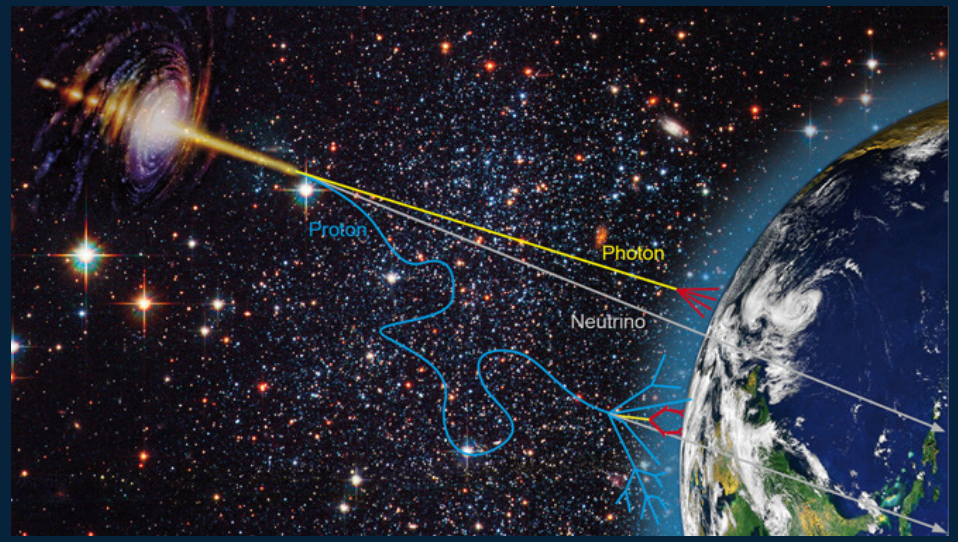
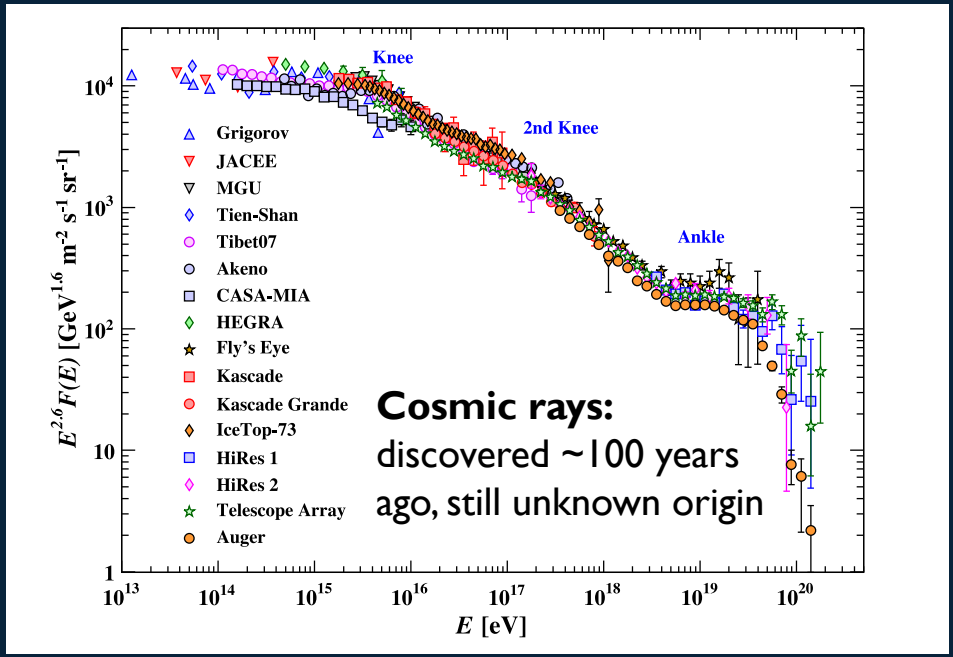
Highlights from the ANTARES neutrino telescope

Giulia Illuminati on behalf of the ANTARES Collaboration

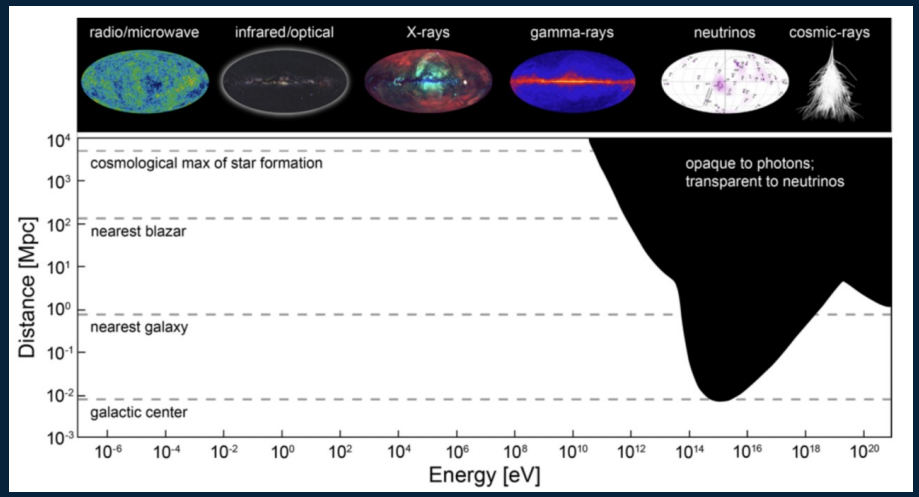
Why Neutrino Astronomy?



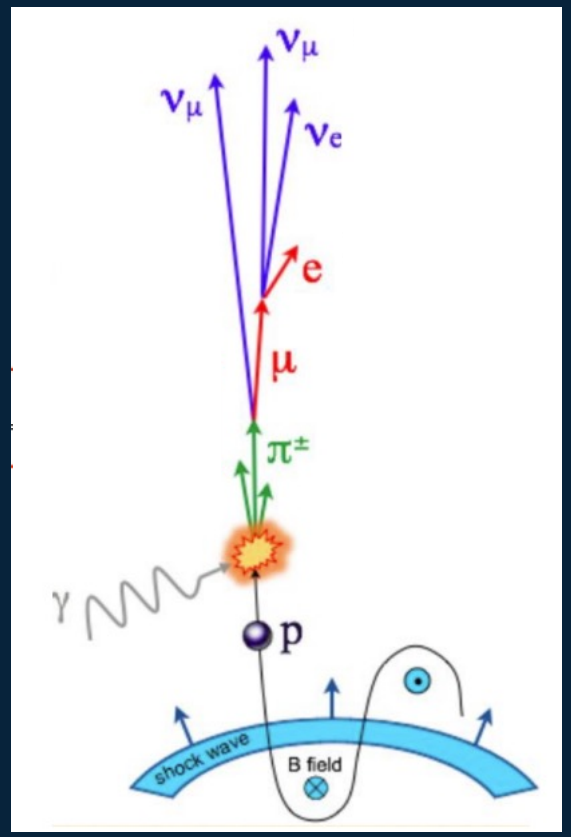


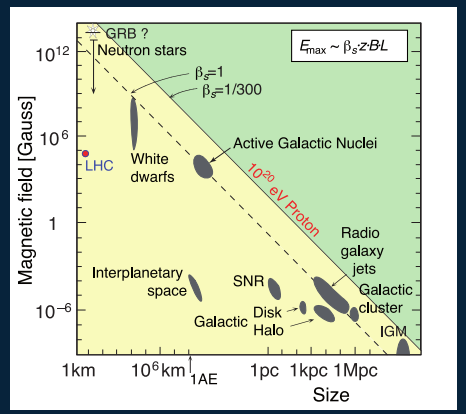
Neutrinos:

- neutral → trajectory not affected by magnetic fields, **point back to the source**
- weakly interacting → **penetrate regions opaque to photons**



Why Neutrino Astronomy?





Hadronic scenario

proton-photon:

$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^0 + p$$
$$\rightarrow \pi^+ + n$$

proton-nucleon:

$$p + p \rightarrow p + p + \pi^0$$
$$\rightarrow p + n + \pi^+$$

$$p + n \rightarrow p + n + \pi^0$$
$$\rightarrow p + p + \pi^-$$

$\pi^0 \rightarrow \gamma + \gamma$

Also produced in the *leptonic* scenario via synchrotron emission + inverse Compton scattering

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

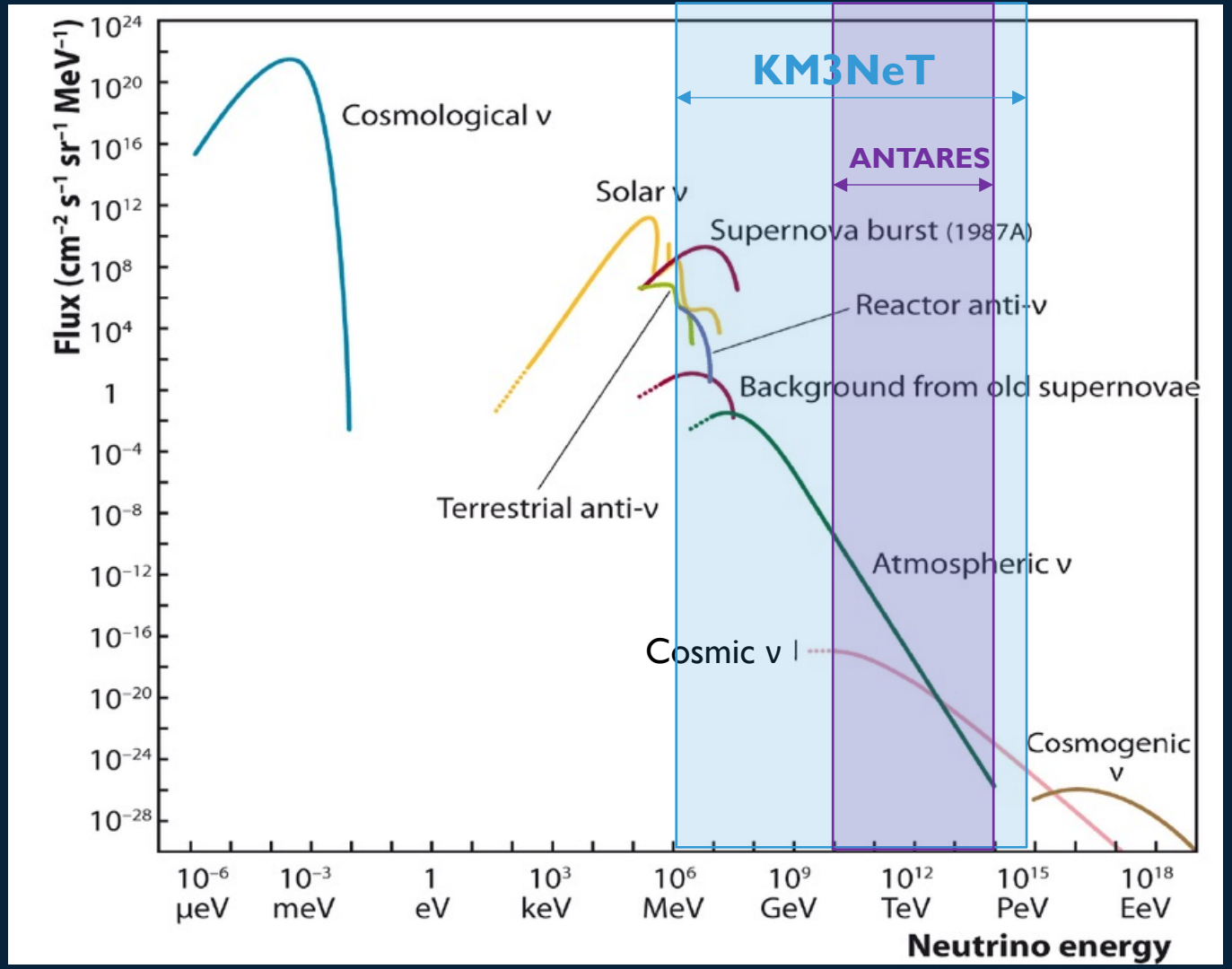
$\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$ at the source

