ANTARES and KM3NeT Overview

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on behalf of the ANTARES and KM3NeT Collaborations

NDM-2020

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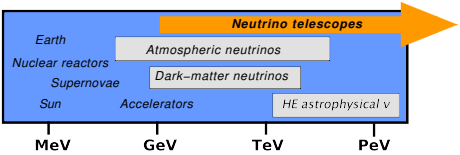
Neutrinos and very-large volume neutrino detectors

The science program of neutrino telescopes is very broad



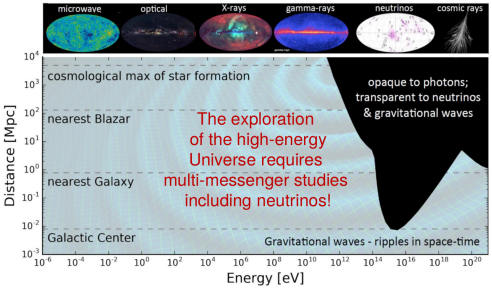
- Extraterrestrial neutrinos accelerated by astrophysical phenomena
  1. Search for sources / acceleration sites
  2. Search for a diffuse excess
- Neutrino oscillations and mass ordering in atmospheric ν
- Indirect searches for dark matter annihilation or decay

Principles of neutrino astronomy

Neutrino astronomy is characterised by **very small** cross-section of neutrino with matter

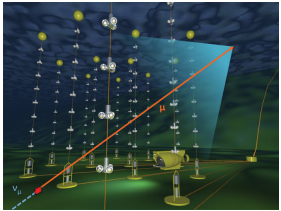
- Extremely powerful messengers, not interacting with: dust, starlight, CMB, IR radiation
- Extremely difficult messengers: not interacting with detector either

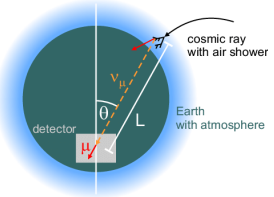
Particle astronomy nowadays strongly relies on multi-messenger effort

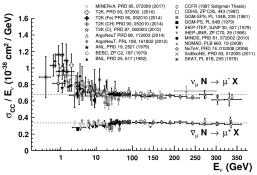


Large-volume Cherenkov telescopes

Cherenkov ν detectors look through the Earth for lepton tracks from $\nu \to l$ conversion.
$\sigma_{\nu \to l} \sim 10^{-38}$ cm^2 at 1 GeV! Extremely large instrumented volumes of water or ice needed.



