The Unique Contribution of Space VLBI Polarimetry

Denise Gabuzda
University College Cork

Outline of talk

o Quest for higher resolution & sensitivity

o Polarization VLBI into the future

o The unique contribution that can be made by space VLBI polarimetry

Ongoing quest for higher resolution & sensitivity

o Scientific picture of AGN jets that has been emerging

➢ Jets are launched electromagnetically, probably by combination of Blandford—Znajek & Blandford--Payne

➢Overall magnetic field structure is due to embedded helical B field (generated and imprinted during launch), superposed by fields due to shocks, shear etc.

➢ Variability is due to turbulence, shocks, reconnection

Of interest both to push inward toward jet base and to study details of the jets themselves – B field structure along and across the jets – need resolution & sensitivity.

Moving toward higher sensitivity

o Data rates of 2048–4096 Mbits/s now possible, total BW per polarization of 256–512 MHz (2-bit sampling)

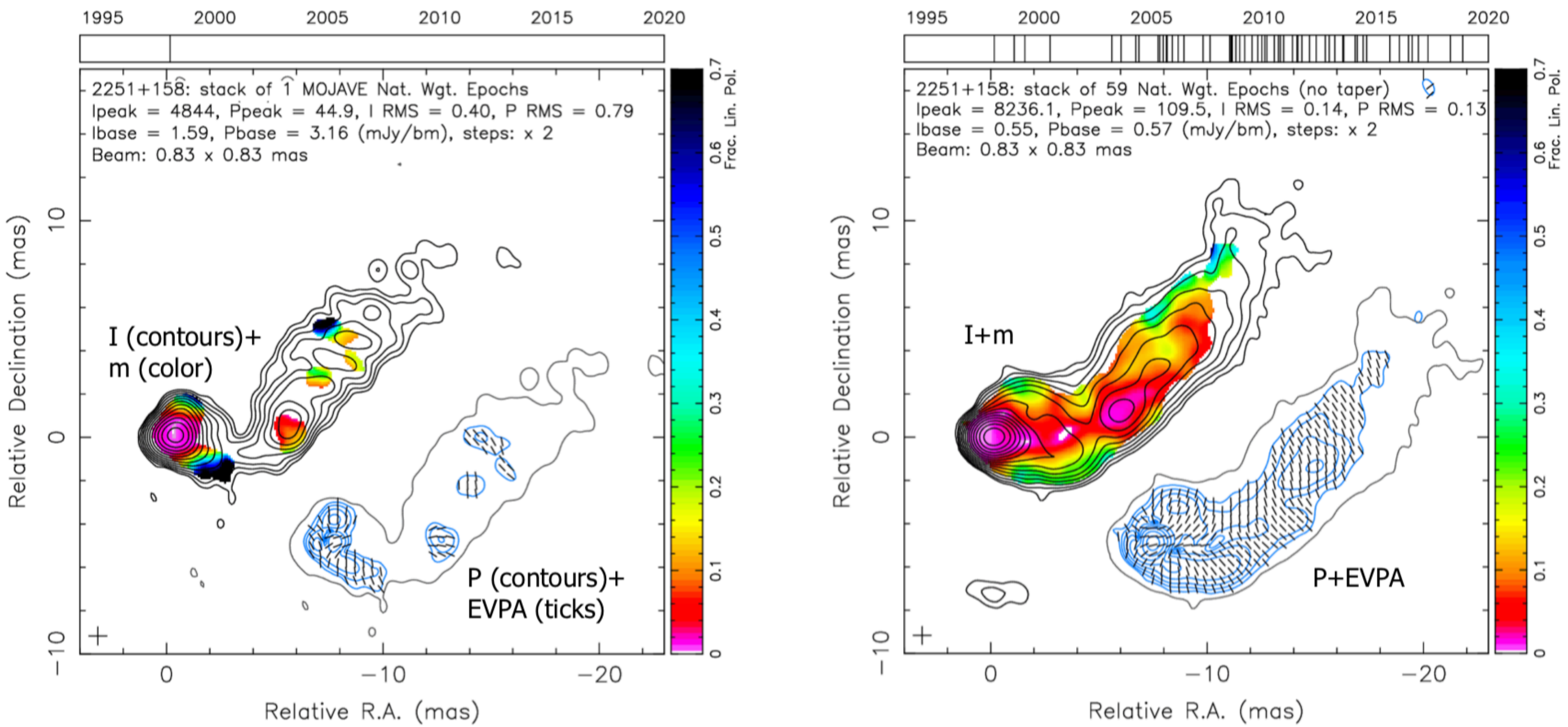
o Large samples (MOJAVE 15-GHz) – stacking of large numbers of images can reveal average or persistent structure

o Real-time correlation (e-VLBI)

o Increased storage capacity of data disks makes all this feasible

Stacking of ~60 MOJAVE images for 3C 454.3

A creative way to get a very long integration and high sensitivity, but lose info on variable structures



Single-epoch map: patchy P detection

Stacked map: complete in P; delineates stable B-field comp.

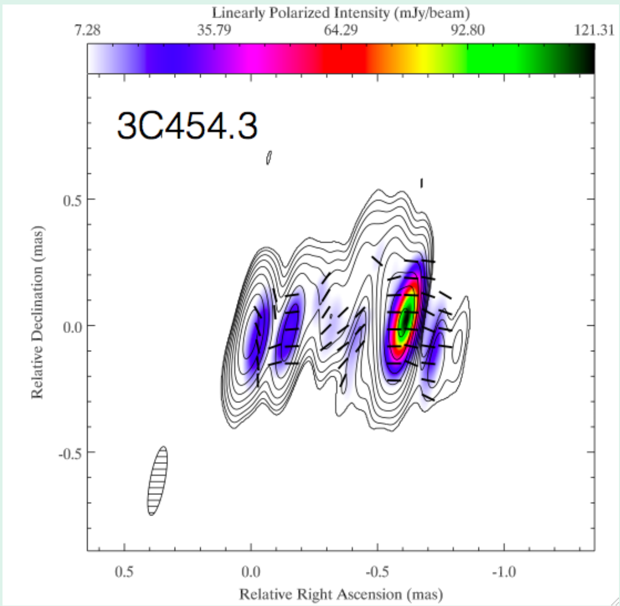
Pushkarev et al. (MNRAS, submitted)

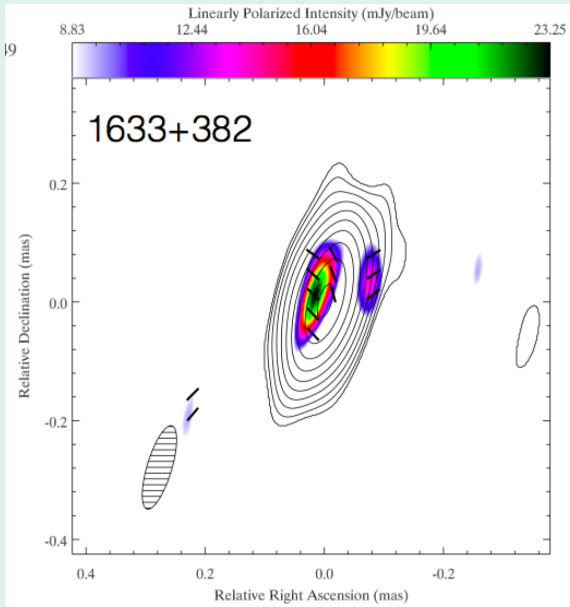
Moving toward higher resolution

o Push toward higher frequencies (GMVA, 86 GHz)

o Gives better resolution and lower opacity, but also technical difficulties – pol VLBI at 86 GHz is still fairly limited, and pol VLBI at 230 GHz is extremely difficult

