Relativistic Jets in AGN: Magnetic Field Structure and Particle Acceleration

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In a collaboration with many colleagues, including
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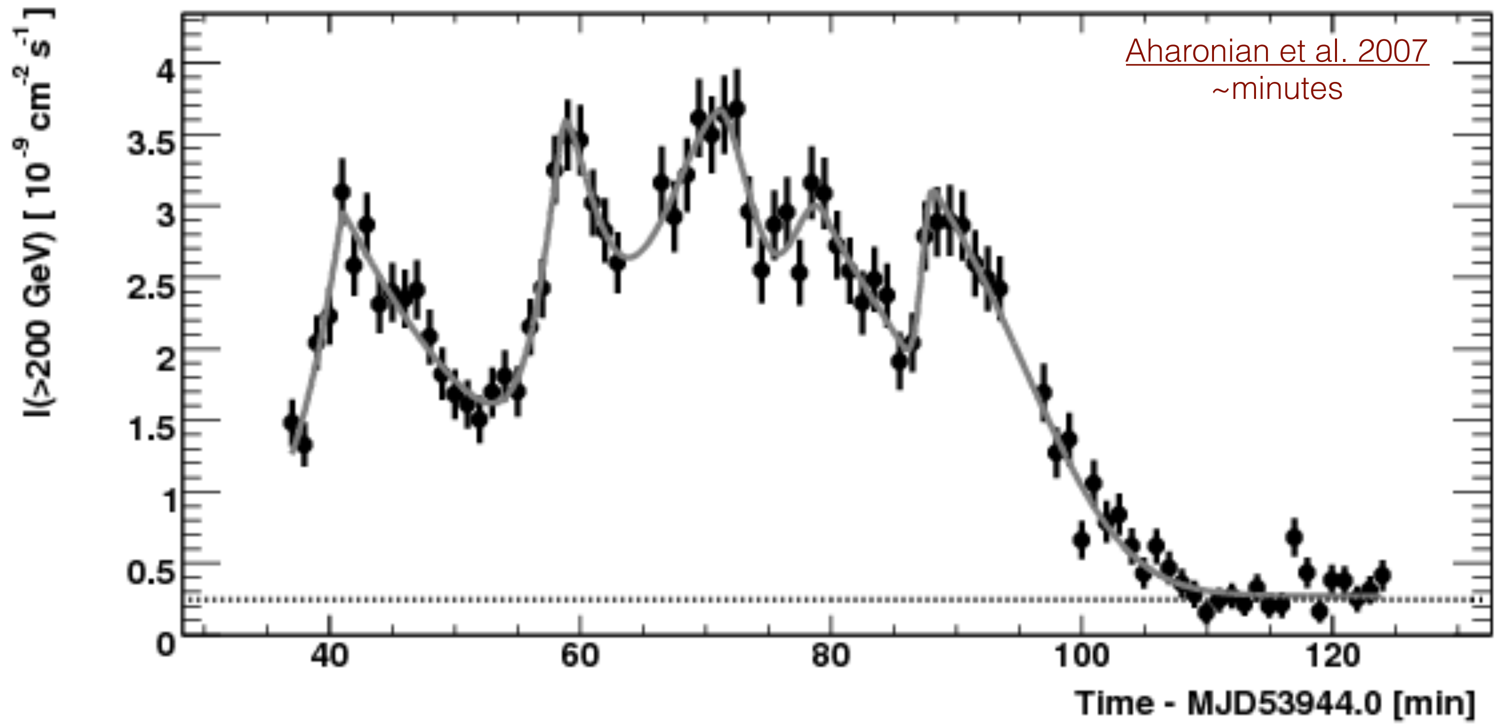
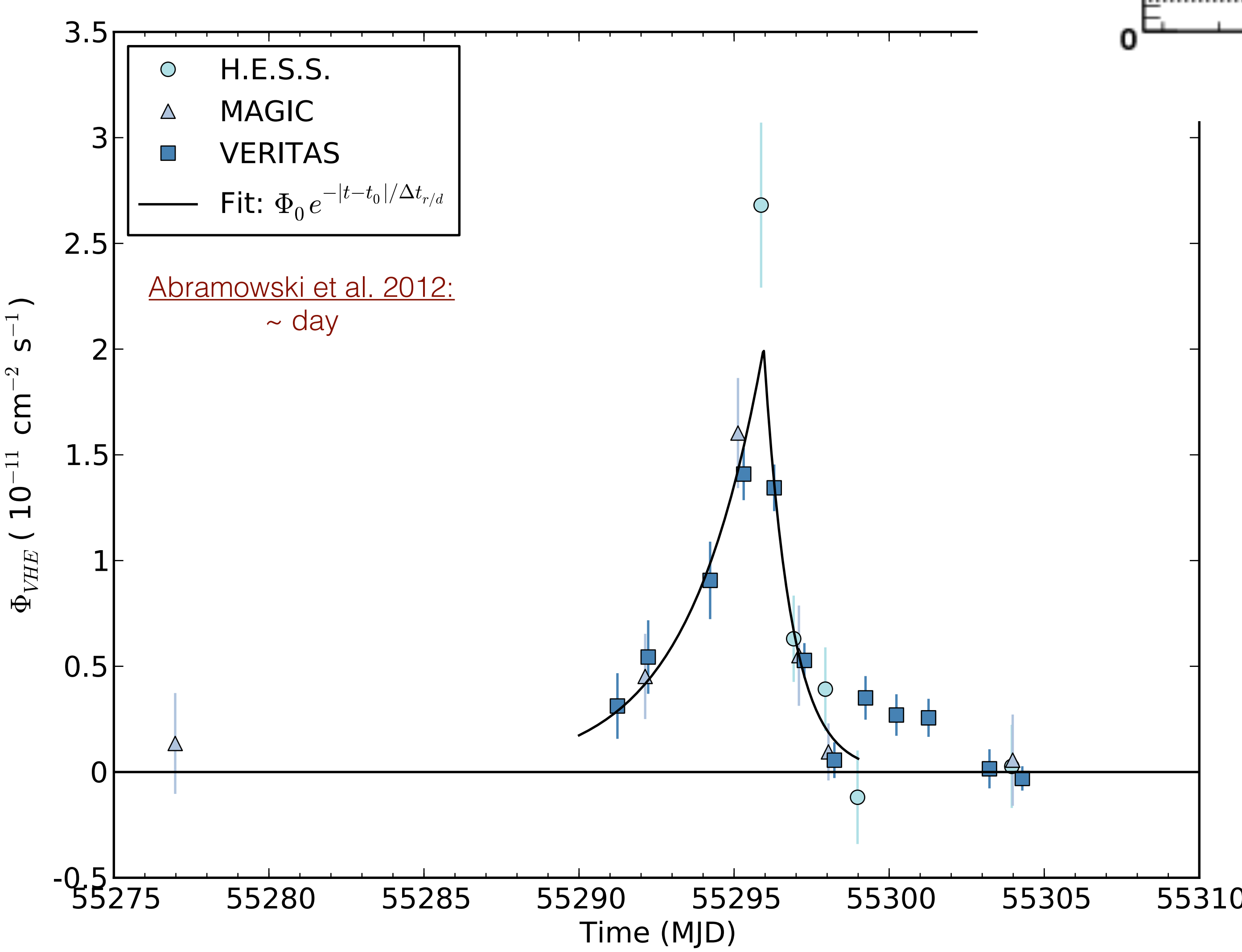
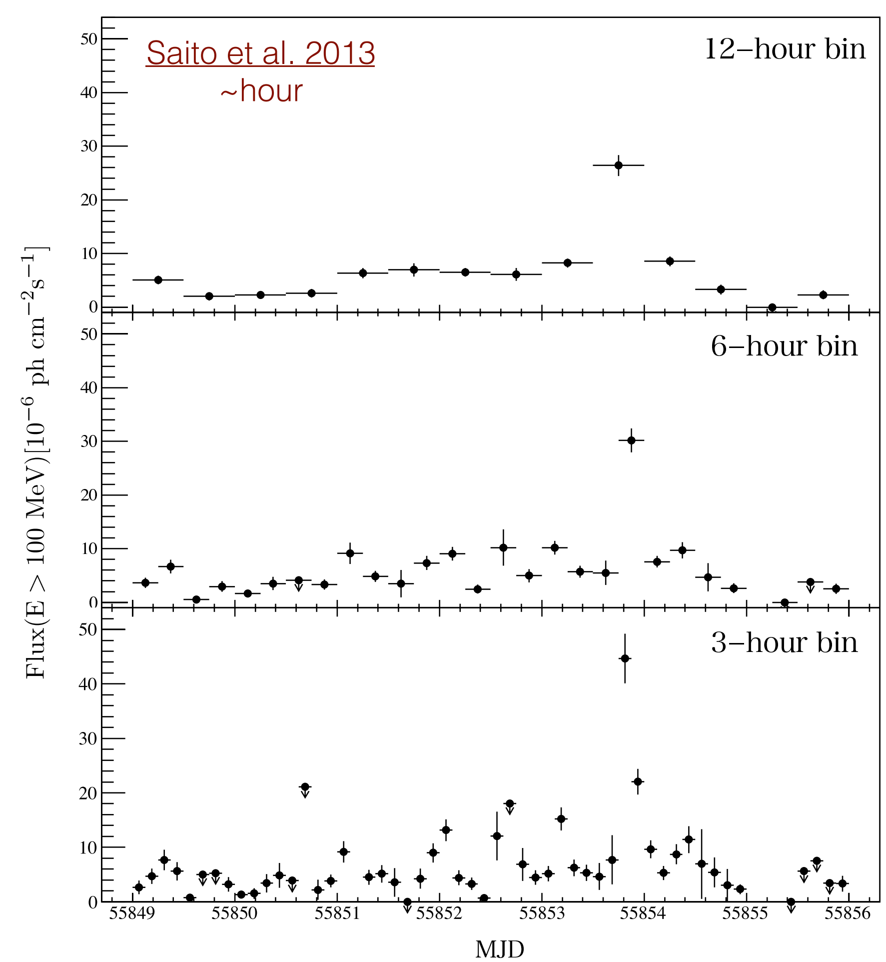
Rapid γ-ray variability

PKS 2155-304
M87
PKS 1510-089

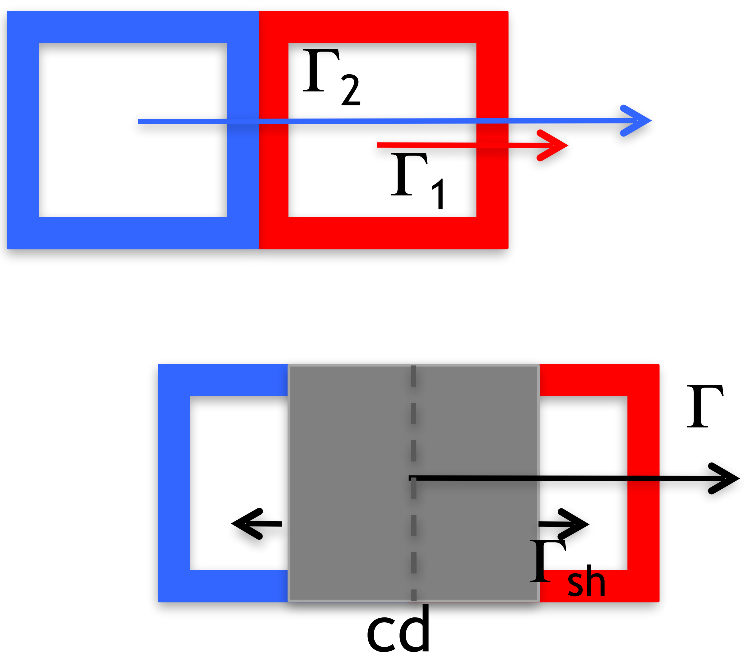
(also 3C 279, IC310, Mrk 501)

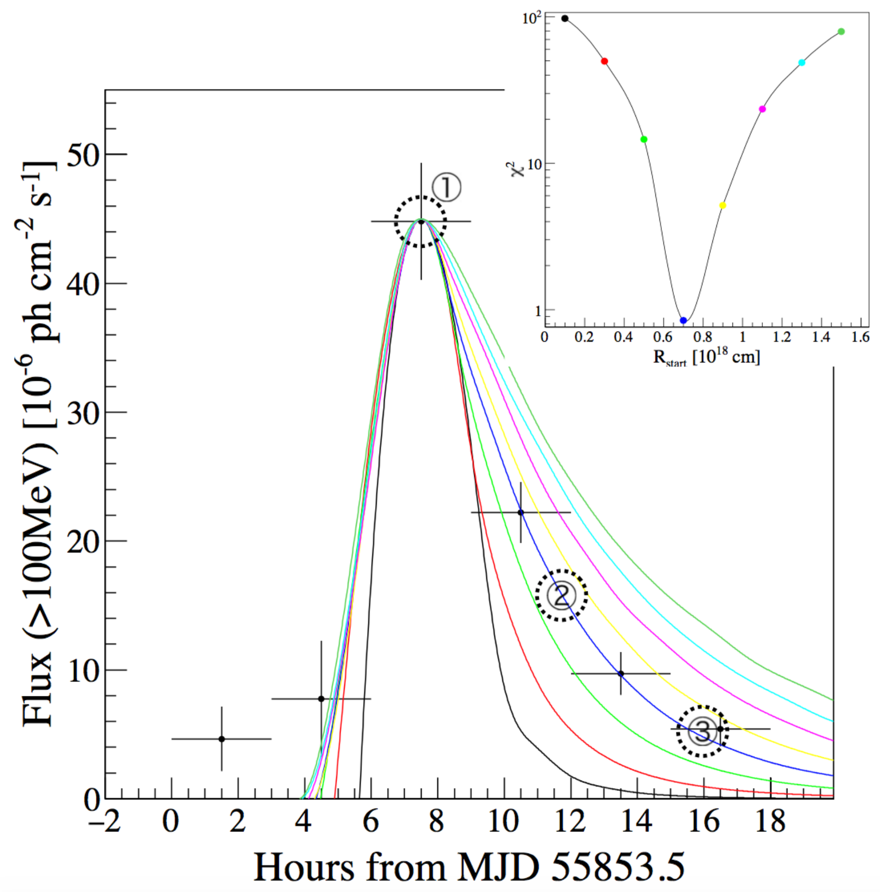


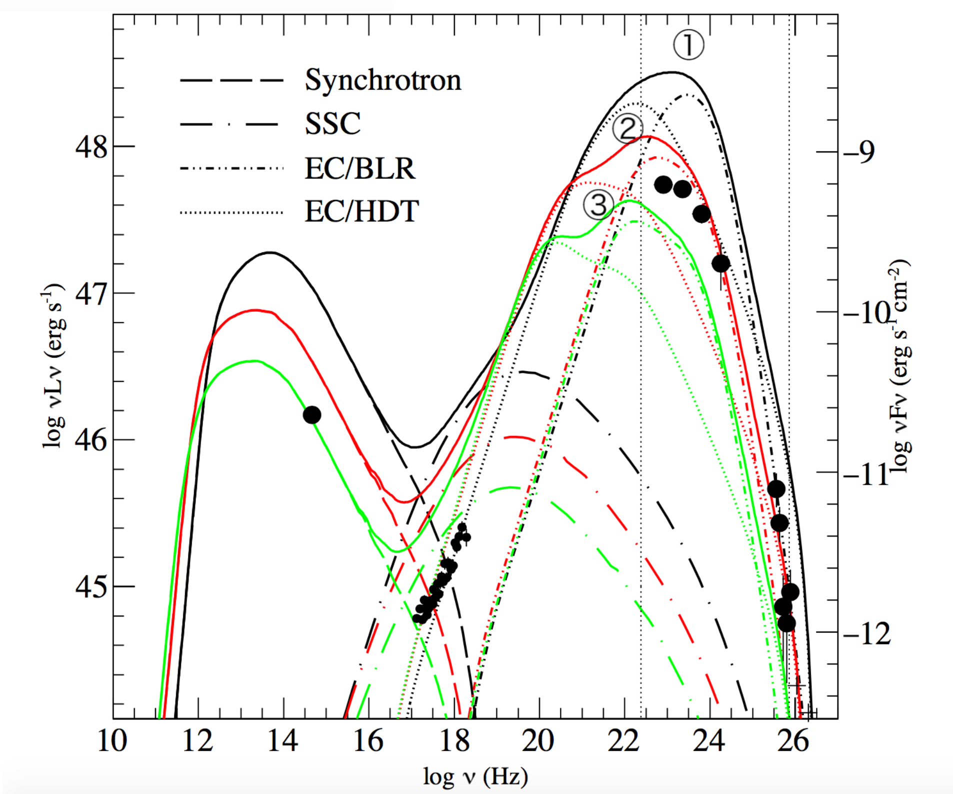




Internal shock model





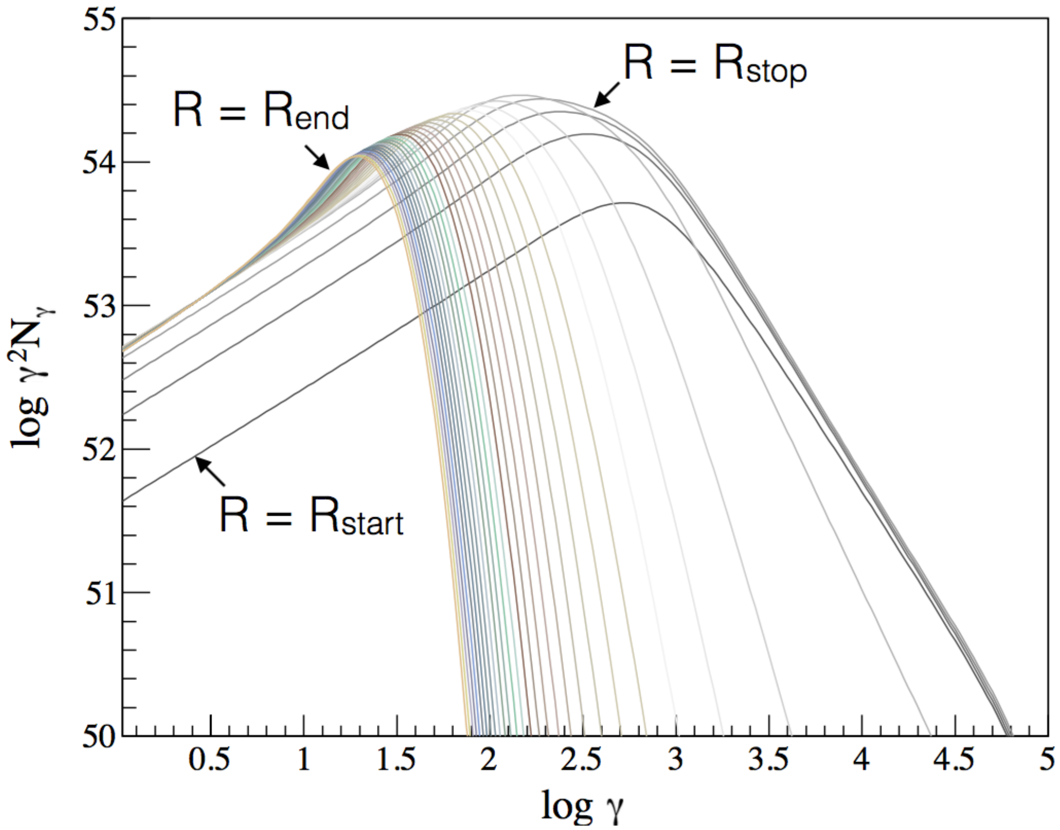


Saito et al. 2015:

modelling of the rapid GeV flare of PKS 1510-089 in the framework of the internal shock model (BLAZAR code by Moderski et al. 2003/05)

Internal shock model has been applied widely to AGN jets over the last decades

Matter-dominated outflows?



