Evidence for Helical Magnetic Fields Associated with AGN Jets

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Outline of talk

- Faraday rotation gradients & helical B fields
- Evidence for the “return” jet B field
- Asymmetries in azimuthal B fields/axial currents
- Summary

Faraday rotation gradients & helical B fields

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

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

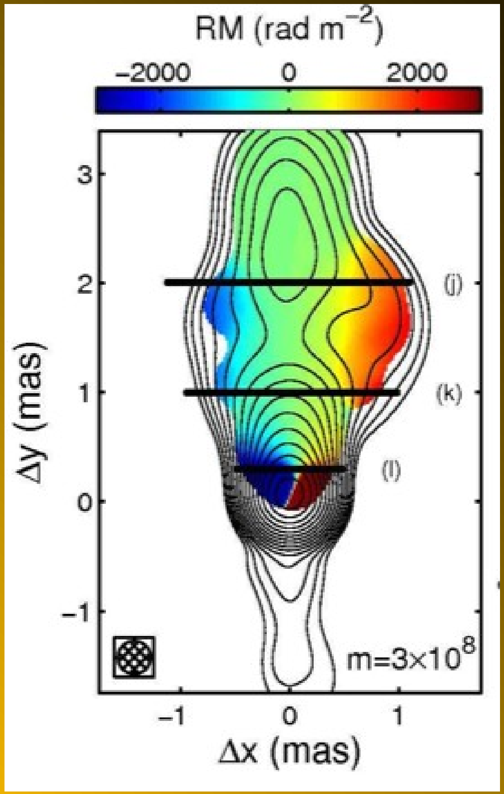
$$RM = (\text{constants}) \int n_e\ B \bullet dl$$

Electron density

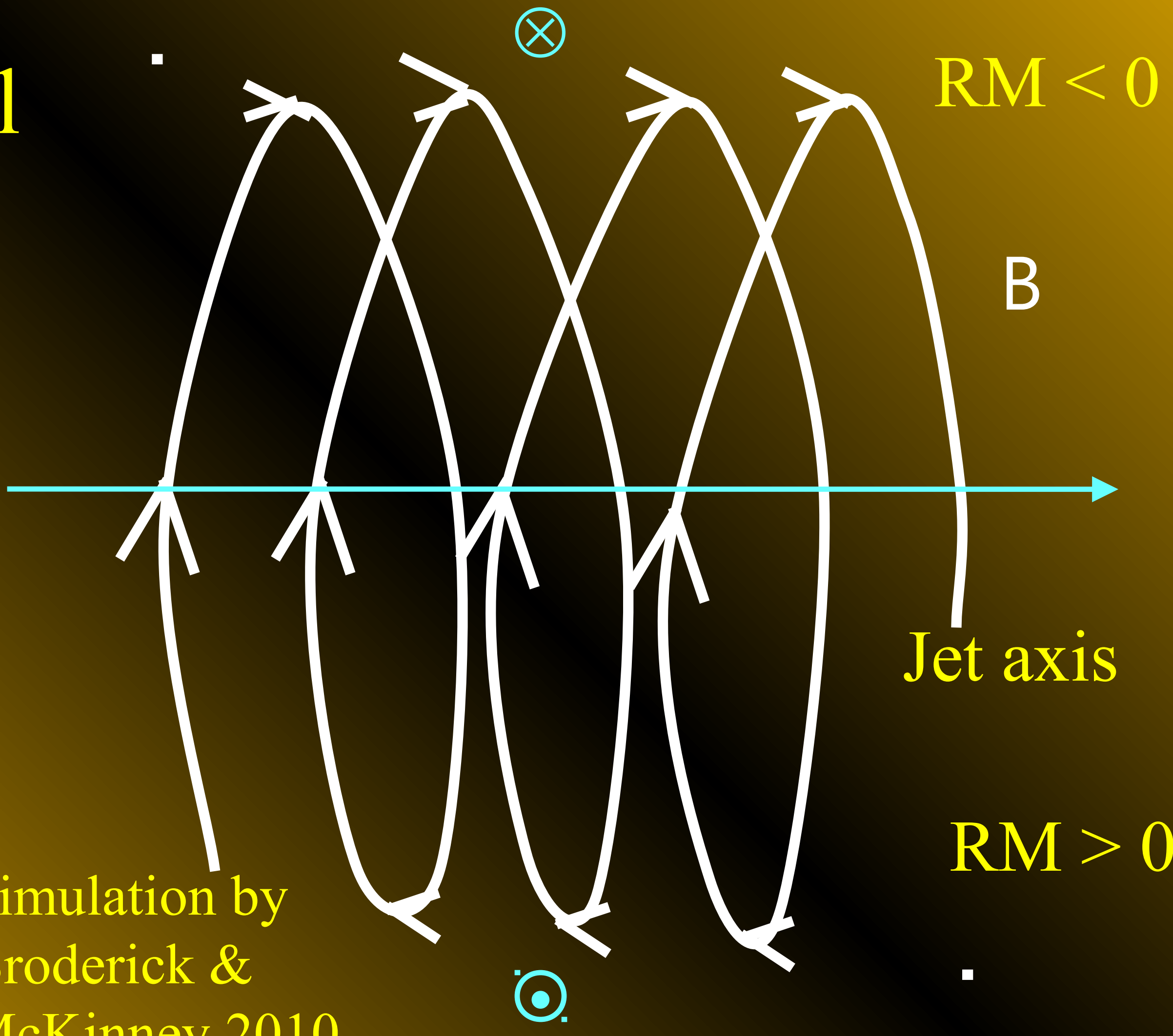
Line of sight B field

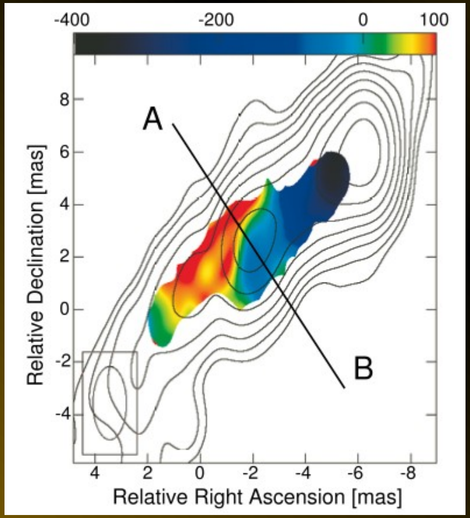
If jet has a helical B field, should observe a Faraday-rotation gradient *across* the jet – due to systematically changing *line-of-sight* component of B field across the jet (Blandford 1993).

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

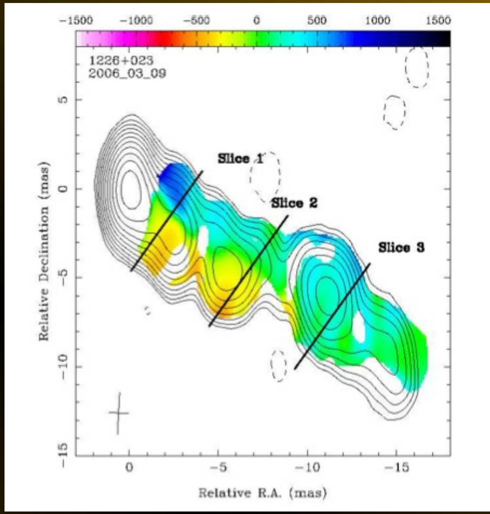


Simulation by Broderick & McKinney 2010

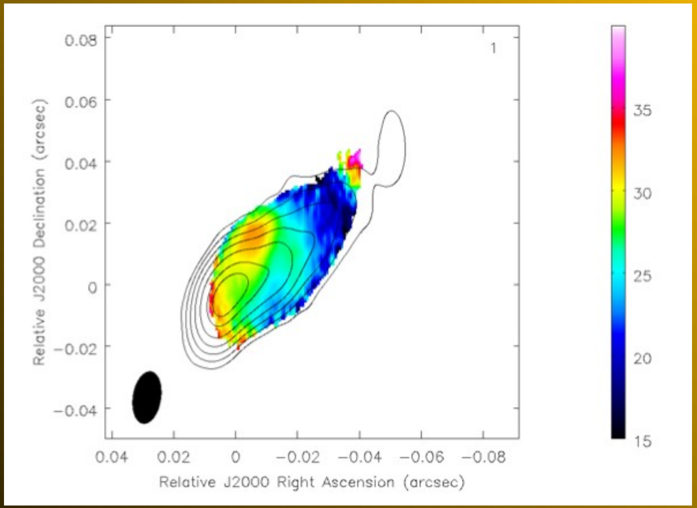




Asada et al. 2008



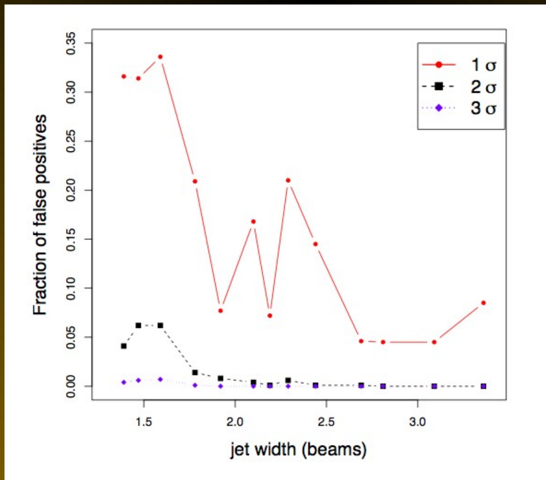
Hovatta et al. 2012



Gabuzda et al. 2013

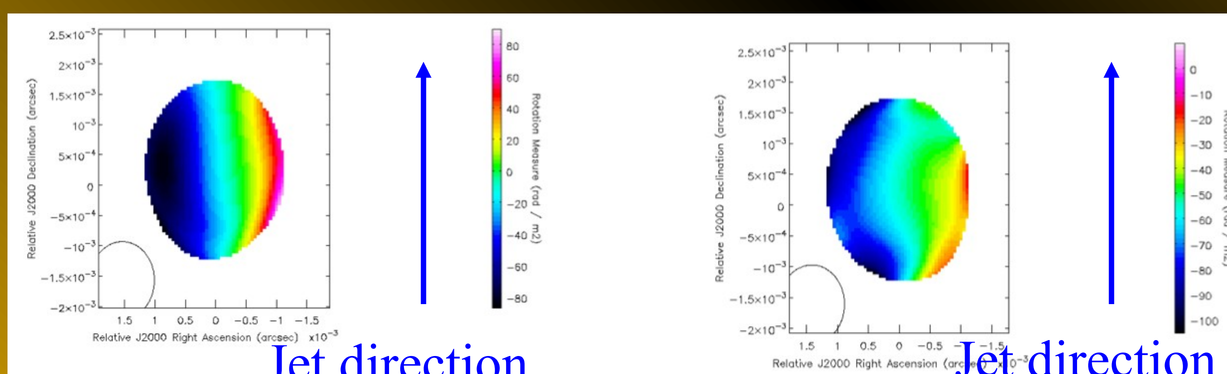
Reports of transverse RM gradients across a number of pc-scale AGN jets — but concerns were expressed about their reliability, as jet structures are usually narrow compared to beamwidth.

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



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

Thus, it is not necessary to impose a width limit on RM gradients — the best test of reliability is monotonicity of gradient and RM range spanned $> 3\sigma$.

