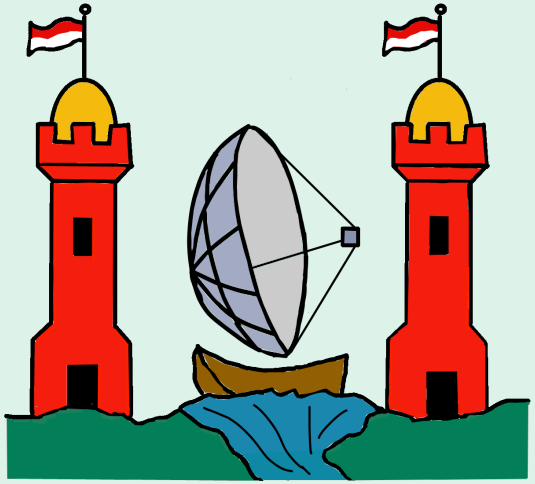


# Active Galactic Nuclei
# Jets in a Nutshell


Denise Gabuzda
University College Cork

Outline of talk

o AGN jets and their helical/toroidal B fields

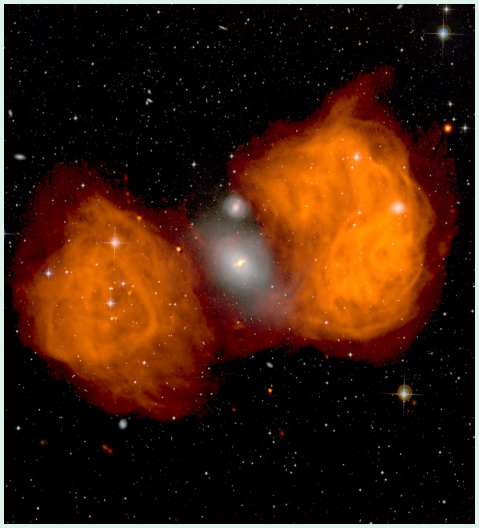
o Characteristic B-field structures of AGN jets: global or local origin?

o Global patterns in the B-fields/axial currents of AGN jets

o Summary

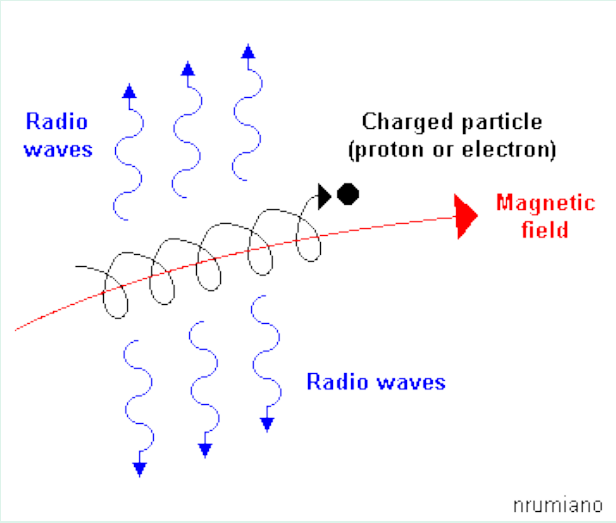
# AGN jets and their helical/toroidal B fields

• The large amount of energy generated in Active Galactic Nuclei (AGN) is due to accretion onto a supermassive (~$10^9$ solar masses!) black hole



• AGN sometimes eject "jets" of radio-emitting plasma extending far beyond the optical (visible) galaxy, which are relativistic on parsec scales.

• Their radio emission is synchrotron radiation given off by energetic electrons during their acceleration by local magnetic (B) fields.




• Natural targets for VLBI!

• The generation of a helical field component at the base of the jets is expected in standard models for launching of the jets (Blandford – Znajek, Blandford – Payne; a poloidal field “wound up” by rotation).

• This ordered field is accompanied by a tangled/turbulent component, which reduces the degree of linear polarization from ~75% (max for synchrotron radiation) to typical values of ~10–15%.

• Main observational approaches to detecting presence of helical/toroidal fields:

➢ Transverse Faraday rotation gradients

➢ Characteristic transverse polarization structure

# Transverse Faraday Rotation Gradients

Faraday rotation of the observed linear polarisation angle $\chi$ occurs when polarised EM wave passes through a magnetised plasma – right- and left-circularly polarized components of the wave propagate at different velocities and so get out of phase.

