ANTARES search for high-energy neutrinosn from TeV-emitting blazars, Markarian 421 and 501, in coincidence with HAWC gamma-ray flares

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Contents

Principle of the analysis

Search for ν/γ time correlation using flares from blazars, Mrk 421 and Mrk 501, visible by the High-Altitude Water Cherenkov Observatory (HAWC).

Physics goal :

- Determine the relative contribution of each component, **S** and **B**, at a given point in the sky at a given time.
  $\Rightarrow$ Calculate the probability to have a **S** above a given **B** model.

Mixture : S + B

as a 2-component parametrization S$\rightarrow$0 $\Rightarrow$ full data sample as B.

$$\left[\frac{n_S}{N} \cdot S_i + (1 - \frac{n_S}{N}) \cdot B_i\right]$$

Time information from the sources :

- improves the analysis by reduce of background ;
- improves the discovery potential over a time integrated search.
  $\Rightarrow$ **LC** can be used as a time probability distribution function

Likelihood :

as a product of all the event probability densities

$$L(n_S) = \prod_{i=1}^{N} \left[\frac{n_S}{N} \cdot S_i + (1 - \frac{n_S}{N}) \cdot B_i\right]$$

Extended Maximum Likelihood

Likelihood

$$\ln(\mathrm{L}) = \sum_{i=1}^{N} \ln\left[n_S \cdot P_S(x) + n_B \cdot P_B(x)\right] - \left[n_S + n_B\right]$$

- **S :** $P_S(x) =$ *spatial term* $\times$ *energy term* $\times$ ~~*time term*~~ $= P_S(\alpha) \cdot P_S(E) \cdot P_S(t)$
- **B :** $P_B(x) =$ *spatial term* $\times$ *energy term* $\times$ ~~*time term*~~ $= P_B(\sin(\delta)) \cdot P_B(E) \cdot P_B(t)$

Test Statistics

as a product of all the event probability densities

$$TS = 2\log\left[\frac{L^{max}(n_S)}{L(n_S = 0)}\right]$$

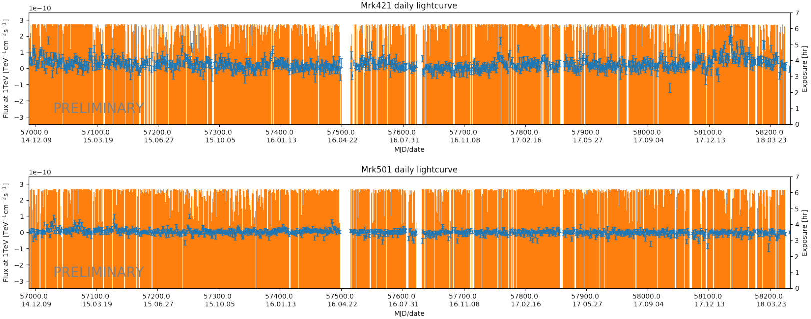
↪ to differentiate between the signal and background.
Pseudo-experiments (PEX) generated to evaluate TS :

- 3×10^5 for **B**
- 3×10^4 for **S** (**1,2,3 ... up to 20 !**)

HAWC LCs : raw-data[1] $\rightarrow$ analysis extension[2]

Period available : 26/11/2014 - 24/04/2018

Extract the shape of the signal from the γ-ray LCs assuming the proportionality between γ-ray and ν fluxes.



- Bayesian blocks application
- One-day binning/re-binning

1. Granted by HAWC collab. in July 2018 (after discussion with Prof. Ignacio Taboada at NEUTRINO 2018 in June)
2. Last analysis : 27/11/2014 - 19/04/2016. Flare blocks from Abeysekara et al., Astrophys.J. 841 (2017) no.2, 100

Bayesian blocks

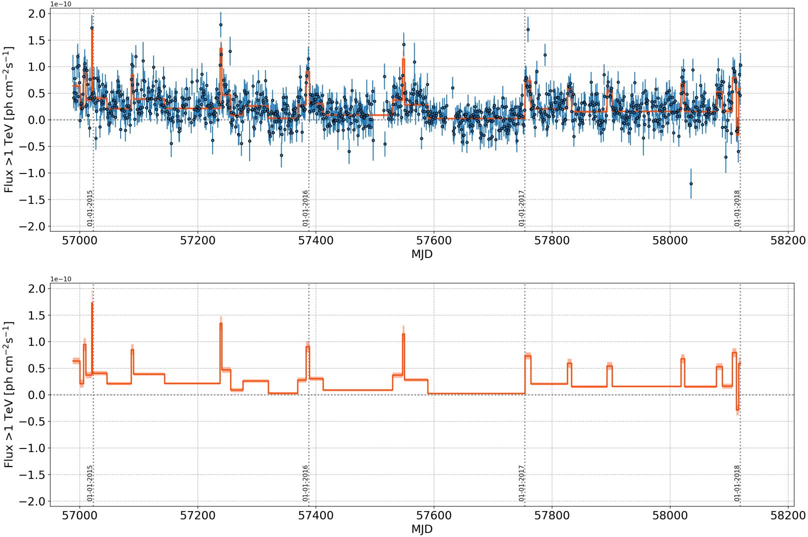
Description

- If LC is variable, the **Bayesian blocks algorithm (Scargle et al. 2013)** can be applied to detect and characterize signals in noisy time series.

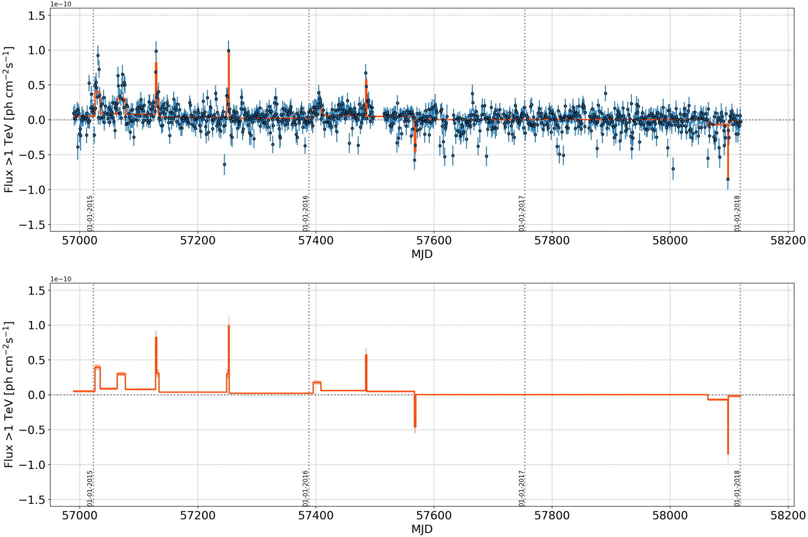
> Bayesian analysis helps to identify changes between flux state via finding change points at transition from one flux state to the next.

- Code for Bayesian blocks with usage of HAWC ideas and methods.
- The algorithm requires the initial choice of a Bayesian prior, called $\mathrm{ncp}_{\mathrm{prior}}$.
  ↪ it is needed for the probability of finding a new change of flux states.
- In HAWC, $\mathrm{ncp}_{\mathrm{prior}} = 6$ was used, and corresponds to predetermined 5% false positive probability for identifying a change point that is not a true flux state change (this $\mathrm{ncp}_{\mathrm{prior}}$ value obtained in simulations in HAWC).
  ↪ This value I used also as a proper $\mathrm{ncp}_{\mathrm{prior}}$ for the analysis.
  ↪ Different $\mathrm{ncp}_{\mathrm{prior}}$ values have been tested (see BACKUP), $\mathrm{ncp}_{\mathrm{prior}} = 6$ seems to be very reasonable.
  ↪ As axample, for Mrk 421/Mrk 501 it has given almost same block profile for first 17 months as obtained from the HAWC published blocks (see comparison later).

