Stochastic blazar variability

Arti Goyal

Astronomical Observatory, Jagiellonian University

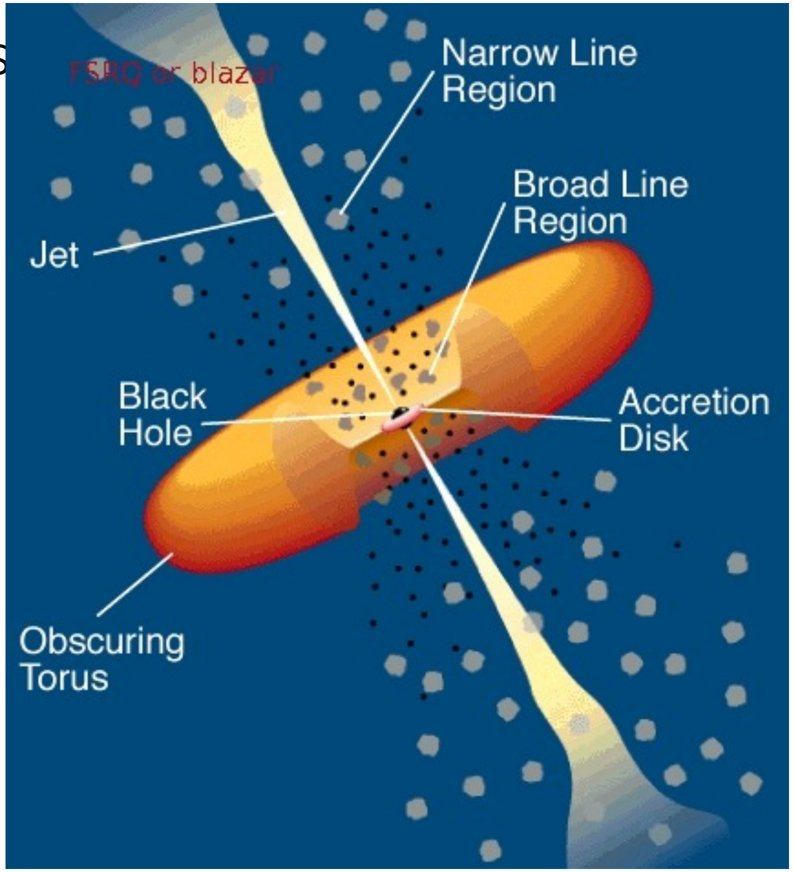
Collaborators: **M. Ostrowksi, L. Stawarz, M. Soida, S. Zola,** P. J. Wiita, Gopal-Krishna, T. Hovatta, A. Baran, M. F. Aller, H. D. Aller, A. Marscher, S. Jorstad and many others

Research grant (NCN): OPUS 2018/29/B/ST9/02298
Computing grants: Cyfronet PL Grid

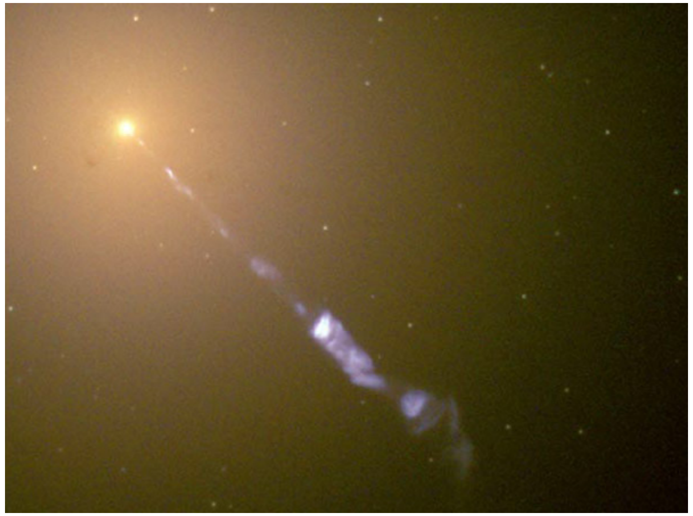
Institute of Astronomy, CAMK, Torun (22 January 2021)

Active Galaxies/ Blazars

- Super-massive black hole (SMBH; 10^{6-10} $M_\odot$), accreting matter from the **accretion disk** ($L_{\_Edd}$ ~ 10^{46} erg/s and T_{BB} ~10^5 deg K for 10^8 $M_\odot$ BH)
- Highly collimated, magnetized, relativistic plasma outflows called "**jets**".
- Emission is boosted with Doppler factor, $\delta \cong \Gamma$ (Bulk Lorentz factor)
- Flux is enhanced (δ^4) and variability timescales are shortened ($\boldsymbol{\Delta} t_{obs} = \boldsymbol{\Delta} t_{int} (1+z)/\delta$)
- Kinetic jet power: ~10^{44-48} erg/s



Urry and Padovani (1995)

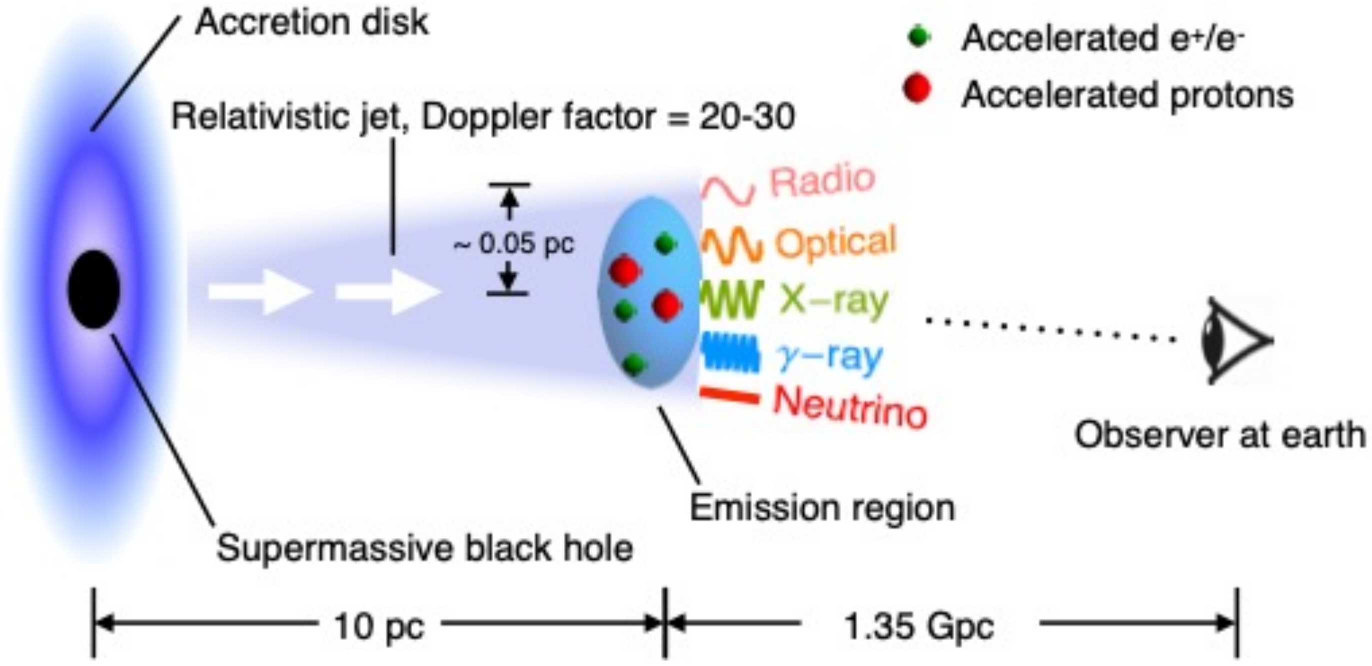


- HST image of M87 (credit: NASA).
- Redshift of 0.0016, luminosity distance of 6.7 Mpc and a linear scale 0.033 kpc/". 1.1 kpc long jet is observed.
- Blazars are viewed along the line of sight of the jet.

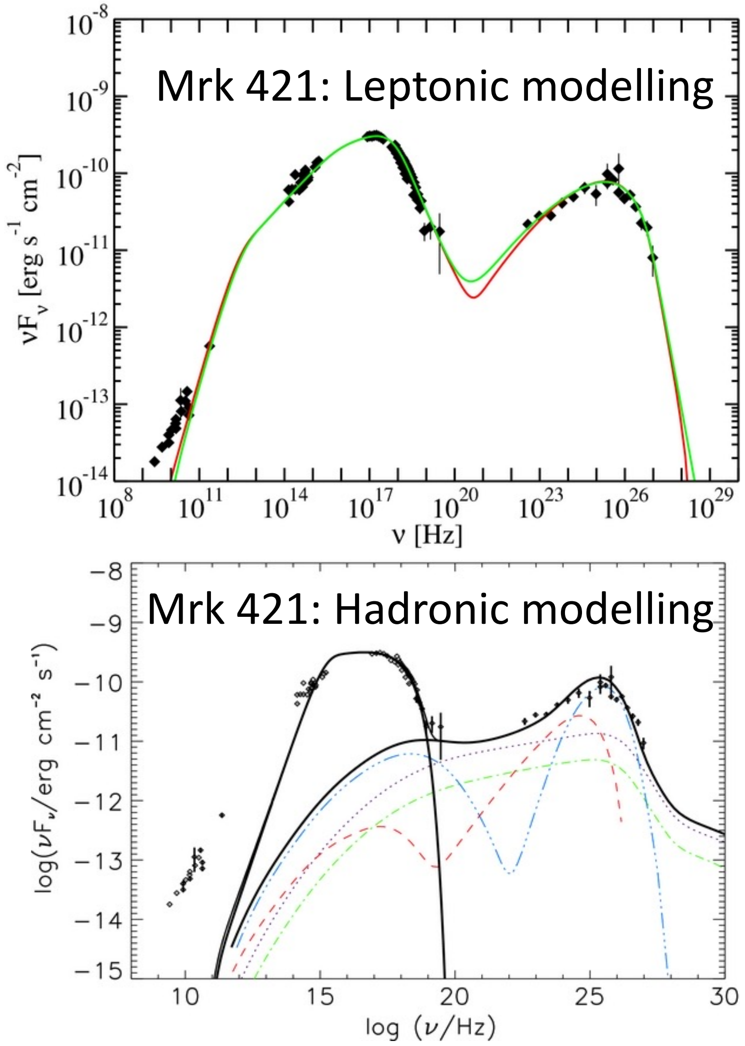
Double peaked blazar Spectral Energy Distribution

- Leptonic scenario: Electron-positron pairs accelerated to GeV/TeV energies emit radio-to-optical/X-ray synchrotron emission and X-ray-to-TeV $\boldsymbol{\gamma}$-rays in the inverse-Compton (IC) process (Ghisellini++98)

- Hadronic scenario: Protons accelerated to PeV/EeV energies produce via direct synchrotron emission or meson decay and synchrotron emission of secondaries in proton-photon interactions (Boettcher++13)



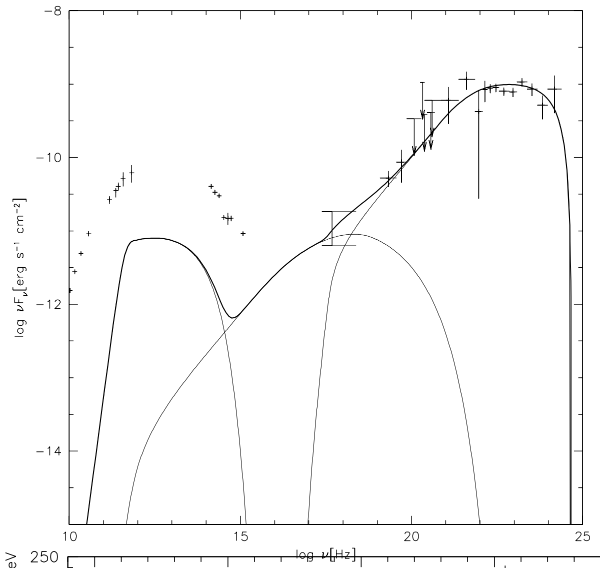
(Gao++19)

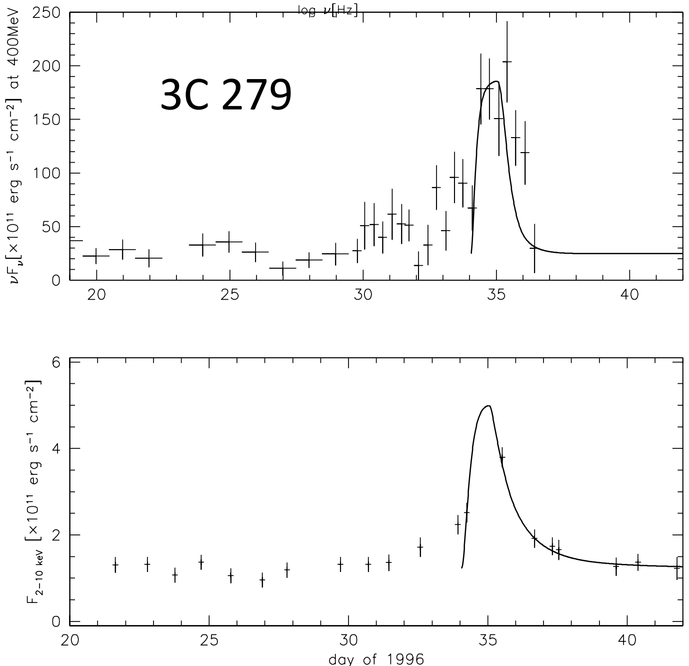


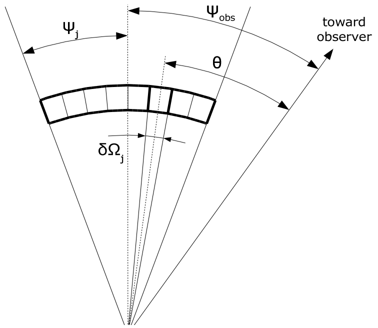
(Abdo++10)

Energy dissipation in blazar jets

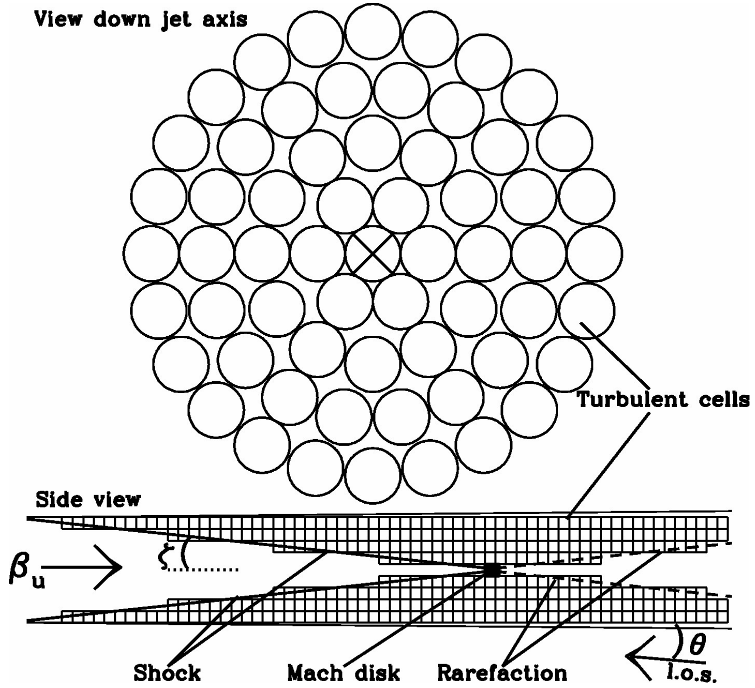
1) Shocks (Hughes++85,Moderski++03)

