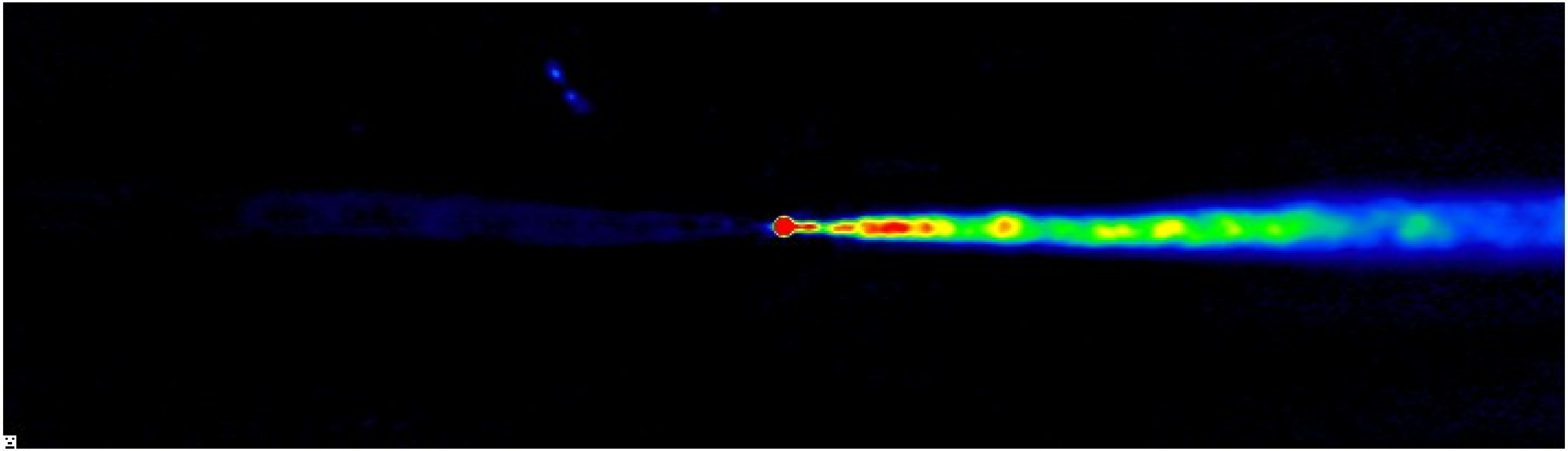
Magnetic fields in kiloparsec-scale Relativistic Jets

Robert Laing (ESO)



Outline

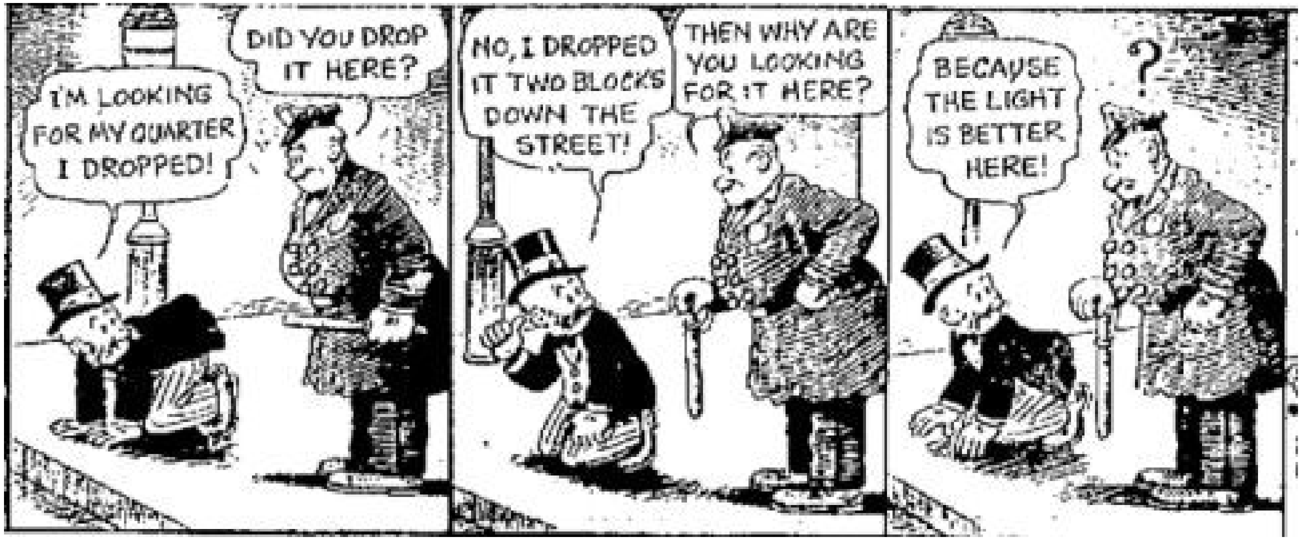
Background

Strong and weak-flavour jets

Jet modelling methods

1 A strong-flavour jet: NGC 6251

2 Weak-flavour jets

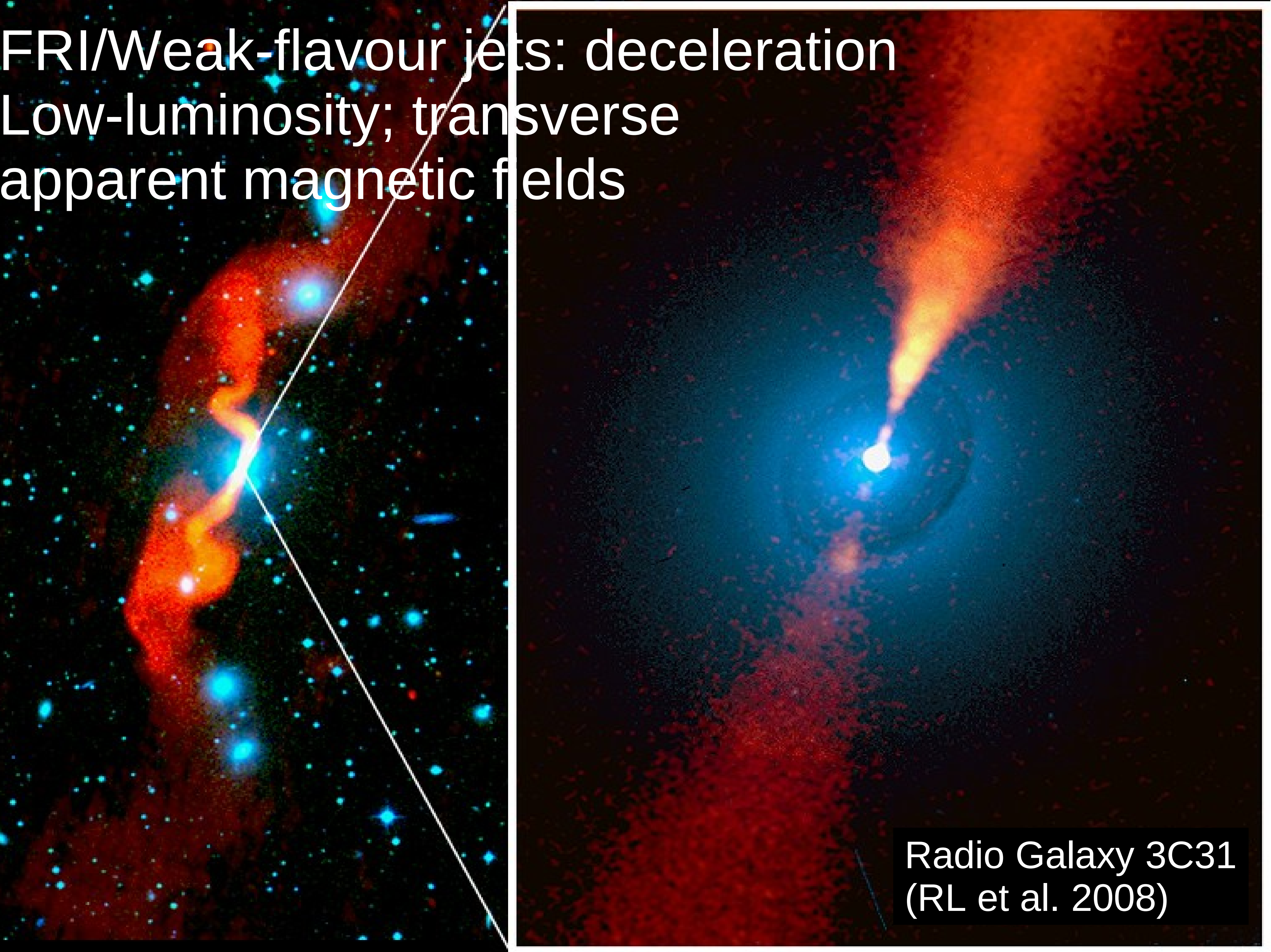


We really want to know how jets are formed – but the (synchrotron) light is brighter two blocks (kpc) downstream

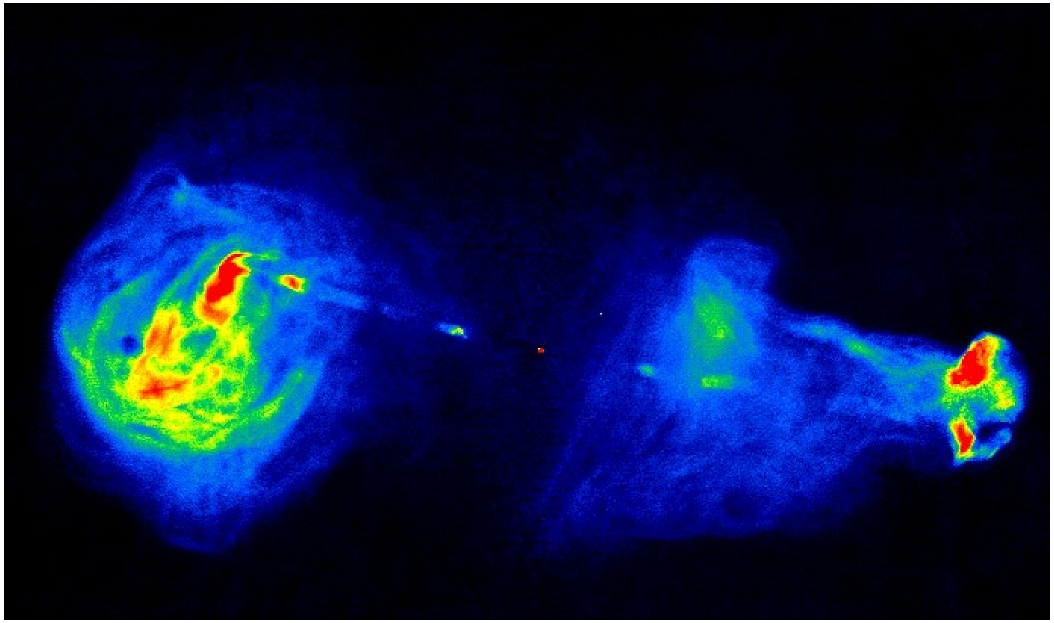
What do we want to know?

- **Magnetic-field topology**
  - **Component ratios: toroidal:longitudinal:radial**
  - **Vector-ordered or disordered?**
- **What are the jet velocity fields**
  - **Deceleration**
  - **Transverse structure**
- How does jet composition change with distance?
  - Leptons and baryons; mass flux and entrainment rates
- What are the energy and momentum fluxes?
- Confinement
  - Gas pressure, B-field, not at all, ...
- Effects on external environment
  - Energy input, shocks, magnetic field

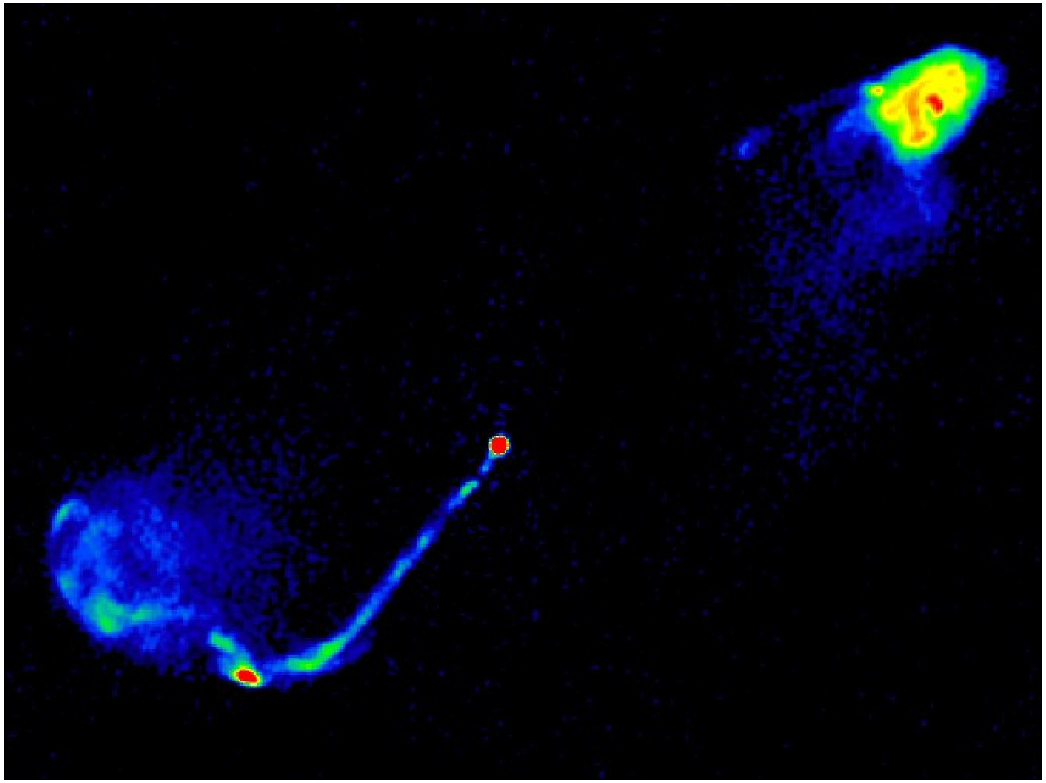
FRI/Weak-flavour jets: deceleration
Low-luminosity; transverse apparent magnetic fields