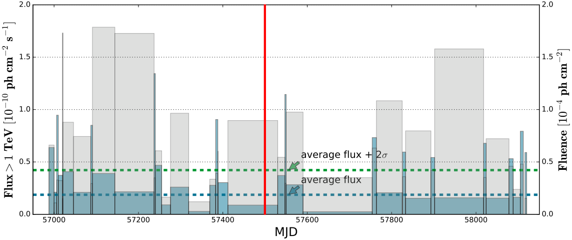
Bayesian Blocks : Mrk 421

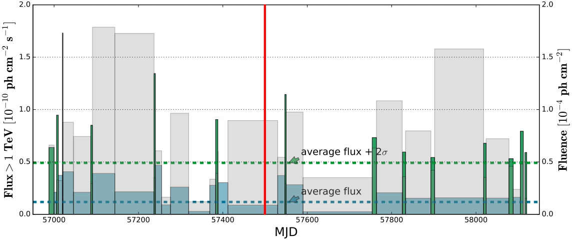


Bayesian Blocks : Mrk 501



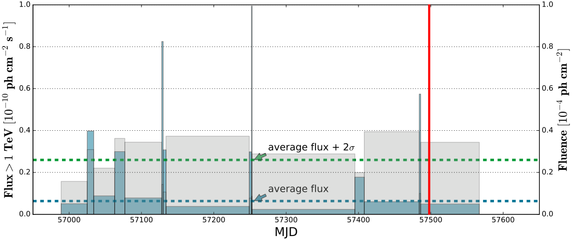
Flare states for Mrk 421 [3]

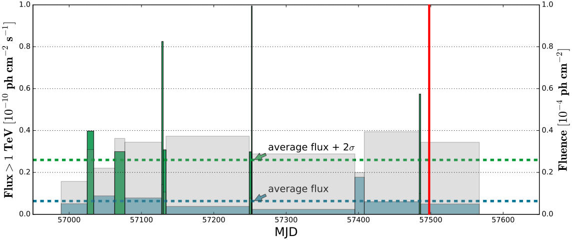




3. Red line represents the edge of the last analysis

Flare states for Mrk 501 [4]





4. Red line represents the edge of the last analysis

DATA/MC set

The ANTARES data set period :

- November 27th, 2014 - January 1st, 2018 [MJD : 56988-58119] $\rightarrow$ Mrk 421
  November 28th, 2014 - June 28th, 2016 [MJD : 56989-57567] $\rightarrow$ Mrk 501
  $\hookrightarrow$ covering the same period of observation as HAWC w.r.t. blocks selected.
- Lead to effective detector livetime : | MC-complete
  Mrk 421 : 1099.93 days [3.009 y] (last : 503.7 days [1.379 y]) | 993.83 d [2.721 y]
  Mrk 501 : 561.55 days [1.537 y] (last : 503.7 days [1.379 y]) | 462.13 d [1.265 y]

Track-like event signatures $\Longrightarrow$ only CC interactions of muon neutrinos are considered.

Runs are selected if the conditions below are fulfilled :

- QualityBasic $>=$ 1
- SCAN $! =$ 1
- Sparking $! =$ 1 (Additional observed sparking runs are removed)

RESCALE : livetime of available complete MC is scaled up to livetime of DATA !

Cuts

Parameters selected (from last analysis)

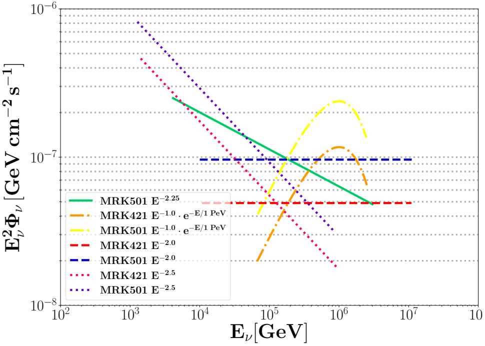
- 1.1 Considered spectra
  - $E^{-\gamma}\exp(-E/E_{cut})$ with $\gamma = 1.0$ and cutoff @ 1 PeV for both sources
  - $E^{-\gamma}$ with $\gamma = 2.0$ for both sources
  - $E^{-\gamma}$ with $\gamma = 2.5$ for both sources
  - $E^{-\gamma}$ with $\gamma = 2.25$ for Mrk 501 only
- 1.2 Considered flares :
  - all flare blocks
  - ~~higher *average*~~
  - ~~higher *average* $+ 1\sigma$~~
  - higher *average* $+ 2\sigma$
- 1.3 Considered cuts :
  - ~~9~~ $\rightarrow$ 7 track reconstruction quality parameters Λ : Λ> ~~-5.8~~ ; ~~-5.7~~ ; -5.6 ; ... ; -5.0
  - 1 final cut on error on the reconstructed zenith cos(θ) : cos(θ)>-0.1
  - 1 final cut on angular error estimate β : $\beta < 1.0$

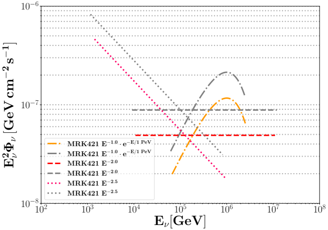
Periods

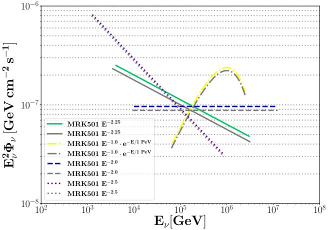
- Mrk 421 : 27/11/2014 - 01/01/2018 [56988-58119]
- Mrk 501 : 28/11/2014 - 28/06/2016 [56989-57567]

Neutrino energy flux sensitivities & comparison for last/current analysis

Obtained with case of all flares, give best sensitivities on ν fluxes

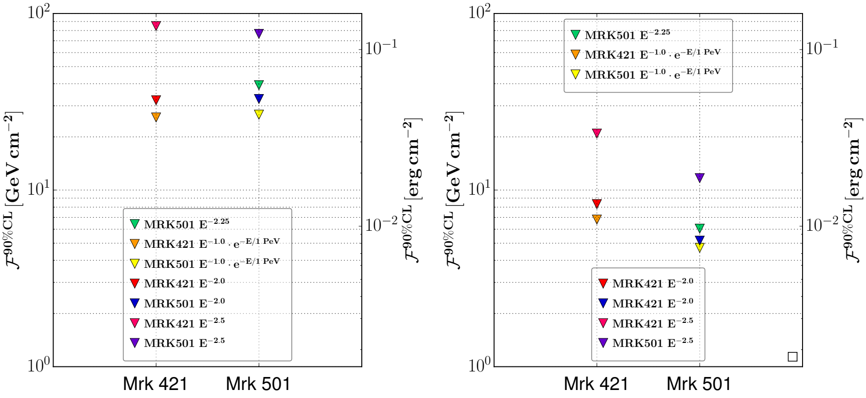






Grey color and colored curves represent HAWC 2014-2016 and HAWC 2014-2017 periods respectively

Neutrino fluence sensitivities [5] [6]



5. Left plot has been obtained with case of *all flares*
6. But best sensitivities on ν fluxes can be obtained with usage of *average flux + 2σ* case (Right plot)

$\hookrightarrow$ gives one order of magnitude improvement w.r.t all flares.

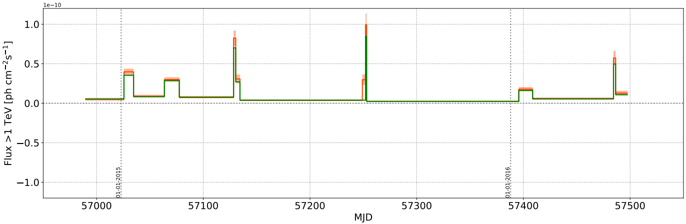
Conclusion

- Neutrino energy flux sensitivities :
  - For Mrk 421 is getting better by factor ∼1.8 w.r.t. last analysis
    ↪ we used ∼ 120% longer LC data for the current analysis.
  - For Mrk 501 is getting worse by factor ∼1.1 w.r.t. last analysis
    ↪ we used ∼ 10% longer LC data for the current analysis.

