Updating the unification of jetted AGN

Olivier Hervet

LLR Seminar
Oct. 2020, Palaiseau *(remote)*

Image credit: Cosmovision, NRAO/AUI/NSF

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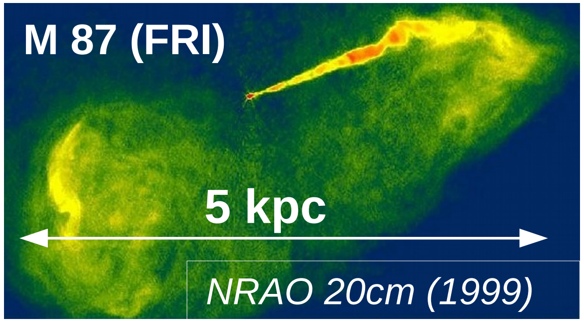
SCIPP
Santa Cruz Institute for Particle Physics

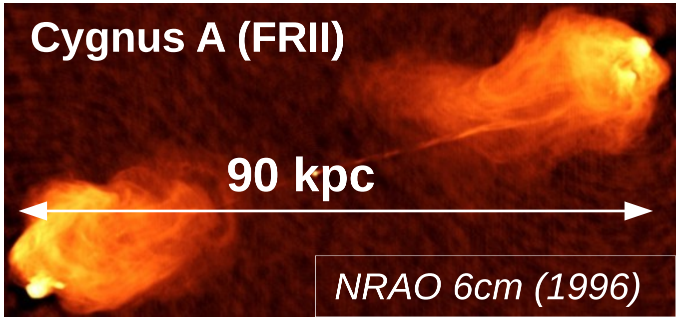
Outline

- Current AGN & Blazar unification scheme
- The game-changing view of radio VLBI kinematics
- HBLs: A bulk Lorentz factor crisis
- Intermediate blazars, a distinctive class
- Updating the unification with recollimation shocks in two-flows jets
- Conclusion

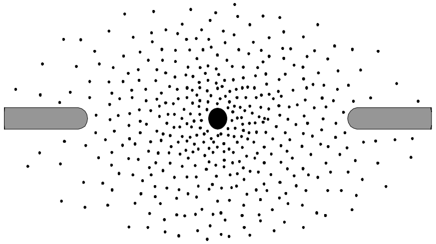
I – AGN & Blazar unification schemes

AGN unification scheme – *Powers and viewing angles*

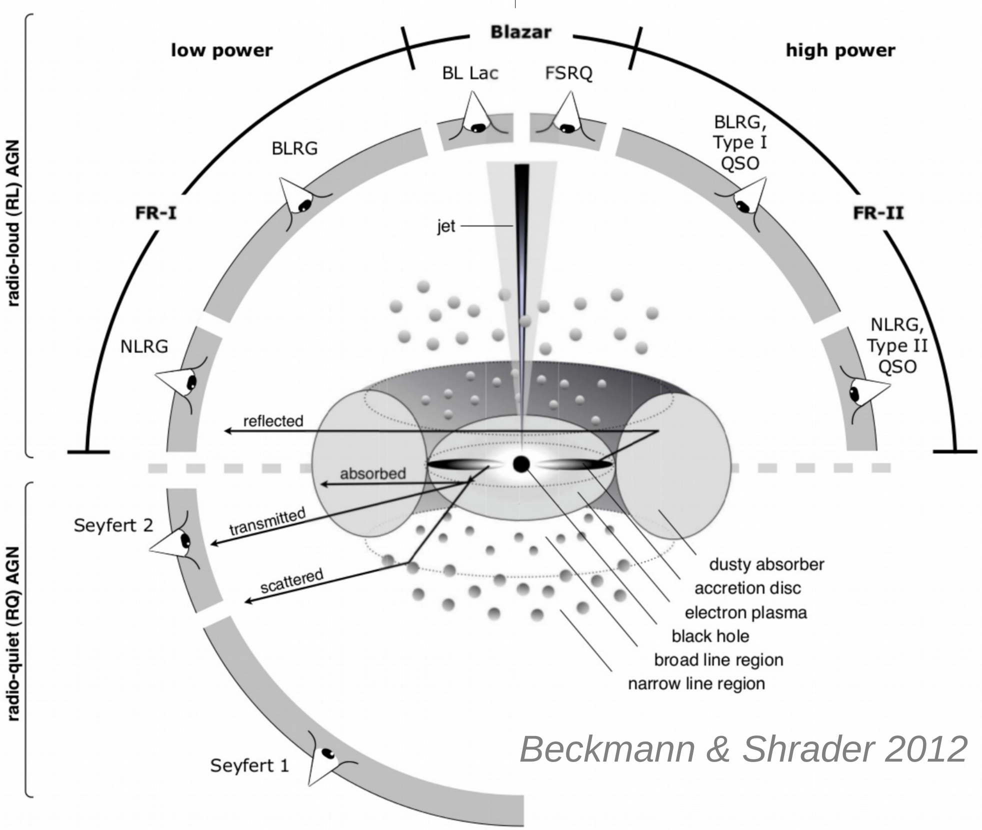




Advection dominated accretion flow (ADAF)

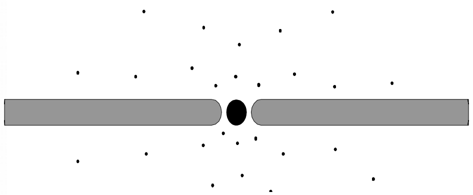


A. Esin et al. 1997



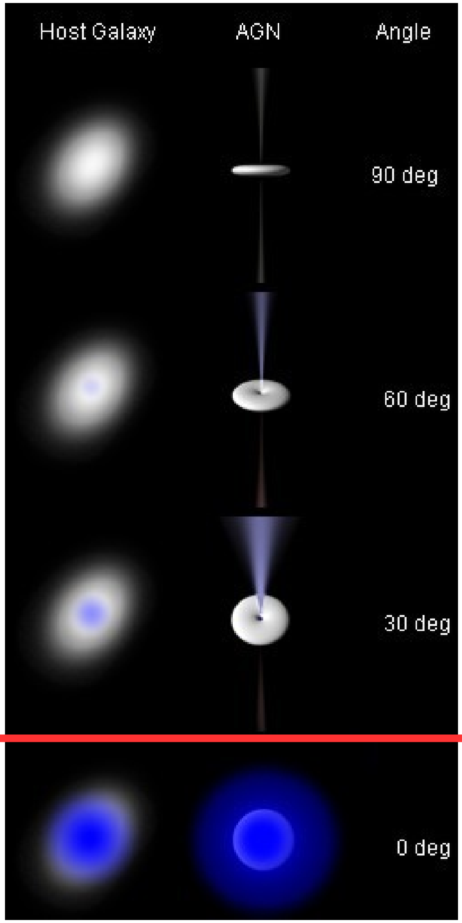
Beckmann & Shrader 2012

Viscous disk (Standard)
"Shakura-Sunyaev"



A. Esin et al. 1997

Blazar effect



Blazar = strong beaming effects

White: thermal
Blue: non-thermal

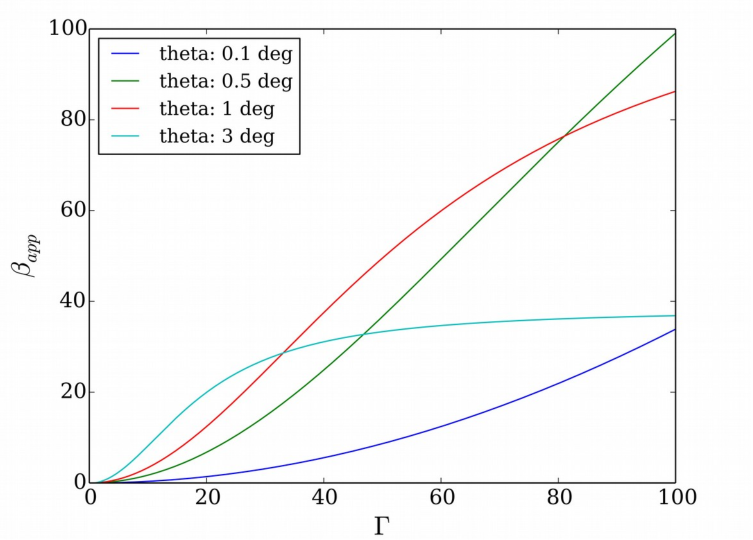
Doppler beaming

$$\delta = \frac{1}{\Gamma(1-\beta\cos\theta)}$$

Intensity boosted by δ^3

Apparent speed

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



Fast forward observations

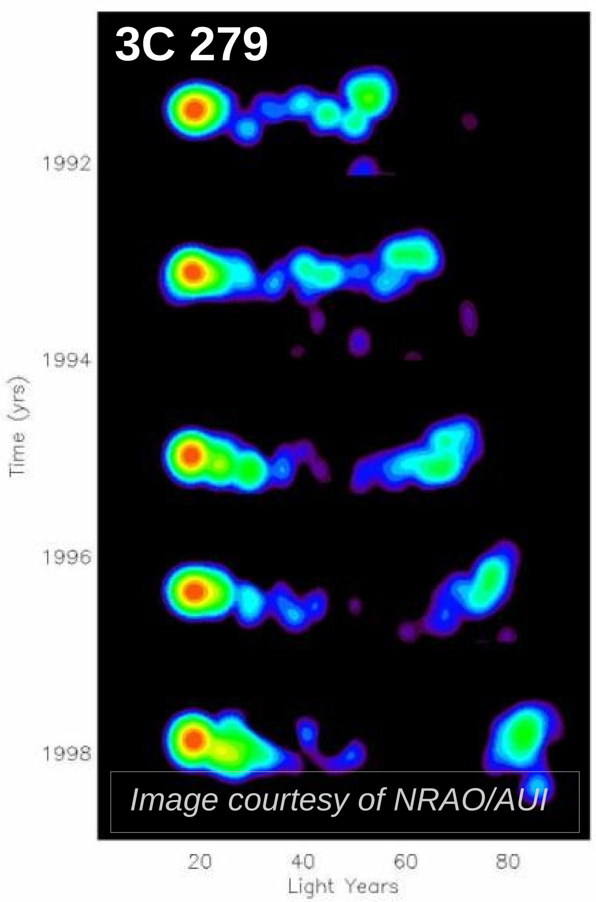
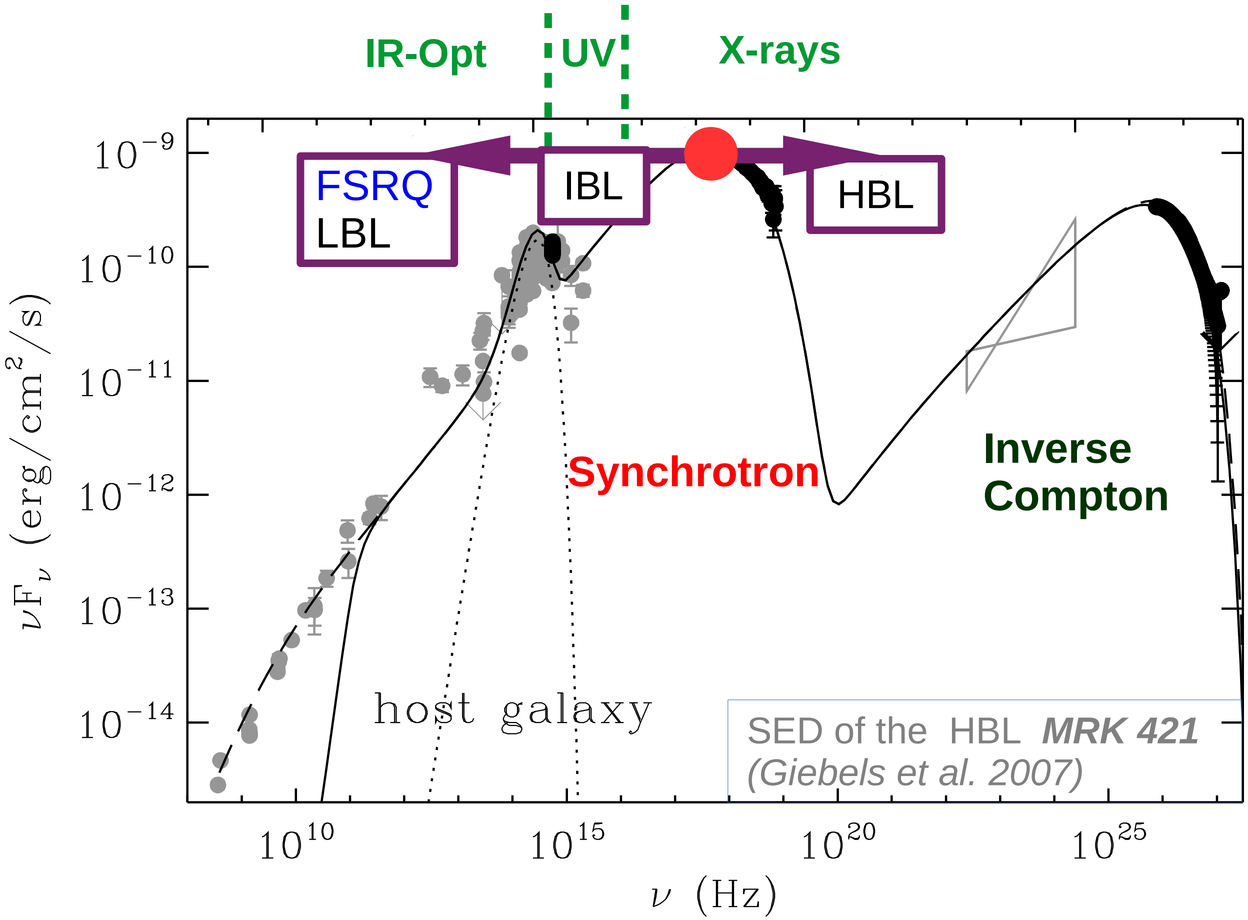
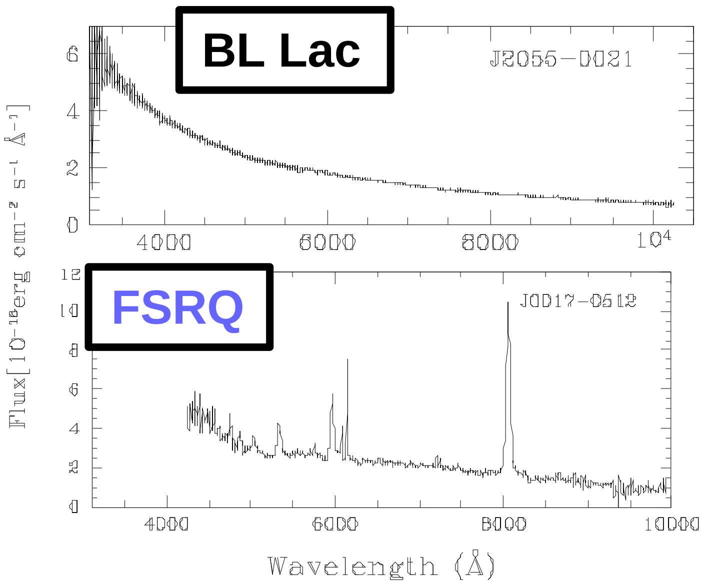


