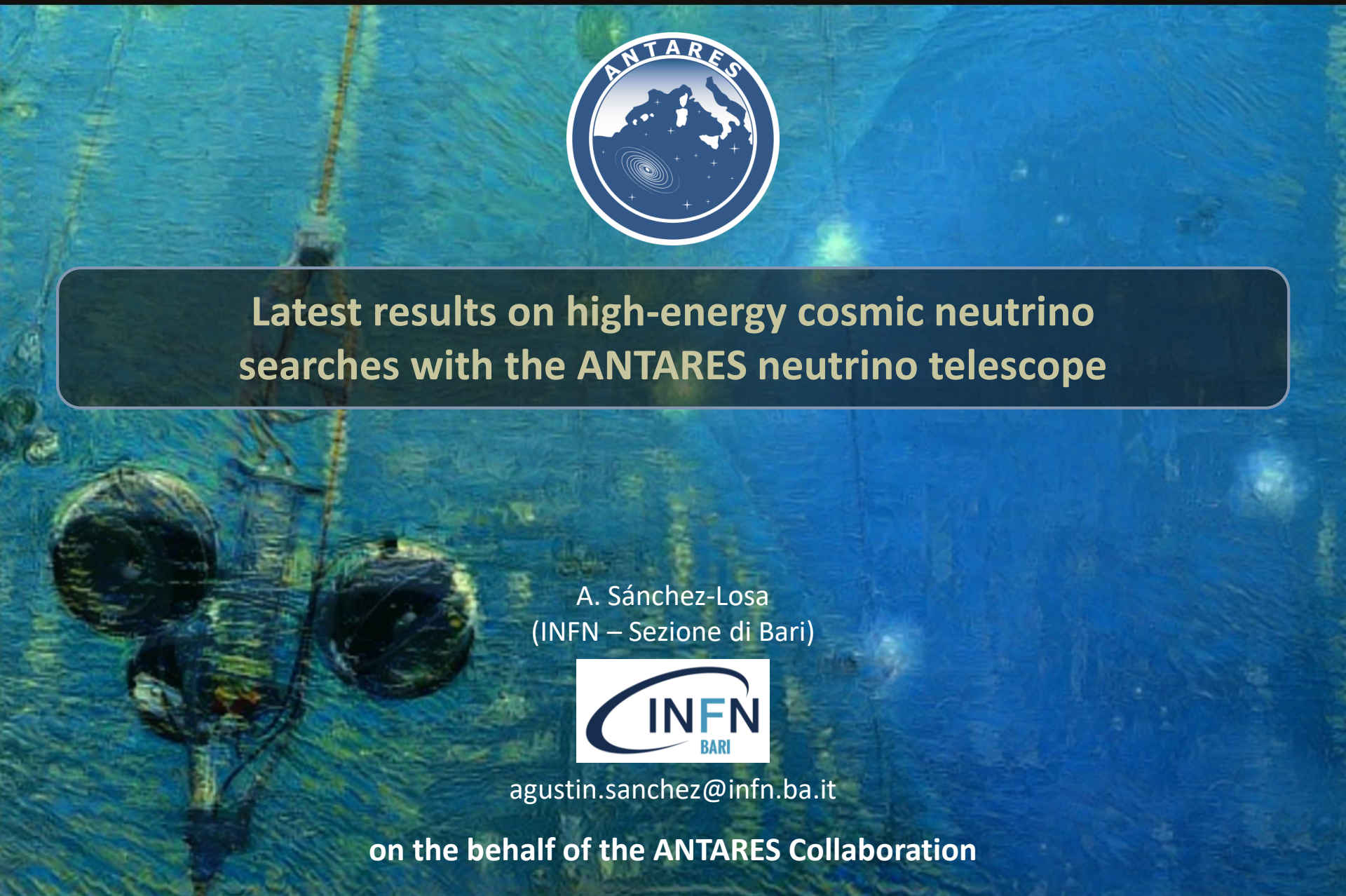
UHECR 2018 Ultra High Energy Cosmic Rays



Latest results on high-energy cosmic neutrino searches with the ANTARES neutrino telescope

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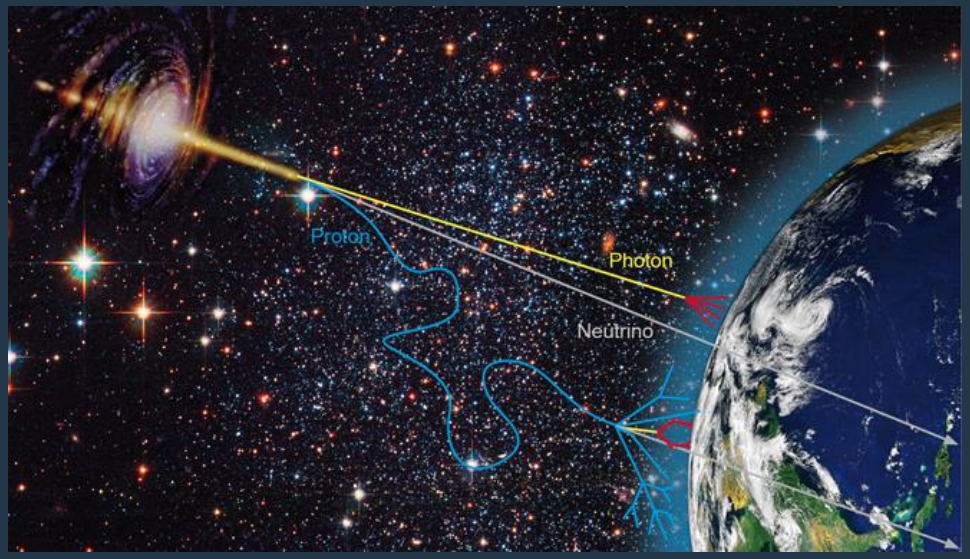
on the behalf of the ANTARES Collaboration

Neutrino as a messenger



hadronic accelerator source surrounding

$$p + p/\gamma \rightarrow \pi + \ldots$$

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

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\pi^- \rightarrow \mu^- + \tilde{\nu}_\mu$$

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

- Neutrino detection → strong indication of hadronic acceleration in astrophysical sources.
- Correlated γ-ray emission expected for most sources.

$$\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$$
$$\nu : \tilde{\nu} = 1 : 1 \quad \text{at source}$$

$$\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$$
$$\nu : \tilde{\nu} = 1 : 1 \quad \text{at Earth}$$

ANTARES

- String-based detector;
- Downward-looking (45°) PMTs;
- 2475 m deep;