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

Neutrinos:

- Provide a **strong indication of hadronic acceleration** in astrophysical sources
- Smocking gun of the **cosmic-ray sources**

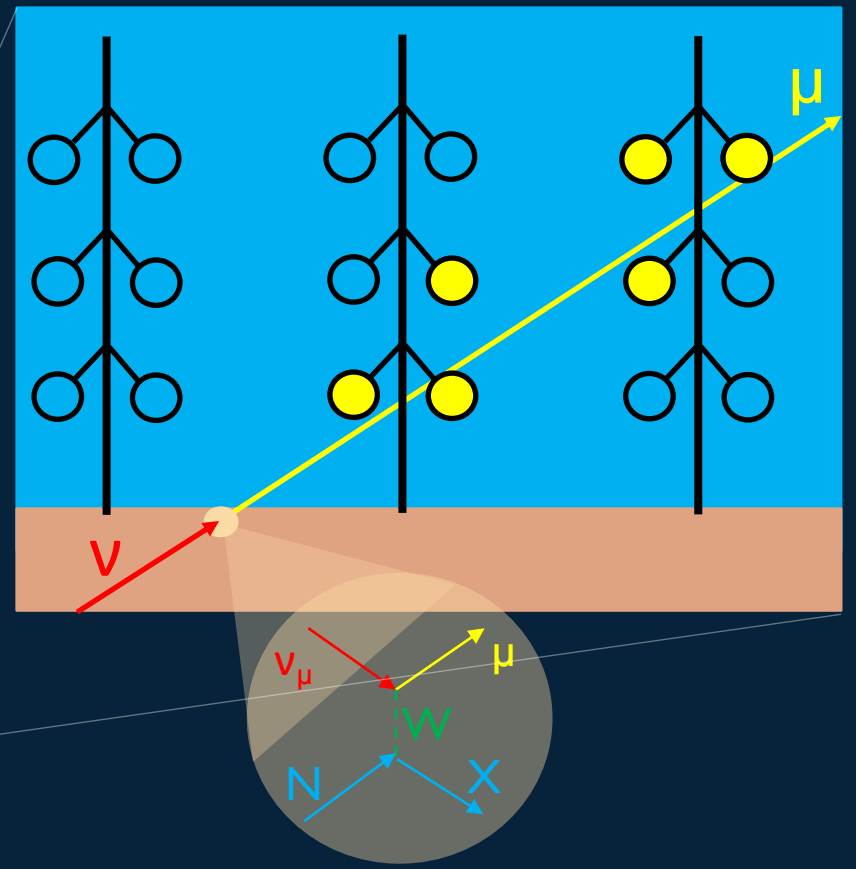
Neutrino fluxes

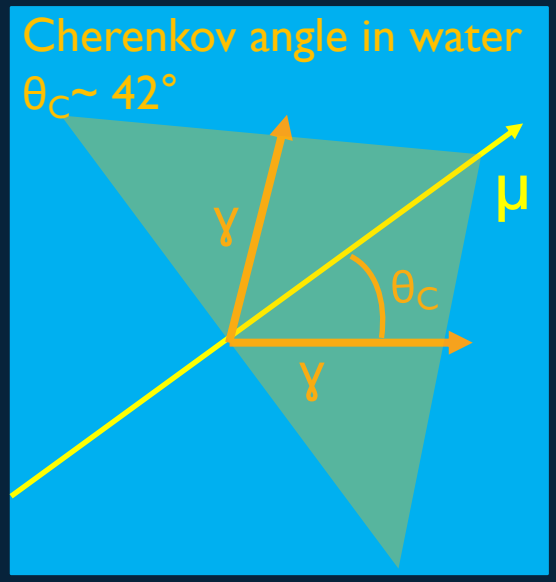


Detection principle

Neutrinos are challenging to detect (large background contamination and low fluxes)

- 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





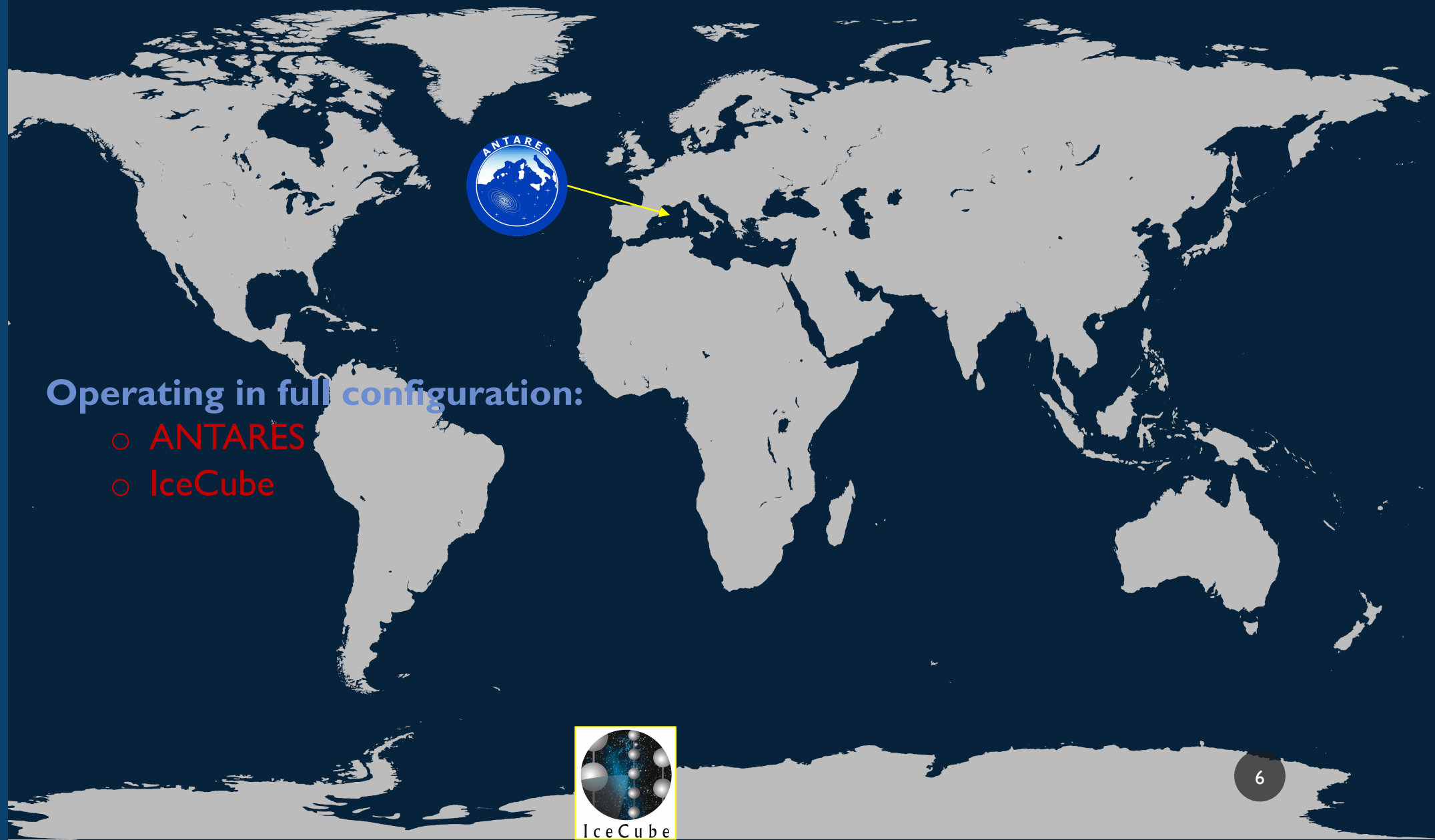
- Cherenkov radiation detected by arrays of PMTs
- Position, time and charge used to reconstruct direction and energy

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

key interaction (CC):

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

Neutrino telescopes



Neutrino telescopes

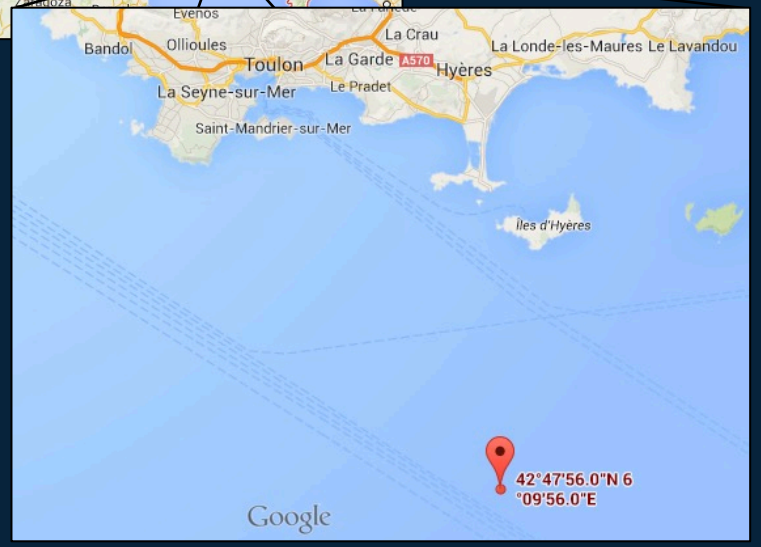
Operating in full configuration:
- ANTARES
- IceCube

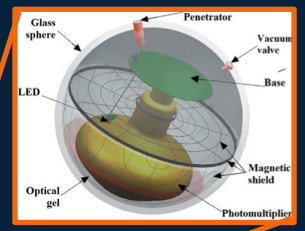
Under construction:
- KM3NeT
- Baikal GVD

