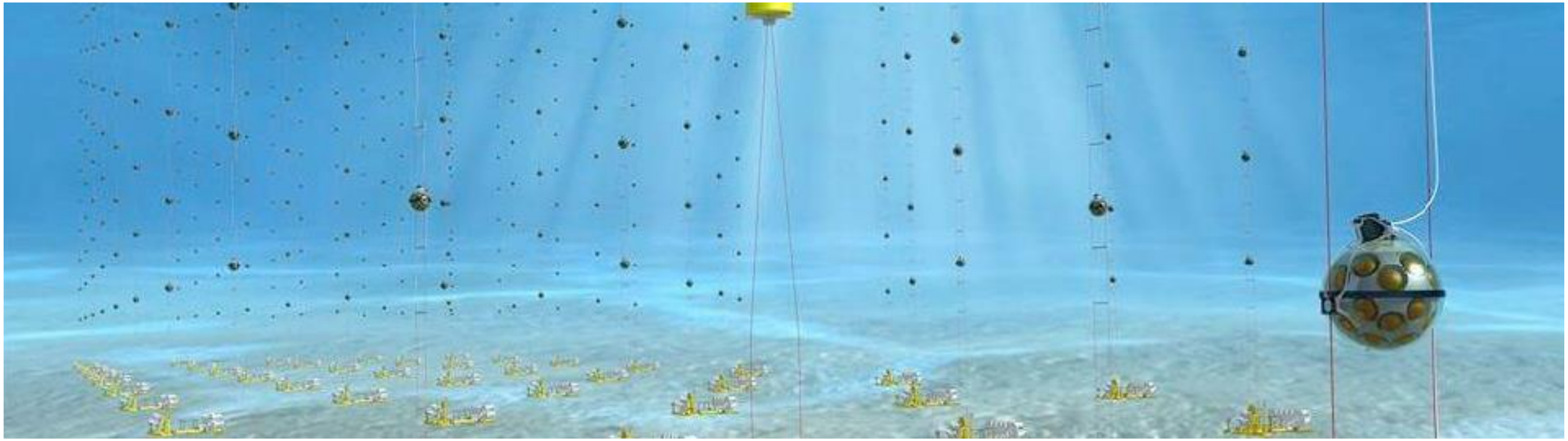
Status and results from the ANTARES and KM3NeT-ARCA neutrino telescopes



Paolo Fermani on behalf of the ANTARES and KM3NeT collaborations

NUFACT 2019
August 26 - 31, 2019
Daegu, Korea

SAPIENZA UNIVERSITÀ DI ROMA
INFN Istituto Nazionale di Fisica Nucleare

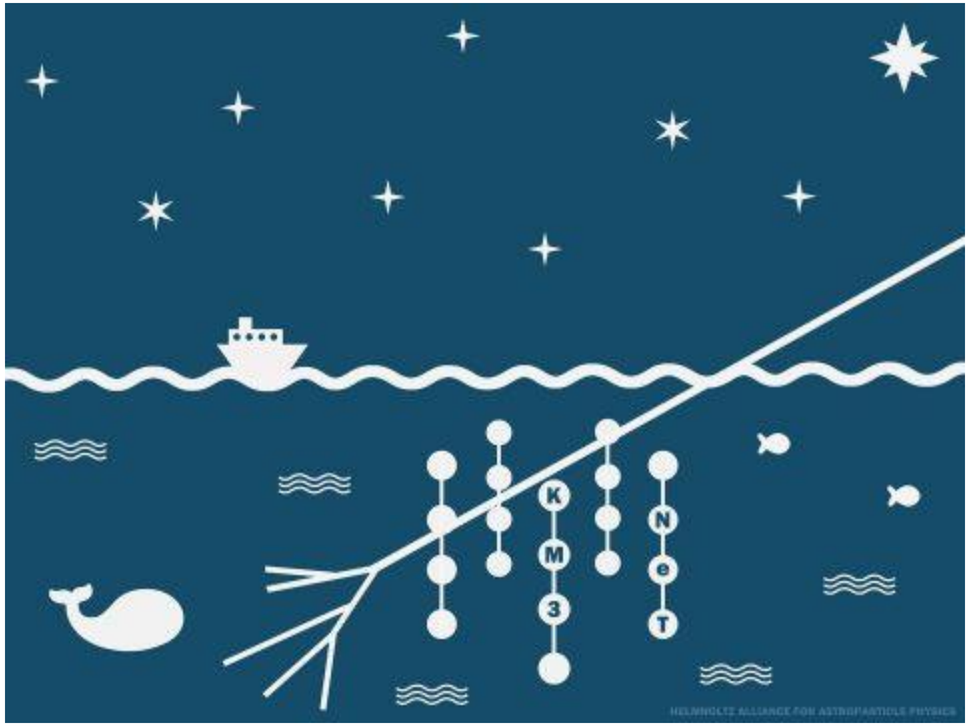
Outline

- **Introduction to large neutrino telescopes**
  - Detection principle
  - Observable sky

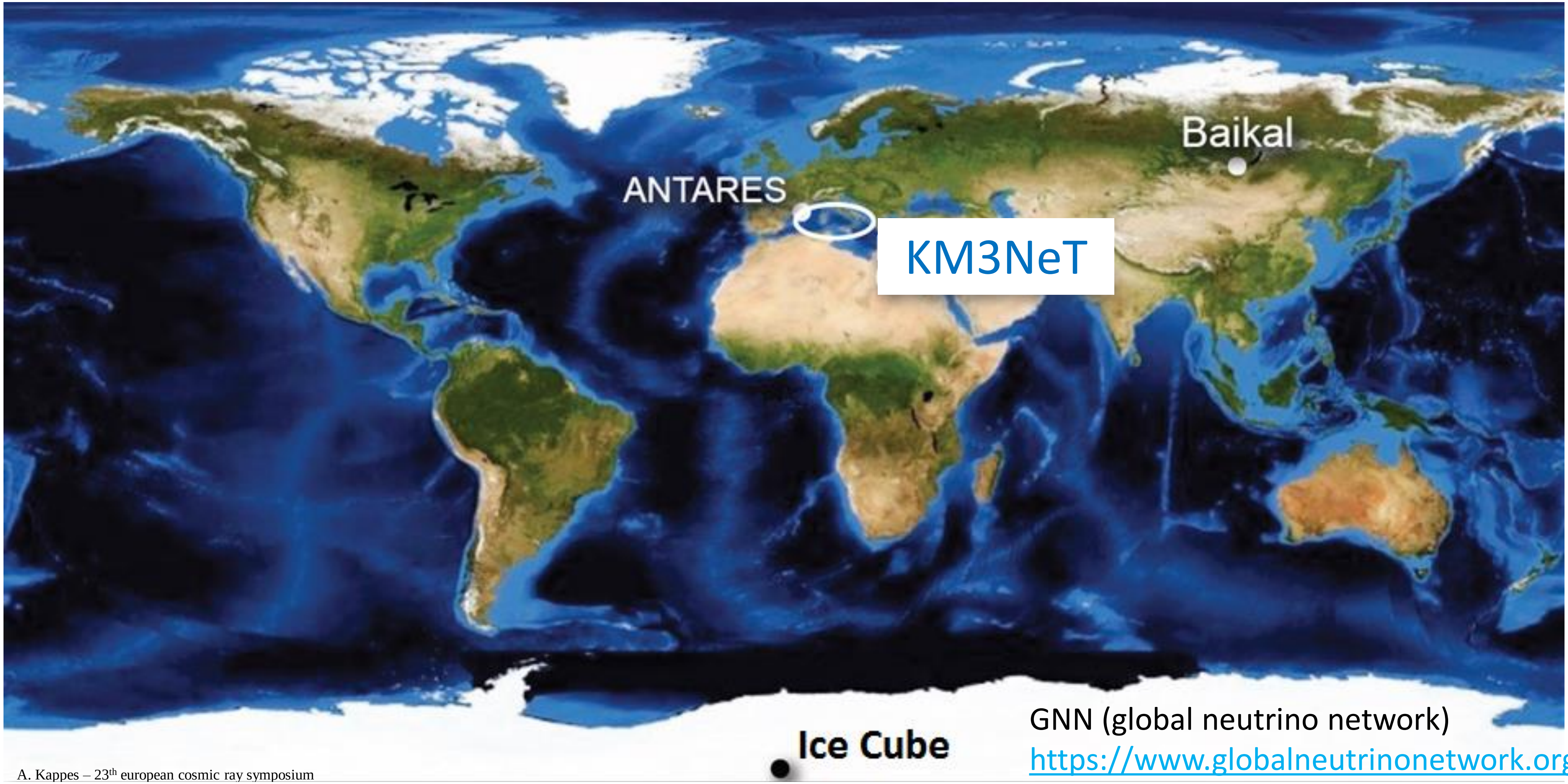
- **ANTARES & KM3NeT-ARCA**
  - Infrastructure

- **ANTARES analysis and KM3NeT sensitivities**
  - Neutrino oscillation physics
  - Cosmic neutrino searches
  - Indirect Dark Matter search

- **Future prospects**



Large neutrino telescopes on Earth



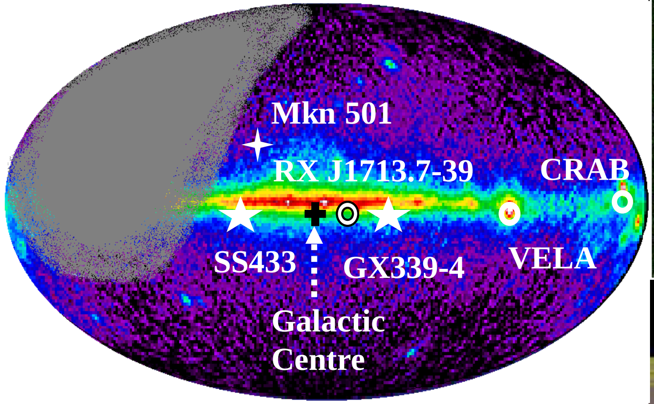
A. Kappes – 23th european cosmic ray symposium

GNN (global neutrino network)
https://www.globalneutrinonetwork.org/

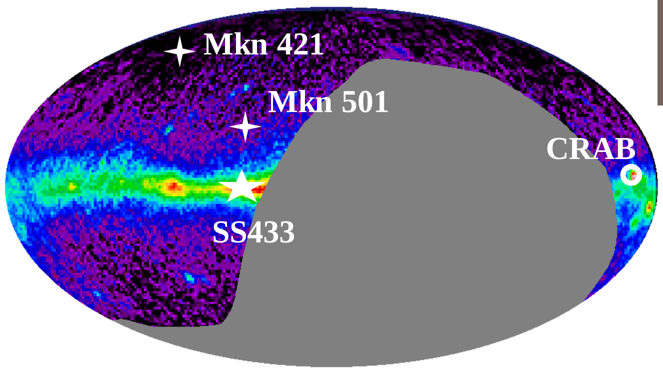
How to detect high energy neutrinos

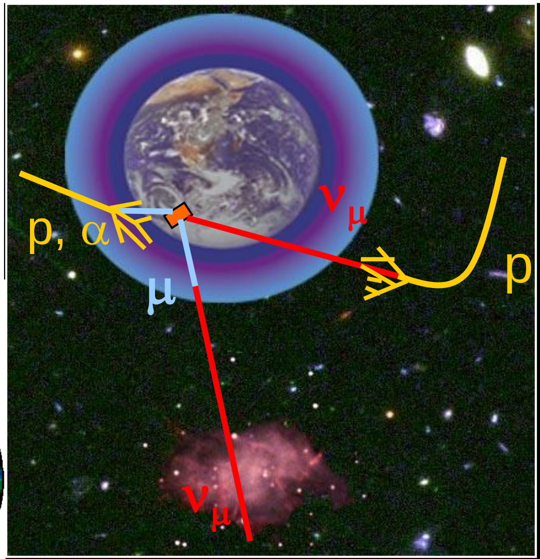
Up-going ν events

ANTARES - KM3NeT
(North Hemisphere)



(South Pole)

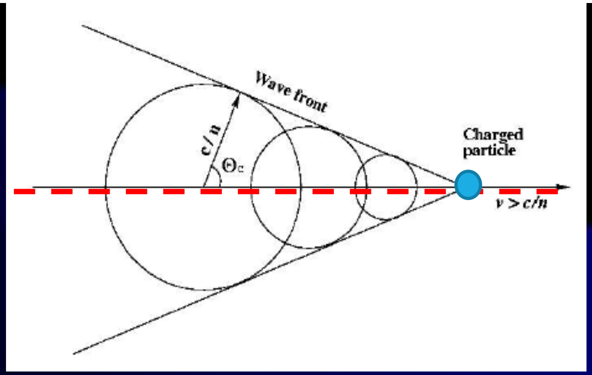




Search for up-going events

$$\nu_l(\overline{\nu_l}) + N \longrightarrow l^-(l^+) + X$$

3.5π sky coverage



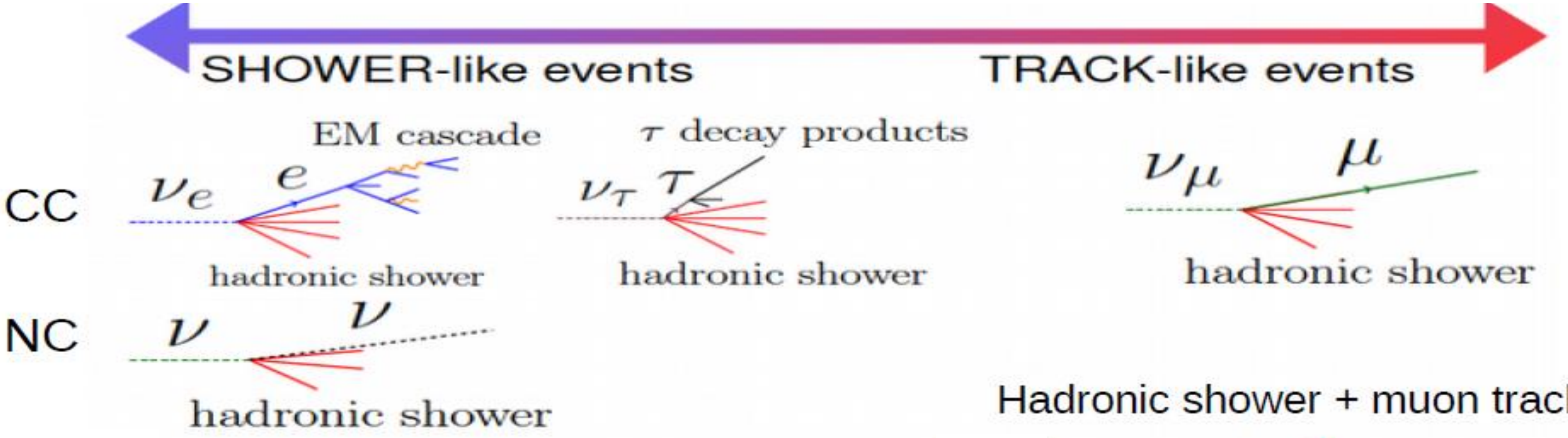
$$\cos\vartheta = \frac{1}{n\beta}$$

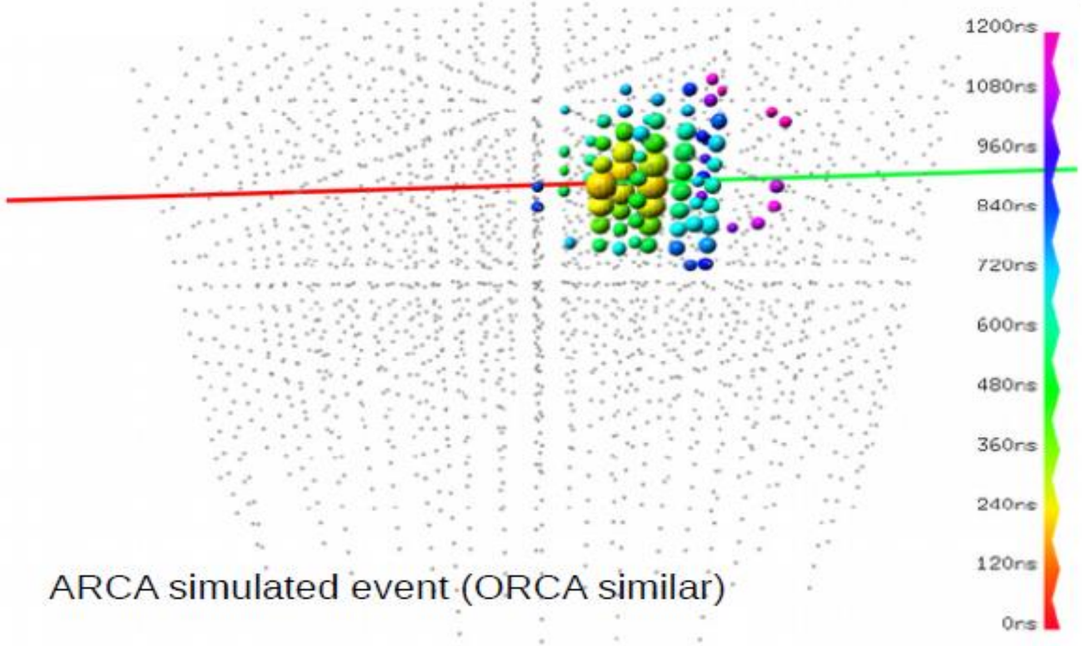
Reconstruction based on local coincidences compatible with a Cherenkov light cone.

Selecting **up-going muon tracks** reduces atmospheric muon background, in 1 year gives:

100˙000˙000˙000	:	100˙000	:	10
atmosheric muons (from above)		atmospheric neutrinos		cosmic neutrinos

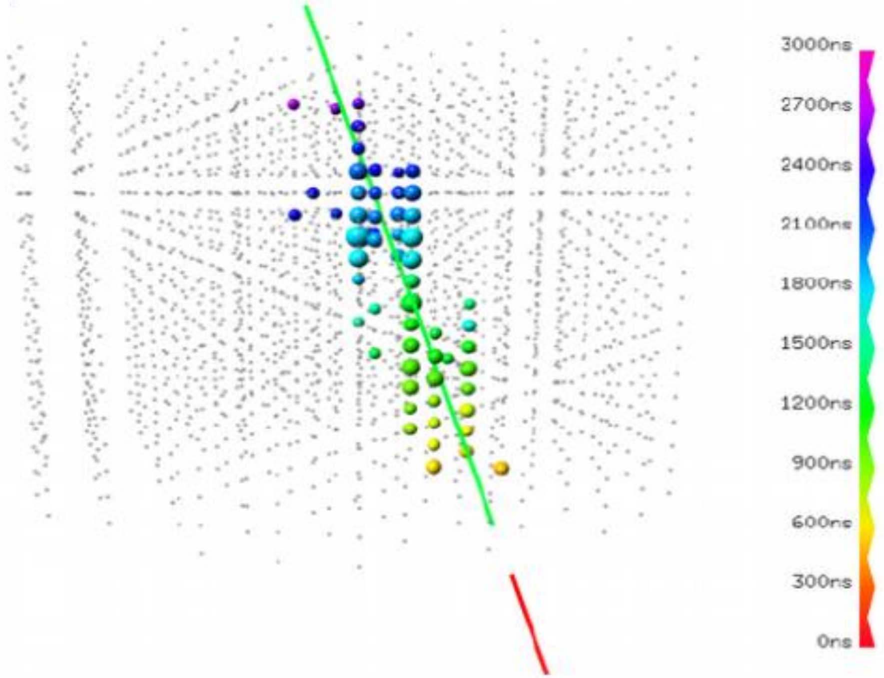
Particle identification in ν telecopes





ARCA simulated event (ORCA similar)