14.5m

~480 m

100 m

~70 m

40 km
cable to shore

Junction Box

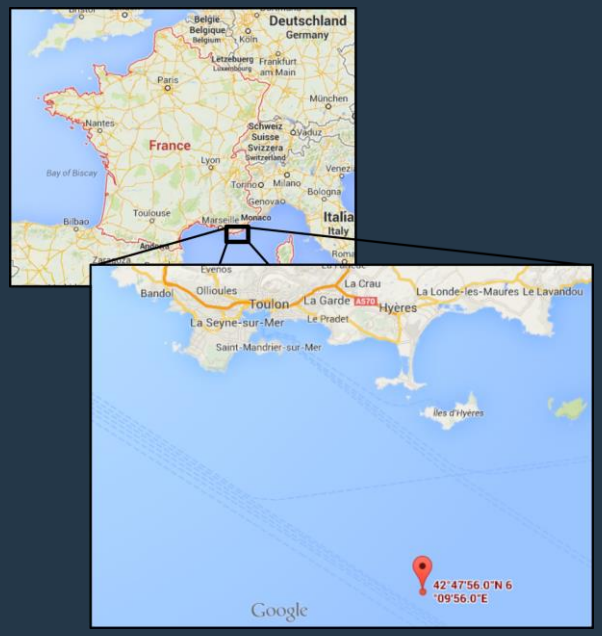
- 12 detection lines
- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs

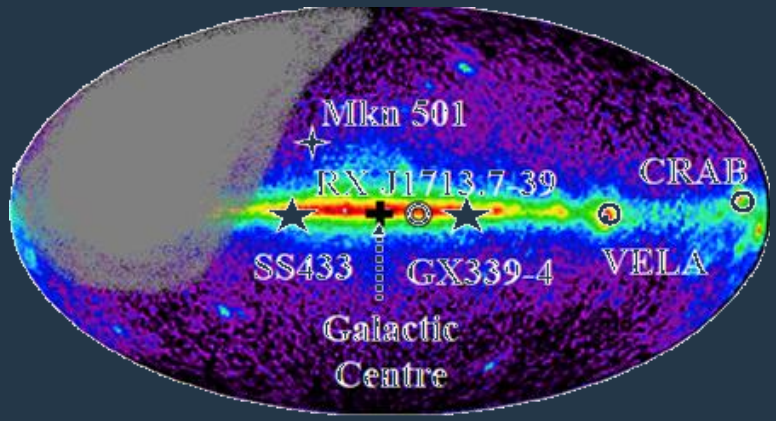
📖 NIM A 656, 11–38 (2011)

© François Montanet

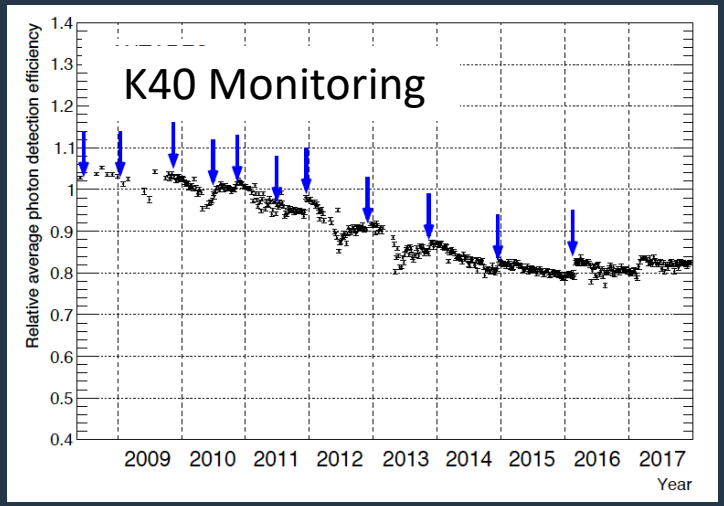
ANTARES

- Effective area ~1 m² @ 30 TeV
- Visibility ¾ of the sky, most of the galactic plane.
- 40 km offshore from Toulon

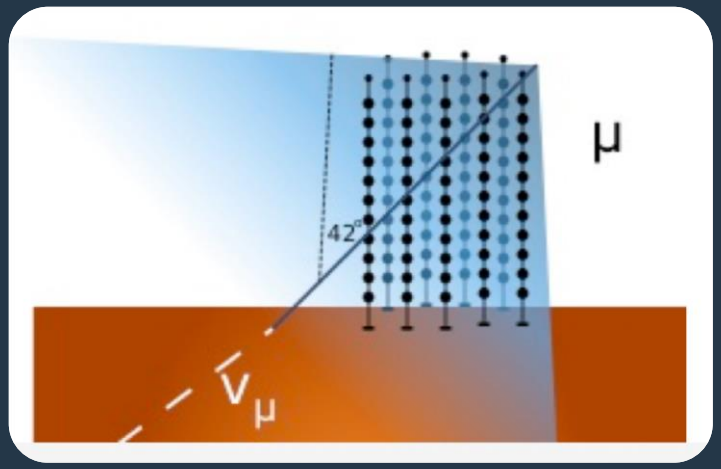




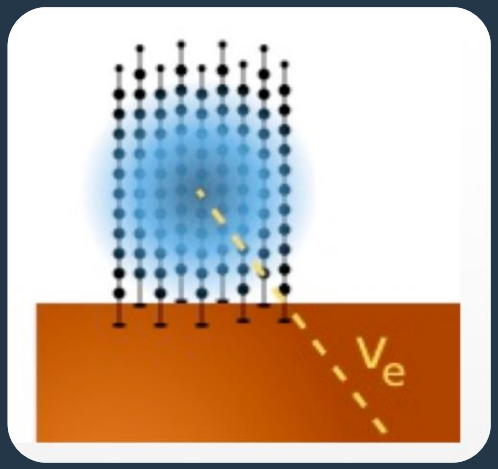
- Only 20% OM efficiency decrease.
- Still running with 11/12 lines