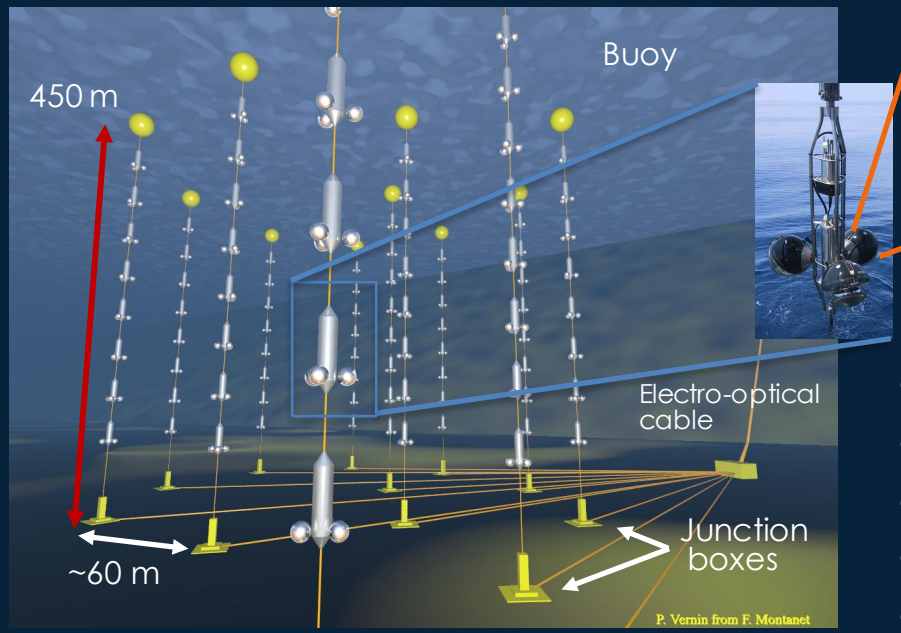
In planning phase:
- IceCube-Gen2
- P-ONE

ANTARES

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

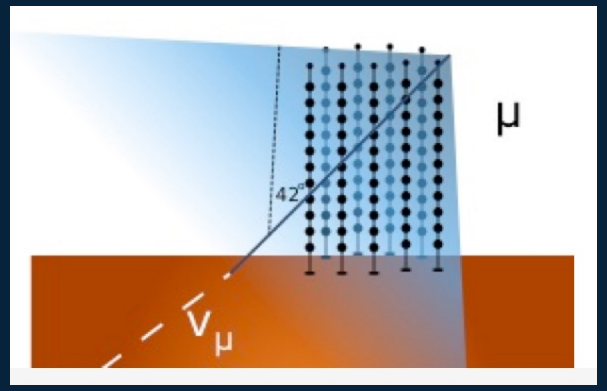




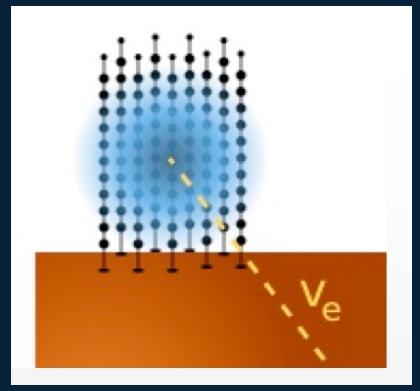


- Three-dimensional array of 885 PMTs
- 12 vertical lines, 25 storeys
- 3 PMTs per storey
- PMT facing 45° downwards
- Instrumented volume ~0.01 km^3

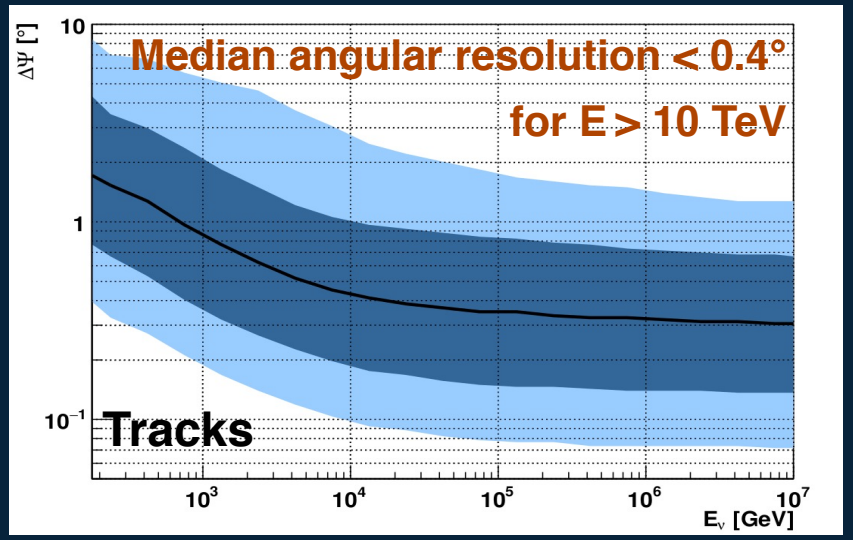
Event Topologies: TRACKS and SHOWERS

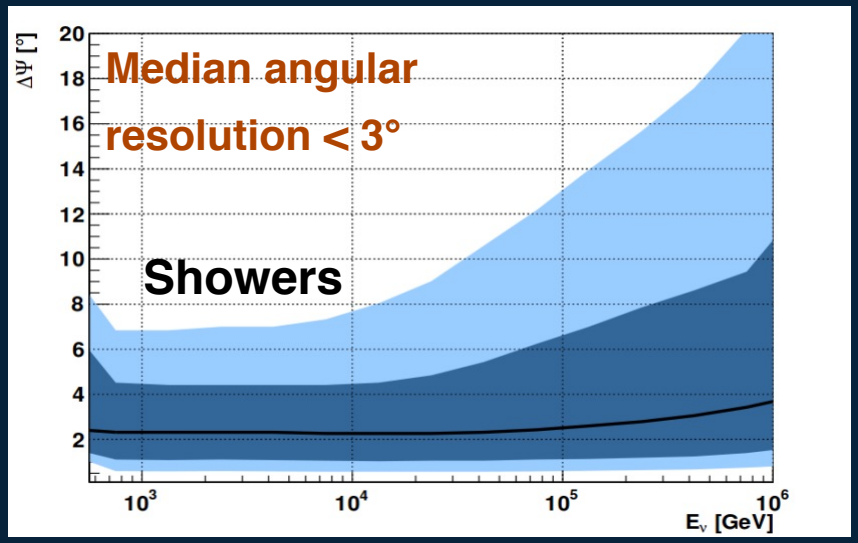


Track-like events:
ν_μ (ν_τ) neutrino CC interaction near the detector



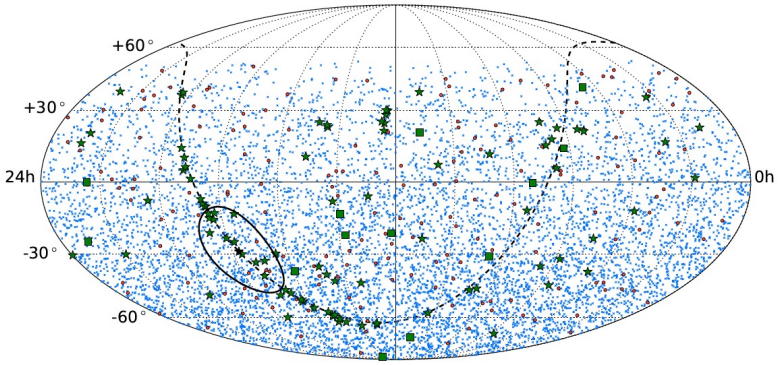
Shower-like events:
all neutrinos NC, ν_e,ν_τ CC interaction inside or very close to the detector



