The 2009 multiwavelength campaign on Mrk 421: Variability and correlation studies

Nina Nowak, David Paneque, Marlene Doert, Ulisses Barres de Almeida, Diego Tescaro

presented by
Francesco Borracci

On behalf of the Fermi-LAT, MAGIC, and other collaborations and groups involved in the multiwavelength campaigns

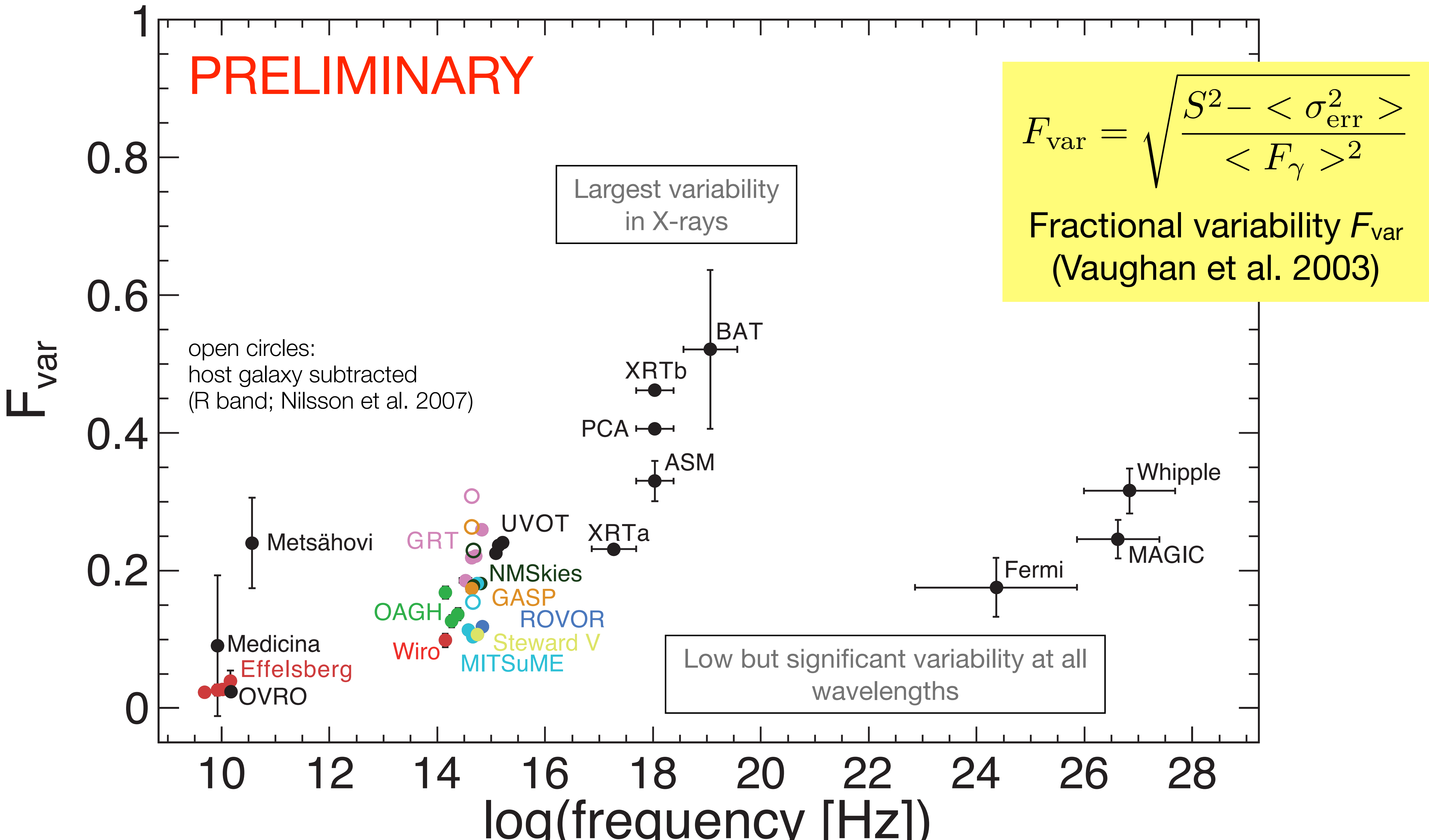
2009 MWL campaign on Mrk421

4.5 months long multiwavelength campaign in 2009 (PI: David Paneque):

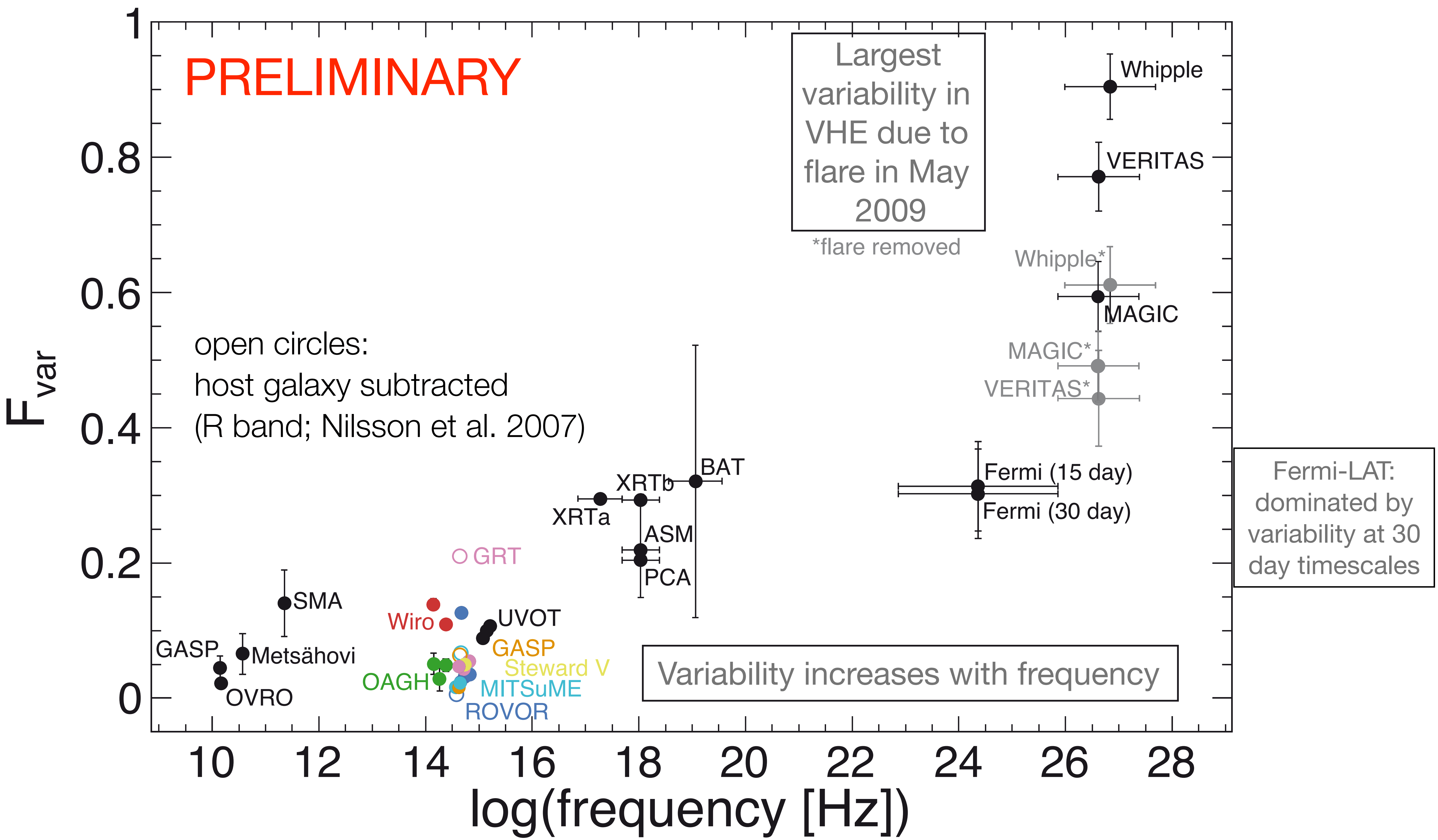
- Mrk421: Jan 19, 2009 (MJD 54850) - June 1st, 2009 (MJD 54983)
- monitored regardless of activity. However, Mrk 421 was in a relatively low state throughout the campaign
- participating collaborations/telescopes/instruments:

  MAGIC, Whipple, *Fermi*-LAT, *Swift*/BAT, *RXTE*/PCA, *Swift*/XRT, *Swift*/UVOT, GASP-WEBT, GRT, ROVOR, New Mexico Skies, MITSuME, OAGH, WIRO, SMA, VLBA, Noto, Metsähovi, OVRO, Medicina, UMRAO, RATAN-600, Effelsberg

Variability amplitude of Mrk 421



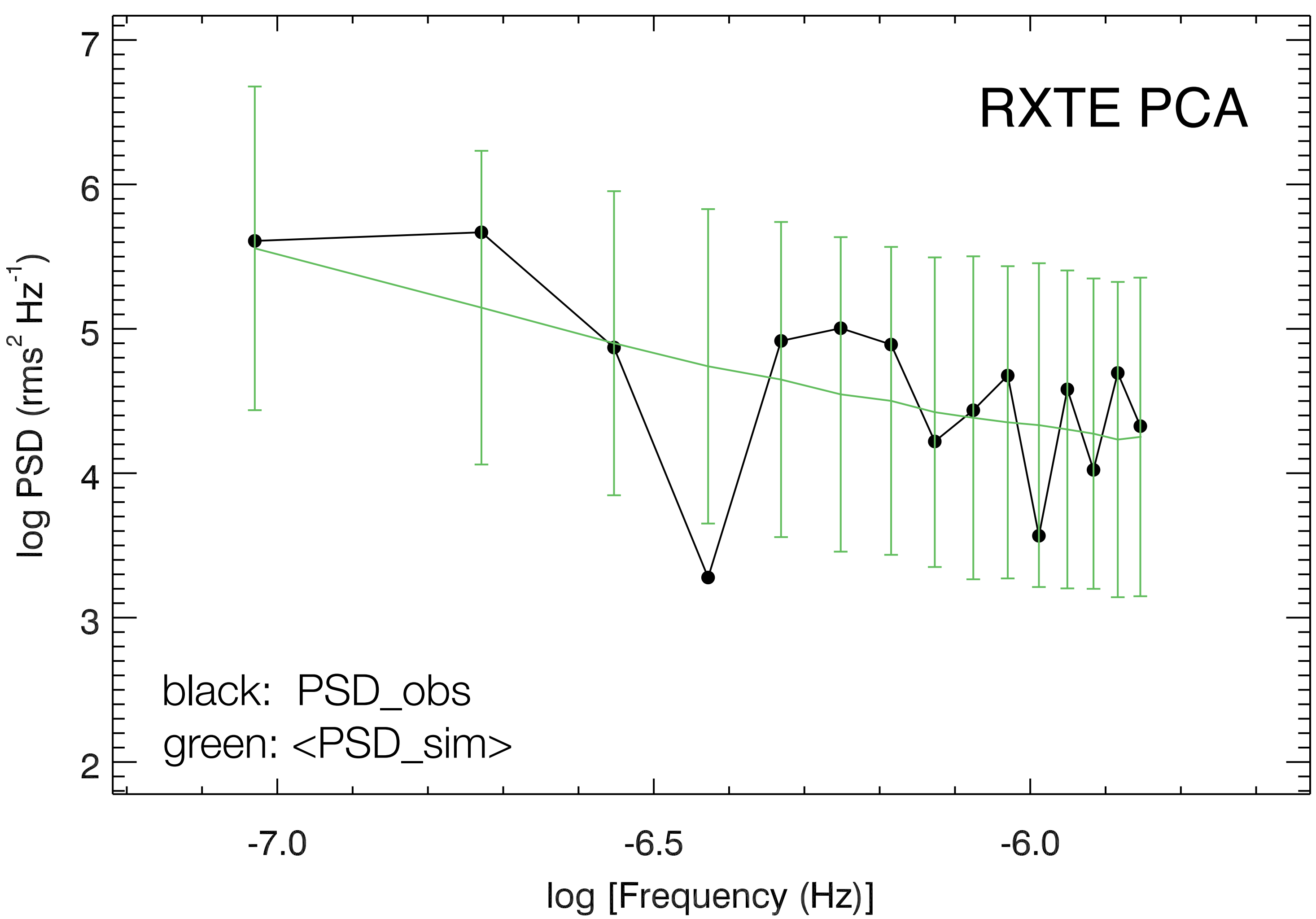
For comparison: Variability amplitude of Mrk 501

