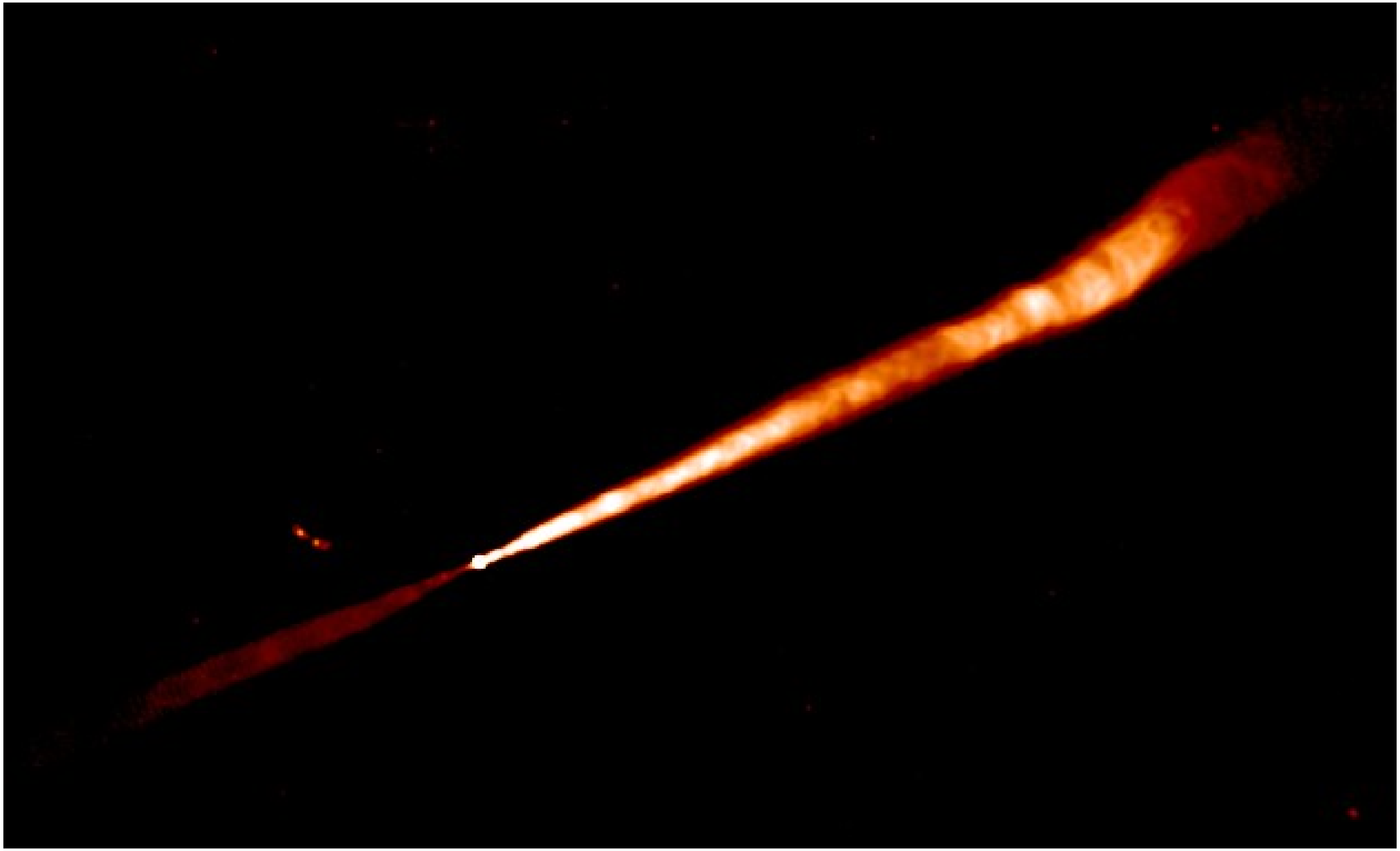
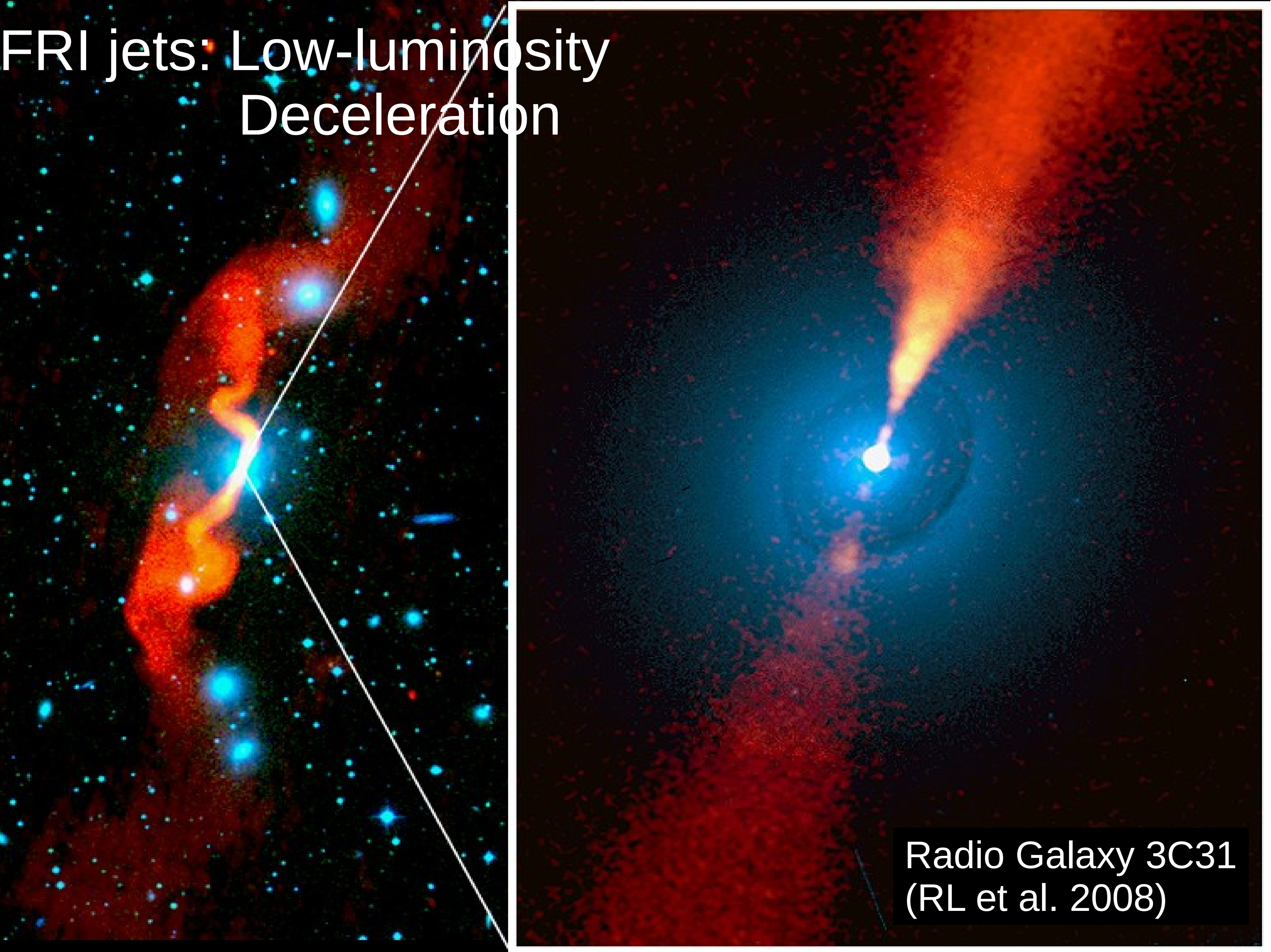
Relativistic speeds in large-scale jets

