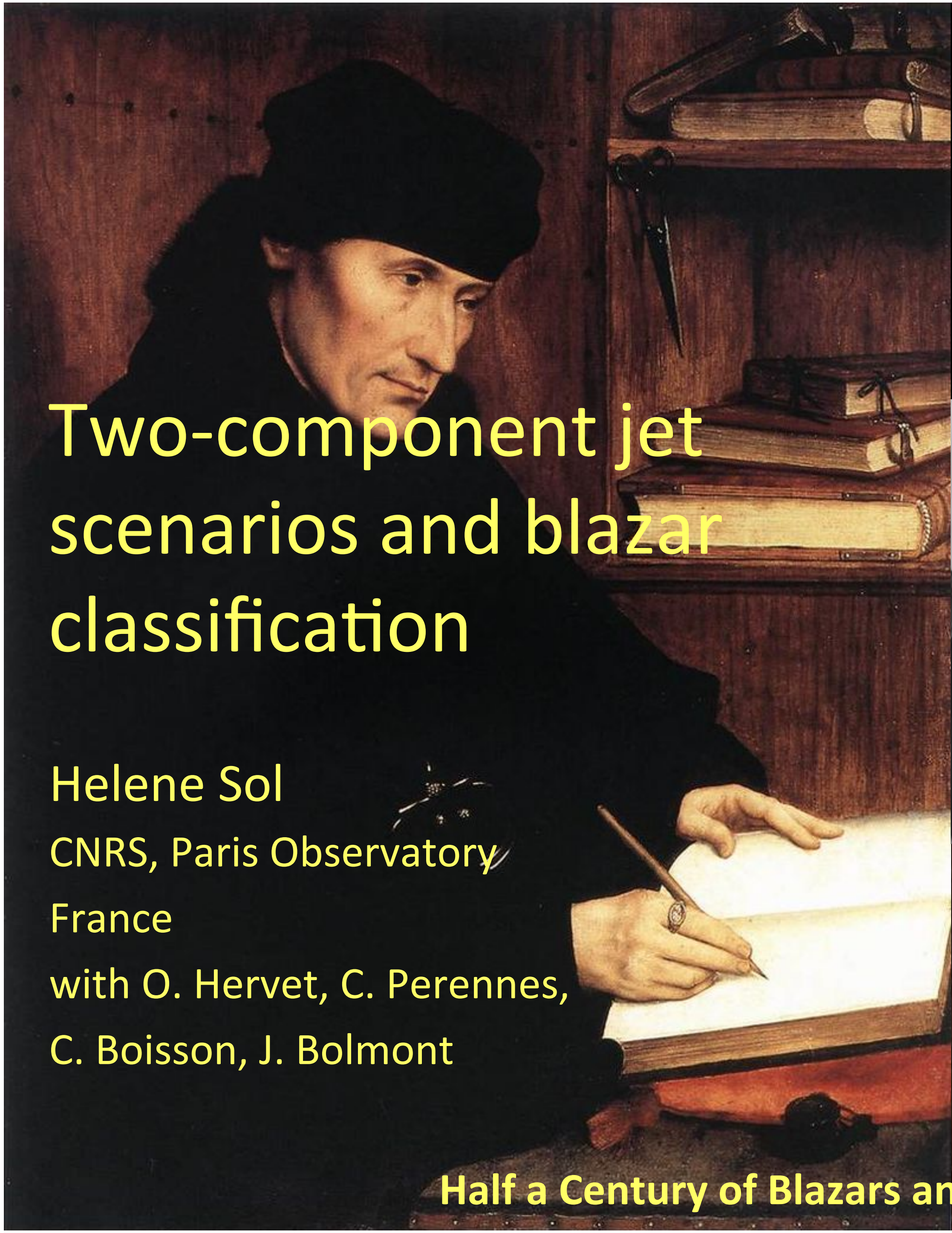
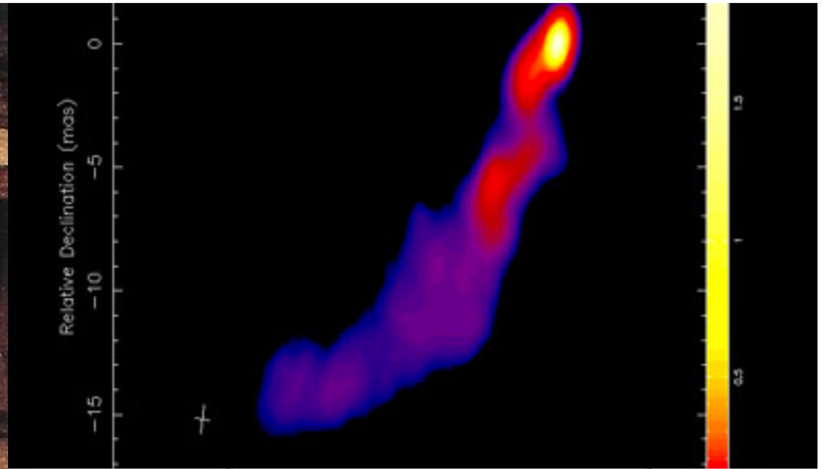


Two-component jet scenarios and blazar classification

Helene Sol
CNRS, Paris Observatory
France
with O. Hervet, C. Perennes,
C. Boisson, J. Bolmont



CTA 102

Half a Century of Blazars and Beyond, Turino, 11-15 June 2018

Outline of the talk

- Various facets of two-component jets
- A few exemplary cases
- Blazar emission from radio to TeV
  - « Blob-in-jet » scenarios
  - Some variability issues
- AP Lib, an intermediate BL Lac object
  - Spectral Energy Distribution (SED)
  - TeV-radio VLBI connection
- Proposal of new classification of blazars
  - Jet kinematic properties versus blazar spectral types

Various facets of two-component jets

- **Various approaches and names**: 2-flow, 2-fluid, 2-stream, spine-sheath, limb-brightened, layered, coaxial, transversely stratified or structured jets

→ strong transverse gradients in the velocity, magnetic field, density, or intensity profiles of the jet

→ inner jet + outer jet :

typically a fast central spine + a slower outer layer

- **Proposed for three decades and applied with increasing success** first mostly on **radio** AGN, and later on **gamma-ray** AGN as well

(Sol et al, 1989; Reid et al, 1898; Owen et al, 1989; Komissarov, 1990; Henri, Pelletier, 1991; Romero, 1995; Appl et al, 1996; Krichbaum et al, 1998; Swain et al, 1998; Katz-Stone et al, 1999; Aloy et al, 2000; Chiaberge et al, 2000; Giroletti et al, 2004; Ghisellini et al, 2005; Jester et al, 2006; Gopal-Krishna et al, 2007; Boutelier et al, 2008; Abramowski et al, 2012; Reynoso et al, 2012; Sol et al, 2013; Aleksic et al, 2014; Tavecchio & Ghisellini, 2015; Boccardi et al, 2016; Mertens & Lobanov, 2016; Sikora et al, 2016; Mertens et al, 2016; Sobacchi et al, 2017; Chen, 2017; Hervet et al, 2017; Boccardi et al, 2017; Gaur et al, 2017; Chhotray et al, 2017, Piner & Edwards, 2018 …)

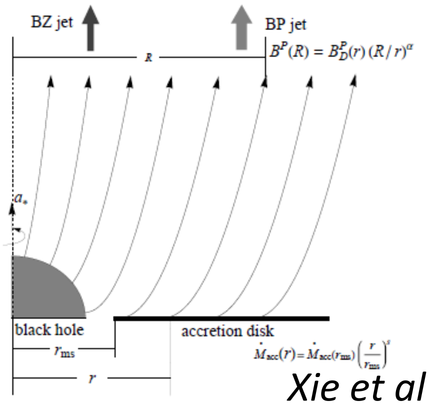
- **Different origins for the 2-components:**

  Initial formation from the central engine itself

(Tsinganos, Bogovalov, 2002; McKinney, 2005; Sikora et al, 2007; Komissarov et al, 2007; Sadowski & Sikora, 2010; Xie et al, 2012; Chantry et al, 2018 …)

  or possibly developed during jet propagation

(Bowman et al, 1996; Rossi et al, 2008; Walg et al, 2014; Gabuzda et al, 2014; Coughlin & Begelman, 2015; Kawakatu et al, 2016; Gabuzda et al, 2018 …)

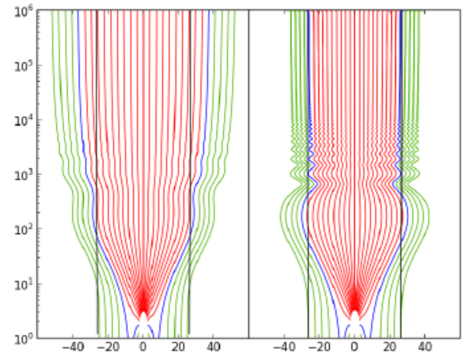


Xie et al

- **Interaction between the 2-components:**

Propagation, deceleration & entrainement, instabilities, shocks, particle acceleration …

(Laing, 1993, 1996; Hanasz & Sol, 1996; Urpin, 2002; Georganopoulos & Kazanas, 2003; Rieger & Duffy, 2004; Bogovalov & Tsinganos, 2005; Perucho et al, 2005; Mizuno et al, 2007; Hardee, 2007; Hardee et al, 2007; Meliani & Keppens, 2007; Walg et al, 2013; Chhotray et al, 2017; McDonald et al, 2017 …)

