

# Search for neutrinos from the Fermi Bubbles with the ANTARES telescope

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on behalf of the ANTARES collaboration

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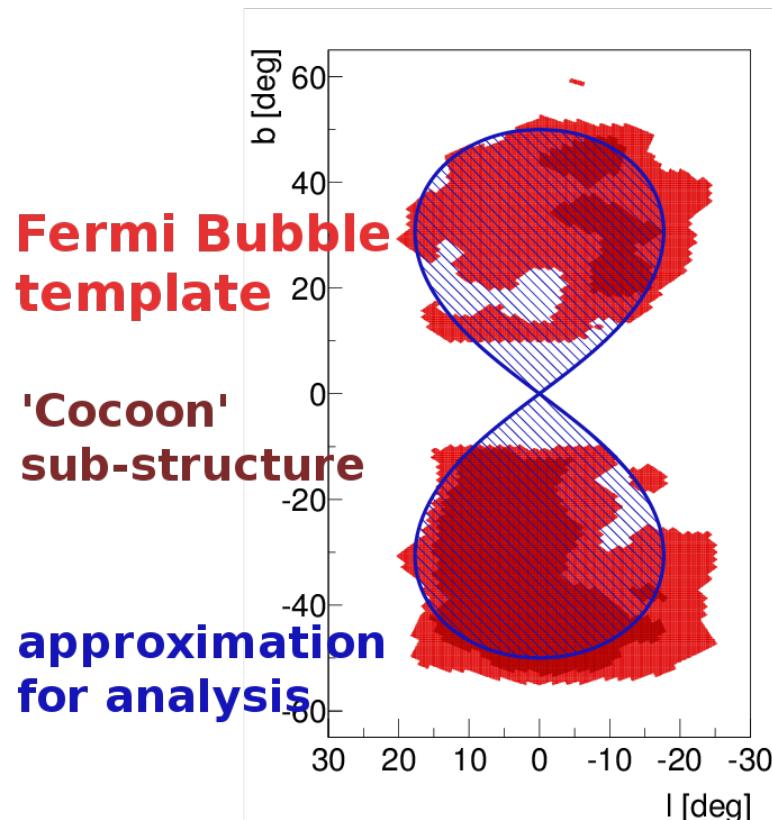
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# The Fermi Bubbles: What do we see?



- giant lobes of  $\gamma$ -ray emission revealed by Fermi-LAT [APJ 724 (2010), 1044]  
**uniform emission profile + sharp edges + hard spectrum  $\approx E^{-2}$**
- more recent analysis on the shape and  $\gamma$ -ray spectrum [APJ 793 (2014), 34]  
**softer spectrum or low cut-off preferred**



## LEPTONIC ORIGIN?

inverse compton + synchrotron  
→ no neutrinos

## HADRONIC ORIGIN?

$$\begin{aligned} p + p &\rightarrow \pi^\pm, \pi^0 \\ \pi^0 &\rightarrow 2\gamma \\ \pi^\pm &\rightarrow \mu^\pm + \overline{\nu}_\mu \end{aligned}$$

→ corresponding neutrino flux

# What is the expected neutrino flux?

- flux model:

$$\Phi_\nu \propto E^{-\alpha} \times \exp(-E/E_{\text{cutoff}})$$

- purely hadronic emission:

$$\Phi_\nu(E) = \text{const}(\alpha) \times \Phi_\gamma(E)$$

[PRD 78 (2008), 3007]

- neutrino cut-off energies:

- expected proton cut-off at 1–10 PeV
- $\approx 20\%$  of the energy transferred to  $\pi^\pm$ , 4 daughters in  $\pi^\pm$  decay

