Scrutiny of recollimation shock in BL Lacertae on sub-pc scales

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

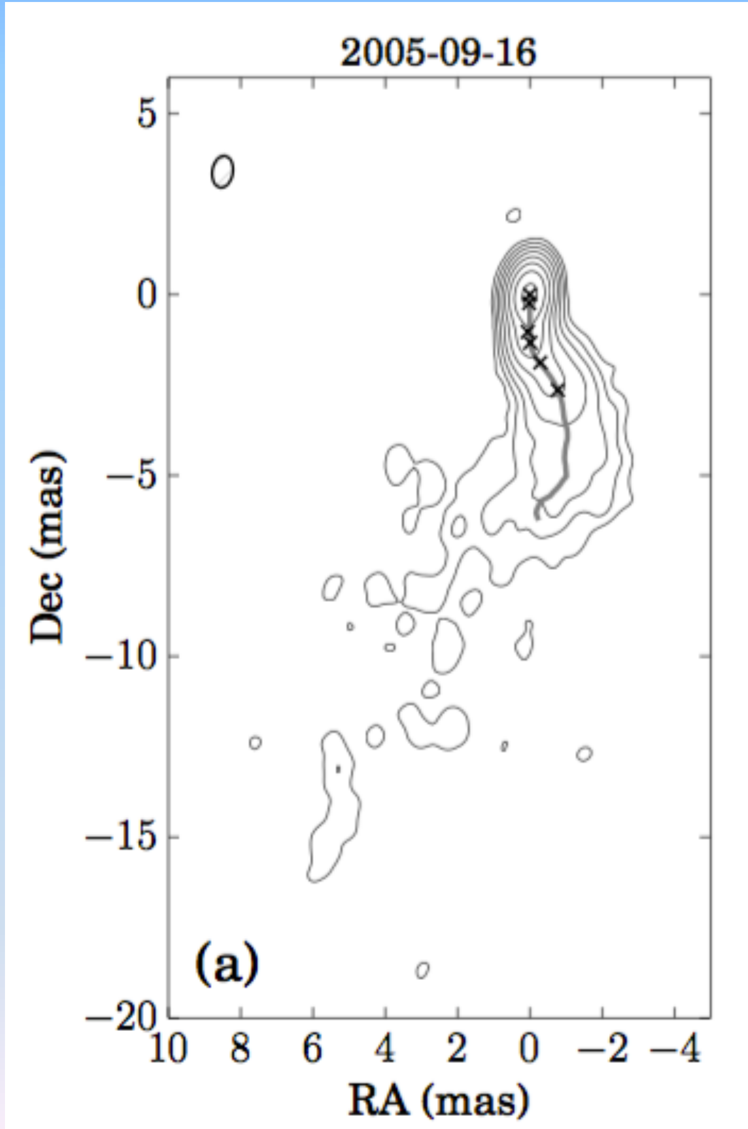
Outline

- Observations and motivation to study a quasi-stationary component (QSC) of the jet.
- Errors of positions and flux leakage effects.
- Trajectory and kinematics of QSC.
- On-sky flux density distribution of QSC.
- Toy emission model.
- Follow-ups and summary.

Monitoring of BL Lac at 15 GHz

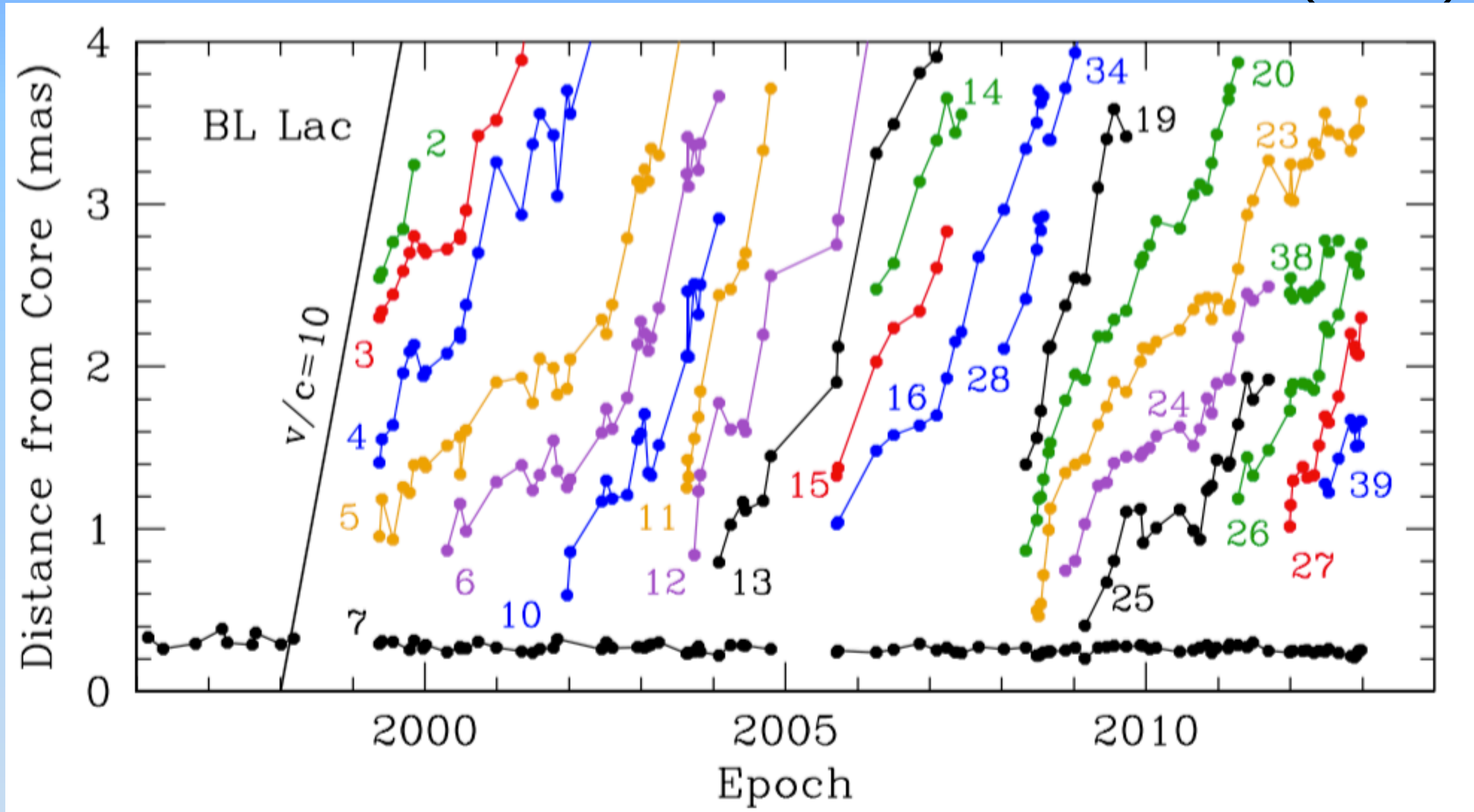
- VLBA monitoring at 15 GHz (1995-2012) in the frame of the MOJAVE program
- Beam size: ~0.9 mas
- 1 mas = 1.29 pc
- Jet viewing angle: 4-12 deg

Cohen et al. (2014)



Core separation

Cohen et al. (2014)

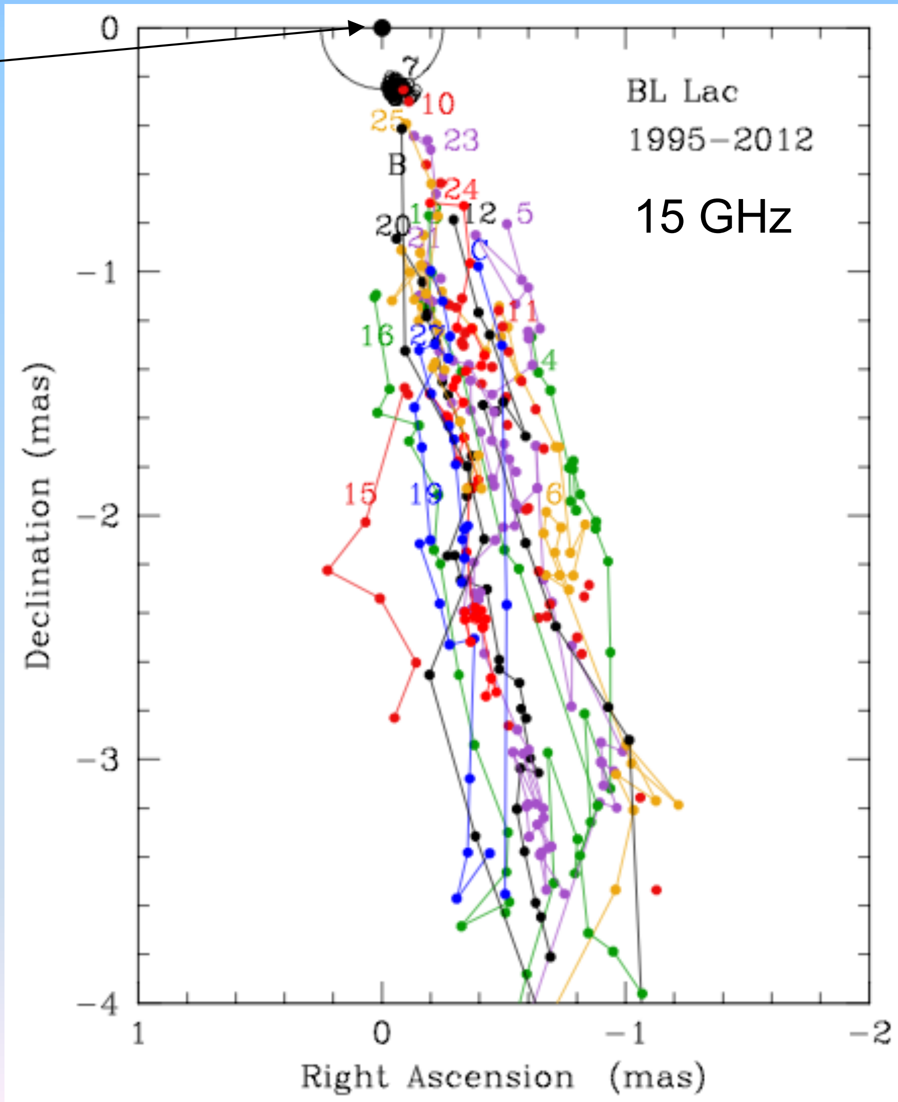


- **D**: radio core
- **C7**: stationary feature
- **[D-C7]**: ~0.26 mas (0.34 pc)
- **C2-C8**: moving features ~(3-10)*c,* max. Lorentz factor ~10

