

The Origin and Global Structure of the Magnetic Fields and Currents of AGN Jets

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Outline of talk

- o Faraday rotation gradients & helical/toroidal B fields
- o Evidence for the “return” jet B field
- o Global patterns in the toroidal B fields/axial currents of AGN jets
- o Summary

Faraday rotation of the observed linear polarisation angle χ occurs when polarised EM wave passes through a magnetised plasma.

$$\chi = \chi_0 + RM \chi^2$$

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

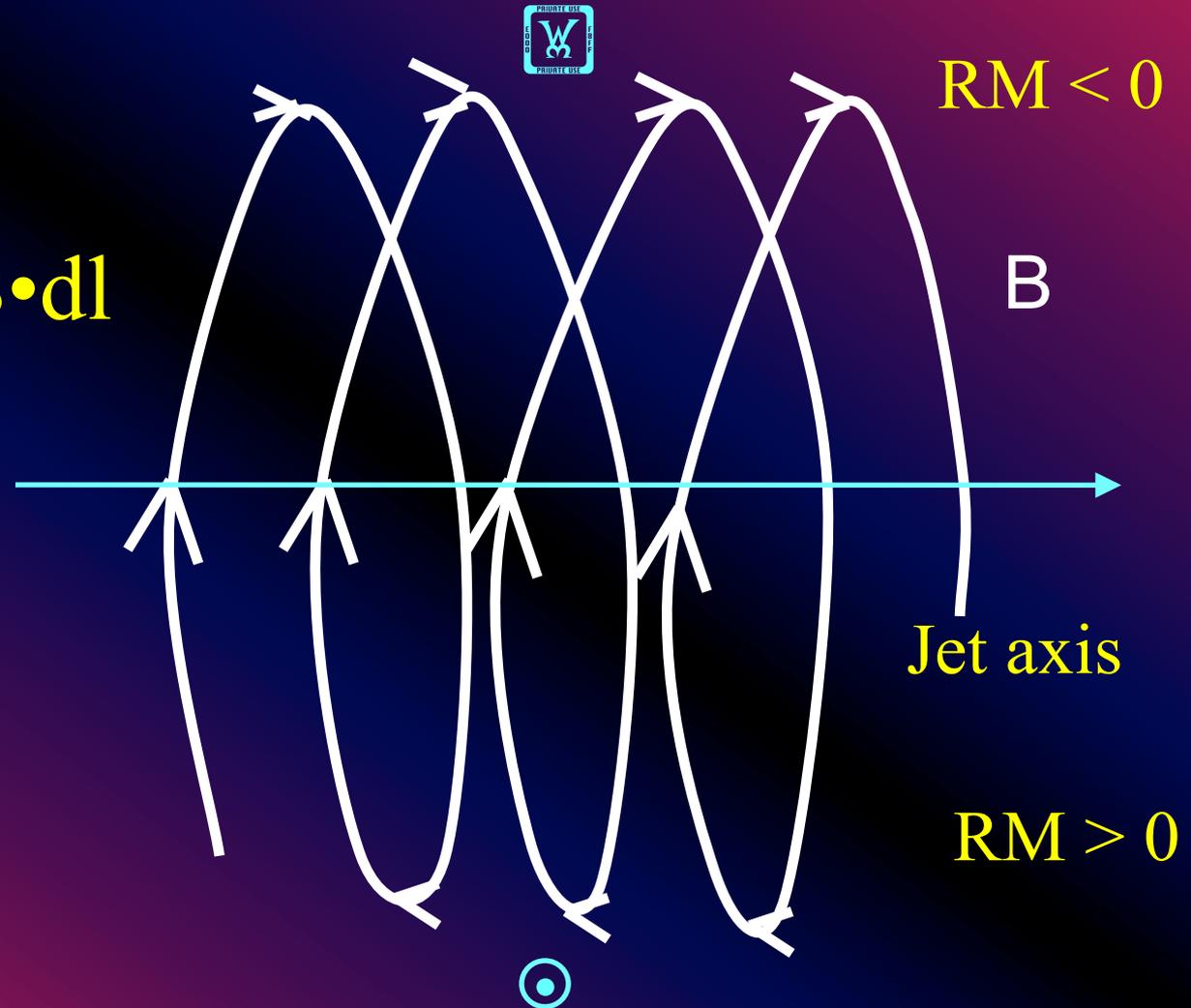
Electron density

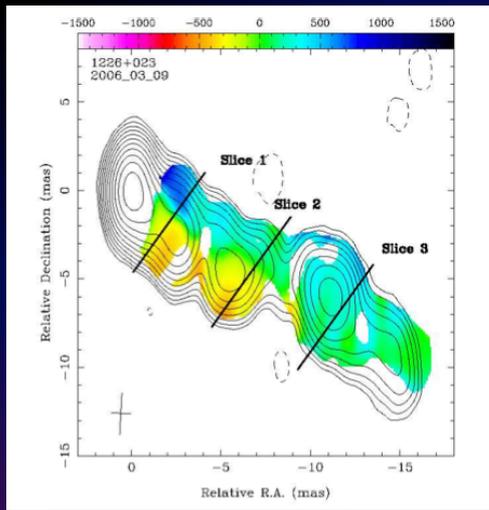


Line of sight B field

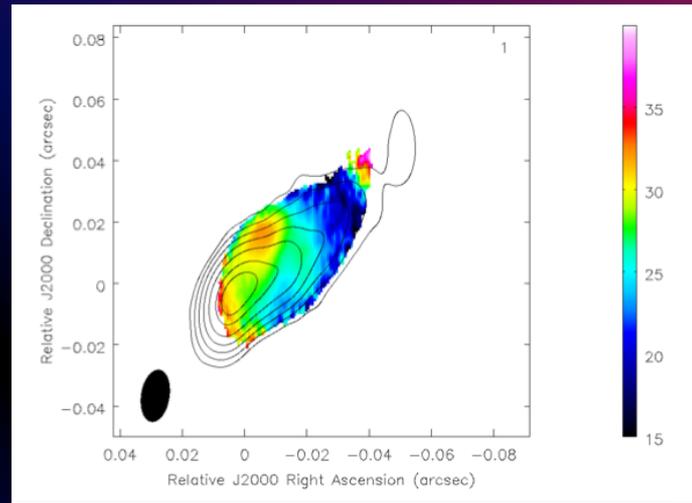
A helical or toroidal jet B field should lead to a **Faraday-rotation gradient across the jet** – systematically changing *line-of-sight* component of B field (Blandford 1993).