Hadronic shower + muon track



KM3NeT

The ANTARES neutrino telescope

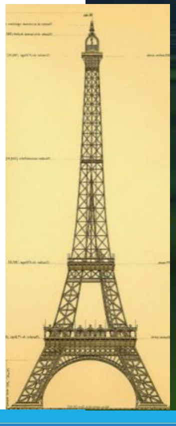
Detector completed in 2008

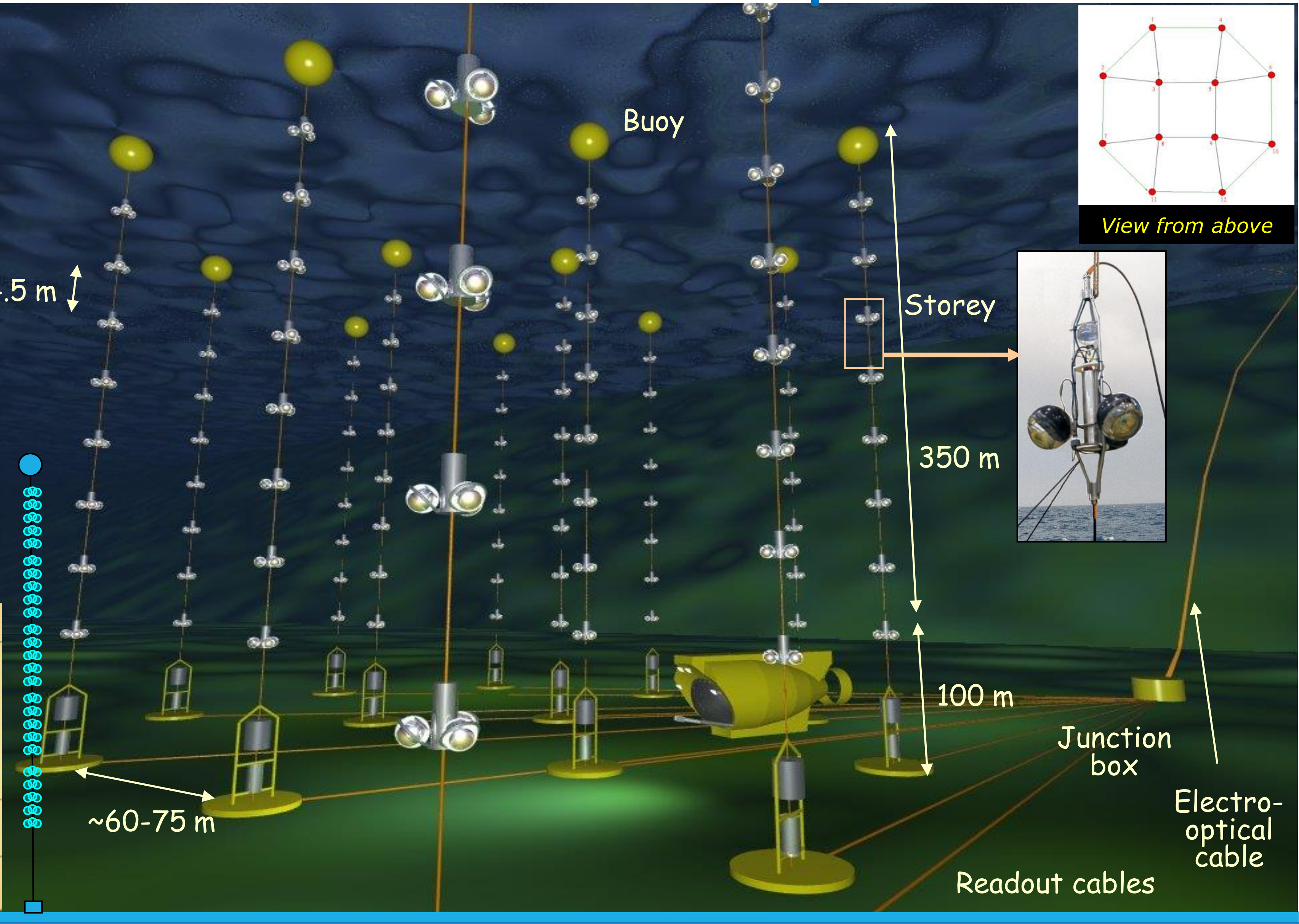
Taking data since 11 years with a duty cycle of ~95%

Placed at a depth of 2475m

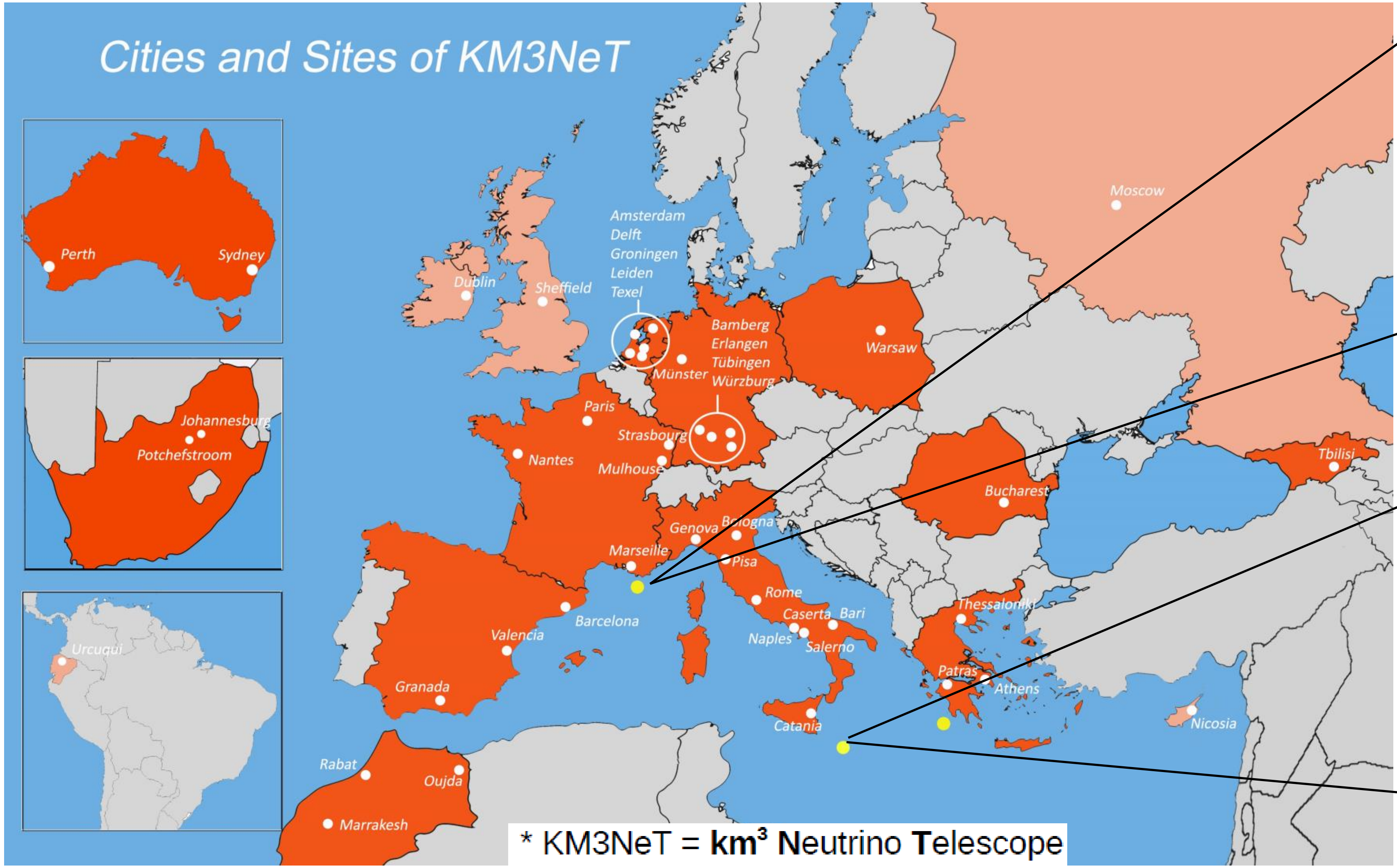
- 12 lines
- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs in total

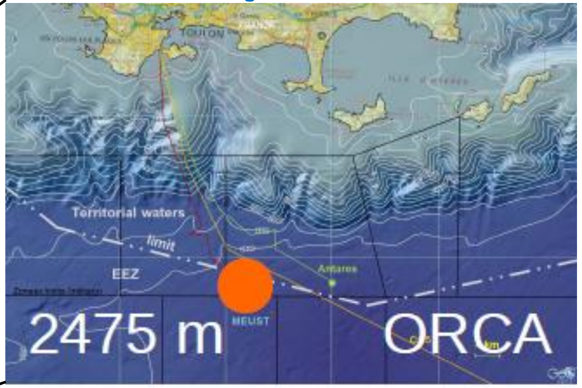
M. Ageron et al., NIM A 656 (2011) 11-38





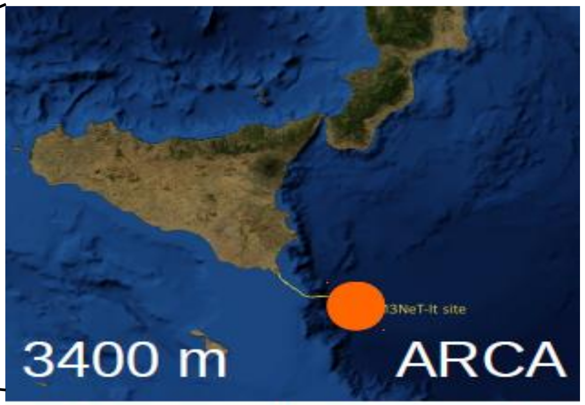
The KM3NeT ARCA and ORCA telescopes





Oscillation **R**esearch with **C**osmics In the **A**byss

See M. Perrin-Terrin's talk!



Astroparticle **R**esearch with **C**osmics In the **A**byss

This talk!

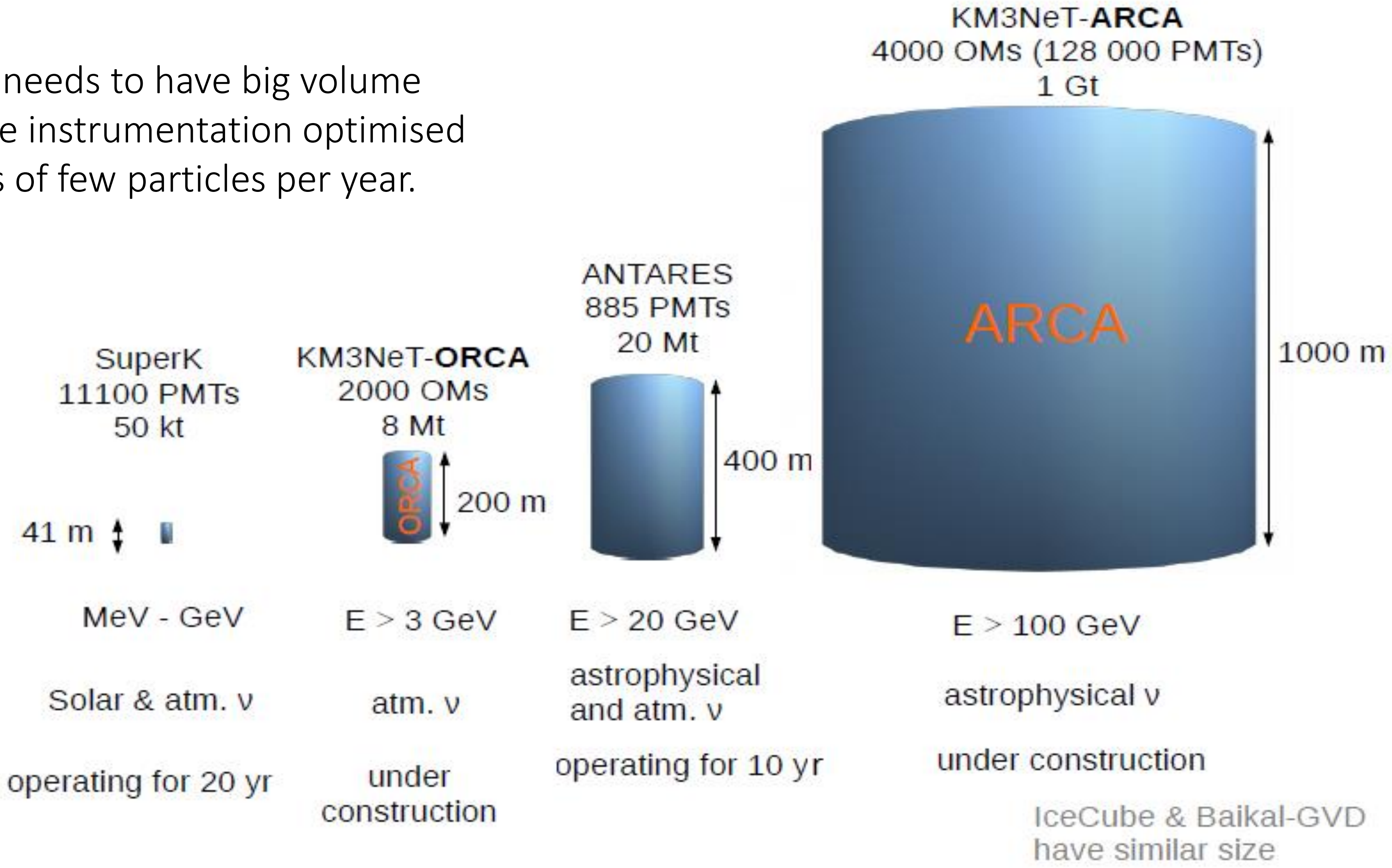
Single collaboration, single technology: 3 blocks of strings in two different sites

S. Adrián-Martínez et al., J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001

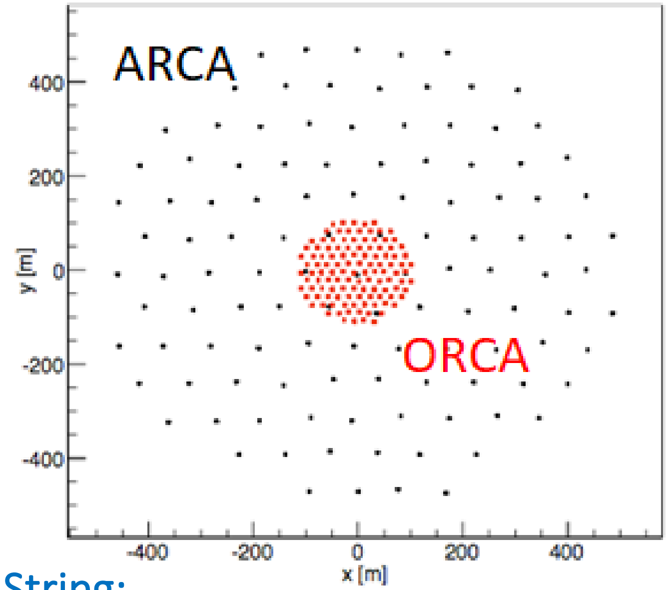
KM3NeT dimensions

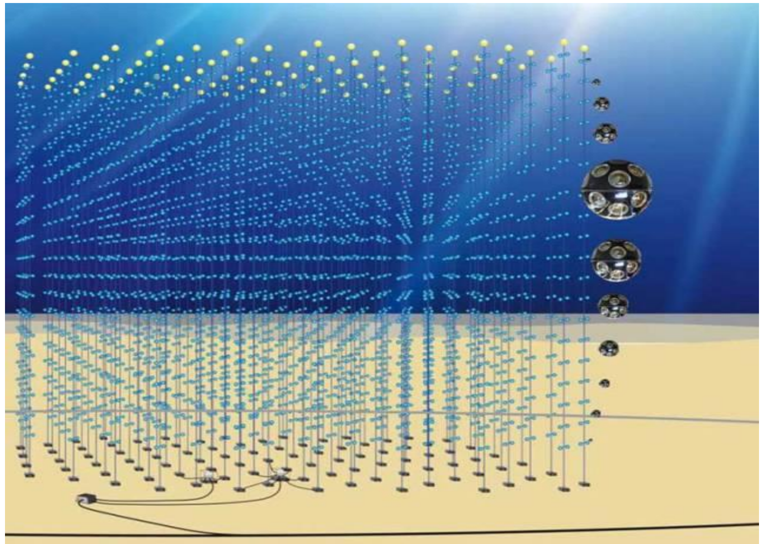
For the high energies one needs to have big volume detectors with a less dense instrumentation optimised for the revelation of fluxes of few particles per year.

For the low energies (less light in apparatus) one needs small and dense instrumented detectors.



KM3NeT configuration & construction





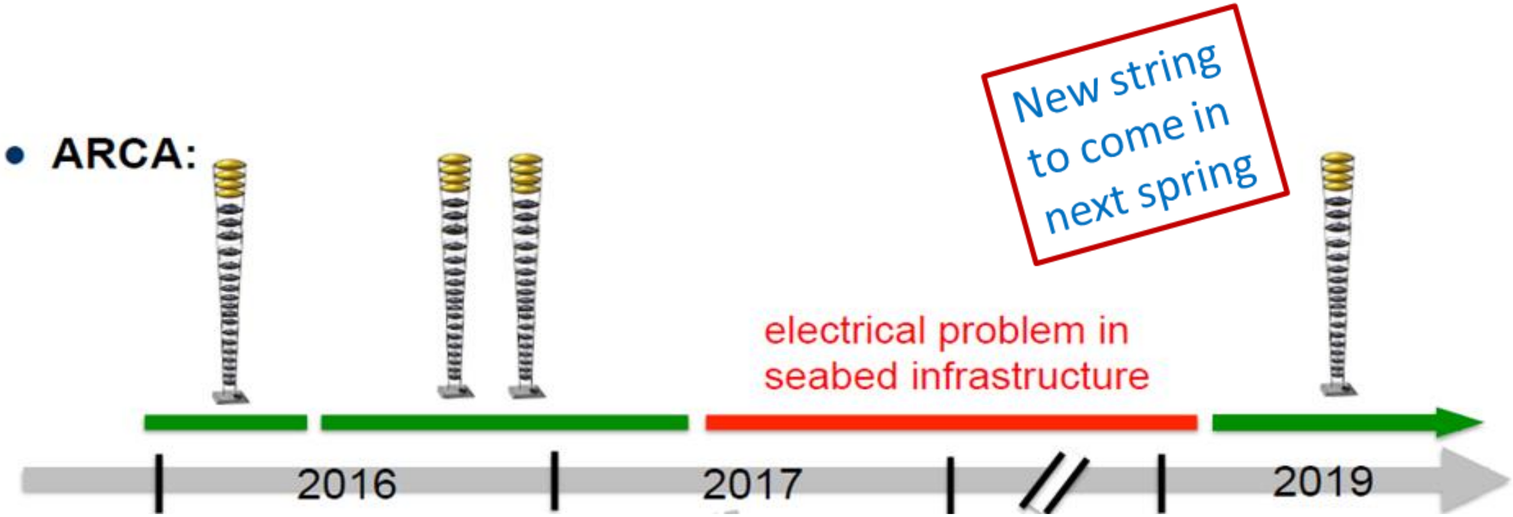
The DOM is a new concept for optical sensors:

a 17” glass sphere hosting:

- 31 x 3” PMTs
- Digital photon counting
- Directional information
- Wide angle of view
- Improved background rejection

String:

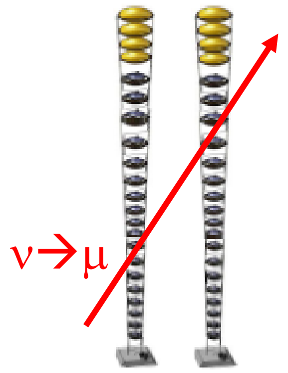
- 1 Buoy, 2 Dyneema ropes
- 18 DOMs
- Electro-optical backbone:
  - 18 fibres, 2 copper wires (375VDC)



Different geometric arrangement for the two ARCA and ORCA:

36 (ARCA) /9 (ORCA) m distance between DOMs
72 (ARCA) /36 (ORCA) m anchor-first storey
750 (ARCA) /250 (ORCA) m total height from seabed

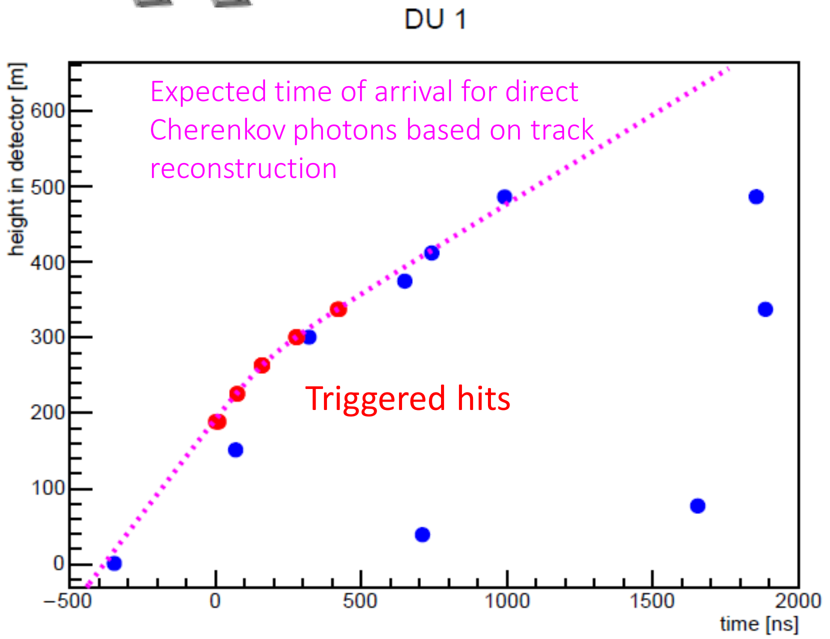
KM3NeT-ARCA first reconstructed neutrinos

