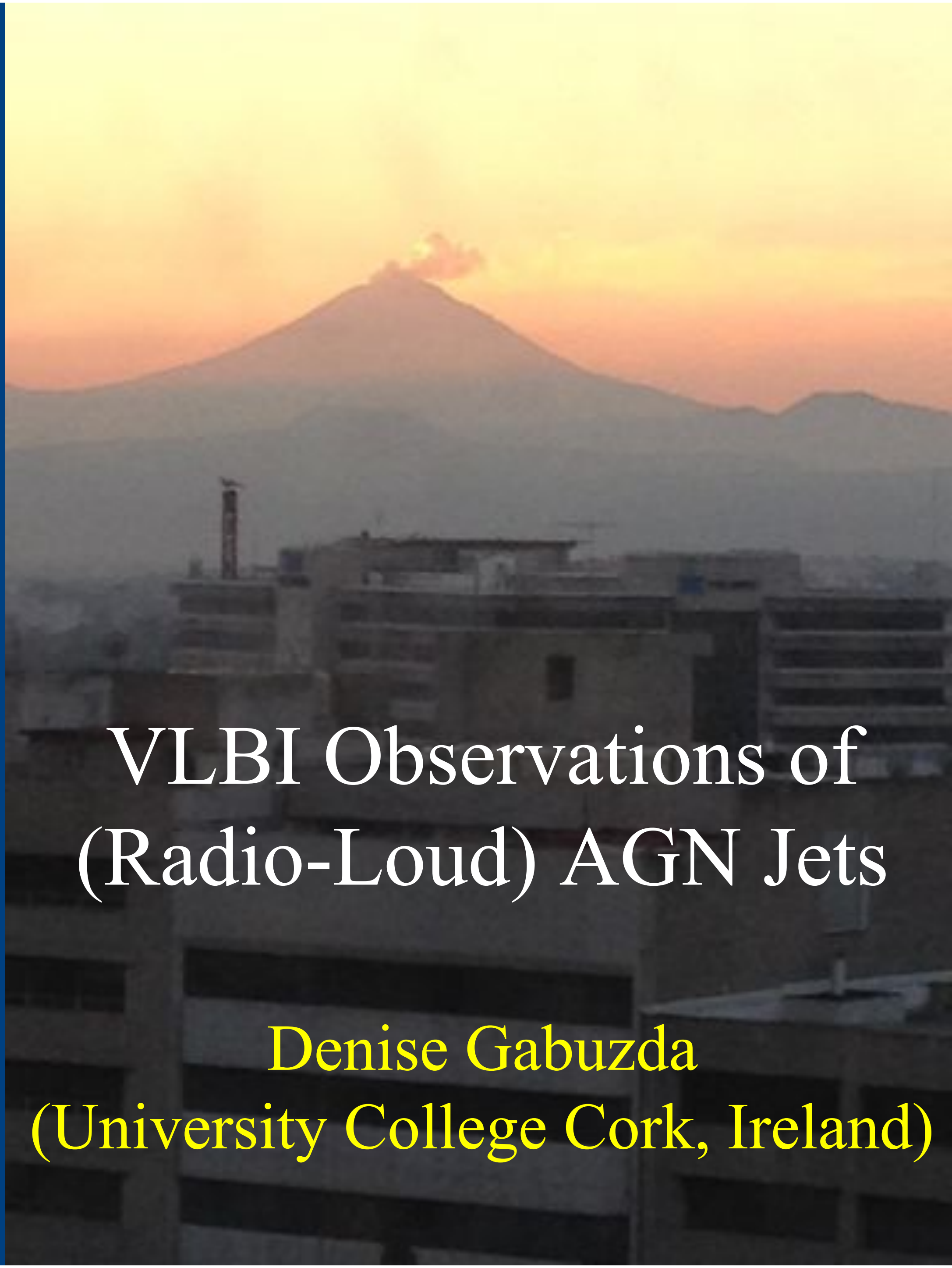


VLBI Observations of (Radio-Loud) AGN Jets

Denise Gabuzda
(University College Cork, Ireland)

Outline of talk

- Some basic physics of AGN jets
- Linear polarization properties/B fields of AGN jets
- Faraday rotation

Some basic physics

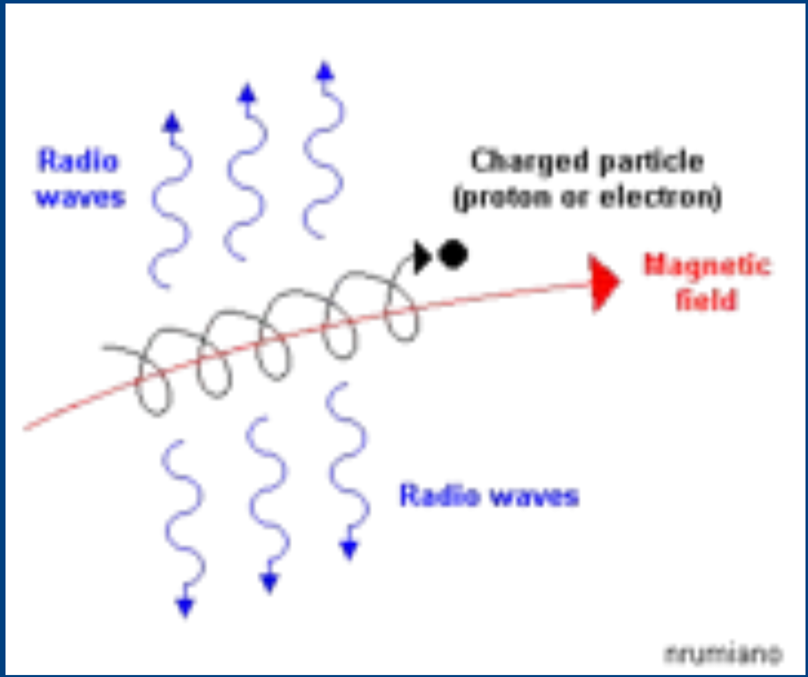
of AGN jets

Active Galactic Nuclei (AGN): extremely compact, generate much more energy than a normal galaxy.

Activity due to accretion onto a supermassive (~10^9 solar masses!) black hole

Sometimes eject "jets" of radio-emitting plasma extending far beyond optical (visible) galaxy.

The processes that launch the jets are almost certainly electromagnetic in nature, underscoring the fundamental connection between jets and magnetic fields.



The radio emission from the jets of radio-loud AGNs is synchrotron radiation emitted by energetic electrons accelerated by local B fields.

Evidence for relativistic motion in AGN jets

VLBI images of AGN jets are one-sided due to Doppler beaming (relativistic aberration)

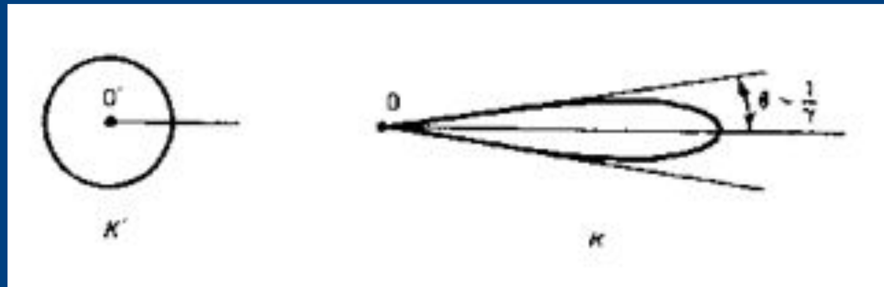
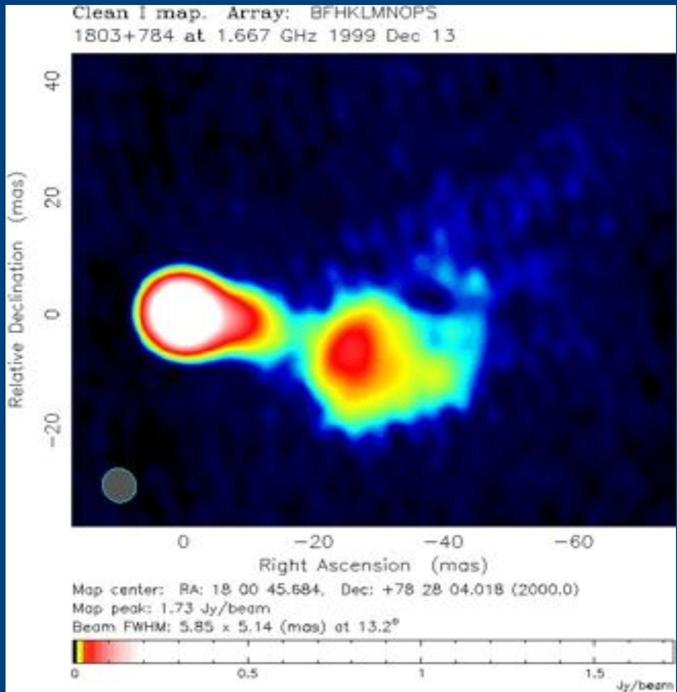
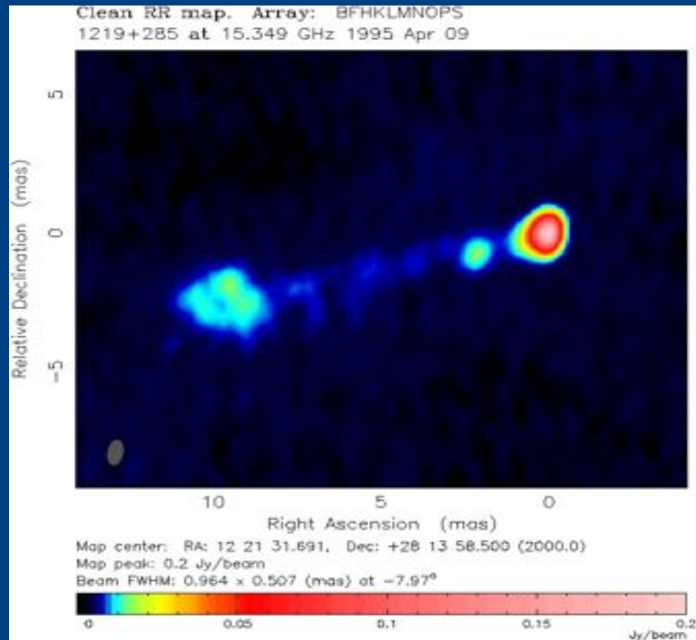


Figure 13: Relativistic beaming





Relativistic aberration for photons

θ = angle in observer's frame

$$\tan\theta = \frac{\sin\theta'}{\gamma(\cos\theta' + \beta)}$$

$$\cos\theta = \frac{\cos\theta' + \beta}{1 + \beta\cos\theta'}$$

θ' = angle in source rest frame

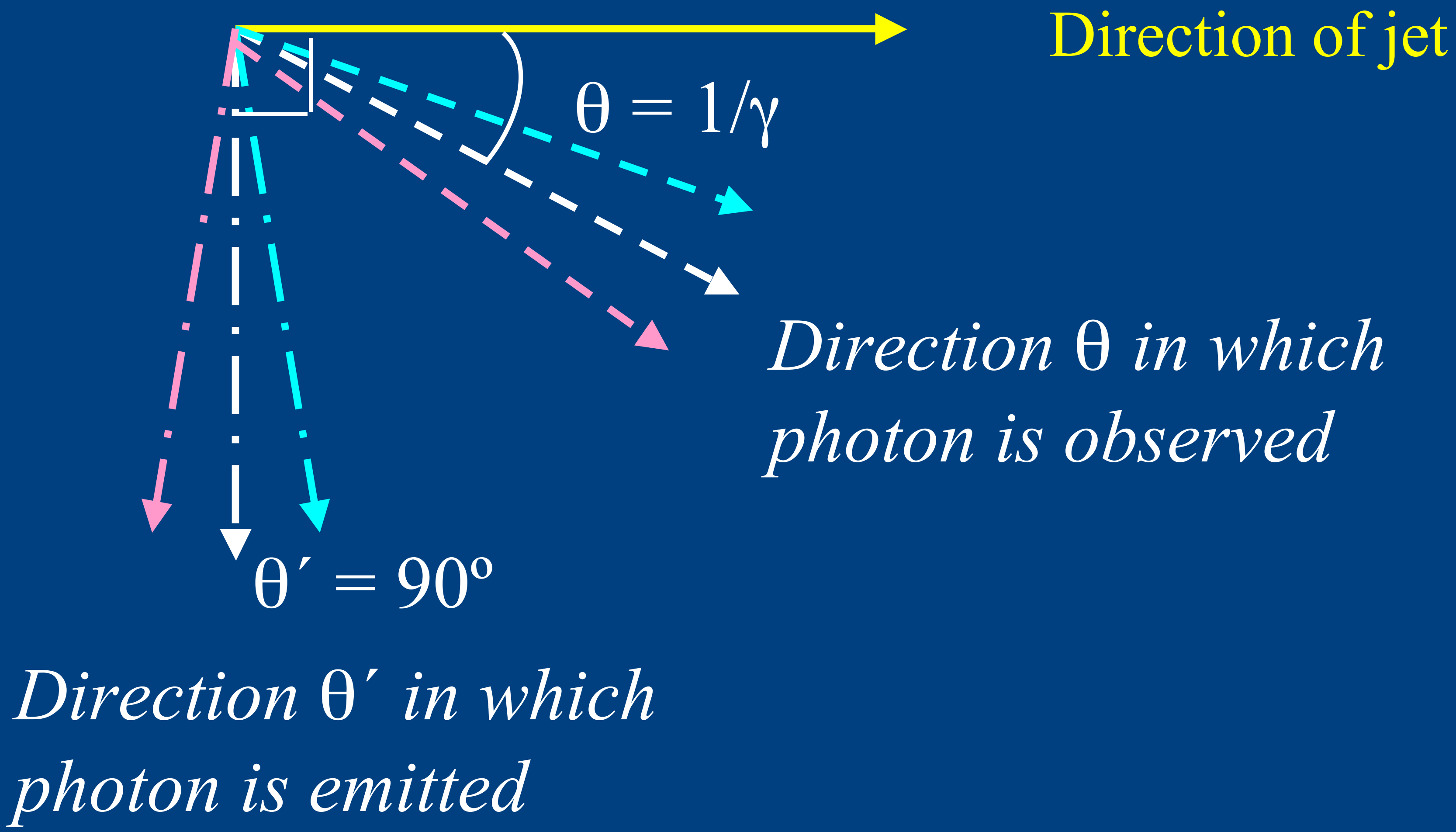
$\beta = v/c$ = relative velocity between frames

