Longitudinal and transverse velocity fields in parsec-scale jets

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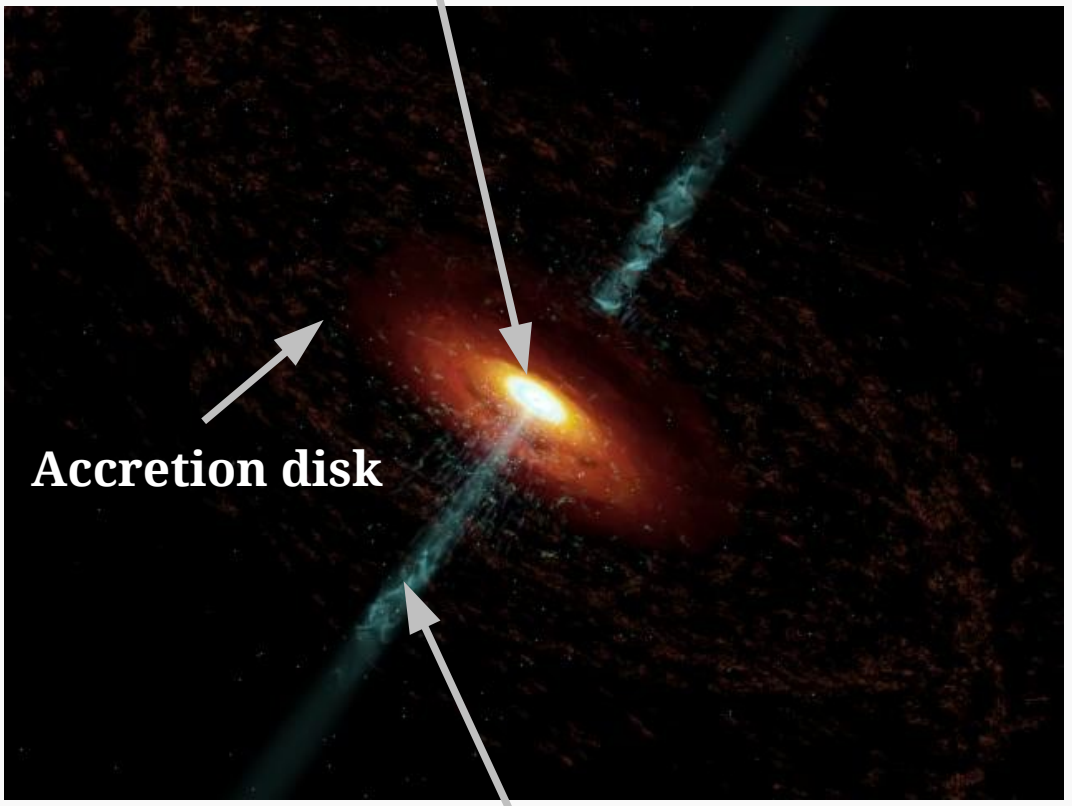
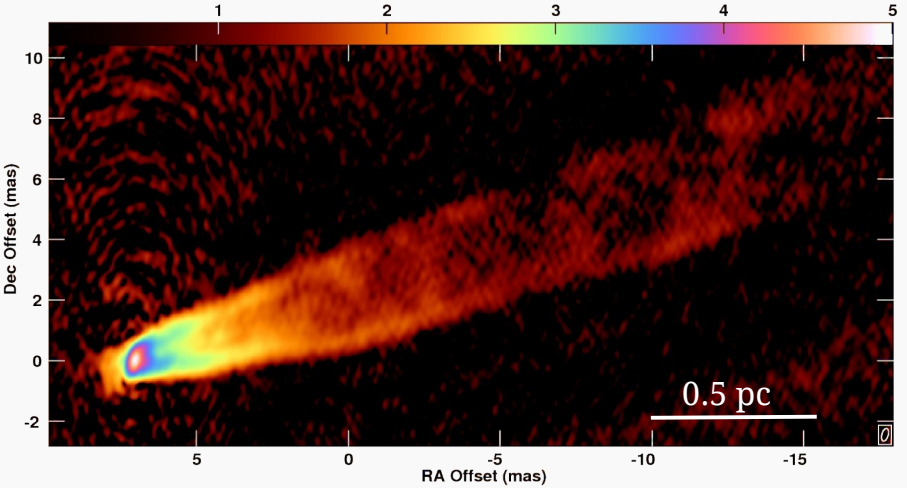
Max-Planck-Institut
für
Radioastronomie

Active Galactic Nuclei

Super Massive Black Hole
10^6 to 10^{10} times solar mass



HST image of M87: Biretta et al.

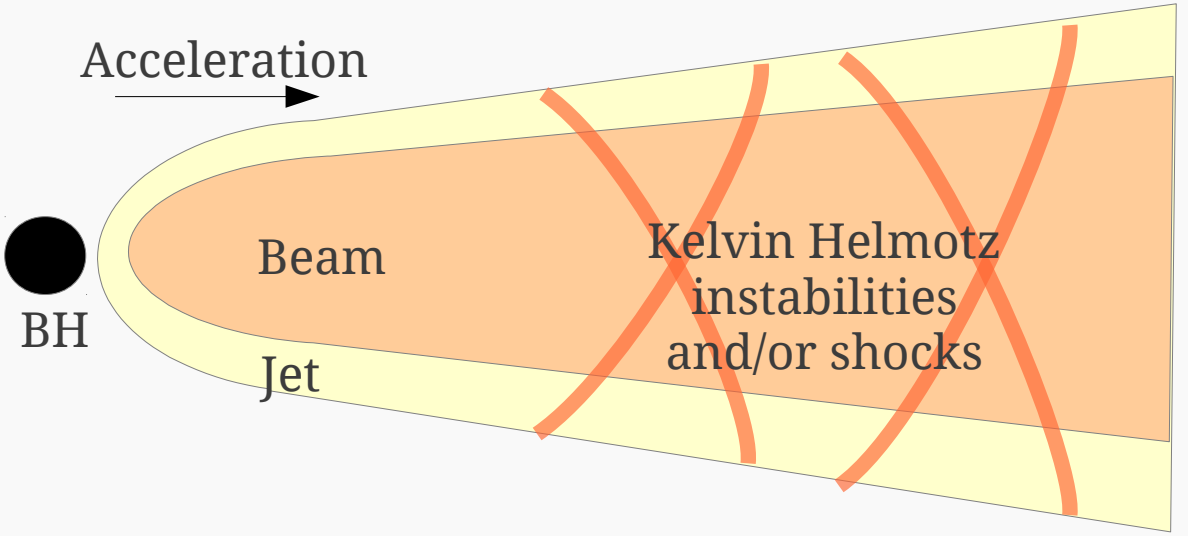


VLBA map of M87 at 43 Ghz: Walker et al.
Resolution: 0.17 mas

Jets of twin, highly collimated, and fast outflows.
Magnetic field accelerate electron and proton
Produce synchrotron radiation observable in radio

2D structure of jets

- Complex flow:
  - Relativistic
  - Stratified
  - Residual rotation
  - Instability and shocks



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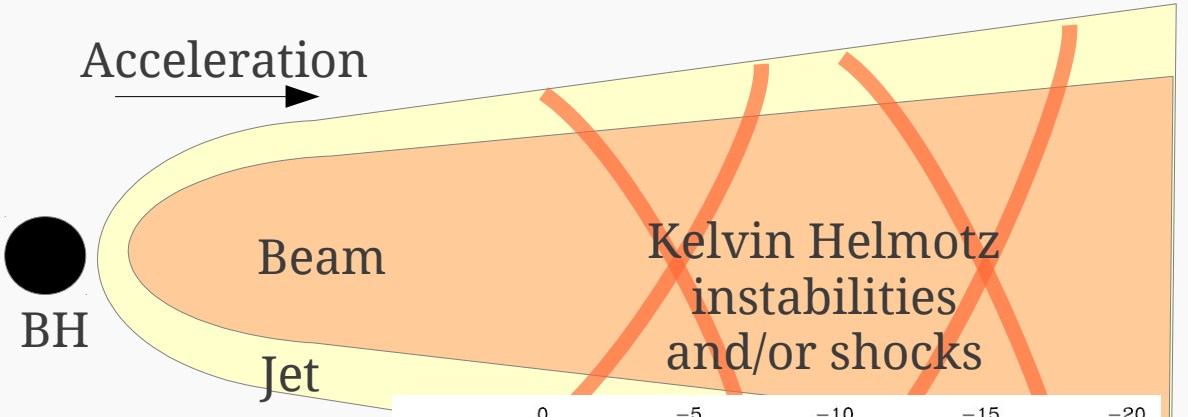
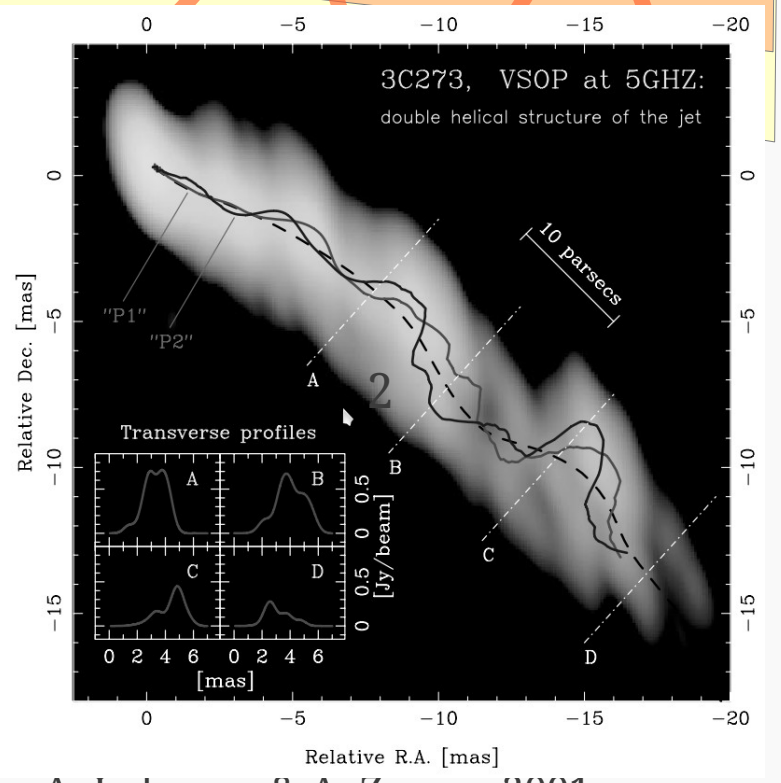
- Current method:
  - Model fitting: 1D
  - Ridge-line analysis
  - Jet transverse profiles





A. Lobanov & A. Zensus 2001

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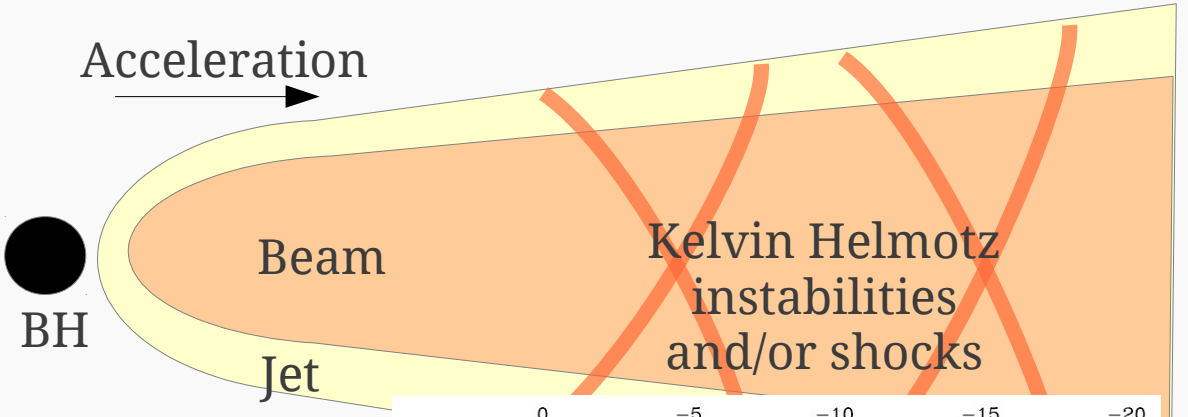
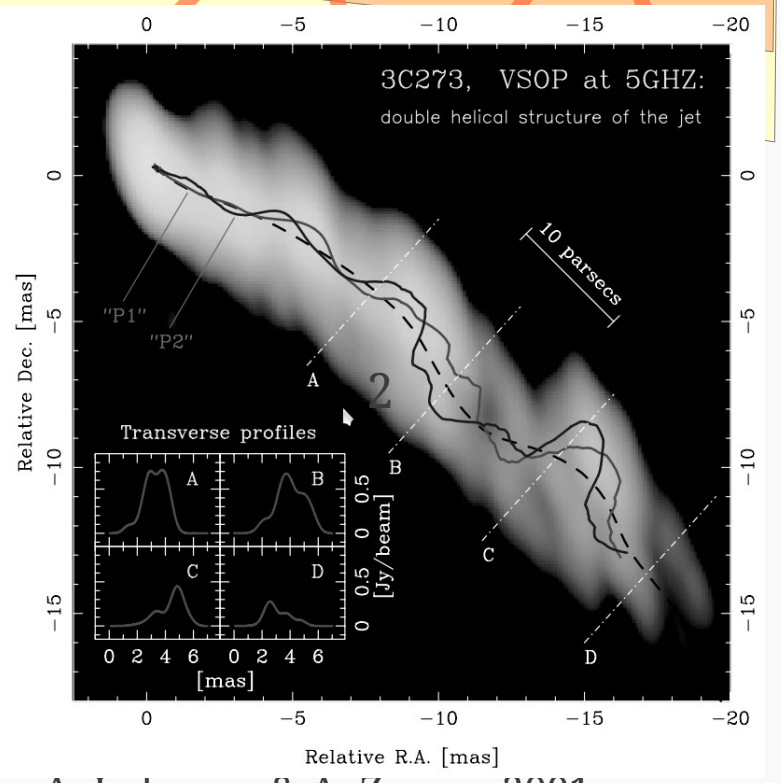