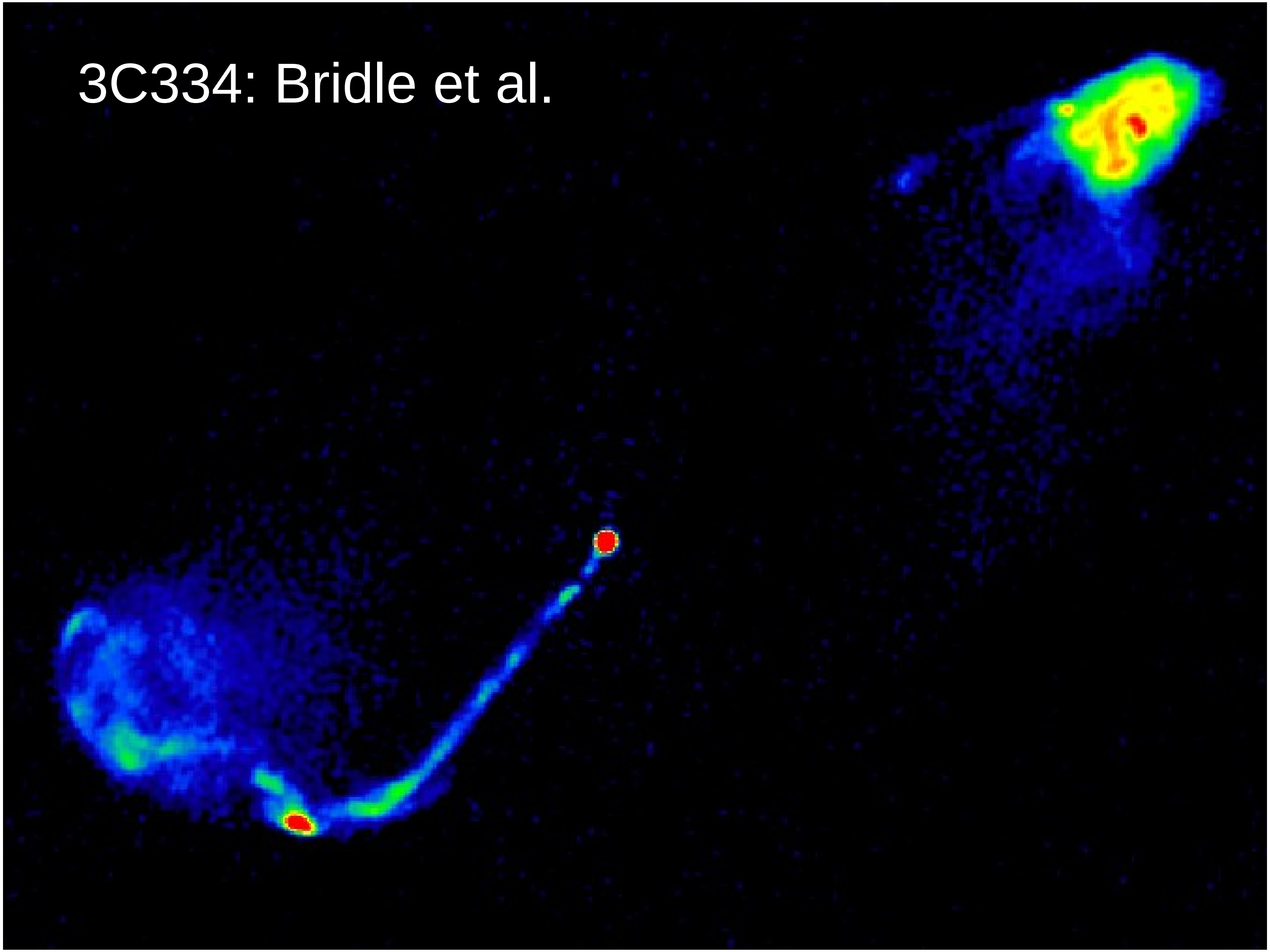
Robert Laing (ESO)



FRI jets: Low-luminosity Deceleration



FRII Jets: Powerful and fast



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?

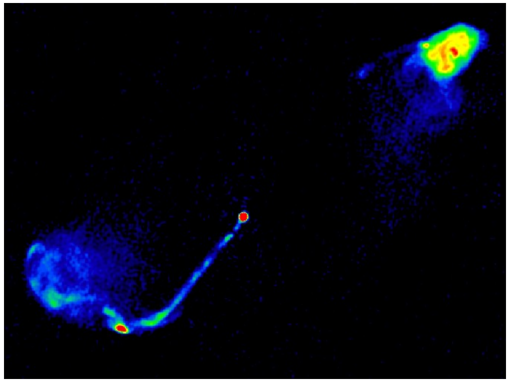
- Assumption of intrinsic side-to-side symmetry **close to AGN**
- Modelling side-to-side asymmetries
  - Total intensity alone is not enough: ratio

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

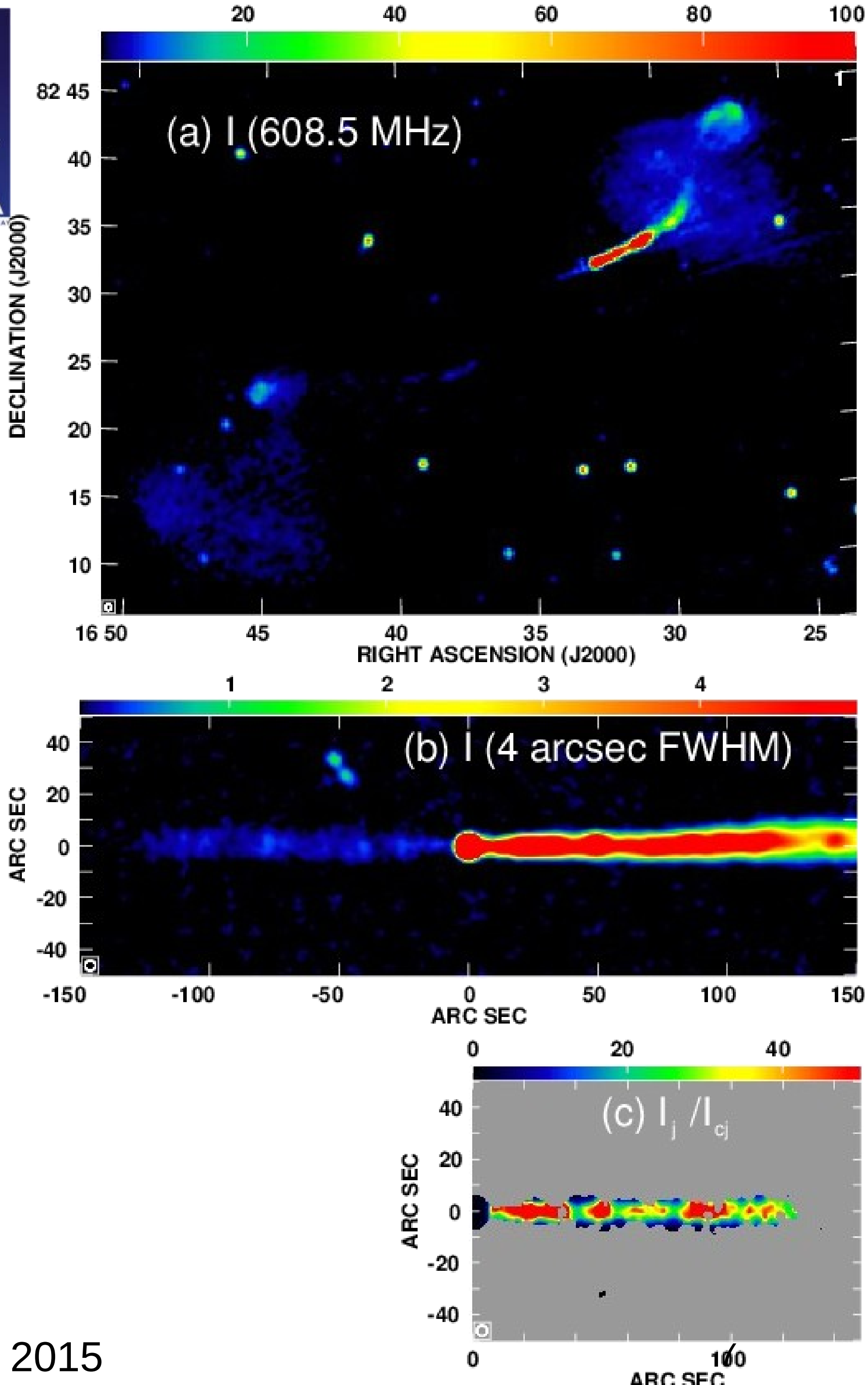
    depends only on $\beta\cos\theta$ for isotropic rest-frame emission ...
  - ... but polarized emission cannot be isotropic in rest frame
  - Use both I and linear polarization, for which asymmetries depend on a different combinations of β and θ
  - Aberration → we look at approaching and receding jets 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