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

Rotation $\propto \boldsymbol{\lambda}^2$

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

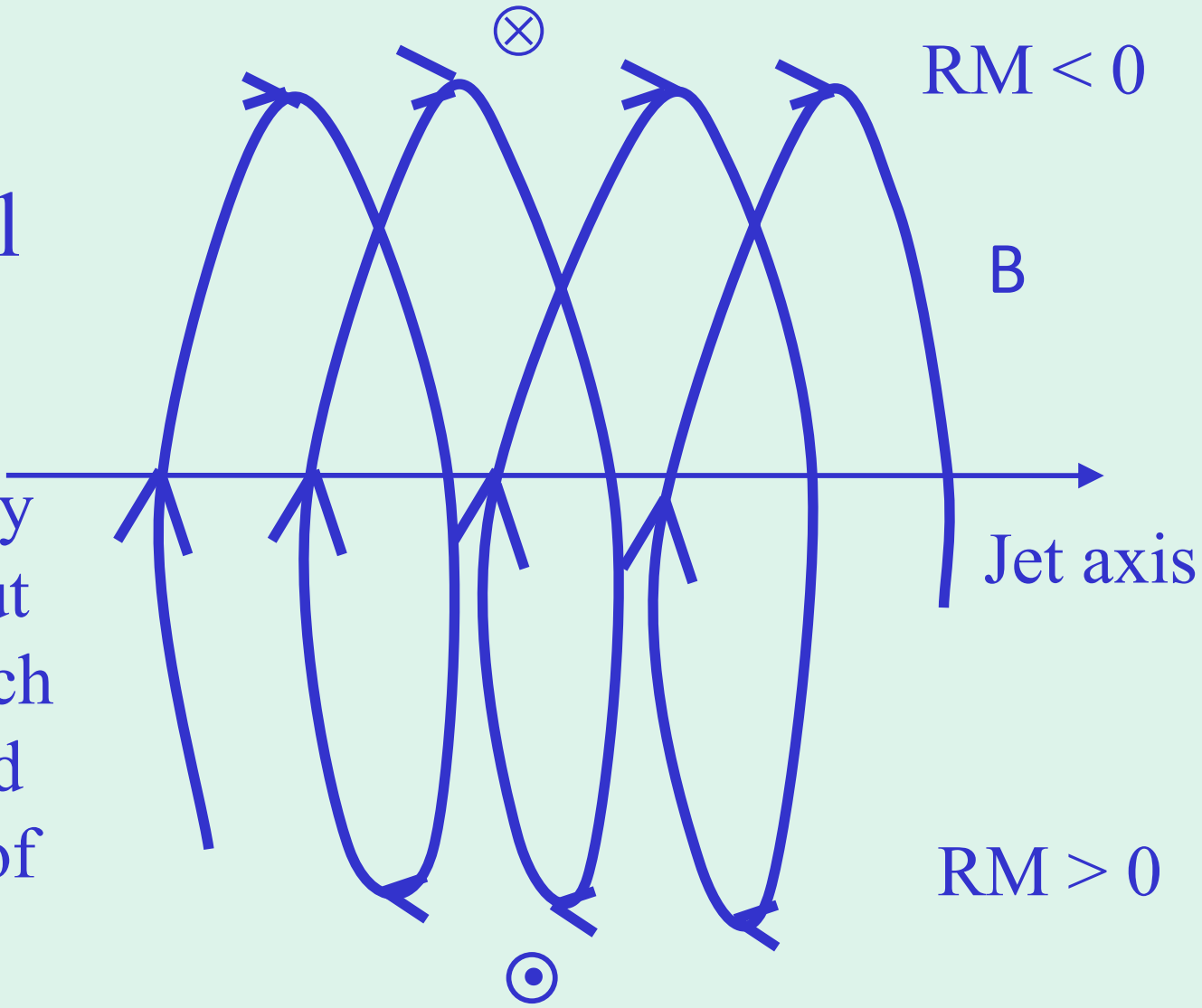
Electron density

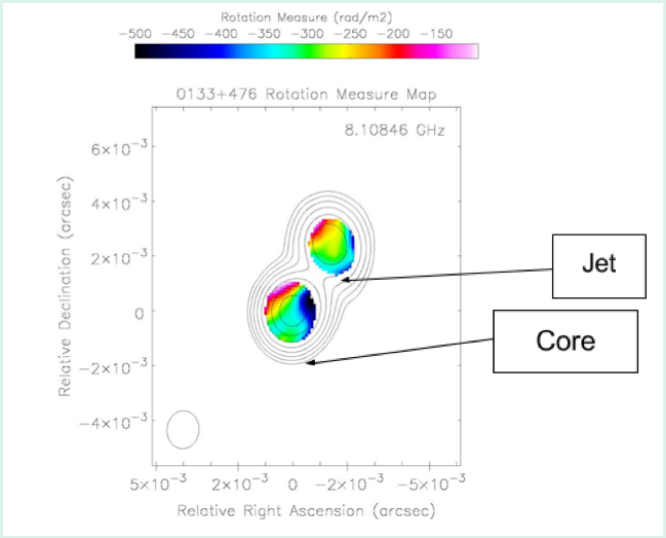
Line of sight B field

A toroidal jet B field component can lead to a Faraday-rotation gradient *across* the jet – systematically changing *line-of-sight* B field (Perley et al. 1984, Blandford 1993).

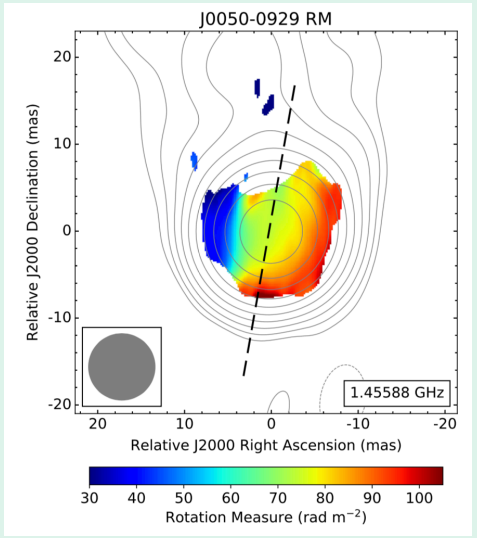
$$RM \sim \int n_e \, B \bullet dl$$

RM distribution may be asymmetric about 0, depending on pitch angle of helical field and viewing angle of jet

