Probing the High Energy Neutrino universe with ANTARES

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Principles of Neutrino Telescopes

- Muon neutrino, CC only (track reconstruction)
- Neutrino or charged lepton
- Atmospheric muon
- All neutrino flavours, CC & NC (shower reconstruction)
Astronomy with a Neutrino Telescope & Abyss environmental RESearch

See talk by J. Barrios-Marti

KM3NeT-Fr = ORCA (GeV neutrinos)
KM3NeT-It = ARCA (TeV neutrinos)

Complementarity with IceCube: visibility of Galactic Plane + Galactic Center
- 10% instantaneous overlap - 40% integrated overlap
Fermi 5-year gamma-ray catalogue (> 1GeV) – instantaneous: 50% overlap
Astronomy with a Neutrino Telescope & Abyss environmental RESEARCH

- Advantages wrt Polar Ice: Less scattering but more absorption
  - $\Delta \theta$ on reconstructed track $\sim O(0.1^\circ)$ compared to $\sim O(1^\circ)$ in Ice
**Requirements**: Measurements of time (ns), position (10cm), amplitude (10%)

Line 1 has celebrated its 10-year anniversary!
Physics studies with Neutrino Telescopes: from GeV to PeV neutrinos!

- **Low Energy**: $3 \text{ GeV} < E_\nu < 50 \text{ GeV}
  - Neutrino Oscillations
  - [Mass spectrum → ORCA]

- **Medium Energy**: $10 \text{ GeV} < E_\nu < 1 \text{ TeV}
  - Dark Matter Searches
  - Exotics

- **High Energy**: $E_\nu > 1 \text{ TeV}
  - Neutrino Astronomy
  - Origin of Cosmic Rays
Tracks & Showers - topologies and resolutions

- Tracks (CC $\nu_{\mu}$ $\nu_{\tau}$)

- $\nu_e$ CC
- $\nu_x$ NC

reaches 2 deg
The IceCube signal...and ANTARES dedicated searches

- Spectral index different for HE tracks (~$E^{-2}$) and for tracks+showers (~$E^{-2.5}$)
- Southern/Northern hemisphere contribution?
- Origin: Galactic (Fermi Bubbles, Galactic Ridge,...) or farther?
The IceCube signal...and ANTARES dedicated searches

- Spectral index different for HE tracks ($\sim E^{-2}$) and for tracks+showers ($\sim E^{-2.5}$)
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Diffuse fluxes in ANTARES - tracks & showers

Track channel
Data 2007 – 2015 : 2451 days

Observed : 19
Expected : 13.5 ± 3 from bkg \(~3 \text{ from IC}\)

Cascade channel
Data 2007 – 2013 : 1405 days

Observed : 7
Expected : 5 ± 2 from bkg \(~1.5 \text{ from IC}\)

Volume of instrumented medium is paramount → KM3NeT
Point Source searches in ANTARES - tracks & showers

- To identify the origin of the signal:
  - Combine ANTARES and IceCube data
  - Reduce the space search window: identify regions of interest
  - Reduce the space+time window: Multi-Messenger programs

6490 tracks
172 showers

Best sensitivity below few $10^2$ TeV

See poster 167 by J. Barrios-Marti on Wednesday 14th
ANTARES/IceCube joint search: complementary telescopes

ANTARES 2007-2012 + IceCube 2008-2011

Relative number of source events for $\gamma = 2.0$

Limits and sensitivities for $\gamma = 2.0$
Zero in on the origin of the IceCube signal...

Galactic Ridge – 2008-2013

Fermi Bubbles – 2008-2013

Looking for the HEN signal: diffuse fluxes & point sources

ANTARES results and the IceCube signal

Multi-Messenger program

Conclusions

Targeted searches
Multi-Messenger Astronomy - Reducing the time+space search window

**Introduction**

ANTARES results and the IceCube signal

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**GeV-TeV γ-rays**

*Fermi, HESS, HAWC*

**UHECR**

*Auger, TA*

**HE neutrinos**

**Radio-Visible-X**

*MWA, SUPERB, TAROT, ZADKO, MASTER, Swift*

**Grav. Waves**

*LIGO-VIRGO-EGO*

**GRBs**

**AGNs**

**X-Ray Binaries**

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T. Pradier, U. Strasbourg & IPHC/DRS

*TeVPA 2016 - Probing the High Energy Neutrino universe with ANTARES*
**From EM observatories to ANTARES**

**GRBs**


**AGNs**

Blazars monitored by FERMI-LAT and Cherenkov Telescopes (*JCAP* 1512 (2015), 014)

\[ \langle N_{\text{events}} \rangle \text{ for a } 5\sigma \text{ discovery} \]

\[ \delta = -40^\circ, E^{-2} \text{ spectrum} \]
ANTARES and the brightest GRBs - Models & constraints

