Searching for High Energy Astrophysical ν from the depths of Mediterranean Sea

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Astrophysical ν detection
- Why?
- How?
- Where?

The ν, γ, HE C.R. connection
- Multimessenger search for H.E. astrophysical sources

Results from Cherenkov ν Telescopes
From Traditional Astronomy (Optics) to Multi-Wavelength Astronomy:

observations of light in the visible band are complemented by radio, X-ray and γ astronomy

Galileo Galilei showing the Doge of Venice how to use the telescope (1858), fresco by Giuseppe Bertini (1825–1898)

... and to Multi-Messengers Astronomy: HE-CR, photons, neutrinos, GW ...
The Cosmic Rays spectrum

~ 1000 particles/(s·m²)

ionized nuclei:

- 90% protons
- 9% α particles
- heavier nuclei

what is their origin?

- a small solar
- most with E< 10^{15-16} eV originated in the galaxy
- extragalactic E> 10^{17-18} eV

The connection

\[ E^2 \Phi_v = [\text{GeV/m}^2\text{s sr}] \]
The “all particle spectrum”

- Observed elementary particles or nuclei carrying a kinetic energy up to $10^{21}\text{eV}$ (like a tennis ball moving at ~150km/h)
- Many open questions:
  - Where they come from?
  - Which acceleration mechanisms

- UHE astrophysical neutrinos will extend the limits of the "visible" Universe.
- Multi-messenger observations
**Which processes characterize the High Energy sources**

**leptonic process**

Inverse Compton scattering

\[ e^- \rightarrow e', \gamma \]

We have to consider also hadronic processes like:

Ambient matter

\[ p \]

Ambient photons

\[ N, \pi^\pm, \pi^0 \rightarrow \gamma, \nu \]

27/01/21 - Antonio Capone

Virtual seminar on multimessenger astronomy - Technische Universität München
Nucleons propagation and interactions in the Universe: the GZK cut-off

\[ \text{p} + \gamma_{\text{CMBR}} \rightarrow \Delta^+ \rightarrow \text{p} + \pi^0 \]

\[ \rightarrow \gamma \gamma \]

\[ \rightarrow \text{n} + \pi^+ \]

\[ \rightarrow \mu^+ \nu_\mu \]

\[ \rightarrow e^+ \nu_e \bar{\nu}_\mu \]

Assuming for the ‘target photons’ \( E_\gamma = 1.4 \cdot 10^{-3} \text{ eV} \):

\[ s_{\text{out}} = \left( m_p + m_\pi \right)^2 \]

\[ s_{\text{in}} = \left( E_p + E_{\text{CMBR}} \right)^2 - \left( p_\pi + q_{\text{CMBR}} \right)^2 = E_p^2 + E_{\text{CMBR}}^2 + 2 E_p E_{\text{CMBR}} - p_\pi^2 - q_{\text{CMBR}}^2 - 2 |\vec{p}_\pi| \cdot |\vec{q}_{\text{CMBR}}| \cos(\theta) \]

\[ s_{\text{in}} = E_p^2 - p_\pi^2 + 2 E_p E_{\text{CMBR}} - 2 |\vec{p}_\pi| \cdot |\vec{q}_{\text{CMBR}}| \cos(\theta) \approx m_p^2 + 2 E_p E_{\text{CMBR}} (1 - \cos(\theta)) \]

the condition for the production of the \( \Delta^+ \) resonance requires

\[ s_{\text{in}} \geq \left( m_p + m_\pi \right)^2 \]

\[ m_p^2 + 2 E_p E_{\text{CMBR}} (1 - \cos(\theta)) \geq m_p^2 + m_\pi^2 + 2 m_p m_\pi \quad \text{per} \quad \theta = \pi \quad \Rightarrow 1 - \cos(\theta) = 2 \]

\[ E_p \geq \frac{2 m_p m_\pi + m_\pi^2}{4 E_{\text{CMBR}}} = \frac{2 \cdot 938 \cdot 10^6 \cdot 140 \cdot 10^6 + \left(140 \cdot 10^6\right)^2}{4 \cdot 1.4 \cdot 10^{-3}} \approx 5.0 \cdot 10^{19} \text{ eV} = 50 \text{ EeV} \sim 8 \text{ J} \]

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Neutrino fluxes: what do we know/expect?