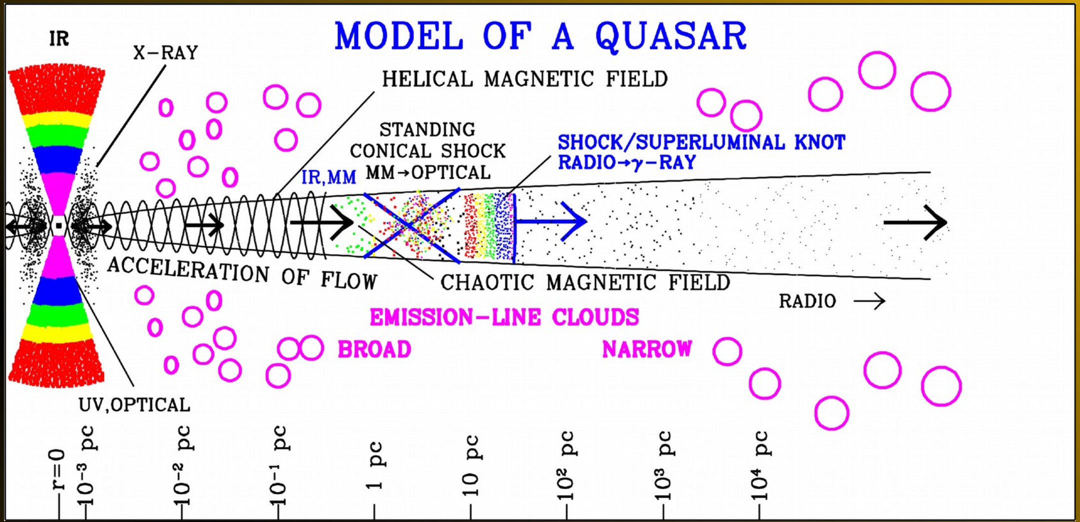
Monte Carlo simulations by Hovatta et al. (2012) also demonstrated that typical on-source uncertainties are about twice usual assumed value (σ_{rms}).

Ongoing work (Gabuzda et al. 2014, 2015, in prep):

- verify significance of previously published results
- search for new transverse RM gradients

The generation of a helical field in the innermost part of the jets is expected according to standard models.

In Alan Marscher's picture, helical field is disrupted by shocks in core region…



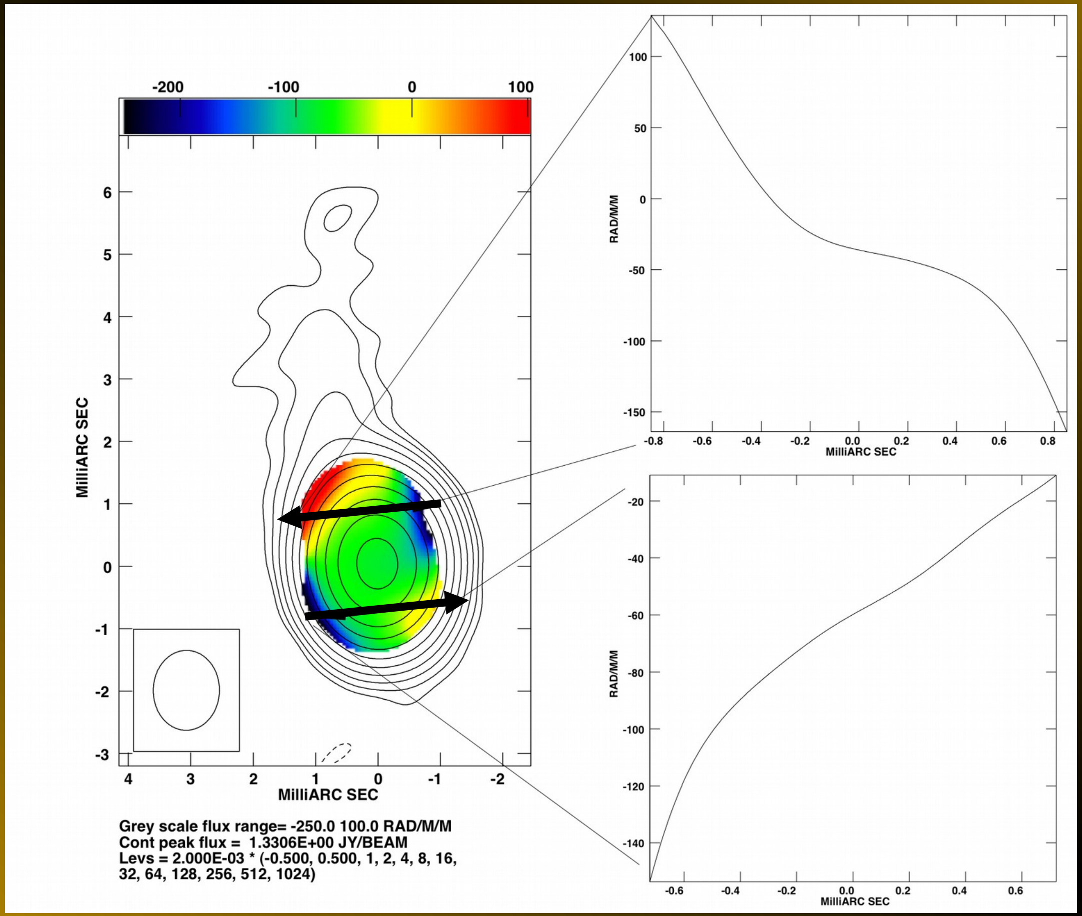
… but RM gradients show that a helical field component survives to scales well outside VLBI core.

Modeling of Marscher (2015) suggests a picture with helical (ordered) + chaotic (turbulent) B components:

Helical B ⇒ RM gradients Chaotic B ⇒ variability

Evidence for the “return” jet B field

“Reversed” RM gradients now detected in four AGN (Mahmud et al. 2013, Gabuzda et al. 2014):



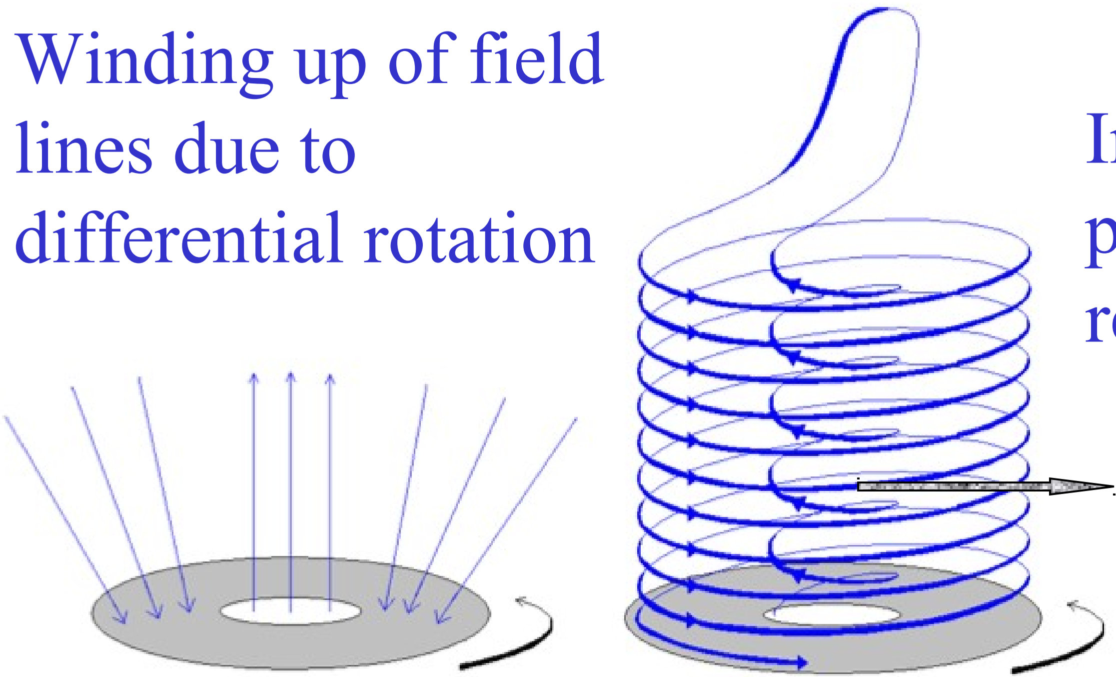
~ 4.4 σ

~ 5.1 σ

2–6 cm RM map of 0716+714 on pc scales (Mahmud et al. 2013)

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



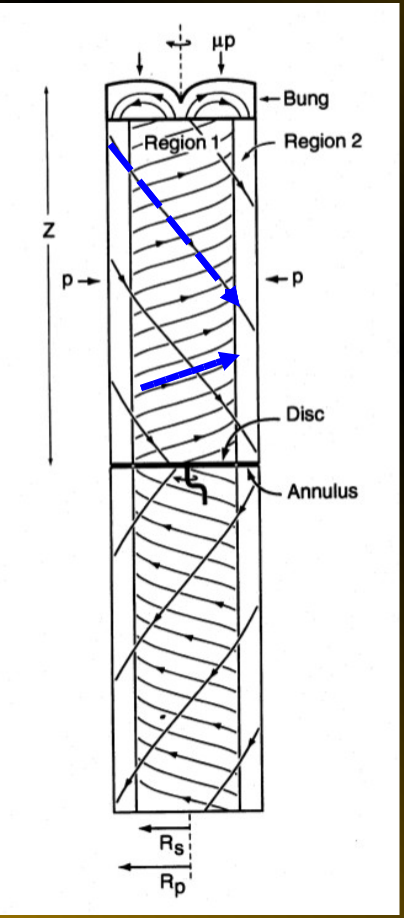
Integration path passes through both regions of helical field

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

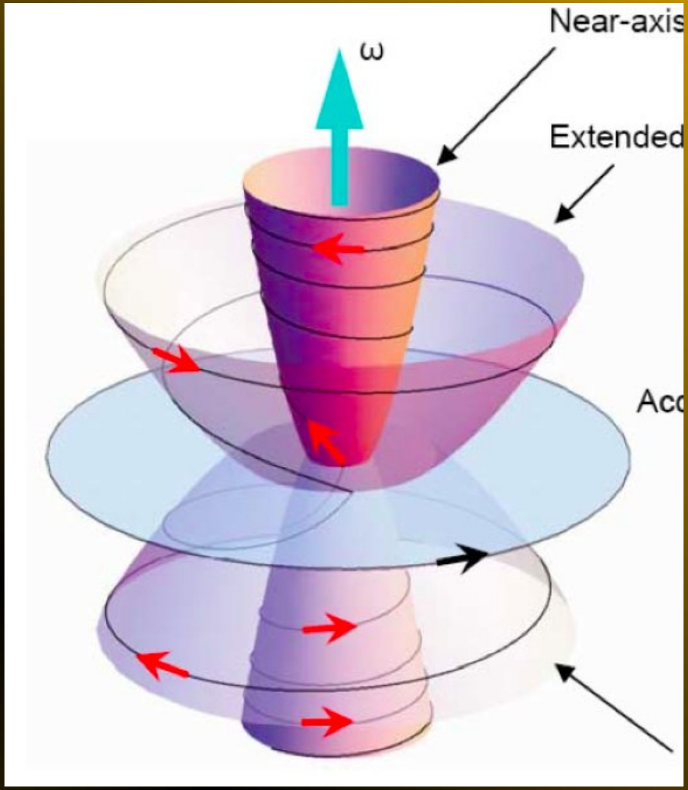
Provides direct evidence for the presence of a "return field" in a more extended region surrounding the jet