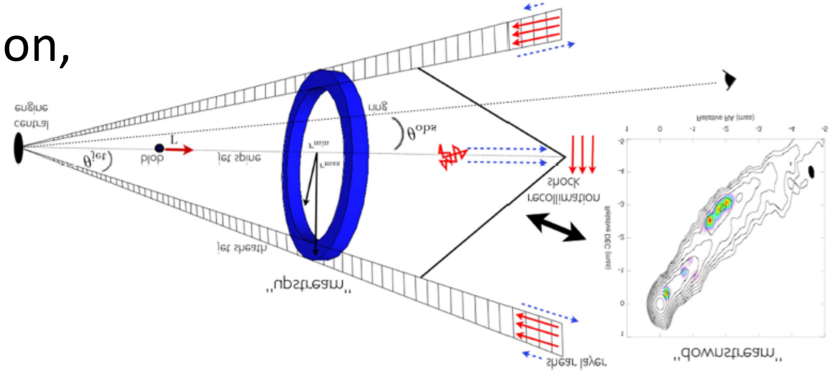


Chantry et al

- **Can explain some AGN/blazar puzzles:**

pc/kpc speed discrepancy, FRI/BL Lac unification, Doppler crisis, orphan gamma-ray flares …

(however, alternatives exist)

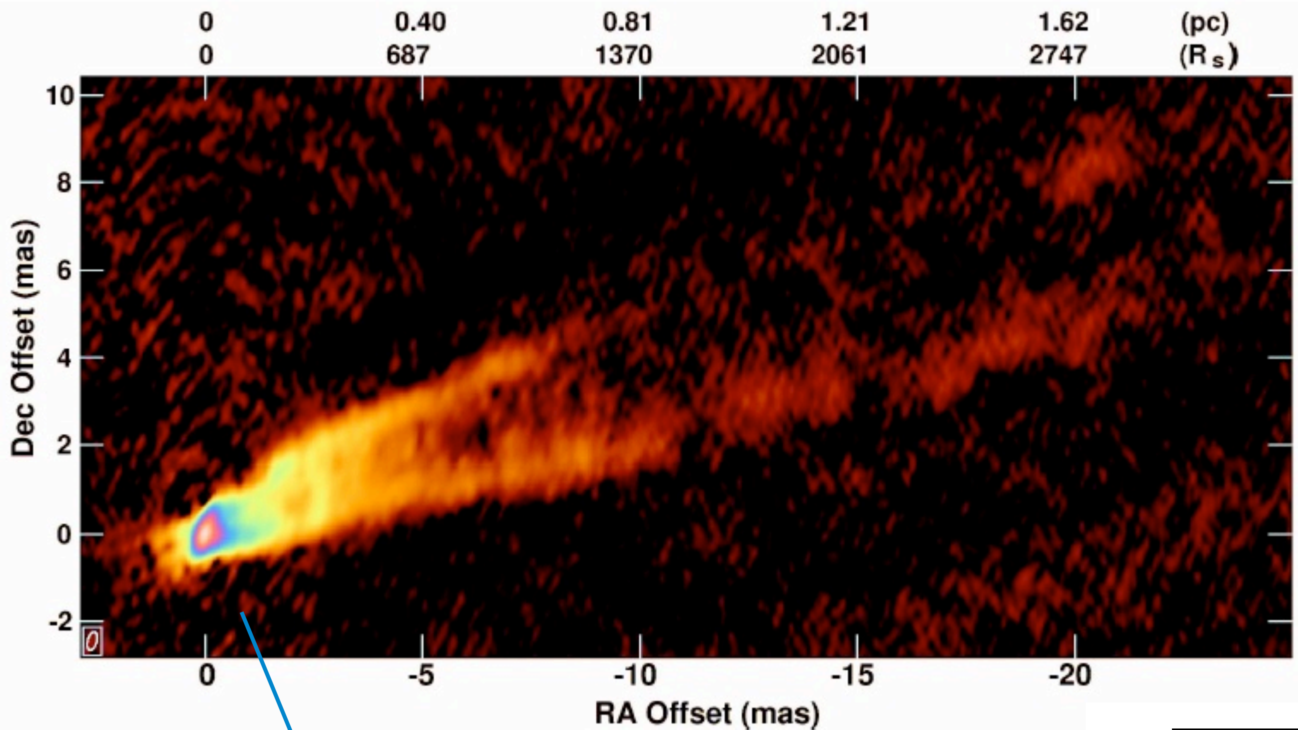


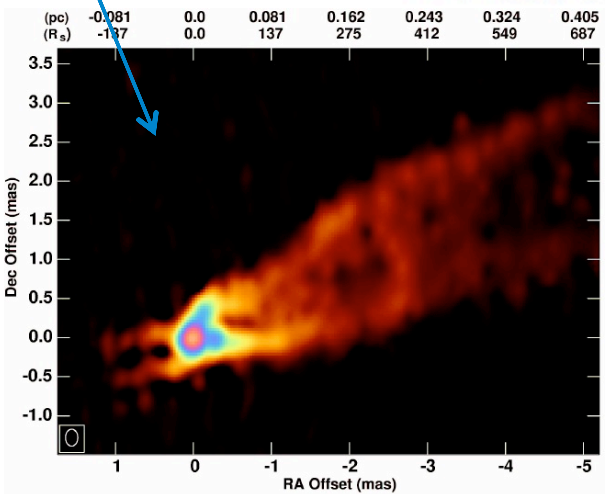
- **Considered also for GRB, microquasars, Tidal Disruption Event …**

(Berger et al, 2003; Peng et al, 2005; Filgas et al, 2011; Granot et al, 2016; Lan et al, 2018 - Petrucci et al, 2006 - Liu et al, 2015 …)

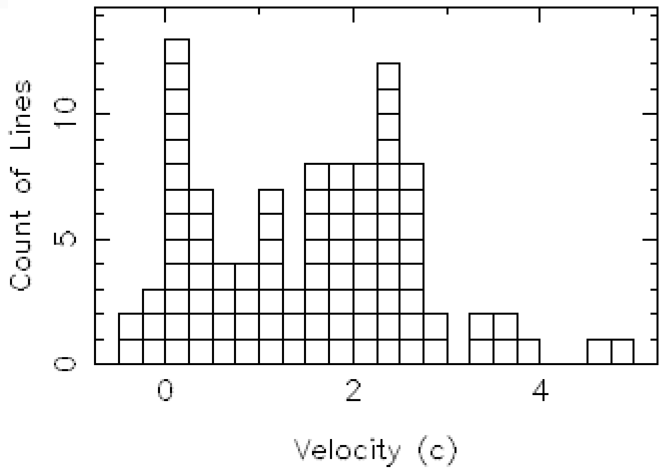
McDonald et al

A few exemplary cases



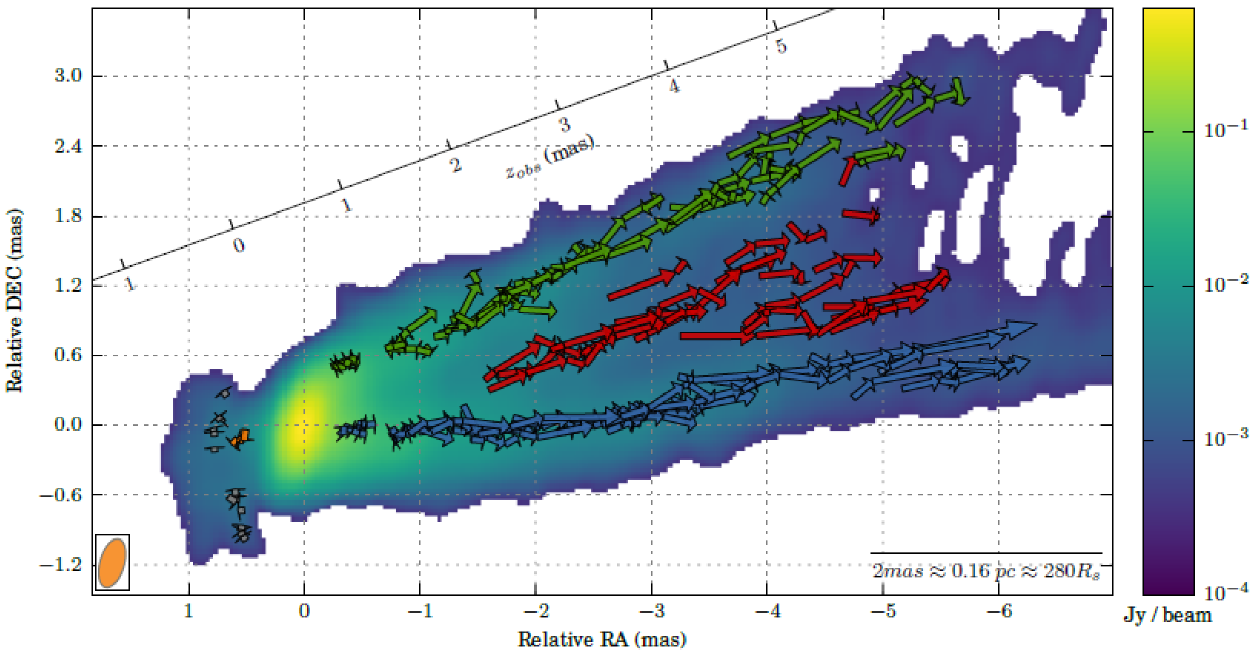


M87:
edge brightened jet
(Walker et al, 2016)

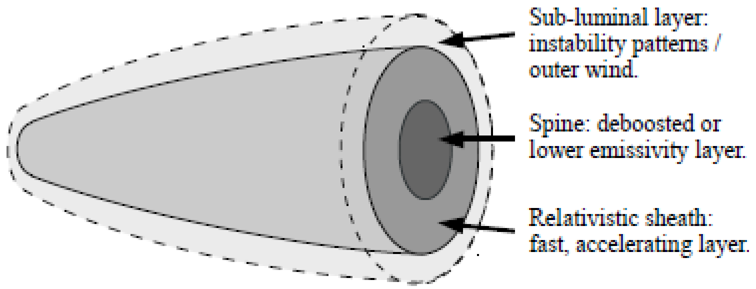


M 87: Deep analysis of 2D structure and kinematics on 11 images by 7 mm VLBA (43 GHz) in Jan-Aug 2007

