VLBI Observations of (Radio-Loud) AGN Jets: A Polarimetrist's Biased View

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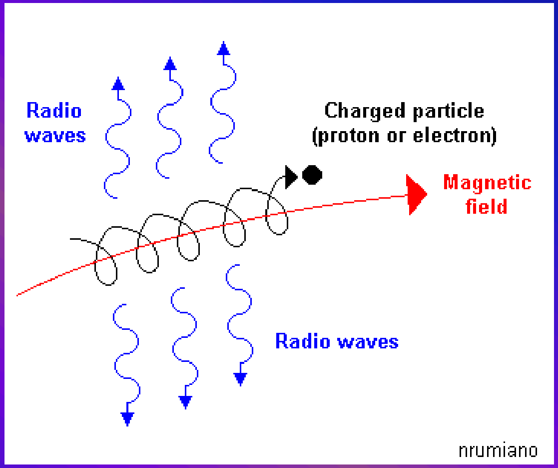
Outline of talk

- General VLBI properties of AGNs
- Linear polarization properties/B fields of AGNs
- Core-region B fields of AGNs
- Faraday rotation
- Circular polarization and “Faraday conversion”

General VLBI properties of AGNs

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

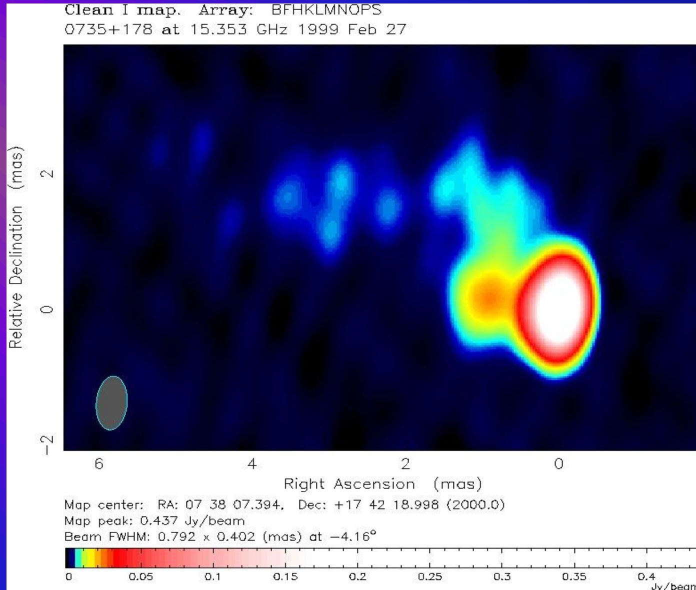


The direction of the linear polarization χ of the radio emission gives direction of the B field giving rise to the synchrotron radiation:

$$B \perp \chi$$

for optically thin regions.

Images of AGN jets obtained with the American VLBA — one-sided structure due to Doppler beaming



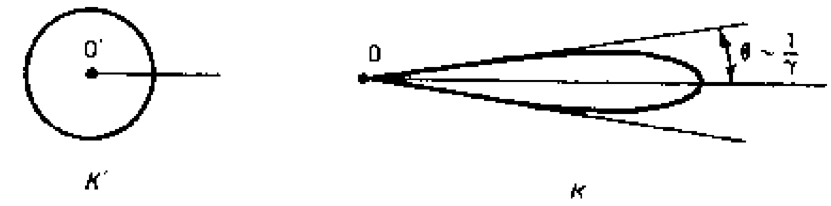
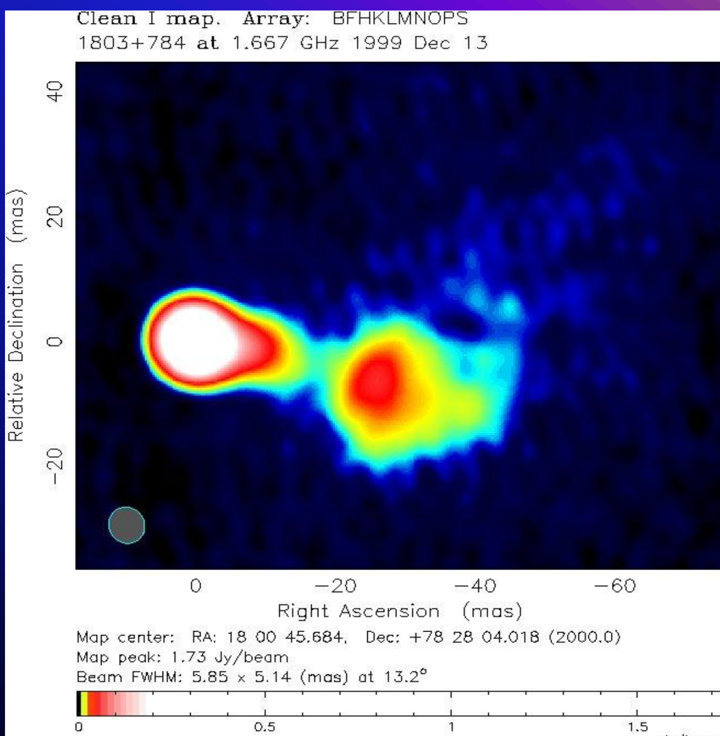
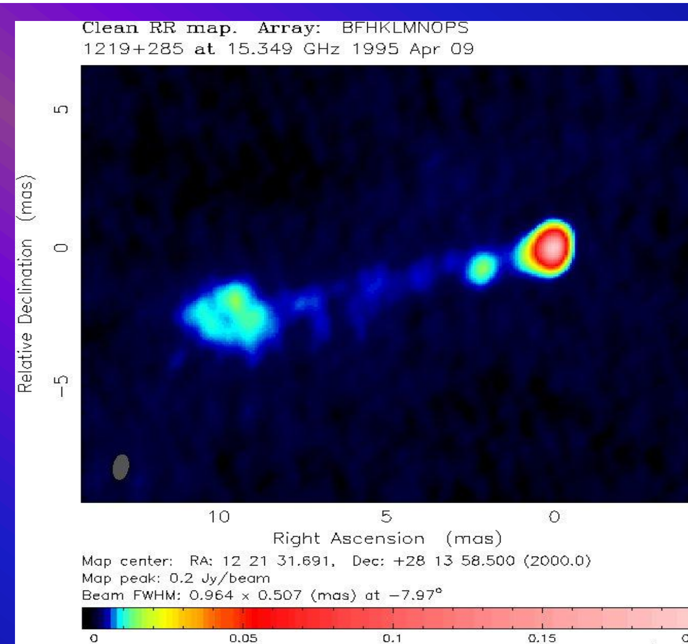


Figure 13: Relativistic beaming





Relativistic "Aberration":

A photon emitted in the source rest frame at right angles to the source velocity ($\theta' < 90°$) will be observed at the angle

$$\sin\theta = 1/\gamma$$

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

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

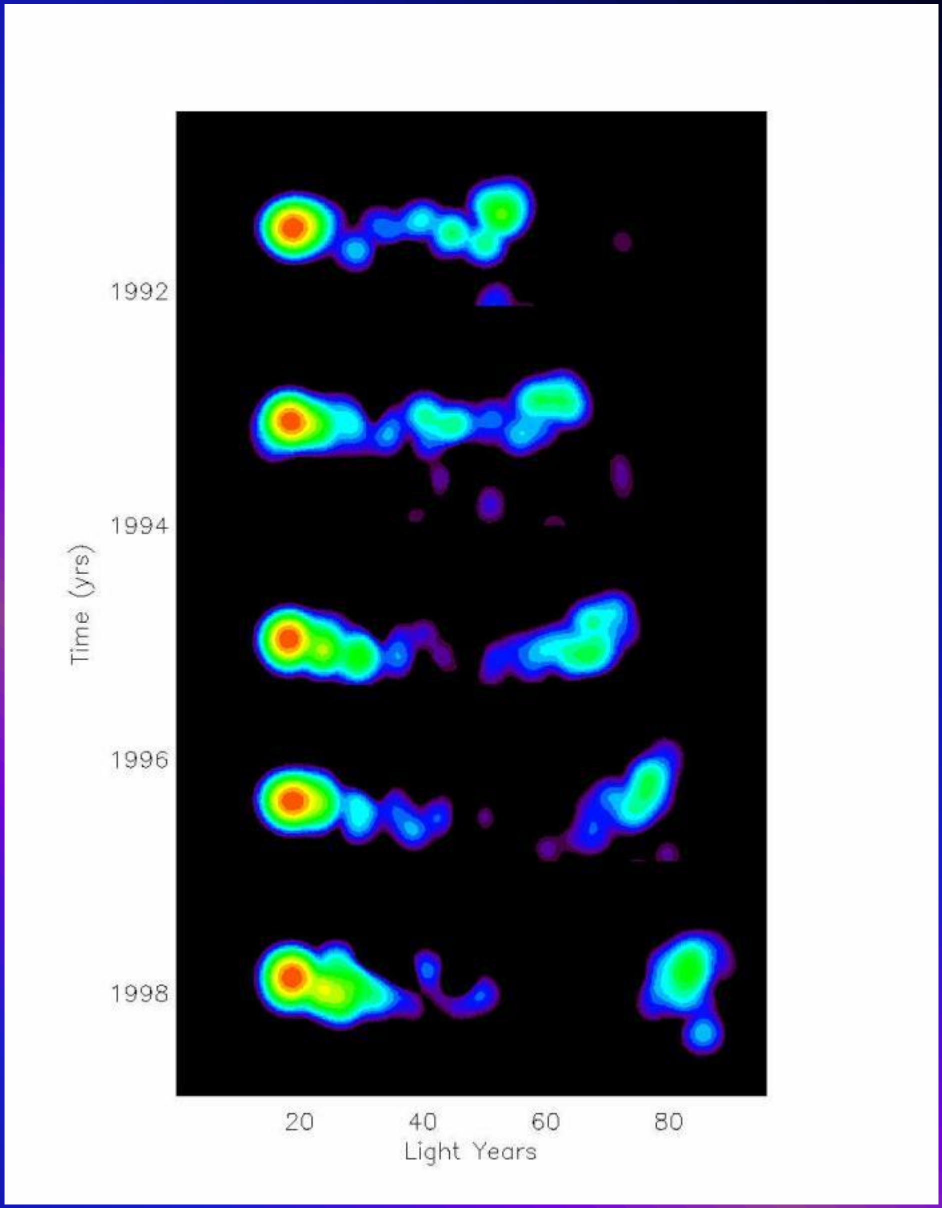
In the latter case, we are detecting photons emitted by the source roughly away from the direction toward the Earth!

Series of images of an AGN usually show apparent superluminal motion due to highly relativistic motion close to line of sight.

Apparent observed speed is:

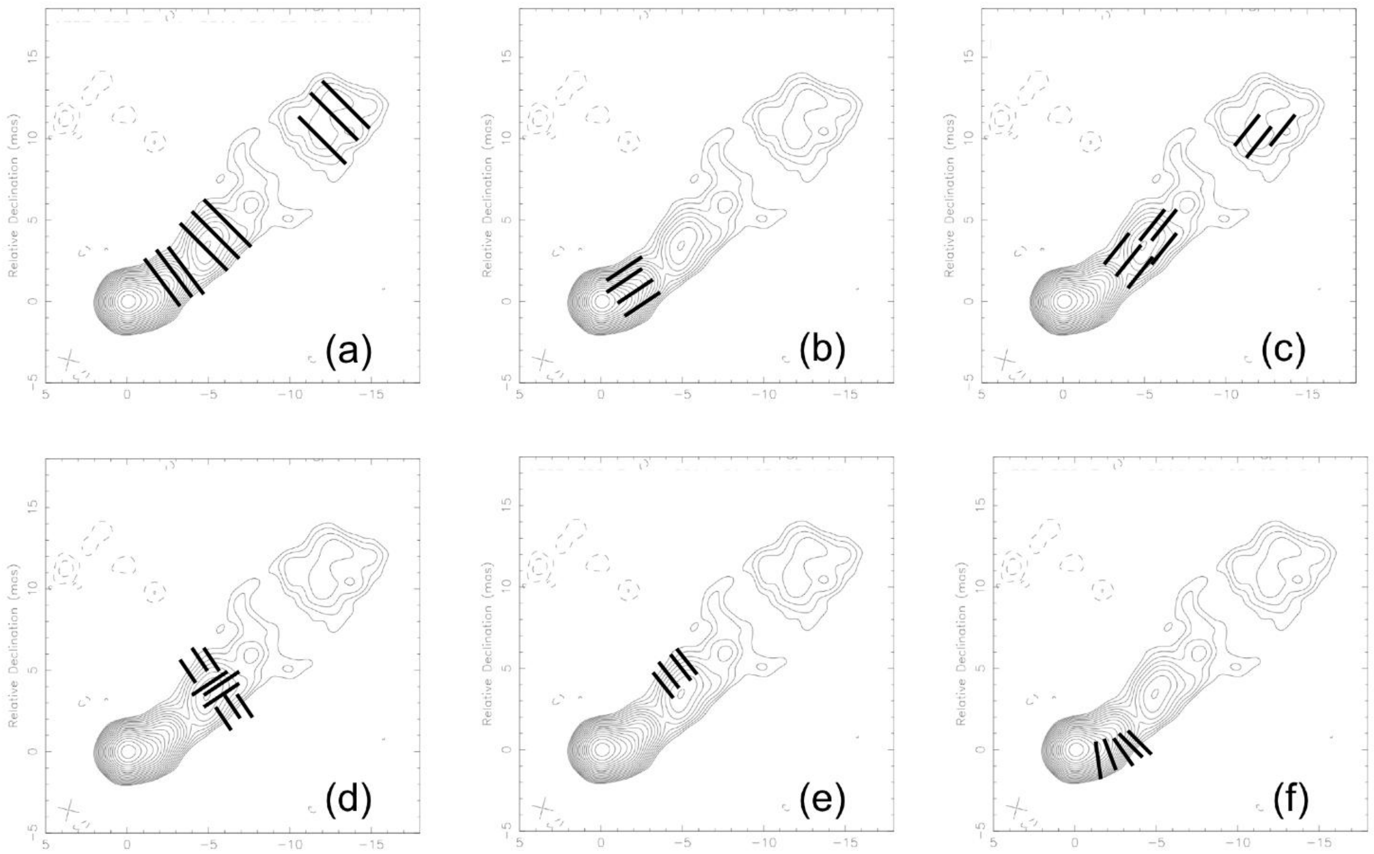
$$\beta_{app} = \frac{\beta \sin\theta}{1 - \beta\cos\theta}$$

