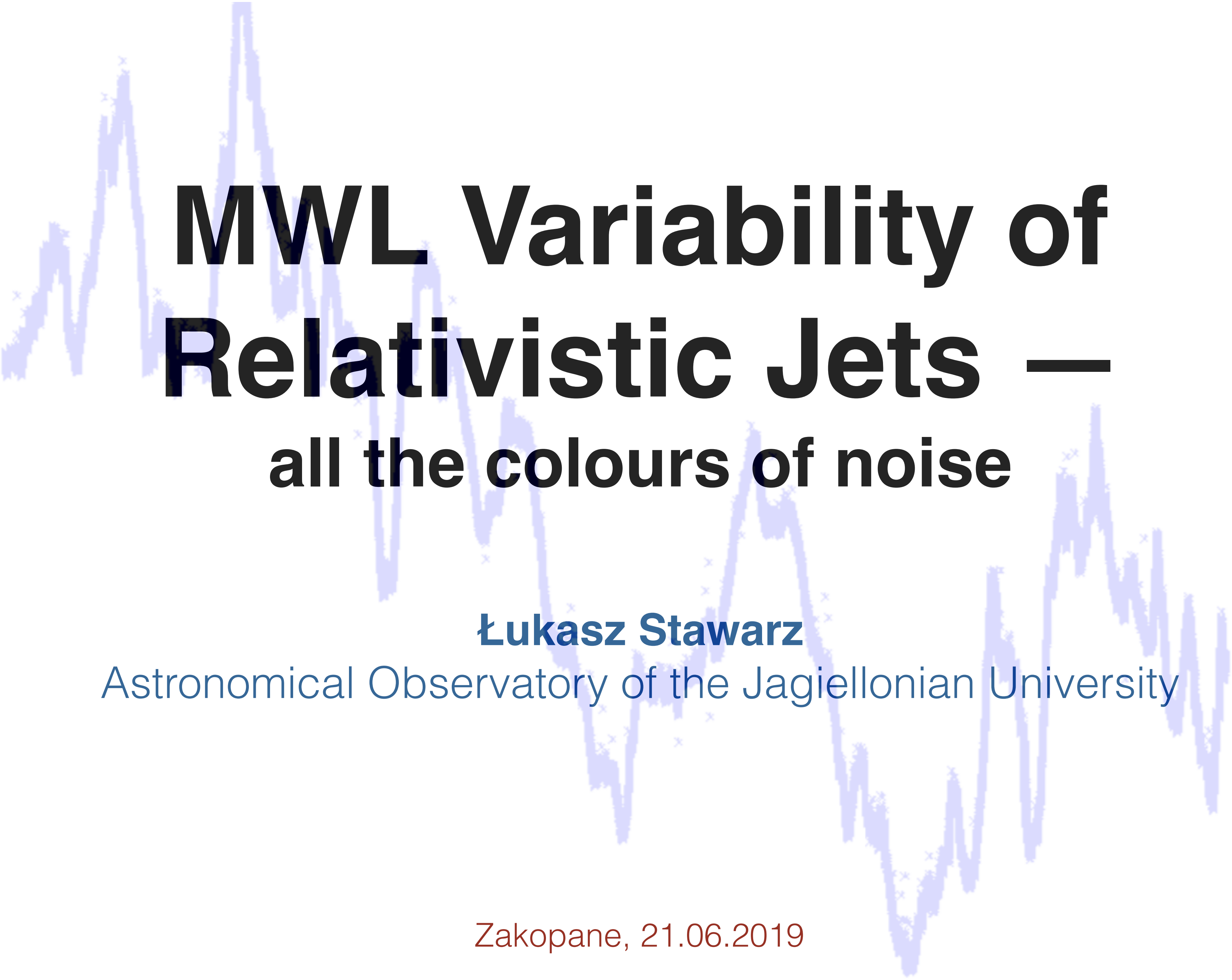


# MWL Variability of Relativistic Jets —

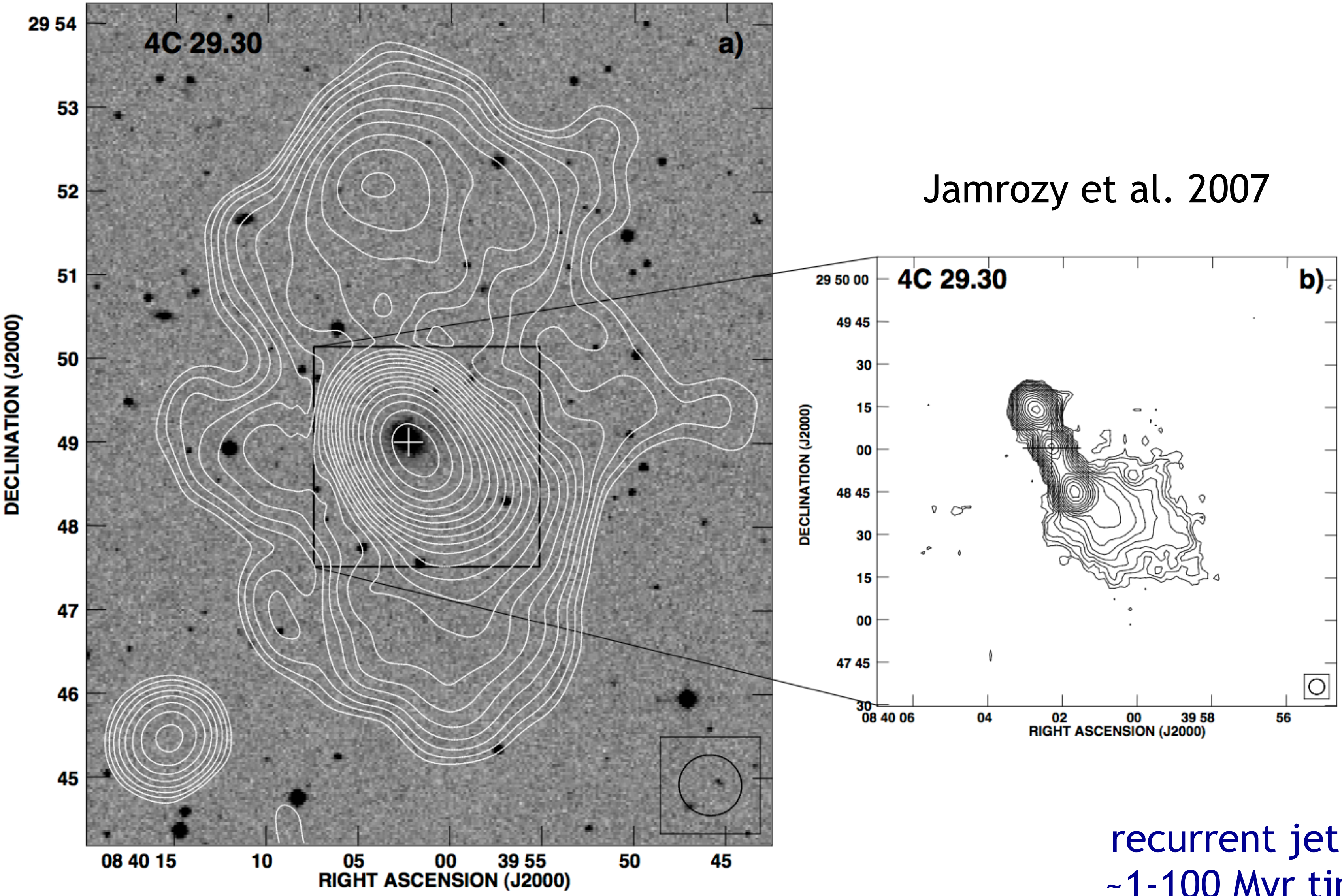
## all the colours of noise

**Łukasz Stawarz**

Astronomical Observatory of the Jagiellonian University

Zakopane, 21.06.2019

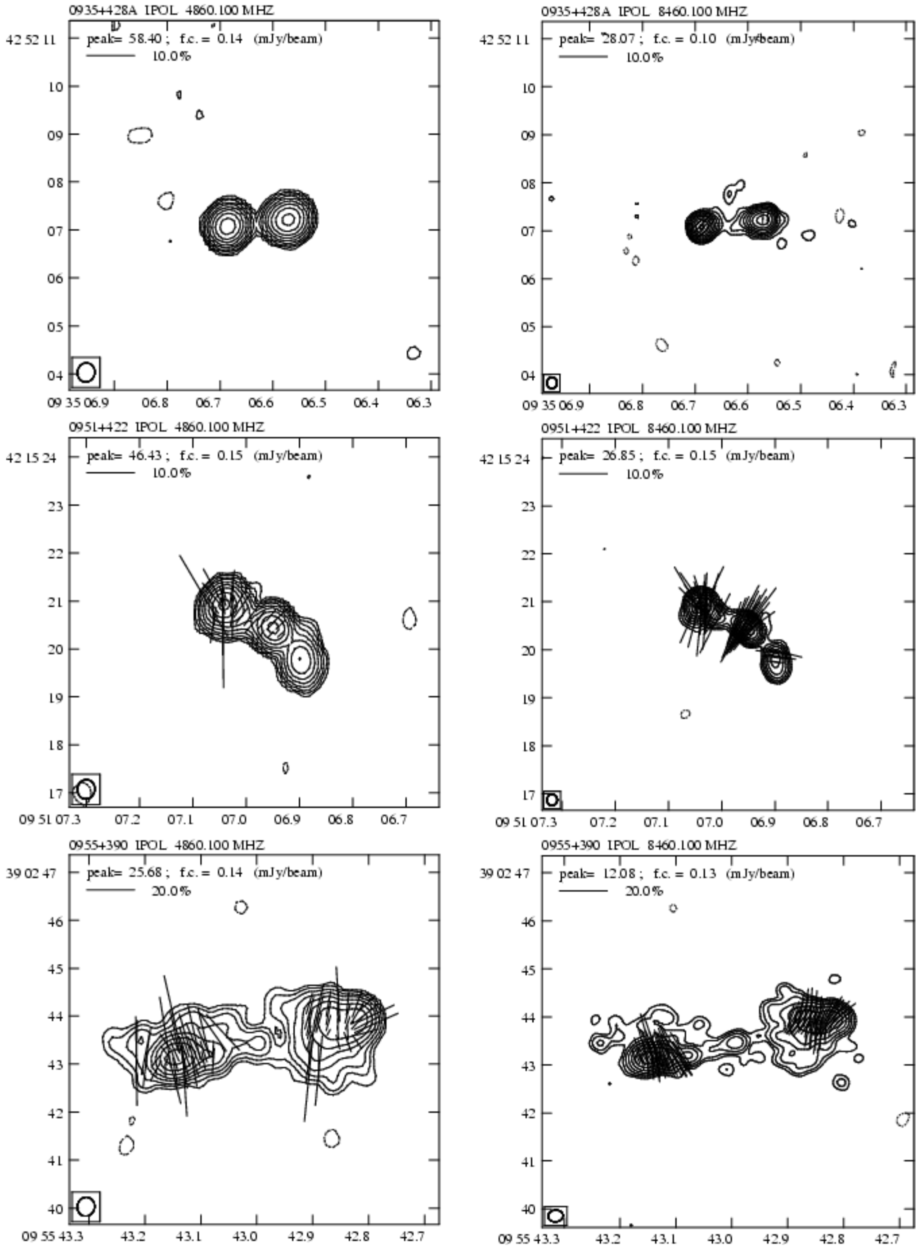
# Intermittent Jet Activity

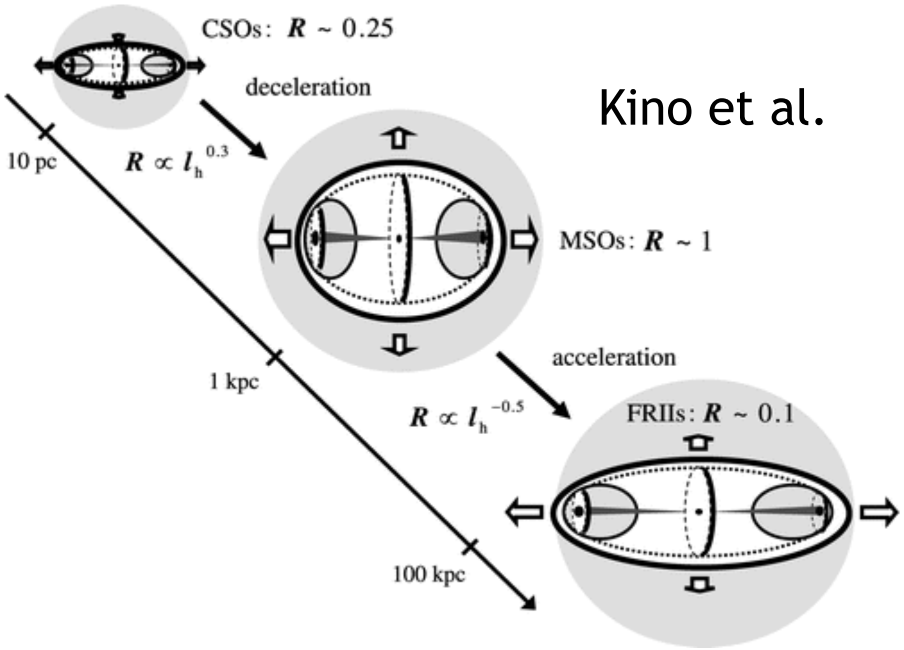


Jamrozy et al. 2007

recurrent jet activity
~1-100 Myr timescales

# Intermittent Jet Activity

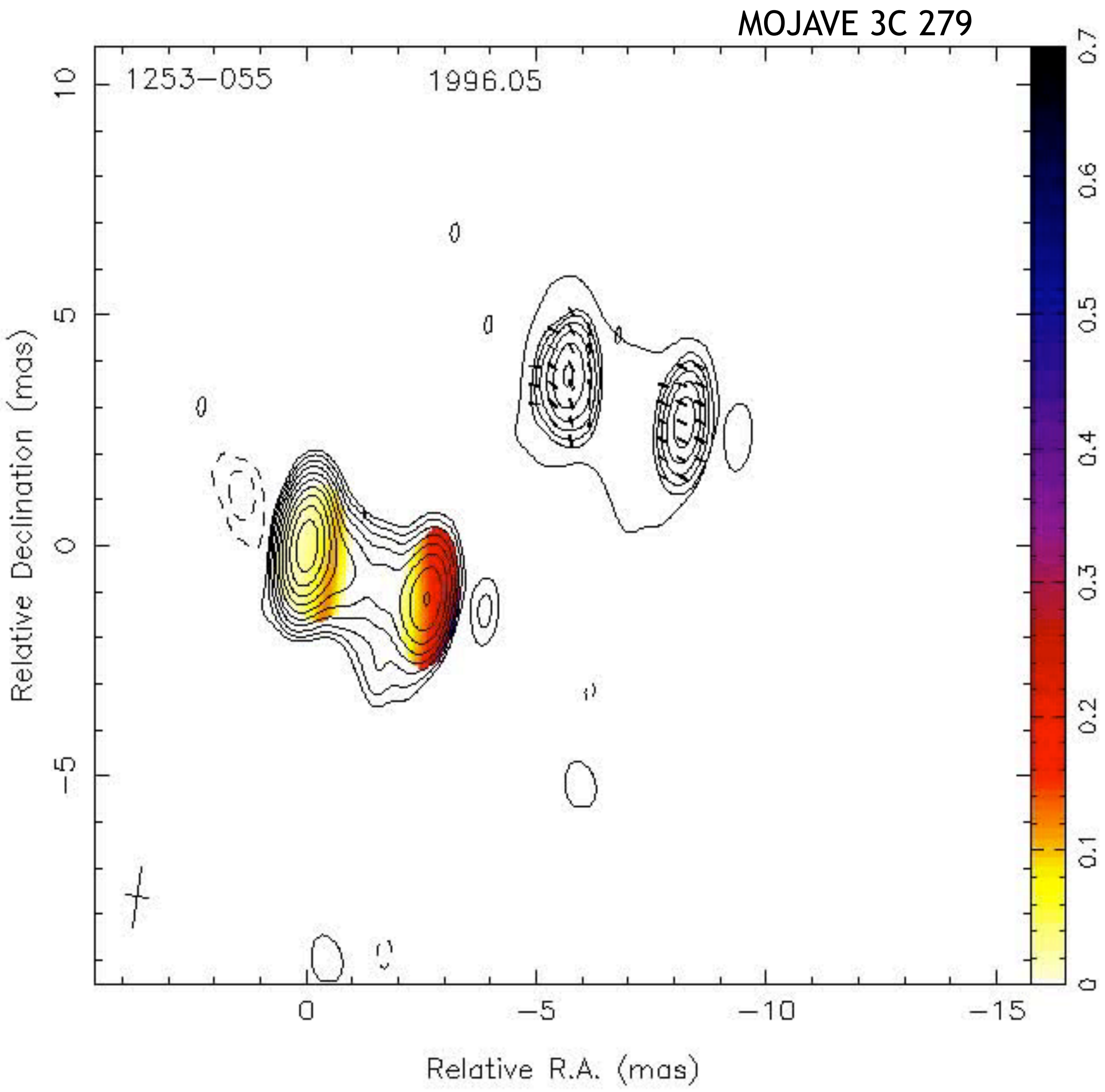




Kino et al.

Reynolds & Begelman 1997:
statistics of young radio sources -
recurrent jet activity on
~0.1-10 kyr timescales

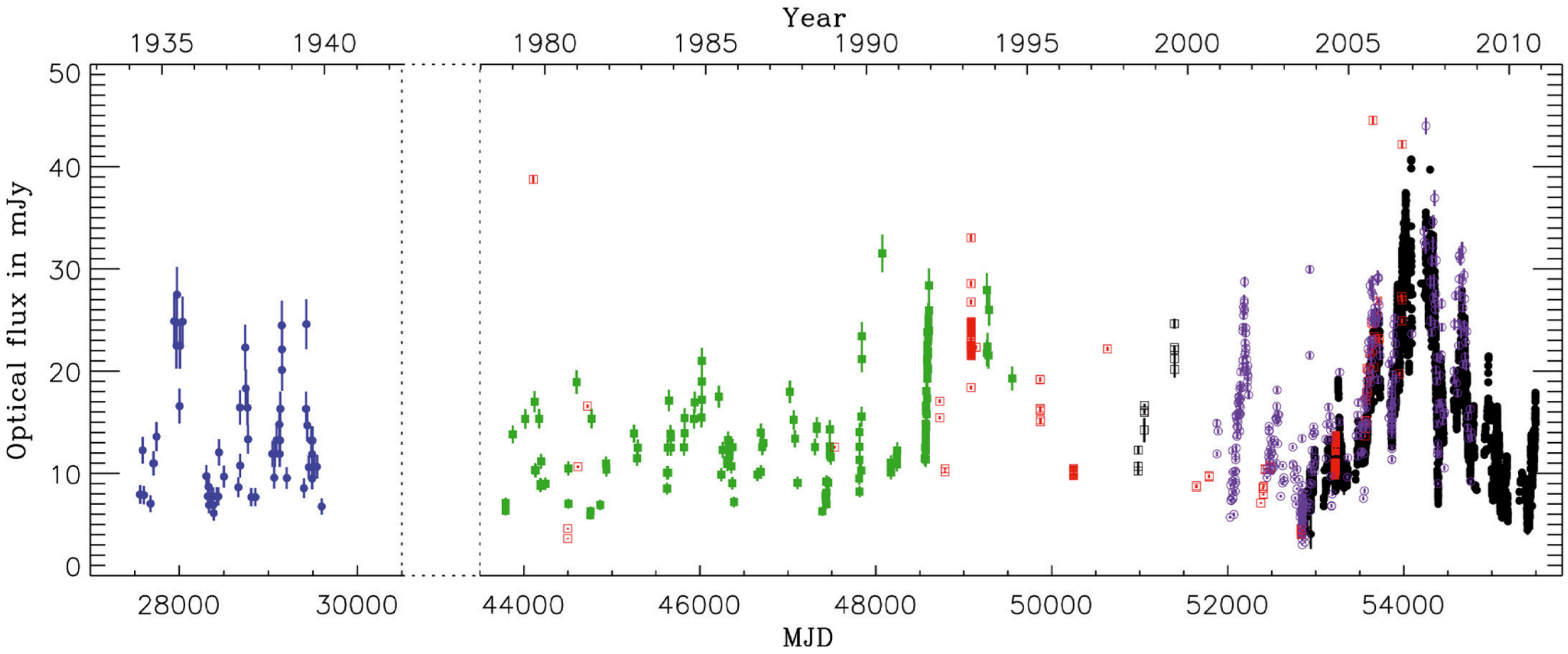
# Blazar Variability: Radio



morphological and flux changes in pc-scale radio jets:
~0.1-10 yr timescale variability