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

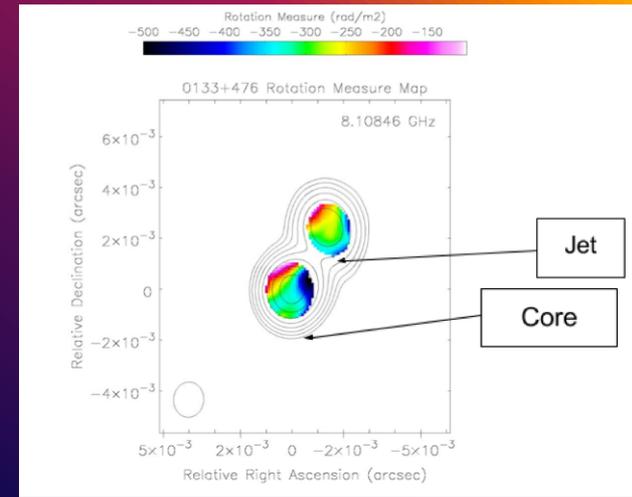




Hovatta et al. 2012

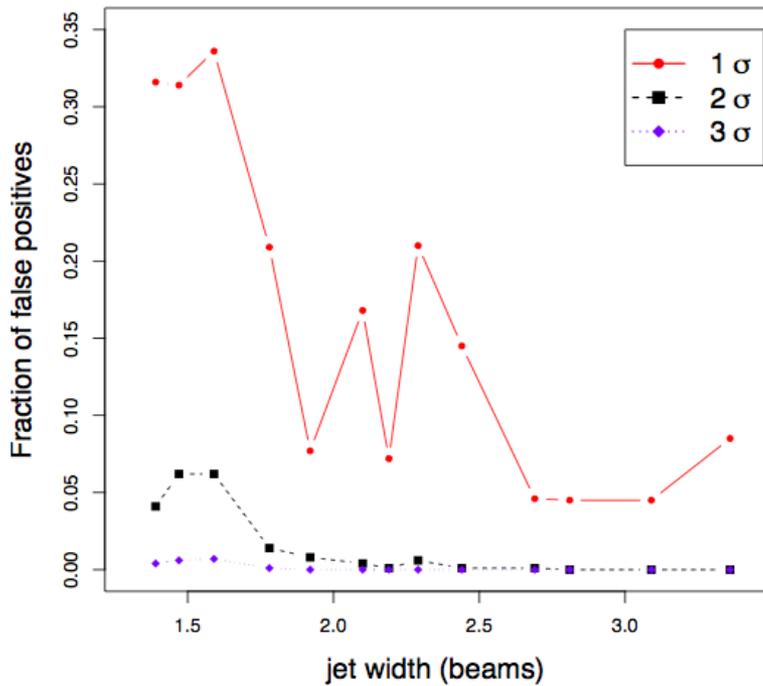


DG et al. 2013



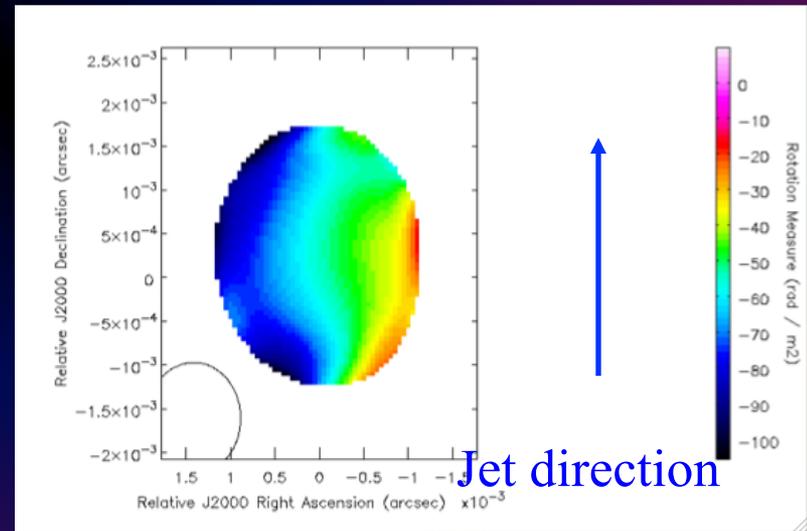
DG et al. in prep

- Reports of firm transverse RM gradients across an increasing number of pc-scale AGN jets.
- Monte Carlo (MC) simulations indicate that the best test of reliability is **monotonicity** of the gradient and ensuring RM range spanned $> 3 \left[\frac{\lambda^2}{8\pi} \right]$.



Hovatta et al. (2012) — fewer than $\sim 1\%$ of MC runs *without* RM gradients give spurious 3σ gradients, even when RM gradient spans only ~ 1.35 beam width

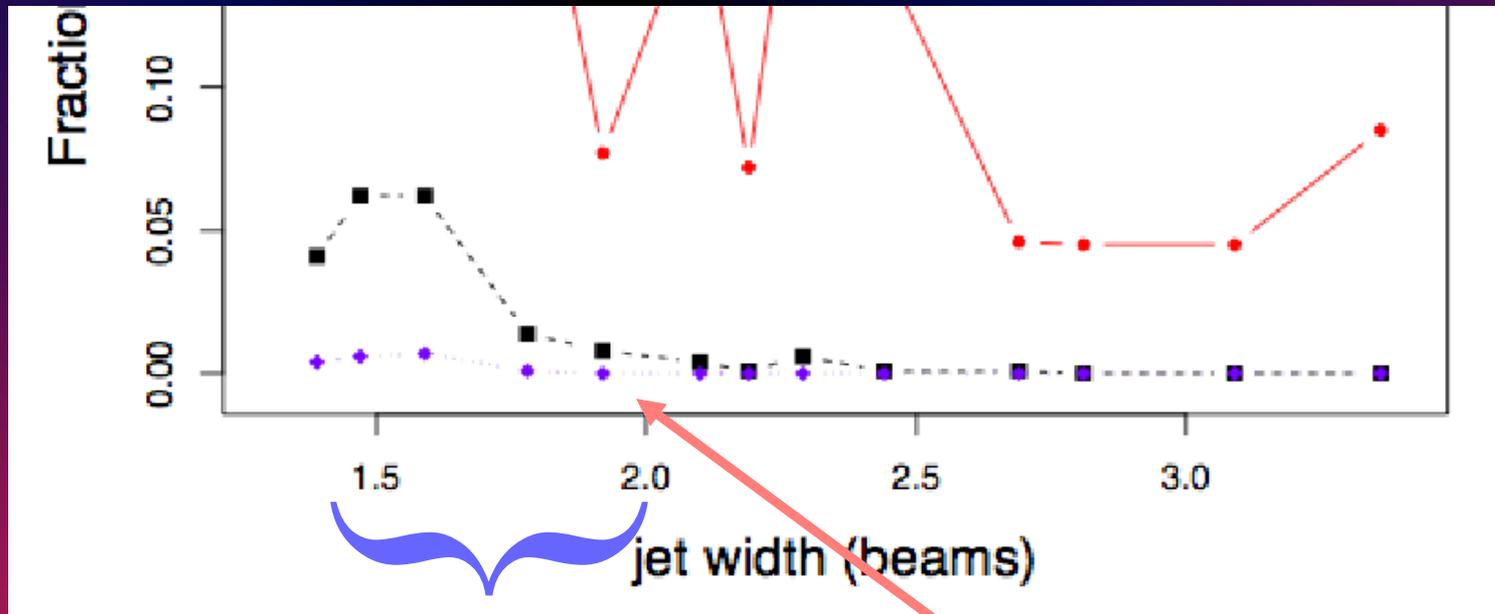
Mahmud et al. (2013), Murphy & Gabuzda (2013) — RM gradients remain visible in MC maps *with* RM gradients when jet width \ll beam width!



