The Multi-Messenger Search Programme and Results of the ANTARES Neutrino Telescope

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on behalf of

the ANTARES Collaboration

http://antares.in2p3.fr/

RICAP-14

Roma International Conference on Astroparticle Physics

September 30th-October 3rd

Noto (SR), Italy

Outline

- The Multi-Messenger approach in Astronomy&Astrophysics
- Multi-Messenger Searches with ANTARES

→ ANTARES Detector Setup

→ Selected Results

  - flaring sources: galactic (μ-Quasars) and extra-galactic (AGNs)
  - GRBs
  - correlation with UHECR
  - TAToO
  - GWHEN

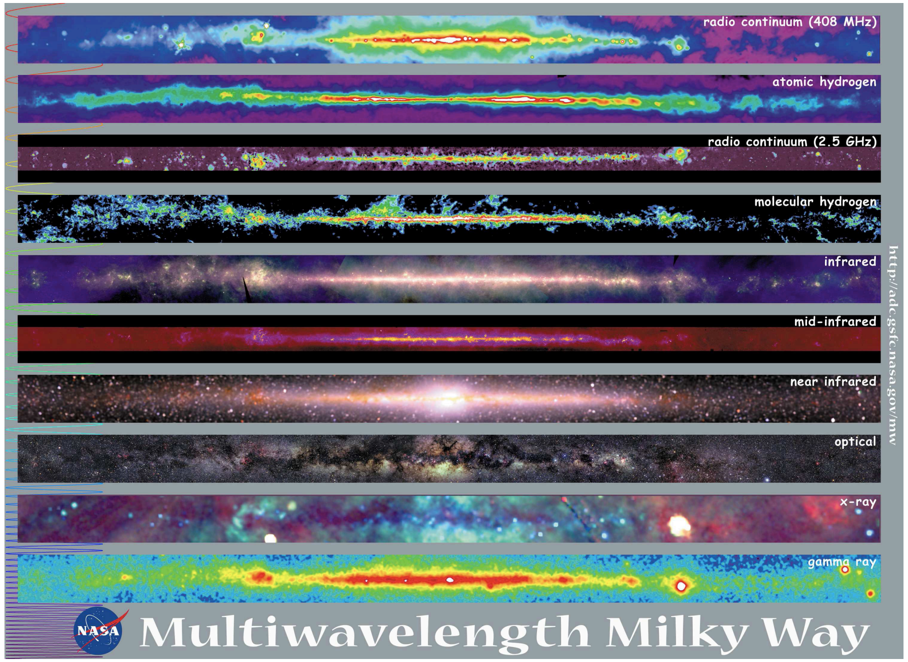
- Conclusions & Summary

The "(r)evolution" of Astronomy

- From Traditional Astronomy (Optics) to Multi-Wavelength Astronomy

Observations of light in the visible band are complemented by radio, X-ray and gamma-ray astronomy

Galileo Galilei showing the Doge of Venice how to use the telescope (1858), fresco by Giuseppe Bertini (1825–1898)

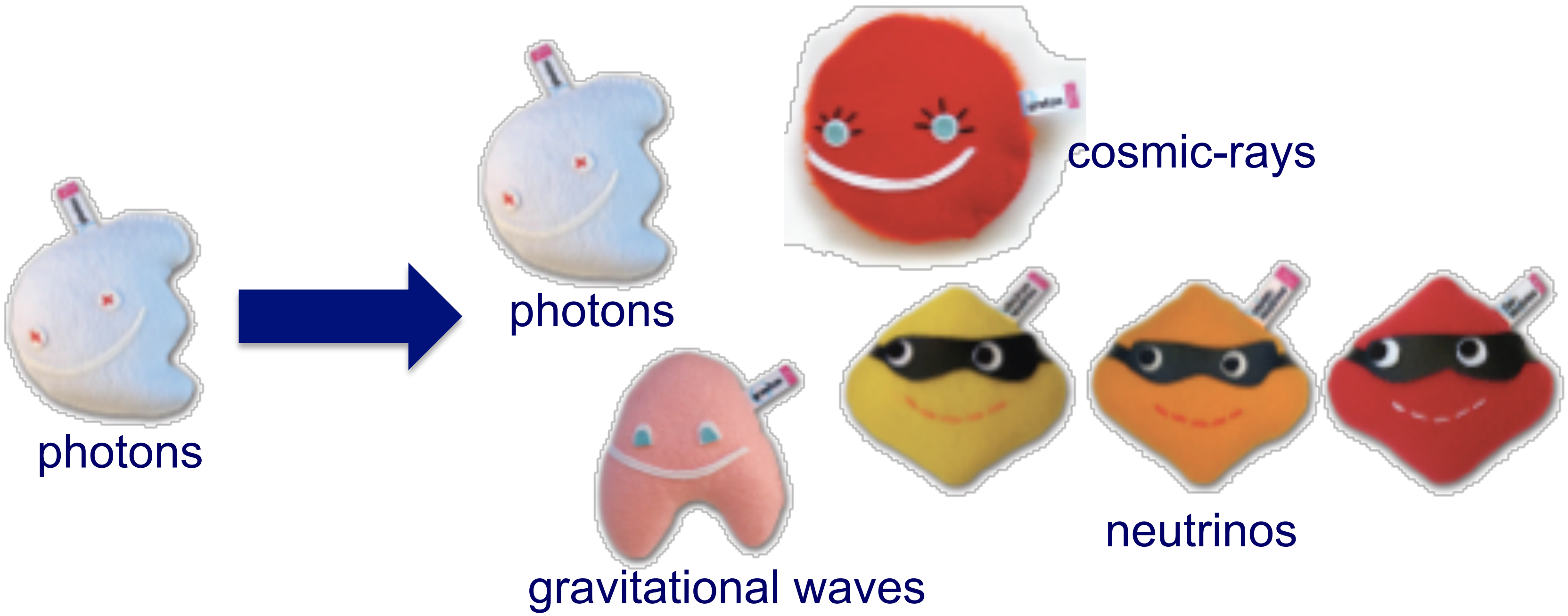


http://mwmw.gsfc.nasa.gov/

Next Step: no more only Photons!

- From Multi-Wavelength Astronomy to Multi-Messenger Astronomy

New “actors” are coming into play in the scene of Astronomy&Astrophysics. **New messengers** from the Cosmos can be added in the list, enriching and complementing the information provided by photons at any wavelength.



CAST by the Particle Zoo
http://www.particlezoo.net/

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The Multi-Messenger Approach

(… a "*manifesto*")

The Multi-Messenger Approach:

- connects Astronomy with Astrophysics and Particle Physics
  → **Astro-Particle Physics** (… and the RICAP Conferences!)
- opens new windows in Cosmology and in the Theory of Gravity;
- gives some hints of New Physics beyond the Standard Model.

- promotes the **collaboration between different experiments**: joining the efforts and skills, additional tools for data analysis can be made available.

