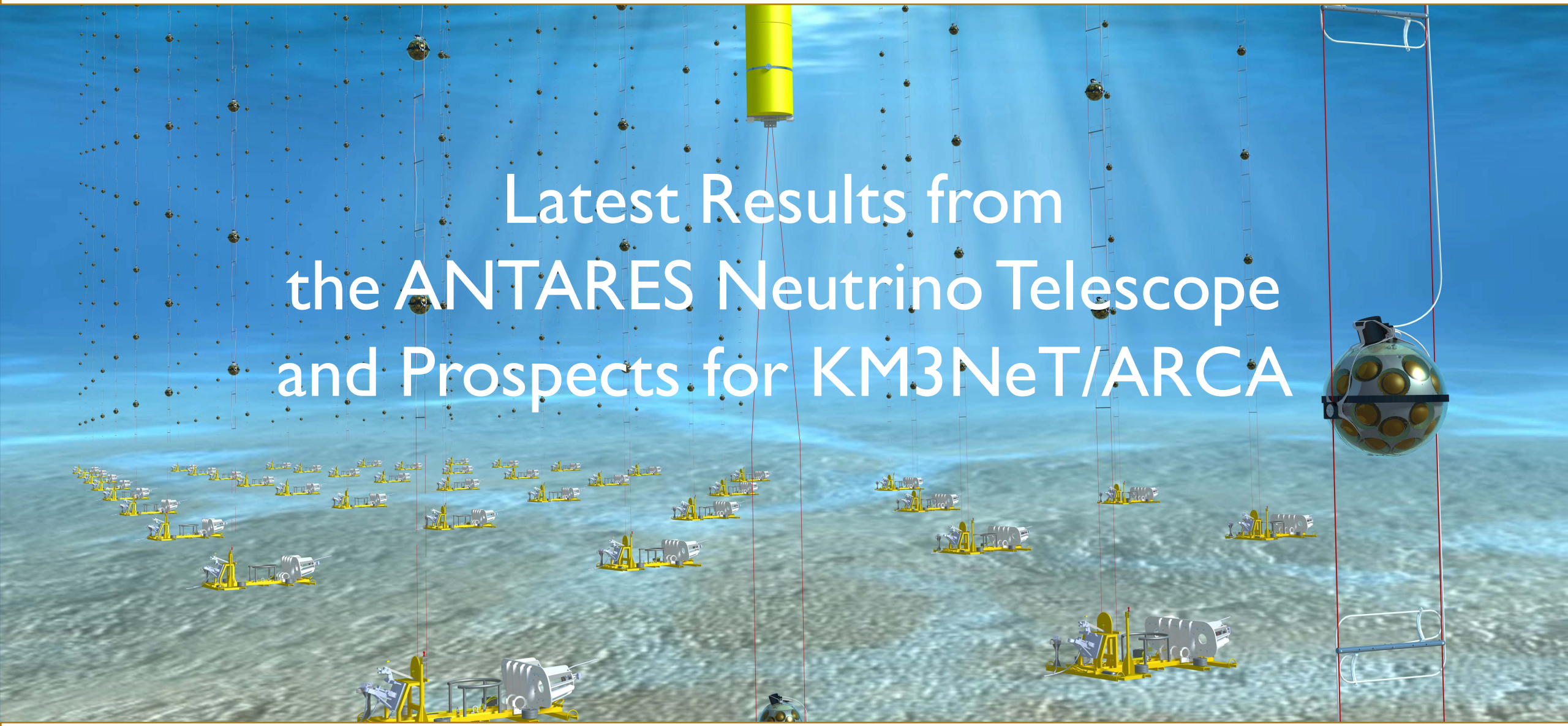
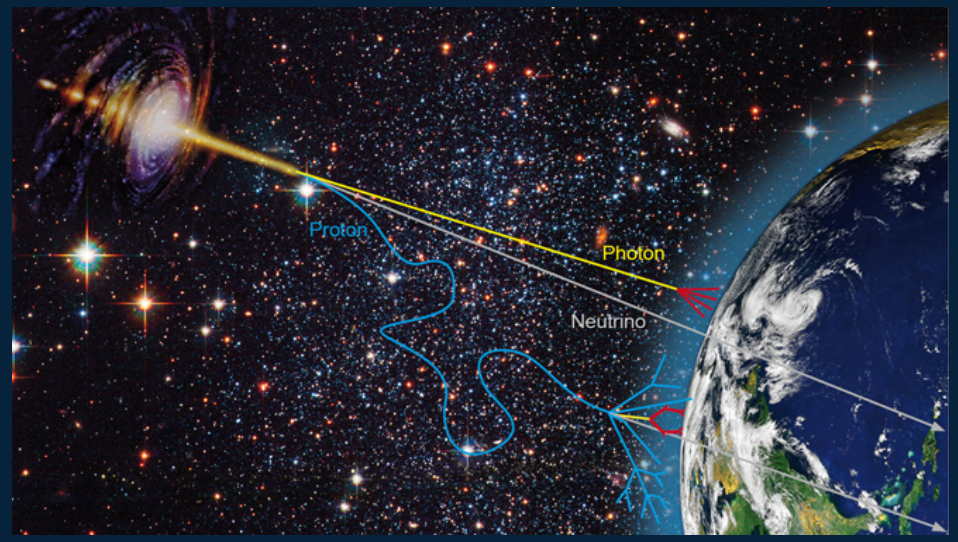


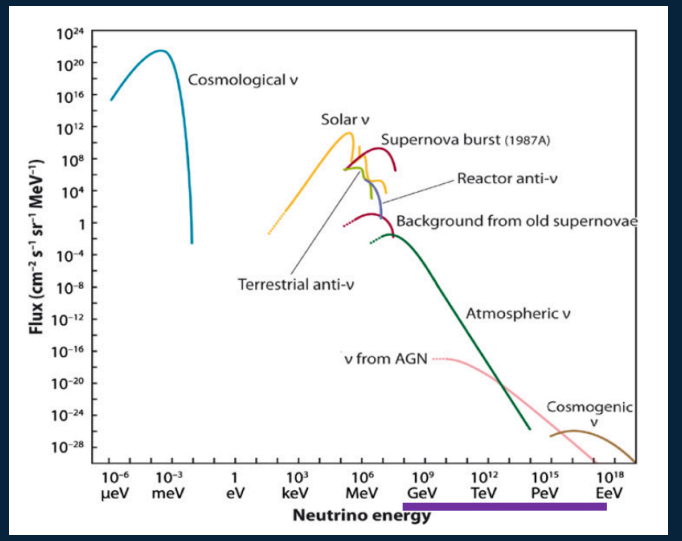
Latest Results from the ANTARES Neutrino Telescope and Prospects for KM3NeT/ARCA

Giulia Illuminati on behalf of the ANTARES and KM3NeT Collaborations

Blois 2019 - 05/06/2019 – Blois, France

Neutrino Astronomy





Neutrinos:

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

➢ Provide a strong indication of hadronic acceleration in astrophysical sources

$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n$$

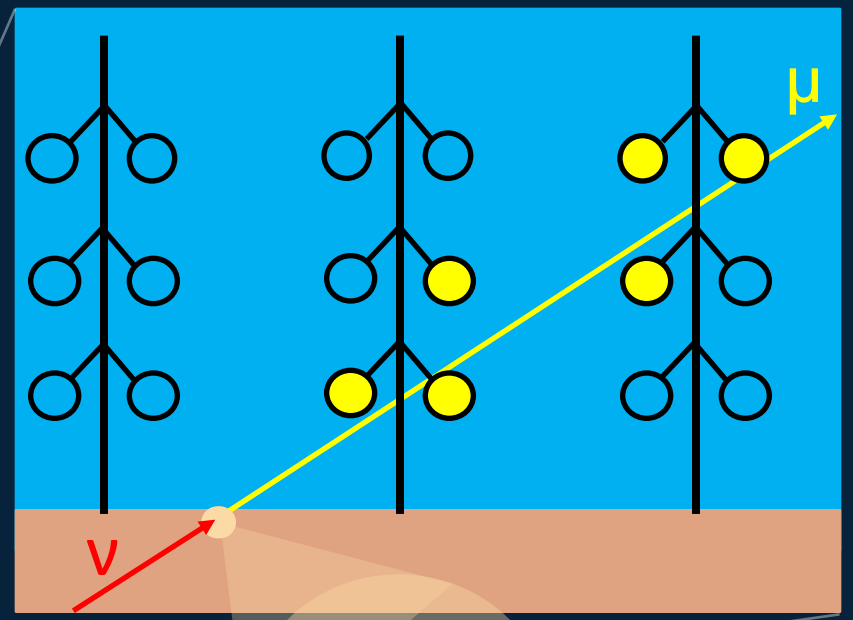
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

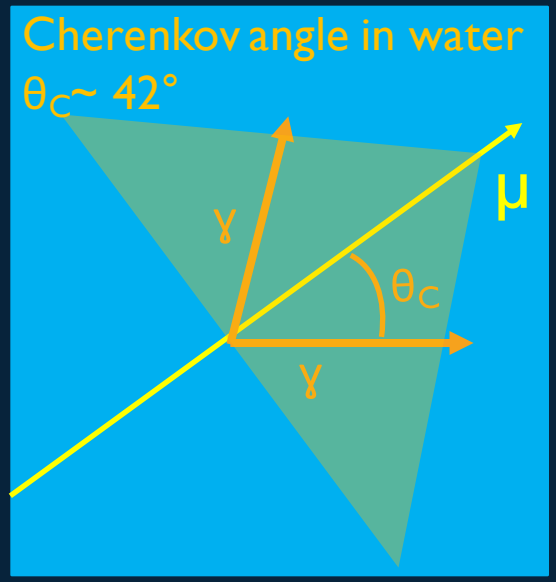
$\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$ at the source

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

Detection principle

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





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

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

key interaction (CC):

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

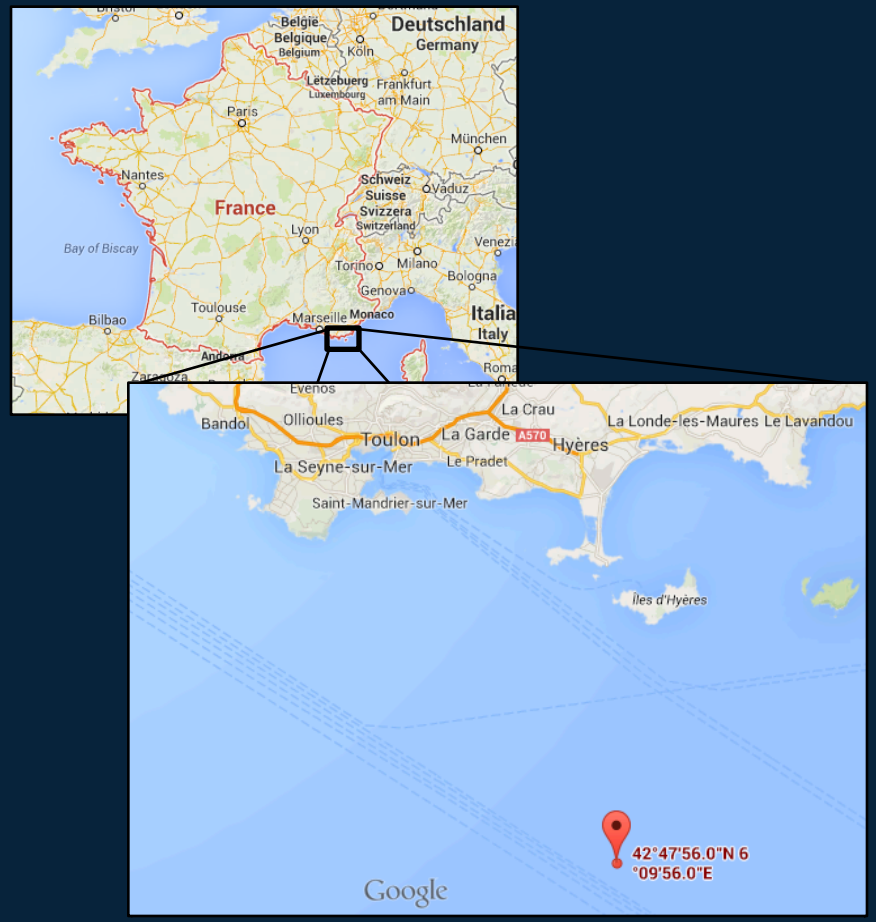
Global Neutrino Network (GNN)

