Search for Neutrino Emission from the Fermi Bubbles with ANTARES
Track – Shower Combination

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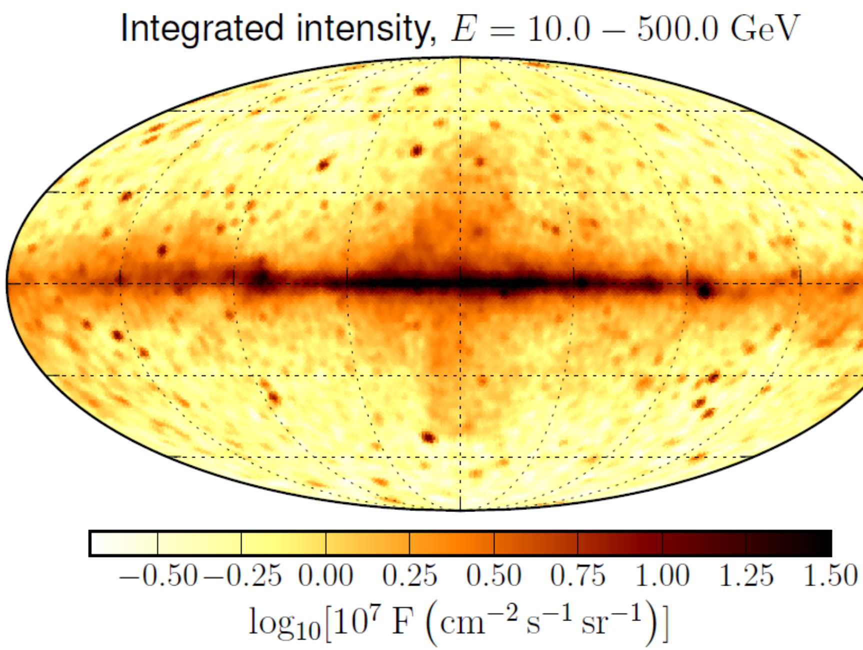
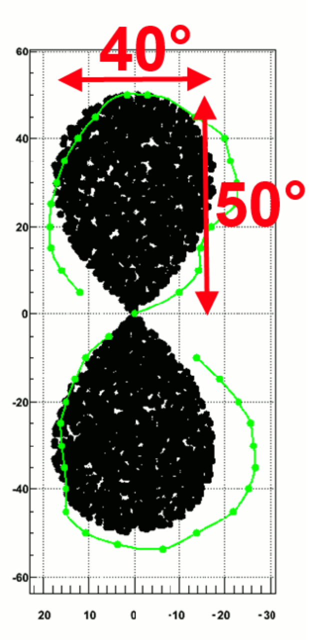
Fermi Bubbles (FB)

- High energy γ-ray emission from two extended lobes **above and below the center of our galaxy** observed by Fermi LAT

[Meng Su et al. 2010 ApJ 724 1044, M. Ackermann et al. 2014 ApJ 793 64]





- relatively uniform, hard emission, sharp edges (median width $\Delta\varphi = 3.4$ deg)

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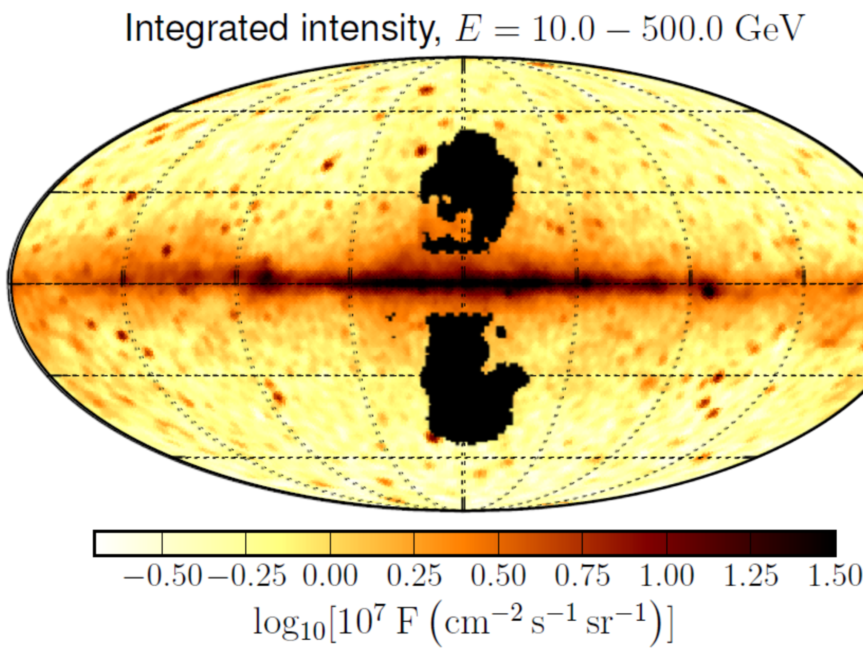