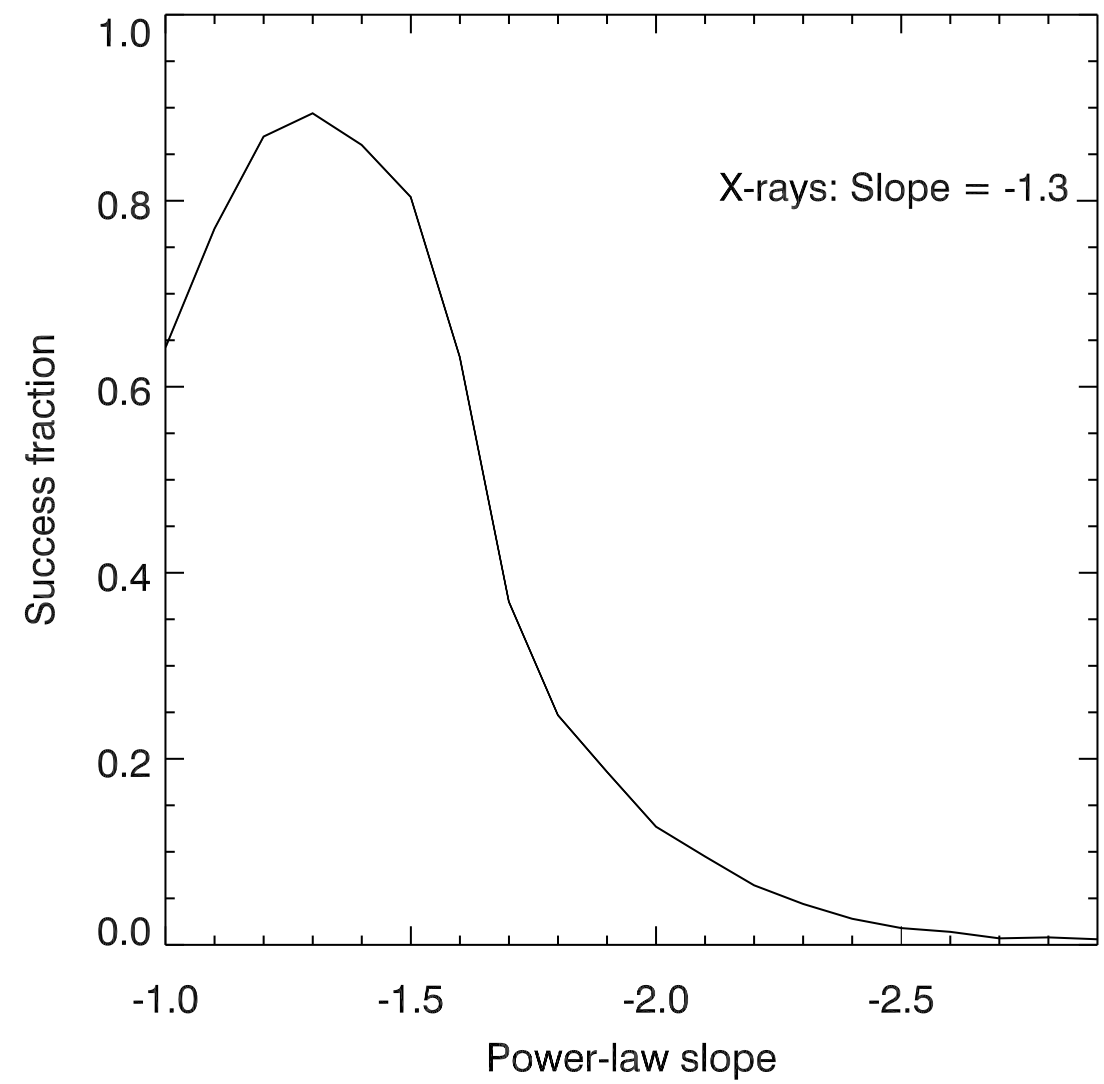


Power spectral density

- Distribution of the variability power among different Fourier frequencies
- obtained by using Discrete Fourier Transform method (problems due to length and sampling of lightcurves, particularly for uneven sampling) or simulation-based modelling (*PSRESP* method, Uttley+2002, Chatterjee+2008)
- Blazars: well described by simple or broken/bending power law $P_\nu \propto \nu^{-\alpha}$, with typical indices $1<\alpha<2.5$ and flattening at long time scales
- breaks indicate characteristic time scales, peaks indicate periodicities and the slope represents the dependence of the variability on time scale (white noise, pink noise, red noise processes)

PSRESP: X-rays





errors: from FWHM of success fraction as fct. of PSD slope

Results from PSRESP

- all PSDs consistent with simple power law without break. Slope between -1.3 and -2.0. Shape and slope consistent with results for other blazars (e.g. Chatterjee et al 2008, X-rays; Abdo et al. 2010, gamma rays)

- *PSRESP* with broken power law (slopes -1.0, -1.5, -2.0), breaks between 1 and 100 days and 100 simulated lightcurves per model does not improve PSD fits for any lightcurve.

- pink/red-noise nature of flux variations at all wave bands (i.e. greater amplitudes on shorter frequencies)

- X-ray PSD slope consistent with slope measured by Kataoka et al. 2001

- no peaks, i.e. no hint of periodicities in the probed frequency range (however, the resolution of the PSD is very low due to the sampling, thus it is not very sensitive to periodicities)

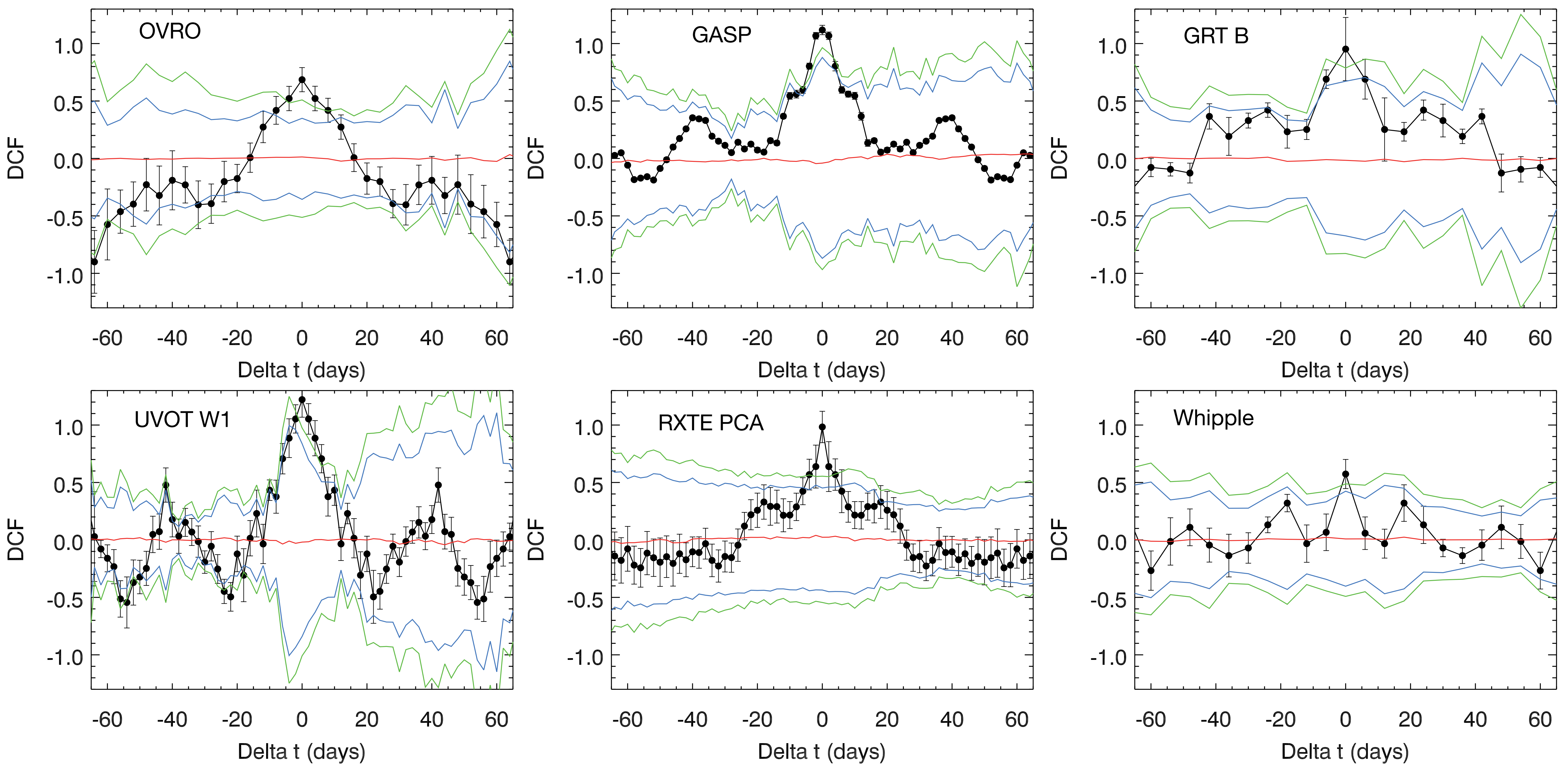
Search for char. timescales: DACF and LSP

- Discrete auto-correlation function (DACF; Edelson & Krolik 1988): equally spaced and repeated peaks or drops may be related to characteristic timescales or quasi-periodicity

- Lomb-Scargle-periodogram (LSP; Lomb 1976, Scargle 1982): LSP peak at a certain time lag can mean that there is a periodicity, but the sampling can also produce peaks.