(Mertens et al, 2016)

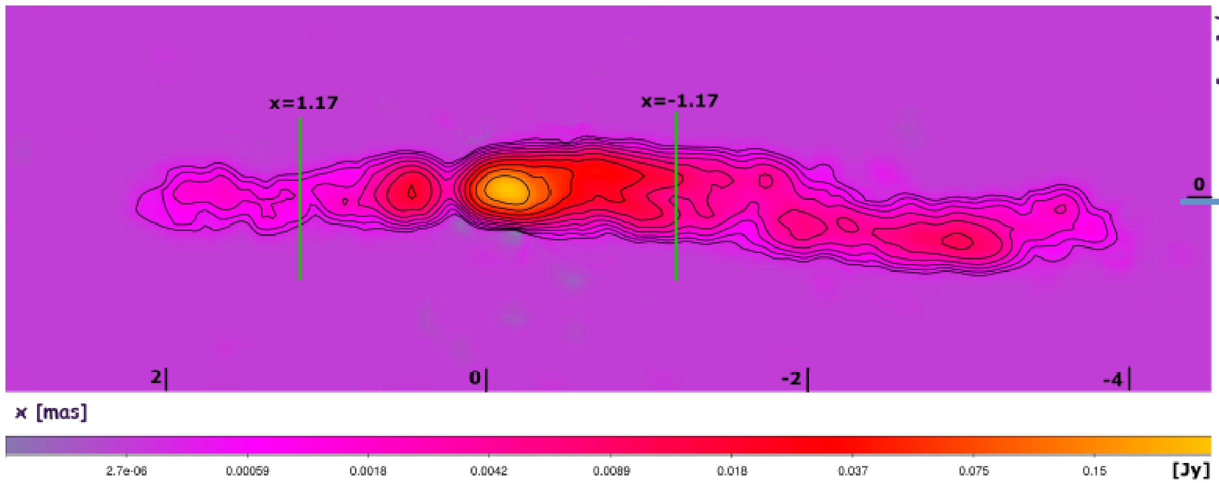


- Stratification of flow
- Fast component detected in the 3 regions
- Central stream and limbs.
- Evidence for jet rotation.

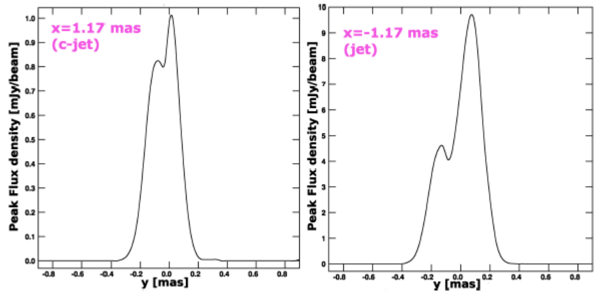


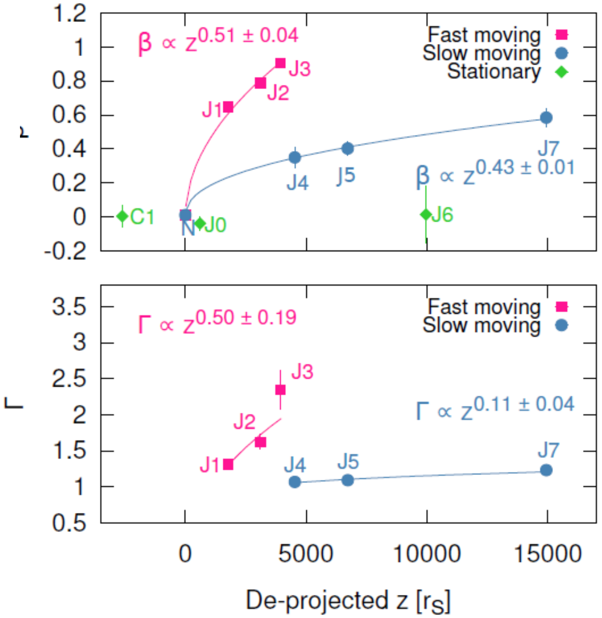
A slow layer (v = c/2) and a
fast accelerating stream line (v = 0.92 c, γ = 2.5)
+ a probably faster spine (not detected here)

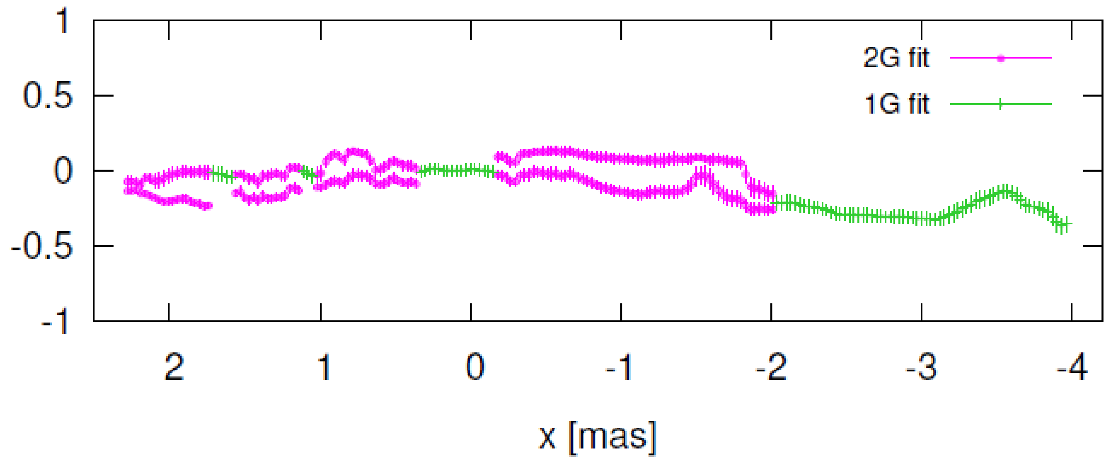
Cygnus A: a stratified two-sided jet, with fast and slow layer in the flow seen in 7 mm VLBI *(Boccardi et al, 2016)*



Stacked 43 GHz images from 2007-2009







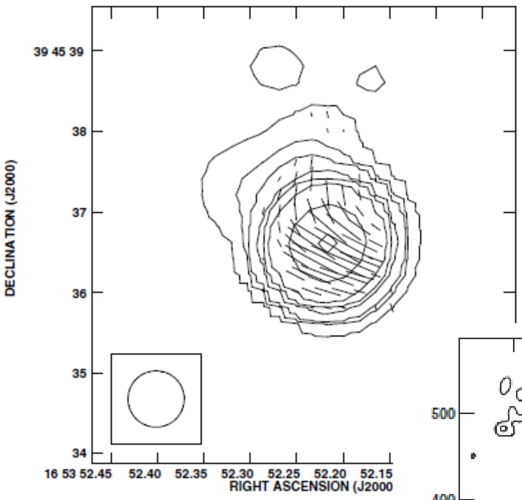
Acceleration with two distinct regimes

Magnetically driven outflows?

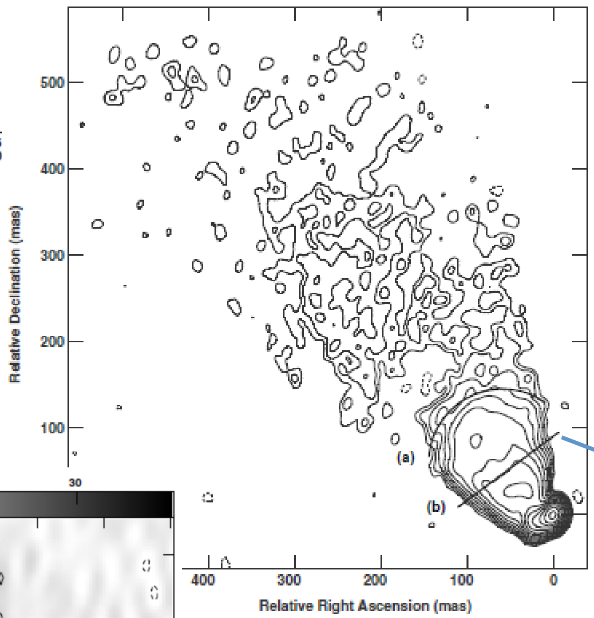
Mrk 501

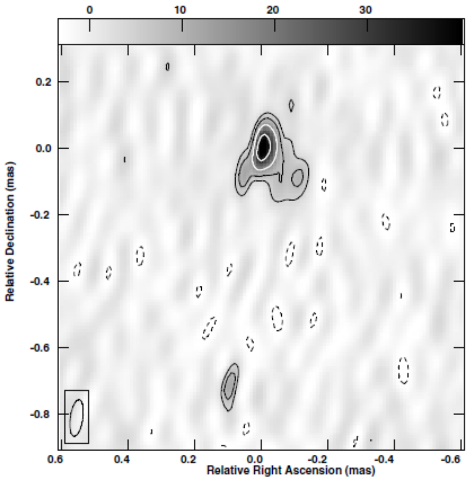
- Highly distorted structure with bends.
- Limb brightening from sub-pc scale to 40 pc, i.e. from 0.1 mas to 60 mas.

