Search for high-energy neutrino emission from Mrk 421 and Mrk 501 with the ANTARES neutrino telescope

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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.

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

Mixture : S + B

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

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

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 :** $P_S(x) = \underline{\text{spatial term}} \times \underline{\text{energy term}} \times \underline{\text{time term}} = \underline{P_S(\alpha)} \cdot \underline{P_S(E)} \cdot \underline{P_S(t)}$
- **B :** $P_B(x) = \underline{\text{spatial term}} \times \underline{\text{energy term}} \times \underline{\text{time term}} = \underline{P_B(\sin(\delta))} \cdot \underline{P_B(E)} \cdot \underline{P_B(t)}$

Test Statistics

as a product of all the event probability densities

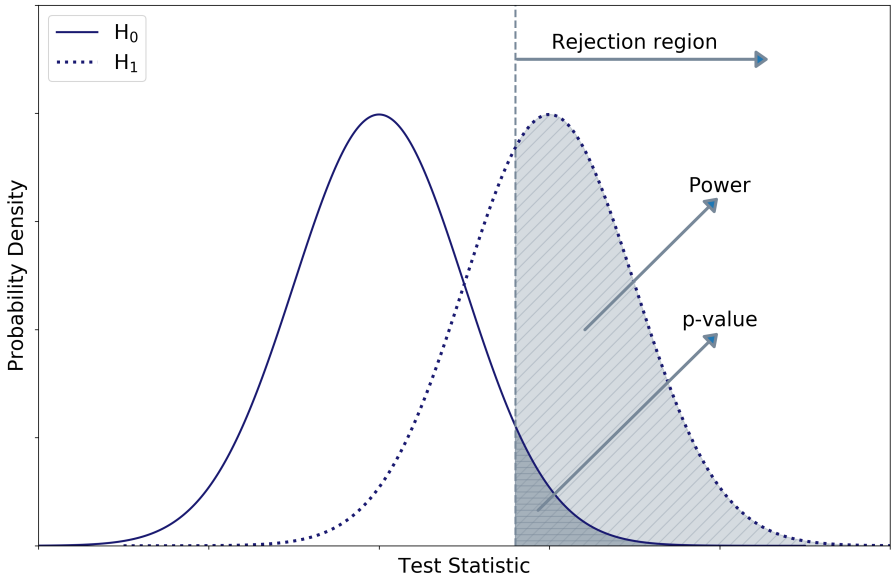
$$TS = 2\log\left[\frac{L^{max}(n_S)}{L(n_S = 0)}\right]$$

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

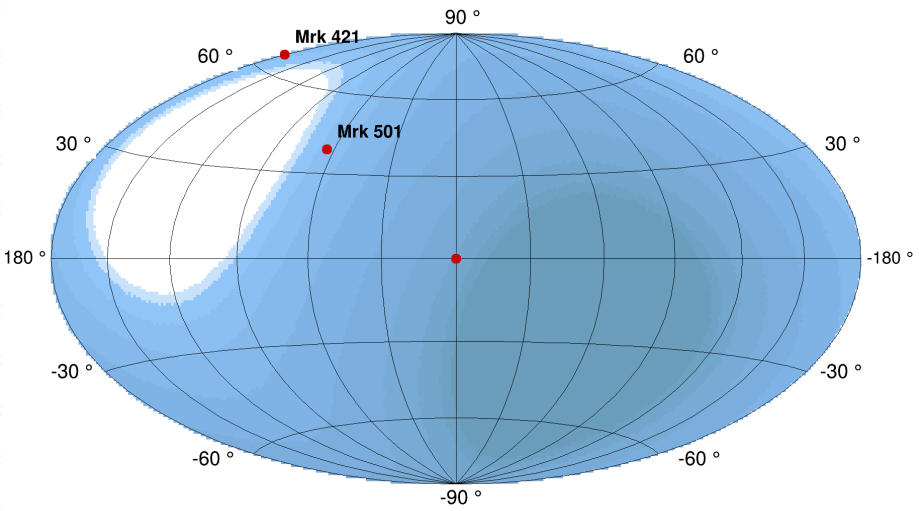
- 3×10^5 for **B**
- 3×10^4 for **S** (**1 .. up to 20 !**)

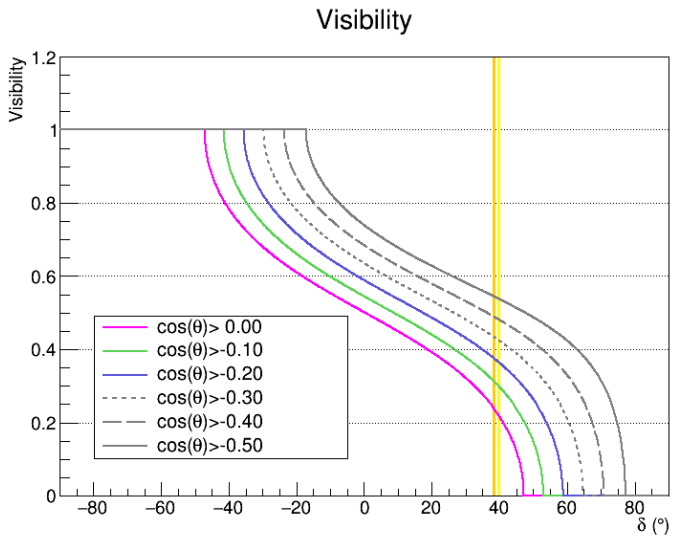
Test Statistics

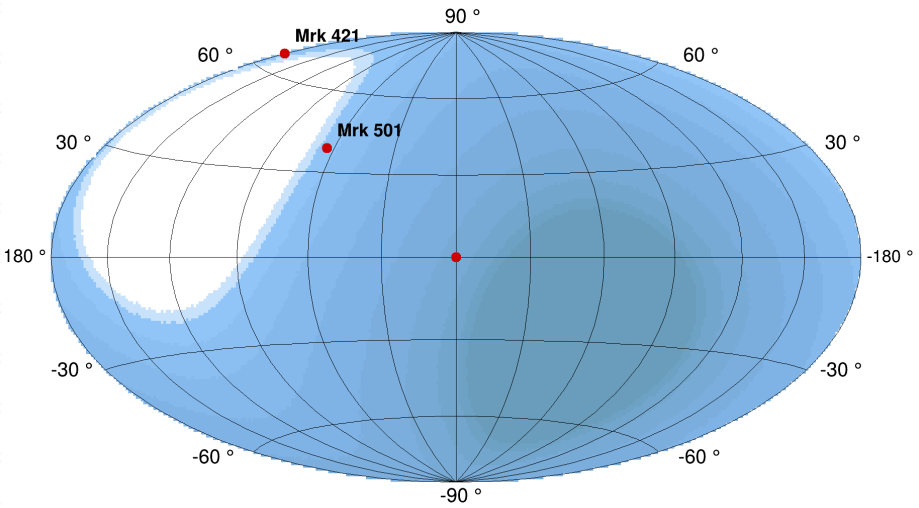
- **p-value** : determines how "likely" or "unlikely" the data with the true background-only hypothesis
  $\hookrightarrow$ the probability to yield $TS > TS_{observed}$
- **significance of a measurement** : determines by its **p-value**
  - Discovery Power at 3σ level for $p < 2.7 \cdot 10^{-3}$ with $TS > TS^{3\sigma}$
  - Discovery Power at 5σ level for $p < 5.7 \cdot 10^{-7}$ with $TS > TS^{5\sigma}$

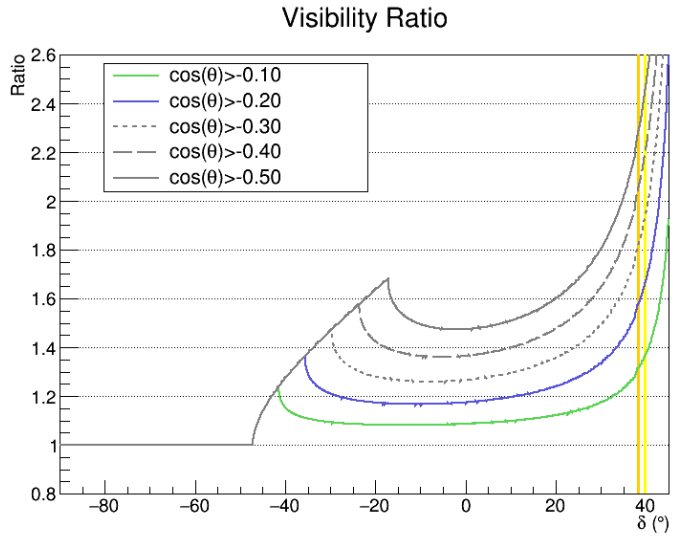


ANTARES Visibility

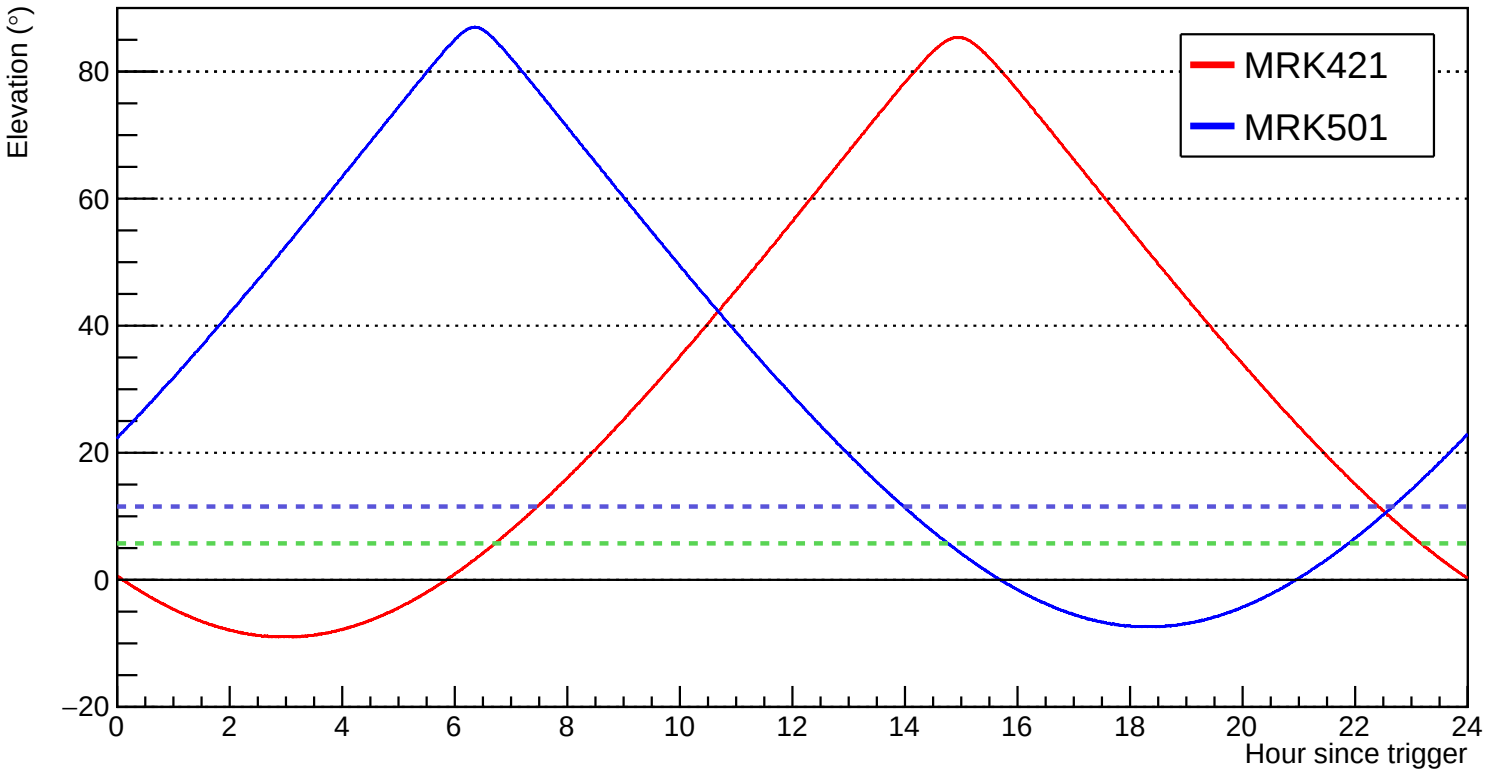








Elevation



- 5.74° for $\cos(\theta) > -0.1$
- 11.54° for $\cos(\theta) > -0.2$

HAWC LCs : paper → table of flare states

First official HAWC Light curves releases

"Daily monitoring of TeV γ-ray emission from Mrk 421, Mrk 501, and the Crab Nebula with HAWC"

- Abeysekara et al., Astrophys.J. 841 (2017) no.2, 100 (2017) arXiv:1703.06968 [astro-ph.HE] DOI:10.3847/1538-4357/aa729e
- 17-Month Crab/Mrk 421/Mrk 501 Lightcurves

Mrk 421 & Mrk 501 : Found clear variability on time scales of one day !
$\Rightarrow$ Extract the shape of the signal from the γ-ray LCs assuming the proportionality between γ-ray and ν fluxes

27/11/2014 - 19/04/2016
56988 - 57497

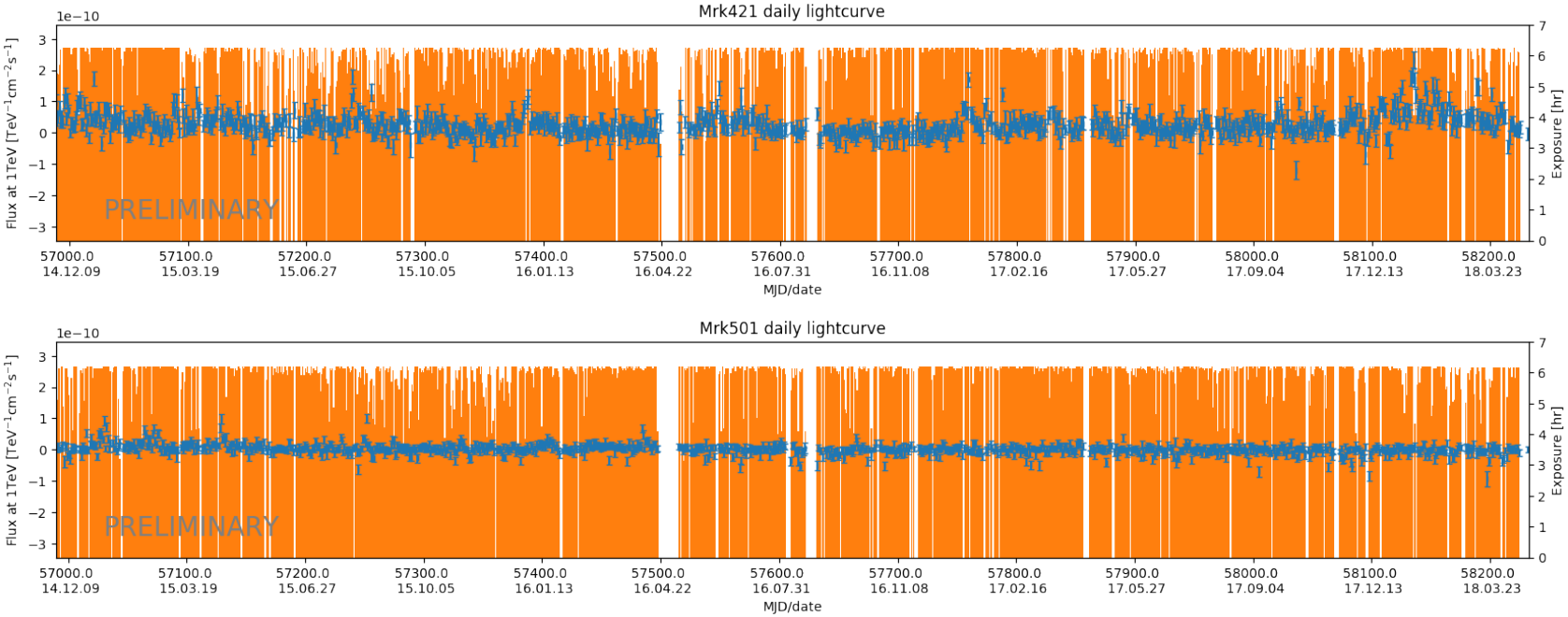
Mrk 421 & Mrk 501
dL = 134 Mpc, z = 0.031 & dL = 143 Mpc, z=0.033
two brightest and closest BL Lac objects known !

As the nearest blazars to Earth, both are excellent sources
to test the blazar-neutrino connection scenario, especially during flares
where time-dependent neutrino searches have a higher detection probability.

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

Period available :

26/11/2014 - 24/04/2018



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

1. Granted by HAWC collab. in July (after discussion with Prof. Ignacio Taboada at NEUTRINO 2018 in June)

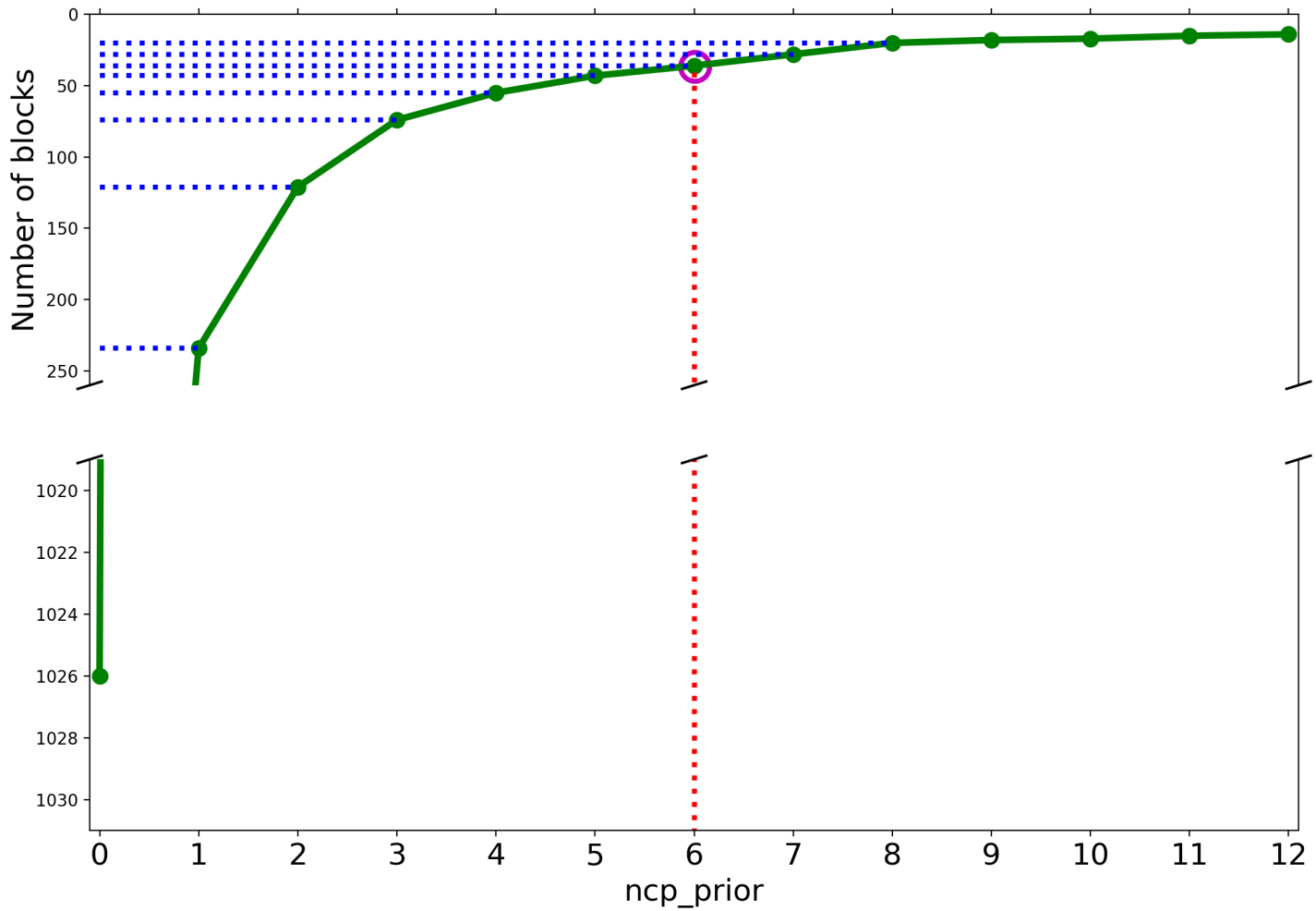
Bayesian blocks

Description

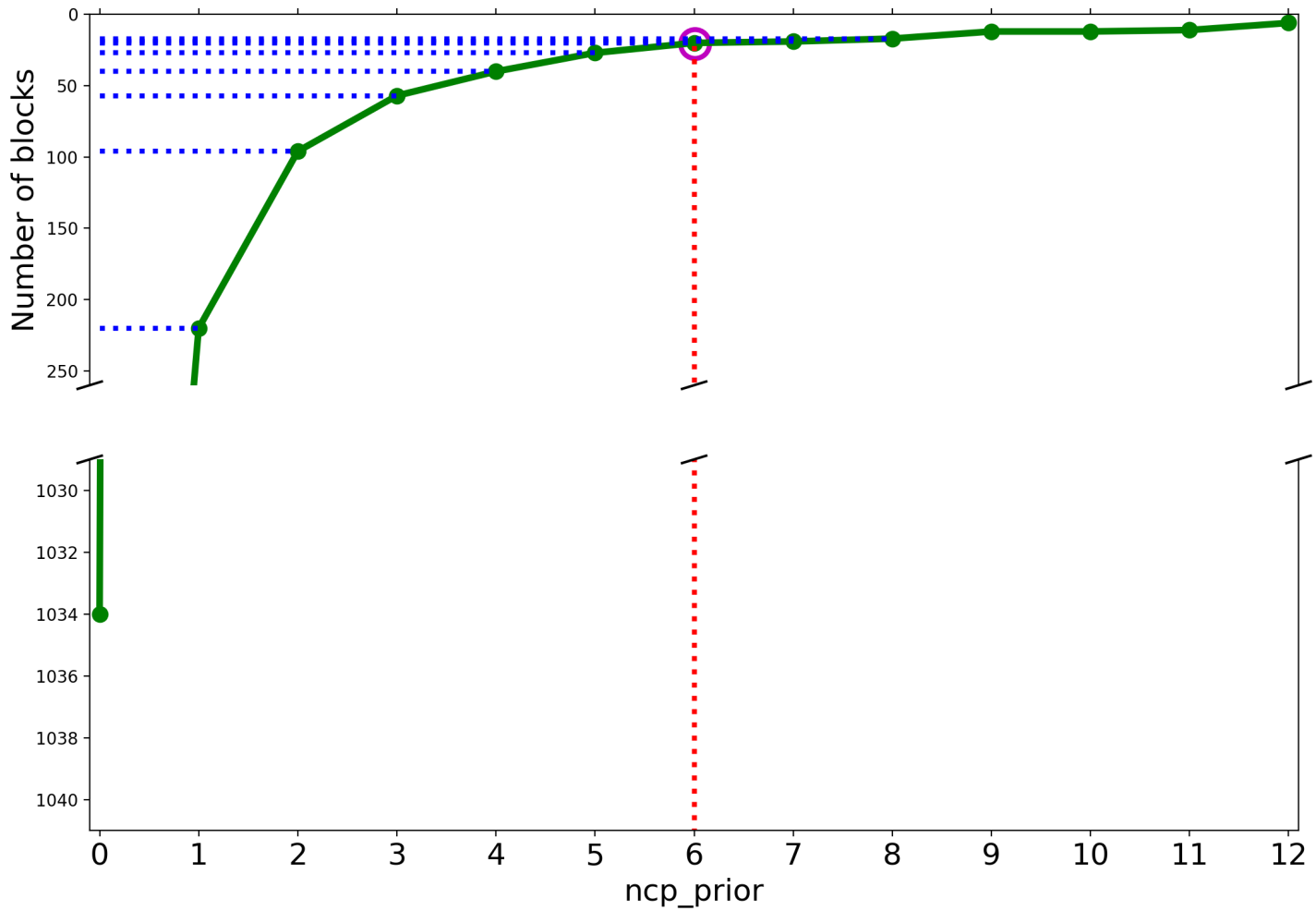
- If LC is variable, the **Bayesian blocks algorithm (Scargle et al. 2013)** can be applied to detect and characterize signals in noisy time series.
  ↪ Bayesian analysis helps to identify changes between flux state via finding change points at transition from one flux state to the next.

- 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 (they have founded it from simulations etc).
  ↪ This value I used also as a proper $\mathrm{ncp}_{\mathrm{prior}}$ for the analysis.
  ↪ Different $\mathrm{ncp}_{\mathrm{prior}}$ values have been tested, $\mathrm{ncp}_{\mathrm{prior}} = 6$ seems to be very reasonable.
  ↪ As axample, for Mrk 421 it has given almost the same block profile for first 17 months as from the paper.