Radio core at 15 GHz

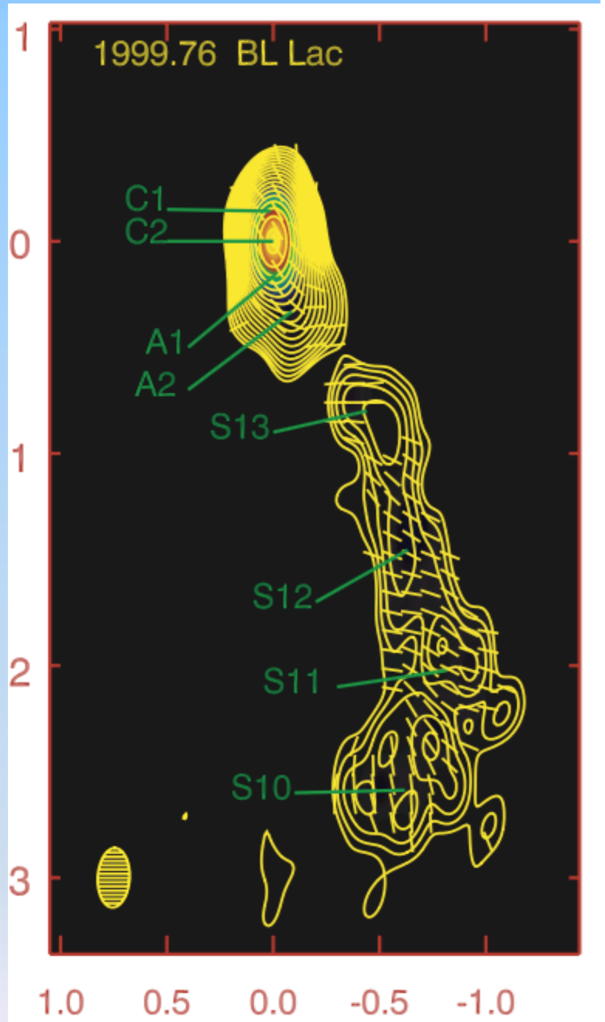
Radio core:
- flat spectrum
- reference point
- compound str.

C7 component:
- Quasi-stationary recollimation shock
- A2 at 43 GHz
- tightness of points



Cohen et al. (2014)

Jorstad et al. (2005)



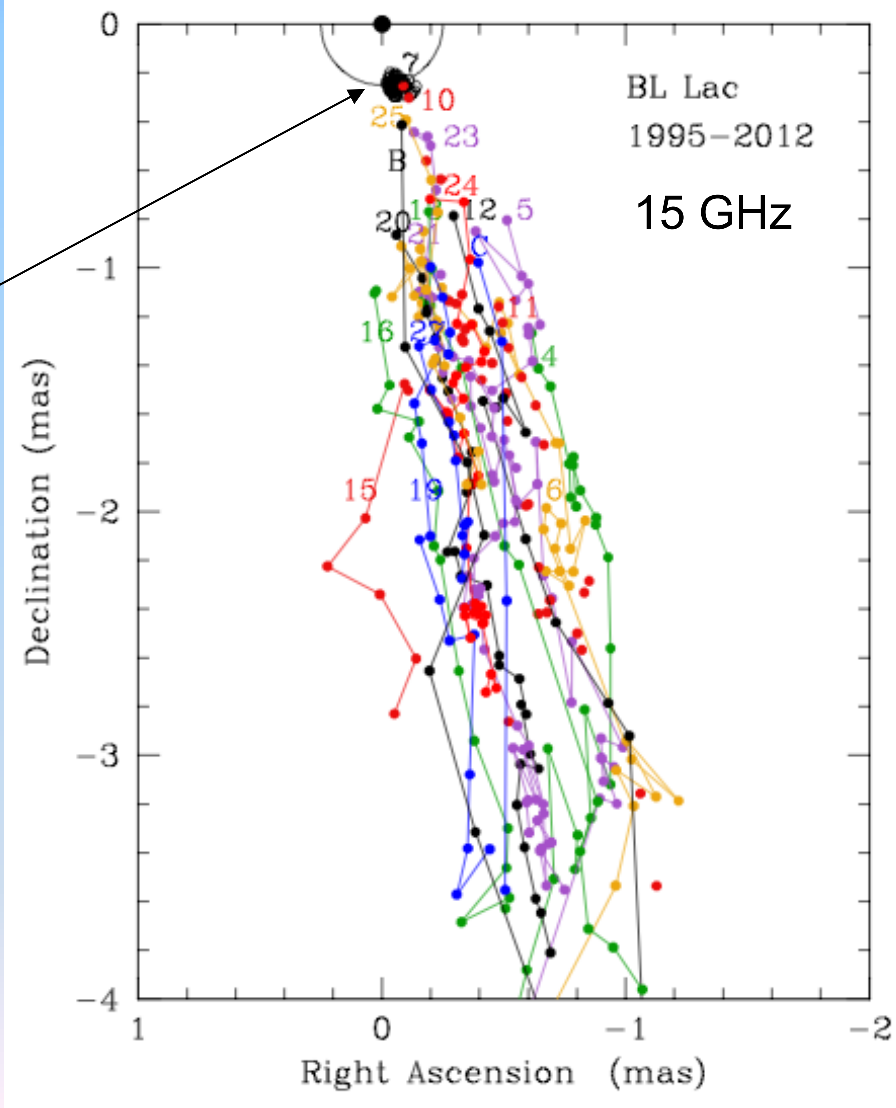
Recollimation shock and moving features

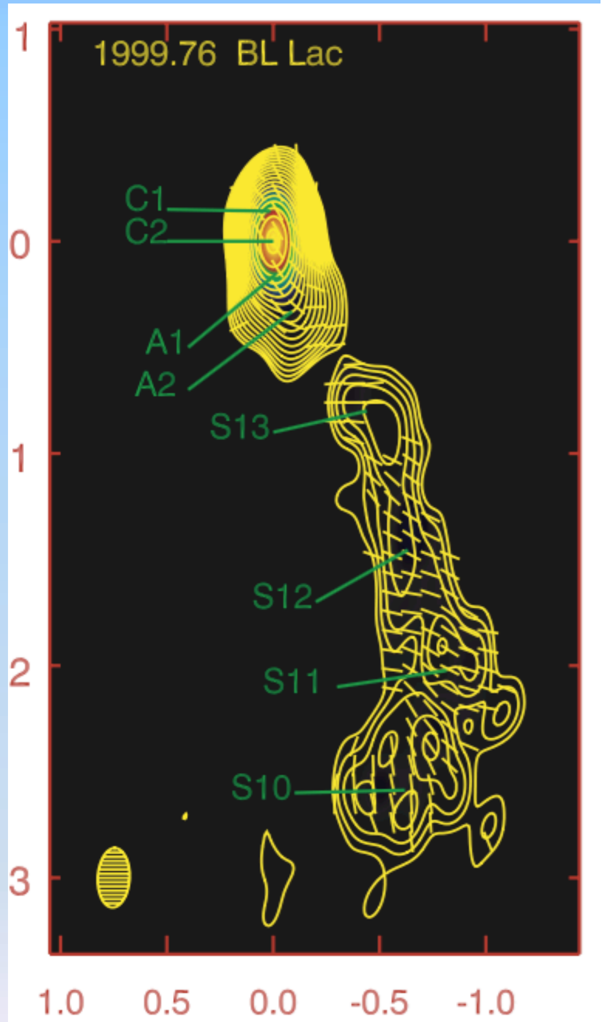
Jorstad et al. (2005)

Radio core:
- flat spectrum
- reference point
- compound str.

C7 component:
- Quasi-stationary recollimation shock
- A2 at 43 GHz
- tightness of points