# Blazar Variability: Optical

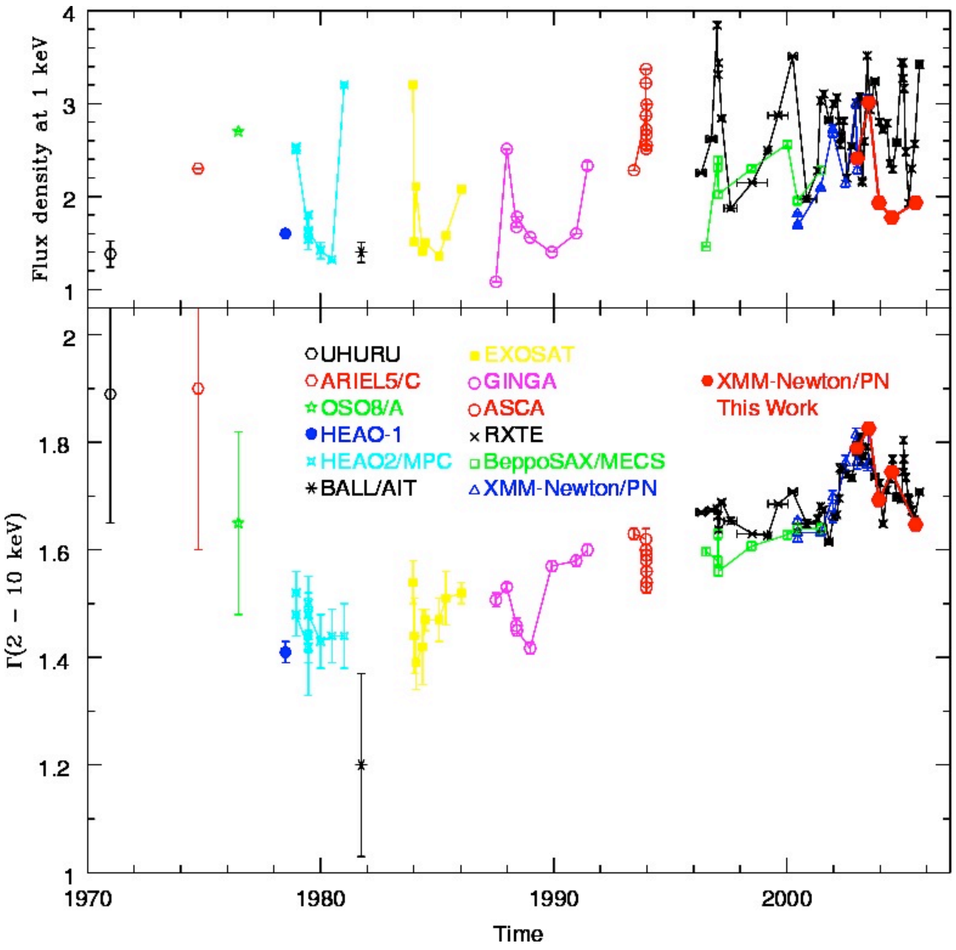
Kastendieck et al. 2011: PKS 2155-304



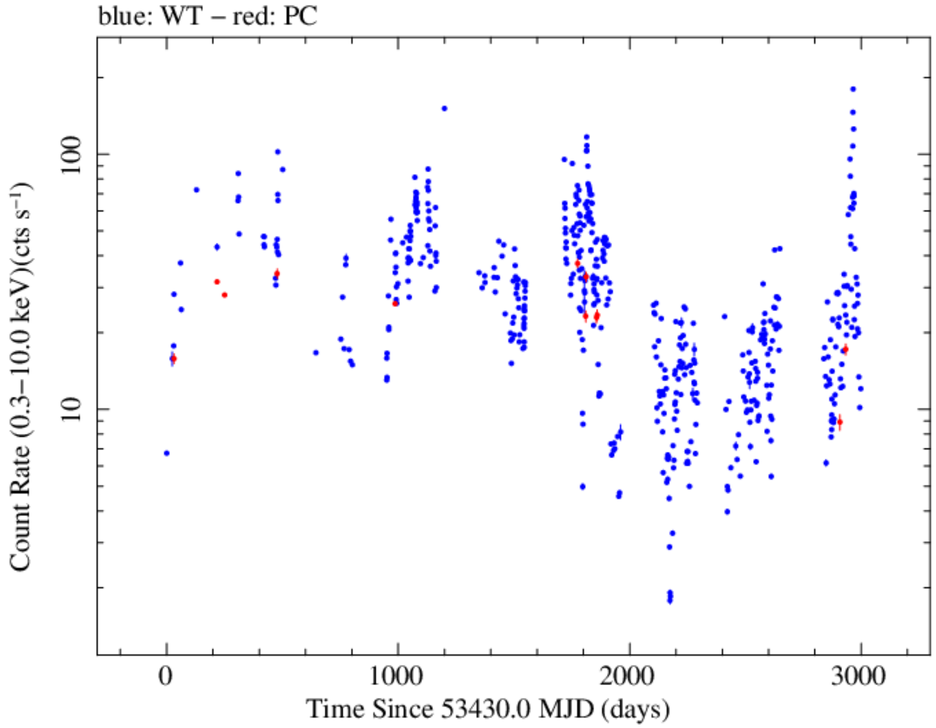
optical flux changes in blazar jets:
hours — decades

# Blazar Variability: X-rays

Soldi et al. 2008: 3C 273



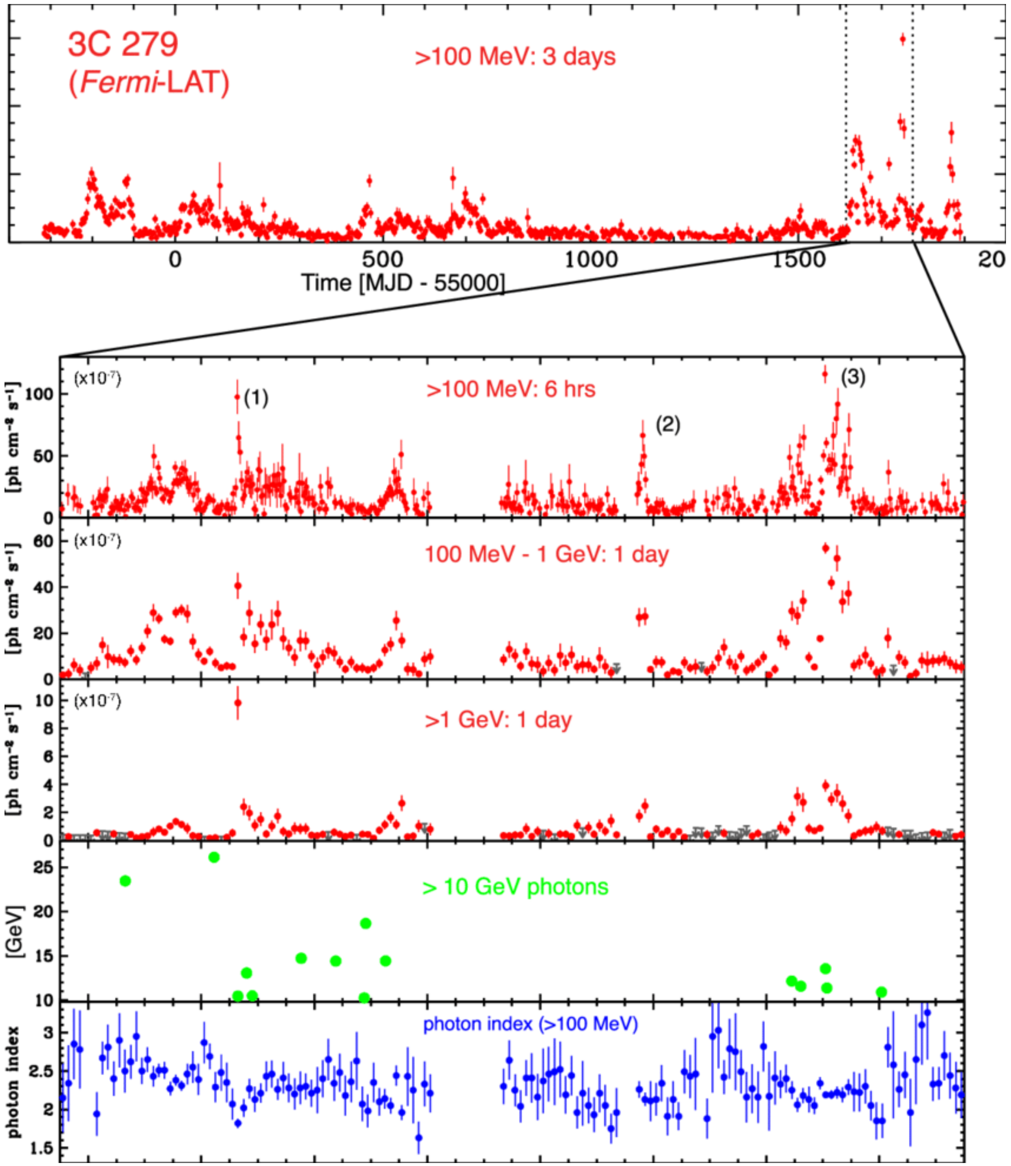
Swift-XRT: Mrk 421



X-ray flux changes in blazar jets:
hours — decades

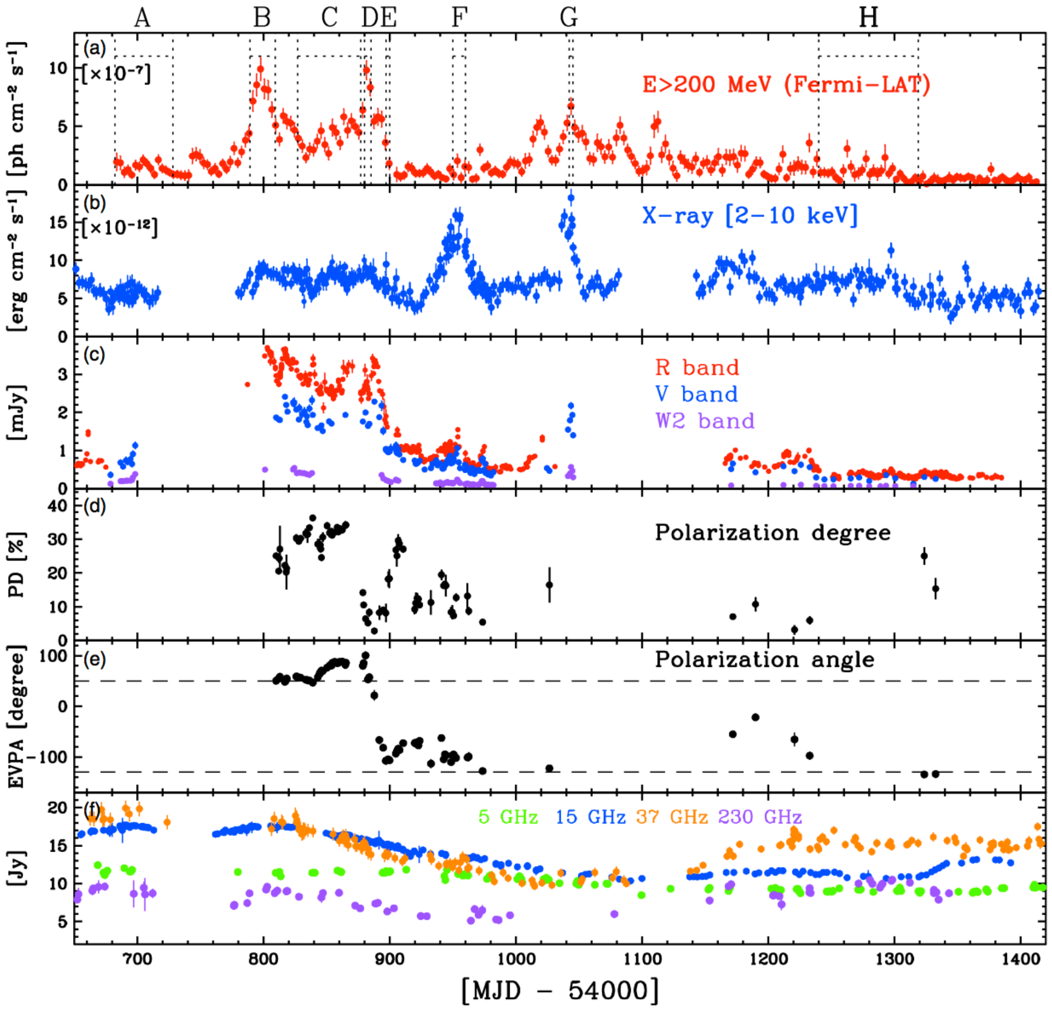
# Blazar Variability: gamma-rays

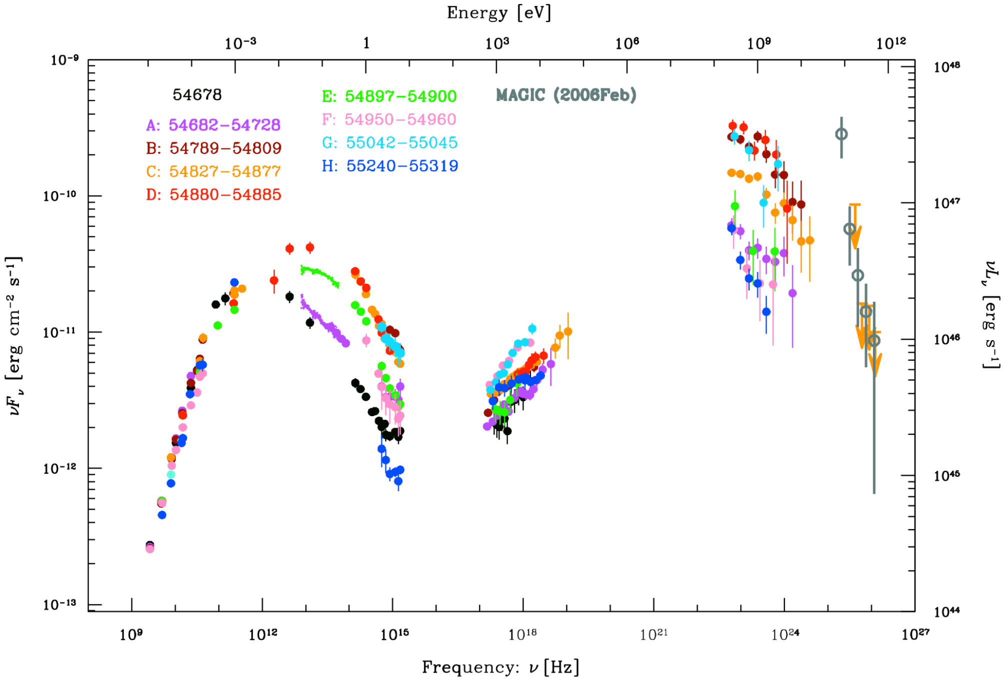
Hayashida et al. 2015



gamma-ray flux changes in blazar jets:
minutes — years

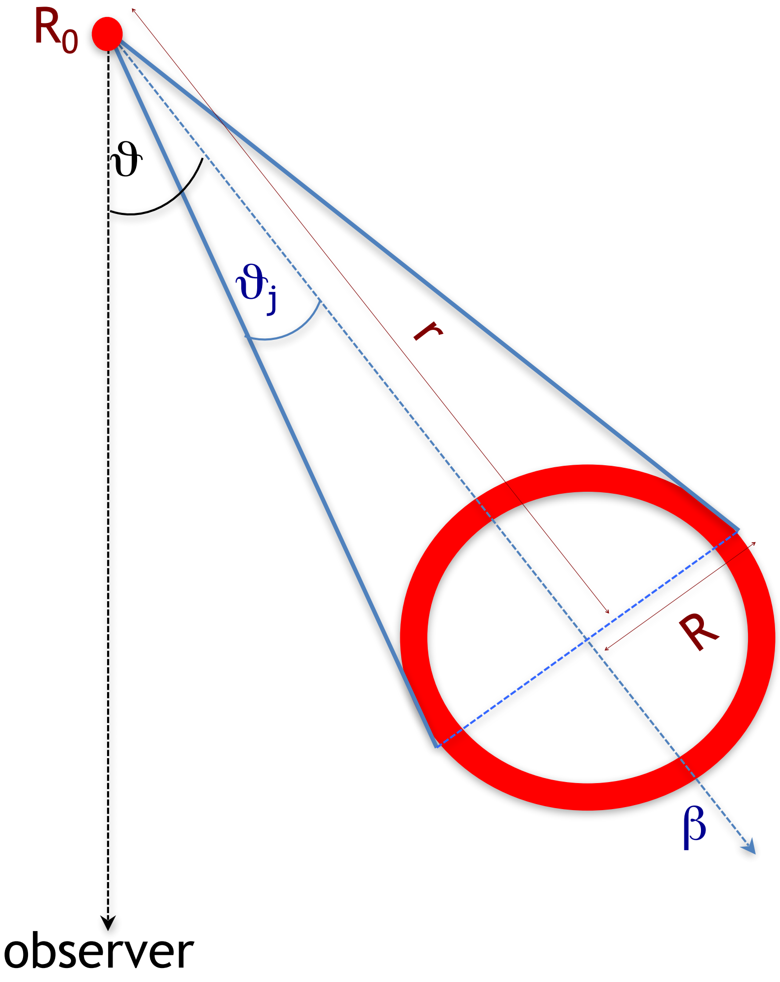
# Blazar Variability: MWL





Hayashida et al. 2012: 3C 279

# Minimum variability timescale?



- SMBH event horizon sets a lower limit on the spatial scale of the jet disturbances:

$$R_0 \gtrsim r_g \equiv \frac{G\mathcal{M}}{c^2}$$

- flow disturbances created at the distance $r_0$ release radiatively their dissipated kinetic energy around

$$r \sim \Gamma^2 \, r_0$$

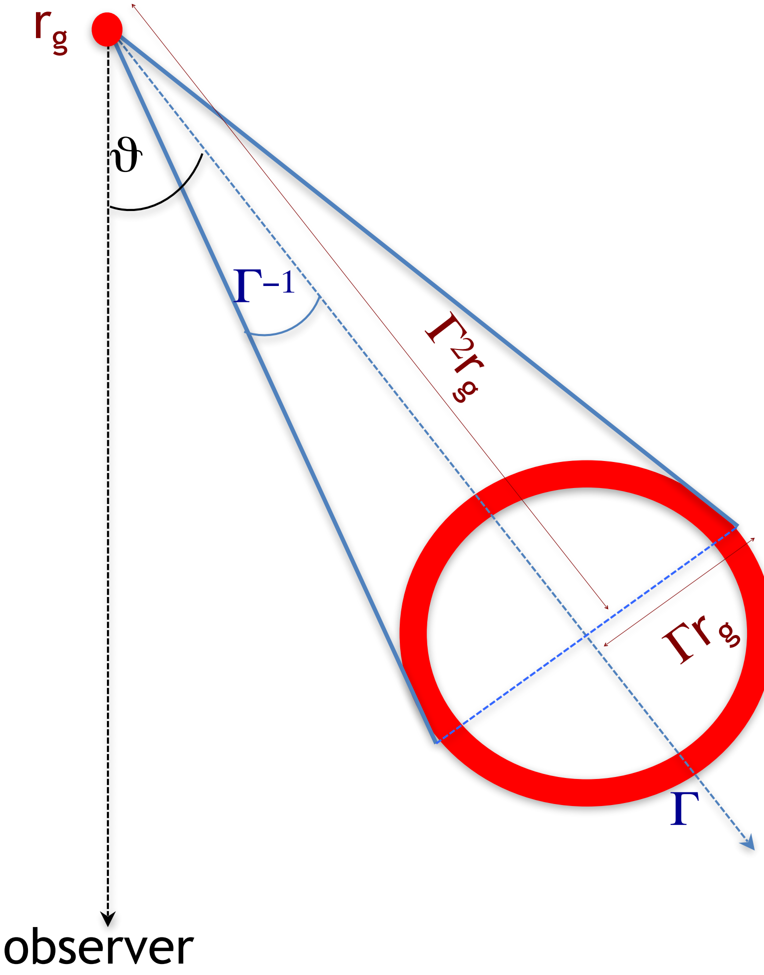
- emission region is casually connected during the observed flaring event with the comoving duration $\tau'$

$$R' \lesssim c\,\tau'$$

- for a relativistic free-expanding jet

$$R \simeq \theta_j \, r \simeq \frac{r}{\Gamma}$$

# Minimum variability timescale?



Time dilation $\tau' = \tau/\Gamma$ combined with the contraction of the arrival time interval for photons emitted by a moving source during the flaring event, $\tau_{obs} = \tau\,(1 - \beta\cos\theta)$, gives therefore

$$R \lesssim c\delta\,\tau_{obs} \quad \text{and} \quad r \lesssim c\Gamma\delta\,\tau_{obs}$$

where $R = R'$; hence, noting that $r_0 \sim R_0 \sim r_g$, and taking the flux doubling timescale as the shortest relevant time interval for the observed flux changes, $\tau_{obs} \sim t_d$, one can easy find out that the shortest observed variability timescale corresponds to the light-crossing time of the SMBH event horizon,

$$t_d \geq t_g \equiv \frac{r_g}{c}$$

$$\delta = \frac{1}{\Gamma(1-\beta\cos\theta)} \rightarrow \Gamma \text{ for small } \theta$$

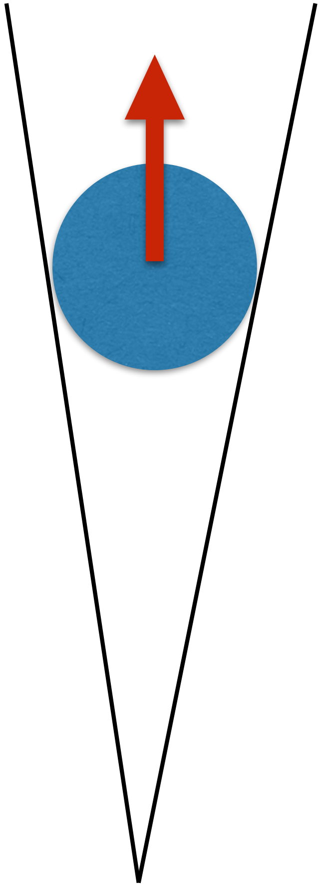
$$\tau_{\rm obs} = \tau'/\delta$$

$$r_g \sim 10^{13}\,\mathcal{M}_8\,[\mathrm{cm}]$$

$$t_g \sim 10^{3}\,\mathcal{M}_8\,[\mathrm{s}]$$

where $\mathcal{M}_8 \equiv \mathcal{M}/10^8 M_\odot$

# “Standard” one-zone modeling



Let’s assume a single homogeneous spherical blob of magnetised plasma moving with a constant bulk velocity along a conical free-expanding jet.

