Recent results from the ANTARES deep-sea neutrino telescope

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Overview

- Neutrino Telescopes
- ANTARES
- Point-like sources search
- Flaring Blazars
- IC HESE
- Conclusions

Neutrino telescopes

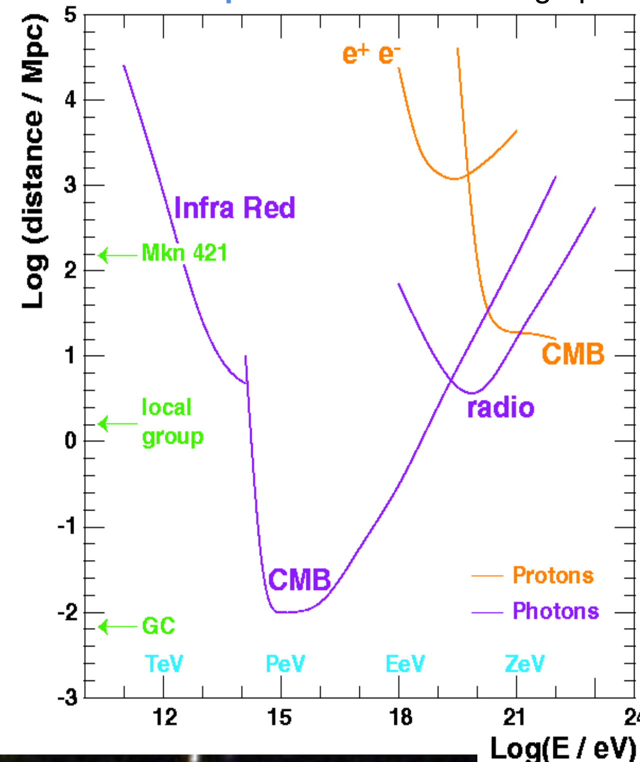
Neutrino Astronomy is a quite recent and very promising experimental field.

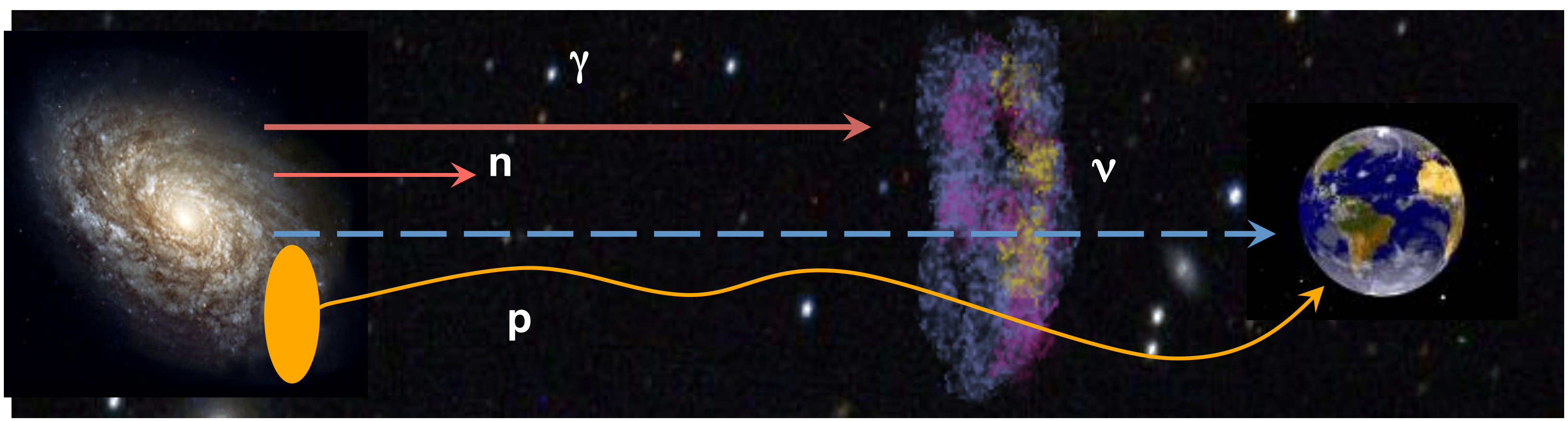
Advantages:

- Photons: interact with CMB and matter (r~10 kpc @100 TeV)
- Protons: interact with CMB (r~10 Mpc @10^{11} GeV) and undergo magnetic fields ($\Delta\theta>1°$, E<$5\cdot10^{10}$ GeV)
- Neutrons: are not stable (r~10 kpc @10^{9} GeV)