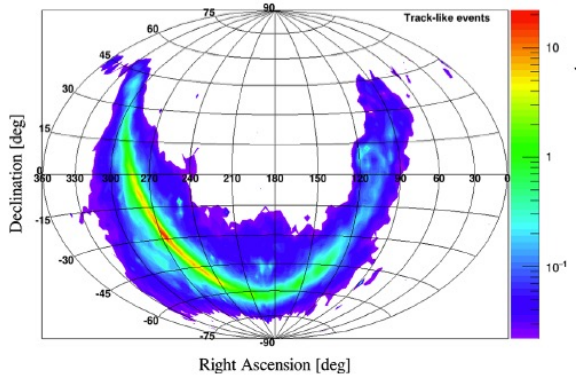


Searches

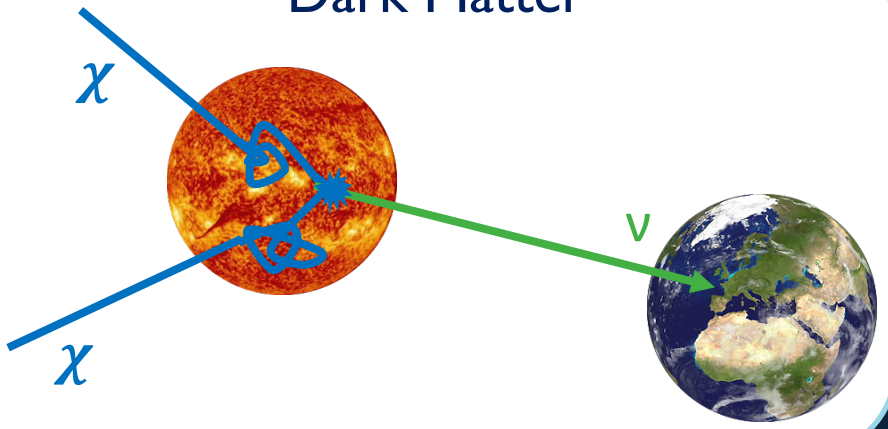
Point-Sources



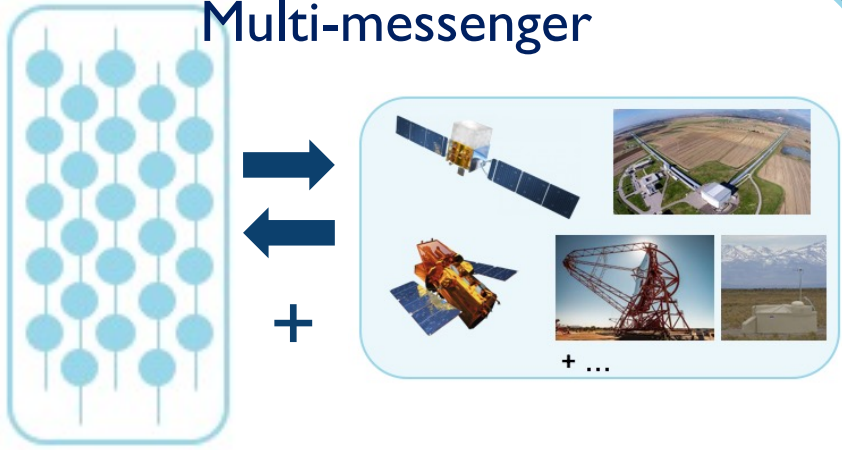
Diffuse Flux



Dark Matter



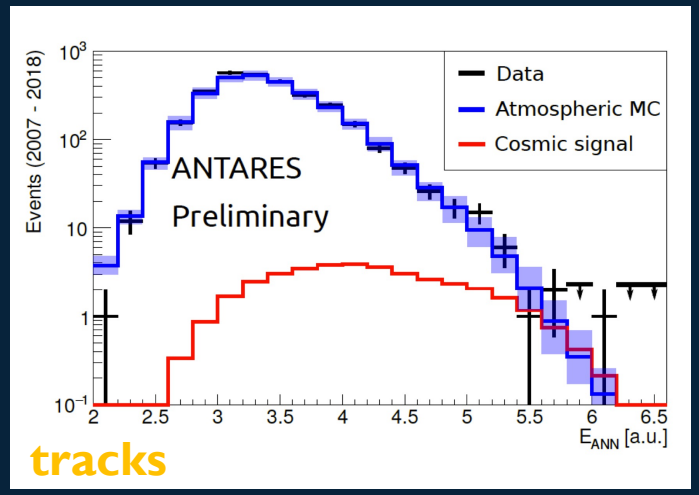
Multi-messenger

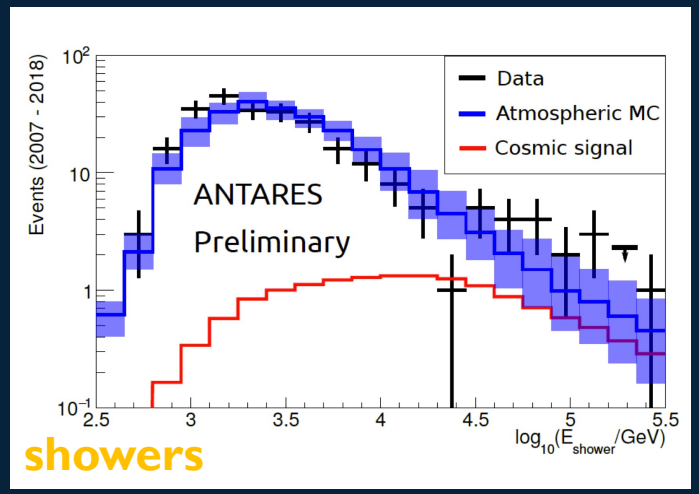


+…

All-sky Diffuse Flux

ApJL 853, L7 (2018)
PoS(ICRC2019)891

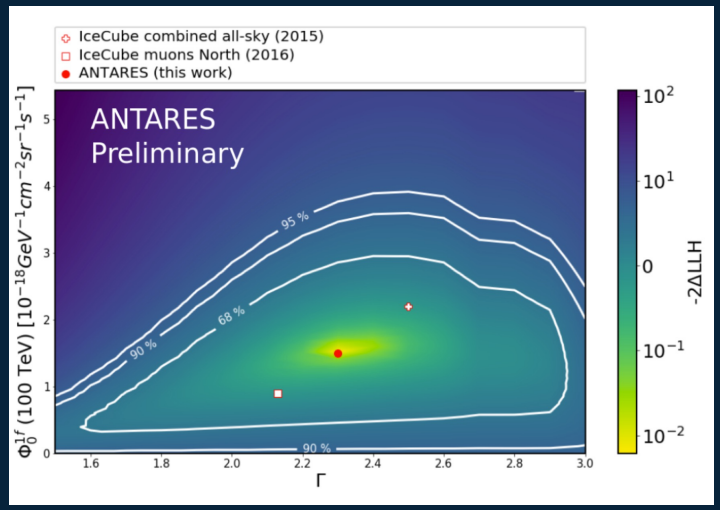




ANTARES 12 years track and shower analysis

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

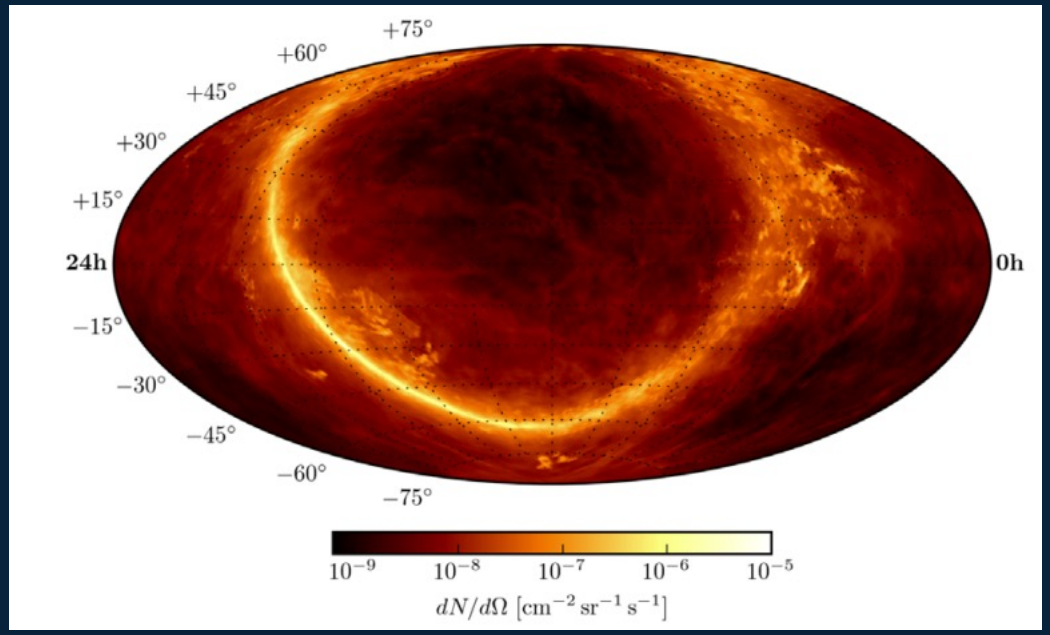
→1.8σ excess



$$\Phi_0^{1f}(\mathbf{100\ TeV}) = (1.5 \pm 1.0) \cdot 10^{-18} \left(\mathrm{GeV\ cm^2 s\ sr}\right)^{-1}$$
$$\Gamma = 2.3 \pm 0.4$$

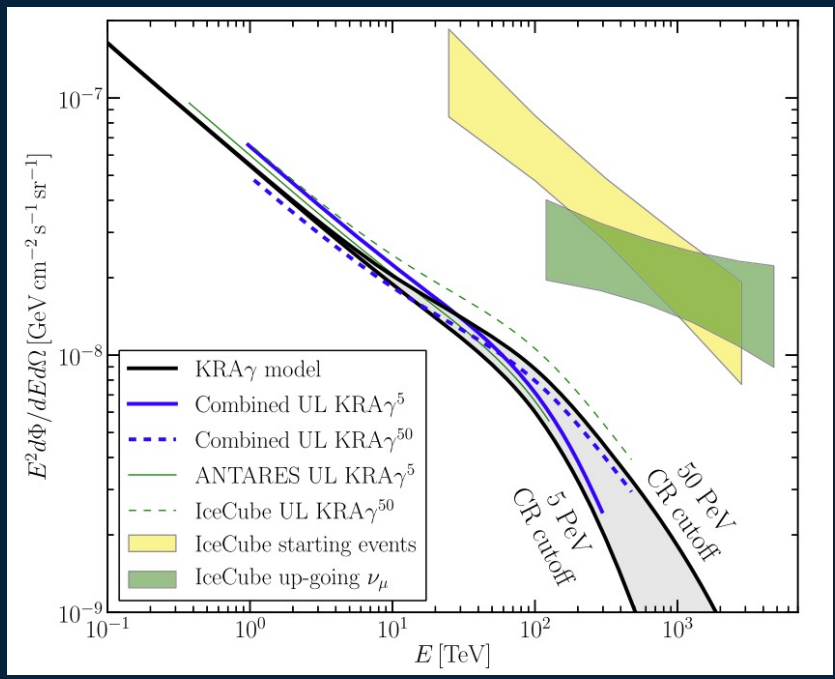
Next analysis update will count on **new event selection** (BDT) + **unbinned maximum likelihood** approach (PoS(ICRC2021)1126)

Galactic Diffuse Flux



Expected neutrino flux from the Kra$_\gamma$ model based on spatial distribution of diffuse γ-ray data

Joint ANTARES+IceCube Constraints on Galactic Diffuse Neutrino Emission



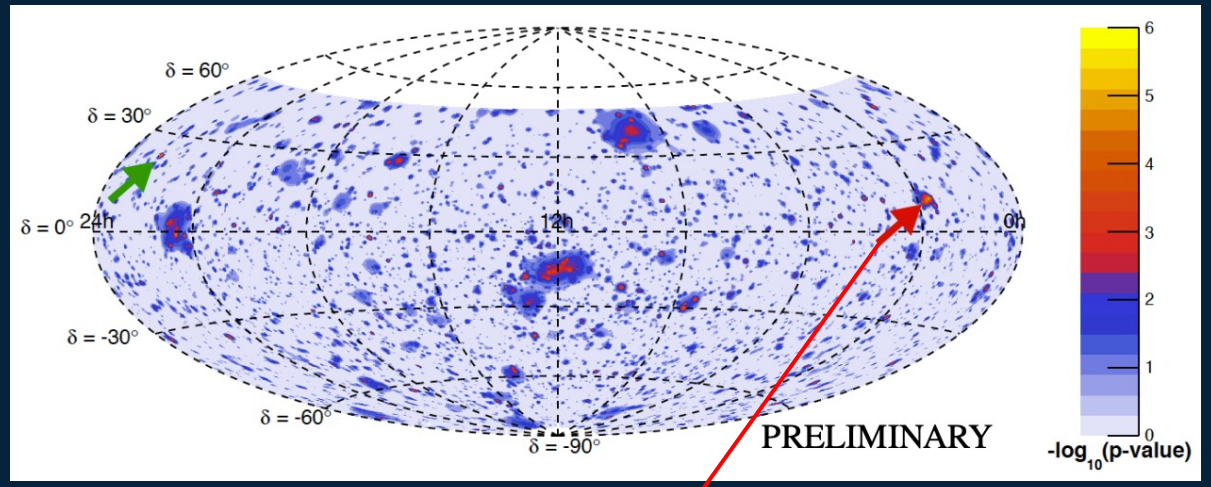
Sensitivities and Results of the Analysis on the KRA$_\gamma$ Models with the 5 and 50 PeV Cutoffs

Energy Cutoff	Sensitivity [Φ_{KRA_γ}]			Fitted Flux [Φ_{KRA_γ}]	p-value [%]	Upper Limit (UL) at 90% CL [Φ_{KRA_γ}]
	Combined	ANTARES	IceCube			
5 PeV	0.81	1.21	1.14	0.47	29	1.19
50 PeV	0.57	0.94	0.82	0.37	26	0.90

