# Some Recent Observational Results on the B Fields of AGN Jets on Parsec to Kiloparsec Scales

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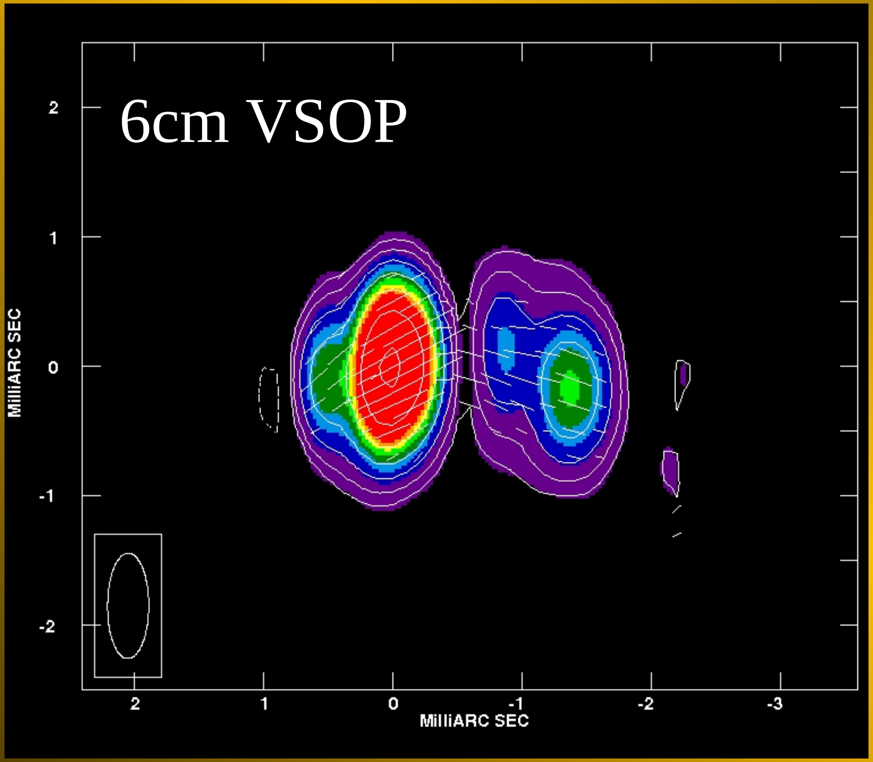
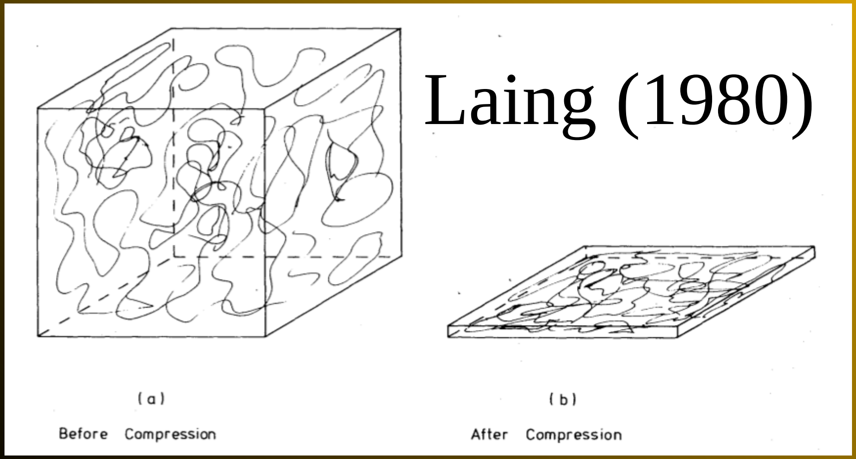
# Outline of talk

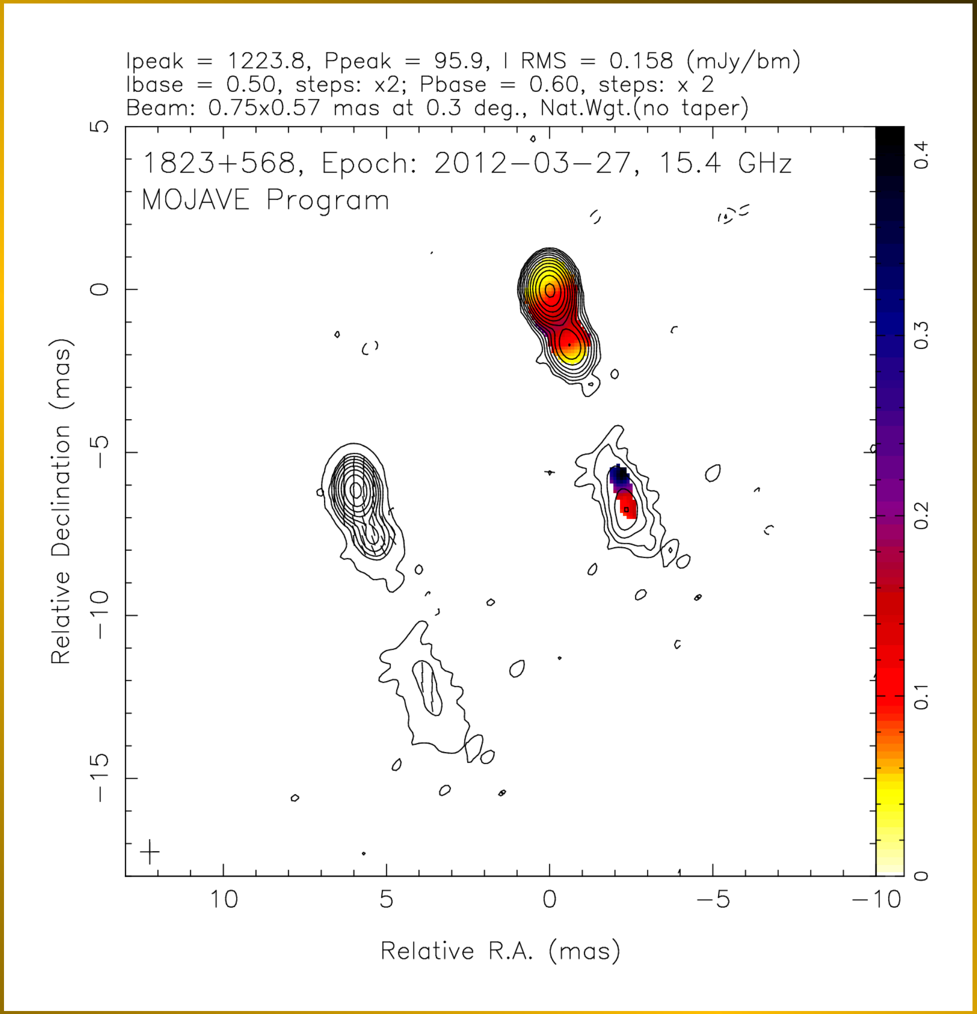
- Polarization & B-field structure of AGN jets
- Faraday rotation gradients & helical B fields
- Evidence for the “return” jet B field
- Asymmetries in RM gradient orientation
- Summary

# Polarization & B-field structure of AGN jets

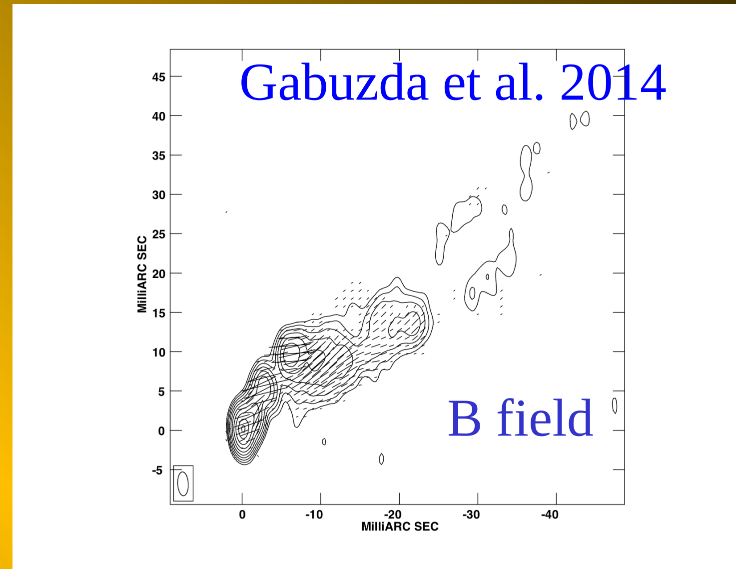
# Distinct bright compact features with orthogonal B may be shocks

