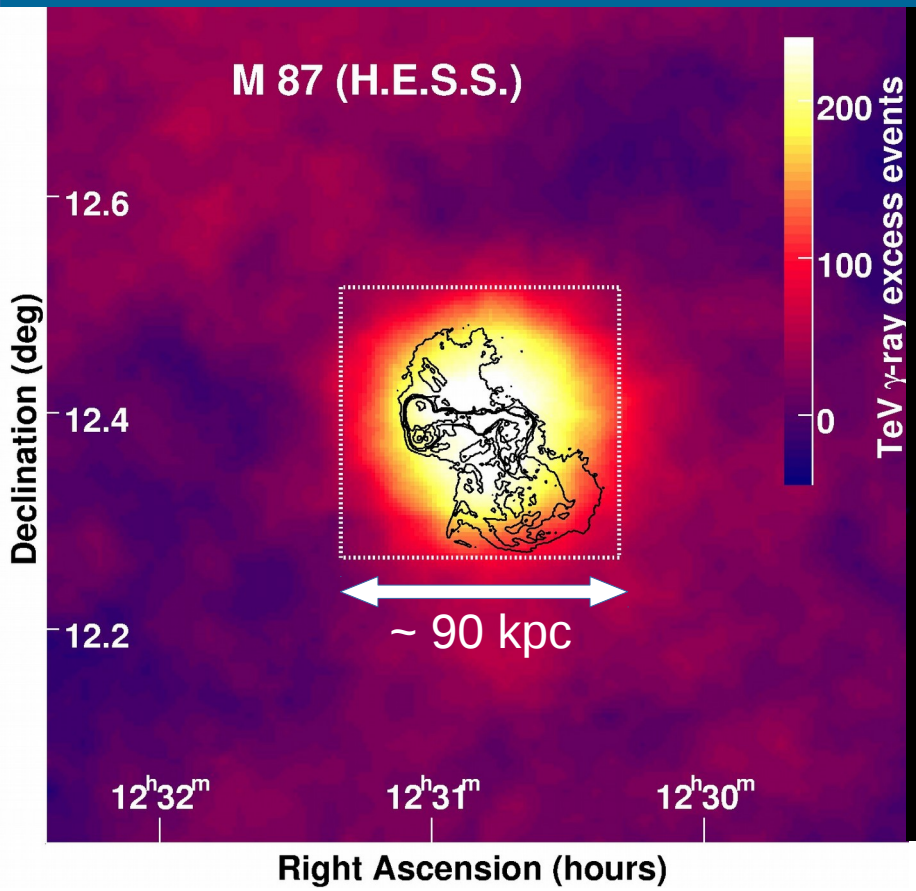
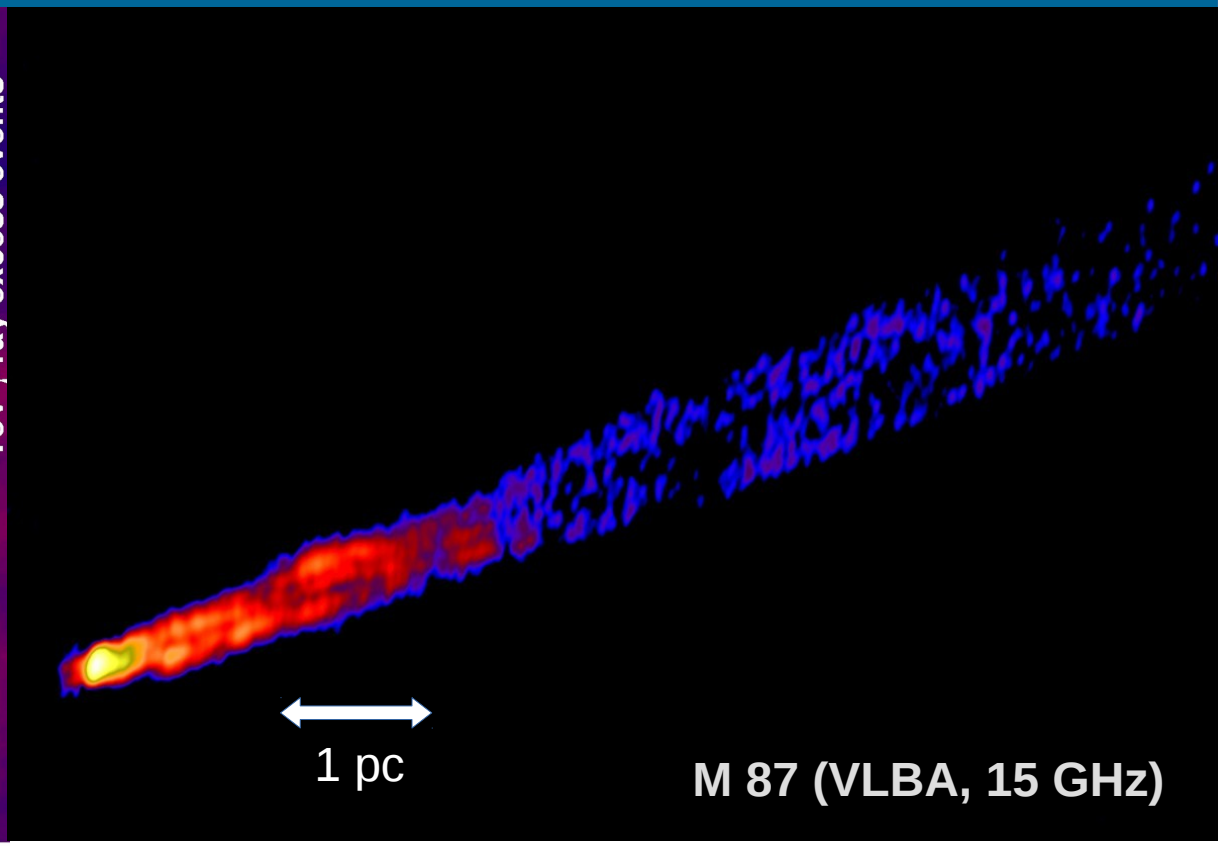
Linking high-energy emission with radio-VLBI jets





Olivier Hervet

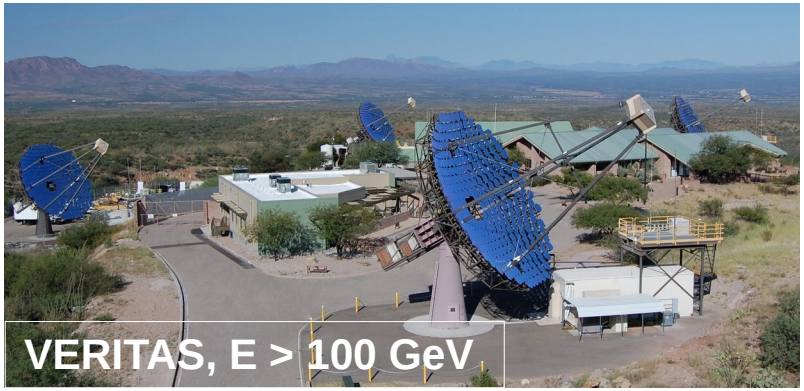
UNIVERSITY OF CALIFORNIA SANTA CRUZ

SCIPP
Santa Cruz Institute for Particle Physics

Simulating the evolution and emission of relativistic outflows
November 2019, Paris Observatory, Meudon

I – Gamma-rays vs radio-VLBI, a complementary view

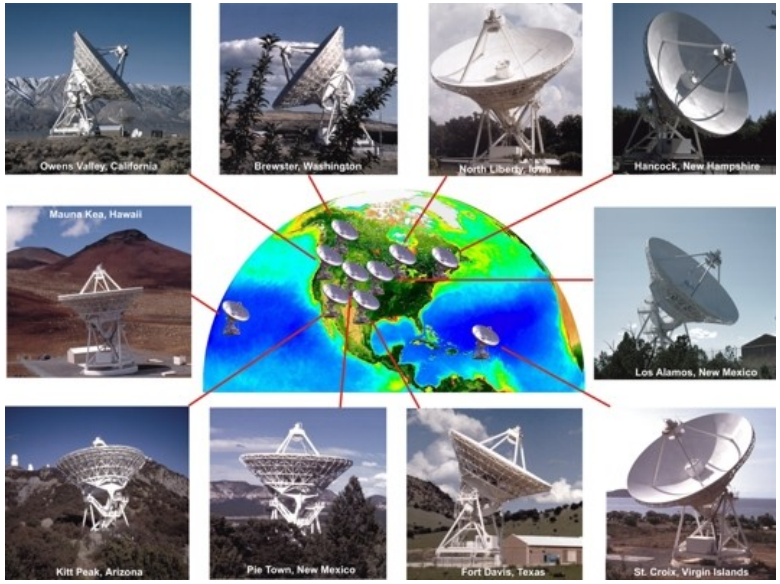
Two very different faces of the same coin



- Address to compact zones (<< pc)
- Constraint particle physics phenomena (acceleration, cooling, particle distribution, particle type...)

	Angular resolution	Min. variability	Spectral reconstruction
Gamma-rays	> arcmin	Few min.	Systematic, wide spectrum
Radio VLBI	~μas to mas	Few days	Rare and difficult

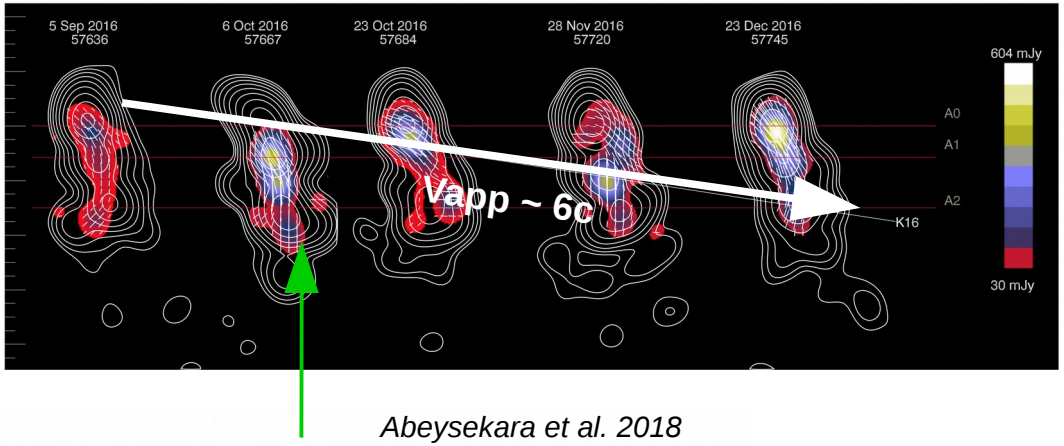
VLBA



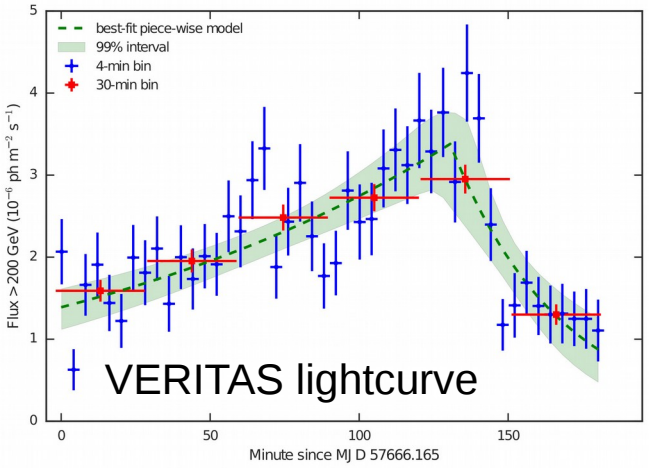
- Address to large jet zones (sub-pc to kpc)
- Constraint jet structure and dynamics
- Informations on magnetic field structure

