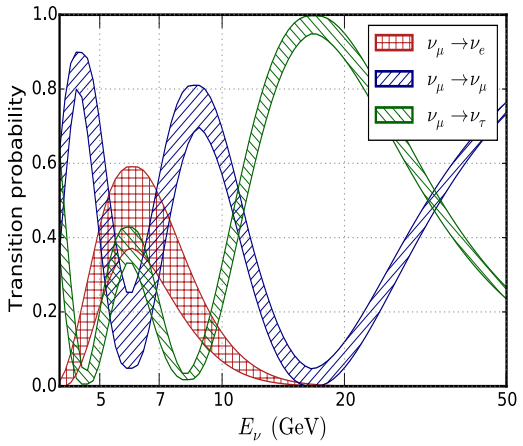
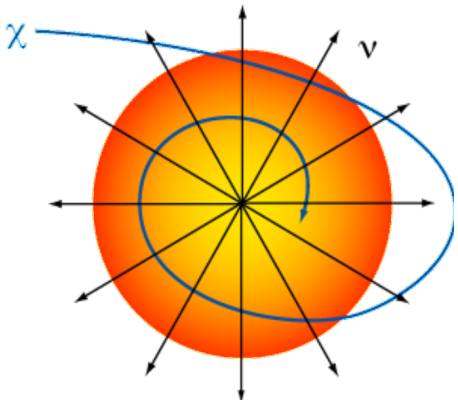
Latest Results from ANTARES

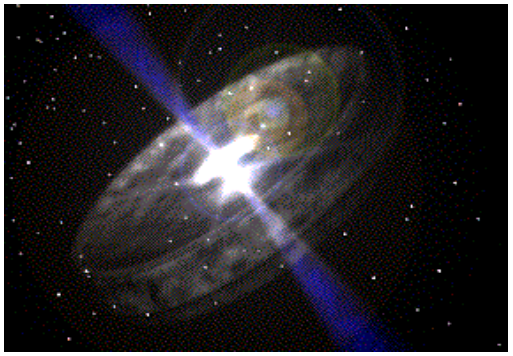
- The ANTARES detector
- Oscillations
- Dark Matter
- High-Energy Astrophysics
  - Diffuse
  - Point-sources
  - Catalog sources
  - Multi-messengers

Antoine Kouchner
for the ANTARES Collaboration

Science scope







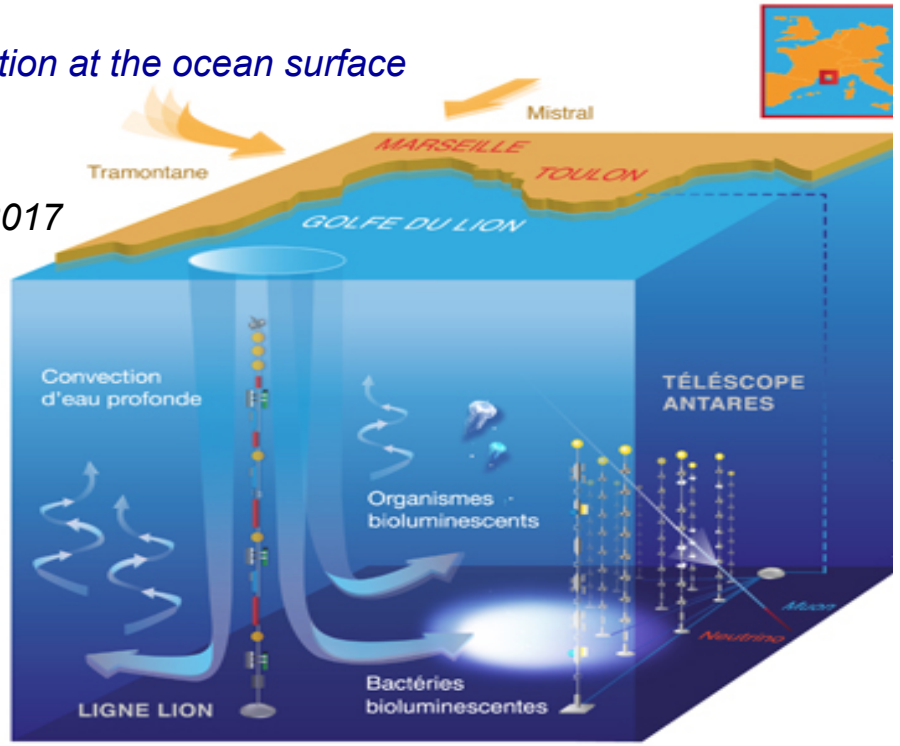
Low Energy > 10 GeV	Medium Energy 10 GeV < E_ν < 10 TeV	High Energy E_ν > 1 TeV
ν Oscillations → ***Mostly covered by A. Heijboer and N. Chowdhury***	Dark matter search + Exotic searches	ν from extra-terrestrial sources Origin and production mechanism of HE CR

ANTARES = multi-disciplinary observatory

Earth and Sea Sciences: oceanography, biology, geology, climate monitoring …

Connections to Earth and Sea sciences

📖 PLoS ONE 8 (7) 2013
Deep-sea bioluminescence blooms after dense water formation at the ocean surface



📖 *Journal of Geophysical Research: Oceans, Vol 122, 3, 2017*
Deep sediment resuspension and thick nepheloid layer generation by open-ocean convection

📖 Deep-Sea Research I 58 (2011) 875–884
Acoustic and optical variations during rapid downward motion episodes in the deep North Western Mediterranean

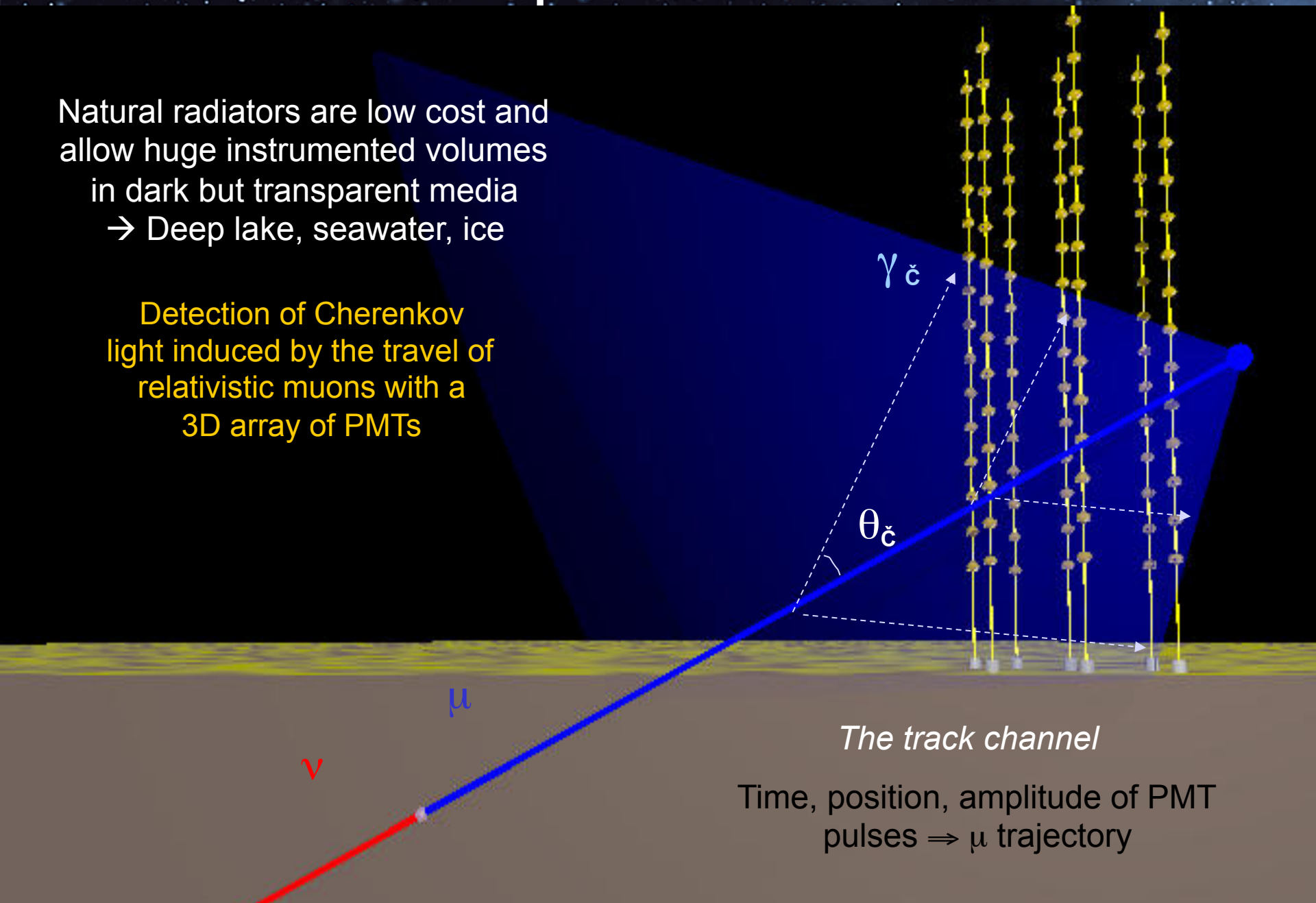
📖 *Sci. Rep. 7 (2017) 45517*
Sperm whale diel behaviour revealed by ANTARES, a deep-sea neutrino telescope

📖 Ocean Dynamics, April 2014, 64, 4, 507-517
High-frequency internal wave motions at the ANTARES site in the deep Western Mediterranean

Detection Principles : Cherenkov

Natural radiators are low cost and allow huge instrumented volumes in dark but transparent media
→ Deep lake, seawater, ice

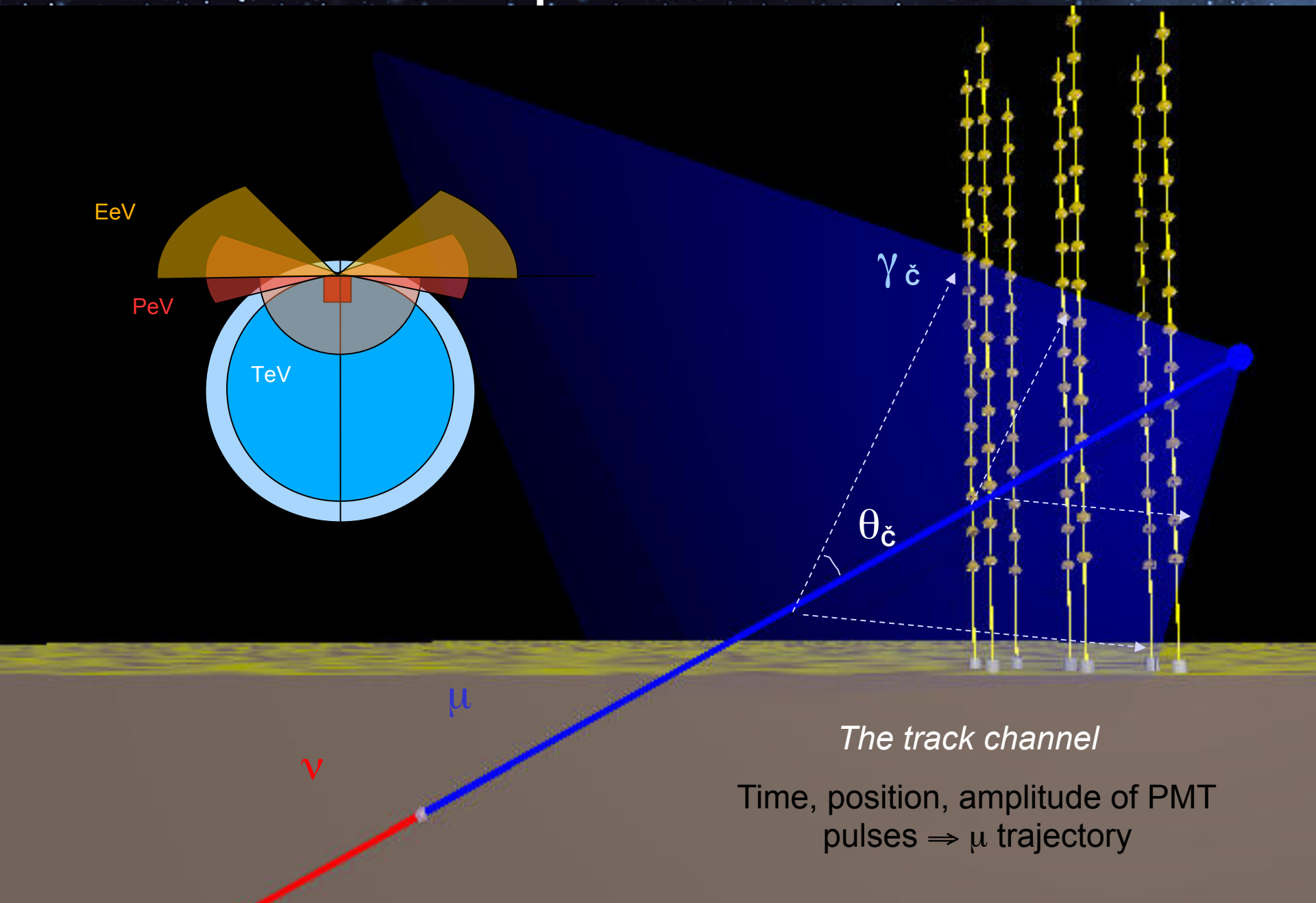
Detection of Cherenkov light induced by the travel of relativistic muons with a 3D array of PMTs



The track channel

Time, position, amplitude of PMT pulses ⇒ μ trajectory

Detection Principles : Cherenkov

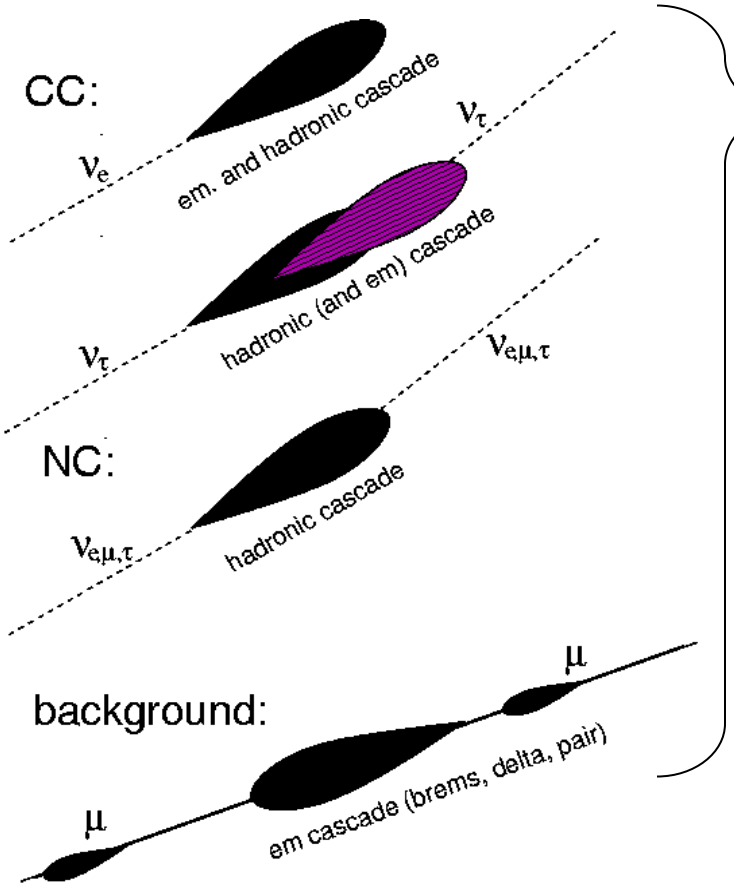


The track channel

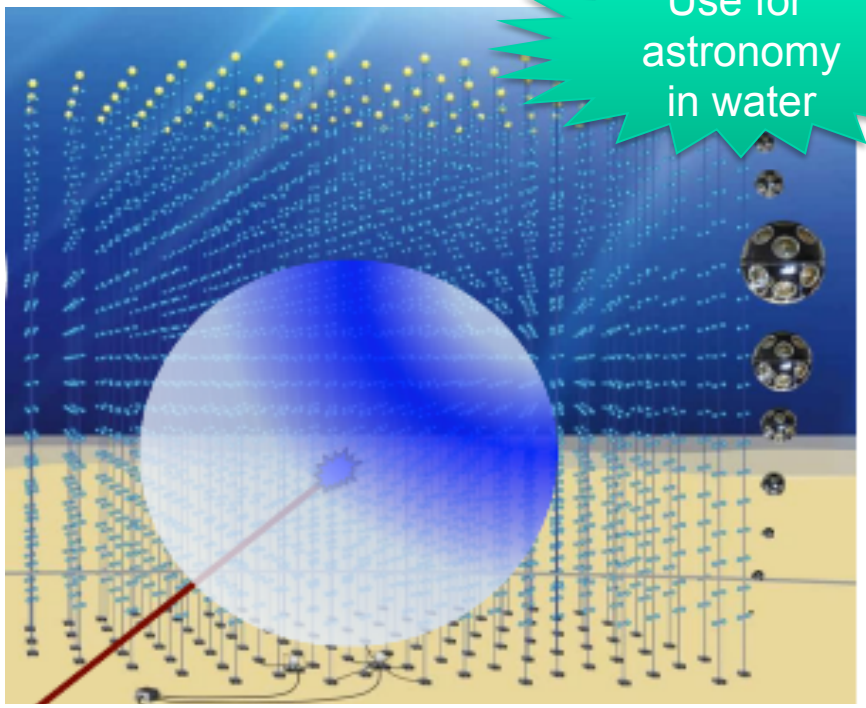
Time, position, amplitude of PMT pulses ⇒ μ trajectory

Cascade topology

$\nu_e:\nu_\mu:\nu_\tau = 1:2:0$ at source $\xrightarrow{oscillation}$ $\nu_e:\nu_\mu:\nu_\tau = 1:1:1$ at Earth !