This is our region of interest.
Neutrino Interactions – what happens

Charged current $\nu_\mu$:

Also charged current $\nu_e \rightarrow e$

and charged current $\nu_\tau \rightarrow \tau$

and neutral current $\nu_\alpha \rightarrow \nu_\alpha$
Neutrino Interactions – what can we “see”

Tracks
(because of $\mu$)

$\nu_\mu$
($\nu_\tau$)

$\mu^-$
($\tau^-$)

$\nu_\alpha$ $\rightarrow$ $\nu_\alpha$

Also charged current $\nu_e$ $\rightarrow$ $e$

and charged current $\nu_\tau$ $\rightarrow$ $\tau$

Cascades

Force carrier

$\rightarrow \mu^- + ...$
A very intense muon flux is coming (downgoing) from the atmosphere ...

Some number to fix the problem ...
- for 1 event by astrophysical $\nu_\mu$
  $\Rightarrow \sim 100$ event by atmospheric $\nu_\mu$
  $\Rightarrow \sim 10^8$ atmospheric muons
Atmospheric muons (down-going): main background

Events with a muon measured in a detector “protected” by > 15km of “water equivalent” are, probably, events where atmospheric neutrinos interact via CC giving a muon.

Deep in a transparent medium

Water or Ice:
- large (and inexpensive) target for ν interaction
- transparent radiators for Cherenkov light;
- large deep: protection against the cosmic-ray muon background
Atmospheric $\mu$’s dominate by many order of magnitude the muons induced by neutrinos.

Upward-going particles are the preferred signature for extraterrestrial neutrino interactions.

Upgoing muons from atmospheric neutrinos represent the irreducible background.
Search for neutrino induced events, mainly \( \nu \mu N \rightarrow \mu X \), deep underwater

- Atmospheric neutrino flux \( \sim E^{-3}_\nu \)
- Neutrino flux from cosmic sources \( \sim E^{-2}_\nu \)
  - Search for neutrinos with \( E_\nu \geq 1 \pm 10 \text{ TeV} \)

- \( \sim \text{TeV} \) muons propagate in water for several km before being stopped
  - go deep to reduce down-going atmospheric \( \mu \) backg.
  - long \( \mu \) tracks allow good angular reconstruction

\[
\text{For } E_\nu \geq 1 \text{ TeV} \quad \theta_{\mu\nu} \approx \frac{0.7^\circ}{\sqrt{E_\nu [\text{TeV}]}}
\]

Neutrinos from cosmic sources induce 1-100 muon evts/y in a km\(^3\) Neutrino Telescope

Up-going \( \mu \) from neutrinos generated in atm. showers \( S/N \sim 10^{-4} \)

Down-going \( \mu \) from atm. showers \( S/N \sim 10^{-4} \) at 3500m w.e. depth

\( \mu \) direction reconstructed from the arrival time of Cherenkov photons on the Optical Modules: needed good measurement of PMT hits, \( \sigma(t) \sim 1 \text{ ns} \), and good knowledge of PMT positions: \( \sigma \sim 10 \text{ cm} \)

Charge current interactions

Cherenkov Neutrino Telescope

Picture from ANTARES

Neutrino Telescope

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Light propagation in water

In a transparent medium the light propagation is limited by absorption (the photon disappears)

$$I(x) = I_o e^{-ax}$$

$$L_a = 1/a$$

by diffusion (the photon changes direction),

$$I(x) = I_o e^{-bx}$$

$$L_b = 1/b$$

by attenuation

$$c = a+b$$

$$I(x) = I_o e^{-cx}$$

$$L_c = 1/c$$

PMT quantum efficiency

Pure water

Sea water

$L_{abs}(440\text{nm}) \sim 70m$

$L_{att}(440\text{nm}) \sim 55m$
Light propagation in South Polar ice

Measurements:
► in-situ light sources
► atmospheric muons

Average optical ice parameters:
\[ \lambda_{\text{abs}} \approx 110 \text{ m } @ 400 \text{ nm} \]
\[ \lambda_{\text{sca}} \approx 20 \text{ m } @ 400 \text{ nm} \]
\[ \lambda_{\text{att}} \approx 27 \text{ m } @ 400 \text{ nm} \]
**A 3-D cosmic-ray detector:**

