High Energy Neutrino detection in multimessenger astrophysics.

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at the

The Future of Research on Cosmic Gamma Rays

La Palma, Canary Islands

26-29 August 2015

- The Multi-Messenger approach in Astronomy&Astrophysics
- HE astrophysical neutrino detection
- Multi-Messenger Searches with Neutrino Telescopes
- ANTARES Detector

→ Selected ANTARES Results

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

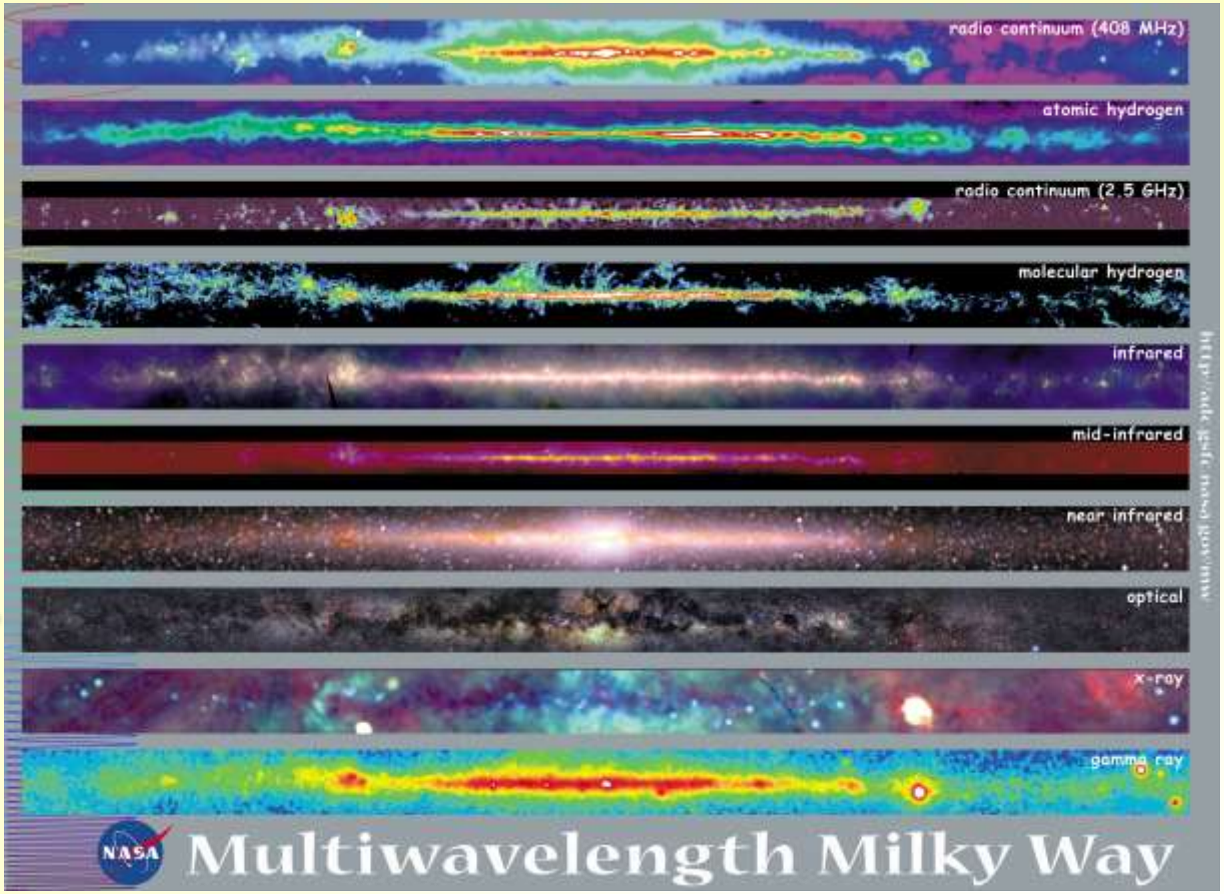
- Conclusions & Summary

The 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 γ 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/

by courtesy of G. De Bonis

Today and tomorrow: Multi-Messenger Astronomy

The search for different messengers from the Cosmos (originated at an astrophysical site)

- **Cosmic rays** (protons, nuclei)
- **Neutrinos**
- **Gravitational waves**

can complement the information provided by **photons** at any wavelength

The Multi-Messenger Approach

- connects Astronomy with Astrophysics and Particle Physics → Astroparticle Physics

- may open new windows in Cosmology and in the Theory of Gravity

- may give hints of New Physics (DM) beyond the Standard Model

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

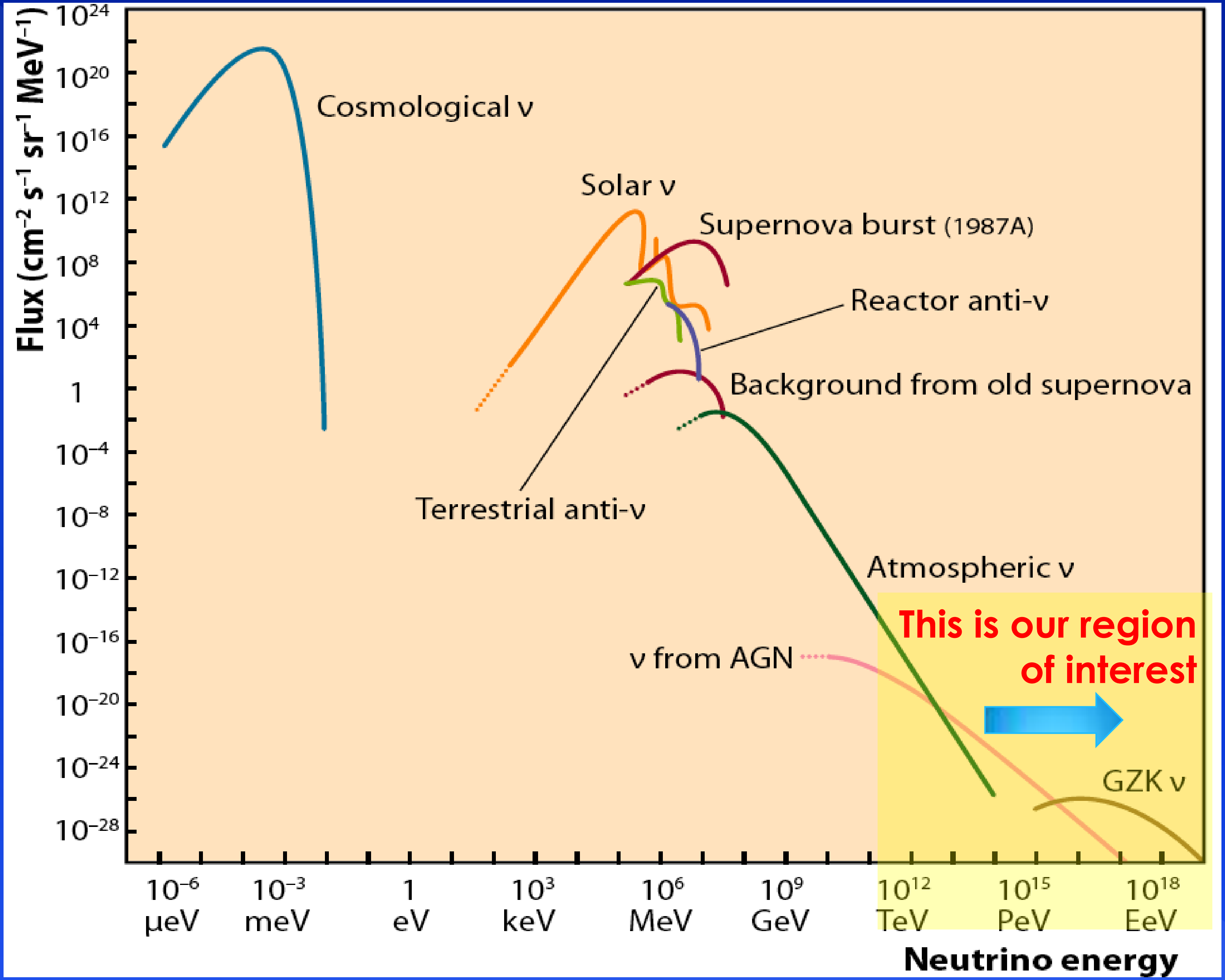
Advantages of the Multi-Messenger Approach

Assuming that **different messengers** (all or some of them, depending on the model and on the type of source) are **produced/accelerated in the same astrophysical site**, 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)
- improves the detection efficiency, by profiting of relaxed cuts (exploiting the advantages of time-dependent analysis)

This is valid 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.

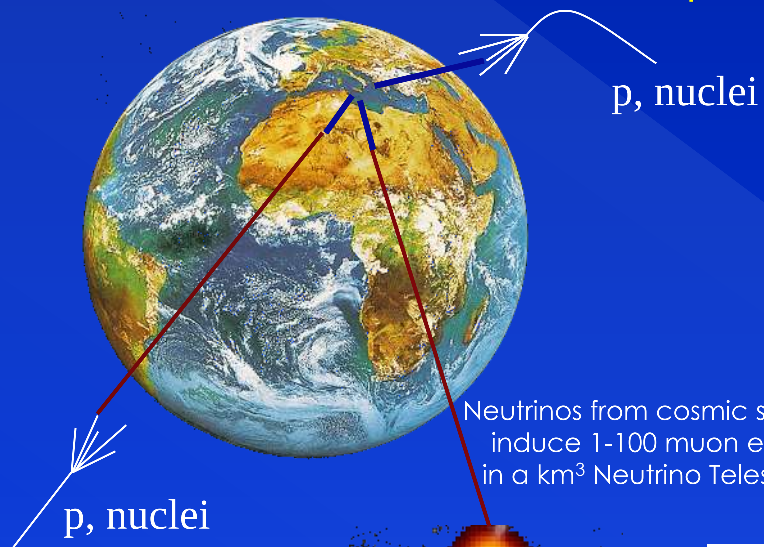
Neutrino fluxes: what do we know/expect ?