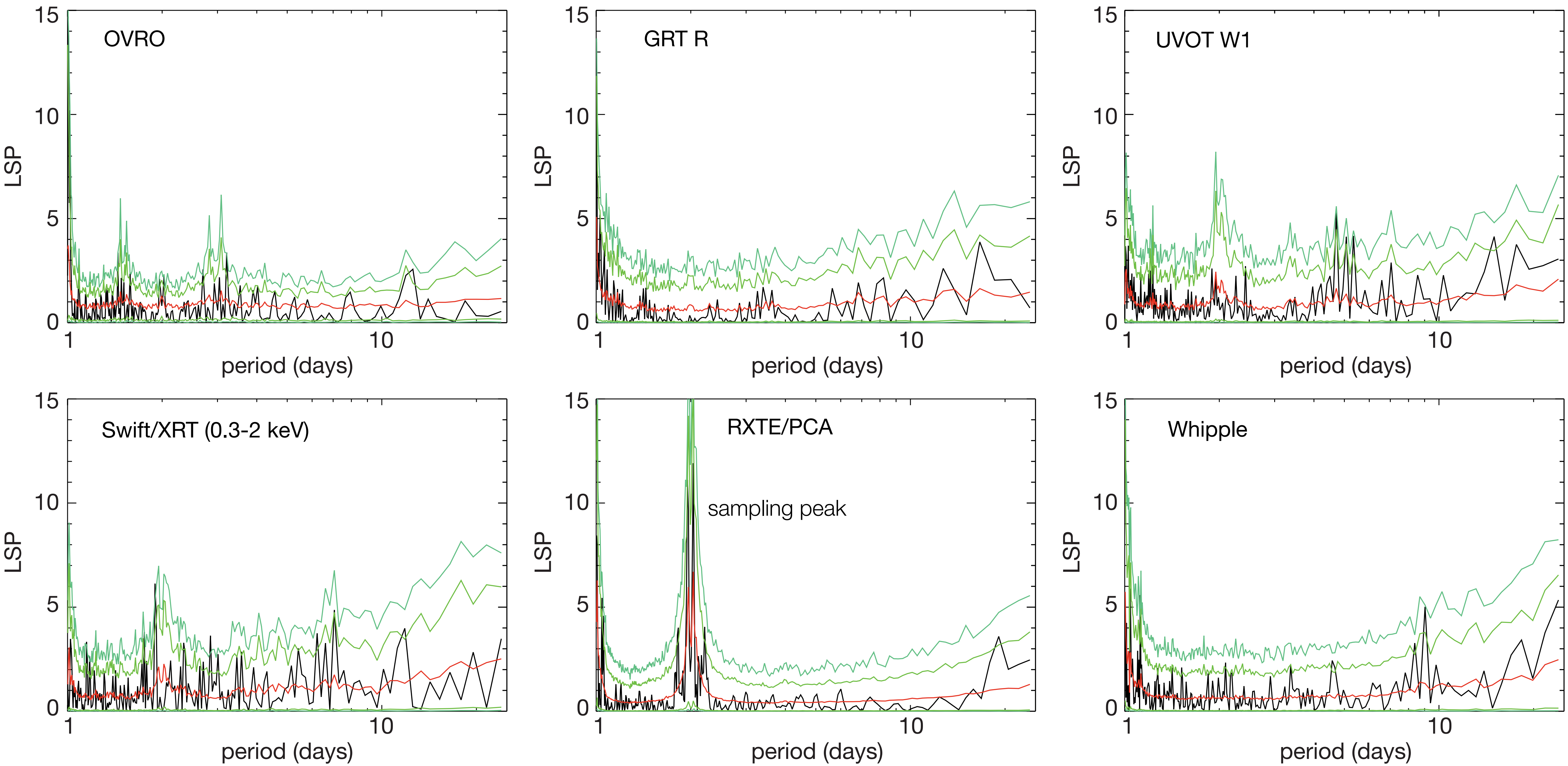
- estimate significance of peaks/drops from simulations: create 1000 simulated lightcurves according to Timmer&König, using the best-fitting PSD determined with *PSRESP*. Resample simulated lightcurves with observed sampling function. Then cross-correlate each simulated lightcurve with the observed lightcurve. Finally determine 95% and 99% confidence limits from the distribution of the 1000 DACFs resp. LSPs.

DACF



Simulations --> only central peak is significant.

LSP

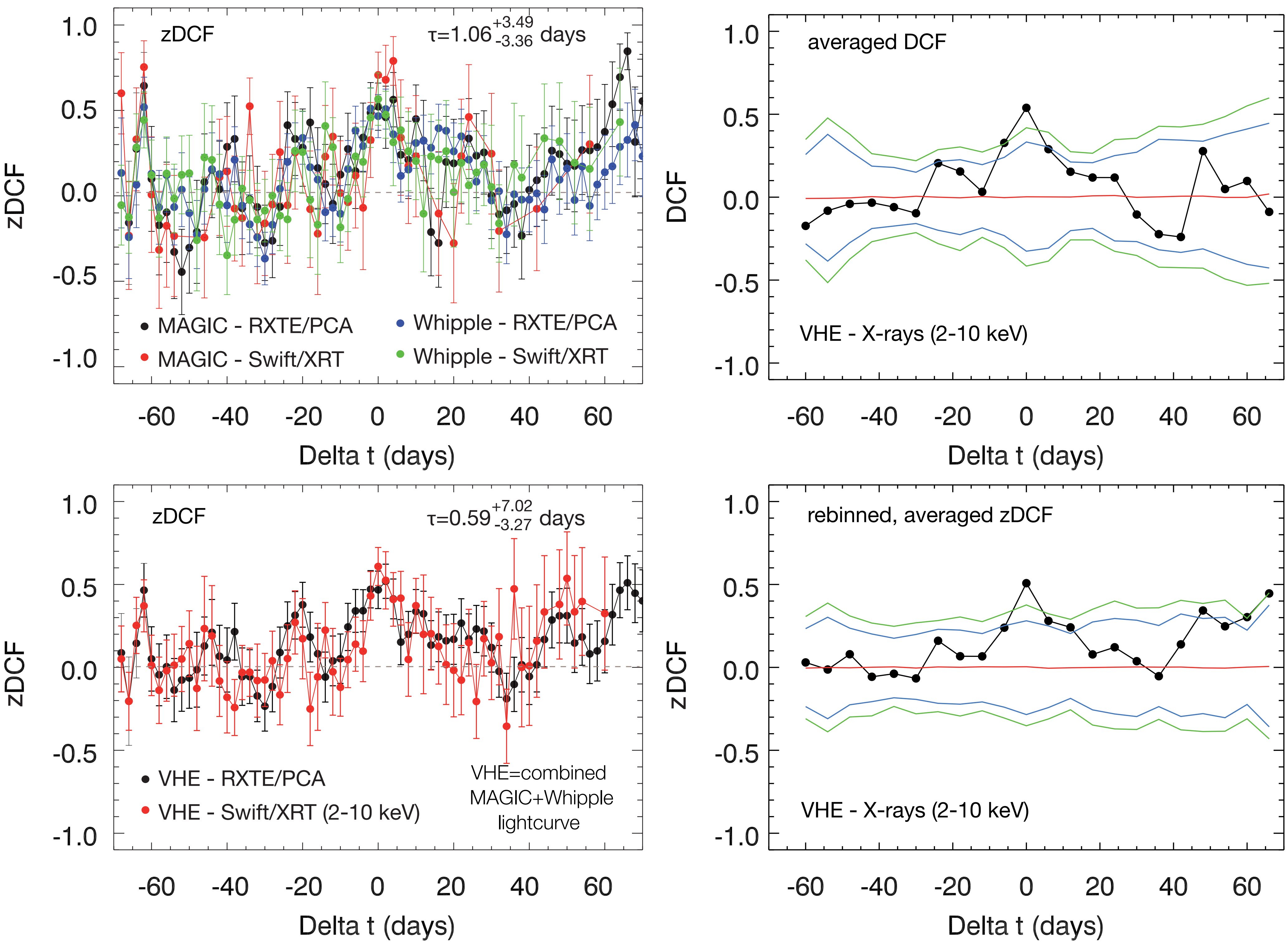


Simulations --> No significant peaks found.

Cross-correlation analysis

- Discrete correlation function (DCF; Edelson&Krolik 1988) and *z*-transformed discrete correlation function (zDCF; Alexander 1997). For well-sampled data DCF and zDCF produce consistent results (Smith&Vaughan 2007), for undersampled data (relative to the variability) the zDCF is more robust.
- significance of the correlation: from simulated lightcurves correlated with observed lightcurve, i.e., same procedure as for DACF and LSP
- DCFs were averaged, when several cross-correlations between identical frequency ranges were present, e.g. the 4 possible combinations between MAGIC, Whipple (>300 GeV) and RXTE/PCA, Swift/XRT (2-10 keV).

