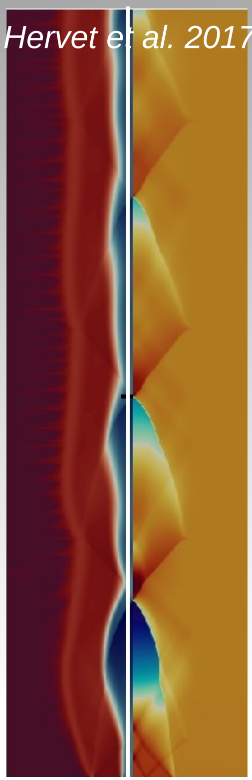
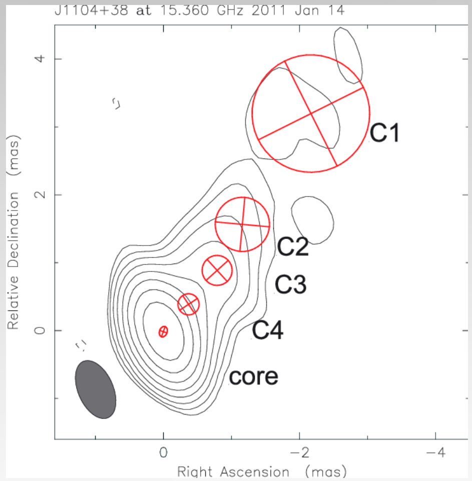
Signatures of recollimation shocks in blazars,

focus on Mrk 421



ρ P



Mrk421, Lico et al. 2012

Olivier Hervet,

D. A. Williams, A. Falcone, A. Kaur

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SF2A

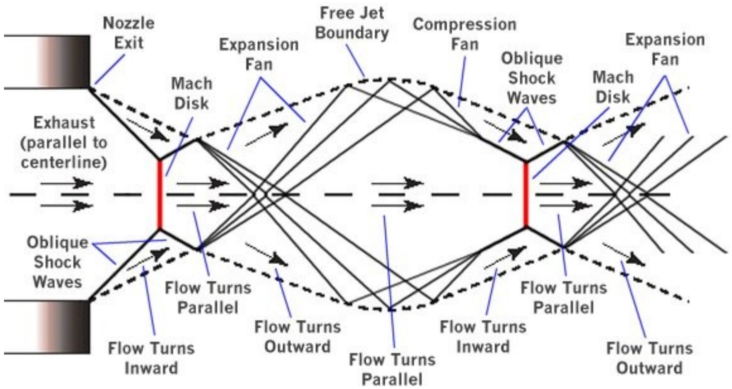
Particle acceleration in astrophysical and space plasmas

May. 2019, Nice

AGN Jets should naturally show multiple recollimation shocks

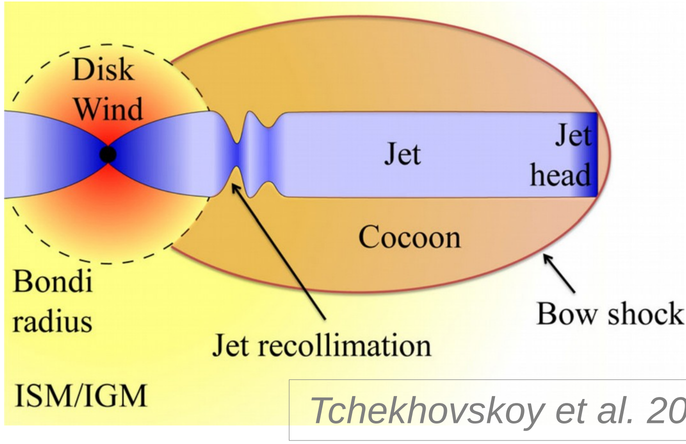
Jet conditions:

- Supersonic/superAlvenic
- Pressure mismatch with external medium
- Locally severe pressure drop

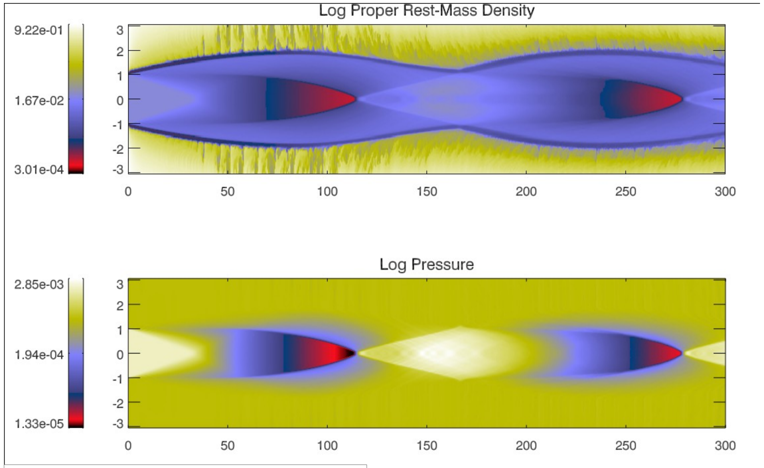


Relativistic (M)HD simulations

(e.g. Lind et al. 1989, Mizuno et al 2015, Fromm et al. 2016, Hervet et al. 2017, ...)



