Physical Properties of Blazar Jets from VLBI Observations

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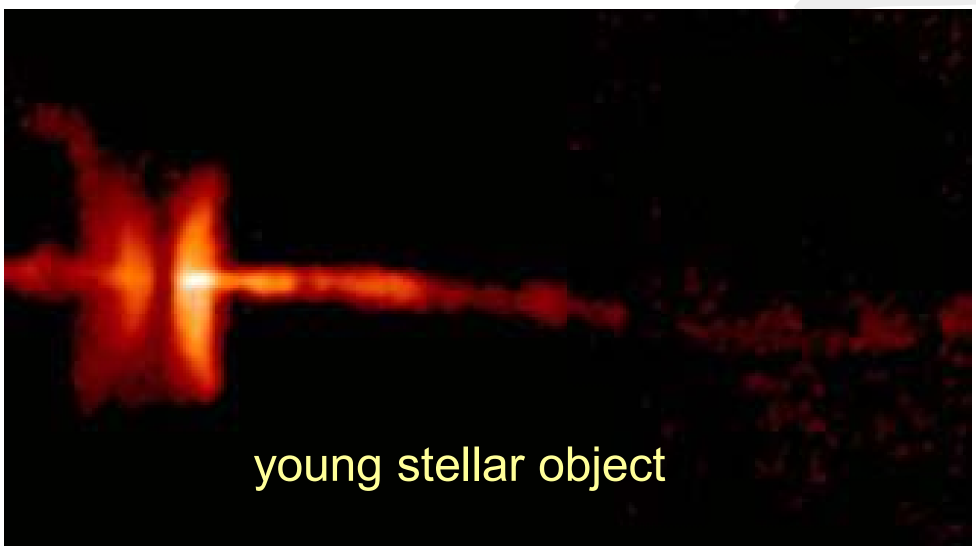
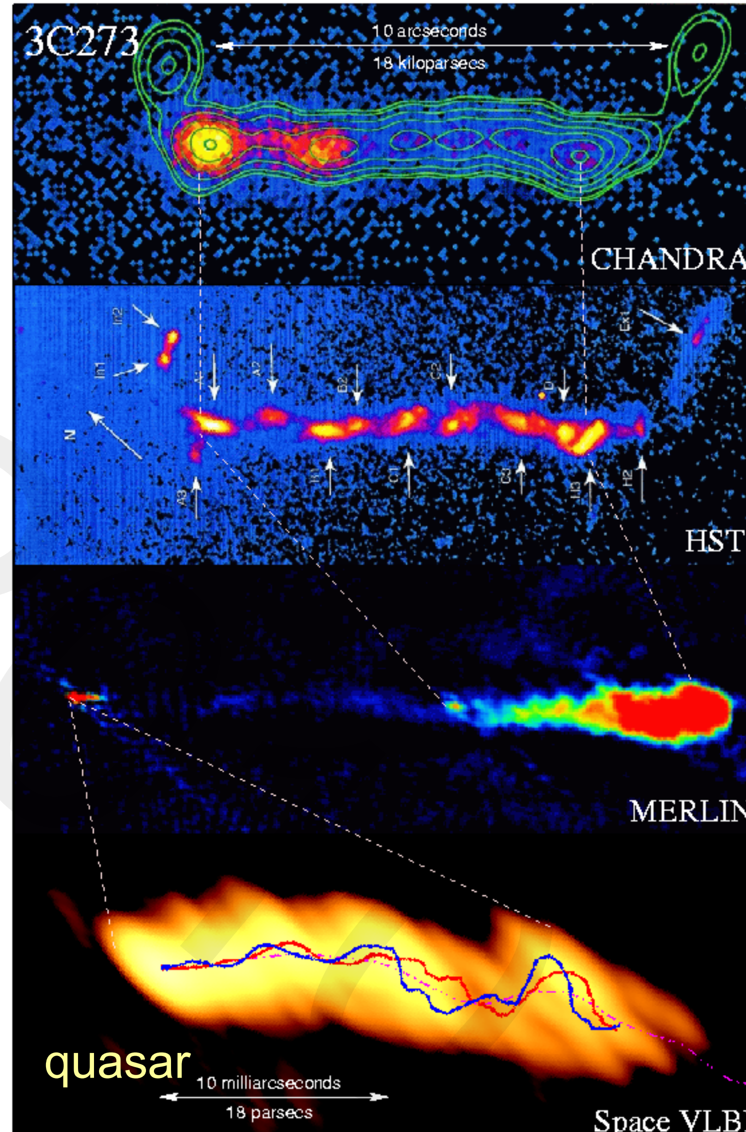
Bipolar Outflows

A. Lobanov

- Bipolar outflows (jets) are common. They have been found in galactic nuclei, pulsars, and stars (including the Sun).
- Generally: bipolar outflows solve the problem of transporting excess energy and angular momentum from compact, rotating, magnetized objects which accrete external matter

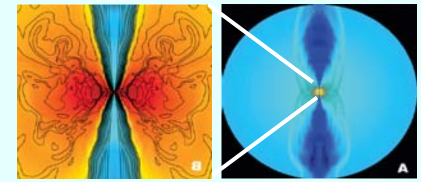


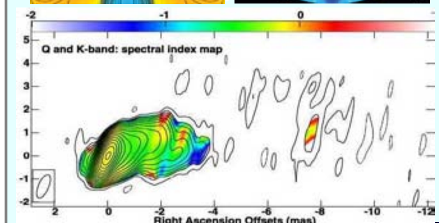


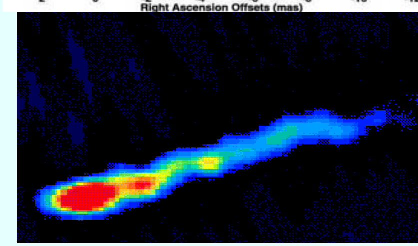
Basics of AGN Jets

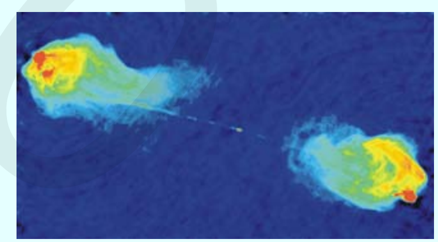
- **Launching Region: The Accretion Flow;**
  ~10 – 100 R_g: 0.05 – 0.5 mpc*, 0.01 – 0.1 μas*
  - Probably unresolved or slightly resolved
- **MHD Acceleration/Collimation Region:**
  ~10 – 10^3 R_g: 0.05 – 5 mpc, 0.01 – 1 μas
  - The Jet "Nozzle"
- **Transition Region:**
  ~10^3 R_g: ~5 mpc, ~1 μas
  - Poynting-Flux-Dominated (PFD) → KFD
- **Kinetic-Flux-Dominated (KFD) Jet:**
  ~10^3 – 10^9 R_g: 5 mpc – 5 kpc, 1 μas – 1"
- **Hot Spot/Lobe:**
  >10^9 – 10^{10} R_g: 5 – 50 kpc, 1 – 10"
  - Outer jet is Kinetic-Flux-Dominated

For a black hole of 10^8 M_{sun} at 1 Gpc (in M87: 10 R_g ~ 0.02 mas)



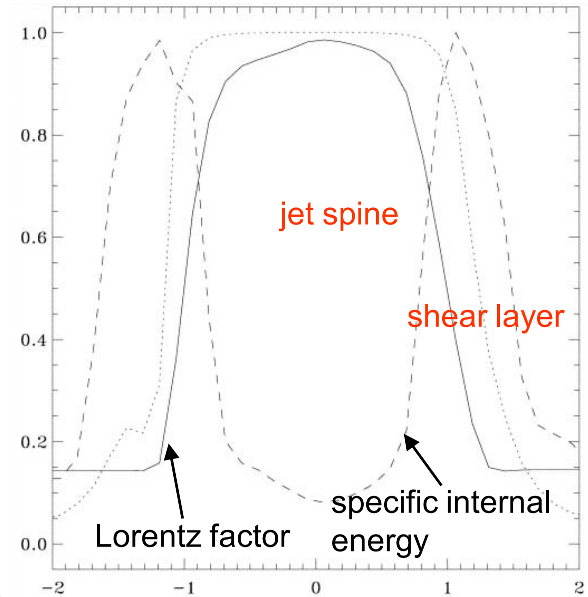




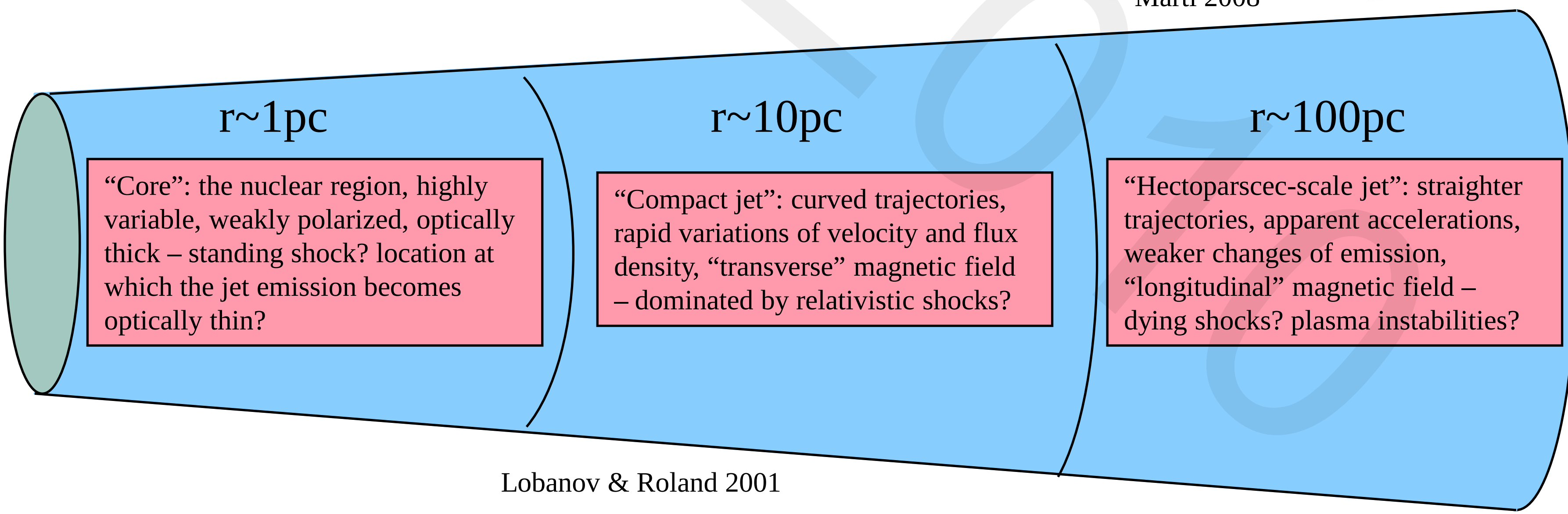


“Flowing” Paradigm

- Strongly stratified flows.
- Shocks and CD/KH instability are determining the observed morphological, kinematic and emission properties.
- Shocks propagate in the faster spine, while instability develops in the outer layers of the flow.



Martí 2008



Lobanov & Roland 2001

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Jets and AGN

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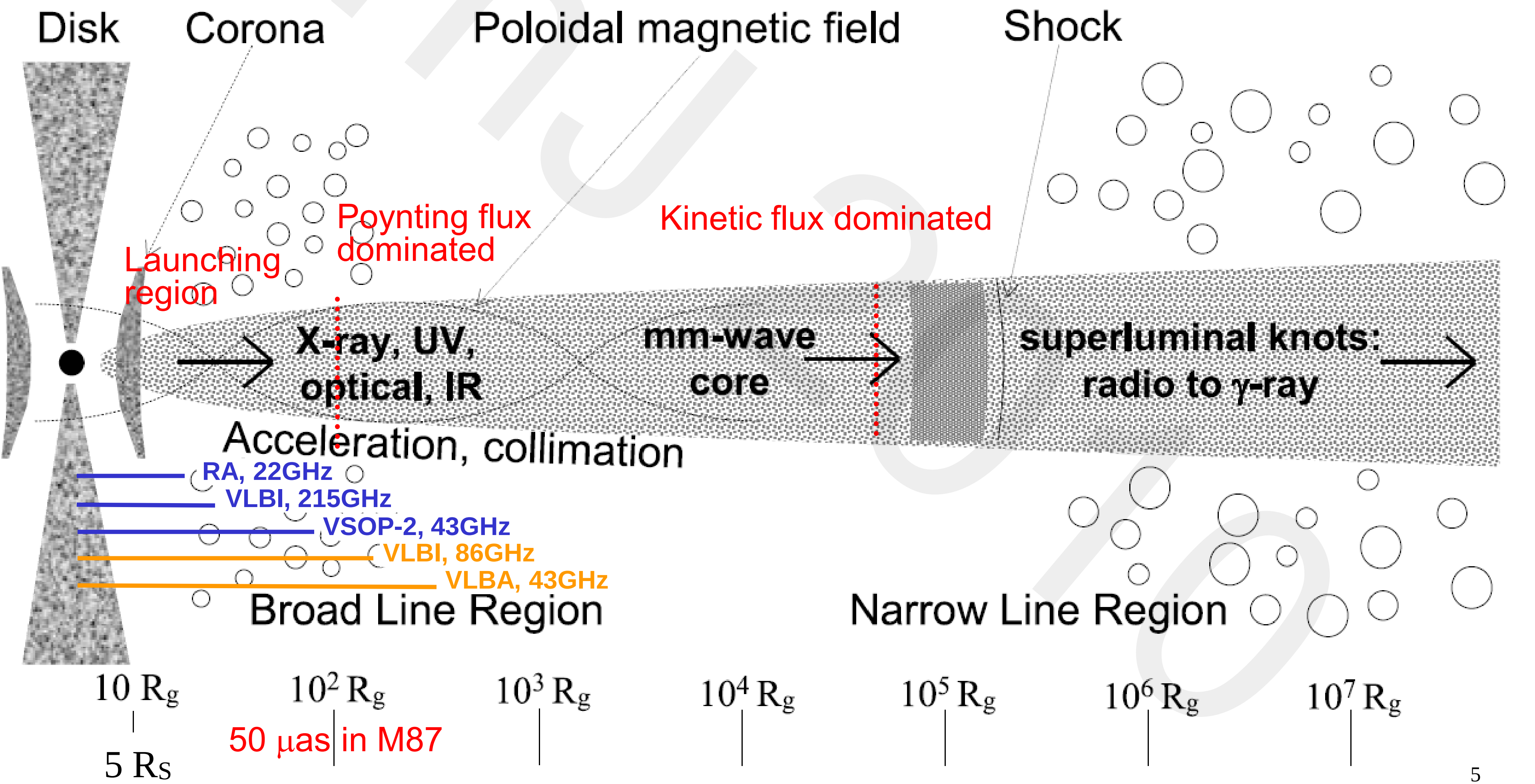
- Collimated outflows are formed close to central black holes and they interact with all major constituents of AGN



Information from VLBI

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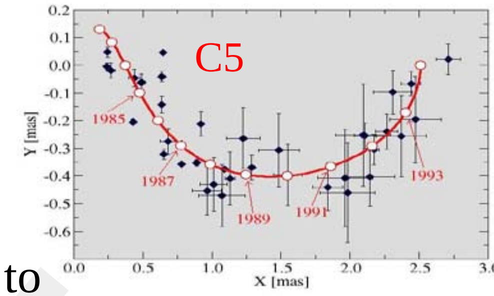
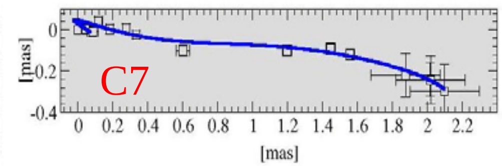
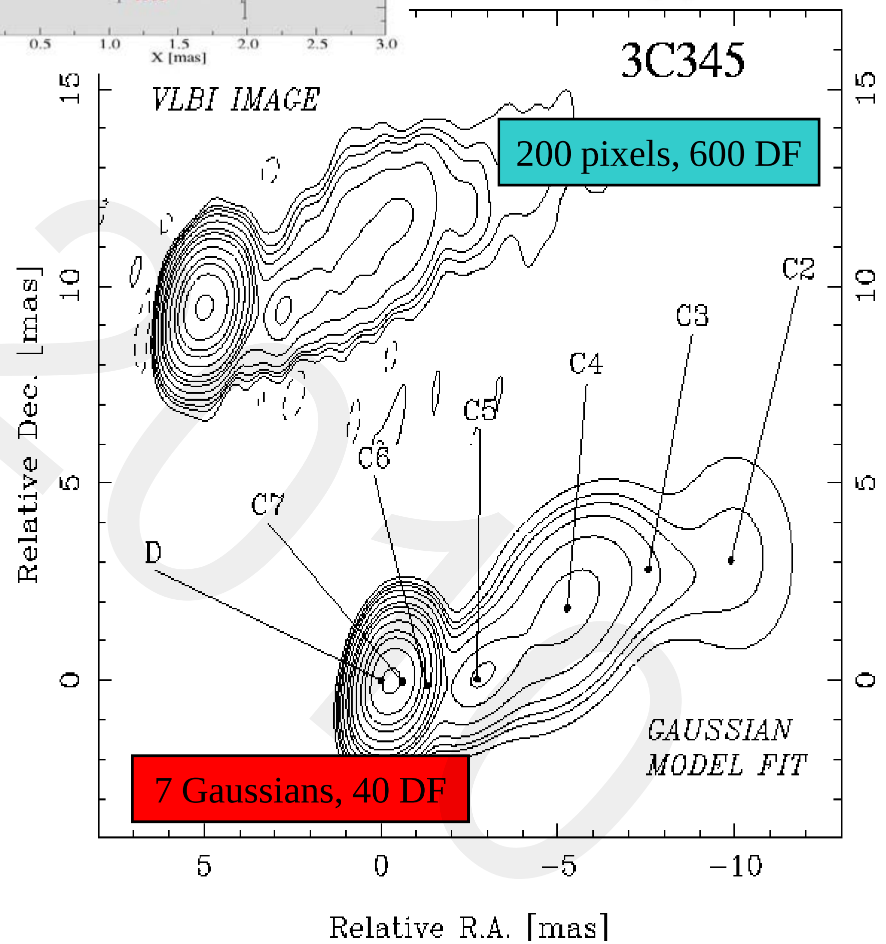
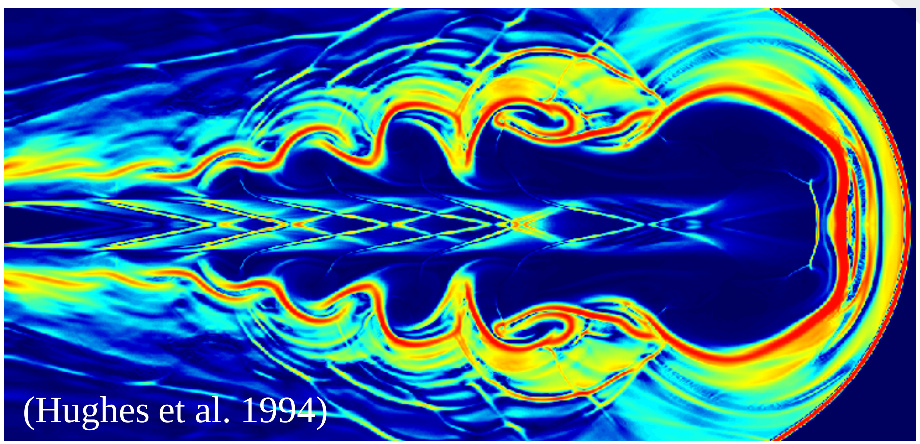
- **Observations:** **<u>1D</u>** (routinely), **<u>2D</u>**(SoA)
- **Models (relativistic).**
  Analytical: **<u>2D</u>** (routinely), **<u>3D(t)</u>** (SoA)
  Numerical: **<u>3D</u>** (routinely), **<u>3D(t)</u>** (SoA)
- **Problems:** connecting predictions (**p**,**v**,❒) to observables (**S**■, ♋, ♌$_{app}$). Elusive **B** , ☝$_j$ and M
- **Solution:** find a way to obtain reliable 2D information from VLBI images. High-resolution and high-fidelity images and novel reduction and analysis techniques are needed





