Search spatial and temporal collective effects in the ANTARES neutrino telescope data

Studies by

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Search Principles

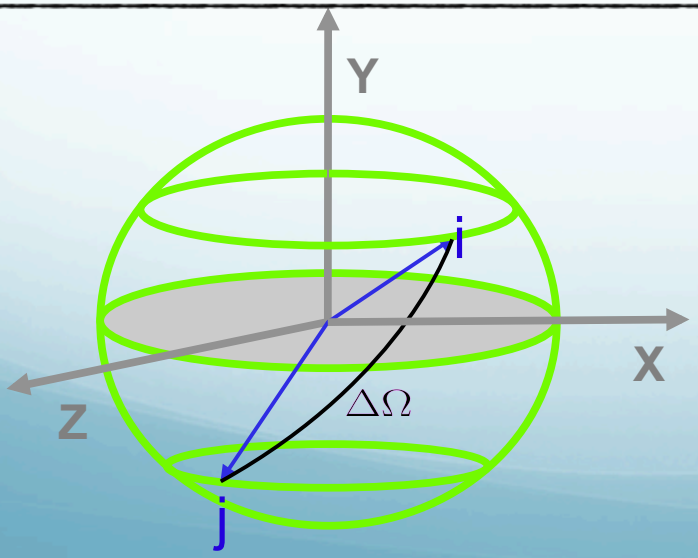
Common approach:
Model-independent search for collective time or space correlations
with a weighted two-point correlation function

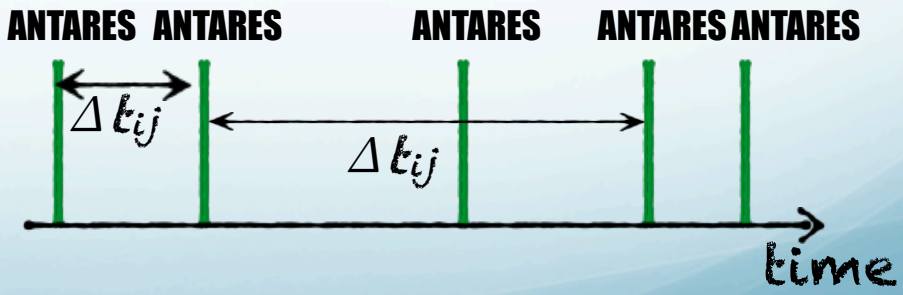
$$N(\Delta\Omega) = \sum_{i=1}^{N} \sum_{j=i+1}^{N} \omega_{ij} \left[1 - H(\Delta\Omega_{ij} - \Delta\Omega)\right]$$

with ω_{ij} = energy proxy

$$\mathcal{N}(\Delta t) = \sum_{i=1}^{N_{IC}} \sum_{j=1}^{N_{ANT}} \omega_{ij} \left[1 - H\left(\Delta t_{ij} - \Delta t\right)\right]$$

with ω_{ij} = energy / angle





Space auto-correlation

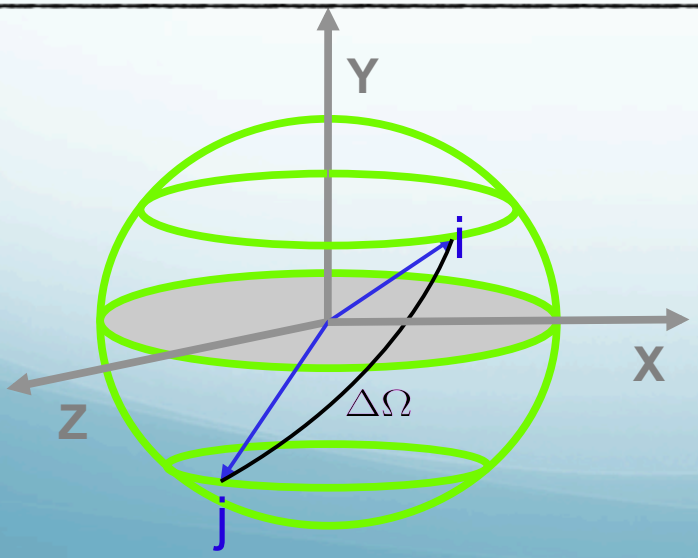
- Allows to find inhomogeneities in a discrete data set
- It is based on the study of the 2 point correlation distribution

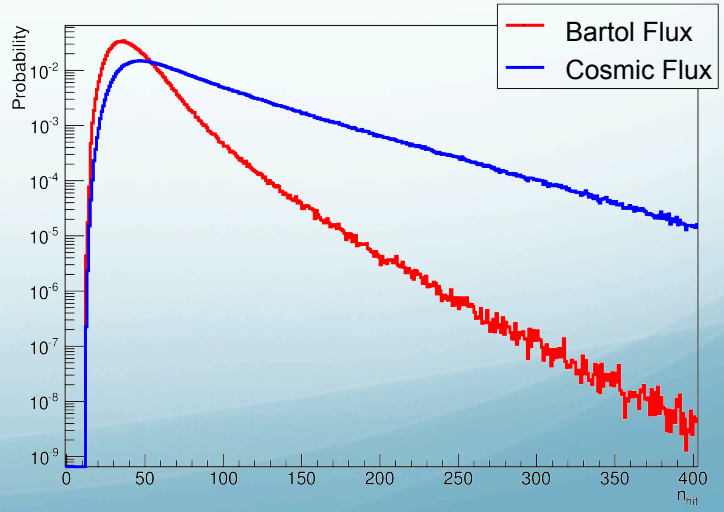
$$N(\Delta\Omega) = \sum_{i=1}^{N} \sum_{j=i+1}^{N} \omega_{ij} \left[1 - H(\Delta\Omega_{ij} - \Delta\Omega)\right]$$

with ω_{ij} = energy proxy

- N_{hit} is the number of optical modules used in the reconstruction of an event
- Wij = w_i w_j

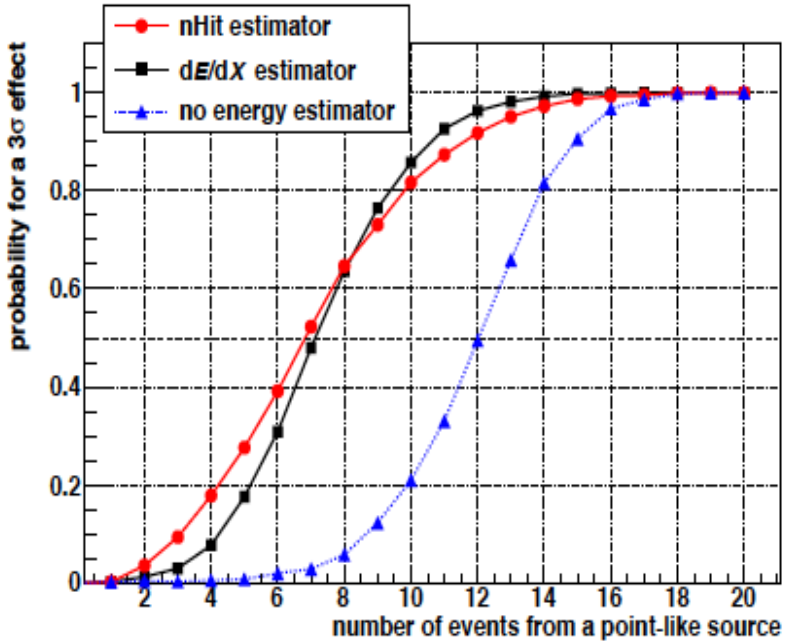
$$\omega(\bar{E}_i) = \int_0^{E_i} f(\bar{E}) d\bar{E}$$

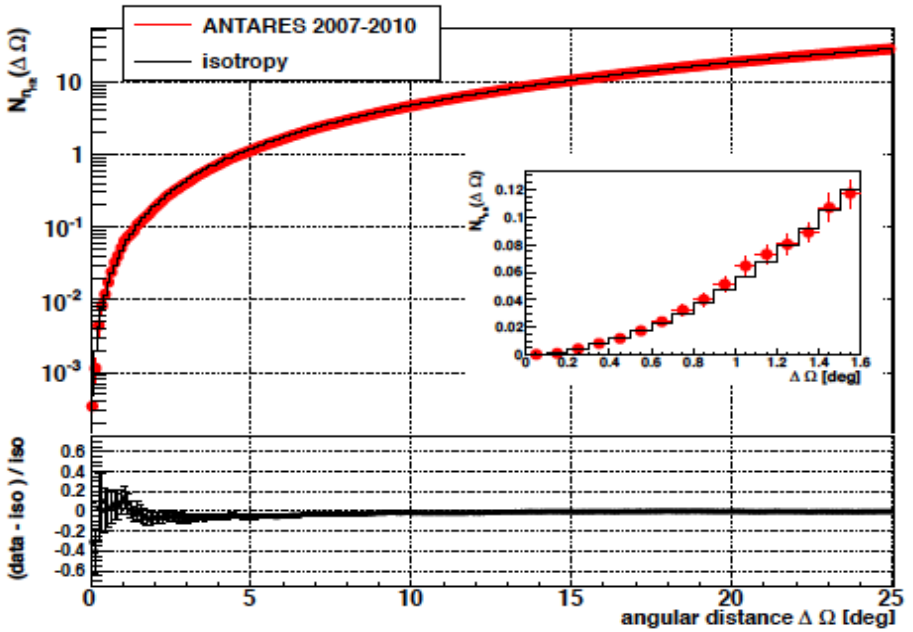




A First Analysis

First analysis on that kind : JCAP05(2014)001
3058 events (2007-2010)

