MULTI-MESSENGER ASTRONOMY WITH ANTARES

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on behalf of the ANTARES collaboration

Rencontres de Moriond 2017 | Very High Energy Phenomena in the Universe
THE ANTARES NEUTRINO TELESCOPE

12 line detector completed in May 2008

- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs

8 countries
31 institutes
~150 scientists + engineers

350 m
100 m
~70 m

Anchor/line socket
Junction box (since 2002)
Interlink cables

Deployed in 2001
40 km
WHY LOOKING FOR TRANSIENT SOURCES?

MULTI-MESSENGER CONTEXT

Neutrino telescopes suitable to look for transient sources: continuously monitoring $2\pi$ sr (at least)

- **Multi-messenger studies of transient & variables sources:**
  - increase the sensitivity + discovery potential (reduce the background)
  - increase the statistical significance (requiring joint detection)
WHY LOOKING FOR TRANSIENT SOURCES?

- Increase discovery potential and sensitivity
- Improve statistical significance
- Better understanding of physical processes

Average number of ANTARES events for a $5\sigma$ discovery (50% probability) in $\sim 3^\circ$ Dec $=-40^\circ$ and $E^{-2}$ energy spectrum

Adrián-Martínez et al., JCAP12(2015)014
LOOKING FOR TRANSIENT MULTI-MESSENGER SOURCES

2 APPROACHES:

Time dependent searches
LOOKING FOR TRANSIENT MULTI-MESSENGER SOURCES

2 APPROACHES:

Real-time analysis → Alert triggering → ...

H.E.S.S.
LOOKING FOR TRANSIENT MULTI-MESSENGER SOURCES

2 APPROACHES:

- Time dependent searches
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]

Multi-messenger correlation:
- Correlation with the UHE events [Auger]
- Correlation with the gravitational wave [Virgo/Ligo]
- 2pt-correlation with 2FGL catalogue, loc. galaxies, BH, IceCube HESE
Neutrino detection: important hint on the jet composition and formation
Assuming neutrino emission coincident in time with electromagnetic outburst emission

Usually keV-GeV emission (wide FoV)
MICROQUASARS (ANTARES coll., arXiv:1609.07372, JCAP in press)

- Start constraining some hadronic microquasar emission models
- High baryonic loading disfavored
**FLARING SOURCES**

**BLAZARS** *(ANTARES coll., A&A 576, L8, 2015)*

- TANAMI collaboration reported observations of 6 bright blazars locally compatible with the 2 first PeV IceCube events IC14 and IC20.
- No event observed by ANTARES from 4 blazars (time integrated analysis)
- If $N_{IC}^{90} <$ nb of events observed by IC: a blazar origin can be excluded
- Relevant constraints on spectral index
Search for muon neutrinos for 4 bright GRB observed between 2008 and 2013.

Two scenarios are investigated: internal shocks and photospheric models.

Stacked search for time shifted neutrinos (during 5 years of ANTARES data): probes wider time windows up to 40 days: no significant detection.
No events within $\Delta T = T_{\text{FRB}} - 250\text{s}; T_{\text{FRB}} + 750\text{s}$ (RoI=2°) - Compatible with the background expectations

$\Rightarrow$ U.L. on the total energy emitted in neutrinos for $E^{-2}$ and $E^{-1}$ spectra:

- $1.4 \times 10^{55}$ erg ($E^{-2}$ spectrum)
- $3.1 \times 10^{56}$ erg ($E^{-1}$ spectrum)

- MoU signed in 2015 between the SUPERB project (FRB discovery) at the Parkes observatory and the ANTARES collaboration
- SUPERB team $\rightarrow$ send the FRB trigger alerts to the ANTARES alert pipeline
- ANTARES coll. $\rightarrow$ fast search for neutrino counterpart in the online neutrino data stream
- 7 FRBs analyses by ANTARES so far
No events within $\Delta T = T_{\text{FRB}} - 250s$; $T_{\text{FRB}} + 750s$ (ROI=2°) - Compatible with the background expectations

