Multi-frequency variability study of blazars from decades to minutes

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Double peaked blazar Spectral Energy Distribution

- **Leptonic scenario :** Electron-positron pairs accelerated to high energies $\geq$ TeV) emit radio-to-optical/X-ray synchrotron emission and X-ray-to-very high energy $\gamma-$rays in the inverse-Compton (IC) process (e.g., Ghisellini et al. 1998).
- **Hadronic scenario :** Protons accelerated to ultra-high energies ($\geq$ *EeV*) produce $\gamma-$rays via either direct synchrotron emission or meson decay and synchrotron emission of secondaries in proton-photon interactions (Boettcher et al., 2013)

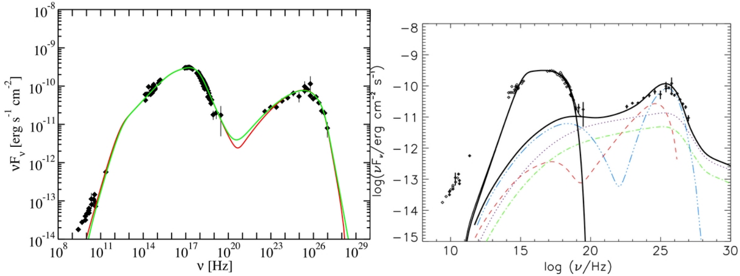


Figure 1: Spectral energy distribution (SED) of Mrk 421 (*left* : Leptonic scenario) and (*right* : Hadronic scenario)

Issues with the current SED modeling

1. TOO simplified model set : "single spherically symmetric blob moving along the jet"– "characteristic/relaxation" timescale.
2. Data used for model fitting is RARELY simultaneous – which flux measurements should really be used in SED modelling?
3. Correlated multi-frequency variability is an ISSUE (data not available, correlation not always persistent (orphan flares!), correlations are not statistically significance (e.g., Max-Moerbeck et al., 2014).

Characteristics of blazar light curves

•Blazars displays strong continuum emission variability from radio to $\gamma-$rays on timescales ranging from decades to minutes.

•The typical shape of power spectral density (PSD; i.e., variability power in the frequency band) is a power-law (COLORED NOISE) indicating that variability is due to underlying stochastic process(es).

Present work

•4 typical low-frequency peaked blazars - **PKS 0735+178, OJ 287, 3C 279** and **PKS 1510-089**

•Redshift = 0.2-2.0 (no contamination from host galaxy)

•Optically bright (average R band magnitude $\sim$ 13-16)

•Good quality, long-duration multi-frequency data exist

•Good quality, densly sampled intra-night optical data is available

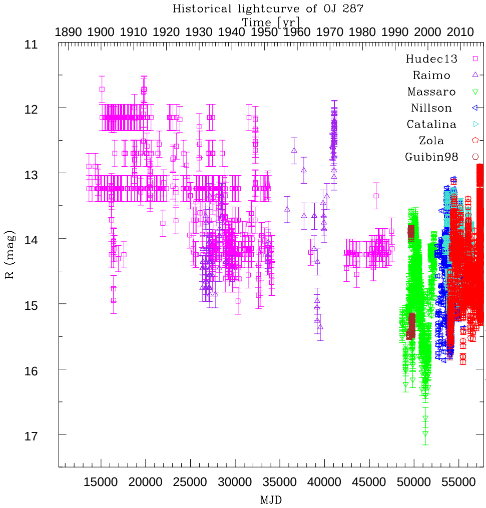
•$\geq$ 100 yr long optical light curve (OJ 287; Hudec et al., 2013)

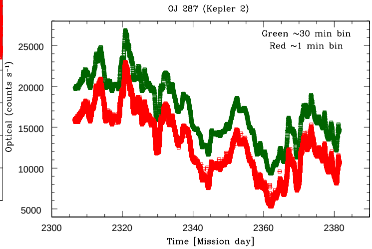
=> Therefore, ideal for characterizing the statistical properties of stochastic processes generating multi-frequency variability over extremely broad temporal frequency range !