Many things play a role here such as :

  - different flare states amplitudes used ; jump to slide
    - the current analysis involve the raw-data LCs with 1 TeV as a threshold, and flare blocks obtained w.r.t. that ; the spectral fit parameters are not similar as well ;
    - the last analysis presumed the Bayesian blocks have already been done, but for that the initial LCs had other thresholds than 1 TeV, e.g., 2 TeV and 3 TeV for Mrk 421 and Mrk 501 respectively.
  - different optimized Λ cuts have impact on sensitivity fluxes $\mathrm{S}^{90\%\mathrm{CL}}_{Median}$; jump to slide
    - For Mrk 501, ∼ 18% difference in used fluxes give roughly worsening by factor proportional to ratio 1.1 (longer time) / 1.18 (worse flux) ≈0.9, which is roughly ∼1.1 worsening that we observe.
    - For Mrk 421, we use ∼2.2 longer duration, but sensitivities better by factor ∼1.8. Hence, using same idea, if assume e.g. ∼ 20% differences, we obtain 2.2/1.2 ≈1.8, exactly what we observe.
  - different data/mc set with new reprocessed data and new mc might cause some affect.
- Comparison with PS for Mrk 421 (with Giovanna's analysis). jump to slide
- Comparison with PS Giovanns's and Luigi's MC). jump to slide
- Short/Long flares discovery powers comparisons). jump to slide
- SED for sources. So, jump to slide for Mrk 421 example.

Flare states (blocks) amplitudes comparison [7] and ratio [8] for Mrk 501



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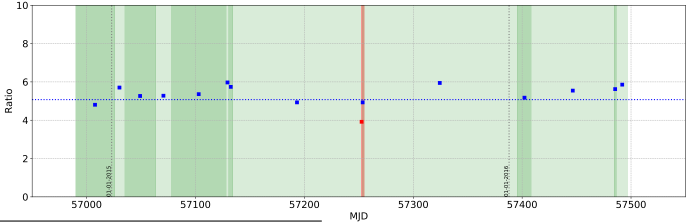
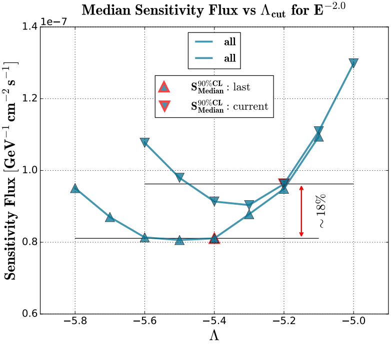
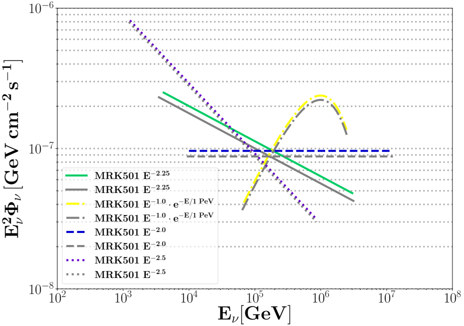


7. *Upper plot* : The last (orange) multiplied by factor ∼5 to make the better comparison with current (green).
8. *Lower plot* : The current/last amplitudes ratios (blue points). The blue dotted line is the average (obtained without red). The green color repesents the width (duration) of the blocks (flares).). The ratio for the block exist in current and not in last analysis is colored by red and divided by factor 10 for better comparison.

Median sensitivity fluxes comparison [9] for last/current analysis for Mrk 501.

Is getting worse by factor ∼1.1 w.r.t. last analysis but we used ∼ 10% longer LC data for the current analysis.





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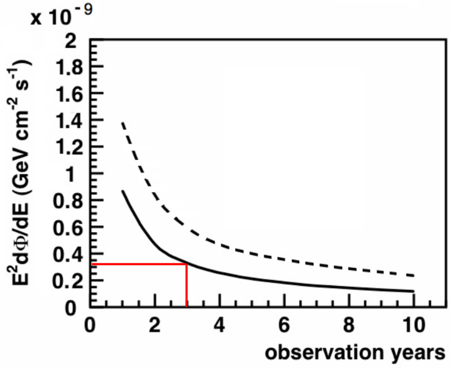
9. As wee see this had impact on final sensitivities (with factor of ∼ 18%) because of different optimum Λ cuts. Moreover, optimum Λ = −5.2 gives ∼ same fluxes. If selected, it would give better sensetivities then. For short case it gives even slightly better fluxes (see BACKUP).

Comparison with PS analysis [10]

- $\Phi_{\mathrm{PS}}(11\mathrm{y}) \sim 2.6 \cdot 10^{-8}$ & $\Phi_{\mathrm{TrMu}}(3\mathrm{y}) \sim 5.0 \cdot 10^{-8}$ $[\Phi]$ = GeV cm^{-2} s^{-1}
- So, finally : $\Phi_{\mathrm{TrMu}}(11\mathrm{y}) \approx 1.7 \cdot 10^{-8}$. If scaled w.r.t. years of observation. $\Phi^{90\%CL}(11y)/\Phi^{90\%CL}(3y)$ 0.33 using Fig.6.11. in KM3NeT Tech. Design Report



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10. with Giovanna's results

Are MC comp. for v4 consistent with Giovanna's/Luigi's comparisons ? [11]

- DATA/MC for β : it can be seen in slide 6 of Giovanna's talk that the DATA/MC comparison presented in this work is a bit better, e.g., for $\beta \to 0$ we have $\sim$1.5 ratio, but $\sim$2.0 in Giovanna's analysis ; for $\beta \to$1.0 we have ratio $\sim$1.0$\pm$0.2, but ratio $\sim$1.0$\pm$0.3 in Giovanna's analysis. Note, this is done for $\Lambda >$-5.3 in this analysis and $\Lambda >$-5.2 in Giovanna's analysis. That more strict cut can lead to such slight worsening in Giovanna's analysis.
- DATA/MC for Λ : it can be seen in slide 6 of Giovanna's talk that for $\Lambda \to$-5.2 both analysis have $\sim$1.0 ratio, and for $\to$-3.8 we have $\sim$1.5 ratio at most, but Giovanna has $\sim$3.0 !.

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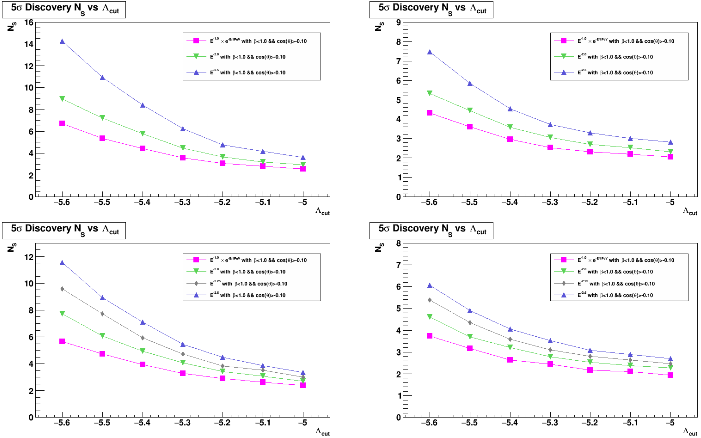
11. The answer is yes.
Note, Giovanna uses another energy estimator, *dEdX*, for me it's *nhit*. Concerning β and cos(θ) cuts, we have same, $\beta <$1 and cos($\theta >$)-0.1.

