AGN Jets on Parsec Scales: Recent Results

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Two (complementary) general approaches

- o Detailed studies of individual objects
- o Statistical studies based on many objects

Types of results discussed here

- o Magnetic fields and Faraday rotation
- o Changes in jet ejection direction
- o Multi-waveband correlations

Well-established characteristics

o One-sided jet structure (due to Doppler beaming/debeaming of approaching/receding jet)

o Superluminal motion of jet "knots" (shocks?) common, as well as stationary features

o Jet B fields tend to be close to aligned with or orthogonal to the local jet direction

o Faraday rotation measures tend to be enhanced in core region compared to jet (higher electron density?)

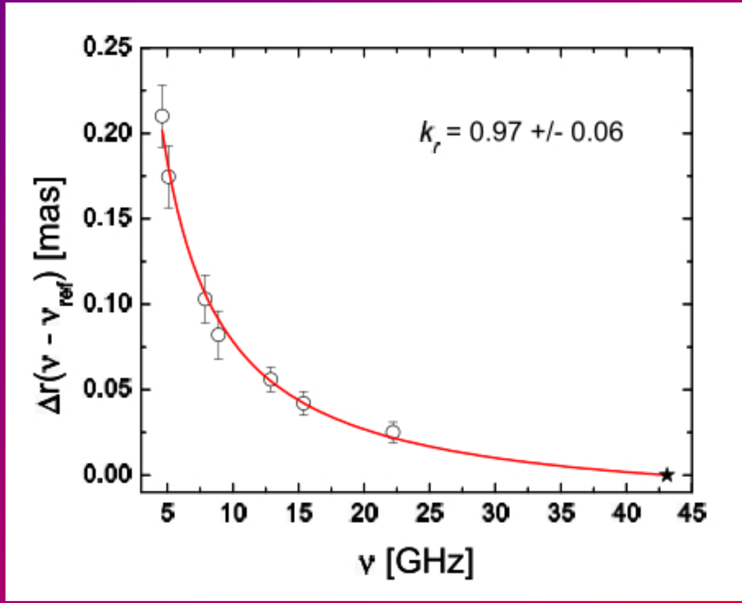
Magnetic Fields & Faraday Rotation

Direct estimation of pc-scale B field strengths possible based on measurement of frequency-dependent position of VLBI core (Konigl 1981; Lobanov 1998)

$k_r = ((3-2\alpha)m + 2n - 2)/(5-2\alpha)$

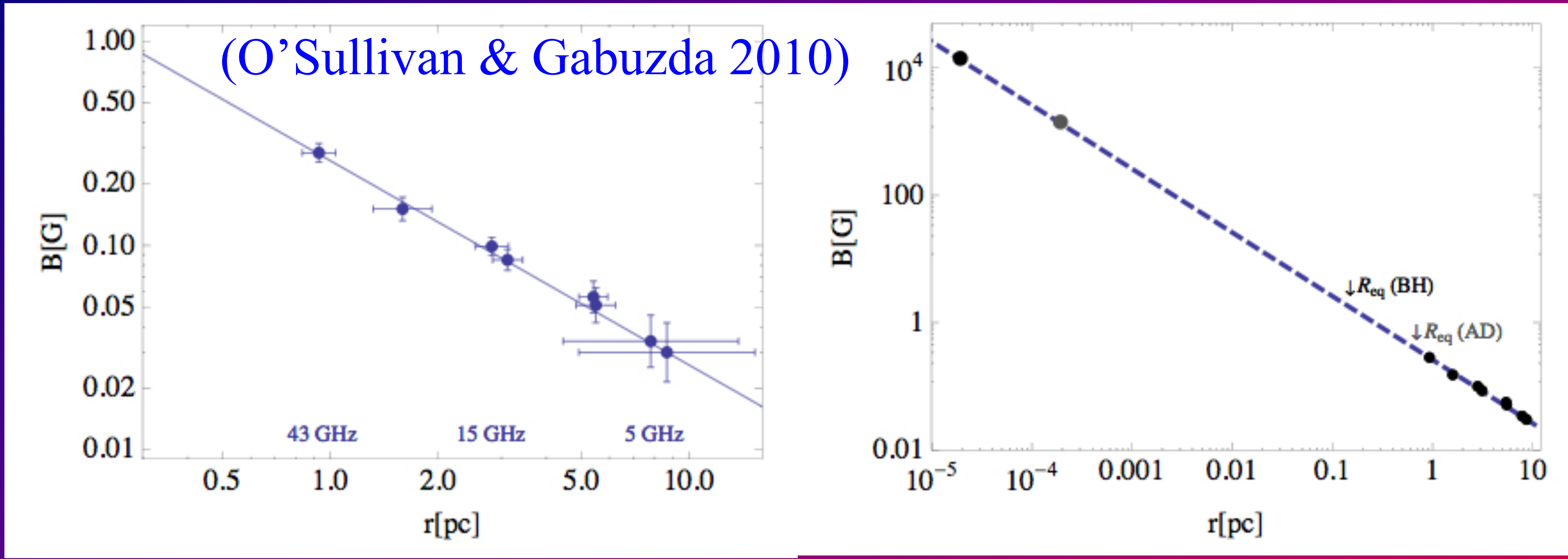
$B \sim r^{-m}$ $N \sim r^{-n}$

$r \sim \nu^{-k_r}$



(O'Sullivan & Gabuzda 2010)

- Behaviour expected for Blandford-Konigl jet is observed
- Evidence for equipartition - values for parameter k_r often (not always) close to 1



- Inferred core-region B fields are usually tenths of Gauss

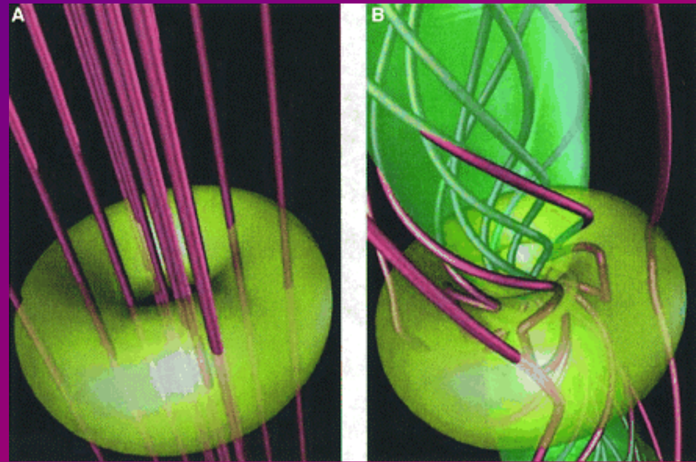
- Data consistent with $B \sim r^{-1}$

- Extrapolation of B field to smaller scales gives values consistent with magnetic launching of jets (points shown are for r_g and $10r_g$; Komissarov et al. 2007)

(See also poster by McCann & Gabuzda)

Do AGN jets carry helical B fields?

Meier, Koide & Uchida 2001



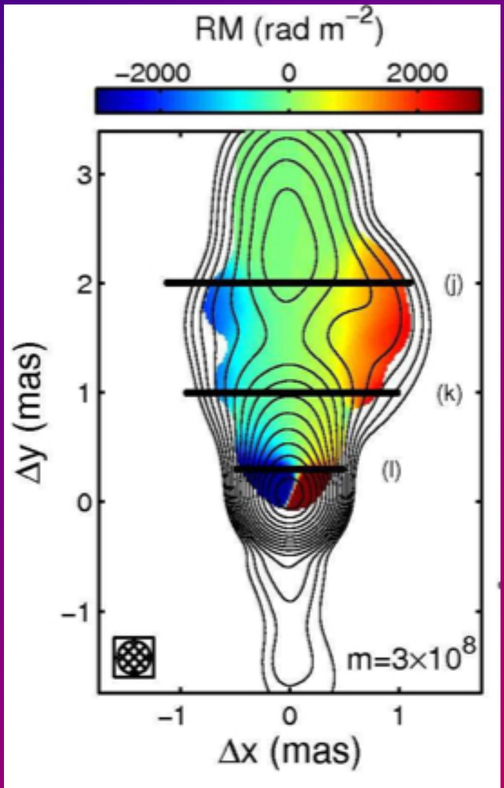
Potential sources of direct observational evidence for AGN jets with helical B fields include:

- Faraday rotation gradients across the jets
- Transverse polarisation and total intensity structures

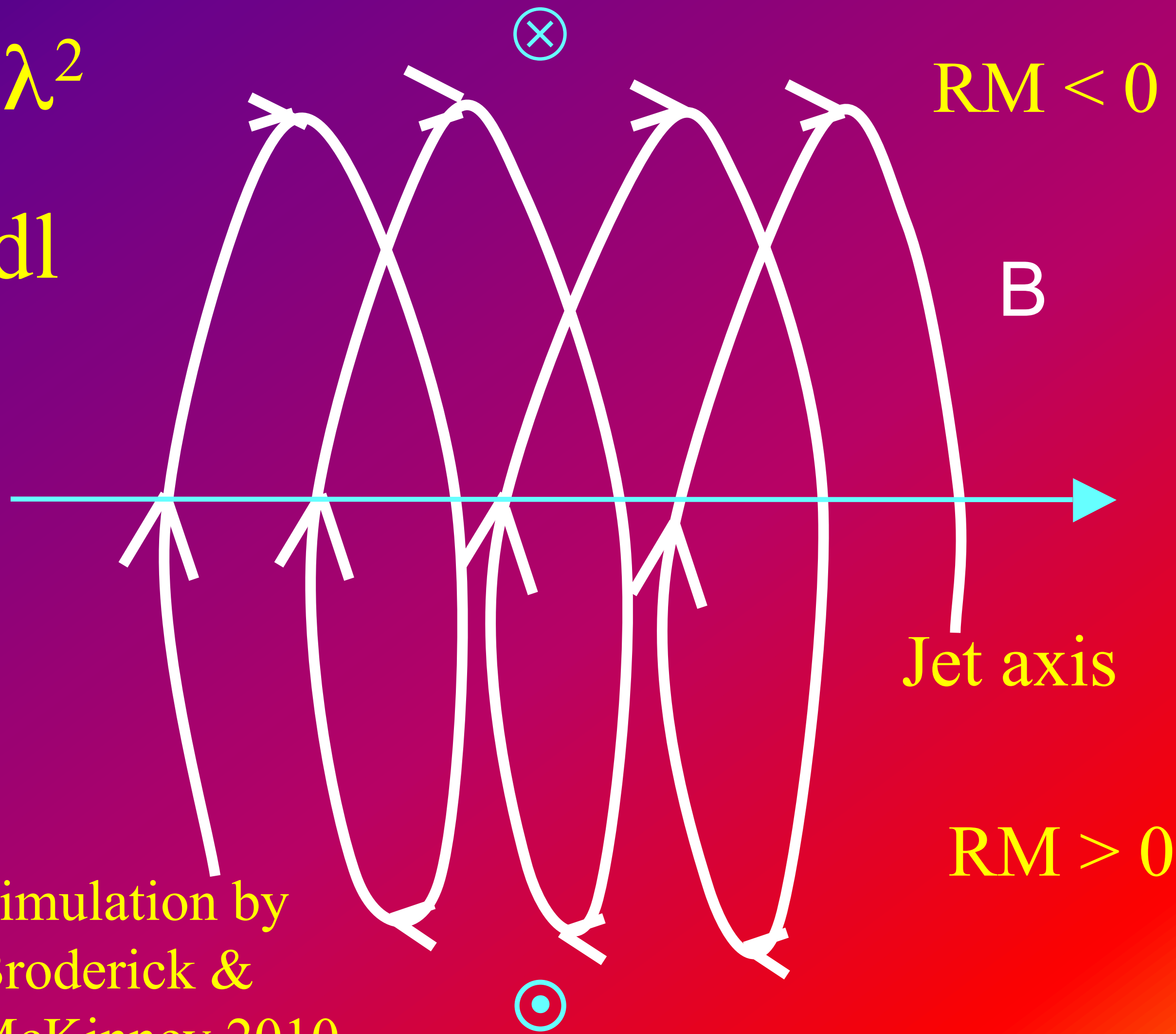
If jet has a helical B field, should observe a Faraday-rotation gradient *across* the jet – due to systematically changing *line-of-sight* component of B field across the jet (Blandford 1993).

