AGN outflows at parsec and sub-parsec scales

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The talk will present an overview of recent results achived by studies of AGN jets with ground-based and space Very Long Baseline interferometry.

Subject :	:	oral
Topics	:	Astrophysics

AGN jets at parsec and sub-parsec scales

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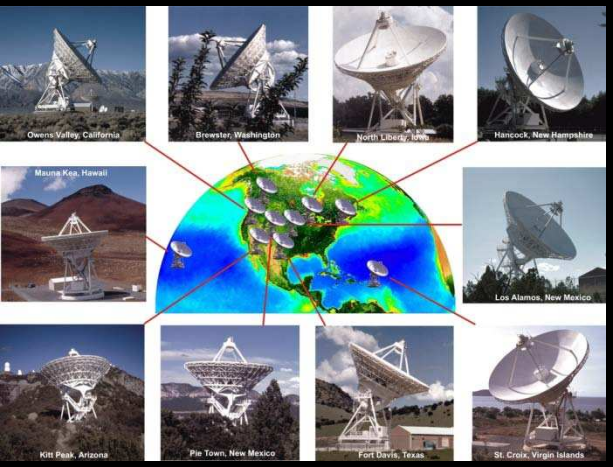
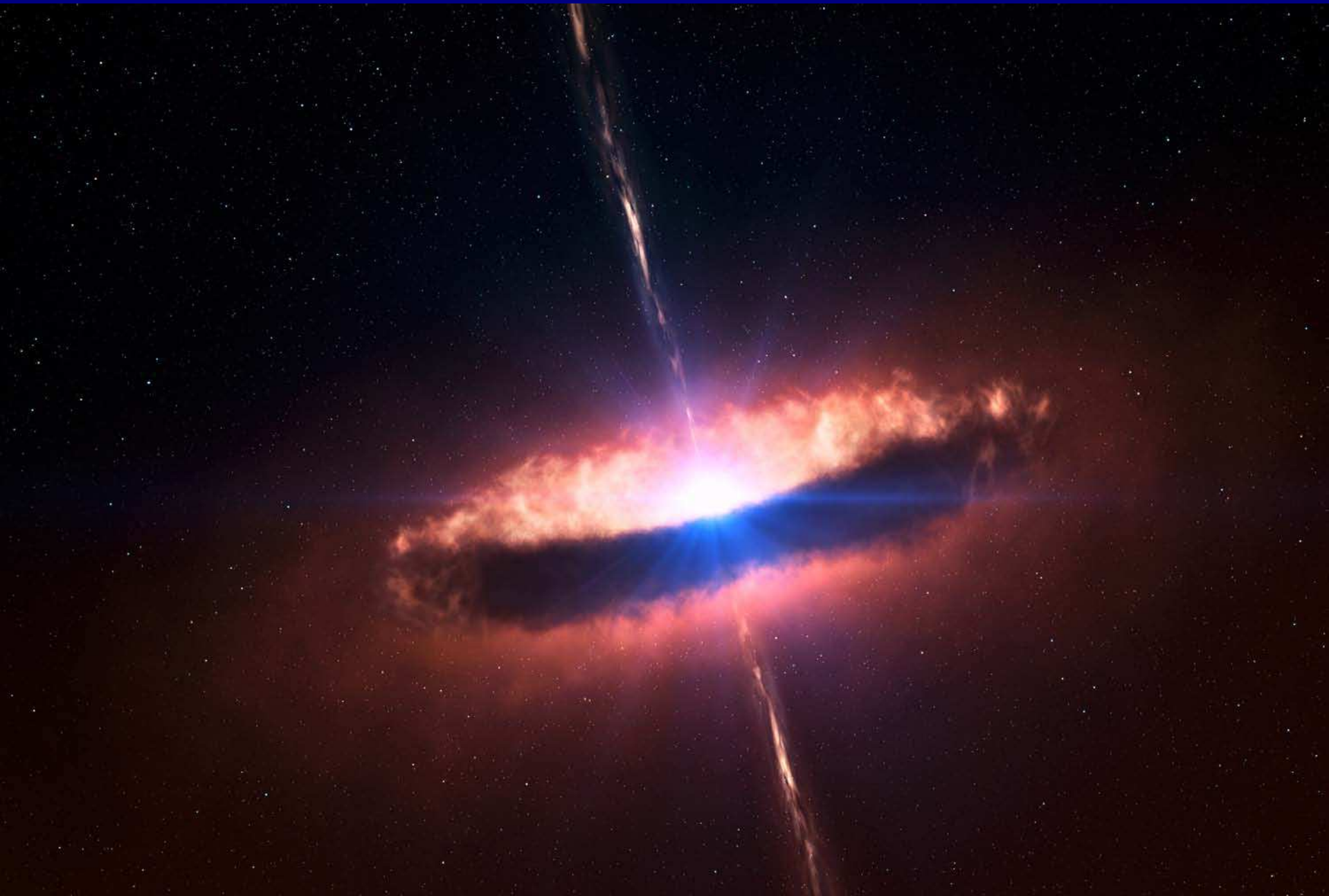


Active galactic nuclei



Outline

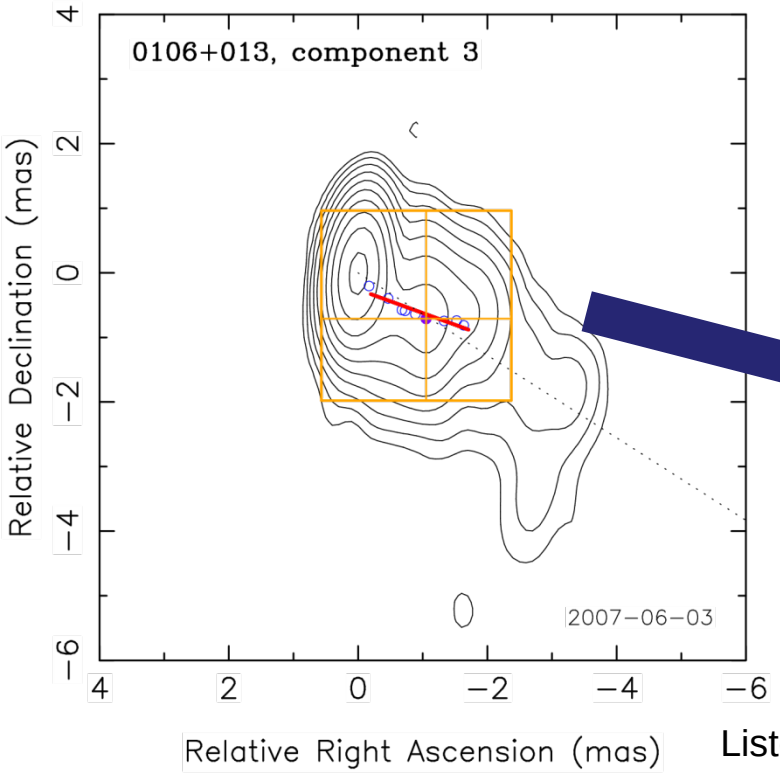
- AGN jets at parsec scales: results of about 20 years of VLBI monitoring
- AGN jets at sub-parsec scales: results of the ongoing AGN SVLBI survey with RadioAstron
- (if time permits) Big fat warning: interstellar medium and scintillations

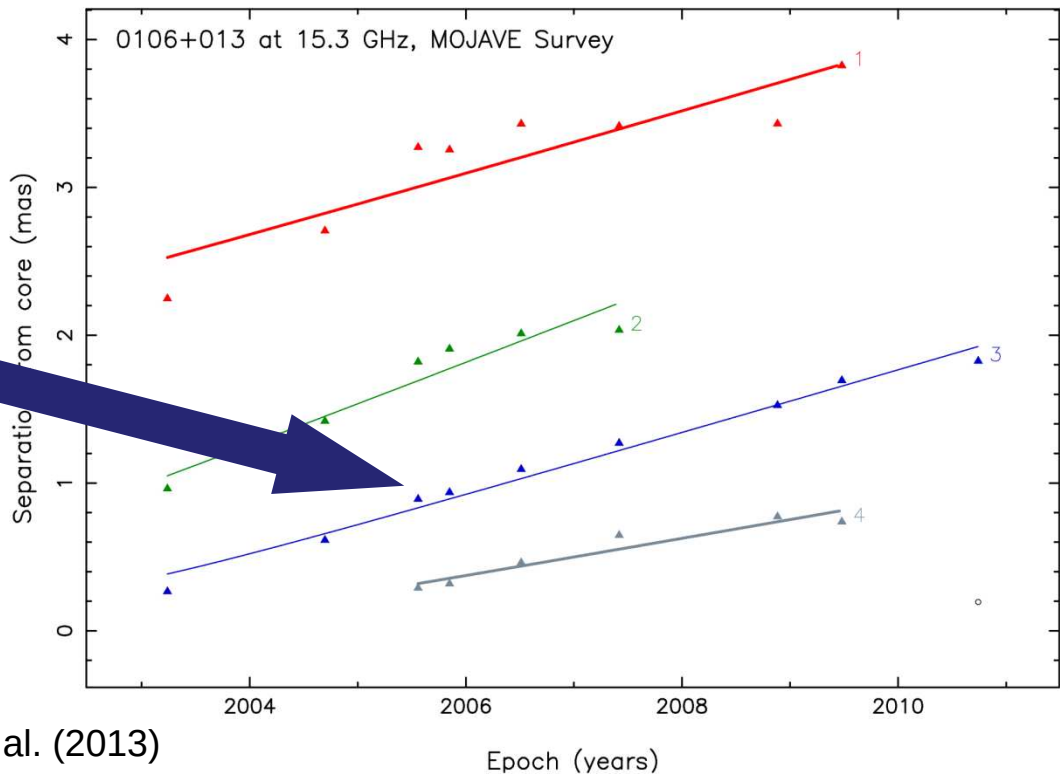
AGN sample discussed in the talk: about 200 brightest objects on the sky North of -30 degrees declination.

Recent 2 cm VLBA monitoring results

Superluminal motions: typical for radio-loud blazars:

- ✓ Typically 10*c*, only two objects have shown features around 40*c*. Maximum Lorentz-factor for the complete sample is estimated to be about Γ=40 (Monte Carlo simulation of the apparent speed versus radio luminosity dependence).
- ✓ Wide range of speeds within a jet but clustered around a typical value. Should be related to the underlying flow.
- ✓ Apparent inward motion (2%): rare. Projection effect or inward pattern speed.