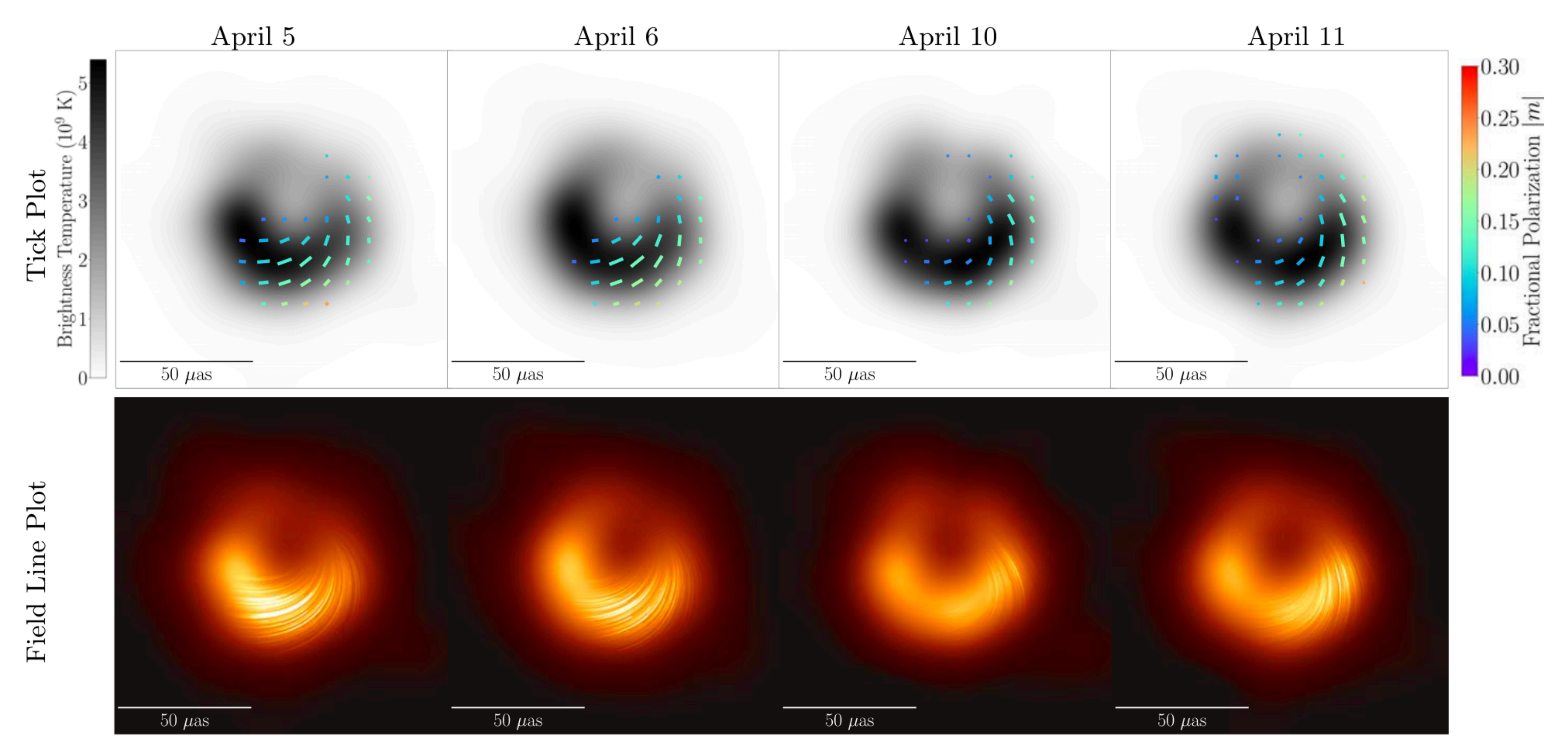
86 GHz intensity and linear pol images by Casadio et al. (2017)





Event Horizon Telescope (230 GHz, 345 GHz) – Innovative work on techniques for deconvolution and pol calibration – first pol results at 230 GHz now available. Focus on only a few objects.

EHT VII, VIII – Akiyama + (2021); simulations – Palumbo + (2022)



Polarization VLBI in the future - what we need

o Higher sensitivity, get pol info for regions of weak or extended emission, not just core and bright knots. Stacking helps, but probes only average or persistent structures

o Routine "D-term" and pol angle calibration

o Routine multi-frequency capability (spectral indices, Faraday rotation)

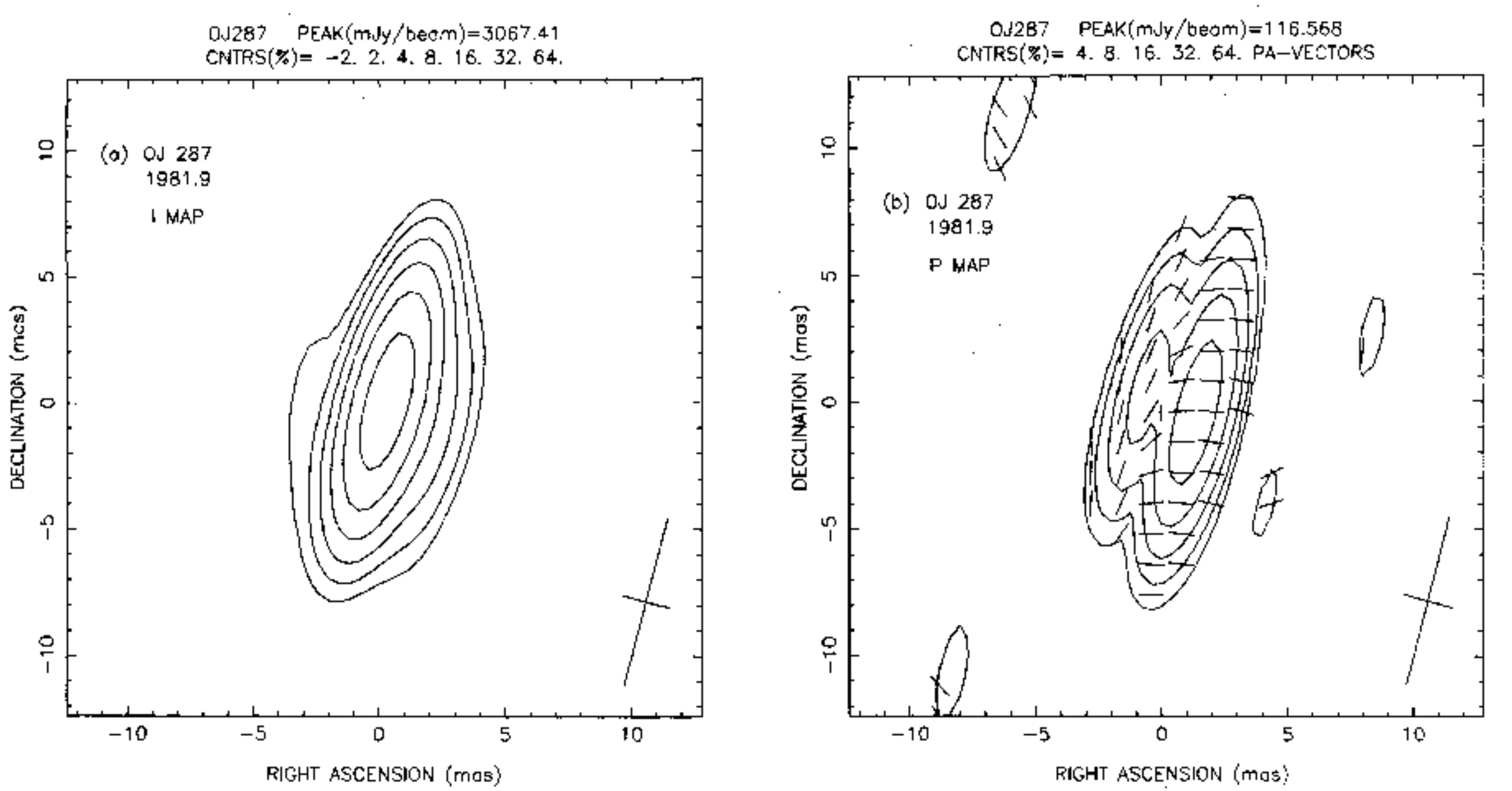
o Circular polarization measurements still require special expertise; need ability to perform CP measurements much more easily

