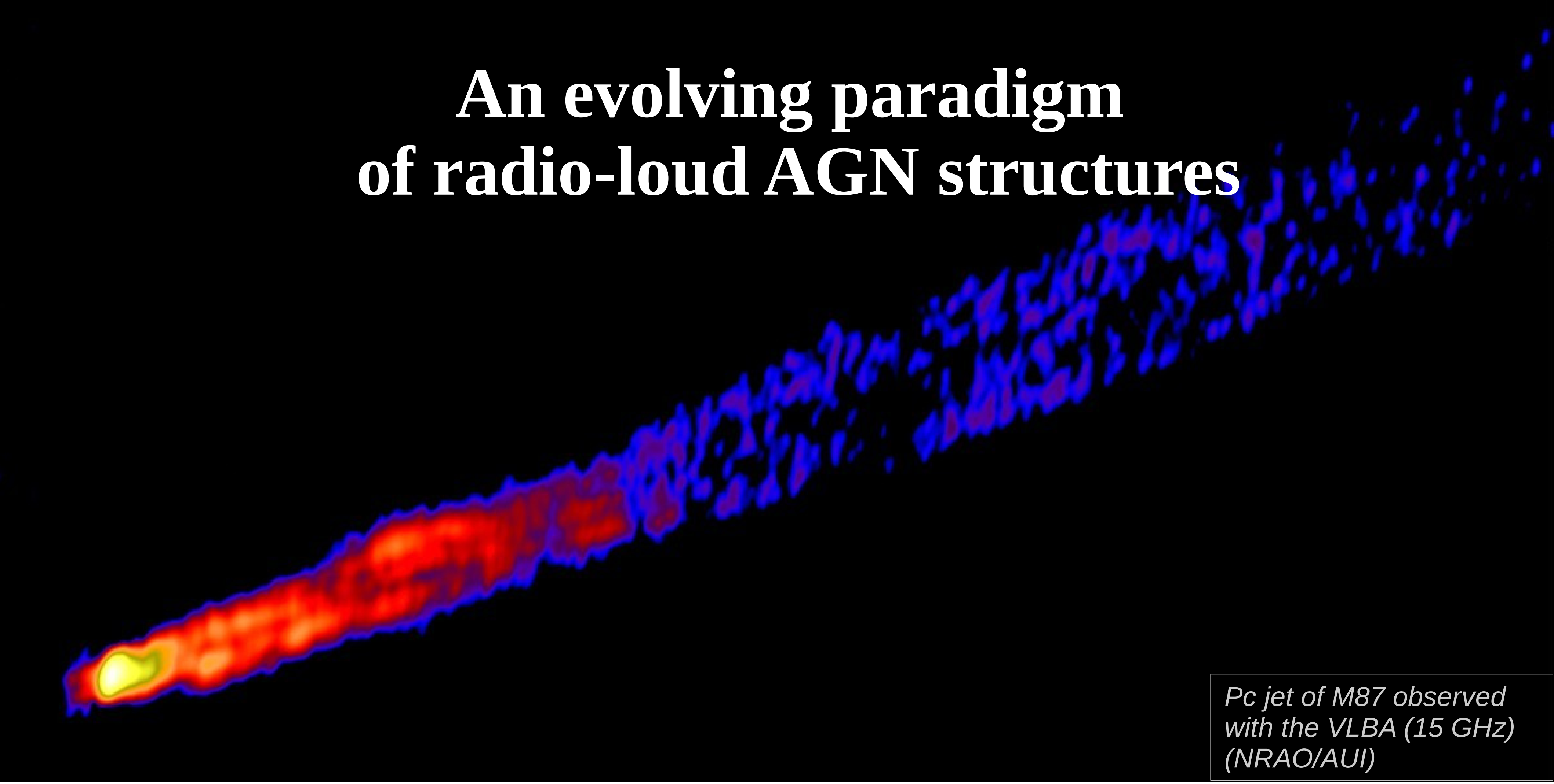
An evolving paradigm of radio-loud AGN structures



Pc jet of M87 observed with the VLBA (15 GHz) (NRAO/AUI)

Olivier Hervet

UNIVERSITY OF CALIFORNIA SANTA CRUZ

LUTH seminar
April 2017, Meudon

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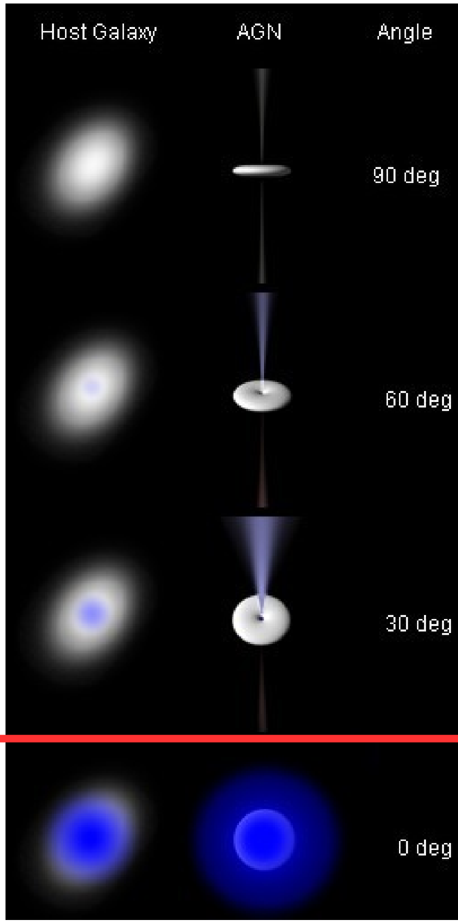
Outline

- Blazars in the AGN classification scheme
- Intermediate blazars, the key sources
- Recollimation shocks in transverse stratified jets
- Conclusion

I - Blazars in the AGN classification scheme

Interest of blazars – *special relativity effects*



Blazar = strong beaming effects

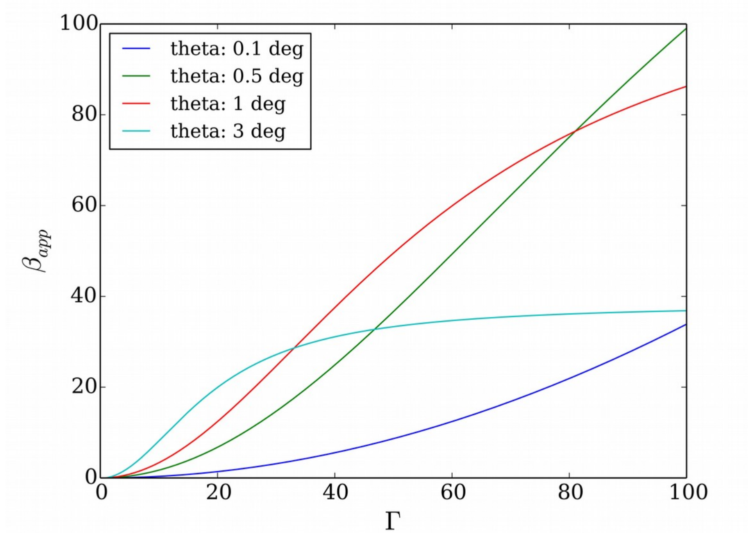
White: thermal
Blue: non-thermal

Doppler beaming

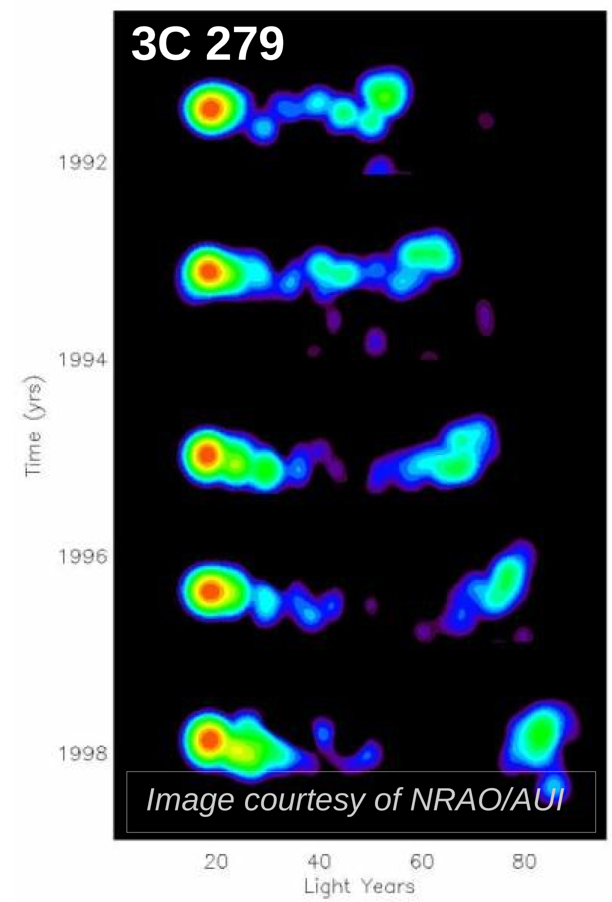
$$\delta = \frac{1}{\Gamma(1-\beta\cos\theta)}$$