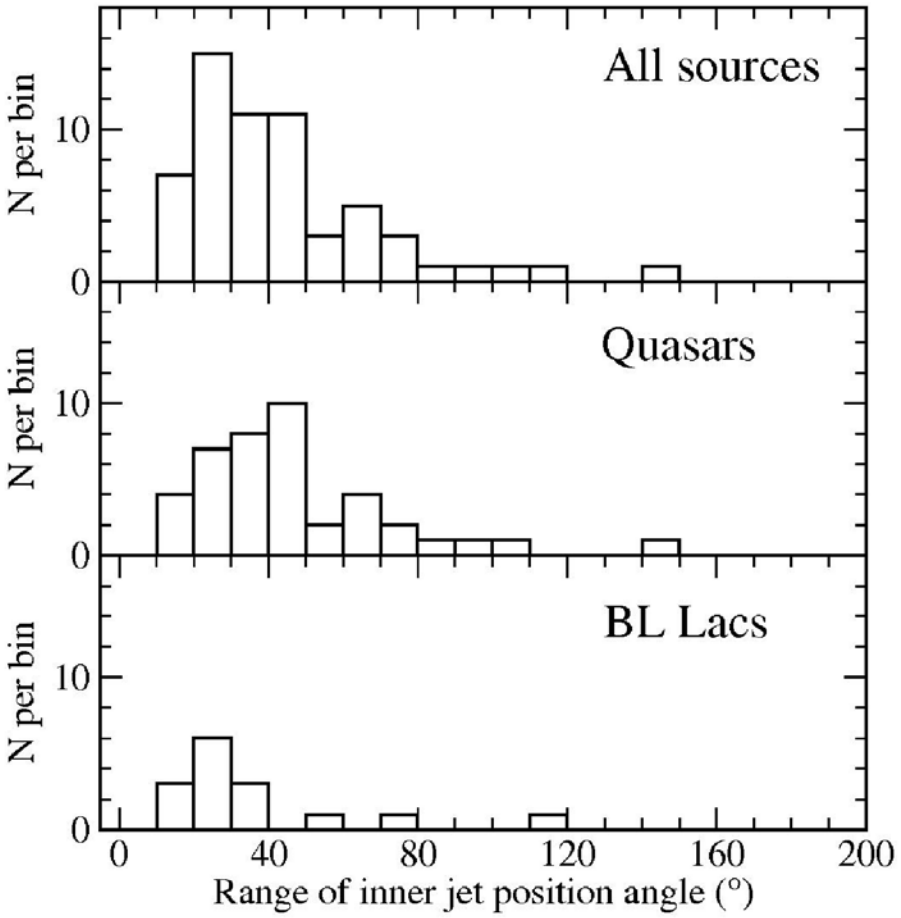




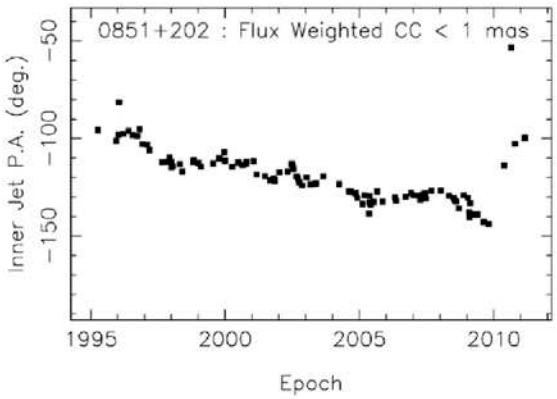
Lister et al. (2013)

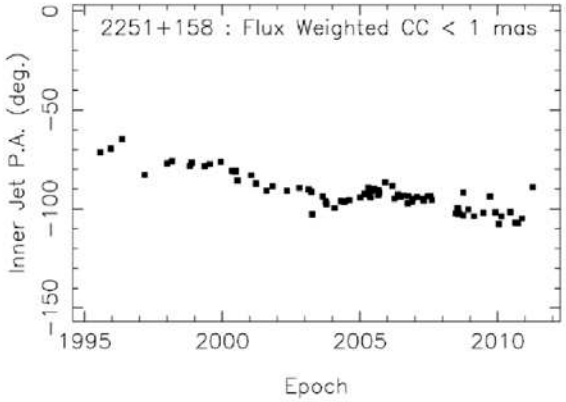
Inner jet orientation variations

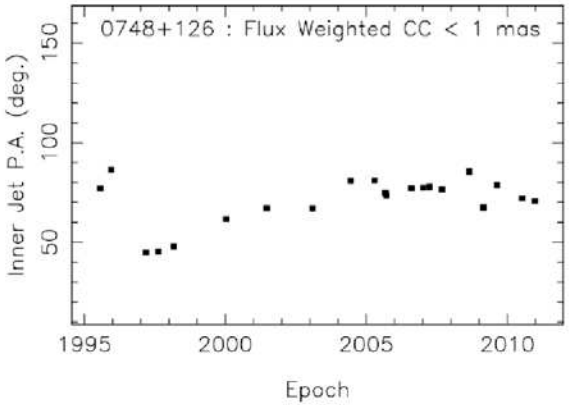
- Half of the jets show significant changes in the inner jet P.A. over 15 years.
  They are primarily driven my emergence of new jet features.
- Typical range: 10 to 50 deg on the sky, corresponds to intrinsic variations 0.5-2.0 deg.
- This suggests that superluminal AGN jet features occupy only a portion of the entire jet cross-section and may be energized portions of jet instability structures.

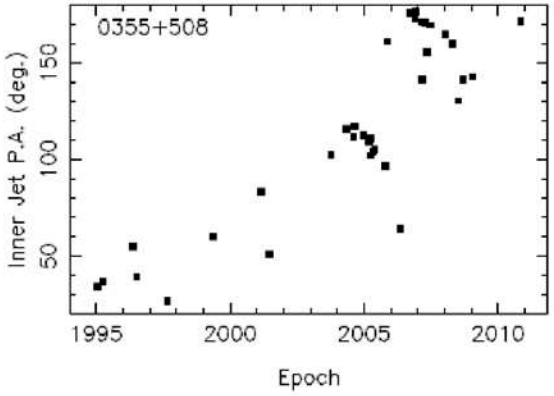


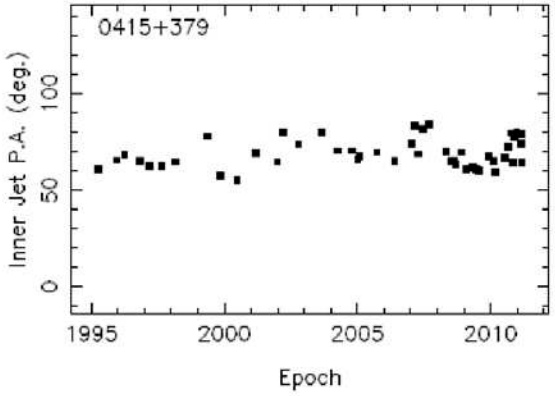
- 50% show no trend with time
- 43% have monotonic swings in position angle
  - Typically 1-3 degrees per year
  - Fastest: NRAO 150 (9.8 ± 1˚ per y)

