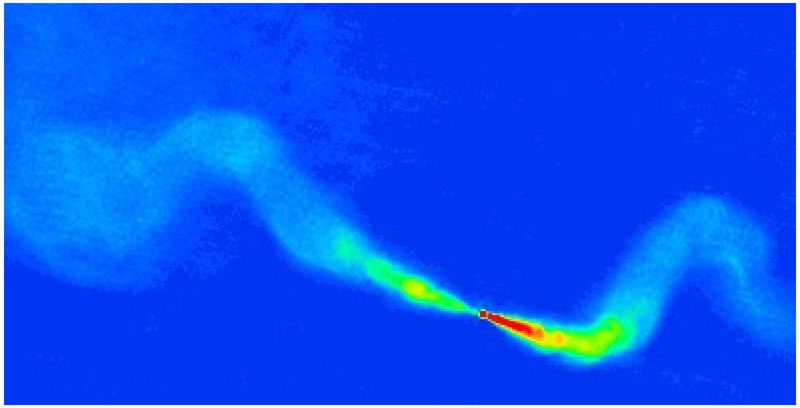
Large-scale Jets and Lobes

Robert Laing (ESO)

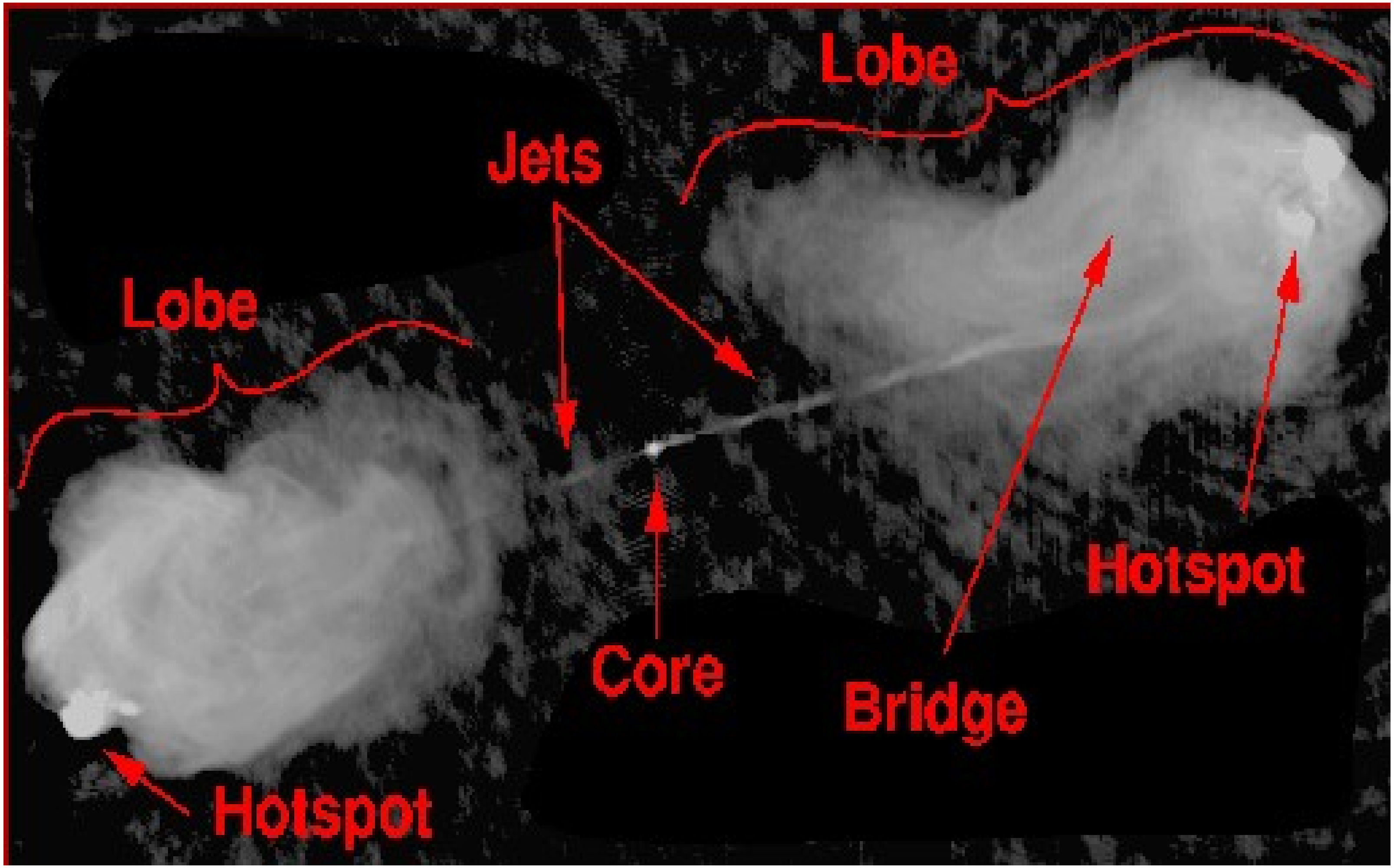


Krakow, May 24th 2011

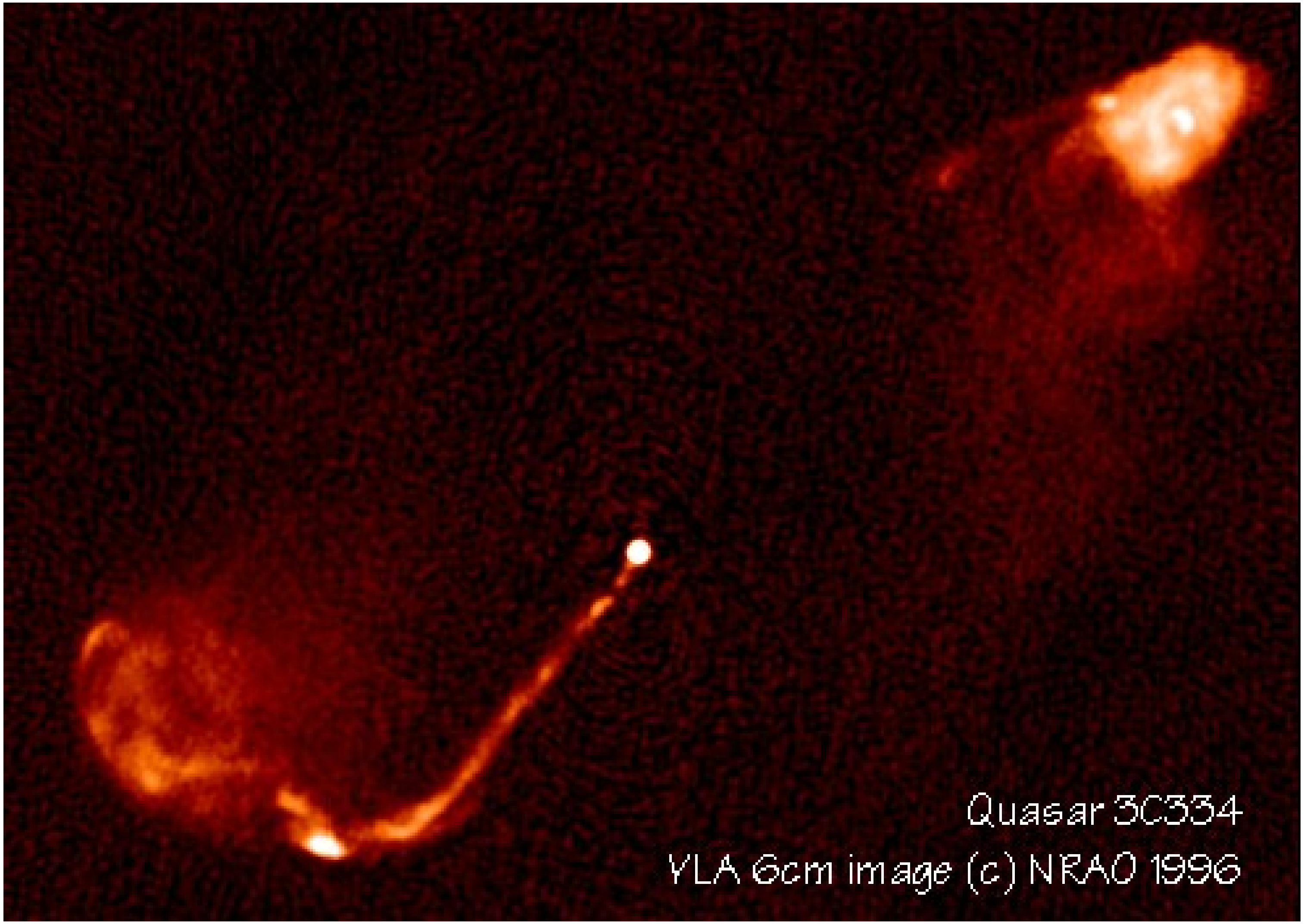
Outline

- Fanaroff-Riley (FR) Classes
- Jet propagation in FRI sources