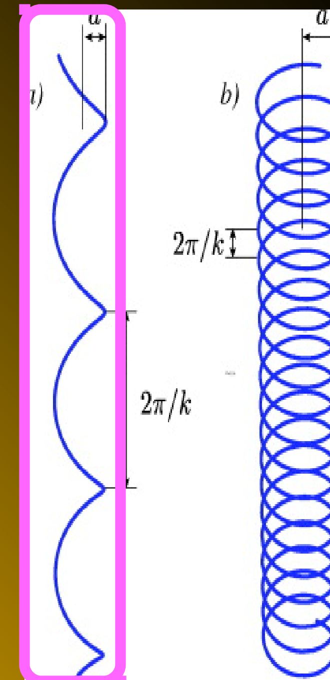


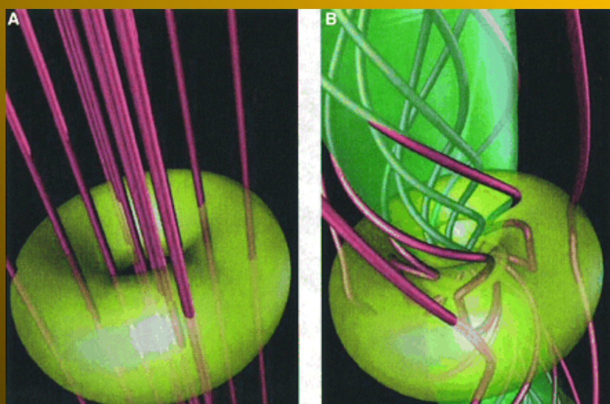



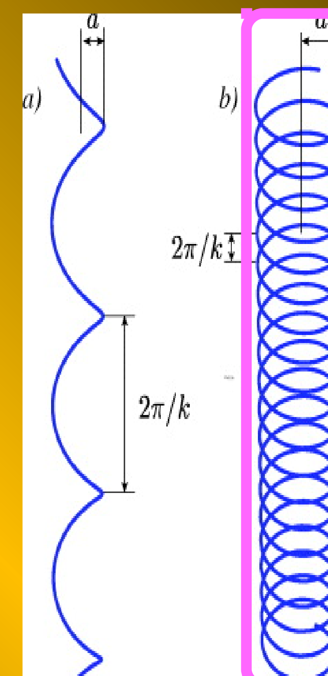
Extended regions with longitudinal B could be due to shear or low-pitch-angle helical B field



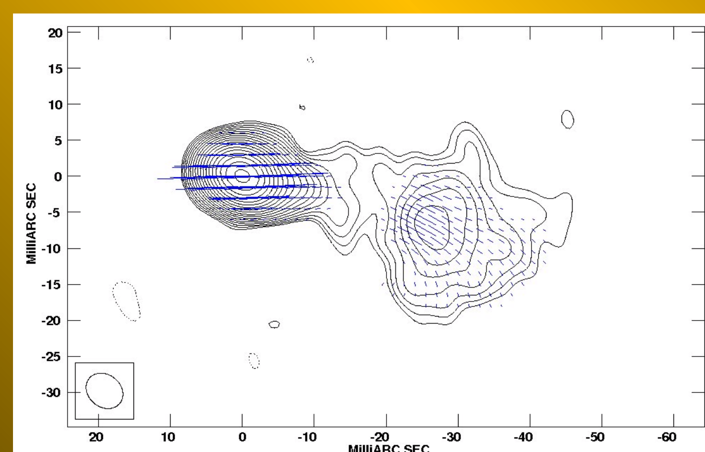



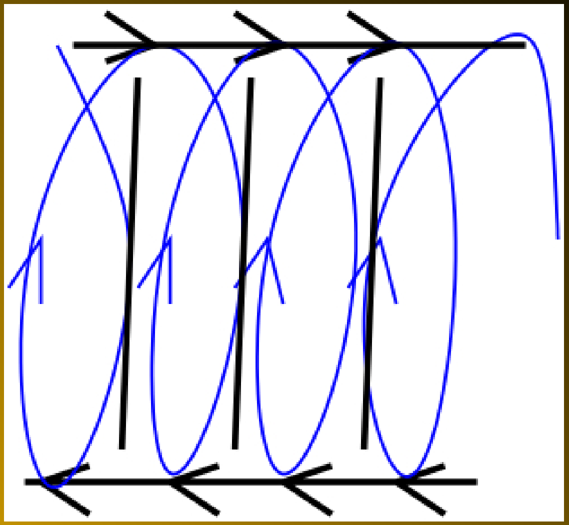

Meier, Koide & Uchida 2001

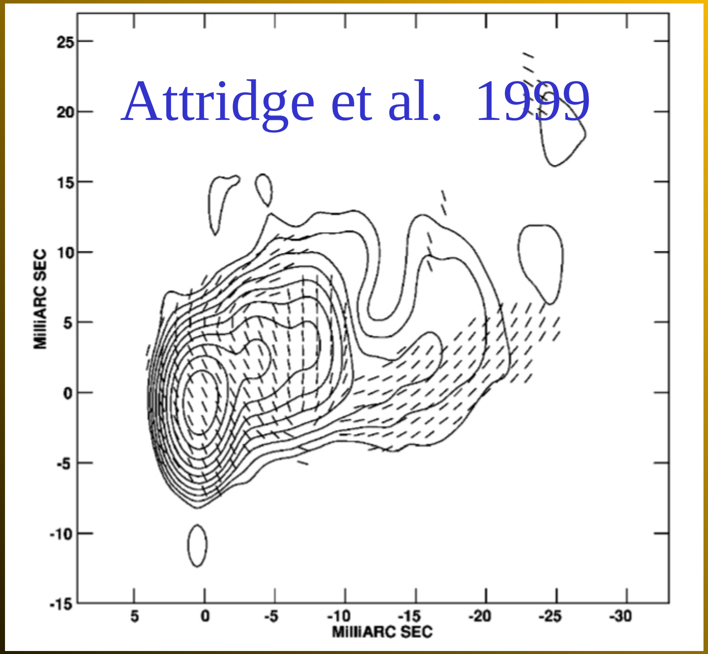


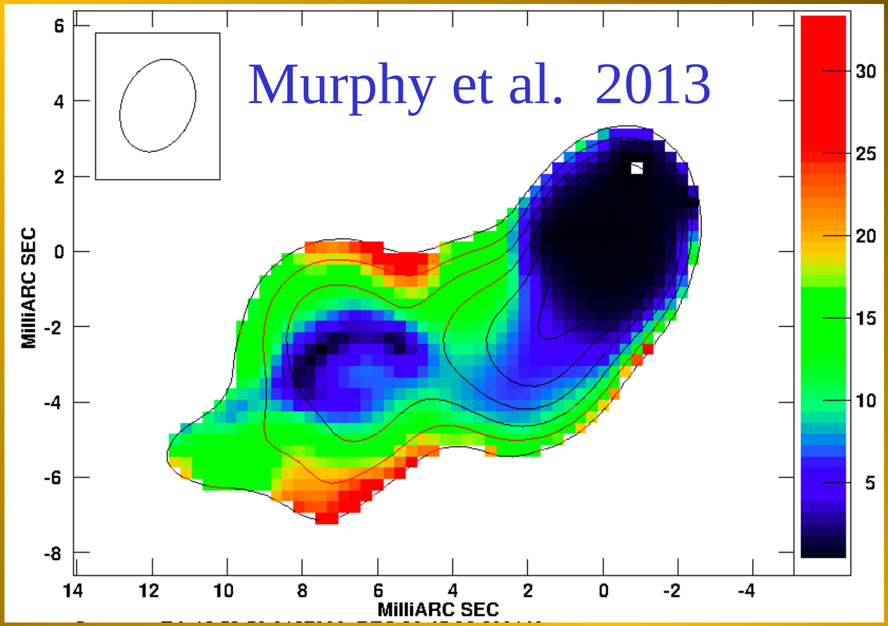
Extended regions with orthogonal B most likely due to toroidal B field or high-pitch-angle