Powerful FRII 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



NGC6251



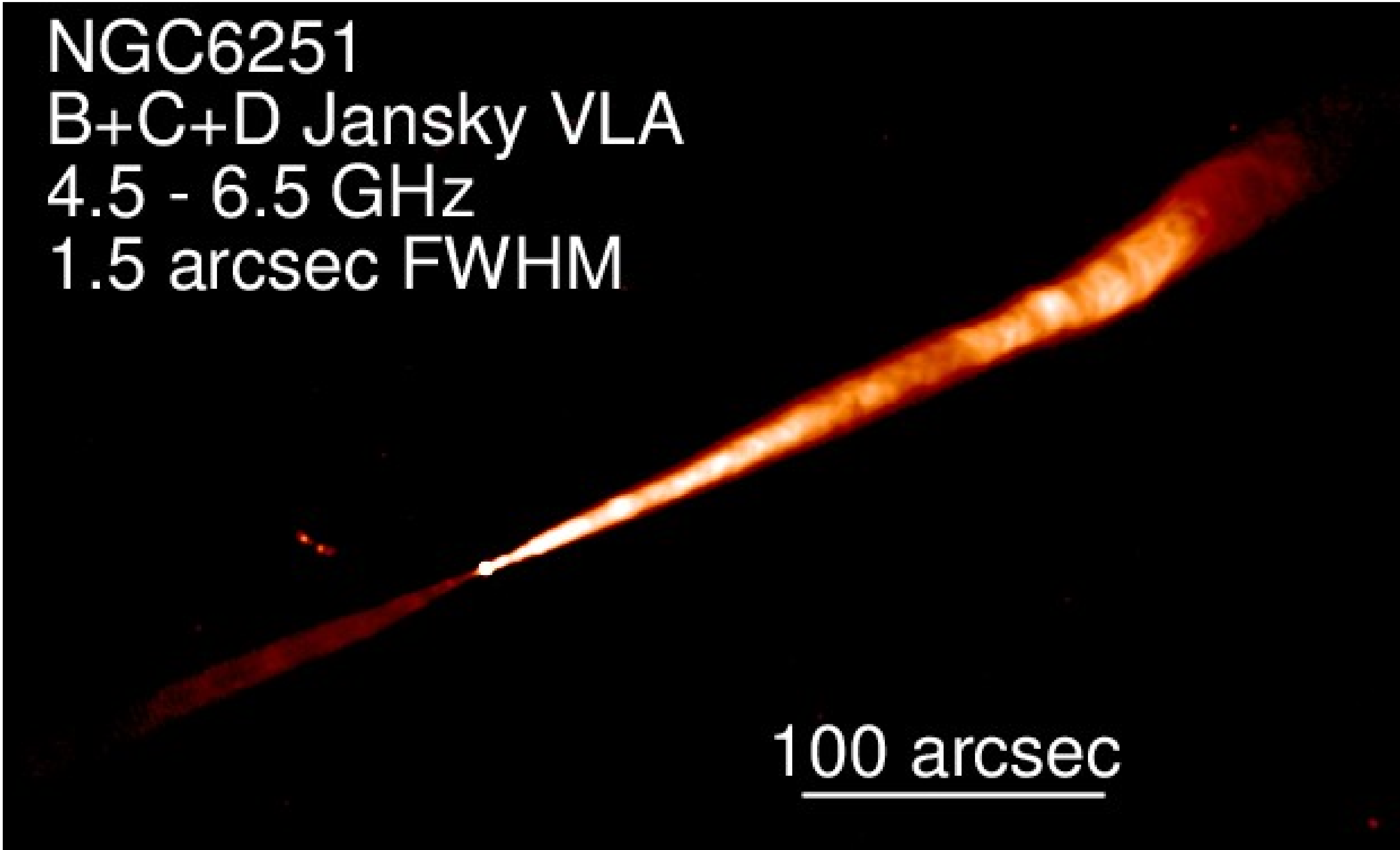
Transition case between FRI and FRII jets

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

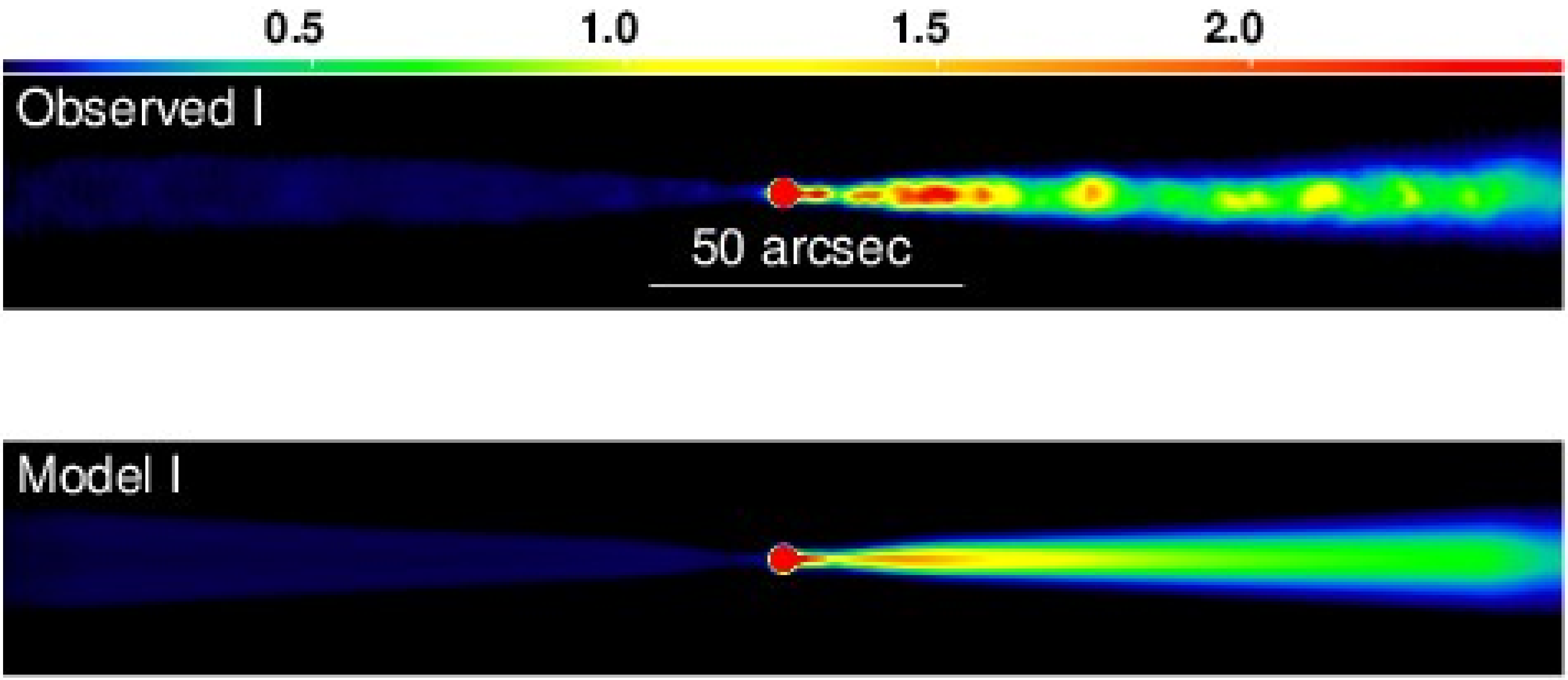
Collimated jets

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)