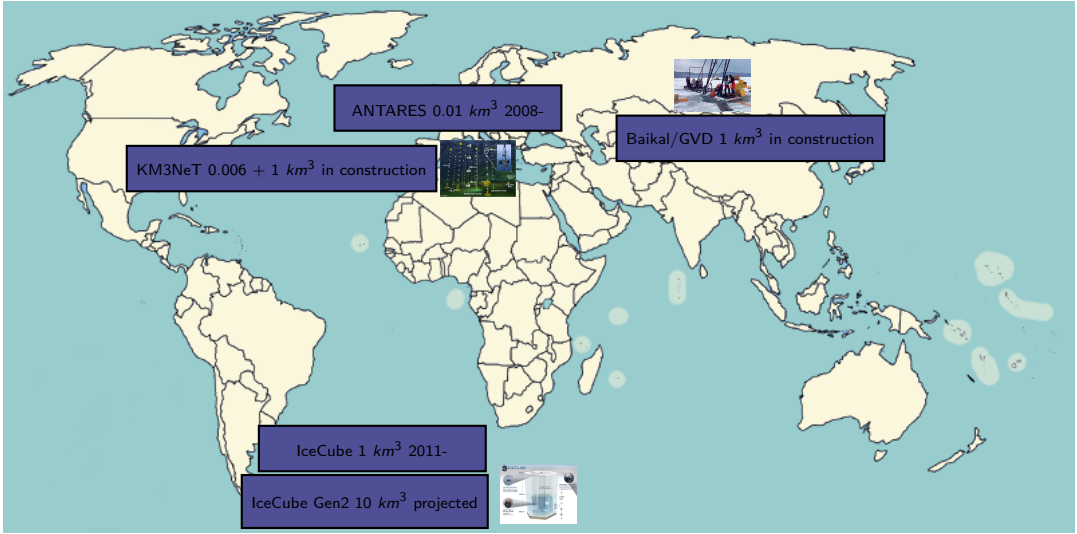




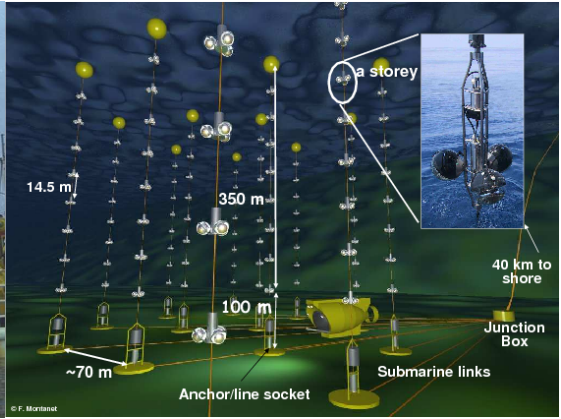
Water with respect to ice

- more noise: radioactive ^{40}K decays, natural luminescence in sea
- uniform optical properties along the detector
- larger scattering length: better angular resolution
- maintainable (but moving)

Atlas of neutrino telescopes

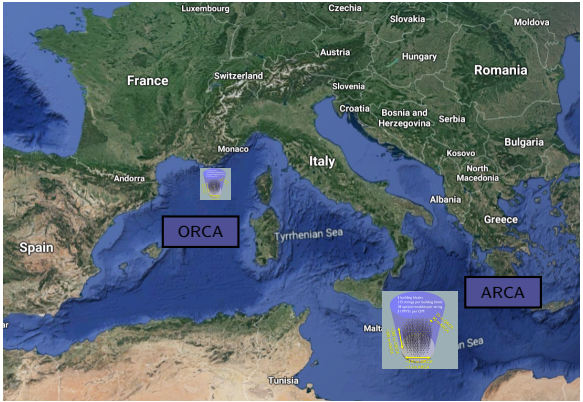


ANTARES



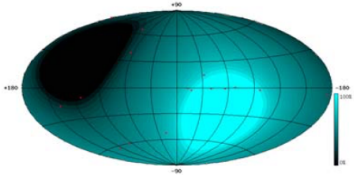
40 km offshore Toulon, 12 lines, 885 PMTs, 2500 m depth, more than 12 years of operation

The multi-site KM3NeT infrastructure



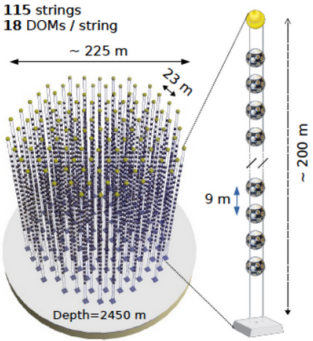
Under construction:

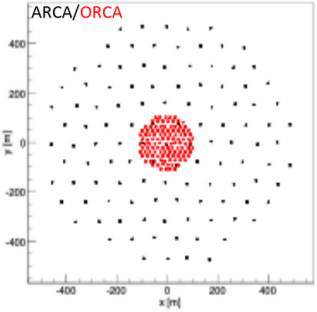
- ORCA: 1 small, dense block (8 Mton, 115 lines) for oscillations / mass hierarchy with atmospheric ν
- ARCA: 2 large blocks (1 Gton, 230 lines), for measuring astrophysical fluxes



Visibility from Mediterranean Sea ($\sim 43°$N): Southern Sky for upgoing events
Sea water has good optical properties for excellent pointing accuracy (low scattering)

Layout of the KM3NeT building block



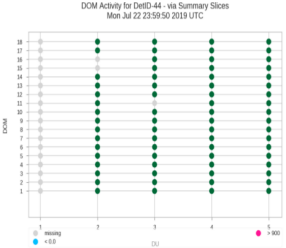


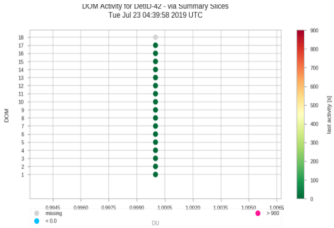
inter-string spacing ORCA: 23 m ARCA: 90 m
inter-DOM spacing ORCA: 9 m ARCA: 36 m