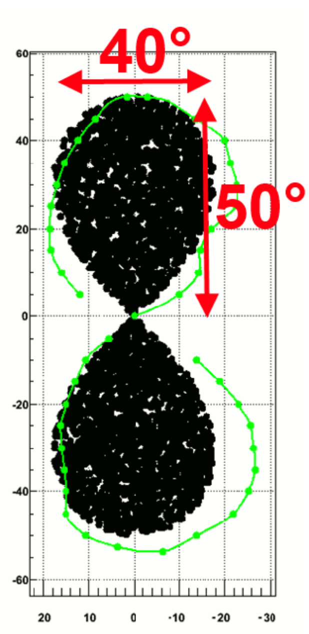

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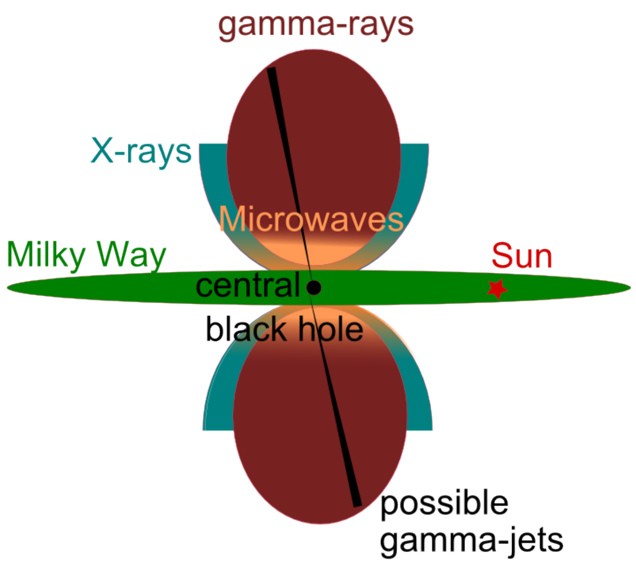
Fermi Bubbles (FB)

Multiwavelength observations show structures related to FB in Fermi data

- X-ray emission (Rosat, Suzaku)
- Microwave emission haze (WMAP, Planck)
- tentative identification of 2 jets [M. Su, D. P. Finkbeiner 2012 ApJ 753 6]



$\rightarrow$ What produces γ-signal? **Hadronic** or **leptonic** origin?

Origin of the Fermi Bubble signal: Hadronic or leptonic?

Electrons: produce γ-rays mainly by **inverse compton scattering**
Protons: in hadronic interactions: γ-rays from π^0 **decay**
additionally neutrinos from $\pi^{\pm}$ decay

Neutrino flux only present in hadronic mechanism

If mechanism is **fully hadronic** and source is transparent to γ-rays:

- Photon flux from 1–100 GeV measured by Fermi-LAT is

$$E_\gamma^2 d\Phi/dE_\gamma \approx 4 \times 10^{-7}\,\text{GeV cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$$

- This transfers to an expected neutrino flux

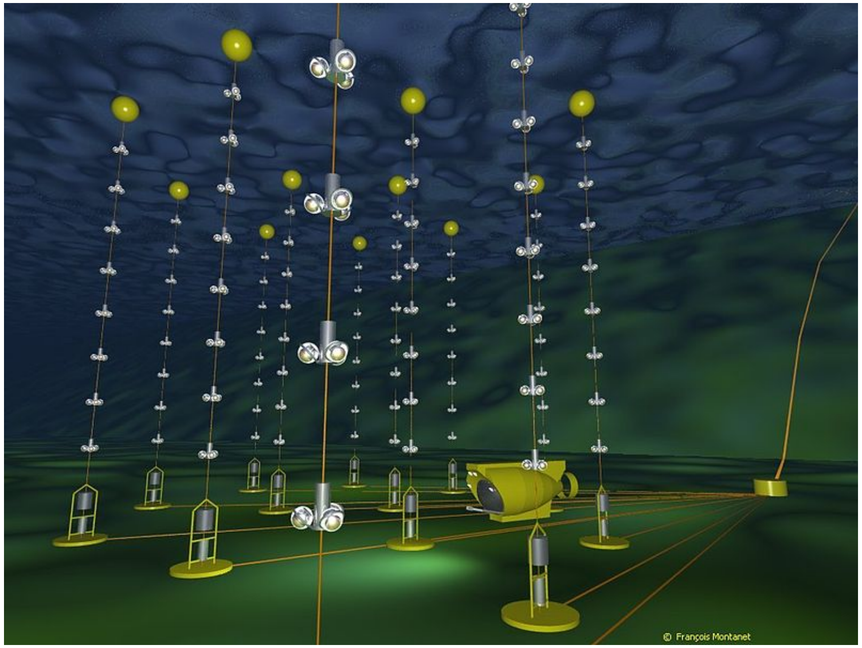
$$E_\nu^2 d\Phi/dE_\nu \approx 1 \times 10^{-7}\,\text{GeV cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$$