- Demographics of FRI and FRII sources: the P - M (Ledlow-Owen diagram)
- Is there a connection between FR classification and accretion rate?

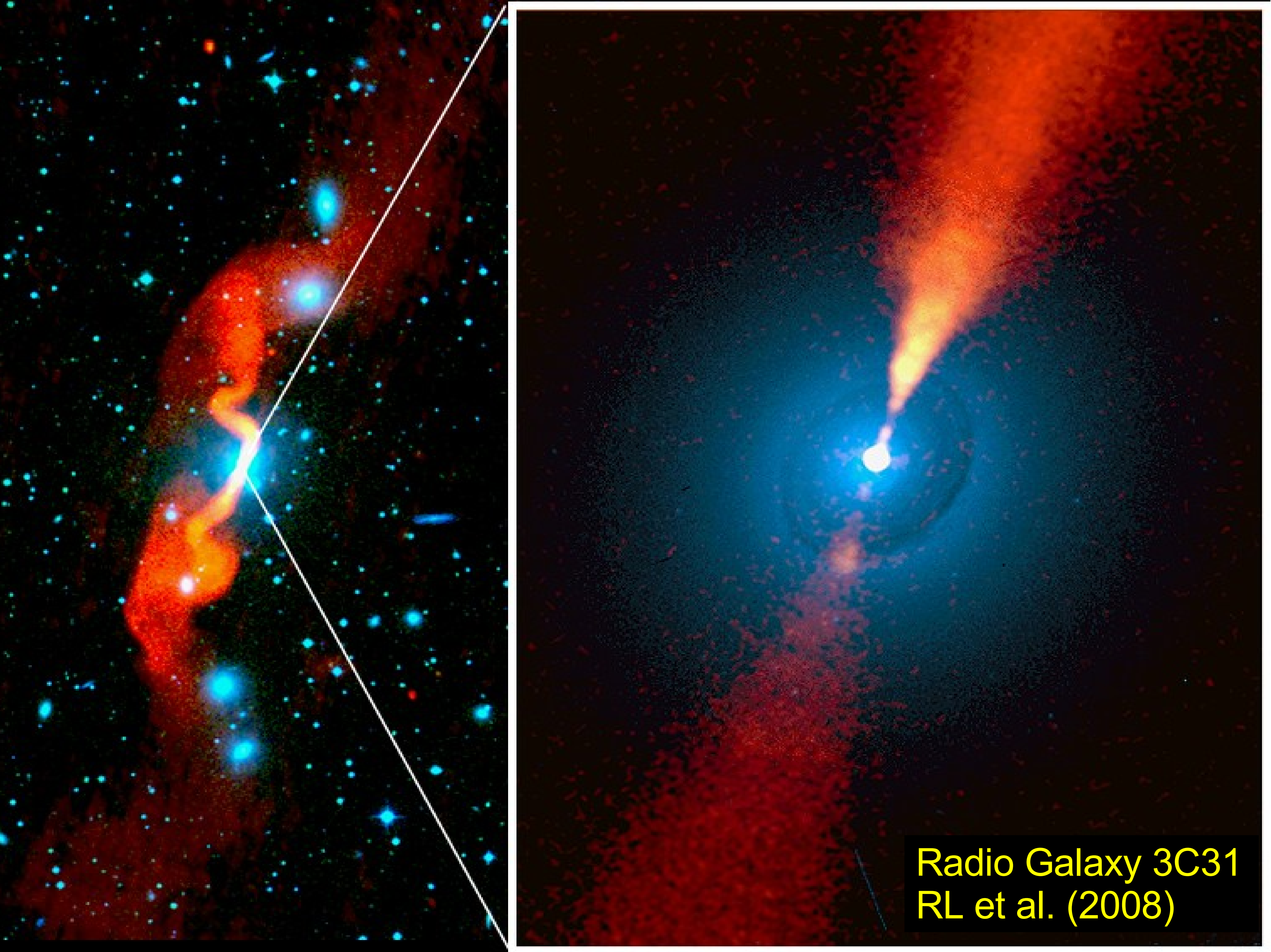
Anatomy of an FRII source: Cygnus A



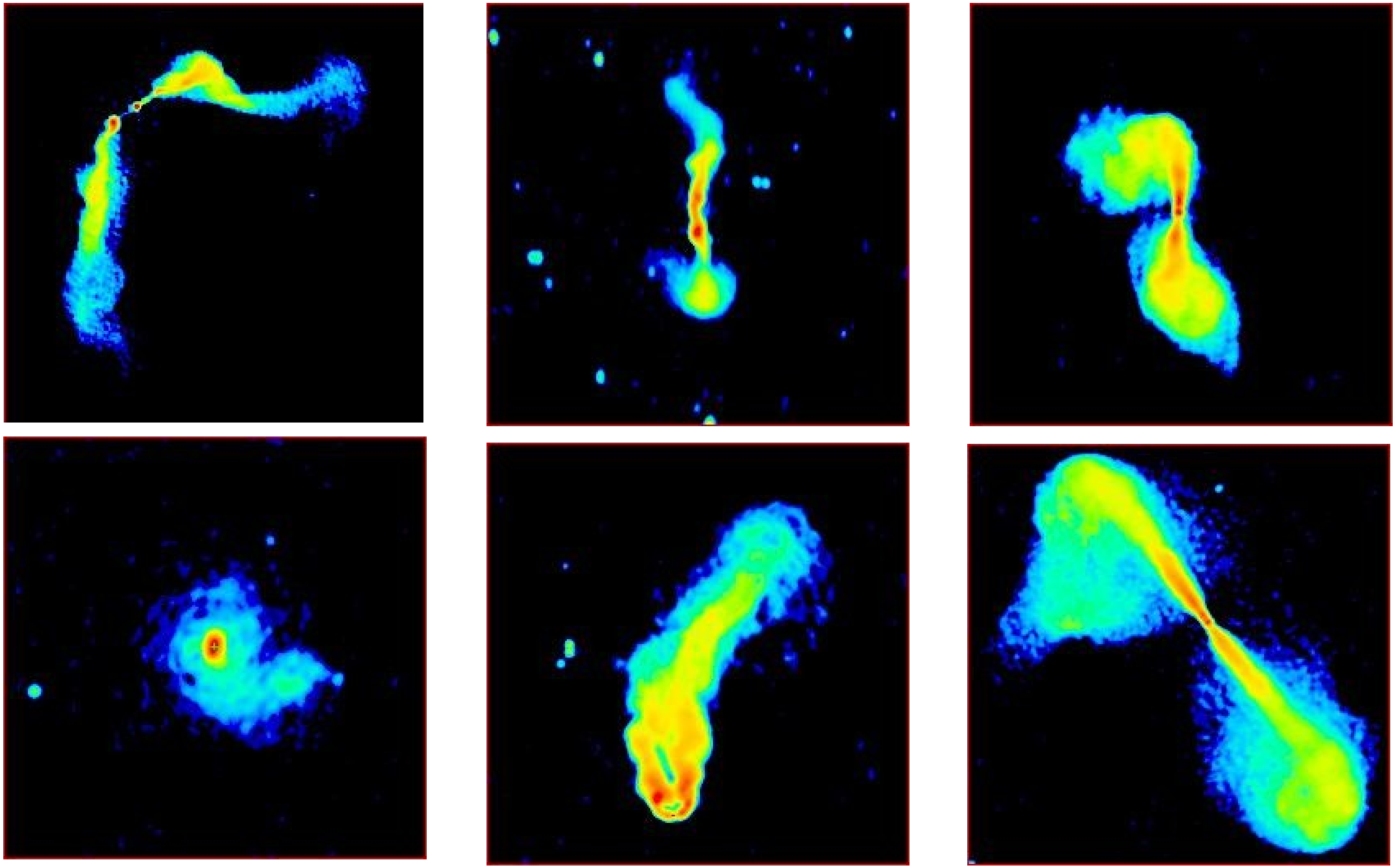
FRII jets remain relativistic on large scales