Model parameter	Flare 1	Flare 2
Minimum electron Lorentz factor, $\gamma_{\rm min}$	1	
Break electron Lorentz factor, $\gamma_{\rm br}$	900	
Maximum electron Lorentz factor, $\gamma_{\rm max}$	1×10^5	
Low-energy electron injection index, p	1.2	
High-energy electron injection index, q	3.4	
Bulk Lorentz factor of the emitting shell, Γ	22	
Jet opening angle, $\theta_{\rm jet}$	2.6 deg	
Jet viewing angle, $\theta_{\rm obs}$	2.6 deg	
Jet magnetic field intensity at 10^{18} cm, B_0	0.75 G	
Characteristic scale of the BLR, $R_{\rm BLR}$	0.12×10^{18} cm	
Central energy density of the BLR photon field, $u_{\rm BLR}$	$0.06\,{\rm erg\,cm^{-3}}$	
Characteristic energy of the BLR photons, $h\nu_{\rm BLR}$	10 eV	
Characteristic scale of the HDT, $R_{\rm HDT}$	1.94×10^{18} cm	
Central energy density of the HDT photon field, $u_{\rm HDT}$	$5 \times 10^{-4}\,{\rm erg\,cm^{-3}}$	
Characteristic energy of the HDT photons, $h\nu_{\rm HDT}$	0.15 eV	
Normalization of the electron injection function, K_e	$1.6 \times 10^{47}\,{\rm s^{-1}}$	$0.6 \times 10^{47}\,{\rm s^{-1}}$
Distance where the injection starts, $R_{\rm start}$	0.7×10^{18} cm	2.3×10^{18} cm
Distance where the injection terminates, $R_{\rm stop}$	0.9×10^{18} cm	3.4×10^{18} cm
Distance where the simulation stops, $R_{\rm end}$	2.3×10^{18} cm	6.9×10^{18} cm

Saito et al. 2015:

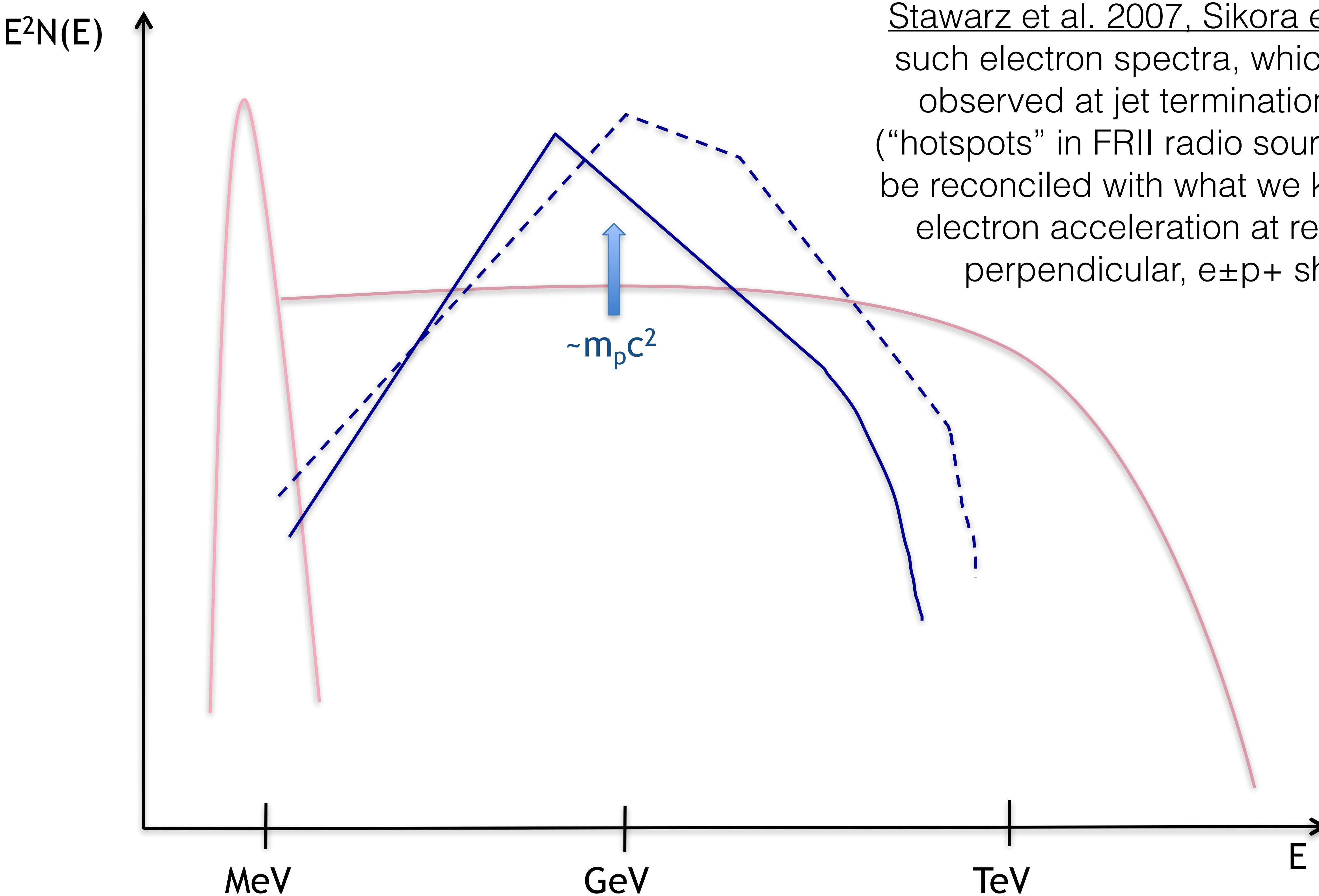
1) thin emitting shells propagating relatively far from the core (modeling results imply l'_{sh}~1.5e15 cm and r'~4e16cm, meaning l'_{sh}/r'~0.035 and $l_{sh}/r \sim \delta\, l'_{sh}/r'$ ~ 0.8)

2) jets dominated by cold protons, at least during the flares (in the case of a pure pair plasma, the energy conservation would then imply unrealistically high bulk Lorentz factor of the faster shell, namely Γ_2 ~ 5000 for the the downstream bulk Lorentz factor Γ_{sh} = 22)

3) "peculiar" broken power-law electron spectra (the low-energy injection index p<<2 and the high-energy injection index q>>2)

Similar results obtained when modelling other blazar flares in the framework of the internal shock model!

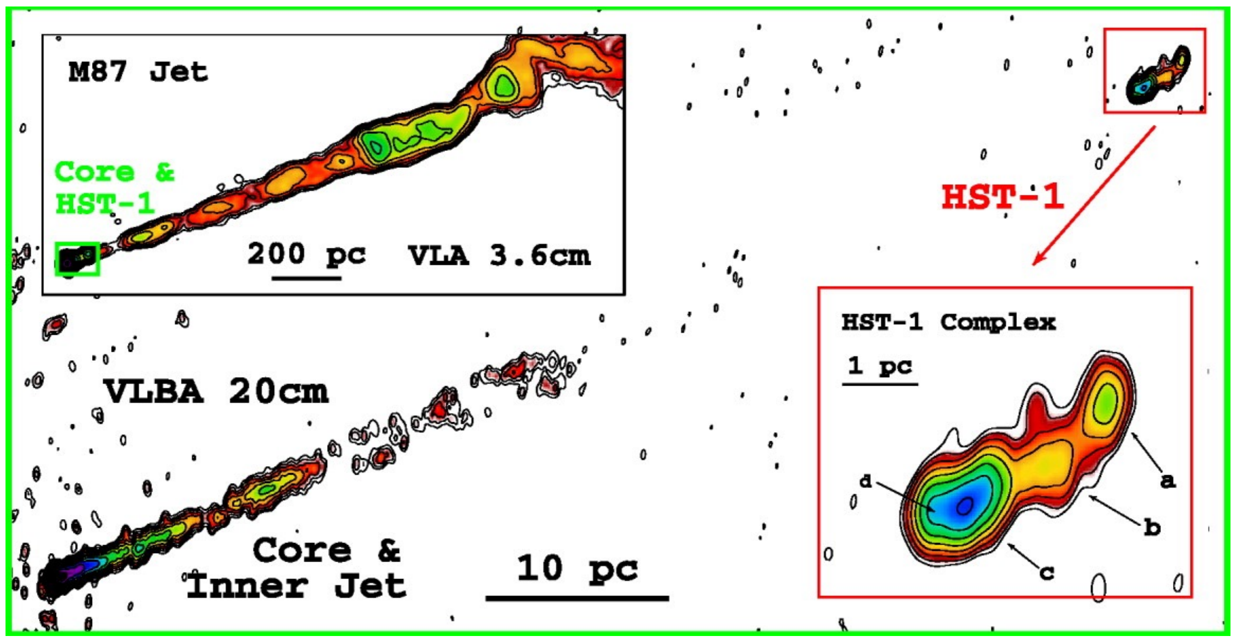
Relativistic e±p+ shocks?



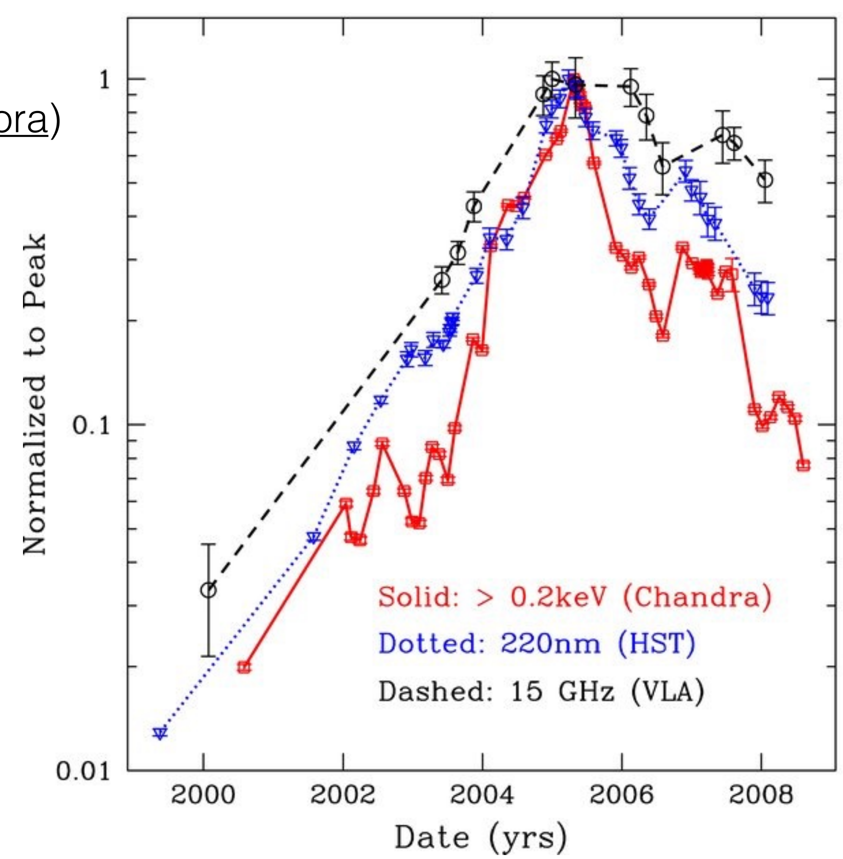
Stawarz et al. 2007, Sikora et al. 2009: such electron spectra, which are also observed at jet termination shocks ("hotspots" in FRII radio sources), could be reconciled with what we know about electron acceleration at relativistic, perpendicular, e±p+ shocks

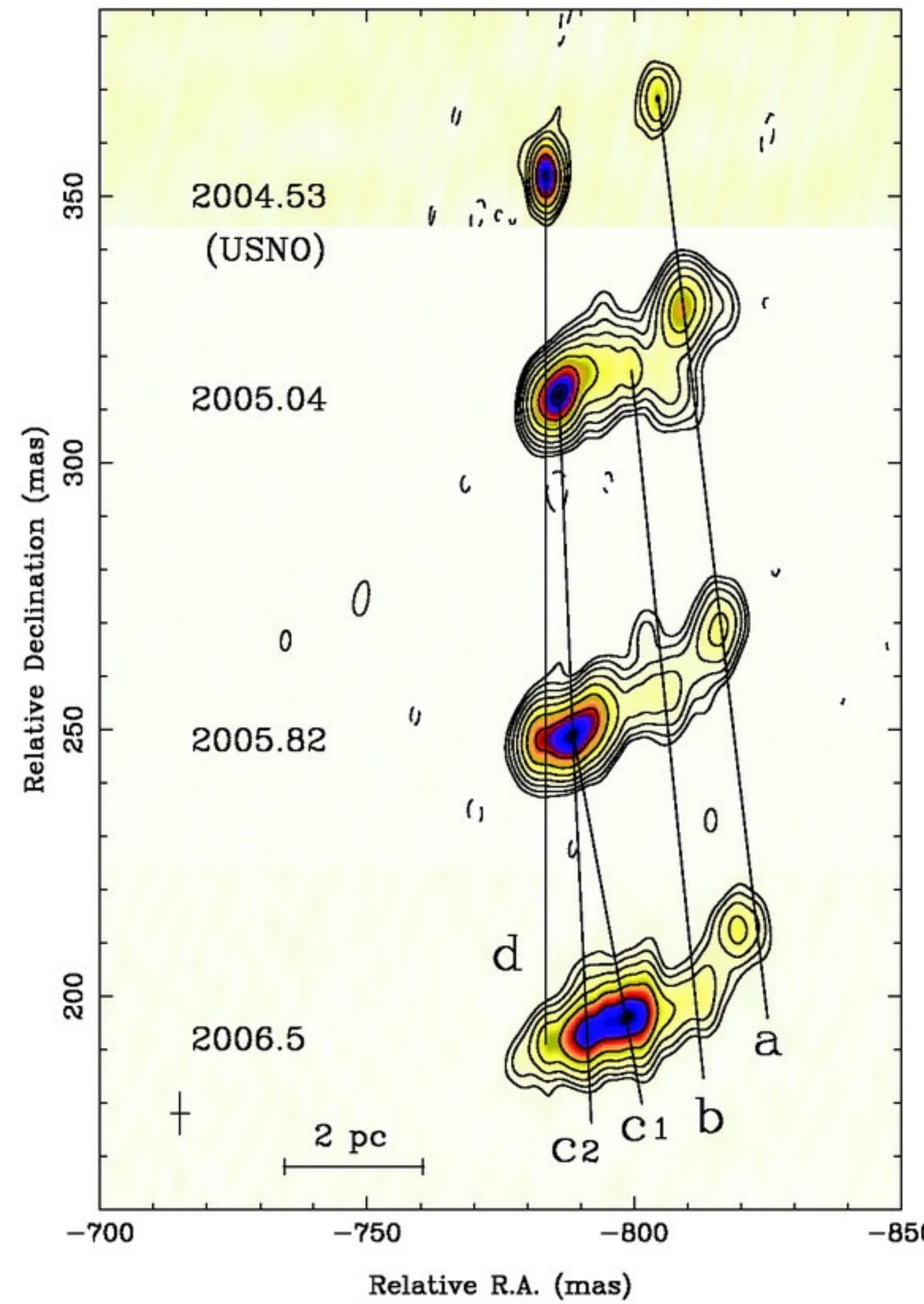
Reconfinement Nozzle

Stawarz et al. 2006, Cheung et al. 2007, Harris 2009:
HST-1 knot as a reconfinement shock, and a plausible γ-ray emission site

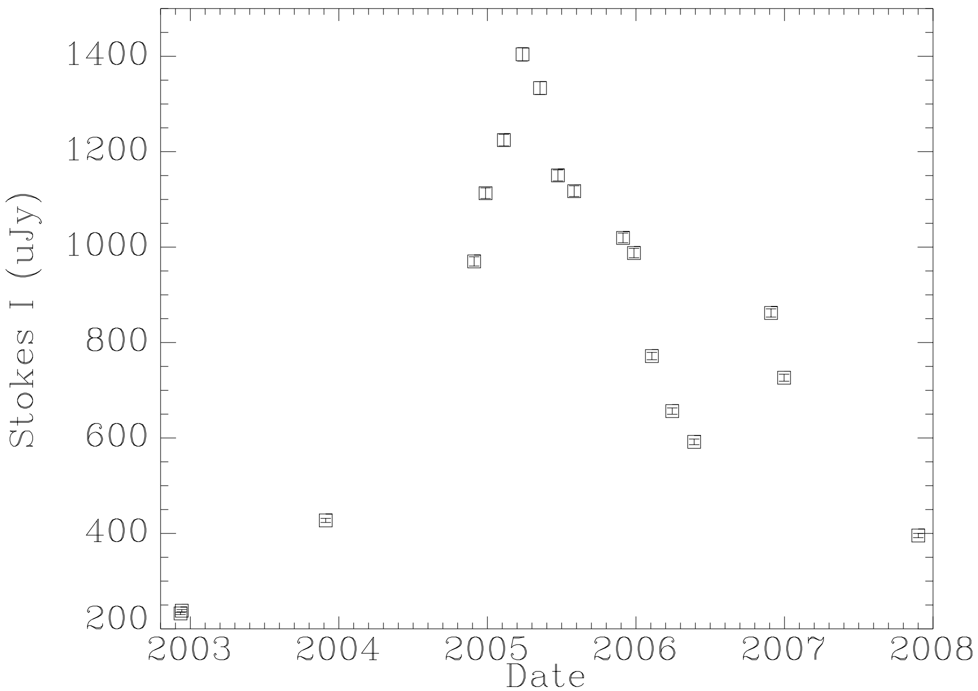


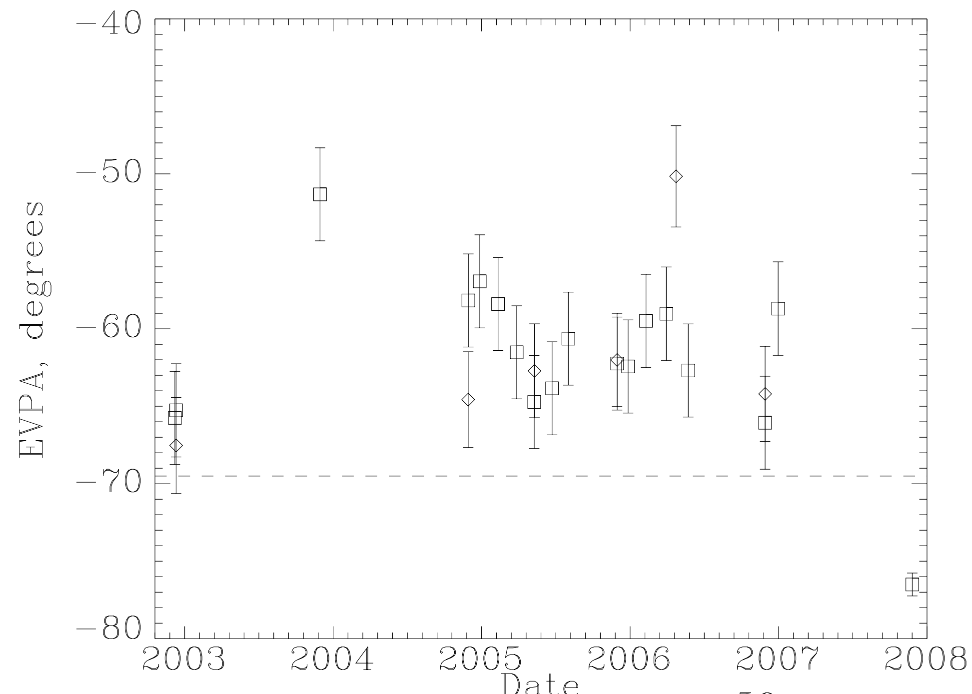
(also Bromberg & Levinson, Nakamura et al., Nalewajko & Sikora)

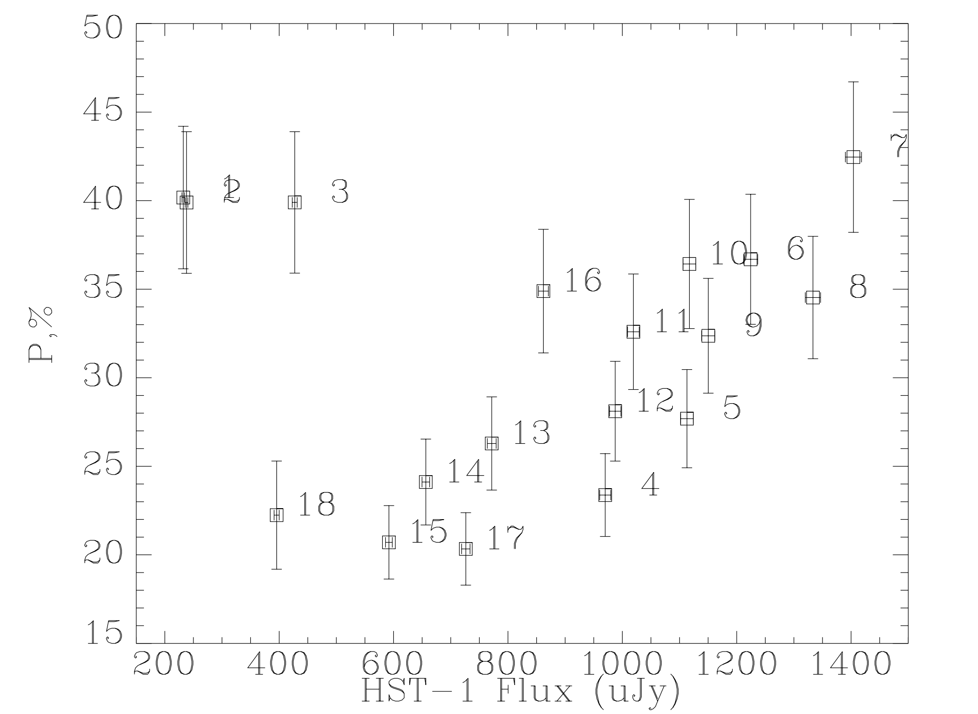




Standing shock?