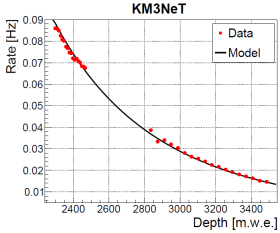
DOM
31 PMT

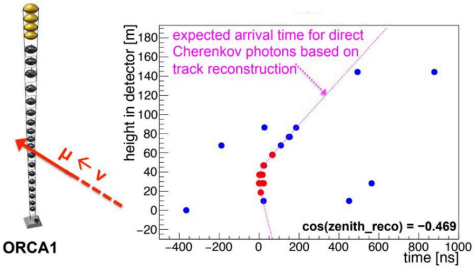
First data from KM3NeT

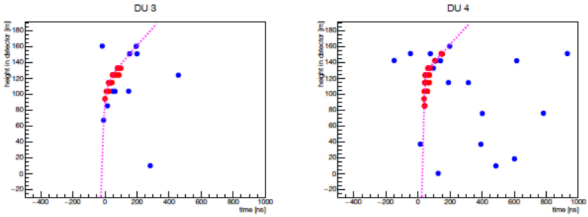
4 DU ORCA and 1 DU ARCA + 2 ready for imminent deployment





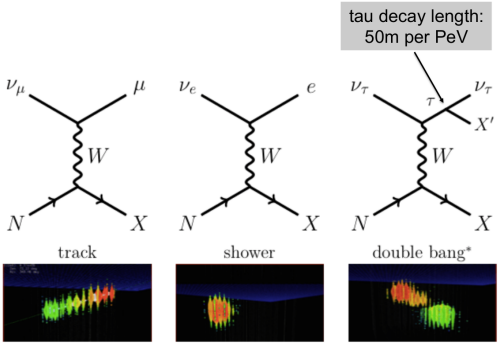






Signatures in neutrino detectors

Astro: atmospheric ν: atmospheric μ = 1:10^4 :10^{10}



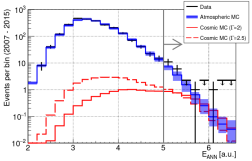
Tracks: predominantly $\nu_\mu CC$; angular resolution $<$ 0.5 degrees (dep. on energy)
Showers: predominantly ν_e, NC, Glashow; angular resolution 3-10 degrees (dep. on energy)

Results: high energy

Types of searches for cosmic neutrinos

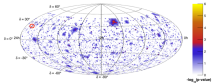
Diffuse search

Excess at high energies without directional information



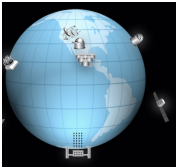
Point source search (all-sky)

Space (-time) clusters of events



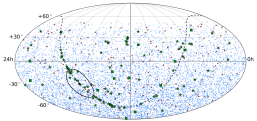
Multimessenger search

Space-time coincidence upon alert from other experiments



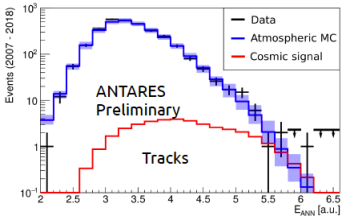
Point source search (catalogue)

Space coincidence with preselected sources

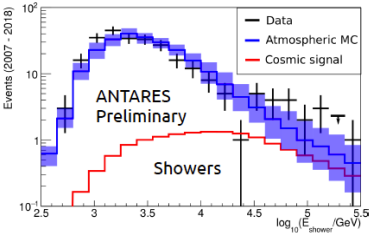


Diffuse cosmic neutrinos with ANTARES

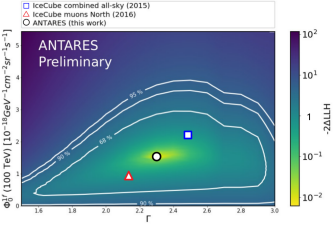
All-flavour search 2007-2018, 3380 days, 50 events observed (27 tracks + 23 showers), 36±8 expected, 1.8 σ excess **[ApJL, 853:L7, 2018][PoS(840)ICRC2019]**