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

Lynden–Bell 1996



Contopoulos et al. 2009

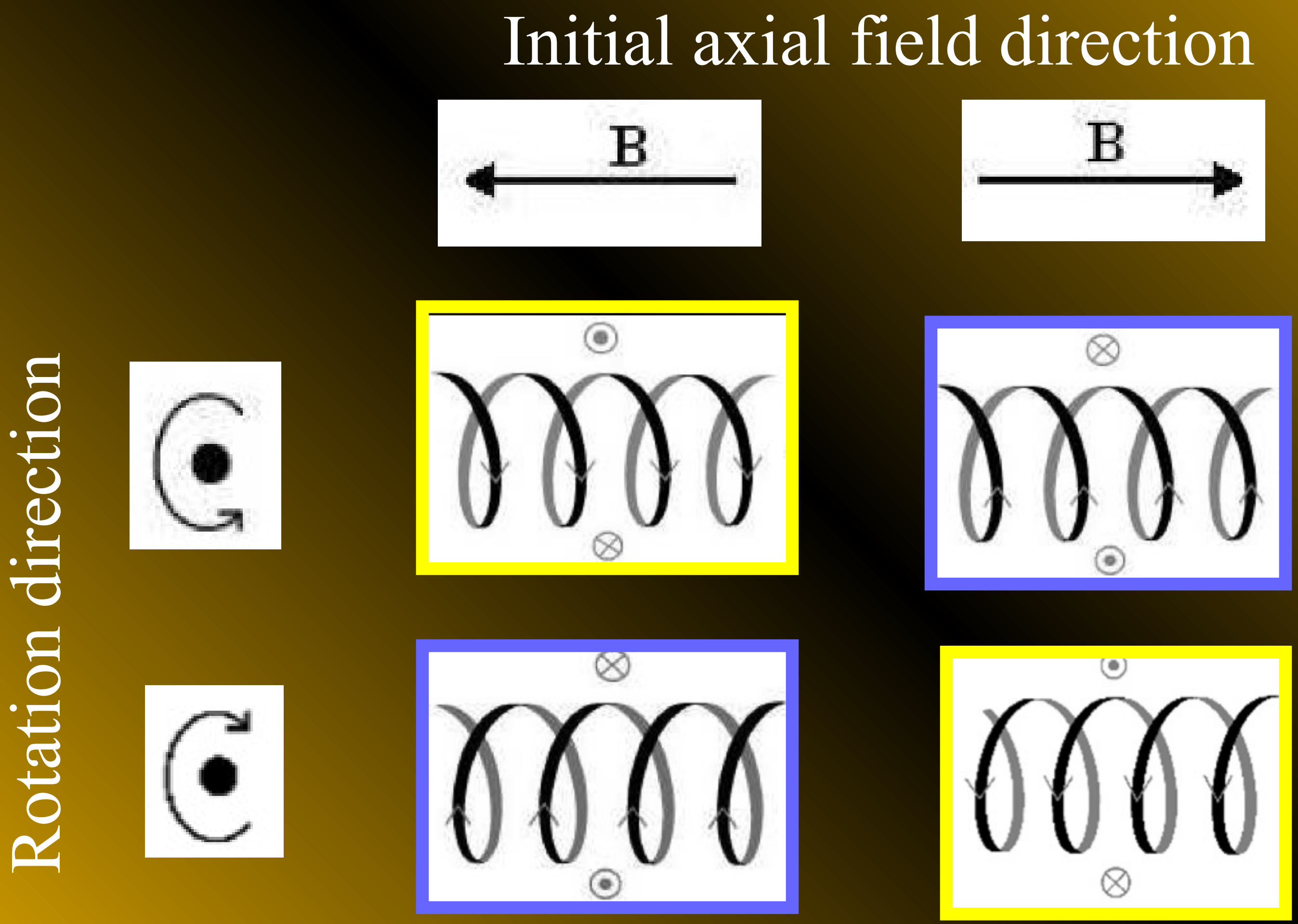


This model will not give a reversal … this one will!

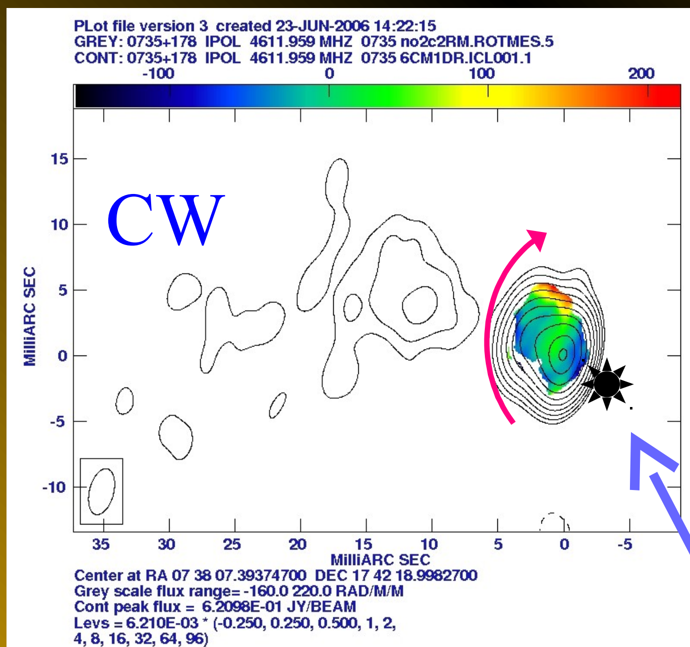
This can place new constraints on the B-field structure and the boundary conditions for theoretical models!

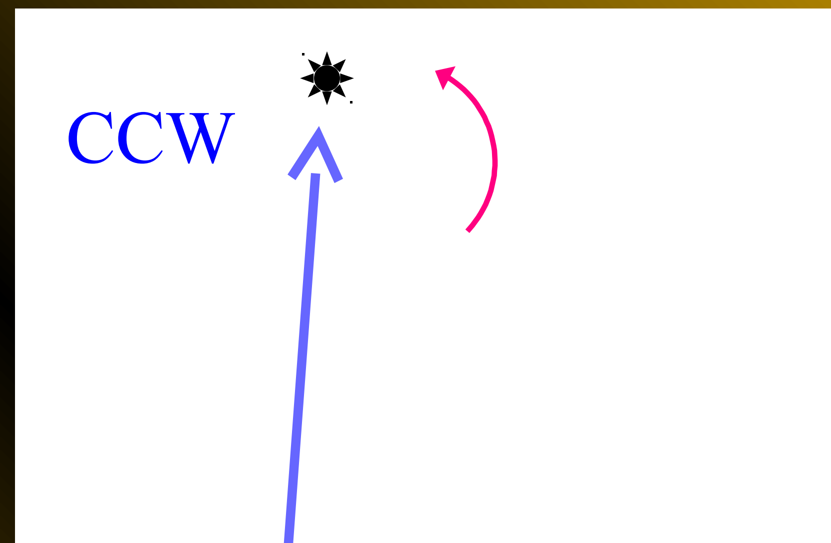
Asymmetries in RM gradient orientation on sky

Combination of rotation direction + direction of initial axial field that is wound up determines resulting azimuthal B-field direction:



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

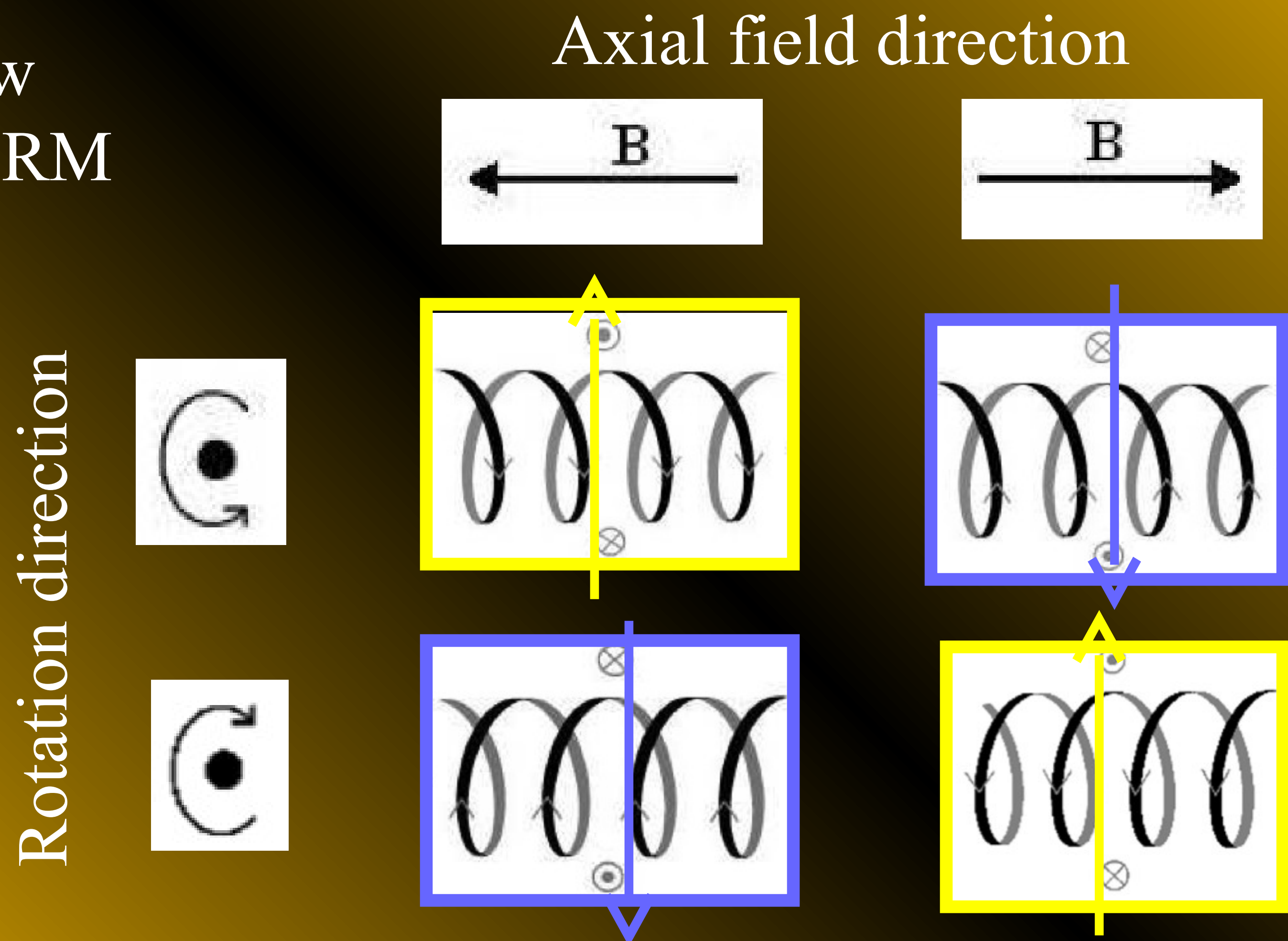




Jet base located somewhere upstream of observed "core"

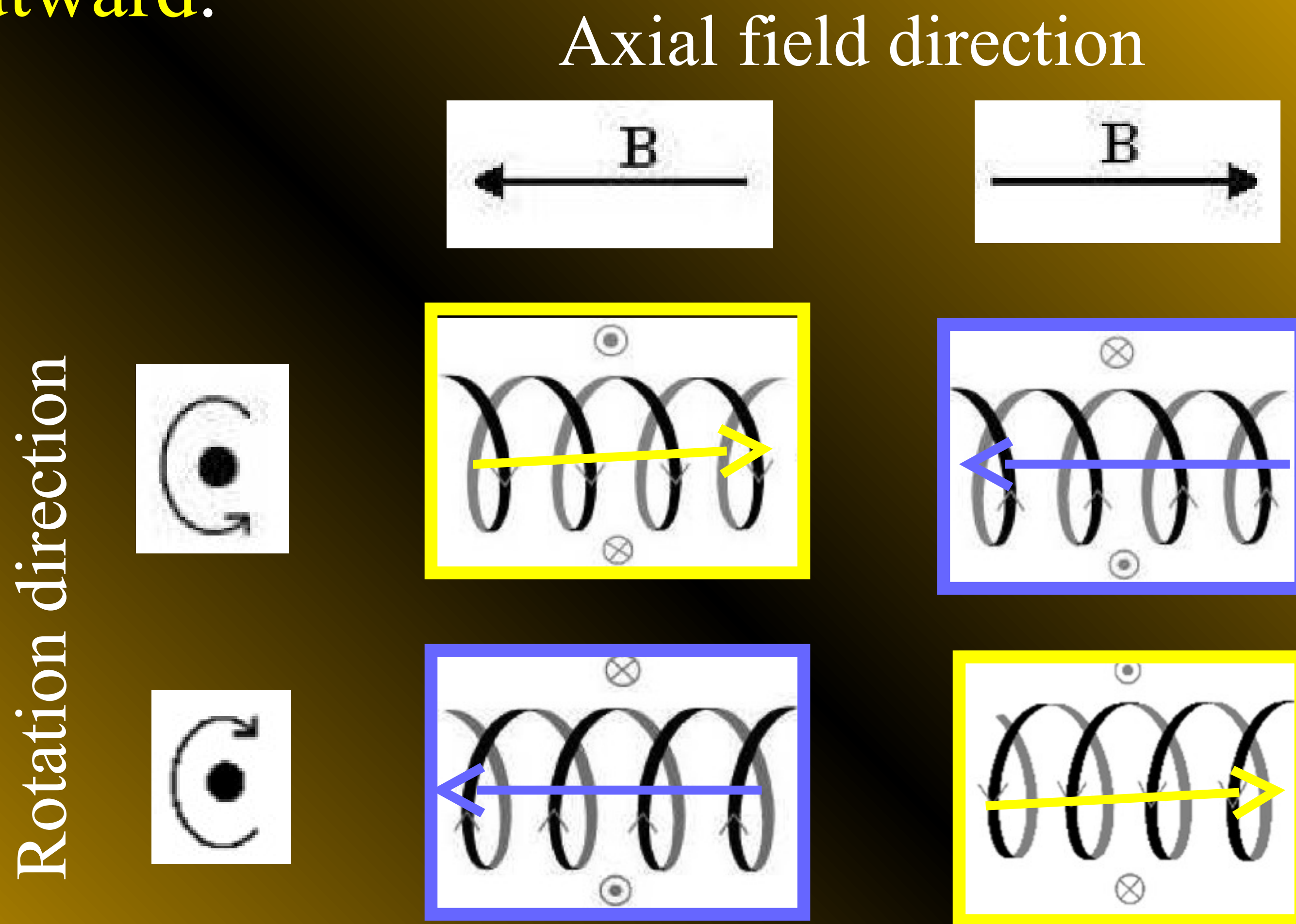
If direction of rotation and direction of axial field are random and independent, we expect equal numbers of CW and CCW gradients.