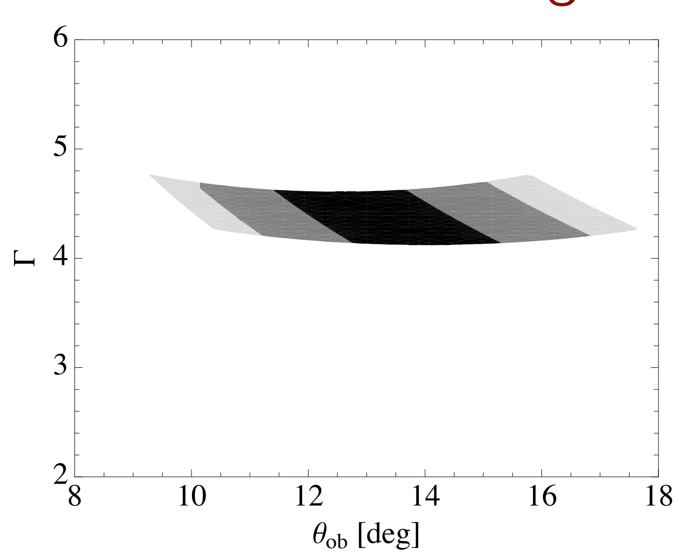




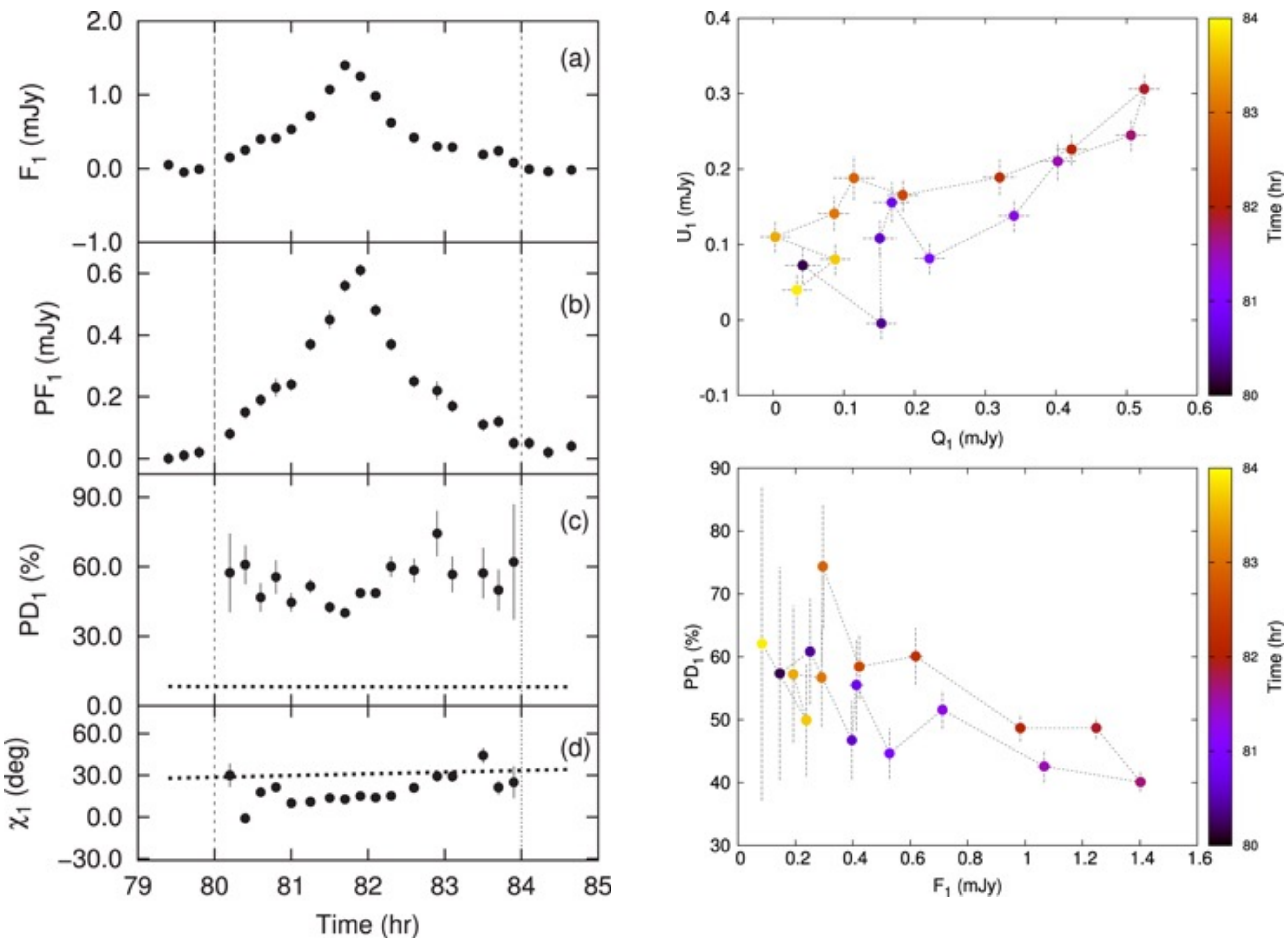


Perlman et al. 2011:

HST-1 behaves like a standing shock indeed…

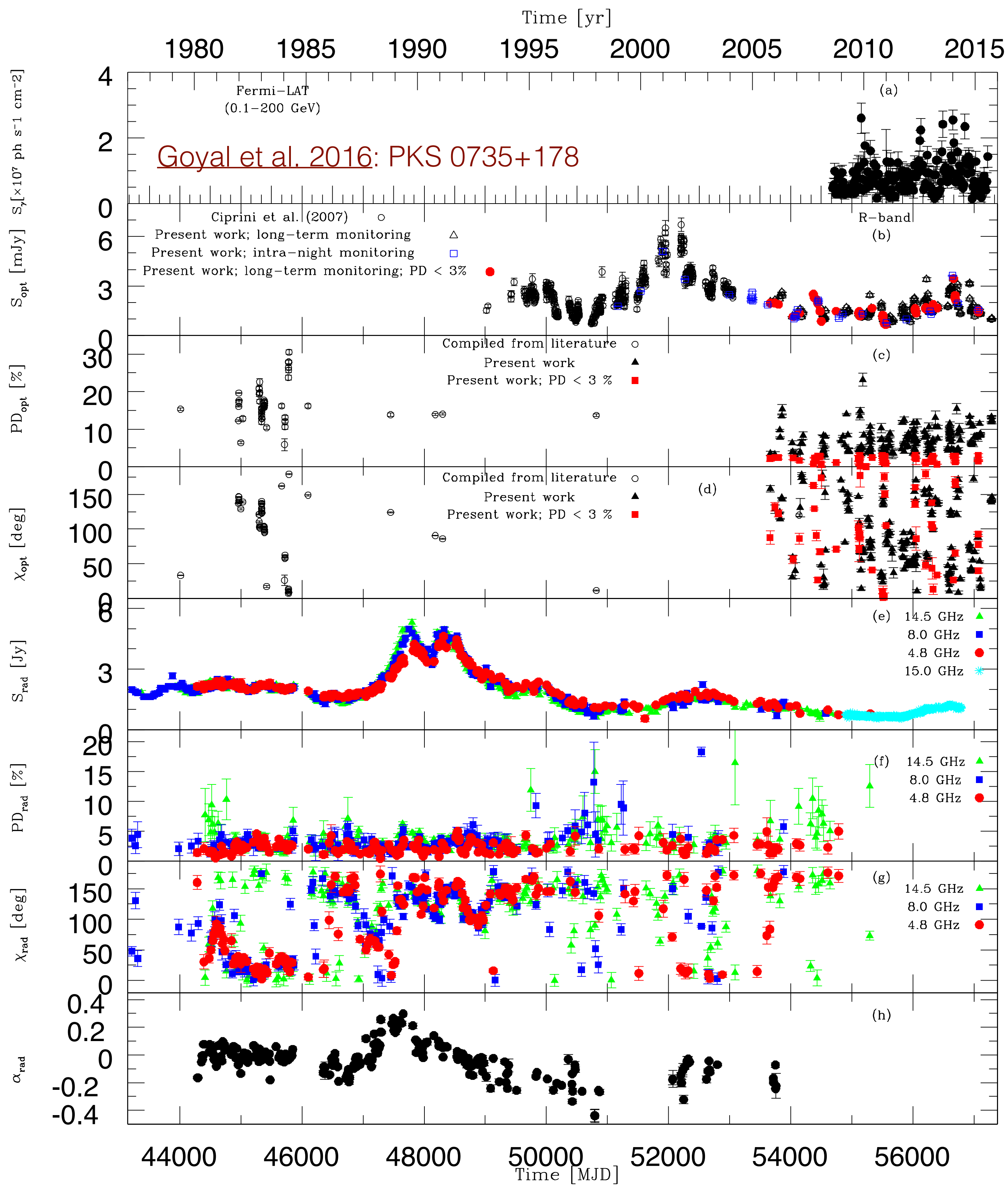


However…



Bhatta et al. 2015: optical microflare in blazar S5 0716+714 looks quite similar, although here we are dealing with the timescales of HOURS, not years…

How fast/common/strong?

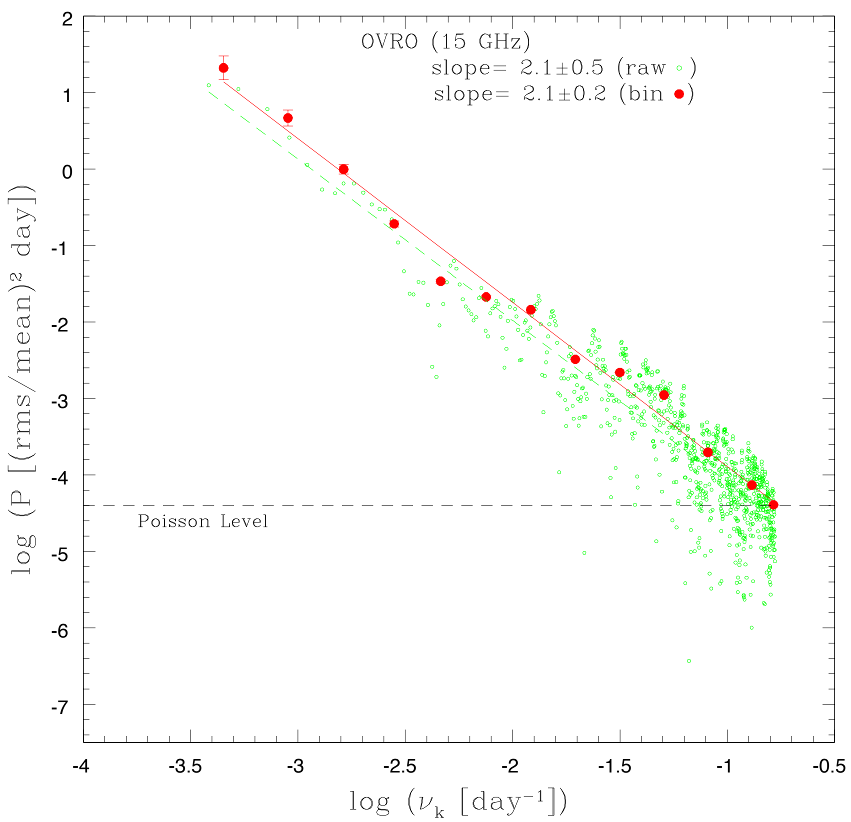


- Can we pinpoint the high-energy emission site from flux doubling timescales and MWL correlations?
- Can we infer robustly the jet parameters from modelling single isolated flaring events?

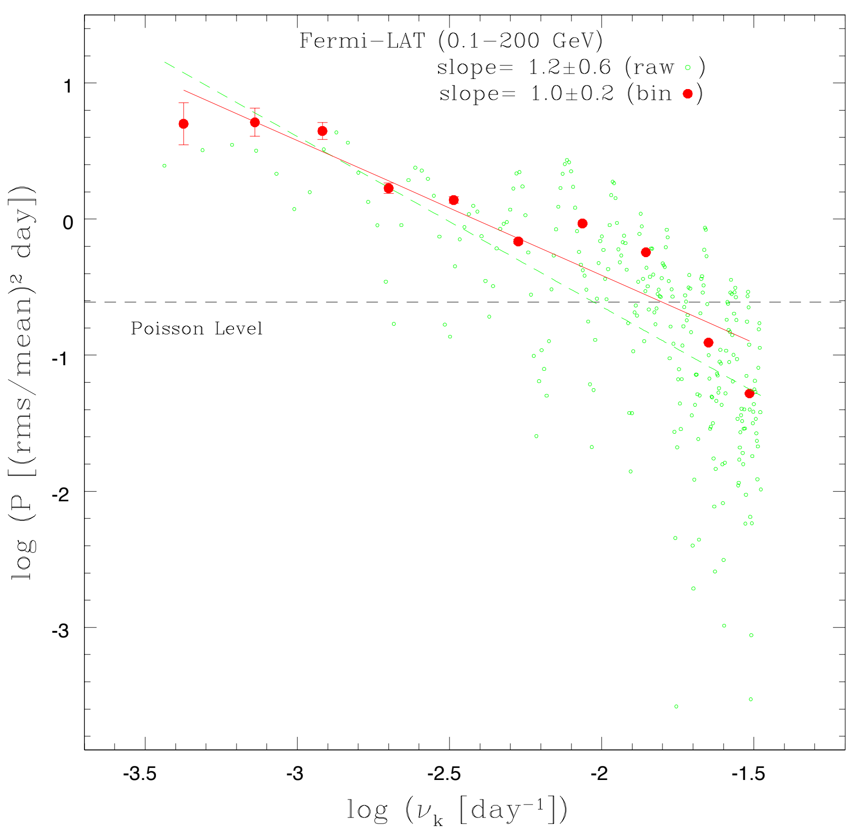
- inconclusive results, contradicting statements; various models applied;
- events claimed to be correlated, are often on different timescales, and have different variability amplitudes;

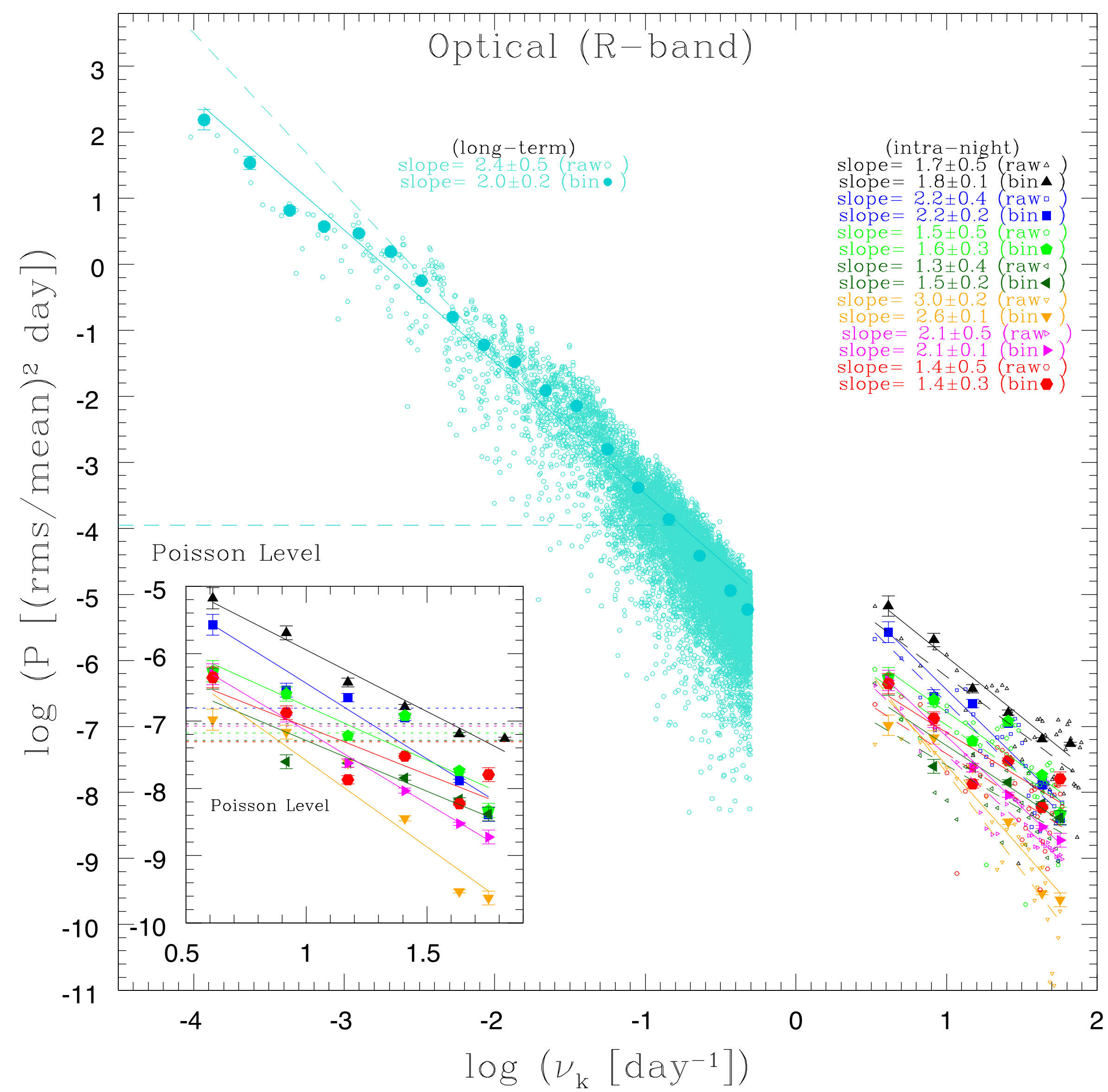
- is there any meaning behind “minimum variability timescales” inferred from single isolated flaring events as “flux doubling timescales”?
- can we say anything robust without continuous, long, and densely sampled MWL monitoring?