Data acquisition

- γ-rays : *Fermi*-LAT (0.1-300 GeV) satellite
- X-rays : *Swift*-XRT (0.3-10 keV) and *RXTE*-PCA (3-20 keV) satellite
- Optical frequencies : Tuorla observatory (thanks to K. Nilsson) several small size (0.5-2m), ground based observatories (Poland, India, Turky, Japan) and Kepler satellite
- Radio frequencies : UMRAO (4.8, 8, 14.5 GHz – thanks to Hugh and Margo Aller) and OVRO (15 GHz – thanks to T. Hovatta and the team) single dish observatories

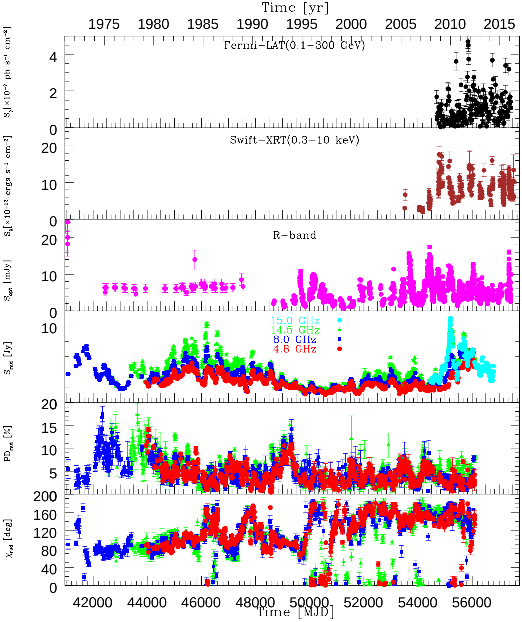
Historical (130 yr) + Kepler 2 mission light curve



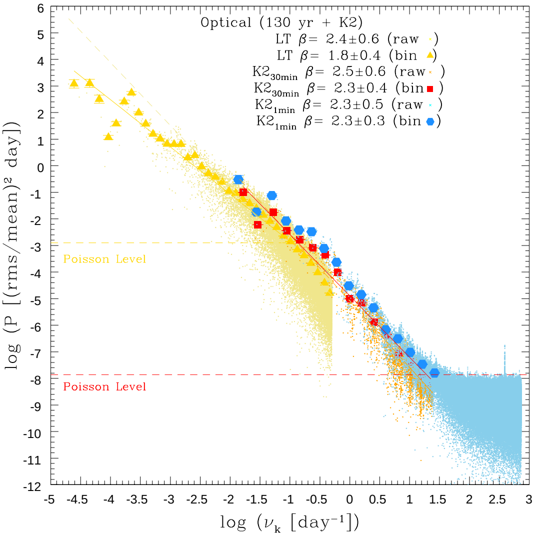


- Different Epochs/sites/observers

OJ 287 - Multi-wavelength light curve

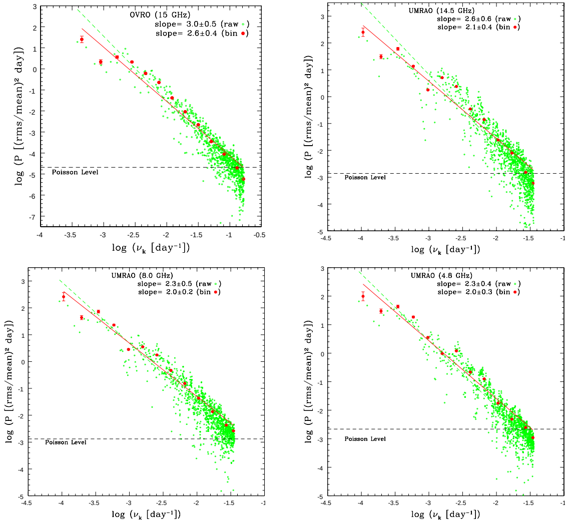


OJ 287 - Optical frequencies



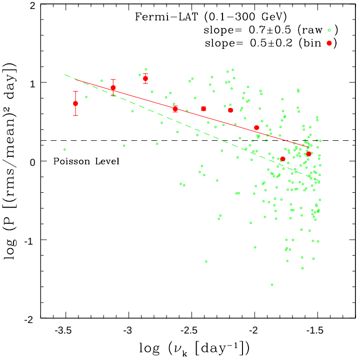
• $\beta \sim 2$: Red/Brownian noise on timescales $\sim$ 100 yrs to minutes (6 decades in temporal frequencies) !

