

# Multi-Frequency Polarization Studies of AGN Jets

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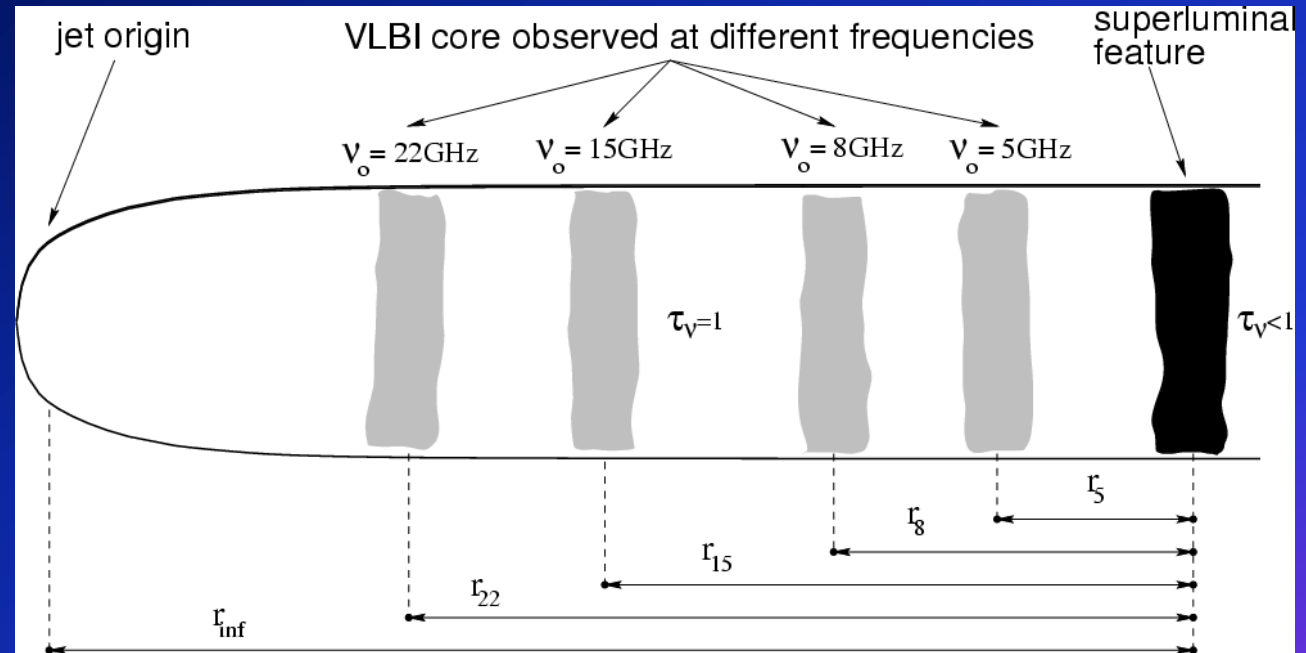
## Outline of talk —

- Image alignment/core shifts/core B fields
- Faraday rotation studies
- Investigations of image properties using Monte Carlo simulations

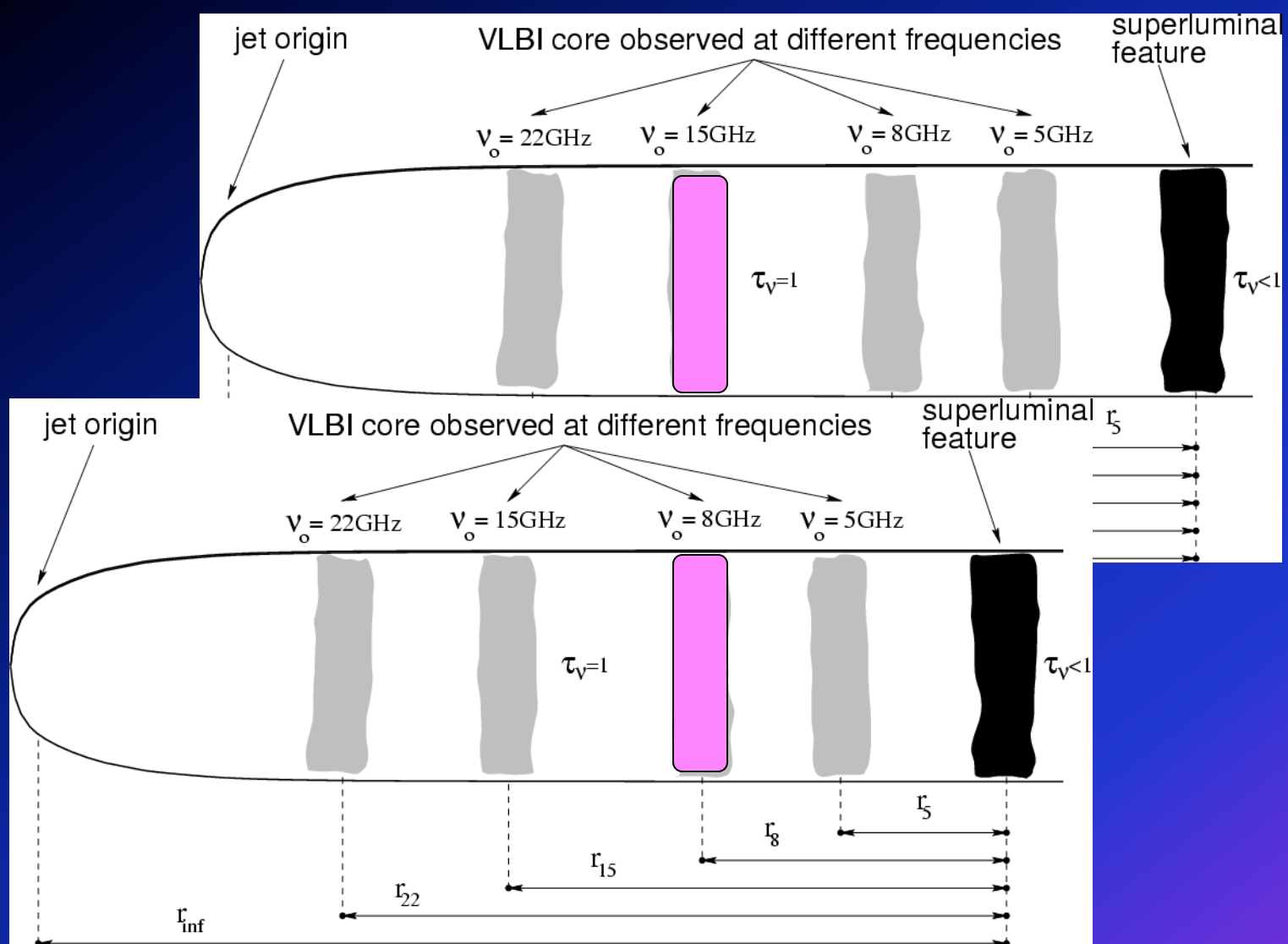
Image alignment, core shifts,  
core B fields

# Why image alignment is necessary

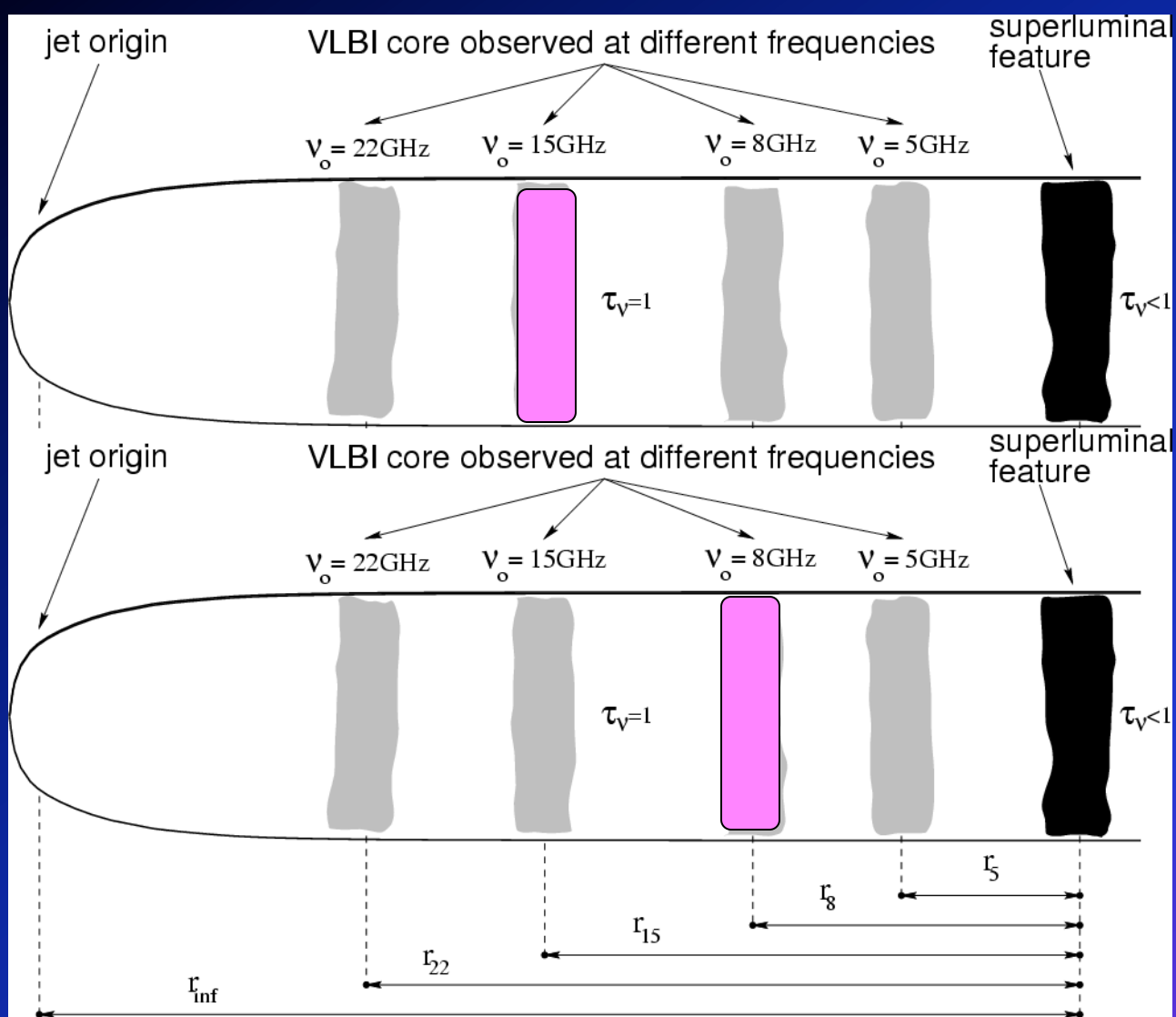
Schematic  
from Kovalev  
et al. (2007)



VLBI “core” = optically thick base of jet, moves further down jet at increasingly lower frequencies



VLBI images align on bright, compact cores rather than optically thin jet features, absolute position info lost, direct superposition yields erroneous spectral indices.



