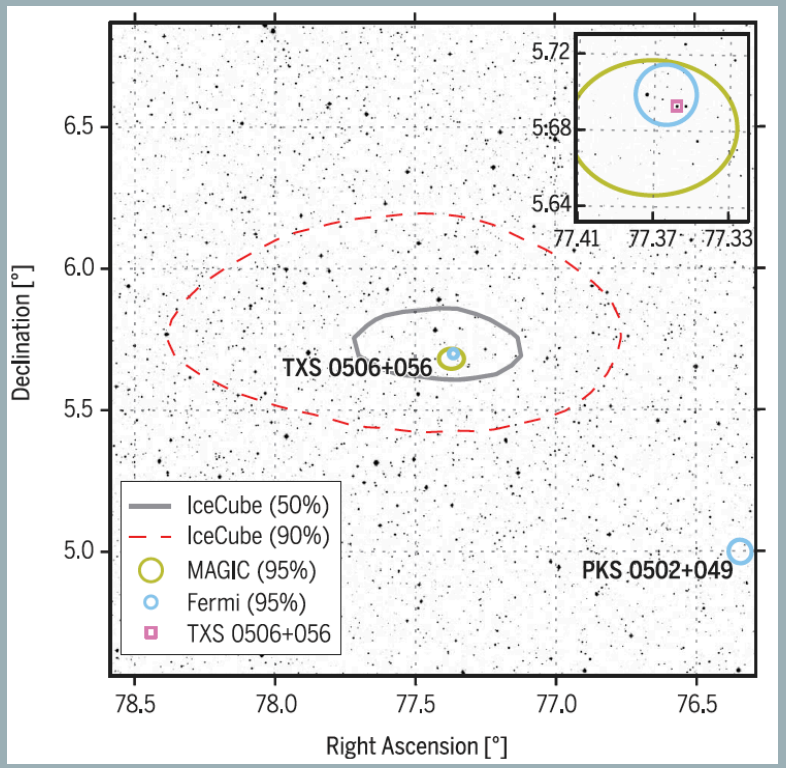
The Search for Neutrinos from TXS 0506+056 with the ANTARES Telescope

IceCube-170922A and TXS 0506+056

- IceCube-170922A detected on 22 September, 2017
- ~290 TeV neutrino induced muon track
- High probability of being of astrophysical origin

- Coincident in direction and time with a gamma-ray flare from the blazar TXS 0506+056 (Fermi-LAT, MAGIC)

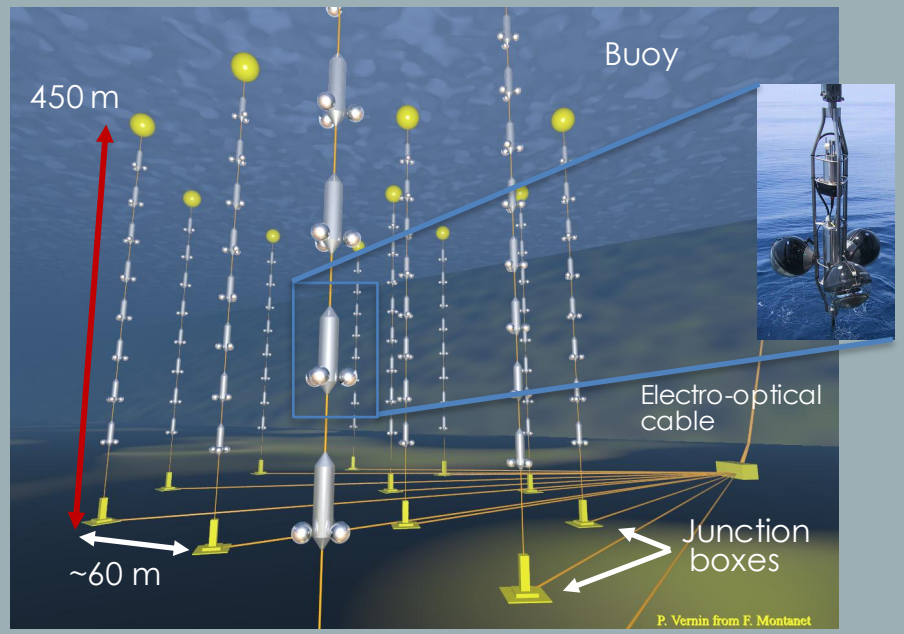
- 9.5 years of IceCube neutrino observations investigated to search for excess emission at the position of TXS 0506+05
- 3.5σ evidence for neutrino emission from the direction of the blazar between September 2014 and March 2015 found