Moving radio components emanate from C7:
-19 comp.
- speed < 10c

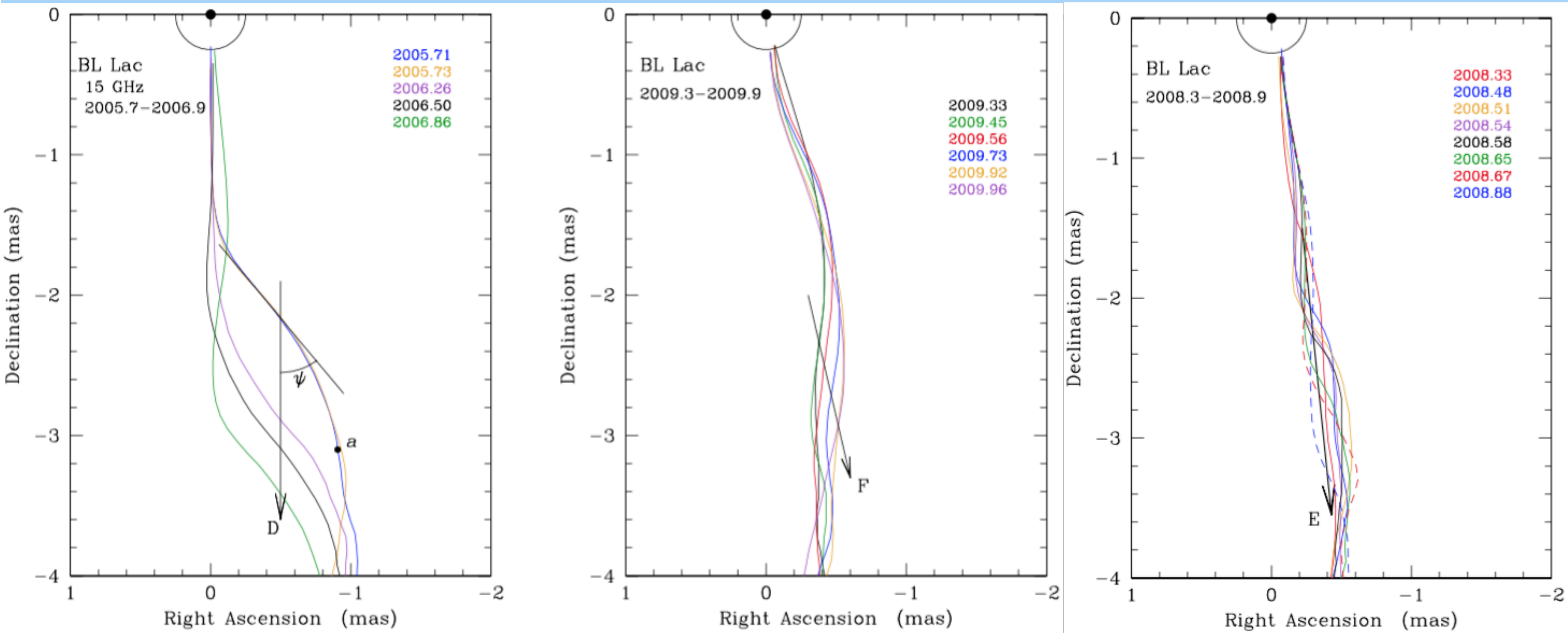




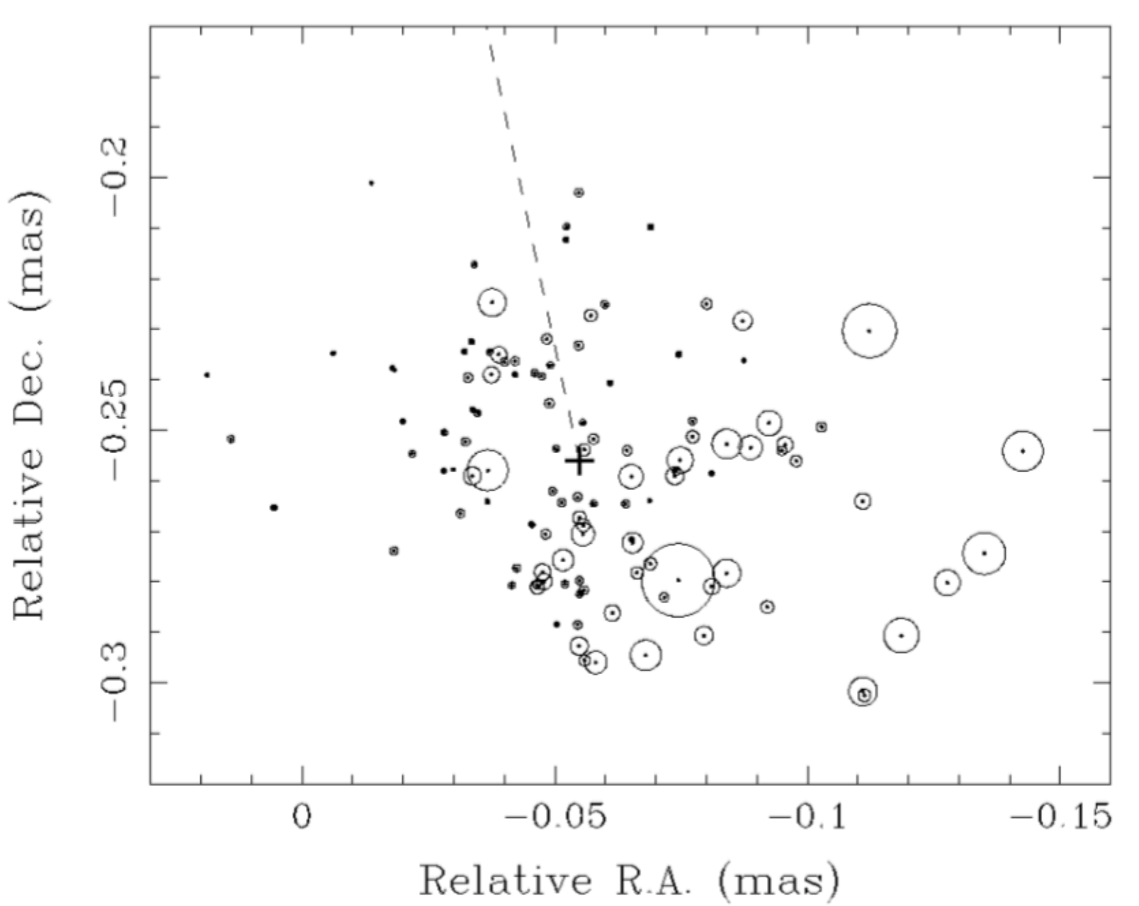
Cohen et al. (2014)

Motivation

- Comp. C7 is a recollimation shock (RCS)
- Link between position angle of RCS and position angle of jet
- RCS drives the shape of the jet on ps-scales
- “Whip” jet model: relativistic, rapidly shaken RCS generates transverse Alfven waves propagating downstream on helical magnetic field (Cohen et al. 2014,2015).



RCS scatter



Data: 116 epochs between 1999-2016

Data reduction as in Cohen et al. (2014)

Reasons of scatter:
- Dynamical/geometry reasons.
- Moving of the core as a result of changes of a pressure/density.
- Intrinsic error of RCS.

Positional uncertainties:
- Fomalont (1999): ~1 μas
- Lobanov (2005): ~4 μas

Limitations:
- Methods apply to an isolated Gaussian -> positional error represents the lower limit.

RCS: Flux leakage effect

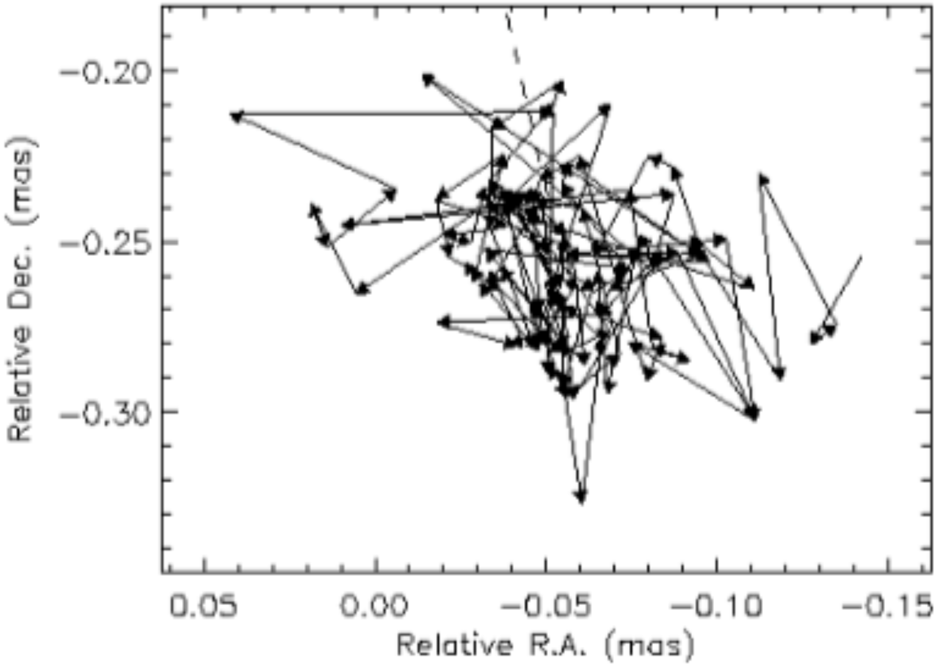
Effects of flux leakage between bright core and RCS:

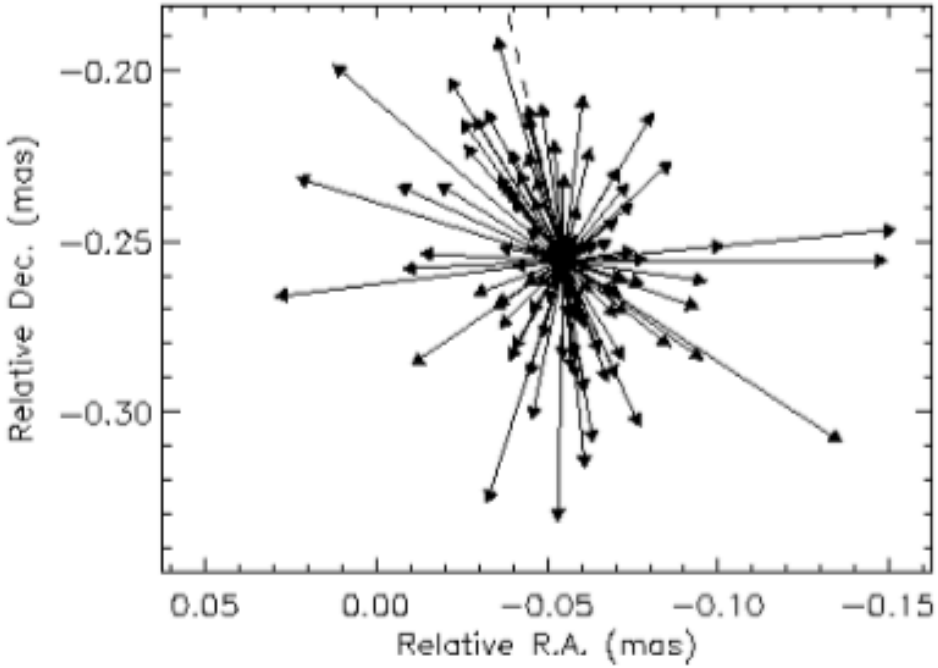
- Simulate 116 "observed" (u,v) data sets with constant fluxes of radio core and RCS (2 Jy and 1Jy)
- Add a noise corresponding to the actual data weights.

- Model fit simulated data sets to check (a) dependence between position of RCS and its flux and (b) flux leakage between radio core and RCS:
  - 110/116: S_{core}=1.99 ± 0.02 Jy and S_{C7}=1.01 ± 0.02 Jy,

We find no dependence between RCS position and flux. Flux leakage is typically small (within 10%) but in rare cases can reach to 50%

RCS trajectory

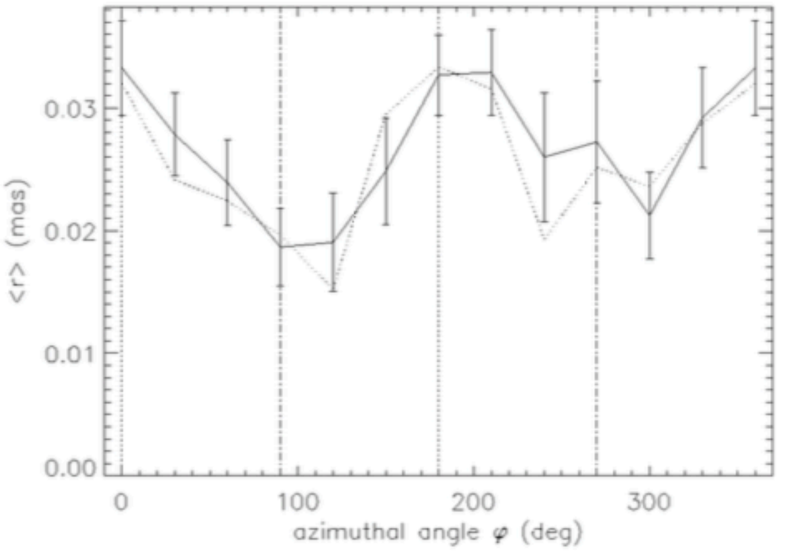




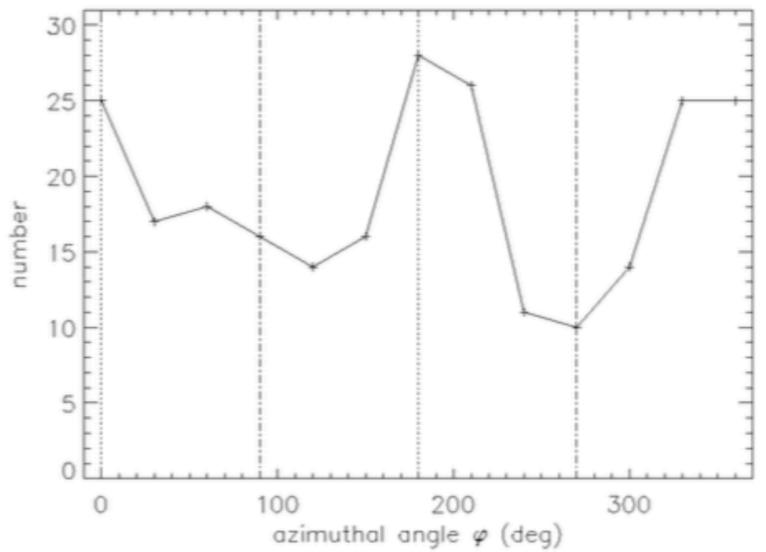
Motion vector – motion of RCS between two consequent epochs.