Tracks



Showers



Best fitted index

Best likelihood fit of the diffuse cosmic flux normalization and spectral index:
$\Phi_0^{1f}(100\,TeV) = (1.5 \pm 1.0) \times 10^{-8}\,GeV^{-1}cm{-}2s^{-1}sr^{-1}$ with spectral index $\Gamma = 2.3^{+0.4}_{-0.4}$

Diffuse flux: KM3NeT

IceCube flux can be seen with 5σ median significance in 6 months.

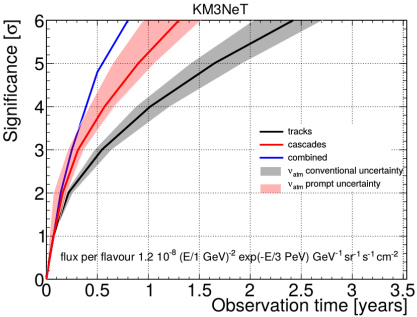


Figure: Significance reached with KM3NeT to IceCube flux benchmark: power law spectrum with a cut-off at a few PeV. Joint set of tracks + cascades.

Point sources: ANTARES

- 2007-2017, 3136 days livetime
- all-flavour: 8754 tracks, 195 showers
- $1^\circ x 1^\circ$ squares over ANTARES visible sky
- No significant excess over background
- Most significant cluster has 1.9 σ
- $E^2 d\Phi/dE = 6 \cdot 10^{-9}$ GeV cm^{-2} s^{-1}

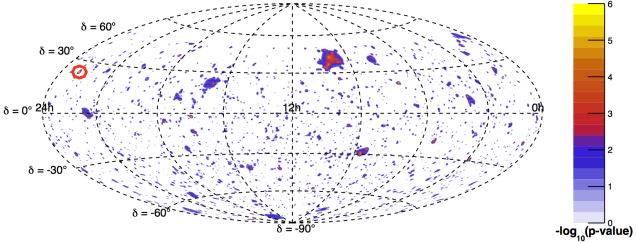
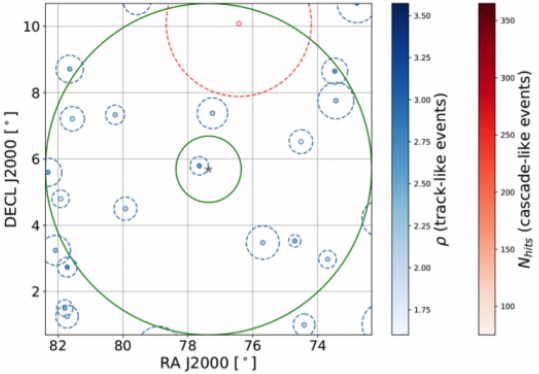


Figure: Pre-trial $p - value$ map for a point-like source of the ANTARES visible sky. The red circle indicates the location of the most significant cluster at (RA, δ) = (343.7°, 23.6°)

Point source: ANTARES follow-up of IceCube detection



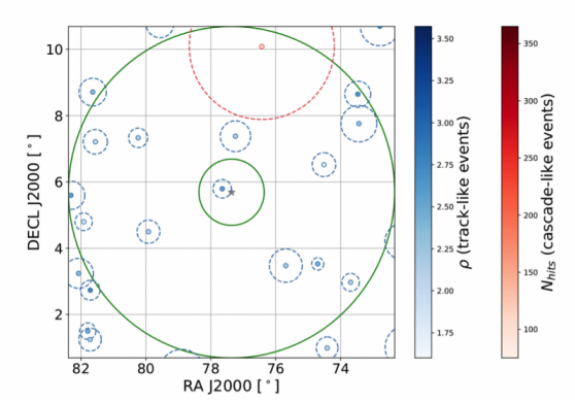
No counterpart seen in ANTARES data

Three searches performed:

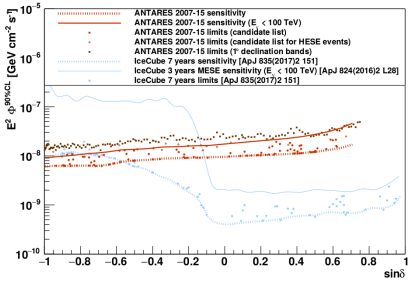
1. online prompt search for neutrinos associated with IC170922A
2. time-integrated search for neutrinos from TXS 0506+056
3. time-dependent search for neutrinos in historical bursting periods of TXS 0506+056

TXS 0506+056 is 3rd most significant source. Fitted number of ANTARES signal ν: 1.03 (2.6% pre-trial, 87% post-trial p-value). **[Phys. Rev. D 96, 082001 (2017)]**

Point source: ANTARES follow-up



No counterpart seen in ANTARES data

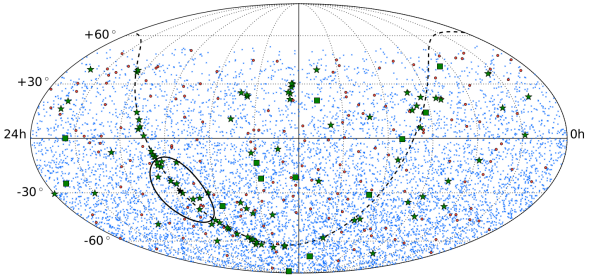


ANTARES is the most sensitive instrument for large fraction of the southern sky < 100 TeV

IceCube is the most sensitive instrument in the northern sky and a fraction of the southern sky assuming a flux $\propto E^{-2}$

Point sources: searches with catalogue

2007-2017, 3136 days livetime, 8754 tracks, 195 showers, all-flavour. No correlation found with a list of preselected sources **[PoS(920)ICRC2019]**



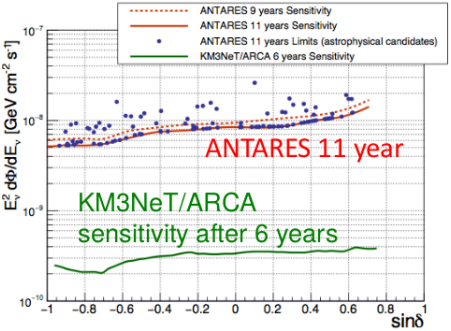


Figure: Dots: ANTARES tracks. Dots: ANTARES showers. Stars: 112 astrophysically interesting source candidates. Squares: 54 IceCube HESE tracks.

Point source sensitivity with KM3NeT

Science case for KM3NeT-ARCA is centered on astronomy. 3σ median sensitivity reached in less than 6 years for the strongest sources

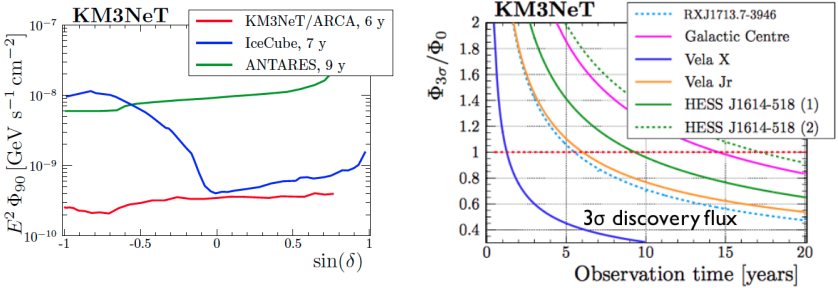
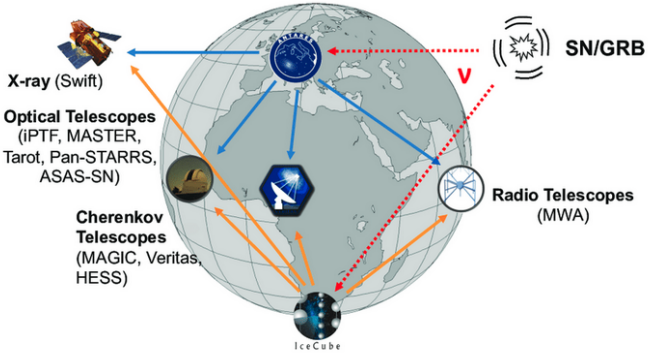


Figure: Left: Best sensitivity on Northern and Southern Sky Right: Discovery fluxes for galactic sources, assuming spectrum from γ-ray measurement and fully hadronic scendario.