When $\theta' = 90°$ (photon emitted at right angles to source motion in source rest frame),

$$\sin\theta \approx \theta = 1/\gamma = \mathrm{sqrt}(1 - \beta^2)$$

When $\theta < 1/\gamma$ then $\theta' < 90°$ ("head-on" view)

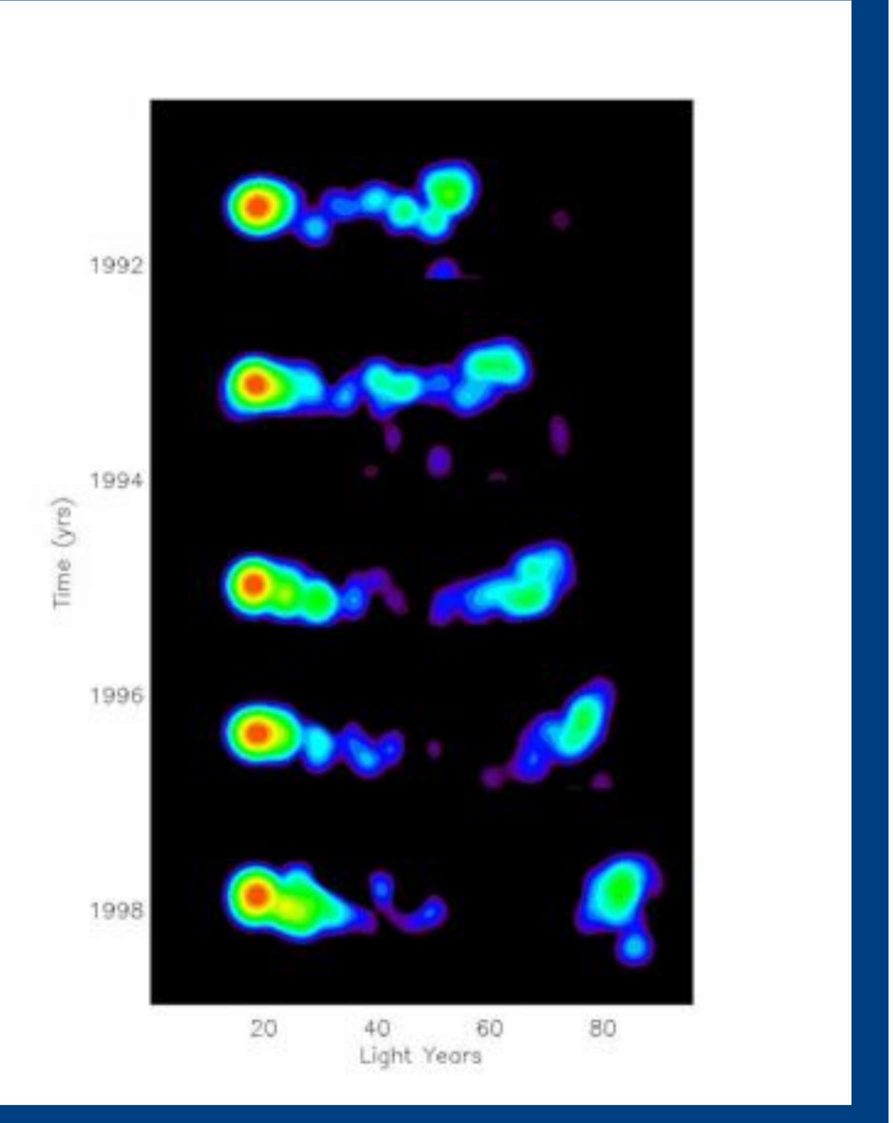
When $\theta > 1/\gamma$ then $\theta' > 90°$ ("tail-on" view)



Something to keep in mind: *radiation arriving at a small angle to the direction of the jet left the source at an angle roughly 90° from the direction of the jet.*

Evidence for relativistic motion in AGN jets

Series of images show apparent superluminal motion, due to highly relativistic motion close to line of sight.



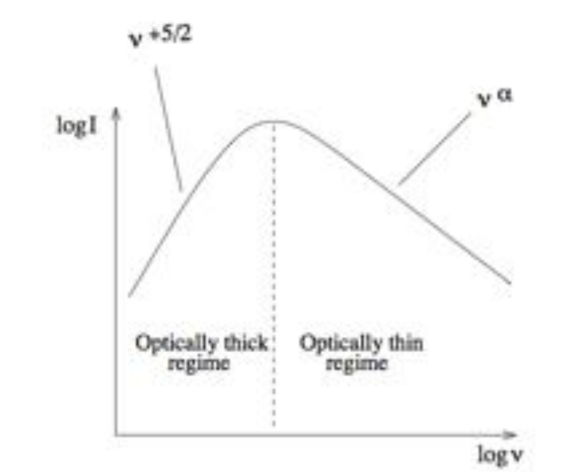
Apparent observed speed is:

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

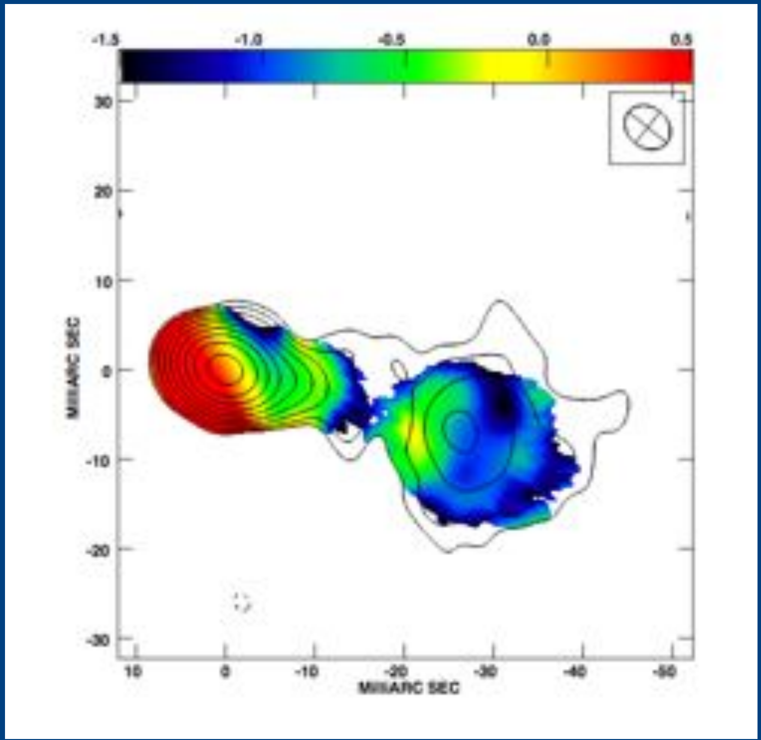
Where β is v/c and θ is angle of the jet to the line of sight.

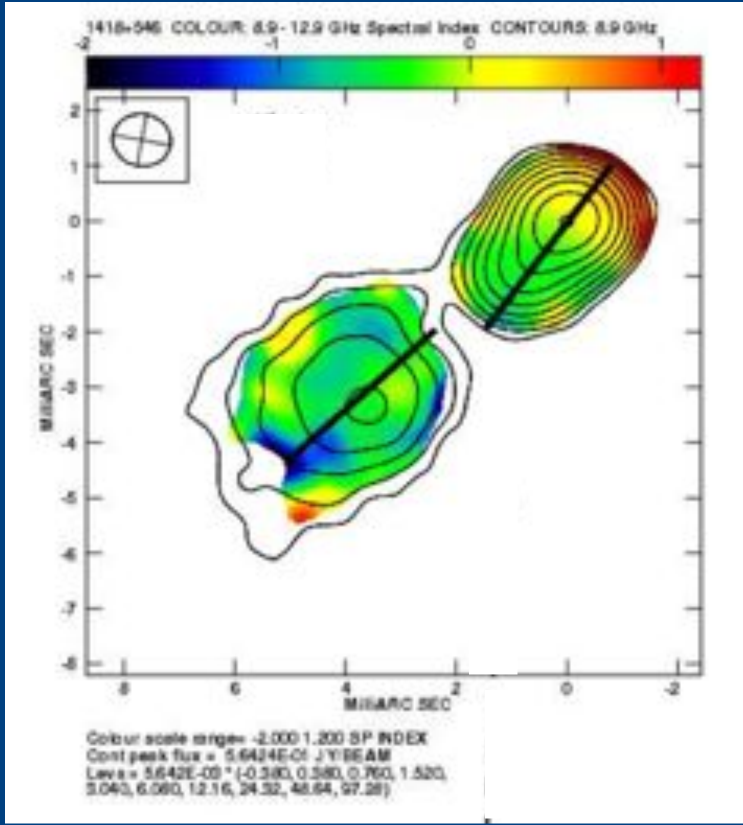
Spectral indices

Core has spectral index $\alpha \sim 0$ or slightly positive (partially optically thick)



Jet has $\alpha \sim -0.7$ (optically thin)





Analysing the dynamics of a cloth model of a core –jet source in a magnetic field.

Linear polarization properties/ B-Fields of AGN jets

For optically thin regions

B field projected onto the sky

$B \perp \chi$

Plane of linear polarization

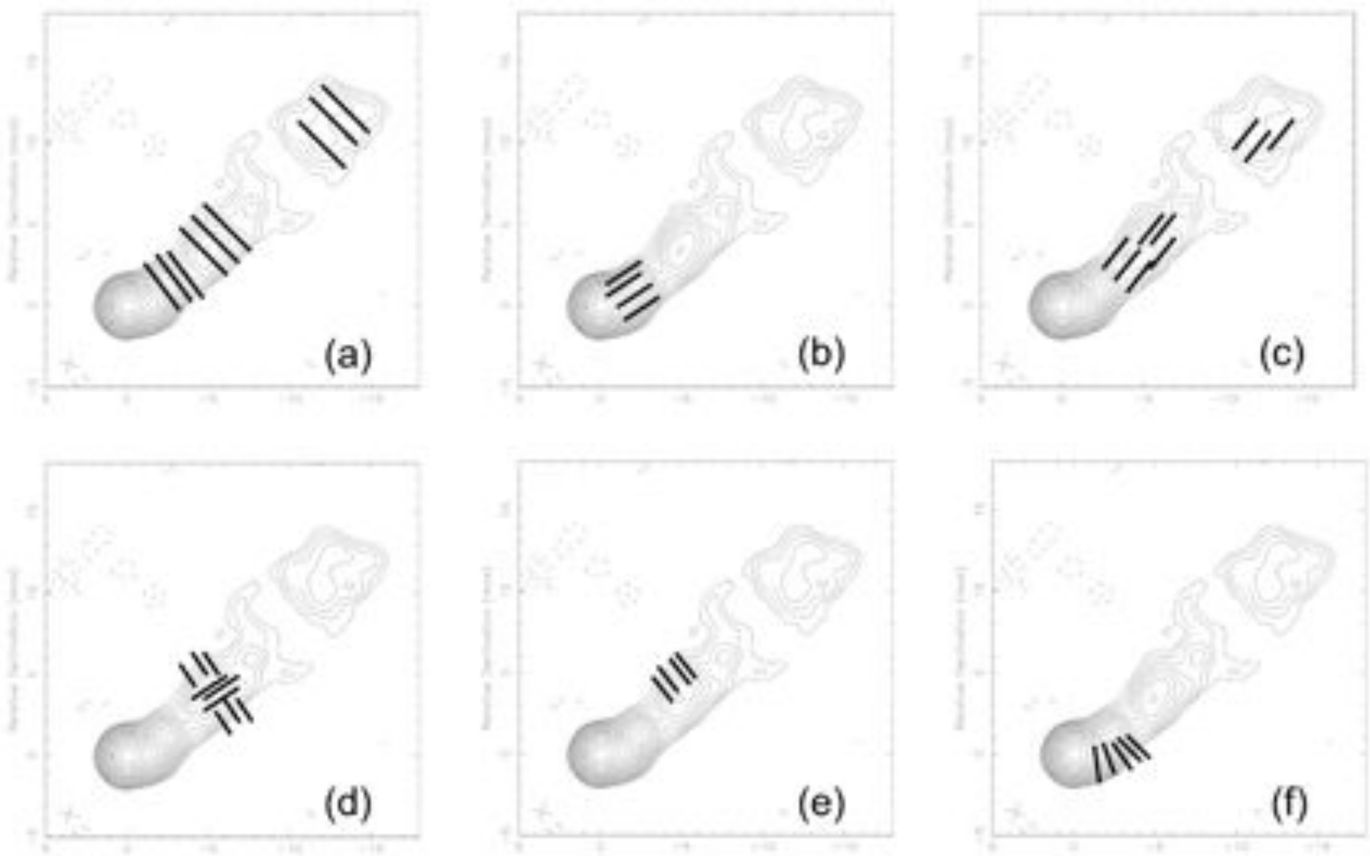
Degree of linear polarization depends on the degree of order of the B field in the plane of the sky:

0% = completely tangled field

70% = completely ordered field, random distribution of electron velocities.

