Timing analysis of blazar sources: All the colors of noise

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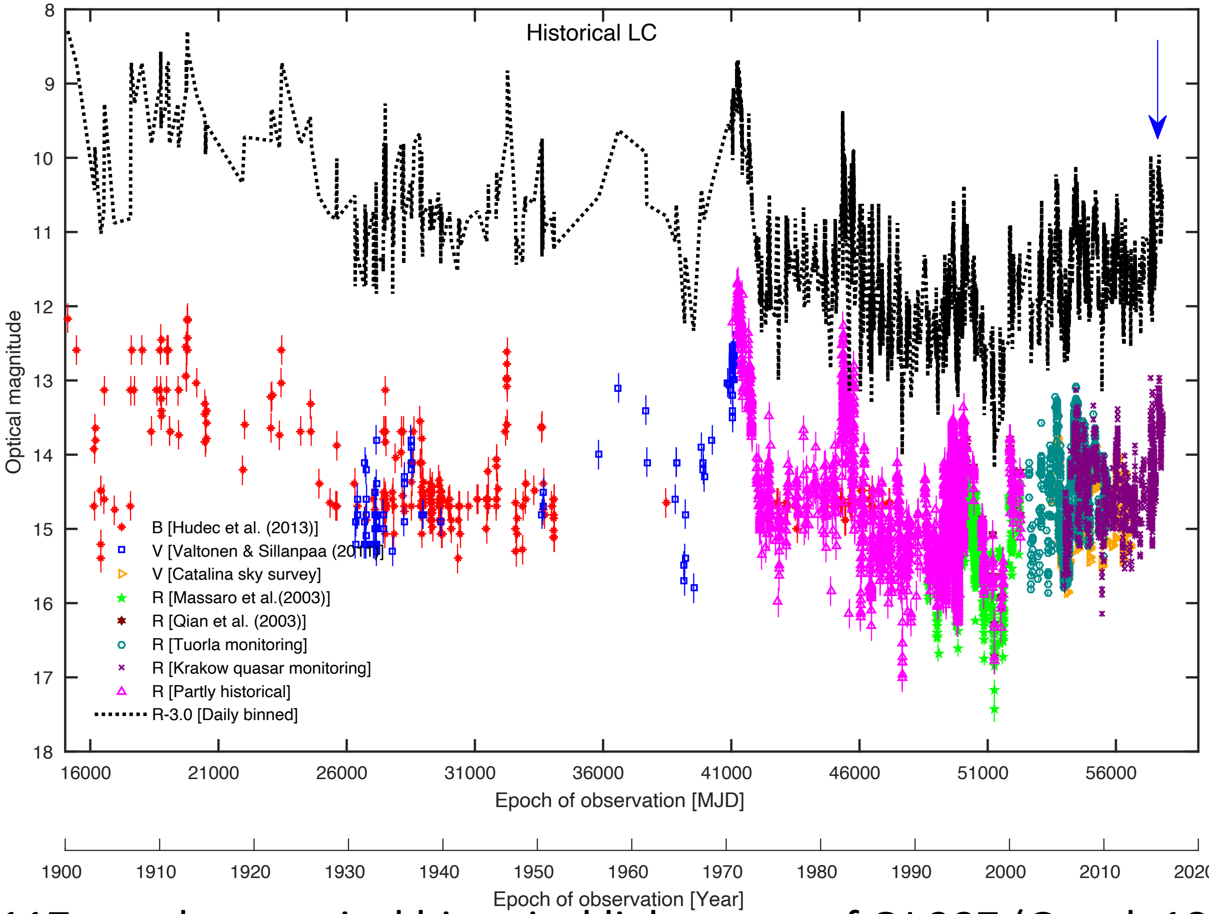
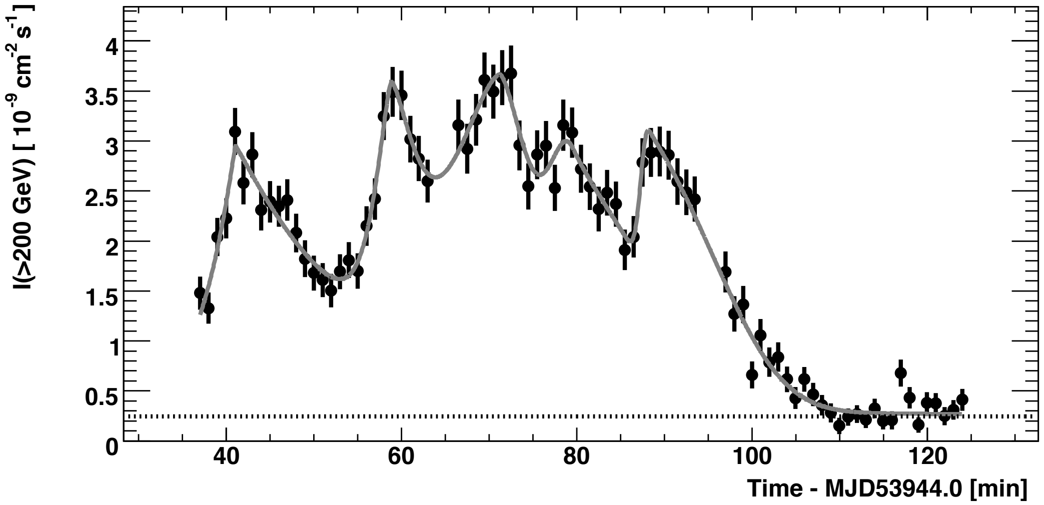
Extragalactic jets on all scales - launching, propagation, termination (Heidelberg, 14-18 June 2021)