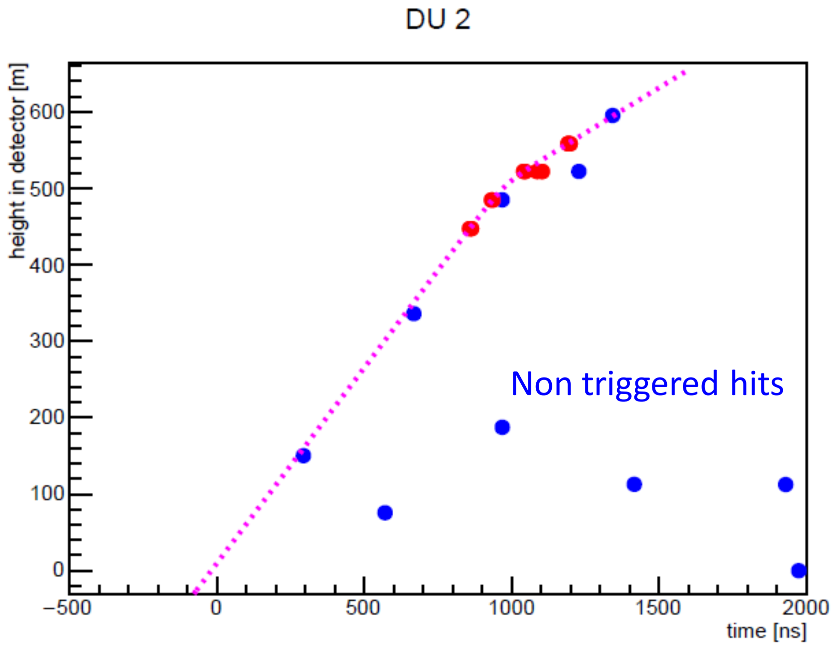


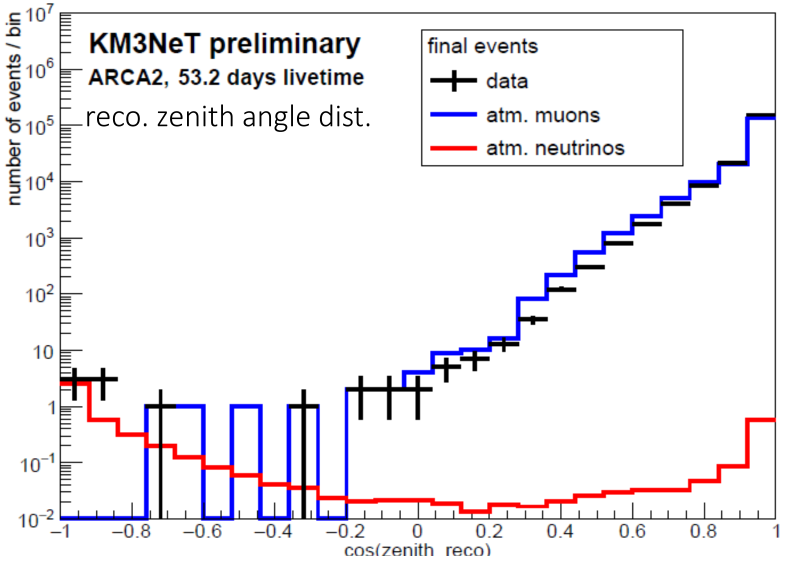
data-sample: 53.2 days of ARCA with 2 DUs

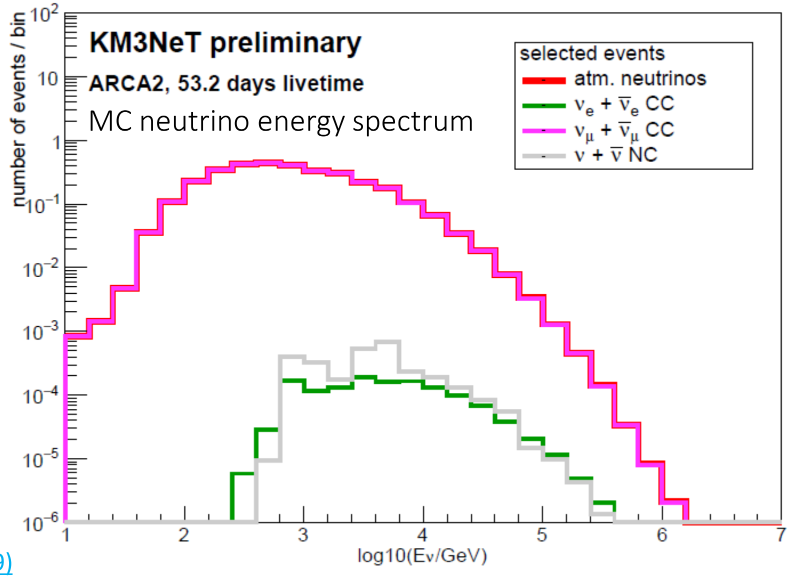
selection: cos(zenith) < -0.8

6 up-going neutrino candidates found!









Height in the detector vs time of recorded PMT hits seen in both DUs of ARCA2 for a neutrino candidate reconstructed as up-going.

J. Hofestaedt et al. (KM3NeT) 36th ICRC,PoS 910, (2019)

KM3NeT muon intensity relation measure

Data sample:

- **ORCA1:** from November 9, 2017 to December 13, 2017
- **ARCA2**: from December 23, 2016 to March 2, 2017

Energy losses in seawater

↓

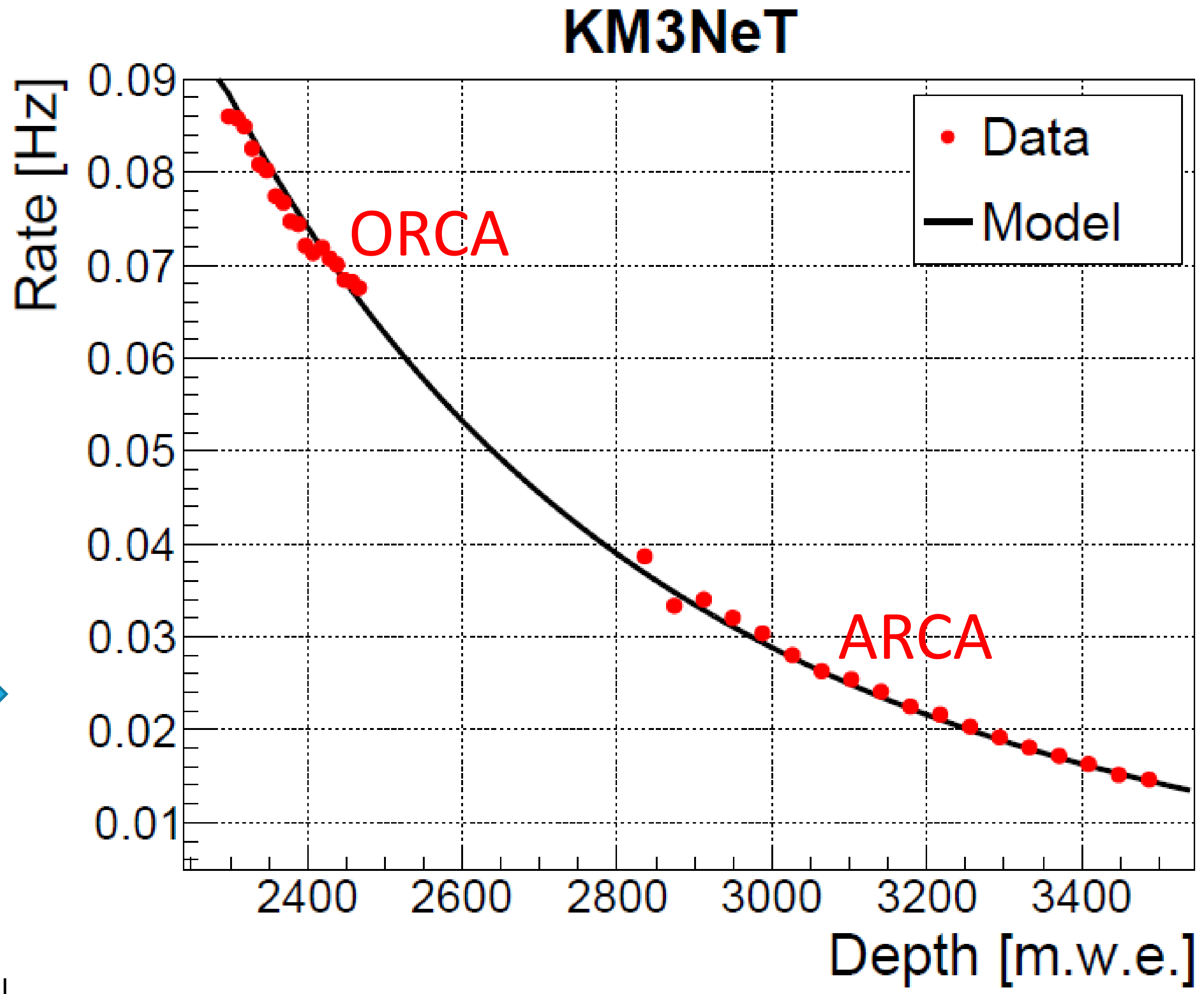
Lower rate of atmospheric μ with increasing depth.

↓

Effect on coincidence rates →

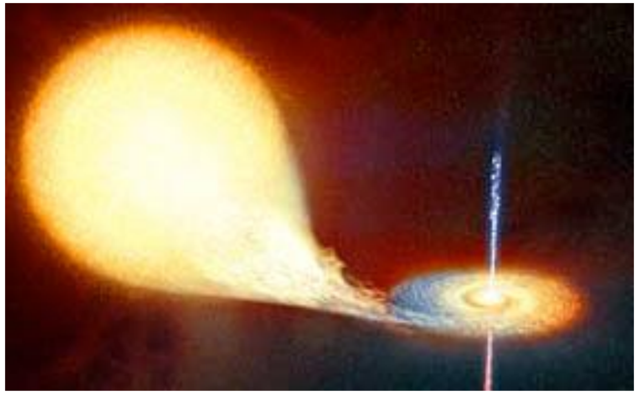
Coincidence rate ∝ muon flux

Parametrization of the underwater muon flux by Bugaev et al.



M. Ageron et al. (KM3NeT) arXiv:1906.02704v1

ANTARES & KM3NeT physics goals



ANTARES & ARCA

Unique aspects of neutrino messengers:

- identify cosmic ray sources;
- qualifies γ-rays hadronic production;
- **discovers blind spot of astronomy to the very high energy Universe.**

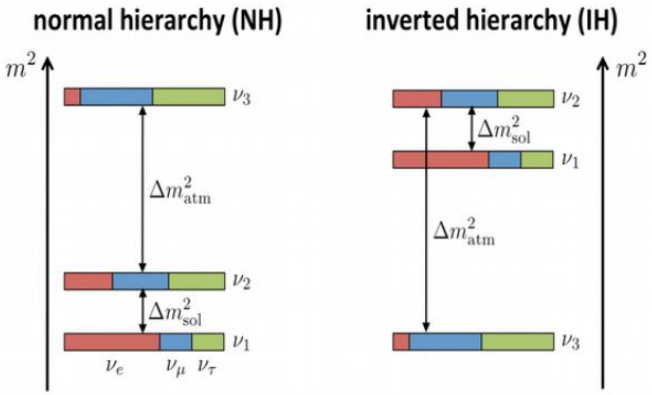
ANTARES & ORCA

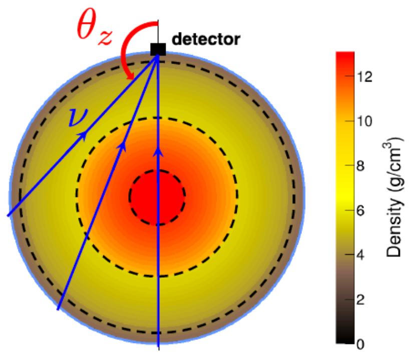
Measuring the ν oscillation & mass hierarchy

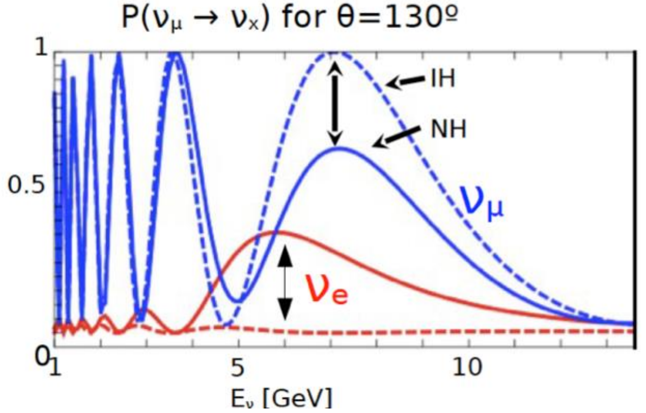
Δm^2_{21} measured (ν solar)

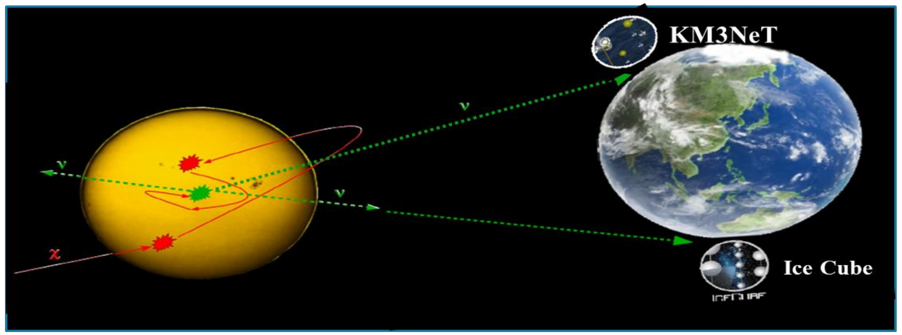
$|\Delta m^2_{32}|$ measured (ν atmospheric)

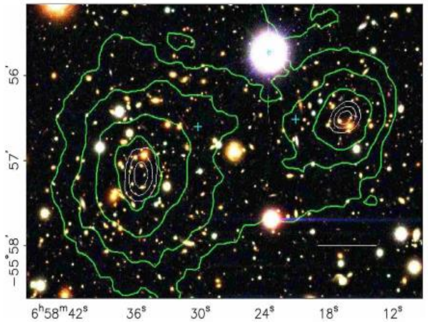
but the sign of Δm^2_{32} still unknown.

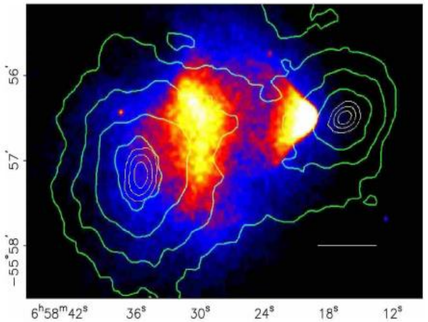












ANTARES & ARCA/ORCA

Indirect search for DarkMatter

ANTARES neutrino oscillations analysis

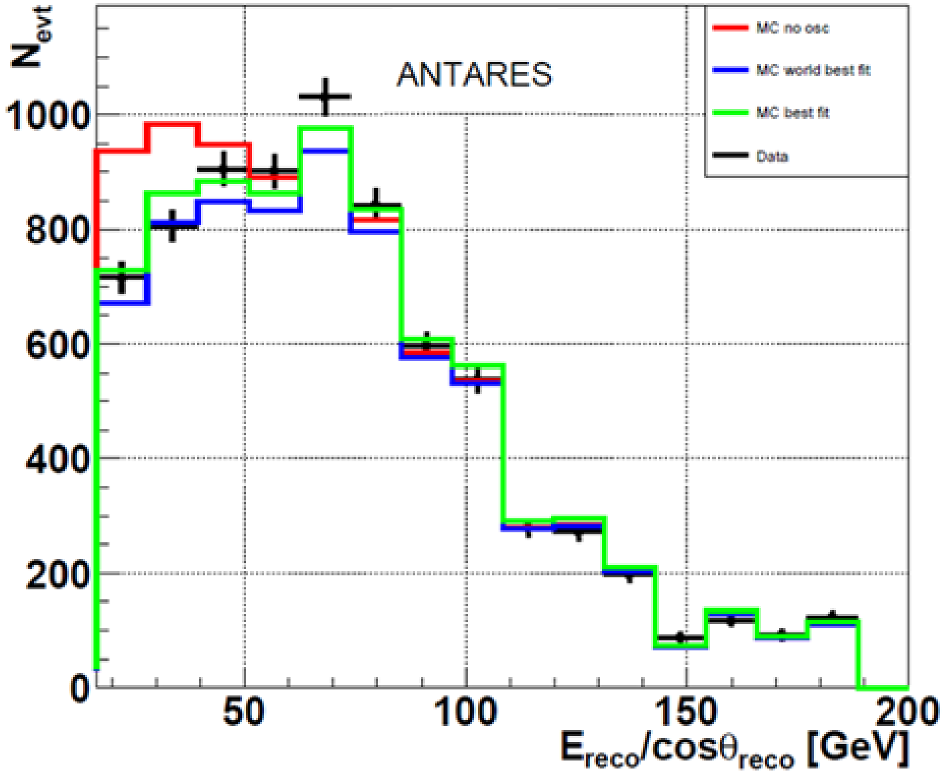
Data sample: 9 years (2007-2016) - 2830 days lifetime, 7710 events selected.

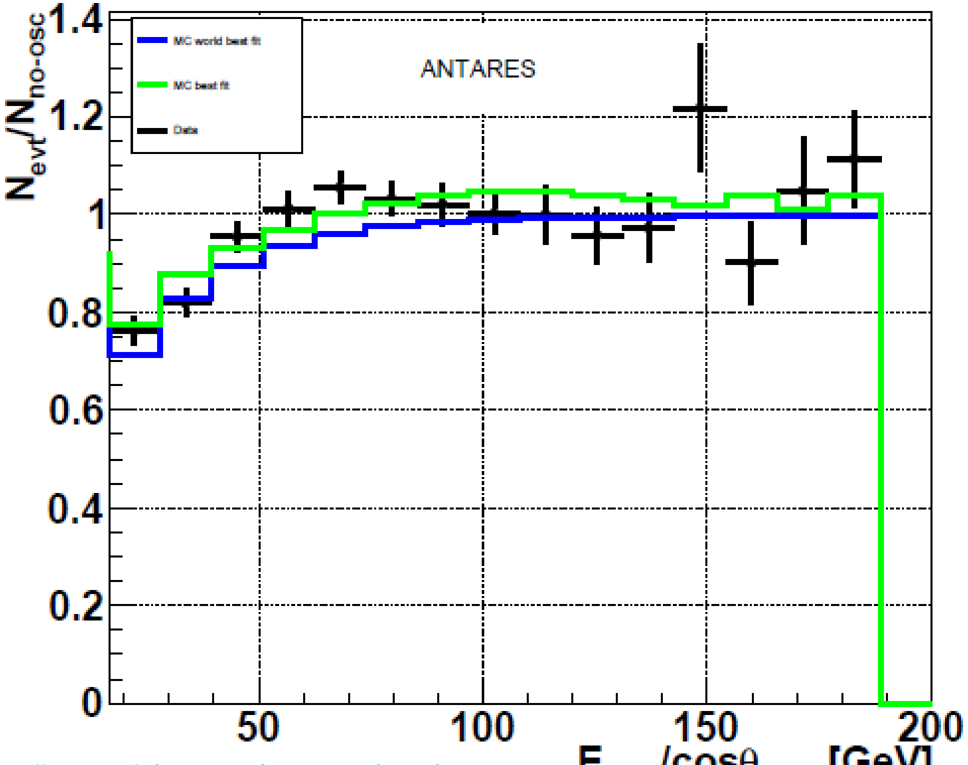
- Two different track reconstruction procedures

ANTARES energy threshold of ≈ 20 GeV → sensitive to the first atmospheric ($P_{\nu\mu\rightarrow\nu\mu}$) oscillation minimum.

→ Study atmospheric ν_μ disappearance due to neutrino oscillations.