Drawback: large detectors (~GTon) are needed

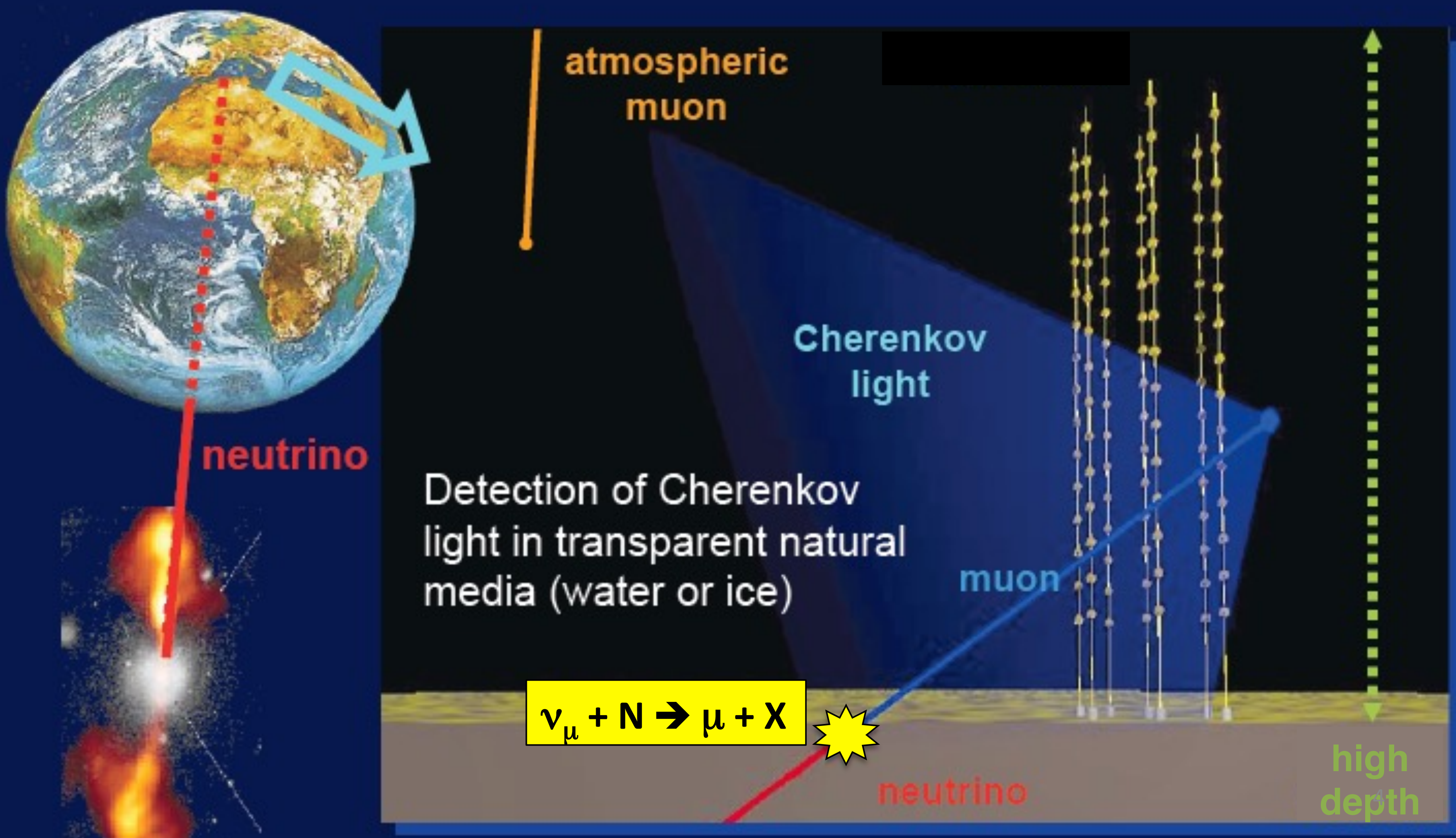
Photon and proton mean free range path



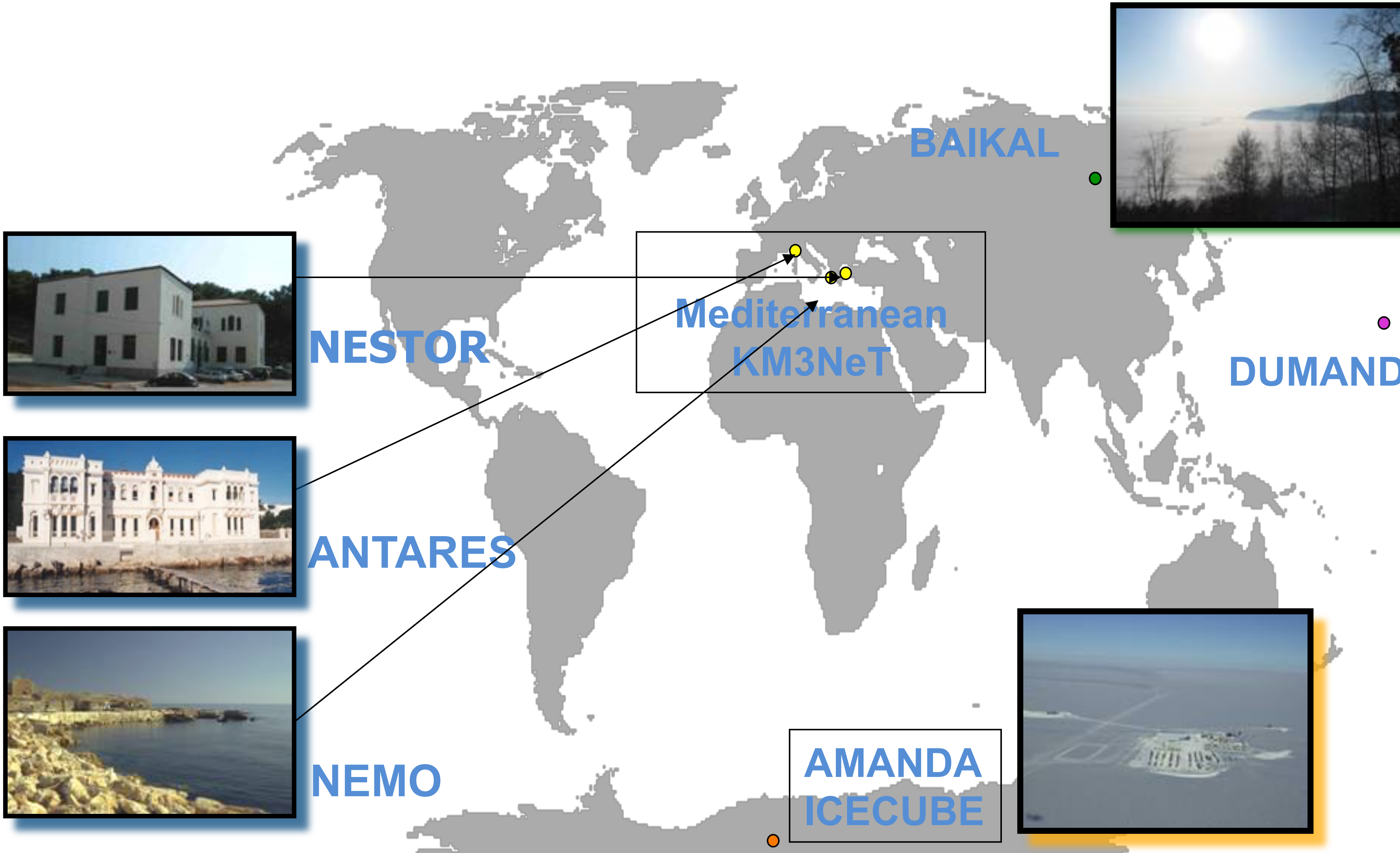


Neutrino telescopes

Detection principle: collection of the visible Cherenkov radiation produced as the high-energy charged leptons (final state of CC interactions) propagate through water



Neutrino telescopes



Neutrino telescopes

Background sources

ATMOSPHERIC μs:

- produced in the interactions of CRs with the atmosphere
- mostly down-going ($\mu_{atm}/\mu_{up} \approx 10^4$)

Discrimination:

- high depth (≈3000m)
- search for up-going events
- use veto region to prevent contamination

ATMOSPHERIC νs:

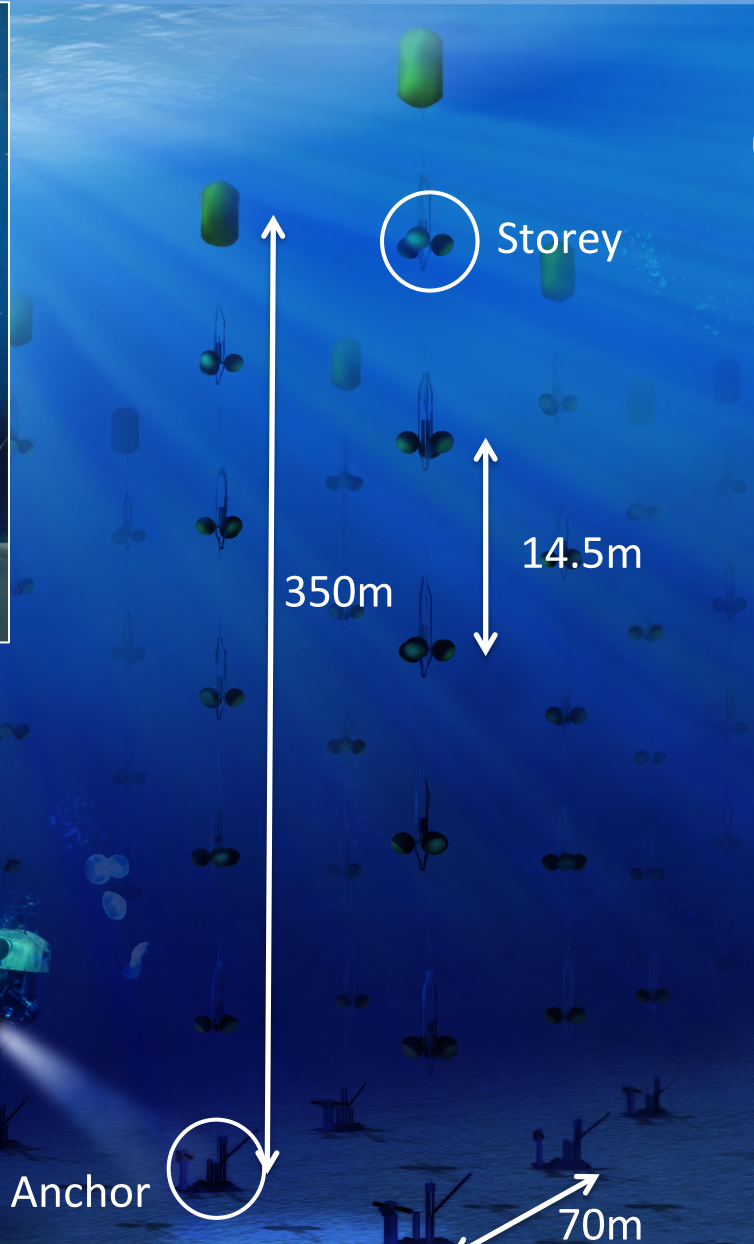
- up-going μ from neutrinos generated in atmo. showers
- $\nu_{astro}/\nu_{atm} \approx 10^{-4}$

Discrimination:

- Energy Reconstruction
  (Atmospheric neutrino flux ~ $E_\nu^{-3.5}$ - Neutrino flux from cosmic sources ~ E_ν^{-2})
- Event Clustering (Search for Point Sources)

Antares

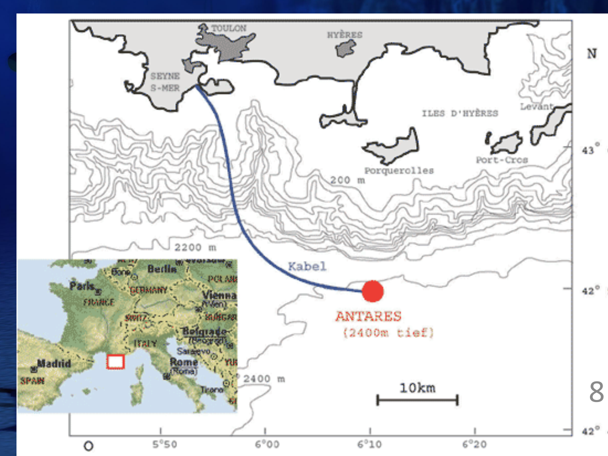
Antares



12 lines
25 storeys/line
3 OM/storey

Total Instrumented Volume
~ 10^{-2} km^3

Construction completed in May 2008
Location: 40 km off Toulon (Fr)
42 48'N, 6 10'E
at a depth of 2475 m



Antares

Scientific goals

- Neutrino astrophysics
- Dark Matter searches
- Multi-messenger studies
- Study of atmospheric neutrinos
- Particle physics: nuclearites, monopoles
- Acoustic neutrino detection
- Sea sciences

Antares

Scientific goals

- **Neutrino astrophysics**
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Point-like sources

Search for clusters of muon neutrinos over a background of diffusely distributed atmospheric neutrinos.

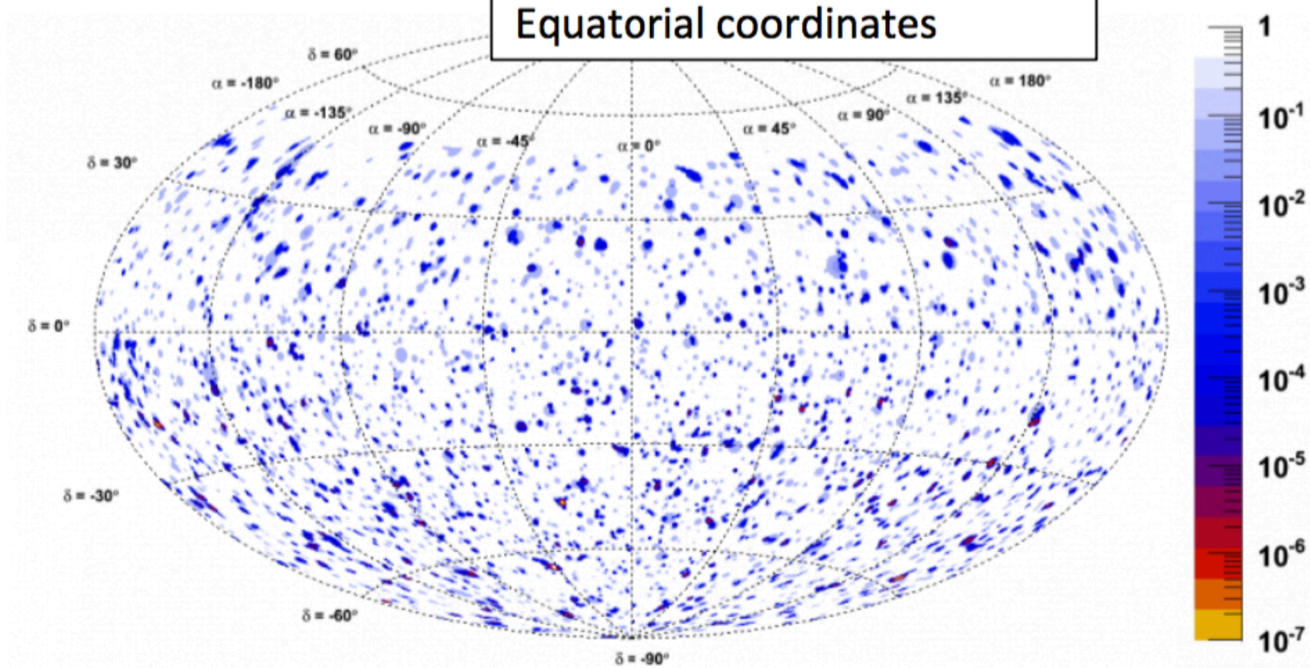
The Astrophysical Journal Letters, 786:L5 (5pp), 2014 May 1 doi:10.1088/2041-8205/786/1/L5

SEARCHES FOR POINT-LIKE AND EXTENDED NEUTRINO SOURCES CLOSE TO THE GALACTIC CENTER USING THE ANTARES NEUTRINO TELESCOPE

Data sample

- six years of data collected by the ANTARES neutrino telescope (from 2007 January 29 to 2012 December 31, total livetime of 1338 days)
- 5516 events, including an estimated 10% background from mis-reconstructed atmospheric muons.