IceCube discovery channel

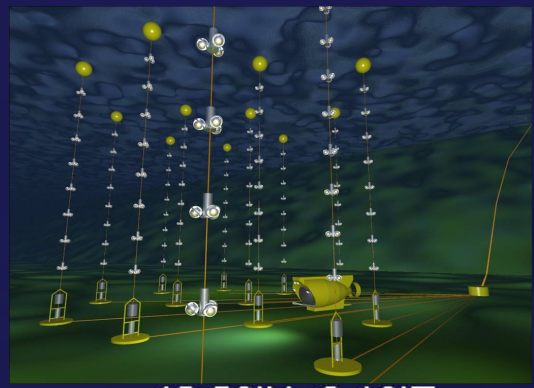


→ Provides sensitivity to all neutrino flavours – Increases overall sensitivity

Toulon

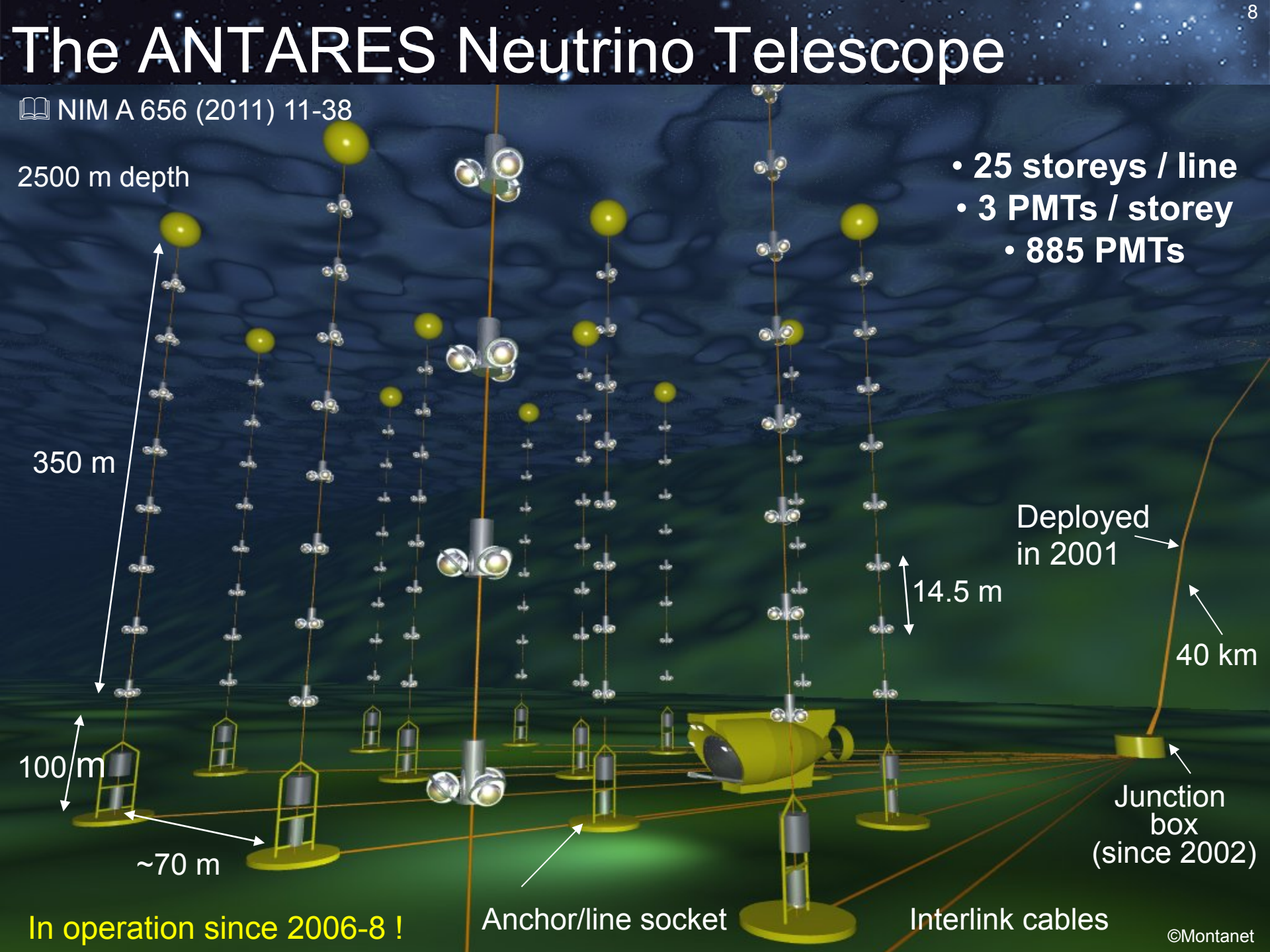
Insitut M.Pacha

Antares



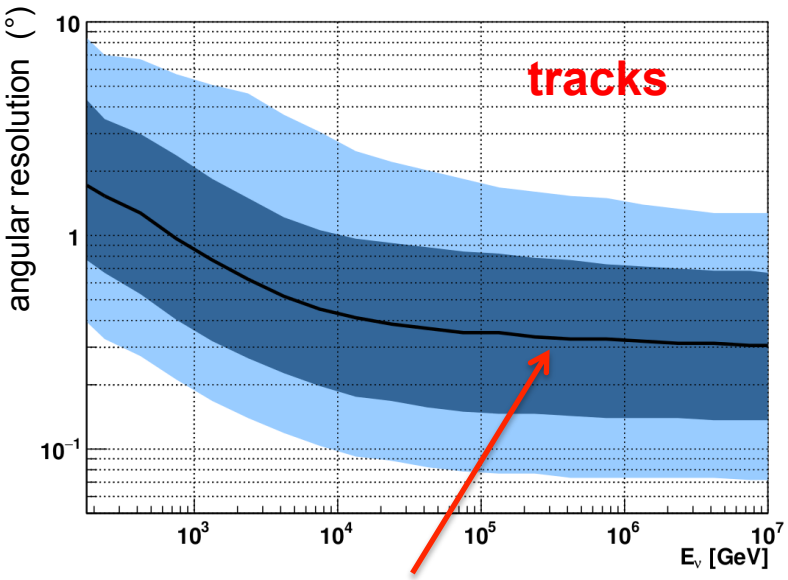
42 50'N, 6 10'E

The ANTARES Neutrino Telescope



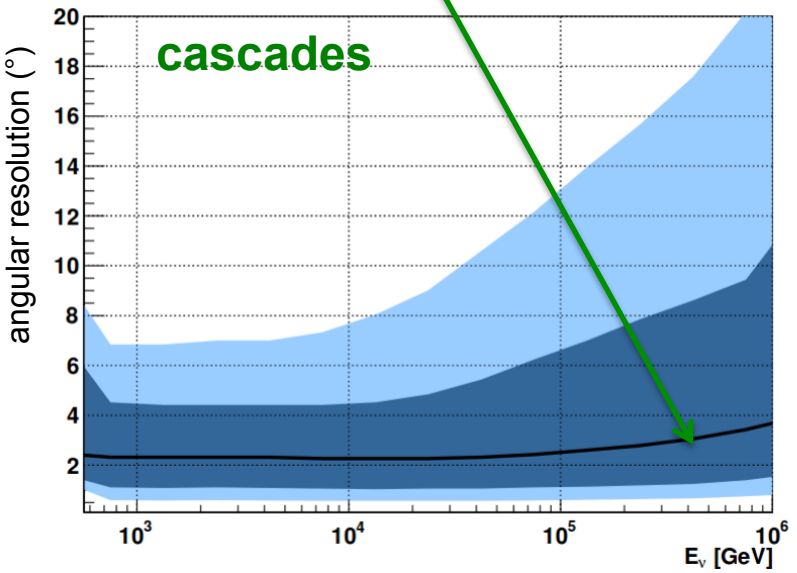
Reconstruction performances

- Upgoing track events (ν_μCC)
- Angular resolution <0.4° for E_ν>10 TeV
- 90% purity
- Energy resolution of about a factor 2



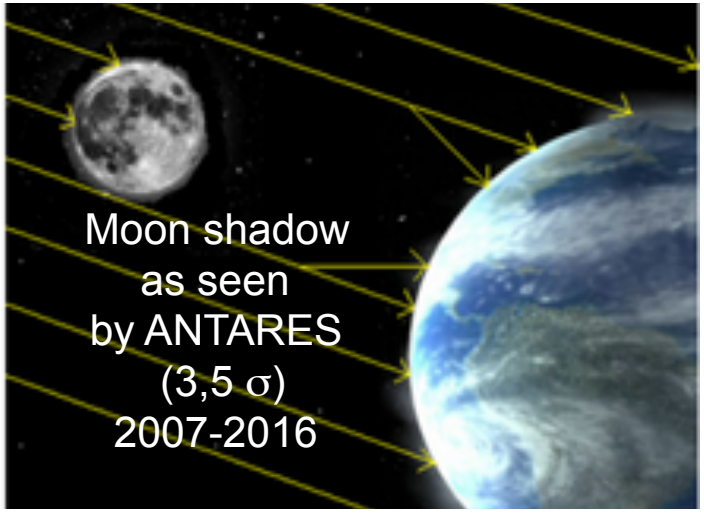
median resolution

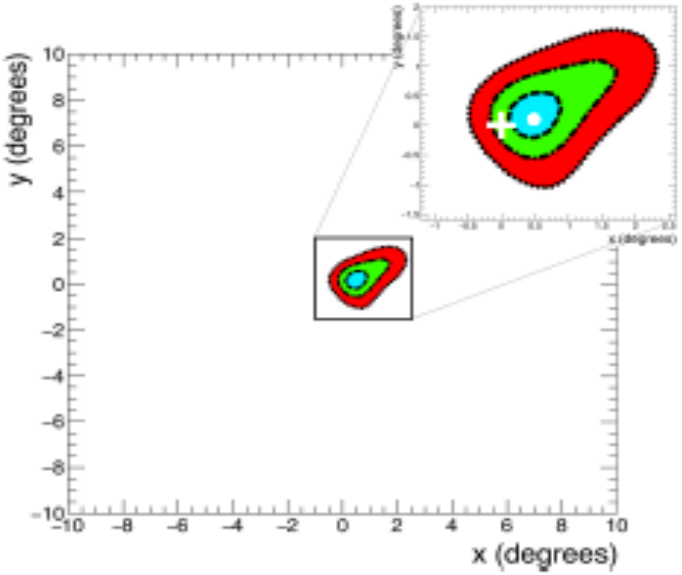
- Upgoing cascade events (ν_e/ν_τ CC, NC)
- Angular resolution < 3°
- Energy resolution for ν_eCC better than 10%



📖 ANTARES Monte Carlo, JCAP01 (2021) 064

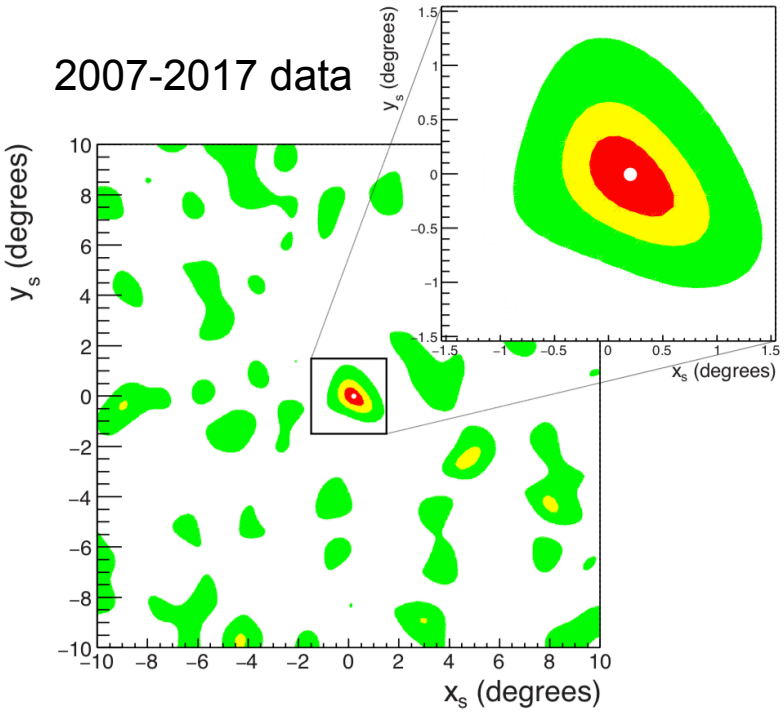
Absolute Pointing – Consistent with expectation





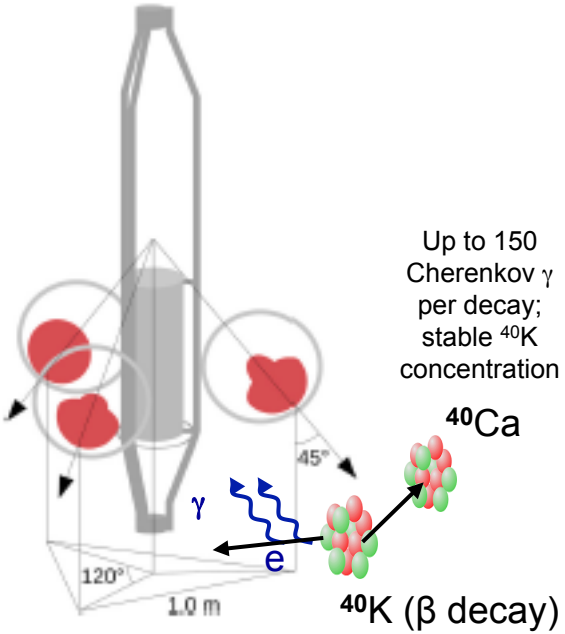
📖 Eur.Phys.J. C78 (2018) no.12, 1006

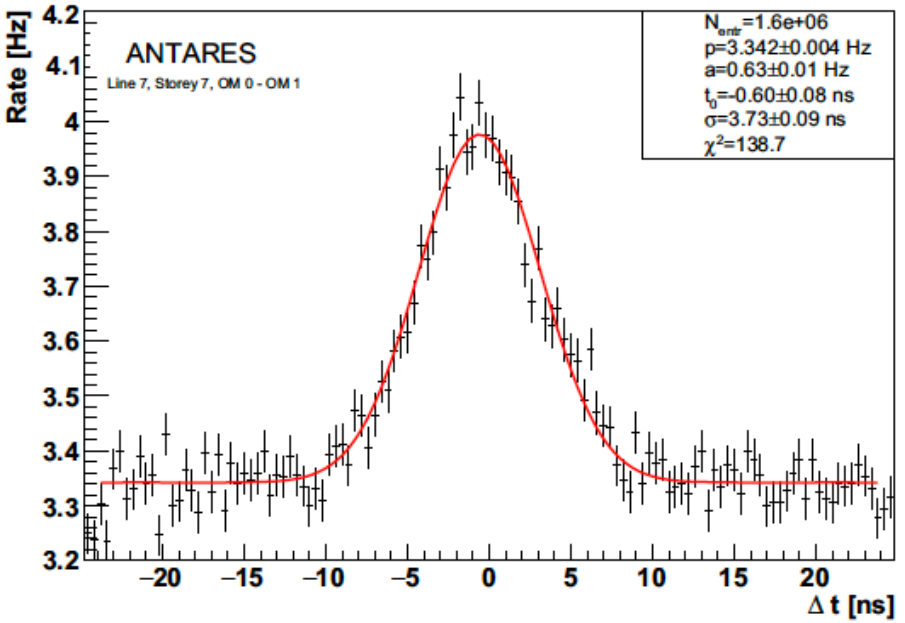
The Sun shadow is also observed with a statistical significance of 3.7σ, and an angular resolution of 0.59° ± 0.10° for downward-going muons.