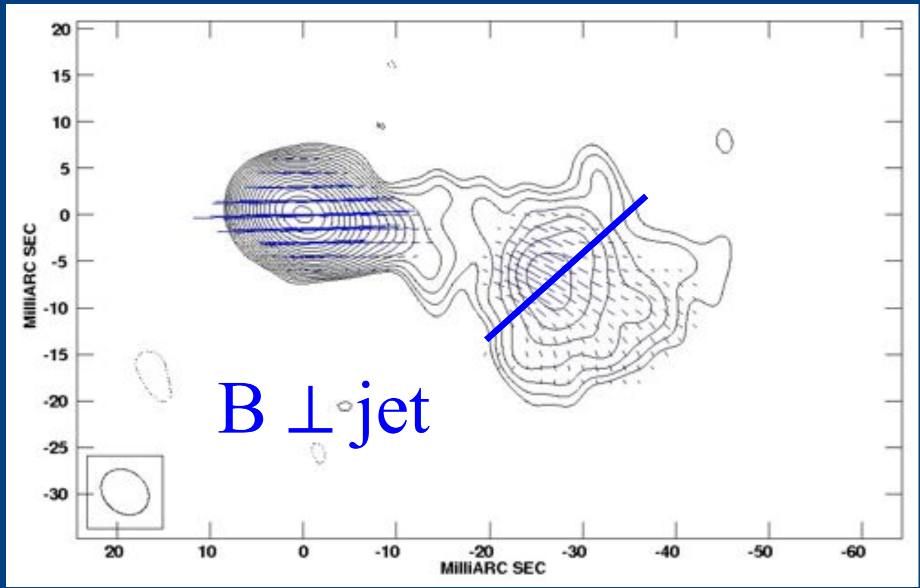
In a truly optically thick region, χ becomes parallel to B – but core regions are only partially optically thick, and in vast majority of cases, $\chi \perp$ B in both jet and core (Wardle 2018).

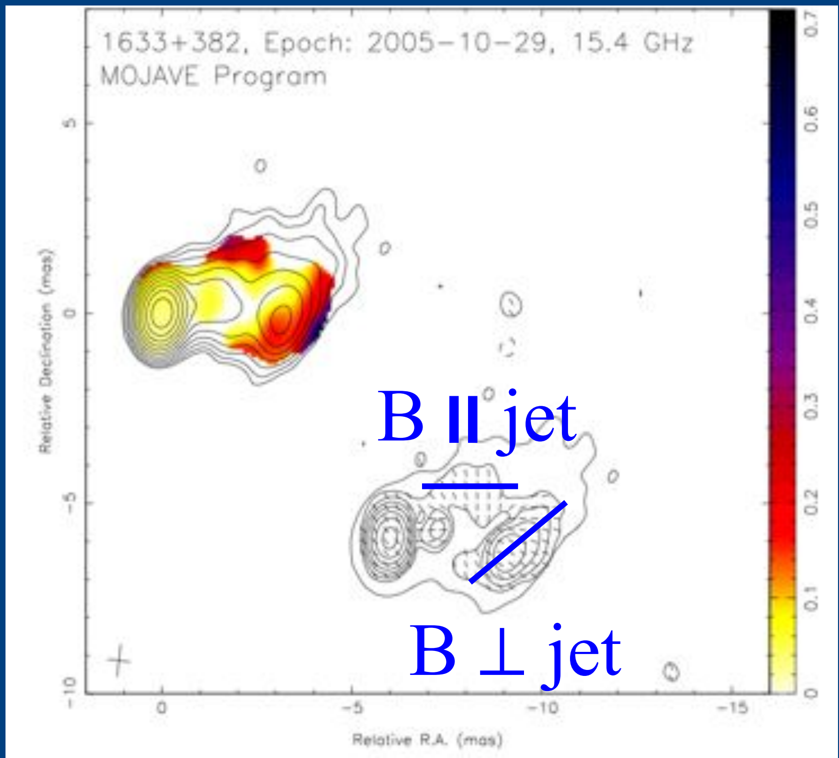
Polarization patterns observed for AGN jets on VLBI scales

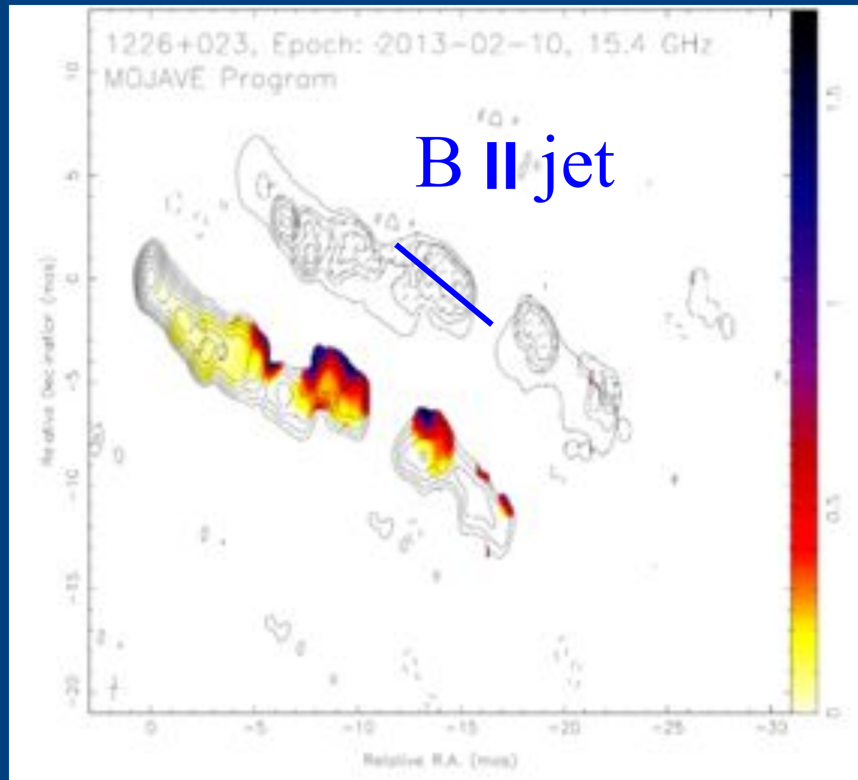


Contour map taken from the Mojave website, sticks added to illustrate various observed polarization patterns (Gabuzda 2014)

Some real examples

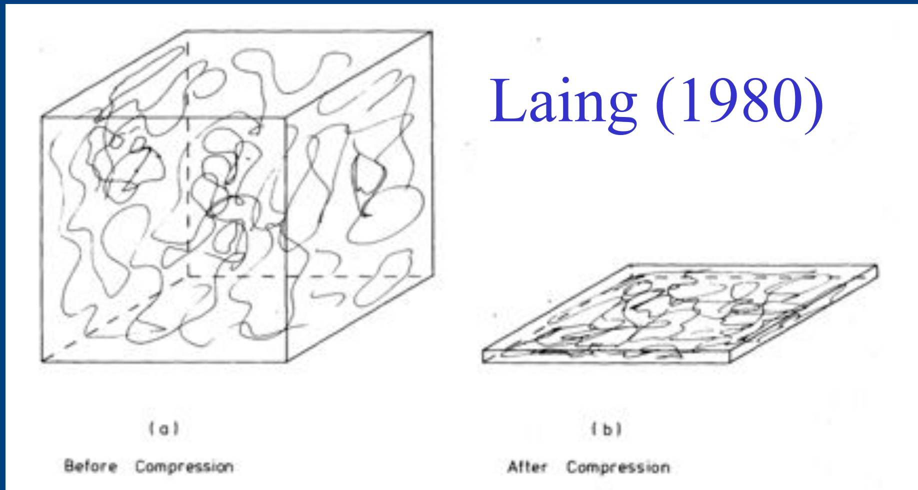






Mechanisms for generating B fields ⊥ to jets

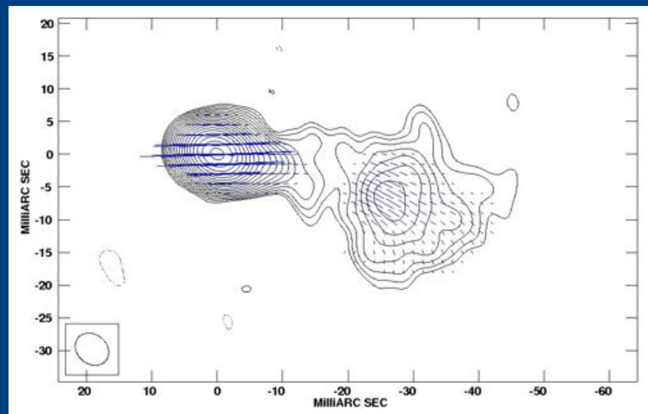
1) Transverse shocks — compress initially tangled B field, field becomes ordered in plane of compression



(If viewing jet at close to 90° in source rest frame, will be viewing roughly along plane of compression)

Advantage: shocks can also help explain variability

Disadvantage: not natural way to explain extended regions of orthogonal B field



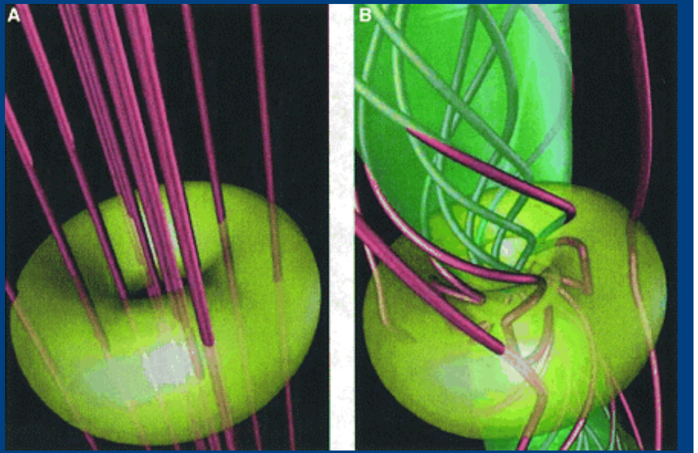
Cats imitating a tangled magnetic field.

Mechanisms for generating B fields ⊥ to jets

2) Helical B fields with relatively large pitch angles

Advantages:

Could come about naturally through rotation of central accretion disk + outflow



Could explain extended regions of orthogonal B field

Disadvantage: cannot help explain variability

Mechanisms for generating B fields || to jets

1) Shear interactions with ambient medium

$\Rightarrow$

Advantage: can explain enhanced longitudinal B field at jet edges, and extended regions of longitudinal B field, if shear is present all along jet

Disadvantage: local, no direct measurements of velocity gradient toward edge of jet available

Mechanisms for generating B fields || to jets

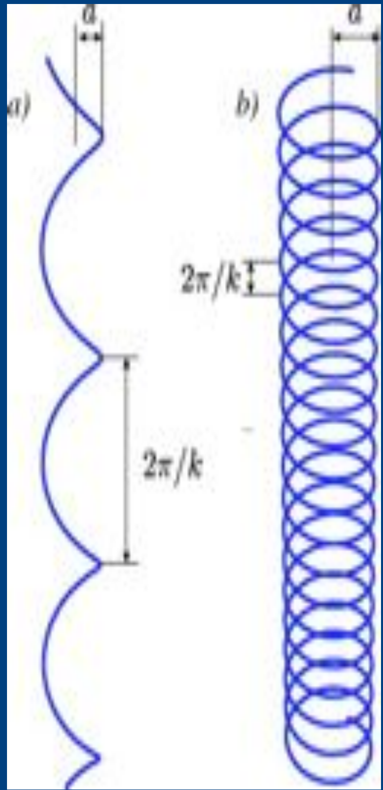
2) Helical B fields with relatively small pitch angles

Advantages:

Could come about naturally through rotation of central accretion disk + outflow

Could explain extended regions of longitudinal B field

Can explain enhancement of longitudinal B field at jet edges (predicted for helical fields)