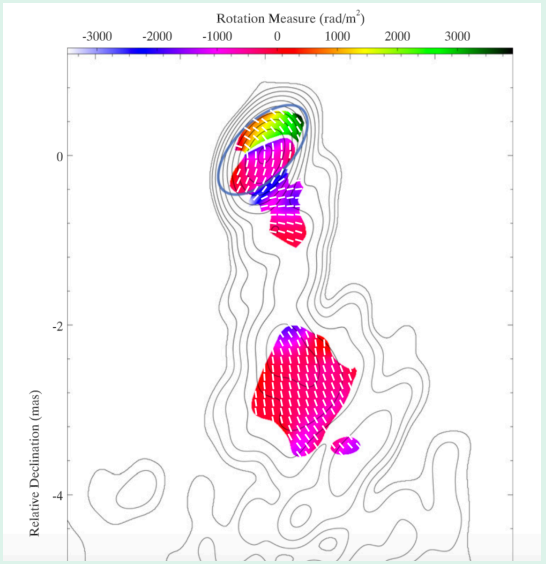





Gabuzda et al. 2018



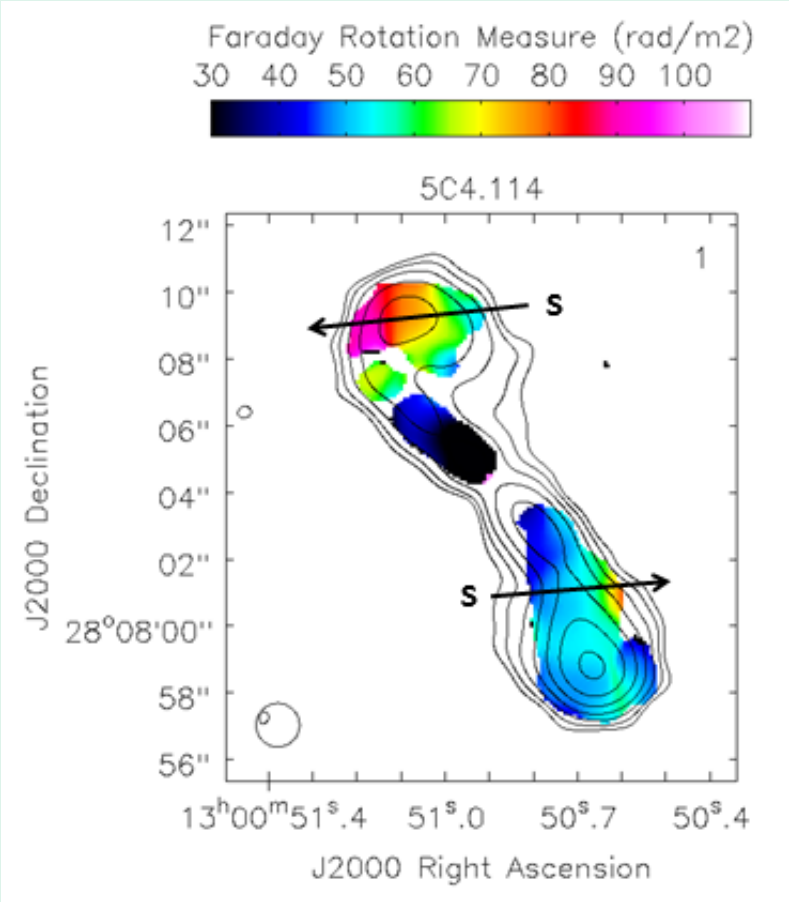

Richardson 2021




Gomez et al. 2016

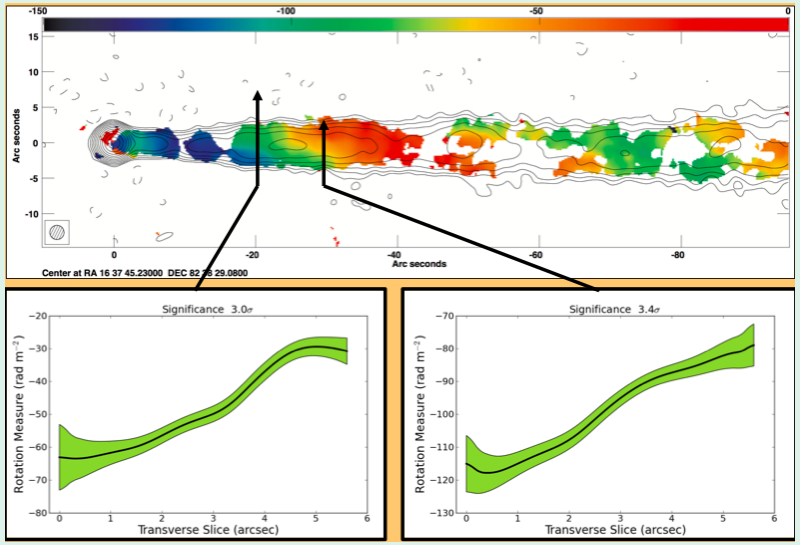
- Statistically significant transverse RM gradients detected across some 50 pc-scale AGN jets (Gabuzda et al. 2018)
- "Core" region polarization dominated by optically thin inner jet, some gradients observed across VLBI "cores"
- Faraday rotation appears to be external – FR gradients due to thermal material in the immediate vicinity of the jet, in which the jet helical B field is embedded

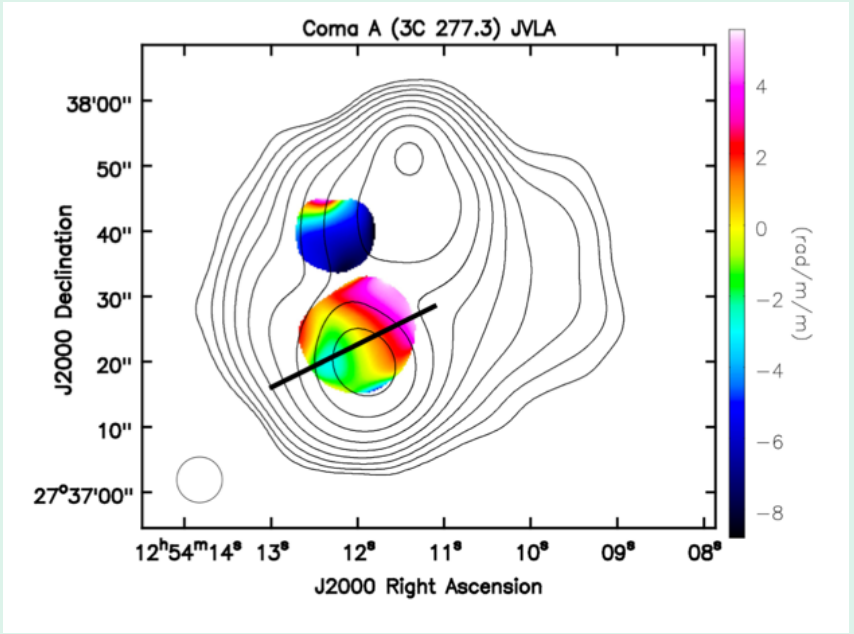
# Significant transverse RM gradients also found out to kpc scales, although these are more rare




Gabuzda et al. 2015

Knuettel et al. 2018




Knuettel et al. 2017

# Characteristic B-field structures of AGN jets: global or local origin?

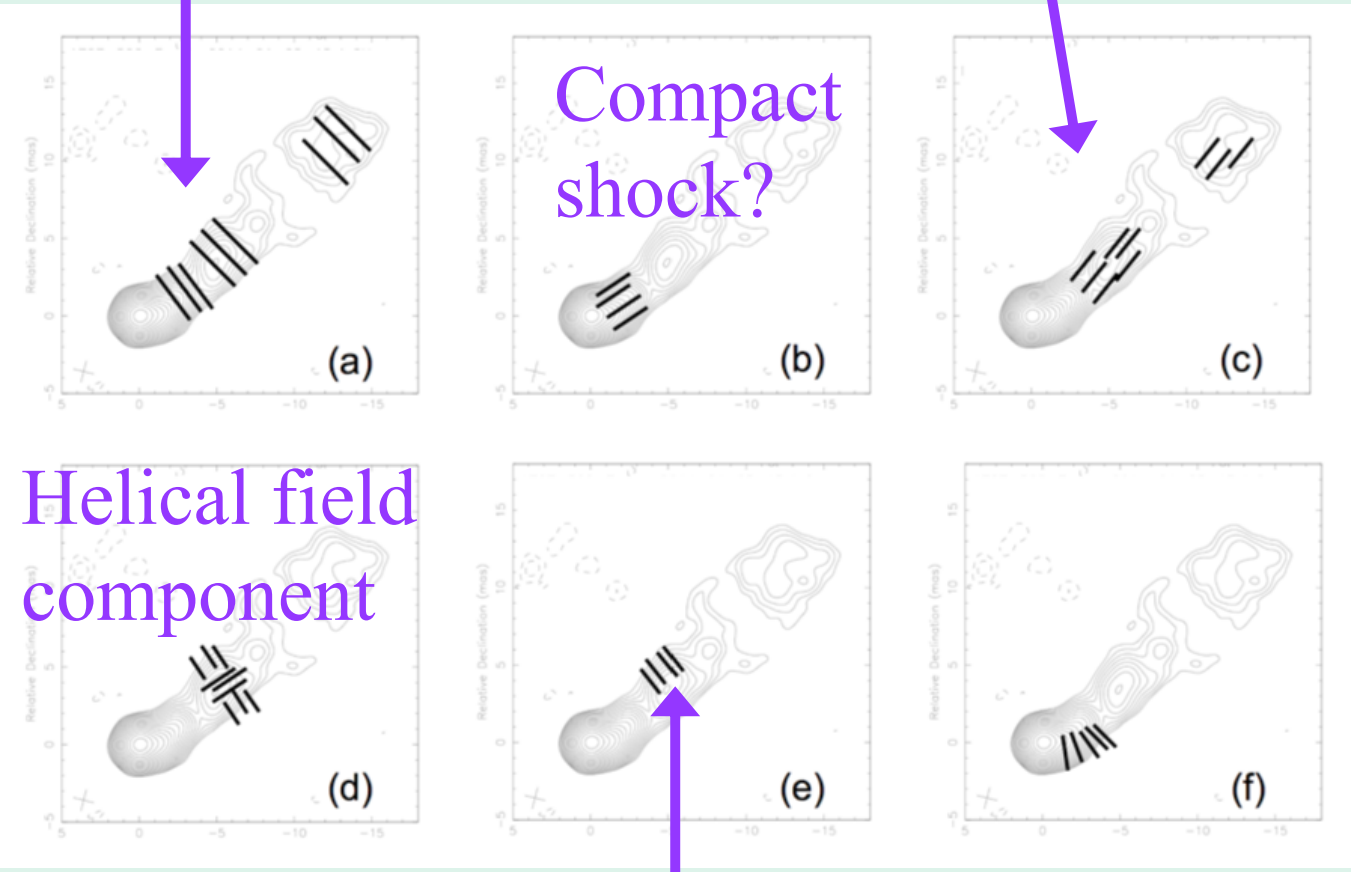
The presence of a helical magnetic field component leads us to expect "global" structures in polarisation. More locally generated polarisation structures are also possible. How can we distinguish between B fields due to global and local phenomena?