Two different kinds of events

Closely related scientifically:

- Cosmic rays after propagation
- Neutrinos from cosmic ray sources

- $\nu_e : \nu_\mu : \nu_\tau = 1:2:0 \rightarrow 1:1:1$

Neutrinos from all directions

- $\nu_\mu$-induced $\mu$ (from below)
- All flavors starting inside detector
ANTARES: Astronomy with Neutrino Telescope and Abyss enviromn. RESearch

The Largest Neutrino Detector in the Northern Hemisphere

Total Instrum. Volume ~ 10^{-2} km^3

- String-based detector
- Downward-looking PMTs
- axis at 45º to vertical

- 12 detection lines
- 25 storeys / line
- 3 PMTs / storey
- ~900 PMTs

MULTIDISCIPLINARITY → associated sciences
(oceanography, marine biology, geology ...)

Nucl. Instr. and Meth. A 656 (2011) 11-38
In the event display:
radius ~ number of photons
time ~ red → purple

In IceCube Detector

muon track
cascade
A cosmic neutrino interacts in IceCube detector

The color code indicate the hit-time:
- red = early time
- blue = late time

> 300 optical sensors; > 100,000 photons; 2 nsec time resolution
Example of a *reconstructed up-going muon* (i.e. a neutrino candidate)
Neutrino Telescope physics’s goal - 1

Search for point-like cosmic Neutrino Sources

- Their identification requires a detector with accurate angular reconstruction
  \( \sigma(\theta) \leq 0.5^\circ \) for \( E_\nu \geq 1\,\text{TeV} \)

Experimental signal: statistical evidence of an excess of events coming from the same direction
Search for Diffuse flux of Cosmic Neutrinos

- Neutrinos from:
  - Unresolved AGN, GRBs, …
  - "Z-bursts"
  - "GZK like" proton-CMB interactions
- Top-Down models ν

Their identification out of the more intense background of atmospheric neutrinos (and μ) is possible at very high energies (E_μ >> TeV) and requires good energy reconstruction.

M. Ahlers, F. Halzen, Progress of Theoretical and Experimental Physics, 2017, 12A105
Neutrino Telescopes in a multi-messenger framework

- Search for Coincident events, in a restricted time and direction windows, with EM/γ/GW counterparts (flaring sources, transient events, ...)
  - Relaxed energy/direction measurement
  - Transient/ multi-messenger information
  - Observing γ, ν, CR, GW, ... from the same source (or cosmic region):
    - propagation models
    - acceleration mechanisms
    - protons or electrons accelerated?

Steady source: data sample collected along large time interval, events integrated over observation period

Flaring source: all Signal events collected, background integrated only during flaring time.

\[ \begin{align*}
B_{\text{tot}} &= 30 \text{ events} \\
S_{\text{tot}} &= 5 \text{ events} \\
T_{\text{tot}} &= 1 \text{ year} \\
B_{\text{flare}} &= 2 \text{ events} \\
S_{\text{flare}} &= 2 \text{ events}
\end{align*} \]
Multi-wavelength observation: Mrk421
an example

The role of multimessenger:
• $\gamma$-ray observations alone in most cases inconclusive.
• Only $\nu$ may tell us if there are accelerated hadrons

Extensive multi-wavelength measurements showing the spectral energy distribution (SED) of Markarian 421 from observations made in 2009. The dashed line is a fit of the data with a leptonic model. Abdo et al. ApJ 736(2011) 131 for the references to the data
2013 - The great IceCube discovery

2-year analysis: Science 342, 1242856 (2013)
Three > PeV events seen in three years, including a 2-PeV neutrino
IceCube 2017 - High Energy Starting Event Analysis

starting events: 6 years $\rightarrow 8\sigma$
IceCube: diffuse $\nu_\mu$ flux with up-going muons

after 7 years $\rightarrow$ 6.4 sigma

Best-fit astrophysical normalization:

$$0.97^{+0.27}_{-0.25} \times 10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

Best-fit spectral index:

$$\gamma_{\text{astr}} = 2.16 \pm 0.11$$

Energy ranges:

$$240 \text{ TeV} - 10 \text{ PeV}$$

Atmospheric-only hypothesis excluded by 6.0$\sigma$
High Energy Staring events (showers) and up-going muons analyses give consistent results?
Where these neutrinos are coming from??