This is actual correct physical alignment!

## Alignment techniques

- o Based on comparing positions of optically thin features
  - Model fitting
  - Image cross-correlation analyses
- o In practice – different approaches work best for different source structures, but both can yield reliable alignments

Lobanov (1998):

- o Approach to estimating pc-scale B field strengths based on measurement of frequency-dependent position of VLBI core (Konigl 1981)
- o Few sources, few frequencies, but a start

More recent studies:

O'Sullivan & Gabuzda (2010) — only a few sources, but 8 frequencies (detailed, redundant information)

Kovalev et al. (2009) — 29 sources, 2 frequencies

Sokolovskii et al. (2011) — 20 sources, 9 frequencies

Pushkarev et al. (2012) — more than a hundred well studied (MOJAVE) sources, four frequencies



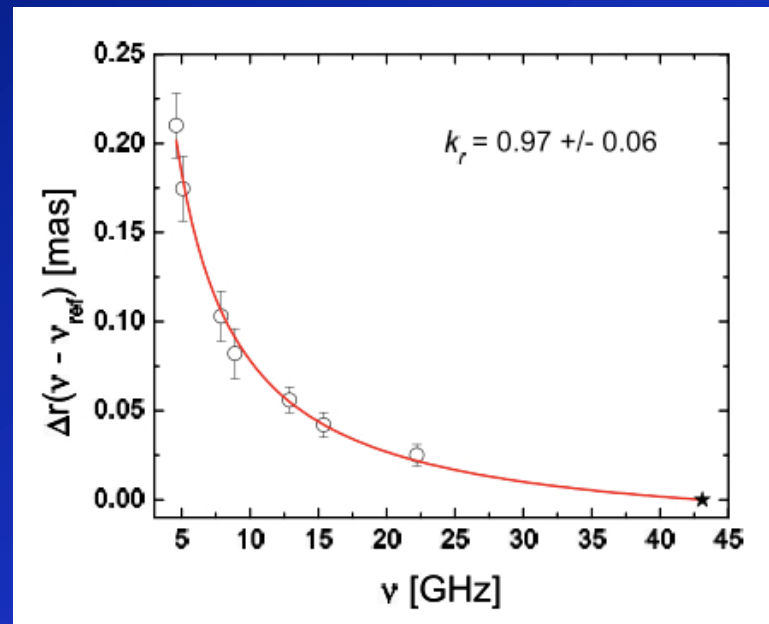
# O'Sullivan & Gabuzda 2010

2007+777

$$k_r = [(3 - 2\left(\frac{W}{\lambda}\right)^2)m + 2n - 2] / (5 - 2\left(\frac{W}{\lambda}\right)^2)$$

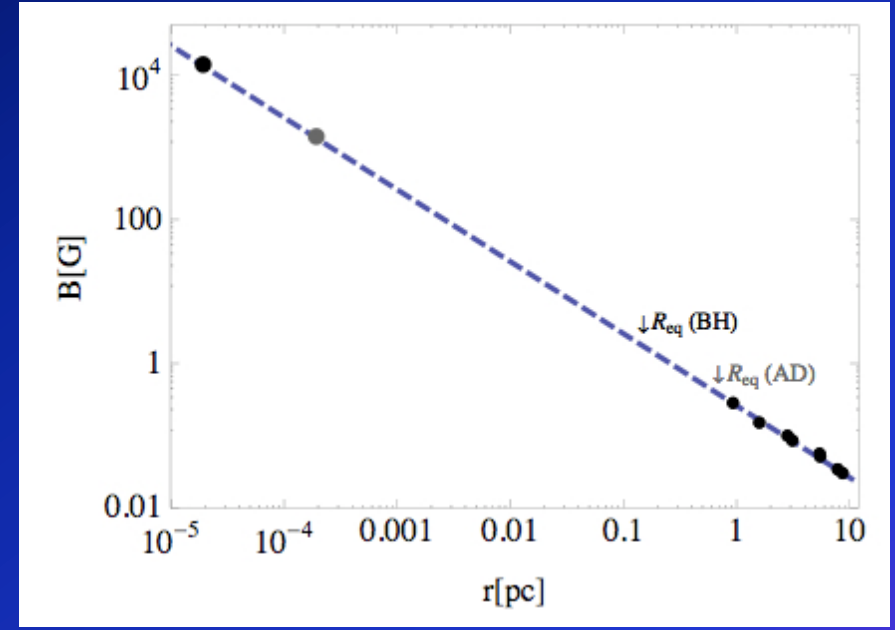
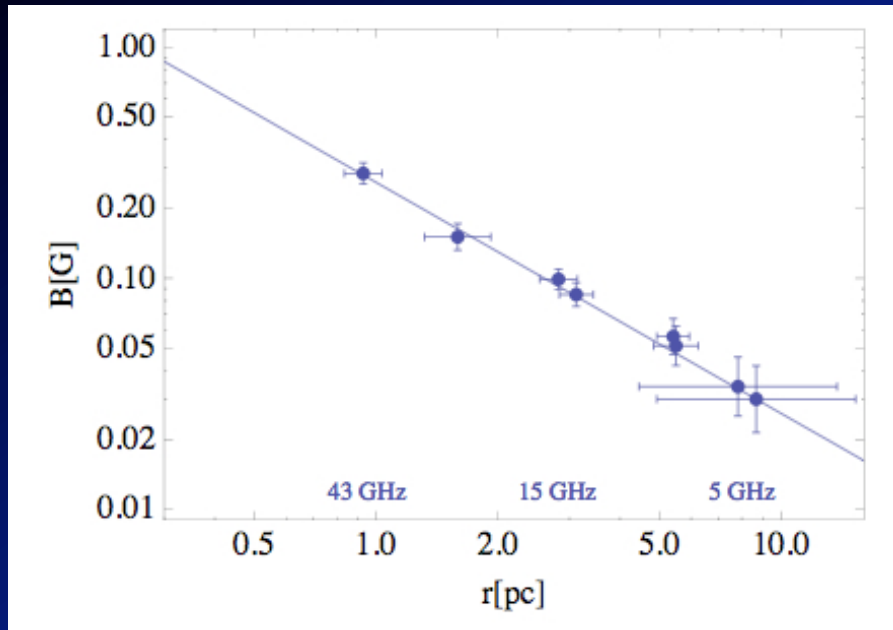
$$B \sim r^{-m} \quad N \sim r^{-n}$$

$$r \sim \left(\frac{W}{\lambda}\right)^{-1/kr}$$



- Behaviour expected for Blandford–Konigl jet is observed
- Evidence for **equipartition** in most cores – values for parameter  $k_r$  often close to 1, suggests  $B \sim r^{-1}$  and  $N \sim r^{-2}$

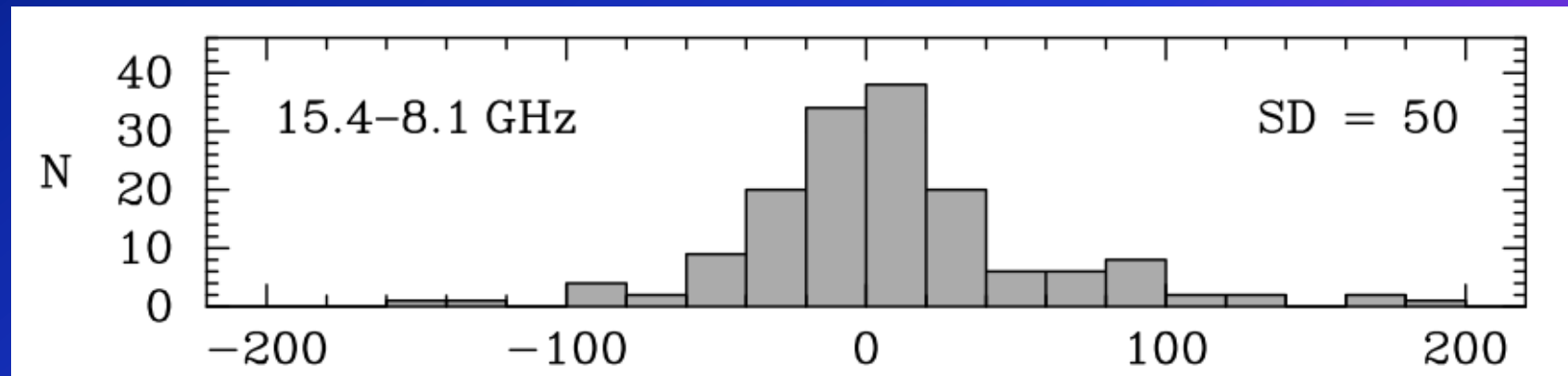
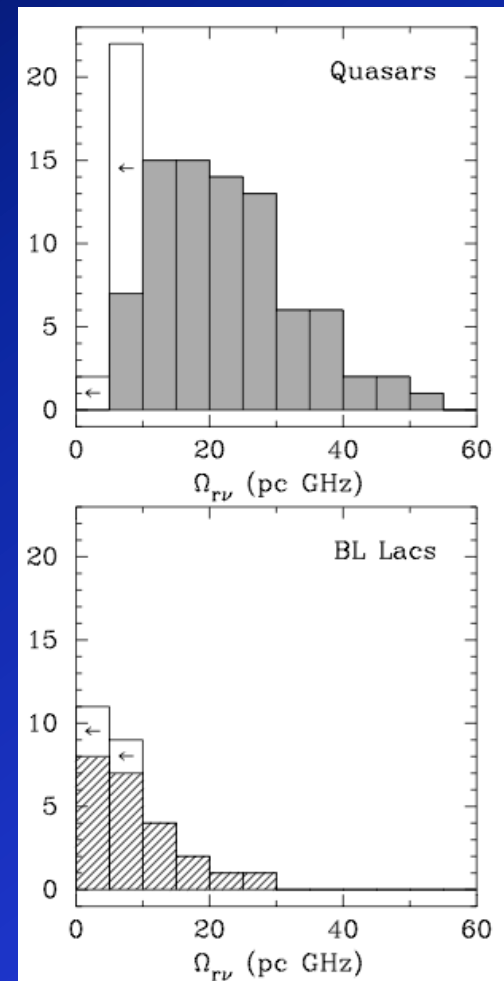
# O'Sullivan & Gabuzda 2010