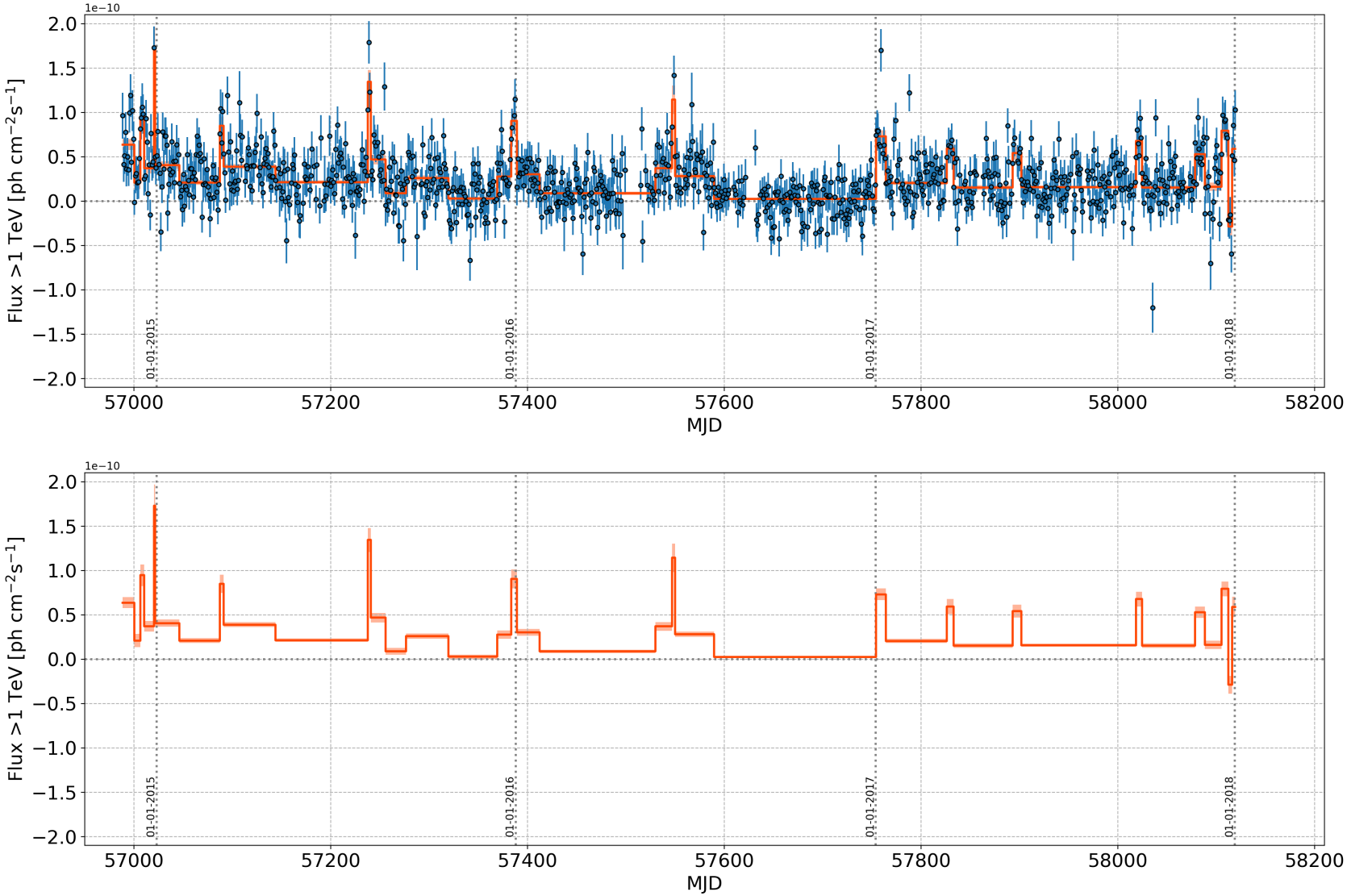
Bayesian blocks vs $\mathrm{ncp}_{\mathrm{prior}}$: Mrk 421



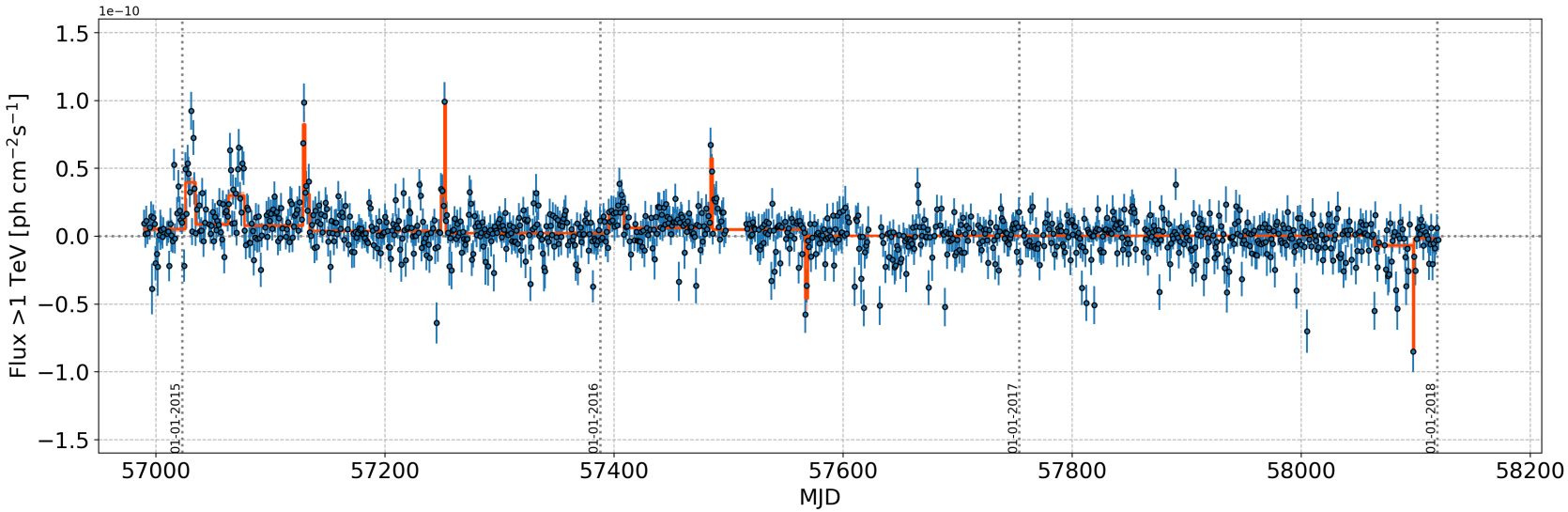
Bayesian blocks vs $\mathrm{ncp}_{\mathrm{prior}}$: Mrk 501

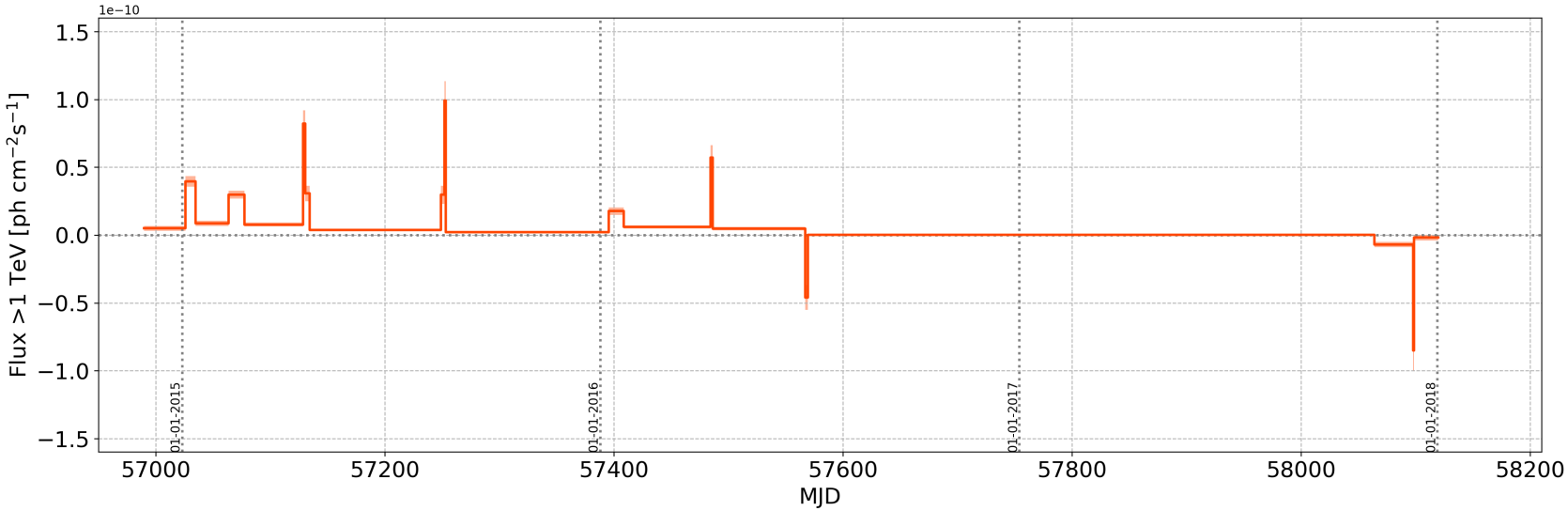


Bayesian Blocks : Mrk 421

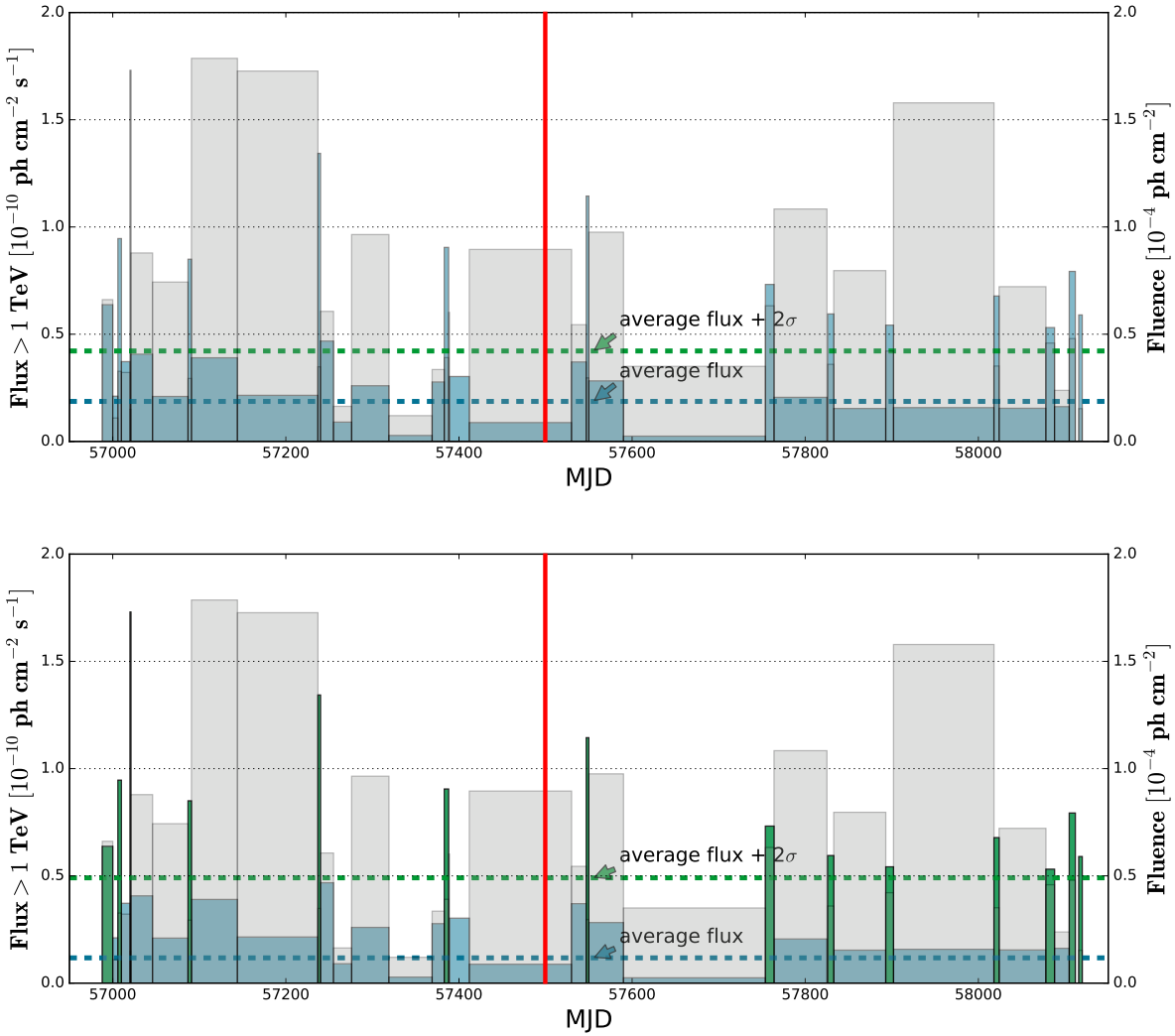


Bayesian Blocks : Mrk 501



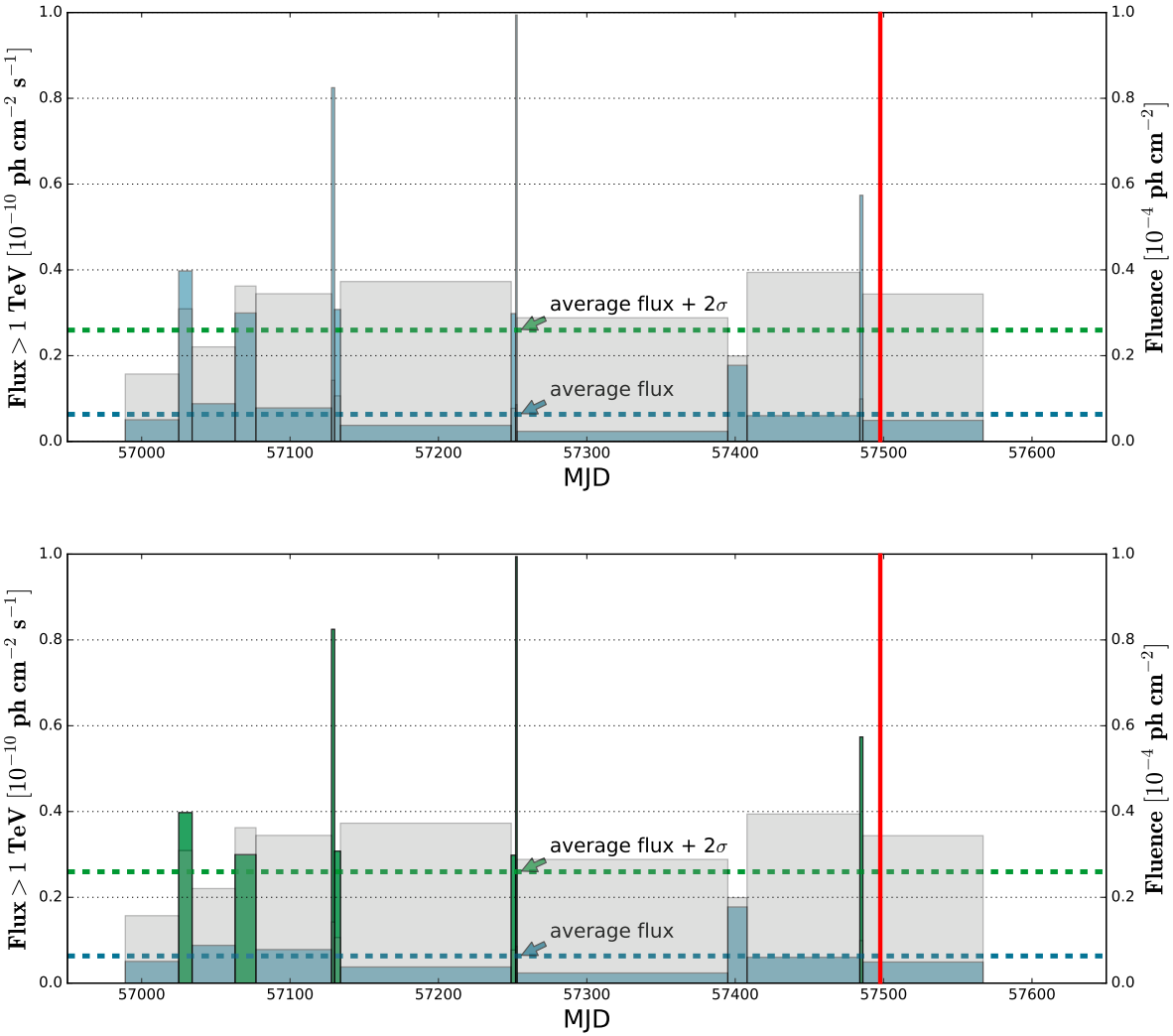


Flare states for Mrk 421 [2]



2. Red line represents the edge of the last analysis

Flare states for Mrk 501 [3]



3. Red line represents the edge of the last analysis

DATA/MC : last analysis

The ANTARES data set period :

- November 26$^{\text{th}}$, 2014 - April 20$^{\text{th}}$ [MJD : 56988-57497]
  $\hookrightarrow$ covering the same period of observation as HAWC.
- Lead to effective detector livetime of 503.7 days [1.379 y]

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

Location of DATA and MC files :

DATA :

- `/sps/km3net/users/antprod/data/Reprocessing_2016_05/`
- `/hpss/in2p3.fr/group/antares/SeaTray/prod_2017-04-03/Line12/sea/2016/12/`

MC :

- ν : `/sps/km3net/users/antprod/mc/rbr_v3_QE/complete/` [$\leq$2015]
- ν : `/hpss/in2p3.fr/group/antares/mc/rbr/v4/reco/AntDST/` [=2016]
- μ : `/sps/km3net/users/antprod/mc/rbr_v3_QE/complete/` [$\leq$2015]
- μ : `/hpss/in2p3.fr/group/antares/mc/rbr/v4/reco/mu_v3/AntDST/` [=2016]

DATA/MC : current analysis

The ANTARES data set period :

- November 27$^{\text{th}}$, 2014 - January 1$^{\text{st}}$, 2018 [MJD : 56988-58119] $\rightarrow$ Mrk 421
  November 28$^{\text{th}}$, 2014 - June 28$^{\text{th}}$, 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 :
  Mrk 421 : 1099.93 days [3.009 y] (last : 503.7 days [1.379 y])
  Mrk 501 : 561.55 days [1.537 y] (last : 503.7 days [1.379 y])

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

Location of DATA and MC files :

DATA :

- `/hpss/in2p3.fr/group/antares/SeaTray/prod_2018-02-01/Line12/sea/`

MC $\nu|\mu$:

- `/hpss/in2p3.fr/group/antares/mc/rbr/v4/reco/final/AntDST/`

Run selection

Runs are selected if the conditions below are fulfilled :

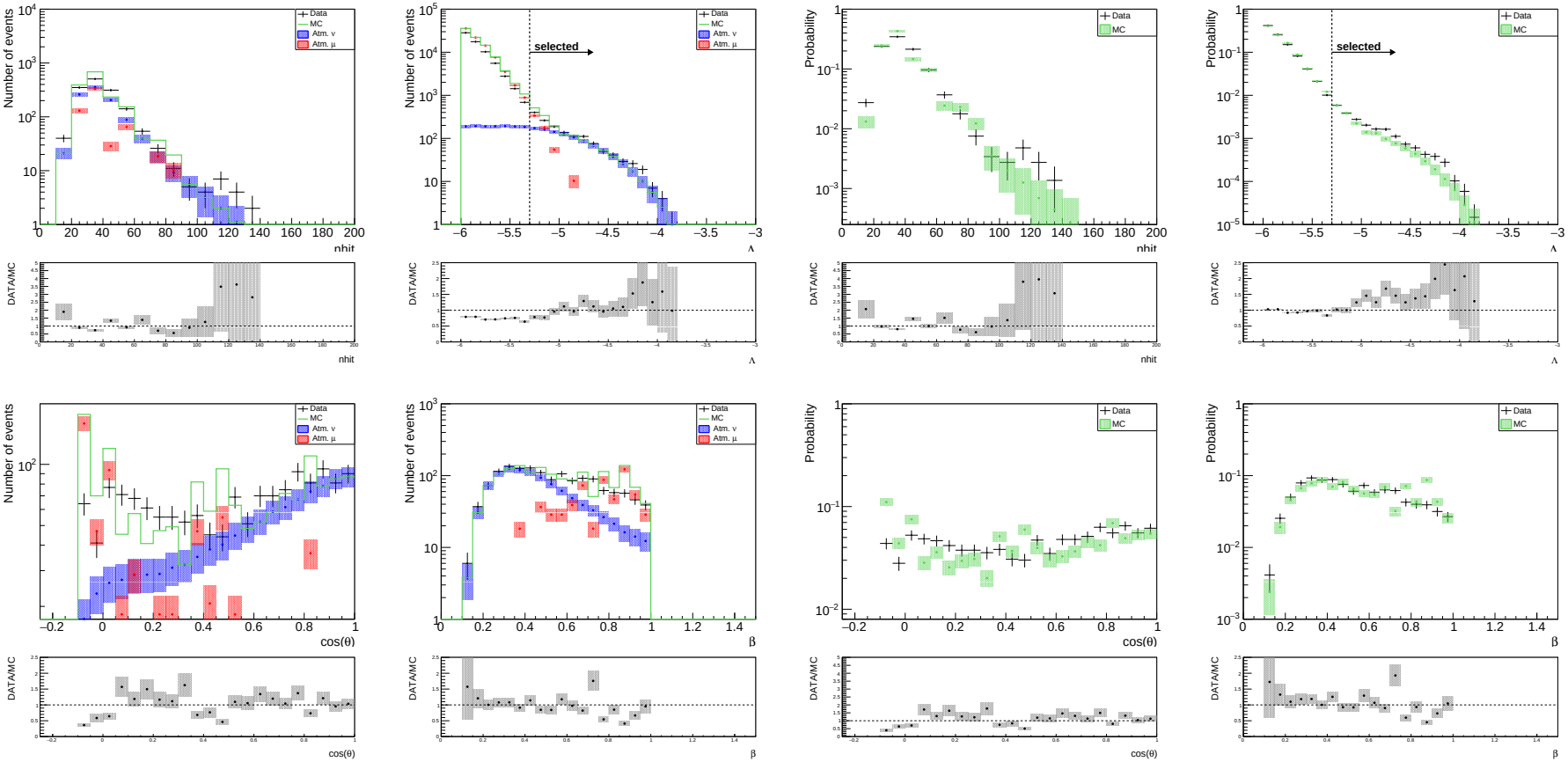
- QualityBasic $>= 1$
- SCAN $! = 1$
- Sparking $! = 1$ (Additional observed sparking runs are removed)

Effective detector livetime | MC-complete livetime
Mrk 421 : 1099.93 d [3.009 y] | 993.83 d [2.721 y]
Mrk 501 : 561.55 d [1.537 y] | 462.13 d [1.265 y]
↪ Last analysis : 503.7 d [1.379 y] | 332.8 days [0.911 y]

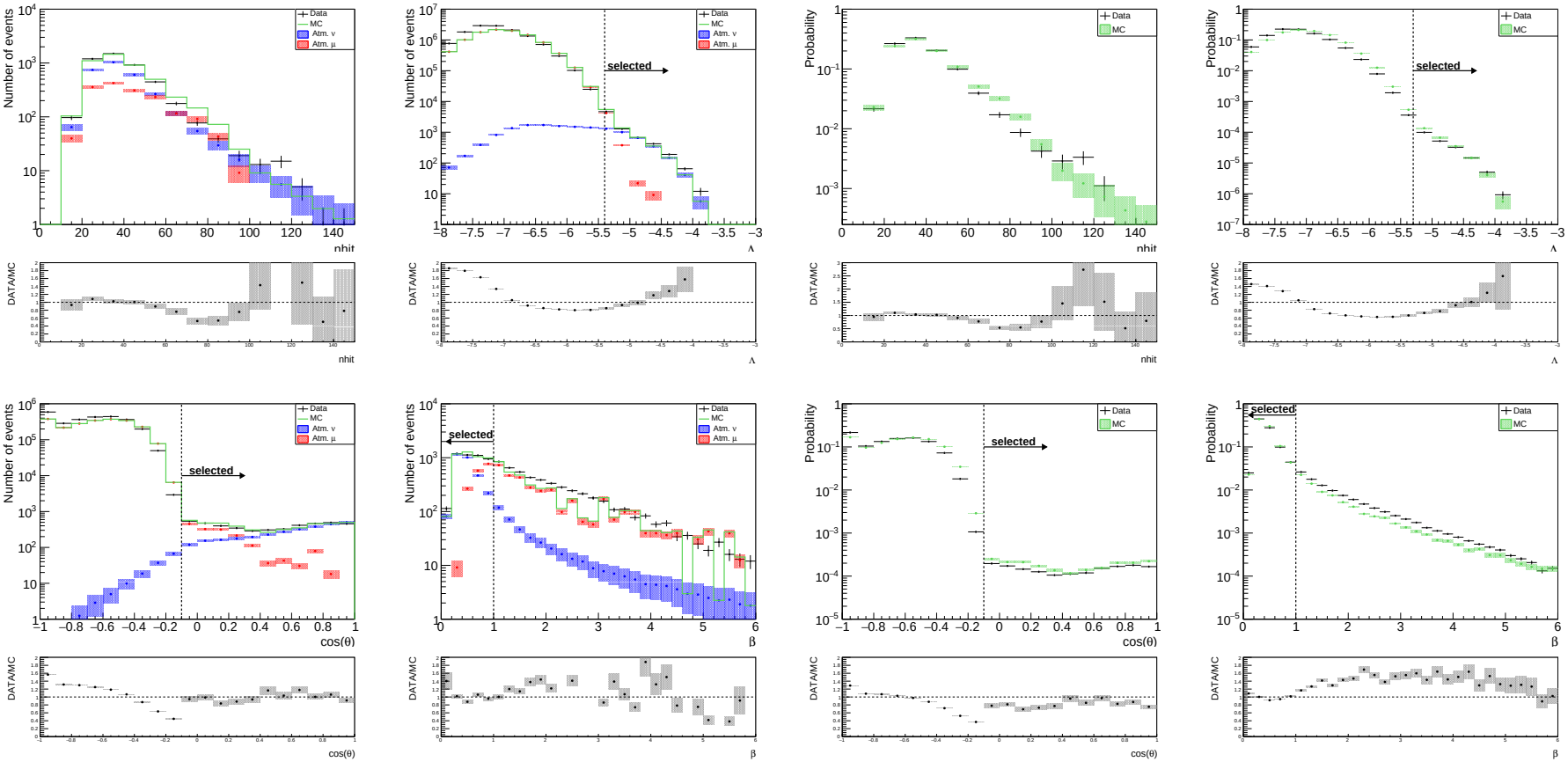
RESCALE :
The livetime of available complete MC is scaled up to the livetime in DATA !

Significant amount of data should be not taken if consider only DATA-MC complete runs. Moreover, some high peaks fall into the period of incomplete MC runs and their removal from the analysis is leading to vast decrease of the discovery potential.