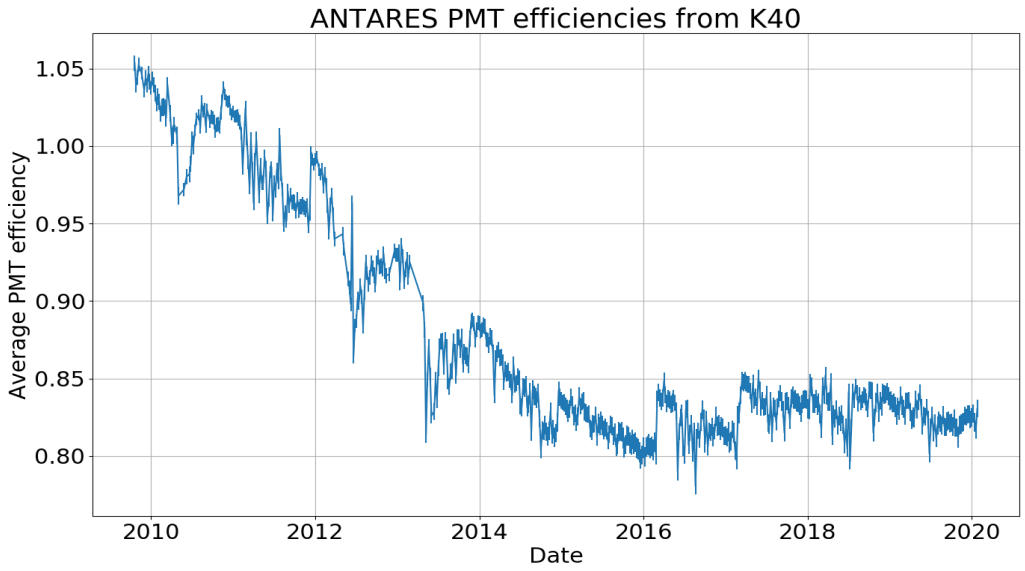


📖 Phys. Rev. D 102, 122007 (2020)

^{40}K (long-term) monitoring





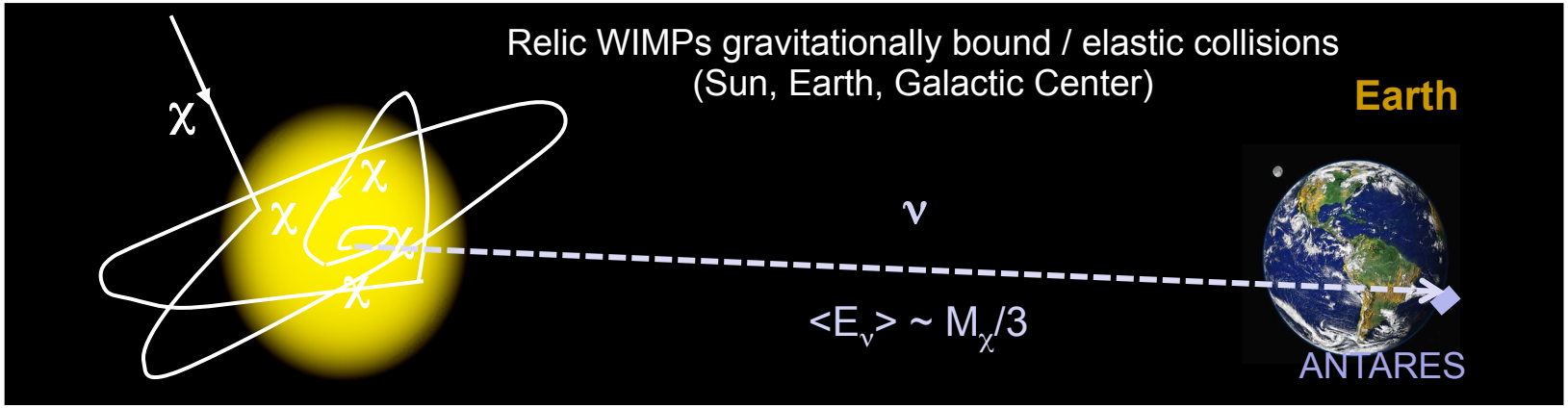


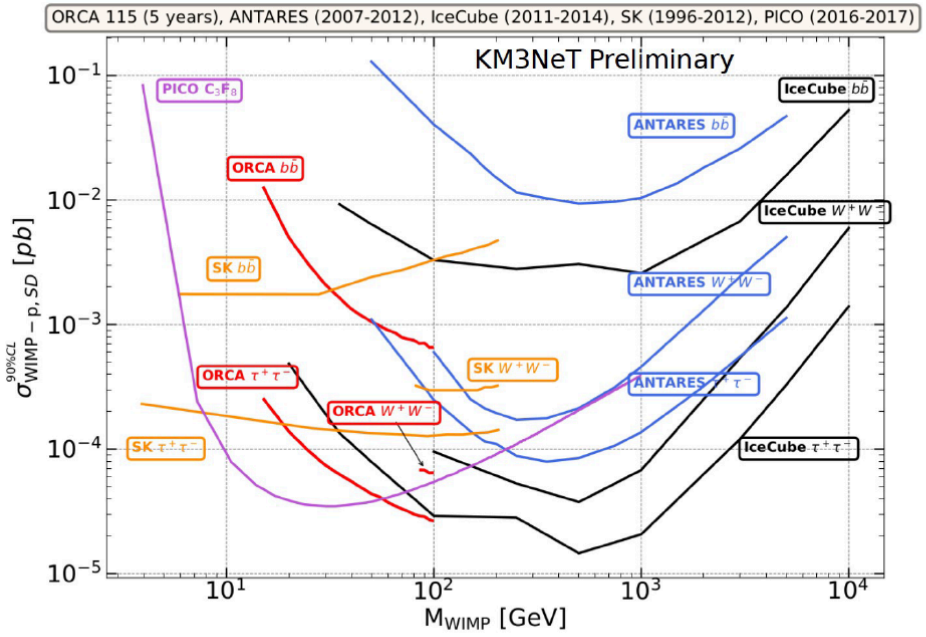
Regular tunings
Only ~20% efficiency loss

^{40}K powerful calibration tool

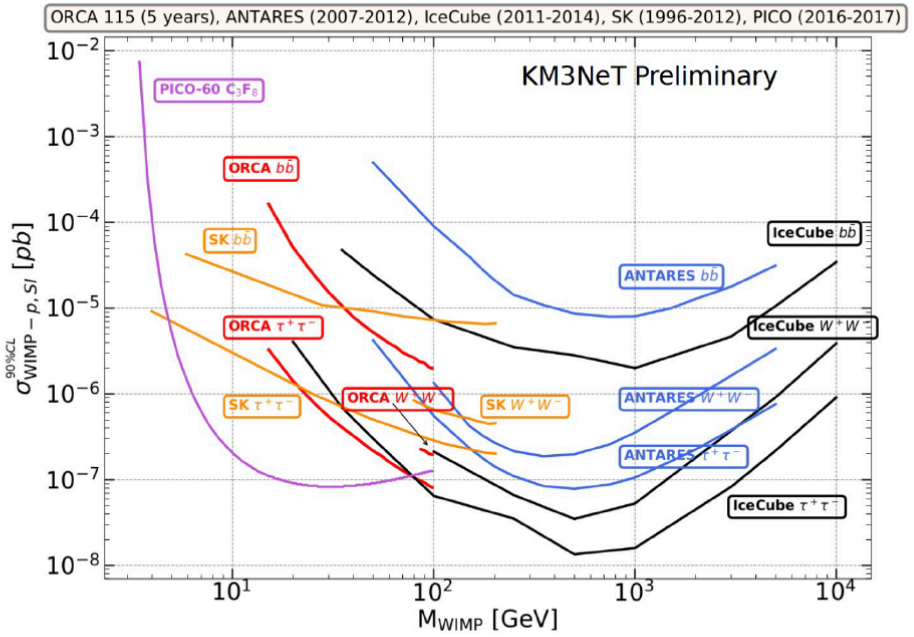
Eur. Phys. J. C (2018) 78: 669

Indirect Search for Dark Matter - Sun





Spin-dependent



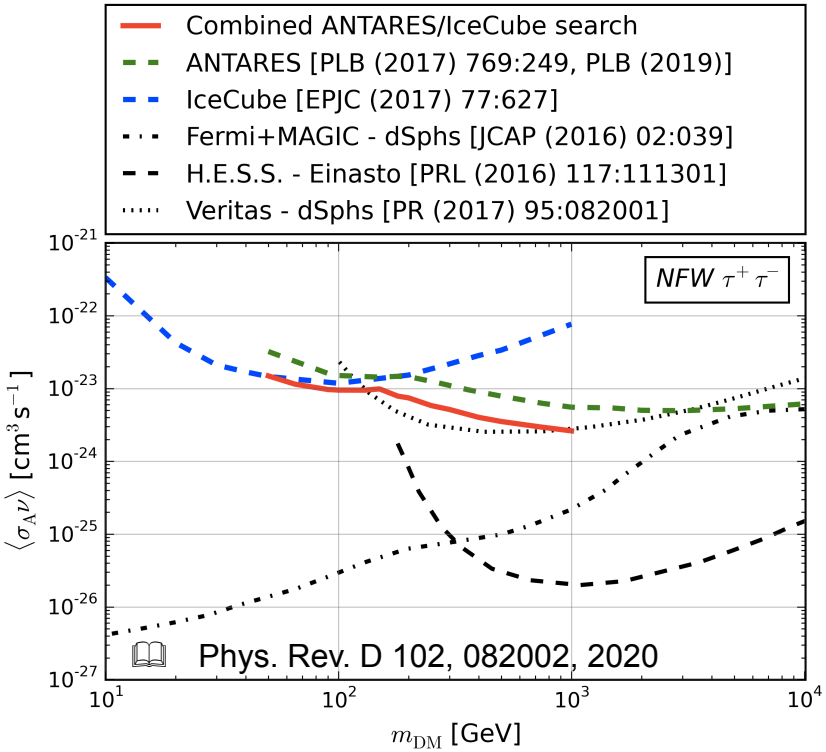
Spin-Independent

📖 Phys.Lett. B759 2016

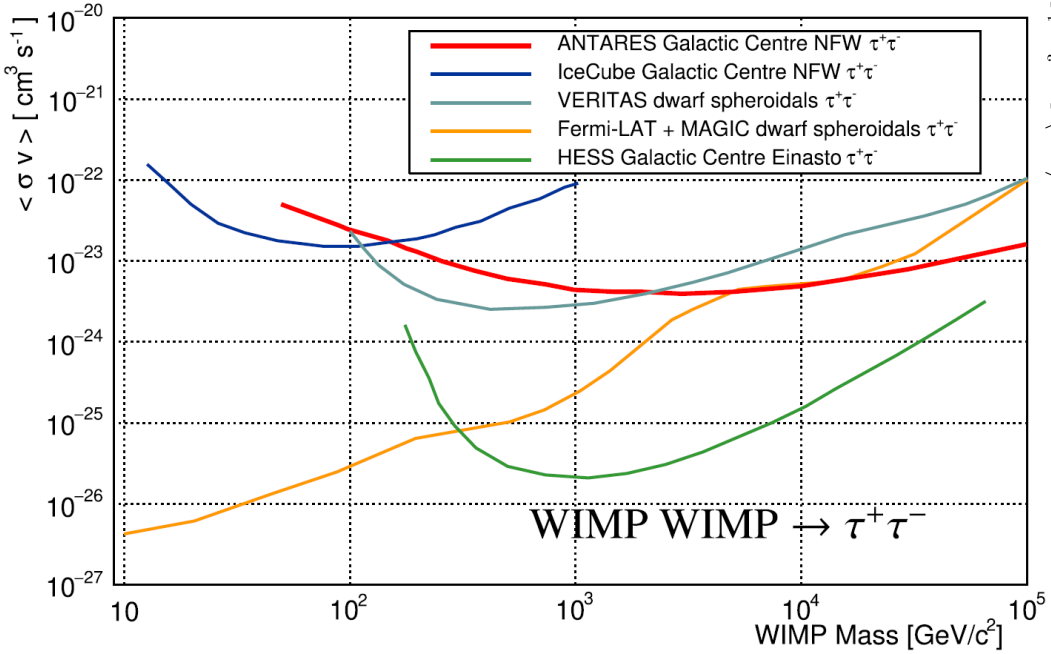
Indirect Search for Dark Matter - GC

Accumulation of (WIMP) dark matter
in massive objects
-> Annihilation to SM particles
-> Neutrinos expected from decay products
-> No excess observed

Complement direct searches



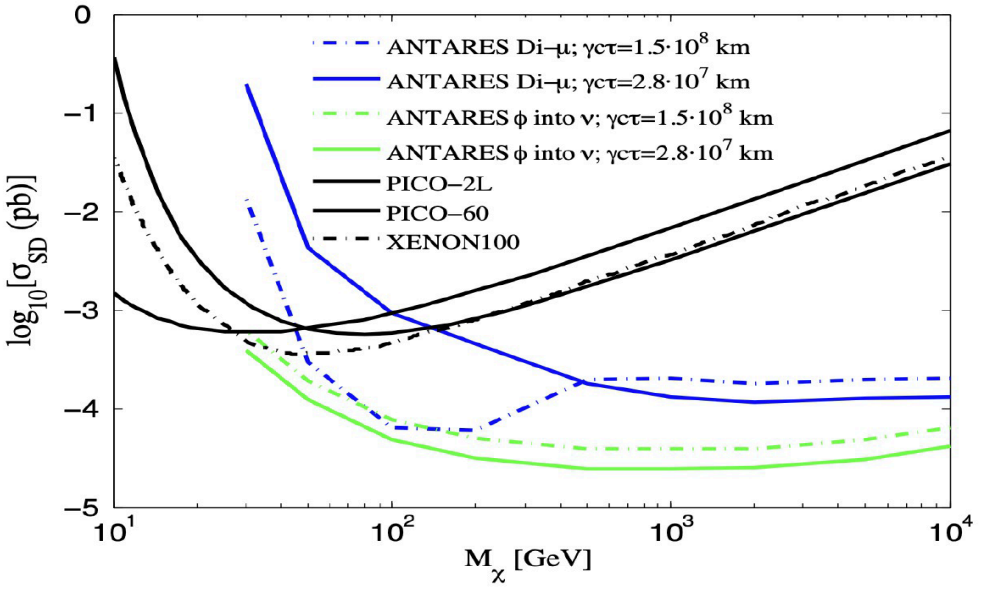
Phys. Lett. B 805 135439 (2020).



Indirect Search for Secluded Dark Matter

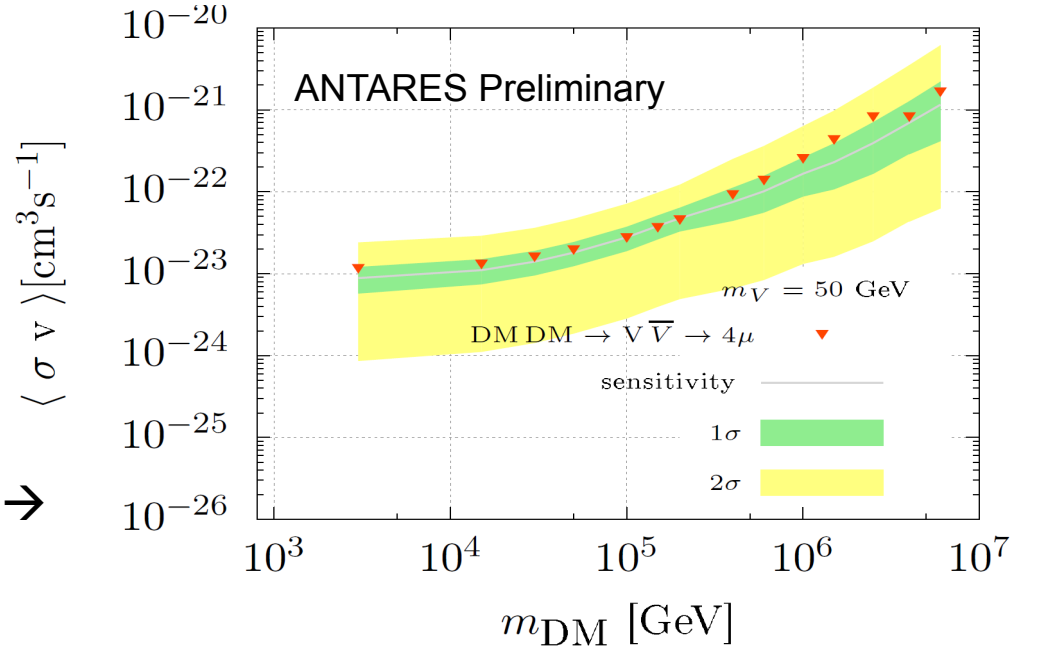
Long-live mediators could escape from Sun and the decay may be detected by ANTARES

📖 JCAP05 (2016) 016



No evidence for WIMP at the GeV-TeV scale

→ Secluded scenarios can provide dark-matter candidates at and above 10-100 TeV, in line with recent interest for BSM physics in heavy sectors at colliders