Starting to constraint the models

Point-like sources

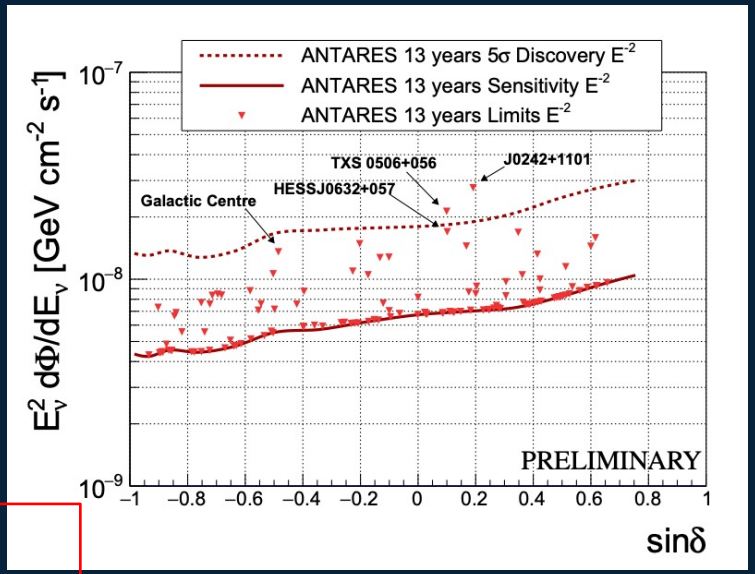
Full-sky search



Most significant spot in the sky
$(\hat{\alpha}, \hat{\delta})$ = (39.6°, 11.1°)
Pre-trial: 4.3σ
Post-trial: 48%

ANTARES 13 years
track and shower analysis

Upper limits on ν-flux from 121 astrophysical sources



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

Second most significant source
TXS 0506+056 (**2.8σ**)

Stacking searches

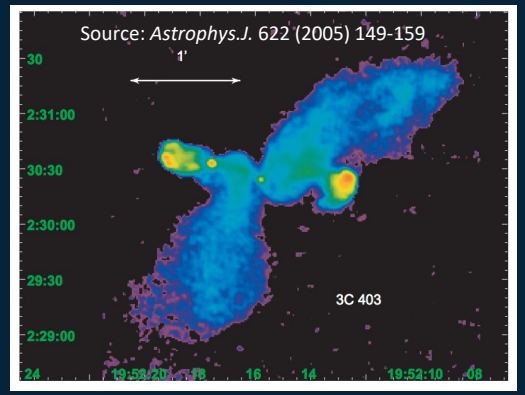
Astrophys.J. 911 (2021) 48

ANTARES 11 years

CATALOG	PRE-TRIAL	POST-TRIAL	DOMINANT SOURCE
Fermi 3LAC All Blazars	0.19	0.83	
Fermi 3LAC FSRQ	0.57	0.97	
Fermi 3LAC BL Lacs	0.088	0.64	MG3J225517+2409
Radio-galaxies	4.8×10^{-3}	0.10	3C403
Star Forming Galaxies	0.37	0.93	
Obscured AGN	0.73	0.98	
IC HE tracks	0.05	0.49	

1.6σ

Radio galaxy 3C403



p-value: 3.7σ
chance probability ($N_{sources}$ = 56) = 2.5σ

BLLac MG3 J225517+2409

p-value: 3.8σ
chance probability ($N_{sources}$ = 1255) = 1.4σ

Neutrinos and Radio Blazars

Promising **associations** between **IceCube neutrinos** and **radio galaxies**

The Astrophysical Journal, 894:101 (13pp), 2020 May 10 https://doi.org/10.3847/1538-4357/ab86bd

ApJ 894 (2020) 101

Observational Evidence for the Origin of High-energy Neutrinos in Parsec-scale Nuclei of Radio-bright Active Galaxies

Alexander Plavin[1,2], Yuri Y. Kovalev[1,2,3], Yuri A. Kovalev[1], and Sergey Troitsky[4]
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[4] Institute for Nuclear Research of the Russian Academy of Sciences, 60th October Anniversary Prospect 7a, Moscow 117312, Russia
Received 2020 January 3; revised 2020 March 16; accepted 2020 April 2; published 2020 May 12

The Astrophysical Journal, 908:157 (10pp), 2021 February 20 https://doi.org/10.3847/1538-4357/abceb8

ApJ 908 (2021) 157

Directional Association of TeV to PeV Astrophysical Neutrinos with Radio Blazars

A. V. Plavin[1,2], Y. Y. Kovalev[1,2,3], Yu. A. Kovalev[1], and S. V. Troitsky[4]
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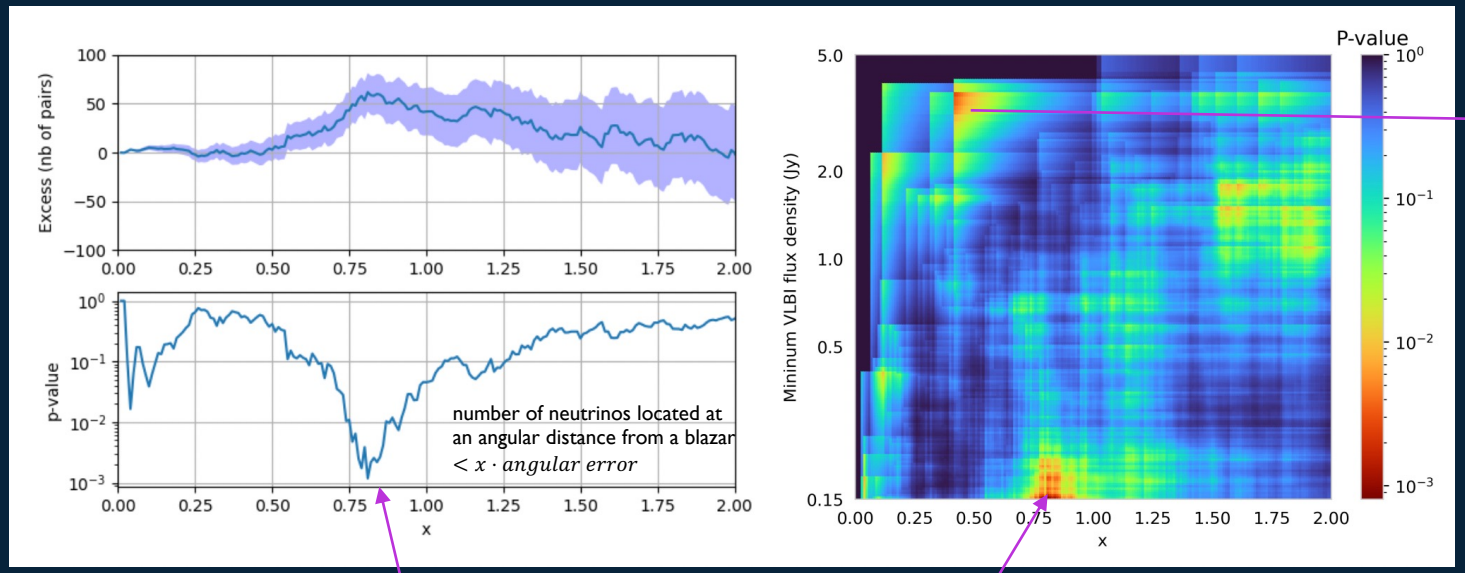
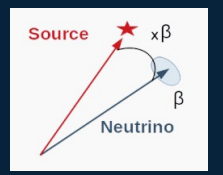
ANTARES **positional correlation** analysis with radio blazars



0.5 expected chance coincidences, 4 neutrino-blazar pairs observed:
- **J0609-1542**
- **J1743-0350**
- **J0538-4405**



451 pairs observed in data, **389** expected from random simulations

3.2σ pre-trial → 2.3σ post-trial

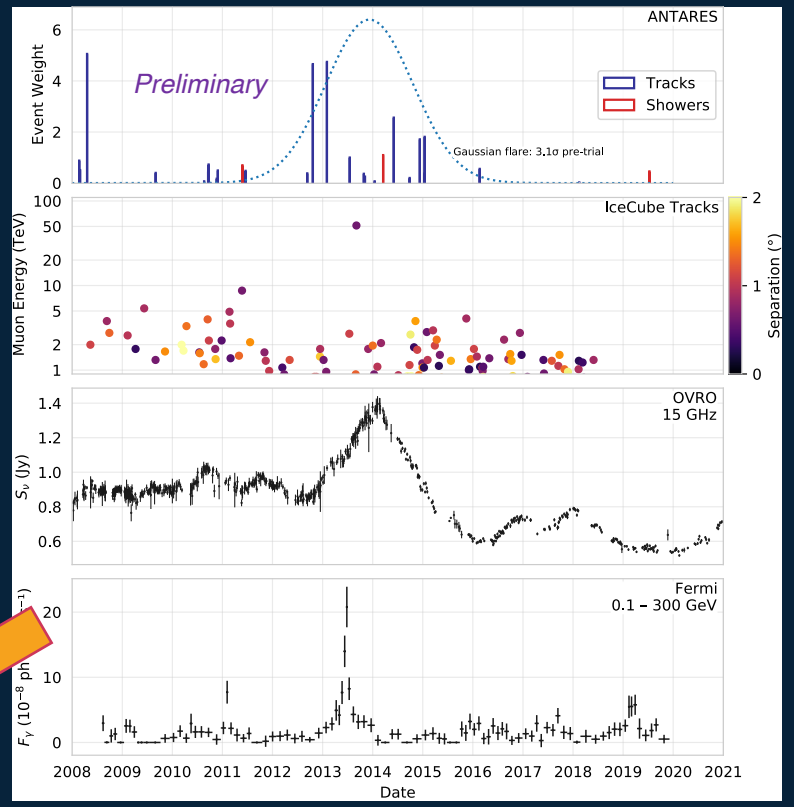
Neutrinos and Radio Blazars

ANTARES search for neutrino flares from 2774 radio blazars

Source			Results									
Name	δ	α	Gaussian-shaped time profile					Box-shaped time profile				
			$\hat{T}_0$	$\hat{\sigma}_t$	$\hat{\mu}_{sig}$	$\hat{\gamma}$	p-value	$\hat{T}_0$	$\hat{\sigma}_t$	$\hat{\mu}_{sig}$	$\hat{\gamma}$	p-value
	[deg]	[deg]	[MJD]	[days]				[MJD]	[days]			
J1500-2358	**-24.0**	**225.2**	**55846**	**4**	**3.7**	**2.2**	**0.00041**	**55846**	**6**	**3.7**	**2.2**	**0.00031**
J1517-4424	-44.4	229.4	57761	361	7.2	3.5	0.00084	57366	529	5.3	3.5	0.0099
J1606+2717	27.3	241.7	58793	1	1.0	1.1	0.00089	58267	538	1.2	1.3	0.0017
J1418-3509	**-35.2**	**214.7**	**58119**	**12**	**3.6**	**3.3**	**0.00095**	**58119**	**14**	**3.8**	**3.3**	**0.00058**
J0242+1101	**11.0**	**40.6**	**56634**	**318**	**5.3**	**2.0**	**0.0011**	**56635**	**413**	**5.6**	**2.1**	**0.00040**
J0732-0150	**1.8**	**113.1**	**55794**	**82**	**4.9**	**3.5**	**0.0012**	**55813**	**117**	**5.2**	**3.5**	**0.00062**
J0641-3554	-35.9	100.3	58084	16	3.0	3.2	0.0017	58080	18	3.0	3.2	0.0013

