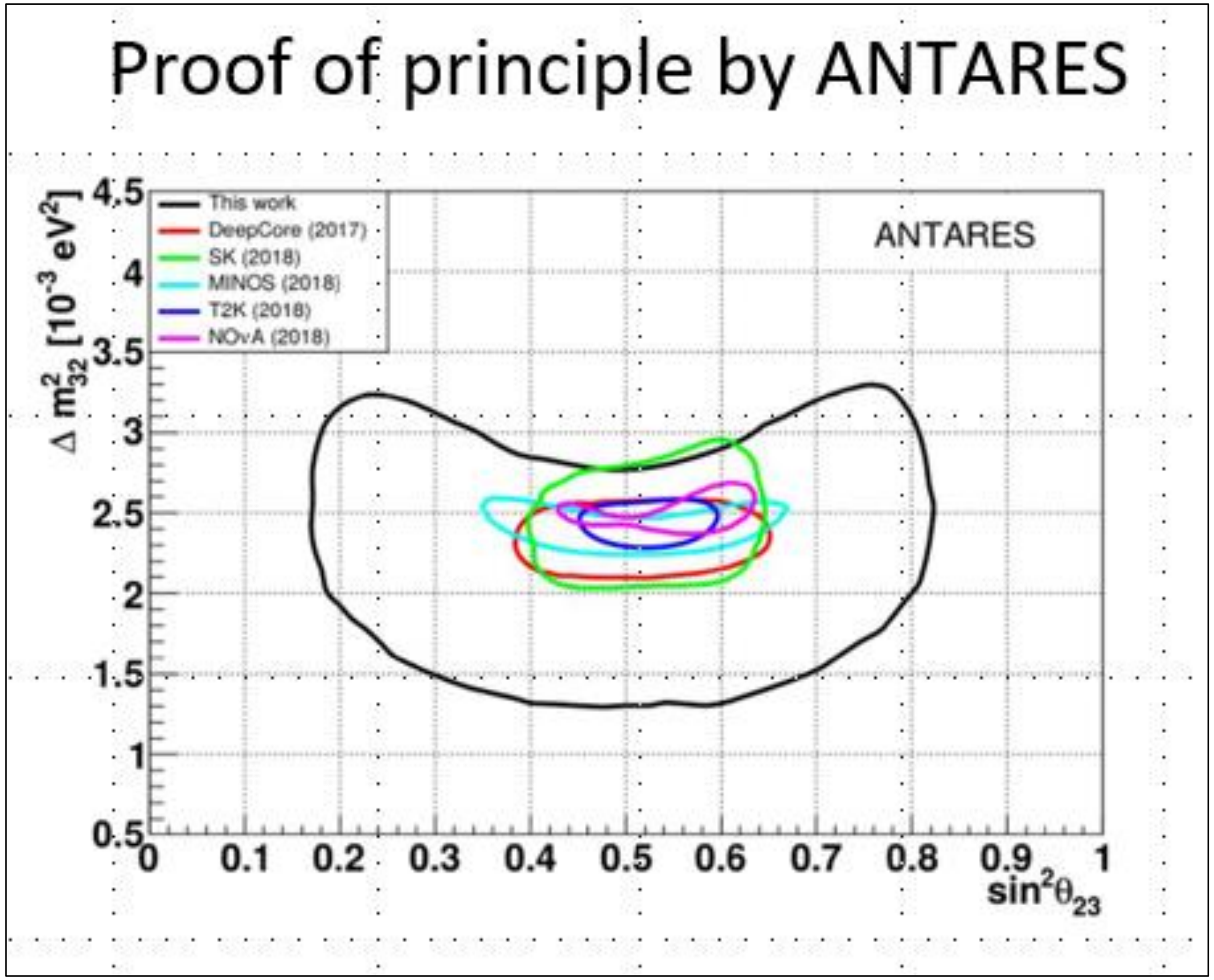
Neutrino Oscillation Physics

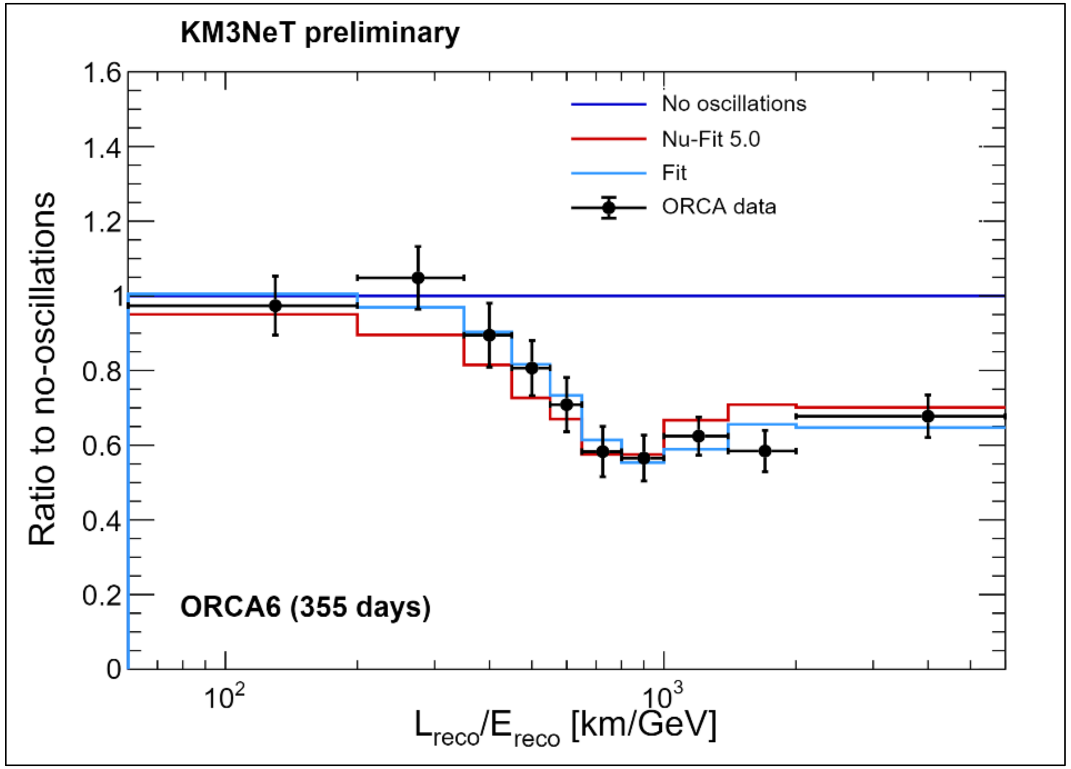