- Inferred core-region B fields are 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)

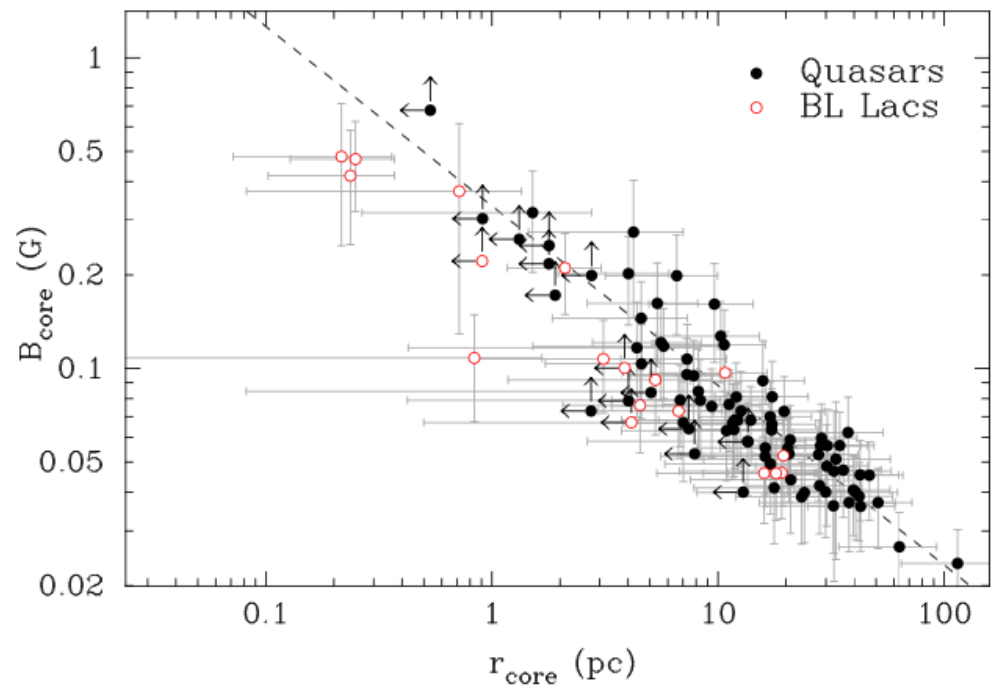
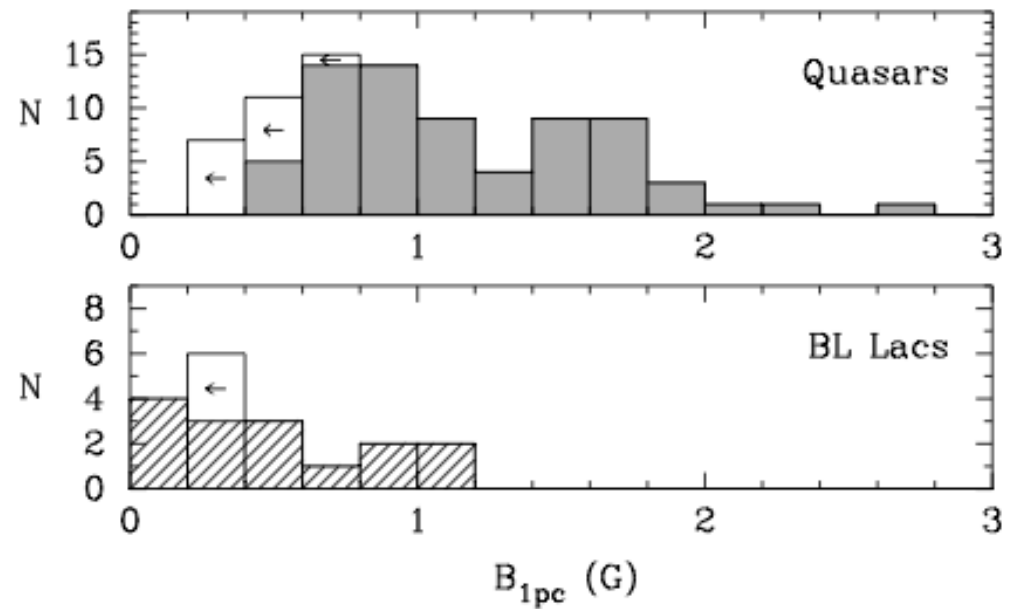
## Pushkarev et al. (2012)

- o Ability to compare shifts for different types of AGNs.
- o Shift distribution peaked in jet direction, as expected



Pushkarev et al. (2012)

- o B fields in quasars somewhat higher than in BL Lac objects



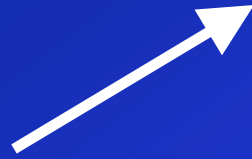
# Faraday Rotation: Studies of Ambient Medium & Jet B Fields

**Faraday rotation** – rotation of the observed linear polarisation angle  $\theta$  when polarised EM wave passes through a magnetised plasma.

$$\theta = \theta_0 + RM \theta^2$$

$$RM = (\text{constants}) \theta n_e B \cdot dl$$

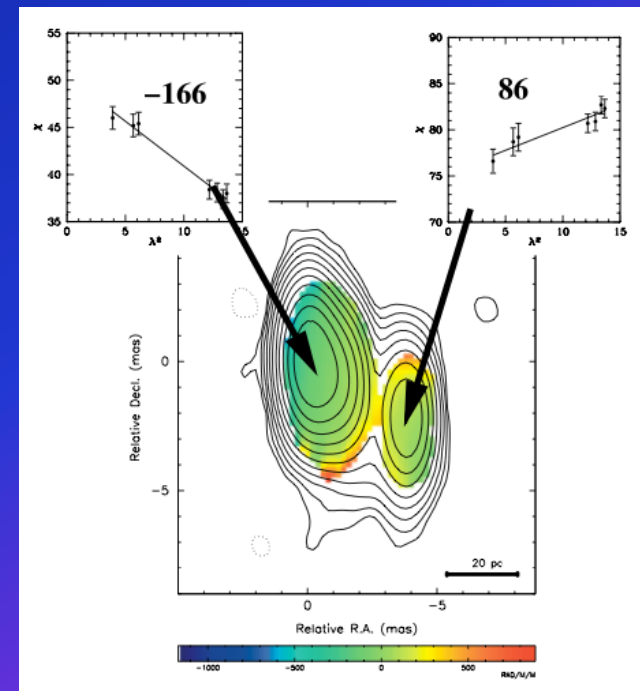
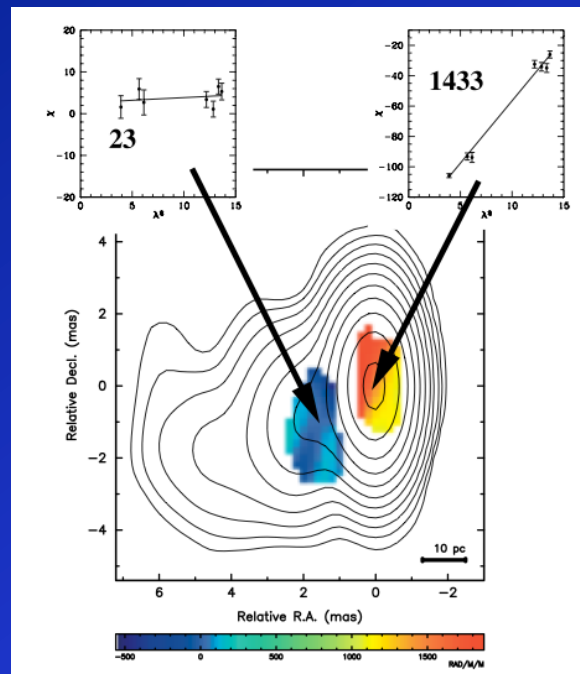
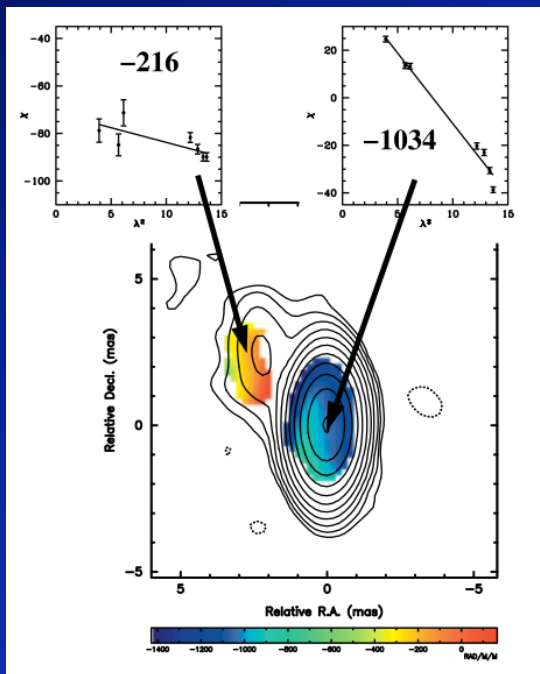
Electron density