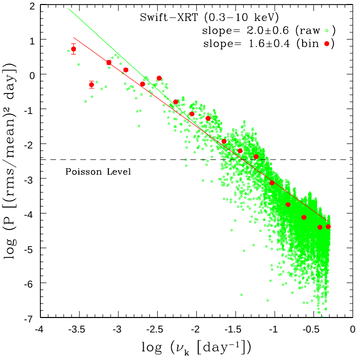
OJ 287 - GHz band radio PSDs



• $\beta \sim 2$: Red/Brownian type on timescales $\sim$ 10000 to weeks (4 decades in temporal frequencies) !

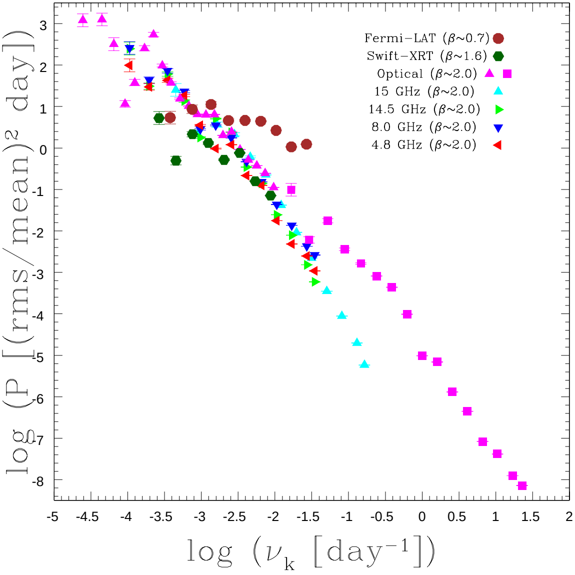
OJ 287 : $\gamma-$ray and X-ray





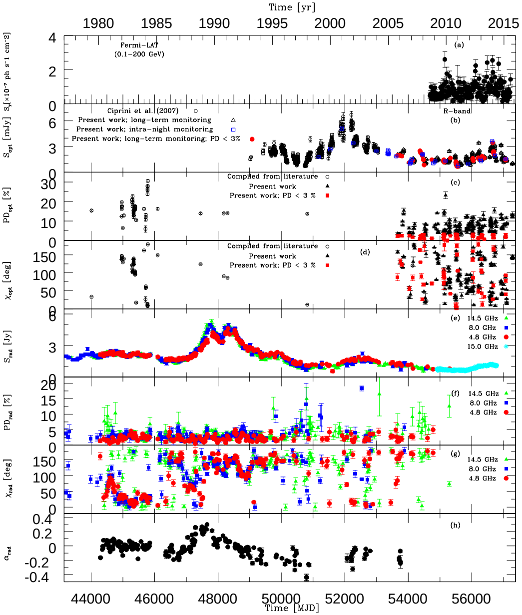
•$\beta \sim 1$: Flicker/pink noise at high energies on timescales $\sim$ 3000 to 50 days (2 decades in temporal frequencies) !