- Extent of region they occupy
- Presence or absence of other signs of global/ local effects (e.g. spectral index structures, pol structure, transverse RM gradients)

*Can be difficult to do this conclusively!*

Observed polarisation structures in AGN jets (DG 2015; B ⊥ polarisation angle in optically thin regions)

Extended regions of a particular orientation of polarisation – most likely due to helical field component




Compact shock?

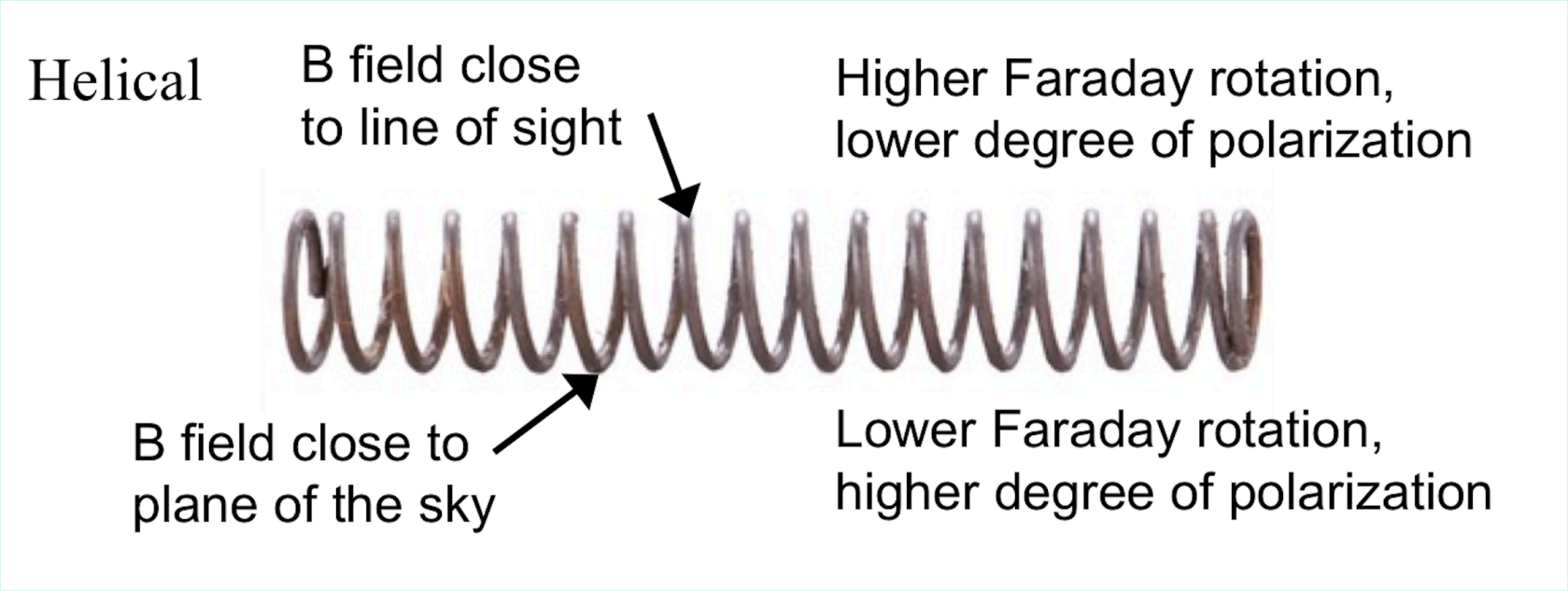
Helical field component

Amplification of longitudinal field due to jet bending?

Shear or a helical field component

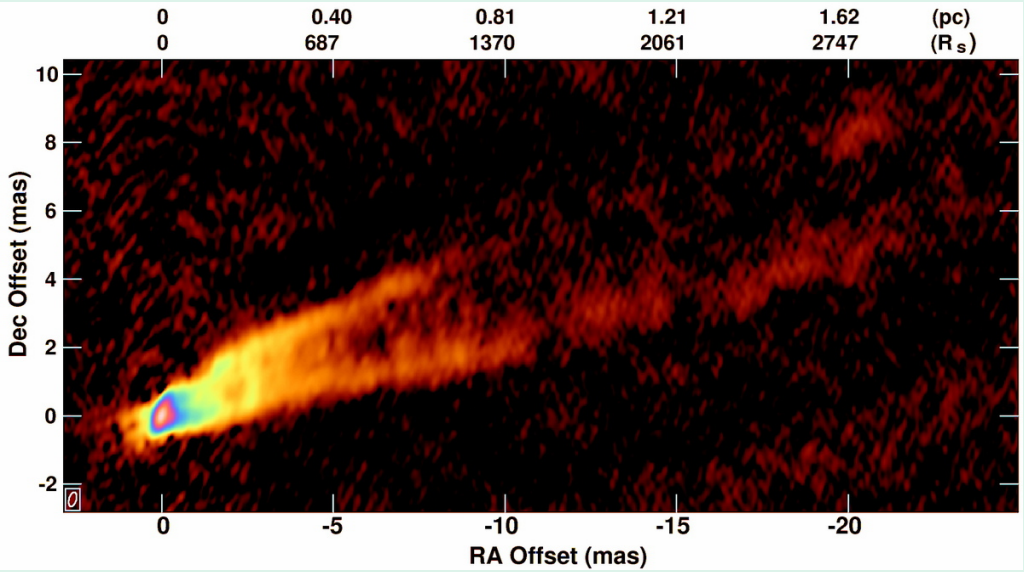
Often difficult to distinguish conclusively between scenarios!

Potentially powerful diagnostic – **correlated patterns in distributions of intensity, polarization, spectral index and Faraday rotation** (e.g. Clausen-Brown et al. 2011)



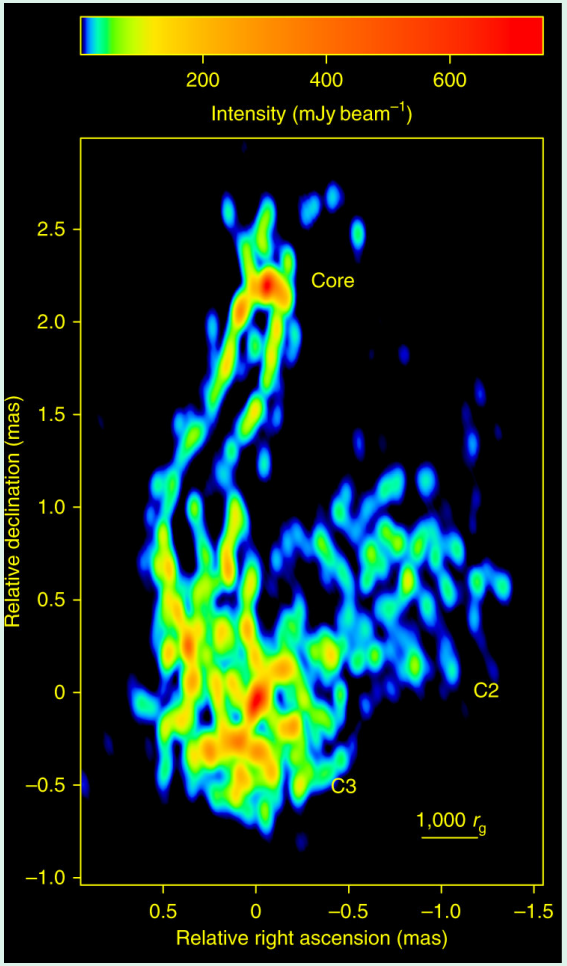

Little exploited thus far, but promising for future work.