Model free parameters: linear size ***R***, bulk Lorentz factor ***Γ***, magnetic field intensity ***B***, equipartition ratio $\boldsymbol{U'_e/U'_B}$, and the electron energy distribution, e.g.,

$$N_e(\gamma) \propto \begin{cases} \gamma^{-s_{\rm low}} & \text{for} \quad \gamma_{\rm min} < \gamma \leq \gamma_{\rm br} \\ \gamma^{-s_{\rm high}} & \text{for} \quad \gamma_{\rm br} < \gamma \leq \gamma_{\rm max} \end{cases}$$

Some parameters may be constrained a priori:

***R*** from the observed variability timescale

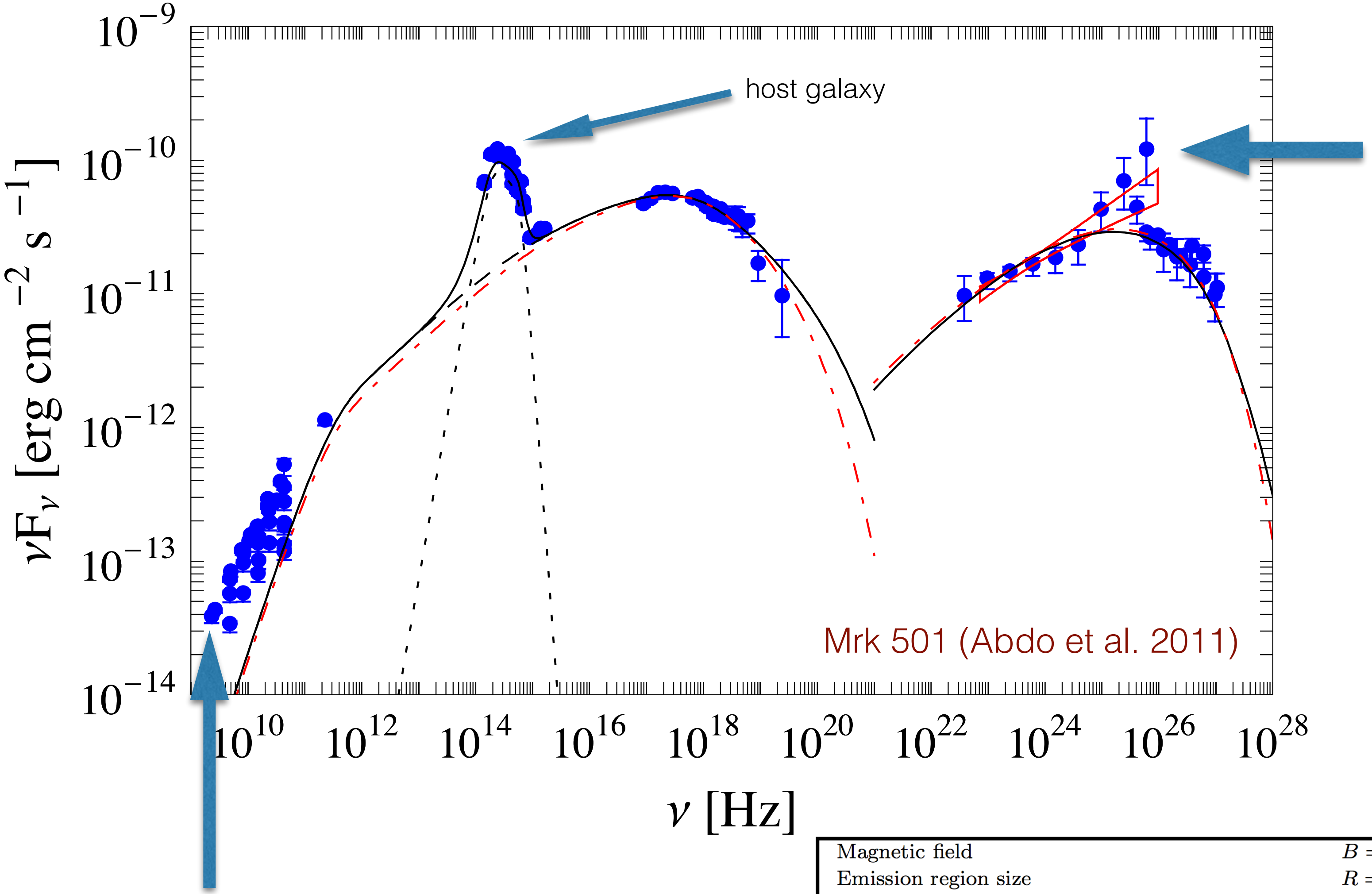
***Γ*** from the observed superluminal radio features

$\boldsymbol{s_{low}\sim 2}$ and $\boldsymbol{\gamma_{min}\sim 1}$ from “common expectations”…

For a given distance from the jet base (*r=ΓR*), estimate photon energy densities (including jet synchrotron, accretion disk, broad-line region, hot dusty torus, starlight).

For the above, calculate synchrotron and inverse-Compton emission components, including all the absorption effects in the gamma-ray range, etc., adjusting model free parameters untill a satisfactory **match** to the spectral datapoints is obtained.

# “Standard” one-zone modeling



host galaxy

dominated by a single “flare” during the 3-month-long campaign

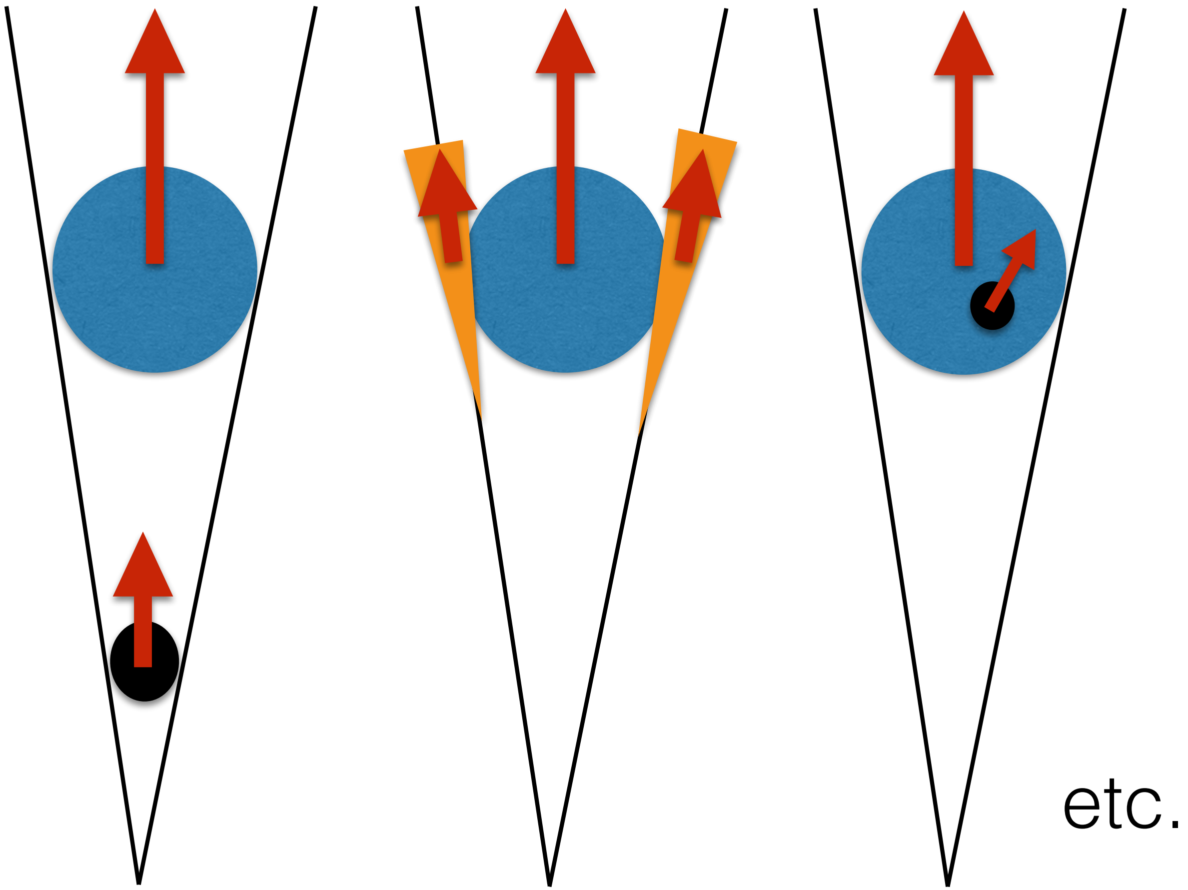
low-frequency radio fluxes dominated by the integrated output of a stratified, self-absorbed outflow

| | | |
|---|---|---|
| Magnetic field | $B = 0.015\,\mathrm{G}$ | $B = 0.03\,\mathrm{G}$ |
| Emission region size | $R = 1.3 \times 10^{17}$ cm | $R = 0.2 \times 10^{17}$ cm |
| Jet Doppler and bulk Lorentz factors | $\Gamma = \delta = 12$ | $\Gamma = \delta = 22$ |
| Equipartition parameter | $\eta_e \equiv U'_e/U'_B = 56$ | $\eta_e \equiv U'_e/U'_B = 130$ |
| Minimum electron energy | $\gamma_{min} = 600$ | $\gamma_{min} = 300$ |
| Intrinsic electron break energy | $\gamma_{br,\,1} = 4 \times 10^4$ | $\gamma_{br,\,1} = 3 \times 10^4$ |
| Cooling electron break energy | $\gamma_{br,\,2} = 9 \times 10^5$ | $\gamma_{br,\,2} = 5 \times 10^5$ |
| Maximum electron energy | $\gamma_{max} = 1.5 \times 10^7$ | $\gamma_{max} = 0.3 \times 10^7$ |
| Low-energy electron index | $s_1 = 2.2$ | $s_1 = 2.2$ |
| High-energy electron index | $s_2 = 2.7$ | $s_2 = 2.7$ |
| Electron index above the cooling break | $s_3 = 3.65$ | $s_3 = 3.5$ |

# “Standard” one-zone modeling

Blazar SEDs in many cases can be matched reasonably well with this “minimum-assumption” model, returning typically $U'_e/U'_B \gg 1$ (worrisome?), and often $s_{low} < 2$ or $\gamma_{min} \gg 1$ (interesting!)

Some sources/SEDs could not be matched easily with this model
-> **should we consider multi-zone/multi-component versions of the model?**
**or an additional hadronic emission component?**



In this way one however doubles the number of model free parameters… More flexibility in matching the data, but the physical setup often more arbitrary/speculative, and the model limitations remain…

# “Standard” one-zone modeling

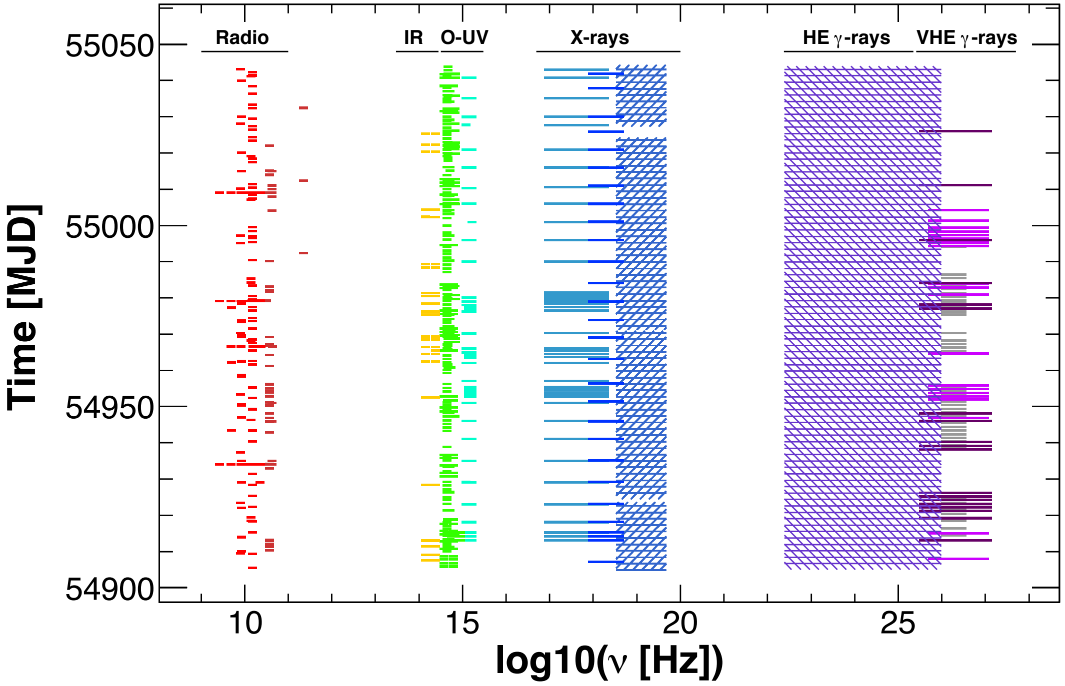
**Steady-state** emission spectra calculated for the **assumed** form of the electron energy distribution.

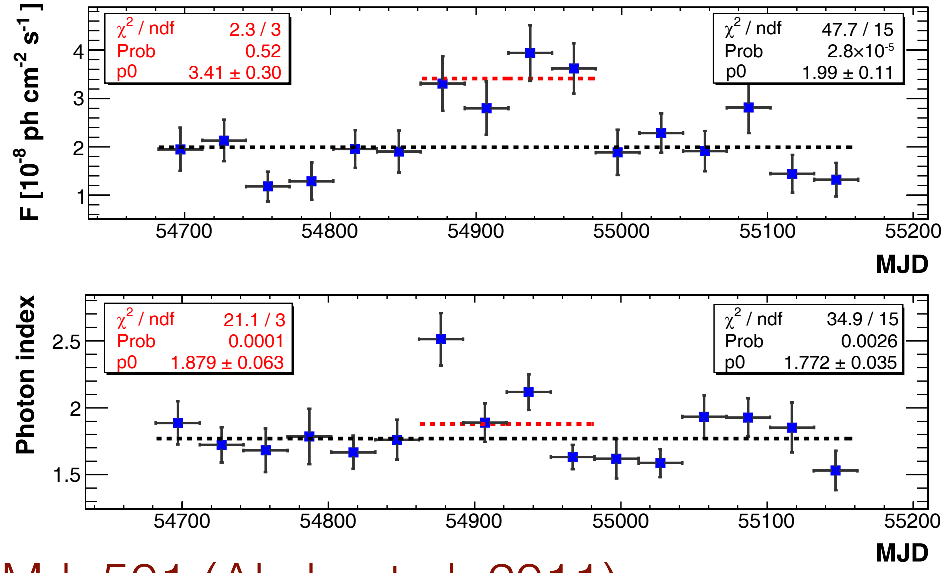
A clear **oversimplification** of the geometry and internal structure of the emission zone.
Good point: a “**minimum-assumption**” model.
But are these assumption even realistic at all?

Assumes that a single zone dominates the observed radiative output of the entire jet at a given time (at least in some selected photon energy ranges of interest, in particular **ignoring the radio frequency domain**!).

One should be using simultaneous data (in those selected photon energy ranges) for that given time.

# Non-simultanous SEDs





Mrk 501 (Abdo et al. 2011)

Broad-band SEDs rarely/never constructed from truly simultaneous data… typically averaged over some longer periods, typically with uneven sampling, different for different photon energy ranges…

When "no strong variability observed", one could argue that the average is representative for the "source quiescence" (where the "source" is some extended portion of an outflow).

So maybe instead of a single moving blob, one should try to calculate some **integrated radiative output of a (possibly) stratified outflow**, not ignoring any frequency domain?