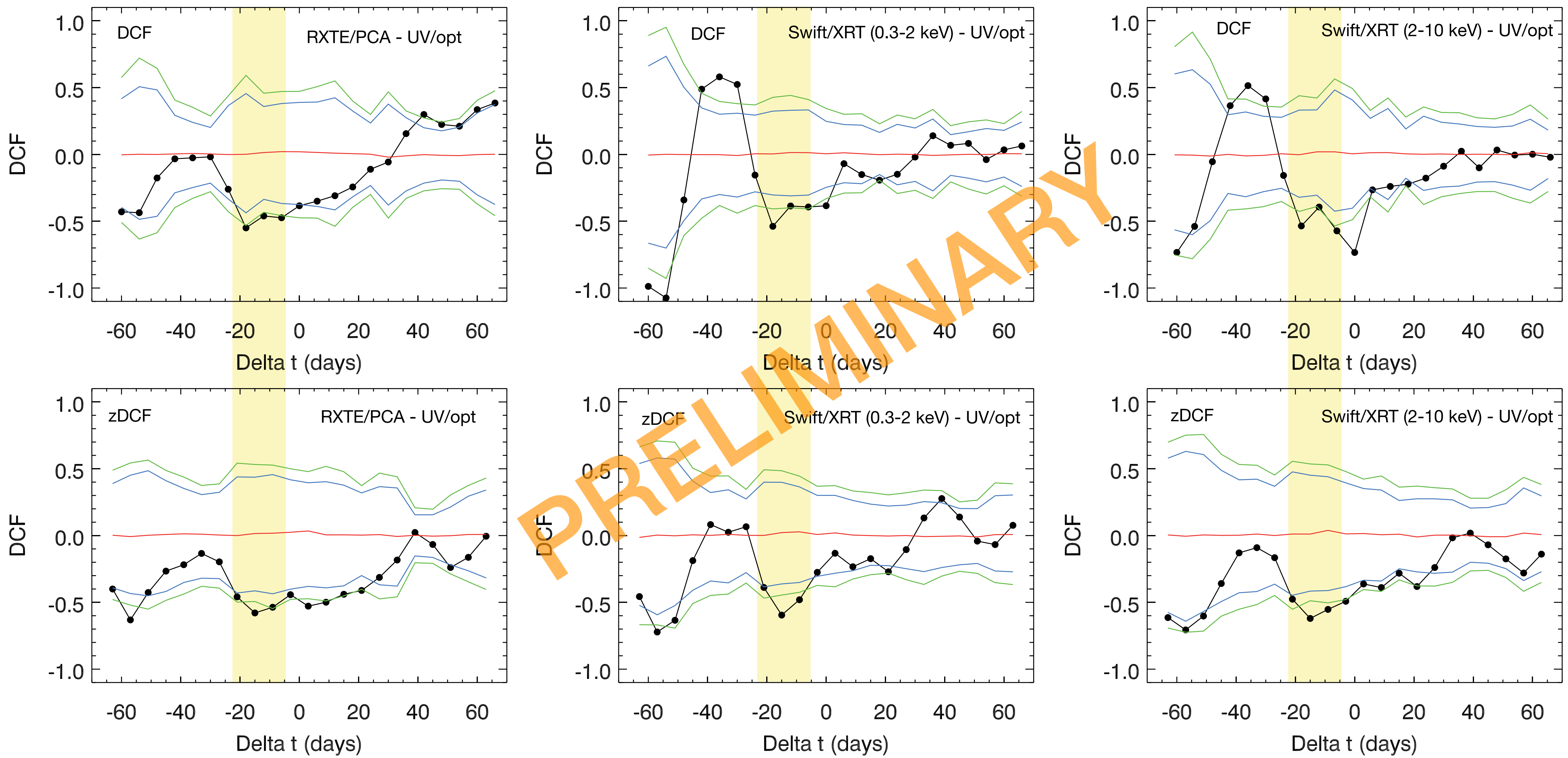
Cross-correlation analysis: VHE – X-ray



VHE and X-rays are correlated, verified by zDCF. When combining the DCFs, the significance is >99%. The time lag is consistent with 0 days

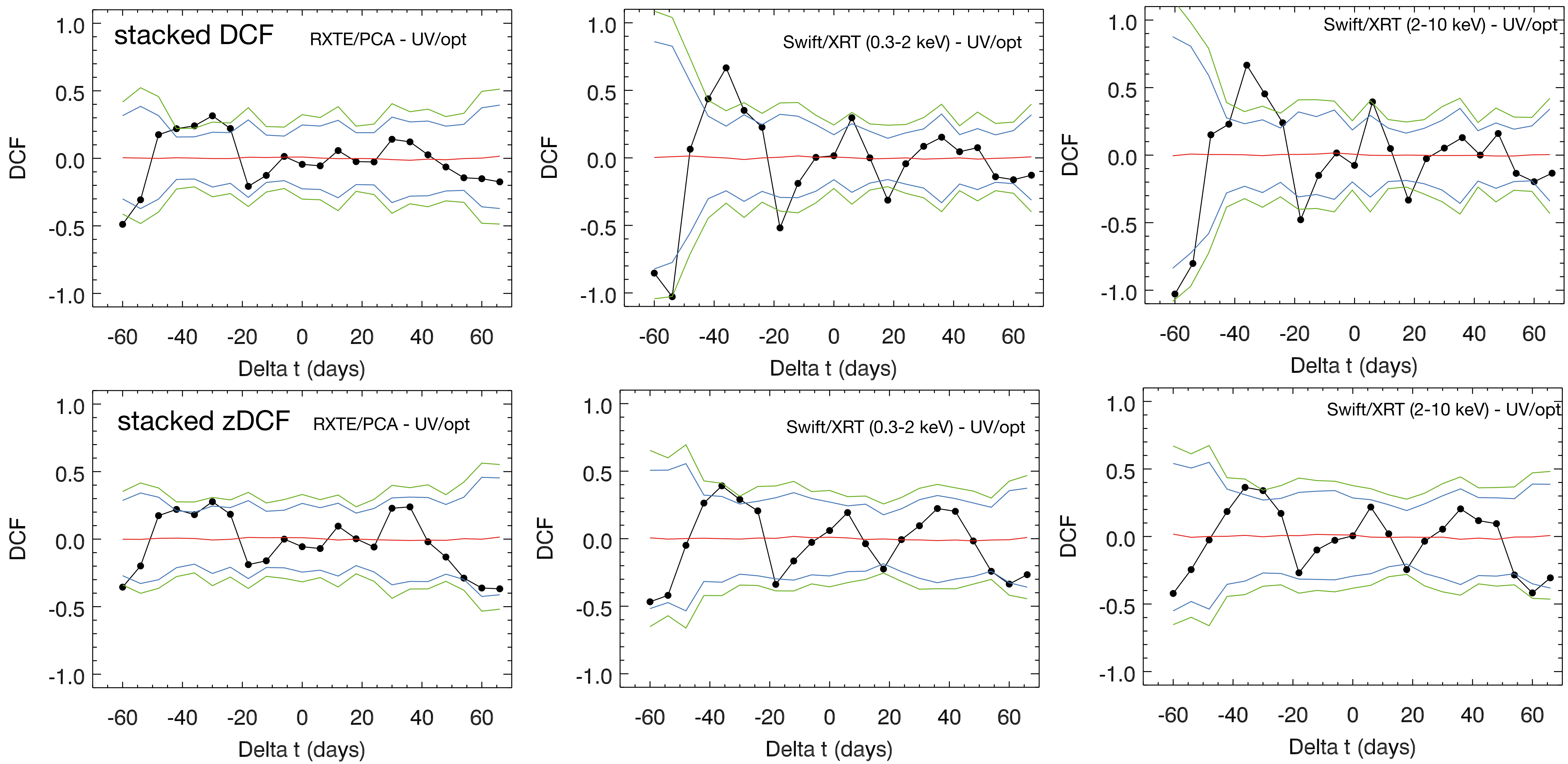
see http://www.weizmann.ac.il/weizsites/tal/research/software/ for the zDCF software and details of the method

Cross-correlation analysis: X-ray – optical



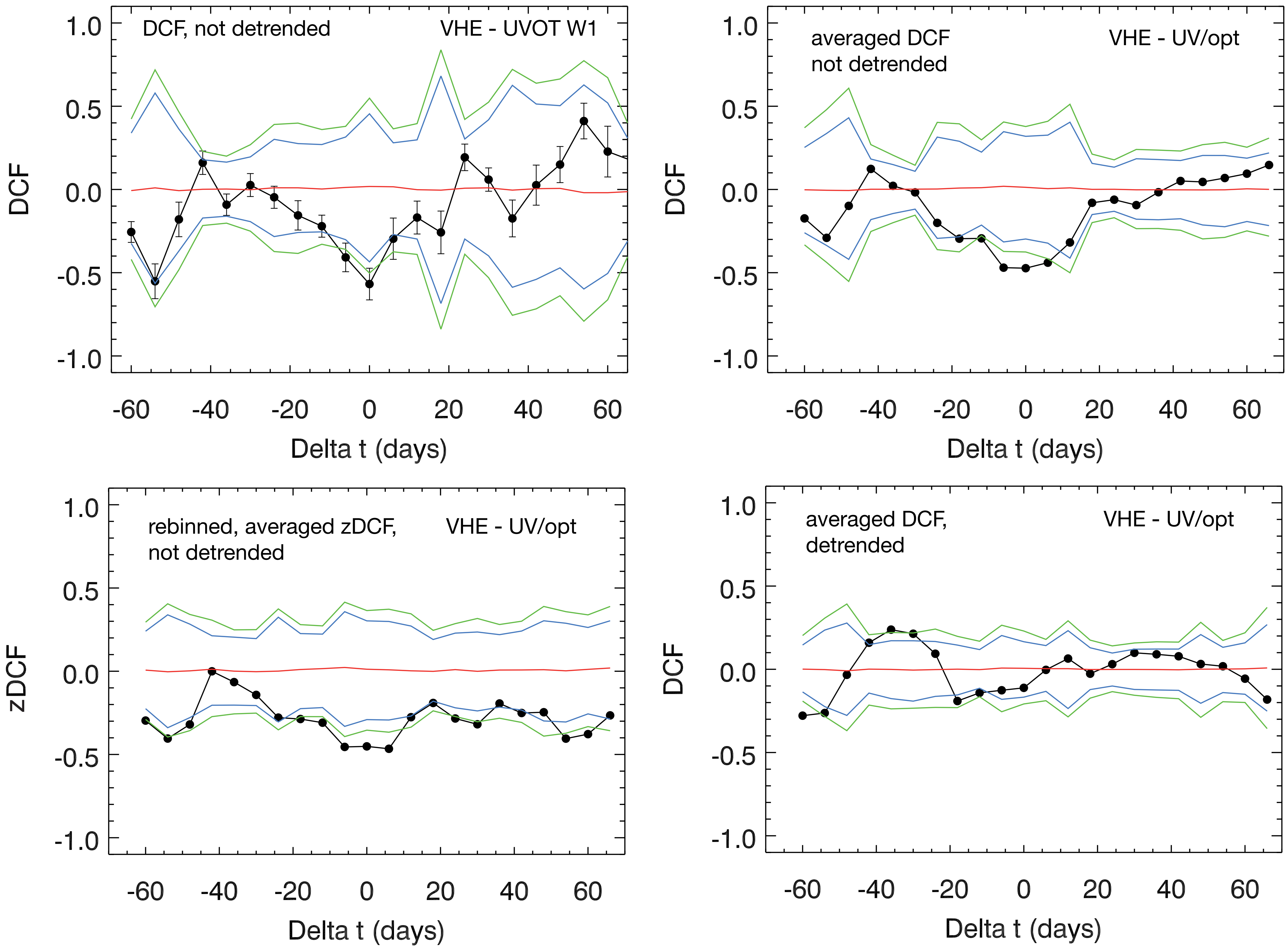
One feature common in all DCFs and zDCFs (marginally significant in single (z)DCFs, significance >99% in averaged (z)DCFs): anticorrelation at time lag around -15 days (i.e. optical/UV variations lead X-rays by 15 days)

Cross-correlation analysis: X-ray – optical



- after detrending the lightcurves: significance clearly decreases, several (very) weak (anti-)correlations @ time lags t=-36, -18, 6 and 18 days.
- need more data

Cross-correlation analysis: VHE – optical



VHE and optical/UV seem to be anticorrelated with significance >99%, time lag is consistent with 0 days. However, after detrending the lightcurves, the anticorrelation is gone, the DCF is now similar to the X-ray - optical one.