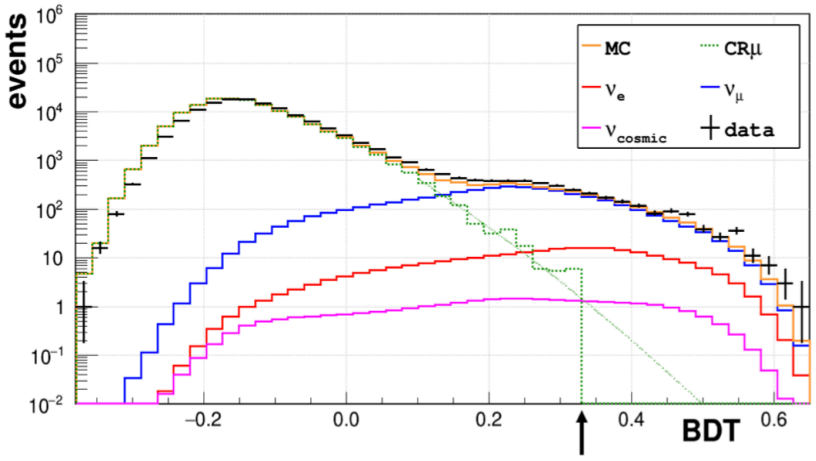
Constraints from the Galactic Center → 90% CL limits

Atmospheric neutrinos

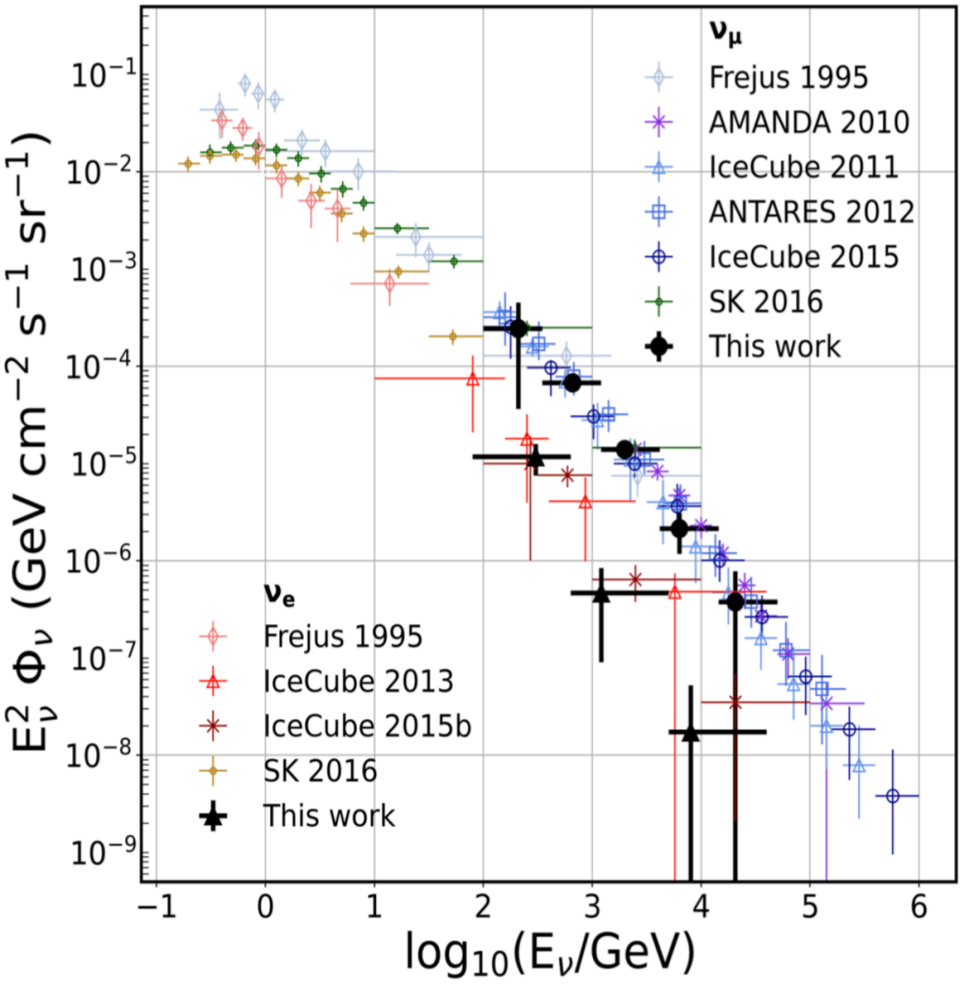
Data collected from 2007 until the end of 2017

BDT selection on 15 parameters

	Preselection $+ \Lambda > -5.7$	$+\text{BDT} > 0.33$
CRμ	136700	$\sim$3
Atmospheric ν_e CC	242	96
Atmospheric ν_e NC	22	9
Atmospheric ν_μ CC	3780	620
Atmospheric ν_μ NC	400	180
Cosmic ν	30.4	9.2
MC sum	141200	917
Data	133676	1016



Unfolded spectrum



Worldwide consistent results

arXiv:2101.12170

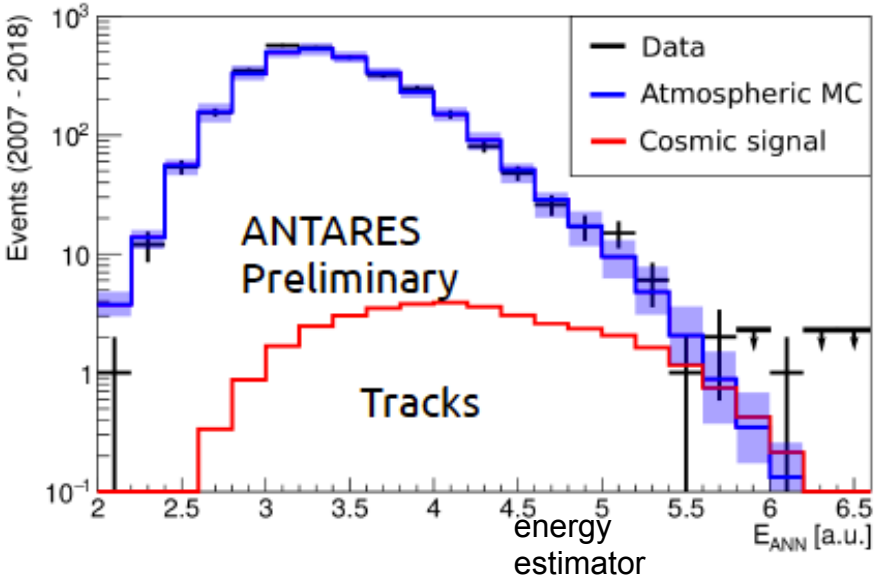
Diffuse flux

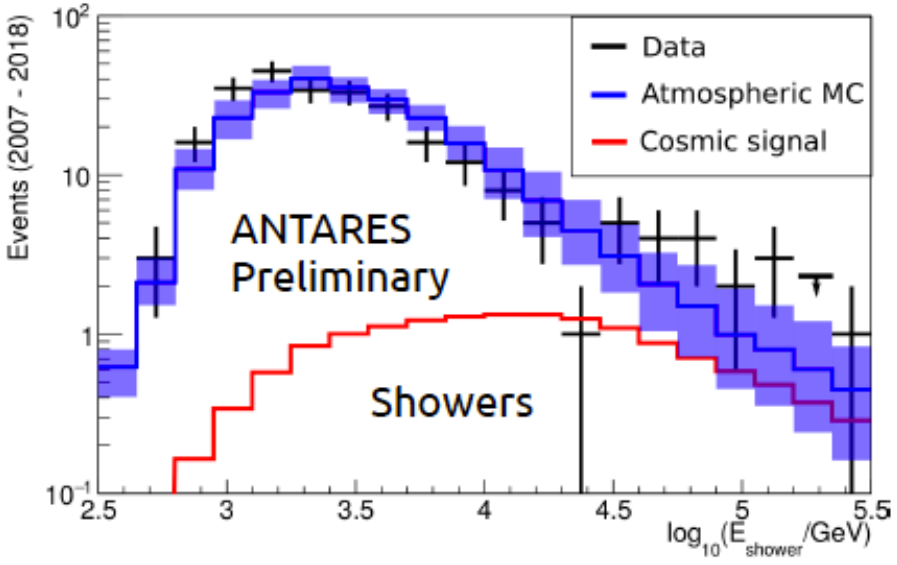
https://pos.sissa.it/358/891/pdf -(ICRC 19)

Updated data sample @ ICRC2019: 2007-2015 (2450 days) → 2007-2018 (3330 days)

All-sky / All-flavor neutrino search

- Selection cuts optimized with MRF procedure (assumed spectral index $\Gamma = 2.5$)
- Look for excess above a given E_{th}
- Combine track & shower samples





Data: 50 events (27 tracks + 23 showers)

Background expectation (atm. flux, HONDA + Enberg, scaled x ~1.25) :
36.1 ± 8.7 (19.9 tracks and 16.2 showers) – stat. + syst.

Results not really constraining… but fully compatible with IceCube

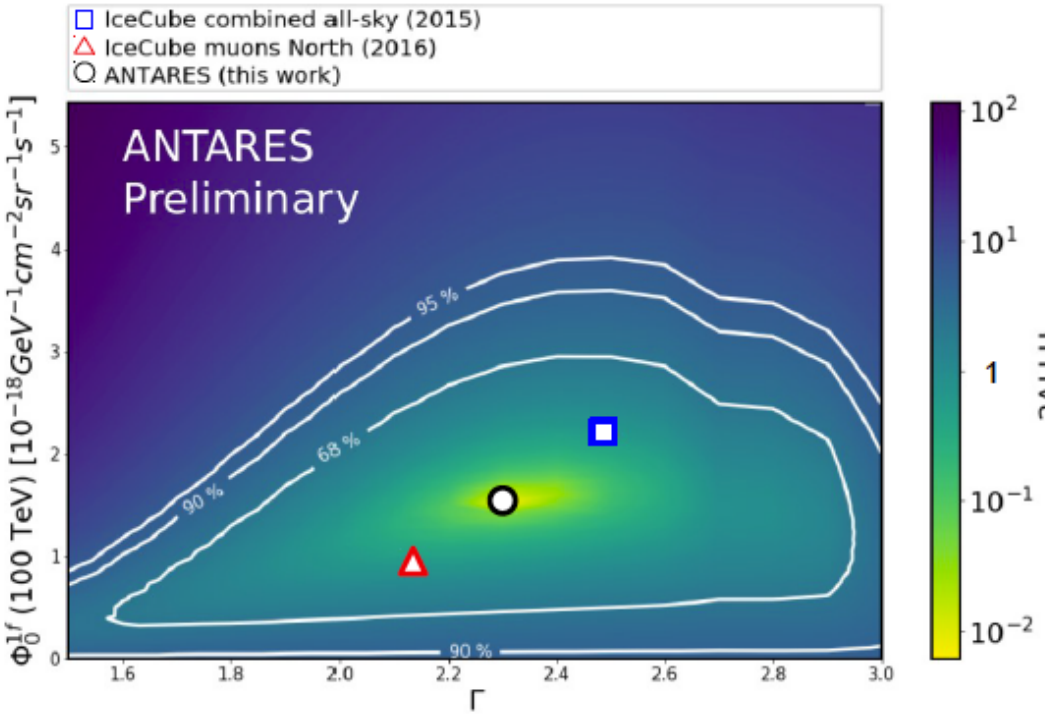
Diffuse flux

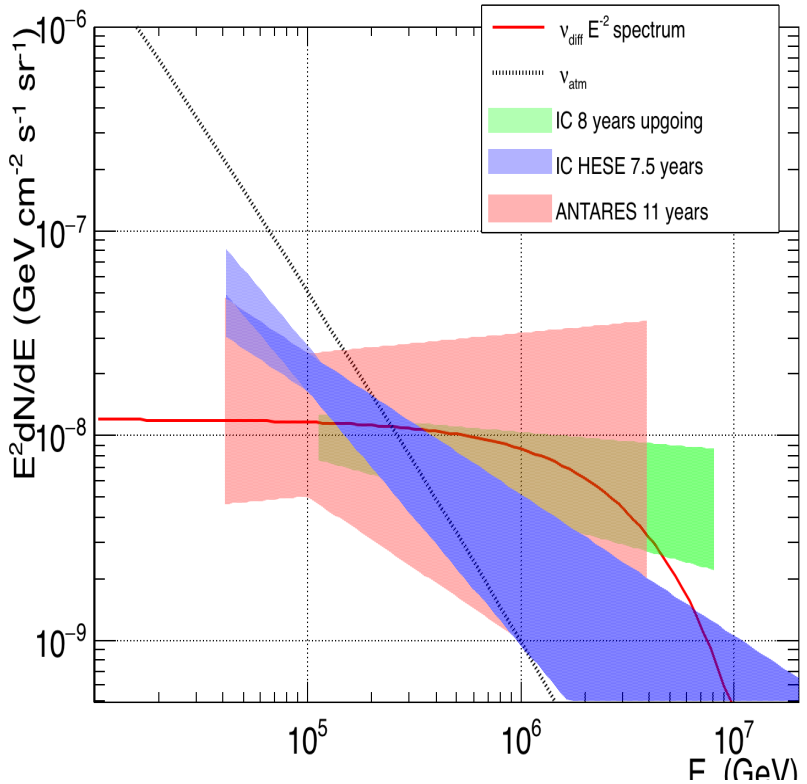
Combined (tracks+showers) likelihood fitting:

Atmospheric: $\Phi_{atm} = 1.25 \times (\mathrm{Honda} + \mathrm{Enberg})$

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

$\Gamma = 2.3 \pm 0.4$

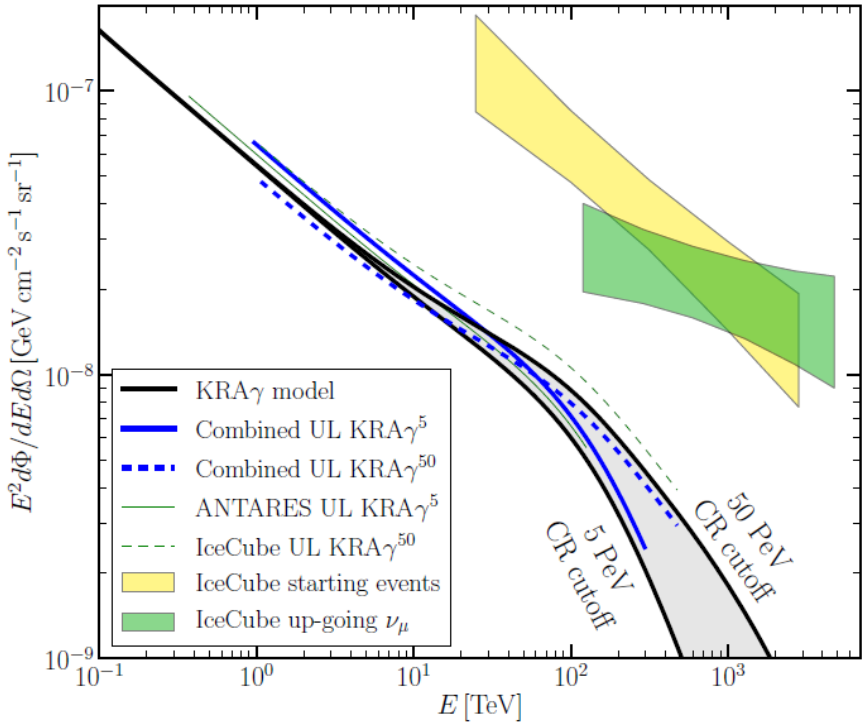




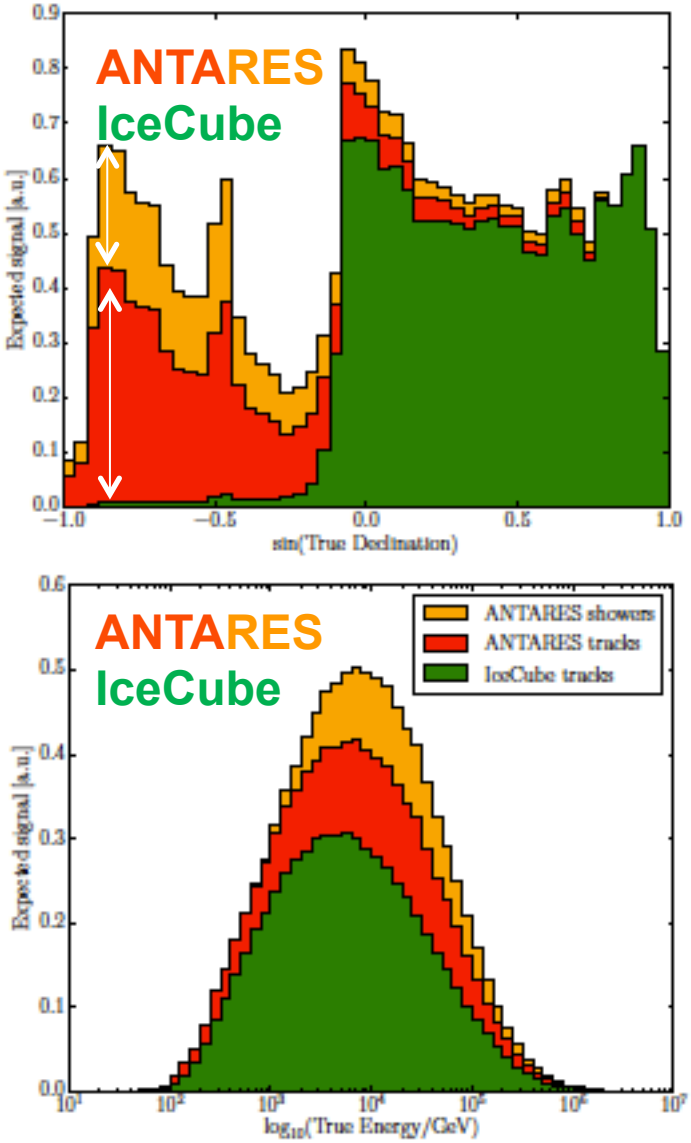
Results not really constraining… but fully compatible with IceCube

Search for diffuse flux from Galactic ridge

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



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



Result: total flux contribution of **diffuse Galactic neutrino** emission <9% *of the total diffuse IC astrophysical signal (E_ν>* 30 TeV)

Updates ongoing...