Jet width = $1/20$ beam!

Ongoing work — complementing MOJAVE studies by searching for more ≥ 3  RM gradients on pc scales:

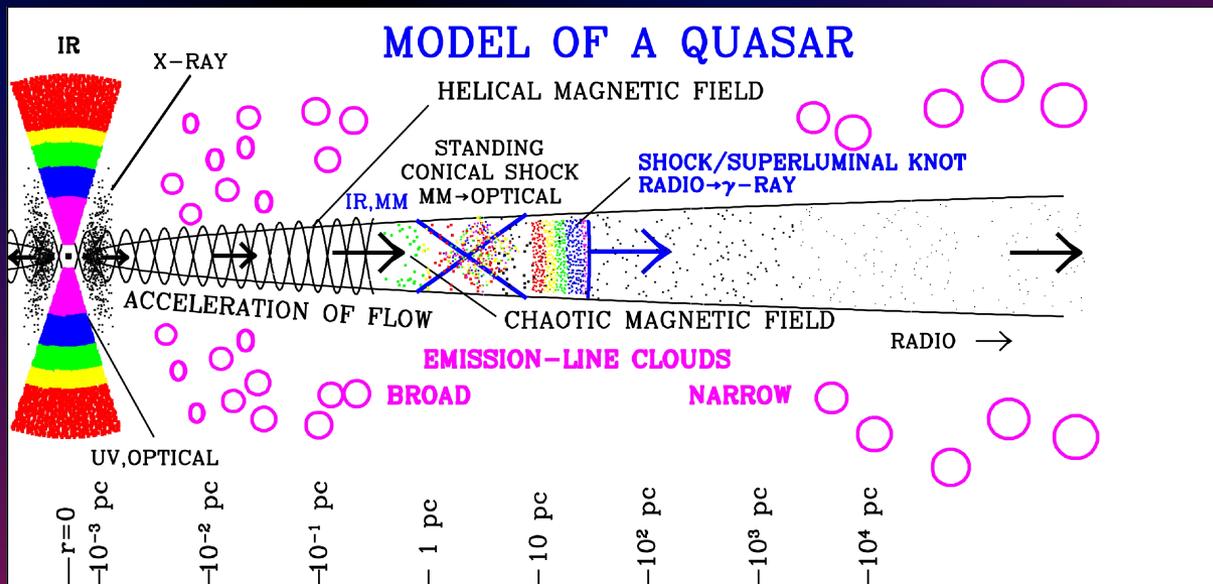
- Analyzing new data (DG et al. 2014, 2015, in prep)
- Analyzing data of Hovatta et al. (2012) for RM gradients spanning < 2 beamwidths (DG et al., in prep)



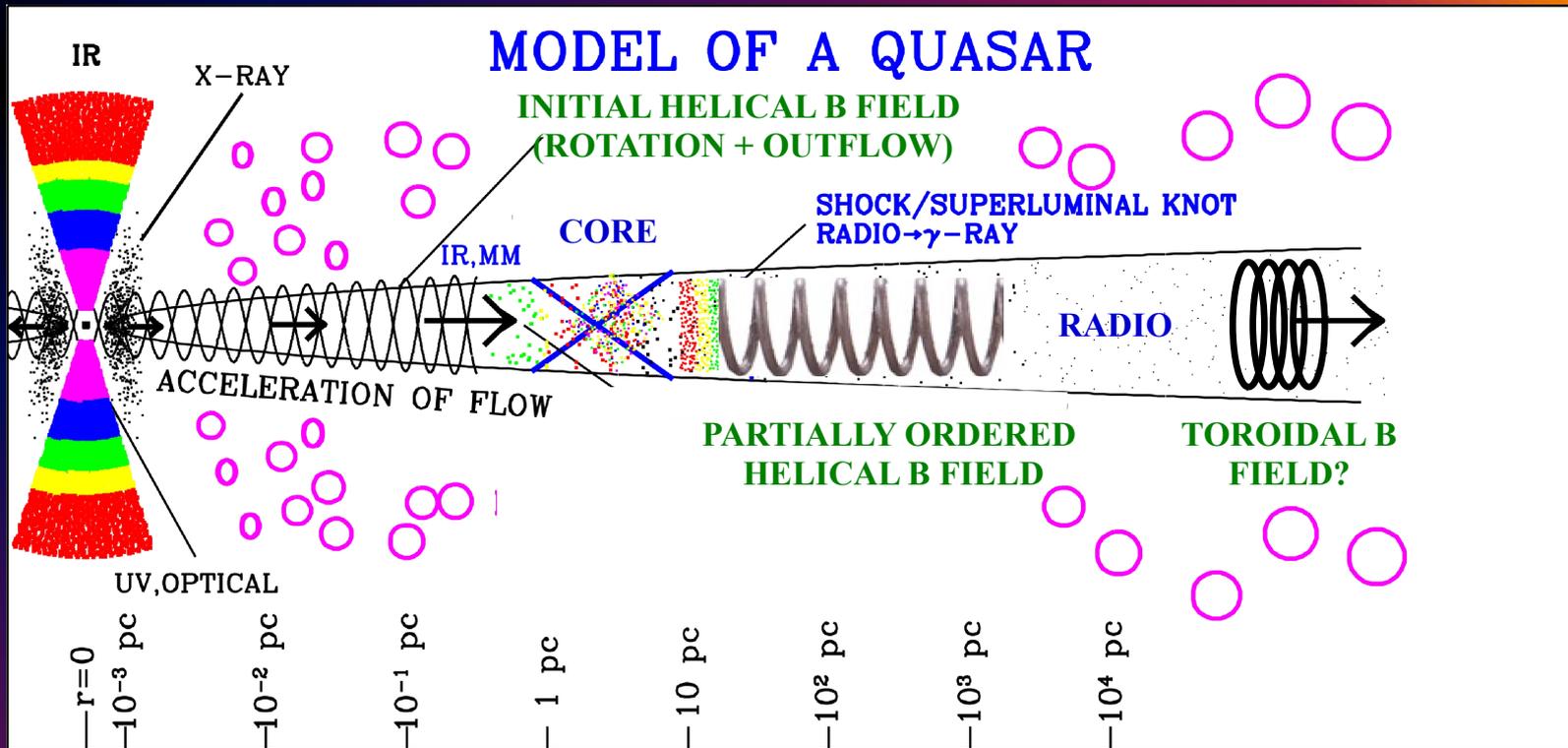
RM grads with smaller widths also reliable if significance $\geq 3\sigma$

Width limit used by Hovatta et al. (2012)

- The generation of a helical field in the innermost part of the jets is expected according to standard models.
- In Alan Marscher's much-viewed figure, this 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!