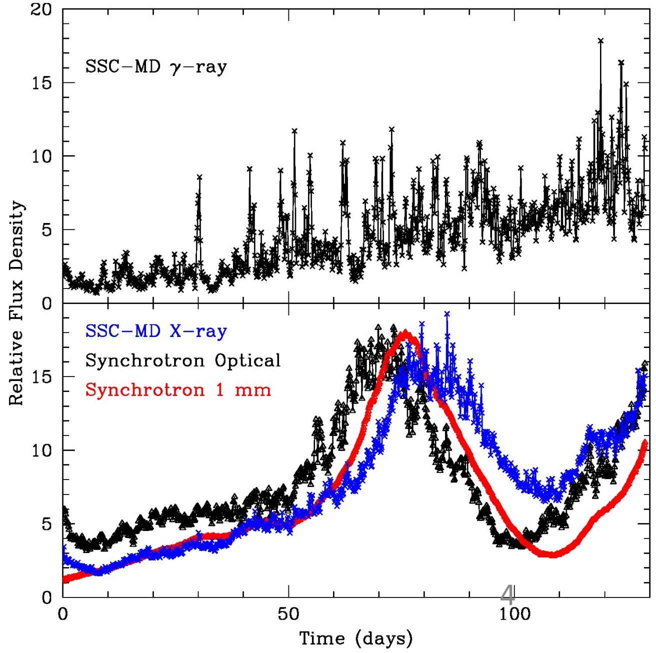




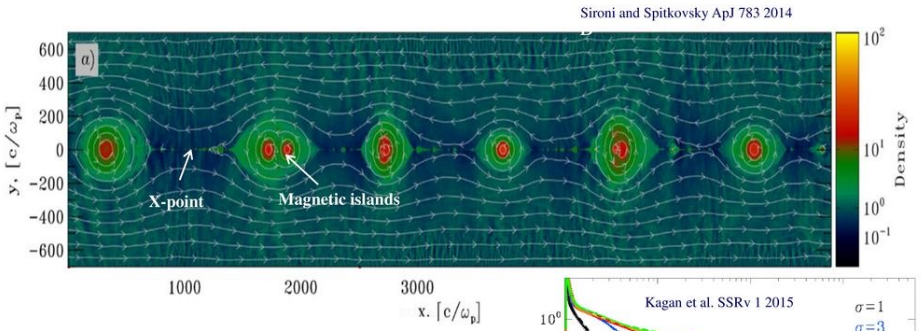


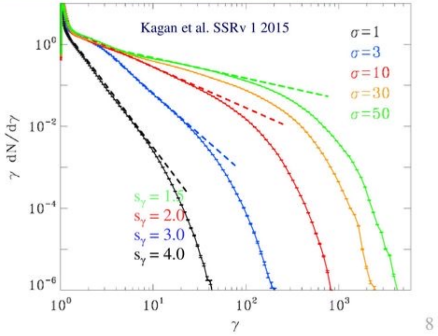
2) Turbulence (Marscher, 14)





3) Magnetic reconnection (Sironi++15)

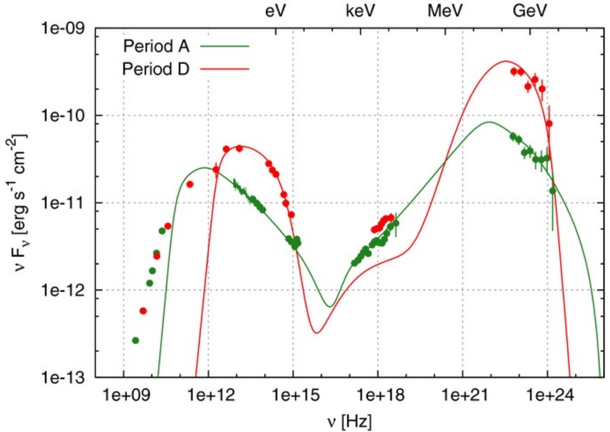


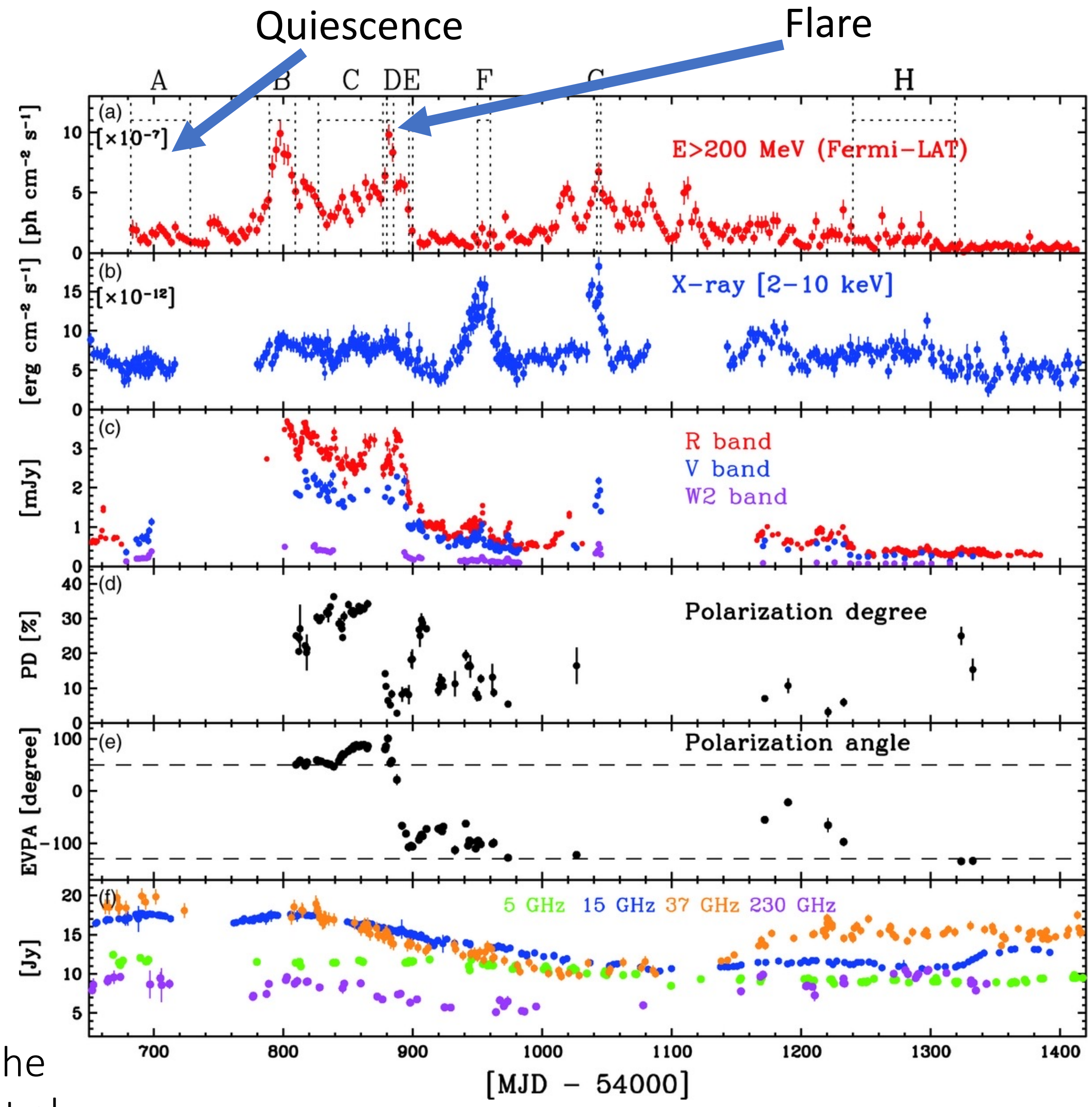


Particles are accelerated predominantly at X-points and by scattering on magnetic islands

Issues with the current SED modeling

- Single emission zone models (flare vs. quiescence states): ``homogeneous spherically symmetric blob moving along the jet”
- Characteristic/relaxation timescale: t_{var} =(1+z)*R/ **δ***c
- **Location of zone is debated**: ~1 pc (Sikora++09) or >15pc (Agudo++15)
- Data used for model fitting is RARELY simultaneous - **which flux measurements should be used?**
- **Correlated multi-frequency variability is an issue-** -unavailability of data/correlation not persistent (ORPHAN FLARES)/correlations are not statistically significant (Max-Moerbeck++14)

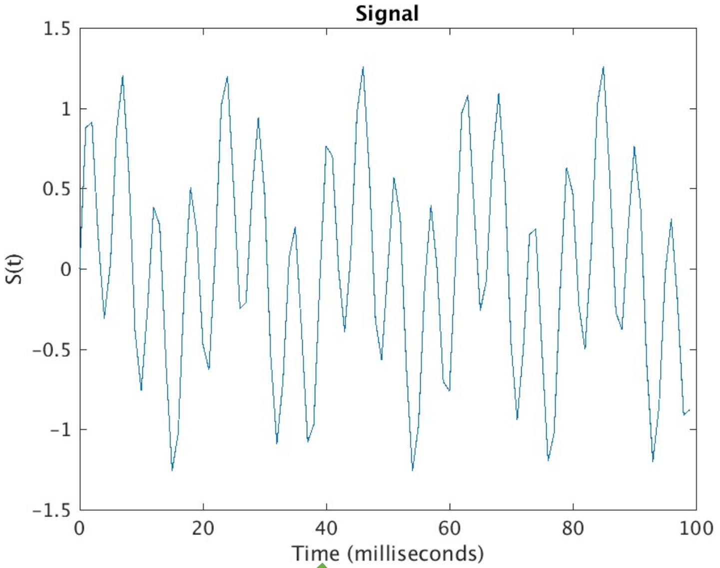




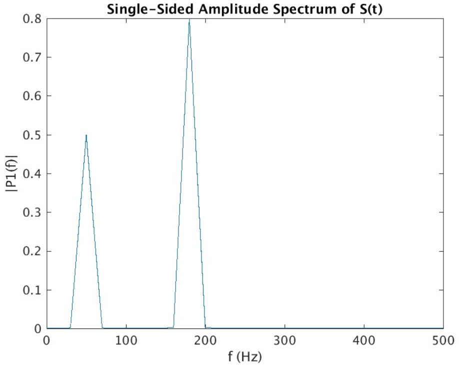
3C 279: MW light curves and the single zone SED fitting (Abdo et al. 2010).

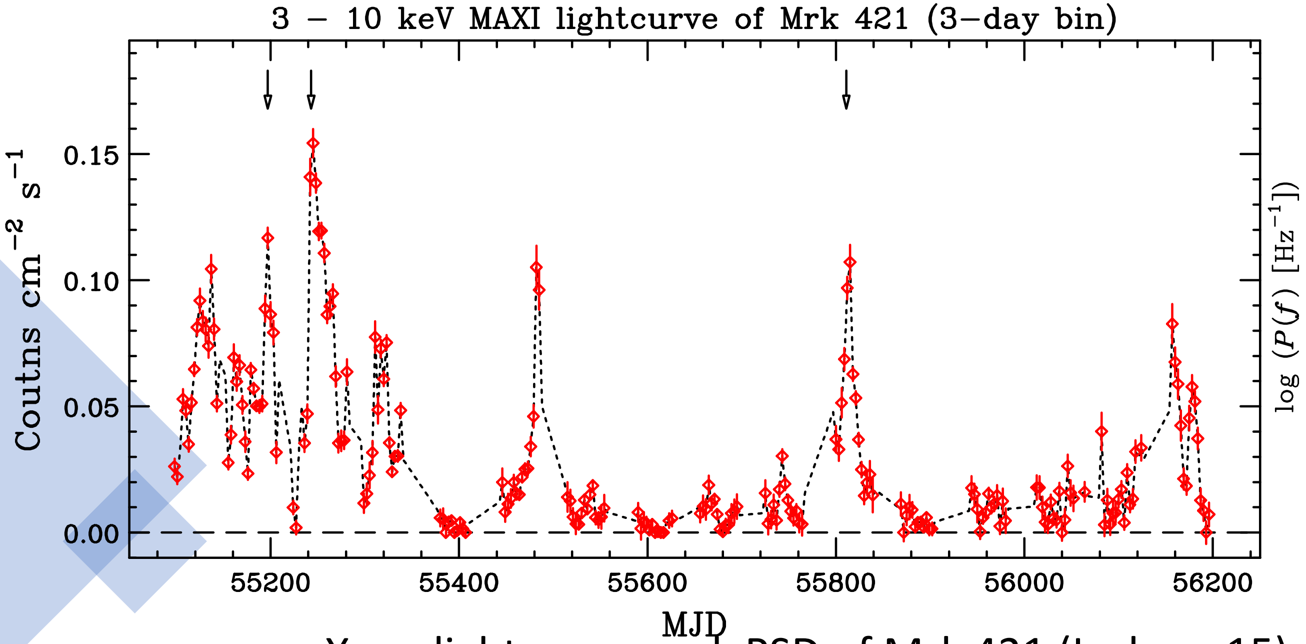
Blazar variability– A STOCHASTIC PROCESS

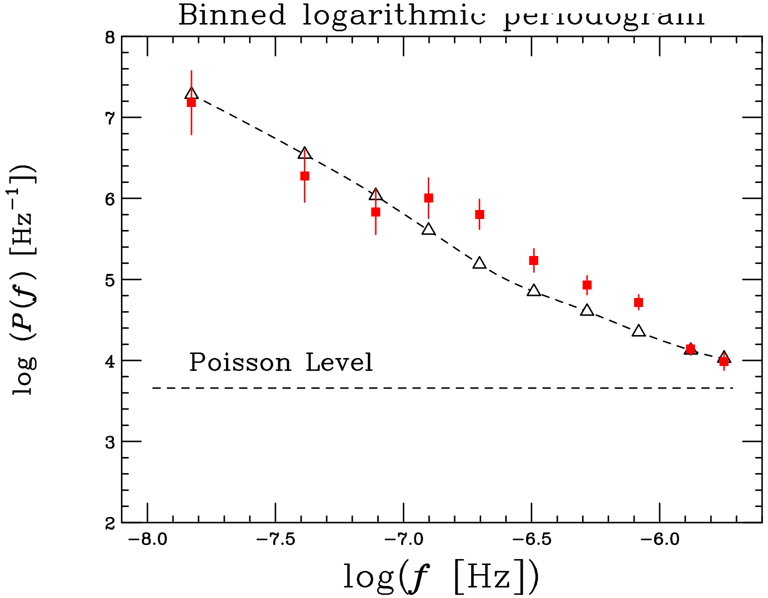
- Random, aperiodic intensity variations across ALL wavebands and on ALL timescales
- Typical power-law shapes of variability power spectral densities (PSDs): $P(\nu_k) \propto \nu_k^{-\beta}$ where β is the slope and ν_k is the temporal frequency (=timescale^{-1})
- β = 1-3 refers to correlated COLORED NOISE type stochastic process.