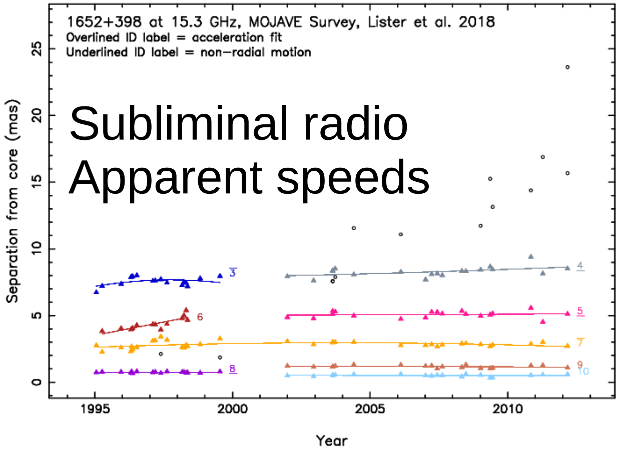
Tchekhovskoy et al. 2016



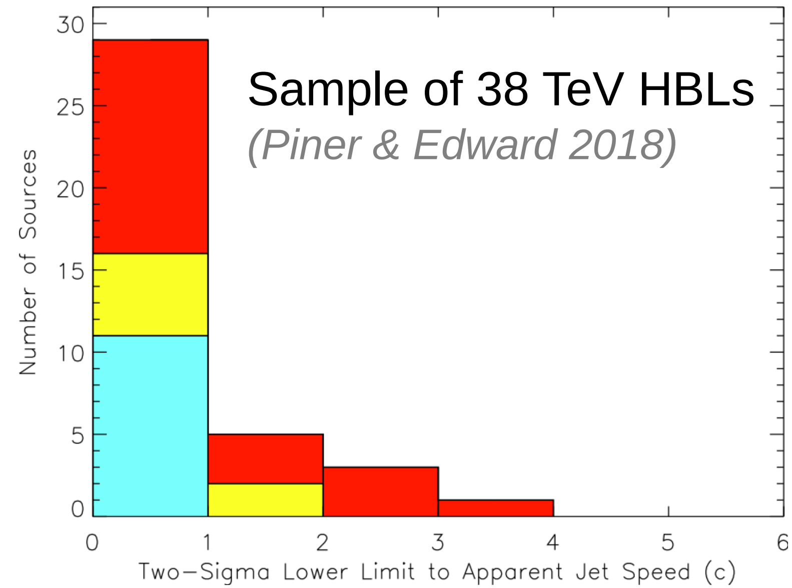
Fromm et al. 2016

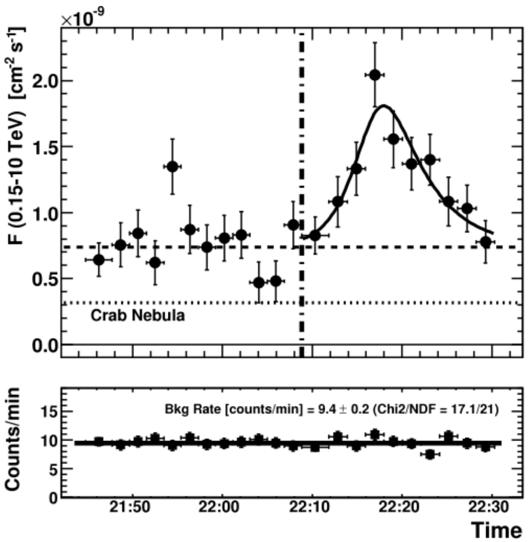
Stationary components in high frequency peaked BL Lacs (HBLs)

Example of Mrk 501



TeV HBLs are the blazars presenting the most stationnary/slow VLBI radio knots
(Hervet et al. 2016, Piner & Edward 2018)





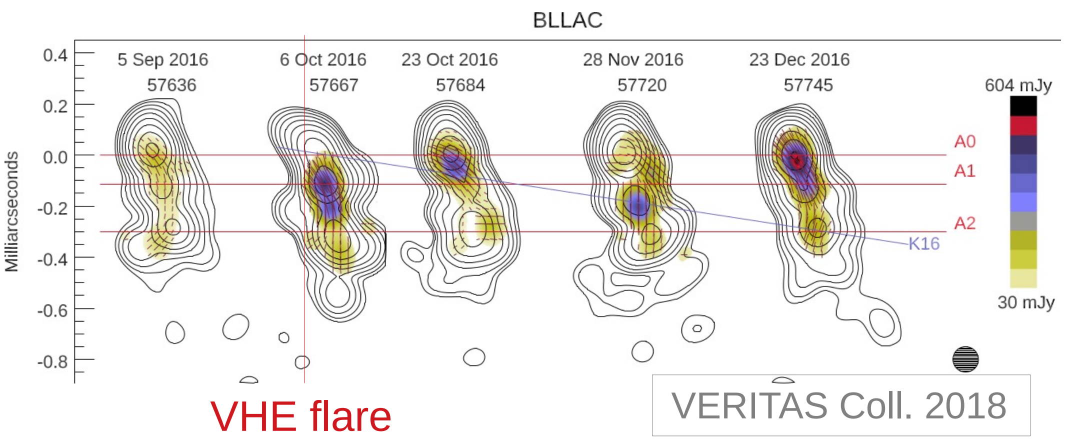
20 min TeV Flare in 2005
$\delta \sim 25 - 50$