Tracks only. A binned likelihood fit is performed in two dimensions (E_{reco}, $\cos\theta_{reco}$)





A. Albert et al. (ANTARES), JHEP 13 (2019)

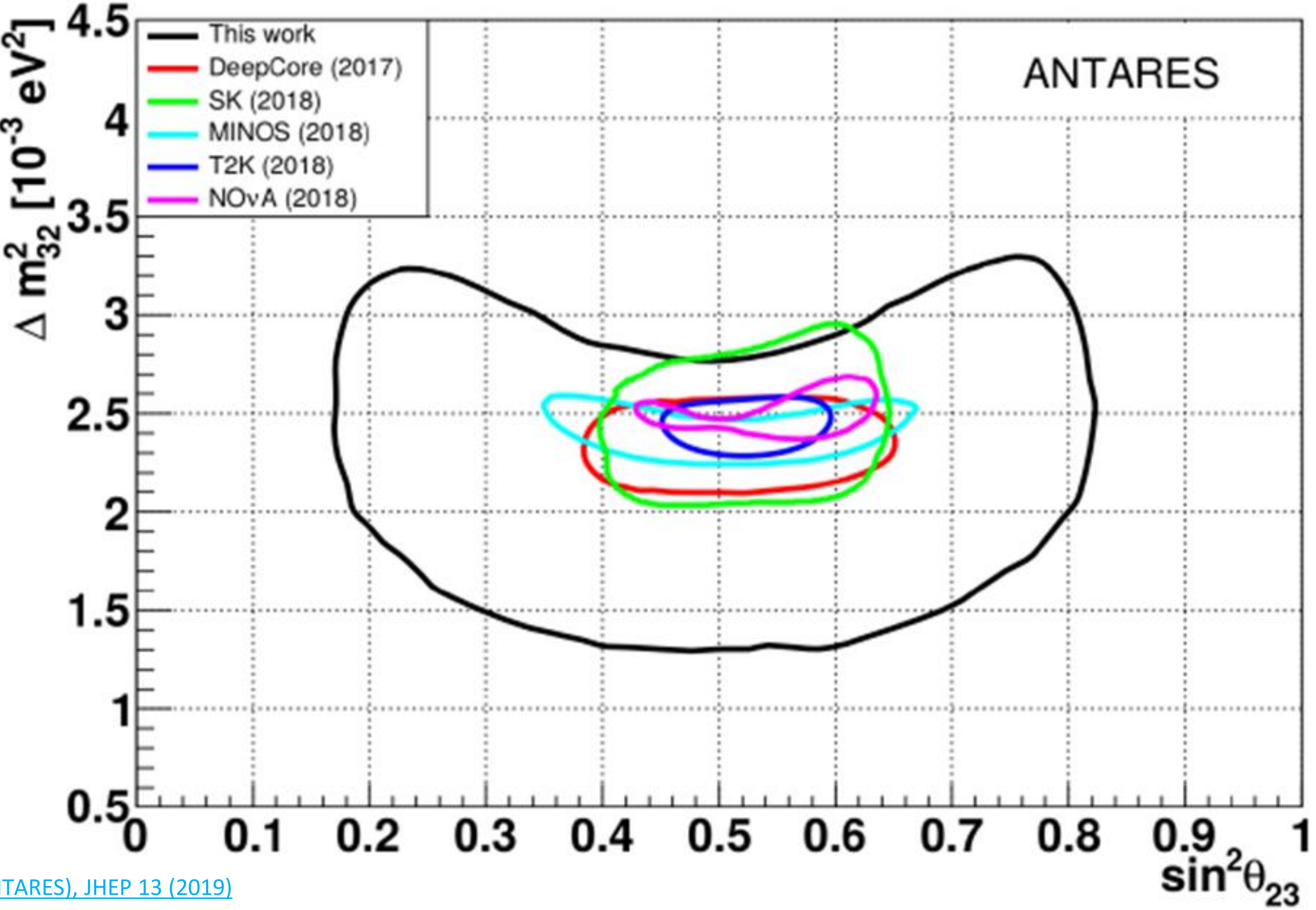
ANTARES neutrino oscillations analysis

Data sample: 9 years (2007-2016) - 2830 days lifetime, 7710 events selected.
- Two different track reconstruction procedures

Bets fit with systematics

Parameter	Prior	Fit result
Δm^2_{32} $[10^{-3}\,\mathrm{eV}^2]$	none	$2.0^{+0.4}_{-0.3}$
θ_{23} $[°]$	none	45^{+12}_{-11}
n_ν	none	$0.81^{+0.10}_{-0.09}$
$\nu/\overline{\nu}$ $[\sigma]$	0.0 ± 1.0	$1.10^{+0.64}_{-0.56}$
$\Delta\gamma$	0.00 ± 0.05	-0.003 ± 0.036
N_μ	740 ± 120	414^{+48}_{-24}
θ_{13} $[°]$	8.41 ± 0.28	8.41 ± 0.28
M_A $[\sigma]$	0.0 ± 1.0	0.0 ± 1.0

The non-oscillation hypothesis is discarded with a signicance of
4.6 σ

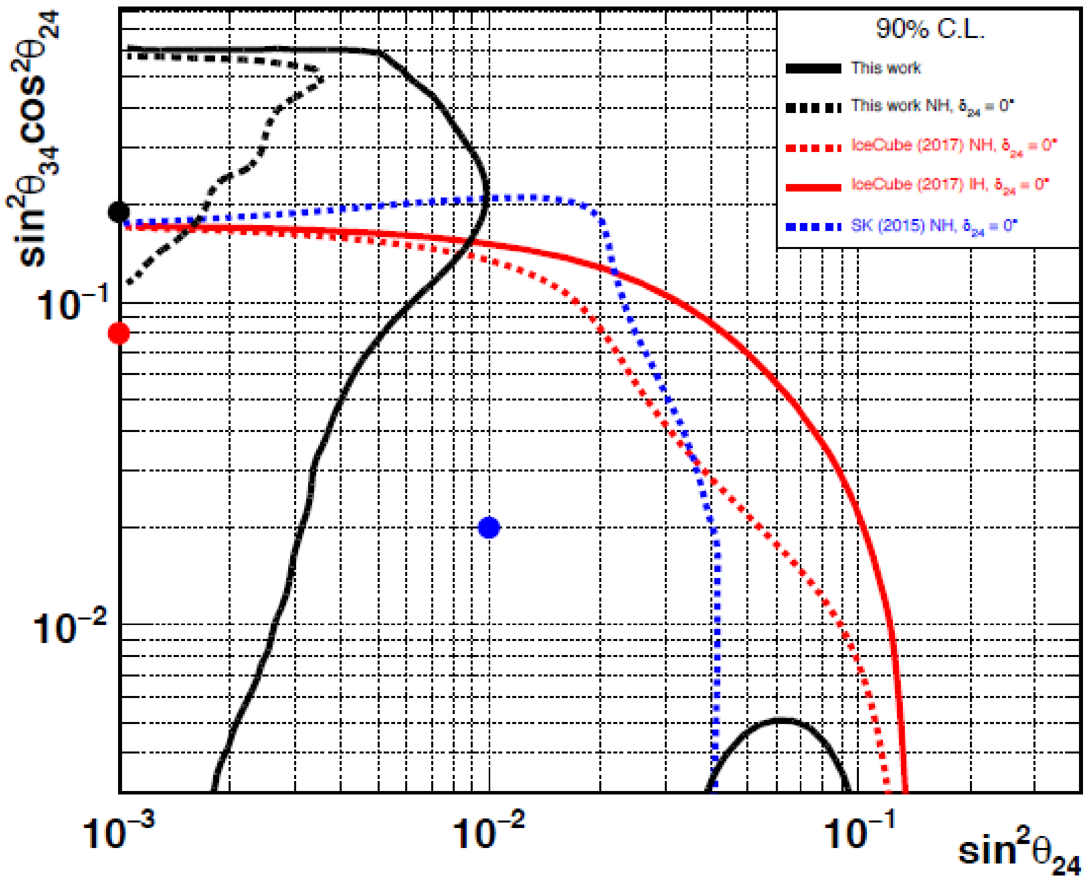


A. Albert et al. (ANTARES), JHEP 13 (2019)

ANTARES sterile neutrino analysis

Sterile neutrino not interact as the active flavors

Still modify the oscillation pattern of the standard neutrinos



A. Albert et al. (ANTARES), JHEP 13 (2019)

Adamson et al. convention used for the mixing matrix U (4 flavors).

$$U_{\mu 4} = e^{-i\delta_{24}} \sin\theta_{24},$$
$$U_{\tau 4} = \sin\theta_{34}\cos\theta_{24}.$$

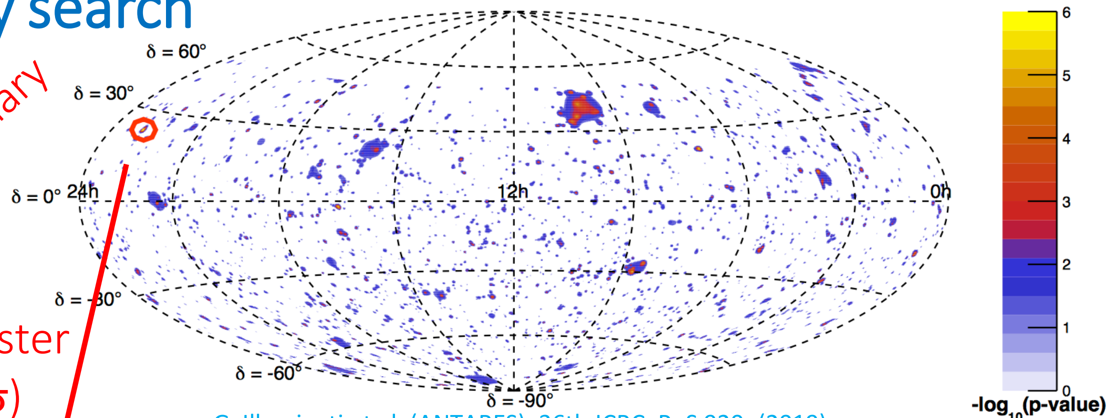
Parameter	Prior	Fit NH	Fit IH
θ_{24} [°]	none	$1.5^{+2.0}_{-5.0}$	$1.5^{+2.0}_{-5.0}$
θ_{34} [°]	none	$25.9^{+5.1}_{-4.2}$	$25.9^{+5.1}_{-4.2}$
δ_{24} [°]	none	180 ± 71	0 ± 72
n_ν	none	$0.84^{+0.10}_{-0.09}$	$0.84^{+0.10}_{-0.09}$
$\nu/\overline{\nu}$ [σ]	0.0 ± 1.0	$1.07^{+0.63}_{-0.55}$	$1.07^{+0.63}_{-0.55}$
$\Delta\gamma$	0.00 ± 0.05	-0.011 ± 0.036	-0.011 ± 0.036
Δm^2_{32} [10^{-3} eV^2]	none	$3.0^{+0.8}_{-0.6}$	$-3.0^{+0.6}_{-0.8}$
θ_{23} [°]	none	52 ± 8	52 ± 8
θ_{13} [°]	8.41 ± 0.28	8.41 ± 0.28	8.41 ± 0.28
M_A [σ]	0.0 ± 1.0	$0.11^{+0.93}_{-0.97}$	$0.11^{+0.93}_{-0.97}$

$$|U_{\mu 4}|^2 < 0.007\ (0.13)\ \text{at}\ 90\%\ (99\%)\ \text{CL},$$
$$|U_{\tau 4}|^2 < 0.40\ (0.68)\ \text{at}\ 90\%\ (99\%)\ \text{CL}.$$

ANTARES point sources analysis

All-sky search

preliminary



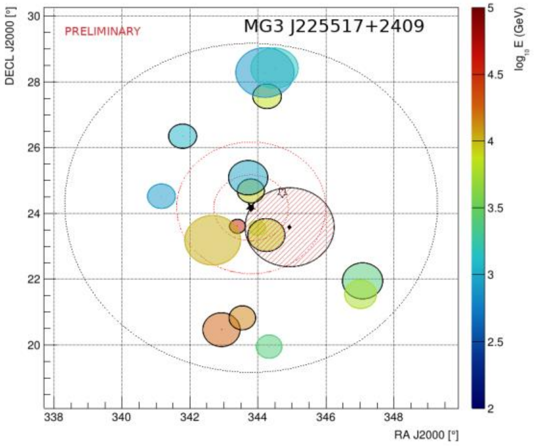
best cluster (1.2 σ)

G. Illuminati et al. (ANTARES), 36th ICRC, PoS 920, (2019)

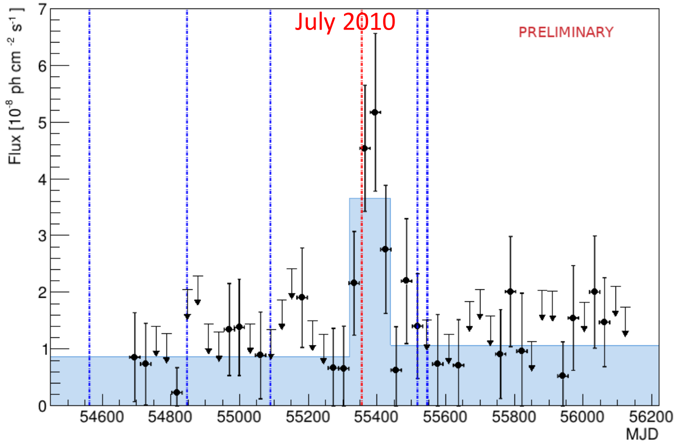
α=343.7° δ=+23.6° Blazar MG3 J225517+2409 (EHE IC#3 event)

3 track events within 1°: 15 tracks + 1 shower within 5°

Candidate list search



J. Aublin (ANTARES), 36th ICRC, PoS 840, (2019)



Time analysis & combining the **IceCube - ANTARES** events: **2.4 σ excess**

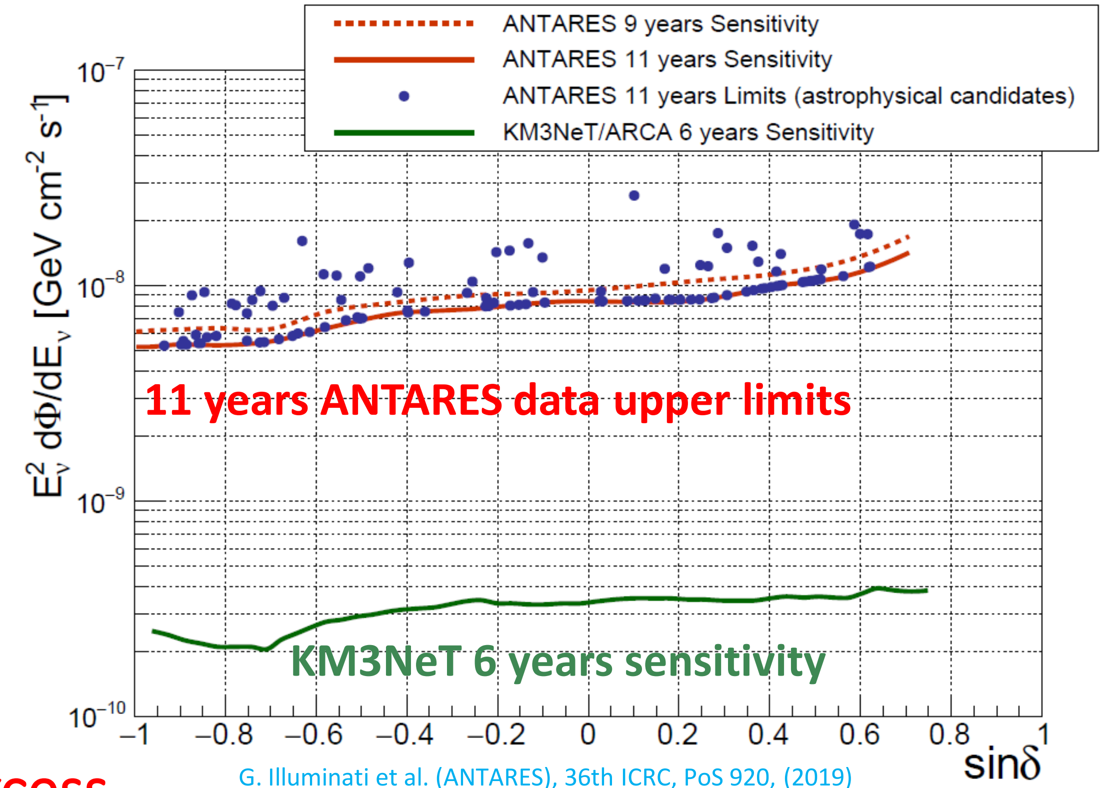
11 yrs of data - 3136 days lifetime

8754 events reconstructed and selected as tracks

Median angular resolution < 0.4° above 10 TeV

1) Global fitting (stacked search)

2) Perform individual fit for each source



G. Illuminati et al. (ANTARES), 36th ICRC, PoS 920, (2019)

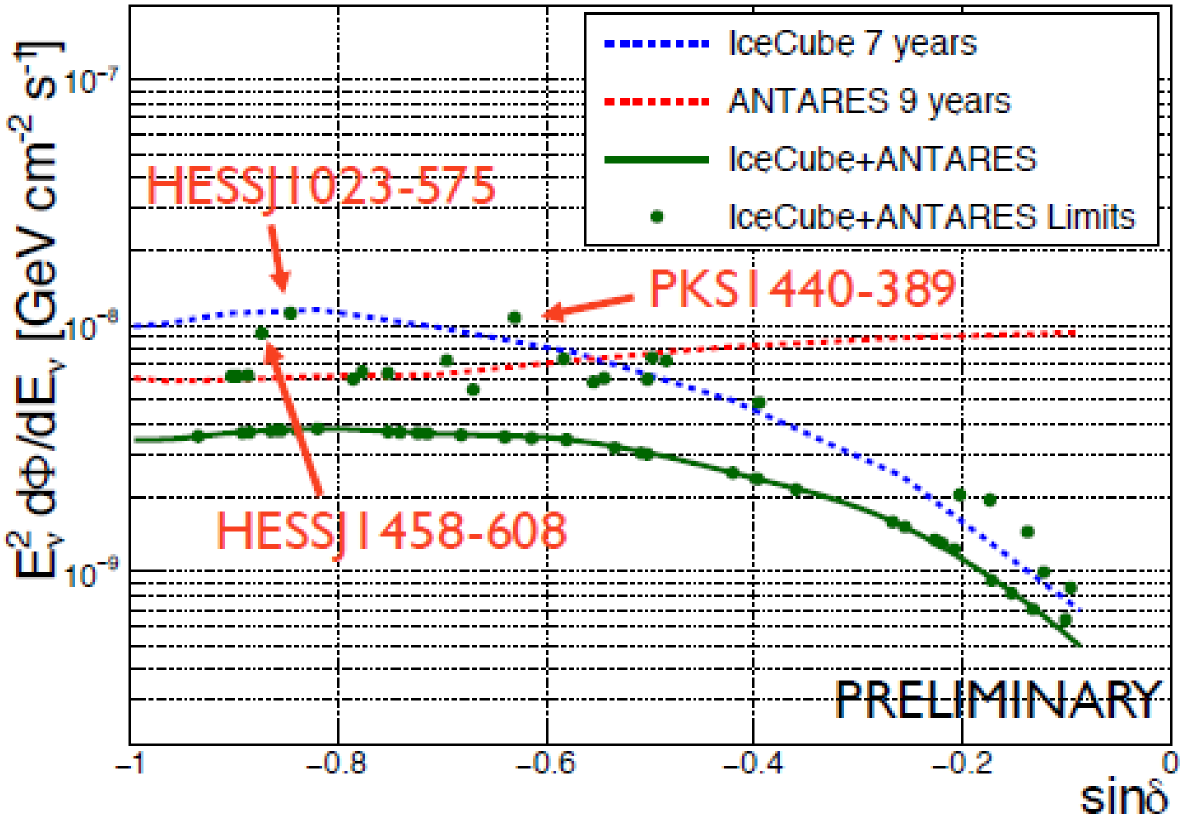
ANTARES + IceCube point sources analysis

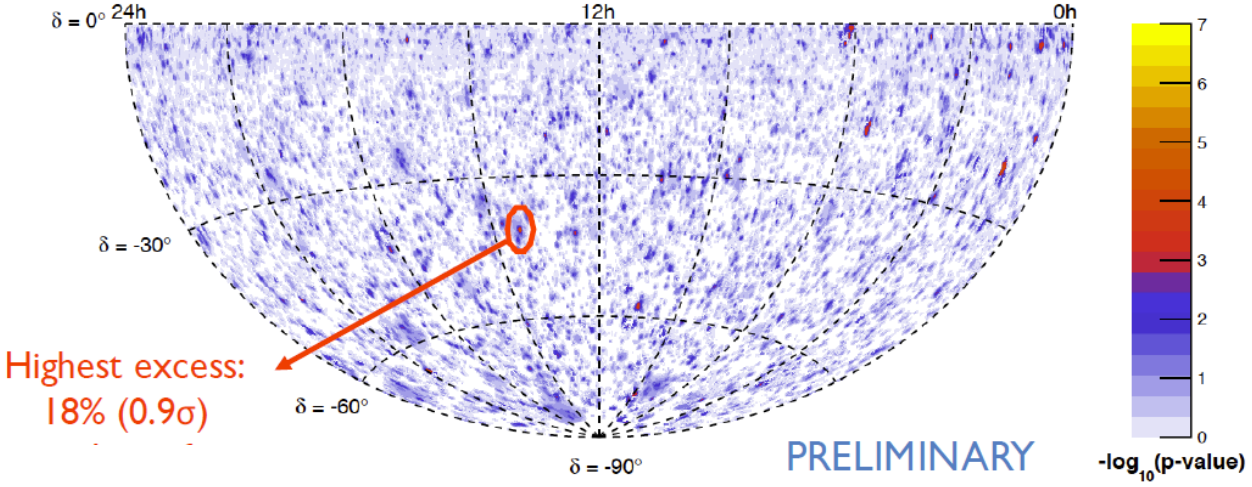
Data sample (look at southern sky):

ANTARES 9 years: tracks and shower (5909 events)

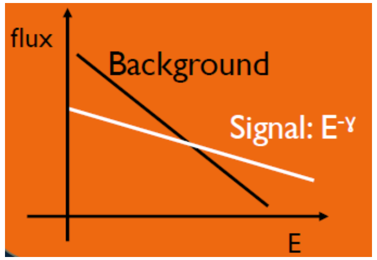
IceCube 7 years: through-going tracks (119 kevents)