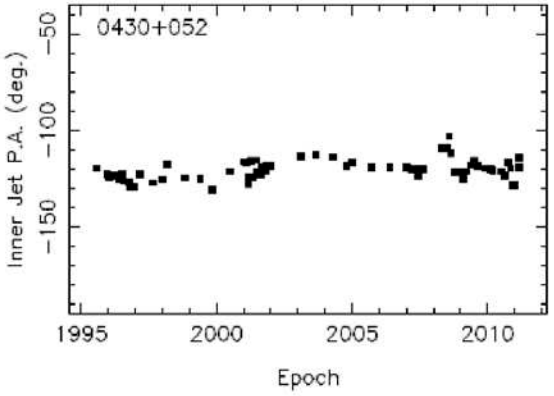




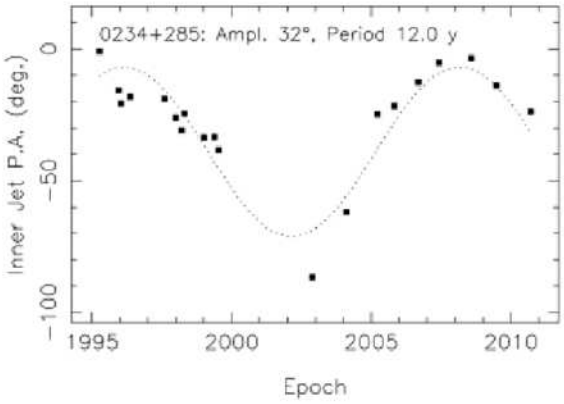


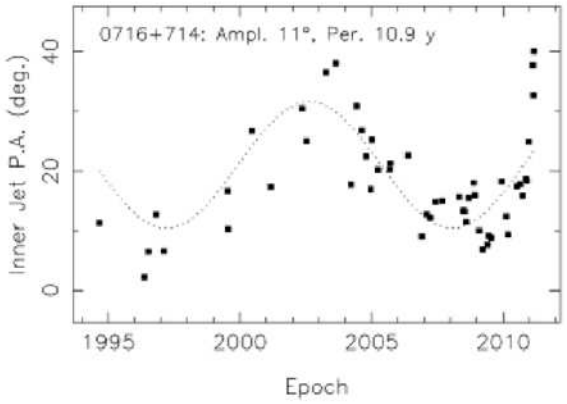


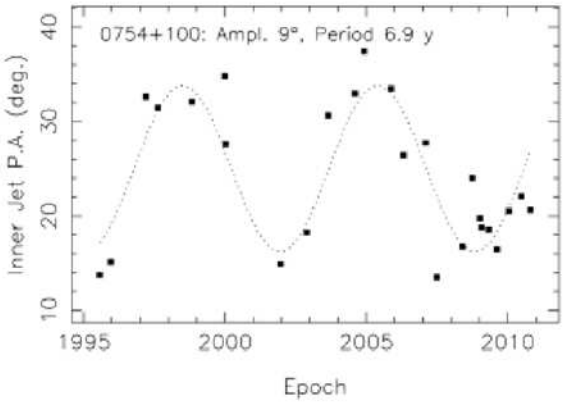


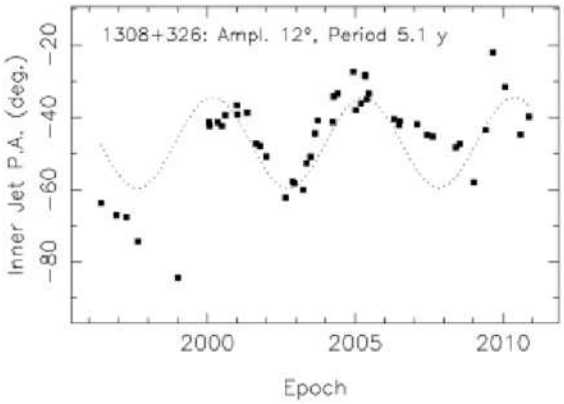


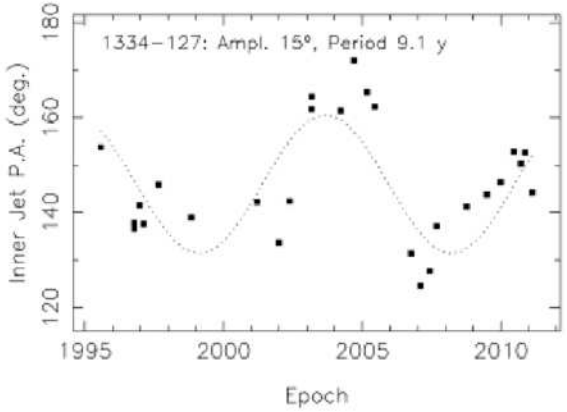
- Sinusoid-like PA variations in 20% of jets
- Variations are too slow to establish periodicity

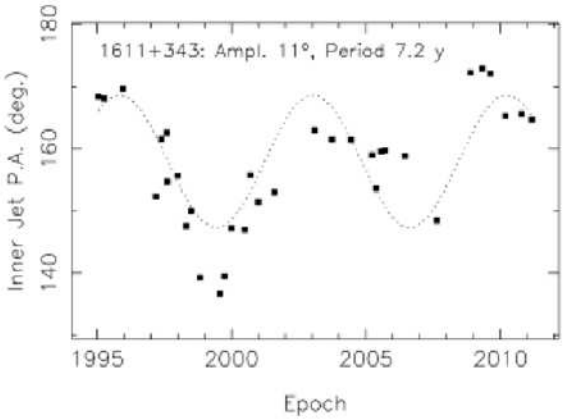






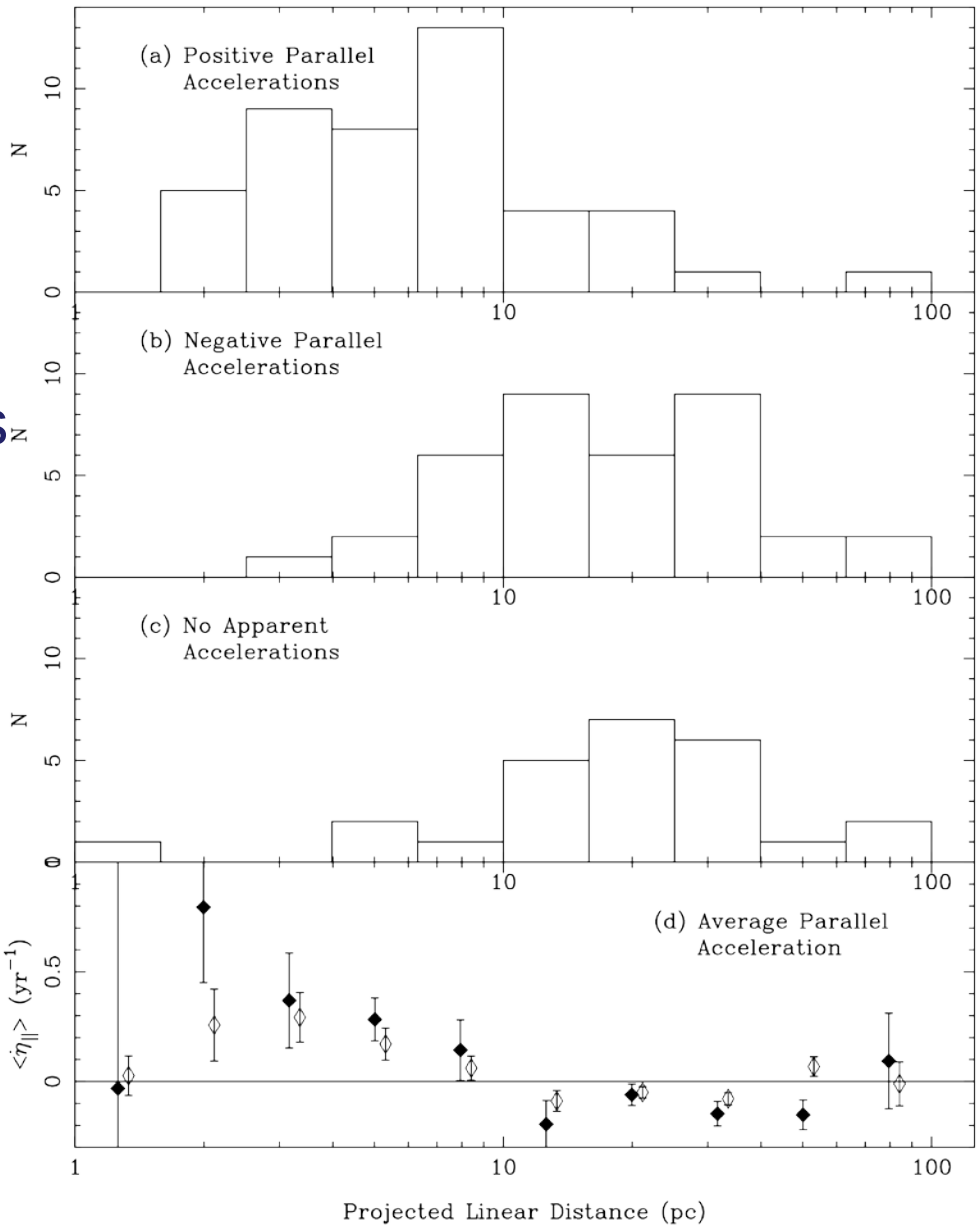






Parallel jet acceleration

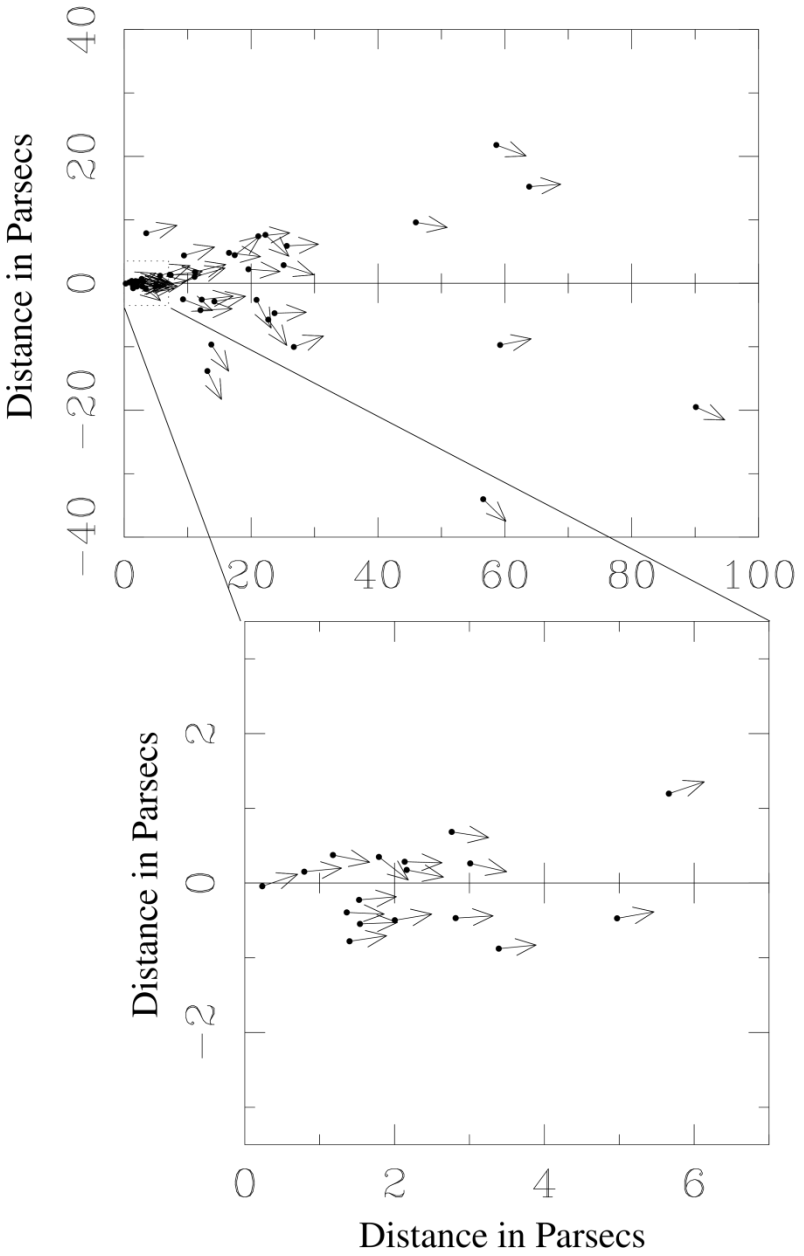
- About one half of features show accelerated motion
- Parallel acceleration is observed more often and is larger than changes in direction
- Positive parallel acceleration is dominant close to the core and negative further away. => We can still see jet acceleration process at these scales. The transition occurs at 10-20 pc.
- This can be produced by an overall acceleration of the jet flow until ~100 pc de-projected.