FRII/Strong-flavour Jets – always fast? Powerful; longitudinal apparent fields

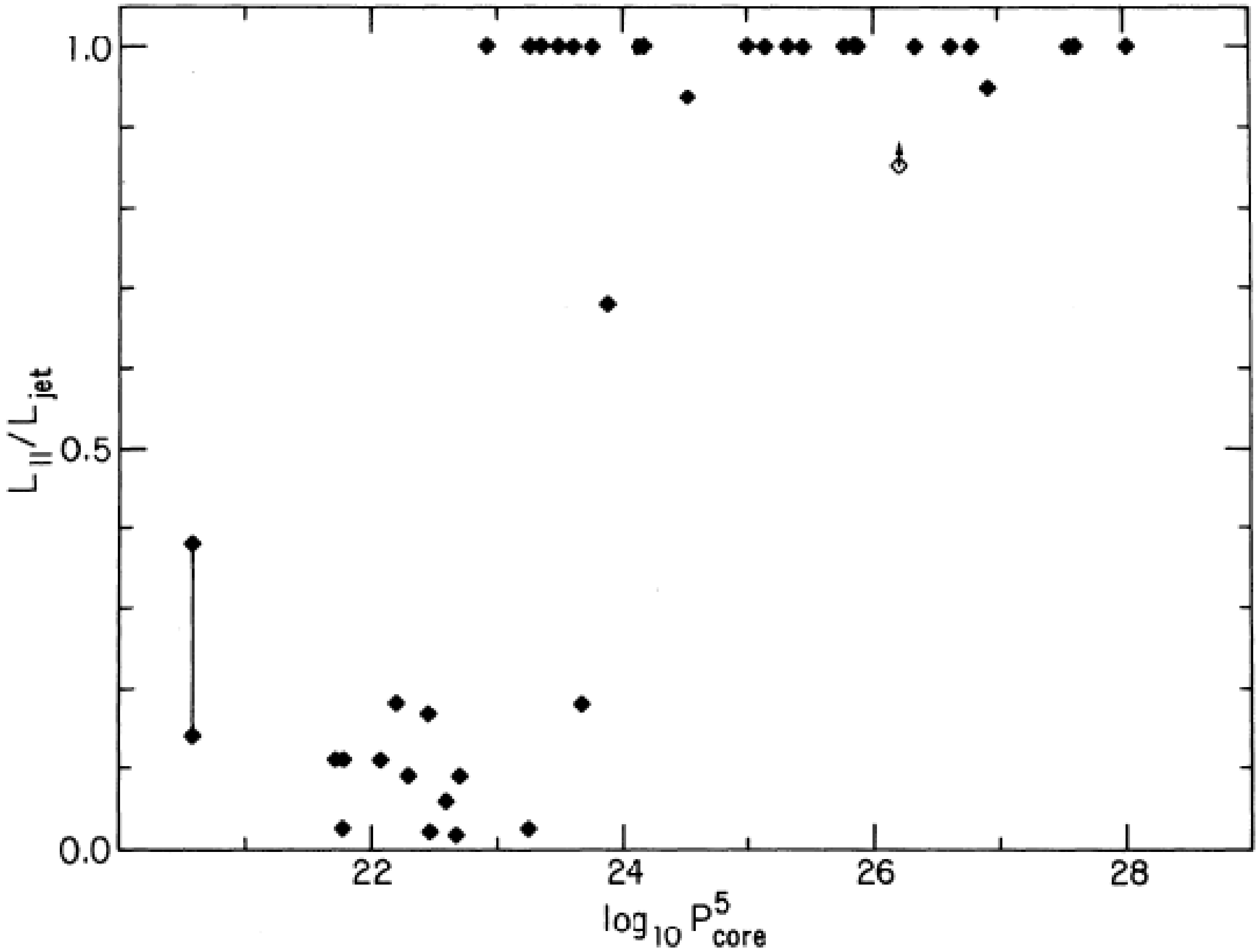


3C353: Swain, Bridle & Baum



3C334: Bridle et al.

Apparent field direction and radio luminosity



Bridle (1984)

Jet Models

- What distributions of flow velocity, field geometry and rest-frame emissivity are consistent with observations?
- Observe:
  - Deep, high-resolution radio images; IQU, corrected for Faraday rotation
- Assume:
  - Symmetrical, axisymmetric, stationary, relativistic flow
  - Power-law energy distribution, optically-thin synchrotron
- Parametrised model of:
  - Geometry
  - Velocity field in 3D
  - Emissivity
  - Magnetic-field component ratios
- Calculate I, Q, U; optimise

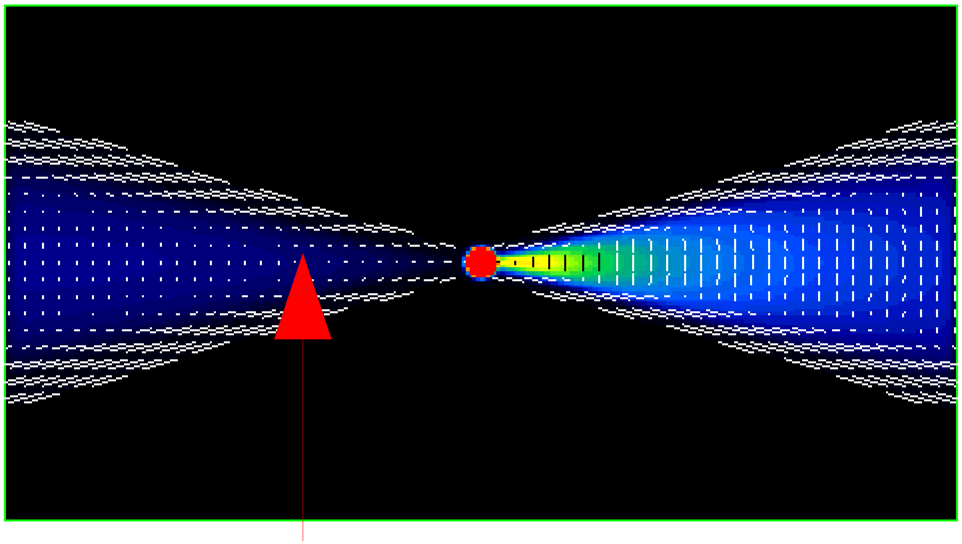
How does this work?

- Assumption of intrinsic side-to-side symmetry **close to AGN**
- Modelling side-to-side asymmetries
  - Total intensity alone is not enough: ratio

    $I_j/I_{cj} = [(1+\beta\cos\theta)/(1-\beta\cos\theta)]^{2+\alpha}$

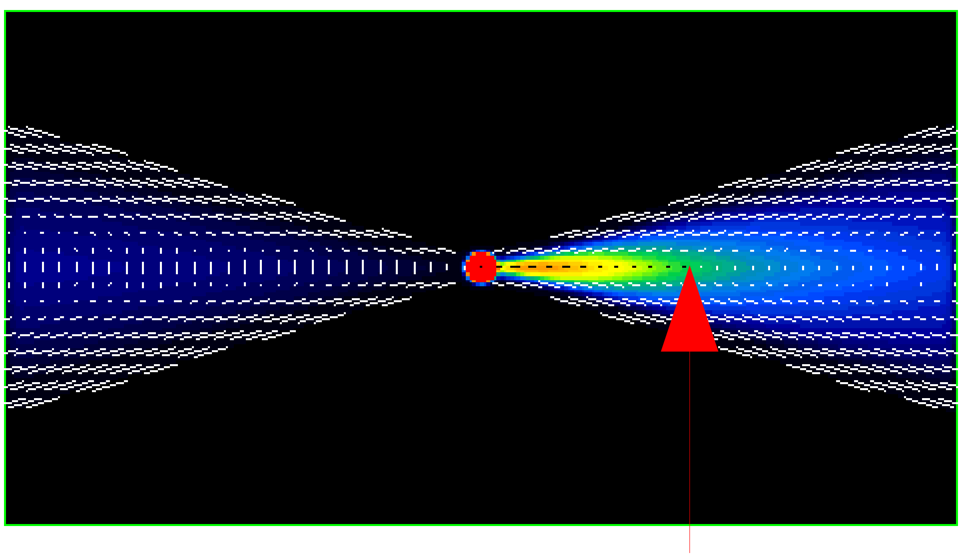
    depends only on $\beta\cos\theta$ for isotropic rest-frame emission ...
  - ... but polarized emission cannot be isotropic in rest frame
  - Use both I and linear polarization, for which asymmetries depend on a different combinations of β and θ
  - Aberration → we look at approaching and receding jets at different angles to the line of sight in the rest frame
  - Enough information to separate β and θ if we know the field structure a priori ....
  - ... which we don't, so need to fit
- Hence need good S/N and transverse resolution in IQU

Understanding the field structure



2D transverse field sheets on-axis + longitudinal field shear layer

Wrong



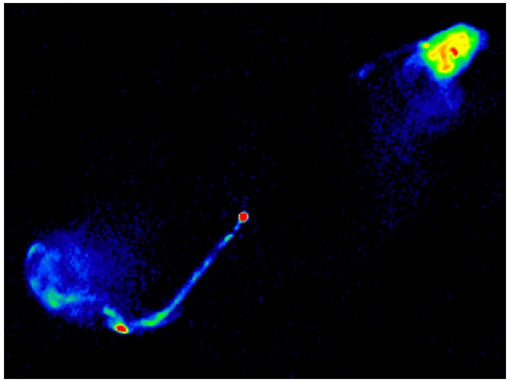
2D toroidal and longitudinal; component rms equal