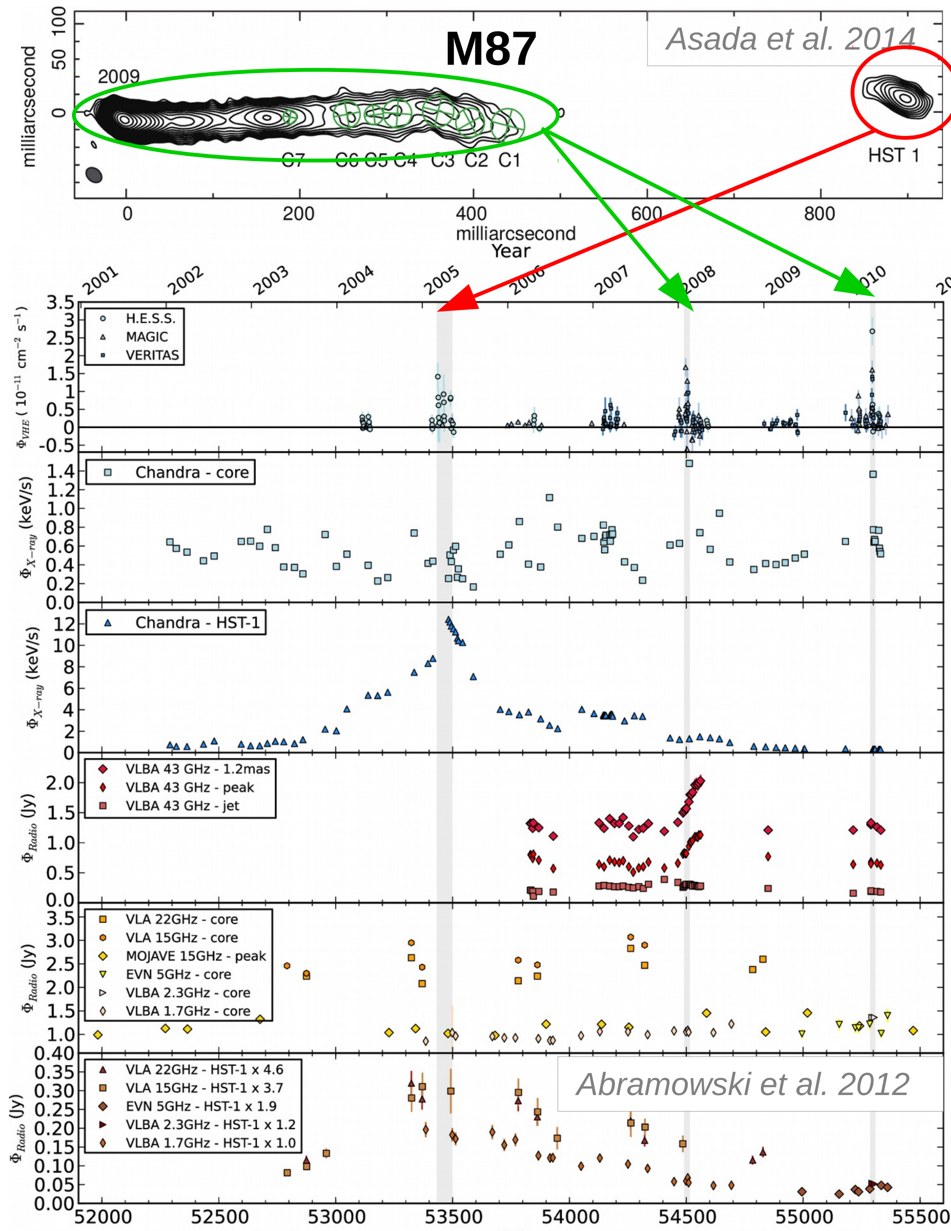
Albert et al. 2007

Impose high compactness of the emission zone, need high Doppler/lorentz factor to cope with causality and gamma-gamma opacity

Stationary knots as recollimation shocks
– MWL flares

Gamma-ray flares can be linked to radio core or radio knots



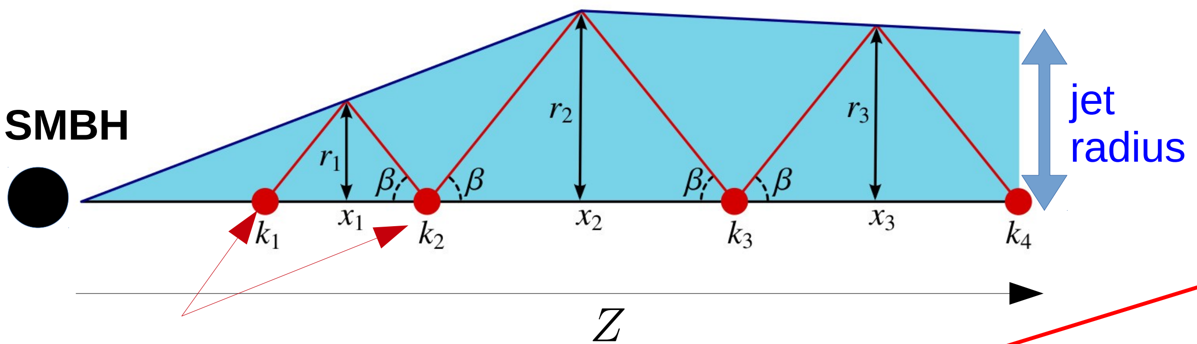


VLBI cores can be unresolved regions with smaller knots *(e.g . BL Lac with Radioastron, 2016)*

Stationary knots as recollimation shocks

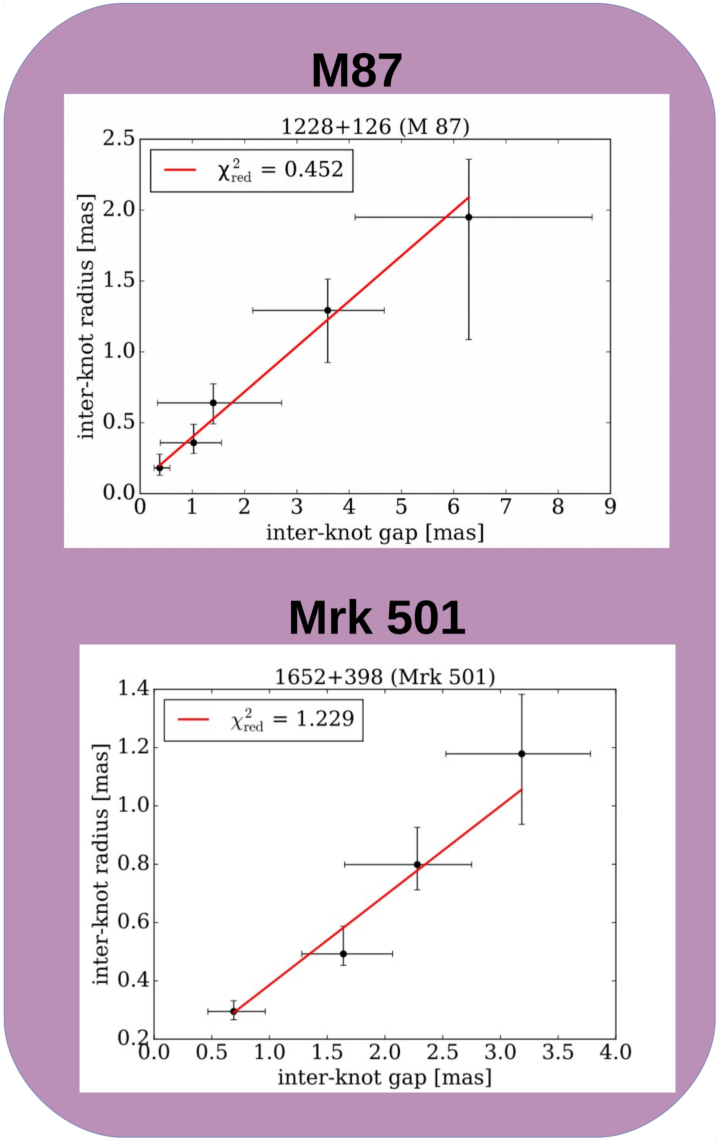
– structure of knot strings

Prediction:
If stationary VLBI radio knots are recollimation shocks, the inter-knot gaps should be proportional to the jet radius (isothermal approximation)



$$r_n \propto \Delta k_n$$

Verified!