Homan et al. (2014, submitted)

Perpendicular jet acceleration

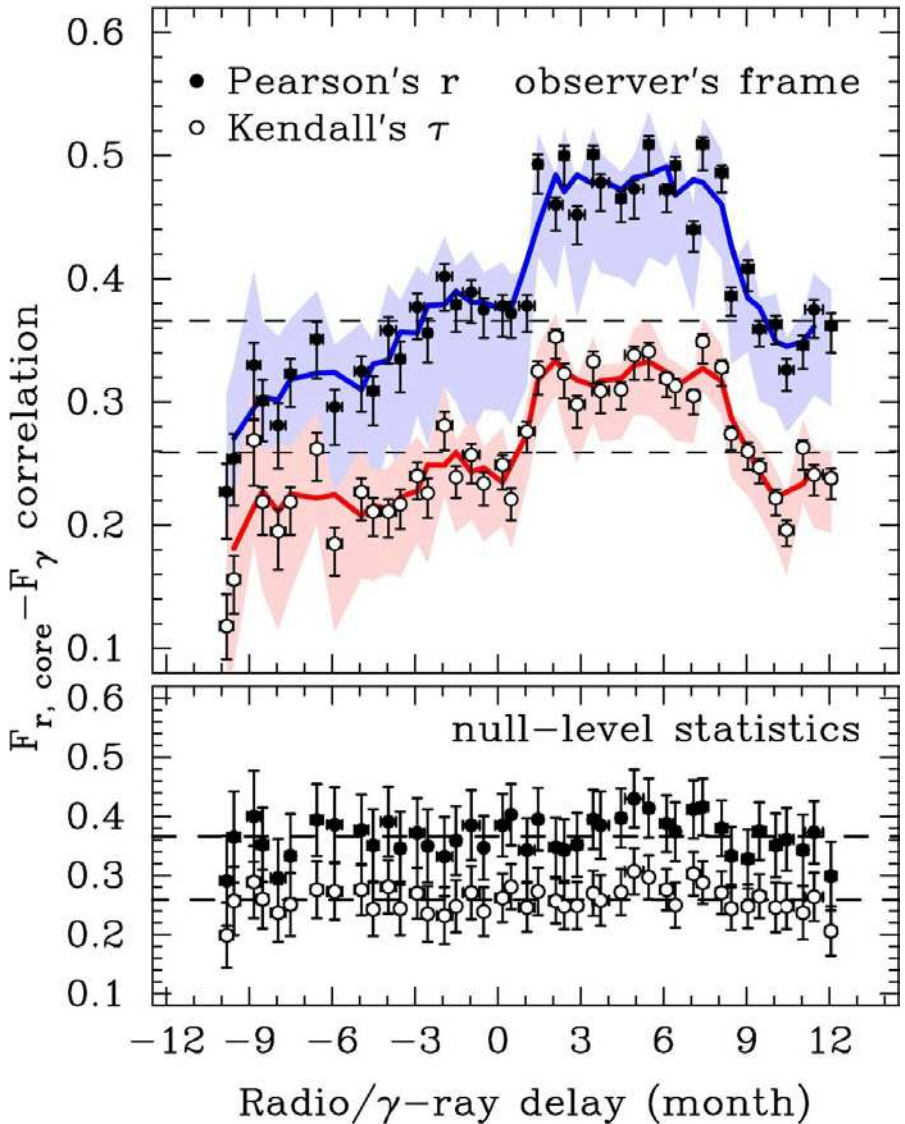
Evidence for collimation for jet features starting with large offsets from the median inner jet P.A.
Typically they are found to move in a direction to better align with the inner jet.
This trend is strongest for jet features at small linear distances (<10 pc de-projected).
Jet still becomes collimated at these distances?

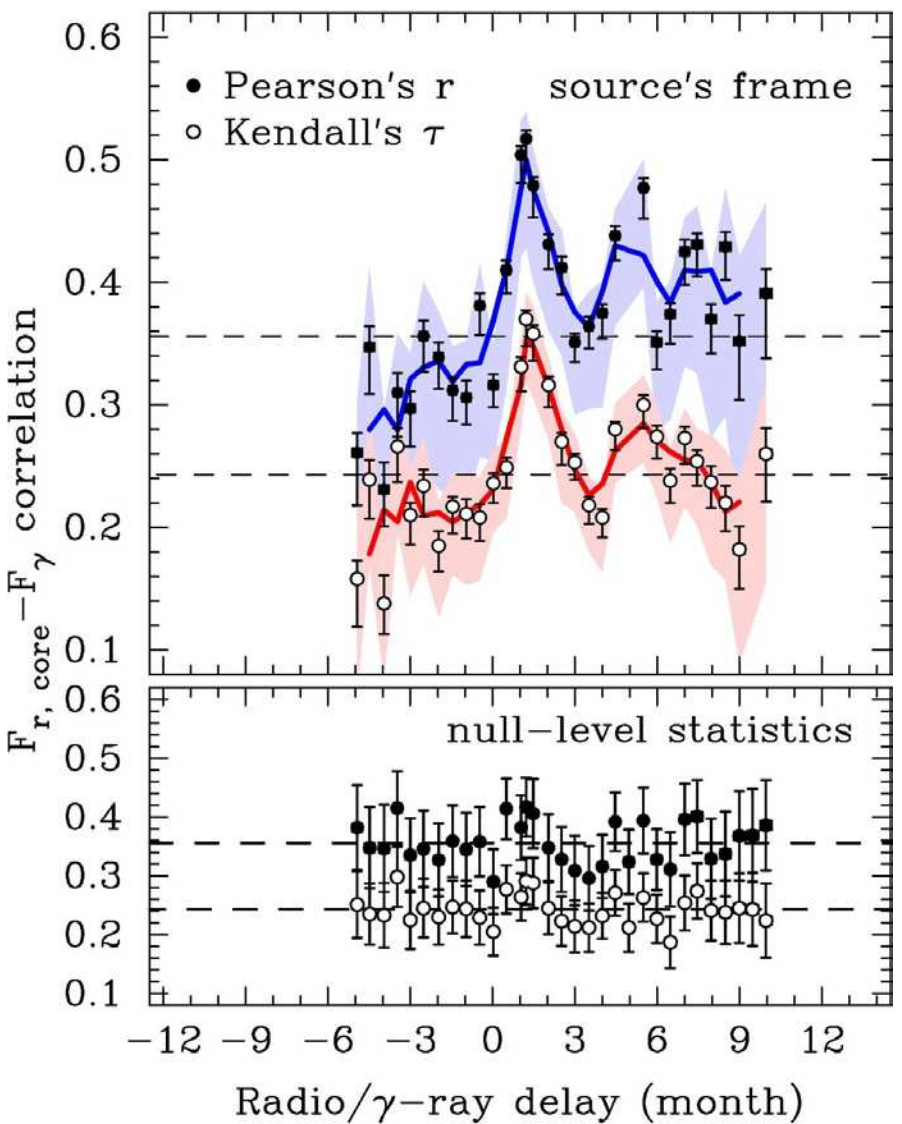


Most of identified γ-ray sources on the sky are blazars.
Radio (synchrotron) and gamma-ray (inverse-Compton) emission is strongly related. Clear correlation is found. The main “connecting” factor is the Doppler factor. E.g., Kovalev et al. (2009), Lister et al. (2009)

Radio - γ-ray delay

Is interpreted by the radio core opacity and locates gamma-ray emission region ~7 pc upstream from the 2 cm jet core. (Pushkarev, Kovalev, Lister, 2010, ApJL)

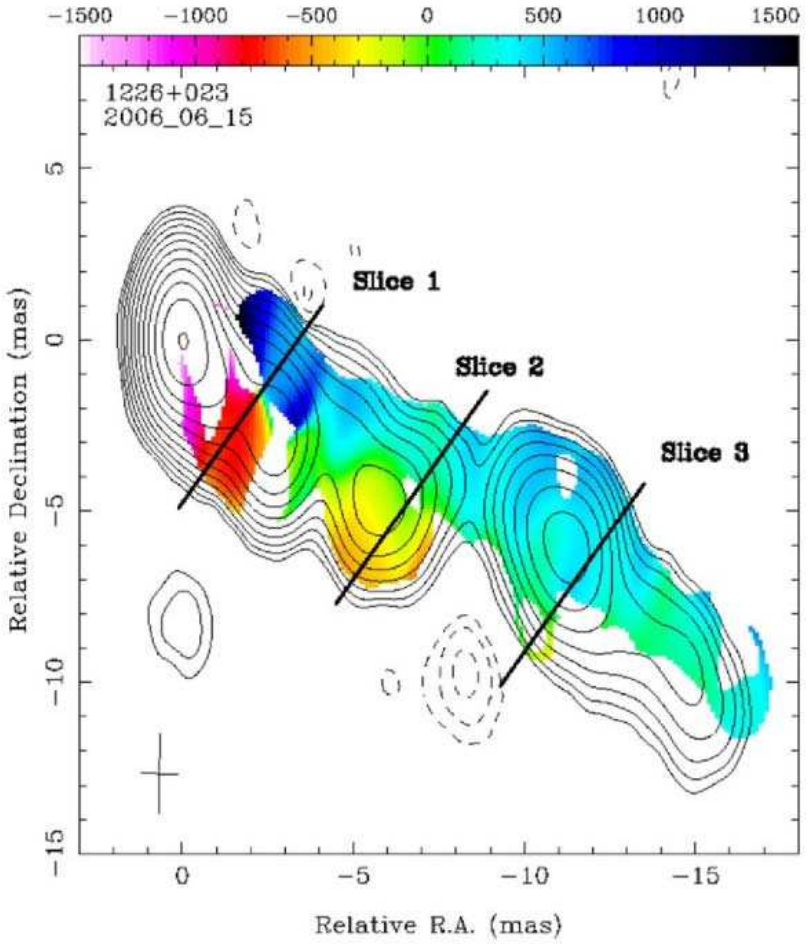




Faraday Rotation measure at parsec scales

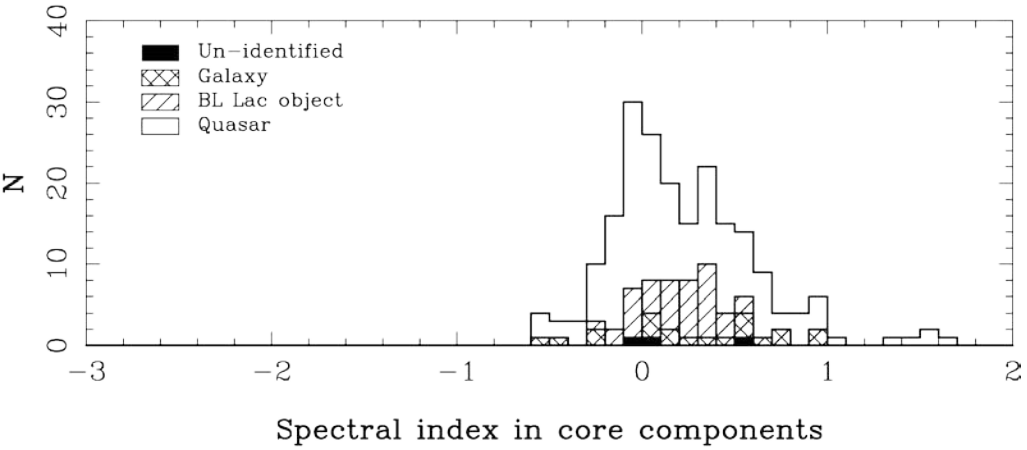
Probes magnetic field weighted by particles. RM gradients and polarization vectors probe magnetic field structure.