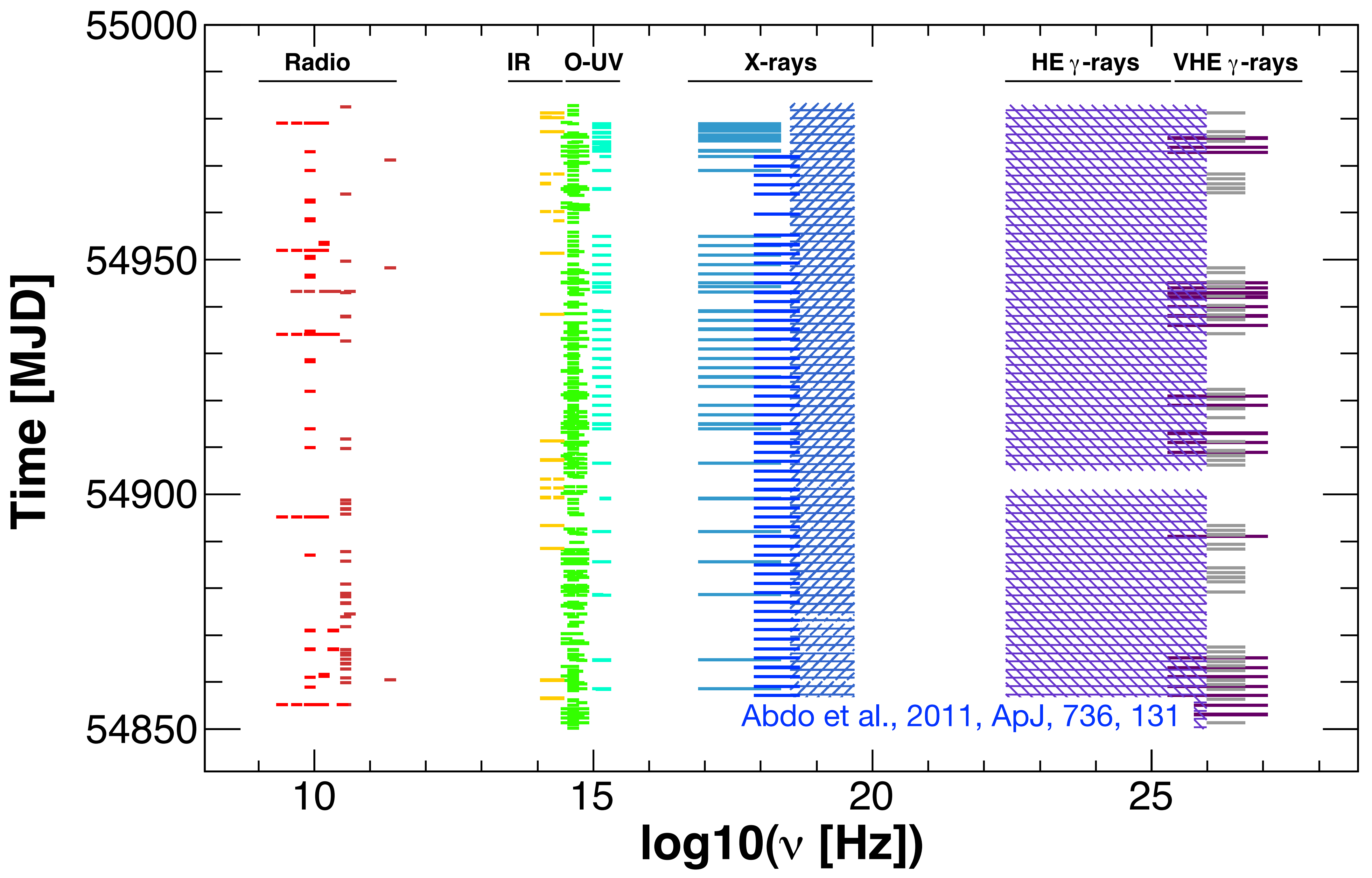
Anticorrelation caused by one event (i.e. opposite trend in the lightcurves) only!

Summary & Outlook

- Results on variability:
  - Mrk421 in low activity state throughout 2009 campaign
  - Fractional variability F_{var} low but significant at all frequencies, largest in X-rays
  - PSDs consistent with simple power law with slopes between -1 and -2
  - no periodicities or characteristic timescales (probed time interval for periodicities ~2-20 days, no flares)
  - clear correlation between VHE and X-rays (time lag = 0 days); possible (anti-)correlations between X-rays and optical