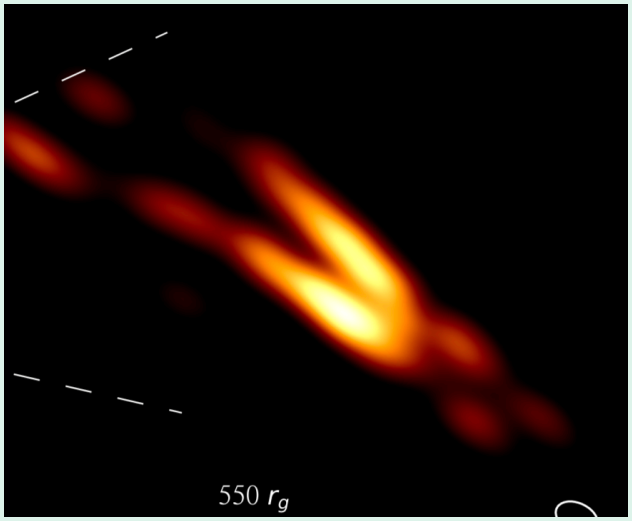
Dramatic limb brightening has been observed in a number of AGN jets on a variety of scales.




M87: Walker et al 2018

3C84: Giovannini et al. 2018



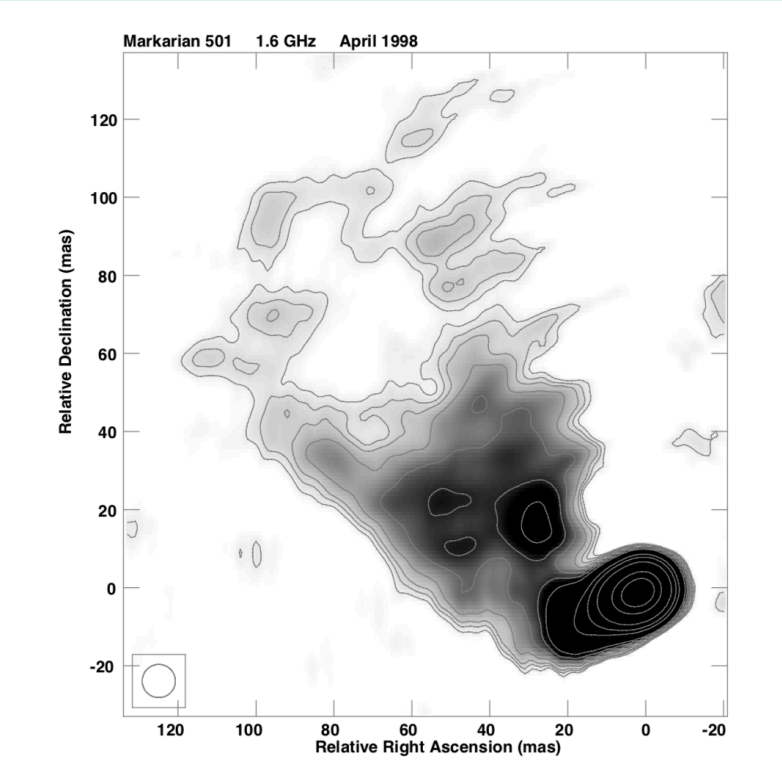

CenA: Janssen et al. 2021

Could this be a common feature of AGN jets?

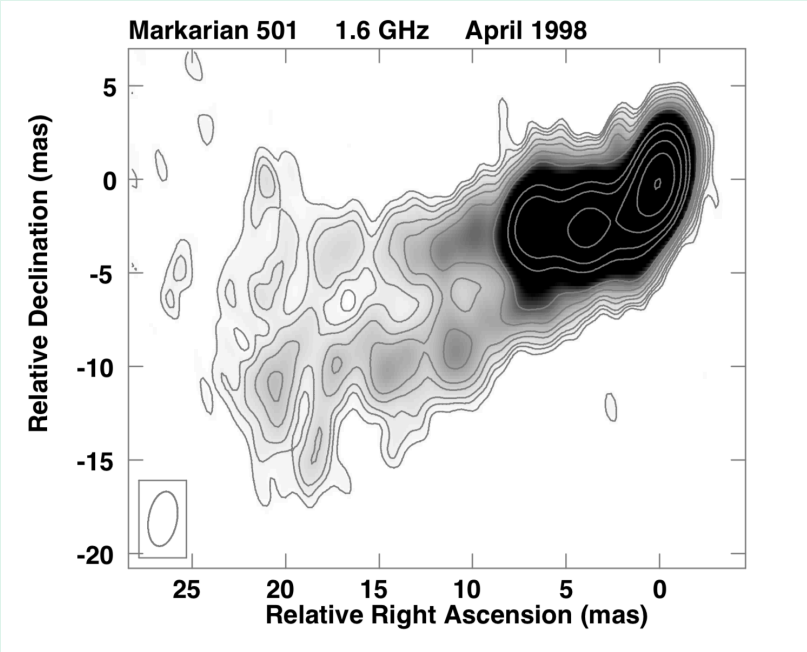
Explanations proposed for this limb brightening include

- Mass loading at edge of the jet
- Kelvin-Helmholtz instability, magnetic reconnection, particle acceleration at edges of jet
- Velocity difference between central spine and slower sheath around jet, with sheath emission beamed toward observer (But Doppler beaming of the sheath/spine emission toward/away from the observer requires a special geometry, and seemingly should not come about as a general rule… )
- Helical field carried by the jet – the synchrotron emissivity is greatest for projected B field in plane of the sky, which arises at edges of the jet (may expect some asymmetry)

In Mrk 501, limb brightening is seen both before and after a large bend in the jet.




Giroletti et al. 2004




Suggests mechanism is related to an intrinsic property of the jet, such as a helical B field, mass loading or particle acceleration at edge of jet.

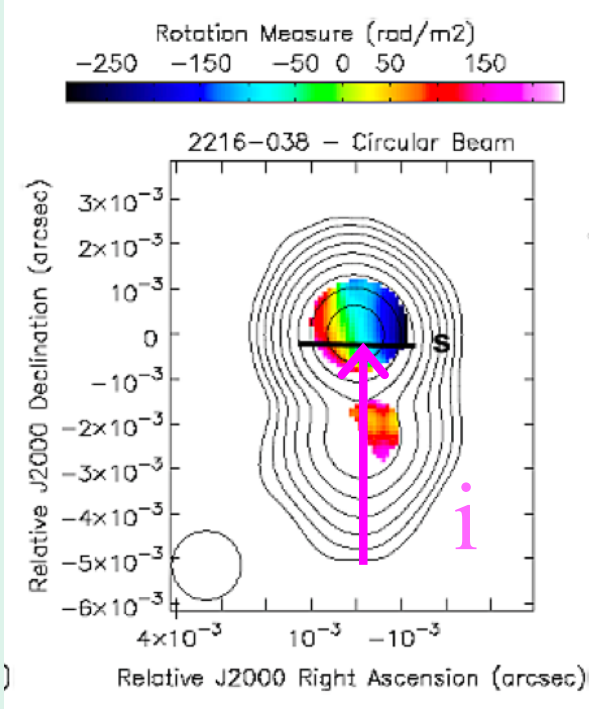
• Observed structures may be due to a combination of inherent and local factors.