Deterministic process







X-ray light curve and PSD of Mrk 421 (Isobe++15)

Colored noise type stochastic process: different colors

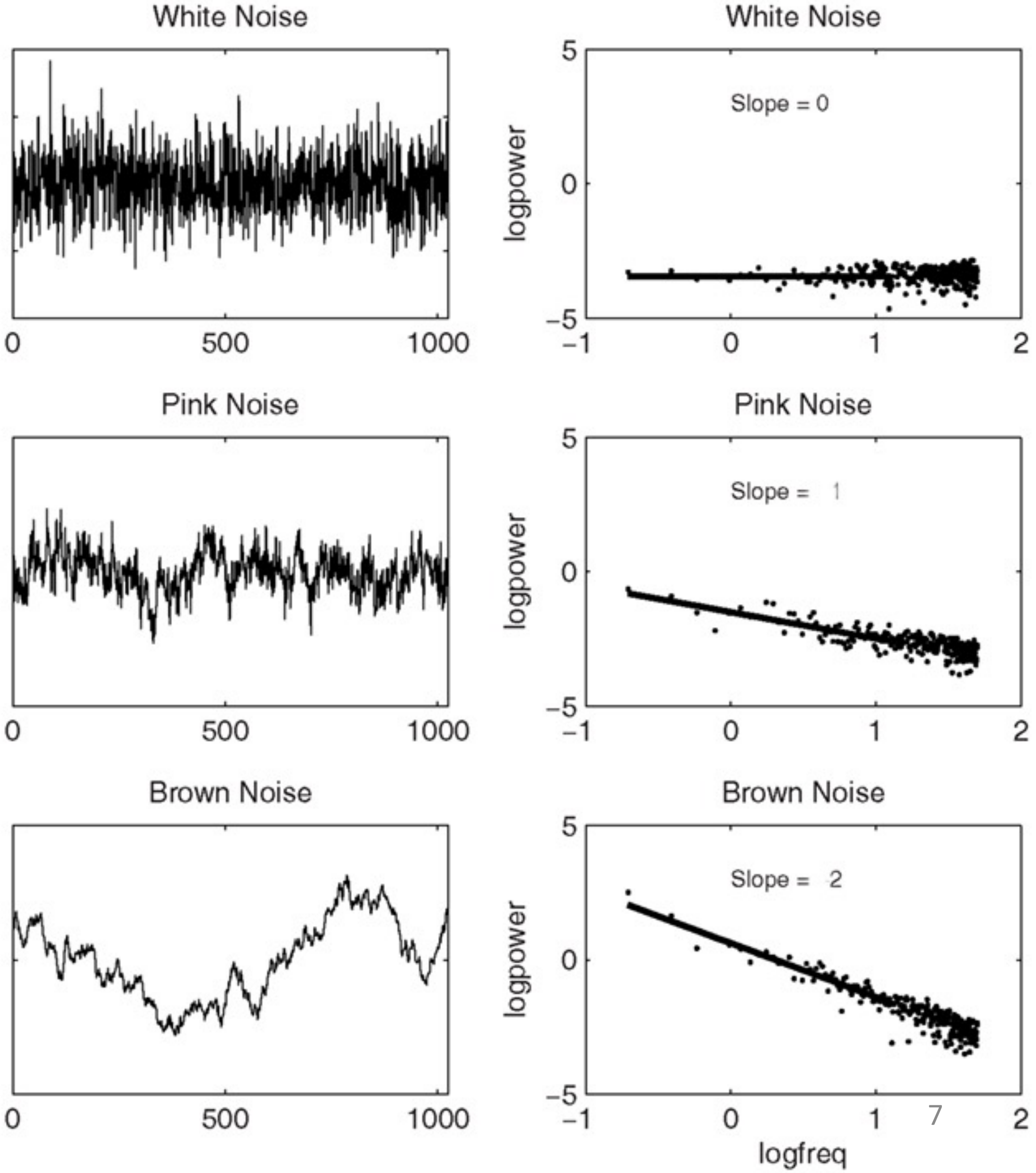
- **β = 0** is a white noise process (no well defined mean or instantaneous value)

- β = 1 is pink/flicker noise process

(well defined mean not the instantaneous value)

- β = 2 is a red/random walk (or brown) noise process (well defined instantaneous value but not the mean)

(Press++1978)



Light curves

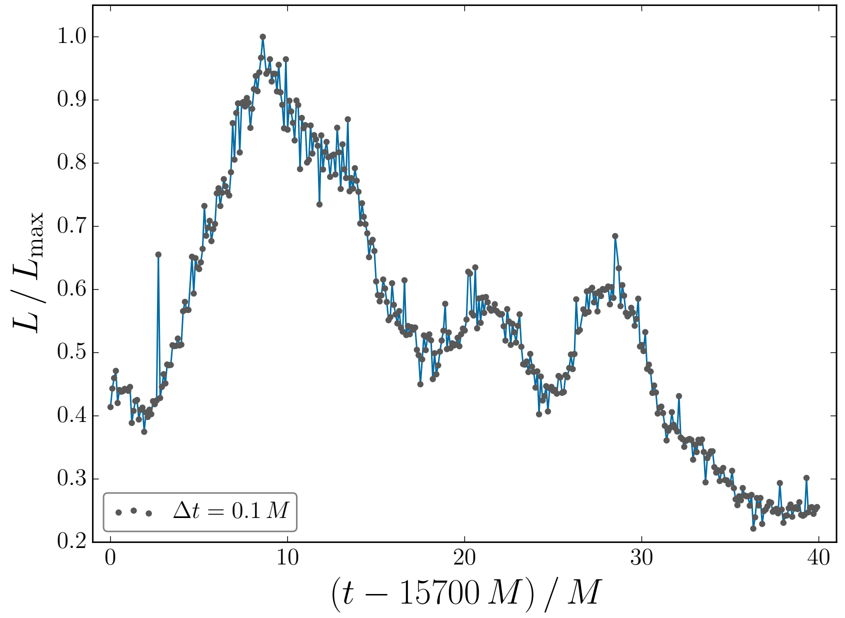
- Each random realization of the process produces a different looking light curve

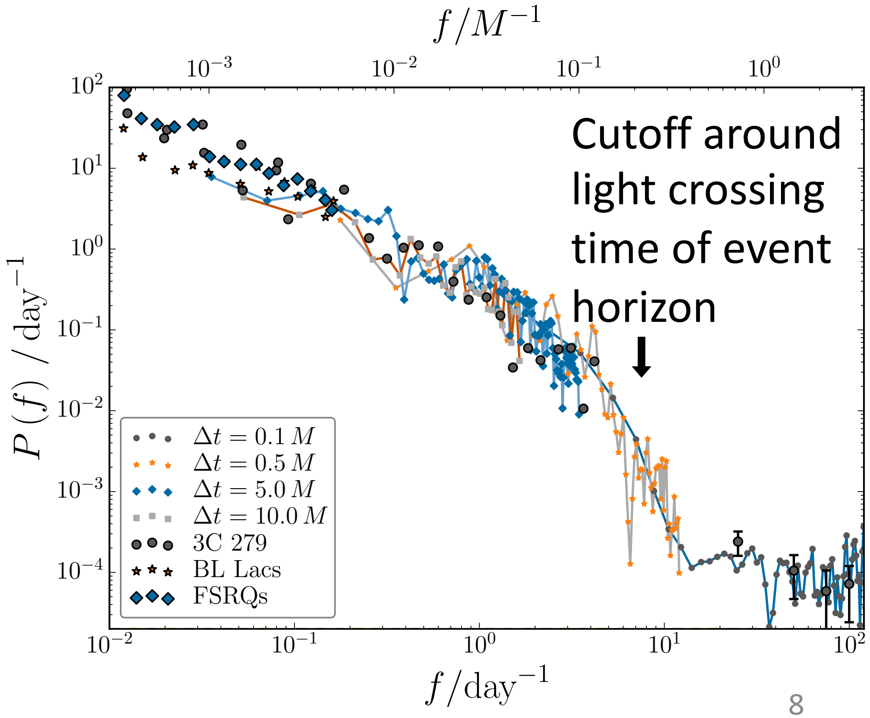
- Fluctuations obey a certain probability density functions, hence if integrated for long time, tend to produce predictable PSDs.

Questions:

- Does the properties of the process change with timescale (change in PSD slope and/or normalization)?

- Breaks in PSDs: characteristic relaxation timescale and the smallest energy dissipation sites?





Cutoff around light crossing time of event horizon

3D GRMHD simulations of LC and the PSD (O'Riordan++17)

Multiwavelength light curves: data aquisition

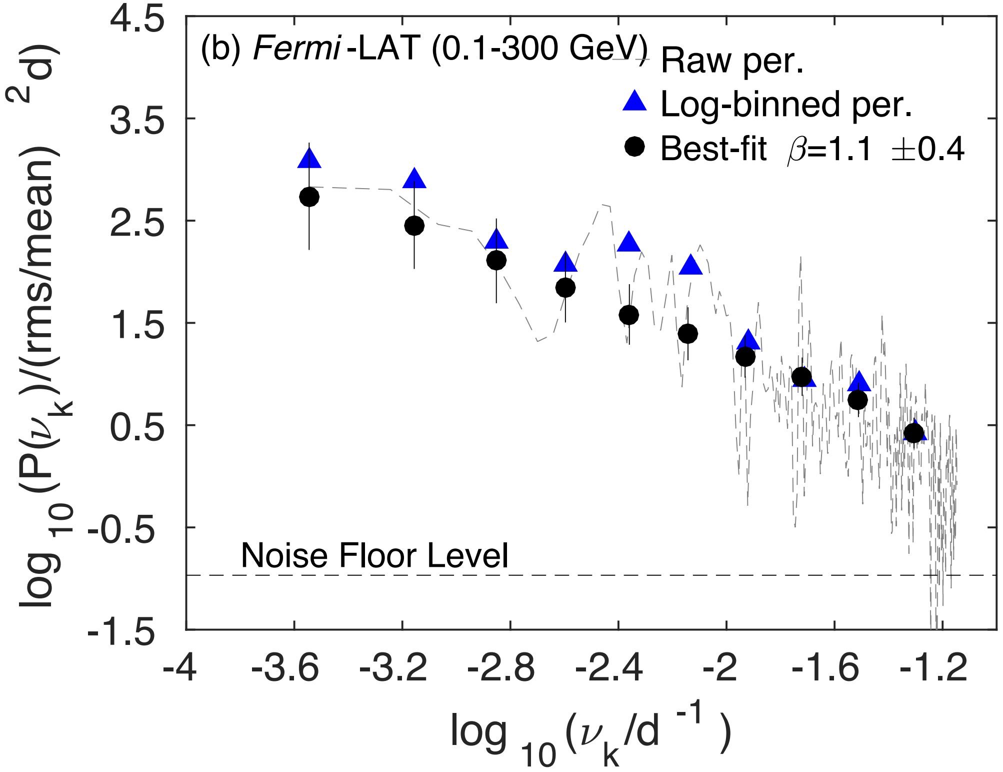
- TeV $\boldsymbol{\gamma}$-rays: High Energy Stereoscopic Systems (HESS) and VERITAS observatories (> 200 GeV) (upon request)
- GeV $\boldsymbol{\gamma}$-rays: Fermi-LAT (0.1-300 GeV) satellites (public archive)
- X-rays: RXTE-PCA (3-20 keV) and Swift-XRT (0.3-10 keV) satellites (public archive)
- Optical and Infrared: optical (BVRI) and infrared (JHK) light curves from several ground based facilities and observing programs like SMARTS, REM, Tuorla, etc., as well as Kepler satellite (public archive)
- GHz band radio light curves from MRO (22, 37 GHz), UMRAO (4.8, 8, 14.5 GHz), and OVRO (15 GHz) single dish observatories (upon request)
- Intranight light curves at optical frequencies (1-2m telescopes and 50cm OA UJ)

Obtain all possible datasets!

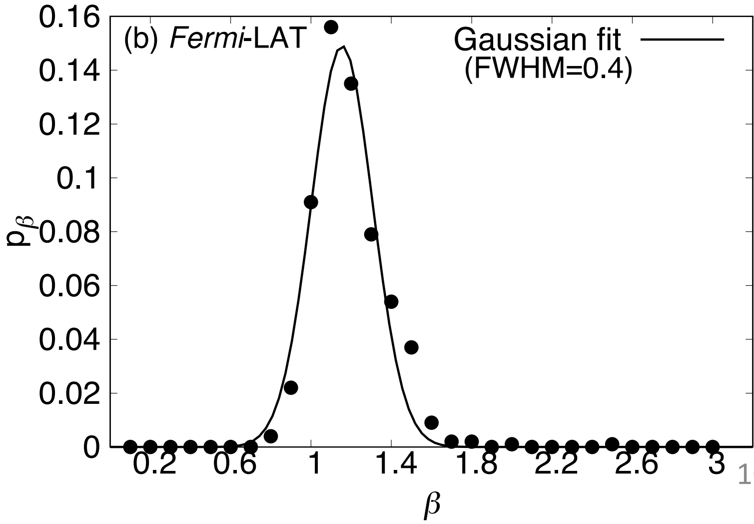
PSD analysis -- Fourier domain

- PSD of an evenly sampled light curve at points f(t_i) of mean µ and length N, is given by a periodogram defined to be squared modulus of the discrete Fourier transform (DFT):

$$P(\nu_k) = \frac{2\,T}{\mu^2\,N^2}\left\{\left[\sum_{i=1}^{N} f(t_i)\,\cos(2\pi\nu_k t_i)\right]^2 + \left[\sum_{i=1}^{N} f(t_i)\,\sin(2\pi\nu_k t_i)\right]^2\right\}$$



- Power Spectral Response (PSRESP) method: Best fit PSD model is chosen among the set of models through Monte-Carlo simulations of light curves (Emmanoloupolus++13; Uttley++02)

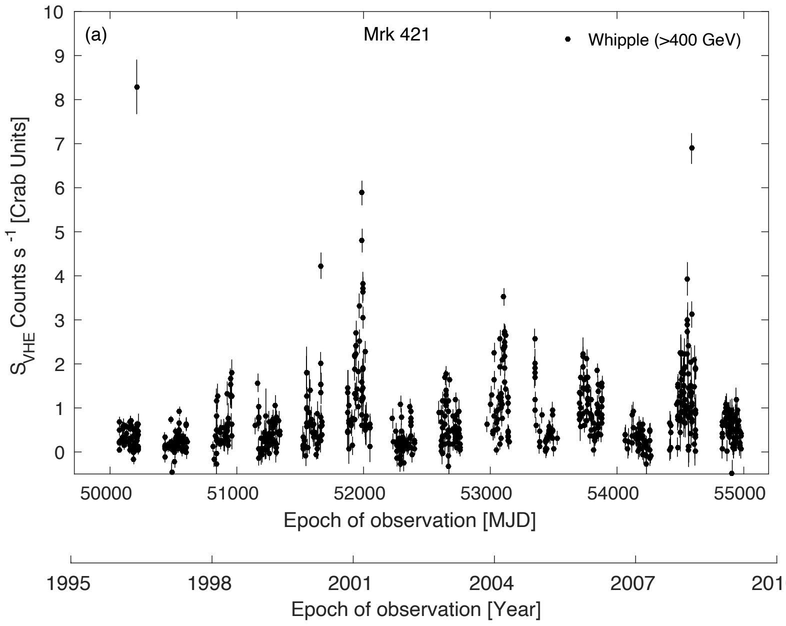


PSD model: $P(\nu_k) = A\,\nu_k^{-\beta}$ (simple Power-law, in our case)

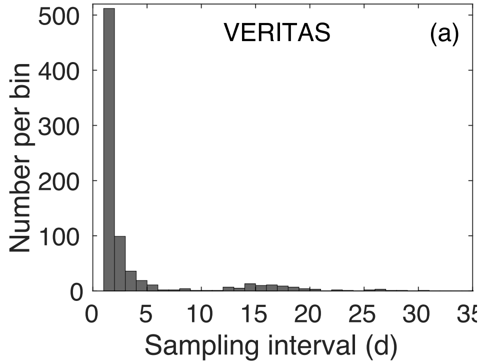
Caveat: linear interpolation is necessary!