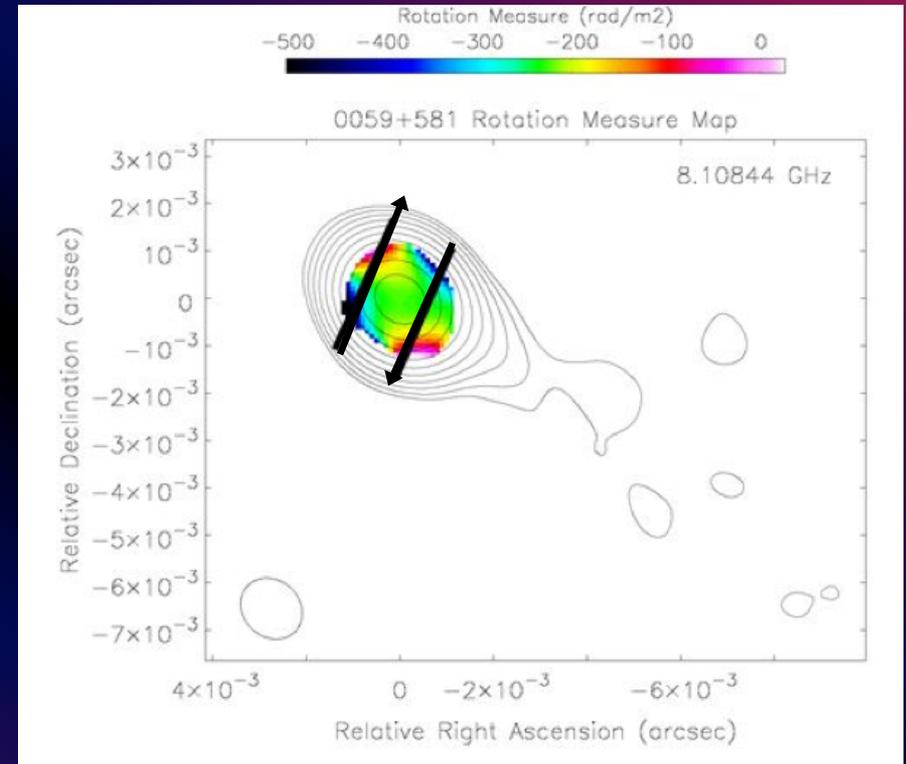
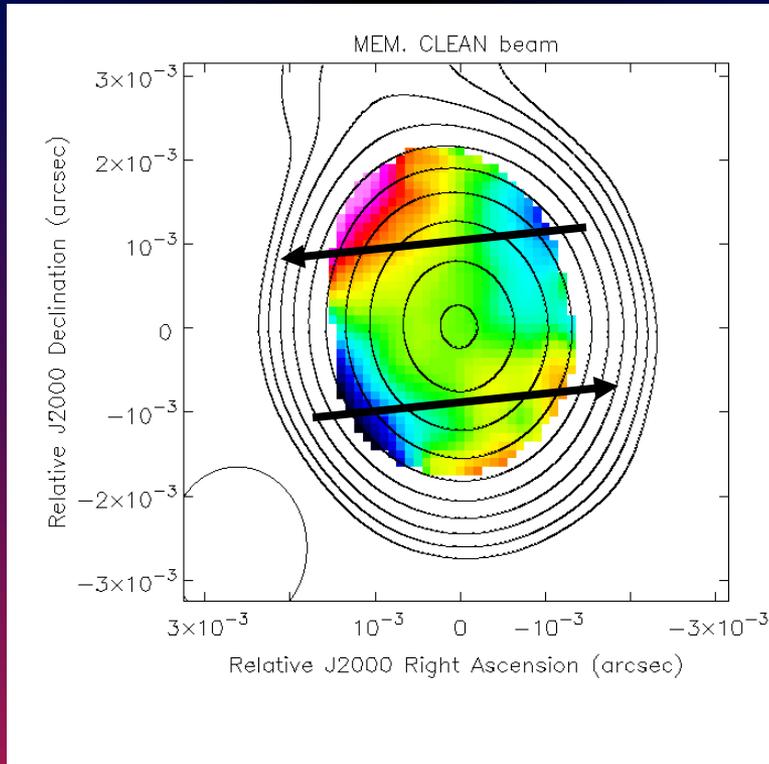


- Observation of transverse RM gradients + modeling of Marscher (2015) suggest a picture with both helical (ordered) + chaotic (turbulent) B components in jet:

Helical B  RM gradients

Chaotic B  variability

“Reversed” RM gradients now detected in six AGN (Mahmud et al. 2013, DG et al. 2014, in prep):

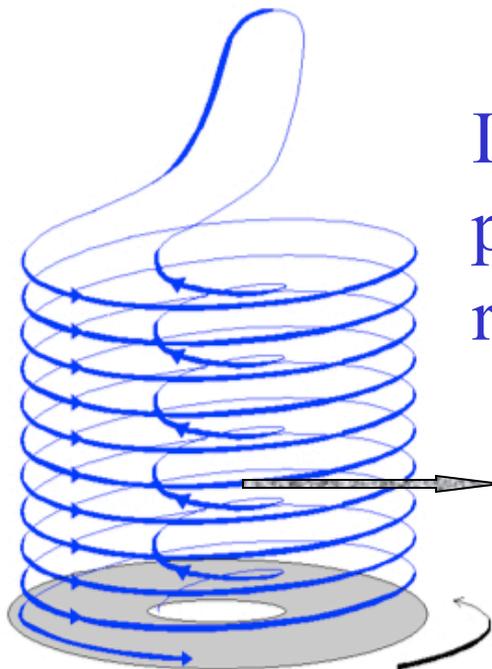
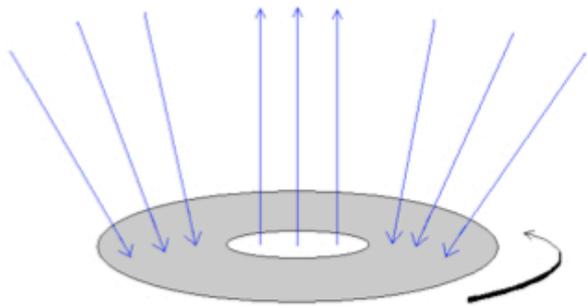