The unique contribution of Space VLBI

o Unique feature: ***high resolution at low frequencies***

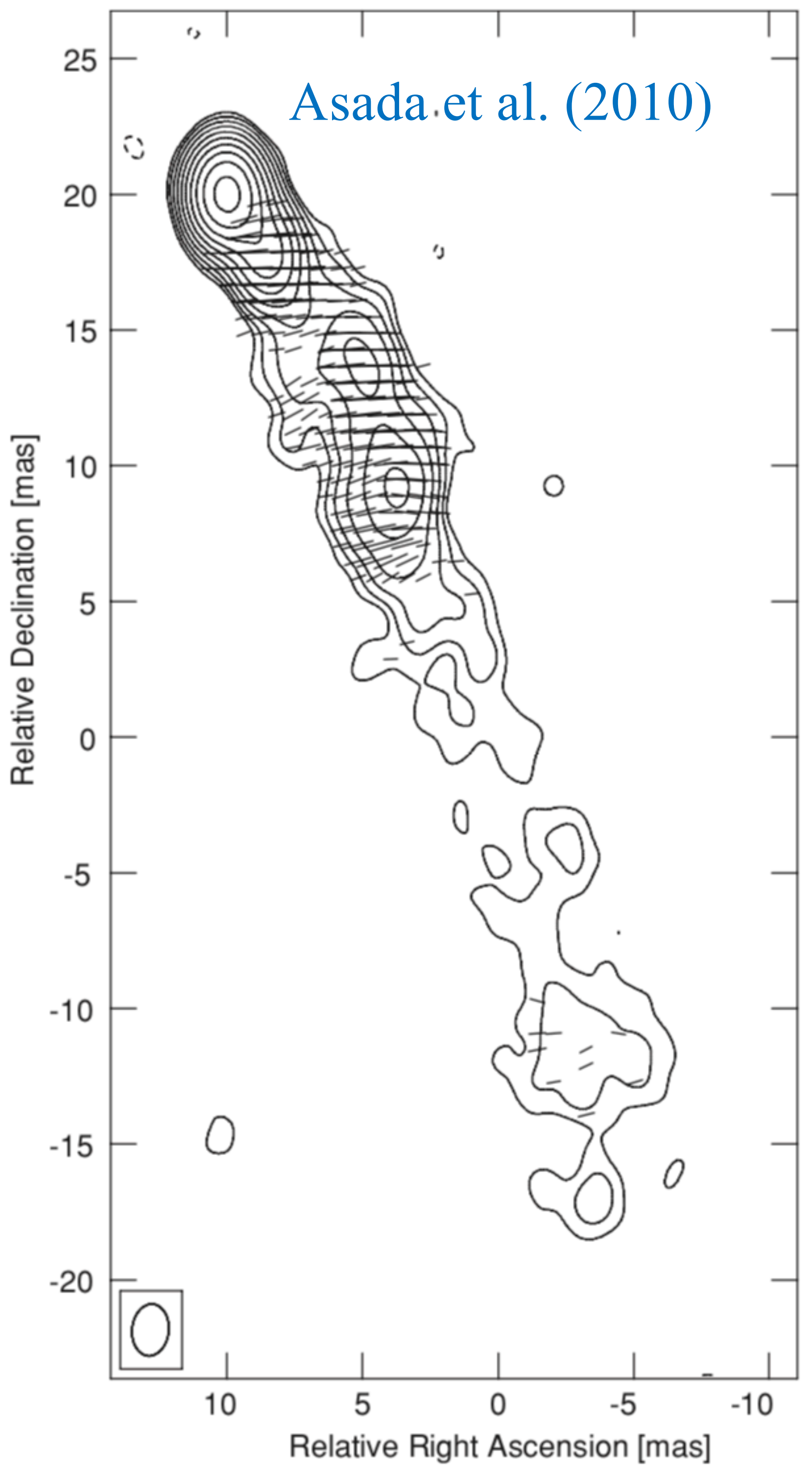
o Enables more detailed and deeper imaging of optically thin regions (e.g. AGN jets) at lower frequencies, where they are more prominent

o Enables study of effects that are inherently stronger at lower frequencies – opacity effects, Faraday rotation – providing physical information that cannot be obtained with high frequency observations