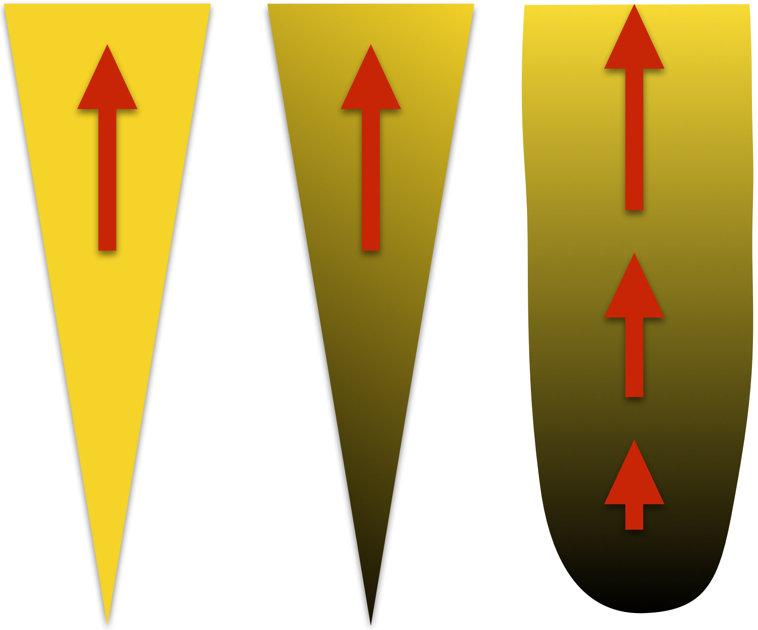
# Steady stratified ouflows

**Models for the underlying steady jet component:**

a) constant bulk velocity, free-expanding, particle-dominated jet, with the electron distribution maintained (by some unspecified dissipation process) along the outflow, and the magnetic field scaling according to the conservation of magnetic energy (Blandford & Konigl 1979)

b) as above, but with the evolving electron energy distribution calculated self-consistently (radiative and adiabatic losses) for a given (assumed) injection function

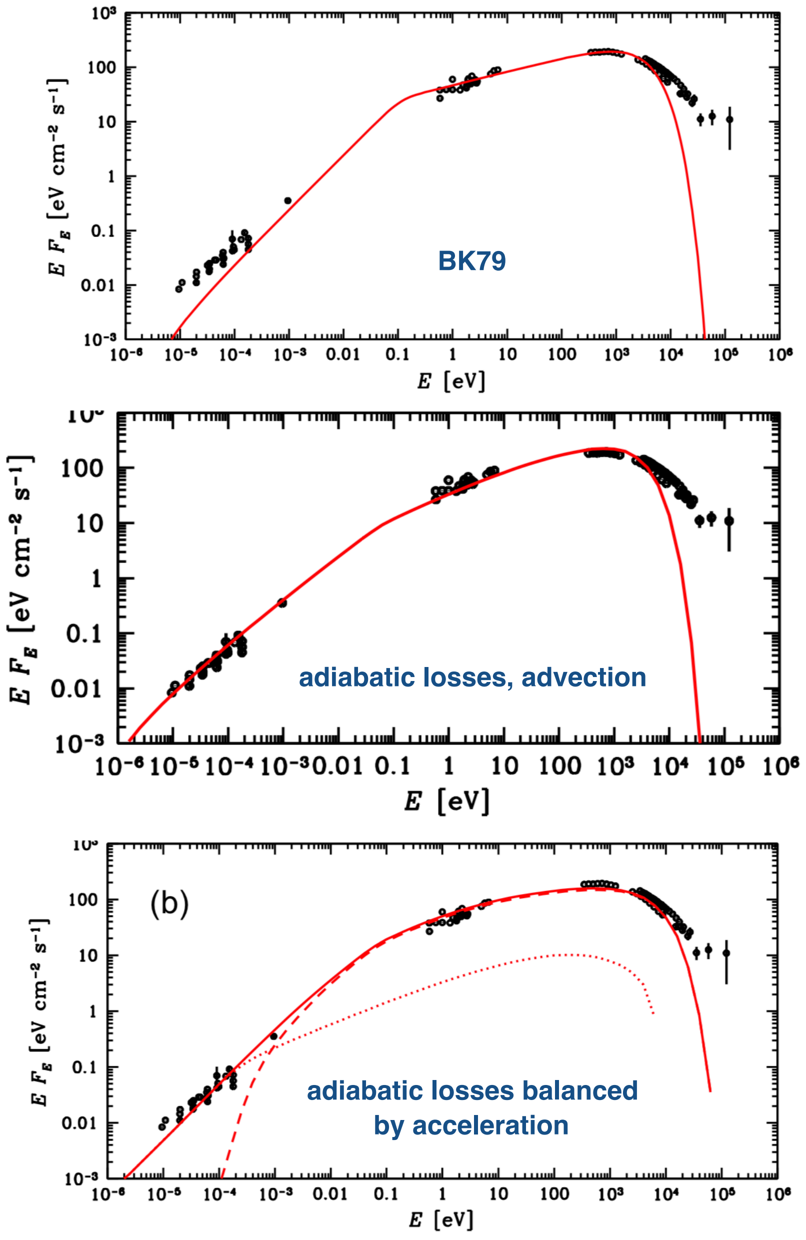
c) slowly collimating and accelerating MHD outflow (Komissarov et al., Lyubarsky, etc.) with the evolving electron energy distribution calculated self-consistently (radiative and adiabatic losses) for a given (assumed) injection function



**model parameters:**
**profiles R=R(r), Γ=Γ(R,r), B=B(r,R), σ=σ(R,t), Q=Q(γ,R,r)**

$$\frac{\partial \mathcal{N}_{\rm e}(\gamma,t)}{\partial t} = \frac{\partial}{\partial \gamma}\left\{|\dot{\gamma}|\, \mathcal{N}_{\rm e}(\gamma,t)\right\} + Q(\gamma,t)$$

# Steady stratified ouflows



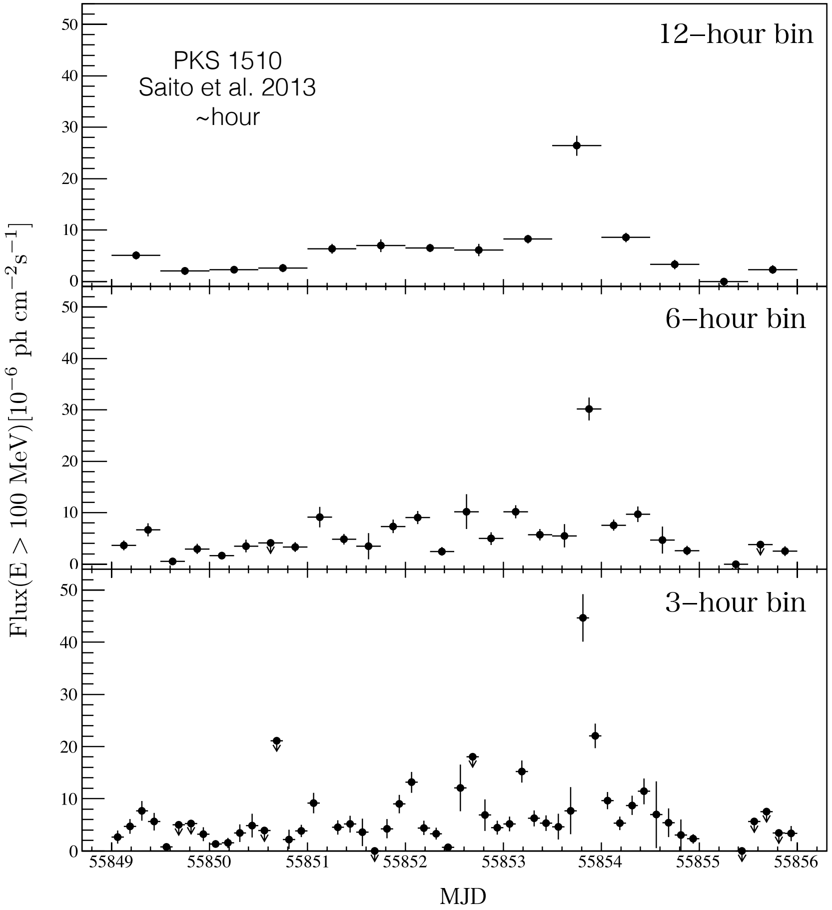
Mrk 421 (Zdziarski, LS, Sikora, 2019)

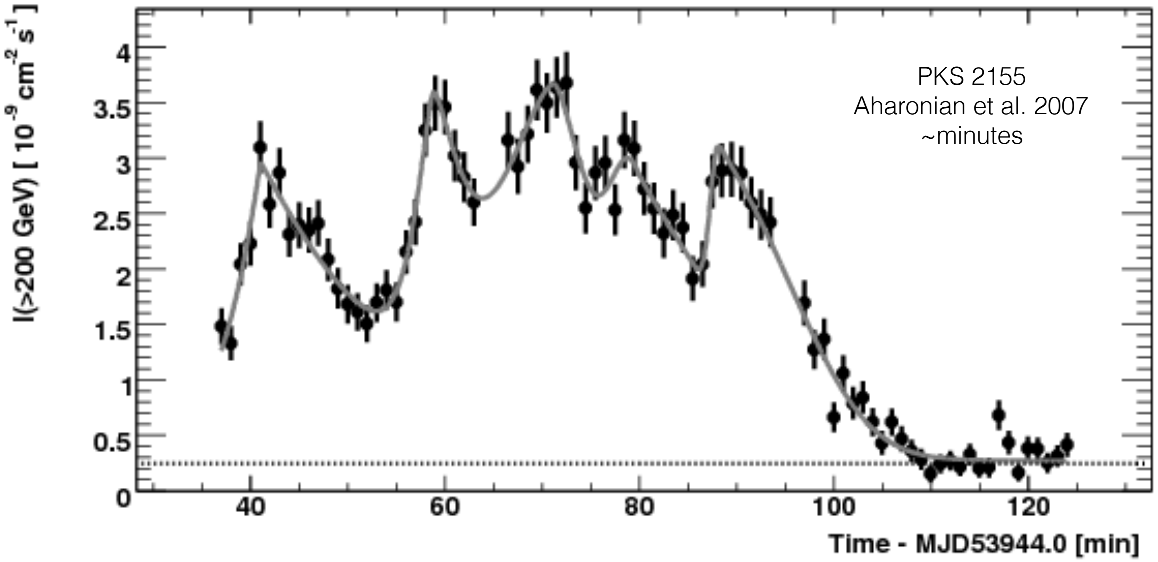
**Well-posted** models for the underlying jet structure; e.g., MHD model well supported by theory and (G)RMHD simulations.

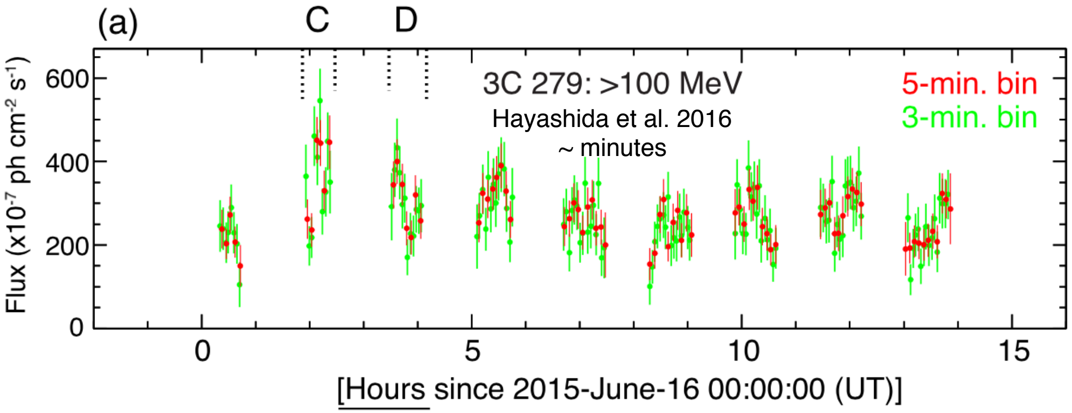
The main uncertainty here is the energy and radial dependence of the electron **injection function**.

Could be ~OK if the time-average “quiescence” spectrum does indeed reflect radiative output of the underlying jet component. **But are there really “quiescence periods”?**

# And how about those rapid flares?

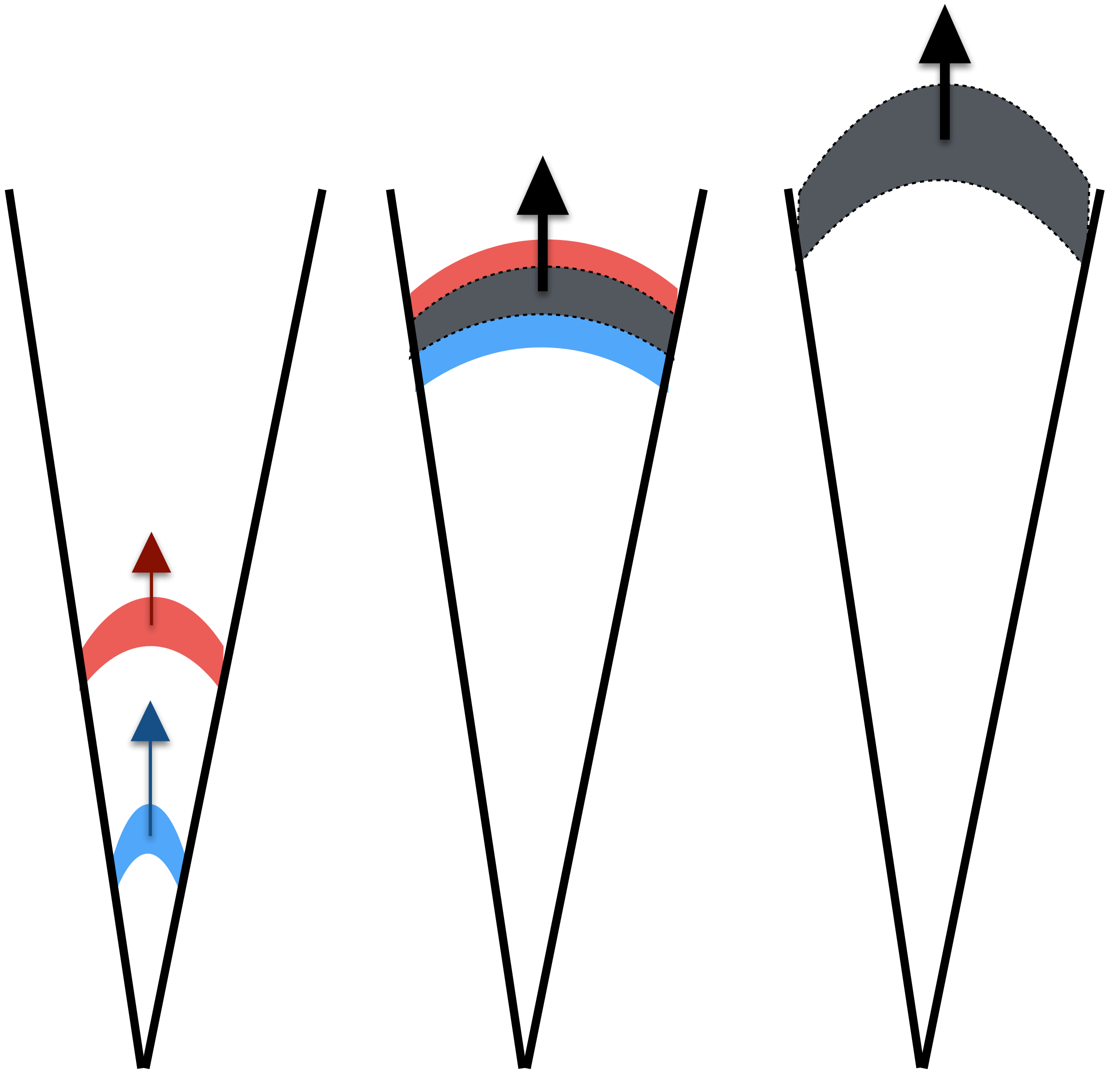






Clearly, a fully time-dependent and self-consistent modelling is needed

# Evolving internal shocks



Internal shock developing in a conical jet
with a given opening angle
(not necessarily 1/Γ)

Assume basic parameters of colliding shells (total kinetic energies, bulk velocities), and follow the kinematics of the evolving double-shock structure along with the energy evolution of radiating electrons injected at the shock front with a given (assumed) injection function Q(γ)

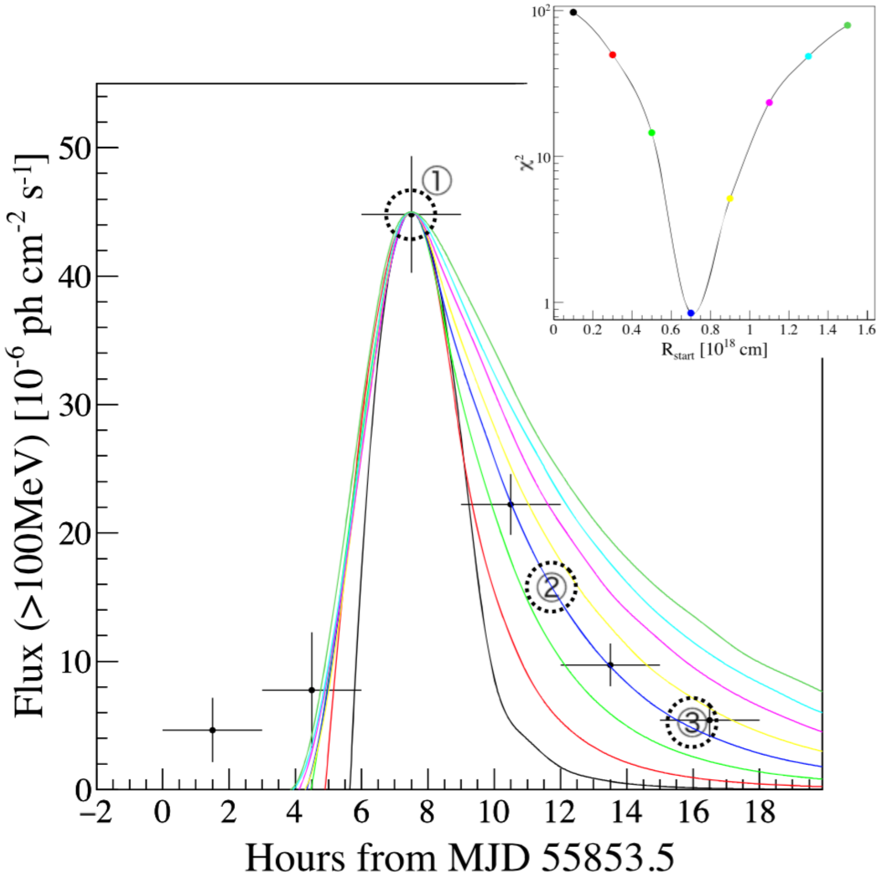
$$\beta_{\rm ct} = \frac{\beta_1\Gamma_1 + \beta_2\Gamma_2}{\Gamma_1 + \Gamma_2}$$

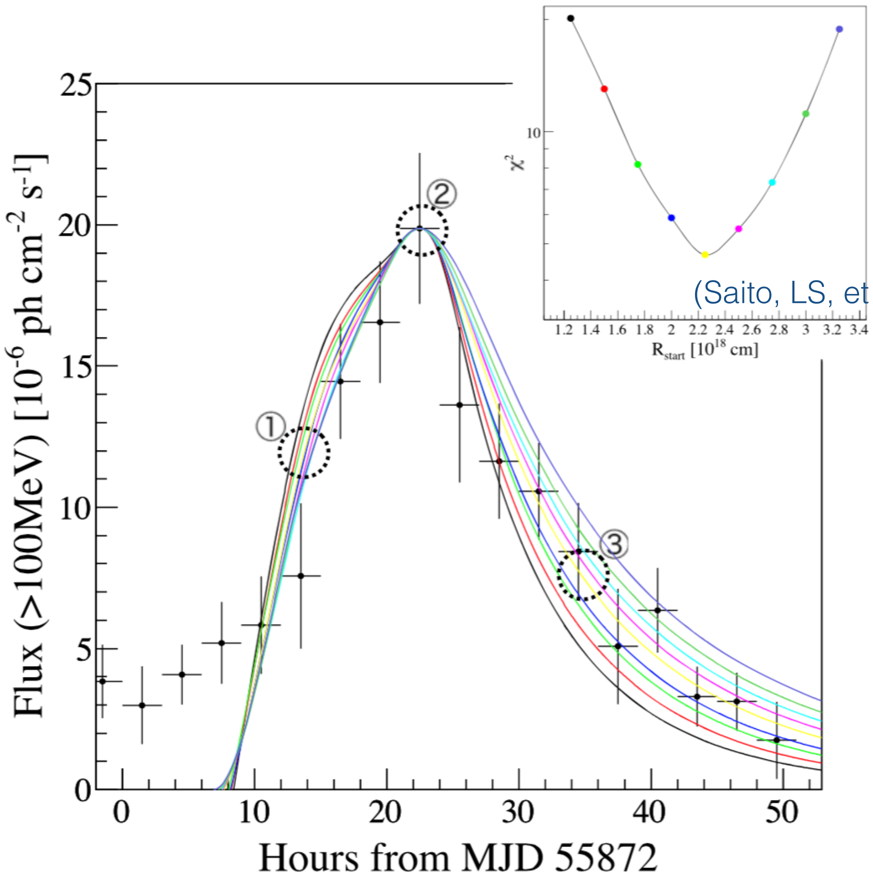
$$\Gamma_{\rm sh}^{(1)} = \sqrt{\frac{\left(\Gamma_{\rm ct}^{(1)} + 1\right)\left[\hat{\gamma}_{\rm ct}\left(\Gamma_{\rm ct}^{(1)} - 1\right) + 1\right]^2}{\hat{\gamma}_{\rm ct}(2 - \hat{\gamma}_{\rm ct})\left(\Gamma_{\rm ct}^{(1)} - 1\right) + 2}}$$

$$\Delta l' = 2c\left|\beta'_{\rm sh}\right|\Delta t'$$

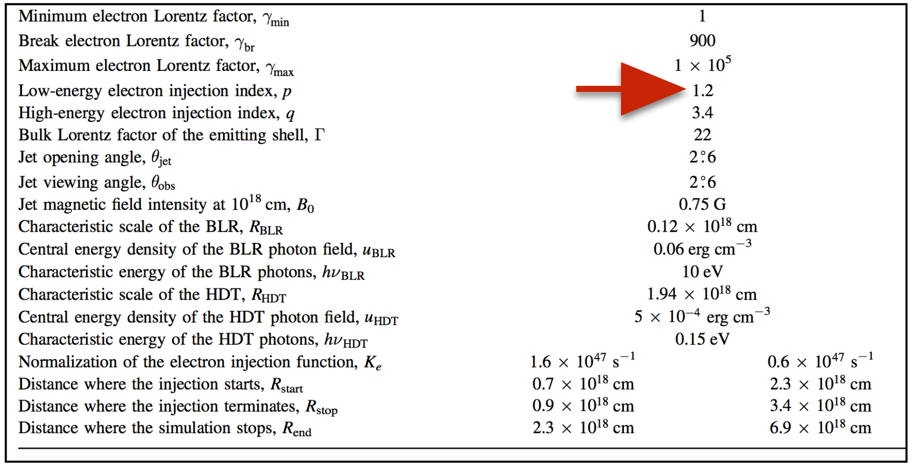
$$\frac{\partial \mathcal{N}_{\rm e}(\gamma,t)}{\partial t} = \frac{\partial}{\partial \gamma}\left\{|\dot{\gamma}|\ \mathcal{N}_{\rm e}(\gamma,t)\right\} + Q(\gamma,t)$$