Equatorial coordinates



Point-like sources

Search for clusters of muon neutrinos over a background of diffusely distributed atmospheric neutrinos.

Data sample

- six years of data collected by the ANTARES neutrino telescope (from 2007 January 29 to 2012 December 31, total livetime of 1338 days)
- 5516 events, including an estimated 10% background from mis-reconstructed atmospheric muons.

STRATEGY

Event selection: blind procedure on pseudo-experiments before performing the analysis on data

Cuts on reconstructed tracks: $\Lambda > -5.2$, $\beta < 1°$, $\cos\theta < 0.1$
(minimization of neutrino flux to make a 5σ discovery in 50% of the experiments)

Neutrino energy spectrum: proportional to E^{-2}

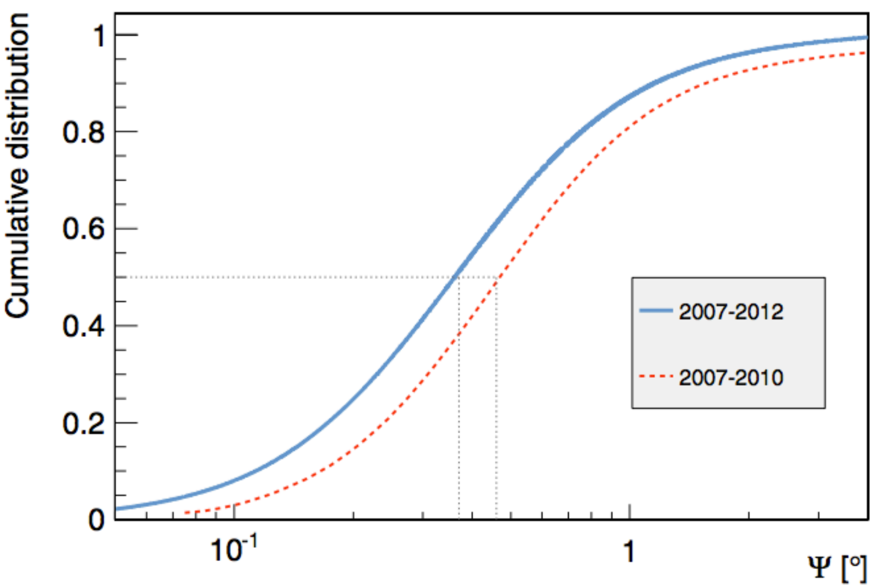
Point-like sources

Angular resolution and acceptance for events passing the selection cuts are computed.

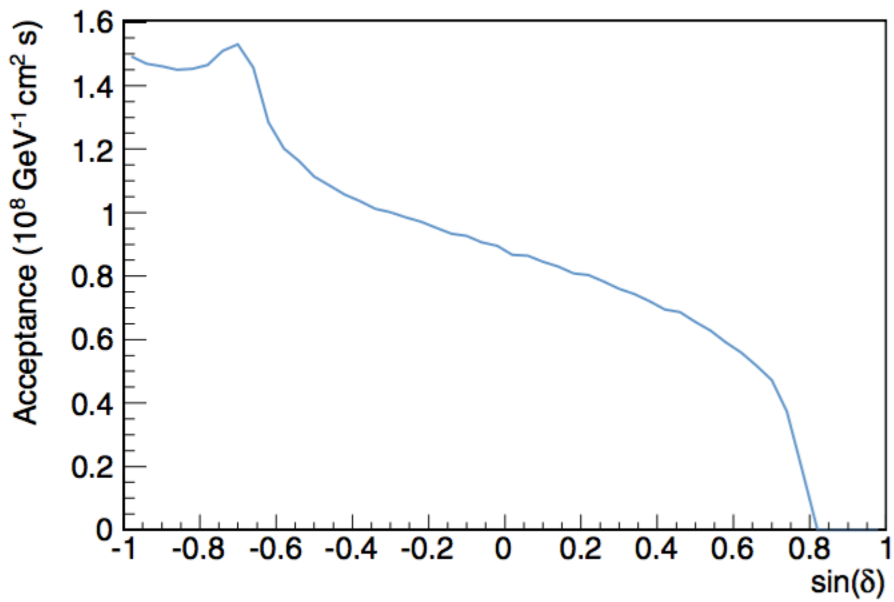
The estimated median neutrino angular resolution is 0.38°

The acceptance for a source located at a declination δ is

$$A(\delta) = \Phi_0^{-1} \int dt \int dE_\nu A_{\rm eff}(E_\nu, \delta) \frac{d\Phi}{dE_\nu}$$



cumulative distribution of the angle Ψ between the reconstructed muon direction and the true neutrino direction.



Time integration extending over the whole period of 1338 days
$A_{\rm eff}$ is the neutrino effective area

Point-like sources: full-sky search

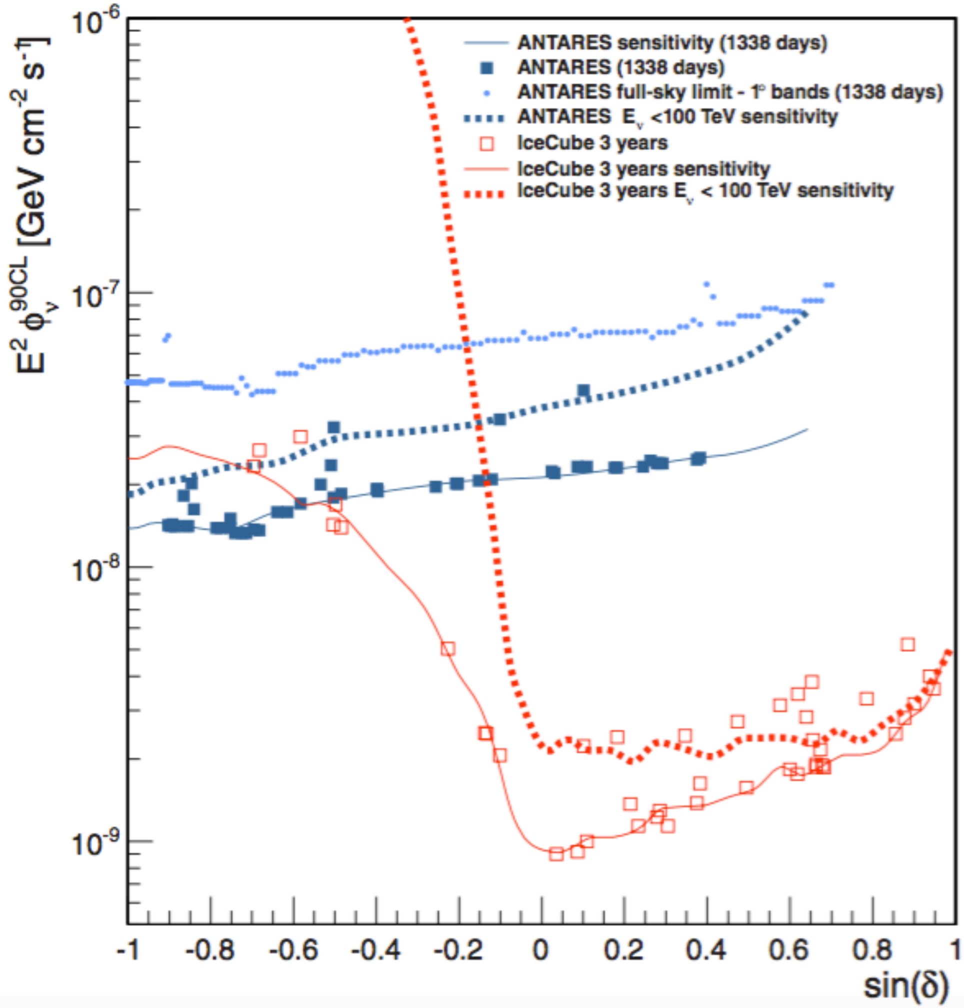
Full-sky search looking for an excess of signal events located anywhere in the whole ANTARES visible sky.

Pre-clustering: selection of candidate clusters with at least 4 events in a cone of half-opening angle of 3°

Most significant cluster found at
(α, δ) = (–46.8, –64.9)
post-trial p-value of 2.7 (2.2σ)

Number of fitted signal events $n_s = 6.2$
A total of 6 and 14 events are found in a cone of 1° and 3° around the fitted cluster center, respectively

Upper limits at 90% CL on muon neutrino flux from point sources located anywhere in the visible ANTARES sky are set