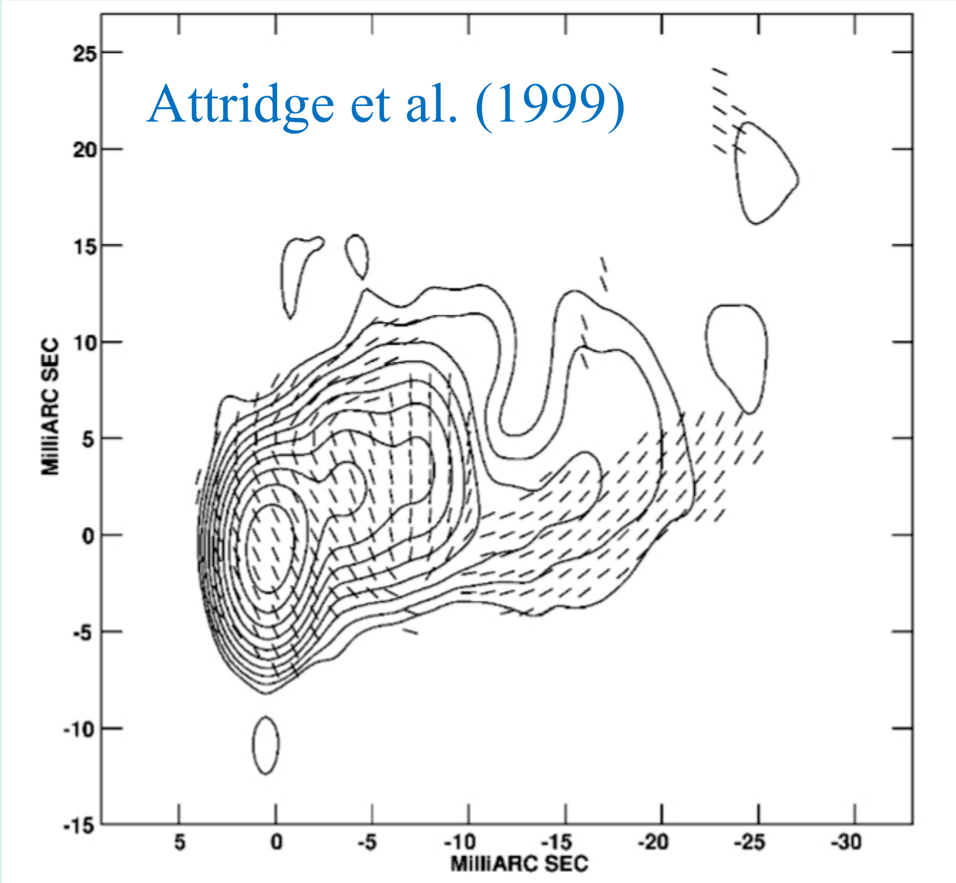


Roberts, Gabuzda & Wardle 1987

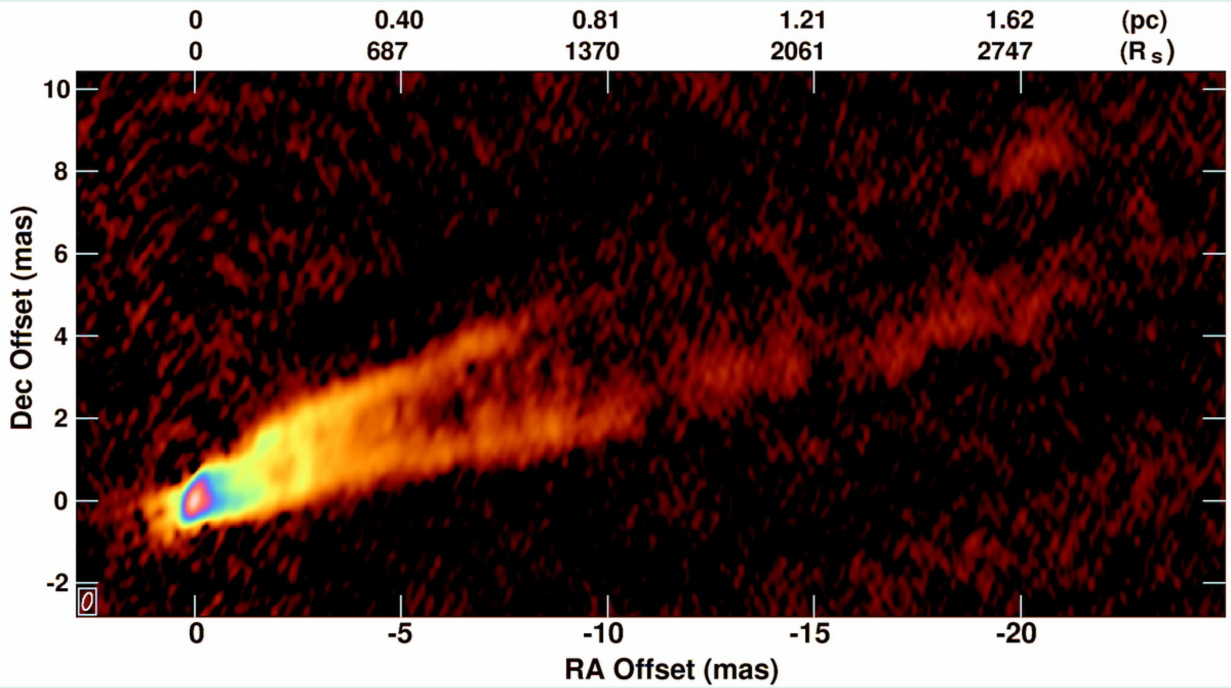
Polarization effectively provides enhanced resolution due to its vector nature — the improved resolution of space VLBI can increase match between I and P structures – and hence our physical understanding.



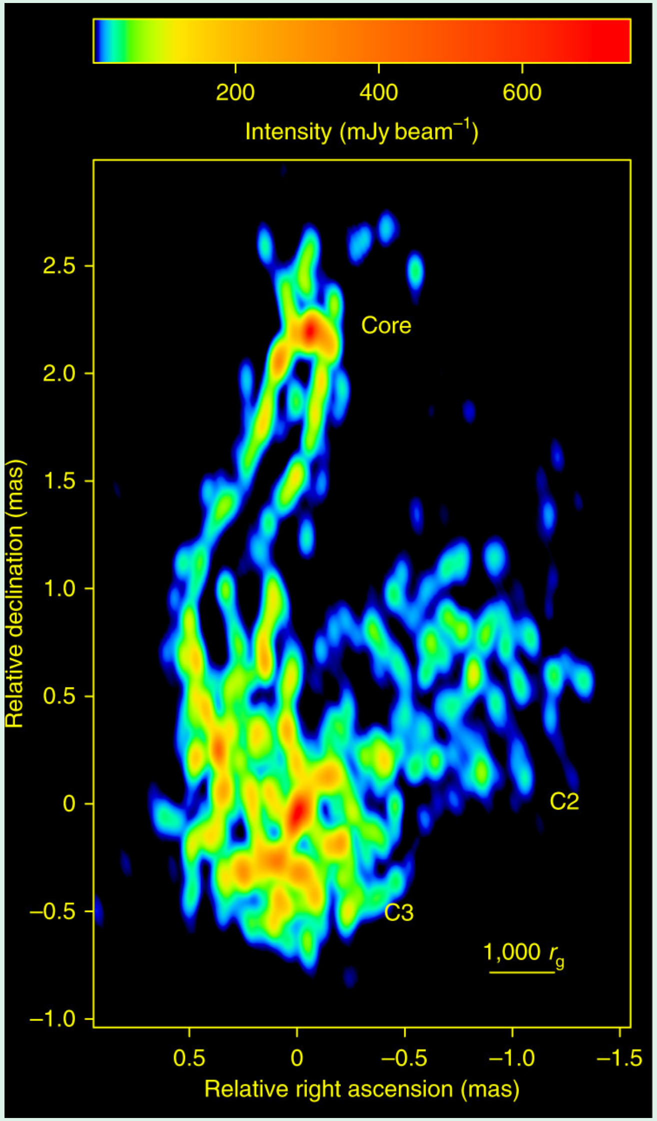
Polarization can also give effective increased resolution across the jet



Need for resolution: several jets with striking edge brightening have been found. Want to detect polarization all across these well resolved jets!



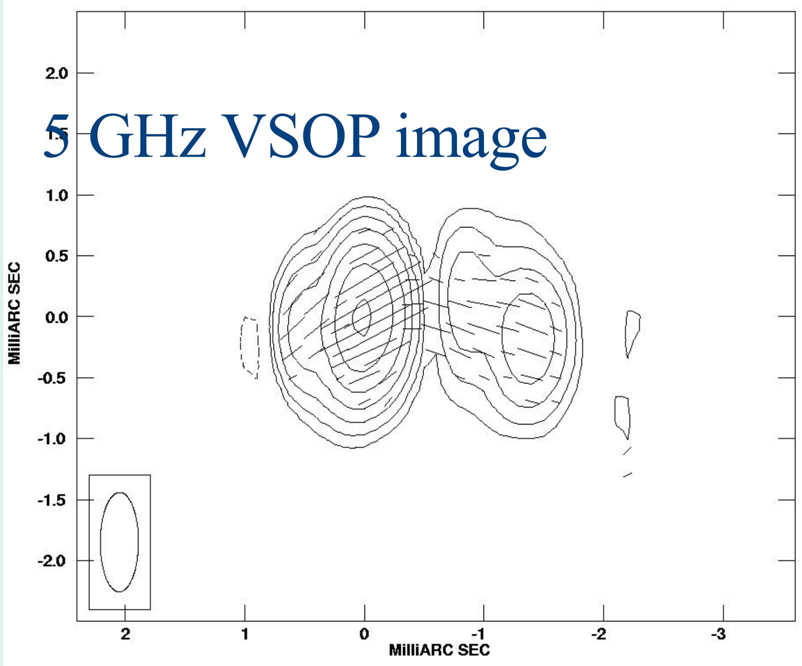
M87: Walker et al 2018



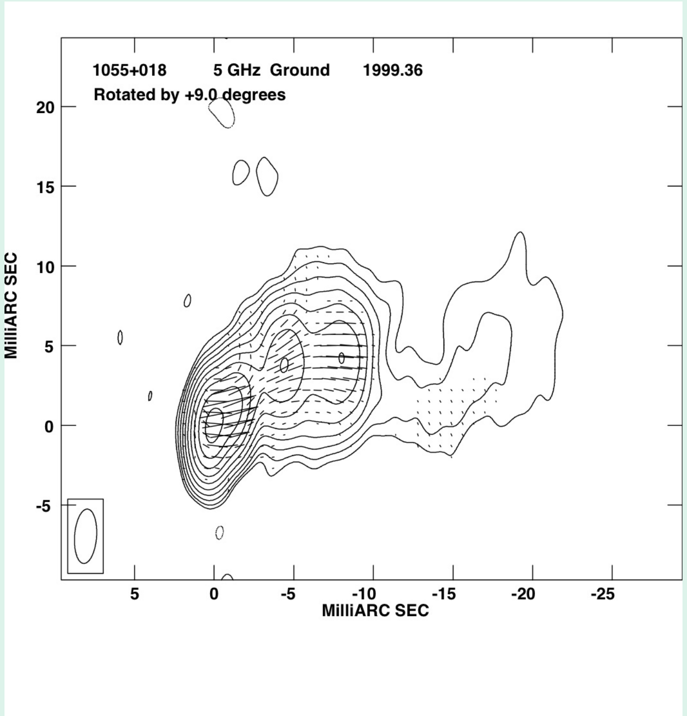
3C84: Giovannini et al. 2018

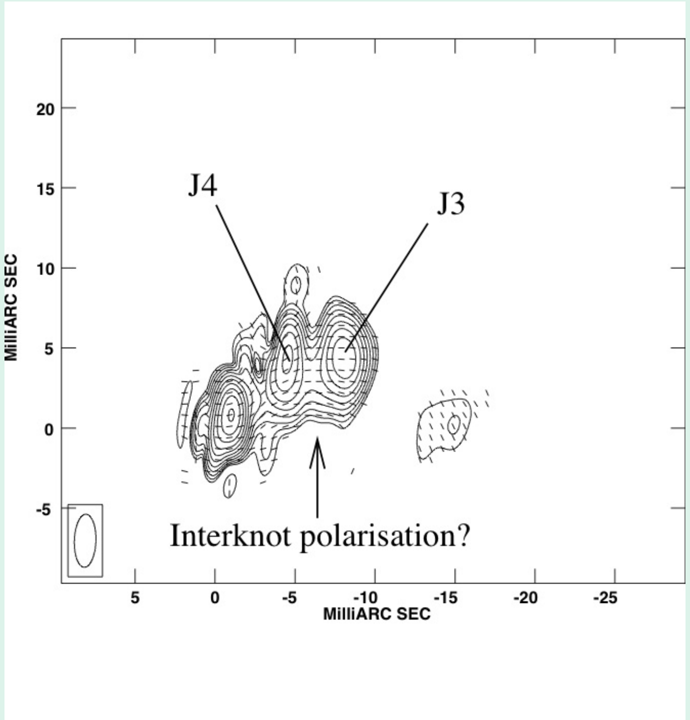
Need for sensitivity: want to detect polarization in regions of weak emission and interknot regions (underlying B field)