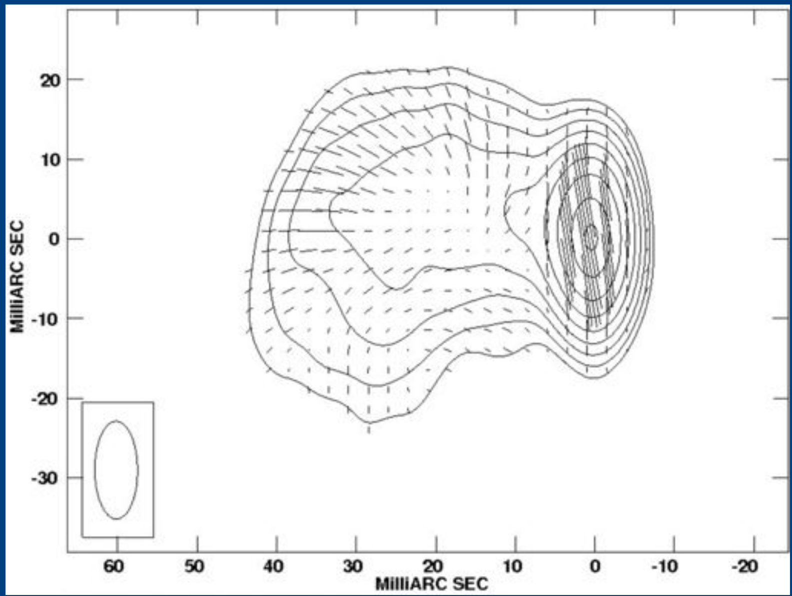
Mechanisms for generating B fields || to jets

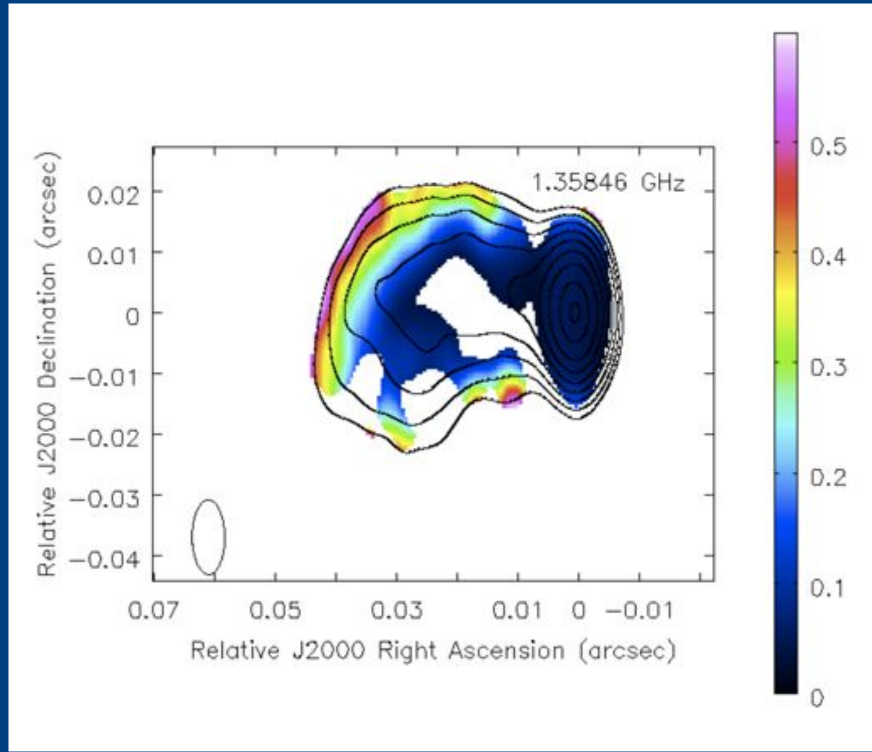
3) Curvature of the jet

Enhances longitudinal B field component at outer edge of bend (example here is for helical field).

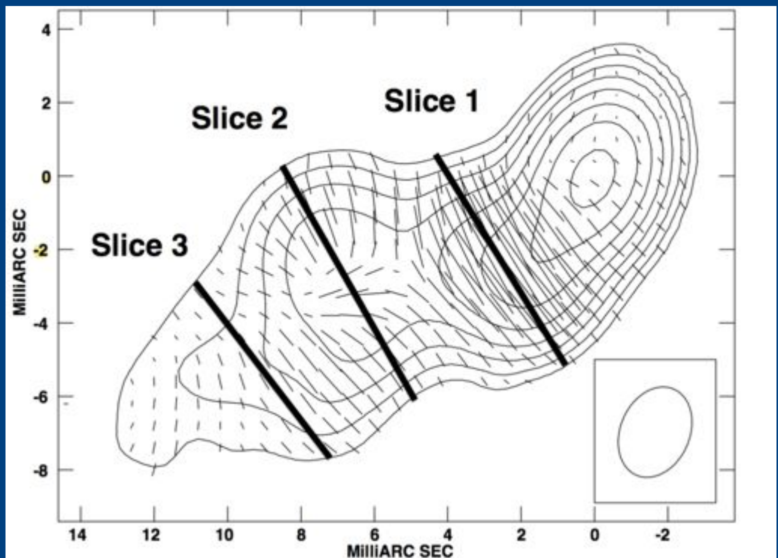
We are Cork.

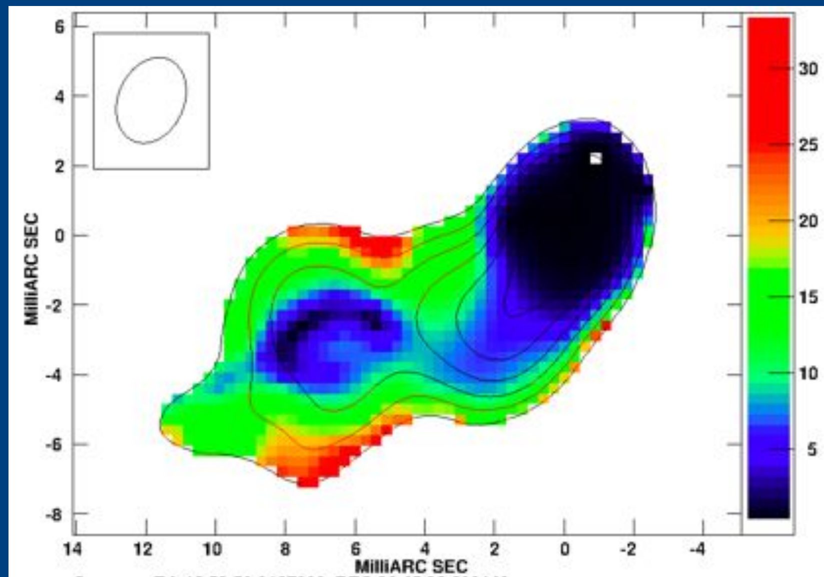
Diagnostic: should have longitudinal B field, higher degree of polarization along outer edge of jet bend


MilliARC SEC
MilliARC SEC


1.35846 GHz
Relative J2000 Declination (arcsec)
Relative J2000 Right Ascension (arcsec)

√


Slice 1
Slice 2
Slice 3
MilliARC SEC
MilliARC SEC


MilliARC SEC
MilliARC SEC

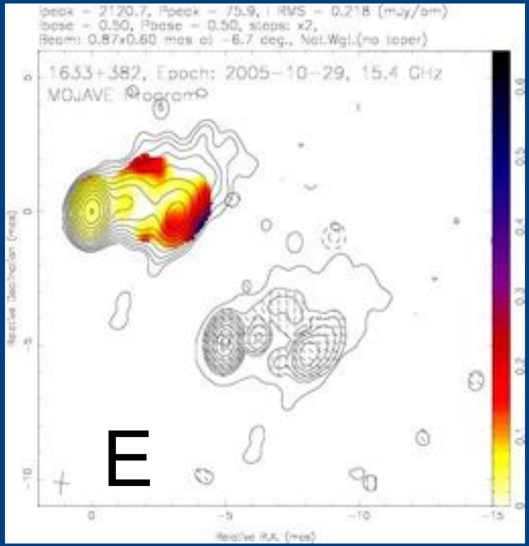
X

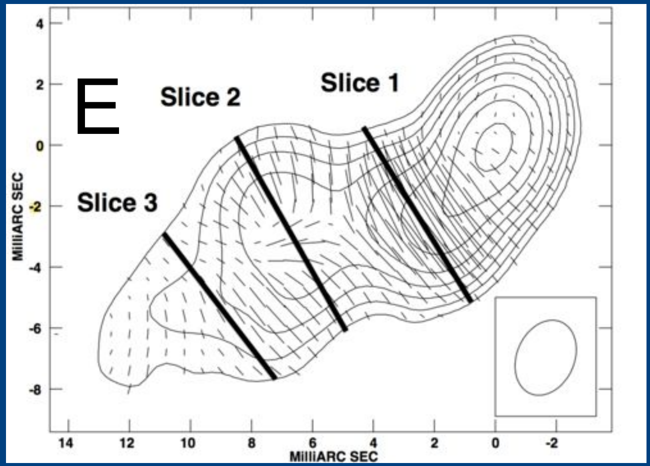
Tendencies for B-field structures in AGN jets

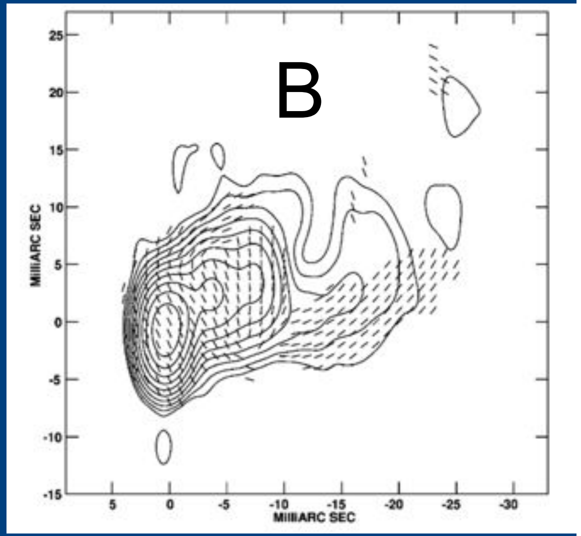
- Most complete studies carried out using MOJAVE sample (Monitoring Of Jets in AGN with VLBA Experiments) [e.g. Lister & Homan 2005, see also other pubs on MOJAVE website]
- Core B fields often either $\perp$ or $\parallel$ jet direction, but can also have arbitrary orientations
- Jet B fields are predominantly $\perp$ or $\parallel$ jet direction

Other types of B field structures

"Spine+Sheath"