NGC6251
B+C+D Jansky VLA
4.5 - 6.5 GHz
1.5 arcsec FWHM
100 arcsec

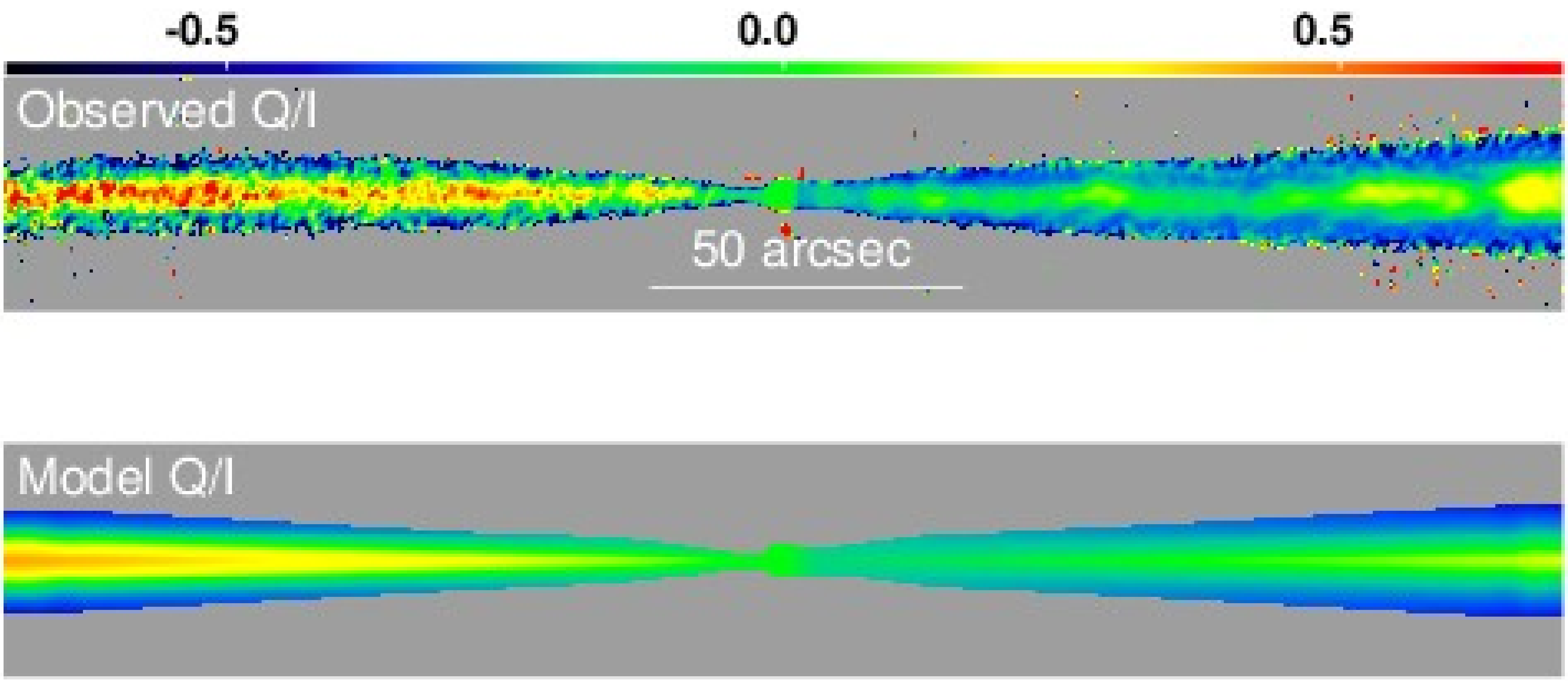
Observed and model I



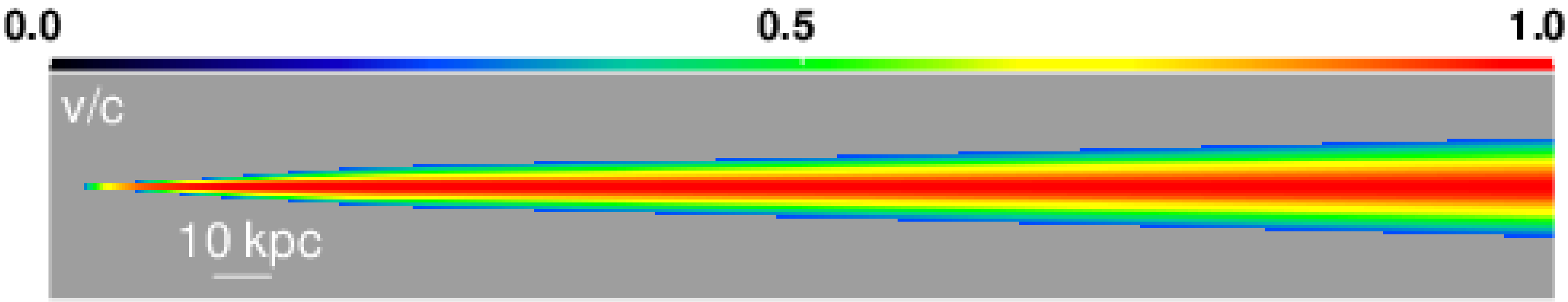
Transverse brightness profiles of the jets are very different:
brighter jet: centrally peaked – fainter jet: flat or limb-brightened
Signature of flow that is faster on-axis than at its edges

Observed and model Q/I

Parallel | Perpendicular



Velocity Structure



Best fit (so far)

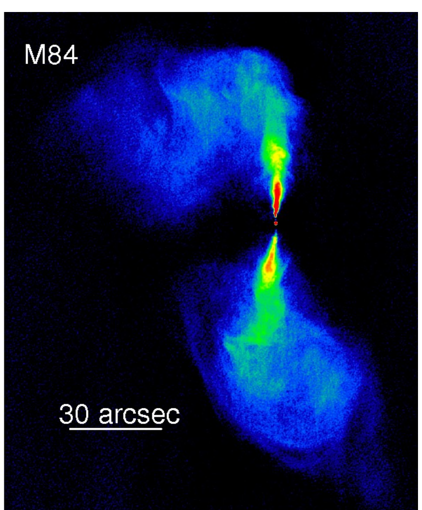
- Geometry
  - $\theta \approx 28^o$ (upper limit $\approx 35^o$)
- Velocity
  - $\beta \approx 0.97$ ($\Gamma \approx 4$) on-axis at large distances; well constrained
  - Marginal evidence for deceleration from $\beta \approx 0.99$ close to AGN
  - Edge velocity ~constant ($\beta = 0.27$)
- Magnetic field
  - Longitudinal and toroidal components comparable close to AGN; toroidal becomes dominant at larger distances

At least one powerful jet does indeed remain fast on large scales and has a spine-shear layer structure.

How does NGC6251 compare with FRI jets?

Laing & Bridle (2014)

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

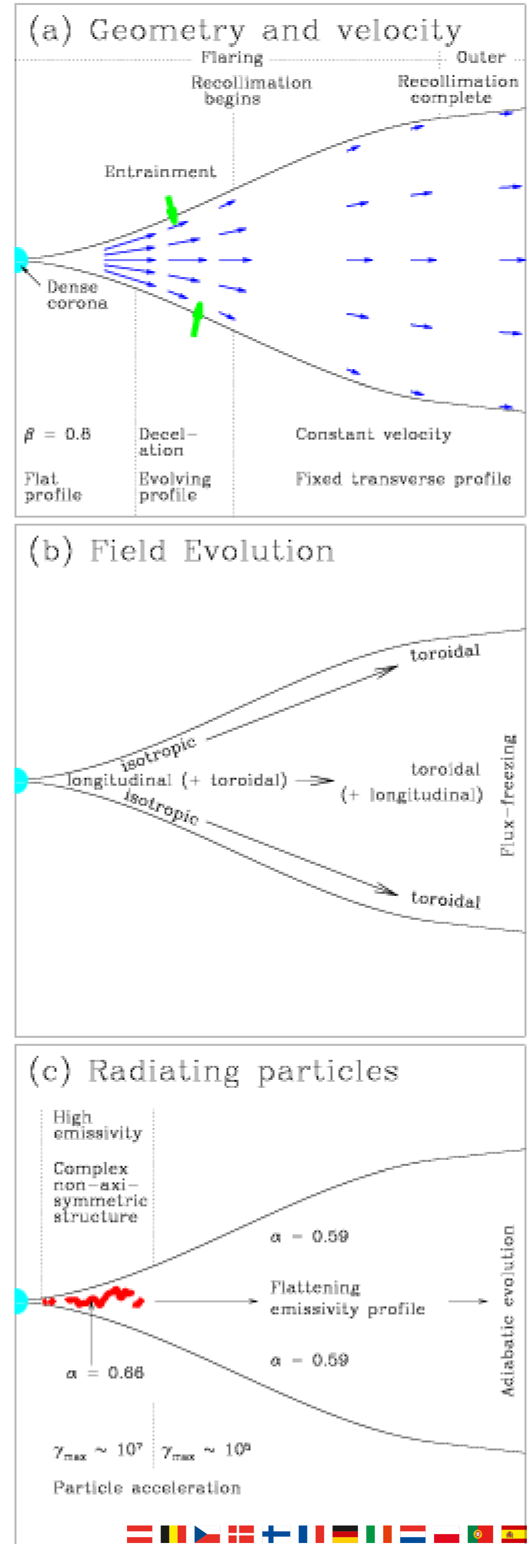


Differences:

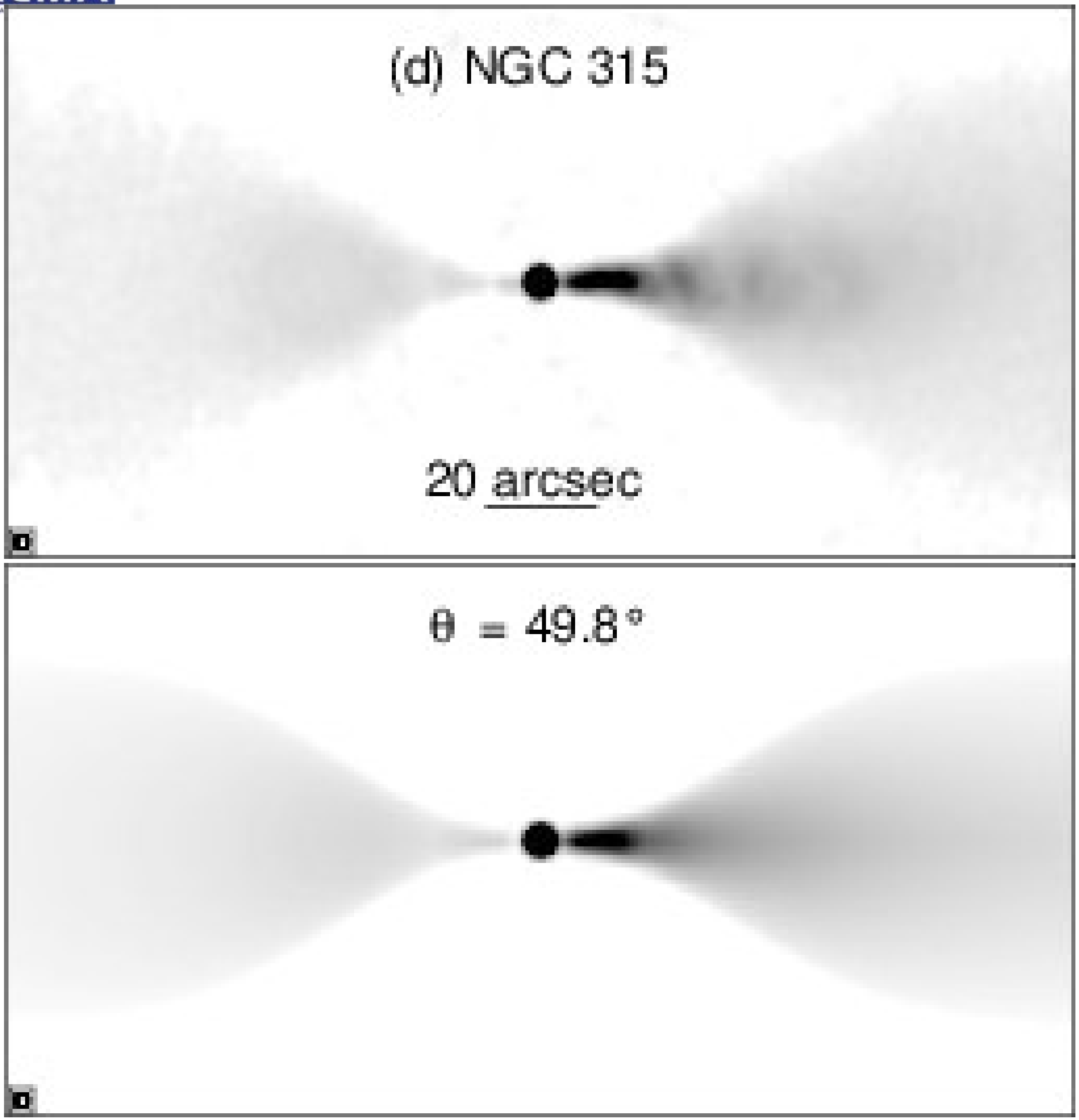
FRI jets:
- expand rapidly
- decelerate from $\Gamma \approx 2$ to $\Gamma \approx 1$

Similarities:

- Longitudinal → toroidal field
- Transverse velocity gradients



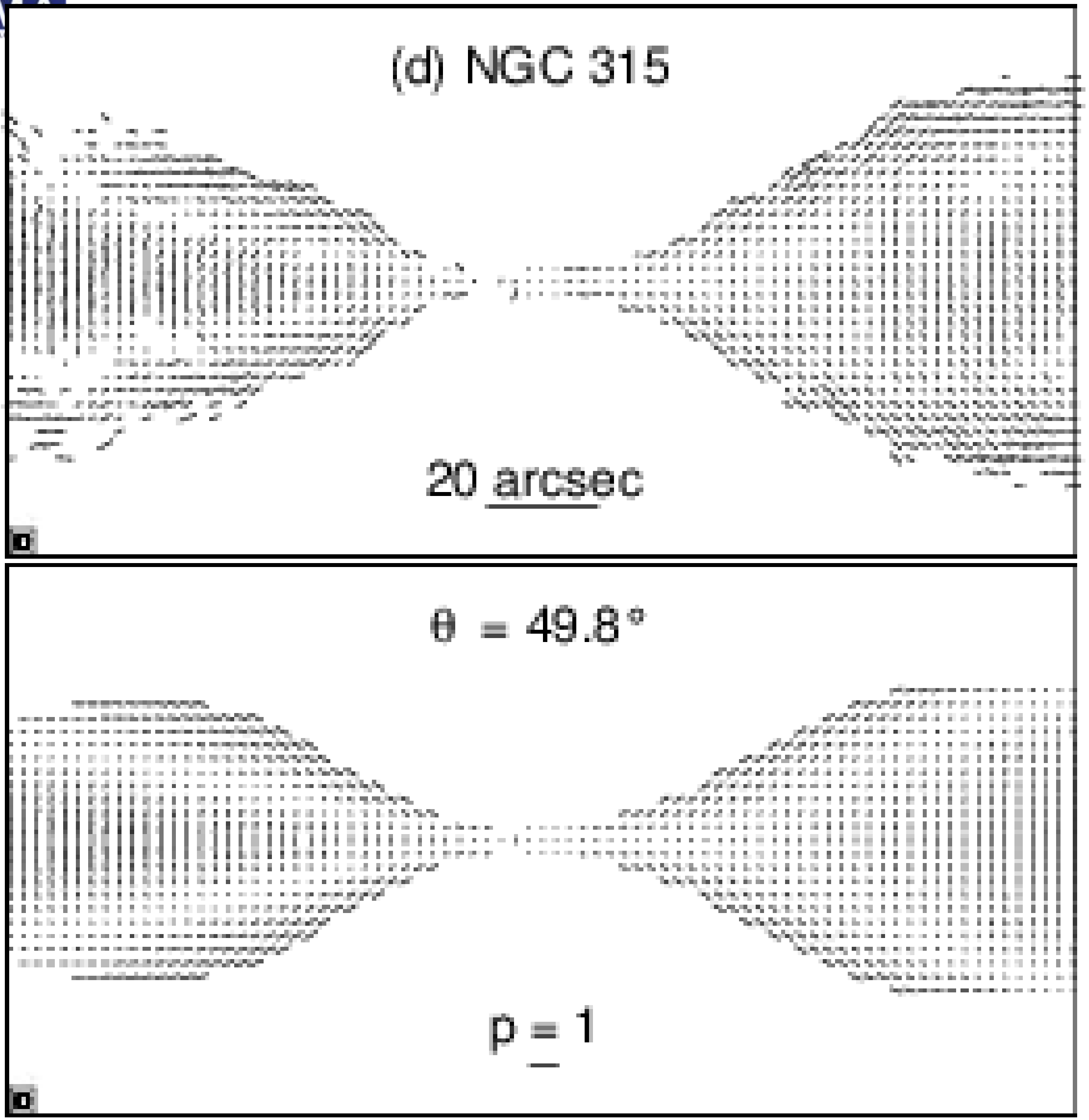
An example: I model



How important are intrinsic asymmetries?