Image courtesy of NRAO/AUI

Blazar classification – *Spectral energy distribution and emission lines*

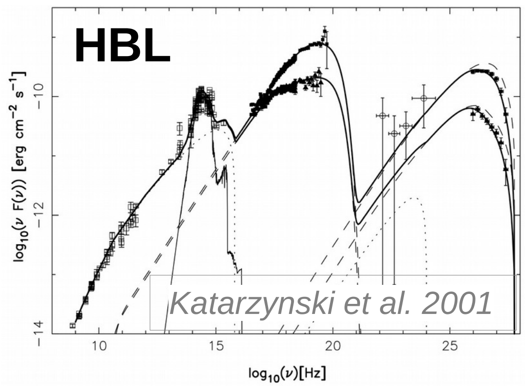




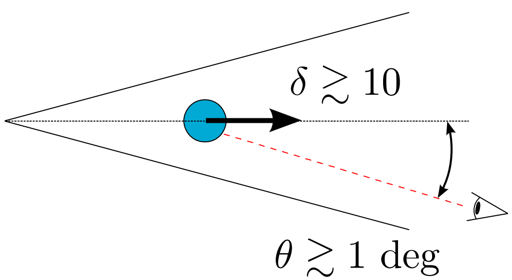
FSRQ: **F**lat **S**pectrum **R**adio **Q**uasar
LBL: **L**ow frequency peaked **BL** **L**ac
IBL: **I**ntermediate frequency peaked **BL** **L**ac
HBL: **H**igh frequency peaked **BL** **L**ac

Blazar unification scheme – *Smooth transition?*

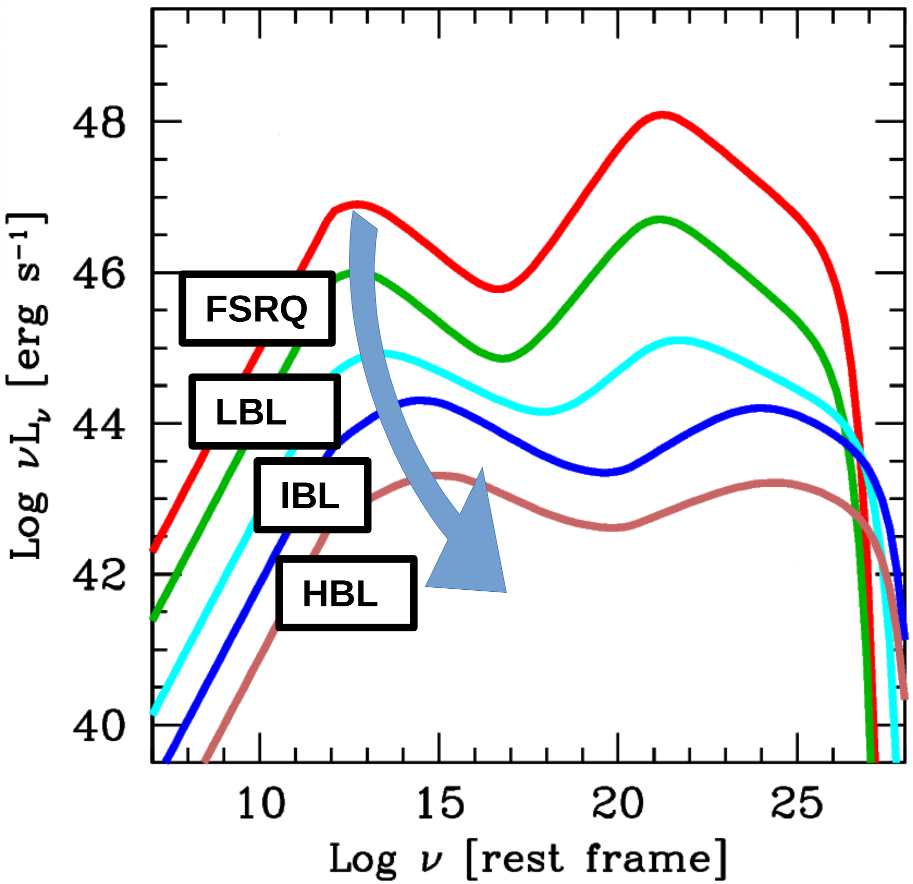
Low Power



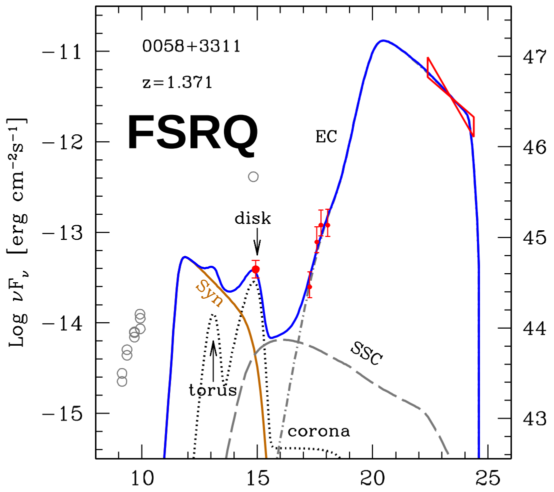
SSC model



The "new" blazar sequence
(Ghisellini 2016)

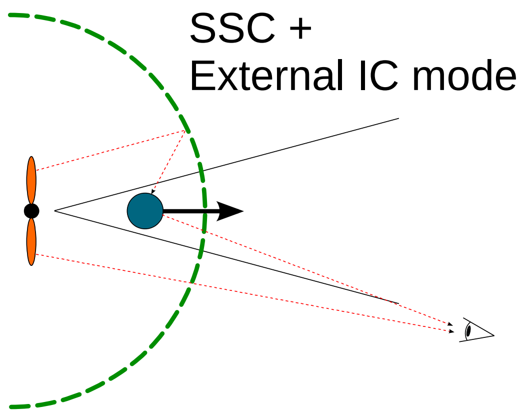


High Power



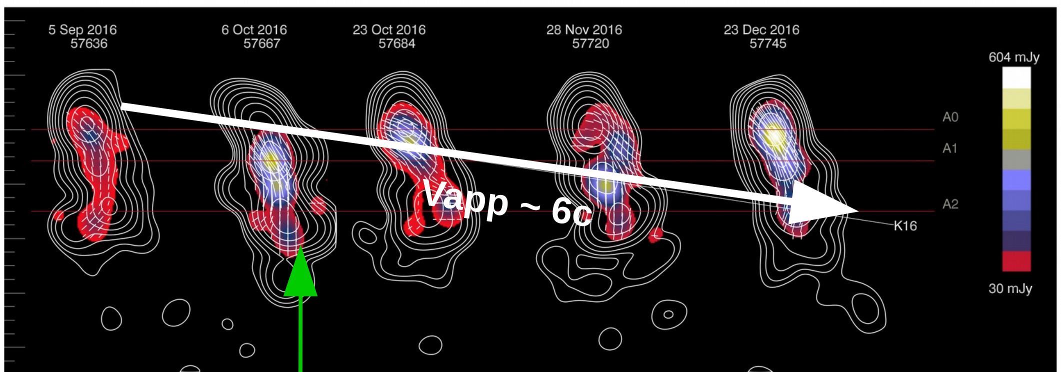
Ghisellini et al. (2011)

SSC +
External IC model

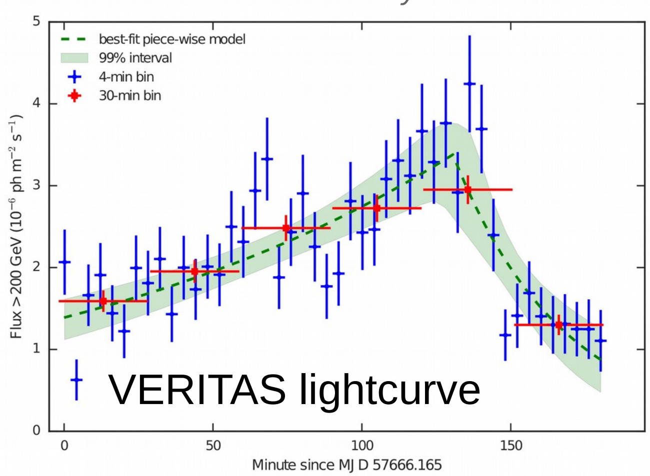


Gamma / VLBI events – *Gamma-ray flare simultaneous with an ejecta from (close to) the core*

e.g BL lacertae 2016



Abeysekara et al. 2018



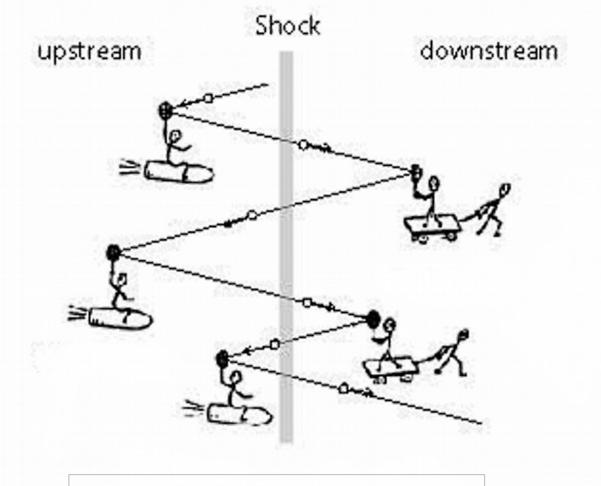
Also seen in:

- **3C 120** in 2012-2014 *(Casadio et al. 2015)*
- **S4 0954+658** in 2011 *(Morozova et al. 2014)*
- **BL Lacertae** 2011 *(Arlen et al. 2013)*
- **3C 454.3** in 2010 *(Wehrle et al. 2012)*
- **OJ 287** in 2009 *(Agudo et al. 2010)*
- **PKS1510-089** in 2009 *(Marscher et al 2010)*
- **BL Lacertae** in 2005 *(Marscher et al. 2008)*
- **...**

Seen in IBLs, LBLs, FSRQs, and radiogalaxies
HBLs missing!

Master recollimation shock – *the dominant paradigm*

Diffuse shock acceleration



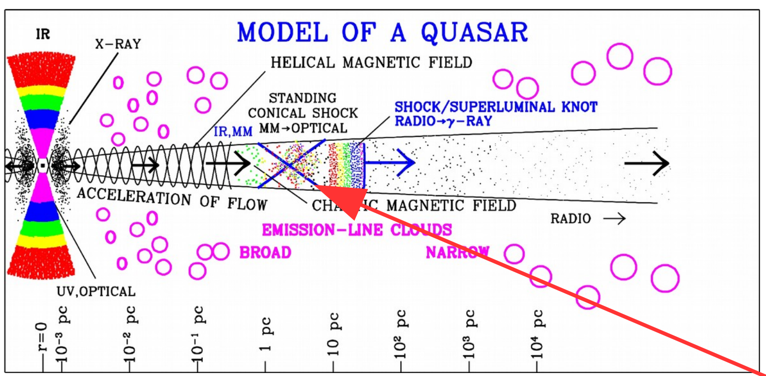
Credit: Hoshino 2001

Theoretical power law particle spectrum:

$$N(E) \sim\propto E^{-2}$$

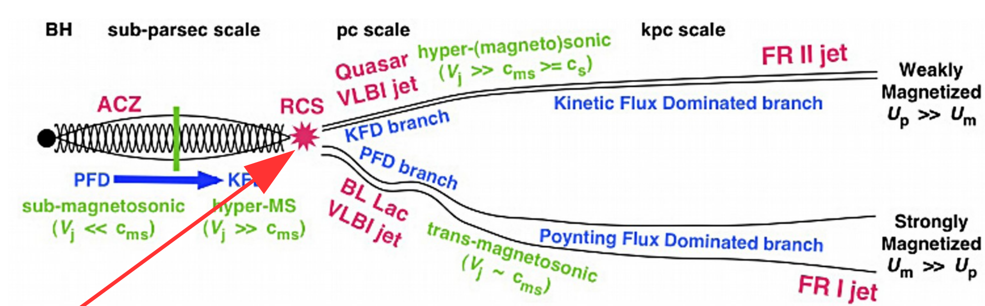
→ Globally consistent with synchrotron-self-Compton models

Master recollimation shock (MRCS)



Marscher & Gear 1985

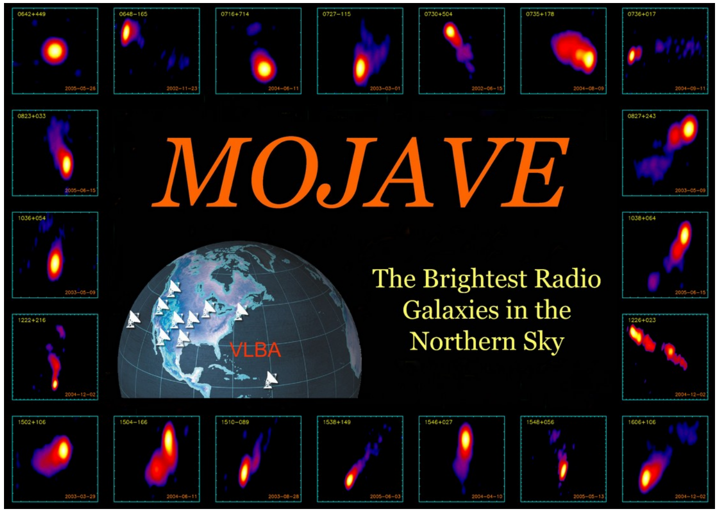
- Mostly consistent with blazar variability, moving radio knots, polarization changes
- Could explain FR I – FR II differentiation *(Meier 2013)*