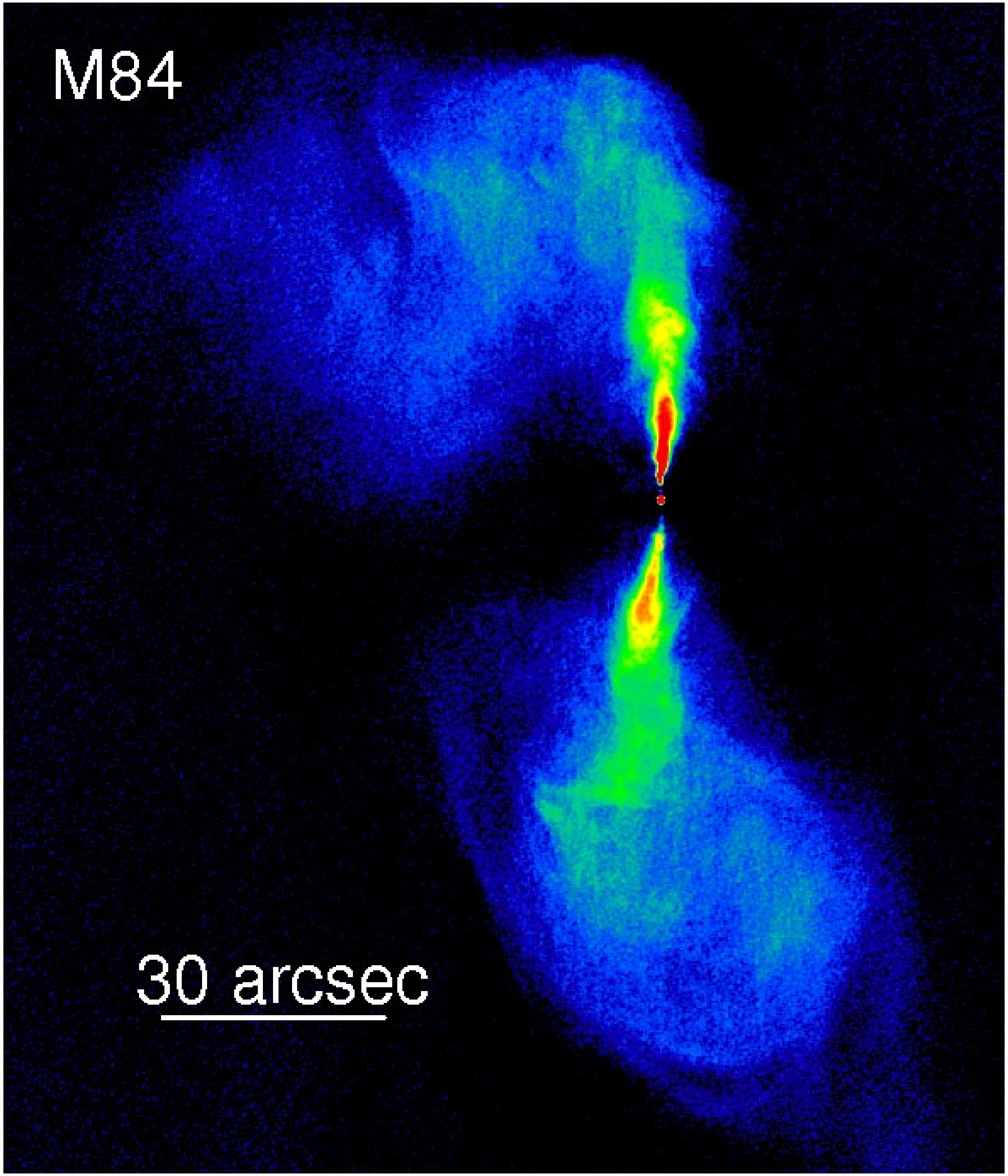
But we do not know how relativistic


Radio Galaxy 3C31
RL et al. (2008)