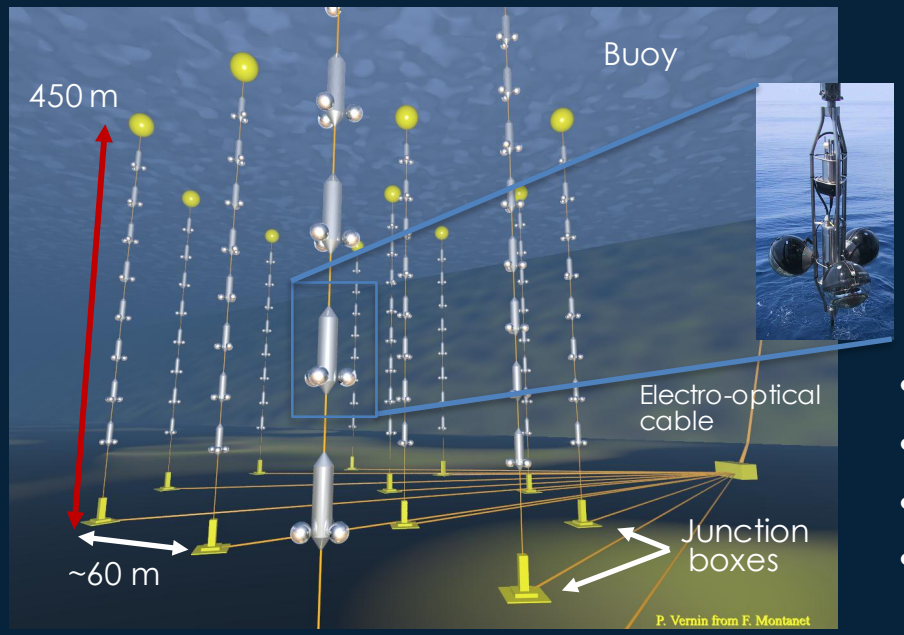
- ANTARES and KM3NeT
  Mediterranean Sea
- IceCube
  Antarctic Ice
- Baikal-GVD
  Lake Baikal

IceCube

ANTARES

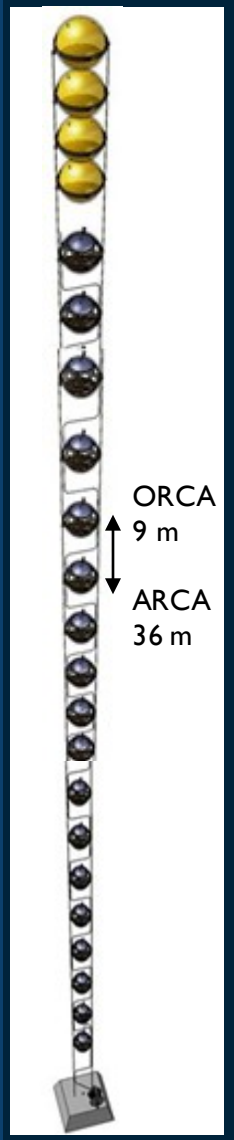
- First detection line installed in early 2006
- Completed in 2008
- 2475 m depth in the Mediterranean Sea
- 40 km offshore from Toulon





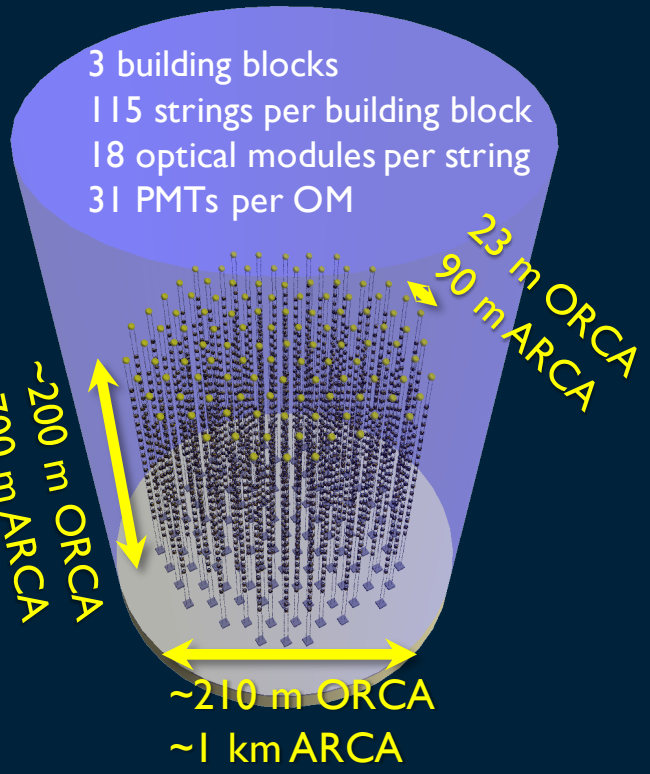
- Three-dimensional array of 885 PMTs
- 12 vertical lines, 25 storeys
- 3 PMTs per storey
- PMT facing 45° downwards

KM3NeT



KM3NeT/ORCA

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

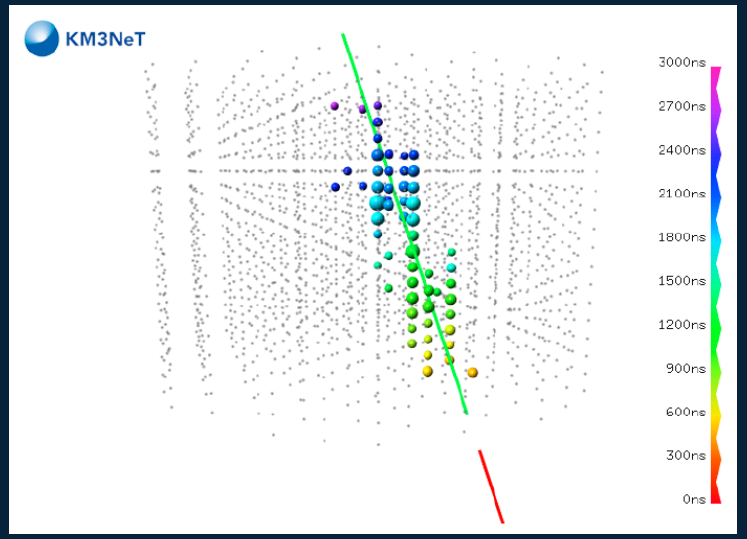


KM3NeT/ARCA

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

Event Topologies:

TRACKS



ν_μ (ν_τ) CC interaction ➔ track

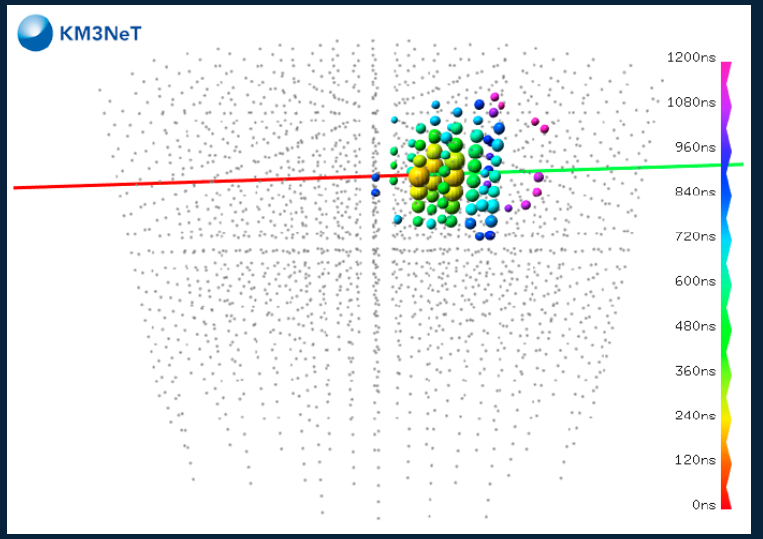
ANTARES

Angular resolution < 0.4° for E_ν > 10 TeV

KM3NeT/ARCA

Angular resolution < 0.1° for E_ν > 100 TeV

SHOWERS



ν_e, ν_τ CC + any flavour NC interaction ➔ shower

ANTARES

Angular resolution < 3°

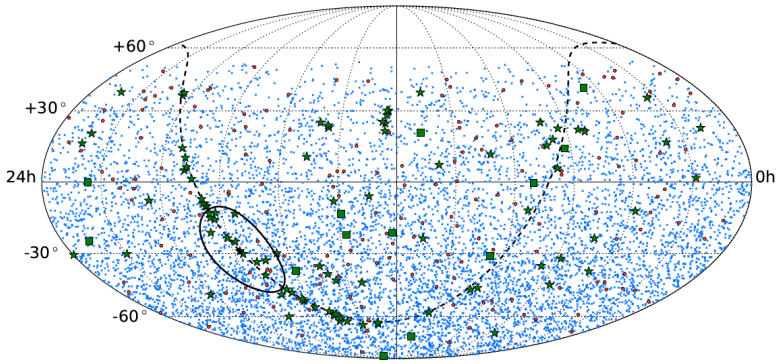
KM3NeT/ARCA

Angular resolution < 2°

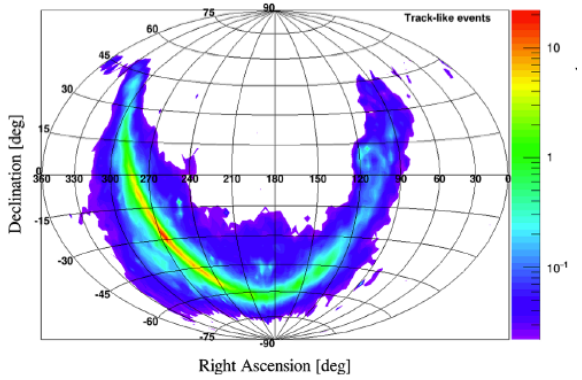
Energy resolution ~ 5%

Searches

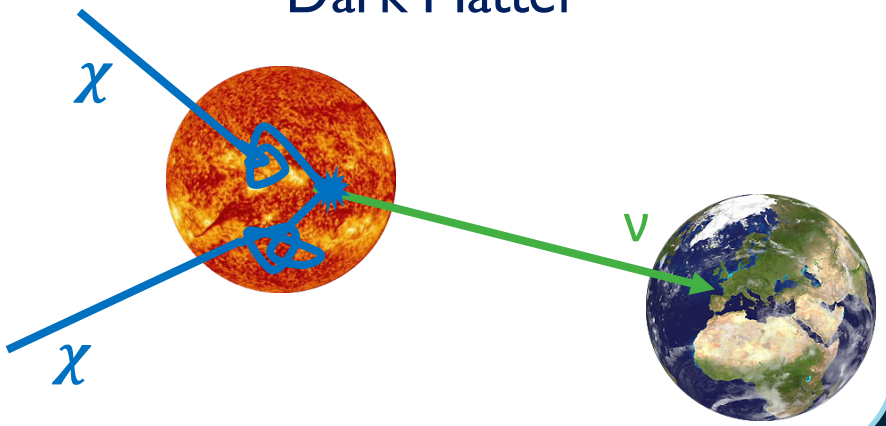
Point-Sources



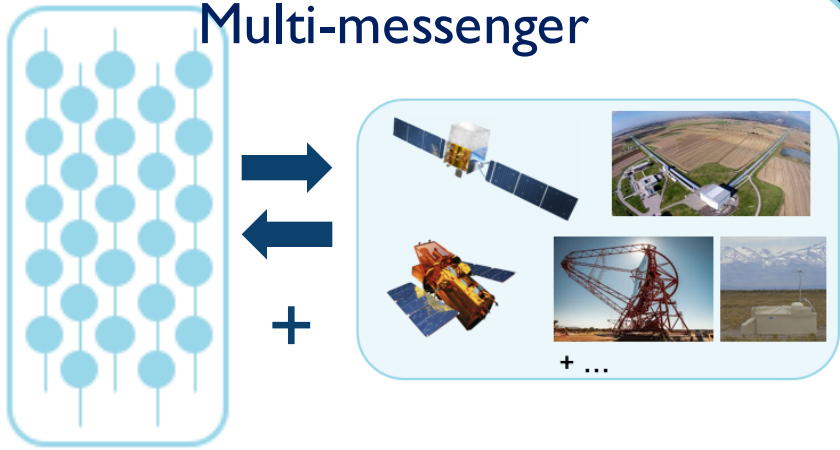
Diffuse Flux



Dark Matter



Multi-messenger



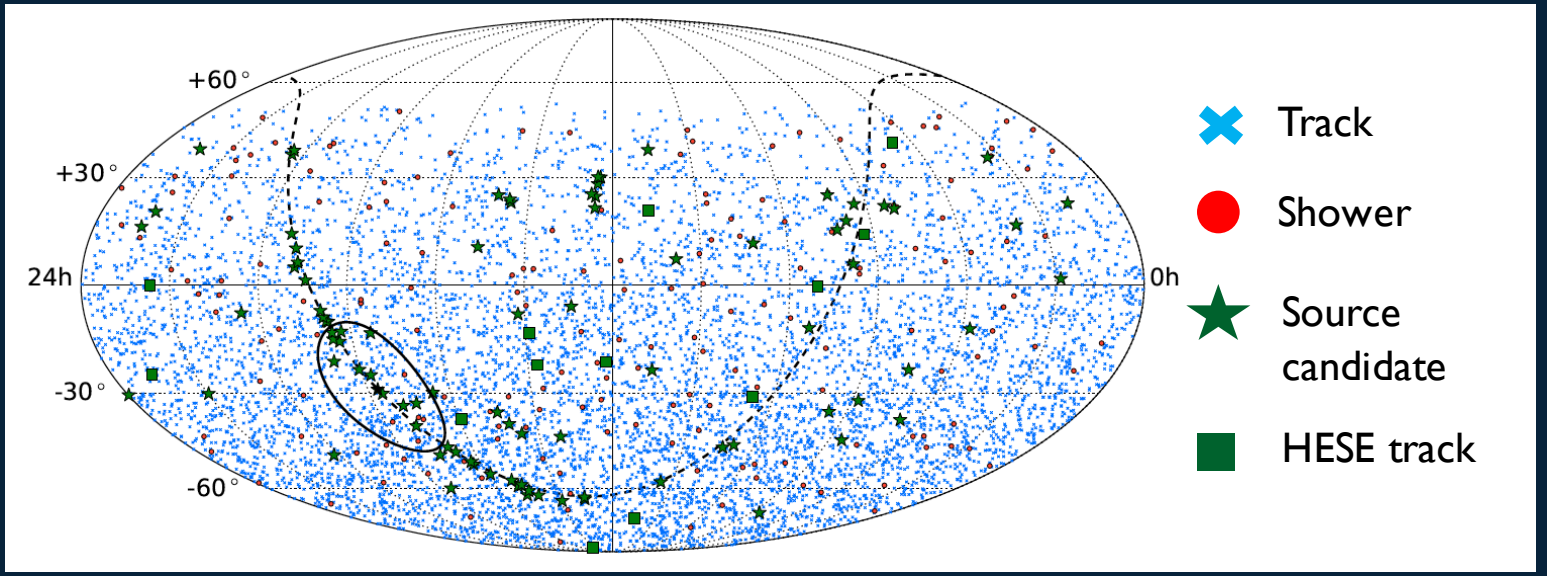
+…

Point-sources

ANTARES – Point sources

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

Neutrino Sample:
- 9 years: 2007 - 2015
- tracks and showers



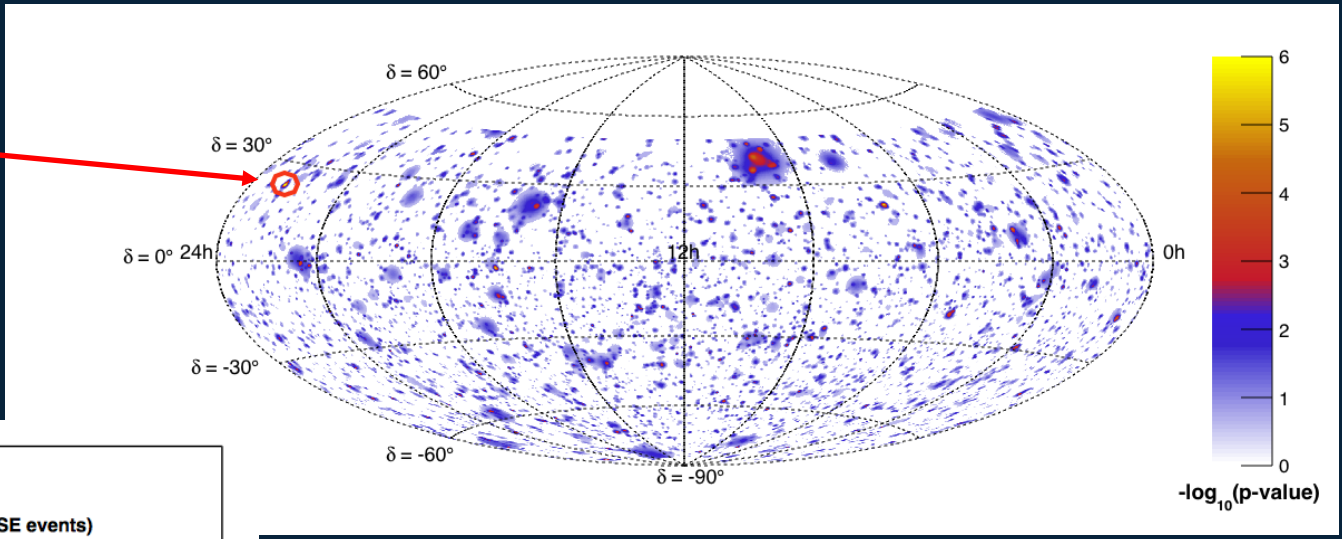
Search strategy:
- Full-sky search:
  - 1°x1° squares over ANTARES visible sky
- Candidate list search:
  - 106 known astrophysical objects (Pulsars, SNRs, …)
  - 13 IceCube HESE tracks

- $\frac{dN_\nu}{dE_\nu} = \Phi_0 E_\nu^{-2}$ neutrino flux assumed
- Maximum likelihood method

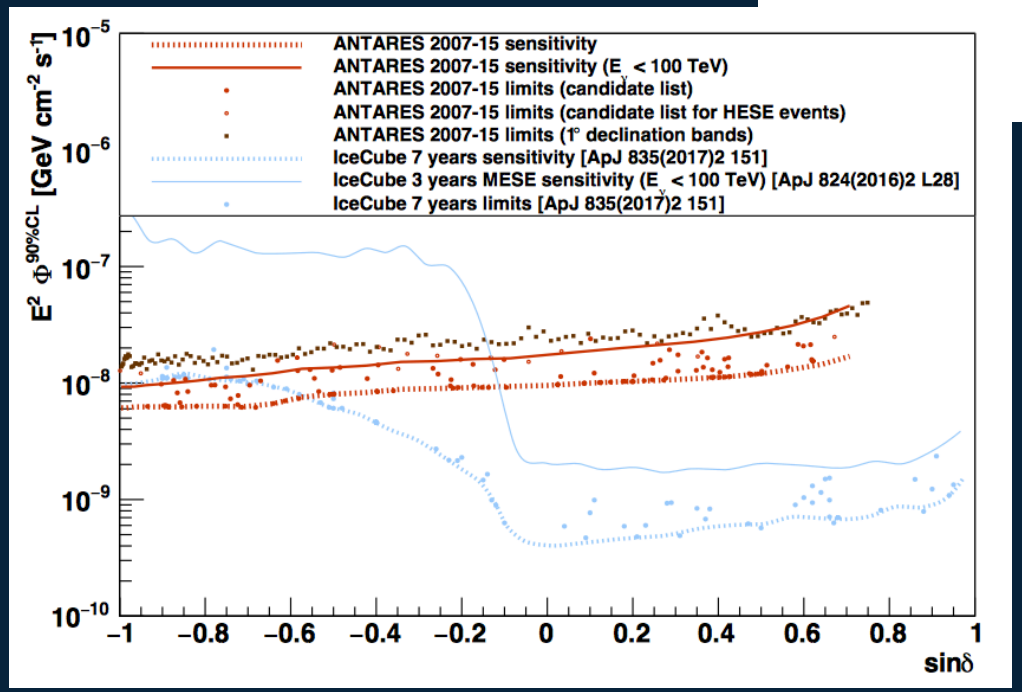
ANTARES – Point sources

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

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



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



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

COMING SOON! PS analysis update (2007-2017)
COMING SOON! Combined analysis (ANTARES + IceCube)
COMING SOON! Stacking search

ANTARES – TXS 0506+056

Astrophys.J.863 (2018) no.2,L30

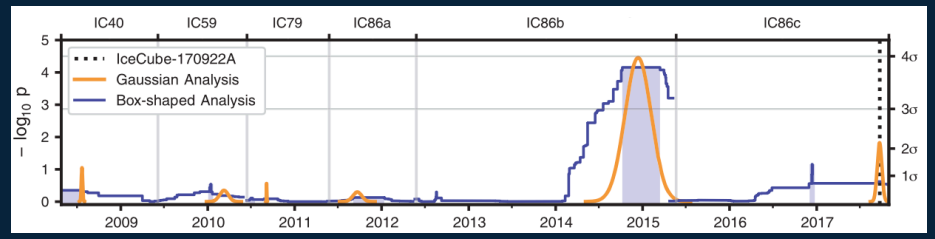
- IceCube-170922A detected on 22 September, 2017
- High probability of being of astrophysical origin
- Coincident in direction and time with a gamma-ray flare from the blazar TXS 0506+056 (Fermi-LAT, MAGIC)

Three ANTARES searches performed:

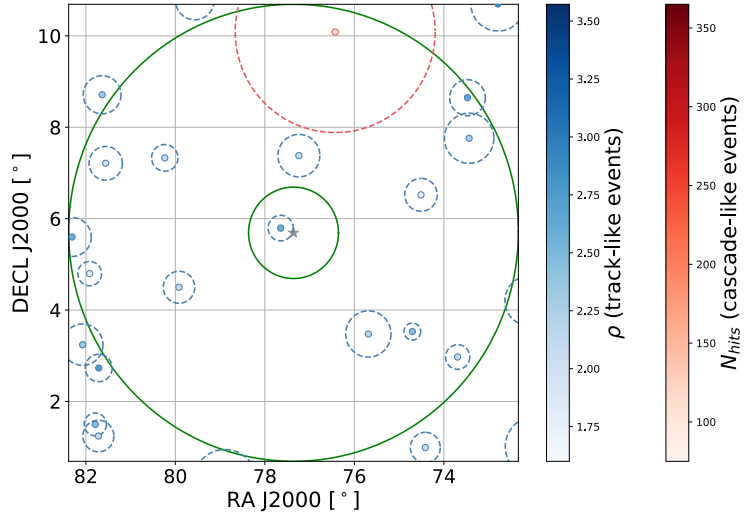
1) Online searches for neutrinos associated to IceCube-170922A

2) Time integrated search for neutrinos from TXS 0506+056

3) Time dependent search for neutrinos in the bursting period reported by the IceCube Coll.