MRCS

II – The game-changing view of radio VLBI kinematics

Radio VLBI monitoring – *reaching a statistical level for population studies*



http://www.physics.purdue.edu/MOJAVE/

MOJAVE
(Monitoring Of Jets in Active galactic nuclei with VLBA Experiments)

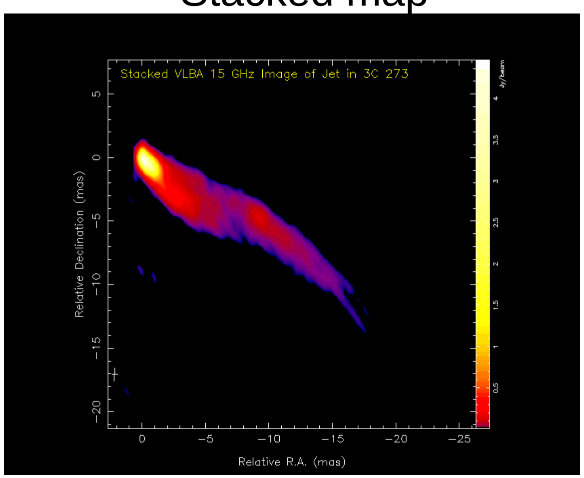
The largest database of analysed radio VLBI AGN jet

VLBA Observations at 15 GHz since 1994, Angular resolution < mas

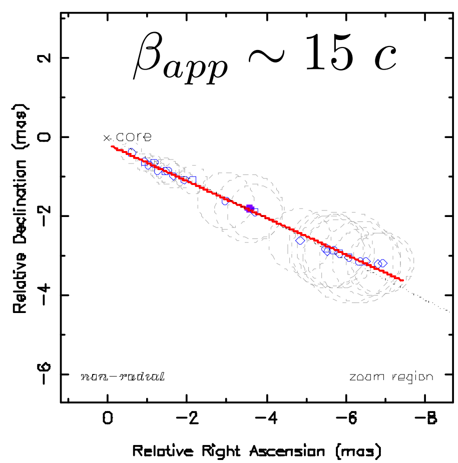
2019 paper, MOJAVE XVII:
- parsec-scale jet kinematics study of 409 AGN jets
- 1744 individual bright features in 382 jets over at least 5 epochs

e.g. **3C 273**

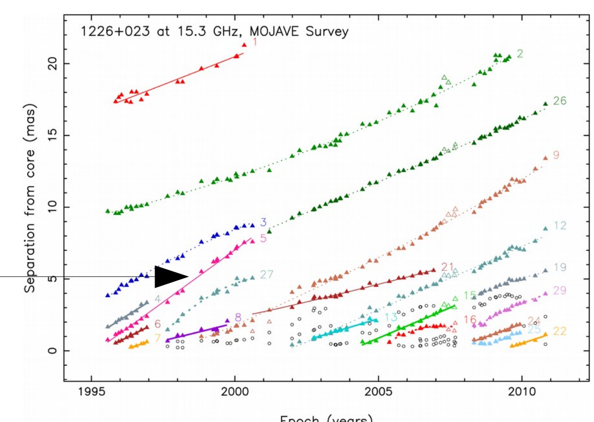
Stacked map



Fastest component



Jet components monitoring

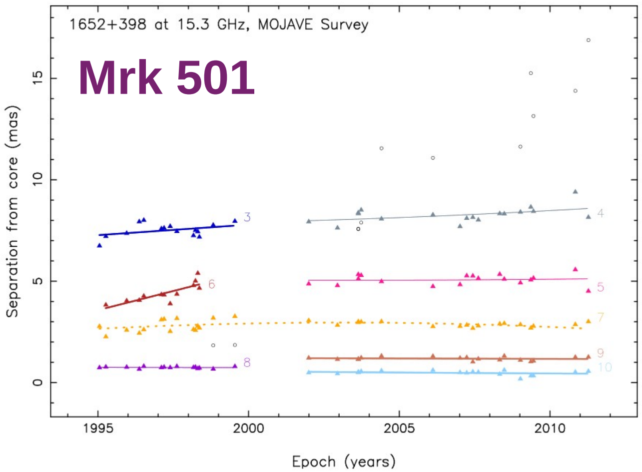


Blazar kinematic classification

- Work on the AGN radio VLBI sample from MOJAVE (based on *Lister et al. 2013*)
- 161 blazars selected with known redshift and sufficient monitoring

3 kind of kinematics representative of the MOJAVE blazar sample

Class I

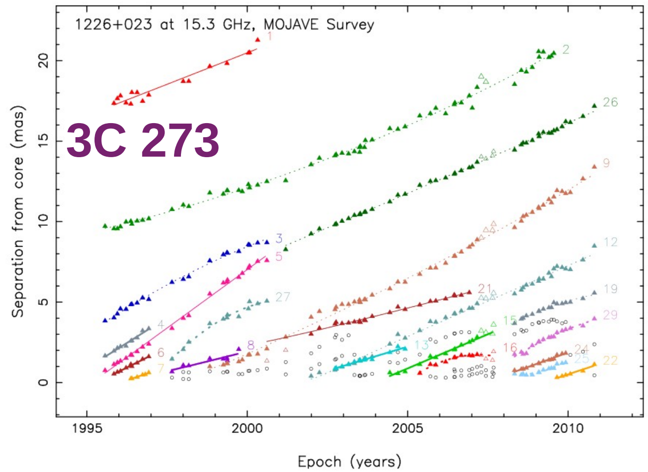


Quasi stationary knots

$\max \beta_{app} < 2c$

25 sources

Class II



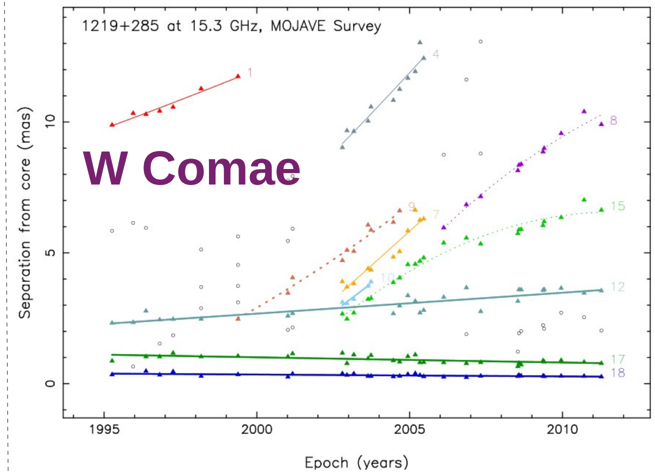
High velocity knots

$\max \beta_{app} > 2c$

$\min \beta_{app} > c$

99 sources

Class I/II



Hybrid kinematics

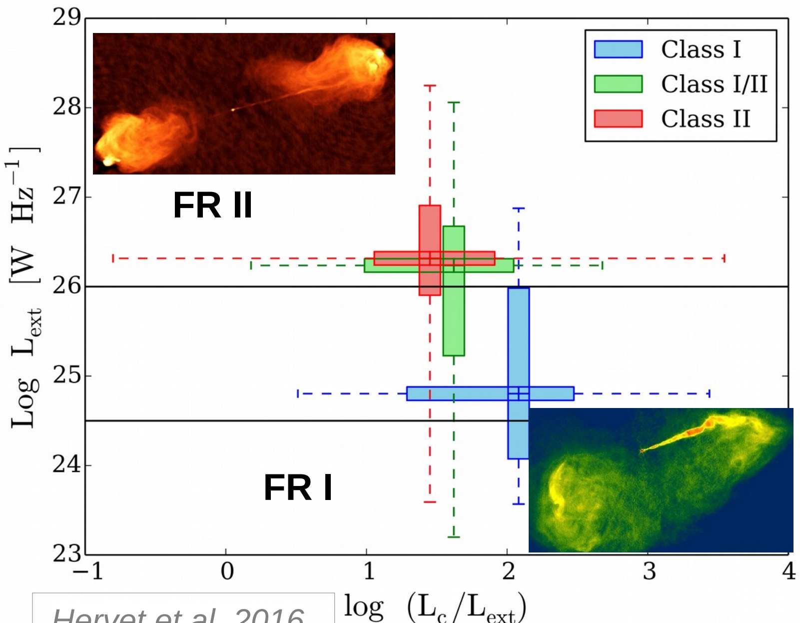
$\max \beta_{app} > 2c$

$\min \beta_{app} < c$

37 sources

VLBI kinematics in the AGN classification scheme

With kpc radio jets...



Hervet et al. 2016

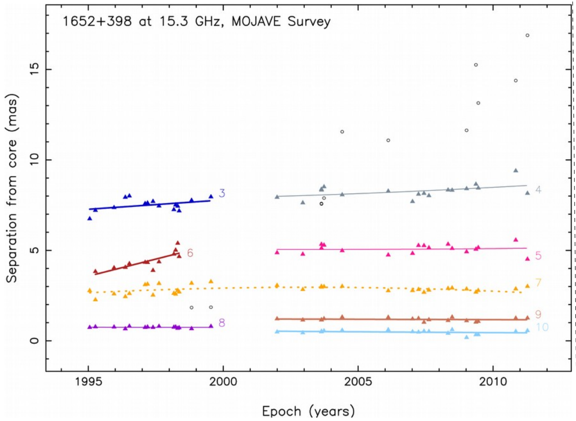
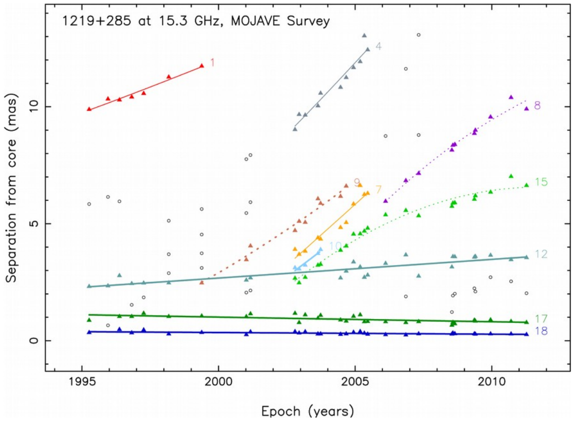
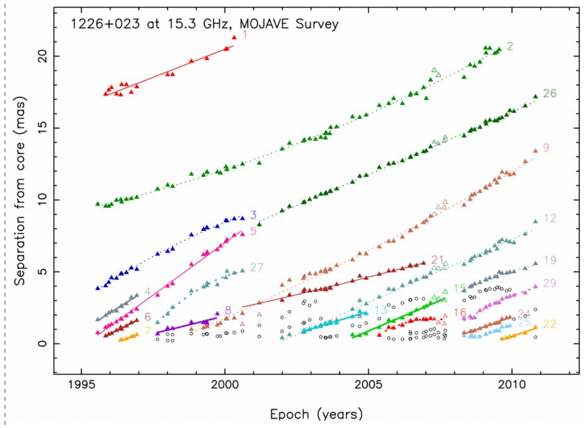
With spectral classes...

Spectral classes	# sources	Class I	Class I/II	Class II
HBLs	5	100 %	0 %	0 %
LBLs/IBLs	24	32 %	56 %	12%
FSRQs	125	8 %	16,5 %	75,5 %

HBLs unfortunately under-represented in the MOJAVE database

Low apparent speeds in TeV HBLs confirmed by *Piner et Edward 2018* (38 sources)

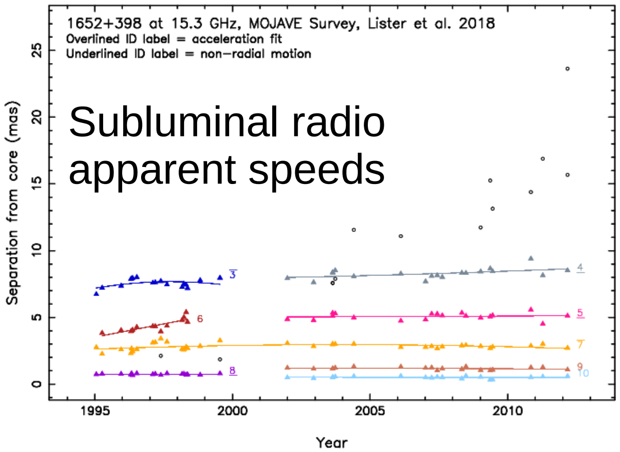
Kinematics with spectral classification

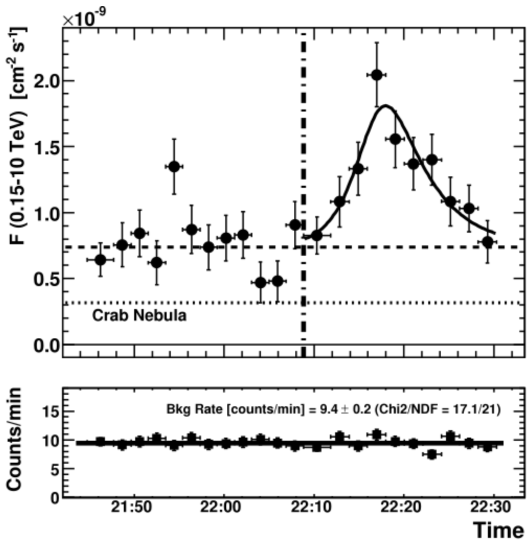
	HBLs	IBLs & LBLs	FSRQs
Main VLBI kinematics	 **Mildly relativistic or stationary knots**	 **Hybrid speeds**	 **Highly relativistic knots**
Synch. peak frequency	X-rays	IR-UV	IR-Opt
Jet Power	$\sim 10^{42} - 10^{45} \mathrm{erg\ cm^{-2}\ s^{-1}}$		$\sim 10^{46} - 10^{48} \mathrm{erg\ cm^{-2}\ s^{-1}}$