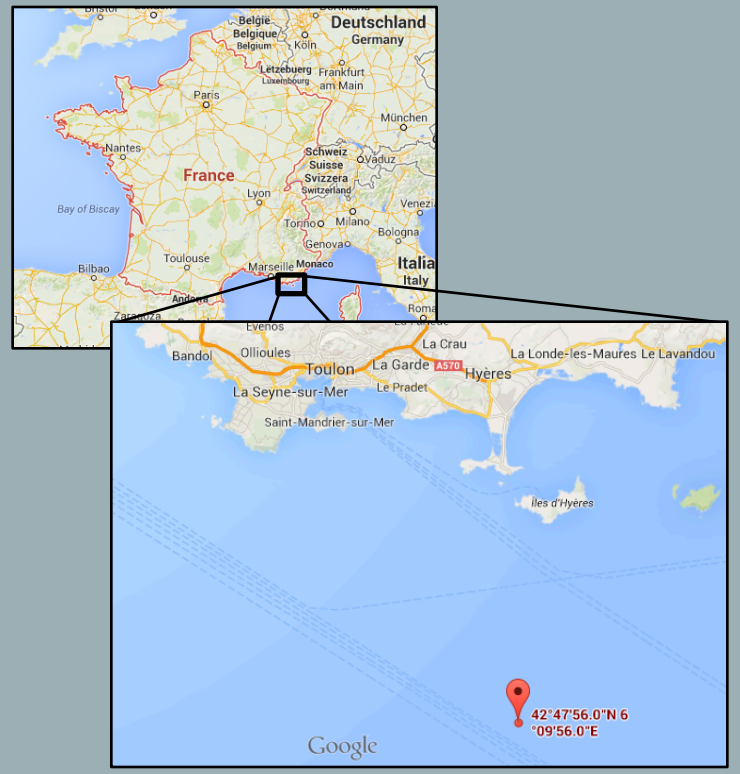


We present the results of three different searches for neutrino candidates, associated with the IceCube-170922A event or from the direction of TXS 0506+056, by the ANTARES neutrino telescope

The ANTARES neutrino telescope

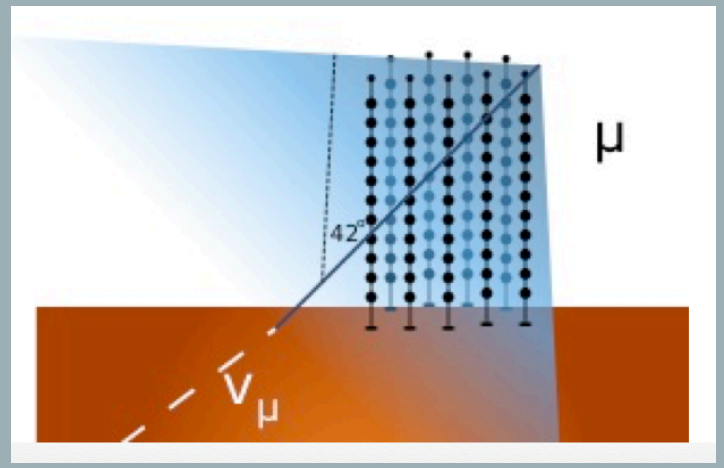
- First detection line installed in early 2006
- Completed in 2008
- 2475 m depth in the Mediterranean Sea
- 40 km offshore from Toulon