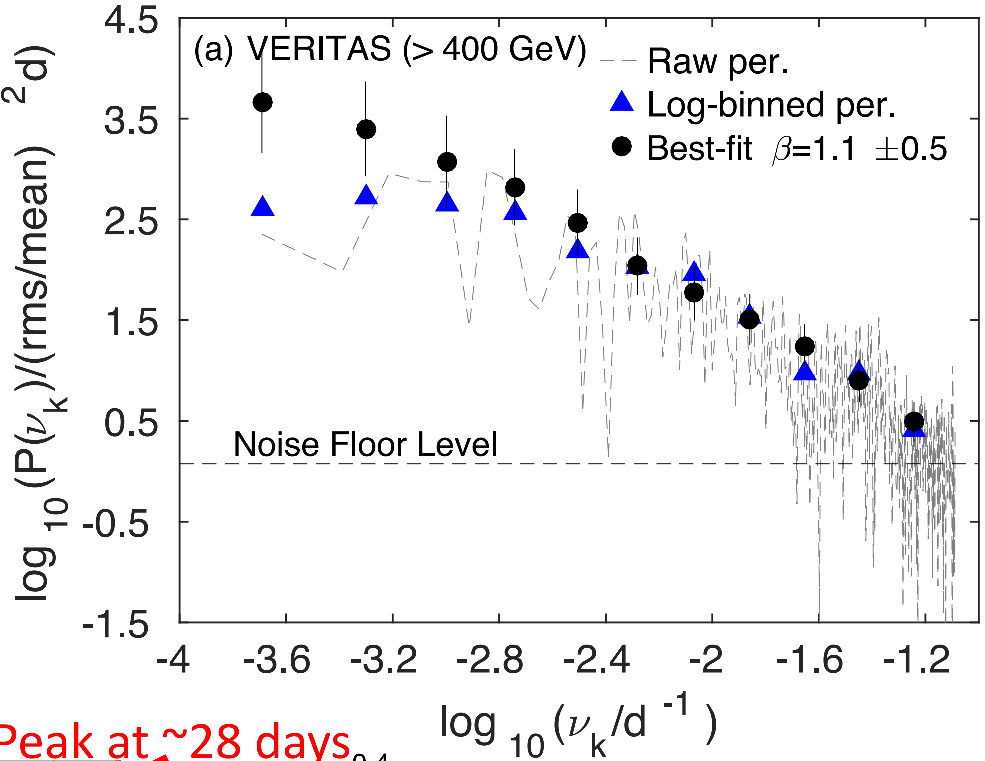
(introduction of false data in the time series, red-noise leak and aliasing)

- Convolution of true power spectrum with the spectral response of Fourier transformation



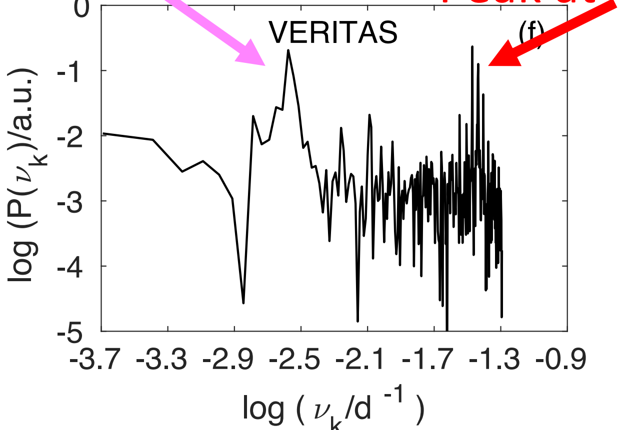
(Example of TeV light curve of the source Mrk 421 (Goyal,20)

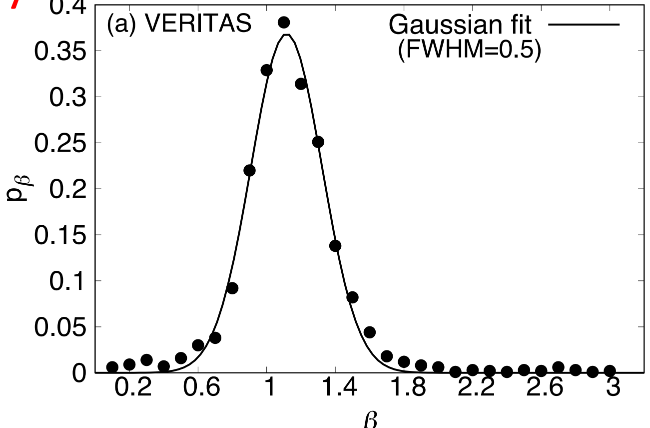




Peak at ~300 days

Peak at ~28 days

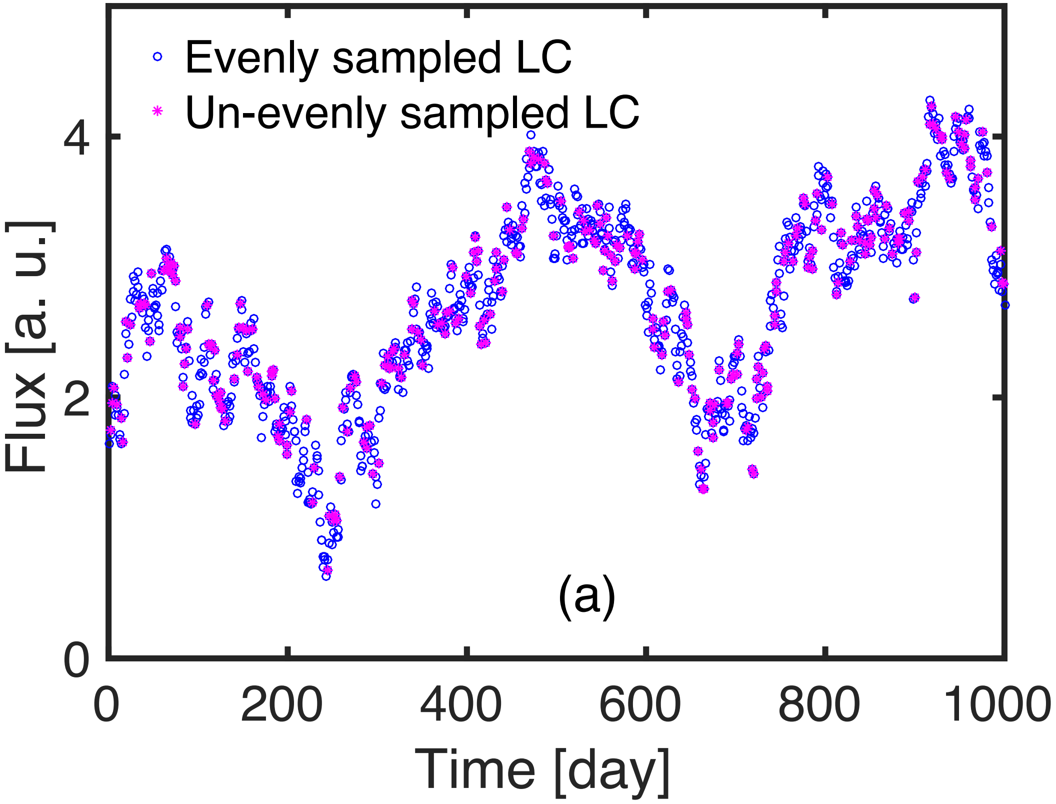




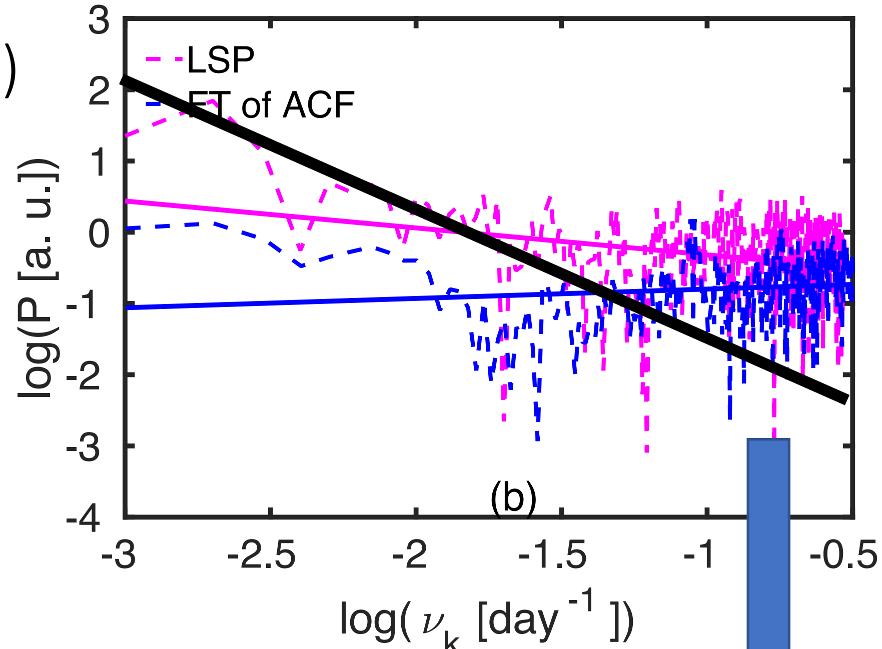
Other methods of PSD generation in Fourier-domain

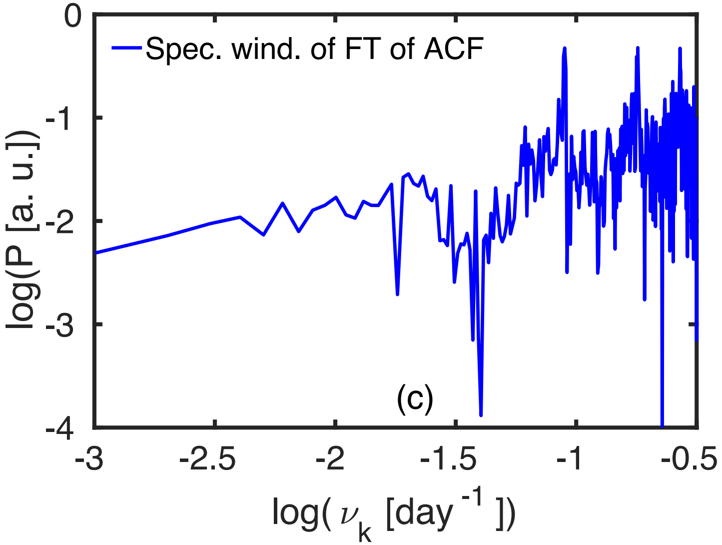
1. Lomb-Scargle Periodogram (LSP) method (Scargle, 82)

2. Fourier Transfrom of Autocorrelation function (Edelson++98)



LC is simulated with β =2 and 30% of data is kept





Flatter than β =2 (black line)!

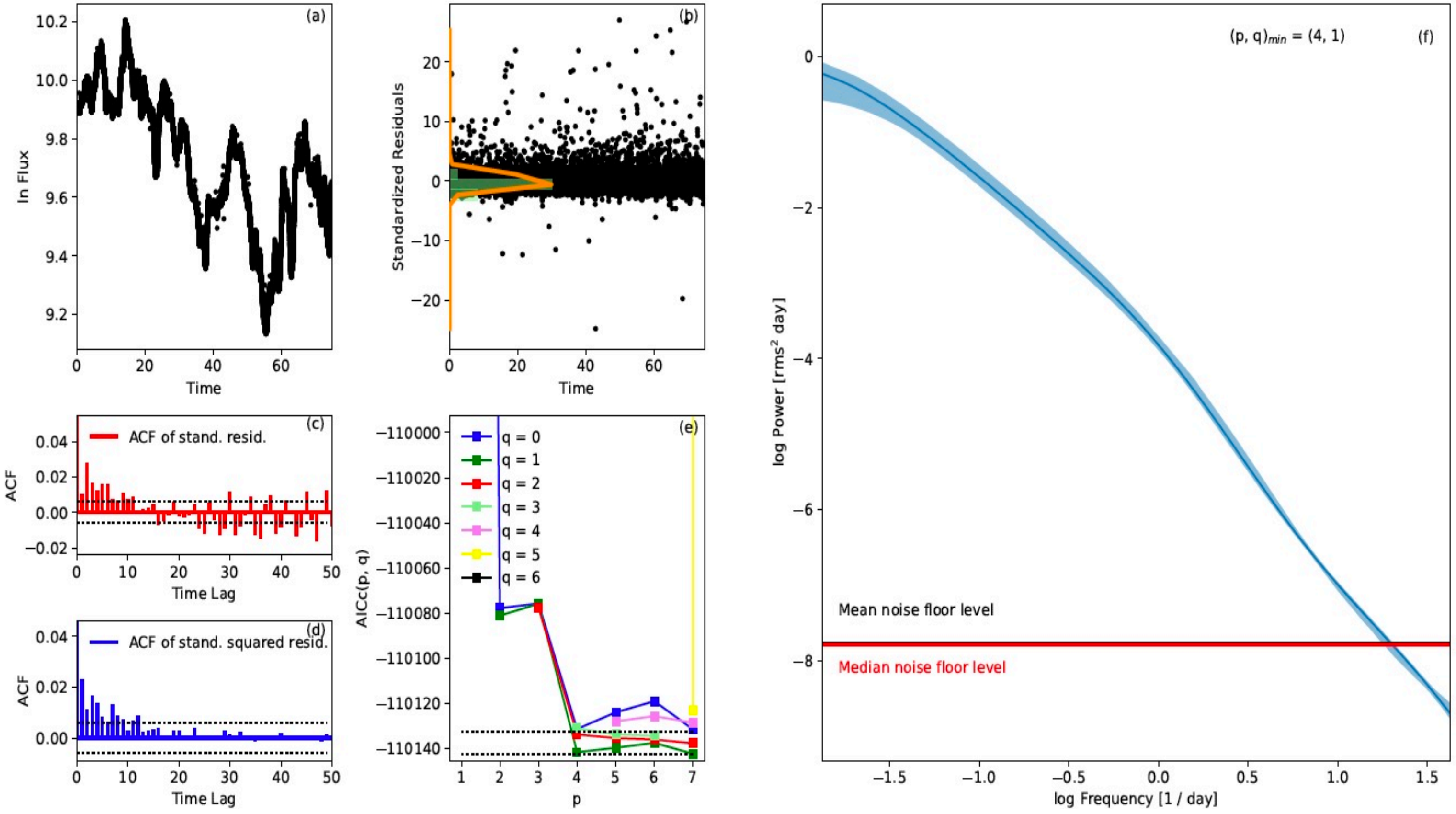
PSD analysis: time-domain approach using CARMA modeling (Kelly++14)

- Continuous-time Auto Regressive (AR) Moving Average (MA): y(t) is the solution to the stochastic differential equation