Arrows show direction of RM gradients



We can also think about this in terms of the direction of the axial current implied by the observed RM gradient (azimuthal B field) — inward or outward.

Arrows show direction of implied current



What is observed?

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

20 CW (I in), 7 CCW (I out)

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

P ~ 0.95 %

Very suggestive that there is an asymmetry — which must be explained!

Understanding the origin of this asymmetry amounts to identifying a system of currents and associated B fields that leads to this.

A preference for a particular orientation of the transverse RM gradients is equivalent to a preferred direction for the axial current — inward or outward.

One mechanism that can provide this asymmetry is the "Cosmic Battery" model of Contopoulos et al. (2009):

- Charges in rotating accretion disc absorb photons from central AGN
- Photons are re-radiated isotropically in rest frame of charges, radiation is "beamed" in direction of their motion in observer's frame
- The charges feel a reaction force:

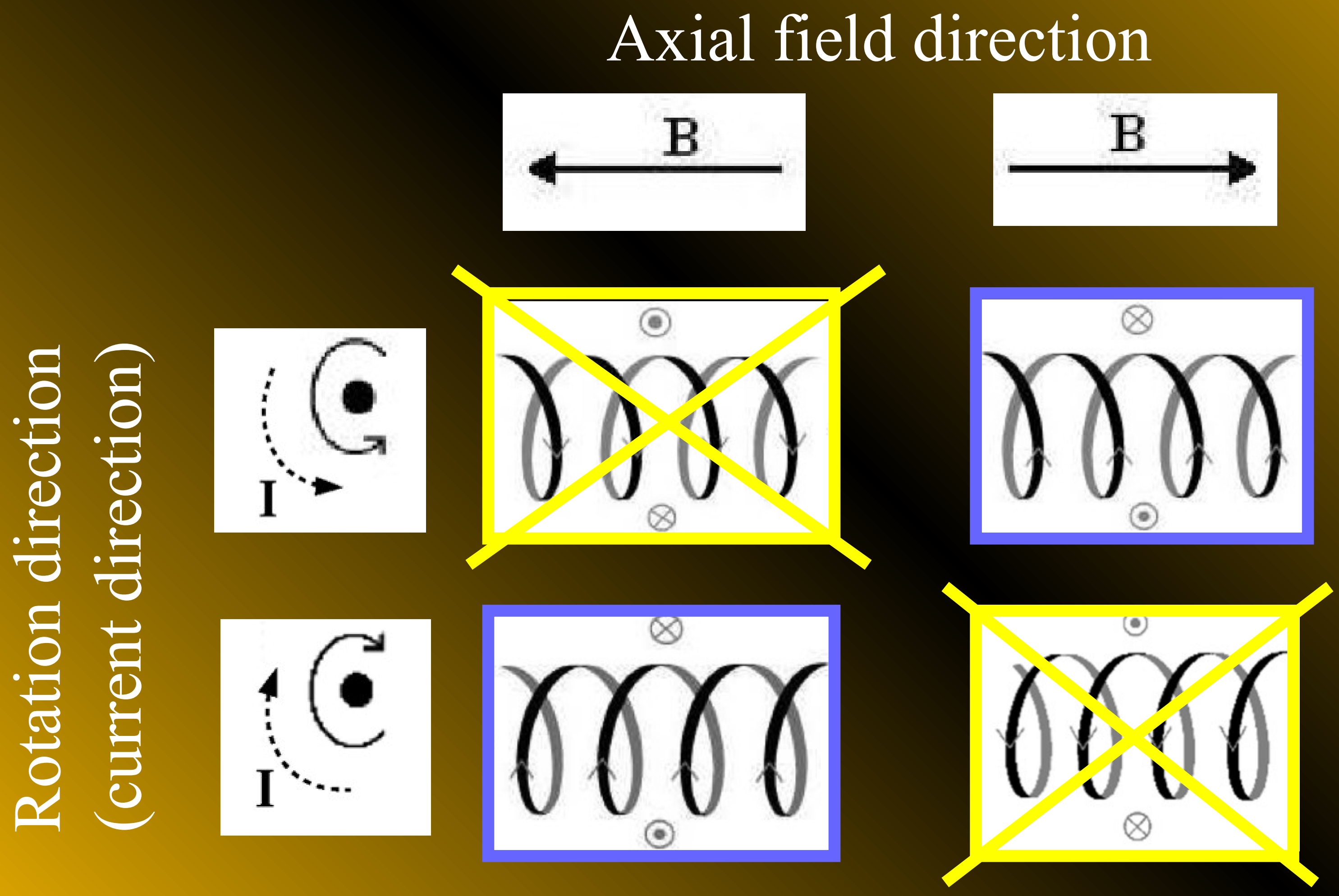
$$F_{\text{P-R}} = -\frac{L\sigma_{\text{T}}}{4\pi r^2 c}\frac{v_\phi}{c}$$

Force on electrons

- Force on e^- >> force on p because $\sigma_T \propto m^{-2}$

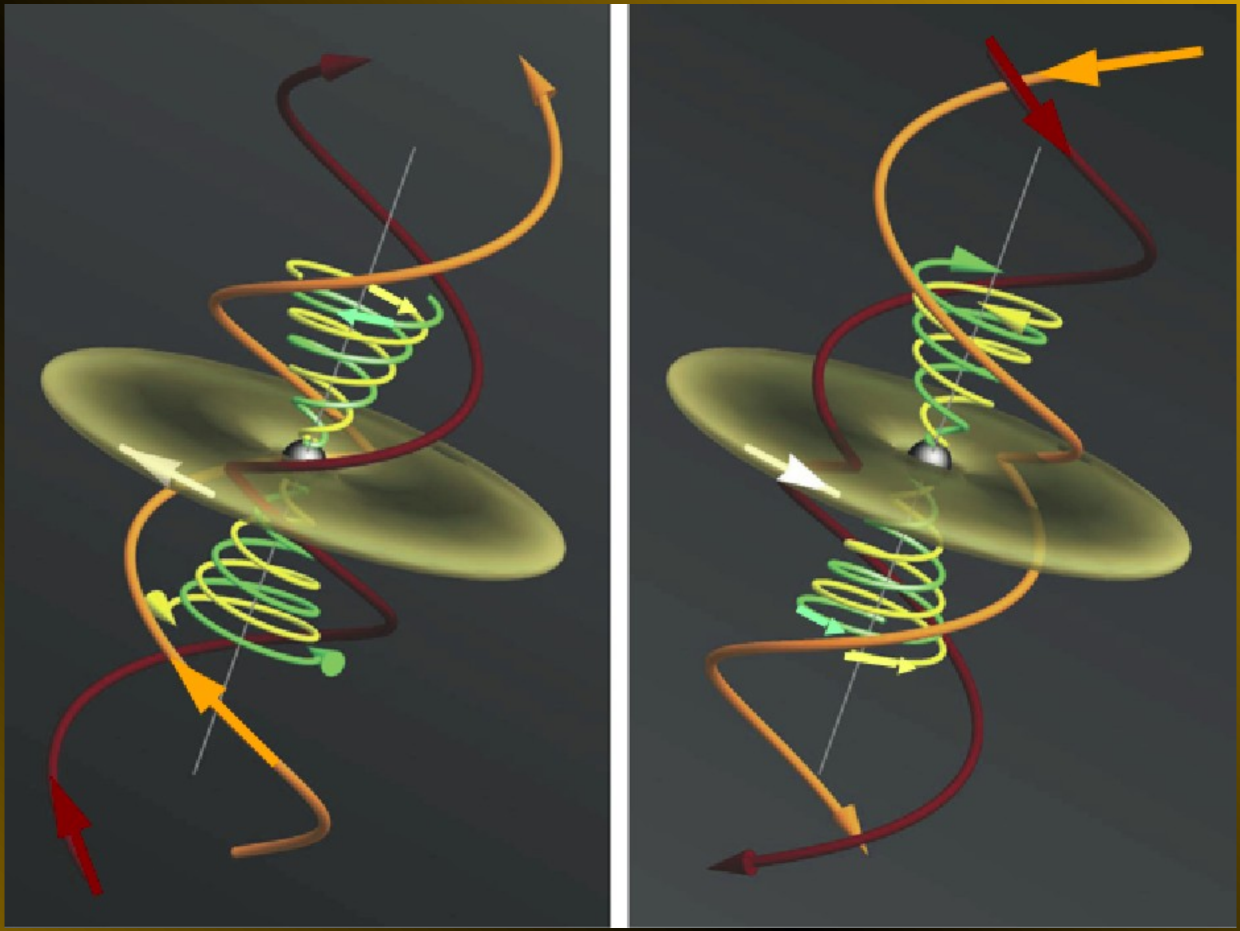
==> Electric current in direction of rotation

Rotation and axial B field are coupled — current in accretion disk provides initial axial B field that is wound up:



Resulting azimuthal components for inner and outer helical B fields have specific directions relative to rotation:

Christodoulou et al. (2015)



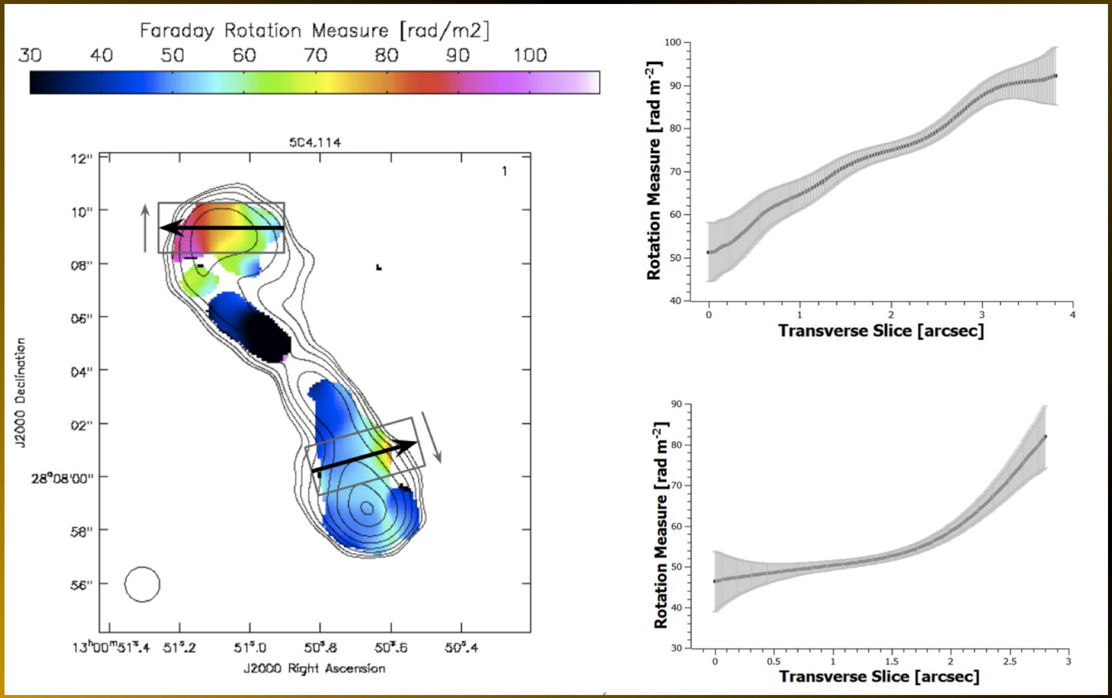
Corresponds to inward current near jet axis, outward current in region surrounding jet.