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

e.g BL lacertae 2016



Abeysekara et al. 2018



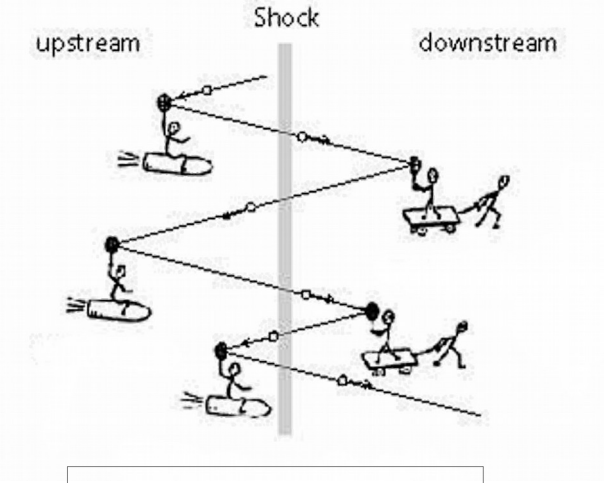
Also seen in:

- **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 → *See Martin Lemoine & Fabien Casse presentations*



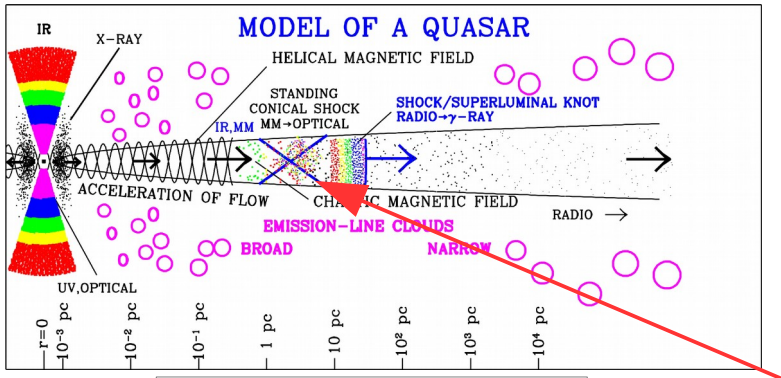
Credit: Hoshino 2001

Theoretical power law particle spectrum:

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

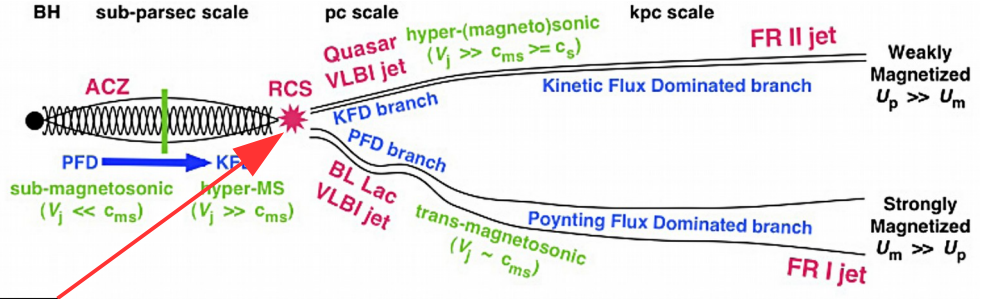
→ Globally consistent with synchrotron-self-Compton models

Master recollimation shock (MRCS)



Marscher & Gear 1985

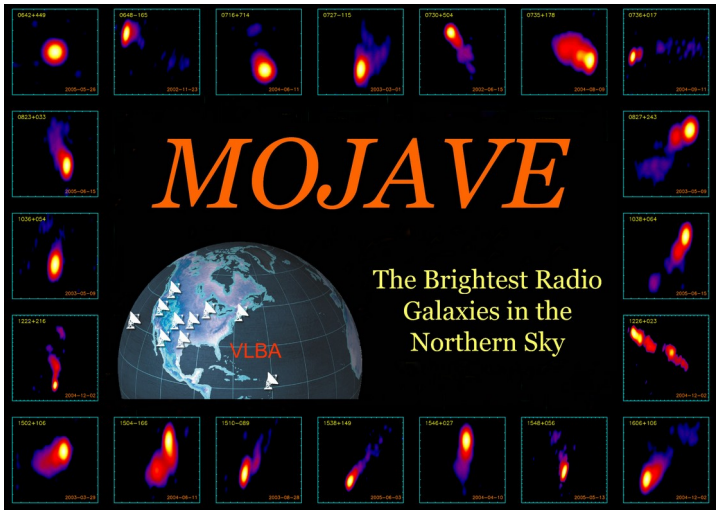
- Mostly consistent with blazar variability, moving radio knots, polarization changes
- Could explain FR I – FR II differentiation *(Meier 2013)*



MRCS

II – Link between broadband SED and radio VLBI jets

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)

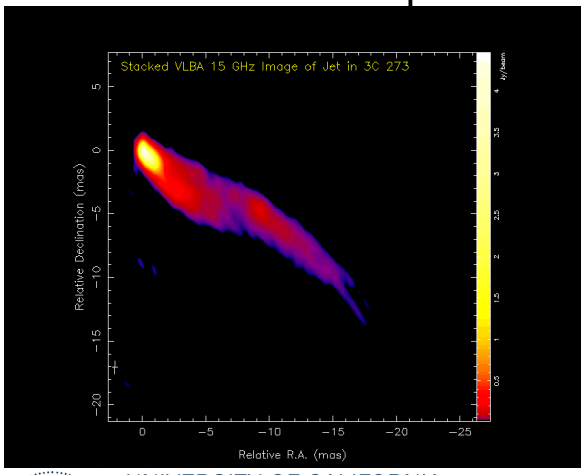
The largest database of analysed radio VLBI AGN jet

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

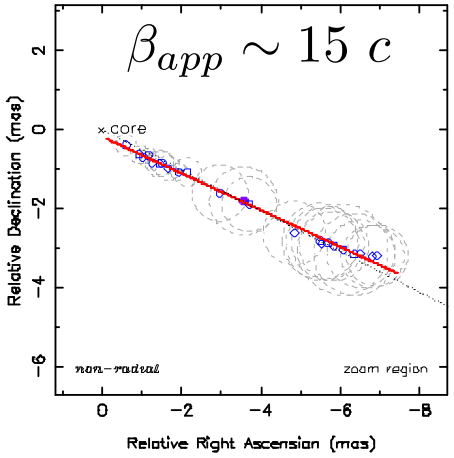
2019 paper, MOJAVE XVII:
- parsec-scale jet kinematics study of 409 AGN jets
- 1744 individual bright features in 382 jets over at least 5 epochs