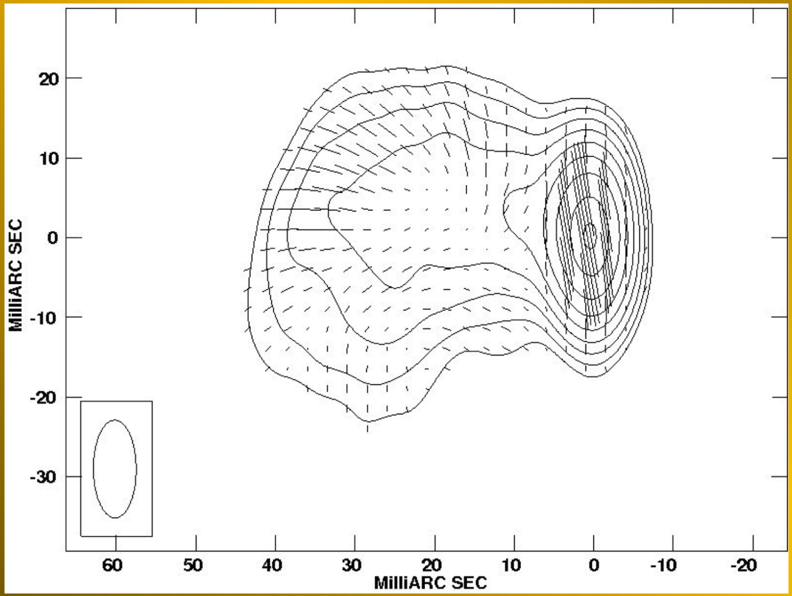


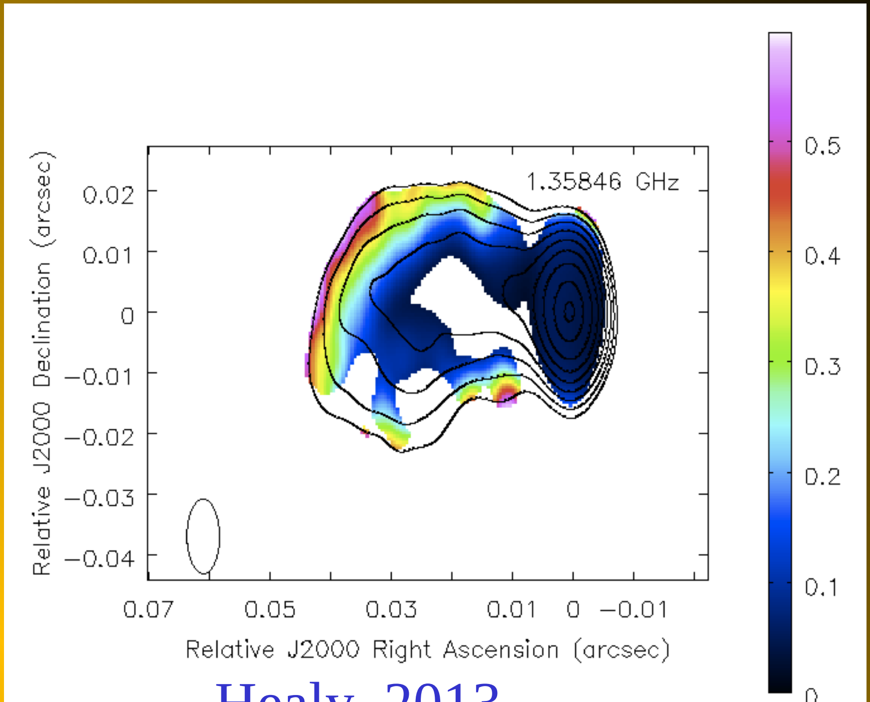
Toroidal or helical jet B fields can give rise to characteristic transverse I and P structures *across* a jet, such as "spine+sheath" polarization structure and a rise in degree of polarization at jet edges







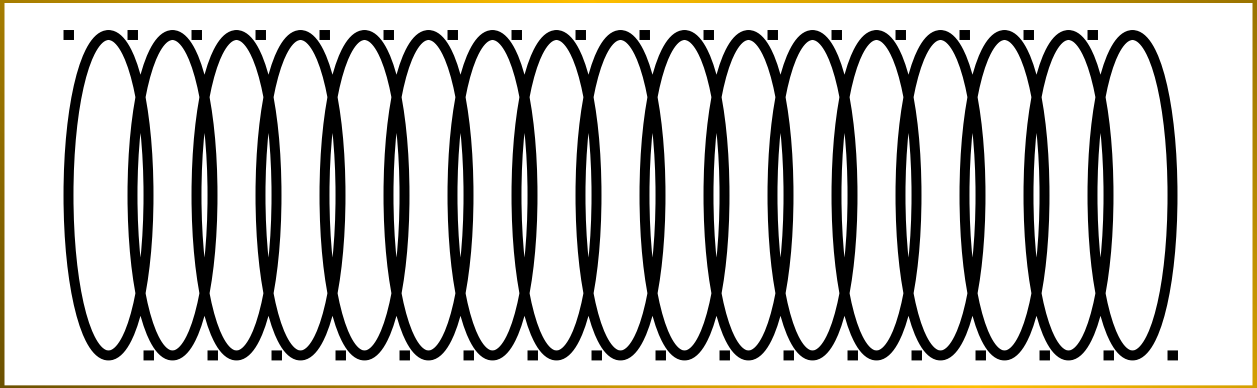




Healy 2013

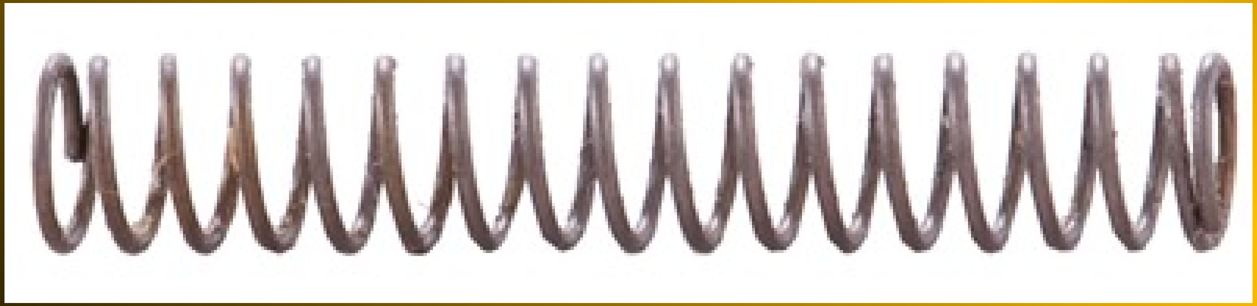
Longitudinal B field and high degree of polarization at a jet edge may also be due to shear or jet curvature

# Toroidal versus helical B fields

Key difference: A toroidal field creates symmetrical transverse intensity and polarization profiles, a helical field often gives asymmetrical profiles.



Toroidal



Helical

Observation of asymmetrical transverse profiles provides evidence for specifically helical fields.

# Faraday rotation gradients & helical B fields

Faraday rotation – rotation of the observed linear polarisation angle $\chi$ when polarised EM wave passes through a magnetised plasma, due to different propagation velocities of RCP and LCP components of the wave.

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

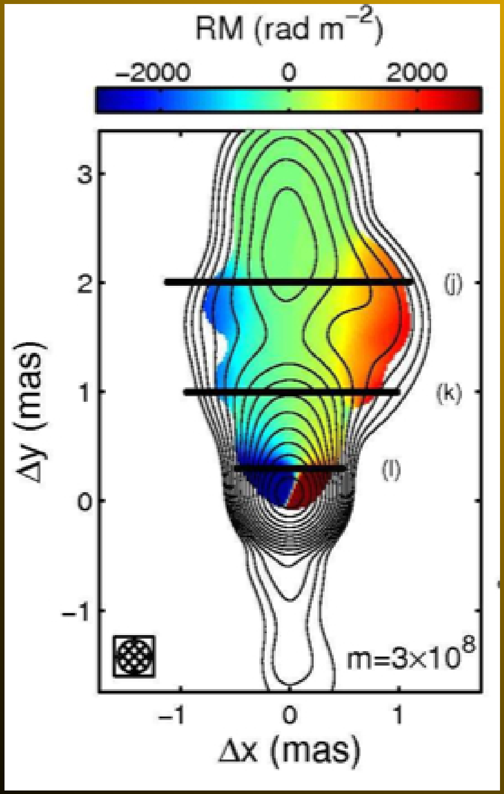
$$RM = (\text{constants}) \int n_e\, \mathbf{B} \cdot d\mathbf{l}$$