Multi-messenger program

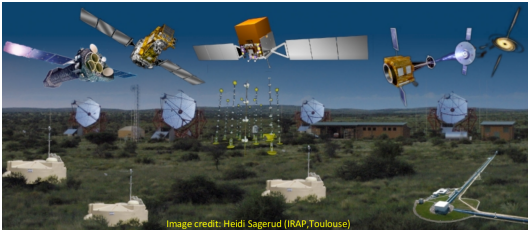


Optical, X-ray, radio, γ ray and gravitational wave follow-up and space/time correlation.
Quick real-time alerts for interesting neutrino events.

Multi-messenger program

ANTARES both receives and sends alerts.

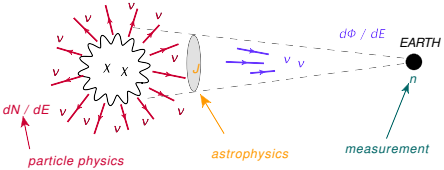
1. Receives GCN notices (γ-ray Coord. Network) from IceCube, MAGIC, HESS, VERITAS, Fermi, optical or radio instruments, and gravitational wave alerts from VIRGO, LIGO.
2. Processes online reconstruction within $\sim$5 sec (transmits data to shore, filter for physics events, run rapid reconstruction).
3. Sends out alert to partners in network (TAToO) or run prompt online searches for counterparts to transient events.



Cosmic neutrinos from dark-matter pair annihilation

Relic WIMPs accumulate in massive celestial bodies like the Sun or the Galactic Centre

WIMP annihilations or decays can yield significant flux of medium-to-high energy ν as secondary products, sensitive to halo models, in a range between $\sim$ 10 GeV and $\sim$ 100 TeV

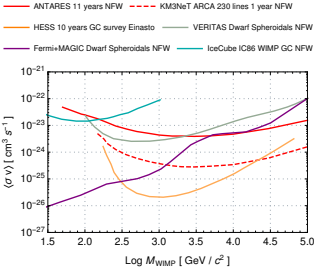


$$\mu_{90} = \frac{\Phi}{\mathcal{A}(M_\chi)\,t} = \frac{\langle \sigma v \rangle}{2} \int_0^M \frac{dN}{dE} dE \, \frac{J}{4\pi} \, \frac{1}{M_\chi^2} \, \mathcal{A}(M_\chi)\, t$$

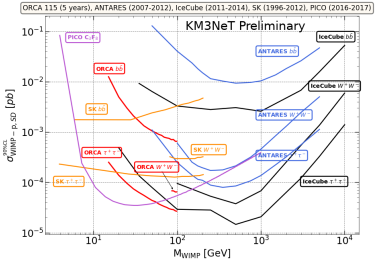
number of events observed = annihilation rate * average number of particles per collision * source geometry * acceptance * time

Neutrinos as dark-matter trackers

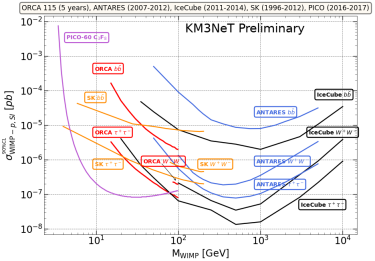
ν source: WIMP collision. Search for cluster of events with dark-matter spectral features



Galactic Centre
ANTARES and ARCA



Sun, spin-dependent
ORCA



Sun, spin-independent
ORCA

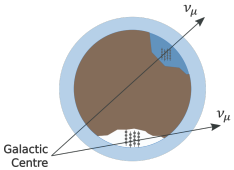
Figure: Limits on cross section for WIMP pair annihilation $\chi\bar{\chi} \to b\bar{b}/W^+W^-/\tau^+\tau^-/\mu^+\mu^-, \nu\bar{\nu} \to \nu\bar{\nu}$