Right

Longitudinal – transverse field transition

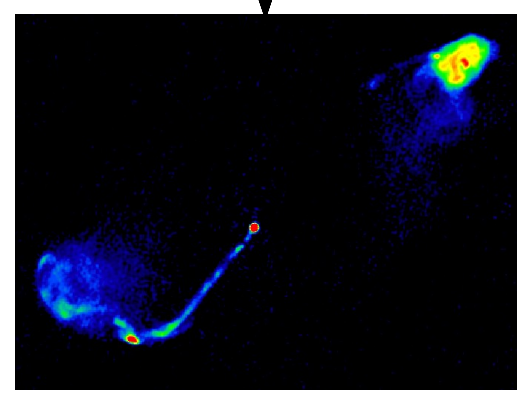
(1) Strong-flavour jets

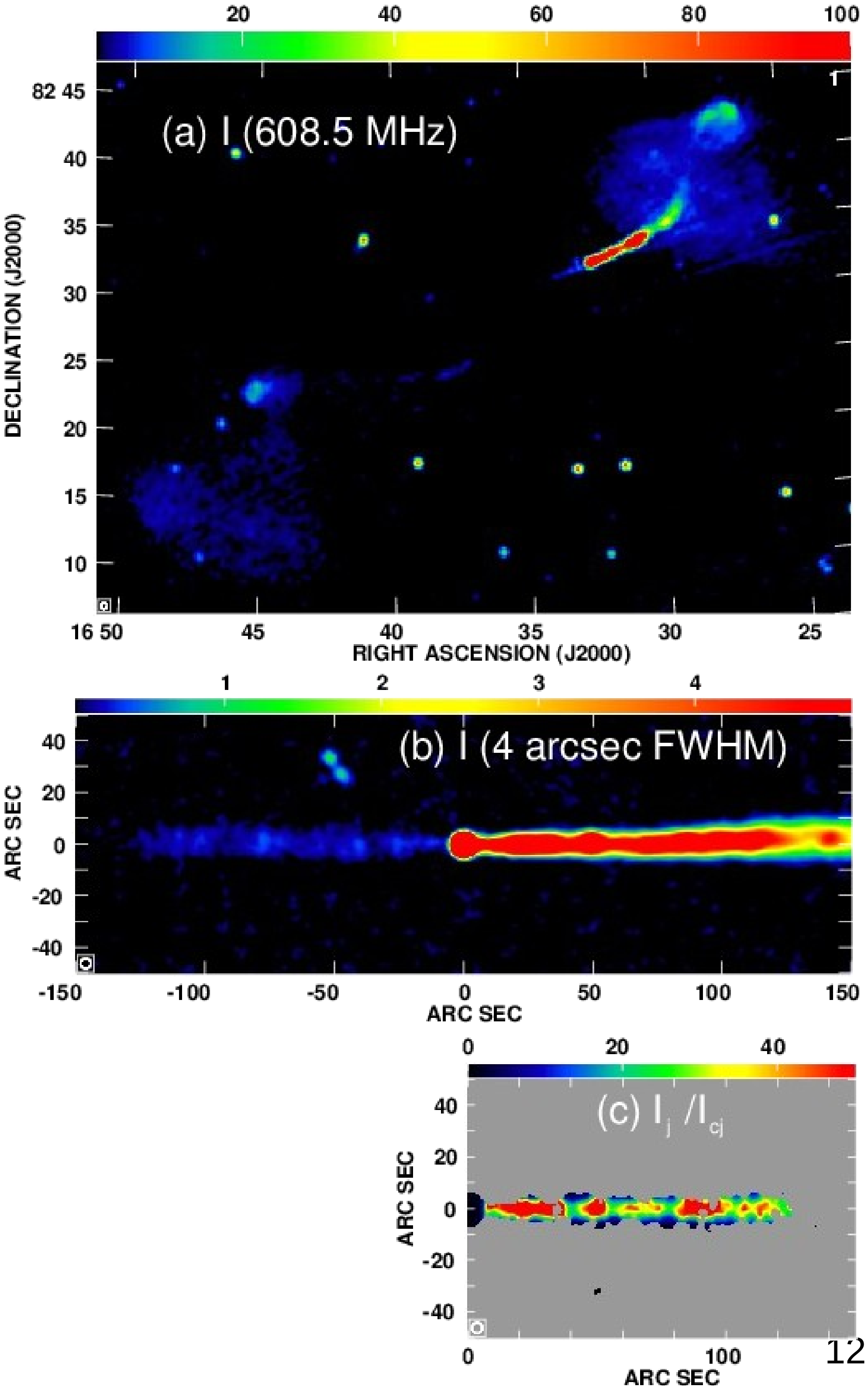
- At least mildly relativistic velocities on kpc scales:
  - Depolarization asymmetry (RL, Garrington et al. 1988)
  - Continuity of sidedness from pc scales, where there is ample evidence for highly relativistic motion ....
  - ... very hard to decelerate powerful jets without destruction
- But:
  - Integrated jet/counter-jet rations → $\beta \approx 0.6$ (Wardle & Aaron; Mullin & Hardcastle)
  - Beamed inverse Compton X-rays require $\Gamma \approx 10$ (Tavecchio et al.;Celotti et al.) ....
  - ... as do proper motions on pc scales
- Spine/layer models?
  - $\Gamma \approx 10$ spine surrounded by $\Gamma \approx 2$ (shear?) layer?
- Longitudinal apparent field
  - What is the 3D structure?



Observing strong-flavour jets is painful

- Narrow
- Faint (especially the counter-jets)
- Emission superimposed on lobes, which have filaments and other ~~junk~~ emission of great interest
- Really need resolution <0.05 arcsec; sensitivity <10 nJy/beam and dynamic range >10^7
- While waiting for this, try
  - Cygnus A (very bright) - in progress
  - NGC 6251 (a transition case)
    - Jansky VLA
    - 5-7 GHz
    - 1.5 arcsec resolution
    - Fighting interference, dynamic range and leakage corrections, but can show preliminary results .....





NGC6251

Transition case between weak and strong flavour jets

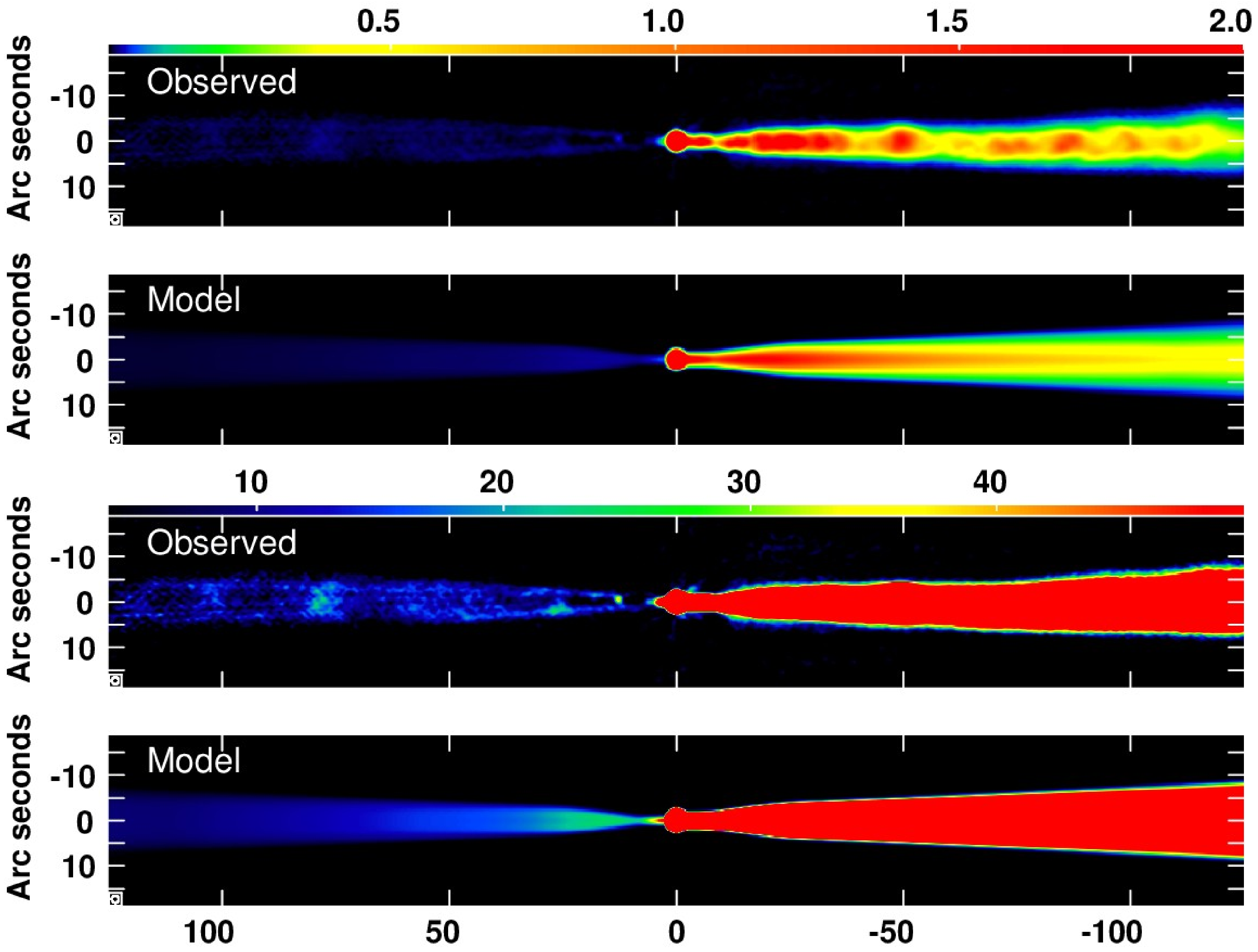
Giant radio galaxy NGC6251 (z=0.0247;1.8 Mpc projected)

Collimated jets

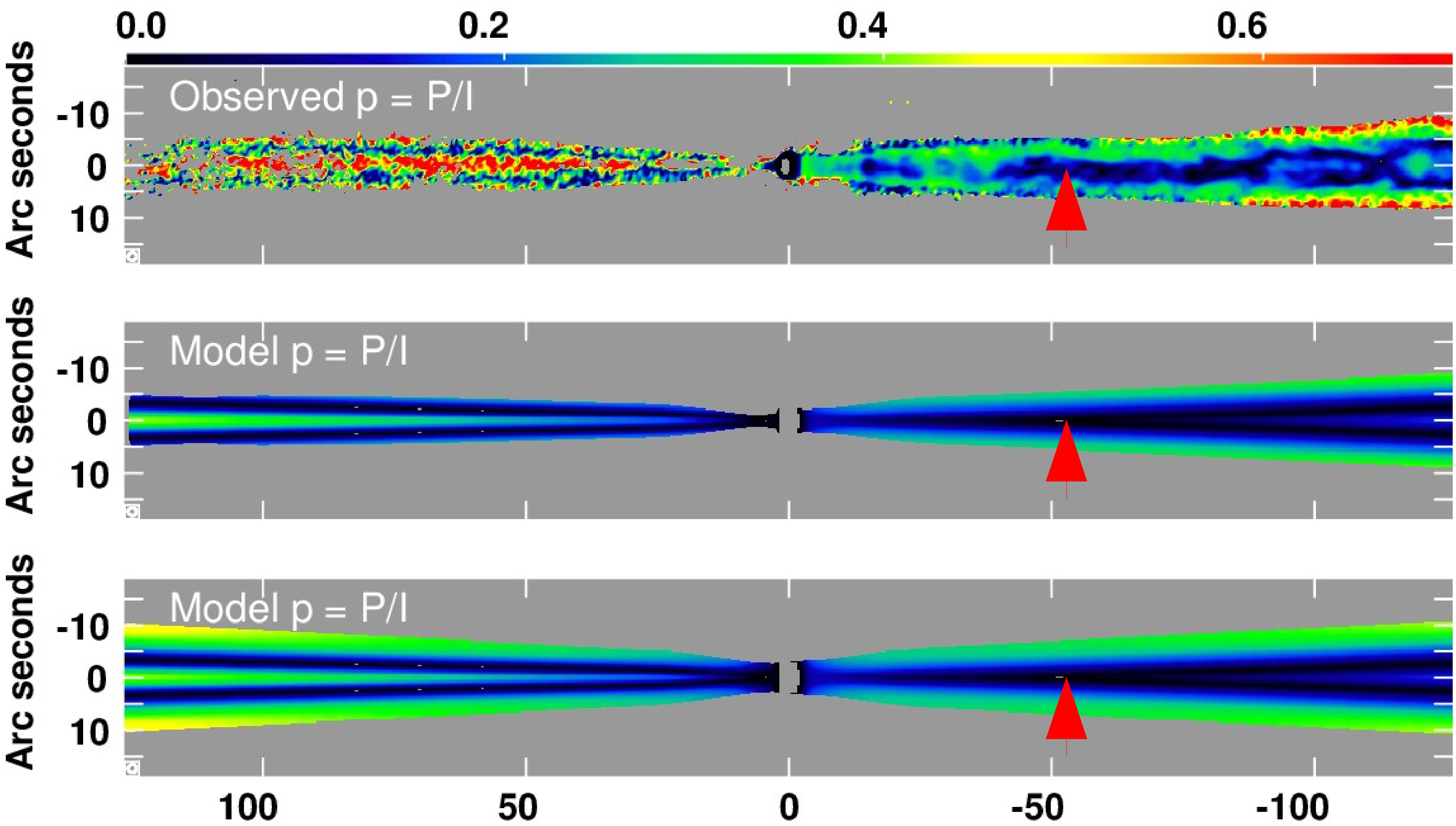
Jet/counter-jet ratio is high at all distances

Fermi LAT detection:
- variable
- emission from outer main jet instead of/as well as core? (Abdo et al. 2010; Grandi et al. 2013)

