Results from the ANTARES neutrino telescope
• PART 1: Summary of Physics motivations for Cherenkov Neutrino Telescopes

• PART 2:
  • ANTARES - overview
  • Diffuse flux search
  • Point sources search and Galactic center
  • Dark Matter search
  • Neutrino Oscillations
  • Multi Messenger activities
Motivations for Astrophysics Neutrino Measurement.

- Low energy particles
- Protons (50 Mpc)
- HE $\gamma$ (10 Mpc)
- Neutrons (unstables)
- Galactic
- Extra Galactic

- Exotics:
  - Magnetic Monopoles
  - Nuclearites
  - TeV-PeV
  - PeV-EeV

- Galactic
- Extra Galactic

More details in G. de Wasseige’s talk, on Thursday
**Very small neutrino cross-sections** with matter \( \sigma_{\nu N} \approx 7.8 \times 10^{-36} \left( E^{0.36} / \text{GeV} \right) \text{ cm}^2 \) for \( E_{\nu} > 1 \text{ TeV} \)

**Multi-km\(^3\) volume size detector**

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**Glashow Resonance**

Enhancement of cross-section in the anti-\( \nu_e - e^- \) interaction @ \( \sim 10^6 \text{ GeV} \)

Good for energy calibration

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"We propose to install detectors deep in a lake or in the sea and to determine the direction of the charged particles with the help of Cherenkov radiation"
Neutrino detection: constraints.

- Astronomy:
  \( \downarrow \mu_{\text{atm}} \Rightarrow \text{looking for upgoing (\uparrow)} \)

- Energy spectrum deformation
  \( \uparrow \nu_{\text{atm}} \Rightarrow \text{energy cuts (E>10-100 TeV)} \)

Quantity of detected light is a good energy proxy. In case of cascades the telescope can act as a calorimeter. Need of very large instrumented volumes.

Exploiting the background:

- \( \mu_{\text{atm}} \Rightarrow \text{study of sytematics} \)
- \( \nu_{\text{atm}} \Rightarrow \text{neutrino oscillations} \)
ANTARES Collaboration (quasi overlaps to that of KM3NeT).

34 European Institutes
8 Extra-European Institutes
The ANTARES undersea neutrino telescope.

- Running since 2007
- 885 10” PMTs
- 12 lines
- 25 storeys/line
- 3 PMTs / storey
- 0.05 km³ instr. vol.

40 km to shore
450 m
Junction Box
Interlink cables
SHOWERS:
$\nu_e$ CC, $\nu_{\text{all}}$ NC

Ang. Res. < 0.4 deg @ $E_\nu > 10$ TeV

Ang. Res. < 3 deg

TRACKS:
$\nu_\mu$ CC
Data taking period: 2007-2015

Event selection chain + energy-related cut applied to
• obtain a high-purity neutrino sample
• maximise sensitivity

Reconstructed events after quality cuts:

<table>
<thead>
<tr>
<th></th>
<th>Bkg expectation</th>
<th>Signal expectation</th>
<th>N events measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracks</td>
<td>13.5+/-4</td>
<td>3-3.5</td>
<td>19</td>
</tr>
<tr>
<td>Showers</td>
<td>10.5+/-4</td>
<td>3-3.5</td>
<td>14</td>
</tr>
</tbody>
</table>
**DATA fitting method:**
Maximum likelihood fitting method applied to provide an estimation of the parameters describing the observed excess ($\Phi_0, \Gamma$).