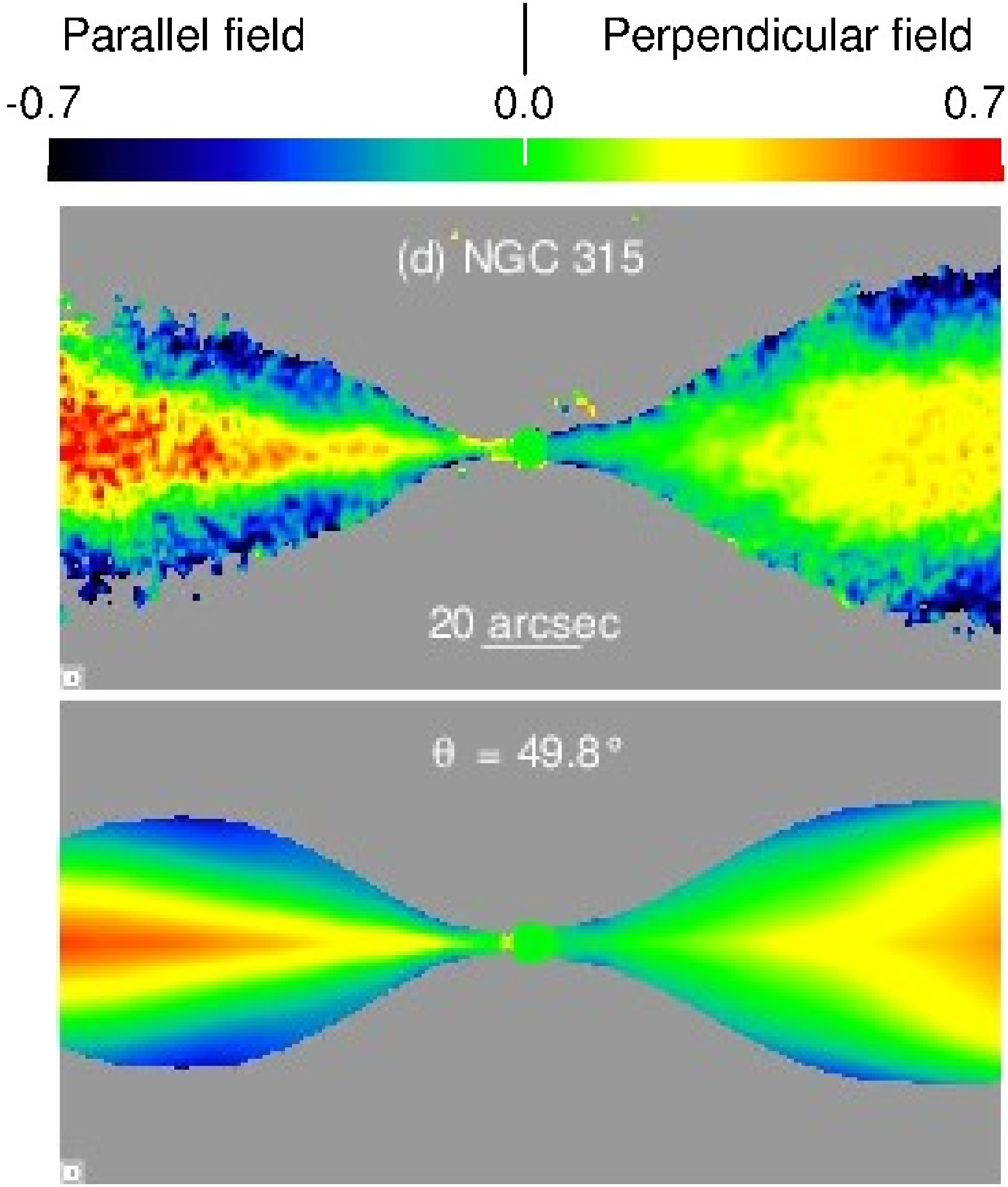
From statistics of jet sidedness reversals, the mean intrinsic emissivity ratio is ≈ 1.5 at 10 kpc.