📖 Phys. Rev. D 96, 062001 (2017)
📖 ApJL 868, L20 (2018)

Combined ANTARES-IceCube PS search

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

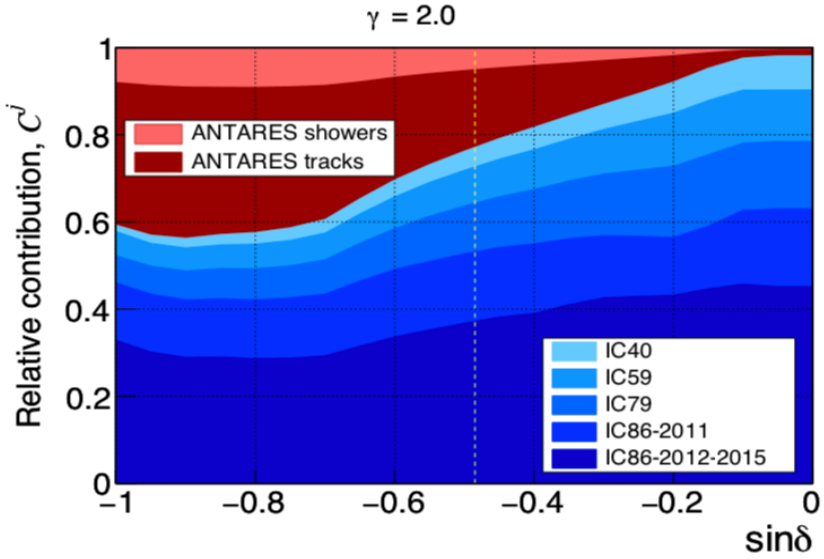
Sample	Livetime (days)	Events
tracks	2415	5807
showers	2415	102

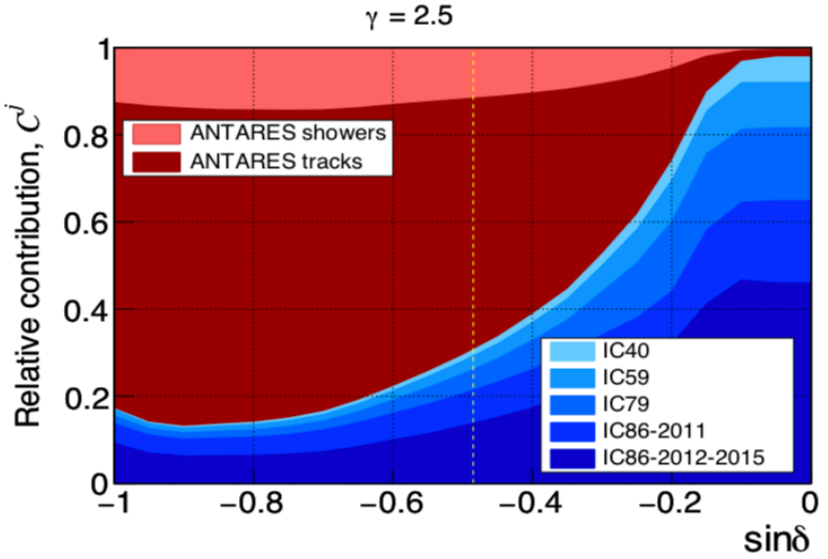
ANTARES 9 years

Through-going tracks

Sample	Livetime (days)	Events
IC40	376	22779
IC59	348	64257
IC79	316	44771
IC86	333	74931
2012-2015	1058	119231

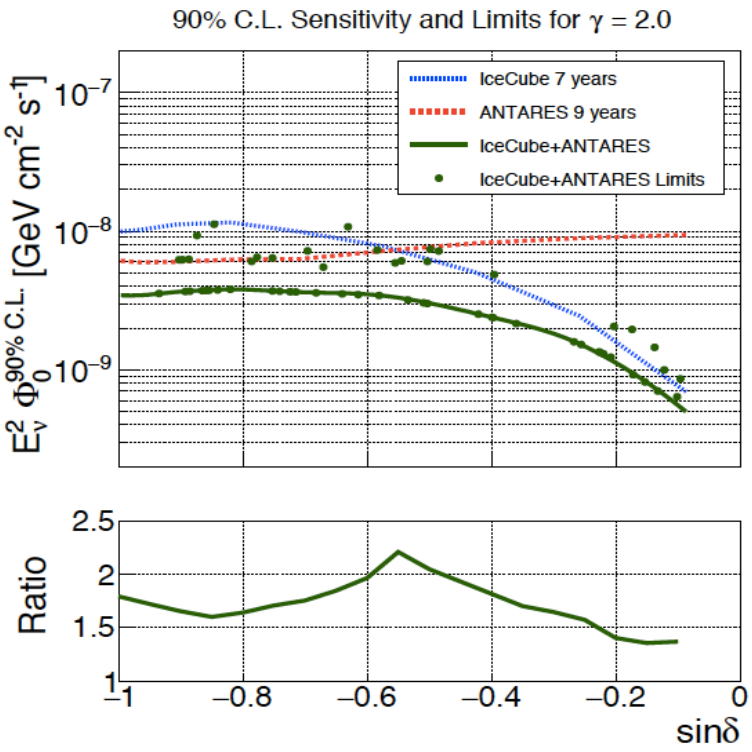
IceCube 7 years

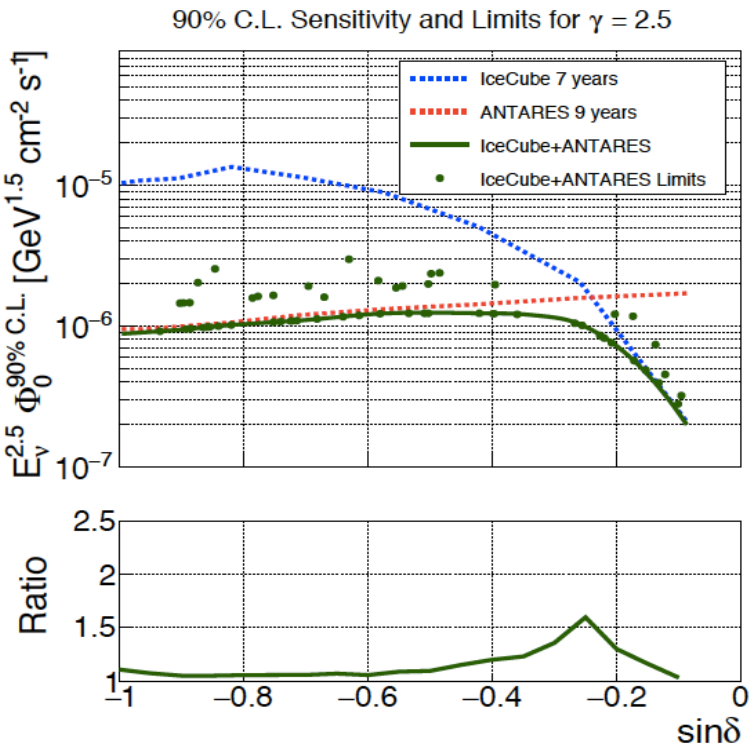




📖 The Astrophysical Journal 892 (2020) 2

Combined ANTARES-IceCube PS search





Significant improvement of limits especially for hard energy spectra
Best limits on neutrino point source emission in Southern Hemisphere

ANTARES data set is public : see https://antares.in2p3.fr

📖 The Astrophysical Journal 892 (2020) 2

Catalog-based searches

arXiv:2012.15082

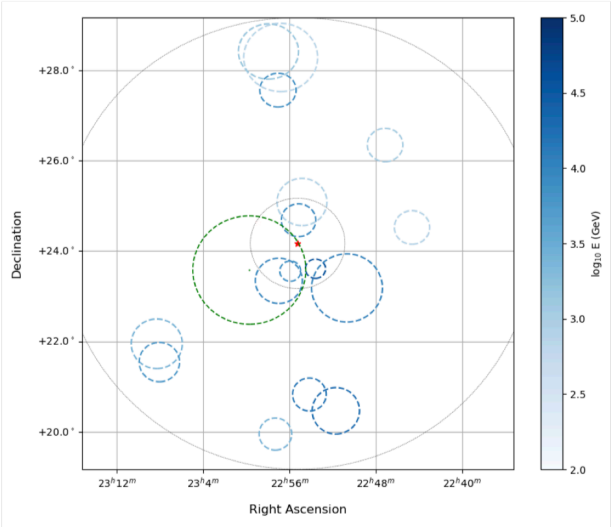
Likelihood based stacking approach

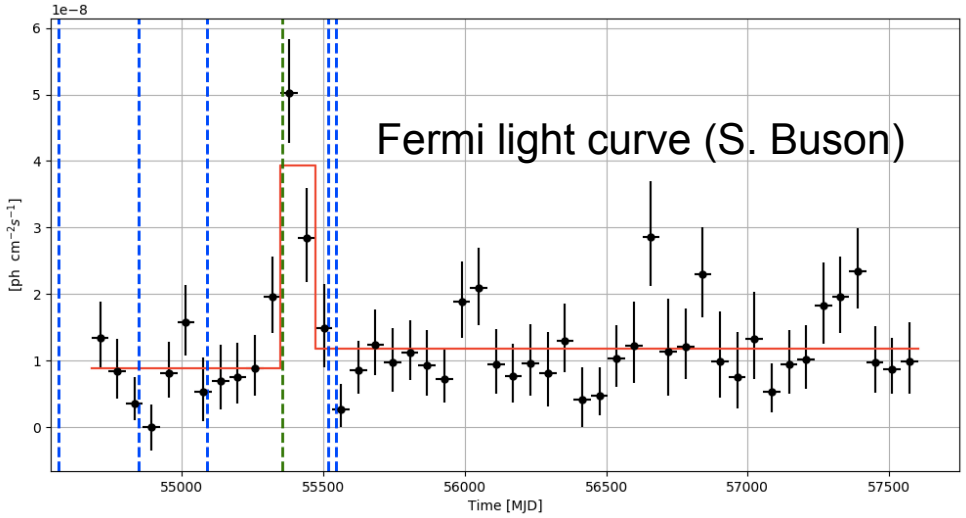
CATALOG	PRE-TRIAL	POST-TRIAL	DOMINANT SOURCE
Fermi 3LAC All Blazars	0.19	0.83	
Fermi 3LAC FSRQ	0.57	0.97	
Fermi 3LAC BL Lacs	**0.088**	**0.64**	**MG3J225517+2409**
Radio-galaxies	**$4.8\ 10^{-3}$**	**0.10**	**3C403**
Star Forming Galaxies	0.37	0.93	
Obscured AGN	0.73	0.98	
IC HE tracks	0.05	0.49	

1.6 σ

Mild excess seen for radio galaxies

Blazar MG3 J225517+2409
ANTARES & IceCube tracks





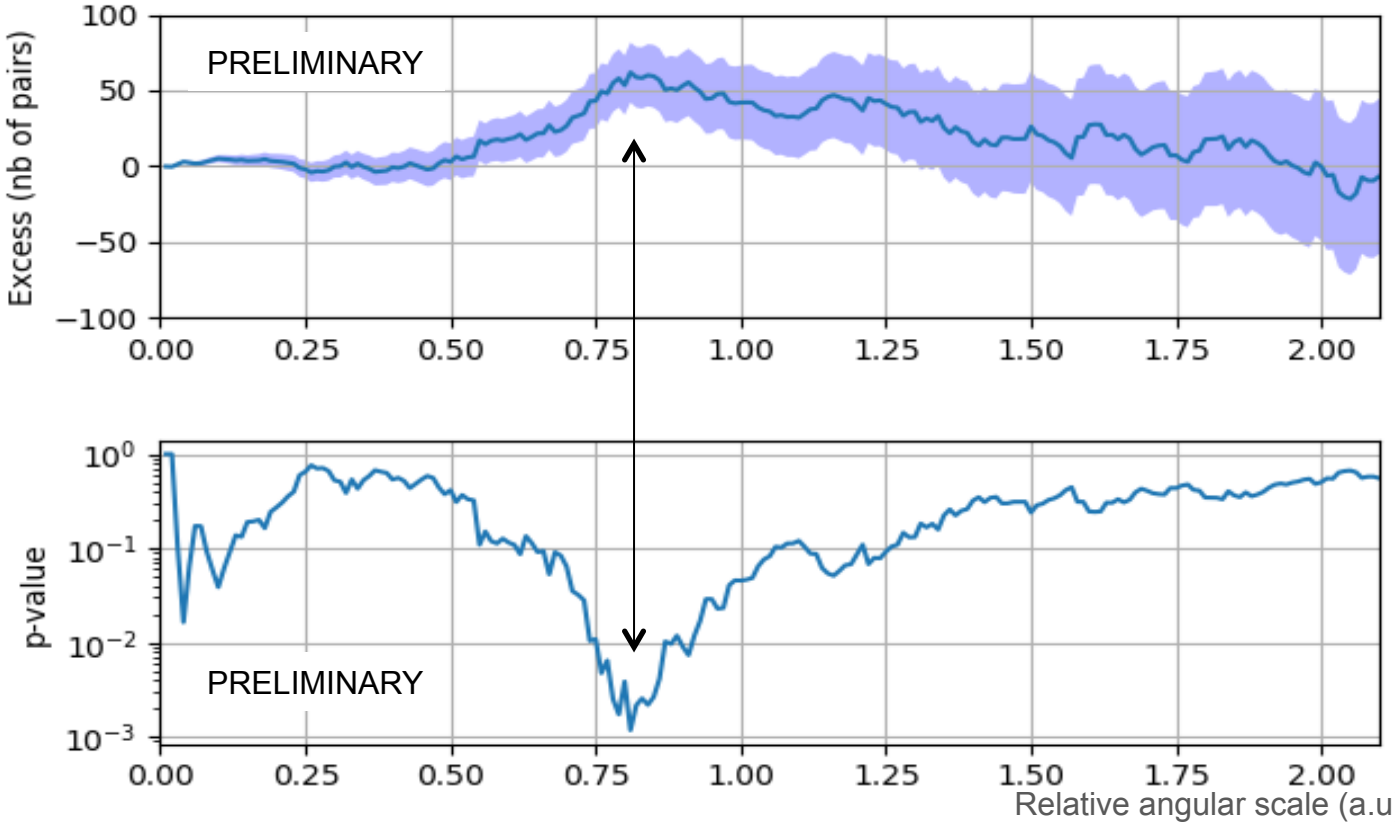
Space-time association: ANTARES -> **2.3σ** & IceCube track -> **2.6σ**

Catalog-based searches

PRELIMINARY !

- Following 🕮 A. V. Plavin *et al* 2021 *ApJ* **908** 157, ongoing search for correlation between neutrino candidates and radio blazars seen in VLBI data (3411 objects)
- Use the ANTARES PS sample 2007-2020 (10162 tracks) with same stacking method yields a p-value of 8.3 10^{-2} (about 1.8 σ)

- Simple pair counting also shows hint of correlation at sub-degree angular scale



Stay tuned for updated results in summer conferences !