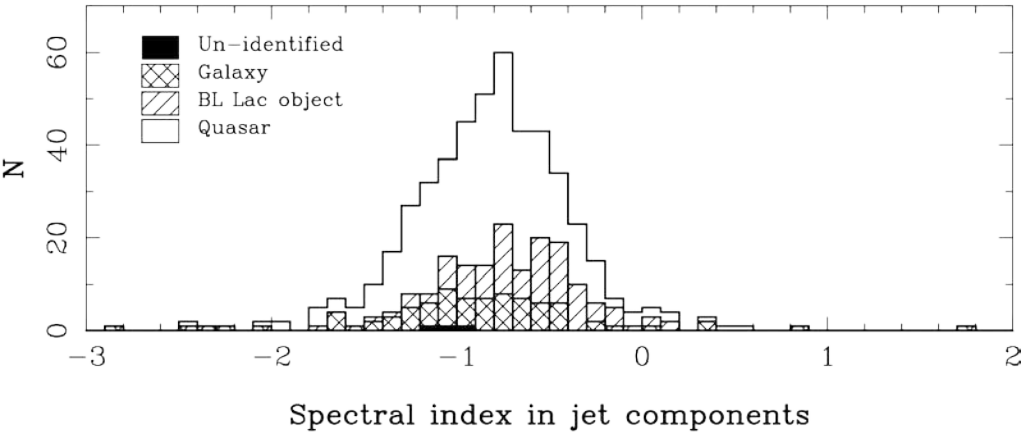
- In 8-15 GHz data values up to $4 \cdot 10^3$ rad/m^2 were found.
- Overall: up to ~100,000 rad/m^2 and higher are observed. A clear trend is seen: Faraday RM increases with increasing the frequency: come closer to the central engine.
- RM gradients are rare but due to observational restrictions. Detected gradients favours helical magnetic field.

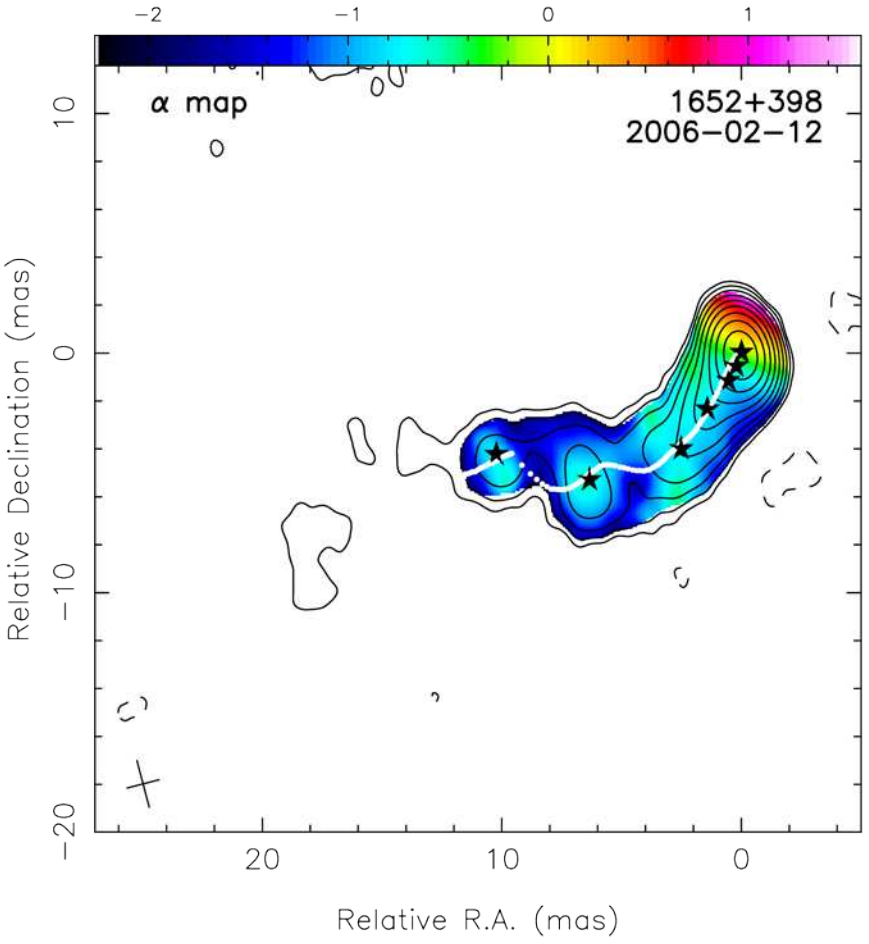


Hovatta et al. (2012)