III – HBLs: A bulk Lorentz factor crisis

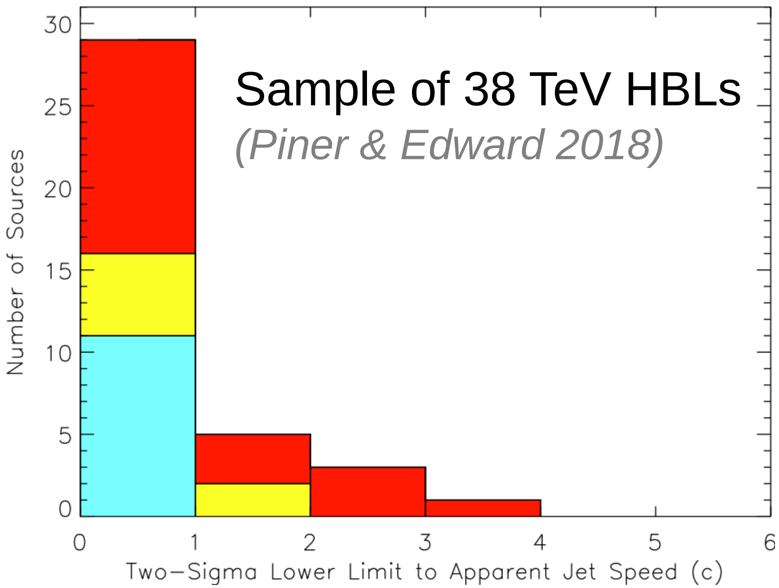
Stationary components in HBLs

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

$$\delta \geqslant \frac{R(1+z)}{c\Delta t_{var}}$$

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

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O. Hervet
LLR Seminar, Palaiseau, Oct. 2020

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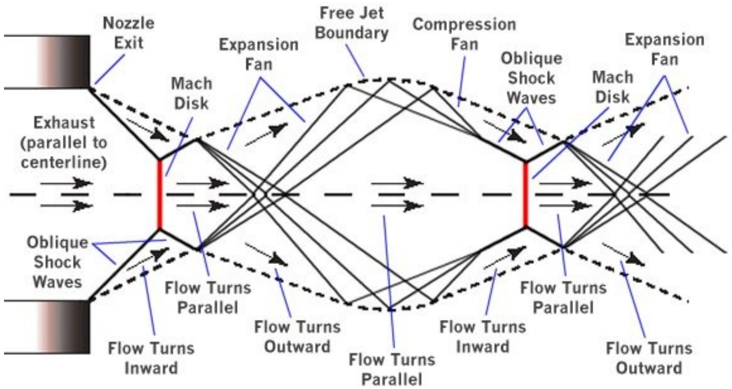
AGN Jets should naturally show multiple recollimation shocks

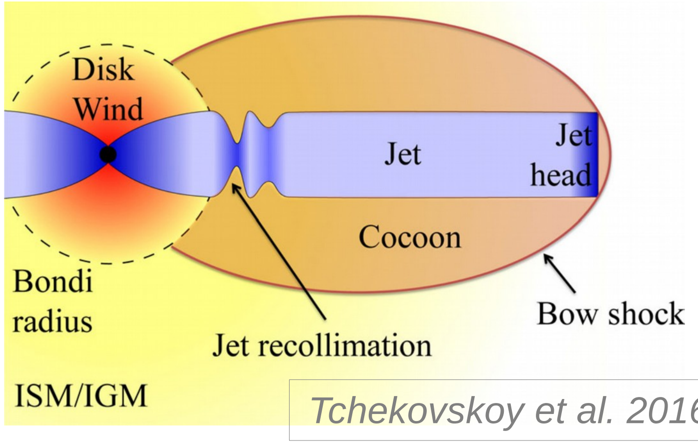
Jet conditions:

- Super(magneto)sonic
- Pressure mismatch with external medium
- Locally severe pressure drop

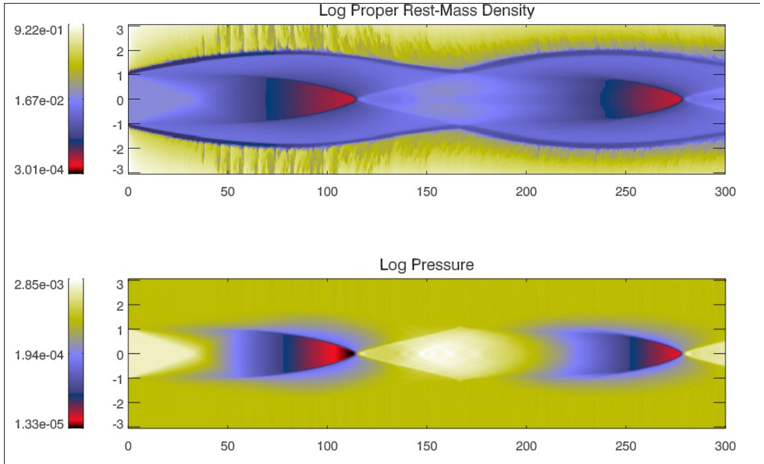


Relativistic (M)HD simulations

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



Tchekovskoy et al. 2016

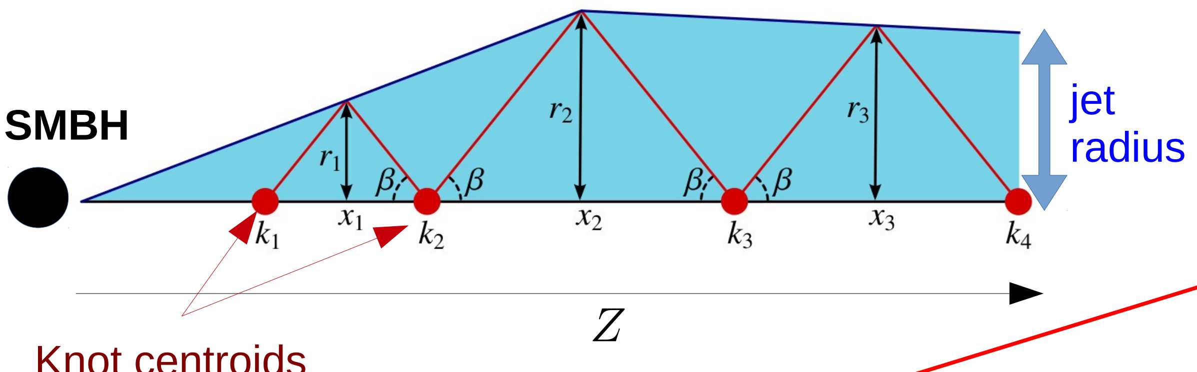


Fromm et al. 2016

Stationary knots as recollimation shocks
– structure of knot strings

Prediction:
If stationary VLBI radio knots are recollimation shocks:

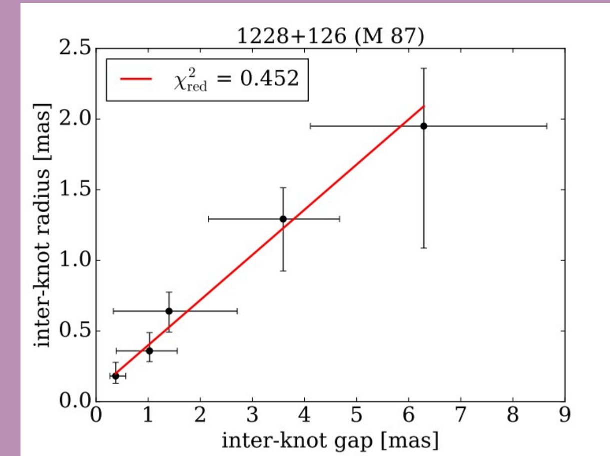
→ the inter-knot gaps should be proportional to the jet radius (isothermal approximation)



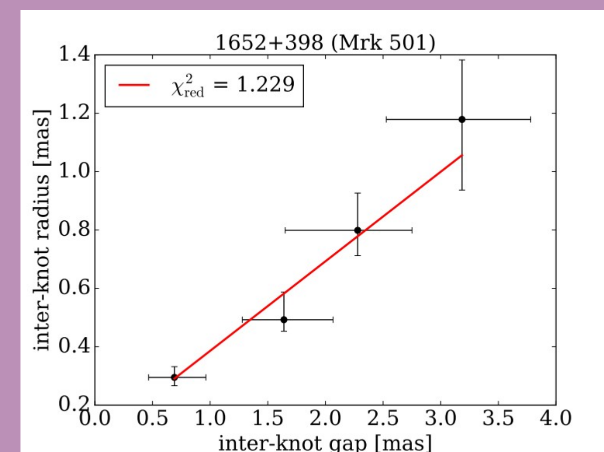
$$r_n \propto \Delta k_n$$

Verified!

M87



Mrk 501



Relation checked on ~10 jetted AGNs with stationary knots

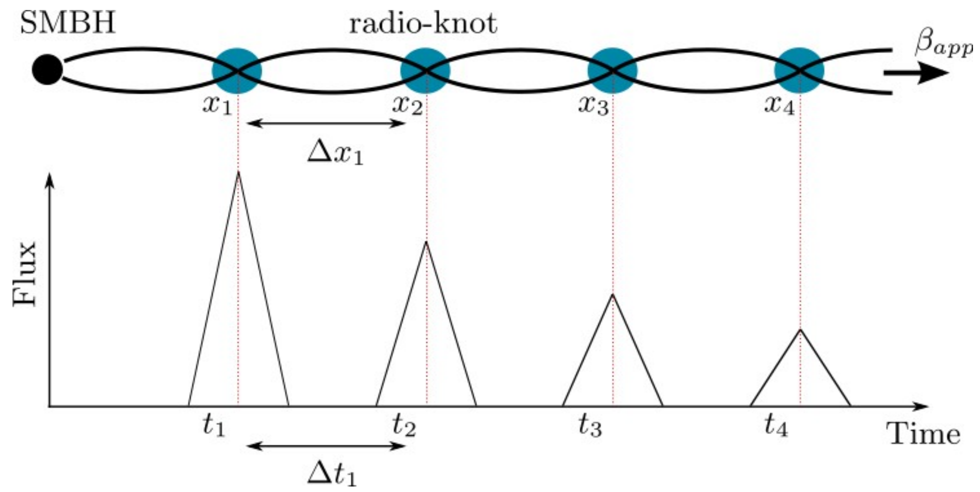
(Hervet et al. 2017)

Expected signature of successive shocks in lightcurves

5 Following slides based on:
"Probing an X-Ray Flare Pattern in Mrk 421 Induced by Multiple Stationary Shocks: A Solution to the Bulk Lorentz Factor Crisis"
Olivier Hervet, David A. Williams, Abraham D. Falcone, and Amanpreet Kaur
The Astrophysical Journal 877, 26 (2019)

If powerful shocks, jets perturbations should show signatures in the lightcurves.

Sketch of expected signature:

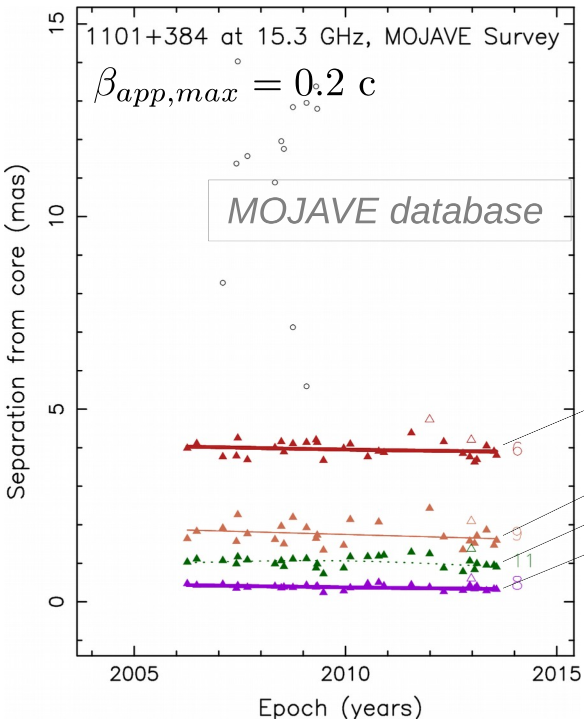


Assuming a constant flow speed:

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

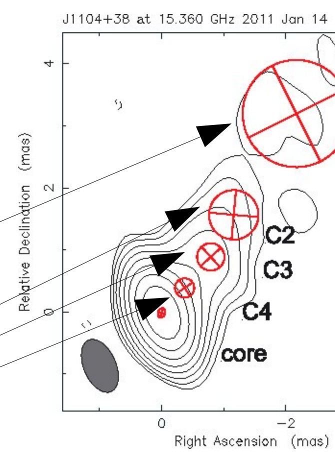
Due to high Doppler beaming, Blazars are the best candidates, with such a pattern expected in a week-to-year timescale.