e.g. **3C 273**

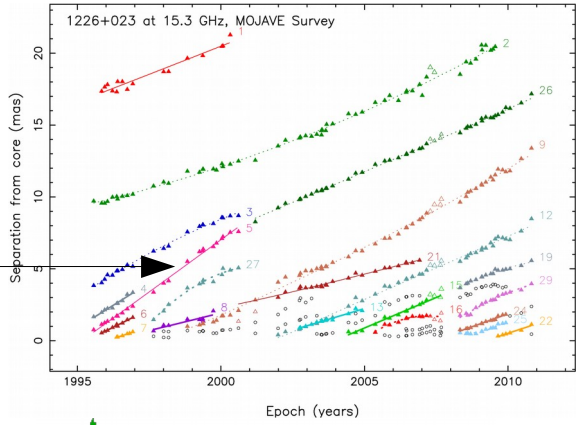
Stacked map



Fastest component



Jet components monitoring

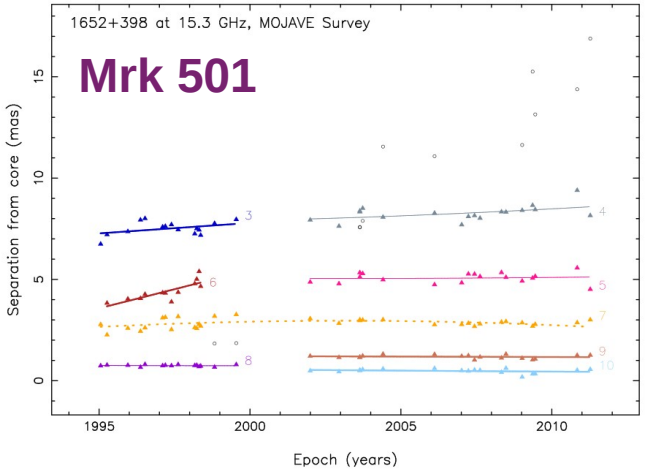


Blazar kinematic classification

- 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

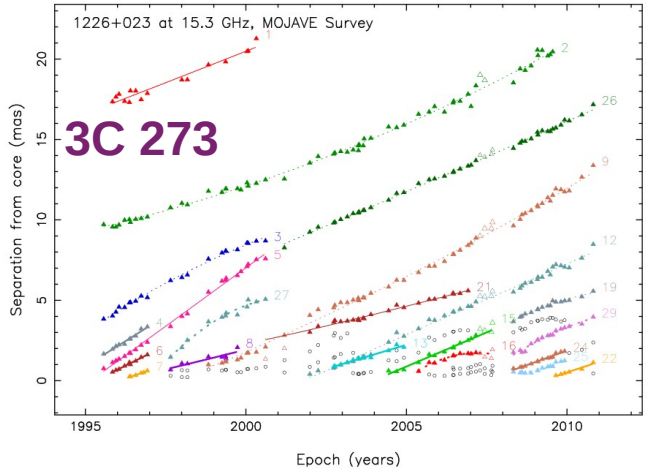


Quasi stationary knots

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

25 sources

Class II



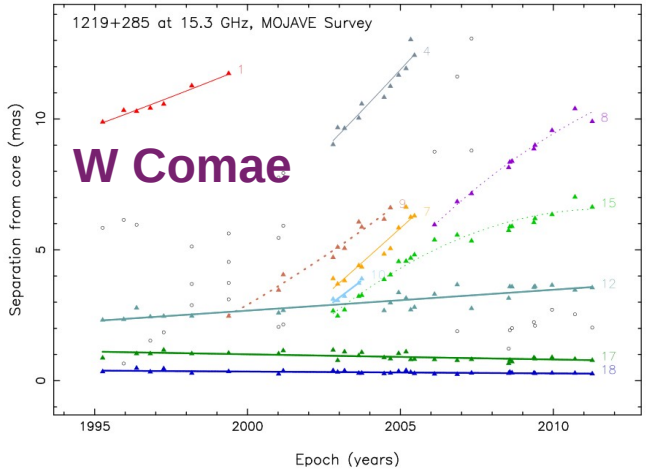
High velocity knots

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

$\min \beta_{app} > c$

99 sources

Class I/II



Hybrid kinematics

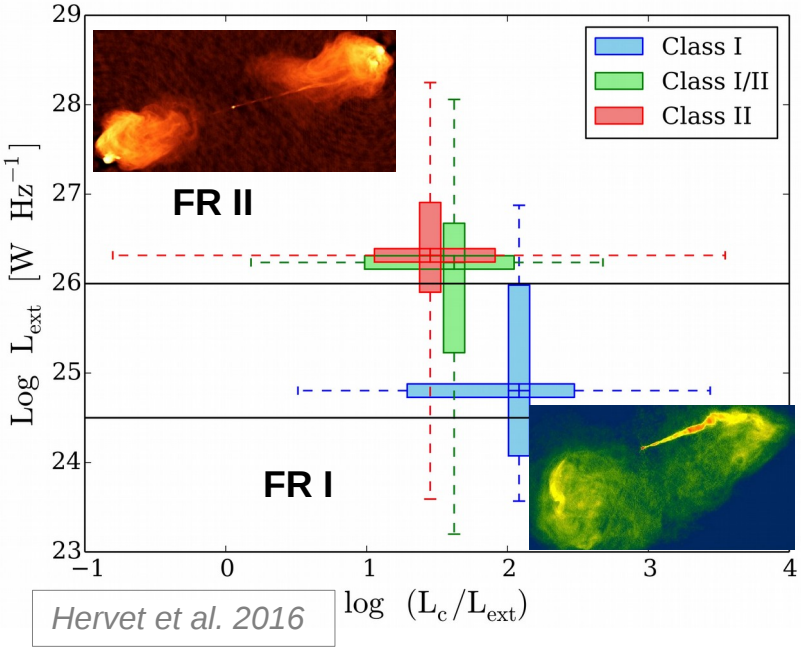
$\max \beta_{app} > 2c$

$\min \beta_{app} < c$

37 sources

VLBI kinematics in the AGN classification scheme

With kpc radio jets...



Hervet et al. 2016

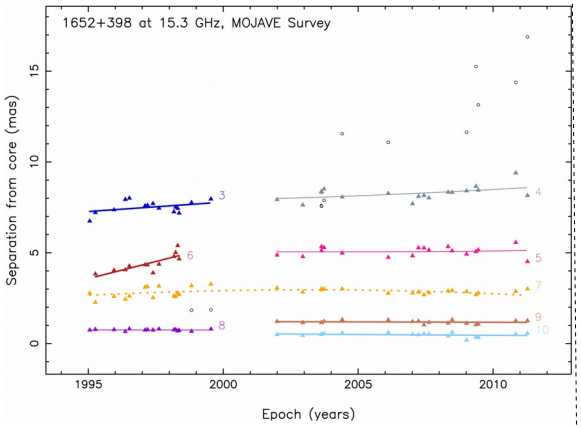
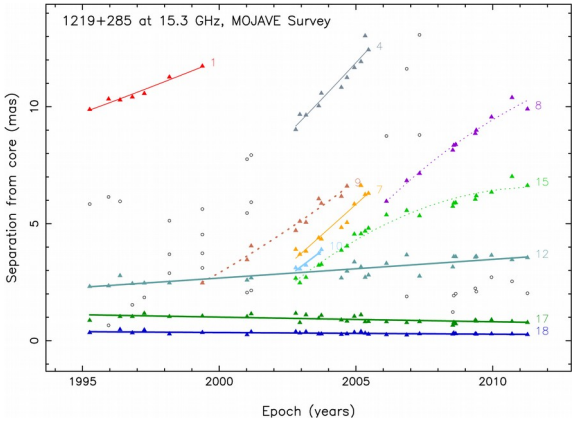
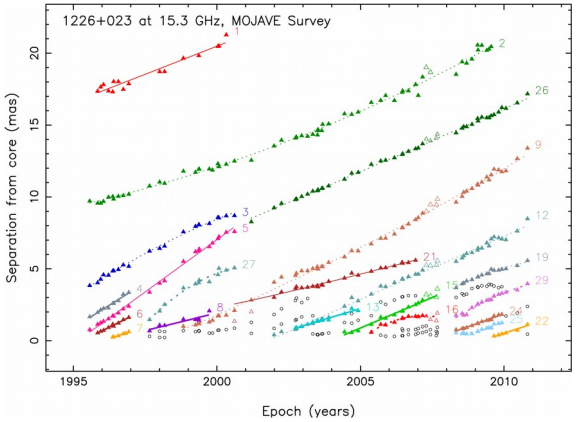
With spectral classes...

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)

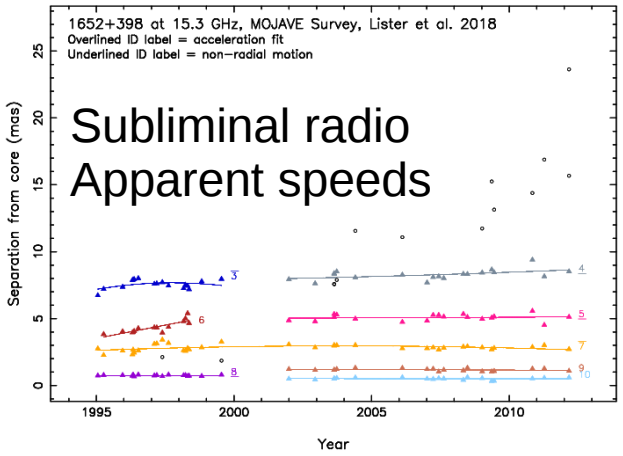
Kinematics with spectral classification

	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	$\sim 10^{42} - 10^{45} \mathrm{erg\ cm^{-2}\ s^{-1}}$		$\sim 10^{46} - 10^{48} \mathrm{erg\ cm^{-2}\ s^{-1}}$

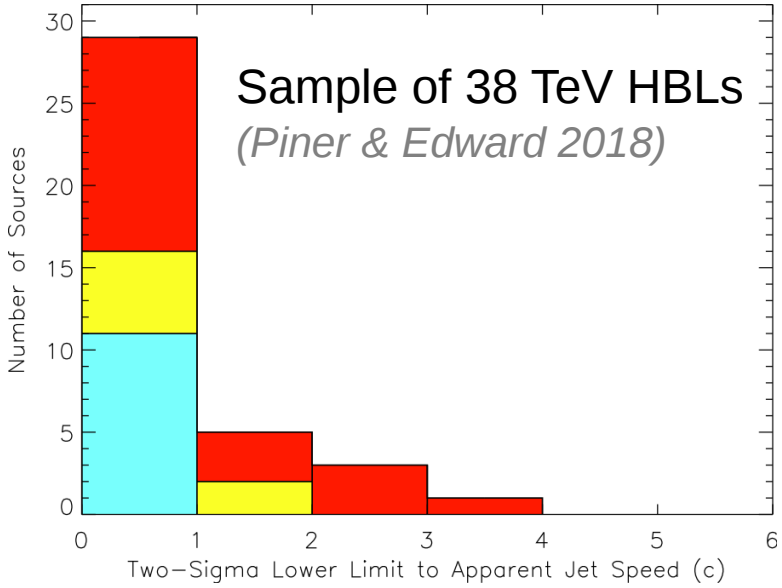
III – HBLs: A bulk Lorentz factor crisis

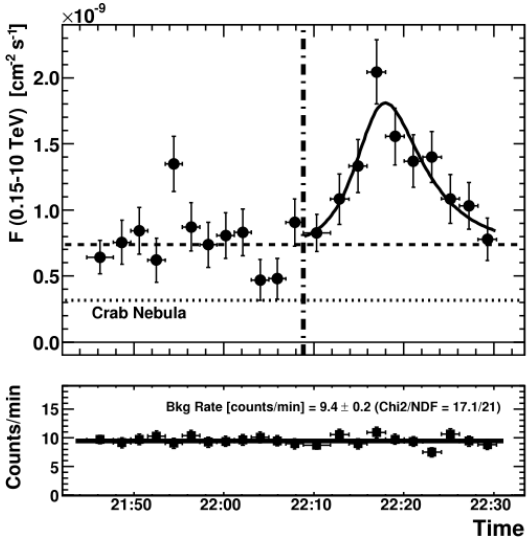
Stationary components in HBLs

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

$\delta \sim 25 - 50$

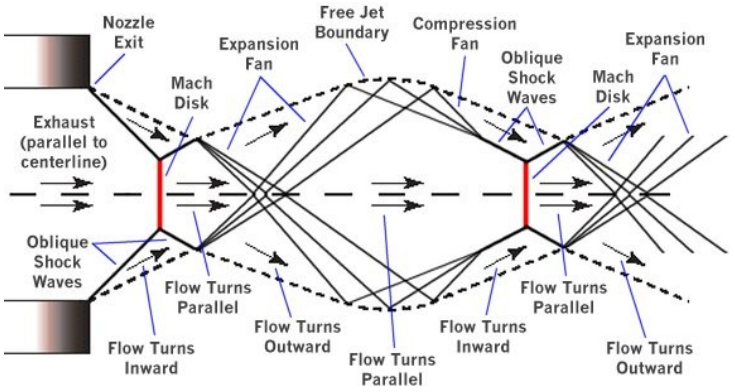
Albert et al. 2007

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

AGN Jets should naturally show multiple recollimation shocks

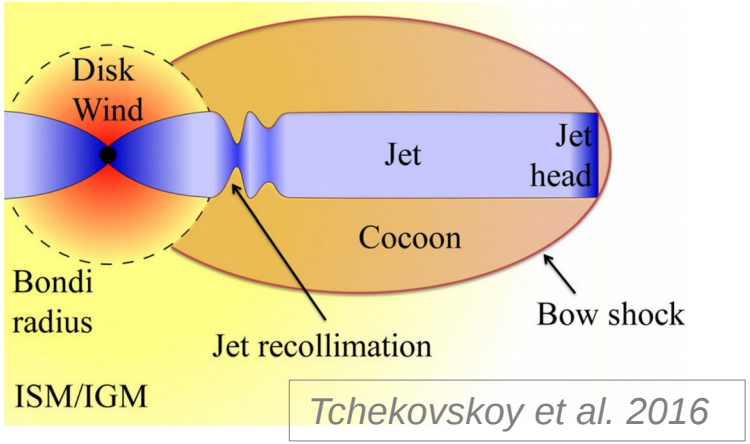
Jet conditions:

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

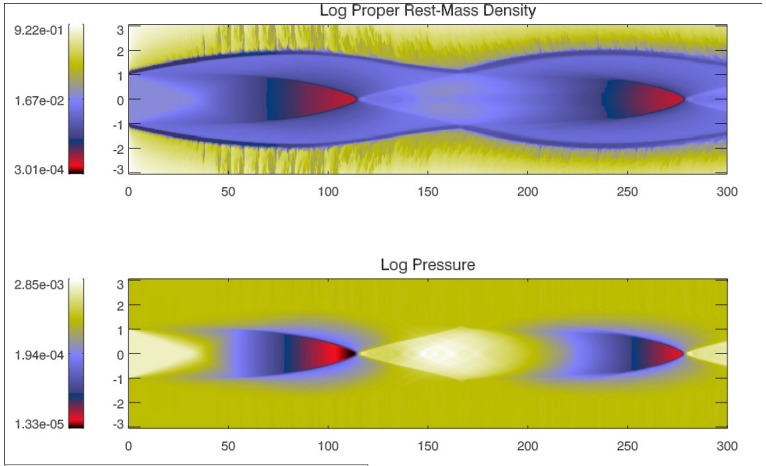


Relativistic (M)HD simulations

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



Tchekovskoy et al. 2016



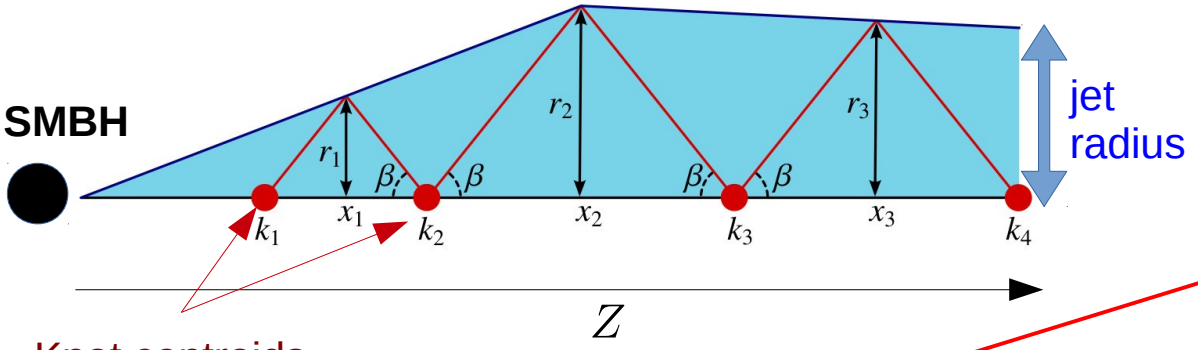
Fromm et al. 2016

Stationary knots as recollimation shocks

– structure of knot strings

Prediction:
If stationary VLBI radio knots are recollimation shocks:

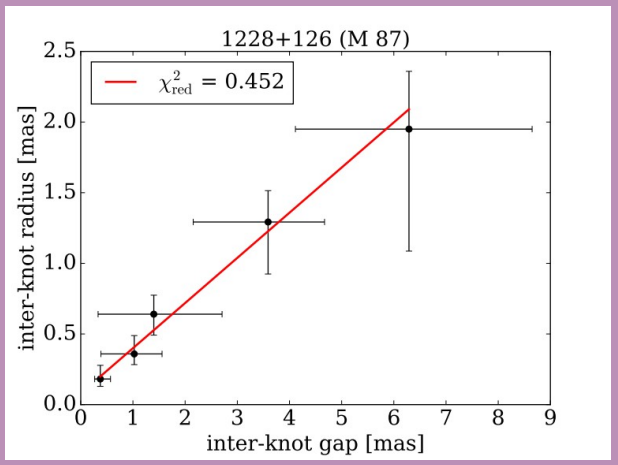
→ the inter-knot gaps should be proportional to the jet radius (isothermal approximation)



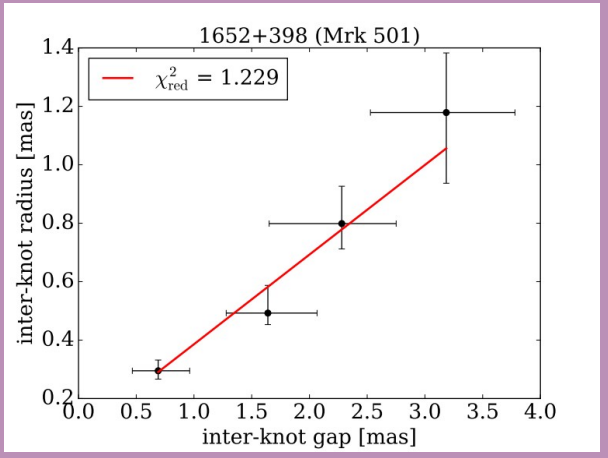
$$r_n \propto \Delta k_n$$

Verified!

M87



Mrk 501



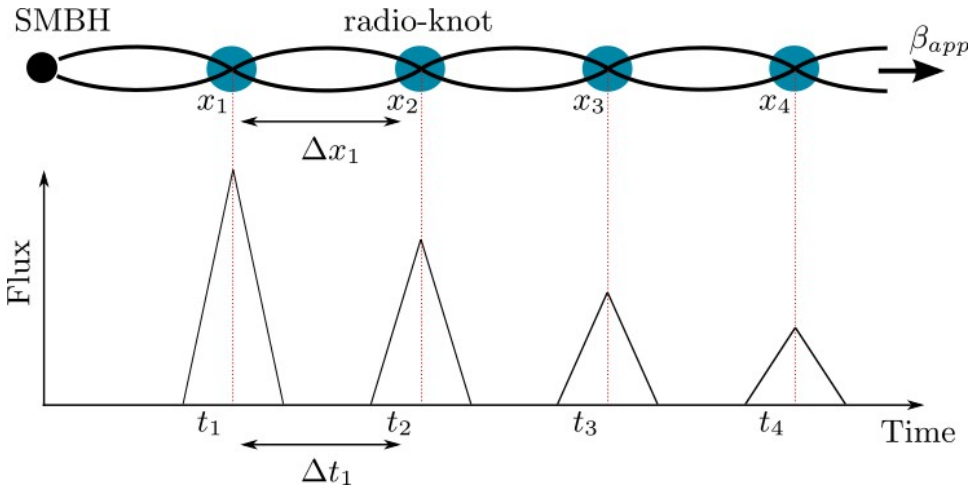
Relation checked on ~10 jetted AGNs with stationary knots

(Hervet et al. 2017)

Expected signature of successive shocks in lightcurves

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

Sketch of expected signature:

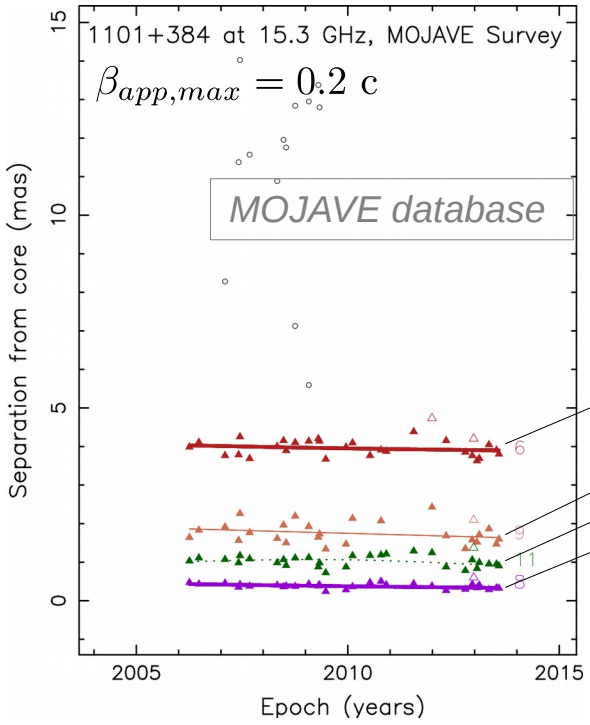


Assuming a constant flow speed:

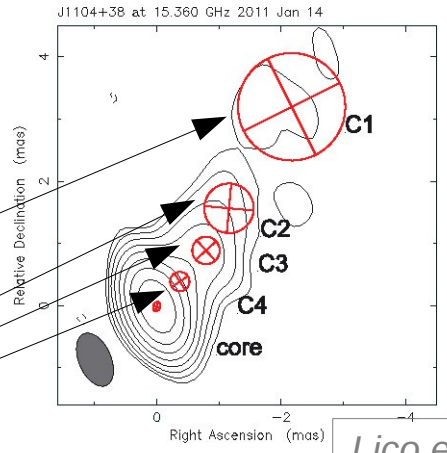
$$\Delta t_i = (1+z)\frac{\Delta x_i}{c\beta_{app}}$$