Detection principle

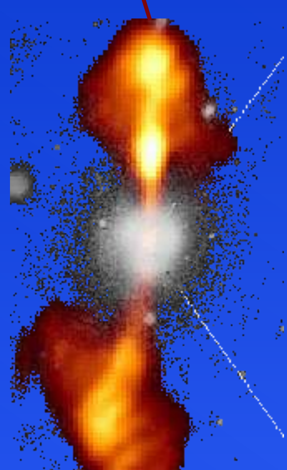
Search for neutrino induced events, mainly $\nu_\mu N \rightarrow \mu X$, deep underwater

Down-going μ from atm. showers
S/N ~ 10^{-6} at 3500m w.e. depth



Neutrinos from cosmic sources induce 1-100 muon evts/y in a km^3 Neutrino Telescope

Up-going μ from neutrinos generated in atm. showers
S/N ~ 10^{-4}

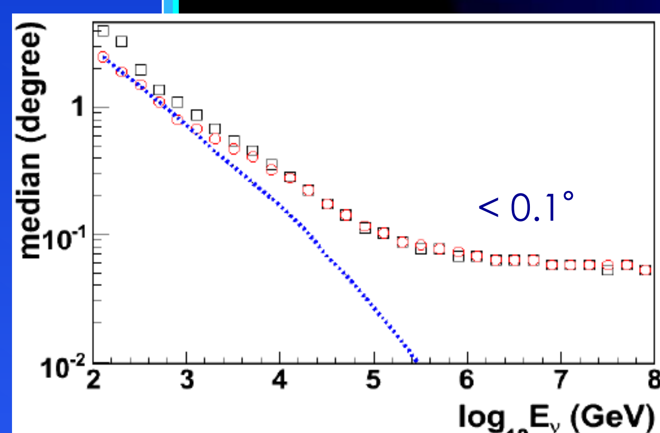


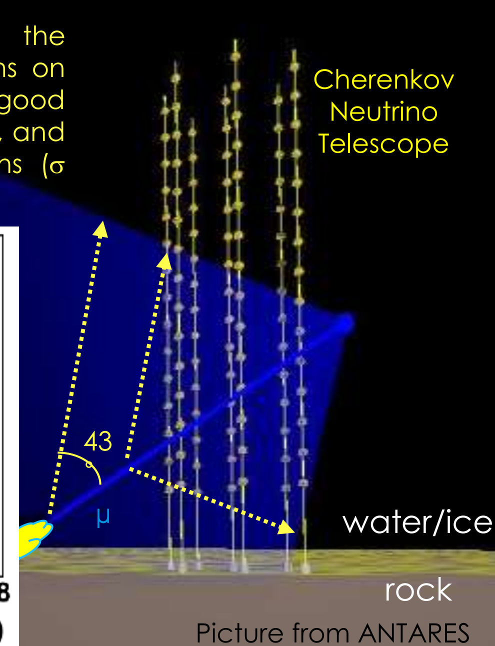
- Atmospheric neutrino flux ~ E_ν^{-3}
- Neutrino flux from cosmic sources ~ E_ν^{-2}
  - Search for neutrinos with E_ν>1÷10 TeV

- ~TeV muons propagate in water for several km before being stopped
  - go deep to reduce down-going atmospheric μ backg.
  - long μ tracks allow good angular reconstruction

$$\text{For } E_\nu \geq 1 TeV \quad \theta_{\mu\nu} \sim \frac{0.7°}{\sqrt{E_\nu[TeV]}}$$

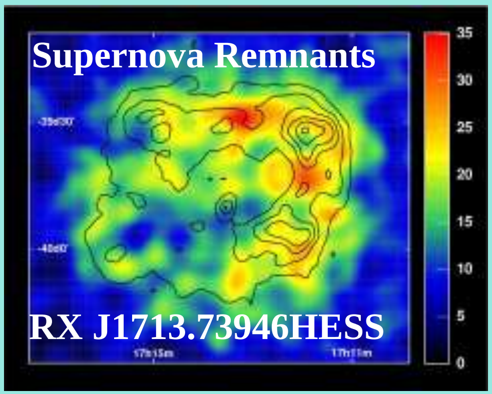
μ direction reconstructed from the arrival time of Cherenkov photons on the Optical Modules: needed good measurement of PMT hits, σ(t)~1ns, and good knowledge of PMT positions (σ ~10cm)

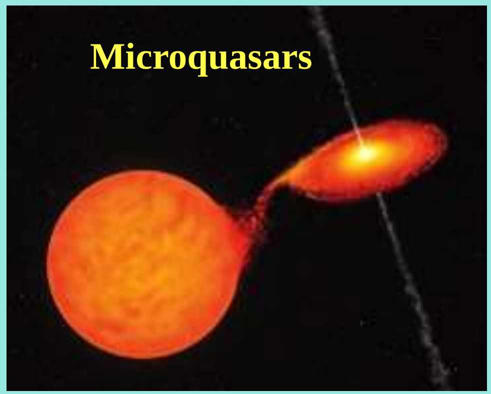




Search for "Point like" cosmic Neutrino Sources

Galactic

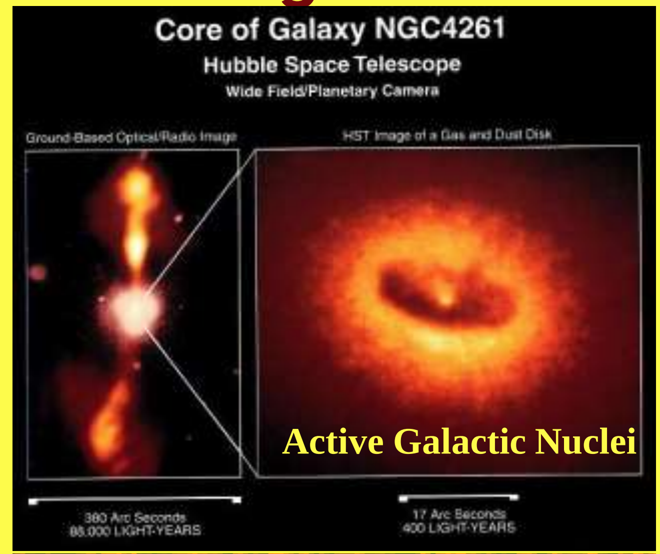


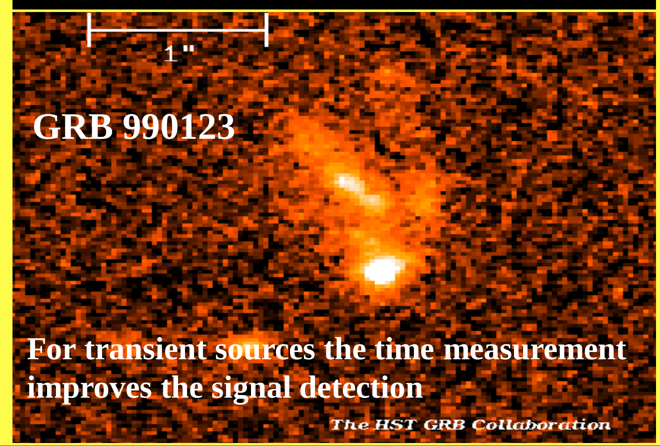


Their identification requires a detector with accurate angular reconstruction

$$\sigma(\vartheta) \le 0.5° \text{ for } E_\nu \ge 1 TeV$$

Extragalactic



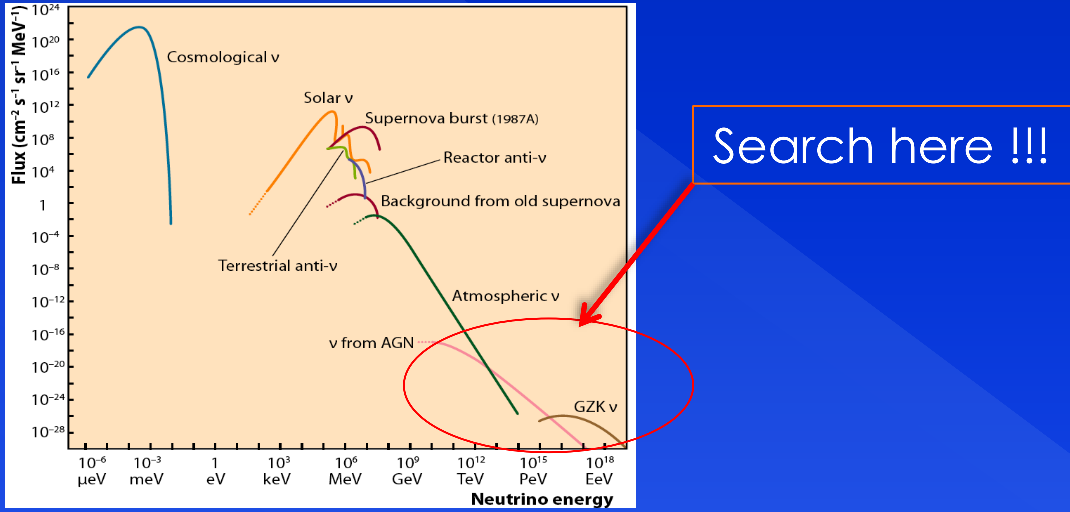


Experimental signal : statistical evidence of an excess of events coming from the same direction

Search for ν from "Diffuse Cosmic Neutrino Sources"

- Unresolved AGN
- Neutrinos from "Z-bursts"
- Neutrinos from "GZK like" p-CMB interactions
- Neutrinos foreseen by Top-Down models
- ….

Their identification out of the more intense background of atmospheric neutrinos (and muons) is possible at high energies (E > TeV) and implies accurate energy reconstruction.



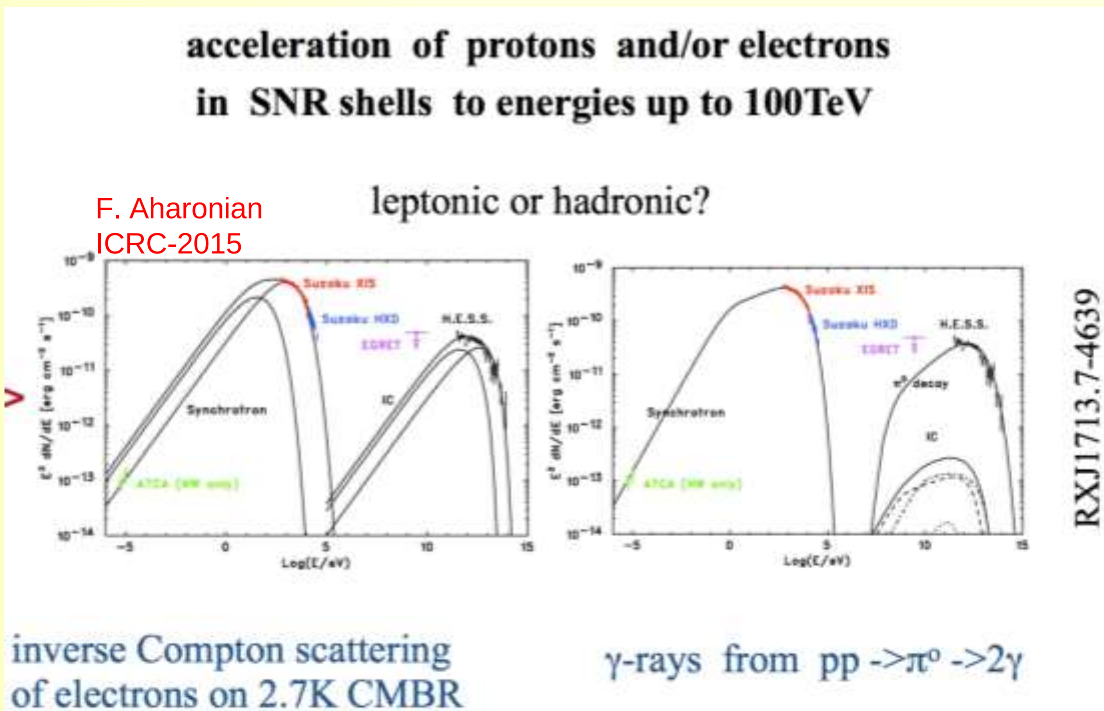
- 2013, first evidence for a diffuse flux of cosmic neutrinos: 28 contained VHE astrophysical ν events reported by IceCube

Neutrinos in multimessenger astrophysics

Neutrino production is strongly related to the acceleration of **cosmic rays** and to the production of **γ-rays**:

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

The detection of neutrinos from a SNR would help in understanding the high-energy γ production mechanism: leptonic (I.C. of accelerated e^- on Synchroton radiation) or hadronic ?