**Best-Fit cosmic flux:**

\[
\Gamma = 2.4^{+0.5}_{-0.4} \\
\Phi_0^{1f}(100 \text{ TeV}) = (1.7 \pm 1.0) \cdot 10^{-18} \text{ (GeV cm}^2\text{s sr)}
\]

- **1.6 \sigma excess** w.r.t the null-hypothesis “no cosmic flux” (profile likelihood)
- Wider 2D Confidence Interval with $\Phi_0 > 0 : 85\% \text{ C.L.}$
- Results compatible with IceCube diffuse flux

Extending the data sample to 2018, a larger significance is expected. New results coming soon.
Full-sky search (2007 – 2015 - livetime: 2424 days)
1°x1° squares over ANTARES visible sky
7622 track-like, 180 shower-like neutrino candidates

Candidate list searches:
• 106 known astrophysical objects (Pulsars, SNRs, …)
• 13 IceCube HESE tracks
Most significant cluster of the full-sky search (1.9σ post-trial significance)

$$\alpha = 343.8^\circ \quad \delta = 23.5^\circ$$

Sky map in equatorial coordinates of pre-trial p-values

Most sensitive limits for a large fraction of the southern sky, especially at neutrino energies below 100 TeV

**Ongoing analysis with extended live time (up to 2018)**

Sensitivities and upper limits at a 90% C.L. on the signal flux from the Full-sky and the Candidate list searches (Neyman method)

Phys. Rev. D 96, 082001

Galactic center
“KRA Gamma model” has been introduced recently to explain the high-energy gamma ray diffuse Galactic emission. This model reproduces Fermi & Milagro data.

Results

Total flux contribution of diffuse Galactic neutrino emission <8.5% of the total diffuse IC astrophysical signal (Eν > 30 TeV) [ApJ 809:98(2015)].

Combined U.L. (ANTARES+ IceCube) excludes the diffuse Galactic neutrino emission as the major cause of the “spectral anomaly” between the two hemispheres measured by IceCube.
WIMPs accumulate in massive celestial objects (Sun, Galactic Centre, …)
- Neutrinos could be produced in WIMP-WIMP annihilation
- Clean signal and low expected background

**Ingredients** used in the analysis:
- Signal energy spectra for each considered WIMP mass and annihilation channel:
  \[ WIMP + WIMP \rightarrow b\bar{b}, W^+ W^-, \tau^+ \tau^-, \mu^+ \mu^- , \nu\bar{\nu} \]
- Spatial distribution of dark matter in the source:
  - Point-like (Sun)
  - NFW, Burkert, McMillan halos (GC)

- No excess above background observed;
- Upper limits derived, as a function of the WIMP mass and annihilation channel on
  - spin-(in)dependent WIMP-nucleon scattering cross-section (Sun)
  - thermally averaged annihilation cross-section (Galactic center)

(Earth) Physics of the Dark Universe 16 (2017) 41
Gamma-ray Coordinates Network (GCN)
https://gcn.gsfc.nasa.gov/

ANTARES: Multi Messenger Searches

Participation to APP35 (2012)530, JCAP02(2016)062

GeV-TeV γ-rays
Fermi, HESS, HAWC, CTA

Radio/Optic /X-ray
TAROT, MASTER, Swift, INTEGRAL, MWA

Neutrinos
IceCube, GVD, SNEWS

UHECR
Auger, TA

Gravitational Waves
VIRGO, LIGO

Receive alerts
Generate alerts

Only spatial coincidence
Multi Messenger Searches: neutrino alerts from ANTARES.

### ANTARES real time alerts:

- **Time to send an alert:** ~5 s
- **Track median angular resolution:** 0.5°
- **Doublet of neutrinos:** ~0.04 events/yr
- **Single neutrino with direction close to local galaxies:** ~1 TeV, ~10 events/yr
- **Single HE neutrinos:** ~5 TeV, 20 ev/yr
- **Single VHE neutrinos:** ~30 TeV, ~3-4 ev/yr

### Sent neutrino alerts (2009-2018)

- 302 to robotic telescopes
- +19 to Swift
- +15 to INTEGRAL (3 followed)
- +22 to MWA (radio)
- +2 to HESS

In 2019 12 alerts (6 DIR, 4 HE, 2 VHE)
Online searches for $\nu$'s associated to IceCube-170922A

**EHE**
- Direction in ANTARES: 14.2° below horizon
- Use of a fast online algorithm that selects only upgoing candidates
- No upgoing $\nu$ candidate recorded within 3° of IceCube event and within ±1 h time-window centred on the event time
- No events within ±1 day