- Six long motion vectors (>0.08 mas) have random orientation – are excluded from further analysis.
- Motion vectors (<0.08 mas) show anisotropy along the jet
- Length of motion vectors are asymmetric wrt the jet axis

Asymmetry and anisotropy of motion vectors



Asymmetry:
Mean length of motion vectors along the azimuthal angle (angular beam = 60 deg, step = 30 deg)



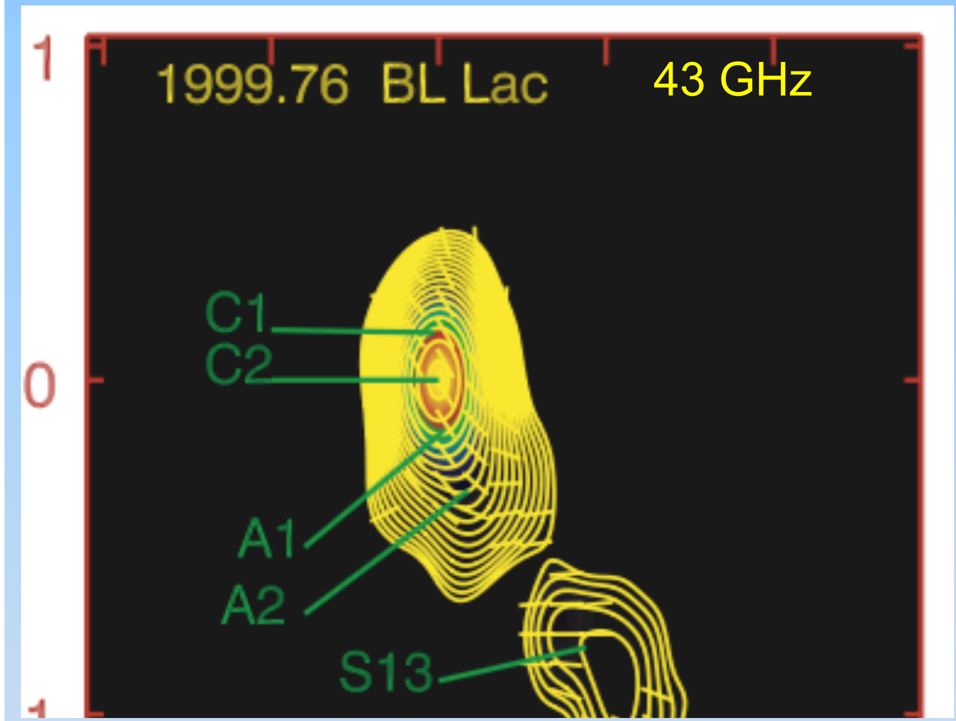
Anisotropy:
Number of motion vectors along the azimuthal angle (angular beam = 60 deg, step = 30 deg)

Core „wobbling“

- Resolution-dependent core shift
- Pressure gradient in the external medium (Agudo et al. 2012)
- Binary BH system (e.g., Valtonen et al 2006)
- Variation of flow injection due to changes in the particle density or magnetic field configuration
- …

Resolution dependent core-shift

Jorstad et al. (2005)



43 GHz:
C1 (week), C2 (strong), A1 (relatively strong), A2 (intermediate)

15 GHz:
• core compounds C2 and A1 components observed at 43 GHz
• RCS is identified with A2

Relative brightness of C2 and A1 components will shift the core at 15 GHz along the jet axis

Estimate of core shift

Apparent (observed) motion-vector of RCS:

$$\vec{r} = -\vec{r}_c + \vec{r}_s + \vec{r}_e$$

r$_c$ – vector of proper motion of the core (along the jet axis)
r$_s$ – vector of proper motion of RCS (random orientation)
r$_e$ – vector of positional error of RCS (random)

$$r_c >> r_s + r_e \longrightarrow \vec{r} \approx -\vec{r}_c$$

$$r_c << r_s + r_e \longrightarrow \vec{r} \approx \vec{r}_s + \vec{r}_e$$

Estimate of core shift

Projections of apparent vector-motion on jet axis (j) and transverse to the jet axis (n):

$$r^j = -r_c^j + r_s^j + r_e^j$$

$$r^n = r_s^n + r_e^n$$

Assumptions: Motion vectors of RCS and its positional uncertainties are oriented randomly

$$f(r^j) = g*(h*k) = g*p = \int_0^\infty \int_0^\infty g(r_c^j)\, p(r^j - r^n)\, dr_c^j\, dr^n$$

f – observed PDF of apparent motion of RCS
g – seeking PDF of core shift
p – observed PDF of true motion of RCS

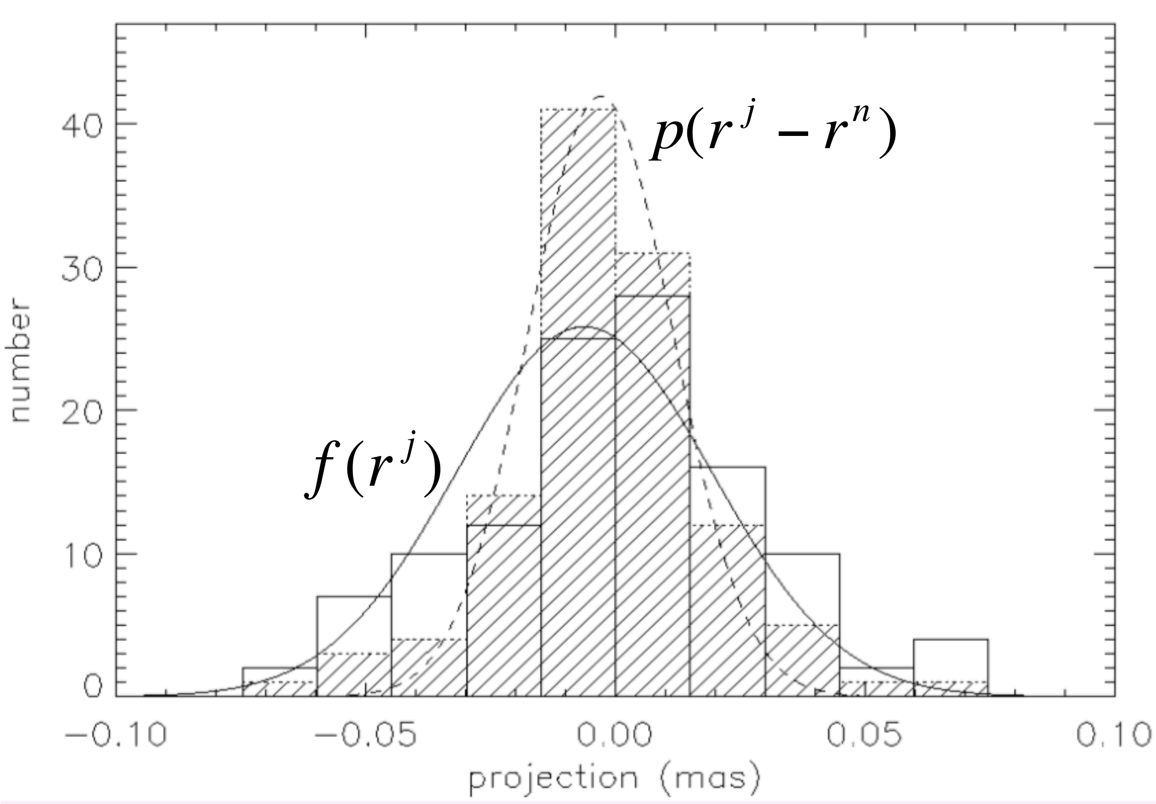
Estimate of core shift: convolution of Gaussians

f and ***p*** are Gaussian like distributions with

$$\sigma_f = 0.025 \pm 0.002\ mas$$
$$\sigma_p = 0.015 \pm 0.001\ mas$$

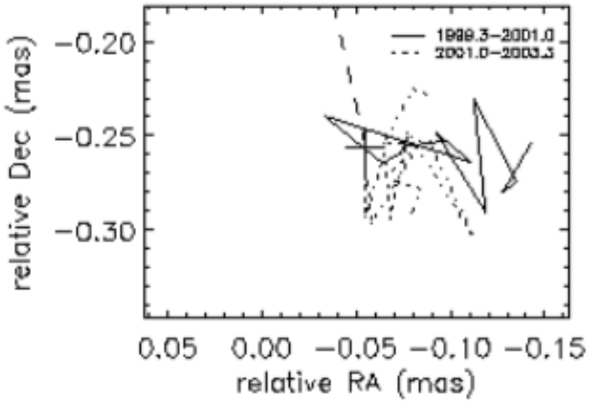
Convolution of two Gaussians (***f* = *g* * *p***):

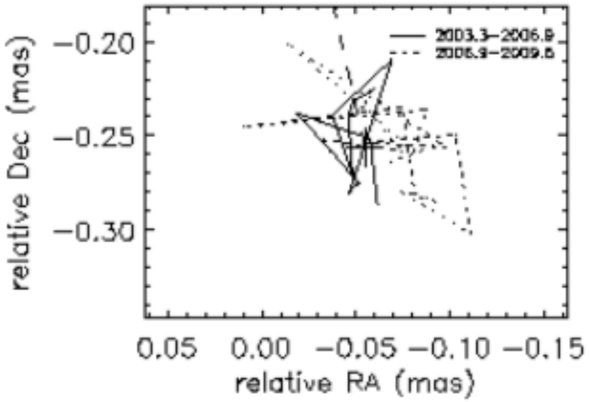
$$\sigma_g = \left(\sigma_f^2 - \sigma_p^2\right)^{1/2} = 0.021 \pm 0.002\ mas$$