Apparent speed

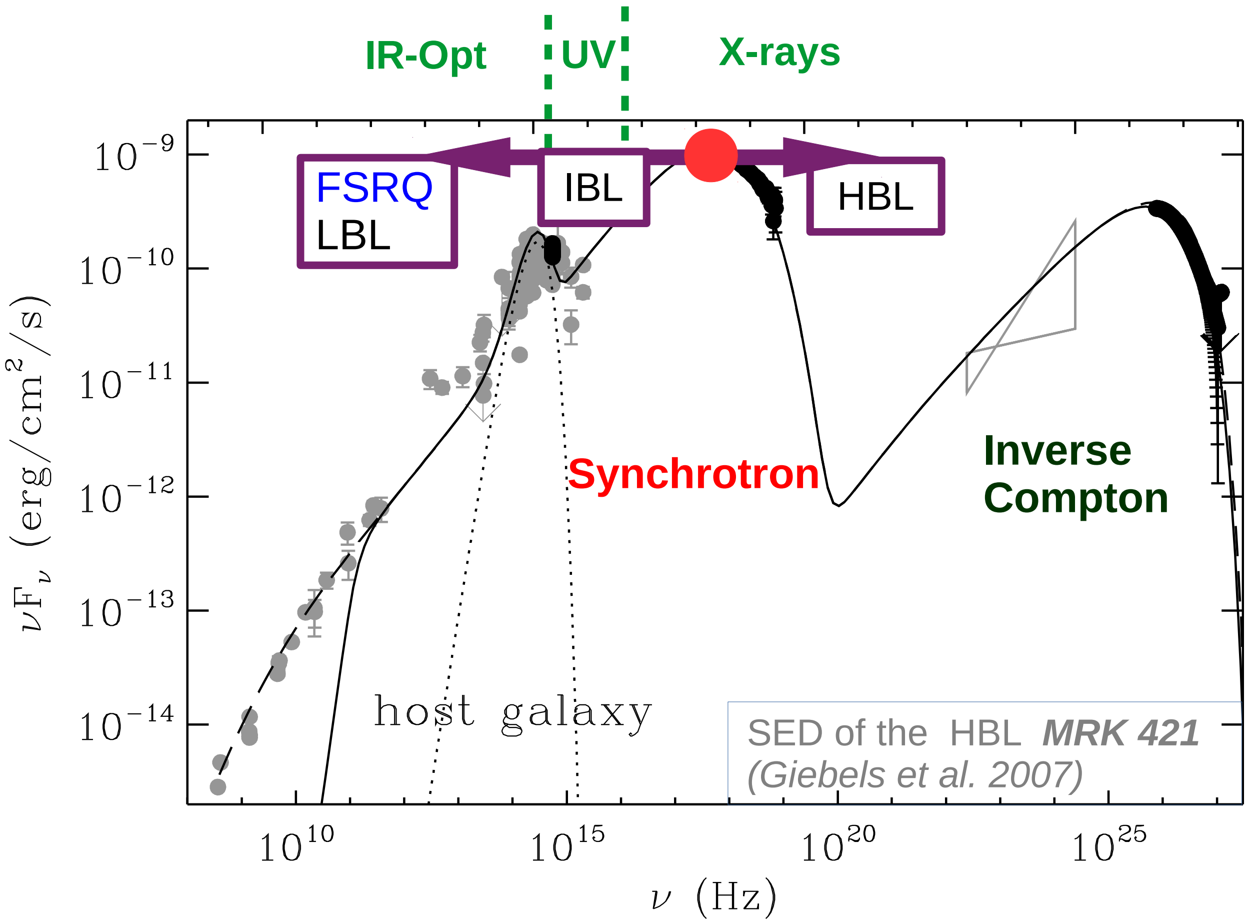
$$\beta_{app} = \frac{\sqrt{1-1/\Gamma^2}\sin\theta}{1-\sqrt{(1-1/\Gamma^2)}\cos\theta}$$



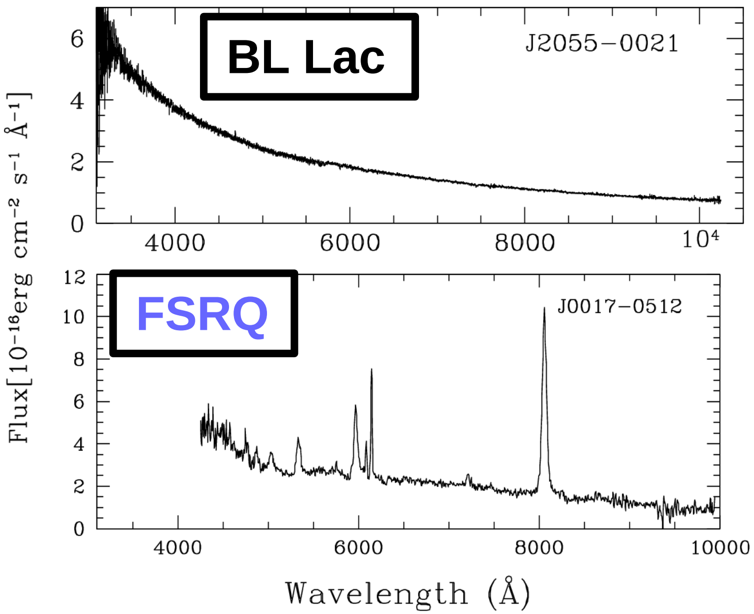
Fast forward observations



Interest of blazars – *Spectral energy distribution*



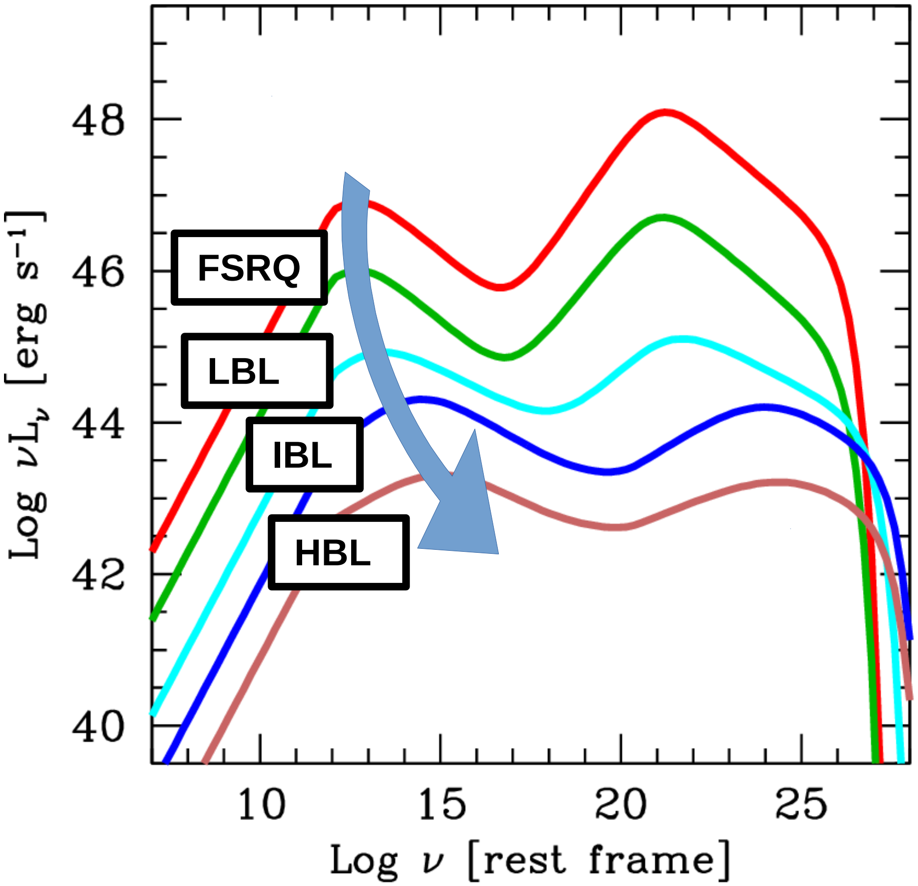
Optical spectrum



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

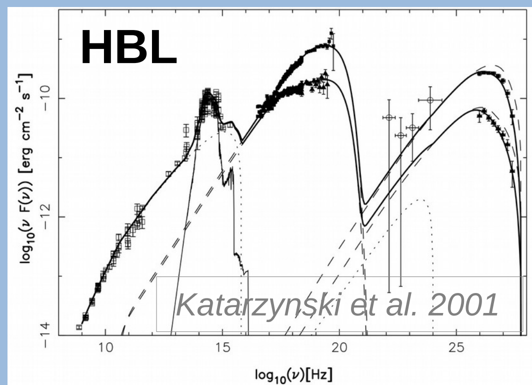
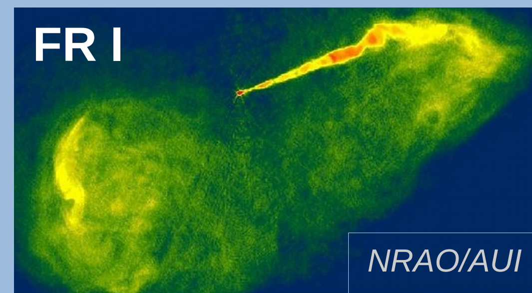
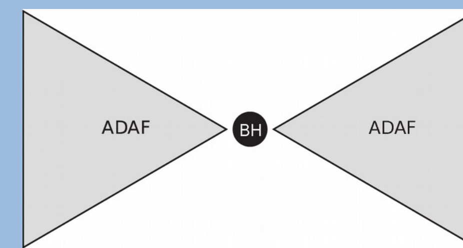
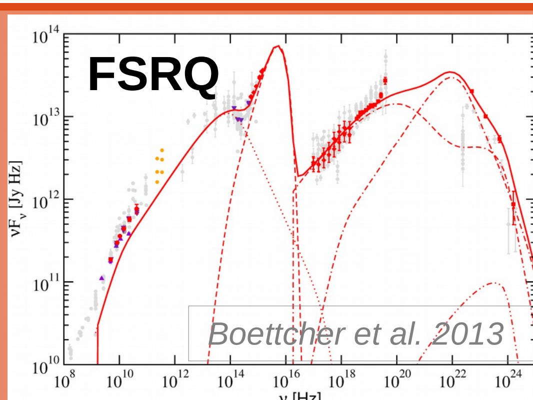
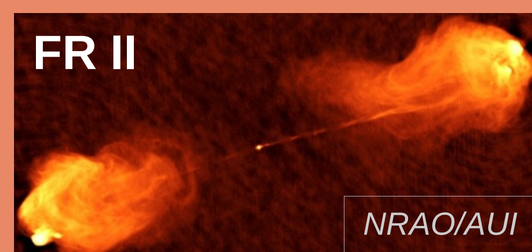
Spectral classification of blazars