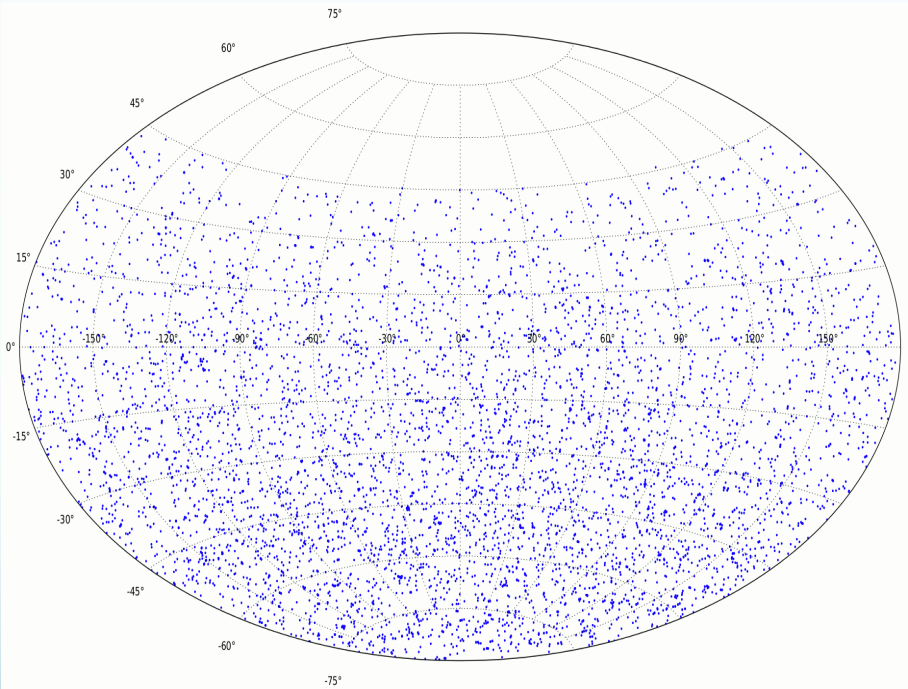


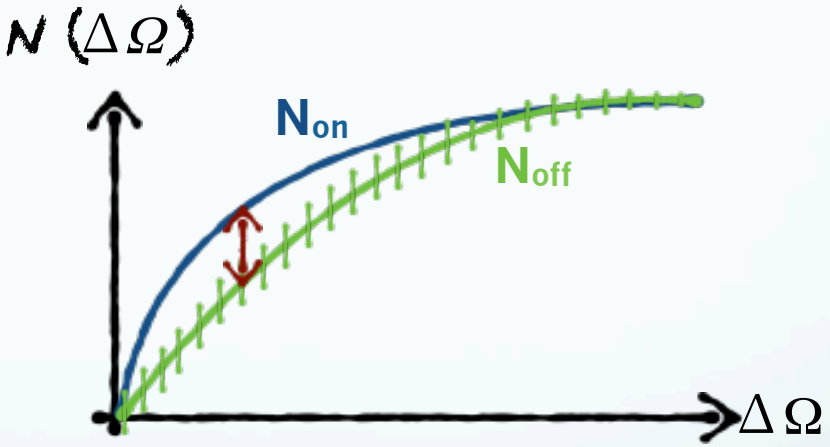


No detection reported

Updated study

- Sample: 5243 events (2007-2012) optimized for a PS search





$$TS = \max\left\{\left(\frac{\mathcal{N}^{data}_{n_{Hit}} - \mathcal{N}^{iso}_{n_{Hit}}}{\sigma}\right)\right\}_{\Delta\Omega_i}$$

- N_{off}: average of pseudo-exp. to simulate the background (=reference distribution)
- N_{on}: data

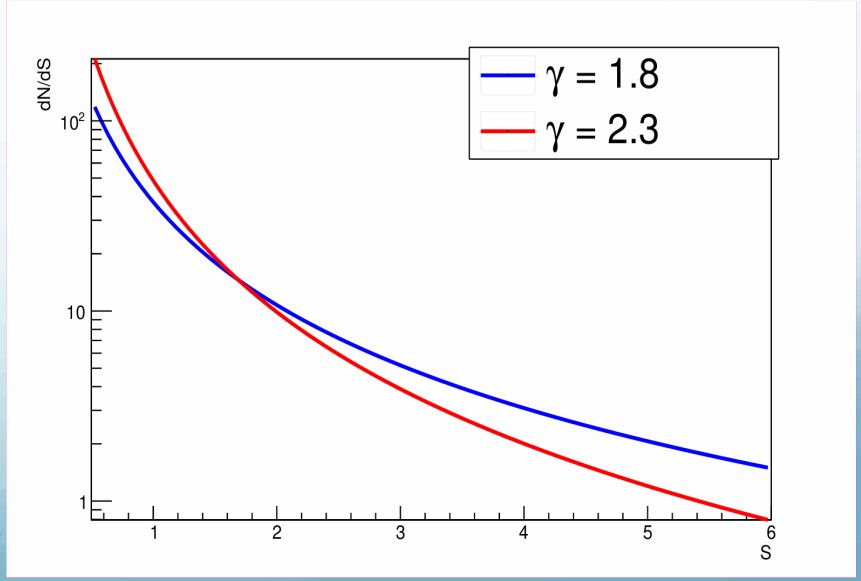
Discovery Potential (I)

- Population of unresolved point sources with mean ν luminosities:

$$\frac{dN}{dS} \propto S^{-\gamma}$$

- S: Number of detected neutrinos, between S_{min} and S_{max}.
- S_{max} fixed by the faintest PS detectable by ANTARES
- S_{min} free parameter.
- A population of sources will be characterized by the γ, S_{min}

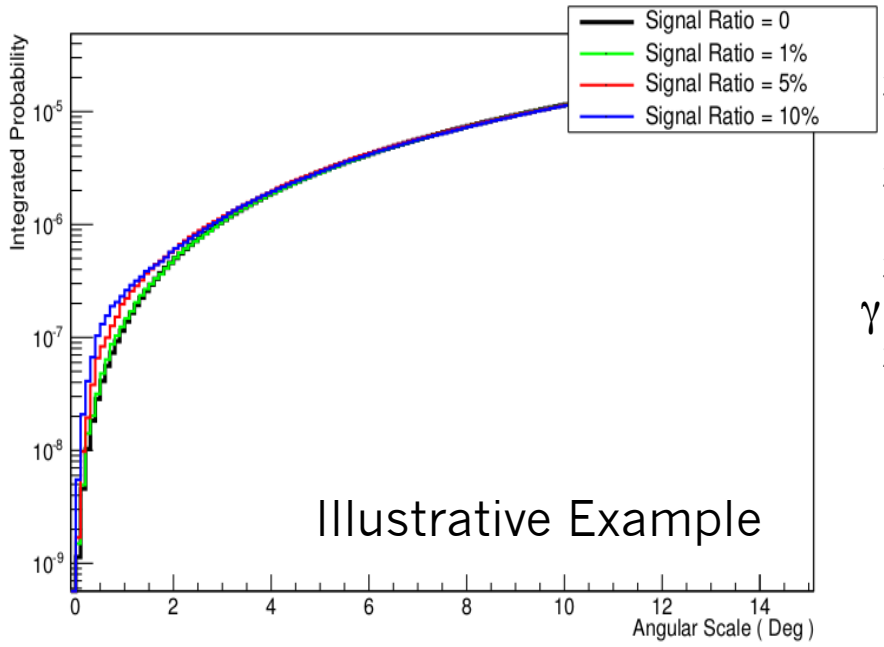
- AGN's well described by γ~2.2 [1]
- Galactic type sources (X-ray binaries in the Milky way or Centaurus A) γ<2.0 [2],[3],[4]

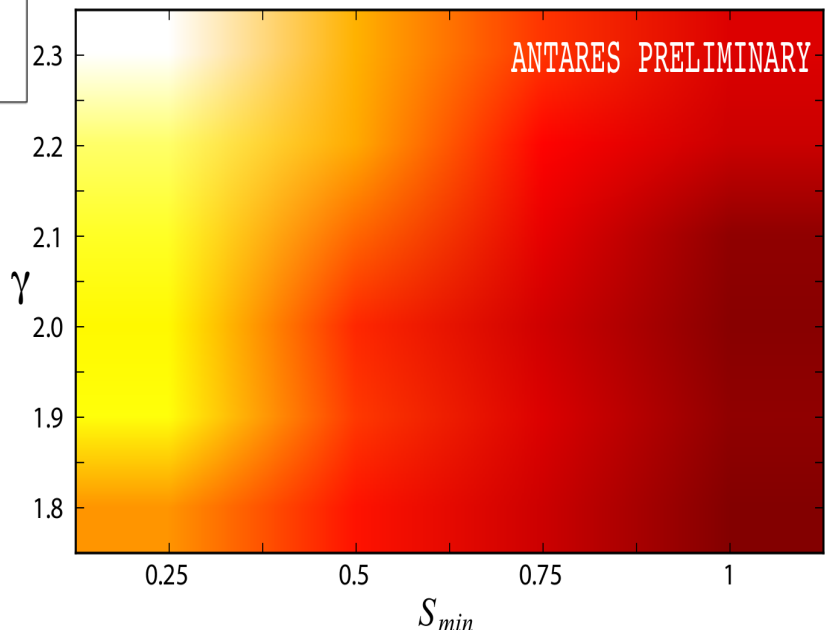


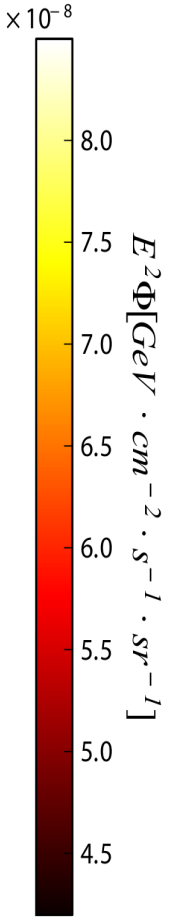
[1] M. Ackermann et al. [Fermi-LAT Collaboration], The Third Catalog of Active Galactic Nuclei Detected by the Fermi Large Area Telescope, arXiv:1501.06054 [astro-ph.HE].
[2] Voss R., et al., Luminosity functions of LMXBs in Centaurus A: globular clusters versus the field, The Astrophysical Journal ,701:471-48
[3] R. Voss, M. Gilfanov The Luminosity Function of X-ray Point Sources in Centaurus A, Astron.Astrophys. 447 (2006) 71
[4] M. Gilfanov, Low mass x-ray binaries as a stellar mass indicator of the host galaxy, Mon. Not. Roy. Astron. Soc. 349 (2004) 146 [astro-ph/0309454].