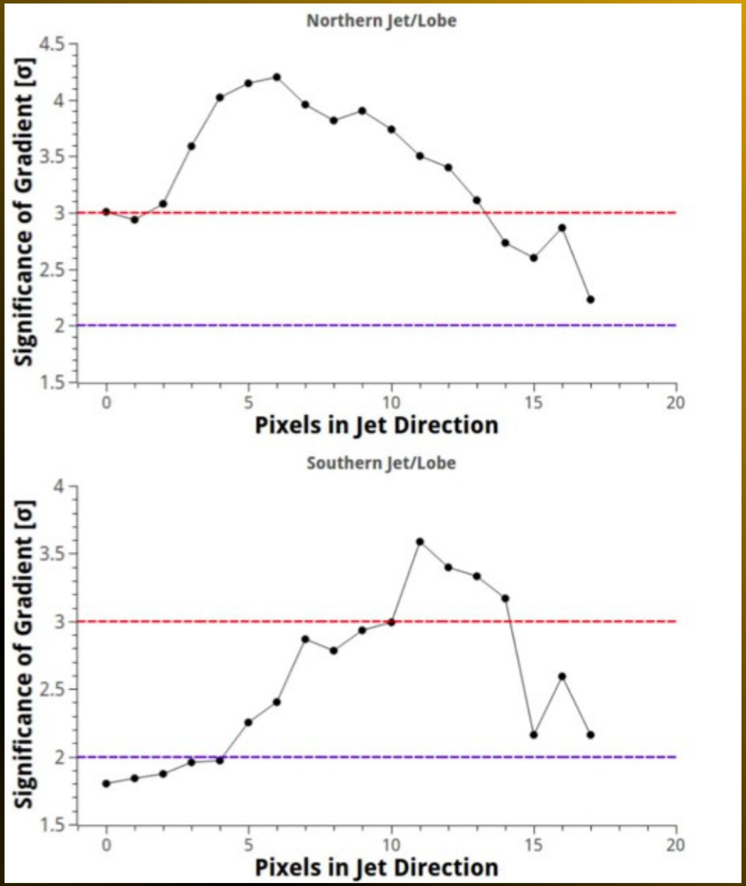
Action of this "Cosmic Battery" can explain the predominance of CW RM gradients (inward axial currents), if the inner part of the nested helix structure usually dominates the overall observed Faraday rotation on pc scales.

May be other mechanisms that can yield a similar system of magnetic fields and currents. Needs work!

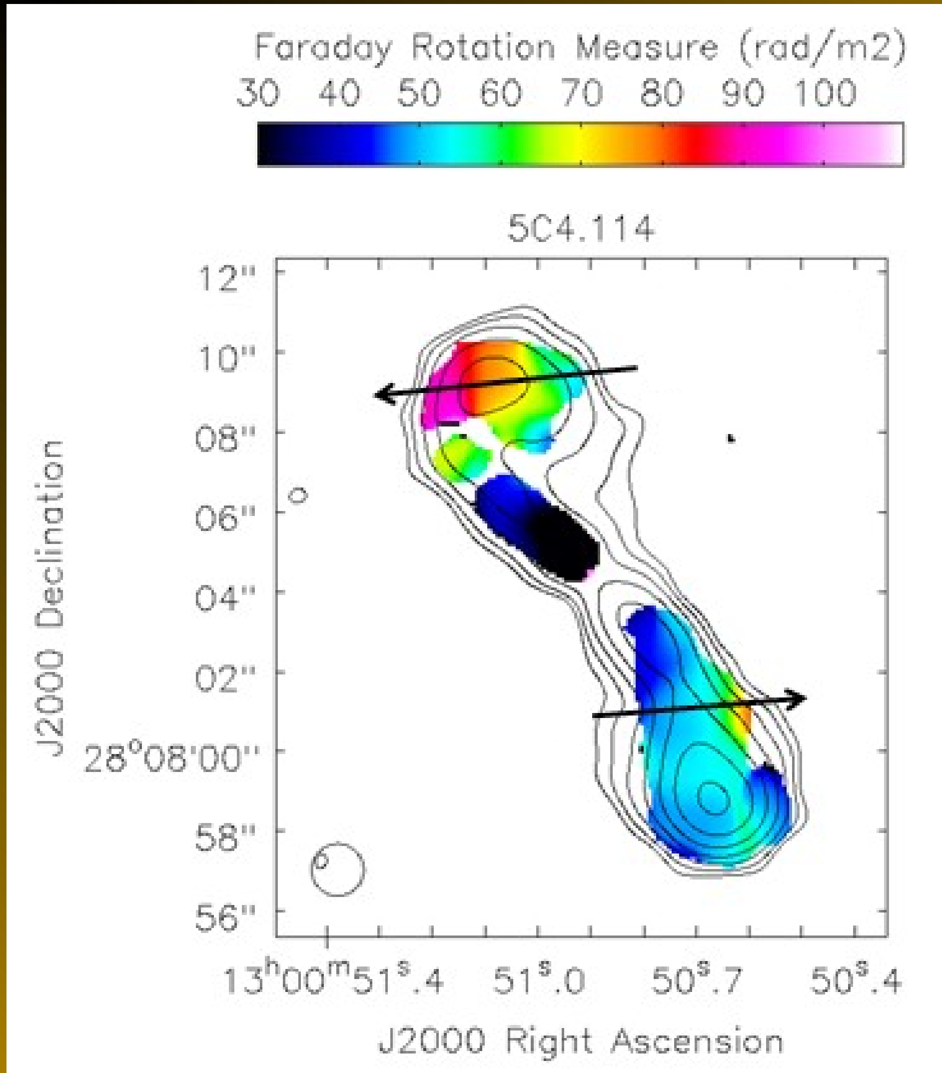
We are obtaining results for additional AGNs with monotonic, transverse RM gradients aimed at improving the statistics (Gabuzda et al., in prep).

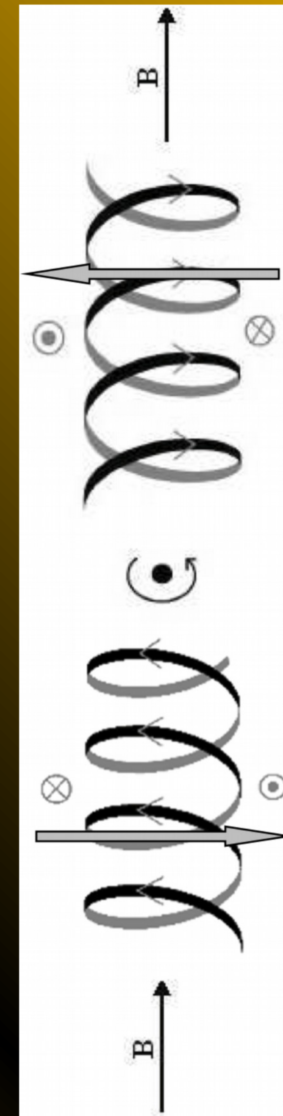
We are also searching for significant transverse RM gradients on kpc scales — one found so far (Gabuzda, Knuettel & Bonafede 2015):





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





Relative orientation of transverse RM gradients in 5C4.114 is consistent with expectation of winding up an initially dipolar-type B field.

Summary

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

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

Summary

- Evidence for a predominance of inward axial currents on parsec scales. Places constraints on system of fields and currents in and around the jet/accretion disk!

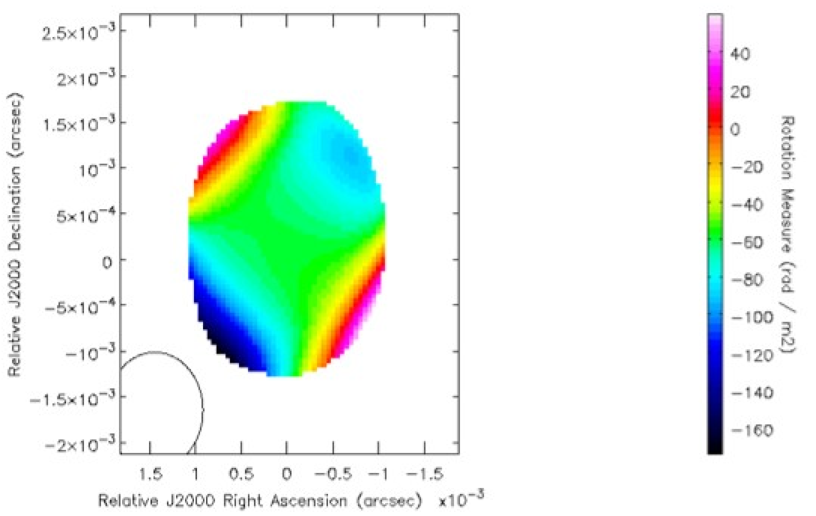
- First detection of $> 3\sigma$ transverse RM gradients on kiloparsec scales recently obtained

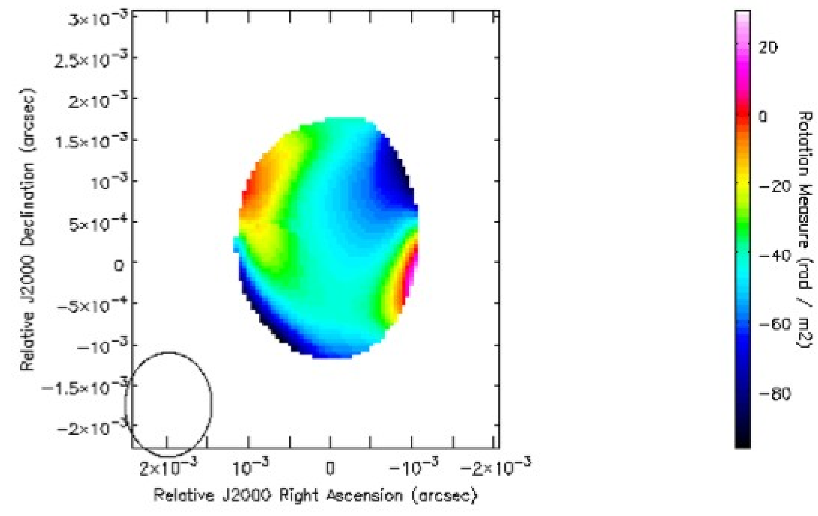
- Magnetic fields carried outward by jets could act as intergalactic seed fields that are subsequently amplified in galactic dynamos

Do not try this experiment with your cat at home!