Both fluxes are expected to have some energy cutoff related to the proton cutoff:

$$E_\nu^{\text{cutoff}} \approx E_p^{\text{cutoff}}/20$$

(20% of the energy is going into charged pions and distributed over 4 daughters in pion decay)

ANTARES detector

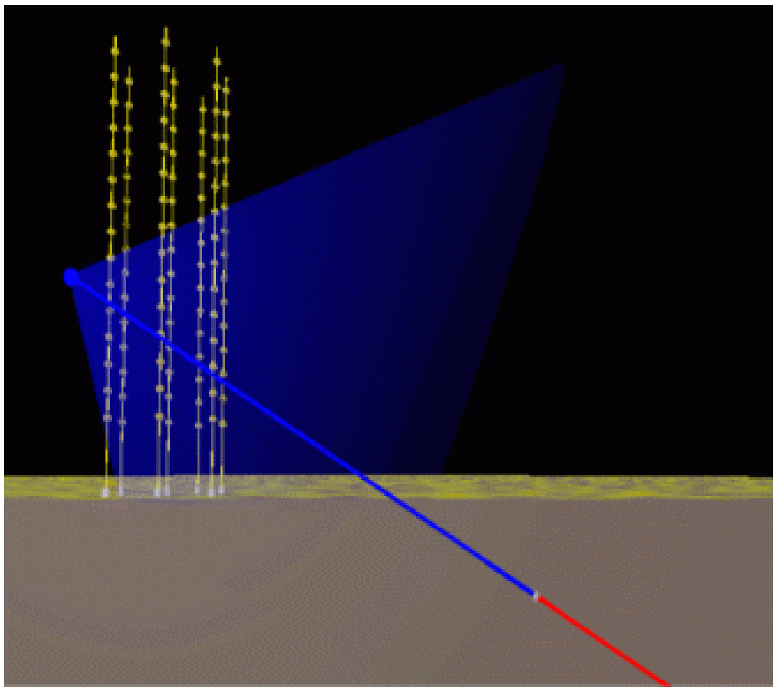


- 30 km off Toulon (Mediterranean Sea)
- detector completed in 2008
- 2.5 km below sea level, 350 m instrumented height
- 885 optical modules (photomultipliers) distributed over 12 strings
- inter-string spacing: $\approx$70 m
  0.01 km^2 instrumented volume

3 **dominant backgrounds** for neutrino detection in sea water:

- atmospheric muons
- bioluminescence
- ^{40}K

"Golden channel" for ANTARES



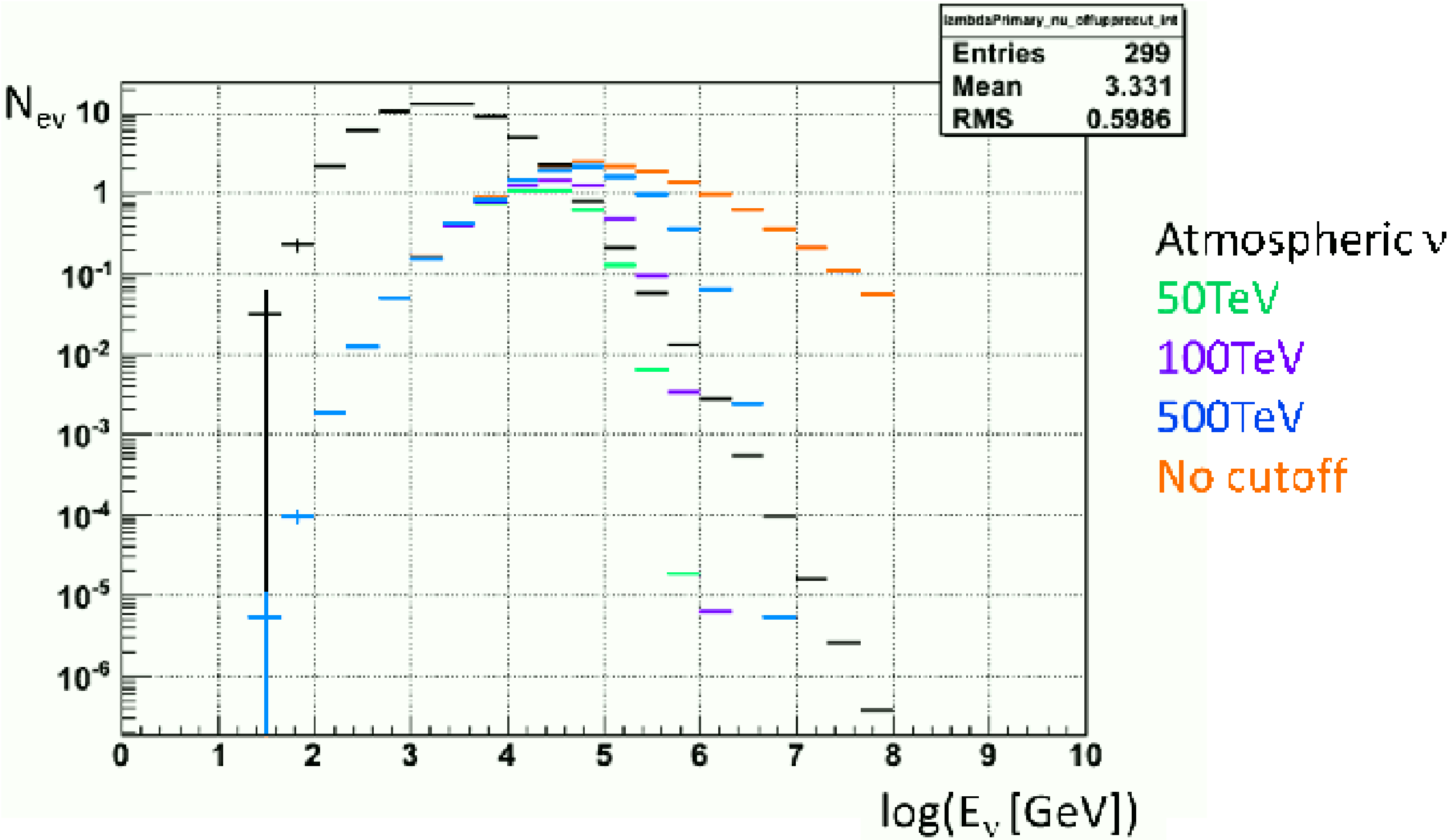
ν_μ **charged current** interaction

$$\boxed{\nu_\mu + N \longrightarrow \mu^- + \text{hadronic shower } (+\text{cc})}$$

- high energetic muon has a long track before it decays/is stopped
- emission of detectable Cherenkov light (angle of 42° in water)
- muon direction $\approx$ neutrino direction +estimate for neutrino energy

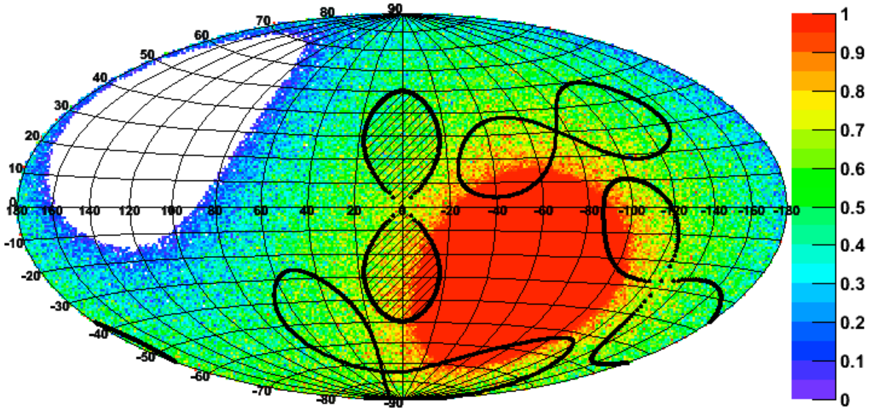
Neutrino signal from the FB

Spectrum: E^{-2}, reconstructed track events in ANTARES (Monte Carlo)