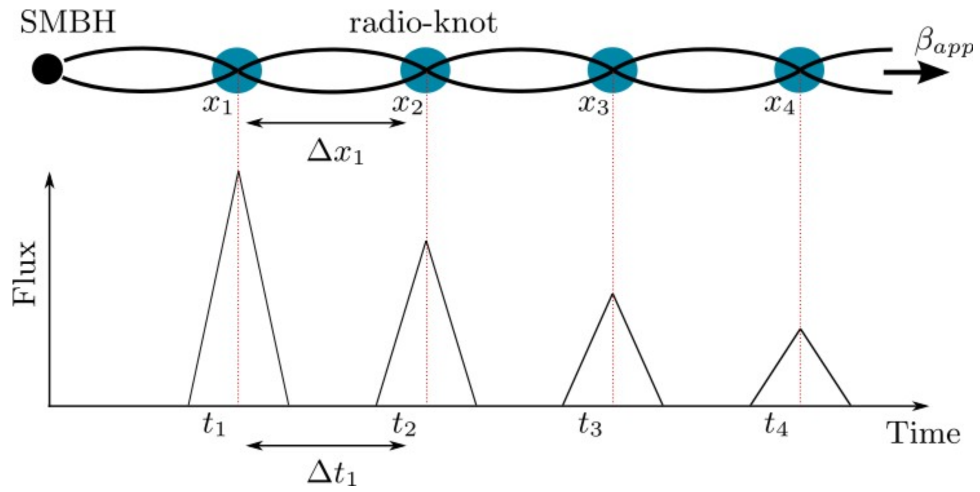


Relation checked on ~10 jetted AGNs with stationary knots

(Hervet et al. 2017)

Expected signature of successive shocks in lightcurves

New prediction to be tested:
If powerful shocks, jets perturbations should show signatures in the lightcurves.

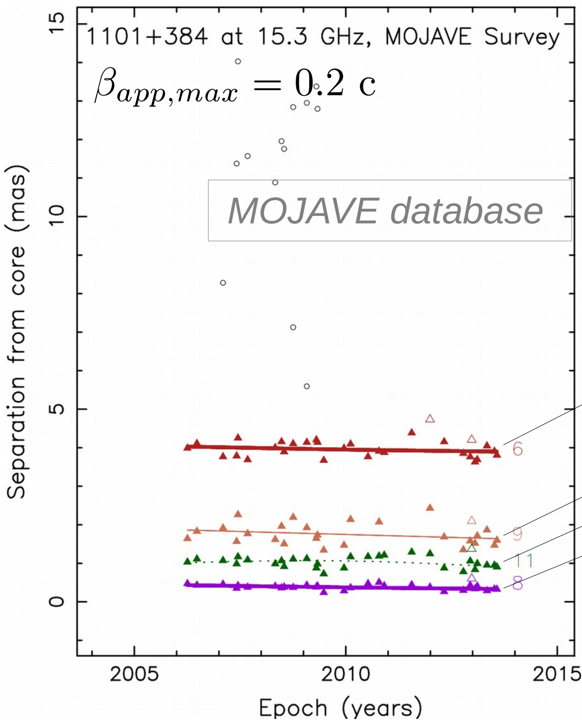


Assuming a constant flow speed:

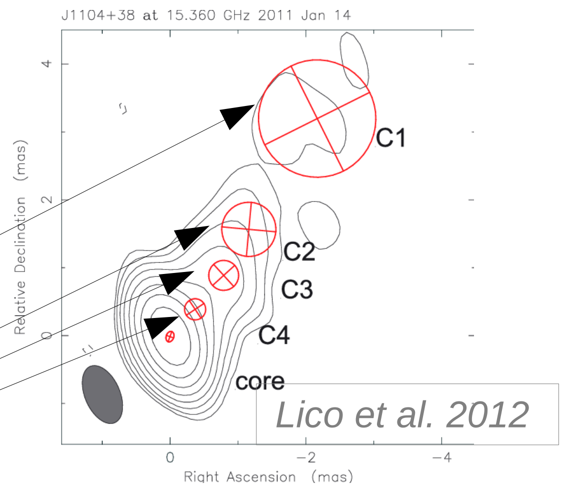
$$\Delta t_i = (1+z)\frac{\Delta x_i}{c\beta_{app}}$$

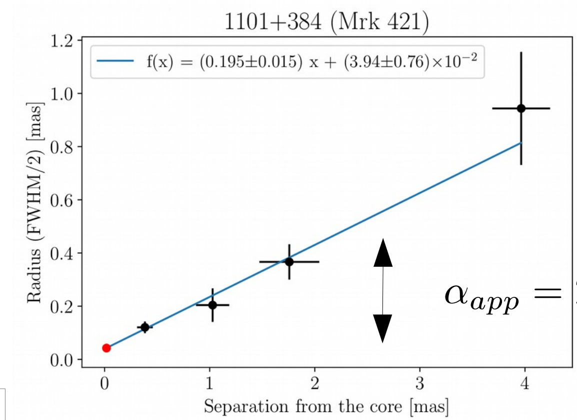
Due to high Doppler beaming, Blazars are the best candidates, with such a pattern expected in a week-to-year timescale.