Mrk 421, the ideal candidate

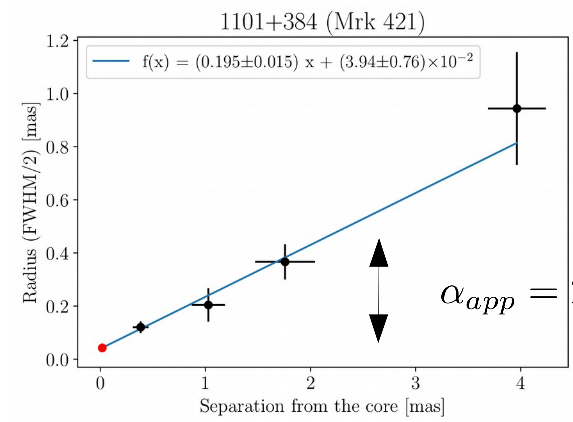


MOJAVE database

4 quasi-stationary knots



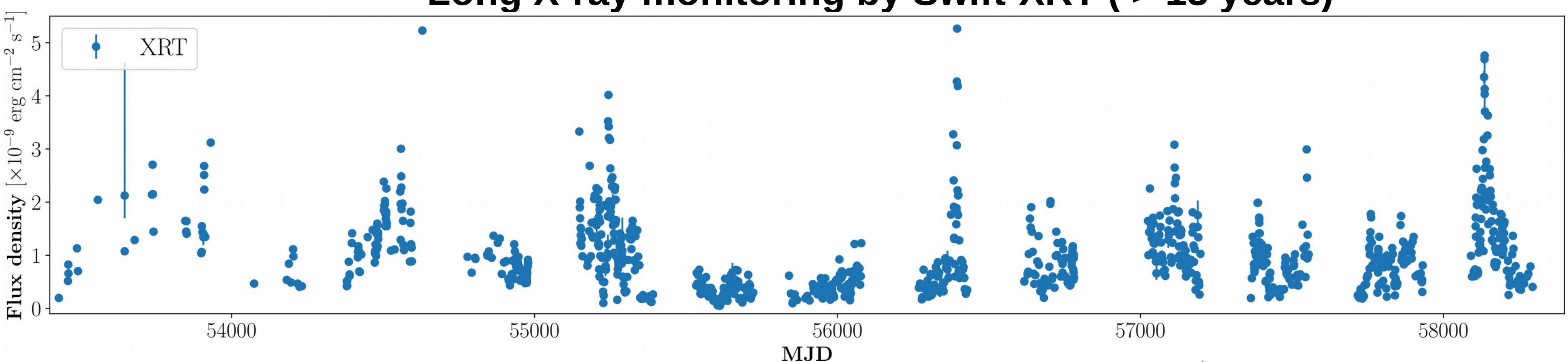
Lico et al. 2012



Conical jet

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

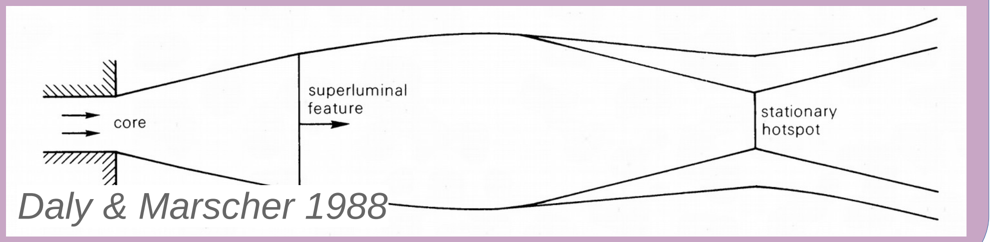
Long X-ray monitoring by Swift-XRT (> 13 years)



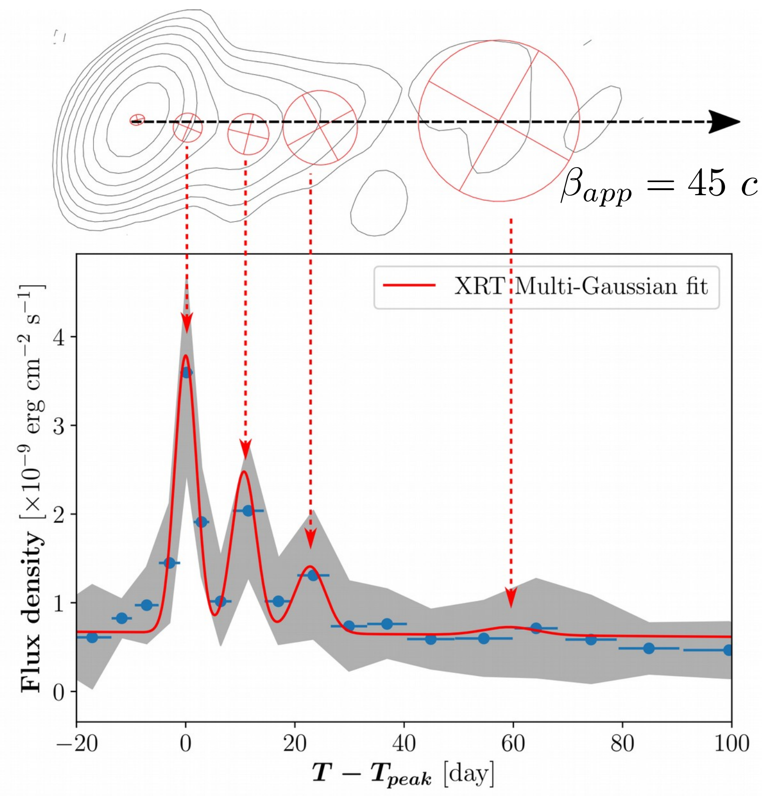
Testing the model on Mrk 421

Model favored:

Core = expanding funnel
4 stationary knots = 4 recollimation shocks



Fit on Flare-stacked XRT lightcurve
(fit done on unbinned dataset, rebinned for display purpose only)



Model validated at > 3.2 sigma level against stochastic fluctuations

Flares fitted by a multi-Gaussian function

$$G_m(t) = \sum_{i=1}^{4} [A_i P_i(t)] + B(t)$$

6 dof

Amplitude — Gaussian — Baseline

- Inter-Gaussian gaps scaled on inter-knot gaps
- Gaussian widths scaled on knot sizes
- Gaussian amplitudes scaled on knot volumes

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)

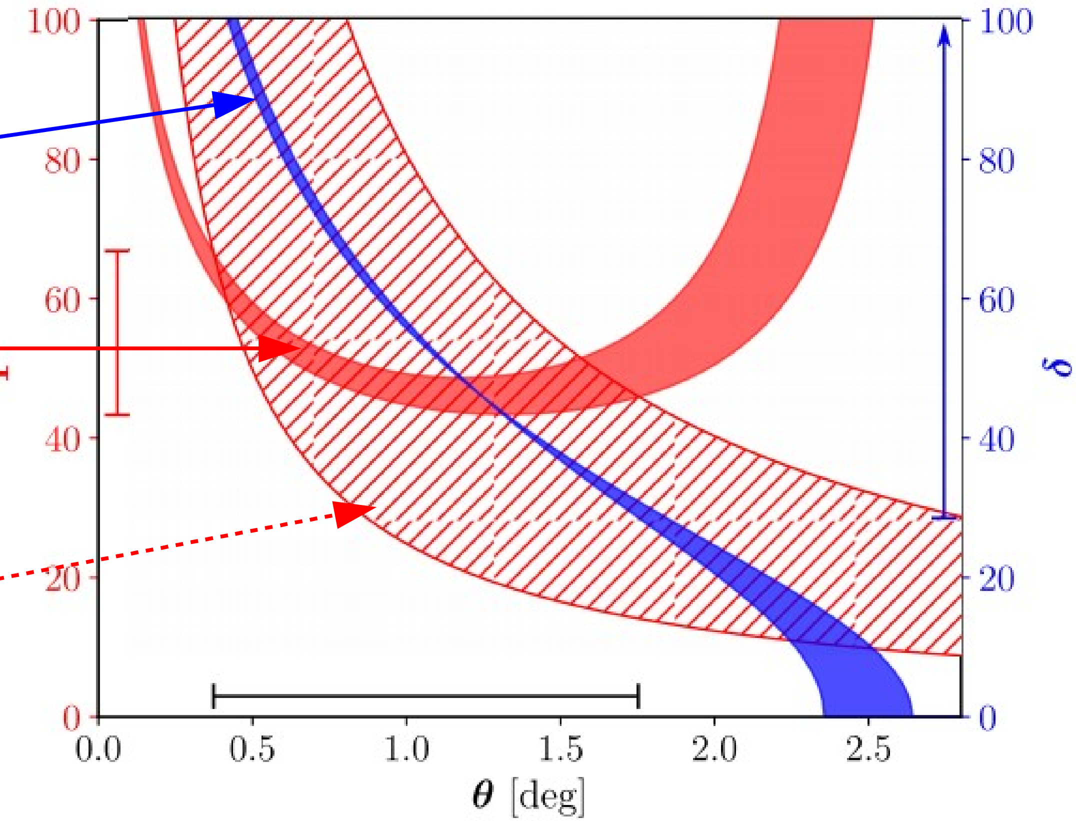
Constraint on beaming parameters

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

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

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

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

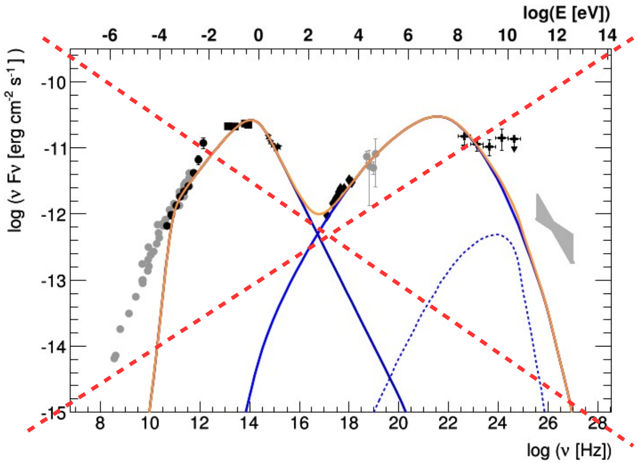
Typical intrinsic width of a perturbation (from the Gaussian widths):

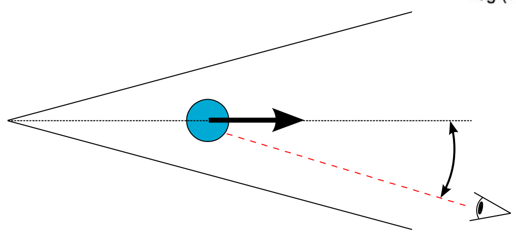
$W_p \in [0.43 - 19] \times 10^{17}$ cm

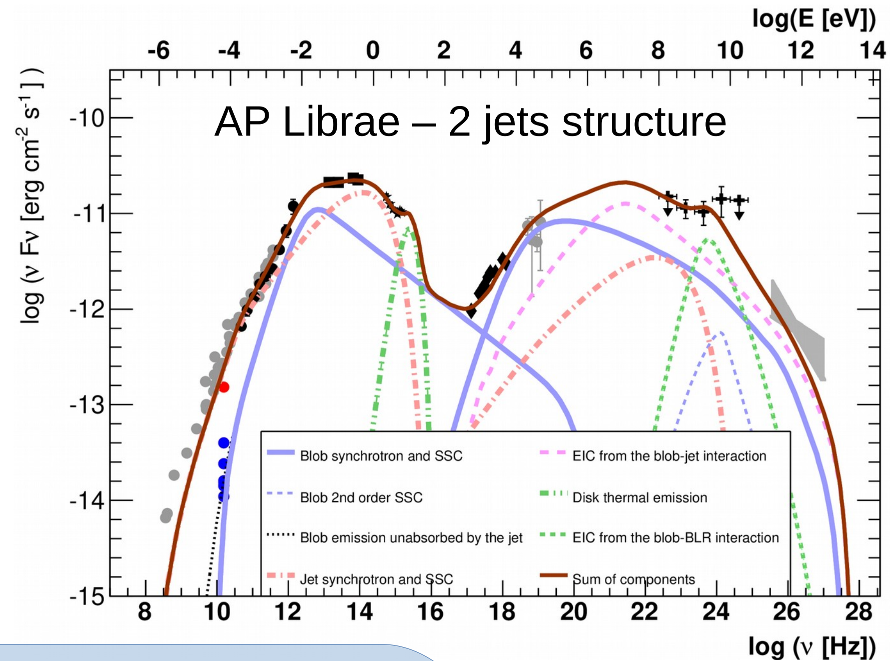
IV – Intermediate blazars, a distinctive class

Intermediate blazars modelling – *beyond the blazar dichotomy scheme*

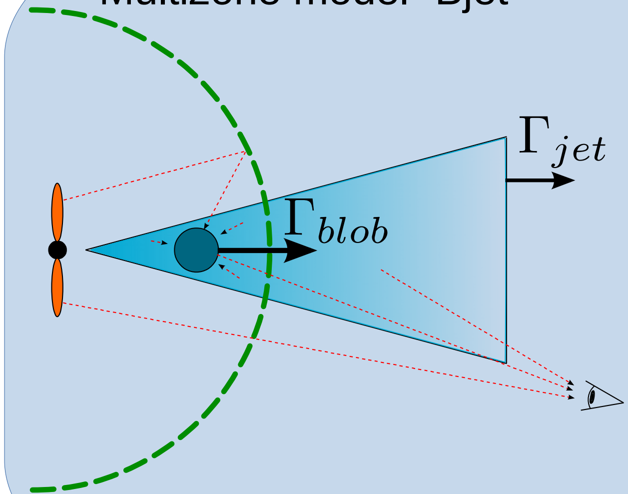
AP Librae - one zone SSC







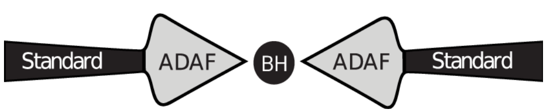
Multizone model “Bjet”



Hervet et al. 2015

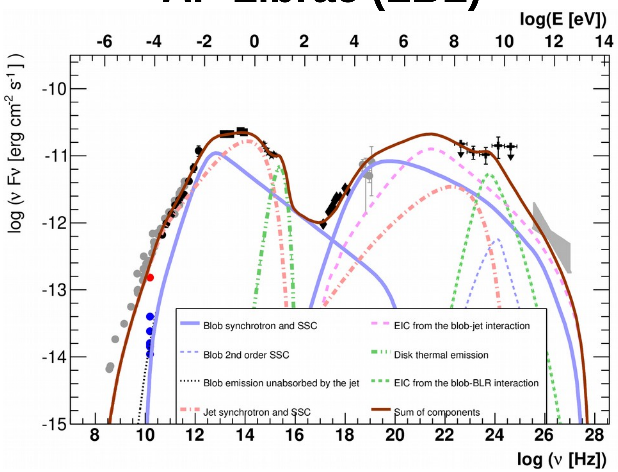
Intermediate accretion efficiency

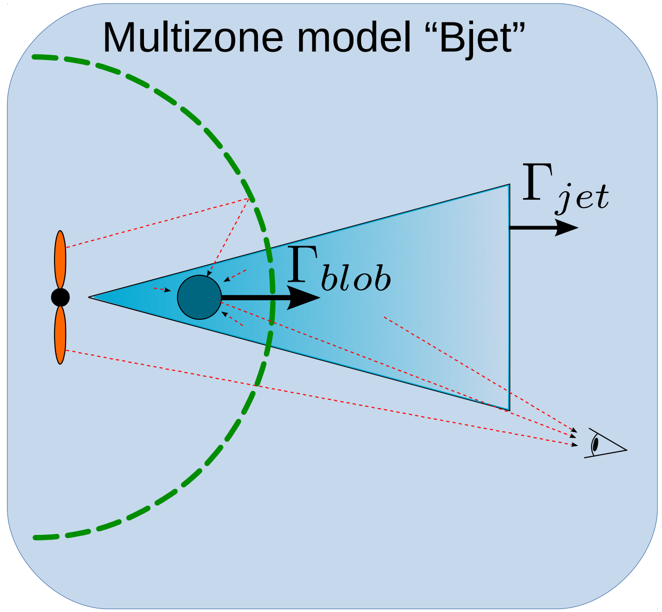
$$\eta = \frac{\dot{M}}{\dot{M}_{Edd}} \simeq 3.1 \times 10^{-3}$$



