Multi-Messenger Analyses with the ANTARES High Energy Neutrino Telescope
Outline

1. Transient Sources Motivation
2. $\mu$-quasar Analysis
3. Blazar Analysis
4. TAToO
5. Conclusions
ANTARES Performance

- 12-line data taking since 2008
- ~7000 detected neutrinos
- Median angular resolution 0.3-0.4° above ~10 TeV
- Effective area ~1m² @30 TeV
- Visibility of 3/4 of the sky, most of the galactic plane
- Real-time data processing
Correlation $\gamma/\nu$

- Motivation: link CR/$\nu/\gamma$ via Fermi mechanism
- “Leptonic”, “Hadronic” and “Lepto-Hadronic” models
- Open questions over jet composition: relativistic fraction, maximum energies, CRs and UHECRs origin...

SED sample for Blazar 3C279
Sources with Transient Emission

Coincidence of $\gamma$ and neutrino emission: different transient sources can be analysed

1. $\mu$-quasars: Galactic variable sources (hours $\leftrightarrow$ months)
2. Blazars: Extra-galactic variable sources (hours $\leftrightarrow$ months)
3. GRBs: Most energetic known events in the Universe (sec $\leftrightarrow$ days)

Analysis presented here: $\mu$-quasars and Blazars
Transient Analyses

- ANTARES can perform a wide range of analyses
- Point Source analyses: discovering of astrophysical neutrino sources
- **Multi-messenger study**: Variable light emission sources time info as expected time for neutrino signal
- Improved performance with respect to not using time info at all
Optical Counterparts

Supported by multi-wavelength telescope observations:

- **Satellites**: Rossi RXTE/ASM and Swift BAT/XRT for X-Rays and Fermi-LAT for $\gamma$-Rays
- **IACT**: HESS, MAGIC, VERITAS for HE $\gamma$-Rays
- **Ground telescopes**: TAROT, ROTSE, ZADKO and IrIS for optical
µ-quasar Analysis
\( \mu\)-quasar Analysis

\( \mu\)-quasars:
- Massive compact objects remains of collapsed stars
- Star companion feed its accretion disk
- Powerful variable X-ray emission

\( \mu\)-quasars with X-ray or \( \gamma\)-ray outbursts in the 2007–2010 satellite data:

- Circinus X-1
- GX339-4
- H 1743-322
- IGRJ17091-3624
- Cygnus X-1
- Cygnus X-3

\( \nu\)-search for 4 black hole binaries split in two cases:
- Hard X-ray states (\( \text{HS} \)): “slow” steady jet
- Transition hard <-> soft (\( \text{TS} \)): “fast” discrete ejection

Relativistic jets \( \rightarrow \) \( \nu\) emission

- Cyg X-3: \( \gamma\)-ray outburst using Fermi/LAT data
- Cir X-1: X-rays + orbital phase/jet connection
μ-quasar Analysis

- ANTARES data period 2007–2010 (813 live time days)
- Multi-messenger info provided by SWIFT, ROSSI and FERMI.

X-ray light curves sample of GX 339-4 between 2007 and 2010 (hard state (HS) and hard–soft transition (TS) filled areas), from top to bottom: SWIFT and Rossi X-ray LCs and hardness ratio.
**Multi-Messenger Analyses in ANTARES**

### Outline
- Transient Sources
- µ-quasars
- Blazars
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### µ-quasar Results

- No neutrino found in time coincidence with µ-quasar emissions
- Upper limits on neutrino flux (F.C. @90% C.L.)
- Interpretation of the results regarding models:
  - Distefano et al. (2002)
  - GX 339-4: Zhang et al. (2010) ruled out for $\eta_p/\eta_e > 100$
  - Cyg X-3: Baerwald & Guetta (2010) and Sahakyan et al. (2014) not ruled out

<table>
<thead>
<tr>
<th>Source</th>
<th>TS</th>
<th>Livetime (days)</th>
<th>Fluence U.L. (GeV cm$^{-2}$) [90% C.L.]</th>
<th>$\eta_p/\eta_e$</th>
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<tbody>
<tr>
<td>Cir X-1</td>
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<td>GX 339-4 (HS)</td>
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<td>18.5</td>
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<tr>
<td>Cyg X-3</td>
<td>0</td>
<td>16.6</td>
<td>5.7</td>
<td>7.0</td>
</tr>
</tbody>
</table>