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

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

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

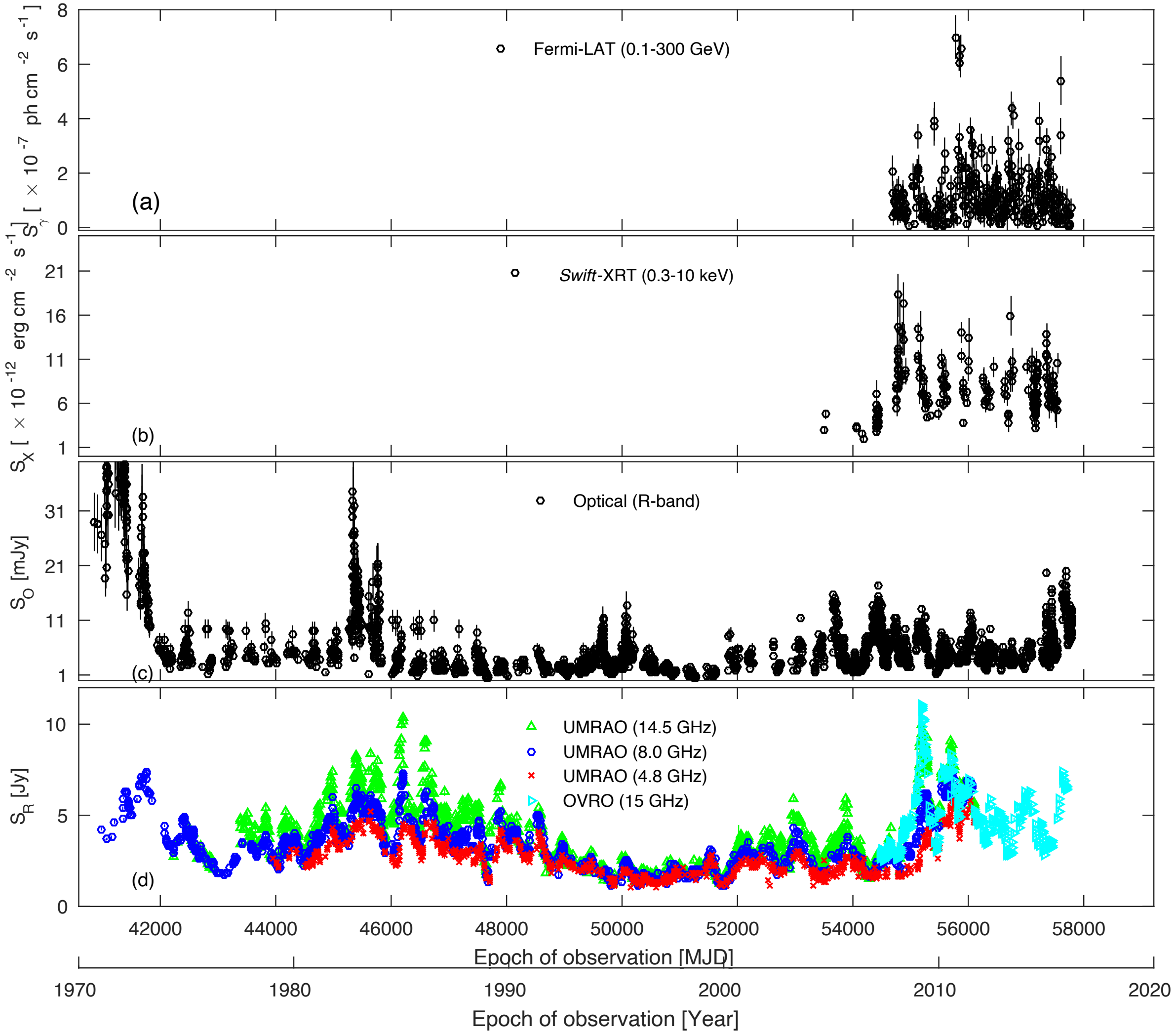


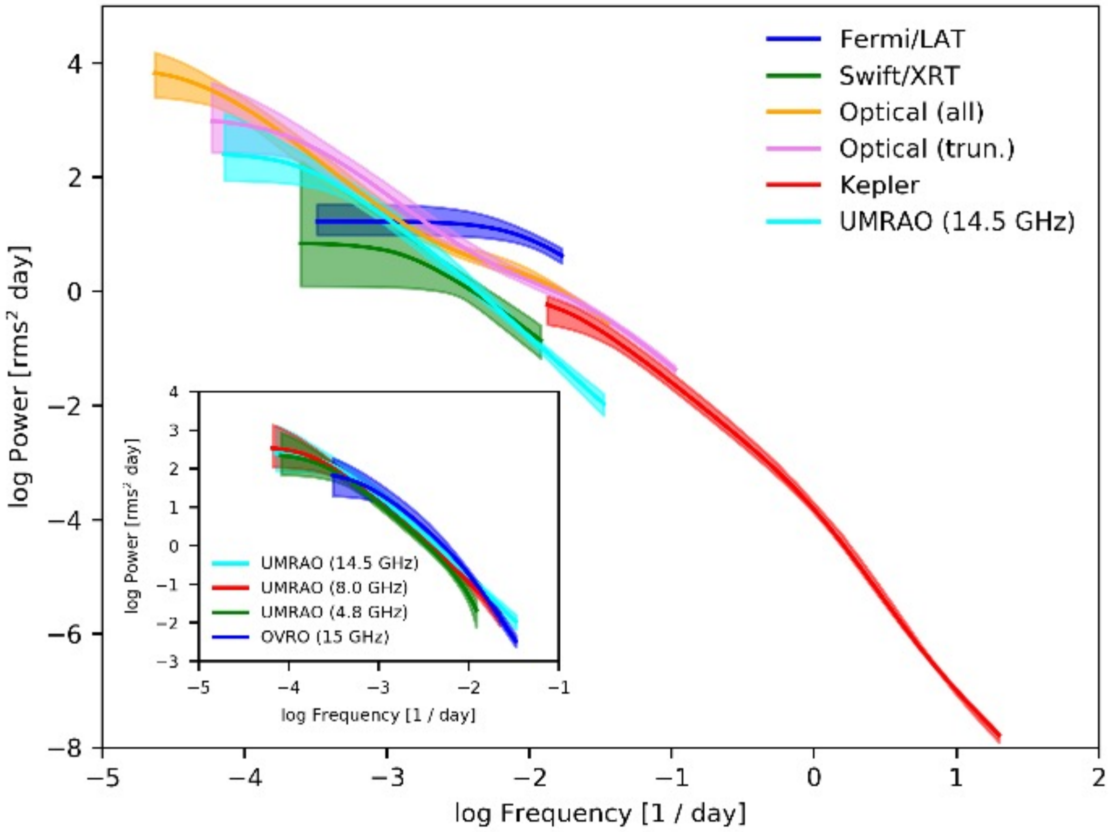
CAR(1,0) or Ornstein-Uhlenbeck process

$$dX(t) = -\frac{1}{\tau}X(t)dt + \sigma\sqrt{dt}\,\epsilon(t) + b\ dt, \quad \tau, \sigma, t > 0,$$

Where τ is the relaxation timescale and σ is the white noise process with mean 0 and variance 1

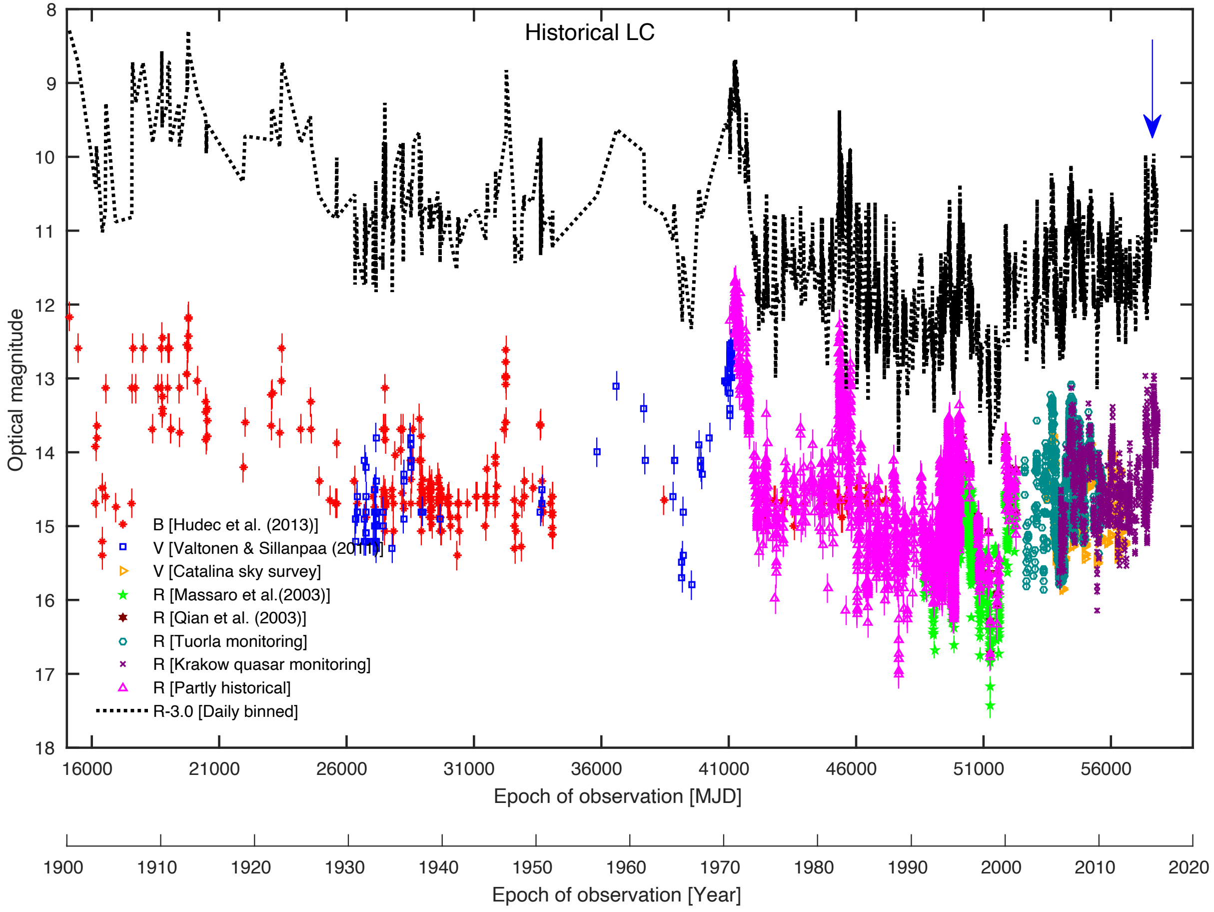
CARMA analysis of the blazar OJ 287

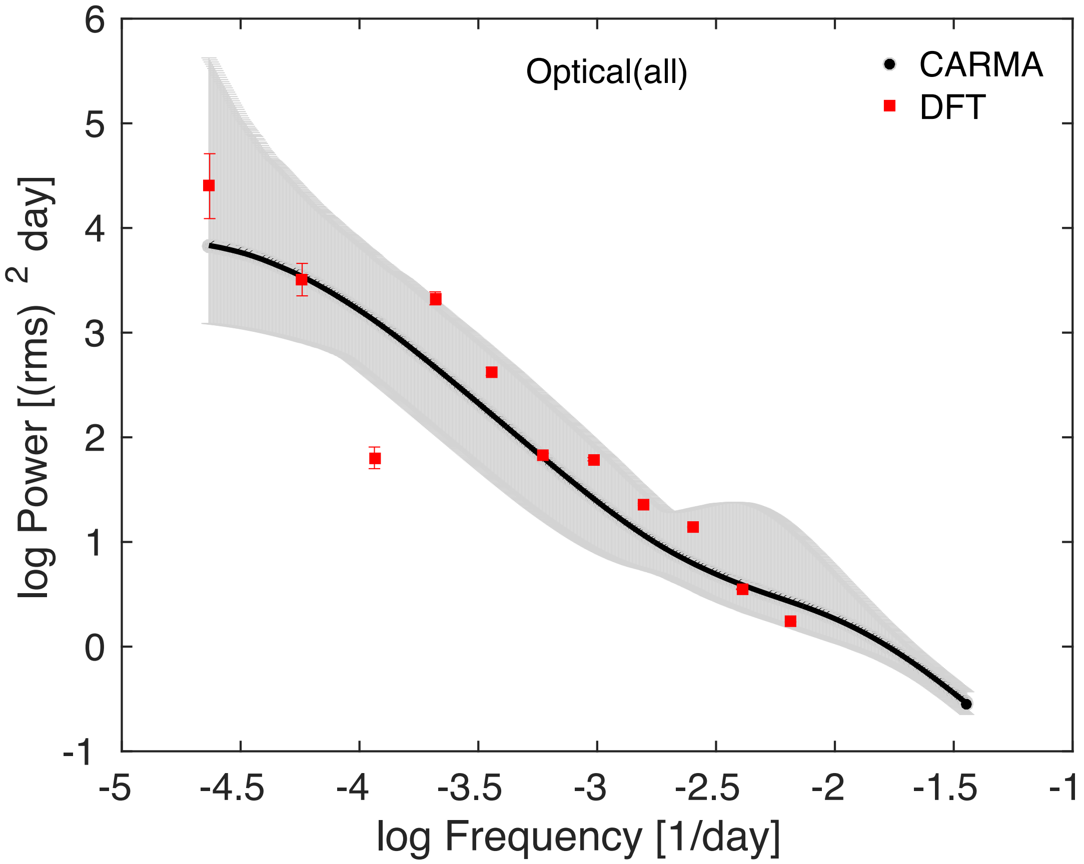




$\boldsymbol{\gamma}$-rays are relaxed at ~ 150 days, unlike the monotonic decrease of power at other frequencies (Goyal++18)!