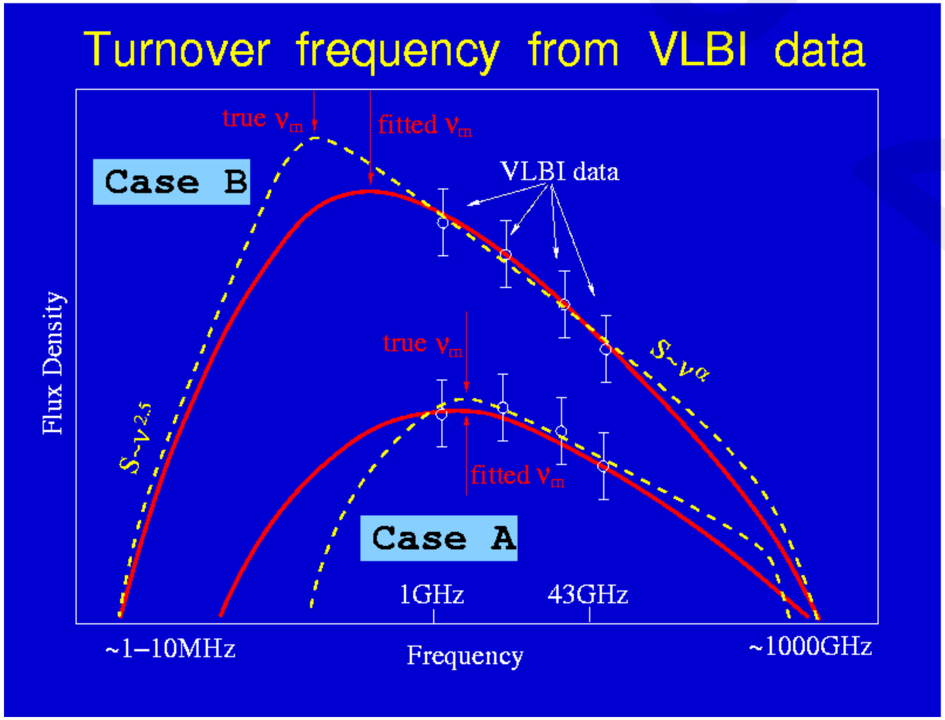


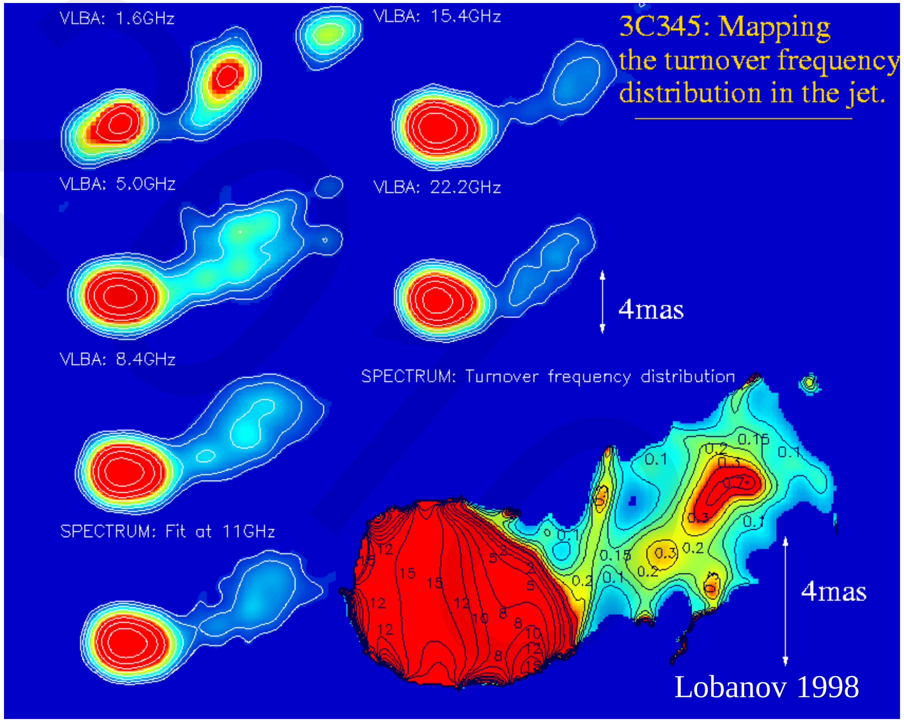


(Hughes et al. 1994)

Plasma Diagnostics

- Distribution of the spectral turnover: a tool to detect patterns induced by plasma instabilities and obtain two-dimensional distribution of particle density and magnetic field in the flows.
- Low frequency observations are the only way to enable imaging the spectral turnover in extended jets





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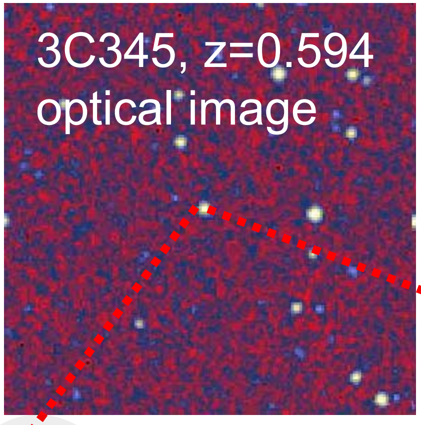
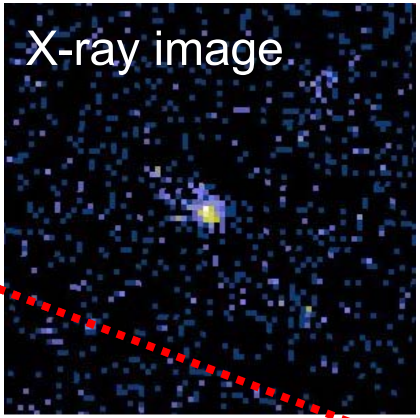
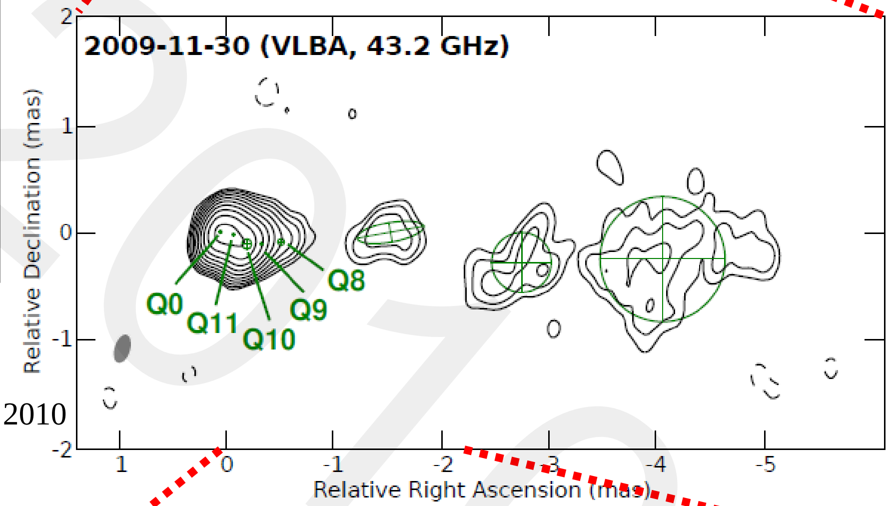
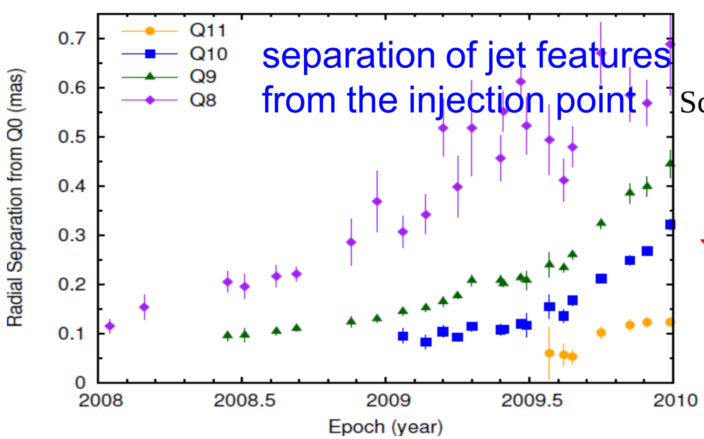
Localisation with VLBI

- VLBI observations now provide a ~50 μas resolution at 3 mm, resolving sub-parsec scale regions in all AGN and reaching down to scales of ~100 R_g in nearby AGN.
- Monitoring of individual regions traces in detail their kinematic and emission evolution – this evolution can be related to variability of high-energy emission.

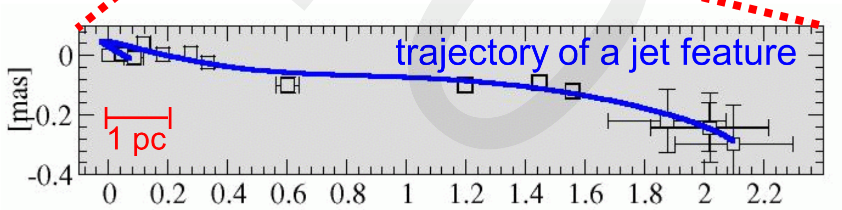








Schinzel et al. 2010

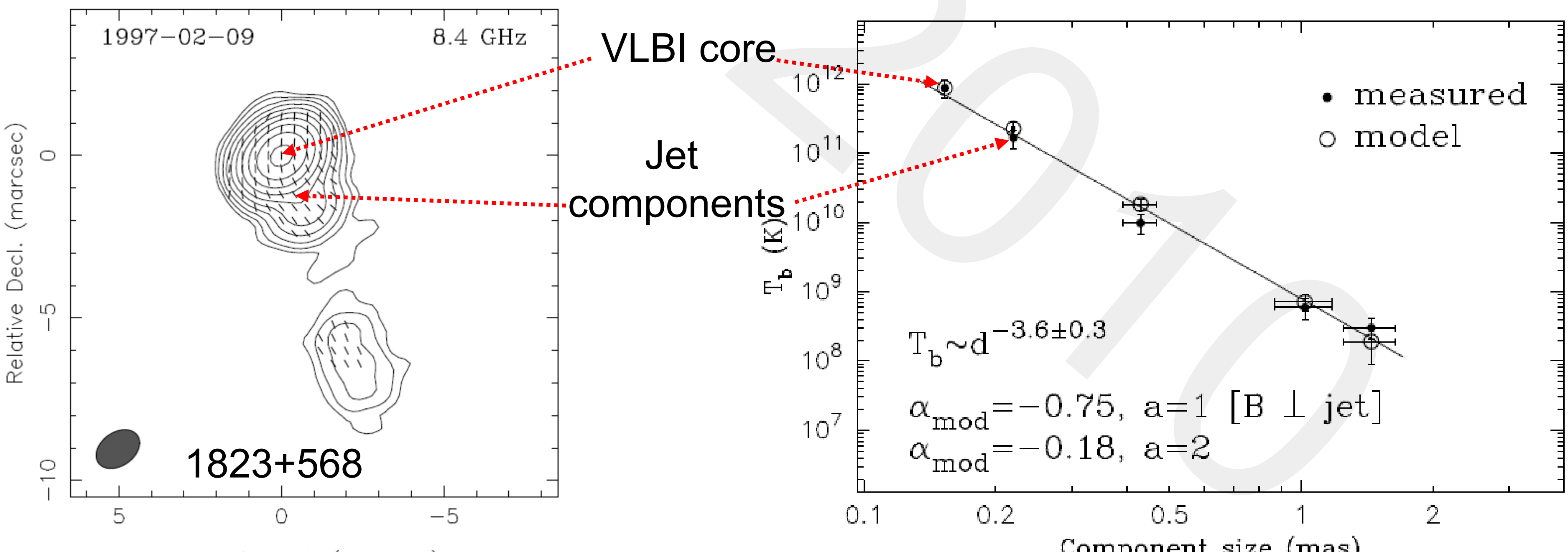


Lobanov & Zensus 1999

Jet Structure

Jet Structure

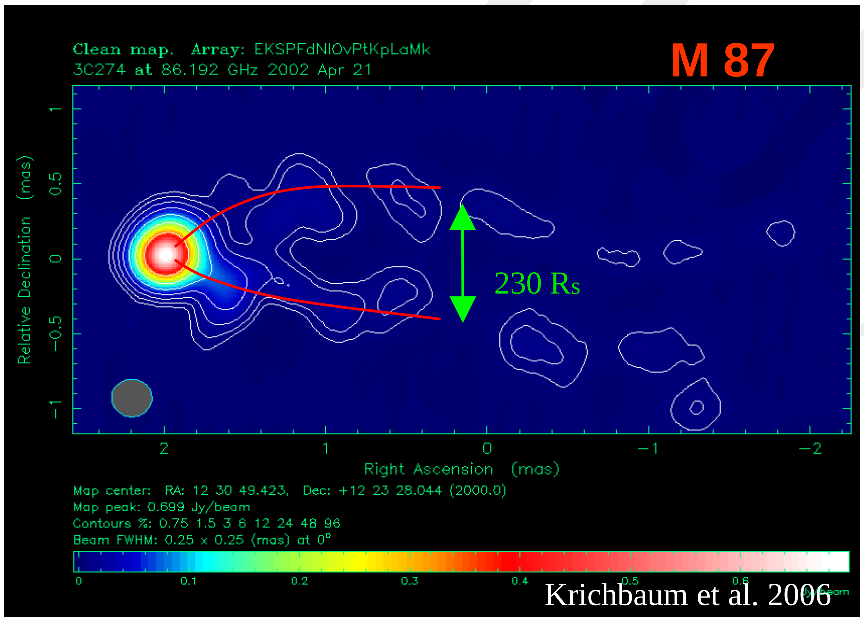
- Bright, often unresolved narrow end of the jet (VLBI core), with intrinsic brightness temperature of ~5*10^{11}K (Lobanov+2001, Homan+2006).
- Moving enhanced emission regions (jet components), with intrinsic brightness temperature of ~5*10^{10}K (equipartition limit, Readhead 1994) and decreasing in agreement with adiabatic losses (Pushkarev+ 2009).