Electron density

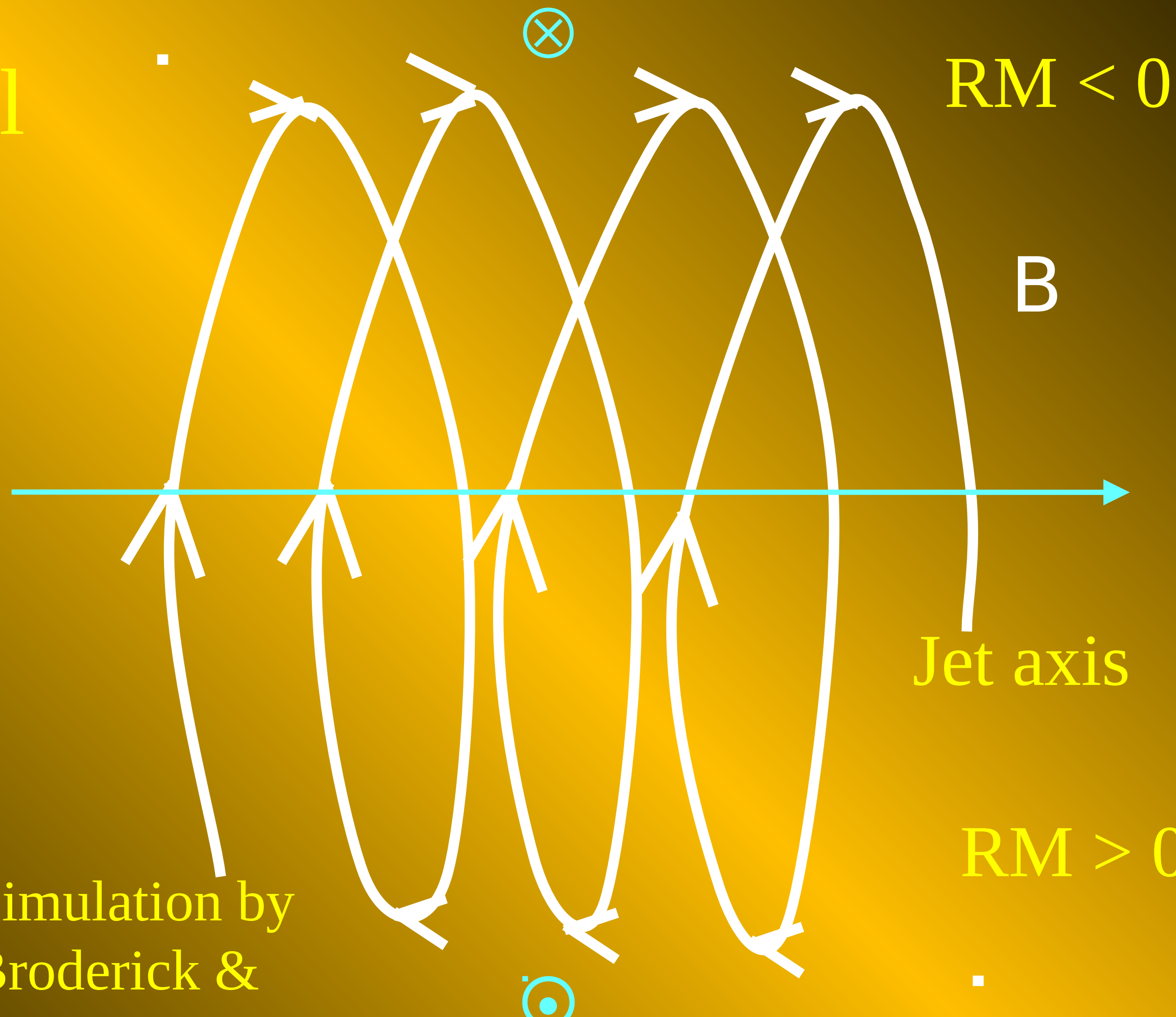
Line of sight B field

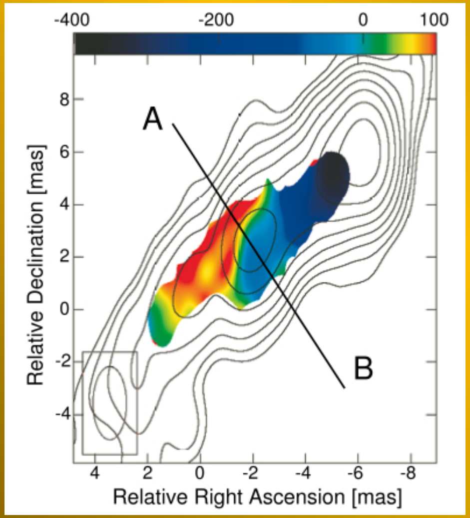
If jet has a helical B field, should observe a Faraday-rotation gradient *across* the jet – due to systematically changing *line-of-sight* component of B field across the jet (Blandford 1993).

$$RM \sim \int n_e \, B \bullet dl$$

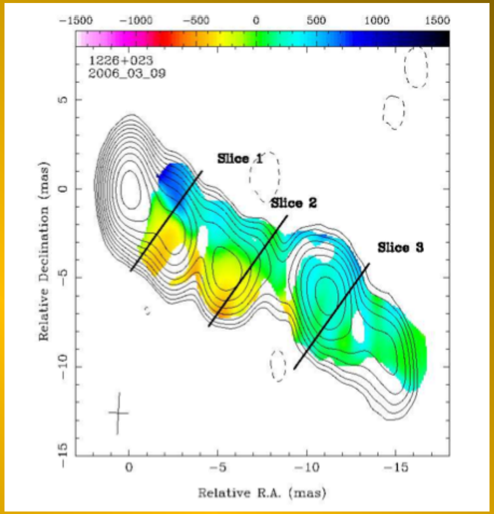



Simulation by Broderick & McKinney 2010

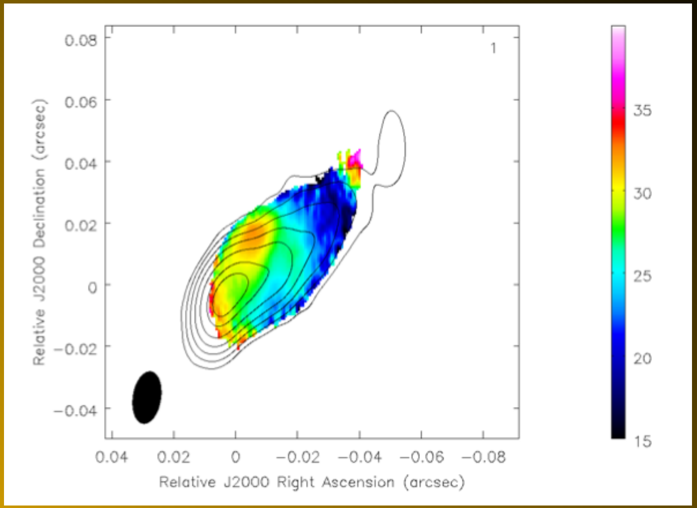





Asada et al. 2008



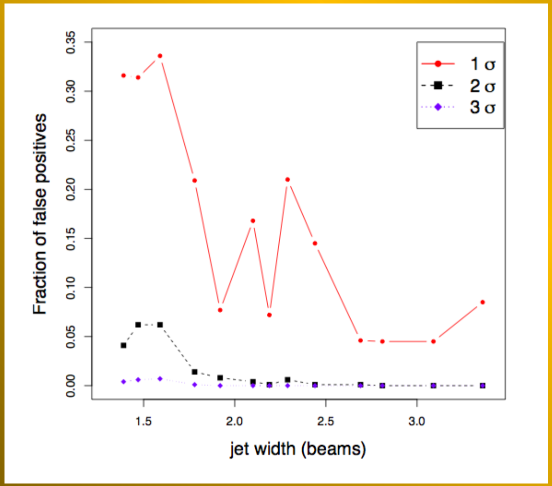

Hovatta et al. 2012




Gabuzda et al. 2013

Reports of transverse RM gradients across a number of pc-scale AGN jets — but concerns were expressed about their reliability, as jet structures are usually narrow compared to beamwidth.