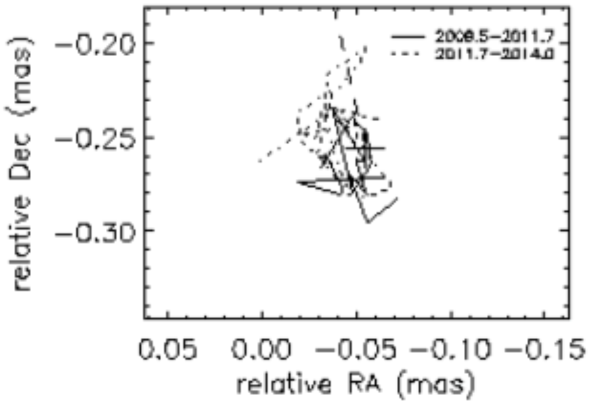


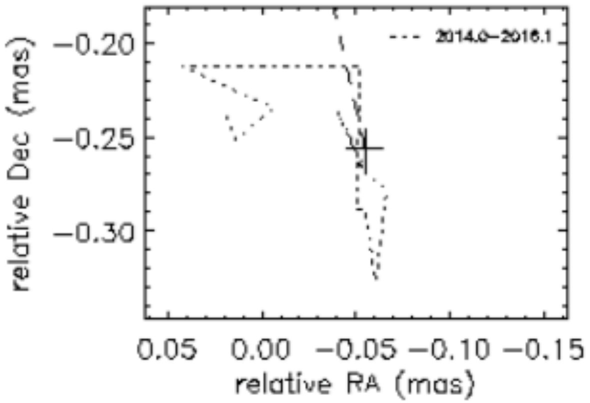
Contribution of core shift to apparent motion of RCS is significant (0.021 mas > 0.015 mas)

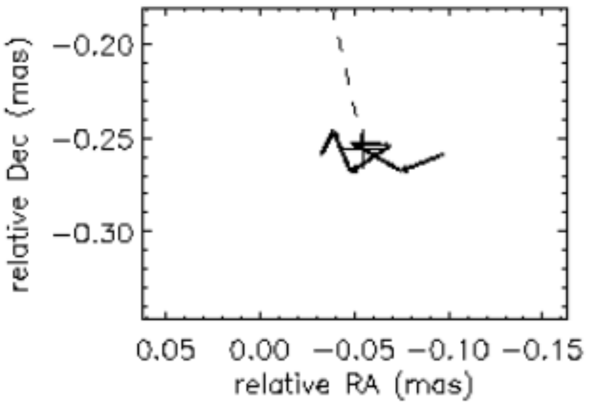
RCS motion







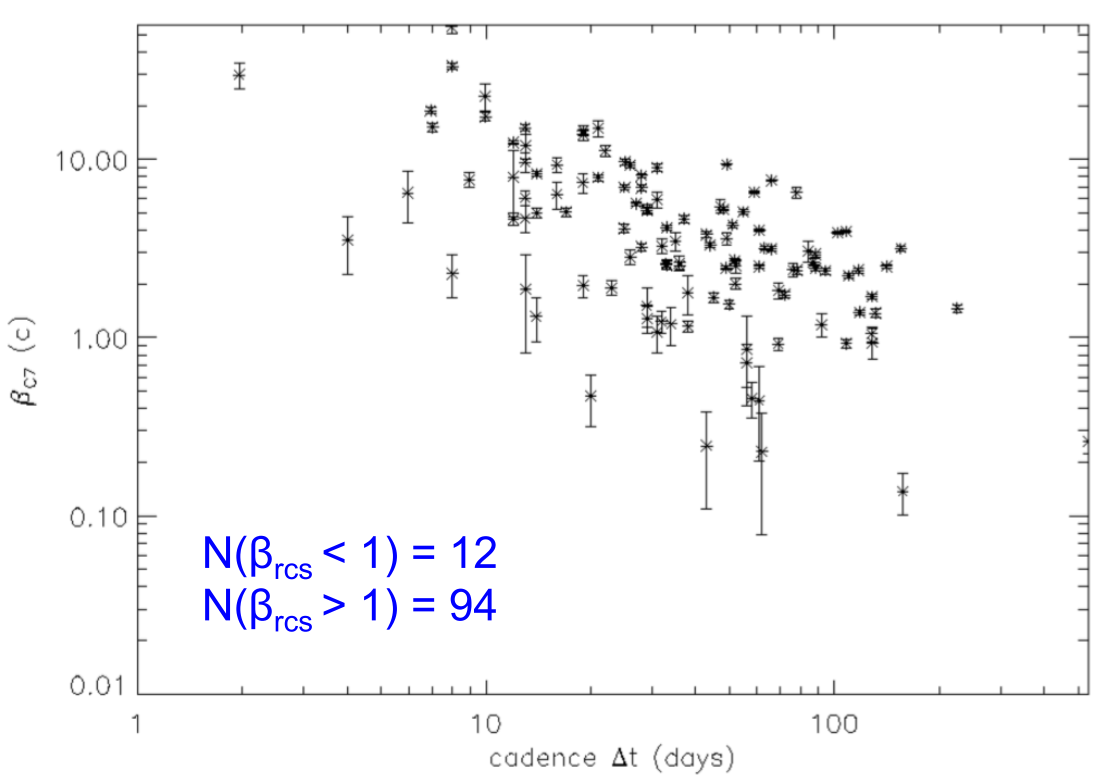




Time scales of weeks-months: erratic motion

Time scales of years: clock-wise motion (chance prob. 3%)

RCS kinematics



1. Mean speed measured from observed trajectories:
$<\beta_{rcs}> = 4.6$!!!

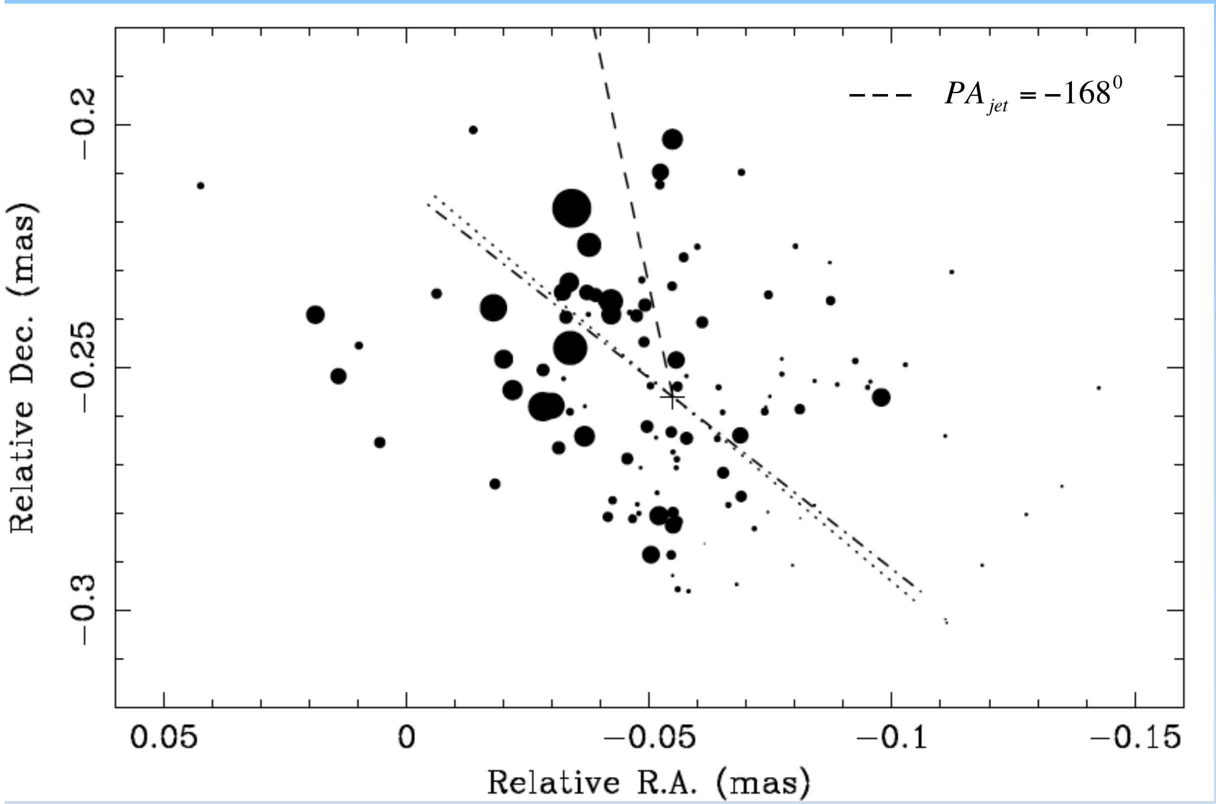
Majority of measured speeds of RCS are superluminal due to resolution-dependent core shift.

2. Mean speed measured from smoothed trajectories:
$<\beta_{rcs}> = 0.071 \pm 0.003$

- RCS is a quasi-stationary component
- RCS swings and excites transverse waves propagating downstream the jet (Cohen et al. 2015)
- RCS should move in near face-on plane-like area

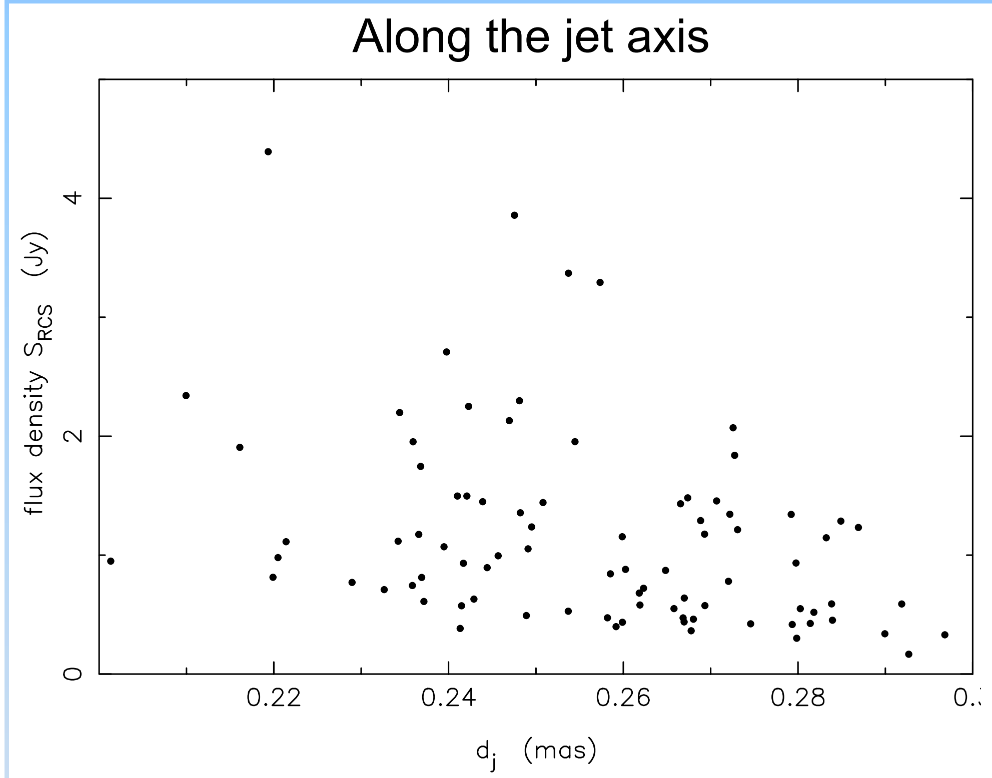
RCS should have speeds less than the speed of the light.