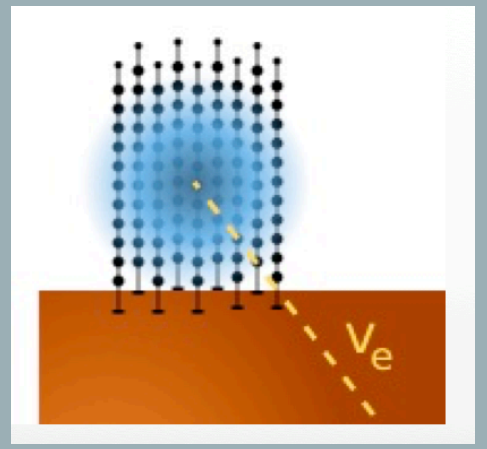


- Three-dimensional array of 885 PMTs
- 12 vertical lines, 25 storeys
- 3 PMTs per storey
- PMT facing 45° downwards
- Cherenkov radiation from up-going particles
- Position, time and charge used to reconstruct direction and energy

Event topologies: TRACKS and SHOWERS

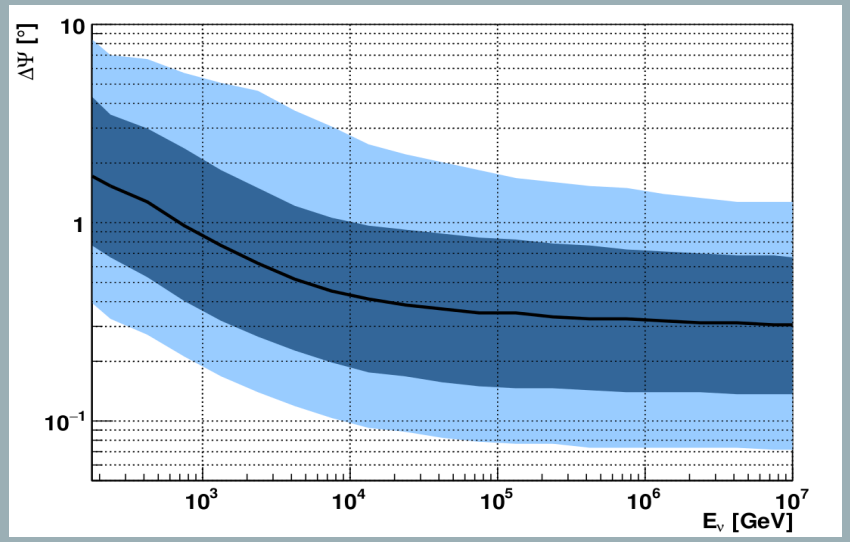


Track-like events:
ν_μ (ν_τ) neutrino CC interaction near the detector
➔ track

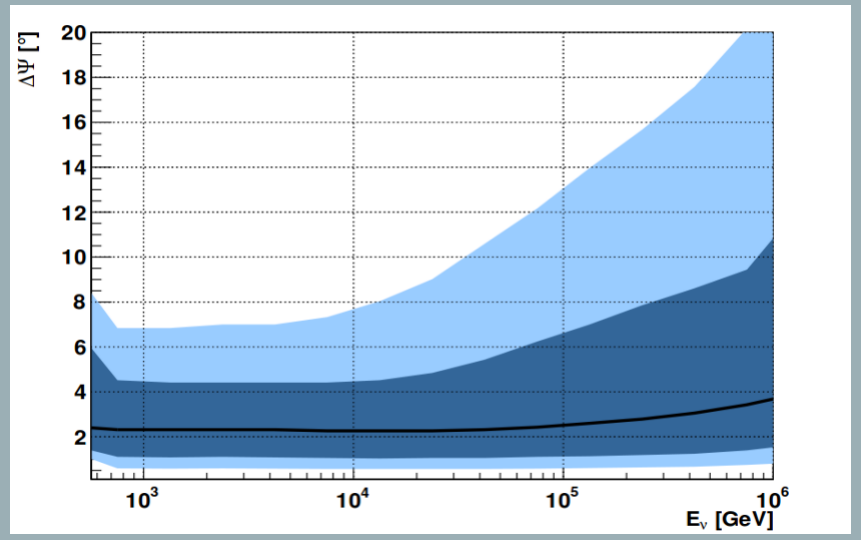


Shower-like events:
all neutrinos NC
ν_e,ν_τ CC interaction inside or very close to the detector ➔ shower

Angular resolution < 0.4° for E_ν > 10 TeV



Angular resolution < 3°



ANTARES searches

1) Online searches for neutrinos associated to IceCube-170922A

- Based on the originally communicated location of IC170922A reported with a GCN circular
- HE neutrino candidates searched for in the ANTARES online data stream

2) Time integrated search for neutrinos from TXS 0506+056