ANTARES results and the IceCube signal

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GWHEN: Gravitational Waves + High Energy Neutrinos

Introduction

ANTARES and Electromagnetic Observatories

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Photo-sphere

Internal Shock

External Shock

GRB130505A

ANTARES – 2008-2013

PRELIMINARY

Baryon loading

Number of neutrinos (log10)

GRB130505A

E^2 Phi (GeV cm^-2)

E_n (GeV)

080918C fluence
080918C UL
130505A fluence
130505A UL
130427A fluence
130427A UL
110918A fluence
110918A UL

Z&K model (PH)
NeuCosmA (IS)
ANTARES and the brightest GRBs - Models & constraints

ANTARES – 2008-2013

PRELIMINARY
X-Ray Binaries during flaring states

**Introduction**

**ANTARES results and the IceCube signal**

**Multi-Messenger program**

**Conclusions**

**ANTARES and Electromagnetic Observatories**

**GWHEN : Gravitational Waves + High Energy Neutrinos**

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1044 days of livetime of muon tracks during 2008–2012

- Study of 33 XRBs during X-ray flares, 8 of them also during hardness transition states
- Time signal: X-ray light curves from Swift-BAT, RXTE-ASM and MAXI, transition states from “The Astronomer’s Telegram” alerts
- No significant excess

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**GX 339−4**

- $f_\nu$, limit 90% CL
- Distefano et al. 2002 ($\eta_p = \eta_e$)

**Equaipartition e-p**

**Uncertainty on jet velocity**

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- $f_\nu$ (erg cm$^{-2}$ s$^{-1}$)
- $E_\nu^2 \langle \phi_\nu \rangle$, GeV s$^{-1}$ cm$^{-2}$

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TeVPA 2016 - Probing the High Energy Neutrino universe with ANTARES
The ANTARES Telescope Neutrino Alert System
One interesting alert from ANTARES...

- September 1st, 2015: TAToO single HE-alert to optical telescopes + Swift
- Unknown, bright and variable X-ray source detected by Swift
- **ATEL 7987 issued**
  - Extensive follow-up (radio – optical – X – VHE) → No γ-ray source
  - Identification as variable star
Alerts to/from ANTARES

Multi wavelength follow-up of neutrinos

Radio
MWA
(Tarot) ZADKO MASTER

Visible
(Parkes)

X-ray
Swift

GeV-ray
Fermi-LAT

TeV-ray
HESS
HAWC

GW
Ligo
Virgo

ν
IceCube

Alerts FROM ANTARES
12/yr 30/yr 6/yr (Offline) (1-10/yr) (Offline) (joint analyses)

Alerts TO ANTARES
FRBs
GRBs, AGN flares, etc.

TeVPA 2016 - Probing the High Energy Neutrino universe with ANTARES

T. Pradier, U. Strasbourg & IPHC/DRS
Gravitational Waves + HE Neutrinos: GWHEN program
Gravitational Waves + HE Neutrinos: « initial » GWHEN analyses

ANTARES results and the IceCube signal

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ANTARES and Electromagnetic Observatories

GWHEN: Gravitational Waves + High Energy Neutrinos
Advanced GWHEN & the discovery of LIGO: GW150914

With only 2 interferometers, the position of the GW signal is not well known!
Size of GW150914: 590 deg$^2$ wrt ANTARES resolution: <0.5 deg$^2$!

Searches in ±500s → compatible with atmospheric background

Limits from ANTARES dominate below 100 TeV (white line)

Limits on total energy radiated in neutrinos <0.2 %-20% of energy in GW

\[ E_{\nu,\text{tot}}^{ul} \sim 10^{52} - 10^{54} \left( \frac{D_{\text{gw}}}{410 \text{Mpc}} \right)^2 \text{ erg} \]

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Conclusions...

- The sources of IceCube Neutrinos are still to be identified...
- ANTARES, in operation for more than 10 years, until mid-2017

- Extensive Multi-Messenger program to zero in on their origin(s)!
  - Time+Space correlations would allow to identify the HEN origin(s)
  - « Underwater » angular resolution crucial → Reduction of background
  - Fast processing of HEN signal → Alert emission towards EM observatories
  - Follow-up programs covering all wavelengths, from visible to HE γ-rays

- GWHEN and the LIGO discovery
  - First limits on HEN emission from BH-BH coalescence
  - Results for GW151226 and LVT151012 published soon...
  - Reception of GW alerts by ANTARES being installed!