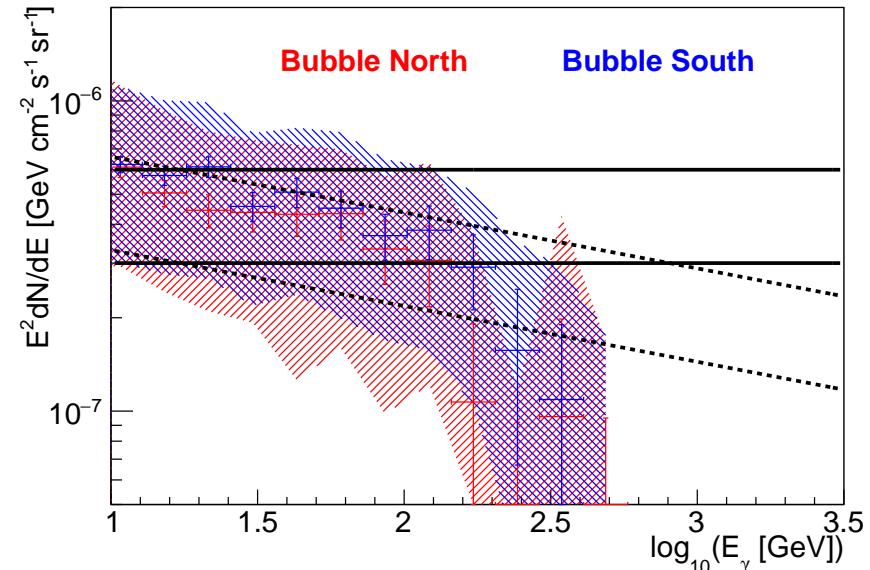
$$E_{\text{cutoff}} = 50, 100, 500, \infty \text{ TeV}$$

Fermi Bubble  $\gamma$ -flux [APJ 793 (2014), 34]

## Used neutrino spectra:

index $\alpha$	2.0	2.18*
norm $\gamma$	3 – 6	5 – 10
norm $\nu$	1.2 – 2.4	1.8 – 3.6 (in $10^{-7} \text{ GeV}^{(\alpha-1)} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ )

\*) [arXiv:1504.07033 + fit to Sibyll flux param.]

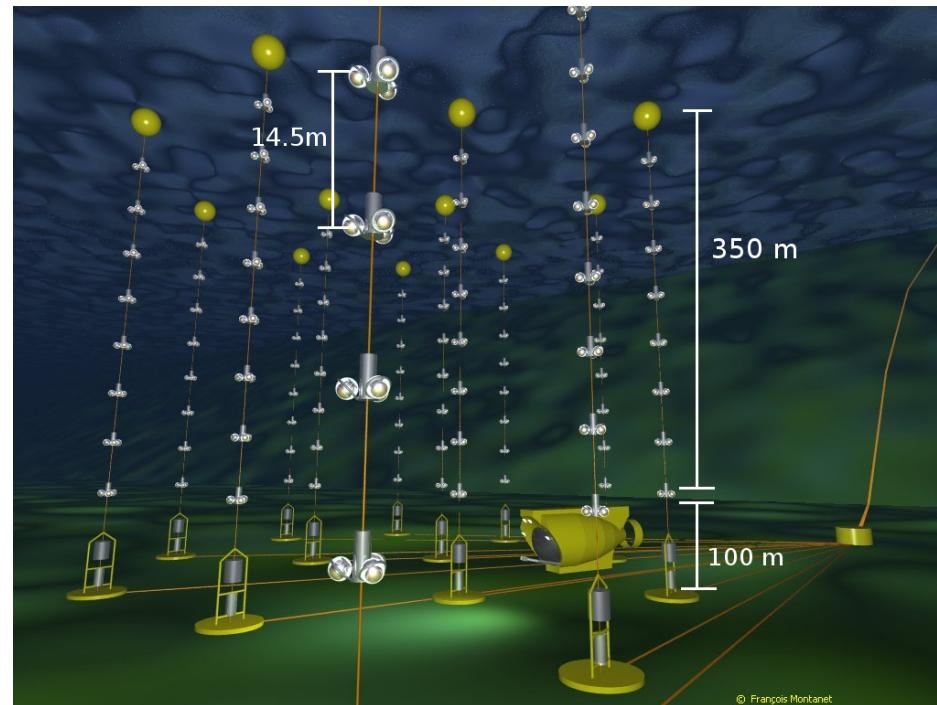


# The ANTARES neutrino detector



[NIM A 656 (2011), 11]