# Evolving internal shocks



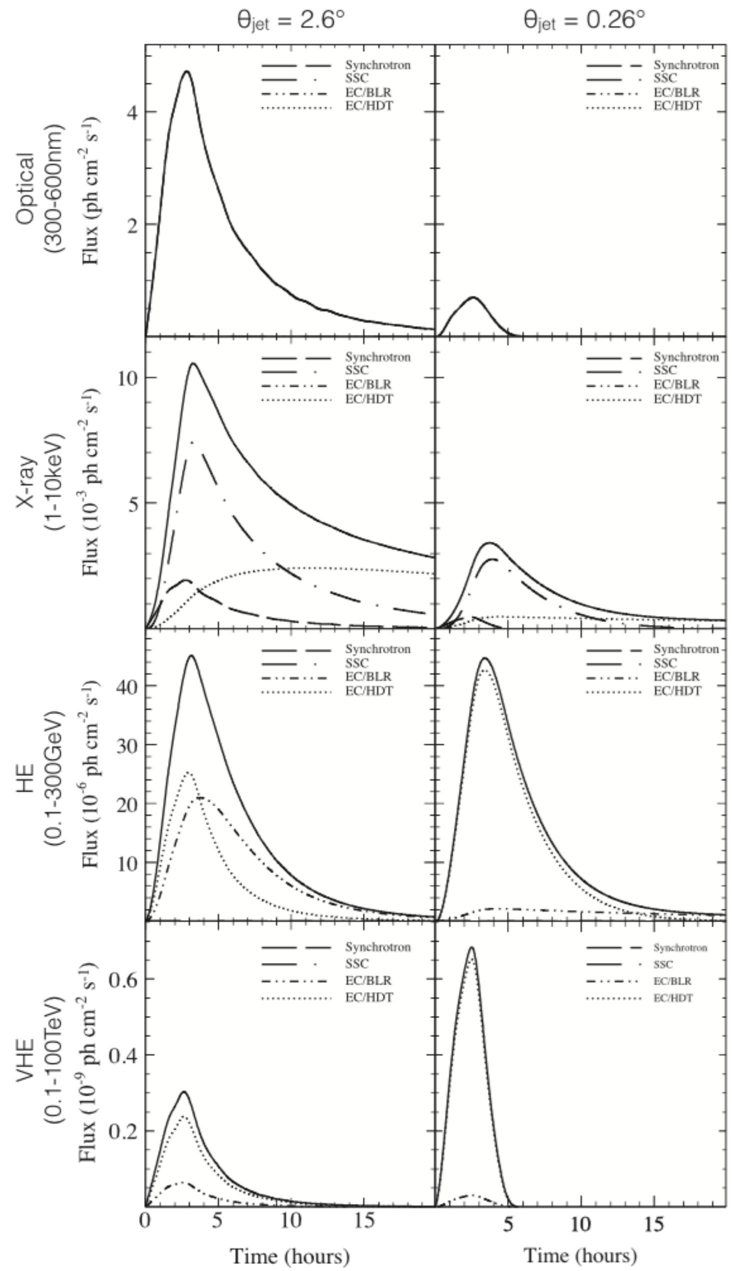


(Saito, LS, et al. 2015)



| | | | |
|---|---|---|---|
| Minimum electron Lorentz factor, $\gamma_{\rm min}$ | 1 | | |
| Break electron Lorentz factor, $\gamma_{\rm br}$ | 900 | | |
| Maximum electron Lorentz factor, $\gamma_{\rm max}$ | $1 \times 10^5$ | | |
| Low-energy electron injection index, $p$ | 1.2 | | |
| High-energy electron injection index, $q$ | 3.4 | | |
| Bulk Lorentz factor of the emitting shell, $\Gamma$ | 22 | | |
| Jet opening angle, $\theta_{\rm jet}$ | 2°6 | | |
| Jet viewing angle, $\theta_{\rm obs}$ | 2°6 | | |
| Jet magnetic field intensity at $10^{18}$ cm, $B_0$ | 0.75 G | | |
| Characteristic scale of the BLR, $R_{\rm BLR}$ | $0.12 \times 10^{18}$ cm | | |
| Central energy density of the BLR photon field, $u_{\rm BLR}$ | 0.06 erg cm$^{-3}$ | | |
| Characteristic energy of the BLR photons, $h\nu_{\rm BLR}$ | 10 eV | | |
| Characteristic scale of the HDT, $R_{\rm HDT}$ | $1.94 \times 10^{18}$ cm | | |
| Central energy density of the HDT photon field, $u_{\rm HDT}$ | $5 \times 10^{-4}$ erg cm$^{-3}$ | | |
| Characteristic energy of the HDT photons, $h\nu_{\rm HDT}$ | 0.15 eV | | |
| Normalization of the electron injection function, $K_e$ | | $1.6 \times 10^{47}$ s$^{-1}$ | $0.6 \times 10^{47}$ s$^{-1}$ |
| Distance where the injection starts, $R_{\rm start}$ | | $0.7 \times 10^{18}$ cm | $2.3 \times 10^{18}$ cm |
| Distance where the injection terminates, $R_{\rm stop}$ | | $0.9 \times 10^{18}$ cm | $3.4 \times 10^{18}$ cm |
| Distance where the simulation stops, $R_{\rm end}$ | | $2.3 \times 10^{18}$ cm | $6.9 \times 10^{18}$ cm |

# Evolving internal shocks



(Saito, LS, et al. 2015)

The modelling gives rather strong constraints on the model parameters, and clear predictions for the expected MWL flaring behaviour.
In particular, points out to **proton-mediated shocks** with dynamically negligible magnetic field.

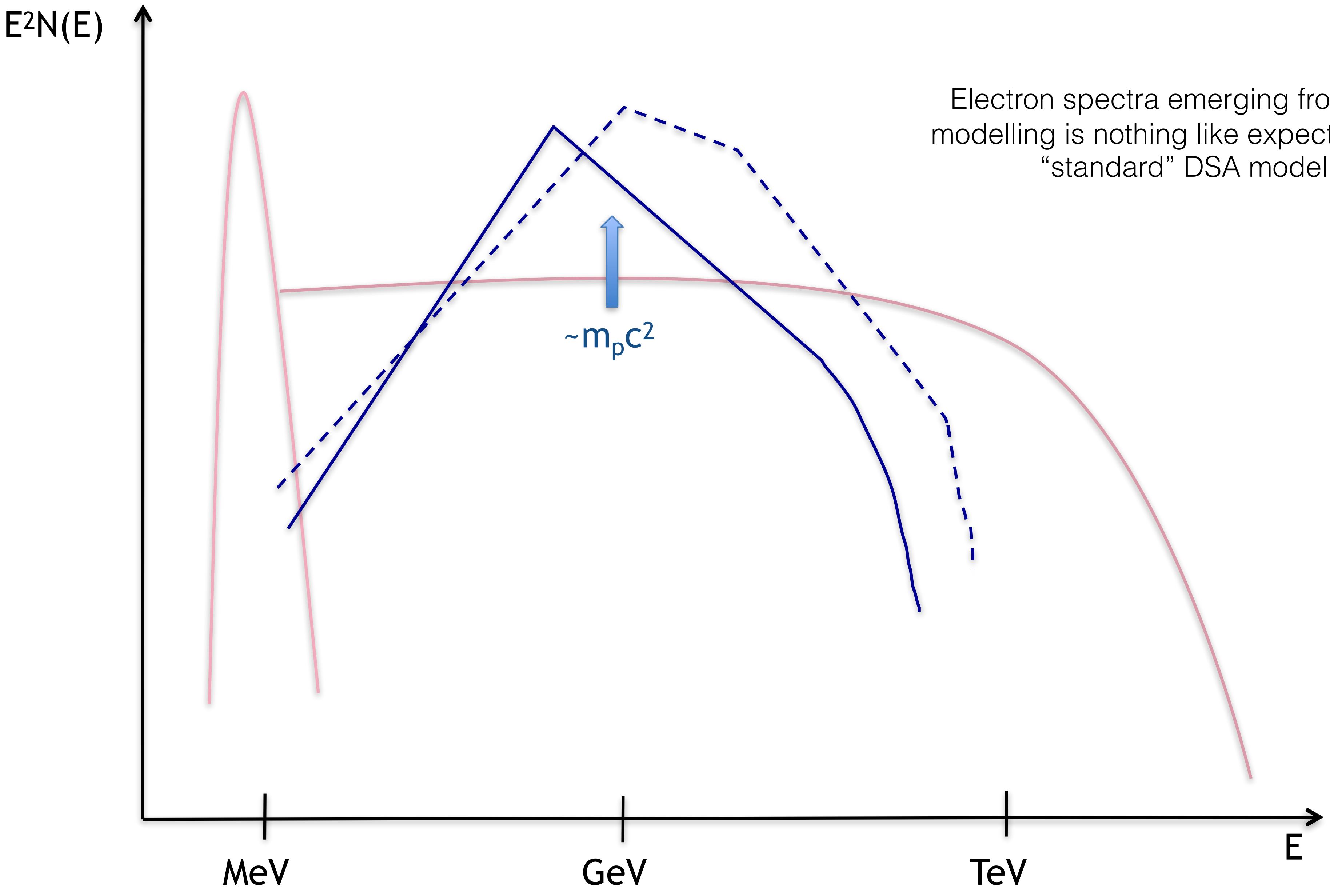
Crucial assumption, again: electron injected at the shock front with a given **injection function**.

Needs **extremely good quality and truly simultaneous MWL data** for well-defined flaring events.

But typically we do not have such MWL datasets available!

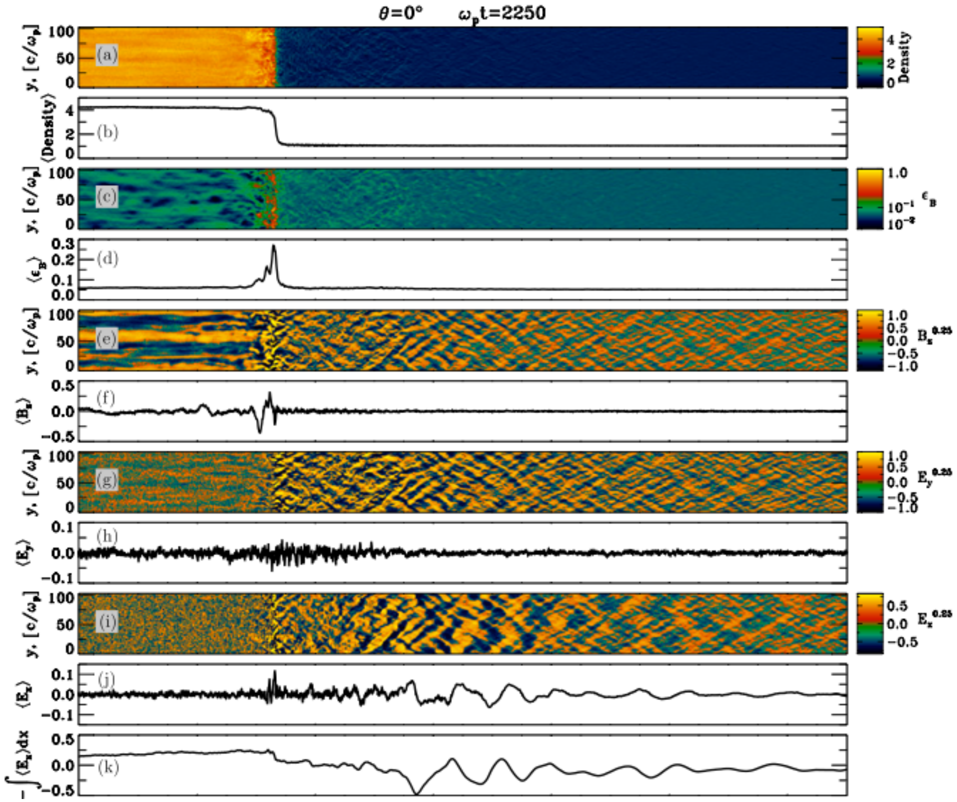
Also, high-amplitude short gamma-ray flares are rather **rare**…
In the case of longer flux enhancements: how sure that these constitute **isolated and coherent events?** Maybe instead a superposition of distinct but just unresolved mini-flares?

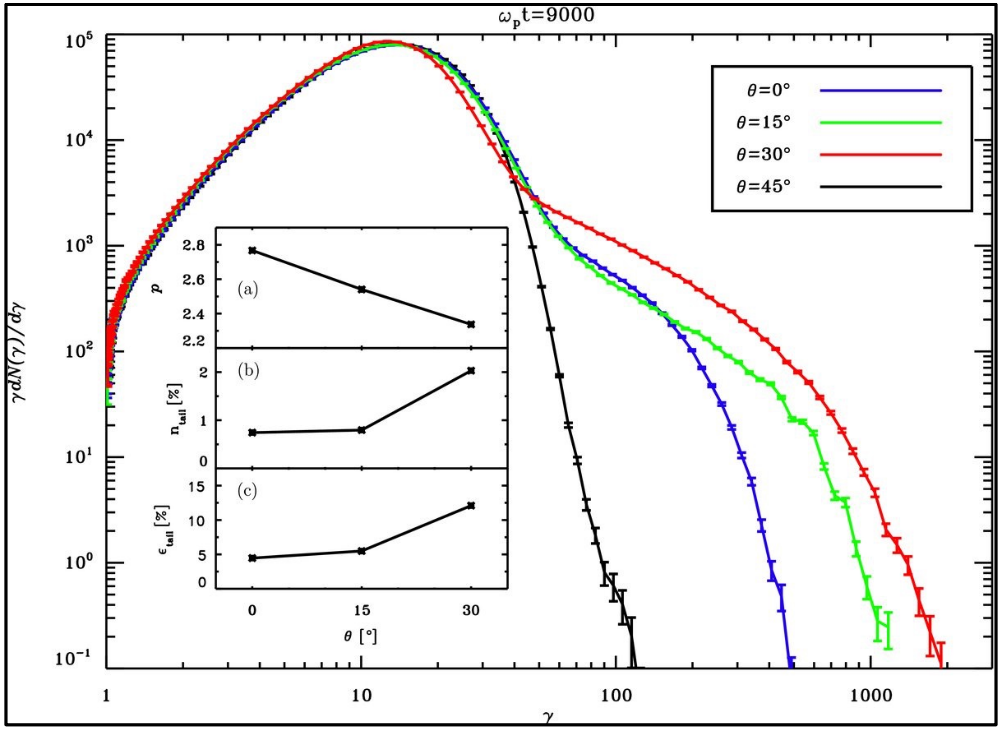
# Electron Spectra



Electron spectra emerging from such modelling is nothing like expected in the "standard" DSA model!

# Relativistic shocks

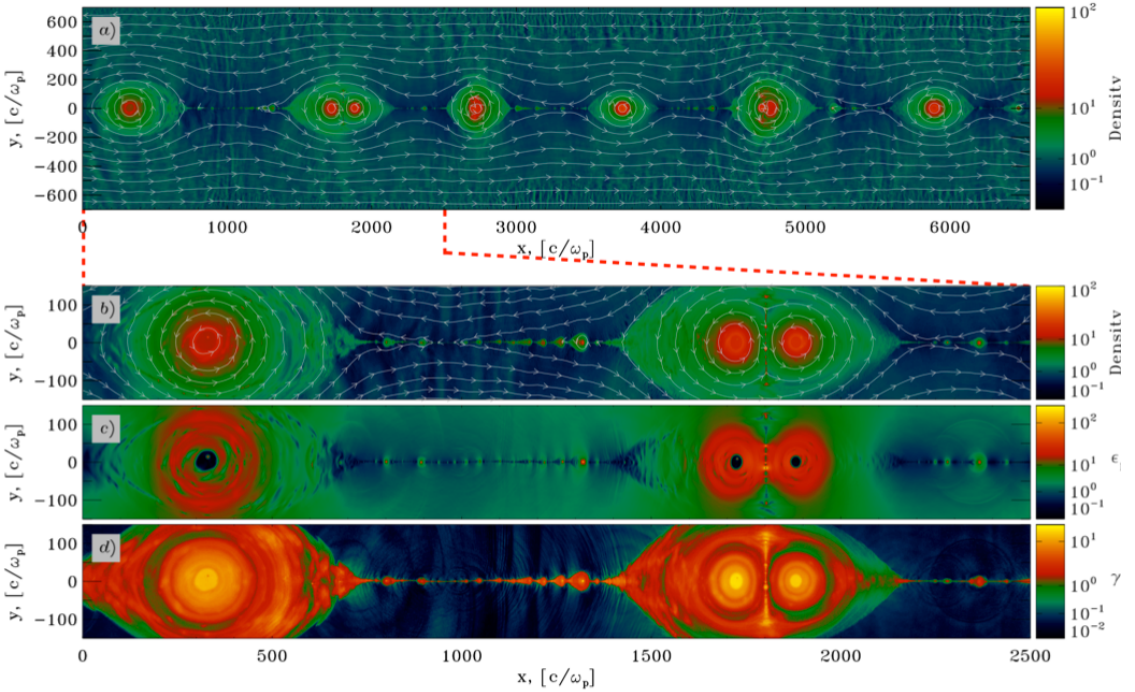


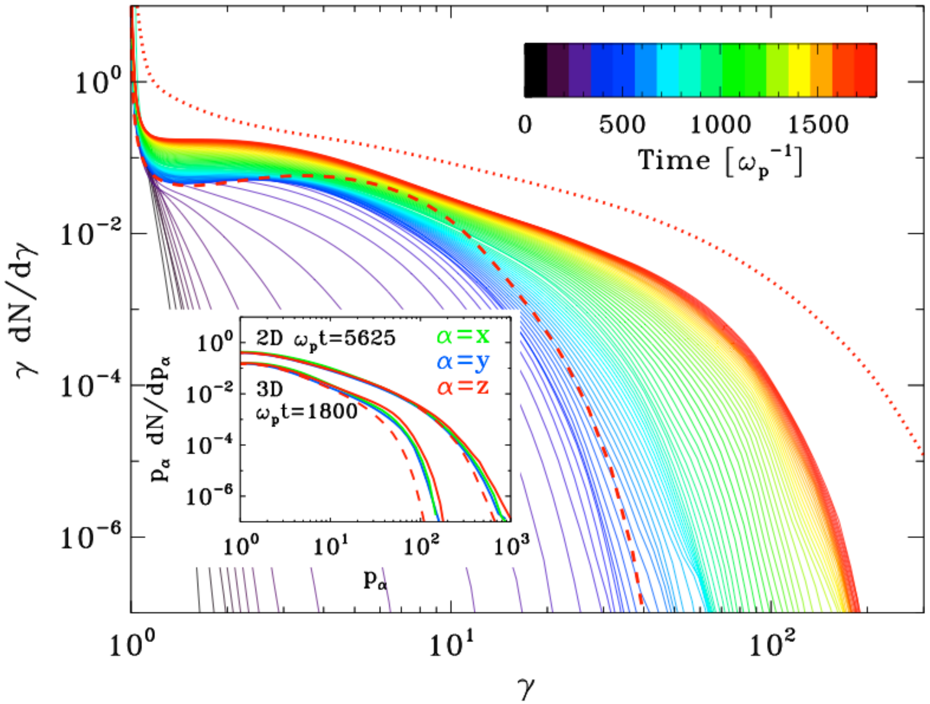


Steep particle spectra (*s>2*) with very limited maximum energies and spectral indices depending on the magnetic field configuration and turbulence spectrum (Niemiec & Ostrowski, Spitkovsky et al.).