2 main topologies: tracks + showers

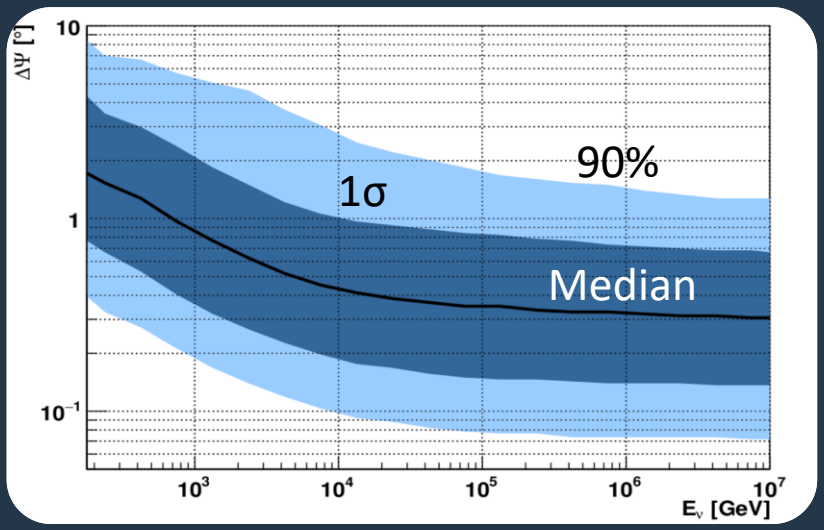


$\nu_{\mu/\tau\to\mu}$-CC

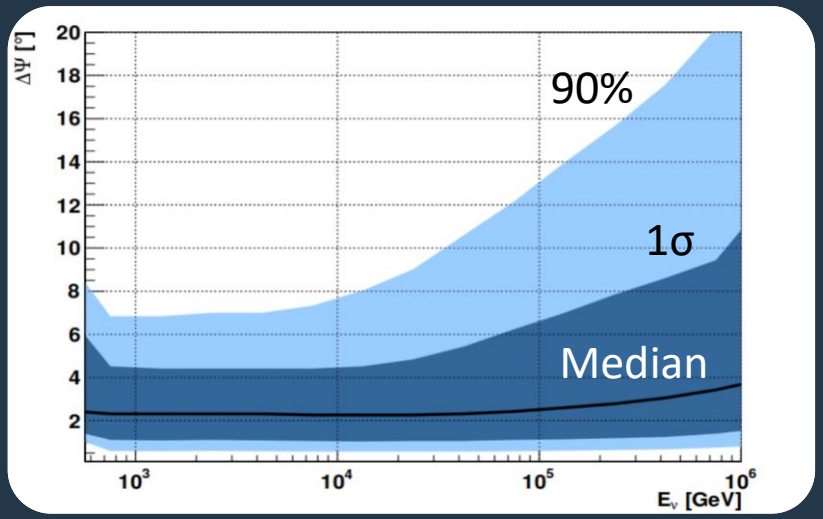


$\nu_{e/\mu/\tau}$-NC + $\nu_{e/\tau\to e}$-CC

Angular resolution: <0.4° @ E_ν>10 TeV
Energy resolution: <0.5 on log E_μ



Angular resolution: ~3°
Energy resolution: ~25% (<10% for ν_e-CC)



Latest cosmic neutrino searches (this talk)

- Special issue: IC170922A & TXS 0506+056 … [📖 ApJL 863, L2 (2018)]

- Diffuse fluxes:
  - All sky … [📖 ApJL 853, L7 (2018)]
  - Galactic plane … [📖 Phys. Rev. D 96, 062001 (2017)]
  - ANTARES-IC combined analysis … [📖 arXiv:1808.03531, submitted to ApJL]

- Point source analyses:
  - All sky & candidate list … [📖 Phys. Rev. D 96, 082001 (2017)]
  - ANTARES-IC combined analysis … [work in progress…]

- Multi-messenger studies:
  - ANTARES-Auger-TA … [📖 PoS 990 (ICRC2017)]
  - …

Other recent analyses (not covered here)

- Multi-messenger studies (Cont.):
  - Fast Radio Burst … [📖 MNRAS 469, 4465 (2017); MNRAS 475, 1427 (2018)]
  - X-ray binaries … [📖 JCAP 04, 019 (2017)]
  - Gamma Ray Burst … [📖 MNRAS 469, 906–915 (2017)]
  - Gravitational Waves … [📖 ApJL 848 L12 (2017); ApJL 850 L35 (2017); Phys. Rev. D 96, 022005 (2017); Eur. Phys. J. C 77, 911 (2017)]
  - Astronomer Telegram ANTARES alerts … [📖 ATEL#7987; PoS 985 (ICRC2017)]
  - TAToO: optical/X-ray follow up of ANTARES alerts … [📖 JCAP02, 062 (2016)]

- Dark matter studies:
  - Galactic Centre … [📖 Phys. Let. B 769, 249 (2017)]
  - Sun … [📖 Phys.Lett. B759, 69–74 (2016)]
  - Earth … [📖 Physics of the Dark Universe 16, 41–48(2017)]

- Updated oscillation study … [📖 soon on arxiv]

- Moon shadow and absolute pointing … [📖 arXiv:1807.11815, submitted to EPJC]

- …

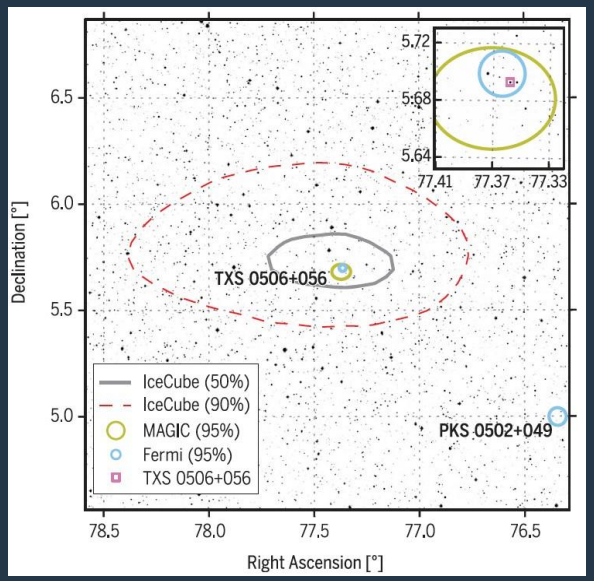
IC170922A & TXS 0506+056

- IC170922A: a ~290 TeV neutrino induced muon track is detected on 22/09/2017…

  …high probability of astrophysical origin
- Time and direction coincident with a gamma-ray flare from the blazar TXS 0506+056 (Fermi-LAT,MAGIC)

↓

IceCube finds a 3.5σ evidence of a transient neutrino emission on TXS 0506+056 direction between Sep'2014 and Mar'2015 with 9.5 years of data [📖 Science 361, 147–151 (2018)]



ANTARES looks for neutrino emission there and then:

[📖 ApJL 863, L2 (2018)]

1) Online search for neutrinos associated to IC170922A: HE neutrino candidates are searched in the ANTARES online data stream in the direction of IC170922A originally reported by IceCube in the GCN circular.
2) Time integrated search for neutrinos from TXS 0506+056: motivated by the potential association between IC170922A and the blazar, TXS 0506+056 position is scrutinized with an standard ANTARES point-source analysis
3) Search for neutrinos in the bursting period: standard time-dependant analysis during the bursting periods found by IceCube

Online search for neutrinos associated to IC170922A

[📖 ApJL 863, L2 (2018)]

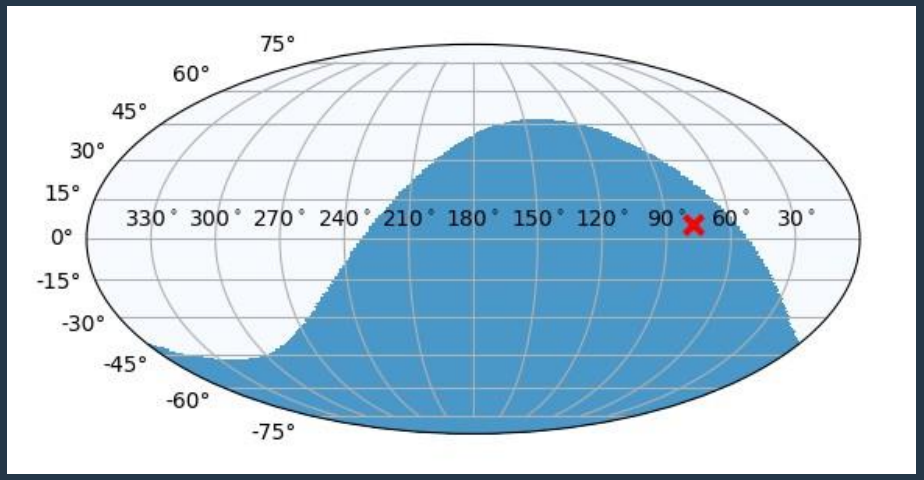
Extremely High Energy track event reported with a GCN circular by IceCube:

- T0 = 17/09/22, 20:54:30.43 UT
- (RA, δ) = (77.43°, 5.72°)
- 14.2° below the horizon

↓

Fast algorithm search in the ANTARES online data stream for up-going High Energy neutrino candidates:

- No dynamical positioning calibration: idealized detector geometry
- Median angular resolution: <0.5° @ E_ν>10 TeV
- Competitive sensitivity w.r.t. IceCube in that sky region for E_ν<100 TeV



Visibility map for the ANTARES detector of IC170922A (x) in equatorial coordinates

Spectrum	90% C.L. Fluence [GeV cm^{-2}]	5% – 95% energy range
$E^{-2.0}$	15	3.3 TeV – 3.4 PeV
$E^{-2.5}$	34	450 GeV – 280 TeV

Searches for up-going muon neutrinos in a 3° cone centred on the IceCube event coordinates with two time windows around the event time:

- ±1 hour
- ±1 day (46% visibility probability)

No coincident up-going muon neutrino recorded

90% C.L. fluence U.L. for a $dN/dE \propto E^{-\gamma}$ source (2h)

Time integrated search for neutrinos from TXS 0506+056

[📖 ApJL 863, L2 (2018)]

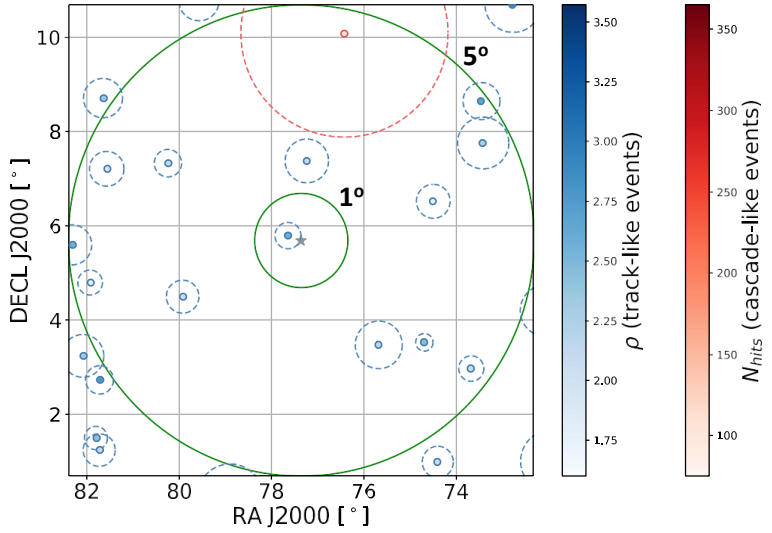
ANTARES standard point source method: Maximum likelihood ratio approach on 107 candidate sources (TXS 0506+056 included)

Data analysed: 2007 – 2017
(livetime 3136 days)

Expected background:

- 0.23/deg^2 for track-like events
- 0.005/deg^2 for shower-like events

Events around TXS 0506+056 in 2007-2017 ANTARES data:
13 tracks + 1 shower within 5°



Spectrum	90% C.L. flux [10^{-18} GeV cm^{-2} s^{-1}]
$E^{-2.0}$	1.6
$E^{-2.3}$	1.4
$E^{-2.5}$	1.0

Results:

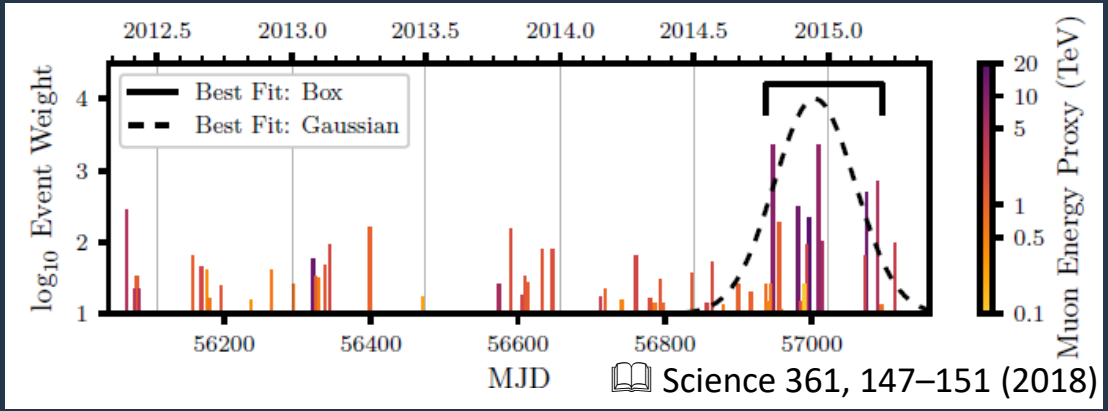
- Fitted signal: $\mathbf{n_{sg} = 1.03}$
- **Pre-trial p-value of 3.4%** (post-trial 87%)
- 1 track at 0.3° from the source on 12/12/2013
- Flux U.L. (@100 TeV) for E^{-2}: 1.6×10^{-18} GeV^{-1} cm^{-2} s^{-1} in the 2 TeV – 4 PeV range

In the 107 list of pre-selected sources, only two have a smaller p-value

Search for neutrinos in the bursting period

[📖 ApJL 863, L2 (2018)]

ANTARES time-dependent analysis: required signal for a discovery 2-3 times lower and less stringent selection cuts w.r.t. time integrated analysis [📖 JCAP 04, 019 (2017), JCAP 12, 014 (2015)]



📖 Science 361, 147–151 (2018)

IceCube most significant flares:

- Box profile:
  - t_{start} = 56937.81 MJD
  - t_{end} = 57096.21 MJD
  - Δt = 158.40 flaring days
- Gaussian profile:
  - t_0 = MJD 57004
  - σ = 55 days
  - Δt = 550 flaring days (±5σ)

Results:

- 10 background events expected during all the period
- 13 events found
- **None of them during flaring periods**

Spectrum	90% C.L. flux [10^{-18} GeV cm^{-2} s^{-1}]	5% – 95% energy range
$E^{-2.0}$	4.6	2.0 TeV – 3.2 PeV
$E^{-2.1}$	4.4	1.3 TeV – 1.6 PeV
$E^{-2.2}$	4.2	1.0 TeV – 1.0 PeV

Diffuse flux

[📖 ApJL 853, L7 (2018)]

2007 – 2015 (livetime 2450 days)
All-flavour analysis: tracks + showers

Optimization:

- Event selection chain
- energy estimator threshold

↓

- obtain a high-purity neutrino sample
- maximise sensitivity

Isotropic neutrino flux assumed, $\frac{dN_\nu}{dE_\nu} = \Phi_0 E_\nu^{-\Gamma}$:

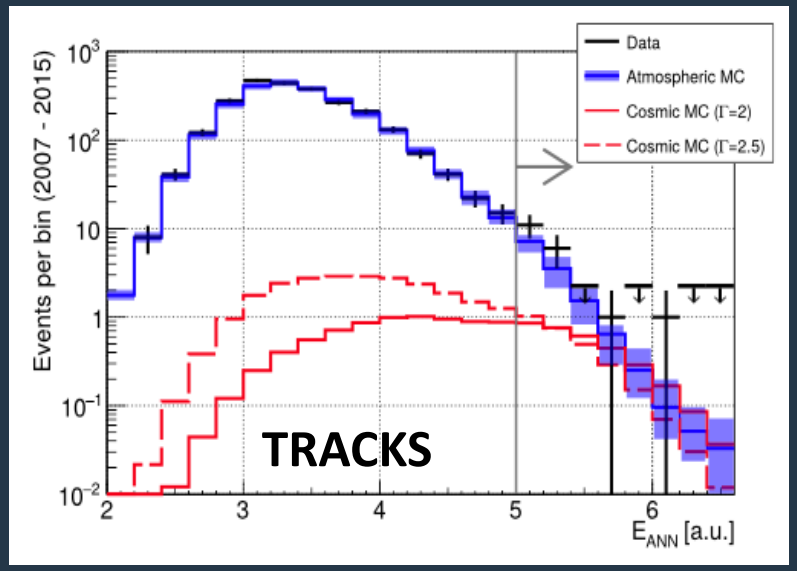
- $\Gamma = 2.0,\ \Phi_0^{1f}(100\ \mathrm{TeV}) = 1.0 \cdot 10^{-18} \left(\mathrm{GeV\ cm^2\ s\ sr}\right)^{-1}$
- $\Gamma = 2.5,\ \Phi_0^{1f}(100\ \mathrm{TeV}) = 1.5 \cdot 10^{-18} \left(\mathrm{GeV\ cm^2\ s\ sr}\right)^{-1}$

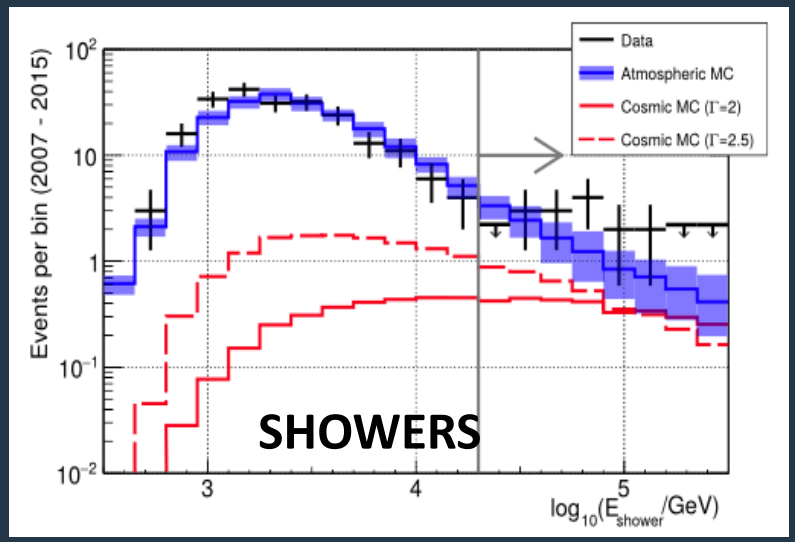
Results:

- MC background: 24 ± 7 (stat.+syst.) events
- Observed events:

33 events (19 tracks + 14 showers)

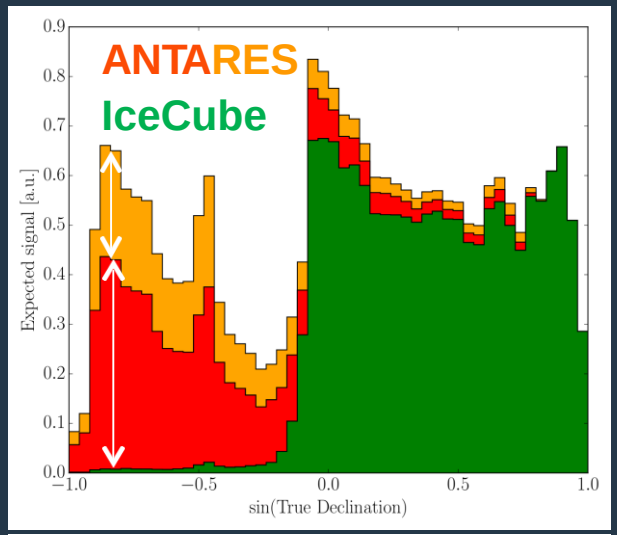
- **Compatible with IceCube flux**
- **1.6σ excess**
- **No-signal hypothesis excluded at 85% C.L.**