The relative contribution of the amount of ν-s expected during the very short high flares to the overall ones.[12]



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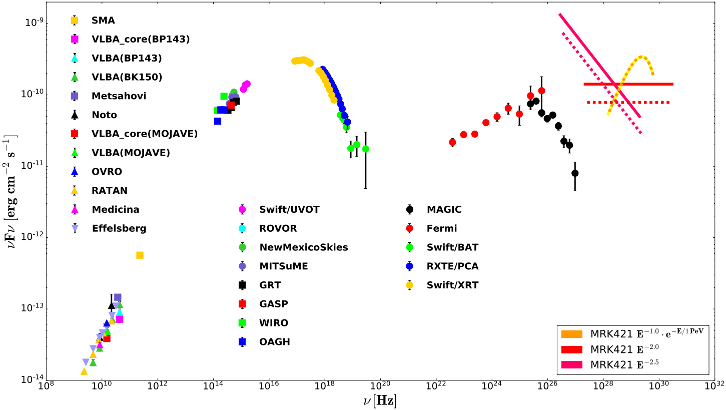
12. For both sources, the number of ν-s expected during short peaks is about 3/4 for better Λ values and about 2/3 for worse Λ values for E^{-2} spectrum considered (for short case the neutrinos are injected exactly at high peaks). For other spectra $\sim$ same behavior.

SED of Mrk 421 [13] and neutrino energy flux sensitivities [14]



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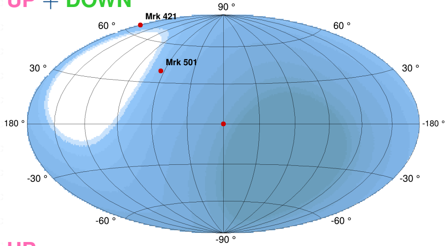
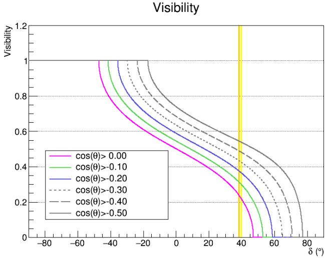
13. Adapted from Abdo et al, 2011, ApJ 736, 131. Raw-data table credit by David Paneque
14. HAWC 2014-2016 (last work) : solid line ; HAWC 2014-2017 (current work) : dotted line

BACKUP

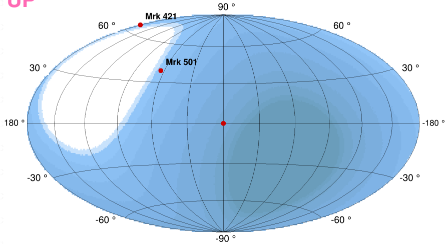
ANTARES Visibility

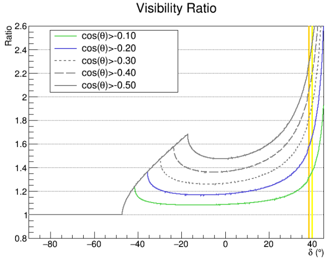
UP + DOWN



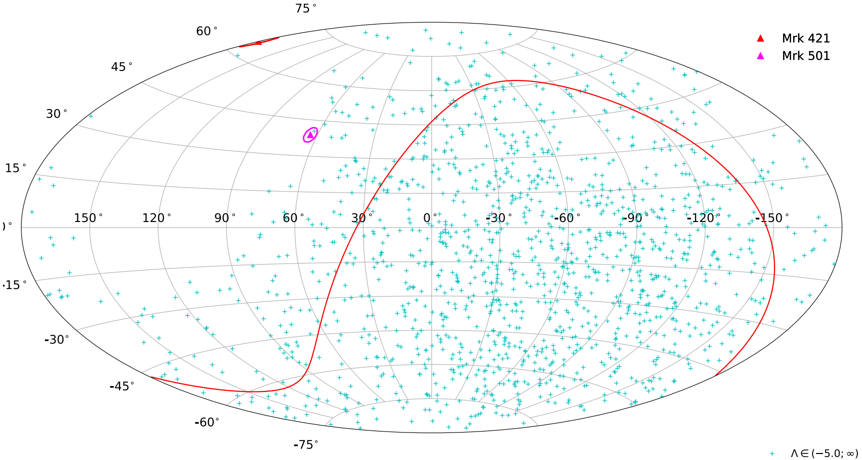


UP





Sky map [15] [16] of the track-like events passing the selection cuts



$N_{ev}(\Lambda > -5.0)$ **: 1358**

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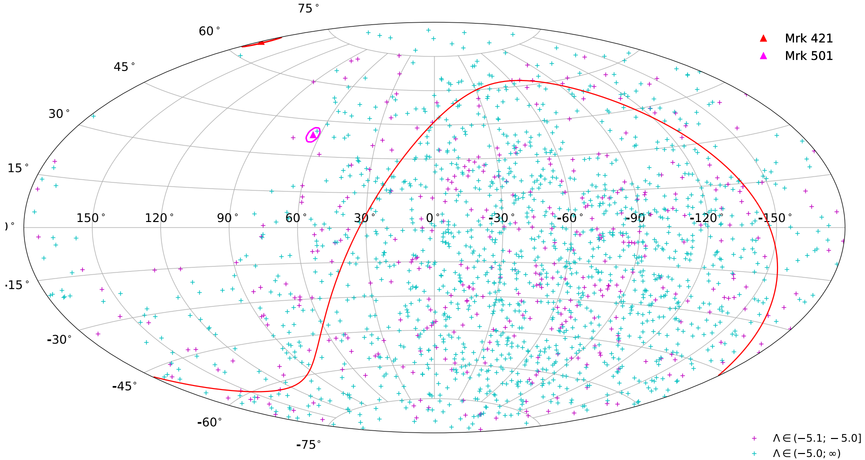
15. In galactic coordinates using Aitoff projection. The red solid curve denotes the equatorial plane.
16. The red circles denote the 3 degree radius region around the sources.

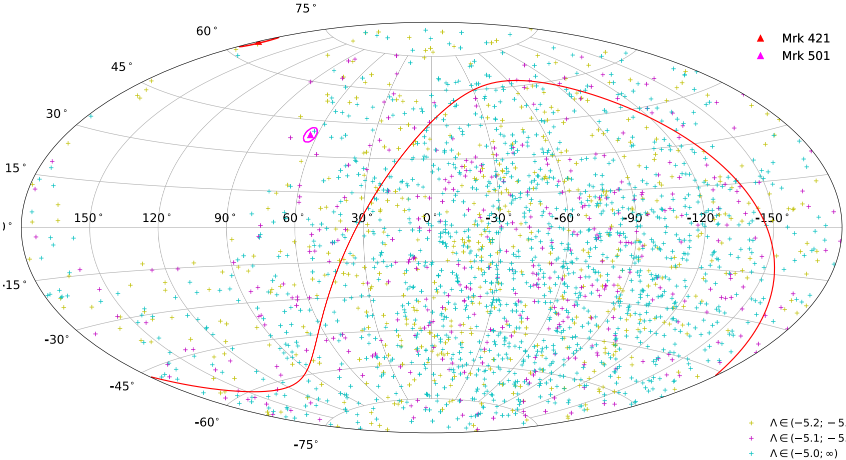
Sky map [15] [16] of the track-like events passing the selection cuts



$N_{ev}(\Lambda > -5.1)$ **: 1741**

15. In galactic coordinates using Aitoff projection. The red solid curve denotes the equatorial plane.
16. The red circles denote the 3 degree radius region around the sources.

Sky map [15] [16] of the track-like events passing the selection cuts



$N_{ev}(\Lambda > -5.2)$ **: 2286**

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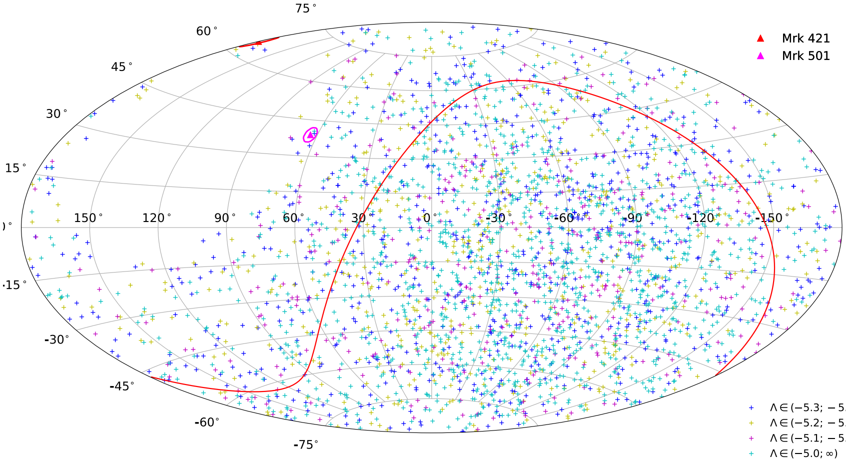
15. In galactic coordinates using Aitoff projection. The red solid curve denotes the equatorial plane.
16. The red circles denote the 3 degree radius region around the sources.