OJ287 : normalization of PSDs

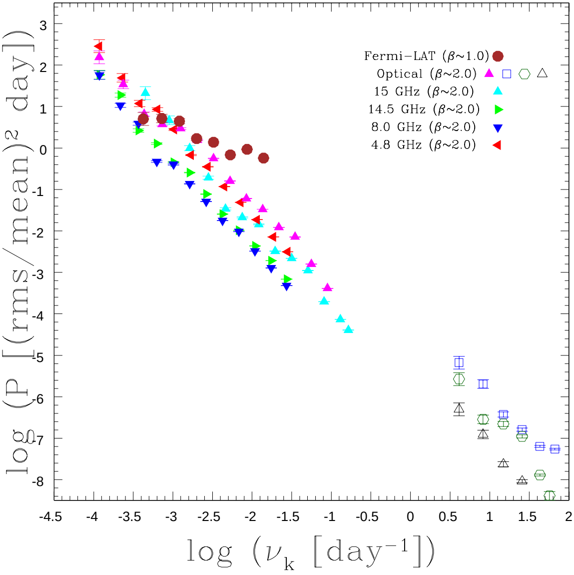


- Increasingly high power at higher energies !

PKS 0735+178 : Multi-wavelength light curve

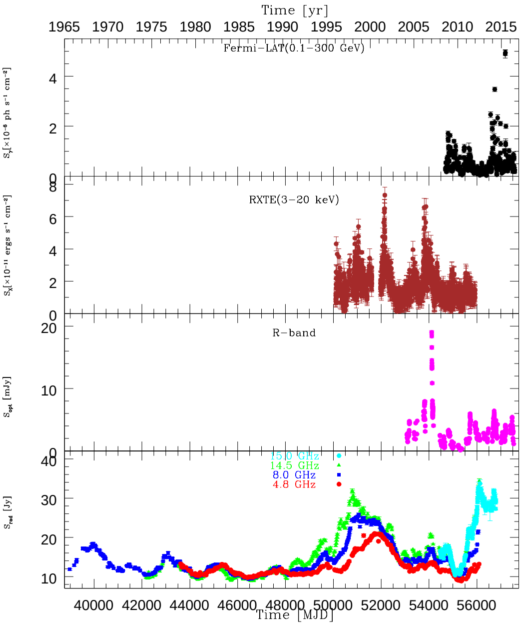


PKS 0735+178 : normalization of PSDs

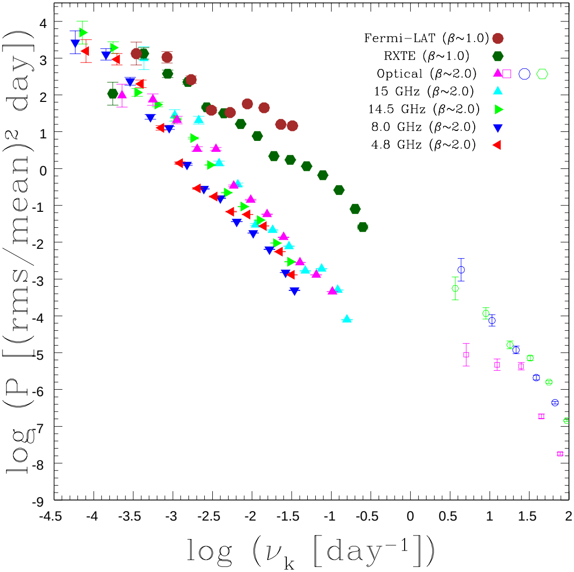


- Increasingly high power at higher energies !