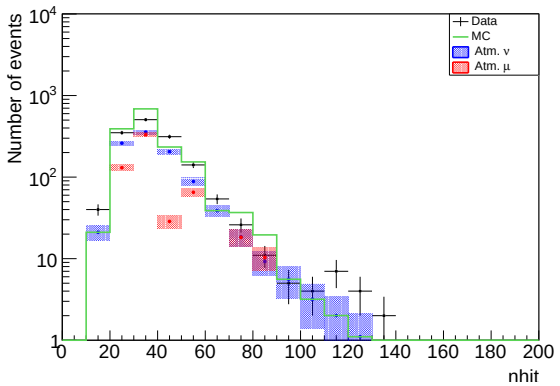
DATA/MC agreement : last analysis

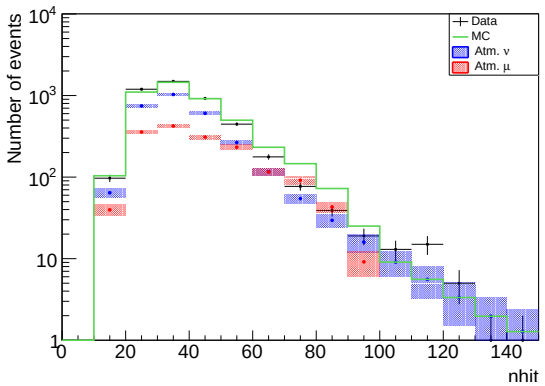


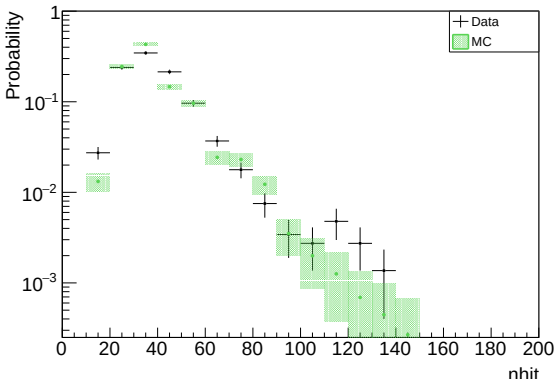
DATA/MC agreement : current analysis

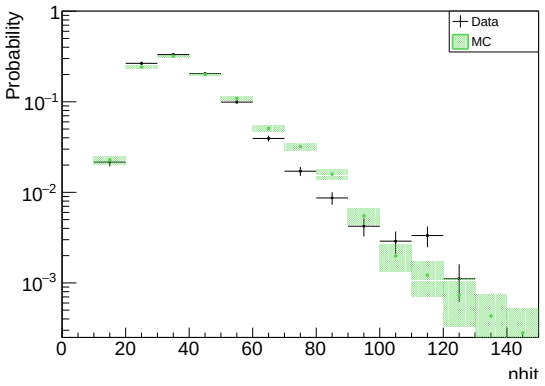


DATA/MC agreement : last/current analyzes comparison for nhit

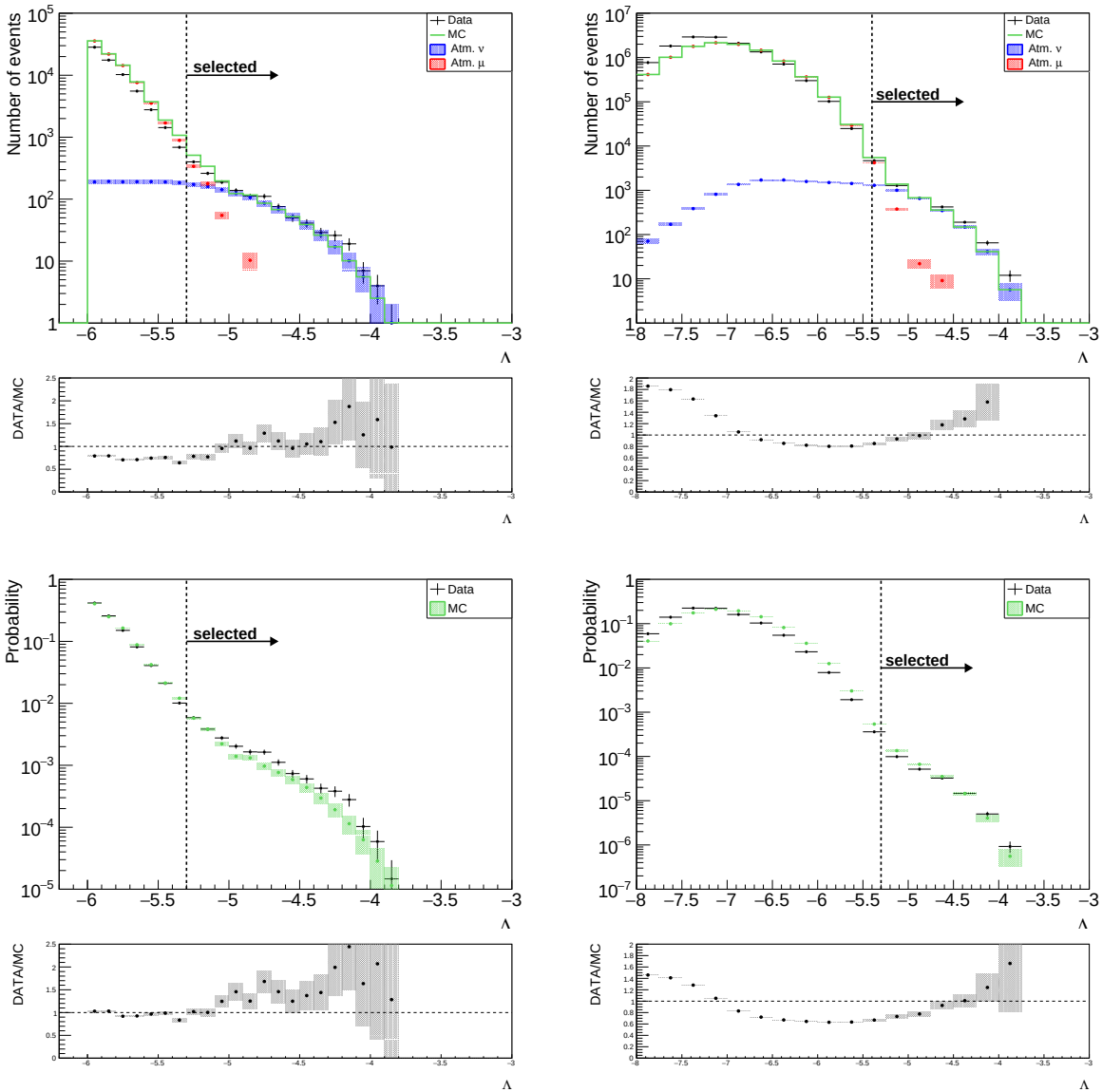




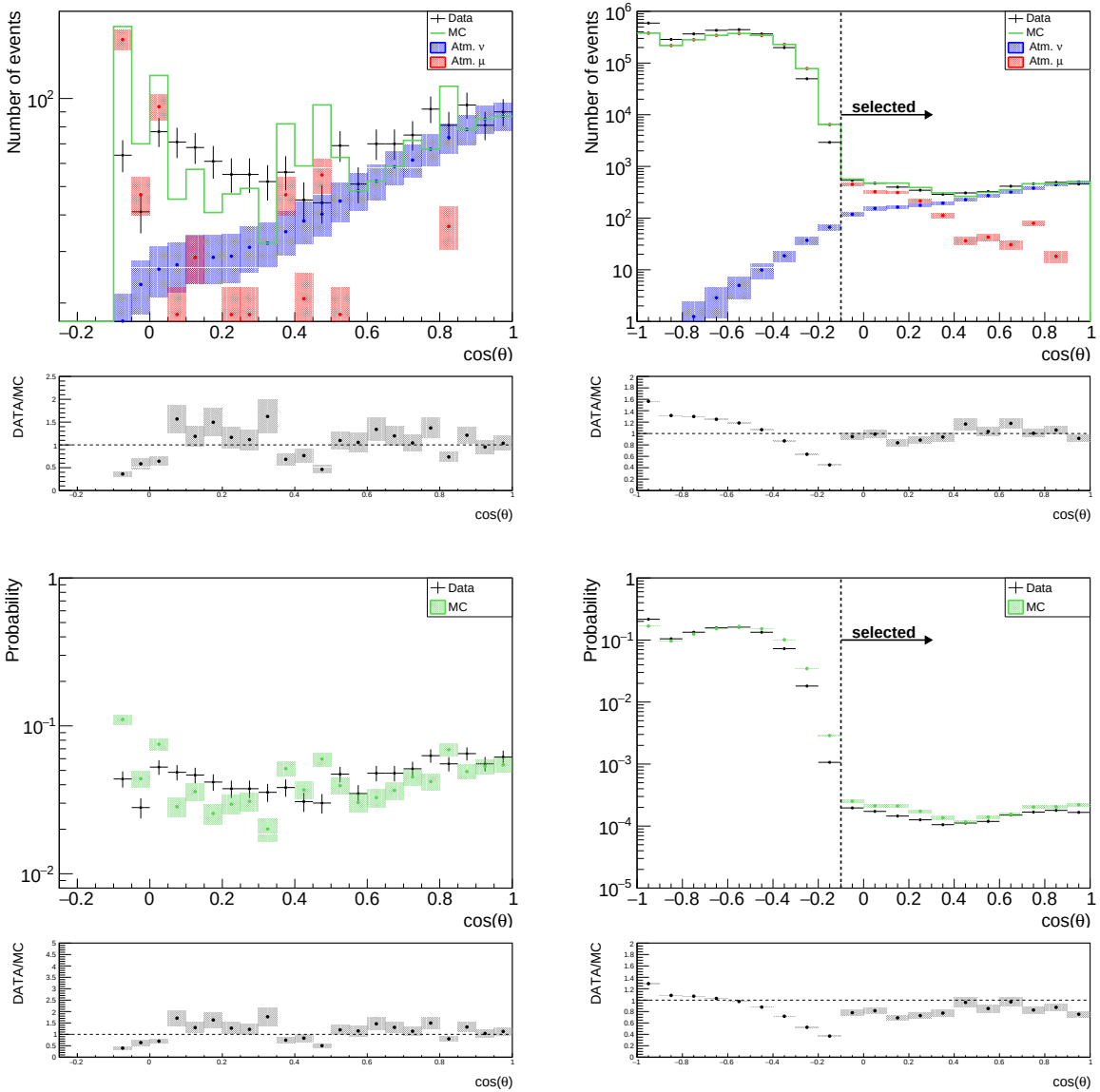




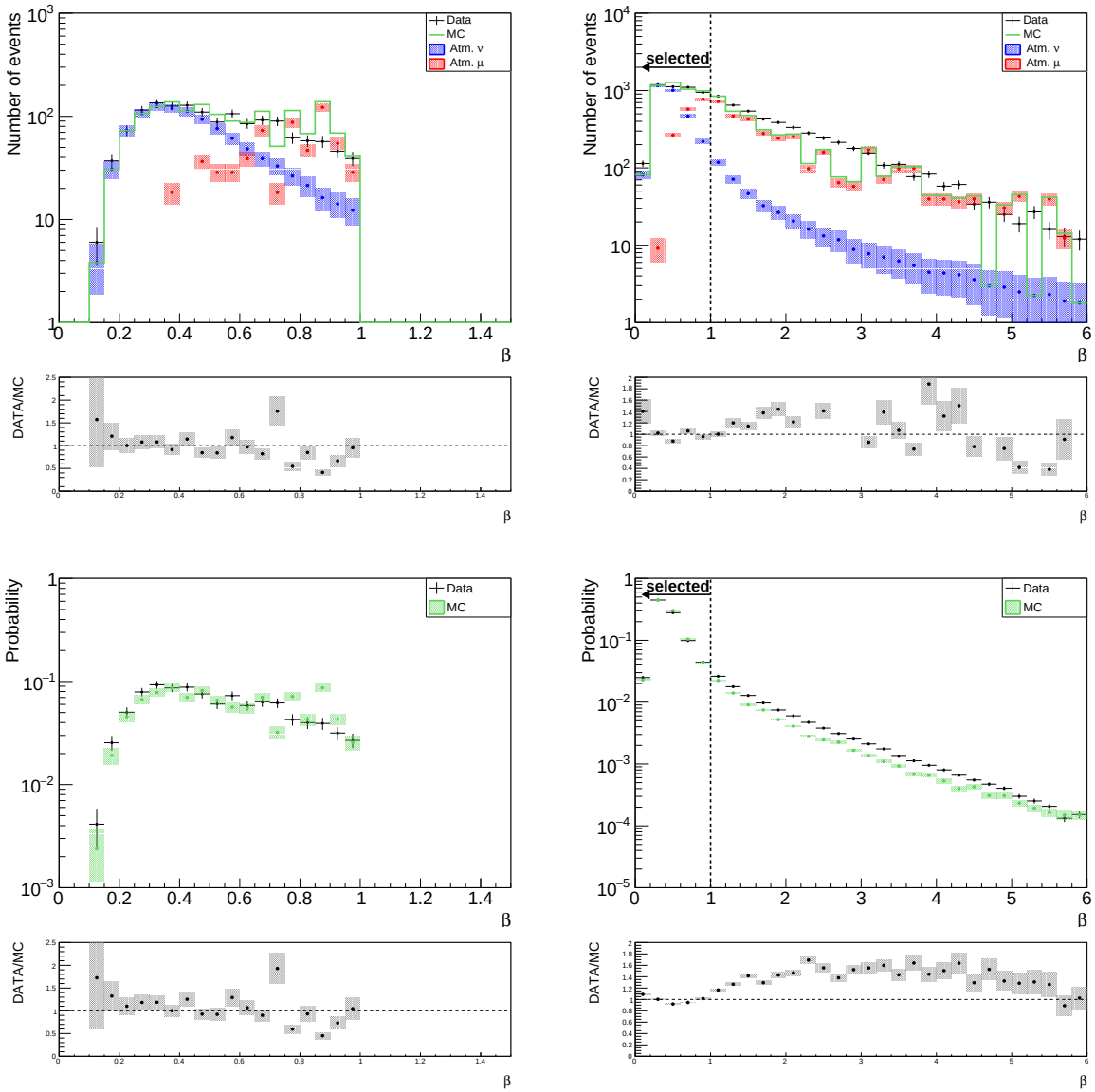
DATA/MC agreement : last/current analyzes comparison for Λ_{cut}



DATA/MC agreement : last/current analyzes comparison for cos(θ)



DATA/MC agreement : last/current analyzes comparison for β



Progress status : up to now

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* + 1σ~~
  - higher *average* + 2σ
- 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

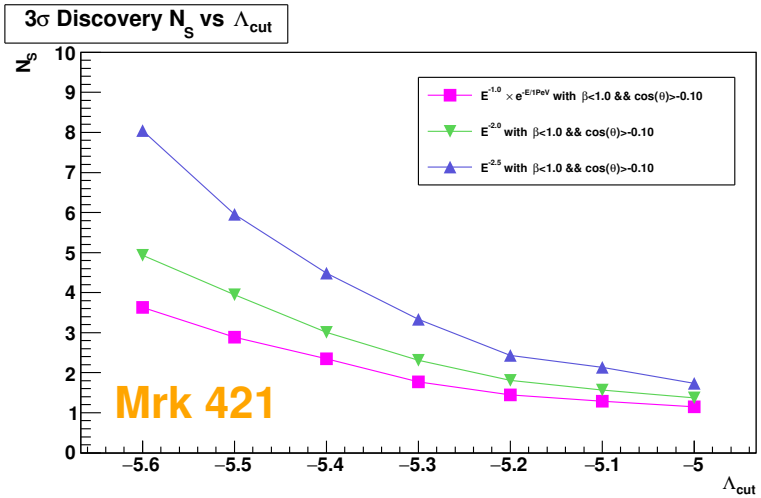
- Mrk 421 : 27/11/2014 - 01/01/2018 [56988-58119]
- Mrk 501 : 28/11/2014 - 28/06/2016 [56989-57567]

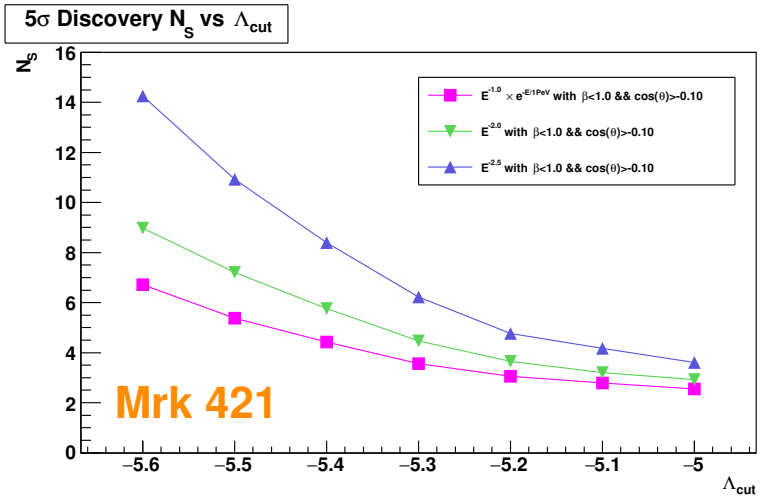
Progress status : up to now

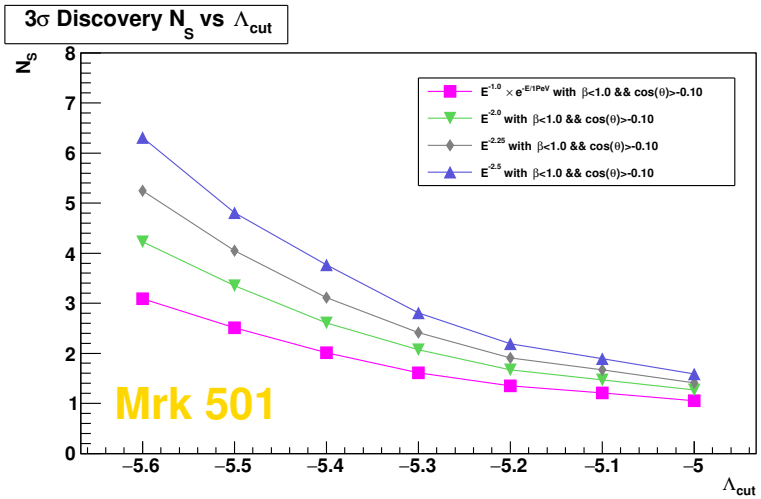
Calculated

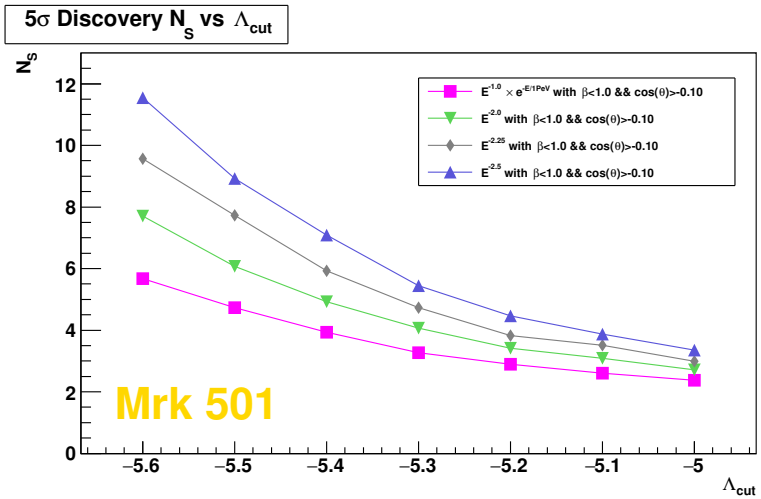
- YES $\rightarrow$ $3\sigma|5\sigma$ Discovery signals N_S
- YES $\rightarrow$ Acceptances
- YES $\rightarrow$ $3\sigma|5\sigma$ Discovery Fluxes
- YES $\rightarrow$ Median Sensitivity Fluxes at 90%CL
- YES $\rightarrow$ Model Discovery Potential
- YES $\rightarrow$ Sensitivities on neutrino energy flux at 90%CL
- YES $\rightarrow$ Sensitivities on neutrino fluence at 90%CL

Discovery signals [4], example for case of *all flares*



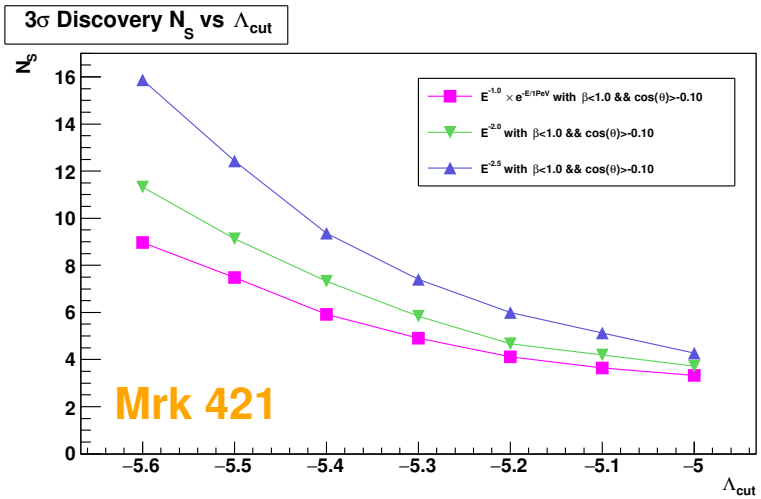


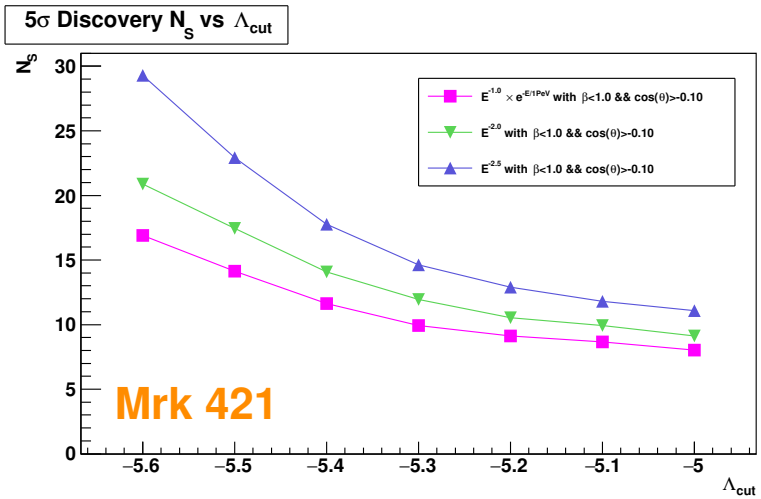


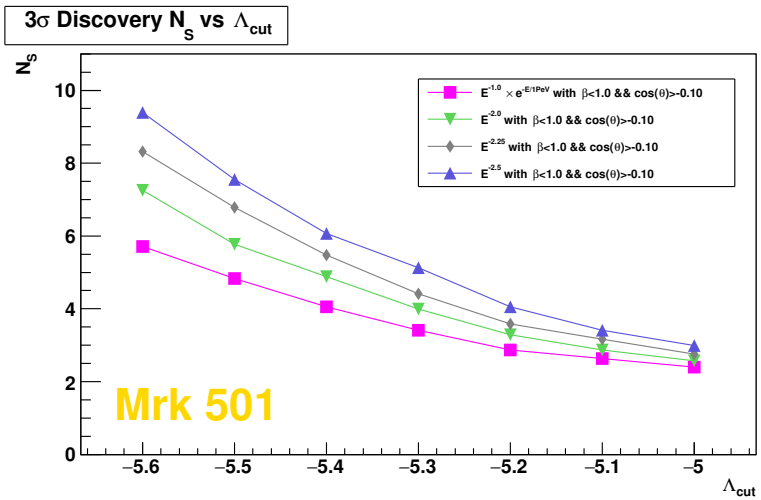


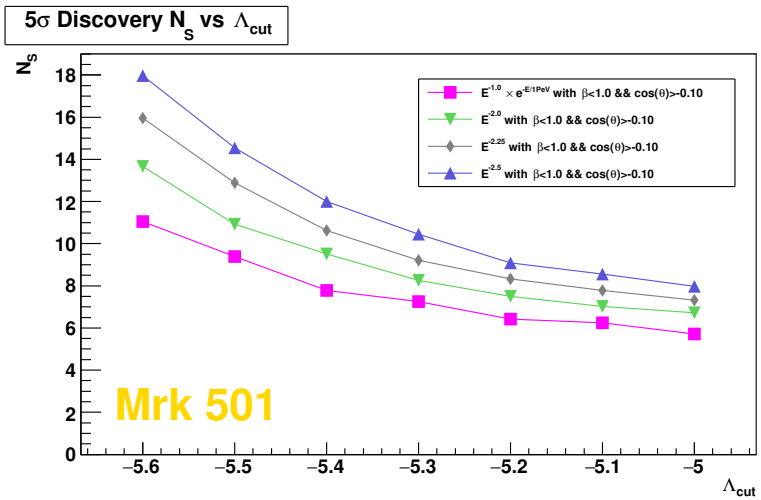
4. Values not scaled for case of all flares

Discovery signals [5], example for case of *average flux + 2σ*



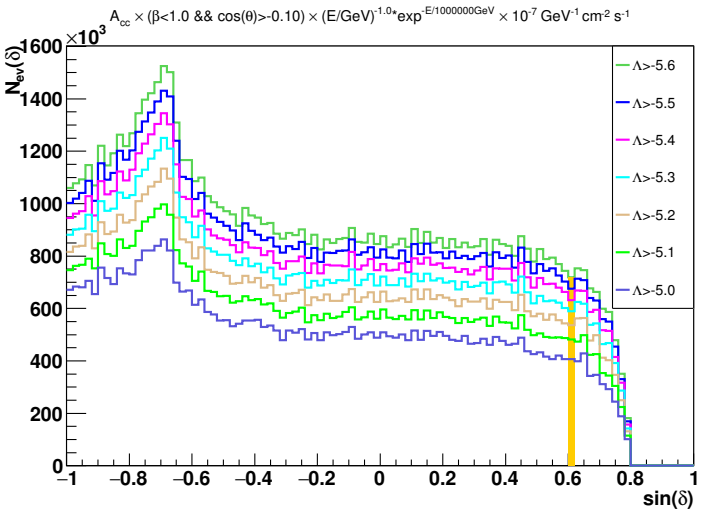


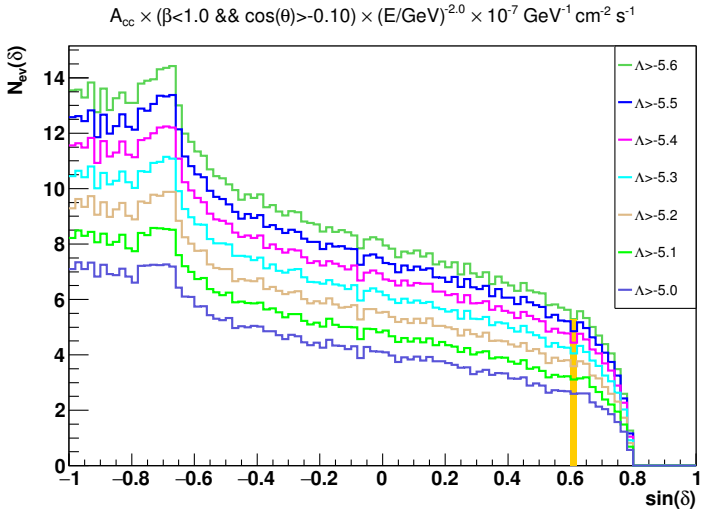


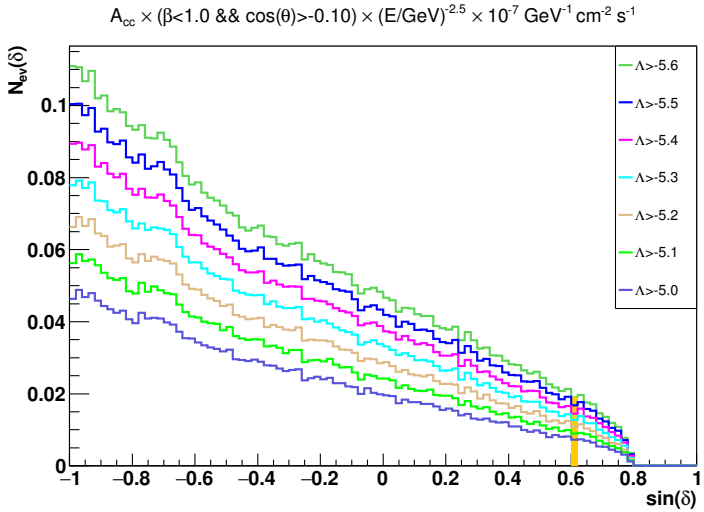


5. Values scaled for case of *average flux + 2σ* => values shown that are required for whole T_{flare} period

Acceptance vs Λ, example for Mrk 421 [6]

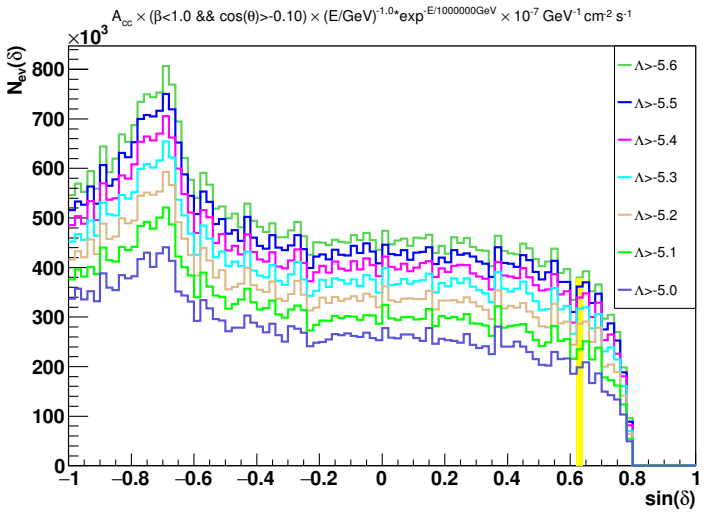


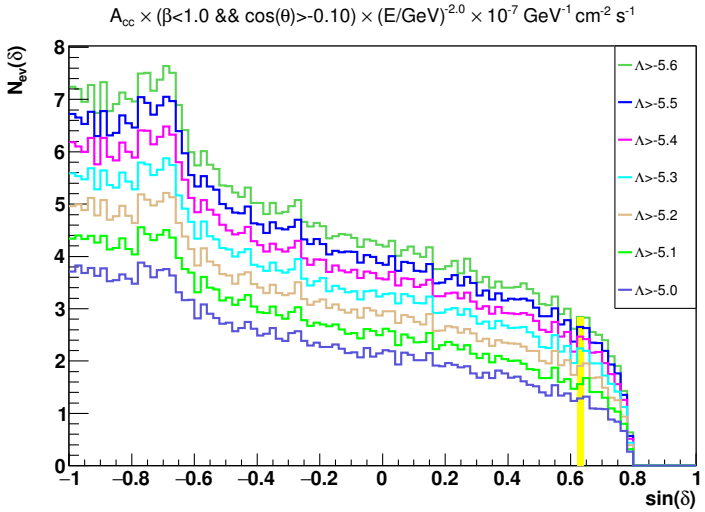


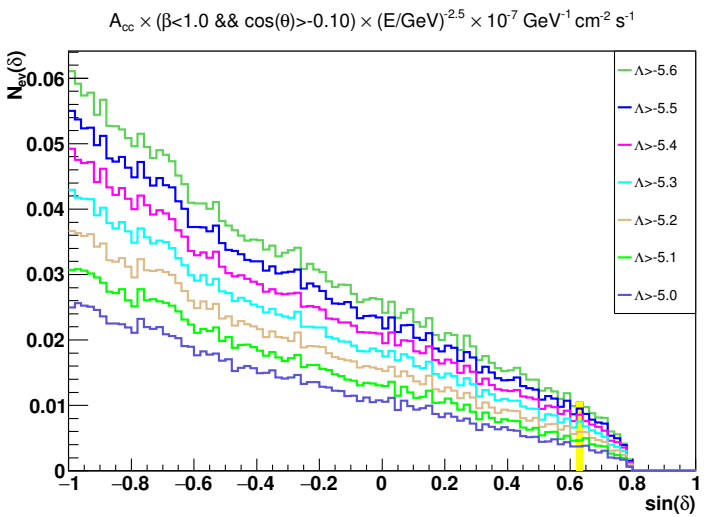


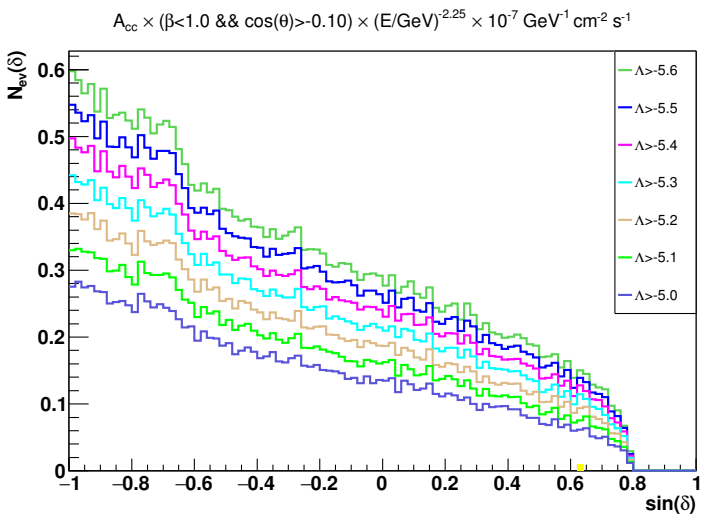
6. The position of the Mrk 421 is colored by orange