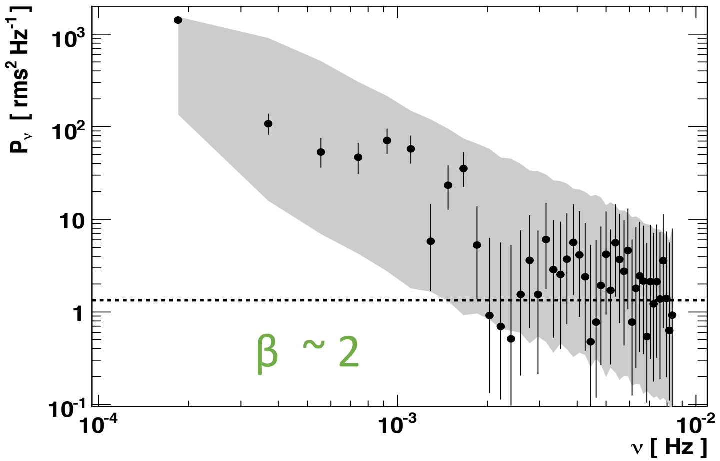
Blazar variability– A STOCHASTIC PROCESS

- Power-law shape of variability power spectral densities (PSDs): $P(\nu_k) \propto \nu_k^{-\beta}$ where β is the slope and ν_k is the temporal frequency (=timescale^{-1}).
- β = 1-3 refers to a correlated COLORED NOISE type stochastic process. β = 1 (pink/flicker noise) and β = 2 (red/damped random walk noise).
- Observed light curve (LC) is one realization.



117 year long optical historical light curve of OJ 287 (Goyal+18)





Intra-night LC at TeV energies for PKS 2155-304 and the PSD (Aharonian+07)