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

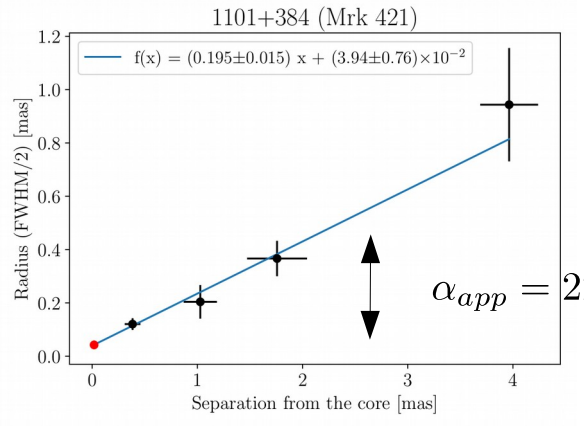
Mrk 421, the ideal candidate



4 quasi-stationary knots



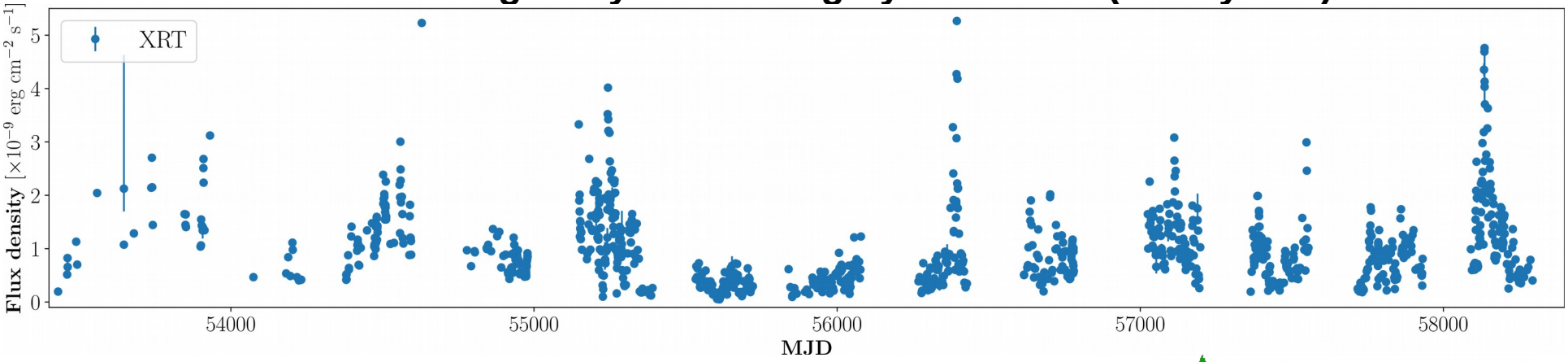
Lico et al. 2012



Conical jet

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

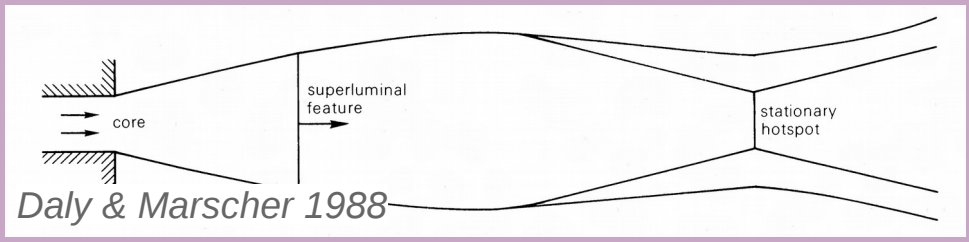
Long X-ray monitoring by Swift-XRT (> 13 years)



Model test on Mrk 421

Model favored:

Core = expanding funnel
4 stationary knots = 4 recollimation shocks



Daly & Marscher 1988

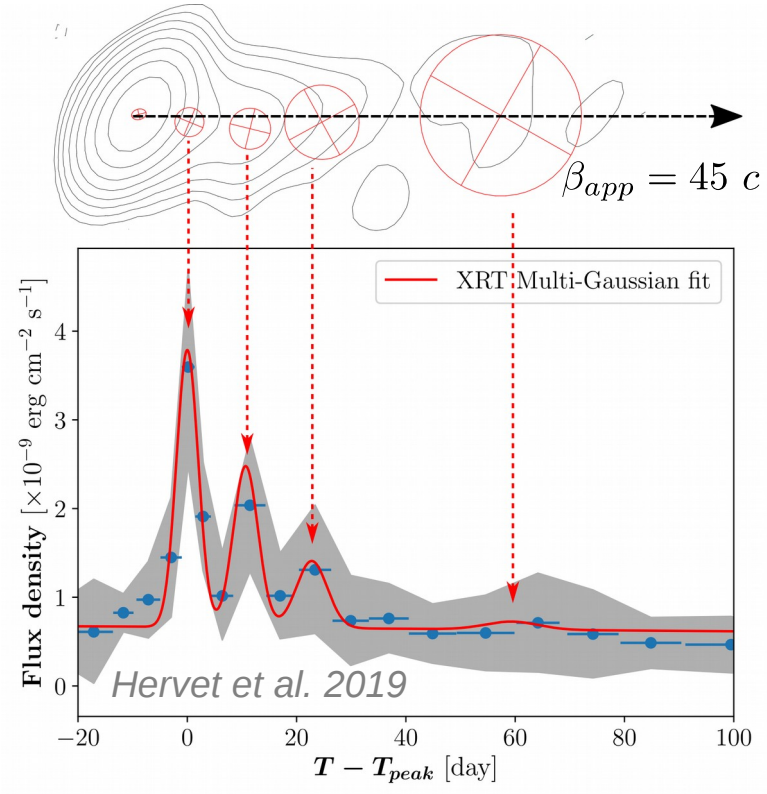
Flares fitted by a multi-Gaussian function

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

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

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)

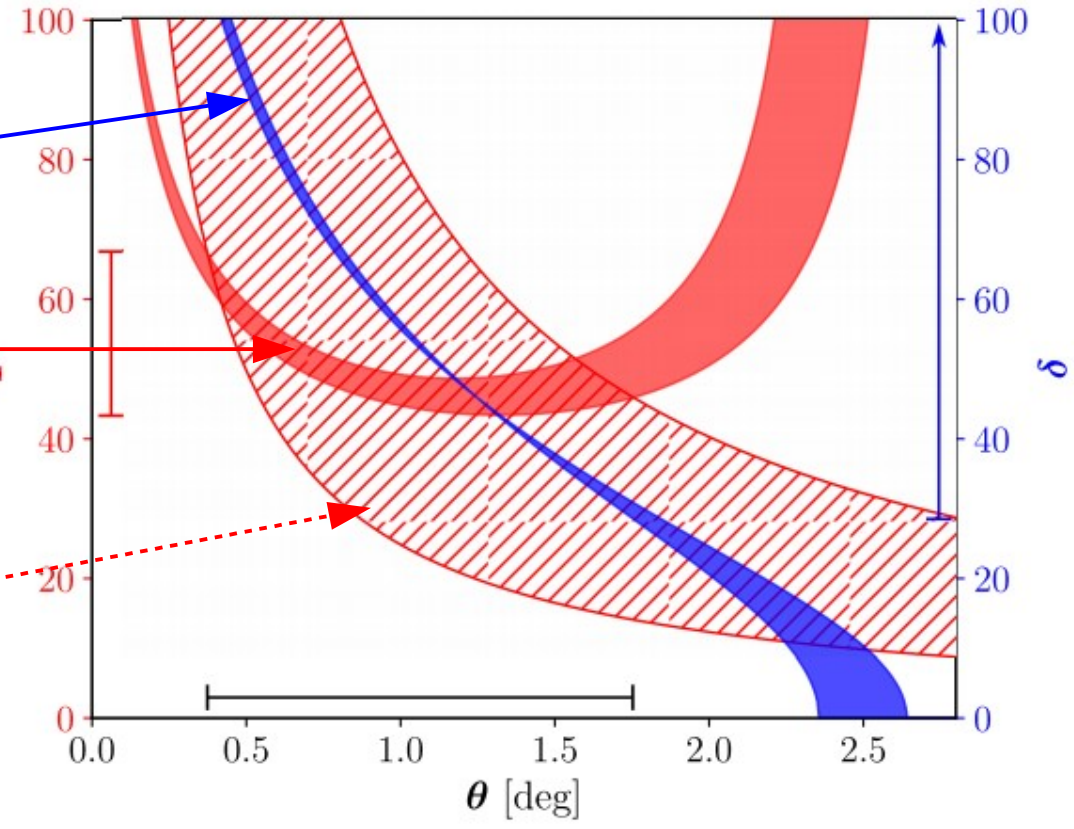
Constraint on beaming parameters

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

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

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

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



System solved for $\delta \geq 31$

$\Gamma \in [43 - 66]$

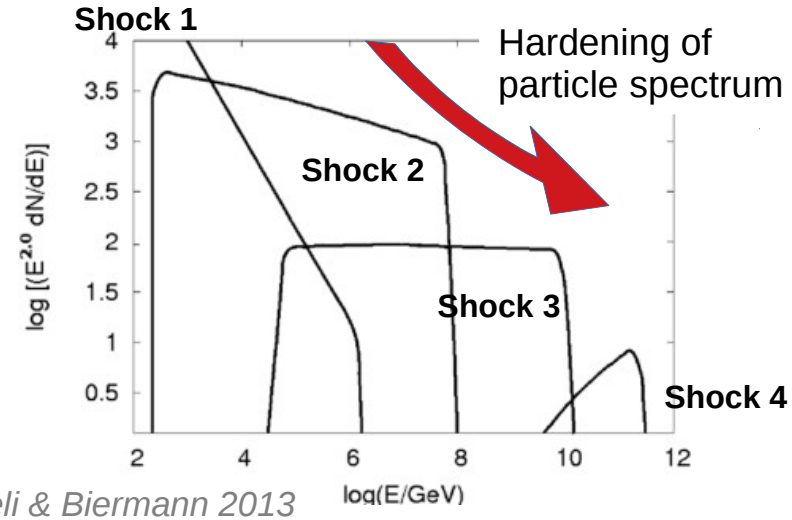
$\theta \in [0.38 - 1.8]$ deg

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

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

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)?



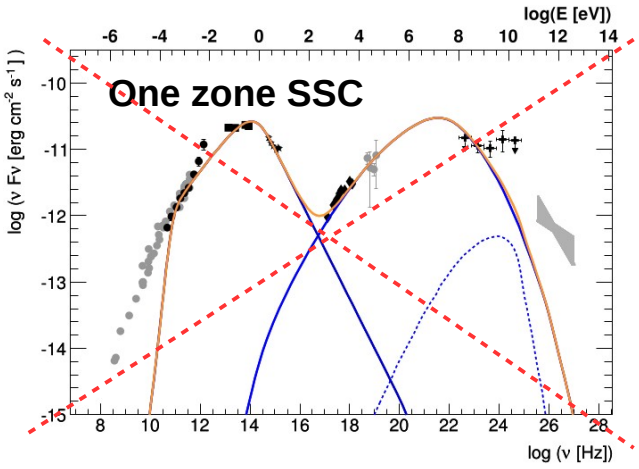
Meli & Biermann 2013

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

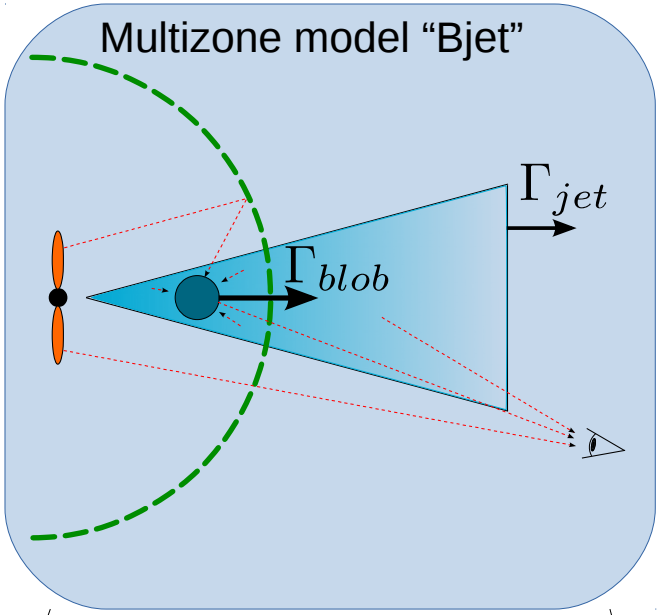
IV – Intermediate blazars, a distinctive class