5 GHz VSOP image



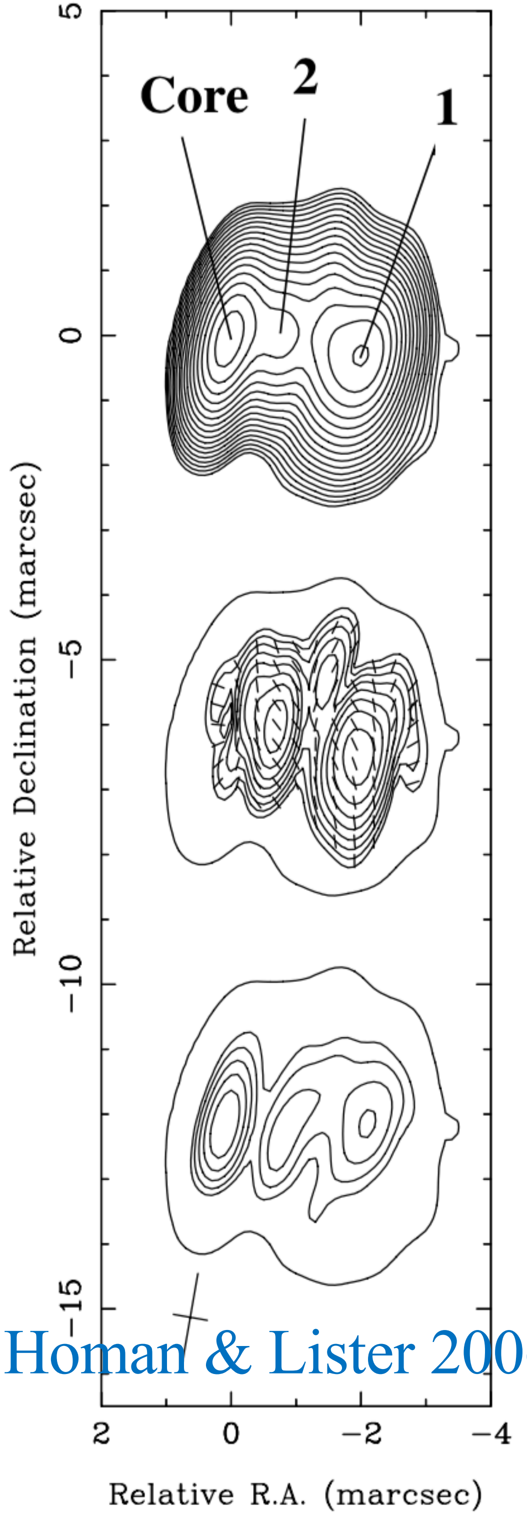
Gabuzda 1999



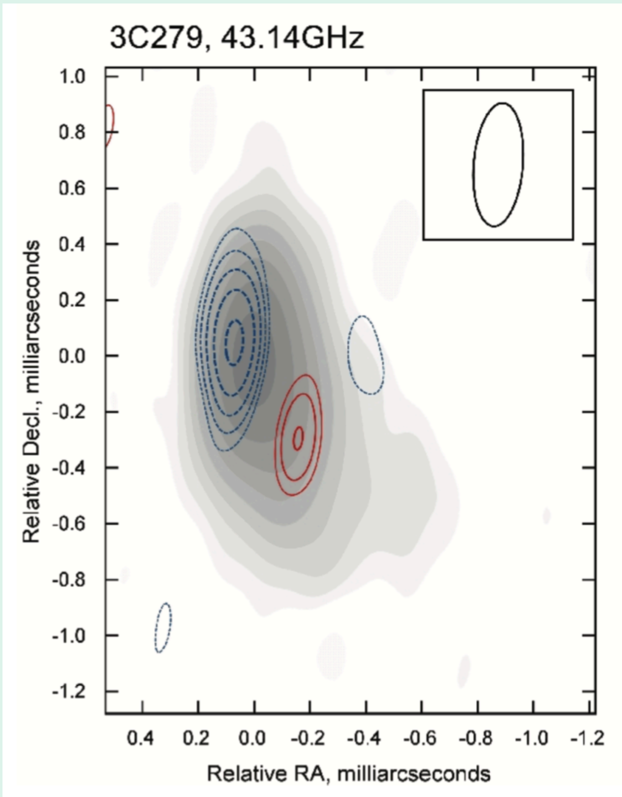


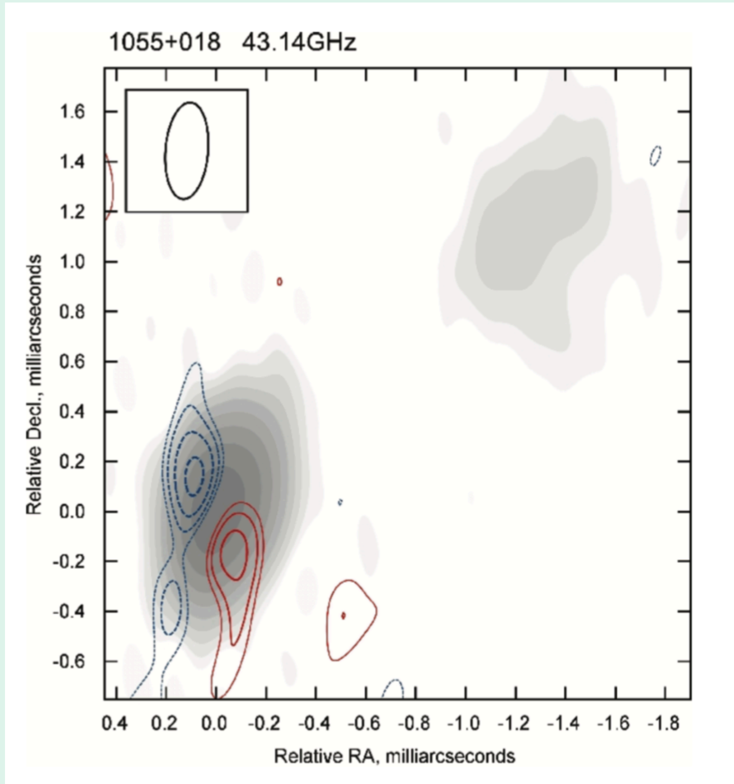
Pushkarev et al. 2005

Circular polarization can also display structure along and across the jet, which needs to be accurately detected and matched to intensity and linear pol structures