Parsec-scale spectral properties

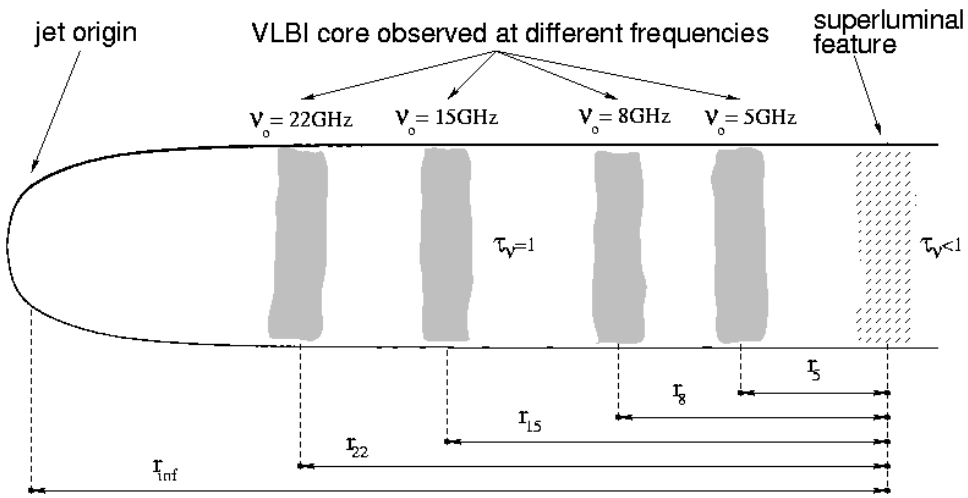


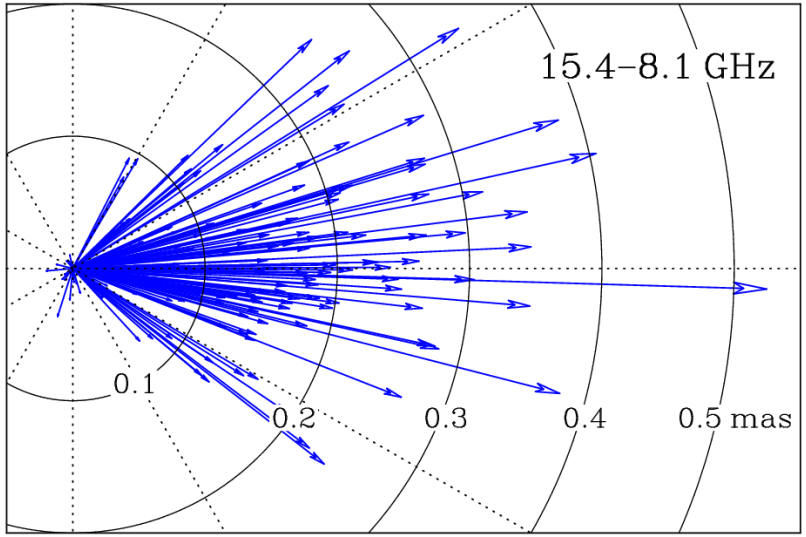


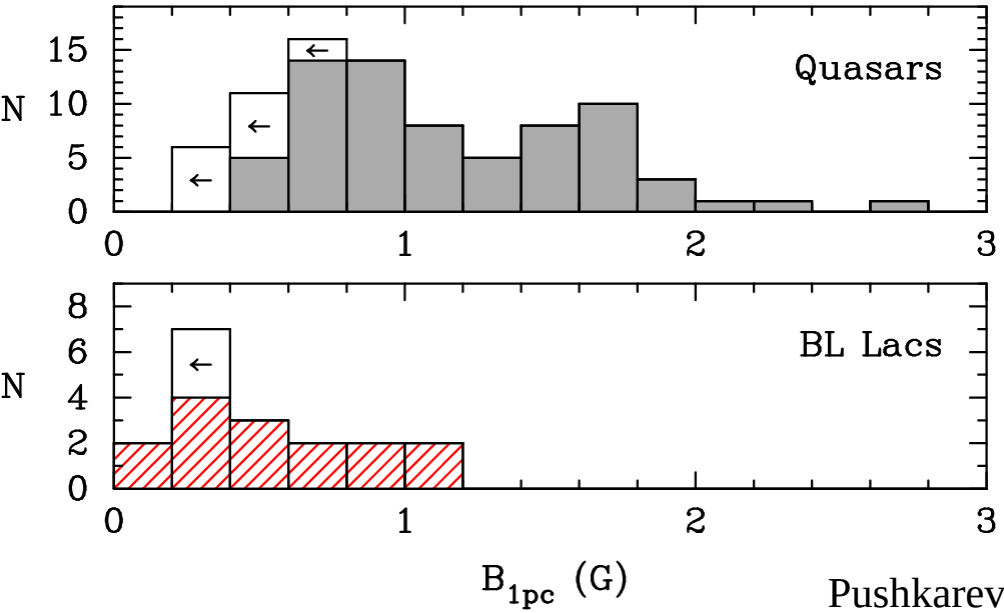


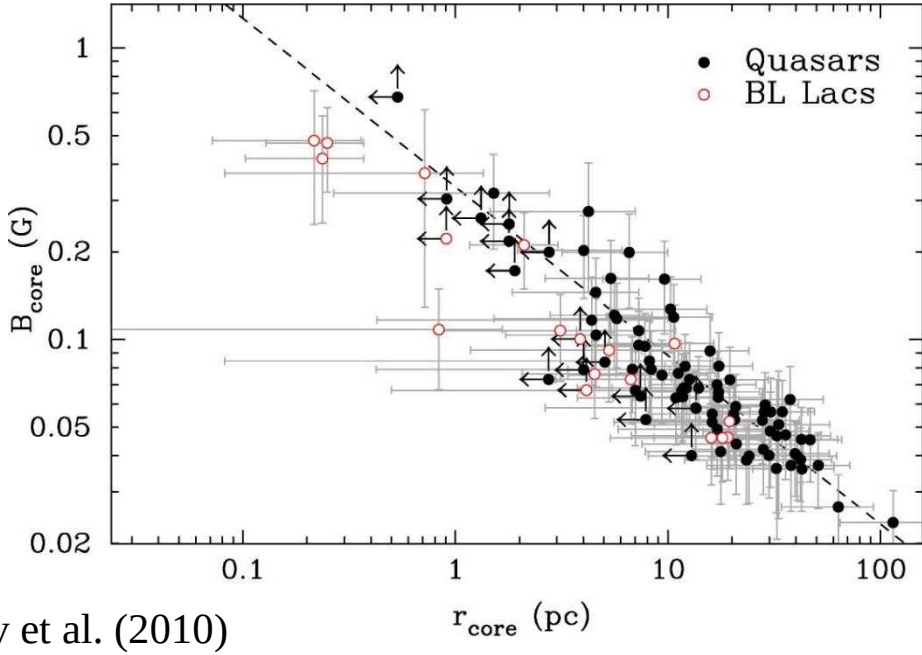
Hovatta et al. (2014)

Apparent shift of the core position and magnetic field estimates



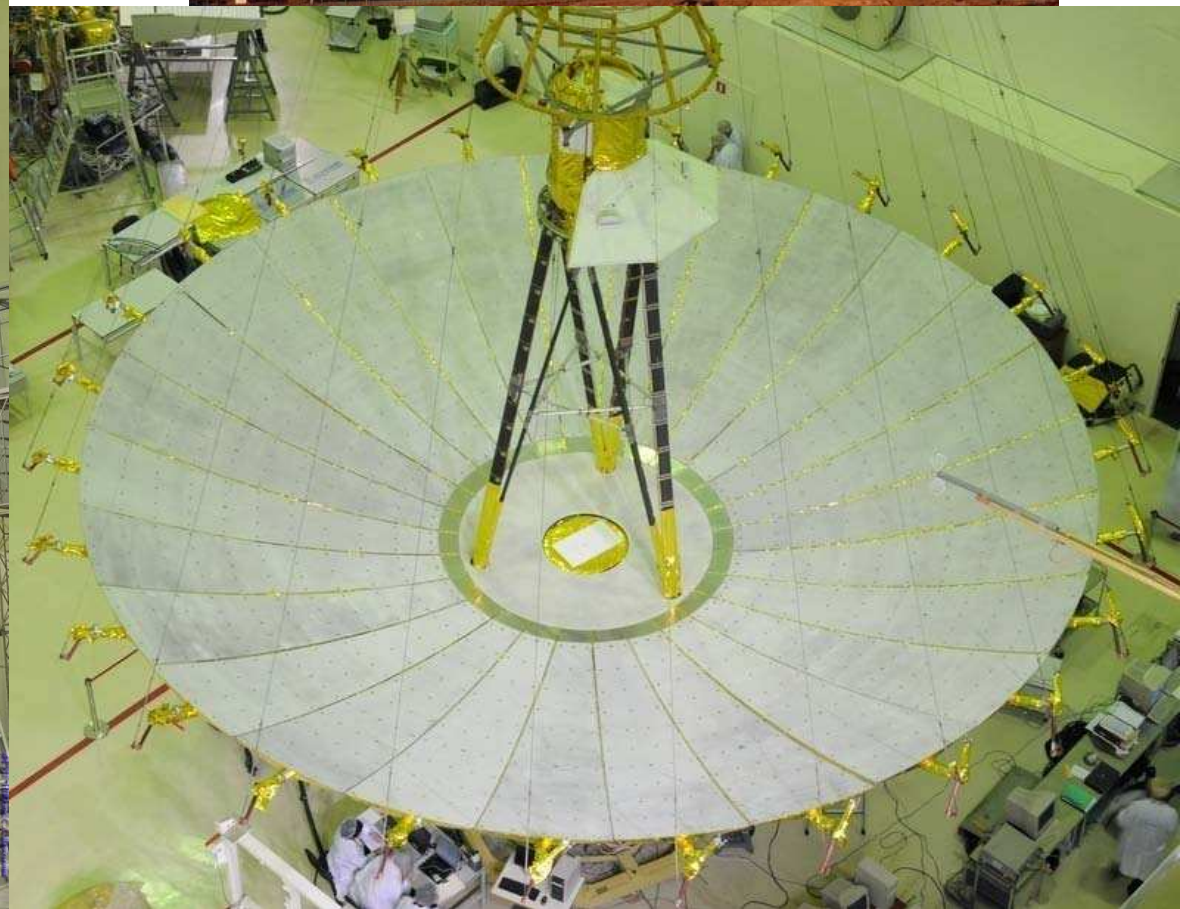


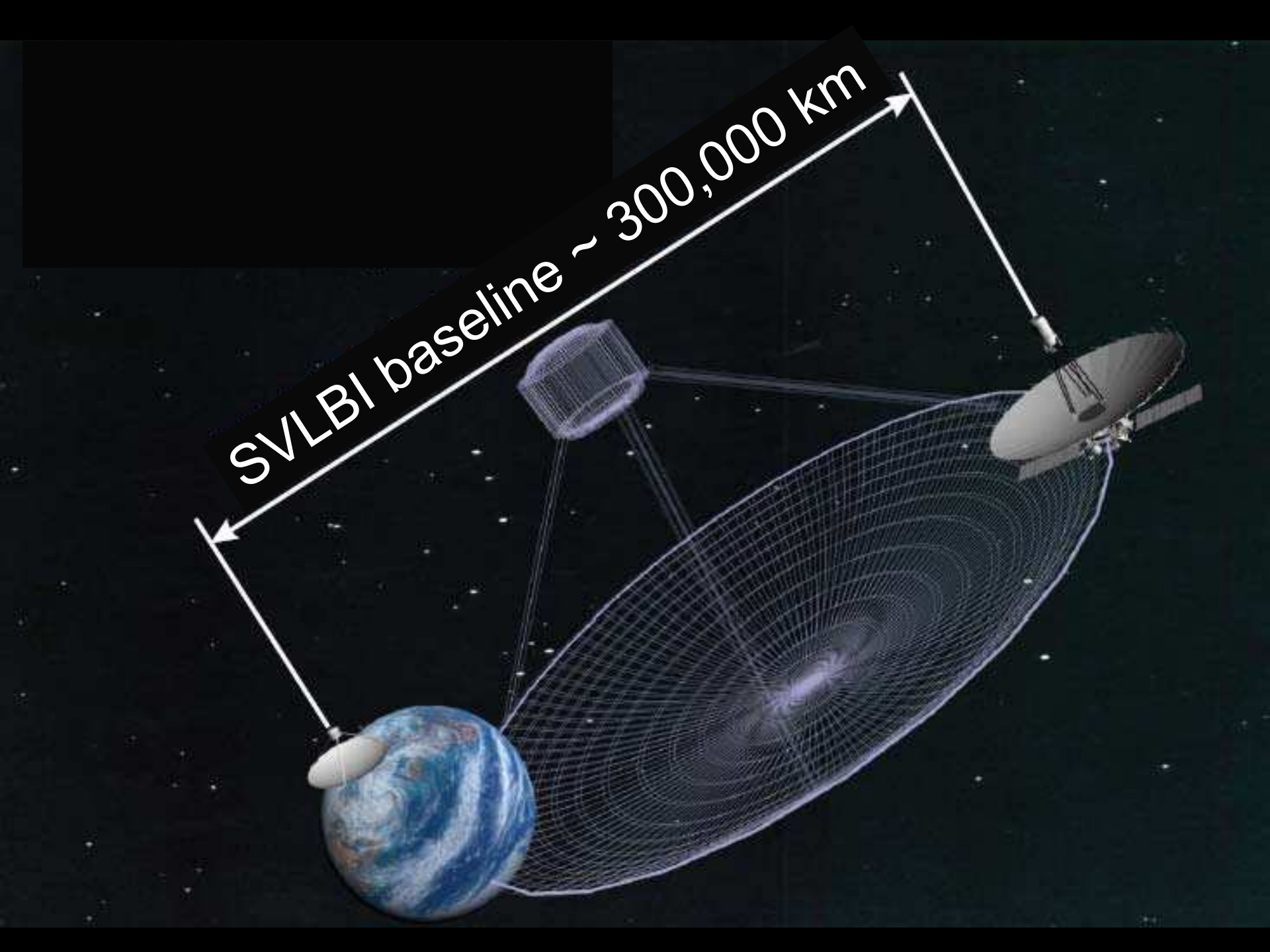




Pushkarev et al. (2010)

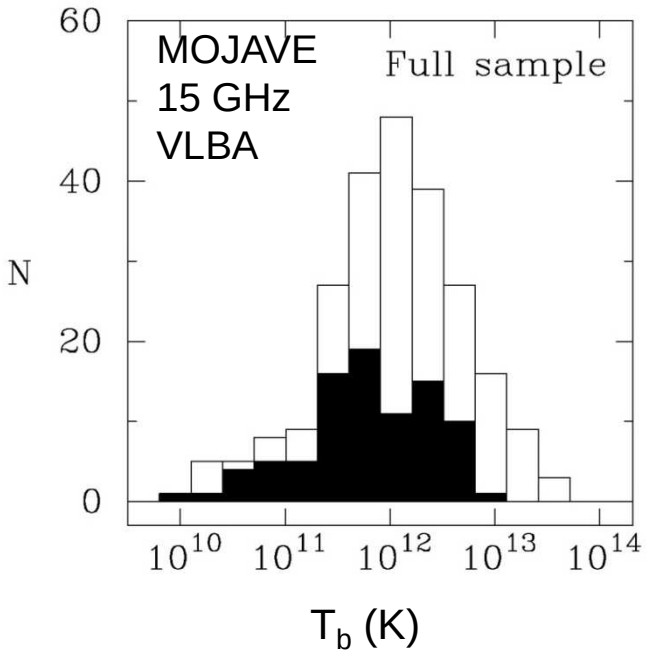
RadioAstron was launched in 2011




SVLBI baseline ~ 300,000 km

RadioAstron AGN survey

SVLBI core size, brightness temperature, beaming, ISM



Ground-based VLBI, 2 cm:
Median $T_b = 10^{12}$ K,
maxTb (limit) $=5 \cdot 10^{13}$ K.
VSOP 6 cm results are similar.
The inverse-Compton limit of 10^{12} K is confirmed if Doppler boosting is involved. And we know from VLBI kinematics measurements (Lorentz factors up to 50 are estimated) that jet emission is indeed boosted.
But! Many lower limits on T_b… ISM…

Special role of RA:
Is there anything beyond 5 Earth diameters (ED)?
RadioAstron AGN survey: estimate correlated flux density, size, brightness temperature of most compact structure(s) in the AGN jet base. Test the IC limit boosted by Doppler. Overcome the Earth-based Tb limit. This can not be done by going to higher frequencies on the ground.
Critical to test emission mechanism. Introduce/support or “kill” exotic models.