$$\chi = \chi_o + RM\,\lambda^2$$

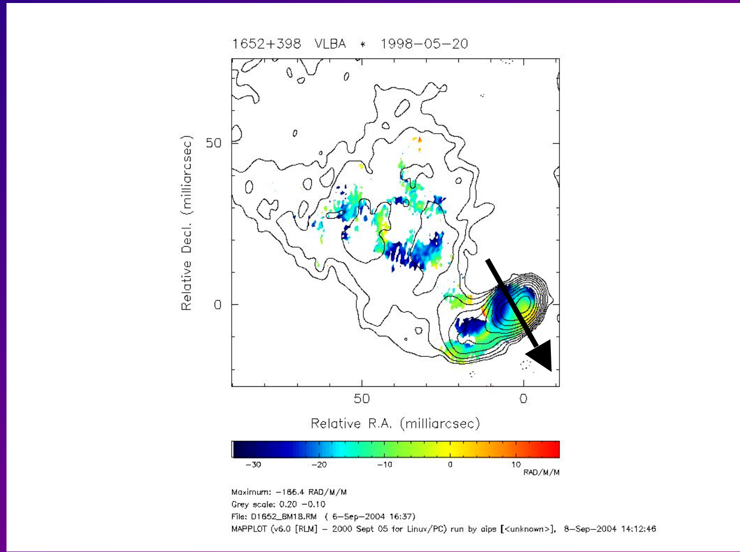
$$RM \sim \int n_e\, \mathbf{B} \bullet d\mathbf{l}$$

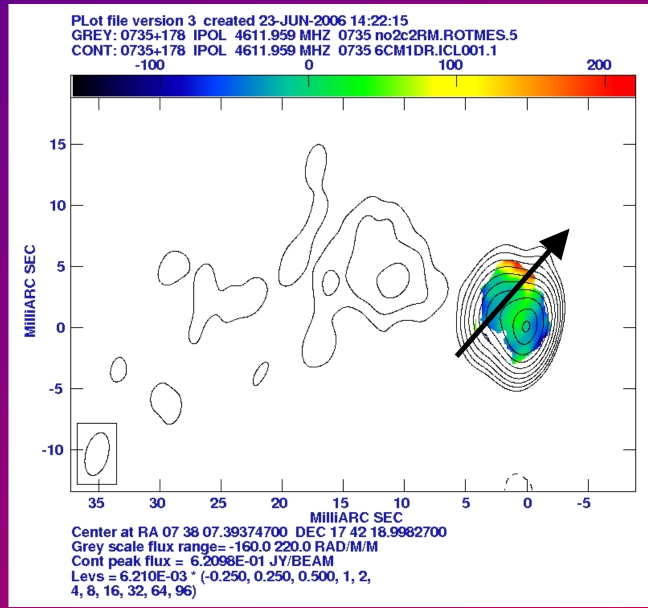


Simulation by Broderick & McKinney 2010

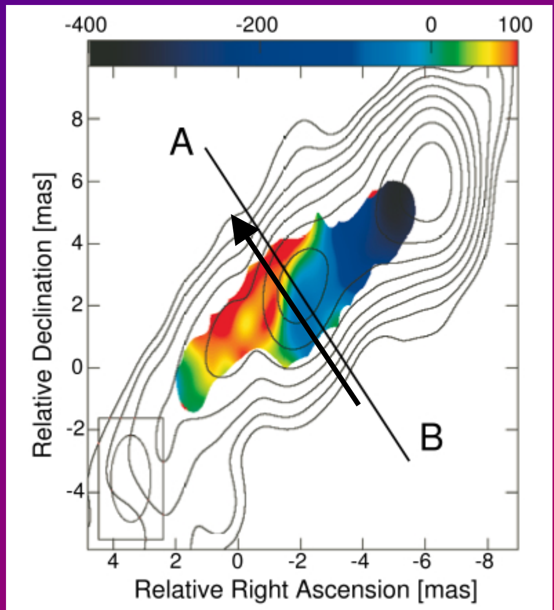


Croke, O’Sullivan & Gabuzda 2010





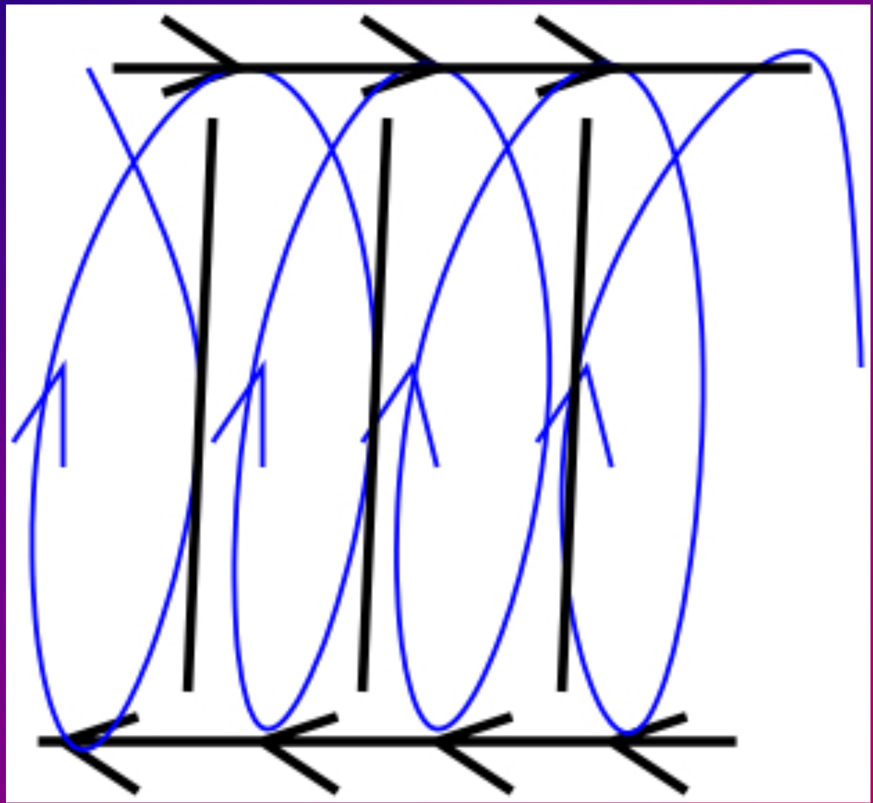
Gabuzda, Vitrishchak, Mahmud & O’Sullivan 2008



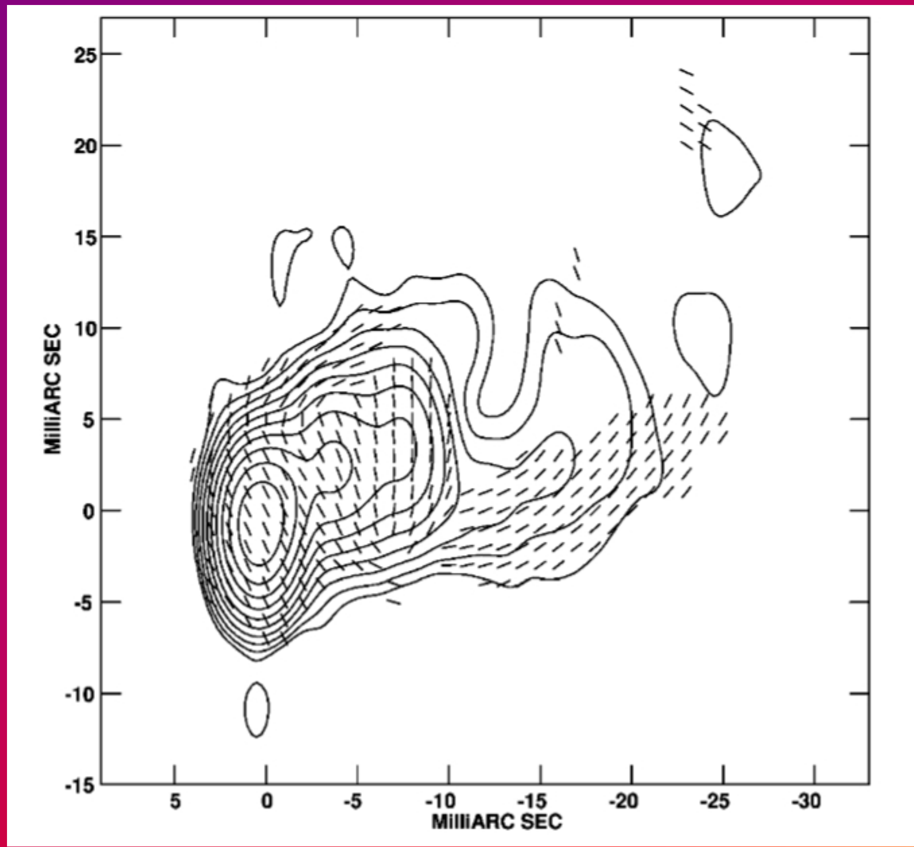
Reports of transverse RM gradients across various pc-scale AGN jets, suggested as evidence for helical B fields

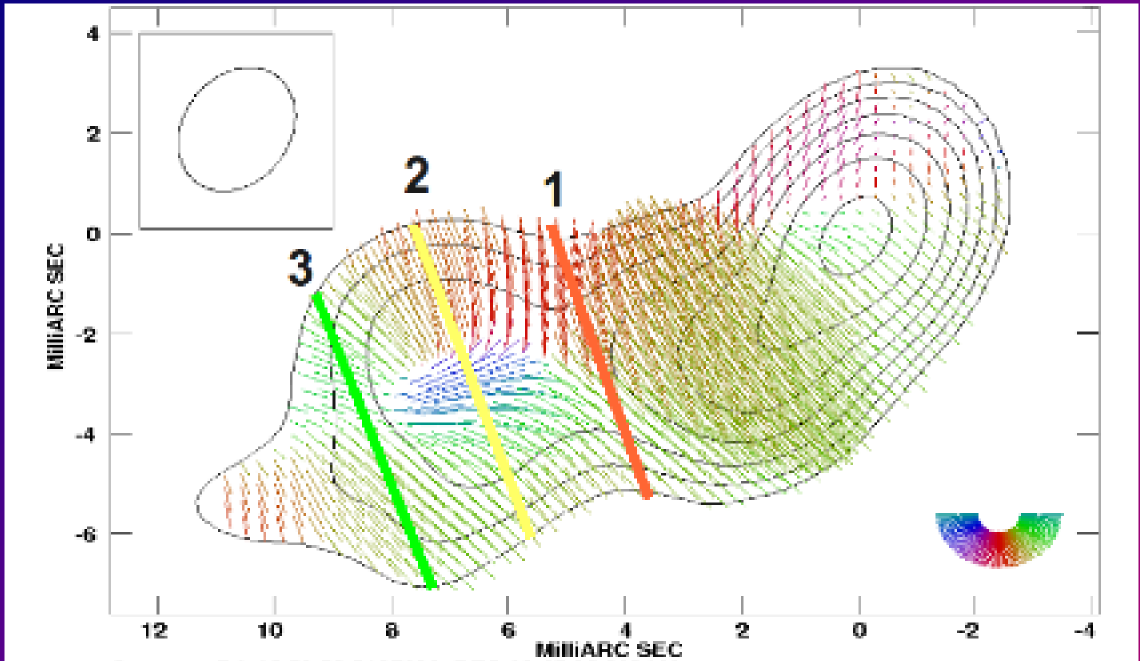
Asada et al. 2008

Helical jet B fields can also give rise to transverse I and P structure *across* the jet (e.g. Laing 1980, Lyutikov et al. 2005), have been observed in various AGN