Events close to TXS 0506+056 in 2007-2017 ANTARES data



13 track-like and 1 shower-like neutrino candidates within 5° from TXS 0506+056

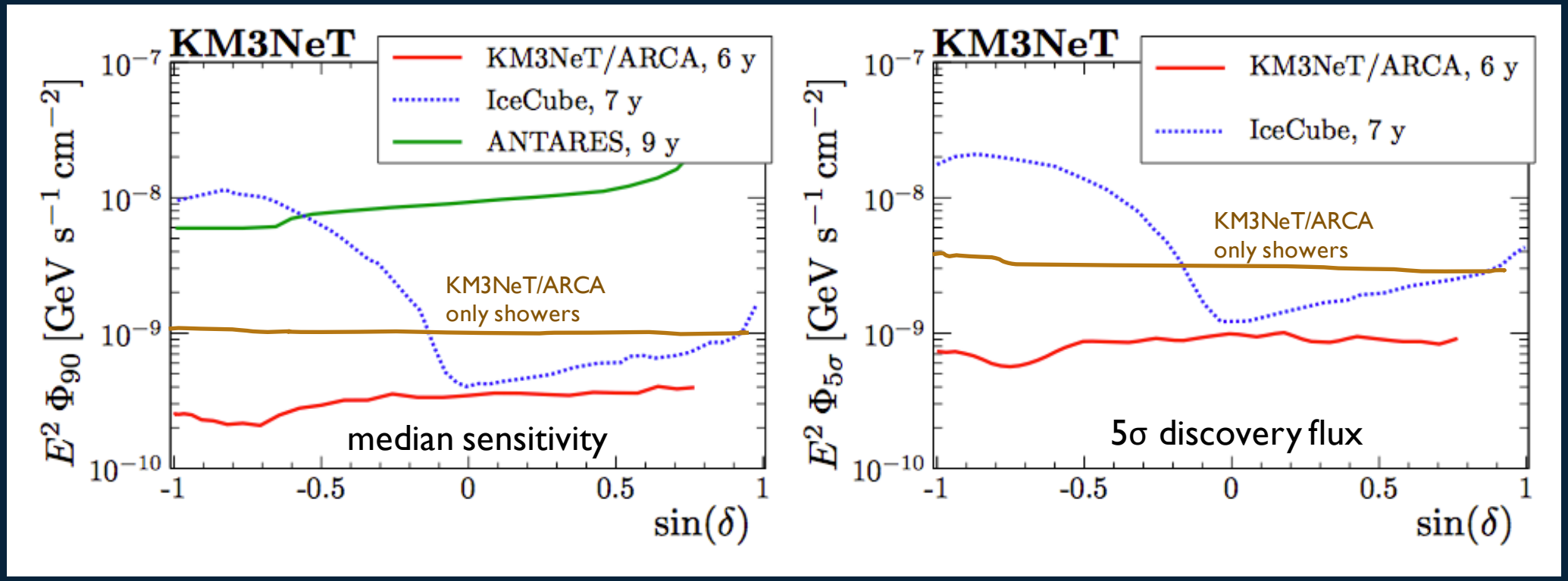
TXS 0506+056 added to the list of 106 neutrino source candidates analysed in the latest ANTARES point-source search (Phys. Rev. D **96**, 082001 (2017))

- TXS 0506+056 third most significant source
- Best fitted # of signal events μ_{sig} = 1.03
- 2.6% pre-trial p-value
- 87% post-trial p-value
- Limits on neutrino flux and fluence set

Astropart.Phys. 111 (2019) 100-110

KM3NeT/ARCA – Point Sources

E^{-2} source



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

Diffuse Flux

ANTARES – Diffuse Flux

ApJL 853,L7 (2018)

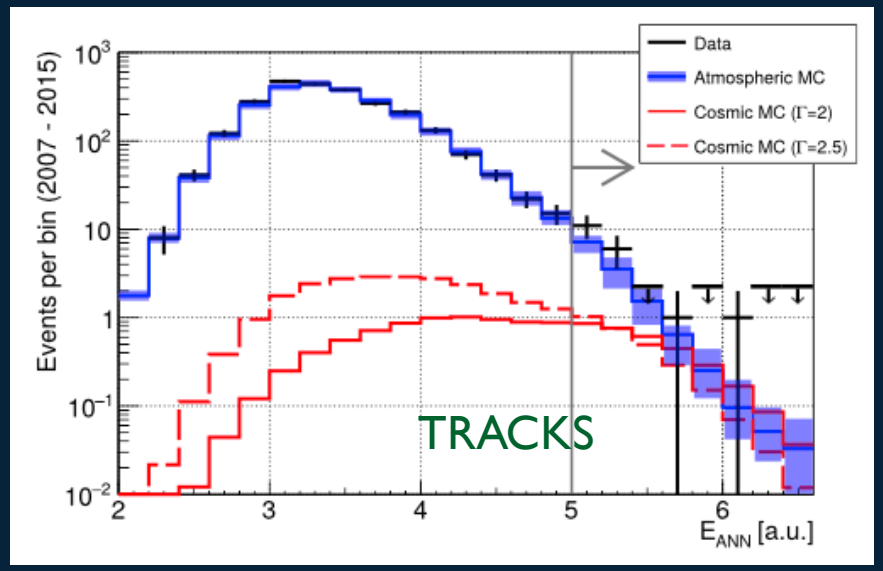
Sample:
- 9 years: 2007 - 2015
- Tracks and showers

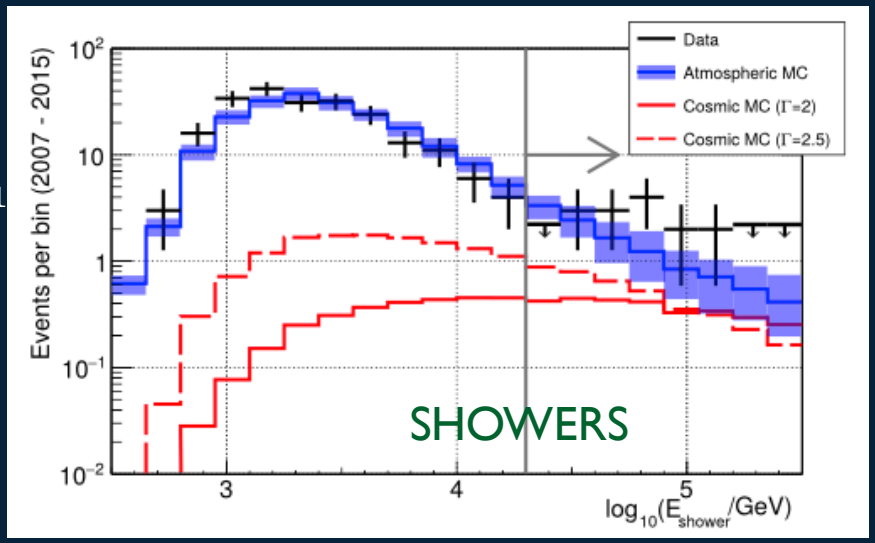
❑ Event selection chain + energy-related cut applied to
- obtain a high-purity neutrino sample
- maximise sensitivity

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

❖ Results:

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





ANTARES – Diffuse Flux

ApJL 853,L7 (2018)

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

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

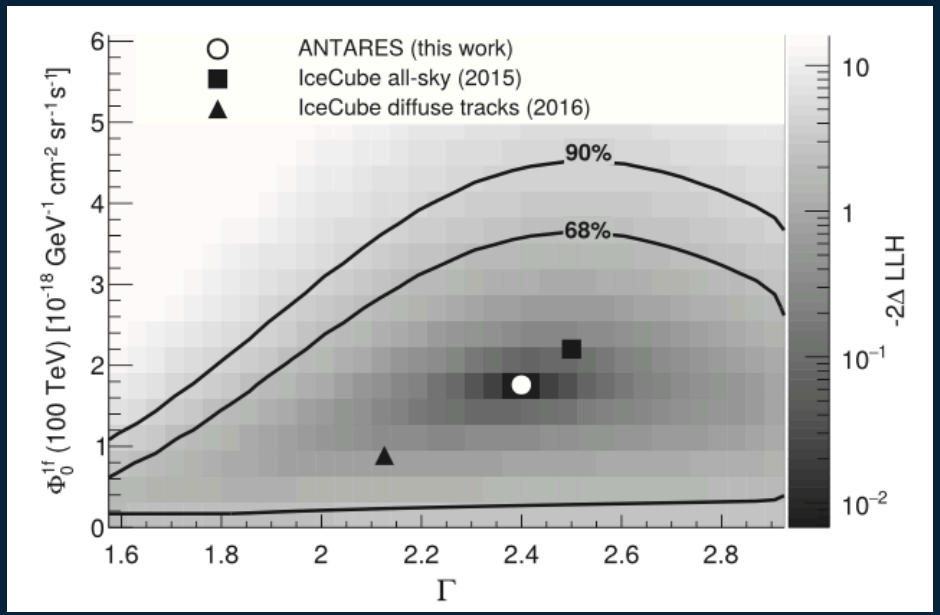
Fitting the data:

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

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

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

Compatible with IceCube signals
1.6σ excess, null cosmic hypothesis rejected at 85% CL



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

COMING SOON!
Diffuse analysis update (2007-2017)

KM3NeT/ARCA – Diffuse Flux

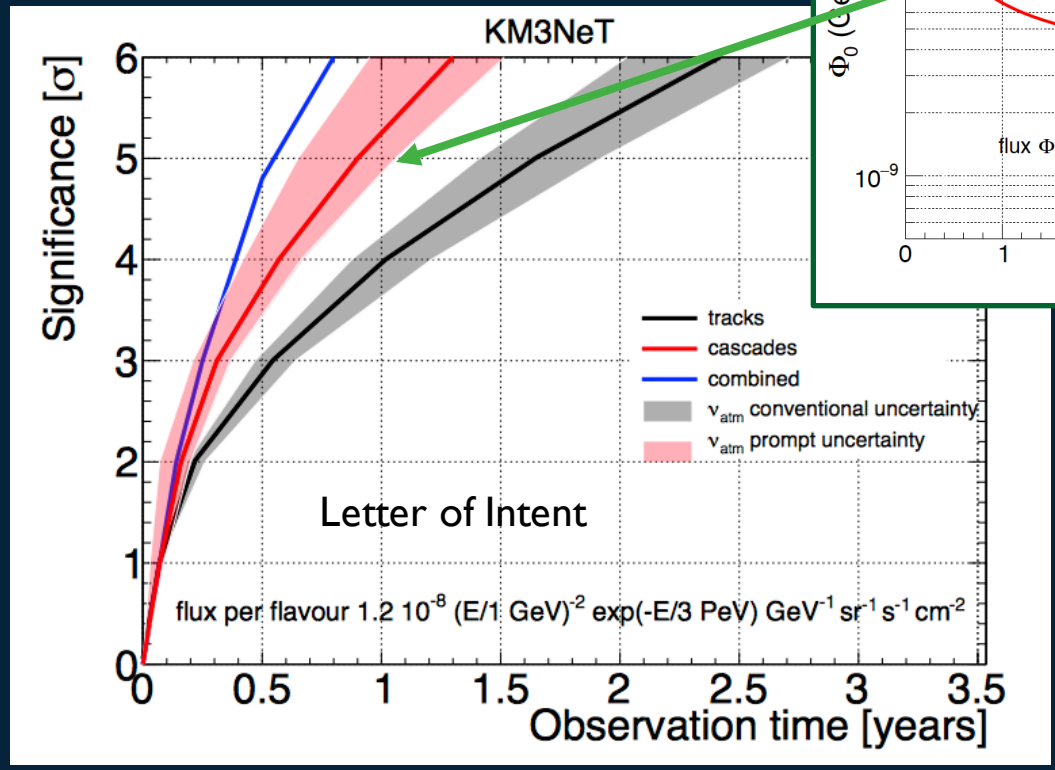
J.Phys. G43 (2016) no.8,084001
PoS(ICRC2017)998

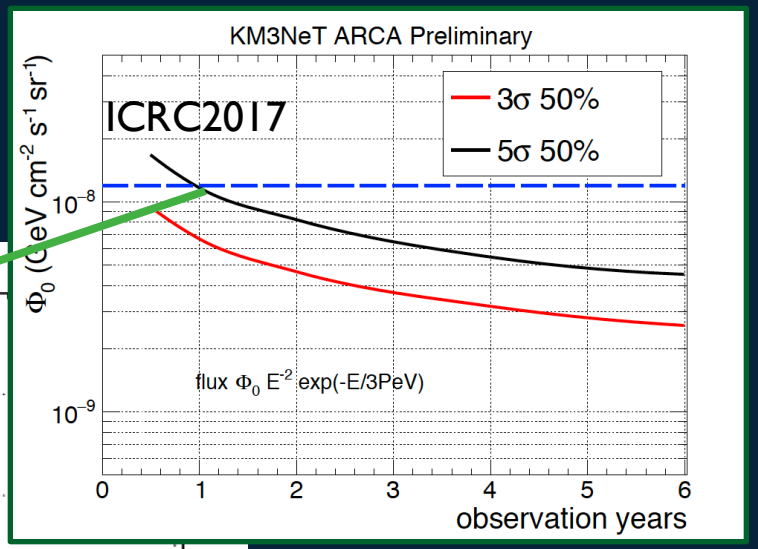
IceCube flux used as benchmark flux:
power law spectrum with a cut-off at a few PeV