No indications of a strong anisotropy from extended emission regions which could indicate a contribution from Galactic sources along the Galactic plane. A subdominant Galactic component cannot be excluded. Hypothesis: H.E. $\nu$ diffuse flux from extragalactic sources.

ANTARES can help to understand the origin of this HE diffuse $\nu$ flux???
Latest ANTARES results on the search for diffuse ν flux

Tracks
Data: 2007-2015 (2451 live-days)
Above $E_{\text{cut}}$: Bkg: 13.5 ± 3 evts, IC-like signal: 3 evts
Observed: 19 evts

Cascades
Data: 2007-2013 (1405 live-days)
Above $E_{\text{cut}}$: Bkg: 10.5 ± 4 evts, IC-like signal: 1.5 evts
Observed: 14 evts

The best fit for a single power-law cosmic neutrino spectrum, in terms of per-flavor flux at 100 TeV, is

$$\phi^1_0 (100 \text{ TeV}) = (1.7 \pm 1.0) \times 10^{-18} \text{ GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$$

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

ANTARES
combined upper limits and sensitivities for 9 years data sample (2007-2015) tracks + cascades

The Astrophysical Journal Letters, 853:L7, 2018
Search for neutrinos from the Galactic ridge - 1

- $\nu$'s and $\gamma$-rays produced by CR propagation
  
  $p_{CR} + p_{ISM} \rightarrow \pi^0 \pi^\pm \ldots$
  
  $\pi^0 \rightarrow \gamma \gamma (EM \ cascade)$
  
  $\pi^\pm \rightarrow \nu_\mu, \nu_e \ldots$

- Search for $\nu_\mu$, data 2007-2013
- Search region $|l| < 30^\circ$, $|b| < 4^\circ$
- Cuts optimized for neutrino energy spectrum
  
  $\sim E^{-\gamma}$ ($\gamma = 2.4 - 2.5$)
- Counts in the signal/off zones
- No excess in the HE neutrinos
- 90% C.L. upper limits: $3 < E_\nu < 300$ TeV

Distribution of the reconstructed $E_\mu$ of up-going muons in the Galactic Plane (black crosses) and average of the off-zone regions (red histogram).
Search for neutrinos from the Galactic plane - 2

New analysis on tracks and showers, based on Maximum Likelihood analysis

\[ L_{\text{sig+bkg}} = \prod_{\tau \in \{\text{tr, sh}\}} \prod_{i \in \tau} \left[ \mu_{\text{sig}} \cdot \text{pdf}_{\text{sig}}(E_i, \alpha_i, \delta_i) + \mu_{\text{bkg}} \cdot \text{pdf}_{\text{bkg}}(E_i, \alpha_i, \delta_i) \right] \]

\[ |l| < 40^\circ |b| < 3^\circ \]

Fermi-LAT $\gamma$

KRA$_\gamma$ new model to describe the C.R. transport in our galaxy. It agrees with C.R. measurements (KASCADE, Pamela, AMS, Fermi-LAT, HESS).

FERMI-LAT diffuse $\gamma$ flux from along the galactic plane ($\pi^0 \to \gamma\gamma$) well explained above few GeV.

KRA$_\gamma$ allows to predict the $\nu$ flux by $\pi^\pm$ decays induced by galactic CR interactions

KRA$_\gamma$, assuming a neutrino flux $\propto E^{-2.5}$ and a CR spectrum with 50 PeV cut-off can explain ~20% of the IceCube observed HESE.

ANTARES, with an good visibility of the Galactic Plane well suited to observe these fluxes or to put competitive limits: no signal found $\rightarrow$ set 90%C.L. upper limits.
Neutrinos from “FERMI Bubbles” ??
Search from a Mediterranean Cherenkov ν Telescope

• FERMI detected hard γ emission (E^{-2}) up to 100 GeV in extended “bubbles” around Galactic Center, hard spectrum not compatible with Inverse Compton mechanism, M.Su et al., Ap.J.724 (2010).