Acceptance vs Λ, example for Mrk 501 [7]



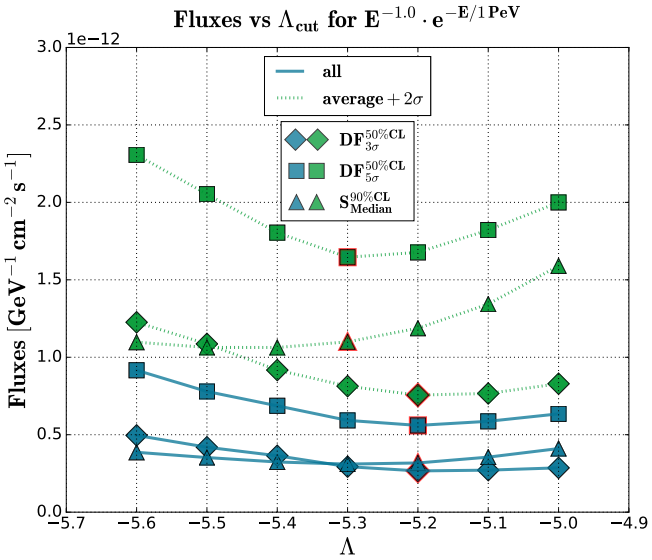


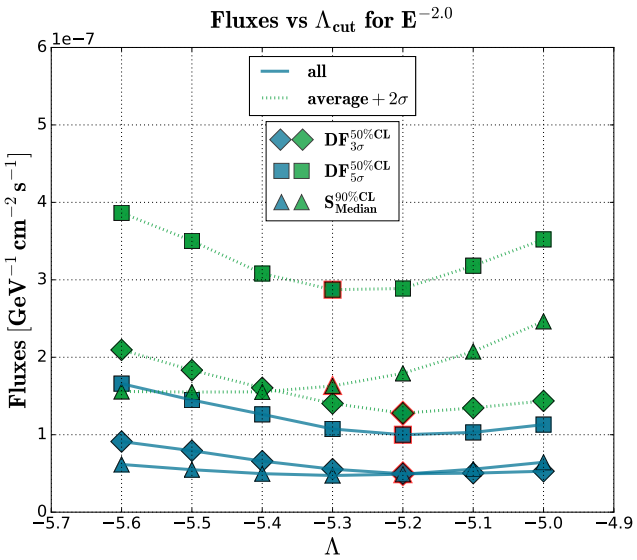


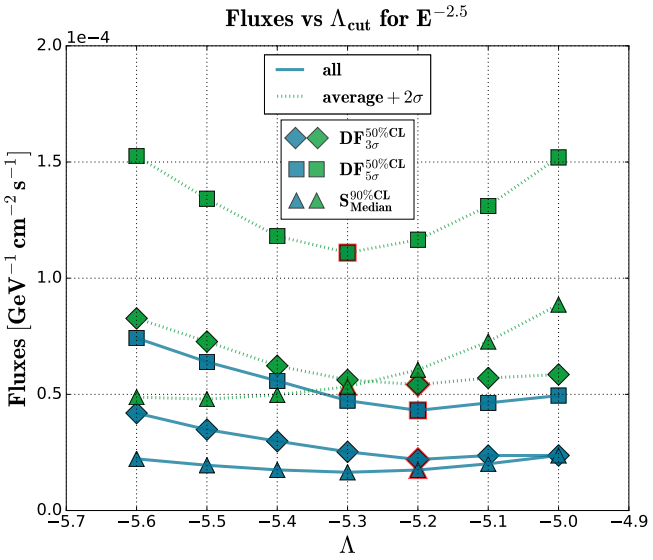


7. The position of the Mrk 501 is colored by yellow

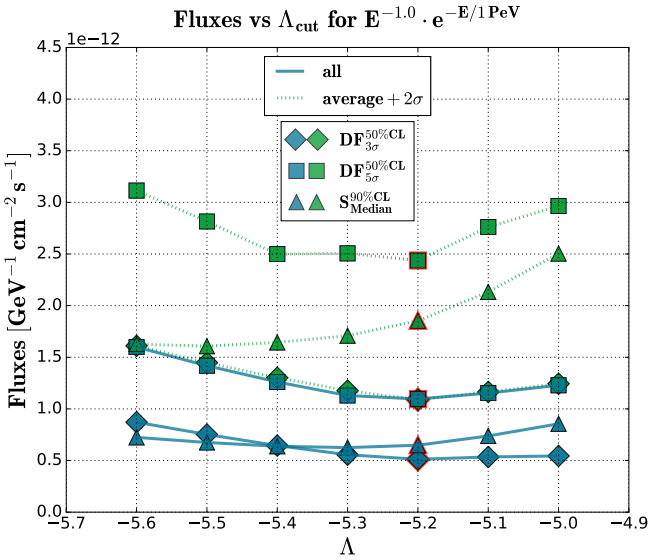
Fluxes for Mrk 421

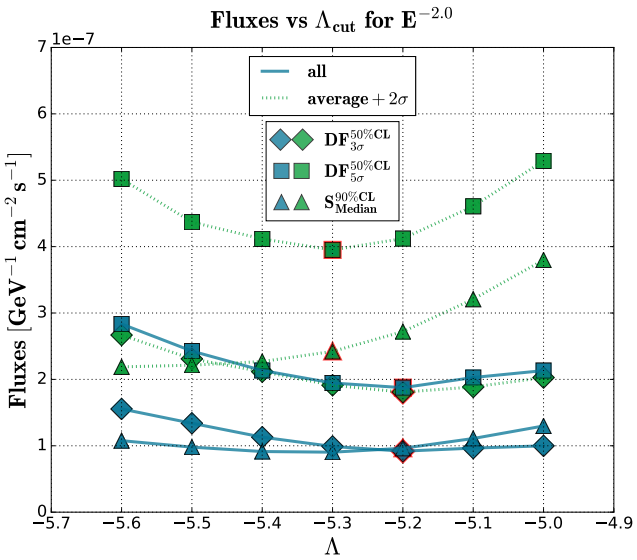


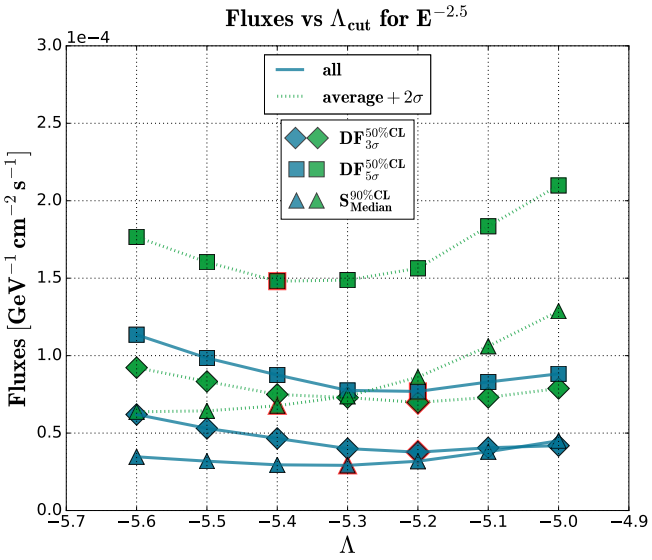


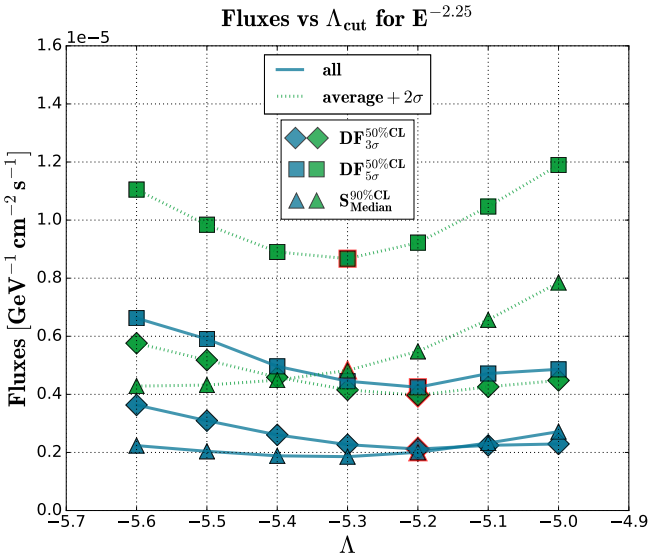


Fluxes for Mrk 501

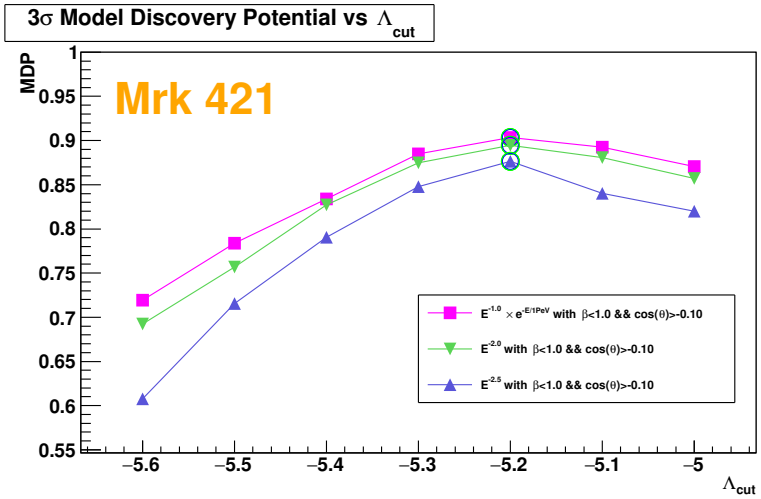


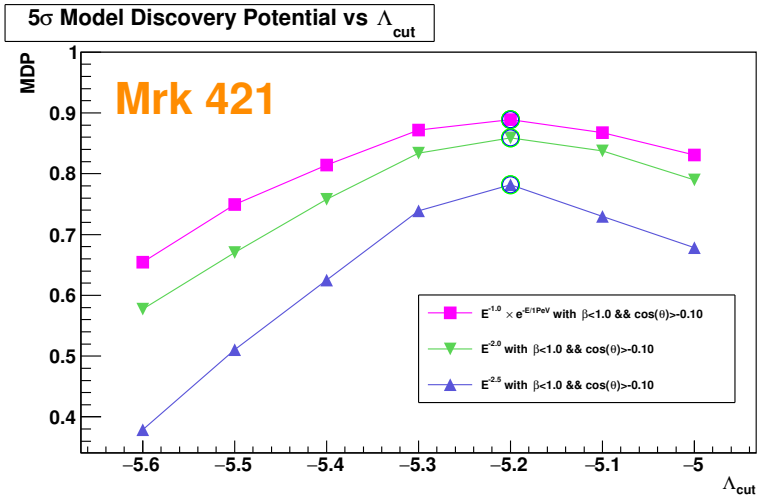


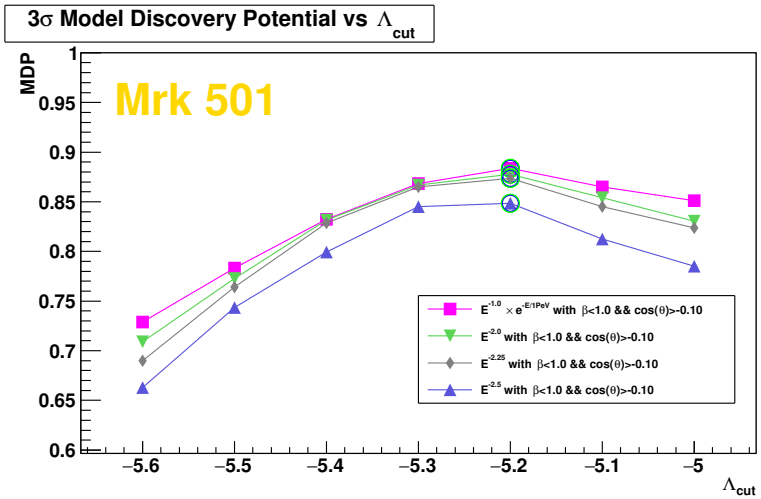


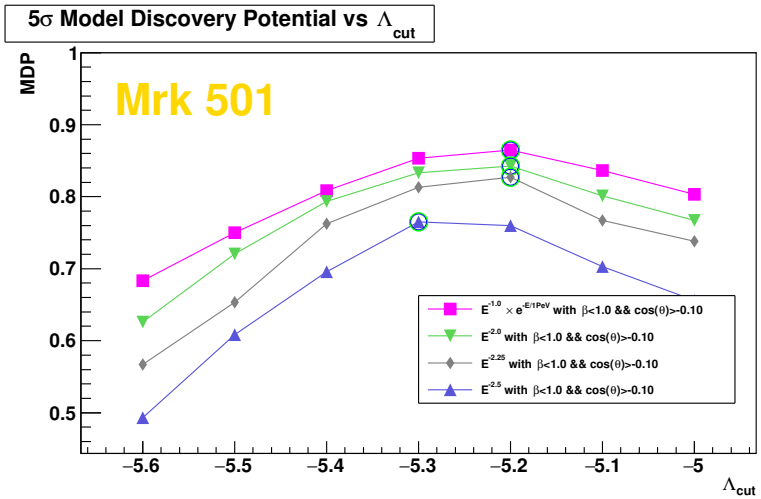


MDP, example for case of *all flares*

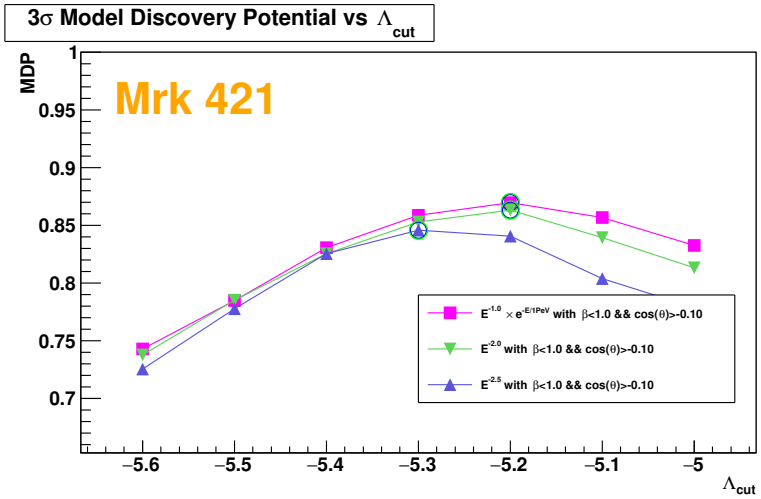


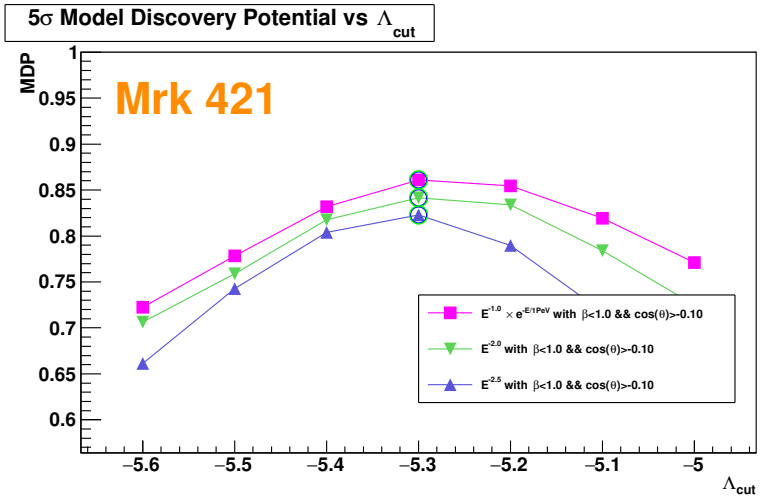


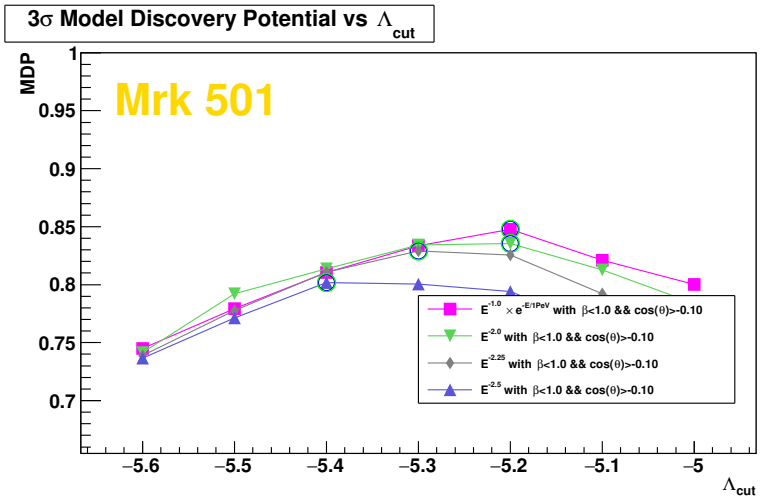


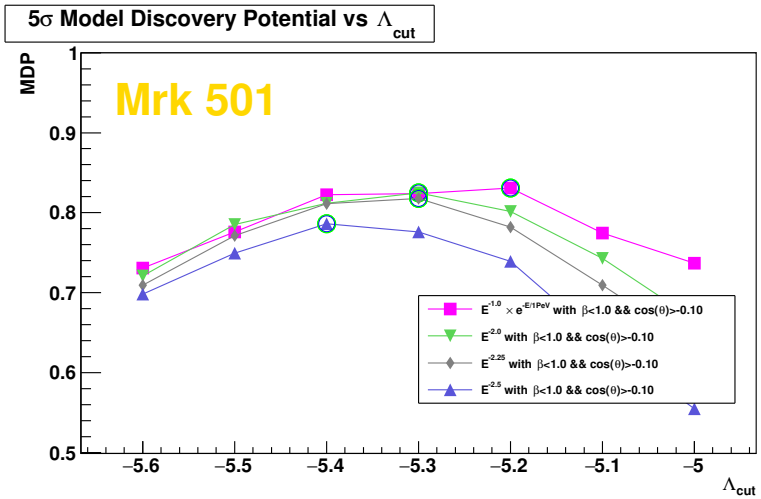


MDP, example for case of *average flux + 2σ*









Sensitivities

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

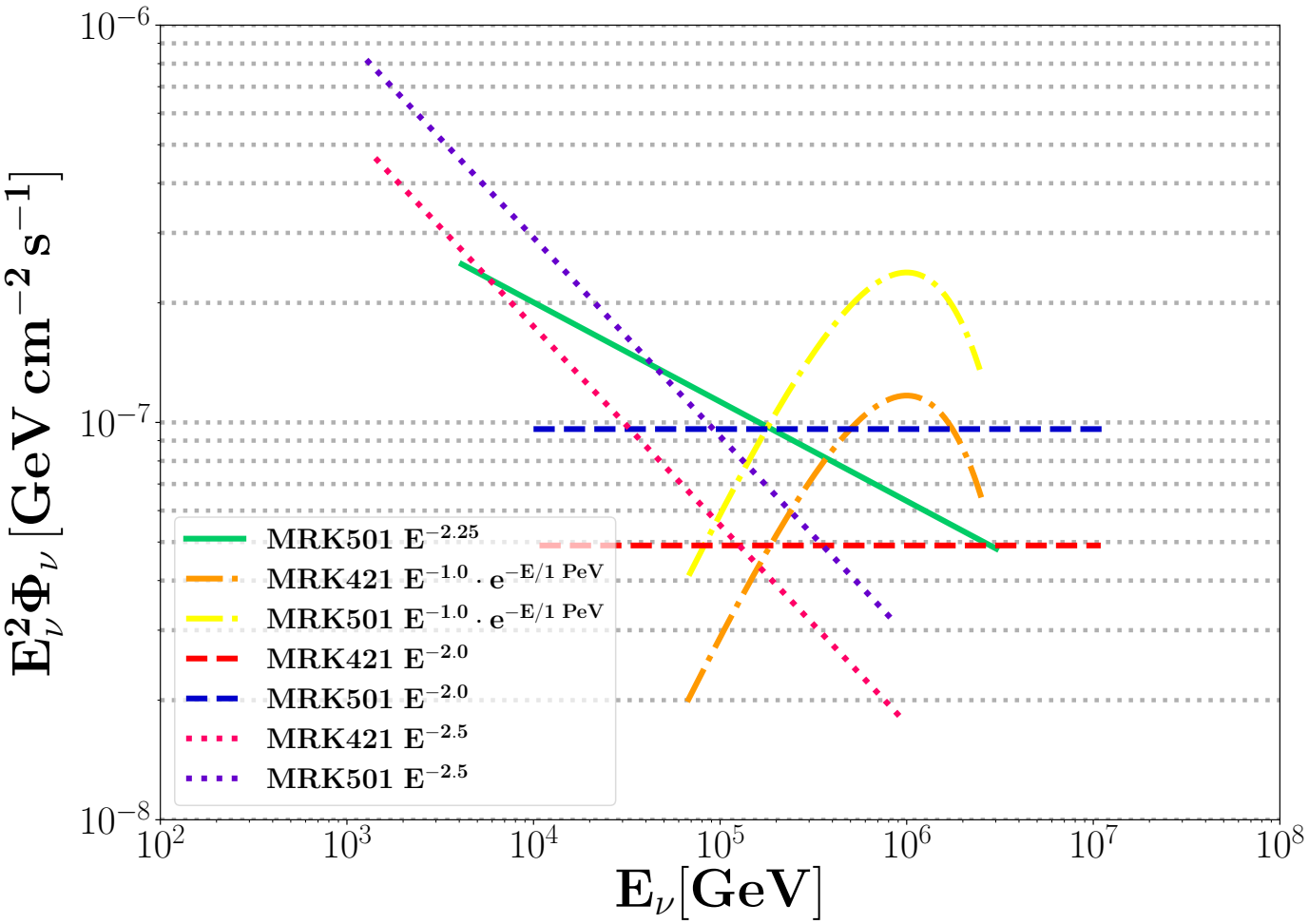
with the energy flux F as the energy per unit area and time $[GeV\, cm^{-2}\, s^{-1}]$:

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

Here :

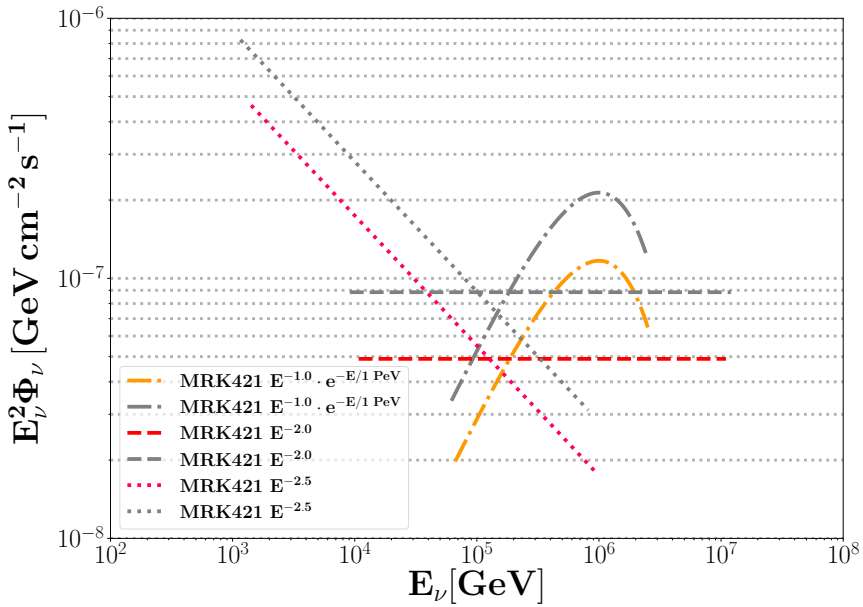
- ΔT is the livetime of the search $[s]$;
- $\Phi_0^{90\%CL} = DF^{90\%CL}$ is the upper limit on the ν flux normalization $[GeV^{-1}\, cm^{-2}\, s^{-1}]$;
- $\Phi_E = \Phi_0^{90\%CL}\, S(E) = DF^{90\%CL}\, S(E)$ is the differential flux $[GeV^{-1}\, cm^{-2}\, s^{-1}]$;
- $S(E)$ is the dimensionless 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.