Cascade selection cuts:
- Containment
- Energy
- BDT training

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

Maximum likelihood method for discovery potential calculation



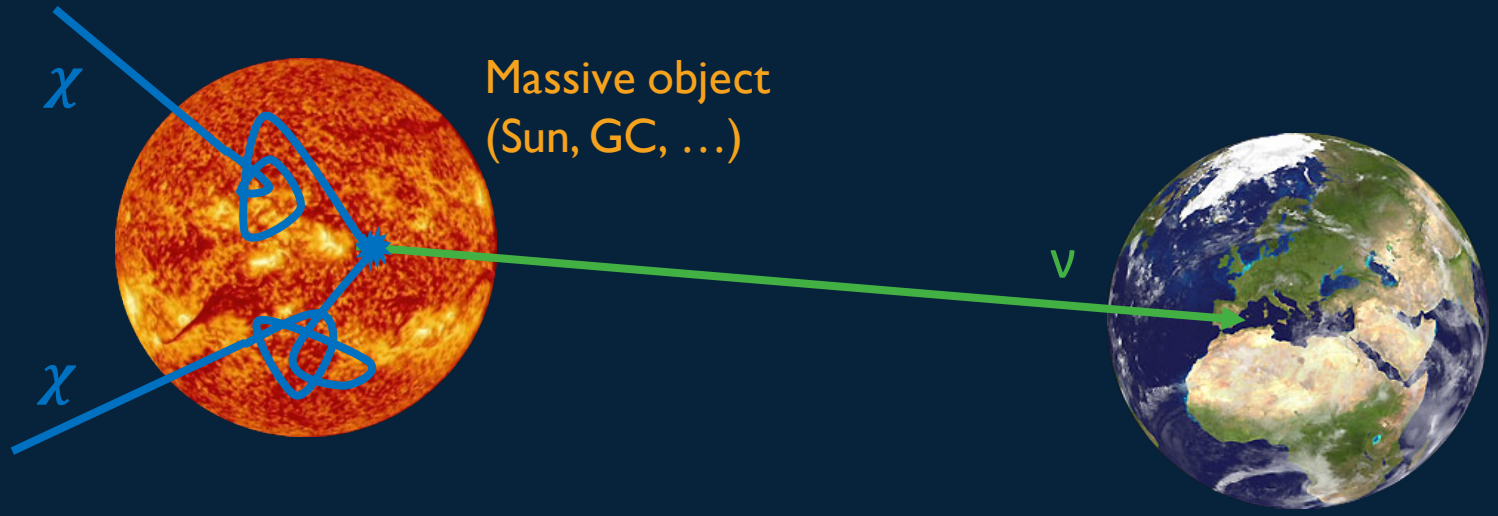


Improved results for tracks from better background discrimination via MVA techniques:

Tracks almost at the level of showers

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

Dark Matter



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

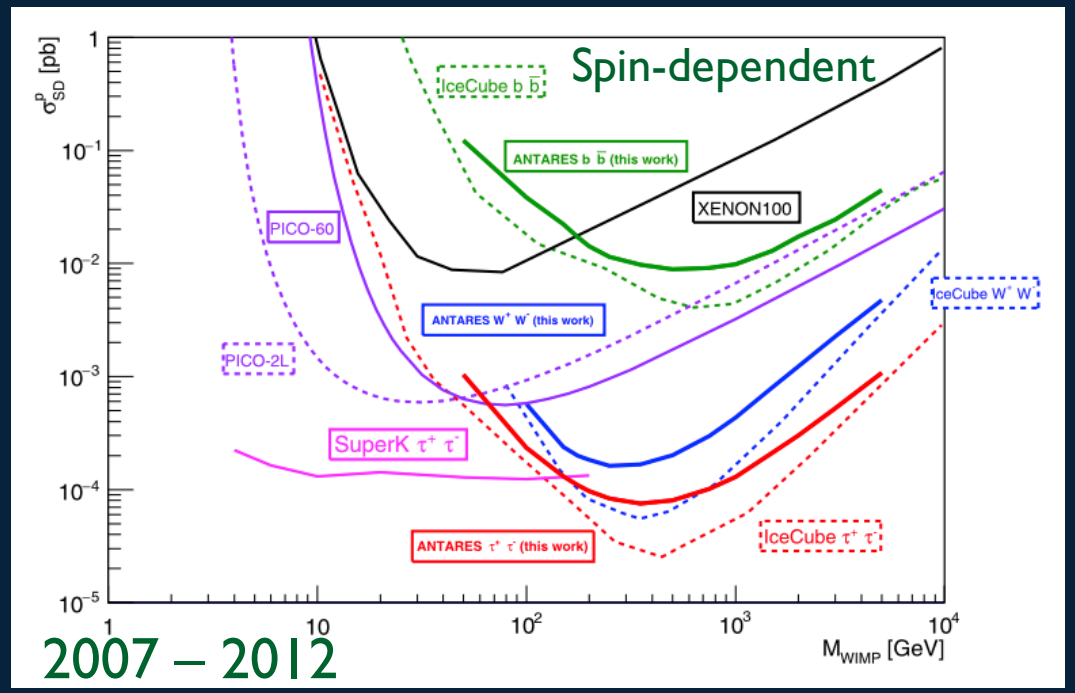
Ingredients:

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

ANTARES – Dark Matter

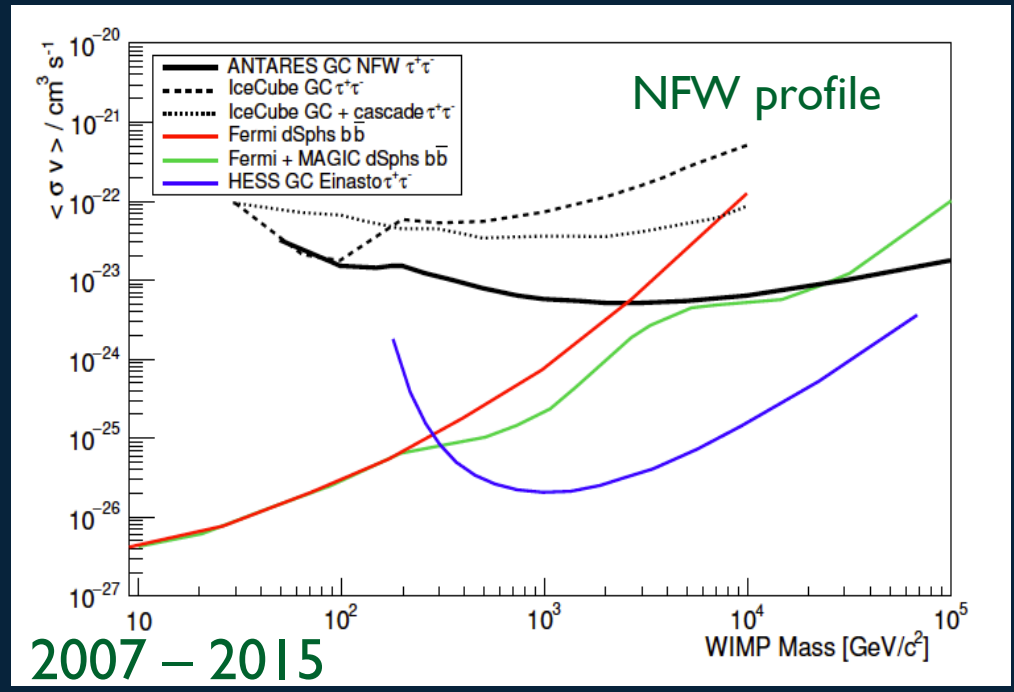
Phys. Lett. B 759 (2016) 69-74
Phys. Lett. B 769 (2017) 249

SUN



Upper limits on spin-(in)dependent WIMP-nucleon scattering cross-section as a function of the WIMP mass

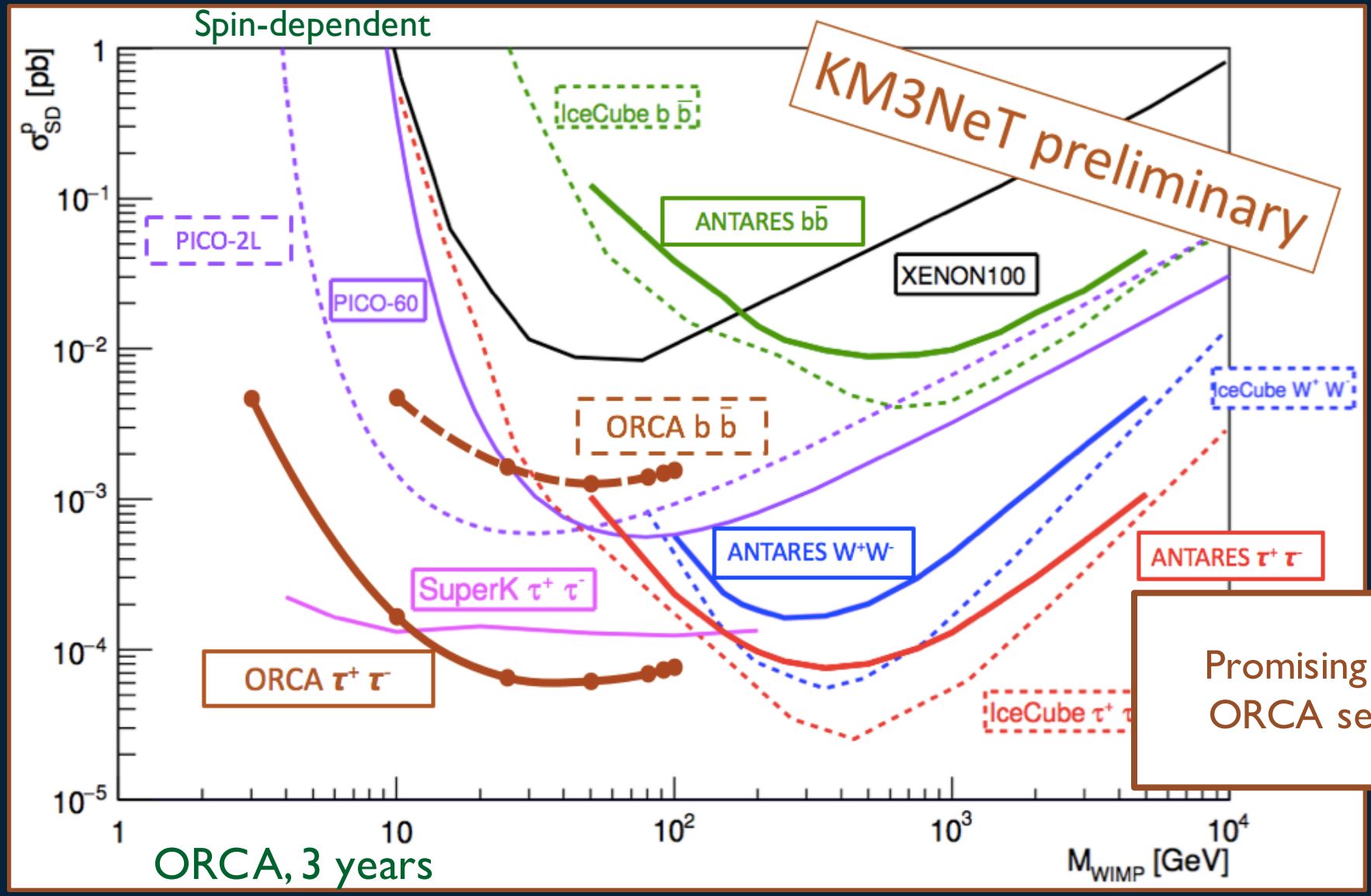
Galactic Centre



Upper limits on thermally averaged annihilation cross-section as a function of the WIMP mass

COMING SOON! GC and Sun analyses update (2007-2017)
COMING SOON! Combined GC analysis (9yr ANTARES + 3yr IceCube)
COMING SOON! Constraints on secluded dark matter models