Mahmud et al. 2013;
Coughlan & Gabuzda 2016

DG et al., in prep

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

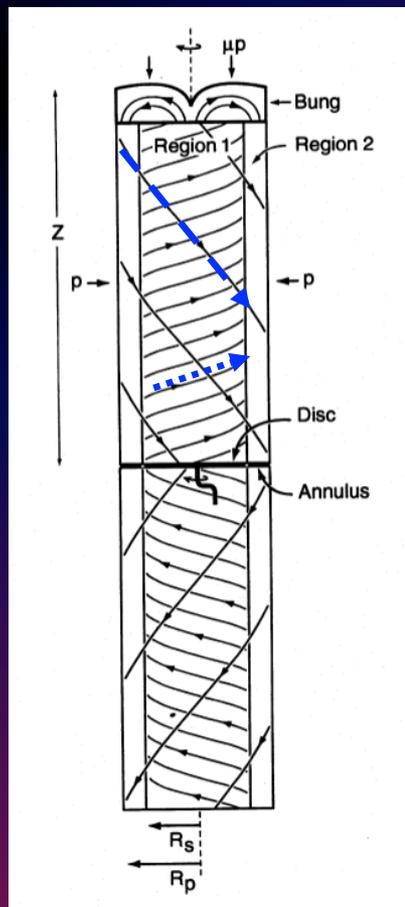


$$n_e \mathbf{B} \cdot d\mathbf{l}$$

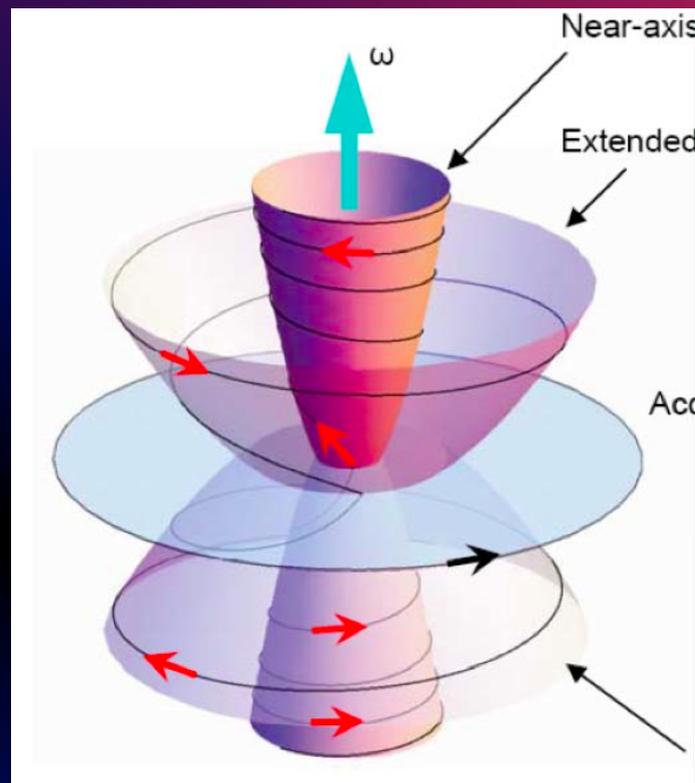
Provides direct evidence for the presence of a “return field” in a more extended region surrounding the jet

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

Lynden-Bell
1996



Contopoulos et al. 2009

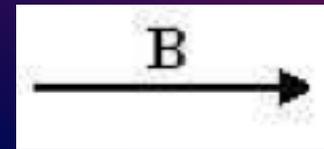
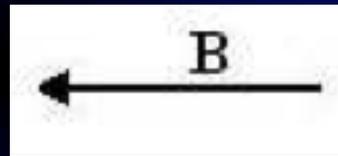


This model will not give a reversal ... this one will!

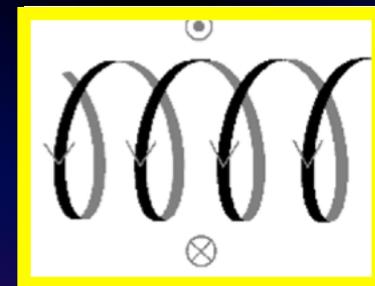
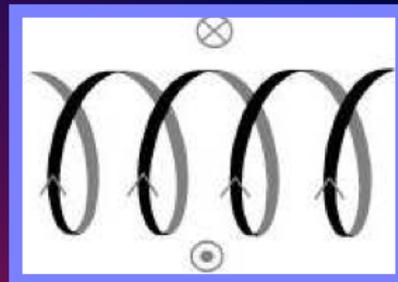
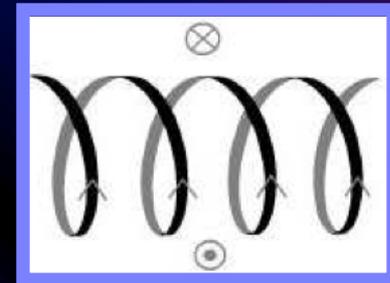
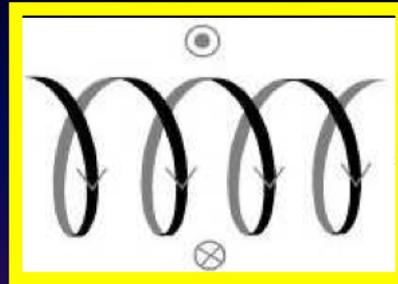
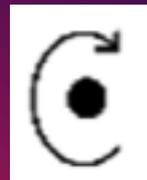
This can place new constraints on the B-field structure and the boundary conditions for theoretical models!

Rotation direction + direction of initial axial field that is wound up determines direction of toroidal B field (and thus RM gradient):

Initial axial field direction



Rotation direction

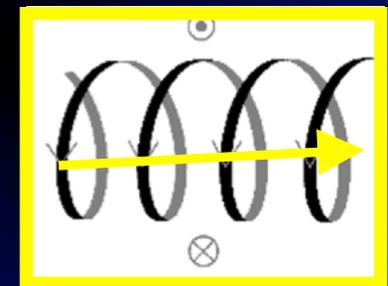
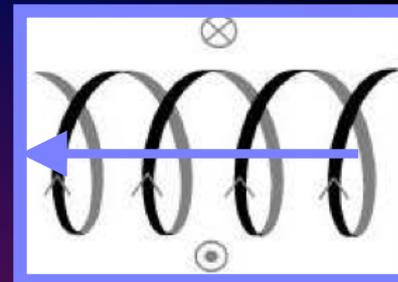
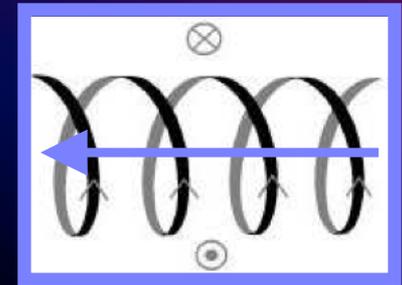
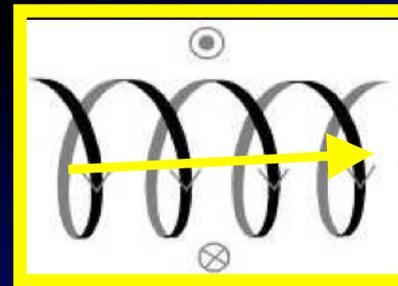
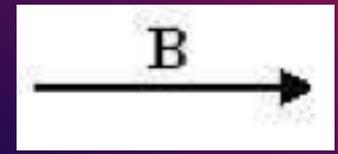
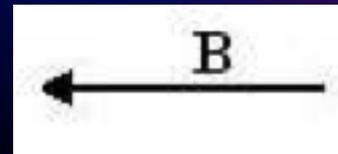
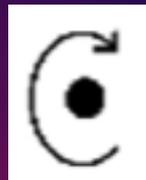
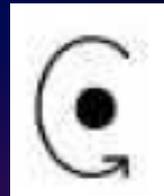