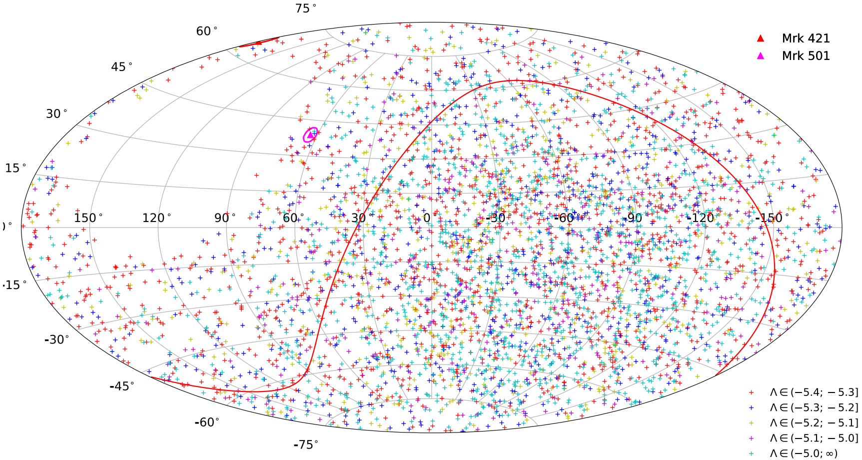
Sky map [15] [16] of the track-like events passing the selection cuts



$N_{ev}(\Lambda > -5.3)$ **: 3050**

15. In galactic coordinates using Aitoff projection. The red solid curve denotes the equatorial plane.
16. The red circles denote the 3 degree radius region around the sources.

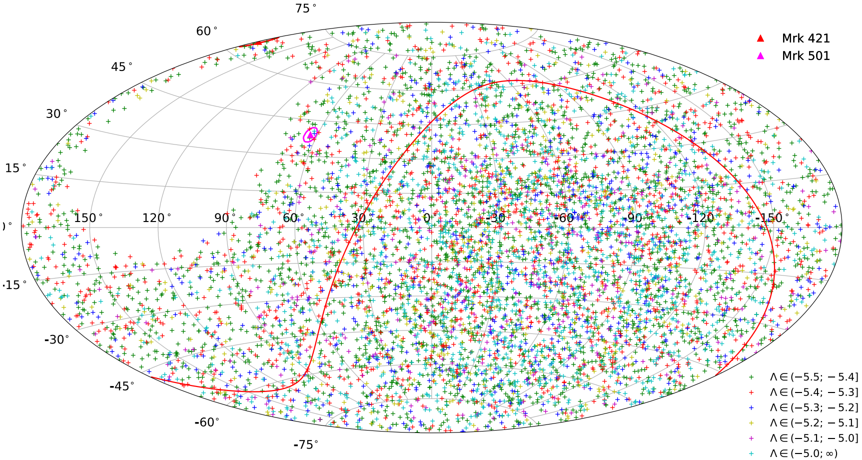
Sky map [15] [16] of the track-like events passing the selection cuts



$N_{ev}(\Lambda > -5.4)$ **: 4498**

15. In galactic coordinates using Aitoff projection. The red solid curve denotes the equatorial plane.
16. The red circles denote the 3 degree radius region around the sources.

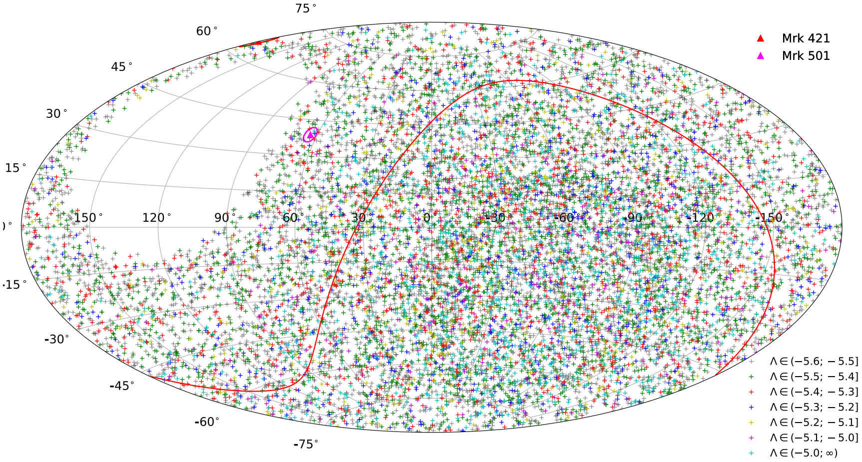
Sky map [15] [16] of the track-like events passing the selection cuts



$N_{ev}(\Lambda > -5.5)$ **: 7314**

15. In galactic coordinates using Aitoff projection. The red solid curve denotes the equatorial plane.
16. The red circles denote the 3 degree radius region around the sources.

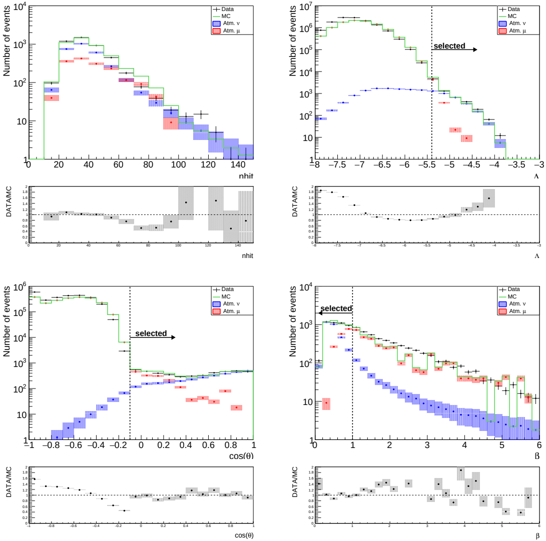
Sky map [15] [16] of the track-like events passing the selection cuts



$N_{ev}(\Lambda > -5.6)$ **: 12827**

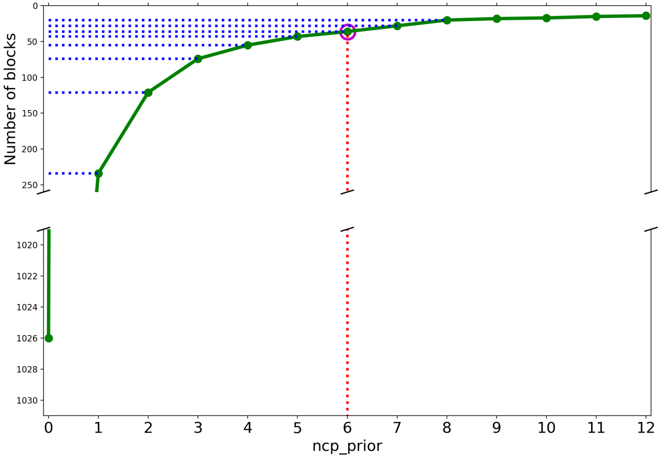
15. In galactic coordinates using Aitoff projection. The red solid curve denotes the equatorial plane.
16. The red circles denote the 3 degree radius region around the sources.