Advantages of the Multi-Messenger Approach

(… in particular for **Neutrino detectors**, since potential astrophysical sources are predicted to emit **faint signals** and the presence of an **isotropic flux of atmospheric background** requires the development of effective search strategies)

The different messengers (all of them or some of them, depending on the model and on the type of source) are expected to be produced in the same astrophysical site. Thus, the Multi-Messenger Approach:

- increases the **discovery potential**, by observing the same source with different probes (noteworthy for transient or flaring sources)
- improves the **statistical significance** of the observations, by coincident detection (sustained by the development of alert systems between the experiments)
- refines the **efficiency** of the detection, by profiting of relaxed cuts (exploiting the advantages of time-dependent analysis)

Neutrino Astronomy in the Multi-Messenger Framework

The strongest connection is with **Gamma** (and X-ray) **Astronomy**, since both γs and νs are expected from cosmic emitters if **hadronic processes** take place: hadrons, confined by magnetic fields inside the astrophisical sites, are accelerated through repeated scattering by plasma shock fronts (Fermi acceleration); collisions of hadrons with ambient plasma produce γs and νs through **pion photoproduction** mechanisms; both γs and νs are linked to CRs.

$$p + N,\gamma \to X + \begin{array}{l} \pi^{\pm} \to \text{neutrinos} \\ \pi^{0} \to \gamma\text{-rays} \end{array}$$

Confirmed gamma-ray sources are the first target of neutrino telescopes observations, see for instance:

- ANTARES results for point-like sources (the list of candidate sources is a list of gamma-ray emitters) [talk by F. Schüssler]
- ANTARES results for the diffuse neutrino emission from Fermi Bubbles and from the Galactic Plane [talk by L.A. Fusco]

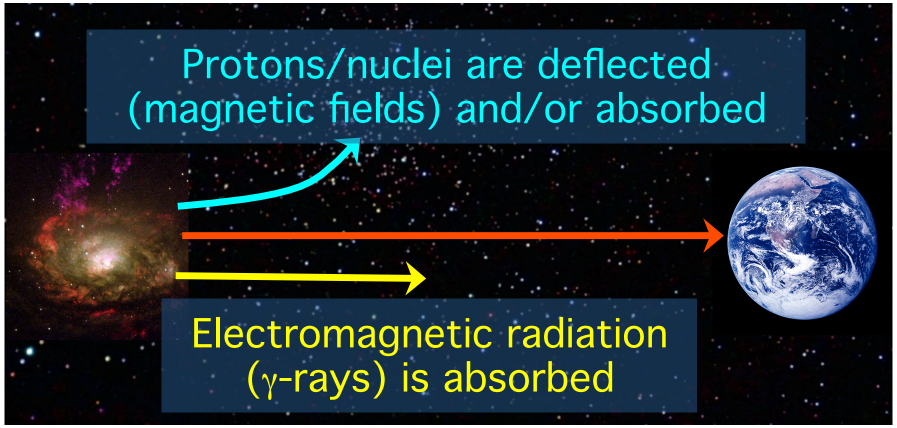
Searches of the ANTARES Multi-Messenger Programme regard specifically **time-dependent analysis** (transient and flaring sources).

More on the Neutrino Case

In the framework of the Multi-Messenger Astronomy&Astrophysics, neutrinos aim at assuming non only a “supporting” role (complementary source of information for photon Astronomy), but a **leading role**.

Astronomy can be done even *without photons!*

Because of their peculiar interaction properties neutrinos can offer unique opportunities **to look further away and deeper inside astrophysical objects**: in contrast to photons and charged cosmic rays, neutrinos can find their way out, without scattering or absorption, from the very inner core of dense astrophysical objects, providing information about sites that are opaque to electromagnetic radiation and revealing the existence of so-far undetected sources (“**hidden sources**”). The neutrino signal, if detected, can provide a **trigger** for other “penetrating” probes (like gravitational waves).



Completed in May 2008

J. Aguilar *et al.*, “ANTARES: the first undersea neutrino telescope”, *Nucl. Instr. and Meth.*A 656 (2011) 11-38 [arXiv:1104.1607v1]

ANTARES

Astronomy with a Neutrino Telescope and Abyss environmental RESearch

The Largest Neutrino Detector in the Northern Hemisphere

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

~~MULTISDISCIPLINARITY~~ → associated sciences (oceanography, marine biology, geology ...)

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

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

The Multi-Messenger Search Programme with ANTARES

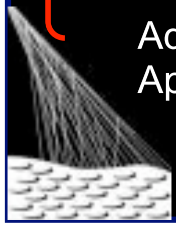
Neutrinos trigger others

Others trigger neutrinos

ANTARES ⟺ VIRGO LIGO

common working group (**GWHEN**)

S. Adrián-Martínez et al.
JCAP 06 (2013) 008



ANTARES ⟺ AUGER

Adrian-Martinez et al.,
ApJ 774 (2013) 008

Flaring Sources

(ν emission from γ-flaring blazars/μQuasars)

ANTARES ⟺ Gamma-Rays X-Rays

blazars: APP 36 (2012) 304;
μQuasars: JHEAp, 3-4 (2014) 9-7

TAToO

(Telescopes – ANTARES Target of Opportunity)

Optical follow-up of **neutrino alerts** for transient source search (GRBs, SNae). **Analysis in progress!**

ANTARES ⟺ Optical Telescopes
TAROT & ROSTE + more

Ageron *et al.*, *Astrop.Phys* 35 (2012) 530-536

GCN

(**GRB** Coordinat. Network)

ANTARES ⟺ GCN

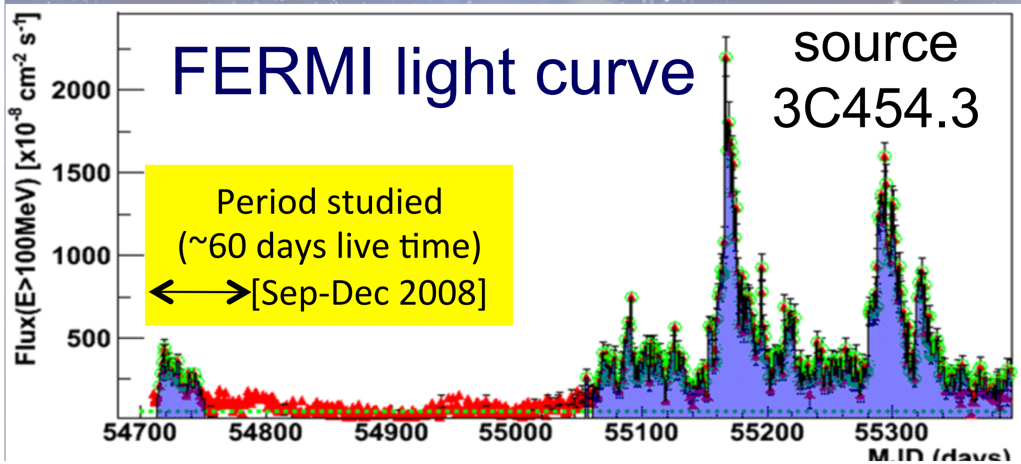
A&A 559, A9 (2013),
JCAP 1303 (2013) 006