(Giroletti et al, 2008)

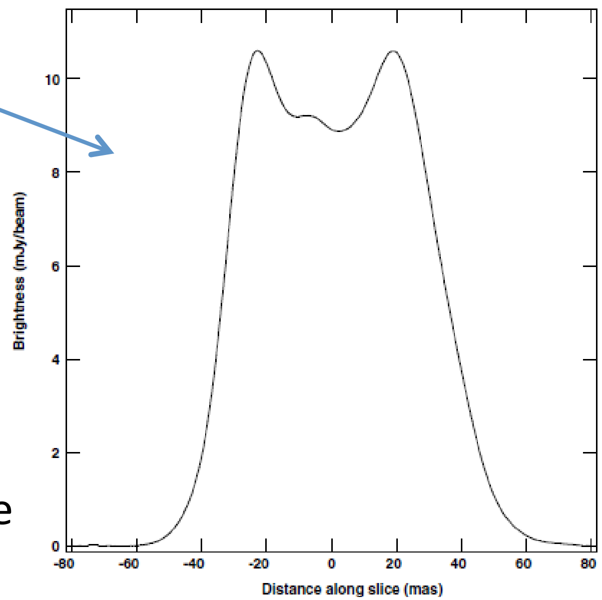


1.4 GHz





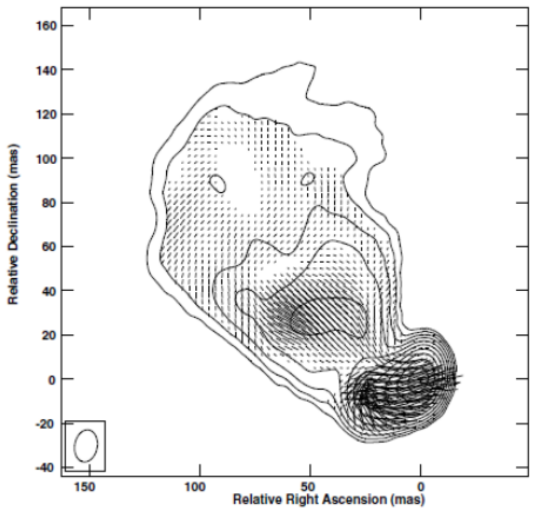
86 GHz

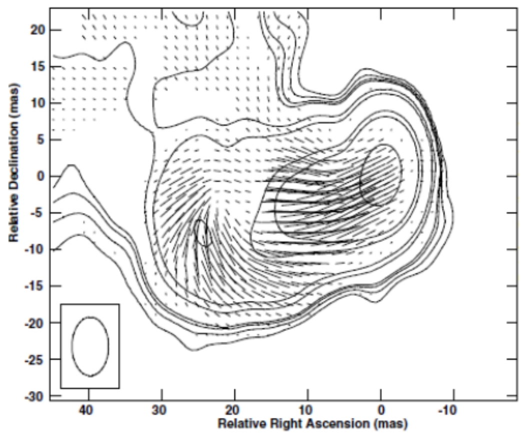


Jet brightness transverse profile

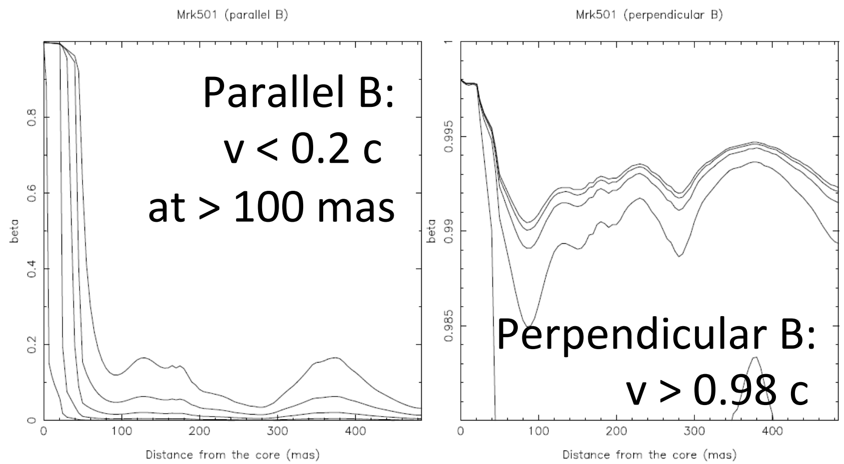
Mrk 501:

- Estimated jet velocities smaller in parallel B than in perpendicular B zones
- Magnetic field B looks perpendicular to main jet axis *(Giroletti et al, 2008)*

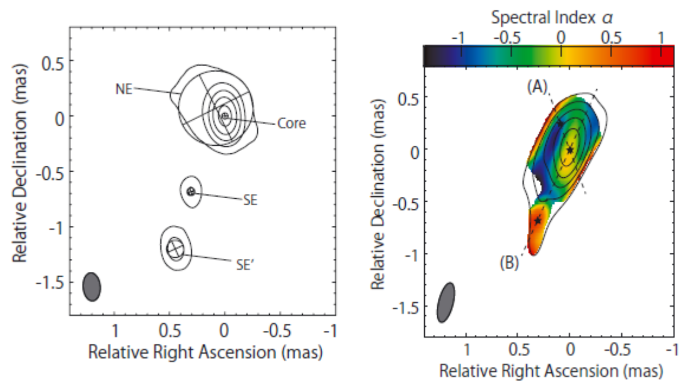


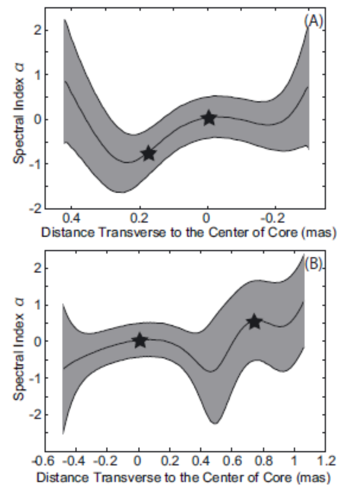


Polarized images of inner and extended jets.
Polarization vectors aligned with the jet spine



Complex B field geometry!
Kharb et al, 2008 and Gabuzda et al, 2014:
HBL dominated by parallel B field

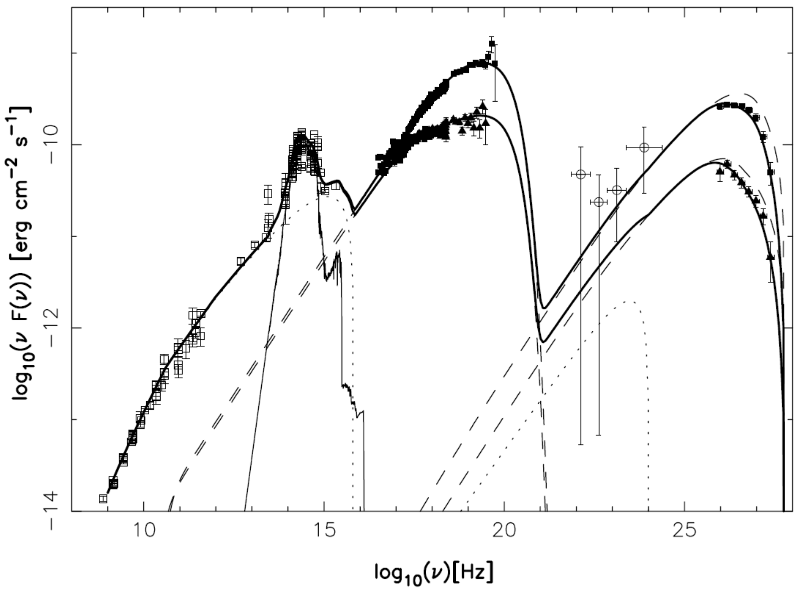




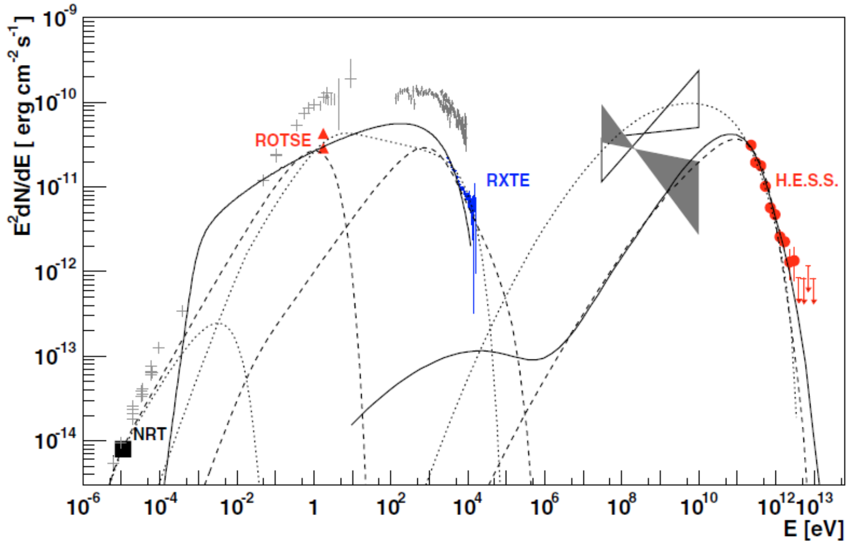
(Koyama et al, 2016)

Blazar emission from radio to TeV

- Basic Synchrotron-Self-Compton (SSC) « blob-in-jet » scenario easily reproduces instantaneous SED from radio to VHE gamma-rays for most HBL: fast moving shock or plasmoid propagating along an extended radio jet.