Line of sight B field

# Zavala & Taylor (2003, 2004)

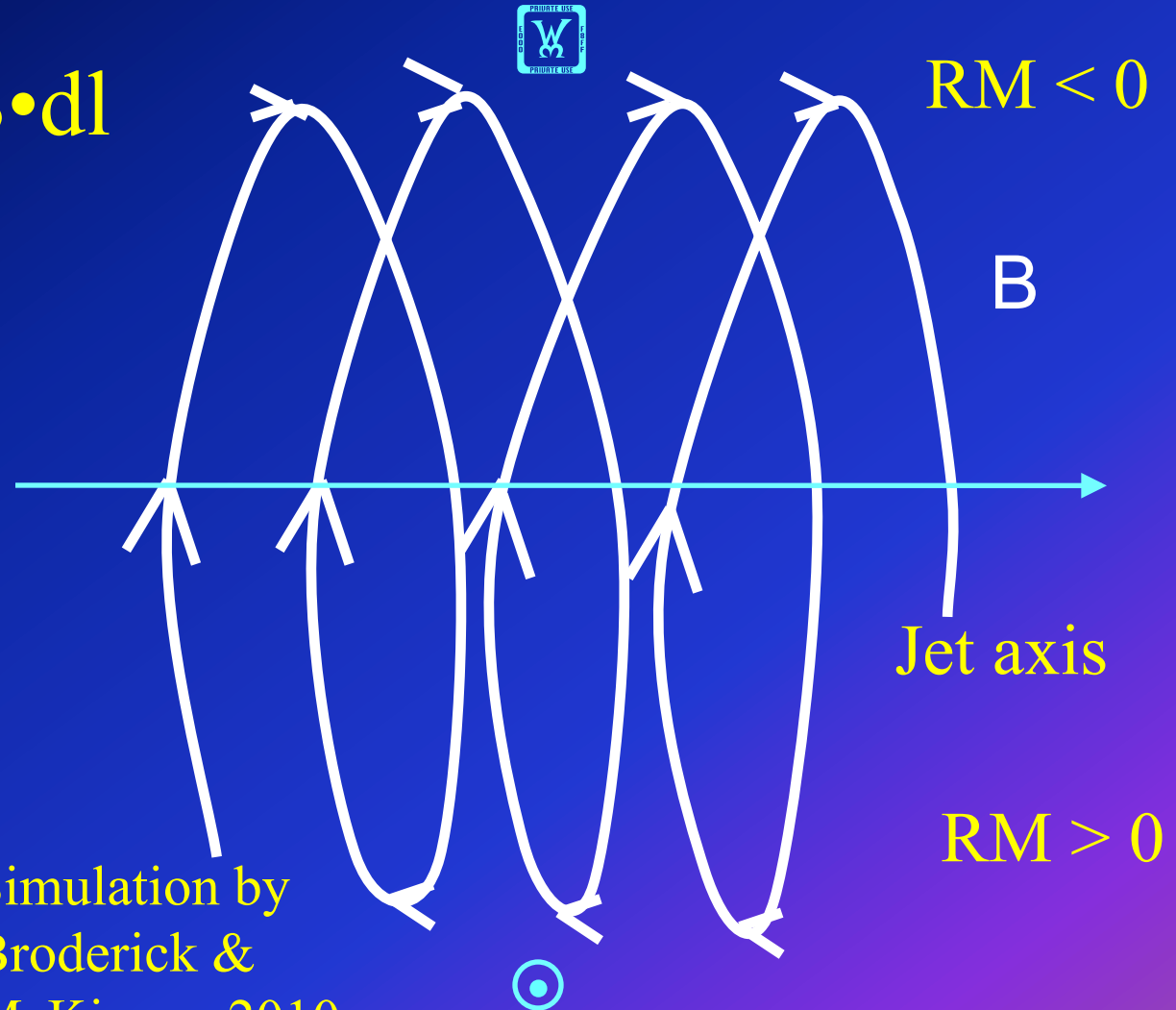
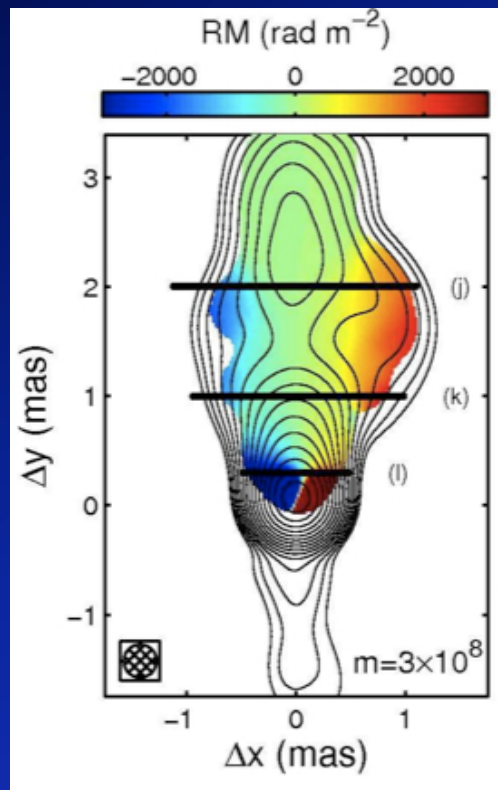
- o 40 objects
- o Core RM > Jet RM
- o Sometimes sign changes (changes in LOS B field)
- o Quasar core RMs > BL Lac core RMs





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).

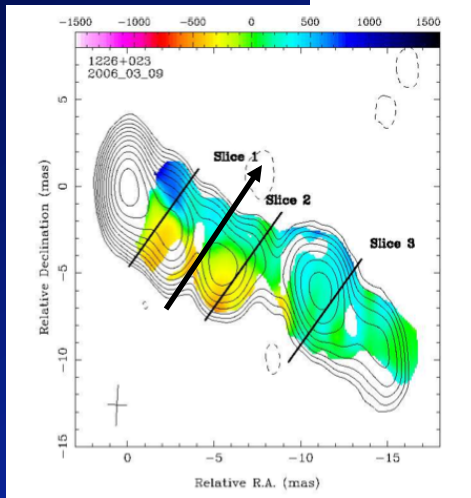
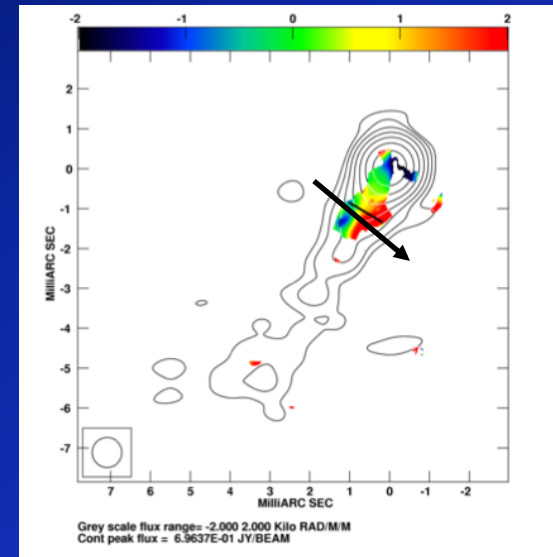
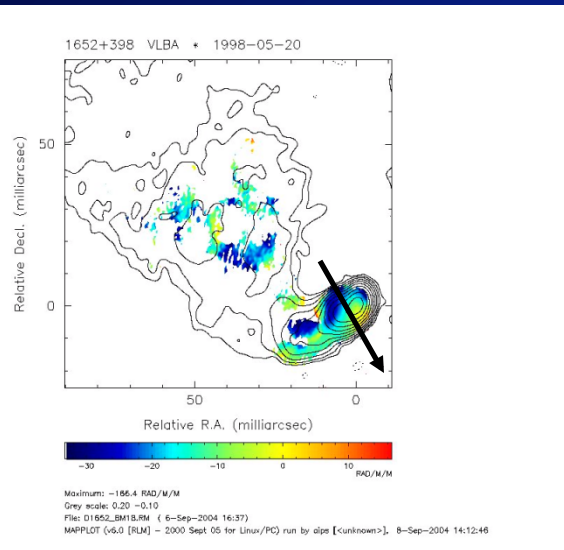
$$RM \sim \left[ \text{W} \right] n_e \mathbf{B} \cdot d\mathbf{l}$$



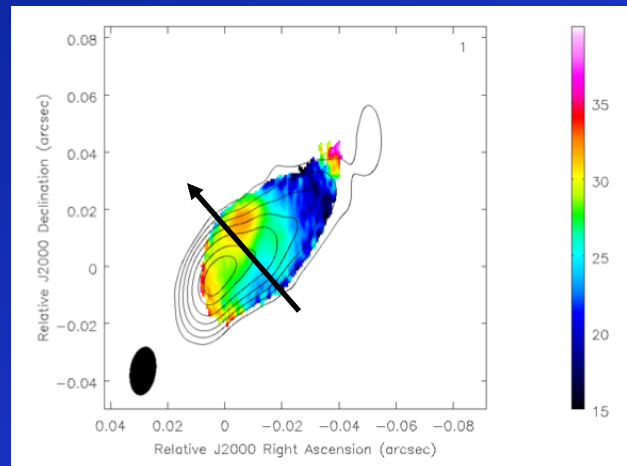
Simulation by  
Broderick &  
McKinney 2010