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



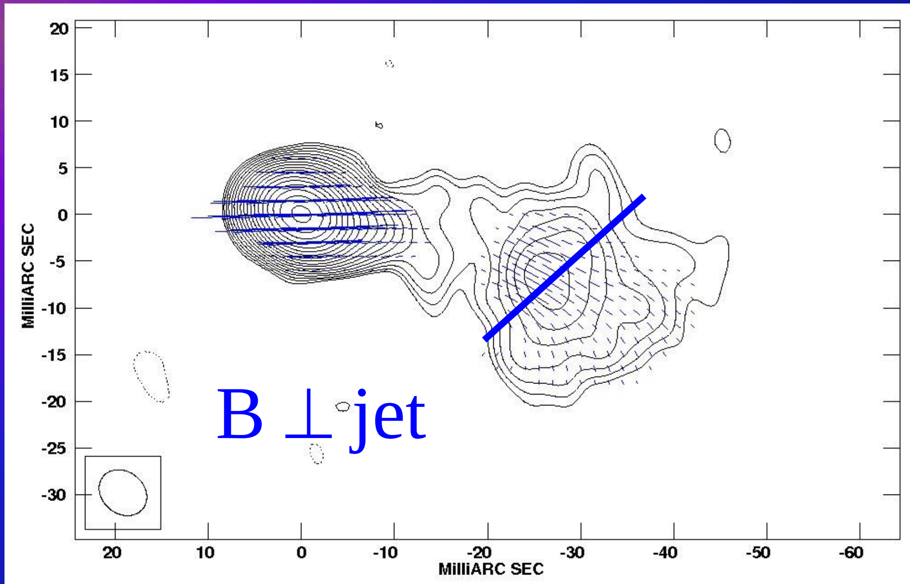
Linear polarization properties/ B-Fields of AGNs

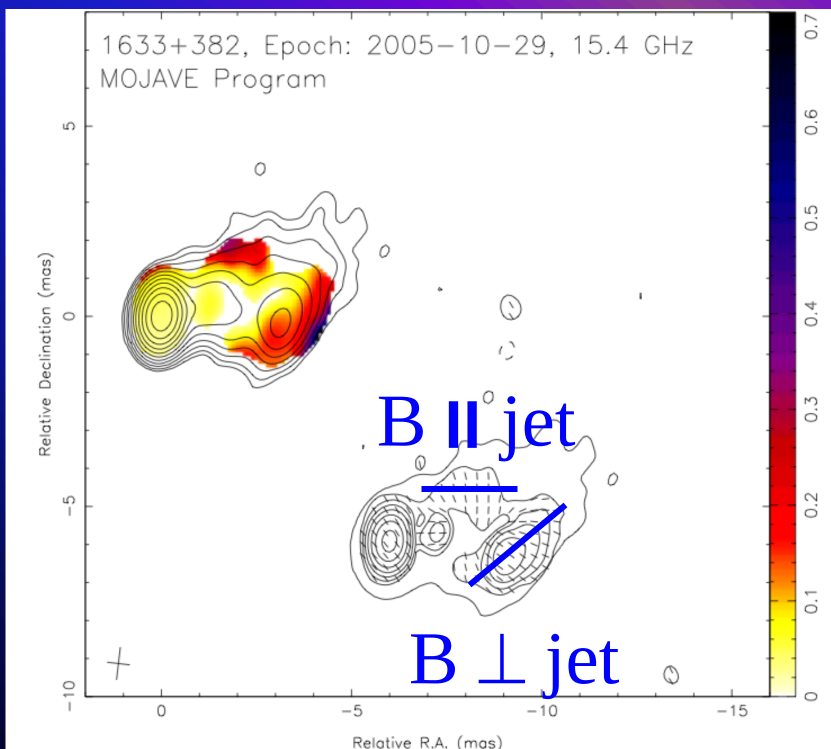
Polarization patterns observed for AGN jets on VLBI scales

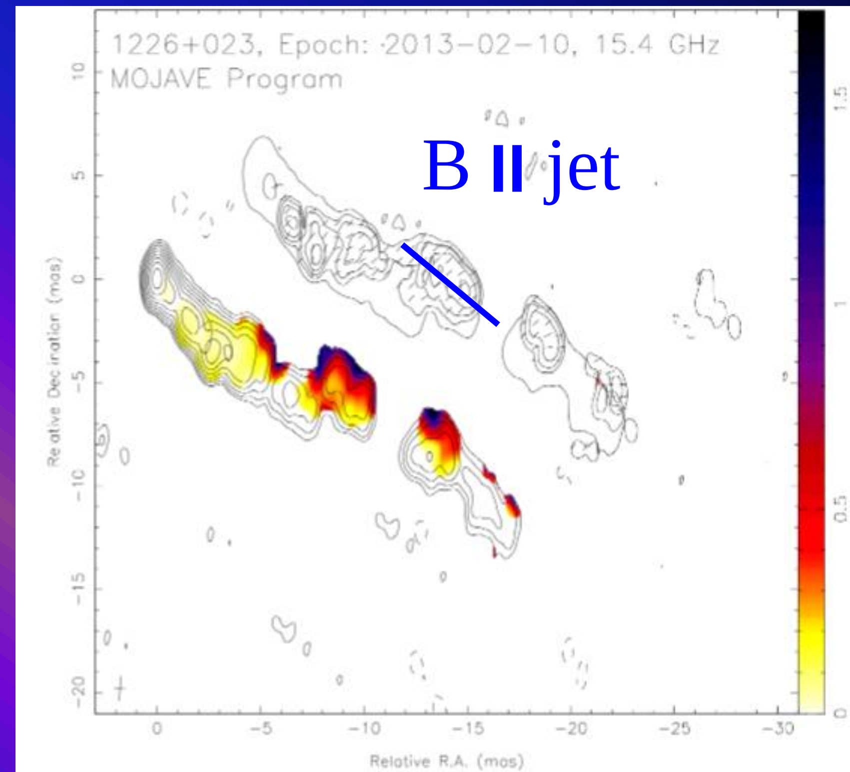


Contour map taken from the Mojave website, sticks added to illustrate various observed polarization patterns.

Some real examples

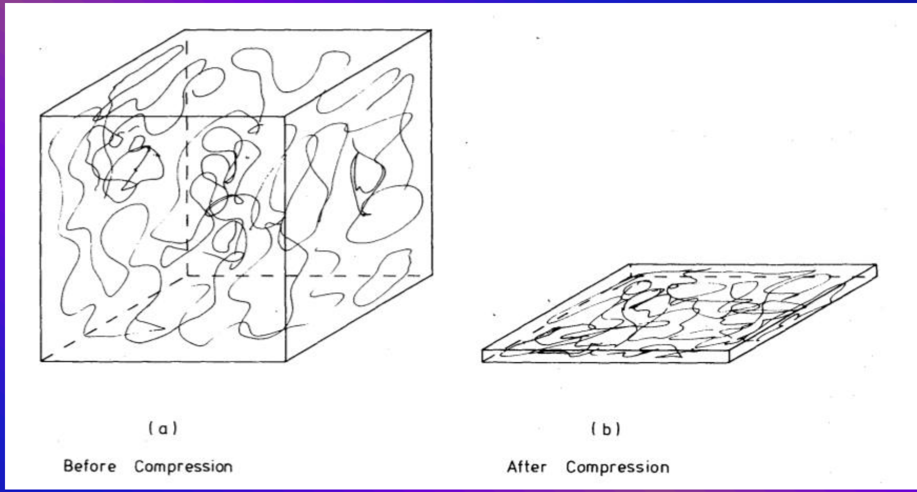






Mechanisms for generating B fields ⊥ to jets

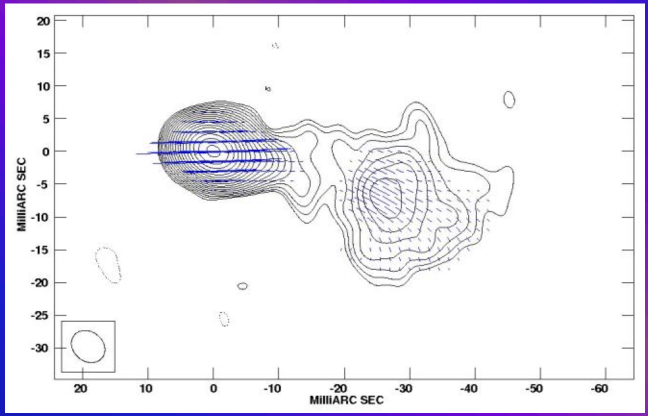
1) Transverse shocks — compress initially tangled B field, field becomes ordered in plane of compression



Laing (1980)

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.

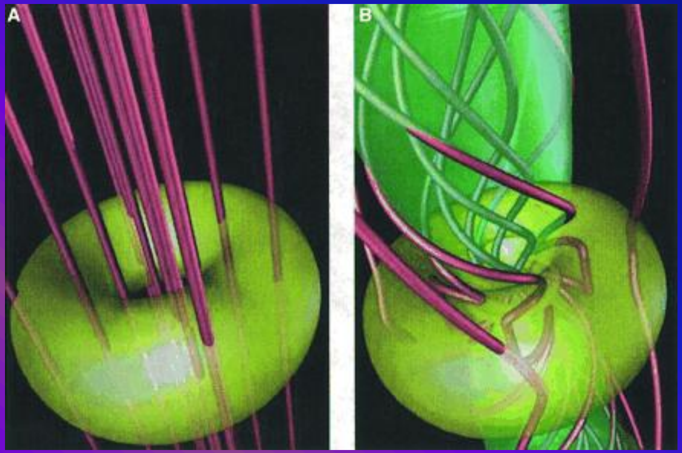
Mechanisms for generating B fields ⊥ to jets

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



Meier, Koide & Uchida 2001

Disadvantage: cannot help explain variability

Mechanisms for generating B fields || to jets

1) Shear interactions with ambient medium

Advantage: can explain extended regions of longitudinal B field, if shear present all along jet

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

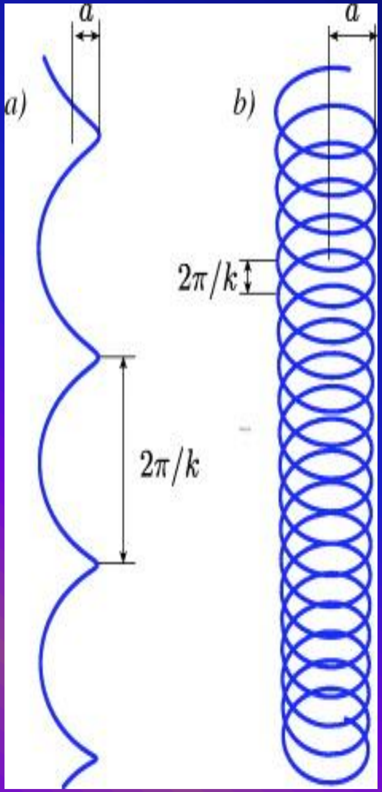
Mechanisms for generating B fields || to jets