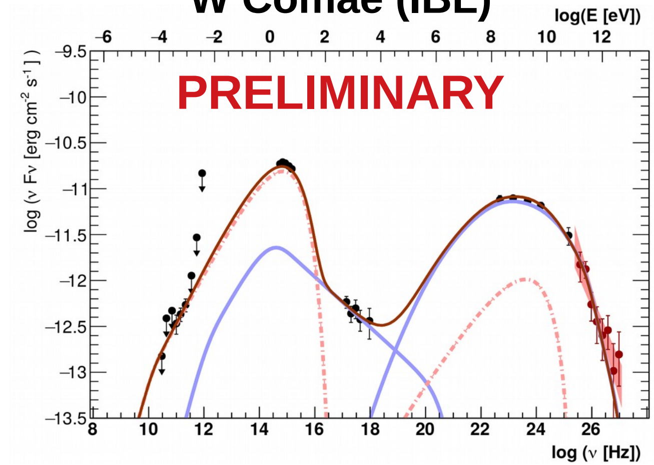
TeV Intermediate blazars – *highlights of 2 imbricated radiative jets*

AP Librae (LBL)

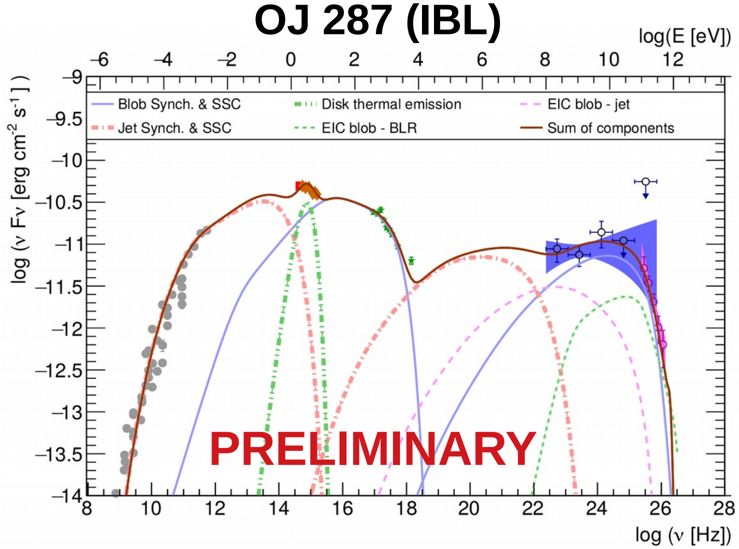




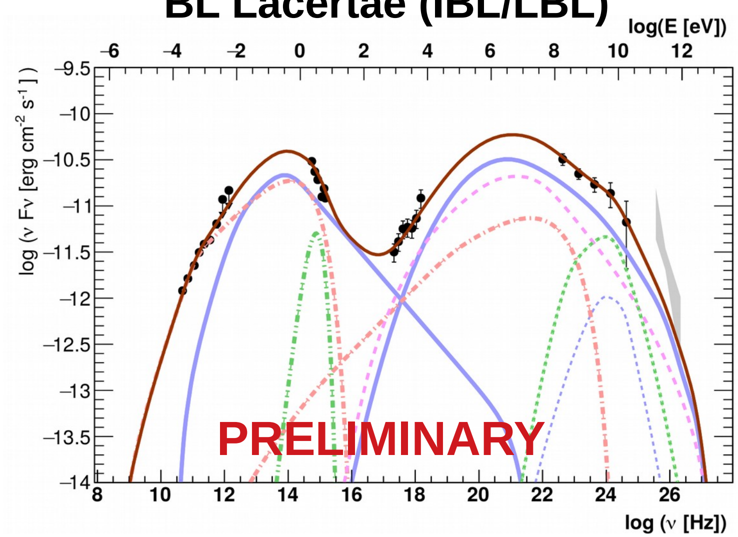
W Comae (IBL)



OJ 287 (IBL)

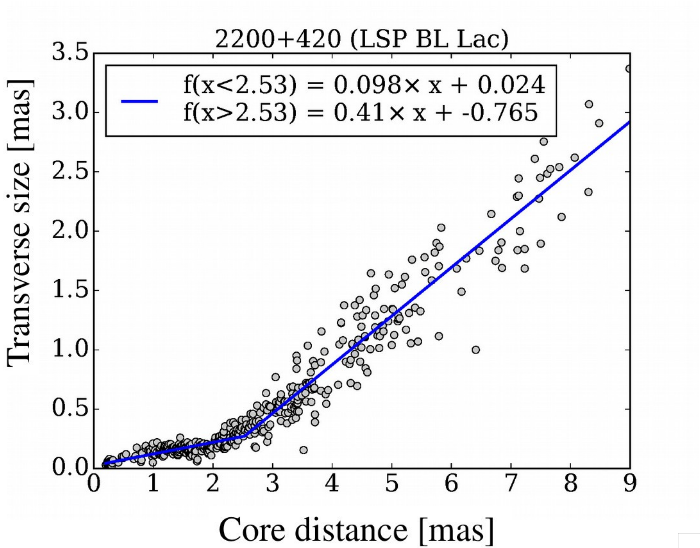


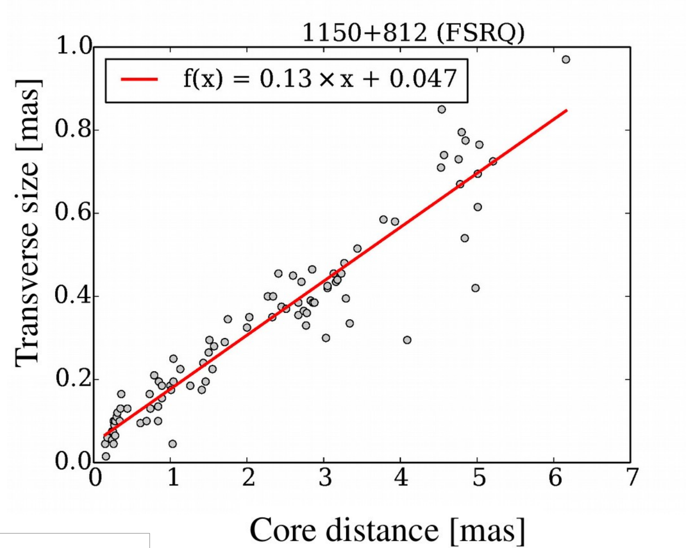
BL Lacertae (IBL/LBL)



Jet aperture increase for intermediate blazars

VLBI radio knots sizes vs core distances



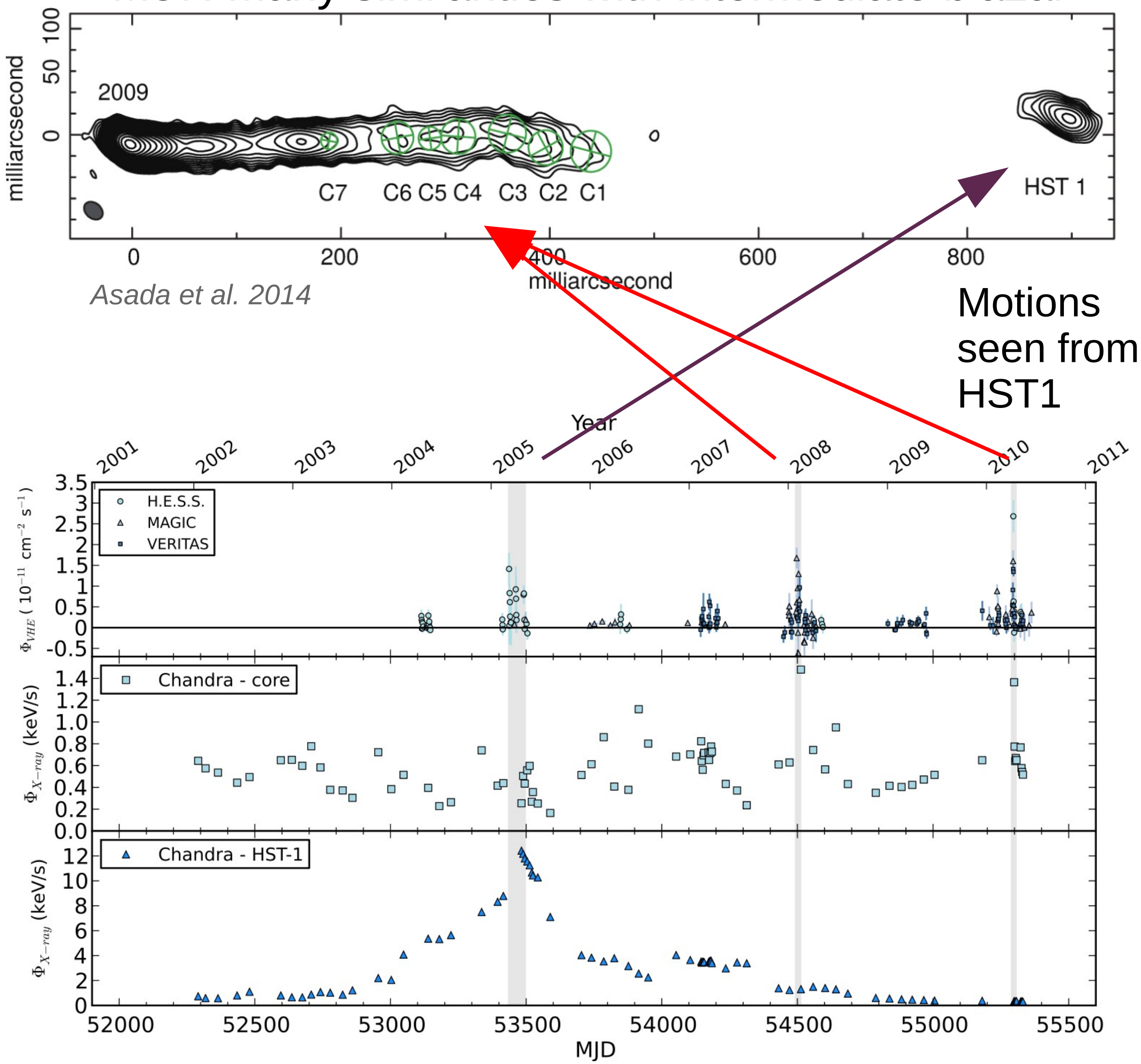


Hervet et al. 2016

Spectral classes	# sources	Significant aperture increase
HBLs	5	20 %
LBLs/IBLs	24	**63 %**
FSRQs	125	15 %

Bright and unstable last stationary knot

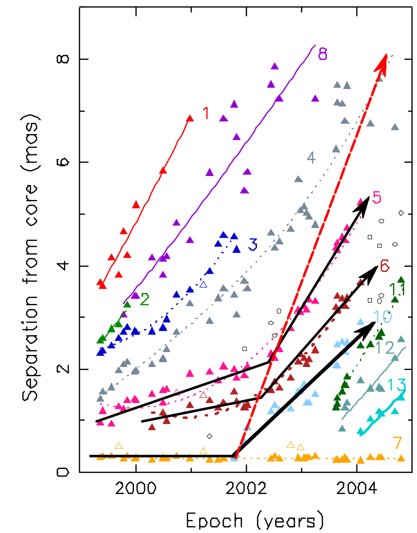
M87: many similarities with intermediate blazar



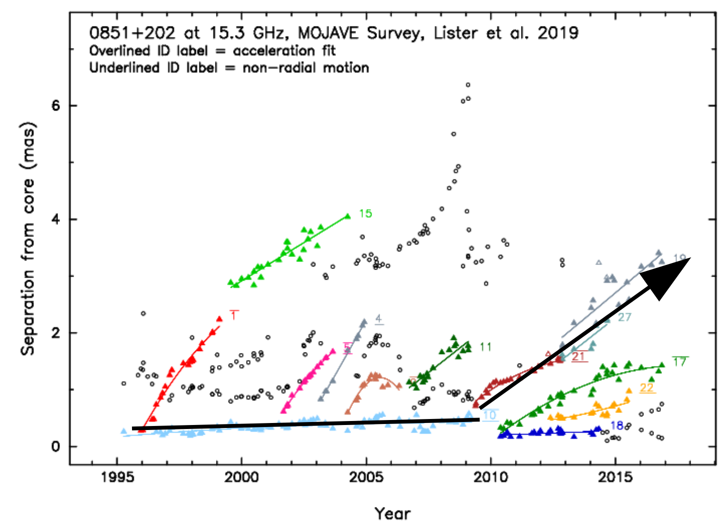
Asada et al. 2014

Abramowski et al. 2012

BL Lacertae



OJ 287



V – Updating the unification with recollimation shocks in 2 flows jets

Two-flows in jets

Two-flow model *(Sol et al. 1989)*

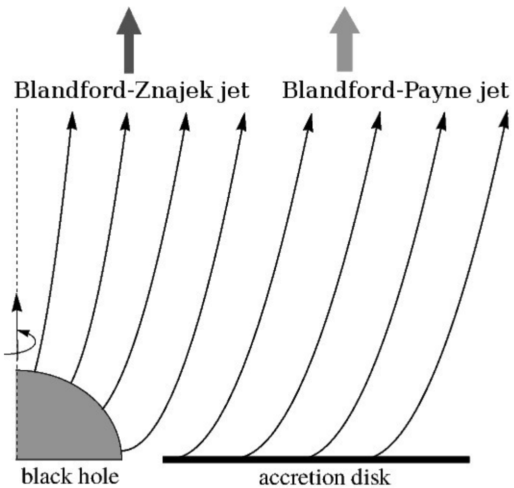
- Mildly relativistic sheath composed of e−/p+ and driven by MHD forces

  → transports most of the kinetic energy

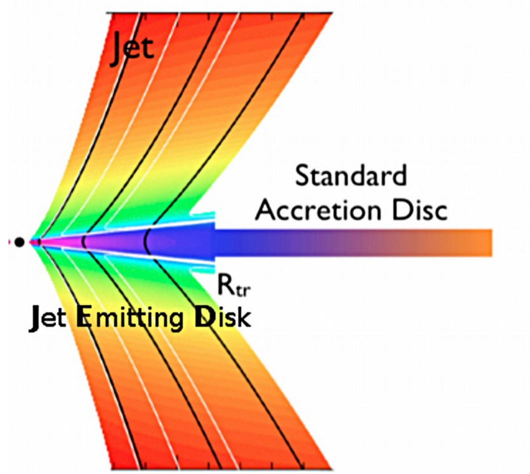
- Ultra-relativistic spine composed of e−/e+ pairs