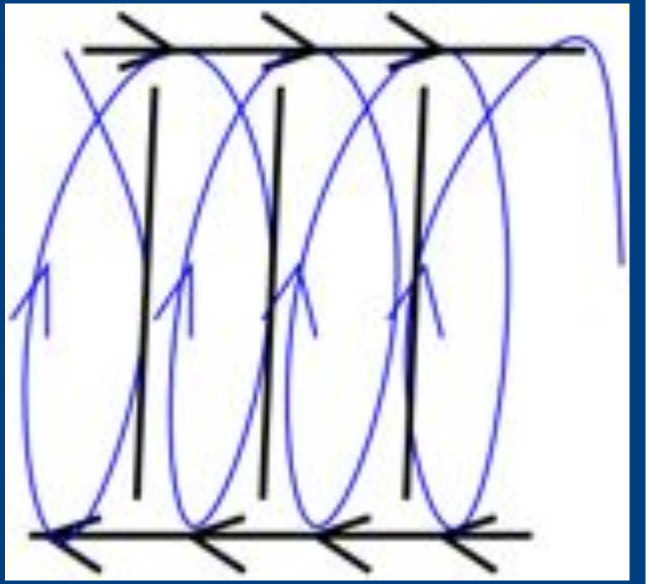




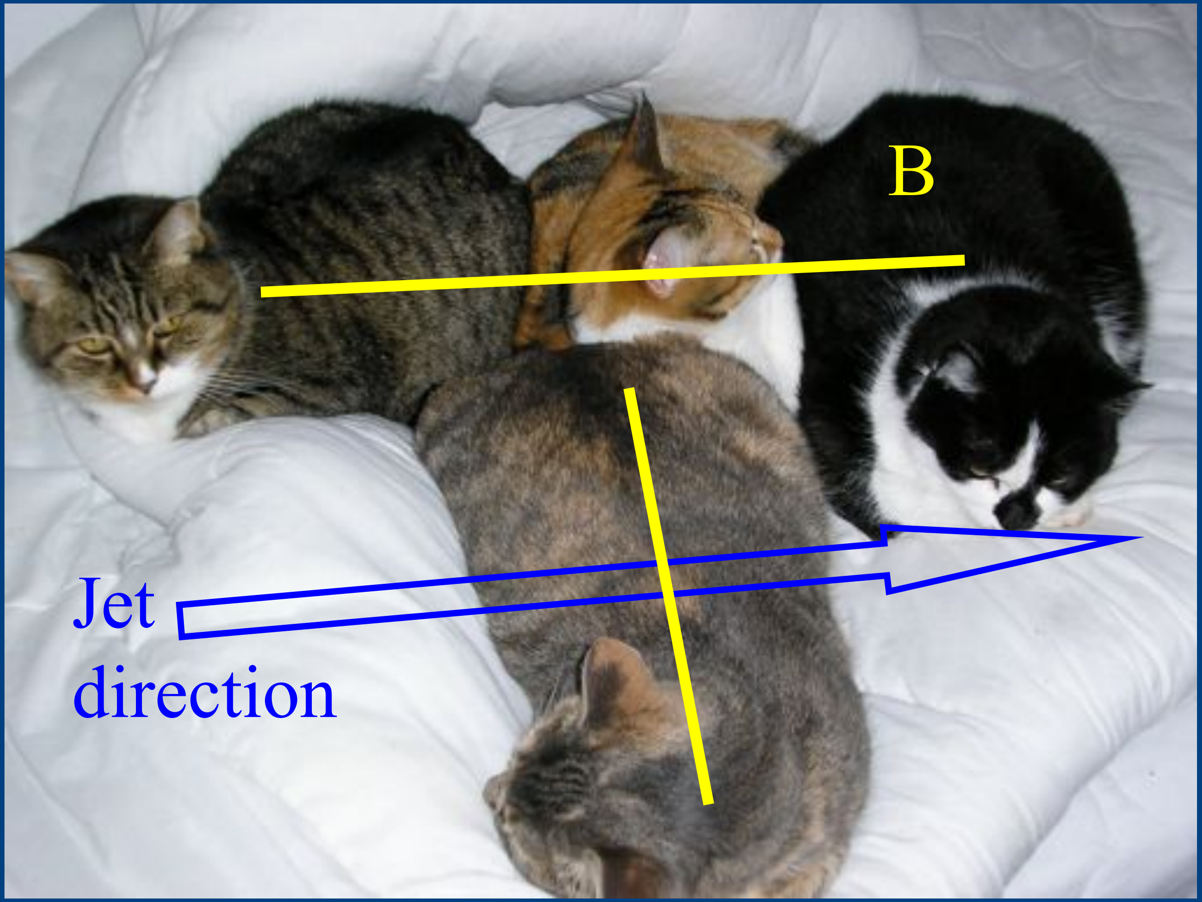


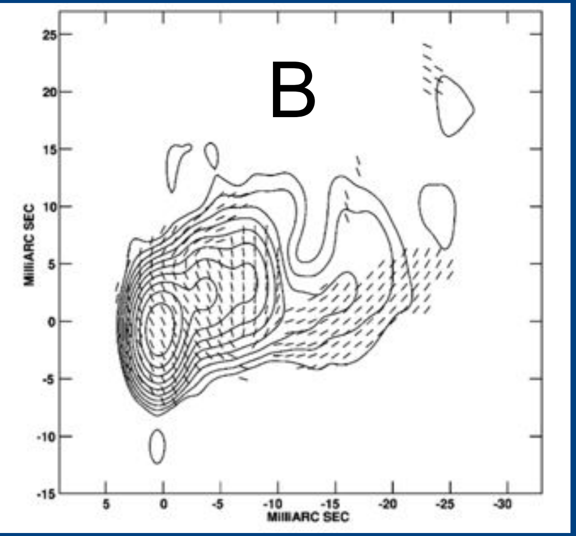
Competing mechanisms:

- Shocks + shear (Attridge et al. 1999)
- Helical B fields (Pushkarev et al. 2005; see right)



Helical B fields provide a simpler interpretation ("Occam's Razor")!





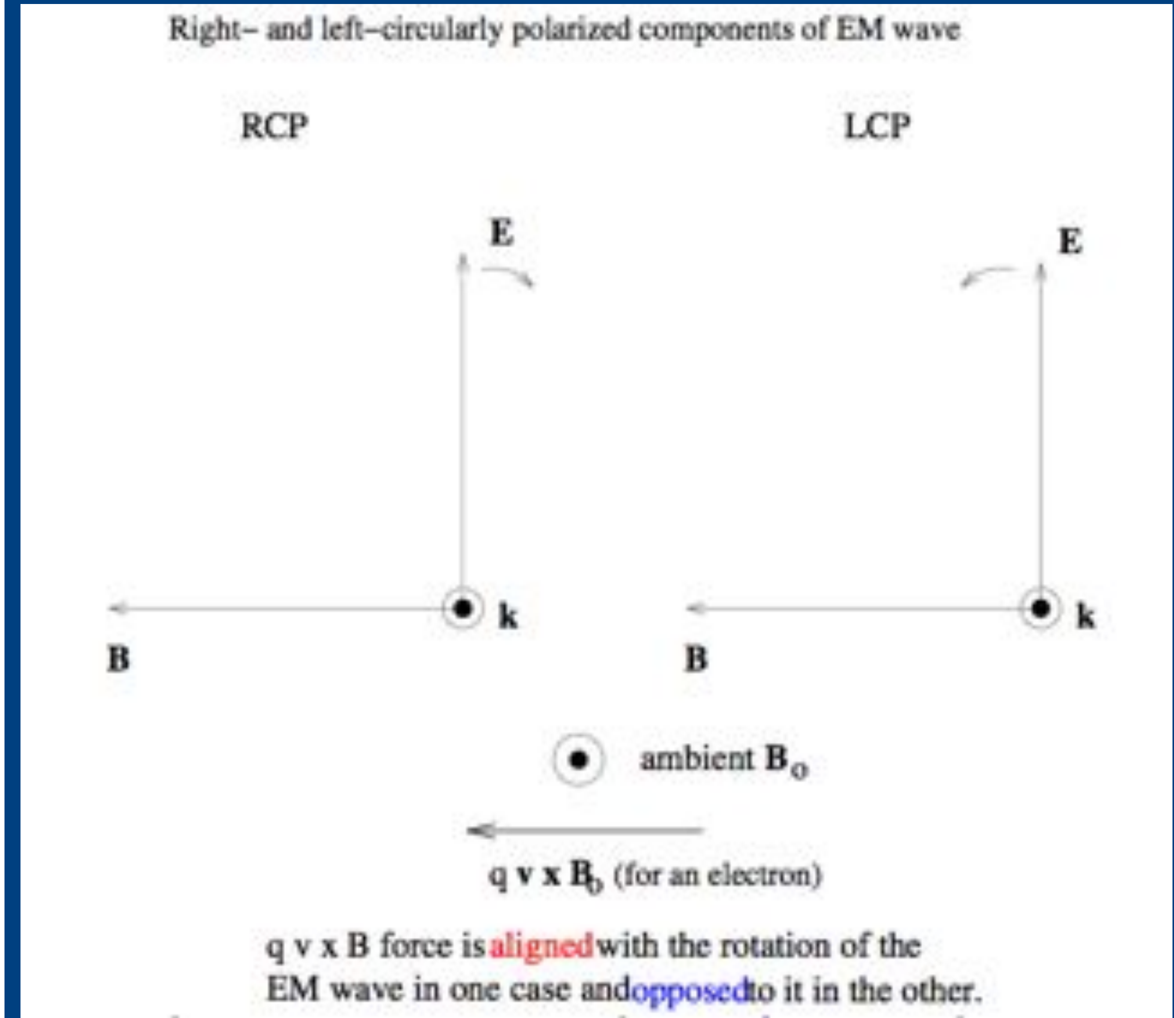
Cats illustrating a partial spine–sheath B-field structure.

Faraday Rotation

Faraday rotation - rotation of plane of linear polarisation that occurs when polarised EM wave passes through region with free electrons and magnetic field (a “magnetised plasma”).

Any EM wave can be described as sum of any two mutually orthogonal components, e.g., right-circular and left-circular polarisations (RCP and LCP).

EM wave propagates towards observer through region with B field aligned with direction of propagation; free electrons move in direction of E, giving rise to a Lorentz force.



RCP and LCP components obtain different velocities due to different direction of Lorentz force on free electrons relative to direction of rotation of E vector.

Equations of motion of electron for RCP and LCP components of EM wave:

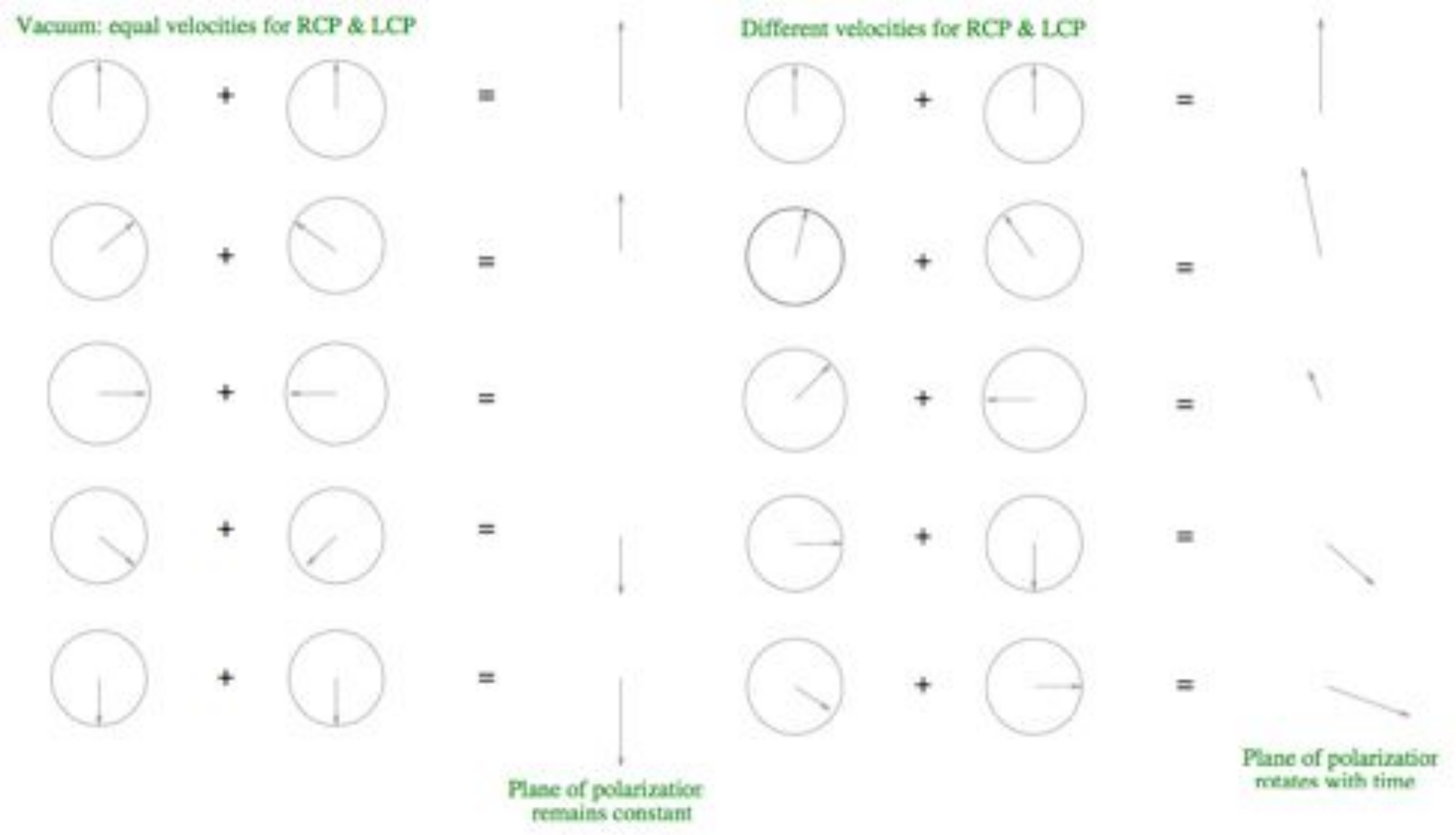
$$-e\vec{E} \pm \frac{eB_o\omega\vec{r}}{c} = -m\omega^2\vec{r}$$

$$\vec{r} = \frac{e}{m}\left(\frac{1}{\omega^2 \pm \frac{eB_o\omega}{mc}}\right)\vec{E}$$

Different indices of refraction for RCP and LCP components of the EM wave in plasma with e⁻ density *n*:

$$\eta = \sqrt{1 - \frac{4\pi n e^2}{m\omega(\omega \pm \frac{eB_o}{mc})}}$$

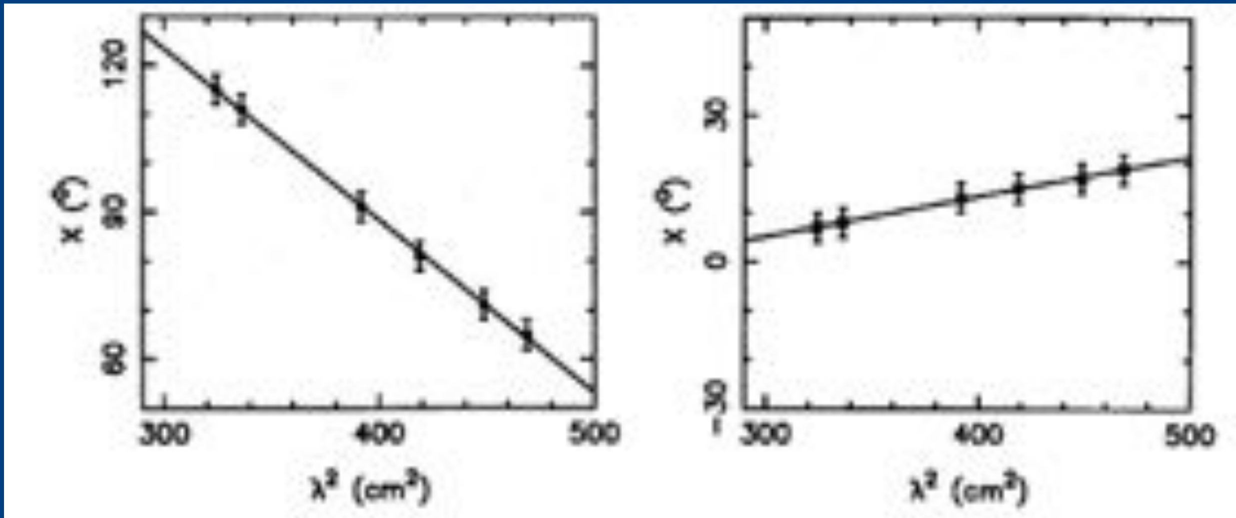
Different speeds of propagation of RCP and LCP componts lead to a rotation in plane of linear polarisation:



Amount of rotation:

$$\Delta\chi = \frac{e^3\lambda^2}{2\pi m^2 c^4}\int n(s)\,\vec{B_o}(s)\cdot ds$$

$$\Delta\chi \propto \lambda^2$$



Integrated Faraday Rotaton of two AGNs observed with the VLA (Wrobel 1993).