• Need theoretical work/simulations to help determine robust ways to identify most plausible mechanisms for particular observed I, P, spectral index and RM structures and correlations between them.

➔ How much can be explained by a helical B field with specified parameters?

➔ What is the possible role of shear with the ambient medium, particle acceleration, Kelvin Helmoltz instability, current-driven instability, and other factors?

# Global patterns in the Azimuthal B-fields/ axial currents of AGN jets




- A transverse RM gradient implies the presence of a toroidal B field component, which has an associated current (right-hand rule!)

- Observed transverse RM gradients can be used to determine if there is a preferred direction for the currents in AGN jets

Parsec scales: observed RM gradients imply a predominance of **inward** currents (Gabuzda et al. 2018)

- 33 out of 47 currents are inward, prob. of coming about by chance is ~0.4%

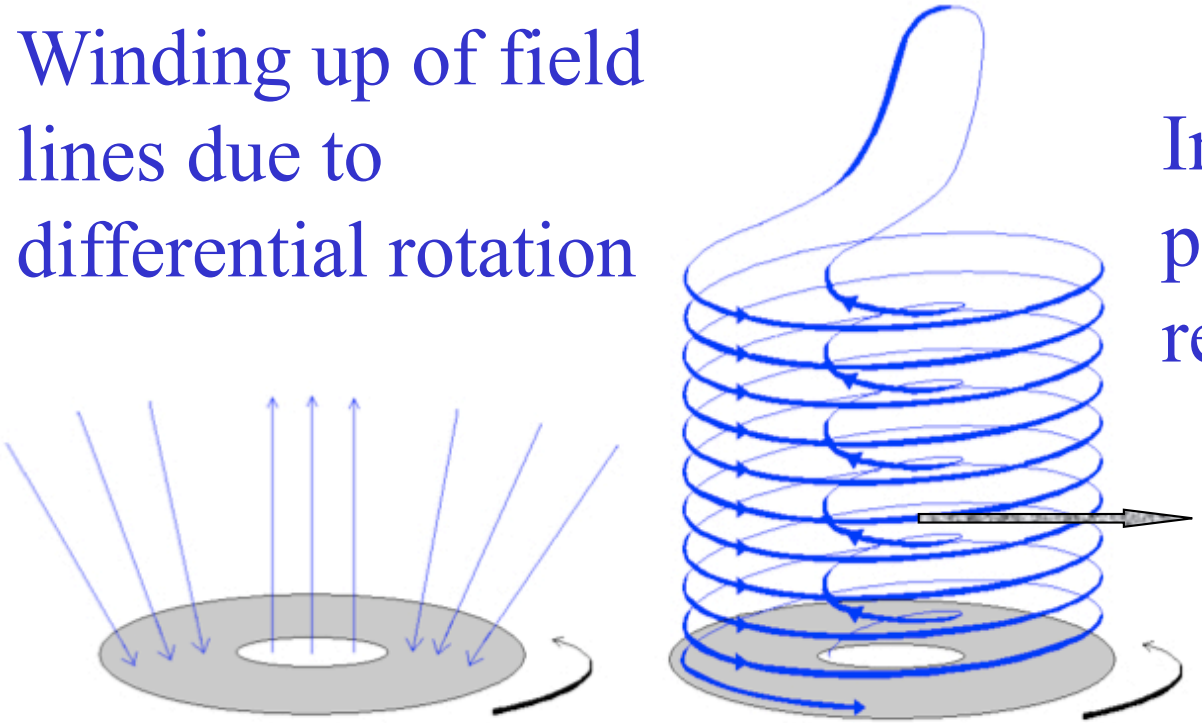
Kiloparsec scales: observed RM gradients imply a predominance of **outward** currents (Knuettel et al. 2017, 2018, 2020)

- 12 out of 12 currents on scales of 20 pc to > 2000 pc are outward, prob. of coming about by chance is < 0.1%

*How can both be true at the same time?*

"Outgoing" B field in jet/inner accretion disc closes in outer disc

Winding up of field lines due to differential rotation

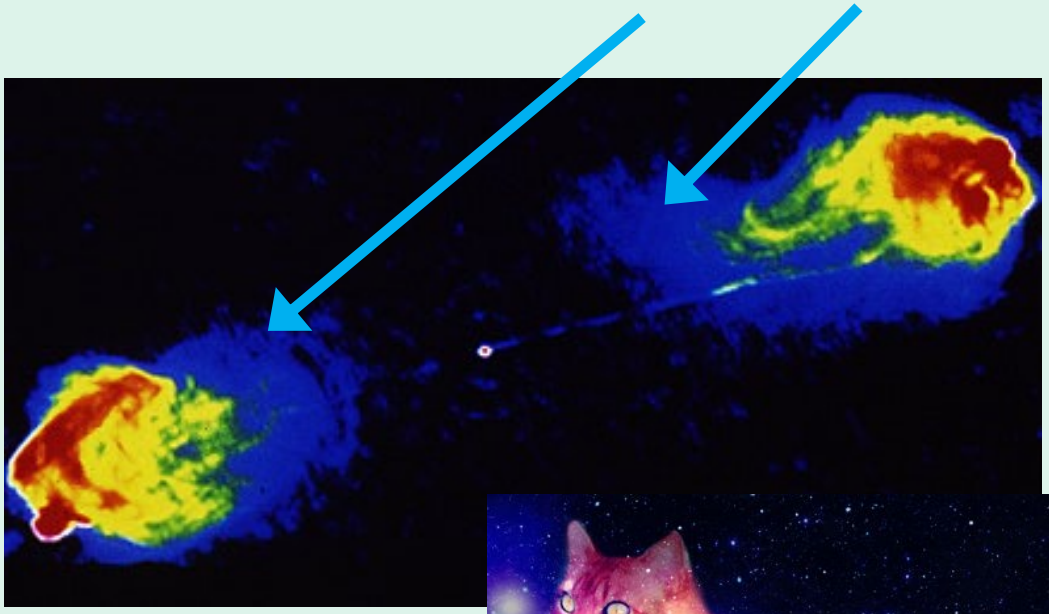


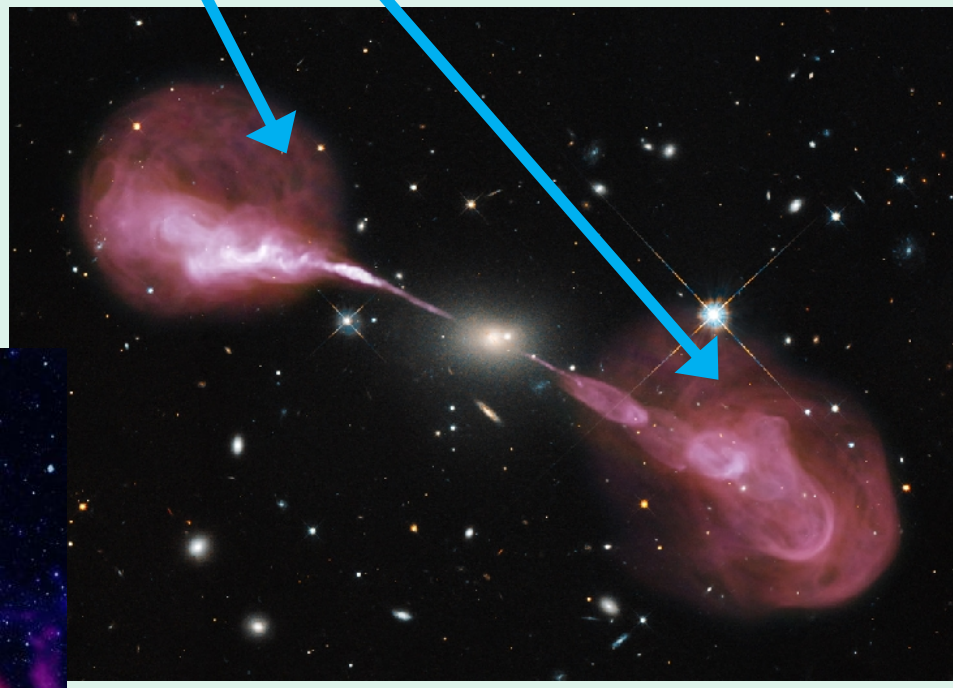
Integration path passes through both regions of helical field