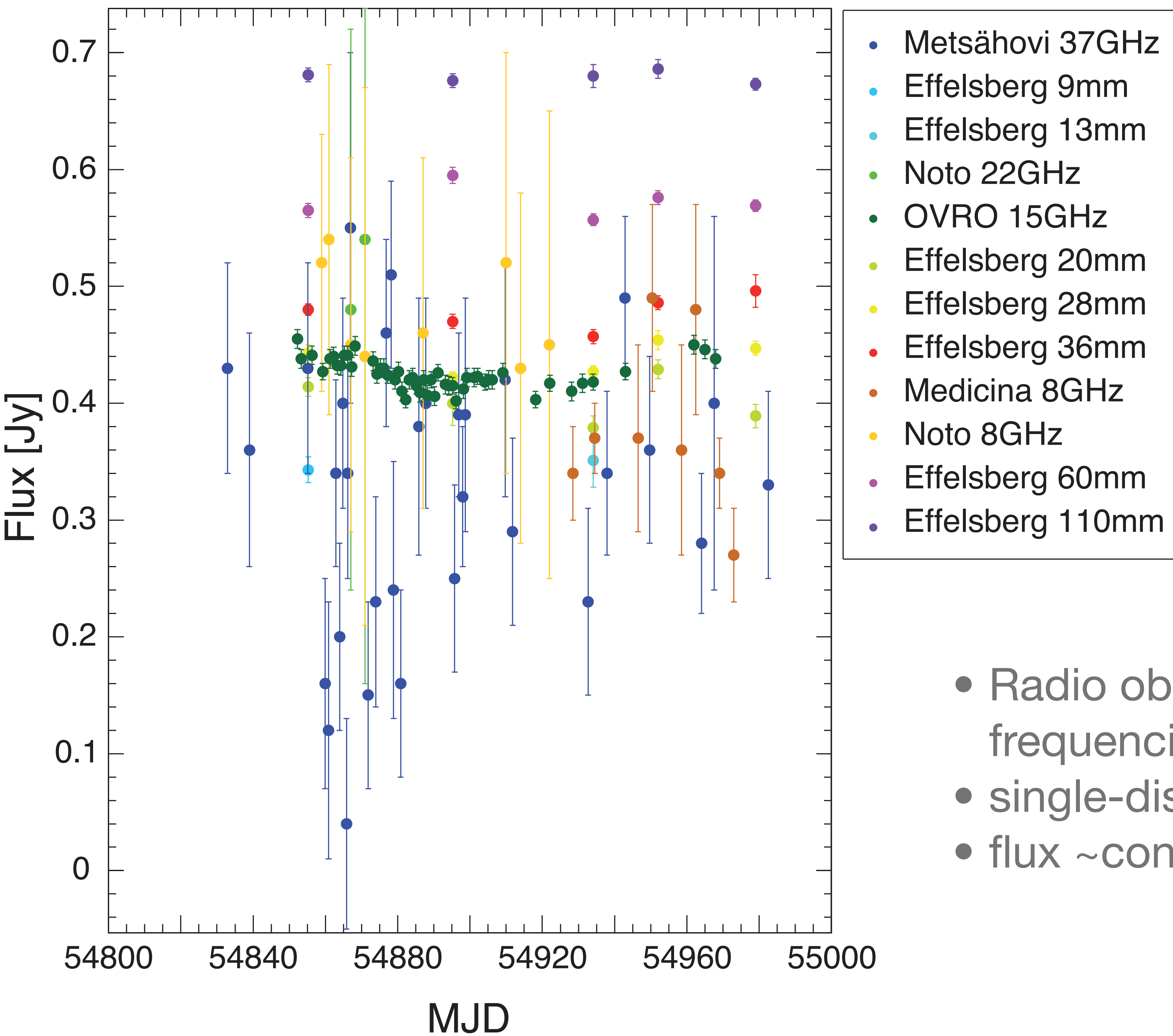
Backup Slides

2009 MWL campaign on Mrk42



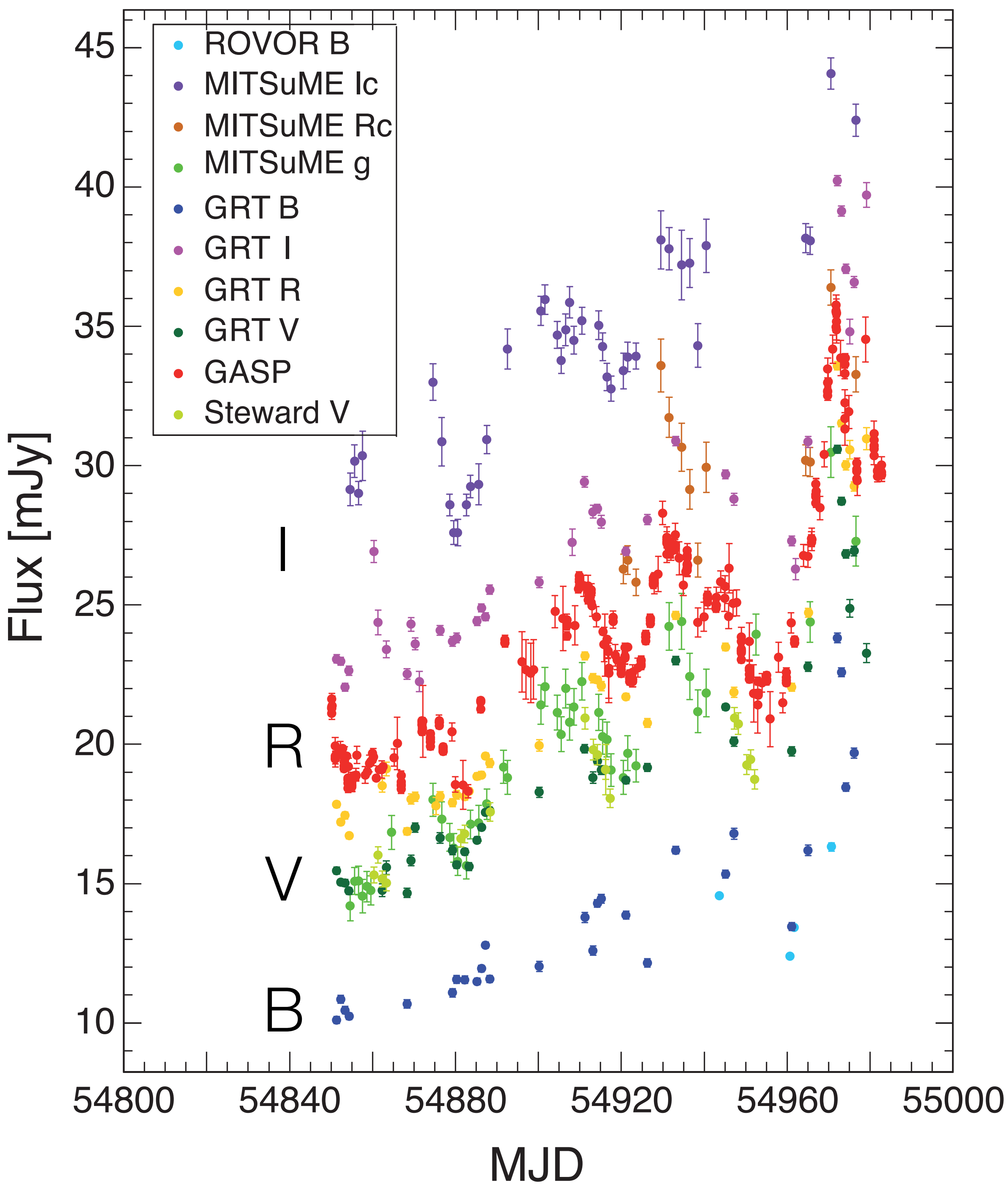
Excellent time and energy coverage

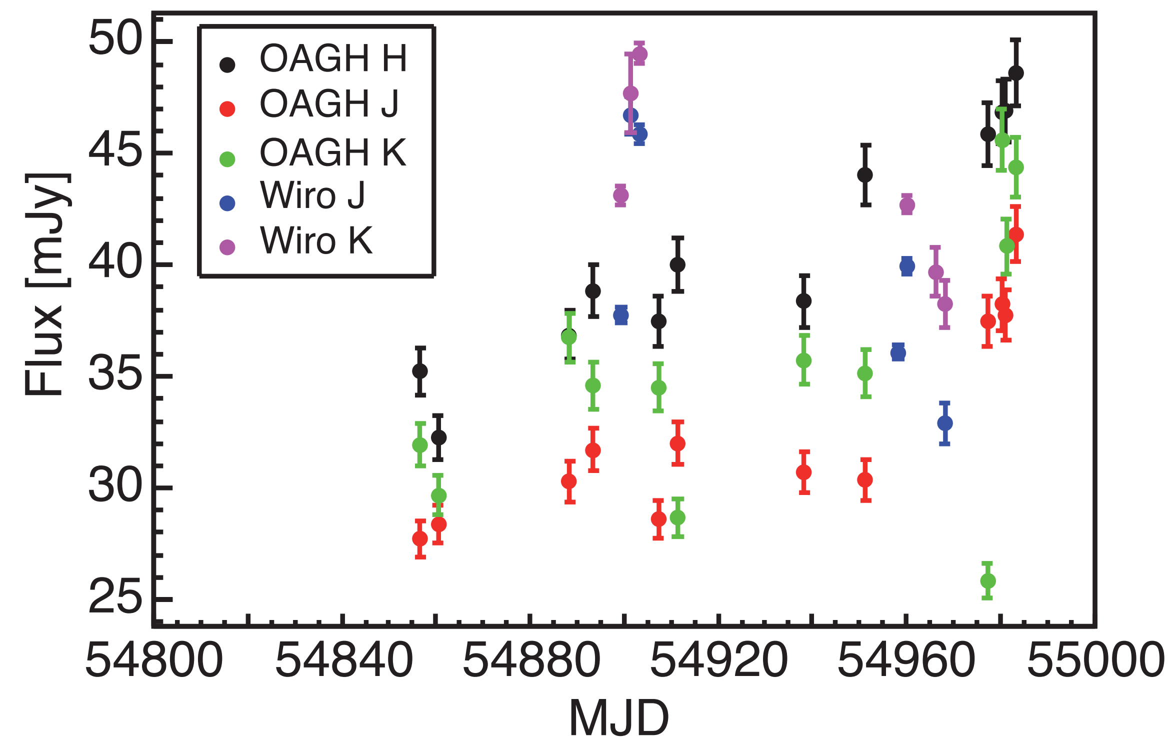
Lightcurves for Mrk 421 – Radio



- Radio observations at different frequencies
- single-dish instruments
- flux ~const., no strong variability

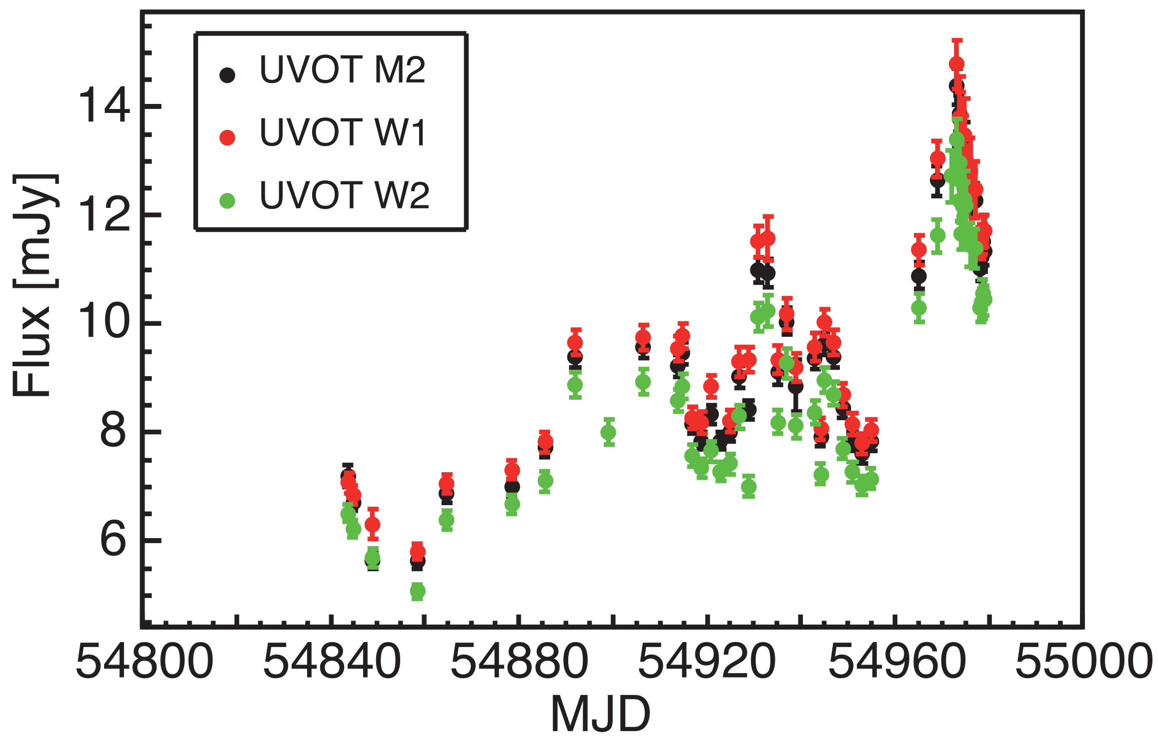
Lightcurves for Mrk 421 – NIR and Optical

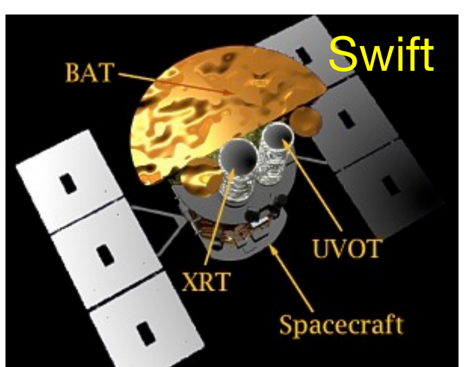


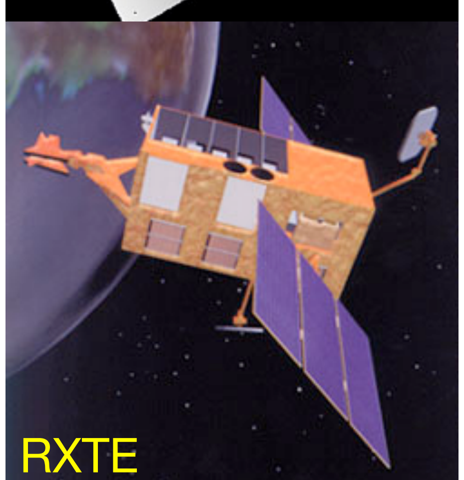


- good coverage of optical-NIR wavelengths provided by many telescopes around the world
- flux increases with time
- significant variability