Astropart. Phys. 36 (2012) 204–210, arXiv:1111.3473 [astro-ph.HE]

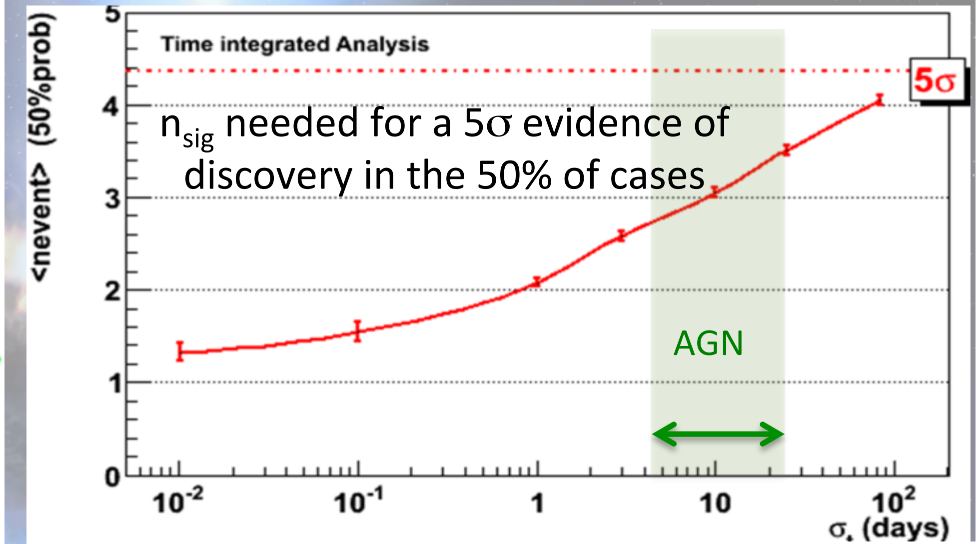
ν emission from γ-flaring blazars

AGN Flares (2008)

ANTARES ⟷ FERMI



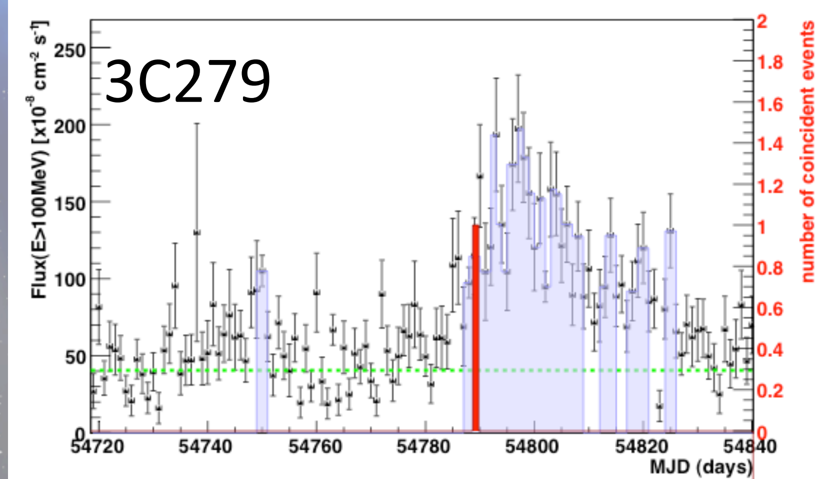
10 sources selected from the FERMI/LAT catalog, showing a large **variability** (flaring state) in the period studied for this analysis.



Performance of the **time-dependent analysis**

RESULTS

- **1 neutrino candidate event** compatible with the time/space distribution ($\Delta\alpha$=0.56°) of 3C279 with probability (p-value) = 1% (but post trial probability = 10%)
- **Fluence Upper Limits**



Astropart. Phys. 36 (2012) 204–210,
arXiv:1111.3473 [astro-ph.HE]

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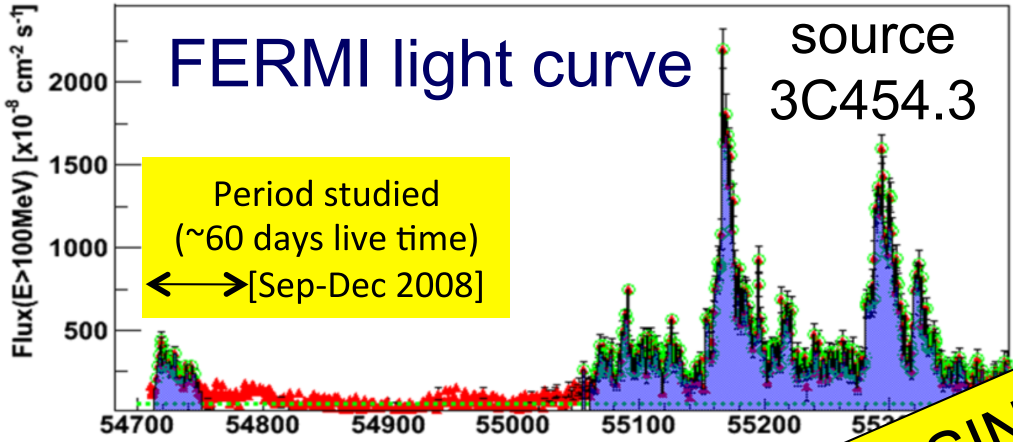
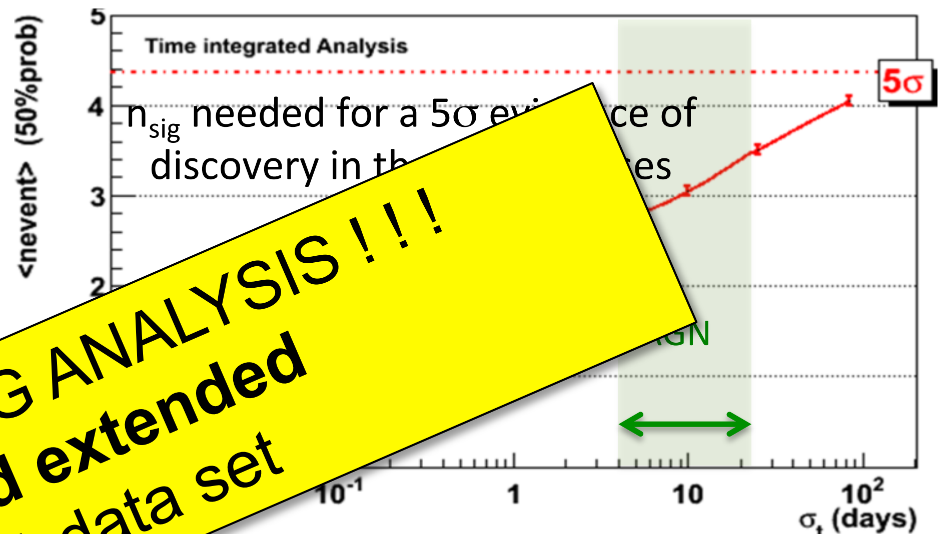
ANTARES ⟺ FERMI