- Triggered by the potential association between IC170922A and TXS 0506+56
- Source position scrutinized following the ANTARES standard point-source method

3) Search for neutrinos in the bursting period

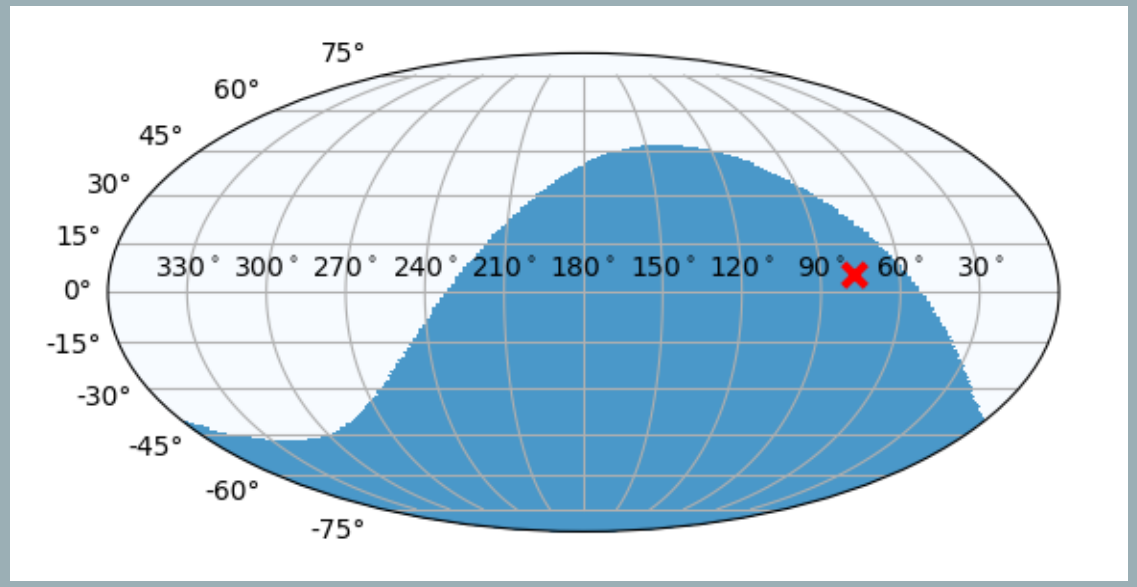
- Following the results of a time-dependent analysis performed by the IceCube Coll.
- Standard time-dependent analysis on a bursting period defined by the emission profiles provided by the IceCube Coll.

1) Online searches for neutrinos associated to IceCube-170922A EHE

- Extremely High Energy (EHE) track

Event reported with a GCN circular

- T0 = 17/09/22, 20:54:30.43 UT
- (RA, δ) = (77.43°, 5.72°)
- 14.2° below the horizon
- Search for up-going HE neutrino candidates in the ANTARES online data stream by means of fast algorithm
  - Idealized detector geometry
  - No information on the dynamical positioning calibration
  - Median angular resolution below 0.5° (E_ν > 10 TeV)



Visibility map for the ANTARES detector of IC170922A (**x**) in equatorial coordinates.