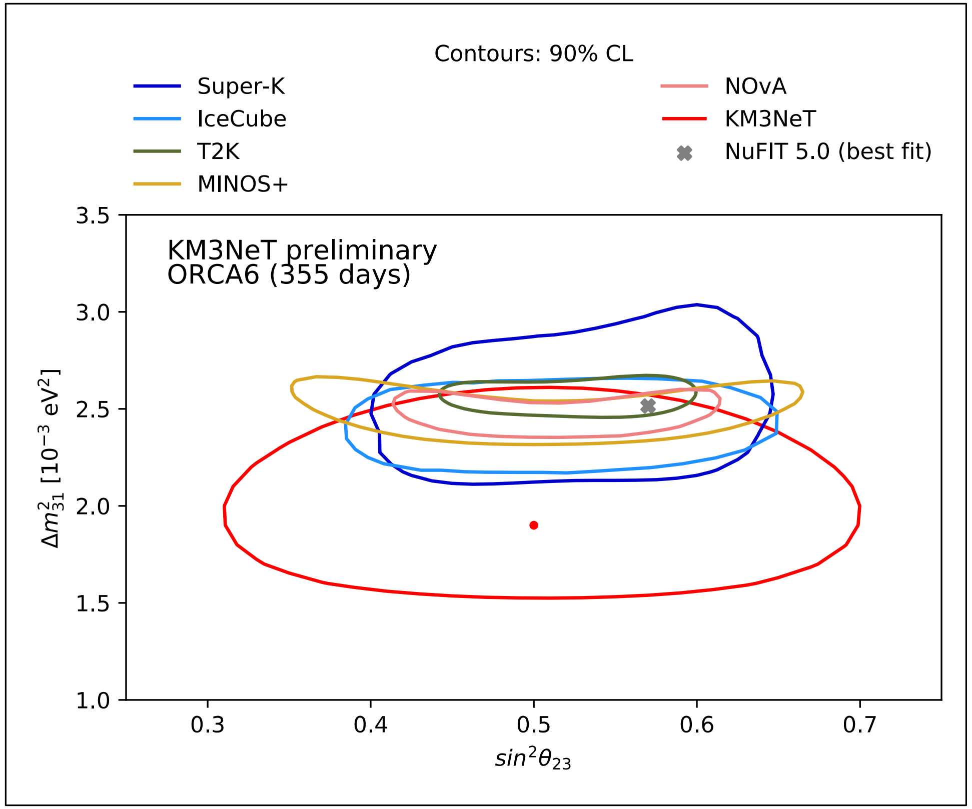




Program (ORCA)
- Measure atm. mixing parameters
- Neutrino Mass Ordering
- New physics (sterile, decay, NSI)

