Multiwavelength blazar variability from radio to TeV photon energies on timescales ranging from decades to minutes

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Stochastic blazar variability

- Random, aperiodic intensity variations across **ALL** wavebands and on **ALL** timescales.

- The typical shape of power spectral density (PSD; $P(\nu_k) \propto \nu_k^{-\beta}$) is a power-law (COLORED NOISE; $\beta \sim 1-3$)–stochastic process.

- Is the process stationary in time?

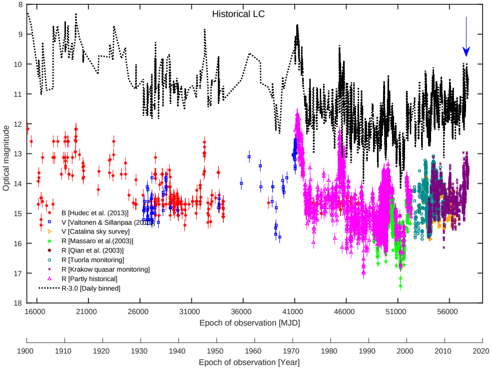


Figure 1: 117 year-long optical light curve (LC) of OJ 287 (Goyal et al., 2018)

Synchrotron and IC-dominated spectral regions

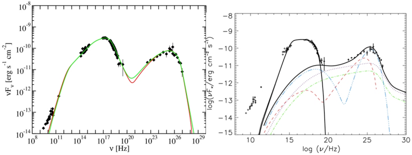


Figure 2: Spectral energy distribution (SED) of Mrk 421 from Abdo et al. (2010a) (*left*: Leptonic scenario) and (*right*: Hadronic scenario)

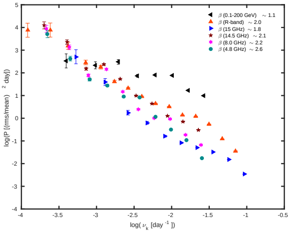


Figure 3: PKS 0735+178 (Goyal et al. 2017)

Problems with SED fitting:

1) Too simplified model setup (single-zone SSC model) – NO **‘characteristic/relaxation’** timescale.

2) Lack of statistically significant correlations (Max-Moerbeck et al. 2014, Lindfors et al. 2016; **Exceptions** Hovatta et al. 2014, Furhmann et al. 2016)

- *Fermi*-LAT energies: $\beta \sim 1$ (Flicker/pink-noise)!
- Radio/optical energies: $\beta \sim 2$ (Brownian/red-noise)!

Variability spectrum from years to minutes timescale

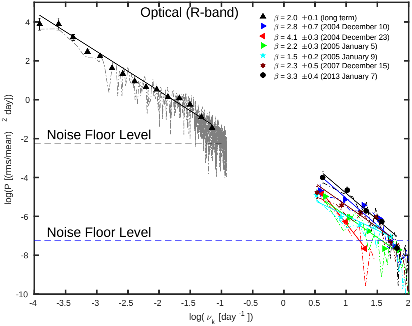


Figure 4: PKS 0735+178 (optical energies; Goyal et al. 2017).

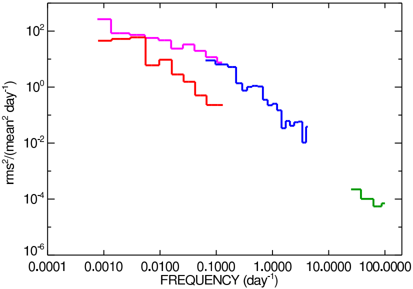


Figure 5: 3C 279 (*Fermi*-LAT energies; Ackermann et al. 2016).

- Optical energies: $\beta \sim$2 (long-term) and $\beta \sim$1–3 on minutes timescale!
- $\gamma-$ray energies: $\beta \sim$1 (long-term) and $\beta \sim$1 on minutes timescale!
- NO change in normalization!