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

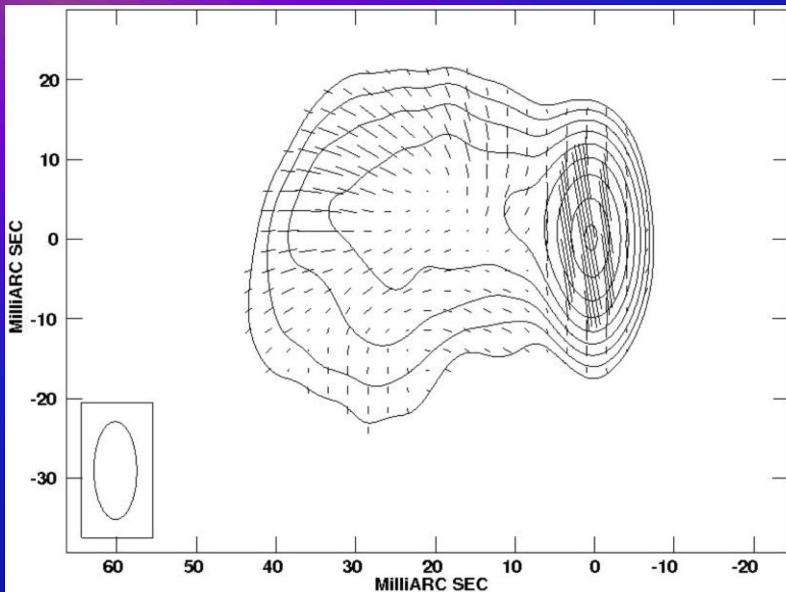


Mechanisms for generating B fields || to jets

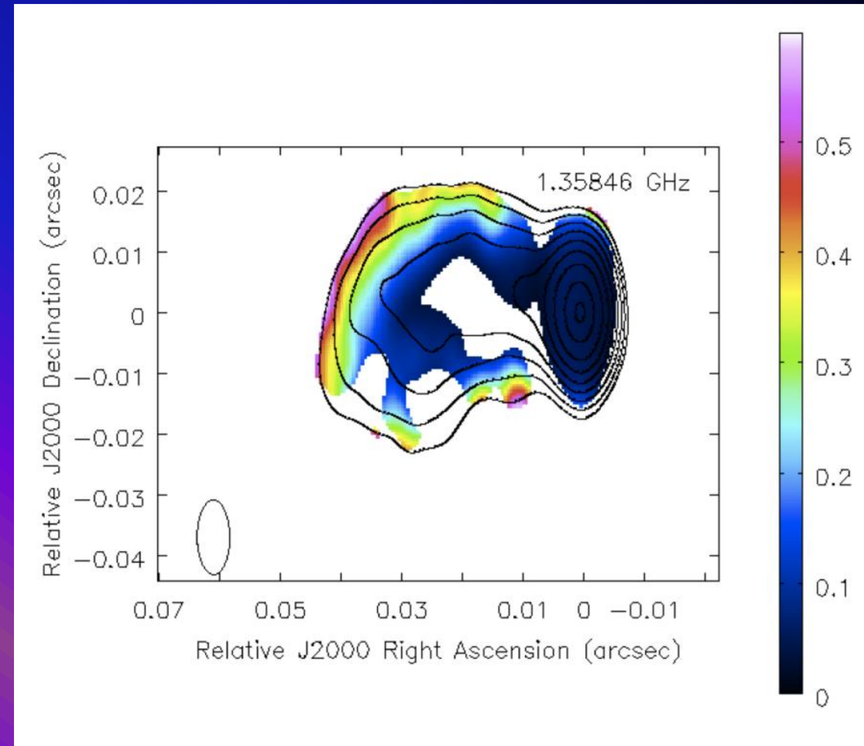
3) Curvature of the jet

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

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

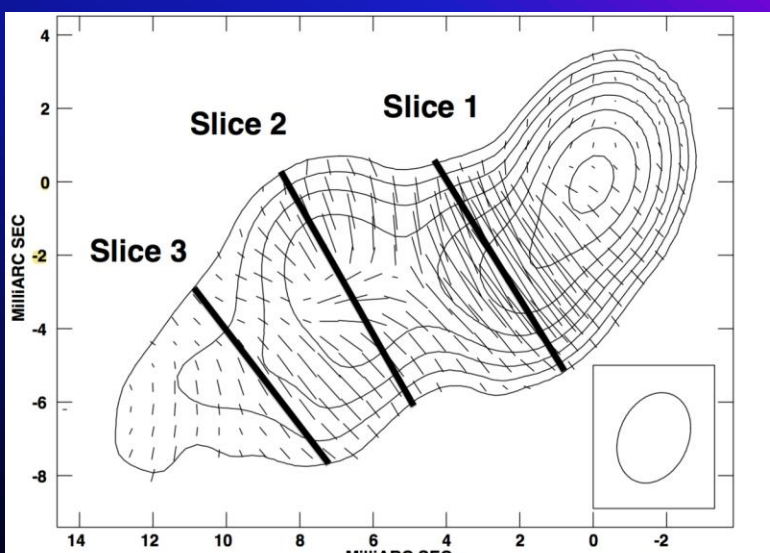


MilliARC SEC
MilliARC SEC

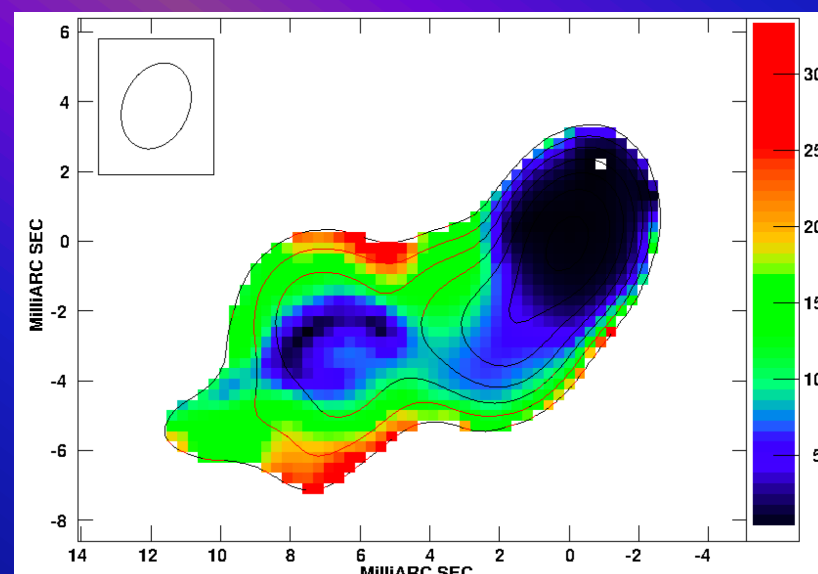


1.35846 GHz
Relative J2000 Declination (arcsec)
Relative J2000 Right Ascension (arcsec)

√



Slice 2
Slice 1
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]

• 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

➢ Vector nature of field – if jet has cylindrical symmetry, either $\perp$ or $\parallel$ component will dominate (e.g. Lyutikov et al 2005)

B-field structures in different AGNs

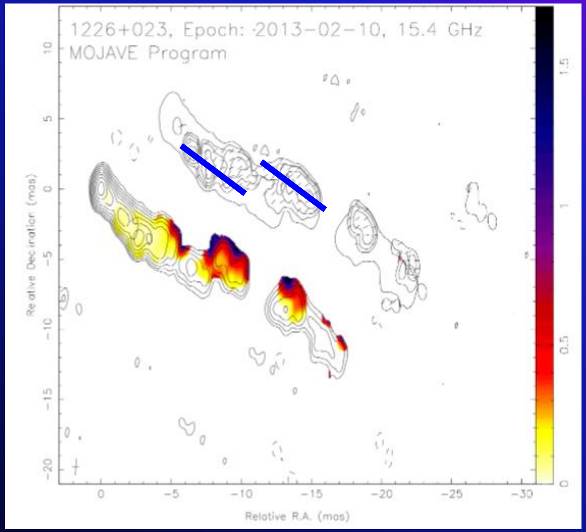
Quasars:

Strong optical emission lines

High radio luminosities

Relatively high apparent component speeds

Longitudinal jet B fields



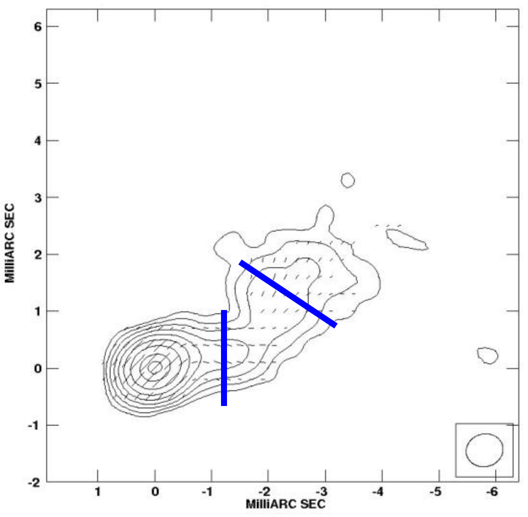
BL Lac objects:

Weak optical emission lines

Lower radio luminosities

Relatively low apparent component speeds

Orthogonal jet B fields



Possible scenarios to explain dichotomy

1) Shocks & shear

Quasars have faster, more stable jets than BL Lacs
⇒ harder for transverse shocks to form in quasar jets, shear with surrounding medium gives longitudinal B field (Gabuzda et al. 1994; Duncan & Hughes 1994)

2) Helical jet B fields

Both quasars and BL Lacs have helical B fields, faster jet speeds in quasars lead to lower pitch angles ⇒ observed fields in BL Lacs mostly orthogonal, in quasars mostly longitudinal (Gabuzda et al. 2000; Asada et al. 2002)

How to tie in observed speeds and B-field structures with strength of optical line emission?

Baum, Zirbel & O'Dea (1995): Optical emission lines of FRI radio galaxies are less luminous than those of FRII RGs, due to weaker ionizing continuum in FRI galaxies.

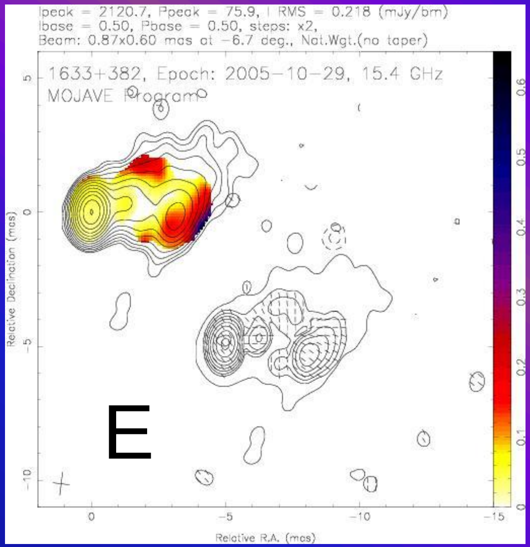
Possible scenario:

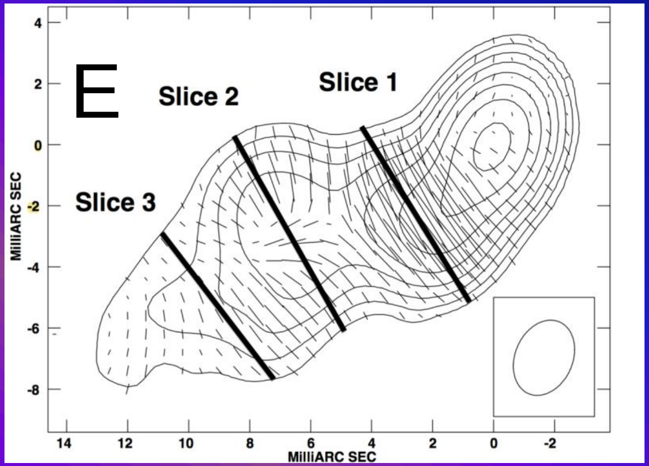
FRI/BL Lac = weak ionizing continuum + low-power jets, low jet speeds, jets with transverse shocks and/or high-pitch-angle helical fields

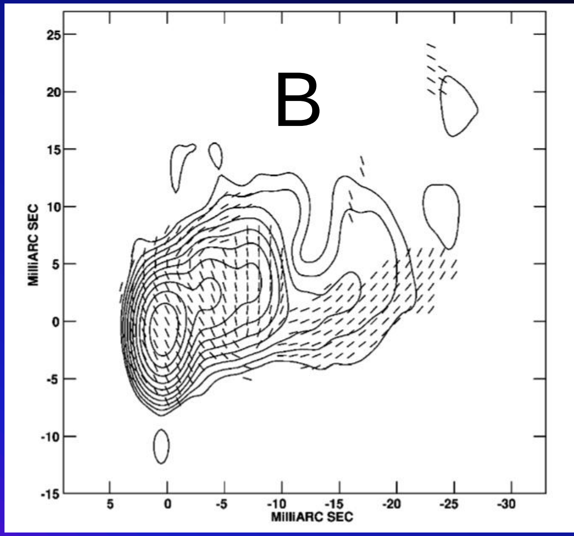
FRII/Quasar = strong ionizing continuum + high-power jets, high jet speeds, jets without transverse shocks and/or low-pitch-angle helical B fields

Other types of B field structures

"Spine+Sheath"

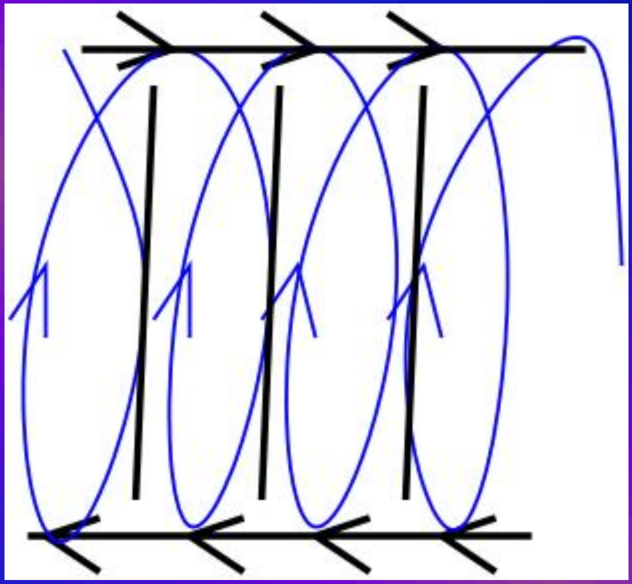


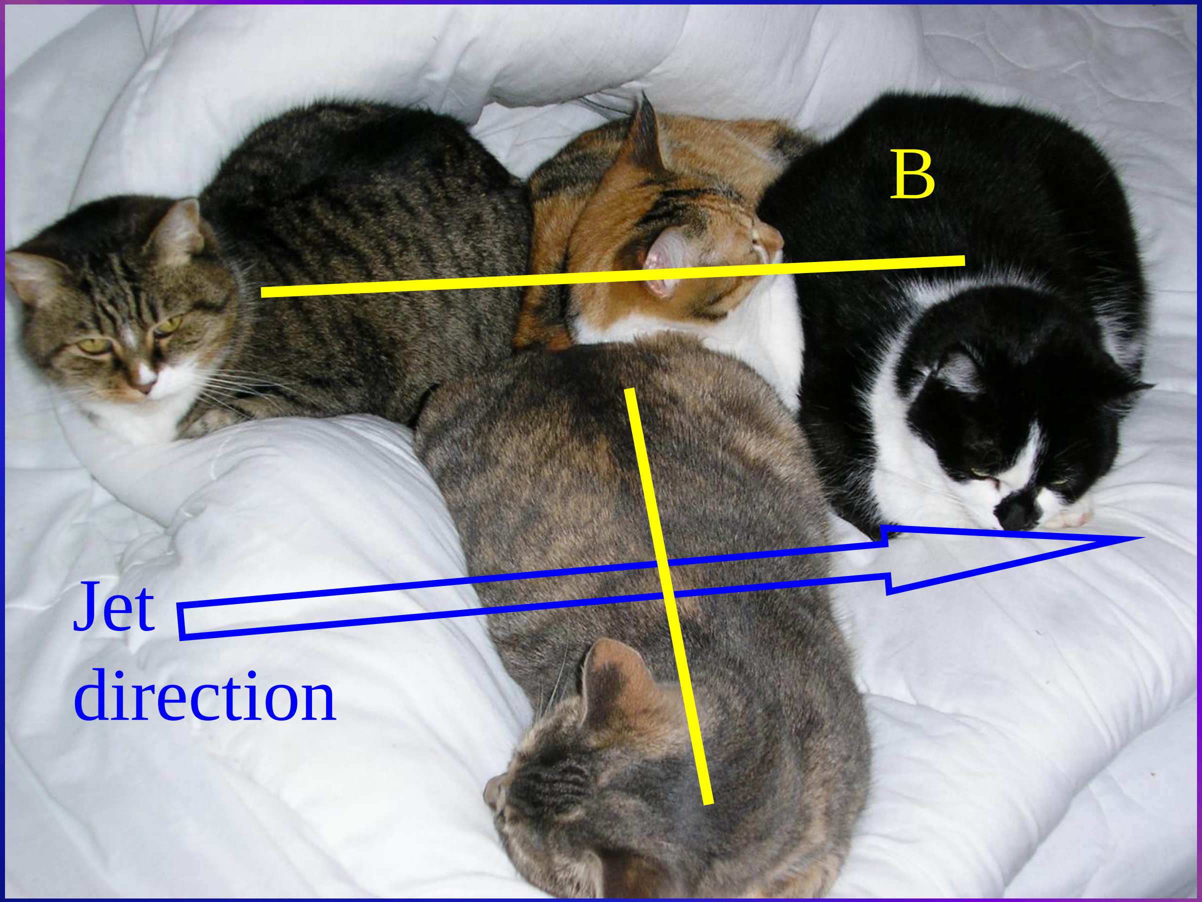


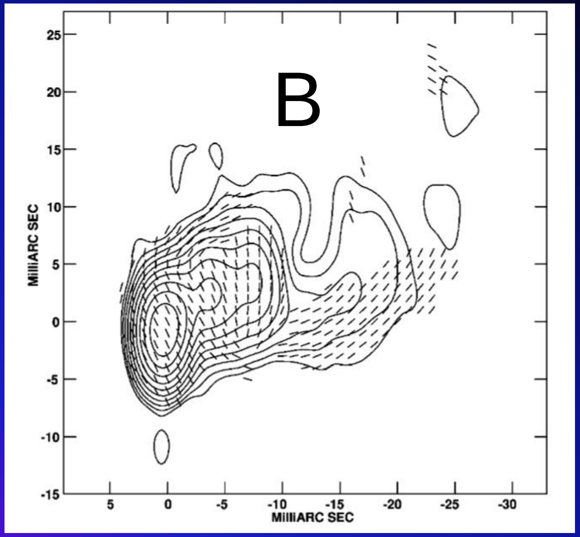


Competing mechanisms:

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







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

Core region B-Fields of AGNs

Estimation of B field strengths

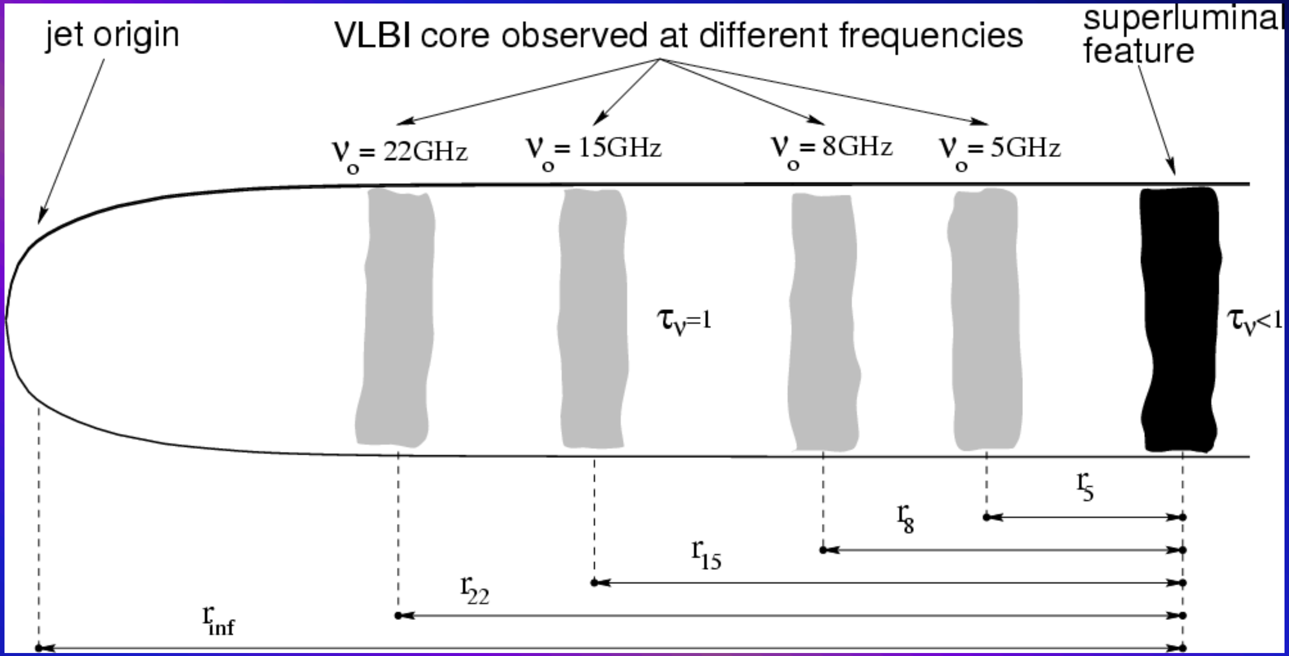
Difficult to use "obvious" direct approaches because observed radio structures are often unresolved or marginally resolved – don't know size of emission regions.

For example, basic synchrotron radiation theory leads to the relation (Longair 1981):

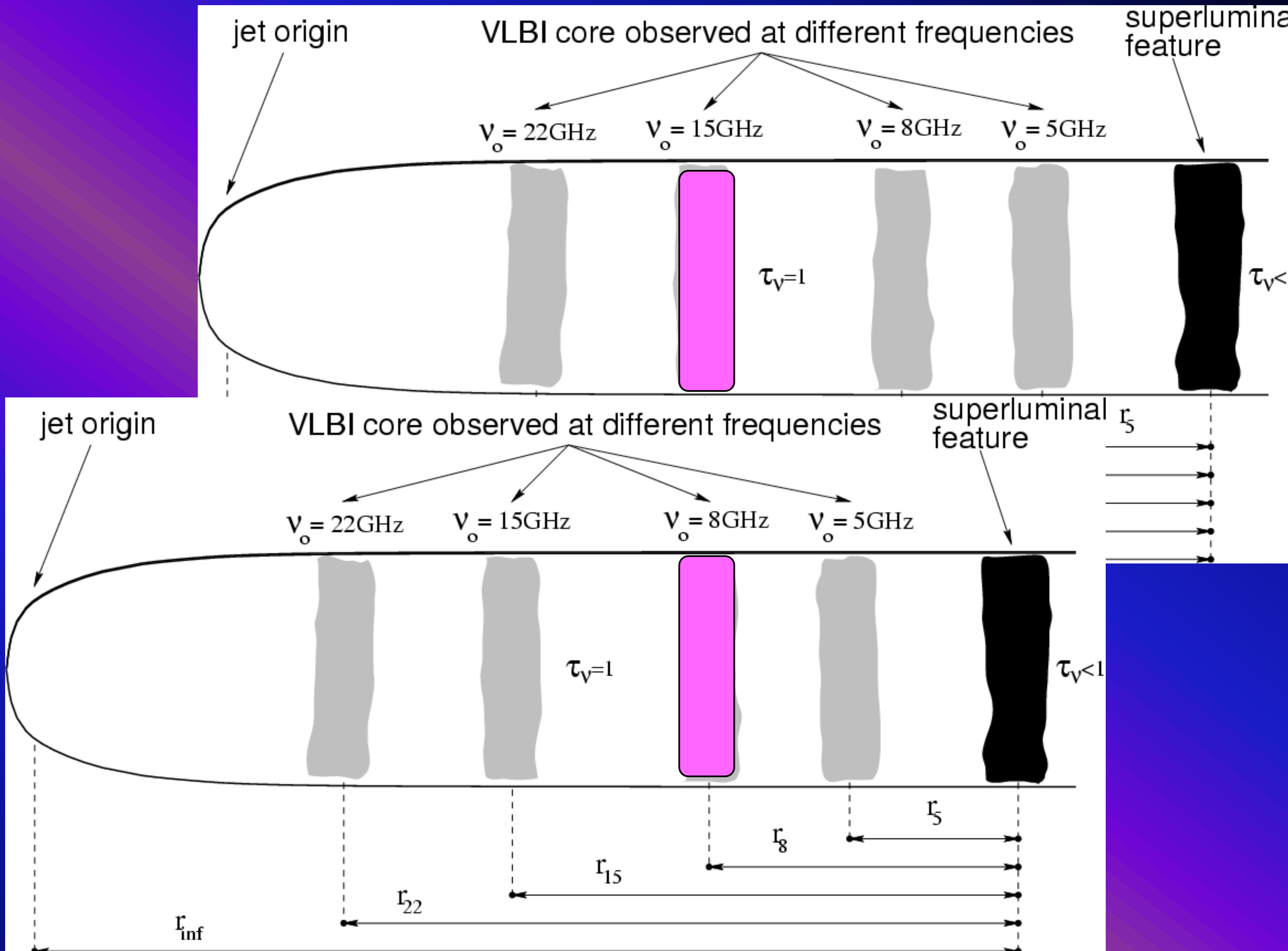
$$B = \left(\frac{8\pi m_e^3}{9e}\right) I_\nu^{-2} \nu_{\text{peak}}^5$$

Although ν_{peak} can be determined well from multi-wavelength VLBI data, measured I_ν is usually only a limit due to unknown true size of emission region.

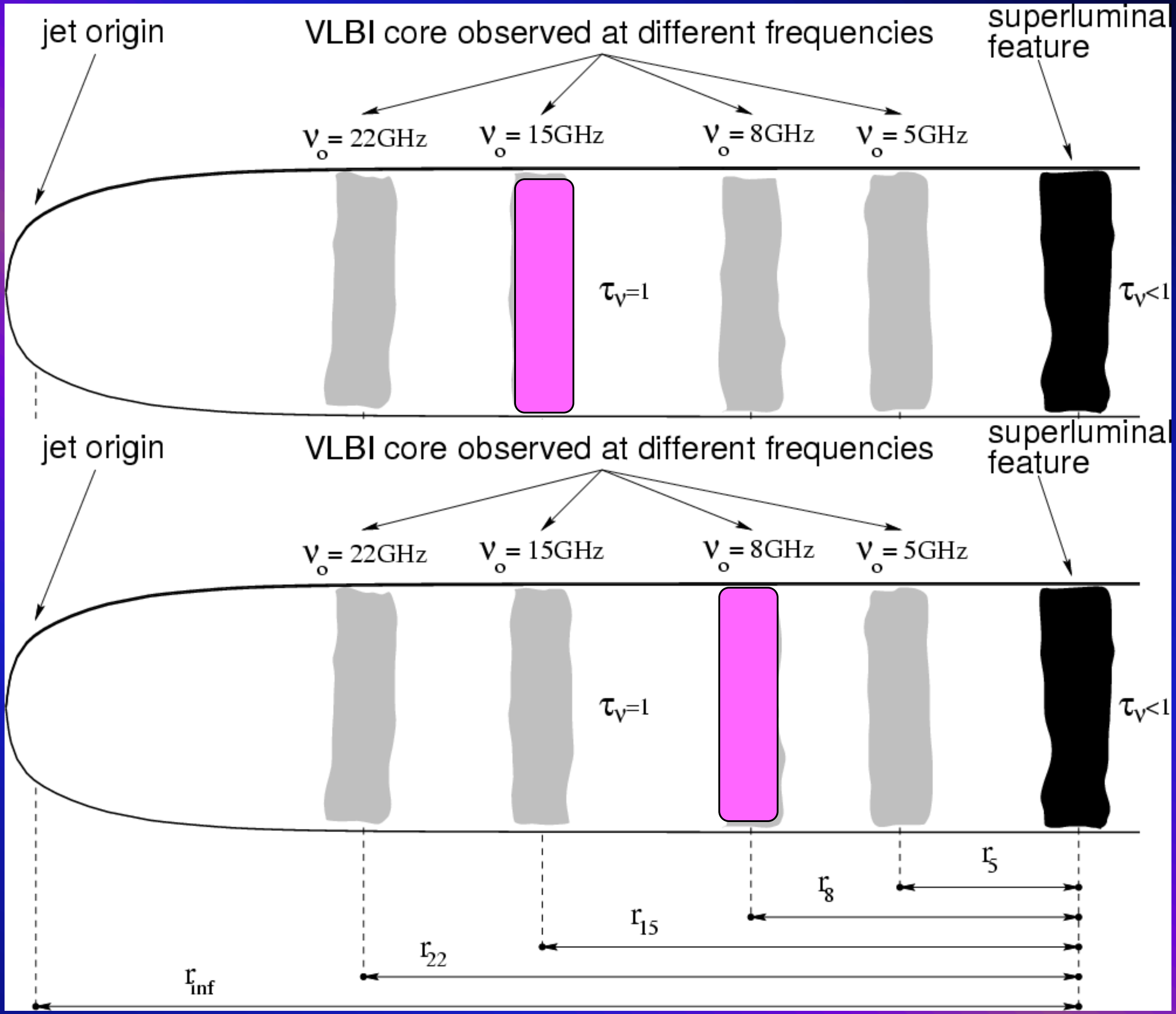
Schematic from Kovalev et al. (2007)



VLBI "core" = optically thick base of jet, moves further down jet at increasingly lower frequencies (Blandford & Königl 1979; Königl 1981)



VLBI images align on bright, compact cores rather than optically thin jet features, absolute position info lost, direct superposition yields incorrect alignment.