Different methods for PSD generation
Fourier domain vs. time domain



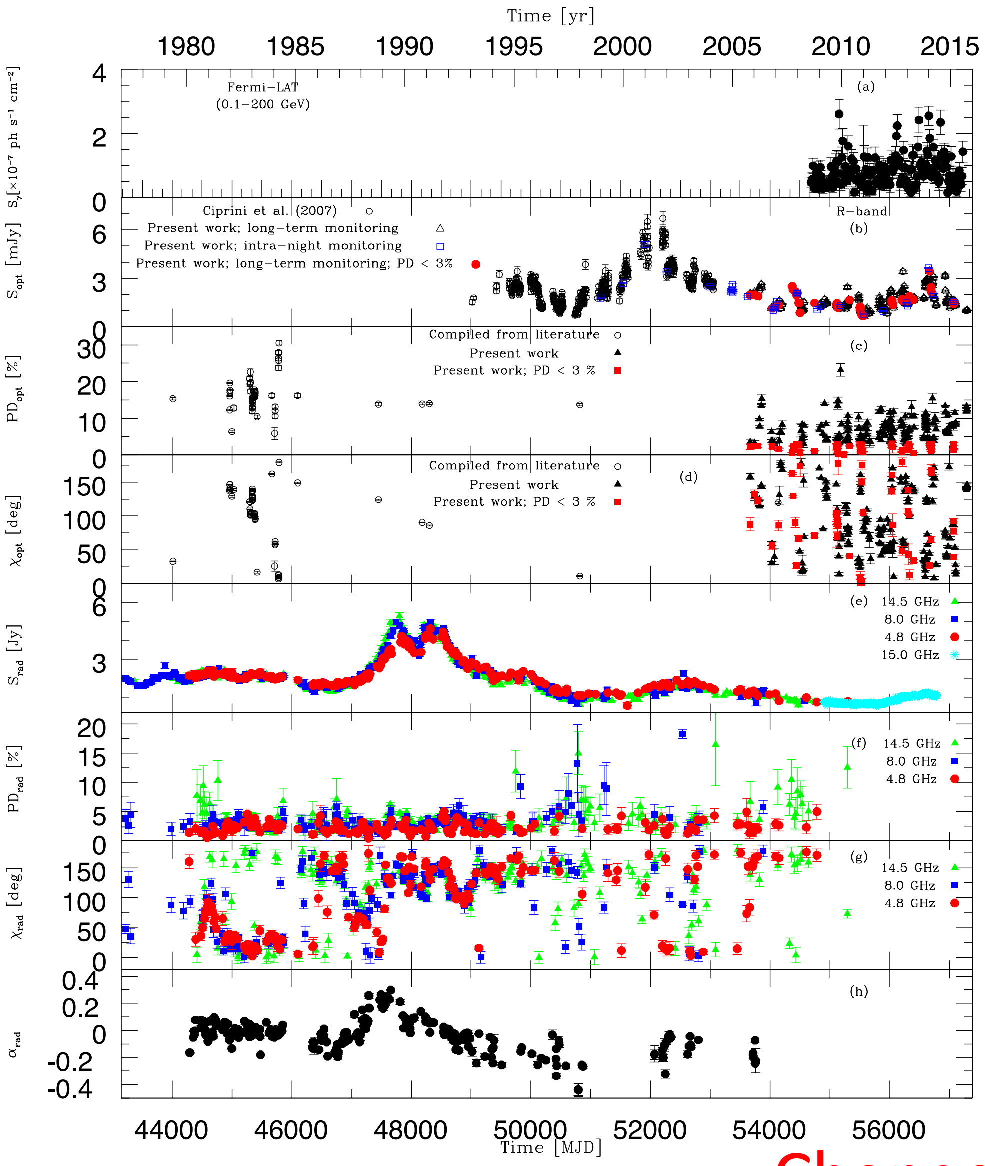


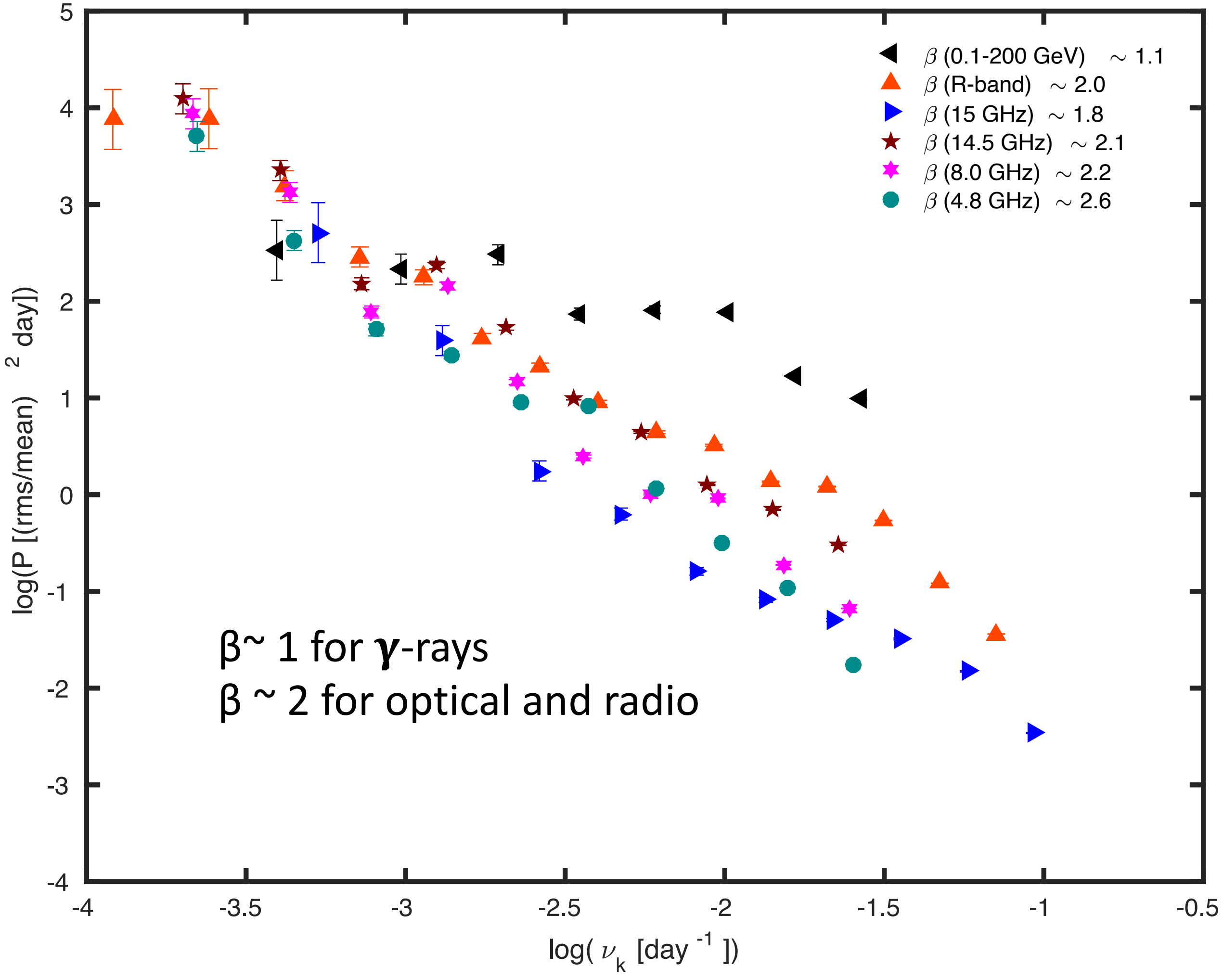
117 year-long optical light curve of the blazar OJ 287

Comparable results (Goyal++18)!

Synchrotron and IC-dominated spectral regions

Multiwavelegth long-term light curves and PSDs for the BL Lac object PKS 0735+178 (Goyal++17)

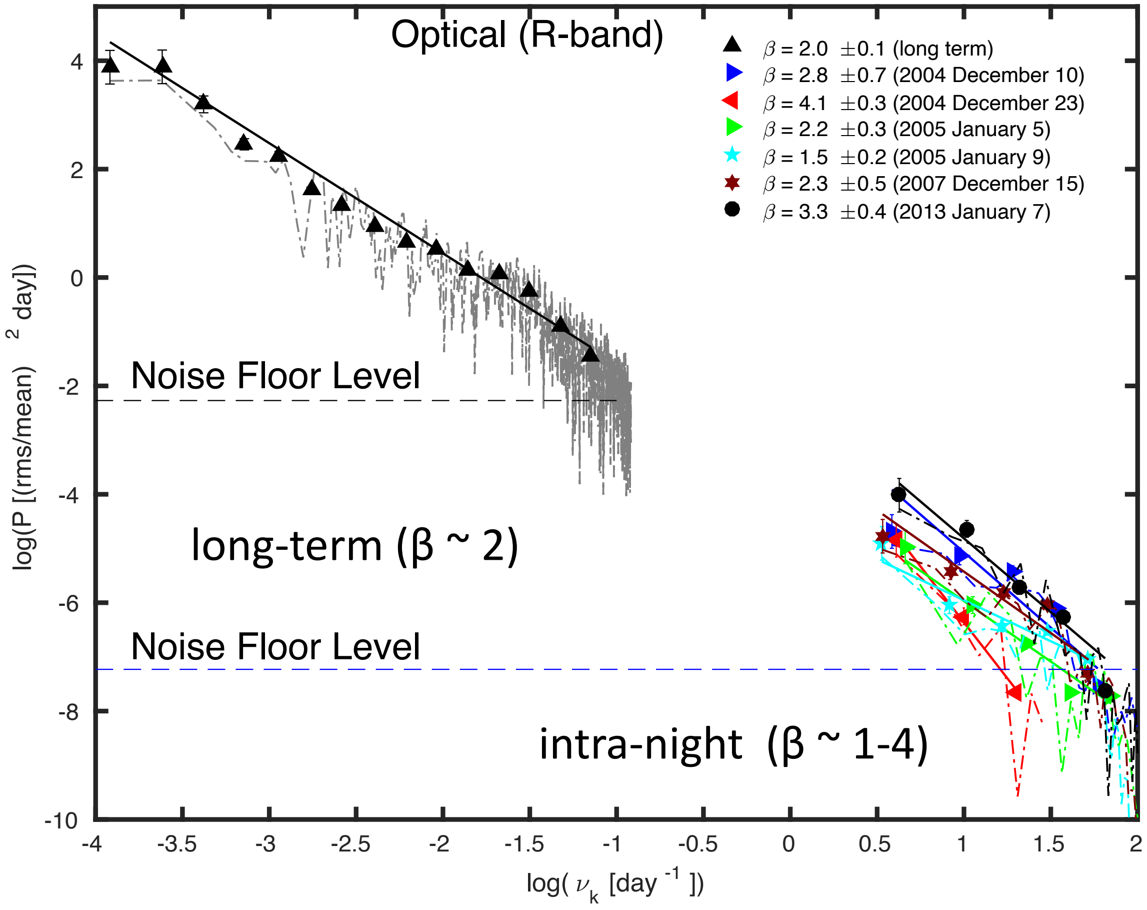




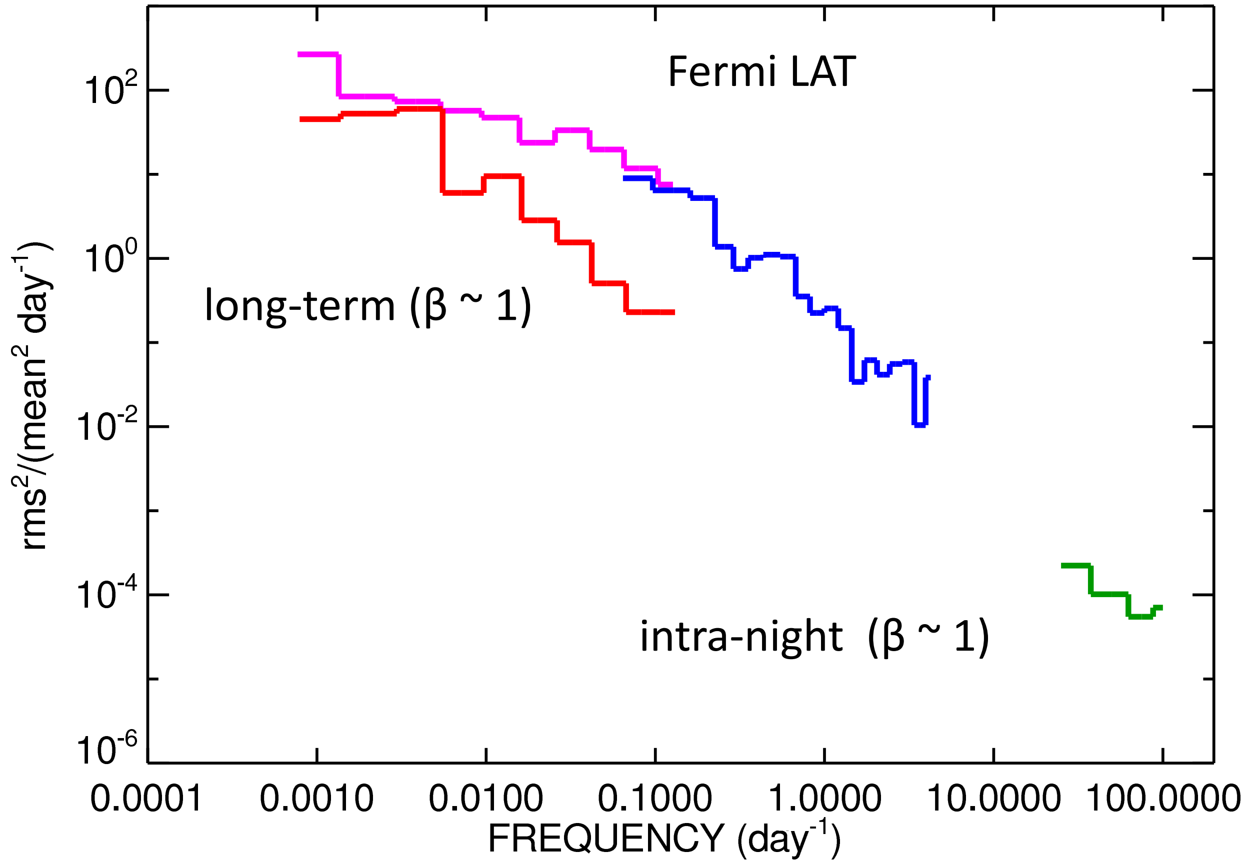
β~ 1 for **γ**-rays
β ~ 2 for optical and radio

Change of slope on decades to days timescale!

Variability spectrum from years to minutes timescale



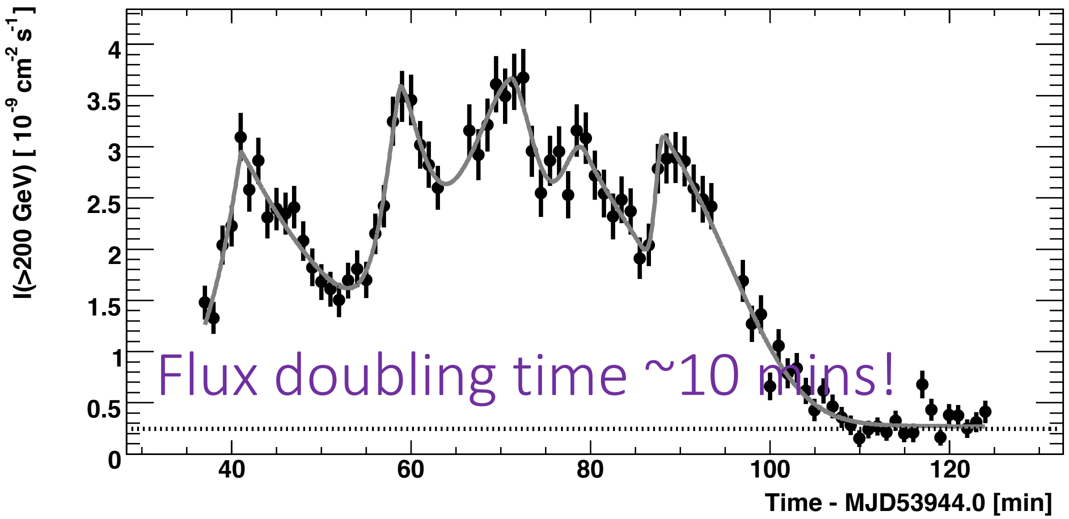
R-band PSDs of PKS 0735+178 (Goyal++17)



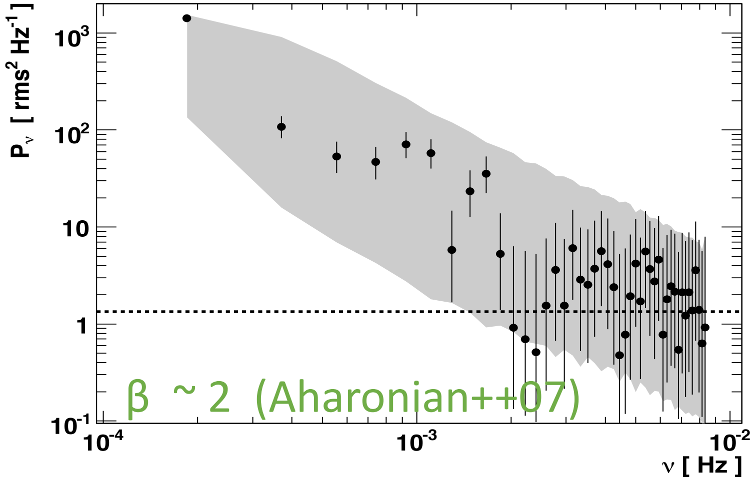
γ-ray PSDs of 3C 279 (Ackermann++16)

Normalization is the same at both Synchrotron and IC frequencies across 6 dex!

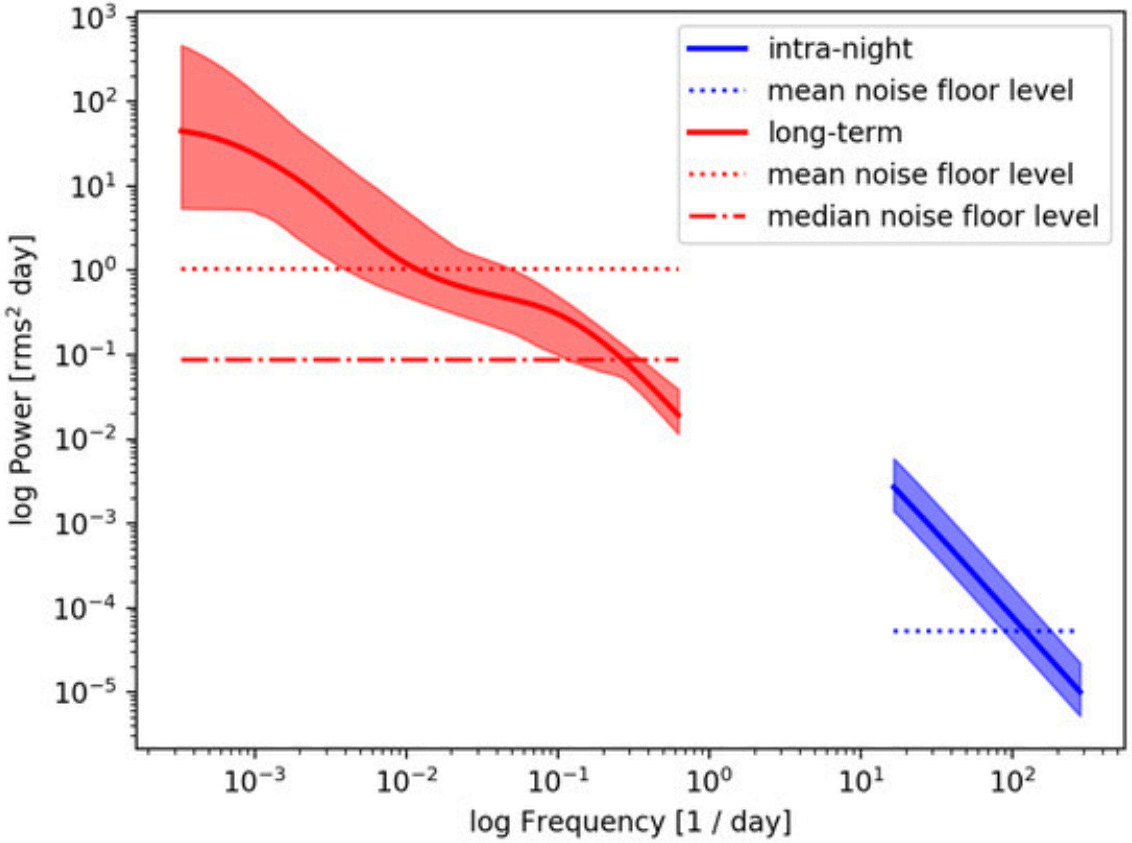
Minute-like TeV flare of PKS 2155-304



Flux doubling time ~10 mins!