Minute-like flare of PKS 2155−304

Yet,

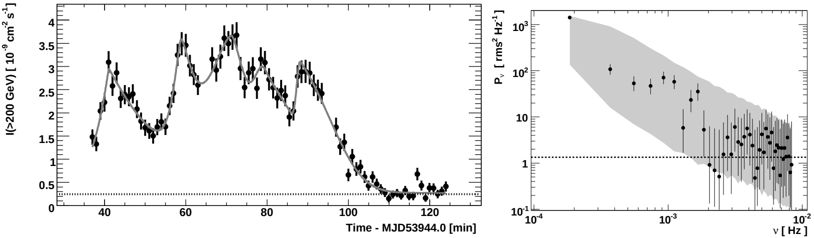


Figure 6: PKS 2155-304 (Aharonian et al., 2007).

•H.E.S.S. energies $\beta \sim$2 (red noise!) on intra-night timesales vs. $\beta \sim$1 on years to weeks timescales (Abdalla et al. 2017).
$=>$ Nature of variability process changes on $\sim$ daily timescales.

Data acquisition and analysis methods

- **TeV-γ-rays**: H.E.S.S. and VERITAS ($\geq$200 GeV)
- **GeV-γ-rays**: *Fermi*-LAT (0.1-300 GeV) satellite
- **X-rays**: *Swift*-XRT (0.3-10 keV) and *RXTE*-PCA (3-20 keV) satellites
- **Optical frequencies** : SMARTS, Tuorla and Kepler satellite
- **Radio frequencies** : UMRAO (4.8, 8, 14.5 GHz), OVRO (15 GHz) and MRO (22 and 37 GHz)

Determination of statistical properties of light curves using PSDs:

- LC analysis in Fourier-domain: Discrete Fourier Transform (DFT; Uttley et al., 2002, Max-Moerbeck et al. 2014, Goyal et al. 2017) – **Biases due to red-noise leak, aliasing and uneven sampling.**

- LC analysis in time-domain: modeling the LC as a continuous-time auto regressive moving average process (CARMA; Kelly et al. 2014, Goyal et al. 2018) – implies that variability is a stationary stochastic process (NOT necessarily true for blazar sources).**NEXT STEP – ARIMA modeling (Zhang et al. 2018).**

CARMA modeling of OJ 287

C̲ontinuous-time A̲uto R̲egressive M̲oving A̲verage: y(t) is the solution to the stochastic differential equation

$$\frac{d^p y(t)}{dt^p} + \alpha_{p-1}\frac{d^{p-1}y(t)}{dt^{p-1}} + ... + \alpha_0 y(t) = \beta_q \frac{d^q \epsilon(t)}{dt^q} + \beta_{q-1}\frac{d^{q-1}\epsilon(t)}{dt^{q-1}} + ... + \epsilon(t)\,, \quad (1$$

where $\epsilon(t)$ is the Gaussian “input” white noise with zero mean and variance σ^2, α’s and β’s are AR and MA coefficients. The corresponding power spectrum

$$P(f) = \sigma^2 \left|\sum_{j=0}^{q} \beta_j \,(2\pi i f)^j\right|^2 \left|\sum_{k=0}^{p} \alpha_k \,(2\pi i f)^k\right|^{-2} \quad (2)$$

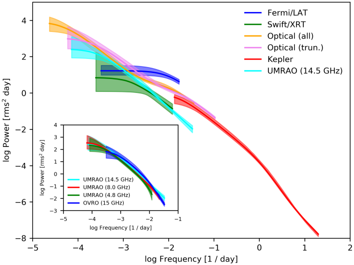


Figure 7: PSD of OJ 287 (Goyal et al. 2018)

=> $\gamma-$rays are relaxed on timescale of $\sim$150 days.