Point-like sources: candidate sources

The search uses a list of 50 neutrino candidate-source positions

Name	α (°)	δ (°)	n_s	p	ϕ_ν^{90CL}	Name	α (°)	δ (°)	n_s	p	ϕ_ν^{90CL}
HESSJ0632+057	98.24	5.81	1.60	0.0012	4.40	HESSJ1912+101	−71.79	10.15	0.00	1.00	2.31
HESSJ1741-302	−94.75	−30.20	0.99	0.003	3.23	PKS0426-380	67.17	−37.93	0.00	1.00	1.59
3C279	−165.95	−5.79	1.11	0.01	3.45	W28	−89.57	−23.34	0.00	1.00	1.89
HESSJ1023-575	155.83	−57.76	1.98	0.03	2.01	MSH15-52	−131.47	−59.16	0.00	1.00	1.41
ESO139-G12	−95.59	−59.94	0.79	0.06	1.82	RGBJ0152+017	28.17	1.79	0.00	1.00	2.19
CirX-1	−129.83	−57.17	0.96	0.11	1.62	W51C	−69.25	14.19	0.00	1.00	2.32
PKS0548-322	87.67	−32.27	0.68	0.10	2.00	PKS1502+106	−133.90	10.52	0.00	1.00	2.31
GX339-4	−104.30	−48.79	0.50	0.14	1.50	HESSJ1632-478	−111.96	−47.82	0.00	1.00	1.33
VERJ0648+152	102.20	15.27	0.59	0.11	2.45	HESSJ1356-645	−151.00	−64.50	0.00	1.00	1.42
PKS0537-441	84.71	−44.08	0.24	0.16	1.37	1ES1101-232	165.91	−23.49	0.00	1.00	1.92
MGROJ1908+06	−73.01	6.27	0.21	0.14	2.32	HESSJ1507-622	−133.28	−62.34	0.00	1.00	1.41
Crab	83.63	22.01	0.00	1.00	2.46	RXJ0852.0-4622	133.00	−46.37	0.00	1.00	1.33
HESSJ1614-518	−116.42	−51.82	0.00	1.00	1.39	RCW86	−139.32	−62.48	0.00	1.00	1.41
HESSJ1837-069	−80.59	−6.95	0.00	1.00	2.09	RXJ1713.7-3946	−101.75	−39.75	0.00	1.00	1.59
PKS0235+164	39.66	16.61	0.00	1.00	2.39	SS433	−72.04	4.98	0.00	1.00	2.32
Geminga	98.31	17.01	0.00	1.00	2.39	1ES0347-121	57.35	−11.99	0.00	1.00	2.01
PKS0727-11	112.58	−11.70	0.00	1.00	2.01	VelaX	128.75	−45.60	0.00	1.00	1.33
PKS2005-489	−57.63	−48.82	0.00	1.00	1.39	HESSJ1303-631	−164.23	−63.20	0.00	1.00	1.43
PSRB1259-63	−164.30	−63.83	0.00	1.00	1.41	LS5039	−83.44	−14.83	0.00	1.00	1.96
HESSJ1503-582	−133.54	−58.74	0.00	1.00	1.41	PKS2155-304	−30.28	−30.22	0.00	1.00	1.79
PKS0454-234	74.27	−23.43	0.00	1.00	1.92	Galactic Center	−93.58	−29.01	0.00	1.00	1.85
PKS1454-354	−135.64	−35.67	0.00	1.00	1.70	CentaurusA	−158.64	−43.02	0.00	1.00	1.36
HESSJ1834-087	−81.31	−8.76	0.00	1.00	2.06	W44	−75.96	1.38	0.00	1.00	2.23
HESSJ1616-508	−116.03	−50.97	0.00	1.00	1.39	IC443	94.21	22.51	0.00	1.00	2.50
H2356-309	−0.22	−30.63	0.00	1.00	2.35	3C454.3	−16.50	16.15	0.00	1.00	2.39

Point-like sources: candidate sources

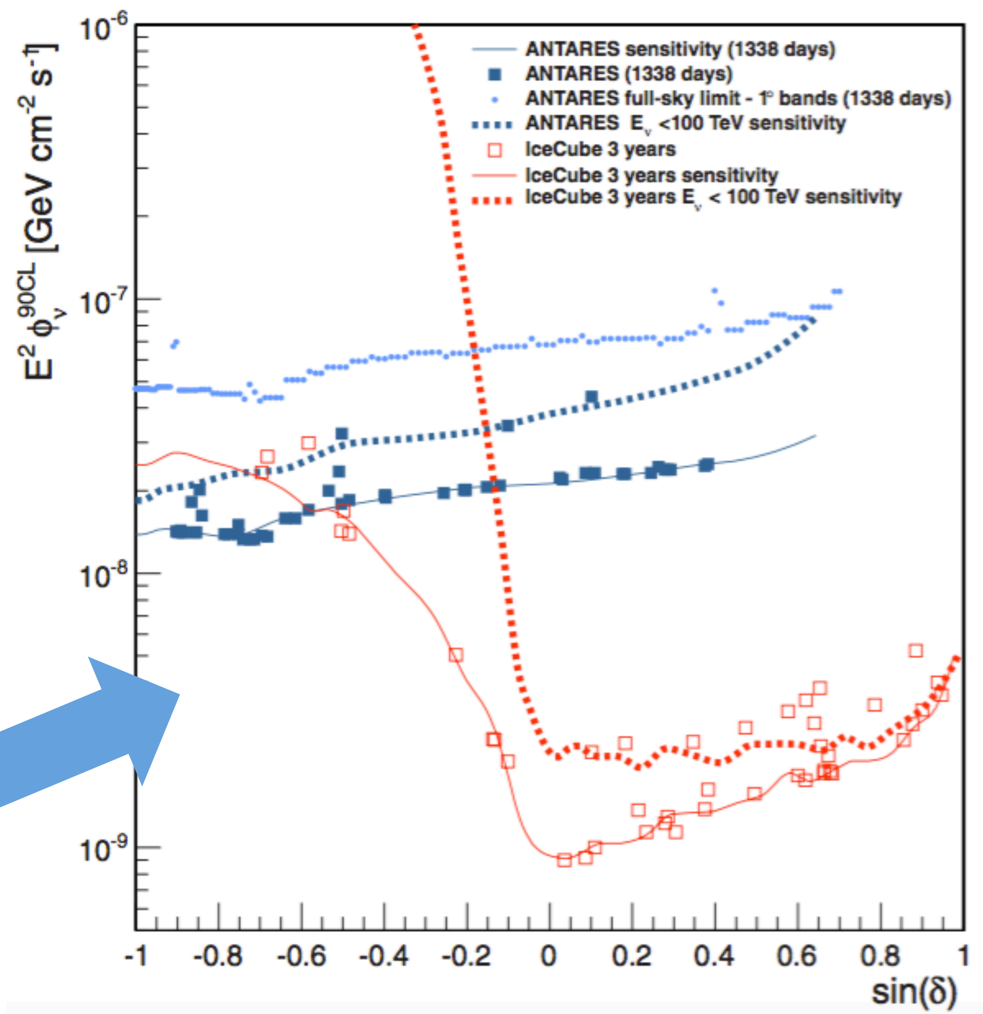
The search uses a list of 50 neutrino candidate-source positions

The largest excess corresponds to **HESS J0632+057**

post-trial p-value 6.1% (1.9σ)
Fitted number of source events n_s= 1.6

Upper limits on the flux normalization of an E^{-2} muon neutrino energy spectrum have been set

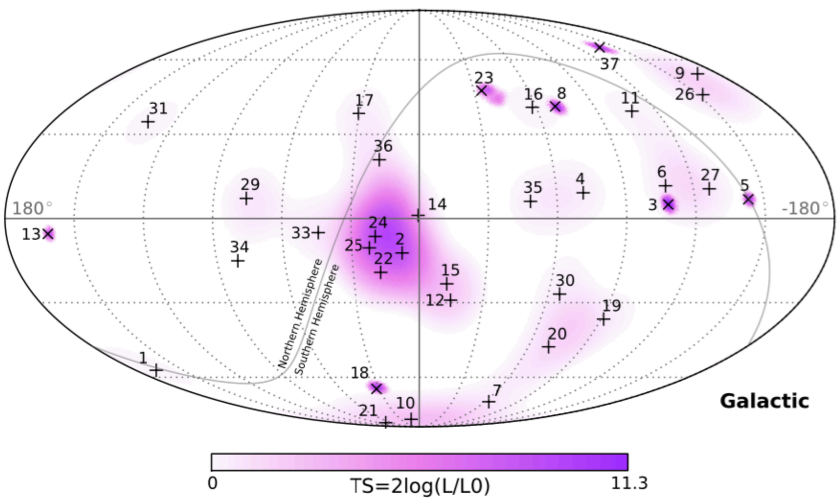
Comparison with IceCube
The derived flux upper limits are the most restrictive in a significant part of the Southern sky.



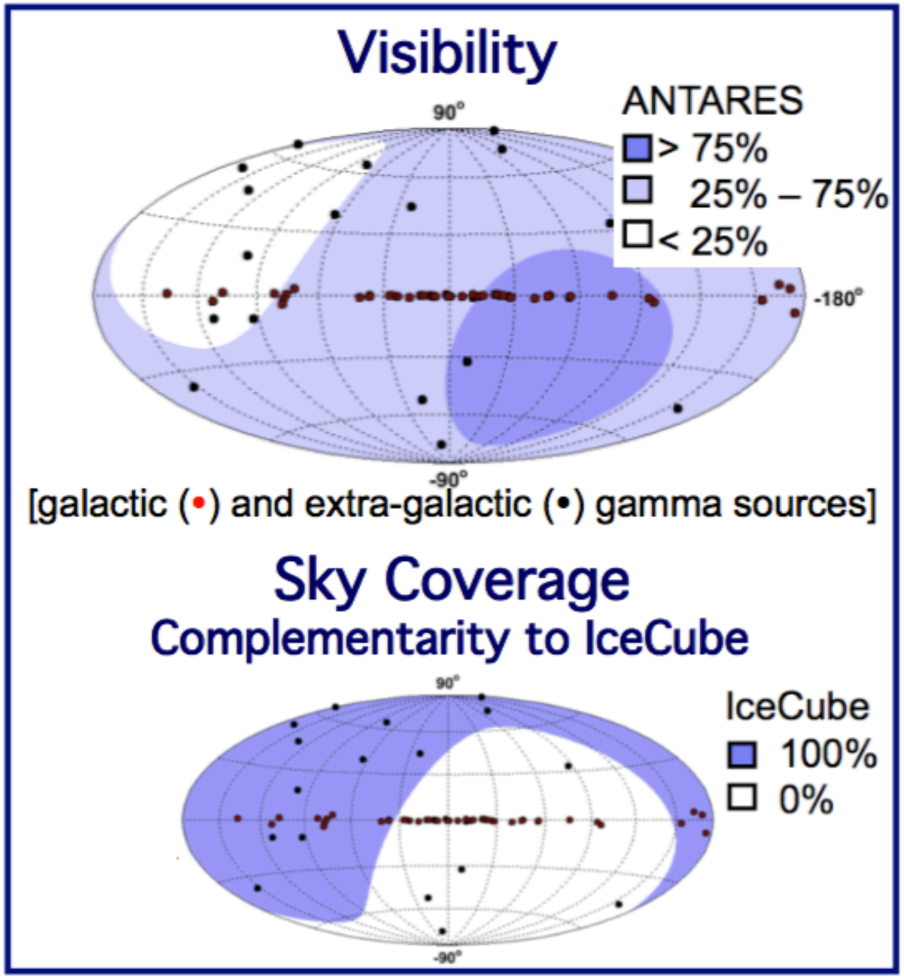
Point-like sources: IC candidates

The IceCube telescope has recently reported an accumulation of seven events relatively close to the Galactic Center