Mrk 421, the ideal candidate



4 quasi-stationary knots

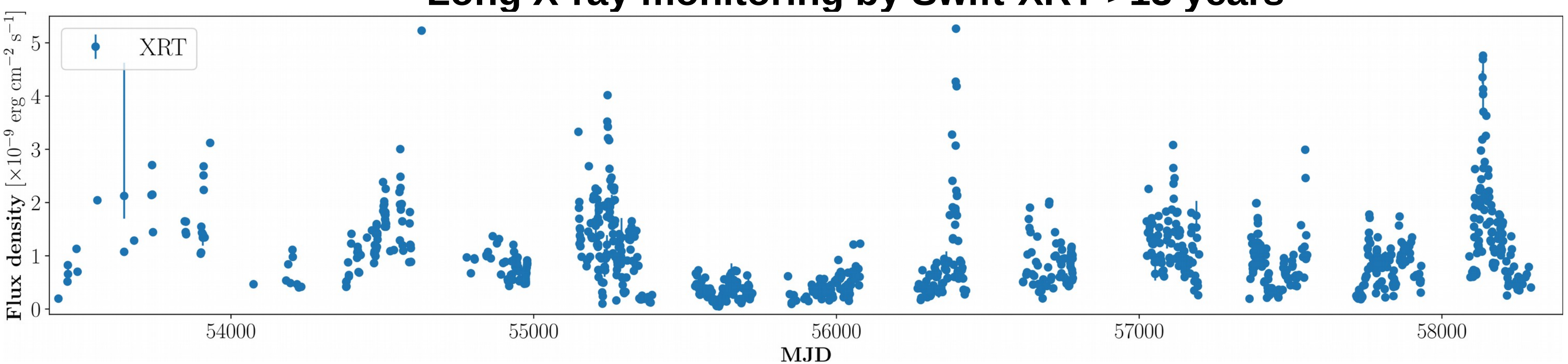




Conical jet

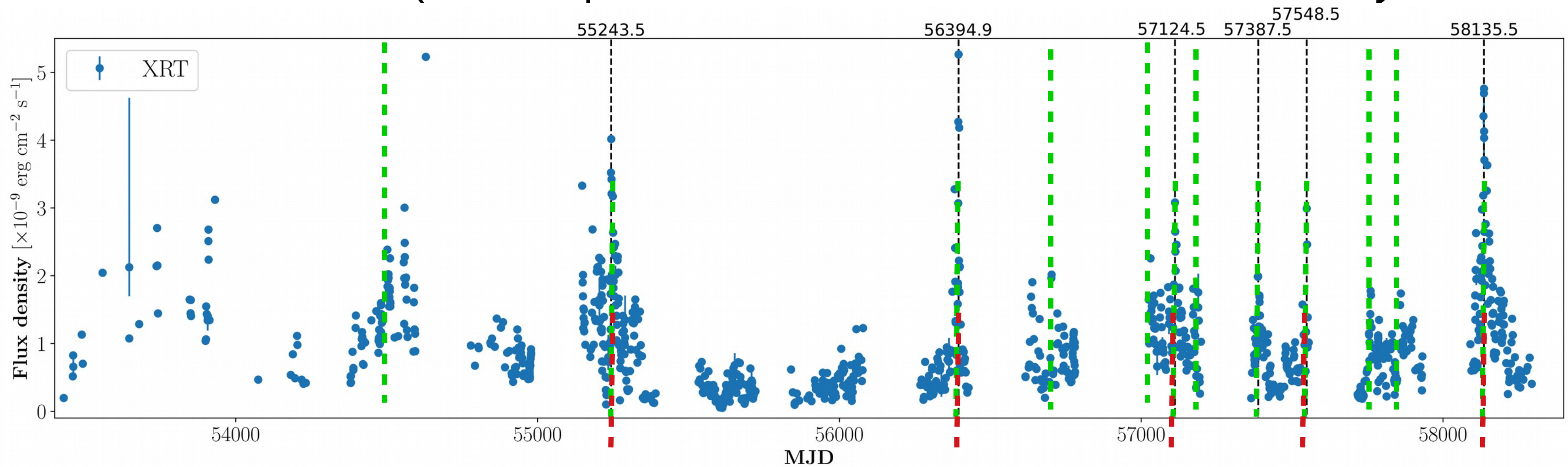
$\alpha_{app} = 22.1 \pm 1.7$ deg

Long X-ray monitoring by Swift-XRT >13 years



13 years of Swift-XRT observations – *Stacking the flares to unveil an intrinsic pattern*

Selected flares (method performed with different cuts to test the systematic errors)



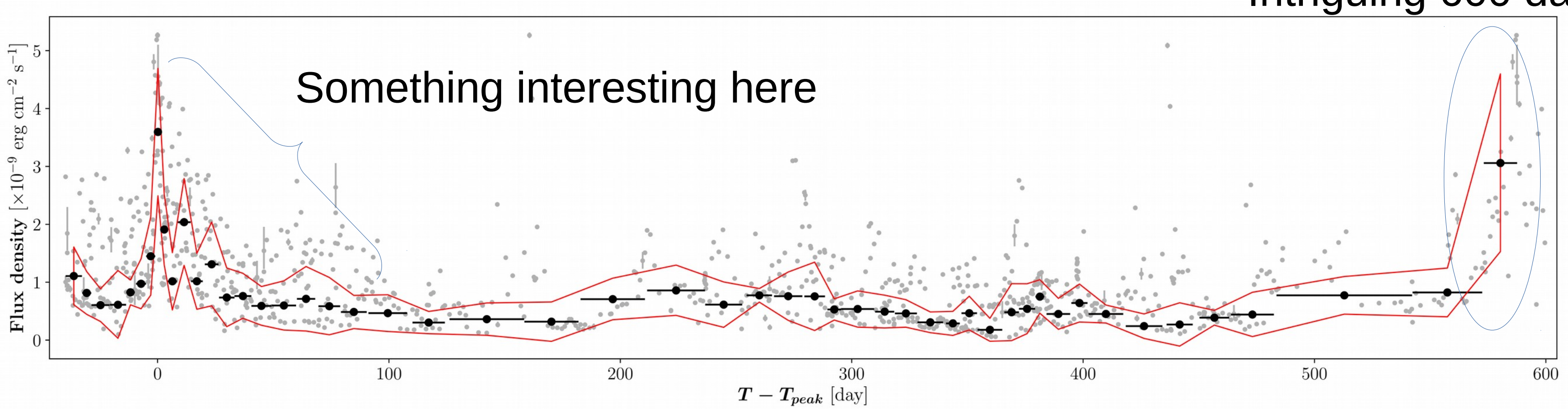
Hard cuts:
5 flares

Default cut:
6 flares

Loose cuts:
13 flares

All flares stacked

Intriguing 600 days excess



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O. Hervet
SF2A – May 2019, Nice

PennState

Theoretical models

I- No pattern after big flares

Fit with a baseline and an exponentially modified Gaussian function (EMG)