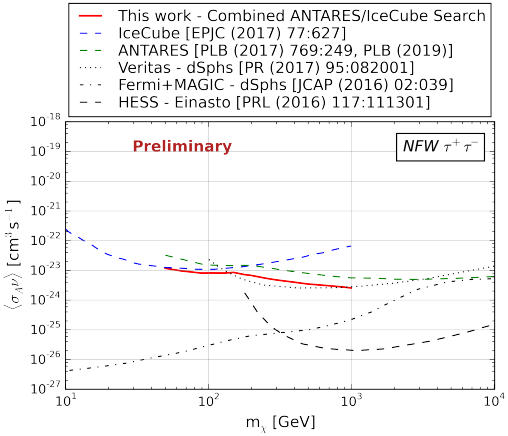
Combined analysis ANTARES + IceCube: dark matter

Search for neutrinos from WIMP annihilations in the region 50 GeV $< E <$ 1 TeV where sensitivities are comparable **[arXiv: 1908.07300]**.

The Galactic Centre is in Southern Sky:

1. 'good' spot for ANTARES: regular DAQ (smaller)
2. 'bad' spot for IceCube: outer layer veto + deep core





Results: low energy

Neutrino oscillations

Oscillation parameter θ_{23} / Δm^2_{23} measured through ν_μ disappearance (muons are seen as tracks from ν_μ CC events), from energy threshold 20 GeV for ANTARES, 3 GeV for ORCA.

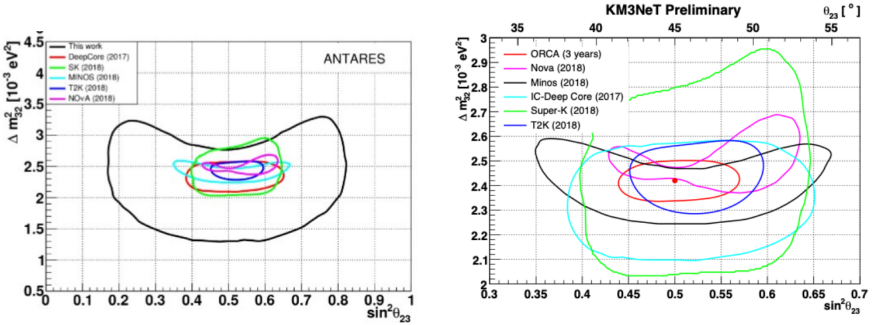
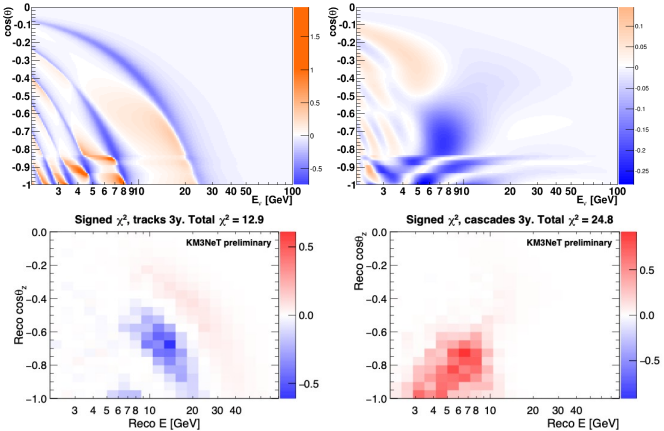


Figure: Left: ANTARES 10 years **[JHEP 1906 (2019) 113]**. Right: sensitivity for ORCA 3 years.

Neutrino mass ordering

Sensitivity due to ν-$\bar{\nu}$ asymmetry in flux and cross-section. Both μ- and e-channels contribute.



Measurement: number of expected events with normal/inverted hierarchy $(N_{IH} - N_{NH})/N_{NH}$

and relative χ^2. Left: muons; right: electrons. Electron channel is more robust against detector resolution.