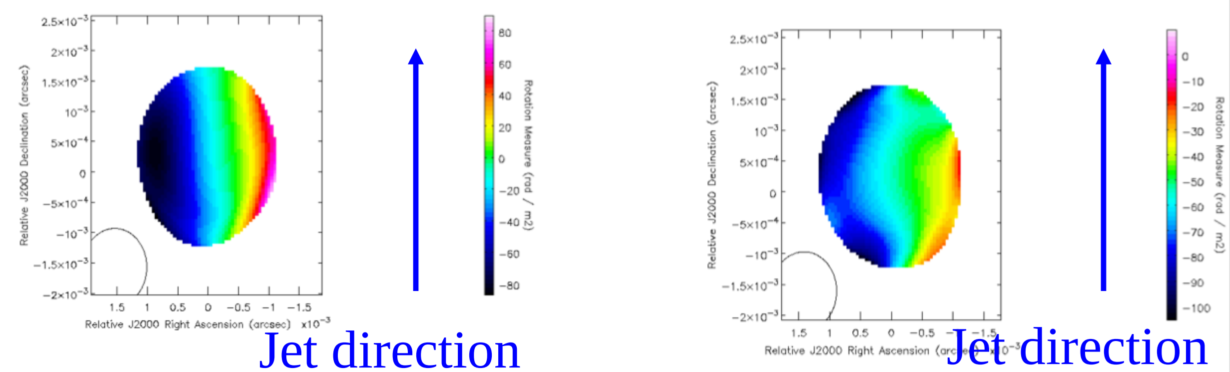
Recent Monte Carlo simulations have resolved this issue!




Hovatta et al. (2012) — considered model maps *without* RM gradients — fewer than ~1% of runs gave spurious 3σ gradients, even for narrow jets

Mahmud et al. (2013), Murphy & Gabuzda (2013) — considered model maps *with* RM gradients — RM gradients clearly visible even when jet width << beam width!

This surprising result comes about because Q and U can be both + and –.




Jet width 1/10 beam Jet width 1/20 beam

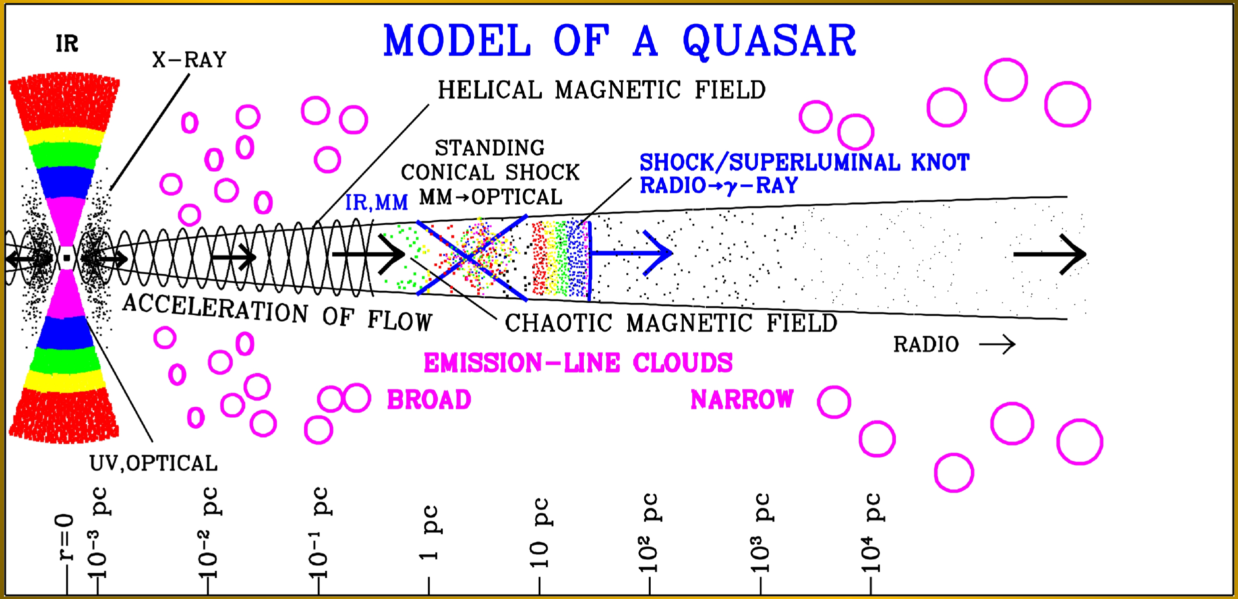
These results demonstrate that it is not meaningful to impose a width limit on RM gradients — the best test of reliability is monotonicity of gradient and RM range spanned $> 3\sigma$.

My group has been working to (1) verify previously published results and (2) search for new transverse RM gradients using modern approaches to estimating uncertainties (Hovatta et al. 2012) and ensuring proper alignment of images at different frequencies.

The vast majority of previously reported RM gradients have significance $> 3\sigma$ (Gabuzda et al. 2014, 2015).

A key implication of the detection of a helical B-field component on parsec scales is that this field (at least partially) survives its passage through the shocked VLBI core region (or perhaps is regenerated after being disrupted).

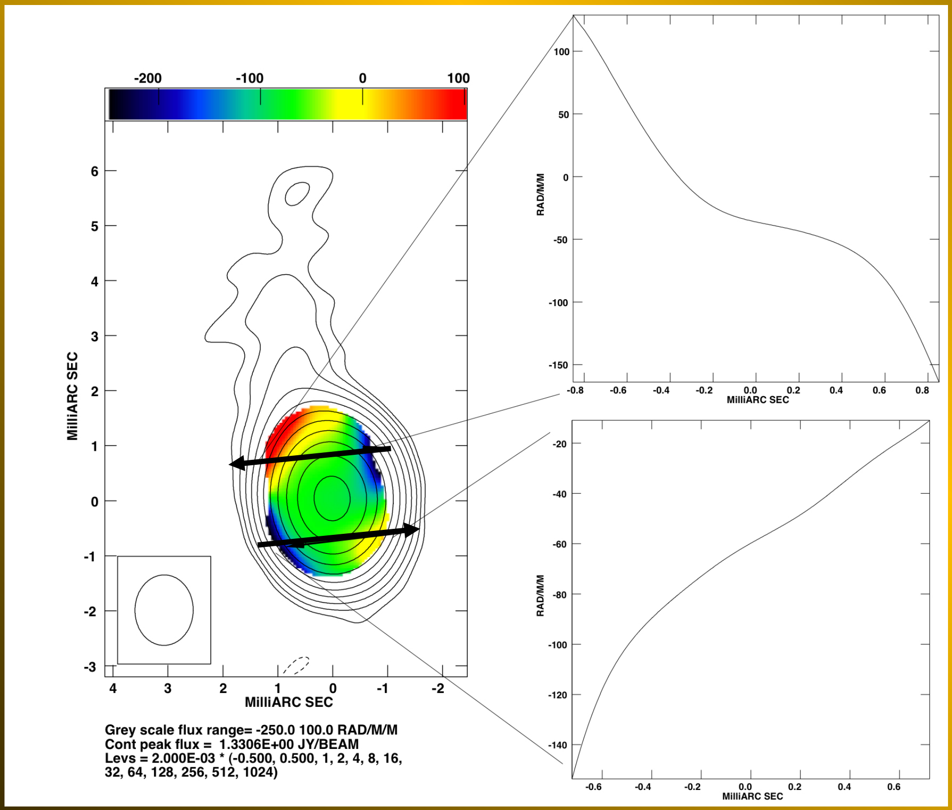
Marscher's picture of the inner-most jet.

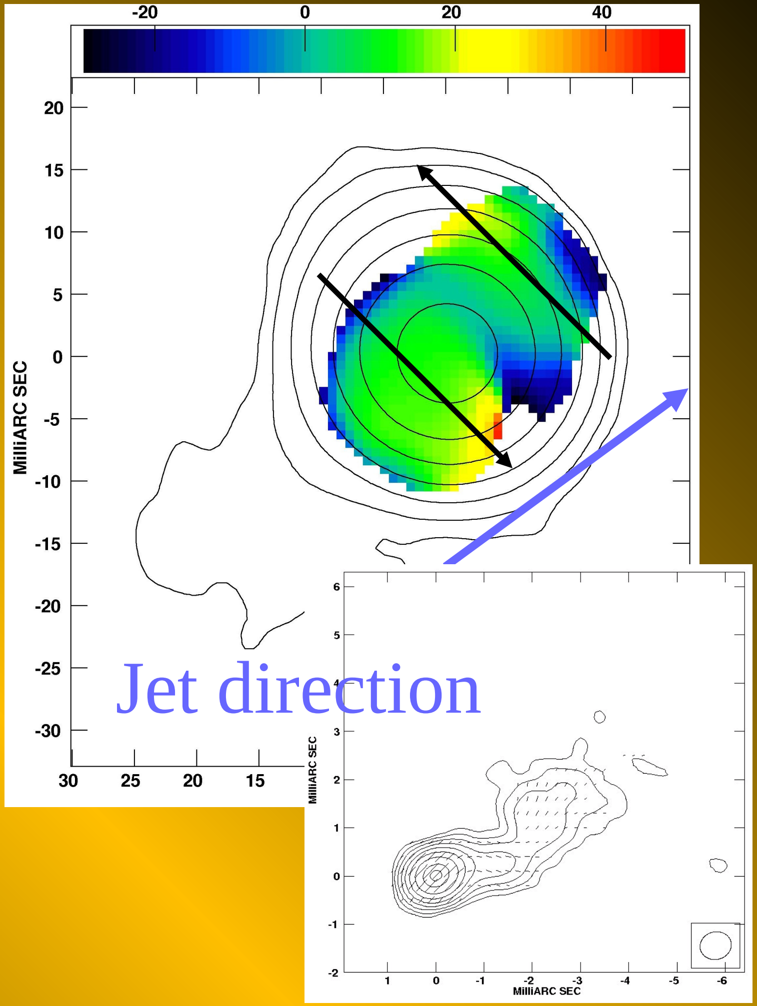



Recent studies by Marscher (2015) also indicate that observed variability allows an appreciable helical (not chaotic) field component.