Competitive sensitivity with respect to IceCube to this position in the sky for neutrino energies below ~ 100 TeV

1) Online searches for neutrinos associated to IceCube-170922A EHE

- Searches for up-going muon neutrinos in a 3° cone centered on the IceCube event coordinates in two time-windows centered on the event time:
  - ±1 h
  - ±1 day (46% visibility probability)

- No coincident up-going muon neutrino recorded

- 90% C.L. fluence upper limit for a $\frac{dN}{dE} \propto E^{-\gamma}$ source:

Spectrum	90% C.L. Fluence$^{U.L.}$ [GeV cm^{-2}]	5%-95% energy range
$E^{-2.0}$	15	3.3 TeV – 3.4 PeV
$E^{-2.5}$	34	450 GeV – 280 TeV

2) Time integrated search for neutrinos from TXS 0506+056

- ANTARES standard point source method
- Maximum likelihood ratio approach

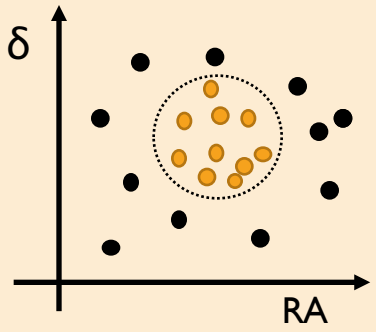
$$\log L_{s+b} = \sum_j \sum_{i \in j} \log\left[\mu_{sig}^j S_i^j + N^j B_i^j\right] - \mu_{sig}$$

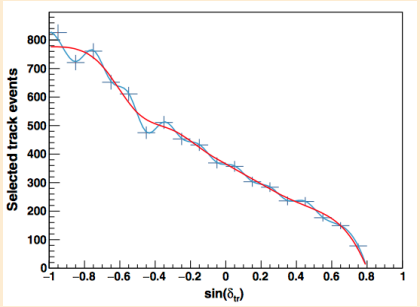
J: sample (tracks or showers)
i: event in sample J

N: total # of events
μ_{sig}: # of fitted signal events

Signal PDFs:

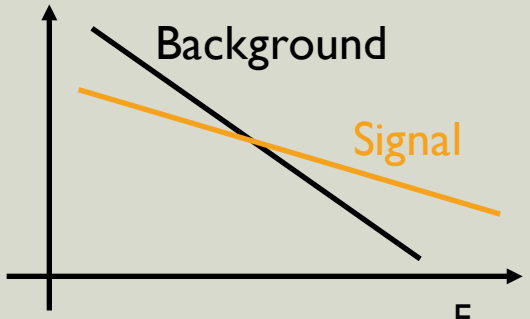
$$S_i = S^{space} \cdot S^{energy}$$





Background PDFs:

$$B_i = B^{space} \cdot B^{energy}$$



Source with E^{-2} spectrum assumed

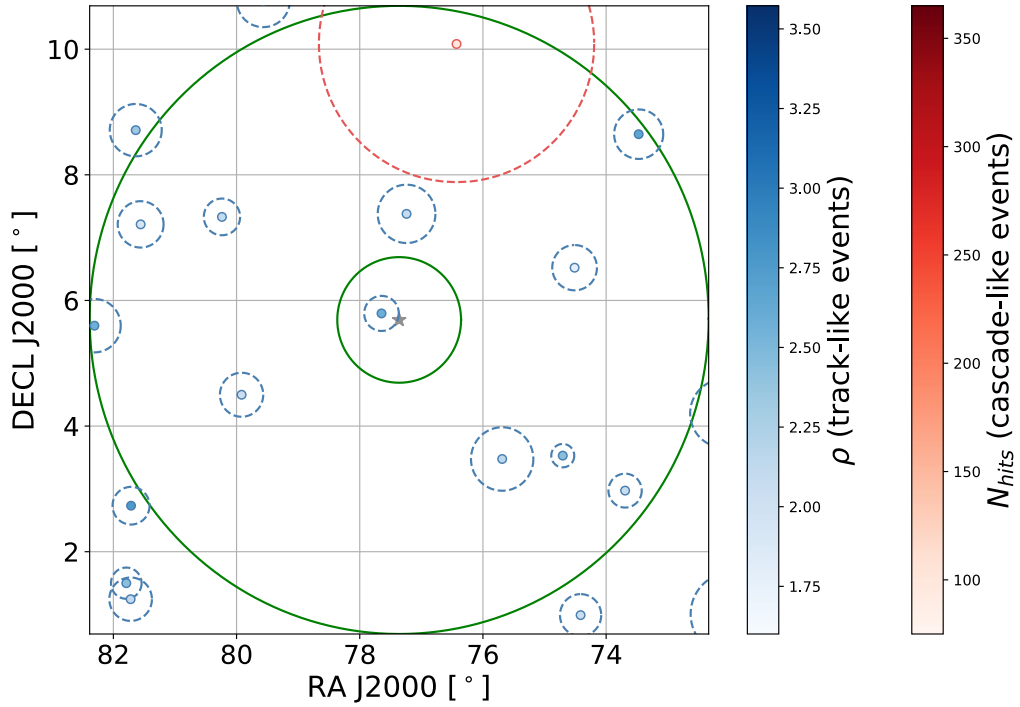
2) Time integrated search for neutrinos from TXS 0506+056

Standard candidate list search applied to the 2007-2015 ANTARES data (livetime: 2424 days)

- TXS 0506+056 added to the list of 106 neutrino source candidates analysed in the latest ANTARES point-source search (Phys. Rev. D **96**, 082001 (2017))
  - TXS 0506+056 third most significant source
  - Best fitted # of signal events μ_{sig} = 1.03
  - 2.6% pre-trial p-value
  - 87% post-trial p-value

- Closest event at 0.3° from the source position
- Recorded on December 12, 2013
- Only 9% of ν events have higher estimated energy

Events close to TXS 0506+056 in 2007-2015 ANTARES data



- 11 track-like and 1 shower-like neutrino candidates within 5° from TXS 0506+056

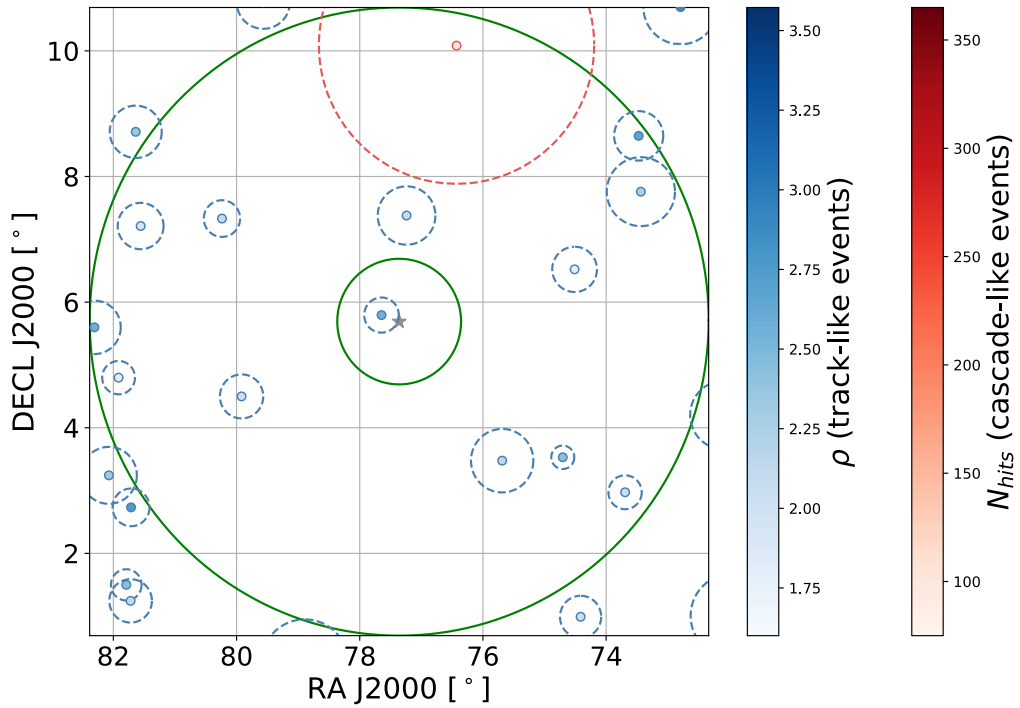
2) Time integrated search for neutrinos from TXS 0506+056