Intermediate blazars modellings – highlights of 2 imbricated radiative jet structures

AP Librae - one zone

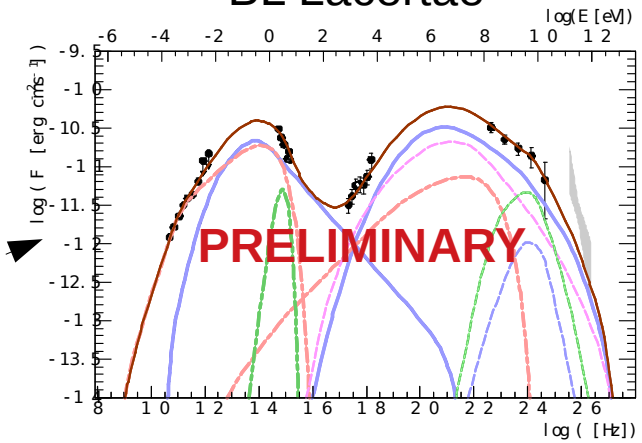


Multizone model "Bjet"

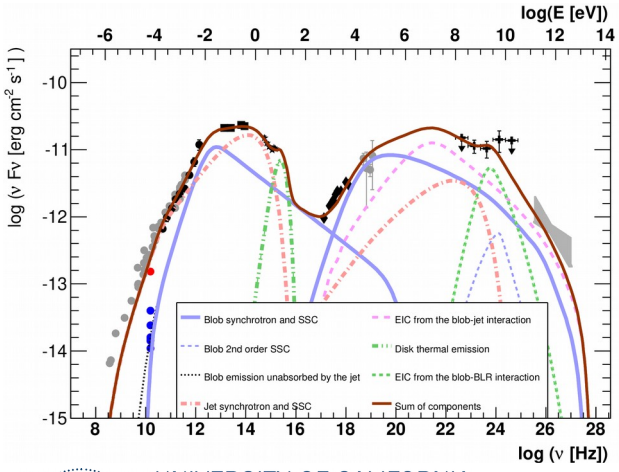


Hervet et al. 2015

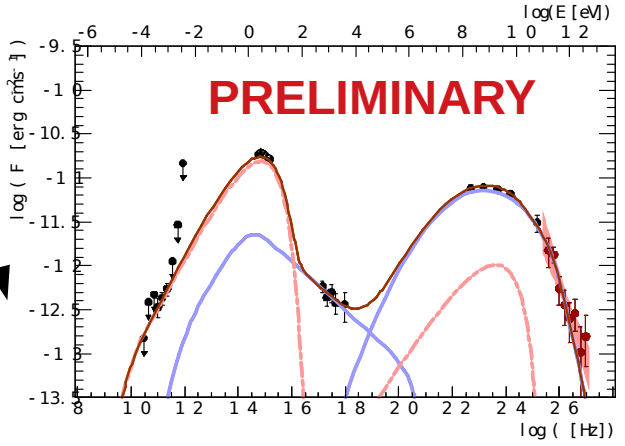
BL Lacertae



AP Librae – Multi zones

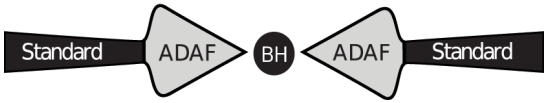


W Comae



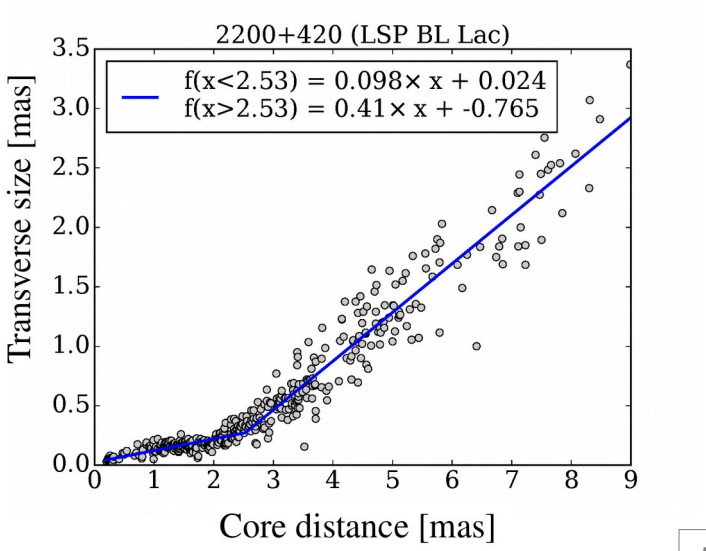
Intermediate accretion efficiency

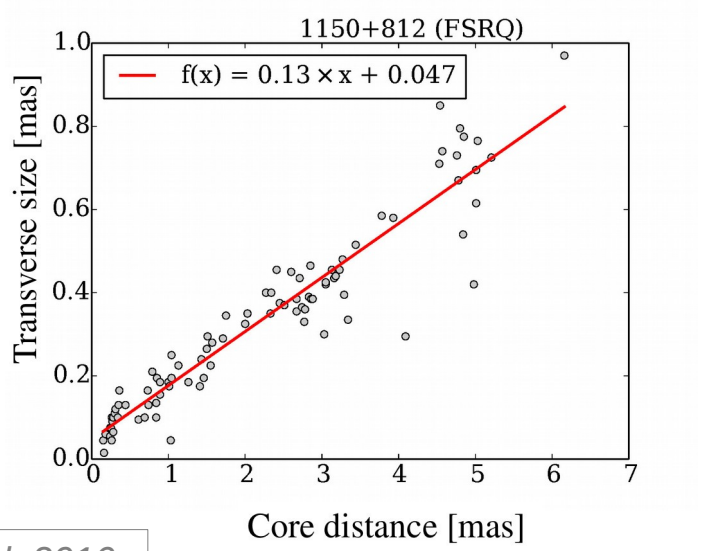
$$\eta = \frac{\dot{M}}{\dot{M}_{Edd}} \simeq 3.1 \times 10^{-3}$$



Jet aperture increase for intermediate blazars

VLBI radio knots sizes vs core distances



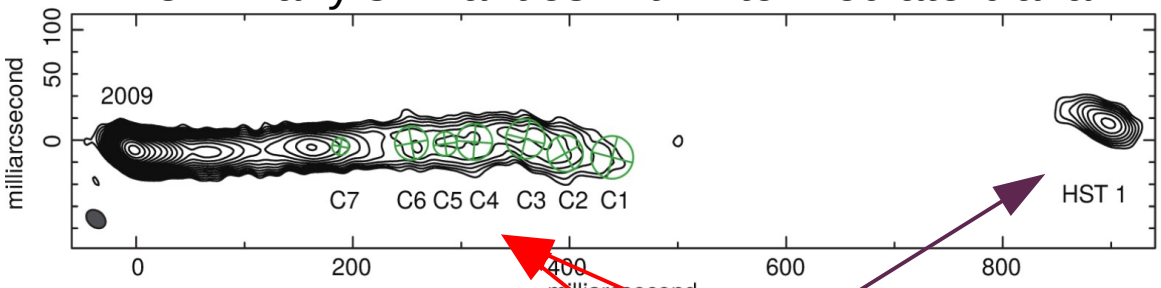


Hervet et al. 2016

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

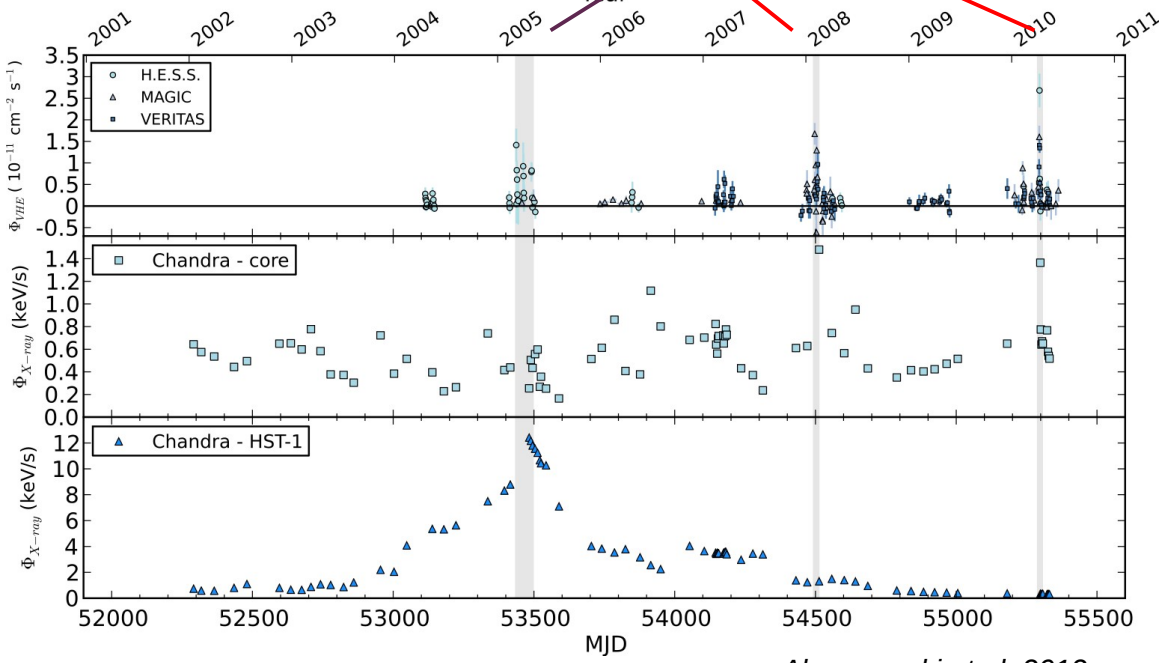
Bright and unstable last stationary knot