Attridge et al. 1999





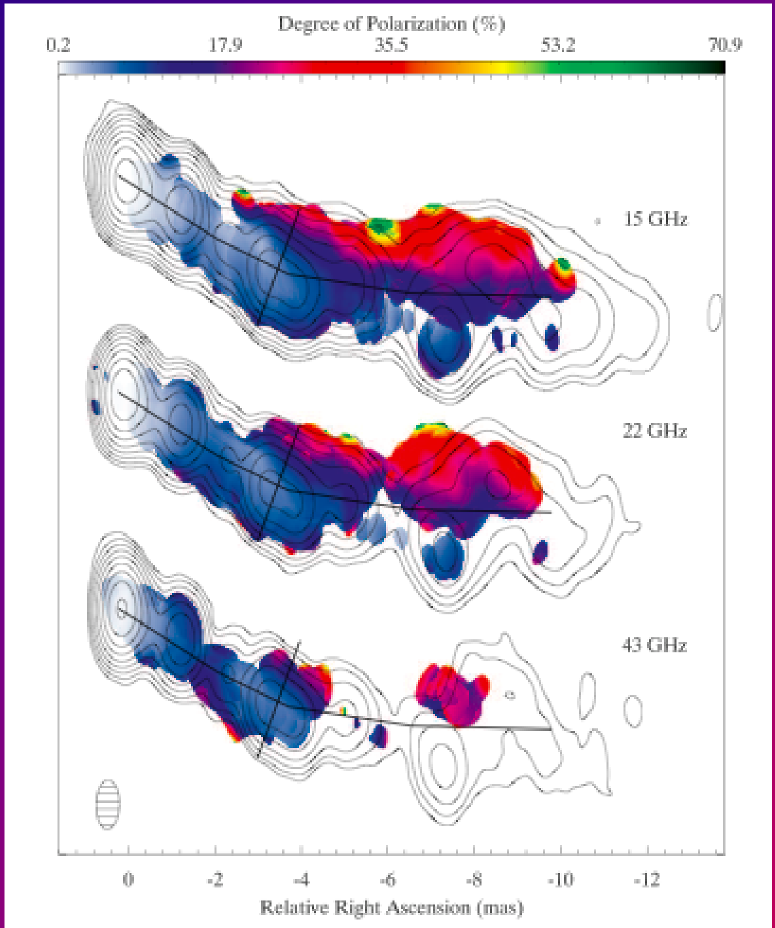
Slice	Best fit helical pitch angle	Best fit viewing angle
1	49 +/-2	78 +/- 2
2	53 +/- 1	80 +/- 4
3	58 +/- 2	78 +/- 2

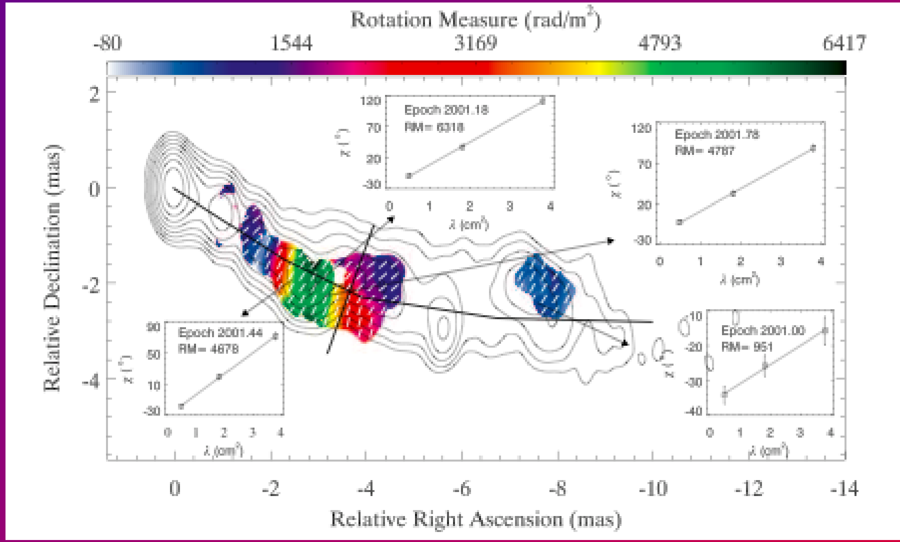
Fitting transverse I and P profiles using helical-field models may yield parameters of jet and field

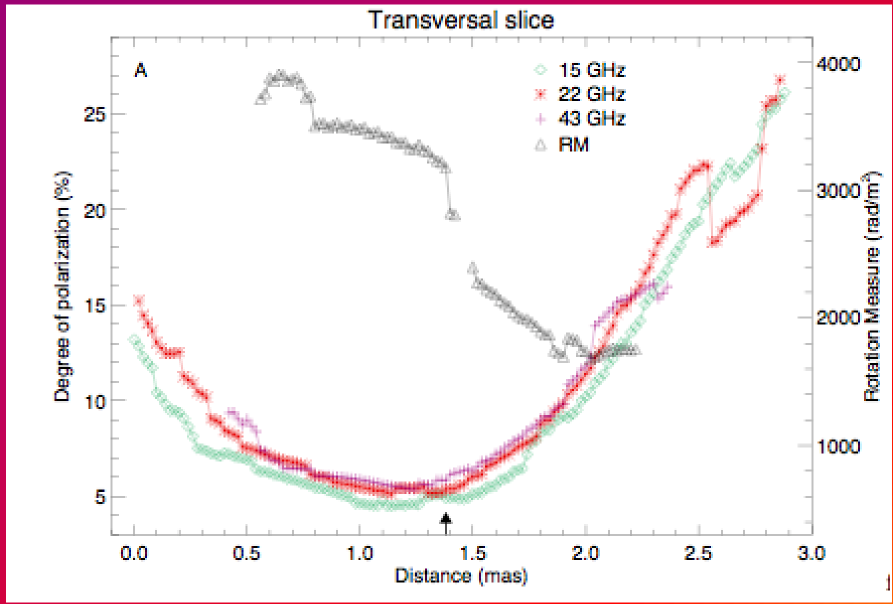
Work in progress; first results seem reasonable, but need to test further & apply to more sources

Murphy, Cawthorne & Gabuzda 2010; see also Claussen-Brown et al. 2011

Interesting new approach — creating maps based on adding results for many epochs; can help identify overall patterns in distributions

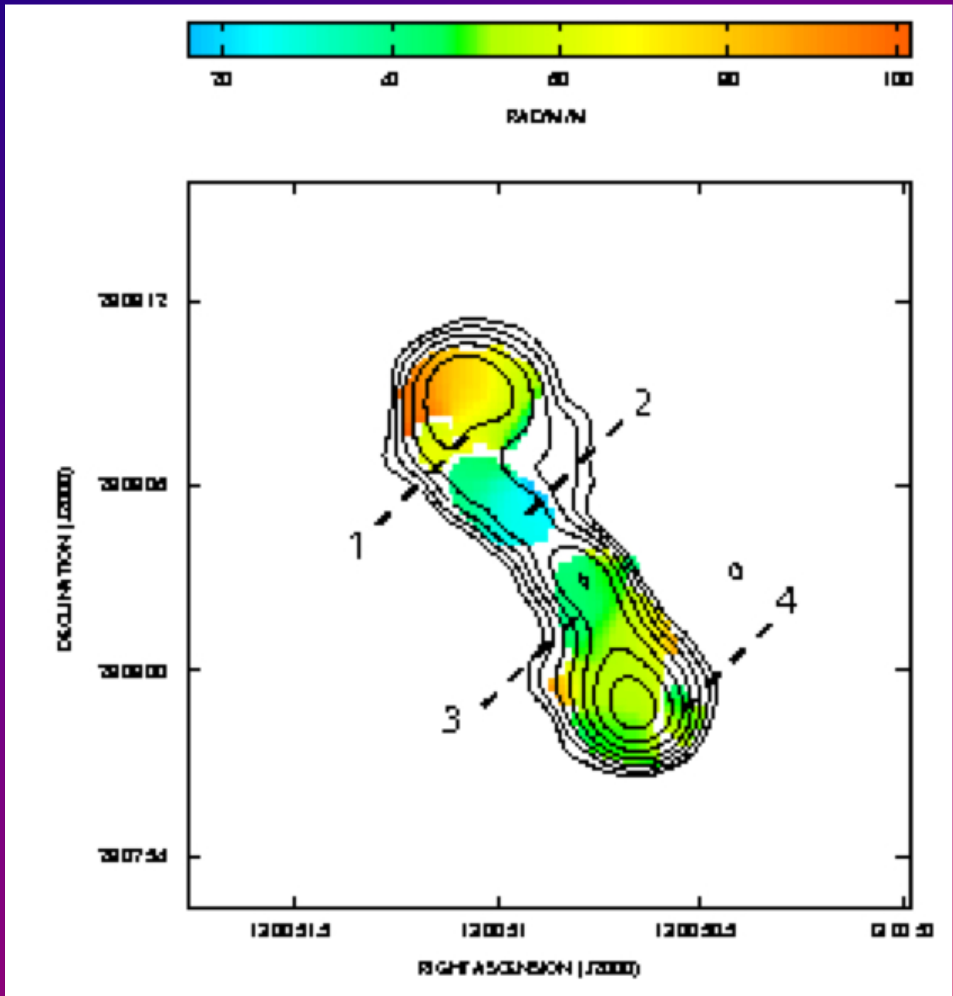






Gomez et al. 2010

Transverse RM gradients also identified on kpc scales (Christodoulou et al. 2011, in prep.)



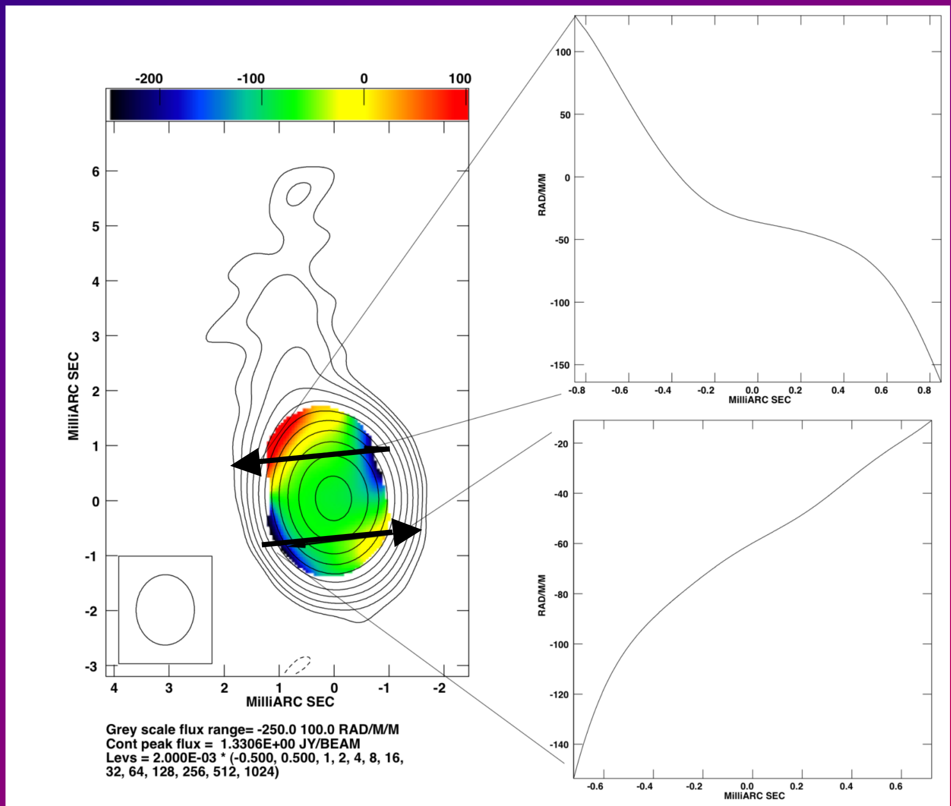
Bonafede et al. 2010

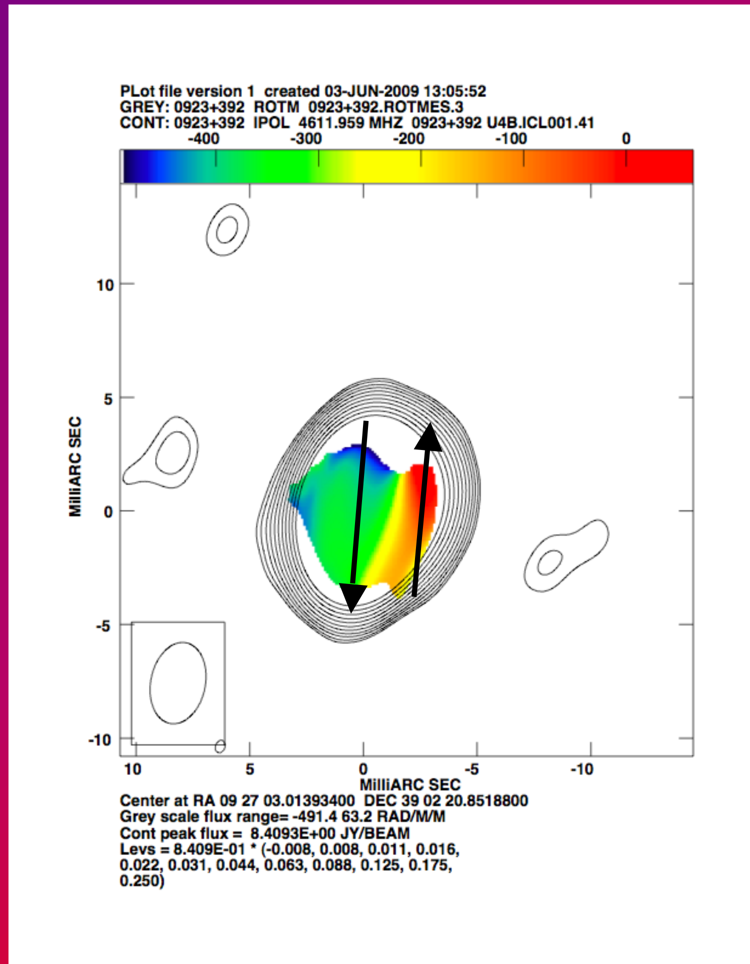
Fewer kpc-scale than pc-scale jets seem to show transverse RM gradients — may reflect different relative RM contributions from systematic (helical field) component and random (turbulent) component on different scales