*Not good news for hadronic emission models and the UHECR/neutrino production…*

# Relativistic reconnection





Efficient leptonic acceleration up to very high energies; power-law spectra with spectral indices depending on the plasma magnetisation —
flat spectra (*s<2*) for highly magnetised plasma, steep spectra (*s>2*) for low magnetisation
(Guo et al., Sironi & Spitkovsky).

# Broad-band SED modeling

1) moving single blobs: could be ~OK for a well-defined “blazar emission zone”, with a given characteristic $t_{var}$

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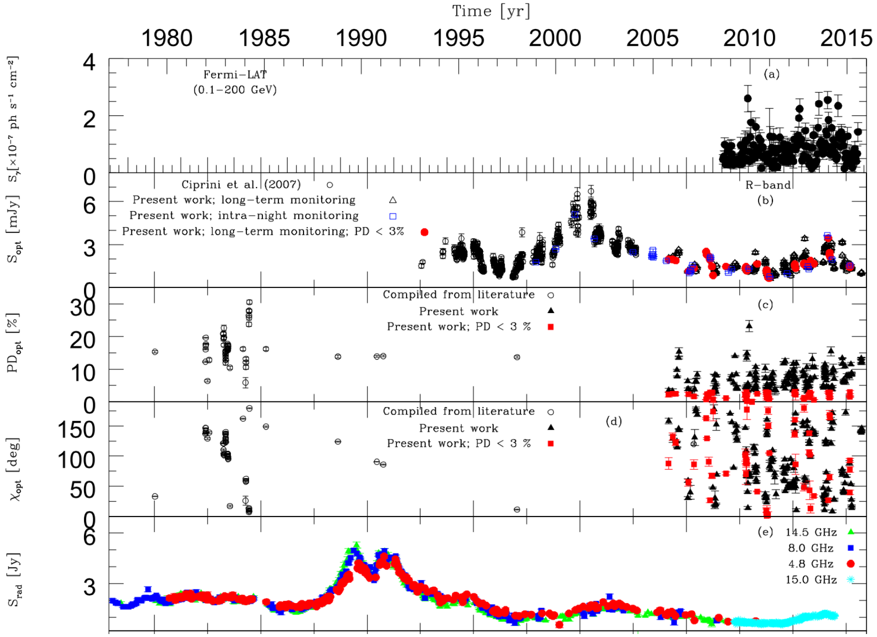
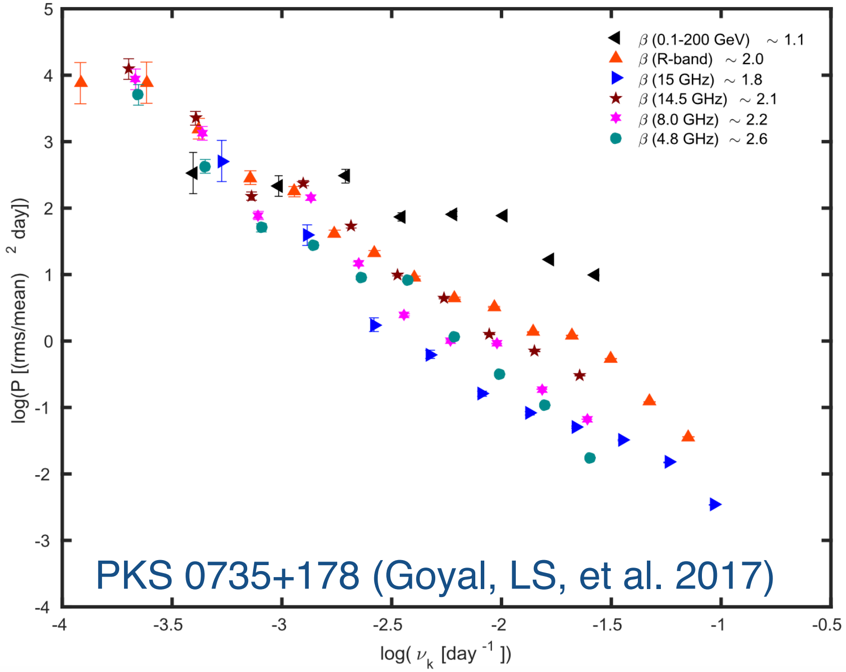
3) evolving internal-shocks: might be considered for single coherent and well-resolved flares seen across various wavelengths

-> but are the flux changes observed at various wavelengths indeed intrinsically correlated, and flares robustly resolved?

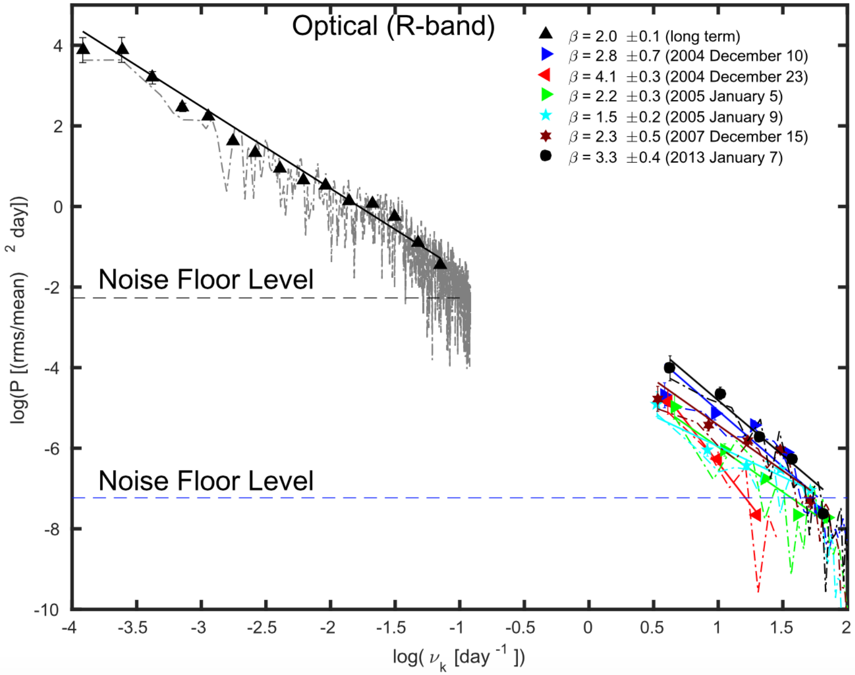
# Variability power spectra



DFT



PKS 0735+178 (Goyal, LS, et al. 2017)

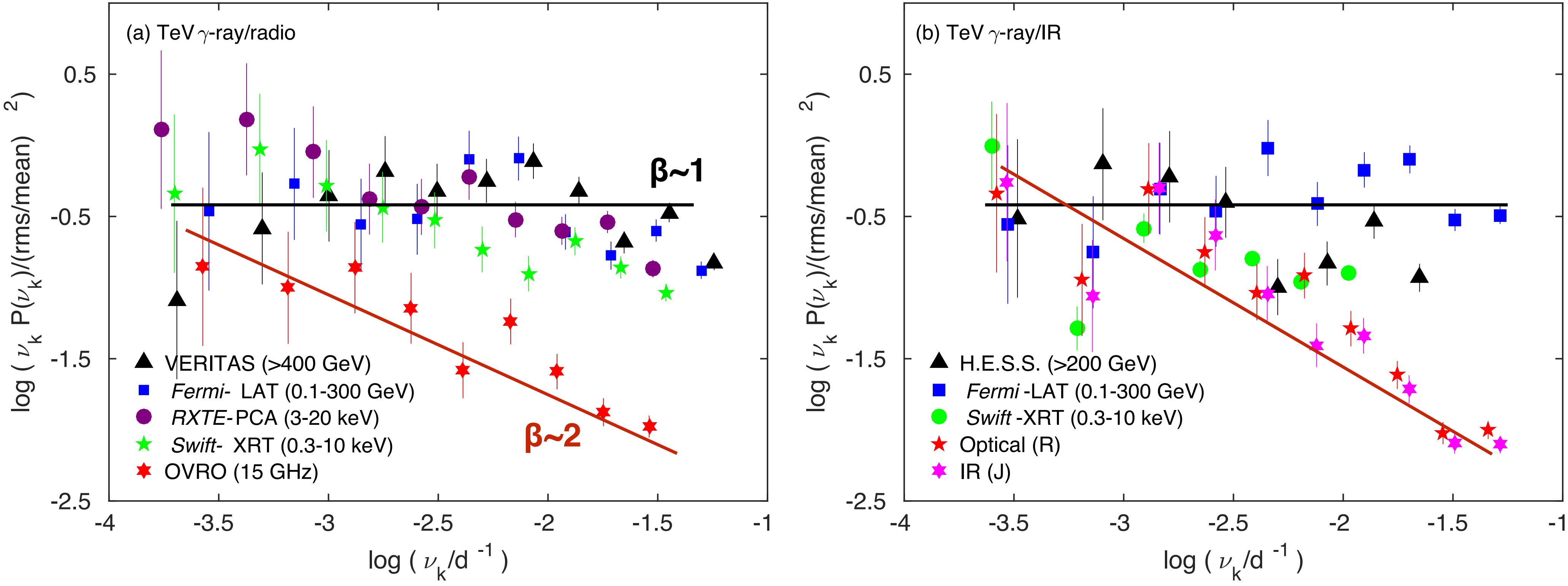


Power spectral density **P(f) ~ f$^{-\beta}$**

**radio and optical: “red noise” (β~2), from decades to hours!**

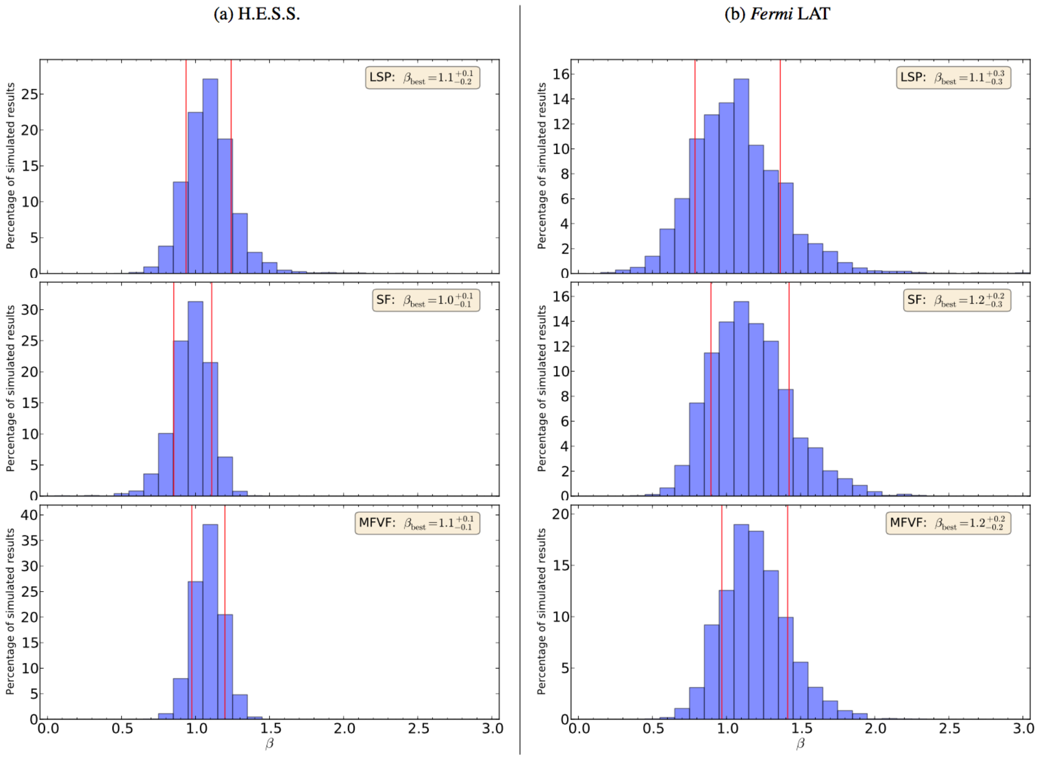
**GeV PSD: more like a “pink noise” (flickering β~1) from years to weeks/days**

# Variability power spectra



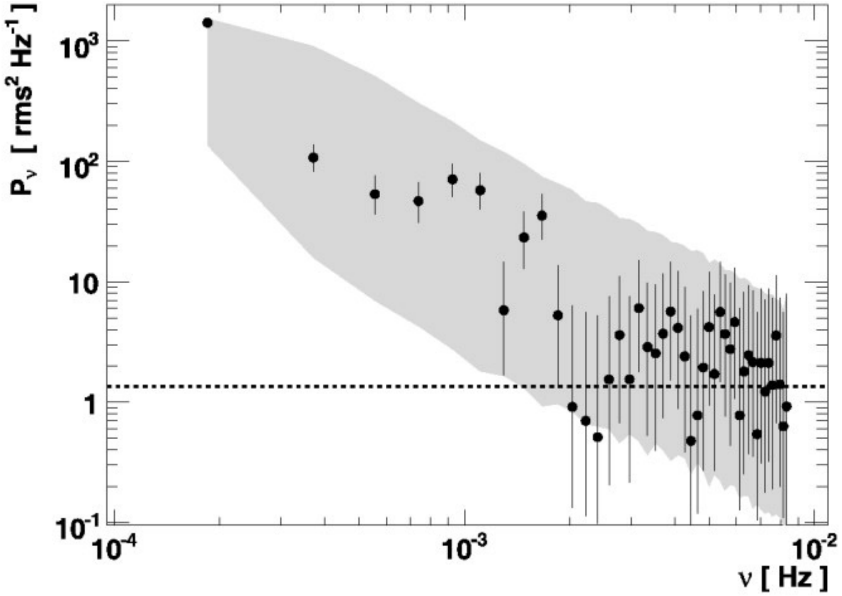
Mrk 421 and PKS 2155 (Goyal 2019, subm.)

# PKS 2155



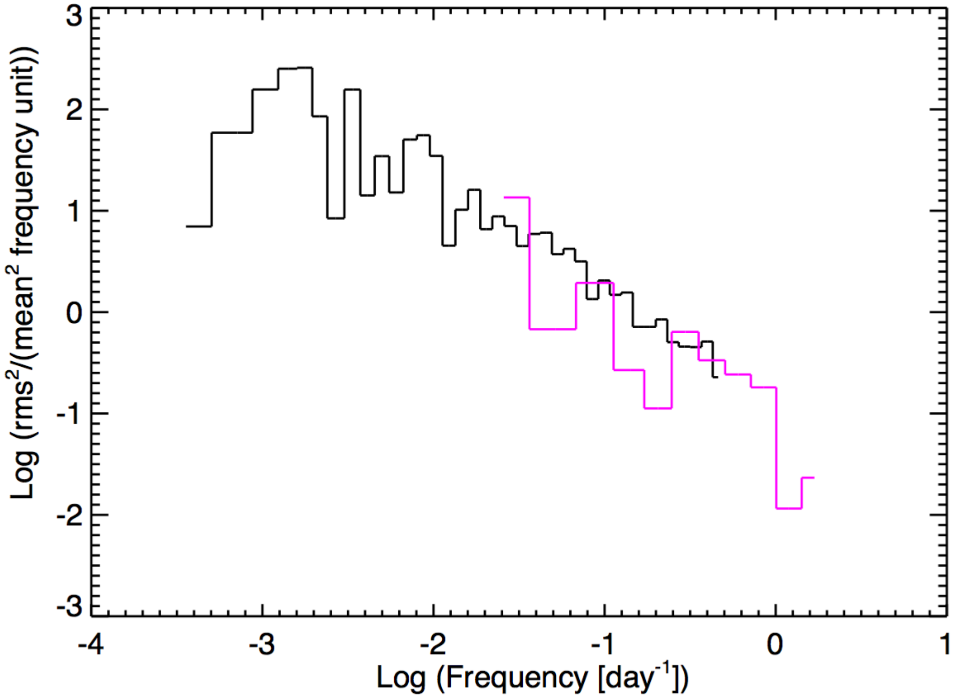
Abdalla et al. 2017
days to years
β~1

Aharonian et al. 2007
minutes-hours
β~2



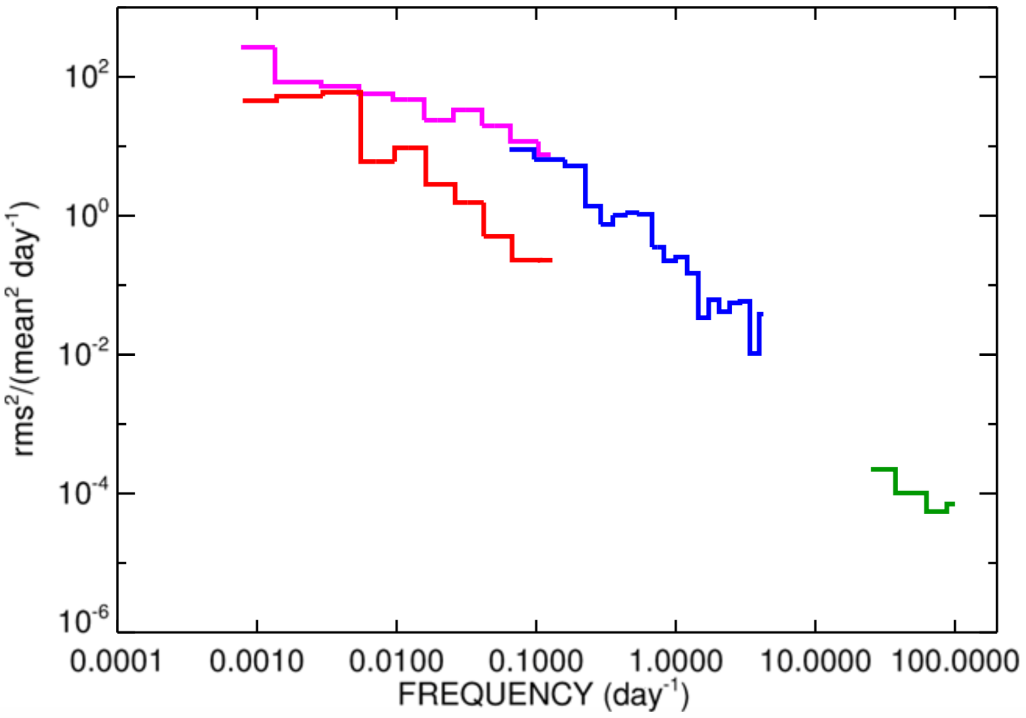
# PKS 1510 & 3C 279

Ahnen et al. 2017
PKS 1510 days to years
β~1



Power density spectrum of PKS 1510 for the mission-long Fermi-LAT light curve (black) and for the 2015 flare epoch (magenta).

Ackermann et al. 2016
3C 279 days to years



Power density spectrum of 3C 279 derived from three different time-binned LAT light curves: 3 days (red and magenta), orbital period (blue), and 3 minutes (green); the PDSs marked in red and magenta were derived using the first and second halves of the first 7 year Fermi-LAT observation, respectively. The second half of the interval contains the giant outburst phase in 2015 June.