90% C.L. Sensitivity and Limits for $\gamma = 2.0$

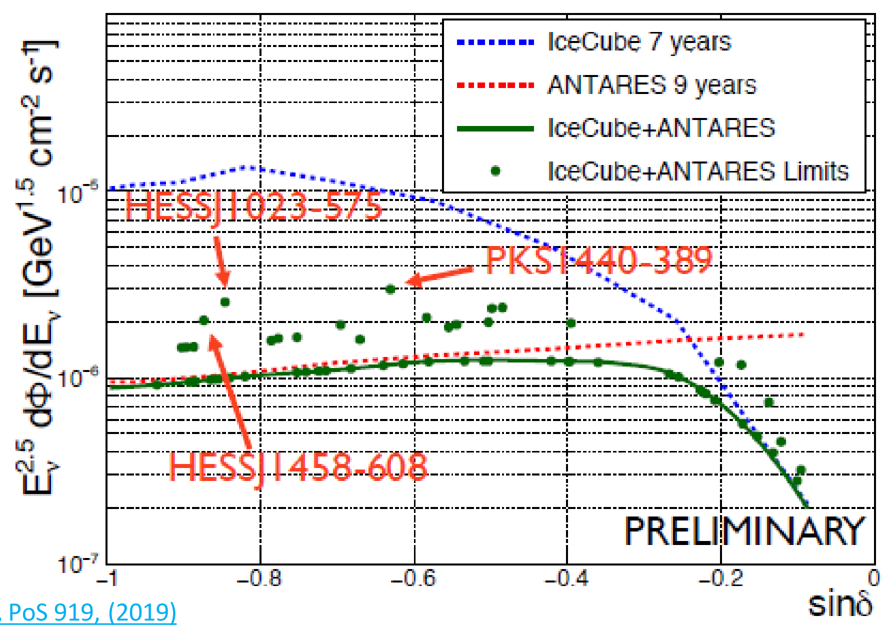




Improvement of a factor ≈2 of the combined search in regions of the Southern sky

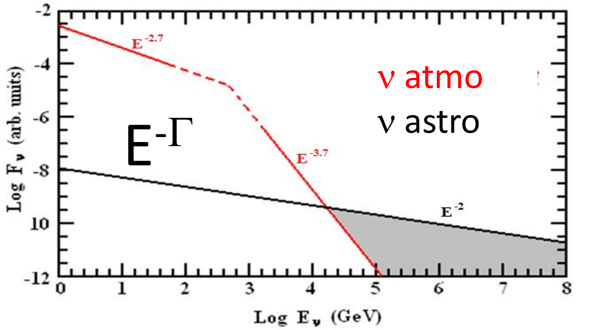


90% C.L. Sensitivity and Limits for $\gamma = 2.5$



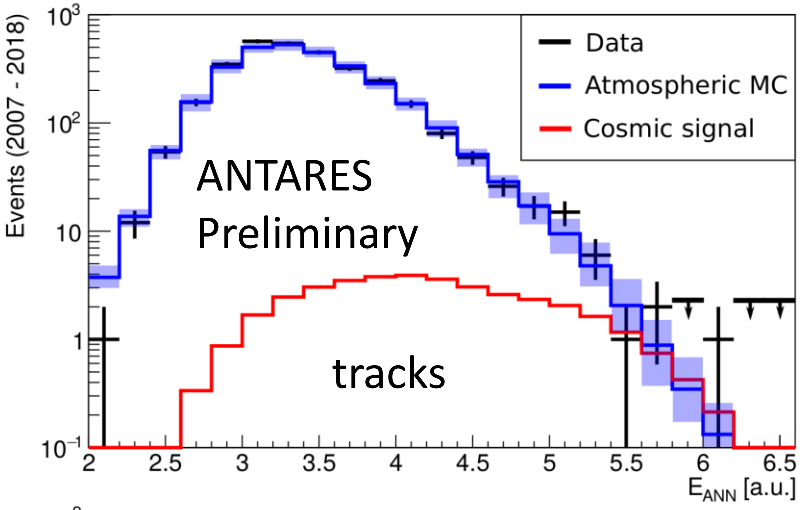
G. Illuminati (ANTARES), 36th ICRC, PoS 919, (2019)

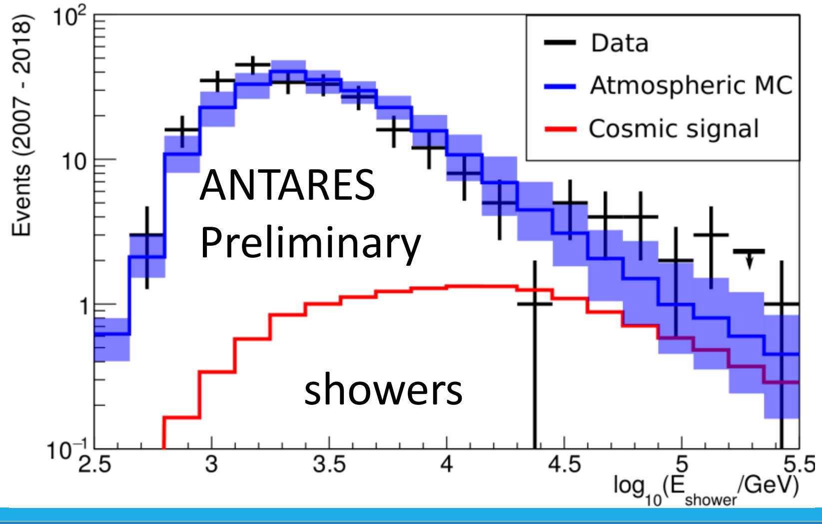
ANTARES diffuse flux analysis



11 yrs of data
3380 days lifetime

data: **50** events (**27** tracks + **23** showers)
bkg MC: **36.1 ± 8.7** (stat.+syst.): **19.9** tracks and **16.2** showers





Likelihood fitting of the high-energy sample

Atmospheric (Honda + Enberg together) fitted simultaneously with the cosmic flux normalisation and spectral index of the track and shower samples together

L. Fusco et al. (ANTARES), 36th ICRC, PoS 891, (2019)

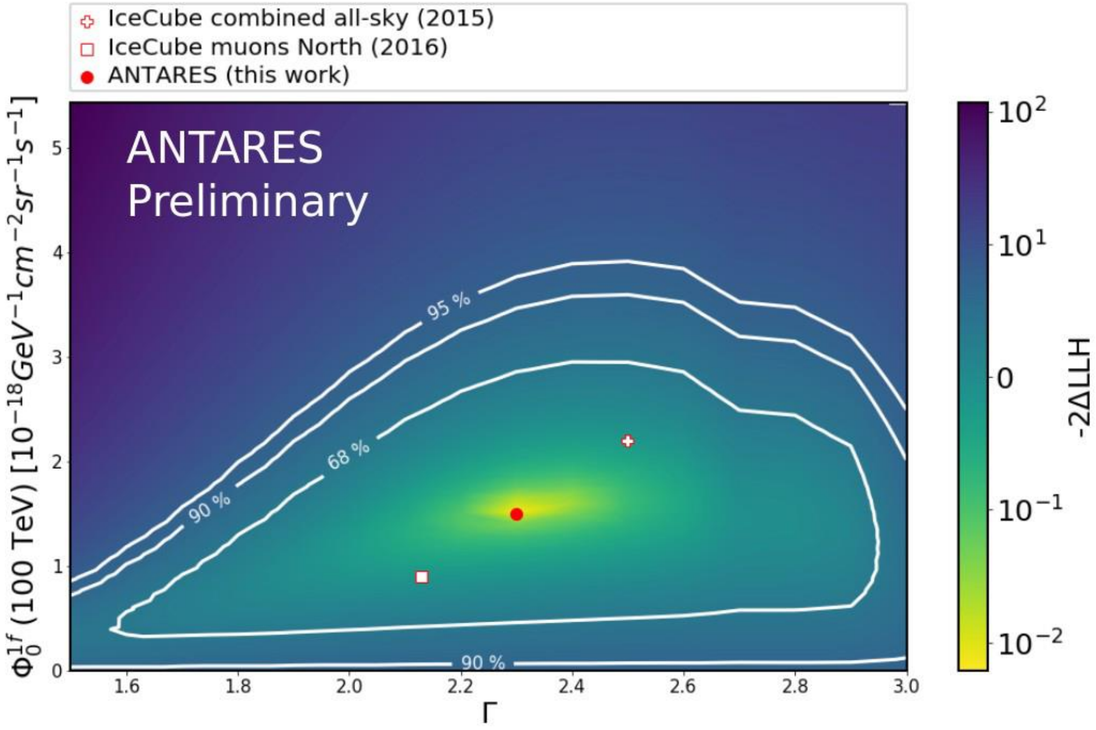
Tracks:

$\Phi(100\ \mathrm{TeV}) = (1.5 \pm 1.0)\times 10^{-18}\ (\mathrm{GeV\ cm^2\ s\ sr})^{-1}$

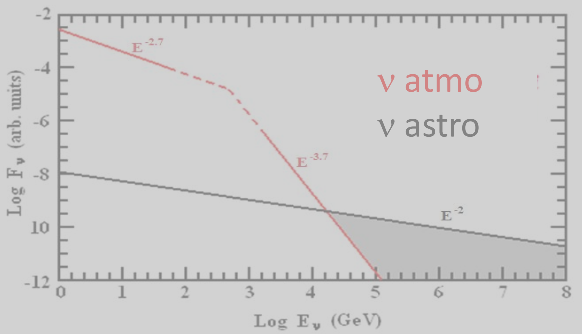
$\Gamma = 2.3 \pm 0.4$

1.8σ excess

0-cosmic excluded c.l. >90%



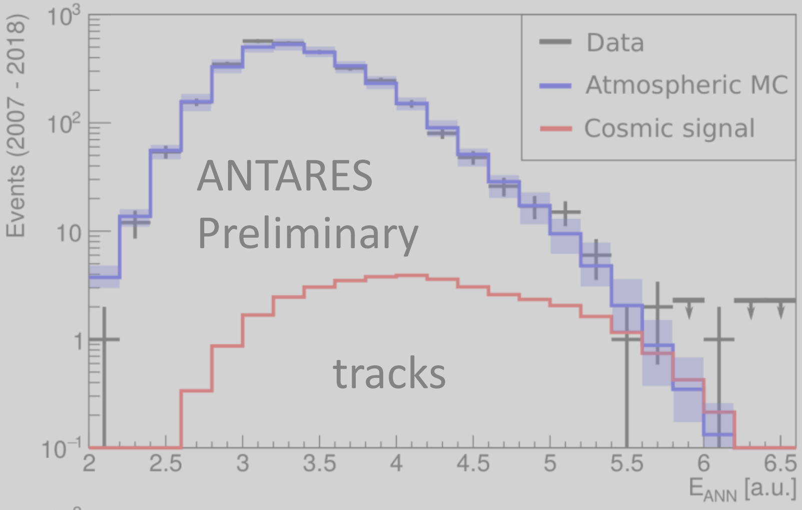
ANTARES diffuse flux analysis

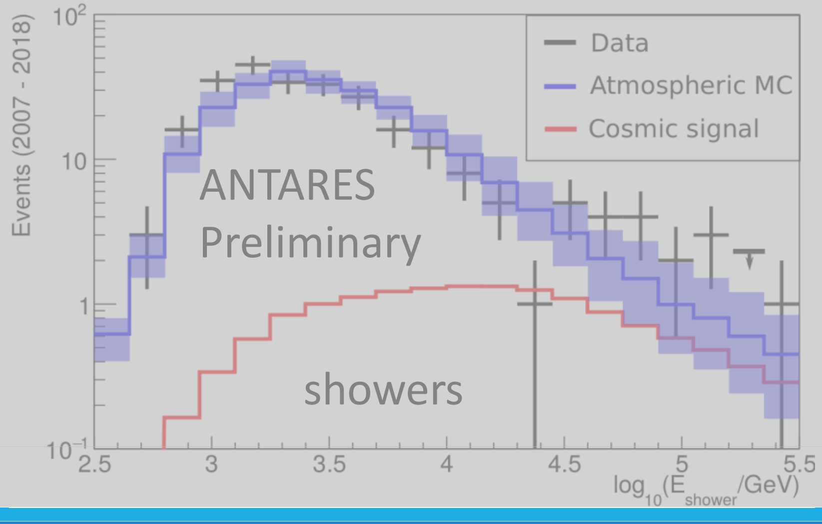


data: 50 events (27 tracks + 23 showers)

bkg MC: 36.1 ± 8.7 (stat.+syst.): 19.9 tracks and 16.2 showers

Null-cosmic rejected at 90% c.l. using counting statistics (*Conrad et al*. method, with syst.), atmospheric background scaled up by ~25%





Likelihood fitting of the high-energy sample

Atmospheric (Honda + Enberg together) fitted simultaneously with the cosmic flux normalisation and spectral index of the track and shower samples together

L. Fusco et al. (ANTARES), 36th ICRC, PoS 891, (2019)

Tracks:

$\Phi(100\ \text{TeV}) = (1.5 \pm 1.0) \times 10^{-18}\ (\text{GeV cm}^2\ \text{s sr})^{-1}$

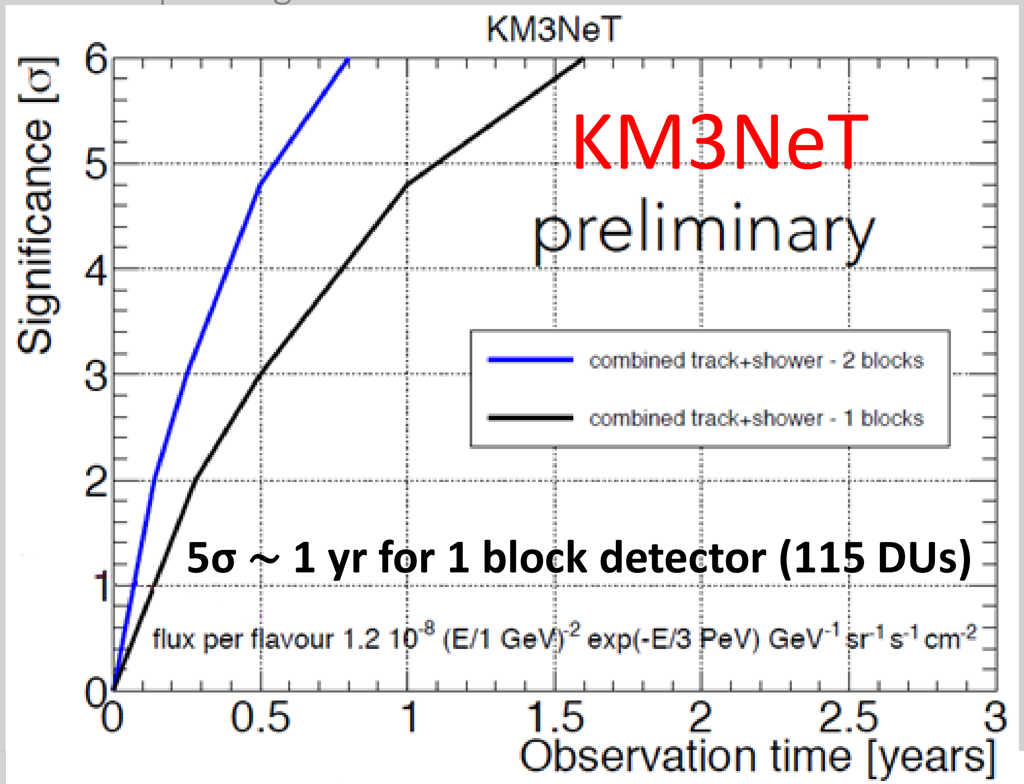
$\Gamma = 2.3 \pm 0.4$

Atmospheric flux

1.25 x (Honda + Enberg)

1.8σ excess

0-cosmic excluded c.l. >90%



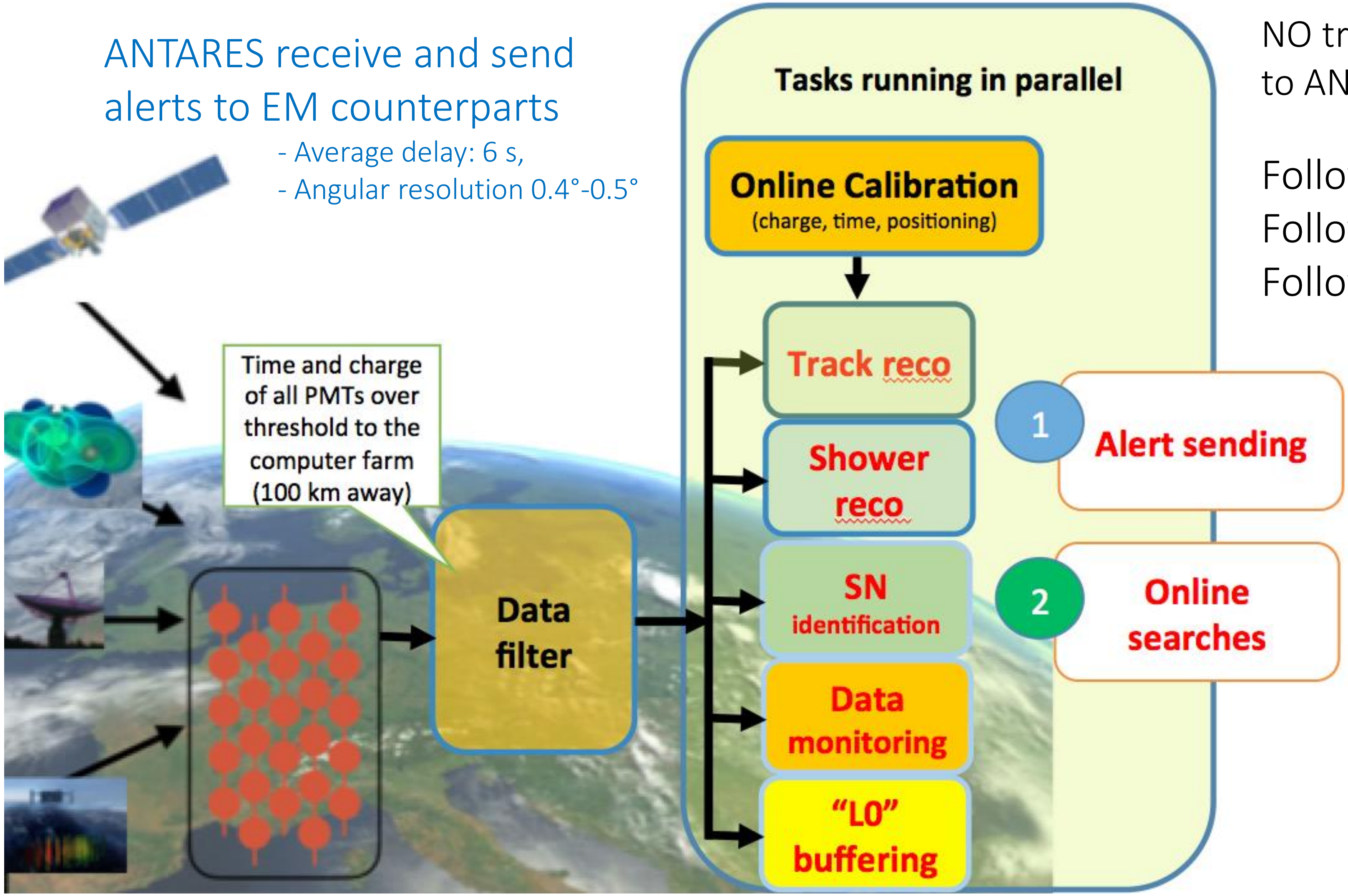
R. Coniglione et al. (ANTARES/KM3NeT), 36th ICRC, PoS 006, (2019)

Multimessenger alert system

Multi-messenger approach: look for neutrinos in coincidence in space and time with signals detected by other observatories

ANTARES receive and send alerts to EM counterparts

- Average delay: 6 s,
- Angular resolution 0.4°-0.5°



NO transient source associated to ANTARES alerts

Follow-up of GW - runs O2 and O3
Follow-up of 11 high energy IC alerts
Follow-up of GRB triggers
(226 Swift and 536 Fermi GRBs.)