Neutrino mass ordering and CP violation

Neutrino mass ordering can be determined with ORCA with 3σ after 3 years of operation

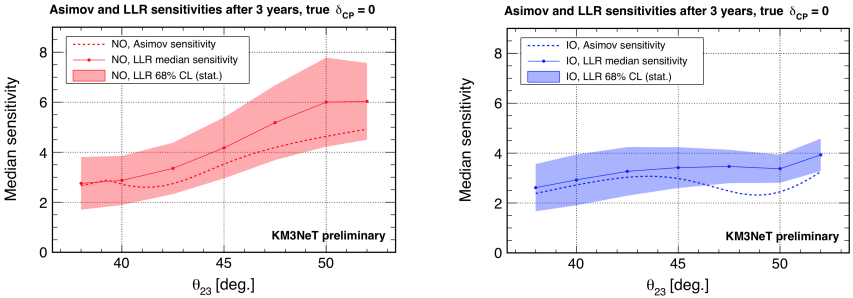


Figure: Sensitivity to Asimov phase with 3 years of ORCA. Right: normal ordering, left: inverted ordering.

Wrap-up

ANTARES succesful operation for more than 12 years has yielded plenty of results with a broad physics program

- Search fro astrophysical neutrinos: diffuse (1.8 σ excess), point source, combined analyses, multimessenger program
- Measurement of oscillation parameters with atmospheric neutrinos
- **Limits on dark-matter annihilation $\rightarrow$ see dedicated talk by M. Ardid**

Other results not mentioned here for lack of time: Galactic Plane emission, multimessenger program, combined searches for sources with Auger, TA, Fermi.

KM3NeT is being deployed and looks forward to breakthrough discoveries

- KM3NeT ARCA: 1 km^2 of instrumented volume to catch high-energy ν fluxes from steady and transient sources, included a strong multimessenger program
- KM3NeT ORCA: Competitive measurements of oscillation parameters, mass ordering, CP violation phase, non-standard interactions, ν_τ appearance and unitarity with high statistics of atmospheric ν.

Backup material

Combined analysis ANTARES + IceCube: point sources

Southern hemisphere search with joint data sets: 9 years ANTARES (5807 tracks + 102 showers) and 7 years IceCube (119231 tracks + showers) **[VLVnT 2018, EPJ 207 (2019)]**

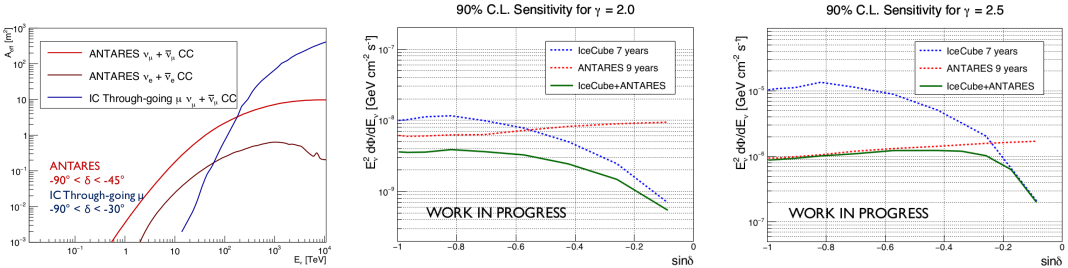


Figure: Analysis effective area (left) and 90% CL flux sensitivity for spectral indices $\gamma = 2.0$ and 2.5

ANTARES + IceCube: time correlation

Search for **time coincidence** between ANTARES events (6894 tracks and 160 showers) and 54 IceCube high-energy neutrinos. No coincidence found.

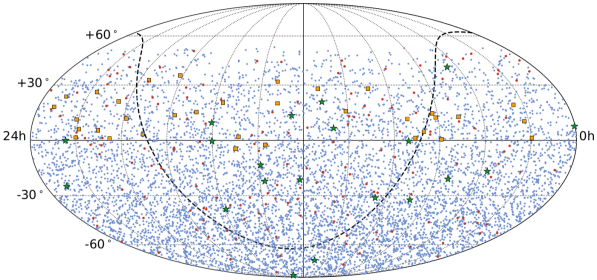


Figure: Blue dots: ANTARES tracks; red dots: ANTARES showers. Green stars: 20 neutrinos from IceCube HESE selection; yellow squares: 34 neutrinos from IceCube muon sample.