• Models involving hadronic processes (e.g. Crocker & Aharonian, PRL 2011) predict significant neutrino fluxes.

• Estimates for the neutrino flux: \( \Phi_{\nu} \approx 0.4 \cdot \Phi_\gamma \Rightarrow E_{\nu}^2 \frac{dN_{\mu+\bar{\nu}_\mu}}{dE_{\nu}} \approx 1.2 \div 2.4 \cdot 10^{-7} \text{GeV cm}^{-1} \text{s}^{-1} \text{sr}^{-1} = A_{\text{theory}} \)

• An exponential energy cut-off could affect the flux

\[
E_{\nu}^2 \frac{dN_{\mu+\bar{\nu}_\mu}}{dE_{\nu}} = A_{\text{theory}} e^{-\frac{E}{E_{\nu}^{\text{cutoff}}}}
\]

• ANTARES, the present Mediterranean ν Telescope, searched for these neutrinos.
Search for a diffuse flux of $\nu_\mu$ from “FERMI Bubbles”

Compare the neutrino-like events coming from 3 "off-zones" (with the same size and shape as the Fermi Bubbles "on-zone") with the events coming from the Fermi Bubbles.

Events selected as up-going and well reconstructed tracks.

Data sample, in the period 2008-2011, includes 806 days.

In the 3 off-zones observed:

- $n_{\text{bkg}} = 9, 12$ and $12$ events

In the Fermi-Bubble region

- $n_{\text{obs}} = 16$ events (1.2$\sigma$ excess)

No statistically consistent signal observed.

Assuming no cut-off

$E^2\Phi(E)_{90\%\text{C.L.}} = 5.7\times10^{-7}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$

Assuming 500 TeV cut-off

$E^2\Phi(E)_{90\%\text{C.L.}} = 8.7\times10^{-7}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$
It's mandatory now !!!!

• To search for neutrino point like sources:
  • Large size detector required (very small fluxes expected) (KM3NeT, IceCube phase2)
  • Very good accuracy in angular reconstruction (high background, the irreducible atmospheric background has to be subtracted statistically)
  • Multimessenger analysis
The ANTARES search for point-like $\nu$ sources based on two kind of events

- Tracks: CC $\nu_\mu$ or $\nu_\tau \rightarrow \mu$
- Interaction can occur far from the detector providing a large Effective Volume
- Angular resol. $< 0.4^\circ$ for $E_\nu > 10$ TeV
- Energy resol. $\sim$ factor 3

- Electronic or hadronic showers: NC and CC $\nu_e$ or $\nu_\tau \rightarrow$ showers
- Events contained in the detector: smaller Effective Volume,
- Energy resolution $\sim 5$-10%
- Median angular resolution $\sim 3^\circ$
ANTARES Search for point-like cosmic \( \nu \) Sources

9 years of ANTARES data searching for all neutrino flavours: 7629 “tracks” + 180 “shower” events passed the selection criteria

\[
\log L_{\text{sig+bkg}} = \sum_{S=\text{tr.,sh.}} \sum_{\tau=S} \log \left[ \mu_{\text{sig}}^\tau \cdot F_{\text{sig}}^\tau(\delta) \cdot P_{\text{sig},i}^\tau(E_i) + N^\tau \cdot B^\tau_i \cdot P_{\text{bkg},i}^\tau(E_i) \right] - \mu_{\text{sig}}
\]

so far …. no significant excess has been found
**ANTARES results: “full sky search” of ν sources**

The visible sky of ANTARES divided on a $1^0 \times 1^0$ (r.a x decl.) boxes. Maximum Likelihood analysis searching for clusters