DATA/MC agreement



Bayesian blocks vs $\mathrm{ncp}_{\mathrm{prior}}$: Mrk 421

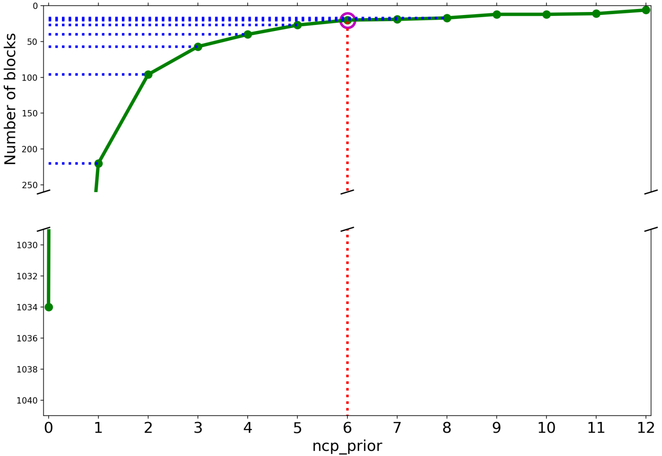
Selected 36 blocks for $\mathbf{ncp_{prior}} = 6$



Total 1026 blocks for $\mathbf{ncp_{prior}} = 0$ shows all data points available

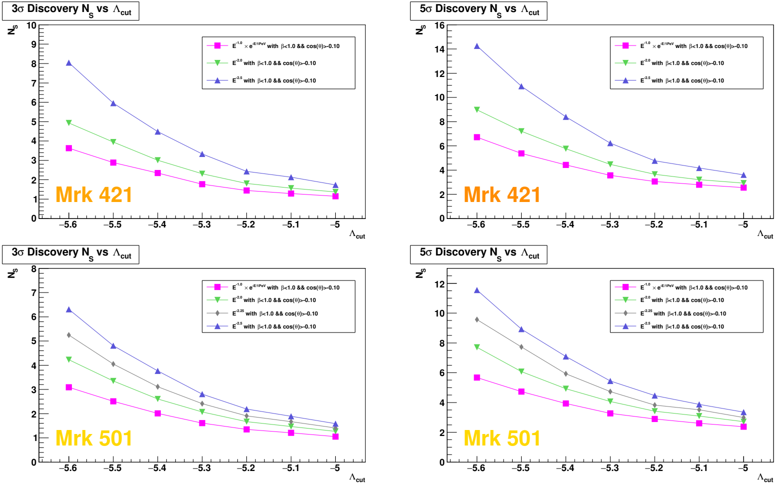
Bayesian blocks vs $\mathrm{ncp}_{\mathrm{prior}}$: Mrk 501

Selected 20 blocks for $\mathbf{ncp_{prior}} = 6$



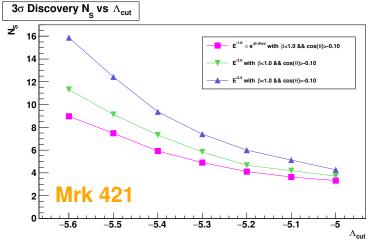
Total 1034 blocks for $\mathbf{ncp_{prior}} = 0$ shows all data points available

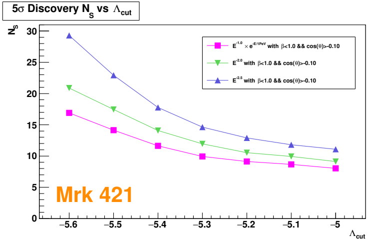
Discovery signals[17], example for case of *all flares*

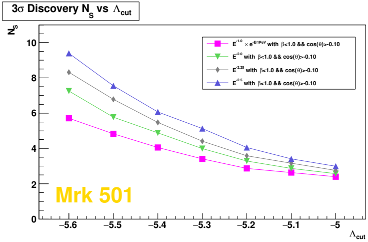


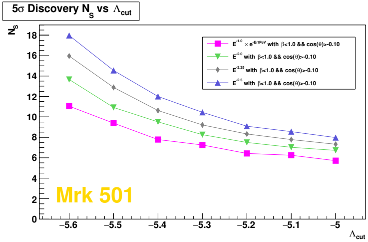
17. Values not scaled for case of all flares

Discovery signals [18], example for case of *average flux + 2σ*



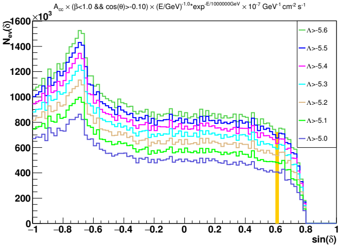


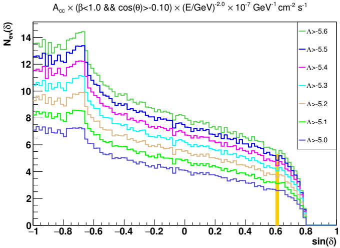


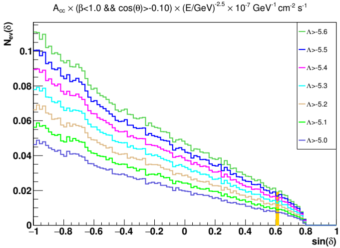


18. Values scaled for case of *average flux + 2σ* => values shown that are required for whole T_{flare} period

Acceptance vs Λ, example for Mrk 421 [19]

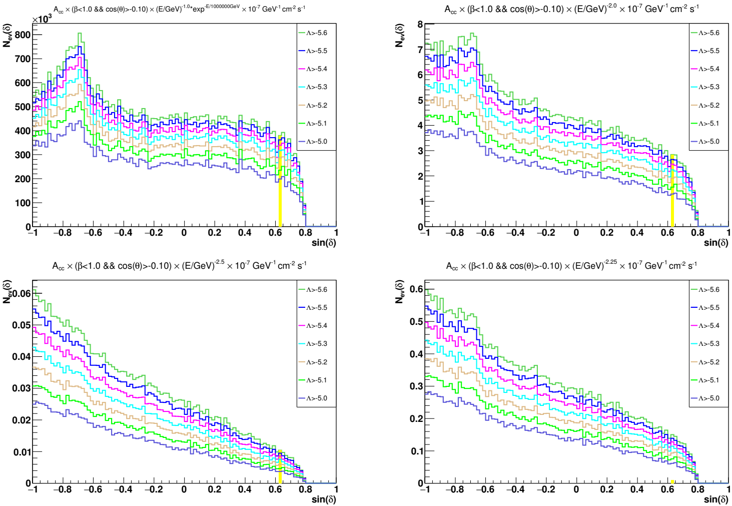






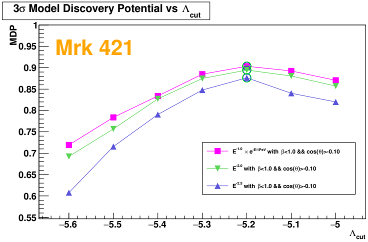
19. The position of the Mrk 421 is colored by orange

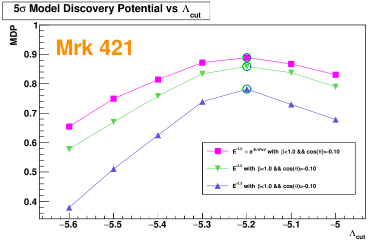
Acceptance vs Λ, example for Mrk 501 [20]

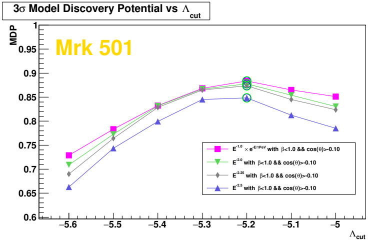


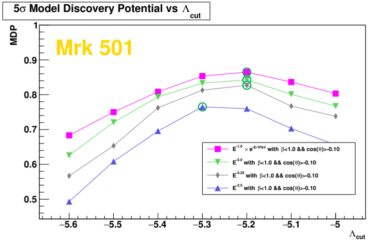
20. The position of the Mrk 501 is colored by yellow