# Stochastic variability

| | |
|---|---|
| but is there any well defined distinct blazar emission zone, with particular characteristic $t_{var}$? | -> **no** single well defined characteristic variability timescale (achromatic noise!) |
| but are there really quiescence states with no flux variability? | -> **no** “quiescence vs. flaring states”: variability seen at all the timescales from decades to hours, just with the variability amplitudes decreasing for shorter and shorter timescales |
| but are the flux changes observed at various wavelengths indeed physically related, and flares robustly resolved? | -> stochastic character of gamma-ray and synchrotron (optical and radio) variability seems rather **different** (red vs pink noise) |

# Stochastic variability

Instead of standard Fourier decomposition methods, one can use a certain statistical model to fit the light curve in the time domain, and thus to derive the source power spectrum.

First-order Continuous-time Auto-Regressive (CAR(1)) model (also known as an Ornstein-Uhlenbeck process): the source variability is essentially described as a damped random walk, i.e. a stochastic process defined by the amplitude and the characteristic (relaxation) timescale (e.g., Kelly et al. 2009, 2011)

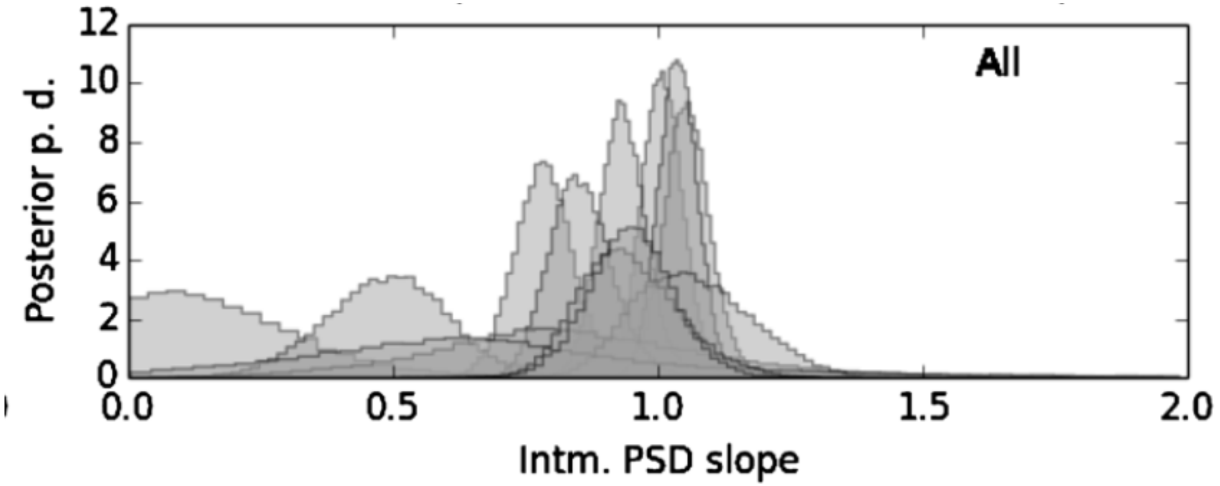
amplitude of the driving Brownian motion W(t)

relaxation frequency

$$dX(t) = -\omega_0(X(t) - \mu)dt + \varsigma dW(t),\ \omega_0, \varsigma > 0.$$

mean of the process X(t)

Soboleska et al. (2014): modelling of gamma-ray (LAT) light curves of blazar sources, on the timescales from years to hours, in terms of a linear superposition of CAR(1) processes



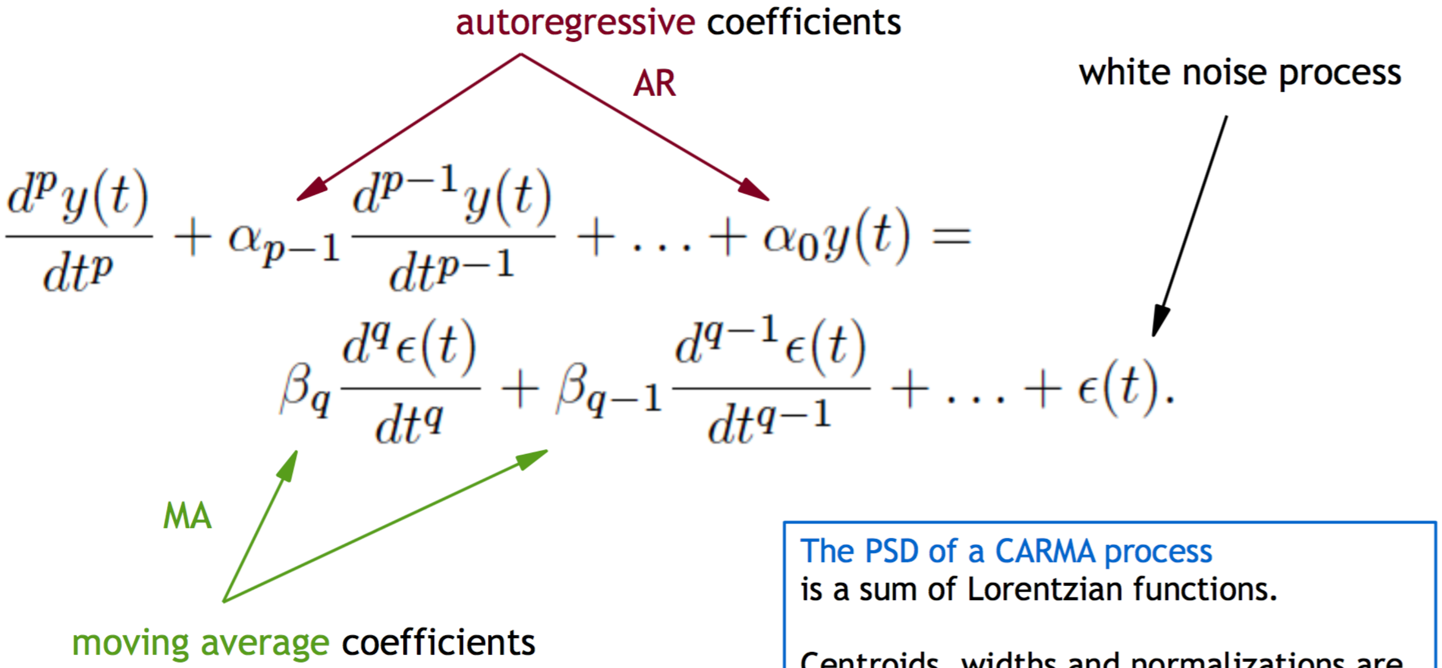
# CARMA Modeling

Continuous-time Auto-Regressive Moving Average (CARMA) mode, which is a generalized version of the first-order CAR(1).

In the CARMA model, the measured time series *y(t)* is approximated as a process defined to be the solution to the stochastic differential equation

## CARMA(p, q)

Continuous time autoregressive moving average process (Kelly+2014).



autoregressive coefficients

AR

white noise process

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

MA

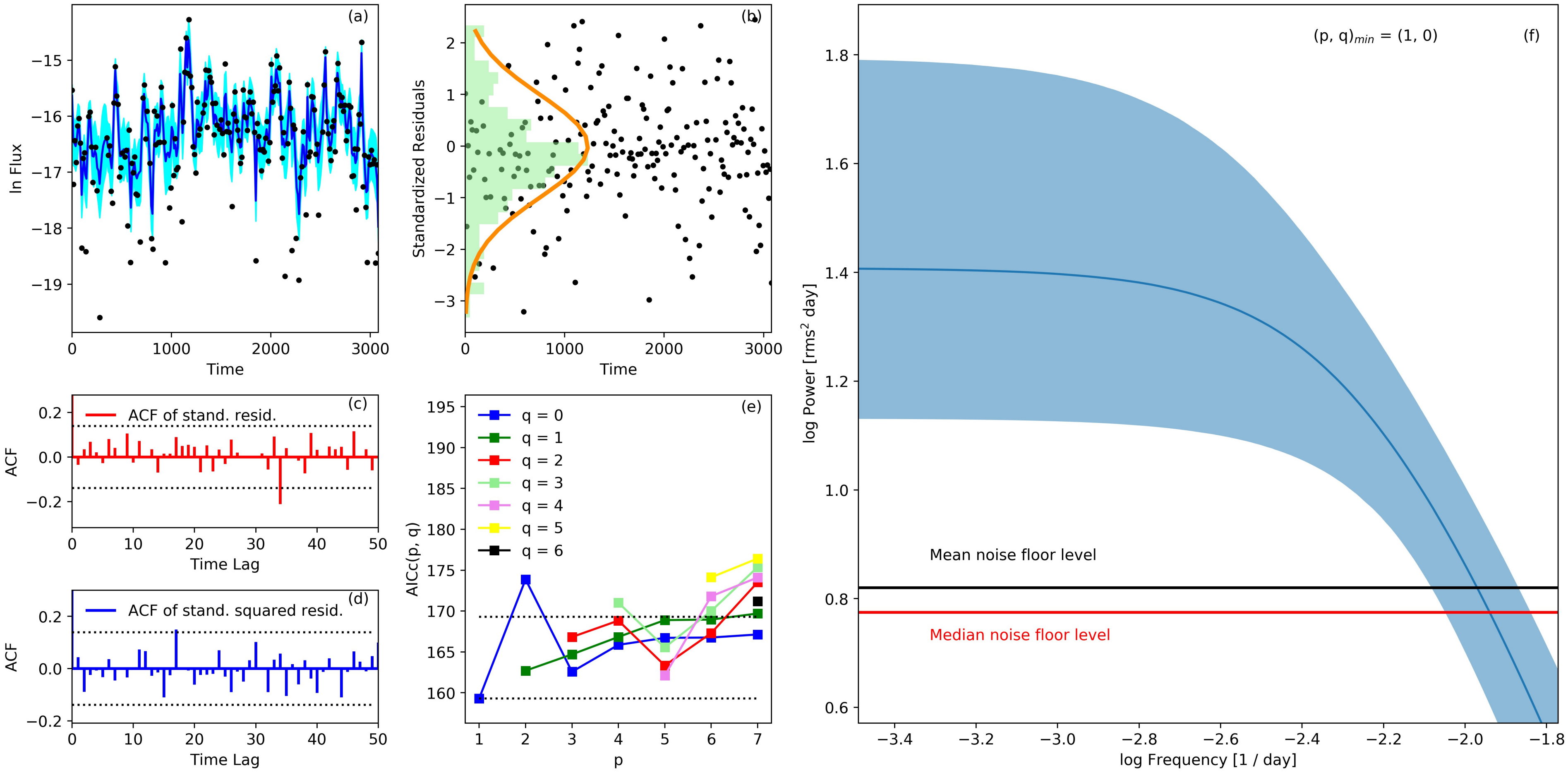
moving average coefficients

The PSD of a CARMA process
is a sum of Lorentzian functions.

Centroids, widths and normalizations are the free parameters.

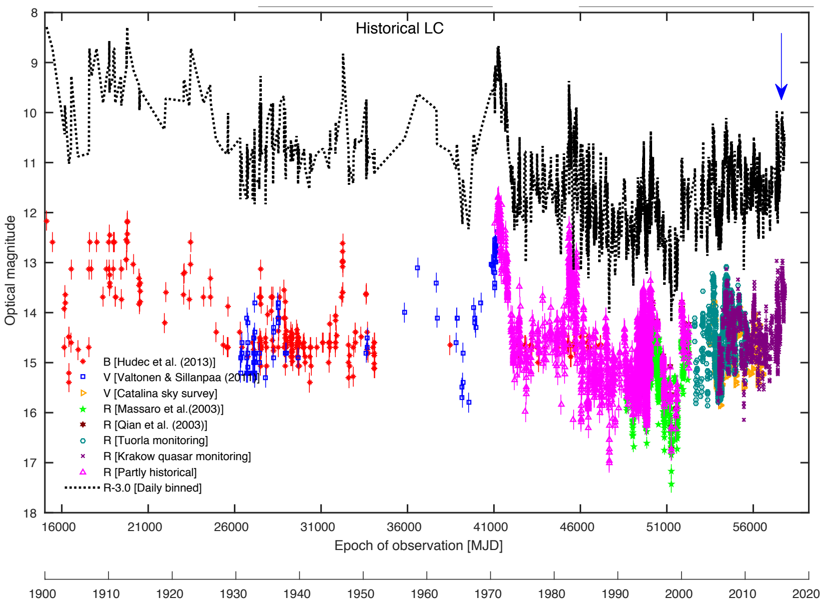
# OJ 287

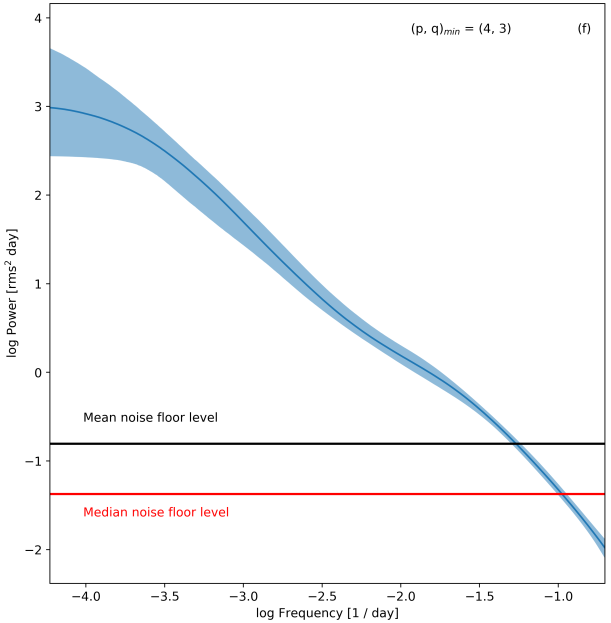
OJ287 — Fermi-LAT (Goyal, LS, et al. 2018)

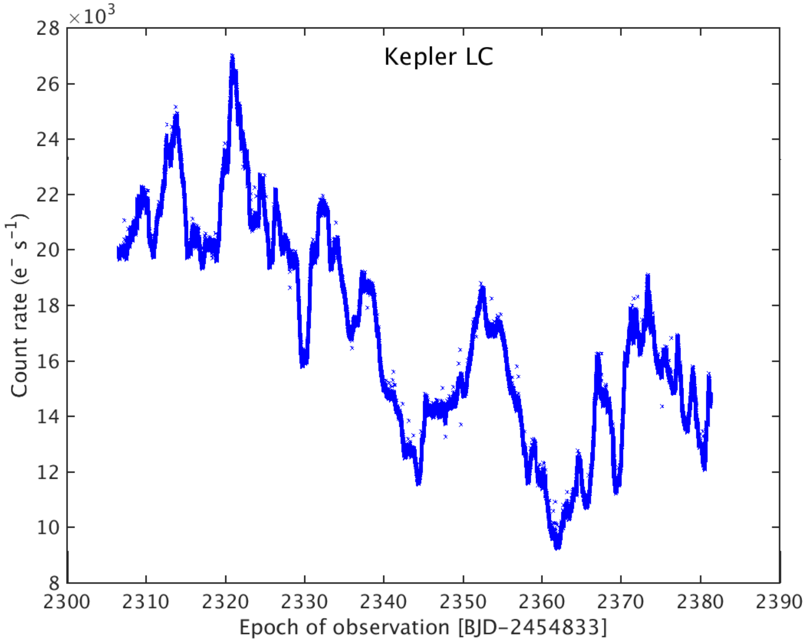


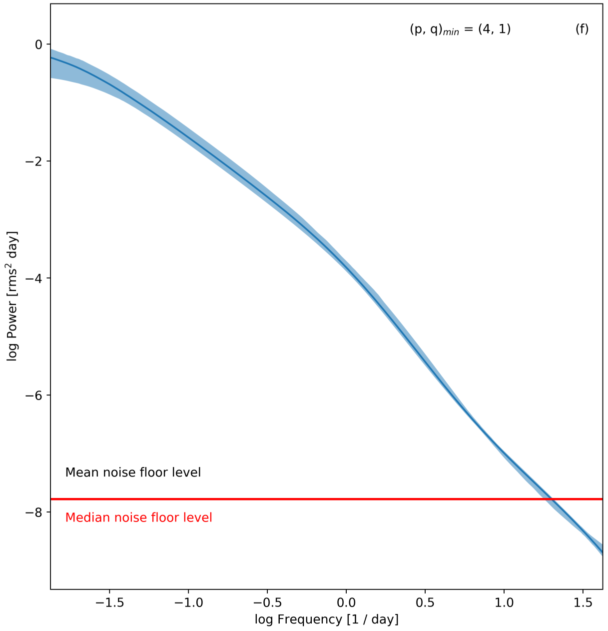
# OJ 287

OJ287 (Goyal, LS, et al. 2018)



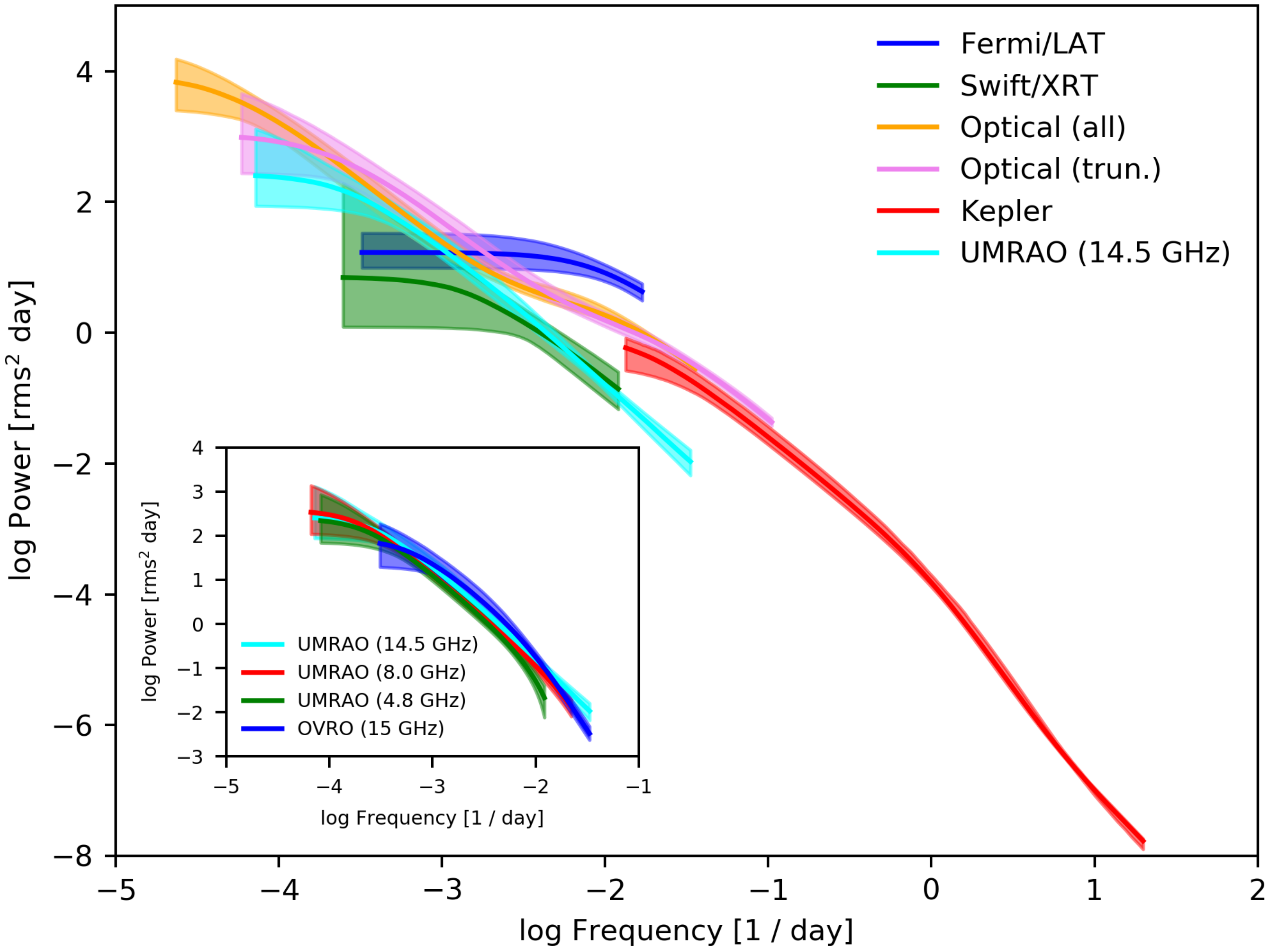






# OJ 287

OJ287 (Goyal, LS, et al. 2018)

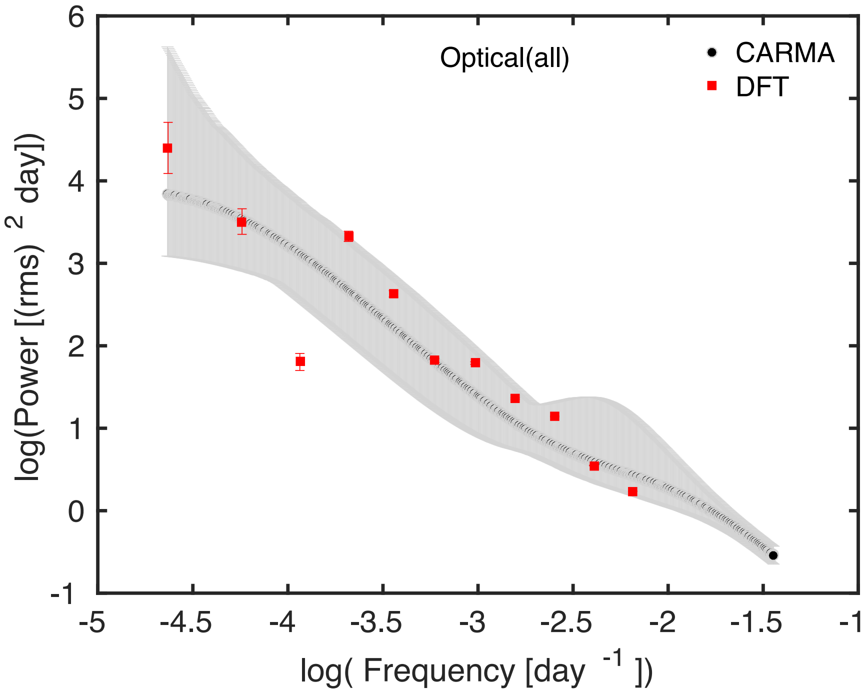


# Analysis methods

Lomb-Scargle Periodogram (LSP; plus power-response method Uttley et al. 2002), discrete Fourier transform (DFT, with linear interpolation of unevenly spaced data; see Goyal et al. 2017), first-order Structure Function (SF; but see Emmanoulopoulos et al. 2010), Multiple Fragments Variance Function (MFVF; Kastendieck et al. 2011), Continuous-time Auto-Regressive Moving Average (CARMA; see Kelly et al. 2009-14)

Colored-noise + uneven sampling + finite duration of the light curves = challenges for the statistical analysis.