ANTARES arXiv:1706.01857v1, 6 June 2017

In the full sky search, the whole visible sky of ANTARES is divided on a grid with boxes of $1^\circ \times 1^\circ$ in right ascension and declination for the evaluation of the $Q$-value defined in Equation (2). This value is maximised in each box by letting the location of the fitted cluster free between the $1^\circ \times 1^\circ$ boundaries. Since an unbinned search is performed, events outside the grid boxes are indeed considered in each $Q$-value maximisation. The pre-trial p-value of each cluster is calculated by comparing the $Q$-value obtained at the location of the fitted cluster with the background-only $Q$ obtained from simulations at the corresponding declination. Figure 7 shows the position of the cluster and the pre-trial p-values for all the directions in the ANTARES visible sky. The most significant cluster of this search is found at a declination of $\delta = 23.5^\circ$ and a right-ascension of $\alpha = 343.8^\circ$ and with a pre-trial p-value of $3.84 \times 10^{-6}$. To account for trial factors, this pre-trial p-value is compared to the distribution of the smallest p-values found anywhere in the sky when performing the same analysis on many pseudo-data sets. It is found that 5.9% of pseudo-experiments have a smaller p-value than the one found in the final sample, corresponding to a post-trial significance of $1.9\sigma$ (two-sided convention). The upper limit on the neutrino flux coming from this sky location is $E^2 \frac{d\Phi}{dE} = 3.8 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$.
ANTARES results: “full sky search” of ν sources

90% U.L.

9 years of ANTARES data:
7629 “tracks” + 180 “shower”
Joint IceCube + ANTARES search for $\nu$ sources

Skymap of pre-trial p-values for the combined ANTARES (9 years) and IceCube 97 years) point-like sources analysis.

The red circle indicates the location of the most significant cluster: (0.9σ post-trial significance)

The Astrophysical Journal, 892:92 (12pp), 2020 April 1
Joint IceCube + ANTARES search for $\nu$ sources

Skymap of pre-trial p-values for the combined ANTARES (9 years) and IceCube 97 years point-like sources analysis.

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

upper limits at 90% C.L. on the one-flavor neutrino flux

The Multi-Messenger Search Programme with ANTARES

- Neutrinos trigger others
- Others trigger neutrinos

Flaring Sources
($\nu$ emission from $\gamma$-flaring blazars/$\mu$Quasars)

- ANTARES
- Gamma-Rays
- X-Rays

- ANTARES
- VIRGO
- LIGO

common working group (GWHEN)
S. Adrián-Martínez et al.,
JCAP 06 (2013) 008

- ANTARES
- AUGER

Adrian-Martínez et al.,

- TAToO
(Telescopes – ANTARES Target of Opportunity)

Optical follow-up of neutrino alerts for transient source search (GRBs, SNae).
Analysis in progress!

- Optimal Telescopes
- TAROT & ROSTE + more

Ageron et al., Astrop.Phys 35 (2012) 530-536

- Flaring Sources

- ANTARES

- GCN (Gamma-ray Coordination Network)

A&A 559, A9 (2013),
JCAP 1303 (2013) 006

- Blazars:
  APP 36 (2012) 304;
- $\mu$Quasars:
  JHEAp, 3-4 (2014) 9-7
Triggering on Neutrino Telescopes site

IceCube 170922 very High Energy Event: Trigger sent to other astrophysical experiments
Triggering on Neutrino Telescopes site

**IceCube Trigger**

43 seconds after trigger, GCN notice was sent

```
---
TITLE: GCN/AMON NOTICE
NOTICE_DATE: Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE: AMON ICECUBE EHE
RUN_NUM: 130033
EVENT_NUM: 50579430
SRC_RA: 77.2853d {+05h 09m 08s} (J2000), 77.5221d {+05h 10m 05s} (current), 76.6176d {+05h 06m 28s} (1950)
SRC_DEC: +5.7517d {+05d 45' 06"} (J2000), +5.7732d {+05d 46' 24"} (current), +5.6888d {+05d 41' 20"} (1950)
SRC_ERROR: 14.99 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE: 18018 TJD; 265 DOY; 17/09/22 (yy/mm/dd)
DISCOVERY_TIME: 75270 SOD {20:54:30.43} UT
REVISION: 0
N_EVENTS: 1 [number of neutrinos]
STREAM: 2
DELTA_T: 0.0000 [sec]
SIGMA_T: 0.0000e+00 [dn]
ENERGY: 1.1998e+02 [TeV]
SIGNALNESS: 5.6507e-01 [dn]
CHARGE: 5784.9552 [pe]
---
```
Triggering on Neutrino Telescopes site