MDP, example for case of *all flares*

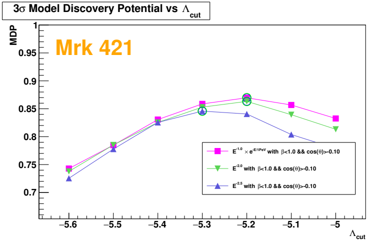


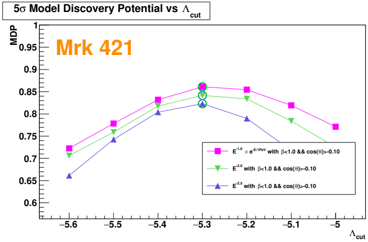


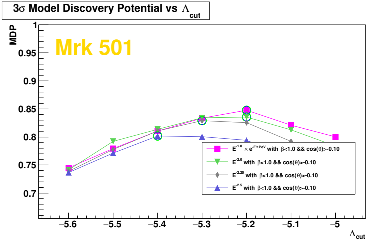


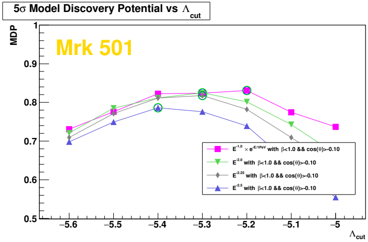


MDP, example for case of *average flux + 2σ*

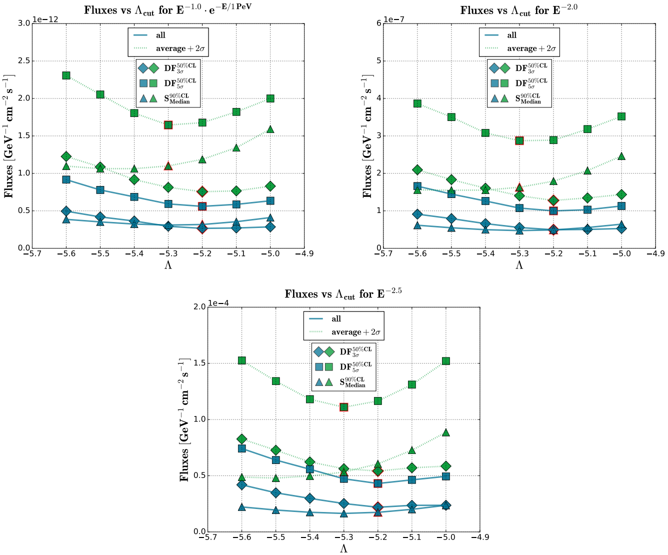




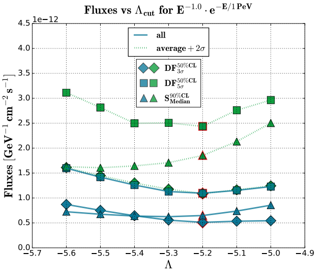


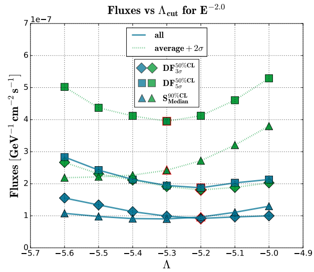


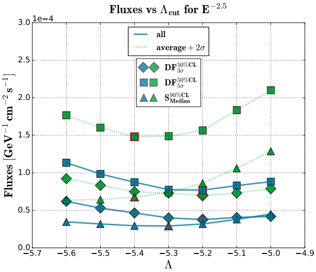
Fluxes for Mrk 421

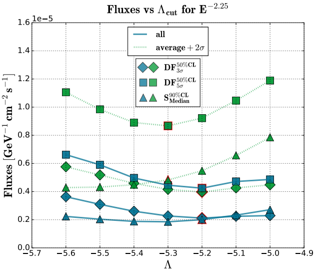


Fluxes for Mrk 501









Sensitivities

$$\mathcal{F}^{90\%CL} = \int F dt = F \Delta T = \Delta T \cdot \Phi_0^{90\%CL} \int_{E_{min}}^{E_{max}} E\, S(E)\, dE$$

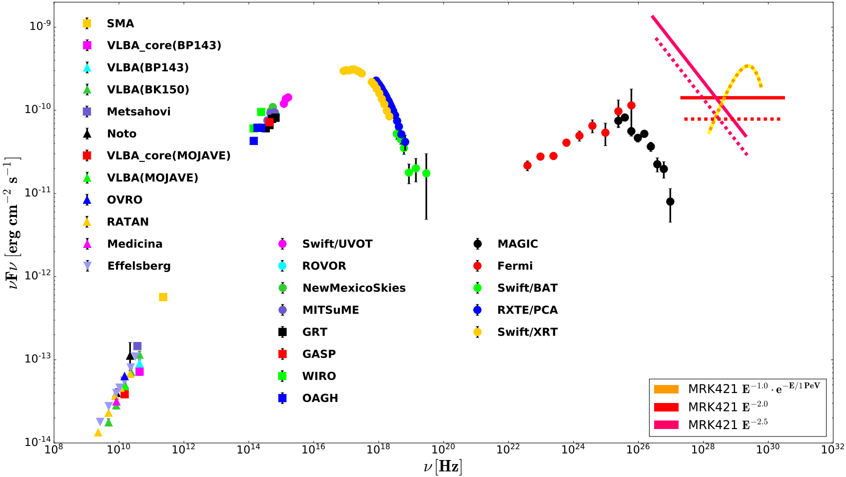
with the energy flux F as the energy per unit area and time $[GeV\, cm^{-2}\, s^{-1}]$:

$$F = \int E d\Phi = \int E\, \Phi_E\, dE = \int E\, \Phi_0\, S(E)\, dE = \Phi_0 \int E\, S(E)\, dE$$

Here :

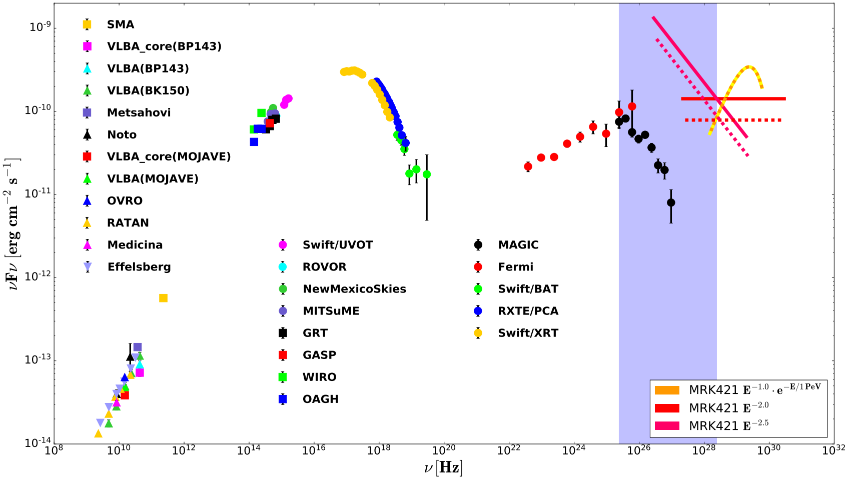
- ΔT is the livetime of the search $[s]$;
- $\Phi_0^{90\%CL} = DF^{90\%CL}$ is the upper limit on the ν flux normalization $[GeV^{-1}\, cm^{-2}\, s^{-1}]$;
- $\Phi_E = \Phi_0^{90\%CL}\, S(E) = DF^{90\%CL}\, S(E)$ is the differential flux $[GeV^{-1}\, cm^{-2}\, s^{-1}]$;
- $S(E)$ is the dimensionless neutrino spectra $\left(\frac{E}{GeV}\right)^{-\gamma}$, and $dN/dE = \Phi_0 \cdot S(E)$;
- E_{min} and E_{max} are 5% and 95% energy limits respectively, defined to contain 90% of the spectrum emission. This is the energy range at which ANTARES is sensible for each spectrum $S(E)$ and source, and computed from the MC $\nu_\mu + \bar{\nu_\mu}$ simulation used in PSF calculation. The MC ν simulation extends up to 10^8 GeV.