Discovery Potential (II)

- Total number of events kept fixed for signal injection.



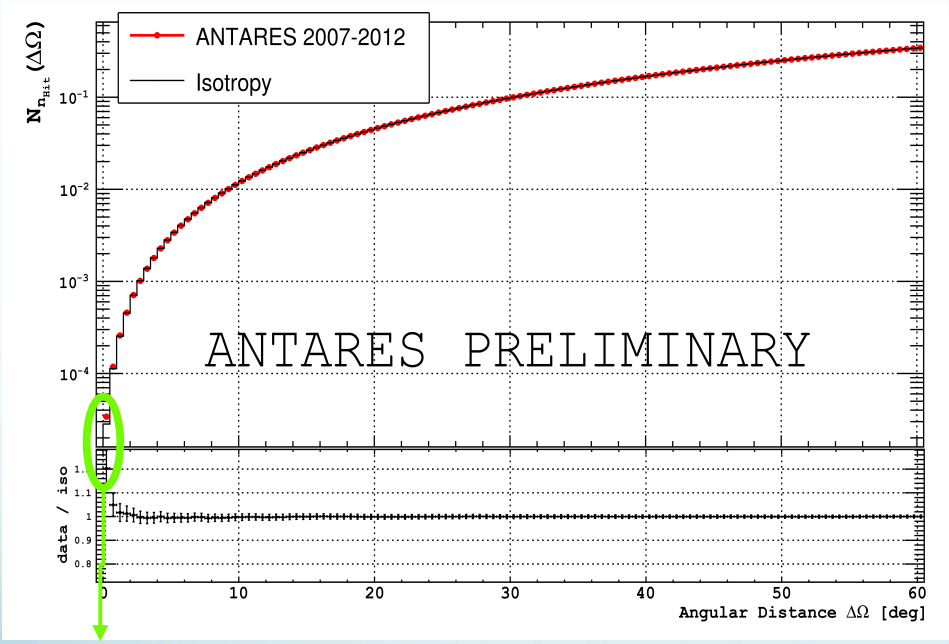


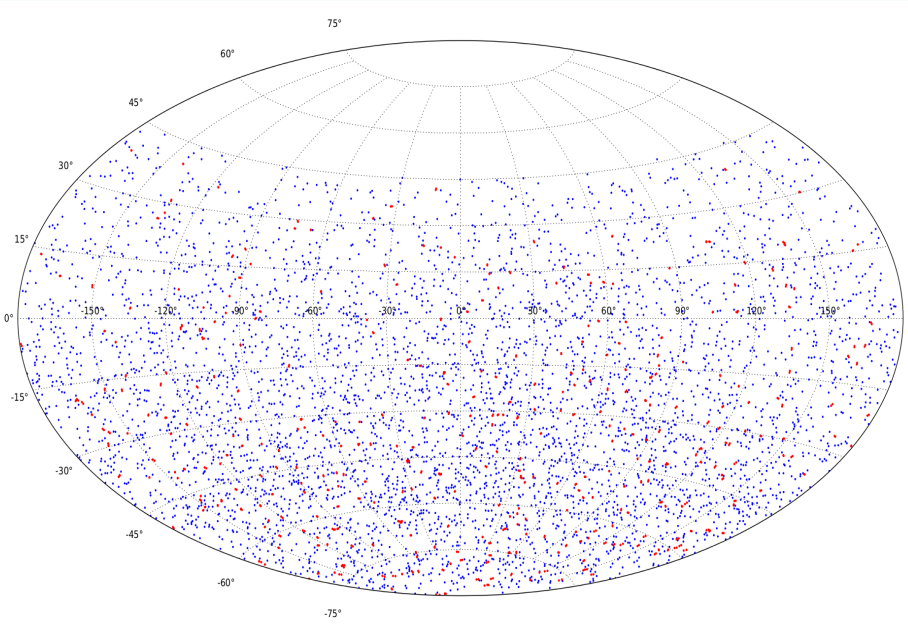


- Cumulative flux (E^{-2}) coming from populations of PS detectable at a 3σ with 90% probability for different configurations (γ, S_{min}).

Results (I)

- Statistical comparison with background leads to a 2.3 σ significance
- In [1],[2] a 2.2 σ excess was found at ($\alpha°, \delta$) = (313.2,–64.9). Removing events closer to 0.5° to this point reduces the significance of the observed excess to ~ 2.15 σ.



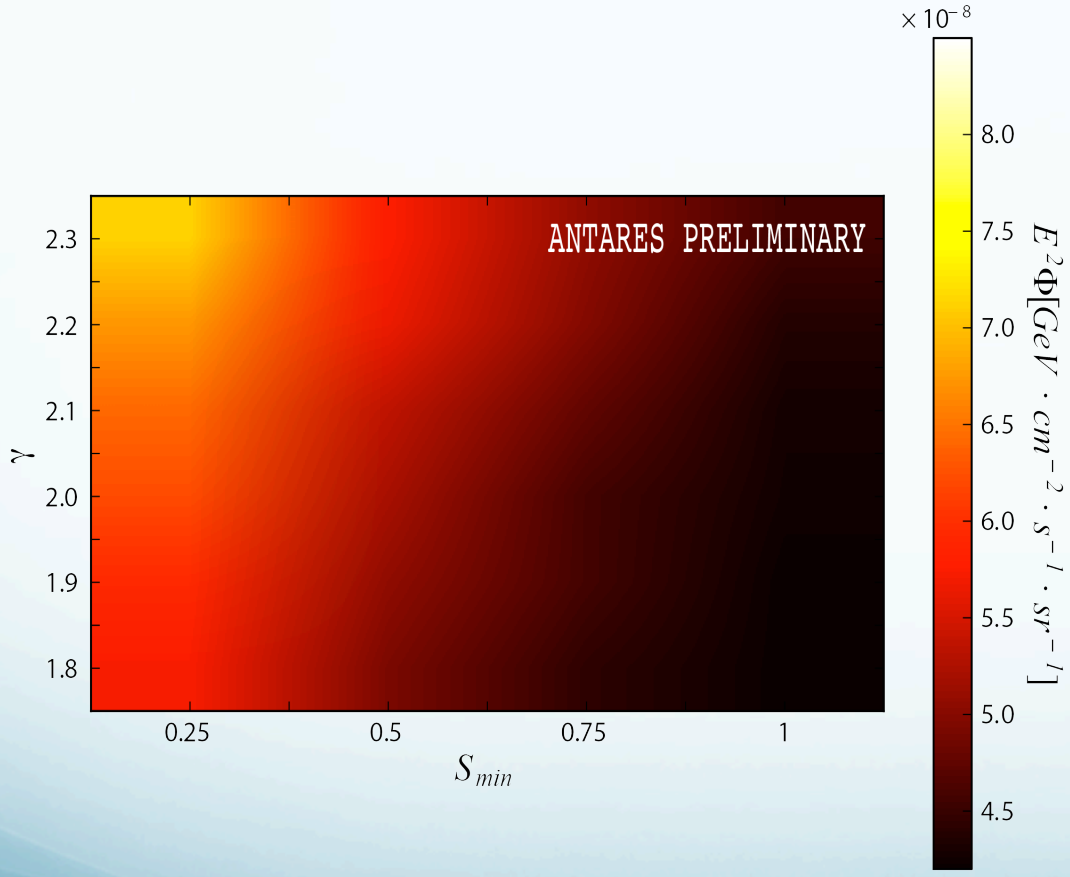


2.3 σ excess

[1] S. Adrian-Martinez et al. Searches for clustering in the time integrated skymap of the ANTARES neutrino telescope, JCAP05 (2014)0001
[2] S. Adrian-Martinez et al. Search for cosmic neutrino point sources with four year data of the ANTARES telescope, The Astrophysical Journal 760:53(2012)

Results (II)

- In absence of a significant excess, 90% confidence level upper limits are set on the flux.



- The method shows better sensitivity for galactic type sources (lower γ)
- Advantage for northern hemisphere neutrino telescopes due to the large coverage of the galactic plane

Future plan : check correlation with catalogues of sources, IC HESE, ...