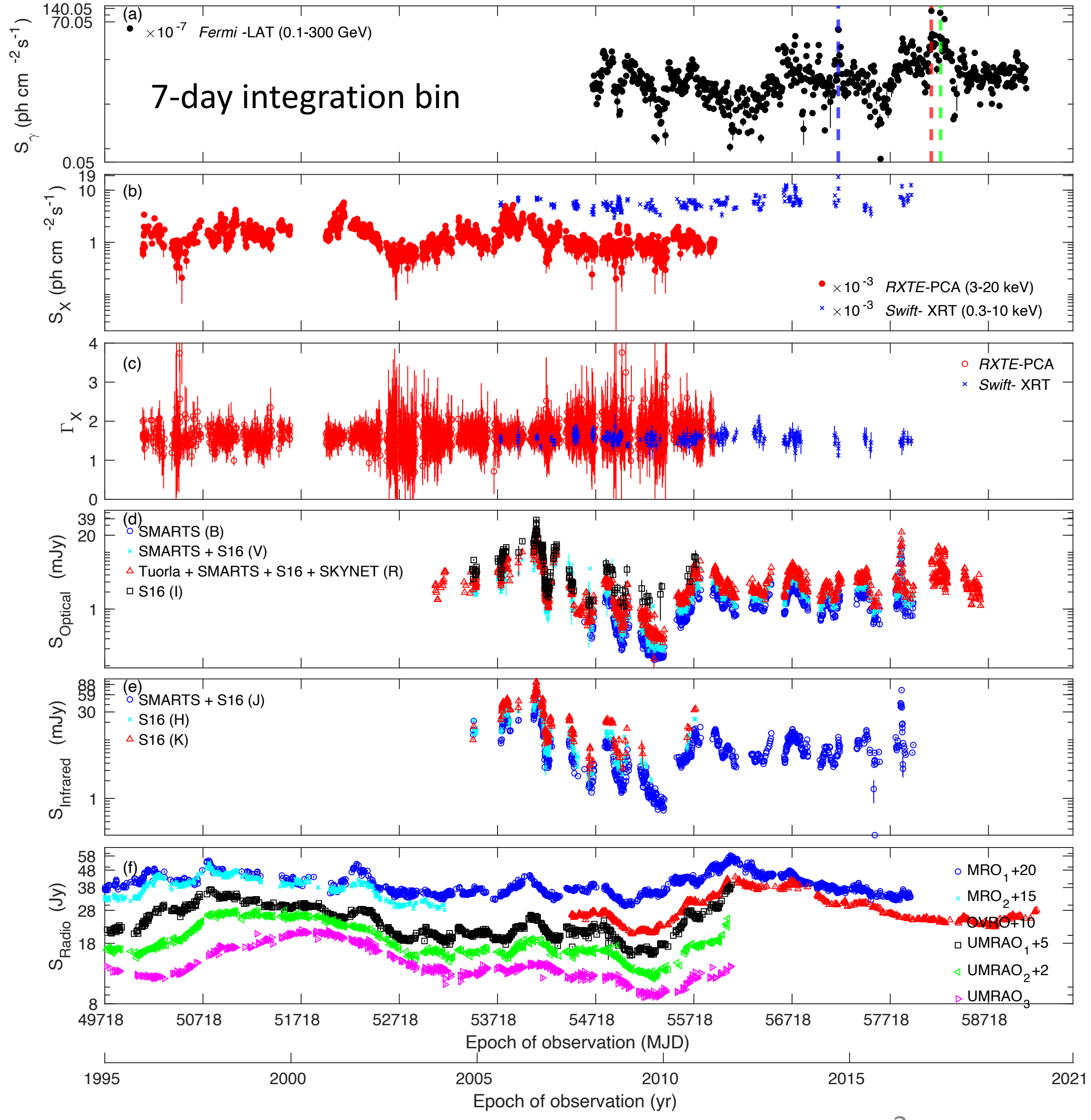
Power Spectral Density (PSD) analysis

- Fourier-Domain: Power spectral response method (PSRESP; Uttley+02)
- Best fit PSD model is chosen among the set of models through Monte Carlo simulations of light curves (Emmanoloupolus+13) using frequentist approach