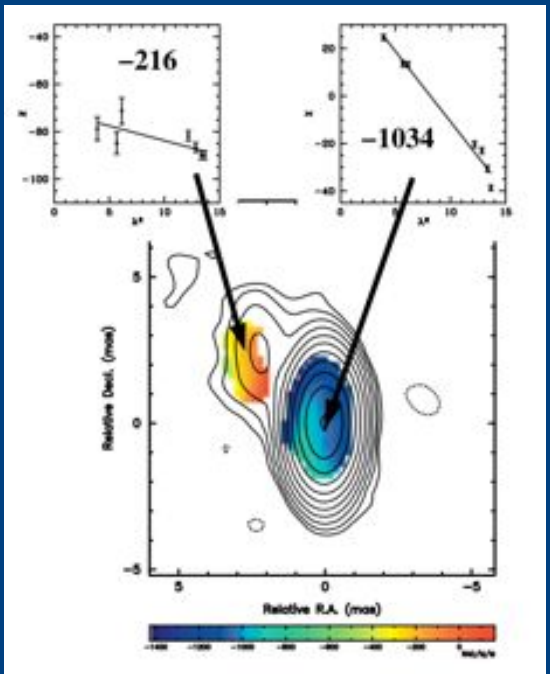
- Linear dependence of rotation of polarisation angle on λ^2.
- Amount of FR depends on n_e and line-of-sight B field
- Line-of-sight component of the ambient B field determines sign of Faraday rotation.

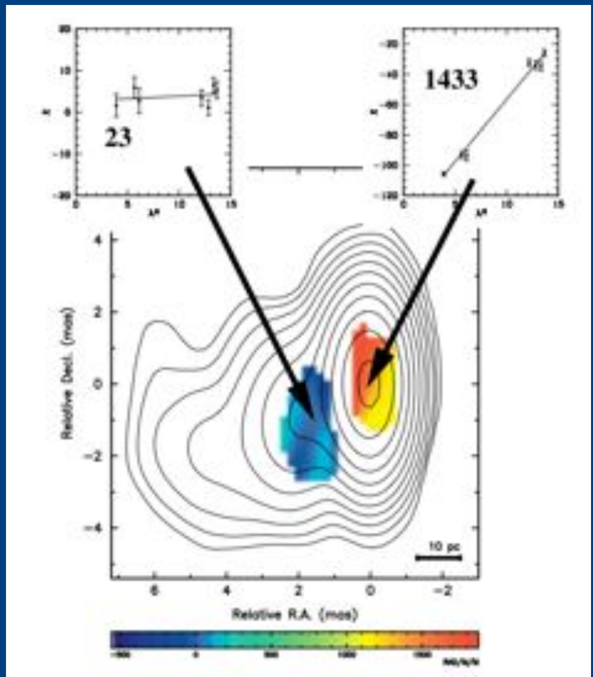
General tendencies

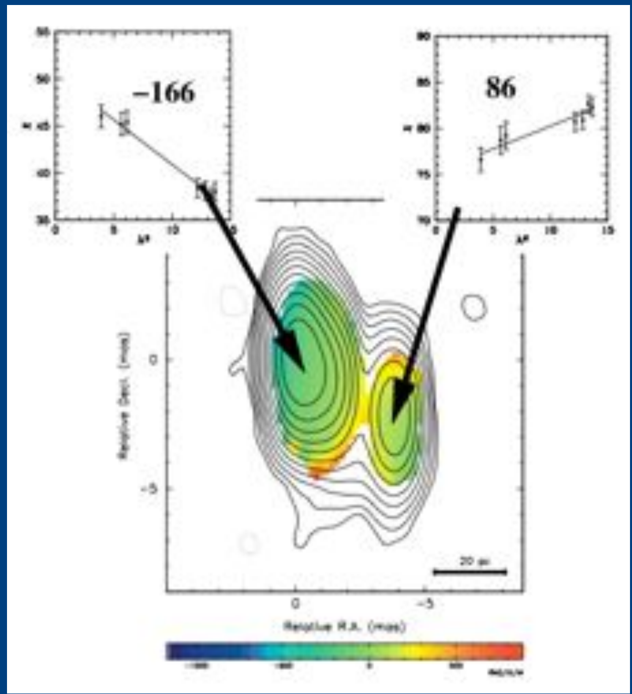
(Zavala & Taylor 2003, 2004; Hovatta et al. 2012)

o Core RM > Jet RM (higher n_e and B)

o Sometimes sign changes (changes in LOS B field)





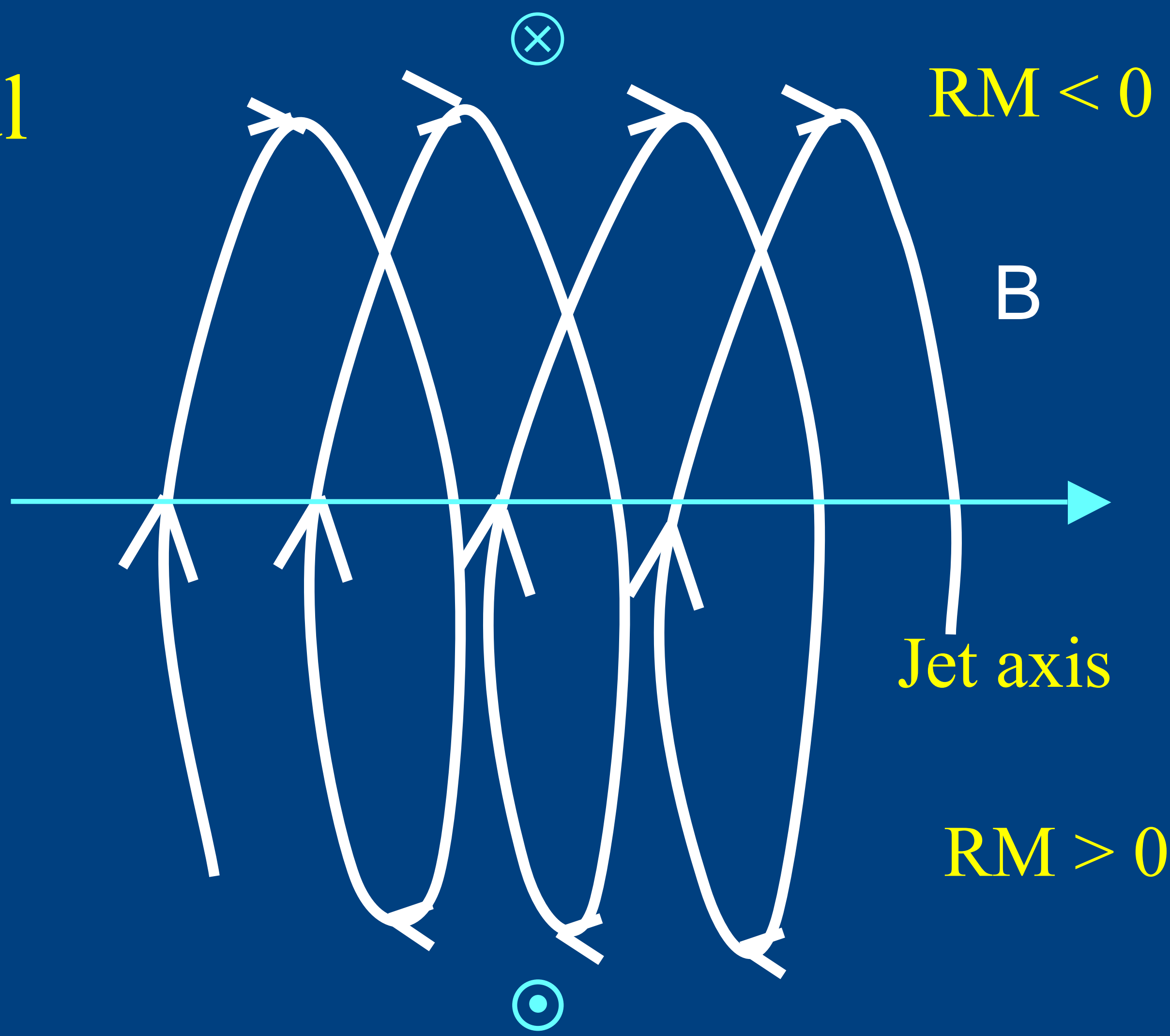


- Direction of polarization gives B-field direction in plane of the sky
- Faraday rotation in vicinity of the jet gives B-field along line of sight

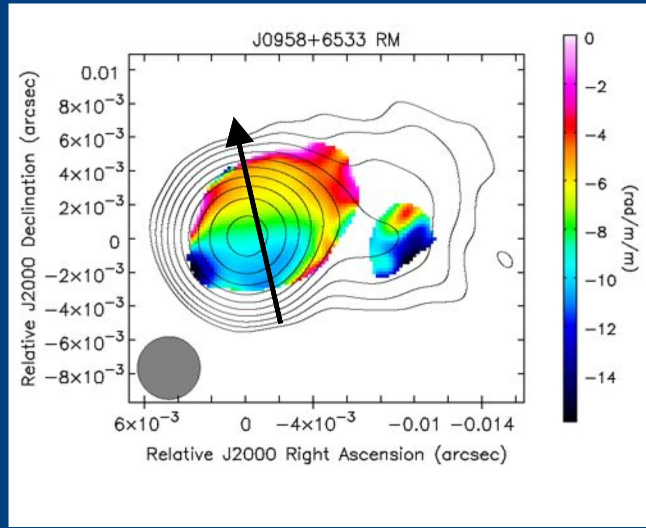
$\Rightarrow$ Together can build up a 3D picture of the B field in and around the jet.

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).

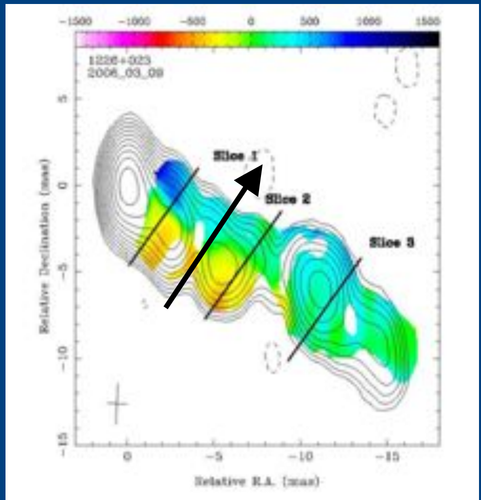
$$RM \sim \int n_e\, B \bullet dl$$

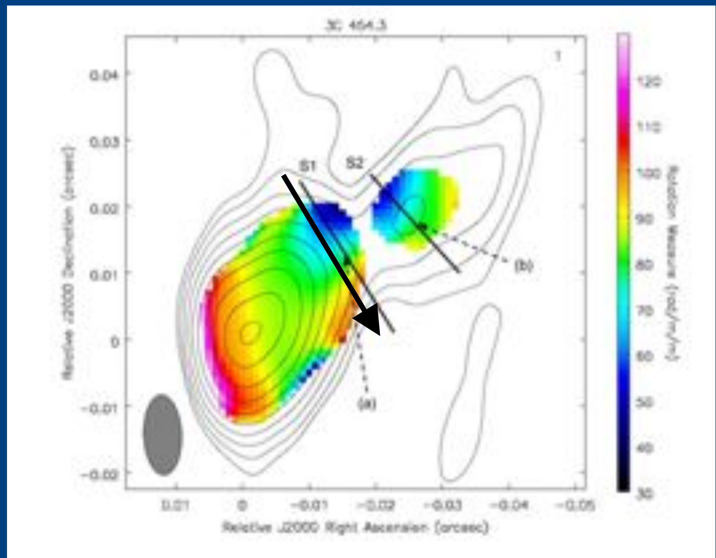


Gabuzda et al. 2019



Hovatta et al. 2012



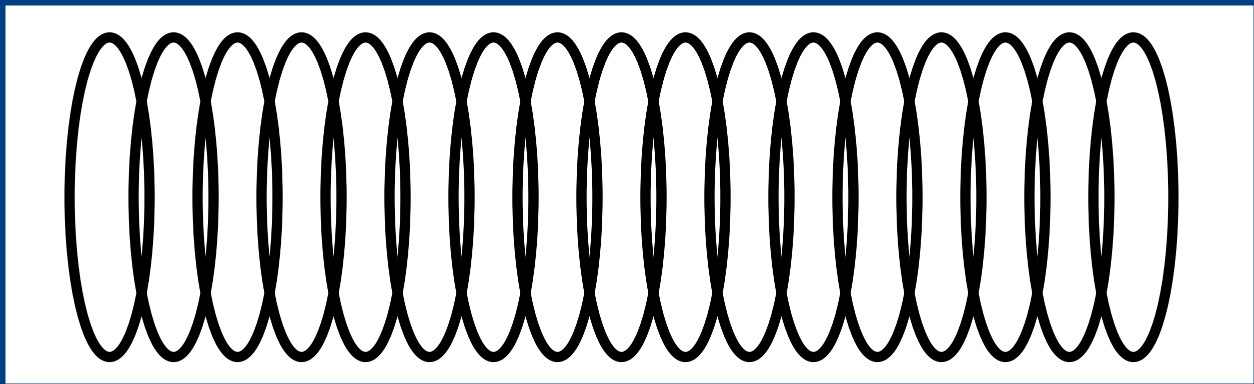


Motter & Gabuzda 2017

Reports of transverse RM gradients across pc-scale AGN jets, interpreted as evidence for helical B fields. Implies jets carry currents, which can collimate jets!