Observed and model I

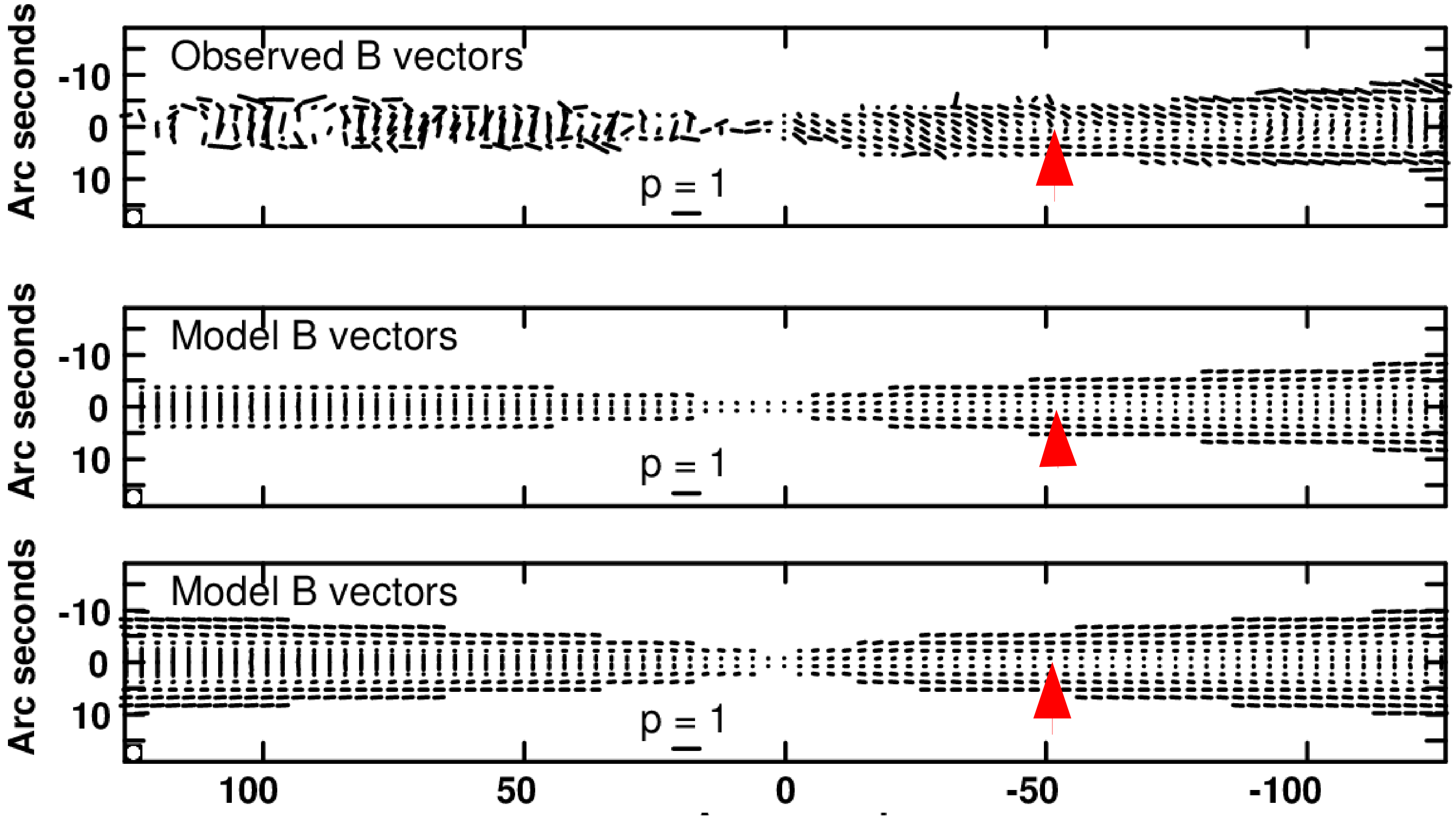


Observed and model fractional polarization



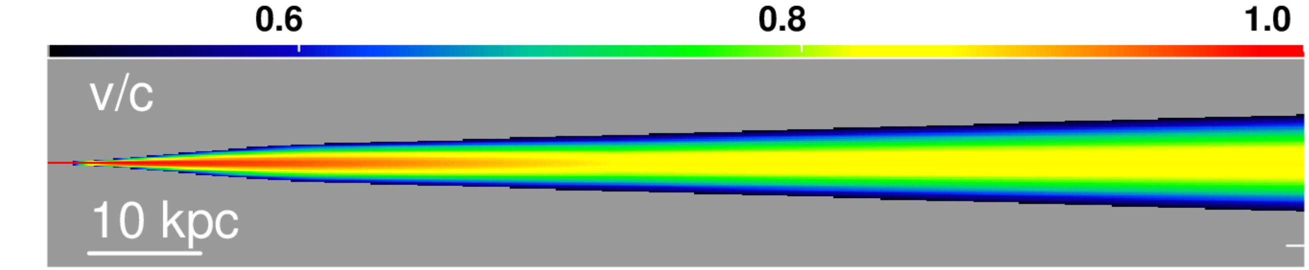
= longitudinal – tranverse apparent field transition

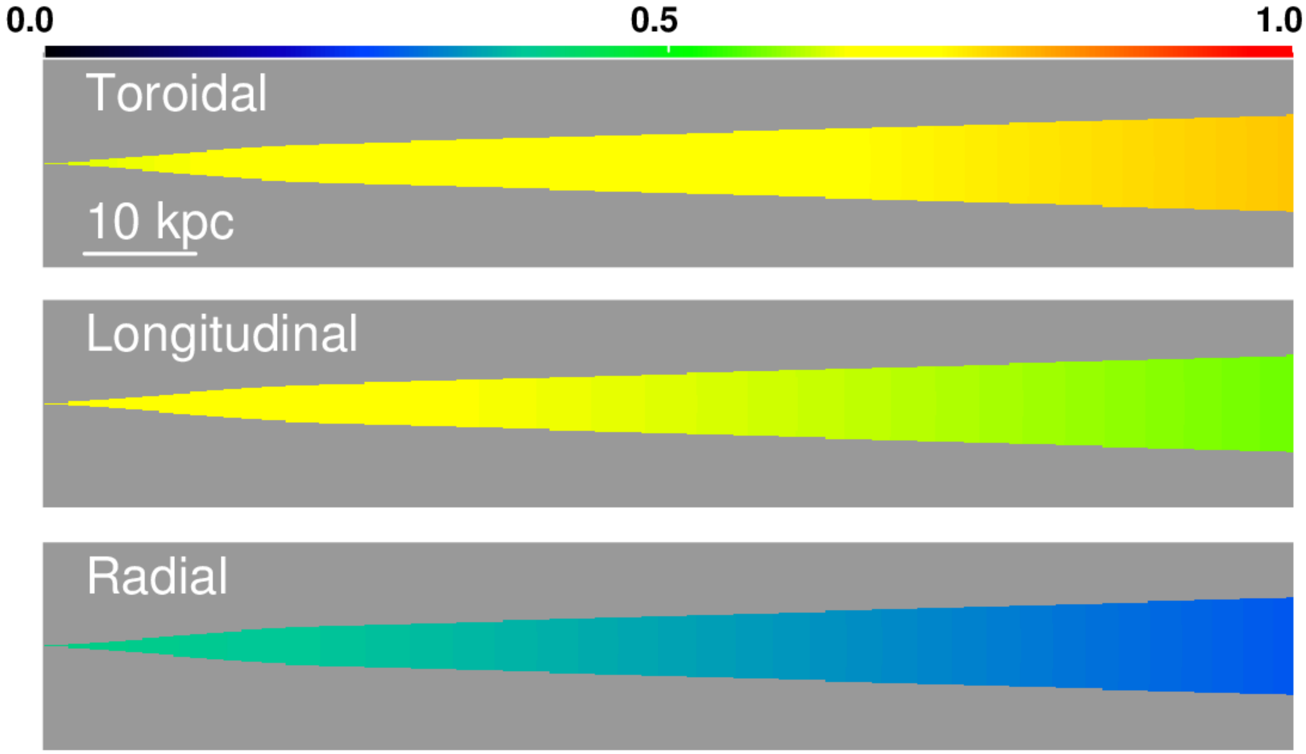
Observed and model B vectors



Caution: Faraday rotation corrections uncertain

Velocity and Magnetic Field Structure





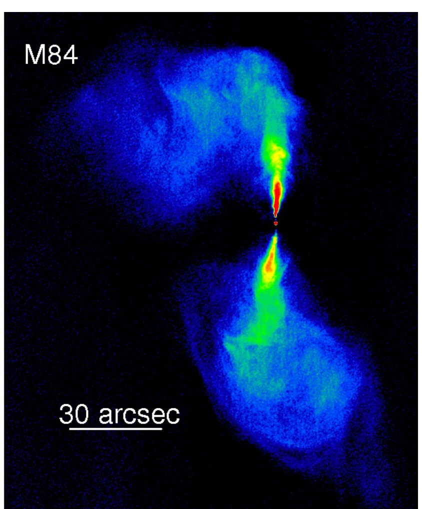
Best fit (so far)

- Geometry
  - $\theta = 34^o$
- Velocity
  - Deceleration from $\beta = 0.992$ ($\Gamma = 8$) to $\beta = 0.86$ ($\Gamma = 2$) on-axis
  - Edge velocity ~constant ($\beta = 0.55$ to $\beta = 0.51$)
  - At large distances, velocity is well constrained at edge; could be larger on-axis
  - **Assumed transverse profile (truncated Gaussian) does not give enough limb-brightening in counter-jet – modify assumed functional form**
- Magnetic field
  - Longitudinal and toroidal components comparable close to AGN; toroidal becomes dominant at larger distances

(2) How does NGC6251 compare with weak-flavour jets?

Laing & Bridle (2014)

10 radio galaxies
0.015 < z < 0.05
Low-power, FRI

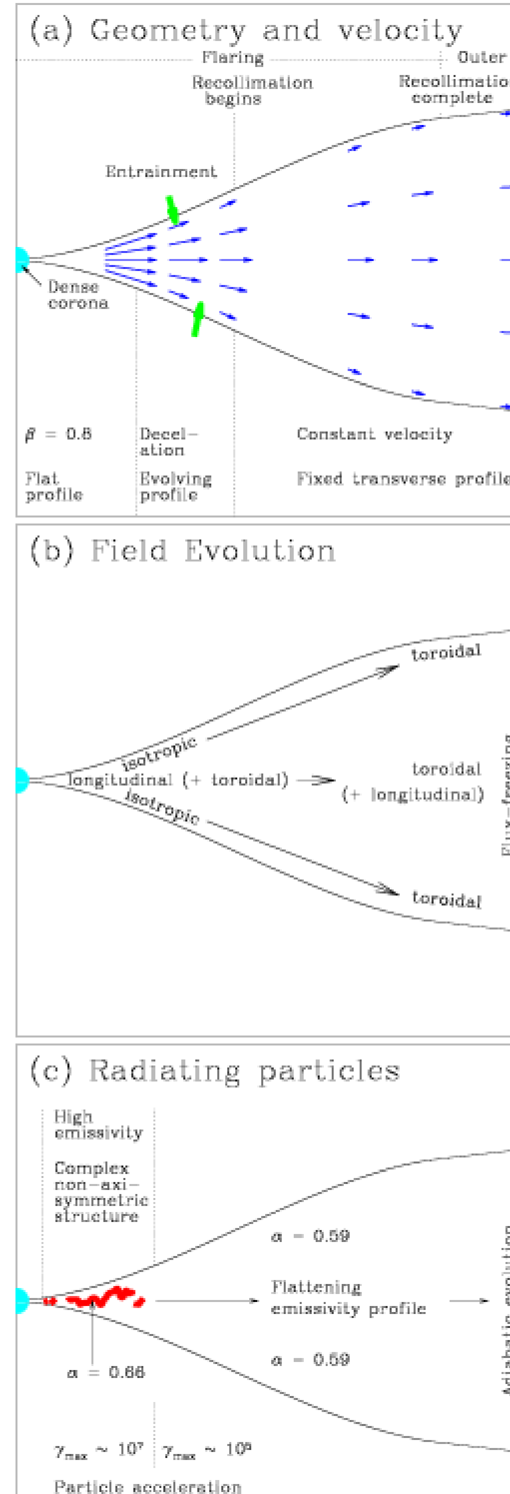


Differences:

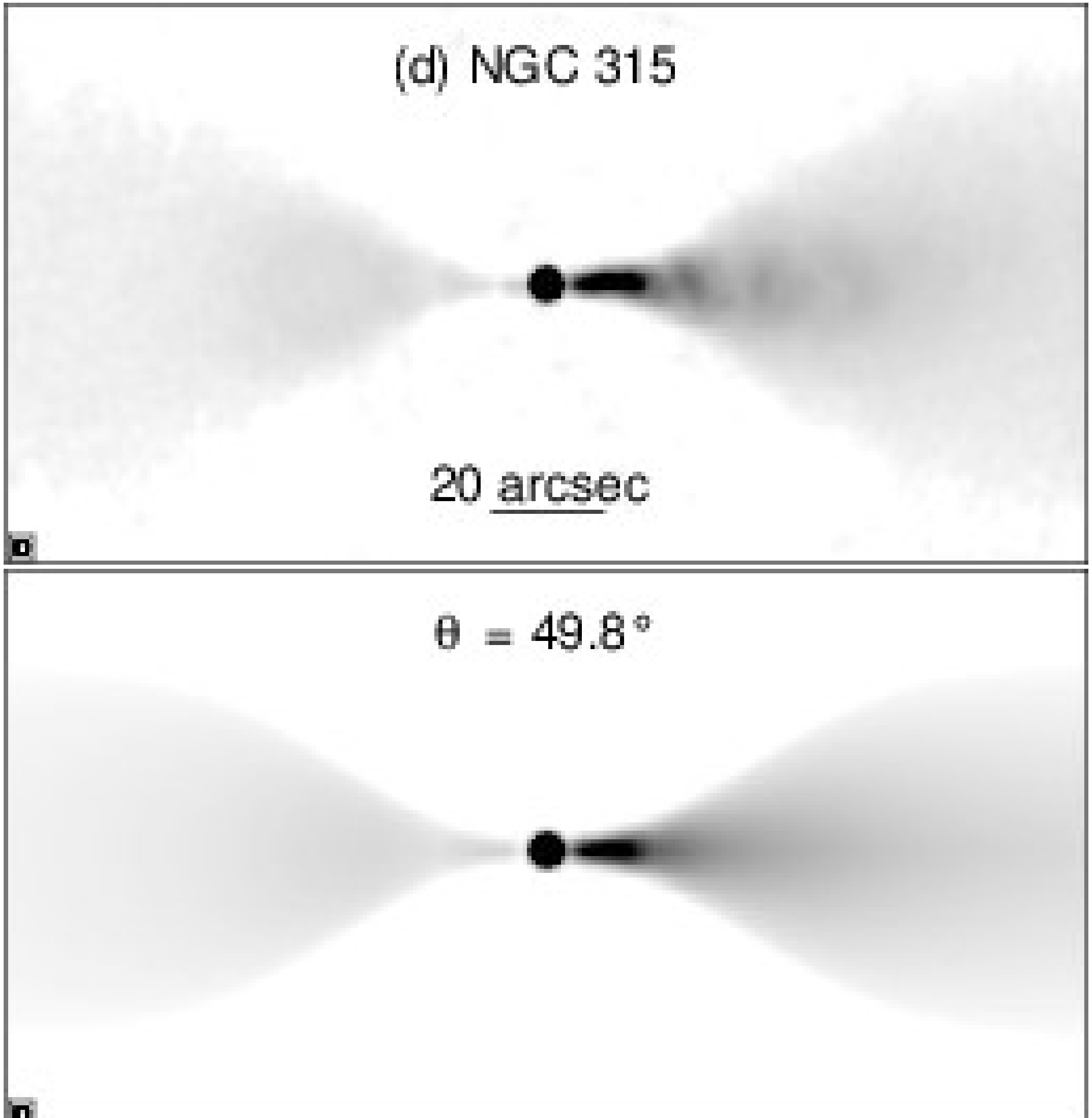
Weak flavour jets:
- expand rapidly
- decelerate from Γ≈2 to Γ≈1

