Observations of HE Neutrino and Multimessenger AstroParticle Physics

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Talk outline

- High Energy Astrophysical Neutrino Detection in a multi-messenger scenario
  - Complementarity
  - Unicity

- H.E. astrophysical neutrino detectors: Baikal, IceCube, ANTARES/KM3NeT... and also Pierre Auger Observatory

- Neutrino Telescopes main physics goal: search for astrophysical neutrinos
  - Search for a diffuse flux
  - Search for point-like sources
  - Indirect D.M. searches, ν oscillations and properties, searches for monopoles/nuclearites

- Search for transient sources and multi-messenger studies
  - Search for neutrinos from GRB sources, flaring sources, GW sources

- Conclusions & Summary

:? in a multi-messenger scenario
:? not discussed in this talk
:? not discussed in this talk
Neutrino fluxes: what do we know/expect?

This is our region of interest.
Cherenkov $\nu$ Telescope: Detection principle

Search for neutrino induced events, mainly $\nu_\mu N \rightarrow \mu X$, deep underwater

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

Down-going $\mu$ from atm. showers $S/N \sim 10^{-6}$ at 3500m w.e. depth

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

Atmospheric neutrino flux $\sim E_\nu^{-3}$
Neutrino flux from cosmic sources $\sim E_\nu^{-2}$

- Search for neutrinos with $E_\nu > 1\div10$ TeV

$\sim$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

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

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

Picture from ANTARES

Neutrino Telescope

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

IceTop

IceCube

South Pole
2835 m.a.s.l.

Cosmic ray showers from above

~5μs

Atmospheric muons
ANTARES: Astronomy with Neutrino Telescope and Abyss environm. RESearch

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

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

• 25 storeys
• 350 m

• 100 m
• ~70 m

• 14.5 m

The Largest Neutrino Detector in the Northern Hemisphere

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

MULTISDISCIPLINARITY ➔ associated sciences (oceanography, marine biology, geology ...)

~2500 m depth

40 km to shore

Junction Box

Nucl. Instr. and Meth. A 656 (2011) 11-38

AANTARESS:: AAsstroonomy wwiitth Neutrriino Teelllescoope aanndd Abyss eenviroonnemnt. RREESSearch
The SD is spread over a surface of $\sim 3000$ km$^2$ at an altitude of $\sim 1400$ m above sea level.

This corresponds to an average vertical atmospheric depth above ground of $X_{\text{ground}} = 880$ g cm$^{-2}$.

The slant depth $D$ is the total grammage traversed by a shower measured from ground in the direction of the incoming primary particle. In the flat-Earth approximation $D = (X_{\text{ground}} - X_{\text{int}})/\cos\theta$, where $X_{\text{int}}$ is the interaction depth and $\theta$ the zenith angle.

The Pierre Auger Observatory can identify UHE neutrinos.
Neutrino Telescope physics’s goals:
search for point-like cosmic Neutrino Sources

- Galactic
  - Pulsar Wind Nebulae
  - Supernova Remnants
  - Microquasars
- Extragalactic
  - RX J1713.7-3946
  - Active Galactic Nuclei

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

Experimental signal: statistical evidence of an excess of events coming from the same direction

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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

The most significant cluster: decl. $\delta = 23.5^0$, r.a. $\alpha = 343.8^0$ has a pre-trial p-value of $3.84 \times 10^{-6}$

$\Rightarrow$ U. L. from this sky location $E^2 \frac{d\Phi}{dE} = 3.8 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$
Neutrino Telescope physic’s goals:

search for Diffuse flux of Cosmic Neutrinos

- Neutrinos from:
  - Unresolved AGN
  - "Z-bursts"
  - "GZK like" proton-CMB interactions

- Top-Down models Neutrinos

- Their identification out of the more intense background of atmospheric neutrinos (and $\mu$) is possible at very high energies ($E_{\mu} >>$ TeV) and requires good energy reconstruction.
The great discovery (from IceCube 2013)
starting events: now 6 years $\rightarrow 8\sigma$
IceCube today: diffuse $\nu_\mu$ flux with up-going muons

after 7 years $\Rightarrow$ 6.4 sigma

Best-fit astrophysical normalization:

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

Best-fit spectral index:

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

Energy ranges:

240 TeV - 10 PeV

Atmospheric-only hypothesis excluded by 6.0σ
High Energy Staring events (showers) and up-going muons analyses give consistent results

IceCube 2017

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Latest ANTARES results on the search for diffuse $\nu$ 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: 5 ± 2 evts, IC-like signal: 1.5 evts
Observed: 7 evts