Extra slides

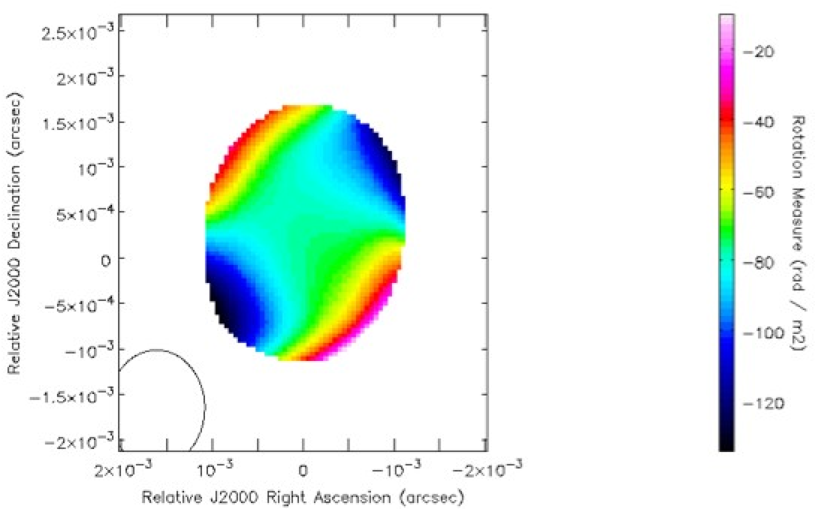
MC simulations with reversals also give detectable gradients

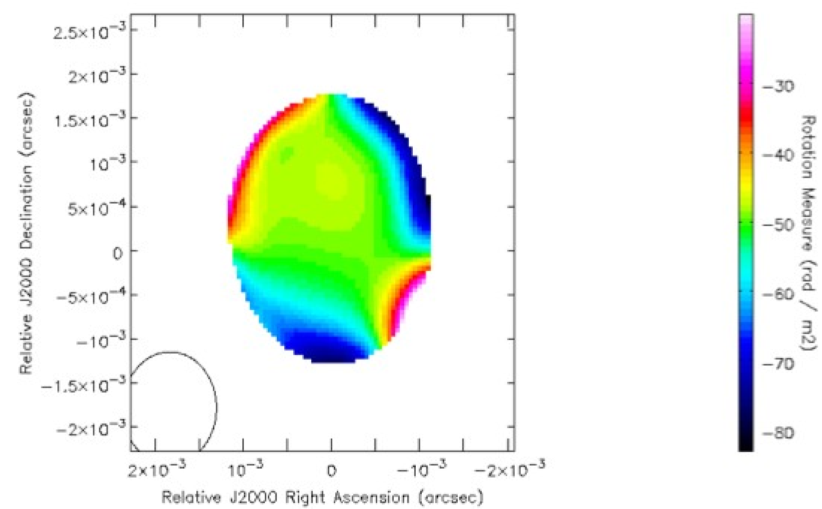




Jet width 1/3 beam

Jet width 1/5 beam

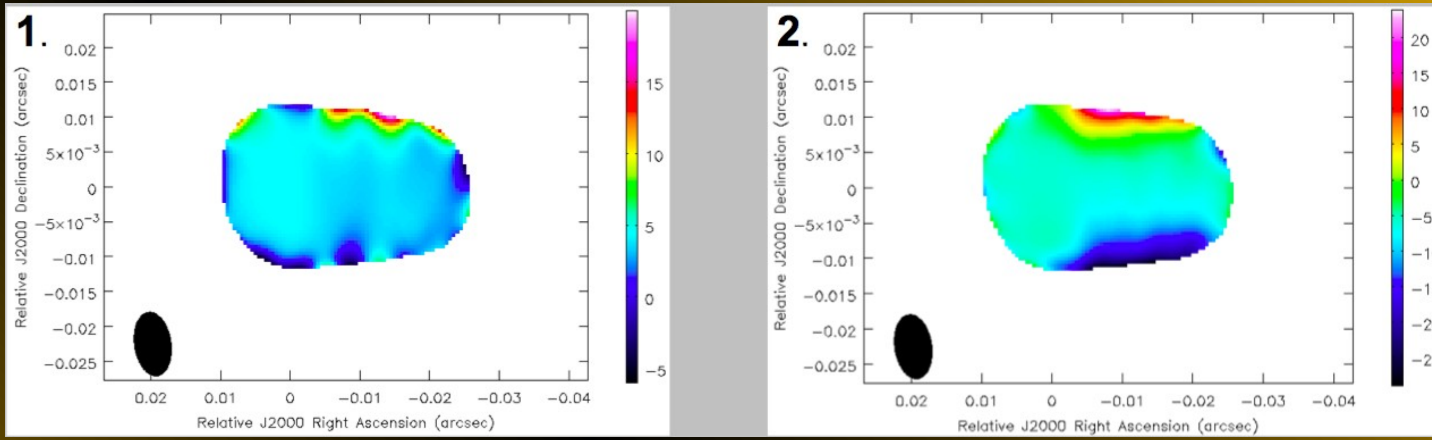




Jet width 1/10 beam

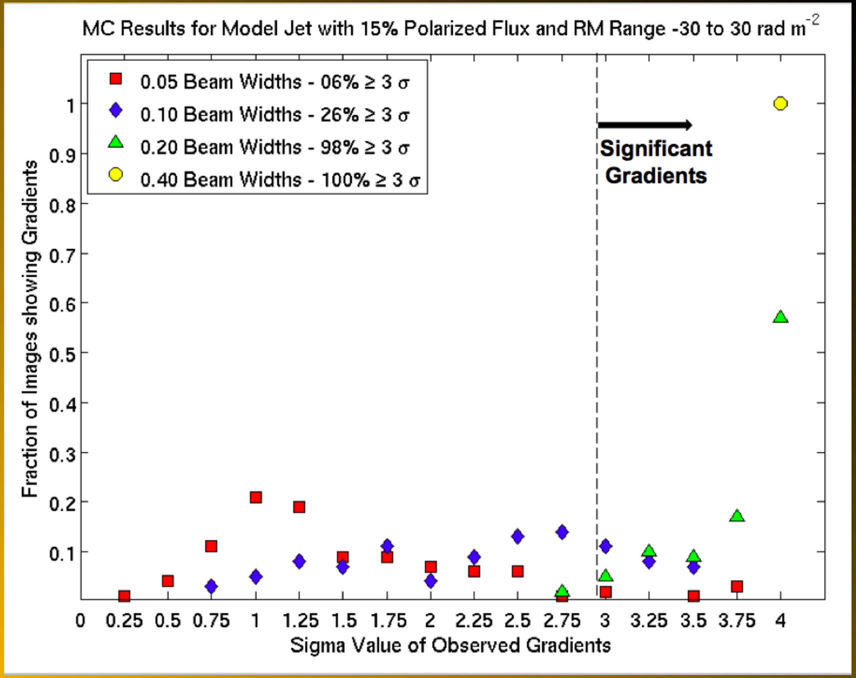
Jet width 1/20 beam

Murphy & Gabuzda (2013): 1.36, 1.43, 1.49, 1.67 GHz

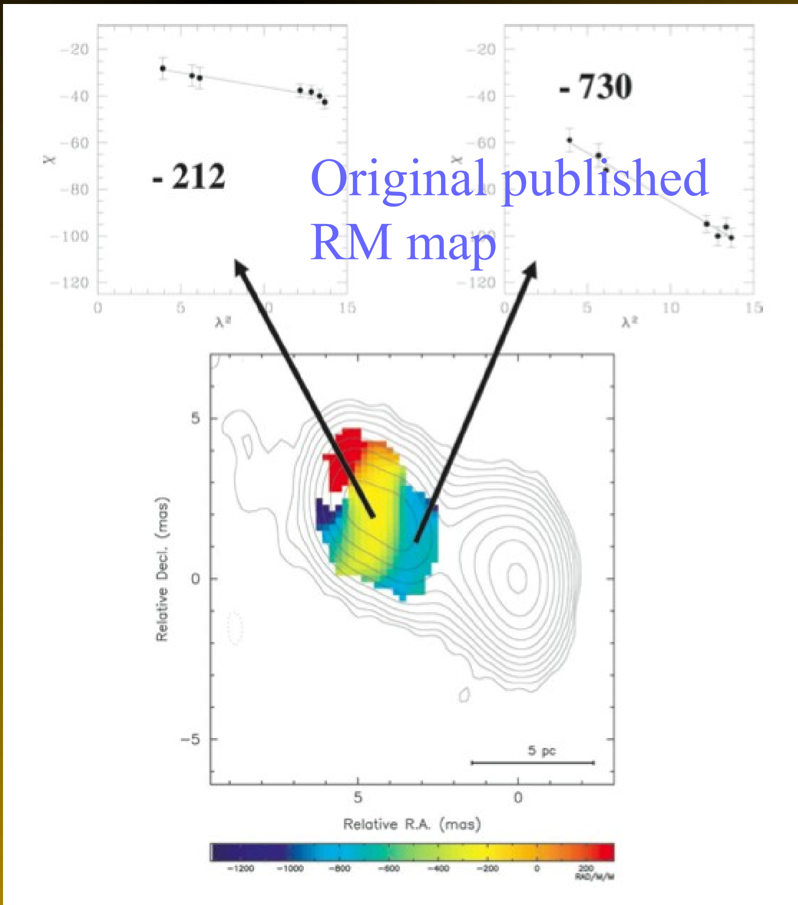


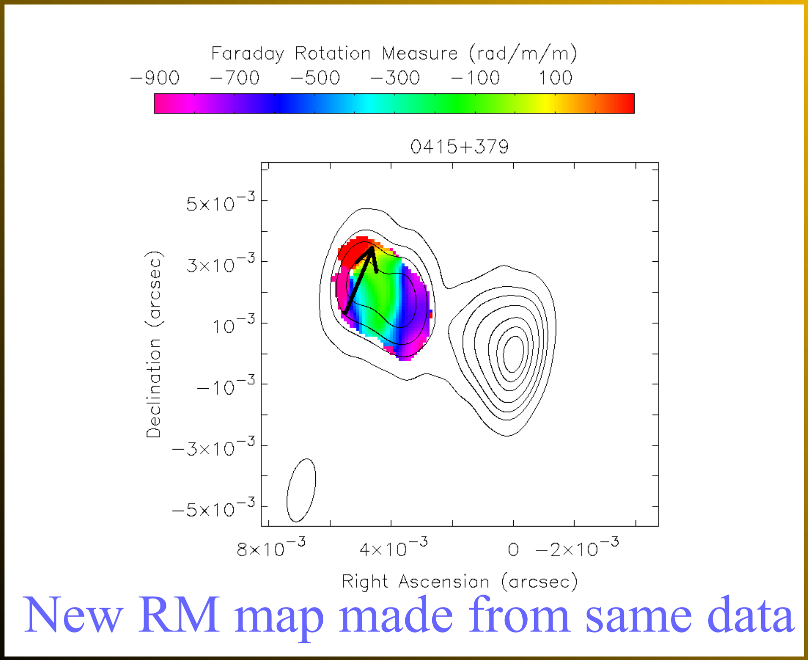
Jet width 0.05 beam

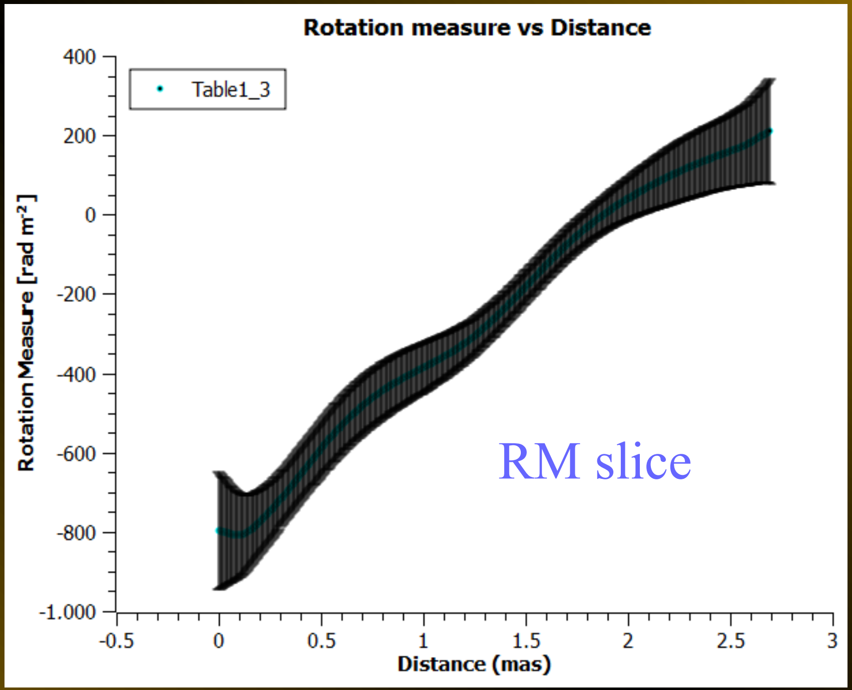
Jet width 0.40 beam



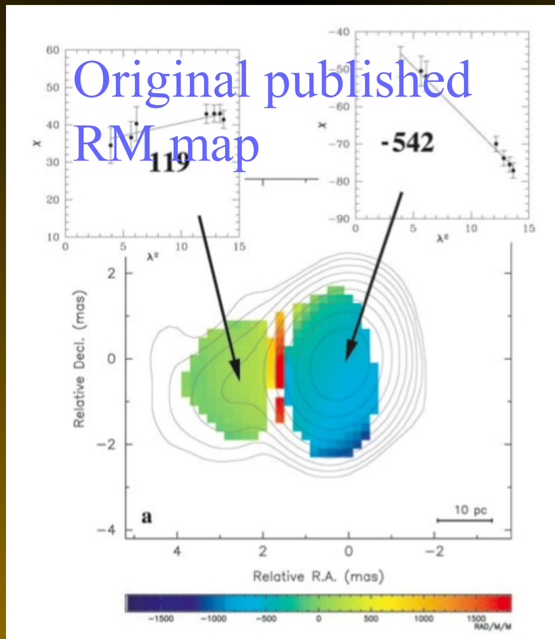
98% or more of simulated maps showed transverse RM gradients > 3σ when intrinsic jet width was at least 0.20 beam widths.