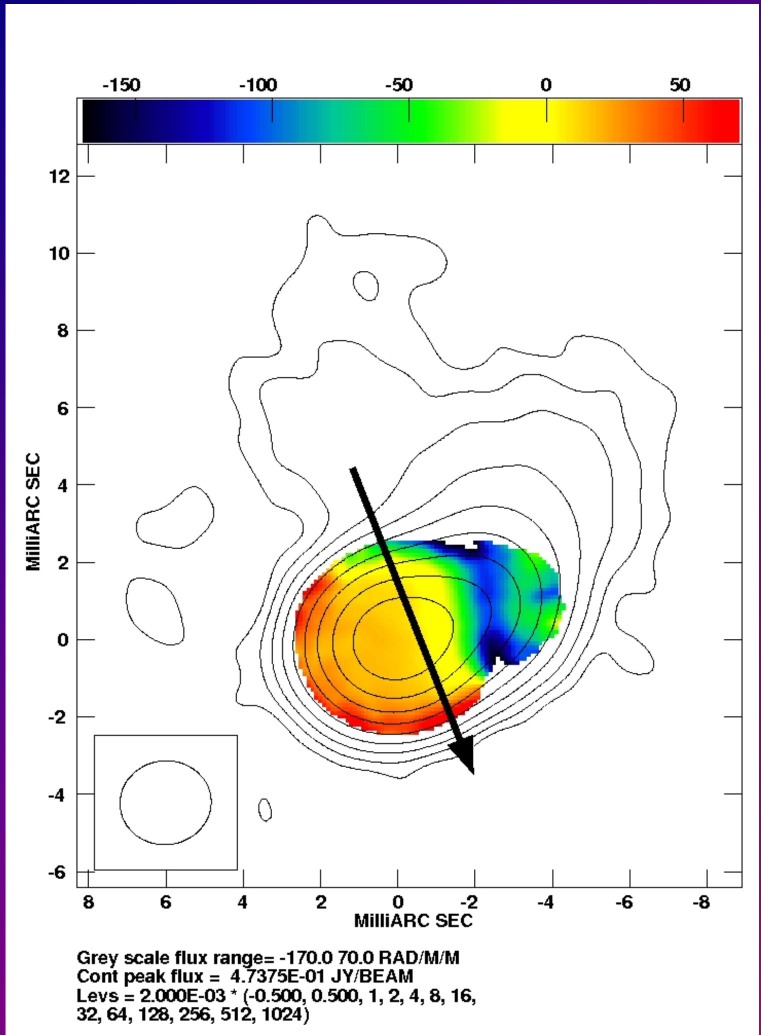
Also evidence that the transverse RM gradients observed on pc/kpc scales display preferred directions — CW and CCW on the sky, respectively. This can come about due to currents flowing in the system (e.g., Contopoulos et al. 2009, Konigl 2010), corresponds to dipolar geometry. Reversal is due to effect of field returing and closing in outer accretion disk.

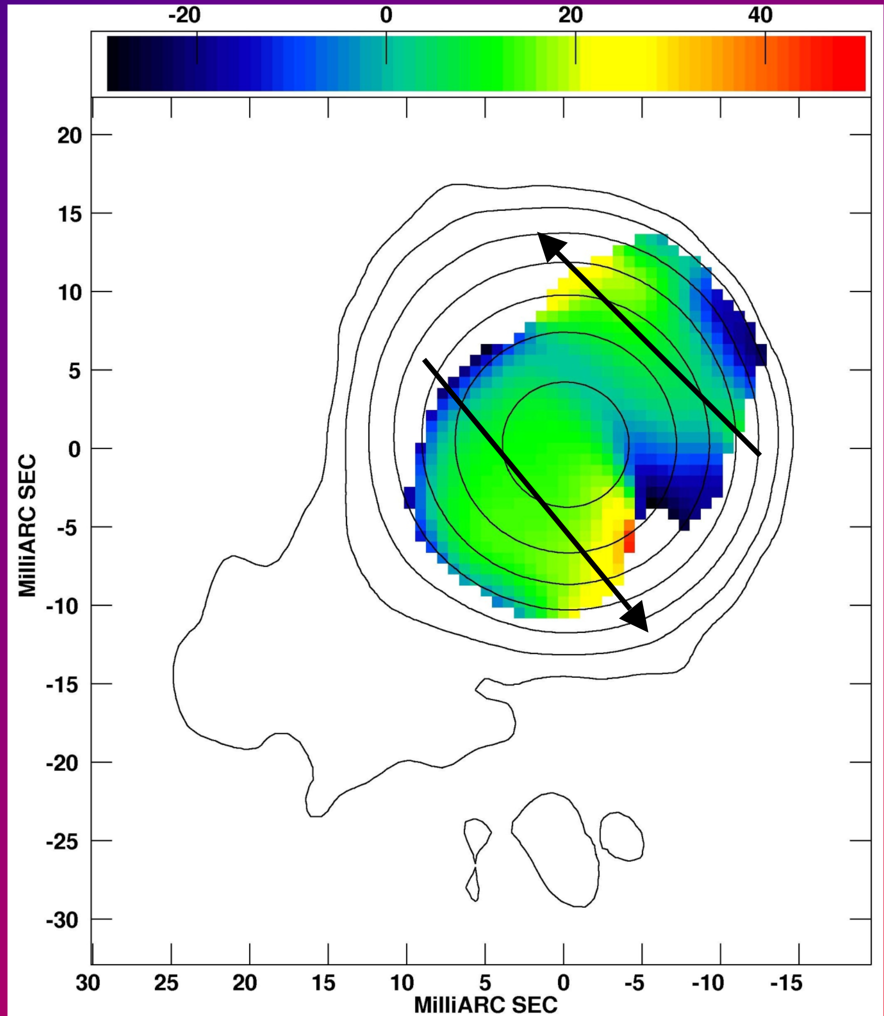
Keep an open mind about this, these results could potentially provide unique information about EM processes occurring in the accretion disk+jet systems!

Have observed reversals of the transverse RM gradient between core region and jet in several AGN (Mahmud, Gabuzda & Hallahan 2009; Reichstein & Gabuzda, in prep)







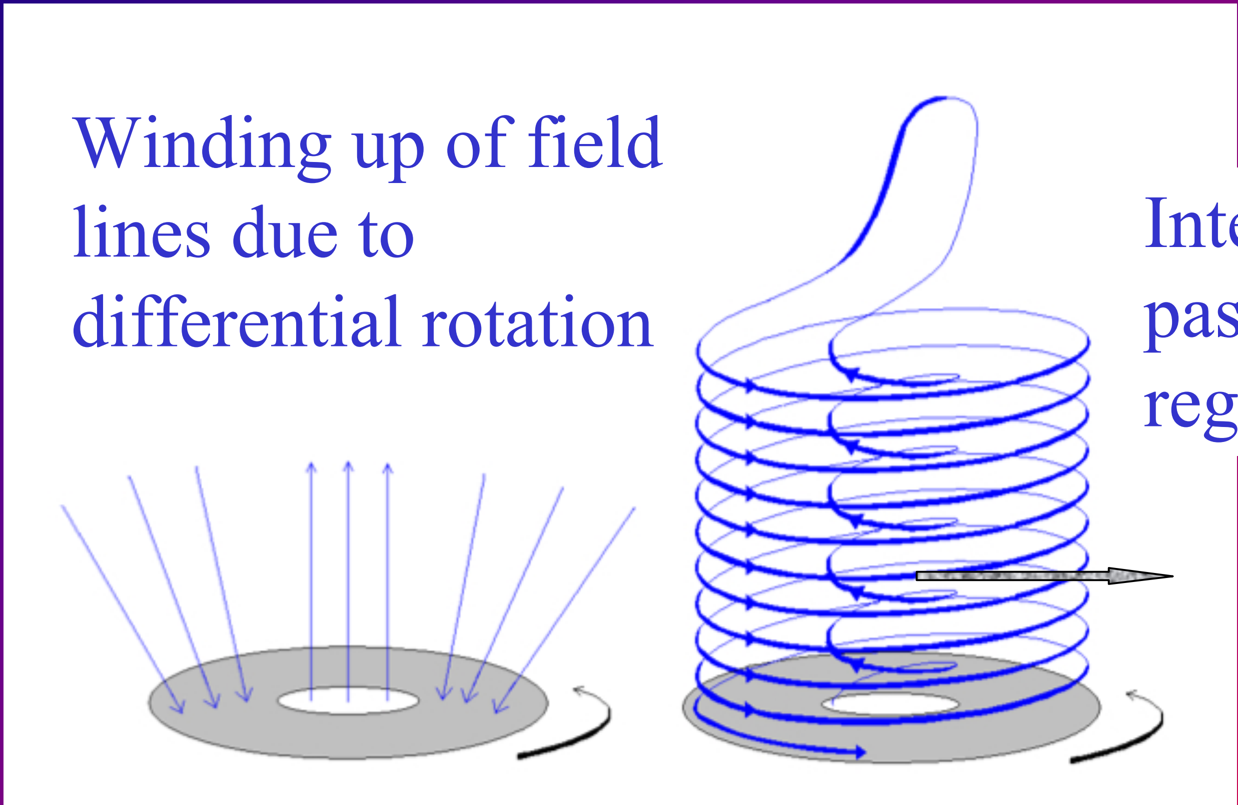


1749+701:

Left: 2-6cm RM map

Right: 18-22cm RM map

Can be explained by models where “outgoing” B field in jet/inner accretion disc closes in outer disc



Integration path passes through both regions of helical field

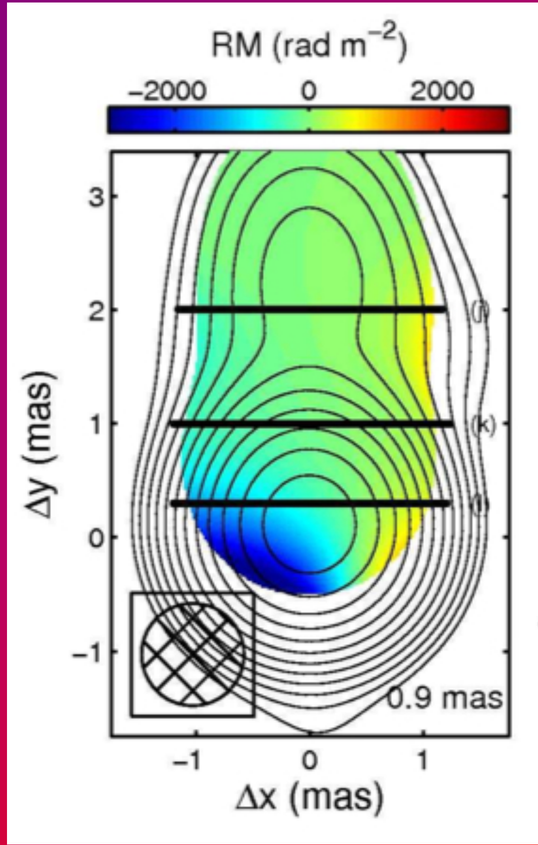
$\int n_e \mathbf{B} \cdot d\mathbf{l}$

Provides direct evidence for the presence of the “return field” in a more extended region surrounding the jet

How well resolved must the jets be to detect transverse polarization structure and RM gradients associated with helical B fields?