IceCube Neutrino Sky Map



3-year data set; 37 neutrino candidates
Energy range: 30-2000 TeV
NO clustering



Point-like sources: IC candidates

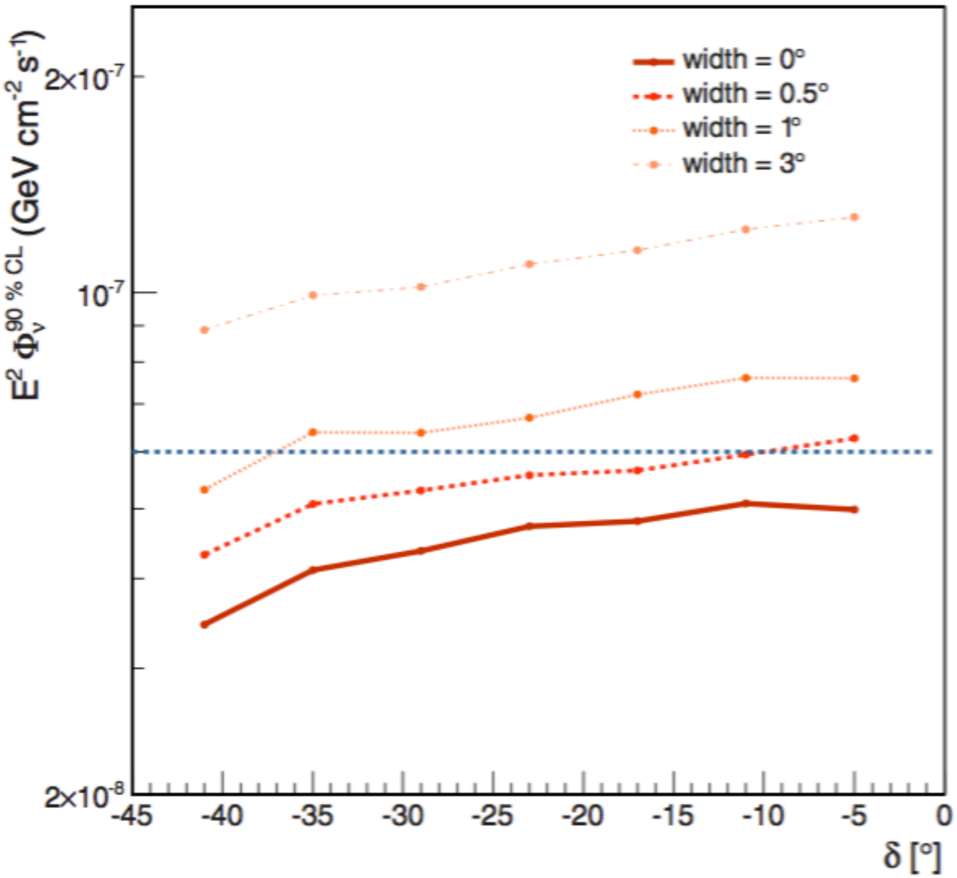
The IceCube telescope has recently reported an accumulation of seven events relatively close to the Galactic Center

STRATEGY

- Search for point sources in a region of 20° around the proposed location
- 3 Gaussian-like source extensions: (0.5°, 1°, 3°)

RESULTS

- No indication of neutrino signal has been found in the ANTARES data
- upper limits on the flux normalization of an E^{-2} energy spectrum of neutrinos from point sources in that region have been set.



Point-like sources: IC candidates

The IceCube telescope has recently reported an accumulation of seven events relatively close to the Galactic Center

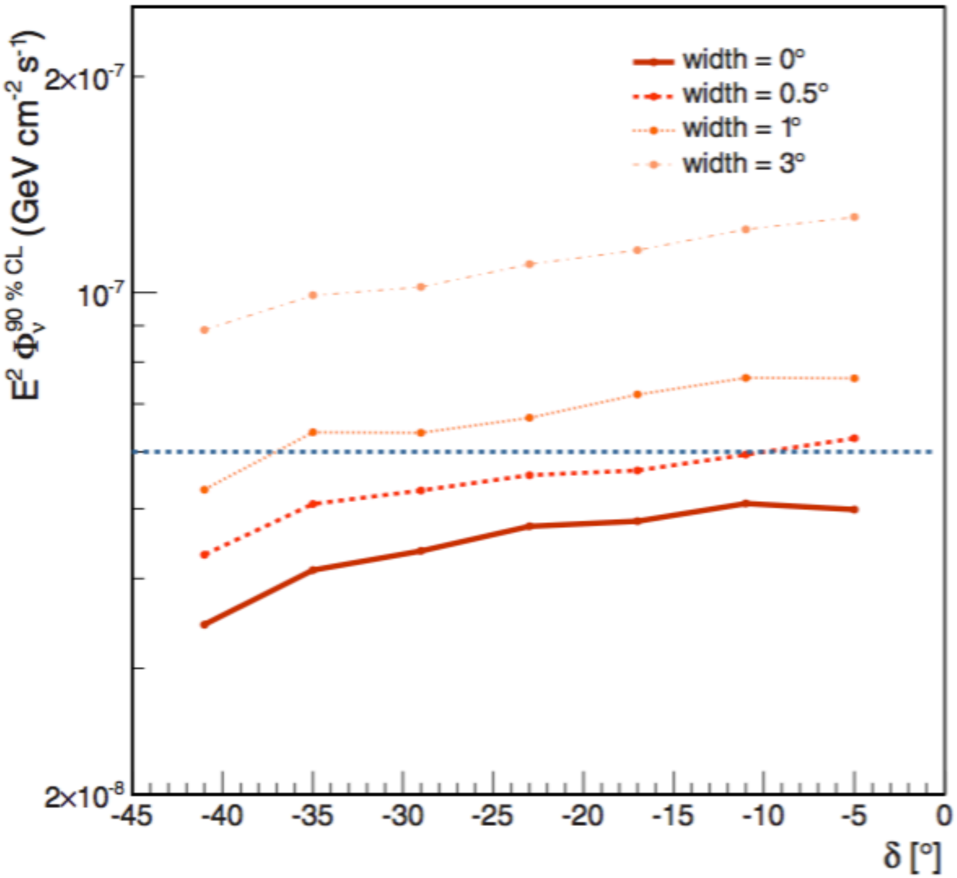
CONCLUSIONS

The presence of a point source with a flux of 6×10^{-8} GeV cm^{-2}s^{-1} anywhere in the region is excluded

↓

the excess found by IceCube in this region cannot be caused by a single point source.

a source width of 0.5 for declinations lower than –11° is also excluded.



Flaring Blazars

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Search for muon-neutrino emission from GeV and TeV gamma-ray flaring blazars using five years of data of the ANTARES telescope

The ANTARES collaboration

Flat-spectrum radio quasars (FSRQs) and BL Lacs are among the most violent variable high-energy phenomena in the Universe

BLAZARS

Relativistic jets pointing almost directly towards the Earth	Time variability at different wavelengths and on various time scales
↓	↓
Hadronic interactions predict neutrino emission in the TeV-PeV range	The associated neutrino emission is expected to exhibit a similar variability

↙

Time-dependent methods to improve the detection probability with respect to time-integrated approaches.

Full detector data: from September 6th, 2008 up to December 31st, 2012.
Filters are applied in order to exclude periods in which the optical background was high
Resulting effective livetime is **1044 days**.

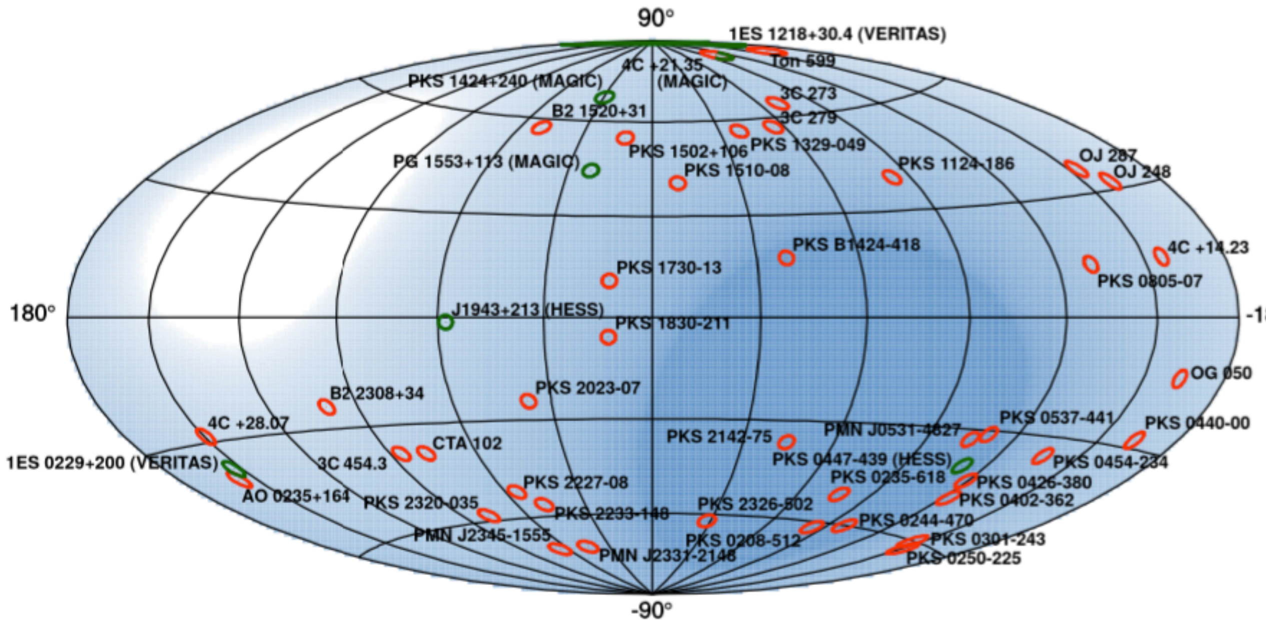
Flaring Blazars: time-dependent search

Time-dependent searches are significantly more sensitive than steady point-source searches thanks to the reduction of atmospheric background over short time scales.