A. Lobanov & A. Zensus 2001

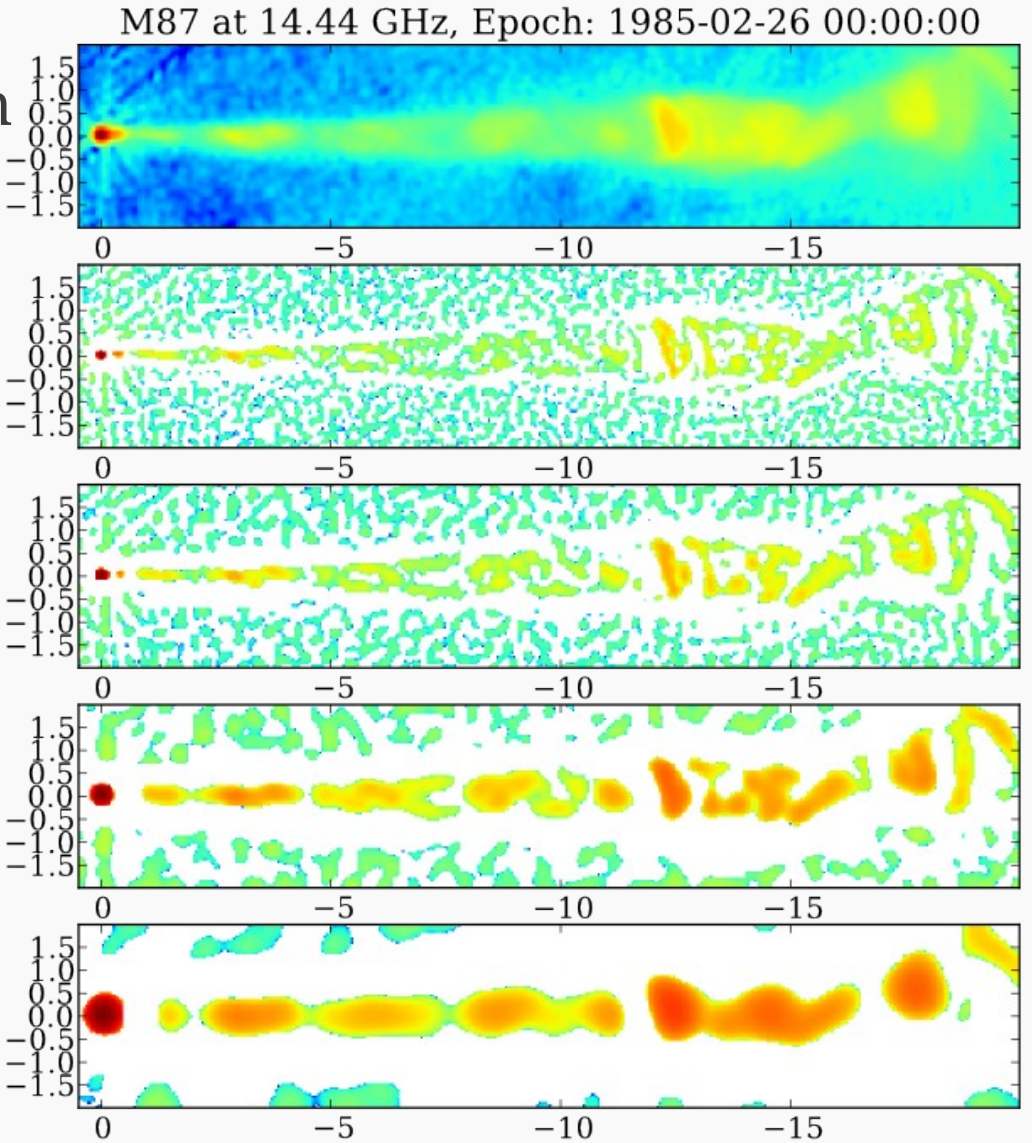
- Margin of improvement between the information from observation and output
- **We need an automatic and robust tool for feature identification**

Talk outline

- Structure analysis (WDS method):
  - **W**avelet **D**ecomposition
  - **S**egmentation
- Kinematic analysis: **M**ulti **S**cale **C**ross **C**orrelation (MSCC)
- Analysis of the velocity field of the jets of 3C273 and M87

Wavelet transform

- Time-frequency transformation
- Representation of signal as a linear combinations of a wave like function which is scaled and translated
- Provides a 2D power distribution over a range of spatial scale in the image
- **Robust tool for identification of significant structural patterns (SSP)**



VLA map: Owen et al. (1989)