Chance probability of the multi-messenger association under study

J0242+1101(PKS 0239+108)



ANTARES best-fit flare for this source

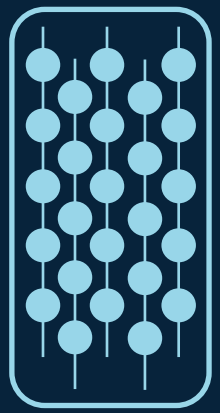
IceCube tracks from 10-years point-source sample
- Tracks within 90% angular error from source
- angular error < 10deg²

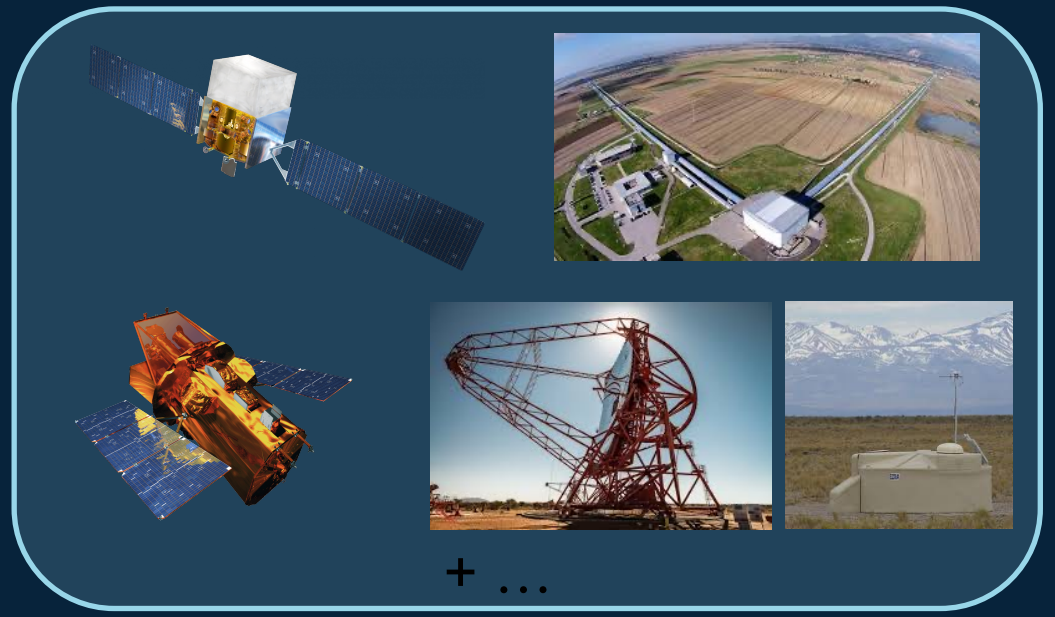
OVRO radio light-curve

Adaptive binned gamma-ray light-curve obtained from Fermi LAT data

Multi-messenger

Real-time analyses → Alert triggering





Offline analyses

Time correlation and Multi-messenger searches

- Neutrinos from IceCube and Baikal-GVD
- GW events
- GRBs
- TDEs
- …

Real-time analyses
ANTARES neutrino **alerts**

What triggers an alert:
- 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)

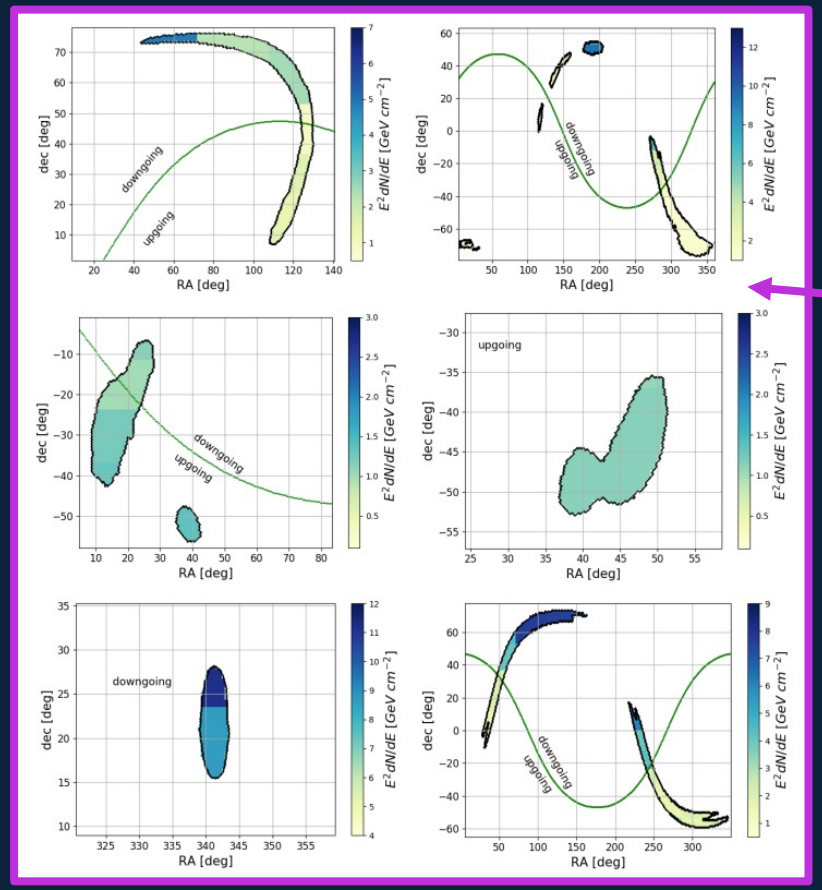
Performances:
- **Time to send an alert: ~5 s**
- **Median angular resolution: ~ 0.4°**

>> 300 ANTARES alerts sent since 2009

Offline multi-messenger follow-up Gravitational Waves

Eur. Phys. J. C volume 80 (2020) 487

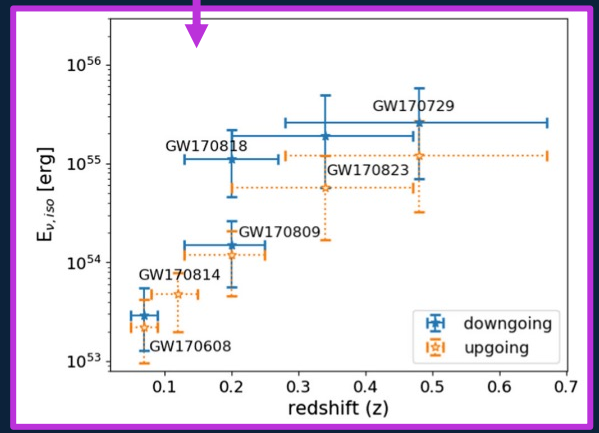
Search for cosmic neutrino candidates reconstructed
inside the **90% CL GW area** (error box) detected during ±500 s around the GW trigger time



Upper limits on the neutrino spectral fluence as a function of the position in the sky in equatorial coordinates

- **~60 GW triggers from** the three LIGO-Virgo observing runs **analyzed online by ANTARES**
- No neutrino found in time and space coincidence

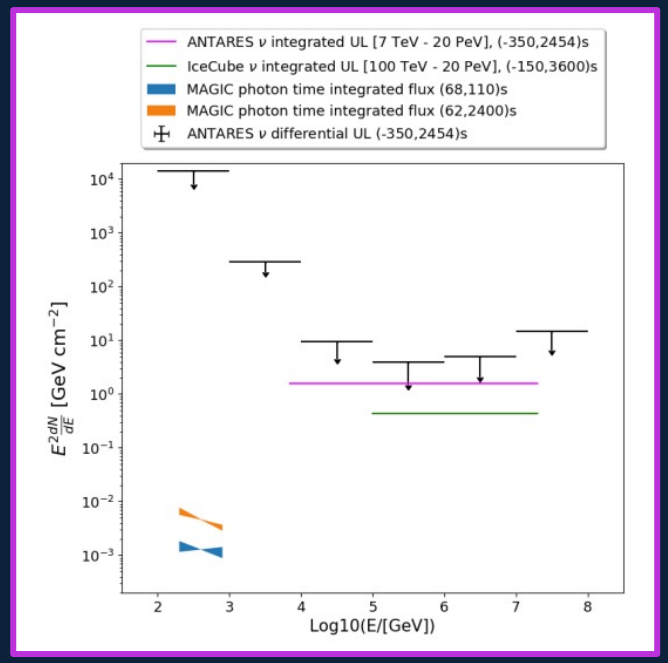
Dedicated offline search from GW events detected during the second observation run (O2)



90% CL upper limits on the total isotropic energy emitted in neutrinos as a function of the estimated redshift

Offline multi-messenger follow-up Gamma-ray Bursts

Search for cosmic neutrino candidates in coincidence with GRBs



ANTARES 90% differential (black arrows) and integrated (pink line) spectral fluence upper limits as a function of the neutrino energy for GRB 190114C

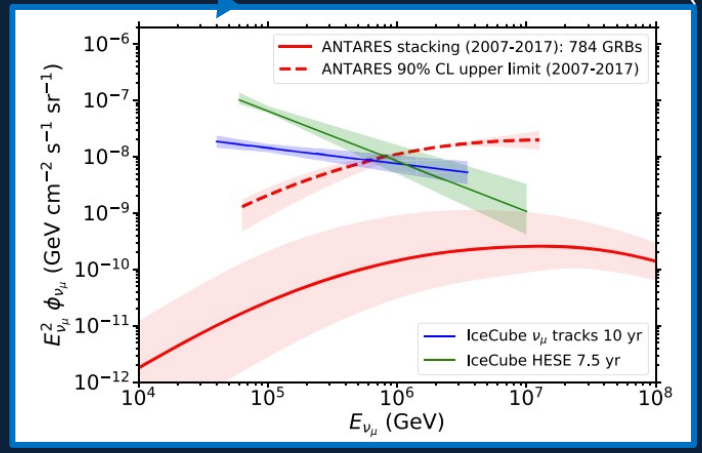
- **~1000 GRB triggers detected by Swift and Fermi analyzed online by ANTARES**
- No neutrino found in time and space coincidence

JCAP03(2021)092

Dedicated offline search from the first O(TeV) GRBs detected by MAGIC and H.E.S.S.