β ~ 2 (Aharonian++07)



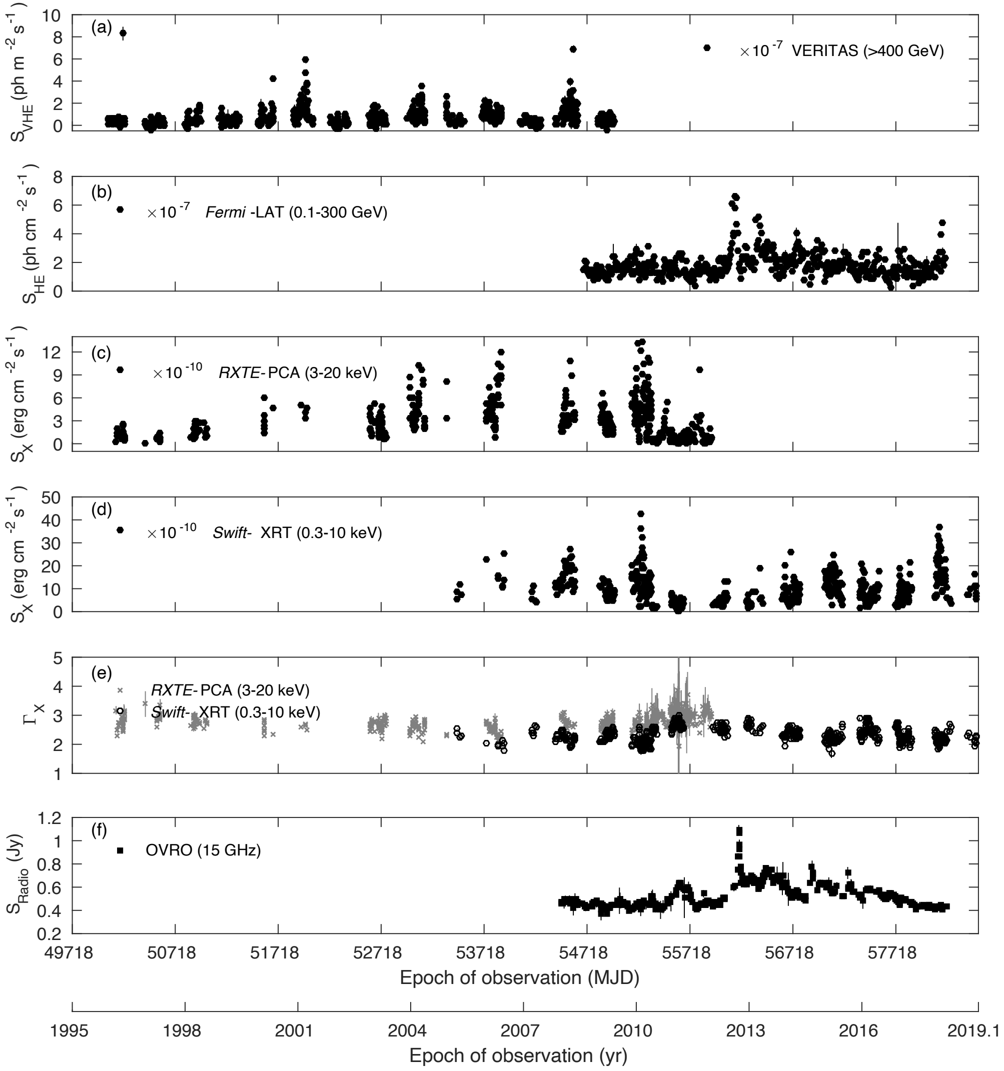
CARMA modeling of PKS 2155-304 (Goyal,19)

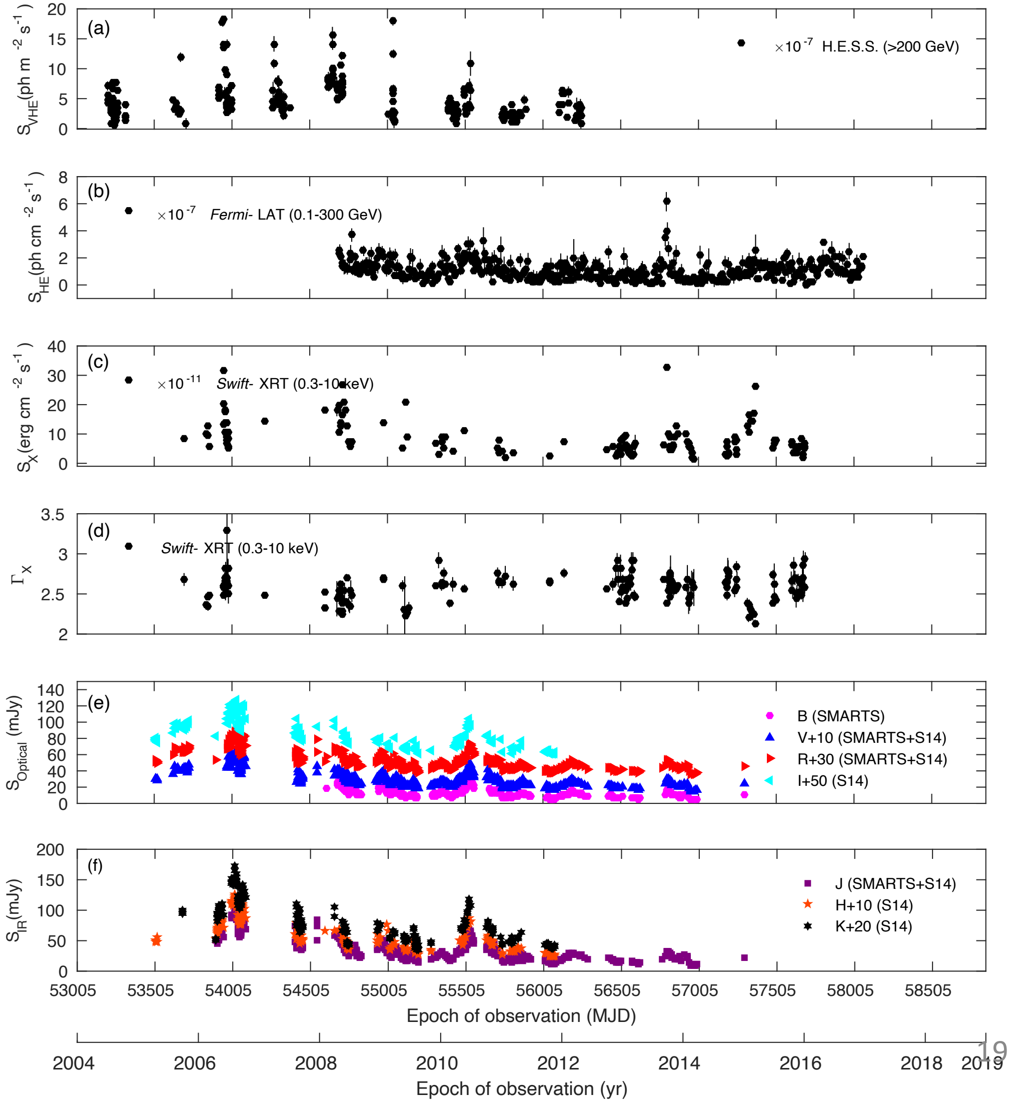
Yet, long-term light curve shows a PSD with β ~1 (Abdalla++17)

Nature of variability process changes on days timescale!

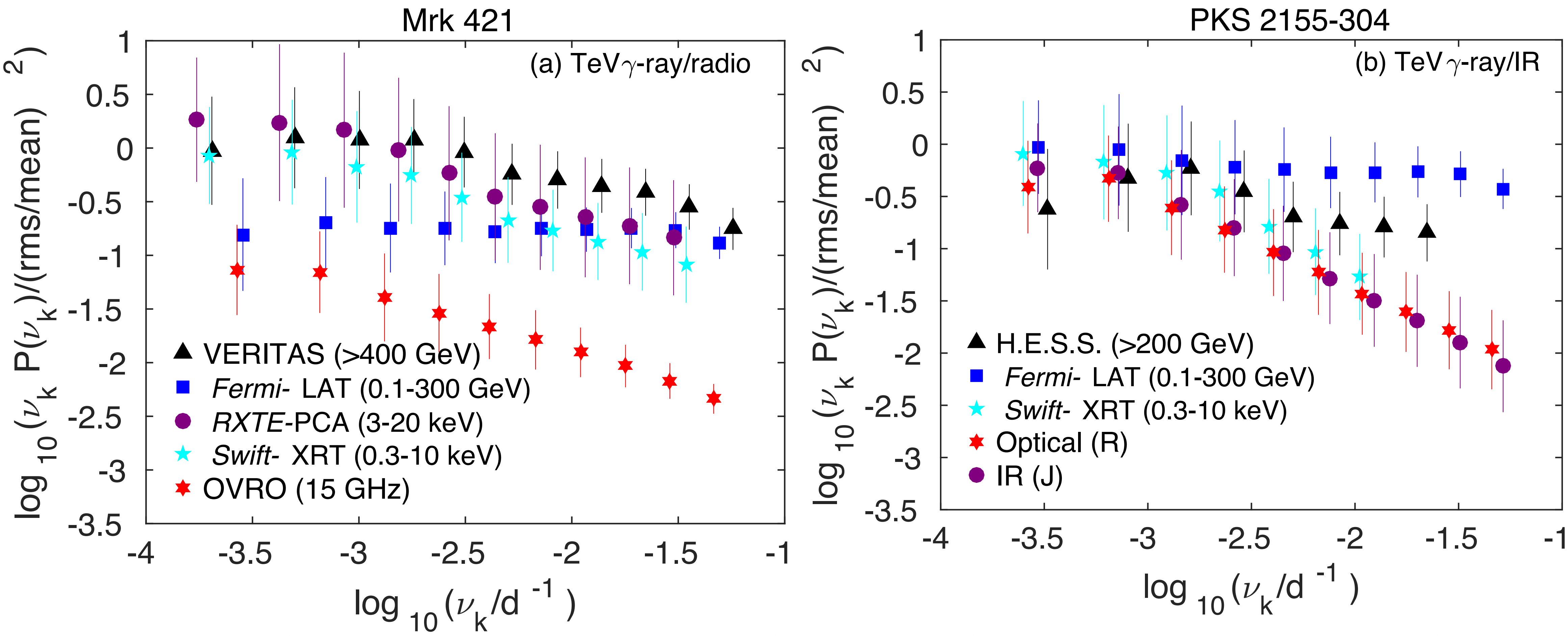
Normalization is the same!

Extending the PSD analysis to TeV energies: case studies of Mrk 421 and PKS 2155-304





Square fractional variability (decade to days!)

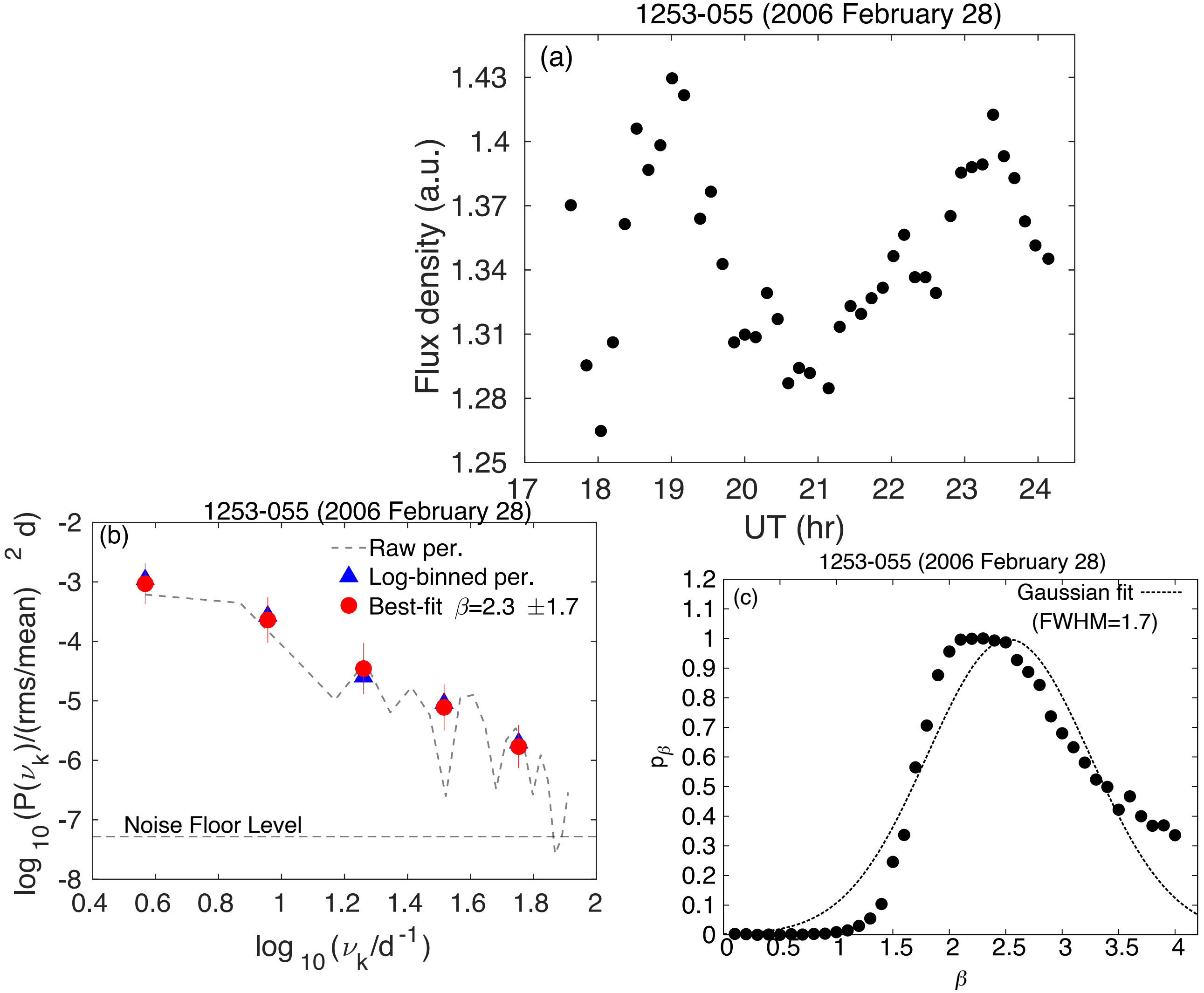


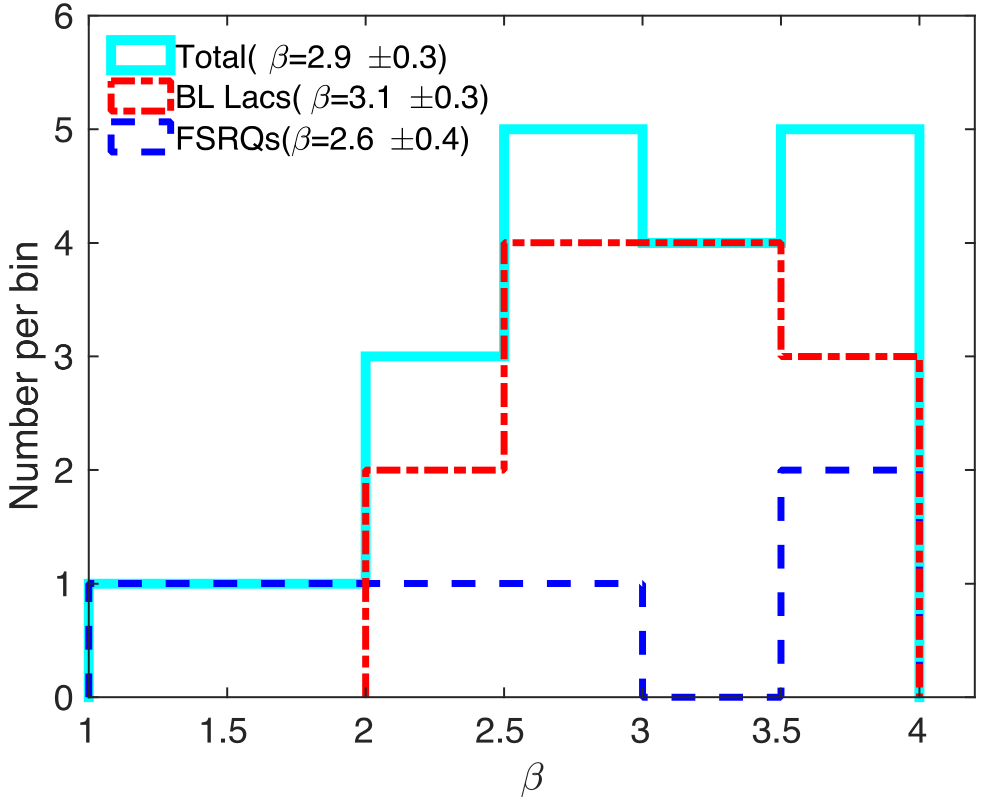
$\beta \sim 1$ (TeV, GeV and X-ray energies) and $\beta \sim 2$ (radio and optical energies)