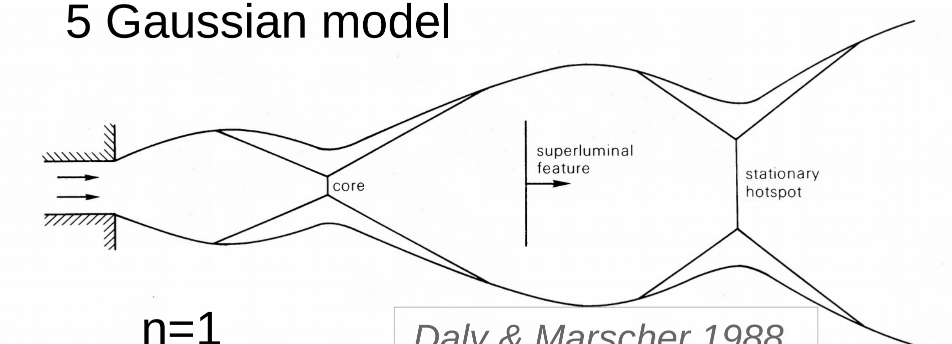
Raise as Gaussian, decrease as exponential

$$EMG(t) = \frac{h\sigma}{\tau}\sqrt{\frac{\pi}{2}}\exp\left(\frac{\sigma^2}{2\tau^2} - \frac{t-\mu}{\tau}\right) \times \operatorname{erfc}\left[\frac{1}{\sqrt{2}}\left(\frac{\sigma}{\tau} - \frac{t-\mu}{\sigma}\right)\right] + B(t)$$

5 dof

baseline

II-The core is a strong shock
Baseline+
5 Gaussian model



n=1

Daly & Marscher 1988

$$G_m(t) = \sum_{i=n}^{5}[A_i P_i(t)] + B(t)$$

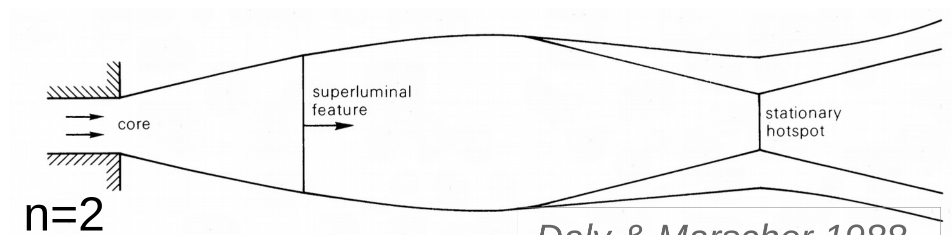
6 dof

Amplitude

Gaussian

Baseline

III- The core is only the expanding funnel
Baseline+
4 Gaussian model



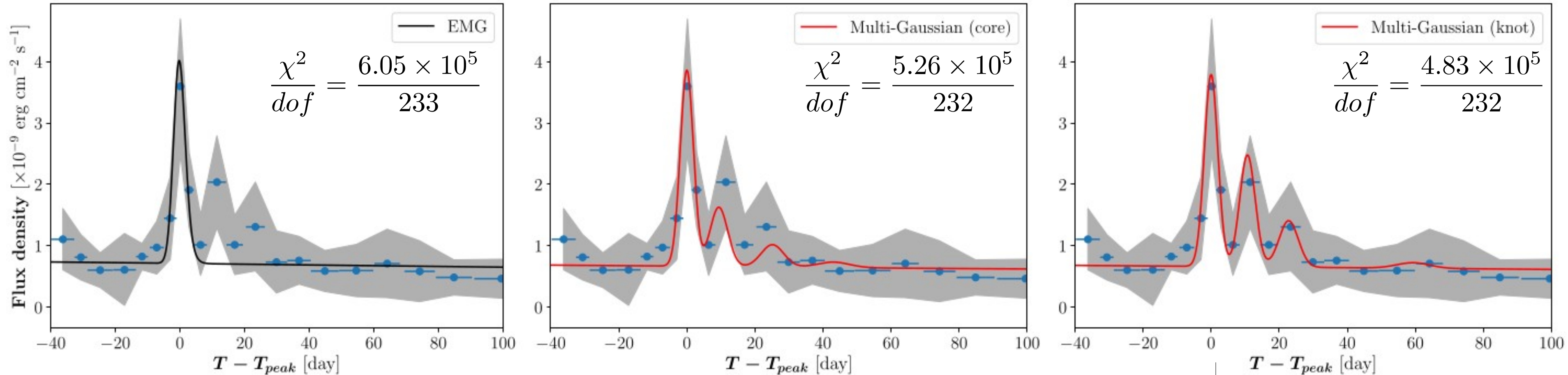
n=2

Daly & Marscher 1988

Observationally constrained model

- Inter-Gaussian gap scaled on inter-knot gap
- Gaussian widths scaled on knot size
- Gaussian amplitude scaled on knot volume

Model comparison



Fit to real stacked data (binned data for displaying purpose only)
Chi2 calculated for [T0-7, T0+70]

A main flaring zone in the upstream radio knot is favored, with an apparent speed of the flow $\beta_{app} = 45^{+4}_{-2}\ c$

Many concerns might arise now...

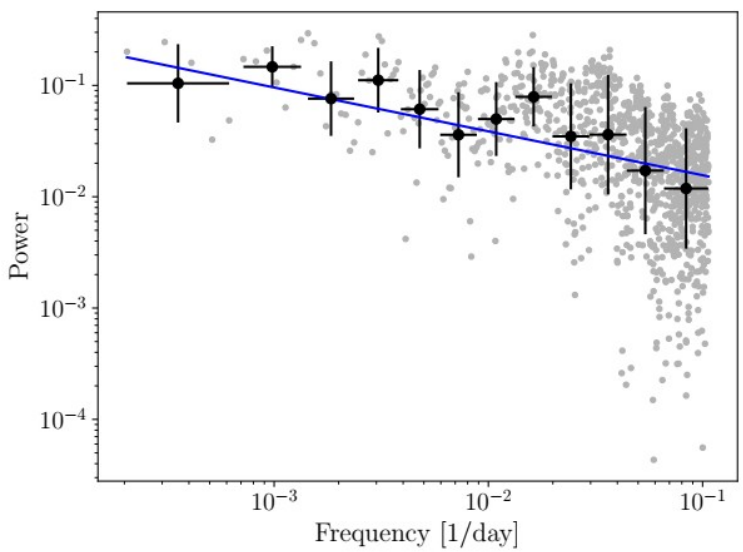
- Probably a false/misleading pattern from stacked uneven data sets
- What if it’s just an happy coincidence of stochastic fluctuations?
- Anyway, we cannot prove anything with such a bad fit