Caveat: red-noise leak, aliasing, and uneven sampling

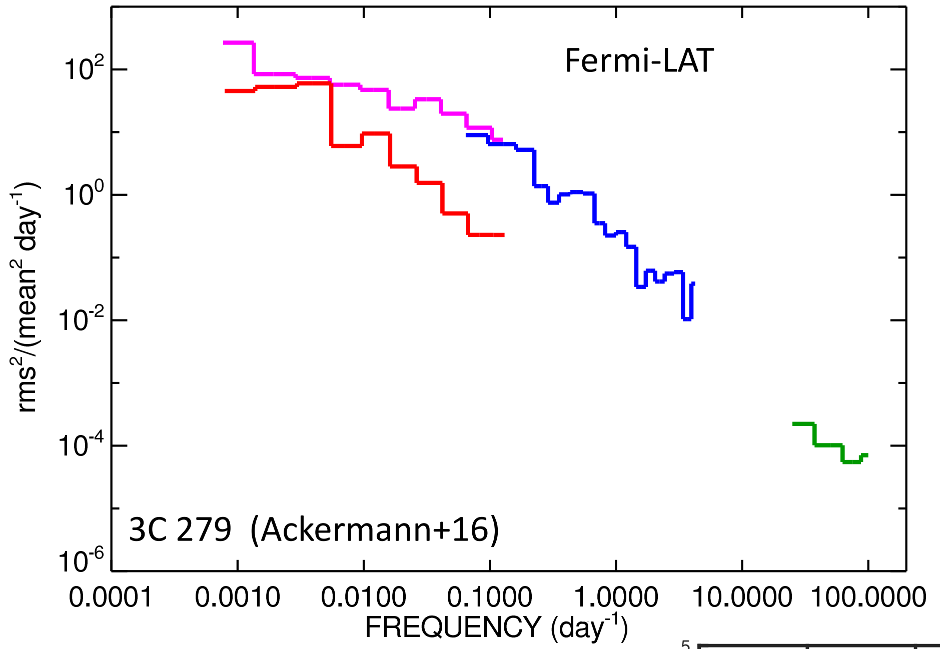
- Time-Domain: Continuous-time Auto Regressive Moving Average (CARMA; Kelly+14)
- Best fit CARMA model is chosen among the set of parameters through Bayesian inference using Akaike information criterion

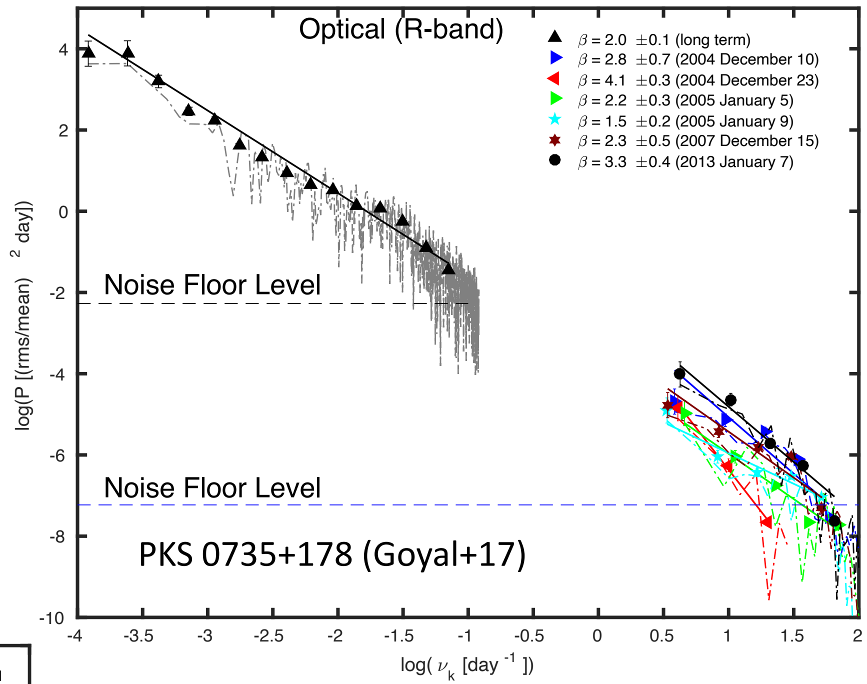
Caveat: CARMA is a stationary process!