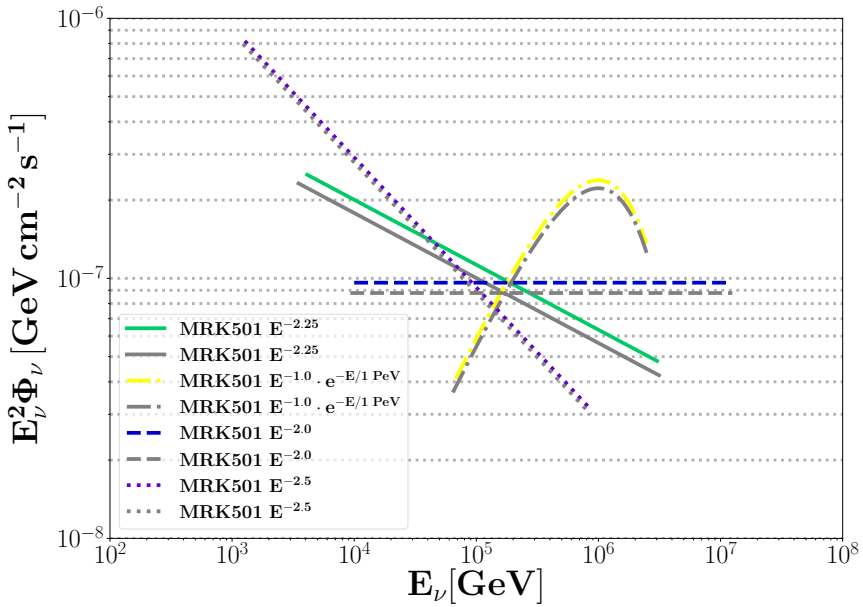
Neutrino energy flux sensitivities [8]



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

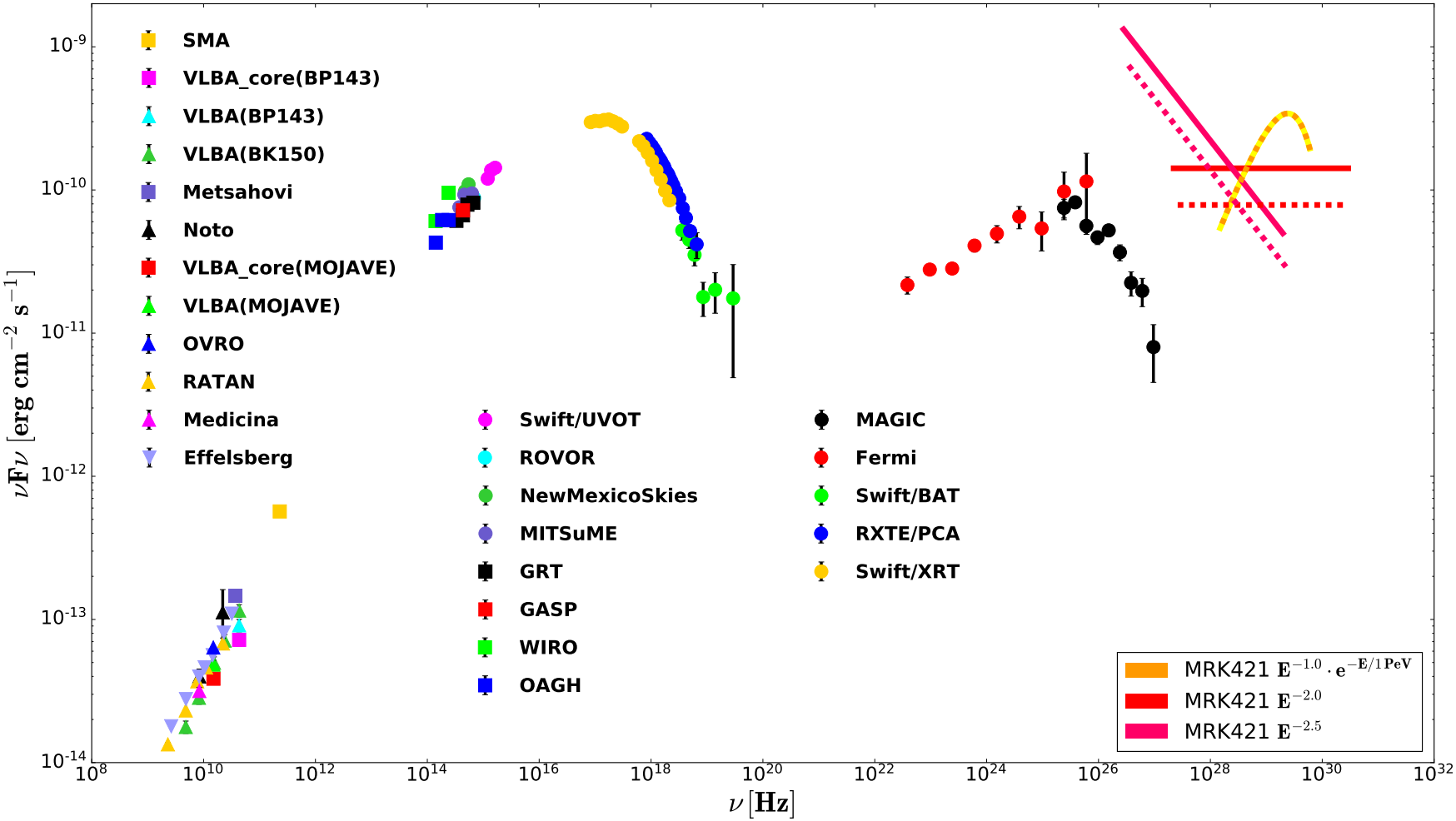
Neutrino energy flux sensitivities comparison [9] for last/current analysis





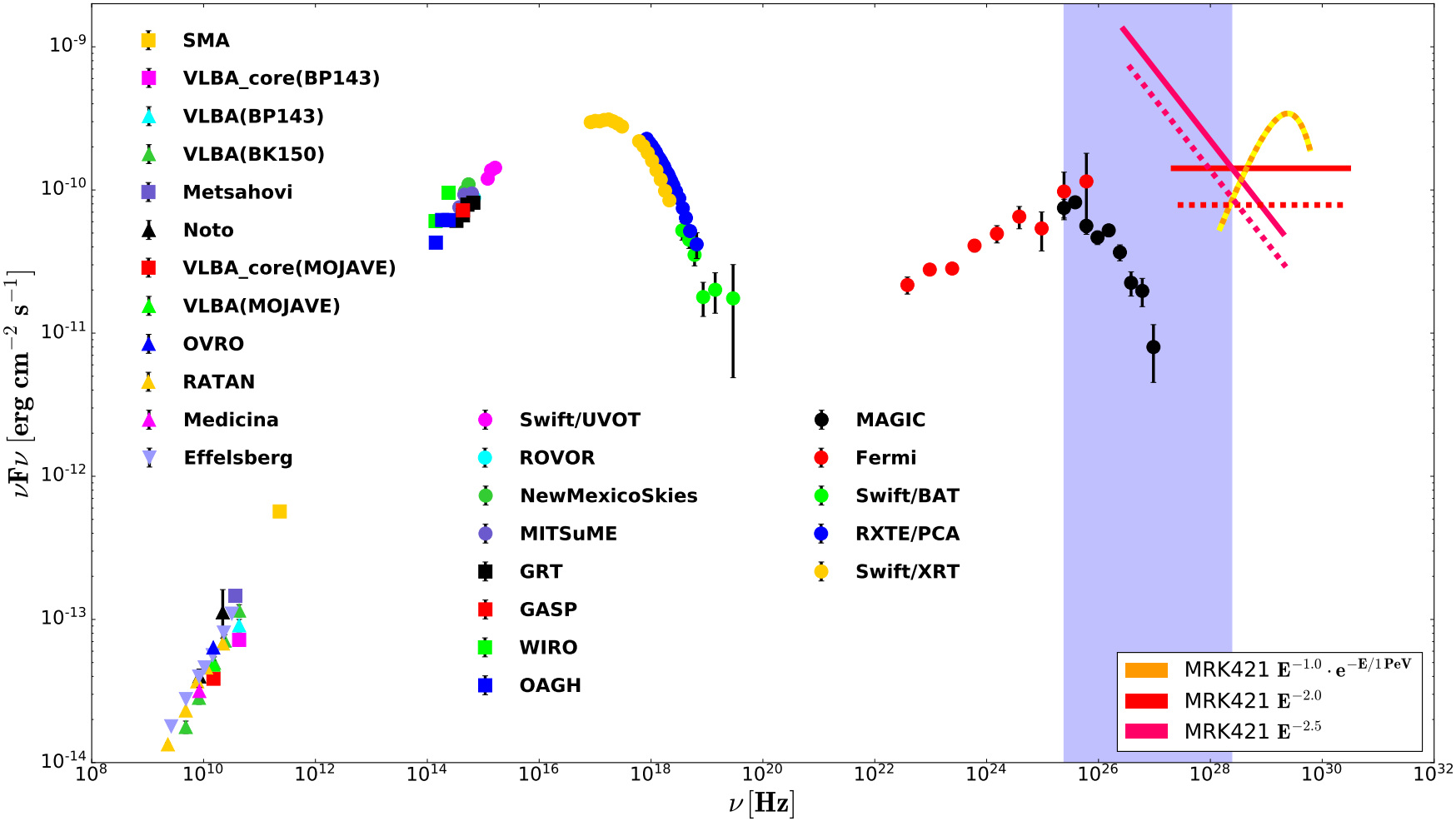
9. Grey color and colored curves represent HAWC 2014-2016 and HAWC 2014-2017 periods respectively.

SED of Mrk 421 [10] and neutrino energy flux sensitivities [11]



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

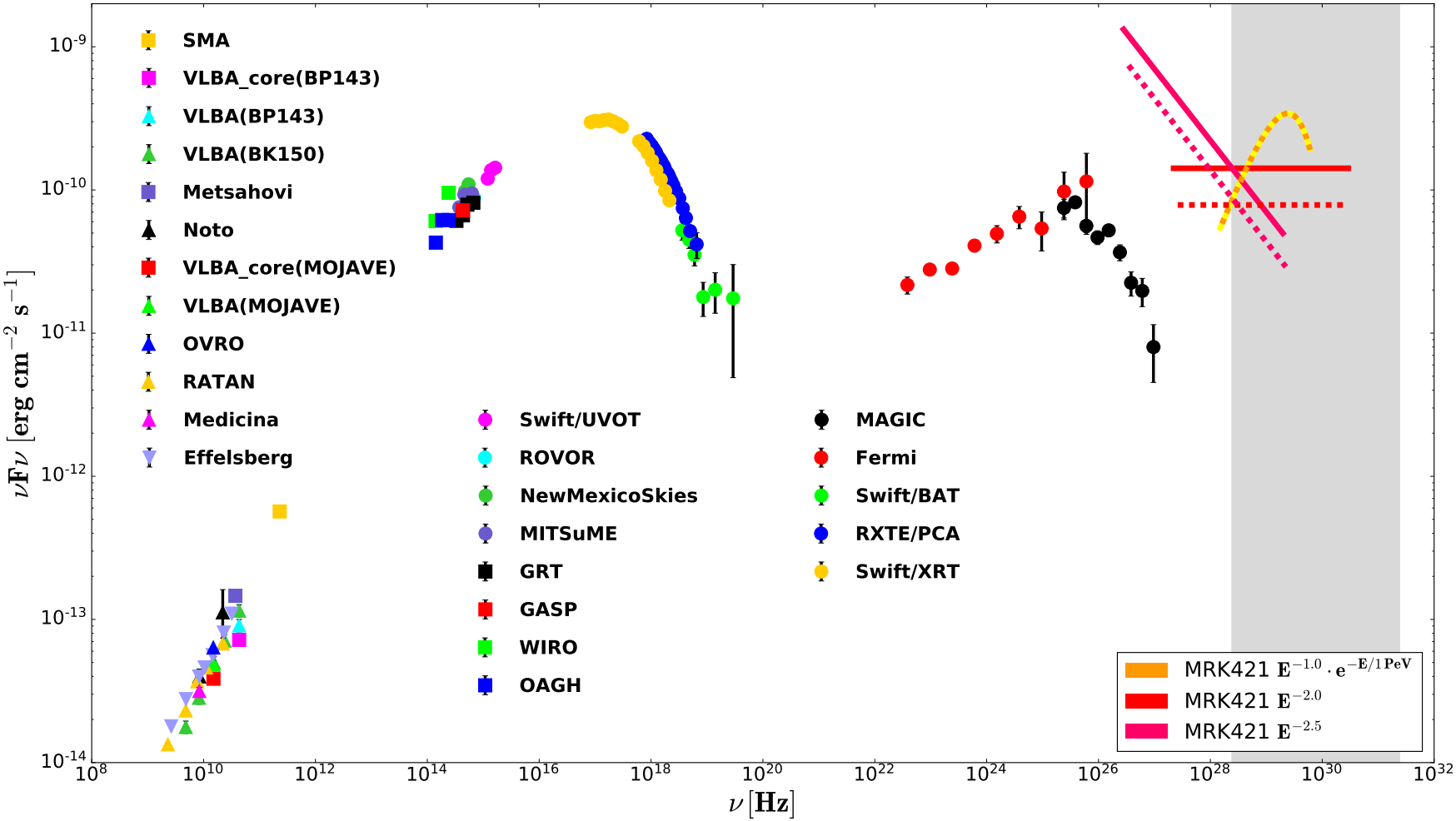
SED of Mrk 421 [10] and neutrino energy flux sensitivities [11]



VHE : 0.1-100 TeV

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

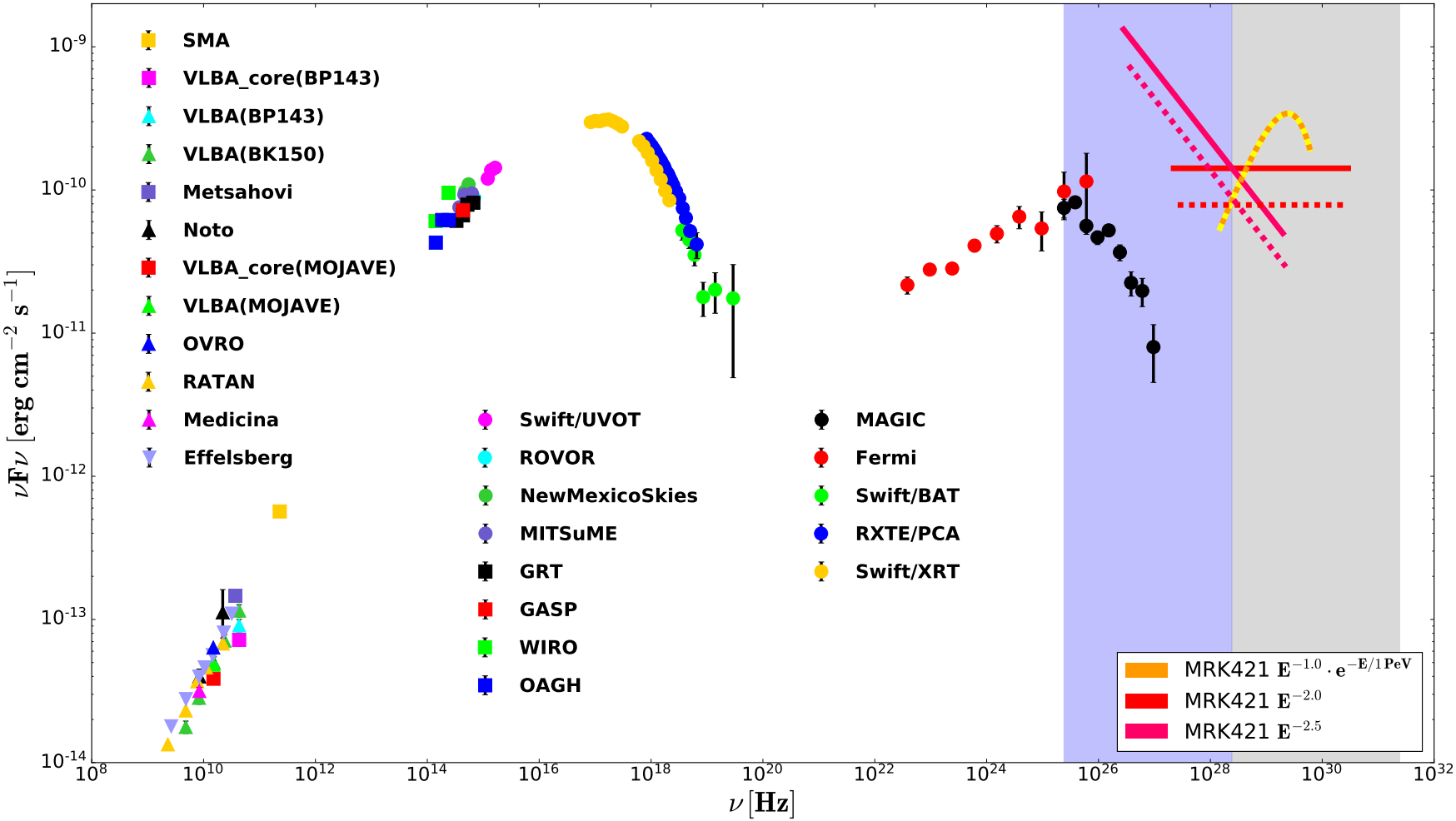
SED of Mrk 421 [10] and neutrino energy flux sensitivities [11]



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

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

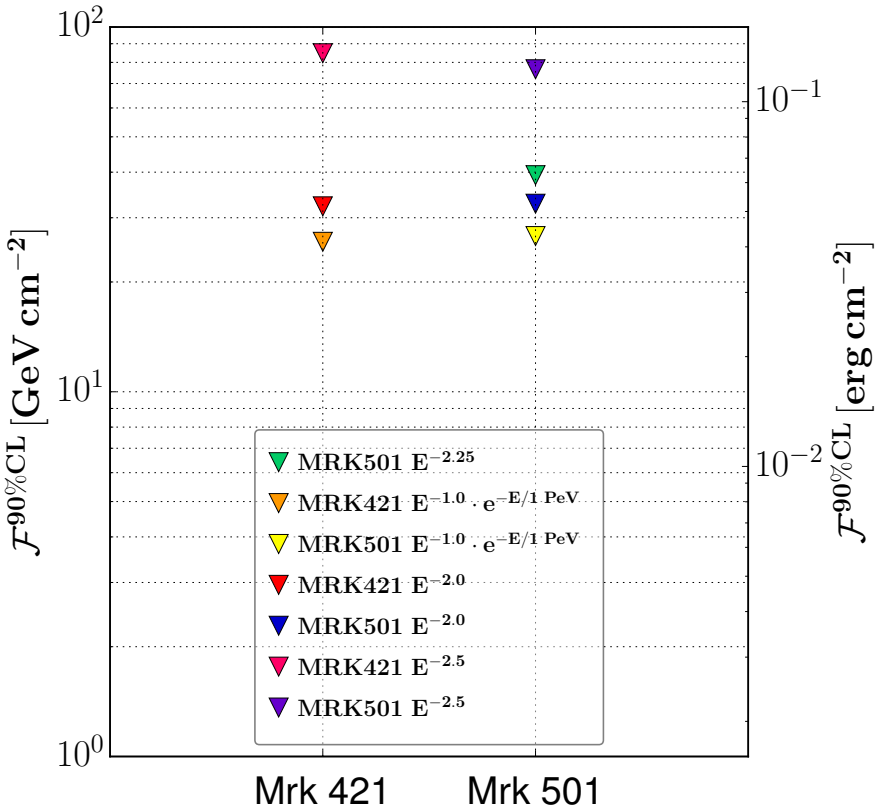
SED of Mrk 421 [10] and neutrino energy flux sensitivities [11]

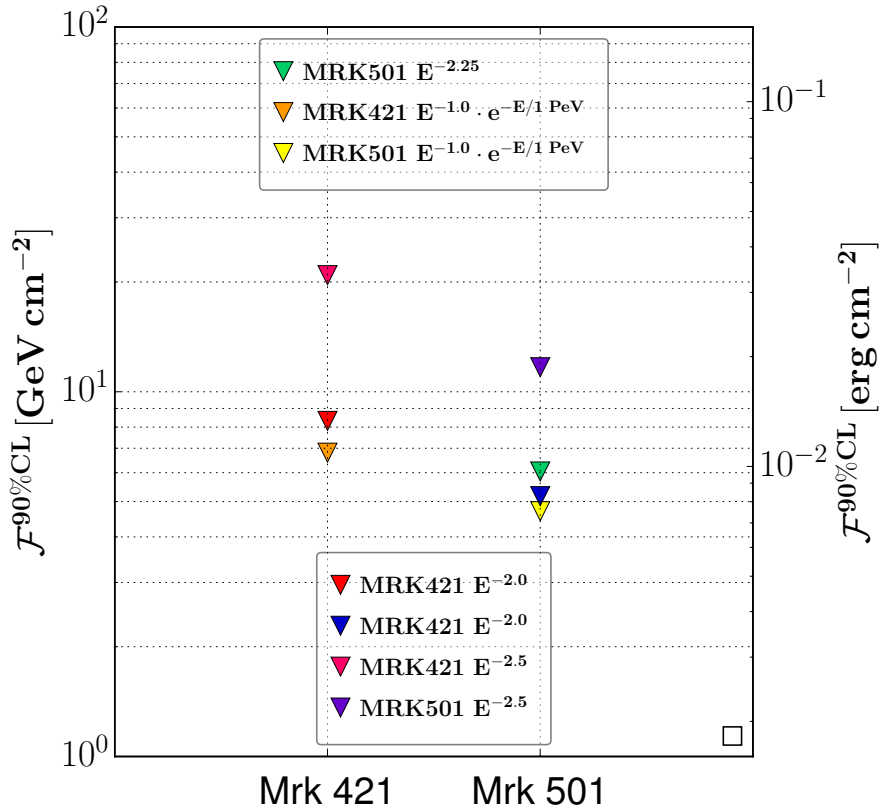


VHE & UHE

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

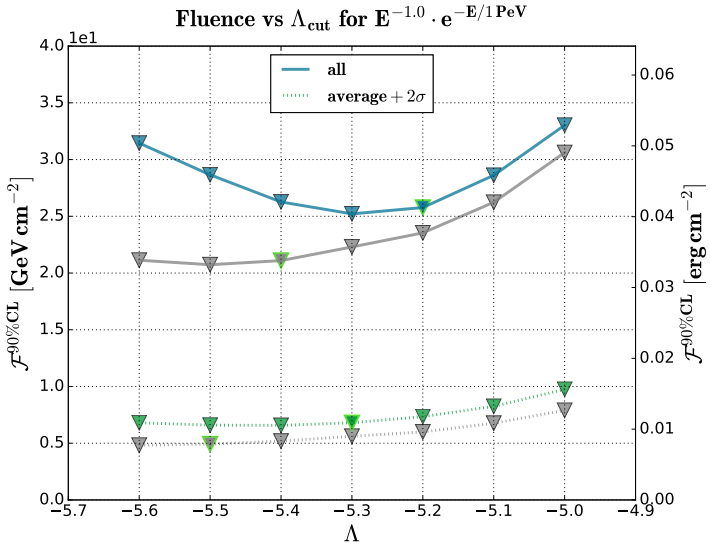
Neutrino fluence sensitivities [12] [13]

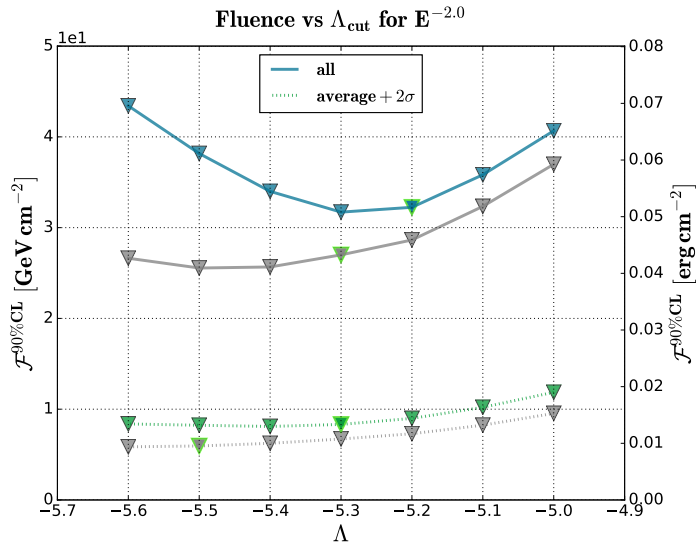


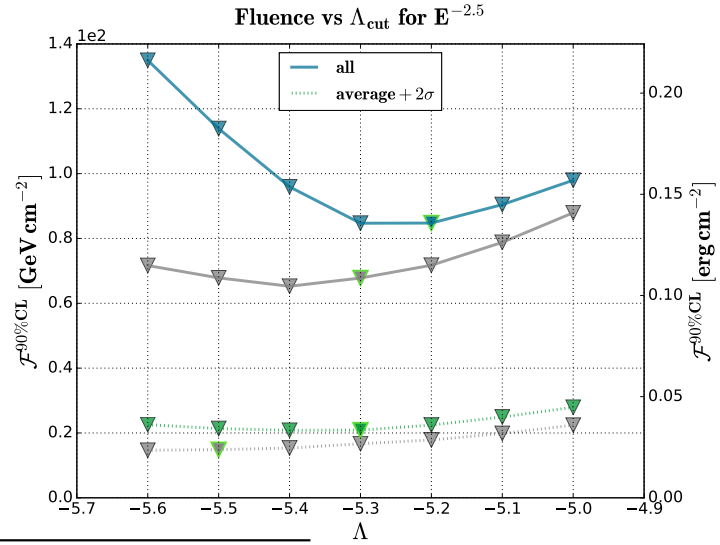


12. Left plot has been obtained with case of *all flares*
13. But best sensitivities on ν fluxes can be obtained with usage of *average flux + 2σ* case (Right plot)
↪ gives one order of magnitude improvement w.r.t all flares.

Neutrino fluence sensitivities vs Λ for Mrk 421 [14]

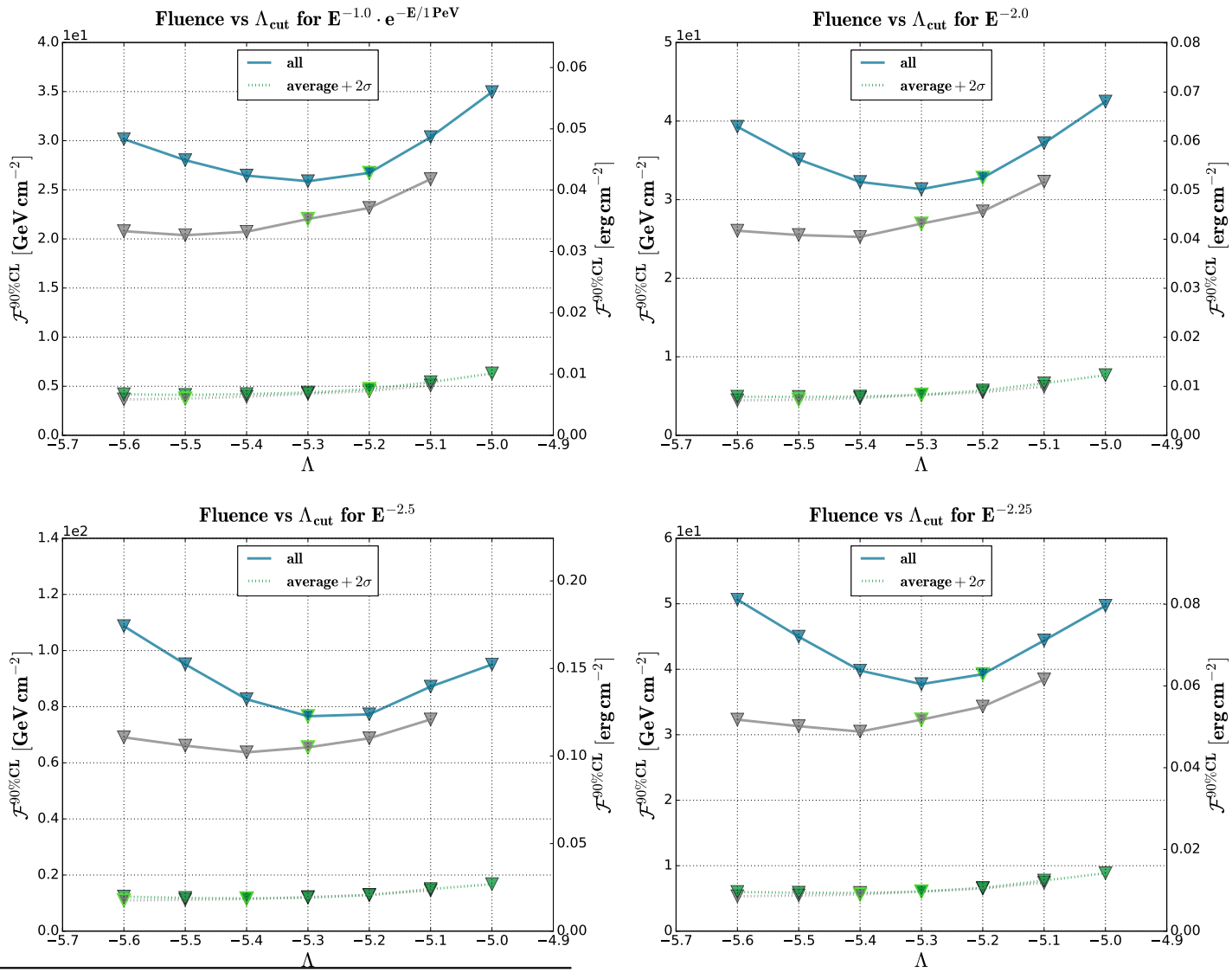






14. Grey color and colored curves represent HAWC 2014-2016 and HAWC 2014-2017 periods respectively.

Neutrino fluence sensitivities vs Λ for Mrk 501 [15]



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

Conclusion

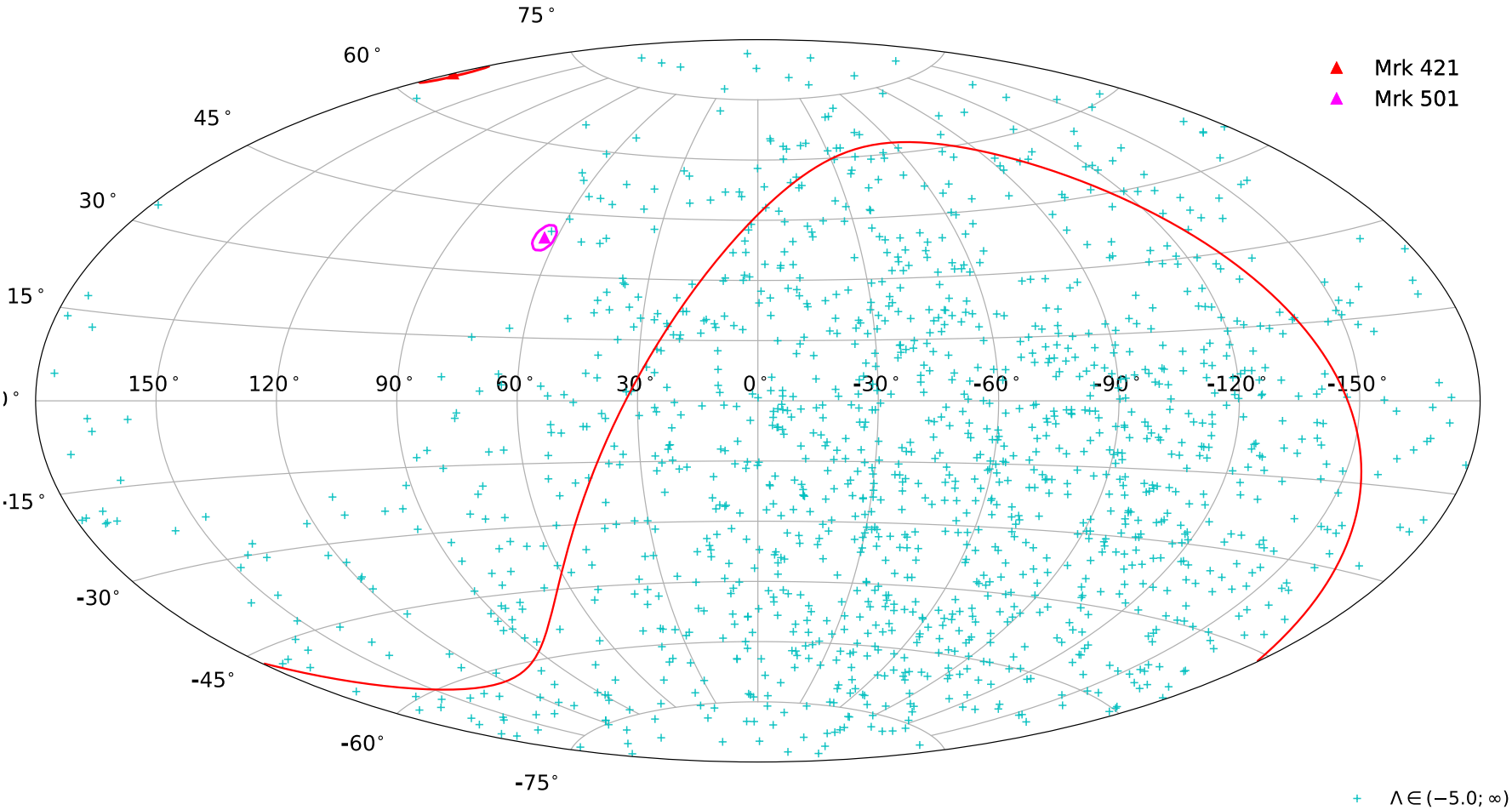
- Neutrino energy flux sensitivities :
  - For Mrk 421 is getting better by factor $\sim$1.8 w.r.t. last analysis
    $\hookrightarrow$ we used $\sim$ 100% longer LC data for the current analysis.
  - For Mrk 501 is getting worse by factor $\sim$1.1 w.r.t. last analysis
    $\hookrightarrow$ we used $\sim$ 20% longer LC data for the current analysis.