Upper limit on the total energy emitted in neutrinos for $E^{-2}$ and $E^{-1}$ spectra:
- $1.4 \times 10^{55}$ erg ($E^{-2}$ spectrum)
- $3.1 \times 10^{56}$ erg ($E^{-1}$ spectrum)

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Preliminary
For BH/NS or NS/NS systems:

- gravitational waves
- electromagnetic
- neutrino emission

Expected if ejection process with baryonic component.
\[ t_{\text{HEN}} - t_{\text{GW}} \in [-500s; +500s] \]

(Baret et al., 2011)

if GW related to GRB event
Fluence U.L. for GW150914
Joint analysis IceCube / ANTARES / LIGO-Virgo, PRD 93, 2016
Published as joint paper with the detection paper (feb. 2016)
Constraints on the total energy radiated in neutrinos

\[
E_{\nu, \text{tot}}^{\text{ul}} = 5.4 \times 10^{51} - 1.3 \times 10^{54} \text{ erg} \\
E_{\nu, \text{tot}}^{\text{ul}(\text{cutoff})} = 6.6 \times 10^{51} - 3.7 \times 10^{54} \text{ erg}
\]

at \(d=410^{+160}_{-180} \text{ Mpc}\)

- Energy radiated in GW: \(\sim 5 \times 10^{54} \text{ erg}\)
- Typical short GRB isotropic-equivalent energies are \(\sim 10^{49} \text{ erg}\)
- May be similar to total energy radiated in neutrinos in GRBs (Meszaros 2015; Bartos et al., 2013)
GRavitational wave follow-ups

- GW151226 + LVT151012 (submitted to PRD very soon)

- ANTARES member of the Virgo/LIGO follow-up effort since dec. 2016
  - Real time follow-up
  - private GCN after each alert

- Electromagnetic follow-up difficult due to uncertain localization
  - benefit from neutrino telescopes
  - could significantly constrain the location of the source
No ANTARES event found in coincidence (ROI=2°, ±500s; ±1h)

⇒ U.L. on the radiant neutrino fluence for $E^{-2}$ and $E^{-2.5}$ spectra:

~15 GeV/cm$^2$ in [2.8 TeV, 3.3 PeV] for $E^{-2}$

~30 GeV/cm$^2$ in [0.4 TeV, 280 TeV] for $E^{-2.5}$
LOOKING FOR TRANSIENT MULTI-MESSENGER SOURCES

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

Real-time analysis

TATOO (TELESCOPE-ANTARES TARGET OF OPPORTUNITY)

- Private MoU with all the observatories

237 alerts sent to optical telescopes since mid 2009
+13 to Swift since mid 2013
TATOO: ANT150109A ALERT

- $E \sim 50-100$ TeV
- Error box = 18 arcmin
- Sent in 10s to Swift and Master
- Swift obs: +9h
- Master obs: +10h

Real-time analysis graph showing Swift/XRT data of J1625.7–2723 – Source 1.
## TATOO: ANT150109A ALERT

**Neutrinos**
- IceCube: ATel 8097

**Optical**
- Pan-STARRS: ATel 7992, 8027
- SALT: ATel 7993
- NOT: ATel 7994 GCN18236
- WiFeS: ATel 7996
- CAHA: ATel 7998, GCN18241
- MASTER: ATel 8000 GCN18240
- LSGT: ATel 8002
- NIC: ATel 8006
- ANU: GCN18242
- GCM: GCN18239
- VLT/X-shooter

**X-rays**
- Integral: ATel 7995
- MAXI: ATel 8003
- Swift: ATel 8124, GCN18231

**Radio**
- Jansky VLA: ATel 7999, 8034

**Gamma-rays**
- MAGIC: ATel 8203
- Fermi-GBM: GCN18352
- HAWC
- HESS

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*Great interest by astro-community*
TATOO: ANT150109A ALERT