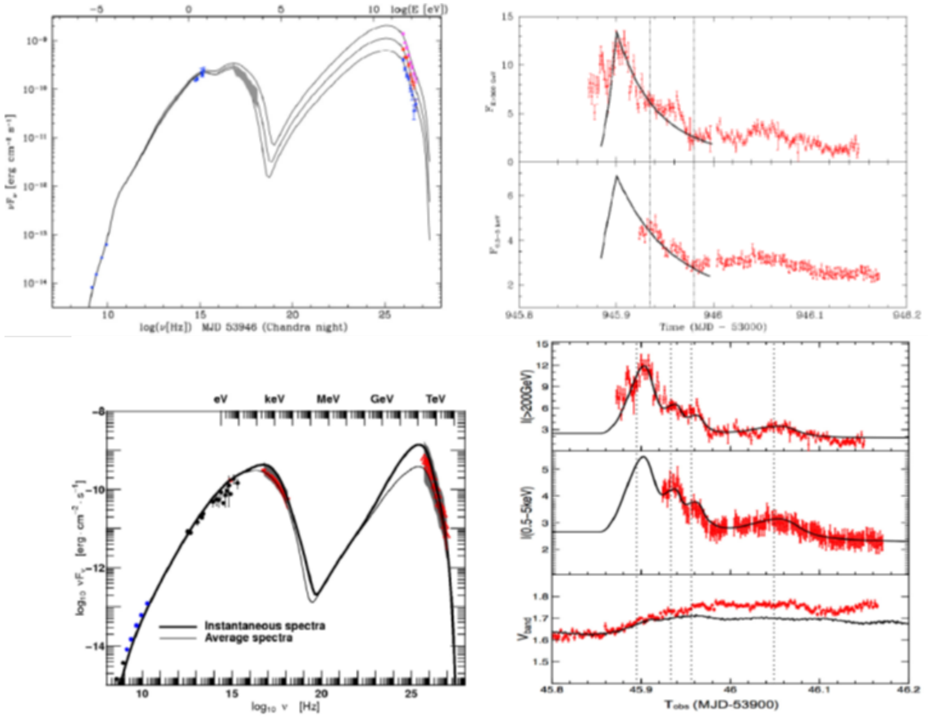


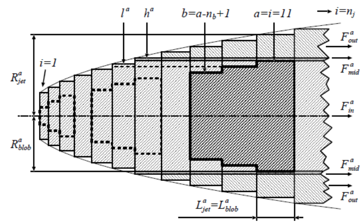
Mrk 501: SED for two activity levels during the 1997 outburst
(Katarzynski, HS, Kus, 2001)



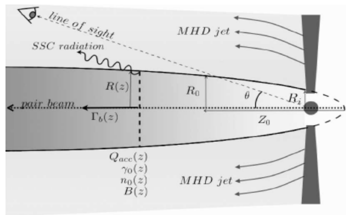
PKS2155-304: 1st multi-wavelength campaign up to TeV in 2003
(Aharonian et al, 2005)

- Blazar flares: different two-component scenarios can offer rather good *(not perfect)* multi-lambda fits for highly variable event, even when keeping a reasonnably small number of free parameters.
- Here the second big flare of PKS 2155 in 2006 *(Abramowski et al, 2012, HESS)*





Fits of SED and multi-lambda light curves by a time-dependent blob-in-jet model *(from Katarzynski, HS, Kus, 2003*) and by a stratified jet scenario *(from Boutelier et al, 2008)*

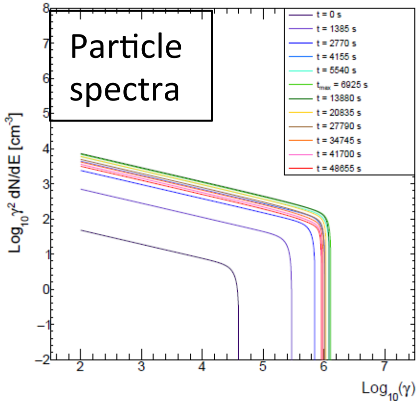


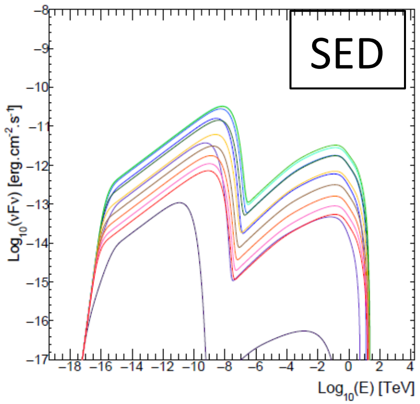
- Clear need to better constrain the physics of the flares (origin of the variability, parameters of emitting zone, location & environment …)

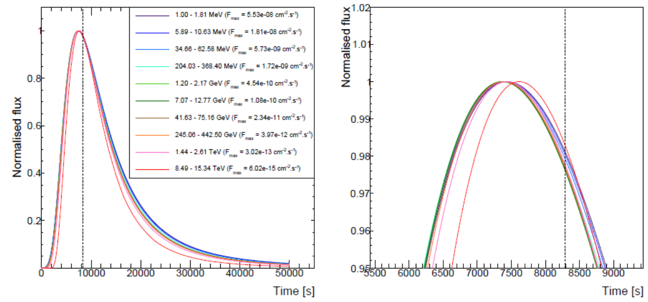
Studying intrinsic arrival time spectral lags Δt(E) in basic SSC flare scenario

$$\frac{\partial N_e(t,\gamma)}{\partial t} = \frac{\partial}{\partial \gamma}\left\{\left[\gamma^2 C^{cool}(t) + \left(C^{adiab}(t) - C^{acc}(t)\right)\gamma\right] N_e(t,\gamma)\right\}$$

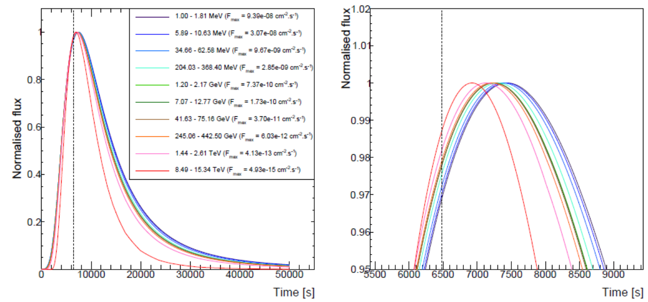
Time evolution of particle spectrum







(a) Scenario 1

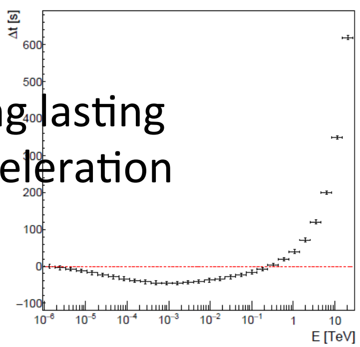


(b) Scenario 2

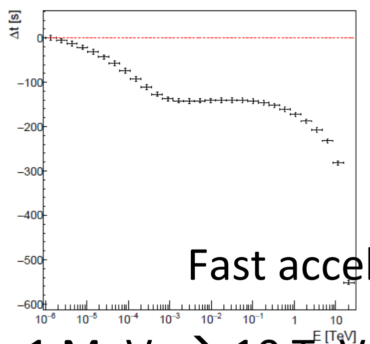
Multi-lambda flares

Different characteristic shapes of intrinsic lags Δt(E) :

Long lasting acceleration



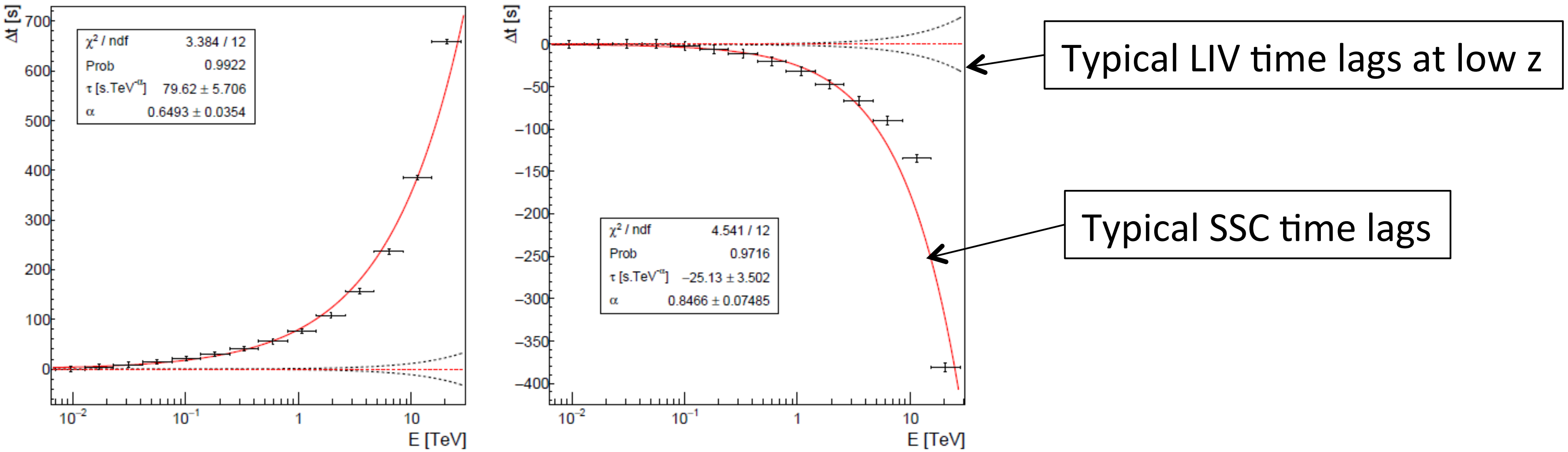
Fast acceleration



1 MeV → 10 TeV

(Perennes, HS, Bolmont, 2017)

Arrival time spectral lags in the VHE range



Intrinsic SSC time lags can reach significant values: for a reasonable set of parameters suitable for Mrk 501, intrinsic Δt(E) could be larger than 100 s between 0.1 and 10 TeV ! *(Perennes, HS, Bolmont, in progress)*