# Croke, O'Sullivan & Gabuzda 2010



# Algaba 2012



# Gabuzda et al. 2013

# Hovatta et al. 2012

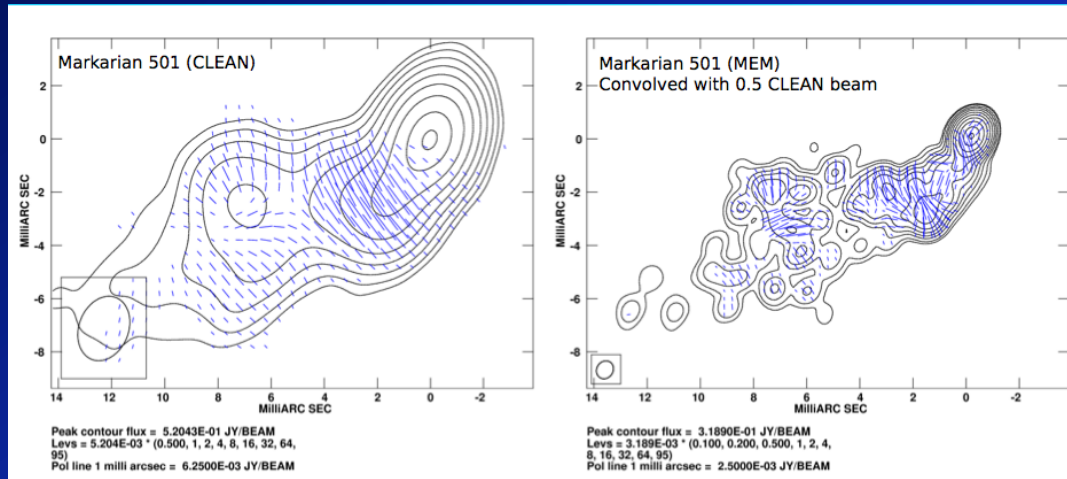
Reports of transverse RM gradients across pc-scale AGN jets, suggested as evidence for helical B fields

# Is the field toroidal or helical on parsec scales?

Murphy et al. (2013)

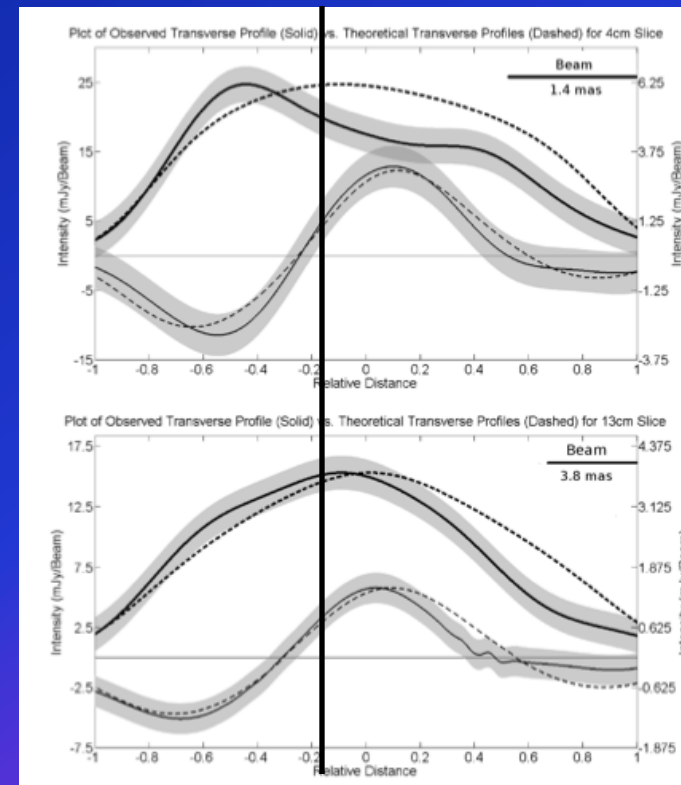


Fitting asymmetric transverse pol profiles for Mrk501 using simple helical field model – yields consistent fits with pitch angle  $\sim 53^\circ$ , viewing angle in jet rest frame  $\sim 83^\circ$



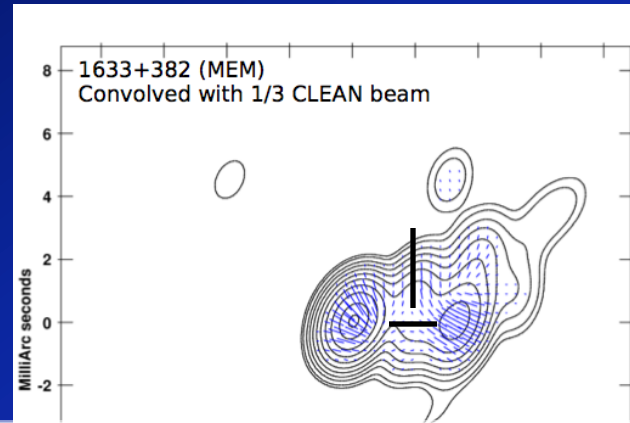
(see Coughlan poster, #21)

Note: Mrk501 also has RM grad (Gabuzda et al. 2004, Croke et al. 2010)



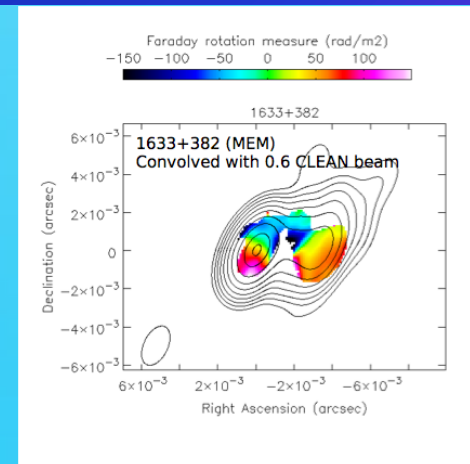
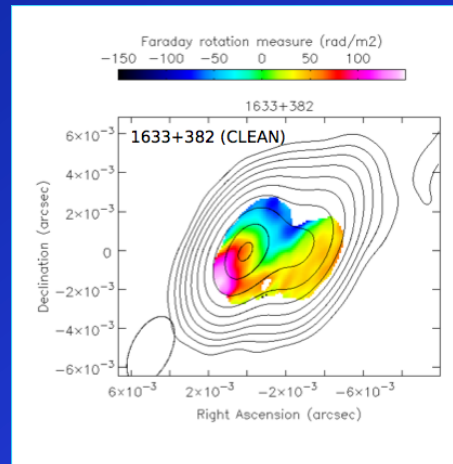
# Coughlan poster (#21) – another example

Asymmetric transverse  
pol structure revealed by  
high-res MEM pol map



+

Transverse RM  
gradient



====> Helical (not just toroidal) field present on pc scales

## Murphy et al. (2013)

Fitted value for viewing angle in jet rest frame  $\delta'$  together with measurement of apparent speeds can give solution for intrinsic jet speed  $\beta$  (Lorentz factor) and viewing angle in rest frame of observer  $\delta$ :