- (1) Distefano et al. (2002) for $\phi \propto E^{-2}e^{-\sqrt{E}/100T_{10}}$
- (2) Regarding jet inclination and Lorentz factor
- (3) No measurements available to estimate the neutrino flux
Upper limits (F.C.@90%) on a neutrino flux $\phi \propto E^{-2} e^{-\sqrt{E/100\text{TeV}}}$ (circles) compared with the expectations of Distefano et al. (2002) in the $\eta_p = \eta_e$ case (triangles). For IGRJ17091-3624 no measurement has been found to estimate the neutrino flux.

Upper limits (F.C.@90%) on the neutrino flux (with and without cutoff at 100 TeV) for GX 339-4 compared with the predicted by Zhang et al. (2010)
Blazar Analysis
## Blazars Analyses

Blazars:
- The most variable AGNs
- Accretion disk and jet emission
- Bright $\gamma$-ray sources

$\gamma$-ray sky as seen by FERMI satellite with the first 2 years of data.

- Flares in two energy ranges: $\gamma$-rays (FERMI) and HE-VHE $\gamma$-rays (IACT)
Blazars Analyses: FERMI

- Catalogue base: 2FGL(+Fermiblog+TANAMI) → 1873(+43+13) sources
- Preselection: (cuts on catalogue parameters)
  - Blazars \( | \text{DS} > 25\sigma \) \( | \text{VI} > 41.64 \) \( | \delta > 35^\circ \)
  - \( \phi_{\text{min}}^{1-100\text{ GeV}} > 10^{-9} \text{ photons} \cdot \text{cm}^{-2} \cdot \text{s}^{-1} \)
- Reduced to 97(+43+13) pre-selected sources.
- Significant flares found on 41 flaring sources: 3C 454.3, 3C 279, 4C +21.35, PKS 1510–08, ...

Skymap in galactic coordinates with the ANTARES visibility (blue) marking in circles of 2° the 41 FERMI sources.
Blazars Analyses: FERMI

LCs extracted from FERMI photon counting data: Maximum Likelihood Block denoising treatment with a fluence threshold

LEFT: 3C 273 CMAP from FERMI data. RIGHT: Corresponding LC with a MLB characterization. The selected flaring periods are done by a fluence threshold.
Blazars Analyses: **IACT**

**7 flaring sources** selected from publications on HESS, MAGIC and VERITAS: 4C +21.35, PG 1553+113, PKS 1424+240, 1ES 1218+30.4, 1ES 0229+200, HESS J1943+213 and PKS 0447–439

Skymap in galactic coordinates with the ANTARES visibility (blue) marking in circles of 2° the **7 IACT sources**.
Blazars Analyses: IACT

LCs extracted from publications: Flat emission assumed during the reported flaring periods

LEFT: 1ES 1218+30.4 photon flux above 200 GeV (5 flaring days) as reported by VERITAS collaboration et al. (2010) as shown in Weidinger and Spanier (2010) [arXiv:1005.3747].

RIGHT: 4C +21.35 photon flux above 100 GeV (1 flaring day) as reported by MAGIC collaboration et al. (2011) [arXiv:1101.4645]
Blazars Analyses

- Analysis with 2008–2012 data: from September 6th to December 31st, 2012 (1044 days of live time)
- Unbinned time-dependent search method with a likelihood ratio
- Implementation of a possible lag (±5 days) in $\nu/\gamma$ signal in the likelihood for avoid missing short flares
- Inclusion of a new energy estimator with a more physical justification, declination dependence considered
- Various energy spectra taken in consideration: $E^{-2}$, $E^{-2}$ with cutoffs @ 1 TeV and 10 TeV, $E^{-1}$
- Re-optimization of preliminary general cuts: $\cos(\theta) > -0.15 \&\& \beta < 1^\circ$ [Discovery Flux @ 3$\sigma$]
- Individual $\Lambda$ quality cut optimization [Model Discovery Potential @ 3$\sigma$]