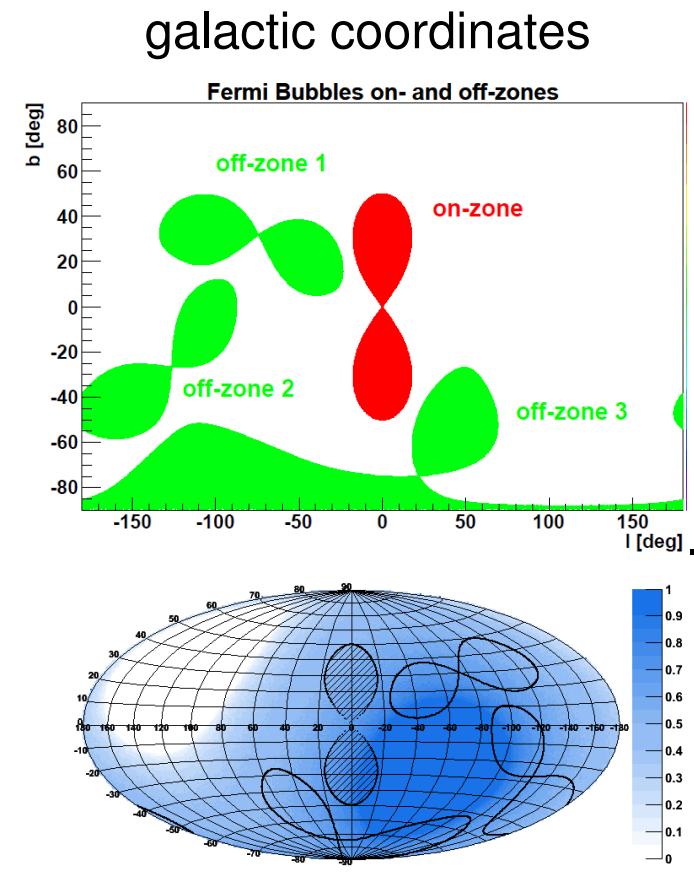
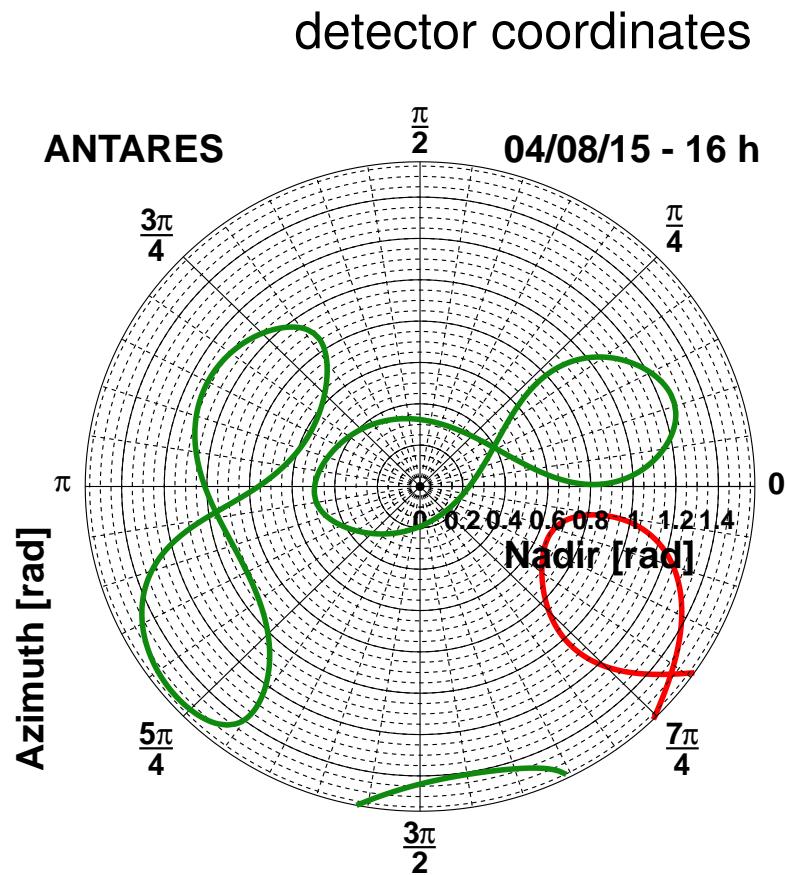
- 40 km off shore from Toulon (Mediterranean Sea)
- detector completed in 2008
- 2.5 km below sea level
- **885 optical modules (10" PMTs)** distributed over **12 strings**