Time correlations

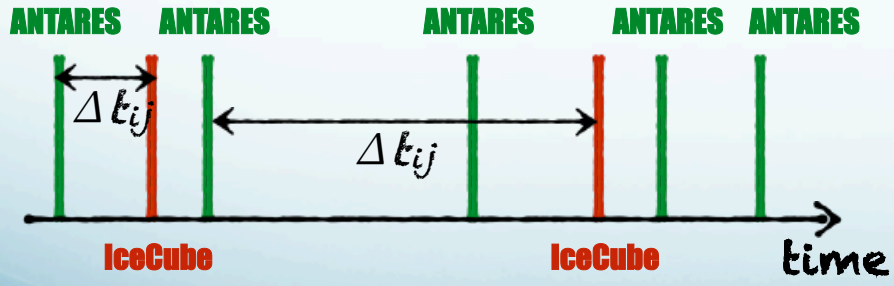
First approach: search for correlations with the IC HESE events

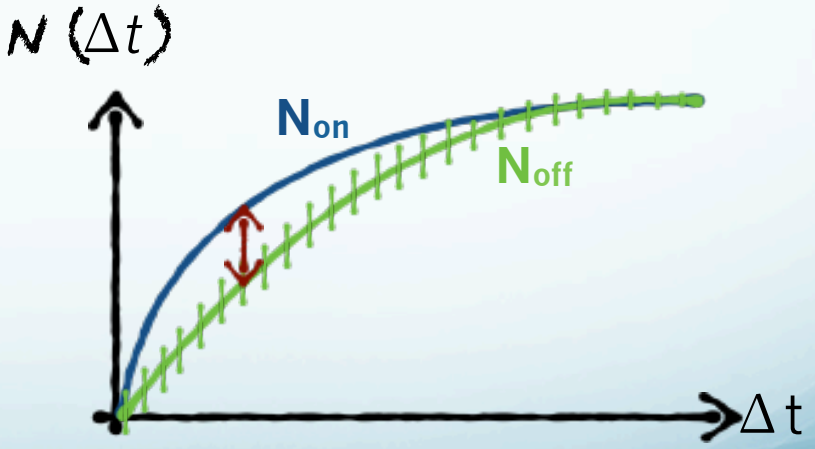
$$\mathcal{N}(\Delta t) = \sum_{i=1}^{N_{IC}} \sum_{j=1}^{N_{ANT}} \omega_{ij} \left[1 - H\left(\Delta t_{ij} - \Delta t\right)\right]$$

$$\text{with } \omega_{ij} = \exp\left(\frac{-\Delta\Omega_{ij}^2}{2\sigma_i^2}\right)$$

- N_{off}: average of 10^4 pseudo-exp (=reference distribution)
- N_{on}: data

$$TS = \max_{\Delta t_i}\left[\frac{N_{on} - N_{off}}{\sigma}\right]$$

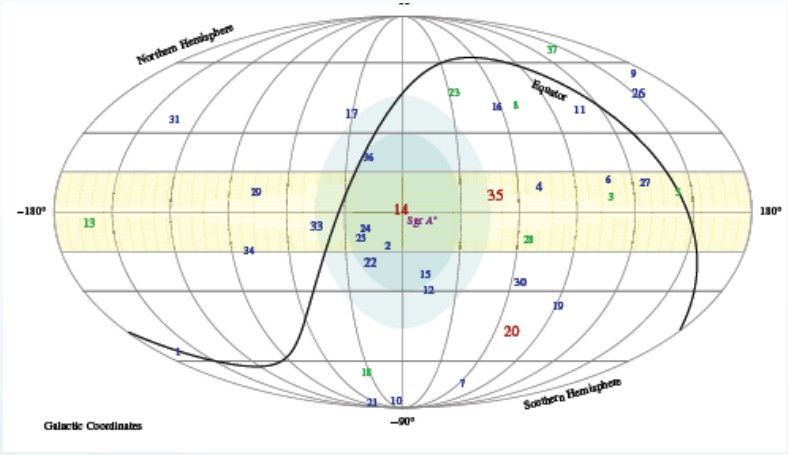


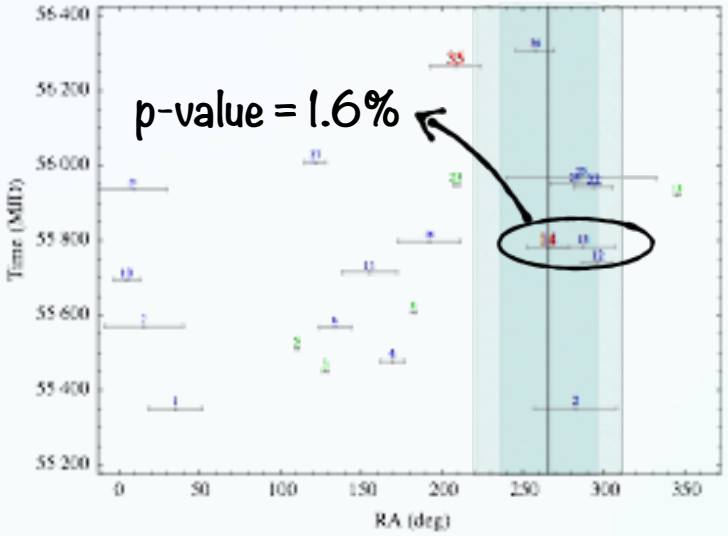


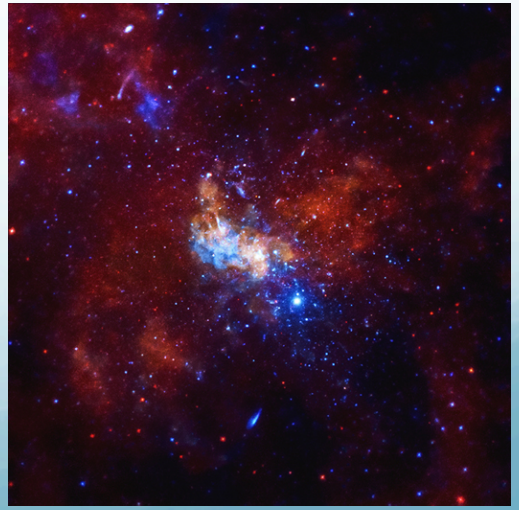
Scanning for time correlation at time scales up to 10 days

Motivations

Trigger: Bai et al., PRD, 2014
"Neutrino Lighthouse at Sagitarius A*"
translated into
"NASA X-ray Telescopes Find Black Hole May Be a Neutrino Factory"





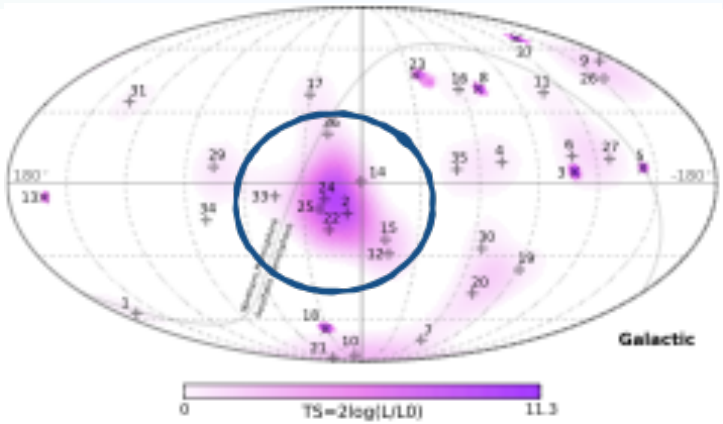


General Aim: Is the IceCube astrophysical signal (HESE) emitted by (a) transient source(s) ?

Data Sets

IceCube HESE: 37 events between 30 and 2000 TeV

Among them: **8 within 45° from the GC and occurring between May 2010 and December 2012:**



Angular error (Deg)	Distance from GC (Deg)
25.4	14.6
9.8	32.5
13.2	1.2
19.7	26.3
12.1	25.9
15.5	20.4
46.3	23.5
13.5	44.8
11.7	27.2