AGN survey: probing jet emission mechanism

Records:

18 cm: 27 ED 0048-096 (RA-GBT) – 349,000 км;

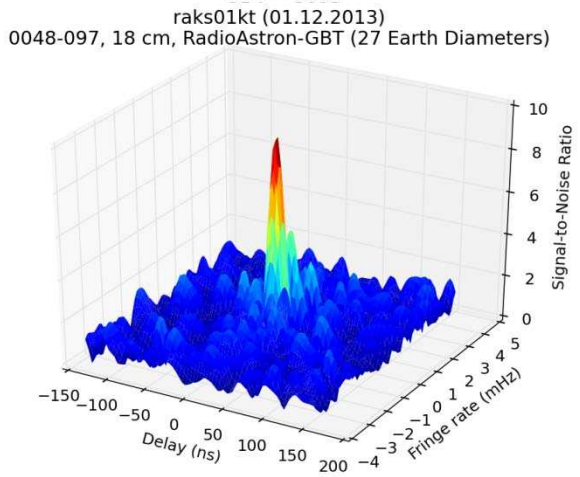
6 cm: 23 ED 0716+714 (RA-Ef);

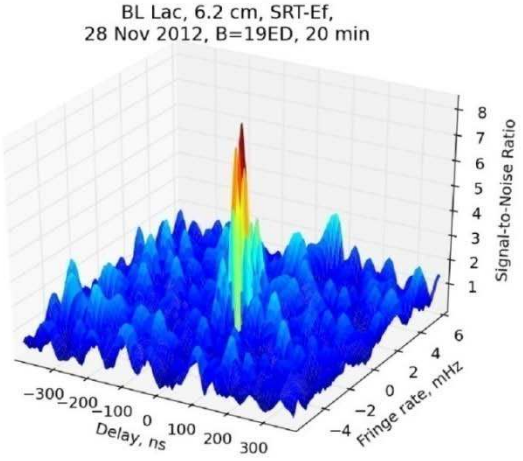
1.3 cm: 15 ED 0235+164 (RA-GBT).

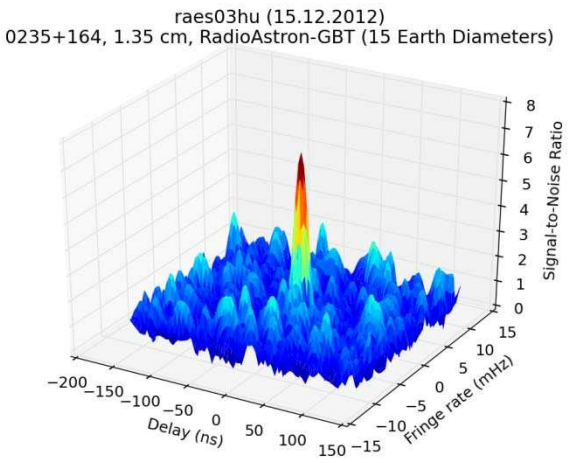
The new record of formal angular resolution: 14.5 μas;

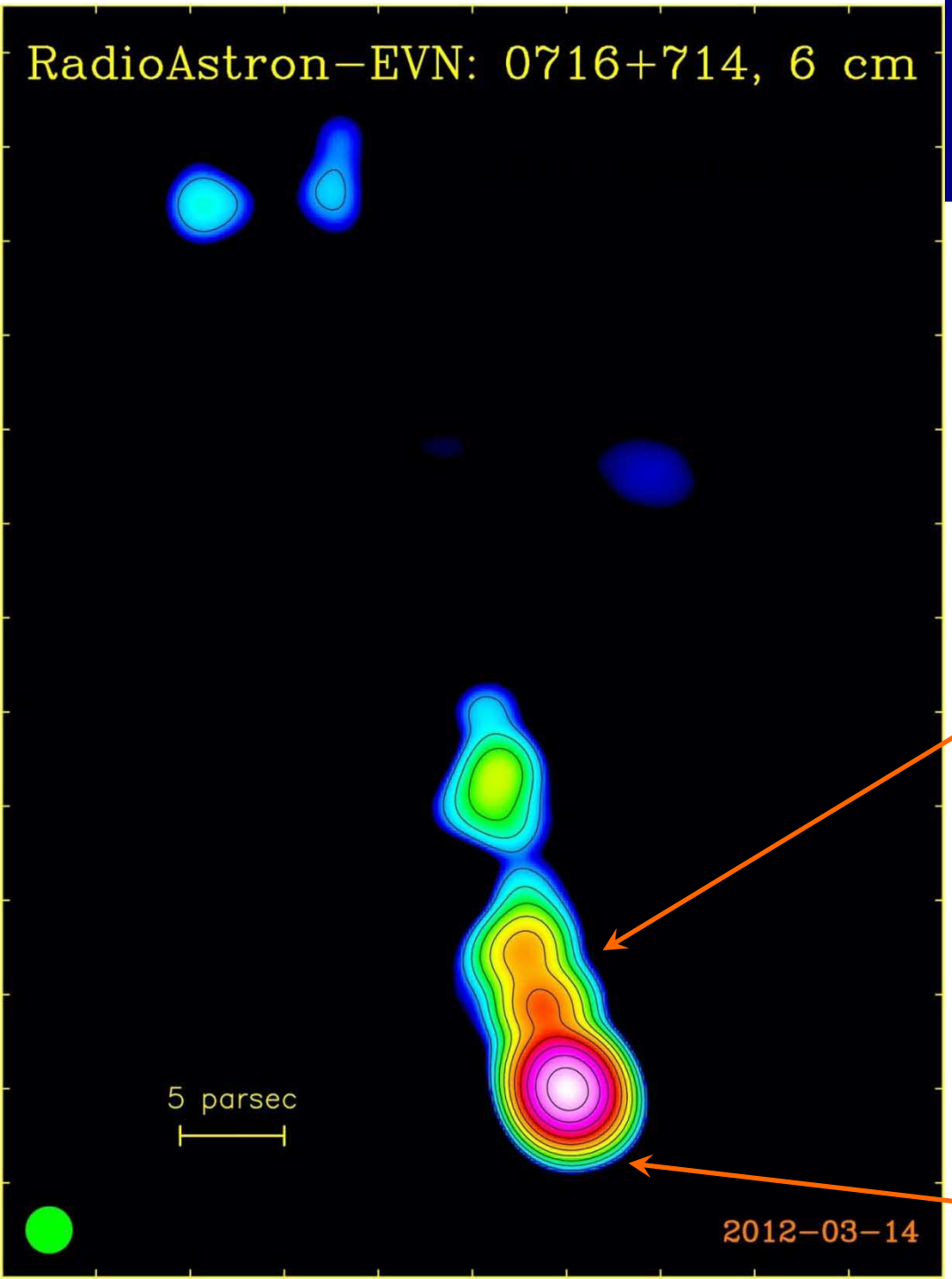
Correlated and post-processed to date 900 segments, significant detections are found for 80 AGNs in 280 of them.

Typical T_b so far are still in the range 10^{12} to $>10^{14}$ K. Requires high Doppler boosting (typical δ~10-100 and higher) if relativistic electrons.



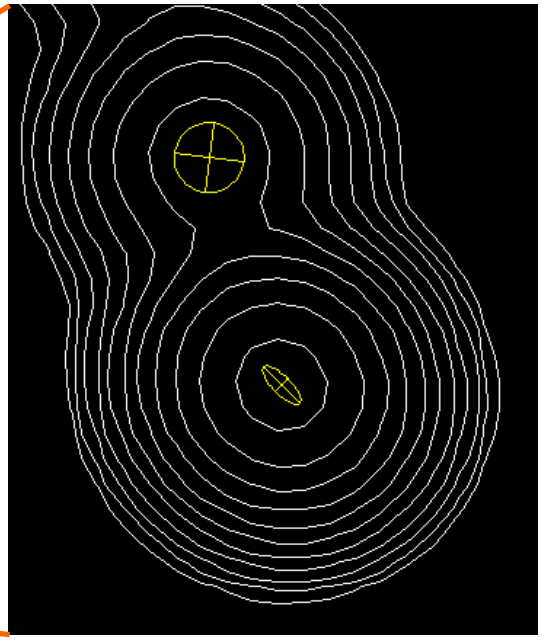






First RA imaging of an AGN: 0716+714, z = 0.3

Apparent jet base width:
0.3 parsec (70 μas).
Brightness temperature:
$3 \cdot 10^{12}$ K *(but low activity state).*
In high activity state Tb increases by more than one order of magnitude.