• Transverse RM gradient still visible in simulations, even with a 1-mas beam

• Spurious non-monotonicity possible in core region for some viewing angles, but observed direction of RM gradient is usually correct



Broderick & McKinney 2010

Taylor & Zavala (2010) propose 4 criteria for transverse RM gradients to be reliable:

1. At least three resolution elements across the jet.
2. A change in the RM by at least three times the typical error.
3. An optically thin synchrotron spectrum at the location of the gradient.
4. A monotonically smooth (within the errors) change in the RM from side to side.

- Criteria 2, 3, 4 have been applied in the majority of previous studies, so do not add anything new
- Criterion 1 is presented by T&Z without justification, but would reject many reported RM-gradient detections

➢ Situation must be clarified!

Resolving the question of resolution:

- Monte-Carlo simulations to investigate reliability of apparent RM gradients (Homan, Hovatta et al., in progress)

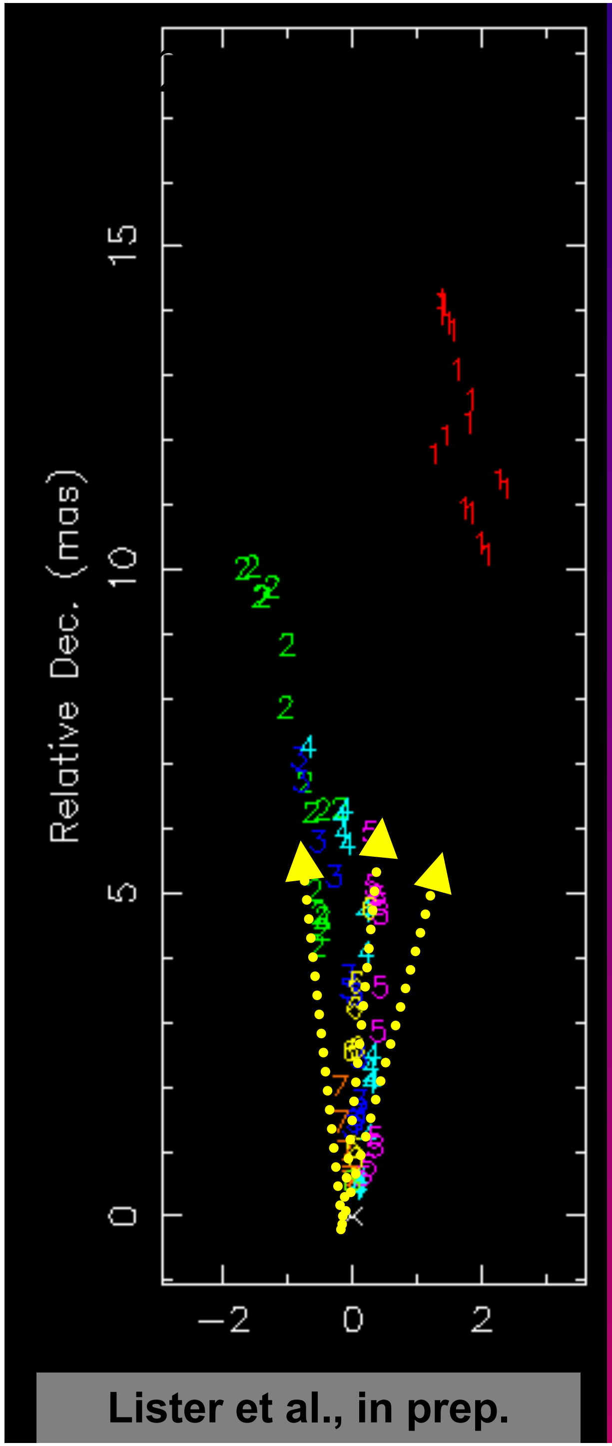
- Construction of simulated I, P and RM profiles to investigate their robustness for various beam sizes (relative resolutions) (in progress, see the poster by Murphy & Gabuzda)

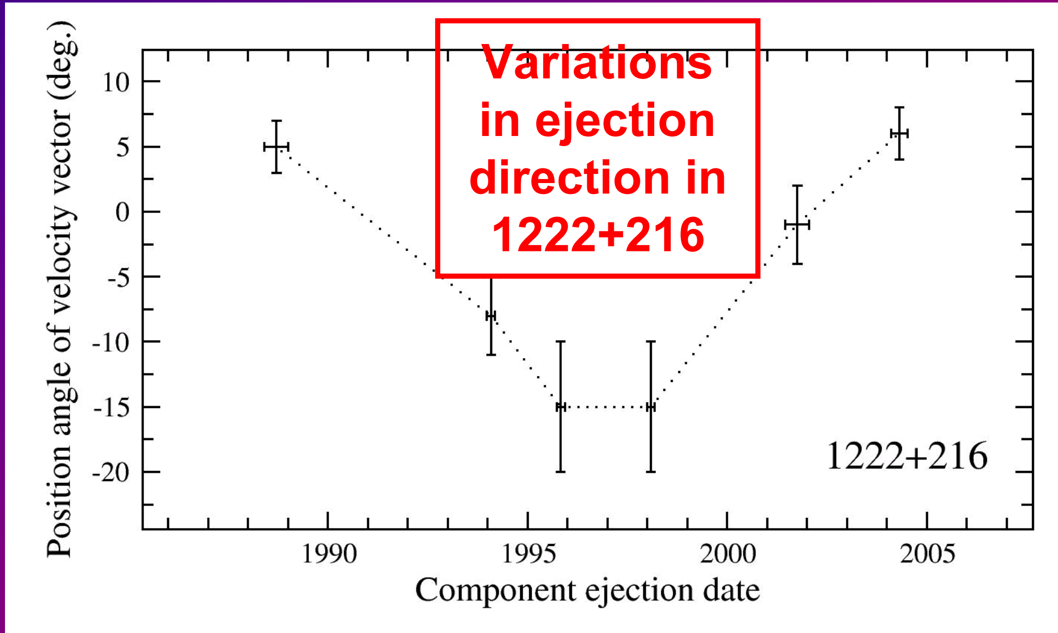
— initial results suggest that qualitative properties of P and RM profiles can be robust, even when beam size significantly exceeds jet size

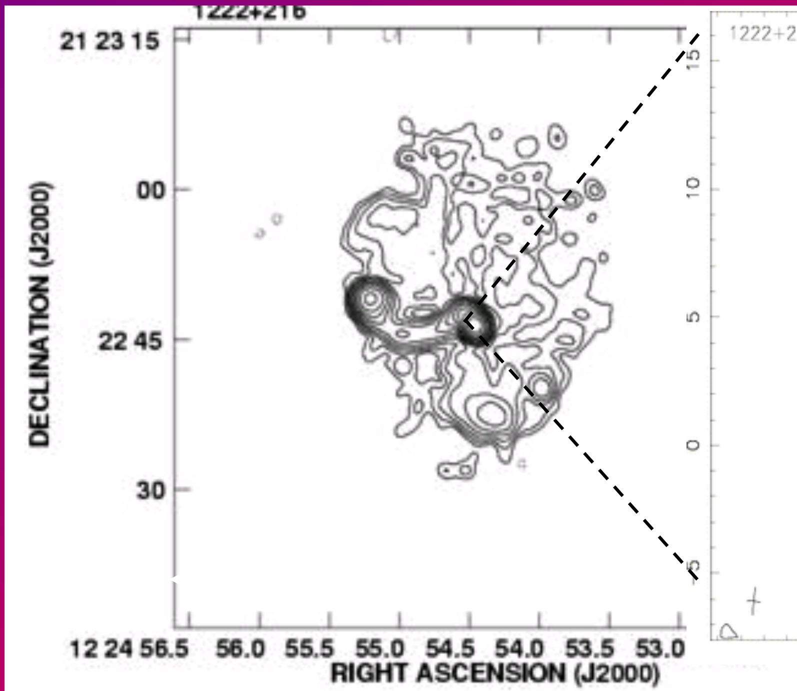
- RM results for full set of MOJAVE sources, currently in prep by Hovatta et al., will also help fill in picture

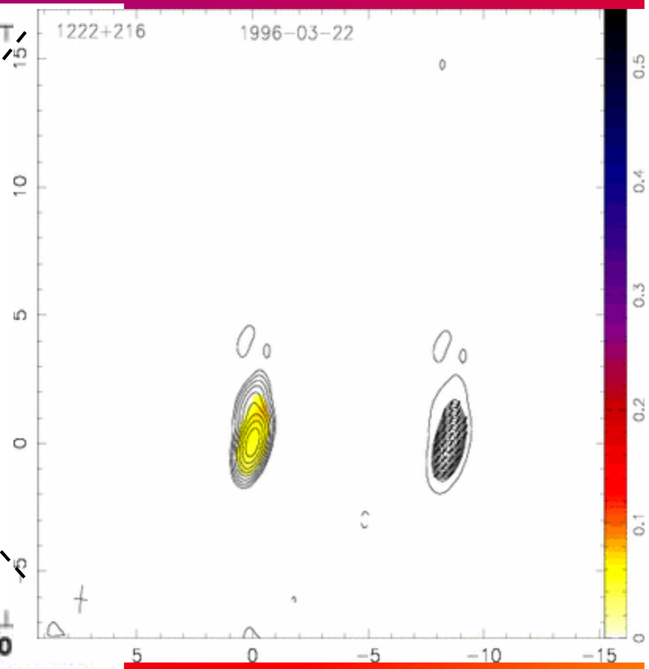
Changes in Jet Ejection Direction

MOJAVE results







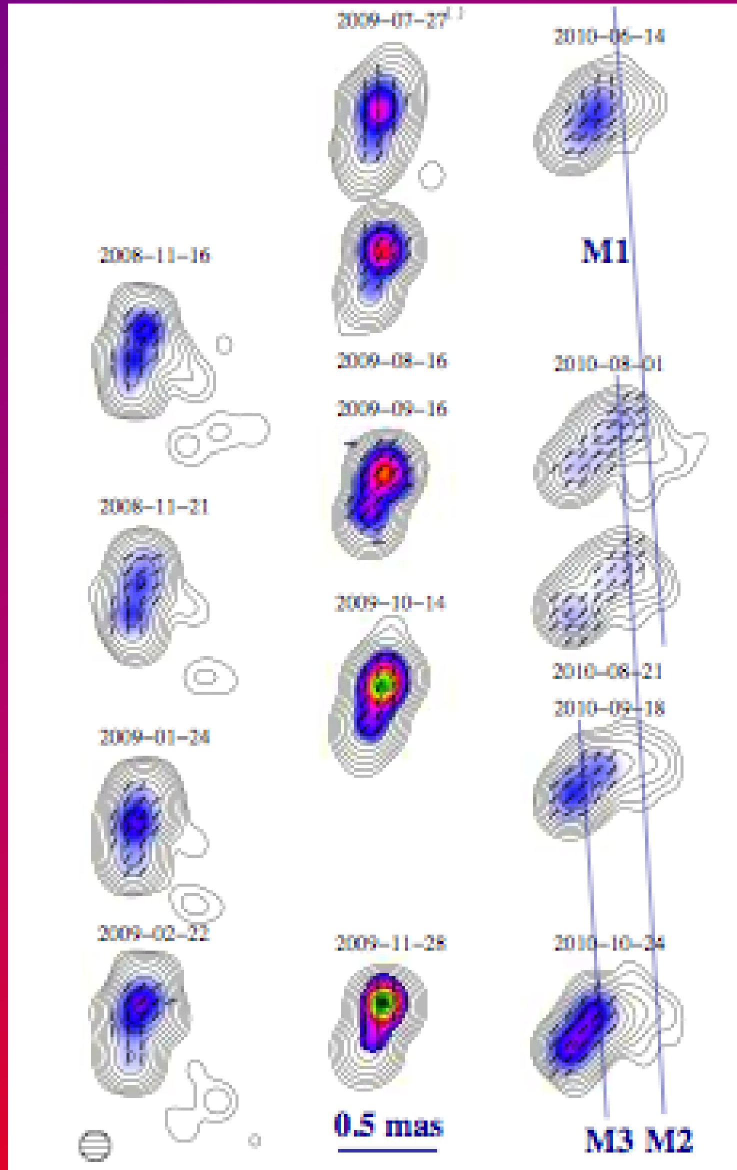


Direction of OJ287 jet has changed dramatically in last few years, compared to previous decades