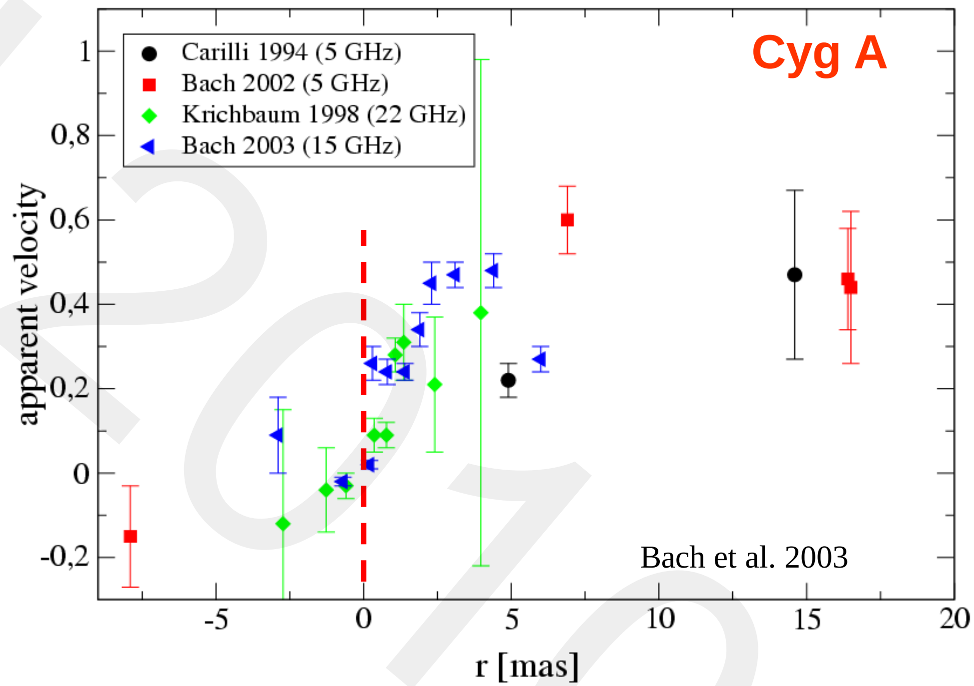


Pushkarev et al. 2009

Collimation and Acceleration

- VLBI observations of compact jets in nearby AGN provide strong evidence for collimation on linear scales of ~$10^3\,R_g$ and strong acceleration on parscec scales (~10^5–$10^6\,R_g$)





- Magnetically driven acceleration is a viable explanation for the observed speeds (Vlahakis & Königl 2004)

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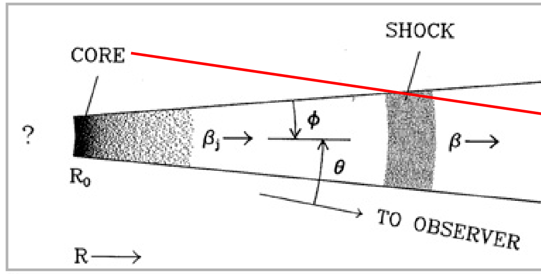
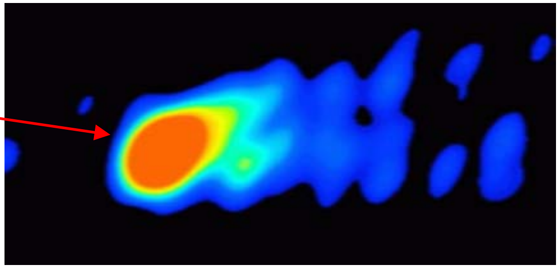
VLBI "Core": Compact Jet

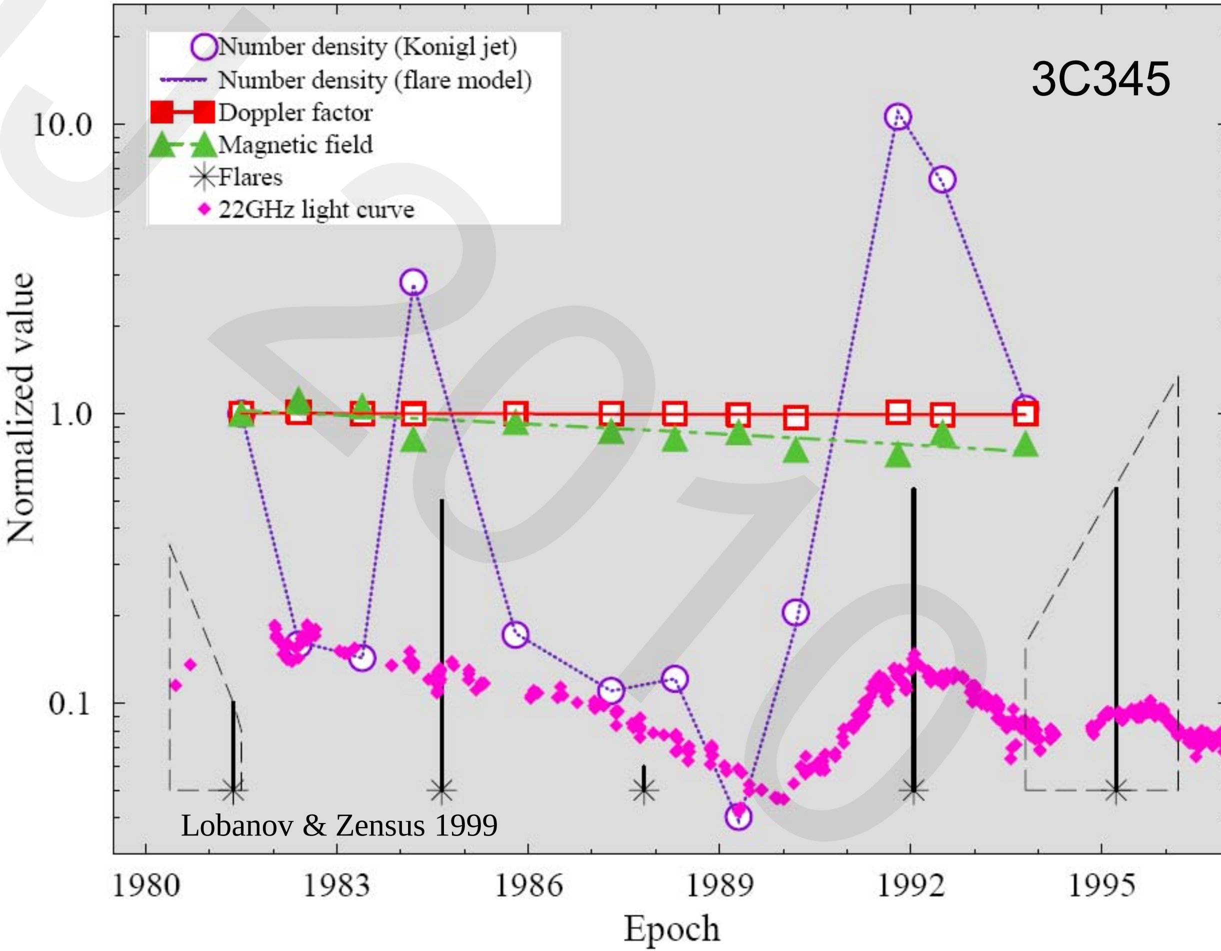
- ❑ Location at which jets become visible in radio is most likely determined solely by the τ=1 condition for synchrotron emisson (Königl 1981).

- ❑ Nuclear flares can be described by relatively modest and smooth variations of particle density.

- ❑ Magnetic fields are either tangled or organized on scales much smaller than the resolution limit.

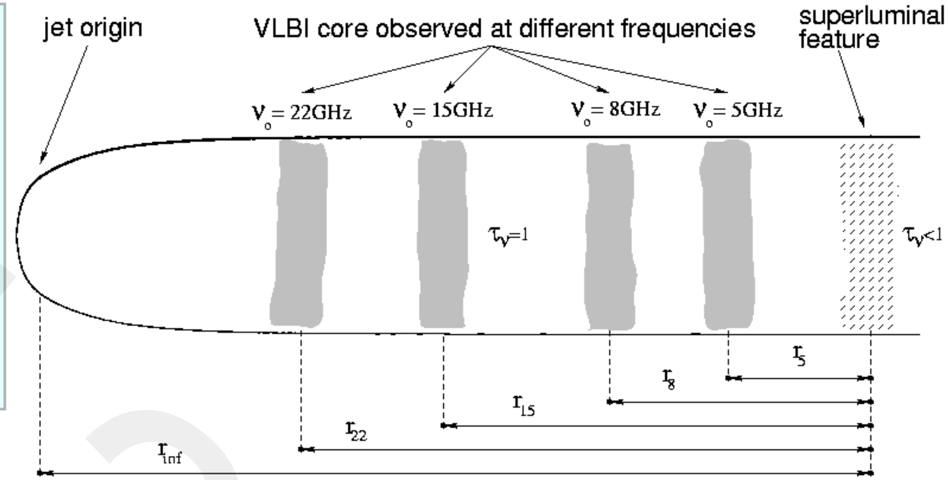






Ultracompact Jets

- ❑ Apparent position of the VLBI core depends on observing frequency, owing to synchrotron self- absorption, and external absorption.



Optical depth in the jet

$$\tau_s(r) = C(\alpha) N_1 \left(\frac{e B_1}{2\pi m_e} \right)^{\epsilon} \frac{\delta^{\epsilon} \phi_o}{r^{(\epsilon m + n - 1)} \nu^{\epsilon + 1}}$$

The condition τ_s=1 determines the location of the core

$$r[\mathrm{pc}] = (B_1^{k_b} F/\nu)^{1/k_r}$$

Can be estimated from observed "core shift"

$k_r = 1$ → Synchrotron self-absorption

$k_r > 1$ → Synchrotron self-absorption + Gradients in pressure

→ Synchrotron self-absorption + External absorption (i.e. free-free absorption in the broad-line region

(Lobanov 1998)

Core Shift

- Position offset of the optically thick „core“ of a VLBI jet can be used to estimate physical conditions in the nuclear region of AGN

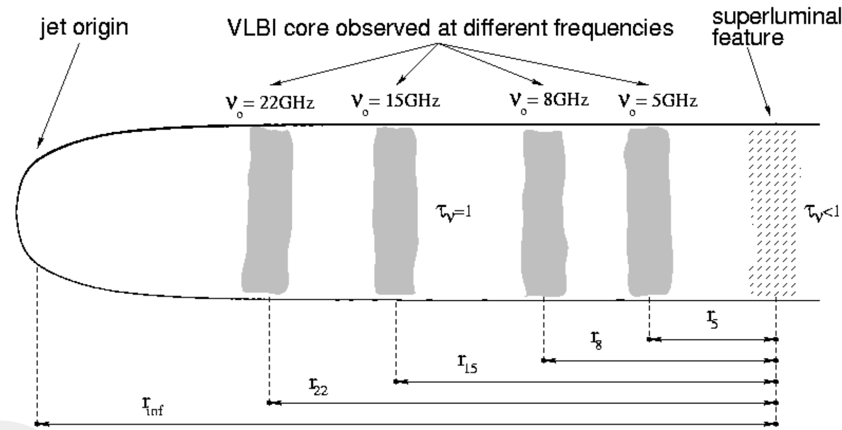
Core offset measure:

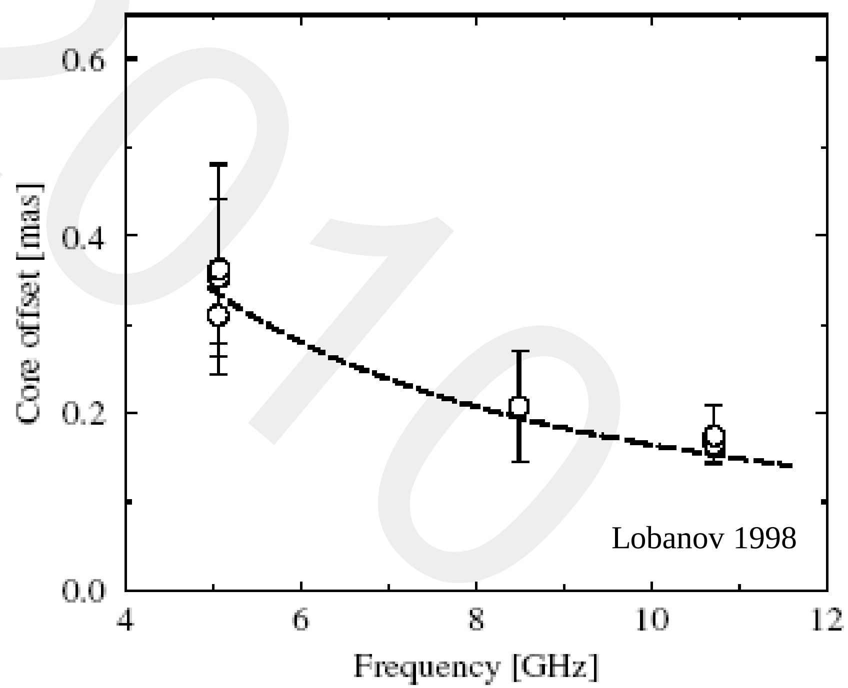
$$\Omega_{r\nu} = 4.85 \cdot 10^{-9} \frac{\Delta r_{\mathrm{mas}} D_{\mathrm{L}}}{(1+z)^2} \cdot \frac{\nu_1^{1/k_{\mathrm{r}}} \nu_2^{1/k_{\mathrm{r}}}}{\nu_2^{1/k_{\mathrm{r}}} - \nu_1^{1/k_{\mathrm{r}}}}$$

Derived magnetic field and distance from the central engine to the core:

$$B_1 = (\Omega_{r\nu} / \sin\theta)^{k_{\mathrm{r}}/k_{\mathrm{b}}} F^{-1/k_{\mathrm{b}}}$$

$$r_{\mathrm{core}}(\nu) = \Omega_{r\nu} \left[\nu^{1/k_{\mathrm{r}}} \sin\theta\right]^{-1}$$





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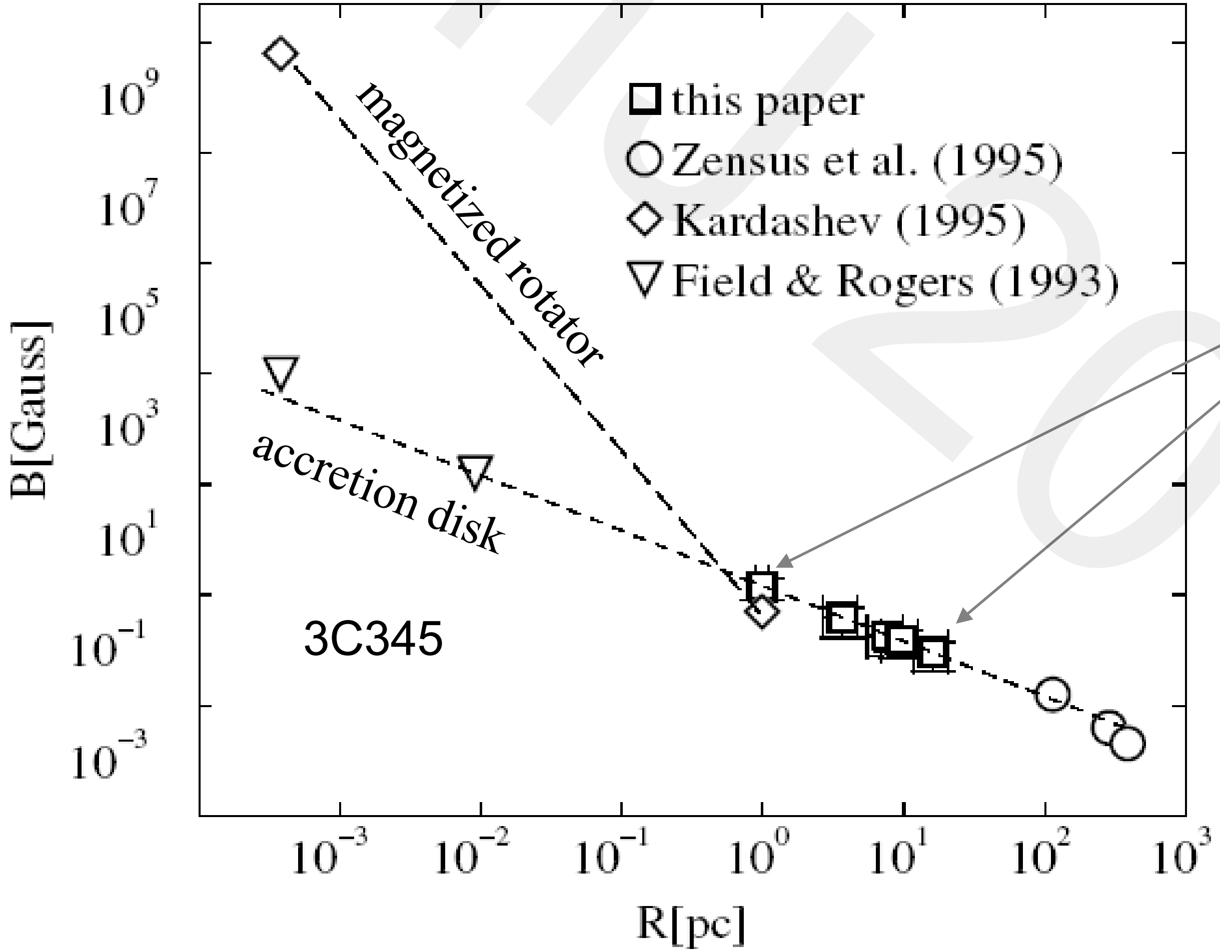
Magnetic Field near SMBH

- Multifrequency measurements of the core shift in 3C345 enable determining properties of the magnetic field on parsec-scales in the jet of this object.



Measured from the core shift

Typical fields of order of ~1G in VLBI cores and less than 0.1G in jet components – see presentation by Kirill Sokolovsky.