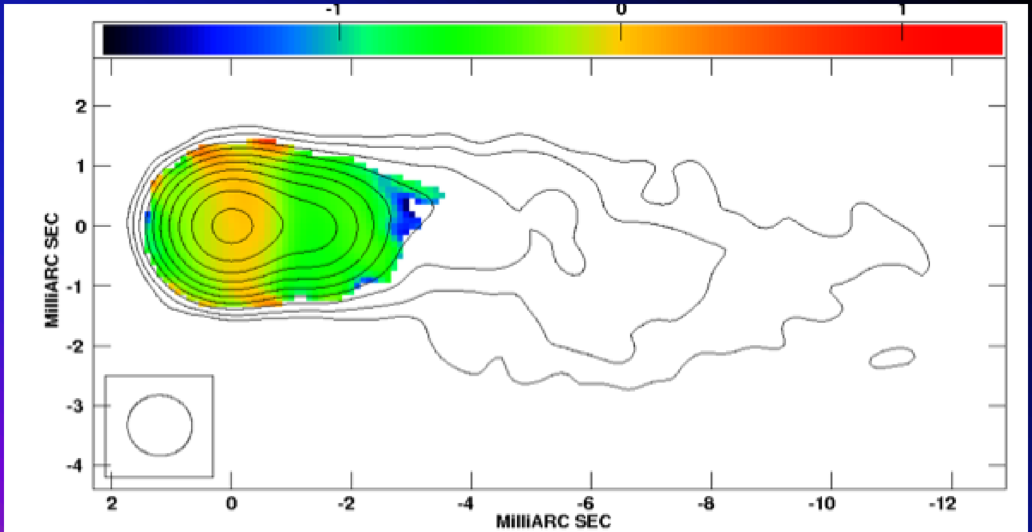
This is actual correct physical alignment!

Alignment techniques

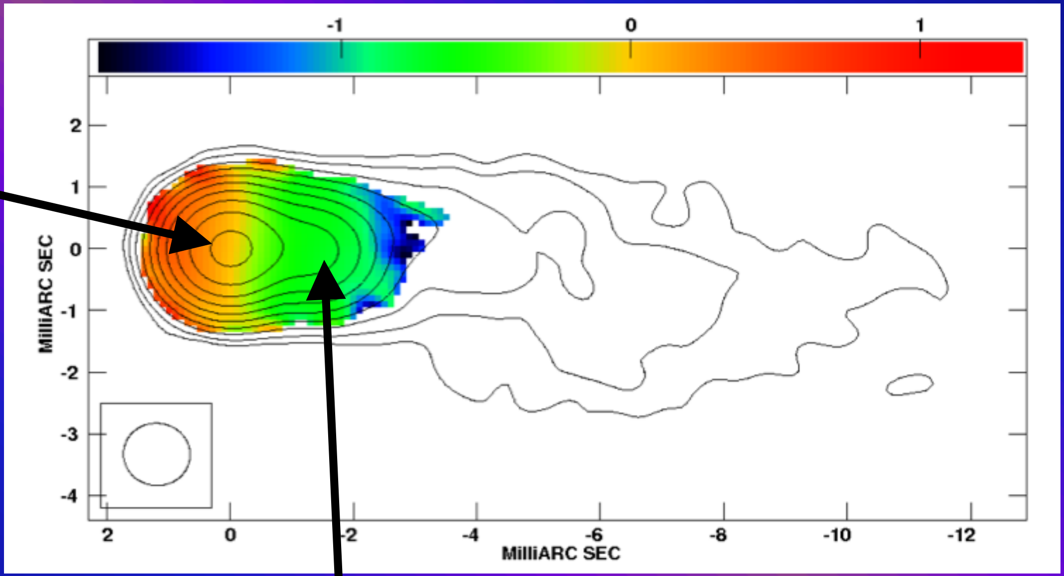
- o Based on comparing positions of optically thin features
  - ➢ Model fitting
  - ➢ Image cross-correlation analyses
- o In practice – different approaches work best for different source structures, but both can yield reliable alignments

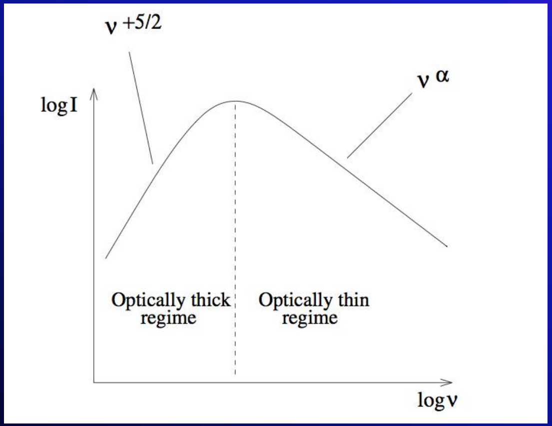
Example of misaligned (top) and correctly aligned (bot)spectral-index maps

(8.9–15.4 GHz)



Partially optically thick observed “core”





Theoretical picture

Optically thin jet

Lobanov (1998):

o Approach to estimating pc-scale B field strengths based on measurement of frequency-dependent position of VLBI core (Konigl 1981)

o Few sources, few frequencies, but a start

More recent studies:

O'Sullivan & Gabuzda (2010) — only a few sources, but 8 frequencies (detailed, redundant information)

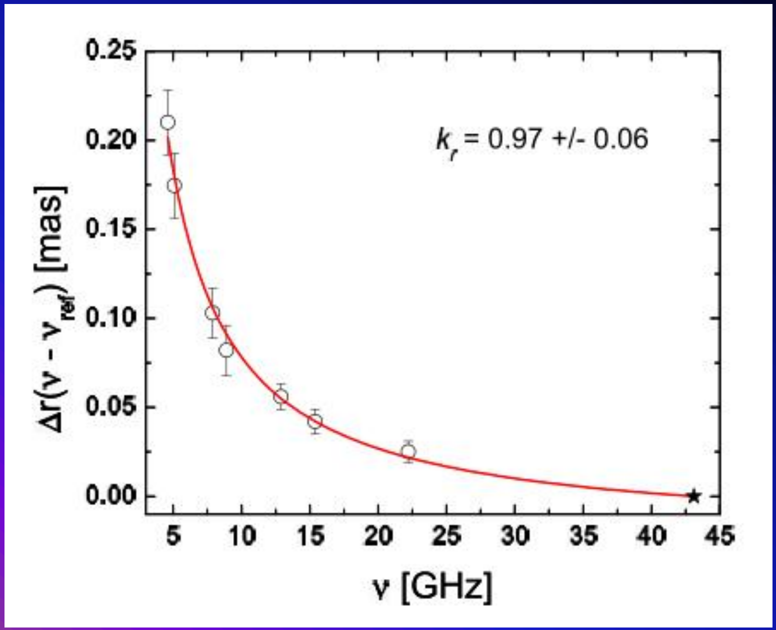
Kovalev et al. (2009) — 29 sources, 2 frequencies

Sokolovskii et al. (2011) — 20 sources, 9 frequencies

Pushkarev et al. (2012) — more than a hundred well studied (MOJAVE) sources, four frequencies

O’Sullivan & Gabuzda 2010

2007+777



$k_r = [(3–2\alpha)m + 2n–2]/(5–2\alpha)$

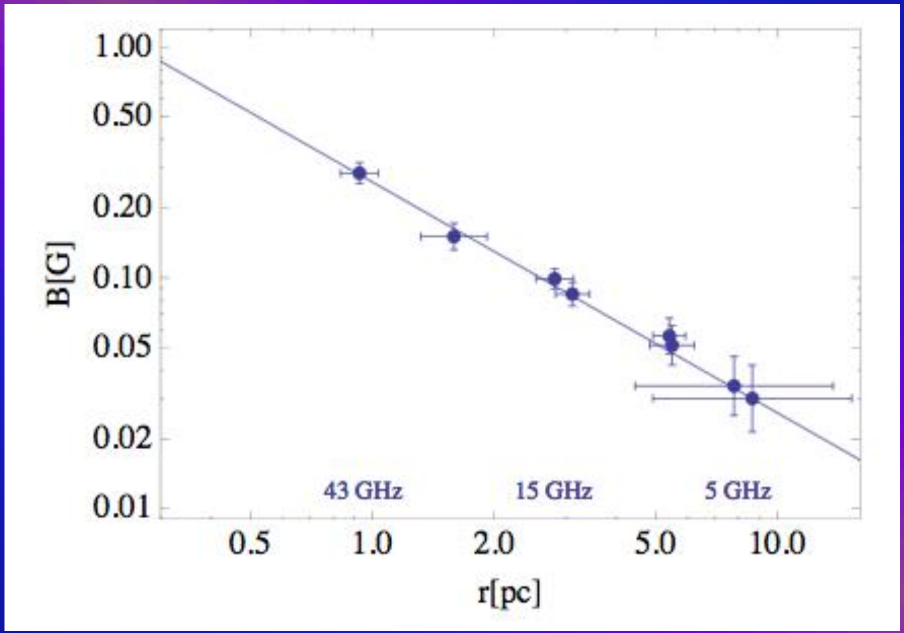
$B \sim r^{–m}$ $N \sim r^{–n}$

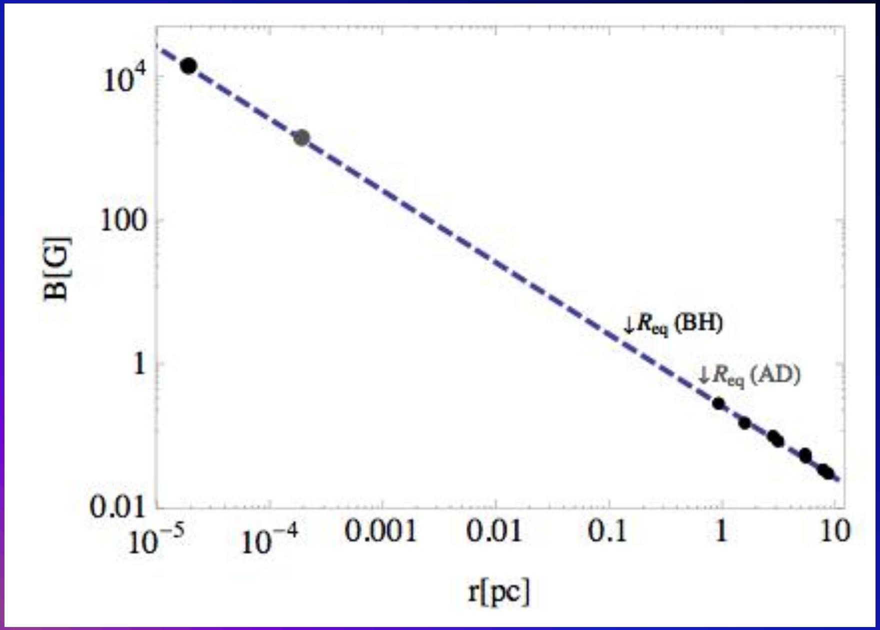
$S \sim \nu^{\alpha}$

$r \sim \nu^{–1/kr}$

- Behaviour expected for Blandford–Konigl (1979) jet is observed
- Evidence for equipartition in most cores – k_r often close to 1, consistent with $B \sim r^{–1}$ and $N \sim r^{–2}$

O'Sullivan & Gabuzda 2010



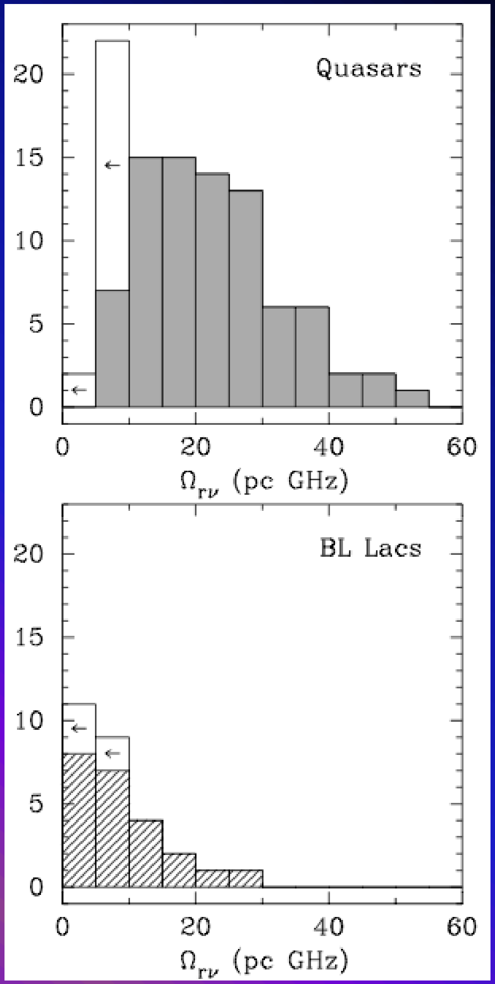


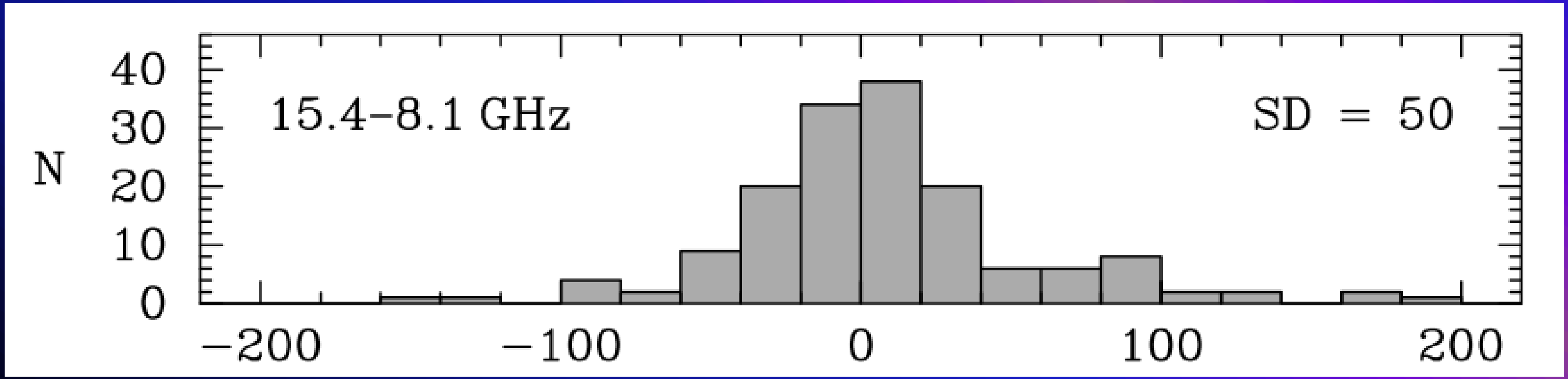
- Inferred core-region B fields are tenths of Gauss
- Data consistent with $B \sim r^{-1}$
- Extrapolation of B field to smaller scales gives values consistent with magnetic launching of jets (points shown are for r_g and $10r_g$; Komissarov et al. 2007)