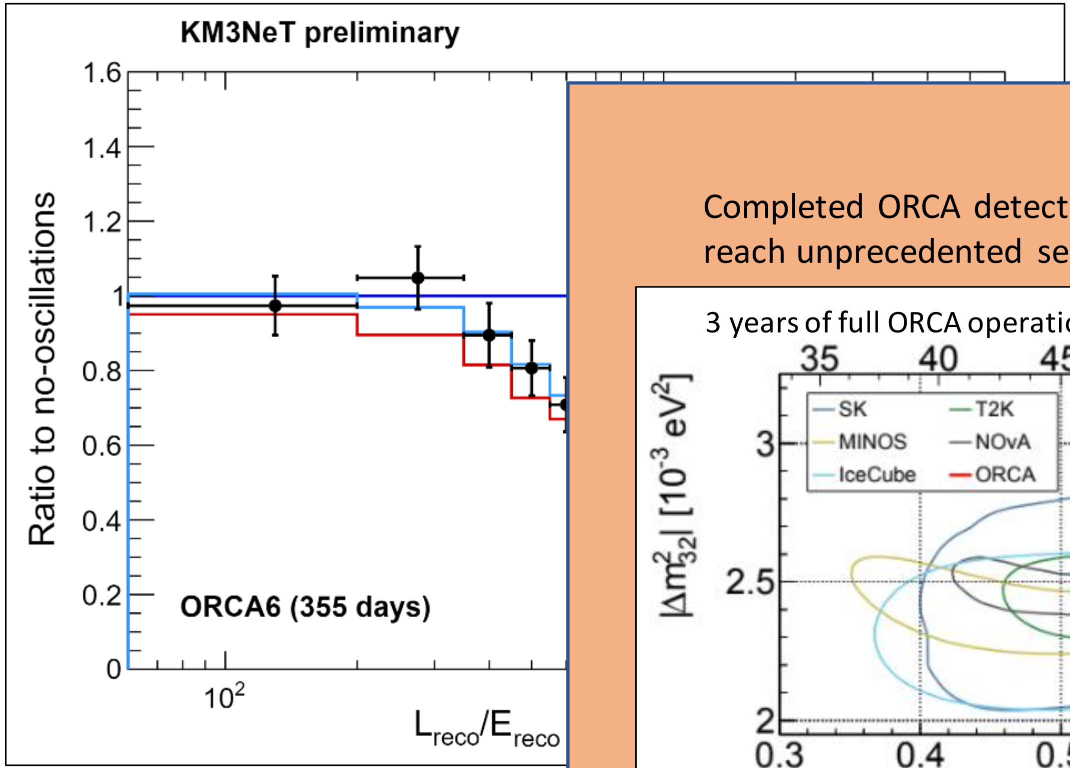
Neutrino Oscillation Physics: ORCA 6

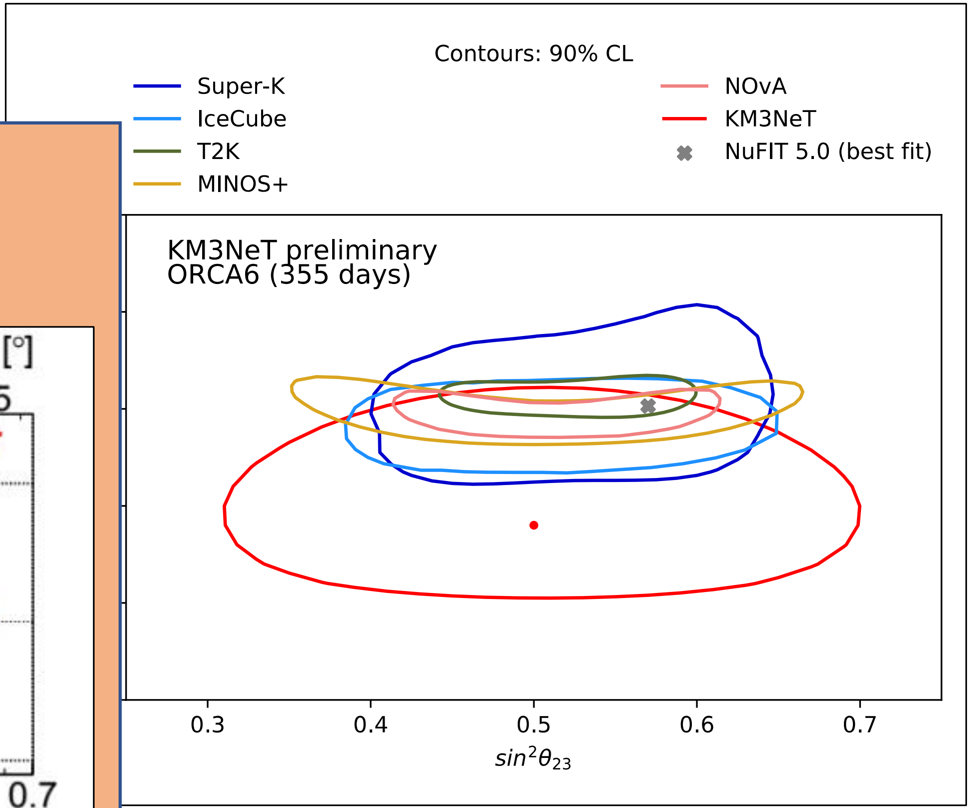




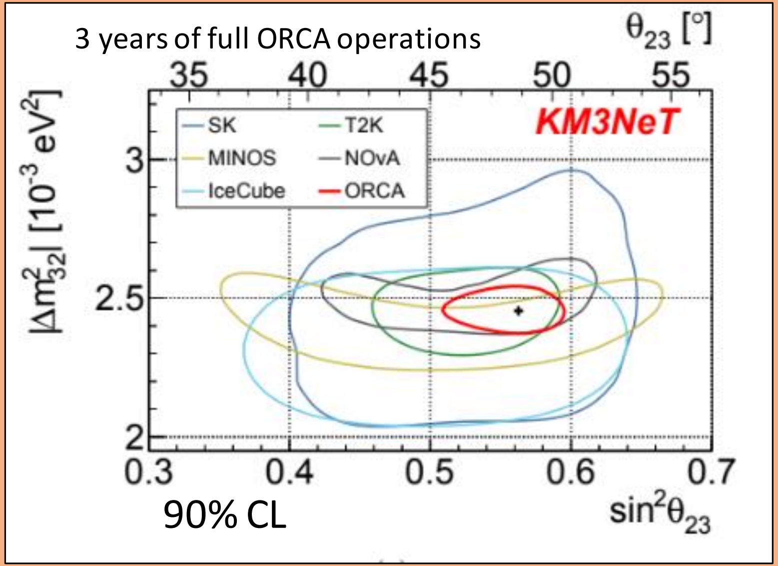
1 year of data with 6 lines of ORCA
≈1 kton-year.