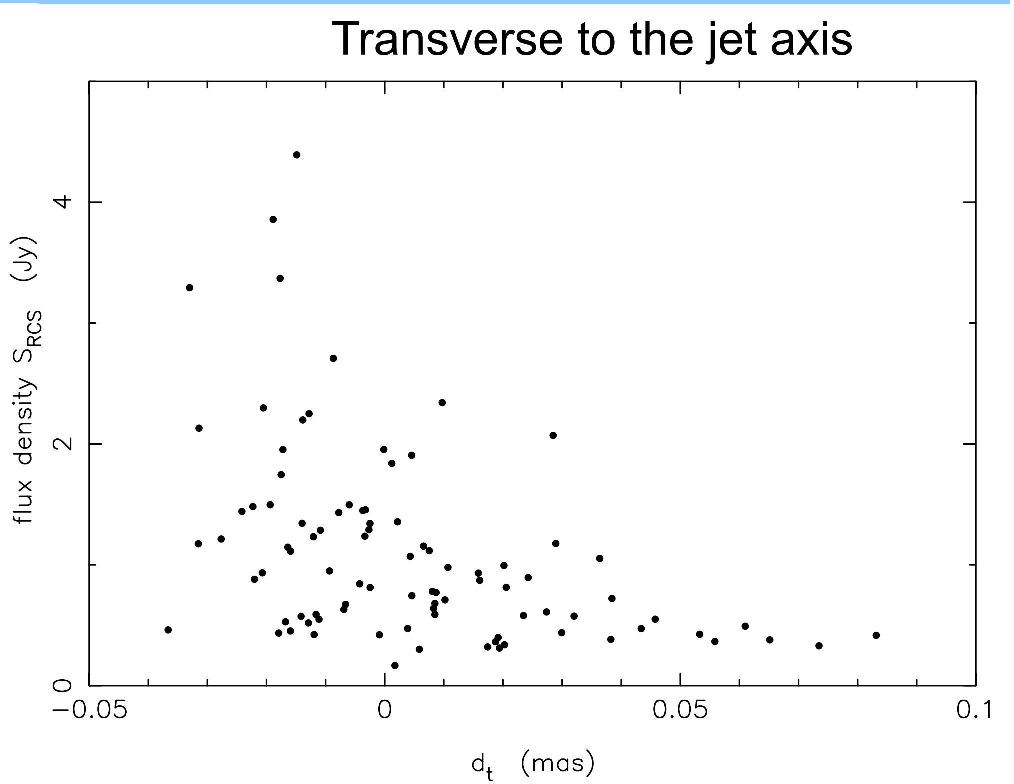
Distribution of flux density of RCS on sky



- Flux density range: 0.17-4.4 Jy
- Flux distribution is **asymmetric** along and transverse to the jet central axis (PA_{jet}=-168^0, dashed line).

Asymmetry of flux along and transverse to the jet axis





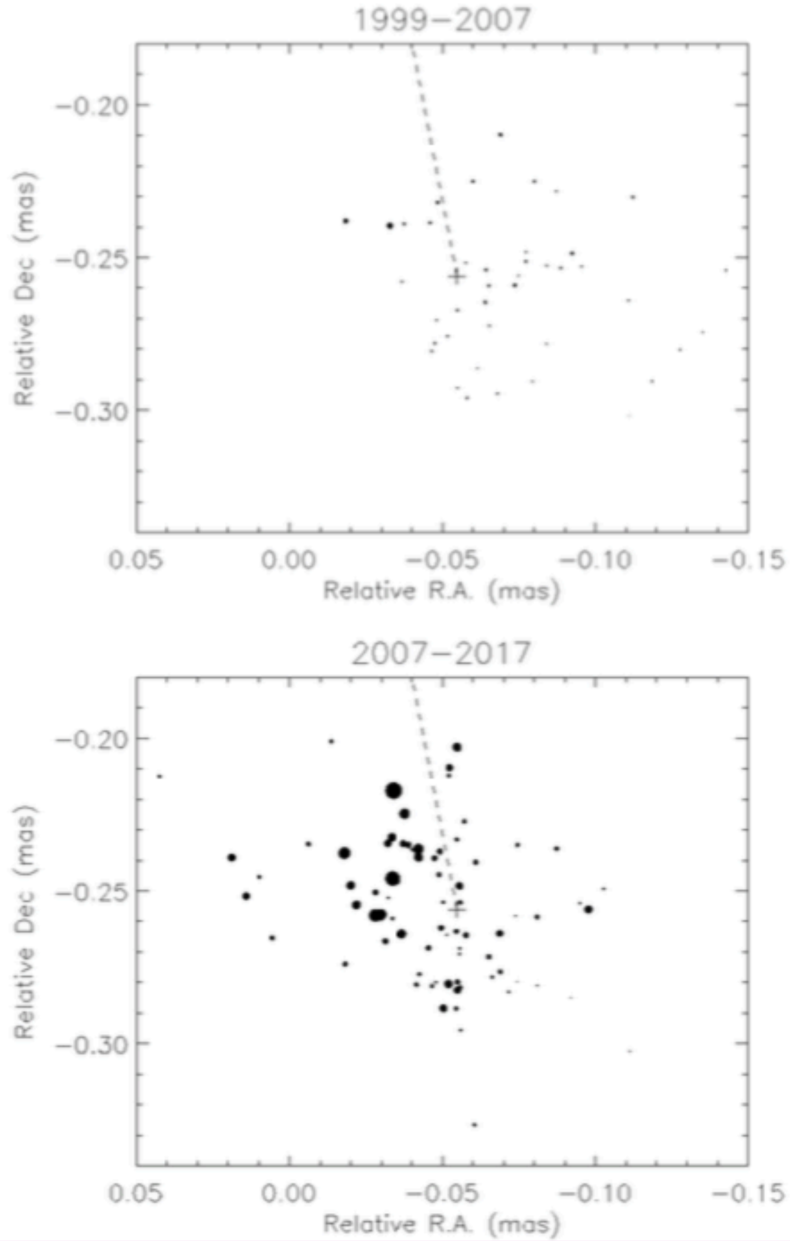
- Kendall's τ rank: ρ=-0.34 (c.l. >99.99%).

Significant brightening of RCS close to the core (no flux leakage effect).

- Kendall's τ: ρ=-0.36 (c.l. >99.99%)

Significant flux asymmetry with respect to the jet axis.

Distribution of flux density



1999-2007

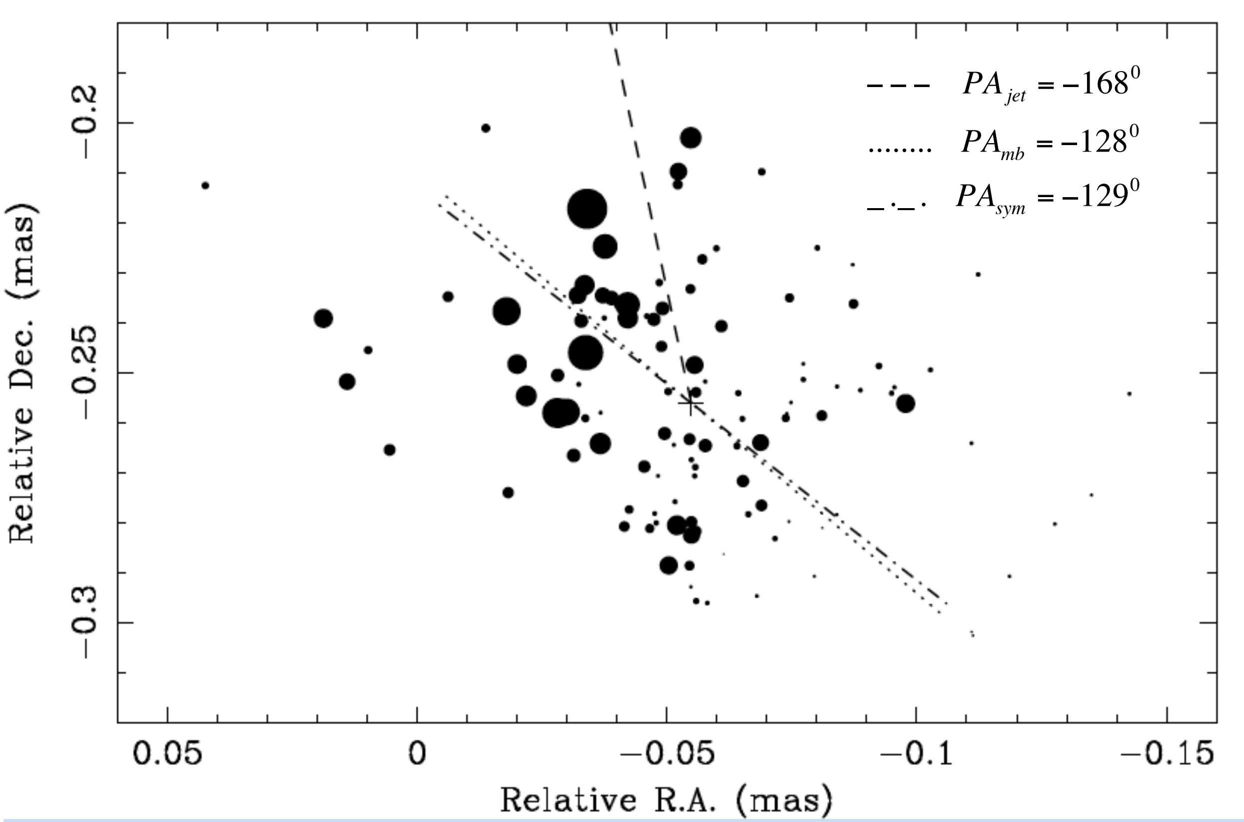
- Asymmetry along the jet:
  Kendall's τ=-0.37 (c.l. > 99.99%)
- Asymmetry transverse to the jet:
  Kendall's τ rank: ρ=-0.28 (c.l. ~ 95%)

2007-2016

- Asymmetry along the jet:
  Kendall's τ=-0.41 (c.l. > 99.99%)
- Asymmetry transverse to the jet:
  Kendall's τ=-0.31 (c.l. ~ 96%)

Flux asymmetry is independent of time

Maximized beaming and flux asymmetry axes



- **Maximized beaming axis:** **Maximum correlation** (Kendall's tau) of the flux happens along the PA_{mb}= -128^0 direction (dotted line).