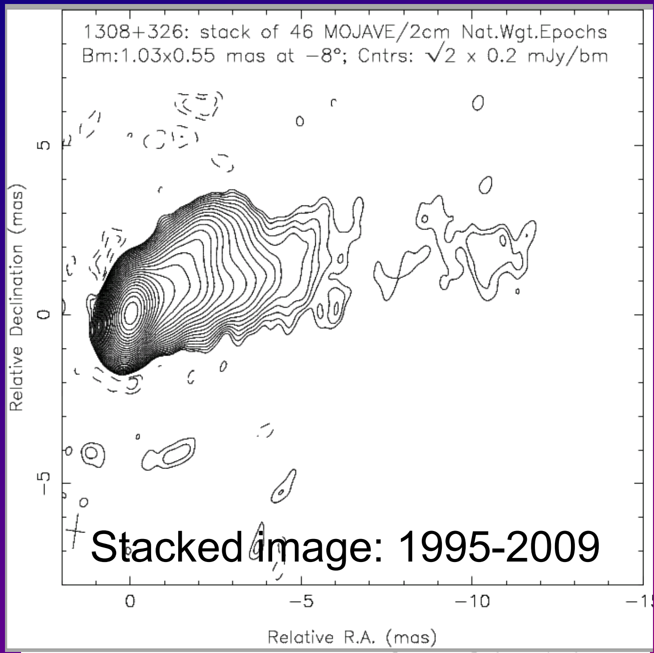
Previous jet direction roughly toward the West (to the right)!

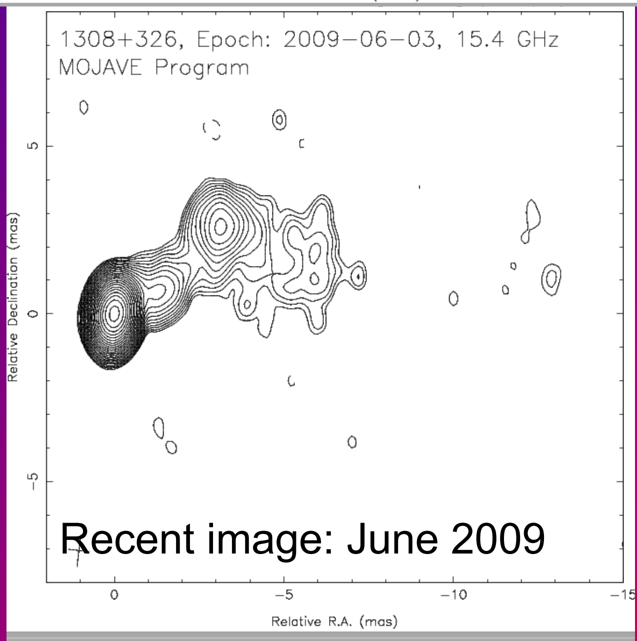
Is jet in these 2008 and 2009 images going *down* or *up*? Hard to tell, because structure basically only two components.

Agudo et al. 2011



1308+326



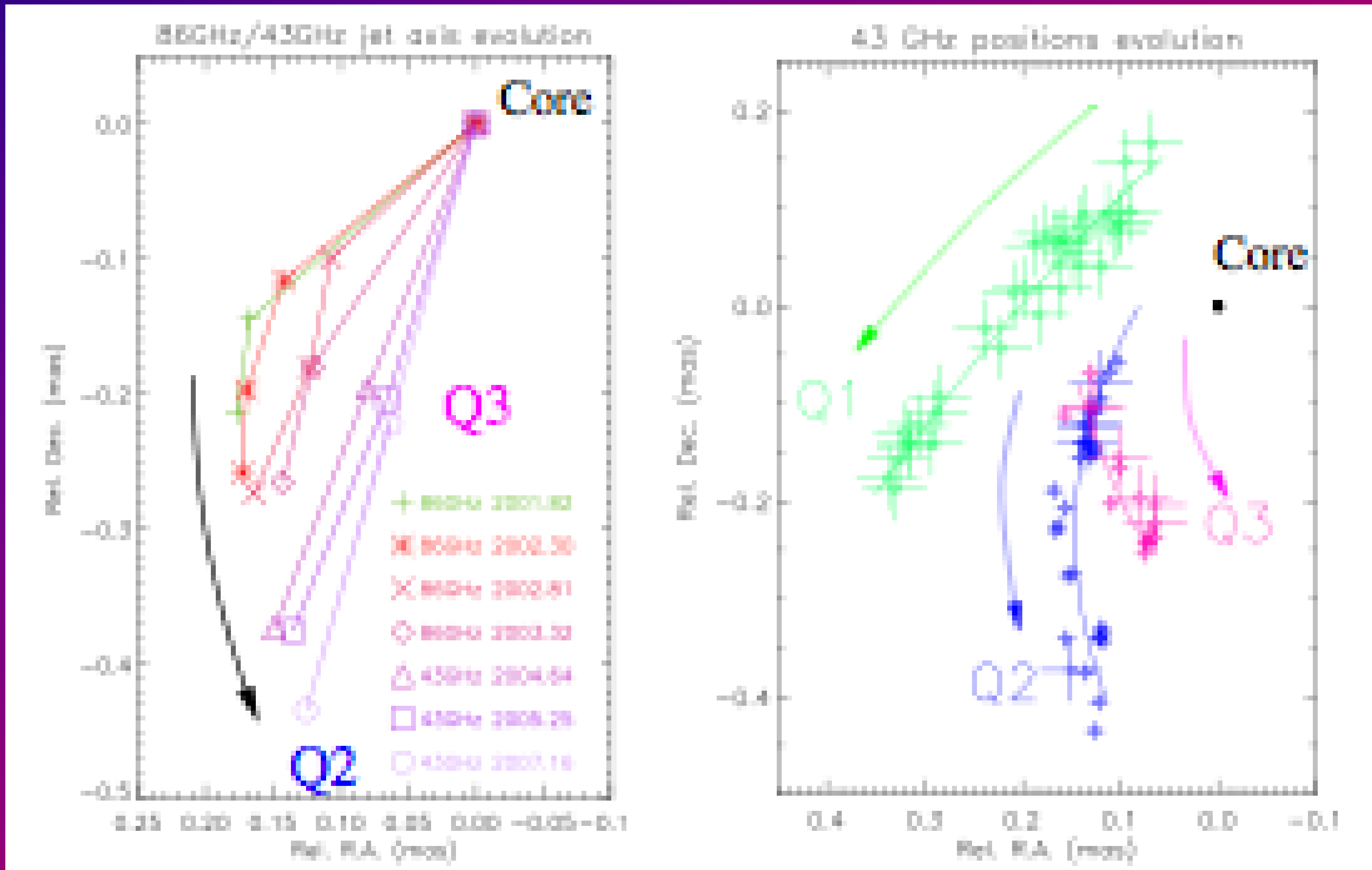


Lister et al. 2009

Lister et al. (2009) suggest that, at any given time, only the energized portion of a broader jet may be visible

Suggests possible test for variable jet-ejection direction - is the jet in a sum of images over many years broader than the typical images at a single epoch?

Jet "swinging" in NRAO150 — non-ballistic motion, with jet acting like a rigid structure — how?



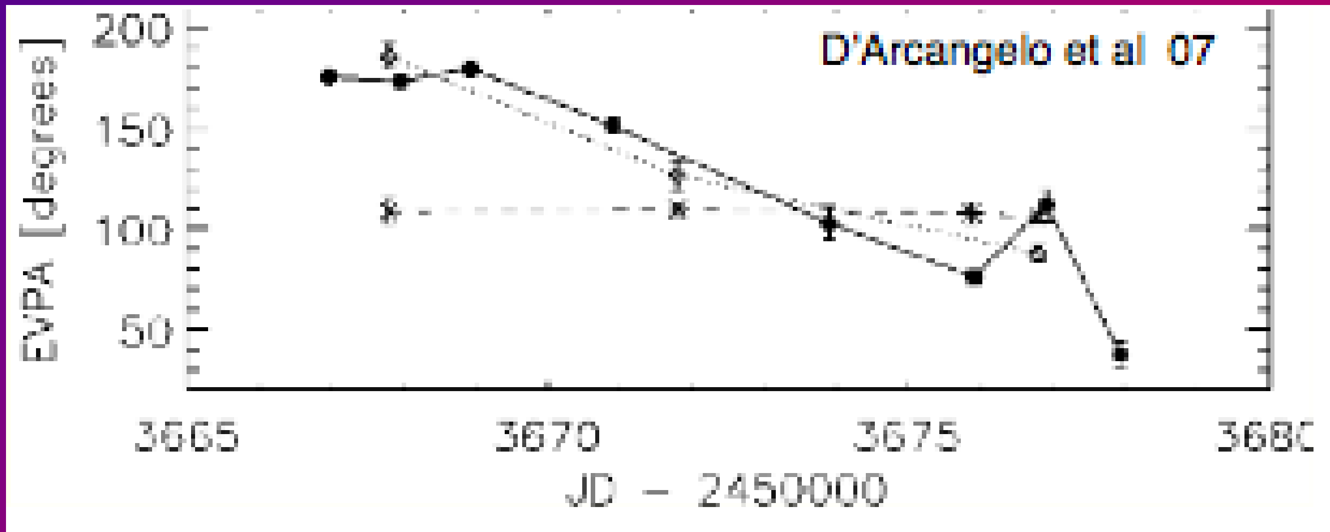
Agudo et al. 2008

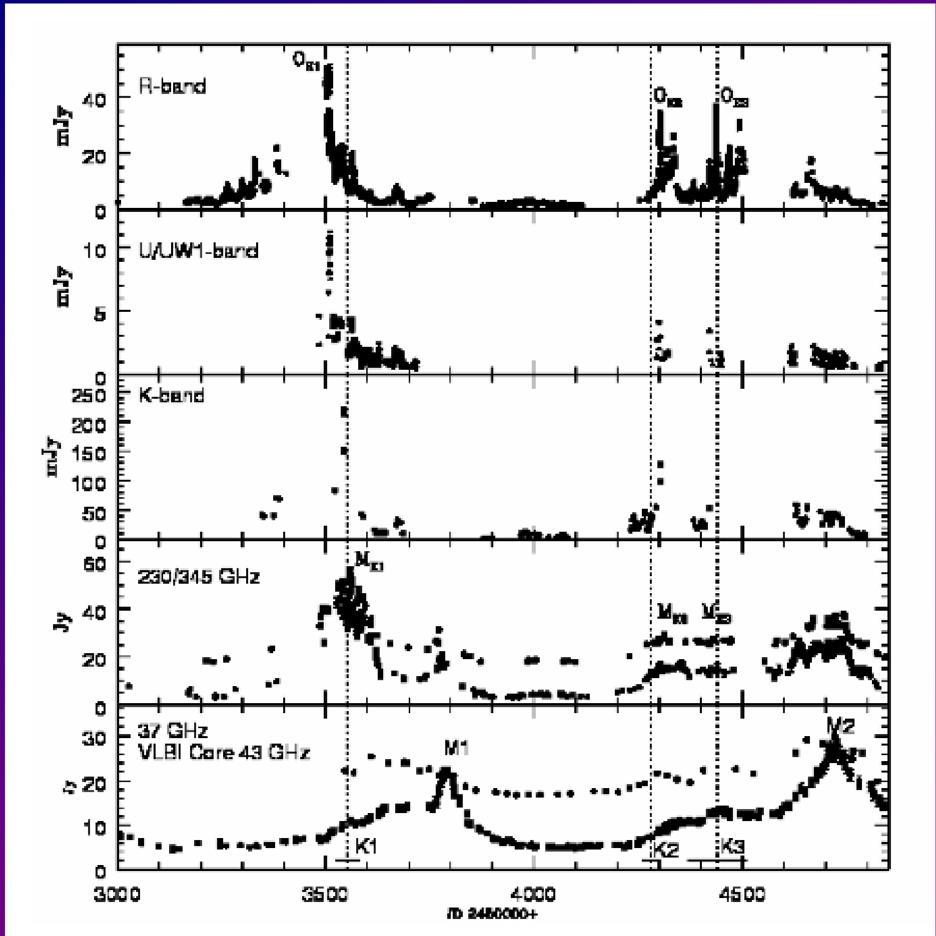
Unresolved questions:

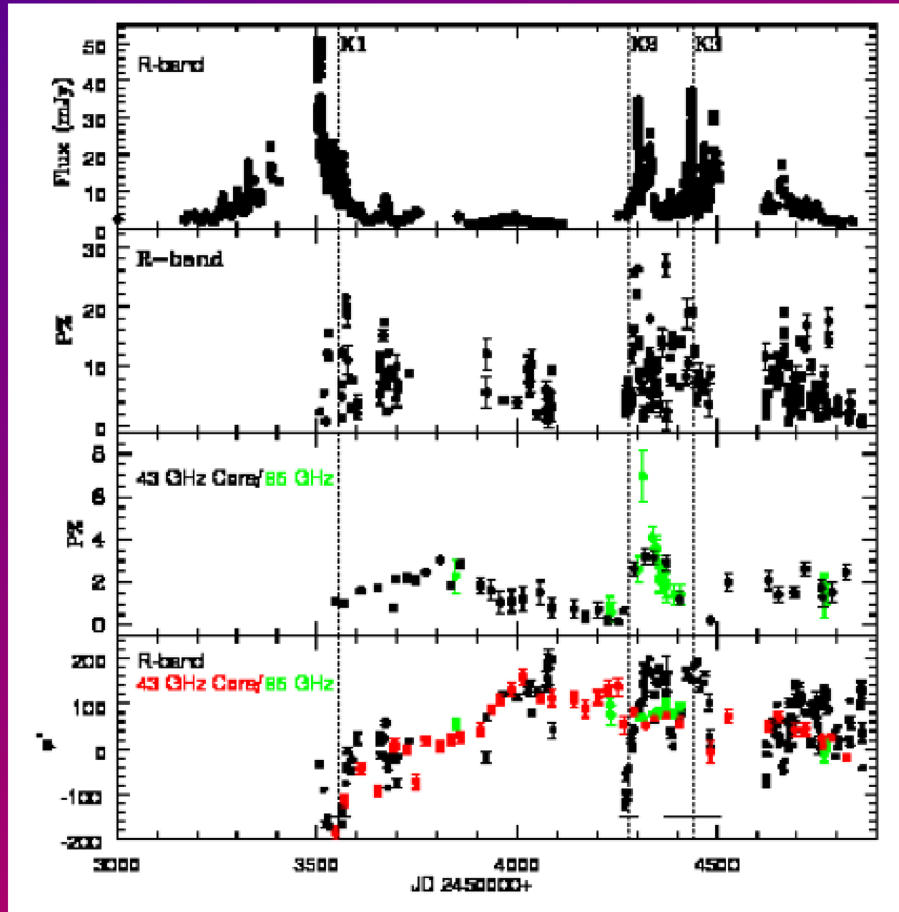
- What is causing changes in jet-ejection direction?
- What is causing “jet swinging”, and how can the jet seemingly move as a whole?
- How common are these phenomena?

Multi-Waveband Correlations

Fairly convincing simultaneous rotation of optical polarization angle and pol angle of 7mm VLBA core (d'Arcangelo et al. 2007) — are emission regions cospatial?

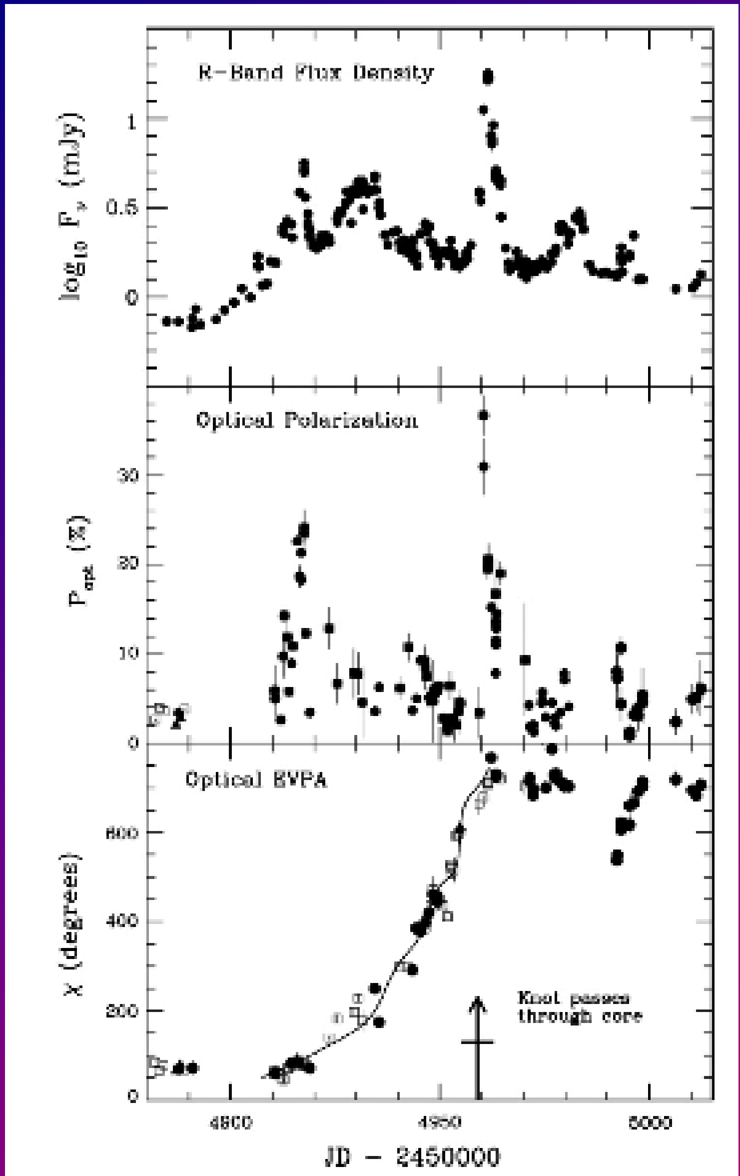




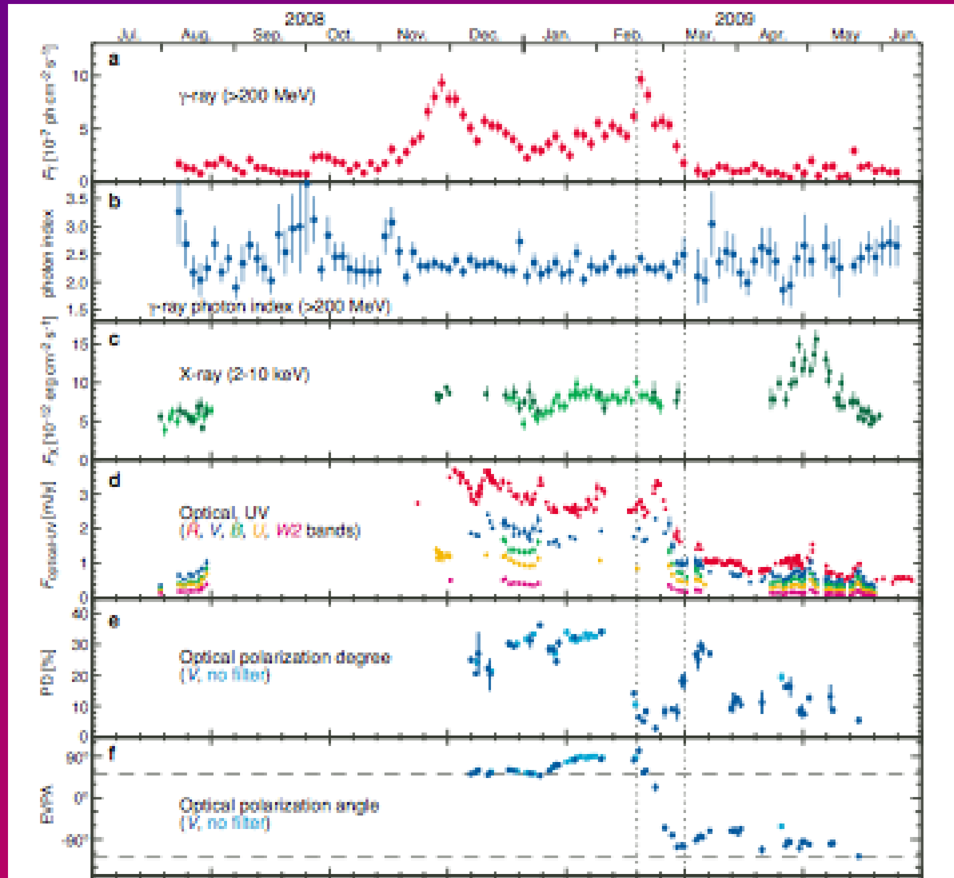


Attempt by Marscher et al. (2011) to relate VLBI, optical and X-ray behaviour in 3C454.3; some indication of connections, but difficult to be sure.

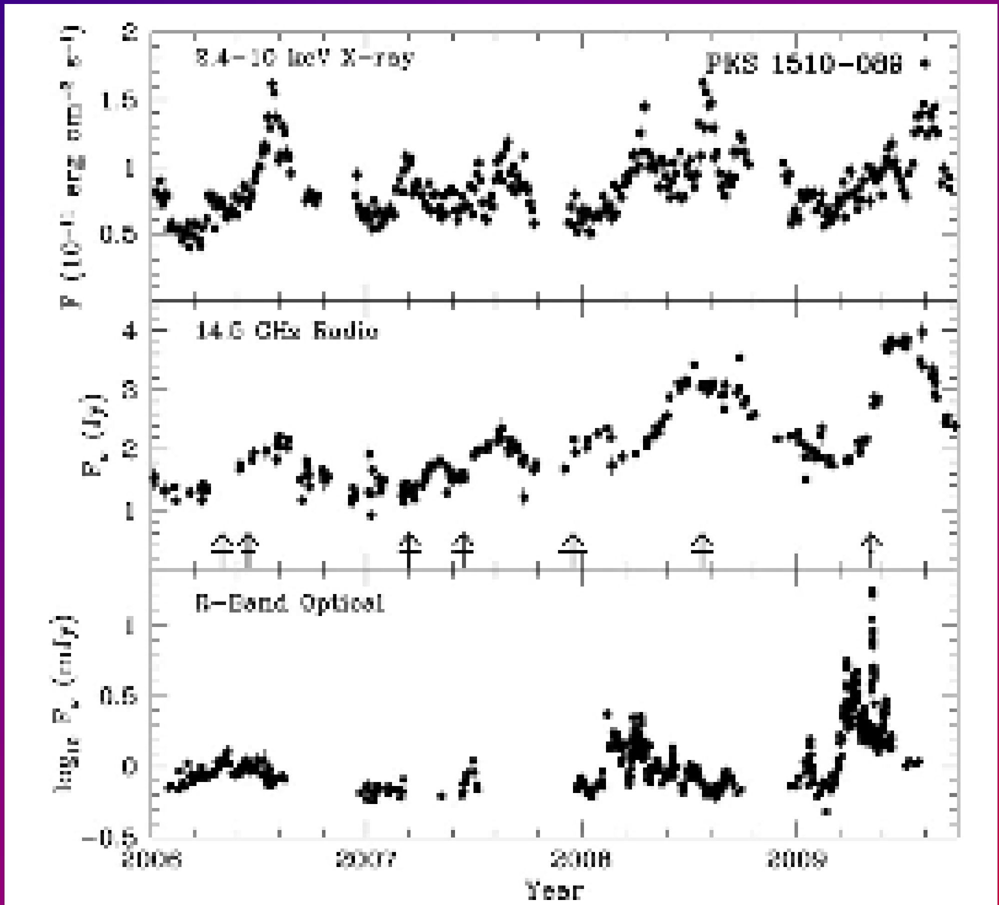
Were there really smooth rotations of these optical polarization angles?