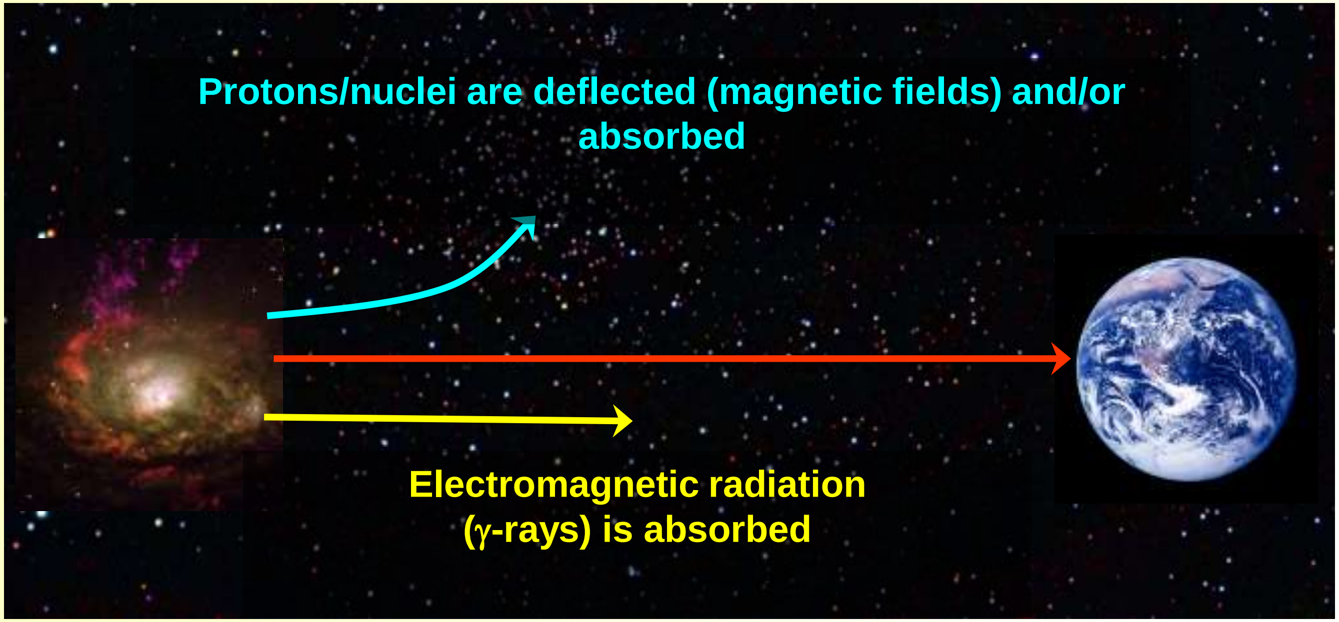


Neutrino searches in multimessenger astrophysics

Confirmed gamma-ray sources are the first target of neutrino telescopes observations:

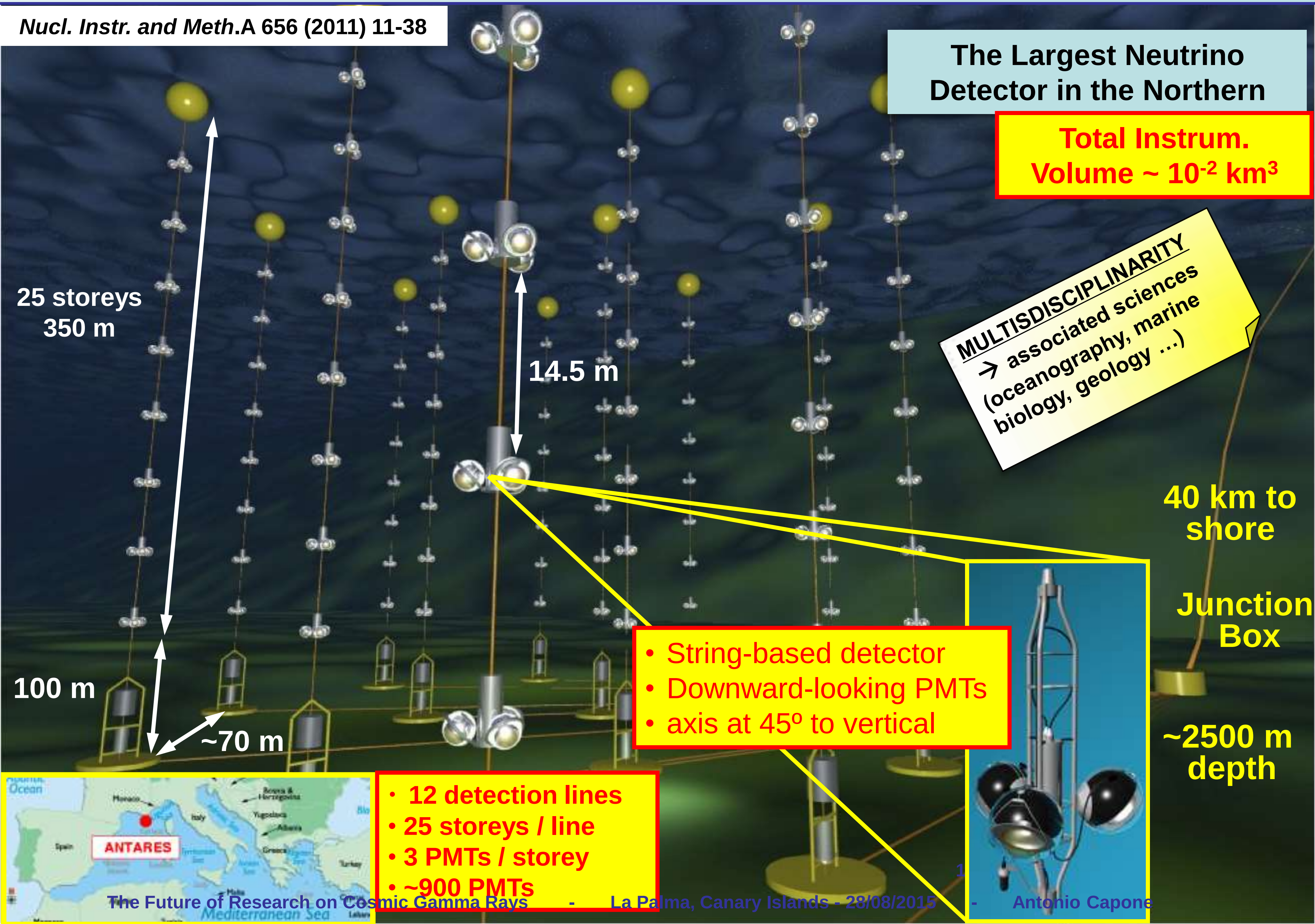
- search for neutrinos from point-like sources (list of known gamma-ray emitters, steady or transient). Measured γ-fluxes allow to evaluate the expected amount of ν events
- search for neutrinos from Fermi Bubbles and from the Galactic Plane;
- …

but let's not forget that neutrinos offer the unique possibility to "look" further away and deeper inside astrophysical objects revealing so far "hidden sources". **The horizon for a Neutrino Telescope is wider.**



ANTARES: Astronomy with a Neutrino Telescope and Abyss environmental RESearch

*Nucl. Instr. and Meth.*A 656 (2011) 11-38



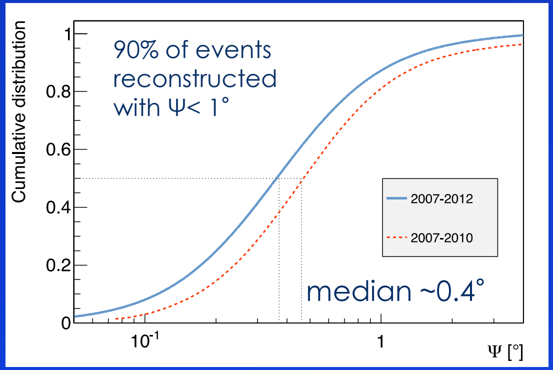
The ANTARES search for point-like ν sources

First time-integrated search with 2007-2010 data (813 days) **ApJ. 760:53 (2012)**

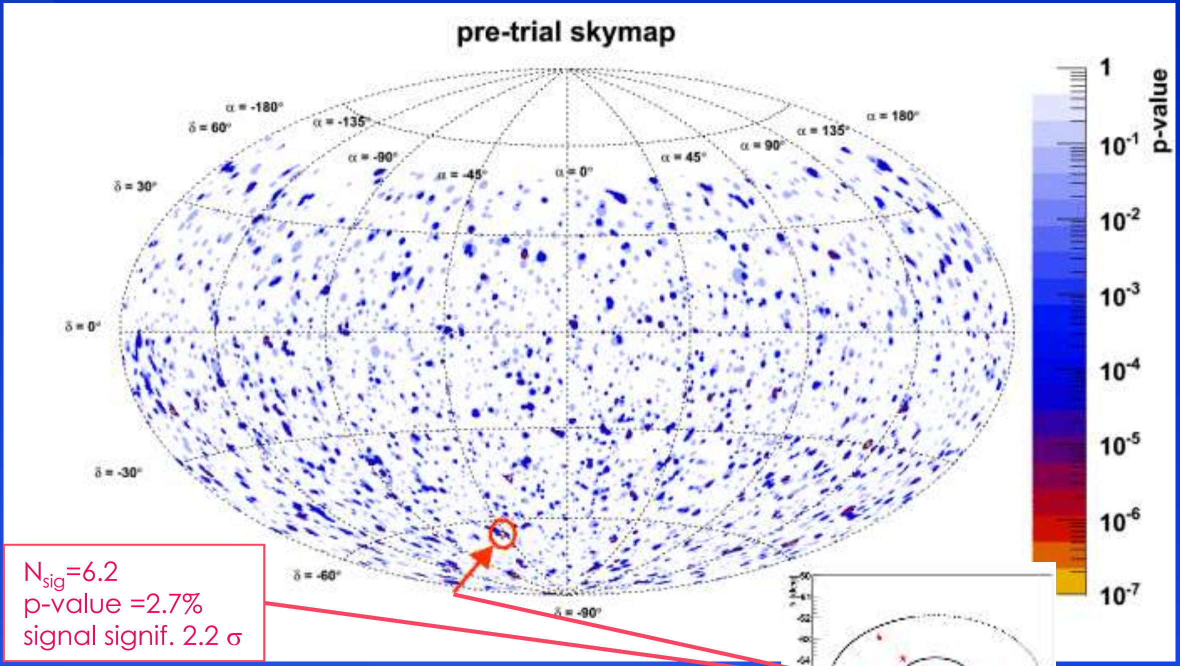
- 3058 neutrino candidates (atmospheric + astrophysical ??)
- No statistically significant excess
- The "best cluster" (-46.5°, -65.0°) compatible with the background hypothesis, p=0.026 (no known source there from ROSAT, Fermi-LAT/HESS)