FB analysis with tracks [arXiv:1308.5260]

- Compare number of events observed in on-zone to expected background
- Background determination from 3 off-zones with same shape and visibility as on-zone



Selection cuts on:

- upgoing events
- quality parameters
  (track?, angular error?)
- energy
  $\log_{10}(E_{\mathrm{Rec}}[\mathrm{GeV}] > 4.03)$

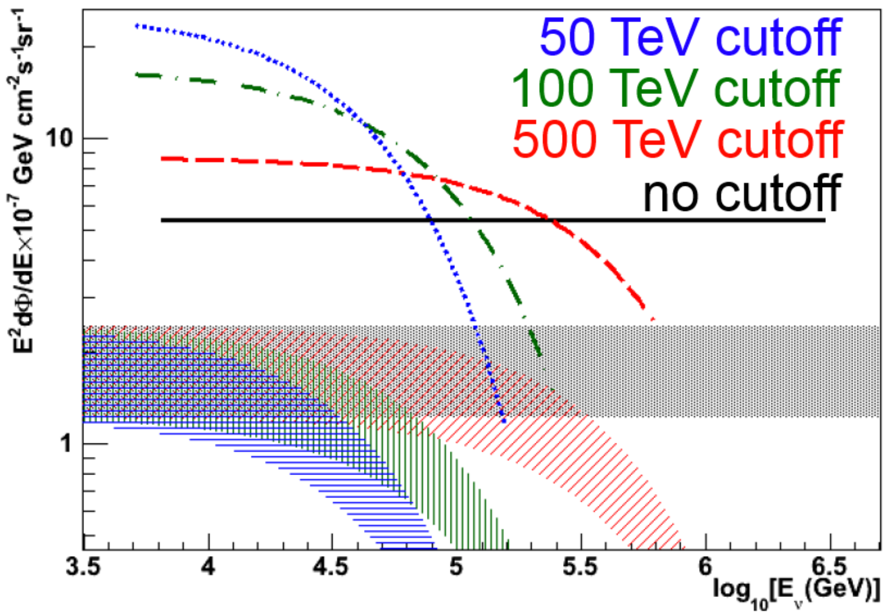
color code: visibility

FB analysis with tracks

Results from analysis with 806 days of data:

- $N_{off} = 9, \quad 12, \quad 12$
- $N_{on} = 16$
- 1.2σ excess using on/off method
- compatible with background only hypothesis

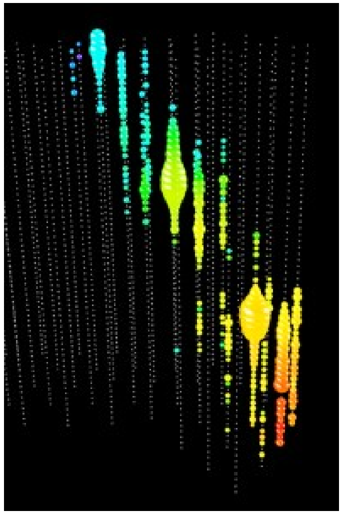
Flux limit (optimistic no-cutoff case):
$5.40 \times 10^{-7}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$



Shower vs. track events in neutrino detectors

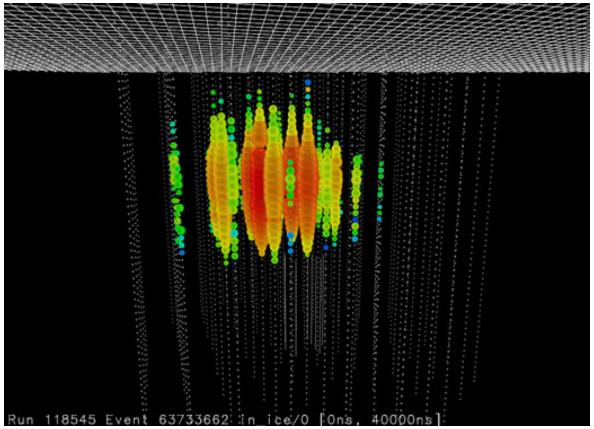
Track events

- from ν_μ charged current interactions
- good angular resolution ($<$ 1 deg)
- limited energy resolution (interaction vertex + long tracks not fully contained in ANTARES)