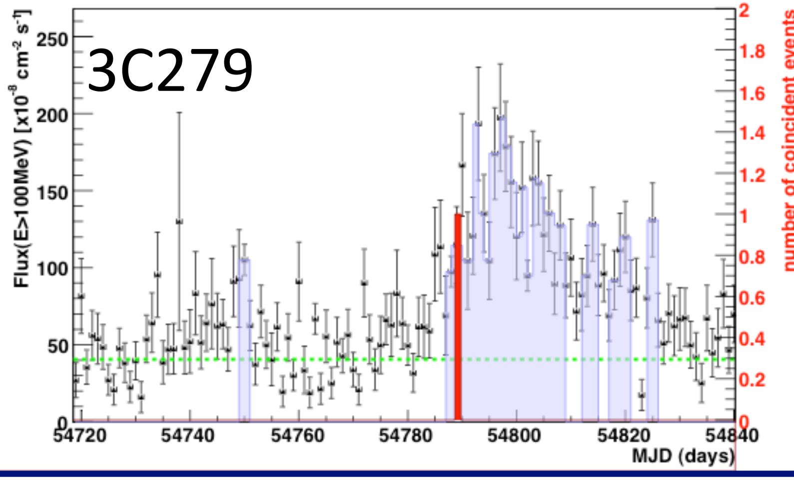
10 sources selected from the ... catalog, showing a large ... state) in the period stu...



...mance of the **time-dependent analysis**

! ! ! VERY PROMISING ANALYSIS ! ! !
studied period extended
to 2008-2011 data set

- **1 neutri**... **event** compatible with the time/sp... istribution (Δα=0.56°) of 3C279 with probability (p-value) = 1% (but post trial probability = 10%)
- **Fluence Upper Limits**



PRELIMINARY

AGN Flares (2008-2011)

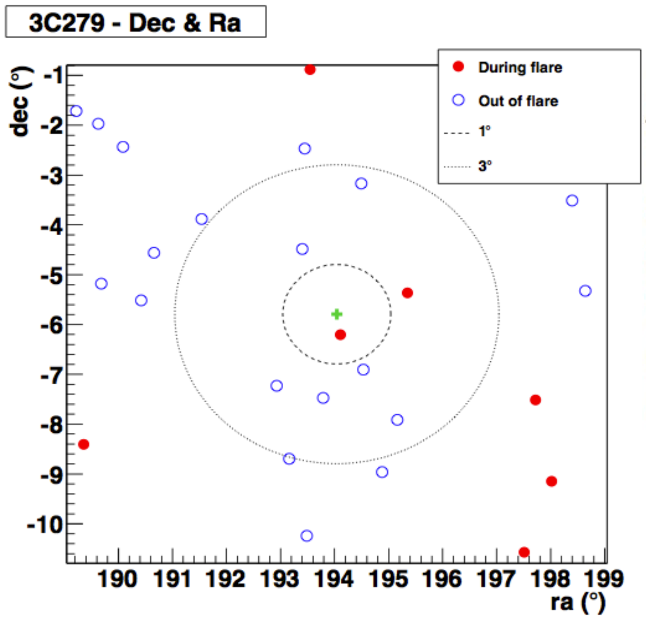
[40 sources, 86 flaring periods]   [ANTARES ⟺ FERMI]

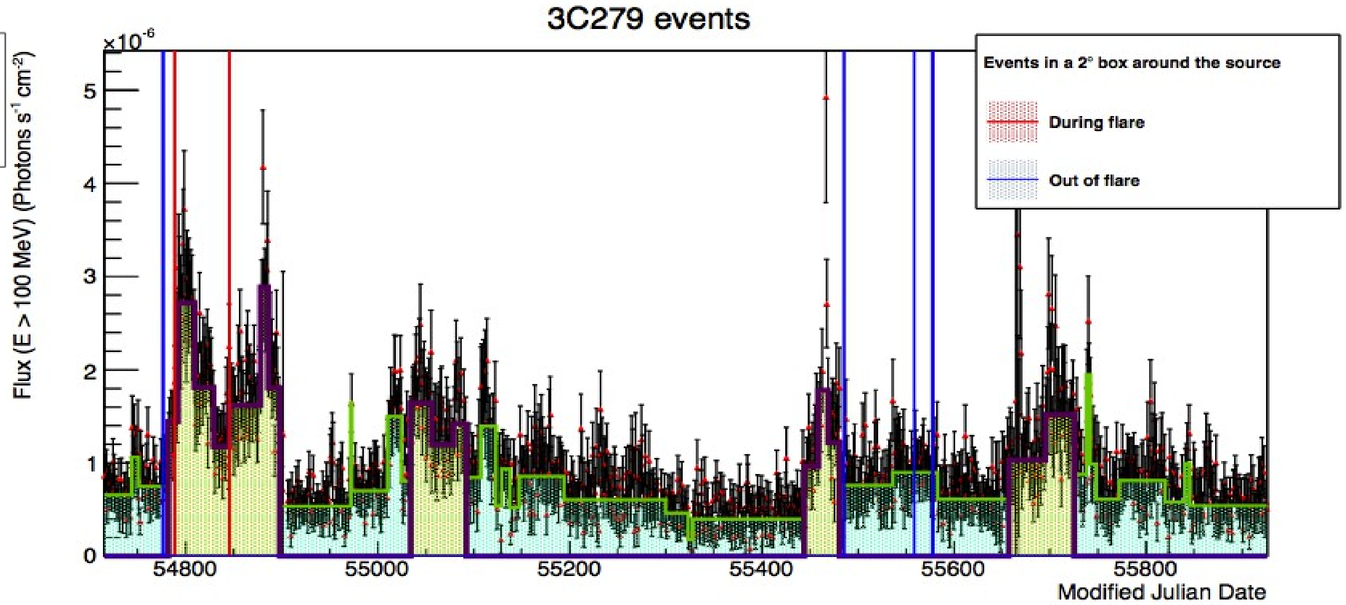
...to be extended to IACT blazars (HESS, MAGIC, VERITAS)