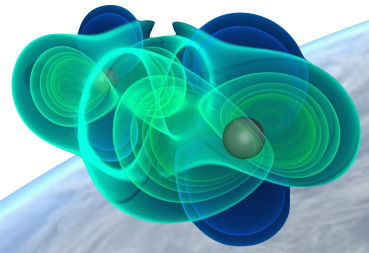
See also A. Franckowiak 's talk yesterday

The multi-messenger program

1ST APPROACH:

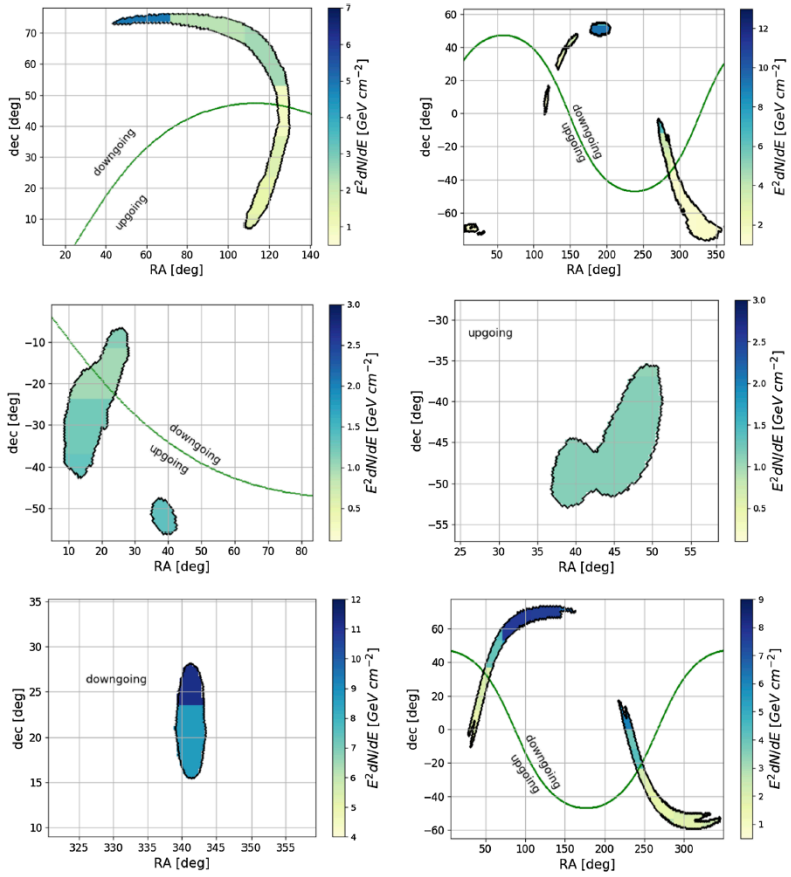
Time dependent searches

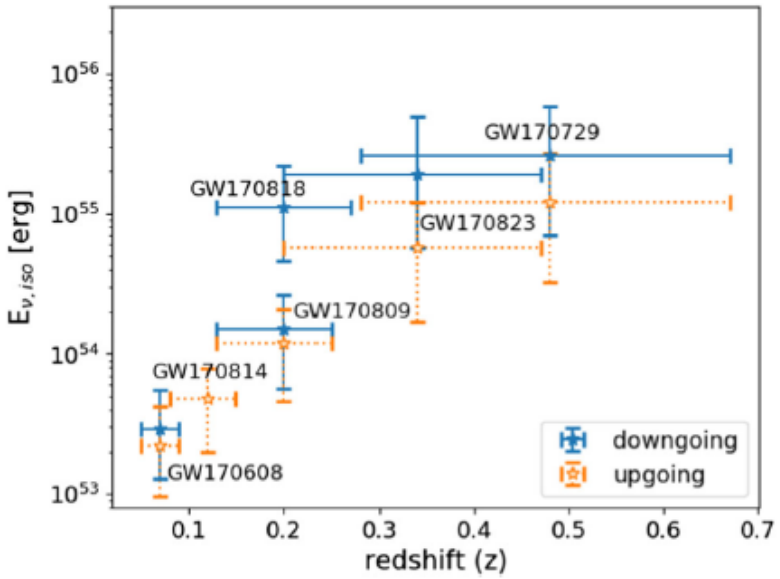
GRB
Microquasar
Gamma-ray binaries
Blazars
Supernovae Ib,c
Fast Radio Bursts



Follow-up of Gravitational Waves

- Online alerts followed. Results from counterpart searches after 24hr through GCN
- Refined offline searches (fully calibrated sample): No events found → limits set.
- Latest O2 BBH: Constraints on fluence and $E_{\nu,iso}$ for BBH





- Run 03 analysis ongoing

📖 Eur. Phys. J. C 80, 487 (2020)
📖 ApJ 870 (2019) 2
📖 ApJL 848 L12 (2017)
📖 ApJL 850 L35 (2017)
📖 Phys. Rev. D 96 (2017) 022005
📖 Phys. Rev. D 93 (2016) 122010
📖 JCAP06(2013)008

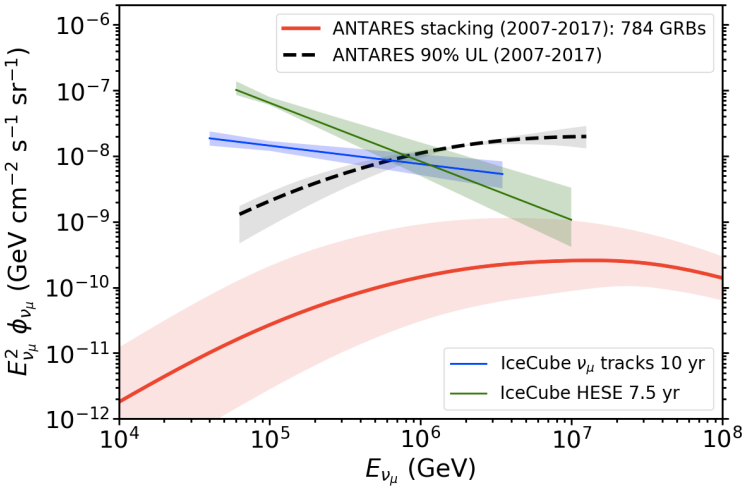
Search for ν counterparts to GRBs

Extremely energetic bursts -> Associated neutrino production detectable?

Stacking analysis of 784 GRBs
ANTARES data 2007-2017

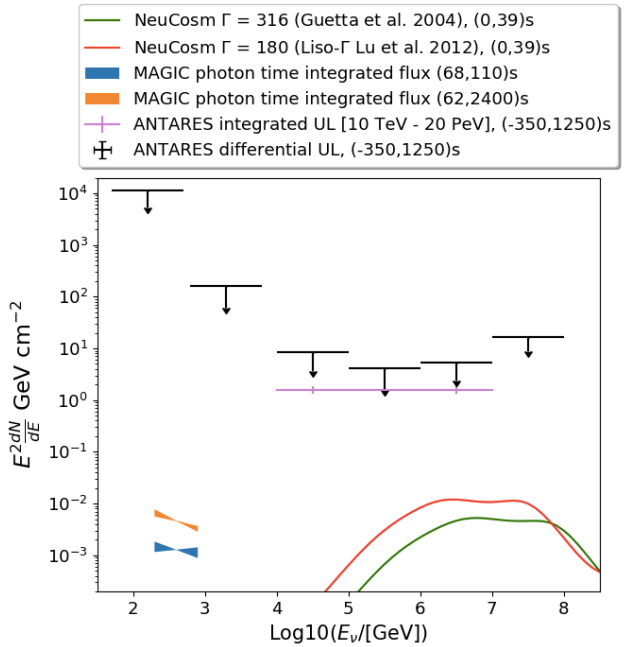
- No coincidences found
- GRBs contribute <10% of astrophysical flux <100TeV

Flash Talk A. Zegarelli



📖 MNRAS, 500, 5614–5628 (2021)

High energy gamma ray emission observed for 3 GRBs by H.E.S.S./MAGIC:
GRB180720A, GRB190829B (H.E.S.S.)
GRB190114C (MAGIC)
-> Follow-up search using ANTARES tracks/showers during time of gamma-ray emission
-> No events found in time & space coincidence

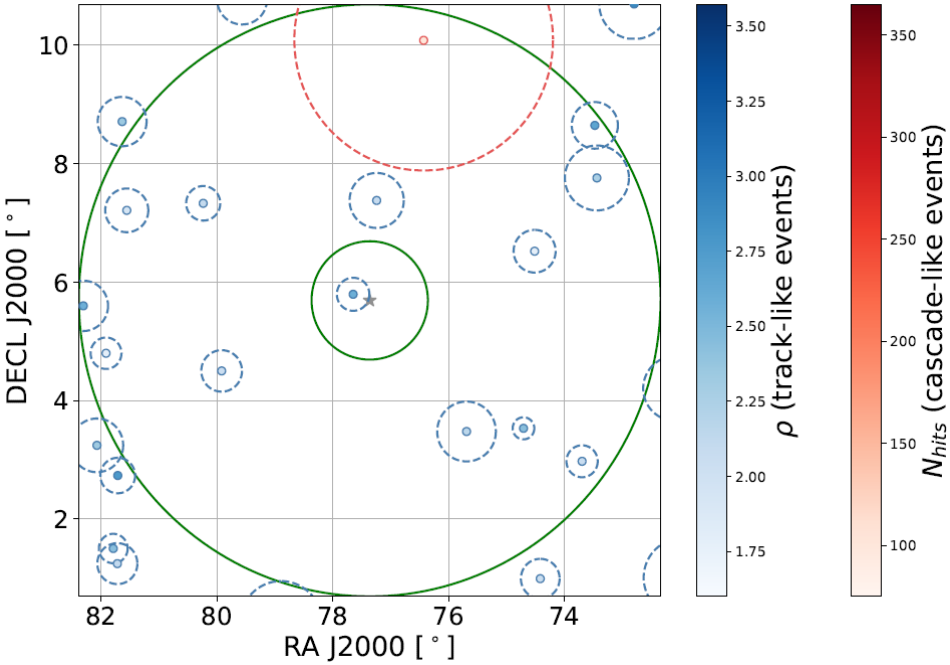


📖 Soon in JCAP arXiv:2011.11411

Search for neutrinos from TXS 0506+056

Time integrated archival search

- Same method as PS searches, +2016/17
- Expected background (3136 days) :
  - 0.23/deg^2 for track-like
  - 0.005/deg^2 for shower-like events
- # of events fitting the likelihood signal function for the source: μ_{sig} **= 1.03**
- **Pre-trial p-value of 3.4%** (post-trial 87%)
- 1 track (12/12/2013) 0.3^o from the source
- Flux U.L. (@100 TeV) for E^{-2}: 1.6x10^{-18} GeV^{-1} cm^{-2} s^{-1} in the range [2 TeV-4 PeV]
- In the list of 107 pre-selected sources, only two have a smaller p-value

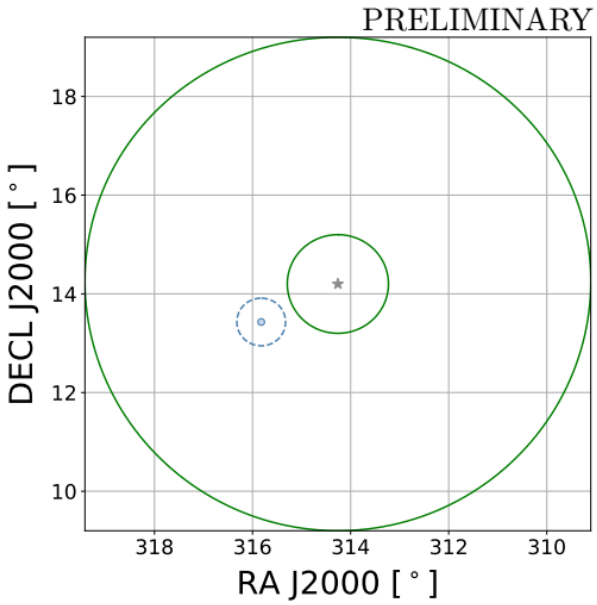


Distribution of the 13 tracks +1 shower events in the (RA,δ) coordinates around (radius=1^o and 5^o) the position of TXS 0506+056.

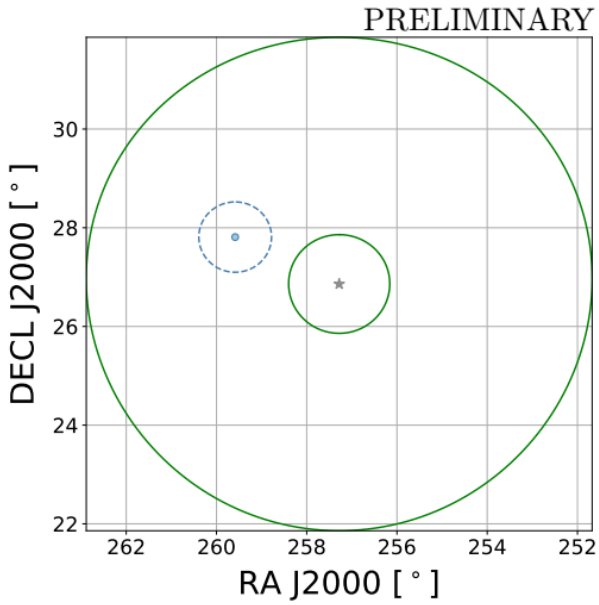
📖 ApJL 863, L2 (2018)

Search for ν counterparts to TDE events

IC191001A & AT2019 dsg



IC200530A & AT2019 dsg



Source		Results						
Name	γ	$\hat{\mu}_{\mathrm{sig}}$	p-value	$\Phi_0^{90\%\mathrm{C.L.}}$		$\mathcal{F}^{90\%\mathrm{C.L.}}$		$\log(\frac{E_{\mathrm{min}}}{\mathrm{GeV}})$ - $\log(\frac{E_{\mathrm{max}}}{\mathrm{GeV}})$
				sensitivity	limit	sensitivity	limit	
AT2019dsg	2.0	< 0.1	12%	7.3×10^{-8}	1.0×10^{-7}	14	19	3.6 - 6.6
	2.5	0.2	10%	1.5×10^{-5}	2.2×10^{-5}	29	43	2.8 - 5.5
	3.0	0.7	8.9%	1.2×10^{-3}	2.0×10^{-3}	230	380	2.1 - 4.7
AT2019fdr	2.0	0.5	6.7%	8.5×10^{-8}	1.3×10^{-7}	15	23	3.6 - 6.6
	2.5	0.5	7.9%	2.1×10^{-5}	3.0×10^{-5}	39	55	2.8 - 5.5
	3.0	0.6	9.1%	2.0×10^{-3}	3.0×10^{-3}	360	540	2.1 - 4.7

See also A. Franckowiak 's talk yesterday

The multi-messenger program: TATOO

Telescope-Antares Target of Opportunity

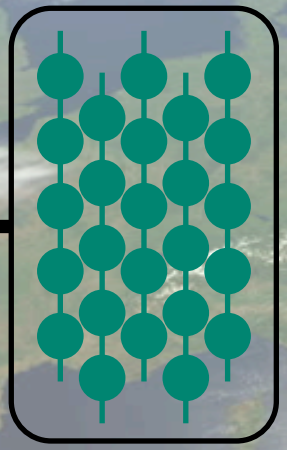
2ND APPROACH:

Alert triggering

Real-time analysis

AMON
Astrophysical Multimessenger Observatory Network

+ ...

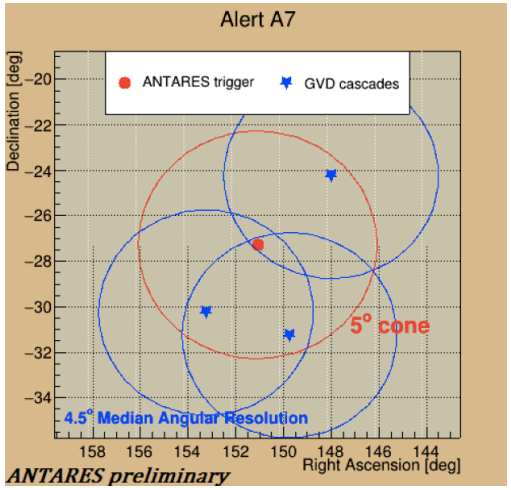


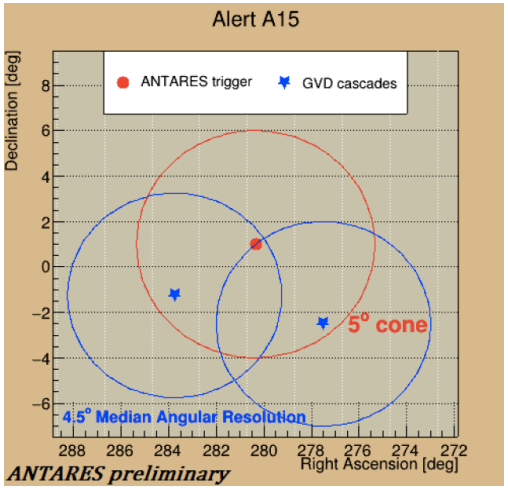
- Time to send an alert: ~5 s
- First optical image <20 s
- Median angular resolution: ~0.3°
- Triggers: single HE, preferred direction, multiplets

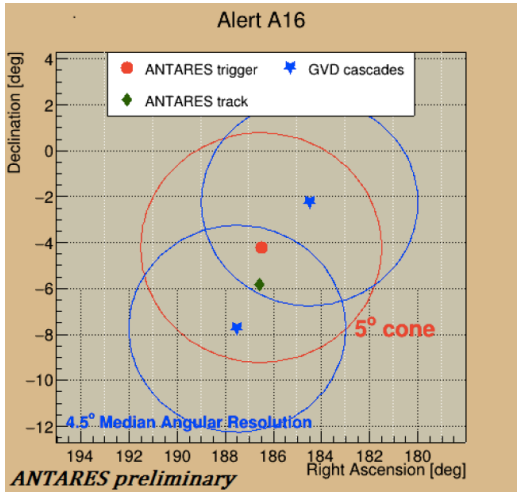
GVD Baikal follow-up of ANTARES alerts

31 ANTARES alerts sent to GVD Baikal, 28 followed up:
Search within ±500s, ±1hour, ±1 day within 5 degree
(cascade median resolution 4.5 degrees)

=> For 3 alerts multiplets of cascades reconstructed within ±1day







5 GVD clusters running during that period
Background events/cluster/day ranging from 0.02-0.05

No additional showers seen in ANTARES for that same direction within ±1 day
Still searching for additional tracks

See Zhan-Arys Dzhilkibaev's talk in few minutes

TATOO and the transients

MNRAS, 48 (2019) 1
ApJ, 886:98 (2019)