→ detect Cherenkov light from secondaries produced in neutrino interactions

# On- and off-zone analysis

- use 3 off-zones shifted by 1/4, 1/2, 3/4 of a sidereal day in time for background estimation

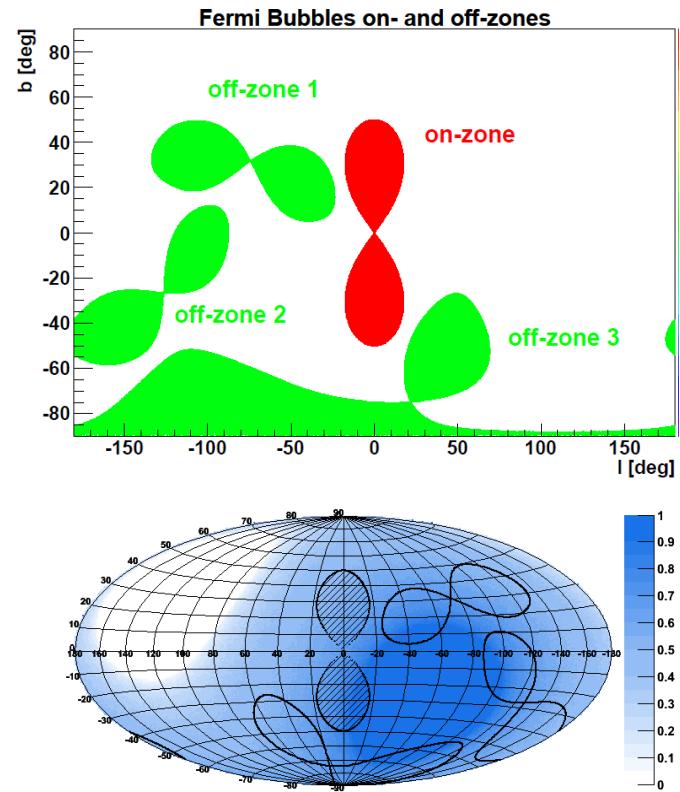


# On- and off-zone analysis

- use 3 off-zones shifted by 1/4, 1/2, 3/4 of a sidereal day in time for background estimation