# Evidence for the “return” jet B field

# Mahmud et al. (2013) detected "reversed" RM gradients in two AGN:



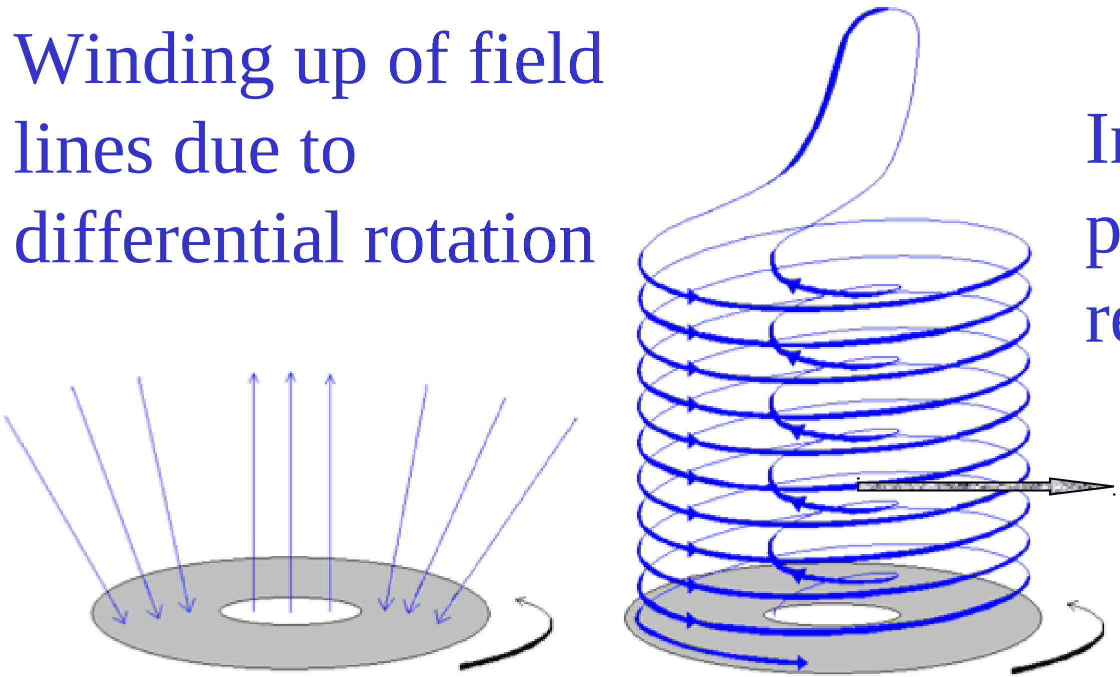




2–6 cm RM map (parsec scales)

18–22 cm RM map (decaparsec scales)

This 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



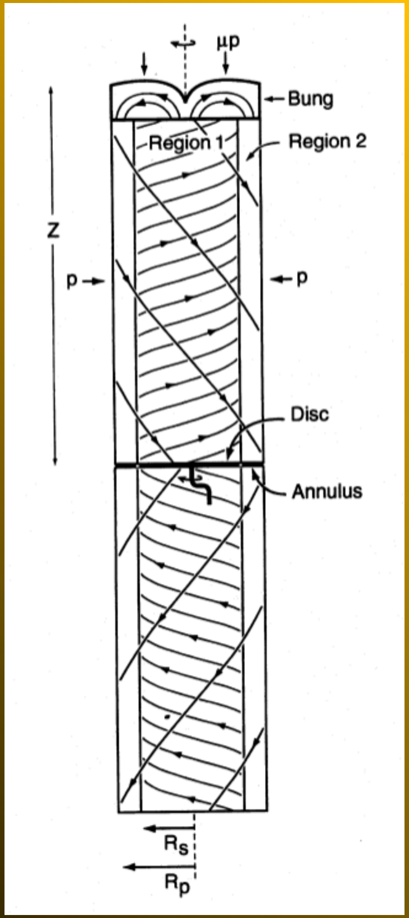
Integration path passes through both regions of helical field

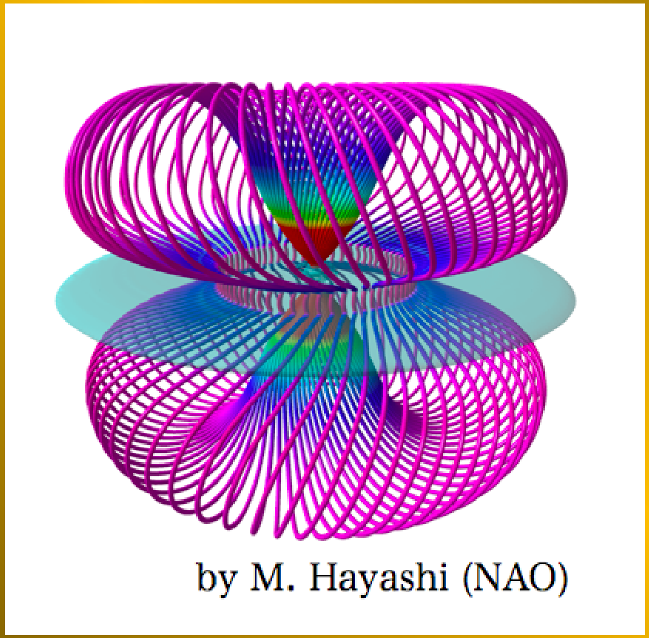
$$\int n_e \mathbf{B} \cdot d\mathbf{l}$$

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

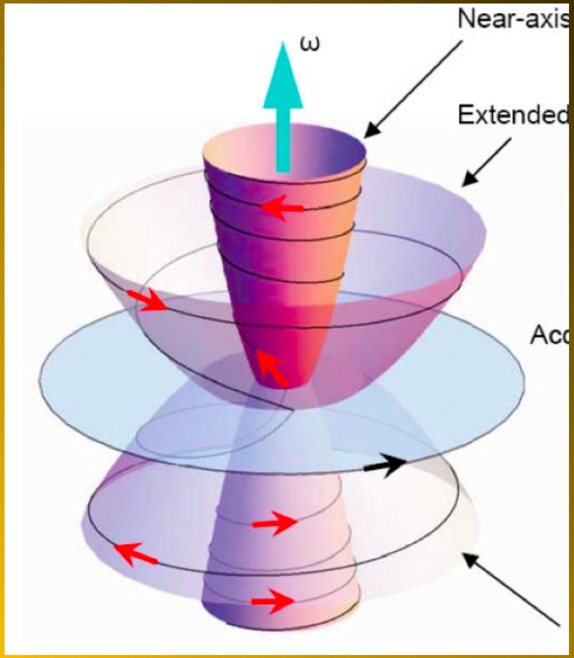
The azimuthal field must reverse when the field returns to get an RM gradient reversal:

Lynden–Bell 1996




Contopoulos et al. 2009




These models will not give a reversal … this one will!