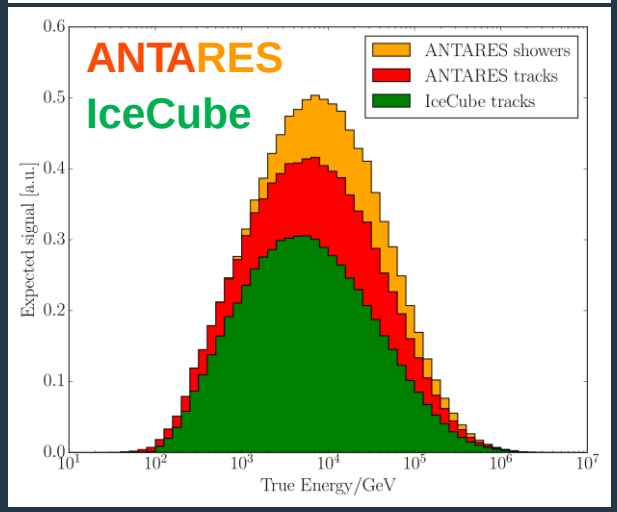




Diffuse flux from the Galactic plane

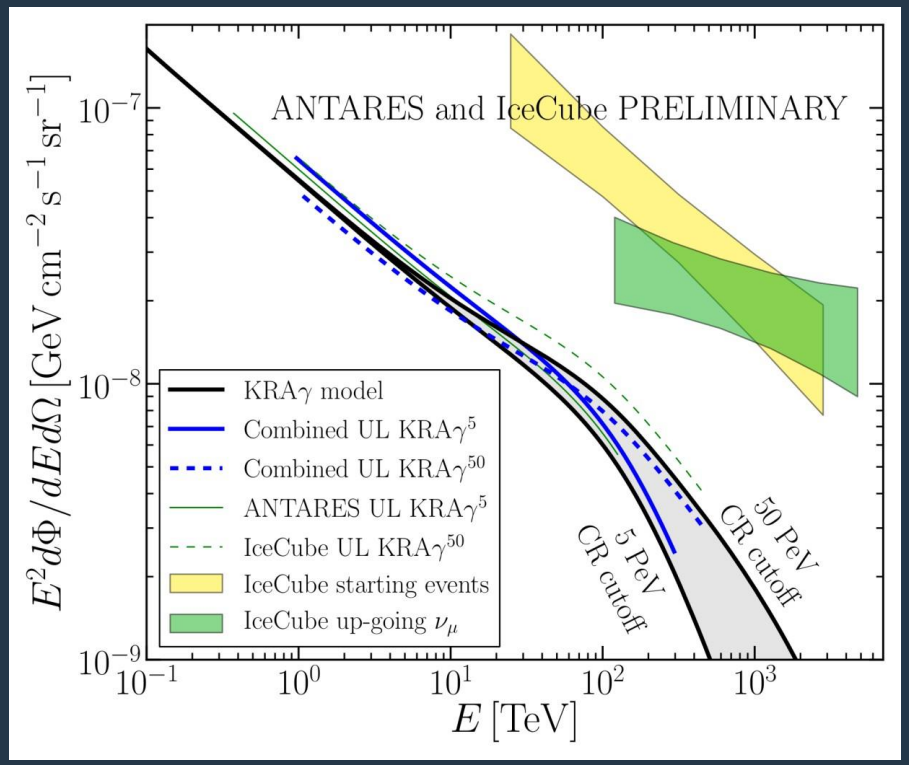
[📖 Phys. Rev. D 96, 062001 (2017), arXiv:1808.03531 submitted to ApJL]





Stacked expected signal vs. δ (top) and energy (bottom)
(colours relative to contribution to sensitivity)

Combined U.L. at 90% CL (blue line) on the 3-flavor neutrino flux of the KRAγ model (5 – 50 PeV cutoff)

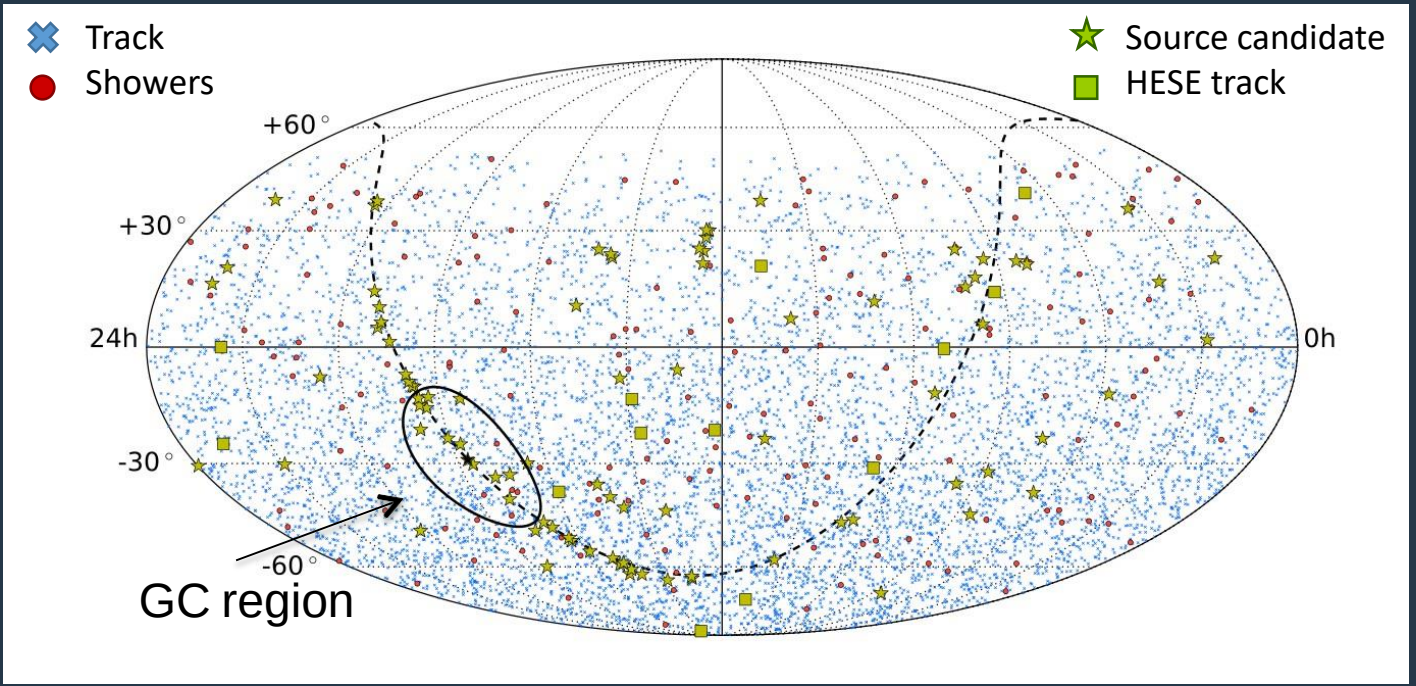


IC/ANTARES begin to constrain KRAγ with 50 PeV CR cutoff from 90 GeV – 300 TeV (not yet for 5 PeV CR cutoff)

Total flux contribution of **diffuse Galactic neutrino** emission contributes <9% of IceCube diffuse flux (E_ν > 30 TeV)

Point source searches

[📖 Phys. Rev. D 96, 082001 (2017)]



2007 – 2015 (livetime 2450 days)

All-flavour analysis: 7622 tracks + 180 showers

- **Full-sky Search**
- **Candidate list Search**

  106 objects (pulsars, SNRs, etc.)

  13 IceCube HESE tracks

- **Galactic Centre Region**

  Ellipse 15° x 20°

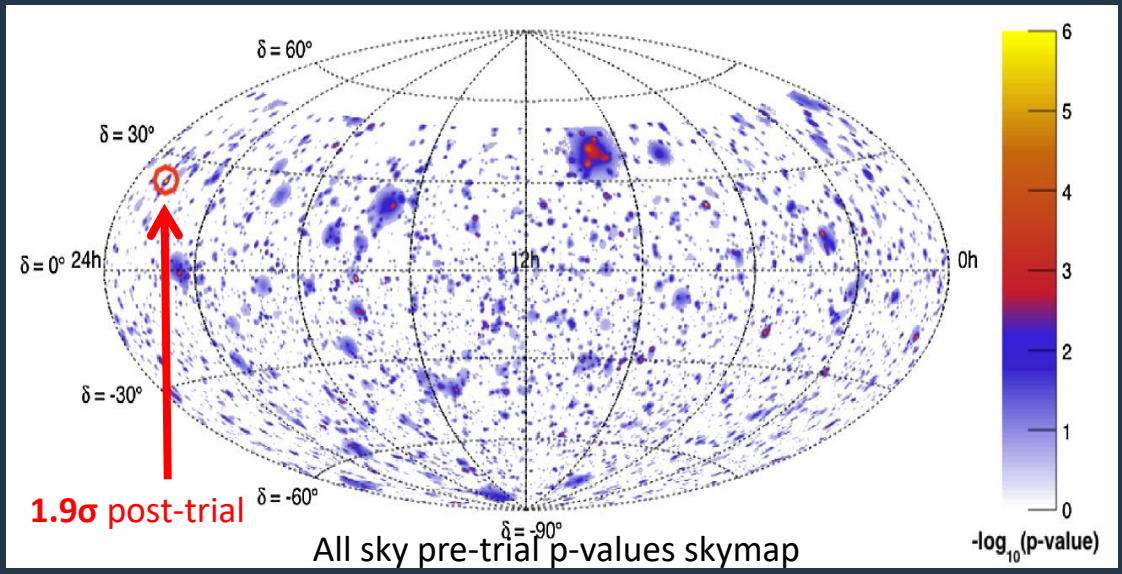
  Test: Spectral indices γ = 2.1, 2.3, 2.5