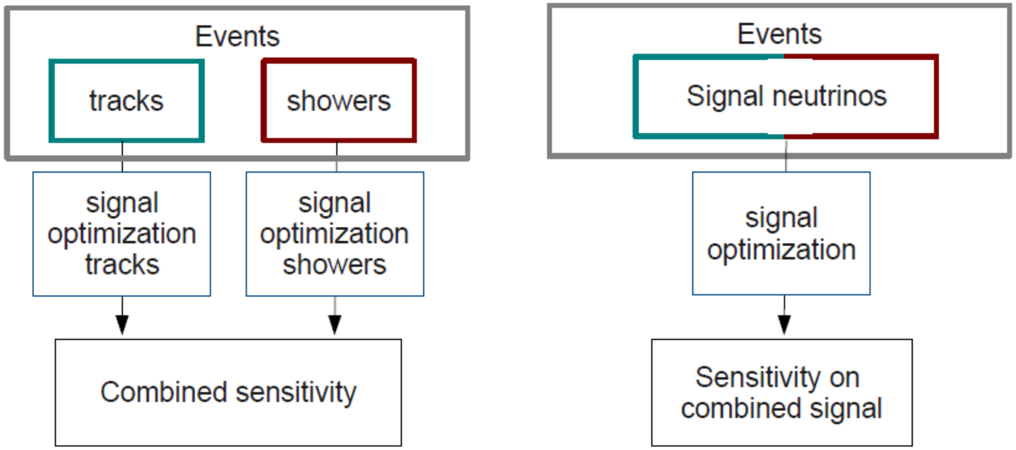
Shower events

- from neutral current, ν_e charged current
- neutral current: neutrino loses only part of its energy
- worse angular resolution ($\mathcal{O}$(5 deg))



Plan: Combined analysis of track and shower events

- 806 $\rightarrow$ 1326 days will increase sensitivity + additional $\approx$ 55% increase in sensitivity when adding shower channel
- two strategies for shower reconstruction available in ANTARES, of which one has median angular resolution of 5 degrees
- Methodology: Until now track and shower analyses separate $\rightarrow$ **combination**



- Enlarged parameter space: Consider using **machine learning algorithms**

Work in progress . . .

Option 1: $\boxed{\text{track}}$ $\boxed{\text{shower}}$

- Separate treatment of tracks and showers, combination as final step of analysis
  - need to separate track from shower events
  - signal optimisation still possible with rectangular cuts (quality parameter, direction, energy)

Option 2: $\boxed{\text{track shower}}$

- do not distinguish tracks and showers
  - choose which reconstruction result to use (direction, energy)
  - need to construct quality parameter
  - analysis similar to track-only analysis

For Option 2 (implemented; classification efficiencies not yet evaluated):

Each reco: zenith, azimuth, quality parameters | Best reco

train machine learning algorithm

Each reco: zenith, azimuth, quality parameters
Best reco: zenith, azimuth | Selected reco: distance from Monte Carlo direction

train machine learning algorithm

Best reco: zenith, azimuth, quality ~ **angular error**

Summary

- Neutrinos can be used to distinguish between hadronic and leptonic models for the Fermi Bubbles
- A similar analysis has been done for track events only
- Fermi Bubble flux can be within reach for ANTARES if tracks and showers are combined
- Combination of track and shower events also of interest for other analyses in the future
- Machine learning algorithms able to cope with increased amount of parameters are being evaluated

Backup

ANTARES

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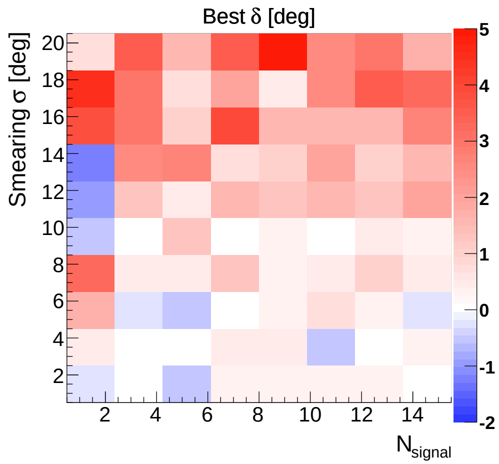
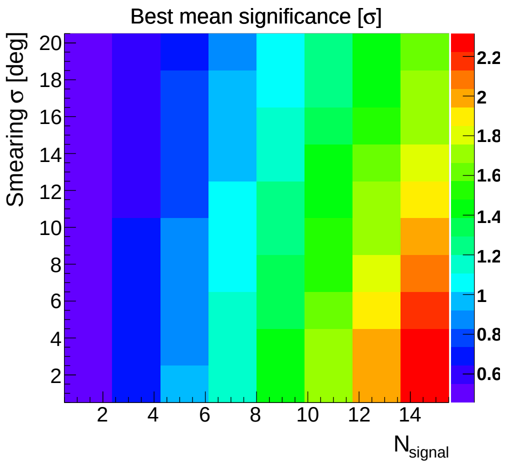
Work in progress: Analysis region

With worse angular resolution on shower events, do we have to modify search region? $\rightarrow$ No!