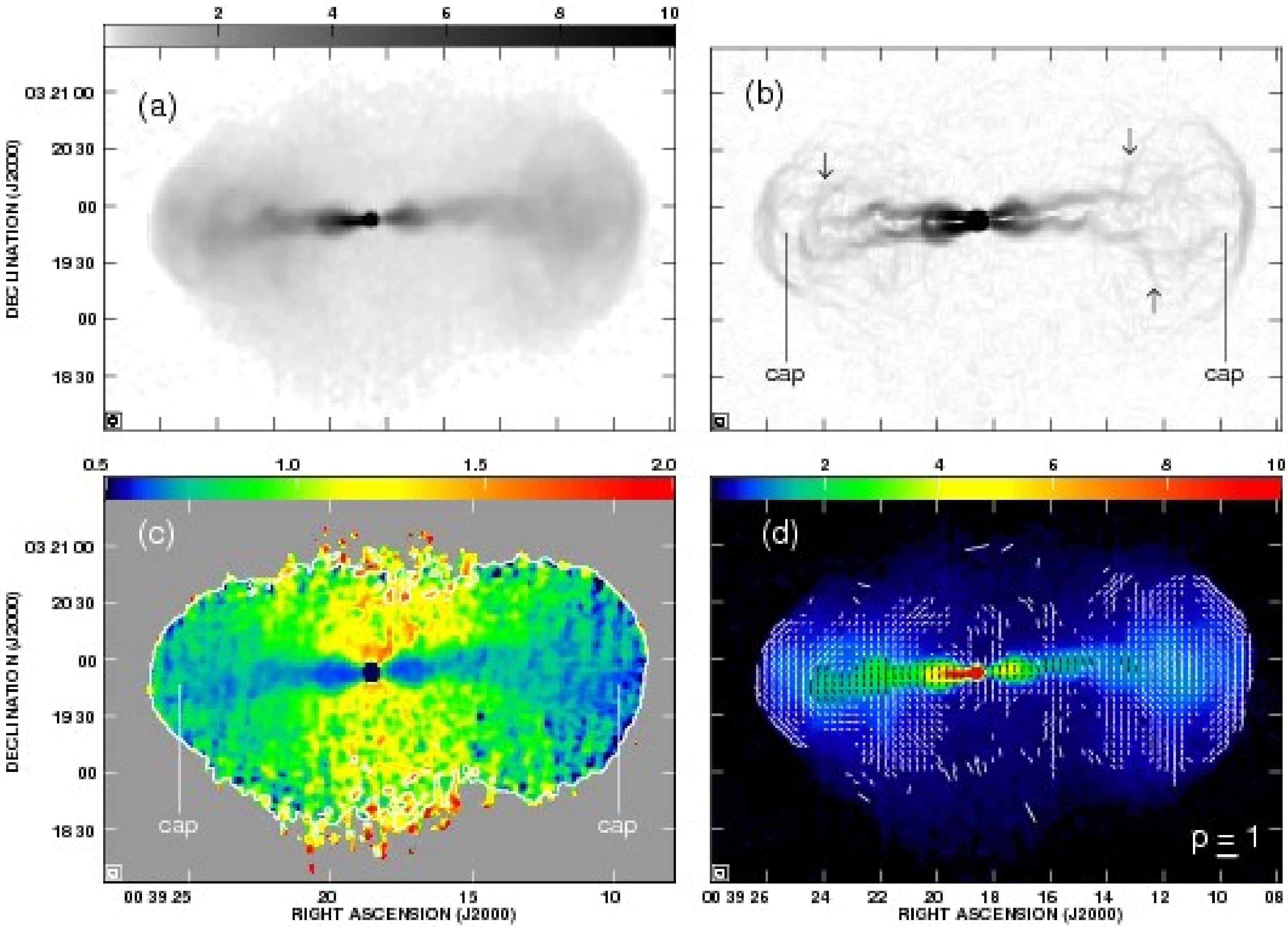
Varieties of FRI

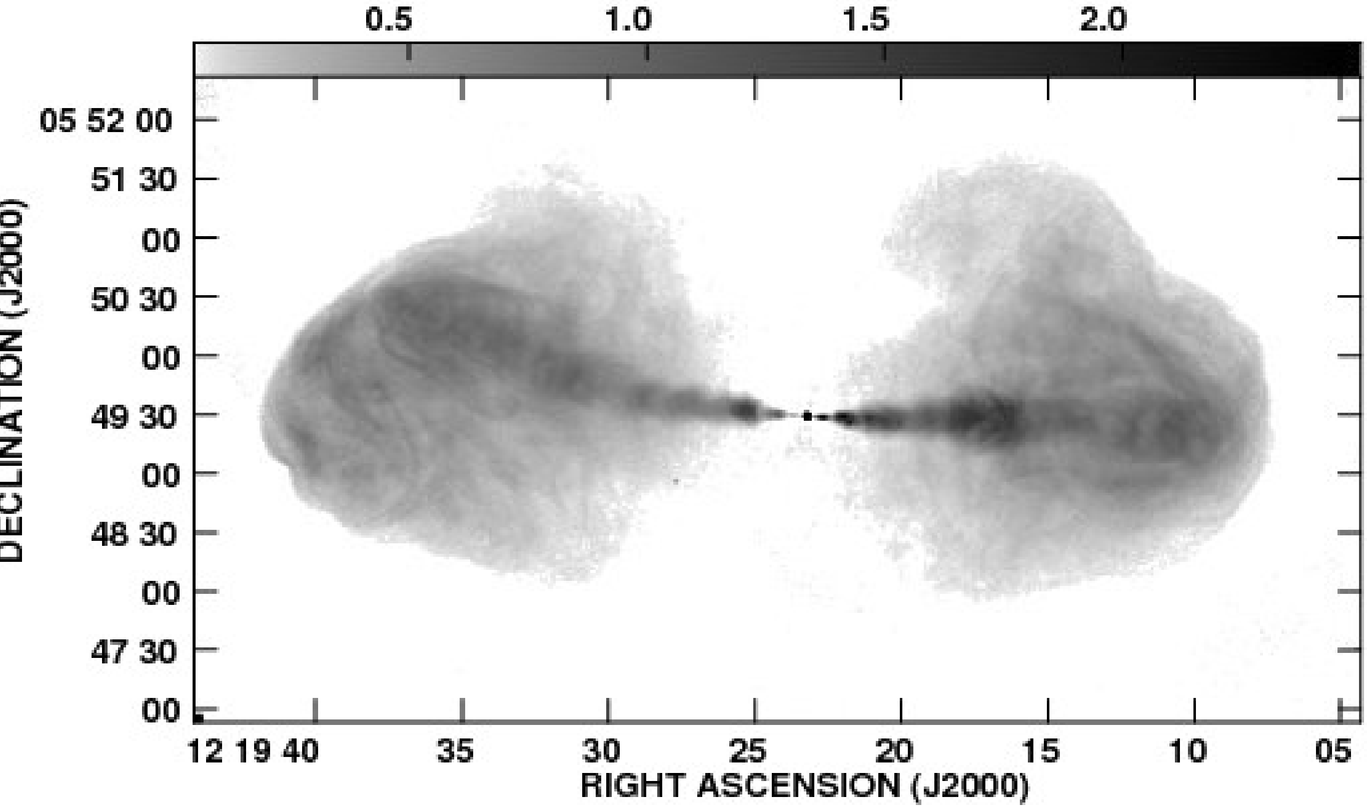


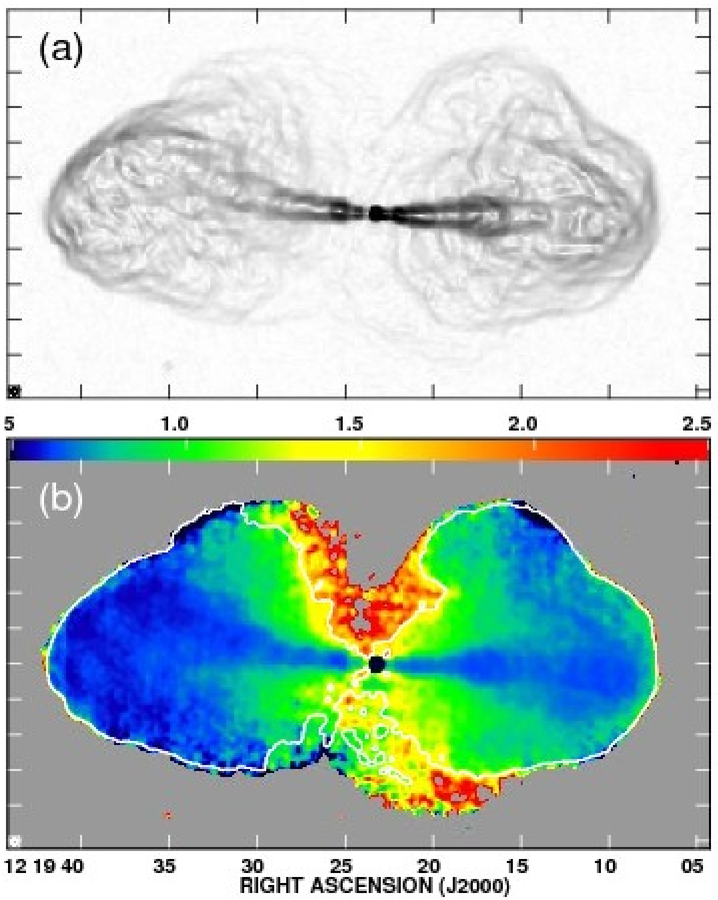
Sources with well-defined lobe edges are in the majority in complete samples