M87: many similarities with intermediate blazar



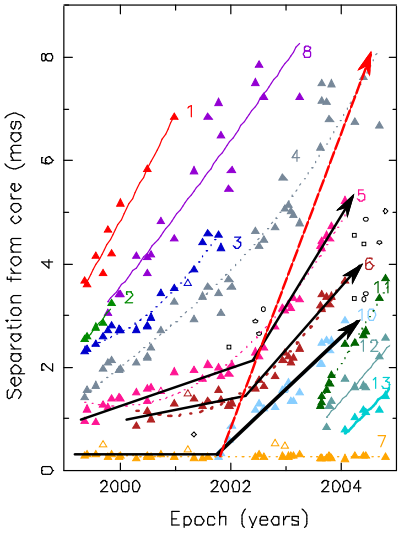
Asada et al. 2014

Motions seen from HST1

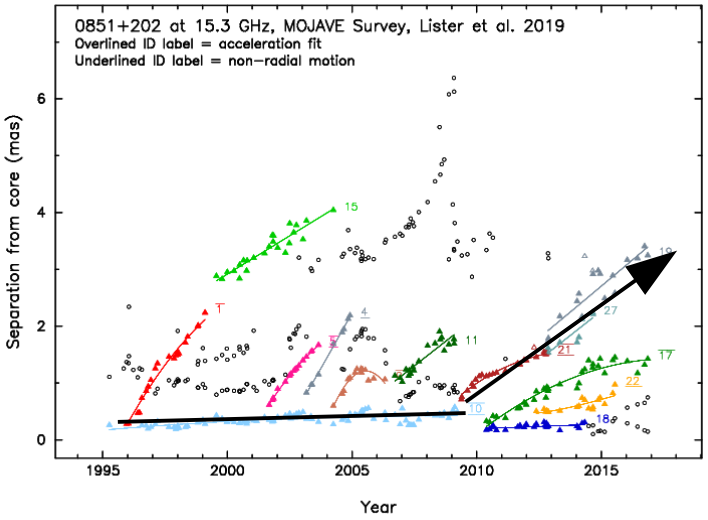


Abramowski et al. 2012

BL Lacertae



OJ 287



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

Two flows in jets

→ *See Gilles Henri presentation*

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

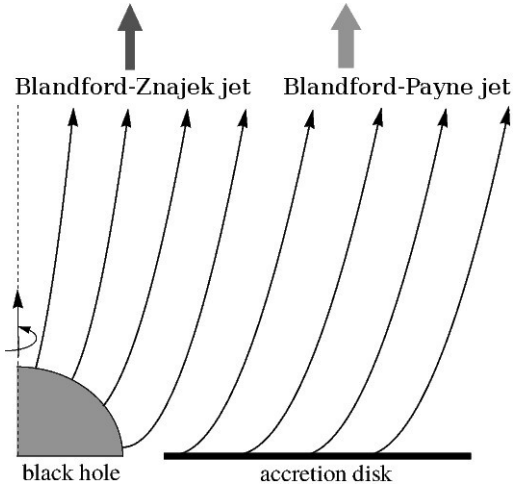
- Mildly relativistic sheath composed of e−/p+ and driven by MHD forces

  → transports most of the kinetic energy

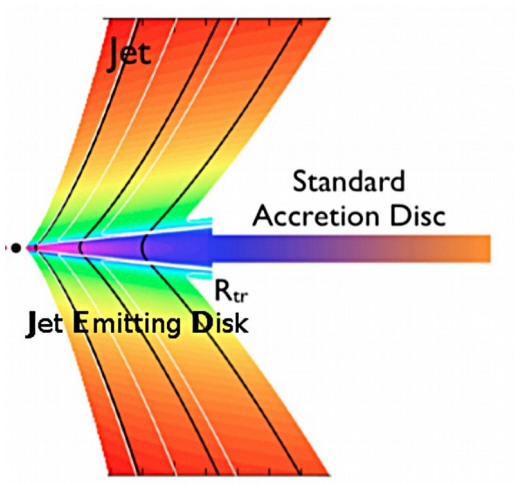
- Ultra-relativistic spine composed of e−/e+ pairs

  → responsible for most of the emission

2 flows expected by different theoretical scenario

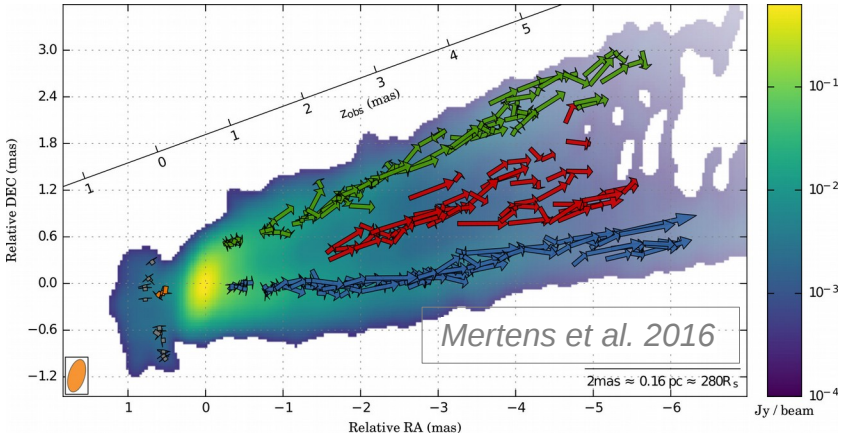


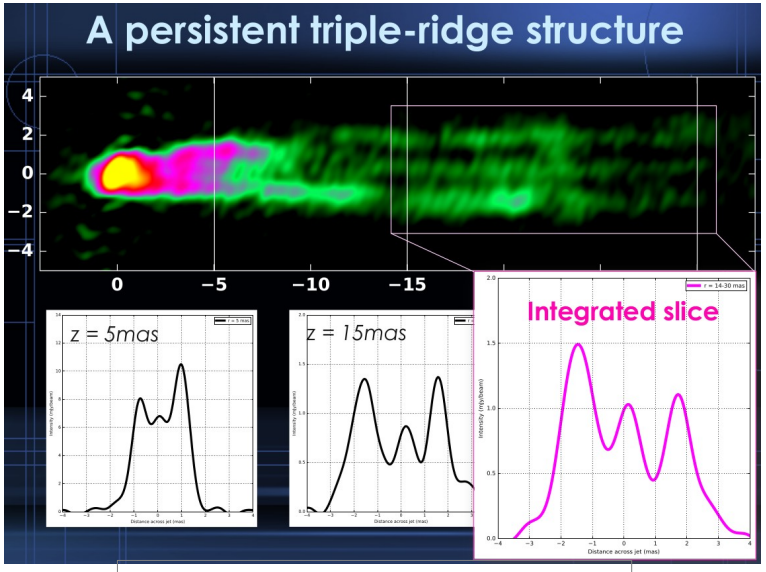
Adapted from Xie et al. 2012



Ferreira & Pelletier 1995

Radio VLBI observations (M87)

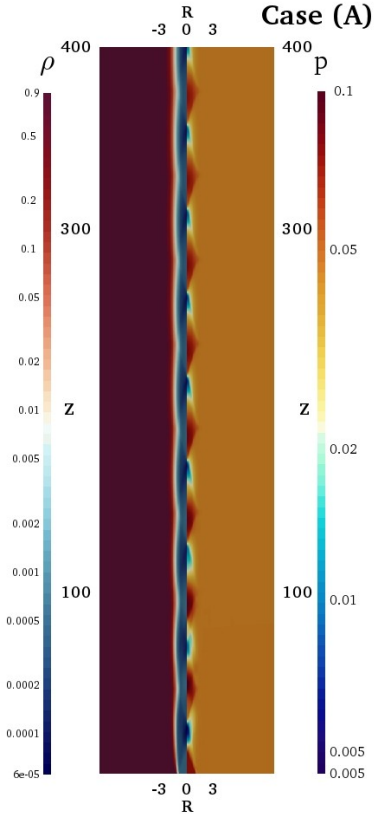




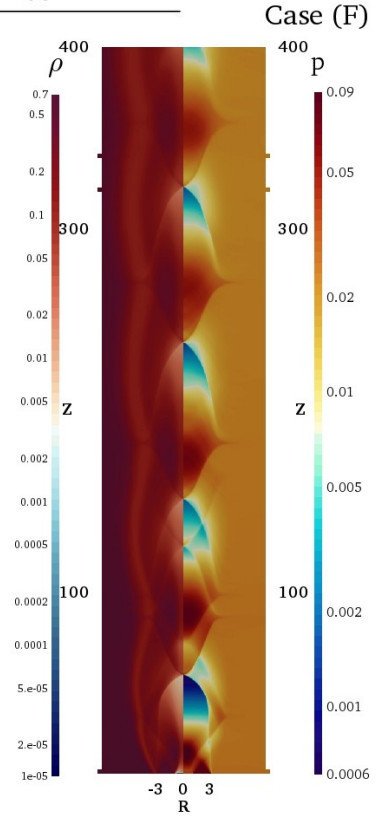
From K. Hada presentation, 2016

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

	external medium	inner jet		outer jet		Structured jet		
case	p_0	$\eta_{\rho,\mathrm{in}}$	$M_{\mathrm{c,in}}$	$\eta_{\rho,\mathrm{out}}$	$M_{\mathrm{c,out}}$	$L_{\mathrm{k,in}}/L_{\mathrm{k,total}}$	$L_{\mathrm{k,out}}/L_{\mathrm{k,total}}$	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



- 2D RHD simulation of jets with AMRVAC code
- 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

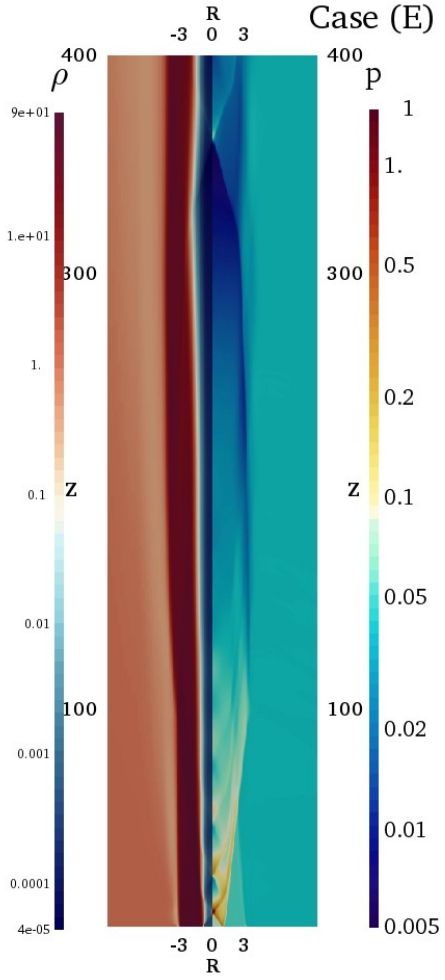


Caveat

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

Powerful outer jet – *Case of intermediate blazars*

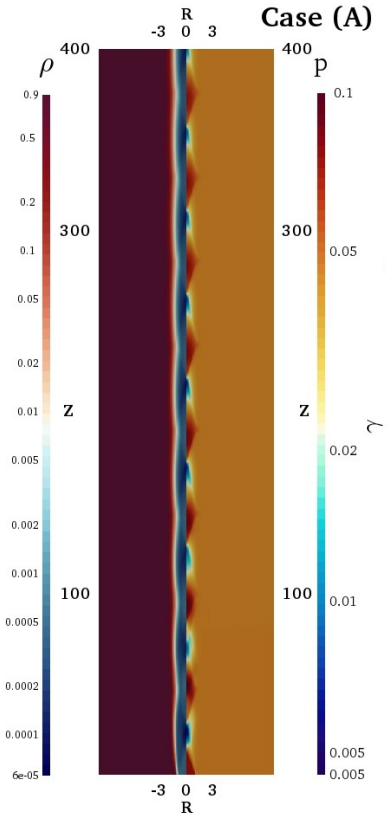
Two-components jet $P_{jet,in} << P_{jet,out}$