  - Many things play a role here like Λ cuts which is selected as optimum ;
  - Might be also the Bayesian Blocks not significantly but can affect on it :
  $\hookrightarrow$ the shape of blocks are almost identical but not completely if, for example, Bayesian Blocks are made for an identical period of current and last analysis like using first $\sim$ 500 days of data.) ;
- Neutrino fluence sensitivities :
  - For Mrk 421 is getting worse w.r.t. last analysis.
  - For Mrk 501 is getting worse w.r.t. last analysis.
- I have asked David Paneque also for SED of Mrk 501 data tables to draw similiar plot as done for Mrk 421 (slide 39). The plot will be updated shortly as soon as I receive the positive response.
- I would like to finish this analysis.
  $\hookrightarrow$ Later when data for first months of 2018 will be ready, it can be added to the existed data and the results can be updated (some ATels during January 2018 convince us to do that, see next slide).
- Internal notes updates with current analysis ? Wiki page ? Both ?

Astronomy Telegram : 17-01-2018 announcements

- **11184 FACT : Exceptional Flare of Mrk 421 at TeV energies**
  Since December 2017, Mrk 421 has been showing already some activity at TeV energies, as reported in the ATels #11077 and #11086 by the FACT and HAWC collaborations. The source was observed by FACT for a total of 5.5 hours between 1:15 UTC and 7:05 UTC (MJD 58135). At the beginning of the observation, the source showed a flux of about 6-7 times that of the Crab Nebula (CU) at TeV energies, then increasing to more than 9 CU. Over the whole observation, the flux was varying between 3 and 10 CU with a decrease towards the end of the night and an average flux of roughly 6 CU.
- **11186 MAXI/GSC : detection of a rapid X-ray brightening from Mrk 421**
- **11194 HAWC : observation of Mrk421 reaching peak TeV flux in month-long enhanced activity**
  (6 equivalent CU) between 2018-01-17 06:39 and 09:47 UTC. This is about 10 times the all-time averaged flux measured by HAWC and the highest one since the beginning of this enhanced period. Enhanced emission has also been reported by FACT (ATel #11086 and #11184), and MAXI/GSC (ATel #11186).
- **11195 Swift/BAT : finds hard X-Ray flaring activity correlated with an ongoing TeV flare of Mrk421**
- **11199 TACTIC : detection of a strong TeV flare from Mrk 421**
  Multi-wavelength observations of this enhanced activity of the source have also been reported by FACT (ATels : #11184), HAWC (ATel : #11194), MAXI/GSC (ATel : #11186) & Swift/BAT (ATel : #11195). An exceptional flare was reported by FACT at TeV energies between 1:15 UTC and 7:05 UTC on Jan 17 (MJD 58135) with a maximum of >10 CU and a decrease towards the end of the night.
  The ongoing flaring activity of Mrk421 at TeV energies was already reported since December 2017 by the FACT and HAWC collaboration (ATels #11077 and #11086).

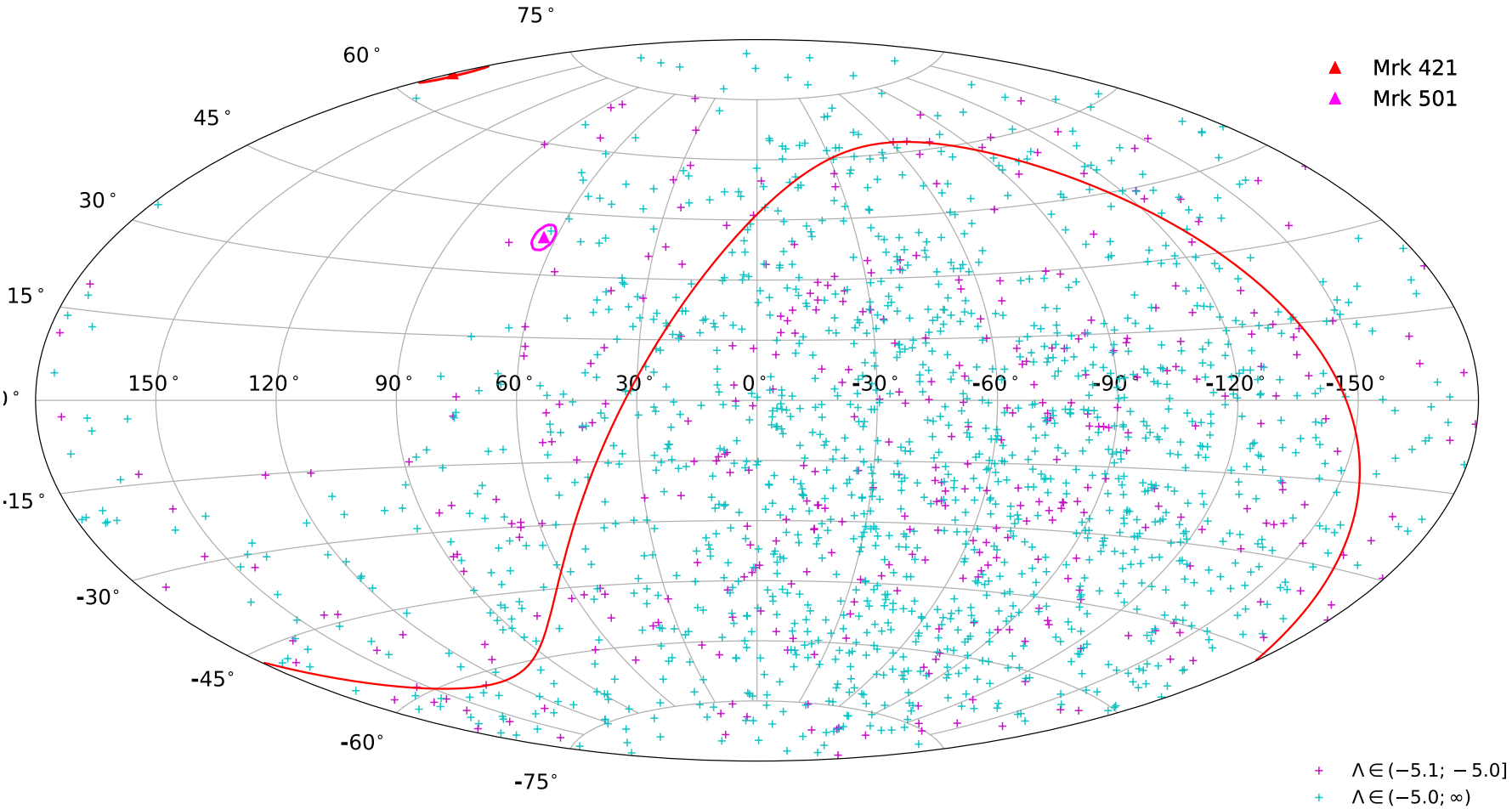
Sky map [16] [17] of the track-like events passing the selection cuts



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

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

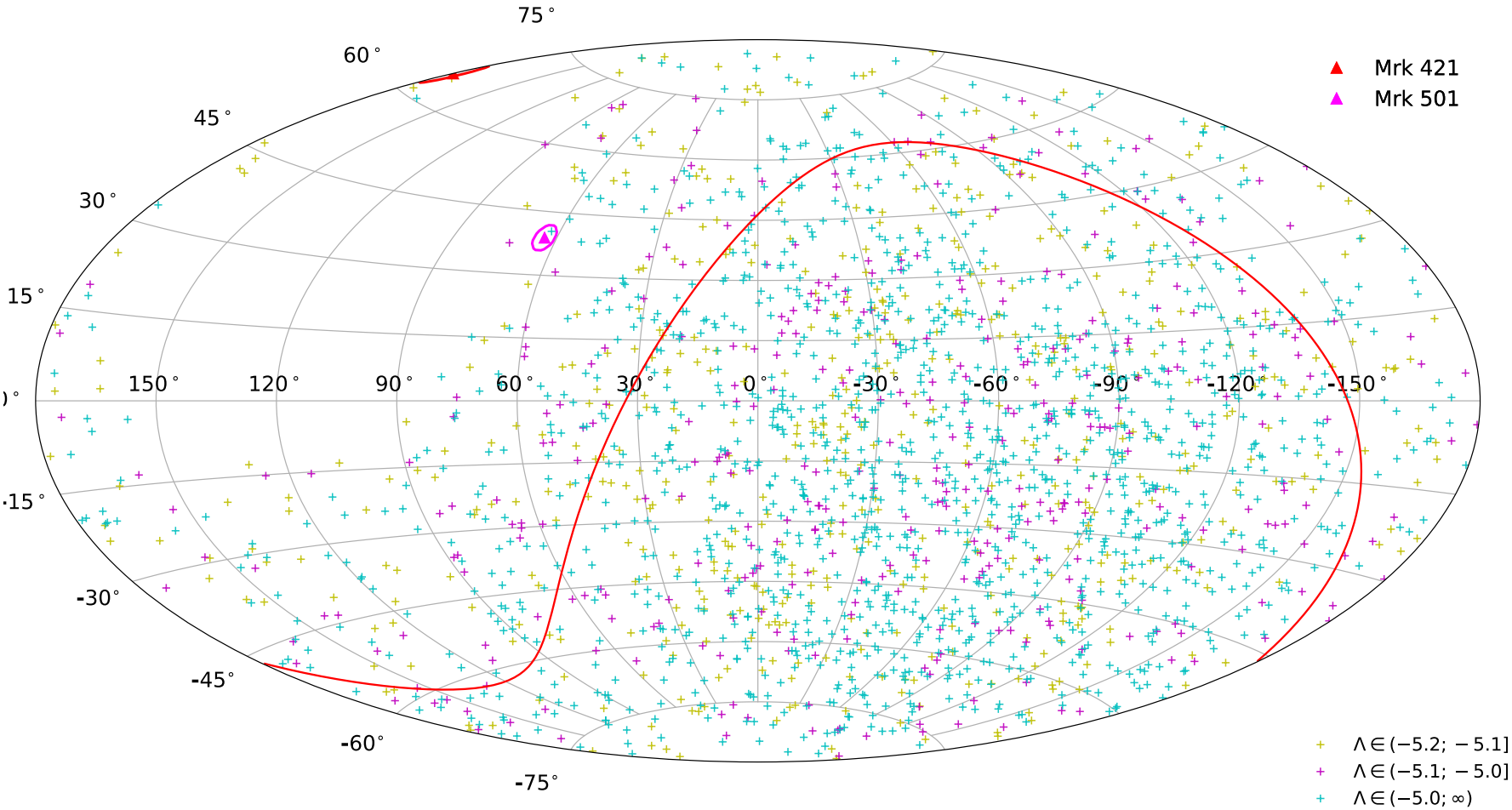
Sky map [16] [17] of the track-like events passing the selection cuts



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

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

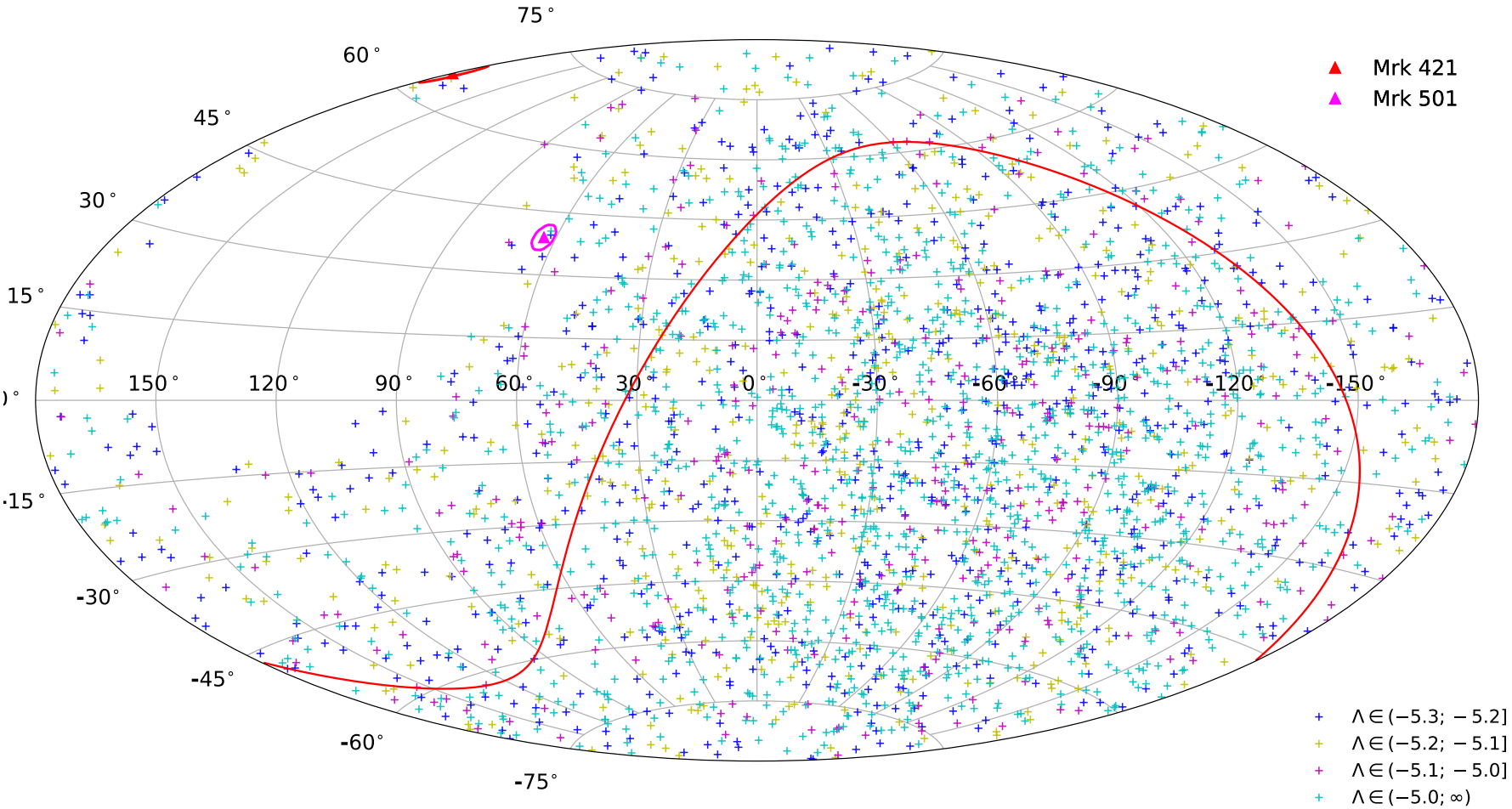
Sky map [16] [17] of the track-like events passing the selection cuts



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

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

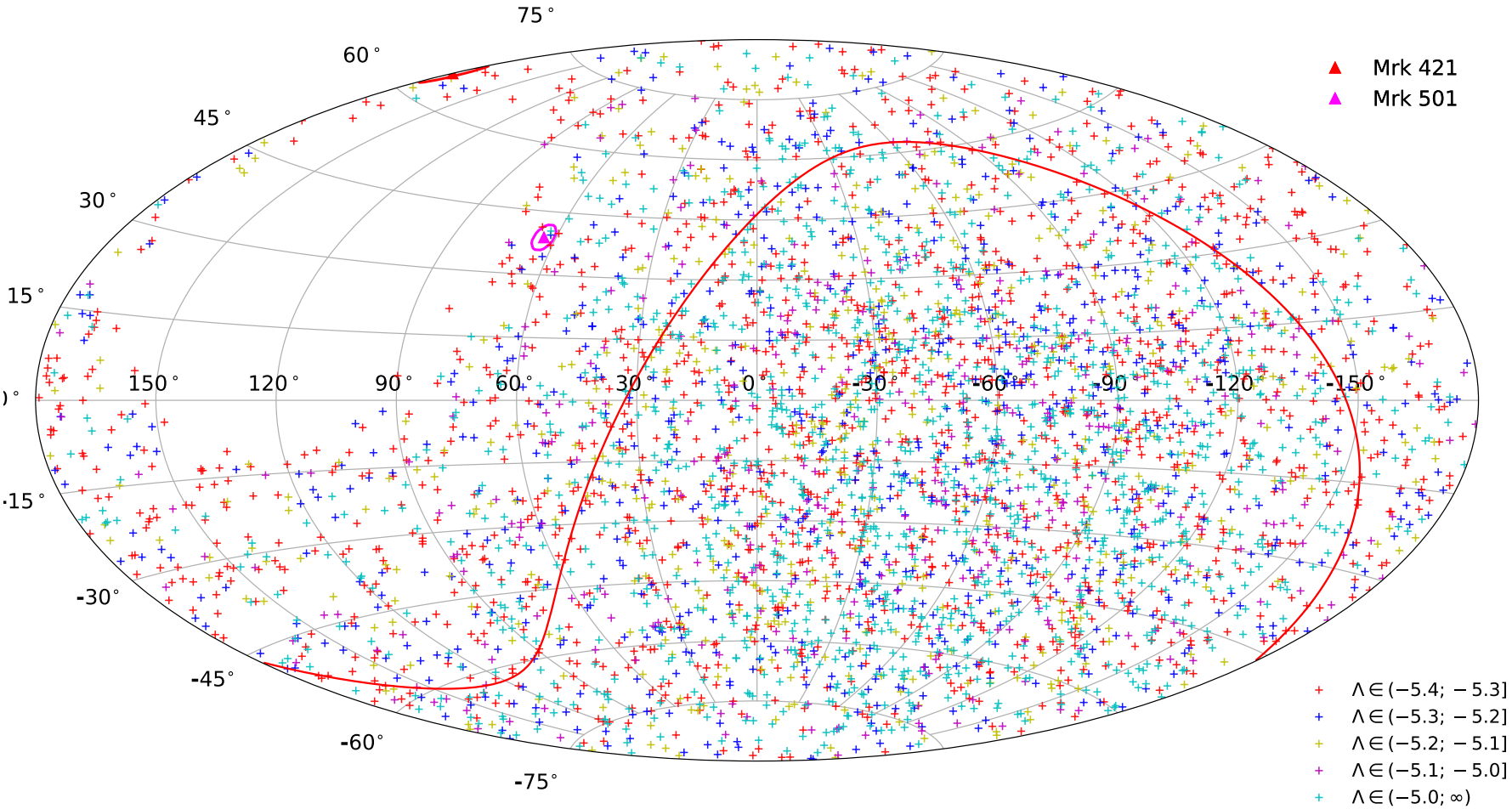
Sky map [16] [17] of the track-like events passing the selection cuts



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

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

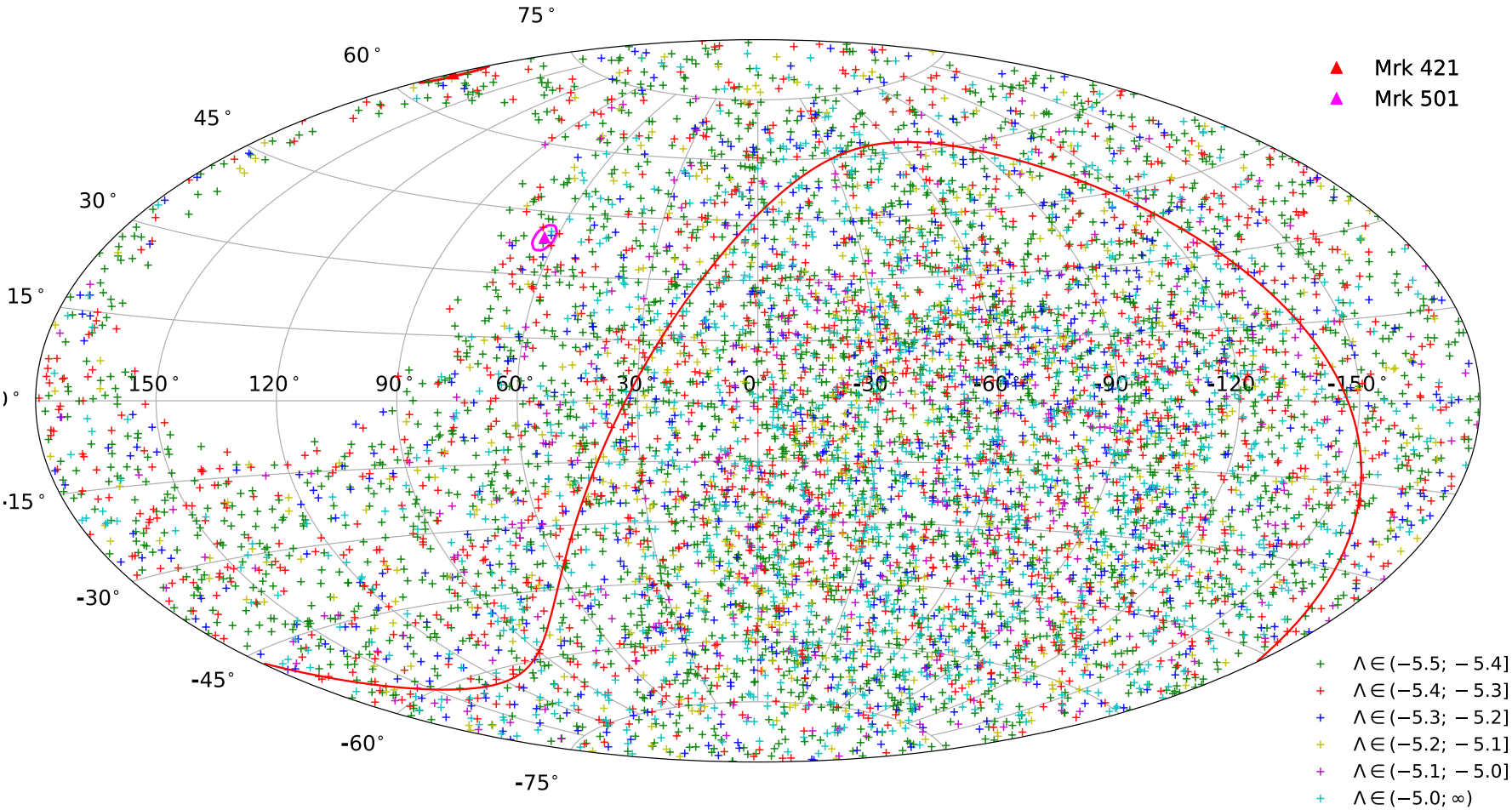
Sky map [16] [17] of the track-like events passing the selection cuts



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

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

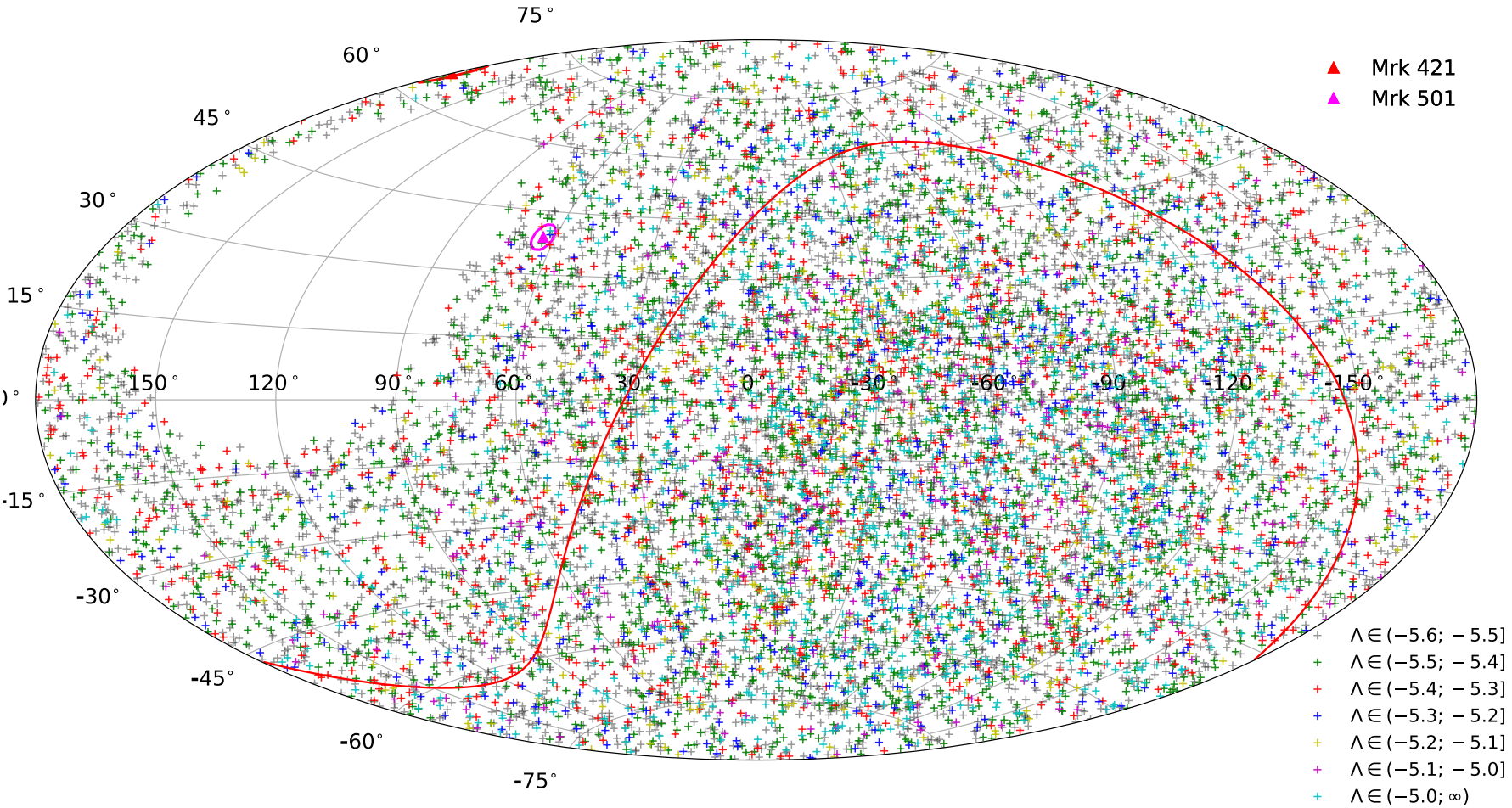
Sky map [16] [17] of the track-like events passing the selection cuts



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

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

Sky map [16] [17] of the track-like events passing the selection cuts



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

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

BACKUP

HAWC LCs : paper

First official HAWC Light curves releases

"Daily monitoring of TeV γ-ray emission from Mrk 421, Mrk 501, and the Crab Nebula with HAWC"

- Abeysekara et al., The Astrophysical Journal, Volume 841, Issue 2, article id. 100 (2017) arXiv:1703.06968 [astro-ph.HE]
- 17-Month Crab/Mrk 421/Mrk 501 Lightcurves

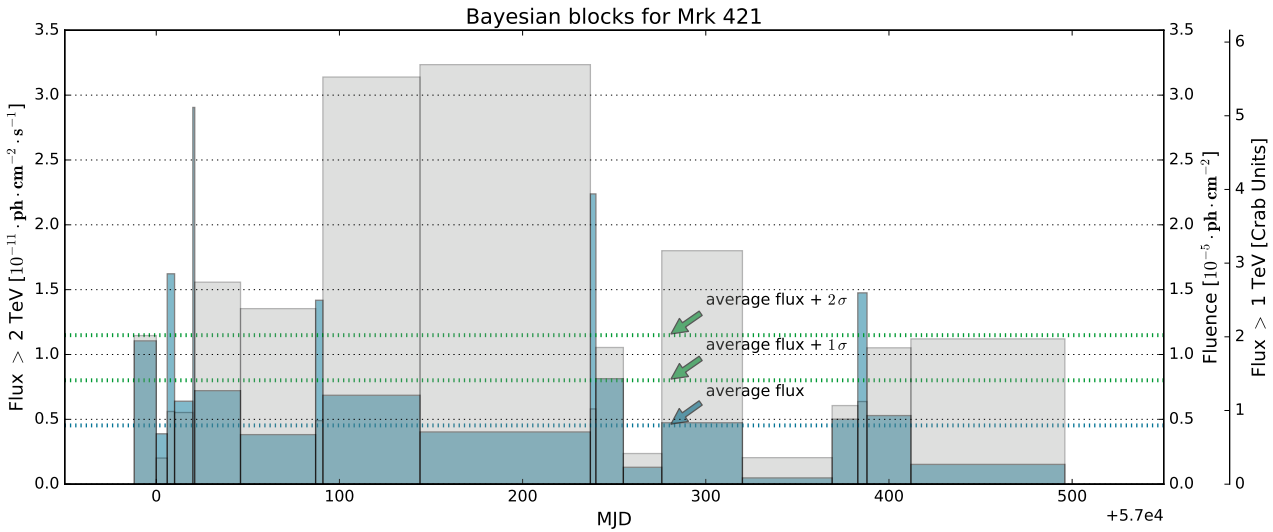
Mrk 421 & Mrk 501 : Found clear variability on time scales of one day !
$\Rightarrow$ Extract the shape of the signal from the γ-ray LCs assuming the proportionality between γ-ray and ν fluxes

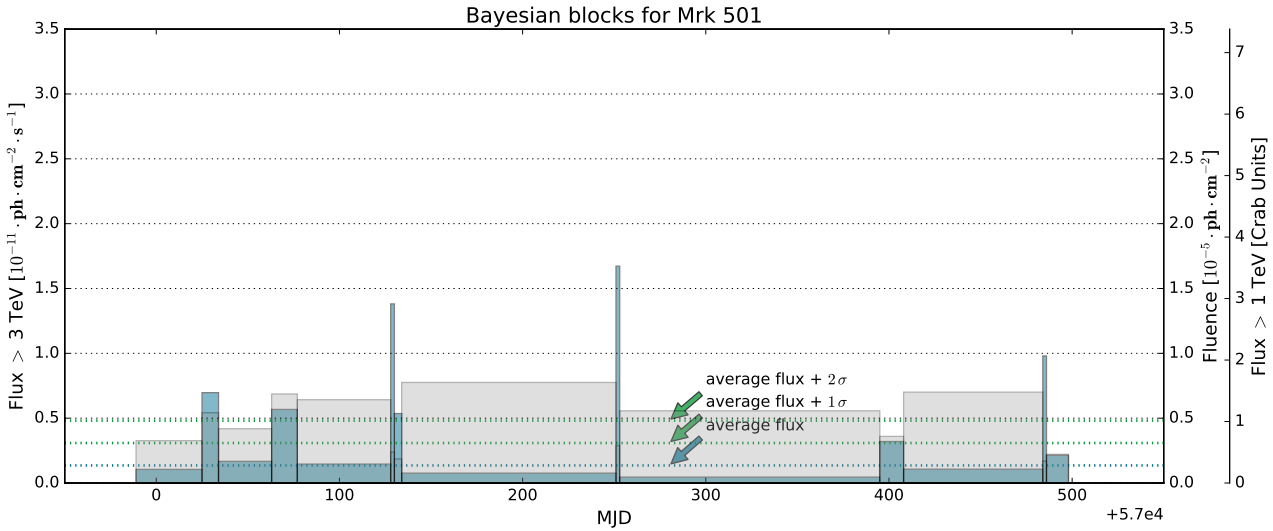
27/11/2014 - 19/04/2016
56988 - 57497

Mrk 421 & Mrk 501
dL = 134 Mpc, z = 0.031 & dL = 143 Mpc, z=0.033
two brightest and closest BL Lac objects known !