Polarization fits



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

Q/I

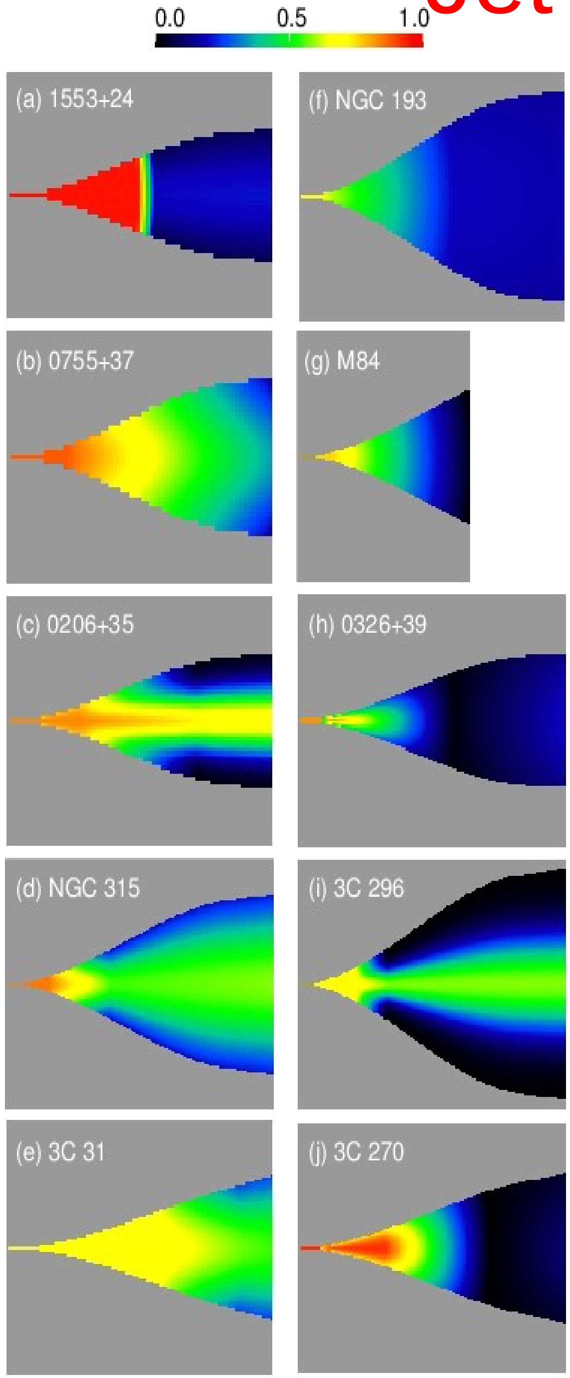


Q/I > 1
apparent field transverse

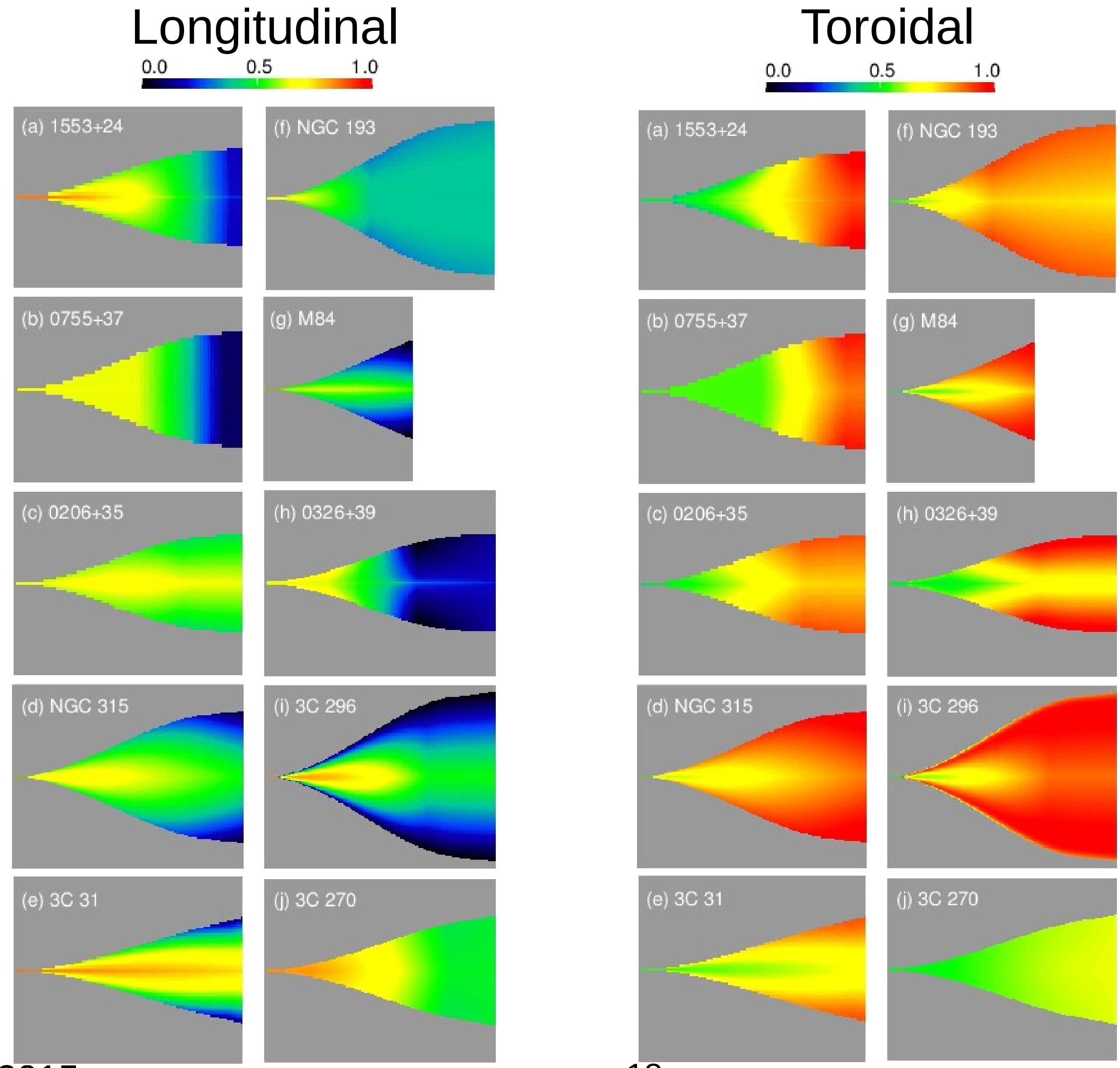
Q/I < 1
apparent field longitudinal

U ≈ 0

Jet velocities

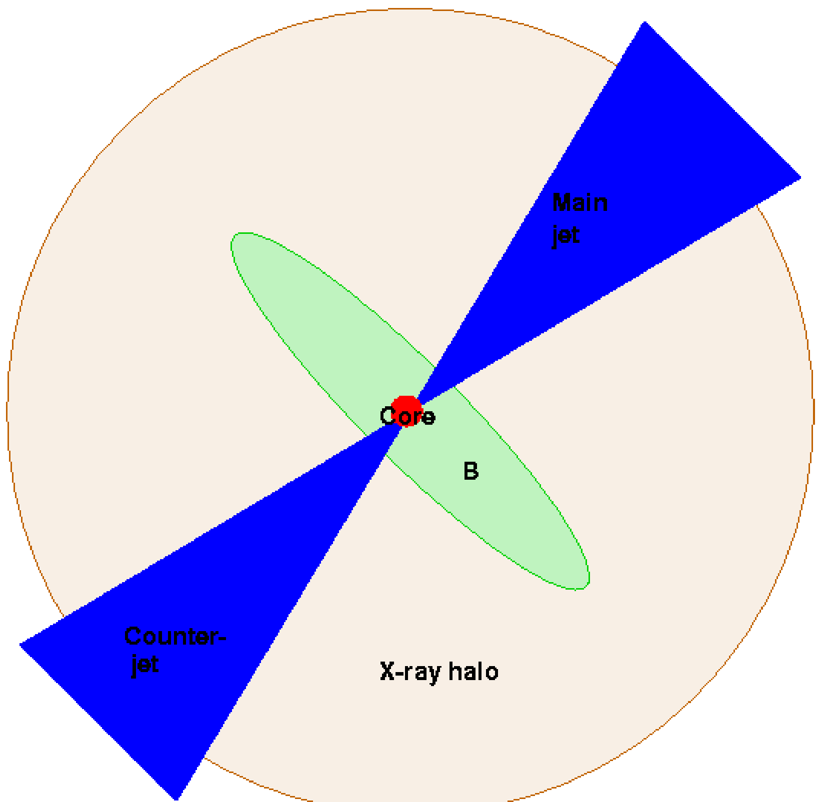


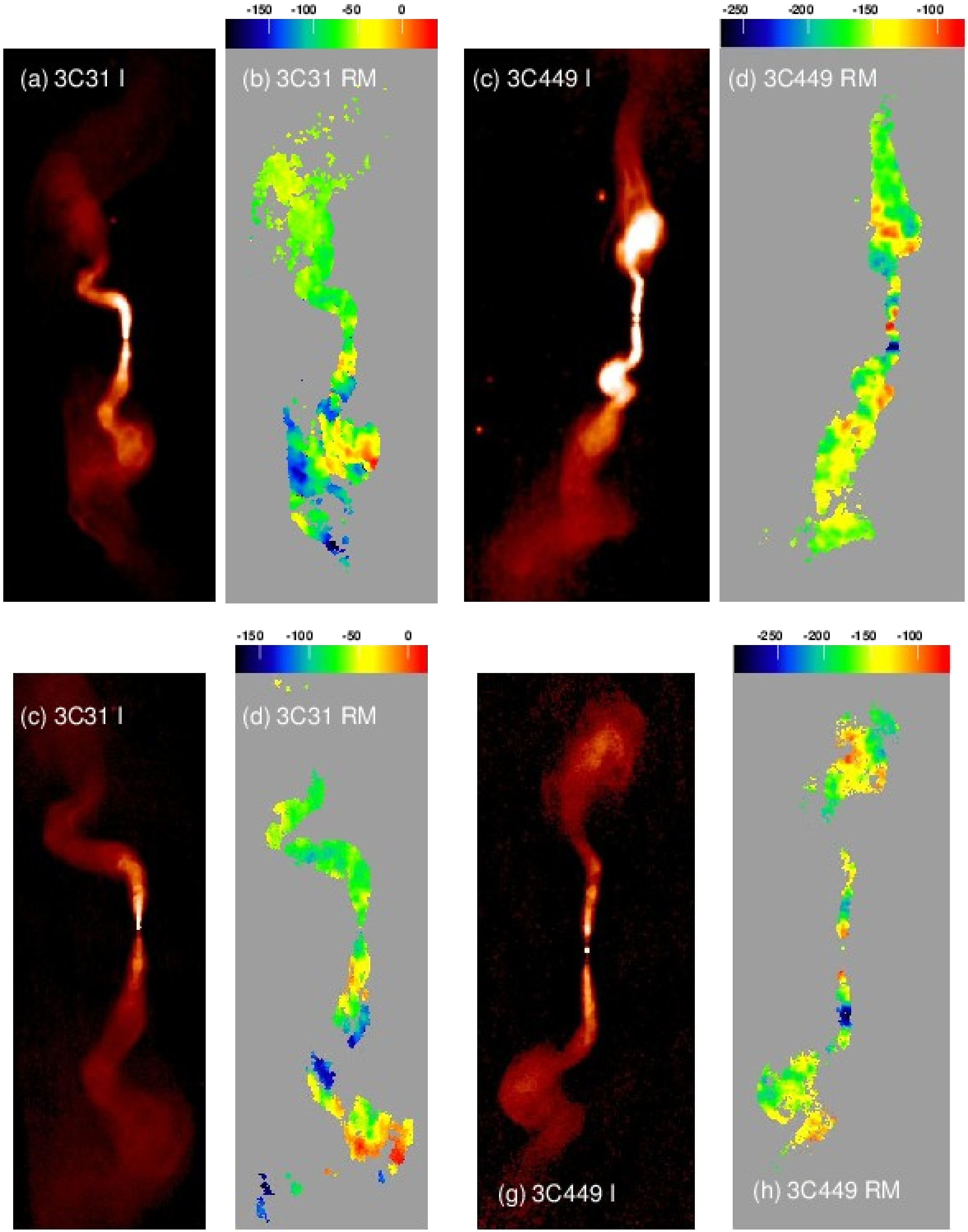
Fractional magnetic field components

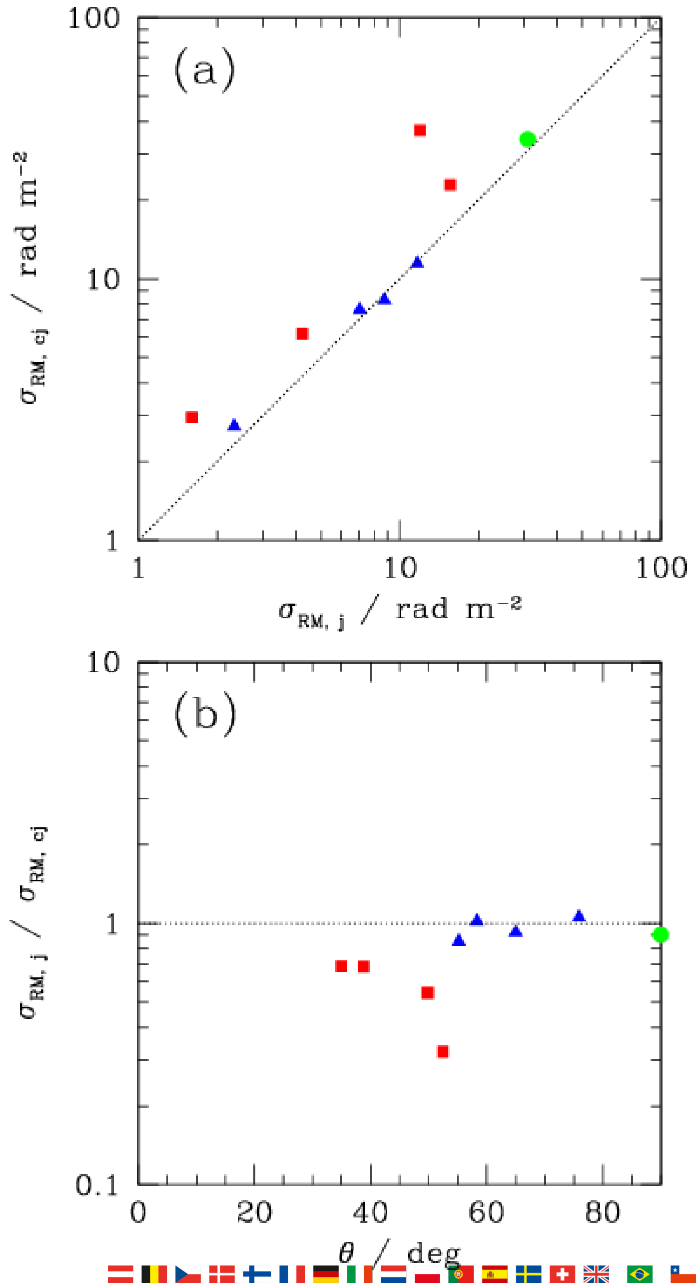


Consistency test 1:

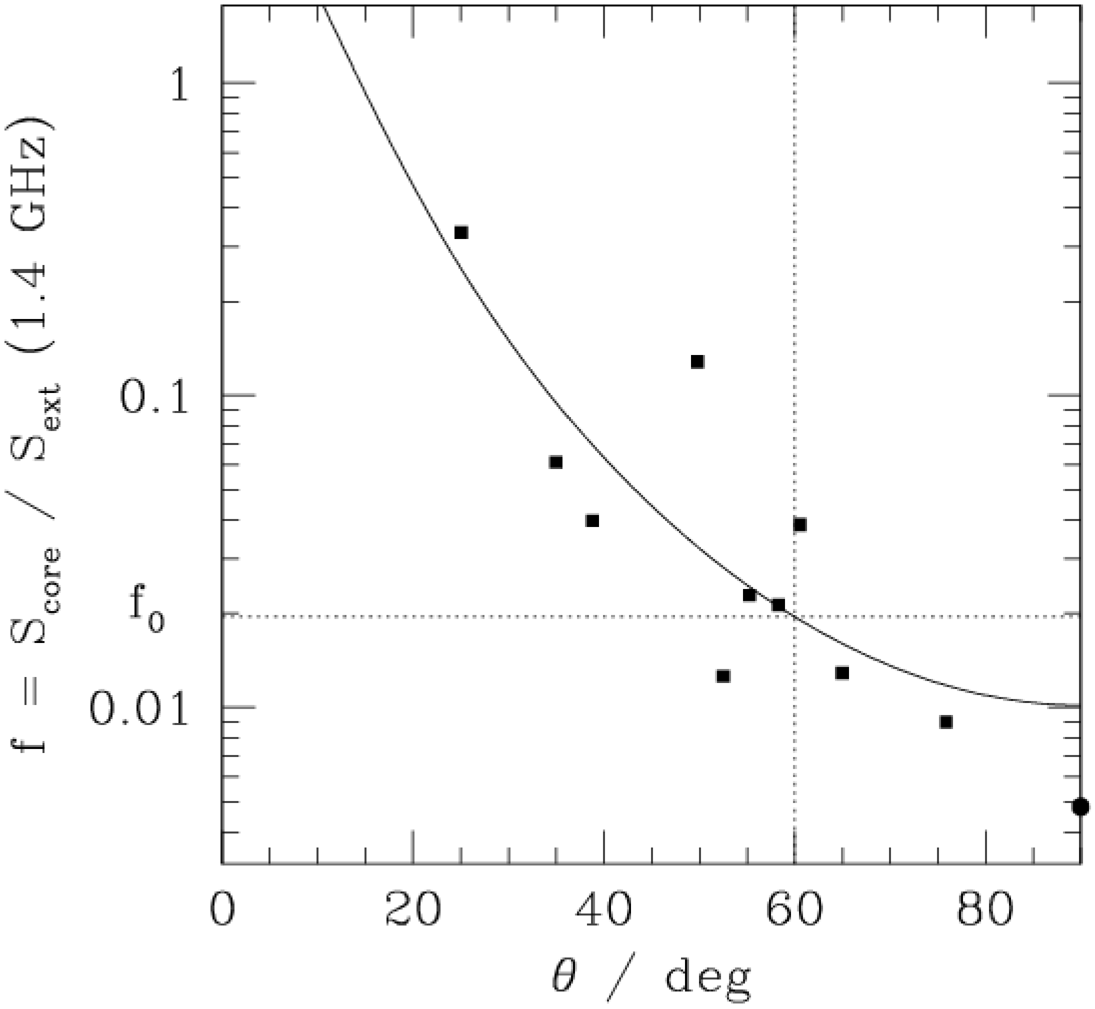
External Faraday Rotation




(a) 3C31 I
(b) 3C31 RM
(c) 3C449 I
(d) 3C449 RM
-150 -100 -50 0
-250 -200 -150 -100
(c) 3C31 I
(d) 3C31 RM
(g) 3C449 I
(h) 3C449 RM


(a)
$\sigma_{RM,\,cj}$ / rad m^{-2}
$\sigma_{RM,\,j}$ / rad m^{-2}
1
10
100
(b)
$\sigma_{RM,\,j}$ / $\sigma_{RM,\,cj}$
θ / deg
0.1
1
10
0
20
40
60
80

Consistency test 2: 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

Summary and Next Steps

- FRI 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 model for a transition jet implies
  - Fast ($\Gamma \approx 4$) spine and slower shear layer on ~100 kpc scales
  - On-axis deceleration possible but not certain
- FRII and pc-scale jets are hard to study, even with the new generation of arrays, but watch this space