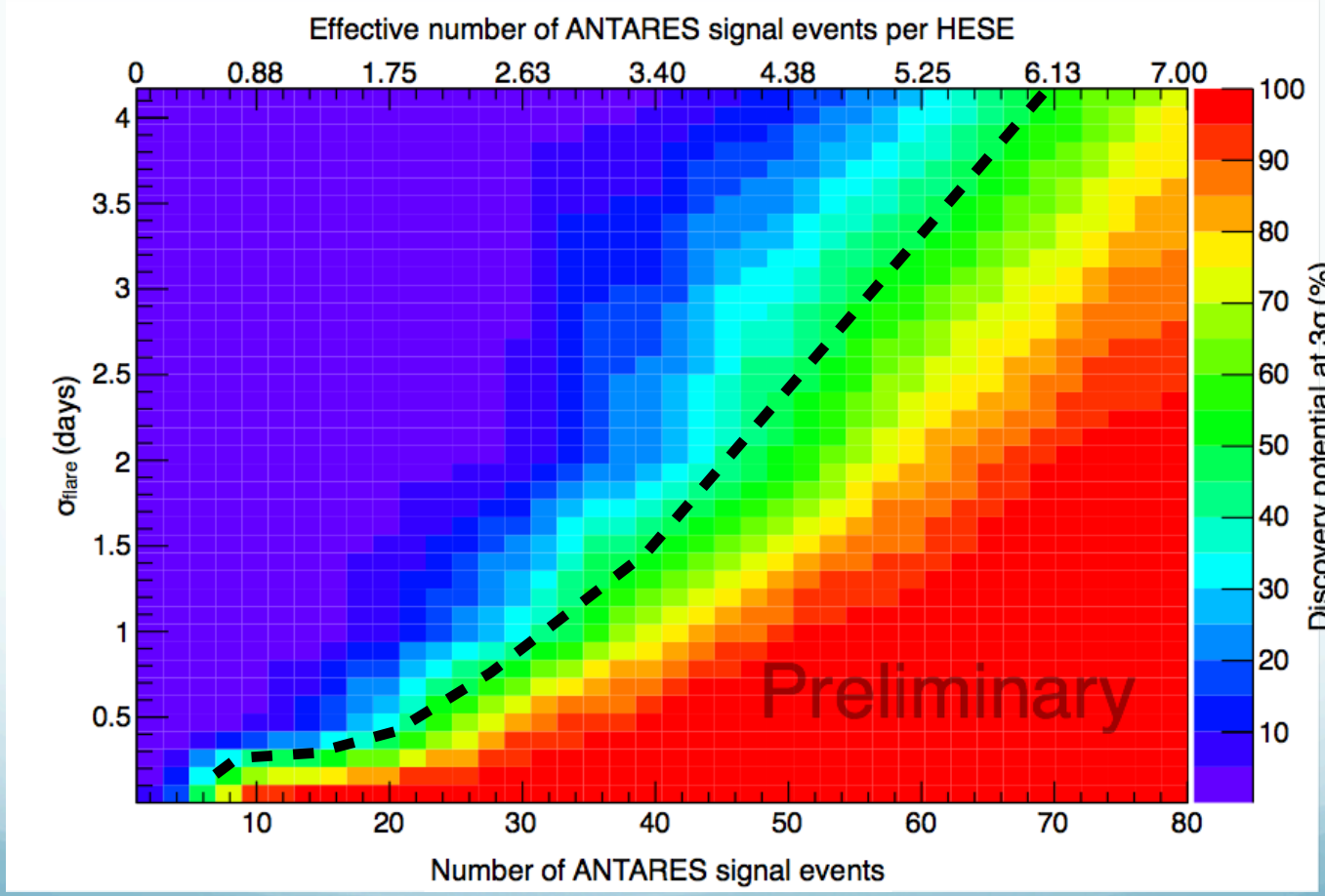
IceCube Collab., PRL

ANTARES: data between May 2010 and December 2012

ANTARES data stream not constant over time (due to data taking conditions in the sea)
➔ Dataset optimized for different ranges of data taking conditions to reach a constant neutrino candidate rate
➔ Final sample composed of 4337 events

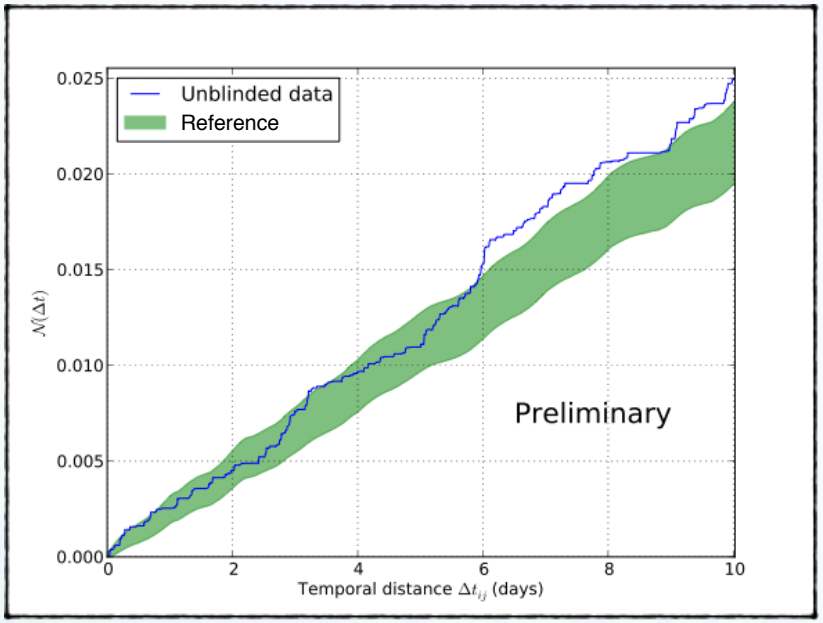
Discovery potential at 3σ

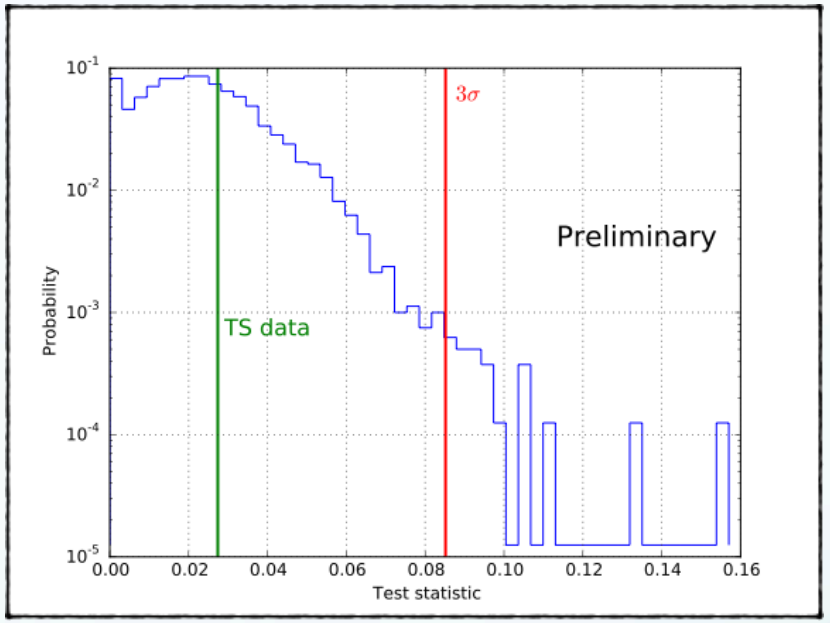
Estimated using pseudo-experiments ➔ Signal events generated assuming a gaussian flare (std dev = σ_{flare}) and taking into account the IceCube HESE PSF



Results (I)

Reference distribution = expected for the background of atmospheric neutrinos





p-value = 35% (~0.95 σ) for a time scale of ~6 days

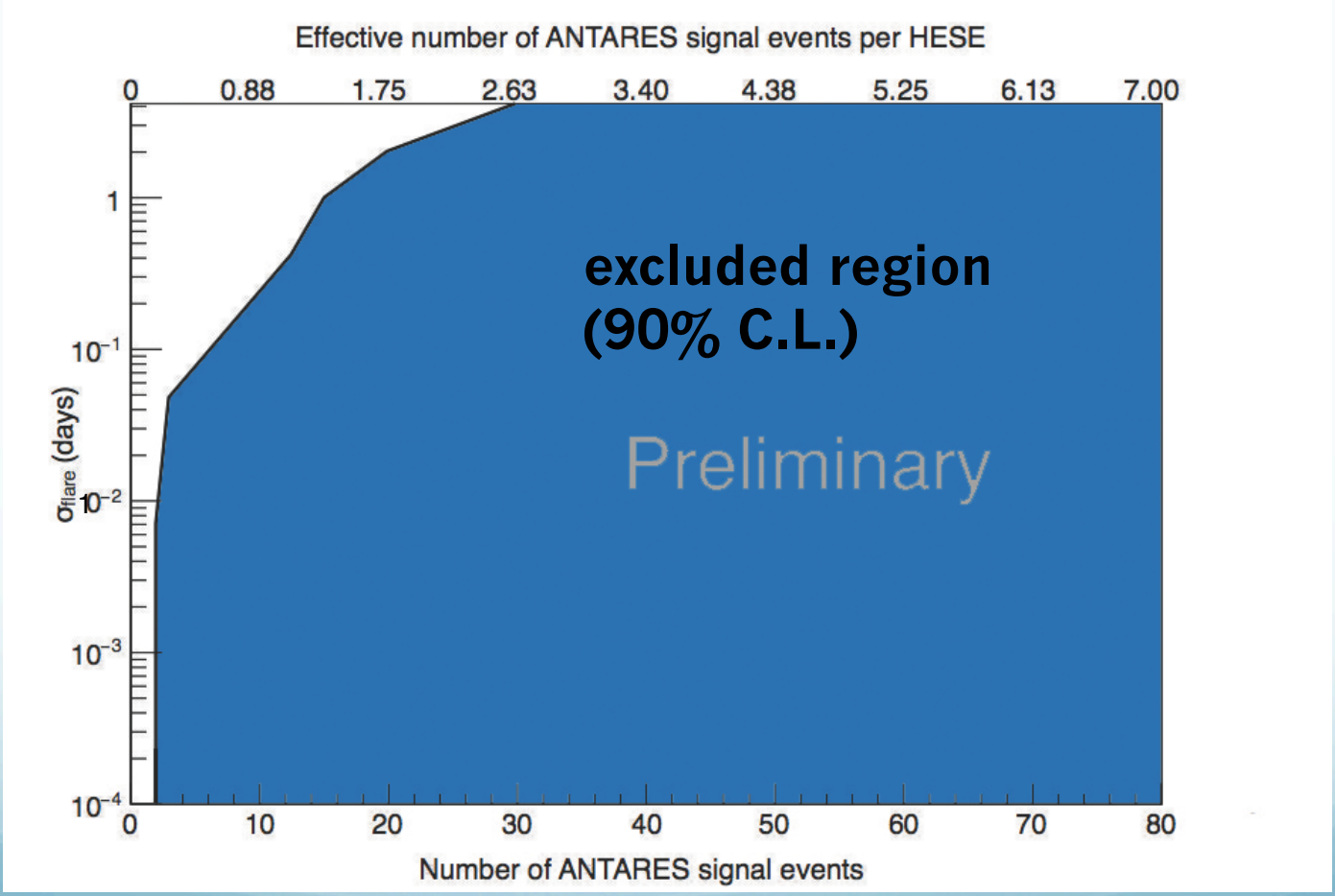
⇔ probability to measure TS above the measured value in the bkg only hypothesis