Similarities:

- Longitudinal → toroidal field
- Transverse velocity gradients



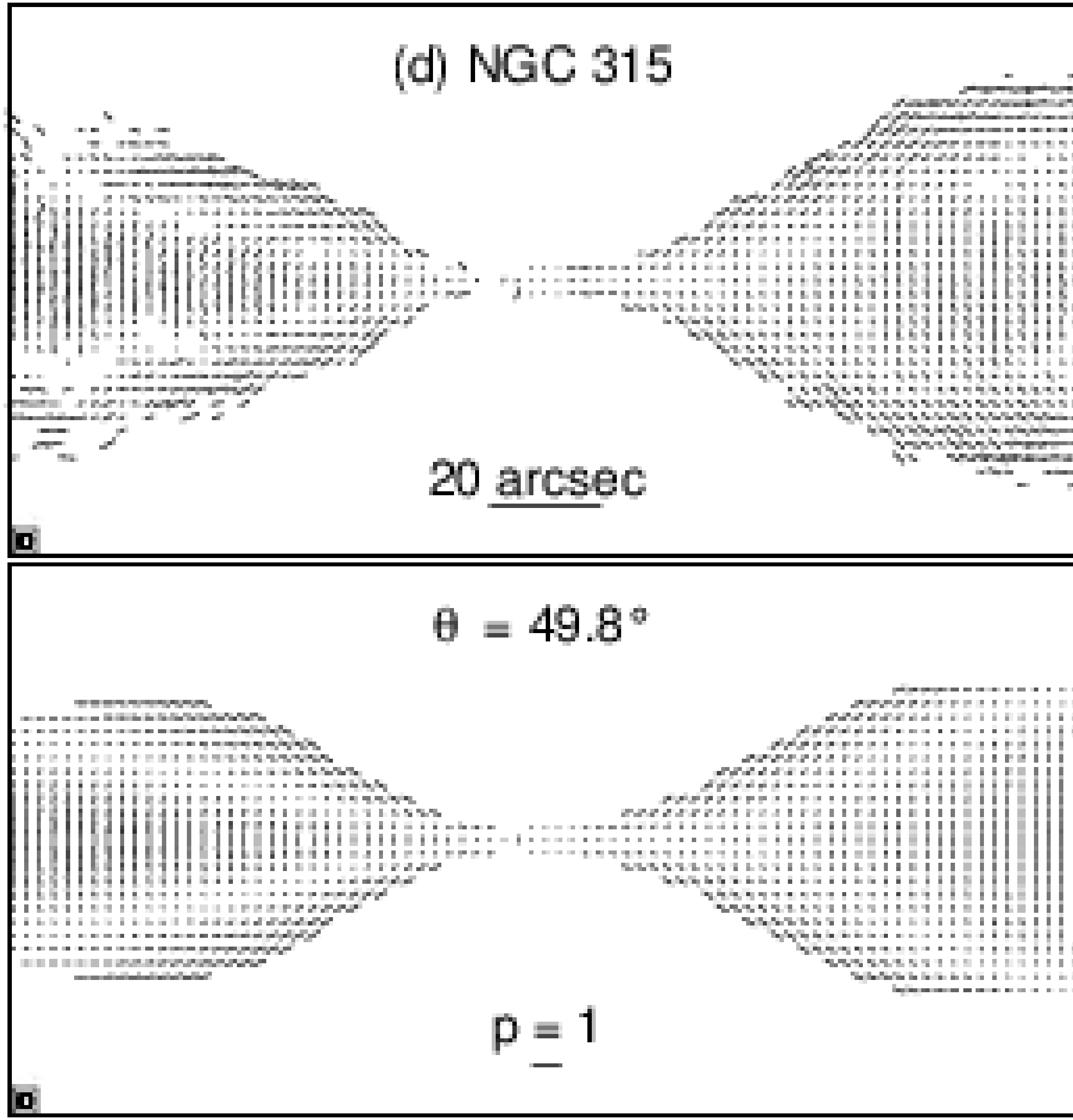
An example: I model



How important are intrinsic asymmetries?

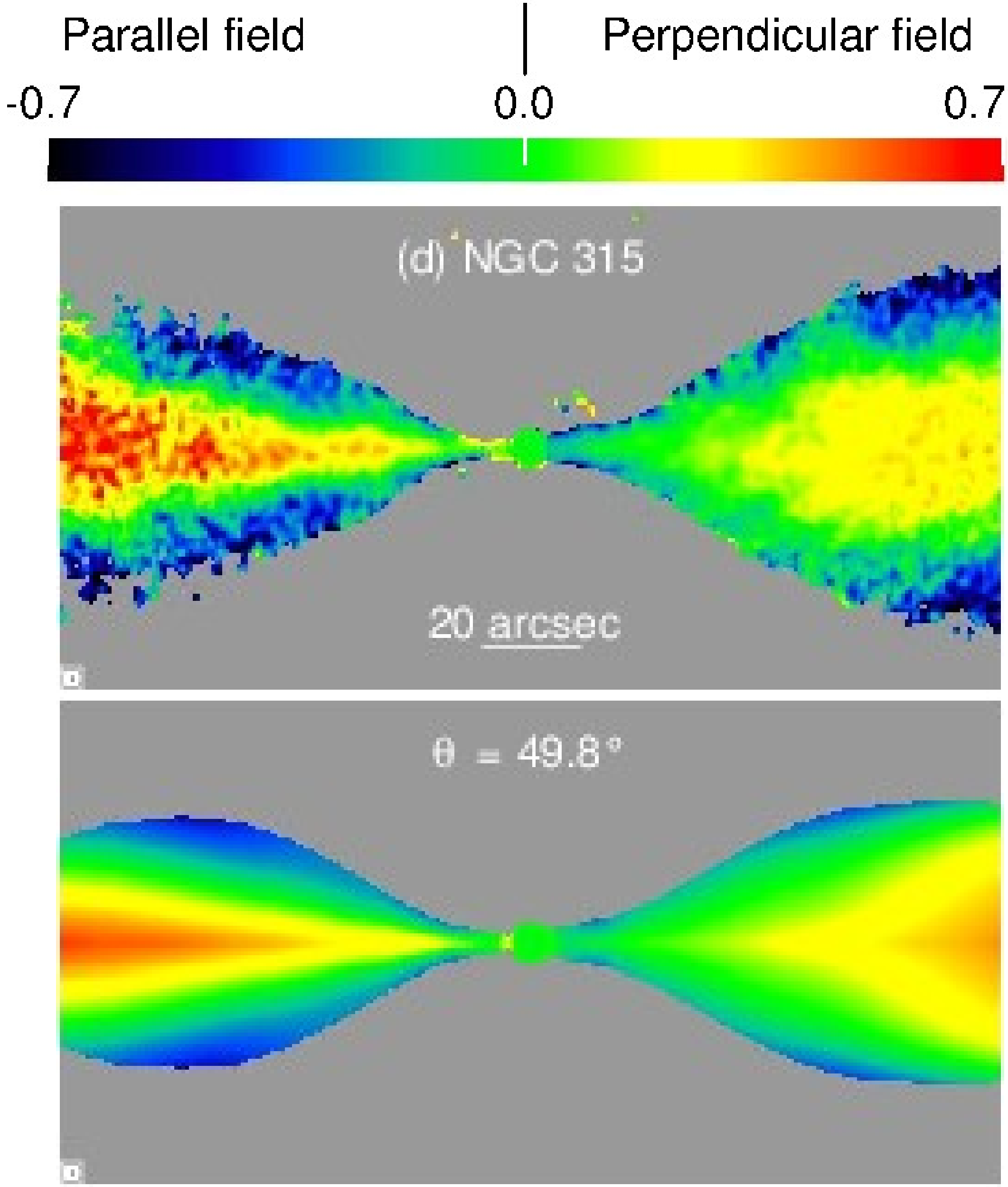
From statistics of jet sidedness reversals, the mean intrinsic emissivity ratio is ≈ 1.5 at 10 kpc.

Polarization fits



Vectors
- along apparent magnetic field direction
- lengths ∝ degree of polarization