Feature detection

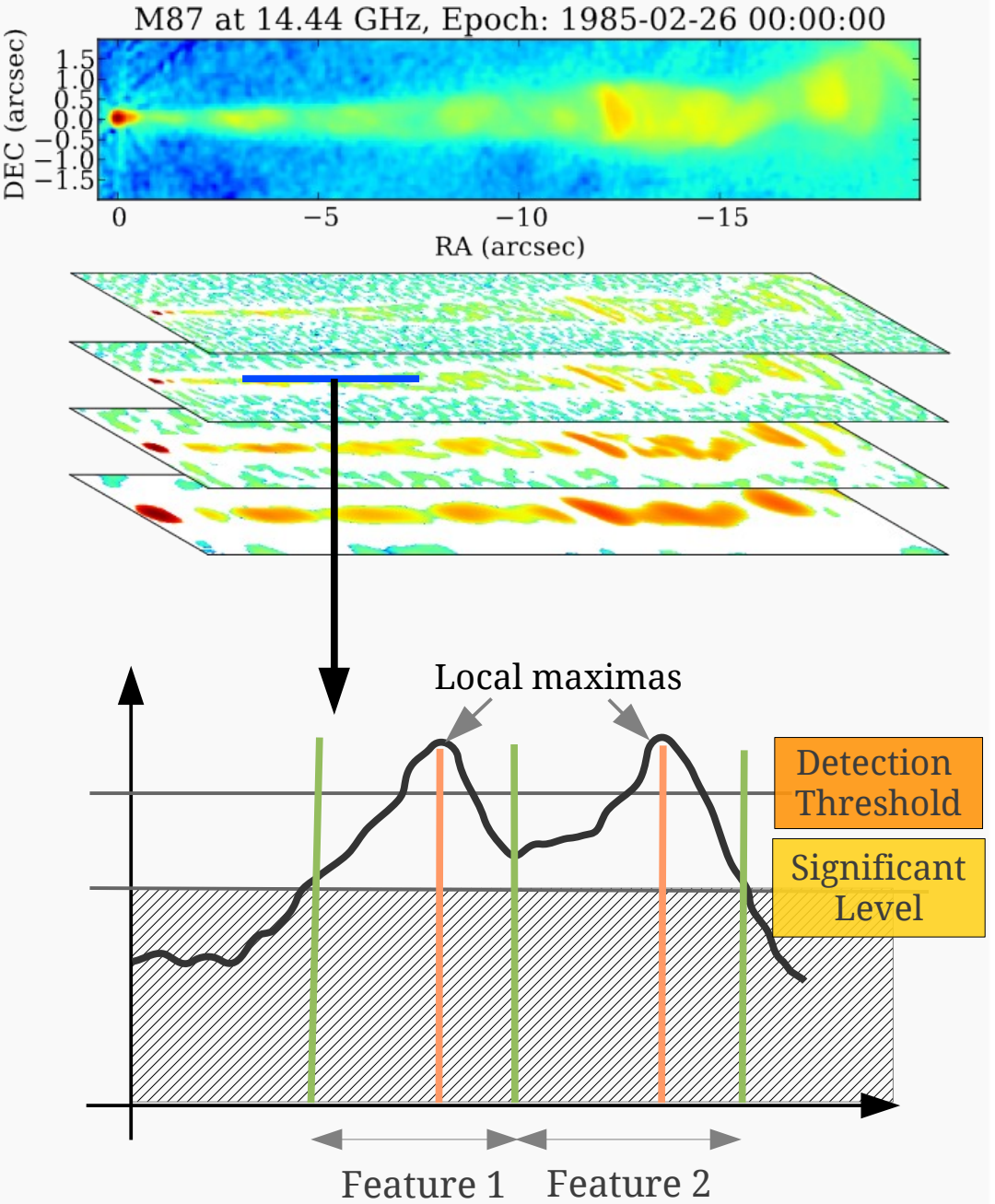
1. Wavelet decomposition

2. Thresholding: Statistically significant wavelet coefficients are extracted at each scales.

3. Detection of features: Local maxima in the wavelet space are the positions of features

4. Segmentation: Watershed segmentation is used to delimit the regions (segments) associated with those positions

This result in a set of **SSP**

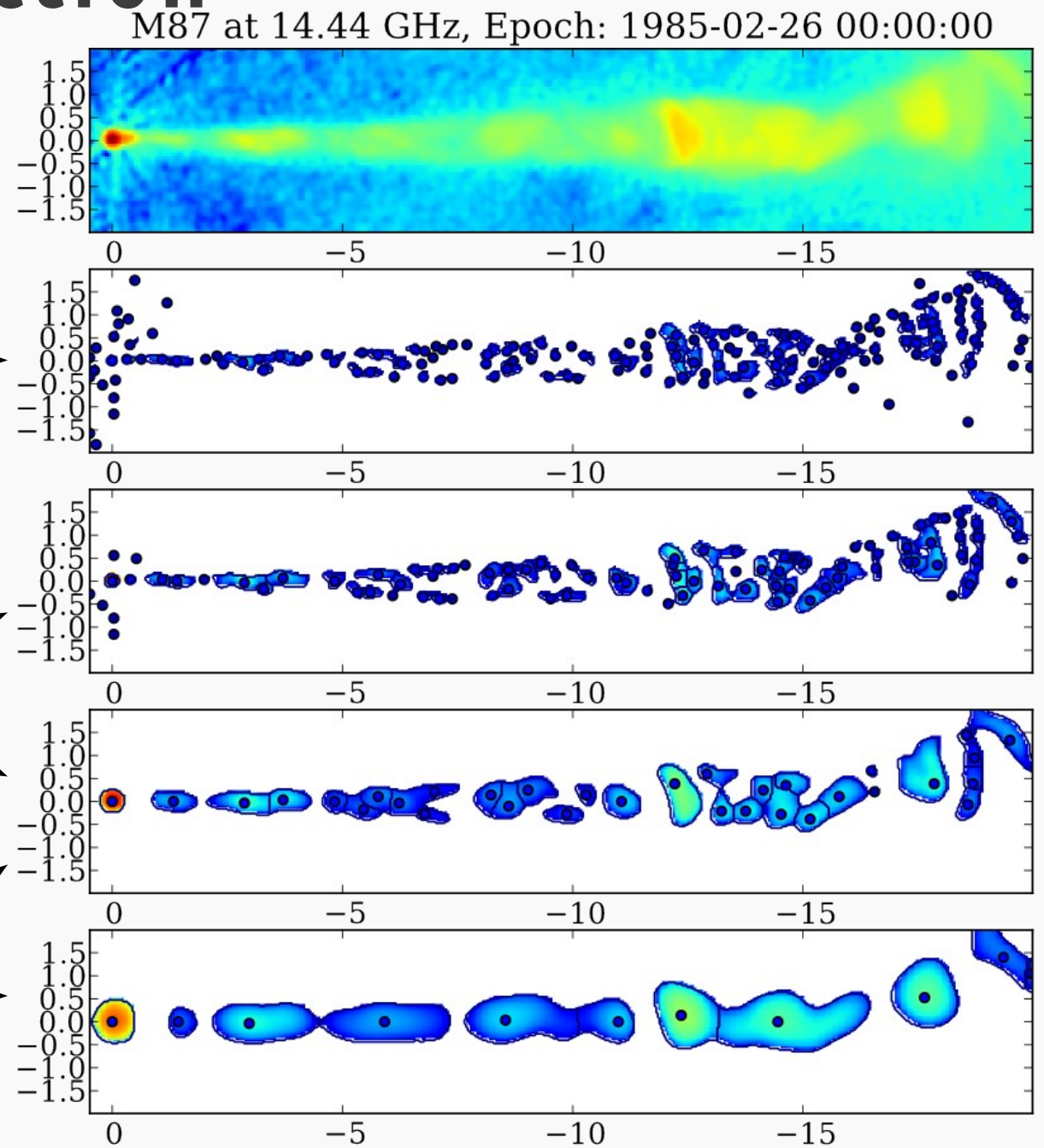


Feature detection

Finest scales:
Detailed description down to ~0.25 FWHM
Provide 2D velocity field

Intermediate scales:
Ridge-line detection

Coarse scales:
Equivalent to model-fit



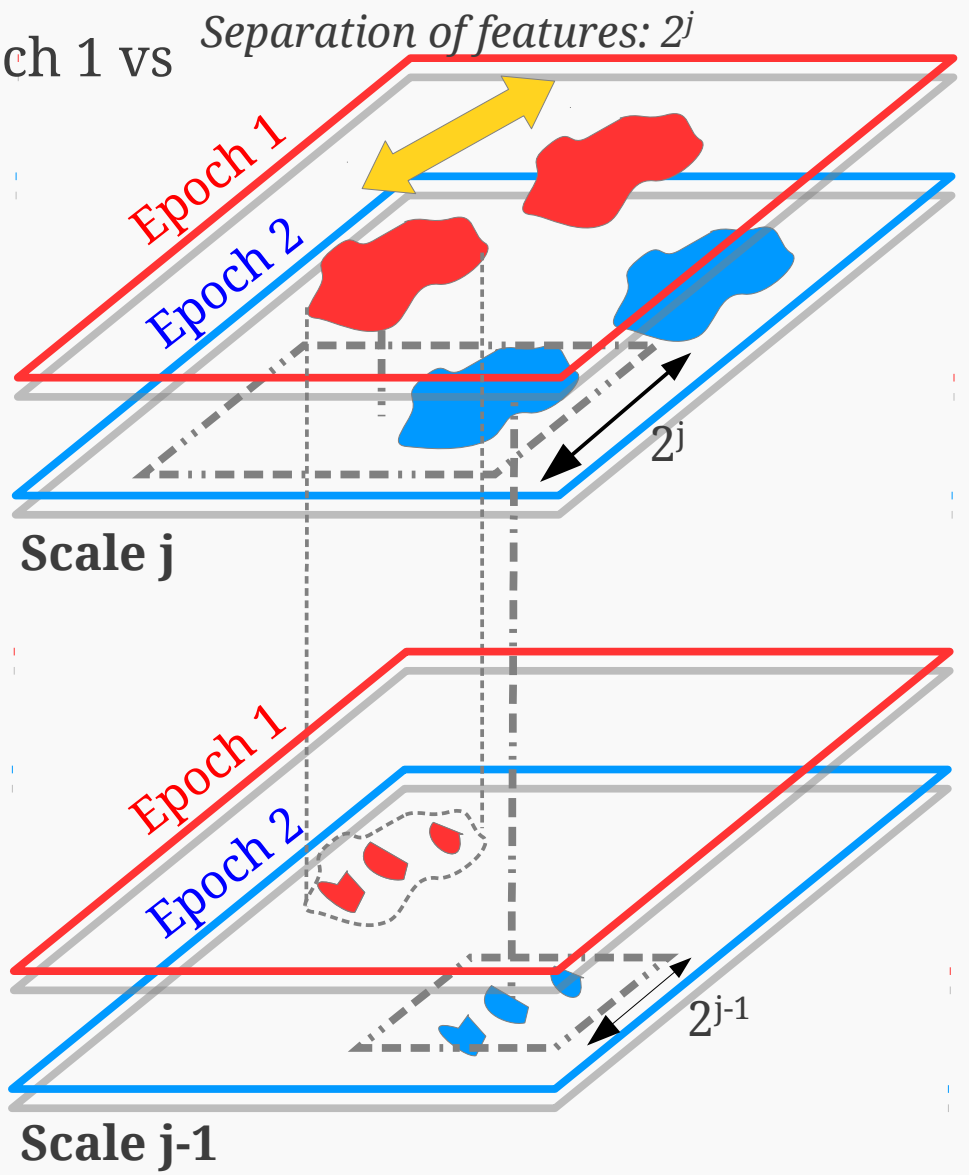
MSCC detection of structural changes

- Cross Correlation of each SSP at epoch 1 vs image at epoch 2
  → Weighted Normalized CC

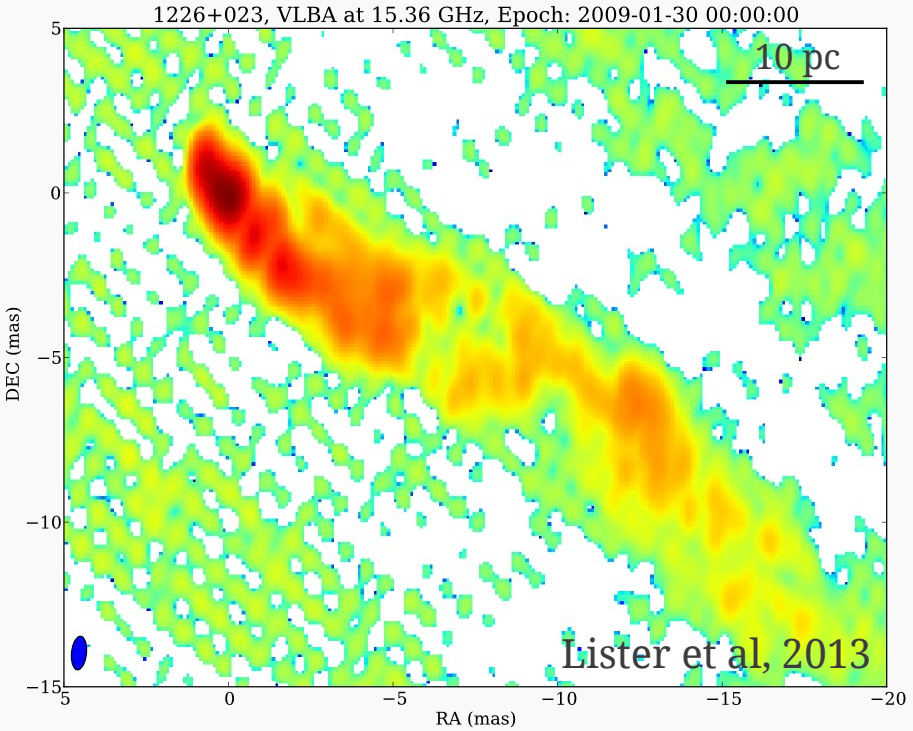
- Separation of features at scale j ~ 2^j
  → j chosen so that expected $\Delta < 2^j$
  → CC on a 2^j x 2^j window

- Features inside a same upper scale feature move in average like it:
  → Define the location of the CC window

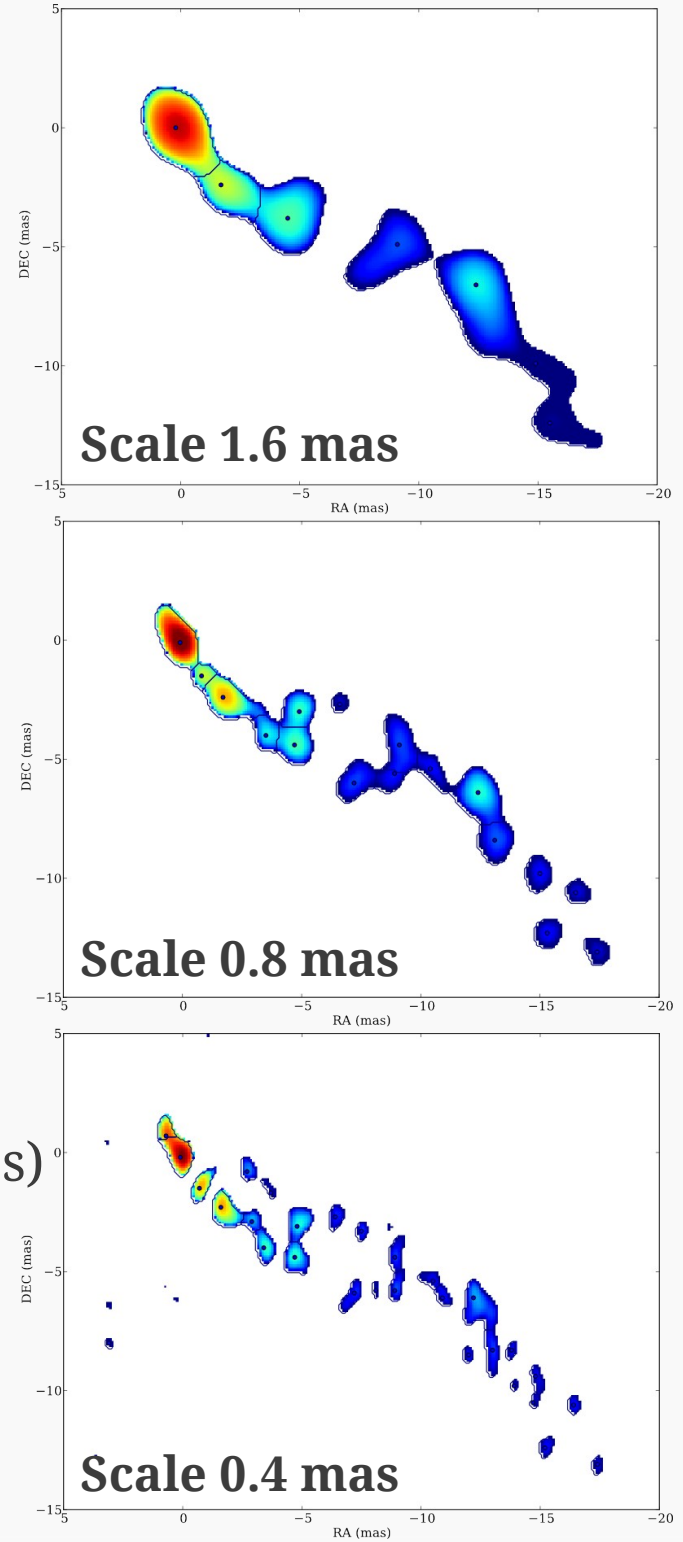
Joined analysis at all wavelet scales provide robust match of structural changes up to **~5 beam sizes**



3C273



WDS

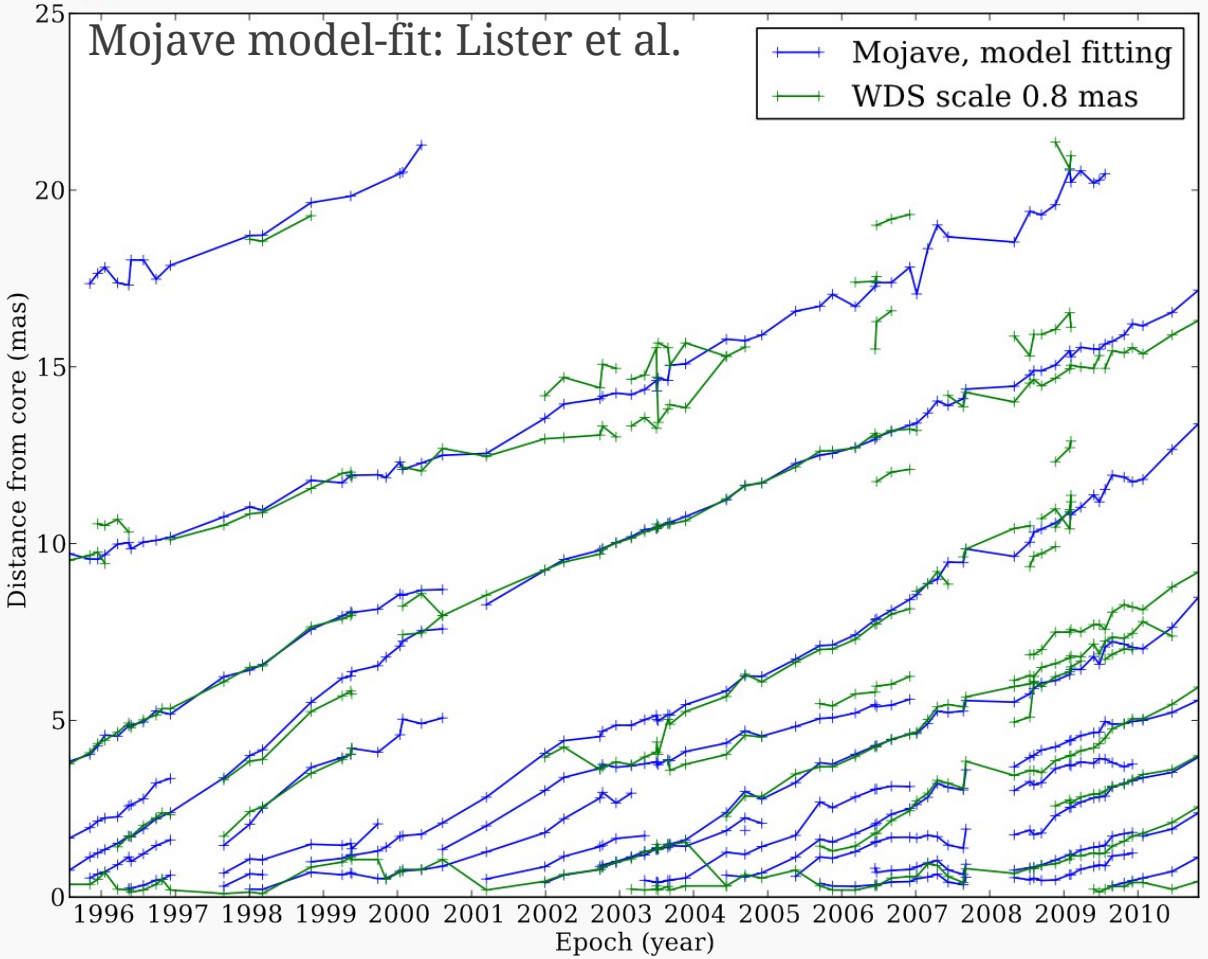


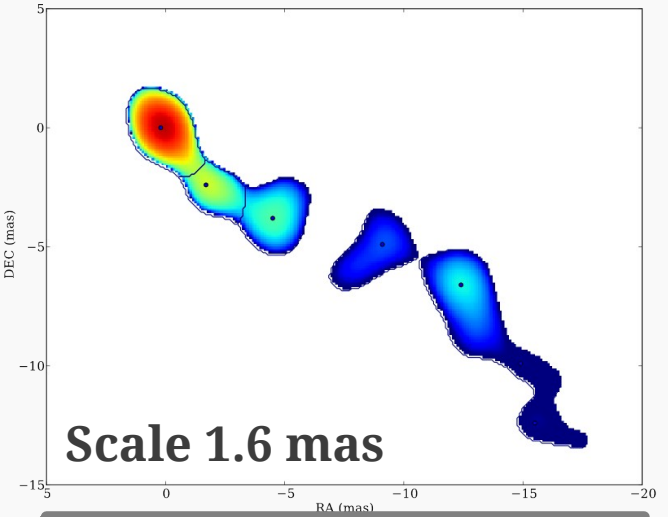
- In Virgo constellation, z ~ 0.1583
- Most luminous quasar
- Transversely resolved flow (Beam ~ 1 x 0.5 mas)
- Observed as part of the MOJAVE survey

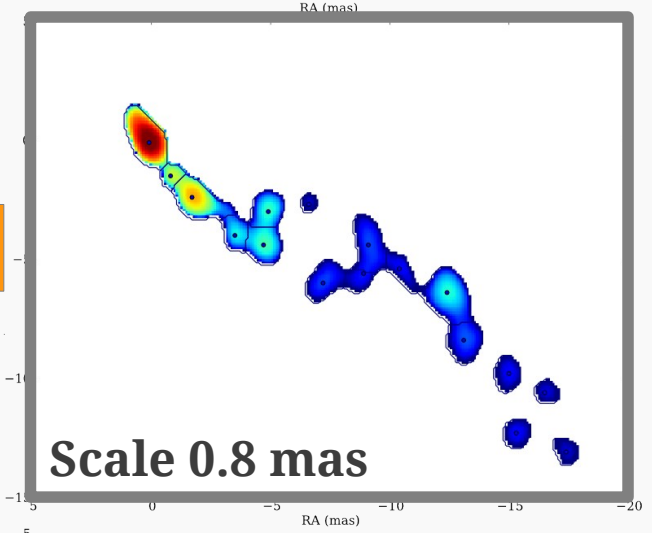
MOJAVE
The Brightest Radio Galaxies in the Northern Sky