  → responsible for most of the emission

2 flows expected by different theoretical scenario

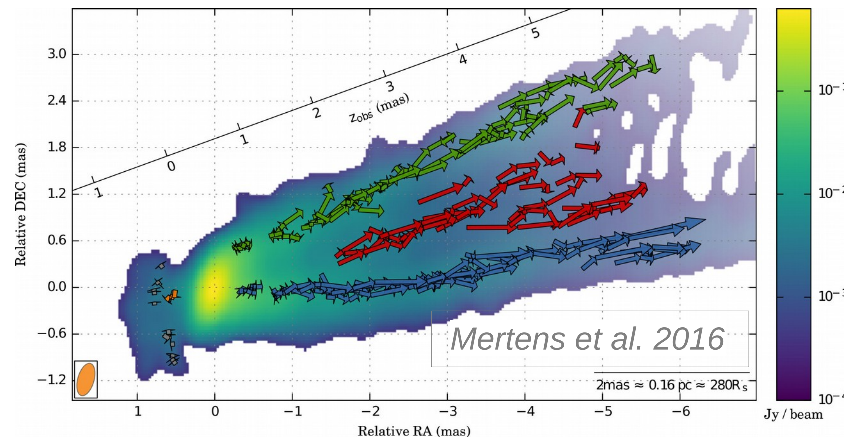


Adapted from Xie et al. 2012

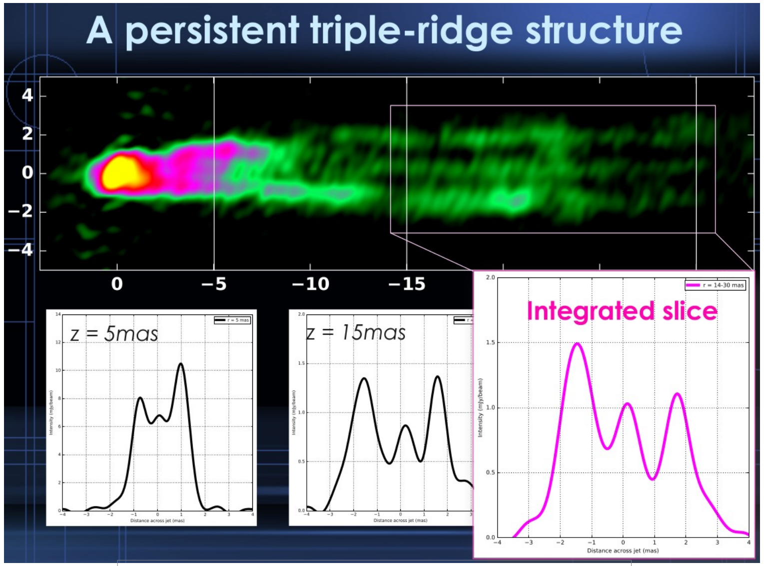


Ferreira & Pelletier 1995

Radio VLBI observations (M87)



Mertens et al. 2016

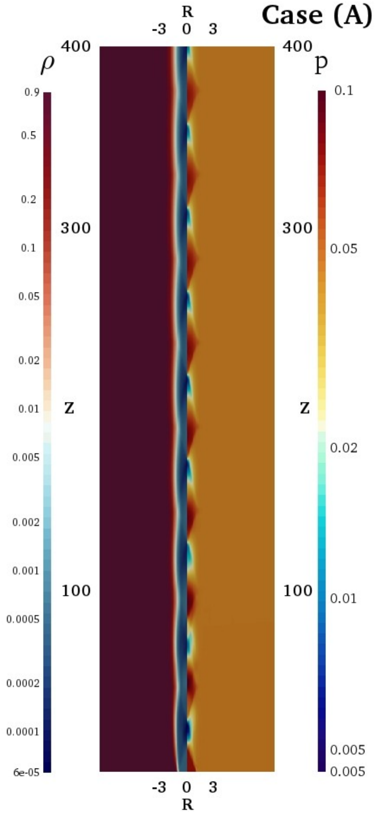


From K. Hada presentation, 2016

Successive recollimation shocks in two-flows jets – *Simulations*

	external medium	inner jet		outer jet		Structured jet		
case	p_0	$\eta_{\rho,\text{in}}$	$M_{\text{c,in}}$	$\eta_{\rho,\text{out}}$	$M_{\text{c,out}}$	$L_{\text{k, in}}/L_{\text{k, total}}$	$L_{\text{k, out}}/L_{\text{k, total}}$	Two-component jet
A	5×10^{-2}	4.5×10^{-4}	1.22			1	0.0	No
B	1×10^{-3}	5×10^{-1}	4.34	5×10^{-6}	1.16	0.95	0.05	Yes
C	5×10^{-2}	5×10^{-3}	1.22	5×10^{-1}	16.34	0.70	0.30	Yes
D	1×10^{-3}	5×10^{-6}	1.22	1×10^{-1}	6	0.25	0.75	Yes
E	5×10^{-2}	5×10^{-3}	1.22	5×10	19.0	5×10^{-3}	0.995	Yes
F	5×10^{-2}	1×10^{-3}	0	5×10^{-2}	6.0	0	1	Yes

Case (A)

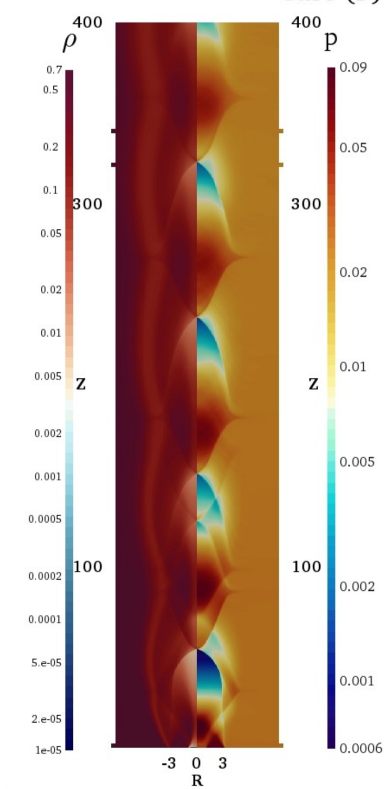


- 2D RHD simulation of jets with MPI-AMRVAC code *(Keppens et al. 2012)*
- 5 types of two-flow jets simulated
- Two initial Lorentz factors: $\Gamma_{in} = 10 \;\; \Gamma_{out} = 3$
- Jet radius $R_{out} = 3R_{in}$
- Classified following the kinetical power between inner and outer jets

Caveat

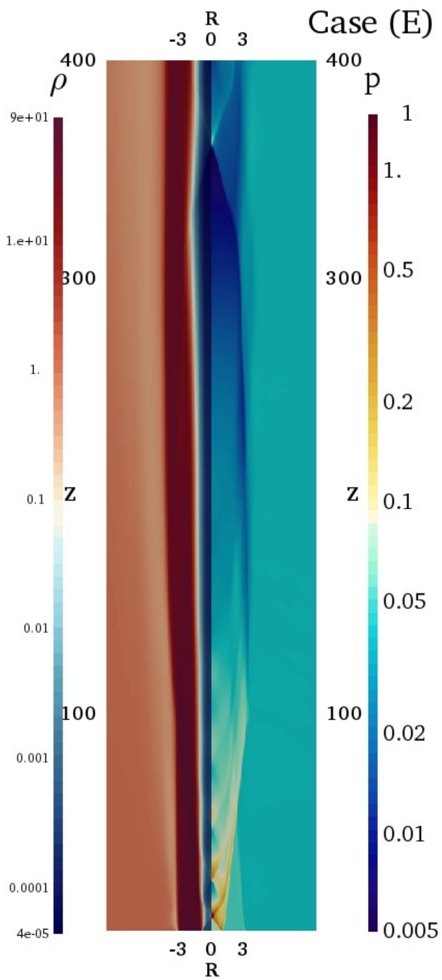
Fast motions observed in jet are not reproduced by these simulations
→ No injected perturbations, no magnetic field...

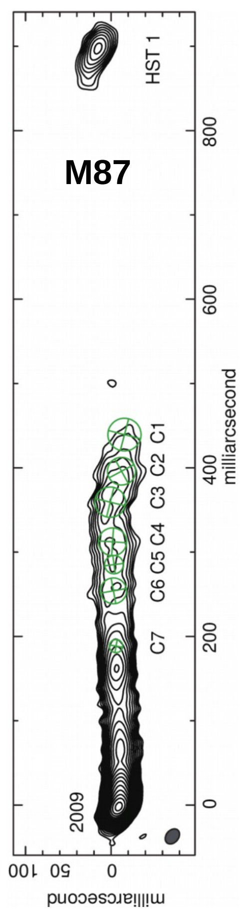
Case (F)



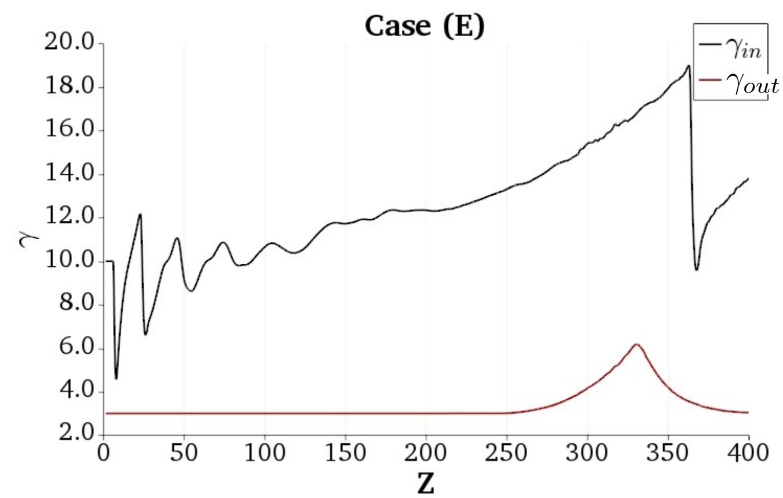
Powerful outer jet – *Case of intermediate blazars (and M87)?*

Two-components jet $P_{jet,in} << P_{jet,out}$





Asada et al. 2014

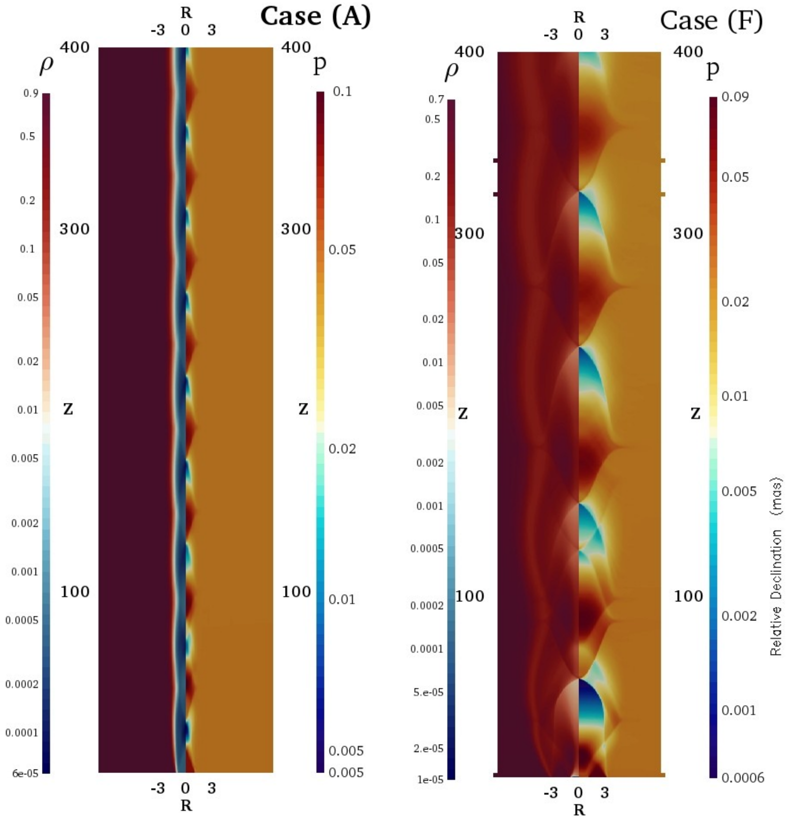


- Outer jet acting as a wall for the inner jet
- Fast damping but close successive shocks at the jet base
- Long rarefaction wave from the outer jet induces a powerful flow acceleration and unstable shock far downstream
- Increase of jet aperture after the outer jet shock

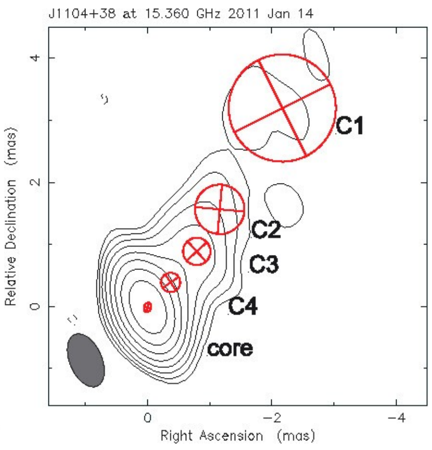
One component jet – *Case of HBLs?*

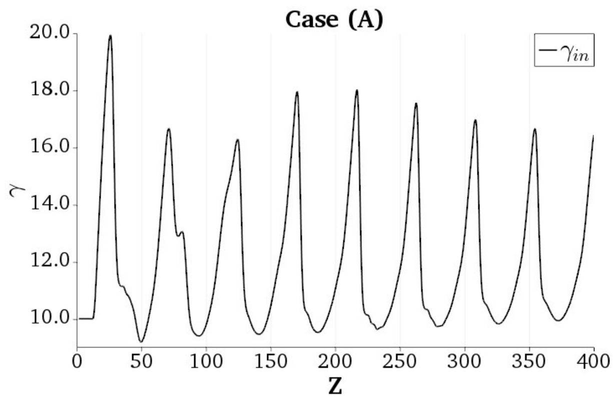
Or 2 jets with $P_{jet,in} >> P_{jet,out}$

Inner jet? Outer jet (empty spine)?