Standard fixed source analysis applied to the 2007-2017 ANTARES data (livetime: 3136 days)

- Search limited to the position of TXS 0506+056
  - Best fitted # of signal events μ_{sig} = 1.03
  - 3.4% pre-trial p-value
  - 90% C.L. flux upper limits on the flux:

Spectrum	$\Phi^{90\%}_{100\text{TeV}}$ $[10^{-18}\ \text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}]$
$E^{-2.0}$	1.6
$E^{-2.3}$	1.4
$E^{-2.5}$	1.0

Events close to TXS 0506+056 in 2007-2017 ANTARES data



- 13 track-like and 1 shower-like neutrino candidates within 5° from TXS 0506+056

3) Search for neutrinos in the bursting period

- ANTARES time dependent search method
- Maximum likelihood ratio approach
- Bursting period defined by the two profiles provided by the IceCube Collaboration:
  - Gaussian flare (centered on December 13, 2014)
  - Box flare (centered on December 26, 2014)

Signal PDFs:

$$S_i = S^{space} \cdot S^{energy} \cdot S^{time}$$

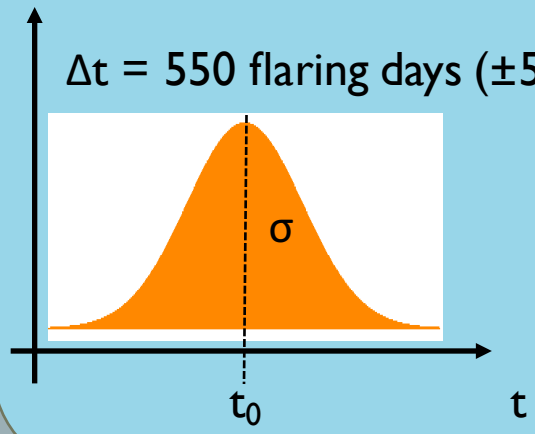
Background PDFs:

$$B_i = B^{space} \cdot B^{energy} \cdot B^{time}$$

Gaussian flare

t_0 = MJD 57004
σ = 55 days

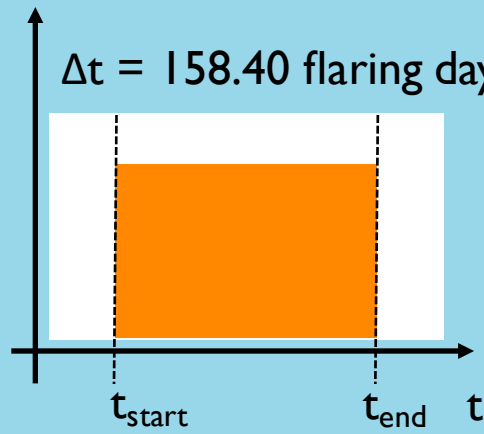
Δt = 550 flaring days (±5σ)