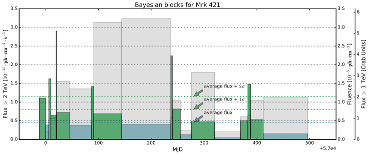
As the nearest blazars to Earth, both are excellent sources
to test the blazar-neutrino connection scenario, especially during flares
where time-dependent neutrino searches have a higher detection probability.

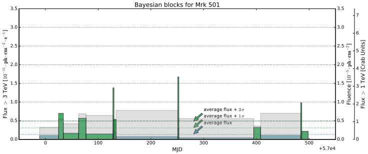
LC profiles

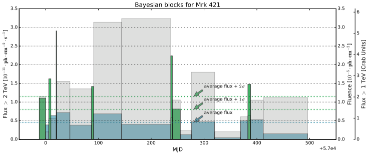

Bayesian blocks for Mrk 421
Flux > 2 TeV [$10^{-11} \cdot \mathrm{ph} \cdot \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$]
Fluence [$10^{-5} \cdot \mathrm{ph} \cdot \mathrm{cm}^{-2}$]
Flux > 1 TeV [Crab Units]
average flux + 2σ
average flux + 1σ
average flux
MJD
+5.7e4

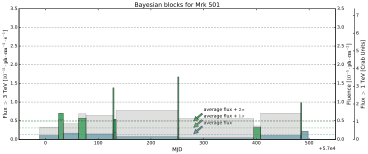

Bayesian blocks for Mrk 501
Flux > 3 TeV [$10^{-11} \cdot \mathrm{ph} \cdot \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$]
Fluence [$10^{-5} \cdot \mathrm{ph} \cdot \mathrm{cm}^{-2}$]
Flux > 1 TeV [Crab Units]
average flux + 2σ
average flux + 1σ
average flux
MJD
+5.7e4

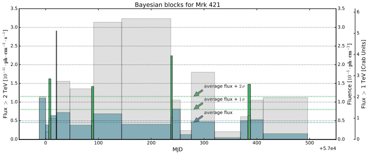
Peaks selection criteria

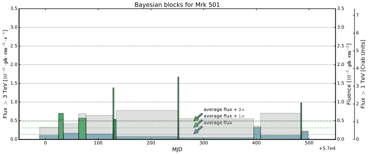












DATA/MC : last analysis

The ANTARES data set period :

- November 26$^{\text{th}}$, 2014 - April 20$^{\text{th}}$ [MJD : 56988-57497]
  $\hookrightarrow$ covering the same period of observation as HAWC.
- Lead to effective detector livetime of 503.7 days [1.379 y]

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

Location of DATA and MC files :

DATA :

- `/sps/km3net/users/antprod/data/Reprocessing_2016_05`
- `/hpss/in2p3.fr/group/antares/SeaTray/prod_2017-04-03/Line12/sea/2016/12/`

MC :

- ν : `/sps/km3net/users/antprod/mc/rbr_v3_QE/complete/` [$\leq$2015]
- ν : `/hpss/in2p3.fr/group/antares/mc/rbr/v4/reco/AntDST/` [=2016]
- μ : `/sps/km3net/users/antprod/mc/rbr_v3_QE/complete/` [$\leq$2015]
- μ : `/hpss/in2p3.fr/group/antares/mc/rbr/v4/reco/mu_v3/AntDST/` [=2016]

Run selection : last analysis

Runs are selected if the conditions below are fulfilled :

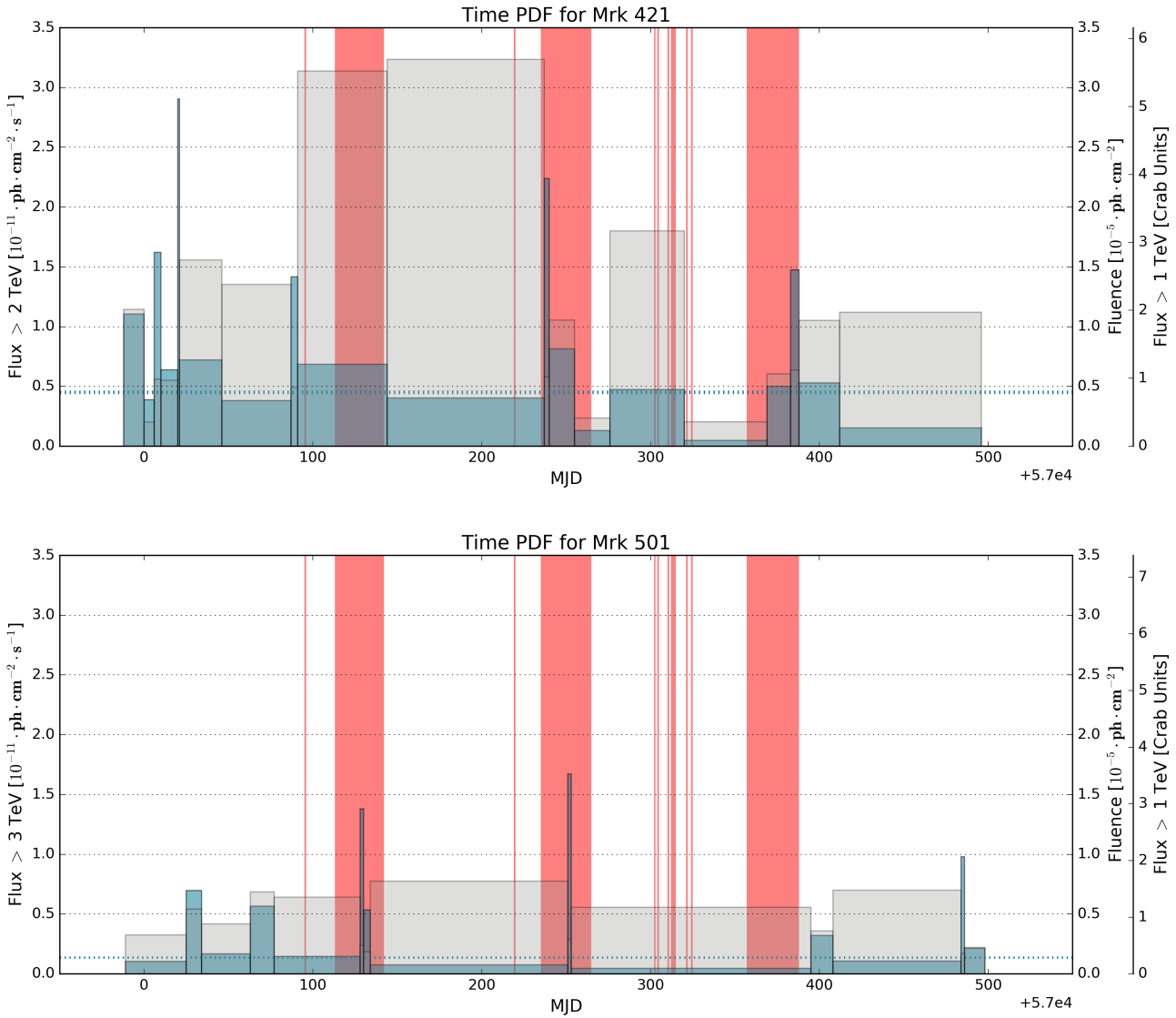
- QualityBasic $>= 1$
- SCAN $! = 1$
- Sparking $! = 1$ (Addition observed sparking runs are removed)

$\hookrightarrow$ This gives a livetime of 503.7 days [1.379 y]. Only 332.8 days [0.911 y] are with MC-complete (MUPAGE and all track-like (a)numu files are available).

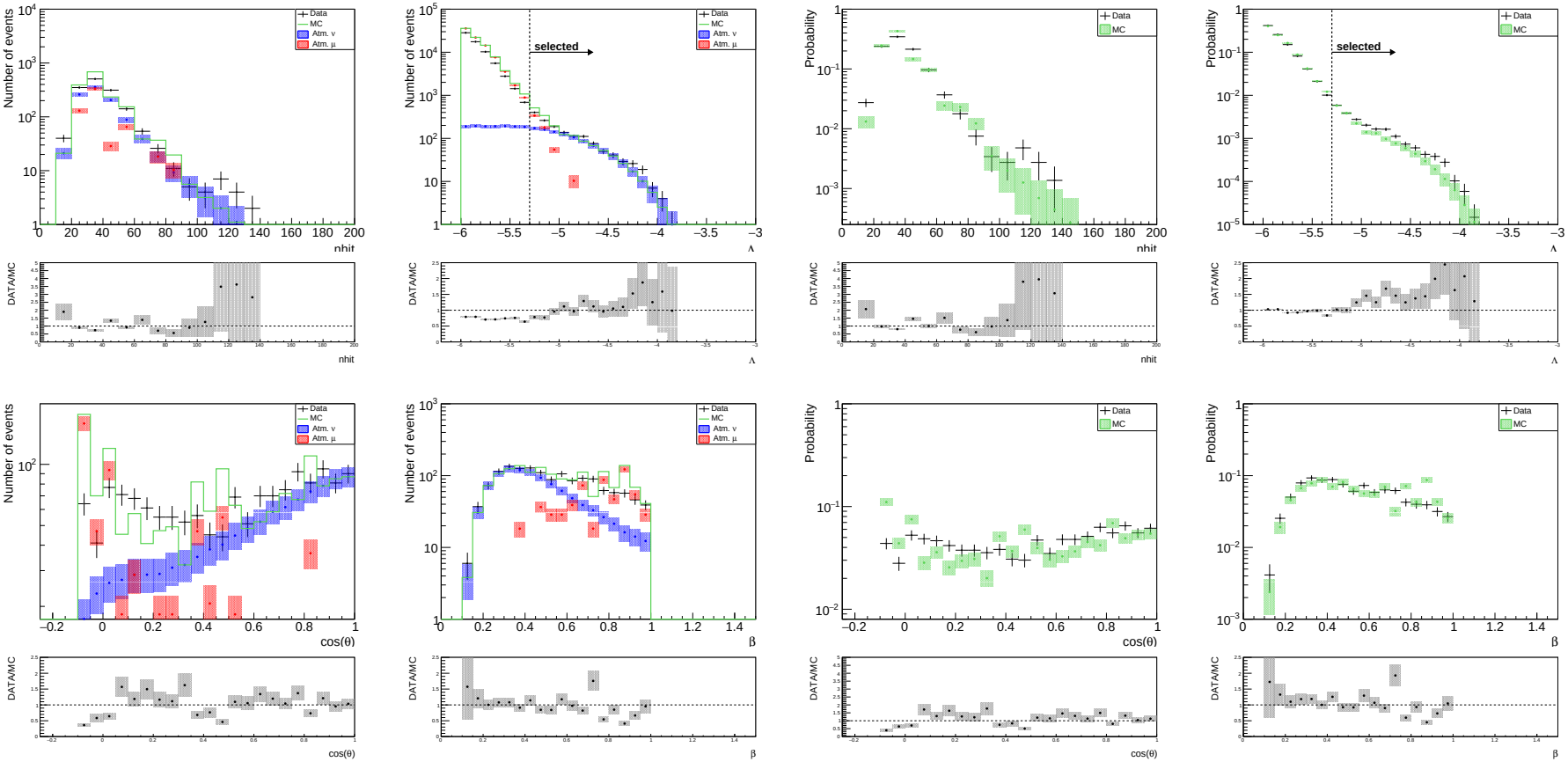
RESCALE :
The livetime of available complete MC is scaled up to the livetime in DATA !

As seen from next figures, significant amount of data should be not taken if consider only DATA-MC complete runs. Moreover, most high peaks are under time of incomplete MC runs and removing them from the analysis is leading to vast decrease of the discovery potential.

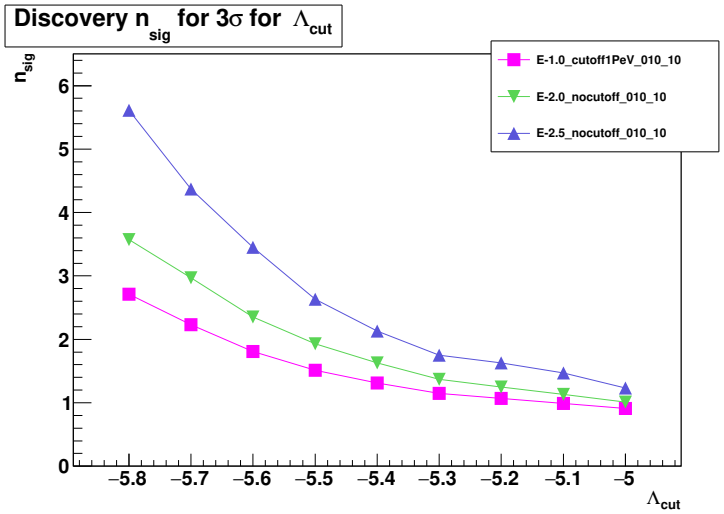
LC vs MC missing runs

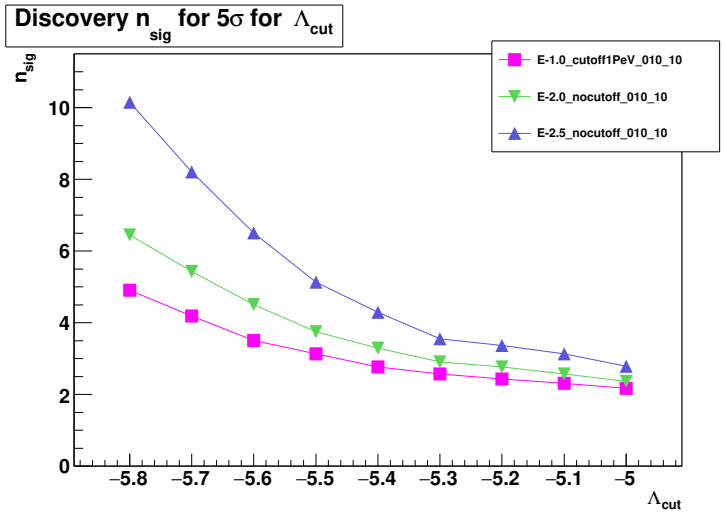


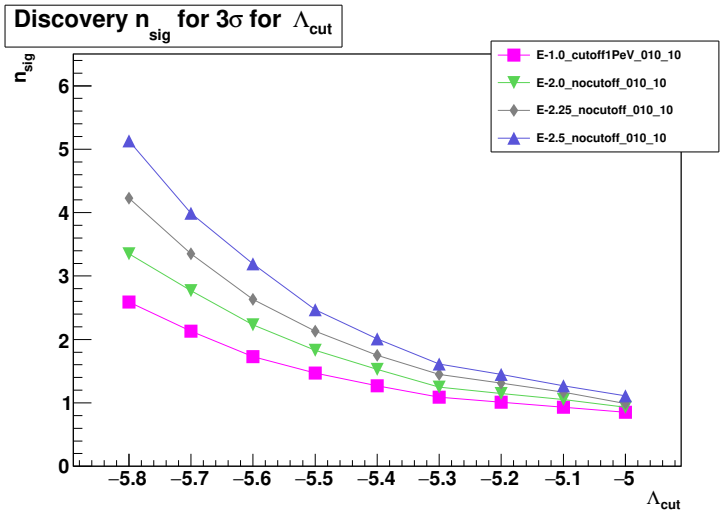
DATA/MC agreement : last analysis

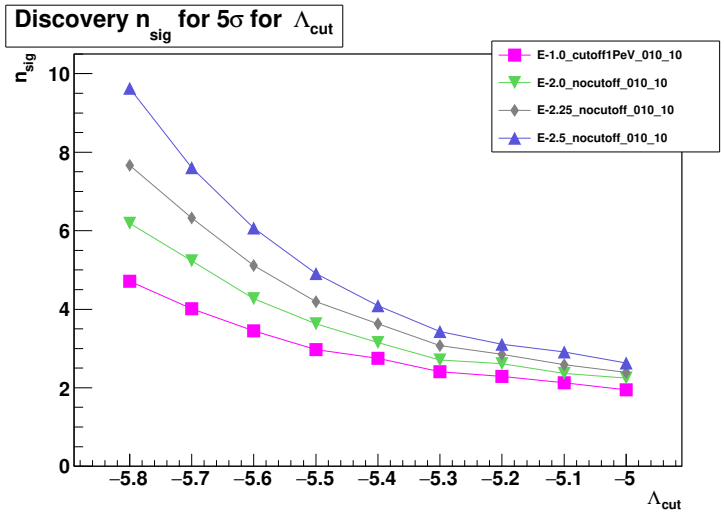


Discovery signals [18], example for case of all flares [19]



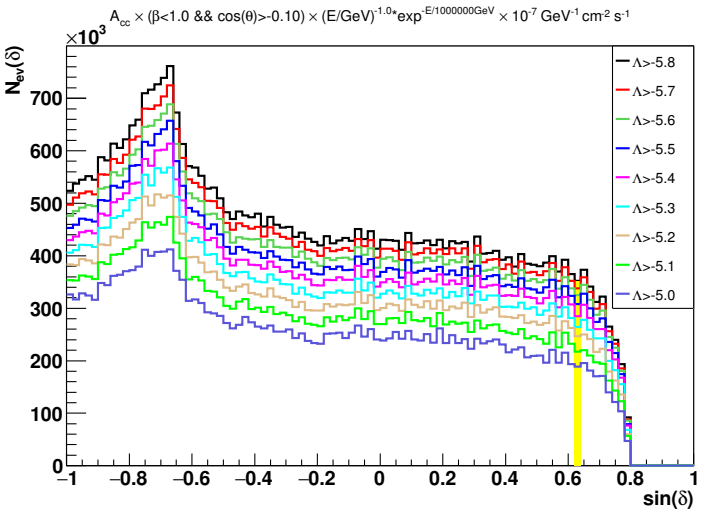


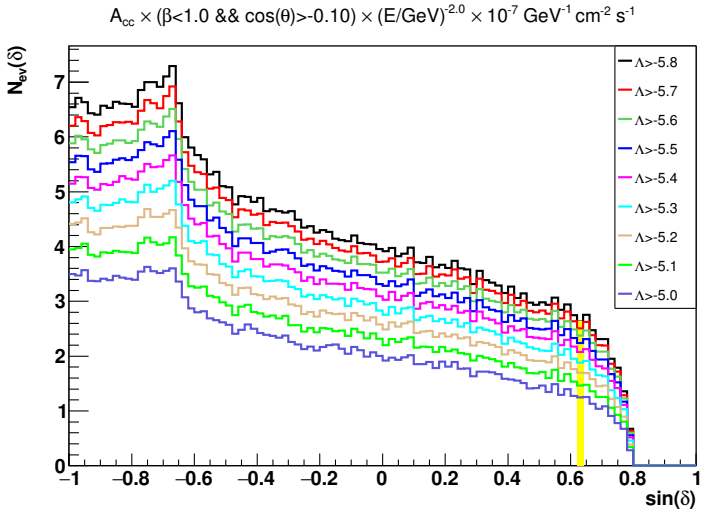


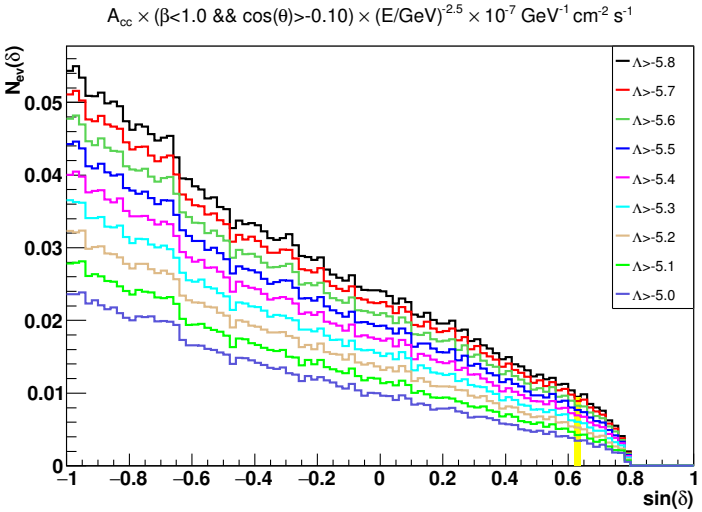


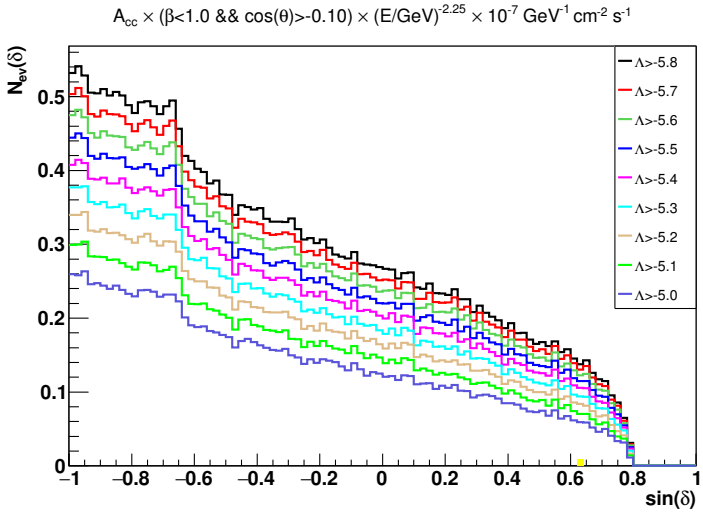
18. Values scaled => required for whole T_{flare}
19. +3 set : plots for *average flux*, *average flux + 1σ*, *average flux + 2σ*

Acceptance vs Λ, example for Mrk 501 [20]



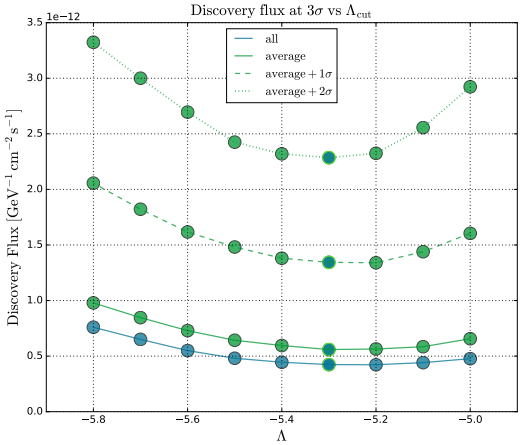


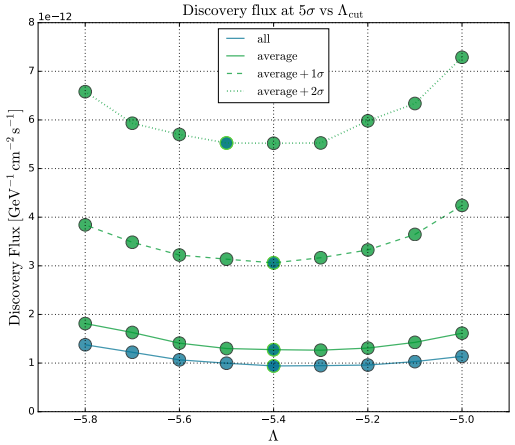


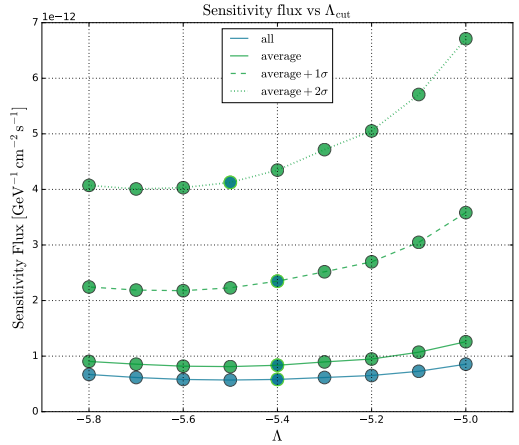


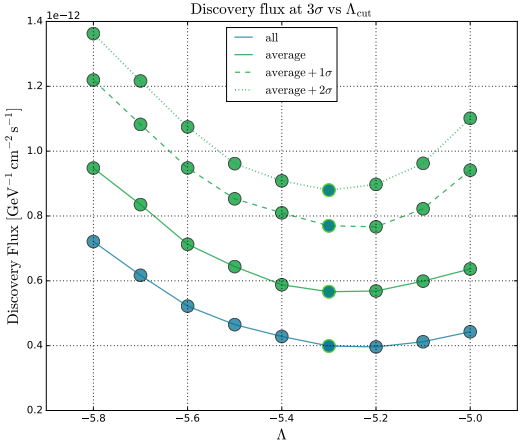
20. +1 set : plots for Mrk 421

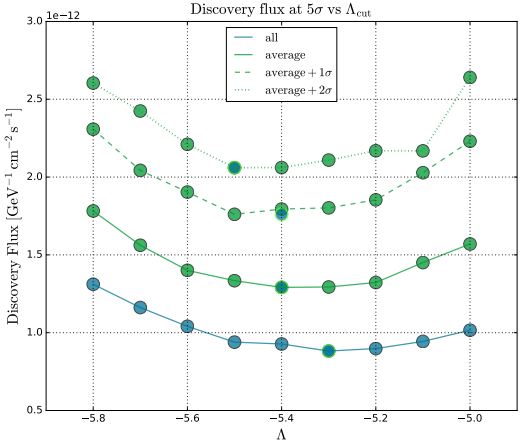
Discovery fluxes for $E^{-1.0}\exp(-E/1\,\mathrm{PeV})$