Red/pink Noise!

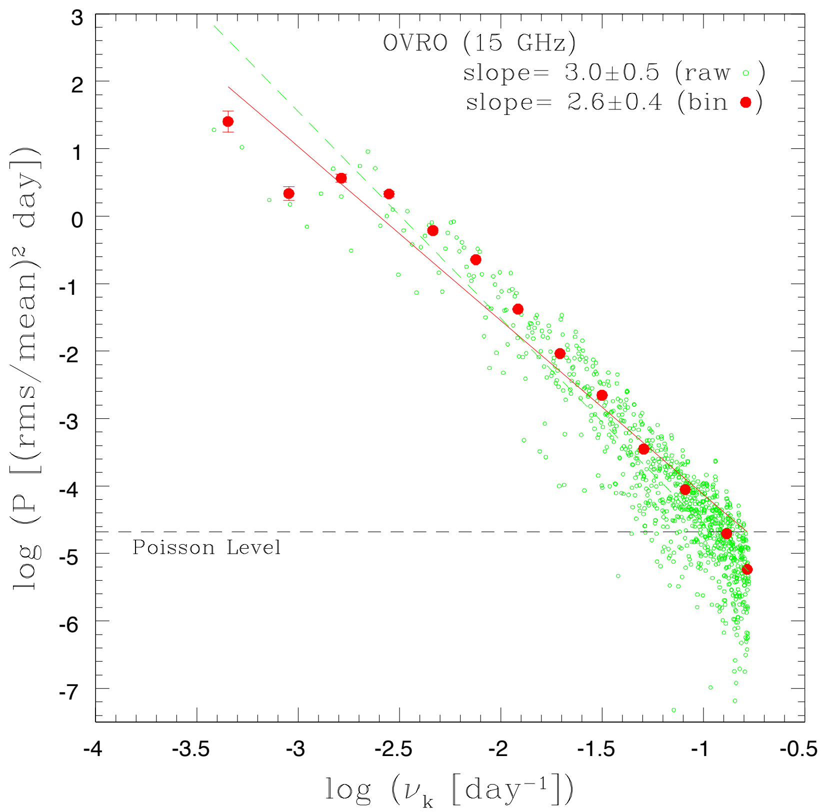


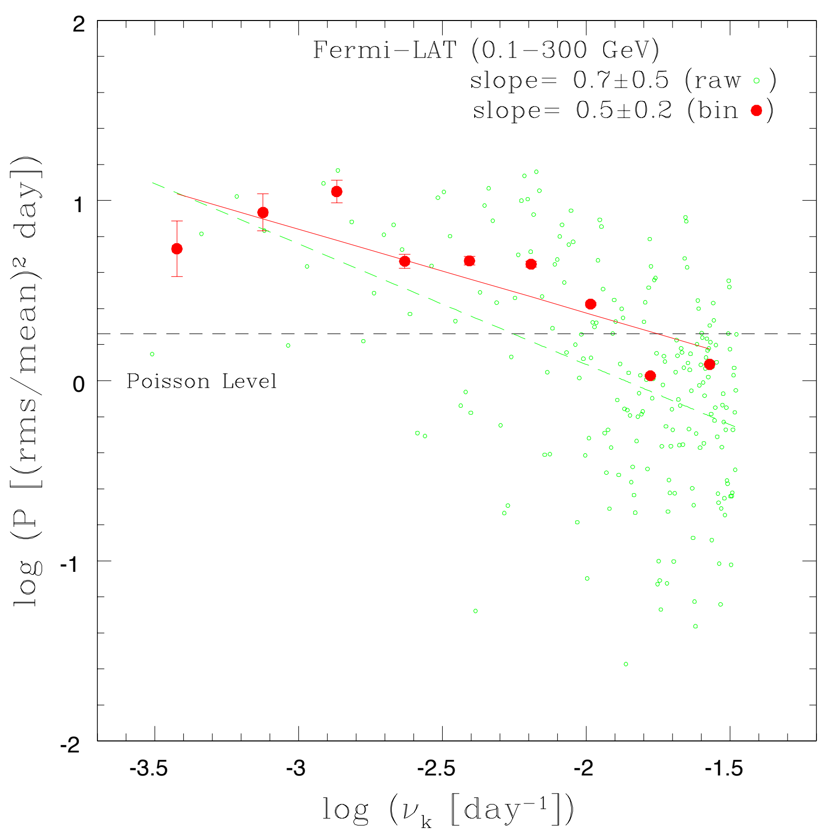
Goyal et al. 2016: variability analysis for the blazar PKS 0735+178 reveals a pure red noise ("random walk") type variability from hours to decades at radio and optical frequencies, with no "characteristic" timescales… interestingly, the PSD in gamma-rays seems more consistent with the pink noise ("long-memory") type variability!



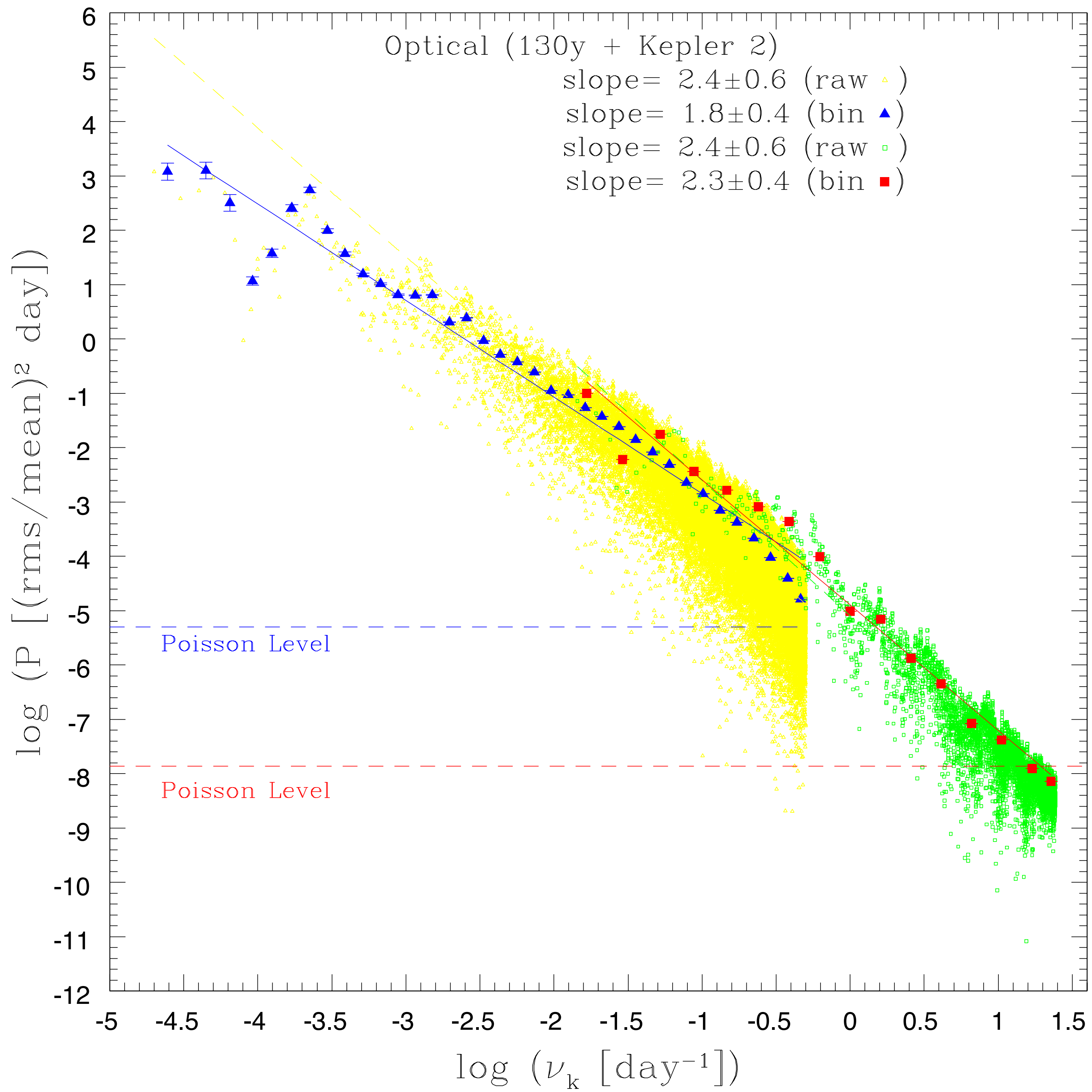


All the blazars are red/pink!



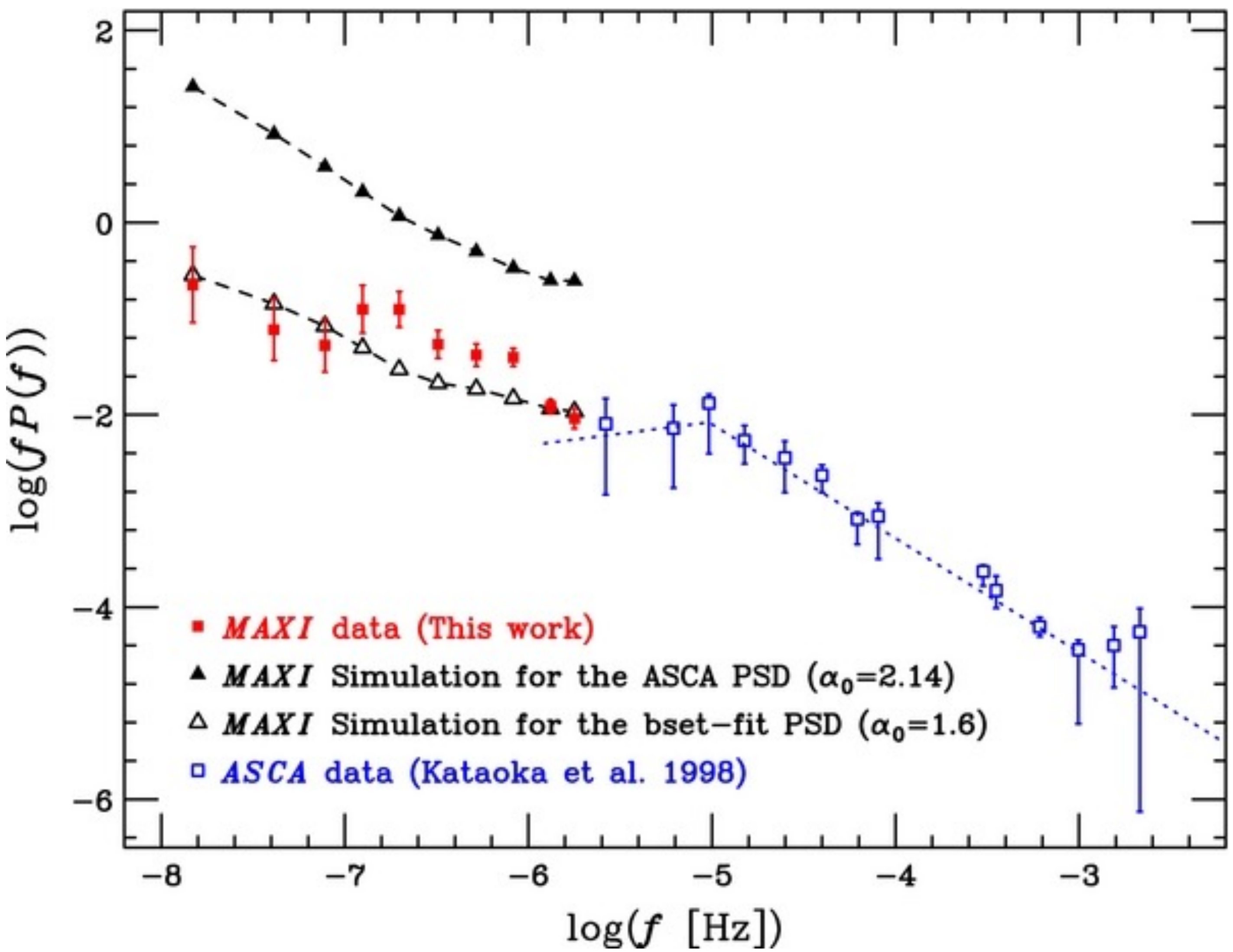


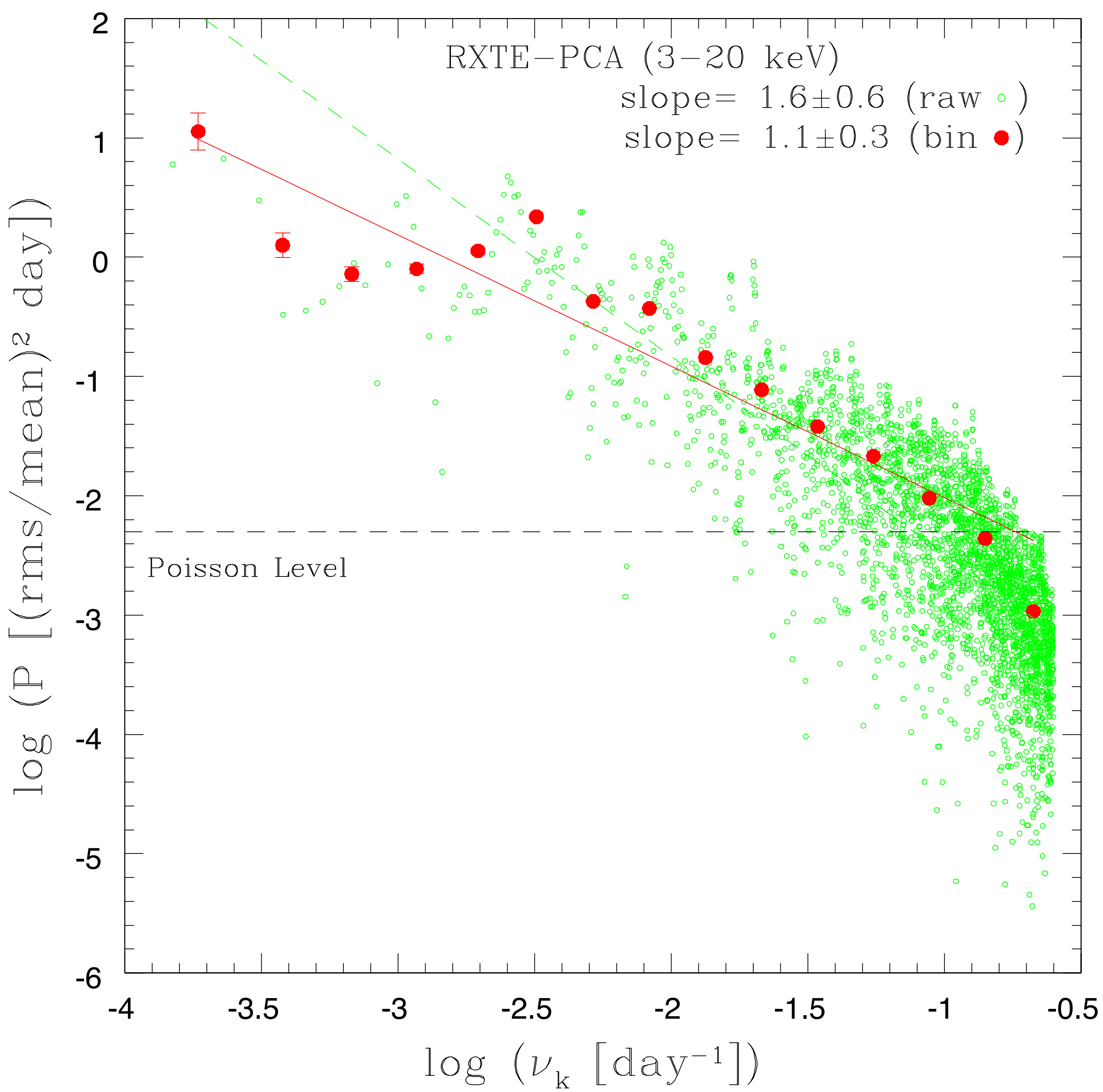
Goyal et al. 2016, in prep.: OJ 287



see also Chatterjee et al. 2013/15, Isobe et al. 2015, Sobolewska et al. 2014

Synchrotron vs. Inverse-Compton





<u>Isobe et al. 2015</u>: Mrk 421 in X-rays (synchrotron!)

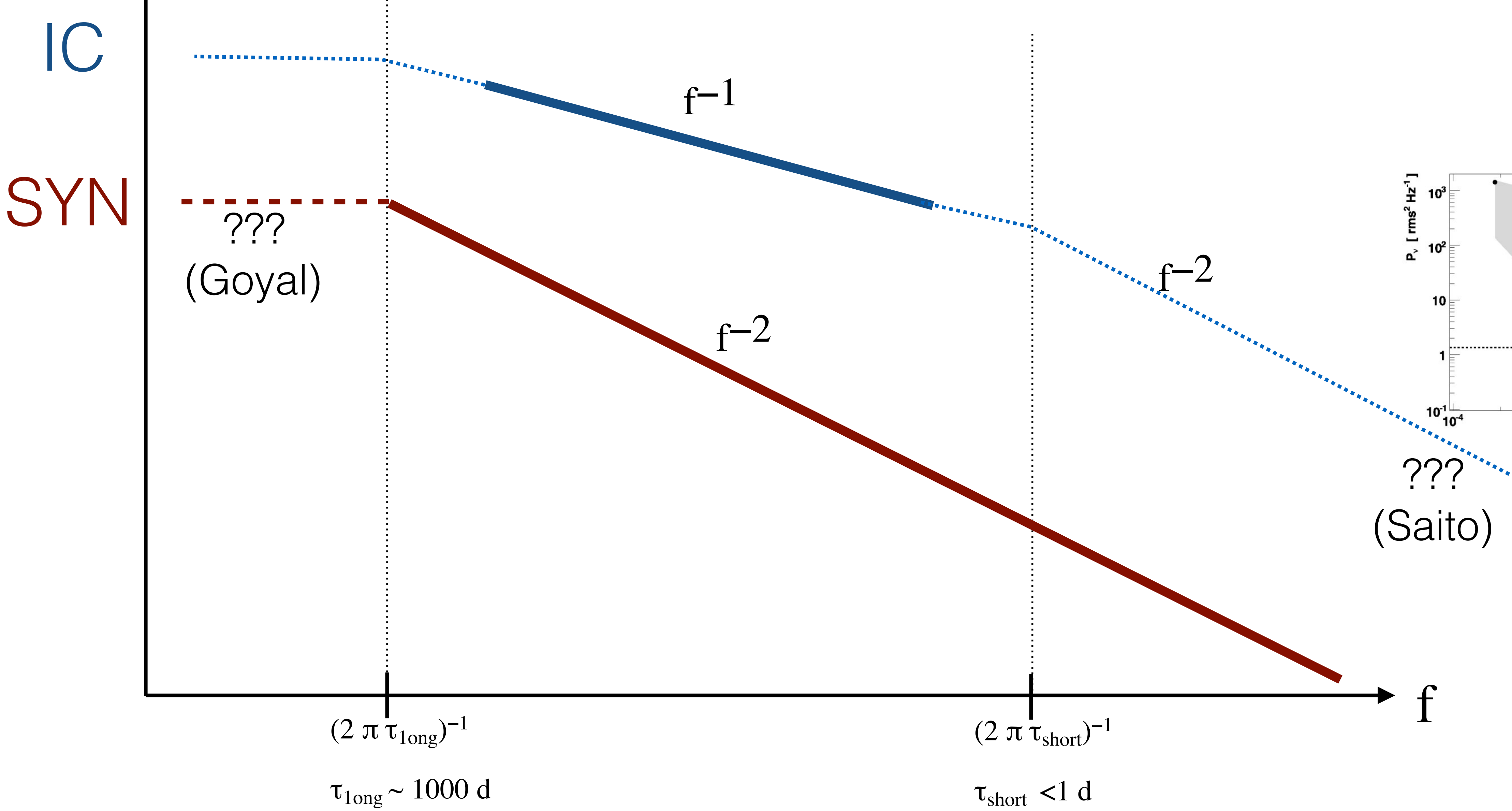
<u>Goyal et al. 2016, in prep</u>: PKS1510 in X-rays (IC!)