Magnetic Field Structure

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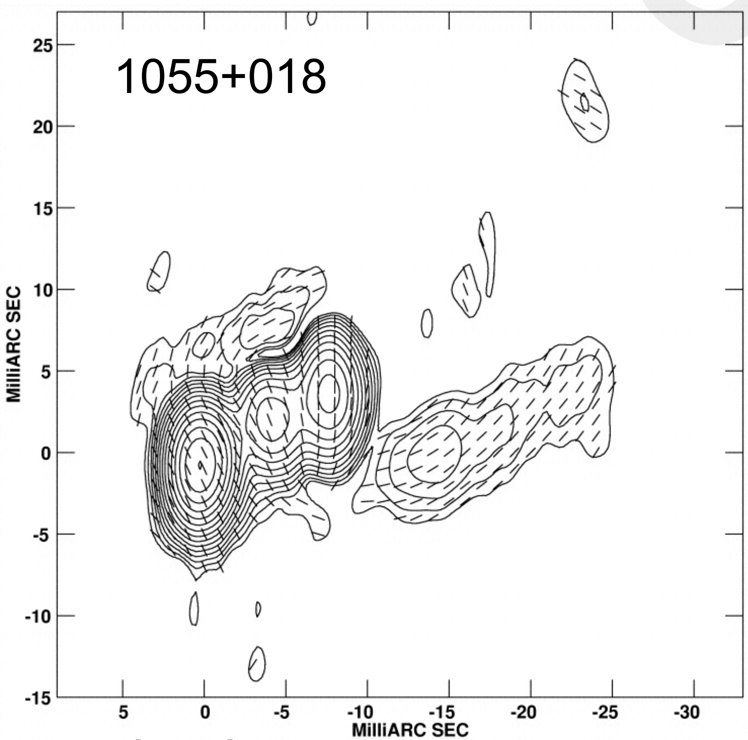
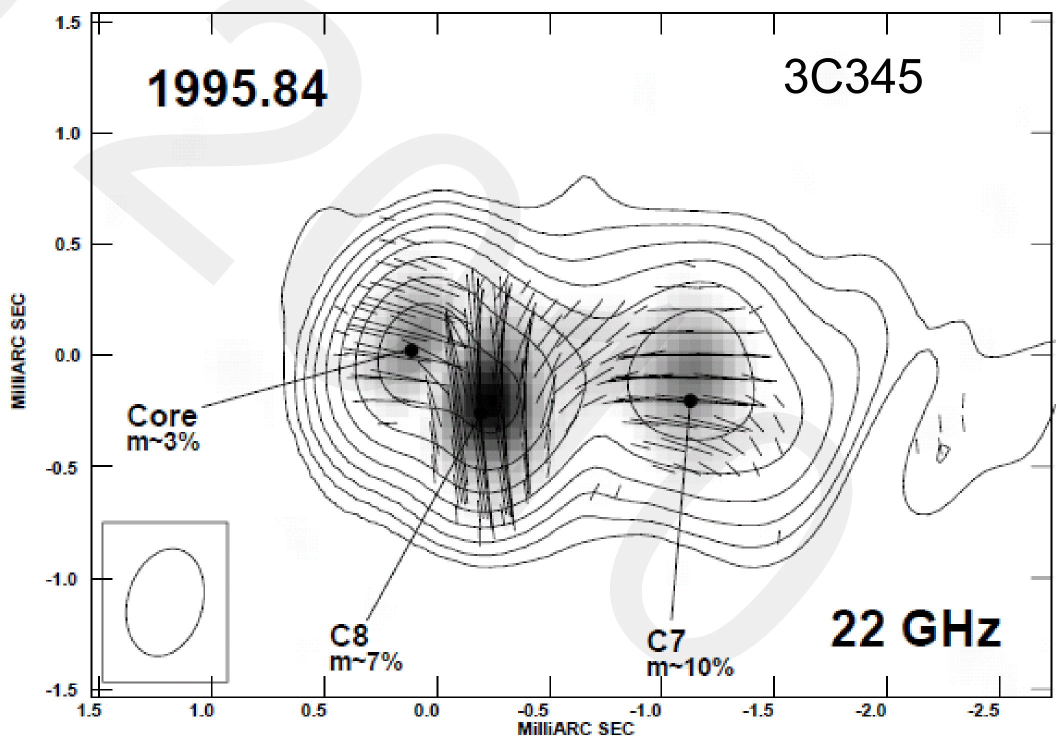
- Jet spine: poloidal field + shock compressed regions. Presence of helical magnetic field is also suggested from EVPA rotation and rotation measure gradients.
- Outer layers: toroidal field + shear stretched regions.



Attridge et al. 1999



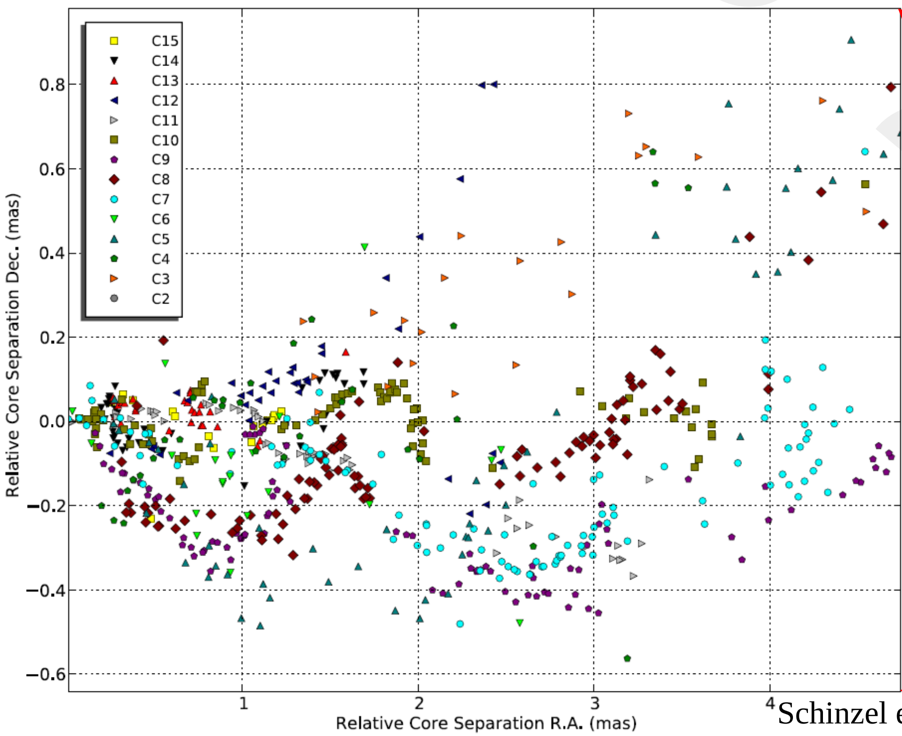
Ros et al. 2000

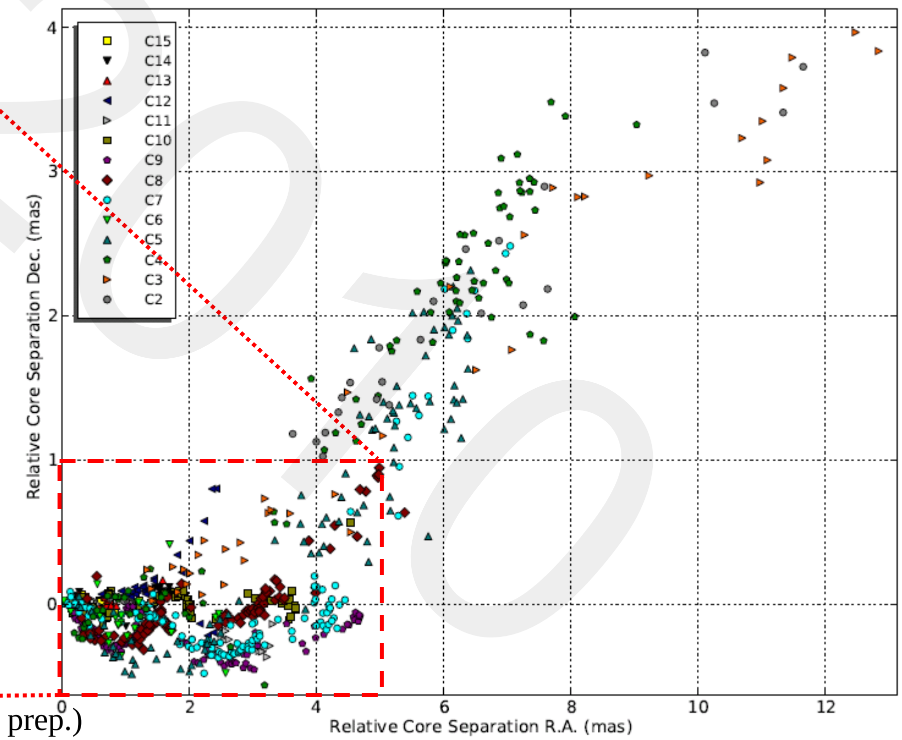
Kinematics

Component Trajectories

- Trajectoris of individual jet components often differ substantially in the vicinity of the VLBI core, but later align well with the general direction of the jet.
- Filaments inside a straight flow? Rotating flow? Strongly dominating magnetic field?

positions of jet components in 3C345

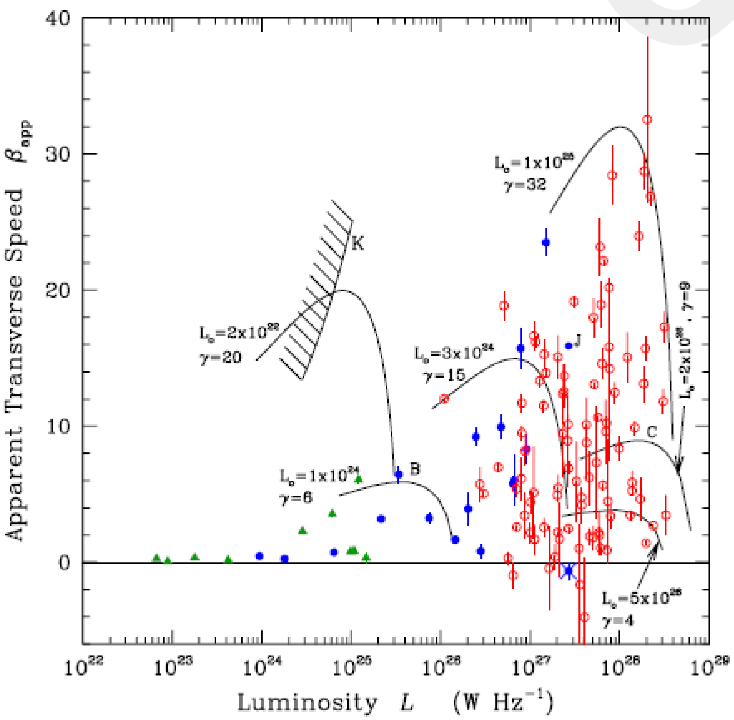




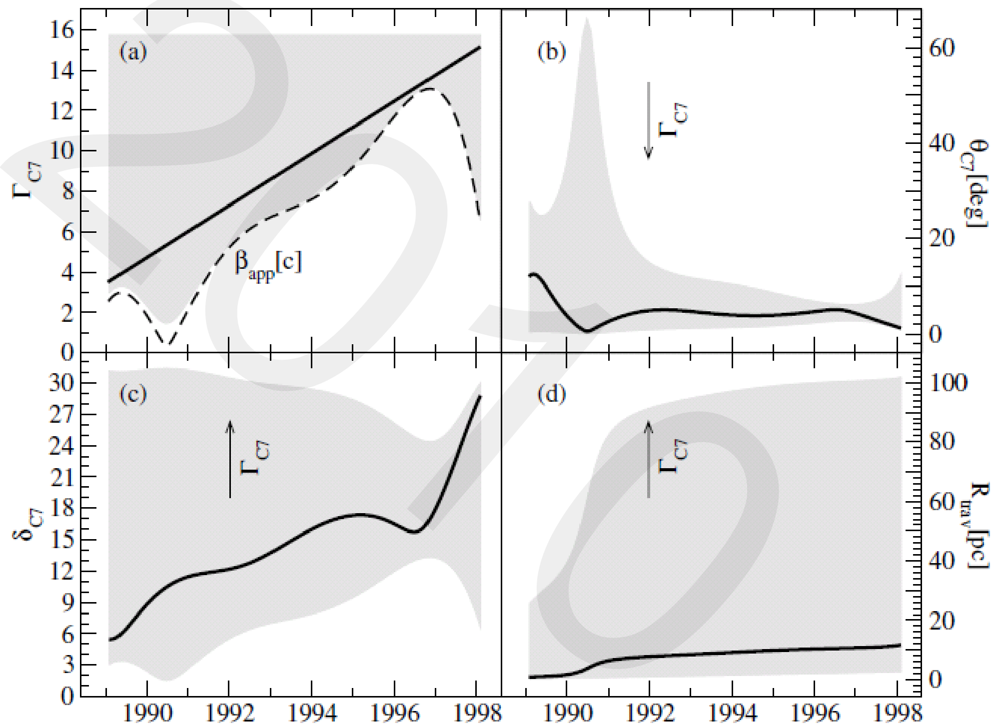
Schinzel et al. (in prep.)

Proper motions

- Proper motions reflect underlying flow speed (Lister+2009). An envelope with Γ_j~30, possibly varying in different source types.
- Accelerated motions are common, as well as presence of quasi-stationary regions (Homan+2006)
- Rest frame acceleration is likely, with acceleration scales of ~10 pc.



Cohen et al. 2006

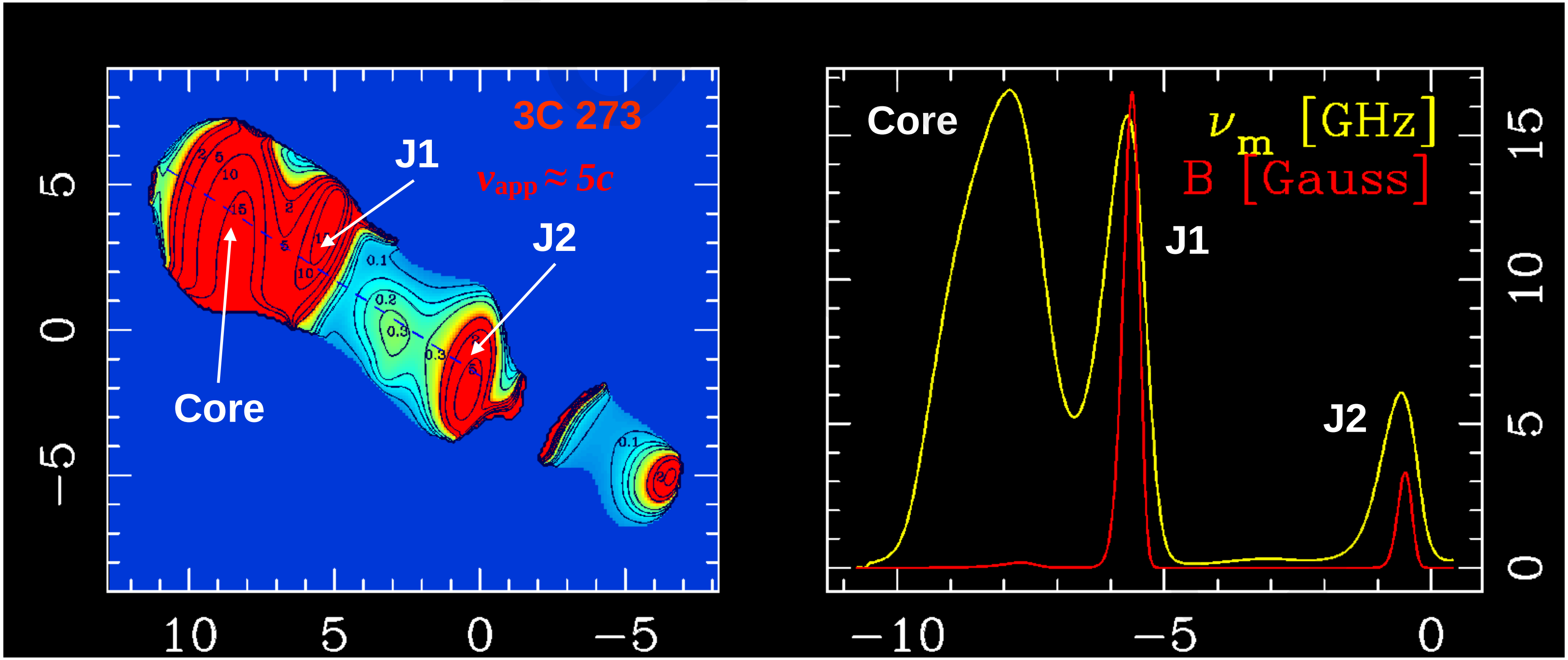


Lobanov & Roland 2005

Shocks and Plasma Instability

Shock-Dominated Regions

- Strong shocks are present in jets on scales of several deca-parsecs(10^6–10^7 R_g) – revealed by polarization of radio emission and distribution of the synchrotron peak frequency.