The “new” blazar sequence *(Ghisellini 2016)*



Counter-intuitive Classification:
The less powerful sources are the most energetic ones
→ more efficient particle acceleration process for low powers

Current scheme of R-L AGN classification

	Spectral class	Kpc radio morphology	Accretion regime
Low power			
High power			

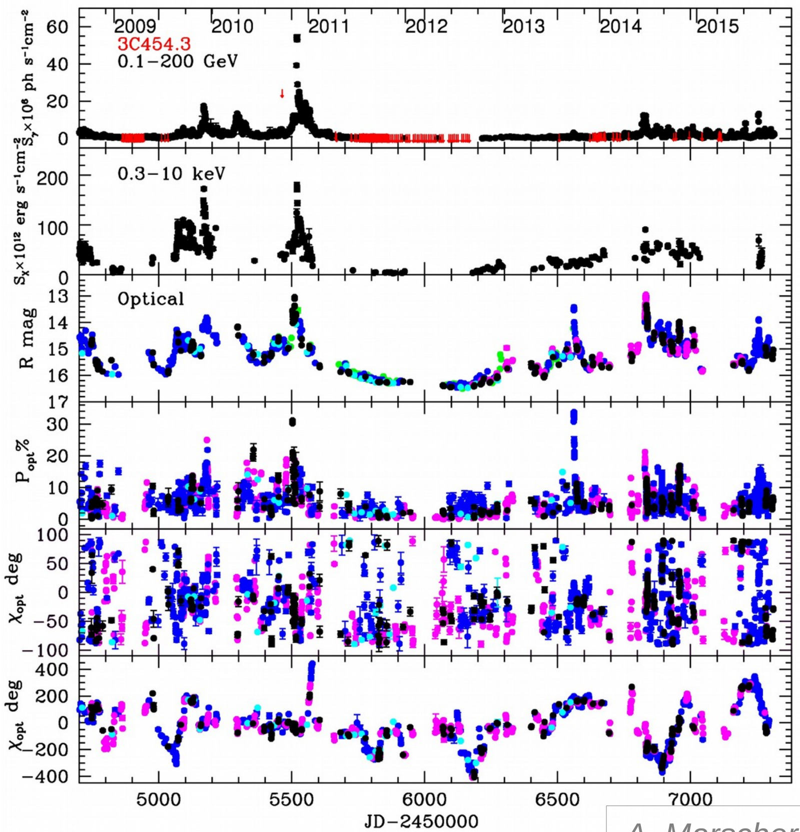
Advection **D**ominated **A**ccretion **F**low

Optically thick
Geometrically thin
(Shakura-Sunyaev)

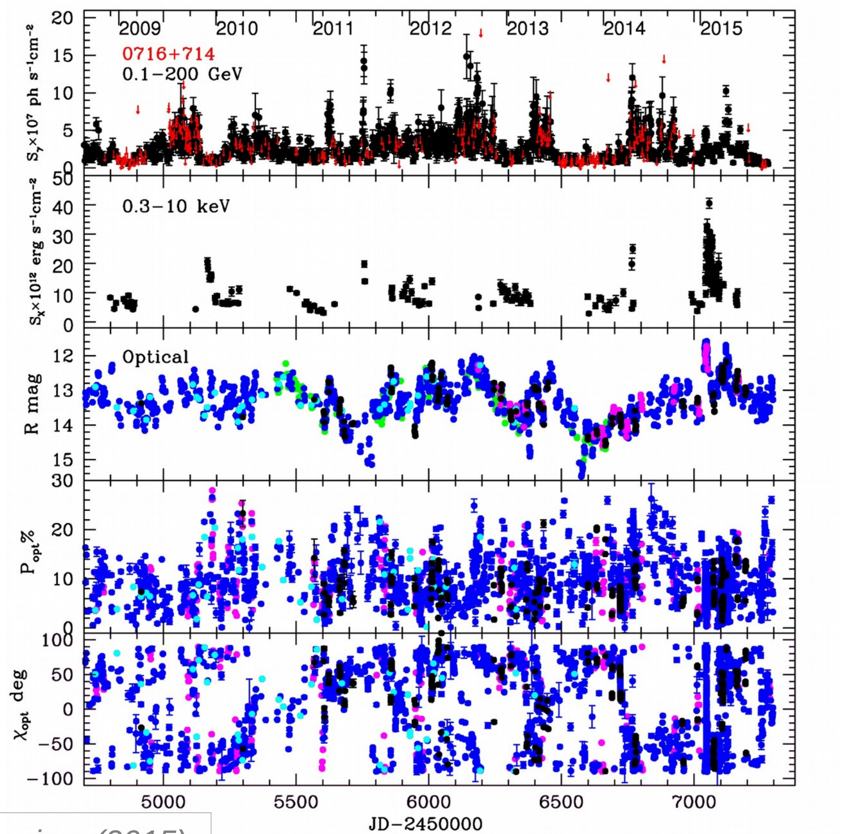
- Scheme from the 90's , no significant change since then
- Transition/evolution between low and high powers still not well known

Questions on variability – *source differentiation*

FSRQ 3C 454.3



BL Lac S5 0716+714

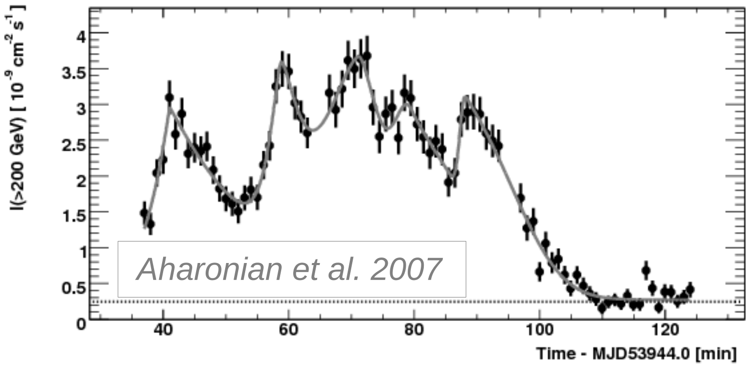


A. Marscher, 6th Fermi symposium (2015)

- **FSRQs :** Occasional powerful flares between quiescent states
- **BL Lacs:** Erratic variability with some very powerful flares

Questions on variability – *fast flares and low flow apparent speed*

Minute-scale gamma flare of the HBL PKS 2155-304



Doppler factor from variability: $\delta \leq \frac{c\ R\ t_{var}}{1+z}$

→ Lorentz factor: $\Gamma \sim \delta \sim 30$ *(Katarzyński et al. 2008)*

- **BL Lacs :** Usually slow motion in their radio jet but high Lorentz factor deduced from fast variability
- **FSRQs :** Usually slower flare but higher observed apparent speeds…

Majority of gamma ray flares are associated with a radio knot ejection

But majority of radio knot ejection are **not** associated with gamma ray flares *(Jorstad et al. 2001)*

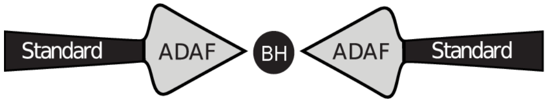
II - Intermediate blazars, the key sources