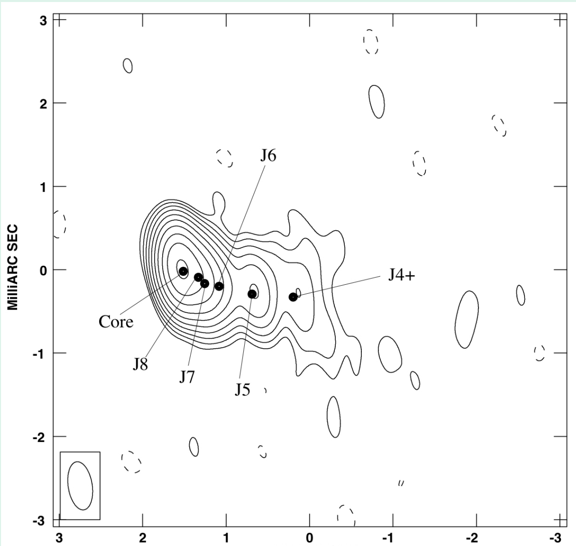
Homan & Lister 2006

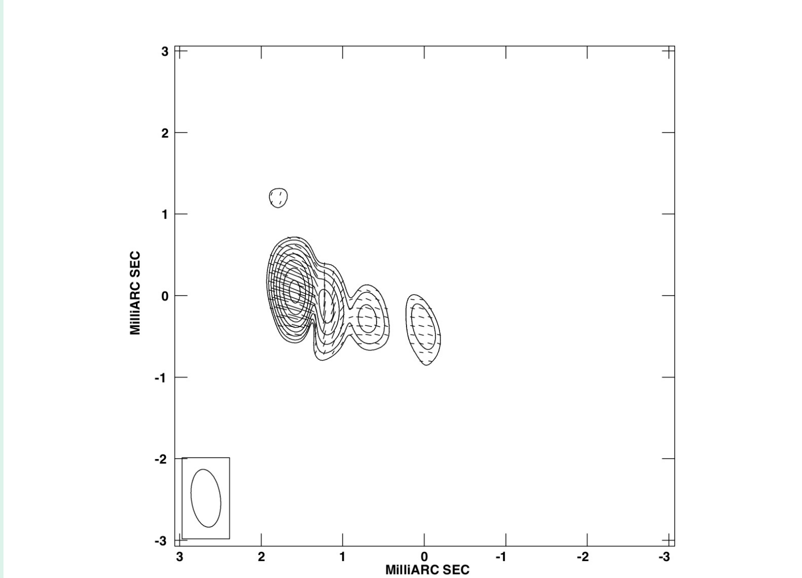


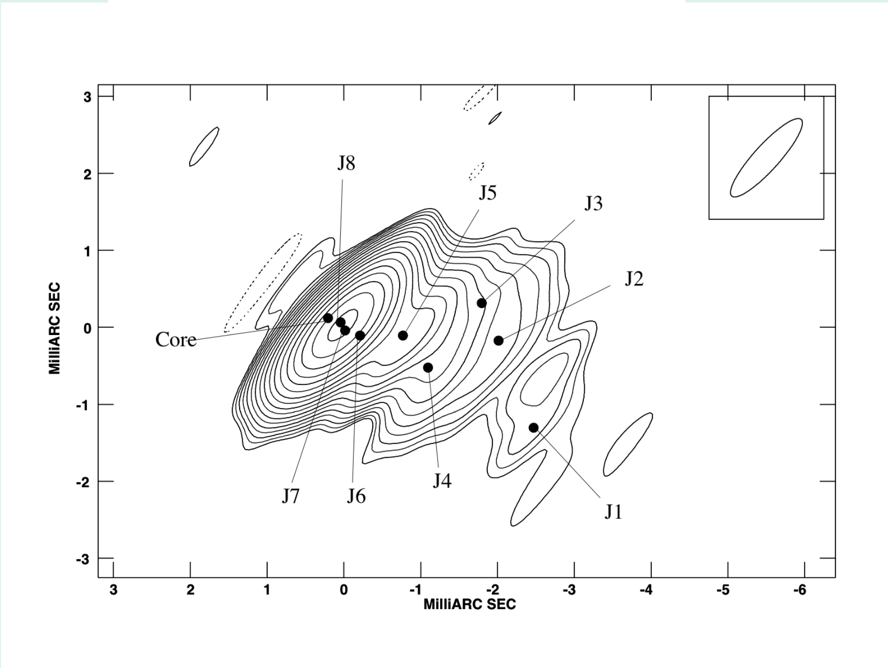


Vitrishchak et al. 2008

Has a 90° flip in pol angle associated with optically thick – thin transition been observed? (5 GHz VSOP + 22 GHz VLBA observations of OJ287 – Gabuzda & Gomez 2001)







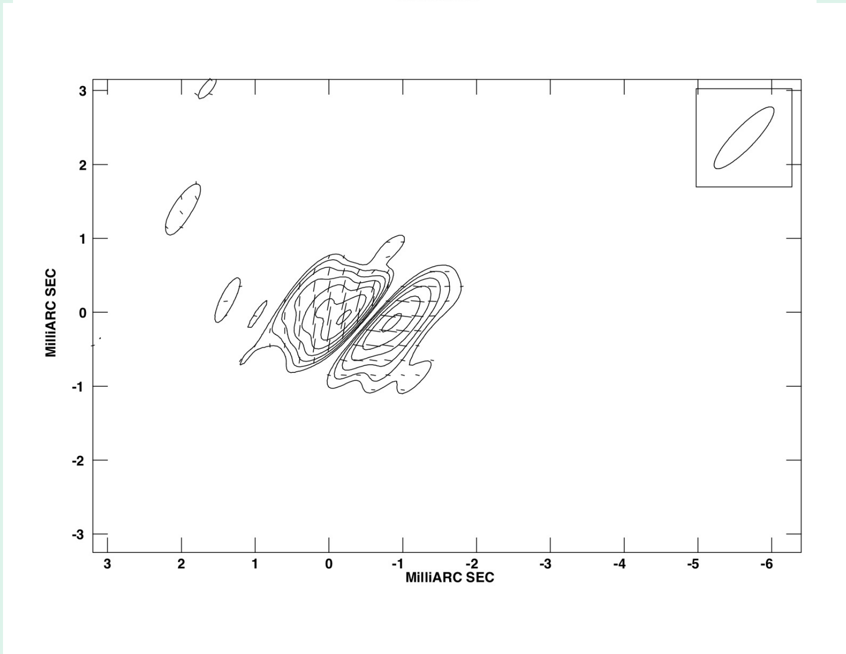


Table 2. Component spectral indices.

	I_{6cm} (mJy)	$I_{1.3cm}$ (mJy)	α
C	300	1238	+0.92
J8	400	194	−0.47
J7	598	274	−0.51
J6	194	106	−0.39
J5	214	79	−0.65

5 GHz space & 22 GHz ground have comparable resolution.

Core: χ differs by ~70^{o}

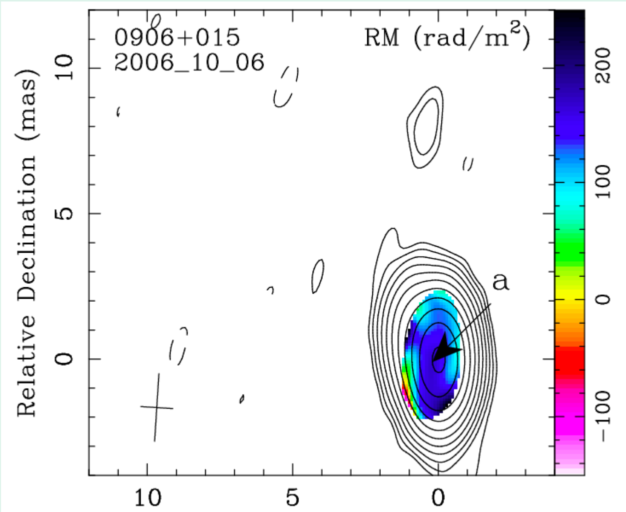
Jet: χ differs by < 10^{o}

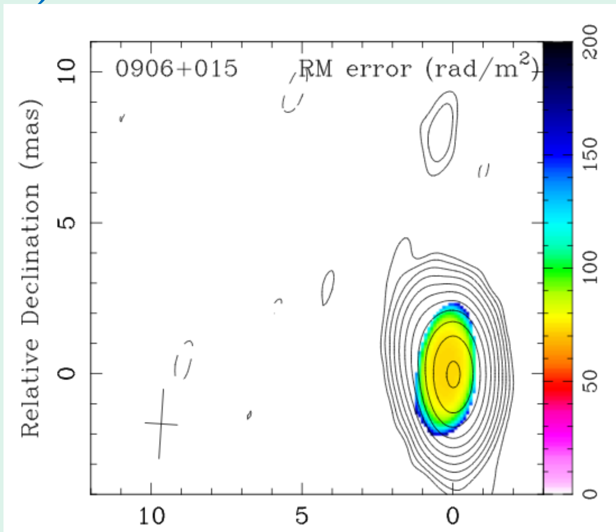
Is the core difference offset from 90^{o} due to Faraday rotation?