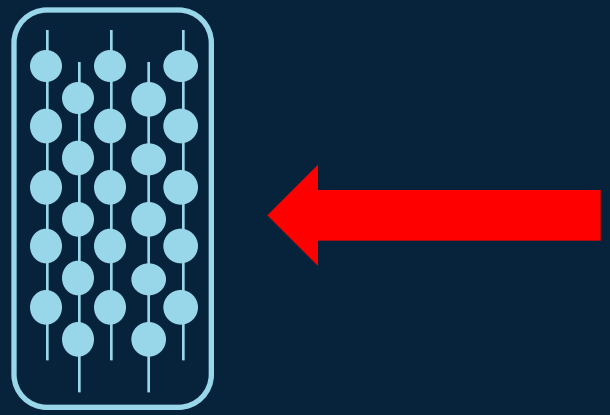
KM3NeT/ORCA – Dark Matter

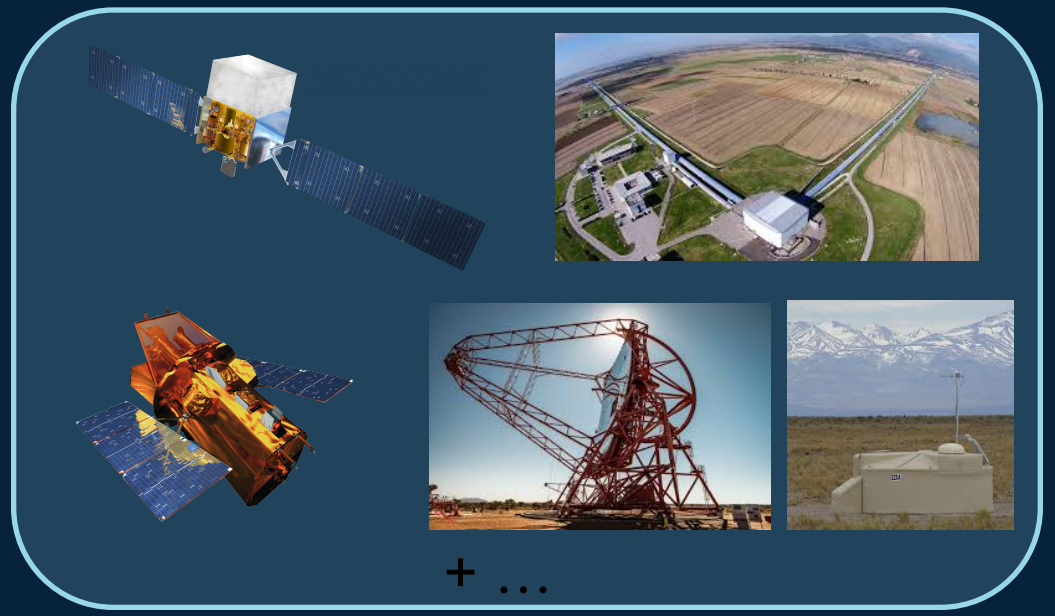


Promising estimated ORCA sensitivities!

Multi-messenger

Real-time analysis → Alert triggering





Offline analyses

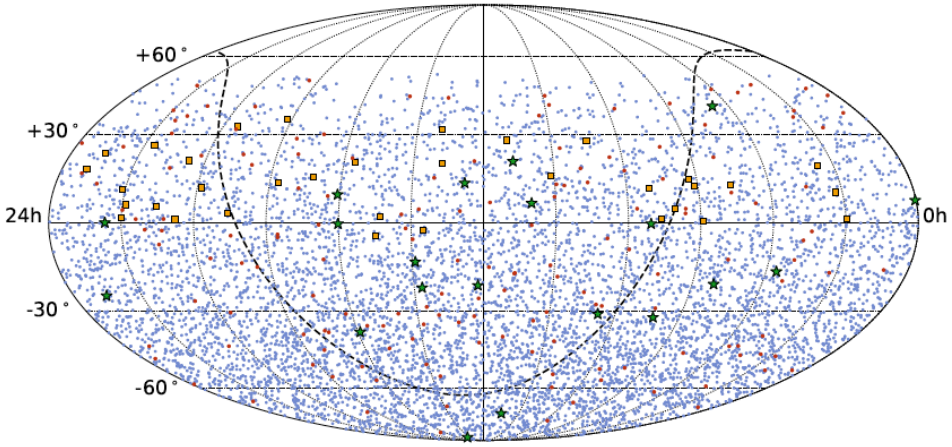
Time correlation and
Multi-messenger searches

arXiv:1902.09462 [astro-ph.HE]

ANTARES – Multi-messenger
Time correlation with IceCube events

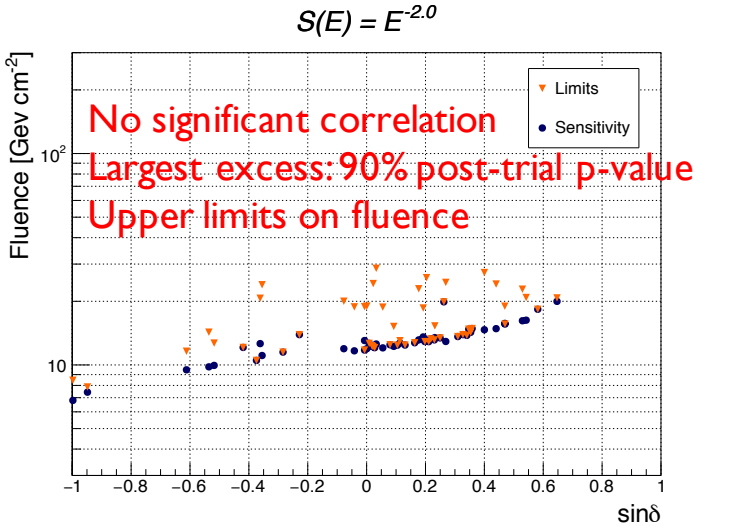
34 from the IceCube up-going tracks sample

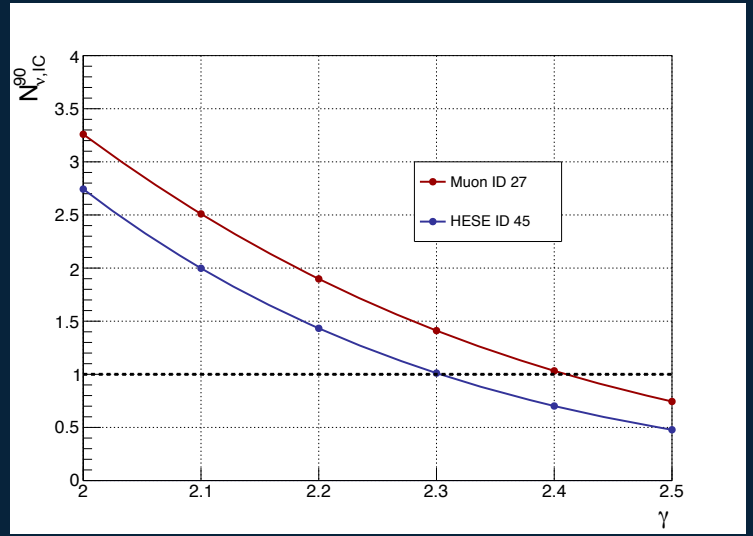
20 from the IceCube HESE sample



Search strategy:

- Search for correlations in time and space between ANTARES data and 54 IceCube neutrino events
- Maximum likelihood method
- Gaussian signal time PDF assumed with σ (emission duration) fitted in the likelihood maximization within 0.1 and 120 days





Constraint on the spectral index γ of the neutrino spectrum of a flaring source (σ < 0.1 days) responsible for the two most energetic IceCube events:

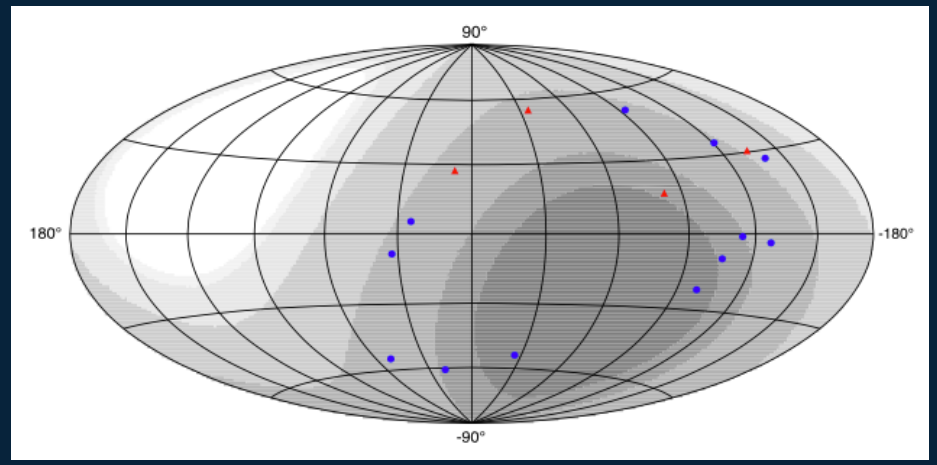
γ < 2.3 and γ < 2.4

Compatible with the IceCube best-fitting spectral indices for the neutrino flare from TXS 0506+056

ANTARES – Multi-messenger

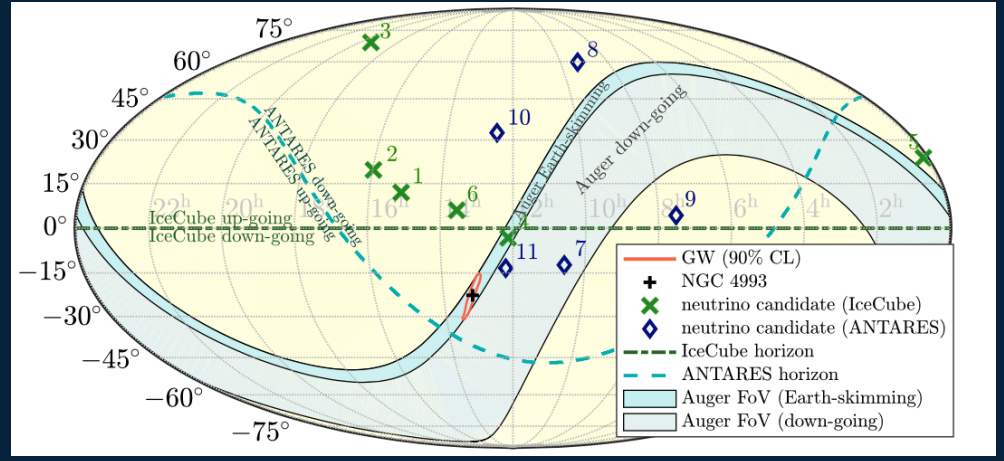
MNRAS 482, 184–193 (2019)
Astrophys.J.848 (2017) no.2,L12

Fast Radio Bursts



- Search for correlations in time and space between ANTARES high-energy neutrinos and 12 FRBs detected in the 2013-2017 period
- Search time window: ± 6h around the source observation time

Gravitational Waves

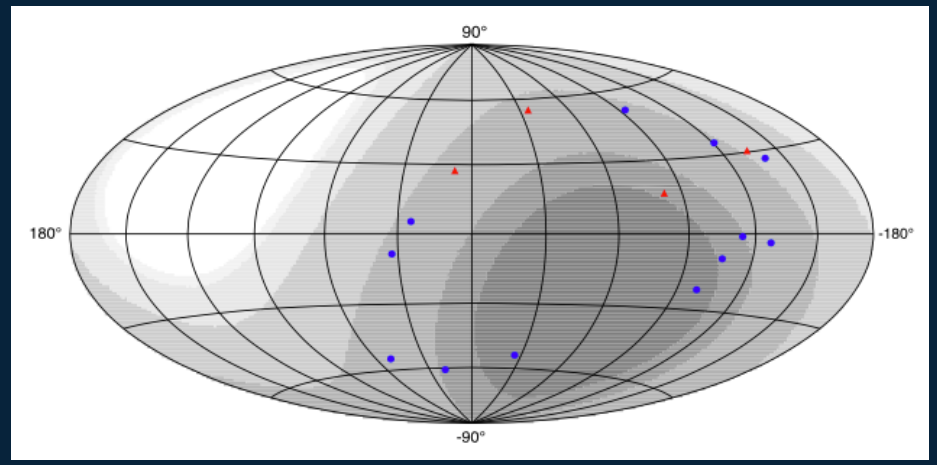


- Follow-up of GW events
- Joint search: ANTARES + IceCube + Auger
- Search for neutrinos in a ±500 s window around GW170817 (BNS merger)
- No significant coincidences → Limits on neutrino fluence