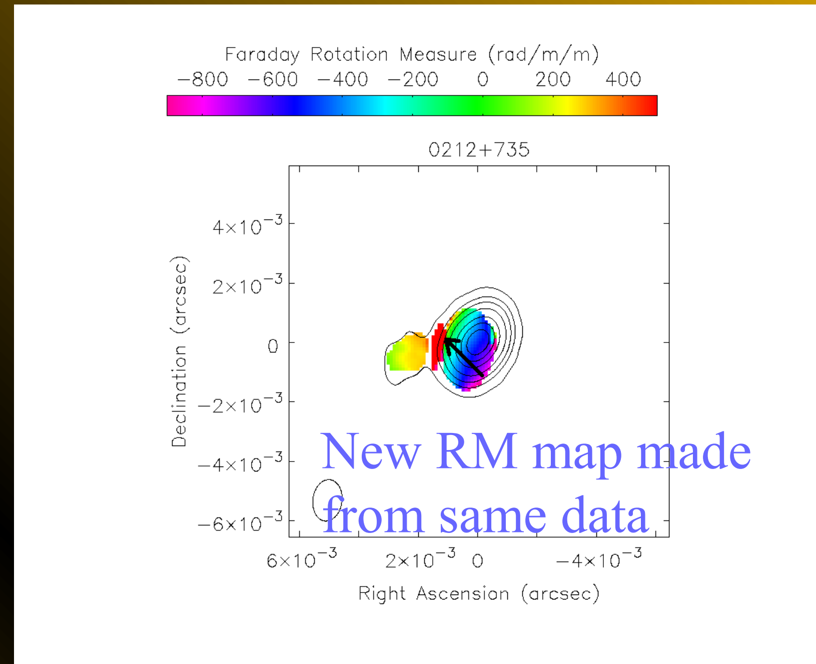




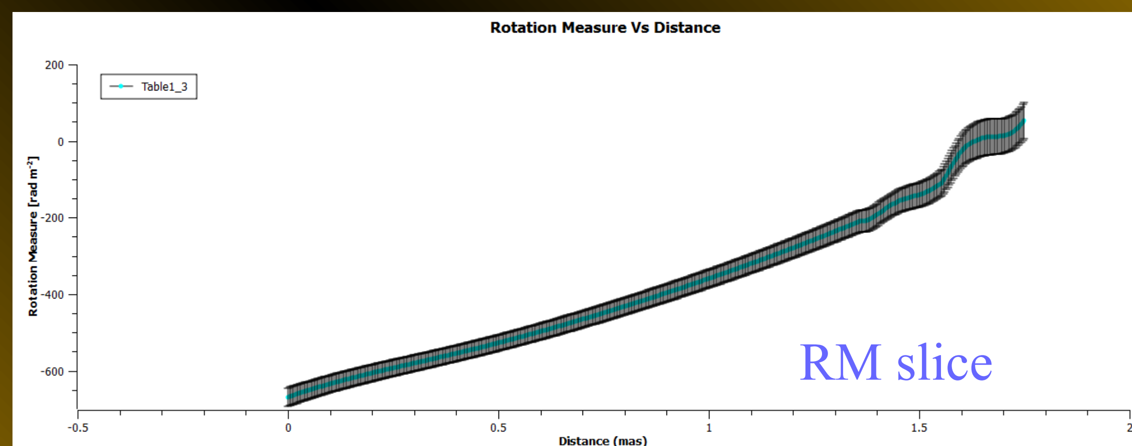


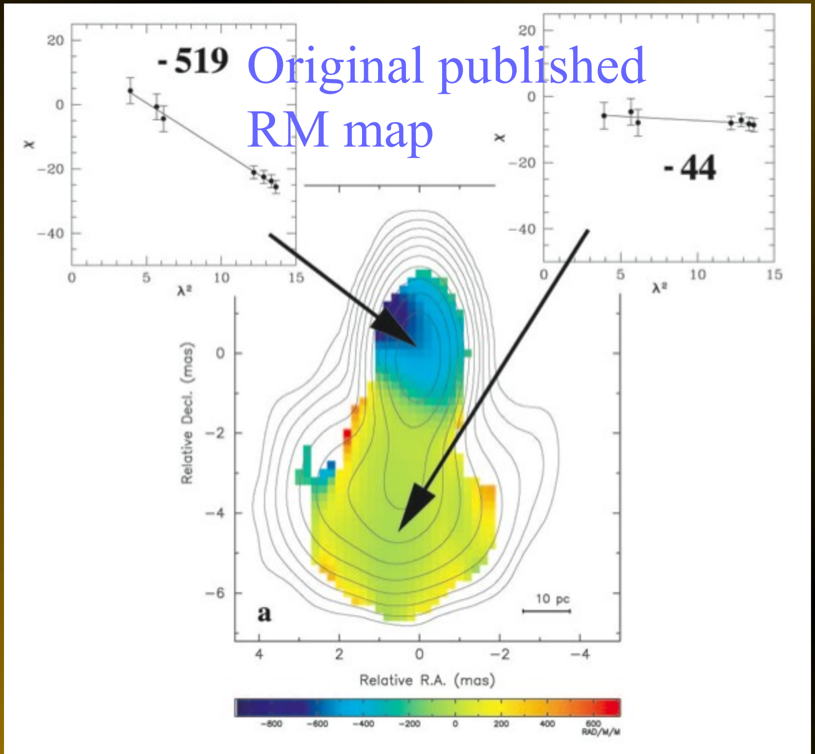
RM map of 3C111 (Zavala & Taylor 2002) has CW gradient with significance ~ 5σ

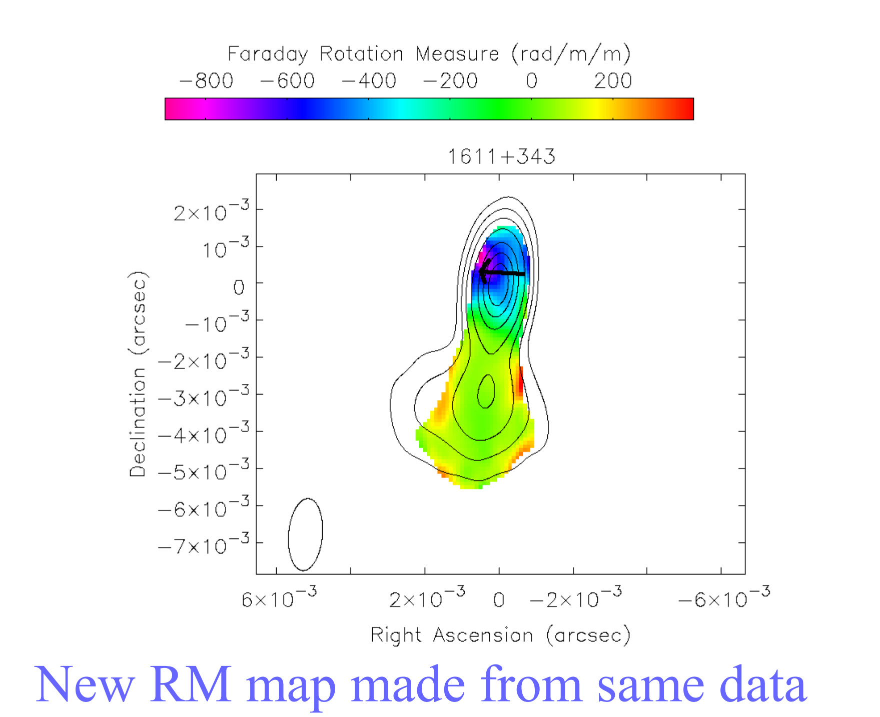


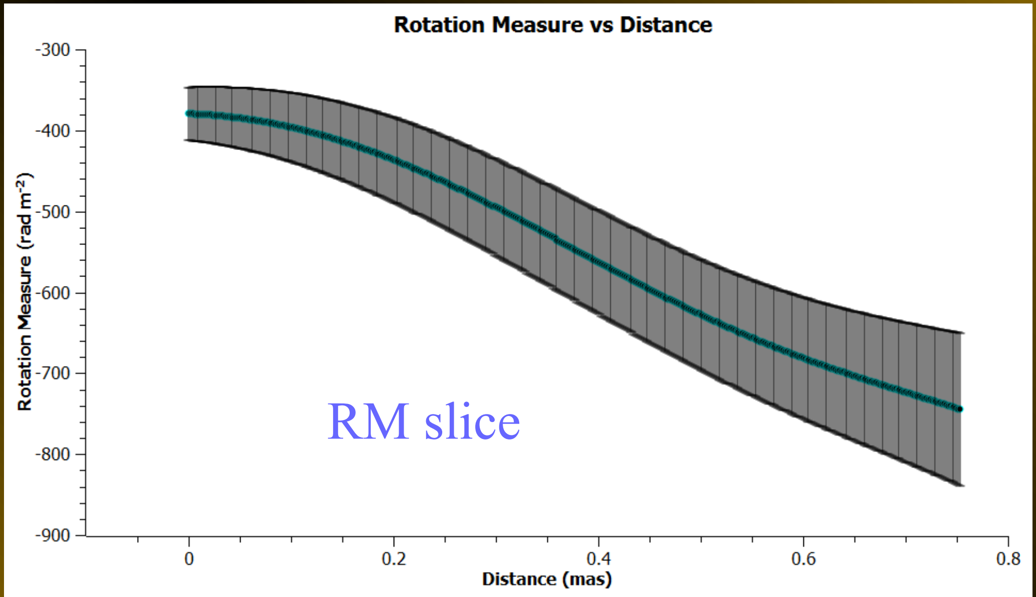


RM map of 0212+735 (Zavala & Taylor 2003) has CW gradient with significance ~ 13σ









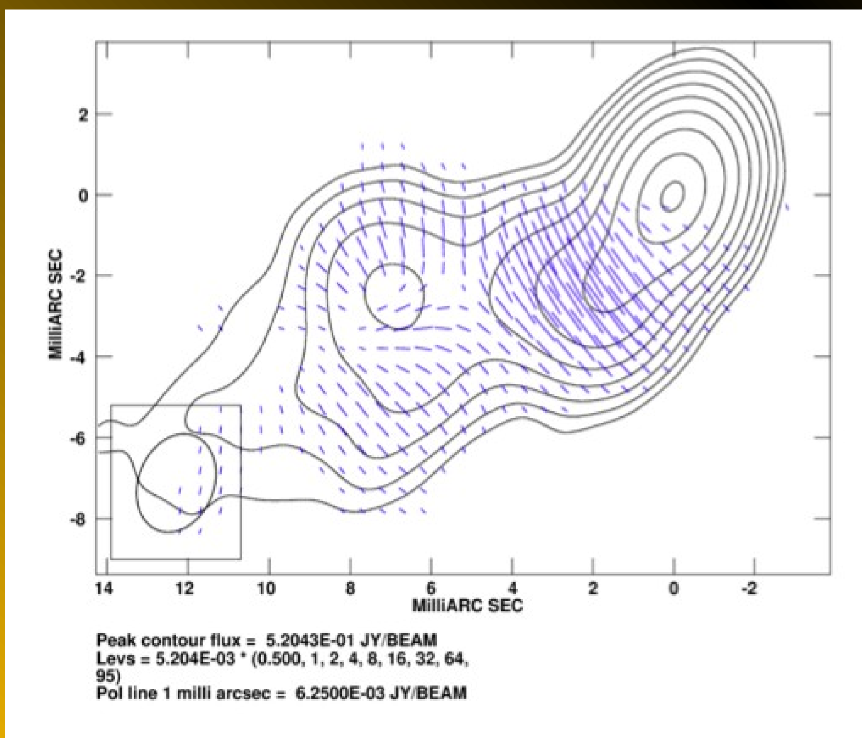
RM map of 1611+343 (Zavala & Taylor 2003) has CCW gradient with significance ~ 4σ