Different methods for PSD generation

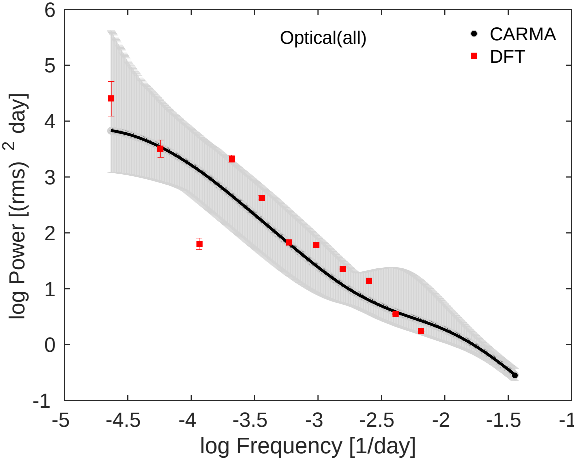


Figure 8: PSD of OJ 287 (Goyal et al. 2018)

=> Comparable results from Fourier and time-domain analysis!

Multiwavelength LCs including TeV

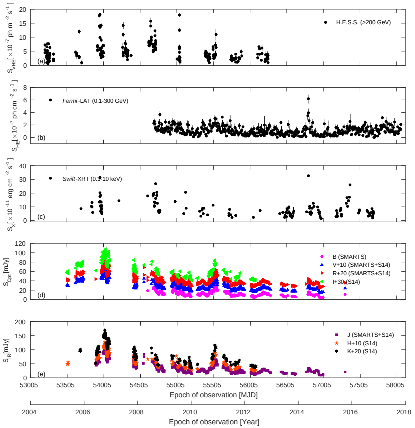


Figure 9: PKS 2155−304 (TeV from HESS; thanks to David Sanches)

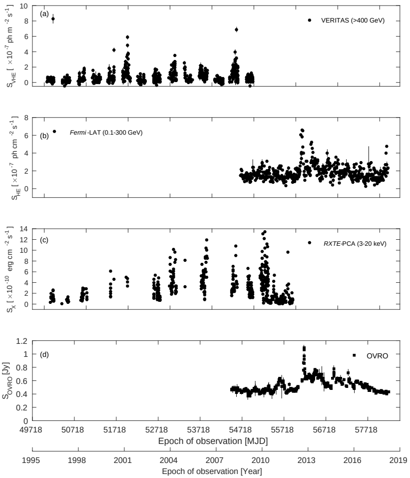


Figure 10: Mrk 421 (TeV from Acciari et al., 2014)

Squared fractional variance

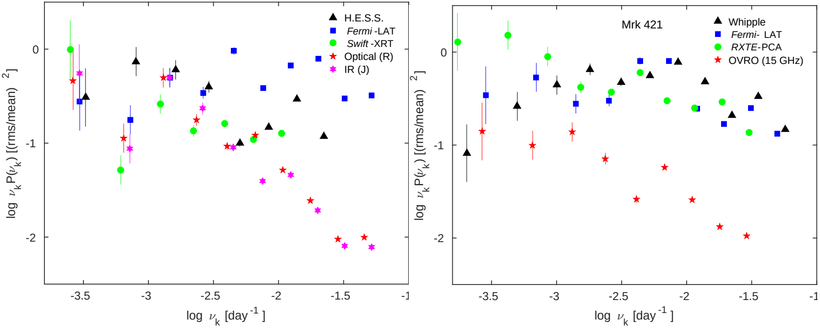


Figure 11: Squared fractional as a function of timescale. PKS 2155−304 (left) and Mrk 421 (right).

- In this representation: $\beta \sim 0$ for keV/GeV/TeV frequencies (pink noise) and $\beta \sim 1$ for radio/optical frequencies (red-noise)!
- Fractional variance does not increase with frequency for these HBLs on timescales ranging from years for weeks!
- Against the expectations of single one-zone model!

Fourier-resolved spectroscopy (FRS) or rms spectra

- rms as a function of radiation frequency for difference timescales corresponds to FRS spectra (First applied in the context of X-ray binaries; Revnivtsev et al. 1999).