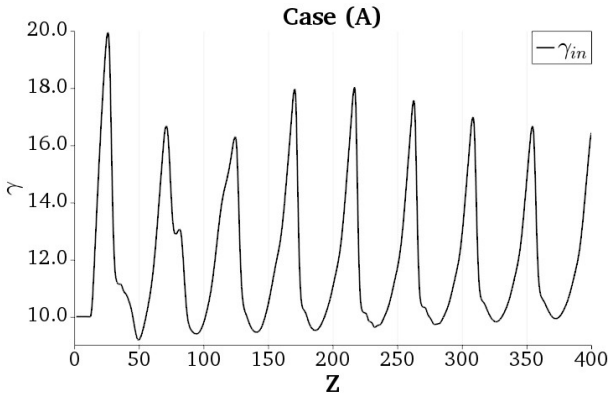


- Short inner-jet shock waves not interacting with the long ones of the outer jet
- Fast damping but close successive shocks at the jet base
- Long rarefraction wave from the outer jet induces a powerful flow acceleration and unstable shock far downstream

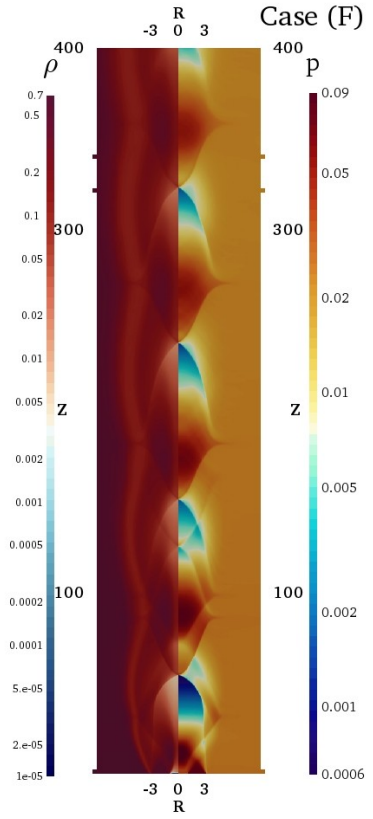
One component jet – *Case of HBLs*

Inner jet?





Outer jet (empty spine)?

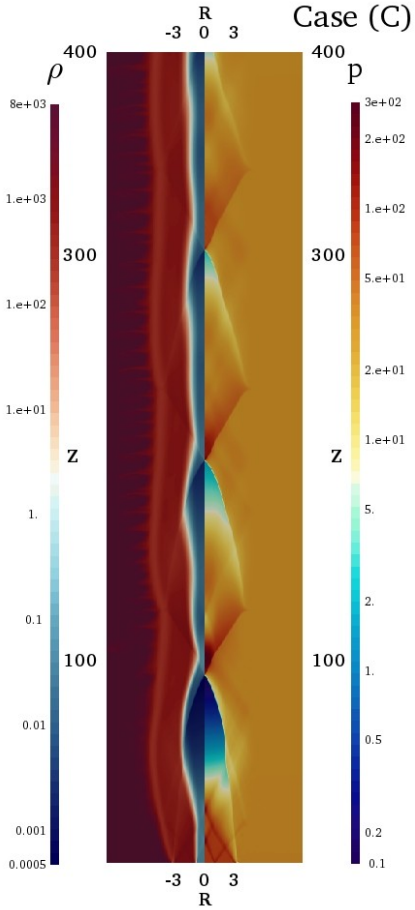


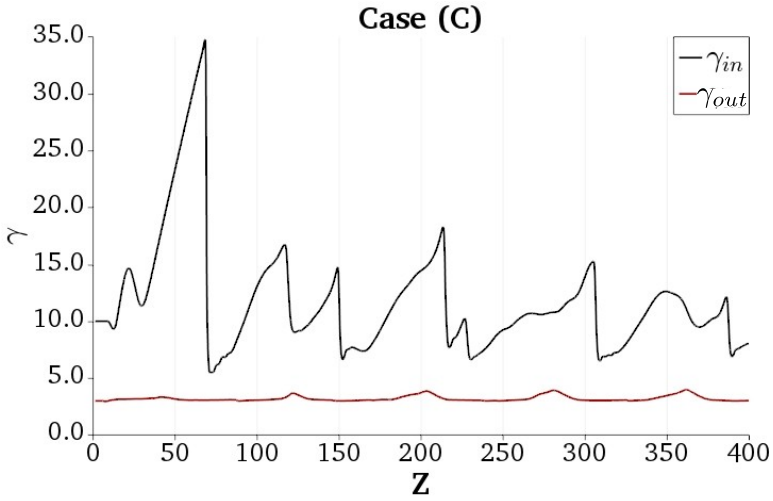
- One component jet, inner or outer produces similar structure
- Multiple successive stationary shocks

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 RL AGN scheme

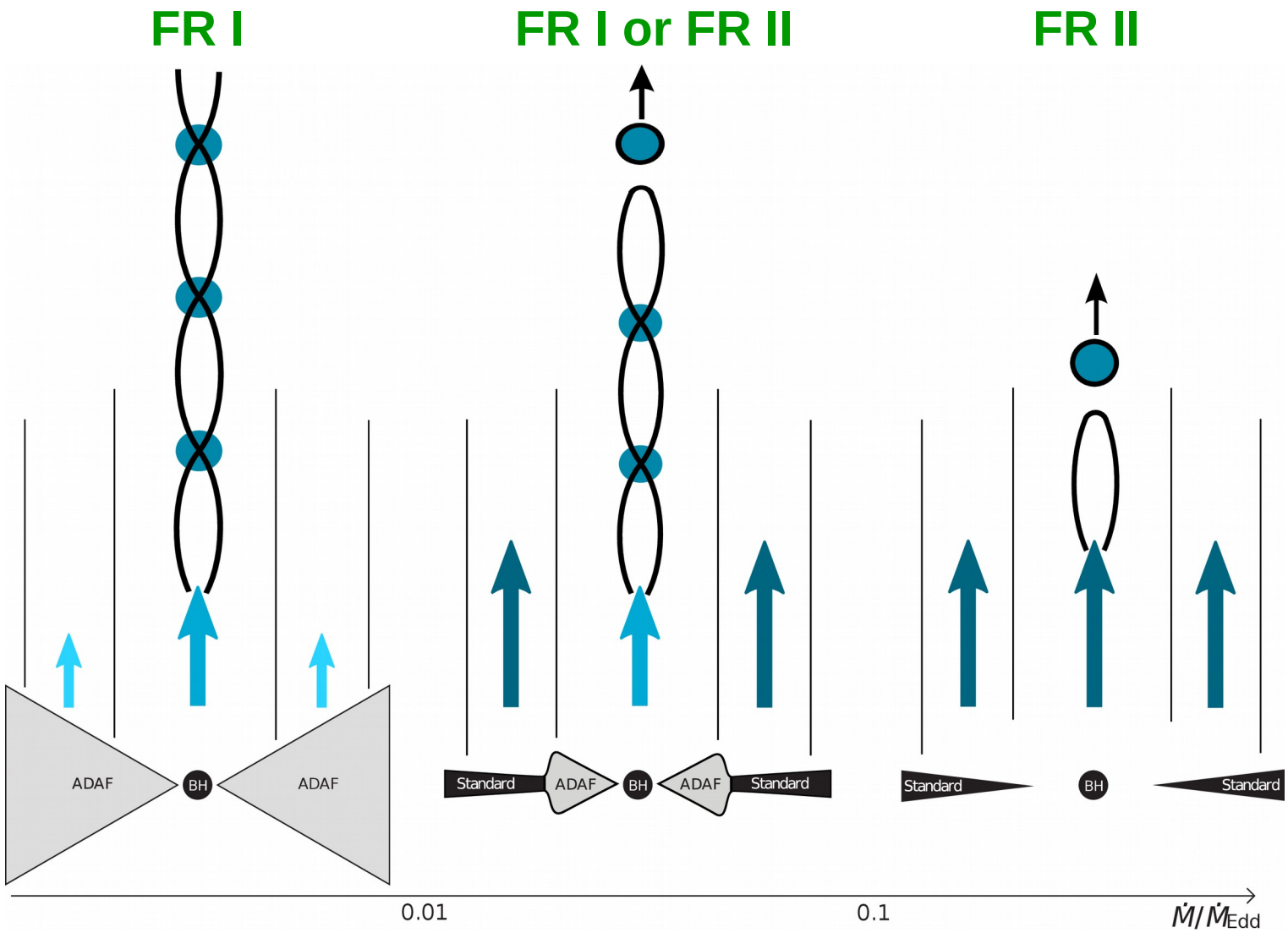
Large scale structure

Pc scale structure

Jets kinetic powers

Accretion regime

Spectral class



HBL **LBL-IBL** **FSRQ**

Conclusion & Outlook

The high energy – radio-VLBI link in AGN support recollimation shocks in two flows jets
Addresses well many AGN jets properties and behaviours in a consistent scheme:

- Resolve Bulk Lorentz factor crisis
- Match the various distributions of stationary radio-knots in jets
- Consistently considers the specific broadband SED and jet structure of intermediate blazars

**Jet classification not only depending on the total power,
but also on the power equilibrium between inner/outer jets**

Next works:

Study of emission signature for perturbation crossing shocks in MHD simulation (handled by the LUTH PHE team) ⟶ *See Gaëtan presentation*

Deep gamma+VLBI study to check the multiple shock scenario in Mrk 421
- Combined study VERITAS+FACT (very-high energy)
- Fermi-LAT proposal accepted
- VLBA proposal accepted

Promising future gamma- radio VLBI synergies with the commissioning of CTA and SKA-VLBI during the next decade