$$\sin \delta' = \frac{\sin \delta}{\Gamma[1 - \beta \cos \delta]}$$

$$\beta_{app} = \frac{\beta \sin \delta}{1 - \beta \cos \delta}$$

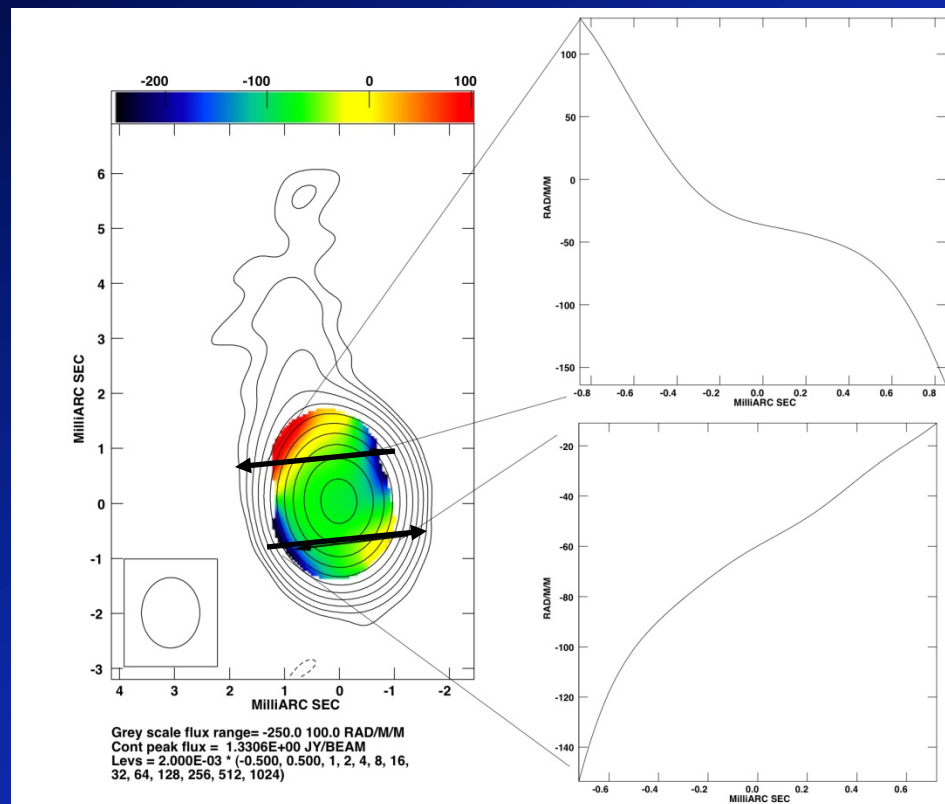


$$\beta = \left[ 1 + \frac{\sin^2 \delta'}{\beta_{app}^2} \right]^{-1/2}$$

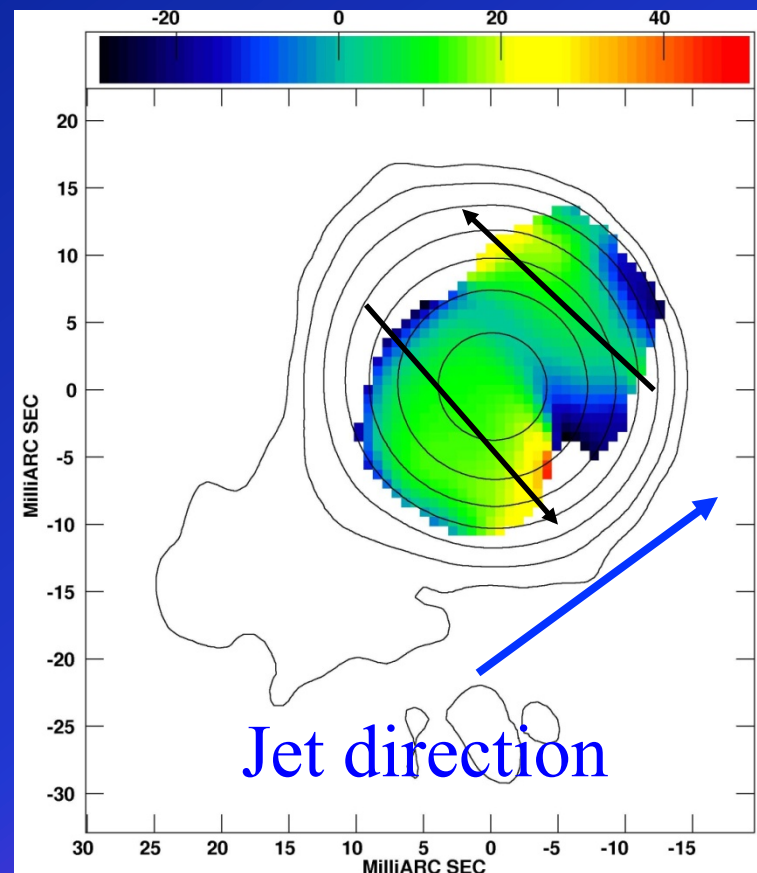
Yields for Mrk501  $\beta = 0.96$  and  $\delta' = 15^\circ$ , consistent with results of Giroletti et al. (2004),  $\beta \geq 0.88$  and  $\delta' \leq 27^\circ$

# Mahmud et al. (2012)

## Reversals of the transverse RM gradient between core region and jet on parsec scales in two AGNs



4.6, 5, 7.9, 8.4, 12.9, 15.4 GHz

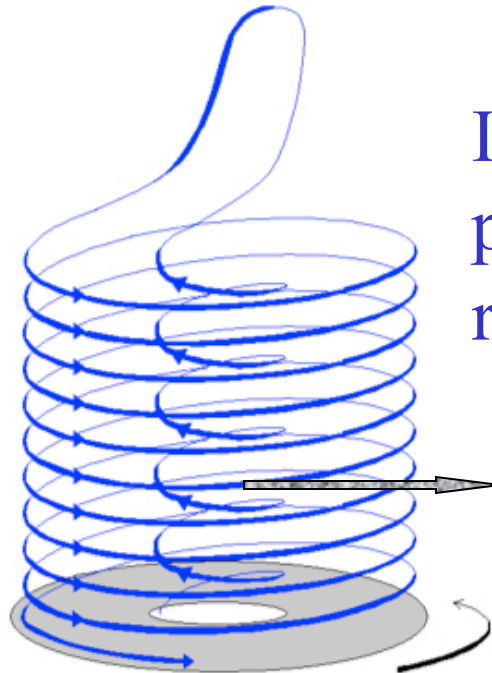
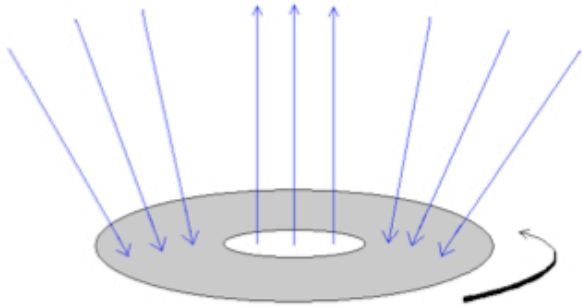


1.35, 1.43, 1.49, 1.67 GHz



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

Winding up of field lines due to differential rotation

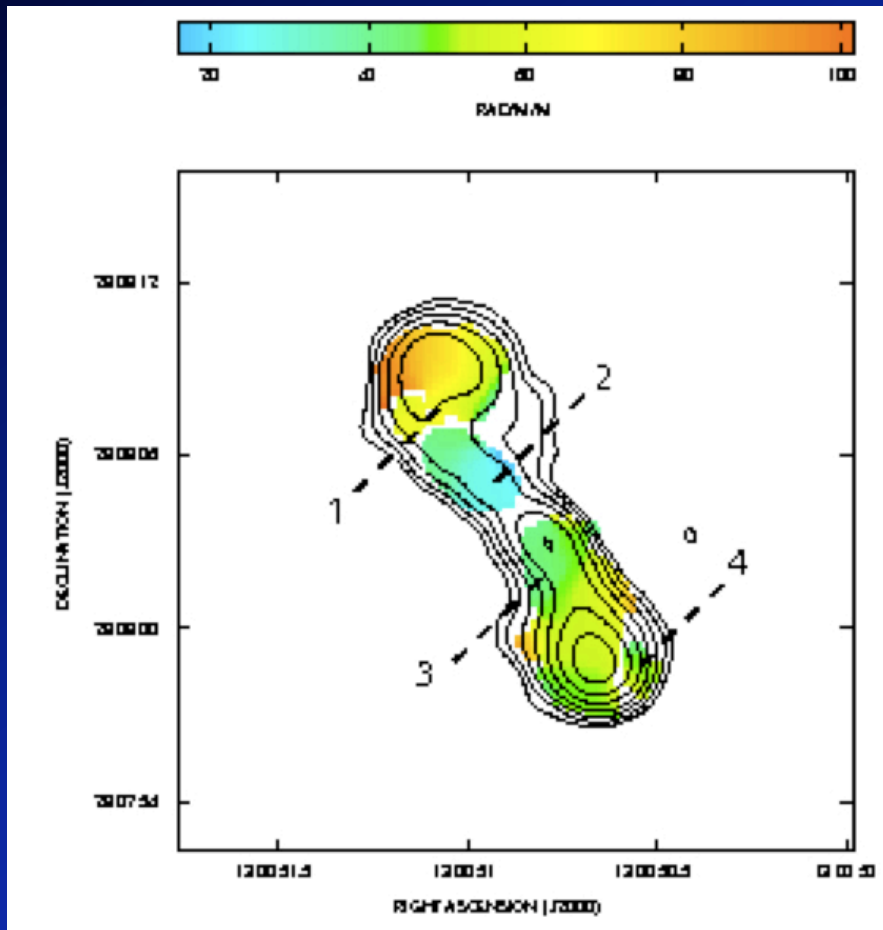


Integration path passes through both regions of helical field



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

Christodoulou et al. (in prep), Gabuzda et al. (2012) – finding some transverse RM gradients on kpc scales in literature



Fewer kpc-scale than pc-scale jets show transverse RM gradients — may reflect different relative contributions from systematic (helical/toroidal) and random (turbulent) RM components on different scales

(also talk by J. C. Algaba)

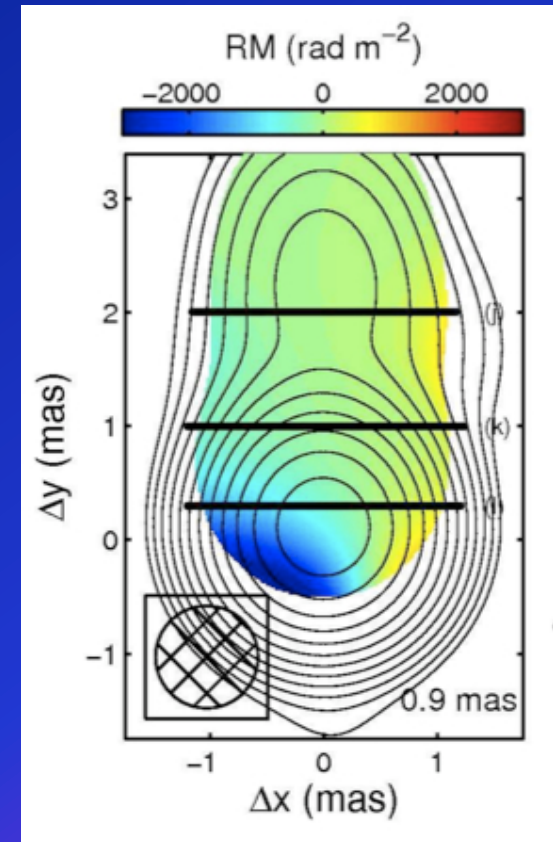
**Bonafede et al. 2010**

# Monte Carlo simulations



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

- Transverse RM gradient visible in theoretical simulations of Broderick & McKinney (2010), 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
- Suggests we should be able to observe this effect



Broderick &  
McKinney 2010

Taylor & Zavala (2010) proposed 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.