Time-integrated search for neutrinos from TXS 0506+056
- Maximum likelihood ratio approach used in PS searches (Phys. Rev. D 96, 082001)
- Expected background from the source in 2424 days livetime:
  - 0.18/deg$^2$ for track-like
  - 0.004/deg$^2$ for shower-like events
- # of signal events, $\mu_{\text{sig}}$, fitting the likelihood signal function for the source: $\mu_{\text{sig}} = 1.03$
- Pre-trial p-value of 2.6% to be compatible with background only
- In the list of 107 pre-selected sources, only two have smaller p-value

Time-dependent search for neutrinos from TXS 0506+056
- Two time window shapes: Gaussian (500 days) and rectangular (158 days)
- Selection cuts which optimise the MRF with flux $\sim E^{-\gamma}$ ($\gamma = 2.0, 2.1, 2.2$)
- No signal found after data unblinding.
Recent spotlight on the GW events detected by the Ligo-Virgo Collaboration:

- GW150914 (BBH merger)
- GW151226 (BBH merger)
- LVT151012 (candidate)
- GW170104 (BBH merger)
- GW170817 (NS merger)

So far no coincidences with neutrino from the region of interest at 90% C.L.:

the jet of the NS-NS event (GW170817) was not aligned to our line of sight to provide a visible neutrino signal → upper limit on the neutrino fluence from each events over the whole spectrum

**ANTARES and a few KM3NeT lines operational since the beginning of Virgo/LIGO run O3 (April 2019 - June 2020).**

So far 17 alerts received and 12 follow-ups, without no evidence of neutrino
One possibility to measure the pointing accuracy is to measure the shadow of the Moon, i.e. the deficit in the atmospheric muon flux in the direction of the Moon induced by absorption of cosmic rays.

Data from 2007-2016 -

Moon shadow observed at 3.5 σ significance level;
Angular resolution for downgoing tracks $\sigma_{\text{res}} = 0.73^\circ \pm 0.14^\circ$

The position of the Moon shadow is consistent with the Moon nominal position.
Time Correlation searches with IC:
  https://doi.org/10.3847/1538-4357/ab253c

Fast Radio Bursts:
- arXiv:1807.04045

Gamma ray bursts:
- MNRAS 469,906–915 (2017)

Neutrino Oscillation
- JHEP 06 (2019) 113

Magnetic Monopoles:
- JHEP 07 (2017) 054

Sea and Earth Science
- Scientific Reports 7(2017): 45517
  - Jou. Geophysical Research 122(2017) 2291
  - Ocean Dynamics 64 (2014)507–517
  - Deep-Sea Research I 58(2011)875

During operation on the ANTARES/KM3NeT site, last summer
ANTARES: Neutrino telescope in the Northern hemisphere, in the Mediterranean Sea

More than 10 years of continuous data taking!
... and still stably ongoing!

Results from various searches, from astrophysical neutrino emission to atmospheric neutrinos:
- diffuse
- point-like
- extended regions
- dark matter
- neutrino oscillations

Active multi-messenger program:
- Neutrino alerts distribution, participation to GCN and AMON
- External alerts reception, prompt analysis (looking for neutrinos in coincidence with GW events expected during the Ligo/Virgo O3, waiting for KM3NeT)
- Offline multi-messenger analysis.
- Combined analyses with IceCube (point sources, galactic plane, time correlation...).