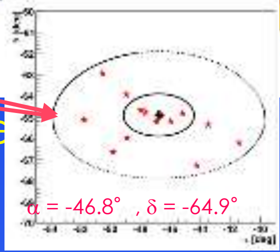
New search on bigger data sample: 2007-2012 data (1340 days) **ApJ-L. 786:L5 (2014)**

- **5516** neutrino candidates (improved angular resolution)



cumulative distribution of the angular resolution for selected events assuming E^{-2} spectrum





- again no statistically significant excess observed
- **The same "best cluster"** with 6 new events (14 total in 3° search cone observed **but compatible with background hypothesis** (p=2.1%)

The ANTARES search for ν from known γ sources

Using the 2007-2012 data (1340 days) we counted the number of events in a 20° cone around a list of pre-selected candidates, searching for an excess over the background. Assuming a neutrino flux from the source like **$d\phi_\nu/dE_\nu = \Phi_0 E_\nu^{-2}$** in absence of a statistically significant excess we can put a limit (at 90% C.L.) on **Φ_0** . Few examples

source	α_s [°]	δ_s [°]	n_s	p-value	$\Phi_\nu^{90\%}$ C.L.
HESSJ0632+057	98.24	5.81	1.60	0.0012	4.40
HESSJ1741-302	−94.75	−30.20	0.99	0.003	3.23
3C279	−165.95	−5.79	1.11	0.01	3.45
HESSJ1023-575	155.83	−57.76	1.98	0.03	2.01
ESO139-G12	−95.59	−59.94	0.79	0.06	1.82
CirX-1	−129.83	−57.17	0.96	0.11	1.62
PKS0548-322	87.67	−32.27	0.68	0.10	2.00
GX339-4	−104.30	−48.79	0.50	0.14	1.50
VERJ0648+152	102.20	15.27	0.59	0.11	2.45
PKS0537-441	84.71	−44.08	0.24	0.16	1.37
MGROJ1908+06	−73.01	6.27	0.21	0.14	2.32
Crab	83.63	22.01	0.00	1.00	2.46

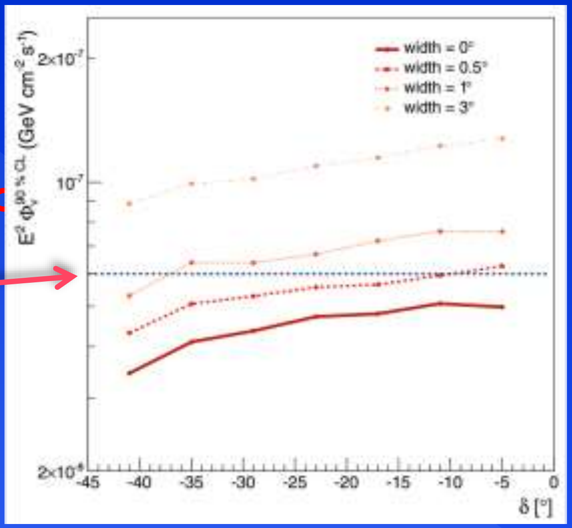
x10^{-8} GeV cm^{-2} s^{-1}

ApJ-L. 786:L5 (2014)

Is there a point-like ν source close to the Galactic Center (α =-79° , δ =-23° , Gonzalez-Garcia et al. arXiv 1310.7194) suc that could explain the recent IceCube evidence ???

The expected flux should have Φ_0 =6•10^{-8} GeV cm^{-2} s^{-1}

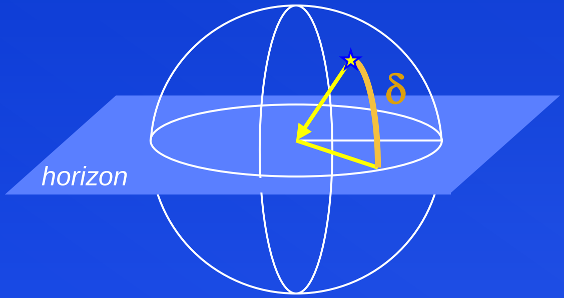
The point like hypothesis as well as extended Gaussian like extended (0.5° , 1° and 3°) sources have been tested: no excess found. No evidence found for a point like-source that could explain the IceCube results

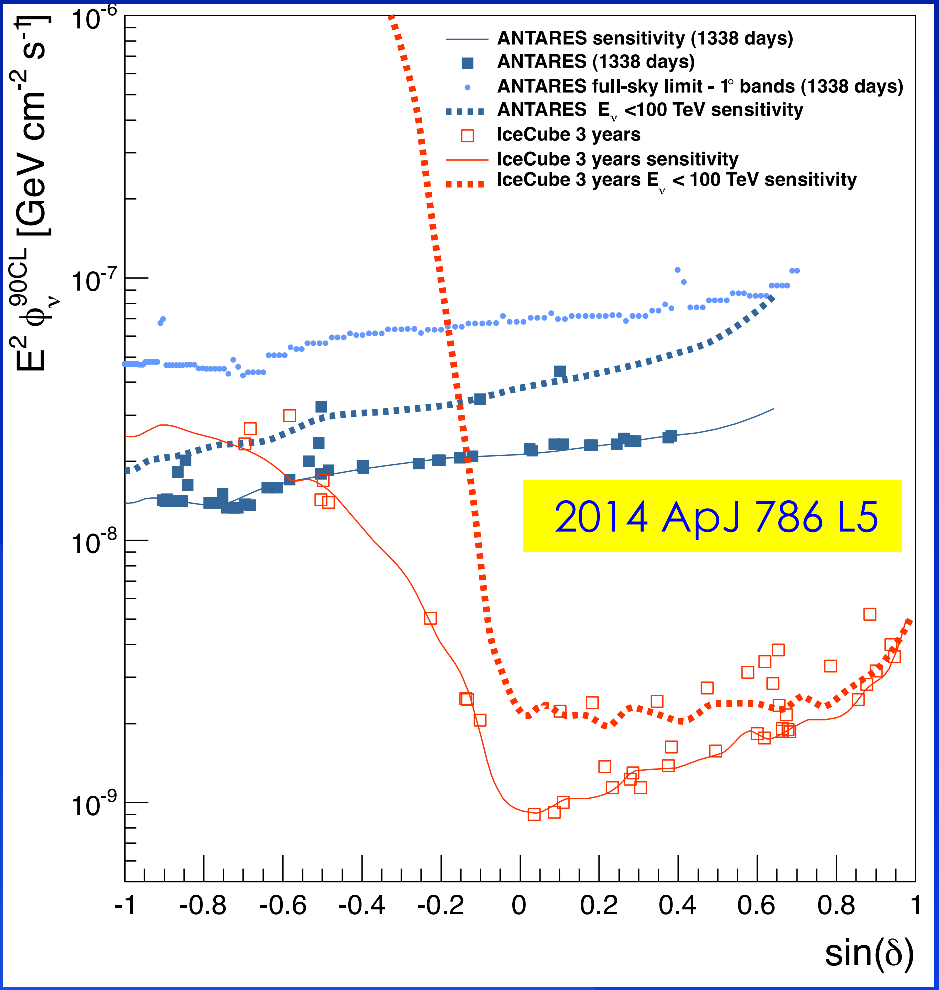


ANTARES search for ν point-like sources

ANTARES data provide the most stringent limits to flux of neutrinos from point-like sources for a large part of the Southern Sky in the TeV region.

IceCube sensitivity to point-like sources in the Southern Sky improves for E_ν > 100 TeV





90 % C.L. flux upper limits and sensitivities on the muon neutrino flux for six years of ANTARES data. IceCube results are also shown for comparison.

The Multi-Messenger Search Programme with ANTARES

Neutrinos trigger others

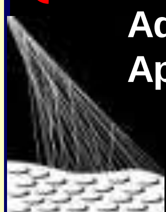
Others trigger neutrinos

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 (Gamma-ray Coordination Network)

ANTARES ⟺ GCN

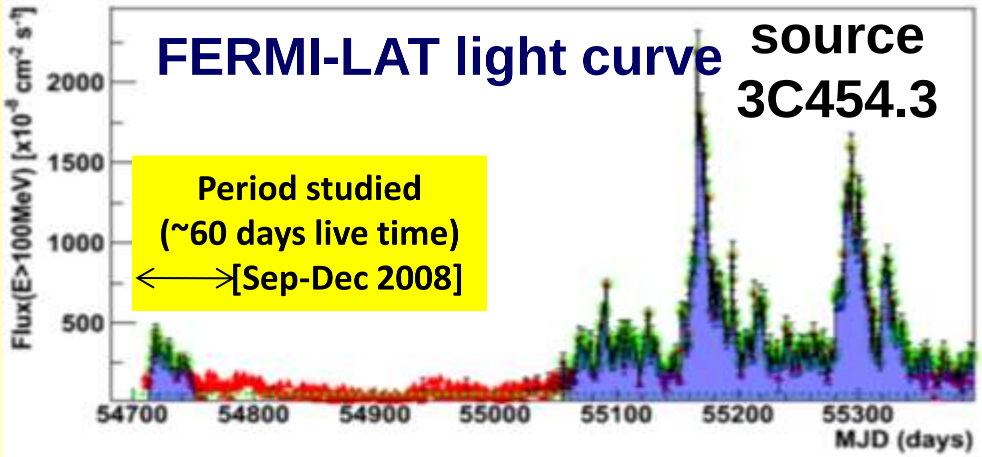
A&A 559, A9 (2013),
JCAP 1303 (2013) 006