ANTARES combined upper limits and sensitivities for 9 years data sample (2007-2015) tracks + cascades
A diffuse flux from extragalactic sources
A subdominant Galactic component cannot be excluded
- search for $\nu$ from point-like sources:
  - hadronic
    \[ p_{CR} + p_{ISM} \rightarrow \pi^0 \pi^\pm \ldots \]
    \[ \pi^0 \rightarrow \gamma \gamma (EM \text{ cascade}) \]
    \[ \pi^\pm \rightarrow \nu_\mu, \nu_e \ldots \]
  - or leptonic? (no $\nu$ expected)
- search for "diffuse neutrino fluxes". Is their origin related to:
  - H.E. C.R. propagation? What is the effect of the Galactic Ridge on their production?
  - diffuse galactic $\gamma$ background?
- search for a connection
  - H.E. $\nu$ (IceCube, ANTARES) - diffuse $\gamma$ fluxes (FERMI)
  - H.E. $\nu$ (IceCube, ANTARES) - U.H.E. C.R. (AUGER and T.A.)
Search for neutrinos from the Galactic ridge - 1

• ν’s and γ-rays produced by CR propagation
  \[ p_{CR} + p_{ISM} \rightarrow \pi^0\pi^\pm \ldots \]
  \[ \pi^0 \rightarrow \gamma\gamma(EM\ cascade) \]
  \[ \pi^\pm \rightarrow \nu_\mu, \nu_e \ldots \]

ANTARES has good visibility of the Galactic Center, can put limits on the flux of ν from the Galactic Ridge

• ANTARES search for ν_μ, data 2007-2013
• Search region |ℓ|<30°, |b|<4°
• 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_ν<300 TeV

Distribution of the reconstructed E_µ of up-going muons in the Galactic Plane (black crosses) and average of the off-zone regions (red histogram).
Assuming a direct connection between the emission of γ-rays and ν from pion decay in hadronic mechanisms, the diffuse γ- flux measured by Fermi-LAT is used to estimate the flux of Galactic neutrinos.

Expected backg. from off-zone= 3.7 events
Observed ν in the on-zone: = 2 events

ANTARES upper limit on the neutrino flux integrated over the solid angle ΔΩ = 0.145 sr corresponding to the Galactic Plane region |ℓ| < 40°, |b|<3°.

This results excludes that in the IC 3 years HESE sample (37 events) more than 3 events are originates from the Cosmic Ray interactions in the Galactic Ridge.
Search for neutrinos from the Galactic plane - 3

ANTARES 9 years data analysis on tracks and showers, based on Max. Lik. signal-backg. separation

\[
\mathcal{L}_{\text{sig+bkg}} = \prod_{r \in \{\text{tr,sh}\}} \prod_{i \in \mathcal{R}} [\mu_{\text{sig}} \cdot \text{pdf}_{\text{sig}}(E_i, \alpha_i, \delta_i) + \mu_{\text{bkg}} \cdot \text{pdf}_{\text{bkg}}(E_i, \alpha_i, \delta_i)]
\]

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 \((\pi^0 \rightarrow \gamma\gamma)\) 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, allows that no more than \(\sim 19\%\) of the IceCube observed HESE can be originated in the Galactic Plane. 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.

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Diffuse galactic fluxes: $\gamma, \nu$ (at least part galactic), CR

todo list:
- Identifying the sources of neutrinos and thereby also of CR
- Connect to extra-gal. CR
Neutrino Telescope physics's goal: search for point-like sources in a multi-messenger framework

Search for Coincident event in a restricted time/direction windows with EM/\gamma/radio/GW counterparts (flaring sources, transient events, ...)

- searches for cluster of events in known positions of the sky
- if transient sources: background integrated only over a short time period, improving the S/B ratio and the detector sensibility

Relaxed energy/direction selection: improved efficiency
a multi-messenger program

A long list of activities:

Real-time (follow-up of the selected neutrino events):

- optical telescopes [TAROT, ROTSE, ZADKO, MASTER]
- X-ray telescope [Swift/XRT]
- GeV-TeV γ-ray telescopes [HESS, HAWC]
- radio telescope [MWA]
- Online search of fast transient sources [GCN, Parkes]

Multi-messenger correlation with:

- Gravitational wave [Virgo/Ligo]
- UHE events [Auger]

Time-dependent searches:

- GRB [Swift, Fermi, IPN]
- Micro-quasar and X-ray binaries [Fermi/LAT, Swift, RXTE]
- Gamma-ray binaries [Fermi/LAT, IACT]
- Blazars [Fermi/LAT, IACT, TANAMI…]
- Crab [Fermi/LAT]
- Supernovae Ib,c [Optical telescopes]
- Fast radio burst [radio telescopes]
Search for $\nu$ from flaring AGN – 2008-2012

[40 sources, 86 flaring periods] [ANTARES ↔ FERMI/LAT]

...to be extended to IACT blazars (HESS, MAGIC, VERITAS)

4 specially significant flares

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta T$</th>
<th>$\Lambda_{opt}$</th>
<th>$N_{3\sigma}$</th>
<th>$N_{fit}$</th>
<th>Lag</th>
<th>P-value</th>
<th>Post-trial</th>
<th>Spectrum</th>
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<tr>
<td>3C279</td>
<td>279 d</td>
<td>-5.3</td>
<td>2.5</td>
<td>0.8</td>
<td>-4 d</td>
<td>0.033</td>
<td>0.67</td>
<td>$E^{-2}$</td>
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<td>PKS1124-186</td>
<td>73 d</td>
<td>-5.4</td>
<td>3.1</td>
<td>0.7</td>
<td>+4 d</td>
<td>0.059</td>
<td>0.94</td>
<td>$E^{-2} \exp(-E/1\text{TeV})$</td>
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<tr>
<td>PKS0235-618</td>
<td>25 d</td>
<td>-5.7</td>
<td>1.5</td>
<td>0.6</td>
<td>-4 d</td>
<td>0.045</td>
<td>0.91</td>
<td>$E^{-2} \exp(-E/10\text{TeV})$</td>
</tr>
<tr>
<td>PKS0447-439</td>
<td>10 d</td>
<td>-5.4</td>
<td>0.75</td>
<td>0.1</td>
<td>+5 d</td>
<td>0.10</td>
<td>0.55</td>
<td>$E^{-2} \exp(-E/1\text{TeV})$</td>
</tr>
</tbody>
</table>

JCAP12(2015)014
μ-Quasars = Galactic X-ray binary systems with relativistic jets

Several models indicate μ-Quasars as possible sources of HEνs, with flux expectations depending on the baryonic content of the jets.

The detection of HEνs from μ-Quasars would give important clues about the jet composition.

ANTARES and ν from μ-Quasars

ANTARES data set: 2007-2010 → 6 sources selected, with requisites:
  - in the ANTARES visible sky;
  - showing an outburst in the period 2007-2010.

Time-Dependent Analysis: for each source, the data analysis has been restricted to the flaring time periods, selected in a multi-wavelength approach (X-rays/γ-rays) and with a dedicated outburst selection algorithm (+ additional criteria, customized for the features of each μQ).
ANTARES and $\nu$ from $\mu$-Quasars

**METHOD**
- unbinned search
- likelihood ratio test statistic
- quality cuts optimized for $5\sigma$ discovery

**RESULTS**
- no statistically significant excess above the expected atmospheric bkg

90% C.L. upper limits on the flux normalization $\phi$

...assuming a neutrino spectrum following:
- a power-law
- a power-law with expo. cut-off

$\Phi = \phi \cdot E_\nu^{-2} \exp \left( -\frac{E_\nu}{\sqrt{100 \text{TeV}}} \right)$


[systematic uncertainties included]

$\eta_p/\eta_e$ = ratio of proton to electron luminosity in the jet
Search for neutrino-like tracks coming in time coincidence with an observed GRB.

The knowledge of the time and the source position:
- reduces the background
- improves the sensitivity

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

GCN alerts trigger the recording of all the low level triggers. 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)
The search was performed for 4 bright GRBs: GRB080916C, GRB 110918A, GRB 130427A and GRB 130505A) observed between 2008 and 2013.

The expected neutrino fluxes evaluated in the framework of:
- the fireball model have with the internal shock scenario ($E_\nu \geq 100\text{TeV}$)
- the photospheric scenario ($E_\nu < 10\text{TeV}$)

No events have been found: 90% C.L. upper limits to the neutrino fluence.
ANTARES Multi-messenger program
ν associated with GeV-TeV γ-ray flaring blazars and X-ray binaries

- Search for ν’s (2008-2012) correlated with high activity state
- Blazars monitored by FERMI-LAT and IACTs (JCAP 1512 (2015), 014)
- 33 X-ray binaries during flares observed by Swift-BAT, RXTE-ASM and MAXI. Transition states from telegram alerts
- No significant excess (best post-trial 72% for GX 1+4), then → Upper limits on ν fluence and model parameters constrain