More variability power on timescales <~ 100 days at IC frequencies as compared to synchrotron frequencies (Goyal,20)

Optical intranight PSDs for blazar sources

Data: light curves with few minutes integratiion time and photometric accuracies ~0.2—0.5% from ARIES monitoring program (1998-2010; Goyal++13)

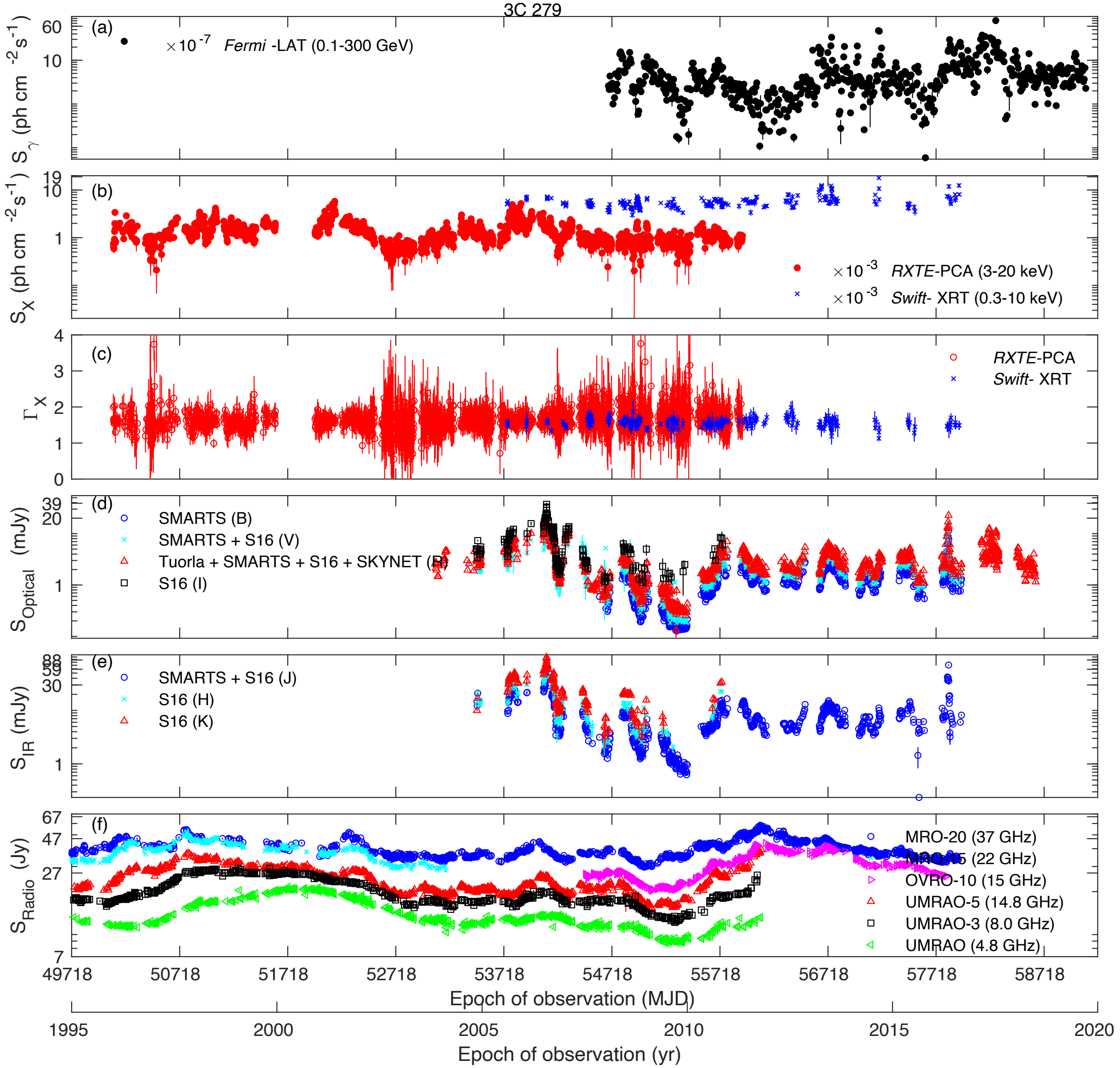


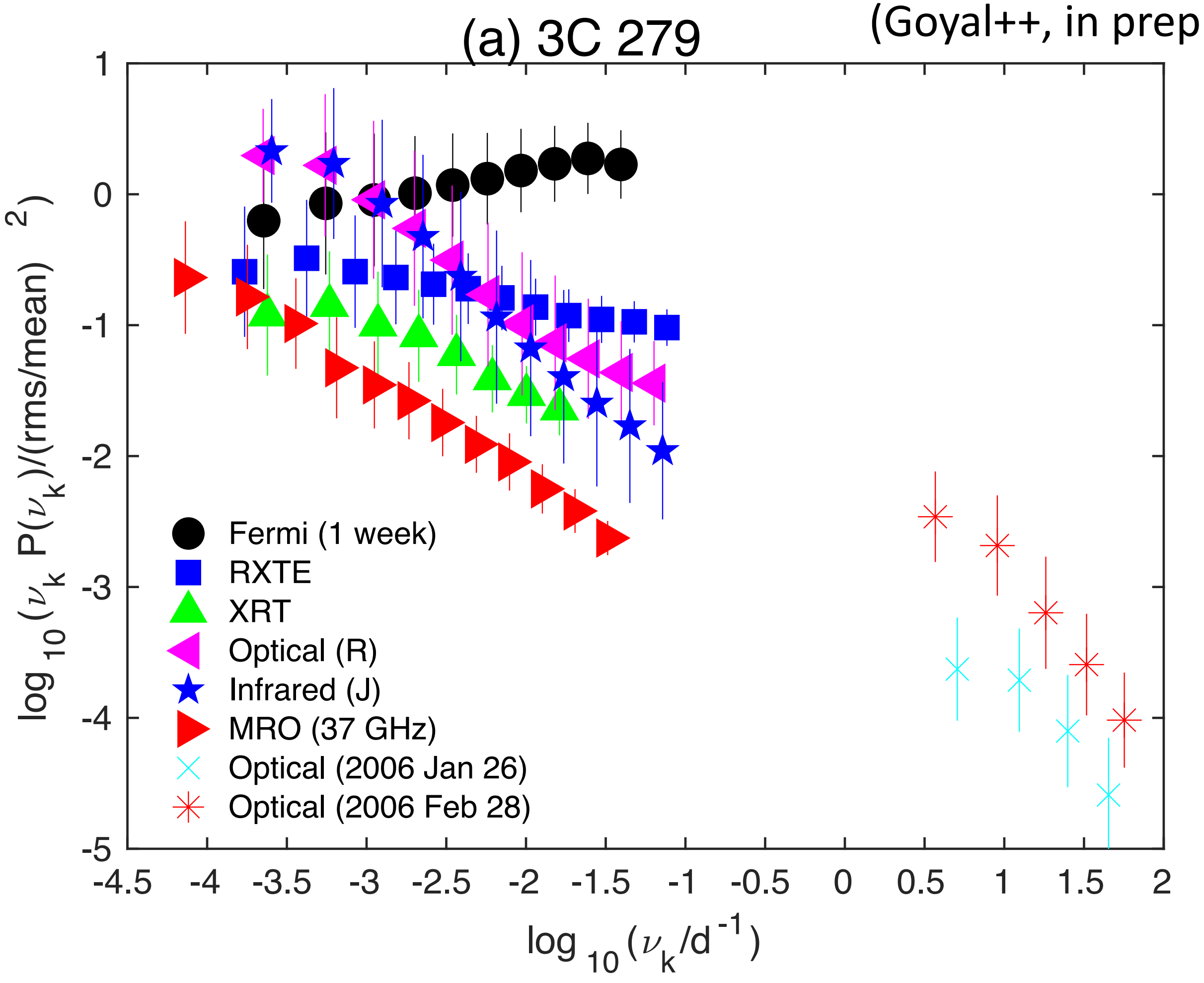


- Steeper than red-noise character on intranight timescales!
- PSD slopes are comparable for BL Lac and FSRQ sources

(Goyal, 21, accepted)

Multiwavelength PSDs of blazar 3C 279





(Goyal++, in prep)

- β ~ 1 (GeV and X-ray energies)
- β ~ 2 (radio and optical energies)
- Normalization is same at optical band

Summary and conclusions

1. Featureless, single power-law power spectral density on timescales ranging from many years down to days timescales (long-term variability) with largest variance on longer timescales –colored noise
2. β ~ 1 at TeV/GeV **γ**-ray energies as compared to β ~ 2 at radio and optical energies. β ~ 1 at X—rays too. Different statistical characters of Synchrotron and IC variability
3. Detection of relaxation timescale of ~150 days for the **γ**-rays (OJ 287), not seen at lower energies (inhomogeneous jet)
4. No flattening of PSDs up to decade timescales (except for OJ 287 in gamma-rays)
5. Change of slope (1—3) on intranight timescales (non-stationarity on short timescales)
6. Steeper than red-noise character of intranight variability (cutoff of variability power around the days)
7. Intranight PSD slopes are comparable for BL Lac and FSRQ populations, indicating jet origin of variability and **NOT** the accretion disk.

Possible Interpretation!

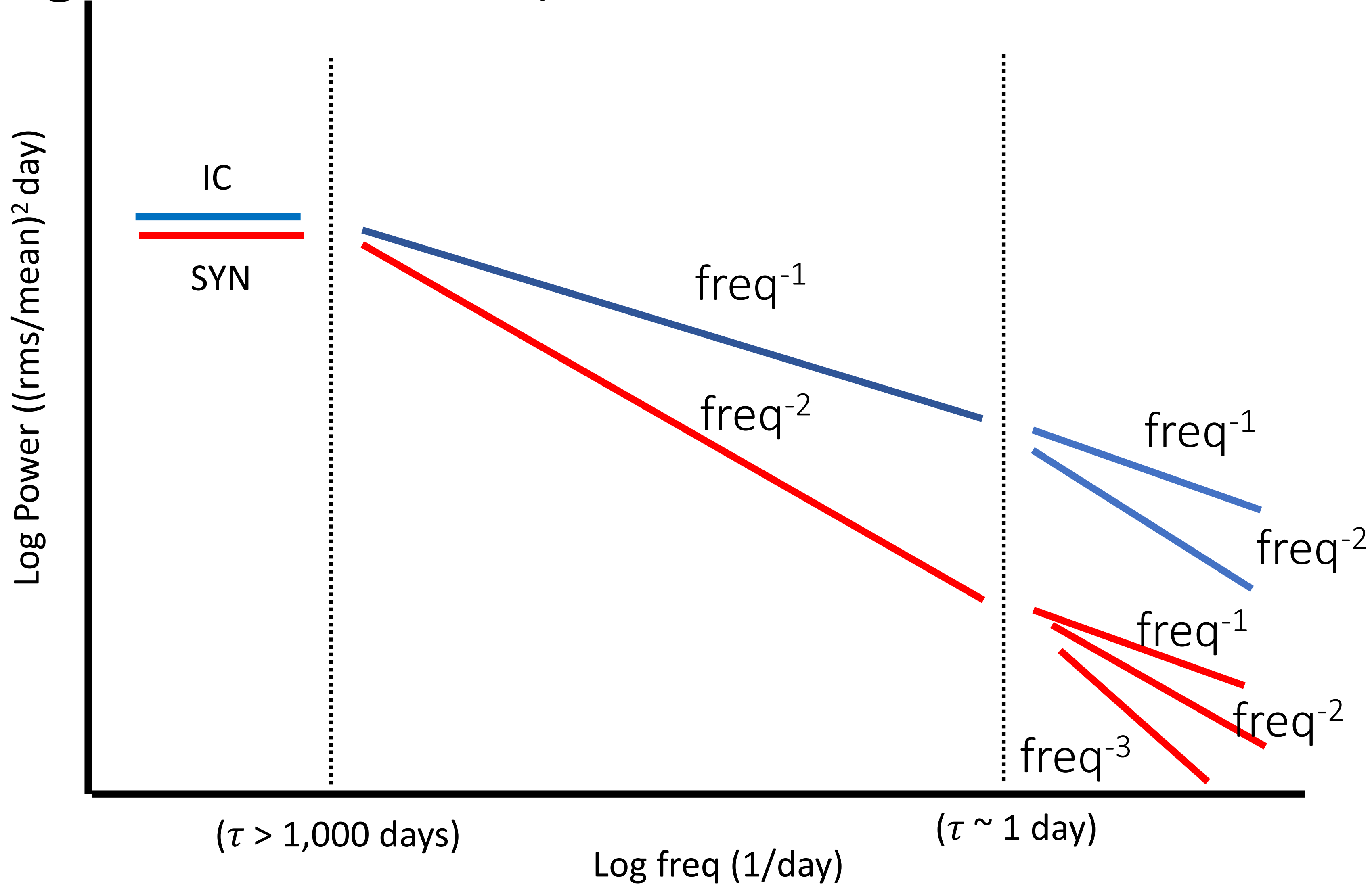
=> Leptonic scenario: different emission sites for γ-rays than optical (why red vs. pink ?)

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

=> Leptonic scenario #2 (Goyal++,17,18,20): synchrotron emission is produced in the same extended region of the jet, which is however highly inhomogeneous or turbulent ; synchrotron variability is driven by a single stochastic process with the relaxation timescales τ_{long} >1,000 days while γ-ray variability is driven by a superposition of two stochastic processes with relaxation timescales τ_{long} > 1,000 to 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.

Leptonic scenario #2

(Multiple relaxation time and non-stationarity on intranight timescales)



3C 279; Fermi-LAT
(Ackermann++16)

PKS 2155-304; HESS
(Aharonian++07)

(Optical and X-rays:
Goyal++17, Goyal,21,
Zhang++21)