An observed RM gradient (toroidal B field) will correspond to a particular axial current direction — inward or outward.

Arrows show direction of implied current

Rotation direction

Axial field direction



Are equal numbers of RM gradients implying inward and outward currents observed?

Currently 38 monotonic transverse RM gradients with significances $\geq 3\sigma$ (e.g. DG et al. 2014, 2015, in prep):

28 σ I inward, 10 σ I outward

Probability of 28 or more of 38 currents being inward by chance (unweighted binomial probability distribution):

$$\underline{P \sim 0.975 \%}$$

Predominance of inward I on pc scales!

One mechanism that can provide this 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:

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

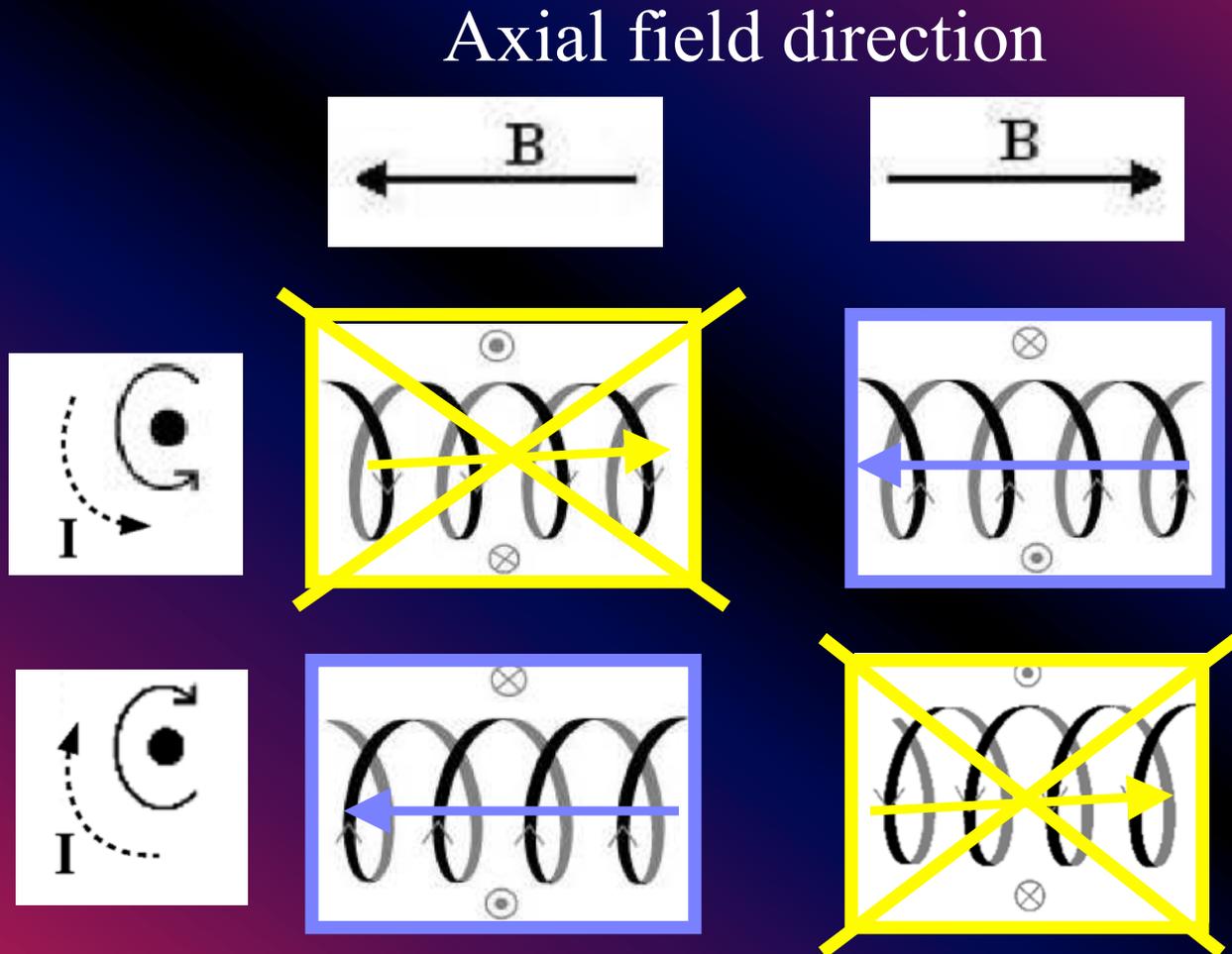
Force on electrons

 Force on $e^- \gg$ force on p because  T  m^{-2}

\implies Electric current in direction of rotation in disc

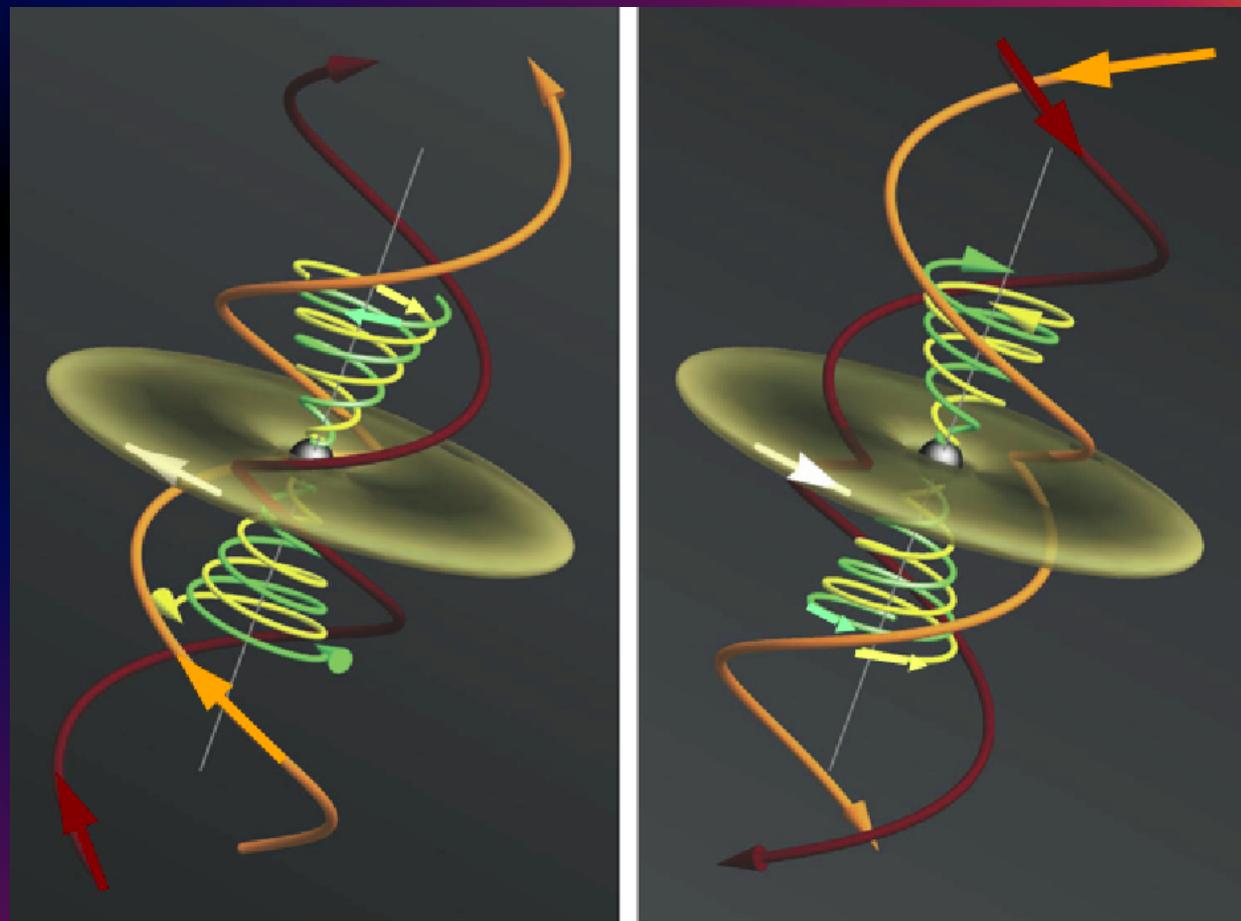
Rotation and axial B field are **coupled** — current in accretion disk provides initial axial B field that is wound up, giving rise to **inward** jet current:

Rotation direction
(current direction)



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

Christodoulou
et al. (2016)

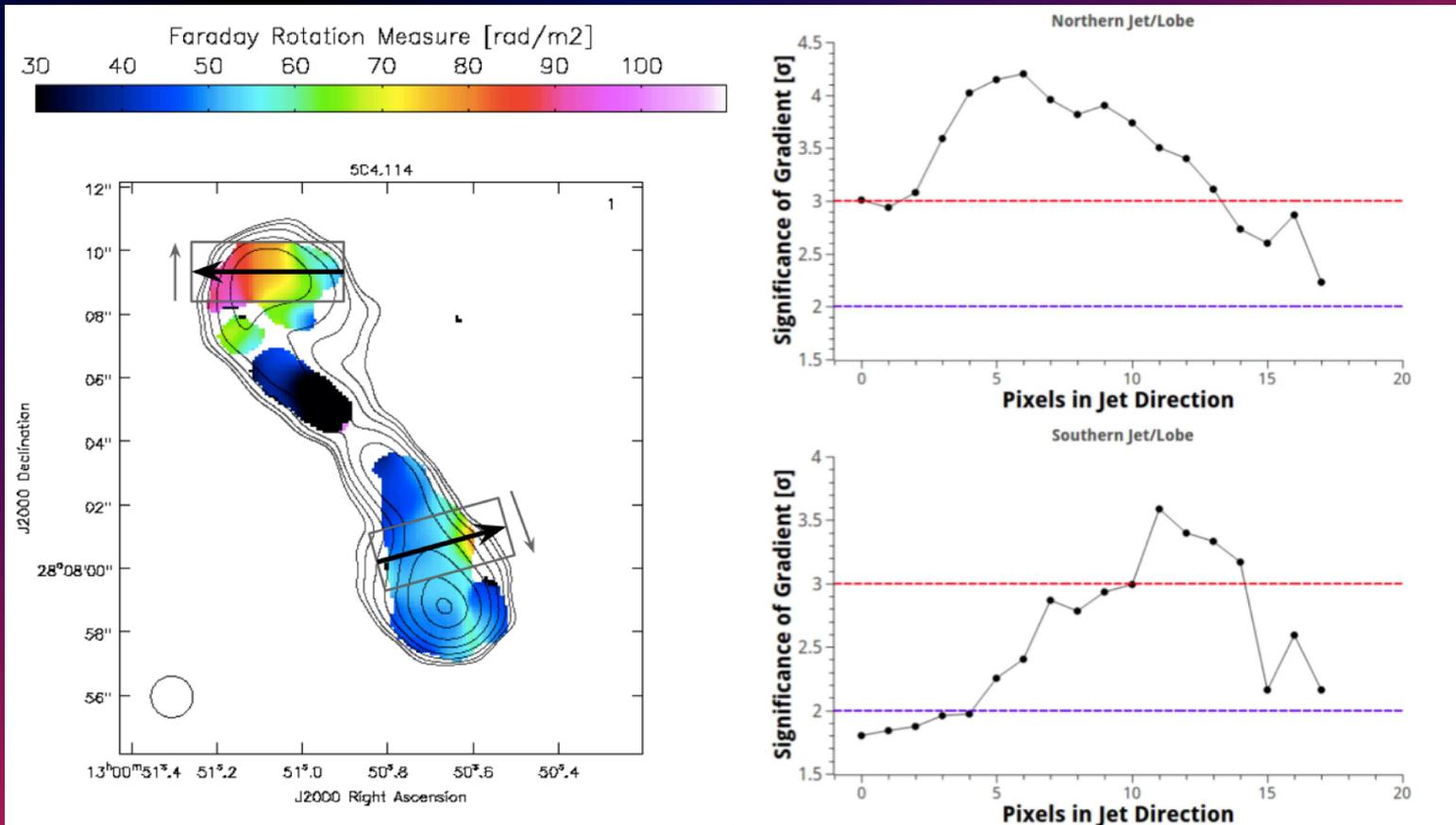


Corresponds to **inward** current near jet axis, **outward** current in region surrounding jet.