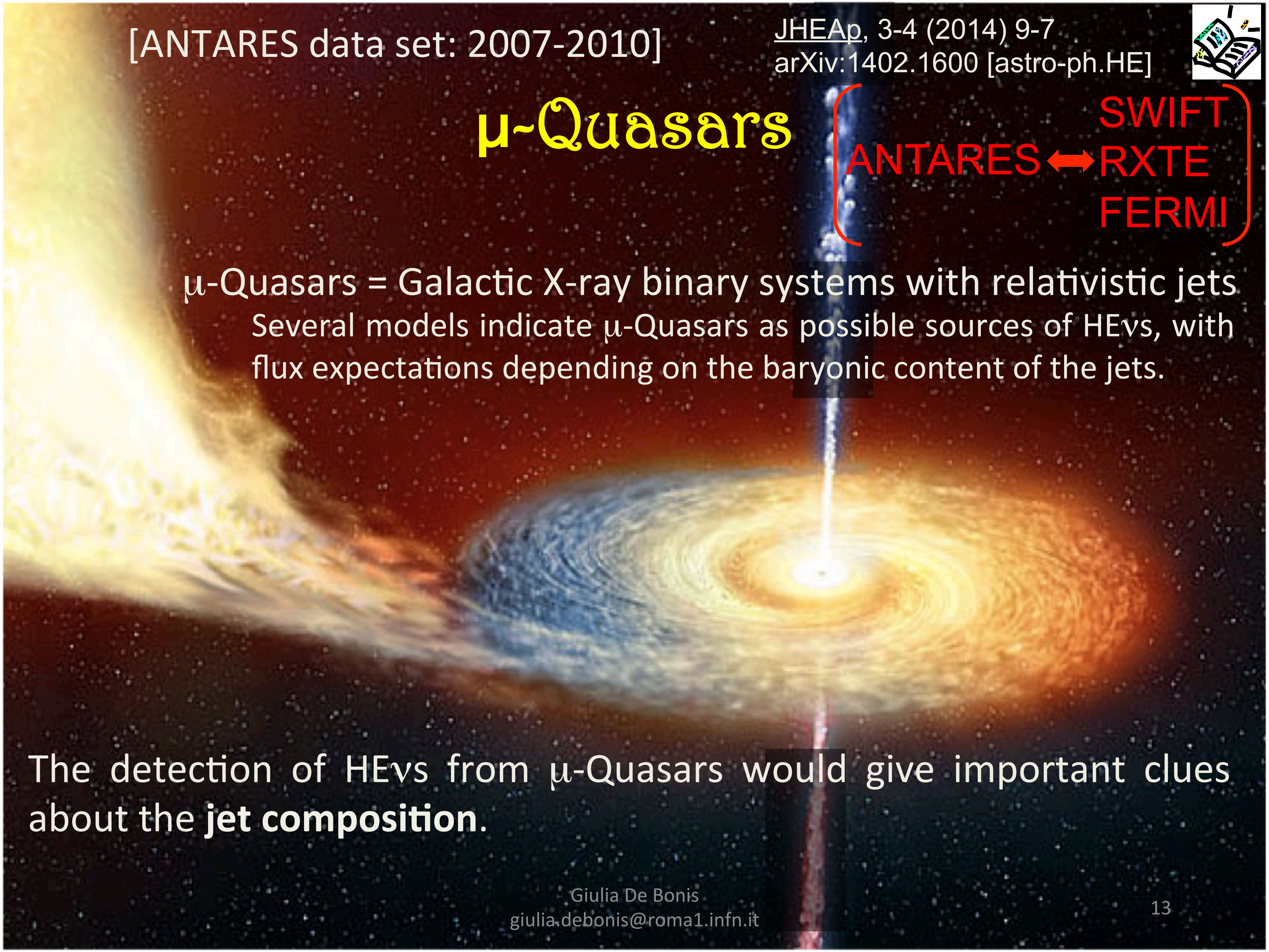
6 specially significant flares

p-values (Pre-trial/Post-trial)				
Source	E^{-1}	E^{-2}	$E^{-2}exp^{-E/10TeV}$	$E^{-2}exp^{-E/1TeV}$
3C 279	**0.17%/9.91%**	0.33%/14.5%	5.31%/73.5%	6.68%/89.4%
PKS 1124-186	1.94%/54.3%	**1.07%/41.29%**	1.68%/55.1%	3.85%/82.2%
PKS 1830-211	2.67%/69.5%	**1.43%/52.8%**	3.08%/72.6%	6.64%/91.6%
3C 454.3	**3.53%/67.7%**	—	—	—
4C +21.35	**3.68%/68.9%**	—	5.31%/73.5%%	—
CTA 102	—	**4.62%/86.5%**	—	—

(—) Those cases have a fitted signal $n_{sig} \lesssim 0.001$ and p-value∼100%







[ANTARES data set: 2007-2010]

JHEAp, 3-4 (2014) 9-7
arXiv:1402.1600 [astro-ph.HE]

μ-Quasars

ANTARES ⬌ SWIFT / RXTE / FERMI

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**.

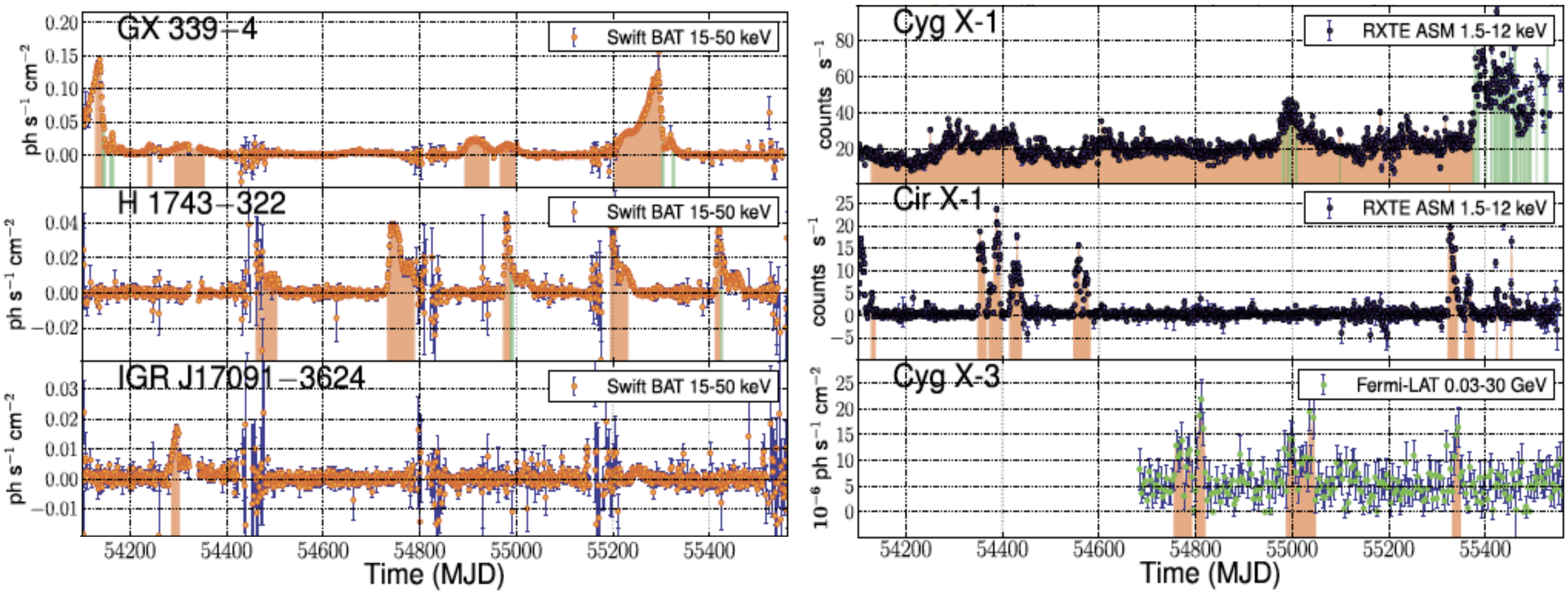
µ~Quasars

JHEAp, 3-4 (2014) 9-7
arXiv:1402.1600 [astro-ph.HE]

ANTARES data set: 2007-2010 → 6 sources selected, with requisites:

- in the ANTARES visibility;
- 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).