Carrara et al. 1997

Shocks on parsec scales

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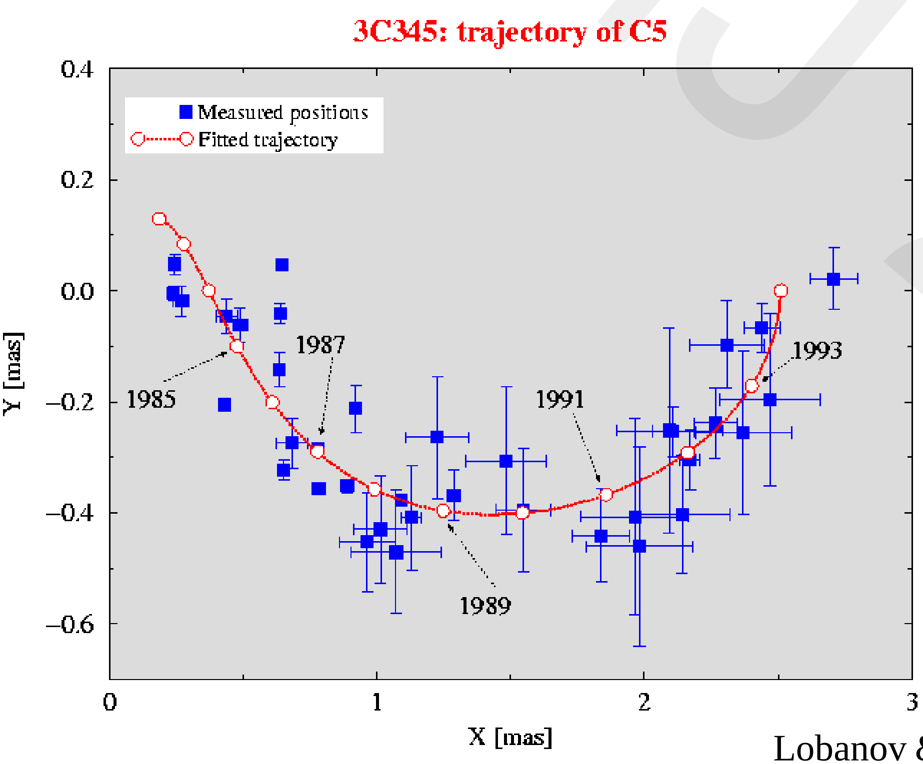
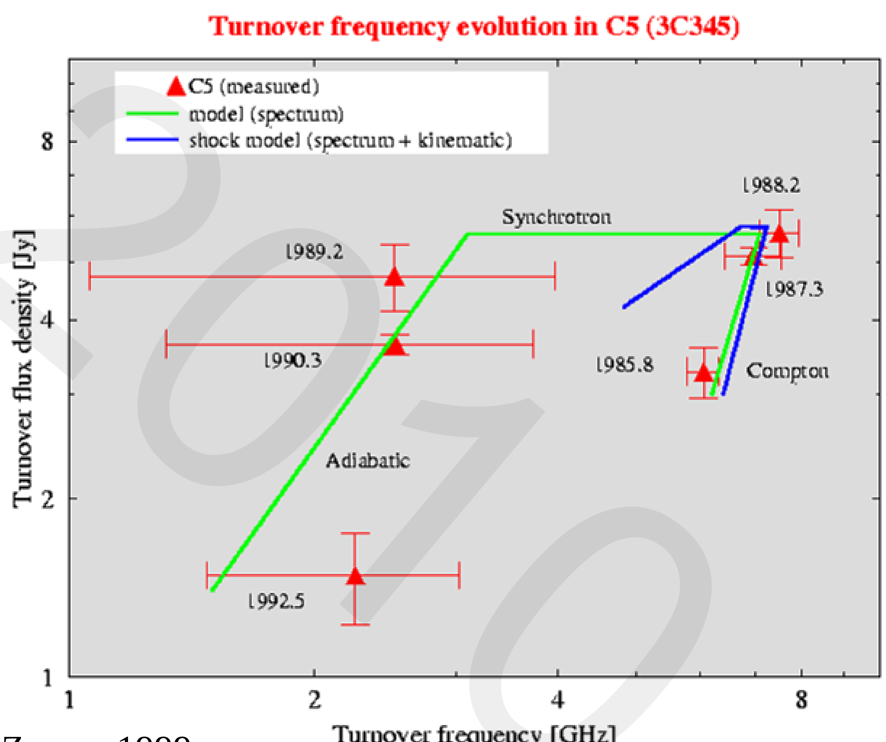
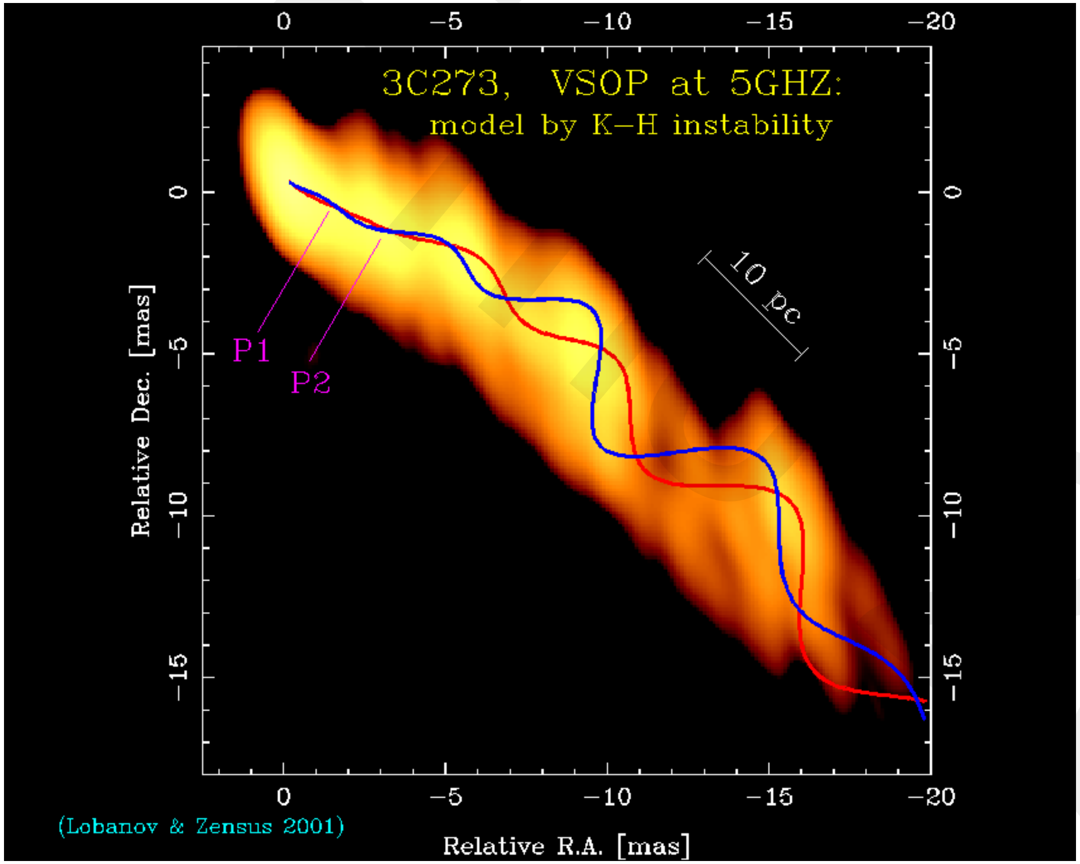
- Shocks dissipate rapidly while approaching hectoparsec scales: shock models can no longer explain kinematic and spectral evolution observed in jets on these scales.



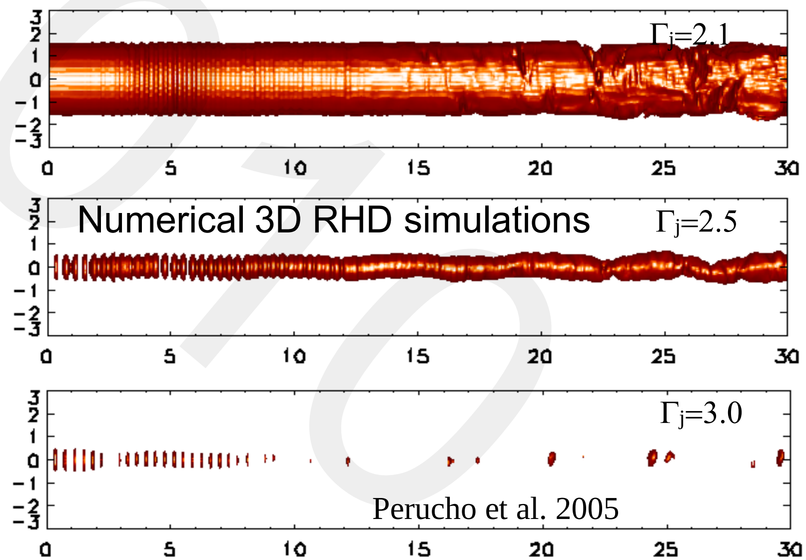


Lobanov & Zensus 1999

Shocks and K-H Instability



- Shocks dissipate at distances of $>10^7\,R_g$, giving way to Kelvin-Helmholtz instability as the major factor determining the morphology and dynamics of the flow. The instability develops in a non-linear regime

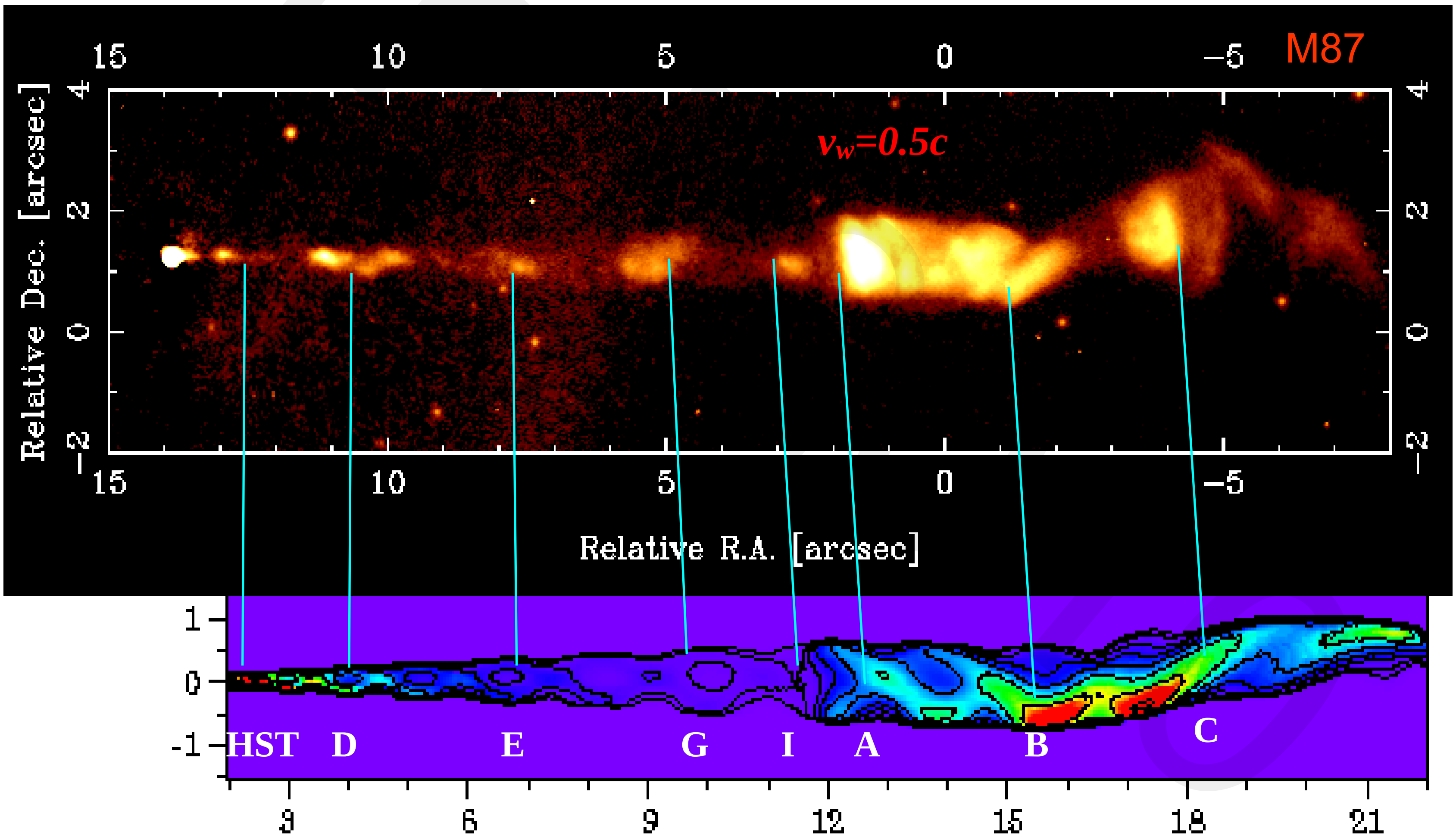


Wavelengths of the modes:
λ_{Hs}=18.0, λ_{Es}=12.0, λ_{Eb1}=4.0, λ_{Eb2}=1.9 [mas]

Jet parameters:
Γ_j=2.1, **M_j**=3.5, **η**=0.02, **a_j**=0.53, ***v_w=0.21c***

Instabilities on Large Scales

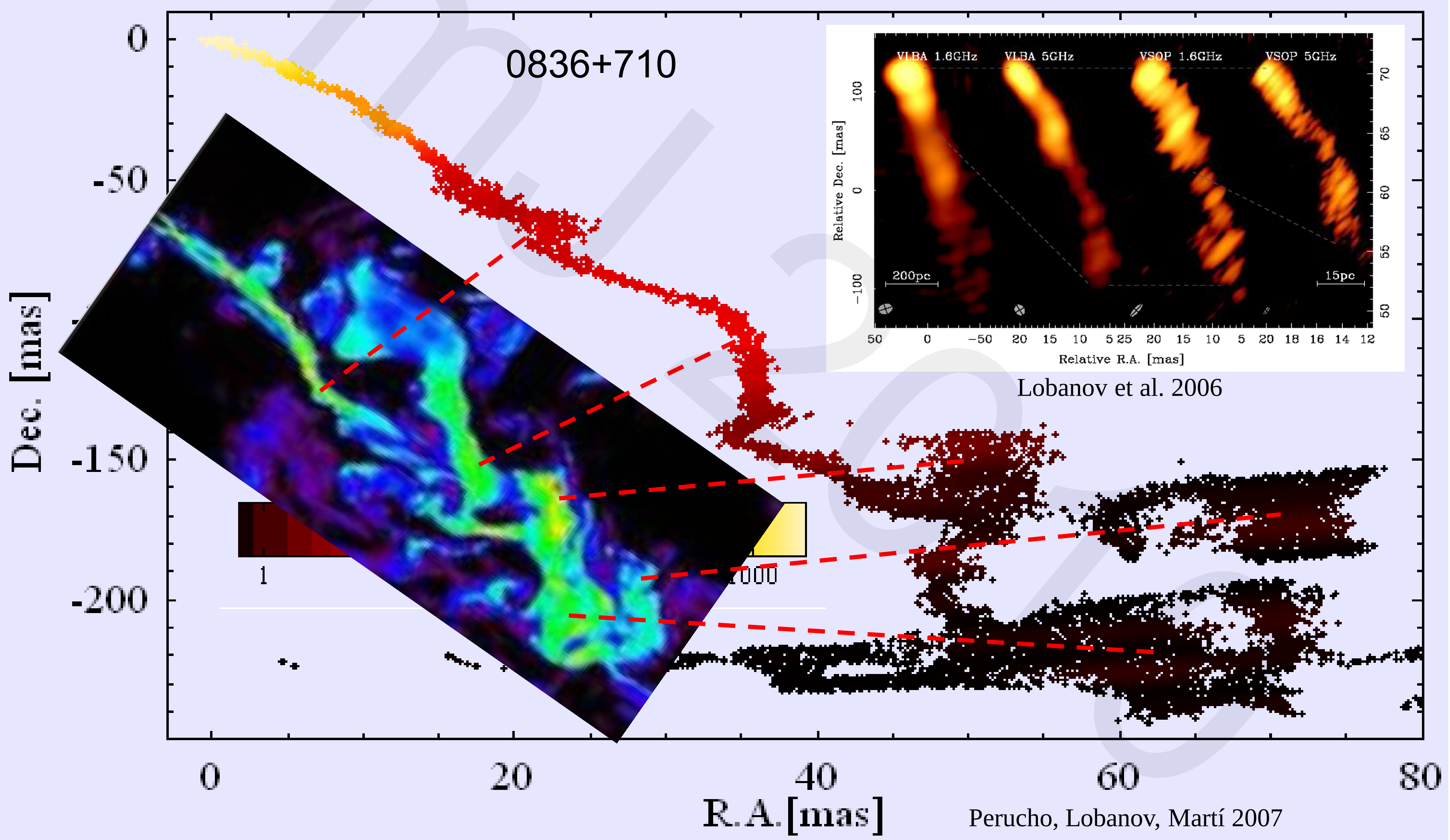
- Kelvin-Helmholtz instability determine the morphology and dynamics of jets on scales of $10^7 - 10^9\ R_g$