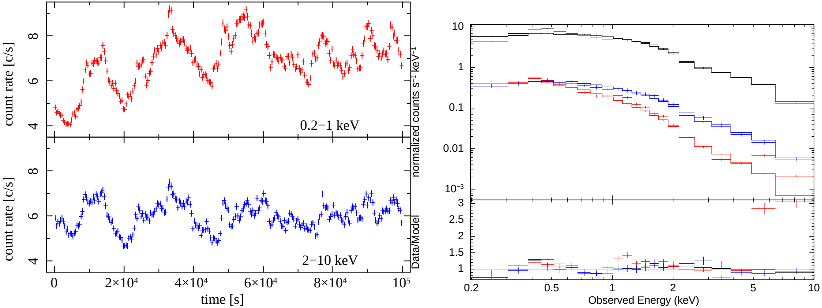


Figure 12: Seyfert galaxy NGC 3227 (Arevalo & Markowitz 2014). *left:* LC. *right:* rms spectra for soft frequencies (red) and hard (blue) and total (black).

=> Two spectral components: (1) hard with $\Gamma \sim 1.7$ dominating on $<$30ks timescales and (2) soft with $\Gamma \sim 3.0$ dominating on $>$30ks timescales.

rms spectra for blazars 3C 279 and PKS 1510−089

=> Good spectral and temporal coverage is mendatory!