JHEAp, 3-4 (2014) 9-7
arXiv:1402.1600 [astro-ph.HE]

ν emission from μ-Quasars

µ-Quasars [Data Analysis & Results]

METHOD

- unbinned search
- likelihood ratio test statistic
- quality cuts optim. for 5σ discovery

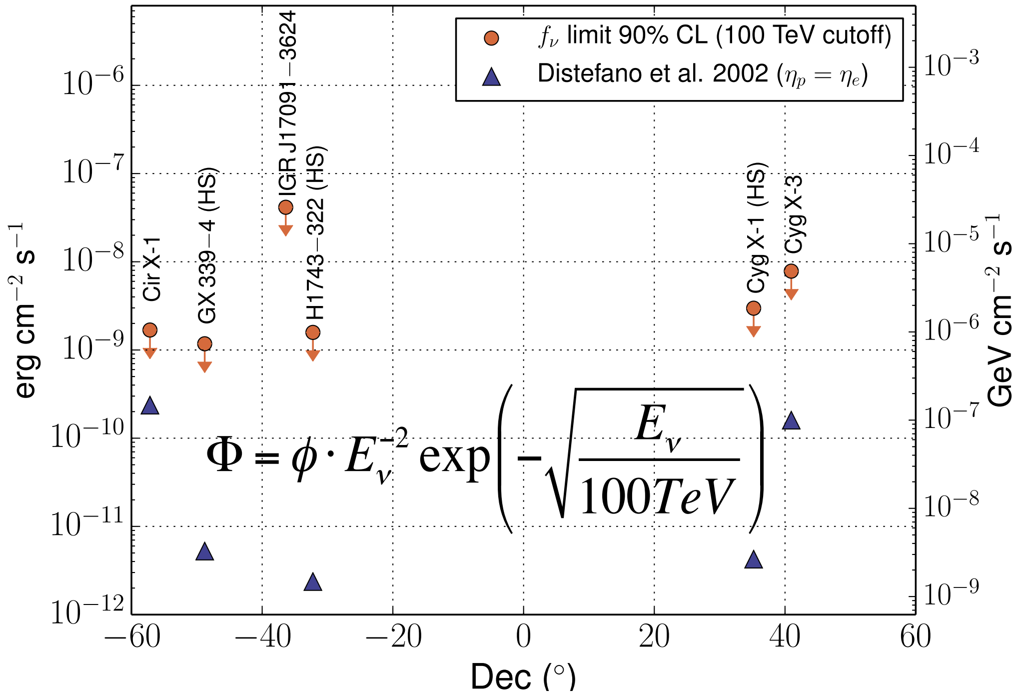
RESULTS

no statistically significant excess
above the expected atmo. bkg

90% C.L. upper limits
on the flux normalization ϕ

…assuming a neutrino spectrum following:

- a power-law
- a power-law with expo. cut-off



[systematic uncertainties included]

→ INFER INFORMATION on JET COMPOSITION: constraints on η_p/η_e
= ratio of proton to electron luminosity in the jet

For some sources, the obtained upper limits already constraint some emission models.

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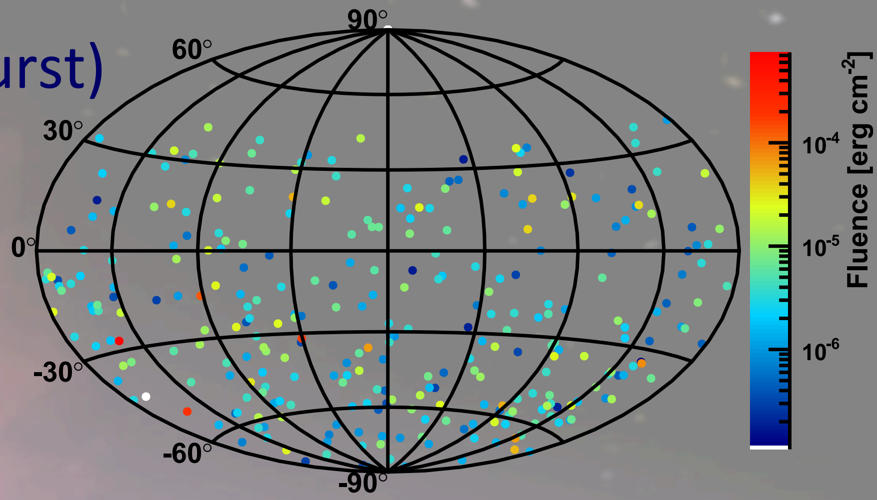
ANTARES ⟺ GCN

A&A 559, A9 (2013)

GRBs

data set: 2007-2011, 296 GRBs (long burst)

Search for muon neutrinos



Multi-Messenger Analysis: the requirement of temporal and spatial (10° around the source) coincidence with a GRB reduces the background to $\mathcal{O}(10^{-4})$ per GRB → **selection cuts can be loosen** (optimised per GRB)

Theoretical predictions for each individual burst

- analytical approach (Guetta 2004)
- numerical approach NeuCosmA (Hümmer 2012) [one order of magnitude smaller]

Stacking Analysis

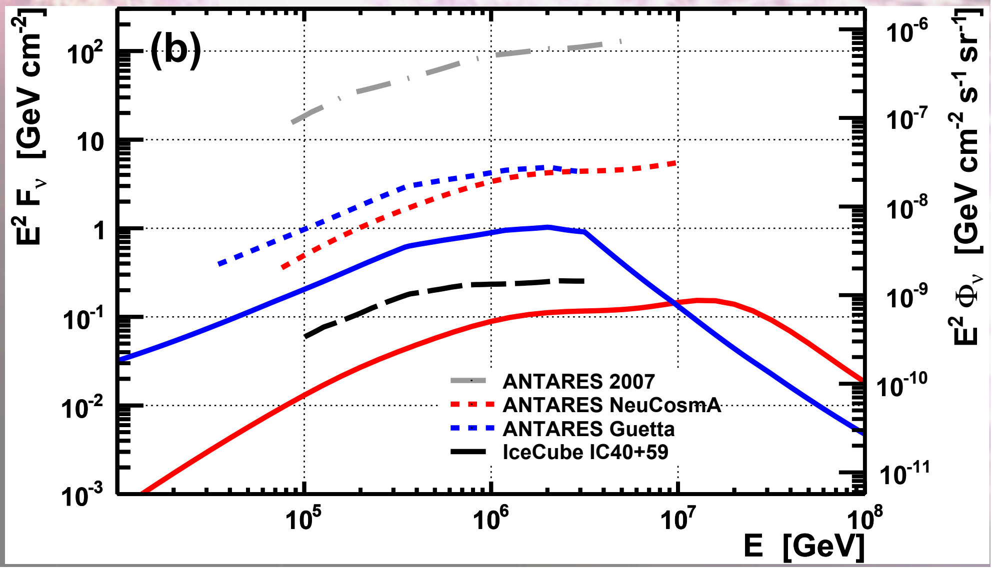
Background extracted from data

RESULTS

no coincident ν_μ found

↓

90% C.L. upper limits



ApJ 774 (2013) 008,
arXiv:1202.6661 [astro-ph.HE]

Correlation with UHECRs

-Search for correlation in the arrival directions of **2190 neutrino candidate events** (detected by ANTARES in 2007-2008, effective live time: 304 days) and **69 UHECRs** (detected by **Pierre AUGER Observatory** in 2004-2009, $E>10^{19.74}$ eV, all the events in the ANTARES telescope field of view).