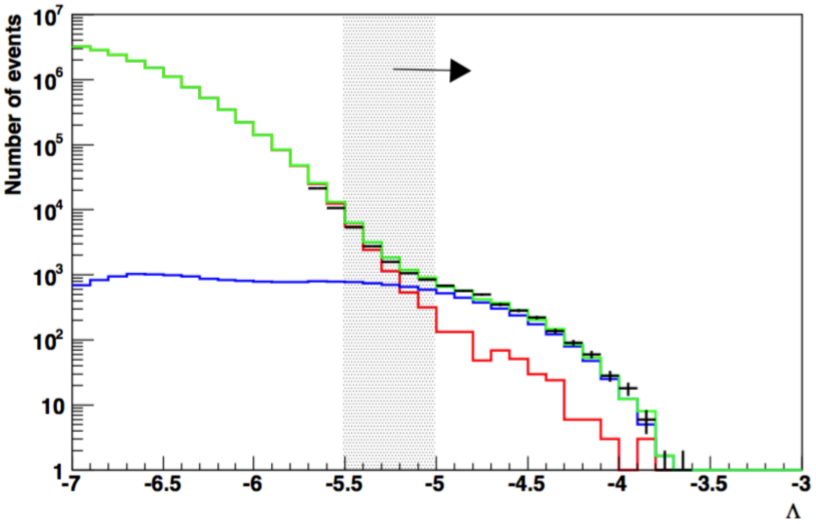
CANDIDATE SOURCES

- 41 very bright and variable Fermi LAT blazars sources reported in the second Fermi LAT catalogue and in the LBAS catalogue (LAT Bright AGN sample),
- 7 TeV flares reported by H.E.S.S, VERITAS or MAGIC telescopes.

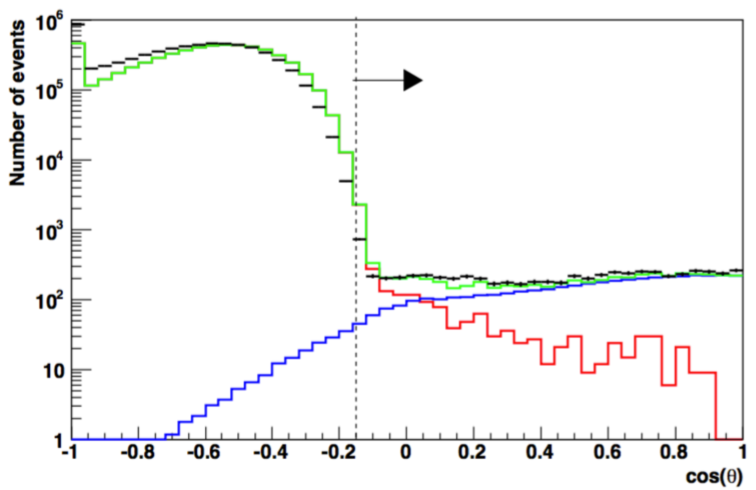
Sources located in the part of the sky visible to ANTARES ($\delta < 35°$) with a flux greater than 10^{-9} photons cm^{-2} s^{-1} above 1 GeV are selected.



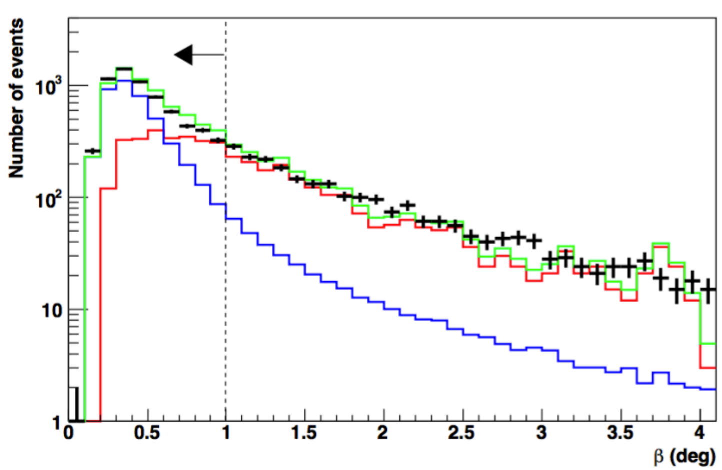
Flaring Blazars: cuts



Λ cut ranging from -5.5 to -5.0, depending on the source and the background characteristics during the flares.
(optimised for each source for the maximization of a model discovery potential for a 3σ significance level for each neutrino spectrum)



zenith angle $\cos(\theta) > 0.15$



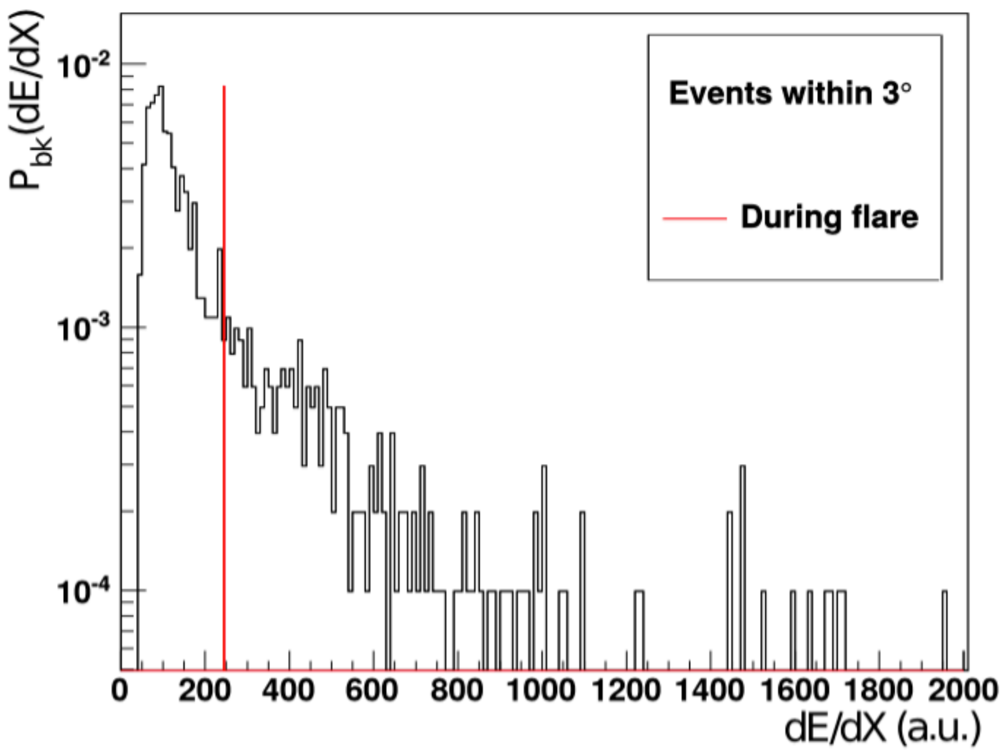
$\beta<1°$ (rejected 47% of atmospheric muons mis-reconstructed as upgoing tracks)

Flaring Blazars: time-dependent search

RESULTS

Only three sources have a pre-trial p-value lower than 10%: 3C279, PKS0235-618 and PKS1124-186

The lowest p-value, 3.3%, is obtained for 3C279 where one event is coincident with a large gamma-ray flare detected by Fermi/LAT in November 2008.



- Coincident event is reconstructed with 89 hits
- The energy deposition of the event in coincidence with the flare in a 1° cone around the source direction is dE/dX = 244 in a.u.
- Track fit quality Λ = -4.4