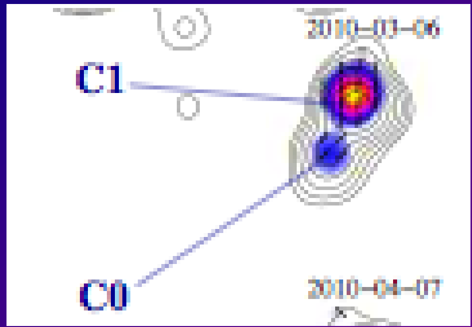
1510-089
(Marscher et al. 2010)



3C279
(Abdo et al. 2010)



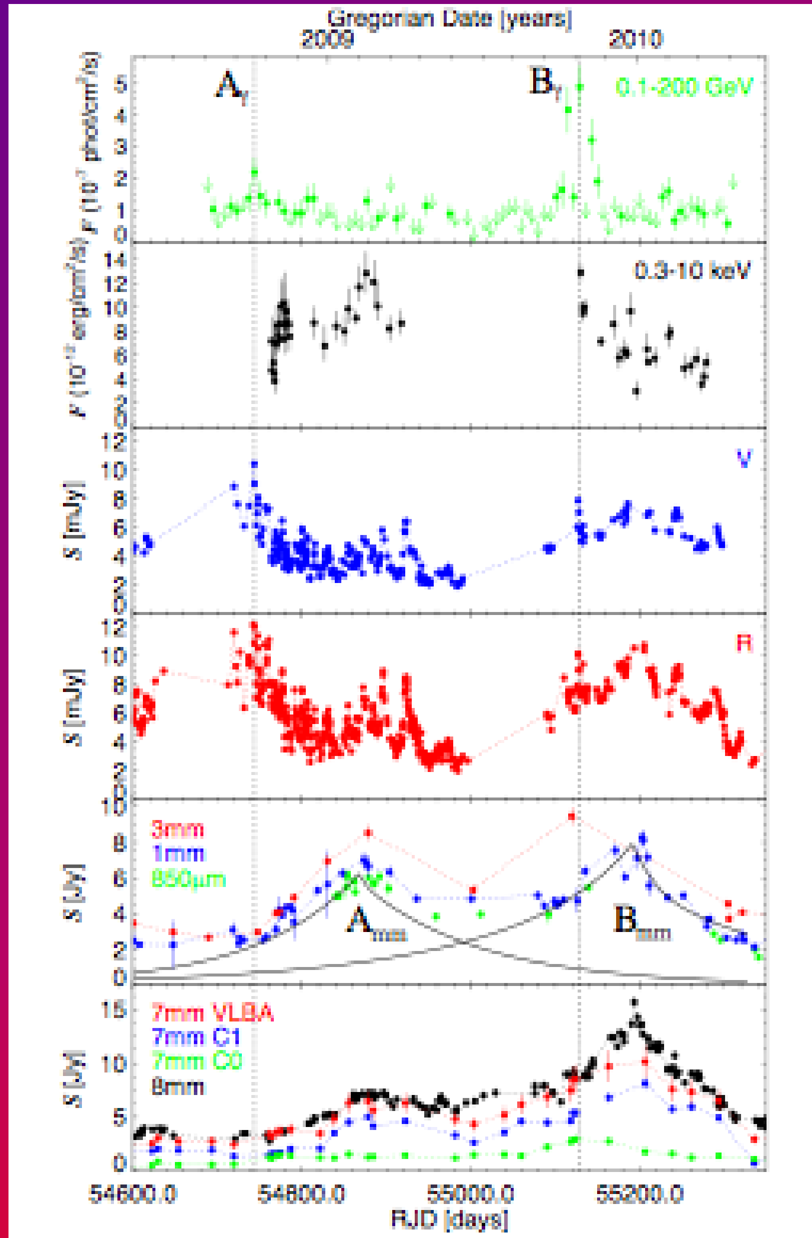
X-ray, radio and optical light curves for 1510-089 (Marscher et al. 2010) - are they related?



The gamma-ray and optical flares are fairly convincingly correlated with component C1 in OJ287, but is this the core or an inner jet component?

Agudo et al. (2011) suggest the latter, and conclude that the gamma-ray flare occurs far down the jet - but I'm not so sure!

Agudo et al. 2011



Summary - B Fields & Faraday Rotation

- Inferred core-region B fields are tenths of a Gauss
- Data consistent with $B \sim r^{-1}$
- Direct evidence that at least some AGN jets have helical B fields (transverse RM gradients, transverse I and P structure), naturally formed by rotation of central BH + jet outflow.

  — Jets are fundamentally EM structures, launching mechanism almost certainly EM

  — Jets carry current – implications for collimation

- Evidence for return field in region surrounding the jet

- Question of resolution required to reliably distinguish transverse polarization and RM structures currently being investigated.

Note: must distinguish between resolution needed to detect *presence* of gradients/structure and to reliably derive *source parameters*!

Summary - Changes in Jet Direction

- Changes in jet-ejection direction and “jet swinging” are being firmly detected in increasing numbers of sources

- Origin of this behaviour is unclear - precession? Chaotic behaviour? … How does jet move coherently in the case of “jet swinging”? Could a helical jet B field cause the jet to act like a rigid structure?

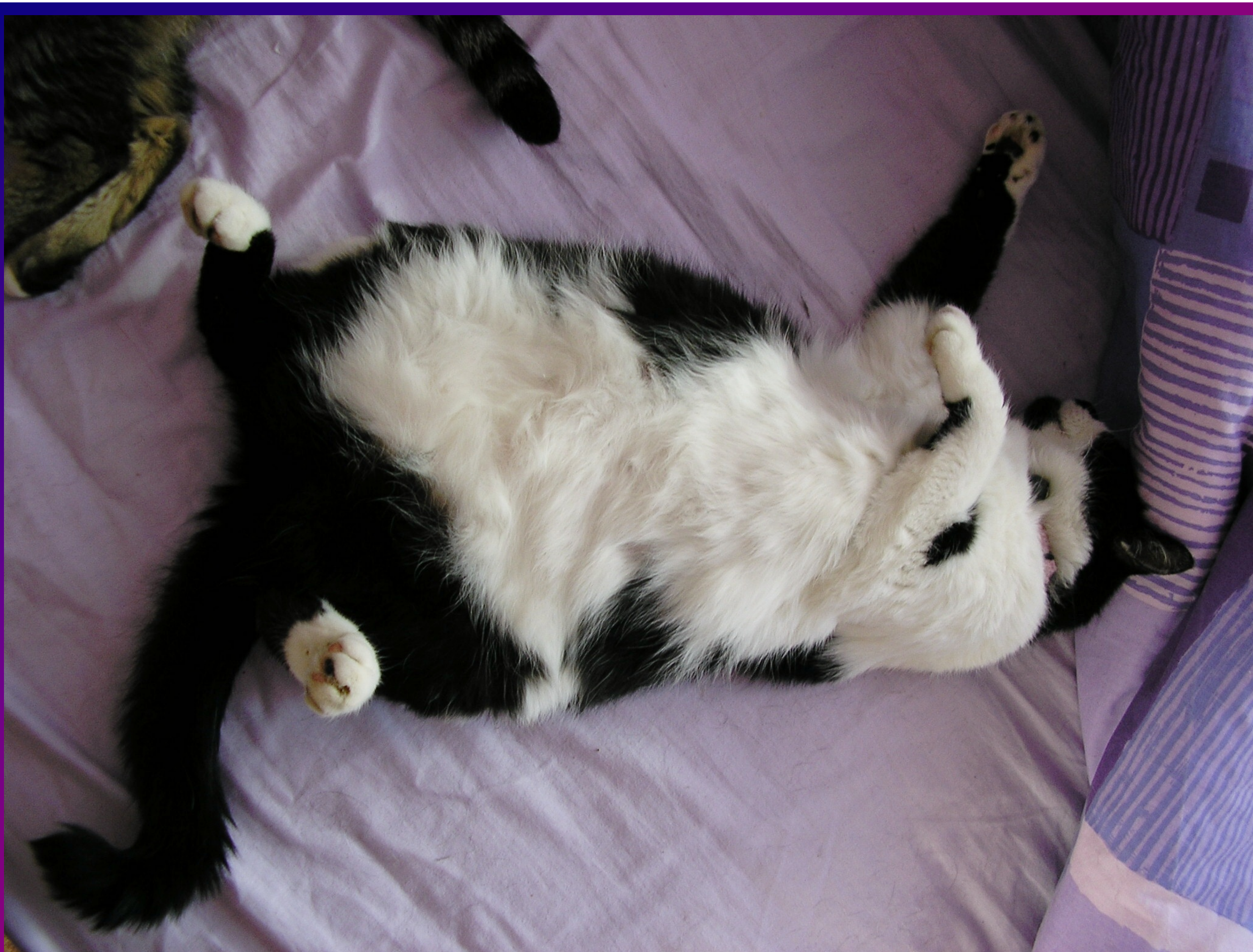
Summary - Multi-wavelength correlations

- Searches for correlations between radio and gamma-ray currently topical due to availability of data from Fermi orbiting gamma-ray observatory

- Some interesting results, but VLBI data probably not dense enough and time baselines probably not long enough to be sure of coincidences in most cases

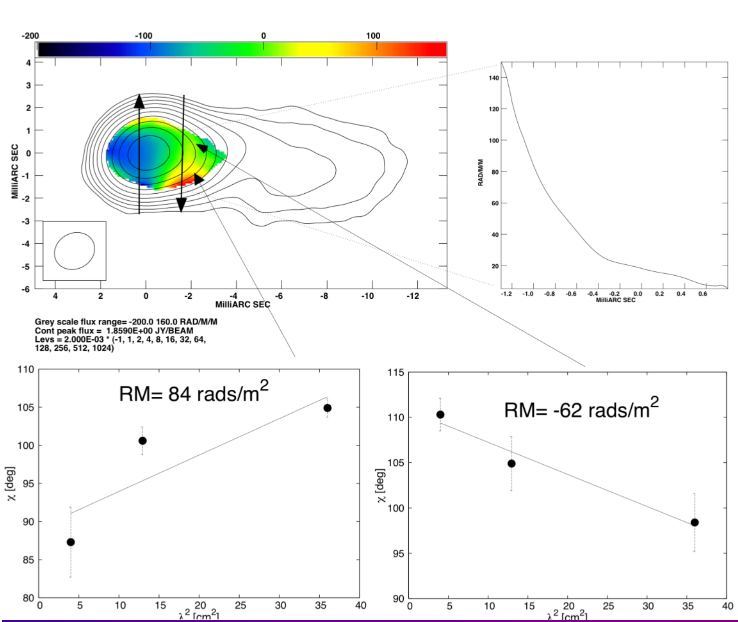
- Some evidence for connections between VLBI core activity and optical/gamma-ray activity

- Must be careful when identifying large rotations in pol angle — variations can seem smoother than they really are when scale is large



An extremely non-relativistic cat
undergoing radiative cooling.

4/1997



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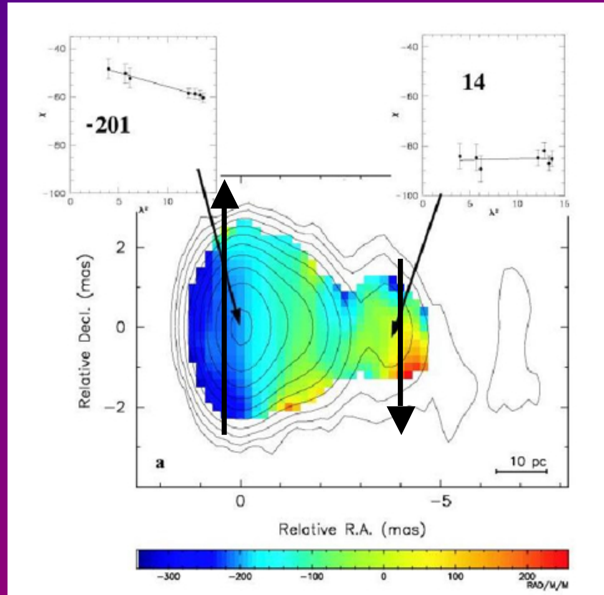

Trans RM gradient in 1803+784 changed direction with time (Mahmud et al. 2009)!

8/2002

8/2003