Search for ν from flaring AGN - 2008

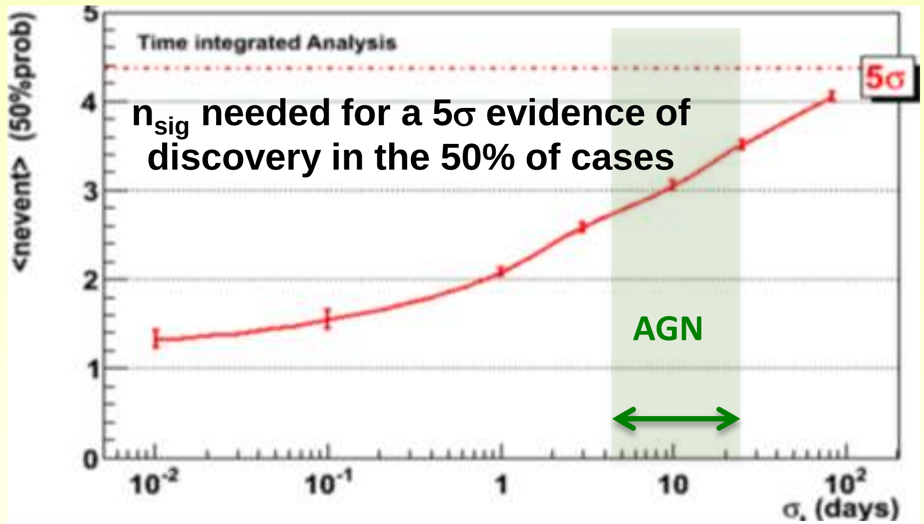
ν emission from γ-flaring blazars

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

ANTARES ⟺ FERMI



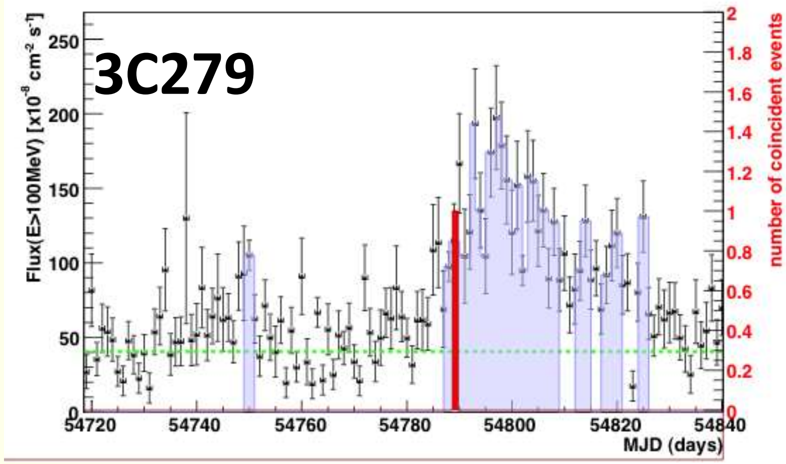
10 sources selected from the FERMI/LAT catalogue, showing a large variability (flaring state) in the period studied for this analysis.



Performance of the time-dependent analysis

RESULTS

- **1 neutrino candidate event compatible with the time/space distribution (Δα=0.56°) of 3C279 with probability (p-value) = 1% (but post trial probability = 10%)**
- **Fluence Upper Limits**
- **RESULTS ARE VERY PROMISING, new analisys going on with 2008-2011 FERMI data**



Search for ν from flaring AGN – 2008-2011

[40 sources, 86 flaring periods] (ANTARES ⬄ FERMI)

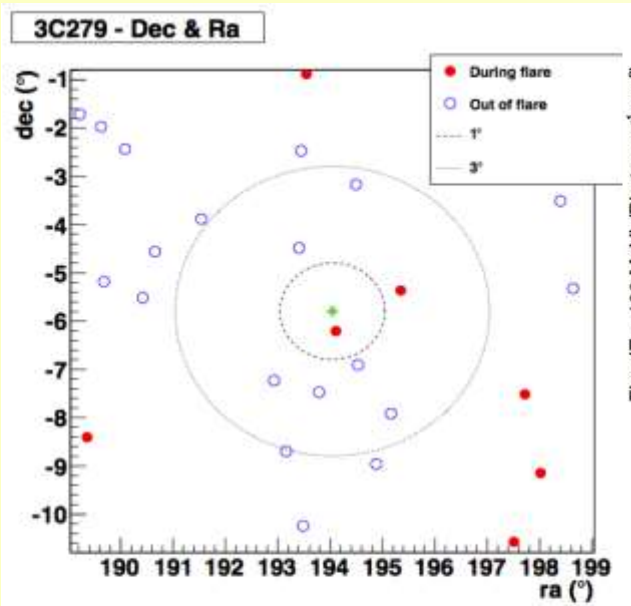
…to be extended to IACT blazars (HESS, MAGIC, VERITAS)

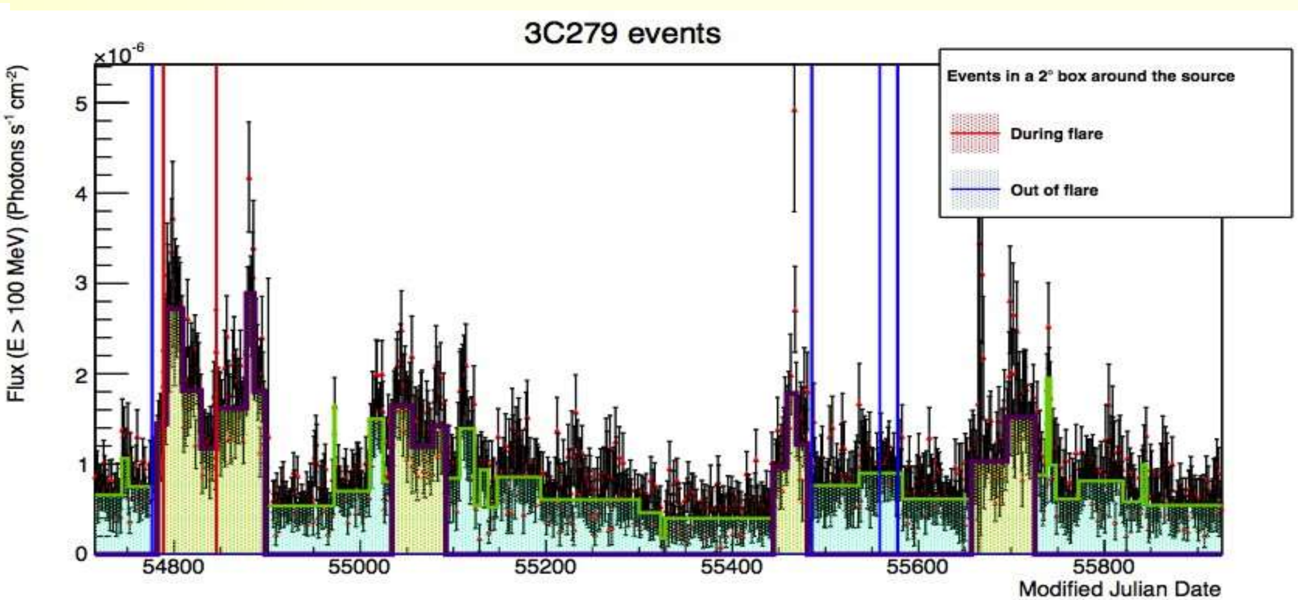
PRELIMINARY

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%



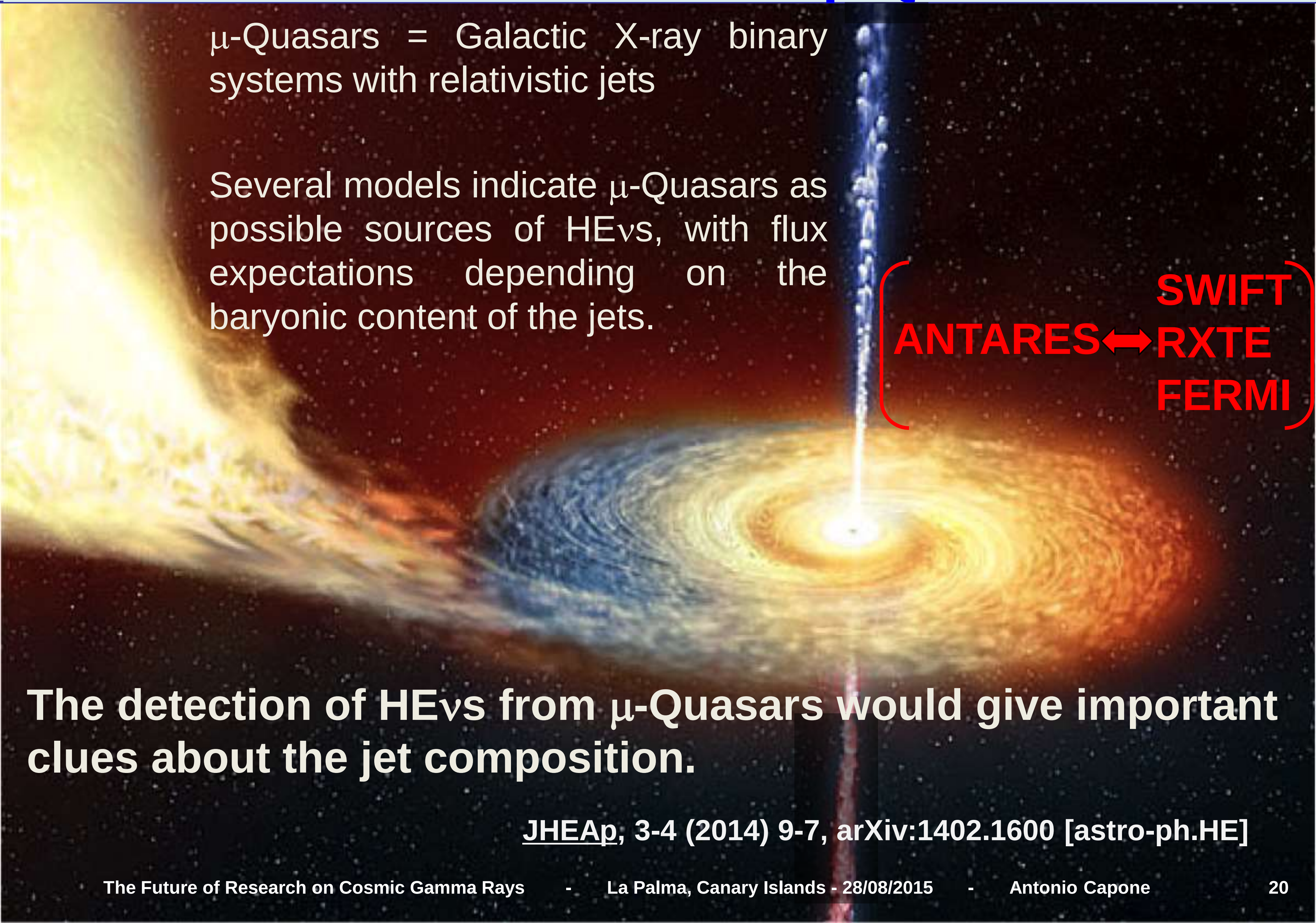


ANTARES and ν from μ-Quasars

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.