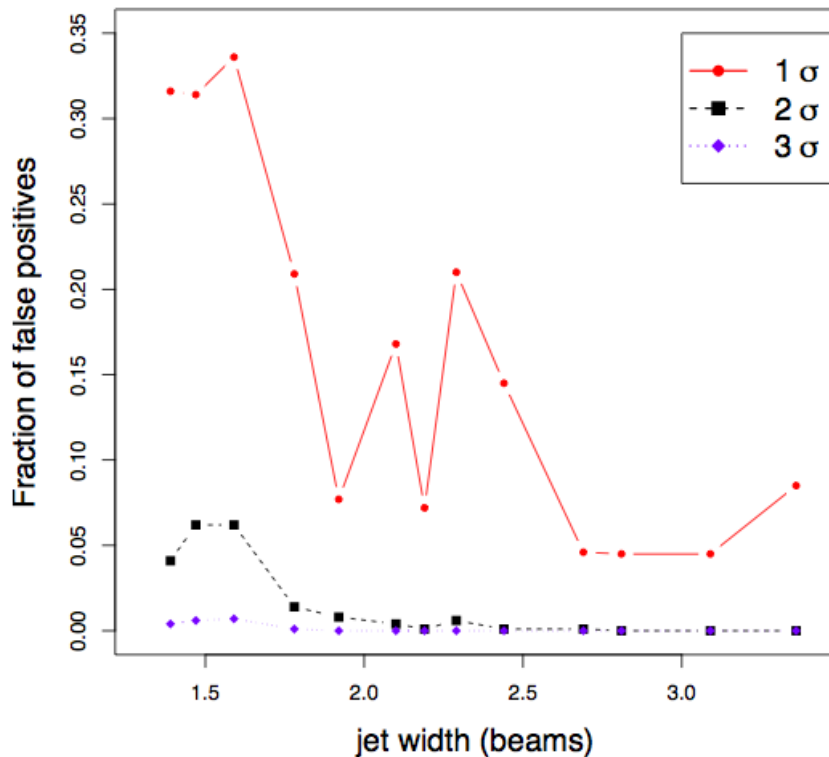
- Criteria 2, 3, 4 have been applied in most previous studies anyway, do not add anything new


- Criterion 1 was presented without justification, but would reject nearly all reported RM-gradient detections


➤ Situation needed to be clarified!

## Hovatta et al. (2012)

o MC simulations to investigate statistical occurrence of spurious RM gradients due to noise and limited baseline coverage for 7.9, 8.4, 12.9, 15.4 GHz VLBA data



o Fewer than  $\sim 1\%$  of runs gave spurious 3  gradients, even for observed jet widths  $\sim 1.5$  beam widths

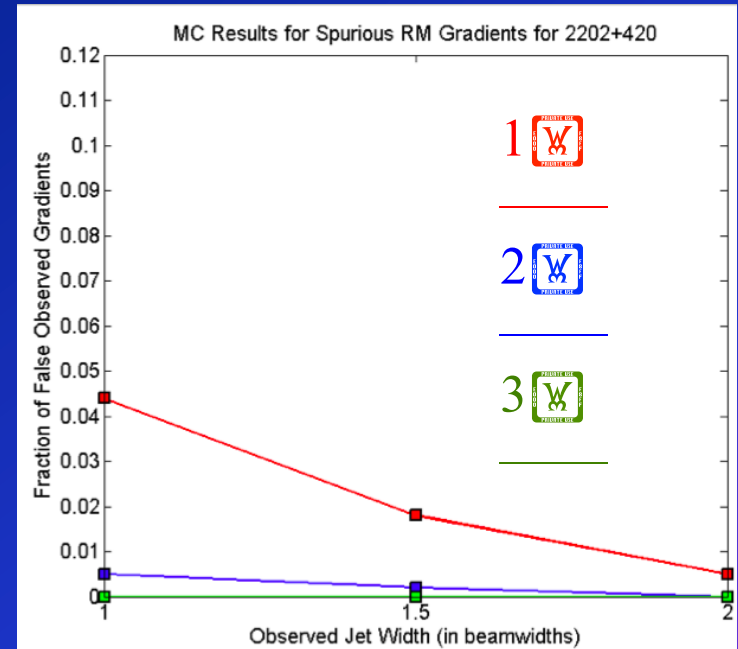
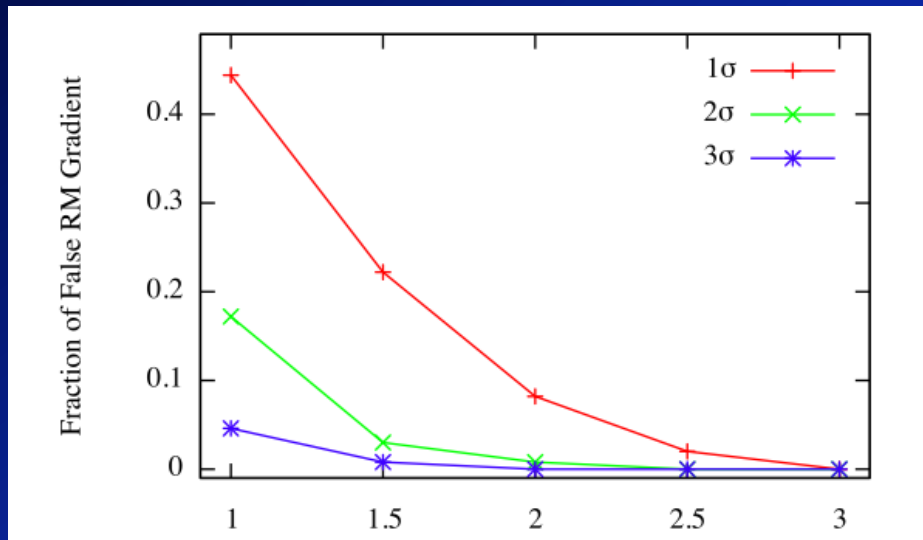
o Few spurious 2  gradients, too, but number can exceed 5% for widths below  $\sim 2$  beam widths

# Results confirmed by

Algaba (2012):  
12, 15, 22 GHz

Murphy poster (#12):

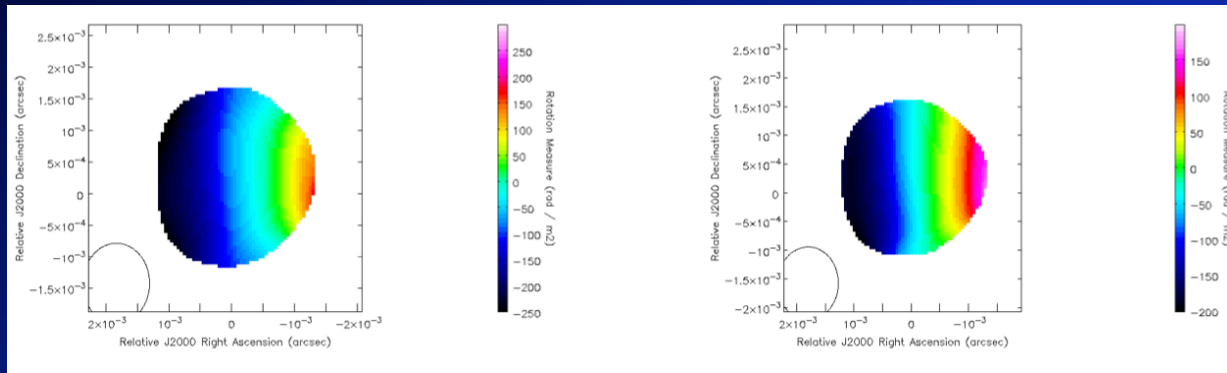
1.36, 1.43, 1.49, 1.67 GHz



Behaviour very similar, details depend on frequency range considered. In all cases, show that the “3 beamwidth” criterion of Taylor & Zavala (2010) is too severe.

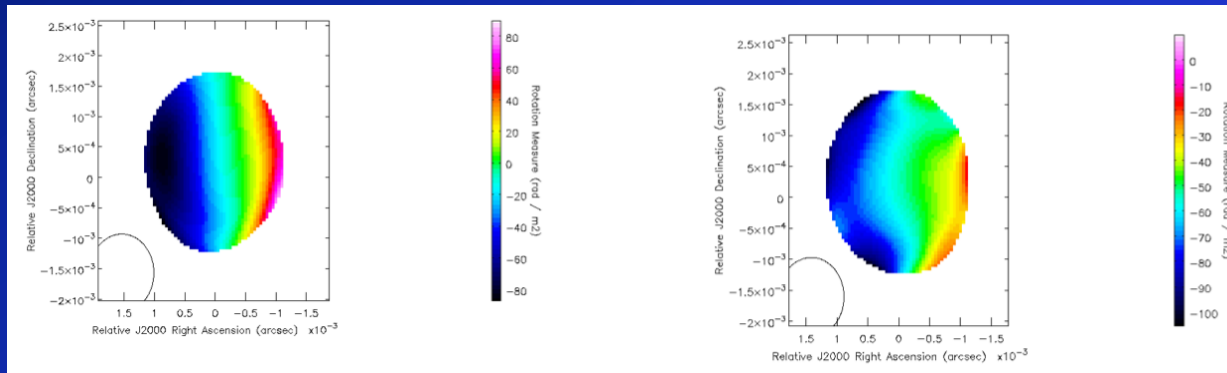
Mahmud et al. (2013): 4.6, 5, 7.9, 8.4, 12.9, 15.4 GHz

o Monte Carlo studies of simulated maps with transverse RM gradients for various intrinsic jet widths