MW light curves of 3C 279 (Goyal++, in prep.)

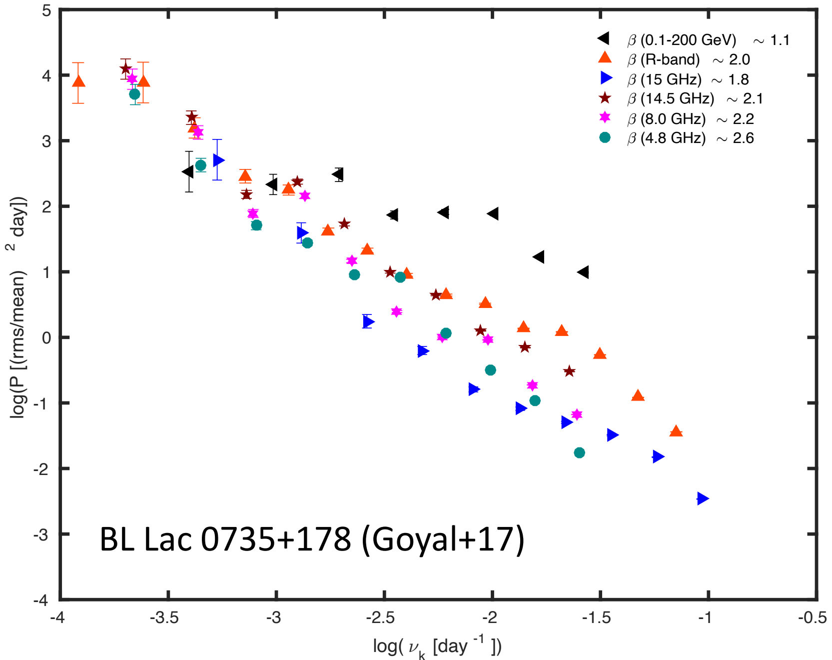
Synchrotron and IC frequencies

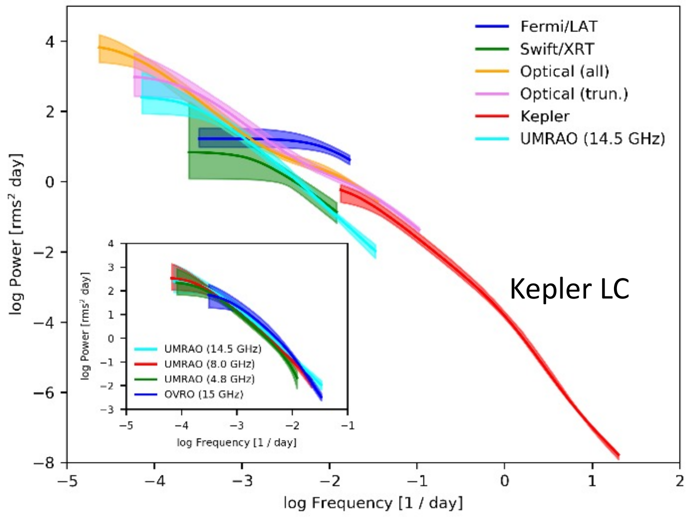




- Covers ~6 decades of the variability spectrum (decades to minutes)
- Normalization of intranight PSDs is smooth extrapolation from longer timescales