ANTARES ⟷ { SWIFT, RXTE, FERMI }



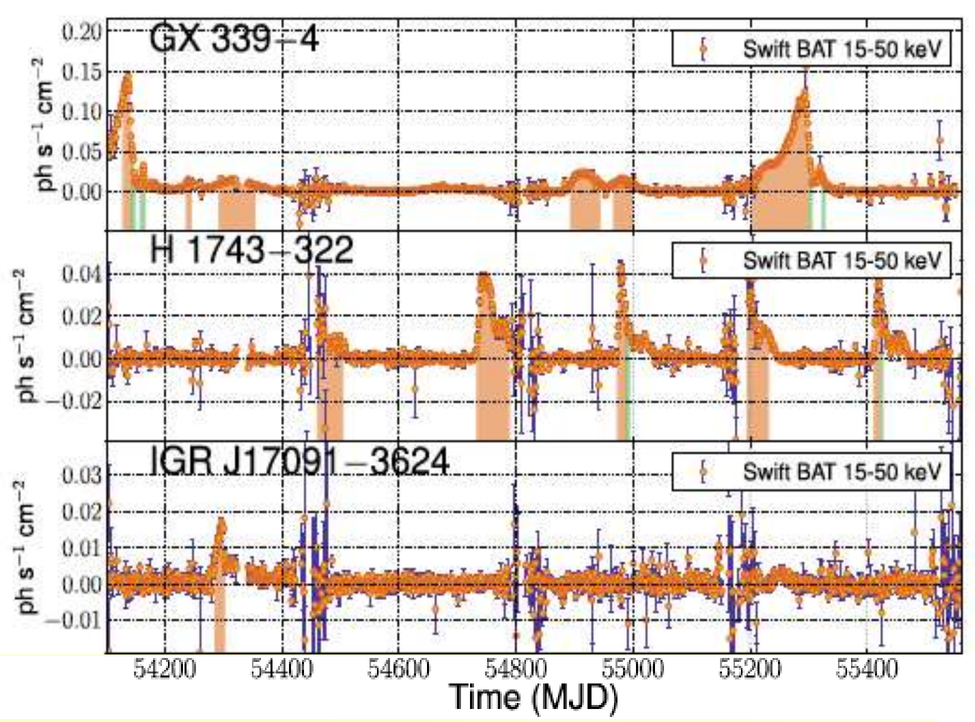
The detection of HEνs from μ-Quasars would give important clues about the jet composition.

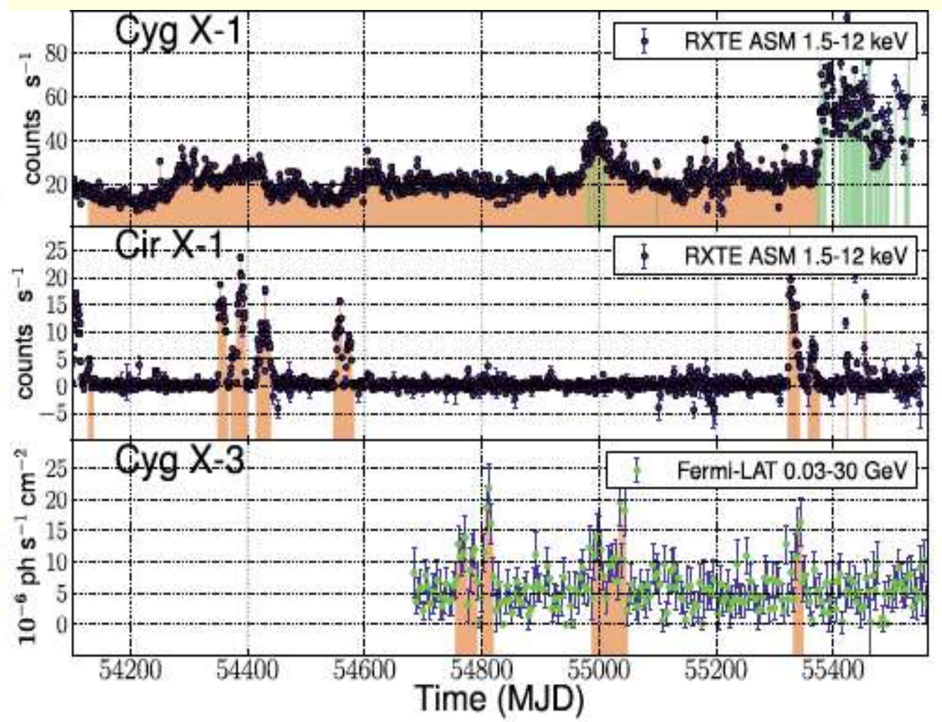
JHEAp, 3-4 (2014) 9-7, arXiv:1402.1600 [astro-ph.HE]

ANTARES and ν from μ-Quasars

ANTARES data set: 2007-2010 → 6 sources selected, with requisites:
- **in the ANTARES visible sky;**
- **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).





ANTARES and ν from μ-Quasars

Data Analysis & Results

METHOD

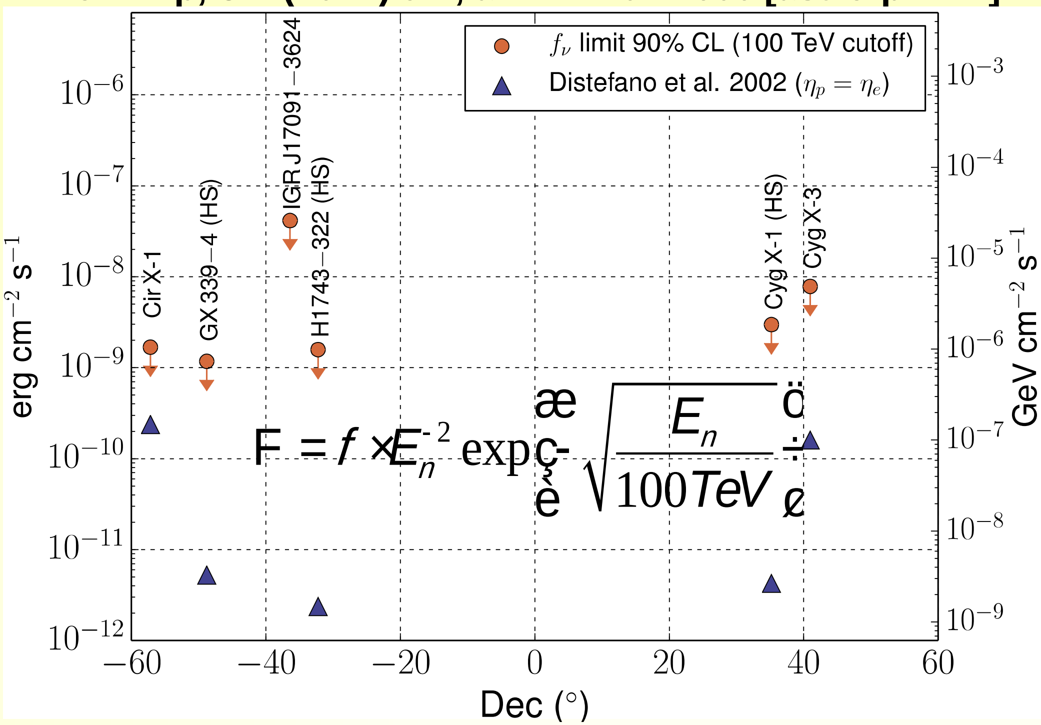
- **unbinned search**
- **likelihood ratio test statistic**
- **quality cuts optimized for 5σ discovery**

RESULTS

- **no statistically significant excess** above the expected atmospheric bkg

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

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



$$\Phi = \phi \times E_\nu^{-2} \exp\left(-\sqrt{\frac{E_\nu}{100\,TeV}}\right)$$

[systematic uncertainties included]

…assuming a neutrino spectrum following:

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

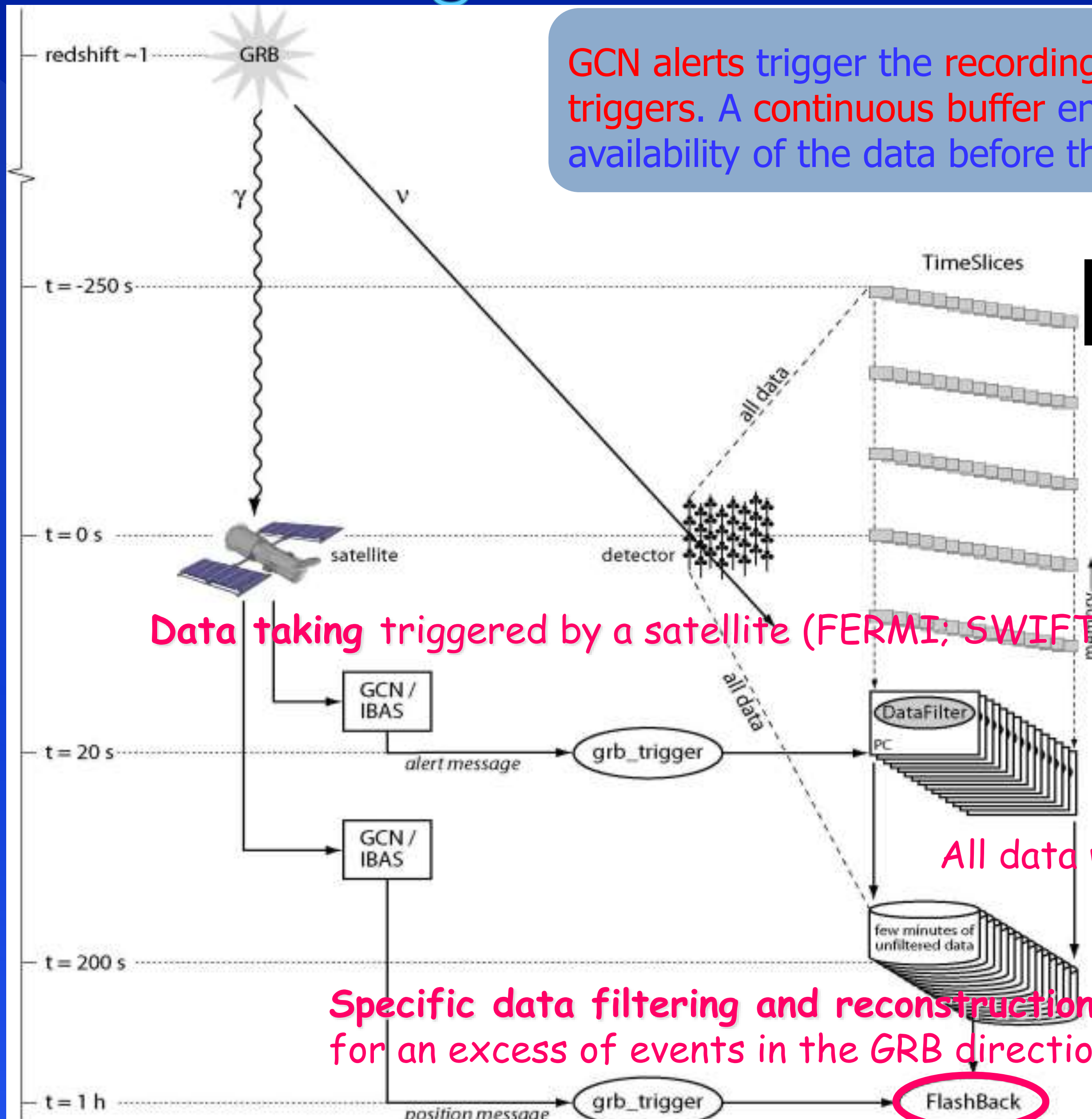
→ INFER INFORMATION on JET COMPOSITION: constraints on η_p/η_e = ratio of proton to electron luminosity in the jet