Lightcurve simulations

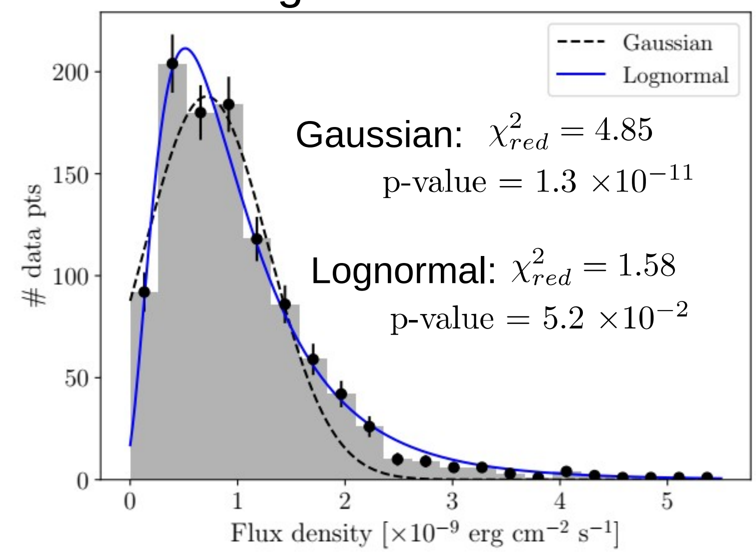
Only way to test the significance of an intrinsic post-flare pattern is through lightcurve simulations:

- Apply the exact same method on realistic Mrk421 simulated lightcurves
- Compare the fit quality of the multi-Gaussian scenario of the real and simulated dataset

Mrk 421 PSD (index: $\eta = 1.35 \pm 0.01$)



Mrk 421 lognormal flux distribution



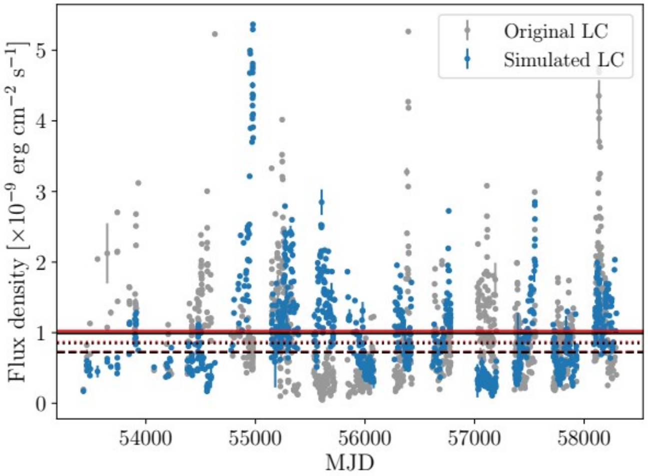
We want simulated lightcurves to have:

- Same PSD
- Same flux and error distributions
- Same data sampling

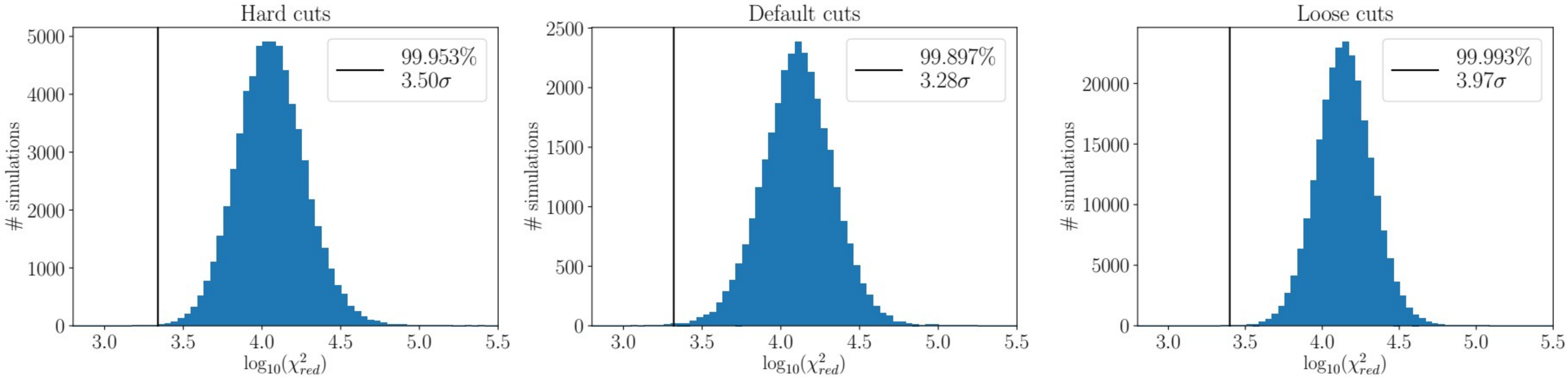
A simulated lightcurve is considered good if within 3 sigma of PSD index and flux distribution parameters

Results

Example of Lightcurve passing the checks



Post-flare pattern tested against numerous simulations



A post-flare variability pattern associated with radio-knots is better than schochastic fluctuations at more than 3.2 sigma (checked by different flare selection cuts)

Jet physics

$\beta_{app} = 45^{+4}_{-2}\ c \rightarrow$ strong constraint on the angle with the line of sight: $\theta < 2\arctan(1/\beta_{app})$

$\theta < 2.69$ deg (90% confidence level)