Lobanov, Hardee, Eilek 2003

Jet Disruption

- Helical surface mode of K-H instability can disrupt jets at ~10^9–10^{10} R_g



Lobanov et al. 2006

Perucho, Lobanov, Martí 2007

Broad-band Continuum

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Accretion disks and BLR

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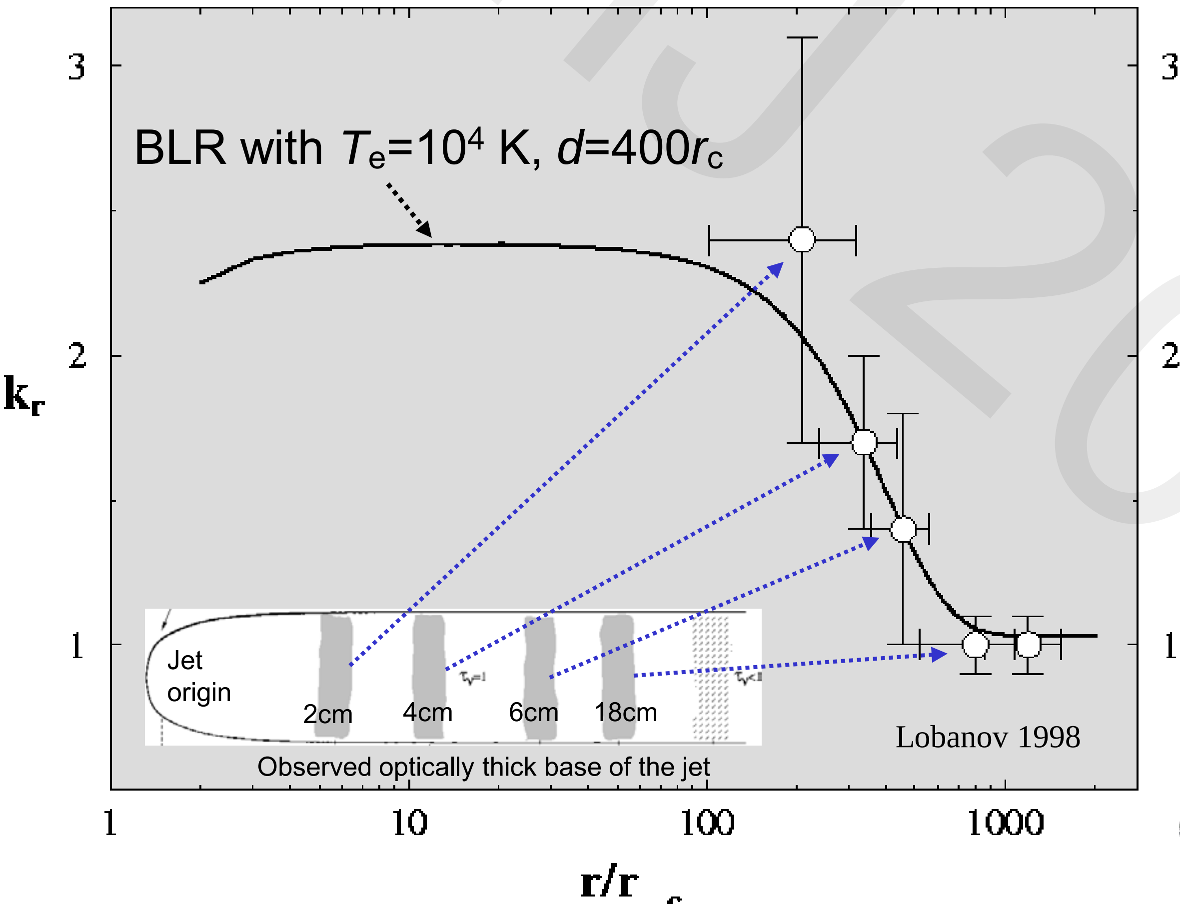
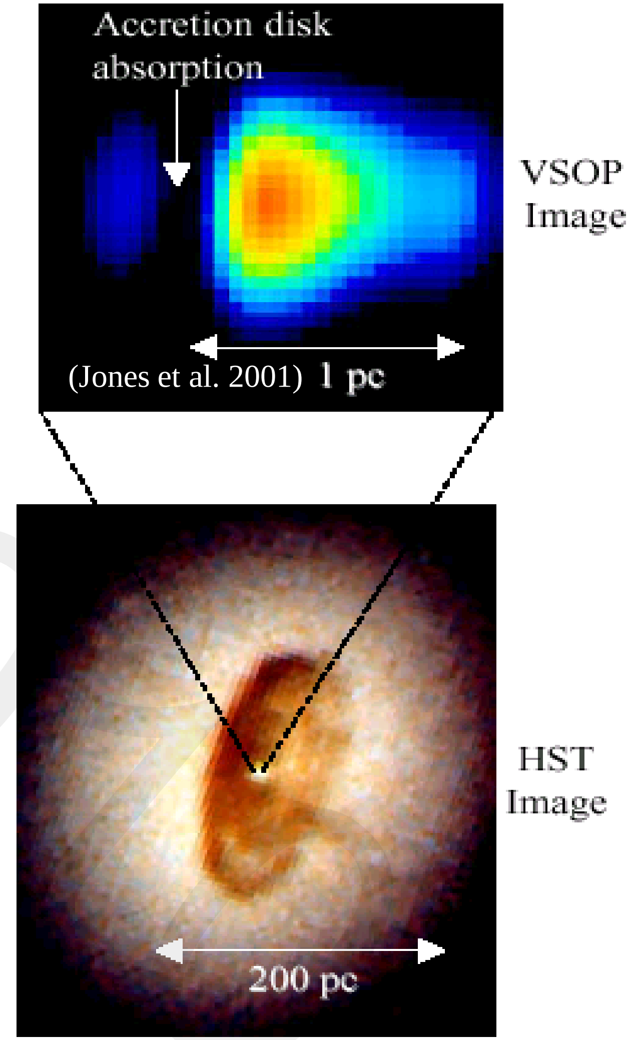
- Nuclear absorption studies of radio emission from jets probe accretion disks and broad-line regions in AGN

3C309.1: opacity in the jet

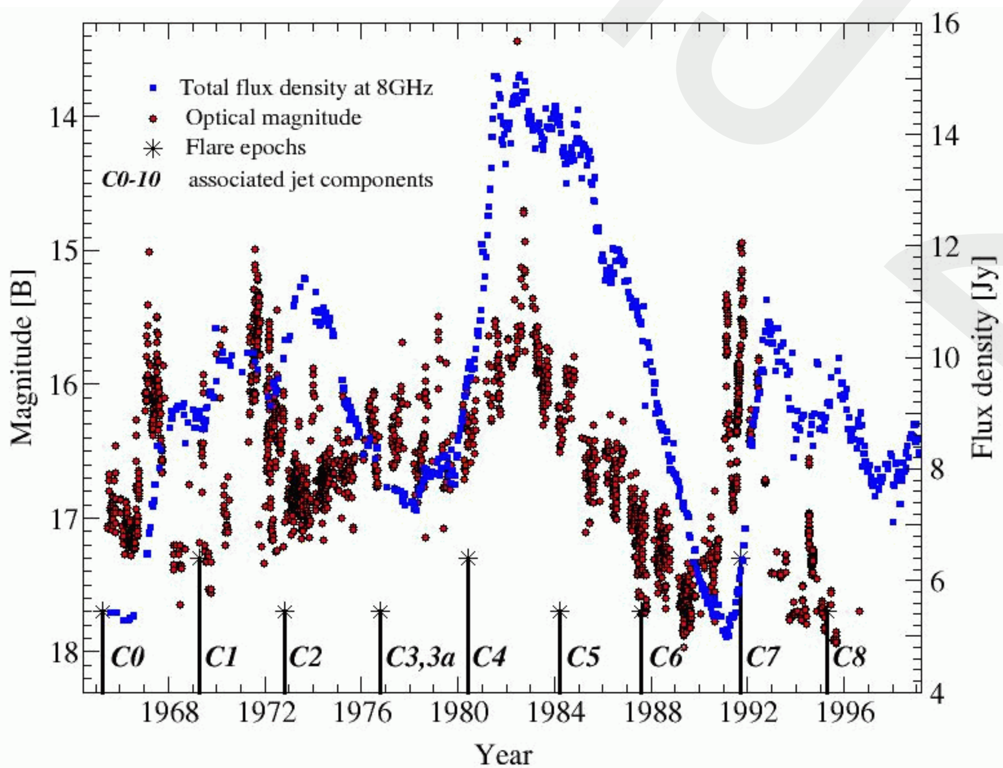


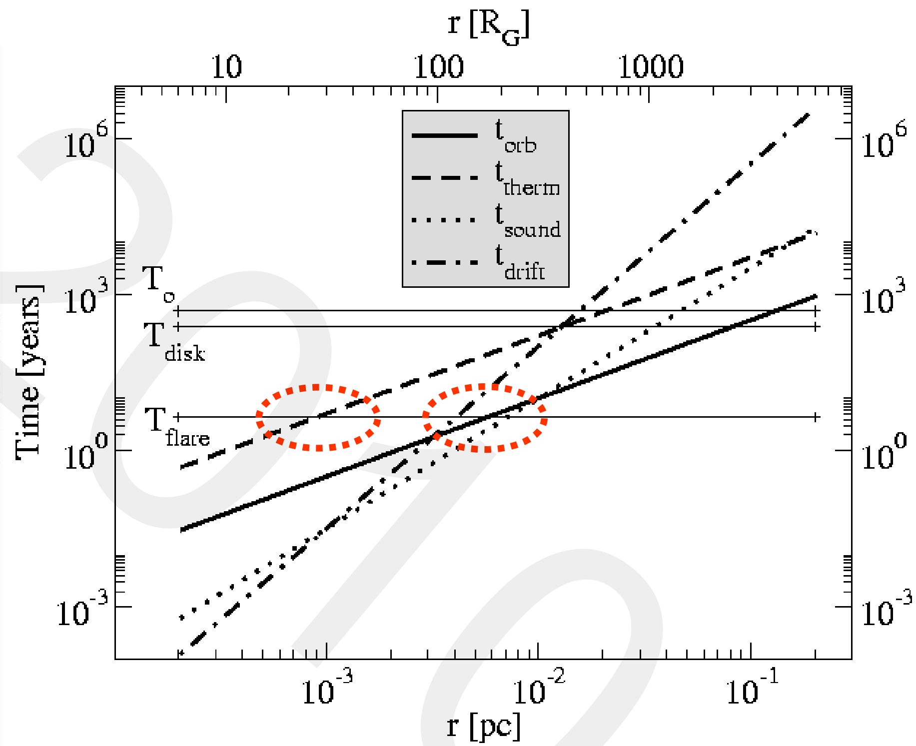


Accretion Disk in NGC 4261

Jet-Disk Connection

- Flares and ejections of new jet components in 3C345 may be related to the characterstic instability timescales in the accretion disk at 20-200 R_g





Lobanov & Roland 2005

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Is Jet Influencing BLR?

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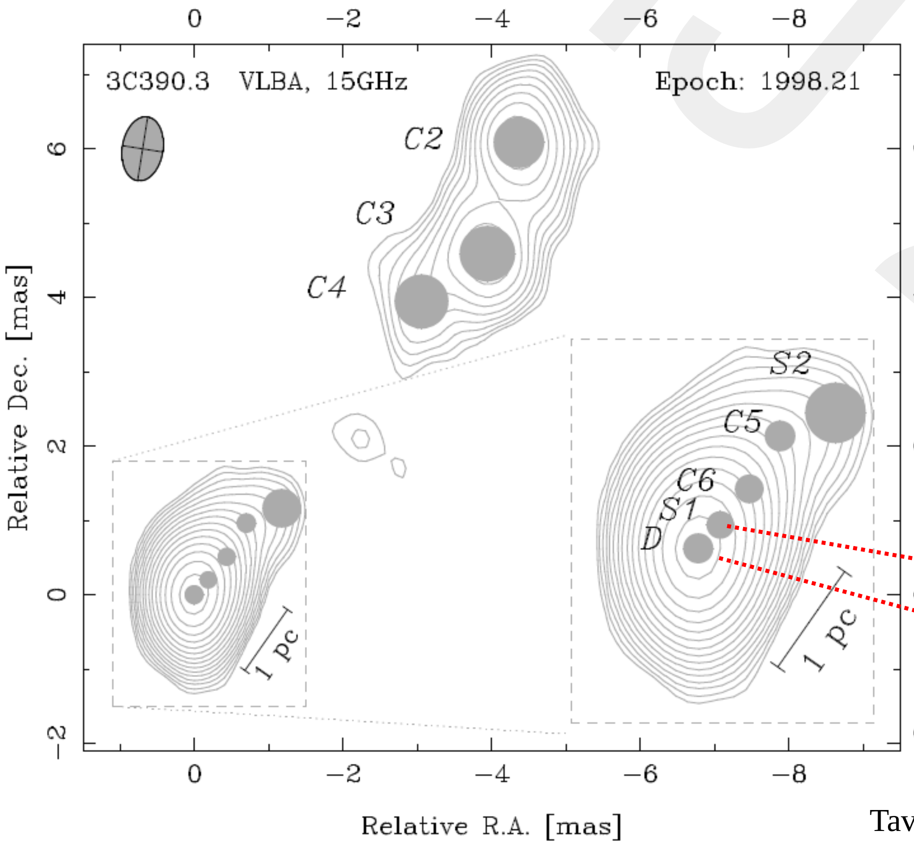
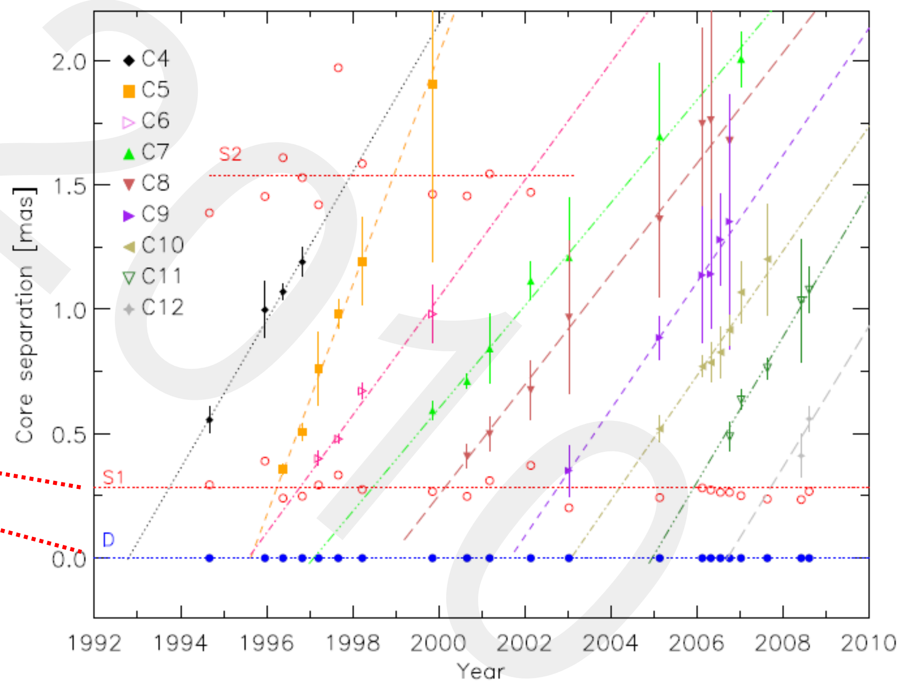
- Using VLBI observations to relate structural changes in the jet to optical variability in 3C390.3
- Linear fits to component separations yield epochs of ejection from the central engine D and passages through the stationary region S1





Tavares 2009, Arshakian et al. 2010

Jet Optical Continuum

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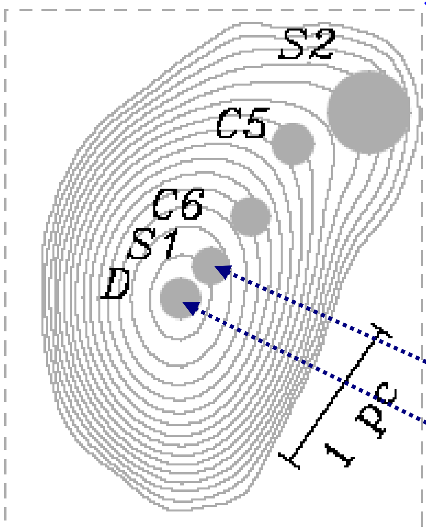
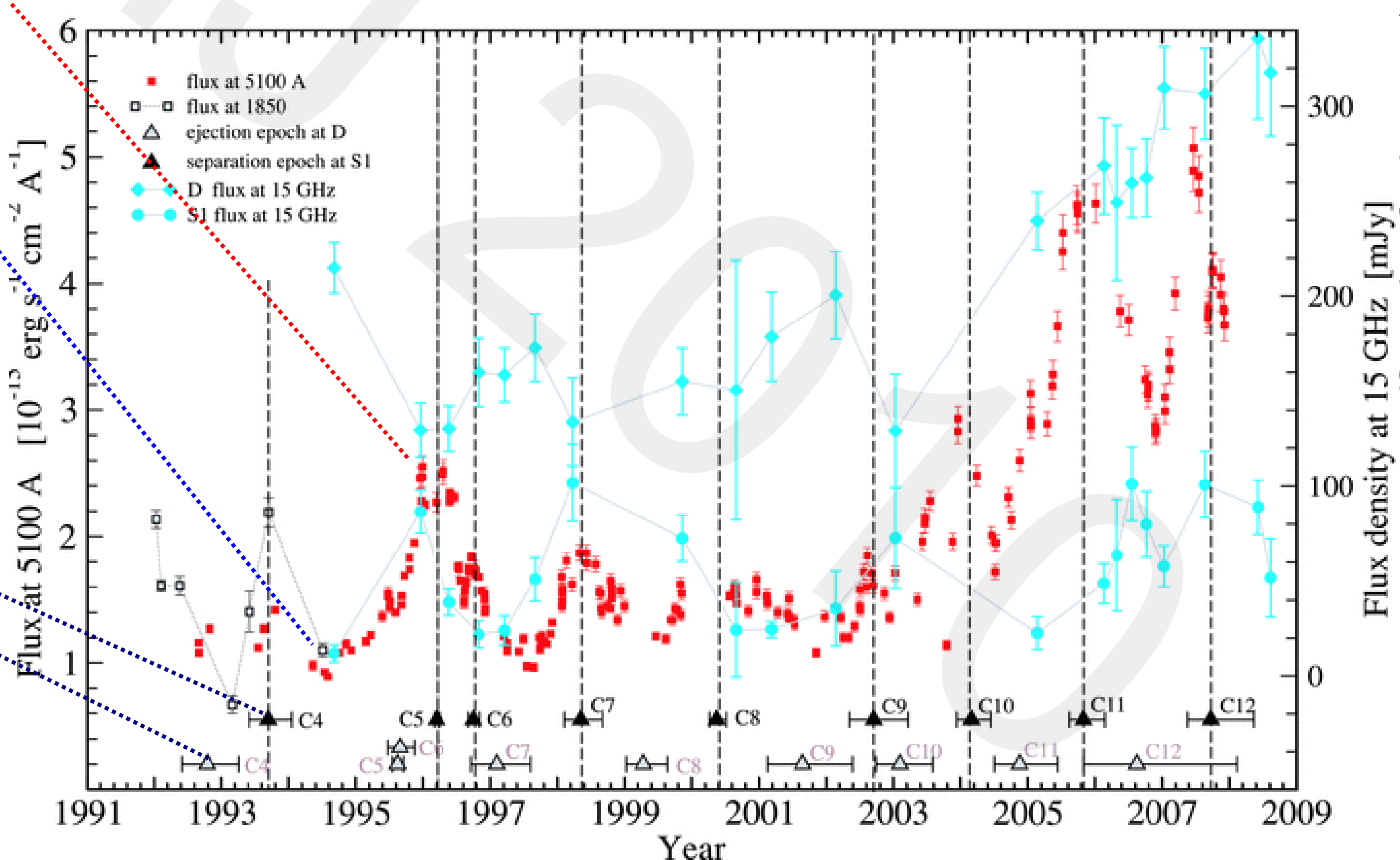
- Two different line components in broad-line emission in 3C390.3 and are driven by two different continuum radiation sources located near the accretion disk (D) and in the jet (S1). S1 is a stationary formation (possibly a recollimation shock or acceleration end zone).