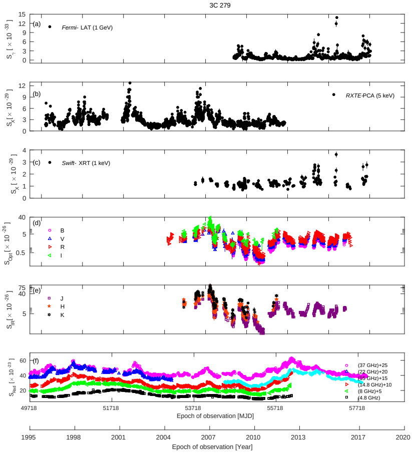


Figure 13: MWL LCs of 3C 279

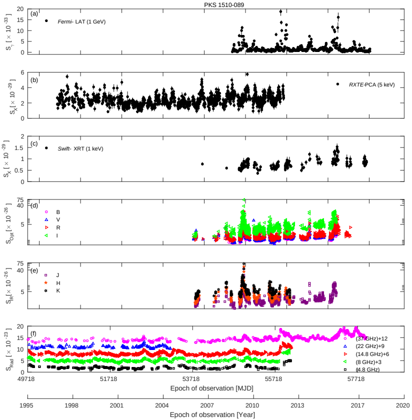


Figure 14: MWL LCs of PKS 1510−089

rms spectra on years/months/weeks timescales

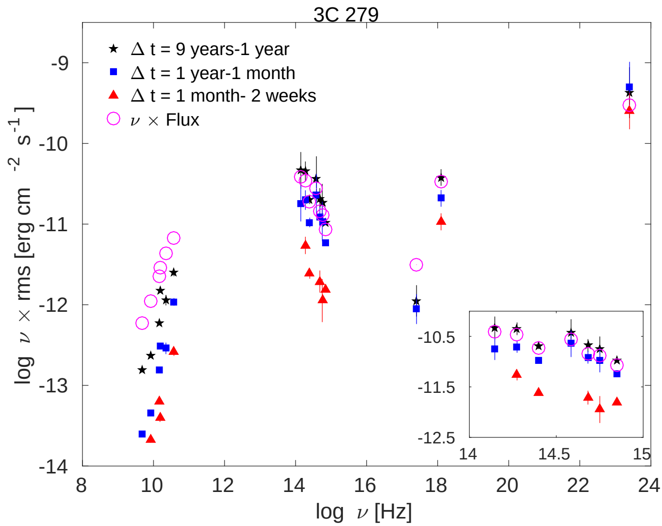


Figure 15: rms spectra of 3C 279

rms spectra on years/months/weeks timescales

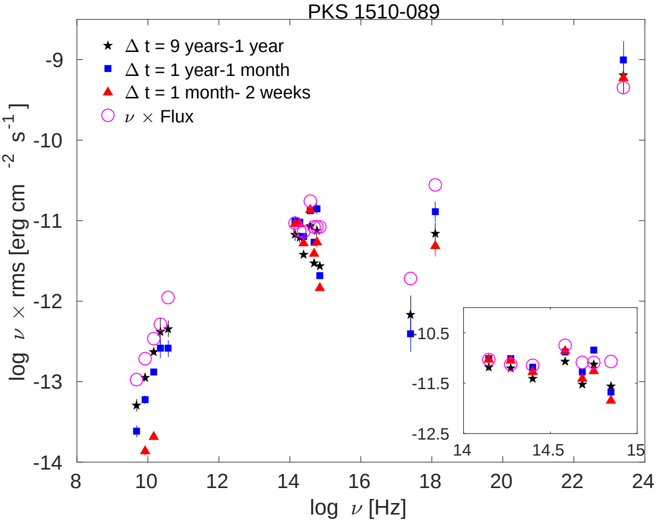


Figure 16: rms spectra of PKS 1510−089

Results

PSD analysis

- Featureless, single power-law power spectral density over timescales ranging from 5-6 decades in temporal frequency range.
- Detection of relaxation timescale of $\sim$150 days for the $\gamma-$rays (OJ 287), not seen at lower energies–inhomogeneous jet!
- Hints of non-stationarity on hourly timescales!

•Statistical character of $\gamma-$ray and X-ray variability (flicker/pink) is different than that of optical and radio (damped/red).

•Results supported for different blazars; $\gamma-$ray (Soboleweska et al., 2014), X–rays by Isobe et al. (2015), optical (Kastendieck et al. 2011), Max-Moerbeck et al. (2014).

•BL Lac objects – single zone SSC modeling(?)

Results

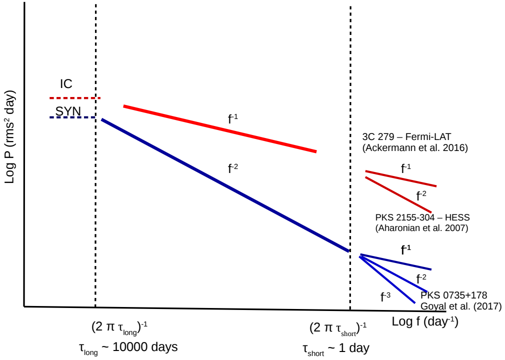
rms spectra

- The largest variance at each frequency is on the longest timescale, along to the expectations of strictly colored-noise PSDs from years to weeks timescales.
- rms is gradually increasing from weeks to months to years timescales for the blazar, however, the exact dependence appears to be different for different photon energies.
- Fractional variability is $\sim$ 100% on years/months/weeks timescales at *Fermi*-LAT energies.

•NO QPOs!

•Different spectral components–varying in both normalization and slope– emission from extended volumes of jet with different particle polpulations, magnetic fields, bulk Lorentz factors, external radiation density.

Different relaxation timescales and non-stationarity !



Synchrotron variability is driven by a single stochastic process with the relaxation timescales $\tau_{\rm long} \gtrsim$ 1,000 days (-> red noise for the variability timescales shorter than $\tau_{\rm long}$), while $\gamma-$ray variability is driven by a superposition of stochastic processes with relaxation timescales $\tau_{\rm long} \gtrsim$ 100 days and $\tau_{\rm short} \lesssim$ 1 day (-> pink noise for the variability timescales between $\tau_{\rm long}$ and $\tau_{\rm short}$, and red noise for the variability timescales shorter than $\tau_{\rm short}$).