Radio → Optical → X-ray → GeV γ-rays → TeV γ-rays

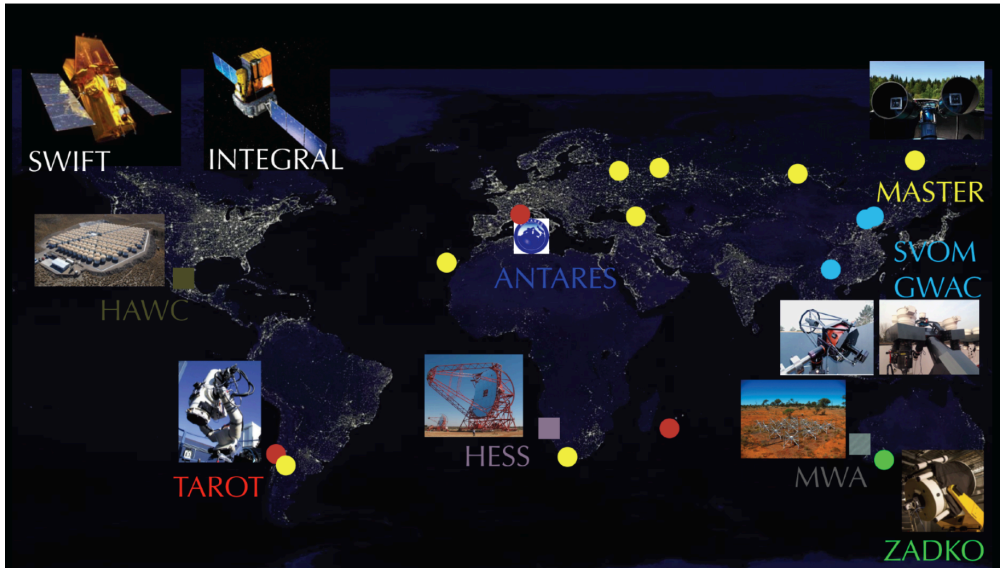
MWA (12/yr)

TAROT ZADKO MASTER (GWAC) (30/yr)

Swift (6/yr) Integral

Fermi (offline)

HESS (2/yr) HAWC (offline)



Triggers:

- Doublet of neutrinos (<3°, <15 min): ~0.04 events/yr
- Single neutrino with direction close to local galaxies: ~1 TeV, ~10 events/ yr
- Single HE neutrinos: ~5 TeV, 20 events/ yr
- Single VHE neutrinos: ~30 TeV, ~3-4 events/ yr

Performances:

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

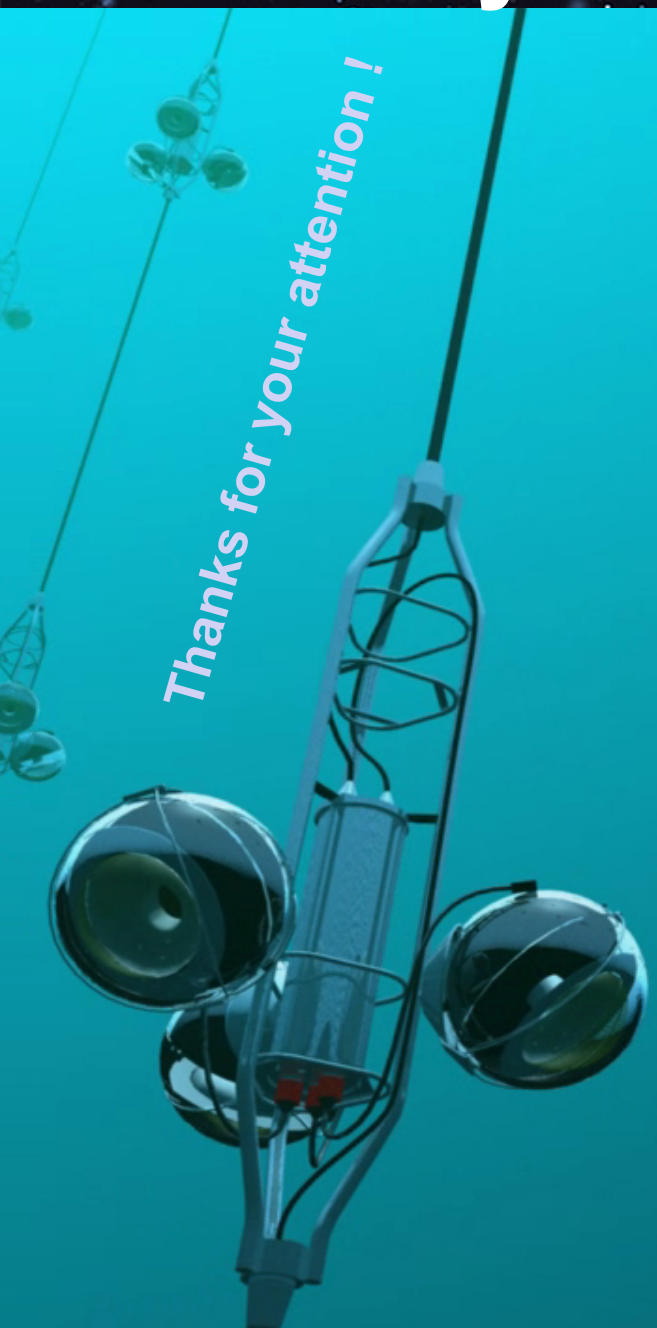
Sent neutrino alerts (2009-2020)

322 to robotic telescopes
+26 to Swift
+12 to INTEGRAL

+~25 to MWA
+2 to HESS

Follow-up efficiencies: ~70% (X-ray / optical) + ~20% (radio)

Summary



Thanks for your attention !

- ANTARES is the largest NT in the Mediterranean Sea.
  A multi disciplinary observatory (associated sciences).
- Competitive physics results & intringuing hints
- Constraints on neutrinos as seen by IceCube.
- Includes cascade-like events in various analyses
  - Good pointing power
- Extensive multi-messenger program.
- Joint studies with several partners
- Although technologically challenging ANTARES
  is working since 2008 according to specifications.
  Proves the feasibility of a deep sea Neutrino Telescope.
  → KM3NeT

ANTARES search for cosmic neutrino point source

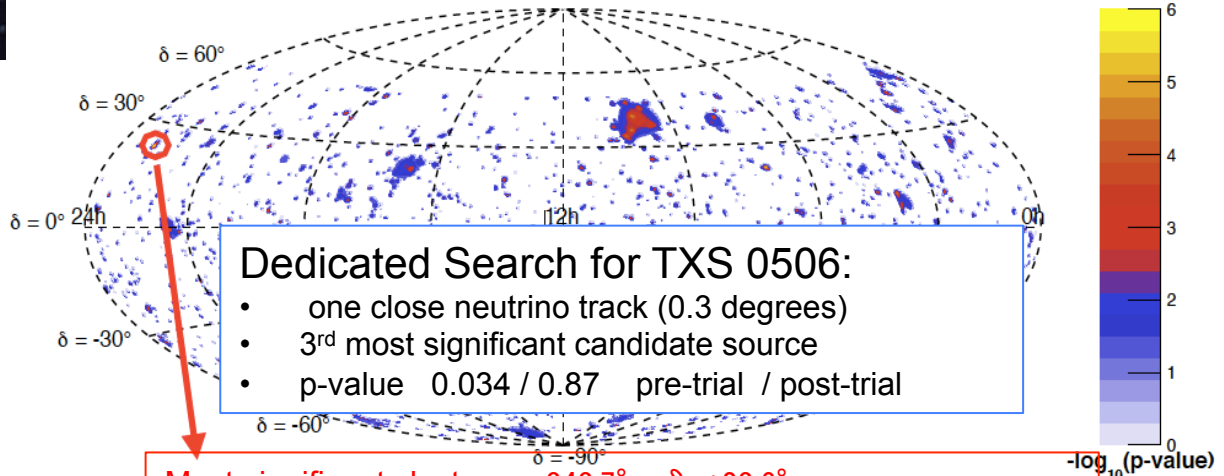
2007-2017, 8754 tracks, 195 showers

- Prominent TeV sources probed
- HE IC neutrino directions probed
- Galactic Plane special search

No significant excess

All-sky spot coincident
with IceCube HE track

Search also for time-correlated
events in vicinity of IceCube
HE tracks -> no excess

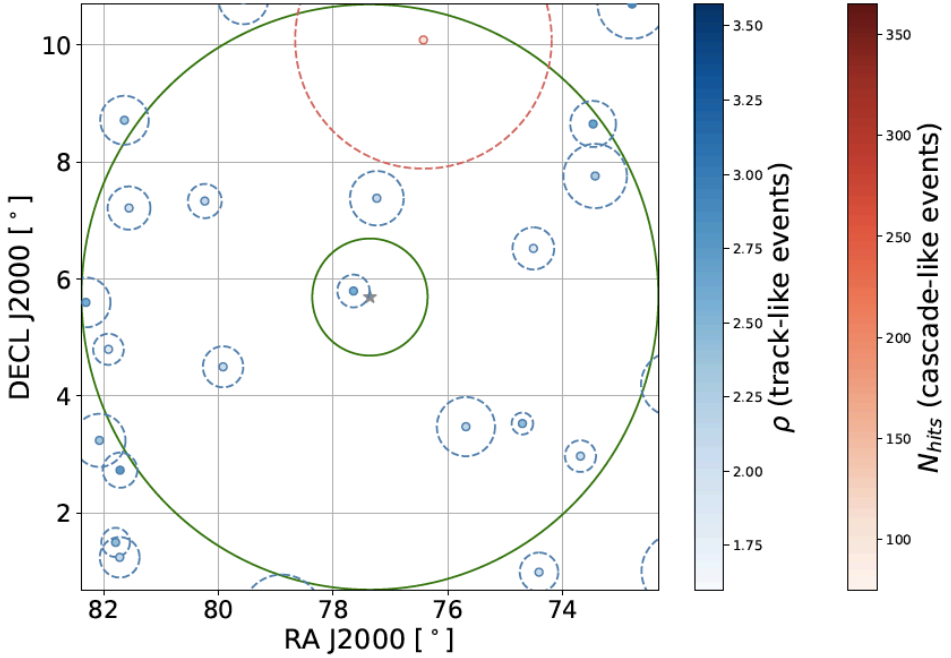


Dedicated Search for TXS 0506:

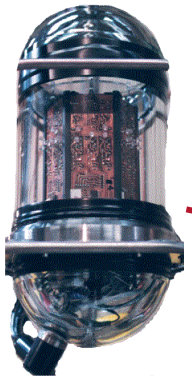
- one close neutrino track (0.3 degrees)
- 3rd most significant candidate source
- p-value 0.034 / 0.87 pre-trial / post-trial

Most significant cluster α=343.7° δ=+23.6°
pre−trial 1.5 10^{-6} (4.8 σ), post trial 0.23 (1.2 σ)
3 track events within 1°, 15 tracks + 1 shower within 5°

ANTARES events observed close to TXS -0506+056

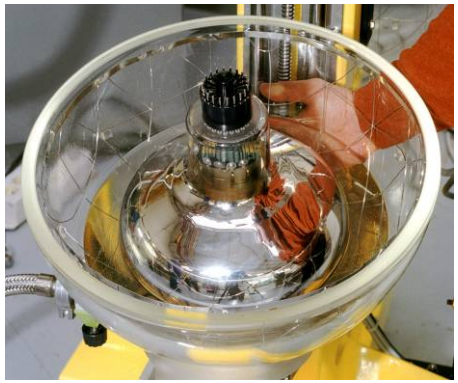


Basic neutrino detector element: storey

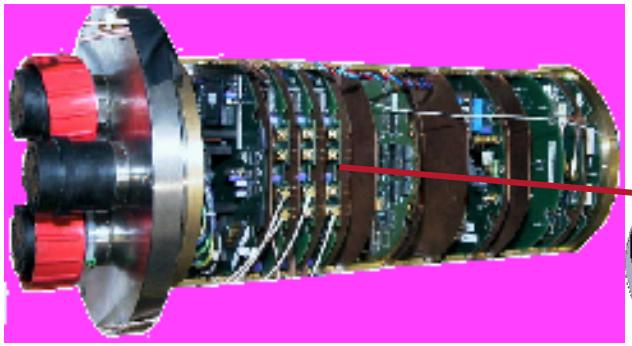


Titanium frame: *support structure*

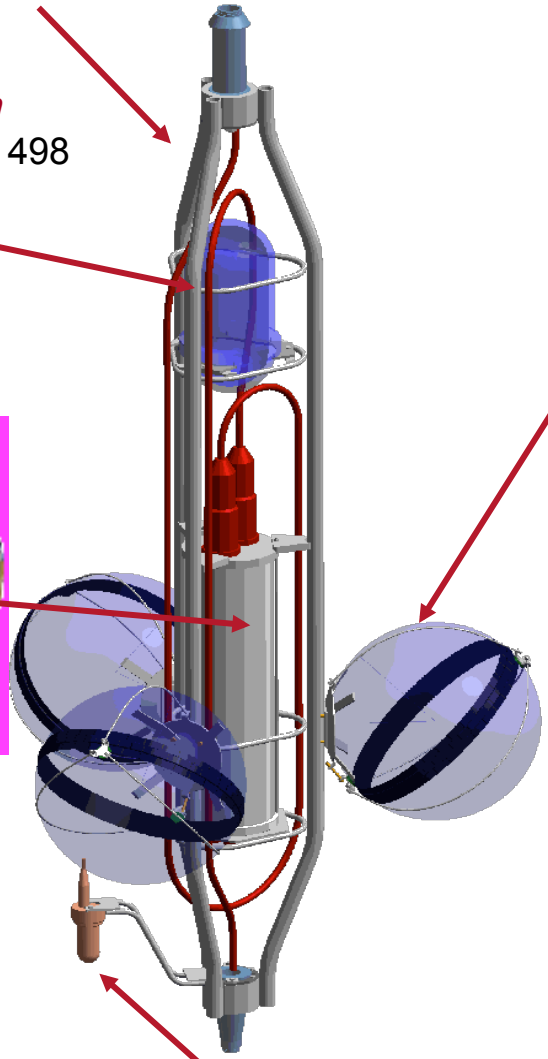
Optical Beacon
with blue LEDs:
timing calibration
📖 NIM A578 (2007) 498



Optical Module:
10” Hamamatsu PMT in
17” glass sphere
photon detection
📖 NIM A484 (2002) 369
📖 NIM A555 (2005) 132

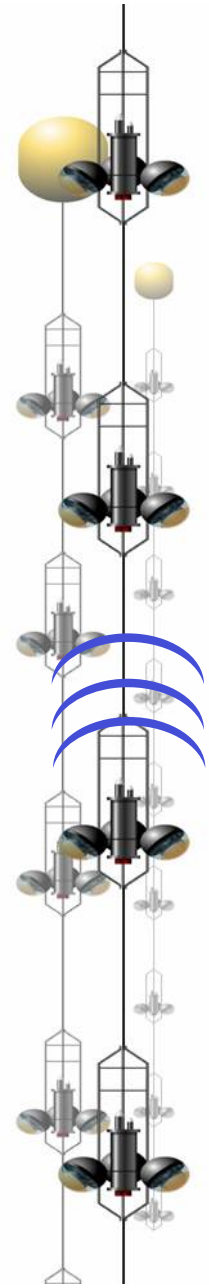


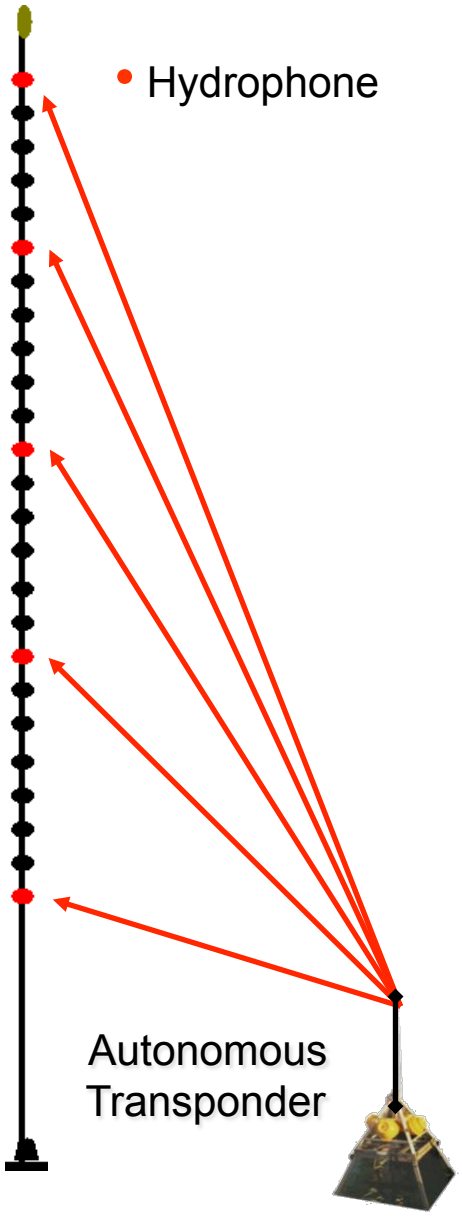
Local Control Module (Ti):
Front-end ASIC, DAQ/SC, DWDM,
Clock, tilt/compass, power distribution…
📖 NIMA 622 (2010) 59-73