Flaring Blazars: time-dependent search

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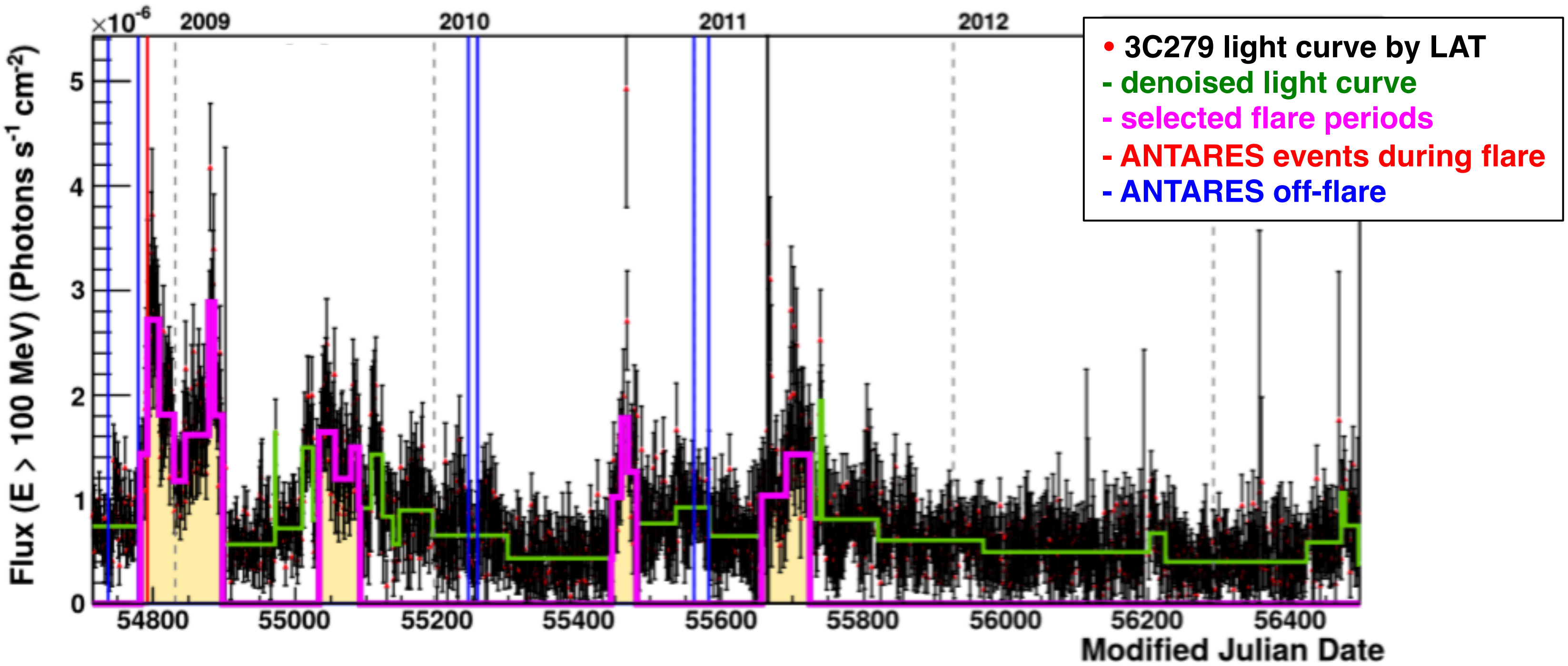
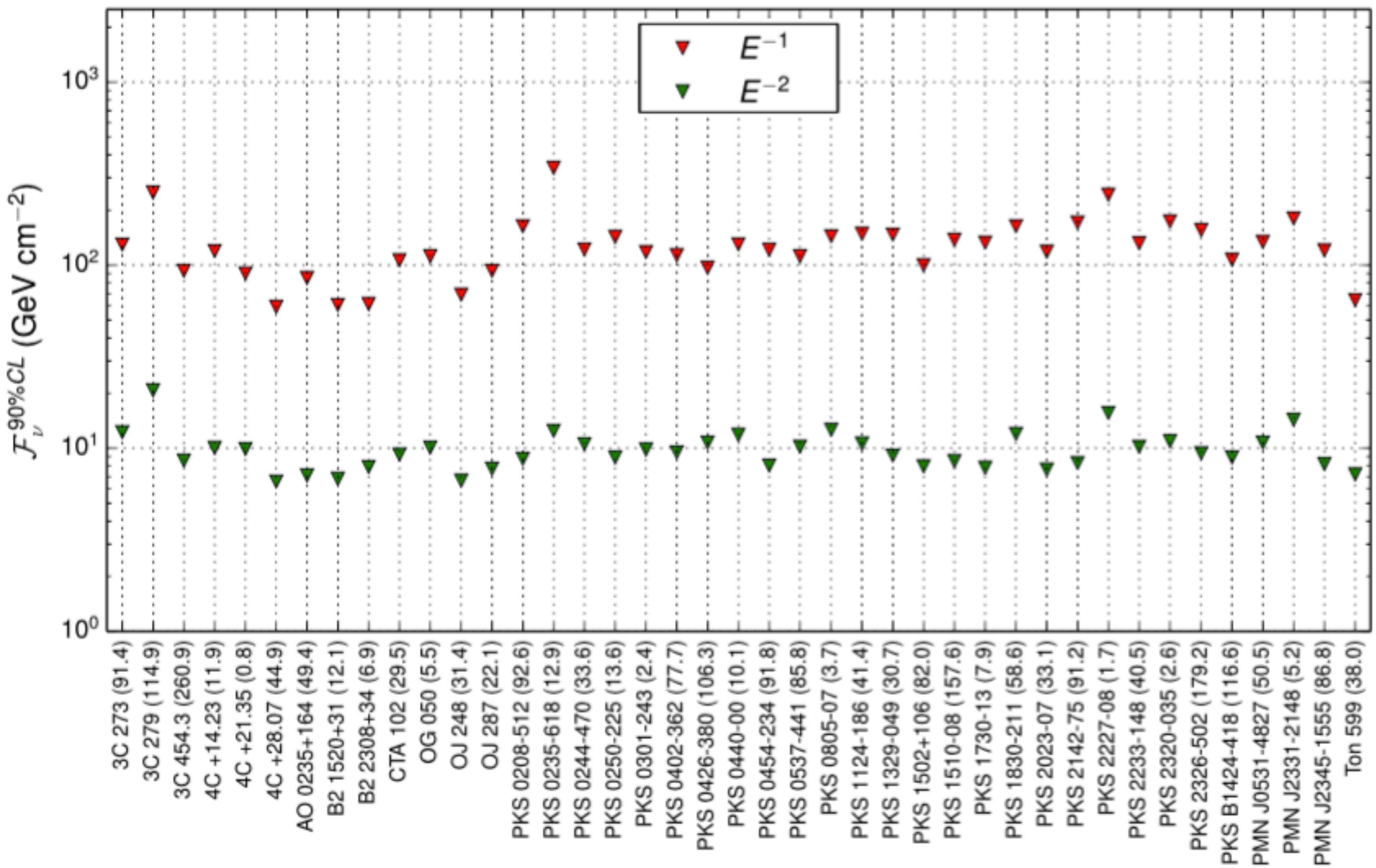


The post-trial probability, computed by taking into account the 41 searches, is 67%, and is thus **compatible with background fluctuations**.

Flaring Blazars: time-dependent search

RESULTS

In the absence of a discovery, upper limits on neutrino fluence at 90% C.L. are computed



Flaring Blazars: time-dependent search

TeV Blazars observed at Ground-based observatories

Ground-based observatories, such as H.E.S.S., MAGIC and VERITAS, can detect photons with energies from a few hundred GeV to a few TeV that may be correlated with the neutrinos to which ANTARES is sensitive.

7 candidate sources

Source	Telescope	RA	Dec	Time	Δt	Refence	E^{-1}					E^{-2}				
							$E_{\rm min}$	$E_{\rm max}$	ϕ_0	F	$\mathcal{F}$	$E_{\rm min}$	$E_{\rm max}$	ϕ_0	F	$\mathcal{F}$
4C+21.35	MAGIC	186.2	21.4	55364-5	0.8	1101.4645	5.5	7.9	37	30	210	3.5	6.6	47	33	24
PG 1553+113	MAGIC	239.0	11.2	55980-91,56037-8	5.3	1109.5860	5.4	7.9	2.9	2.4	110	3.4	6.5	2.8	2.0	8.9
PKS 1424+240	MAGIC	216.8	23.8	54940-60	2.4	1109.5860	5.6	7.9	7.0	5.7	120	3.5	6.6	9.8	7.0	14
1ES 1218+30.4	VERITAS	185.4	30.2	54860-5	2.0	1005.3747	5.6	7.9	5.7	4.7	80	3.7	6.7	7.8	5.5	9.3
1ES 0229+200	VERITAS	38.2	20.3	55118-31	5.7	1307.8091	5.5	7.9	2.8	2.3	110	3.6	6.6	4.3	3.0	15
HESS J1943+213	H.E.S.S.	296.0	21.3	55040-60	3.5	1103.0763	5.5	7.9	4.1	4.3	100	3.6	6.6	7.0	5.7	4.0
PKS 0447−439	H.E.S.S.	72.4	-43.8	55174-84	8.0	1303.1628	5.4	7.9	2.0	16	110	3.3	6.4	2.8	2.0	14
Units:									$\cdot 10^{-12}$	$\cdot 10^{-4}$				$\cdot 10^{-6}$	$\cdot 10^{-5}$	

$[\phi_0] = \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ | $[F] = \mathrm{GeV\,cm}^{-2}\mathrm{s}^{-1}$ | $[\mathcal{F}] = \mathrm{GeV\,cm}^{-2}$

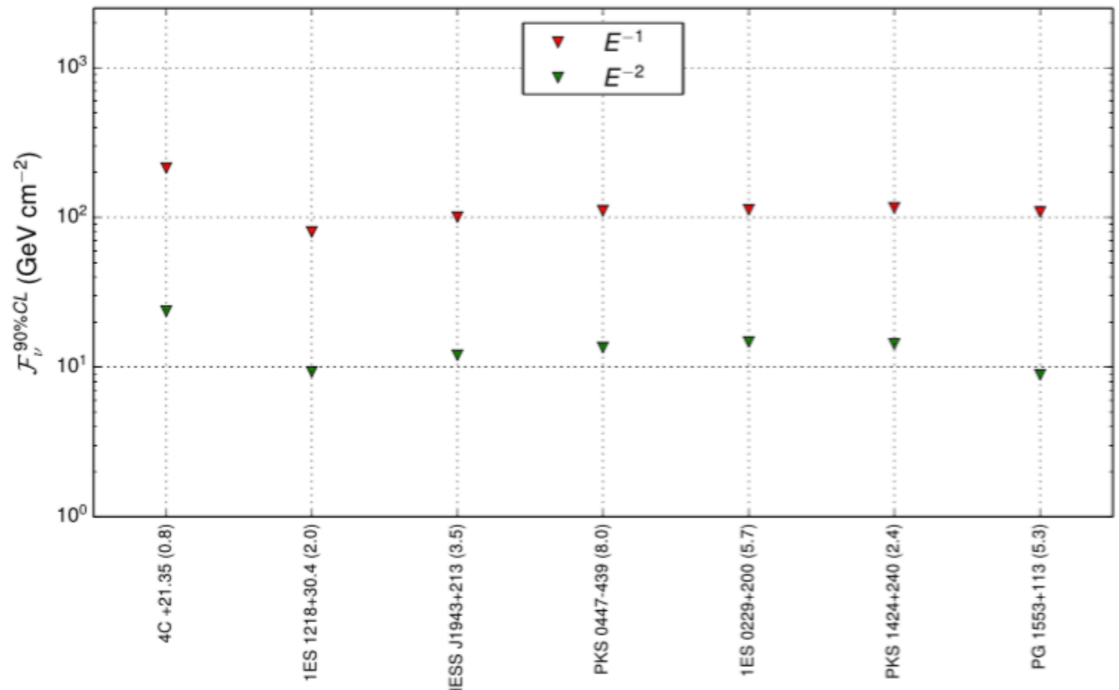
The flares are chosen for this analysis according to the same visibility criteria as for Fermi/LAT observations. The same analysis as described previously is performed assuming the same energy spectra.