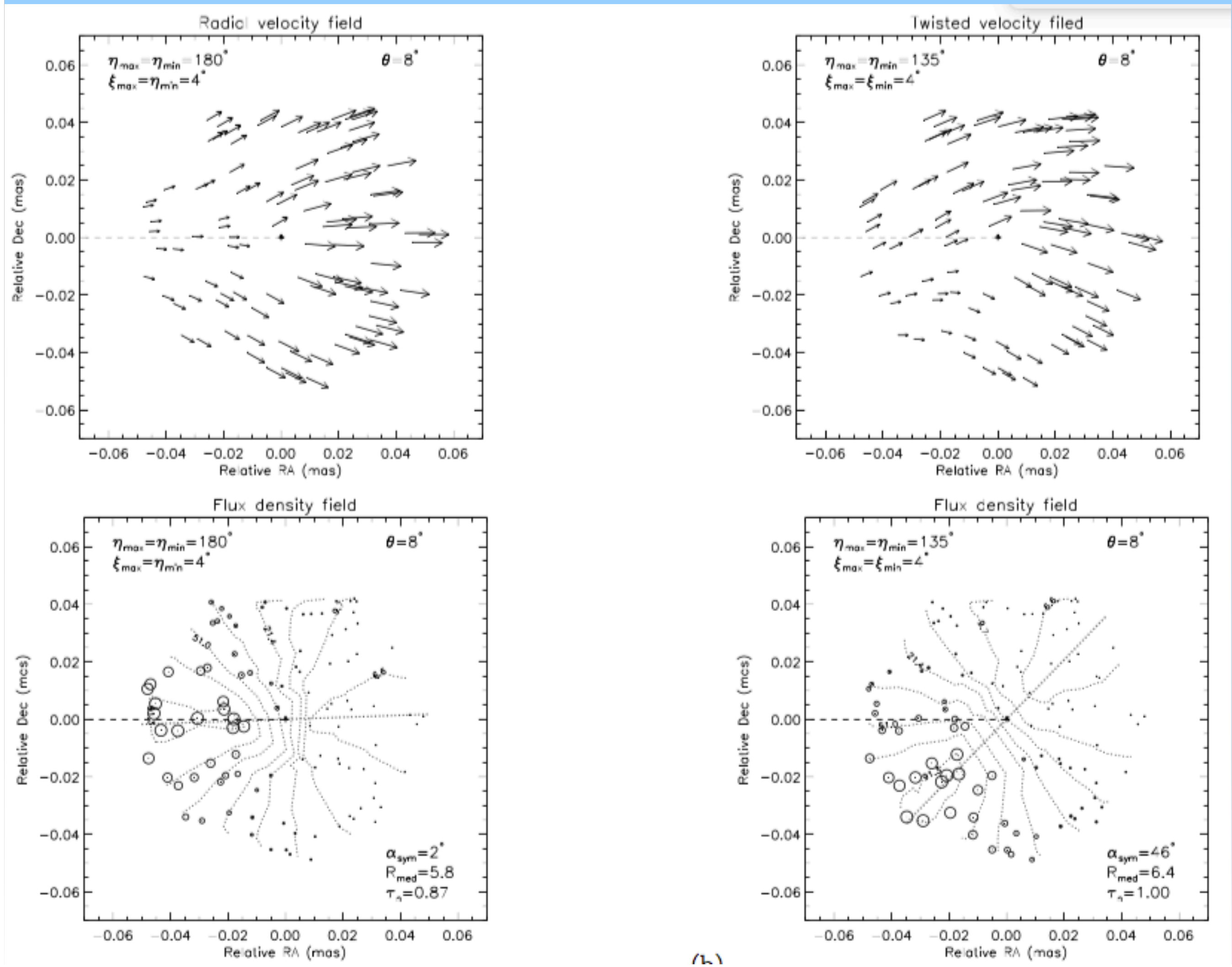
- **Flux asymmetry axis:** This direction represents an axis of reflection symmetry for fluxes transverse to the PA_{sym}= -121^0. **Minimum correlation** of the flux transverse to the direction of PA_{sym}= -129^0 (dash-dot line).

- $PA_{mba} \approx PA_{sym}$: symmetry axis and maximized beaming axis are aligned!

Simulations of RCS emission

Radial velocity field

Twisted velocity field



$$S(r,\varphi) = S_0 D\left(\beta, \theta_j(r,\varphi)\right)^{2-\alpha}$$

Toy model:

- S_0, β are constant
- Beaming is due to jet viewing angle $\theta_j(r,\varphi)$ at RCS's position (r,φ).

Follow-up studies

BL Lacertae:

- Trajectory of RCS and origin of transverse waves of jet
- Origin of γ-ray/optical flares.
- Magnetic field structure: polarization properties of RCS.

RCS data (> 70 epochs) available from the MOJAVE database:

• 0716+714:	BL Lac	(LAT)
• 0415+379 (3C 111):	LSP G	(LAT)
• 0851+202 (OJ 287):	BL Lac	(LAT)
• 1253-055 (3C 279):	LSP HPQ	(LAT)
• 1641+399 (3C 345):	LSP HPQ	(LAT)
• 2251+158 (3C 454.3):	LSP HPQ	(LAT)

- Use of 43 GHz VLBA data

Summary

- Monitoring of BL Lacertae at 15 GHz:

    - Vector motions of RCS (recollimation shock) are asymmetric along the jet axis – evidence of resolution-dependent core shift.

    - Core motion dominates over intrinsic motion of RCS.

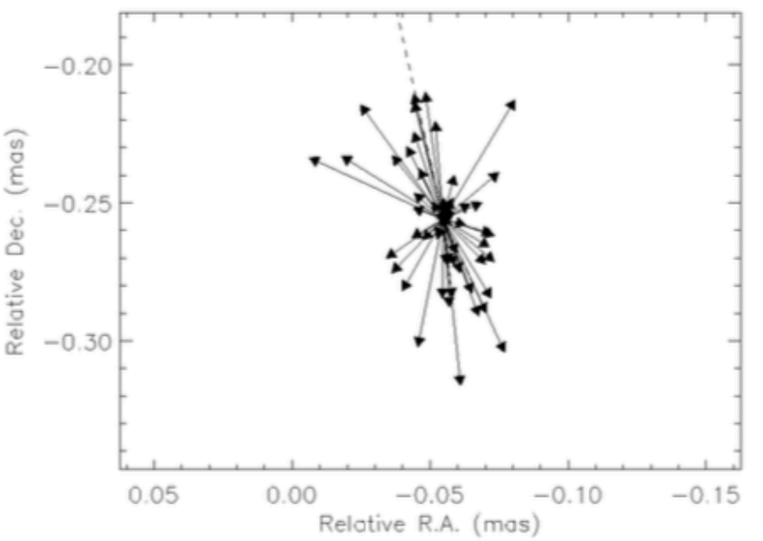
    - RCS moves in clock-wise direction on time scales of few years with subrelativistic speed of about 0.1c.

    - Flux asymmetry along and transverse to the jet axis.

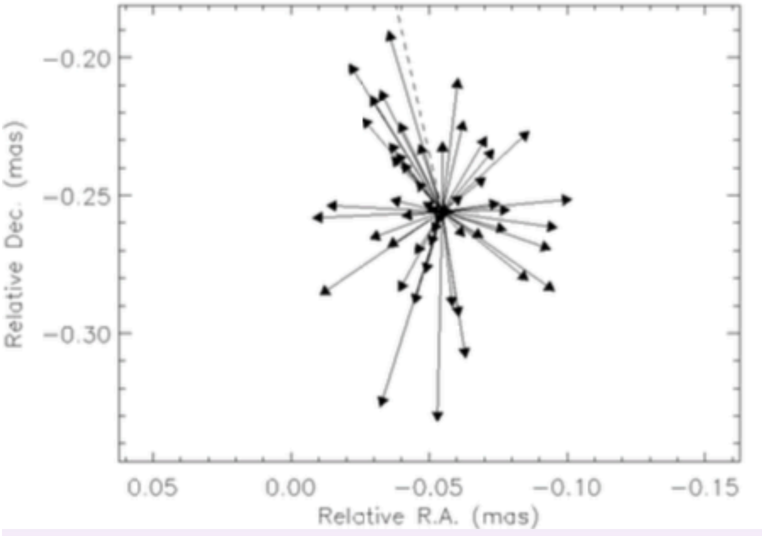
- Simple model of the velocity field of RCS can account for observed flux asymmetry.

- Observations at 43 GHz is important to reveal intrinsic motion of RCS.