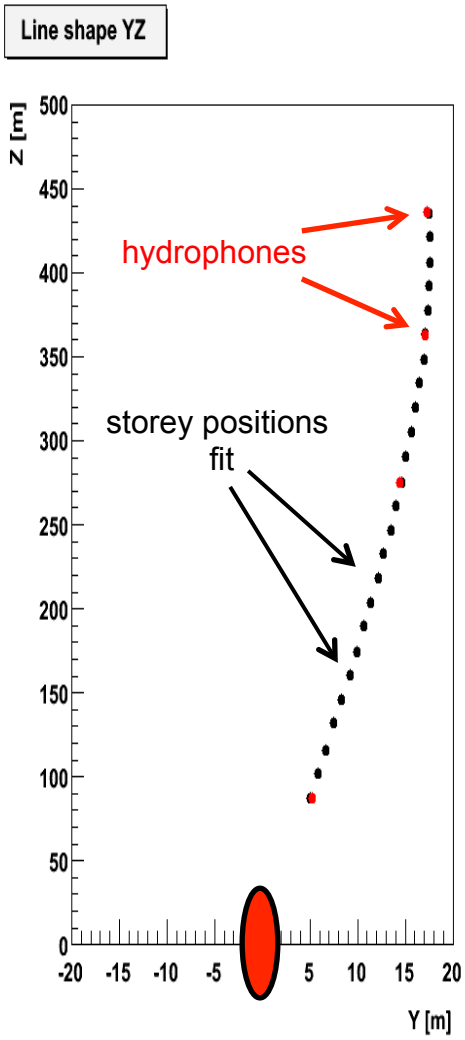


Hydrophone:
acoustic positioning
📖 JINST 7 T08002

Detector Calibration







Led/laser beacons
Intense light:
PMT TTS
negligible

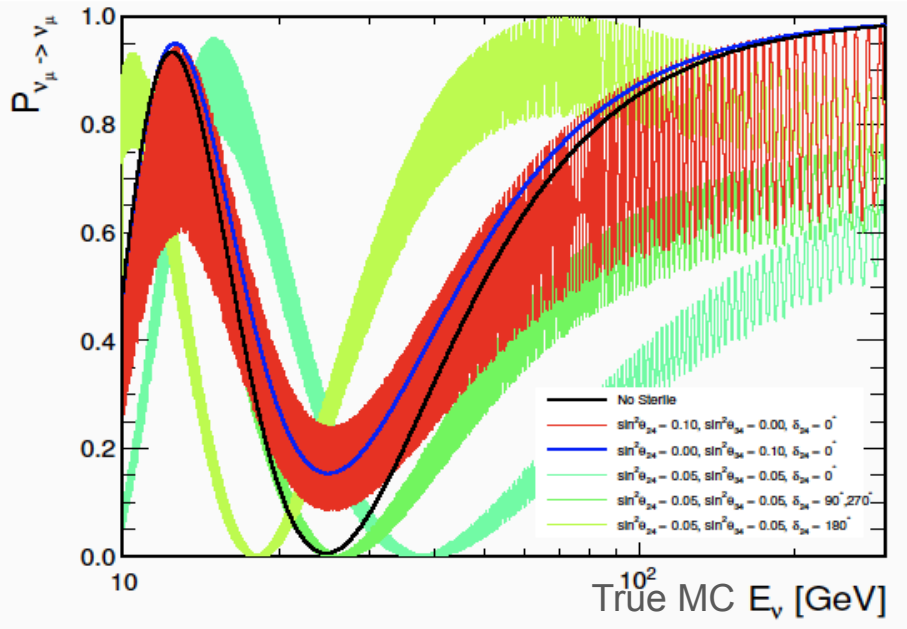
Timing resolution
of electronics
~ 0.5 ns

Positioning
resolution
< 10 cm

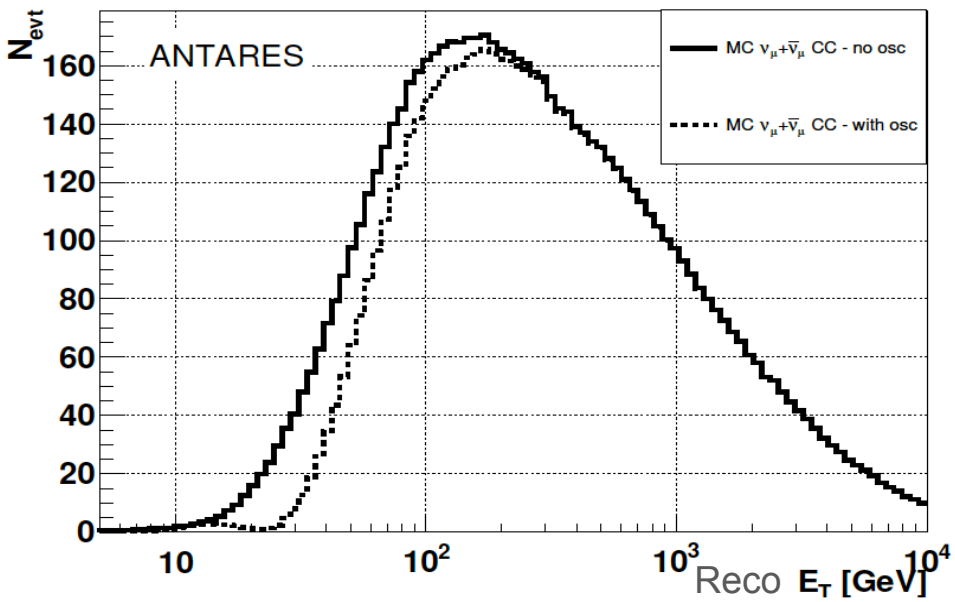
Updated Oscillation Studies

For illustration

Vertical Upgoing



Selected events



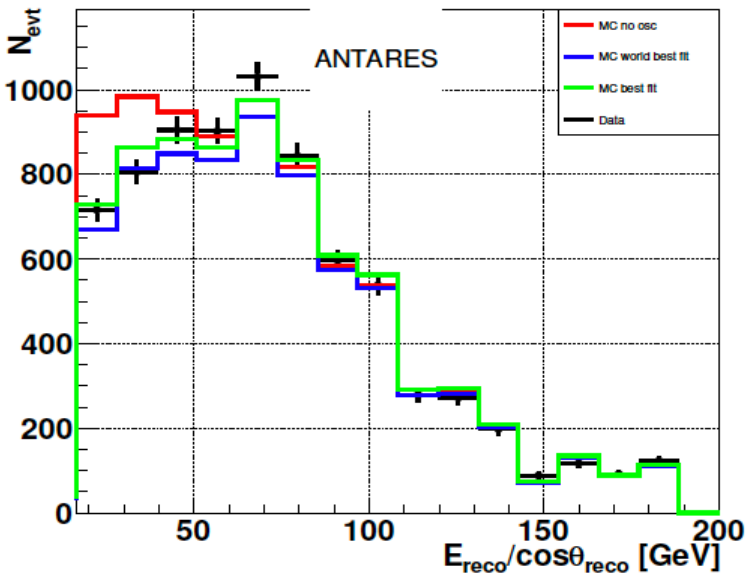
- 9 years of data (2007-2016) - 2830 days of lifetime
- 7710 events selected, two reconstruction procedures
- Track channel only, E_{reco} from muon range
- A binned likelihood fit (Poisson stat.) is performed in two dimensions ($\log_{10}(E_{reco})$, $\cos\theta_{23}^{reco}$)

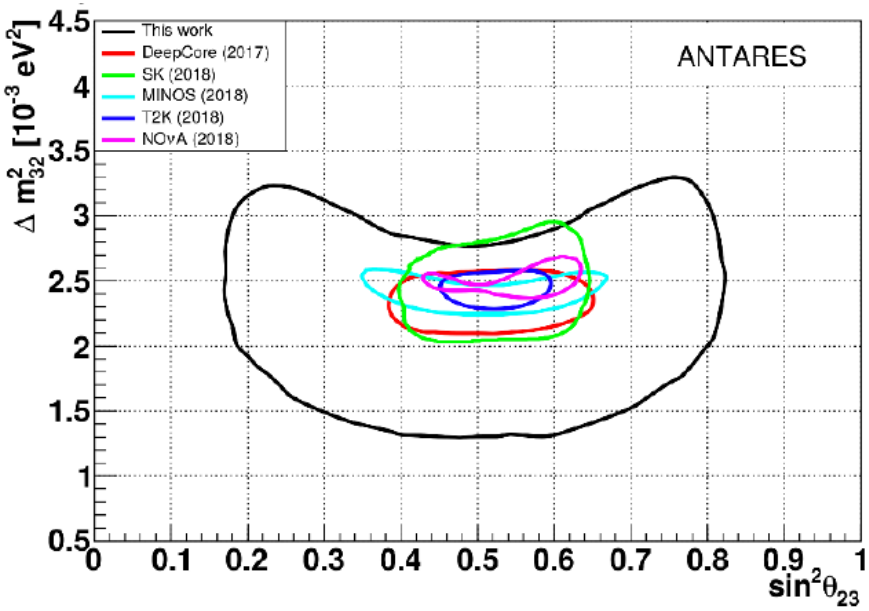
Updated Oscillation Studies

Priors and fitted values obtained from minimisation for all the parameters of the standard oscillation analysis.

📖 J. High Energ. Phys. (2019) 2019: 113

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



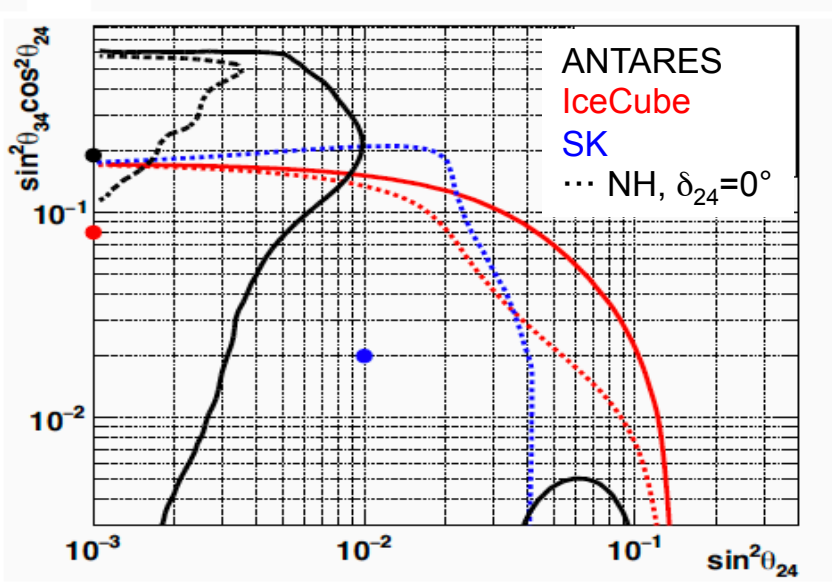


No-oscillation hypothesis excluded at 4.6σ

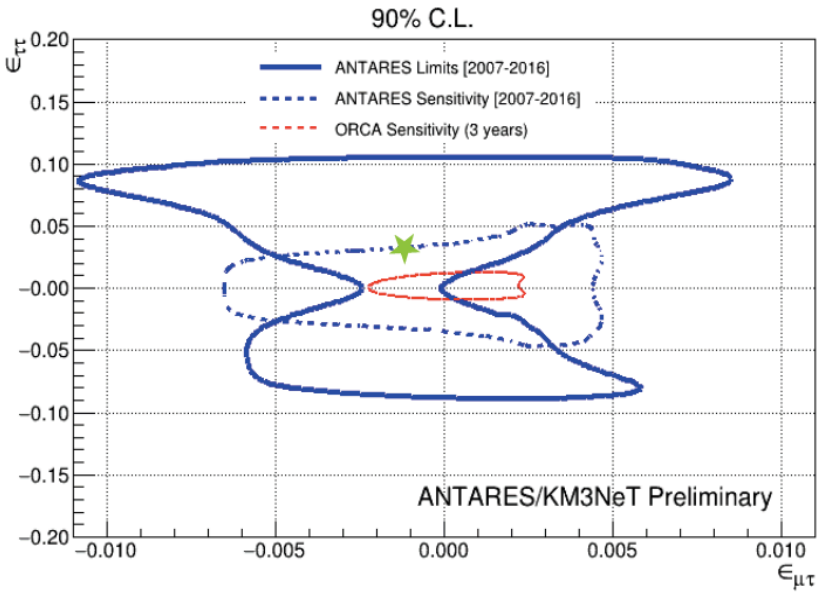
Updated Oscillation Studies Sterile & NSI

- (3+1) sterile neutrino models $\Delta m^2_{41} > 0.5\ eV^2$
- Tight complementary information to eV-scale sterile neutrino searches

Our results (90% CL) exclude regions of the parameter space not yet excluded by other experiments.



- Non-standard interactions signature in neutrino oscillation pattern detectable
- Mild hint for non-standard interactions observed in 10 years of ANTARES data



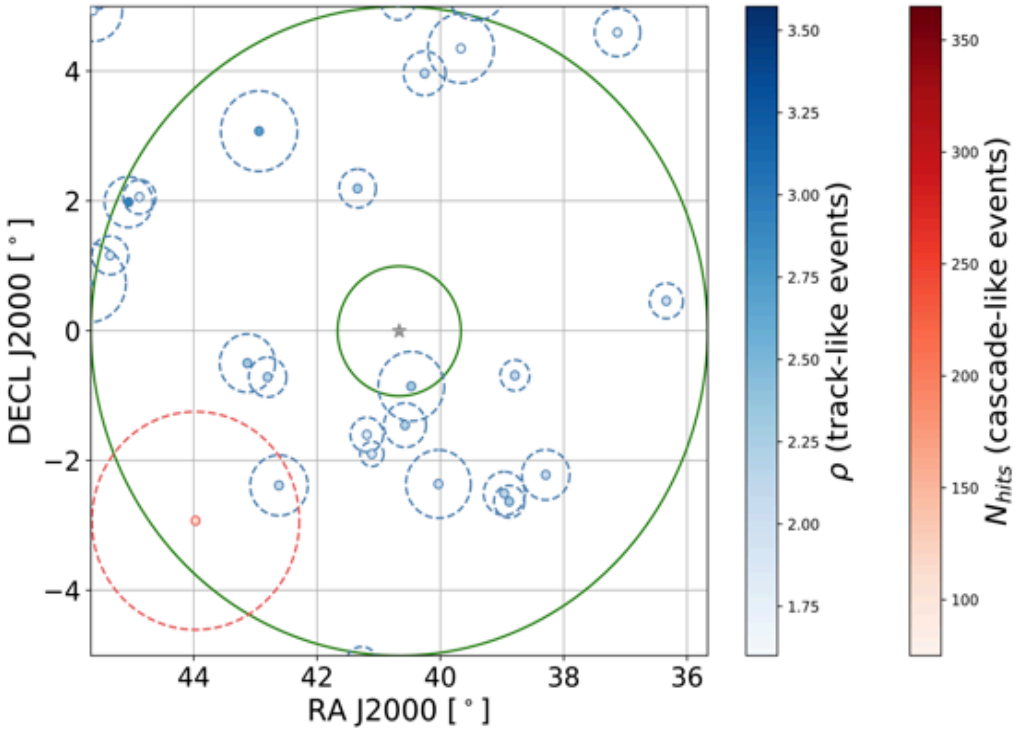
📖 J. High Energ. Phys. (2019) 2019: 113

ANTARES search from M77/NGC 1068

[Published March 22nd, 2019]

The analysis of 10 years of IceCube data (IC40, IC59, IC79, IC86-1, ICII-ICVII) has recently been unblinded, unifying the muon diffuse and point source streams, and presented this week at the XVIII International Workshop on Neutrino Telescopes (Neutel 2019). The results are consistent with background, both for the Northern and Southern hemispheres. A list of 110 targets, motivated by gamma-ray observations, was also unblinded. The hottest source was found to be M77 (RA 40.667°, Dec -0.0069°) some 0.3° away from the all-sky hot spot, with a significance of 2.9σ (post-trial). At a distance of 14 Mpc, M77, also known as NGC 1068, is one of the closest Seyfert galaxies with a supermassive black hole in its core with misaligned jet.

Using data taken between 2007 and 2017, ANTARES has searched for high energy neutrinos in the direction of M77. The results, shown in the figure below, are consistent with background, yielding an upper limit on a possible E^{-2} neutrino spectrum of 8.7×10^{-9} GeV/cm^2/s, with similar values for indices between 1.6 and 2.7.



Distribution of ANTARES events in the (RA, DEC) coordinates around the position of M77. The inner (outer) green line depicts the one (five) degree distance from the position source location, indicated as a gray star. The red point denotes a shower-like event, whereas the blue points indicate track-like events. The dashed circles around the events indicate the angular error estimate. Different shades of red and blue correspond to the values assumed by the energy estimators, the right legend shows the color scales. The number of hits is used for shower-like events and a parameter ρ for track-like events.