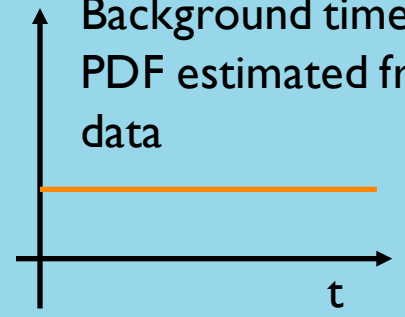


Box flare

t_{start} = MJD 56937.81
t_{end} = MJD 57096.21

Δt = 158.40 flaring days





3) Search for neutrinos in the bursting period

- The reduced observational time window allows for less stringent selection cuts with respect to the time integrated analysis
- More lower energy cosmic neutrinos → analysis sensitive to a softer neutrino energy spectrum

- No signal has been found during either of the considered flares
- 13 events within 2° from the source found in data. None of them lie within either of the two flaring periods
- 90% C.L. upper limits on the neutrino flux derived for the Gaussian-shaped period:

Spectrum	$\Phi^{90\%}_{100\text{TeV}}\,[10^{-18}\ \text{GeV}^{-1}\,\text{cm}^{-2}\,\text{s}^{-1}]$	5%-95% energy range
$E^{-2.0}$	4.6	2.0 TeV – 3.2 PeV
$E^{-2.1}$	4.4	1.3 TeV – 1.6 PeV
$E^{-2.2}$	4.2	1.0 TeV – 1.0 PeV

- For the box-shaped period the flux normalization factors are a factor 3.3 higher.

Conclusions

- Three different searches for neutrino candidates in the ANTARES data promptly triggered by the detection of IC170922A and the subsequent potential association with TXS 0506+56.
- No up-going muon neutrino candidate event recorded within 3° around the IC170922A direction within ±1 h centered on the event time in the online data stream.
- TXS 0506+56 scrutinized following the ANTARES standard point-source method. The result using 11 years of ANTARES data yields a number of fitted signal events μ_{sig} = 1.03 with an associated pre-trial p-value of 3.4%. In the list of 107 pre-selected sources, only two have smaller p-value.
- Standard time-dependent analysis applied to the two bursting profiles defined by the IceCube analysis. The search yielded no events within the Gaussian and the box-shaped periods.

Backup

2) Time integrated search for neutrinos from TXS 0506+056

#	(δ, RA) deg	$\Delta\Psi$ deg	MJD	date dd/mm/year	ρ (a.u.)	$f(>\rho)$
1	(5.79, 77.65)	0.30	56638.70832	12/12/2013	2.58	0.09
2	(7.38, 77.24)	1.69	54601.04530	15/05/2008	2.10	0.40
3	(3.48, 75.69)	2.77	55396.03988	19/07/2010	2.16	0.33
4	(4.50, 79.92)	2.81	55585.28089	24/01/2011	2.05	0.47
5	(6.52, 74.51)	2.95	56143.90394	04/08/2012	1.78	0.87
6	(7.33, 80.24)	3.30	56268.37325	07/12/2012	2.11	0.39
7	(3.53, 74.70)	3.42	56495.86001	22/07/2013	2.45	0.14
8	(7.76, 73.44)	4.41	57455.29659	08/03/2016	2.27	0.24
9	(7.21, 81.56)	4.44	56298.41381	06/01/2013	1.94	0.63
10	(2.97, 73.69)	4.56	54742.73522	03/10/2008	2.06	0.44
11	(4.80, 81.91)	4.62	57392.49813	05/01/2016	1.80	0.83
12	(8.65, 73.47)	4.86	54853.53484	22/01/2009	2.67	0.07
13	(5.60, 82.31)	4.92	55399.13414	22/07/2010	2.57	0.09
S1	(10.08, 76.43)	4.49	55144.74625	09/11/2009	101	0.74

Neutrino candidates registered by the ANTARES detector within an angular distance $\Delta\Psi$ from TXS 0506+056.