detector coordinates

galactic coordinates





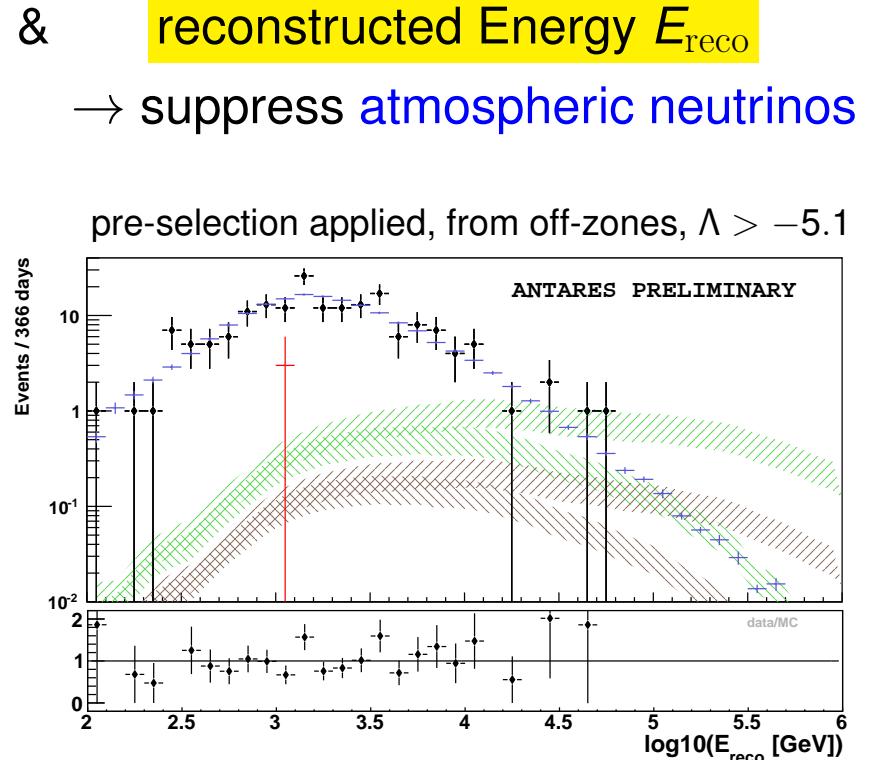
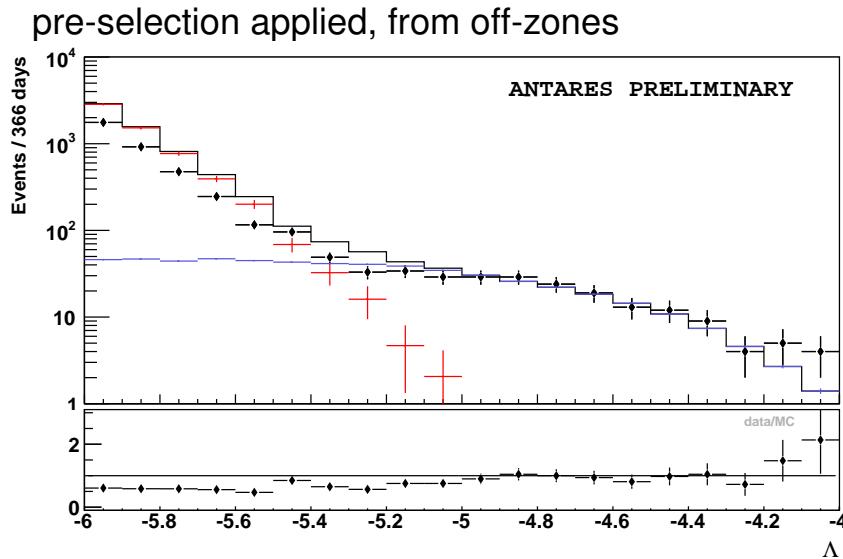
# Analysis procedure

- 2012/13 data with good data-taking conditions and agreement with dedicated simulation
  - total life-time used in the analysis: 366 days  
(cf. 806 days in 2008–11 analysis [*Eur. Phys. J. C74 (2014) 2701*])
- The visibility of the on- and the off-zones agrees at the level of few percent
  - no problematic effect from gaps / inhomogeneities in data-taking
- Blind strategy
  - use simulated data only to optimise selection cuts

# Cut optimisation



- pre-selection: well-reconstructed, upgoing, track-like events
- find optimal cuts on two parameters:  
track reconstruction quality  $\Lambda$  & reconstructed Energy  $E_{\text{reco}}$   
→ suppress atmospheric muons  
→ suppress atmospheric neutrinos



$$E^{-2} + \text{no cutoff} / 50 \text{ TeV cutoff}$$
$$E^{-2.18} + \text{no cutoff} / 50 \text{ TeV cutoff}$$



# Optimal cut values

Optimal cut values for 2012/13 data-set found

- by minimising a variant of the model rejection factor [*Astro.Ph. 19 (2003), 393*] , taking into account the result of the 4–year analysis ( $N_{\text{on}} = 16$ ,  $\bar{N}_{\text{off}} = 11$ )
- for spectral indices  $\alpha = 2$ ,  $\alpha = 2.18$
- for cut-off energies 50 TeV, 100 TeV, 500 TeV,  $\infty$

Obtained cut values

- not strongly dependent on the cut-off and index
- close to the values used in the 4–year analysis [*Eur. Phys. J. C74 (2014) 2701*]

→ can use same single pair of cuts:  $\log_{10}(E_{\text{reco}}[\text{GeV}]) > 4.03$ ,  $\Lambda > -5.14$