Wardle (2018) has noted that the 90^{o} flip actually occurs at high optical depths, $\tau \gg 1$. Is the entire difference of ~70^{o} in the core therefore due to Faraday rotation??

It's crucial that genuine multi-frequency observations become more routine!

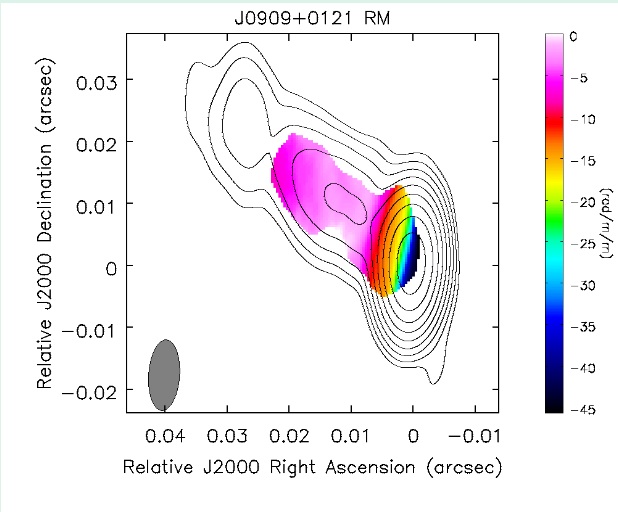
Faraday rotation has a λ^2 dependence: need good resolution at comparatively long wavelengths to distinguish Faraday Rotation Measure (RM) structures!

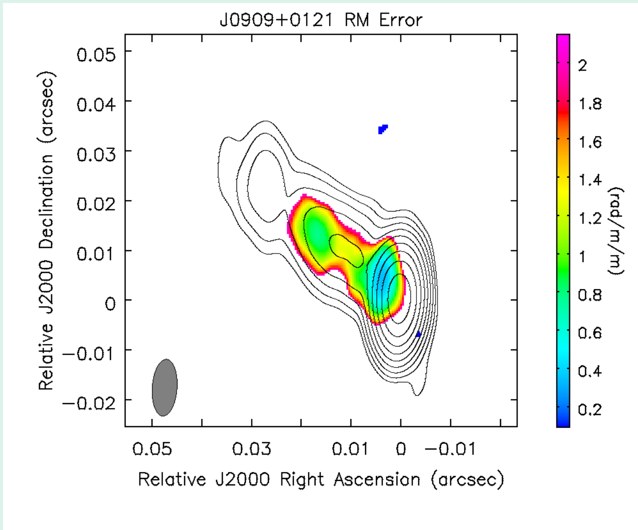




8–15 GHz (Hovatta et al. 2012)

Errors 75-150 rad/m^2



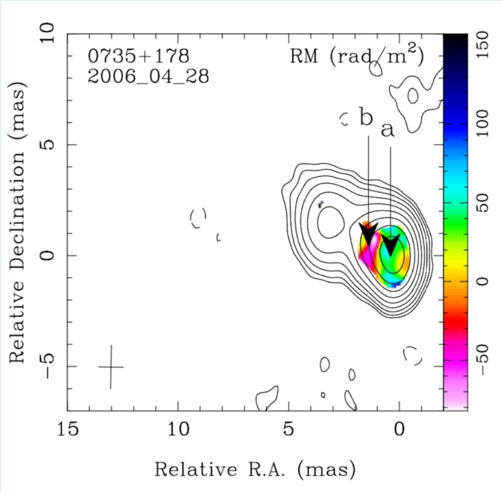


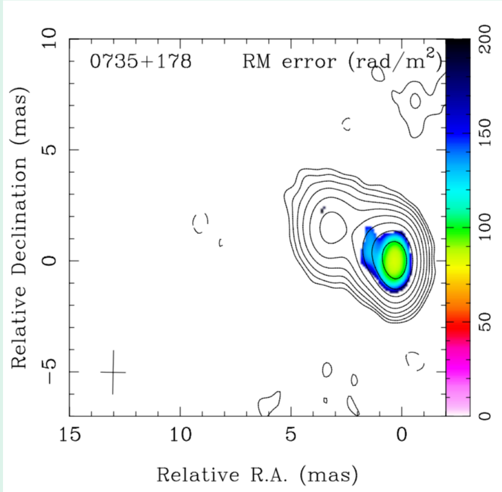
1.4–5 GHz (Gabuzda et al., in prep)

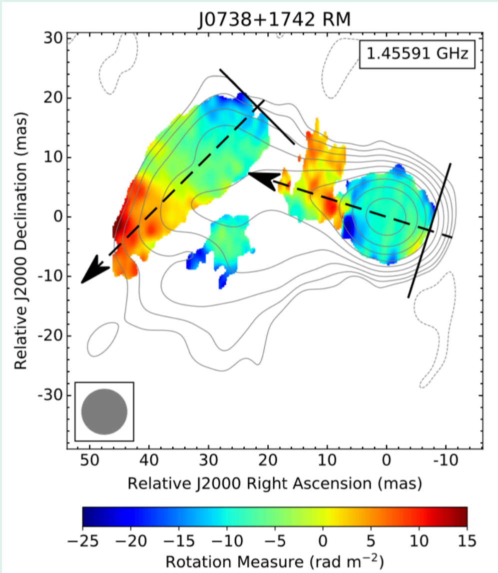
Errors < 2-3 rad/m^2

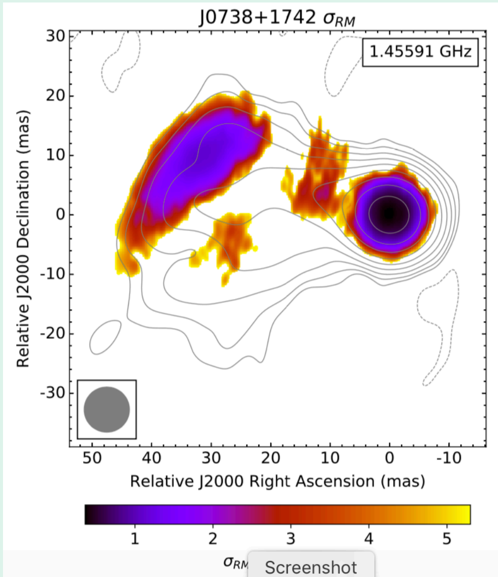
RM maps

RM error maps









8—15 GHz (Hovatta et al. 2012)

Errors 75-150 rad/m^2

1.4—5 GHz (Richardson 2021)