Mrk 421

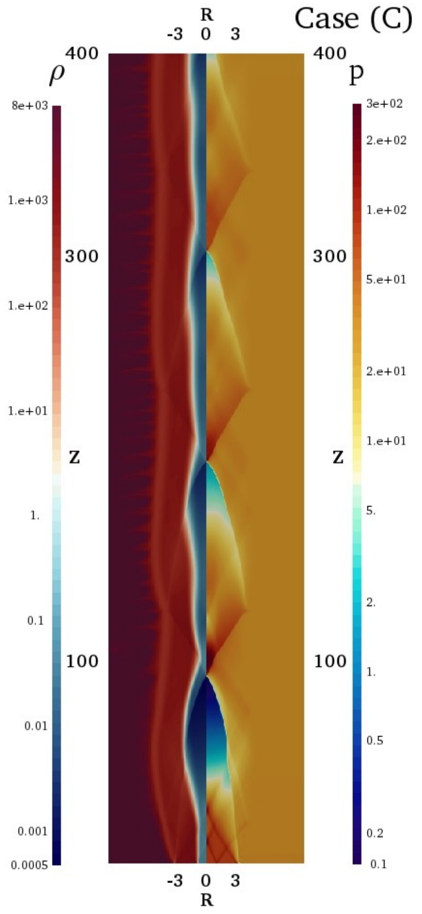


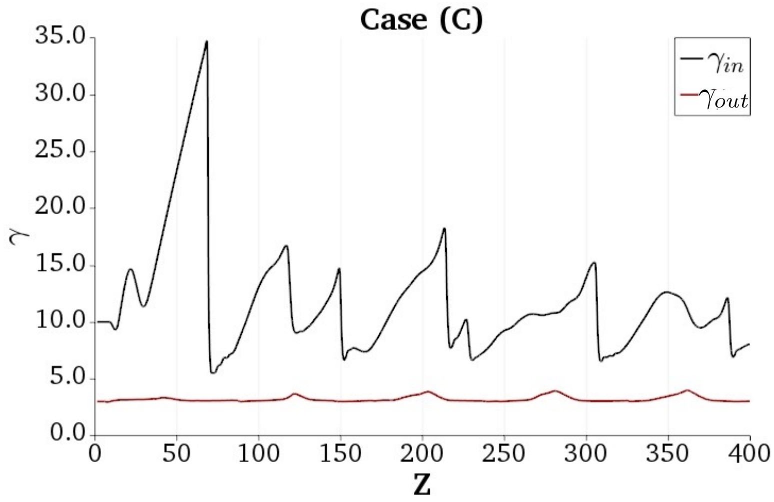


- One component jet, inner or outer produces similar structure
- Multiple successive stationary shocks

Similar two flows powers – *Case of FSRQs?*

Two-components jet $P_{jet,in} \simeq P_{jet,out}$





- Powerful compression from the outer-jet shock waves
- First shock is strongly dominating the energetics (γ : 10 → 35)

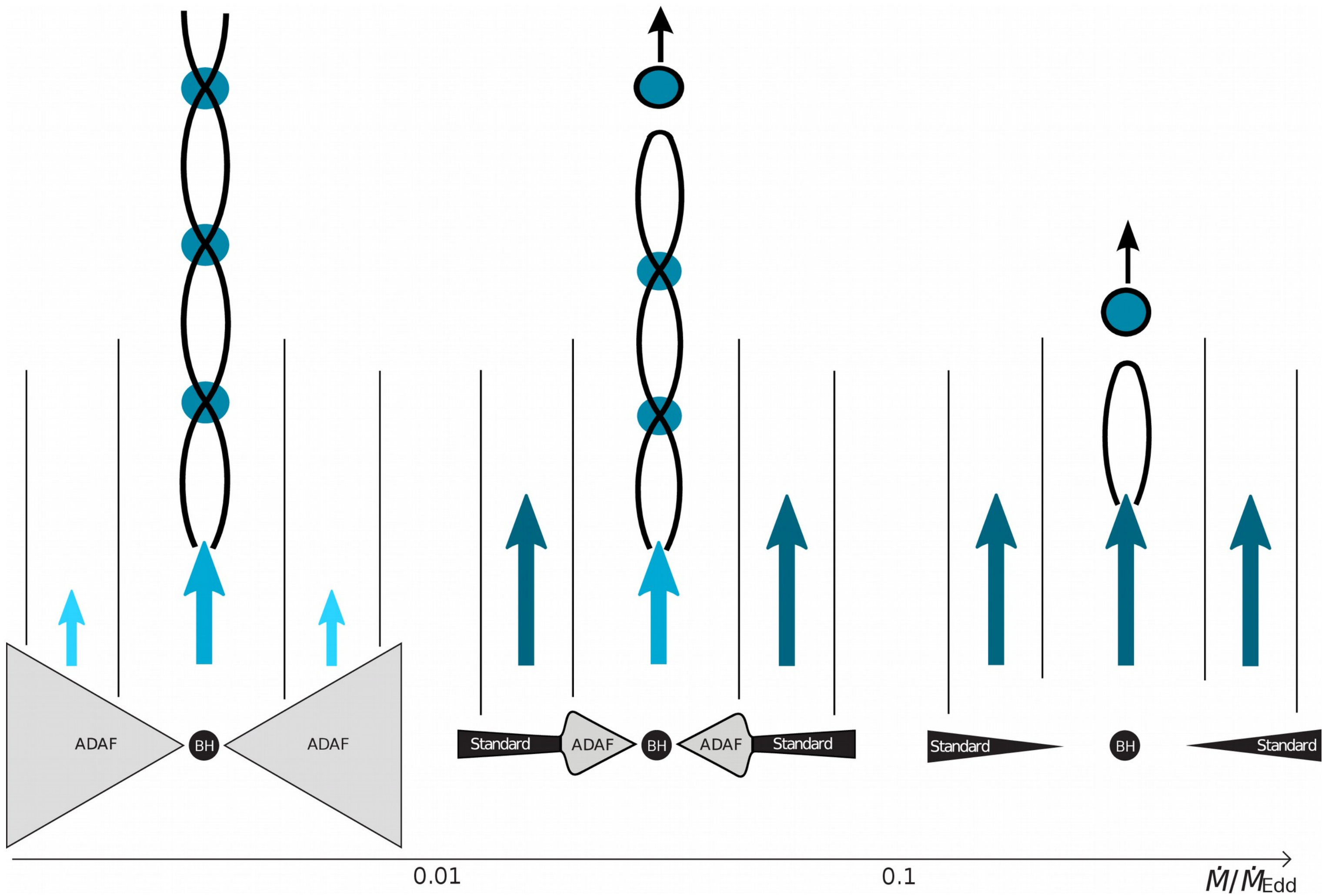
Updating the jetted AGN scheme

Large scale structure — **FR I** — **FR I or FR II** — **FR II**

Pc scale structure

Jets kinetic powers

Accretion regime



Spectral class — **HBL** — **LBL-IBL** — **FSRQ**

Conclusion & Outlook

The usual jetted AGN unification scheme fails to describe some phenomena such as:
- the various pc-to-kpc jet kinematics
- the bulk Lorentz factor crisis in HBLs
- the complex MWL behaviour and jet structure observed in multiple intermediate blazars

We can update the unification in a consistent way if we considers non-thermal emission zones associated with **recollimation shocks in two flows jets** and (at least) **3 physically distinct classes of blazars**

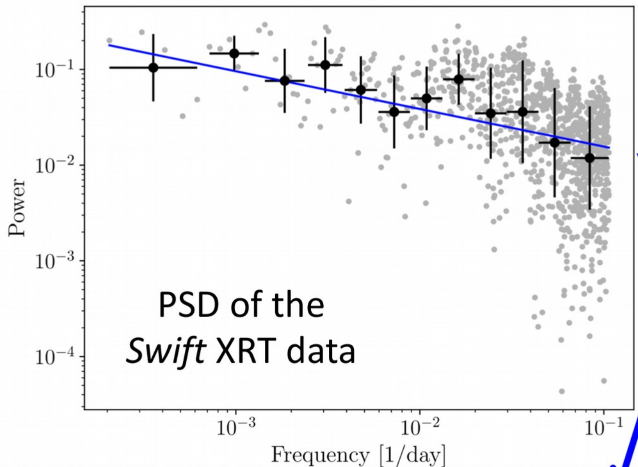
Main proposed update:
The jet classification is not only depending on the total output power, but also on the power equilibrium between inner and outer jets

Long road ahead

- **Improve RMHD simulations:** various kinematics, magnetic field structure, shock radiative power,...
- **Confirm the suggested variability pattern in HBLs**: in other energies and for other sources
- **Increase the sample of intermediate blazars:** coordinated MWL campaigns + modelling
- **Study the particle re-acceleration process potential and emission of successive shocks**

Annexes

What is the Statistical Significance?



Generated millions of **simulated light curves** which match the properties of the data:

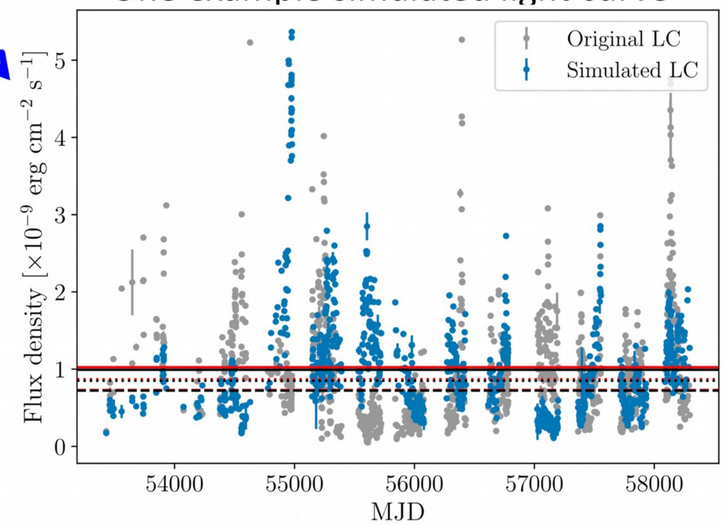
- The **power spectrum density** (PSD)
- The time sampling (from data)
- The **flux distribution**
- The measurement uncertainties (from data)
- The number of flares (subset of curves)

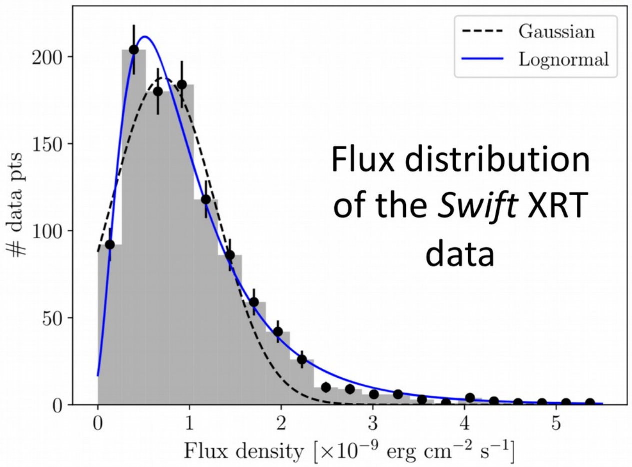
Compare the fit reduced χ^2 to the **distribution from the simulations.**

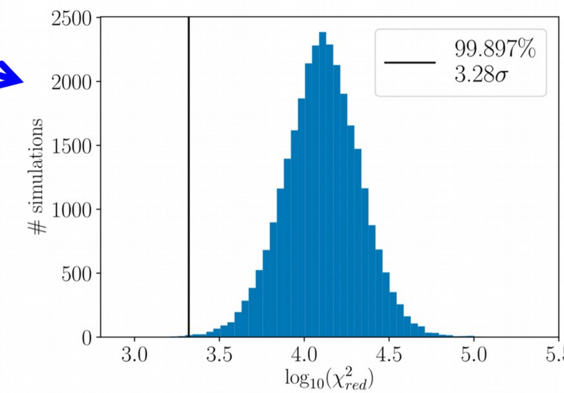
99.897% of the simulations have worse reduced χ^2, corresponding to 3.28σ.

Alternatives that selected fewer (bright) or more (dim) flares for stacking gave 3.50σ and 3.97σ, respectively.

One example simulated light curve



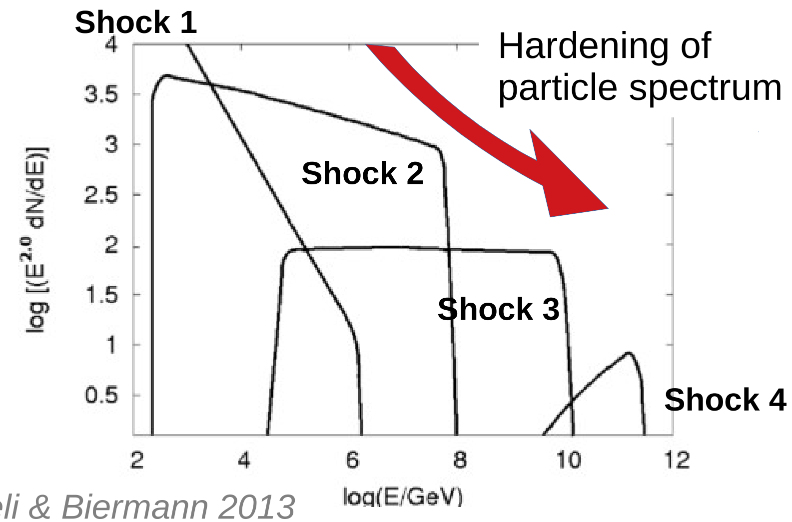




11

Extreme HBLs, probe for particle re-acceleration in radio knots?

- Extreme HBL: synchrotron emission peaking in the X-ray band above 1e17 Hz and gamma-ray emission in the GeV to TeV range (should typically suffer from the Klein-Nishina cut)
- "Too hard" VHE spectra in some sources, seems to be a separate particle population contributing to the extreme gamma-rays
- Currently mostly handled via (lepto-) hadronic models, could it be a sign of particle re-acceleration via successive shocks (I.e. sucessive stationary radio knots)?



Meli & Biermann 2013

May also require radiative protons to avoid too fast particle cooling between successive shocks