$$\int n_e B \bullet dl$$

Presence of a "return field" in a more extended region surrounding the jet forms a nested helical-field structure

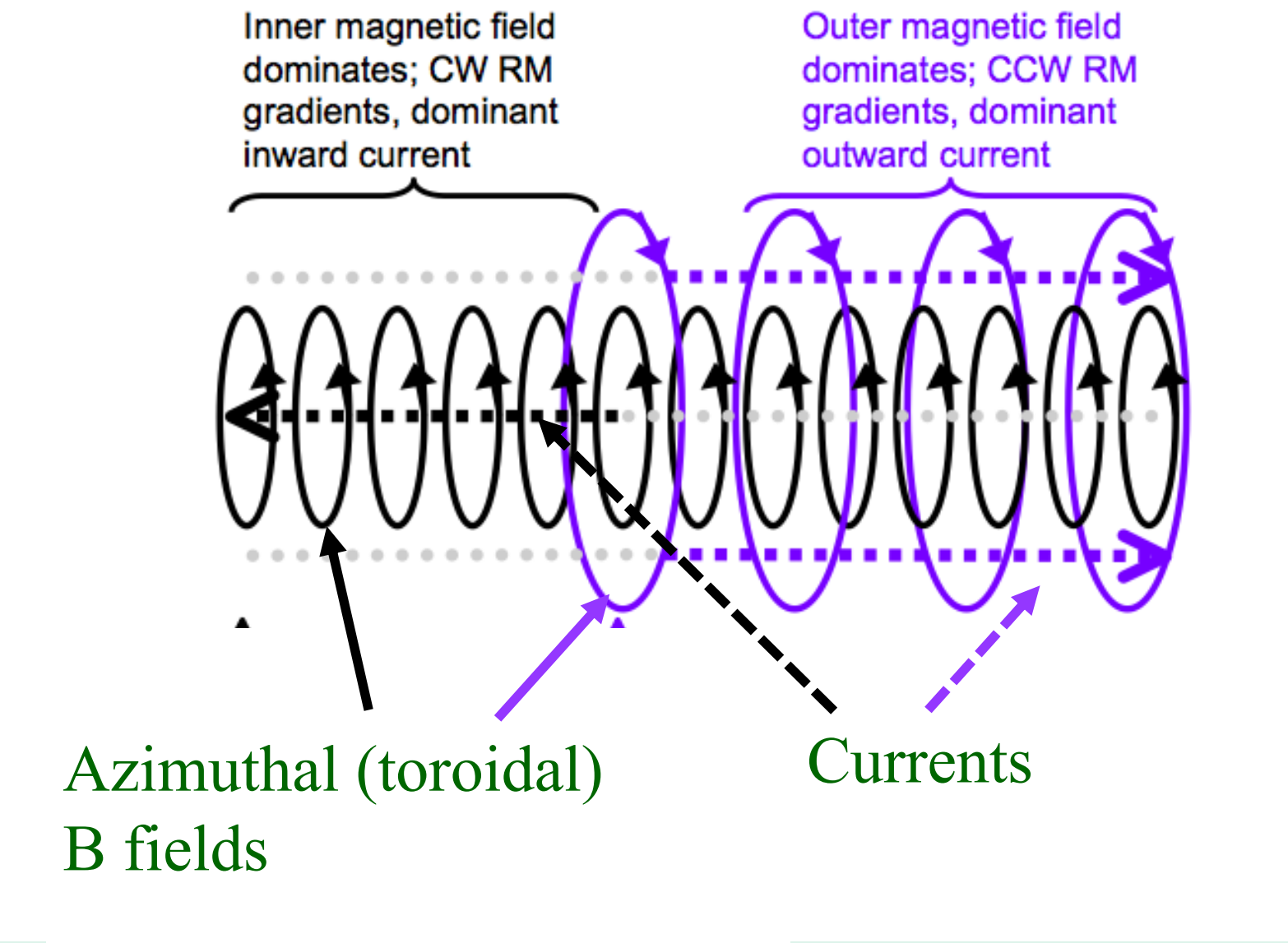
Might regions of “backflow” visible in radio images of radio galaxies carry the “return field” and “return current”?





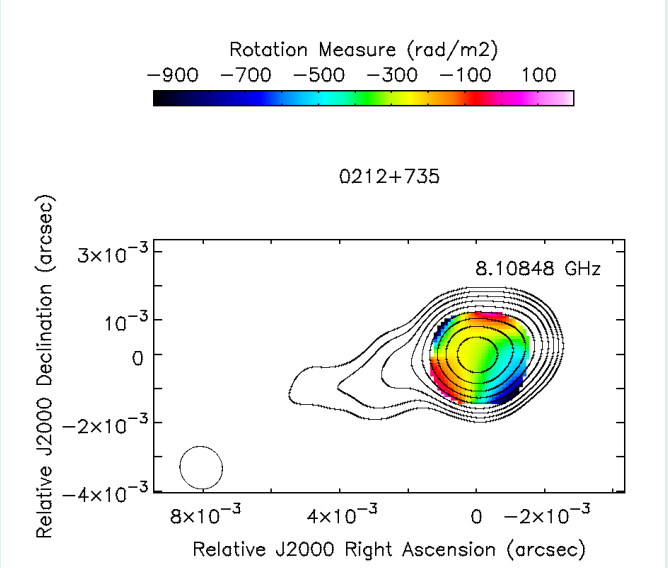
This system of B fields and currents is similar to that of a co-axial cable, with current running inward along the jet axis and outward in a region surrounding the jet (Gabuzda et al. 2018).