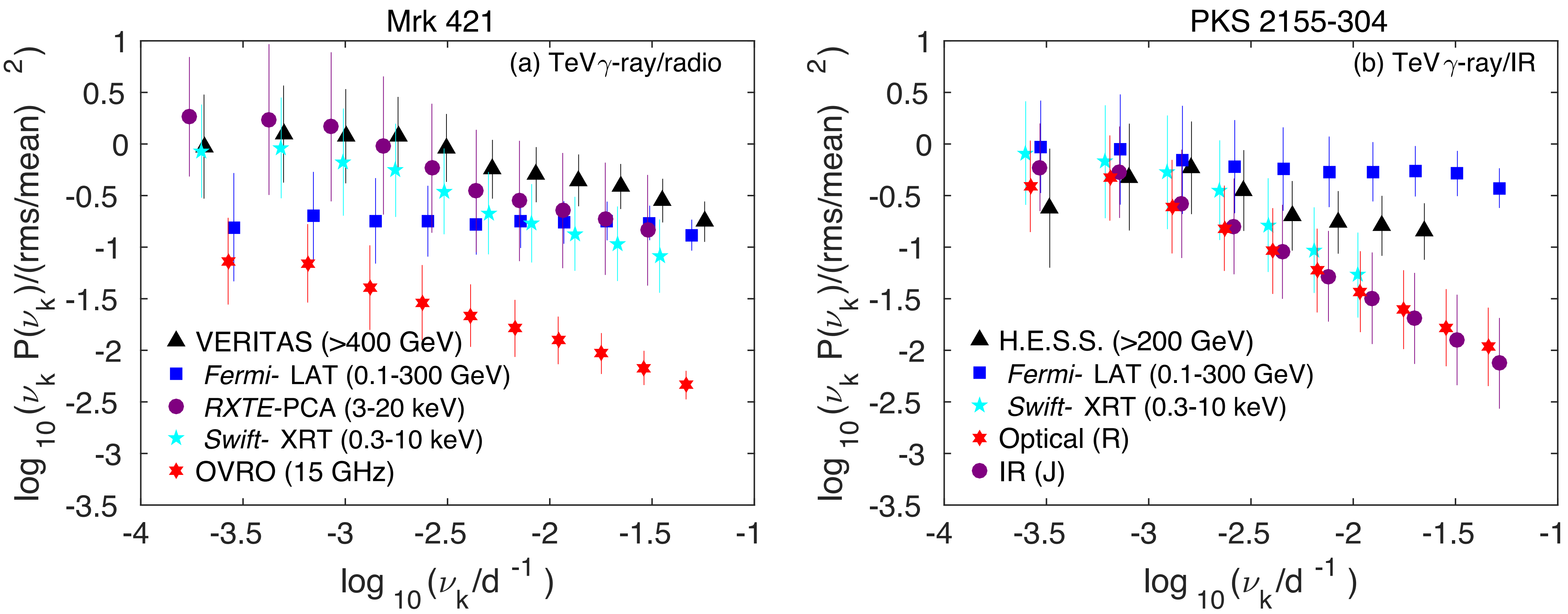
β ~ 1 (flicker; **γ**-rays)
β ~ 2 (red; optical and radio)





CARMA modeling of MW LCs of OJ 287 (Goyal++18)