$W_{H\beta}$ = 10000, 12000 km/s $\tau_{cont\text{-}line}$ = 30, 100 days M_{bh} = $4\times10^8 M_{sol}$, $2\times10^9 M_{sol}$

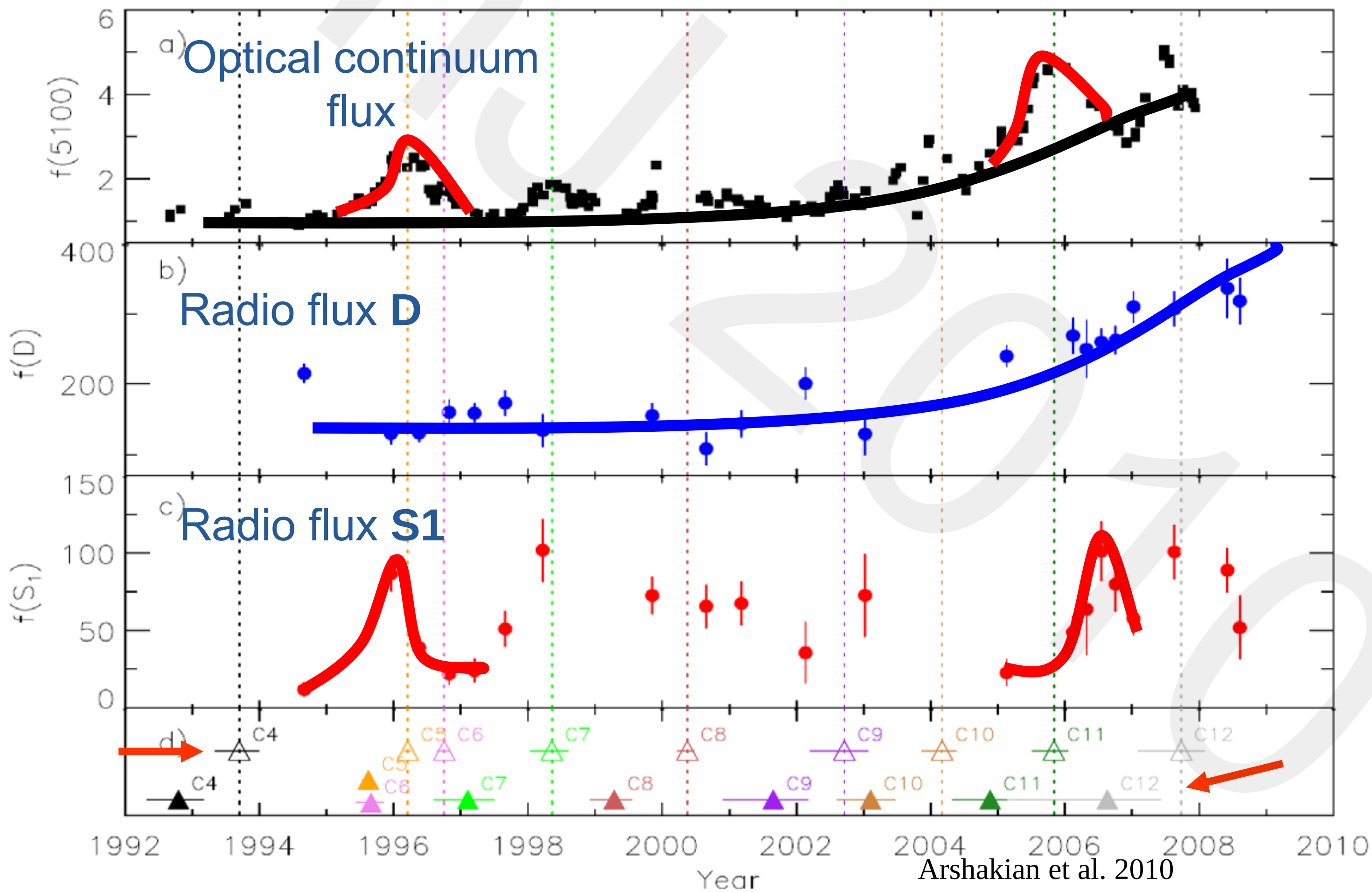


Arshakian et al. 2010



Optical and Radio Variability

- Flaring component of the optical continuum is associated with the stationary region S1 located in the jet, at a ~1.3 pc distance from the putative central engine of 3C390.3



Arshakian et al. 2010

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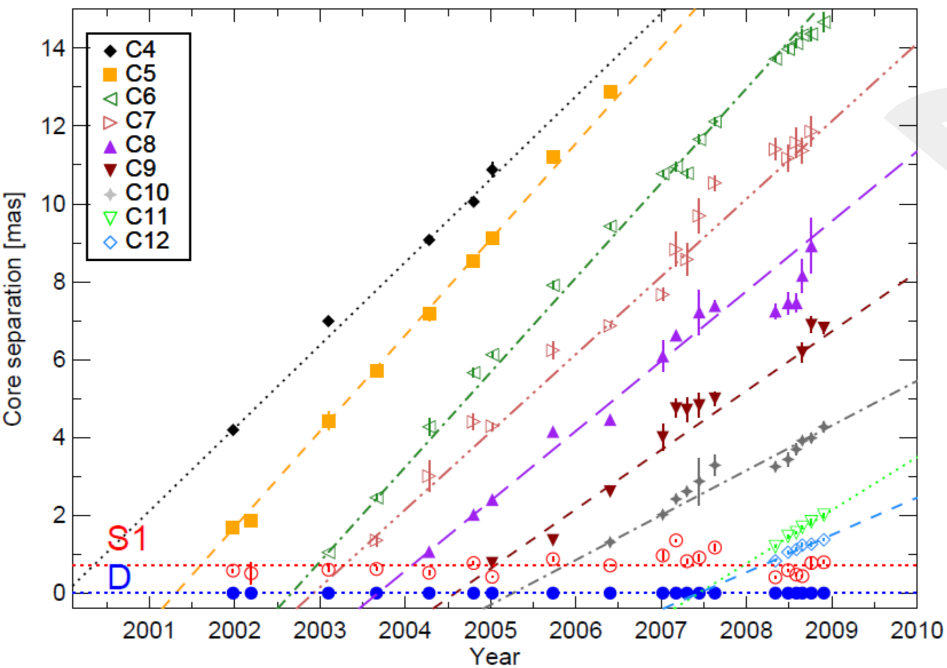
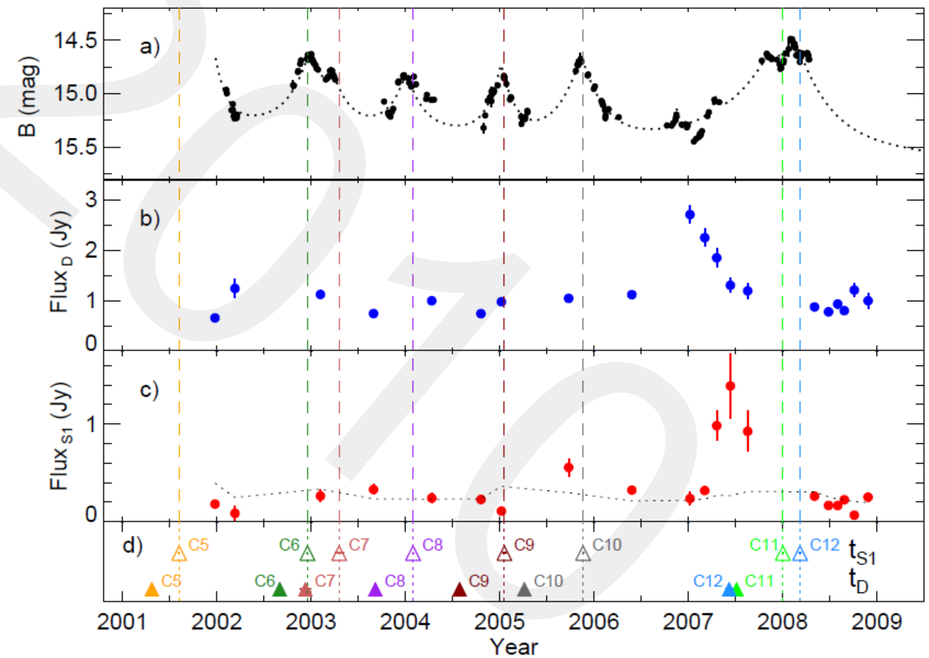
The Case of 3C120

- 3C120: The same relation between optical flares and passages of jet components through a stationary region located at about 1 pc from the jet origin.
- VLBI data are too sparse to make any conclusions about variability of radio emission. However, apparently an „orphan“ radio flare is detected in 2007 that is not immediately visible in the optical light curve.

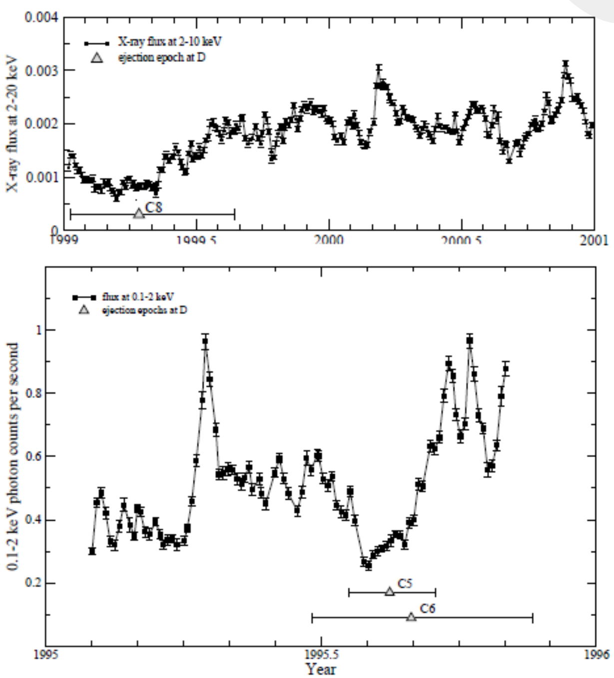




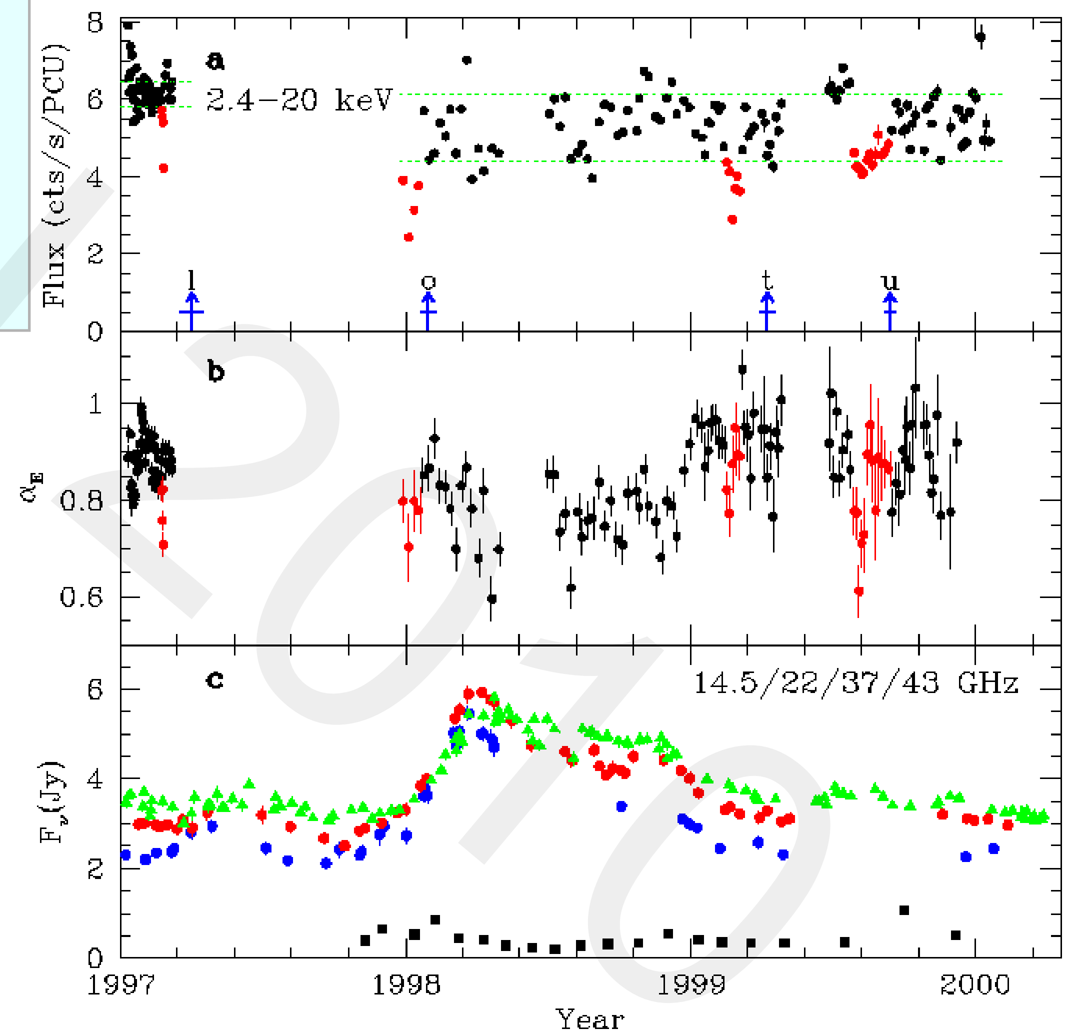
Tavares et al. 2010

X-ray Continuum

- ❑ Ejections of new jet features are correlated with characteristic „dips“ in the X-ray light curve – likely due to disappearance of the inner part of the accretion disk.



3C390.3: Arshakian et al. 2010



3C120: Marscher et al. 2002, Chatterjee et al. 2009

Radio/Optical/X-ray in 3C120

A. Lobanov

- Joint modelling of radio, optical, and X-ray data in 3C120: radio flares and X-ray dips seem to originate near the accretion disk; optical flares are related to the region S1 located about 1 pc downstream.