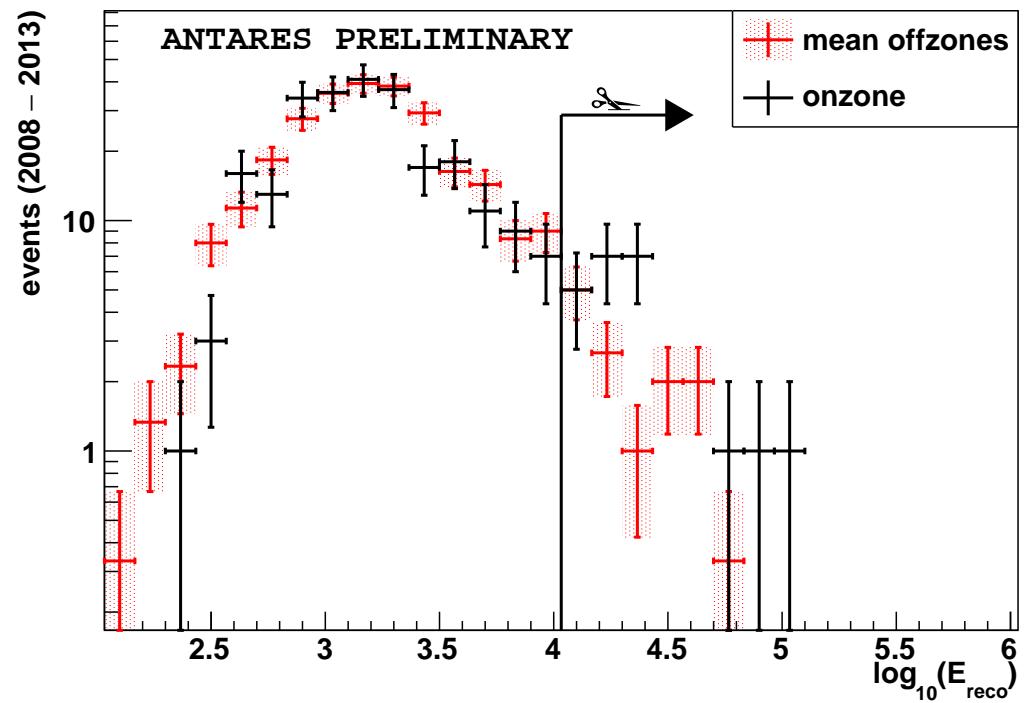
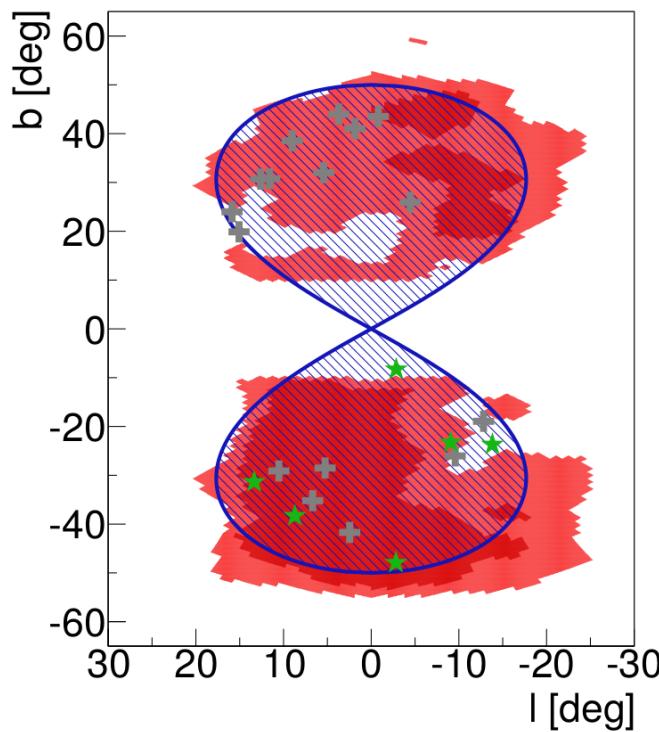
# Analysis result

analysis update:

**6/3** (1, 2, 3) off-zone events, **6** on-zone events

4-year analysis:

**33/3** (9, 12, 12) off-zone events, **16** on-zone events



(pre-selection +  $\Lambda > -5.14$ )