Intermediate blazars, the key sources – *example of the bright LBL AP-Librae*

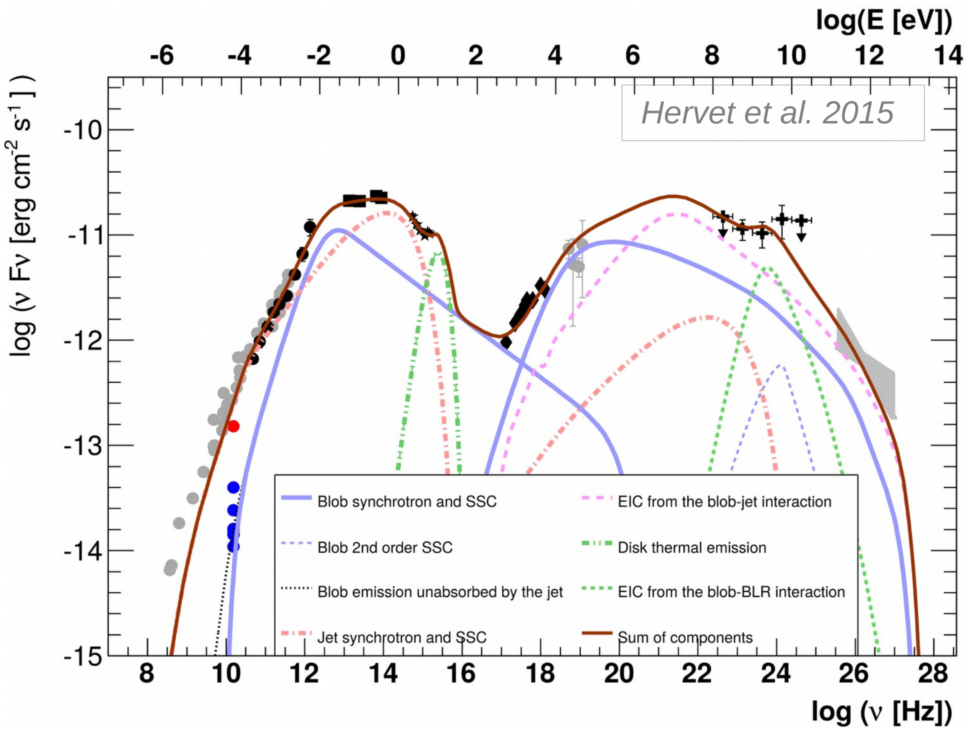
Intermediate blazars:
LBLs & **IBLs**

Intermediate accretion efficiency

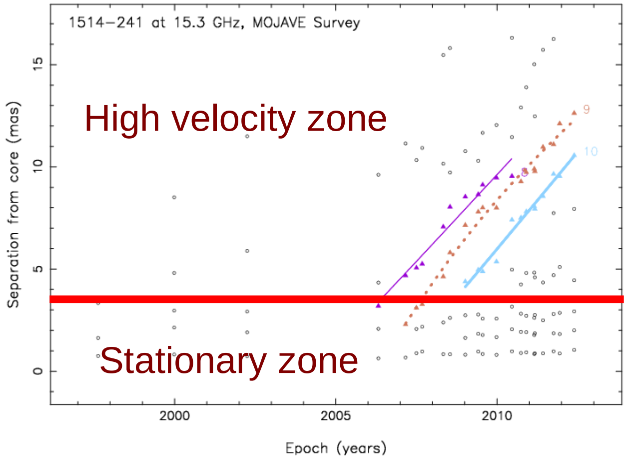
$$\eta = \frac{\dot{M}}{\dot{M}_{Edd}} \simeq 3.1 \times 10^{-3}$$



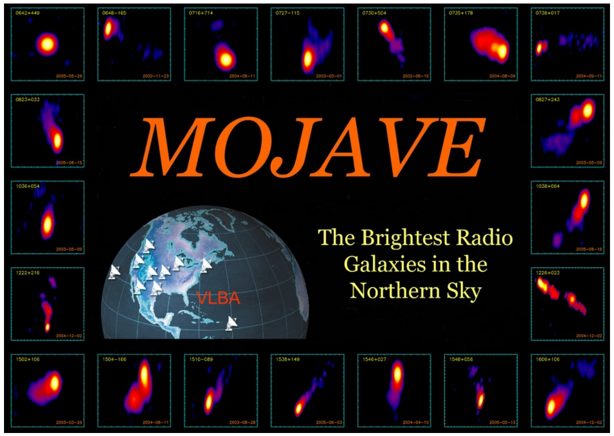
Powerful extended jet emission



Hybrid pc jet kinematics



Classifying blazars from the pc kinematics



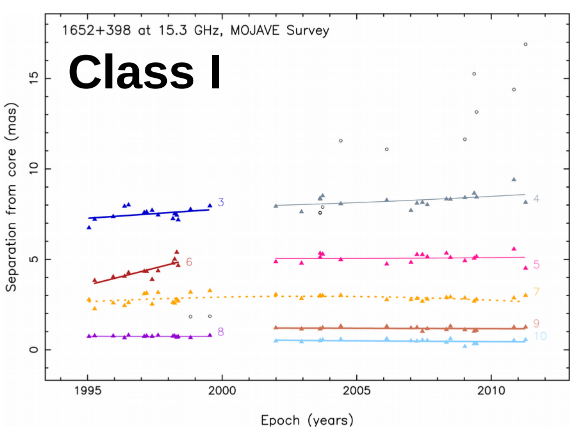
General features of MOJAVE:

VLBA Observations at 15 GHz since 1994
295 AGN jets
Angular resolution < mas

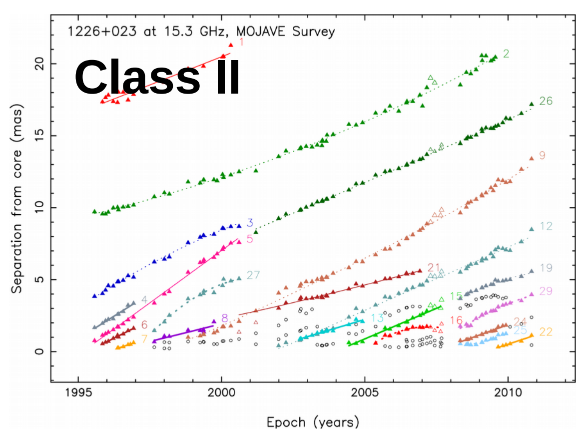
For this study:

161 blazars selected with known redshift and sufficient monitoring

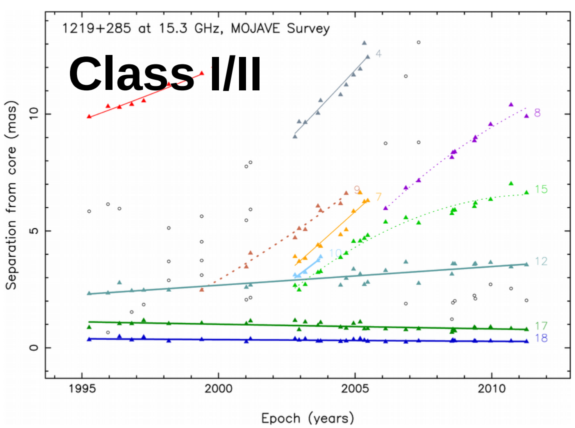
3 kinematic classes defined from the MOJAVE sample



Slow or stationary motion



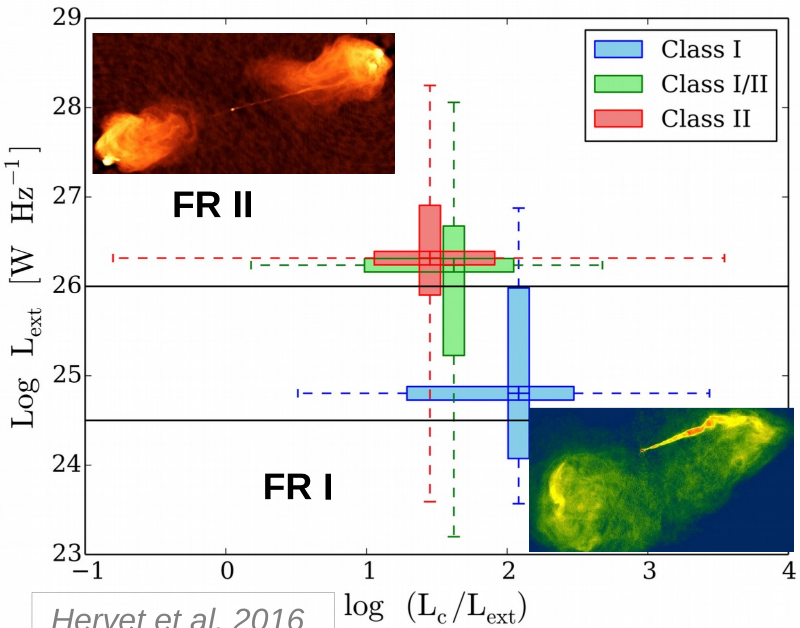
High speed motion



Hybrid motion

Pc kinematics fit well the AGN classification scheme

With kpc radio jets...