X-ray binary 4U 1705-440

NEUTRINO TIME-PDF

2009 2010 2011 2012 2013
Modified Julian Date
54800 55000 55200 55400 55600 55800 56000 56200

Swift/BAT (15 keV < E < 50 keV)

RXTE/ASM (2 keV < E < 10 keV)

MAXI (2 keV < E < 20 keV)

Neutrino Time-PDF
ANTARES Multi-messenger program ν associated to a source of Fast Radio Burst (FRB 150215)

- FRB 150215 observed by Parkes radio telescope (15/02/2015)
- FRB was followed by 11 telescopes to search for radio, optical, X-ray, γ-ray and neutrinos emissions
- No other emissions have been observed
- A neutrino signal was searched in 3 time windows
  - ± 500s, ± 1h, ± 1 day
  - no events was found from the FRB event location
- From this null result ANTARES put a limit

\[ F_{90\%C.L.}^\nu < 1.4 \times 10^{-2} \text{ erg cm}^{-2} \text{ for } E^{-2} \text{ spectrum} \]

\[ \text{or } \]

\[ F_{90\%C.L.}^\nu < 0.47 \text{ erg cm}^{-2} \text{ for } E^{-1} \text{ spectrum} \]

No transients were detected at any wavelength temporally associated with FRB 150215.
H.E. astrophysical ν candidates (like IC-160731) trigger multi-messenger observations (AGILE, ...)

**AGILE Detection of a Candidate Gamma-Ray Precursor to the ICECUBE-160731 Neutrino Event**

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On 2016 July 31 the ICECUBE collaboration reported the detection of a high-energy starting event induced by an astrophysical neutrino. Here, we report on a search for a gamma-ray counterpart to the ICECUBE-160731 event, made with the AGILE satellite. No detection was found spanning the time interval of +1 ks around the neutrino event time \(T_0\) using the AGILE “burst search” system. Looking for a possible gamma-ray precursor in the results of the AGILE-GRID automatic Quick Look procedure over predefined 48-hr time bins, we found an excess above 100 MeV between 1 and 2 days before \(T_0\), which is positionally consistent with the ICECUBE error circle, that has a post-trial significance of about 4σ. A refined data analysis of this excess confirms, a posteriori, the automatic
A short gamma-ray burst (GRB) that followed the merger of this binary system was recorded by the Fermi-GBM ($E_{\text{iso}} \sim 4 \times 10^{46}$ erg) and INTEGRAL.

Advanced LIGO and Advanced Virgo observatories reported GW170817.

Optical observations allowed the precise localization of binary neutron star inspiral in NGC4993 at $\sim 40$ Mpc.

ANTARES, IceCube, and Pierre Auger Observatories searched for high-energy neutrinos from the merger in the $10^{11}$ eV–$10^{20}$ eV energy range.

IceCube detector is also sensitive to outbursts of MeV neutrinos via a simultaneous increase in all photomultiplier signal rates.

The location of this source was nearly ideal for Auger. It was well above the horizon for IceCube and ANTARES for prompt observations. IceCube and ANTARES sensitivity is then limited for neutrinos with $E_\nu < 100$ TeV.
No neutrinos directionally coincident with the source were detected within ±500 s around the merger time.

Additionally, no MeV neutrino burst signal was detected (in IceCube) coincident with the merger.

In Pierre Auger Observatory no inclined showers passing the Earth-skimming selection (neutrino candidates) were found in the time window ±500 s around the trigger time of GW170817.

No neutrino found in an extended search in the direction within the 14-day period following the merger.

GRB170817A’s observed prompt gamma-ray emission, as well as Fermi-GBM’s luminosity constraints for extended gamma-ray emission, are significantly below typical values for observed short GRBs. One possible explanation for this is the off-axis observation of the GRB.

The non observation of neutrinos allow to put limits both extended emission (EE) and prompt emission (scaled to a distance of 40 Mpc): limits are shown for the case of on-axis viewing angle (0) and selected off-axis angles to indicate the dependence on this parameter.

IceCube, BAIKAL, ANTARES neutrino telescopes monitor continuously the sky searching for astrophysical neutrinos. AUGER detector sensitive to U.H.E. neutrinos.

A large multi-messenger effort to characterize the C.R.s composition, spectrum, sources location and dynamics, joining different observations:

- EM radiation: radio, optical, X-ray, γ-rays
- U.H.E. C.R.s
- Gravitational Waves
- neutrino

KM3NeT Neutrino Telescope under construction in the Mediterranean Sea will soon be able to observe the neutrino sky with unprecedented sensitivities.