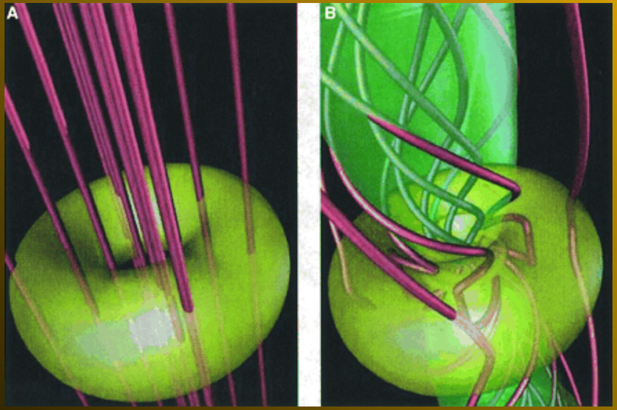
*This can place new constraints on the B-field structure and the boundary conditions for theoretical models!*

# Asymmetries in RM gradient orientation on sky

In the simplest picture, the direction of the azimuthal B field depends on

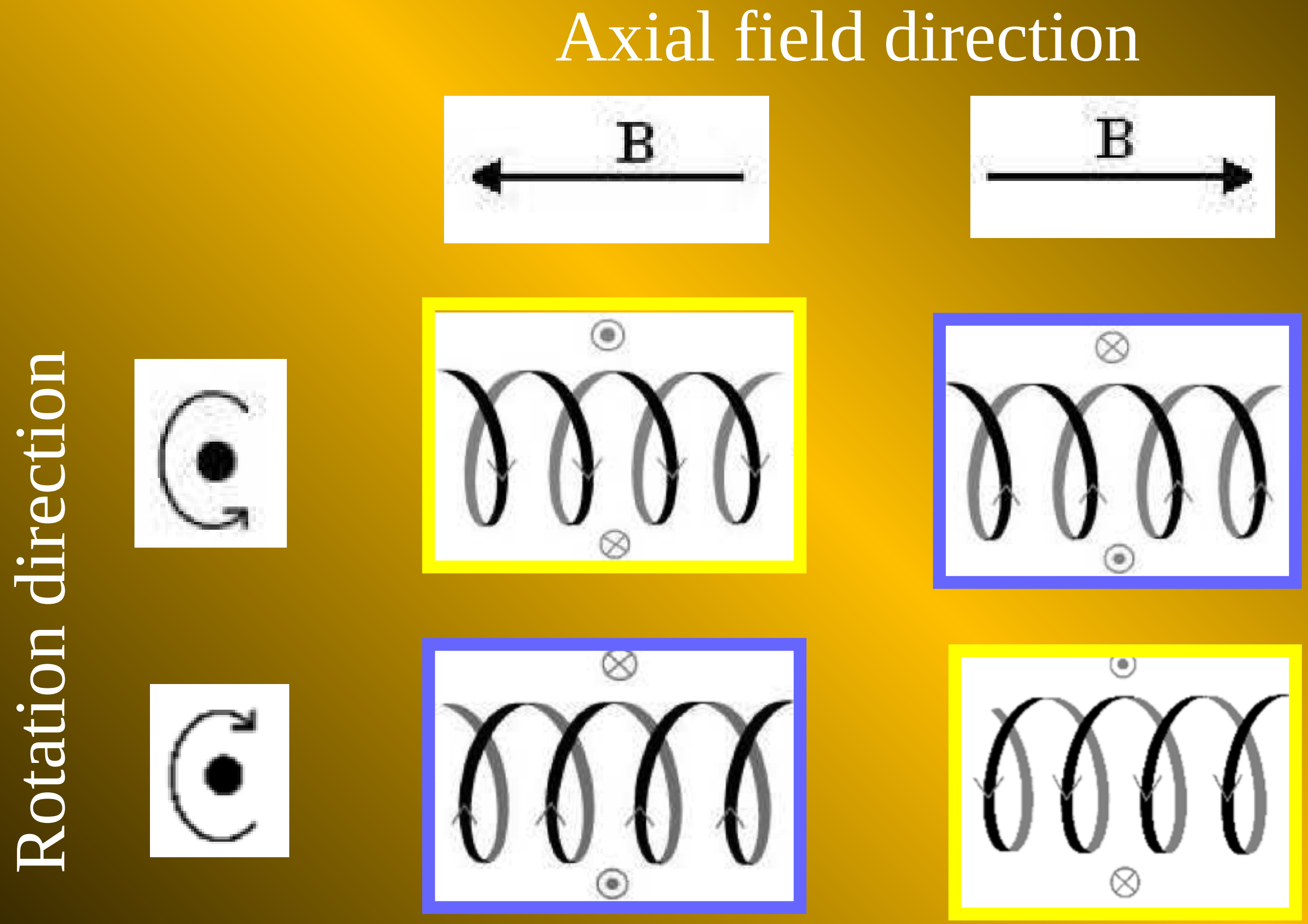
(1) the direction of rotation of the central black hole and accretion disk and

(2) the direction of the initial poloidal (axial) field that is "wound up"

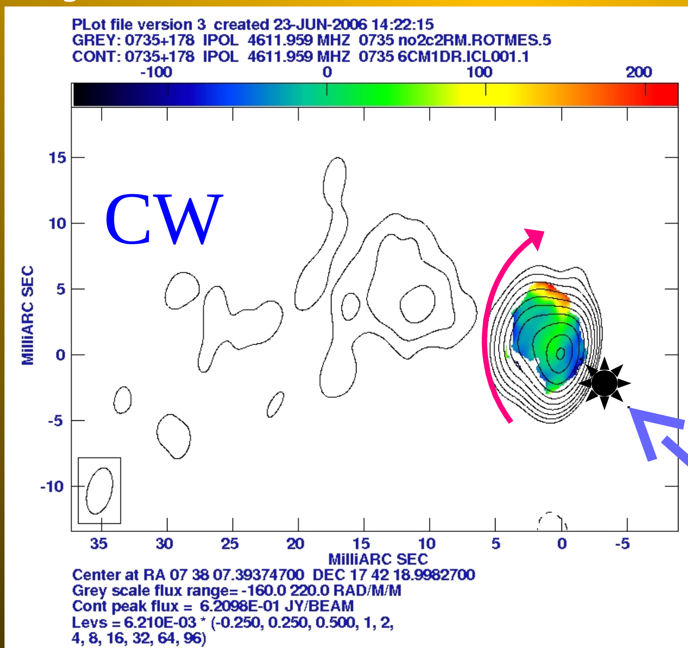


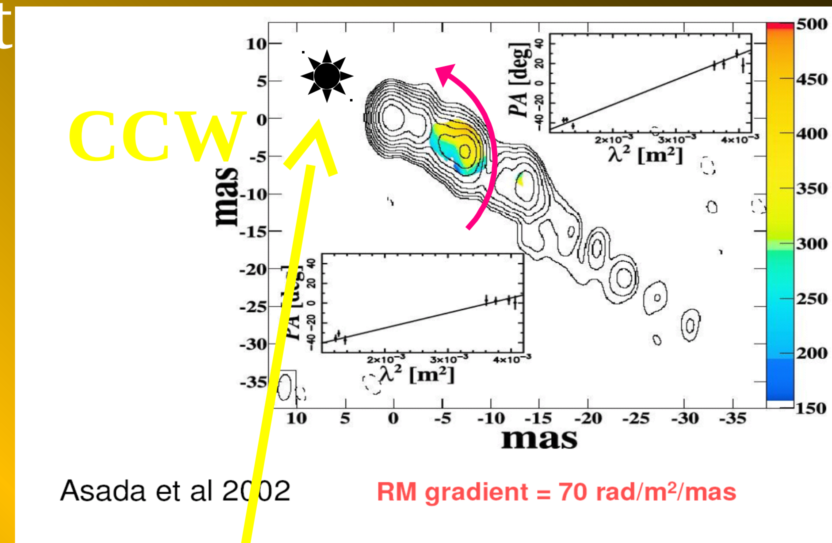

Meier, Koide & Uchida 2001

Four possible combinations of rotation direction + axial field direction give azimuthal B fields in two directions relative to rotation direction:



Can always describe observed RM gradients as “Clock-wise (CW)” or “Counter-clockwise (CCW)” on sky, relative to base of the jet




Jet base located somewhere upstream of observed “core”

If direction of rotation and direction of axial field are both random and independent, we expect equal numbers of CW and CCW gradients.