# How significant is the excess?

- significance of an excess in the signal region is determined using the approach by Li&Ma [*ApJ 272 (1983), 317*]

$$S = \sqrt{-2 \ln \lambda} = \sqrt{2} \left\{ n_{\text{on}} \ln \left[ \frac{1 + \alpha}{\alpha} \left( \frac{n_{\text{on}}}{n_{\text{on}} + n_{\text{off}}} \right) \right] + n_{\text{off}} \ln \left[ (1 + \alpha) \left( \frac{n_{\text{off}}}{n_{\text{on}} + n_{\text{off}}} \right) \right] \right\}^{1/2},$$

where  $1/\alpha = 3$  is the number of off-zones

**in on-zone:**

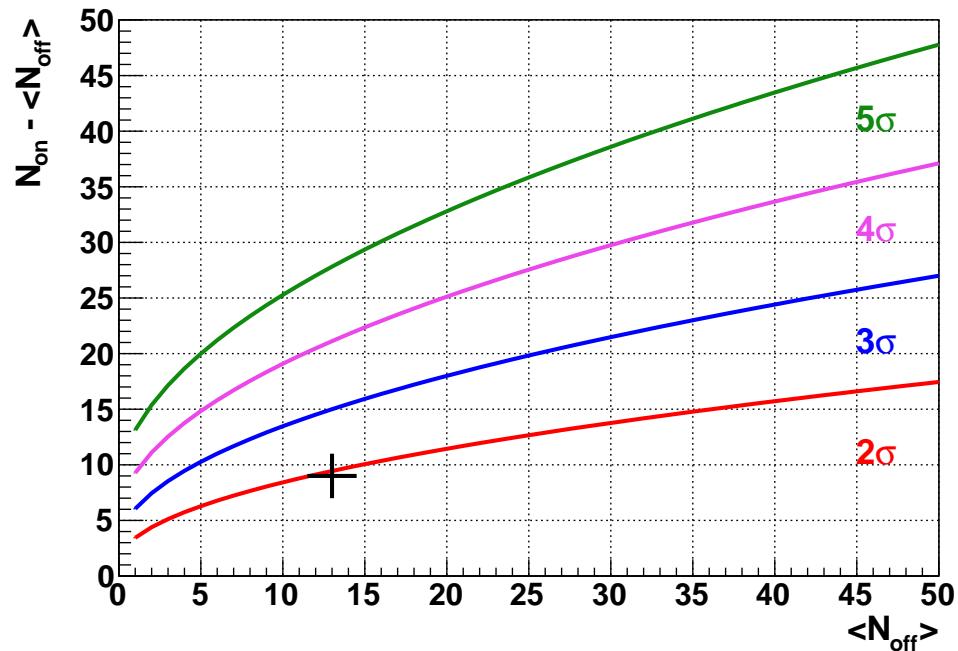
$16 + 6 = 22$  events

**in 3 off-zones:**

$33 + 6 = 39$  events

→ **1.9 $\sigma$  excess**

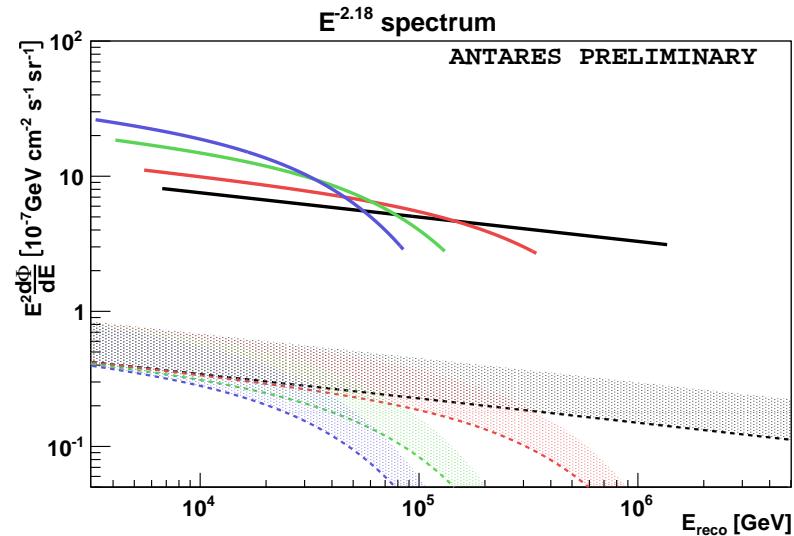
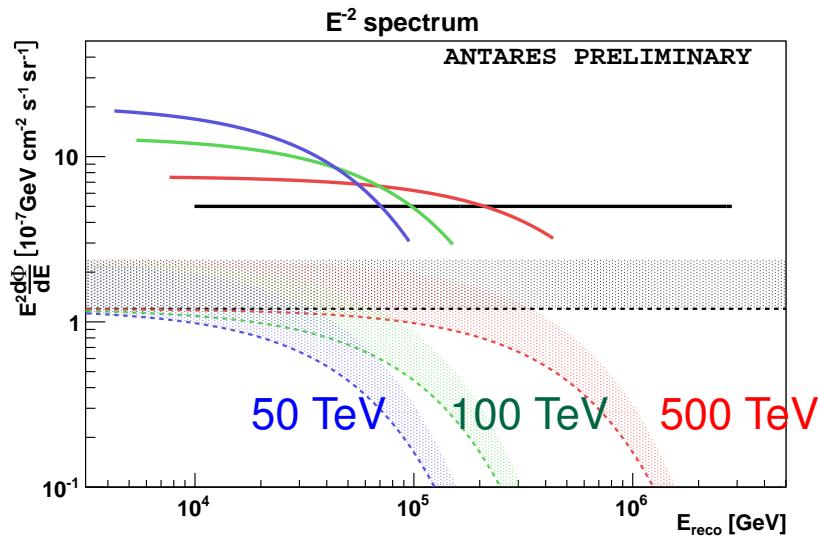
(1.2 $\sigma$  in 4-year analysis)



# Flux limits...

- 90% Feldman&Cousins upper limits on the signal flux:

$$\Phi_{90\%} = \Phi_{\text{model}} \times \frac{\mu_{90\%}(N_{\text{on}}, \langle N_{\text{off}} \rangle)}{s_{\text{MC}}}$$



- systematics checks using  $\pm 10\%$  absorption length & scattering length on the signal Monte Carlo ( $s_{\text{MC}}$ ) are still on-going

## Present analysis:

- excess seen in 2008–2011 analysis also present in 2012/13 data
- 13 events average background, 22 events seen →  $1.9\sigma$  → limit