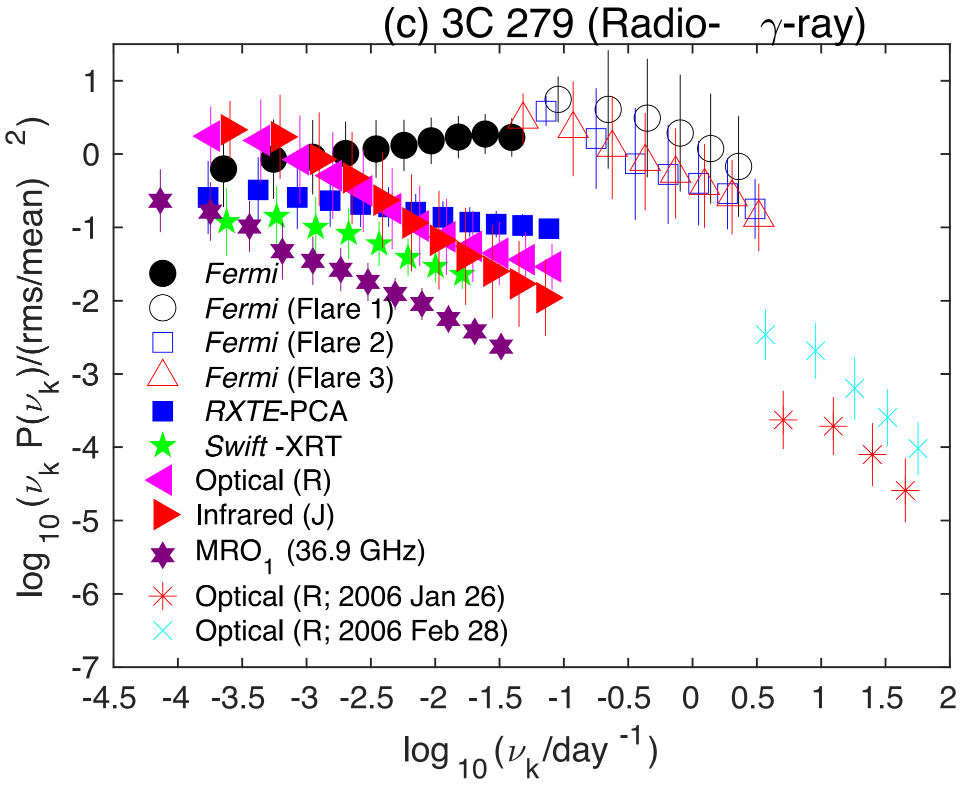
Variability PSDs up to TeV energies (VERITAS and HESS)



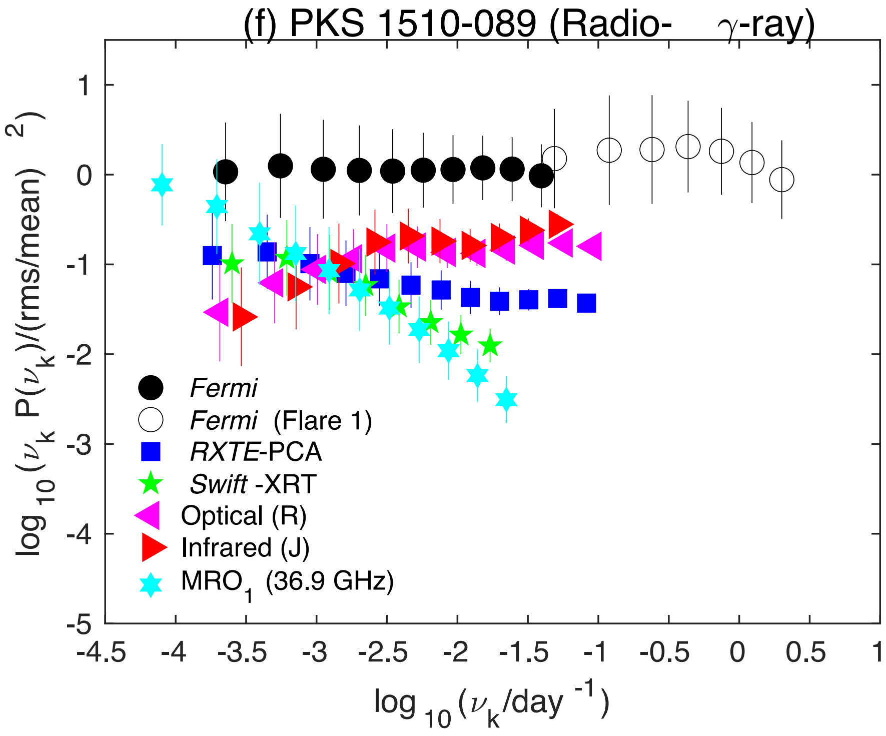
PSRESP best-fit PSDs of Mrk 421 and PKS 2155-304 (Goyal,20)

- More variability power on timescales <~ 100 days at high energies as compared to radio and optical
- TeV PSD slopes: β ~1
- X-ray PSD slope: β ~1 (synchrotron frequencies)