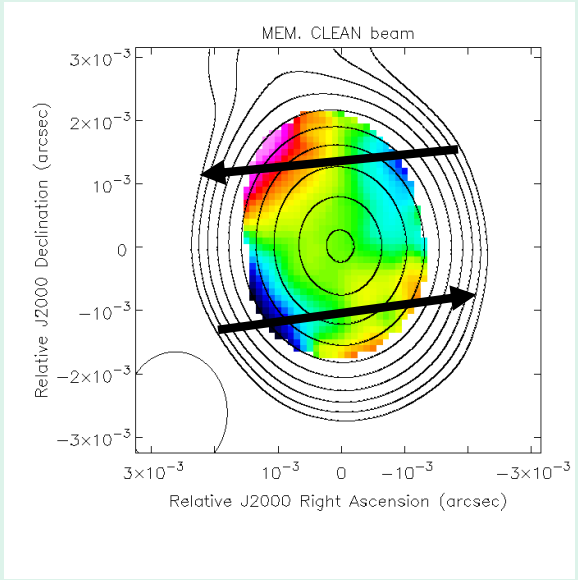
In this case, there should be a distance along the jet where the transverse RM gradient reverses



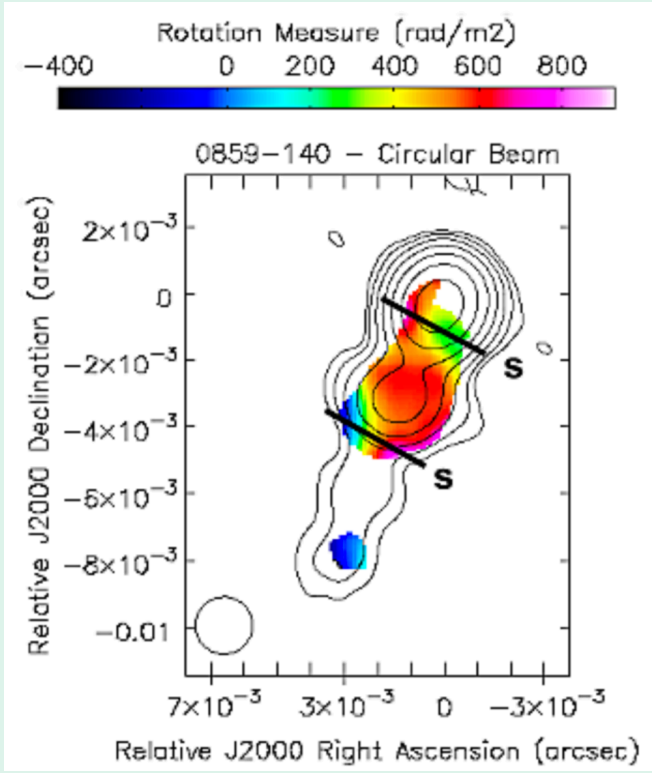
# Reversal of RM gradients directly detected in about 8+ AGN, with several more tentative cases (Gabuzda et al. 2018):

Gabuzda et al. 2018




Mahmud et al. 2013

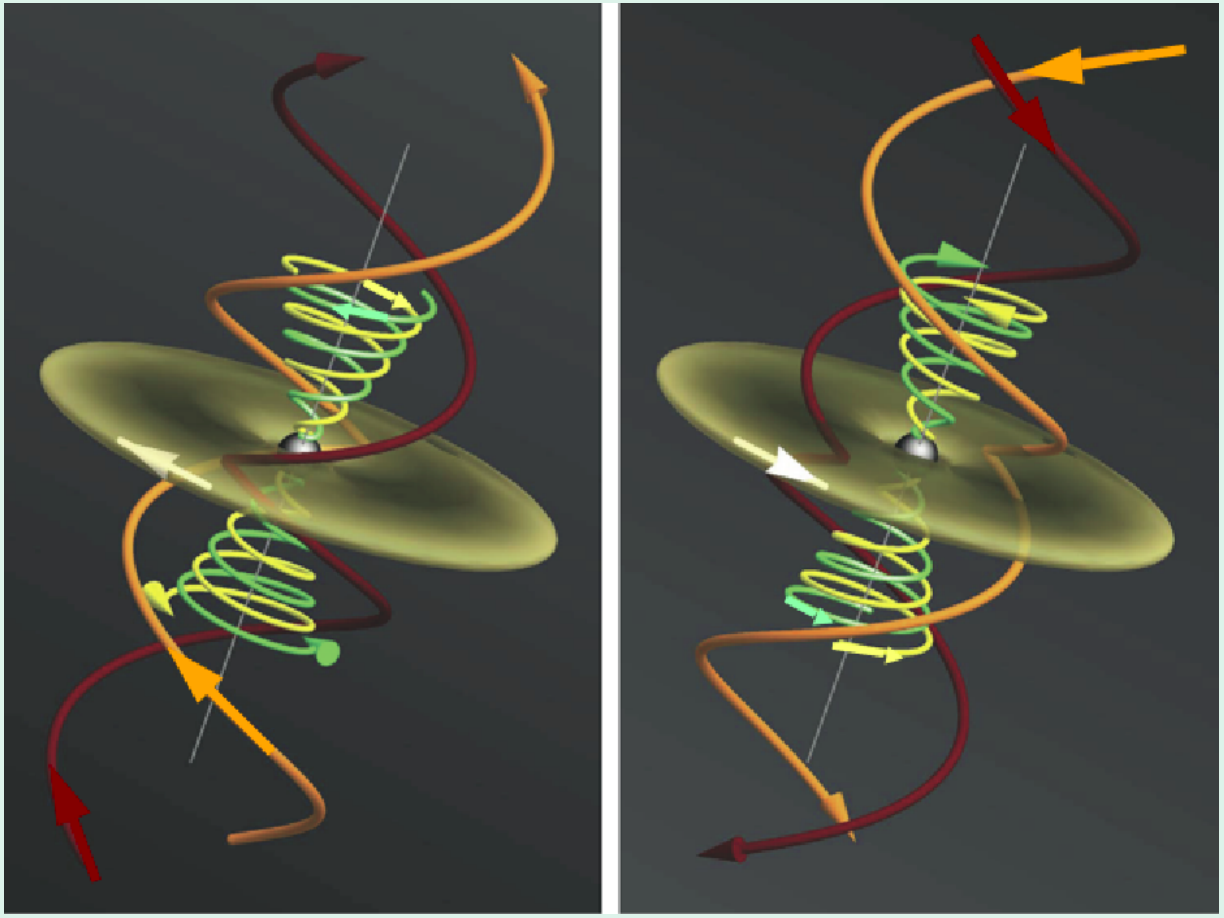



What determines location of transition from dominance of inner to outer helical field is not yet clear.

The “Cosmic Battery” of Contopoulos et al. (2009) predicts inner and outer helical B fields whose toroidal components correspond to inward current near jet axis (smaller scales) and outward current farther from axis (larger scales), as is observed.

*There are certainly other mechanisms that yield a similar system of fields and currents.*

*Needs more work!*



Christodoulou et al. (2016)

**The fact that there is a preference for inward current along the jet axis must be telling us something very fundamental about the jets.**

Could this provide evidence for an admixture of protons in the jet plasma, such that the inward current is provided by a lower outflow velocity of the more massive protons?

In general, we know that the jet plasma moves outward from the jet base. We must identify the forces that lead to different speeds for particles of different signs along the jet!

# Summary

- AGN jets carry helical B fields: predicted theoretically and detected observationally (e.g., transverse RM gradients, transverse pol structure)

- Local effects are superposed (shocks, shear, turbulence, etc), and may sometimes be dominant – need to develop robust approaches to disentangling different factors!

- Overall configuration of fields/currents is like a giant co-axial cable: inward current along axis, outward current farther from axis, with nested helical fields

***Take-away ideas:***

- *The jets are fundamentally electromagnetic structures with inward currents along the jet axes!*
- *We need to more closely connect theoretical ideas/models and observations, so that we are "playing with a full deck" when trying to interpret observations.*

# *Thanks for your attention! Any questions?*


*Thanks to Kazi Rygl for sending me this cartoon!*