M84
30 arcsec

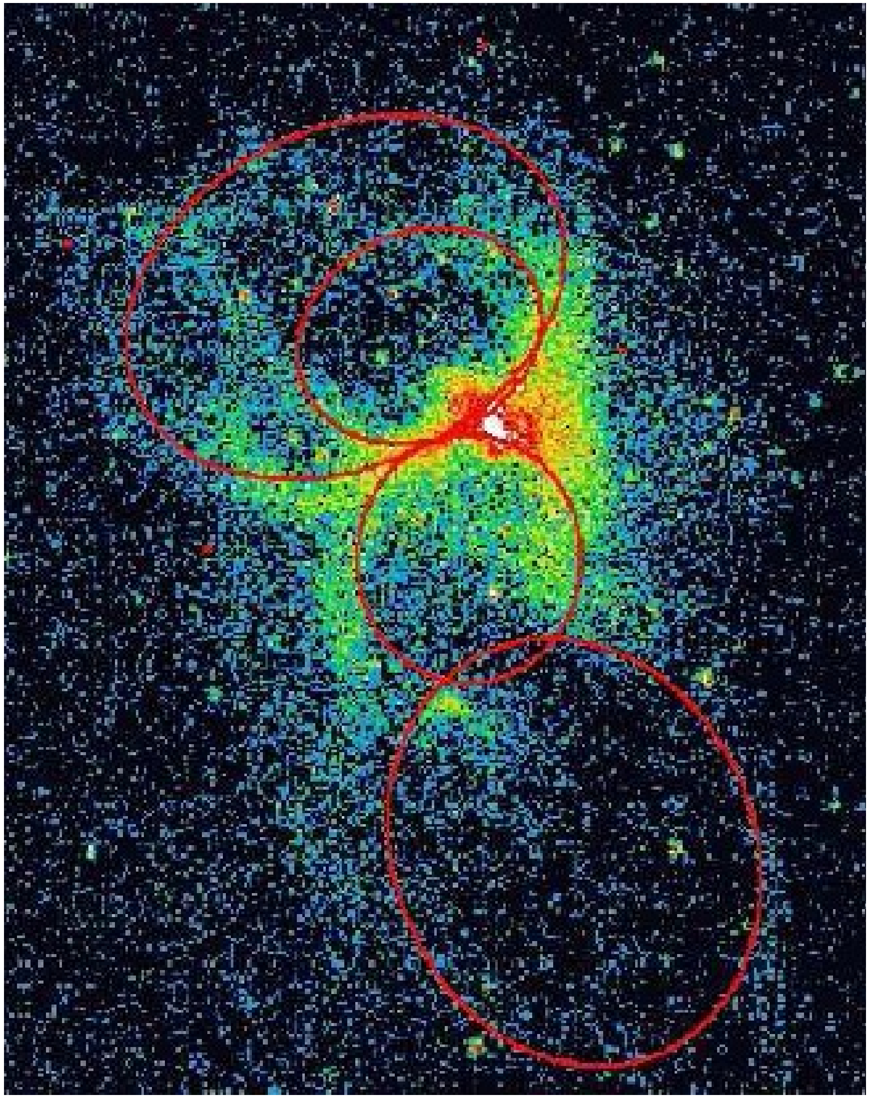
NGC193: a lobed radio galaxy

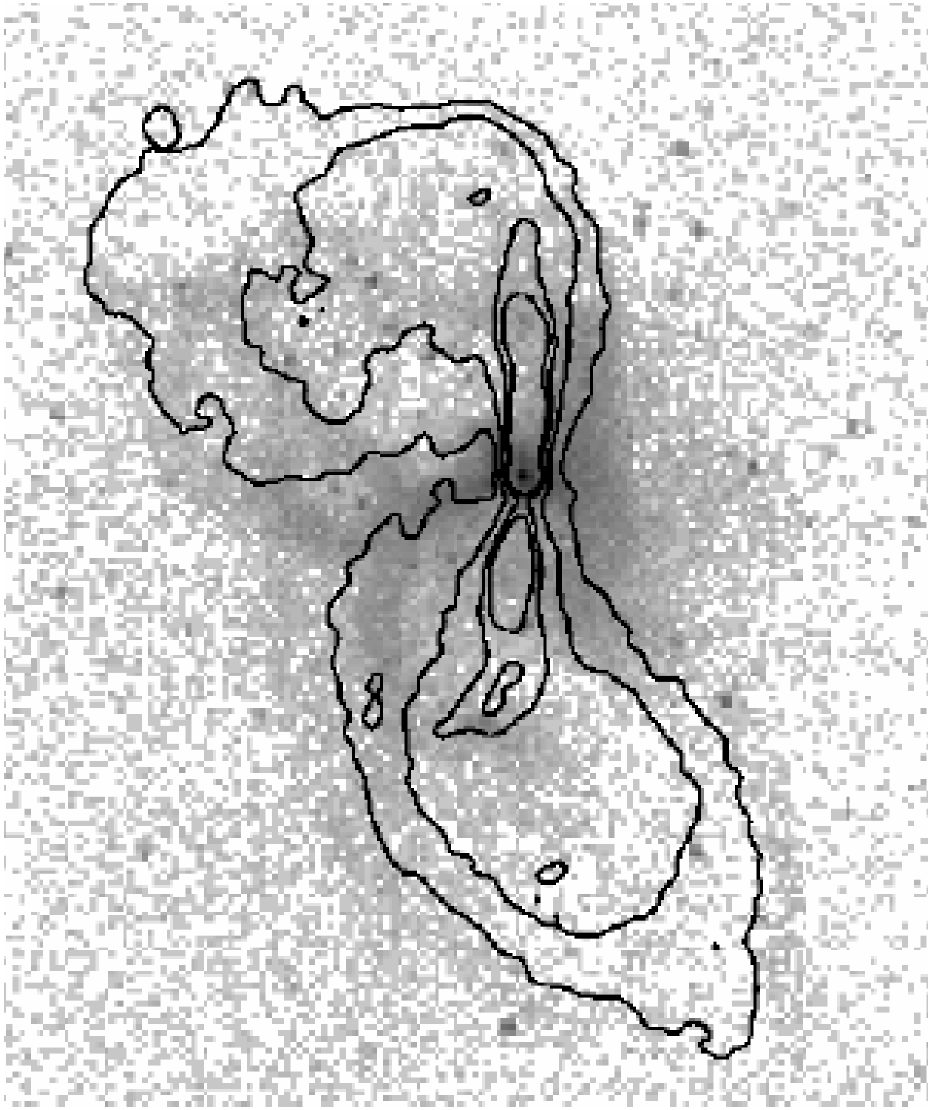



0.5
1.0
1.5
2.0
05 52 00
51 30
00
50 30
00
49 30
00
48 30
00
47 30
00
DECLINATION (J2000)
12 19 40
35
30
25
20
15
10
05
RIGHT ASCENSION (J2000)


(a)
5
1.0
1.5
2.0
2.5
(b)
12 19 40
35
30
25
20
15
10
05
RIGHT ASCENSION (J2000)