Errors < 4 rad/m^2

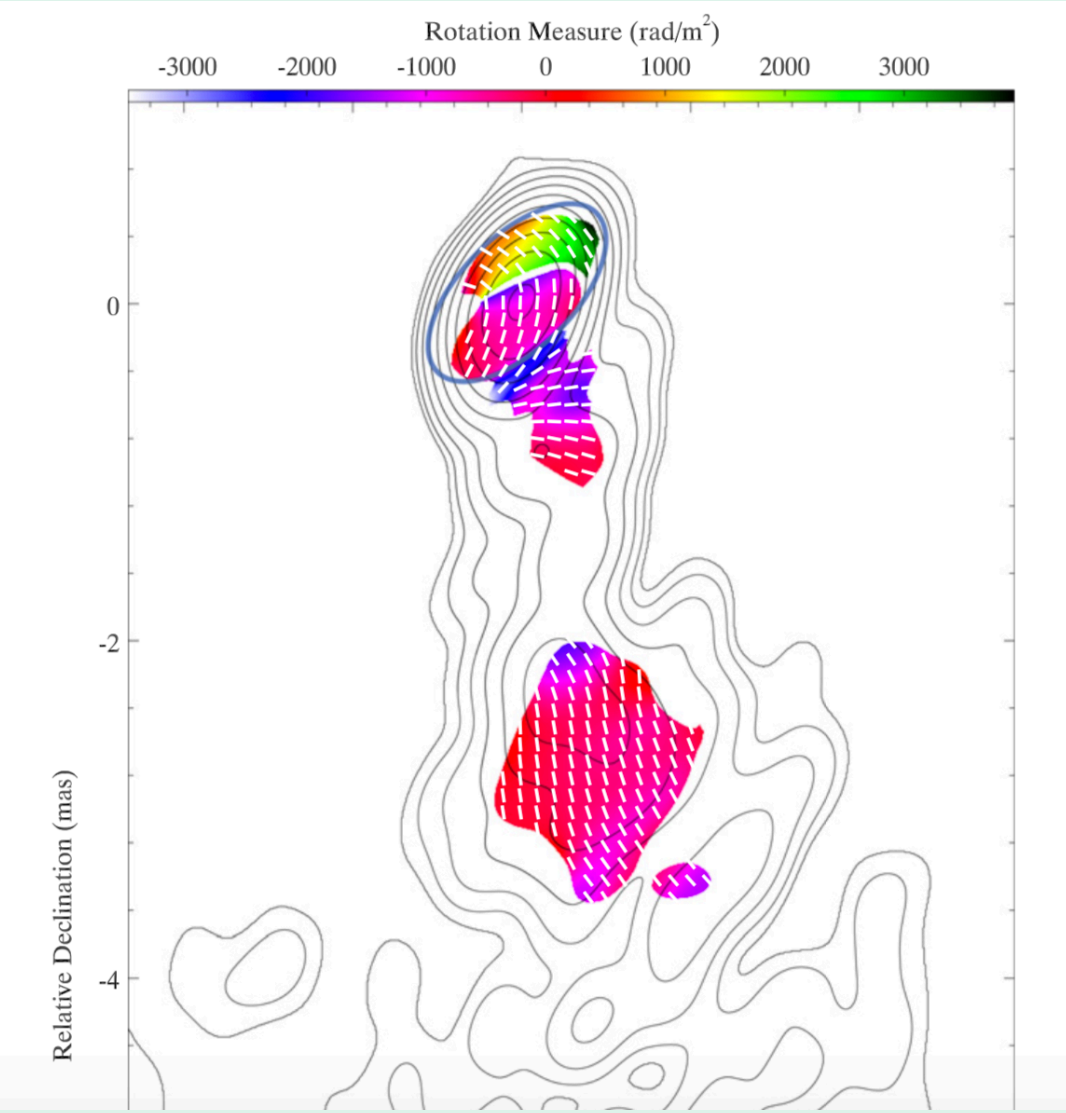
RM maps

RM error maps

Space VLBI at lower + ground VLBI at higher frequencies is ideal for high-resolution Faraday rotation studies – small beam and small RM errors!

•Can choose ground array observation frequencies to have comparable resolution to SVLBI image.

•Can thus make spectral index and Faraday rotation maps with resolution comparable to that provided by the SVLBI array.



An example – RadioAstron at 22 GHz + ground data at 43 and 15 GHz used to produce a Faraday rotation map (Gomez et al. 2016)

Evidence for a helical B field in core region.

Faraday rotations that can be measured are limited by relatively high frequencies used.

Accuracy, detail and resolution of image could be improved using SVLBI pol data at lower frequencies and ground data at higher frequencies, for example:

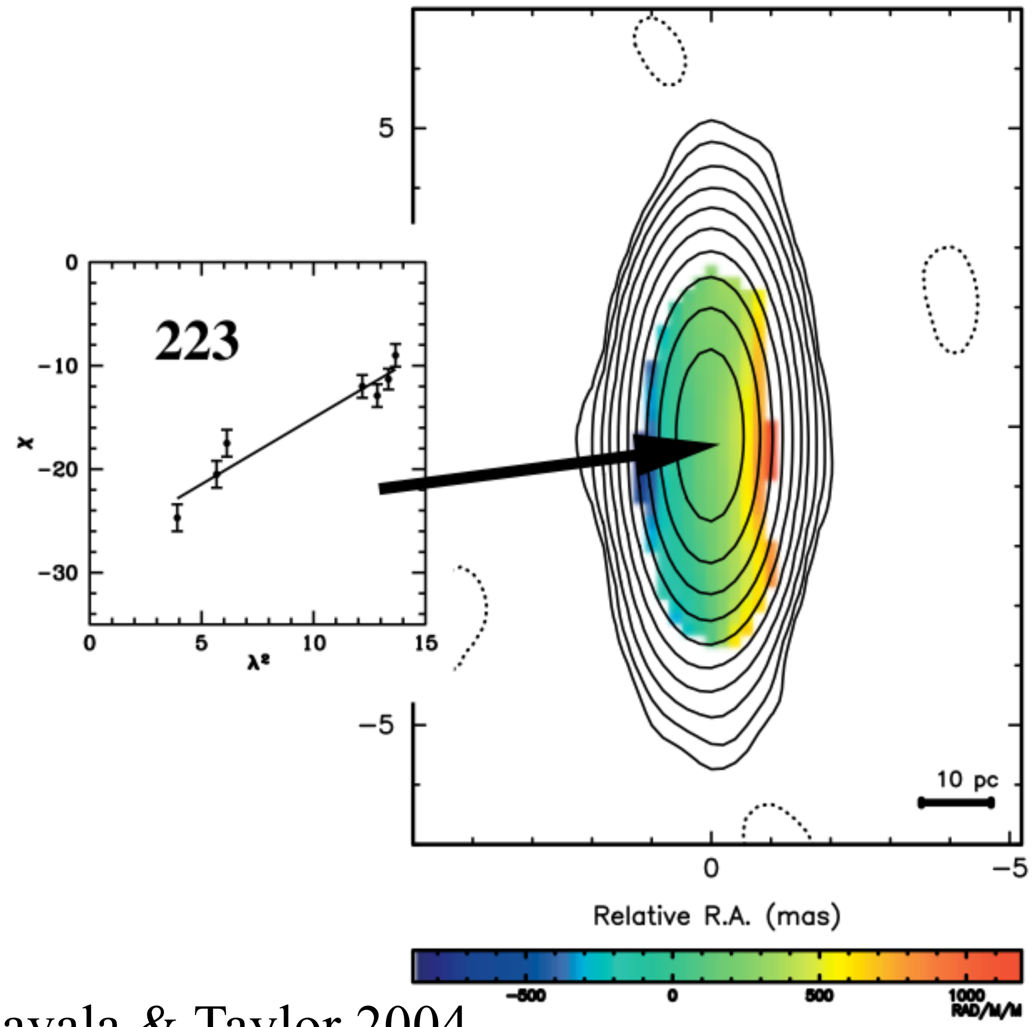
SVLBI 5 – 8 GHz + ground 15 – 22 GHz

$$\sigma_{RM} \sim 35 \text{ rad/m}^2$$

SVLBI 1.4 – 2.2 GHz + ground 5 – 8 GHz

$$\sigma_{RM} \sim 3 \text{ rad/m}^2$$

Which would be preferred depends on trade-off between overall resolution, scales that must be probed, and required RM errors.



Zavala & Taylor 2004

How is this strong RM gradient oriented relative to the jet?

Source is unresolved using ground VLBI: moving to higher frequencies loses sensitivity to jet emission, source remains unresolved.

Space VLBI at relatively low frequencies (high resolution + high sensitivity to jet emission) is needed to resolve I structure and interpret pol and RM structure!

Summary

- Multi-frequency imaging with excellent image quality should become the norm for both ground and space VLBI in the future observations
- Need high sensitivity to detect polarization in regions of weak emission and transverse structure that provide info about nature of B field (in both strong and weak objects)
- Need good resolution at relatively **low** frequencies to distinguish regions with different polarization and Faraday rotation, correctly match and interpret I, P, CP and RM structures

Take-Away Messages

- Don't leave moderate frequencies out when planning space VLBI missions – this would be missing a great opportunity!
- Need moderately low frequencies to probe jets — ideally broadband receivers, such as 5–8 GHz, 1–2 GHz
- Needed to build up a consistent, detailed picture from scales near the event horizon to sub-parsec/parsec scales where the jets are well established.

Cats are at ease in the world of astrophysics.