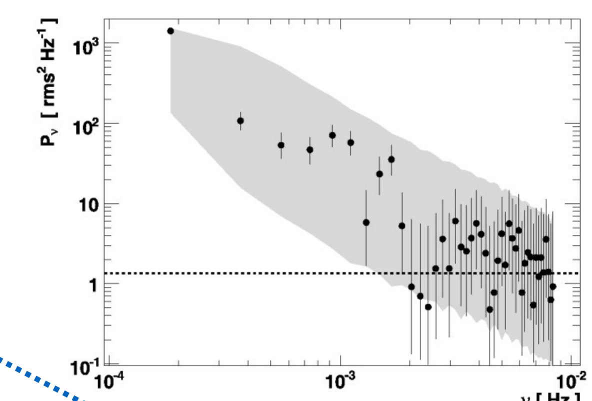
Stochastic process(es)

SYNCHROTRON: variability driven by an underlying **single stochastic process** with the relaxation timescale τ_{long} ~ 1000 d;

INVERSE-COMPTON: variability driven by **a linear superposition of two underlying stochastic processes** with relaxation timescales τ_{long} ~ 1000 d and τ_{short} < 1 d

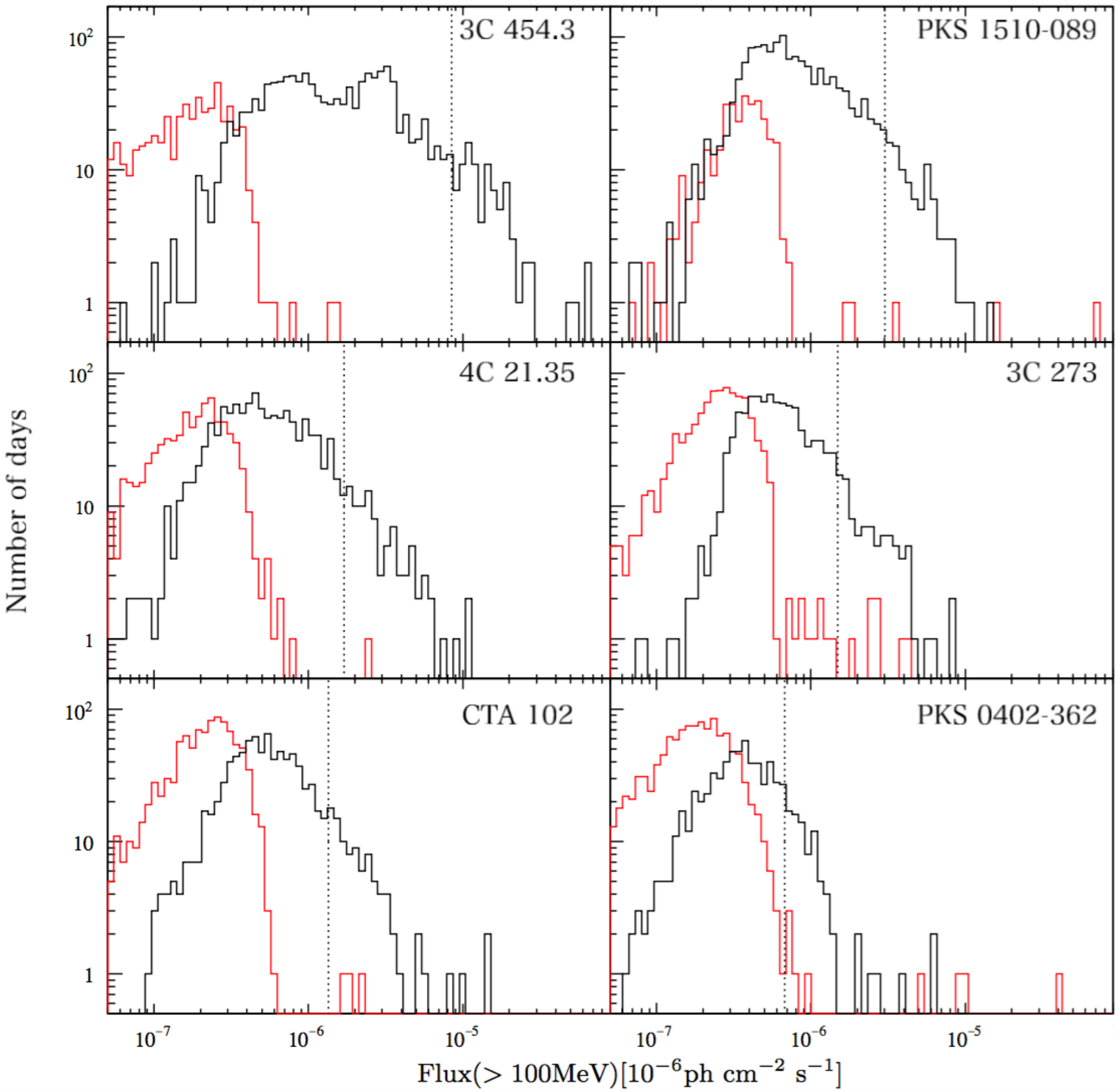
(see in this context Kelly et al. 2009, 2011, **Goyal et al. 2016, Bhatta et al. 2016**)





Short variability: Fermi-LAT

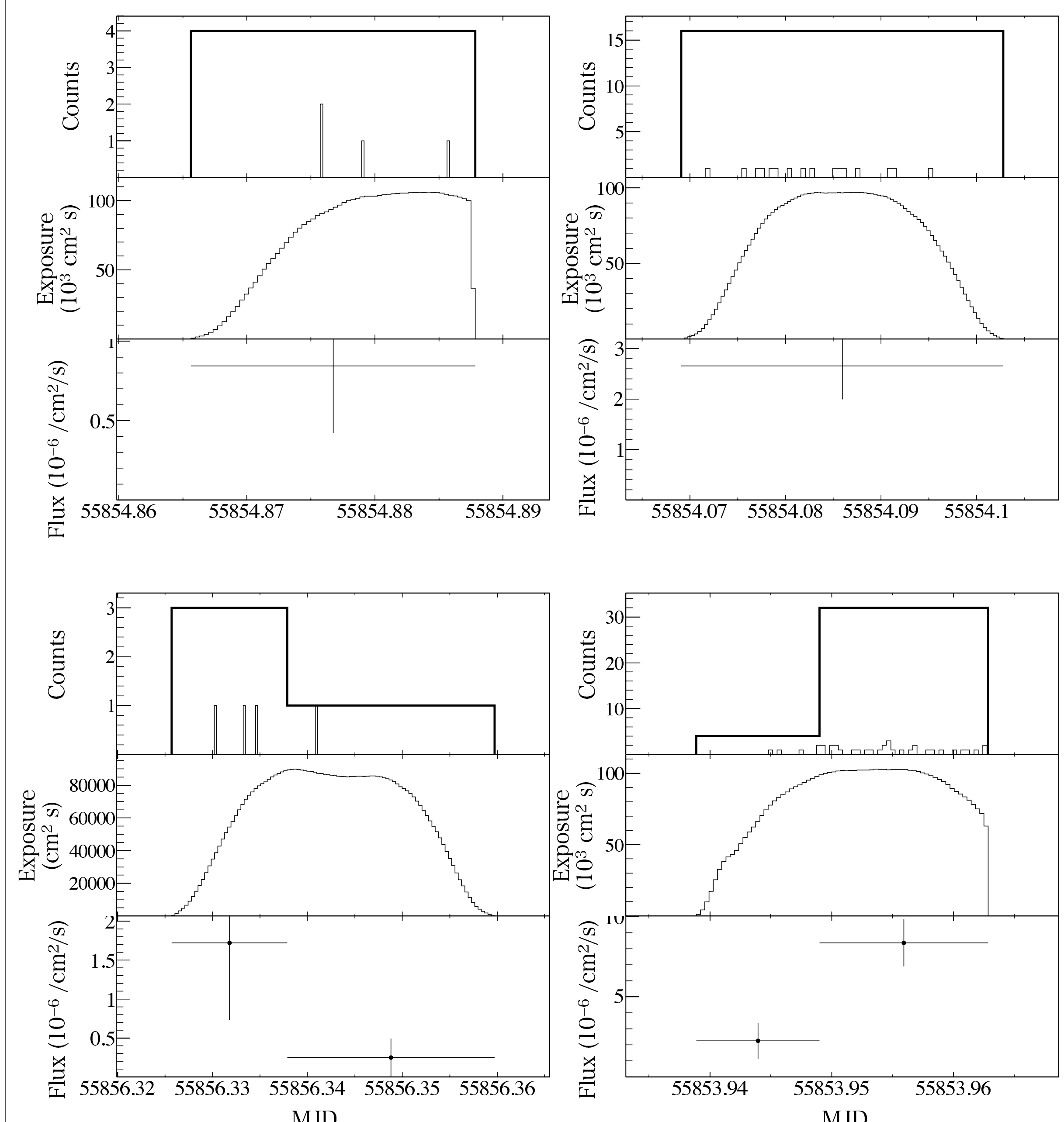
Saito et al. 2016



Duty cycles of the selected blazars created by Fermi-LAT daily flux of 62 months. Daily flux value was calculated via likelihood analysis over 100 MeV. Black histograms represent daily flux value when TS value was above 25. Red histograms represent 95% upper limit flux value when daily flux is under 25. Vertical dotted lines shows 5% flux threshold.

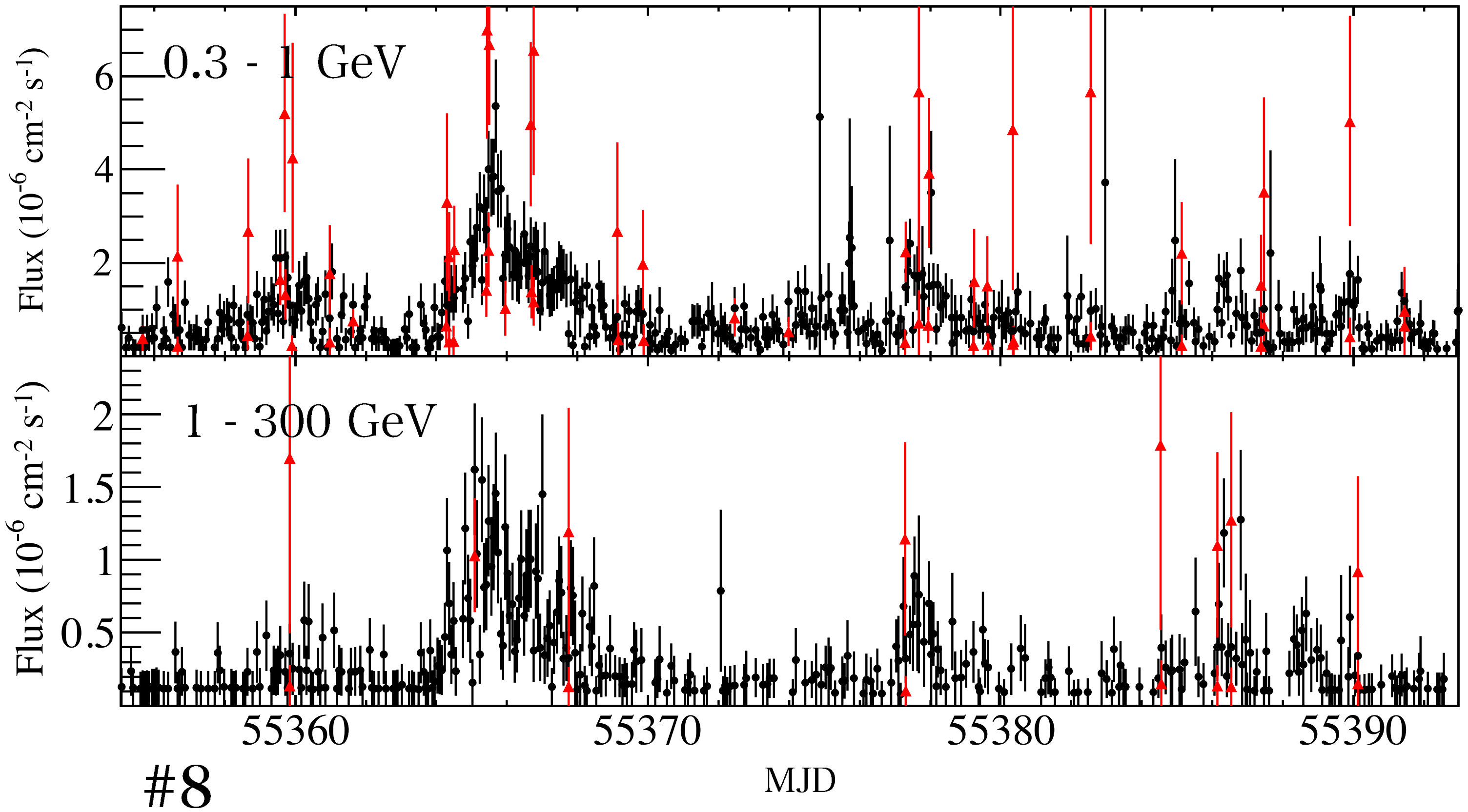
Analysis of very short timescales is limited by the photon statistics (even he brightest flares!)

Bayesian block analysis applied to search for a time variability within sub-orbit timescales of the Fermi-LAT (typically ~ 30 minutes).

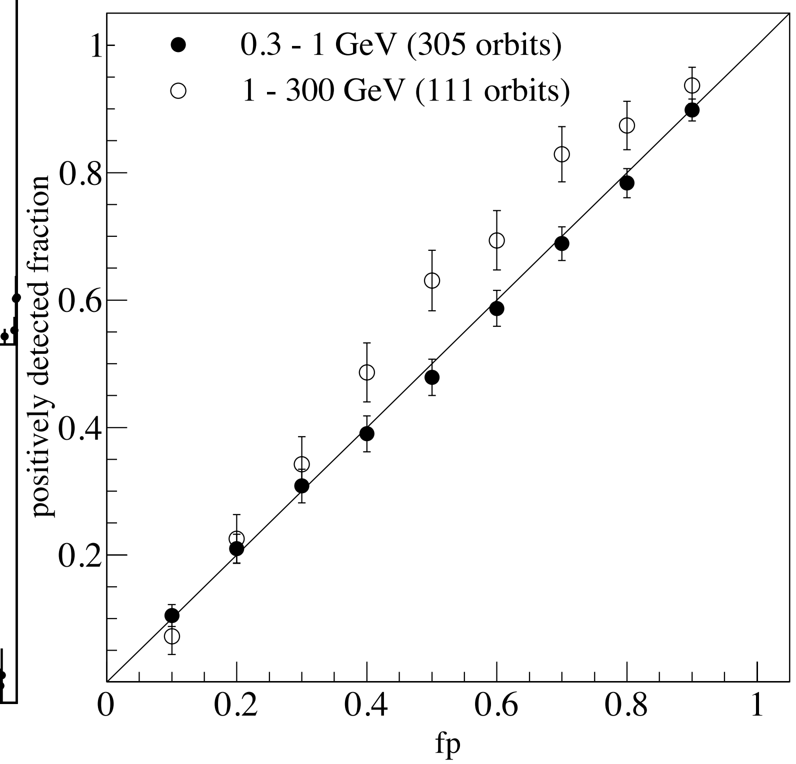


No significant variability!