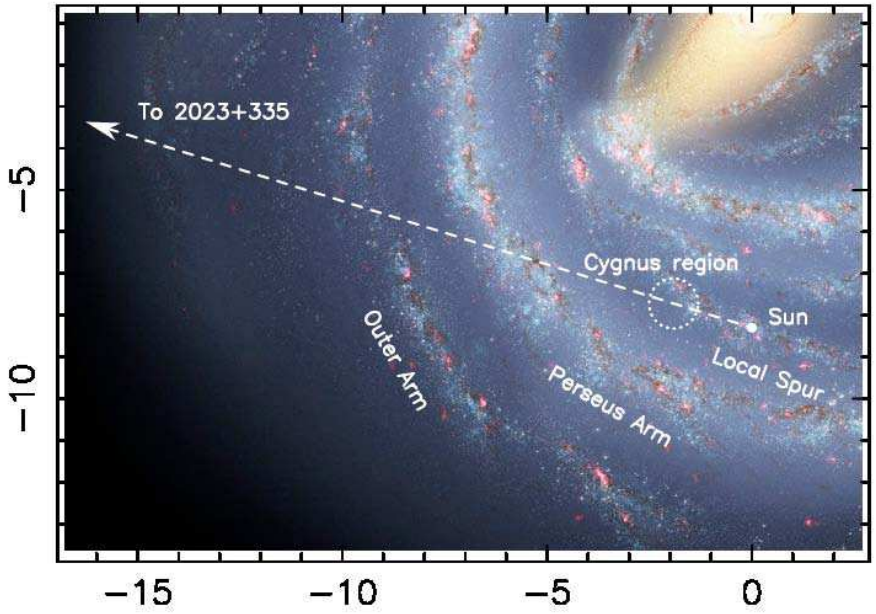
How to generate very high brightness temperature?

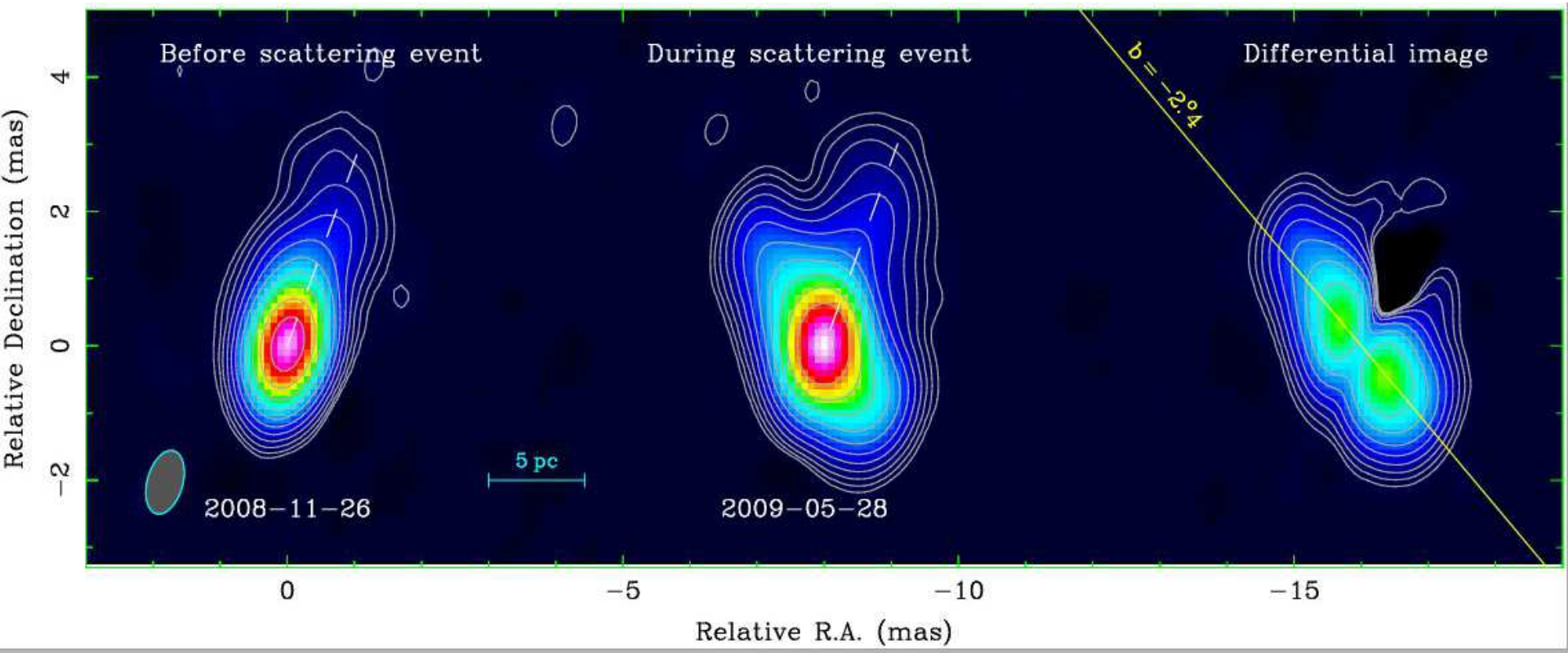
- ✓ Heavy particles – requires very efficient acceleration and high magnetic field.
- ✓ Coherent processes – requires very high magnetic field.
- ✓ Continuous acceleration (supply of energetic particles).
- ✓ Unusual core geometry or electron energy distribution
- ✓ Very high Doppler boosting $\delta \sim 100$ – kinematics does not confirm it.

Quasar 2023+335

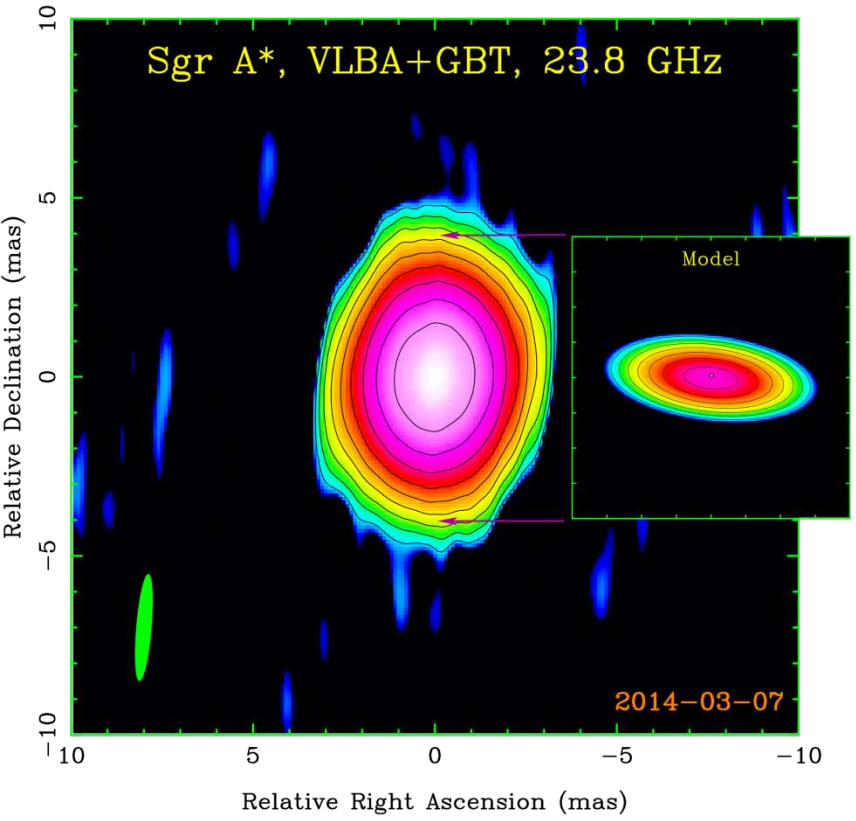
«Multiple imaging» of an AGN by an interstellar refractive scintillations on a dense interstellar cloud of free electrons, screen parameters:
56 km/s, 0.4 AU.

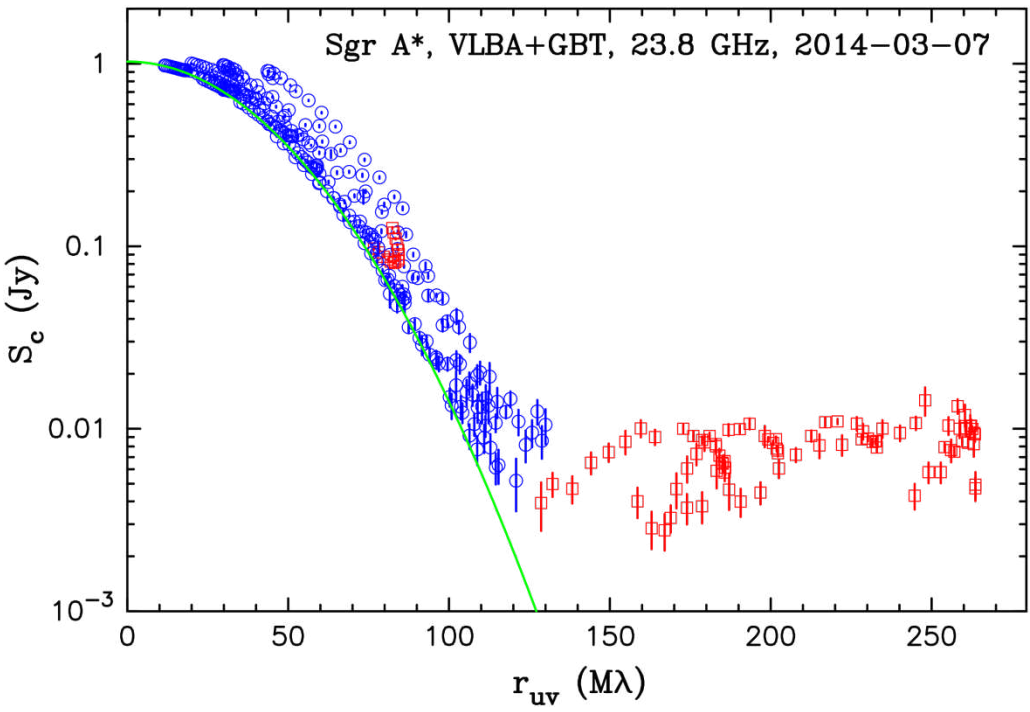
Pushkarev et al. (2013)





SgrA*: Discovery of a substructure in the scattering disc





Gwinn et al. (2014, ApJL, in press)

Thank you

Kinematics Summary

- 98% of motions are outward from core
- 38% have non-radial motions
- 39% have >3σ accelerations
- Speed distribution:
  - peaked at low speeds
  - only 2 jets with $\beta_{app} > 30$
  - high Γ jets are very rare in parent population