- **Sagittarius A* location**

  Extended source: Gaussian profile of various widths (σ = 0°, 0.5°,1.0°, 2.0°)

Point source searches

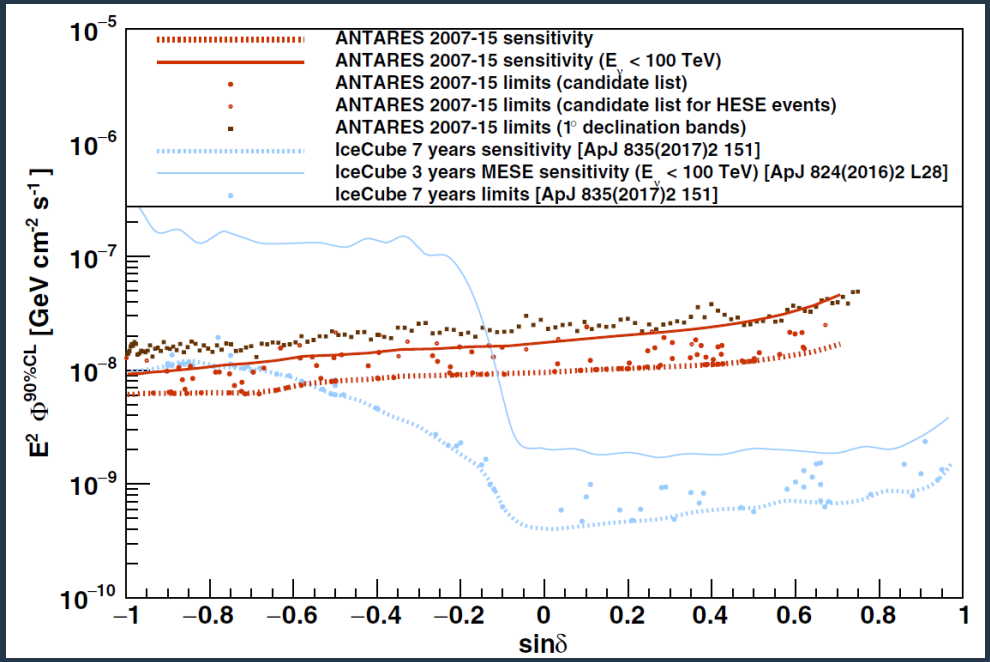
[📖 Phys. Rev. D 96, 082001 (2017)]



All sky pre-trial p-values skymap

No resolved point source:

- Most significant candidate:
  HESSJ0632+057
  $(\alpha,\delta) = (98.24°, 5.81°)$
  p-value = 13%
- Most significant cluster in full sky:
  $(\alpha,\delta) = (343.8°, 23.5°)$
  p-value = 6% (**1.9σ**)



Best limits for part of the Southern Hemisphere

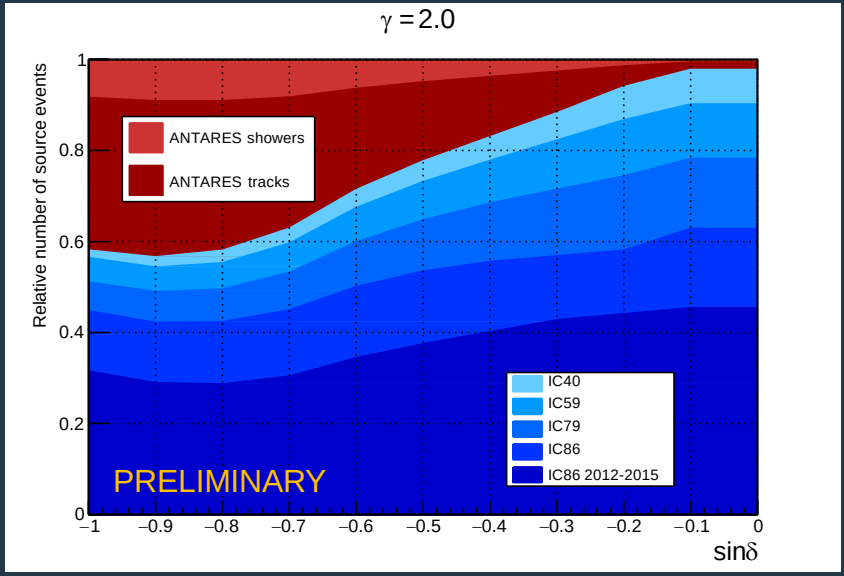
Excellent sensitivity for E_ν <100 TeV

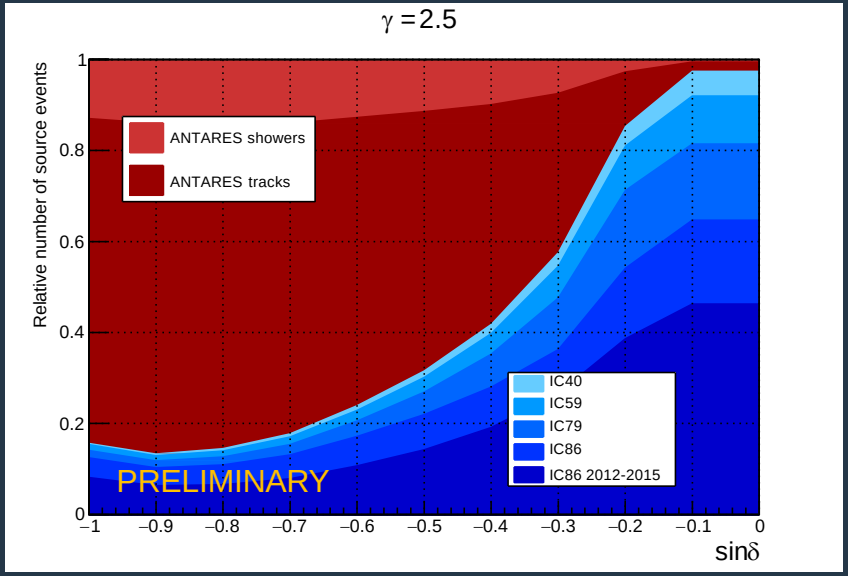
Combined ANTARES-IceCube point source search