No significant time correlation detected

Results (II)

90 % confidence level upper limit:

⇔*90% of the TS lie above the TS value measured for the data*



Results (II)

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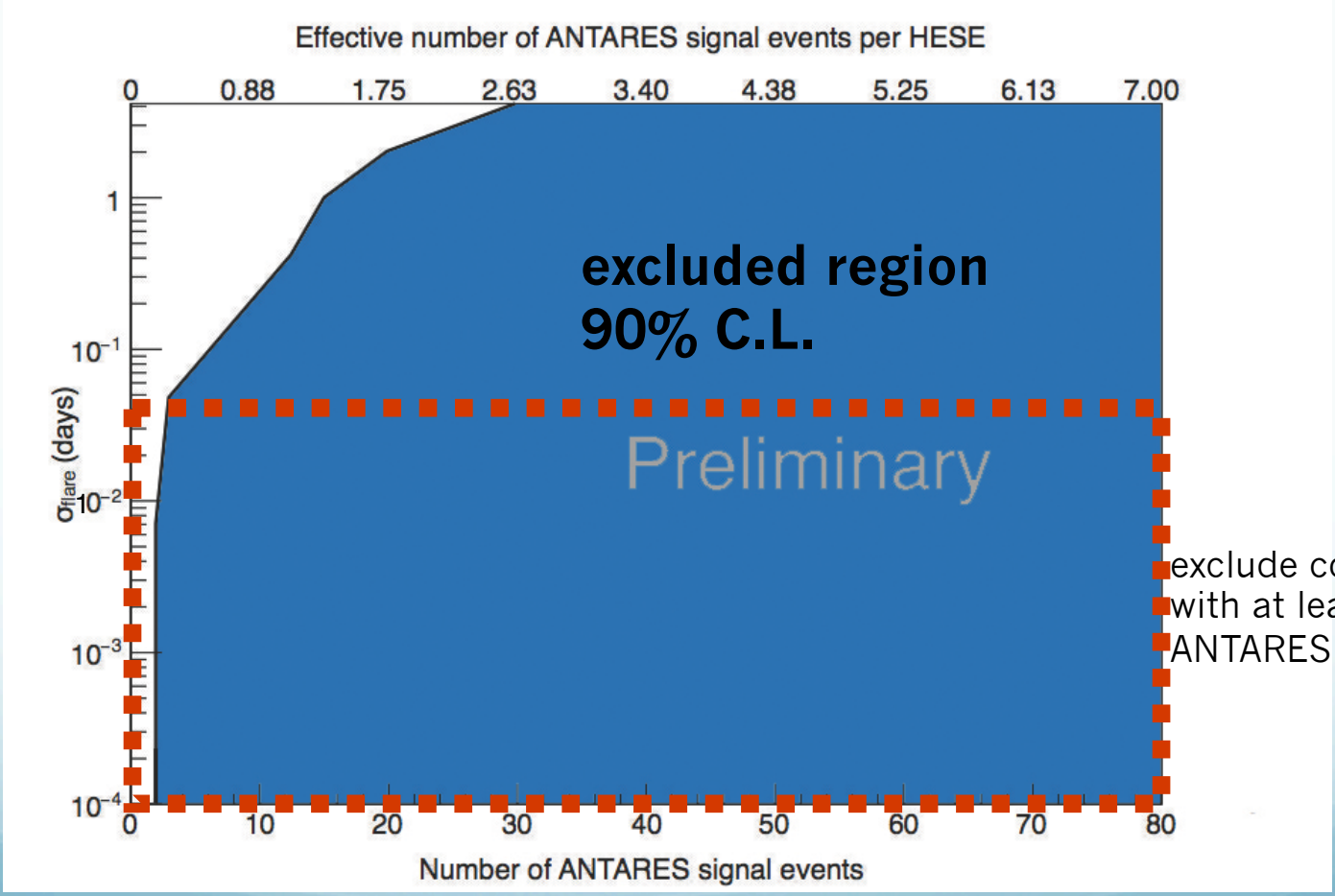
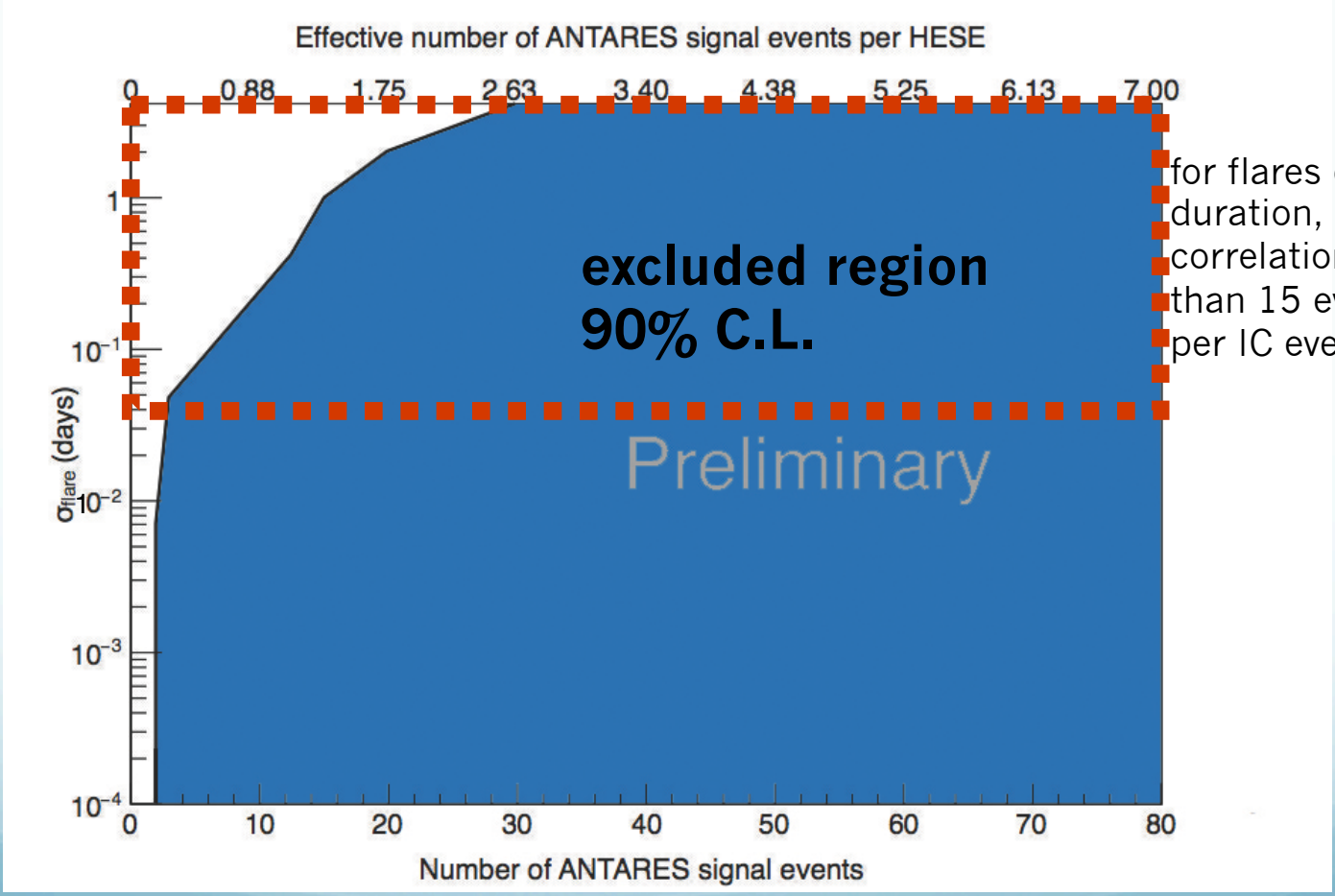


exclude correlation with at least 2 ANTARES events

Results (II)

90 % confidence level upper limit:

⇔*90% of the TS lie above the TS value measured for the data*



for flares of ~1 day duration, excludes correlation with more than 15 events (~1.3 per IC event)

Outlook

General purpose: time-dependent analysis on the Galactic center region.