#7



Saito et al. 2016



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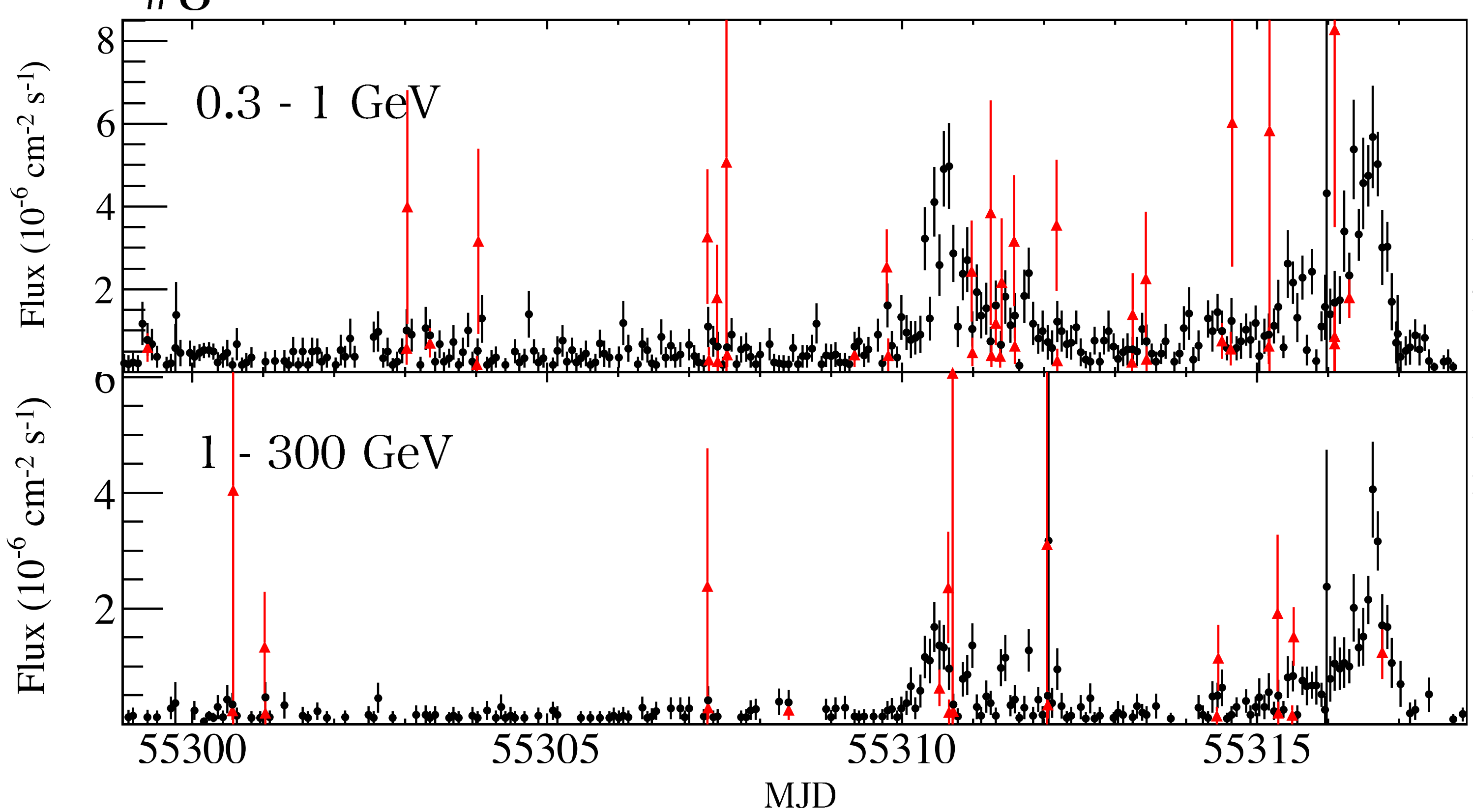
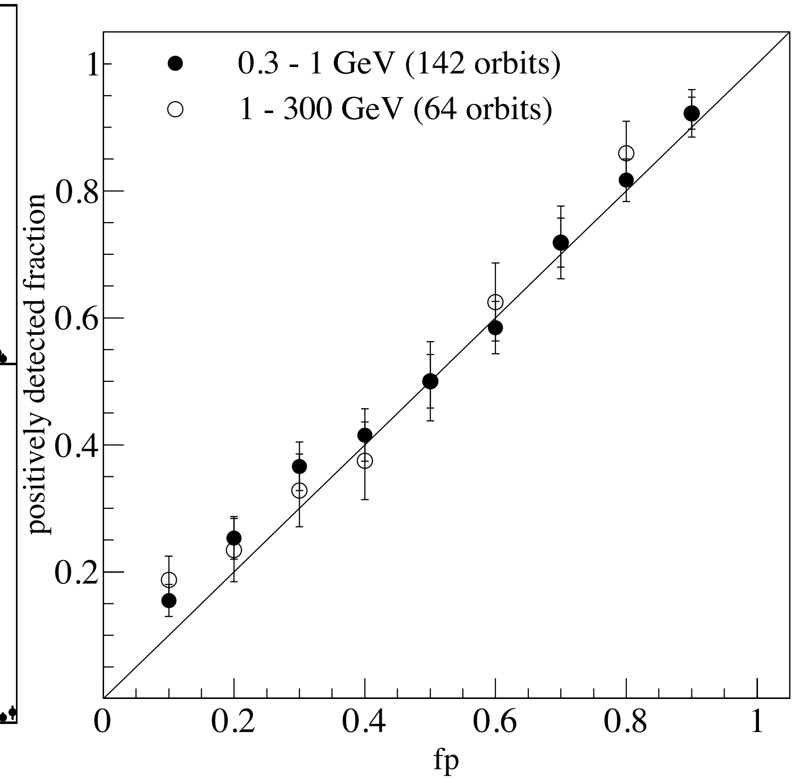
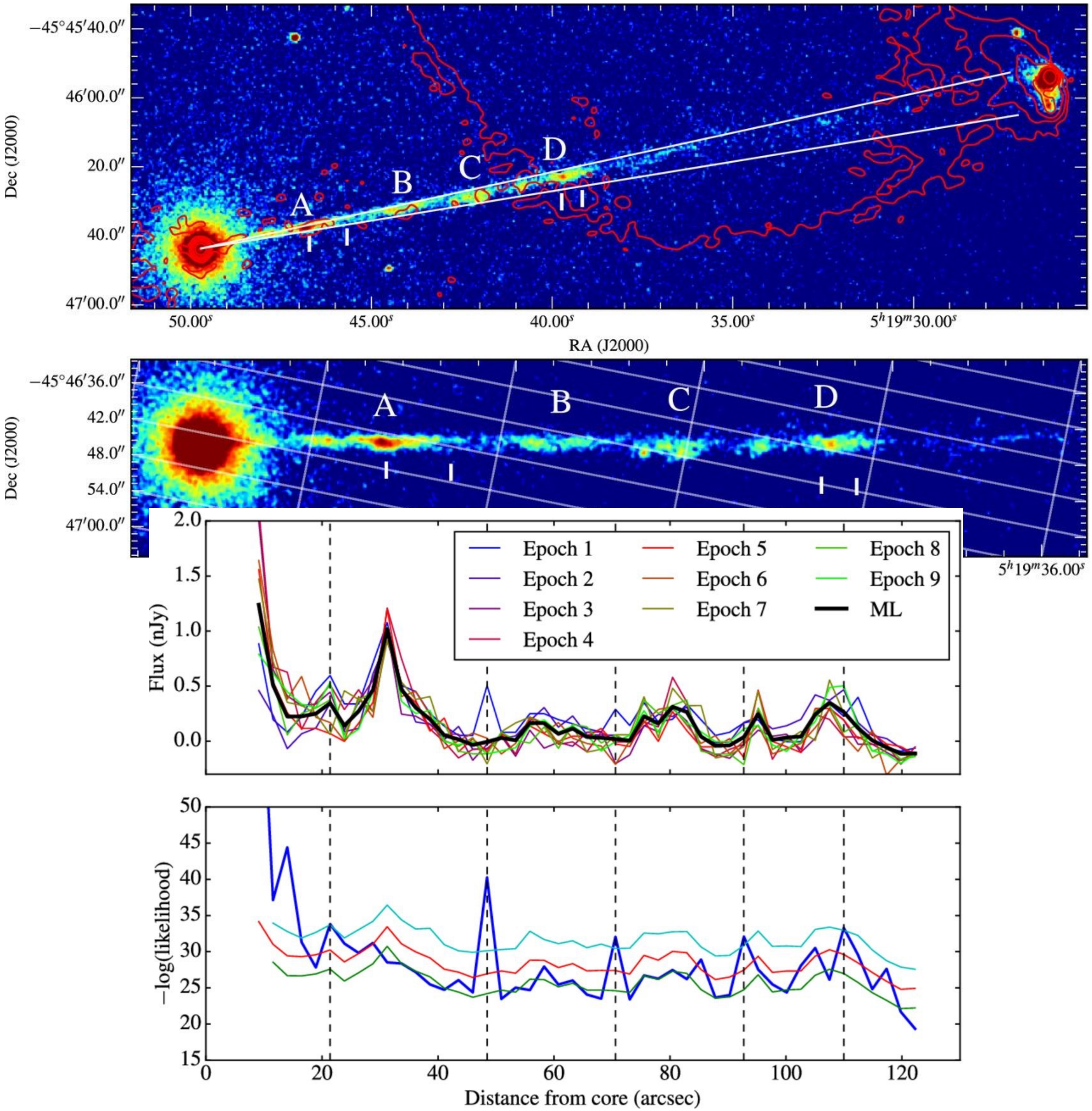
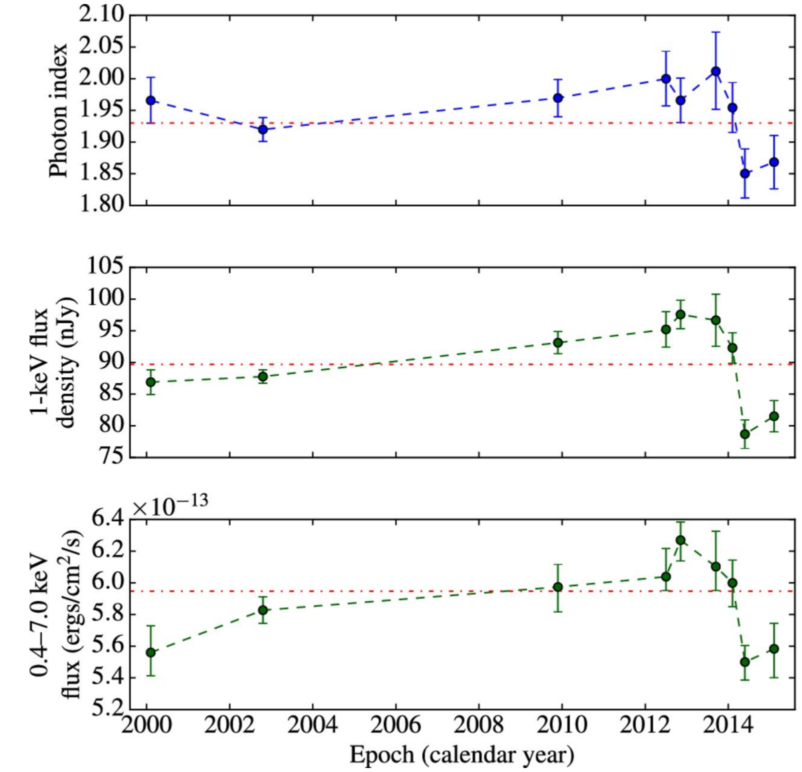




Large-scale quasar jets

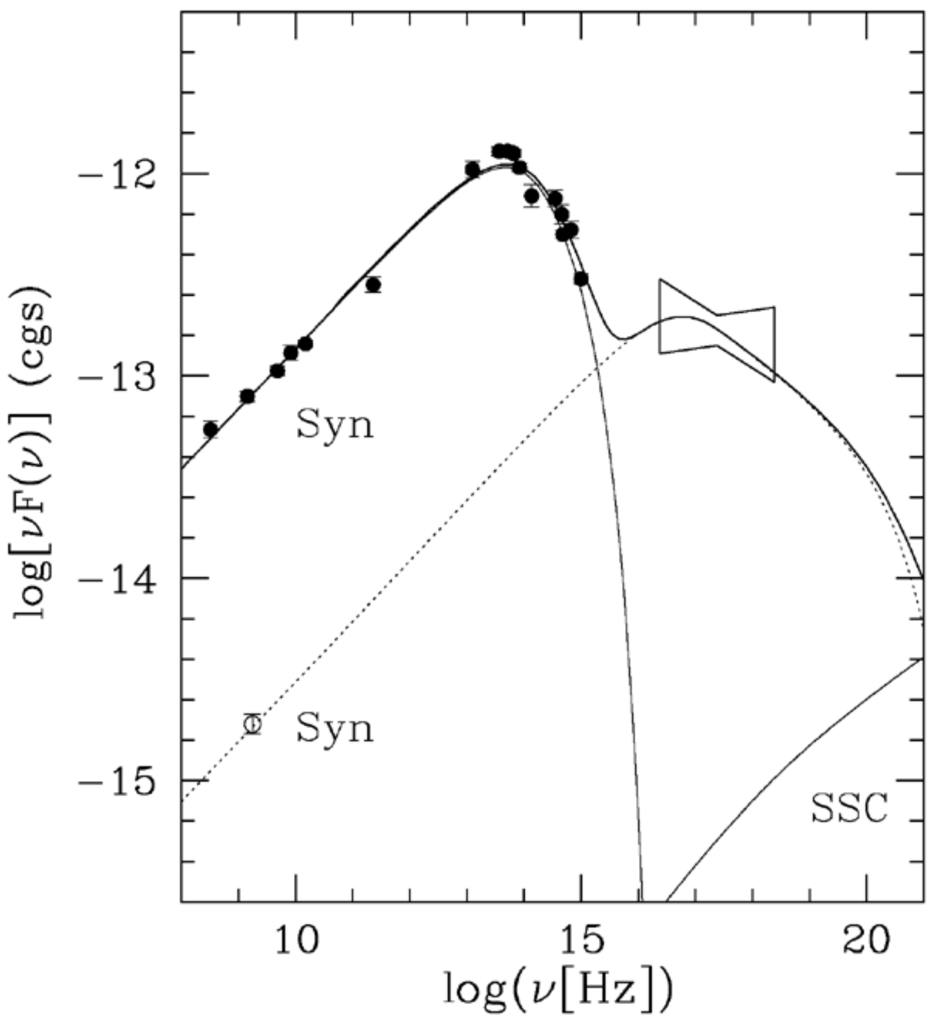


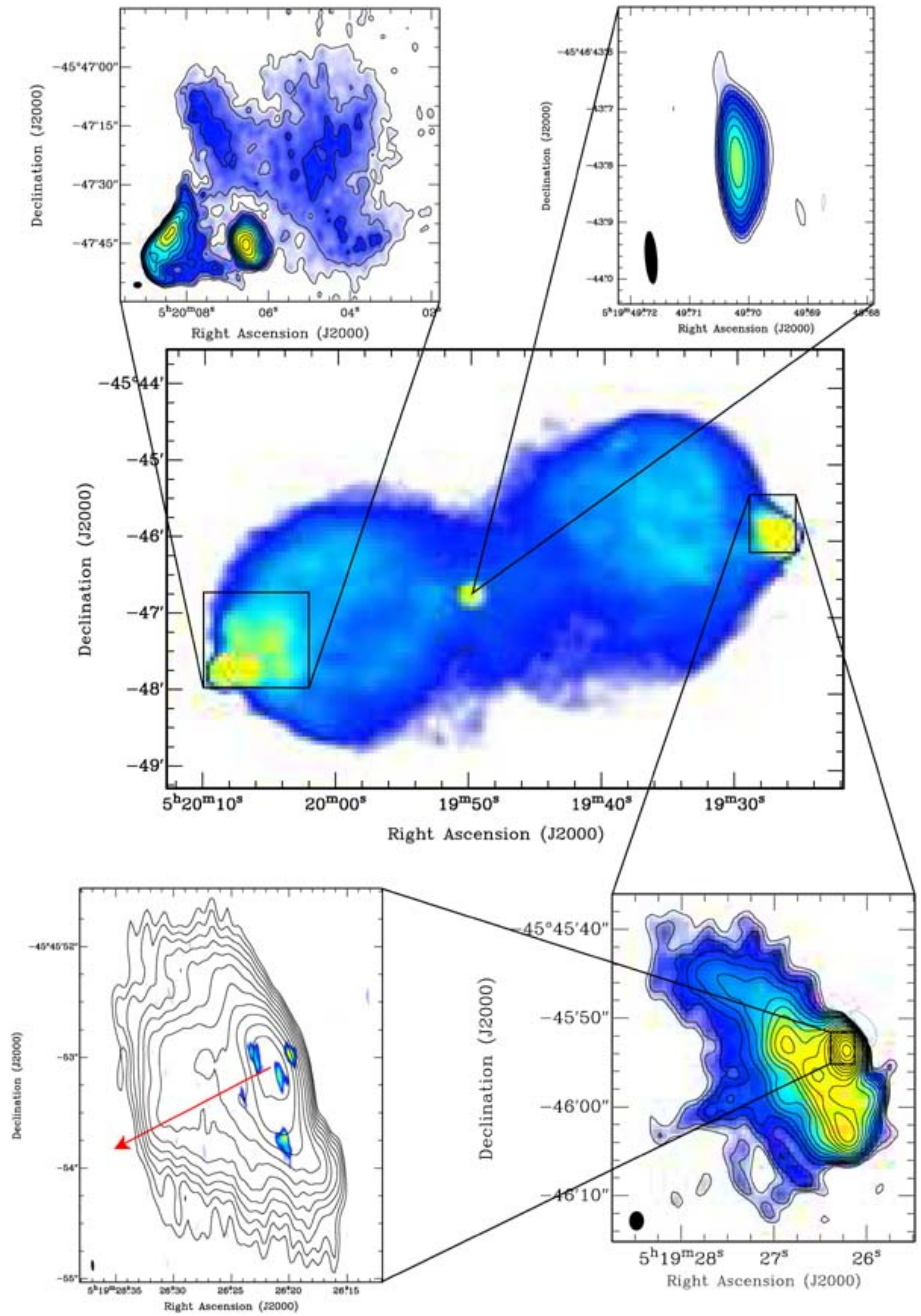


Marshall et al. 2010,
Hardcastle et al. 2016:

~1000yr variability expected,
~1yr variability observed!