ANTARES – Multi-messenger

MNRAS 482, 184–193 (2019)
Astrophys.J.848 (2017) no.2,L12

Fast Radio Bursts



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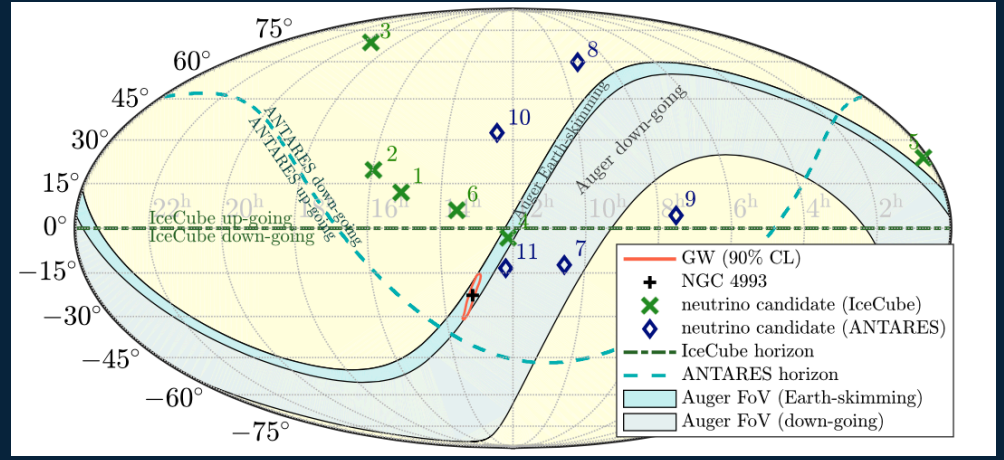
Gravitational Waves



- Follow-up of GW events
- Joint search: ANTARES + IceCube + Auger
- Search for neutrinos in a ±500 s window around GW170817 (BNS merger)
- No significant coincidences → Limits on neutrino fluence

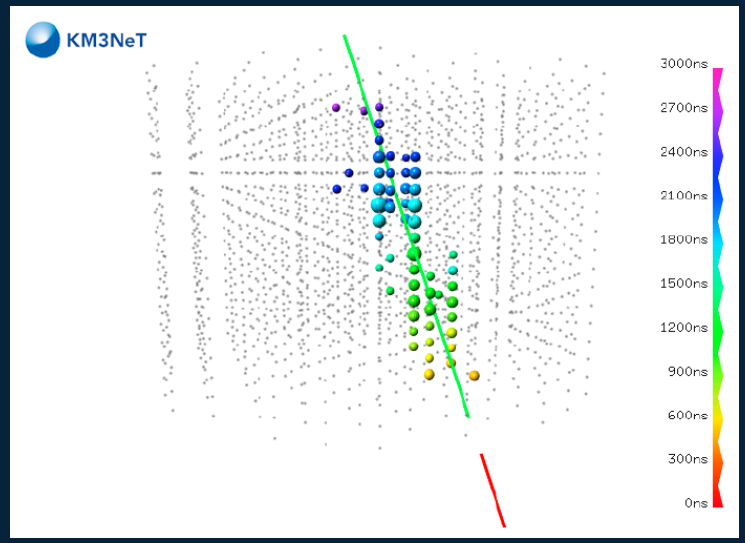
Other searches:
- GRBs
- X-ray binaries
- Blazars
- …

Conclusions

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

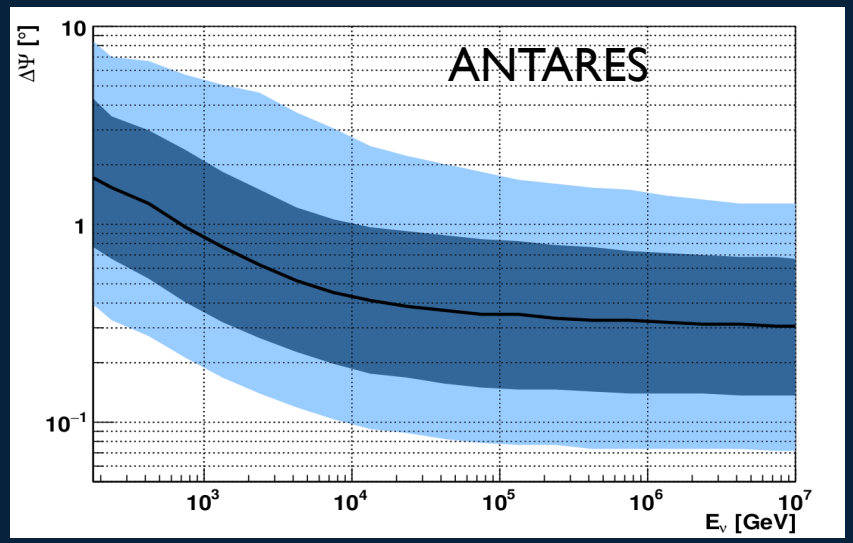
- KM3NeT/ARCA
  - Under construction
  - Cubic kilometre-sized detector with high visibility towards the Galactic Centre
  - Expected to make definite statements about neutrino flux from several Galactic candidates within a few years of operation
  - Observation of HE neutrino flux discovered by IceCube expected in less than 1 year of operation

Event Topologies: TRACKS

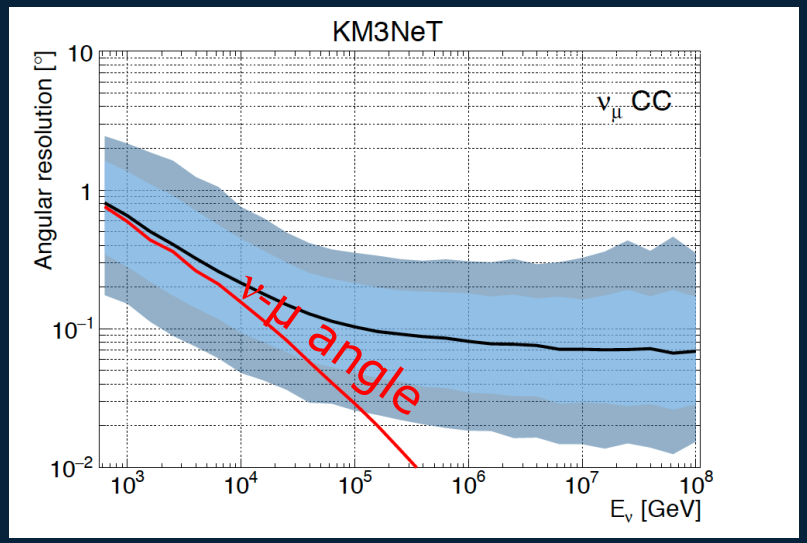


Track-like events:
ν_μ (ν_τ) neutrino
CC interaction near the detector
➔ track

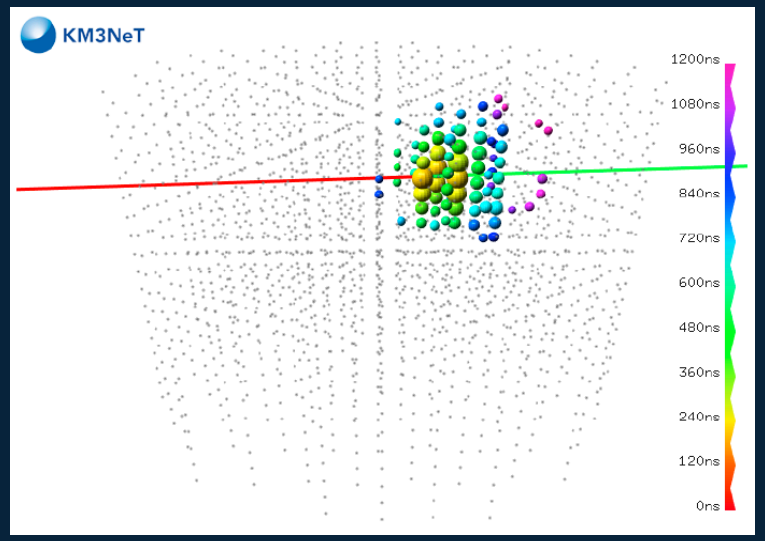
Angular resolution < 0.4° for E_ν > 10 TeV



Angular resolution < 0.1° for E_ν > 100 TeV

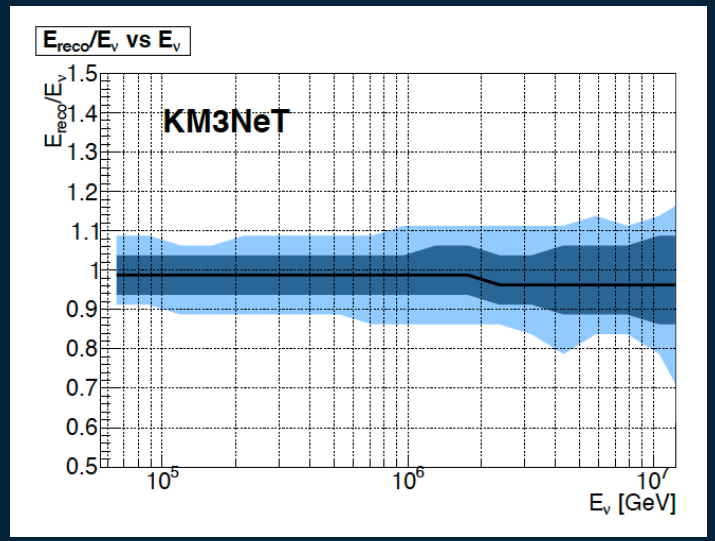


Event Topologies: SHOWERS

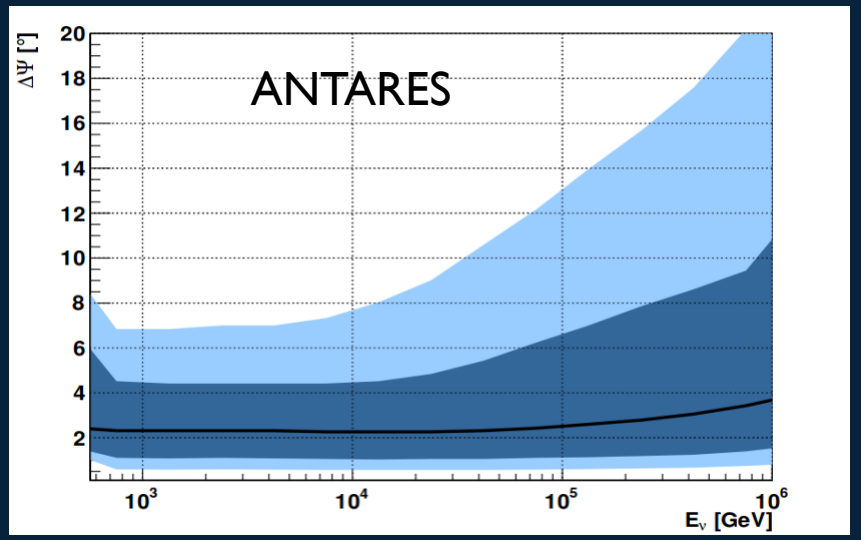


Shower-like events:
all neutrinos NC
ν_e, ν_τ CC interaction inside or very close to the detector ➔ shower