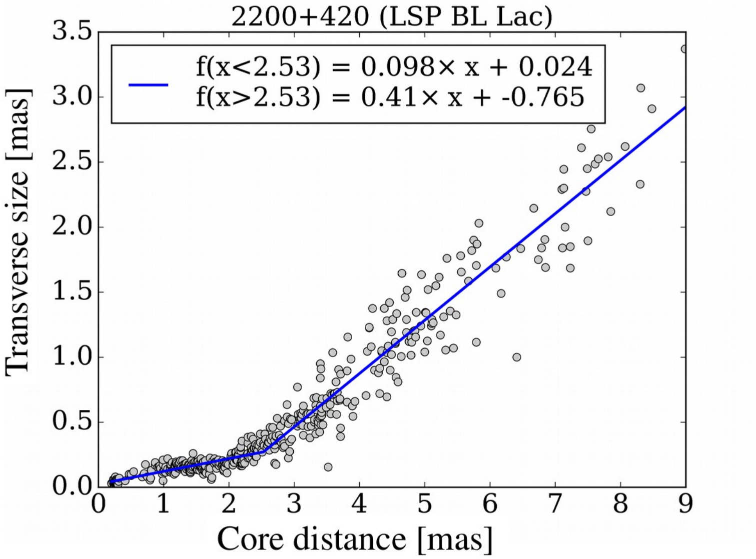
Hervet et al. 2016

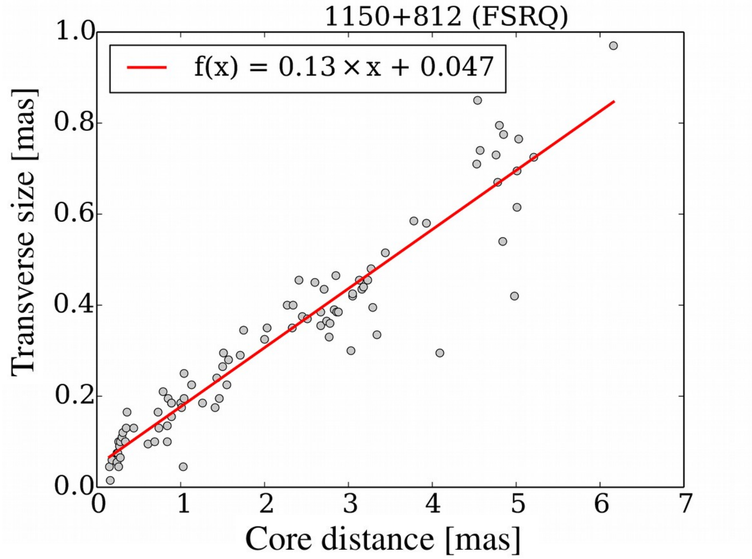
With spectral classes...

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

Jet aperture increase for intermediate blazars





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

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III – Recollimation shocks in transverse stratified jets

Two flows in jets

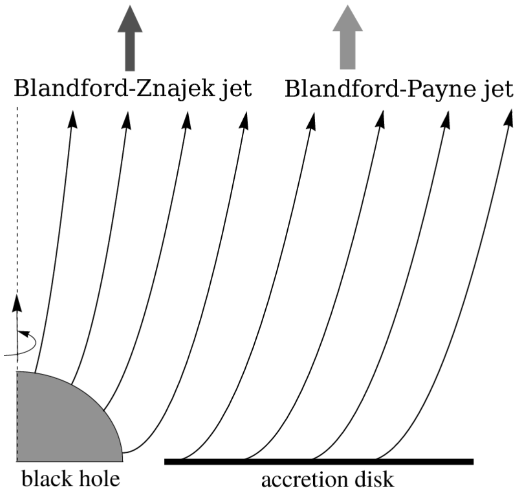
Two flow model *(Sol et al. 1989)*

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

  → transports most of the kinetic energy

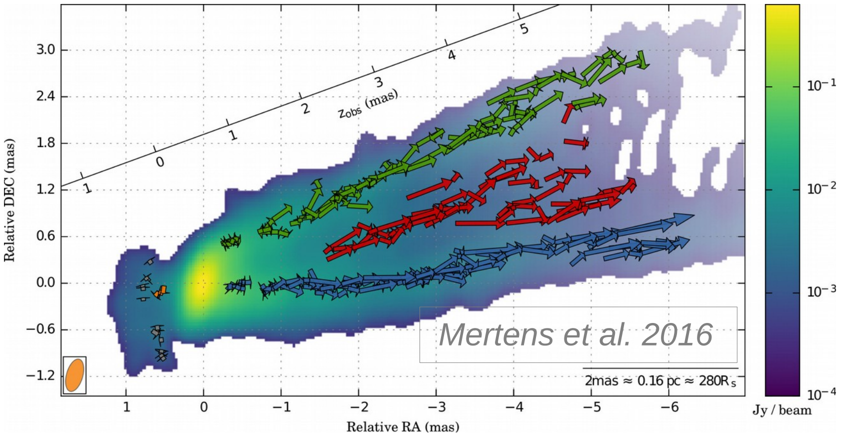
- Ultra-relativistic spine composed of e−/e+ pairs

  → responsible for most of the emission

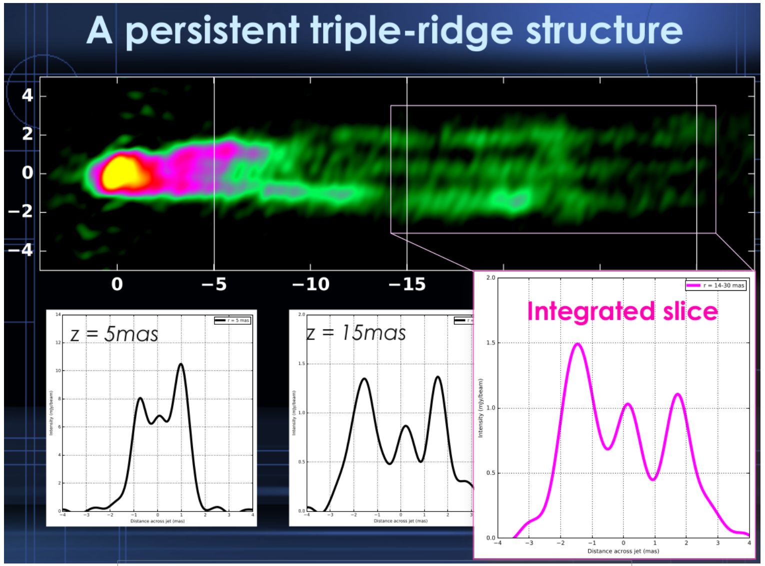


Adapted from Xie et al. 2012

Radio VLBI observations (M87)

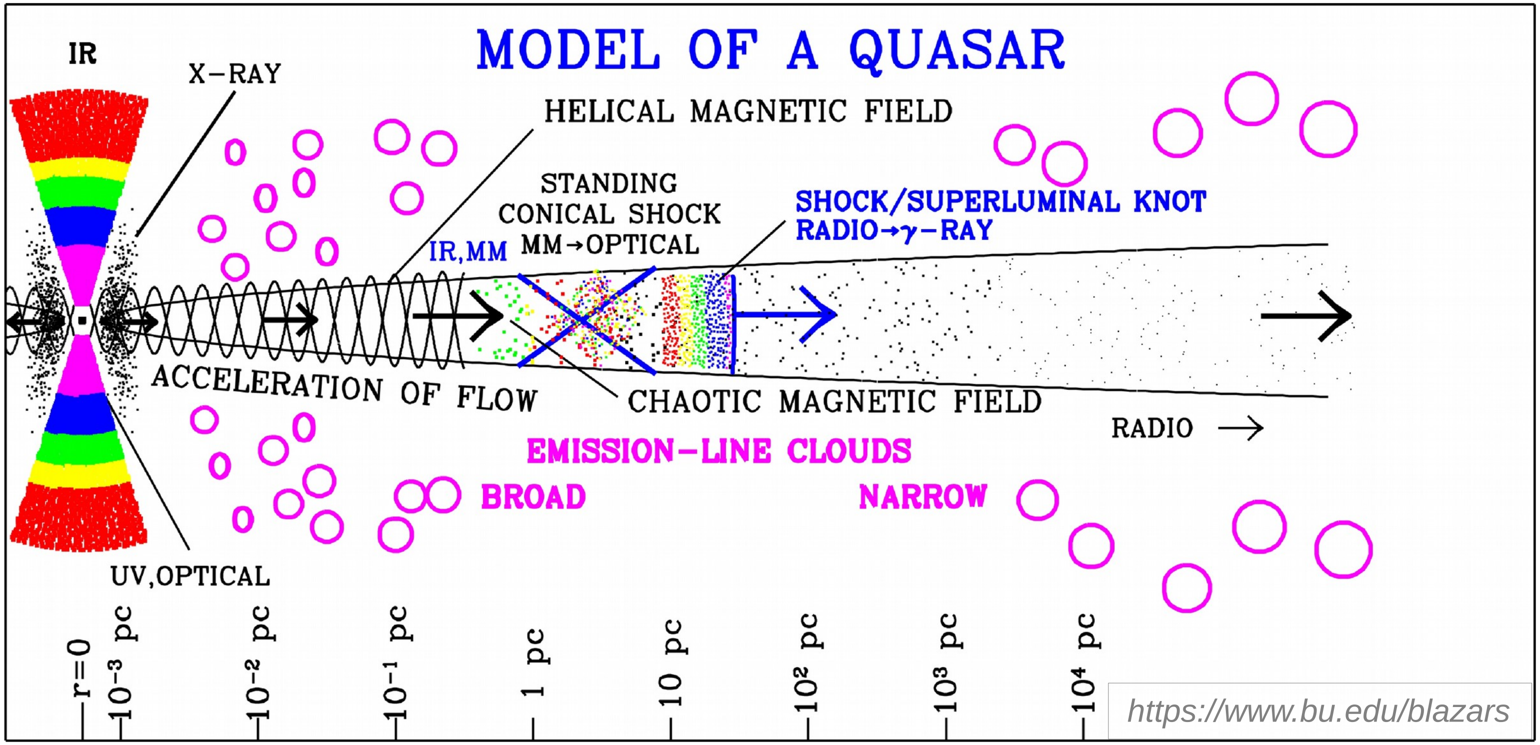


Mertens et al. 2016



From K. Hada presentation, 2016

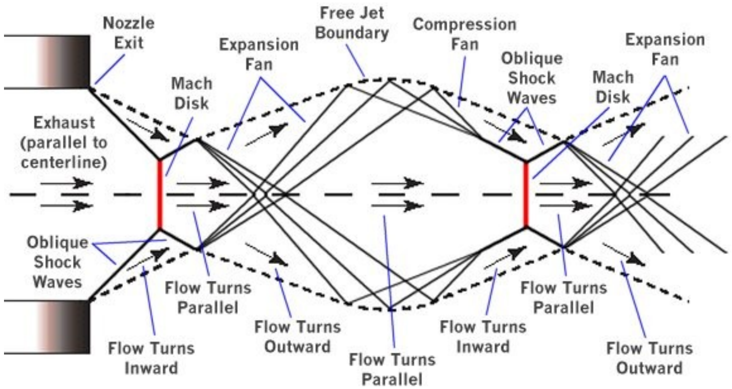
Recollimation shock in AGN jets *– the dominant paradigm*