Stacking search from a catalogue of 784 GRBs occurred from 2007 to 2017

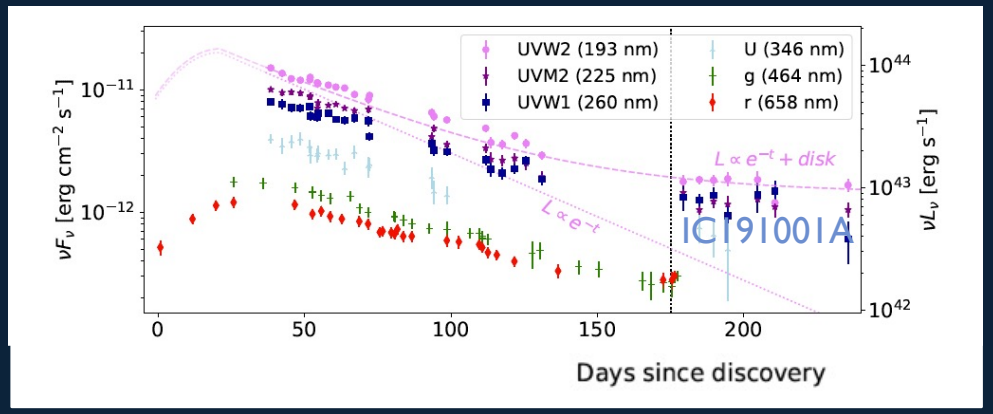
MNRAS 500, 5614–5628 (2021)

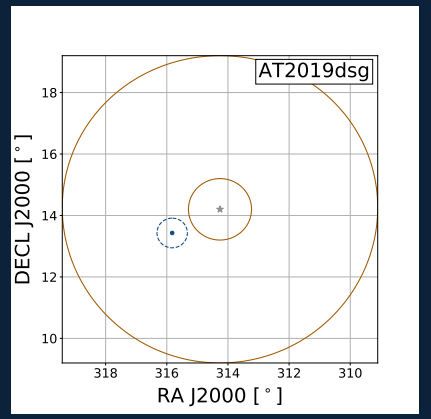


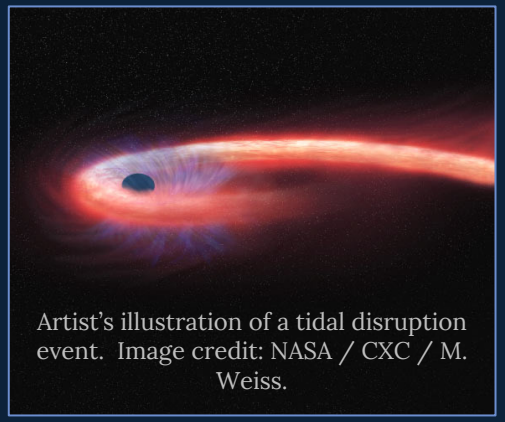
Independent constrain on the contribution of GRBs to the astrophysical neutrino flux to less than 10% at energies around 100 TeV.

Offline multi-messenger follow-up Tidal Disruption Events

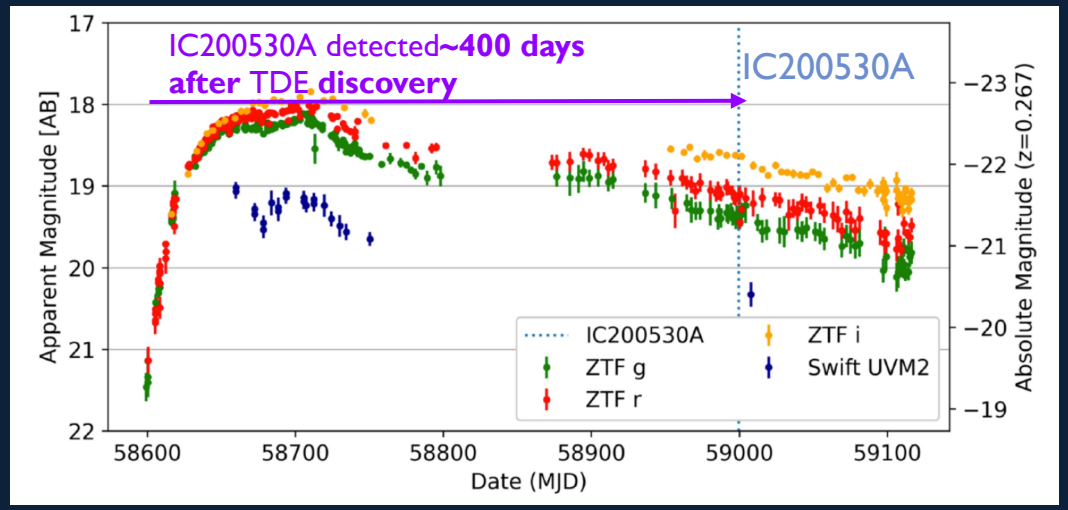
IC191001A and AT2019dsg

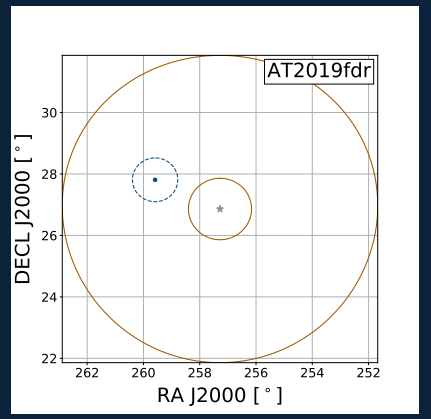





Artist's illustration of a tidal disruption event. Image credit: NASA / CXC / M. Weiss.

IC200530A and AT2019fdr





No significant cluster close to the TDEs found in ANTARES data

Upper limits on v-flux

Dark Matter

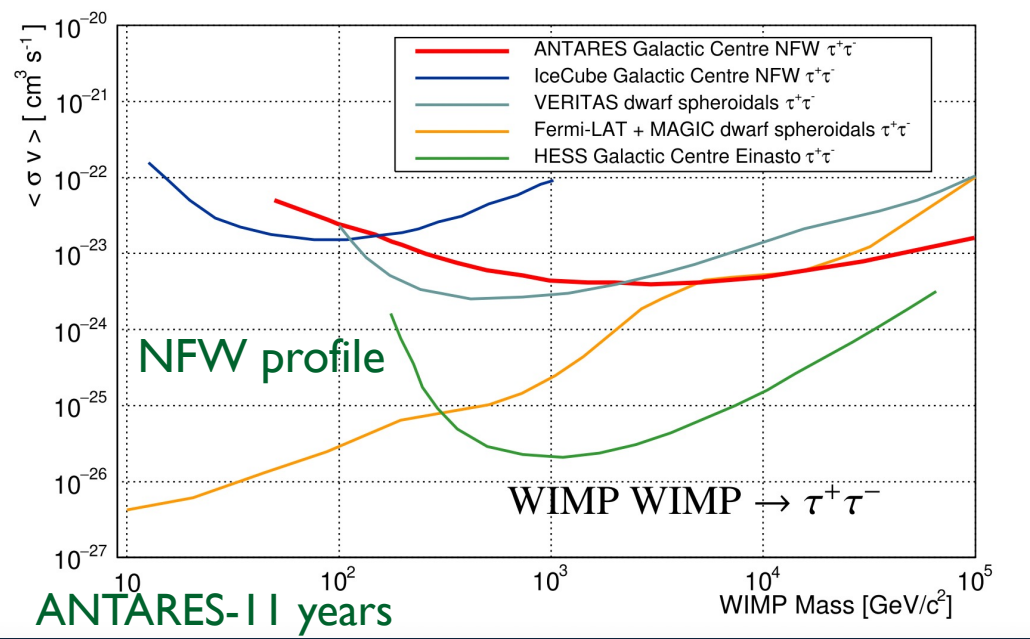
- WIMPs tend to accumulate in massive celestial objects (Sun, Galactic Centre, …)
- Neutrinos could be produced in WIMP-WIMP annihilation
- Clean signal and low expected background

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)

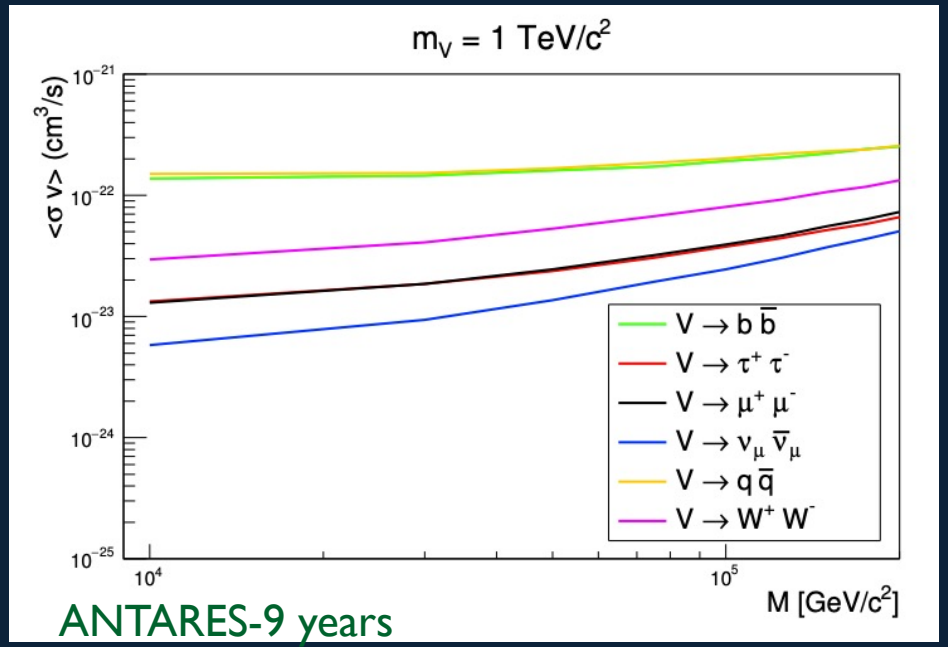
Dark Matter

Phys.Lett.B 805 (2020) 135439
PoS(ICRC2019)519

Dark Matter from the Galactic Centre

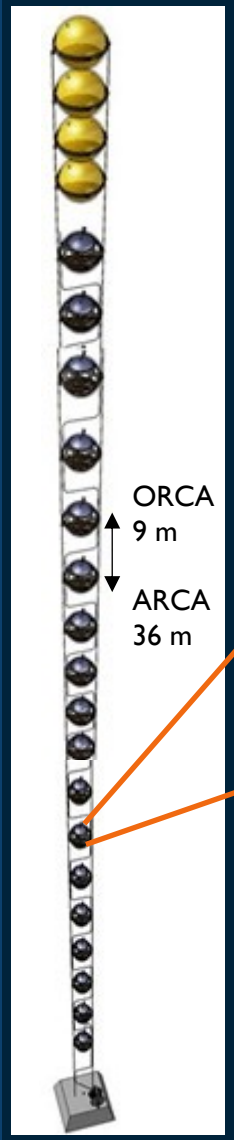


Upper limits on thermally averaged annihilation cross-section as a function of the WIMP mass