Pushkarev et al. (2012)

o Ability to compare shifts for different types of AGNs.

o Shift distribution peaked in jet direction, as expected



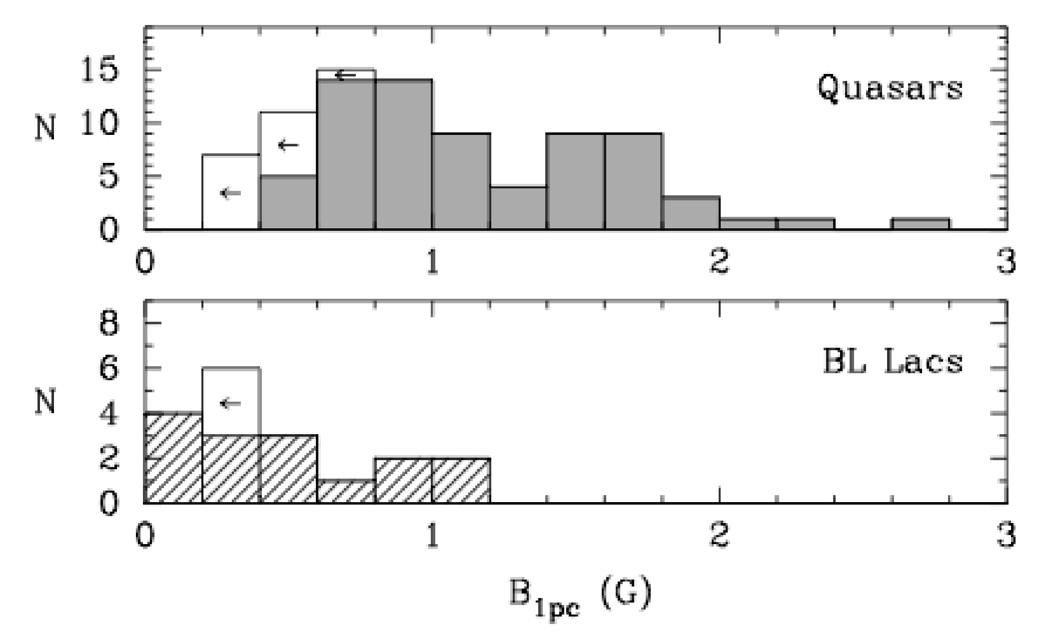


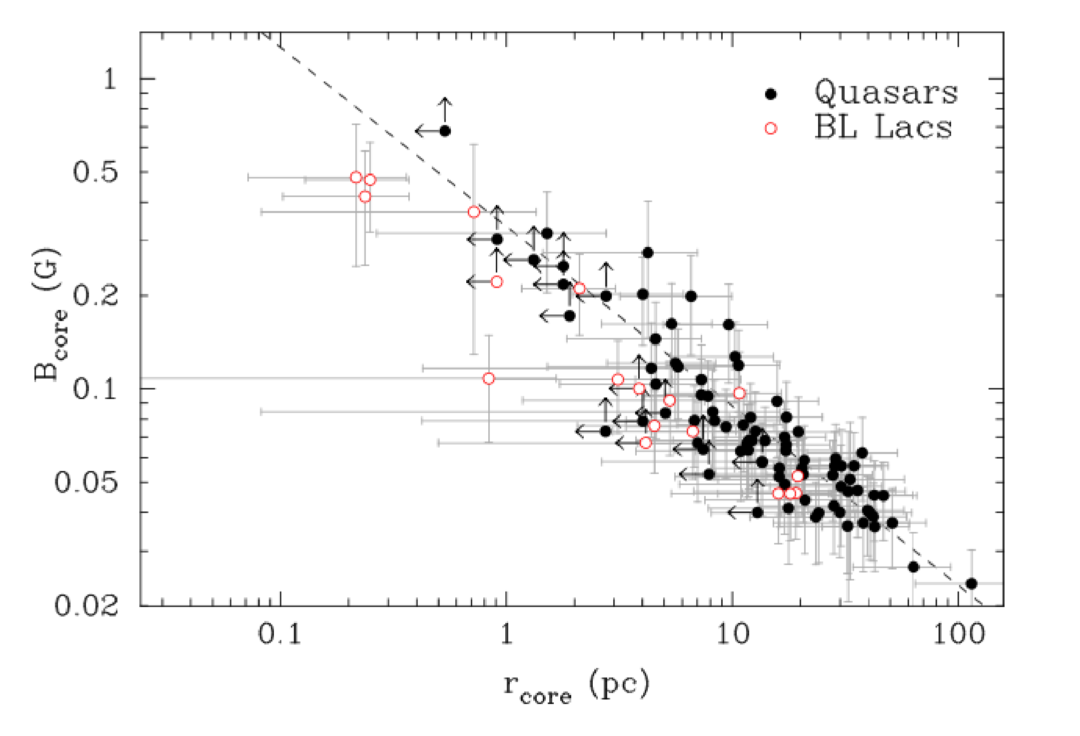
Pushkarev et al. (2012)

o B fields in quasars somewhat higher than in BL Lac objects

Quasar B fields at 1 pc ~ 0.9 G

BL Lac B fields at 1 pc ~ 0.4 G





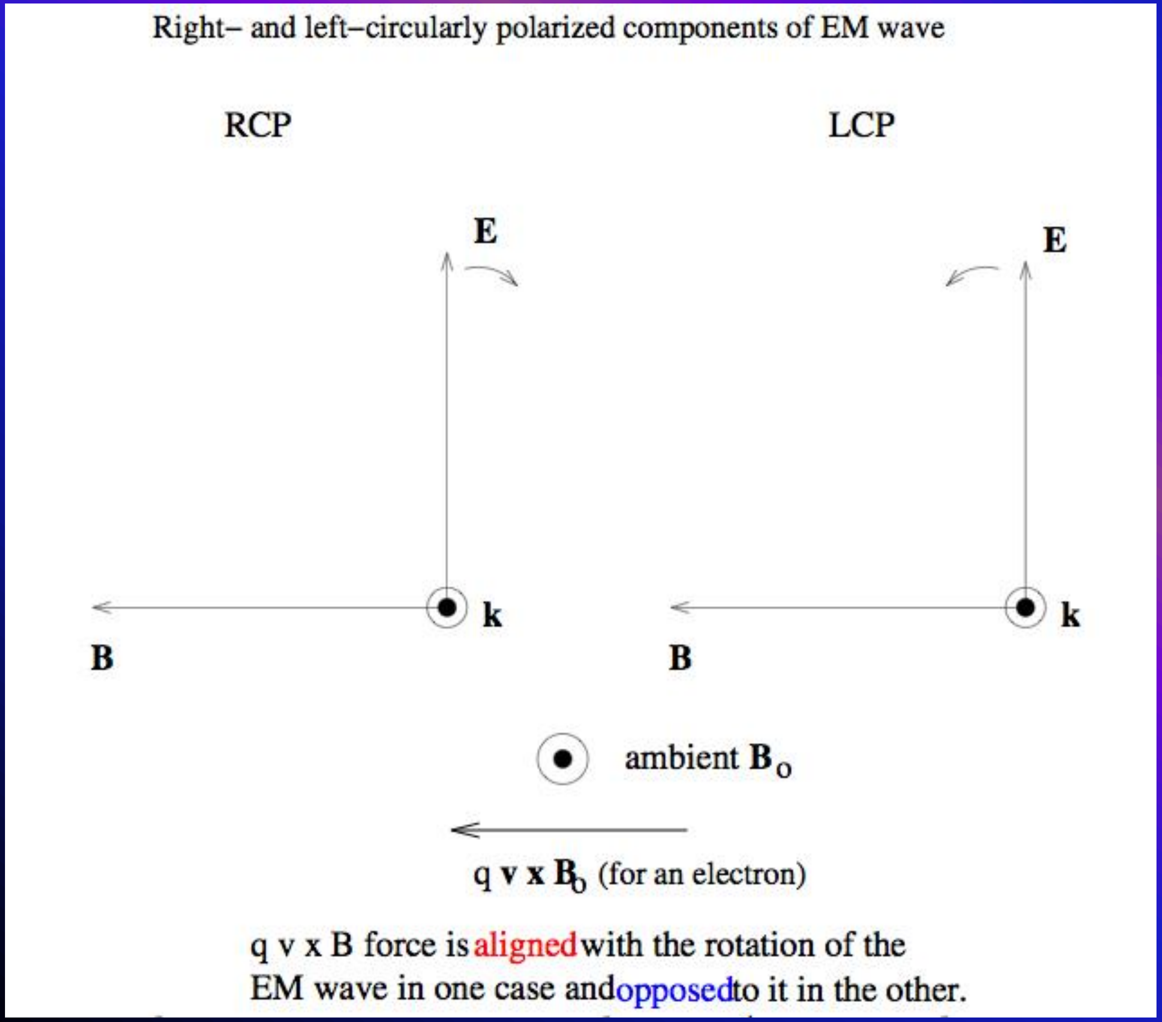
Member of the UCC radio astronomy group analysing the dynamics of a cloth model of a core –jet source in a magnetic field.

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:

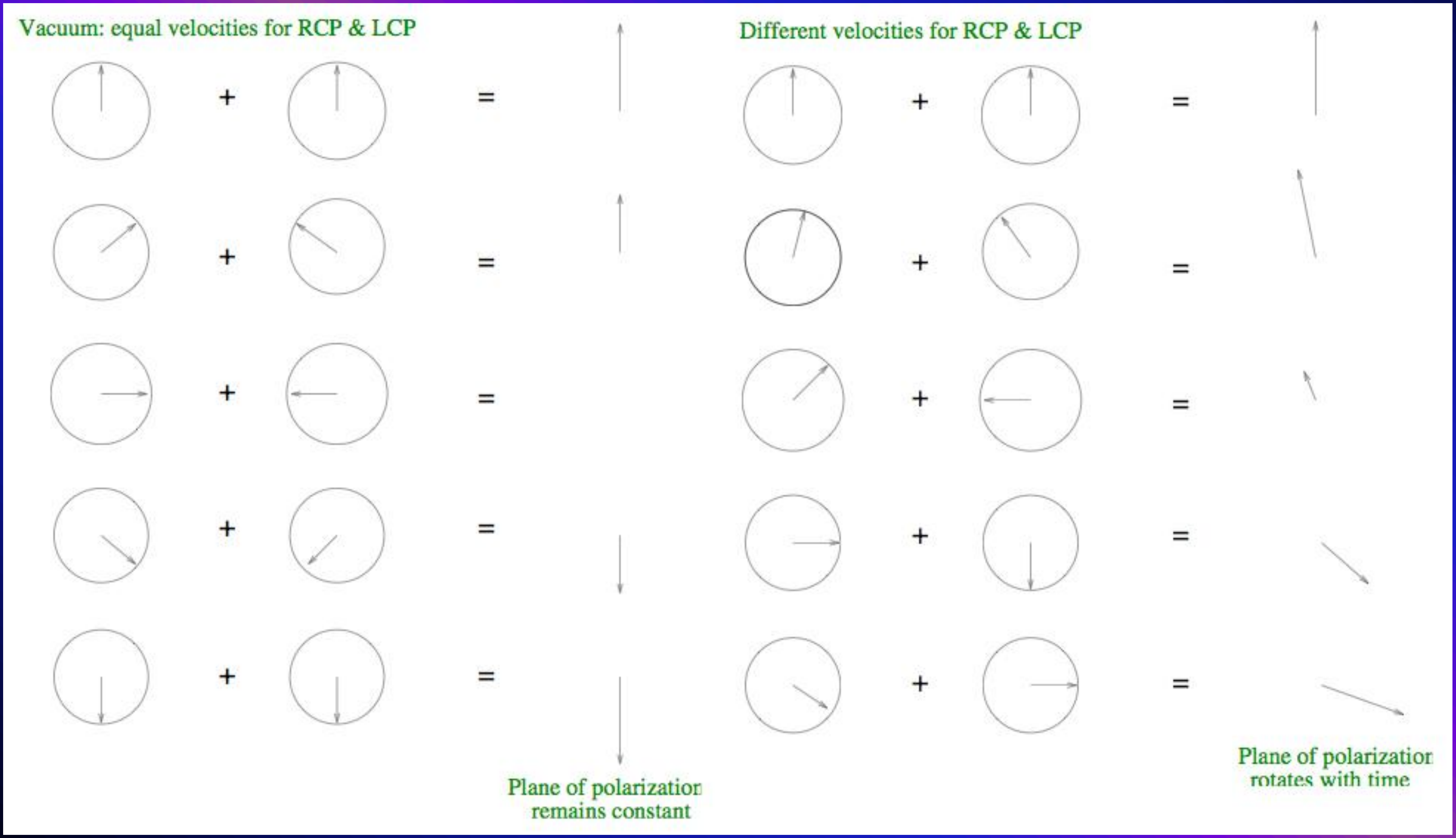
$$-e\vec{E} \pm \frac{eB_o\omega\vec{r}}{c} = -m\omega^2\vec{r}$$

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

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

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

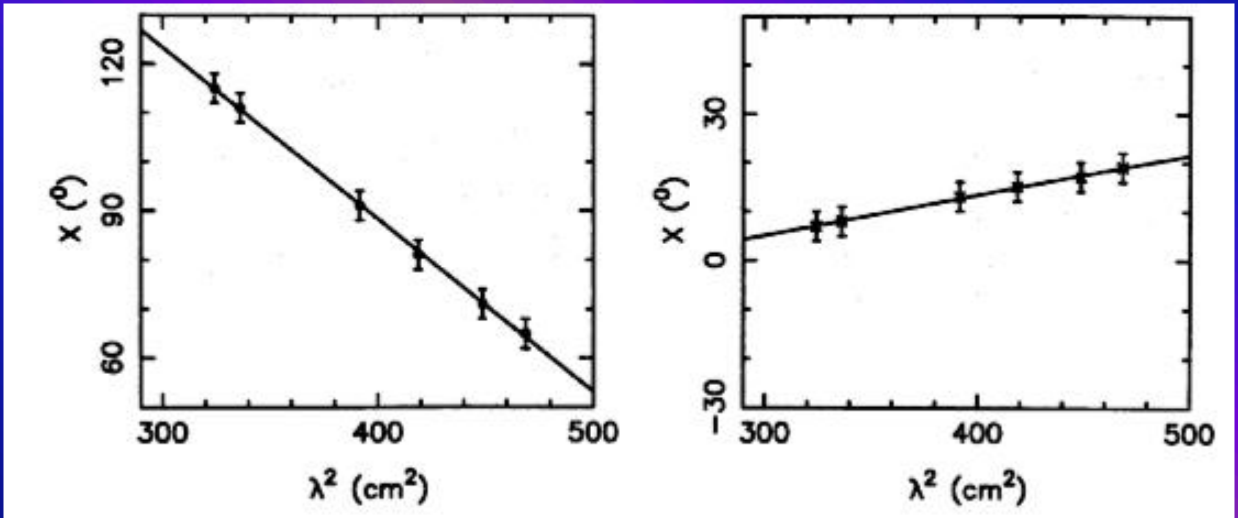
Different speeds of propagation of RCP and LCP componts lead to a rotation in plane of linear polarisation:



Amount of rotation:

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

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

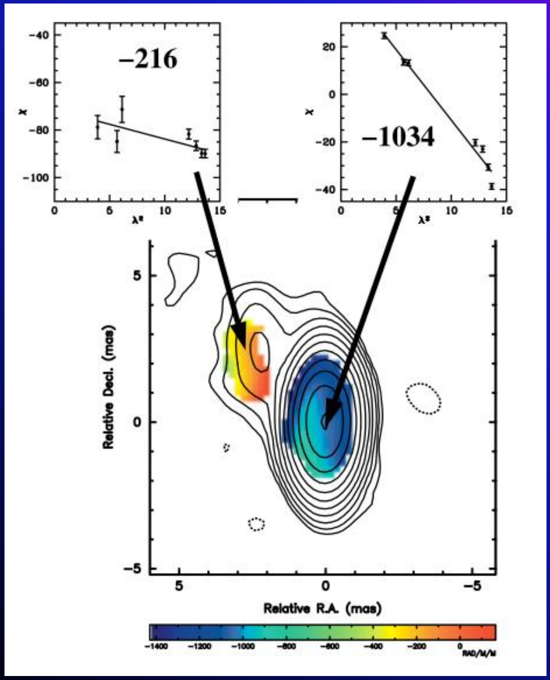


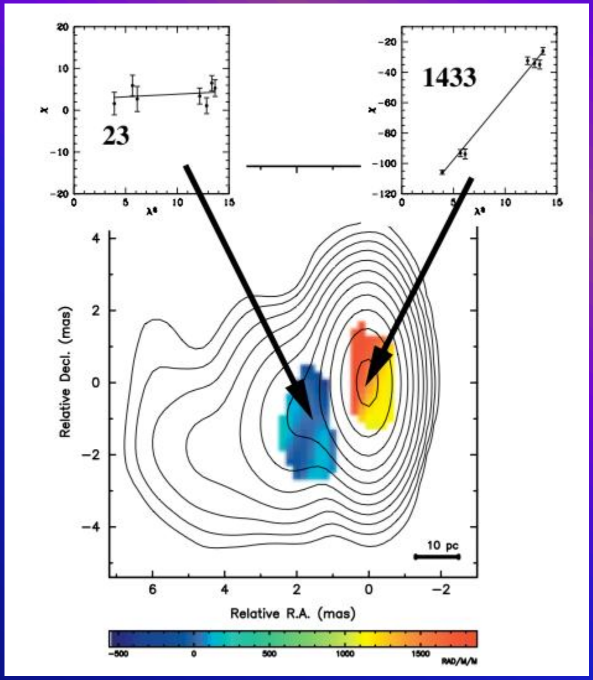
Integrated Faraday Rotaton of two AGNs observed with the VLA (Wrobel 1993).

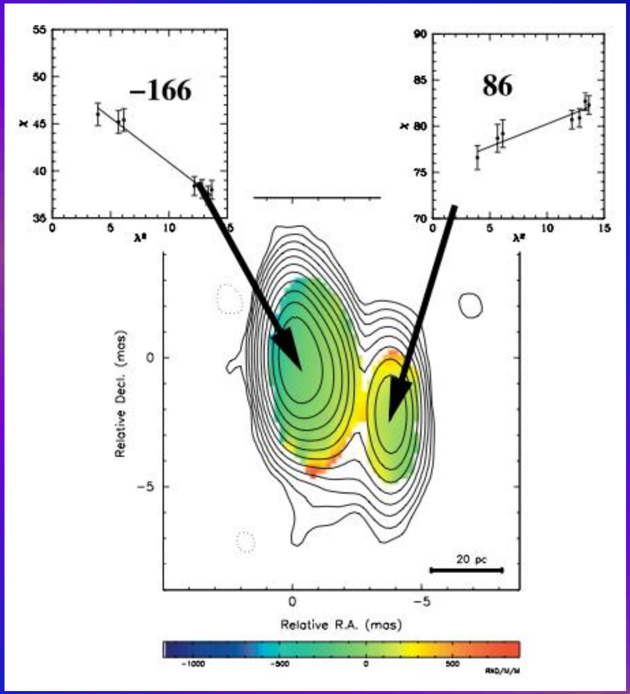
- Linear dependence of rotation of polarisation angle on λ^2.
- Amount of FR depends on n_e and line-of-sight B field
- Line-of-sight component of the ambient B field determines sign of Faraday rotation.

Zavala & Taylor (2003, 2004)

- o 40 objects
- o Core RM > Jet RM (higher n_e and B?)
- o Sometimes sign changes (changes in LOS B field)
- o Quasar core RMs > BL Lac core RMs

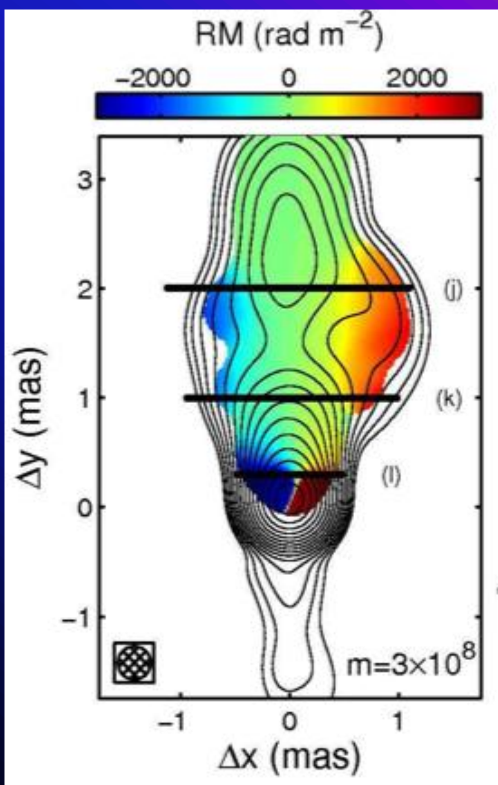




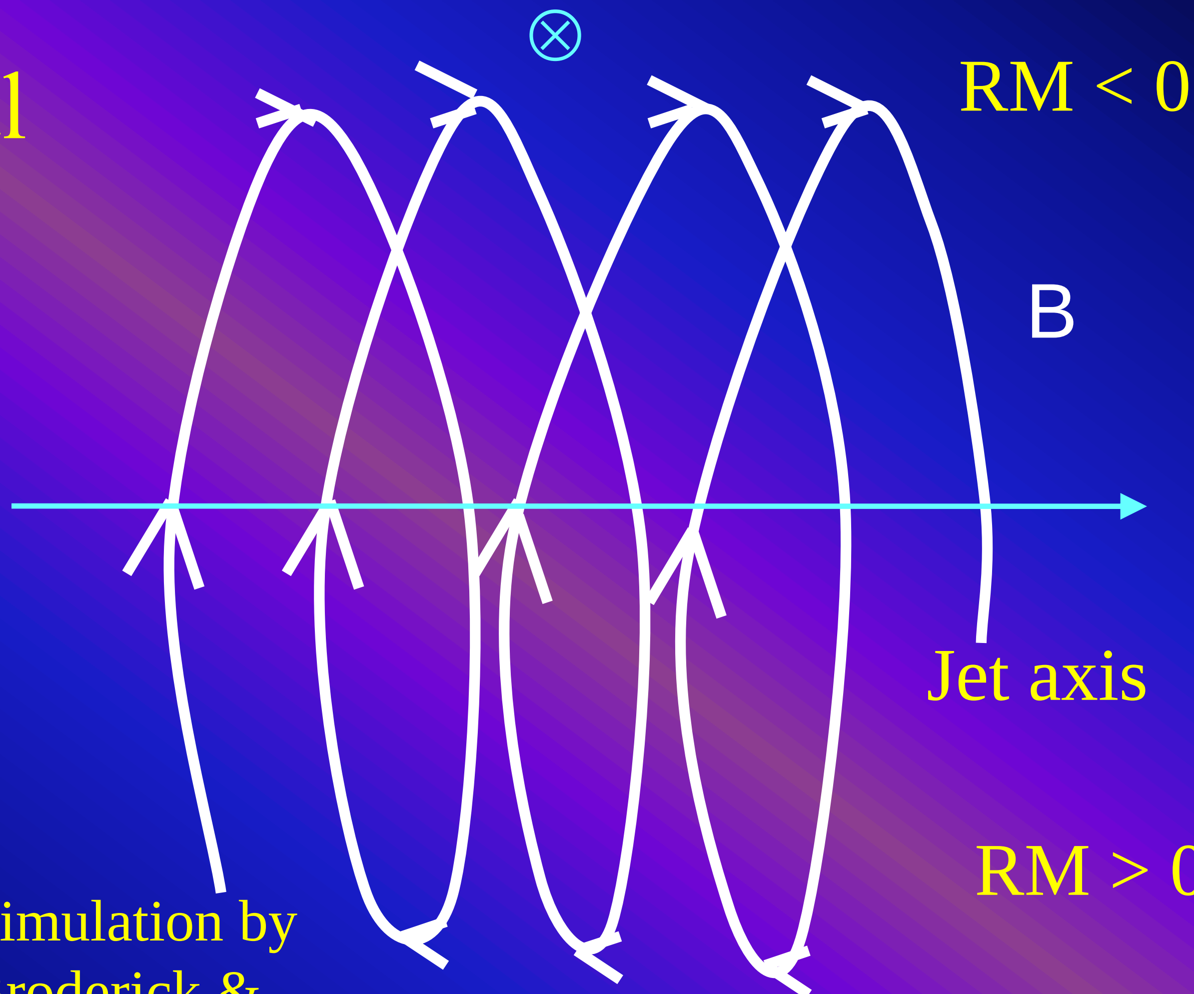


If jet has a helical B field, should observe a Faraday-rotation gradient *across* the jet – due to systematically changing *line-of-sight* component of B field across the jet (Blandford 1993).