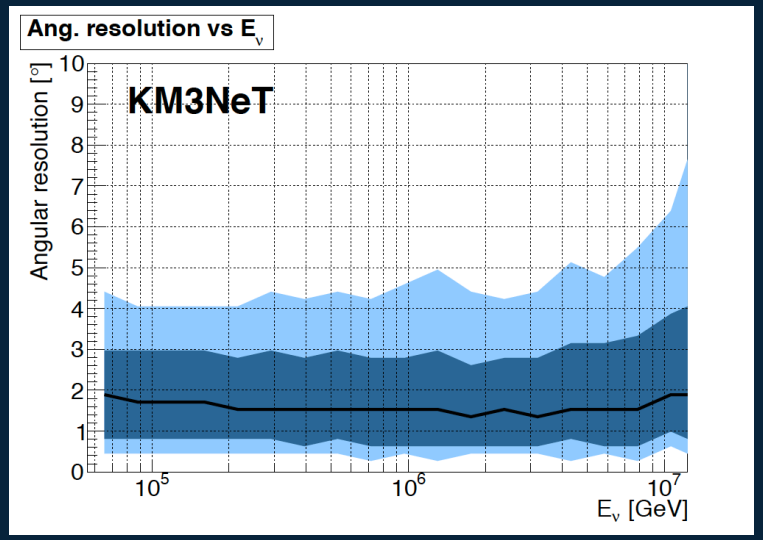
Energy resolution ~ 5%



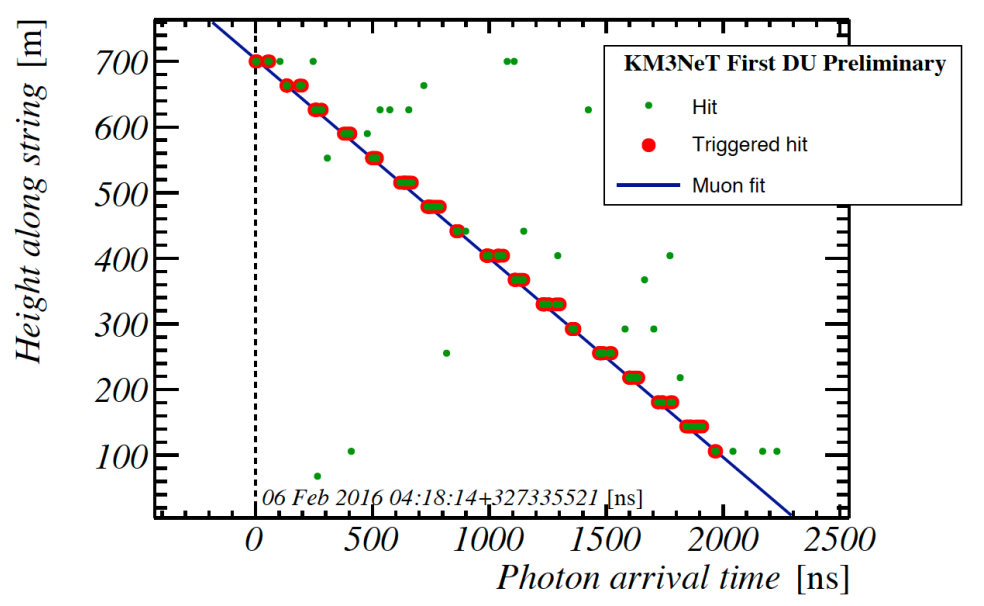
Angular resolution < 3°



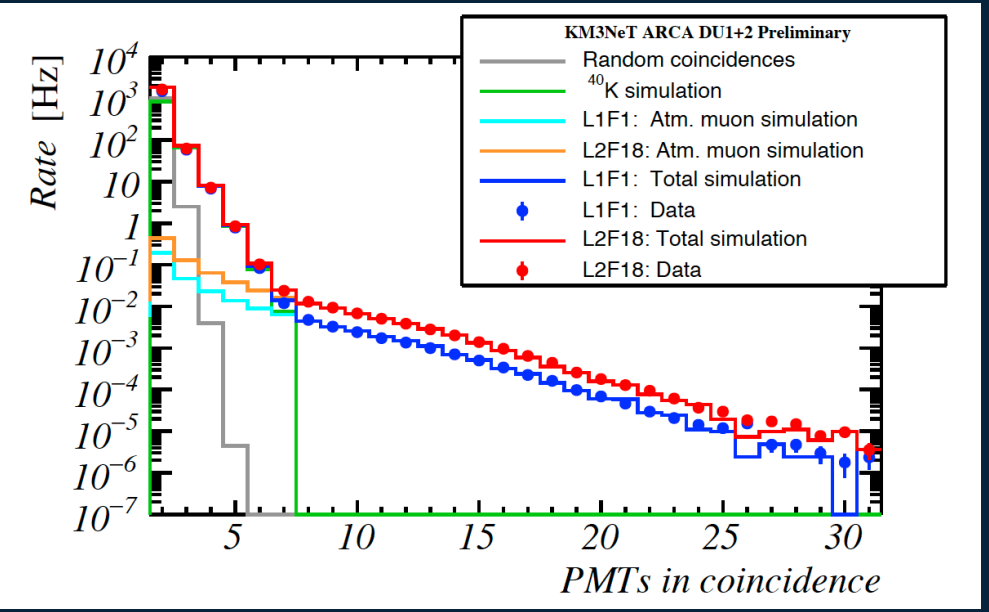
Angular resolution < 2°



KM3NeT/ARCA
First detection lines



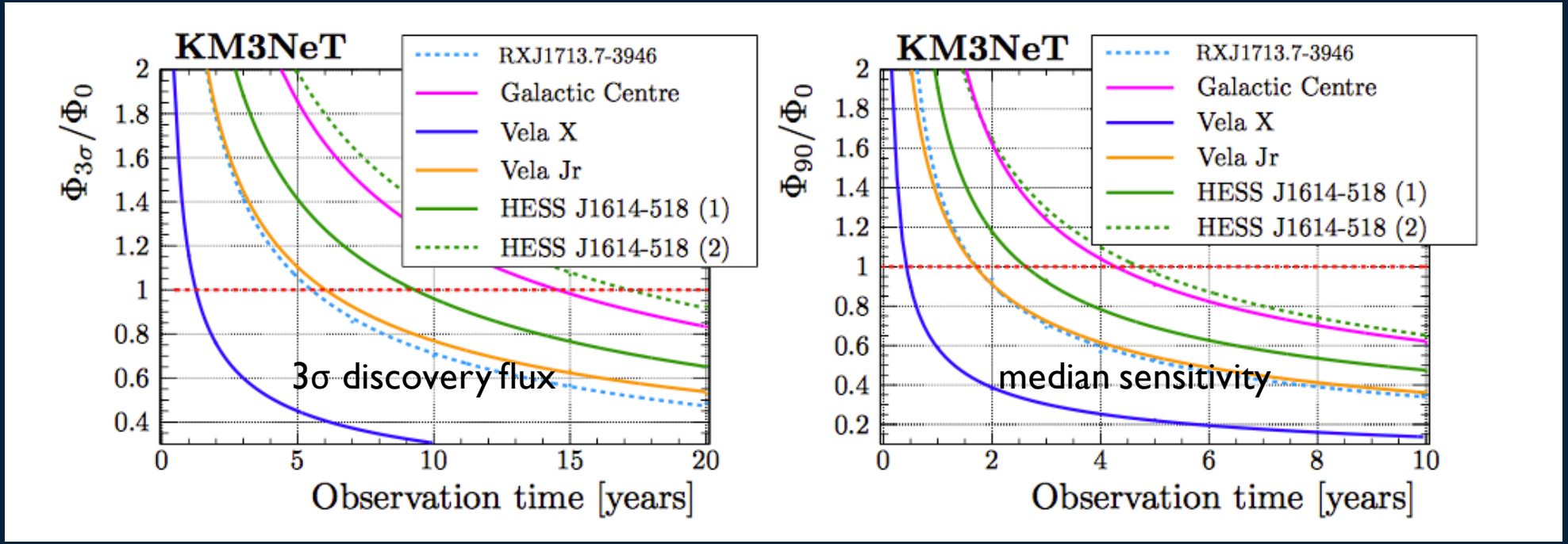
Event display: down-going muon



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

Astropart.Phys. 111 (2019) 100-110

KM3NeT/ARCA – Point Sources
Galactic sources



- Expectations for various Galactic sources
- Assumed neutrino fluxes derived from the measured γ-ray spectrum
- Assumptions:
  - Hadronic scenario for the γ-ray production
  - Transparent sources

3σ median significance in less than 6 years of operation for the most intense sources: Vela X and RXJ1713.7-3946

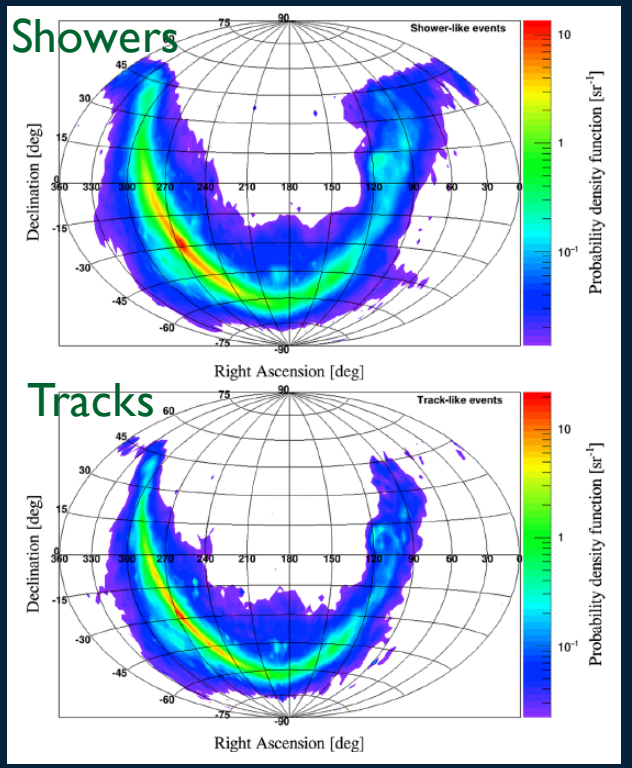
Phys.Rev. D96 (2017) no.6,062001

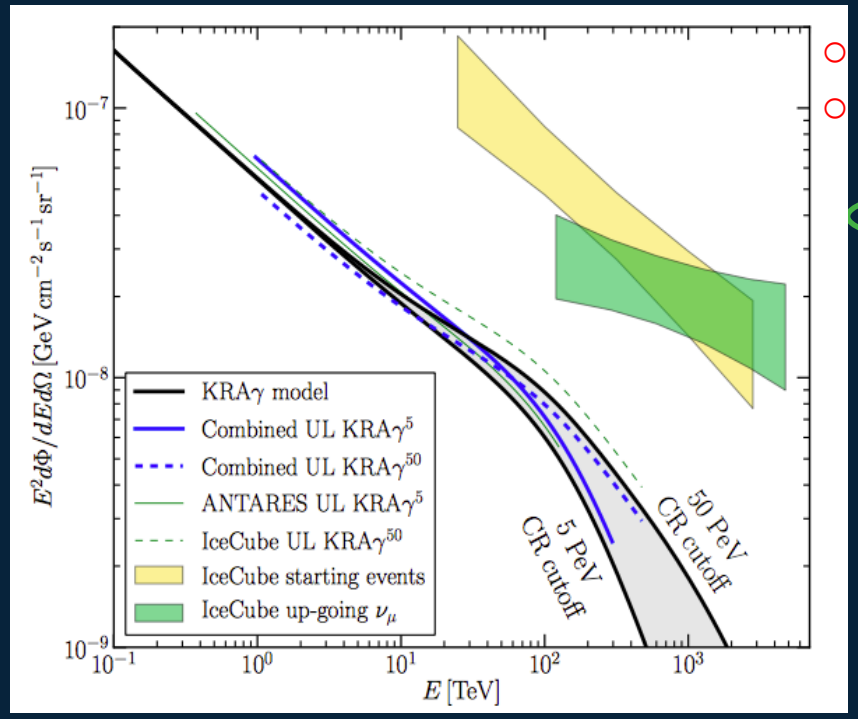
ANTARES – Diffuse Flux

Galactic Plane

Sample:
- 9 years: 2007 - 2015
- tracks and showers

Search strategy:
- Signal map according to KRA_γ modelling
- Two ref models: 5 PeV and 50 PeV cutoffs
- Likelihood ratio test method





- No excess of events
- 90% flux limits for ref models:
  - 1.1 x ϕ(5 PeV)
  - 1.2 x ϕ(50 PeV)

Combined analysis
10yr ANTARES + 7yr IceCube
Astrophys.J. 868 (2018) no.2, L20

0.9 x ϕ(50 PeV)

- Strong constraint on a possible diffuse neutrino emission from the Galactic plane
- Hypothesis of neutrino flux produced by the Galactic CR interaction with gas explaining the IceCube spectral anomaly discarded

ANTARES – Multi-messenger

Real-time analysis

Triggers:

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

Performances:

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

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

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

ANTARES – Multi-messenger

Gravitational Waves

- Follow-up of the GW public alerts
- 11 BBH merger candidates and 3 BNS merger detected since early April
- Search for neutrinos in the online data stream
- Direction: 90% GW error box , Time windows: ± 500 s and ± 1h
- Only up-going, track-like events selected
- No coincidences detected so far