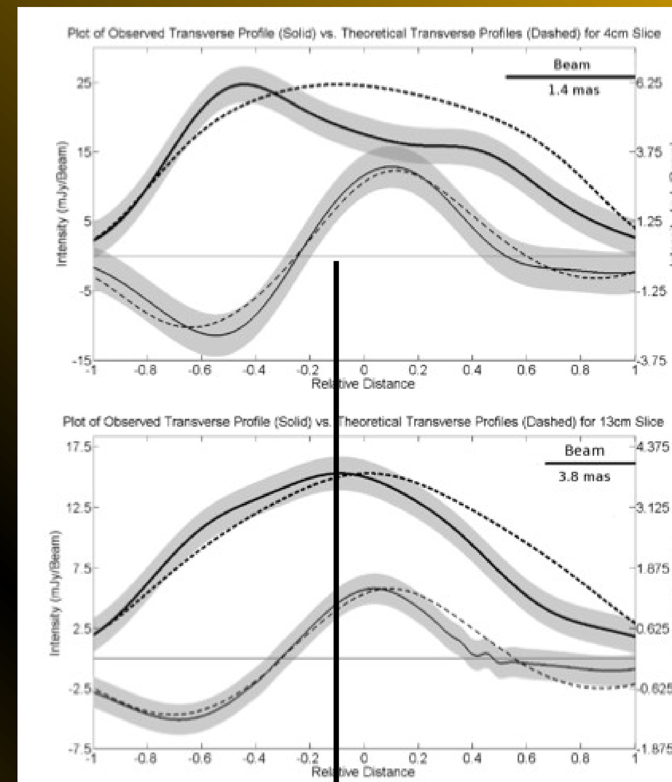
Example – Mrk501 (Murphy et al. 2013)

Fitting transverse polarization profiles for Mrk501 using simple helical B field model yields fits with

Jet rest frame pitch angle γ' ~ 53°

Jet rest frame viewing angle δ' ~ 83°





Upper curve: Stokes I
Lower curve: Stokes Q

Murphy et al. (2013)

Fitted value for δ' plus measured superluminal speed β_{app} gives solution for intrinsic jet speed β (Lorentz factor Γ) and viewing angle in observer rest frame δ:

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

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

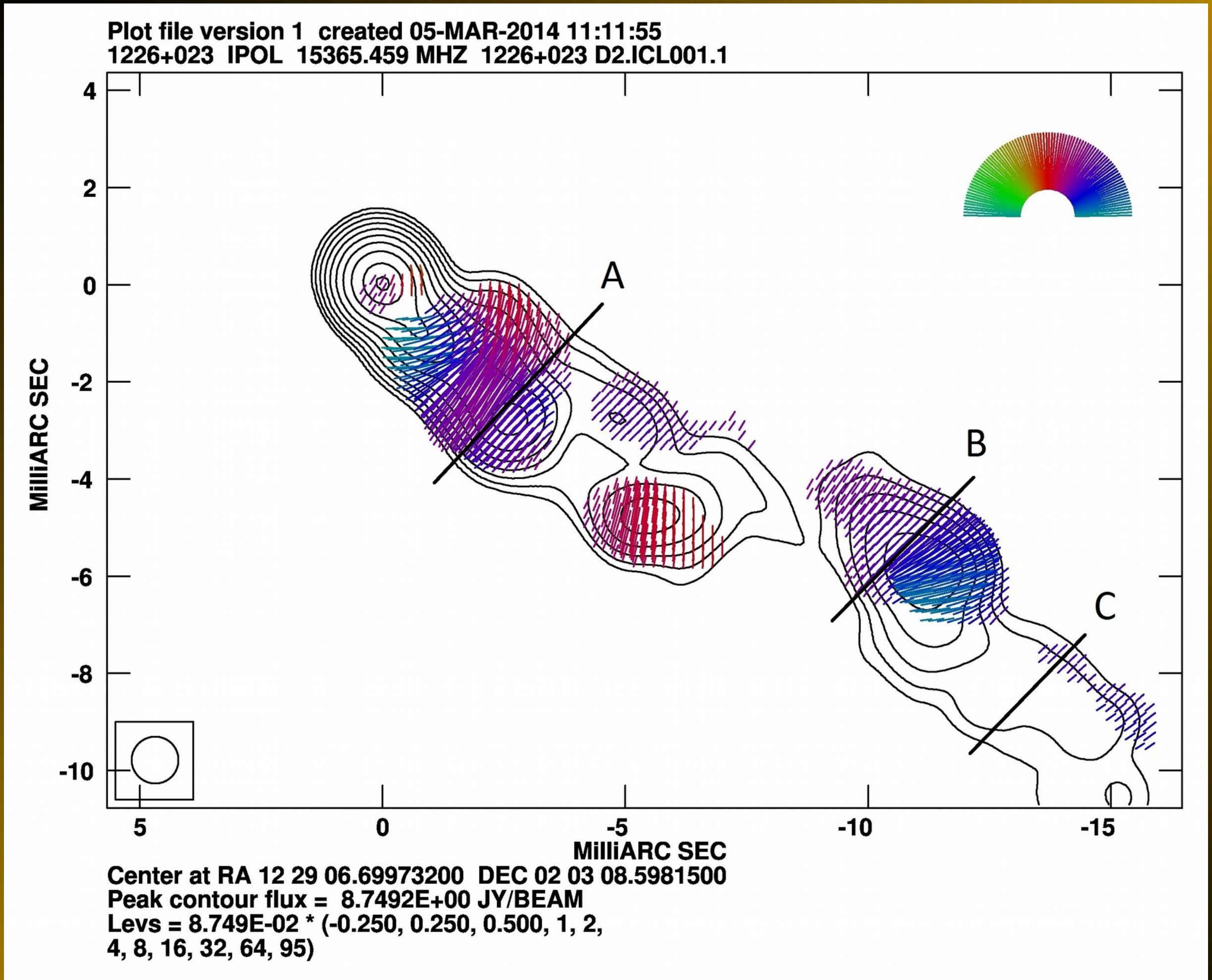
======>

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

Yields for Mrk501 β =0.96 and δ = 15º

Consistent with results of Giroletti et al. (2004), β ≥ 0.88 and δ ≤ 27º

Example – 3C273 (Gabuzda, O'Neill & Murphy, in prep)



3C273 has rich, asymmetrical polarization structure, making it a good source to study in this way.

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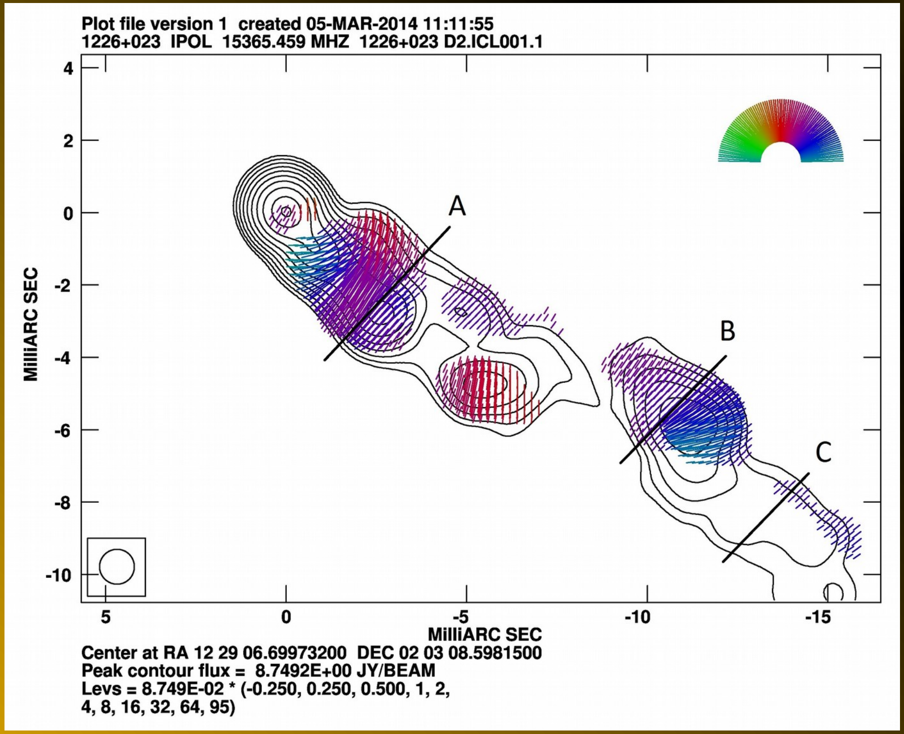

Fitting transverse polarization profiles for 3C273 yields

$\gamma' \sim 45°$, $\delta' \sim 84°$

$\delta = 3.8°$, $\beta = 0.997$, $\Gamma = 13.6$

Hovatta et al. (2009) also estimated $\delta = 4°$, $\Gamma = 14$!

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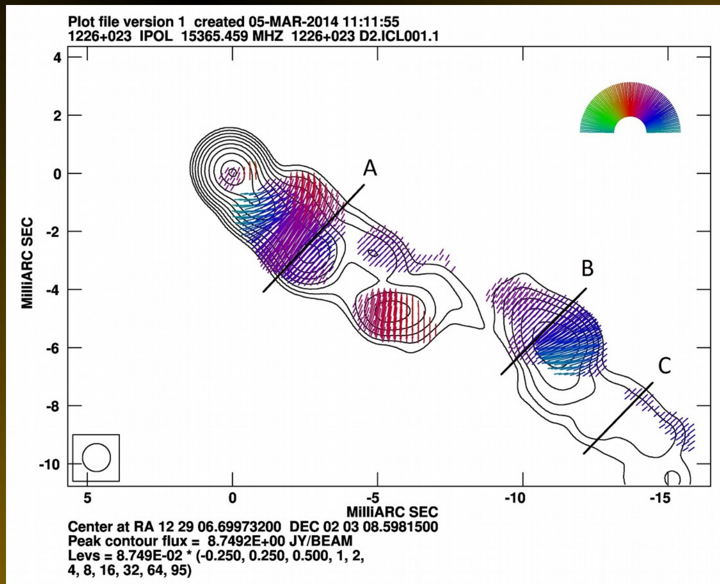

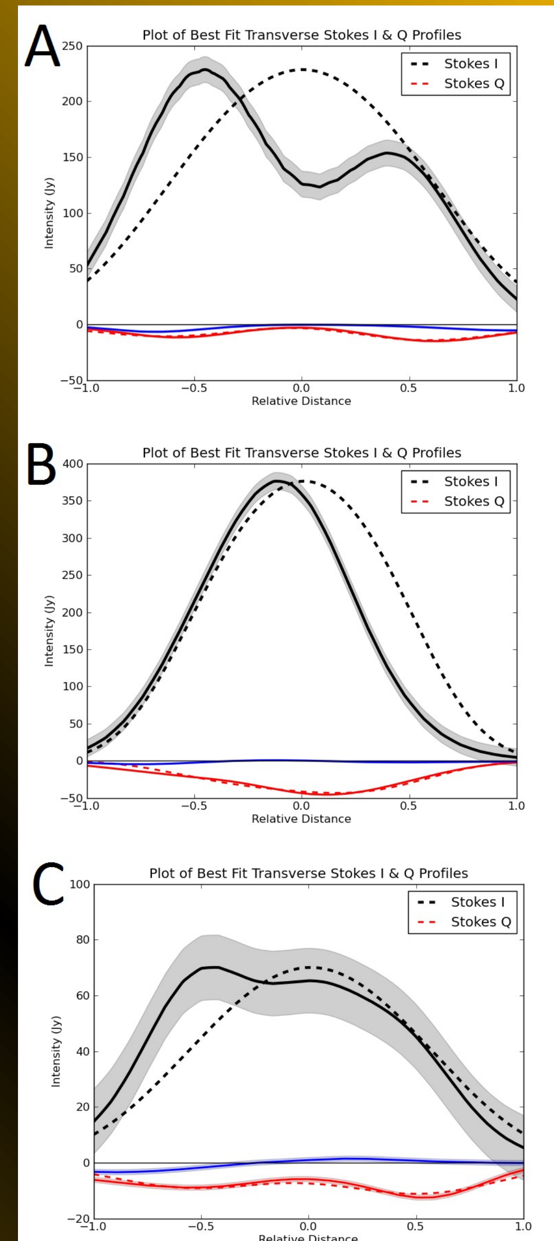

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