PSF sample for 3C 279 (right) built from the MC distribution of the angular differences (left)
Blazars Results

- Only 3 sources show a neutrino event in time and space coincidence with the flare: 3C 279, PKS 1124–186 and PKS 0235–618
- Most significant source: 3C 279 for $E^{-2}$ with p-value 1.9% (54% post-trial)
- Background fluctuation compatible
- Paper in preparation

LEFT: Neutrino events around 3C 279. The circles are the estimated angular error from the reconstruction.
RIGHT: $\gamma$-Ray light curve for 3C 279 with the selected neutrino events within 3$^\circ$ around the source.
[events during and out of the flare]
TAToO
- Optical follow-up of individual $\nu$ direction in real-time
- Model independant: No hypothesis on the nature of the source

TAToO

- 3 types of triggers:
  - Doublet: Two neutrinos in a $3^\circ$ angle and in a time window of 15min (0.04/yr)
  - High Energy: A neutrino with $E > 5$ TeV (12/yr)
  - Directional: A neutrino in the direction ($< 0.4^\circ$) of a local galaxy ($< 20$ Mpc) (12/yr)

- Online processing:
  - Online reconstruction + trigger: $\sim$3-5s
  - Alert sending: $\sim$1-10s depending on the telescope response
  - Telescope slewing: $\sim$1-5s
  Minimum delay between the neutrino and the first image: $\sim$20s

- Optical follow up:
TAToO Telescope Web

Image by Craig Blayney and Robert Simmon, NASA GSFC, based on DMSP data
Multi-Messenger Analyses in ANTARES

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**TAToO Telescope Web**

**TAROT Calern**
- Two 25 cm telescopes
- Fov 1.86° x 1.86°
- Slewing time ~ 10s

**SWIFT**
- X-ray follow-up
- Fov 23.6 x 23.6 arcmin
- 0.3-10 keV energy range

**TAROT**

**ROTSE**

**ZADKO**

**ROTSE 3a**
- Four 45 cm telescopes
- Fov 1.85° x 1.85°
- Slewing time ~ 10s

**Zadko**
- One-metre telescope
- Fov 23 x 23 arcmin
- Max. Slew speed 3°/s
TAToO Alerts

Since 2009 **108 alerts** sent:
- 11 not followed (telescope maintenance, too close to the Sun...)
- 97 followed by at least 1 telescope and at least 1 night
- 90 followed by at least 1 telescope and at least 3 nights
TAToO Results

Hypothesis: neutrino emission simultaneously with photons
- No transient optical counterpart associated with a neutrino detection
- Upper limits on transient sources magnitude

<table>
<thead>
<tr>
<th>Alert</th>
<th>Delay since trigger</th>
<th>U.L. Mag (S/N=5)</th>
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<td>15h 20m 15s</td>
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<td>ANT100302A</td>
<td>24h 20m 08s</td>
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<td>ANT100725A</td>
<td>00h 01m 15s</td>
<td>14.5</td>
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<td>ANT100922A</td>
<td>01h 08m 06s</td>
<td>14.0</td>
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<td>ANT101211A</td>
<td>12h 03m 30s</td>
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</tr>
<tr>
<td>ANT121206A</td>
<td>00h 00m 27s</td>
<td>16.9</td>
</tr>
</tbody>
</table>

Based on only detected light curves [kann2010]

Possible interpretation of the TAToO U.L. compared with a sample of regular optical afterglow LC, corrected for Galactic extinction Kann et al. (2010)
TAToO Results

5 alerts sent to the XRT since June 2013
- After a delay of: 23s 25s 18s 18s 24s
- Processing after: 1h08 6h24 5h06 6h43 5h36

No X-ray counterpart associated to a neutrino detection

Possible interpretation of the TAToO U.L.: Afterglow LC detected by Swift/XRT compared with the TAToO limits
Conclusions