Interaction with the surroundings

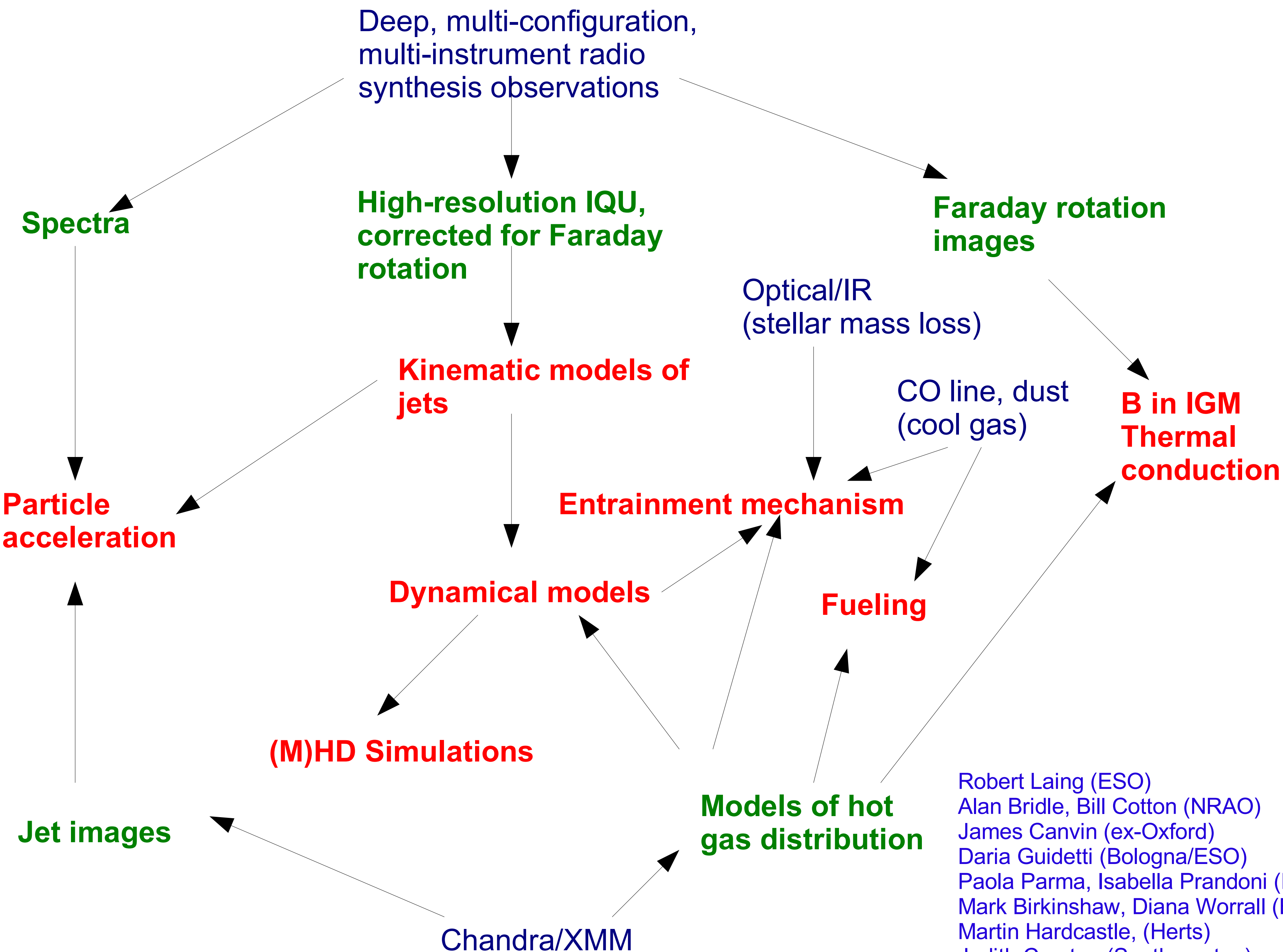




(Finoguenov et al. 2008) Colour/grey-scale soft X-rays (Chandra); contours radio

Lobed and tailed FRI sources

- Jet bases in lobed and tailed sources are very similar: evidence for initital rapid deceleration.
- Jets in lobed sources propagate to the ends of the lobes: dynamics of the lobes probably very similar to those in FRII sources.
- Lobed FRI sources (almost by definition) do not have hot-spots. Hence the flow is internally subsonic, but still very fast.



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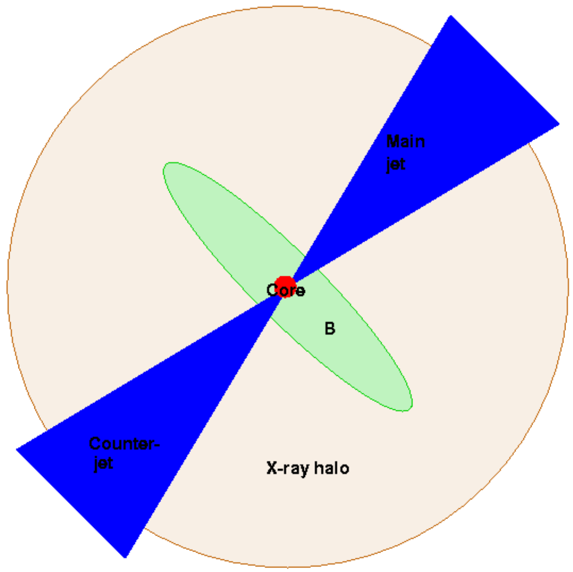
Martin Hardcastle, (Herts)
Judith Croston (Southampton)
Manuel Perucho, Jose Maria Marti (Valencia)

Aims

- Quantify the physics of jets in low-power radio galaxies.
  - Geometry
  - Velocity field
  - Composition (electron, positron, proton, Poynting flux, thermal plasma, ...)
  - Particle energy spectrum, acceleration and loss processes
  - Magnetic field structure and strength – inside and outside
  - Interactions with the external medium; heating/conduction
  - Fueling of AGN (cold/hot gas; EM extraction of BH spin energy)
- Study kpc scales initially, where we have adequate spatial resolution now. Then work towards the nucleus.

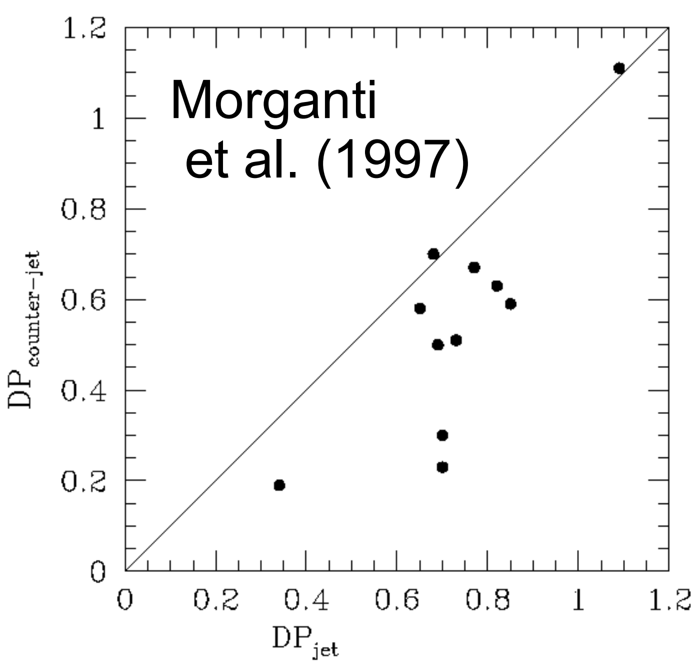
Is the brighter jet really on the near side?

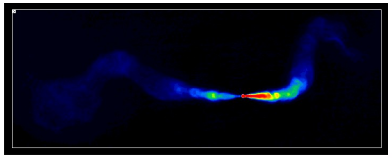


RL (1988); Garrington et al. (1988)

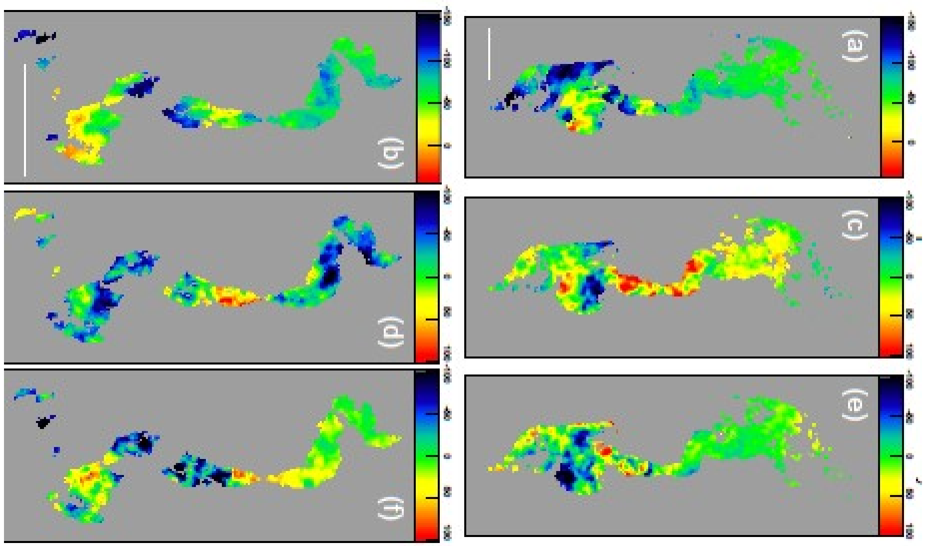
Brighter (approaching) jet shows less Faraday rotation

Now have clear evidence that this is due to foreground plasma





Yes!