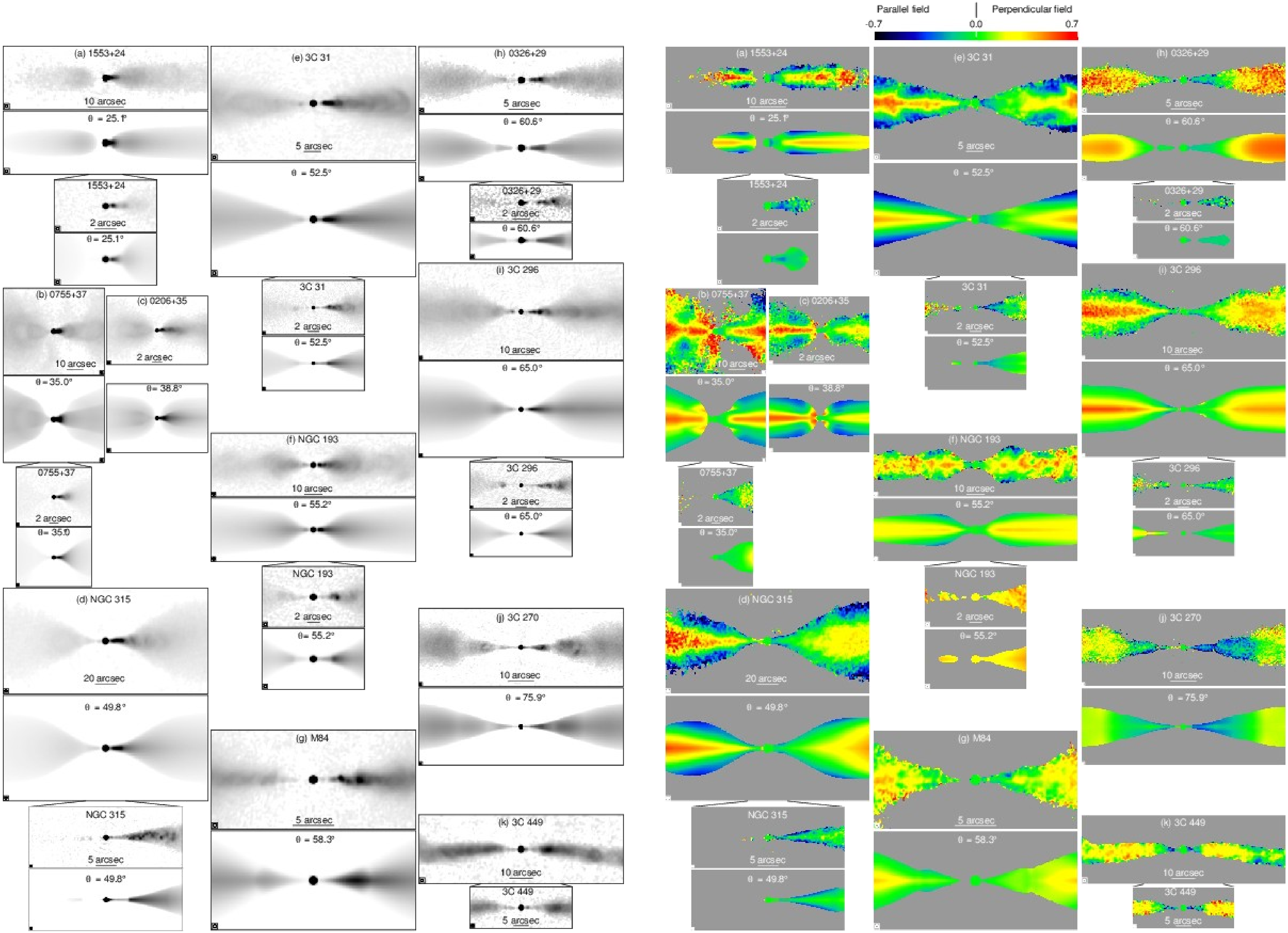
Another representation: Q/I



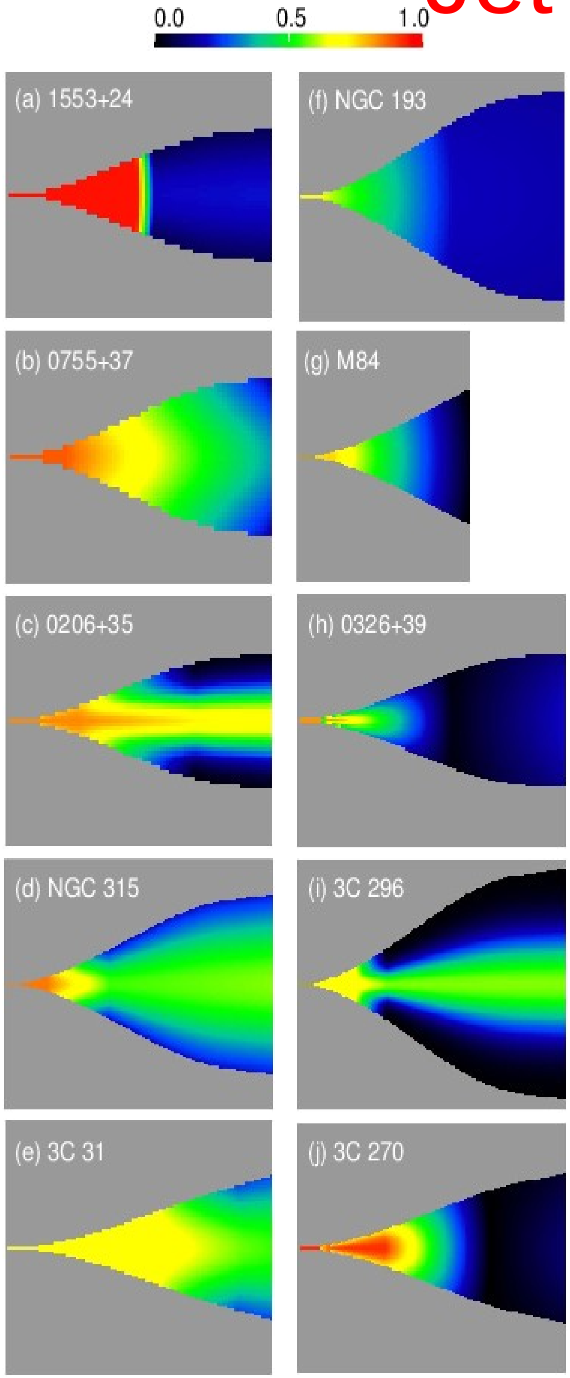
Q/I > 1
apparent field
transverse

Q/I < 1
apparent field
longitudinal

U ≈ 0

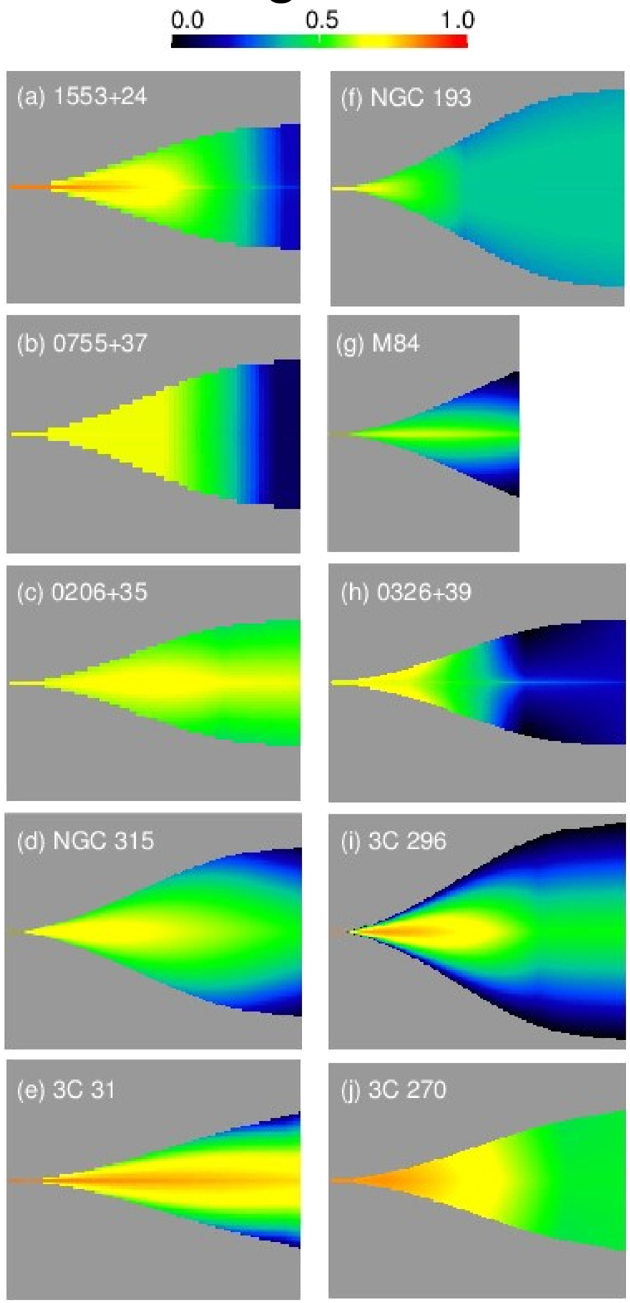

Parallel field
Perpendicular field
-0.7
0.0
0.7
(a) 1553+24
10 arcsec
θ = 25.1°
1553+24
2 arcsec
θ = 25.1°
(b) 0755+37
10 arcsec
θ = 35.0°
(c) 0206+35
2 arcsec
θ = 38.8°
0755+37
2 arcsec
θ = 35.0
(d) NGC 315
20 arcsec
θ = 49.8°
NGC 315
5 arcsec
θ = 49.8°
(e) 3C 31
5 arcsec
θ = 52.5°
3C 31
2 arcsec
θ = 52.5°
(f) NGC 193
10 arcsec
θ = 55.2°
NGC 193
2 arcsec
θ = 55.2°
(g) M84
5 arcsec
θ = 58.3°
(h) 0326+29
5 arcsec
θ = 60.6°
0326+29
2 arcsec
θ = 60.6°
(i) 3C 296
10 arcsec
θ = 65.0°
3C 296
2 arcsec
θ = 65.0°
(j) 3C 270
10 arcsec
θ = 75.9°
(k) 3C 449
10 arcsec
3C 449
5 arcsec

Jet velocities

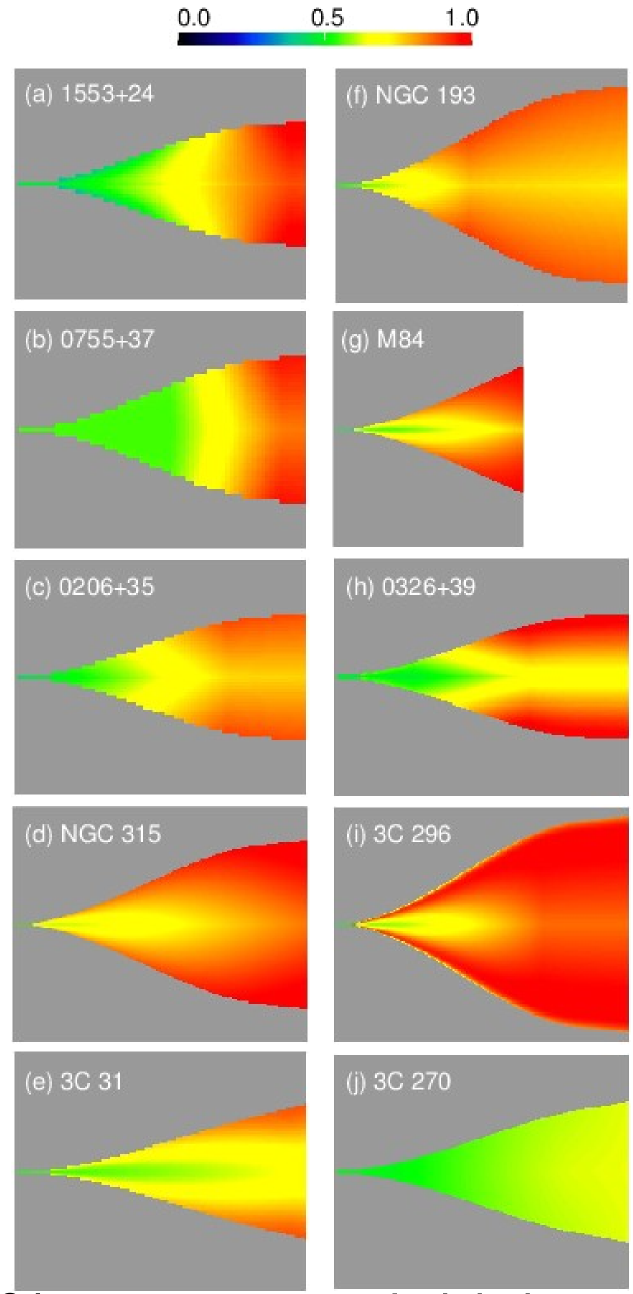


Fractional magnetic field components

Longitudinal



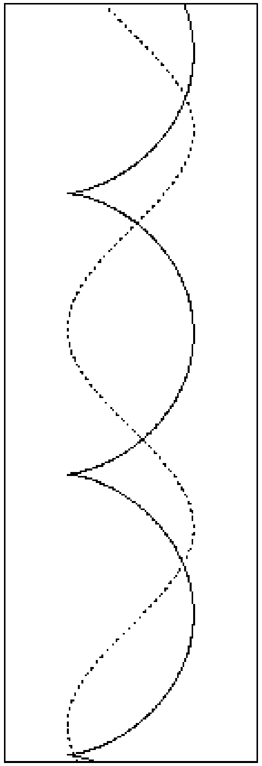
Toroidal

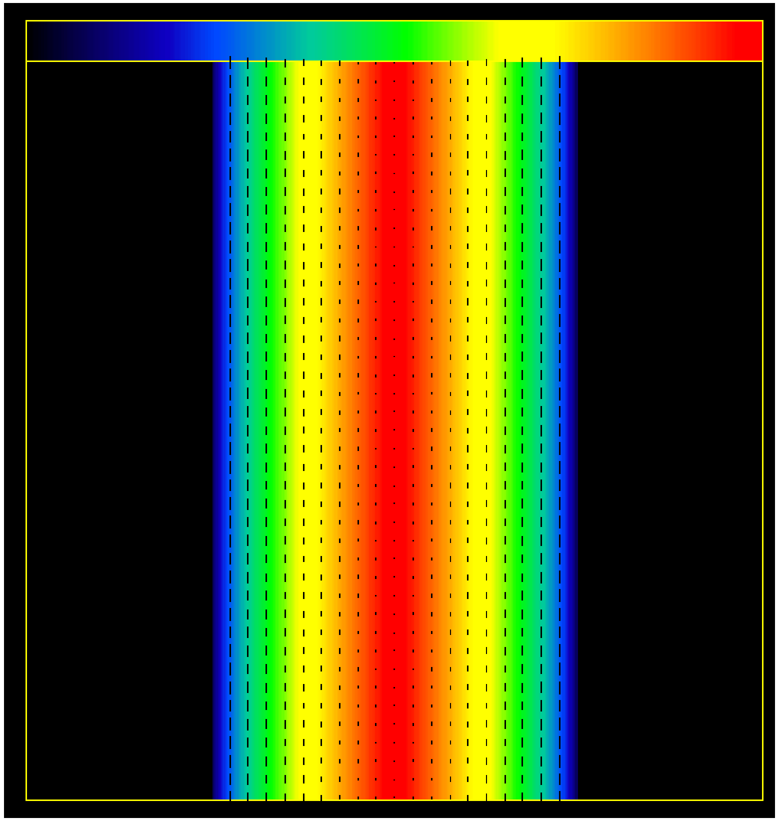


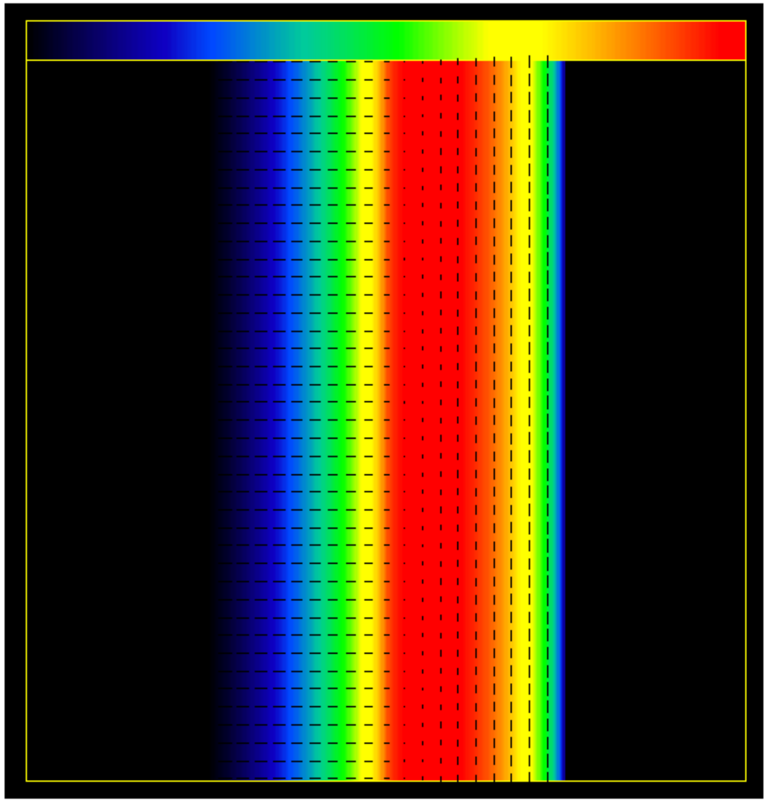
Constraining the field configuration

- From synchrotron emission alone (in the absence of associated Faraday rotation), we cannot tell whether a field is vector-ordered, or disordered with many reversals
- Partially ordered fields can produce very high fractional polarizations (if viewed at the right orientation)
- Specific field configurations can be excluded if they fail to reproduce the observed polarization.
- Ambiguities (especially between vector-ordered and disordered, anisotropic fields with similar component ratios) often remain.
- It helps to see both sides of a relativistic twin-jet source (provided that it is really symmetrical, of course)