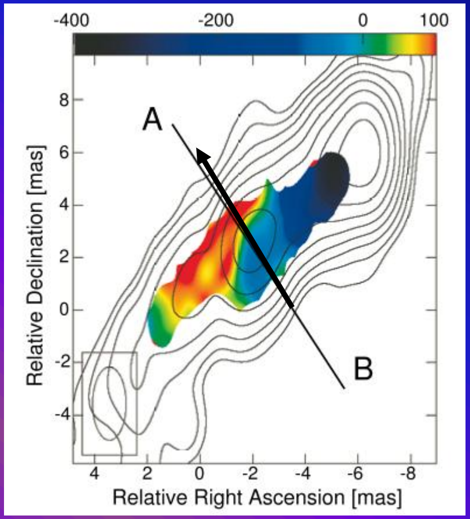
$$RM \sim \int n_e \, B \bullet dl$$



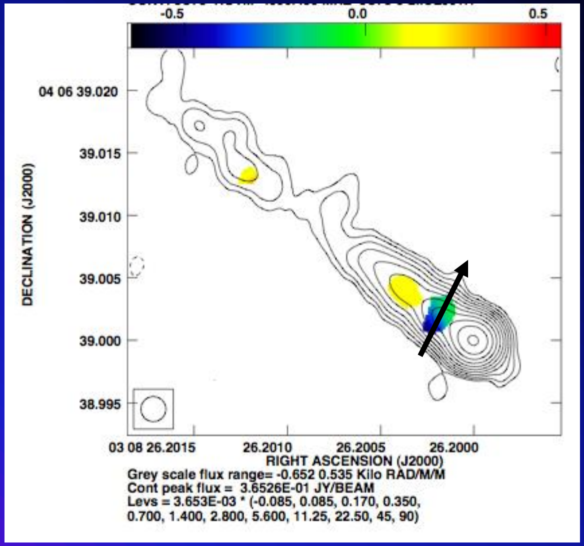
Simulation by Broderick & McKinney 2010

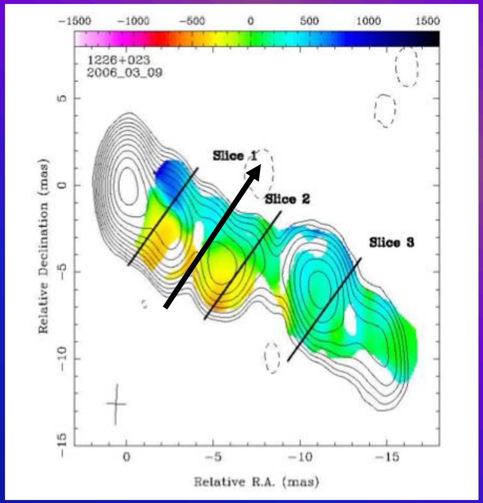


Asada et al. 2008

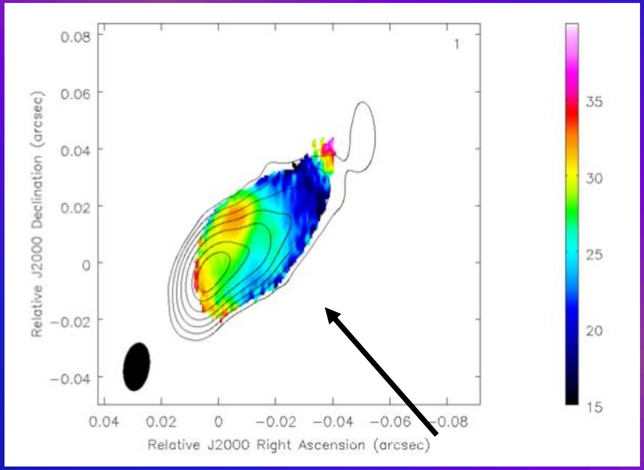


Kharb et al. 2009





Hovatta et al. 2012

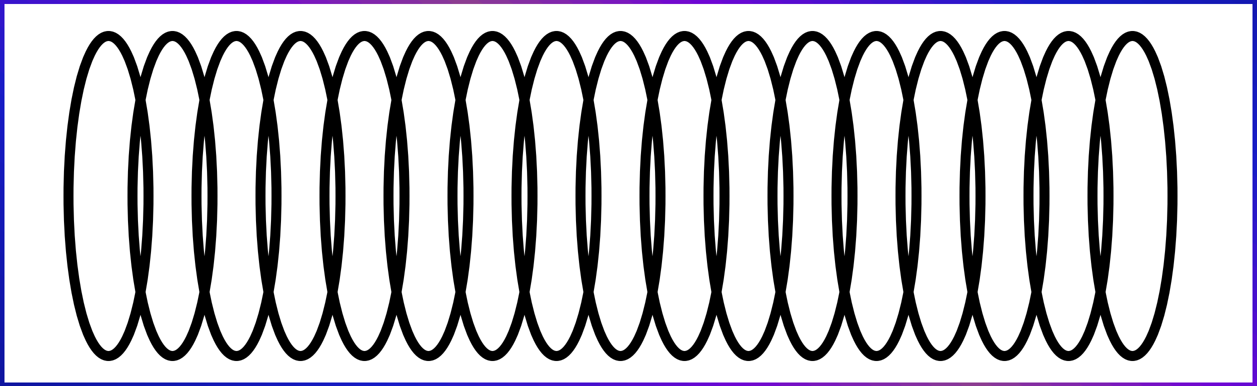


Gabuzda et al. 2013

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

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.



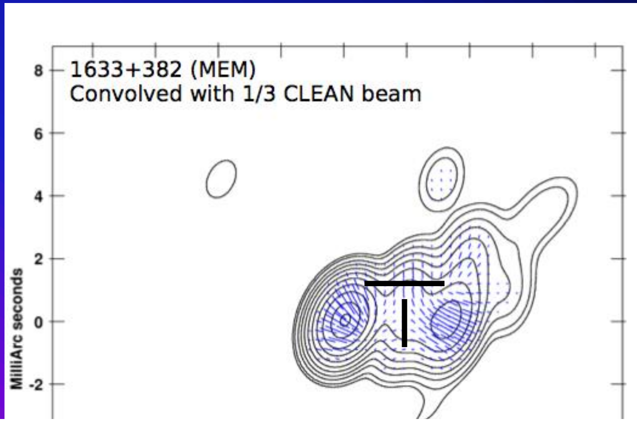
Toroidal

Helical

Observation of asymmetrical transverse profiles provides evidence for helical, not just toroidal, fields.

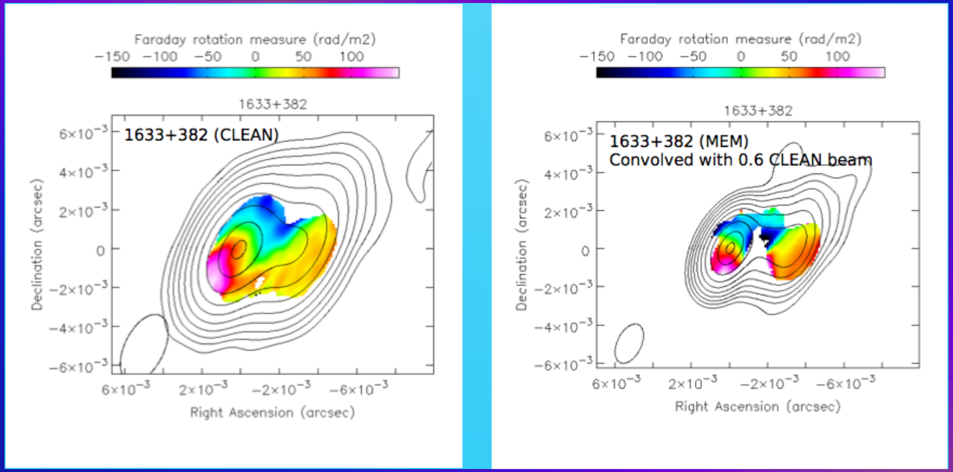
Example – 1633+382 (Coughlan & Gabuzda 2013)

Asymmetric transverse pol structure



+

Transverse RM gradient



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

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

Circular Polarisation and Faraday Conversion

Intrinsic circular polarisation (CP) of synchrotron radiation is low, << 1% for typical core B fields of 0.1–1 G — while observed CP in AGN cores is a few tenths of a percent (e.g. Homan & Lister 2006).

More efficient mechanism: Faraday conversion of linear polarisation (LP) to CP when EM wave passes through magnetised medium (Jones & O'Dell 1977).

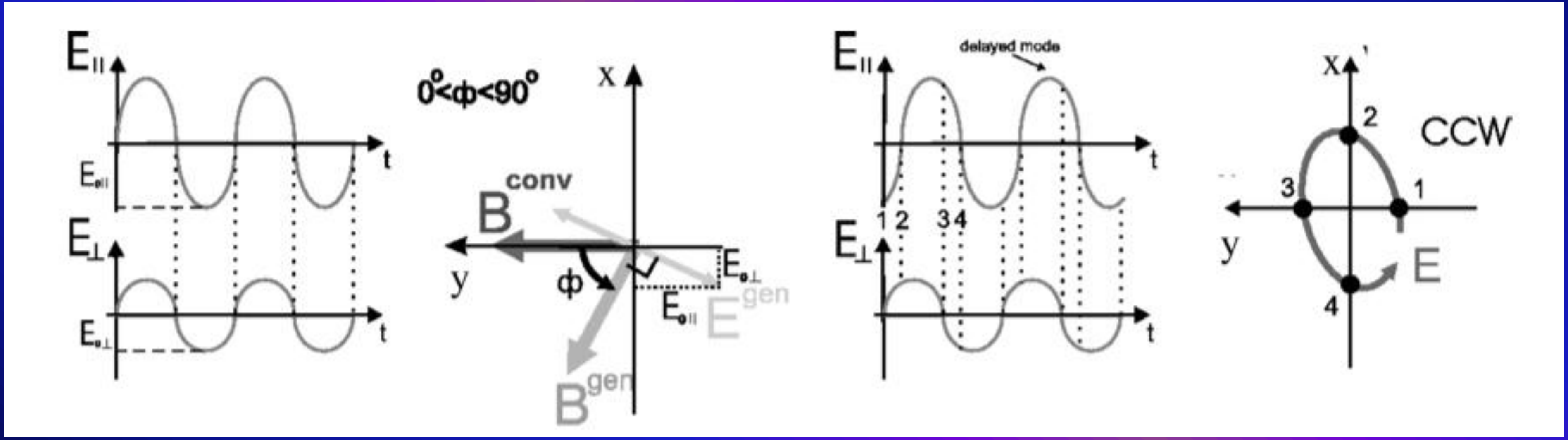
— Describe wave's E field using components parallel to ($E_{\parallel}$) and orthogonal to ($E_{\perp}$) B field in the medium B_{med}

— Free charges in medium can be accelerated by $E_{\parallel}$, but not by $E_{\perp}$ (charges can't move $\perp B_{med}$)

— $E_{\parallel}$ is absorbed + re-emitted (delayed) while $E_{\perp}$ is not

$\Rightarrow$ circular polarisation

Delaying one E component relative to the other is equivalent to introducing a circularly polarised component (figure from Gabuzda et al. 2008):



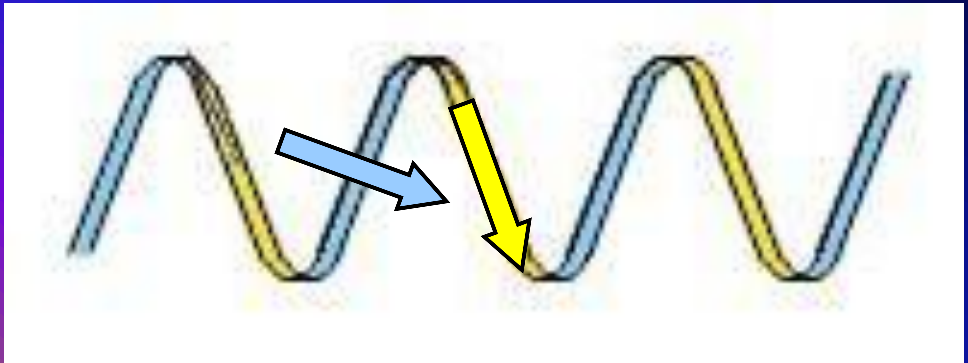
No Faraday conversion will occur when

— LP (E) is orthogonal to B_{med} (electrons in medium cannot move orthogonal to B_{med}, E is not absorbed)

— LP (E) is parallel to B_{med} (all of E is absorbed and re-emitted)

— most efficient when LP (E) neither $\parallel$ nor $\perp$ to B_{med}.

E_{synch}, LP



$B_{hel,fg}$

This makes Faraday conversion efficient in jets with helical B fields (Homan & Wardle 2003, Gabuzda et al. 2008):

• LP emitted at "back" of jet (E_{synch}) is converted to CP as it passes through the foreground helical B field at "front" of jet ($B_{hel,fg}$)

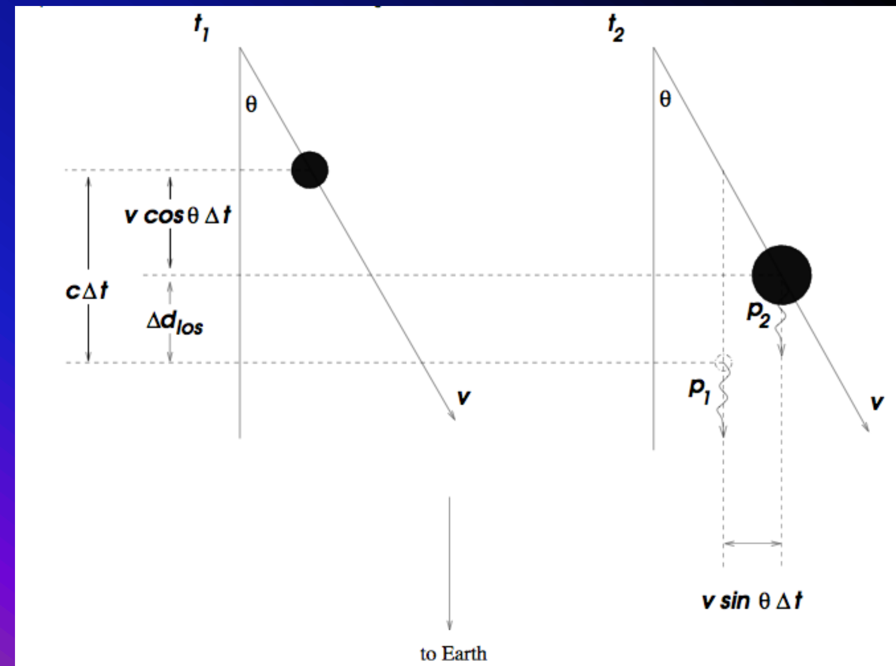
• sign of CP determined by pitch angle & helicity of field

• provides hope for relating observed RM gradients and CP to properties of associated helical jet B fields

A cat who has found something far more interesting than Active Galactic Nuclei!

Derivation of SLM

Measured time between arrival of two photons emitted by source moving roughly toward observer at times separated by time Δt (observer's frame) will be



$$\Delta t_{meas} = \Delta d_{los}/c = (c\Delta t - v \cos\theta\, \Delta t)/c$$

$$\Delta t_{meas} = (1 - \beta \cos\theta)\, \Delta t \qquad \beta = v/c$$

$$v_{app} = d_{sky}/\, \Delta t_{meas} = v \sin\theta\, \Delta t/\, (1 - \beta \cos\theta)\, \Delta t$$

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

Summary – B-field structure

- Jet B fields of AGNs are usually either parallel to or orthogonal to jet direction, expected if jets have roughly cylindrical symmetry

- Core polarizatons show larger range of orientations (reflects higher Faraday rotation present in core region)

- Various mechanisms can give rise to parallel or orthogonal B fields – shocks, shear, curvature, helical B fields. Sometimes not easy to distinguish!

- Helical can be distinguished from toroidal B fields by their asymmetric transverse polarisation structure

Summary - Core B fields

- Core B-field studies now carried out for large numbers of frequencies and large source samples for the first time
- Most results consistent with equipartition in core region
- 15-GHz core B fields range from ~ 0.02 G – 0.8 G
- Data usually consistent with $B \sim r^{-1}$
- Parsec-scale B fields extrapolated to much smaller scales consistent with those predicted for magnetically launched jets
- Core B fields somewhat lower in BL Lac objects than in quasars

Summary – Faraday Rotation

• Core RMs > Jet RMs (higher e^- density and B fields), core RMs lower in BL Lacs than in quasars

• Transverse RM gradients provide direct evidence for helical/toroidal jet B fields

— Jets are fundamentally EM structures, and carry current, which has implications for collimation

• Evidence for return field in region surrounding the jet

• Preference for CW RM gradients across AGN jets (inward axial currents) on pc scales, requires coupling between rotation and axial jet B fields – action of a "Cosmic Battery"? (Contopoulos et al. 2009; Christodoulou et al. 2015).

Summary – Circular Polarisation

- When detected, circular polarisation usually found in VLBI core, at levels of a few tenths of a percent

- Almost certainly due to Faraday conversion, which is much more efficient at generating CP than intrinsic synchrotron radiation, other conditions being equal

- May be efficient in presence of helical jet B fields, providing hope of carrying out joint analyses of pol structure, Faraday rotation structure and CP degree and sign in core