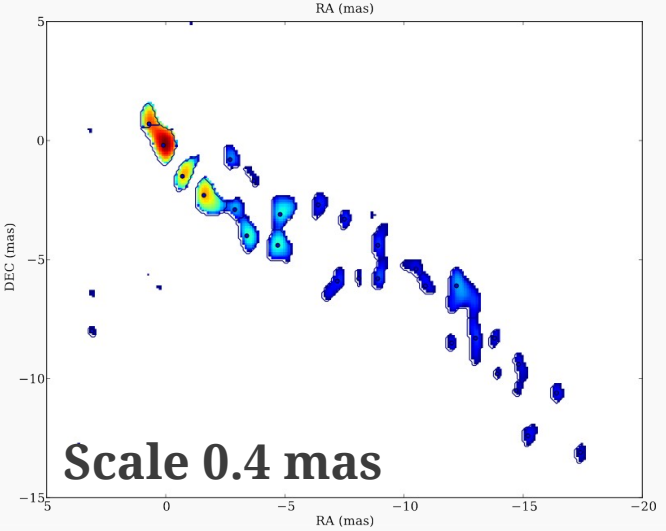
Monitoring Of Jets in Active galactic nuclei with VLBA Experiments
1.5 Jy Flux limited AGN sample in northern sky at 15 GHz, ~ 300 AGN currently monitored

3C273



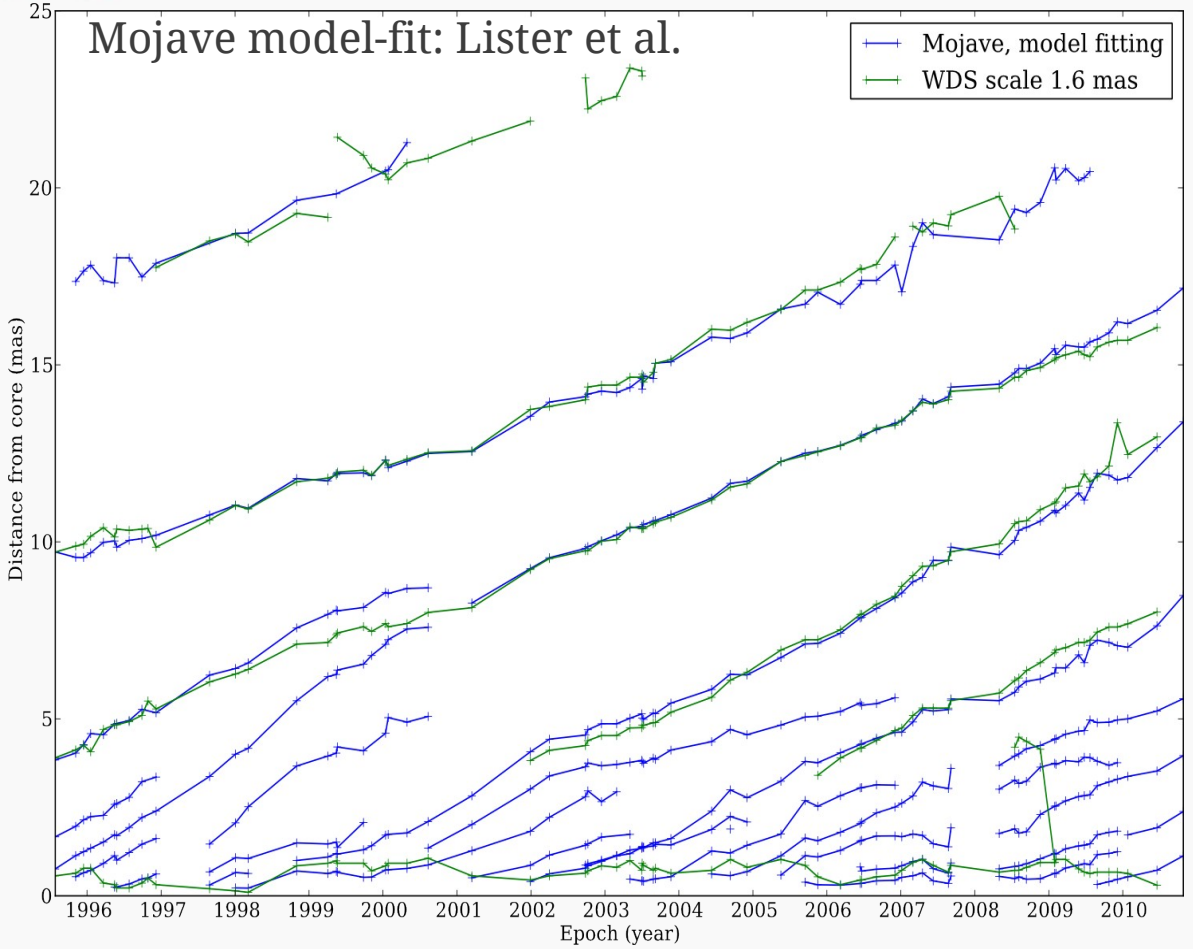


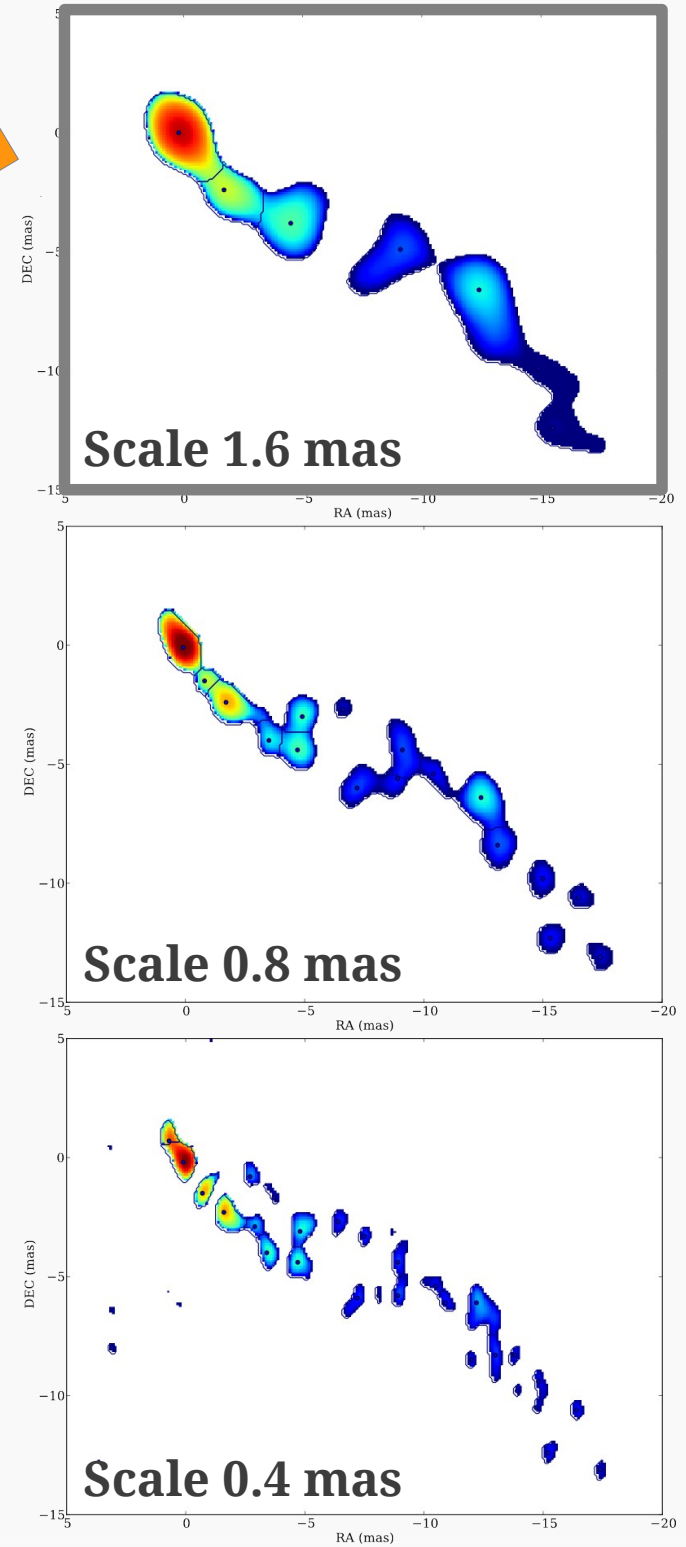




Good agreement between WDS and model-fitting

3C273





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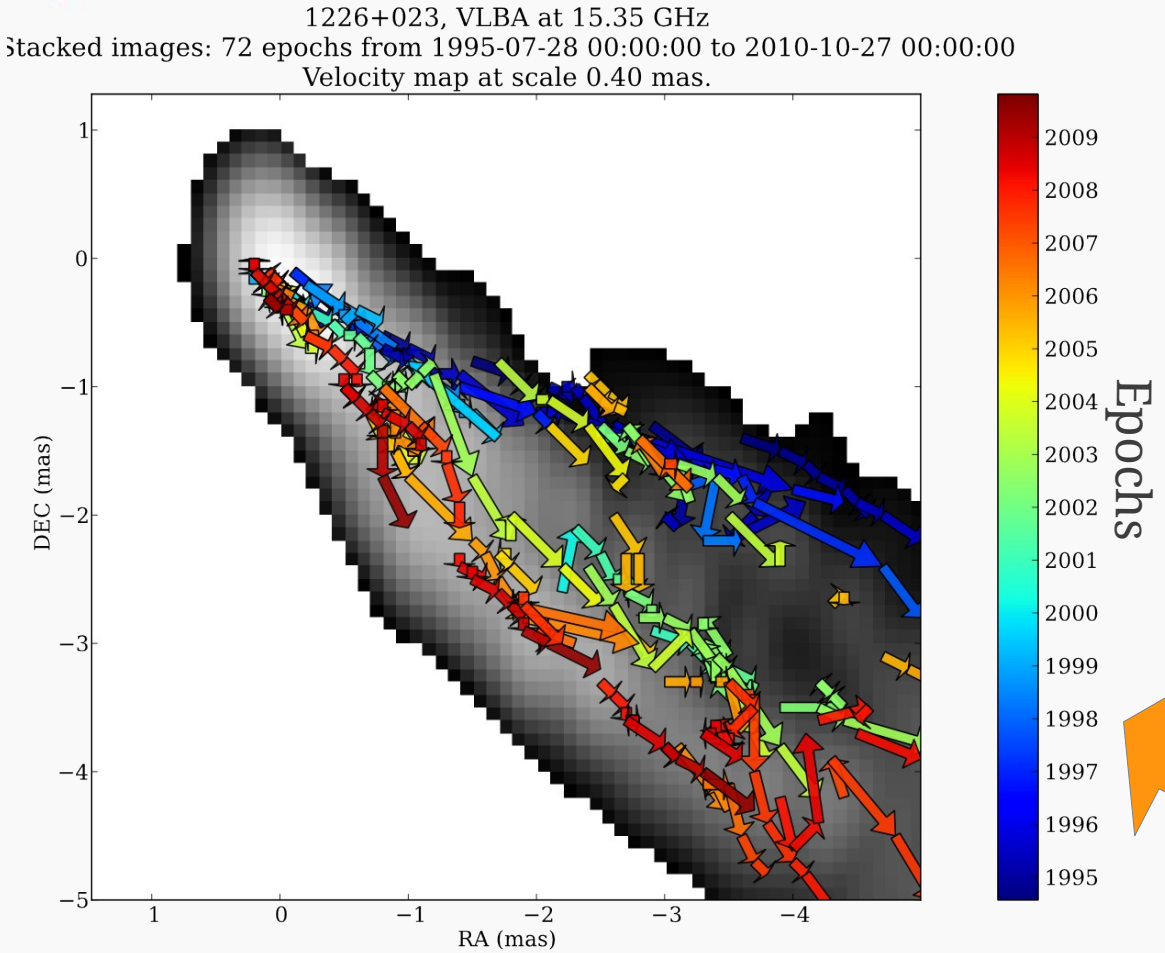
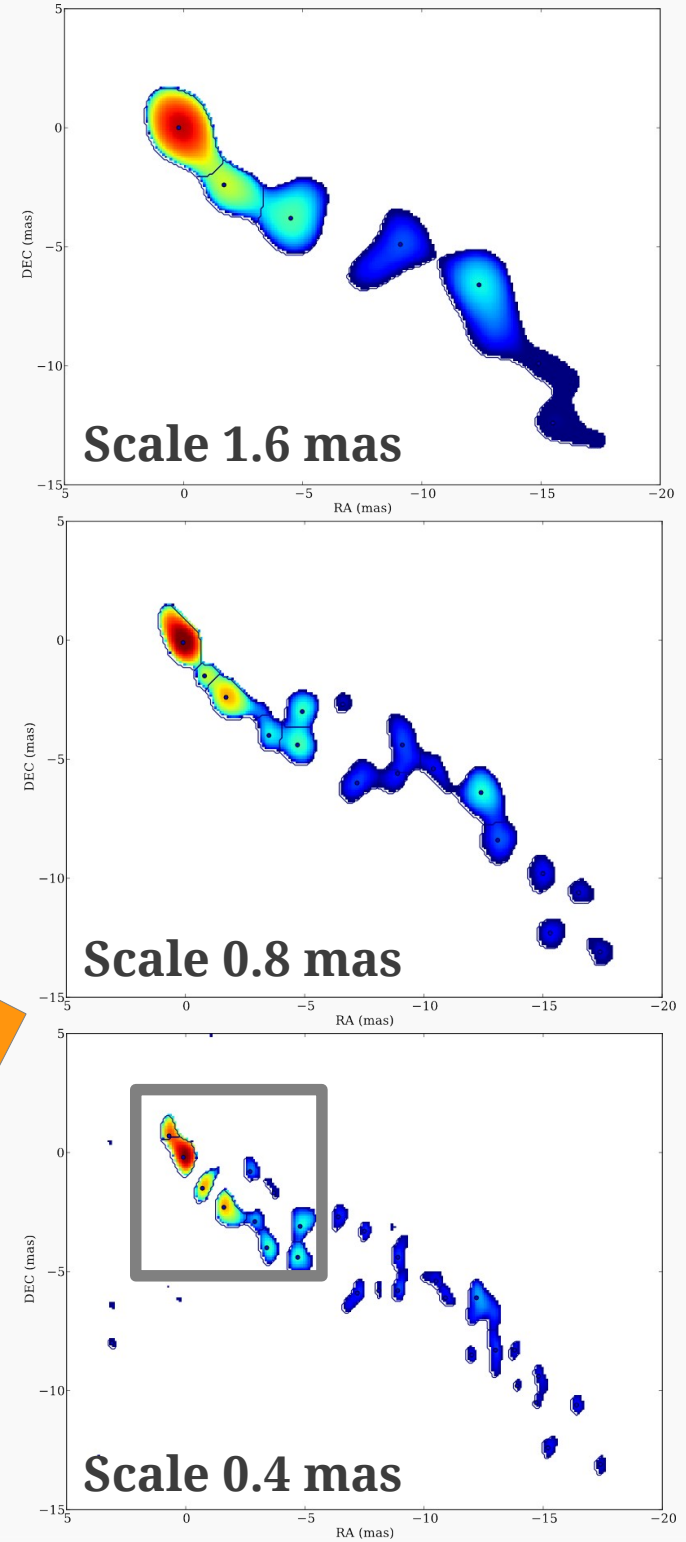