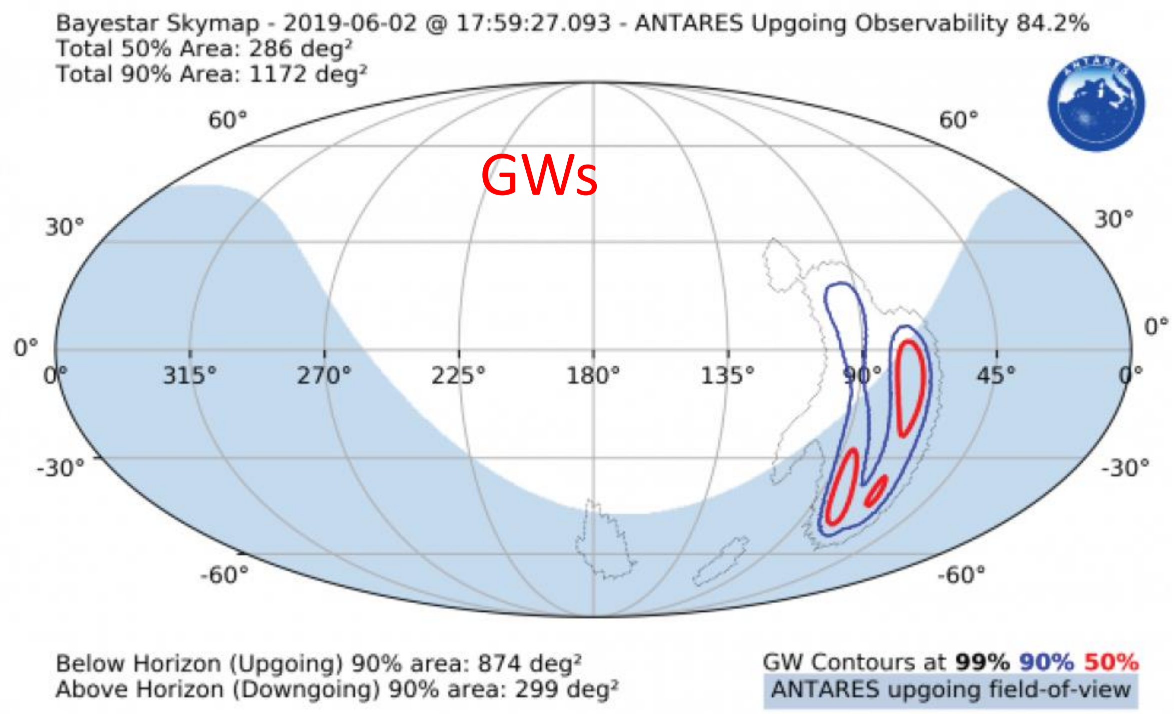
NO ν associated to external alerts

ANTARES real time follow-up of multimessenger alerts

Transient astrophysical events are observed all over the electromagnetic spectrum

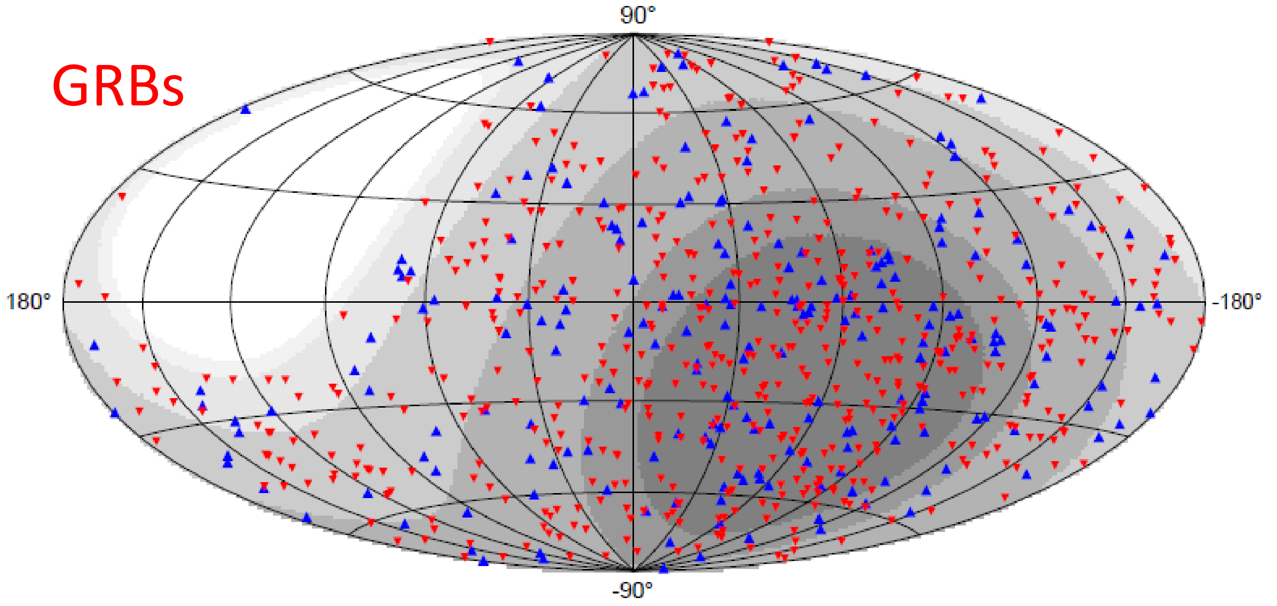
Public alerts of transient source → **Real-time** analyses (**time and space coincidence**) to look for neutrino events.

More optimized offline analyses to search for neutrino counterparts to catalogued transients.



LIGO/VIRGO run O3, S190602aq, BBH

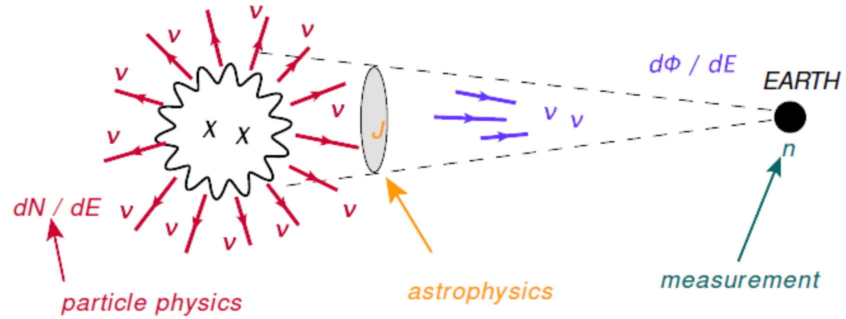
Only bursts with direction visible in the ANTARES horizon analysed



Positions of Fermi and Swift GRBs followed by ANTARES

[A. Coleiro et al. (ANTARES), 36th ICRC, PoS 872, (2019)]

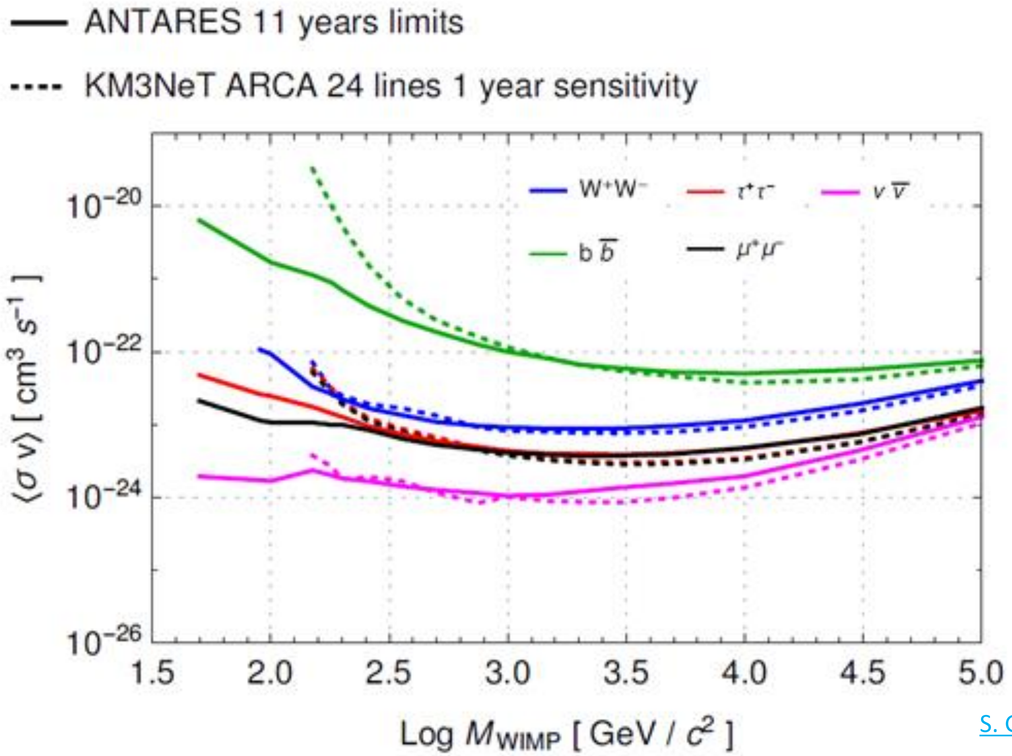
ANTARES & KM3NeT Dark Matter from Galactic Centre



Data: **11 years** (3170 days lifetime) → compatible with background

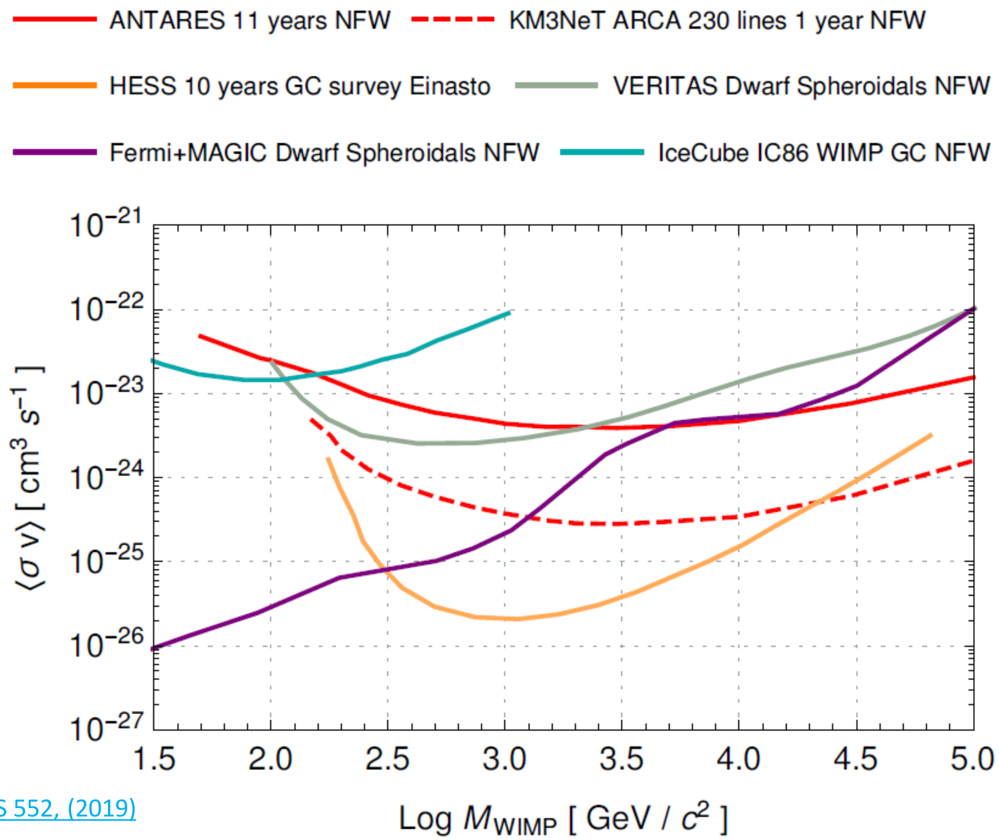
$$\Phi = \frac{n}{\mathcal{A}(M_\chi)\,t} = \frac{1}{4\pi}\frac{1}{M_\chi^2}\frac{\langle\sigma v\rangle}{2}\int_0^M \frac{dN}{dE}dE\,J$$

flux = number of events observed / acceptance * lifetime = annihilation rate * average number of particles per collision * source geometry



Upper limits on $\nu_\mu + \bar{\nu}_\mu$ flux at 90% C.L. converted in <σv> limits.

<σv>: thermally averaged cross section for WIMP pair annihilation



S. Gozzini et al. (ANTARES/KM3NeT), 36th ICRC, PoS 552, (2019)

Conclusions and prospects

- ANTARES is the first neutrino telescope in the northern hemisphere, active since 2008;
- ANTARES provides **unprecedented sensitivity for neutrino source** searches **in the southern sky** at TeV energies;
  - Valuable constraints has been set on the origin of the cosmic neutrinos;
  - Different multi-messenger real-time searches of transient sources are active;
  - Results consistent with the best fit values for neutrino oscillation parameters;
  - Dark matter upper limits competitive with the IceCube ones at low energies.

- KM3NeT-ARCA will be among the larger neutrino telescopes: **more than one km^3 volume**;
- ARCA devoted to high-energy physics and ORCA for low-energy physics;
- Currently there are 5 strings in water, and more in preparation to be deployed in this year.

- First neutrinos seen with KM3NeT and the muon intensity relation measured at the deepest sea lever ever → new valuable results to come!

Thanks for your attention!

Neutrinos in the multimessenger scenario

Cosmic ray (CR) acceleration eventually occurring in cataclysmic events, sometimes are seen in gravitational waves.

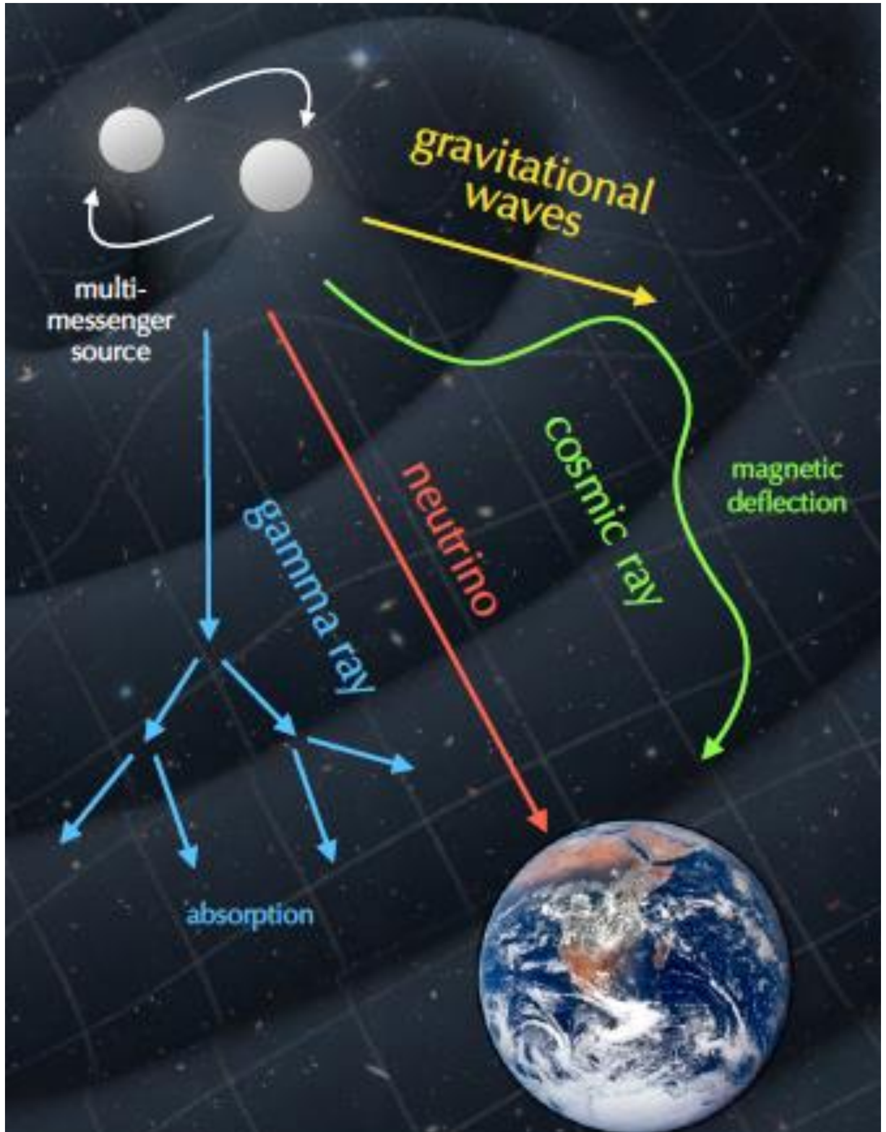
If hadrons accelerated in the source: inelastic collisions with radiation or gas (p+γ or p+N→ X+pions) produce γ-rays and neutrinos, e.g:

$$\pi^0 \rightarrow \gamma + \gamma$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \bar{\nu}_\mu + \nu_\mu$$

- **Photons**: easy to detect and very abundant, but:
  - Hot and dense regions (astrophysical sources) are opaque;
  - High energy photons can be absorbed by CMB via e^+e^- production.
- **Protons**: feel the effect of magnetic fileds and CMB.

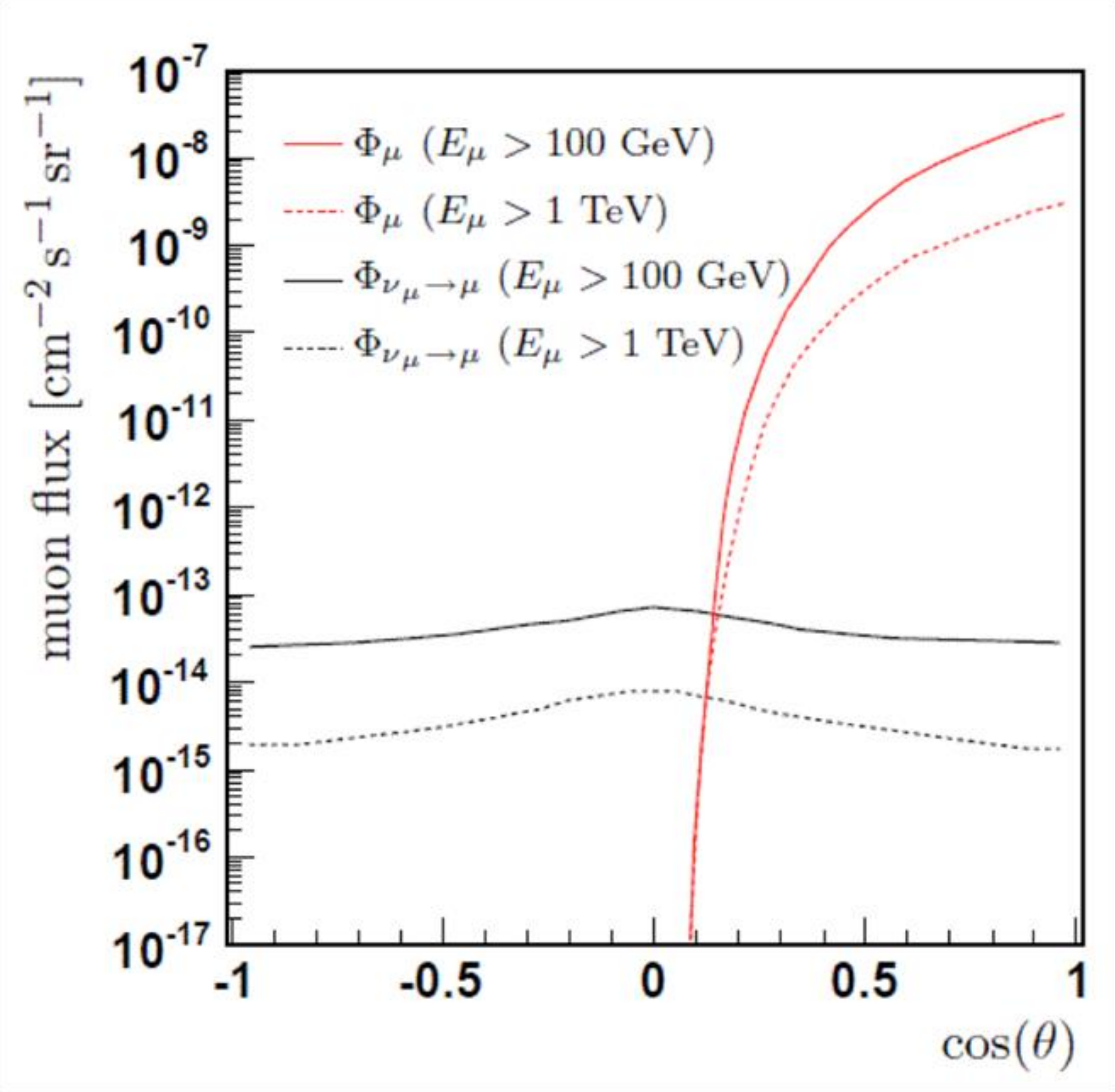
✓ **Neutrinos**:
  - **Weakly interacting** (pass through dense and opaque regions);
  - **Electrically neutral** (not deflected by magnetic fields);
  - **Stable** (travel on long distances unaltered)