Neutrino Oscillation Physics: ORCA 6



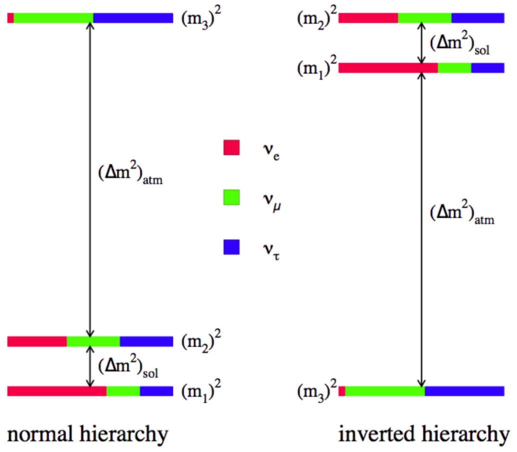


Completed ORCA detector will reach unprecedented sensitivity



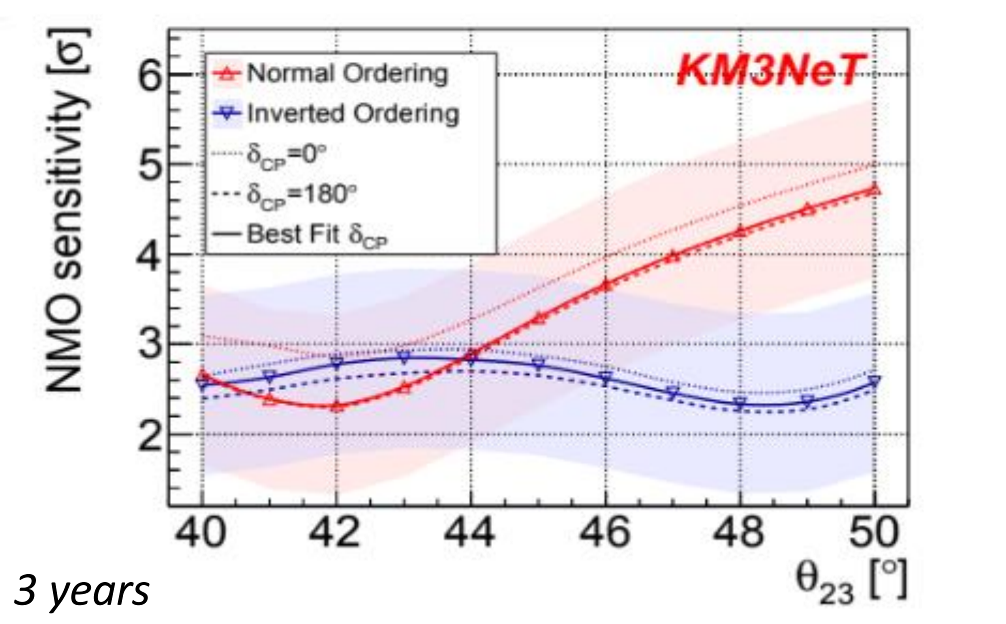
1 year of data with
≈1 kton-year.

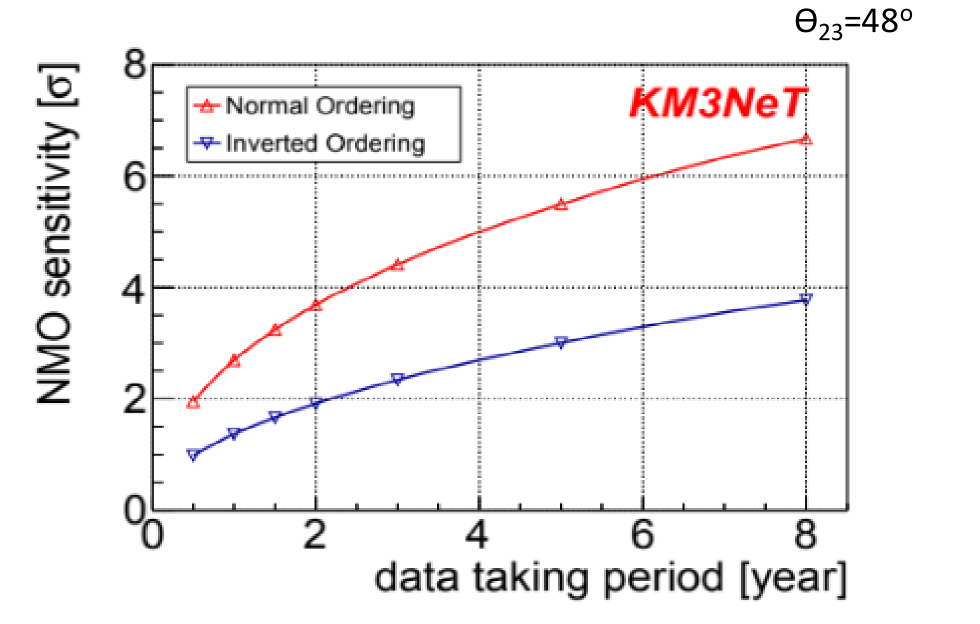
Neutrino Mass Ordering sensitivity of ORCA



Oscillation probabilities are affected by Earth matter (electrons) differently in case of normal or inverted ordering
-> Measure energy vs zenith angle pattern to determine ordering