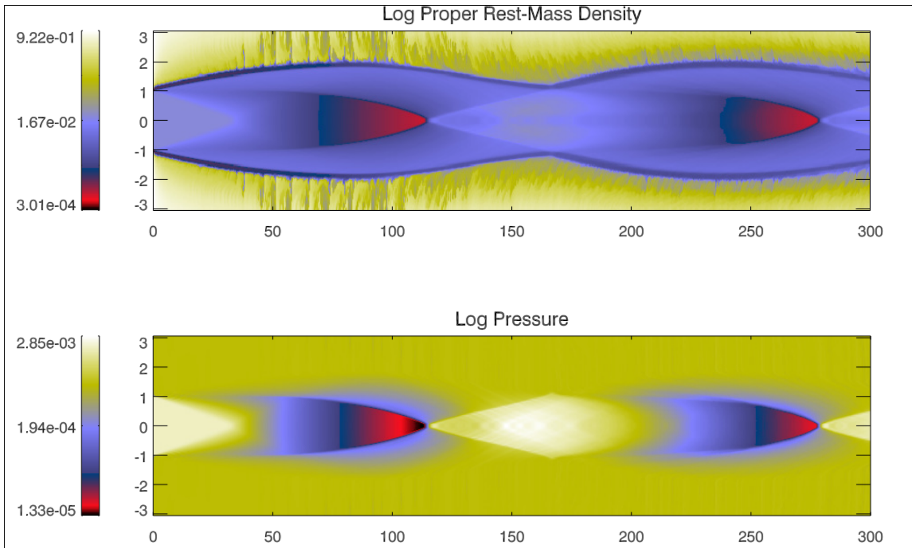
- Developed by Marscher & Gear (1985)
- Deduced from blazar variability, moving radio knots, polarization changes

Successive recollimation shocks structure

Supersonic and overpressured jet



MHD simulations



Fromm et al. 2016

Does VLBI radio knots are tracers of recollimation shocks?

→ If yes <u>they should not be randomly distributed</u>

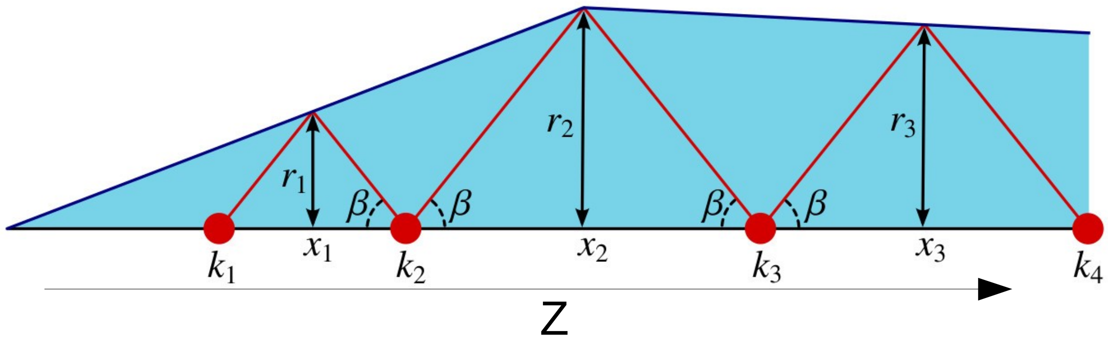
Radio knots as recollimation shocks – *check the idea*

Basic assumptions

- Flow speed: $v(Z) = cste$
- Density: $\rho(Z) \propto Z^{-2}$
- Magnetic field: $B(Z) \propto Z^{-1}$ from radio polarimetry *(Gabuzda et al. 2014)*
- Non-structured magnetic field acting as a pressure: $p(Z) \propto B^2(Z) \propto Z^{-2}$

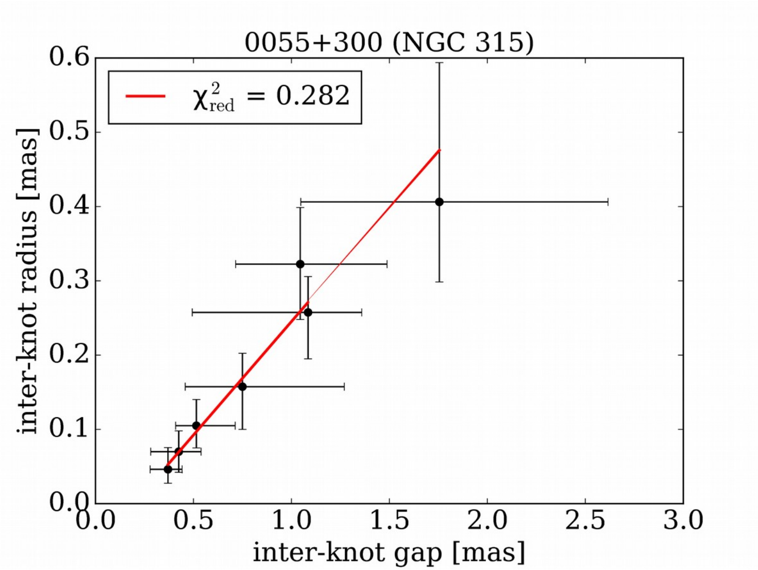
Sound speed: $v_s(Z) \propto \sqrt{\frac{p(Z)}{\rho(Z)}} = cste$ **Mach number:** $\mathcal{M} = \frac{\Gamma v}{\Gamma_s v_s} = cste$

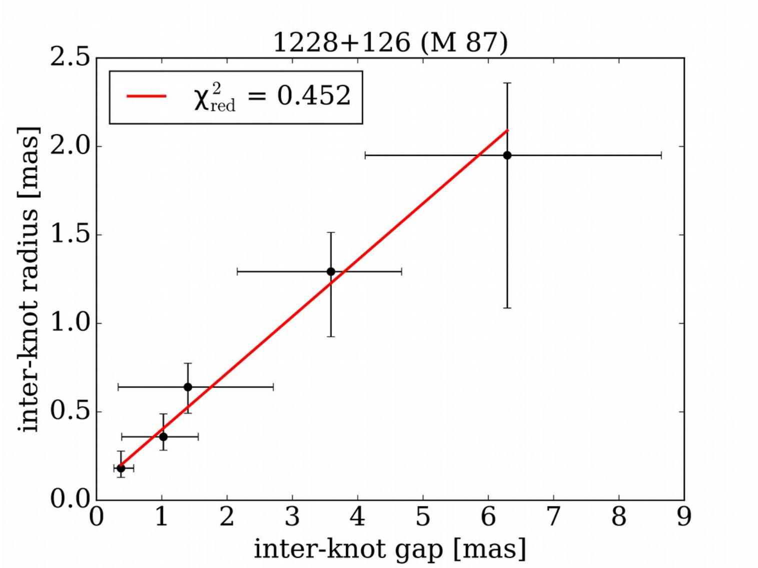
Inter-knot gaps only depending of the inner- jet radius



$r_n \propto \Delta k_n$

Radio knots as recollimation shocks – *results*





- Results in good accordance with a successive recollimation shocks scenario $r_n \propto \Delta k_n$
- Slope coefficient α can be used to deduce the inner jet Mach number

Mach angle: $\beta = \arctan\left(\frac{2\,\alpha}{\sin\theta}\right)$

Mach number (M87): $\mathcal{M} = \frac{1}{\sin\beta} = 1.08^{+0.15}_{-0.06}$

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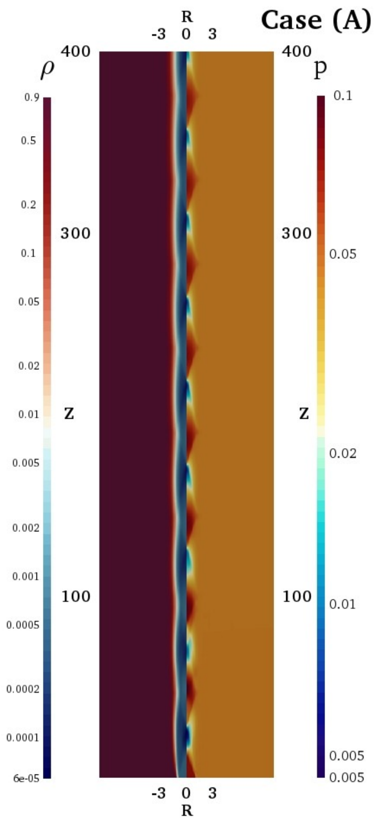
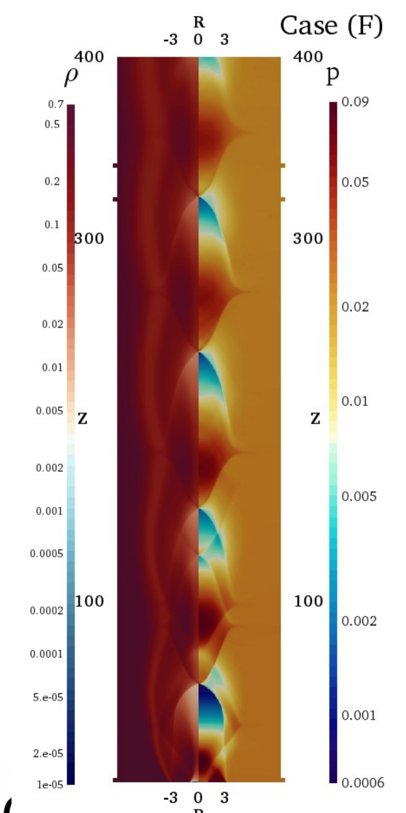
Successive recollimation shocks in transverse stratified jets - *Simulations*