Is the field toroidal or helical?

Key difference: A toroidal field should not give rise to asymmetrical transverse intensity and polarization profiles, but a helical field can.



Toroidal

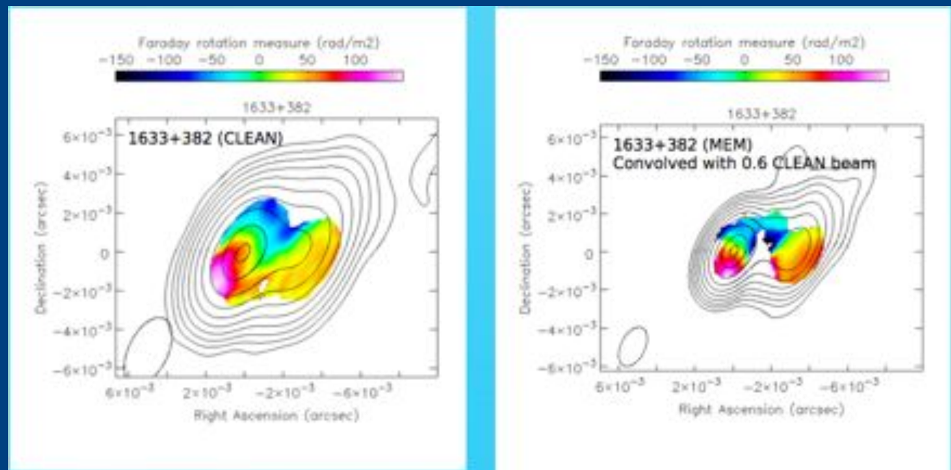
Helical

Example – 1633+382 (Coughlan & Gabuzda 2013)

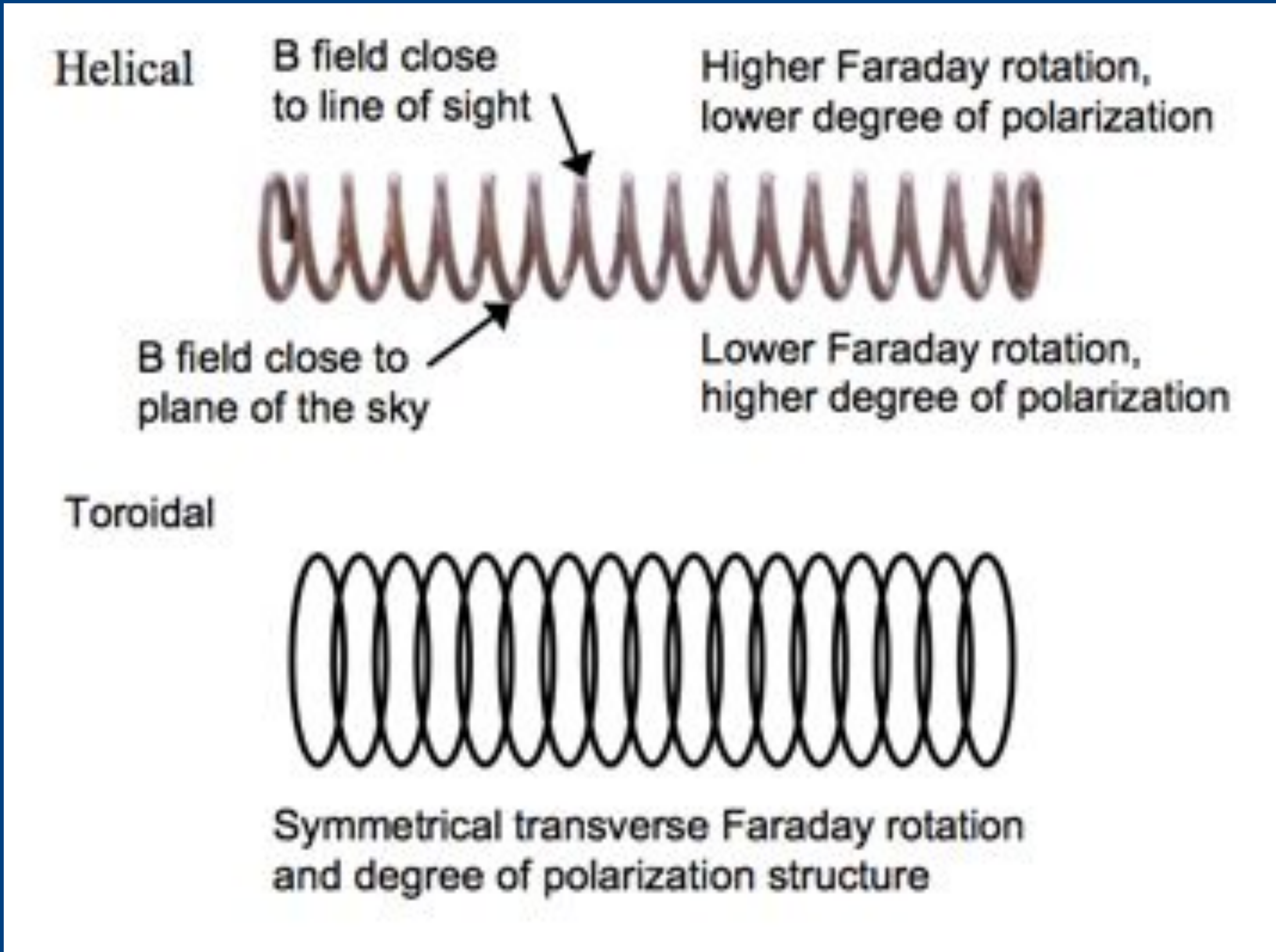
Asymmetric transverse pol structure

+

Transverse RM gradient

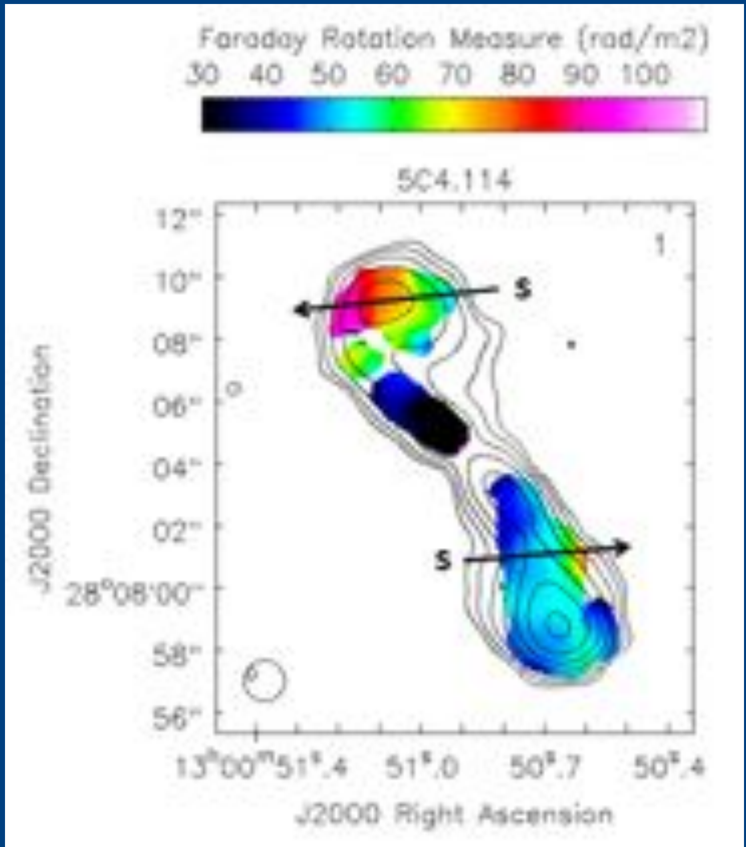


===> Helical (not just toroidal) field present on pc scales

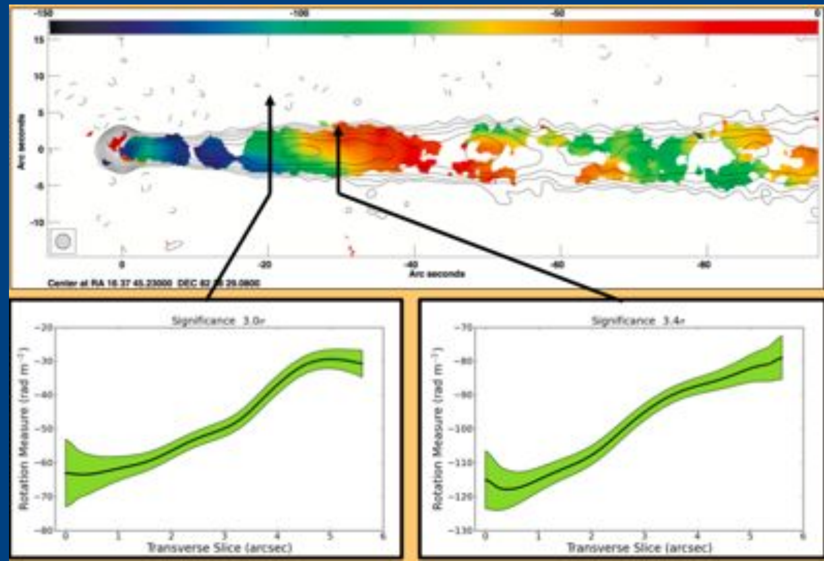


Can also look for expected patterns for polarization and Faraday rotation for helical jet B fields – seen in some AGN jets!

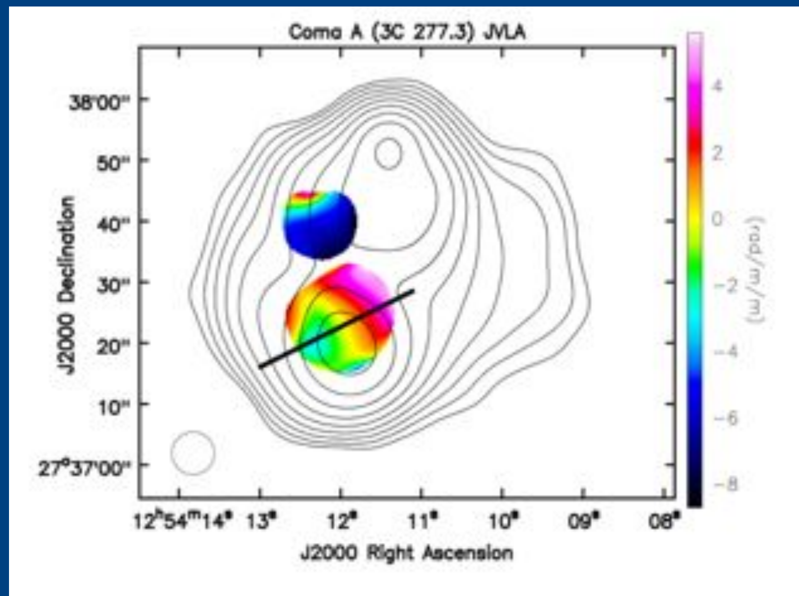
Significant transverse RM gradients also found out to kpc scales:



Gabuzda et al. 2015



Knuettel et al. 2018



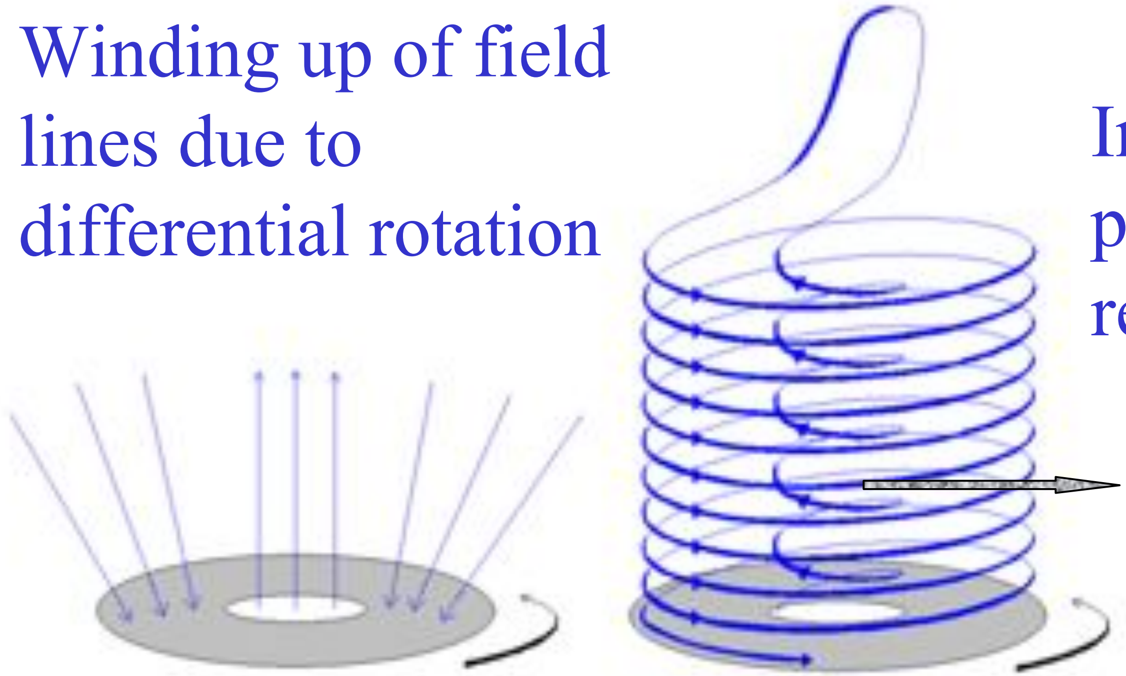
Knuettel et al. 2017

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

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

How can both be true at the same time?