Neutrino astronomy

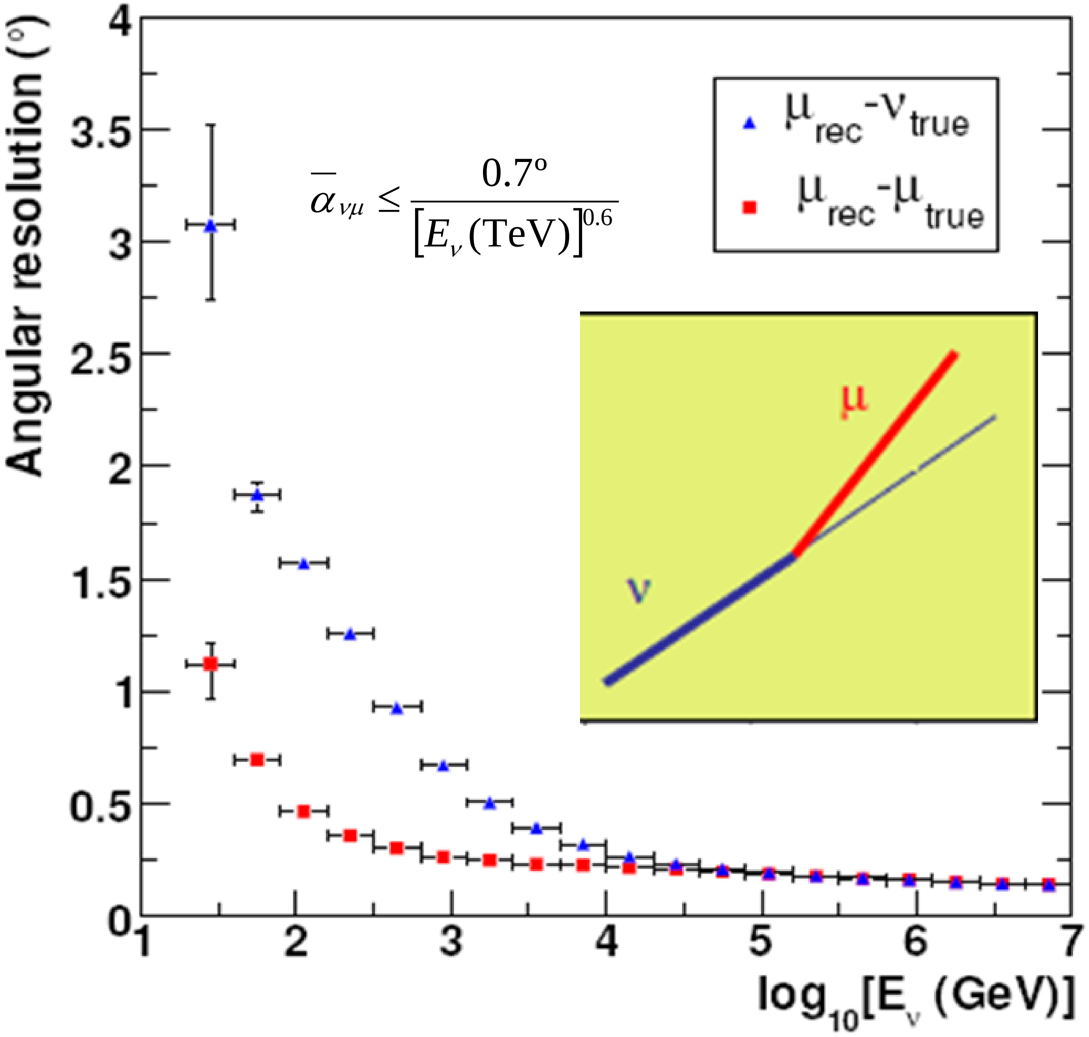


M. Ahlers, RICAP18

ANTARES



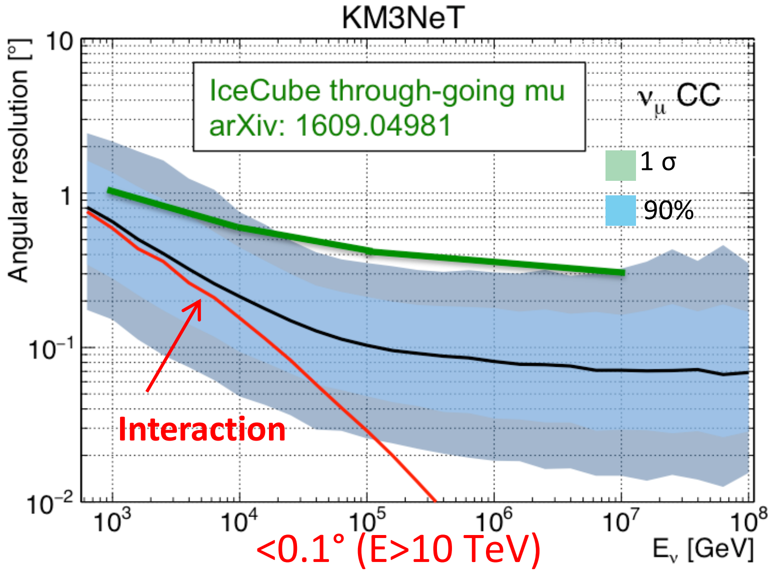
muon flux $[\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}]$
$\Phi_\mu\ (E_\mu > 100\ \mathrm{GeV})$
$\Phi_\mu\ (E_\mu > 1\ \mathrm{TeV})$
$\Phi_{\nu_\mu\to\mu}\ (E_\mu > 100\ \mathrm{GeV})$
$\Phi_{\nu_\mu\to\mu}\ (E_\mu > 1\ \mathrm{TeV})$
$\cos(\theta)$



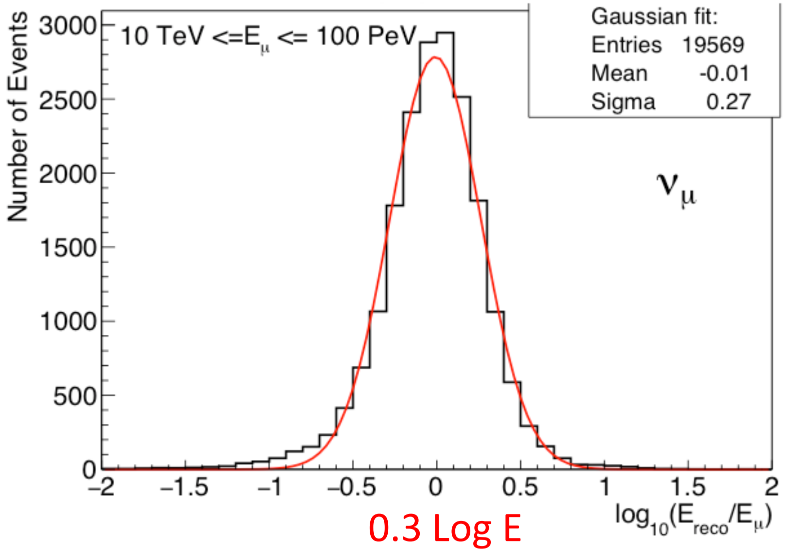
Angular resolution (°)
$\bar{\alpha}_{\nu\mu} \le \frac{0.7^o}{[E_\nu(\mathrm{TeV})]^{0.6}}$
$\mu_{rec}-\nu_{true}$
$\mu_{rec}-\mu_{true}$
μ
ν
$\log_{10}[E_\nu\ (\mathrm{GeV})]$

KM3NeT - ARCA

Track events

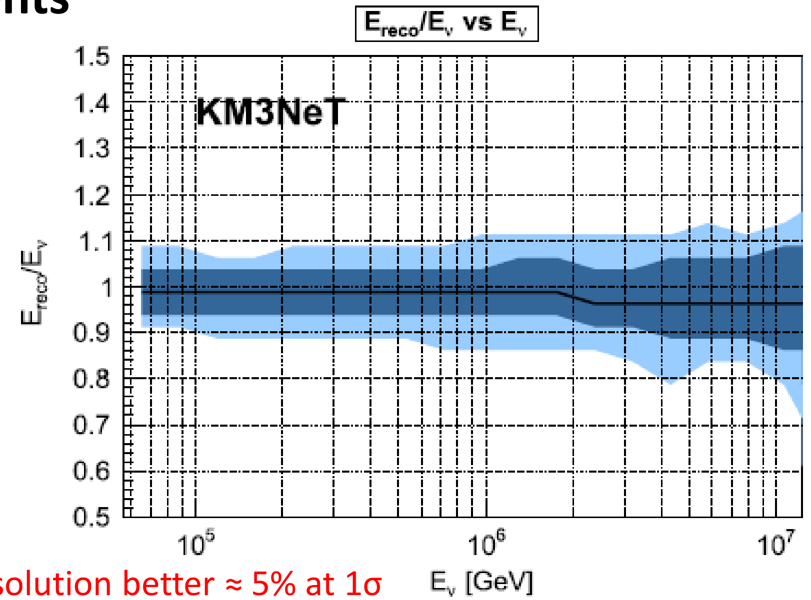


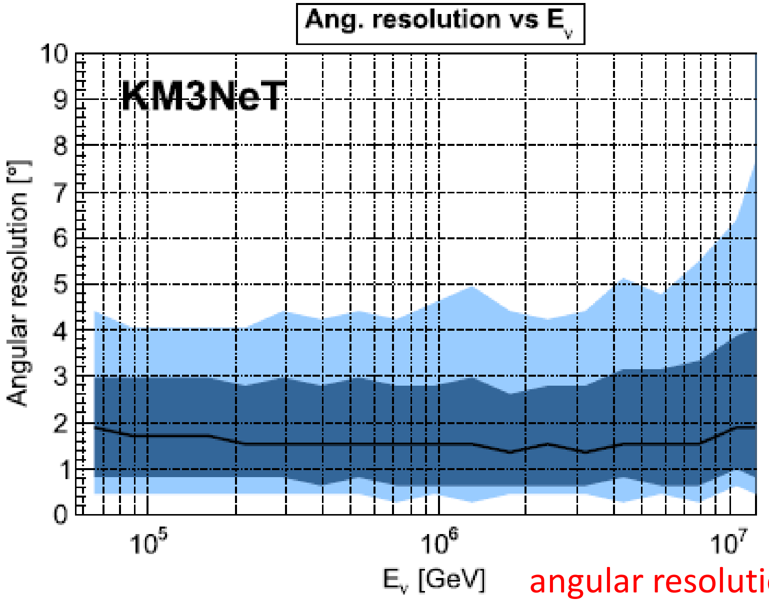
<0.1° (E>10 TeV)



0.3 Log E

Shower events



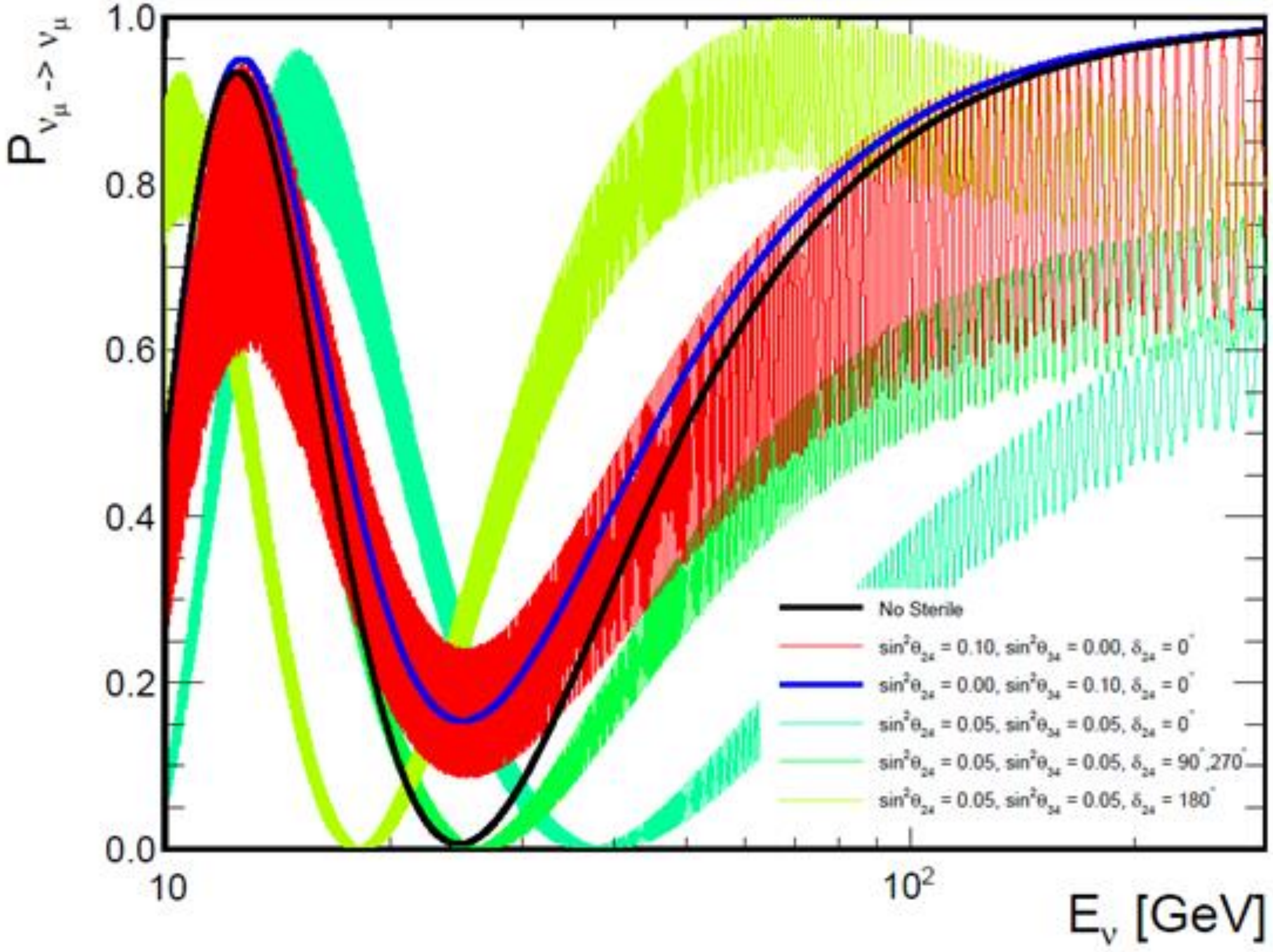


energy resolution better ≈ 5% at 1σ

angular resolution better than 2°

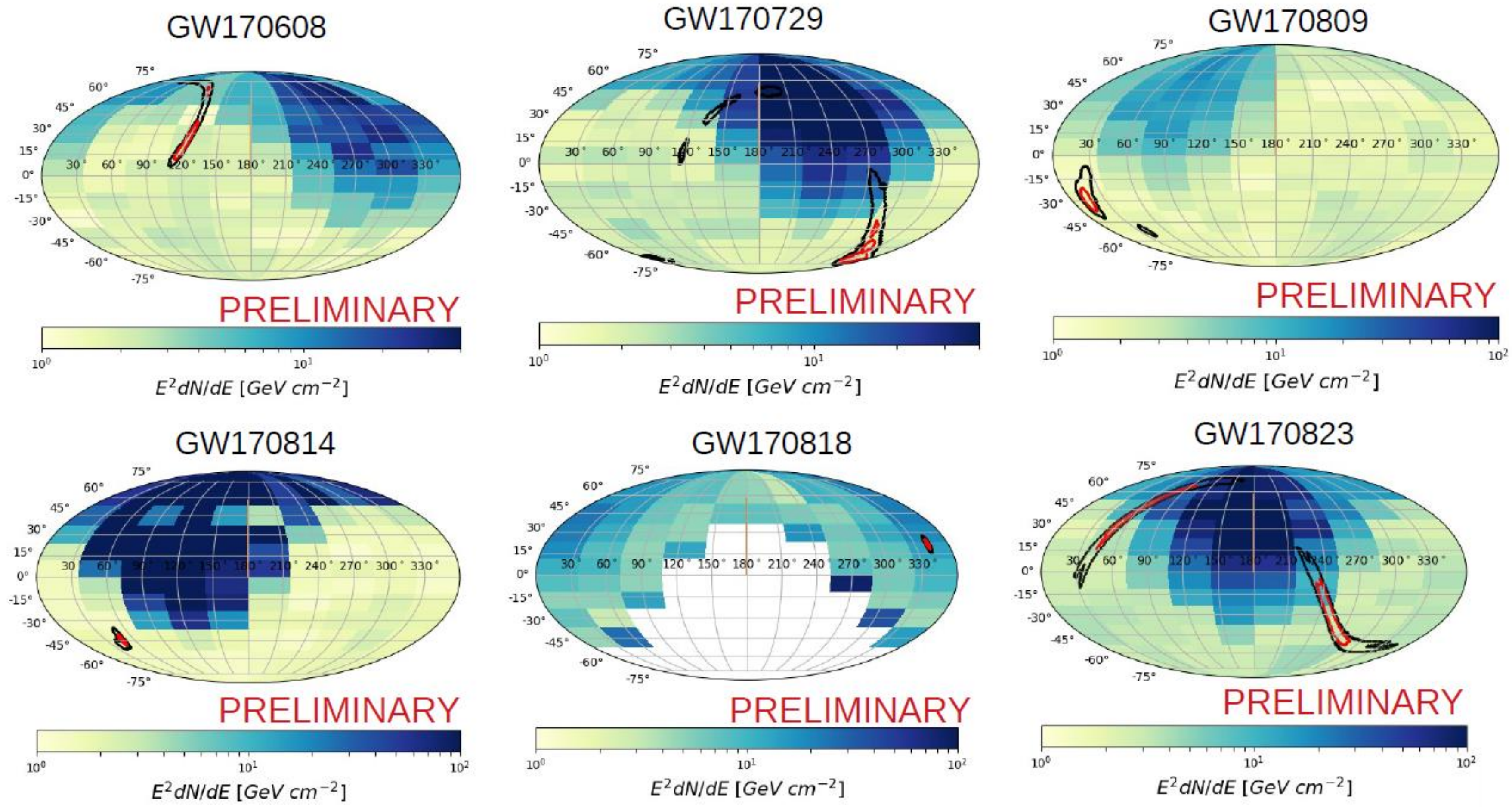
ANTARES sterile neutrino analysis

Survival probability of vertically up-going
for different values of: mixing angles, Δm^2



ANTARES GW analysis

Search for a neutrino counterpart to gravitational-wave events detected during the second observing run of advanced-LIGO and Virgo, performed with the ANTARES data looking for a prompt neutrino emission within 500 s around the time of the GW alerts.



Full sky upper limits (colored scale)

6 new analyzed GW signals correspond to the coalescence of binary black-hole (BBH). In the case of hadronic emission, secondary neutrinos are expected to be produced.