Small-scale substructure

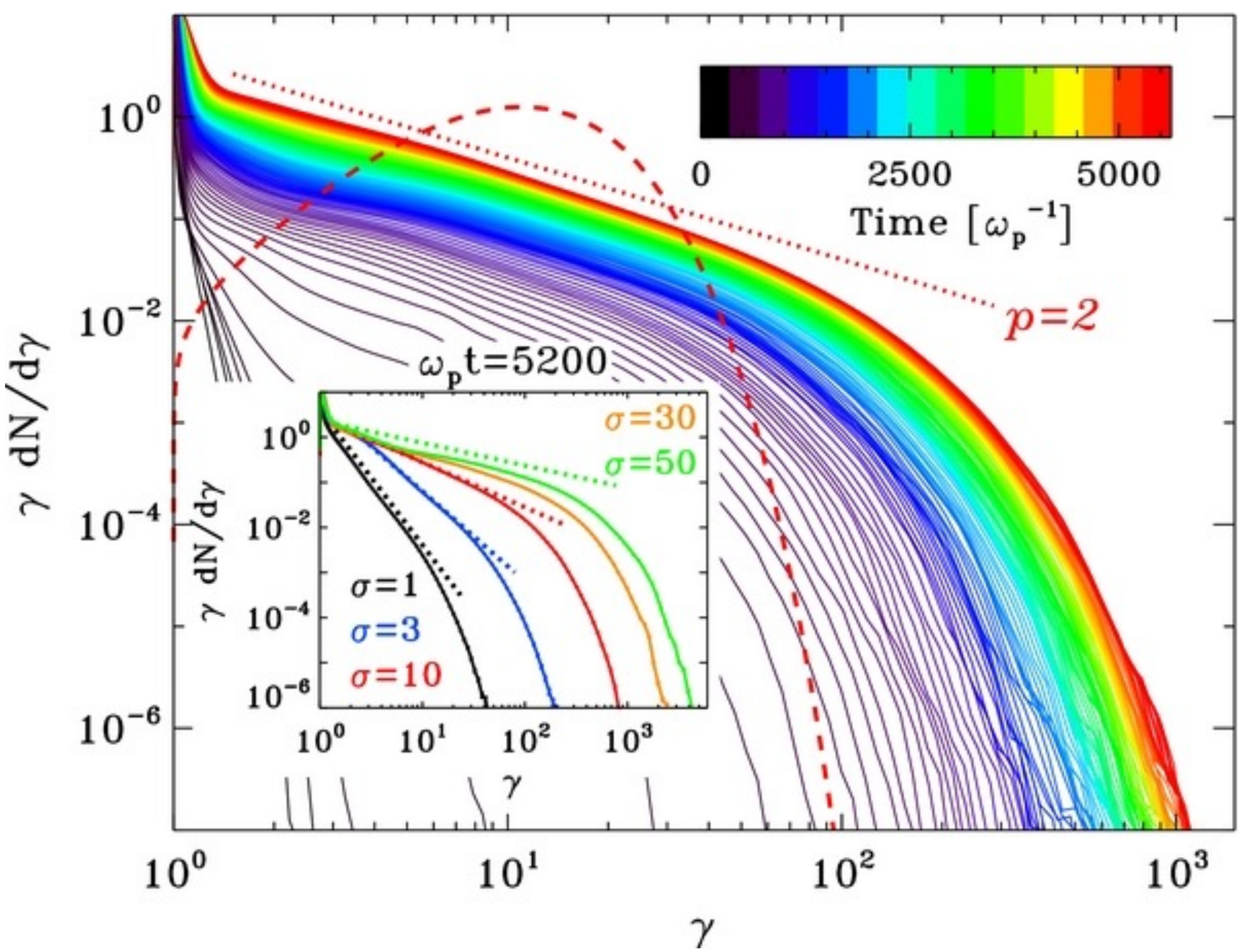




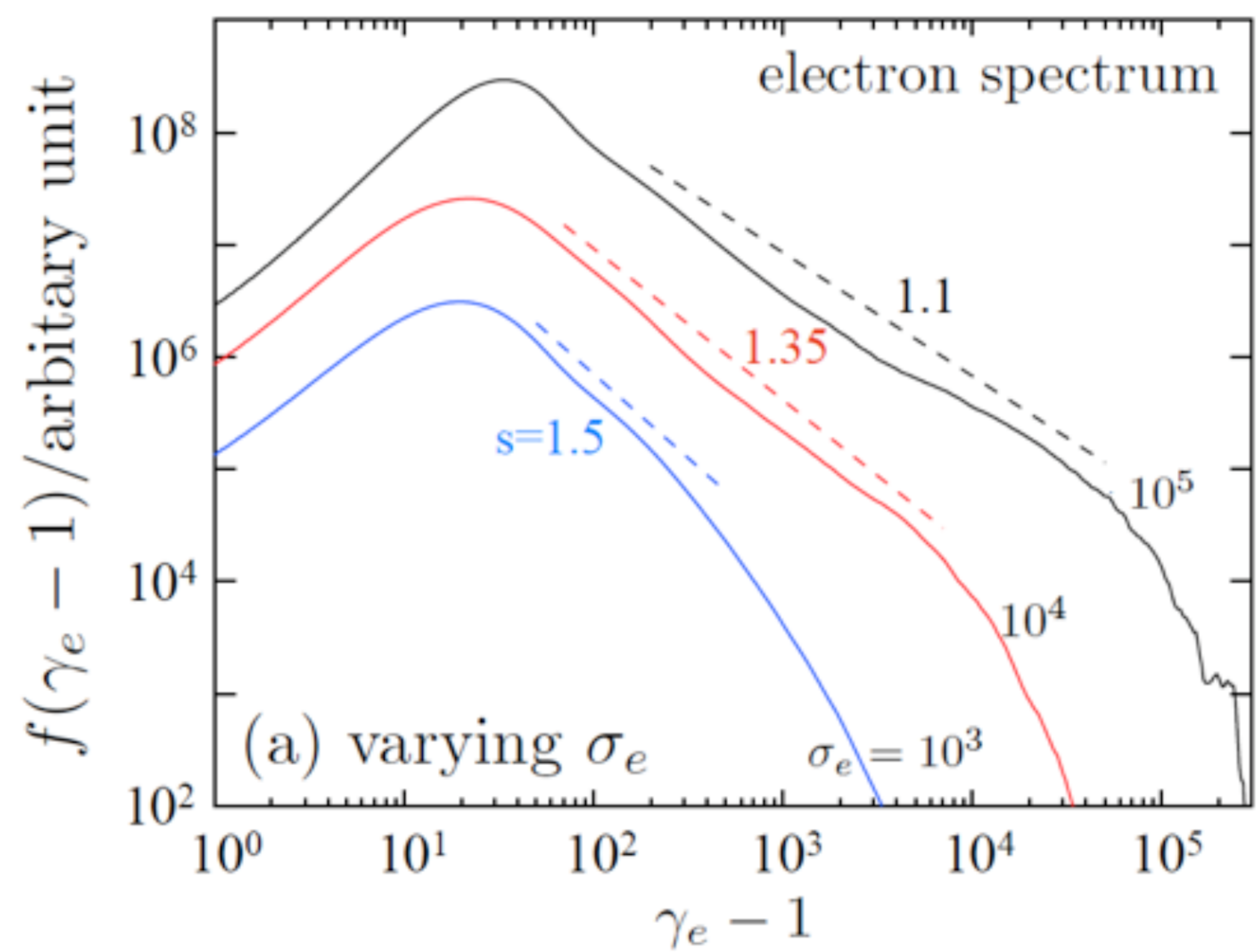
Tingay et al. 2008:
two distinct electron populations:
low-energy population/extended emission zone, and
high-energy population/compact emission zones
(consistently with the X-ray variability observed)

Relativistic reconnection?

Sironi et al. 2014-16



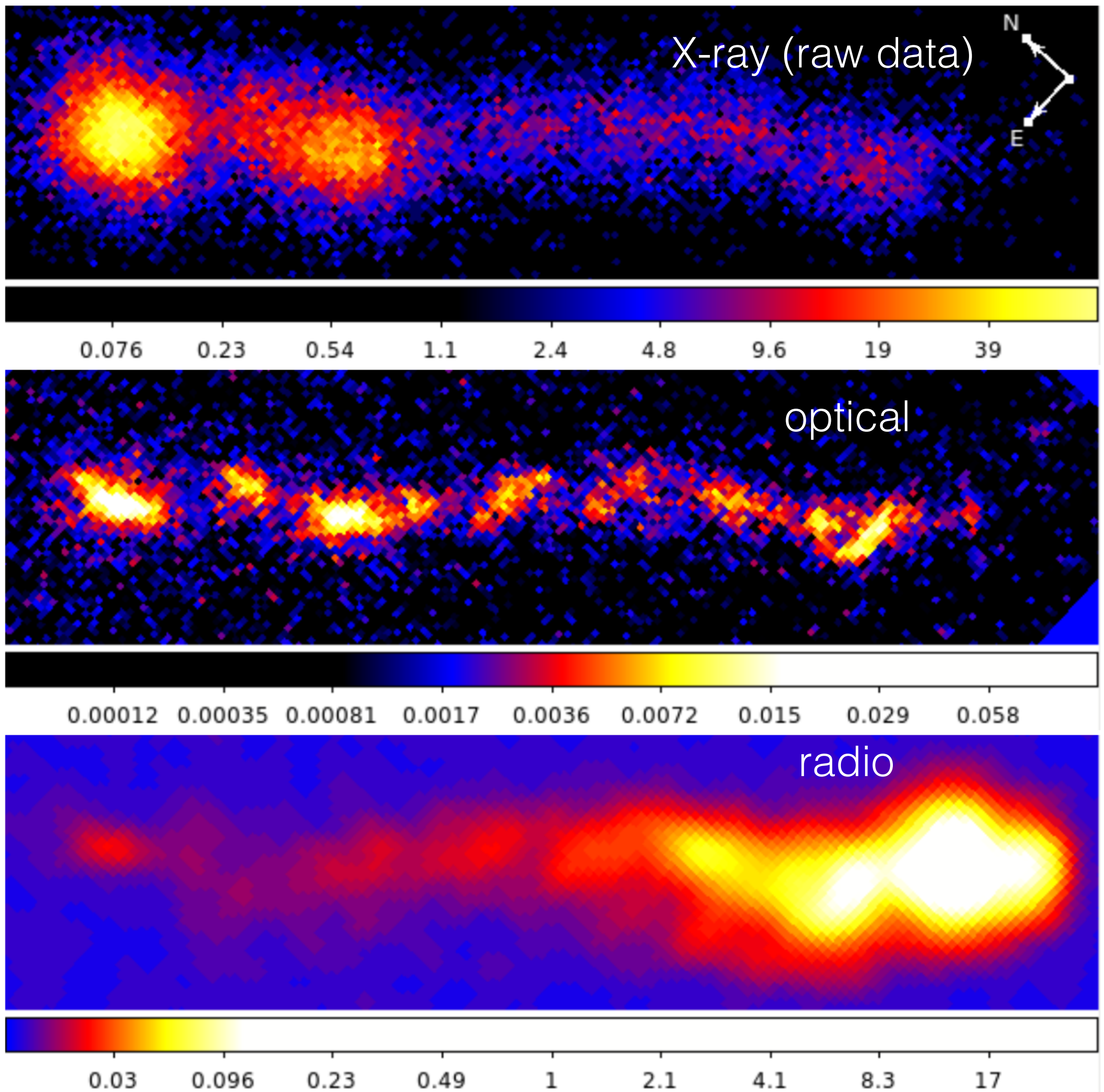
Guo et al. 2014-16

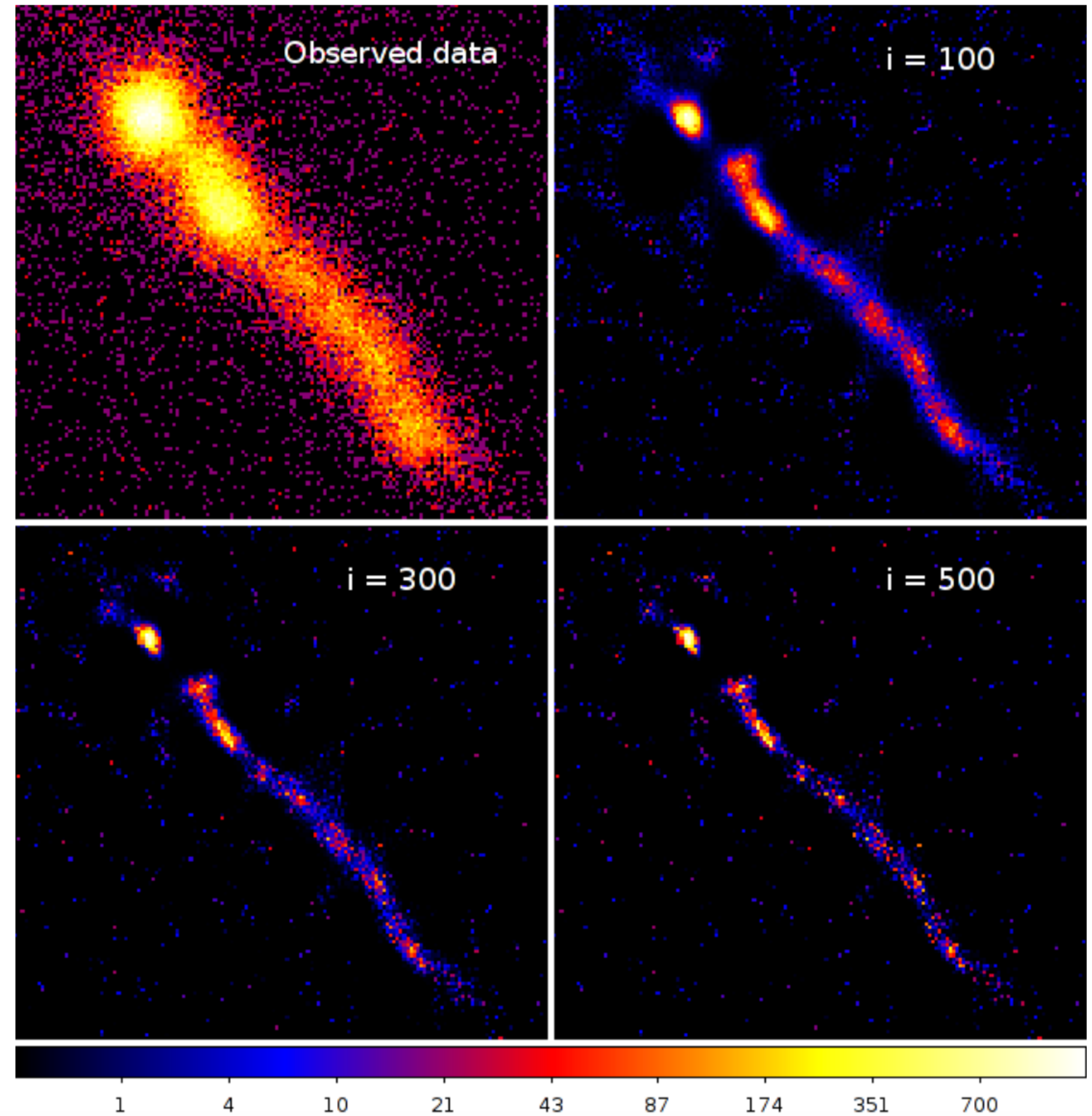


OR turbulent acceleration?
(see Stawarz & Petrosian 2008, Kakuwa et al. 2015/16)

“OR” or “AND”?

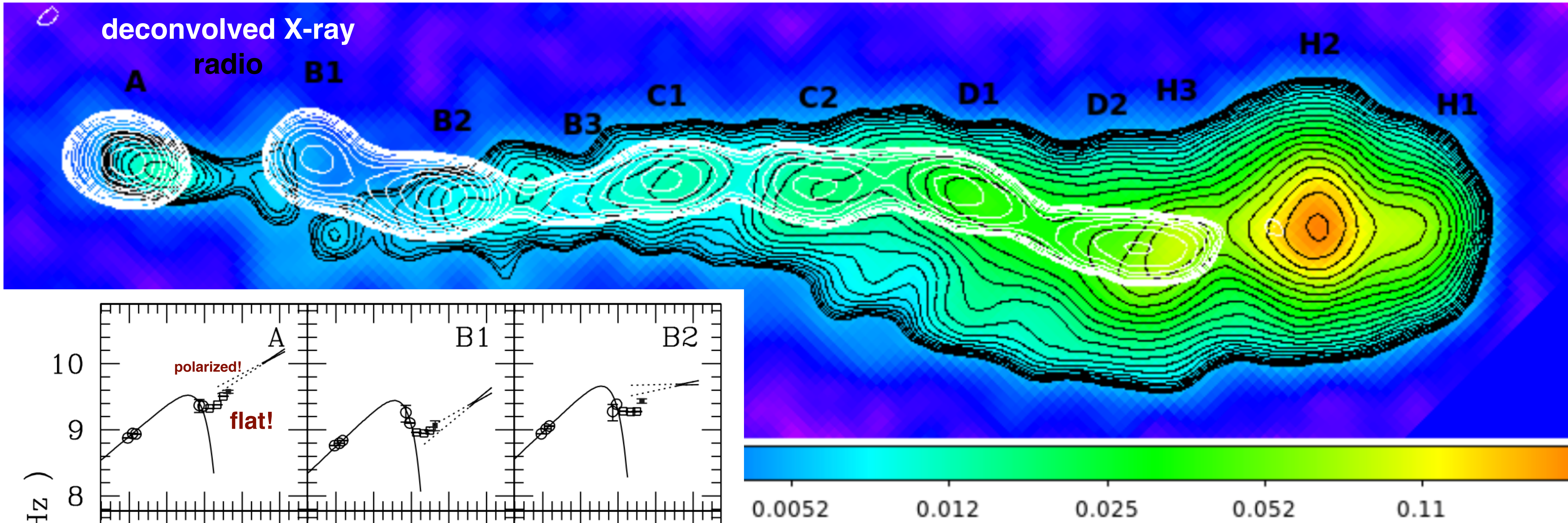
MWL jet structure

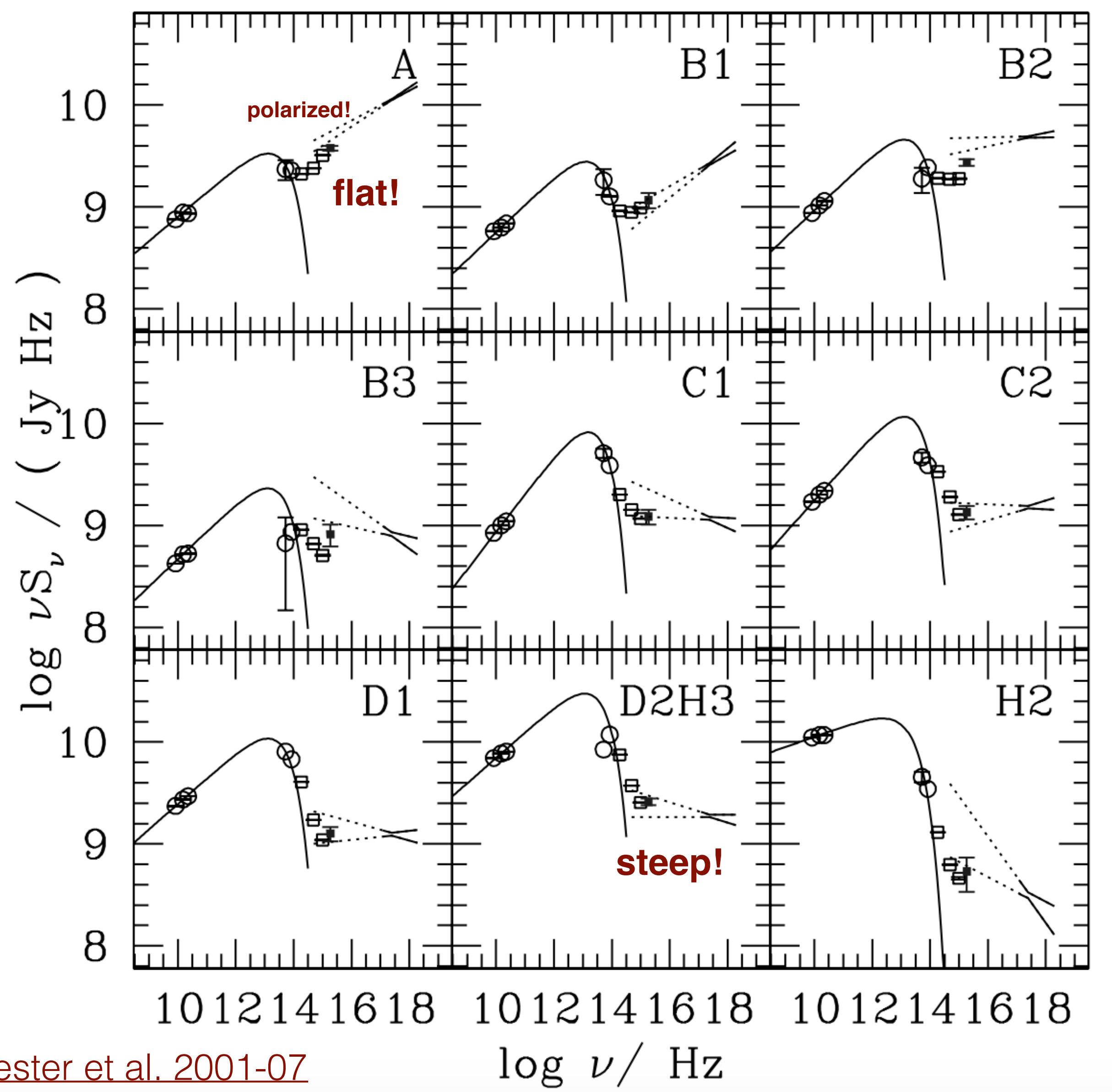




Marchenko et al. 2015: analysis of all the archival observations of 3C273 jet with Chandra, HST, and VLA; precise modelling of the Chandra and HST point spread functions, Lucy-Richardson Deconvolution Algorithm applied to the Chandra data.

Spine/sheath structure





Jester et al. 2001-07

Marchenko et al. 2016:

two distinct synchrotron emission components; radio outflow is wider than the deconvolved X-ray/ultraviolet jet; the intensity peaks of the X-ray knots are located systematically upstream of the corresponding radio intensity peaks.

Jet spine with **σ** decreasing from **>>1** to **<1**?