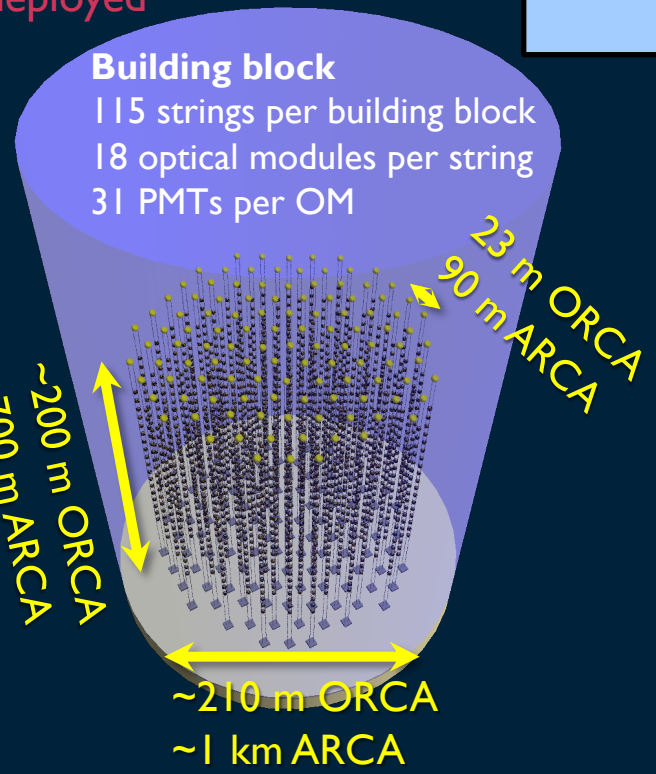
First sensitivities on effective cross-section for DM pair annihilation into a mediator pair, assuming secluded dark matter

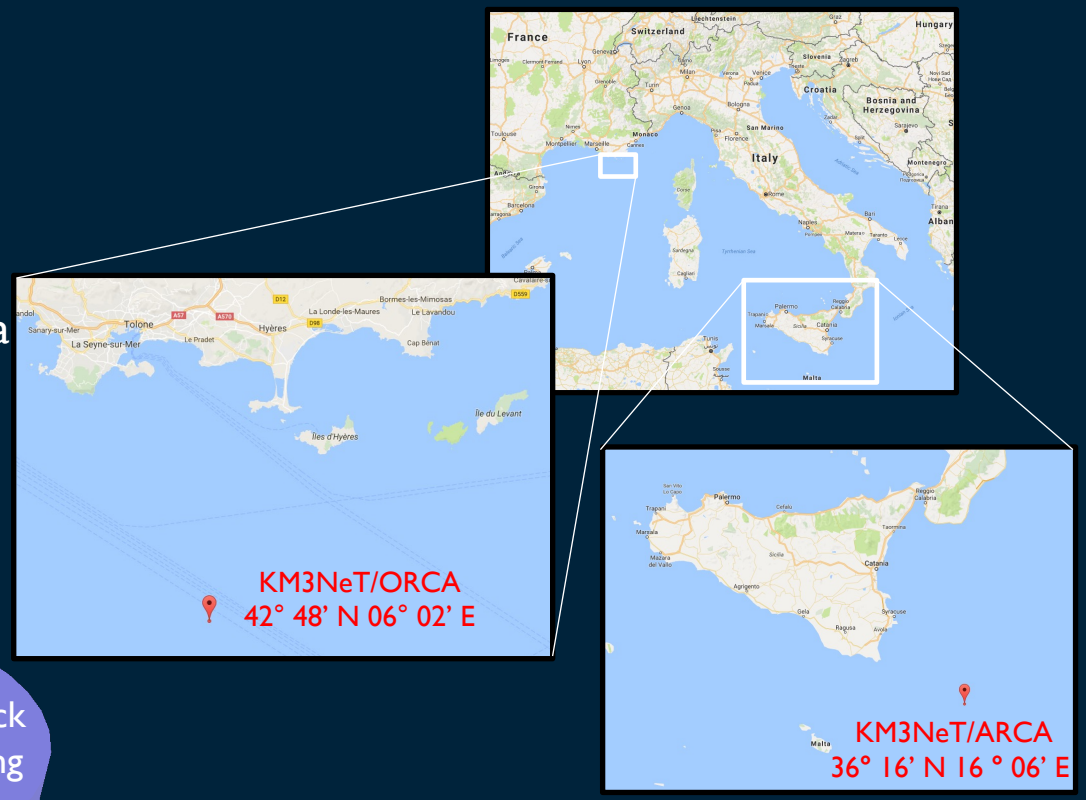
KM3NeT



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
- 10 strings deployed

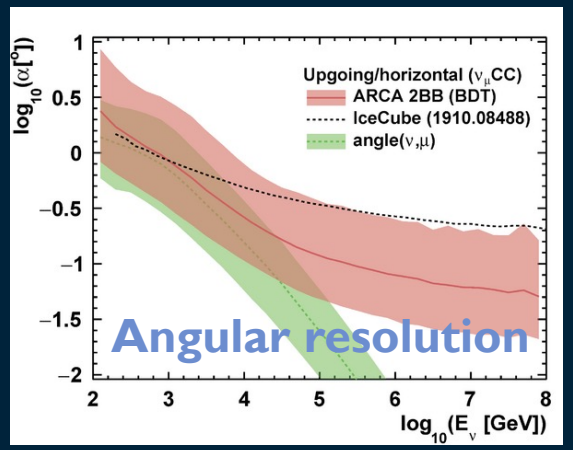




KM3NeT/ARCA

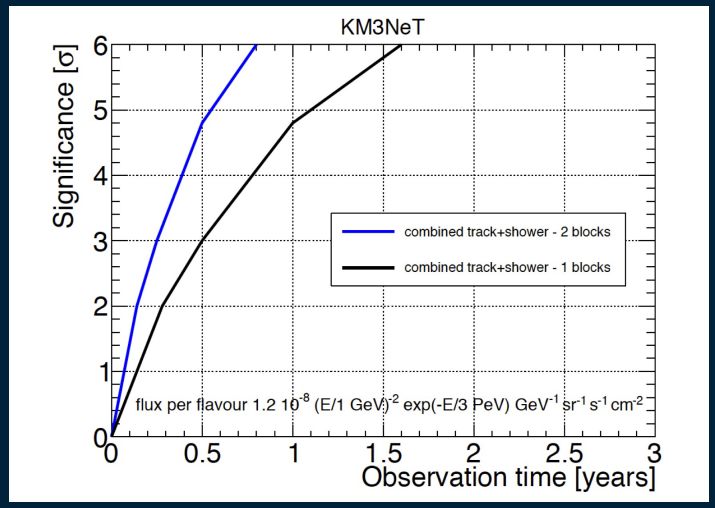
- Under construction
- 3500 m depth in the Mediterranean Sea
- 100 km offshore from Sicily
- 2 sparse building blocks
- 1-10 TeV energy threshold
- High-energy neutrino astronomy
- 8 strings deployed

KM3NeT

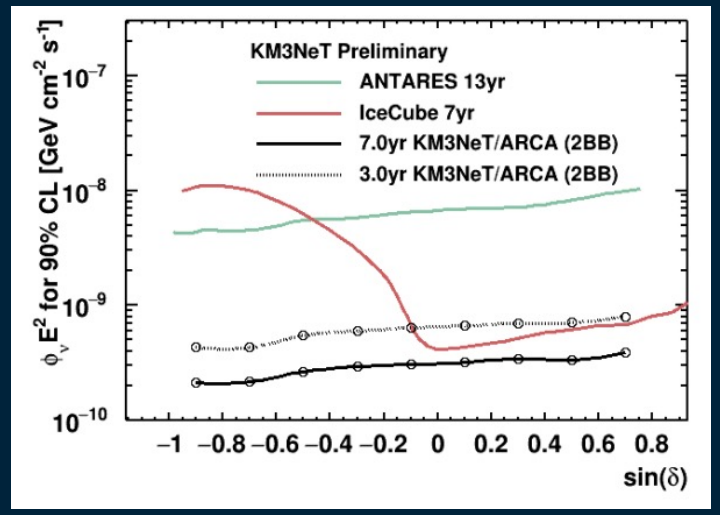


The diffuse flux will be detected by KM3NeT/ARCA with
5σ in ~0.5 year with the full detector
5σ in ~1 year with one building block

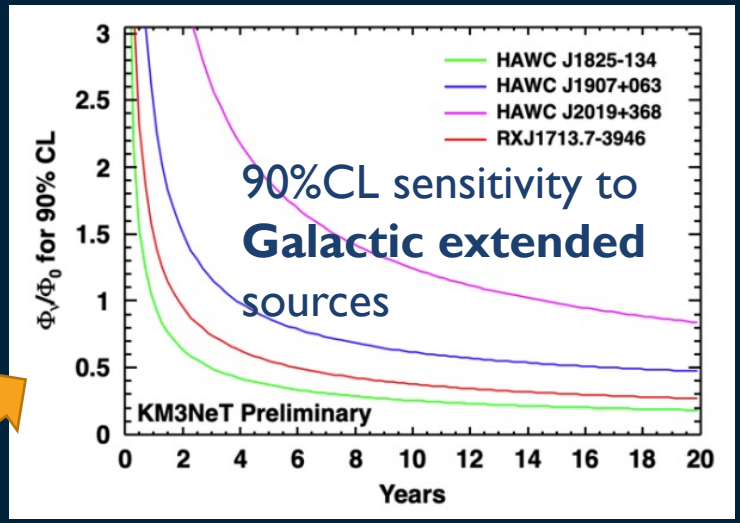
Significance of diffuse flux detection



90%CL sensitivity to point-like sources



90%CL sensitivity at the level of the expected neutrino fluxes reached in **few years of operation for several Galactic** neutrino source **candidates**



Summary and Outlook

ANTARES

- Almost 15 years of continuous data taking with high duty cycle (~95%)
- Solid results from various searches for neutrino emission (point-like, diffuse, dark matter, …)
- Rich multi-messenger program with follow-ups and alert sending program
- Several combined analyses with IceCube

KM3NeT

- Under construction: currently running with 8 DUs (ARCA) and 10 DUs (ORCA)
- Same view of the Galactic Centre as ANTARES
- Better median angular resolution (~0.1°) and x100 ANTARES instrumented volume
- Sensitivity at the level of the expected Galactic neutrino fluxes reached in few years of operation
- Observation of IceCube diffuse neutrino flux expected in less than 1 year of operation