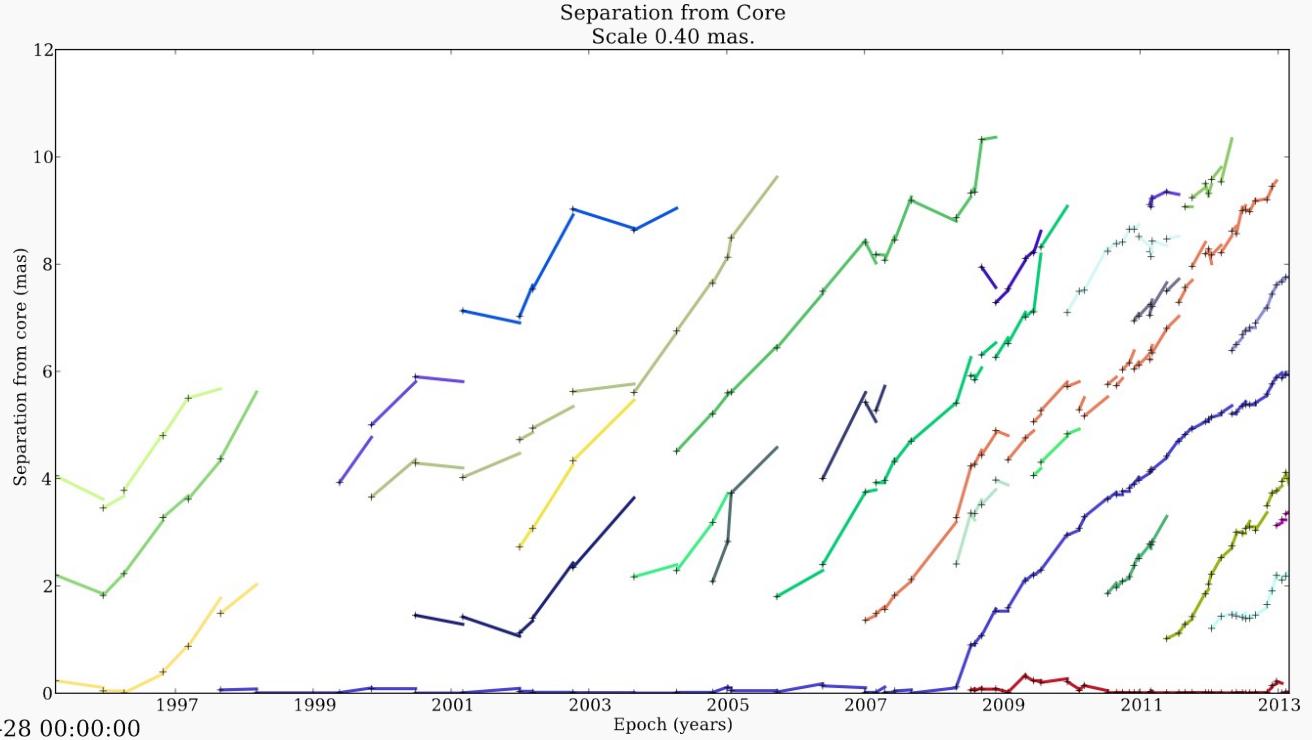


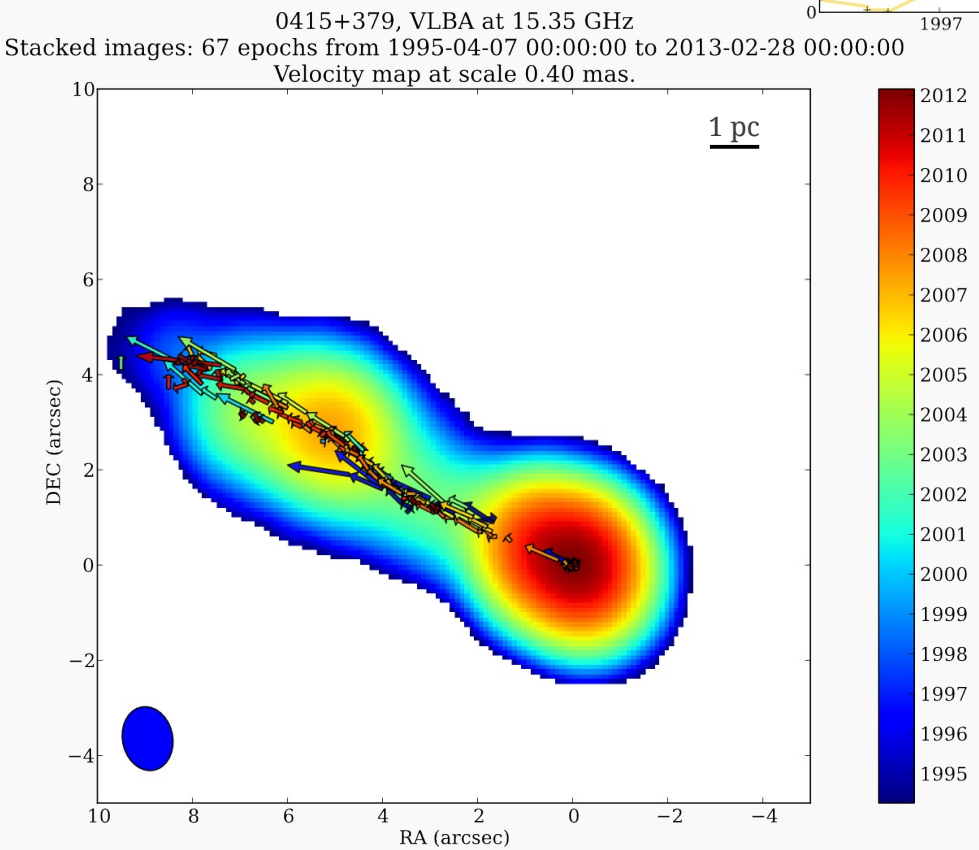
- 2D velocity field
- Helical patterns propagating in the flow
- Change of flow direction