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

A Multi-Messenger Search of ν from GRB

GCN alerts trigger the recording of all the low level triggers. A continuous buffer ensures the availability of the data before the alert

GCN=Gamma Ray Burst Coordination Network



t =-250 s

t = 0 s

t = 20 s

t = 200 s

t = 1 h

Data taking triggered by a satellite (FERMI, SWIFT, INTEGRAL)

All data written to disk

Specific data filtering and reconstruction by searching for an excess of events in the GRB direction (offline)

A Multi-Messenger Search of ν from GRB

Astronomy & Astrophysics 559, A9 (2013)

2007-2011 data:
- alerts and data from FERMI – SWIFT - GCN
- analysis of 296 long GRBs (total prompt emission 6.6 hours)

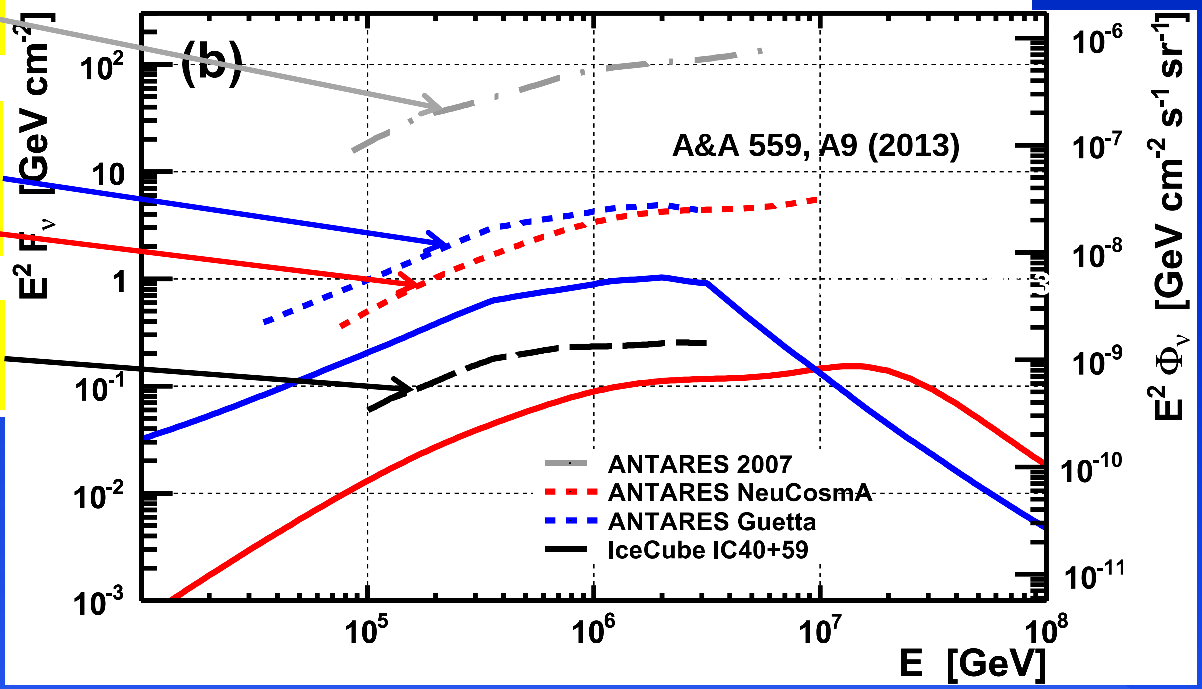
Simulation of neutrino fluxes from GRB:
- NeuCosmA (Hümmer et al 2010) → expected 0.061 events
- Guetta (Guetta et al. 2004) → expected 0.48 events
- Expected background 0.051 events

No events found in stacked GRB search within 10° window:

Previous ANTARES result, 40 GRBs
JCAP 1303 (2013) 006

ANTARES upper limits 90% C.L. for
Guetta fluxes
NeuCosmA fluxes

IceCube upper limits 90% C.L.
IC40+59 for 215 GRBs



Correlating ANTARES ν 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 with $E>10^{19.74}$ 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.

ANTARES ⟺ AUGER

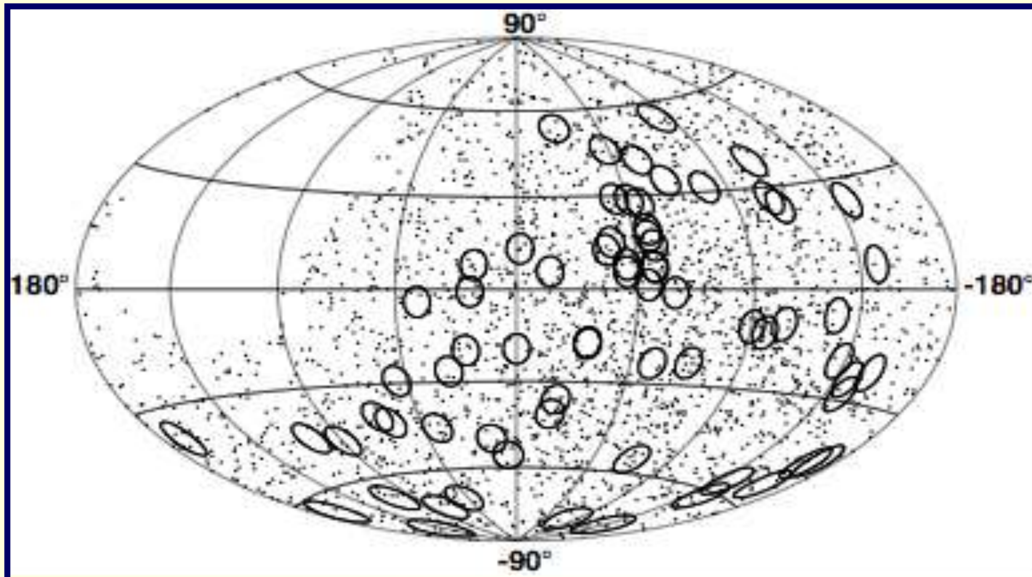
no significant correlation observed

⬇

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.

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

GWHEN: Gravitational Waves + High-Energy ν

ANTARES in 5-line config. (2007)
T_{obs}=91 days, 158 HEN selected
(14 reconstructed with ≥ 3 lines)

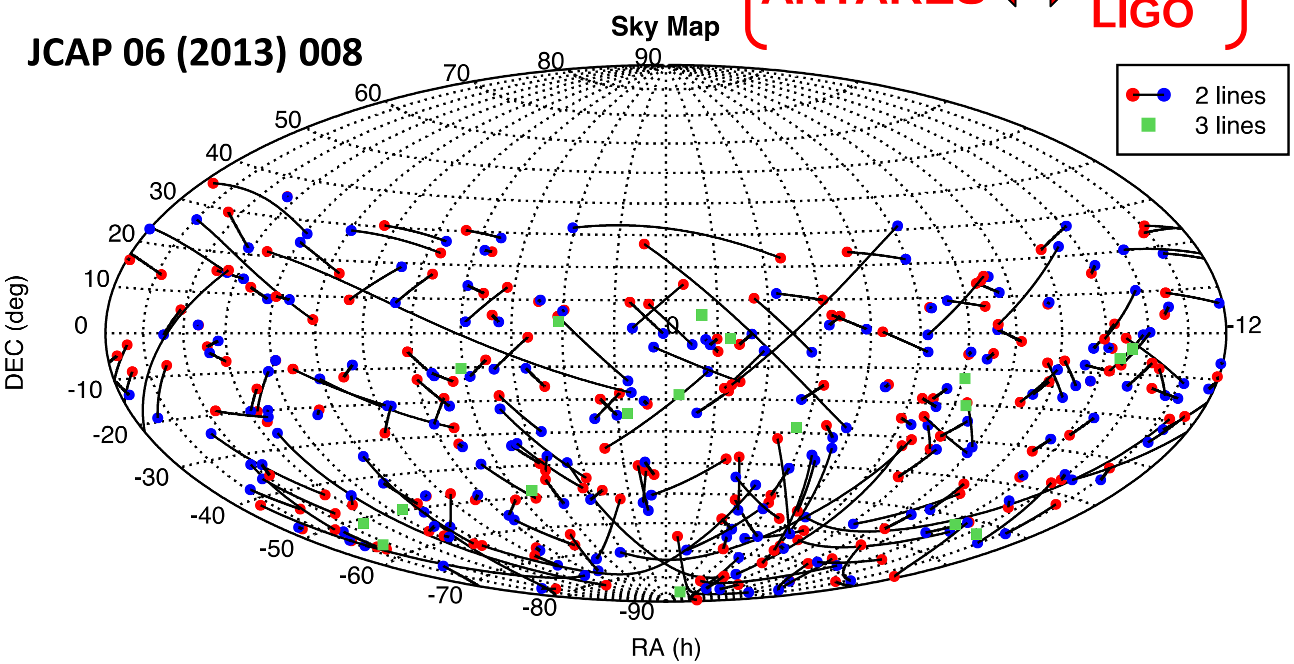
LIGO/VIRGO:
Search for gravitational wave signals coincident in time and direction with neutrino events.

CANDIDATE SOURCES GW+HEN

- **GRBs [extra-galactic]**
- **bursting magnetars (SGRs) [galactic]**
- **topological defects**
- **sources with no electro-magnetic counterpart ("hidden sources")**

ANTARES ⟺ VIRGO LIGO

JCAP 06 (2013) 008



The sky map contains the full set of 216 selected HEν, 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.

GWHEN (2007) - Results

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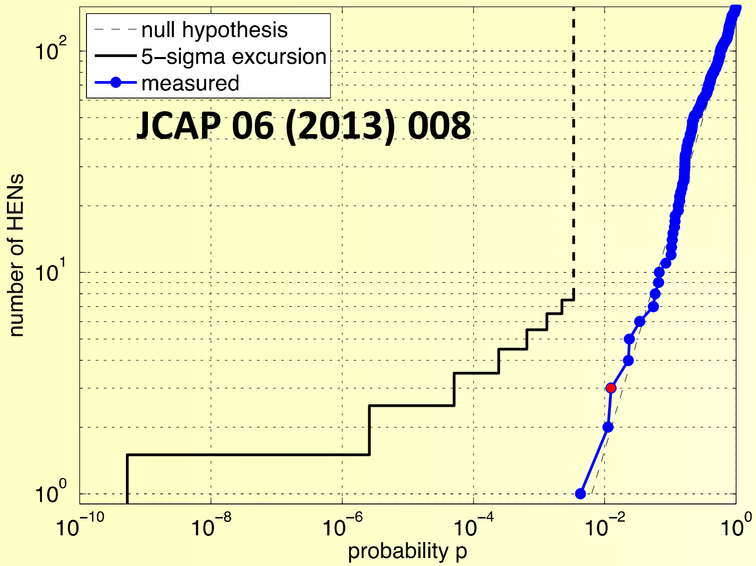


no gravitational wave burst associated with any selected neutrinos (p-values compatible with the null hypothesis)