Active X-ray star

REAL-TIME ANALYSIS

ATel #7999

USNO-B1.0 0626-0501169

Hα

Preliminary

Normalized flux

Normalized flux

Normalized flux
REAL-TIME ANALYSIS

TATOO AND GAMMA-RAY BURSTS
JCAP 02:062, 2016

- 93 alerts with early (<24h) optical follow-up analyzed (01/2010 - 01/2016)
- 13 follow-ups with delay <1min (best: 17s)
- no transient candidate associated to neutrinos
- Constraints on origin of individual neutrinos
- GRB origin unlikely
13 X-ray follow-ups

delay of 5-6 h on average

no transient candidate associated to neutrinos

Constraints on origin of individual neutrinos

GRB origin unlikely
Multi-messenger astronomy era ! (GW + neutrino diffuse flux)

Further constrain physical processes at play in HE sources

Increase discovery potential of neutrino telescopes (by observing the same source with different probes)

Refines the efficiency of the detection, by profiting of relaxed cuts (exploiting the advantages of time-dependent analysis)

Would improve the statistical significance of the observations, by coincident detection (sustained by the development of alert systems between the experiments)

Stay tuned (KM3NeT, GW/neutrinos, IceCube alerts,...) !
The disk is at least comparable with that of the companion BH (Lodato et al. 2009). The timescale; however, the effect is expected to be significant only if the mass of generally influence the angular momentum of the binary, and hence the merger what seen in numerical simulations of extended disks sur-

event rather than a quasi-stationary process, analogously to

part of the disk, likely becoming an impulsive, shock-driven

in the outer rim cannot accrete, and hence piles up at the outer

concentrated in the outer rim of the accretion disk (Papaloizou

radius in this case is 

affect the conclusions of this argument. The tidal truncation

the same plane, even though a different geometry should not

becomes smaller than the viscous one. From that point on the two BHs merge

timescales as a function of the orbital separation for a system of two

BH configuration, maintaining an MRI active outer rim push-

in the outer rim cannot accrete, and hence piles up at the outer


Duration of accretion (GRB)

Shock-heated disk, MRI active and actively accreting onto BHS

Catastrophic, full disk-heating

Steady-state outer rim heating

Gravitational timescale

Viscous timescale

Free-fall timescale

Tidally heated outer rim, MRI active

Dead disk

Black Holes

Supernova

Black hole

Perna et al. (2016)
\begin{align*}
\ln \mathcal{L} &= \left( \sum_{i=1}^{N} \ln[\mathcal{N}_S S_i + \mathcal{N}_B B_i] \right) - [\mathcal{N}_S + \mathcal{N}_B] \\
S_i &= S_{\text{space}}(\Psi_i(\alpha_s, \delta_s)) \cdot S_{\text{energy}}(dE/dX_i) \cdot S_{\text{time}}(t_i + \text{lag}) \\
B_i &= B_{\text{space}}(\delta_i) \cdot B_{\text{energy}}(dE/dX_i) \cdot B_{\text{time}}(t_i)
\end{align*}

Adrián-Martínez et al., JCAP12(2015)014
Adrián-Martínez et al., arXiv:1609.07372
Figure 1. Scatter plot of the number of photomultiplier hits vs. the total amplitude (in photoelectrons) for neutrino candidates. The high-energy trigger criterion is fulfilled by events inside the red box. Events inside the blue box correspond to the very high-energy trigger for the Swift-XRT.
Figure 10. Cumulative distribution of afterglow magnitudes for 301 detected GRBs (figure 9). Each line corresponds to different times after burst. The vertical dashed line represents the limiting magnitude of the optical telescopes.
**Fluence** = flux integrated over a certain emission period of interest (useful for transient phenomena)

- Spectral fluence: \( \frac{dN}{dE} = \phi_0 E^{-2} \)

- Spectral fluence normalisation: \( \phi_0 = \frac{dN}{dE} E^2 \)

- Energy fluence: \( \mathcal{F} = \int_{E_{\text{min}}}^{E_{\text{max}}} E dN = \int_{E_{\text{min}}}^{E_{\text{max}}} E \phi_0 E^{-2} dE \)