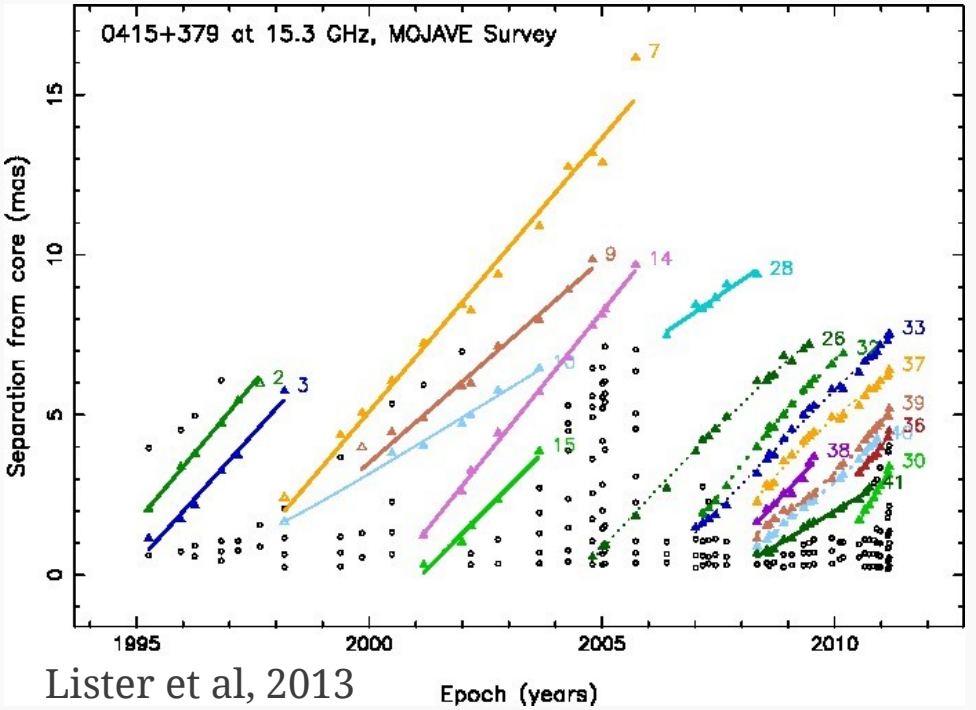
3C111

Radio Galaxy, z ~ 0.0491
Observed as part of MOJAVE

67 epochs
from 04/1995 to 02/2013





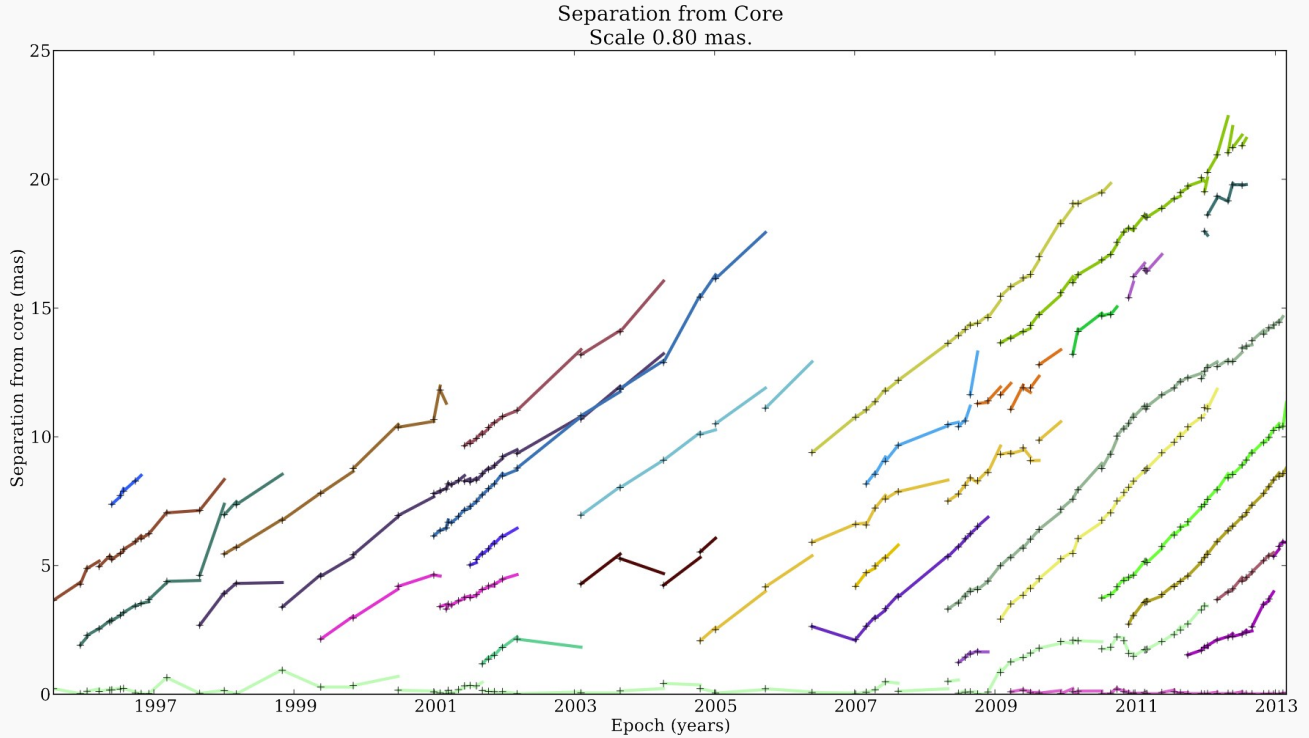


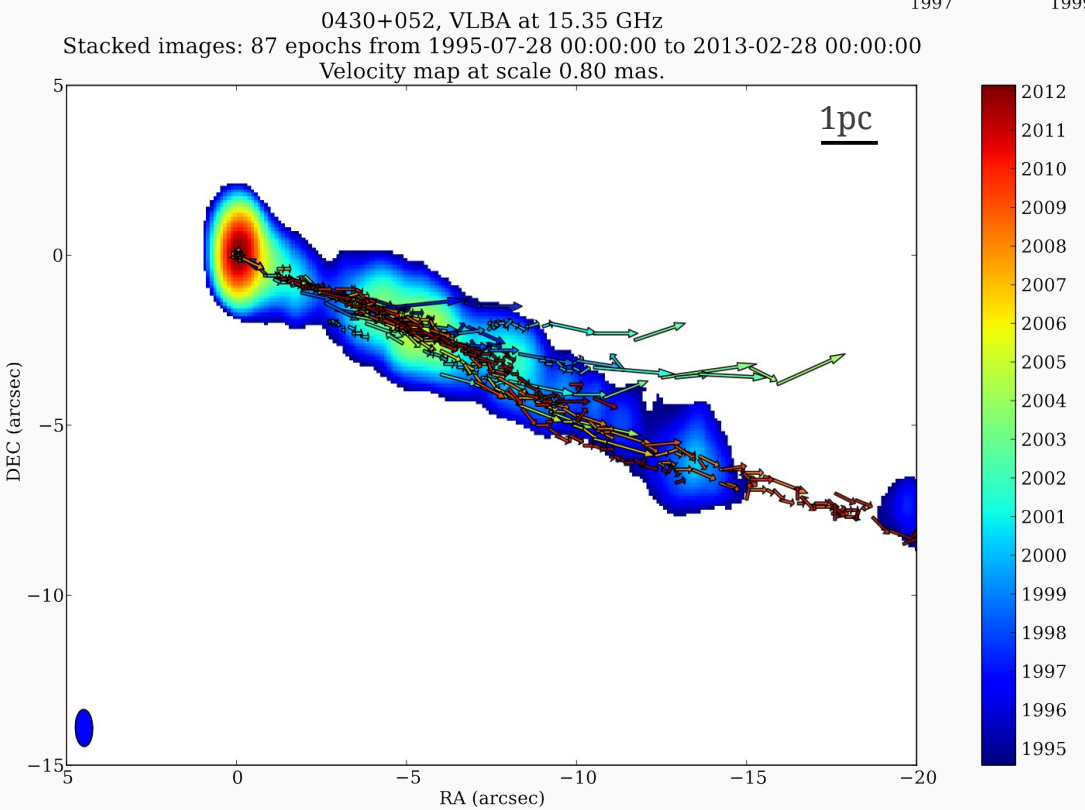
Lister et al, 2013

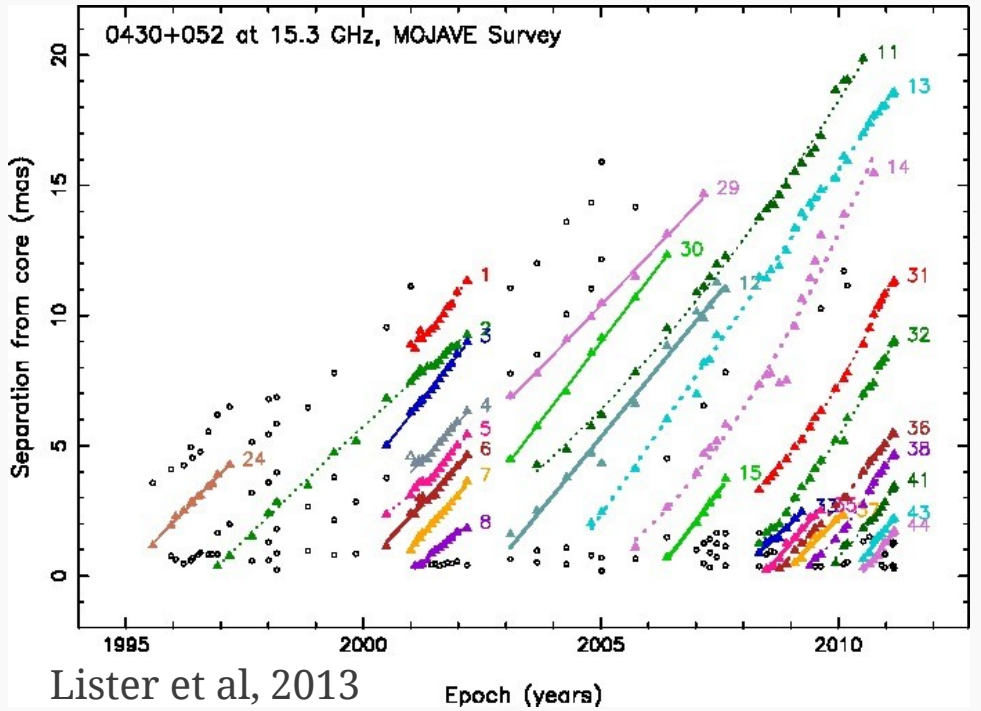
3C120

Radio Galaxy, z ~ 0.033
Observed as part of MOJAVE

87 epochs
from 07/1995 to 02/2013

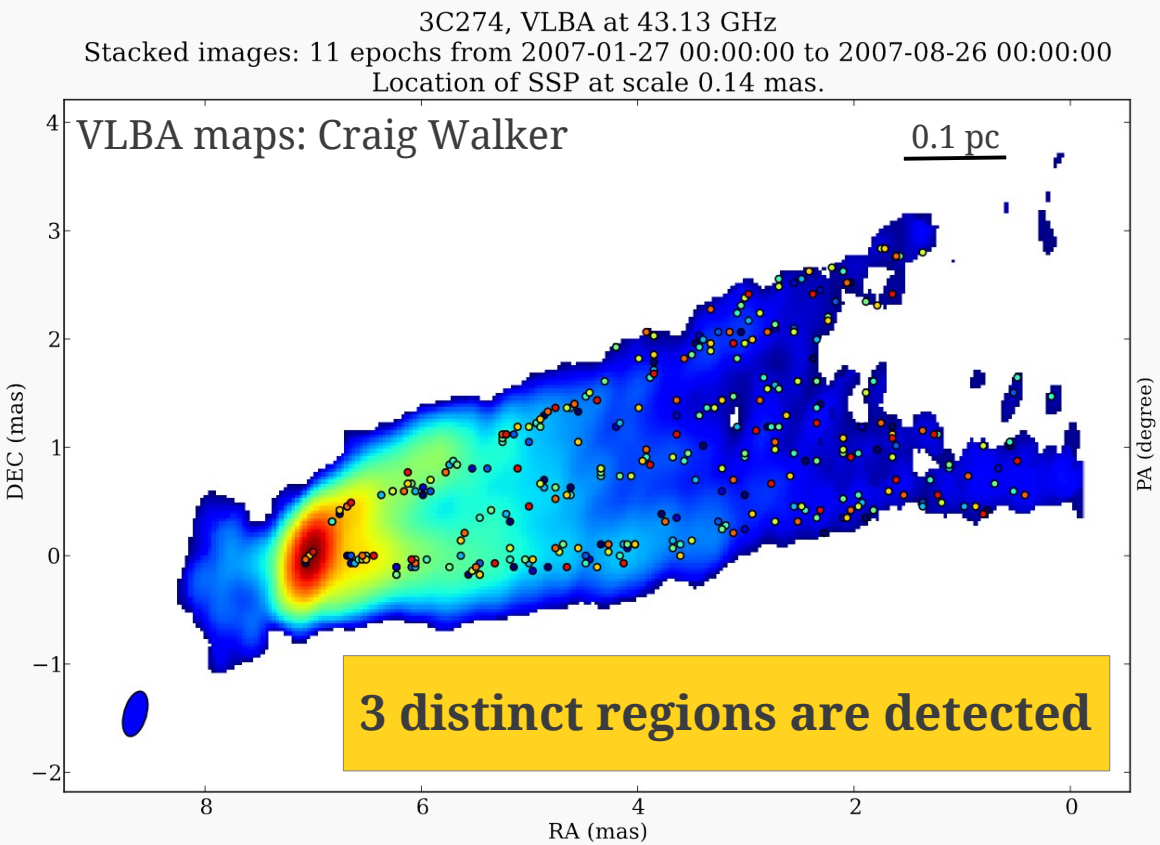


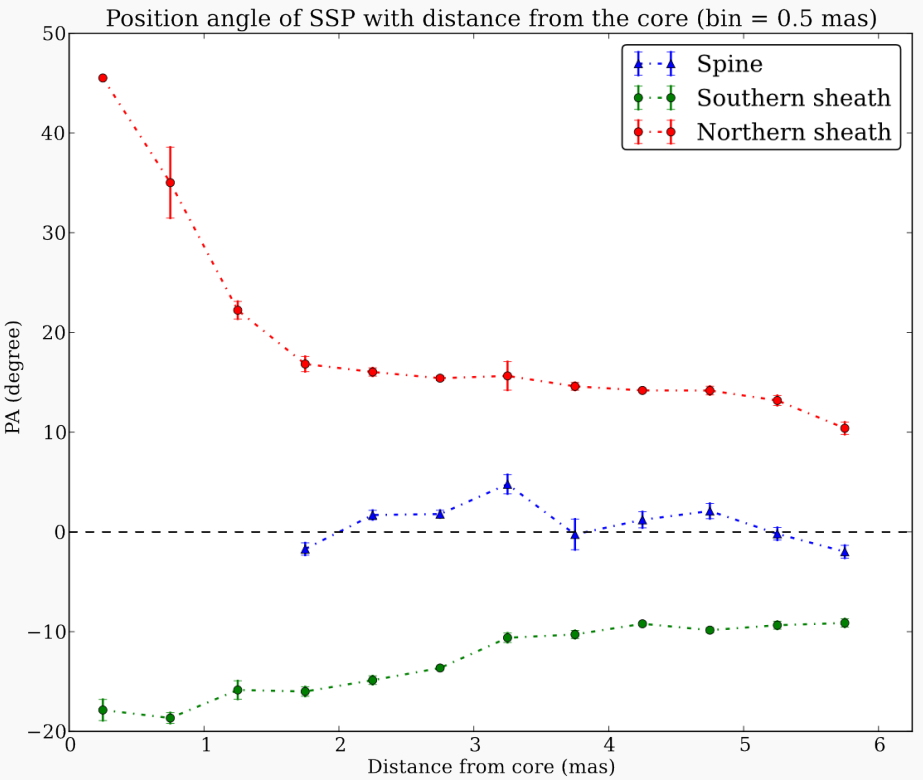




Lister et al, 2013

M87



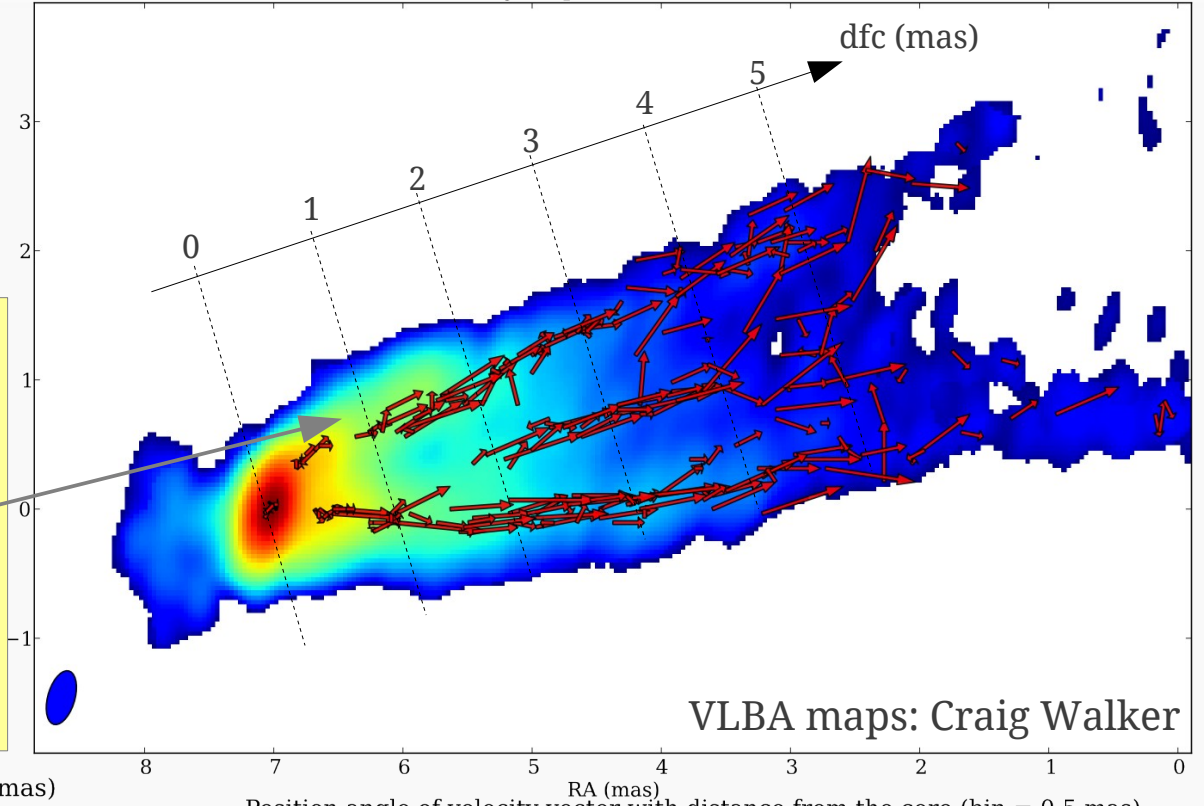


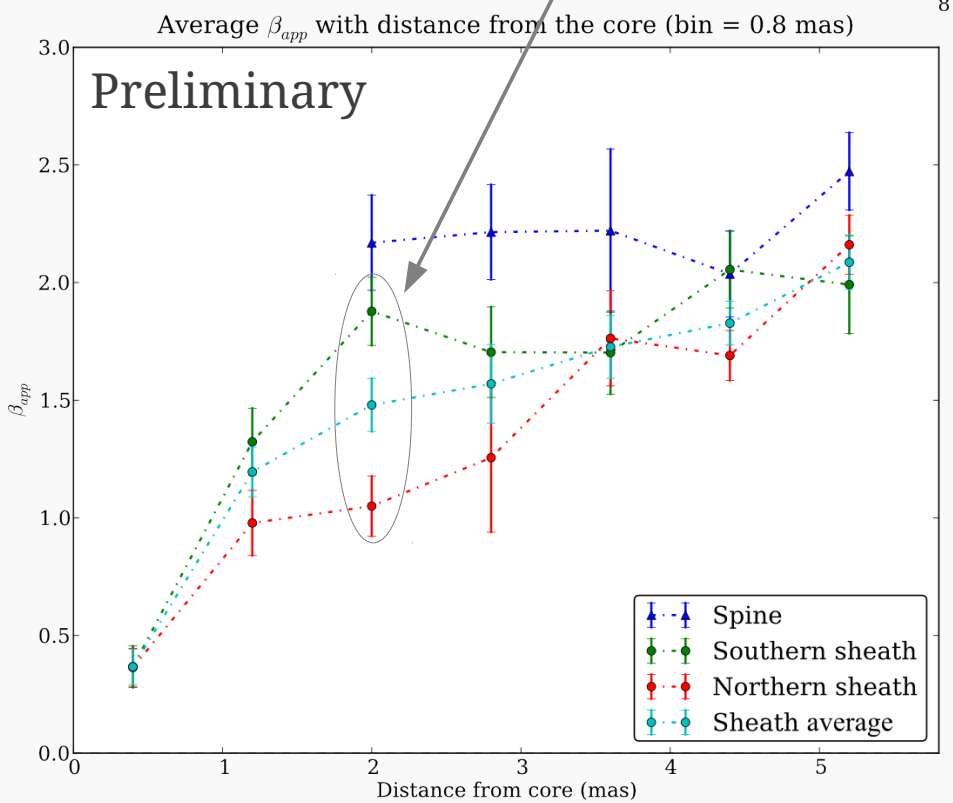
One of the closest radio galaxy (z = 0.0043, **1 mas ~ 0.089 pc**)