RL et al. (2008)

Relativistic effects in jets

$$n(E)dE \propto E^{-(2\alpha+1)}dE$$ Energy spectrum

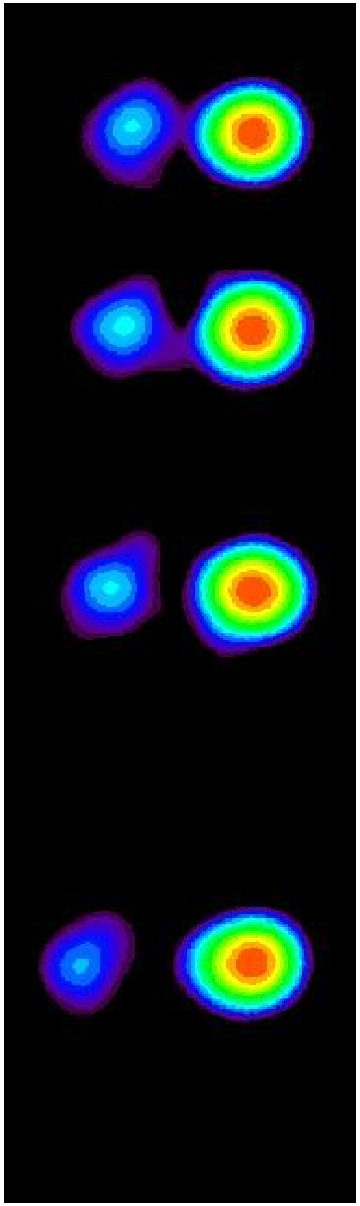
$$S(\nu) = D^{2+\alpha}S_0(\nu)$$ Doppler boosting

$$D = [\gamma(1-\beta\cos\theta)]^{-1}$$ Doppler factor

$$S_j/S_{cj} = \left(\frac{1+\beta\cos\theta}{1-\beta\cos\theta}\right)^{2+\alpha}$$ Jet/counter-jet ratio (isotropic emission)

$$\sin\theta_0 = D\sin\theta$$ Aberration

$$\beta_{\rm app} = \frac{\beta\sin\theta}{1-\beta\cos\theta}$$ Superluminal motion →



v_{app} = 30c

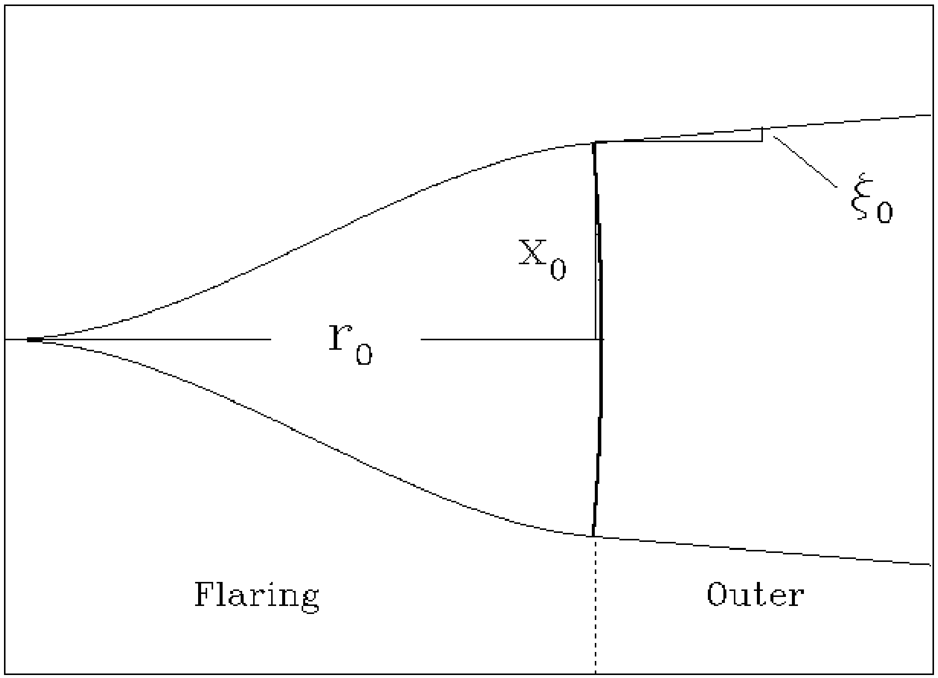
Breaking the $\beta - \theta$ degeneracy

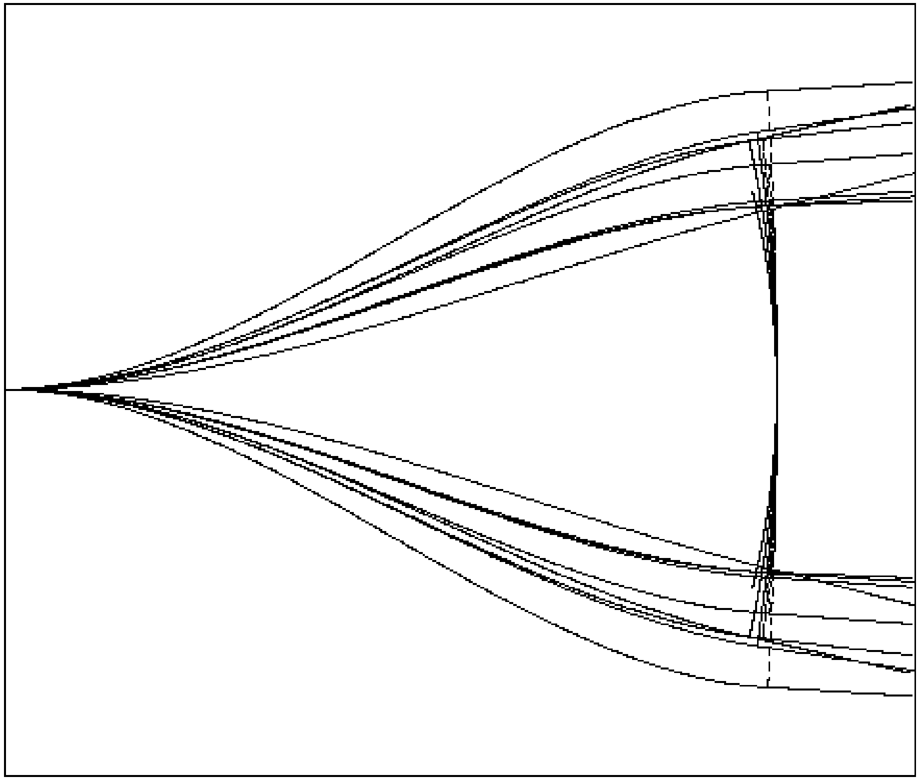
- Suppose that the jets are intrinsically symmetrical and axisymmetric. Then any observed differences are due to relativistic aberration.
- For isotropic emission in the rest frame, jet/counter-jet ratio depends on $\beta\cos\theta$ – how to separate?
- **B** is not isotropic, so rest-frame emission (IQU) depends on angle to line of sight in that frame θ_0
- $\sin\theta_0 = D \sin\theta$ and $D = [\Gamma(1 \pm \beta\cos\theta)]^{-1}$ is different for the main and counter-jets
- So the polarization is different for the two jets
- If we knew the field, we could separate β and θ
- We don't, but we can fit the transverse variation of polarization and determine field component ratios
- Need good transverse resolution + linear polarization

Making a model

- Very deep VLA observations, Stokes IQU. 1500-3000 independent points.
- Model assumes intrinsic (side-to-side) symmetry, axisymmetry and stationary flow. Symmetry assumption must fail badly at large distances, but seems to be accurate close in.
- Best estimate of intrinsic emissivity asymmetry is factor of 1.5 at 10 kpc, compared with 10 - 100 for relativistic effects.
- Select the inner jet regions and average over local weather
- Choose parameterised functional forms for the geometry (angle to line of sight, flow streamlines; velocity field; ratios of toroidal:longitudinal:radial field; emissivity.
- Calculate Stokes parameters, taking proper account of relativistic aberration (beaming); convolve and evaluate χ^2 between model and data (IQU). Optimise.