Transverse profiles can help







$\theta = 90^0$

45^o pitch angle helix

$\theta = 45^0$

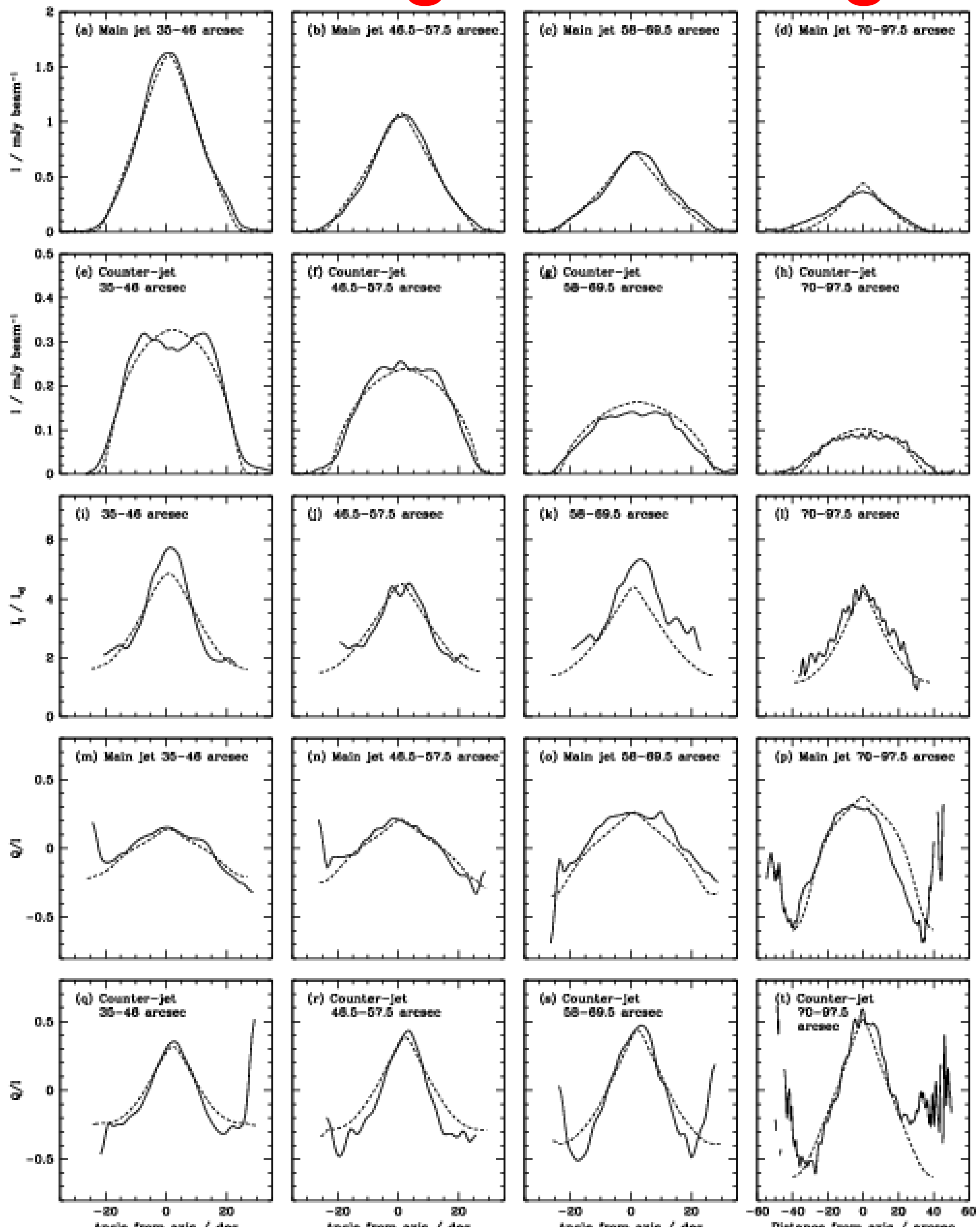
Measured transverse profiles for NGC315: field is not a grand-design helix

Ambiguity

Field is toroidal + longitudinal

We do not know whether the toroidal field is vector-ordered

(Suspect ordered toroidal + longitudinal with reversals)