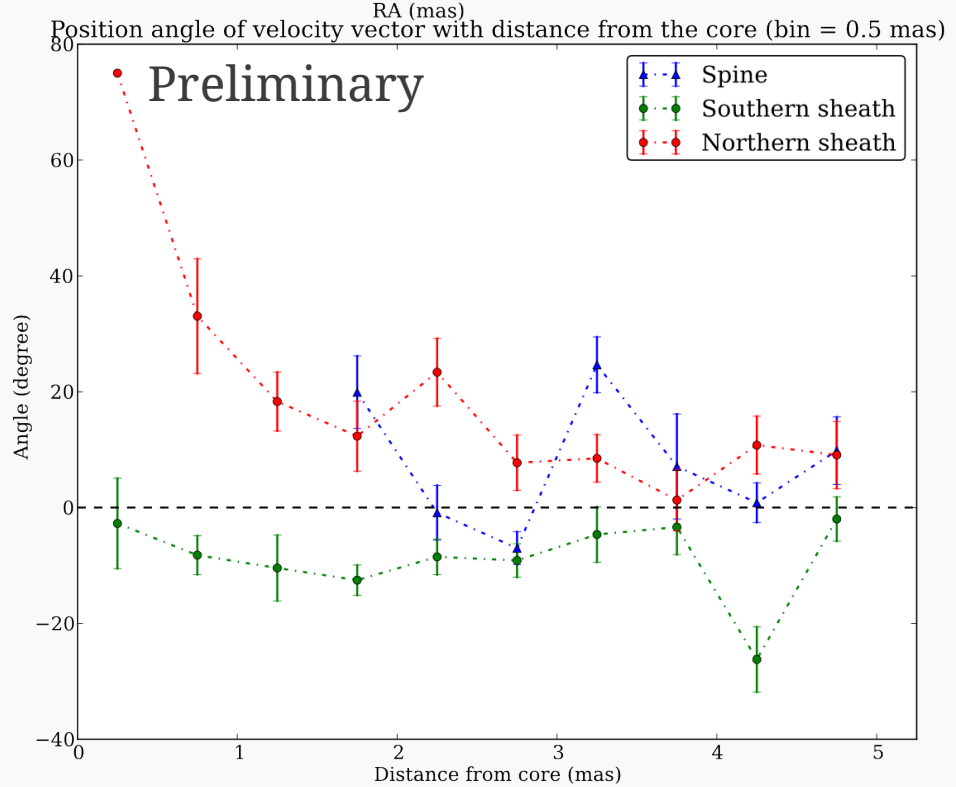
11 VLBA observations between 2007/01/27 and 2007/08/26,
at 43 GHz (**Beam ~ 0.4 x 0.2 mas ~ 56 x 28 Rs**) with **3 weeks** interval (Craig Walker)
Few persistent features: **model fit not possible**

M87

- Fast spine, slower sheath: **stratified flow**
- **Acceleration in the sheath**
- Velocity difference between northern and southern sheath: suggests **clockwise rotation** (jet or K-H instability pattern rotation)







M87

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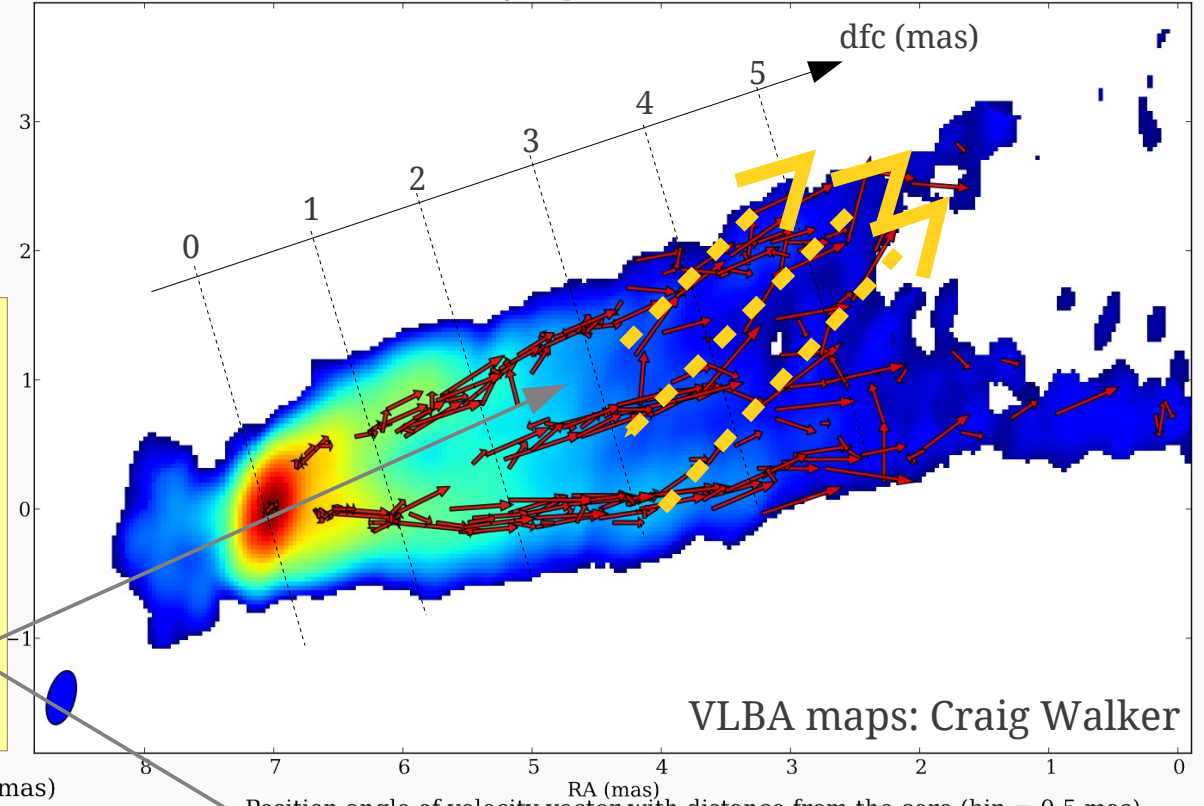
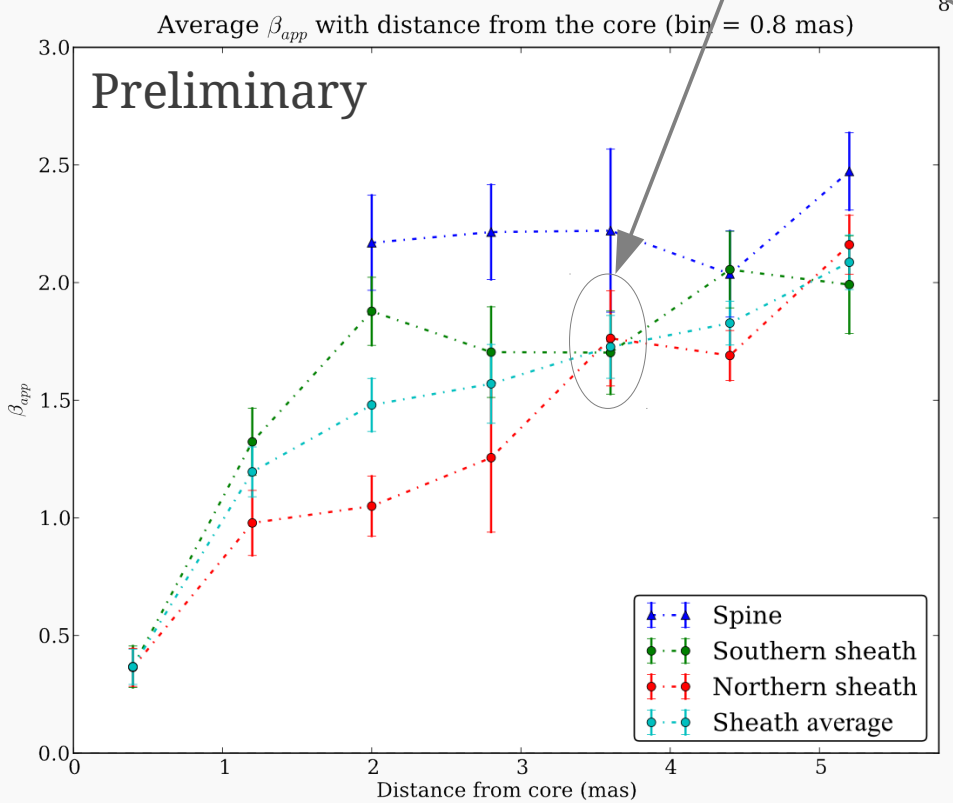
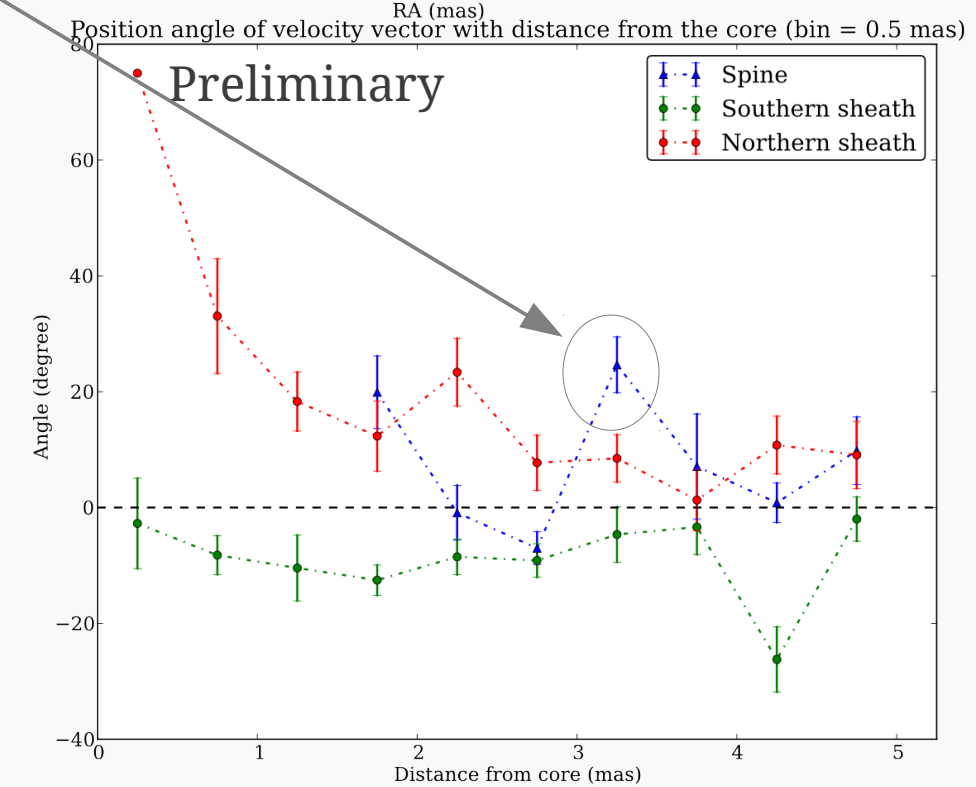
- Lateral displacement due to rotating pressure enhancements: visible > 3 mas







Summary

- The WDS technique provides reliable reconstruction of the velocity field in transversely resolved flows.
- This can considerably enhance the output of high resolution radio images.
- Result shows **excellent agreement** with global kinematic changes obtained from model-fit analysis of VLBI images.
- Ongoing detailed analysis of M87 velocity field promises interesting results:
  - We detect an **acceleration in the sheath**
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Thank you for your attention!

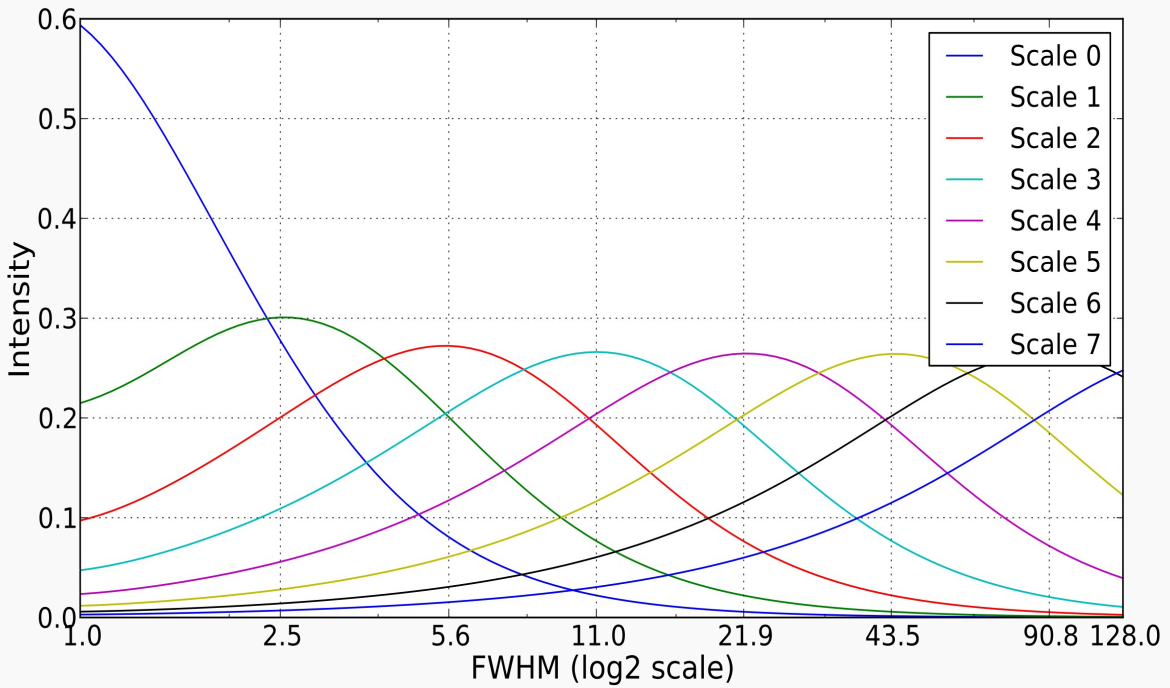
Email: fmertens@mpifr.de

Extra slides....