Toy Monte Carlo:

- produce **uniform background** in 4π, **uniform signal** in circular area
- apply **Gaussian smearing** to signal
- calculate **signal significance** in circular area (radius modified by δ)

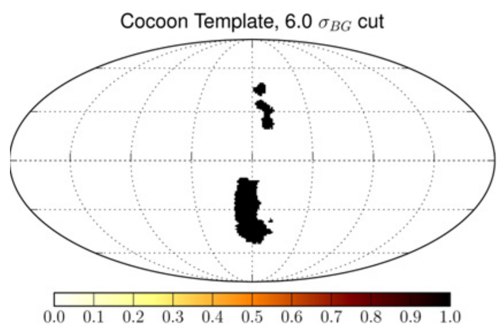


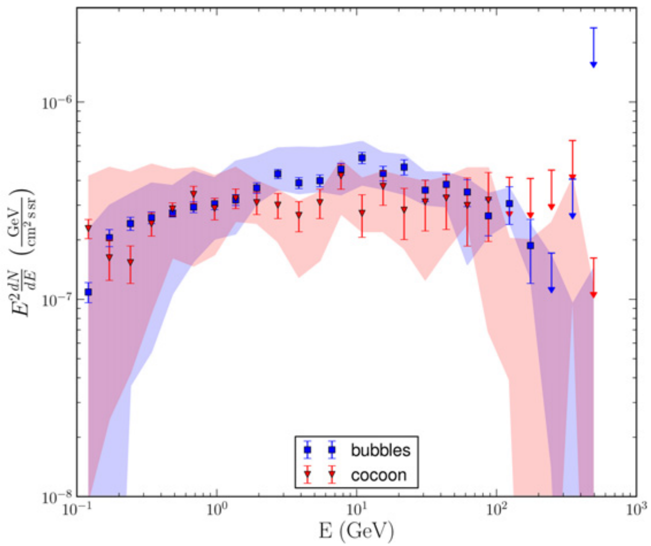


4×10^4 pseudo experiments with size of the emission region $\vartheta_{\mathrm{em}} = 25^\circ$ and mean background $\overline{N_B^\Omega} = 520$.

FB energy spectrum

In the recently (20/09/14) published 50 months Fermi-LAT paper:





- Cutoff at lower energies than expected
- Want to restrict to "cocoon" area?

$\rightarrow$ which area for the Fermi Bubbles to choose in the analysis is still a question to be answered