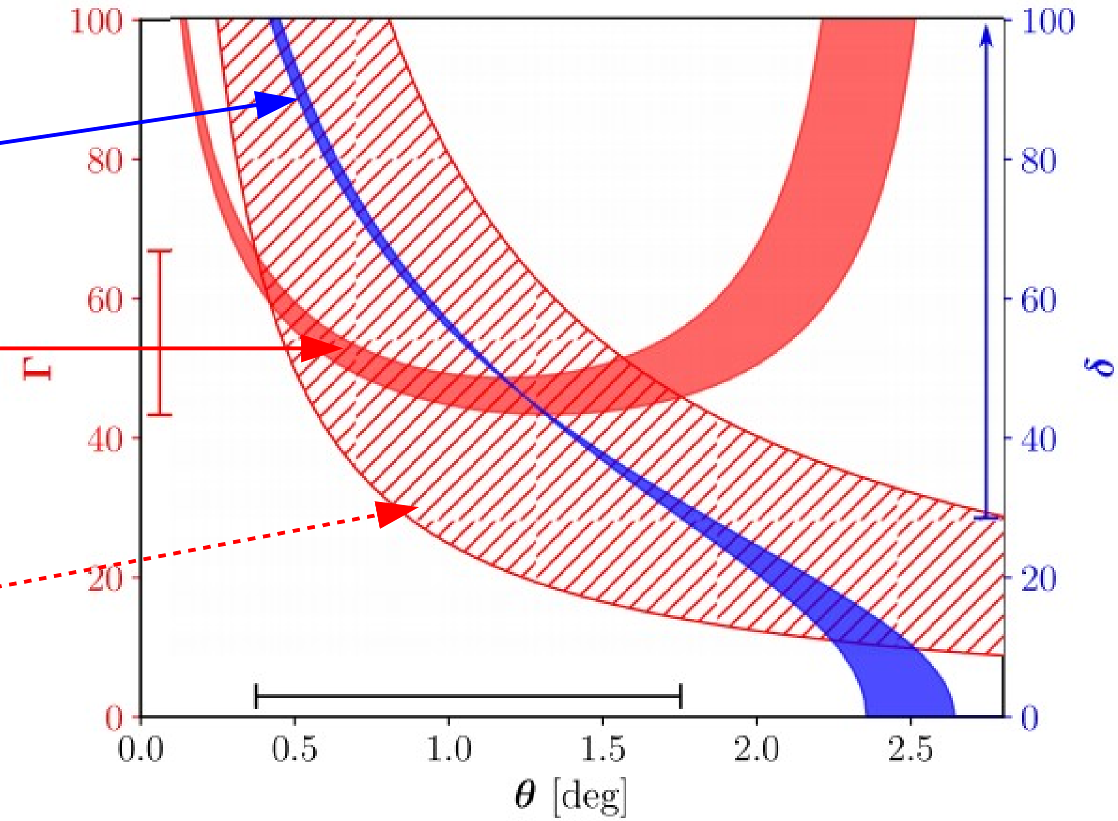
Constraint on beaming parameters

$$\delta = \sqrt{1 - \left(\frac{\sin\theta}{\beta_{app}} + \cos\theta\right)^{-2}} \left(1 + \frac{\beta_{app}}{\tan\theta}\right)$$

$$\Gamma = \frac{1}{\sqrt{1 - \left(\frac{\sin\theta}{\beta_{app}} + \cos\theta\right)^{-2}}}$$

$$\Gamma = \frac{2\rho}{\alpha_{app}\sin\theta}$$

Defined by *Jorstad et al. 2005*, with $\rho = 0.17 \pm 0.08$



System solved for $\delta \geq 31$

$\Gamma \in [43 - 66]$

$\theta \in [0.38 - 1.8]$ deg

Typical intrinsic width of a perturbation (from the Gaussian widths):

$W_p \in [0.43 - 19] \times 10^{17}$ cm

Particle re-acceleration in TeV HBLs?

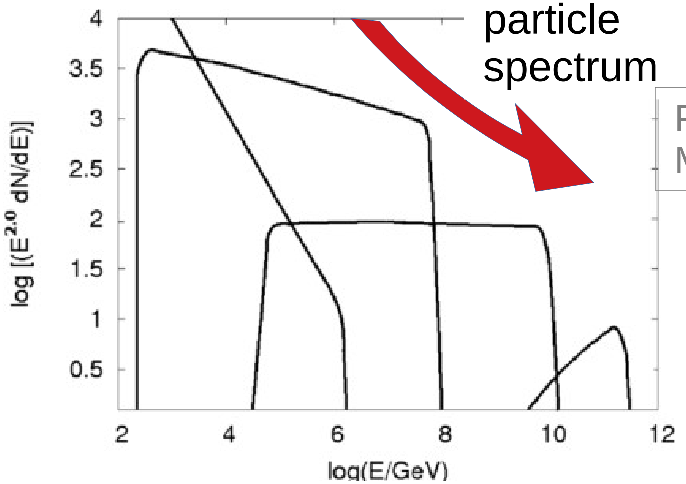
- Mrk 421 (among other TeV HBLs) shows a challenging, too hard, TeV spectrum for standard SSC models (Fossati et al. 2008)
- Fossati et al. (2008) : [Mrk 421 is] “very suggestive of acceleration or injection of the higher energy end of the electron population”

→ This issue is mostly addressed with lepto-hadronic scenarios
(e.g. for Mrk 421: Abdo et al. 2011; Mastichiadis et al.2013; Zech et al. 2017)

Other approach

If a fraction of the particles accelerated in the first shock are not fully cooled before reaching other shocks, they will be re-accelerated.

Hardening of particle spectrum



Particle spectrum for 4 subluminal shocks
Meli & Biermann 2013

Successive shocks predict a possible hardening and differential variability of TeV spectra

Conclusion & Outlook

- Mrk421 shows evidence of a flaring variability pattern associated to the passage of perturbations through the radio knots at more than 3 sigma significance compared to stochastic fluctuations
- The deduced physical values of the jet (angle, Lorentz, Doppler) are relatively close to the estimations from SED modelling, and are not contradicting the minimum Doppler factors estimated from photon-photon absorption *(e.g. Tavecchio et al 1998)* $\delta \geq 15$
- Very fast observed variability (~15min, Gaidos et al. 1996; Paliya et al. 2015) is not contradicting this approach if we consider that jets perturbations are subject to have small size clumps/ turbulences *(e.g. Marscher et al. 2014)*
- Clear VHE/X-ray correlation observed for all the possible state of the source *(Fossati et al. 2008; Horan et al. 2009; Acciari et al.2011)*

  It means same(s) zone(s) for X-ray and VHE in Mrk 421

  Following our study we expect VHE also originating from (inside) the radio-knots

Future work

→ Check the relevance of this scenario of Mrk 421 with VHE data

→ Check if other TeV HBLs present similar patterns

Hervet, Williams, Falcone, Kaur, “Probing an X-ray flare pattern in Mrk 421 induced by multiple stationary shocks: a solution to the bulk Lorentz factor crisis”
https://arxiv.org/pdf/1904.06802.pdf (accepted in ApJ)