Wavelet transform

Wavelet transform: A trou (Shensa, 1992)
Advantages: stationary, isotropic and shift invariance transform

$$s(l)=\sum_k c_{J,k}\phi_{J,l}(k)+\sum_k\sum_{j=1}^{J} w_{j,k}\psi_{j,l}(k)$$

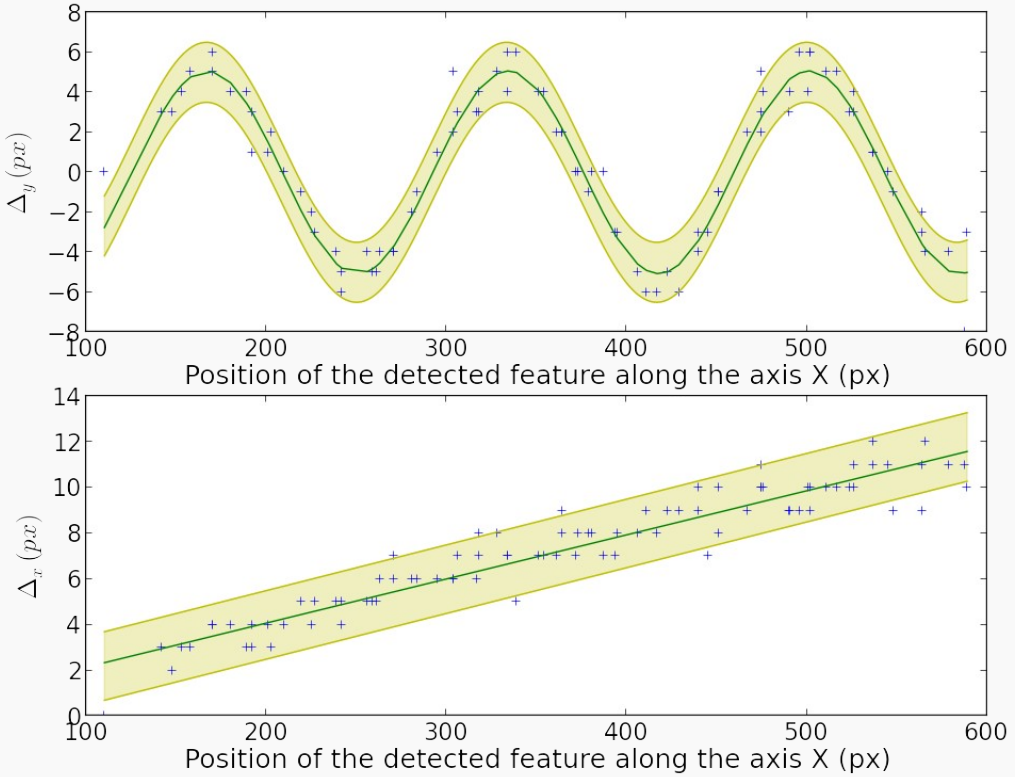


Result of the wavelet transformation of a Gaussian shape function of varying width, using the triangle function as scaling function.

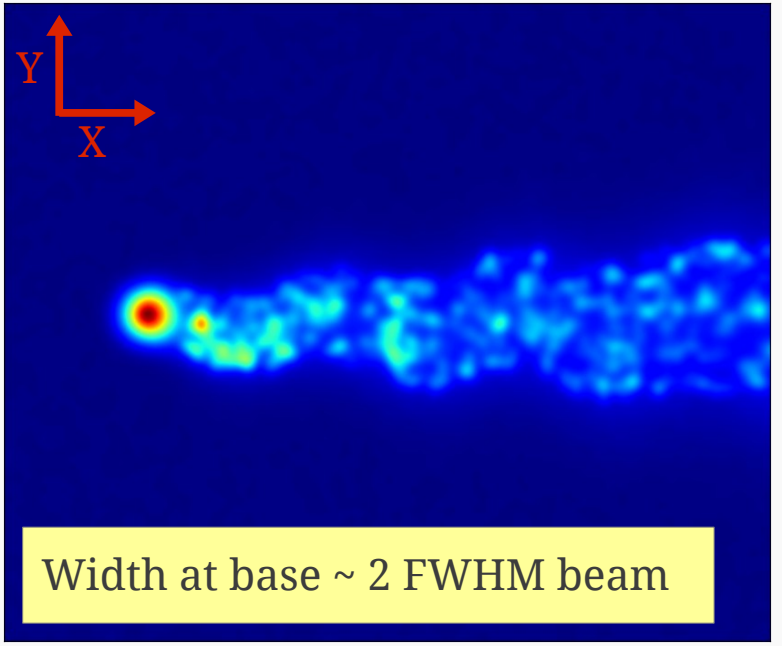
Testing the WDS and MSCC

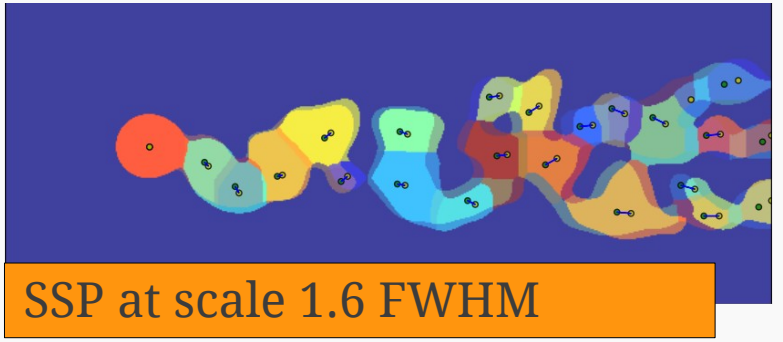
WDS and MSCC has been tested on simulated image with analytically defined model and:

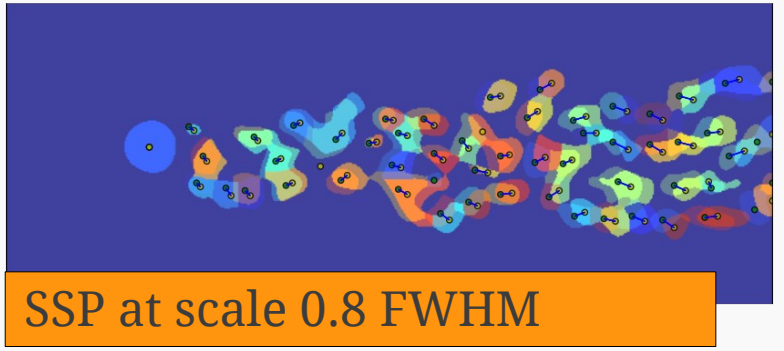
- Gaussian noise
- Uncertainty on features positions



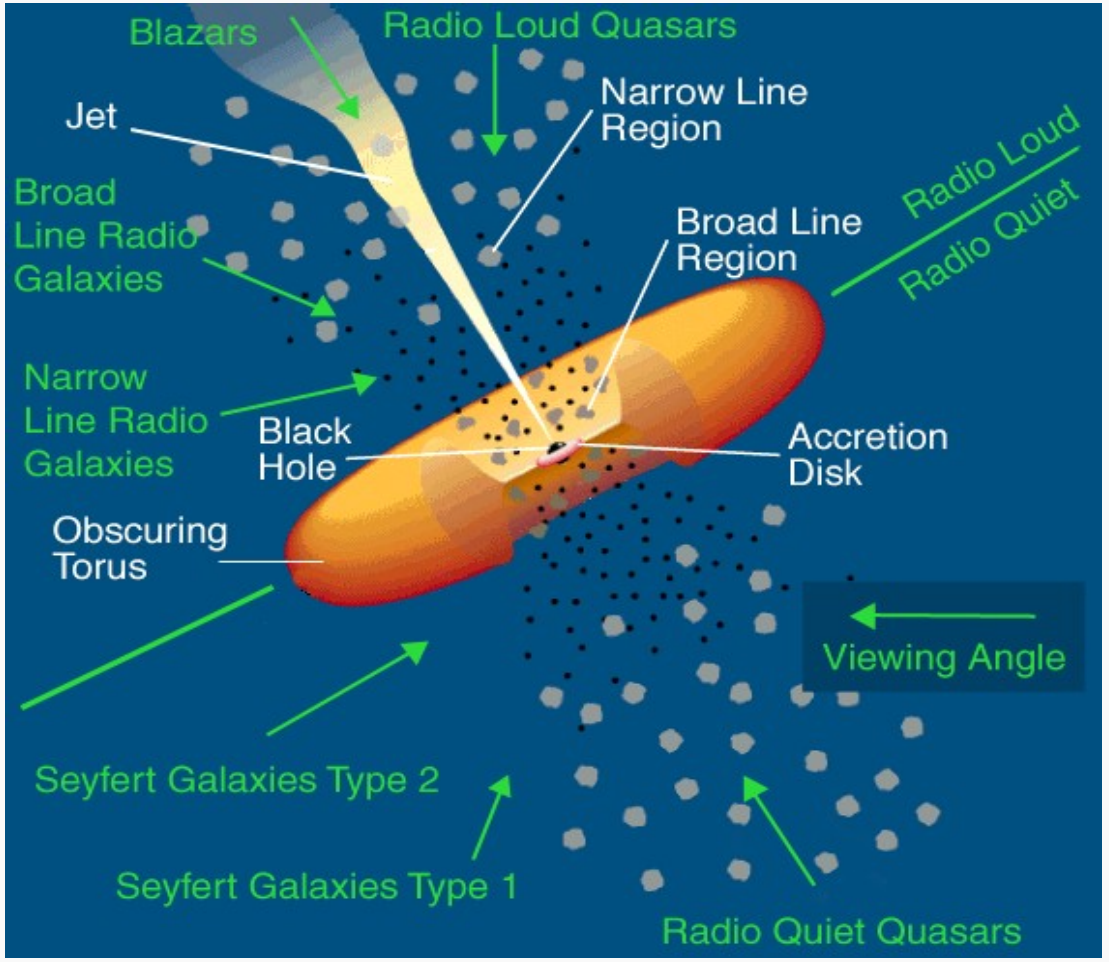
Input: sinusoidal velocity field

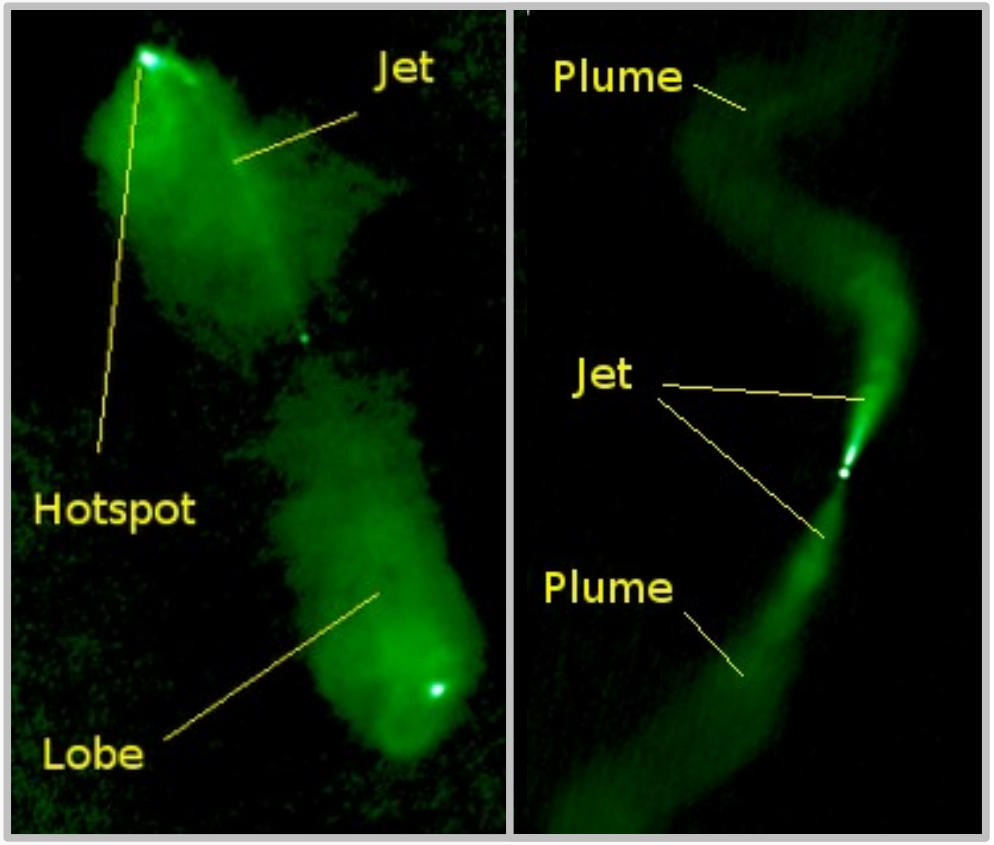






AGN zoologies





Radio Galaxies: left FRII ; right FRI