Li and Ma method for on/off zones

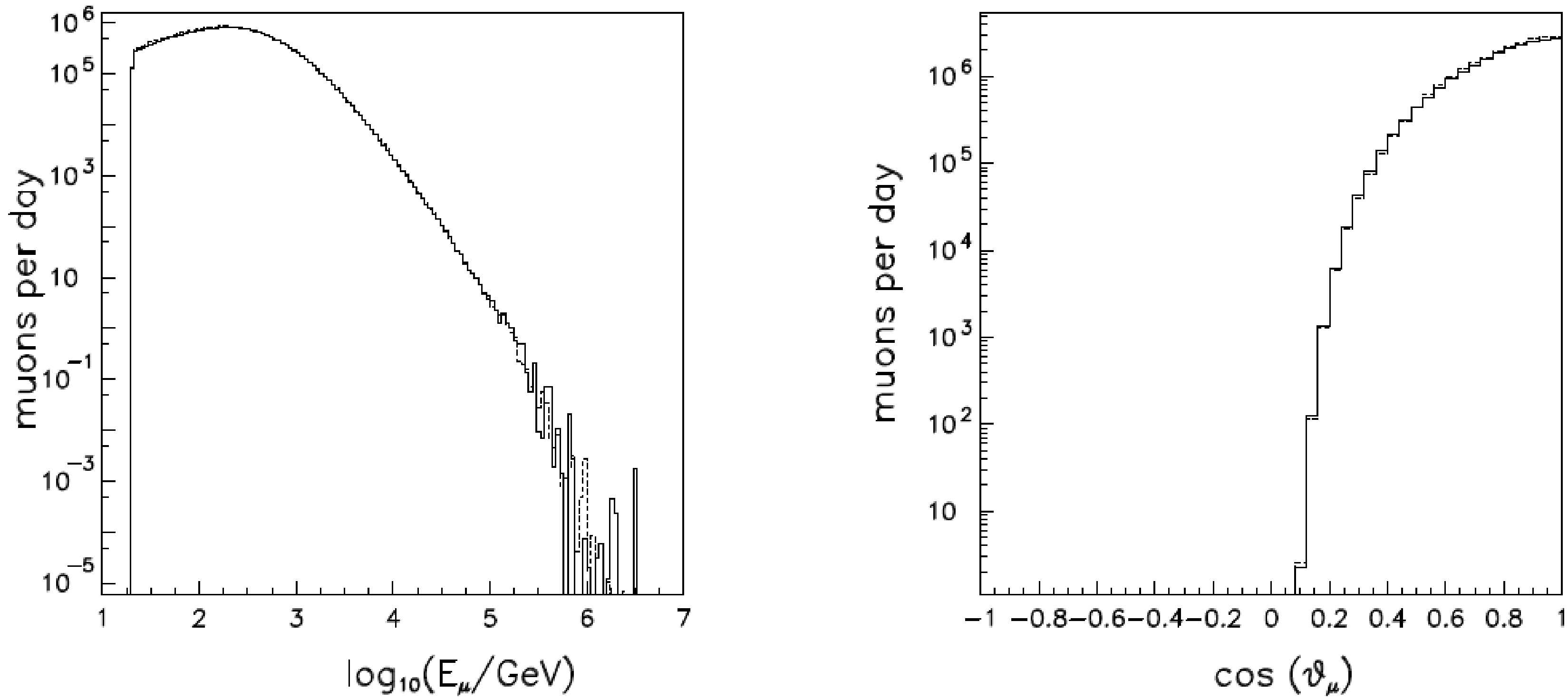
[Li,Ma, ApJ 272(1983), 317–324]

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

where α is the ratio of on- to offzone area. If this significance is calculated only when $n_{\rm on} > n_{\rm off}/\tau$ (for the search of a positive signal) then it corresponds to a single tail of a Gaussian distribution.

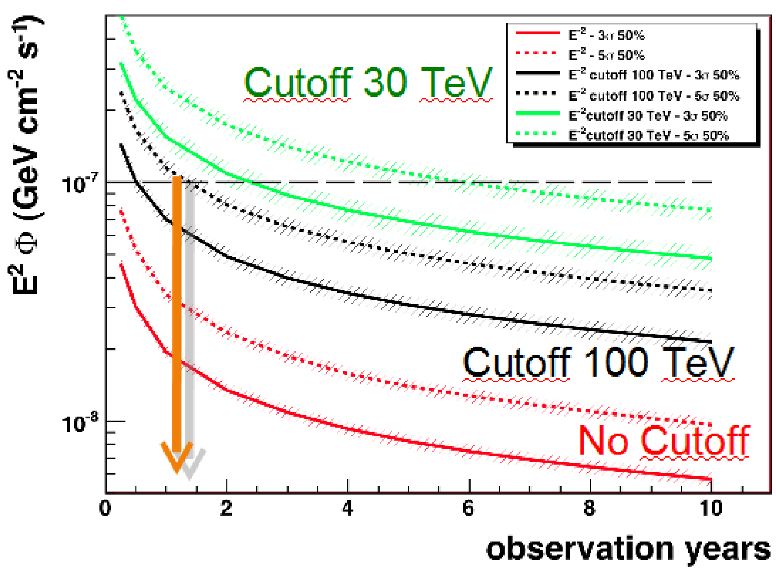
Atmospheric muons in ANTARES

[arXiv:astro-ph/0510799v1]



Visibility of the Fermi Bubbles to other neutrino detectors

- IceCube at the south pole the sensitivity to detect a neutrino signal from the FB is not very high
- Sensitivity study has shown that FB are a promising source for KM3NeT:
  - Assuming E^{-2} spectrum with cutoff at 100 TeV:
  - Discovery (5σ) in **1.5 years** with full KM3NeT detector
  - Evidence (3σ) in $\approx$ **2.5 years** in first construction phase ($\approx$ 15% of optical modules installed)



[arXiv:1208.1226]