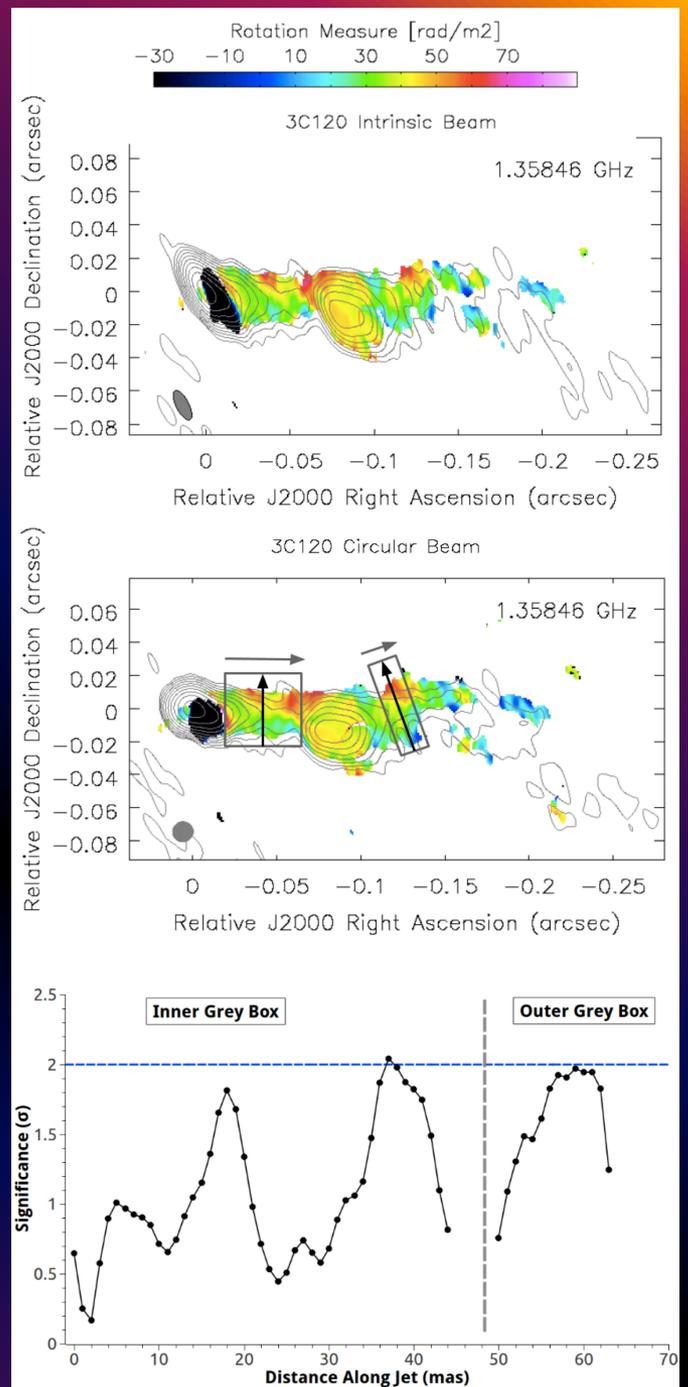
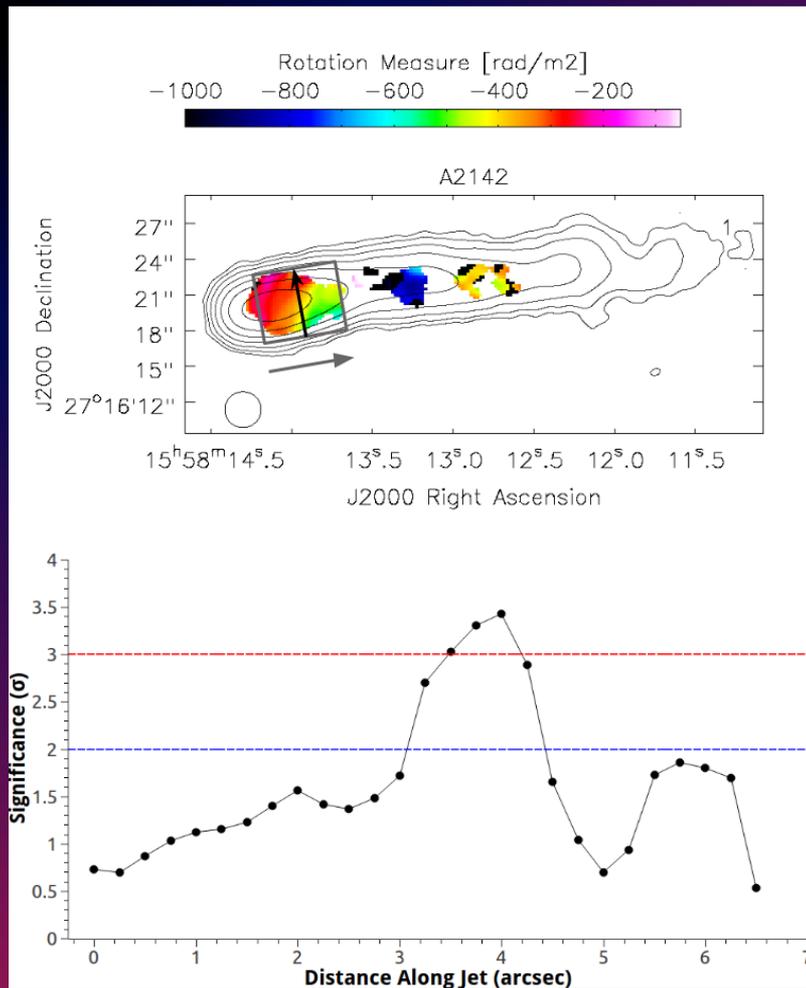
Predominance of **inward** axial currents on pc scales, implies that inner part of the nested helix structure usually dominates the overall observed Faraday rotation on these scales.

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

We have also found transverse RM gradients on larger (out to kpc) scales, implying the presence of an ordered toroidal B field component:



Gabuzda, Knuettel & Bonafede 2015



Christodoulou et al. 2016

(See also Juliana Motter's poster!)

Christodoulou et al. (2016) found that 9/9 observed RM gradients on scales  20 pc corresponded to **outward** currents on these scales!

The probability of this occurring by chance is only 0.2% !

Thus, now conclusive evidence:

Jet currents implied by detected toroidal fields are predominantly

- ❖ **Inward** on pc scales
- ❖ **Outward** on scales \geq tens of pc

Summary

- Transverse RM gradients providing direct evidence for helical/toroidal jet B fields have been reliably detected in 38 AGN on parsec scales so far  a helical field component survives to distances well beyond the VLBI core.
- Observation of RM gradient reversals provides observational evidence for a “return B field” forming a nested helical-field structure

Summary

- Firm evidence for a predominance of **inward** axial currents on **parsec** scales and **outward** (“boundary”) currents on scales \geq **tens of parsec**. Places constraints on system of fields and currents in and around the jet/accretion disk!

This is giving us fundamental information about the jets as electromagnetic structures!



*Do not try this experiment
with your cat at home!*