# Is this observed?

There are currently 27 monotonic transverse RM gradients with significance > 3σ (e.g. Gabuzda et al. 2014, 2015), with

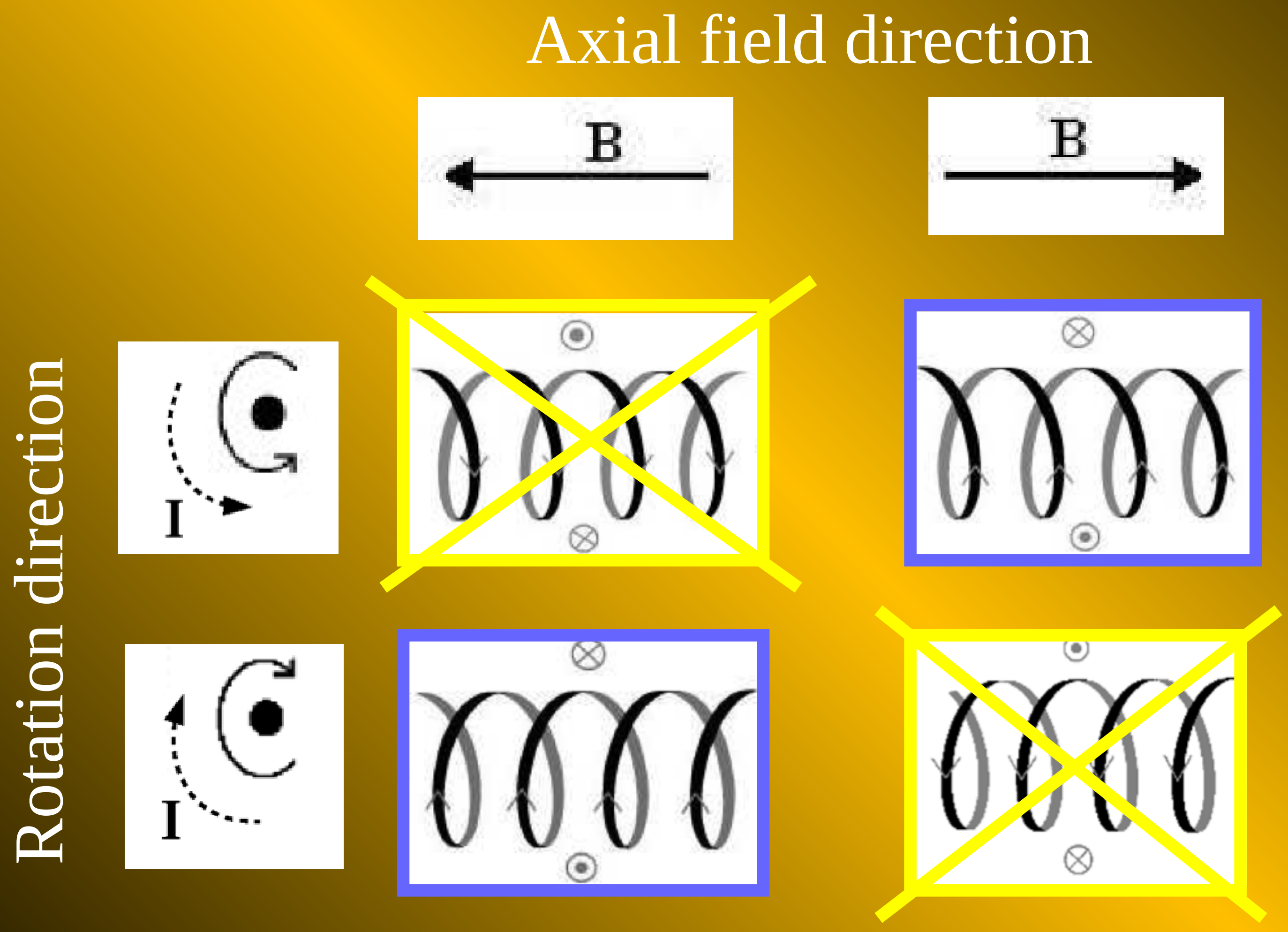
<u>20 CW</u>, <u>7 CCW</u>

Probability of 20 or more of 27 gradients being CW by chance (unweighted binomial probability distribution):

<u>P ~ 1 %</u>

Not 100% conclusive (“3σ”), but very suggestive that there is an asymmetry — which must be explained!

This asymmetry can arise if the directions of rotation and axial B field are coupled, so that only two of four possible combinations are realized:



One mechanism that can provide this is the “Cosmic Battery” model of Contopoulos et al. (2009), but any mechanism that provides the “right” kind of system of currents and associated B fields can do this!

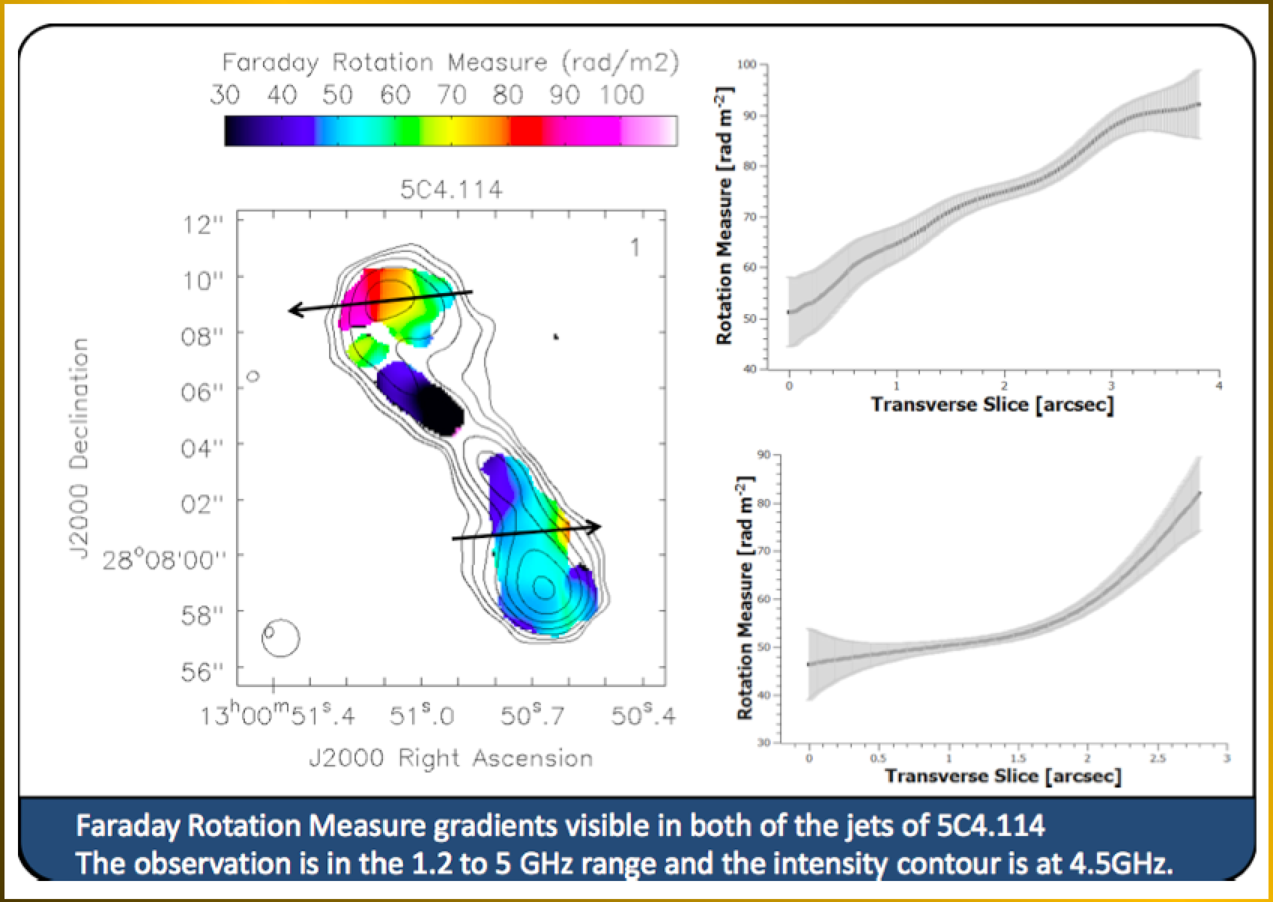
We are in the process of finalizing results for an additional 9 AGNs with monotonic, transverse RM gradients. If these are all > 3$\sigma$, the total will be 36 gradients, with

26 CW,     10 CCW

P ~ 0.5 %

*Stay tuned!!*

My undergraduate student Sebastian Knuettel is also searching for significant transverse RM gradients on kpc scales — one found so far:




This implies that a helical field component can sometimes survive all the way out to kpc scales!

# Summary

- Polarization structures of AGN jets provide key information about origin of jet B fields. Helical jet B fields should give rise to characteristic polarization structures.

- Transverse RM gradients can provide direct evidence for helical/toroidal jet B fields; reliably detected in 27 (probably 36) AGN so far, based on monotonicity and RM differences > 3$\sigma$. This means that a helical field component survives to distances well beyond the VLBI core.

# Summary

- Observation of RM gradient reversals provides first observational evidence for a “return B field” forming a nested helical-field structure

- Growing evidence for a predominance of CW RM gradients on parsec sales (!). Can be explained if an appropriate system of currents is present in and around the jet/accretion disk.