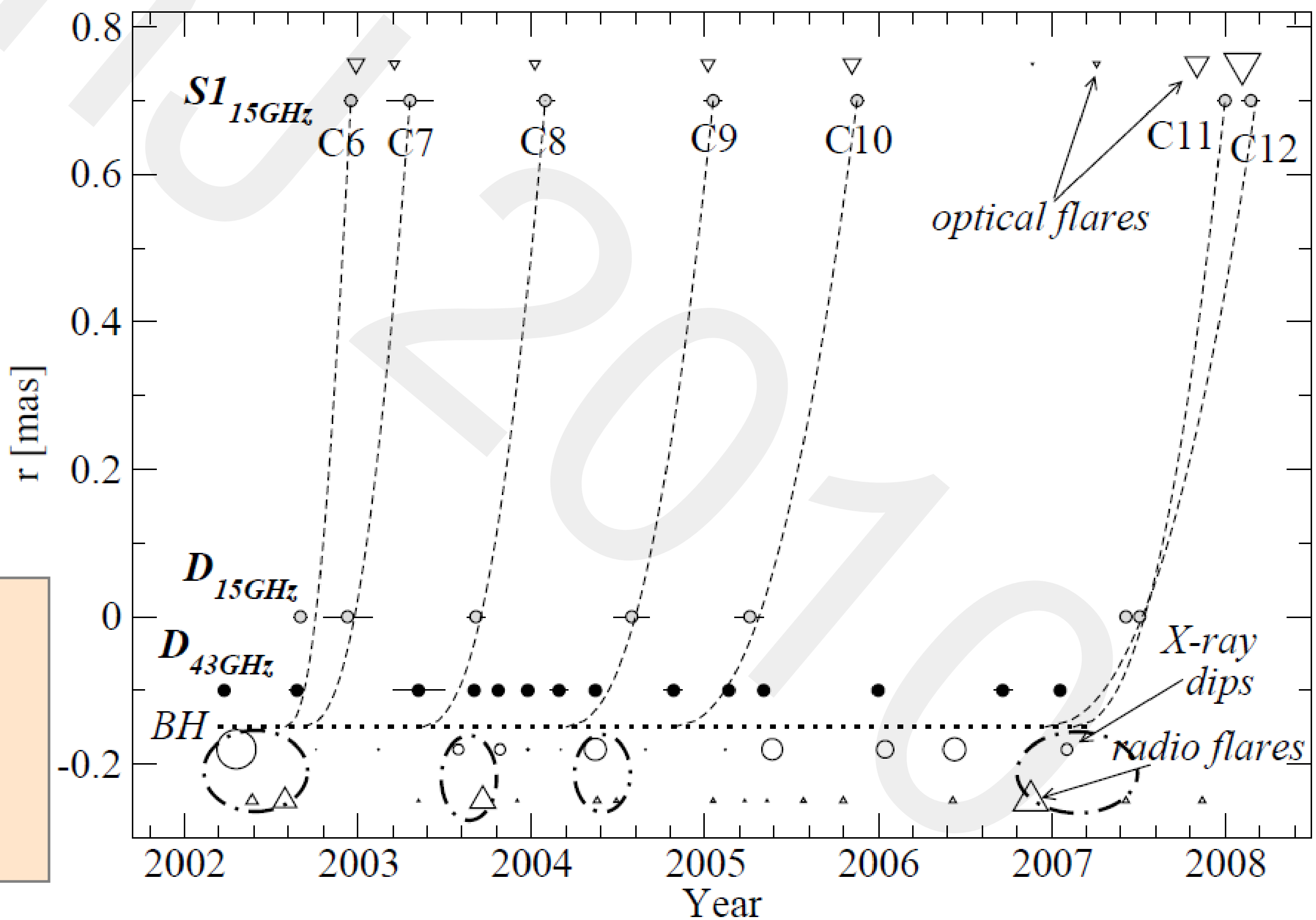
Chatterjee et al. 2009:
X-ray, 43 GHz VLBI, and 37 GHz total flux density data

Tavares et al. 2010:
Optical and 15 GHz VLBI data

Jet acceleration modelling following the MHD acceleration model of Vlahakis & Königl 2003

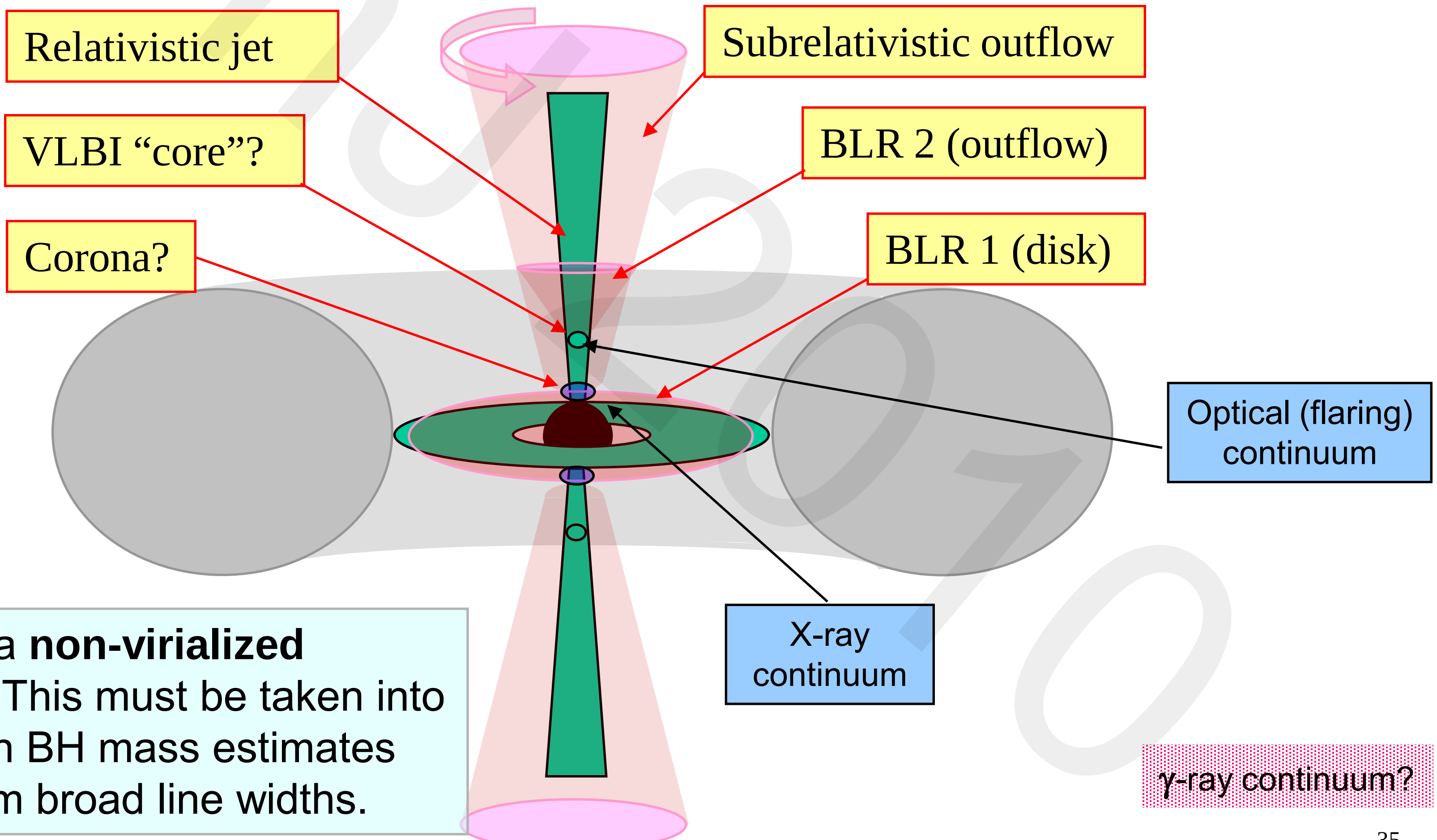
Nuclear opacity and absolute geometry of the jet is determined from the core shift, according to Lobanov 1998.

Instantaneous SEDs are likely to result from several physically different plasma components!



Radio-loud AGN

- In radio-loud AGN, relativistic jets may power a BLR associated with a subrelativistic outflow from the nucleus.



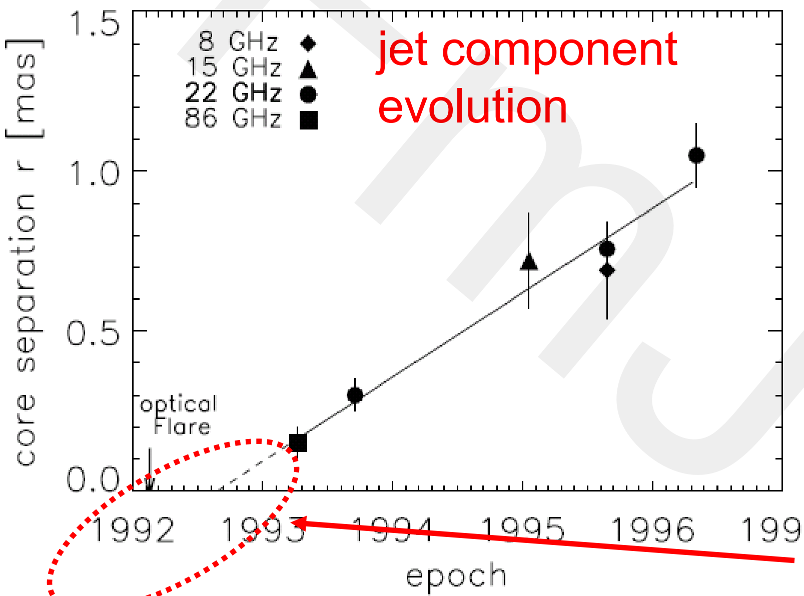
BLR 2 is a **non-virialized** complex. This must be taken into account in BH mass estimates made from broad line widths.

Max-Planck-Institut für Radioastronomie

A. Lobanov

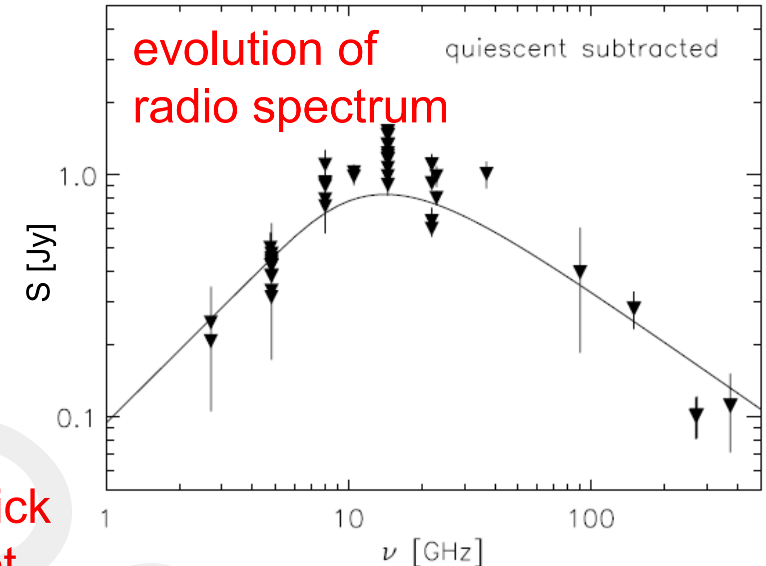
MAX-PLANCK-GESELLSCHAFT

The γ-ray Connection



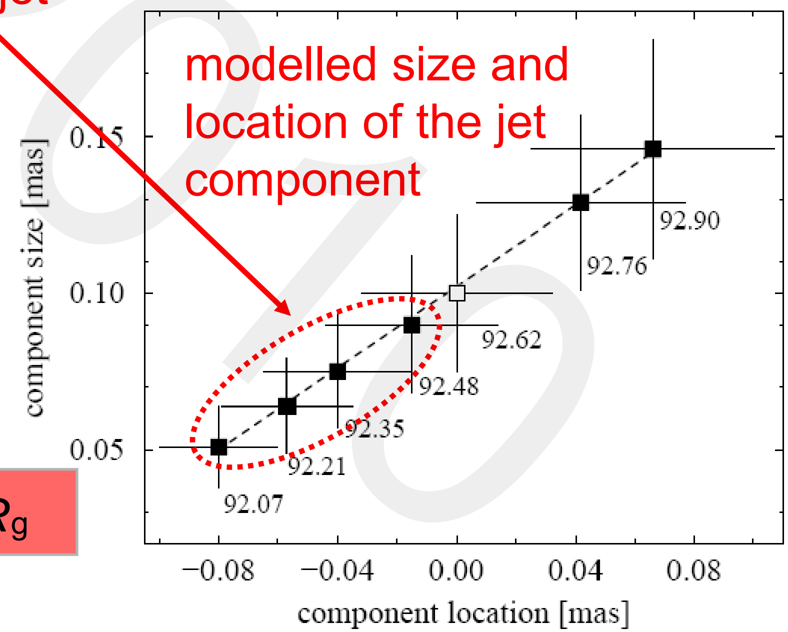
jet component evolution

+



evolution of radio spectrum

optically thick region of jet



modelled size and location of the jet component

Lorentz factor, $\Gamma_j = 11.8$
Viewing angle, $\theta_j = 3.2$ deg
Doppler factor, $\delta_j = 16.4$
Opening angle, $\phi_j = 2.1$ deg
Magnetic field, $B_{core} = 0.2$ G

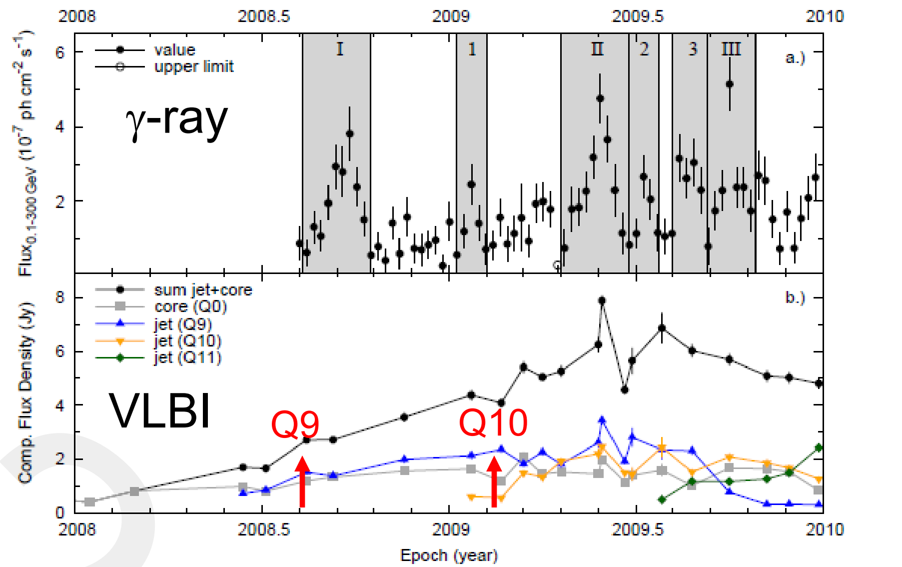
γ-ray flare occurred in the VLBI core, at ~10^3 R_g

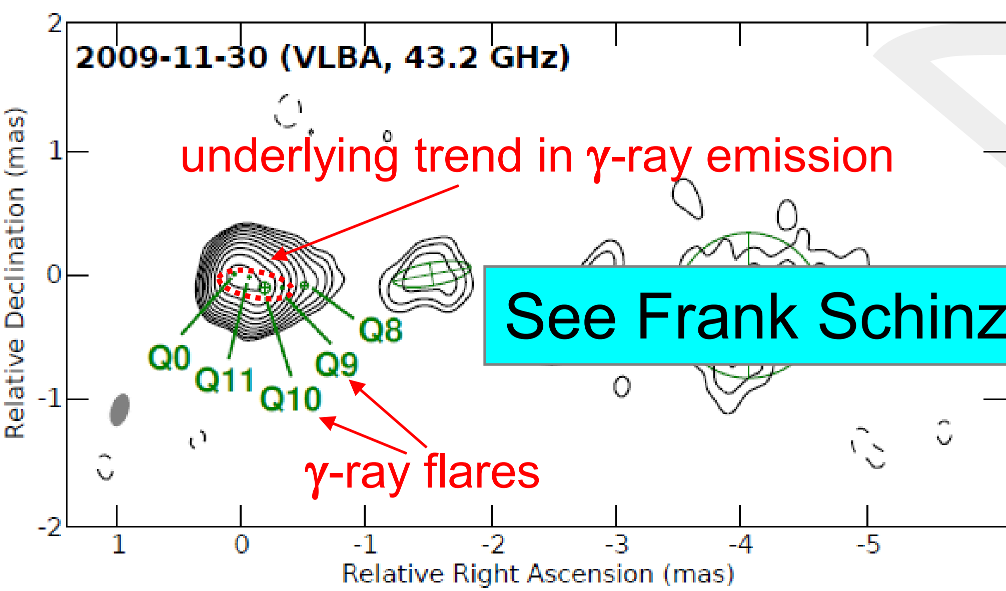
Otterbein et al. 1998

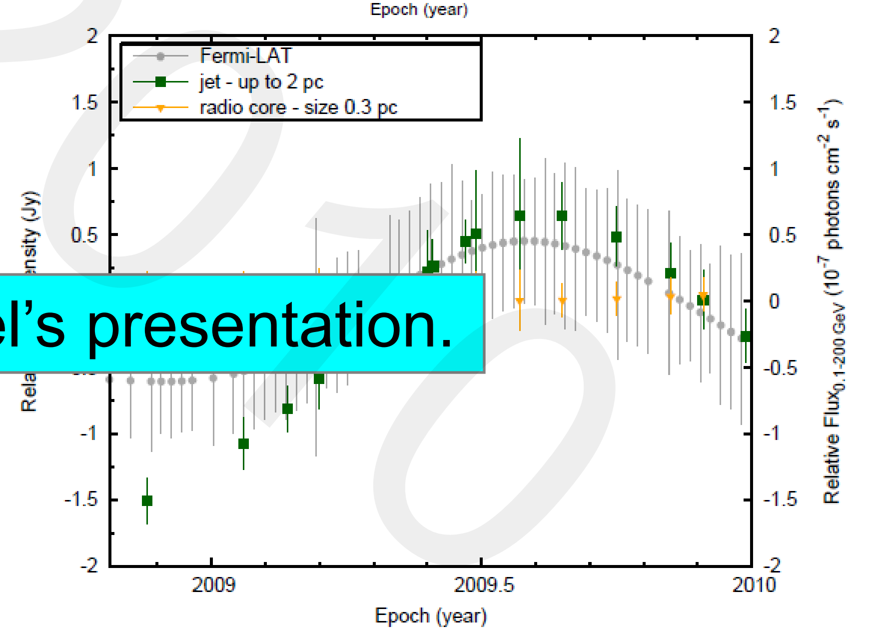
A. Lobanov

Jet γ-ray Continuum

- The γ-ray emission in 3C345 is generated in a region of the jet of about 10 pc in extent, with individual flares likely associated with shocks moving through this region of the jet. The moving features also show a strong acceleration over this region.







See Frank Schinzel's presentation.

Summary

- Radio observations of jets in AGN jets probe physics and evolution of radio emission on scales of 10^2–10^9 R_g.
- AGN jets can be divided into three qualitatively different regions:
  – collimation (~10^3 R_g) and acceleration region (up to 10^6 R_g; with likely release of strong, broad-band non-thermal continuum);
  – shock dominated region (up to 10^7 R_g, with fast shocks pervading slower underlying flow);
  – instability dominated region (up to 10^9 R_g, with Kelvin-Helmholtz instabilties shaping up the morphology and dynamics of the flow).
- Jets are major contributors to non-thermal continuum, and this contribution is not localised in a single region.
- VLBI offers an effective tool for accurate spatial localisation of sites of non-thermal continuum production, which is indispensable for modelling physical properties of blazars.