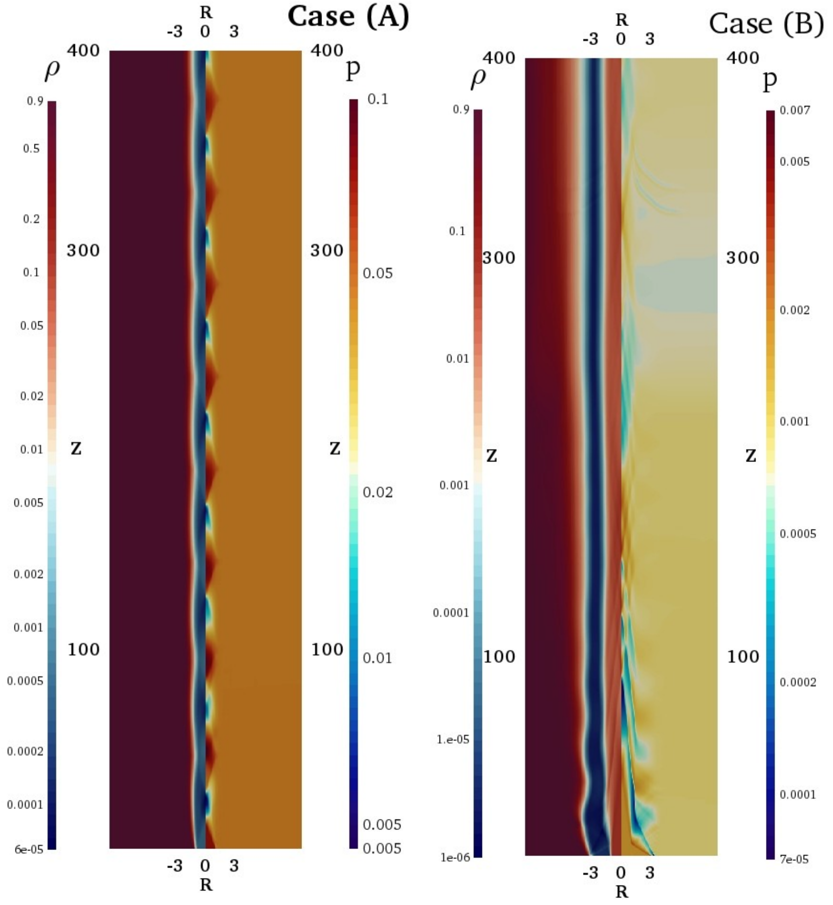
	external medium	inner jet		outer jet		Structured jet		
case	p_0	$\eta_{\rho,\text{in}}$	$M_{\text{c,in}}$	$\eta_{\rho,\text{out}}$	$M_{\text{c,out}}$	$L_{\text{k, in}}/L_{\text{k, total}}$	$L_{\text{k, out}}/L_{\text{k, total}}$	Two-component jet
A	5×10^{-2}	4.5×10^{-4}	1.22			1	0.0	No
B	1×10^{-3}	5×10^{-1}	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



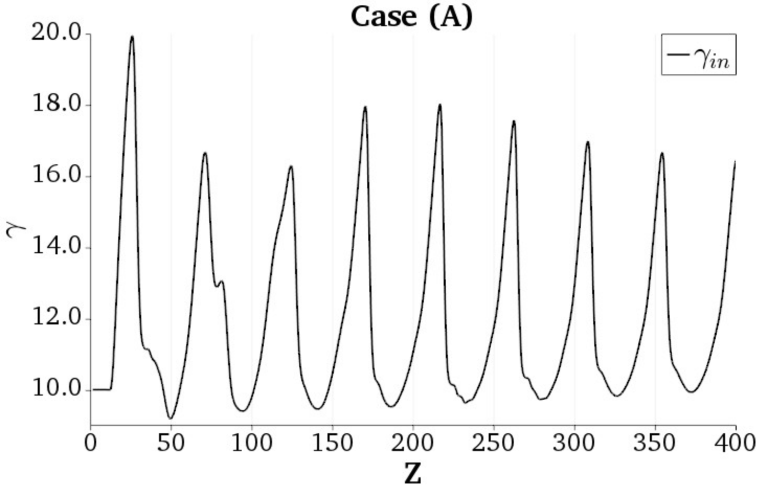
- 2D RHD simulation of jets with AMRVAC code *(Meliani et al. 2007)*
- 5 types of two flows jets simulated
- Two initial Lorentz factors: $\Gamma_{in} = 10 \;\; \Gamma_{out} = 3$
- Mainly classified following the kinetical power between inner and outer jets



Link with the blazar classification - ***HBLs***



Lorentz factor profile

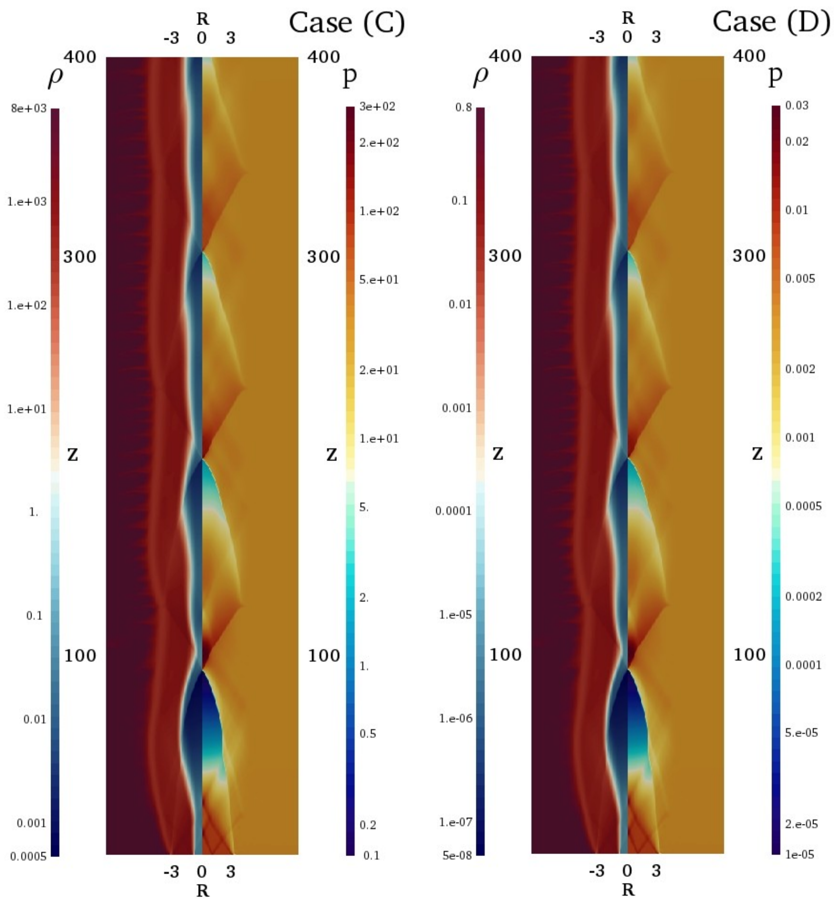


Strong inner jet, weak (or absent) outer jet
→ Consistent with their spectral energy distribution

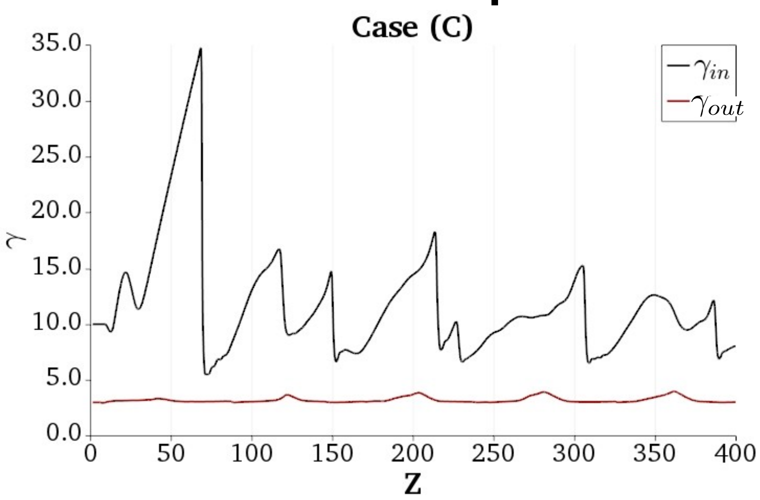
Multiple stationary shocks
→ Consistent with radio VLBI observations