1. Transient and multi-messenger analyses are performed, on-line and off-line
2. First results on $\mu$-quasar analysis with ANTARES (2007-2010)
3. The $\mu$-quasar analysis is being updated with new data and new sources
5. Long term TAToO follow-up are currently analysed to look for long transient (core collapse SN)
6. More multi-messenger analysis:
   - Gravitational waves (VIRGO/LIGO)
7. GRB, SGR and Blazars analysis moving to real-time
PLEASE STAND BY...
The ANTARES Neutrino Telescope
The ANTARES Neutrino Telescope

ANTARES is a Neutrino Telescope placed underwater in the sea bed of the Mediterranean Sea at the south of Toulon (France)
Multi-Messenger Analyses in ANTARES

The ANTARES Neutrino Telescope

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

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

Atmospheric muons \( \sim 10 \) per second
Atmospheric neutrinos few per day
Cosmic neutrinos few per year (may be)

- Atm muons: quite easy to remove (zenith + quality cuts)
- Atm neutrinos: irreducible isotropic background, low energy
- Optimization cuts selects 3058 neutrino candidates \( (\lambda_{cut} > -5.2) \) and 5709 neutrino candidates \( (\lambda_{cut} > -5.4) \)

ANTARES skymap for the 3058 neutrino candidates in the case of a \( \lambda_{cut} > -5.2 \) in equatorial coordinates (ANTARES events and studied \( \mu \)-quasars)
Blazar Previous Analysis

- Previous ANTARES AGN analysis:
  

- From 06/09/2008 to 31/12/2008 (60.8 days of live time)

- High variability, brightness and visibility Fermi Blazar sources (reported in 1FGL / LBAS catalogue): **10 selected sources**

- $\gamma$-Ray light curves extracted from FERMI public data

- One neutrino event compatible with 3C 279 in time and direction ($\Delta\alpha=0.56^\circ$) → **post trial value 10%**

- Upper limits on neutrino flux (F.C. @90% C.L.)

| Source          | $n(5\sigma)$ | $n_{\text{obs}}$ | Fluence U.L. (GeV cm$^{-2}$) [90% C.L. | $\phi \propto E^{-2}$] |
|-----------------|--------------|------------------|------------------------------------------|
| PKS 0208-512    | 4.5          | 0                | 2.8                                      |
| AO 0235+164     | 4.3          | 0                | 18.7                                     |
| PKS 0454-234    | 3.3          | 0                | 2.9                                      |
| OJ 287          | 3.9          | 0                | 3.4                                      |
| WComae          | 3.8          | 0                | 3.6                                      |
| 3C 273          | 2.5          | 0                | 1.1                                      |
| 3C 279          | 5.0          | 1                | 2.8                                      |
| PKS 1510-089    | 3.8          | 0                | 2.8                                      |
| 3C 454.3        | 4.4          | 0                | 23.5                                     |
| PKS 2155-304    | 3.7          | 0                | 1.6                                      |

*Neutrino event during 3C 279 flare*
Blazars Results

- Upper limits on neutrino flux (Neyman @90% C.L.)
- May be describe the fluence computation criteria
- ...
- Paper on the way...

Preliminary upper limits on the fluence for the FERMI analysis

\[ \Phi_\nu @ 90\% \text{ C.L. (erg/cm}^2) \]
## Angular performances:

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Angular resolution</th>
<th>Fraction events in FoV</th>
<th>Mean Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>HE</td>
<td>0.25–0.3°</td>
<td>96% (GRB)</td>
<td>~7 TeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>68% (SN)</td>
<td></td>
</tr>
<tr>
<td>Directional</td>
<td>0.3–0.4°</td>
<td>90% (GRB)</td>
<td>~1 TeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50% (SN)</td>
<td></td>
</tr>
</tbody>
</table>

**PSF trigger HE**

- HE 0.25–0.3°: 96% (GRB), 68% (SN)
- Directional 0.3–0.4°: 90% (GRB), 50% (SN)

**Mean Energy**

- HE: ~7 TeV
- Directional: ~1 TeV
TAToO Image Subtraction

Image subtraction:

- Image from TAToO follow-up
- Reference image (no signal)
- Residual image

- PSF matched

- Cuts on:
  - SNR
  - Flux variation
  - FWHM...