[work in progress…]

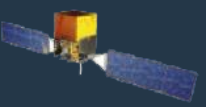
ANTARES 2007-2015 and the IC40, IC59, IC79, IC86 samples for the Southern Hemisphere

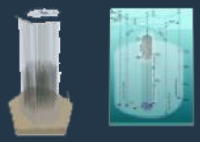
Sample		Livetime (days)	# events
ANTARES (9 years)	tracks	2415	5807
	showers	2415	102
IceCube (7 years)	IC40	376	22779
	IC59	348	64257
	IC79	316	44771
through-going tracks	IC86	333	74931
	2007 – 2015	1058	119231





ANTARES multi-messenger strategies



neutrinos
IceCube, GVD, SNEWS

GeV-TeV γ-rays
Fermi, HESS, HAWC, CTA

UHECR
Auger, TA

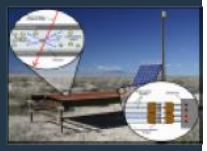
only spatial coincidence

ANTARES

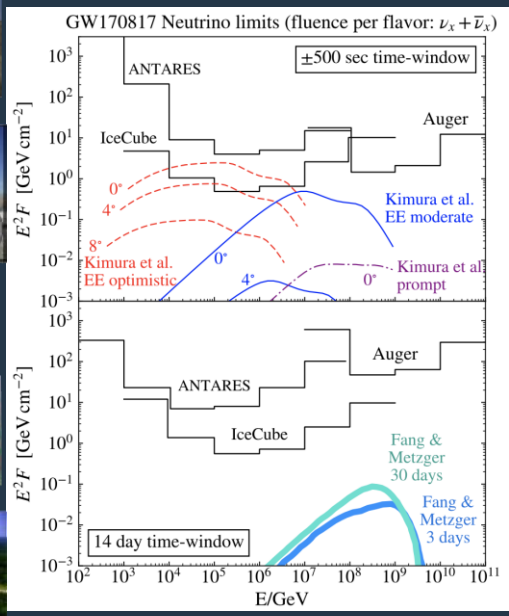
Receive alerts
Generate alerts

Radio/Optic /X-ray
TAROT, MASTER, Swift, INTEGRAL, MWA

Gravitational Waves
VIRGO, LIGO

…also offline:



- Space/time correlation → reduced background (improved sensitivity)
- Track & shower topologies
- Rapid (few secs) real-time alerts for interesting neutrino events
- Allows event-by-event identification of neutrino origin

Search for neutrinos from Auger & TA CRs

[📖 PoS 990 (ICRC2017)]

ANTARES: 2007 – 2015 (livetime 2424 days)

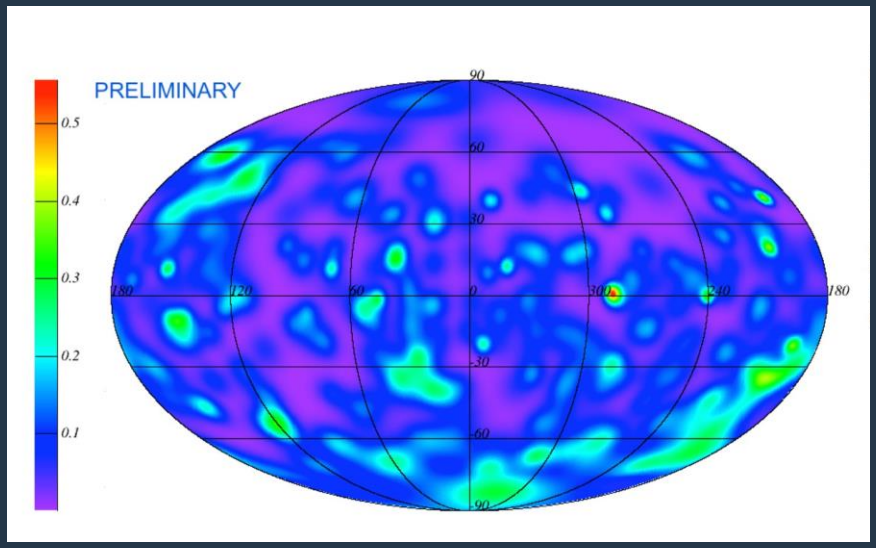
7629 tracks + 180 showers

Auger(SD): 2004 – 2014 [📖 ApJ 804:15 (2015)]

231 CRs ($\theta \leq 80^o$; $E_{CR} \geq 52$ EeV)

TA: 2008 – 2014

87 CRs ($E_{CR}\downarrow 13\%$)



f_{CR} function in equatorial coordinates

Maximum likelihood ratio: $Q = \ln \mathcal{L}_{sg+bk}^{max} - \ln \mathcal{L}_{bk}$

$$\ln \mathcal{L}_{sg+bk} = \sum_{ch}^{tr,sh} \sum_{i} \ln \left[\frac{n_{ch}}{N_{ch}} \cdot S_\gamma^{ch} + \left(1 - \frac{n_{ch}}{N_{ch}}\right) \cdot B^{ch} \right]$$

$$B^{ch}(\delta, E) = f(\delta) \cdot g(E); \quad S_\gamma(\alpha, \delta, E) = f_\gamma(\alpha, \delta) \cdot g_\gamma(E) \quad \rightarrow \quad f_\gamma(\alpha, \delta) = A_\gamma(\delta) \cdot \left(f_{CR} \circ PSF_\gamma\right)(\alpha, \delta)$$

$$f_{CR}(\alpha_i, \delta_i) = \sum_{j}^{N_{CR}} \frac{\Phi}{2\pi\sigma_j^2} \exp\left(-\frac{d_{ij}^2}{2\sigma_j^2}\right) \quad \rightarrow \quad \sigma_j(E) = \sqrt{\left(\sigma_{Auger/TA}^2 + \sigma_B^2\left(E_j^{CR}\right)\right)} \quad \rightarrow \quad \sigma_B\left(E_j^{CR}\right) = 3^\circ \times \frac{100}{E_j^{CR}(EeV)}$$

- **Non-significant result**
- 90% C.L. fluence U.L. for a E_ν^{-2} flux:

$$\Phi_{tot}^{UL} = 1.5 \cdot 10^{-7} \ \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

$$\downarrow$$

$$\Phi_{diff}^{UL} = \Phi_{tot}^{UL}/4\pi = 1.2 \cdot 10^{-8} \ \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$

Summary

ANTARES is the largest undersea NT, in the Mediterranean Sea
The most sensitive one in the TeV-PeV range
(and will keep running until 2020)

- Competitive physics results:
  - Constraints on neutrinos as seen by IceCube and on CR correlations
  - Impact on modelling of CR production and transport in the Milky Way
- All flavour analyses with good pointing power
- Extensive multi-messenger program
- Joint studies with GNN partners very welcome!
- Although technologically challenging ANTARES is working according to specifications: proves the feasibility of a deep sea Neutrino Telescope

Thank you for your attention