Jet width 1/3 beam

Jet width 1/5 beam



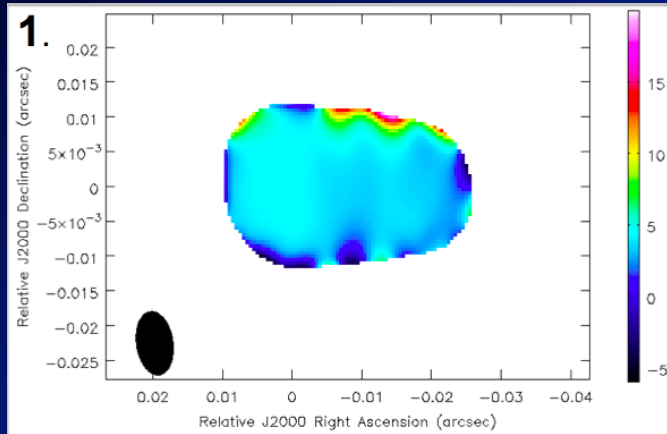
Jet width 1/10 beam

Jet width 1/20 beam

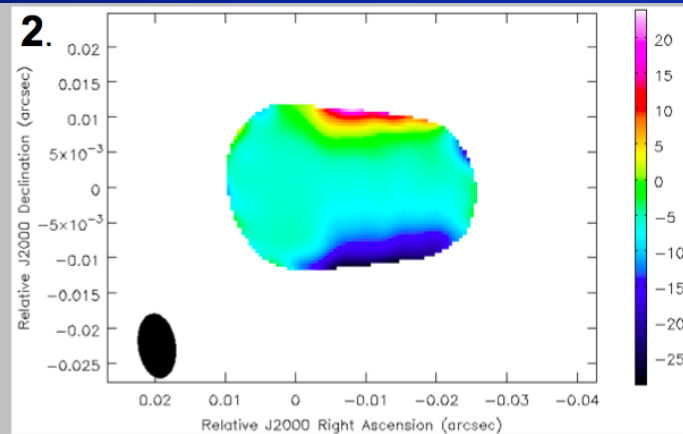
With realistic noise and baseline coverage, simulated RM gradients clearly visible even when jet width  $\ll$  beam width!



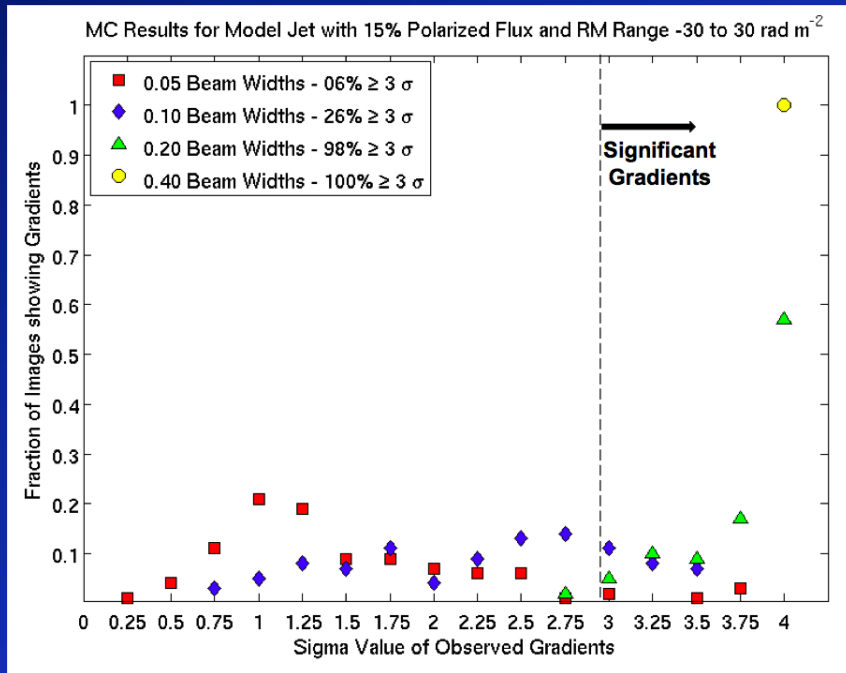
# Murphy poster (#12): 1.36, 1.43, 1.49, 1.67 GHz



Jet width 0.05 beam



Jet width 0.40 beam



98% or more of simulated maps showed transverse RM gradients  $> 3 \left[ \frac{\text{W}}{\text{W}} \right]$  when intrinsic jet width was at least 1/5 of a beam width.

## Summary - Core shifts, core B fields

- Variety of image–alignment techniques have been developed and are being actively used
- Core shift/core B-field studies carried out for large numbers of frequencies and large source samples for the first time
- Most results consistent with equipartition in core region
- 15-GHz core B fields range from  $\sim 0.02 \text{ G} - 0.8 \text{ G}$
- Data consistent with  $B \sim r^{-1}$
- Core B fields somewhat lower in BL Lac objects than in quasars

## Summary – Faraday Rotation

- Core RMs  $>$  Jet RMs (high electron density and B fields)
- Core RMs lower in BL Lacs than in quasars
- Transverse RM gradients (and transverse pol structure, EVPA rotations) provide direct evidence for helical/toroidal jet B fields, naturally formed by rotation of central BH + jet outflow.
  - Jets are fundamentally EM structures, launching mechanism also probably EM
  - Jets carry current – implications for collimation
- Evidence for return field in region surrounding the jet



## Summary – Monte Carlo Simulations

- “3 beam width” criterion of Taylor & Zavala (2010) for reliability of transverse RM gradients is too severe
- Best criteria for reliability are RM difference ( $> 3 \sigma_{\text{W}}^{\text{rms}}$ ) and monotonicity
- Transverse RM gradients in simulated images can be visible even when intrinsic jet width is  $\ll$  beam width
- Note: need less resolution to detect *presence* of gradients than to reliably derive *source parameters*!
- Usual practice of assigning I, Q or U errors to be equal to  $\sigma_{\text{W}}^{\text{rms}}$  appreciably underestimates uncertainties (by about a factor of 2 off peak) (Hovatta et al. 2012)

## Key future “technical” work:

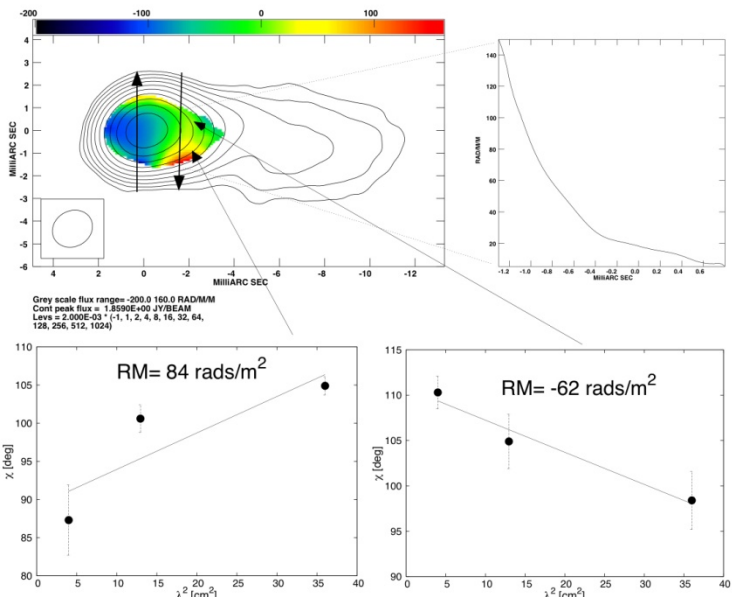
- o Improve understanding of uncertainties in fluxes measured in individual pixels
- o Mathematical description of correlations between fluxes measured in nearby pixels
- o Development of alternative imaging techniques for VLBI (e.g. MEM, RM synthesis)



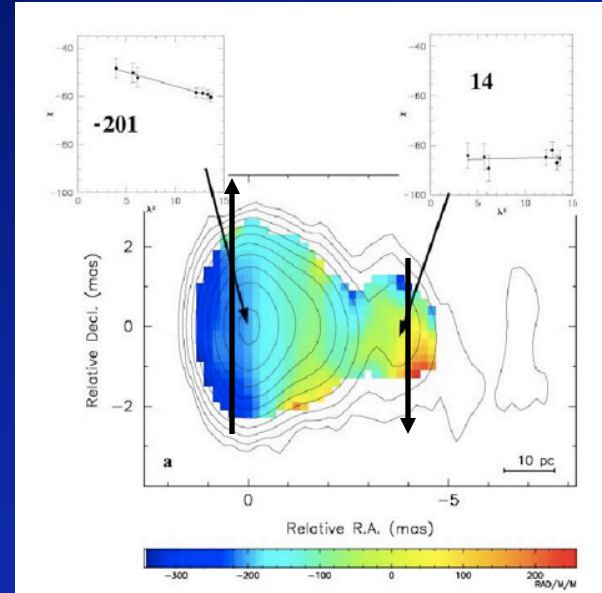
A cat who is has found something far more interesting than multi-frequency polarization measurements.



4/1997

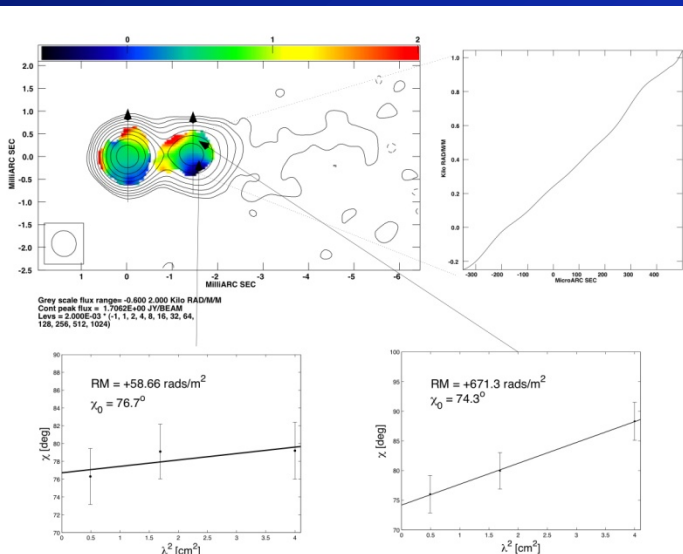


6/2000



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

8/2002



8/2003