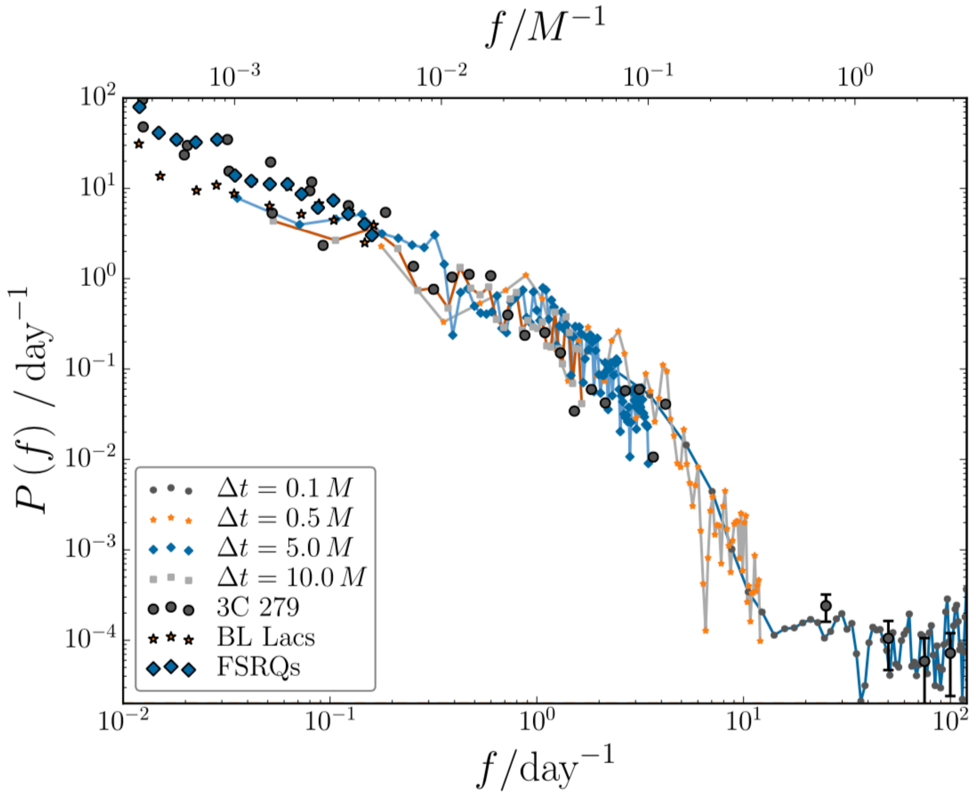
On the other hand, different analysis tools and methods applied, some more well established some less, seem to give similar results

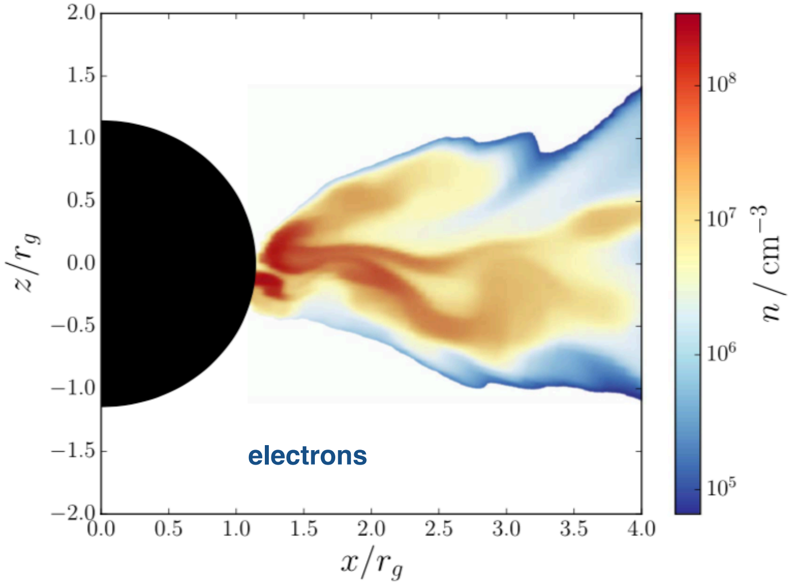


# Magnetically Arrested Disks

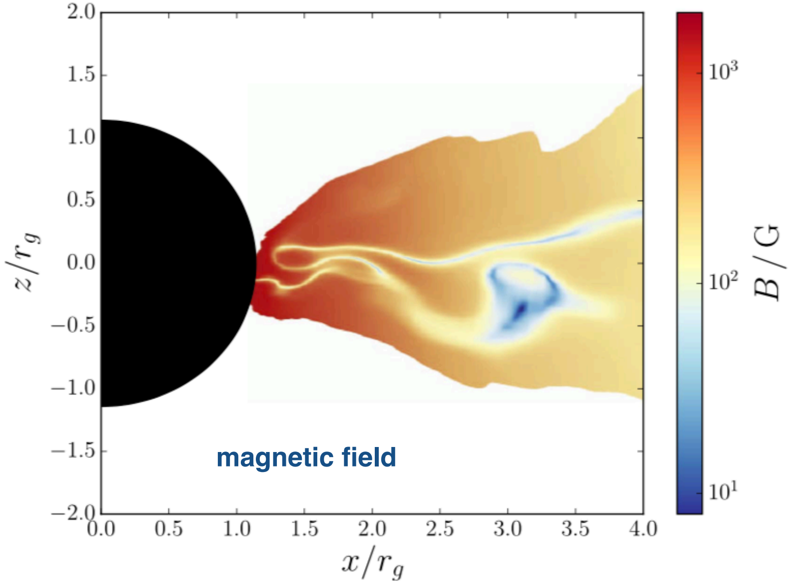
## O’Riordan et al. 2017:

Variability power spectra produced by turbulence in relativistic jets launched by magnetically arrested accretion flows (MADs) are of a power-law form, and extend down to very short variability timescales (in the relativistic turbulence model by Narayan & Piran 2012, magnetohydrodynamic turbulence in the jet produces compact blobs on scales smaller than the horizon radius, similar to those in the “jets in a jet” scenario).



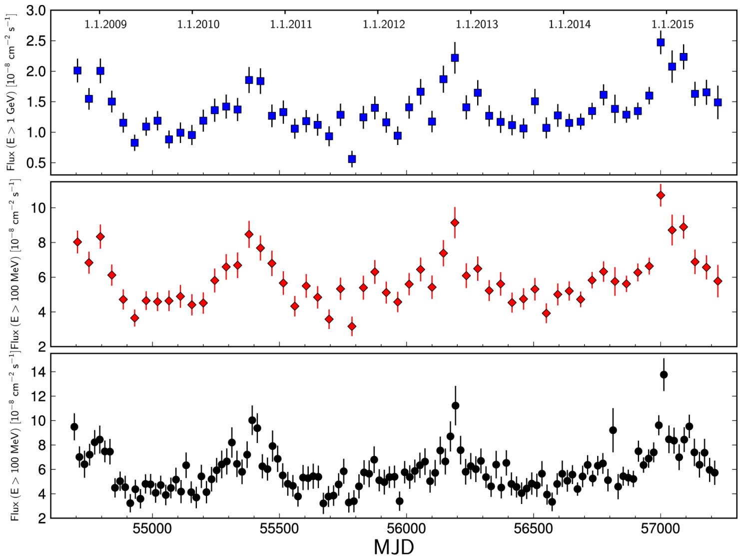


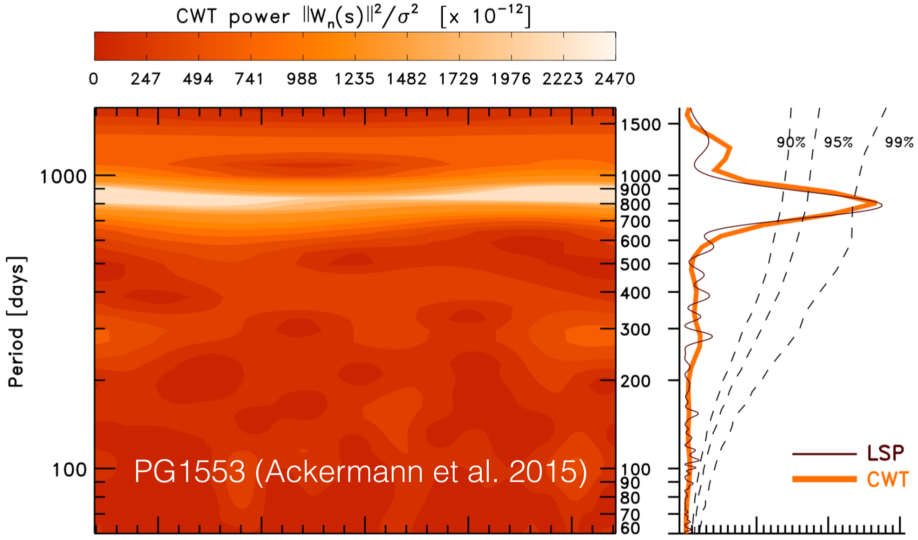
**electrons**



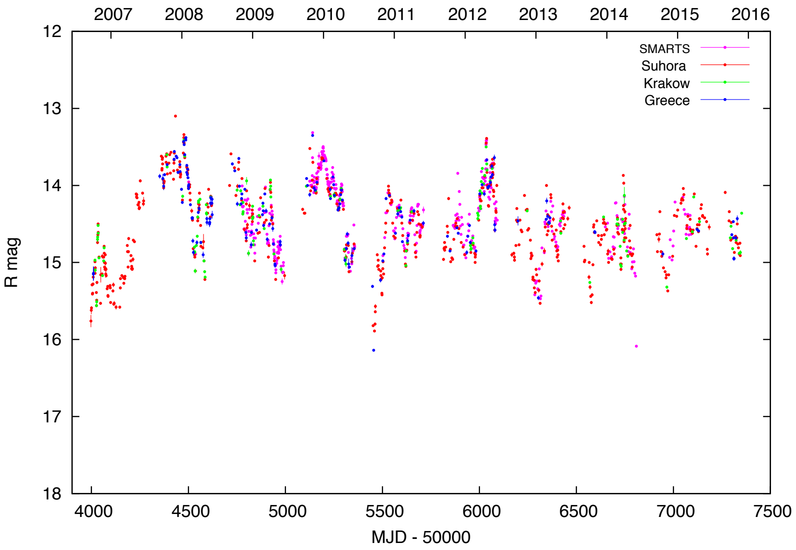
**magnetic field**

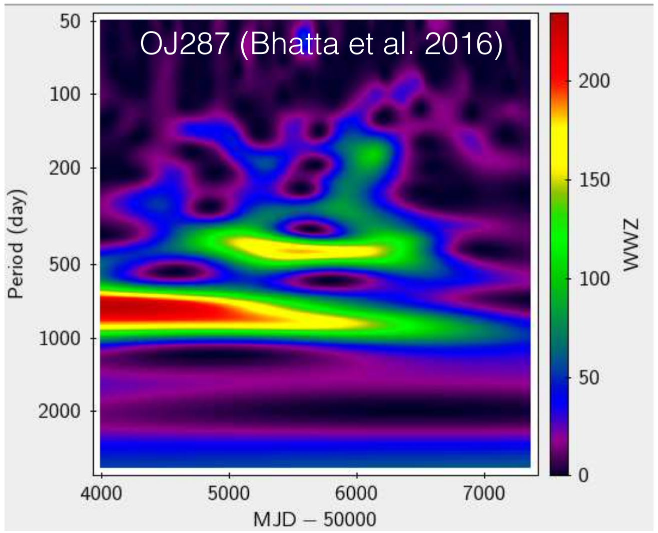
# (Quasi-)periodic oscillations?

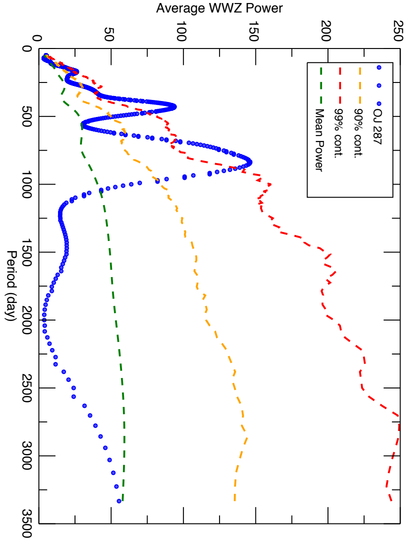




marginal significance, timescales of a few years, seem to be related to accretion disks rather than binary SMBHs

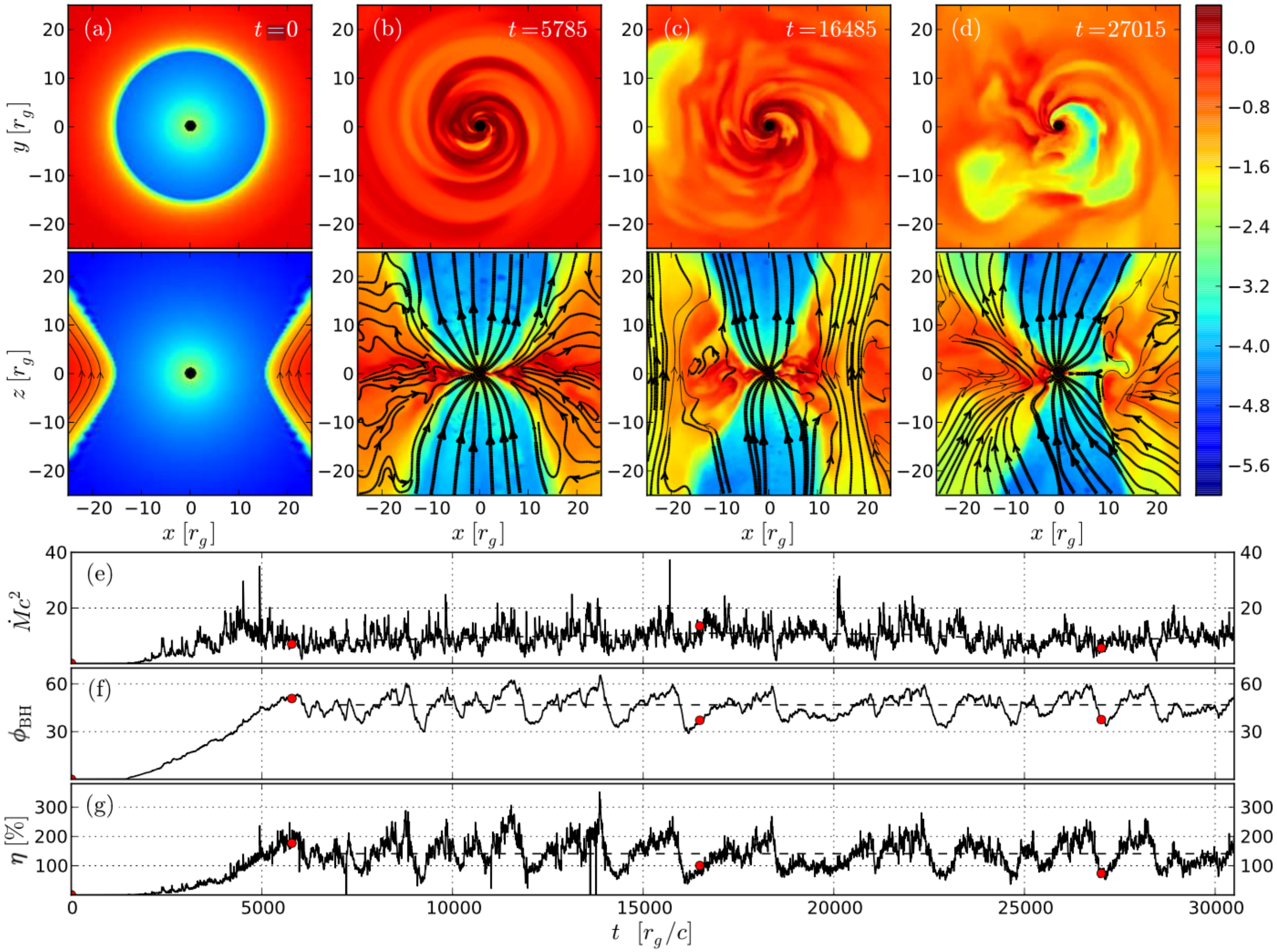






# Chocking Magnetized Disks

*A. Tchekhovskoy, R. Narayan and J. C. McKinney*



In the case of magnetically arrested disks, the characteristic timescale of quasi-periodic oscillation in the jet production efficiency set by the rotating and unstable ("chocking") magnetic field accumulated at the saturation level around the horizon of a spinning black hole, corresponds to tens/hundreds of the gravitational radius light-crossing times (Tchekhovskoy et al. 2011; McKinney et al. 2012).

# Concluding remarks

1) Various approaches for modelling the blazar SEDs; the most commonly invoked one-zone models, including time-dependent analysis in the framework of the internal shock scenario, imply typically $U'_e/U'_B \gg 1$ and broken EED with $s_{low} < 2$ below $\gamma_{br} \sim 100\text{-}1000$ and $s_{high} > 2$ above $\gamma_{br}$ .

2) The most recent simulations (PIC) of the relativistic magnetic reconnection, reveal efficient electron acceleration leading to formation of flat $s<2$ electron spectra for high plasma magnetisation $U'_e/U'_B \ll 1$; on the other hand, simulations of relativistic shocks reveal rather steep $s>2$ electron spectra, in addition strongly depending on the magnetic field configuration.

3) Various approaches for constraining the blazar PSDs, revealing however in accord a general colored-noise-type variability, extending from the variability timescales of decades down to hours, in addition with an excess variability power at gamma-rays (when compared to the optical or radio domain) on the variability timescales shorter than a year (pink vs. red noise); could possibly be understood as driven by relativistic turbulence.