'Main physics topic' for ORCA



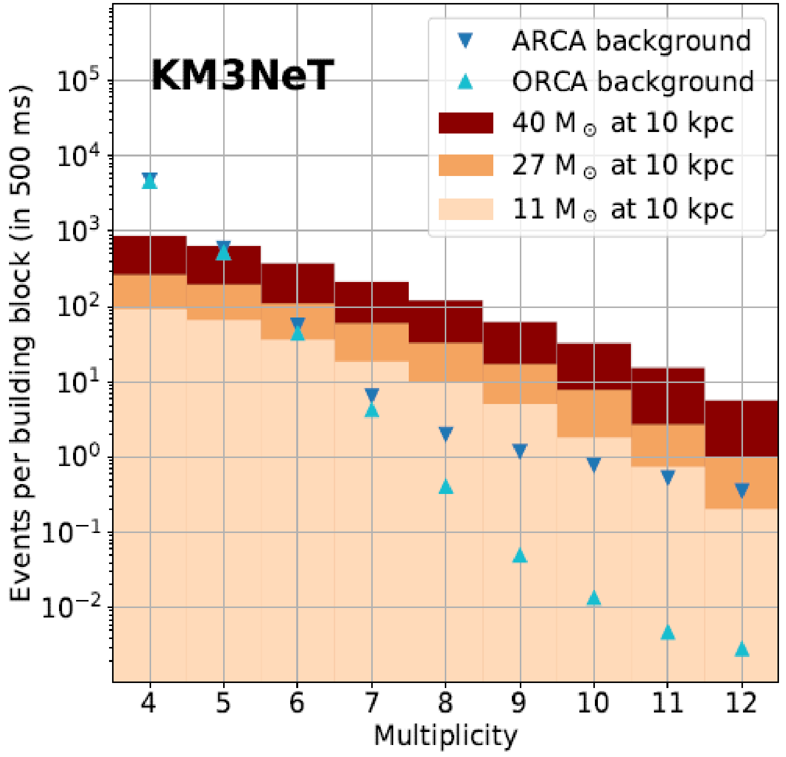


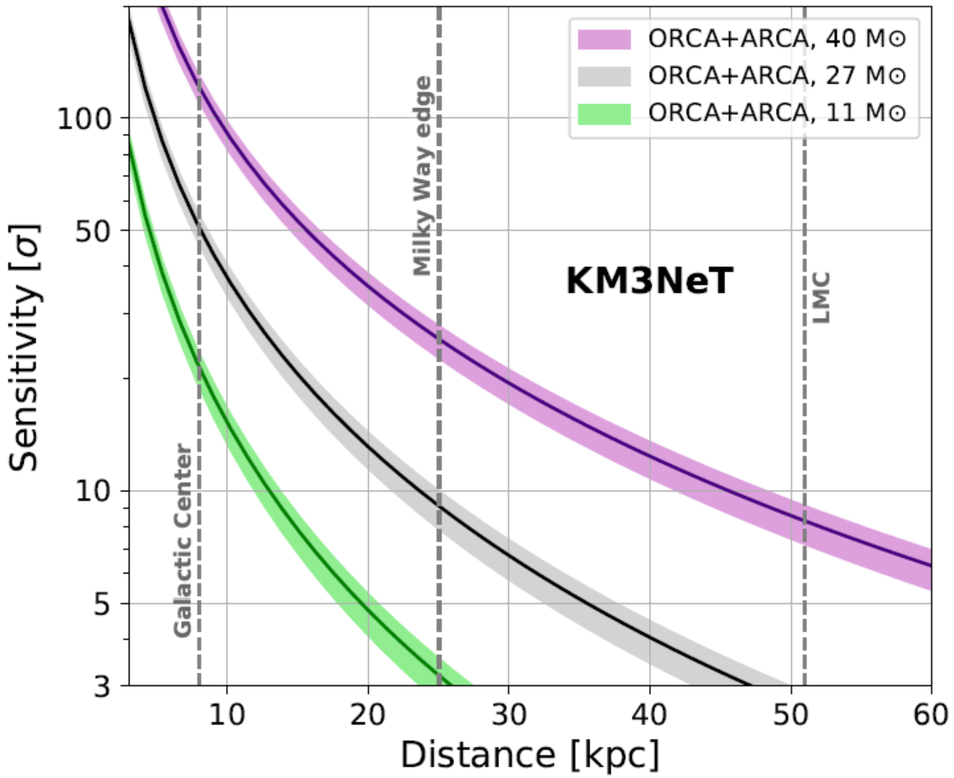
Sensitivities for full ORCA

Supernova Detection (~MeV neutrinos)

~10 MeV supernova neutrinos can not be resolved individually

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

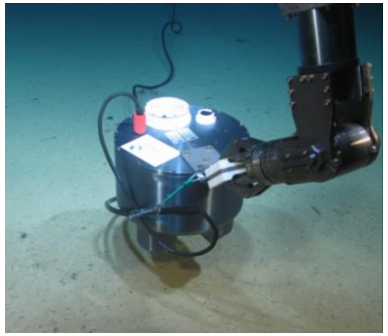


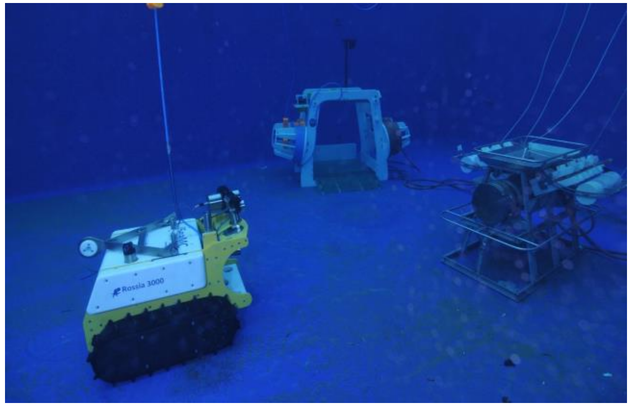


- Alert system already operational!
- Integrated in SNEWS network
- ORCA6 would trigger on e.g. 27 $M_\odot$ at ~10 kpc