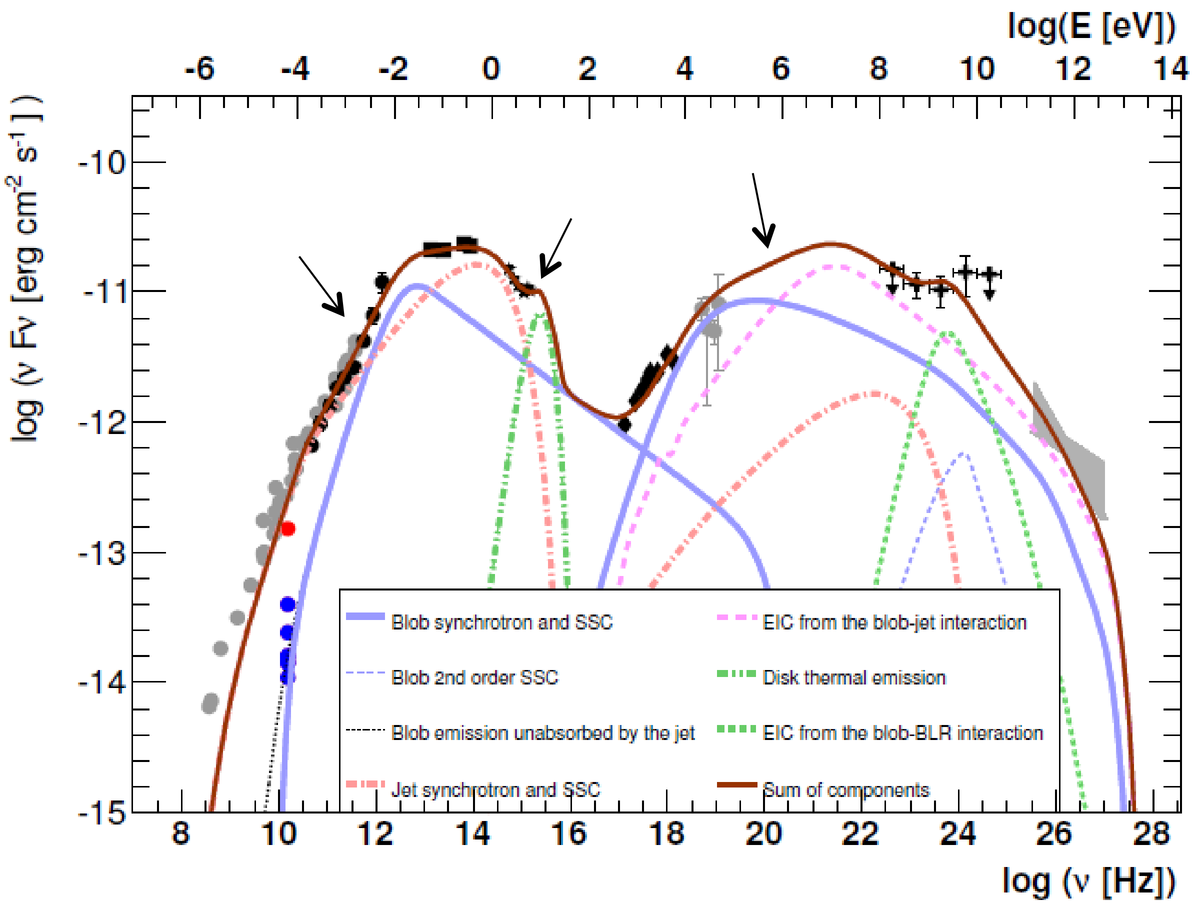
Such lags could be detected in high quality multi-lambda light curves.

However no lags firmly detected and confirmed yet, only upper limits are available *(one single positive case seen in Mrk 501)*

→ Broad-band next generation VHE instruments (CTA) will likely detect lags

→ Strong new constraints expected on VHE emission models.

AP Librae : an intermediate BL Lac object

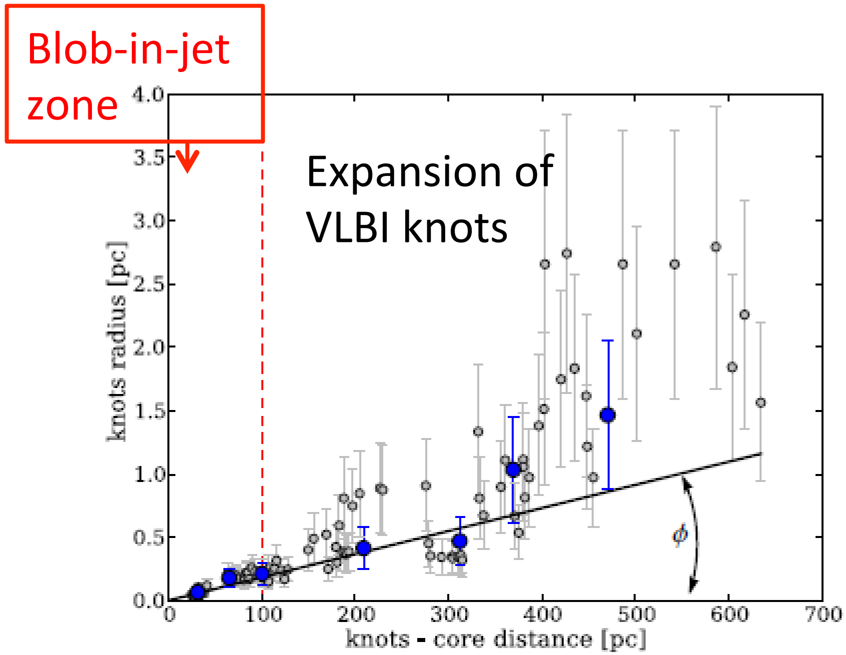


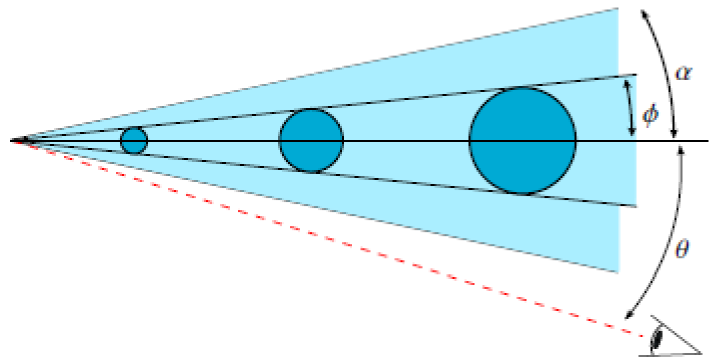
Blob parameters	Value	Unit
δ_b	22	–
θ_b	1.4	deg
K_b	2.0×10^5	cm^{-3}
n_1	2.0	–
n_2	3.6	–
$\gamma_{min/b}$	600	–
$\gamma_{max/b}$	4.0×10^6	–
$\gamma_{break/b}$	8.0×10^2	–
B_b	6.5×10^{-2}	G
R_b	6.2×10^{15}	cm
Jet parameters		
δ_{jet}	10.0	–
$K_{1,jet}$	50.0	cm^{-3}
n_{jet}	2.0	–
$\gamma_{max/jet}$	1.65×10^4	–
$B_{1,jet}$	8.0×10^{-2}	G
$R_{1,jet}$	2.5×10^{16}	cm
L	100	pc
α	0.4	deg
$D_{blob-BH}$	7.9×10^{18}	cm
nb_{slices}	50	–
Nucleus parameters		
T_{disk}	3.2×10^4	K
L_{disk}	5.0×10^{43}	erg s^{-1}
R_{BLR}	7.9×10^{18}	cm
τ_{BLR}	3.5×10^{-2}	–

Adaptation of a « blob-in-jet » scenario to a source with a bright extended X-ray jet: include radiative interaction between blob and jet which is no more negligible.
VHE & radio VLBI allows to further constrain the source and its jet structure

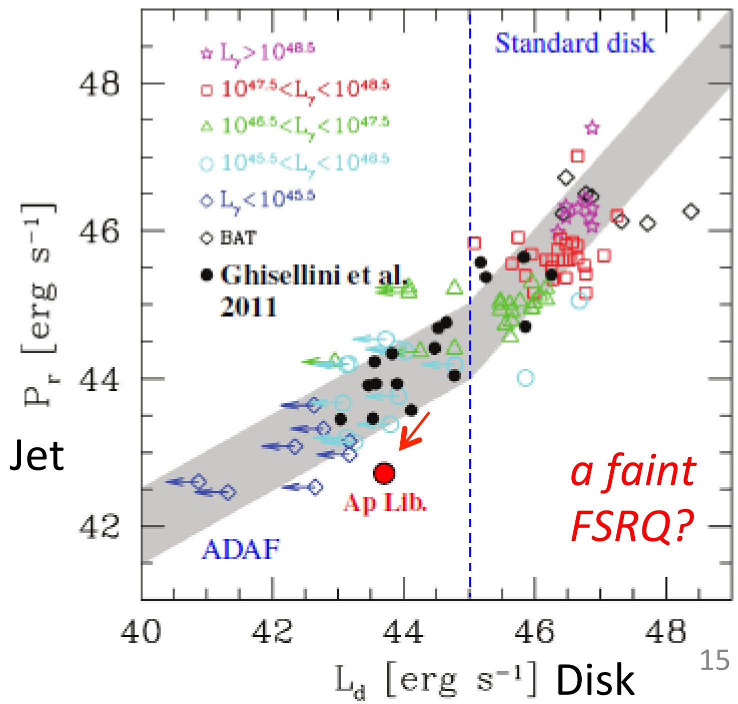
(Hervet, Boisson, HS, 2015)

Modelling AP Librae, combining VHE & radio VLBI data:
VHE blob at the base of the jet = possibly evolving into radio knot



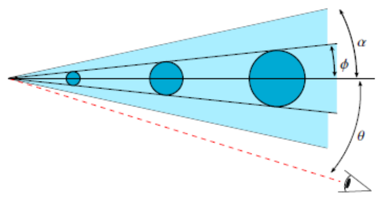


Power	Blob	Jet	Total
Radiation	42.7	41.7	42.7
Magnetic	40.9	41.2	41.4
Cold electrons	43.5	42.6	43.5
Non-thermal electrons	43.9	42.0	43.9
Protons	46.8	45.5	46.8