Time correlation
with IceCube events

Done

Time clustering
of ANTARES events

Time-dependent
analysis based on
multi-wavelength
lightcurves

Still to be done

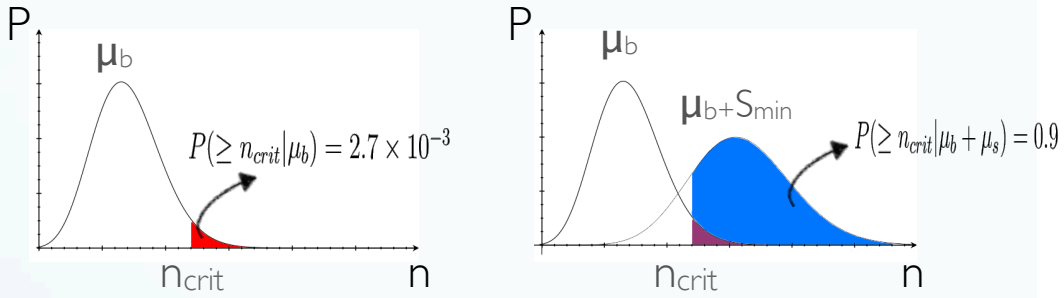
Envisaged evolution : merge the 2 approaches into one

SPARE material

ANTARES data optimization

We define $MDP = \frac{S_{min}}{\mu_s}$ (we do not apply spatial or time cut here)

with S_{min} = least detectable signal at 3σ with a 90% CL

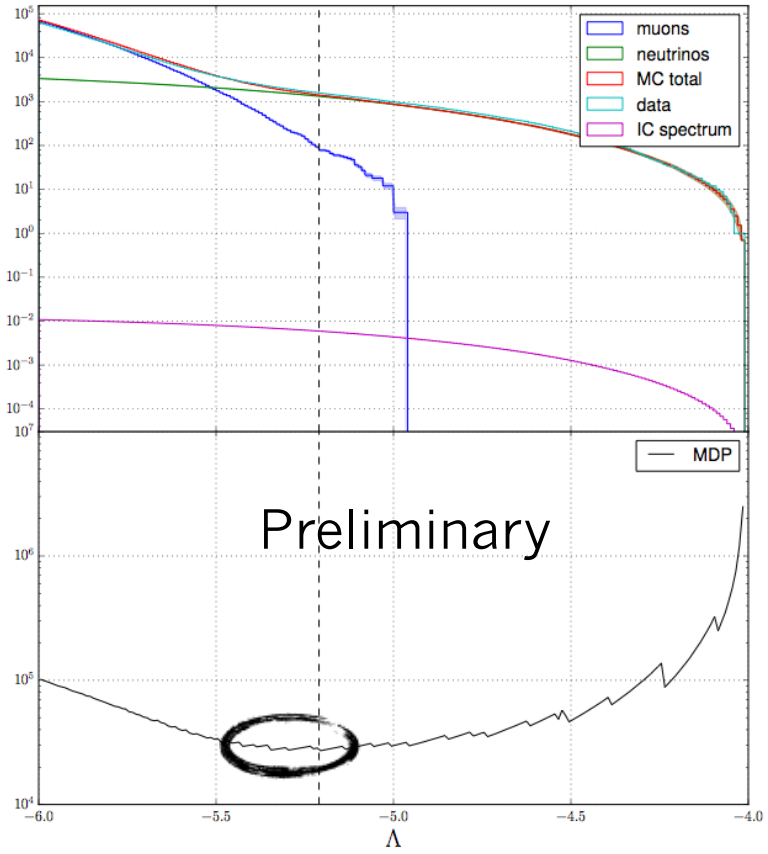


and μ_s = expected signal computed with a $E^{-2.5}$ spectrum and IC normalisation *(IC collab., Phys.Rev., 91, 2015)*
Simulated thanks to rbr MC neutrinos with weights defined as:

w2 x Ω x ϕ_{IC} x $E^{-2.46}$ x run duration x ngen

do not impact the position of min(MDP)

50 kHz <MRO<100 kHz

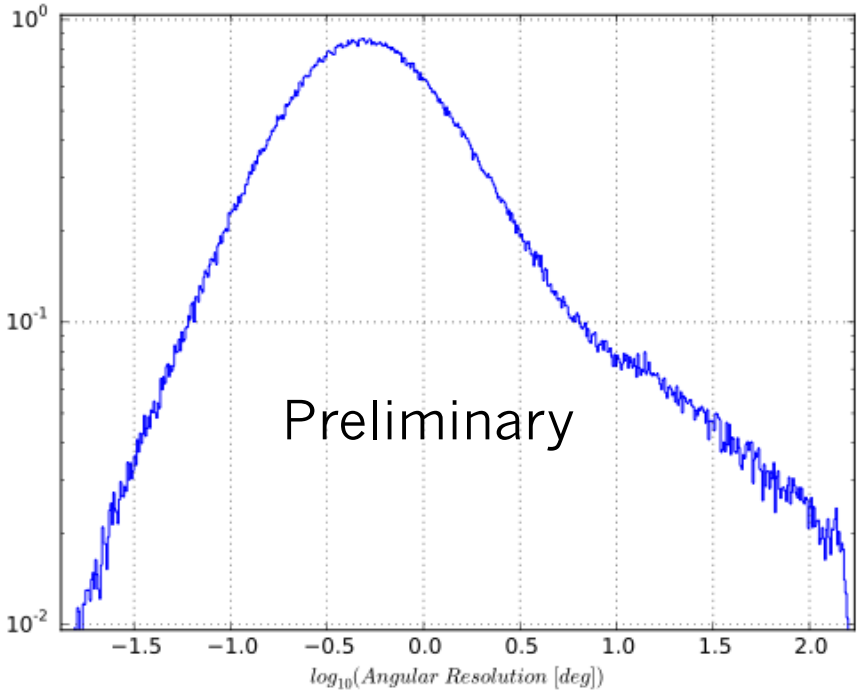


ANTAREs sample properties

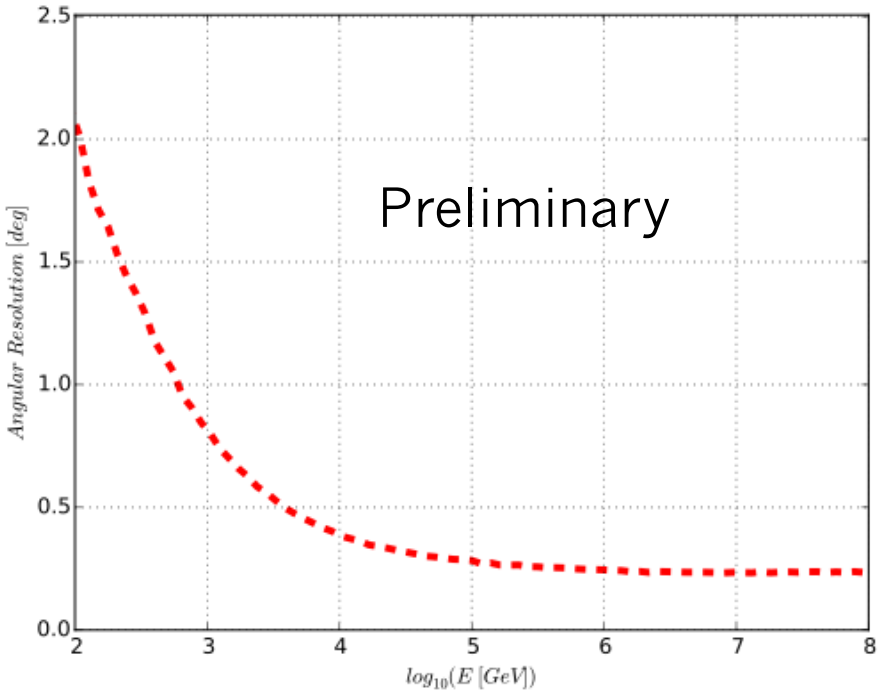
Angular resolution - neutrinos

(based on run-by-run MC with the same quality cuts than in the dataset)

angular resolution distribution



median angular resolution w.r.t. the energy

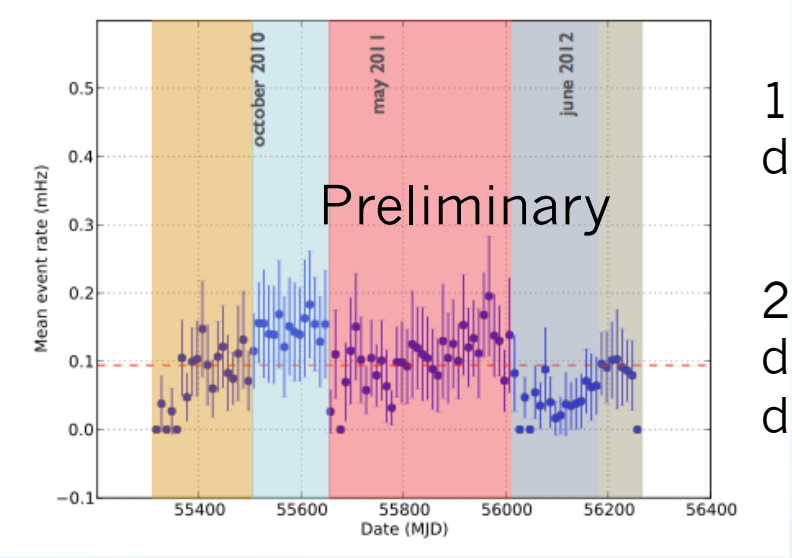


Pseudo-experiments

10^4 pseudo-experiments generated to built a background reference cumulative correlation distribution

Time generation:

Mean neutrino candidates rate (bins of 10 days)