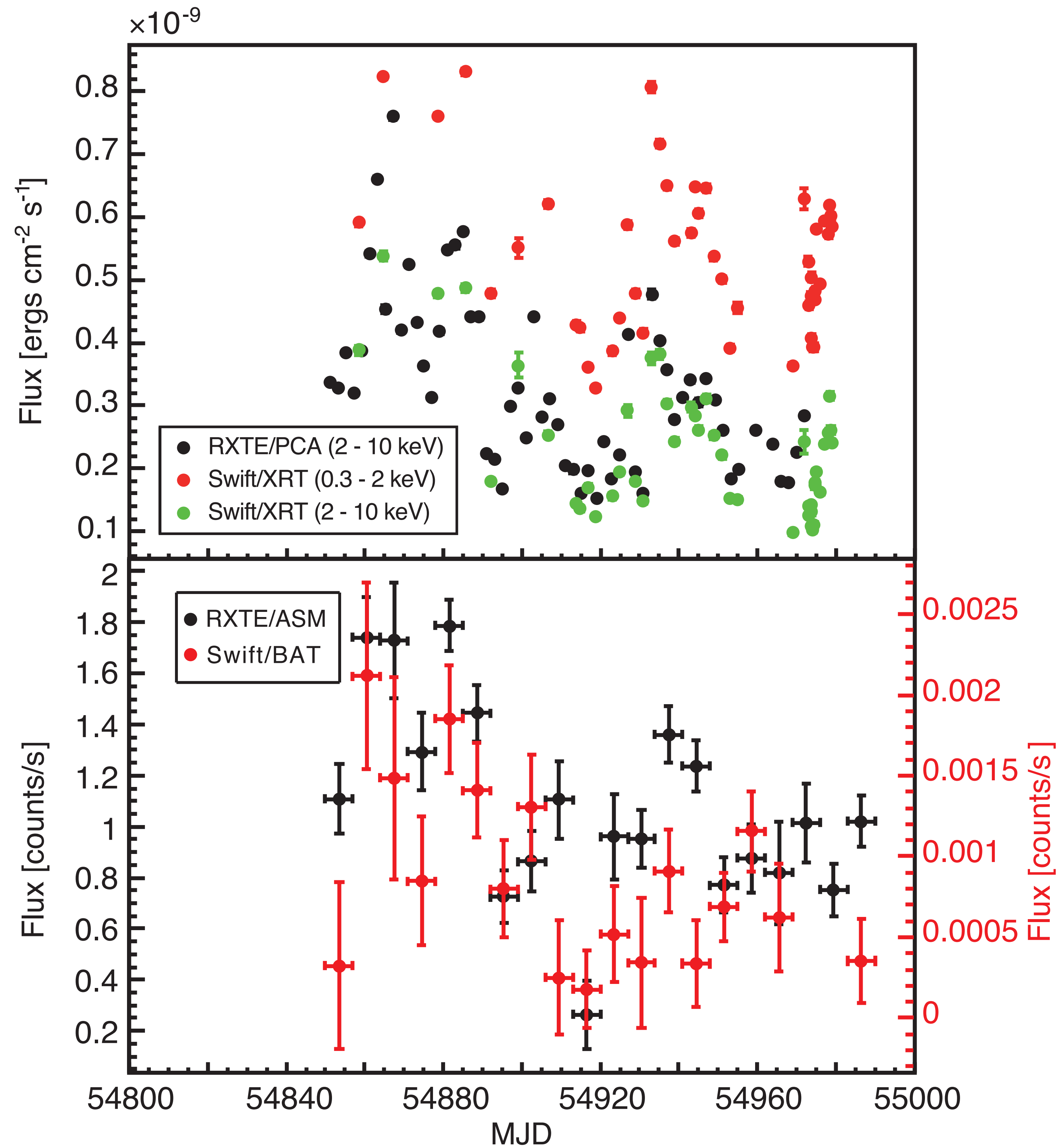
Lightcurves for Mrk 421 – UV and X-rays



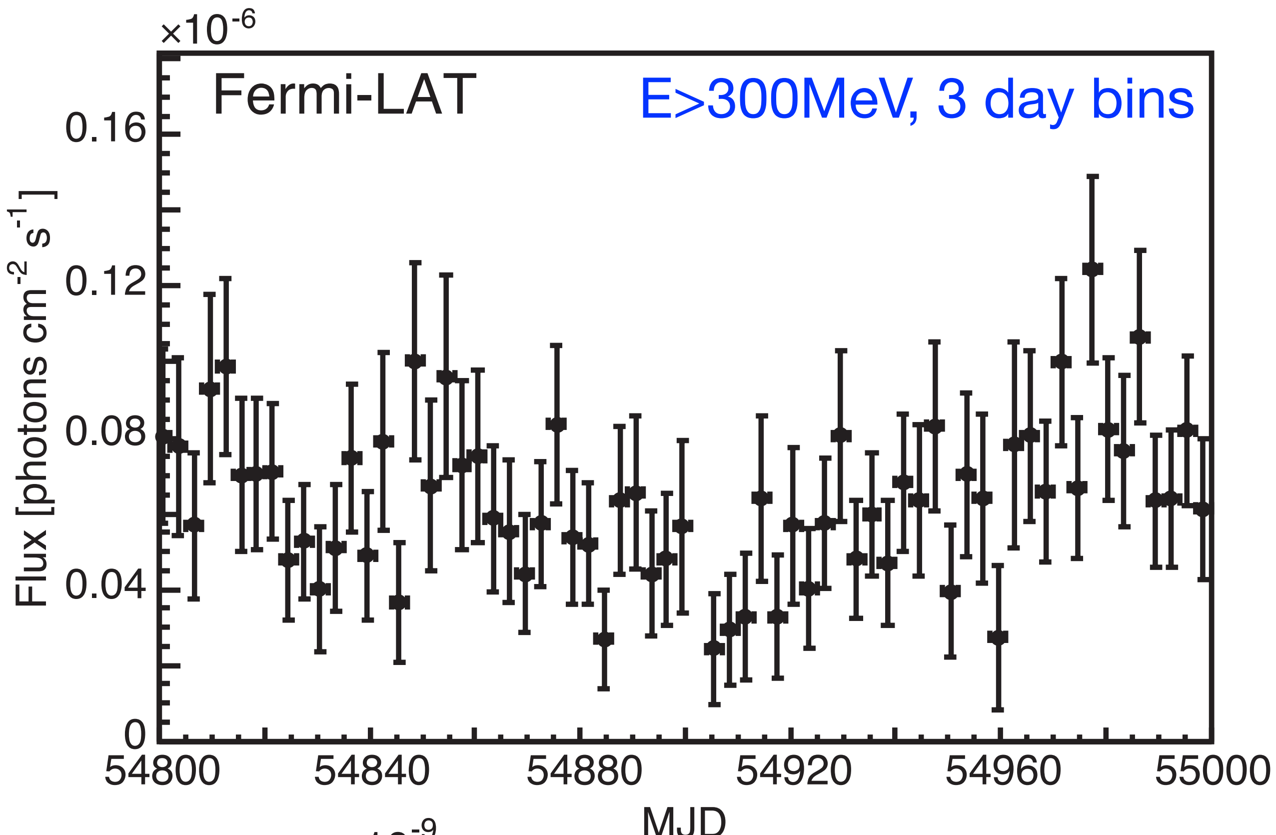




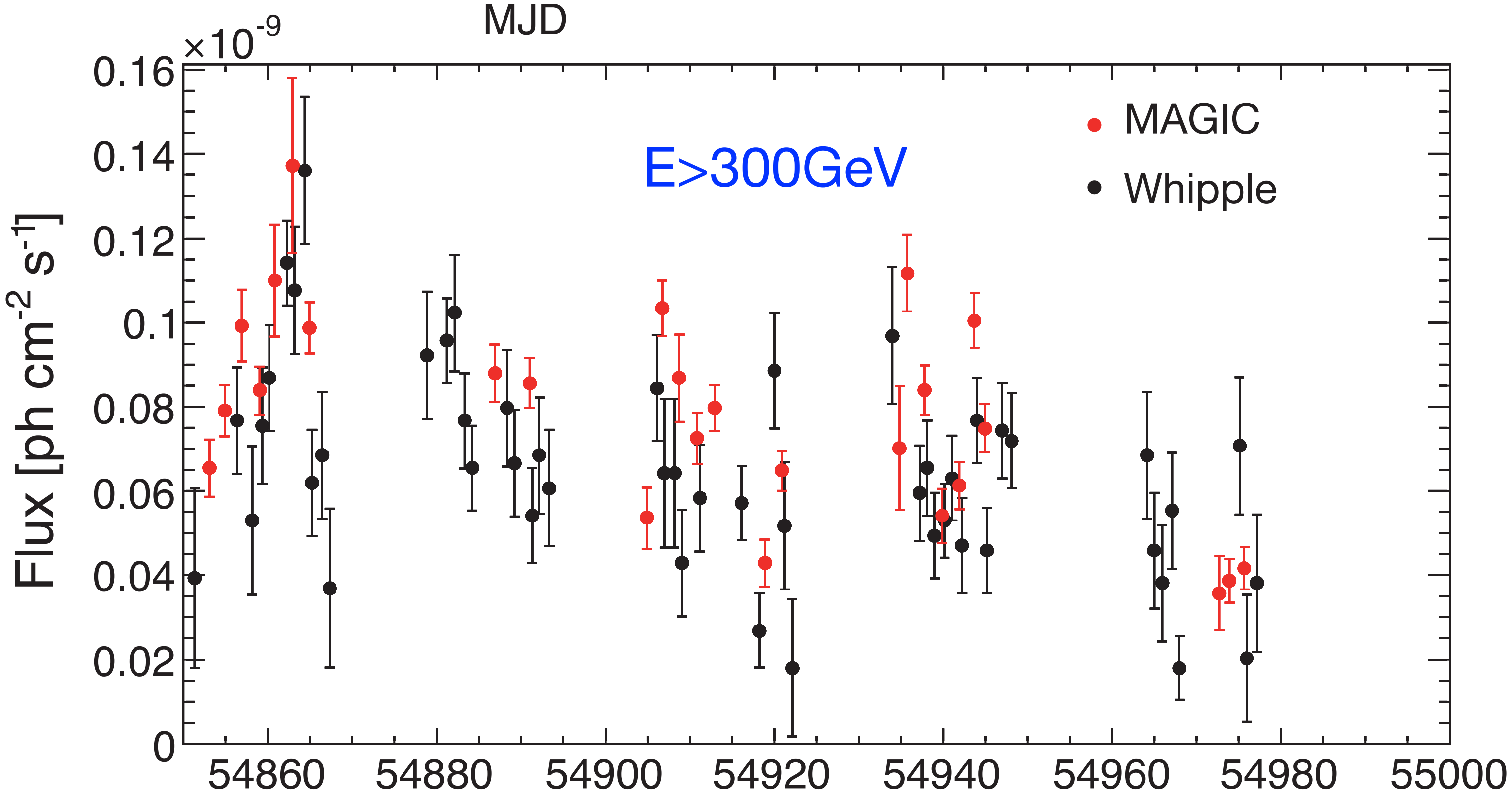
- UV: flux increases with time, significant variability
- X-rays: large variability amplitudes of ~factor 2

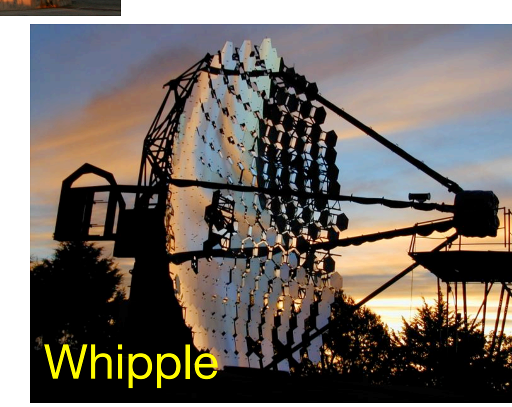


Lightcurves for Mrk 421 – γ-rays and VHE



- γ-rays and VHE: some level of variability
- no significant flaring activity





Simulation-based modelling

PSRESP method (Uttley+2002, Chatterjee+2008) to determine PSD shape:

- calculate PSD_{obs} of observed lightcurve
- simulate N lightcurves with trial PSD shape (e.g., trial values for slopes α_1 and α_2 and break frequency f_{br}) using Timmer&König 1995
- resample simulated lightcurves with observed sampling function
- calculate $PSD_{sim,i}$ of each resampled simulated lightcurve, determine model average $\langle PSD_{sim} \rangle$ and standard deviation ΔPSD_{sim}
- repeat for reasonable number of models
- use χ^2 analysis to determine model that best fits the observations:

$$\chi^2_{\rm obs} = \sum_{\nu=\nu_{\rm min}}^{\nu_{\rm max}} \frac{\left(\mathrm{PSD}_{\rm obs} - \overline{\mathrm{PSD}}_{\rm sim}\right)^2}{\left(\Delta\mathrm{PSD}_{\rm sim}\right)^2}$$

$$\chi^2_{{\rm dist},i} = \sum_{\nu=\nu_{\rm min}}^{\nu_{\rm max}} \frac{\left(\mathrm{PSD}_{{\rm sim},i} - \overline{\mathrm{PSD}}_{\rm sim}\right)^2}{\left(\Delta\mathrm{PSD}_{\rm sim}\right)^2}$$

- renormalization of $\langle PSD_{sim} \rangle$ to minimize χ^2
- goodness-of-fit from comparison of $\chi^2_{\rm obs}$ with $\chi^2_{{\rm dist},i}$, i=1 ... *M*: *m* = number of $\chi^2_{{\rm dist},i} > \chi^2_{\rm obs}$, m/M=success fraction (Chatterjee+2008)

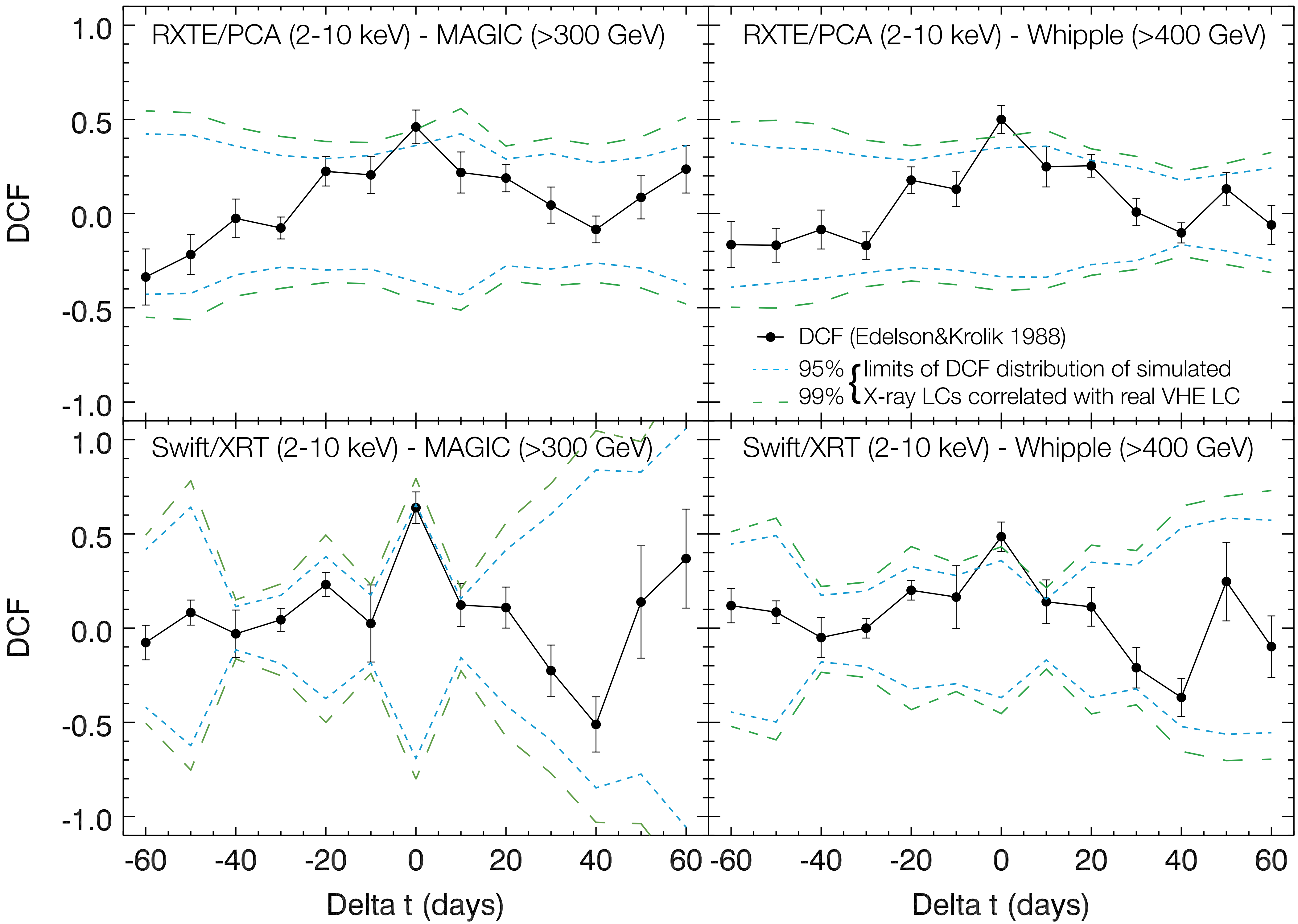
Simulation-based modelling

- *PSRESP* takes proper account of errors on PSD and distorting effects due to red-noise leak, aliasing, rebinning and large gaps (implicitly included in lightcurve simulation)
- disadvantages:
  - computationally very expensive (e.g., for a 3-parameter model with 10 trial values each, N=1000 and for 20+ different observed lightcurves we would have to create already $2x10^7$ simulated lightcurves)
  - time-consuming (optimize binning of each LC; optimize PSD binning to reduce scatter; judge if all this is worth the effort given the relative shortness and sparse sampling of the LCs etc.)
  - rebinning and interpolation of the data necessary, which might introduce distortions (e.g., due to many and/or large gaps) and reduces resolution
- done: simple power law with slopes between -1.0 and -2.9 in steps of 0.1 for selected LCs (OVRO, Metsähovi, GASP R, GRT BVRI, MITSuME, UVOT, RXTE PCA, Swift/XRT, Fermi-LAT, Whipple, MAGIC)

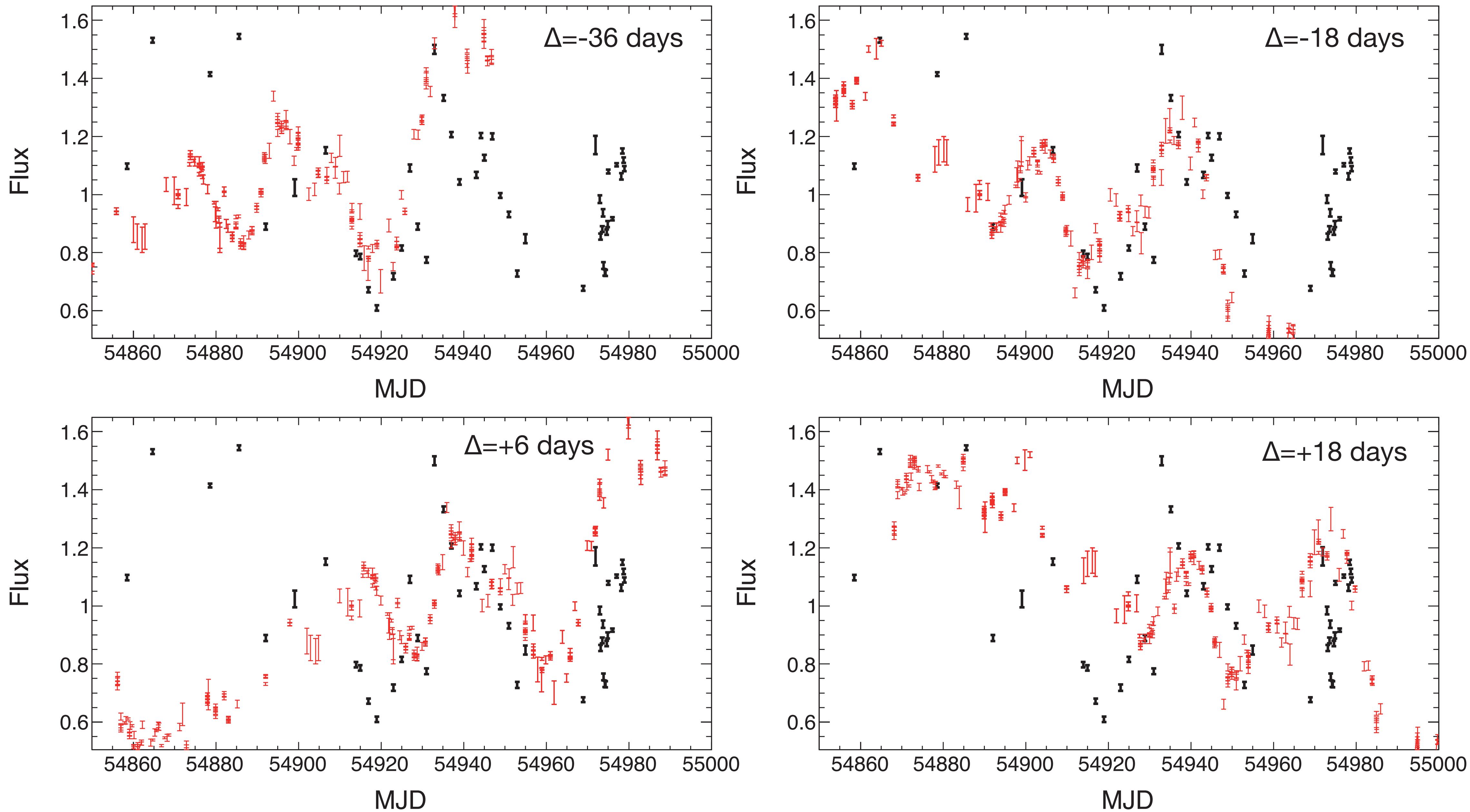
PSRESP: Results

Instrument	**α**
OVRO 15GHz	2.0
Metsähovi 37GHz	1.3
GRT I	1.5
MITSumE Ic	1.6
GASP R	1.9
GRT R	1.4
GRT V	1.5
MITSumE g	1.4
GRT B	1.4
UVOT W1	1.4
Swift/XRT (0.3-2 keV)	1.5
Swift/XRT (2-10 keV)	1.4
RXTE/PCA	1.3
MAGIC	1.5
Whipple	1.3

Cross-correlation analysis: VHE – X-rays



VHE and X-rays are correlated, Edelson&Krolik errors overestimate true significance due to red-noise nature of lightcurves (≈5-6σ vs. ≈2-3σ



- black: normalized XRT (0.3-1 keV) lightcurve
- red: normalised GASP (R-band) lightcurve, rescaled and shifted by -36, -18, +6 and +18 days, flipped in case of anti-correlation.
- just from visual inspection: no clear 1:1 correlation. There are always features that seem to correlate quite well while others do not. From this short time interval one cannot say more than “there might be a correlation - or not” in agreement with DCF results.