SED of Mrk 421 [21] and neutrino energy flux sensitivities [22]



21. Adapted from Abdo et al, 2011, ApJ 736, 131. Raw-data table credit by David Paneque
22. HAWC 2014-2016 (last work) : solid line ; HAWC 2014-2017 (current work) : dotted line

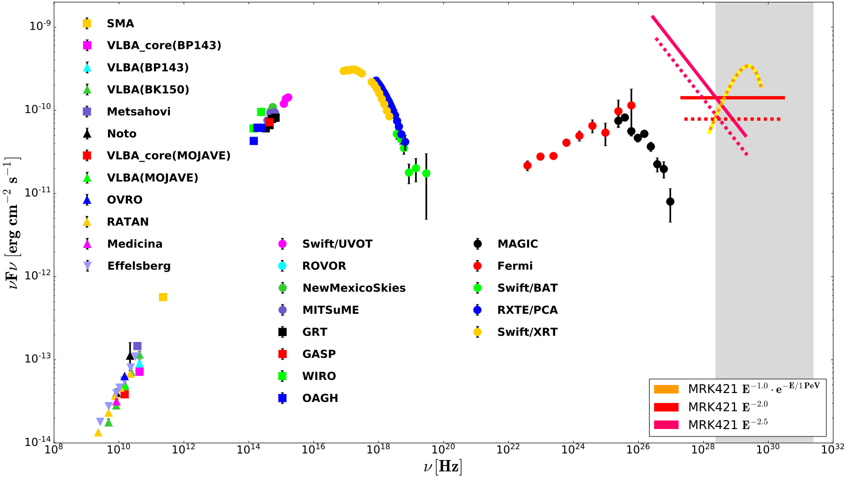
SED of Mrk 421 [21] and neutrino energy flux sensitivities [22]



VHE : 0.1-100 TeV

21. Adapted from Abdo et al, 2011, ApJ 736, 131. Raw-data table credit by David Paneque
22. HAWC 2014-2016 (last work) : solid line ; HAWC 2014-2017 (current work) : dotted line

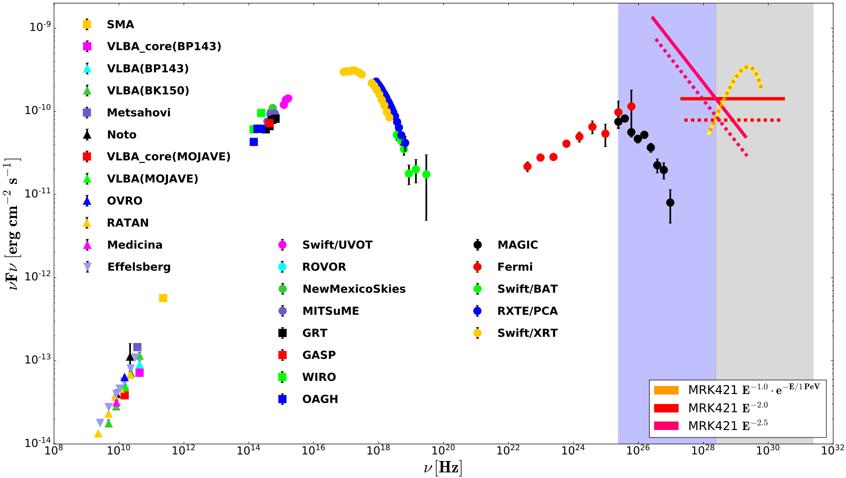
SED of Mrk 421 [21] and neutrino energy flux sensitivities [22]



UHE : >100 TeV (0.1-100 PeV drawn)

21. Adapted from Abdo et al, 2011, ApJ 736, 131. Raw-data table credit by David Paneque
22. HAWC 2014-2016 (last work) : solid line ; HAWC 2014-2017 (current work) : dotted line

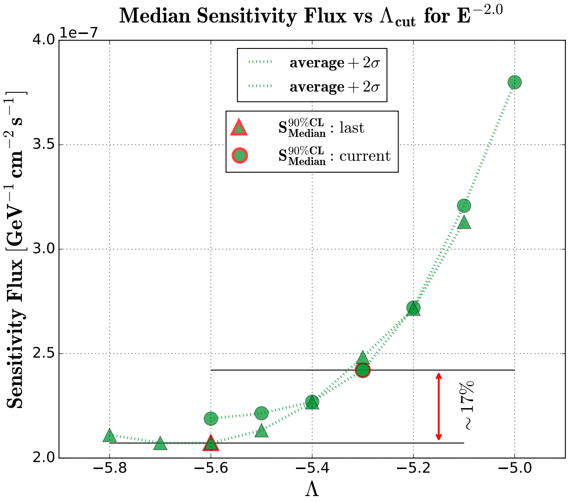
SED of Mrk 421 [21] and neutrino energy flux sensitivities [22]



VHE & UHE

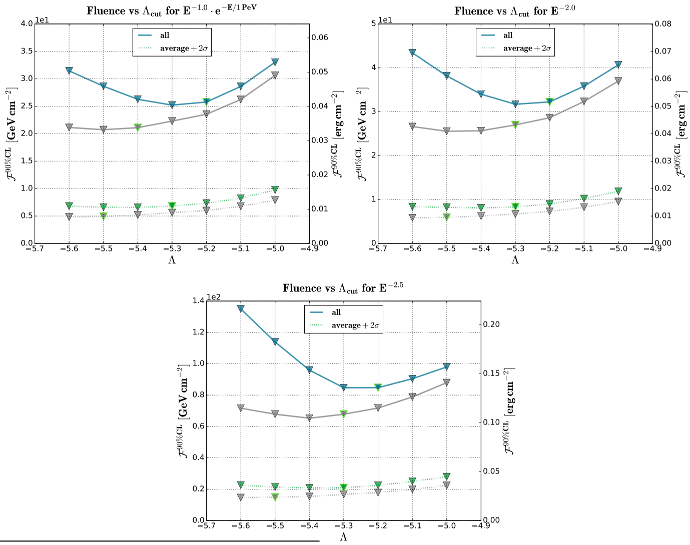
21. Adapted from Abdo et al, 2011, ApJ 736, 131. Raw-data table credit by David Paneque
22. HAWC 2014-2016 (last work) : solid line ; HAWC 2014-2017 (current work) : dotted line

Median sensitivity fluxes comparison [23] for last/current analysis.



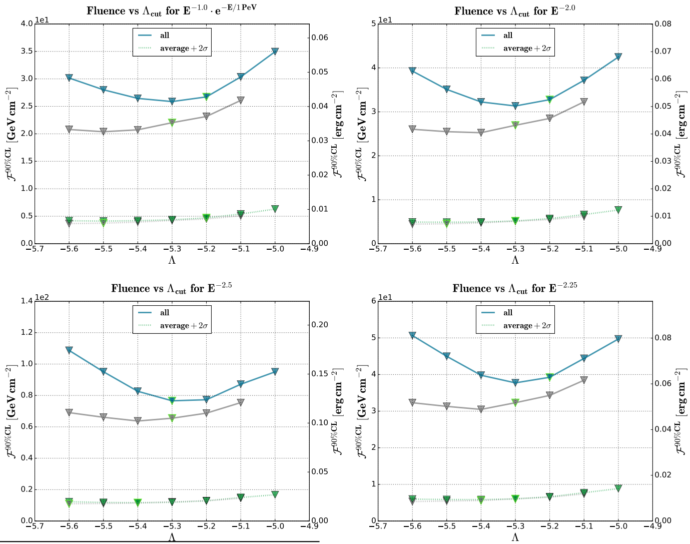
23. As wee see this have impact on final sensitivities (with factor of $\sim$ 17%) because of different optimum Λ cuts. Moreover, optimum $\Lambda = -5.3$ gives slightly better fluxes. If selected, it would give better sensetivities then.

Neutrino fluence sensitivities vs Λ for Mrk 421 [24]



24. Grey color and colored curves represent HAWC 2014-2016 and HAWC 2014-2017 periods respectively.

Neutrino fluence sensitivities vs Λ for Mrk 501 [25]



25. Grey color and colored curves represent HAWC 2014-2016 and HAWC 2014-2017 periods respectively.