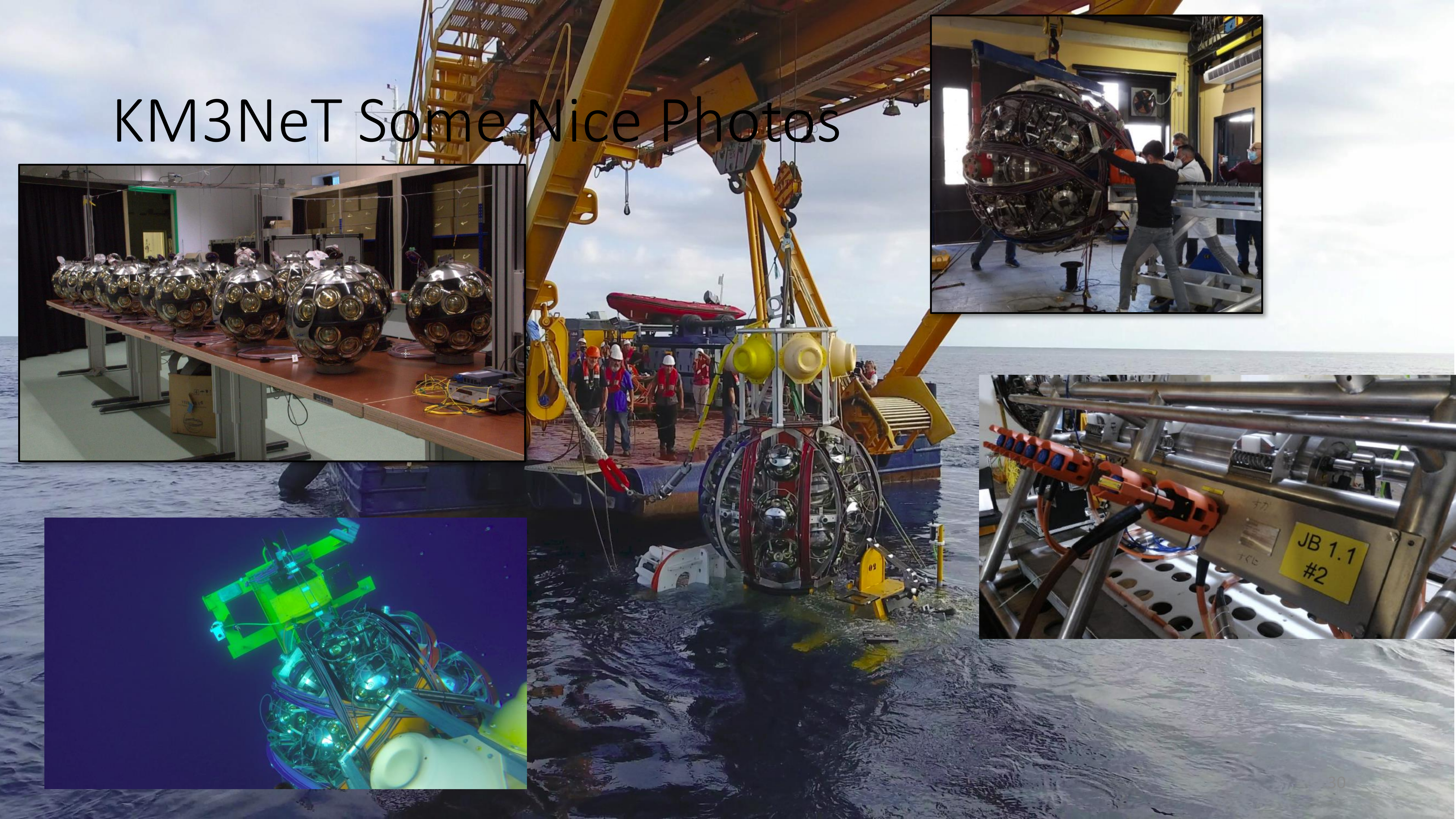
Other KM3NeT ('Low Energy') Physics Topics

- Indirect detection of Dark Matter
- NMO analyses (JUNO)
- Tau-neutrino appearance
- Non-Standard Interactions and Sterile Neutrinos
- Earth Tomography and Composition
- Earth and Sea Sciences





KM3NeT Some Nice Photos



Summary

- Antares
  - After 16 years Antares has come to and end, leaving a great legacy
- KM3NeT
  - Excellent successor of Antares
  - Construction well underway
  - First promising oscillation results
  - Already interesting pilot analyses

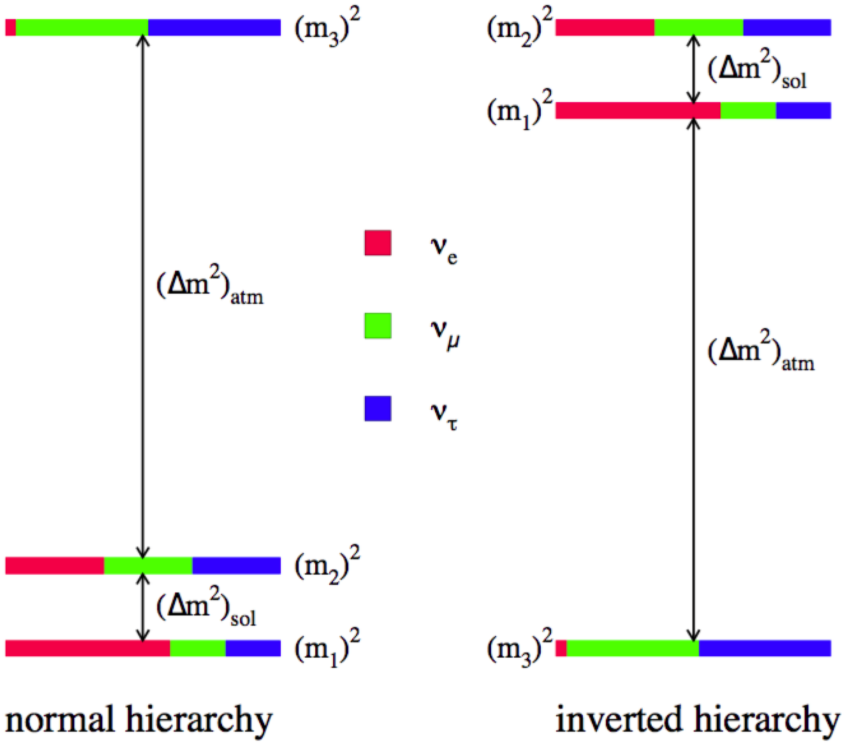
KM3NeT/ORCA Goal: Neutrino Mass Hierachy

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:

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

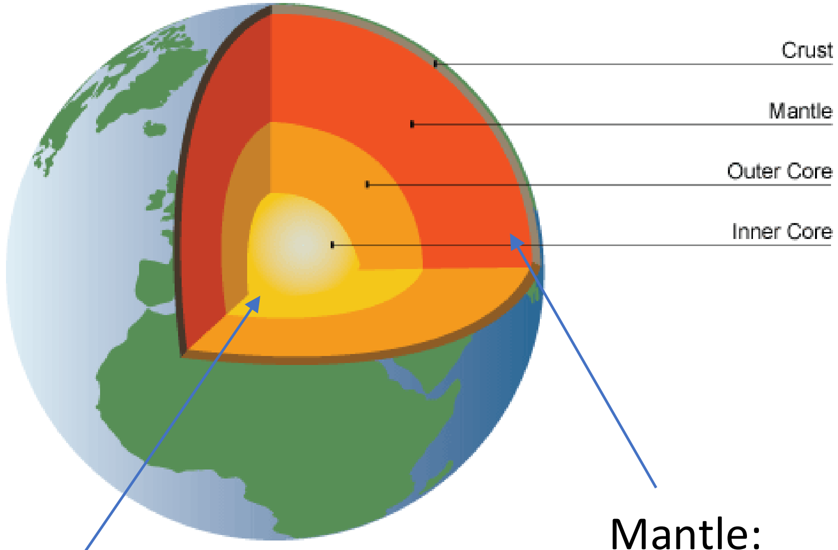
$$P_{3\nu}(\nu_\mu \to \nu_\mu) \approx 1 - 4\cos^2\theta_{13}\,\sin^2\theta_{23}\,(1-\cos^2\theta_{13}\,\sin^2\theta_{23})\,\sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right)$$

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:

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

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



Core:

$E_{res} \approx 3GeV$

Mantle:

$E_{res} \approx 7GeV$

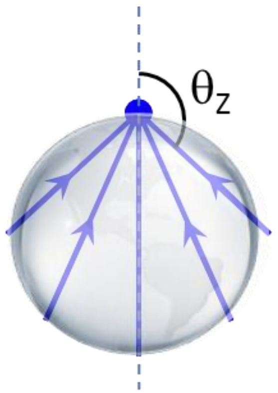
See: Akhmedov, E.K., Razzaque, S. & Smirnov, A.Y. J. High Energ. Phys. (2013) 2013: 82.

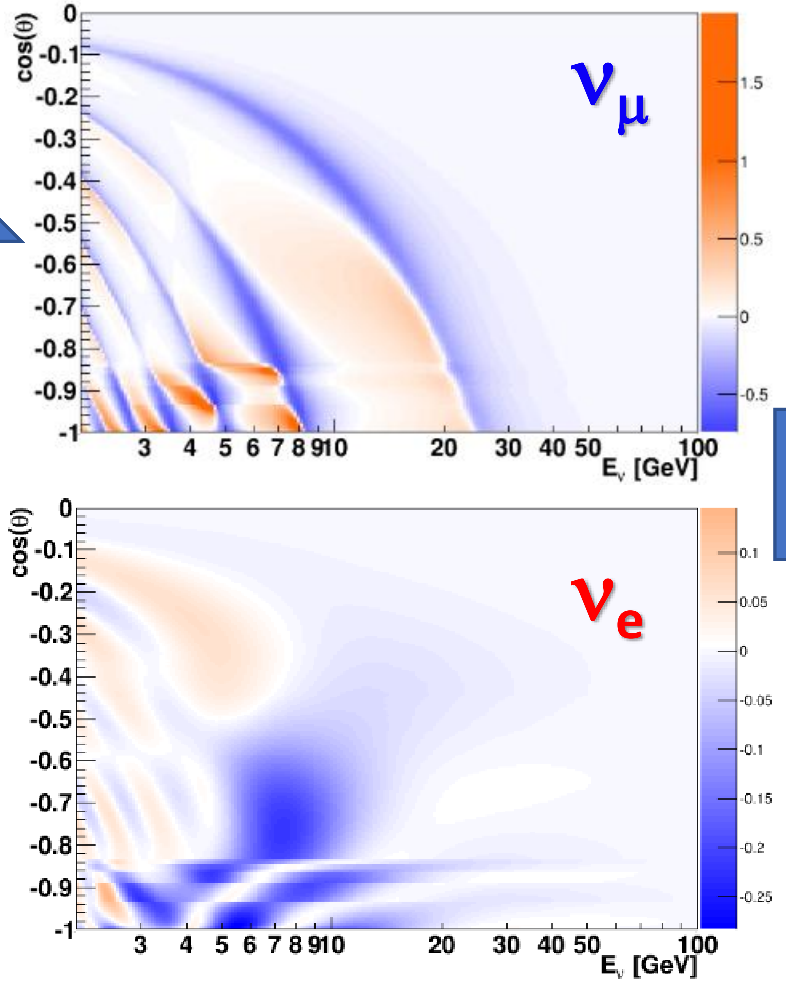
Measure atmospheric neutrino flux as function of energy and zenith angle!