Trajectory of RCS

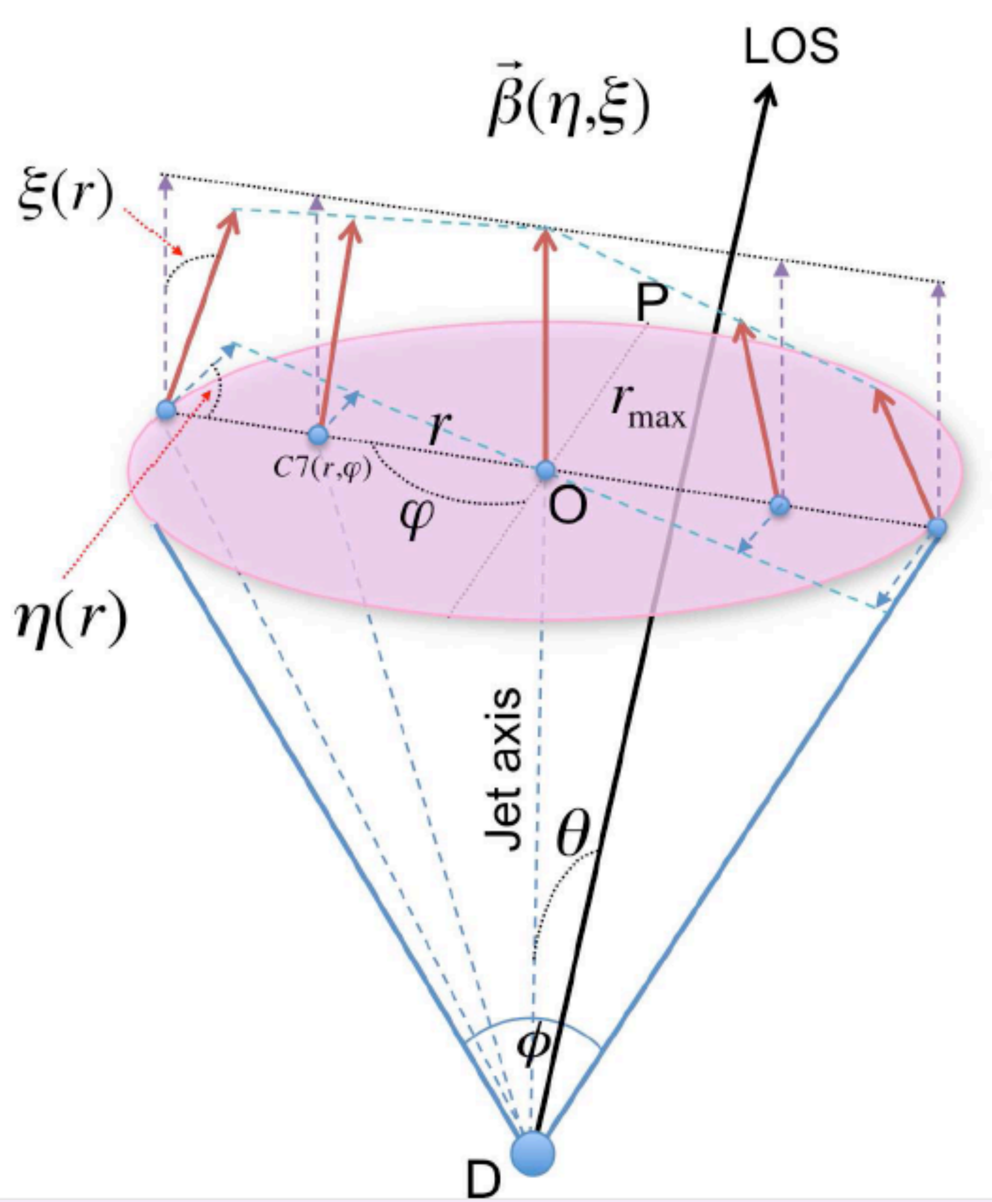


Cadence range: Δt < 35 days



Cadence range: Δt > 35 days

RCS model: Velocity field



Geometry of RCS:

- Plane of RCS motion is normal to the jet axis and within a circle of radius r_{max}.
- Location of RCS is given by (r,φ).
- Jet opening angle: $\phi = 2\mathrm{atan}^{-1}(R/r_{max})$, where R is a distance between the RCS plane and the core D (DO).

Ordered axisymmetric jet velocity field:

- Jet velocity orientation is given by *ξ(r)* and *η(r)*, where *r* is a distance of RCS from the jet axis (O).

$$\xi(r) = \frac{\xi_{max} - \xi_{min}}{r_{max}} r + \xi_{min}$$

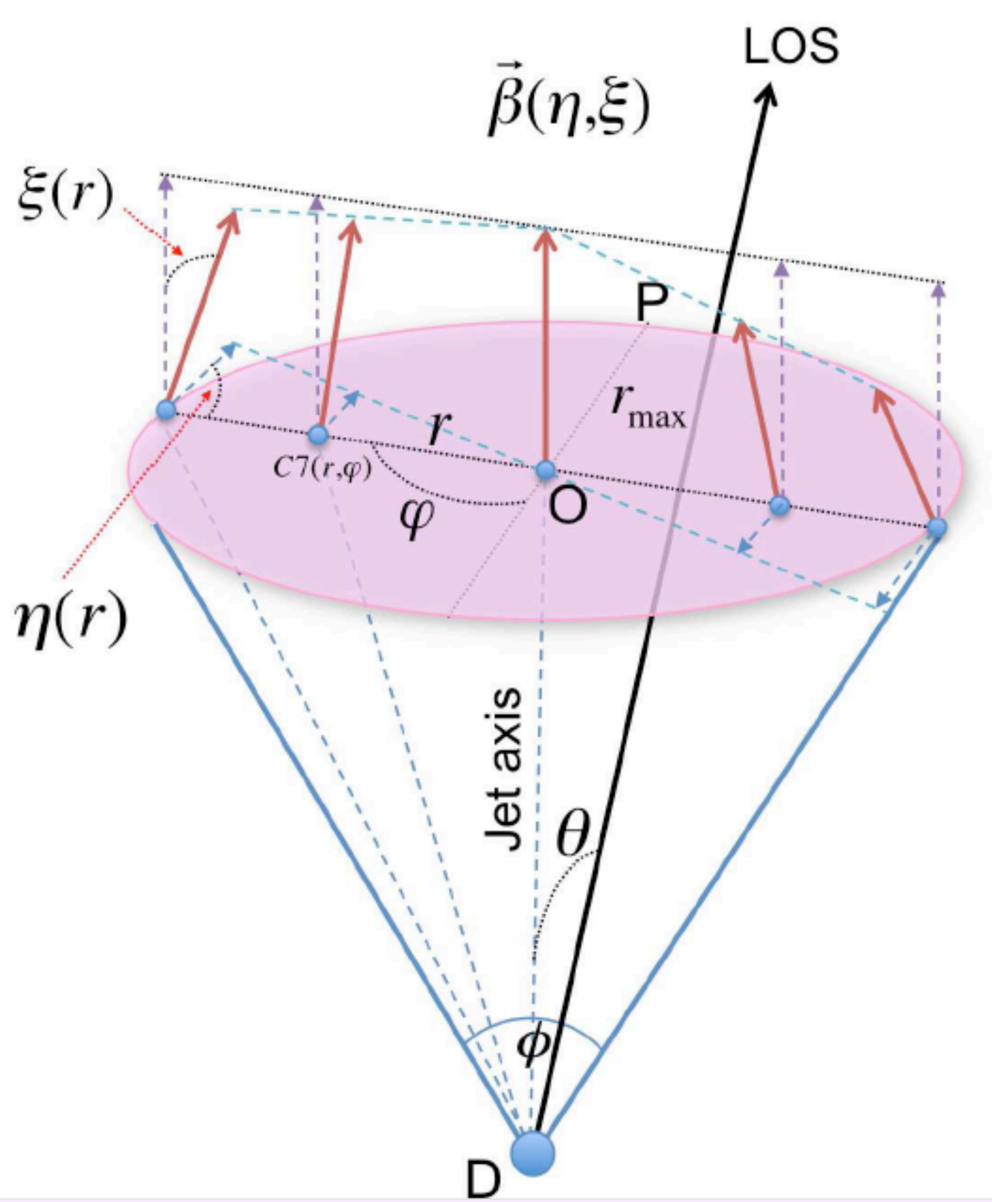
$$\eta(r) = \frac{\eta_{max} - \eta_{min}}{r_{max}} r + \eta_{min}$$

- Jet speed β at RCS is constant:

$$\vec{\beta}\left(\xi(r),\eta(r)\right): \quad \beta = \sqrt{\beta^2{}_n(r) + \beta^2{}_t(r)}$$

$$\beta_n(r) = \beta\cos\xi(r), \quad \beta_t(r) = \beta\sin\xi(r)$$

RCS model: Beaming



Viewing angle of the jet central axis
θ : Angle between the jet central axis and the LOS.

Viewing angle of the jet, $\theta_j(r,\varphi)$, at the location of RCS(r,φ) :
Angle between the jet velocity vector at RCS(r,φ) and the LOS.

Intrinsic flux density of RCS:
S_{int} is constant.

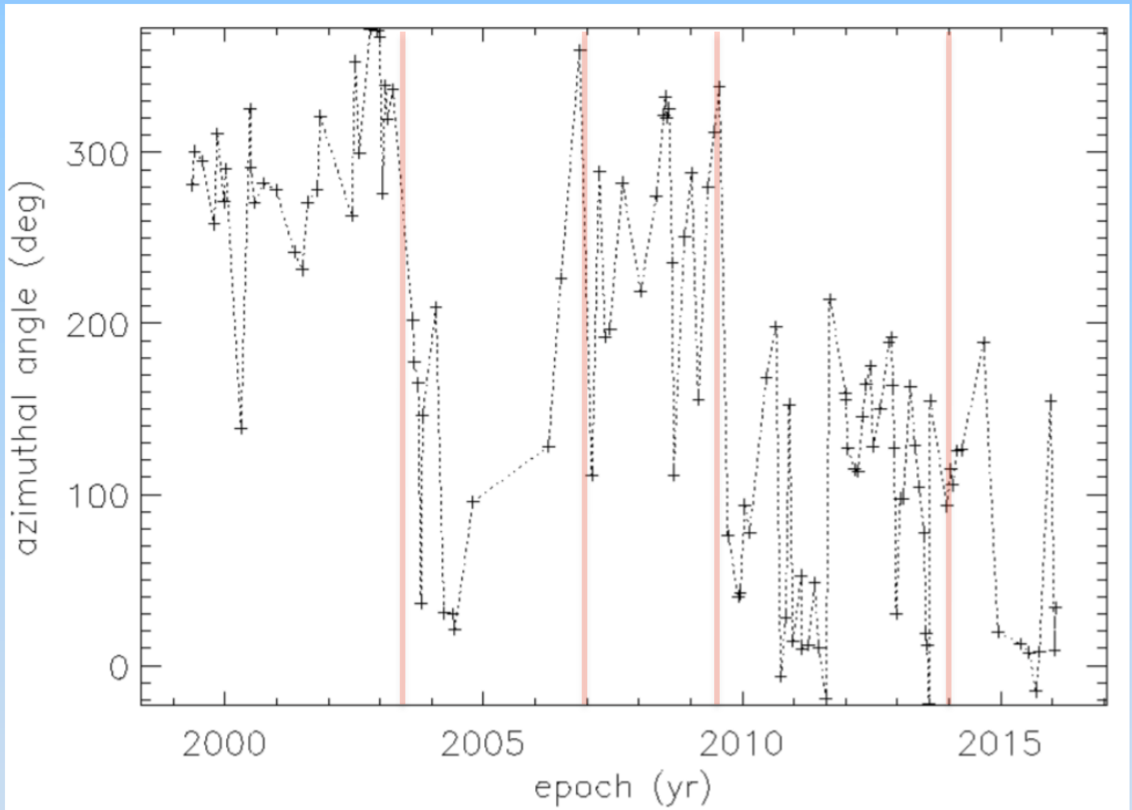
Simulated flux density of RCS at the location defined by *r* and *φ*:

$$S_{C7}(r,\varphi) = S_{int} D^{p-2}(\beta,\, \theta_{C7}(r,\varphi))$$

$$D(\beta,\, \theta_{C7}) = \frac{1}{\gamma(1-\beta\cos(\theta_{C7}(r,\varphi)))}$$

RCS motion

Azimuthal angle – epoch



Clustering of azimuth. angles with epoch:

1. < 2003.3 yr
2. 2003.3-2006.9
3. 2006.9-2009.5
4. 2009.5-2014
5. > 2014