- Selection: 1 event passing the cuts inside the GW 90% localization error box found in time window → 3σ detection
- Only muon neutrinos
- Search below & above the horizon

No neutrino found in time and space coincidence with any of the six GW events in ANTARES data

M. Colomer et al. (ANTARES), 36th ICRC, PoS 856, (2019)

ANTARES + IceCube Dark Matter from Galactic Centre

Unification of ANTARES and IceCube analysis

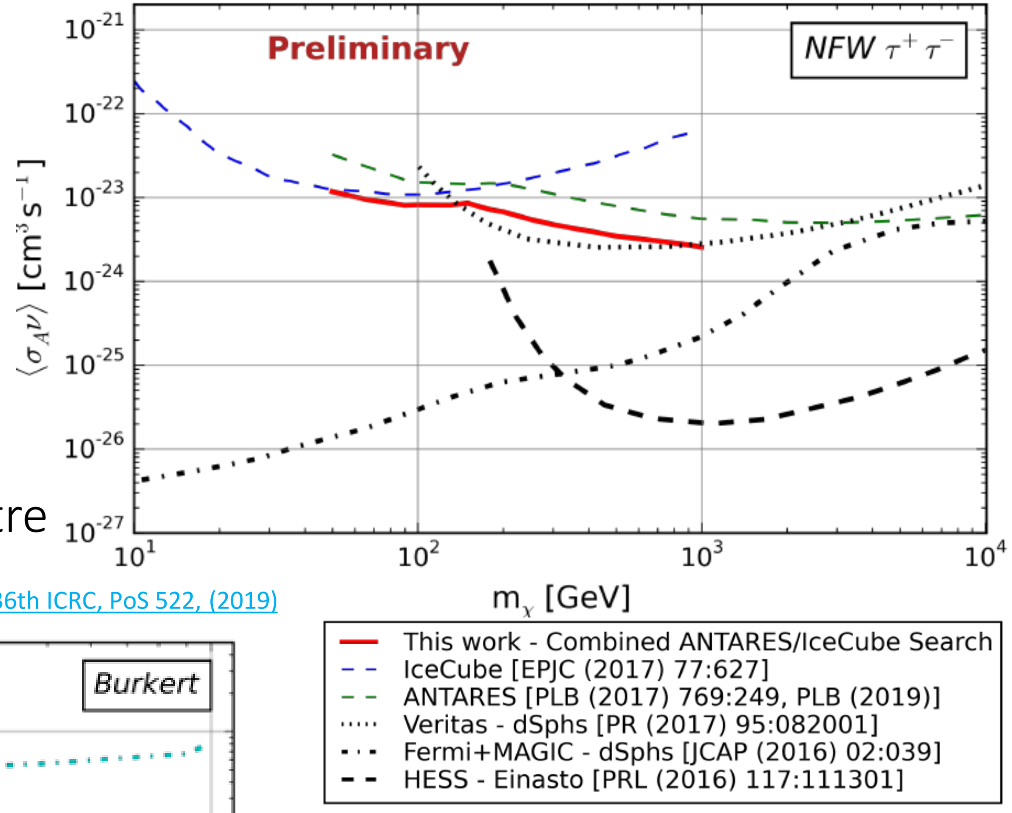
WIMP channels:

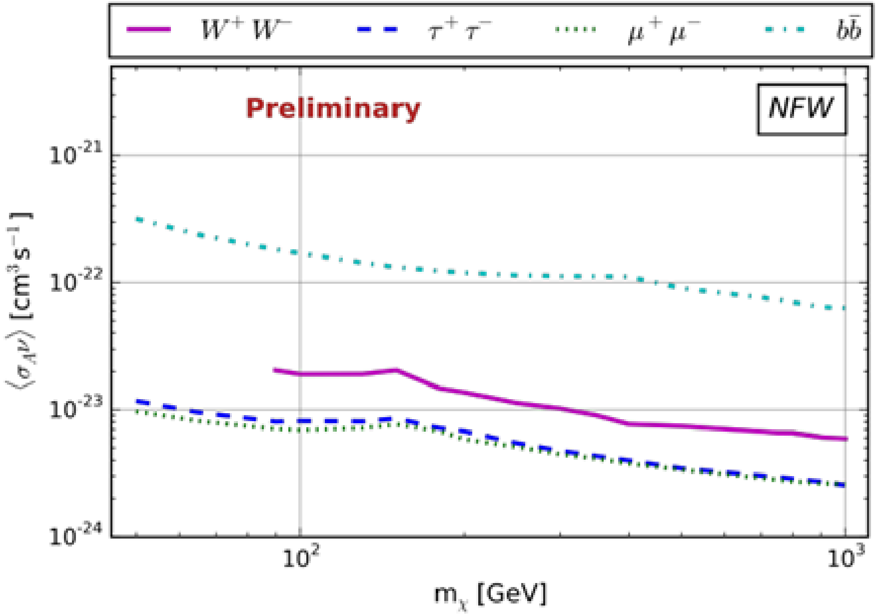
WIMP masses: 17 masses ranging from 50 to 1000 GeV

ANTARES lifetime: **2101.6 days** from 2007 to 2015

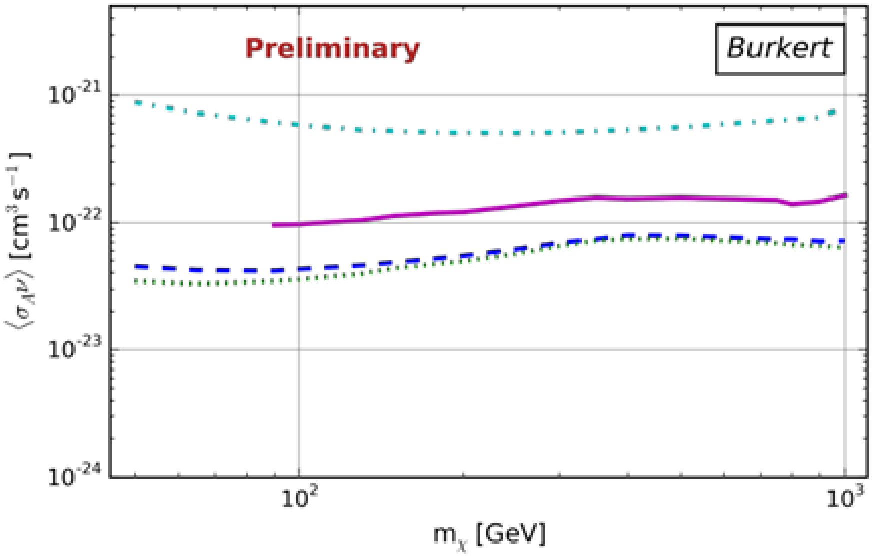
ICECUBE lifetime: **1006 days** from May 2012 to May 2015 (IC86)

No excess of signal neutrino seen in the direction of the Galactic Centre



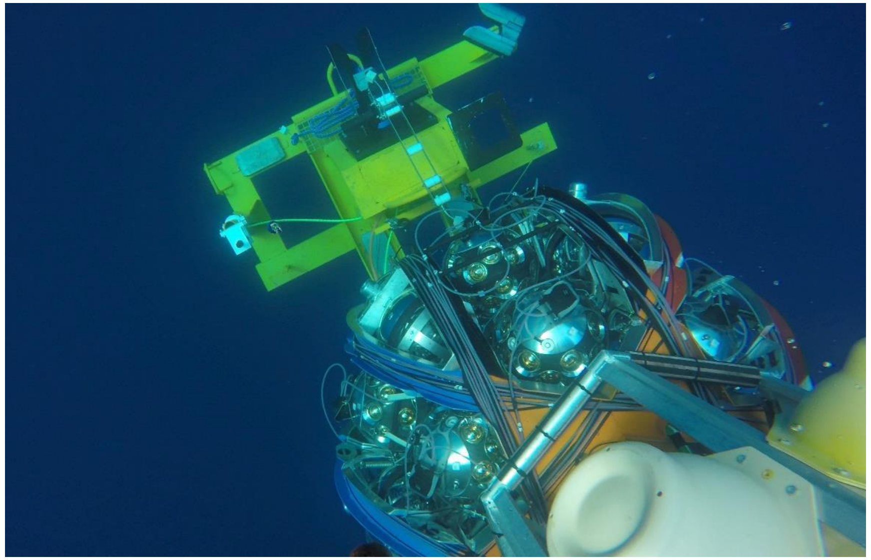


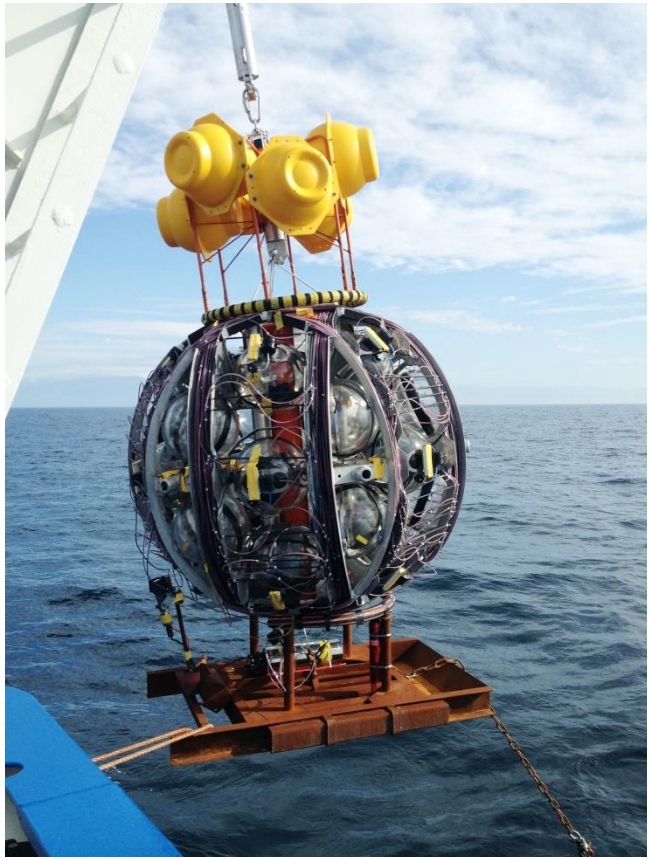
J.A. Aguilar et al. (IceCube), S. Gozzini (ANTARES), 36th ICRC, PoS 522, (2019)

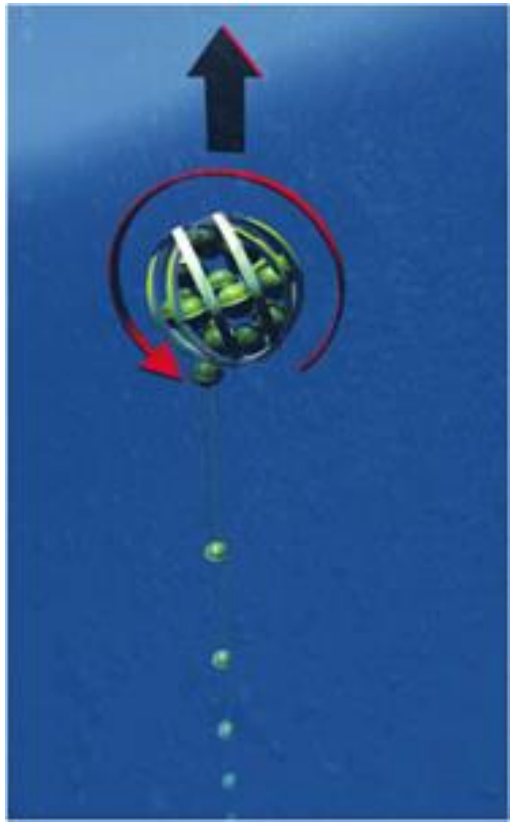


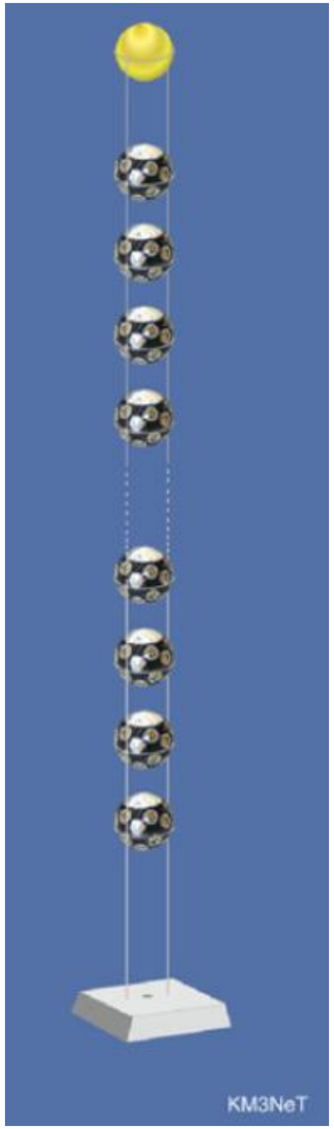
Upper limit using Feldman-Cousins method.

KM3NeT construction

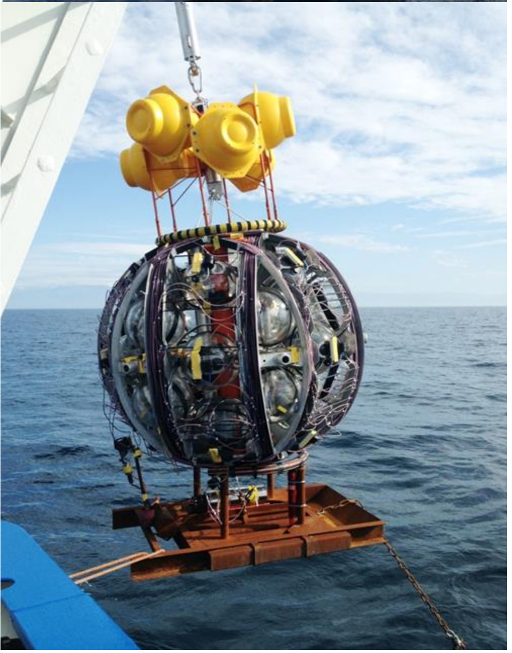


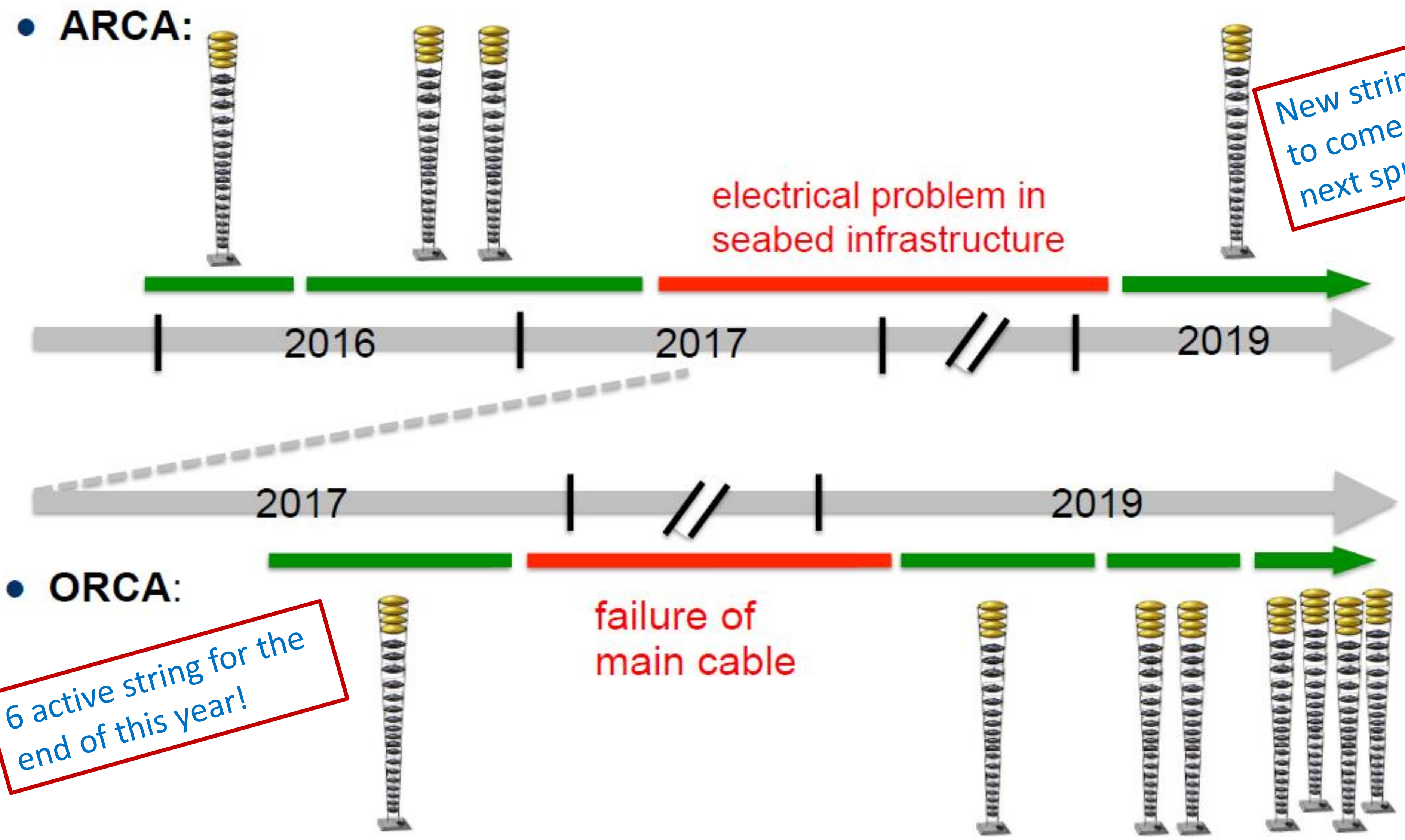






KM3NeT construction status





New string to come in next spring

6 active string for the end of this year!

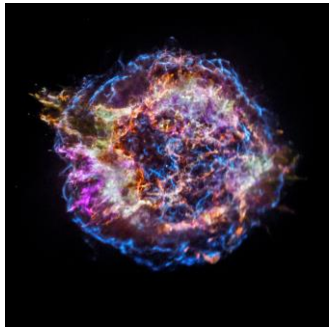
J. Hofestaedt, 36th ICRC

KM3NeT Core Collapse SuperNova limits

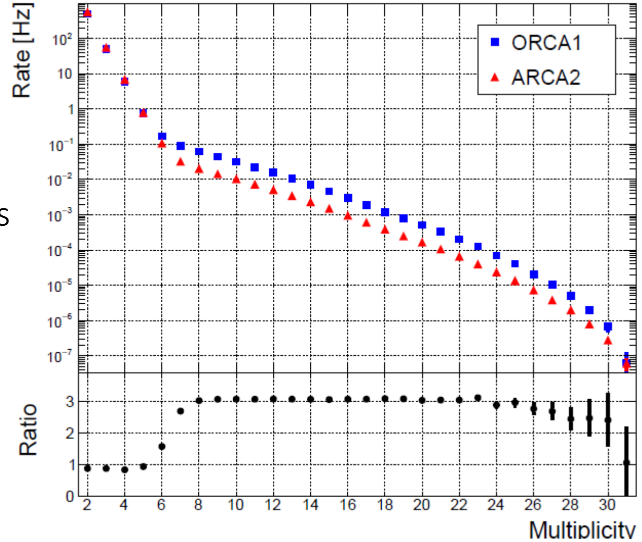
Galactic source of MeV neutrinos

MC and first KM3NeT data used.

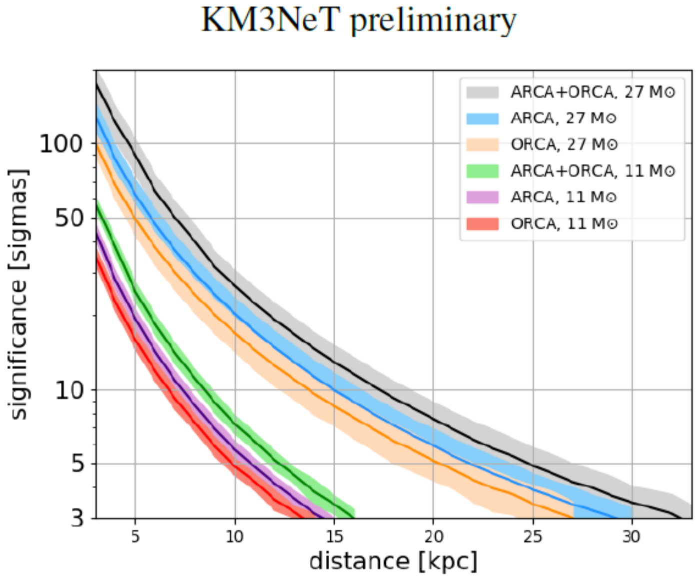
Simulation for the accretion phase of CCSN with stellar progenitors of 11 and 27 solar masses.

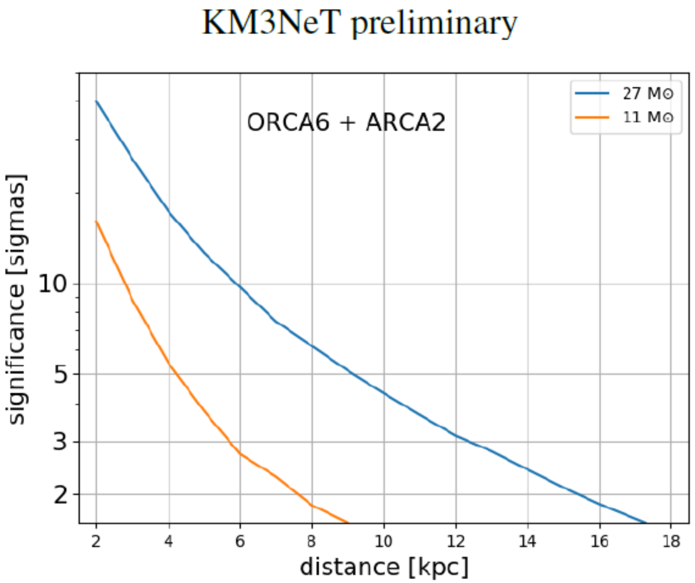


Main contributions:
- Radioactive decays in sea water
- atmospheric μ



[M. Ageron et al. (KM3NeT) arXiv:1906.02704v1]



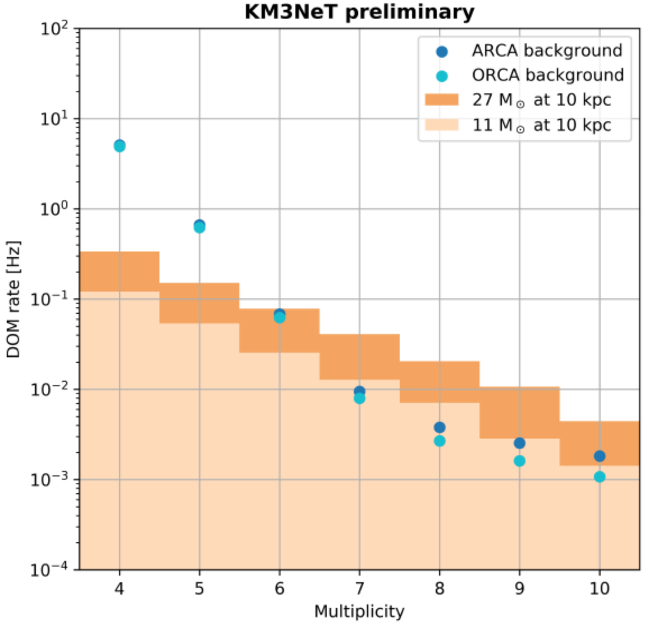


ARCA 2 DU + ORCA 6 DU		
Threshold	11 $M_\odot$	27 $M_\odot$
1 / 8 days	4.5 kpc	8.5 kpc

ARCA 230 DU + ORCA 115 DU		
Threshold	11 $M_\odot$	27 $M_\odot$
1 / 14 days	12.5 kpc	23 kpc

Multiplicity: number of hit PMTs in a coincidence

Estimated DOM background rates after muon rejection w.r.t the signal expectation at 10 kpc



[M. Colomeret al. (KM3NeT), 36th ICRC, PoS 857 (2019)]