Approaching jet I

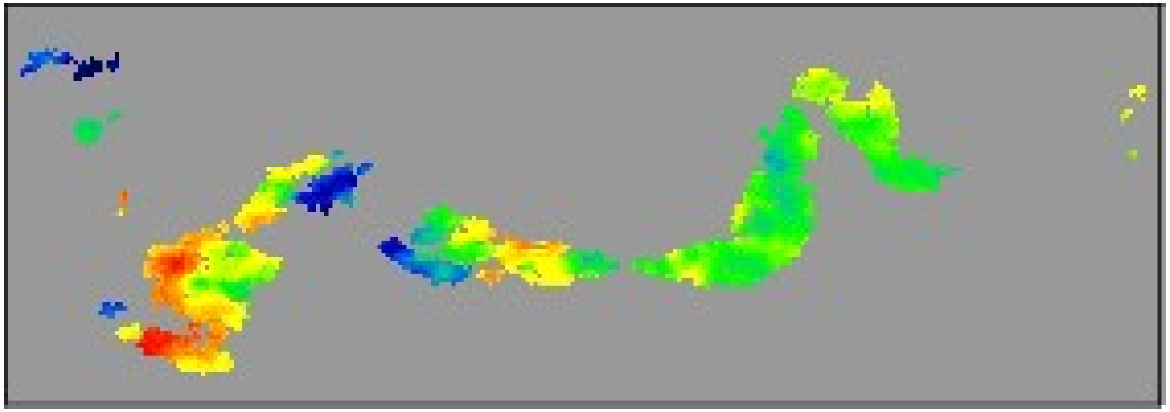
Receding jet I

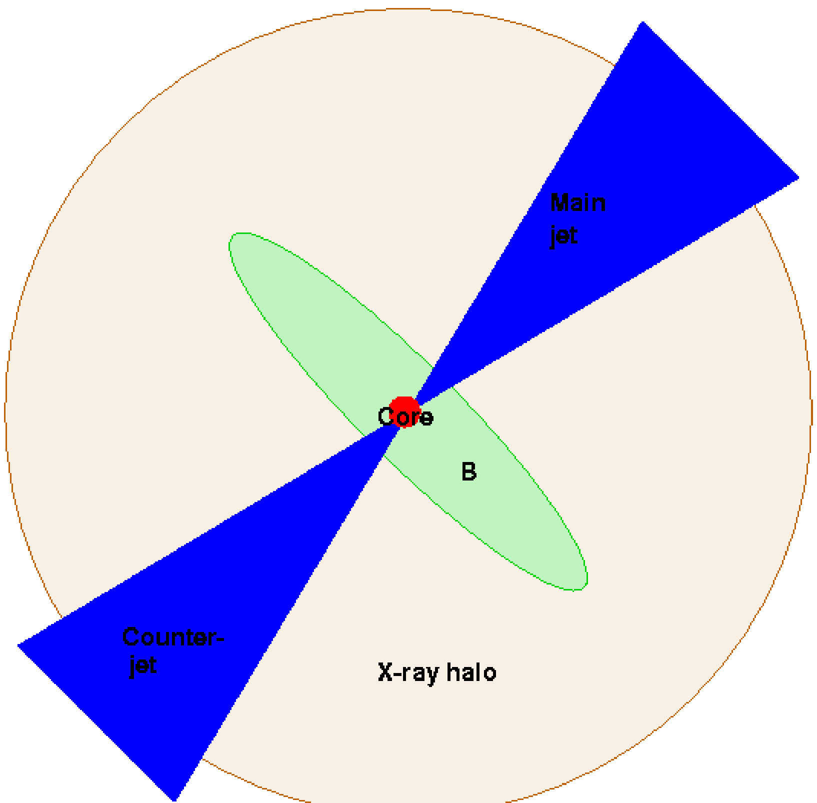
Approaching jet Q/I

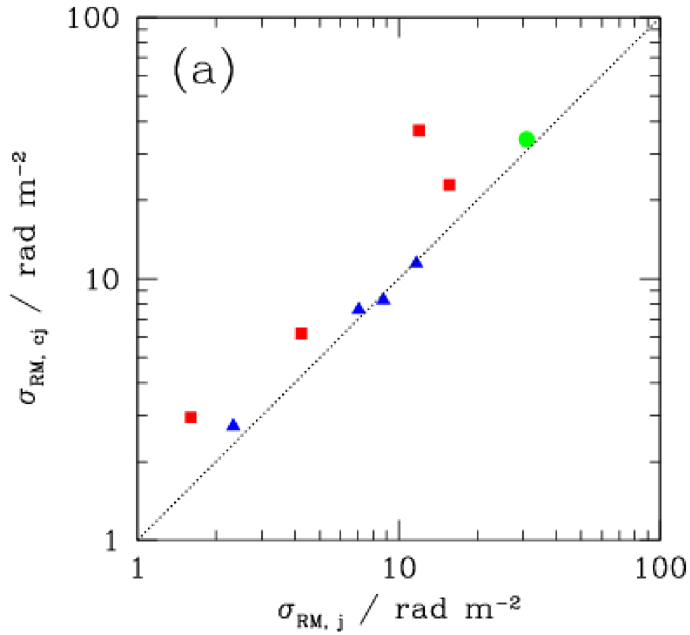
Receding jet Q/I

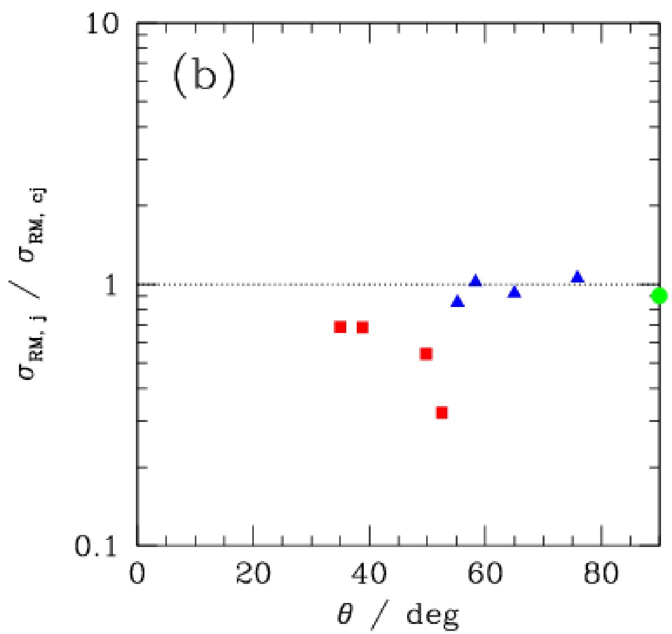
Sidedness ratio

A consistency test: Faraday Rotation

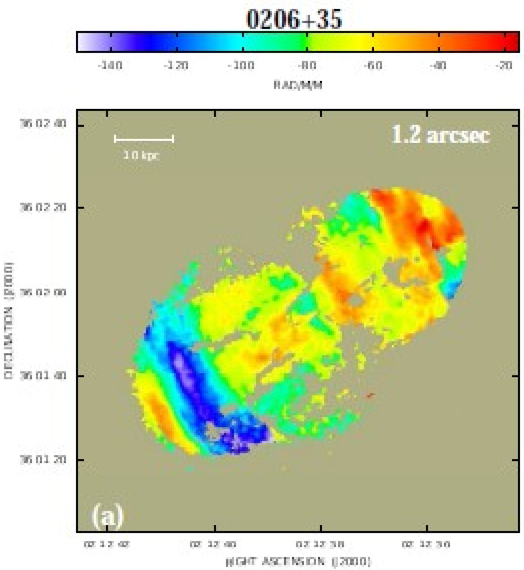


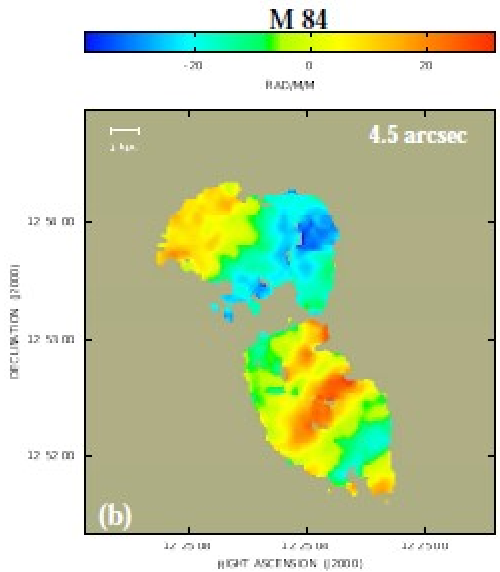




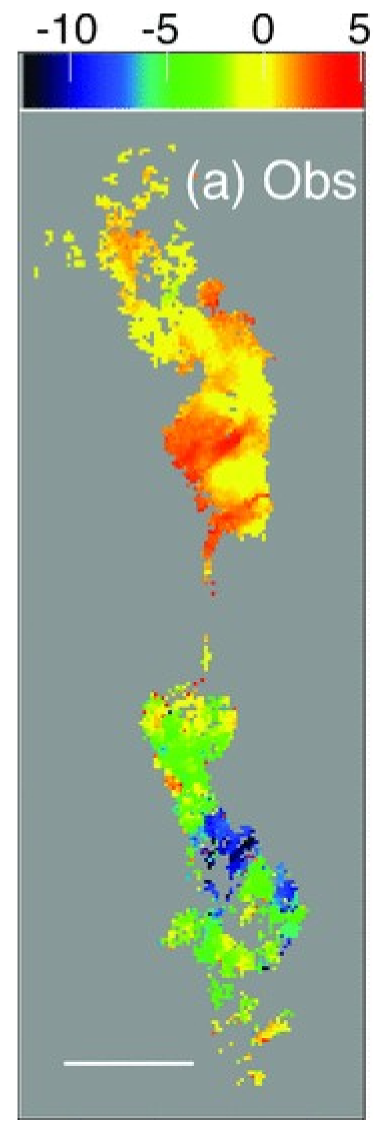


Rotation measure gradients on kpc scales

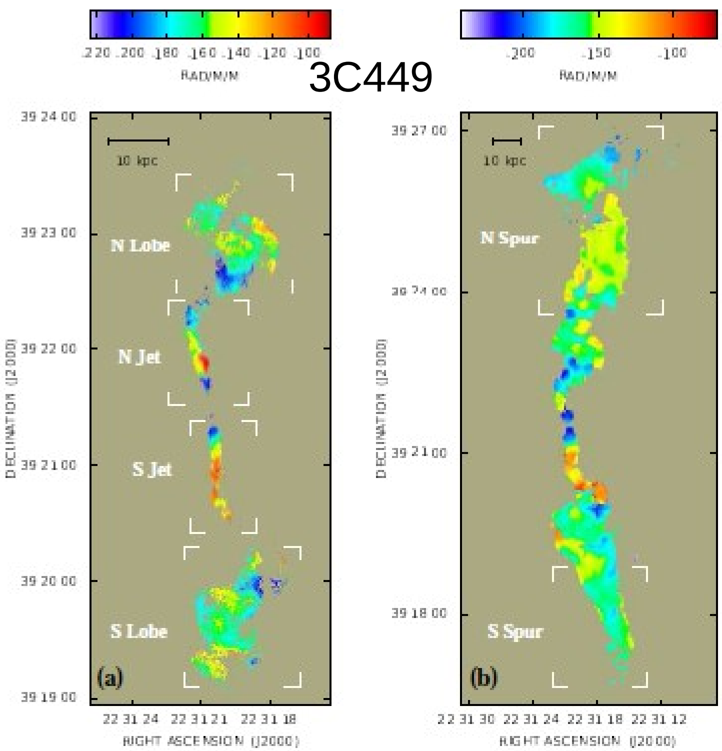




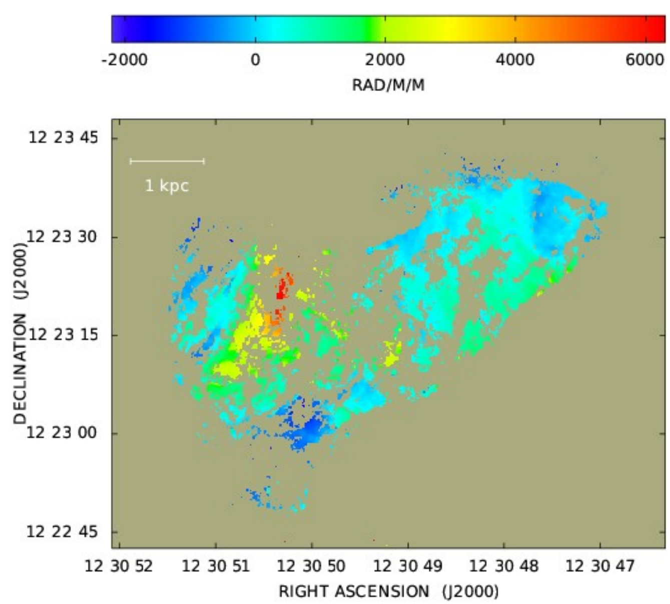
Hydra A



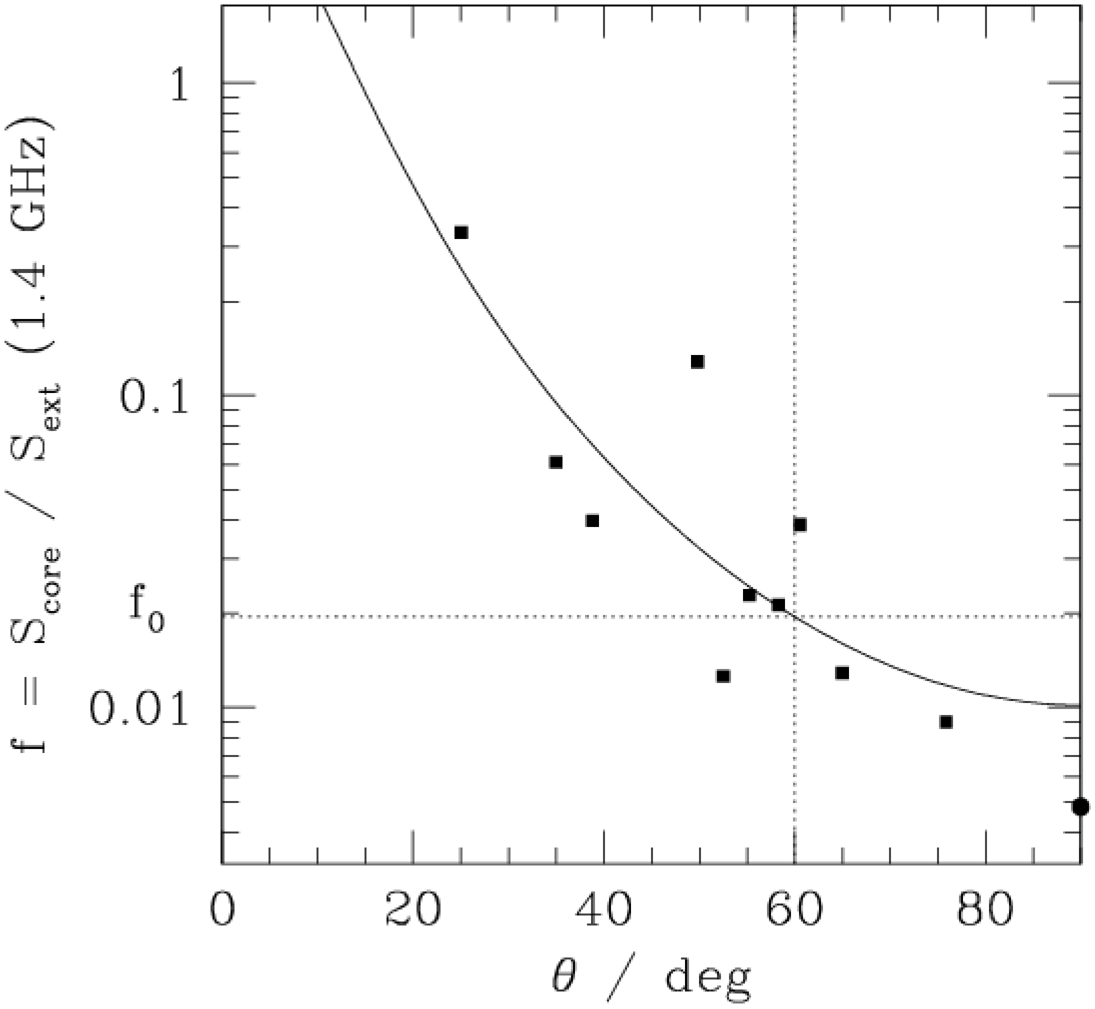
Guidetti et al. (2010,2011)
RL et al. (2008)
Data from F. Owen



M87



A second consistency test: core fraction

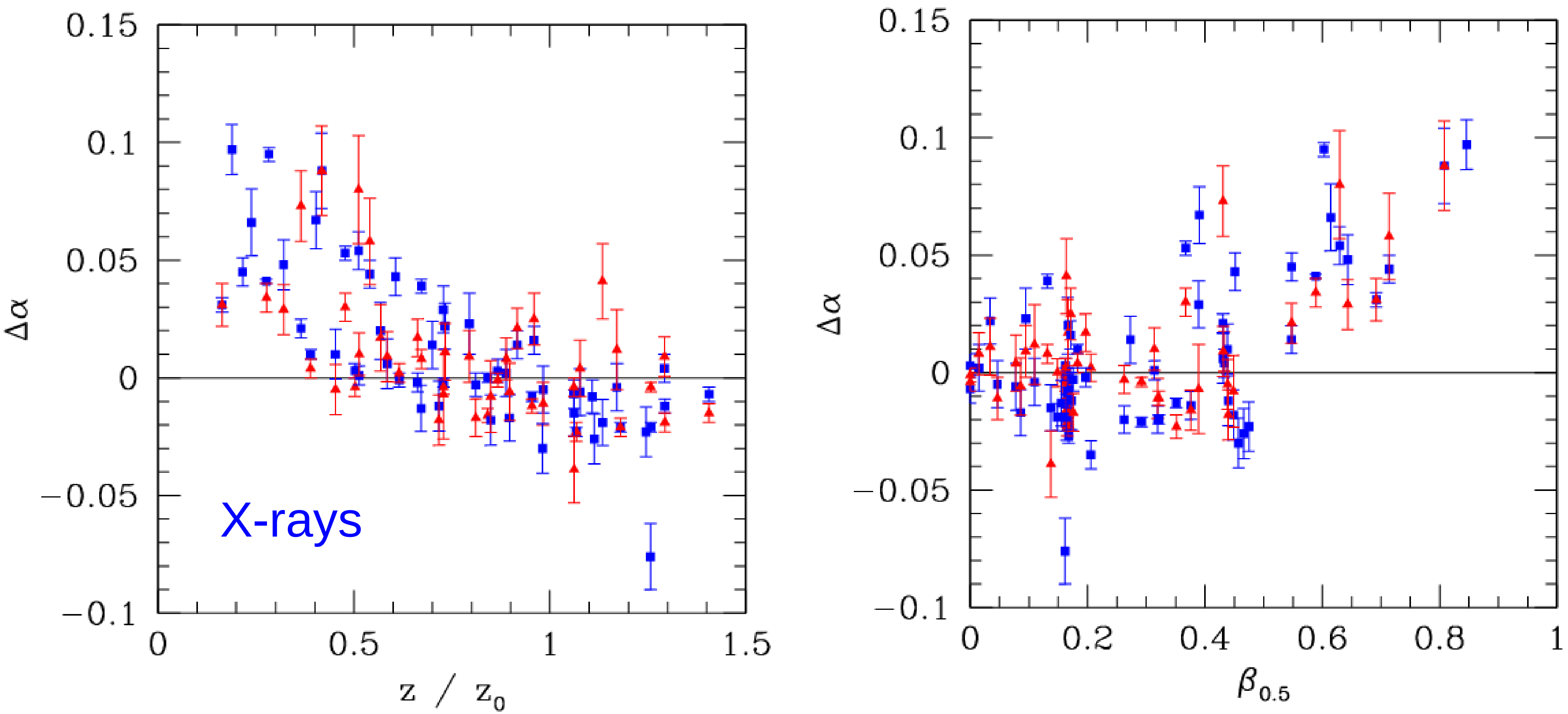


Core is the optically-thick base of the jet

Assume intrinsic ratio of core/extended emission is constant

Doppler beaming causes observed ratio f to be anticorrelated with θ

Spectrum and speed



Spectrum becomes flatter with increasing distance from AGN
Opposite to effect of synchrotron losses
Velocity-dependent particle acceleration?

Laing & Bridle (2013)

Summary and Next Steps

- Weak flavour jets can be described in quantitative detail
  - Deceleration and transverse velocity gradients
  - Field evolution longitudinal to toroidal
  - Flattening spectrum and decreasing particle acceleration
- First attempt at strong-flavour jet model implies
  - Initially very fast ($\Gamma = 8$) spine and slower shear layer
  - On-axis deceleration possible but not certain
- Strong-flavour jets are hard to study, even with the new generation of arrays, but watch this space