“Outgoing” B field in jet/inner accretion disc closes in outer disc



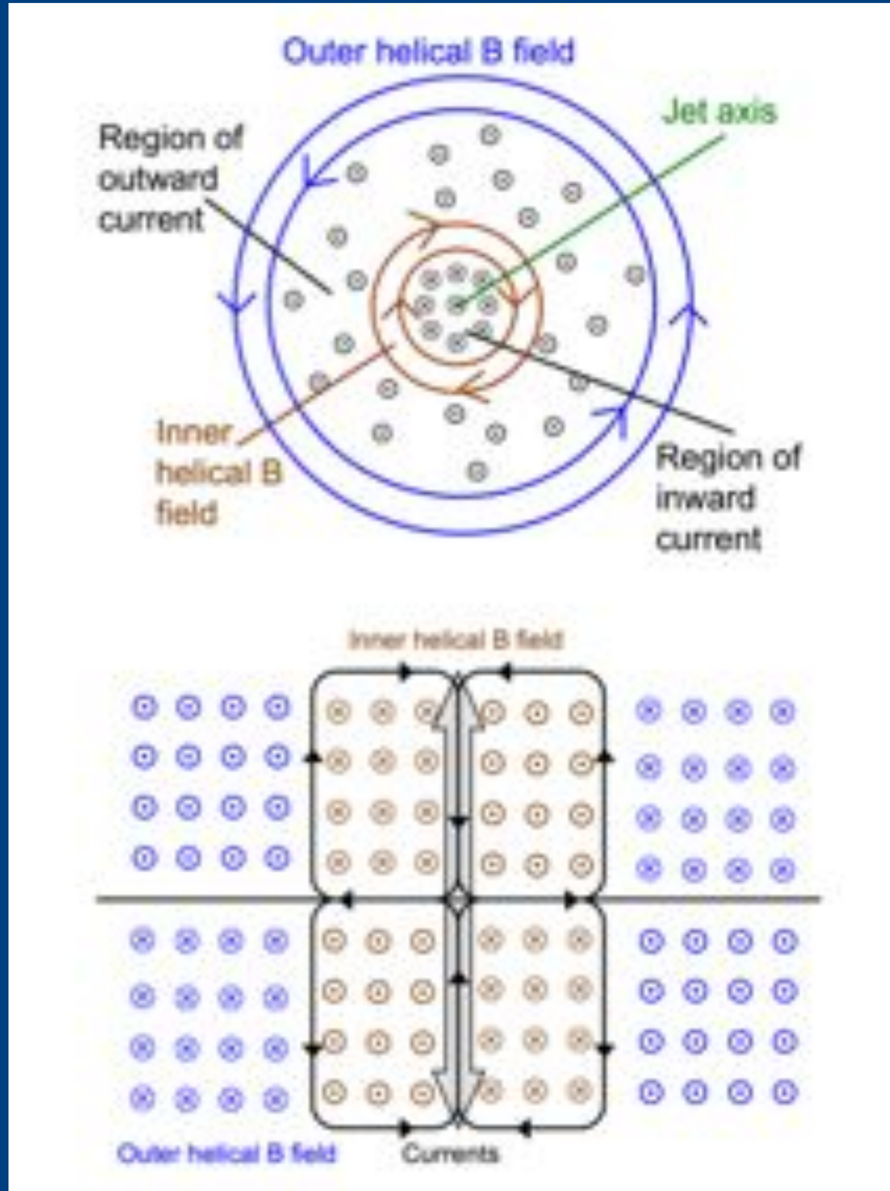
Winding up of field lines due to differential rotation

Integration path passes through both regions of helical field

$\int n_e B \bullet dl$

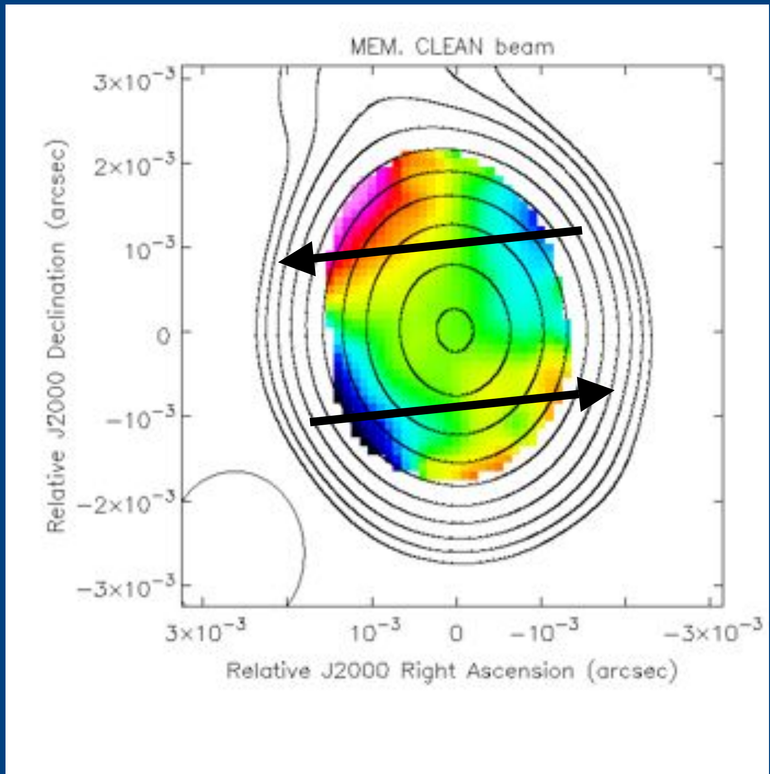
Presence of a “return field” in a more extended region surrounding the jet forms a nested helical-field structure

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.

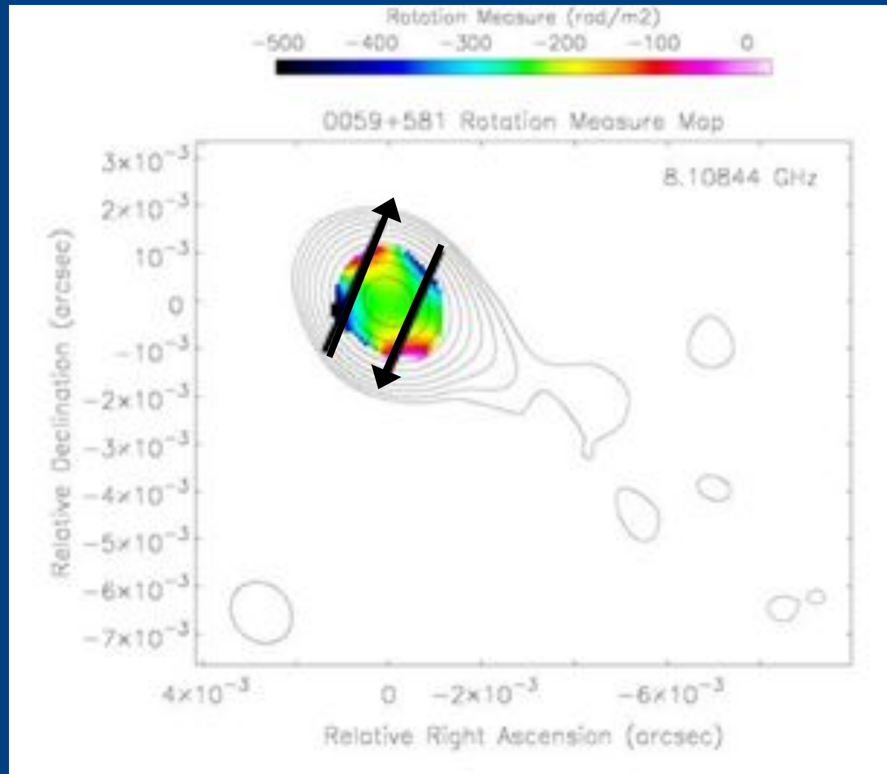


Gabuzda et al. 2018

Reversal of RM gradients also directly detected in seven AGN (e.g. Gabuzda et al. 2018):



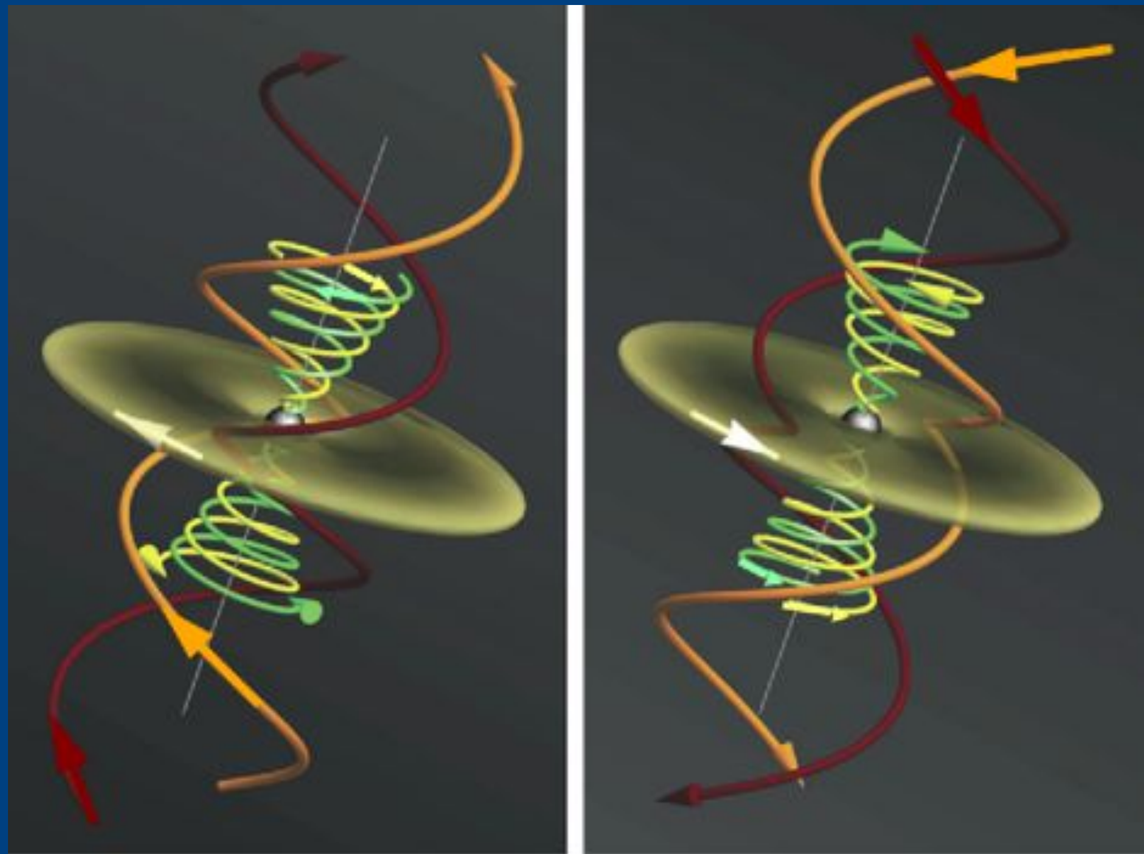
Mahmud et al. 2013



Gabuzda et al. 2018

The "Cosmic Battery" model 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.

We are starting to build up a picture of the overall "global" 3D structure of currents and B fields associated with AGN jets!



Christodoulou et al. (2016)

Some other factors that can be added into the mix:

- Magnetic field strength in “cores”
- Circular polarization
- Relationship between ejection of new jet components and flares at higher energies
- Lots more…!

For many studies related to these and other questions, see the publications on the MOJAVE website:

https://www.physics.purdue.edu/MOJAVE/

Hope you're not yet **cat***atonic!*

And I hope I've persuaded some of you to peer into the polarized hearts of AGNs