1) mean neutrino candidates rate defined for each sub-period

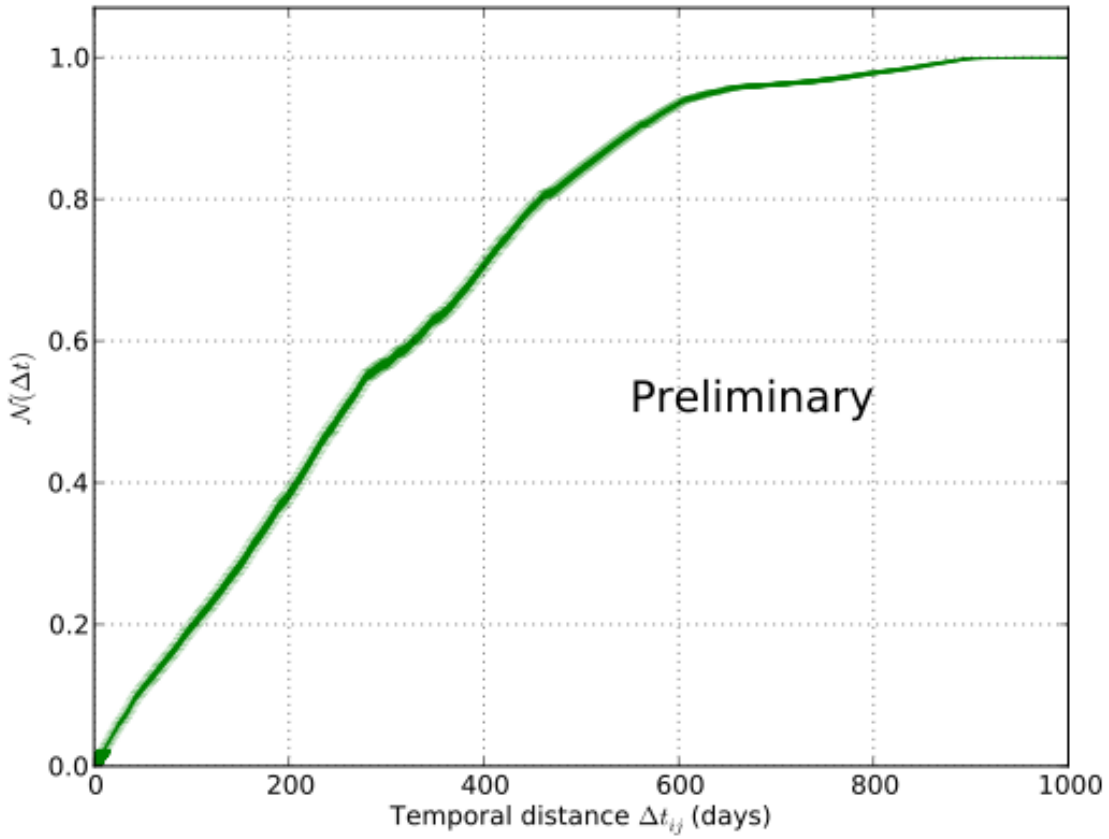
2) nb of events: drawn from a poissonian distribution with mean = rate x run duration

Local coordinates:

Drawn from the 2D distribution of the local coordinates. Equatorial coordinates finally computed knowing the event time

Pseudo-experiments

Average of 10^4 pseudo-experiments:



Signal generation

Remove one bkg event in the pseudo-experiment

↓

Randomly choose one IC evt

↓

Assume a gaussian flare with (μ, σ)

↓

Draw time of the generated event in this normal distribution

↓

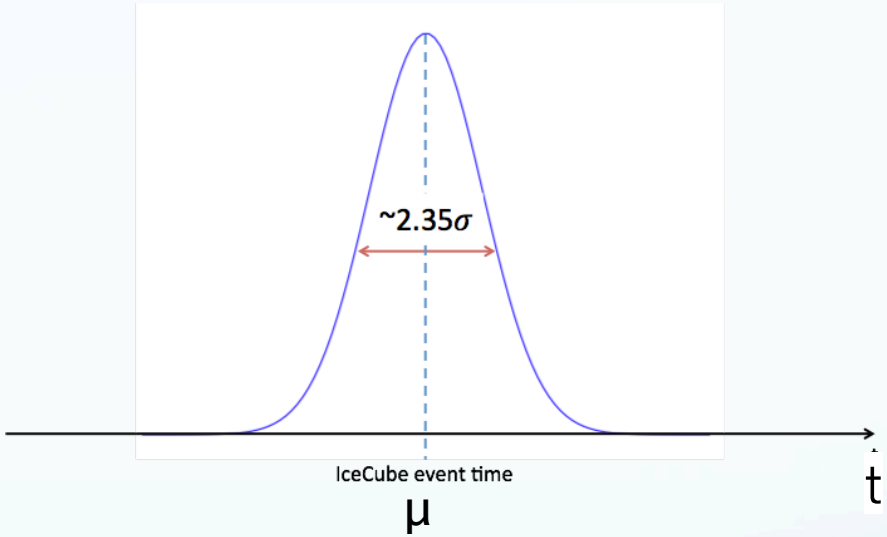
Draw (RA, Dec) from IC PSF

↓

Convert (RA, Dec) in (Az, Zen)

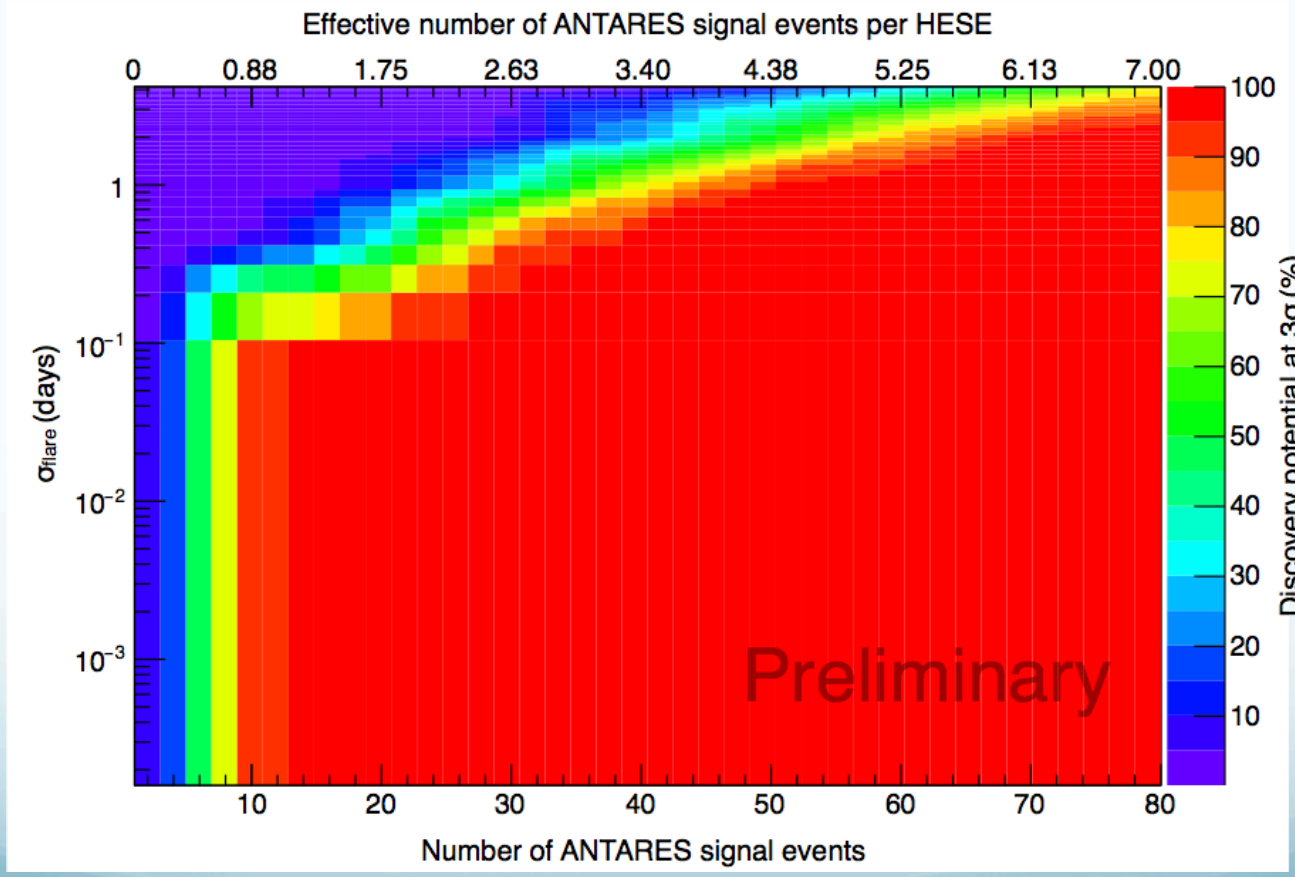
↓

Check if (Az, Zen) $\in$ (Az, Zen) seen by ANTARES → Include it in the pseudo-experiment



Discovery potential at 3σ

Signal events : generated assuming a gaussian flare (std dev = σ_{flare}) and taking into account the IceCube HESE PSF



Conclusion

- Look for possible signature of transient neutrino emission in the Galactic Center region
- Time correlation analysis based on IceCube HESE and ANTARES events positionally consistent with the Galactic Center
- p-value of ~0.95σ (at a time scale of 6 days)
- But absence of evidence is not evidence of absence...
- Next: ANTARES data time clustering: constrain a potential transient phenomenon in the Galactic Center region ?

Dataset

ANTARES data between May 2010 and December 2012.

ANTARES data stream not constant over time (due to data taking conditions in the sea) ➔ **need to optimize the sample consequently to get a constant neutrino candidates rate**

Optimization approach :

1) Quality cuts were adjusted separately for different ranges of data taking conditions to reach the constant neutrino candidates rate.

2) The constant rate is defined by a MDP optimization from the best range of data taking conditions with an expected signal equal to the IC astrophysical flux (*IceCube Collab., PRD 91, 2015*):

$$\Phi_\nu = 2.06^{+0.4}_{-0.3} \times 10^{-18} \left(E_\nu/10^5 \mathrm{GeV}\right)^{-2.46 \pm 0.12}$$

➔ Final sample composed of 4337 events