Outlook: continue data taking possibly for all the Ligo-Virgo O3 run - upgrade the analyses with the full livetime.
Thank You
- **ANTARES** Alert VHE (Sept. 1, 2015) $\rightarrow$ E$\sim$50 TeV; RA=246.3°; $\delta$=-27.4°
- Sent after 10 s to MASTER, Swift-XRT

- IceCube: no event detected
- H.E.S.S.: No VHE transient source
  $\Phi(E > 320\text{GeV};99\%\text{C.L.}) < 2.7 \times 10^{-8}\text{m}^{-2}\text{s}^{-1}$

- Unknown, relatively bright and variable X-ray source-(0.5-1.4)$\times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ detected by Swift XRT 9h after the ATEL
- Great interest in the community (15ATels+6 GCN)
- Later, the X-ray source associated with a **young accreting G-K star**, or a binary system of active stars undergoing a **flaring episode** with X-ray emission.
- No relevant accelerator of CR, then no $\nu$ source, is connected to this object.
4 bright GRBs have been selected: 
GRB080916C, GRB110918A, GRB130427A and GRB130505A

**Upper limits**
Two models investigated:
- internal shock (IS)
- photospheric (PH)

**Constraints** on baryonic component $f_p$ and Lorentz factor $\Gamma$

- 90% C.L. (solid line)
- 50% C.L. (dashed line)

The red dot shows the benchmark values $f_p = 10$ and $\Gamma = 316$.

(a) IS constraints on GRB130505A.
(b) PH constraints on GRB130427A.
16 FRB (Parkes, UTMOST, ASKAP) → 12 in the FoV during the data taking.
± 6h search period in 2°.
Event selection optimization – 1 seen neutrino = 3σ discovery.
No events found → limits set.

Fluence 90% C.L for $E^{-\gamma}$
- $\gamma = 1.0$
- $\gamma = 2.0$
- $\gamma = 2.5$
- 2830 days of live-time
- Track channel only
- 7710 events selected
- 3-flavor oscillation through matter taken into account
- Atmospheric $\mu$ background extrapolated from data
- Binned likelihood fit in 2D ($\log_{10} E_{\text{reco}}$ and $\cos \theta_{\text{reco}}$)

No-oscillation hypothesis excluded at 4.6$\sigma$ (was 2.3$\sigma$ in former analysis)

JHEP06(2019)113

90% C.L. Contours
Flux decreases with energy
Need larger and larger detectors
Do diffuse Galactic vs contribute to the IceCube astrophysical signal?

- Neutrinos allow testing **CRs propagation**
- Dense matter regions boost $\gamma$ and $\nu$ fluxes
- Models can be tuned to $\gamma$ and CR observations
- Northern Hemisphere optimal point of view for galactic CR
• 2830 days of livetime
• Track channel only
• 7710 events selected
• 3-flavor oscillation through matter taken into account
• Atmospheric $\mu$ background extrapolated from data
• Binned likelihood fit in 2D ($\log_{10} E_{\text{reco}}$ and $\cos \theta_{\text{reco}}$)

The best fit value is found for $\Delta m_{32}^2 = 1.9 \times 10^{-3} \text{eV}^2$
and for $\theta_{23}$ compatible with maximal mixing.

No-oscillation hypothesis excluded at 4.6$\sigma$ (was 2.2$\sigma$ in former analysis)
Distribution of ANTARES events in the (RA, δ) coordinates around the position of TXS 0506+056. The inner (outer) green line depicts the 1° (5°) distance from the source. The blue (red) points indicate track(shower)-like events. Different tones of red and blue correspond to the values assumed by the energy estimators.
### SHOWERS:

- $\nu_e$ CC, $\nu_{\text{all}}$ NC

### TRACKS:

- $\nu_\mu$ CC

### ANGULAR RESOLUTIONS:

#### ANTARES

- $\nu_e$ CC, $\nu_{\text{all}}$ NC
  - $\Delta \theta < 0.4$ deg
  - $\Delta \theta < 0.1$ deg @ $E_\nu > 100$ TeV
  - $\Delta \theta < 0.4$ deg @ $E_\nu > 10$ TeV

#### KM3NeT ARCA

- $\nu_\mu$ CC
  - $\Delta \theta < 0.1$ deg @ $E_\nu > 100$ TeV
  - $\Delta \theta < 2$ deg

#### SHOWERS:

- $\nu_e$ CC, $\nu_{\text{all}}$ NC
  - $\Delta \theta < 3$ deg