-**Source Stacking Method**.

-UHECR magnetic deflection = 3° (light composition assumed)

-Statistical significance and optimal angular search bin is determined by 10^6 pseudo-experiments, each containing the 69 AUGER events at fixed coordinates and the 2190 neutrino events scrambled in right ascension.

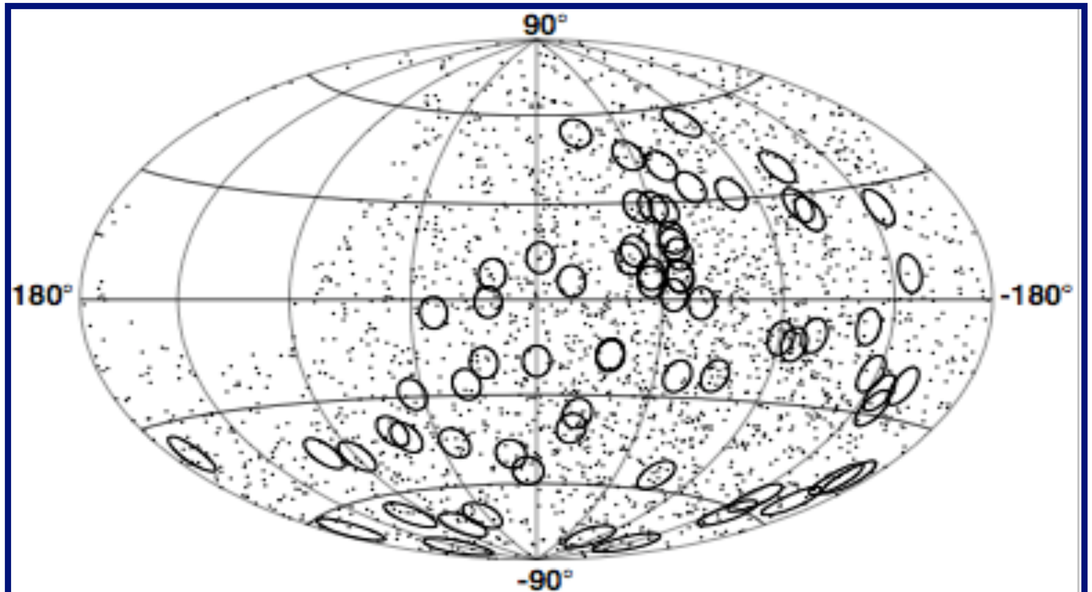
no significant correlation observed

↓

Upper Limit on the Neutrino Flux

4.99×10^{-8} GeV cm^{-2} s^{-1}

(assuming a E^{-2} energy spectrum)



Skymap in Galactic Coordinates; neutrino events are represented with black dots and angular search bins of 4.9° centered on the observed UHECRs with black circles.

ANTARES ⟷ VIRGO LIGO

JCAP 06 (2013) 008

Gravitational Waves + High-Energy Neutrinos

GWHEN (2007)

ANTARES in 5-line configuration

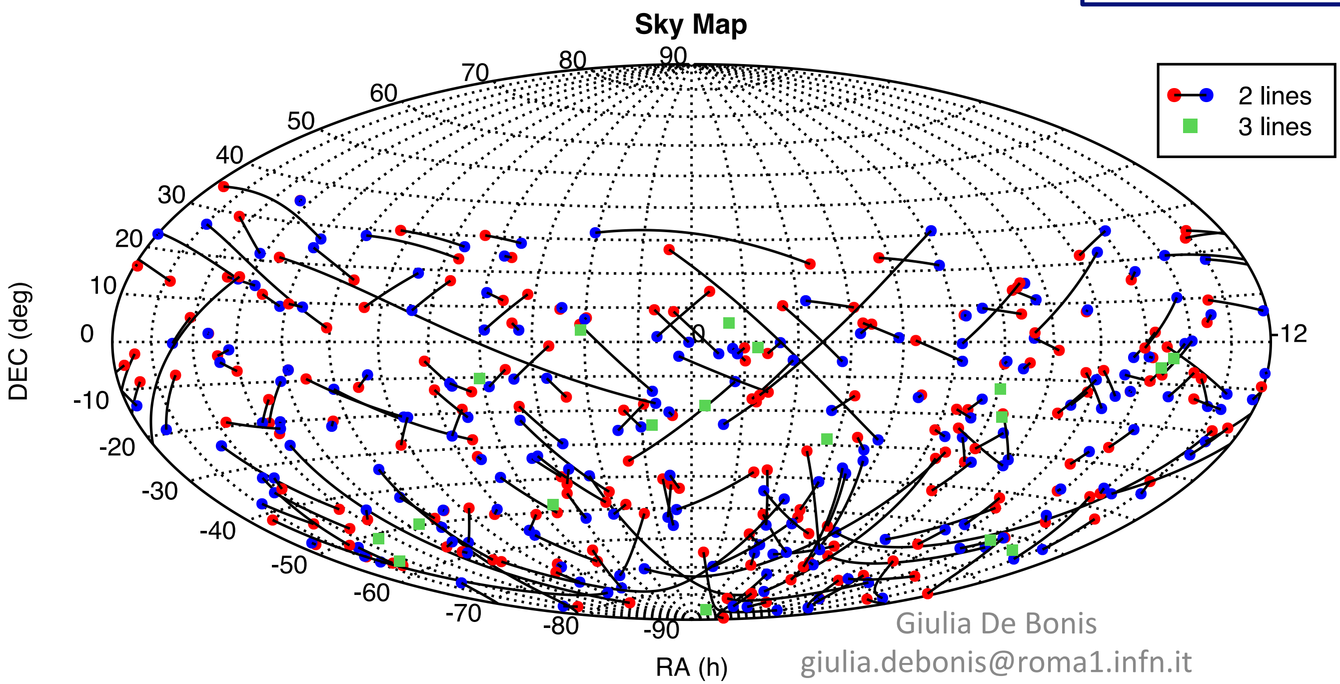
T_{obs}=91 days, 158 HEN selected
(14 reconstructed with ≥ 3 lines)

Search for gravitational wave signals coincident in time and direction with neutrino events.