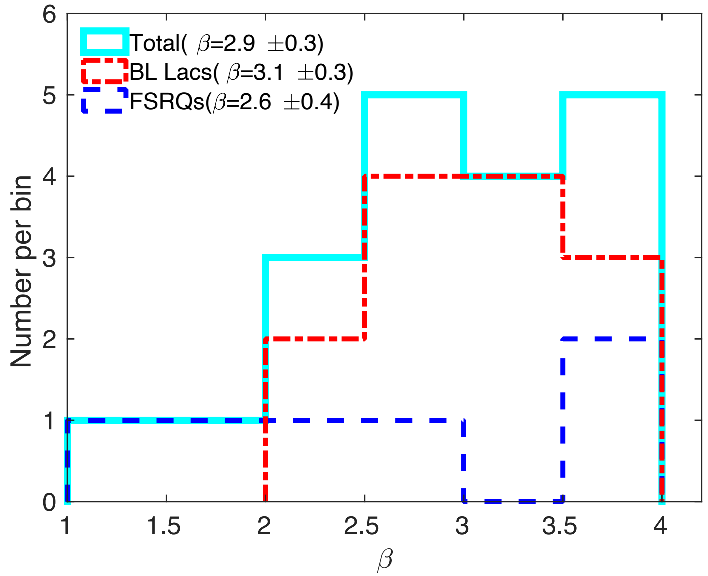
MW PSDs of 3C 279 and PKS 1510-089



- β ~1 at X-rays, gamma-rays
- β ~2 at optical and radio frequencies
- Exception PKS 1510-089 as β ~1 at optical/infrared), (Goyal+in prep)



Intra-night timescales: Optical variability is routinely detected down to 1-2% amplitude



Distribution of PSRESP PSD slopes on intra-night timescales for blazar sources (Goyal,21)

Summary and future directions:

- Featureless, single power-law power spectral density on timescales ranging from decades/many years down to days with largest variance on longer timescales. What is flare/quiescence?
- β ~ 1 at TeV/GeV γ-ray and X-ray energies as compared to β ~ 2 at radio and optical frequencies on decades to days timescales. Different statistical characters of Synchrotron (red) and IC (flicker) long-term variability.
- Characterization of optical variability spectrum across 6 decades. The normalization appears to be smooth extrapolation from those at longer timescales. Continuous variability process!
- γ-ray LC of OJ 287 indicated a relaxation timescale of ~150 days, which was not seen at lower energies. Inhomogeneous jets.
- The γ-ray PSD cover 4 decades of the variability spectrum. No detection of breaks in the PSDs (except for OJ 287; see also, Sobolewska+14).
- On average, the character of variability process is steeper than red noise type process which is observed on longer timescales. Indicate a cutoff of variability power on days timescales (similar to Mrk 421 in X-rays; Chatterjee++18)!

Small sample results!

Possible Interpretation!

=> Leptonic scenario: different emission sites for γ-rays than optical (why red vs. pink ?)

=> Hadronic scenario: different acceleration processes and emission sites for electrons and protons (why red vs. pink ?)

=> Leptonic scenario #2 (Goyal+,17,18, Goyal, 20):
synchrotron emission is produced in the extended region of the jet, which is however highly inhomogeneous and turbulent (TEMZ; Marscher,14); synchrotron variability is driven by a single stochastic process with the relaxation timescales τ_{long} ~>1,000-10,100 days while γ-ray variability is driven by a superposition of two stochastic processes with relaxation timescales τ_{long} ~> 1,000-10,000 days and τ_{short} < 1 day (> pink noise for the variability timescales between τ_{long} and τ_{short}, and red noise for the variability timescales shorter than τ_{short}. This additional process could be light crossing time around day for a jet with bulk Lorentz factor ~30. Bulk Lorentz factor changes and turbulence can produce PSDs with β=2.1-2.9 and 1.6-2.3, res. (2DRHD; Pollack+16).