Follow-up detections of IC170922 based on public telegrams

IceCube  
September 22

Swift  
September 26

Fermi, ASAS-SN  
September 28

SALT, Kapteyn  
October 7

MAGIC  
October 4

Liverpool, AGILE  
September 29

Kanata, NuSTAR  
October 12

VLA  
October 17

Subaru  
October 25
IceCube 170922

Fermi detects a flaring blazar within 0.06°

MAGIC detects emission of > 100 GeV gammas
multiwavelength campaign launched by IC 170922

IceCube, Fermi—LAT, MAGIC, Agile, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, KISO, Liverpool, Subaru, Swift, VLA, VERITAS

- neutrino: time 22.09.17, 20:54:31 UTC
  energy 290 TeV
  direction RA 77.43° Dec 5.72°

- Fermi-LAT: flaring blazar within 0.06° (7x steady flux)

- MAGIC: TeV source in follow-up observations

- follow-up by 12 more telescopes

→ IceCube archival data (without look-elsewhere effect)

→ Fermi-LAT archival data
search in archival IceCube data:

- 150 day flare in December 2014 of 19 events (bkg <6)
- $10^{-5}$ bkg. probability
- spectrum $E^{-2.1}$
From sources of GRBs

GRBs are the brightest gamma ray sources in the Universe lasting from a few milliseconds to several minutes. With a total luminosity, under the hypothesis of isotropic emission, of about $L_{\text{GRB}} = 10^{51}$ erg/s, these sources are four orders of magnitude brighter than Active Galactic Nuclei, the most luminous steady sources in the sky, with luminosity ranging from:

$L_{\text{AGN}} = 10^{44}$ erg/s to $L_{\text{AGN}} = 10^{47}$ erg/s.

Map of observed GRB in galactic coordinates: the plane of the Milky Way galaxy is along the horizontal line at the middle of the figure. The burst locations are color-coded based on the fluence, which is the energy flux of the burst integrated over the total duration of the event.

Schematic view of the GRB fireball model. The three phases of the GRB development are displayed together with characteristic times and dimensions.
A Multi-Messenger Search for $\nu$ from GRBs

GCN Gamma-ray Coordination Network) alerts trigger the recording of all the low level triggers.

Data taking triggered by a satellite (FERMI; SWIFT, INTEGRAL)

A continuous buffer ensures the availability of the data before the alert

All data written to disk

Specific data filtering and reconstruction by searching for an excess of events in the GRB direction (offline)
GRBs: intense flashes of high-energy electromagnetic radiation observed isotropically in the sky. If hadrons are accelerated in GRBs, following the $p\gamma$ interactions both $\nu$ and $\gamma$ are expected.

Search for neutrinos in coincidence with GRBs occurred in the period 2007-2017.

784 long GRBs ($T_{90}>2$ s) selected out of FERMI/SWIFT catalogues, below ANTARES horizon at the trigger time. NeuCosmA software used to evaluate individual $\nu$ fluxes.

Total $\nu$ fluence from GRBs stacking and the contribution to the diffuse $\nu$ flux evaluated.

No neutrino events are found in spatial and temporal coincidence with the GRB sample.

GRBs are not the main contributors to the observed IceCube diffuse $\nu$ flux below $E_\nu \sim 1$ PeV.
Summary

• ANTARES studied the **Southern sky** with $\nu_{\mu}$ competitive sensitivities and excellent angular resolution for both *tracks* and *cascades*
  - Upper limits on known GeV-TeV $\gamma$-ray sources $<10^{-8}$ GeV/(cm$^2$ s)
  - Sensitivity for a diffuse flux close to the level of the IC signal

• Detailed study of **extended** regions (Galactic plane, Fermi Bubbles)
  - no $\nu_{\mu}$ excess from the Galactic ridge/IC hot spot

• A large **multi-messenger** effort
  - EM radiation: radio (MWA), optical, X-ray, $\gamma$-rays (LAT, IACTs)
  - Gravitational Wave observatories and IceCube

• ANTARES contribute to the indirect searches for **Dark Matter**
  - Most competitive limits for spin-dependent cross-section
  - Competitive $<\sigma v>$ limits from the Galactic centre

• **KM3NeT-Arca** Neutrino Telescope under construction will soon be able to observe the neutrino sky with unprecedented sensitivities.