CANDIDATE SOURCES GW+HEN

- GRBs [extra-galactic]
- bursting magnetars (SGRs) [galactic]
- topological defects

also sources with no electro-magnetic counterpart ("hidden sources")



The skymap contains the full set of 216 selected HEN, but events used for the joint analysis are only those occurred when ≥2 GW detectors were in operation. Azimuthal degeneracy of the reconstruction causes mirror tracks for events reconstructed with 2 lines.

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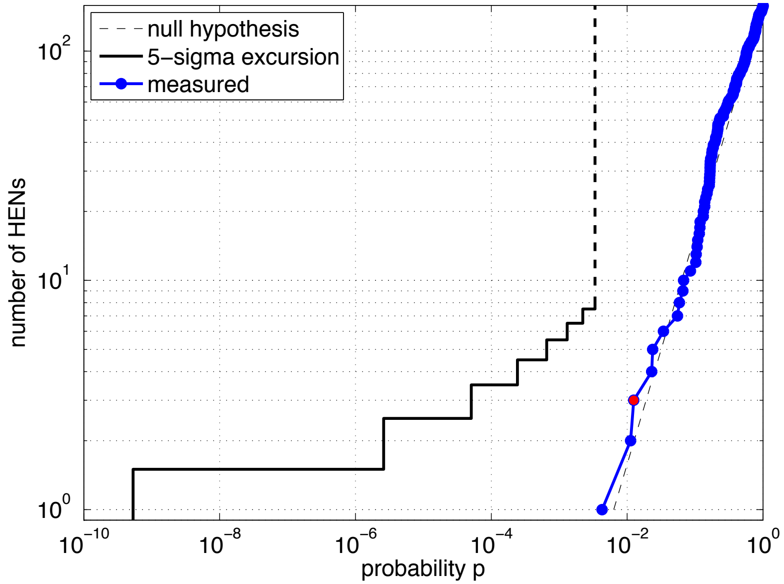
ANTARES ↔ VIRGO LIGO

JCAP 06 (2013) 008

GWHEN (2007) - Results



no gravitational wave burst associated with any selected neutrinos

(p-values compatible with the null hypothesis)

⬇

- ***90% C.L. limits on the EXCLUSION DISTANCE of the sources***
- ***90% C.L. limits on the rate density of common (GW+HEN) sources***

(the limits are computed with assumption on the type of source and on the emission model)

Work in progress: GWHEN 2009

(extended data set, ANTARES 12 lines, better reco. algo. for GW & HEN)

129 days of common data taking → 1986 neutrino candidates

➡ factor 7 improvement in sensitivity and discovery potential

ANTARES ⟷ Optical Telescopes
TAROT & ROSTE + more

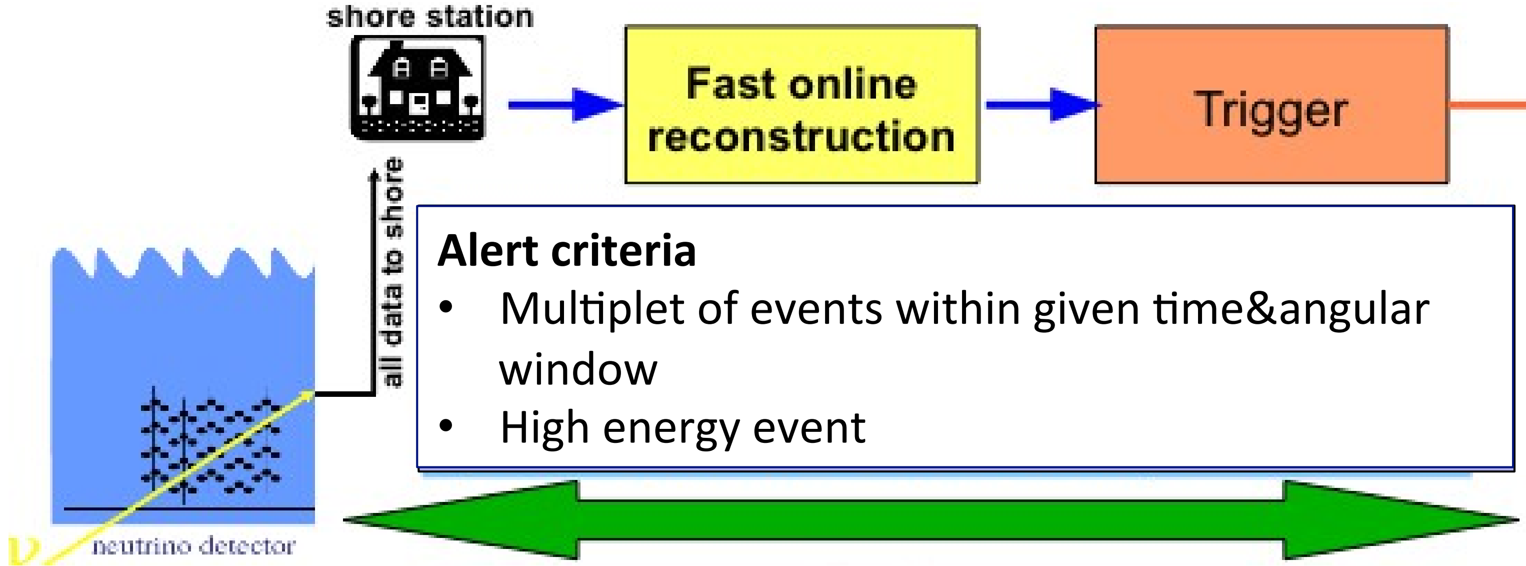
Astrop.Phys 35 (2012) 530-536
(performance improved!)

Telescopes-ANTARES Target of Opportunity

TAToO
alert system

Coincident observations of νs and optical signals from transient sources

A fast online muon track reconstruction to trigger a network of small automatic optical telescopes (**optical follow up**) [offline reconstruction for refined direction]



Alert criteria
- Multiplet of events within given time&angular window
- High energy event

optical telescopes (TAROT/ROTSE/ ZADKO/Skymapper)

Total latency: reco+trigger (<5s) alert sending (<10s) + repositioning (<5s)

The ANTARES opportunity:
- large sky coverage
- high duty cycle
- pointing accuracy < 0.5°

data analysis IN PROGRESS!

Summary

- Data analysis of Neutrino Telescopes is performed following a **Multi-Messenger Approach**, looking for connections with the information carried by the other messengers from the Cosmos (Gamma-Rays, Cosmic Rays and Gravitational Waves) and promoting correlations with the outcomes of other experiments.
- The ANTARES Multi-Messenger Programme focuses in particular on **transient and flaring sources**, exploiting the timing information provided by coincident detection.
- Both "**neutrinos trigger others**" & "**other trigger neutrinos**"
- The connection with Gamma-Rays and Cosmic Rays can give **evidence of hadronic processes** in the Universe and indications on CRs sources.
- The connection with Gravitational Waves can reveal the presence of "**hidden sources**", enlarging the horizon of Gamma-Astronomy.
- ANTARES results are competitive; data taking is on-going and **updated results** will be **soon released**.