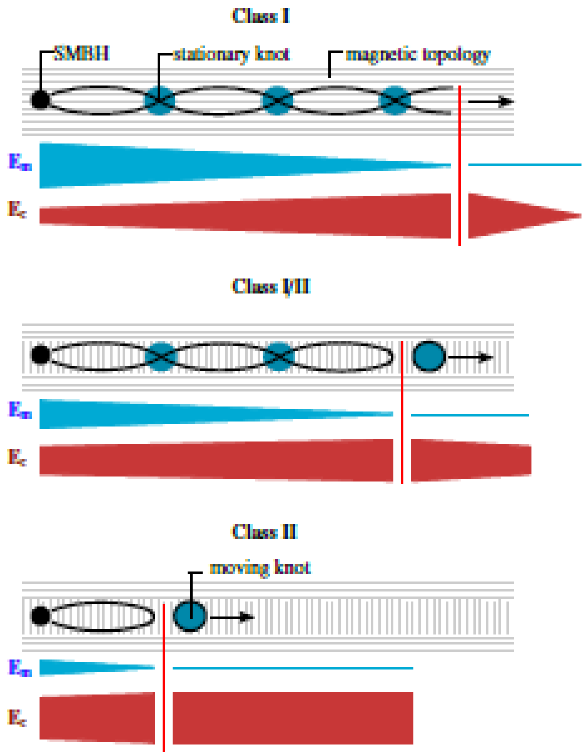
(Hervet, Boisson, HS, 2015)

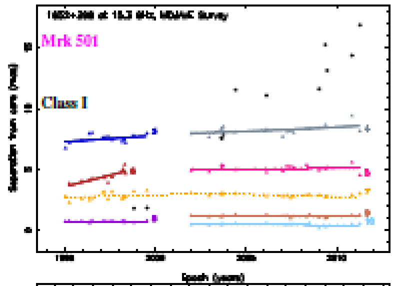
Proposal of new classification of blazars



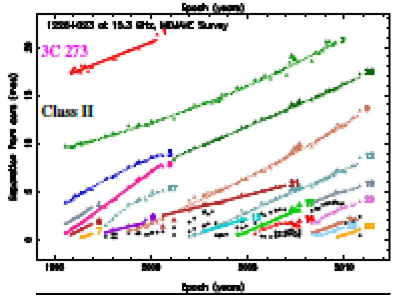
Proposal: Classify blazars according to kinematic properties of « blobs » seen in VLBI jets (= VLBI knots)

Sample: 161 blazars mapped by MOJAVE

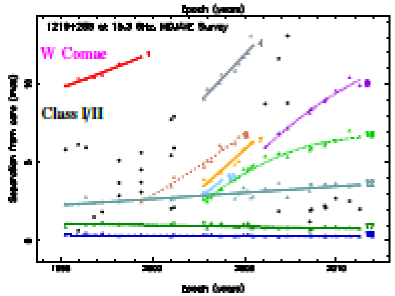




← **Class I**: quasi-stationary knots



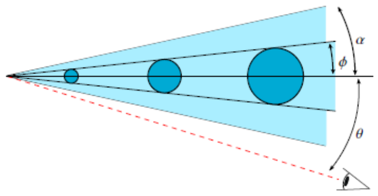
← **Class II**: only superluminal knots



← **Class I/II**: both types of knots (as in AP Lib)

(Hervet, Boisson, HS, 2016)

Proposal of new classification of blazars



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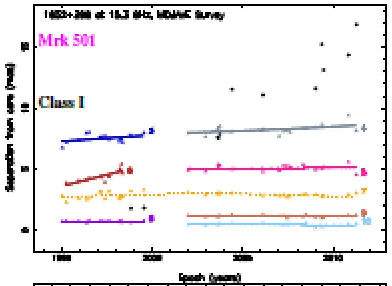
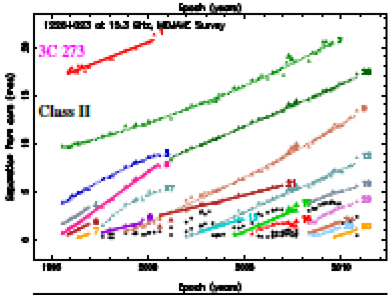


← **Class I**: quasi-stationary knots



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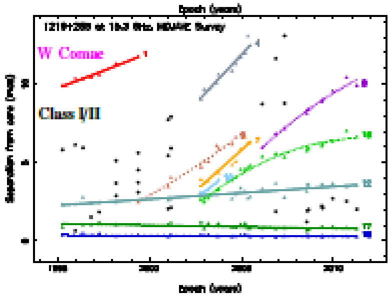

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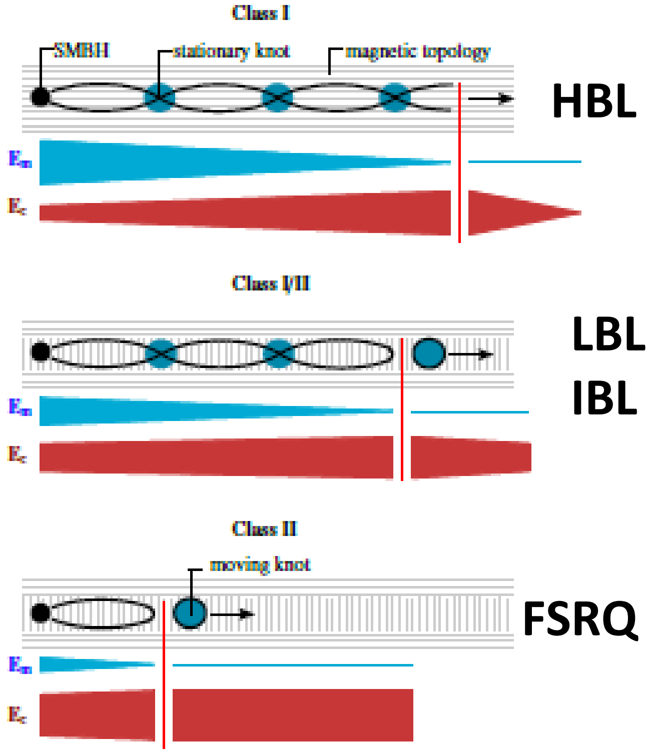


Good overlap with spectral classification

Class I → HBL

Class II → FSRQ

Class I/II → IBL/LBL

(Hervet, Boisson, HS, 2016)

Overlap of the kinematic classification with spectral classification

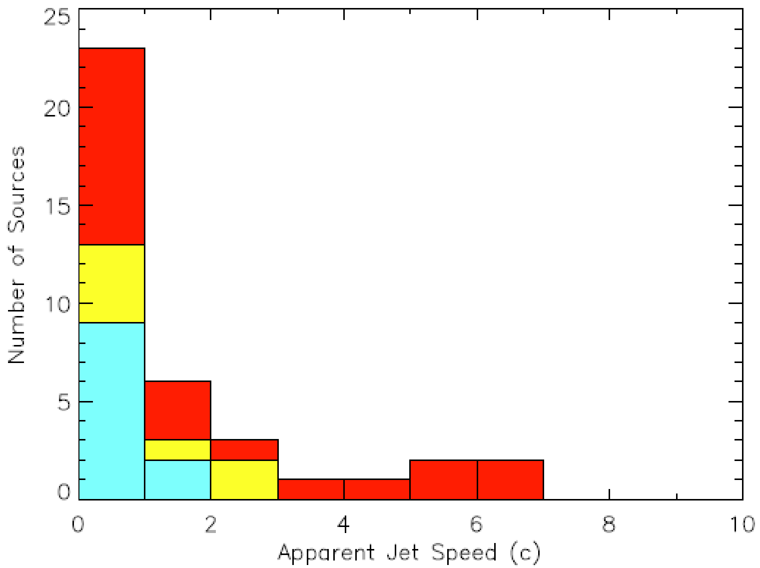
Spectral class	number	Class I	Class I/II	Class II
HBLs	5	100%	0%	0%
IBLs/LBLs	23	32%	56%	12%
FSRQs	125	8%	16.5%	75.5%

HBL are under-represented in the 2016 sample

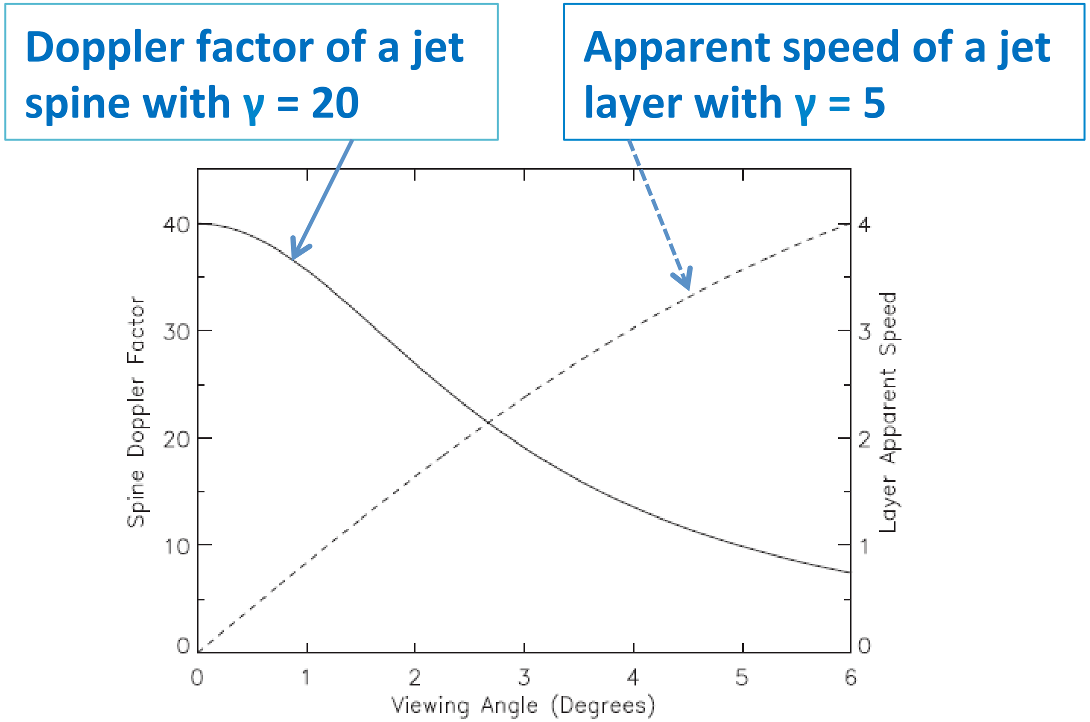
Various biaises difficult to handle

(Hervet, Boisson, HS, 2016)