3C 279 : Multi-wavelength light curve

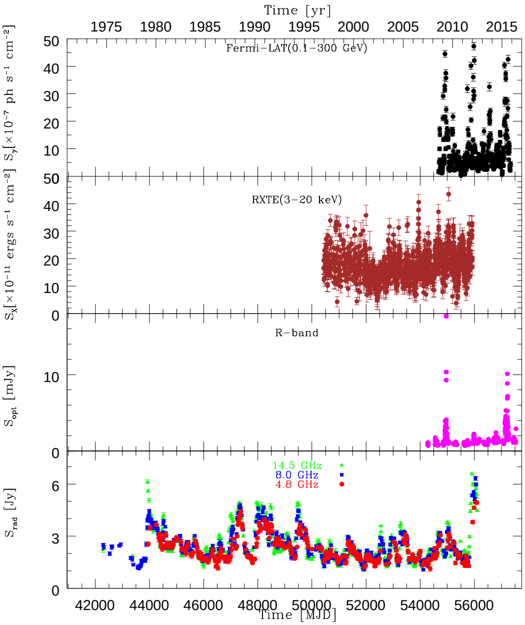


3C 279 : normalization of PSDs

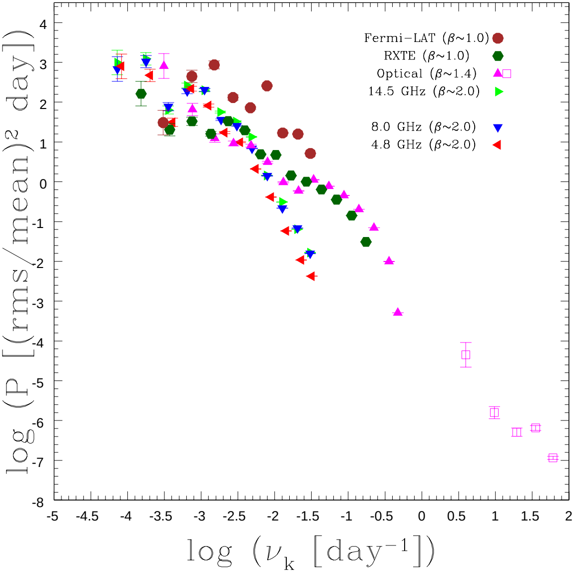


- Increasingly high power at higher energies !

PKS 1510-089 : Multi-wavelength light curve



PKS 1510-089 - normalization of PSDs



Summary of observational results

•Strongly variable at all frequencies on timescales on **minutes/days/months/years/decades** .

•Featureless, single power-law power spectral density over the extremely broad variability frequency range; Radio frequencies (decades to weeks/months), Optical frequencies (decades to minutes), X-ray enegies (decades to weeks), and γ-ray enegies (years to weeks).

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

Possible interpretation

•**Leptonic scenario** $\#1$: synchrotron emission is produced in different *regions* of the jet than $\gamma-$rays
(but then why exactly red vs. pink ?)

•**Hadronic scenario** : different acceleration & emission sites and processes for electrons and protons
(but then why exactly red vs. pink ?)

•**Leptonic scenario** $\#2$ (Goyal et al. 2016, submitted): synchrotron emission is produced in the same *extended region* of the jet, which is however highly inhomogeneous/turbulent ; 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 two stochastic processes with relaxation timescales $\tau_{\rm long} \gtrsim$ 1,000 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 $\tau_{\rm short}$).

Different relaxation timescales !

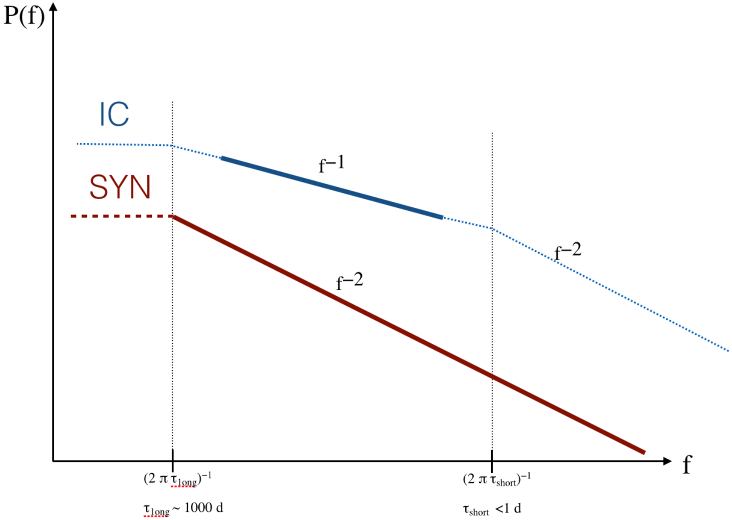


Figure 2: Leptonic scenario #2.