- **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

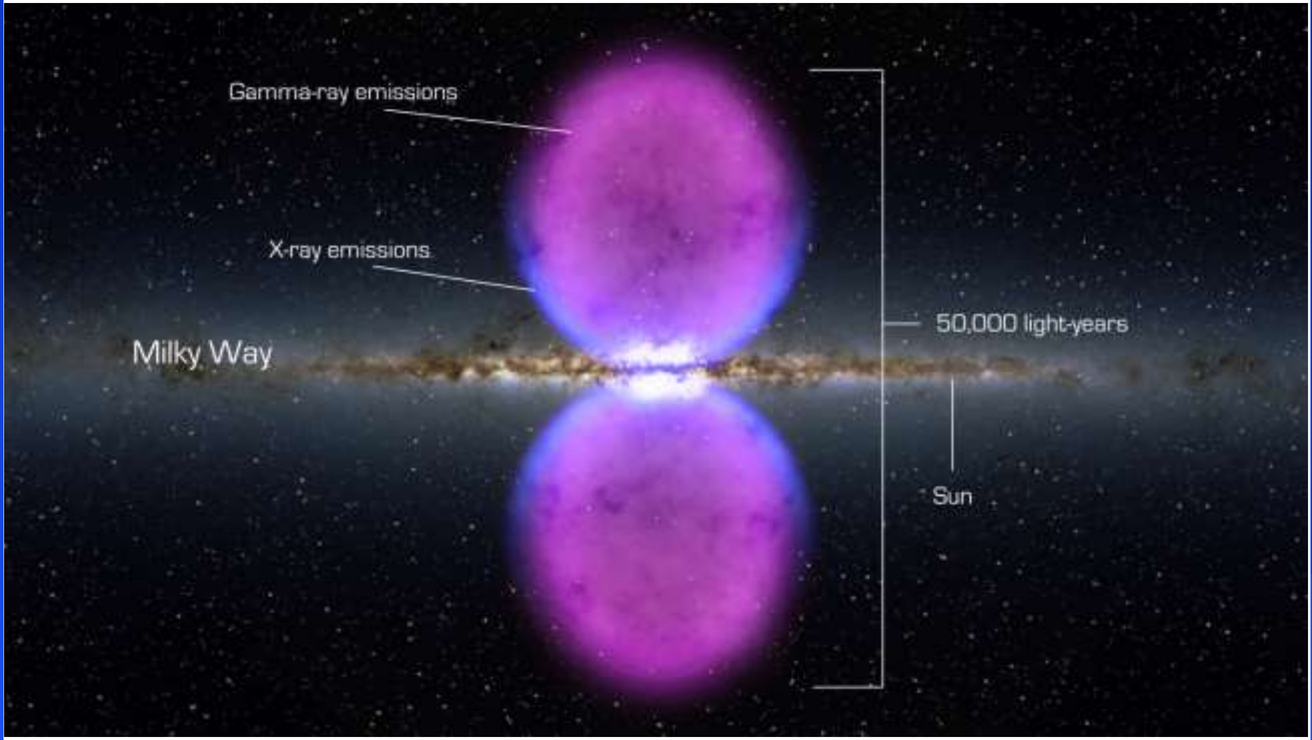
- **(extended data set, ANTARES 12 lines, better reconstruction algorithms for GW & Heν)**
- **129 days of common data taking → 1986 neutrino candidates**

➡ **factor 7 improvement in sensitivity and discovery potential**

Neutrinos from "FERMI Bubbles" ??

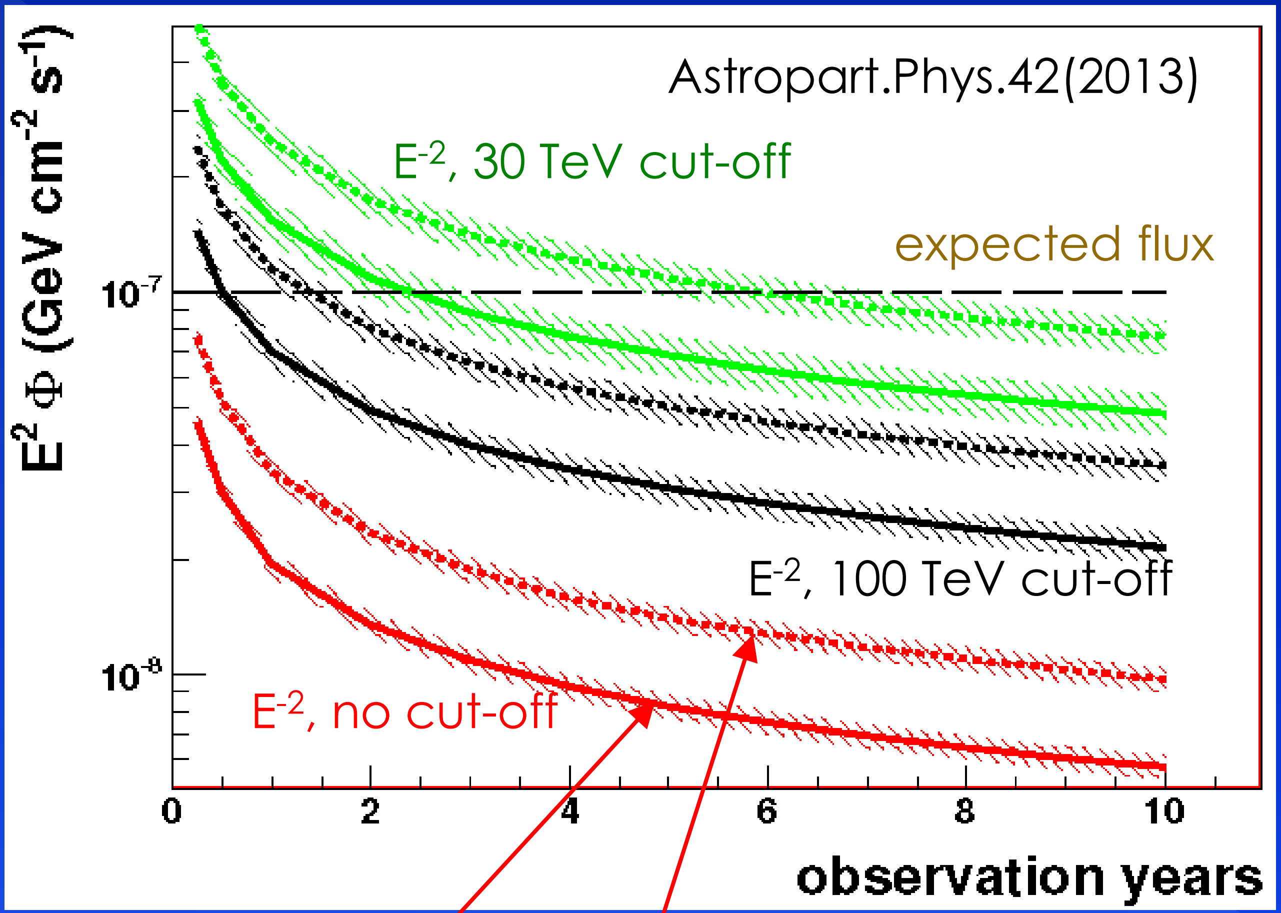
Search possible for a Mediterranean Cherenkov ν Telescope

- FERMI detected hard γ emission (E^{-2}) up to 100 GeV in extended "bubbles" around Galactic Center, hard spectrum not compatible with Inverse Compton mechanism, M.Su et al., Ap.J.724 (2010).
- Models involving hadronic processes (e.g. Crocker & Aharonian, PRL 2011) predict significant neutrino fluxes.
- This could be one of the first neutrino "source" for the Mediterranean ν Telescope.



KM3NeT Sensitivity to H.E. ν from "FERMI Bubbles"

for a ≈ 5km³ Mediterranean Cherenkov ν Telescope



3σ @ 50%

5σ @ 50%

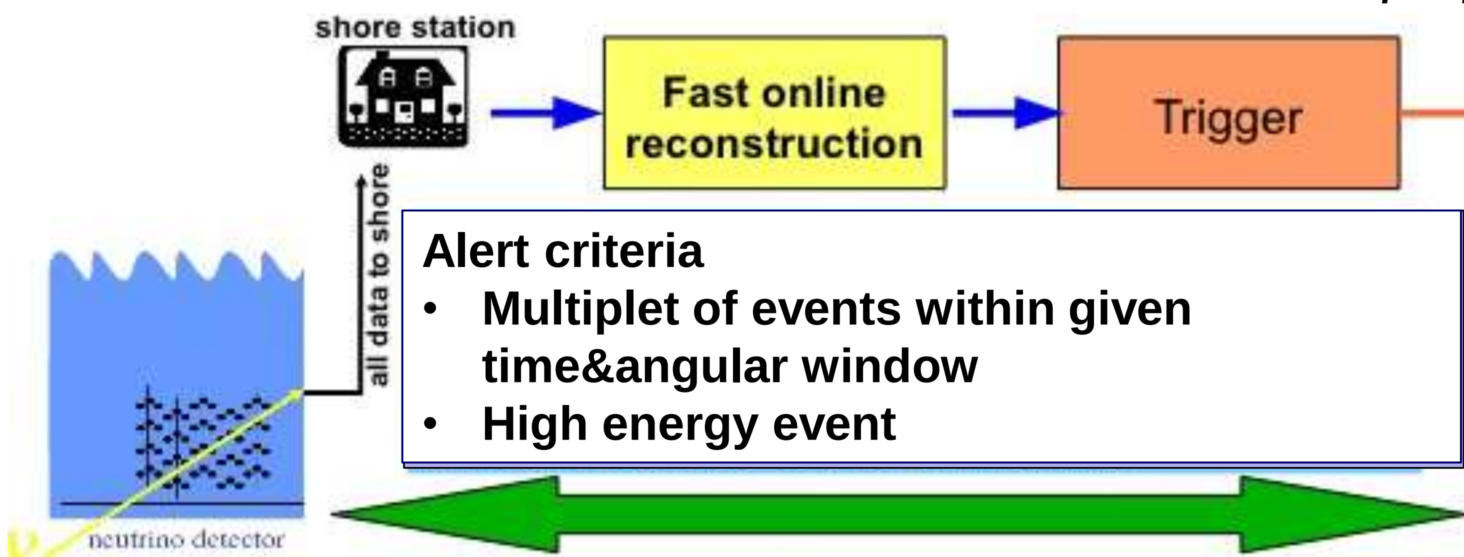
TAToO: Telescopes-ANTARES Target of Opportunity

ANTARES ⟺ Optical Telescopes TAROT, ROSTE, …

Coincident observations of νs and optical signals from transient sources

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

Astrop.Phys 35 (2012) 530-536



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 performed following a **Multi-Messenger Approach** looks for connections with the information carried by other messengers from the Cosmos (Gamma-Rays, Cosmic Rays and Gravitational Waves).
- The ANTARES Multi-Messenger Programme focuses in particular on **transient and flaring sources**, exploiting the timing information provided by coincident detection.
- Two schemes: “**ν trigger others**” & “**other trigger ν**”
- 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 and IceCube are pro-active in the multi-messengers astrophysical research.