Determining the NMH with atmospheric υ´s

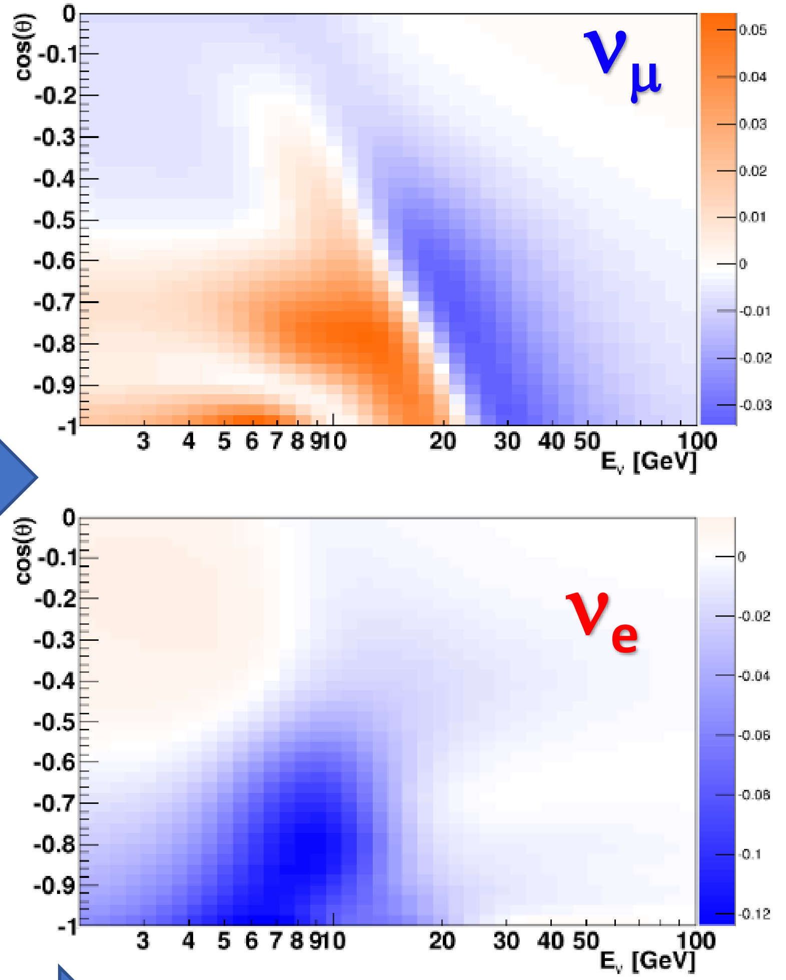
Relative difference in event numbers between normal and inverted hierarchy $(N_{IH}-N_{NH})/N_{NH}$

Zenith angle
corresponds with different distance and density profile !



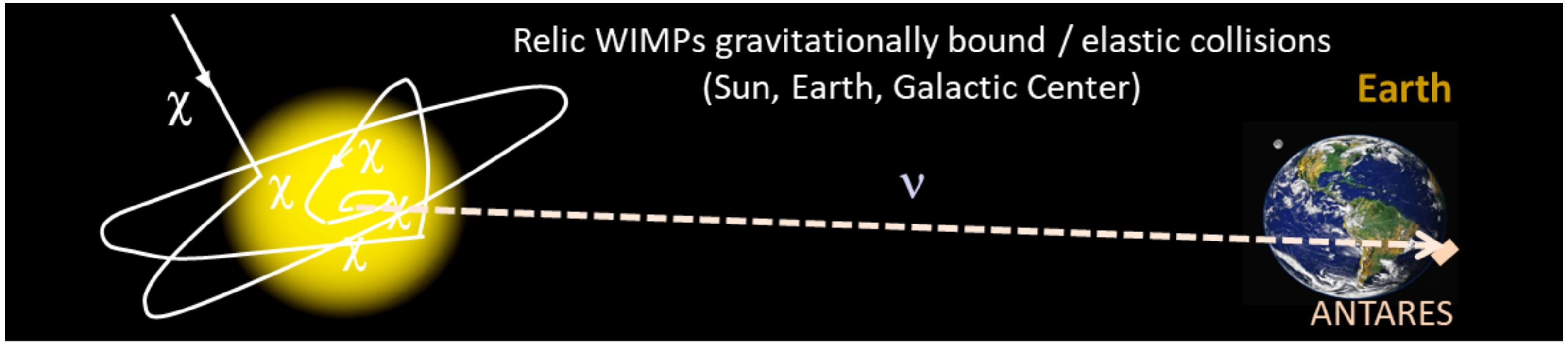


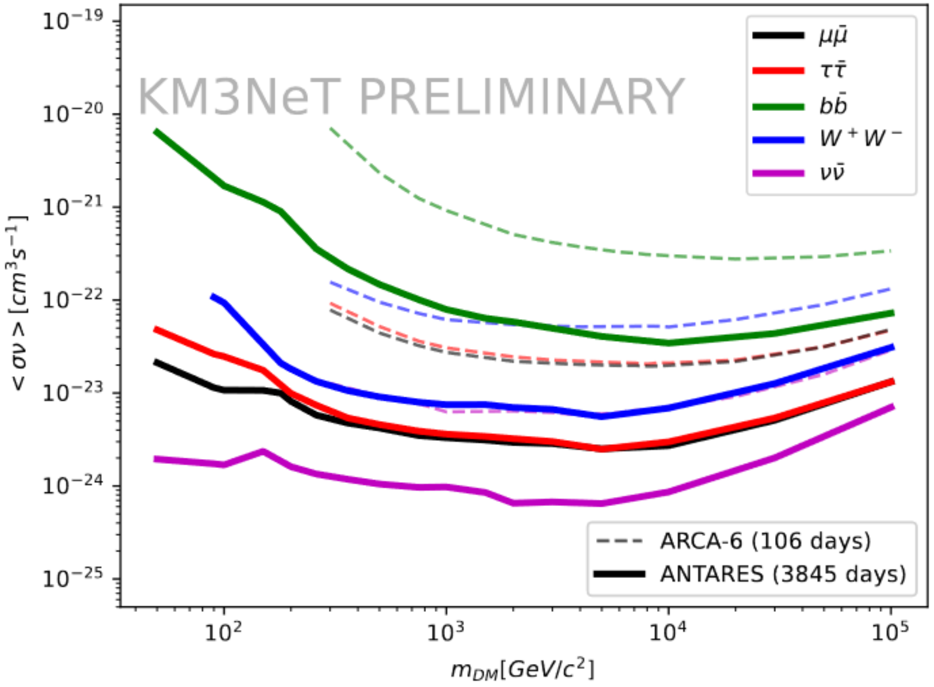
Resolutions



Neutrino Energy

Indirect detection of Dark Matter





Limits on thermally averaged cross-section for WIMP annihilation in the Galactic Centre – ANTARES (solid)

Sensitivities for ARCA 6 (dashed)