## Next step:

- $5^\circ$  angular resolution on showers with ANTARES
- all flavour search with full data-set

## Promising future:

- 1 order of magnitude better sensitivity with KM3NeT [ApJ 42 (2013), 7]

GEFÖRDERT VOM



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# Backup



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# Finding the optimal cuts ...

Optimal cuts found by **minimising the average upper limit** or, equivalently, the **model rejection factor (MRF)** [A.Ph. 19 (2003), 393]

$$\bar{\Phi}_{90\%} = \Phi_{\nu_\mu + \bar{\nu}_\mu} \frac{\bar{\mu}_{90\%}(b_2 | n_{\text{on},1}, n_{\text{off},1})}{s_1 + s_2} = \Phi_{\nu_\mu + \bar{\nu}_\mu} \times \text{MRF}, \quad (1)$$

$$\bar{\mu}_{90\%}(b_2 | n_{\text{on},1}, n_{\text{off},1}) = \sum_{k=0}^{\infty} \mu_{90\%}(k + n_{\text{on},1}, b_2 + n_{\text{off},1}) \times \text{Poisson}(k | b_2), \quad (2)$$

$s_2$ : simulated signal of the update,

$b_2$ : simulated background of the update

$\mu_{90\%}$ : 90% Feldman&Cousins upper limit

**Modification to standard MRF** [A.Ph. 19 (2003), 393] **applied here:**

- $s_1$ : Signal MC in 4–year analysis
- $n_{\text{on},1}$ : 16 on-zone events found in the 4–year analysis
- $n_{\text{off},1}$ : 11 average off-zone events found in the 4–year analysis