Flaring Blazars: time-dependent search

RESULTS

- Six of the seven flares tested show **no excess of events** in the vicinity of the corresponding sources in the selected time windows.
- Only the blazar **PKS0447-439** shows a pre-trial p-value lower than 10%.
- The corresponding post trial p-value is 55%, and is also consistent with background fluctuations.

Again, in the absence of a signal, upper limits on the neutrino fluence at 90% C.L. are computed including the systematic errors



IC HESE

ANTARES constraints on a Galactic component of the IceCube cosmic neutrino flux

Maurizio Spurio[1,2,a]

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[2] *Istituto Nazionale di Fisica Nucleare - Sezione di Bologna - Viale Berti Pichat 6/2, 40127 Bologna (Italy)*

The IceCube evidence for cosmic neutrinos has inspired a large number of hypothesis on their origin, mainly due to the poor precision on the measurement of the direction of showering events.
A North/South asymmetry in the present data set suggests the presence of a possible Galactic component.

High Energy Starting Events (HESE) flux observed by IC:

- compatible with flavor ratios $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$, as expected from charged meson decays in CR accelerators and neutrino oscillation
- non-observation of events beyond 2 PeV, leading to two hypotheses:
  - neutrino flux with a power law $E^{-\Gamma}$ with hard spectral index (Γ=2.0) and an exponential cutoff
  - unbroken power law with a softer spectrum, e.g. Γ=2.3.

IC HESE

New IC search for neutrinos with energy between 1 TeV and 1 PeV - 641 days livetime
An excess of downgoing events with respect to expectation seems to be present.

HESE [2] $E_{dep} > 60$ TeV	Data	Bck	n_{IC}	N_{IC} E^{-2}
Up (North)	5	1.4	3.6	6.7
Down (South)	15	1.3	13.7	11.5
All	20	2.7	17.3	18.2

6.2 events are expected from the South

Assuming:
- $E^{-2.0}$ spectrum,
- symmetric contribution from the North/South extragalactic sources ,
- different acceptances for events coming from the North and South hemispheres.

The 7.5 events excess in the Southern sky corresponds to the 40% of the total signal.

IC HESE

An even stronger excess from the South is derived using events with $E_{dep} > 25$ TeV.

New ν sample [4] $E_{dep} > 25$ TeV	Data	Bck	n_{IC}	N_{IC} $E^{-2.46}$
Up ($\sin\delta > 0.06$)	11	5.3	5.7	12.1
Down ($\sin\delta < -0.06$)	29	4.8	24.2	15.0
All	43	11.7	31.3	29.1

7.2 events from the South with $\sin\delta < 0.06$

Assuming:

- $E^{-2.0}$ spectrum,
- symmetric contribution from the North/South extragalactic sources ,
- different acceptances for events coming from the North and South hemispheres.

Excess of 15 events in the Southern sky, corresponds to the 50% of the total signal.

Two scenarios:

- non-isotropic cosmic component, likely of Galactic origin,
- contribution from transient extragalactic objects located in the Southern sky

IC HESE: point-like sources

ANTARES constraints for the IC signals

normalization factor $\Phi_0^{p,\Gamma}$ for a point-like source:

$$\Phi=\Phi_0 E^{-\Gamma}$$

	units: (GeV cm^{-2} s^{-1})					
	$\Phi_0^{p,\Gamma}$ (from HESE)					ANTARES
$\Gamma =$	$n_p = 1$	$n_p = 2$	$n_p = 3$	$n_p = 4$	$n_p = 5$	90% C.L. limit
2.0	$6.9\ 10^{-9}$	$1.4\ 10^{-8}$	$2.1\ 10^{-8}$	$2.8\ 10^{-8}$	$3.5\ 10^{-8}$	$4.0\ 10^{-8}$
2.2	$9.0\ 10^{-8}$	$1.8\ 10^{-7}$	$2.7\ 10^{-7}$	<u>$3.6\ 10^{-7}$</u>	-	$3.2\ 10^{-7}$
2.3	$3.3\ 10^{-7}$	$6.6\ 10^{-7}$	<u>$9.9\ 10^{-7}$</u>	-	-	$8.4\ 10^{-7}$
2.4	$1.2\ 10^{-6}$	<u>$2.3\ 10^{-6}$</u>	-	-	-	$2.2\ 10^{-6}$

The ANTARES 90% C.L. upper limit constraints:

- a single point-like source with Γ=2.0 cannot produce more than 5 HESE
- for Γ=2.3 a single point-like source cannot yield a cluster of more than 2 events
- the presence of a cluster made of two or more events is excluded for Γ>2.3

IC HESE: diffuse flux

Larger background due to atmospheric neutrinos

The sensitivity depends on the background rate

↓

different optimizations must be deduced for diferent spectral indexes

it can be assumed that the background level increases for softer spectral indexes

Sensitivities extrapolated from the ANTARES FB analysis for $\Gamma > 2.0$

$\Delta\Omega$ (sr)	$\Gamma =$	units: (GeV cm^{-2} s^{-1} sr^{-1}) $\Phi_0^{D',\Gamma}$ (from HESE) $n_{\Delta\Omega} = 3$	$n_{\Delta\Omega} = 4$	$n_{\Delta\Omega} = 5$	$n_{\Delta\Omega} = 6$	ANTARES sensitivity
0.06	2.0	$3.5\ 10^{-7}$	$4.6\ 10^{-7}$	$5.8\ 10^{-7}$	$7.0\ 10^{-7}$	$3.1\ 10^{-7}$
	2.2	$4.5\ 10^{-6}$	$6.0\ 10^{-6}$	$7.5\ 10^{-6}$	$9.0\ 10^{-6}$	$3.6\ 10^{-6}$
	2.3	$1.7\ 10^{-5}$	$2.2\ 10^{-5}$	$2.8\ 10^{-5}$	$3.3\ 10^{-5}$	$1.1\ 10^{-5}$
	2.4	$5.9\ 10^{-5}$	$7.8\ 10^{-5}$	$9.8\ 10^{-5}$	$1.2\ 10^{-4}$	$3.4\ 10^{-5}$

a dedicated search for a directional neutrino flux would produce a positive result for any spectral indexes $\Gamma \geq 2.0$, if $\Delta\Omega \leq 0.06$ sr and $n_{\Delta\Omega} > 2$.

Conclusions

- ANTARES can provide an important contribution to understand the origin of cosmic neutrinos observed by IceCube;
- Southern sky studied with effective area comparable with IC-contained events and better angular resolution (~0.4°-water properties);
- Large ANTARES sensitivity for potential point-like sources;
- Extended sources: a common origin of few HESE in a region of $\Delta\Omega$<0.2 sr in the Southern Sky can produce a signal in ANTARES;
- Multi-messenger studies (flaring blazars by TANAMI correlated with PeV HESE);
- ANTARES will continue data taking until the end of 2016.

COMING SOON

KM3NeT-ARCA (Phase 1)

- 8 Towers (NEMO-style) + 24 DU (in construction phase)
- Effective areas > x3 ANTARES

Backup slides

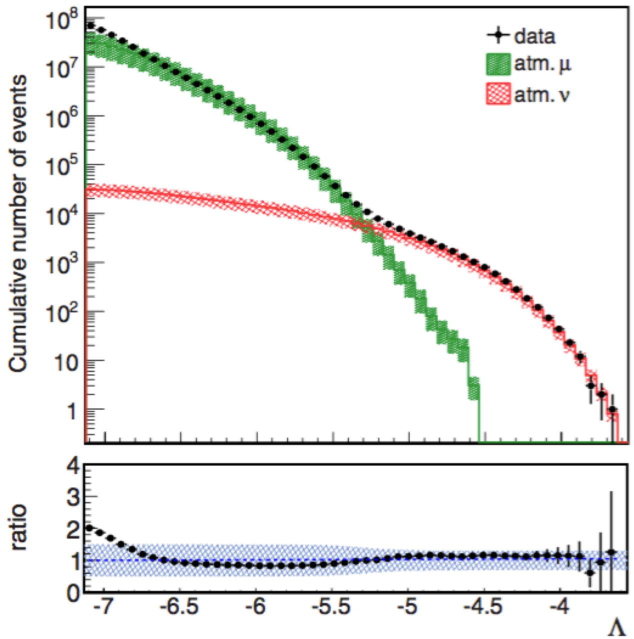
Antares: track reconstruction

Track reconstruction algorithm

Multi-step procedure: muon track parameters are obtained maximising a likelihood function built from the difference between the expected and the measured arrival times of the hits from the Cherenkov photons emitted along the muon track.

Two quality parameters:

- track-fit quality parameter Λ,
- estimated angular uncertainty on the fitted zenith and azimuth angles β



Data vs simulation comparison of the Λ distribution for zenith angles θ with cos θ < 0.1

Atmospheric neutrino simulation uses the Bartol flux

Flaring Blazars: time-dependent search

STRATEGY

Unbinned method based on a likelihood-ratio maximisation.

Goal:
- determine, in a given direction in the sky and at a given time, the relative contribution of signal and background components;
- calculate the probability to have a signal above a given background model.

METHOD

Test statistic λ, defined as the ratio of the probability for the hypothesis of background and signal ($H_{sig+bkg}$) over the probability of only background (H_{bkg})

$$\lambda = \sum_{i=1}^{N} \ln \frac{\mathcal{P}(x_i | H_{\mathrm{sig+bkg}}(\mathcal{N}_{\mathrm{S}}))}{\mathcal{P}(x_i | H_{\mathrm{bkg}})}$$

where N_S is the unknown number of signal events in the considered data sample, and x_i are the observed event properties (δ_i, RA_i, dE/dX_i and t_i)

Flaring Blazars: time-dependent search

METHOD

- Null hypothesis: $N_S = 0$ (λ_0) (background-only hypothesis);
- The obtained value of λ for the data is then compared to the distribution of λ_0 obtained by pseudo-experiments;

The fraction of trials above data is referred to as the p-value.

Discovery potential: average number of signal events required to achieve a p-value lower than 2.7 10^{-3} (5.7 10^{-7}) (3(5)σ) in 50% of the trials.