Magnetic structure and σ

For the purely toroidal magnetic field in sheared cylindrical jet, the only non-zero component of the current number density (along the jet axis)

$$J' = \frac{c}{4\pi r'}\ \partial_{r'}\left(r' B'_\phi\right)$$

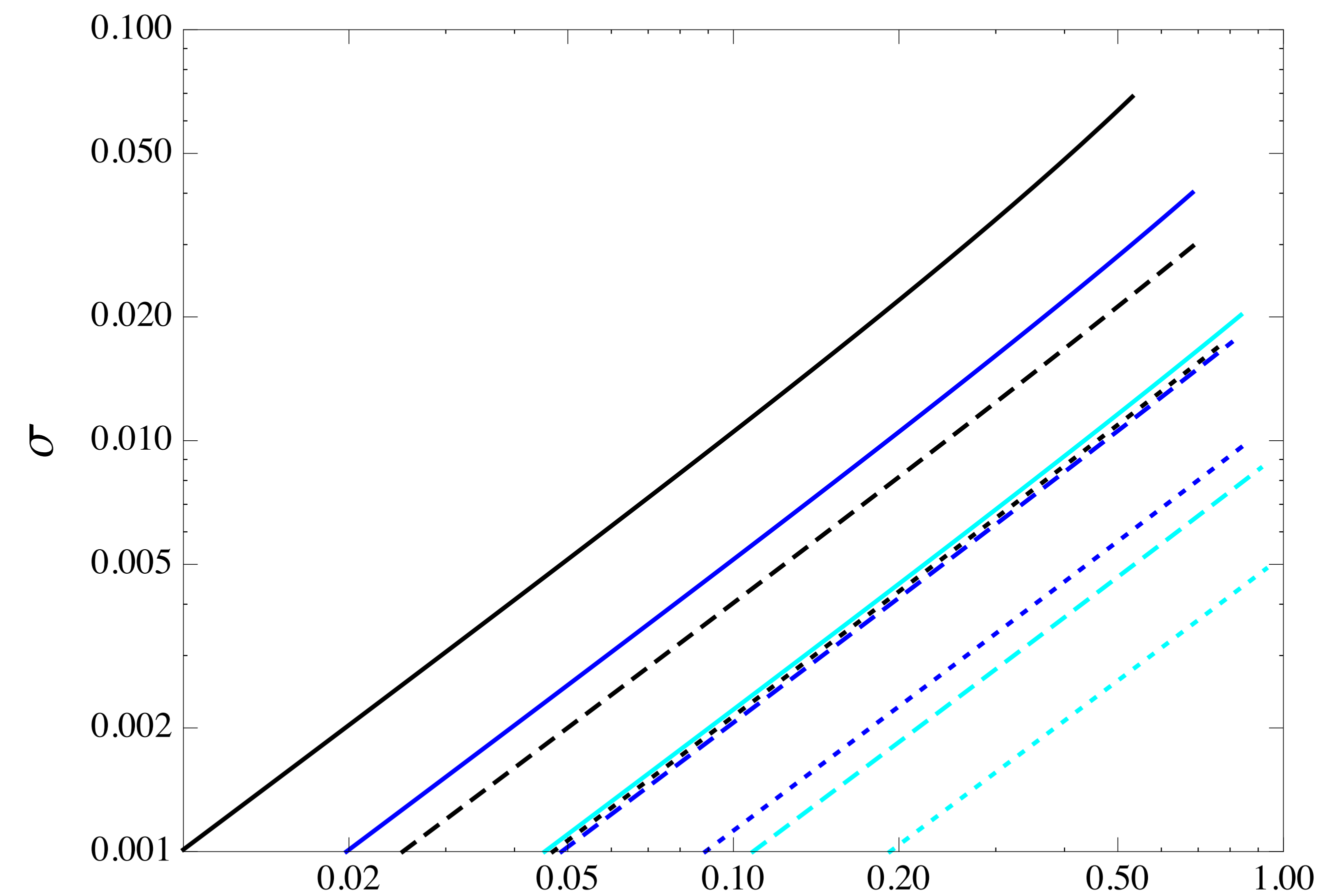
Magnetohydrostatic equilibrium condition gives the jet radial profile of the particle pressure

$$\partial_r P = -\frac{1}{8\pi r^2}\ \partial_r\left(\frac{r^2 B_\phi^2}{\Gamma^2}\right)$$

with such, σ < 1 !

Highly magnetised jets (σ>1) must contain a significant poloidal magnetic field component (maybe just a narrow spine? good against kink instabilities anyway)

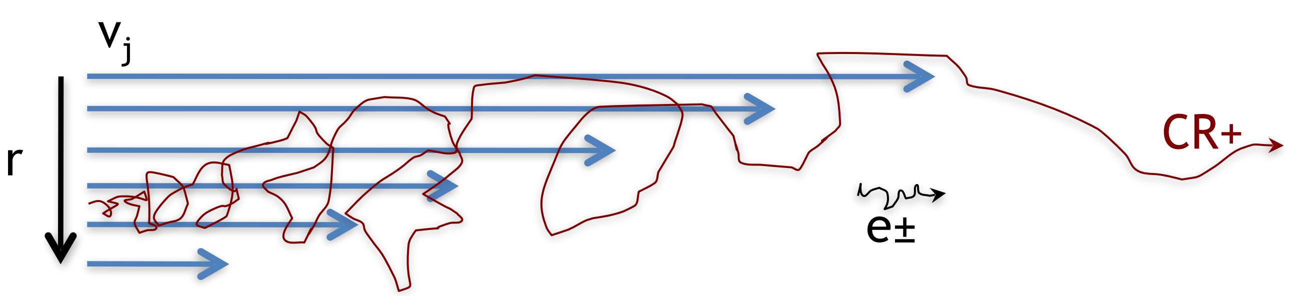
Stawarz, Begelman, et al., in prep



$$q \equiv \frac{B_j^2}{8\pi\, P_j} \equiv \frac{U_B(1)}{P(0)}$$

$$\sigma \equiv \frac{L_B}{L_p} = \frac{1}{16\pi}\,\frac{\int dr\, r\, \beta\, B_\phi^2}{\int dr\, r\, \beta\, \Gamma^2\, P}$$

Shear layers & acceleration



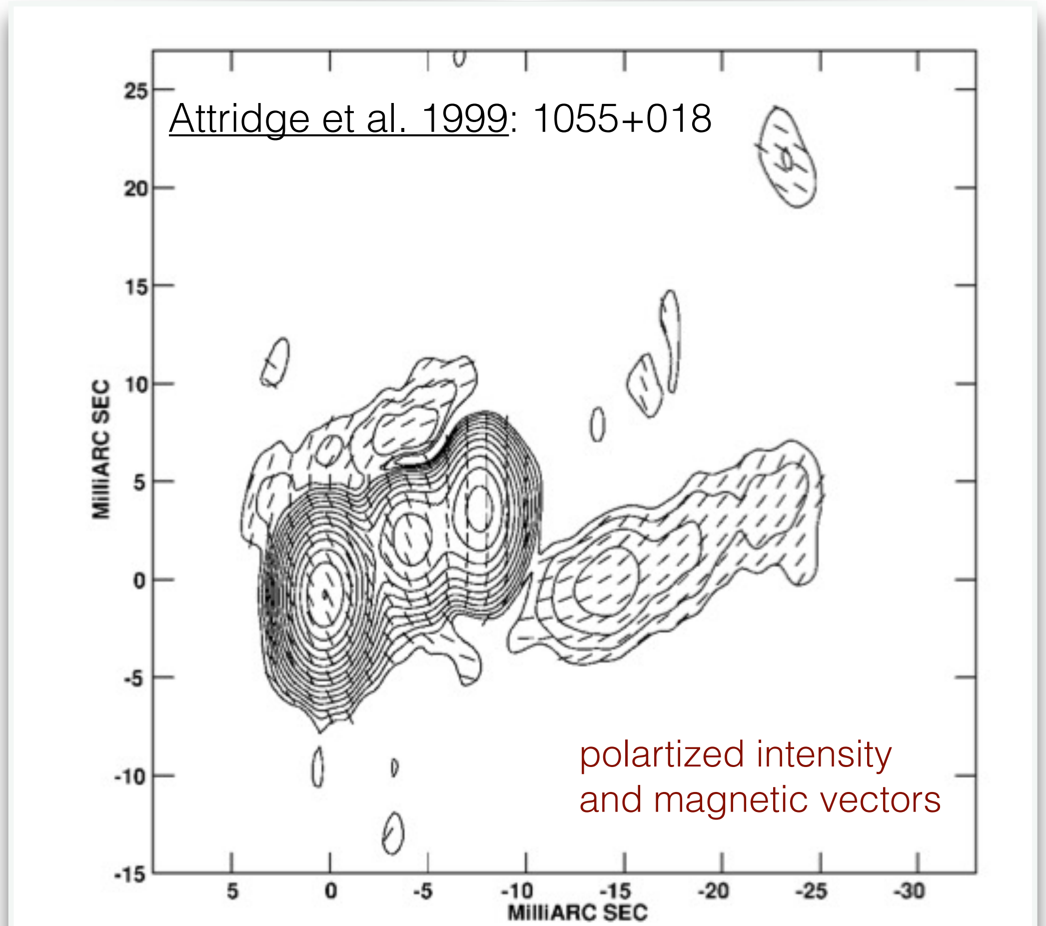


FIG. 1b

$$\tau_{\rm shear}(r) \simeq 3\,\frac{c}{\lambda(\gamma)}\,\frac{1}{\left(\Gamma_j^2(r)\,\frac{\partial v_j(r)}{\partial r}\right)^2}$$

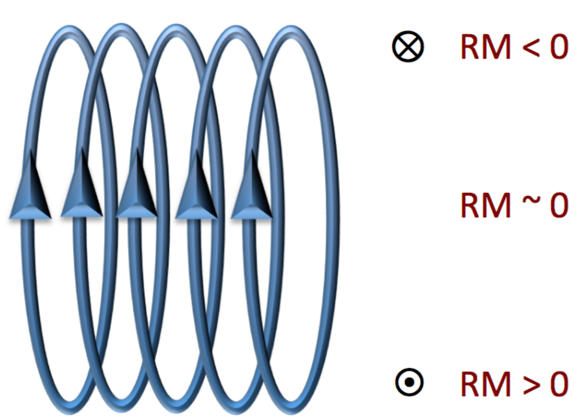
inversely proportional to particle mean free path λ(γ)!
(Ostrowski 2000, Stawarz & Ostrowski 2002)

$$\tau_{\rm turb}(r) \simeq 3\,\frac{\lambda(\gamma)}{c}\,\frac{c^2}{v_A^2(r)}$$

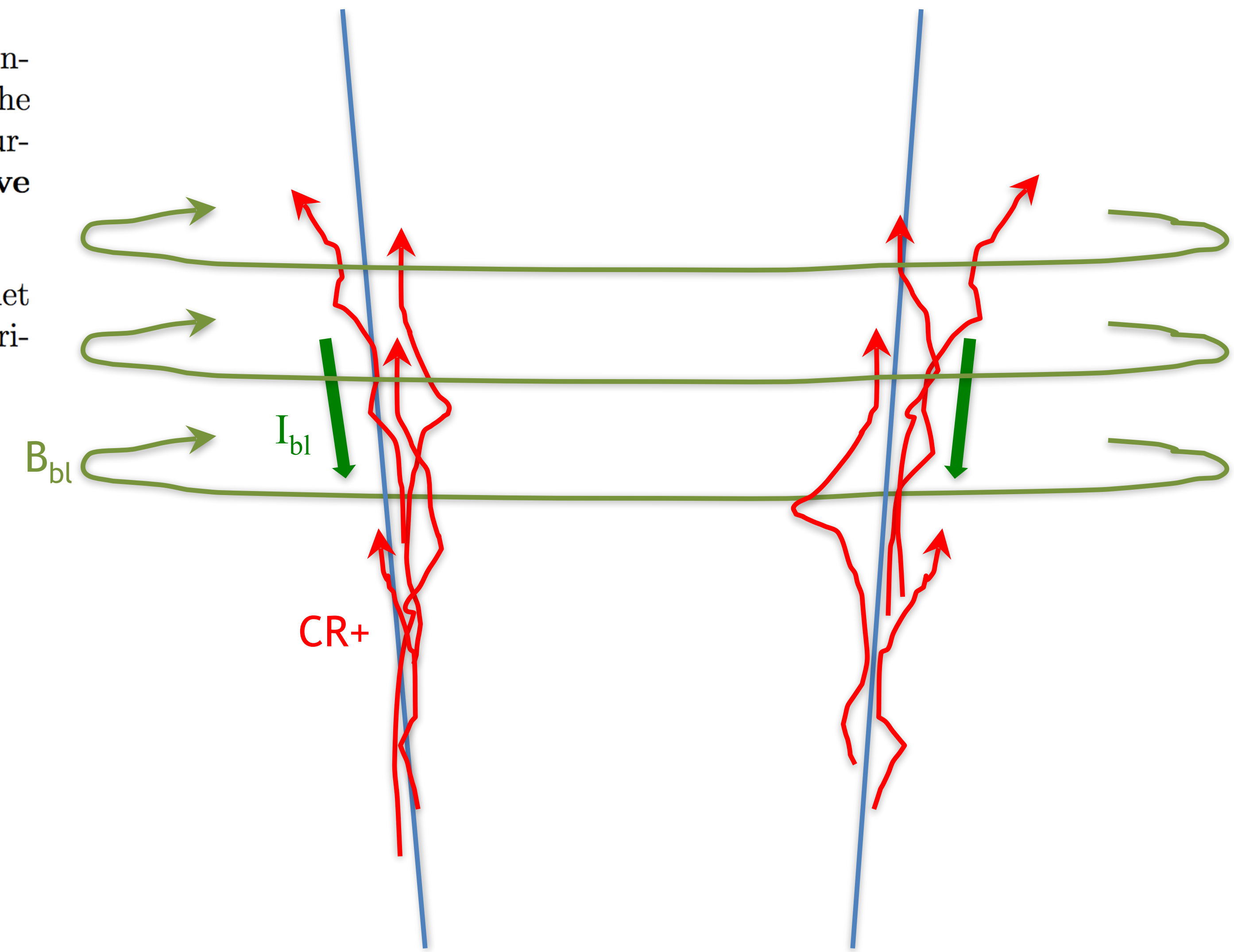
Boundary layer current

Shear acceleration within turbulent boundary layers of relativistic jets:

- operates preferentially on hadronic CRs rather than $e\pm$ pairs, due to the fact that in the case of $e\pm$ pairs a regular turbulent acceleration is more efficient for the typical parameters of AGN jets (only higher-energy hadronic CRs have mean free paths large enough to experience a sufficient bulk velocity gradient between subsequent scatterings, since maximum energies of leptonic CRs are limited by radiative losses);
- $e\pm$ pairs follow therefore the bulk flow rigorously, but the higher energy protons sample a range of velocities (since they "know" about the transverse velocity gradient), so inside the jet, where the electron current is the largest, they lag behind on average, giving **a net negative current outward**, $I_{\rm bl}$;
- there will be a toroidal magnetic field $B_{\rm bl}$ associated with this net current, which can be responsible for the RM gradients with CW orientation across pc-scale jets.



Stawarz, Begelman, et al., in prep



RM gradients

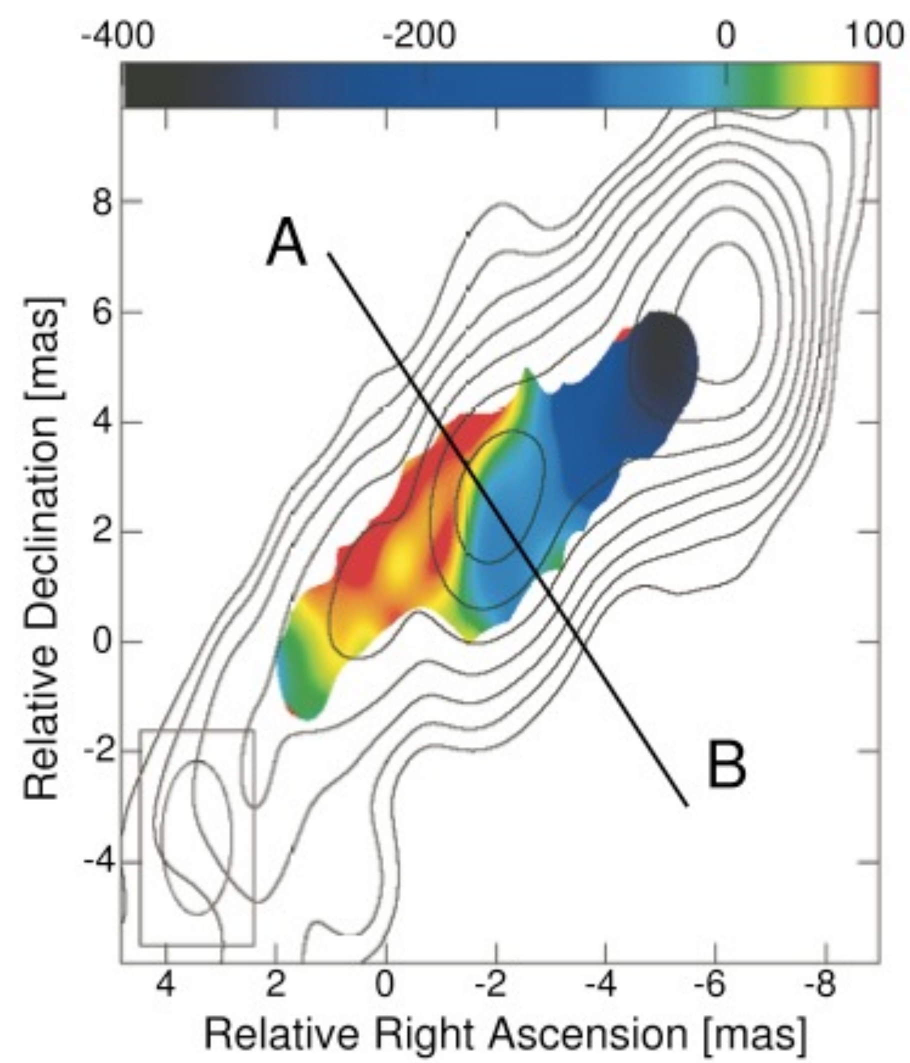
- Gradients of RM often observed on pc scales in AGN jets
- Faraday screen seems to be external to the emission region because

    (i) $\Delta\chi \sim \lambda^2$ dependence
    (ii) >45deg rotations observed
    (iii) RM gradients seen around the jet/ISM interaction regions
    (iv) a decrease of RM along the jets sometimes observed
    (v) high fractional polarization from the RM gradient regions

- Faraday screen cannot be completely unrelated to the jets, since RM gradients vary on timescales of years

- RM gradients require toroidal MF in the depolarizing medium; meanwhile, polarization properties often imply that the MF within emitting regions contains a substantial poloidal component

- **In the majority of cases RM gradients on pc scales are "clock-wise" (CW), and not counter clock-wise (CCW)!**



Asada et al.
Hovatta et al.
Gabuzda et al.

Conclusions

1) Internal shock model implies matter-dominated jets (at least during flaring states); but maybe rather magnetic turbulence/reconnection?

2) Red/pink noise-type variability of AGN jets on timescales from hours to years, at different wavelengths!

3) Variability driven by an underlying single stochastic process, or at most a linear superposition of two stochastic processes -> magnetic turbulence?

4) Large-scale jets as important and fascinating as small-scale (blazar) jets!

5) High jet magnetisation ($\sigma > 1$) seems to require a substantial poloidal magnetic field component

6) "Boundary layer/spine" structure of AGN jets

7) Shear CR acceleration -> boundary layer currents -> RM gradients?