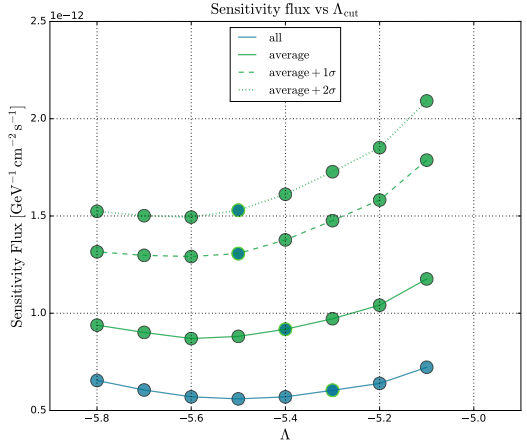




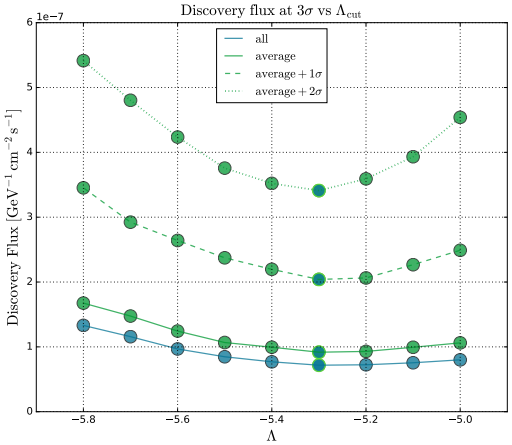


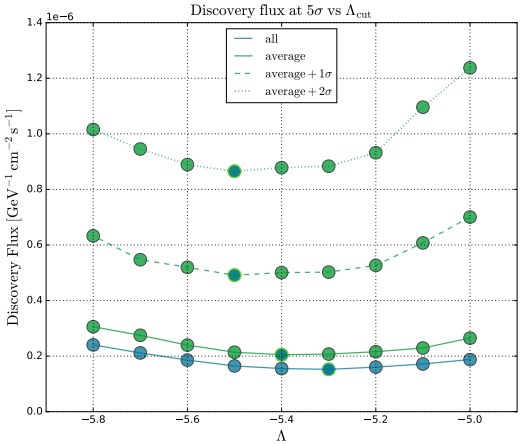


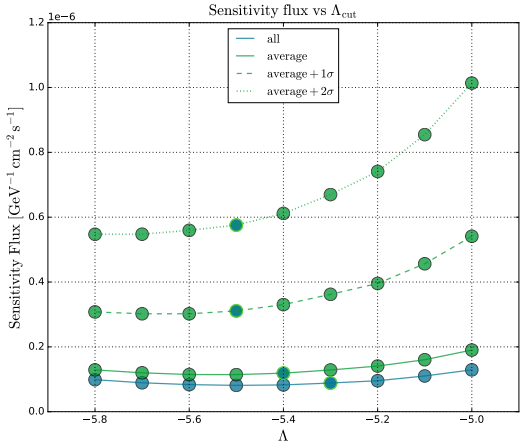


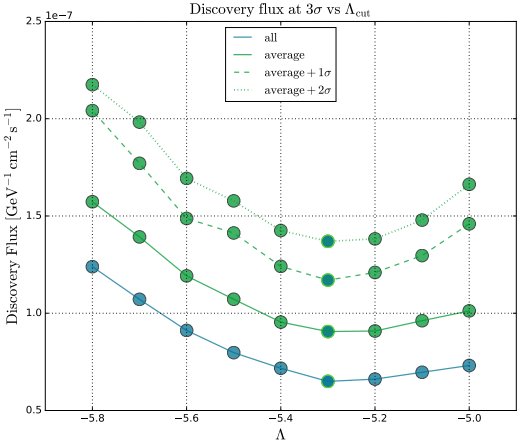


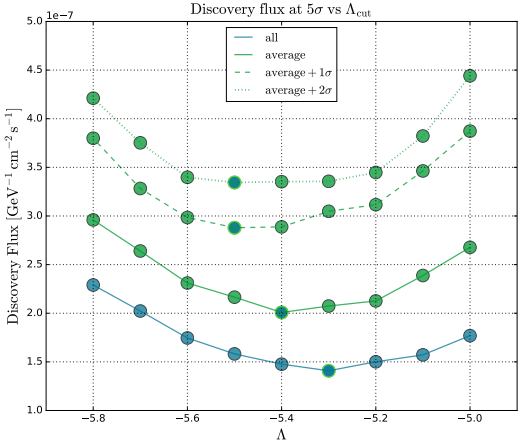
Discovery fluxes for $E^{-2.0}$

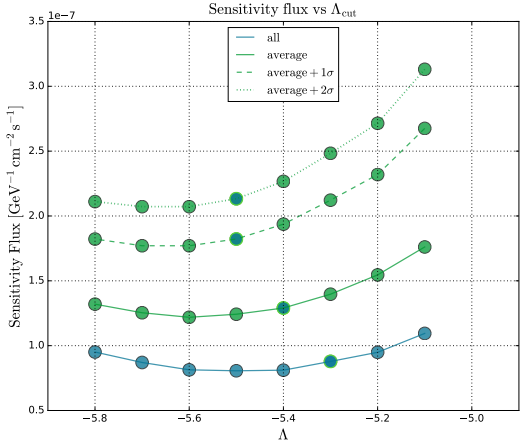




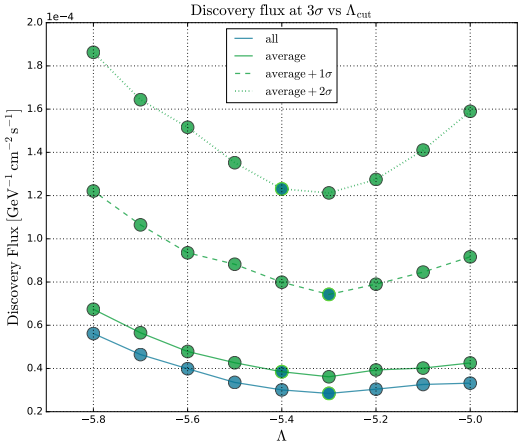


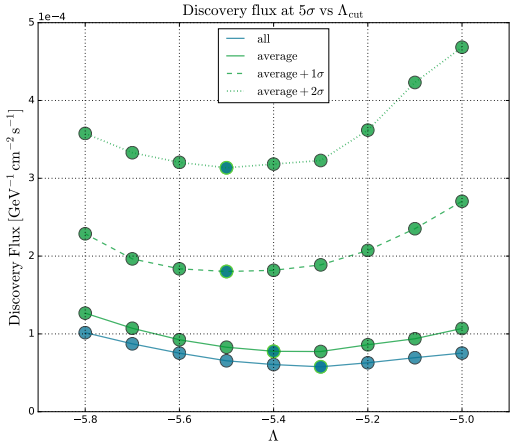


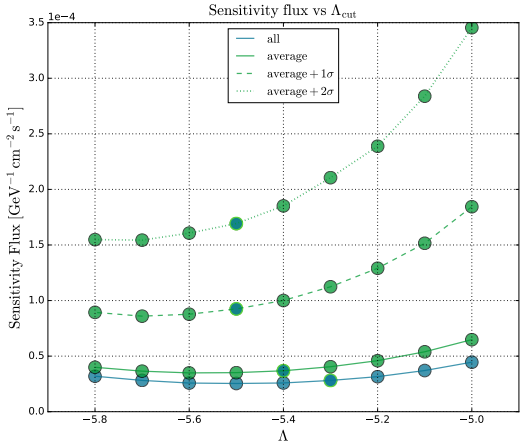


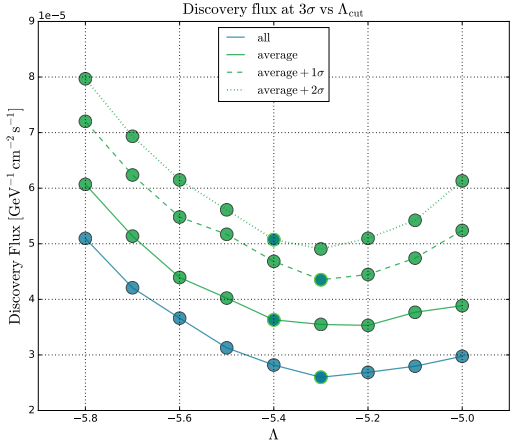


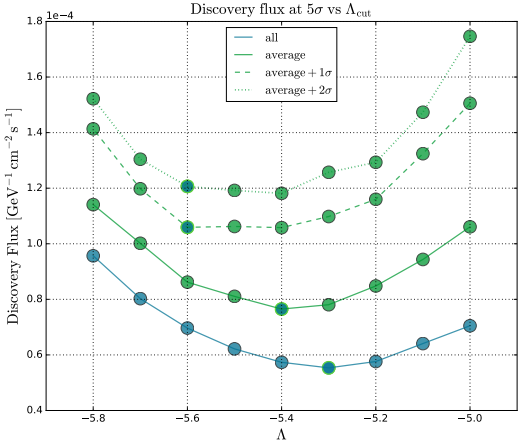
Discovery fluxes for $E^{-2.5}$

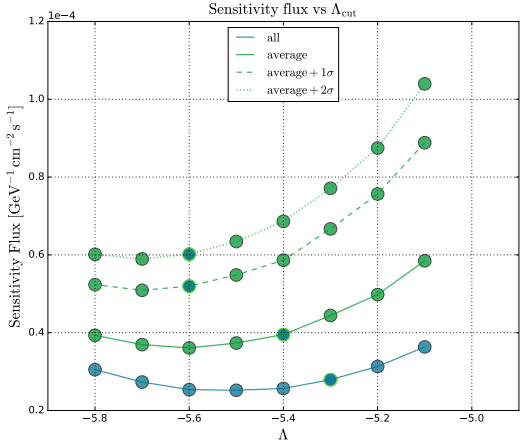




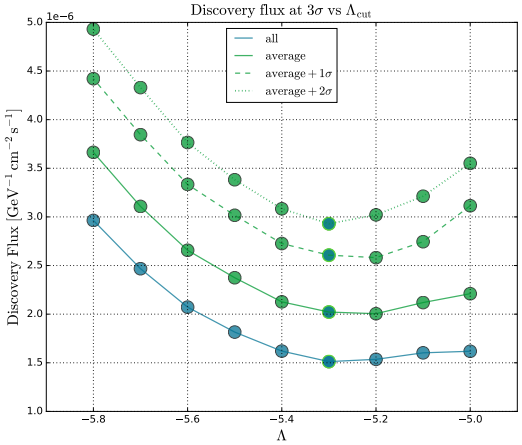


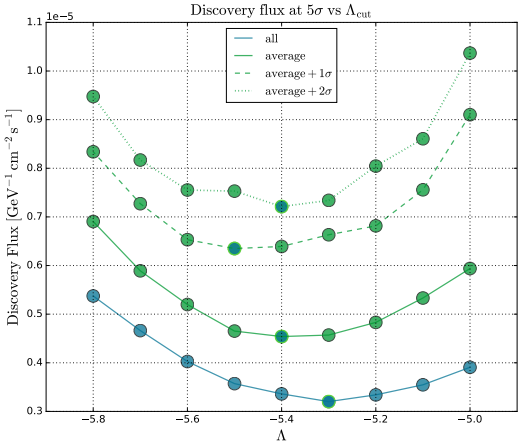


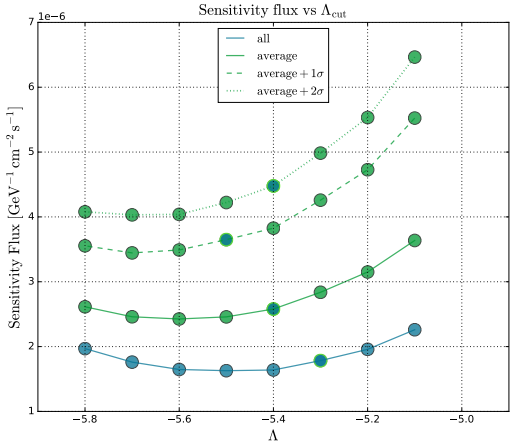




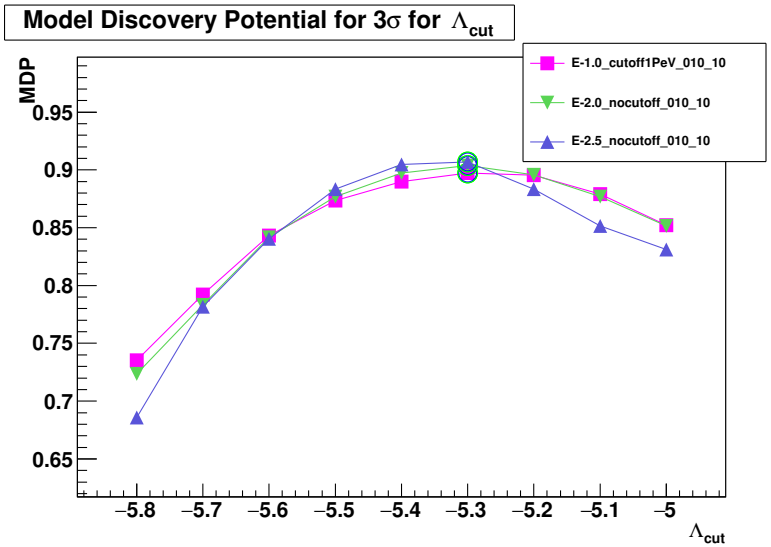
Discovery fluxes for $E^{-2.25}$ (Mrk 501 only)

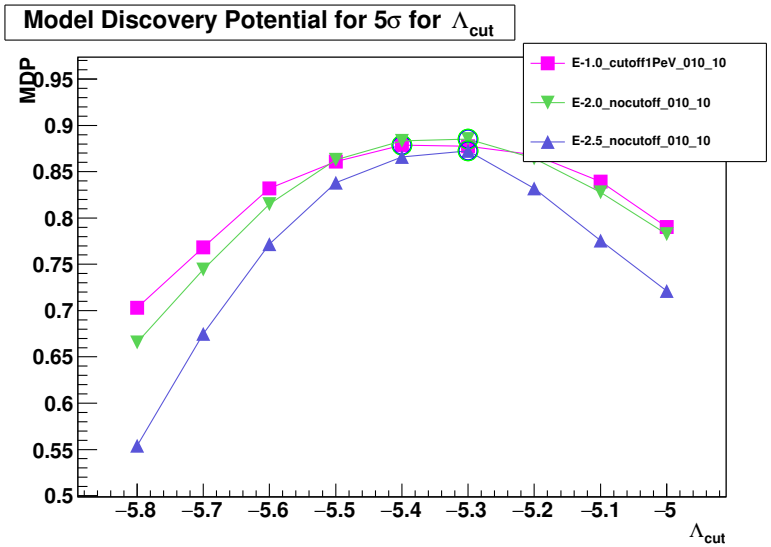


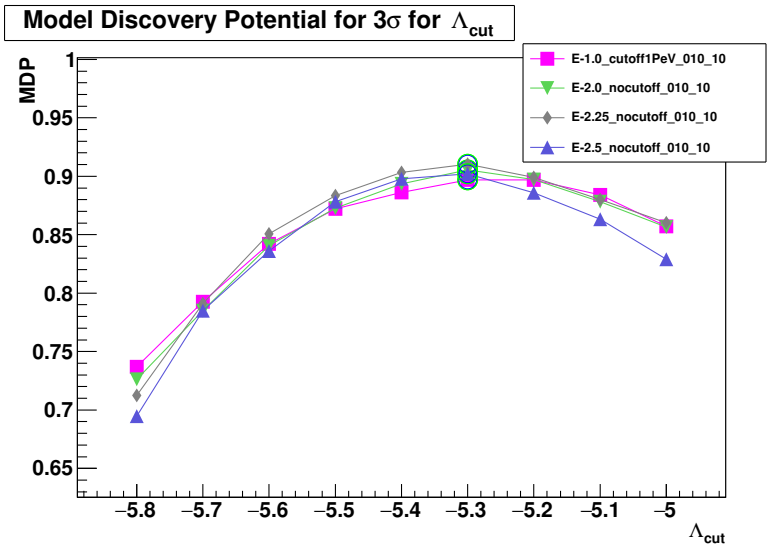


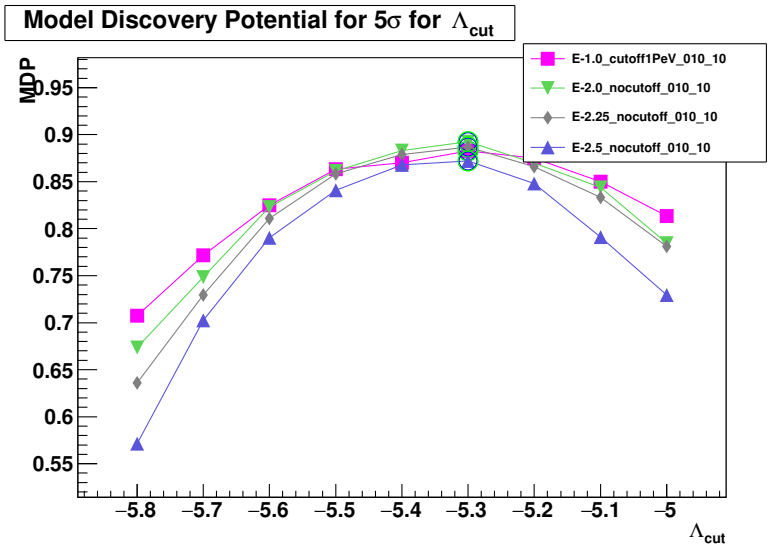


MDP, example for case of all flares









Sensitivities

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

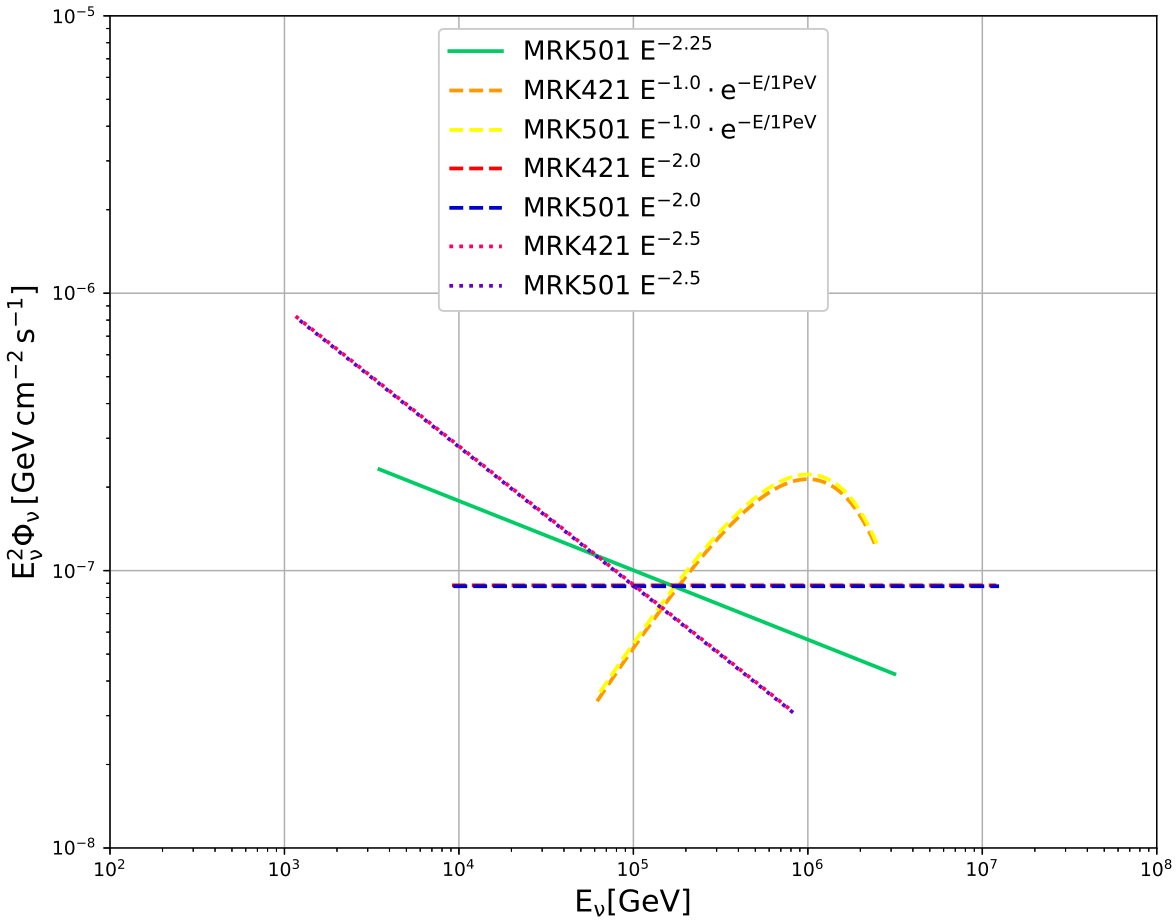
with the energy flux F as the energy per unit area and time $[GeV\, cm^{-2}\, s^{-1}]$:

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

Here :

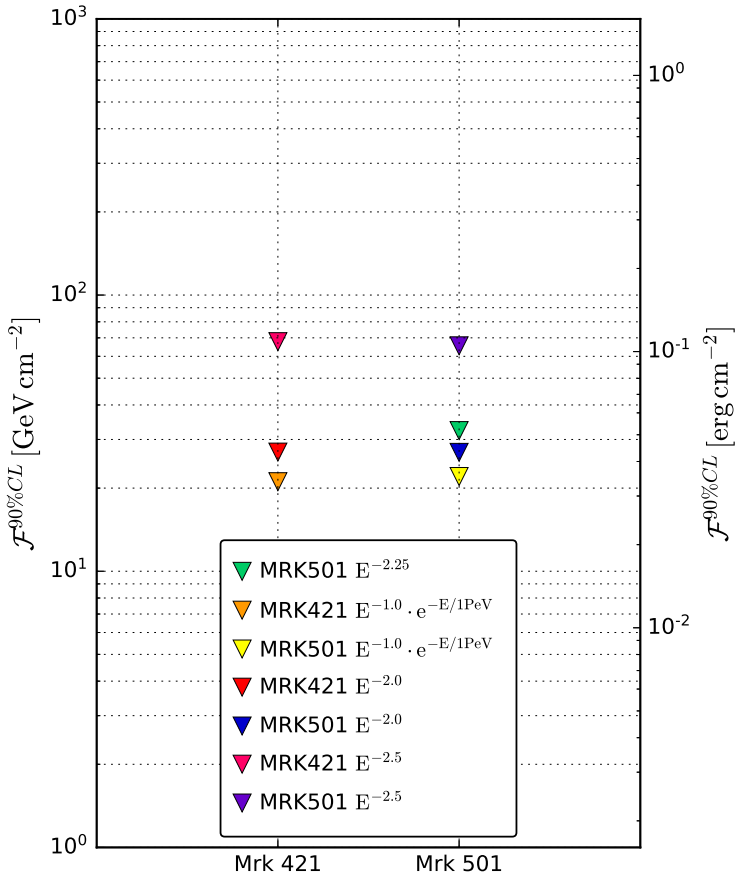
- ΔT is the livetime of the search $[s]$;
- $\Phi_0^{90\%CL} = DF^{90\%CL}$ is the upper limit on the ν flux normalization $[GeV^{-1}\, cm^{-2}\, s^{-1}]$;
- $\Phi_E = \Phi_0^{90\%CL}\, S(E) = DF^{90\%CL}\, S(E)$ is the differential flux $[GeV^{-1}\, cm^{-2}\, s^{-1}]$;
- $S(E)$ is the dimensionless 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.

Neutrino energy flux sensitivities [21]



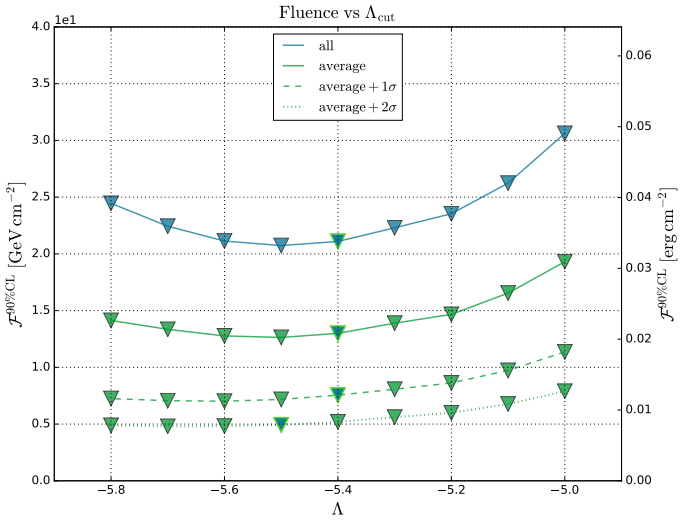
21. Obtained with case of all flares, give best sensitivities on ν fluxes

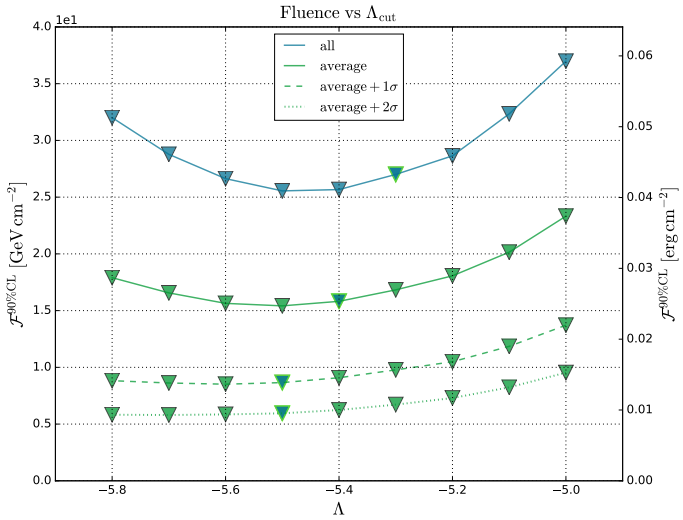
Neutrino fluence sensitivities [22] [23]

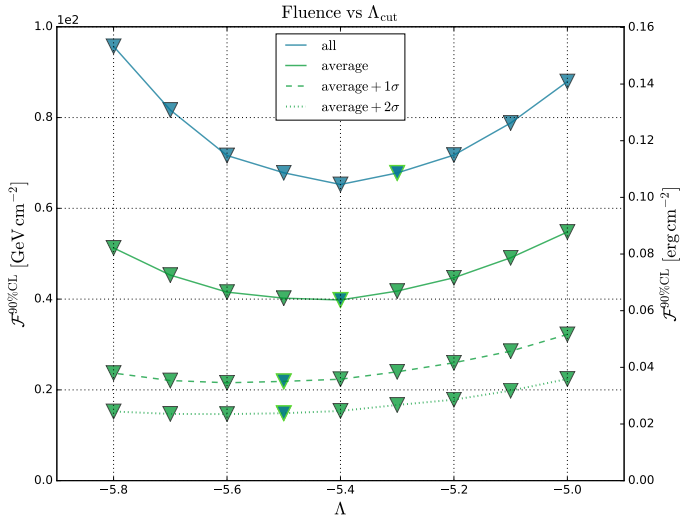


22. Obtained with case of all flares
23. But best sensitivities on ν fluxes can be obtained with *average flux + 2σ* ↪ gives one order of magnitude improvement w.r.t all flares.

Neutrino fluence sensitivities vs Λ, example for Mrk 421







Neutrino fluence sensitivities vs Λ, example for Mrk 501