Successive shocks can re-accelerate particles
(Meli & Biermann 2013)
→ Consistent with higher sync. peak frequencies

Link with the blazar classification - *FSRQs*



Lorentz factor profile

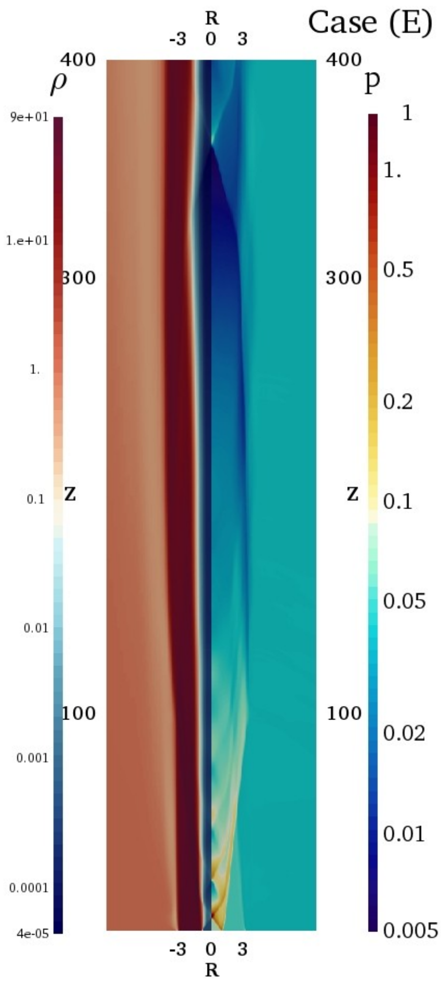


Strong inner and outer jets
→ Consistent with their spectral energy distribution

Powerful first shock
→ Consistent with usual variability pattern
→ Consistent with emission zone close to the nucleus (deduced from external IC radiation)

Fast damping of successive shocks
→ Consistent with lower sync. peak frequencies

Link with the blazar classification - *LBLs & IBLs*



Lorentz factor profile

Weak inner jet and strong outer jets
→ Consistent with their spectral energy distribution

Jet aperture increase
→ Consistent with VLBI observations

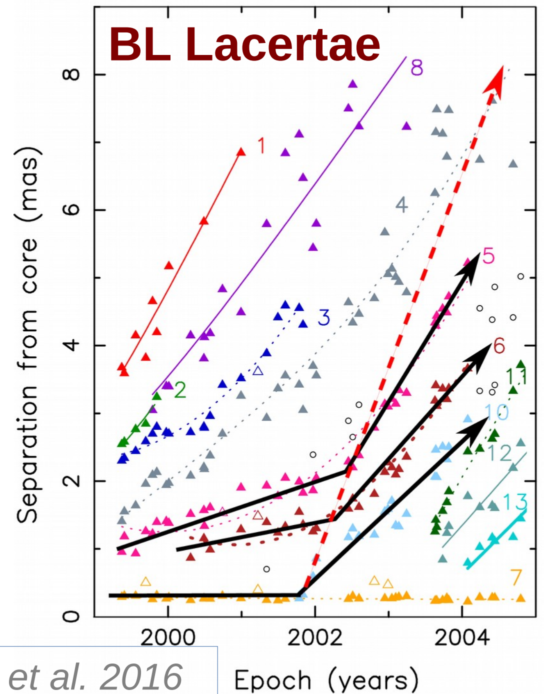
Fast damping but close successive shocks
→ Consistent with intermediate sync. peak frequencies

Powerful shock seen far from the stationary structure
→ Seen in M87 (HST1 knot)

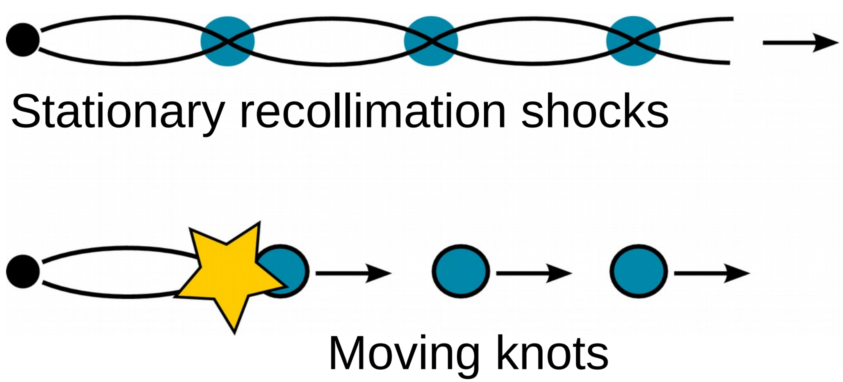
Caveat

Fast motions observed in jet are not reproduced by these simulations
→ Not enough perturbations to break the recollimation shock structure

Clues of perturbation breaking the VLBI jet structure



Hervet et al. 2016



A new global scheme

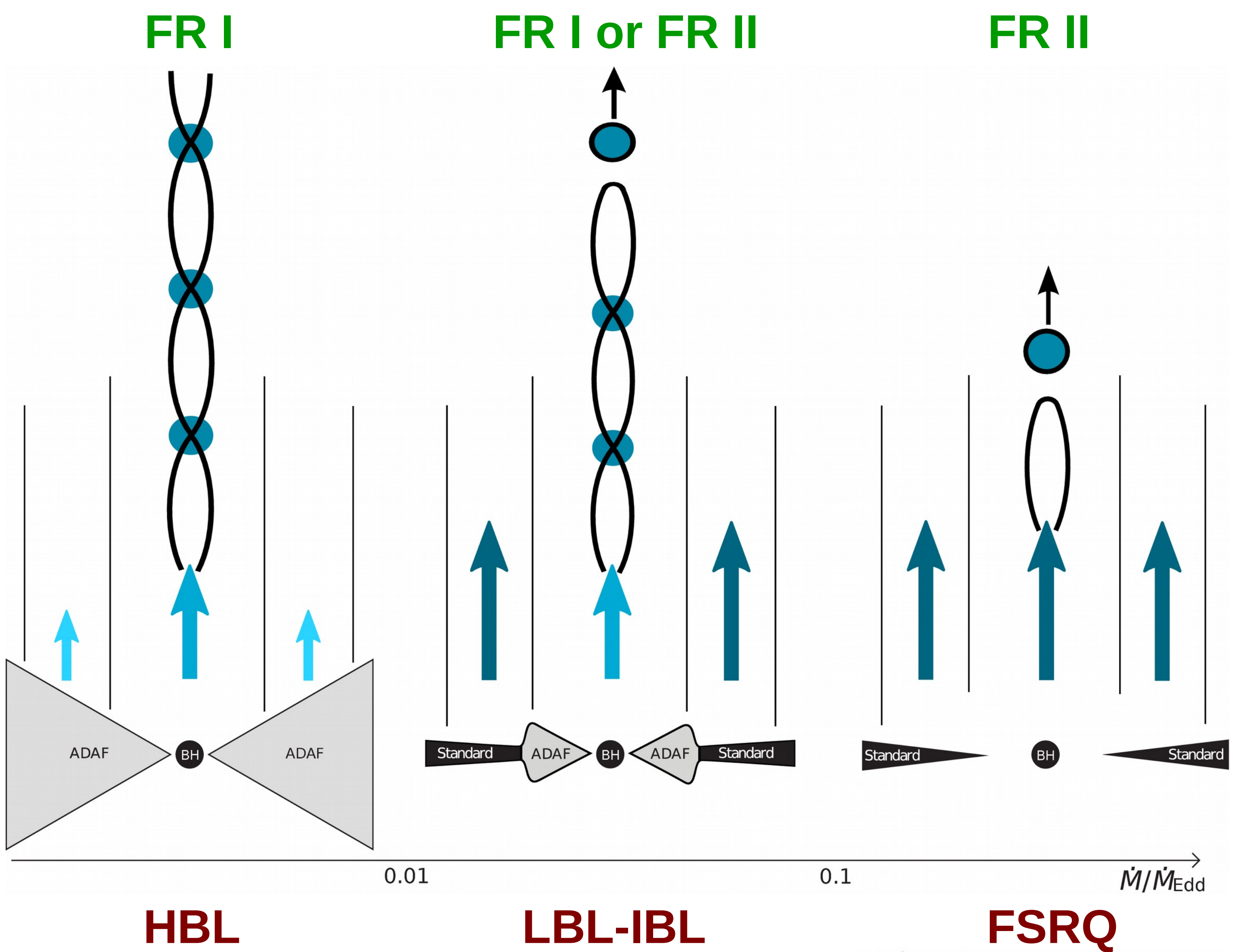
Large scale structure

Pc scale structure

Jets kinetic powers

Accretion regime

Spectral class



Conclusion & Outlook

- Radio-loud AGN can be differentiated following the relative kinetic powers between inner and outer jets
- This AGN differentiation is favoured to be linked to intrinsic properties of the accretion disk rather than influence of the external medium

Next steps

- Reproduce the fast motions in jets by injecting perturbations
- Check the consistency of radio knots as powerful particle accelerator by looking the non-thermal variability of blazars
- Study the influence of a structured magnetic field in the recollimation shocks configuration
- Study the particle re-acceleration process of successive shocks