- New sample of 20 additional TeV HBL with multi-epoch VLBA images by Piner & Edwards: apparent speeds relatively low, 2/3 show no motion



Histogram of apparent speeds for the component in each HBL with the highest speed lower limit



Resolving the Doppler crisis within two-component jet scheme

- Apparent VLBI speeds in the current sample of TeV HBLs can be analyzed in the context of two-component jets

(Piner & Edwards, 2018)

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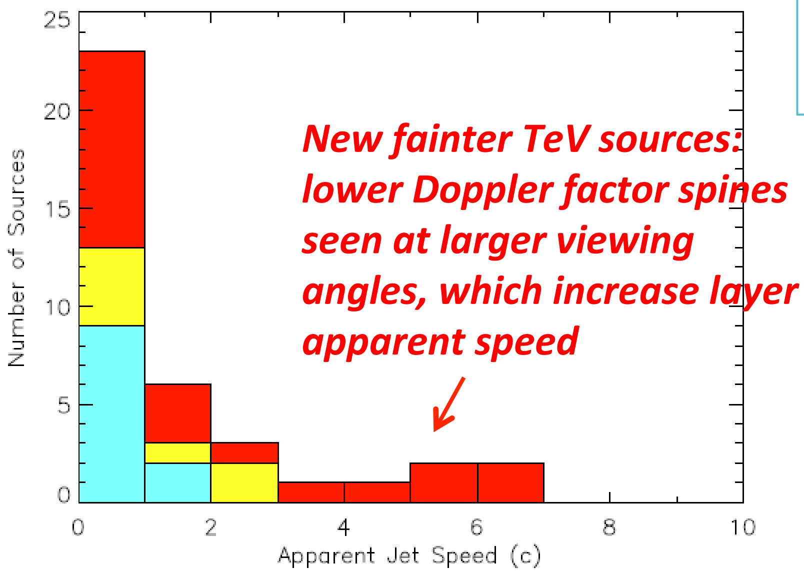

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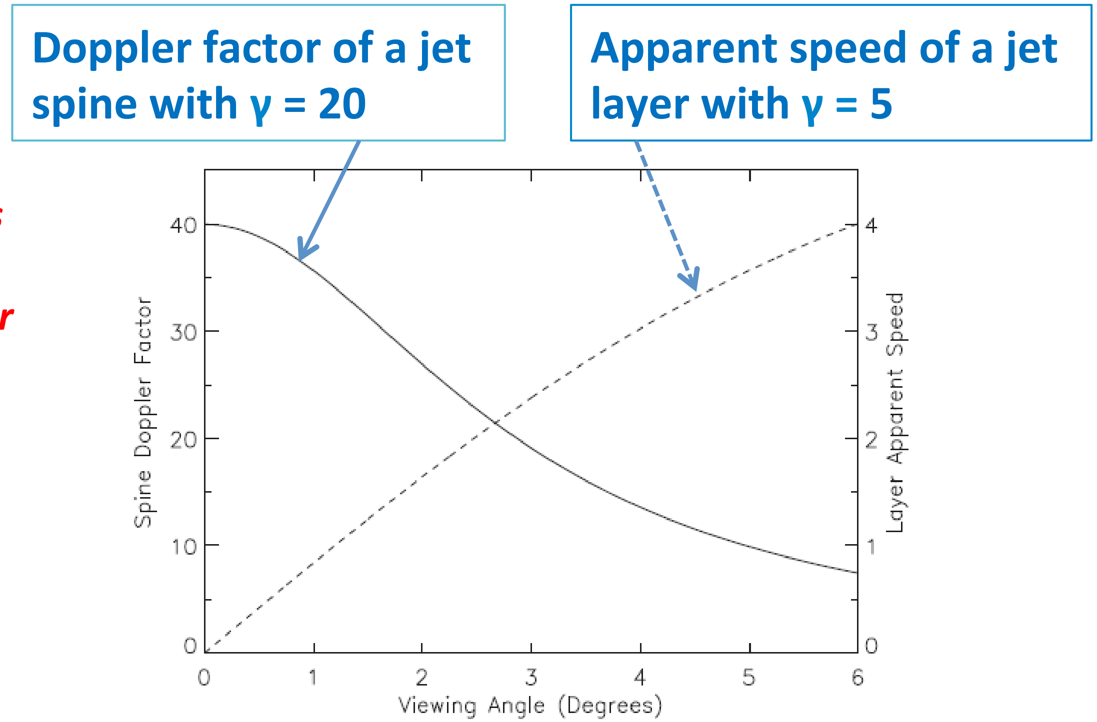


Resolving the Doppler crisis within two-component jet scheme

- Apparent VLBI speeds in the current sample of TeV HBLs can be analyzed in the context of two-component jets

(Piner & Edwards, 2018)

Overlap of the kinematic classification with spectral classification *(updated)*

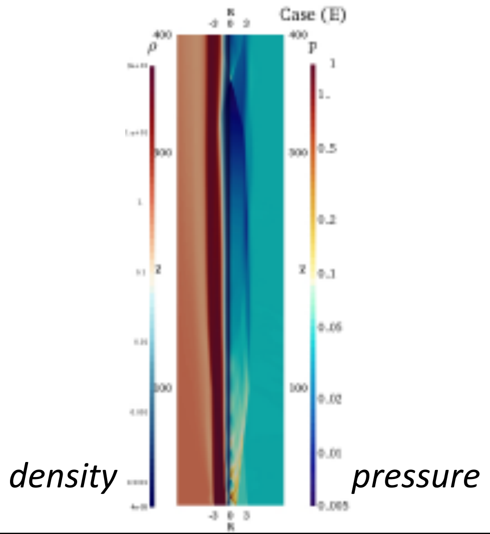
Spectral class	number	Class I	Class I/II	Class II
HBLs	**25**	**76%**	**16%**	**8%**
IBLs/LBLs	23	32%	56%	12%
FSRQs	125	8%	16.5%	75.5%

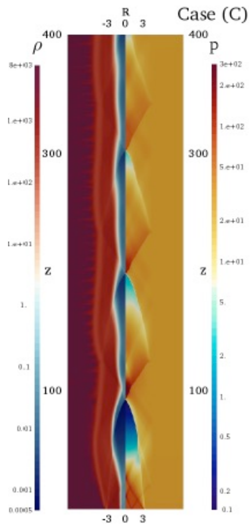
HBL were under-represented in the 2016 sample

Here with the 20 new HBL, deduced from Piner & Edwards, 2018 *(preliminary)*

Now almost all known TeV HBL have been monitored with VLBI
→ VLBI-TeV samples need new VHE data!

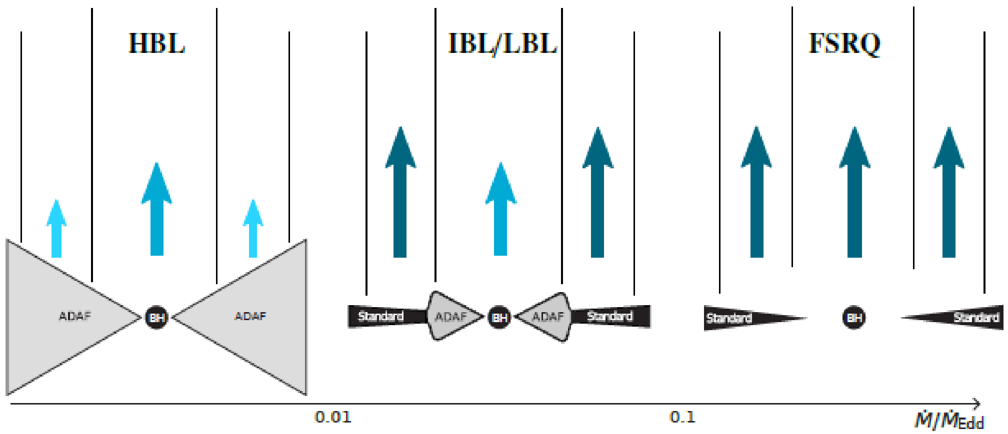
MHD simulations of two-component jets





Weak inner jet:
Outer jet reflect shock waves
Shock at large distance

Similar P_{cin}:
Strong shock
at jet base



Transverse structure of 2-component jets (inner jet + outer jet/envelope) appears linked to the different blazar classes

HBL: strong stationary shocks structure, weak outer envelope, dominated by inner jet *(cf Mizuno et al, 2015 for parallel B)*
IBL/LBL: dominated by outer jet
FSRQ: strong inner and outer jets

Increasing accretion regime from HBL (# ADAF) to FSRQ (# standard disk)

(Hervet et al, 2017; see also Meliani's poster, this conference)

New hope to close the loop on accretion-ejection cycle with spectral & kinematic classification of blazars!