Geometry

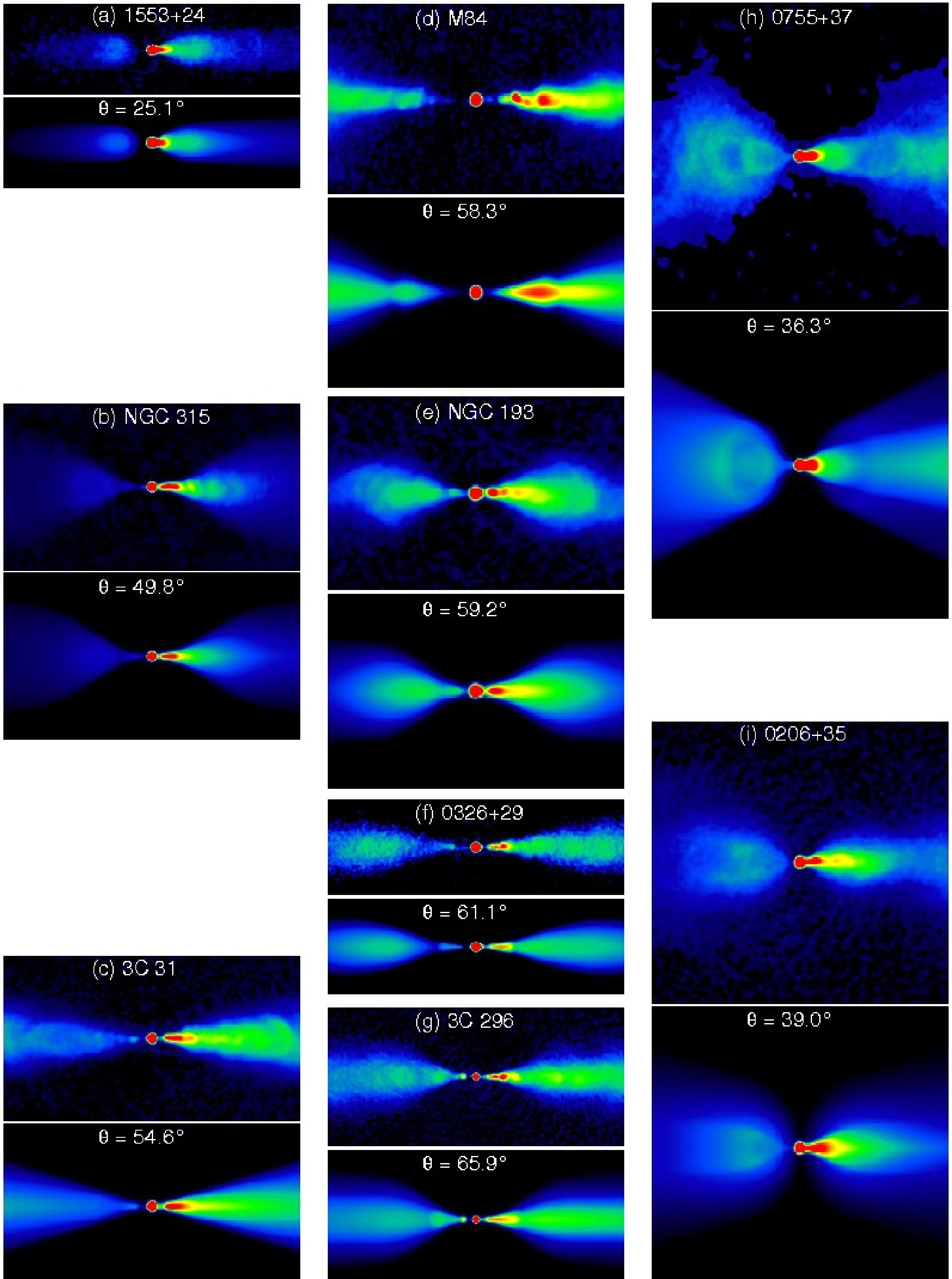




Flaring and outer regions

Flaring region outlines, normalised to r_0

Remarkably similar

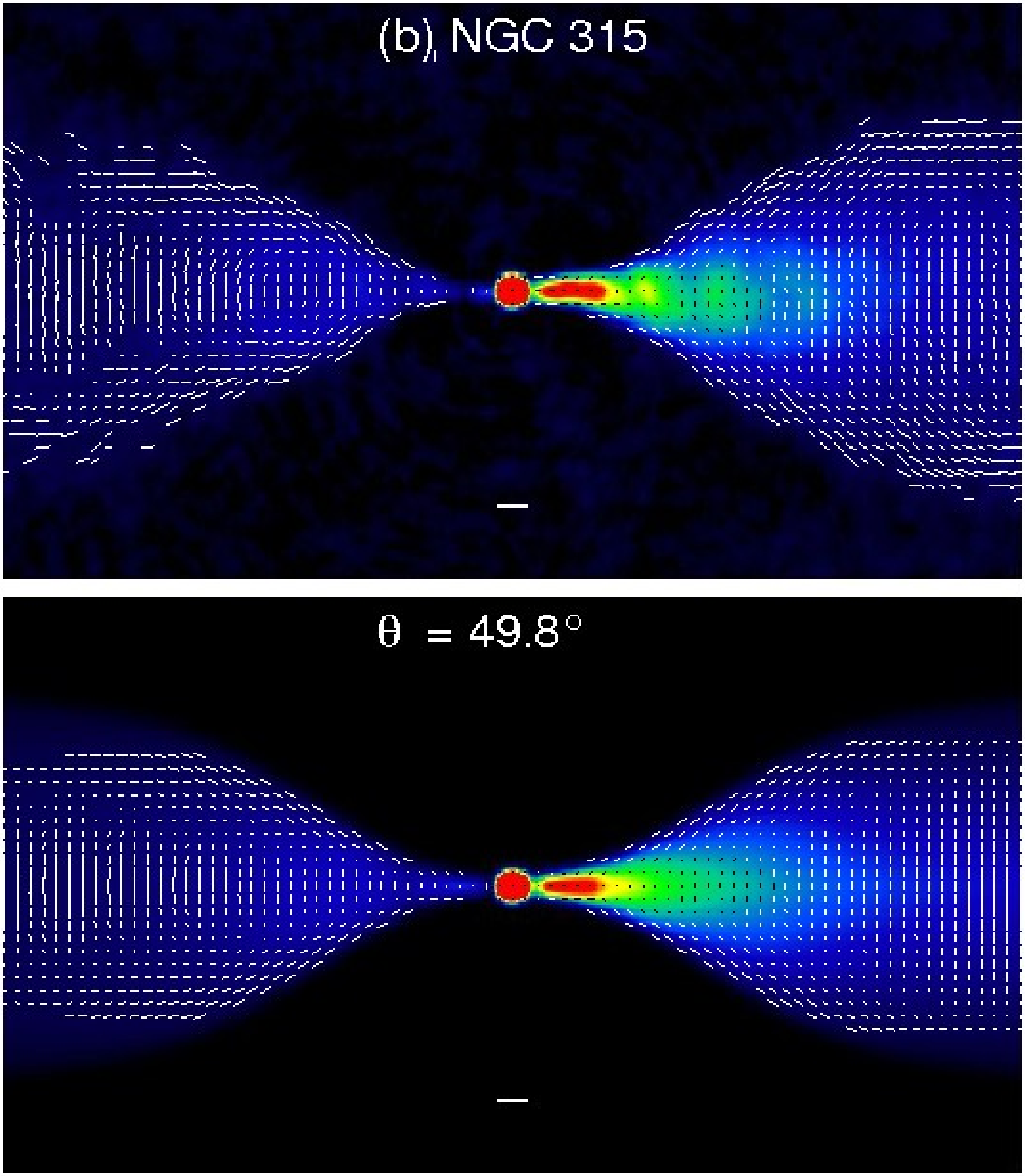


Total intensity fits

9 sources

Top panel data
Bottom panel model

Approaching jet is to the right

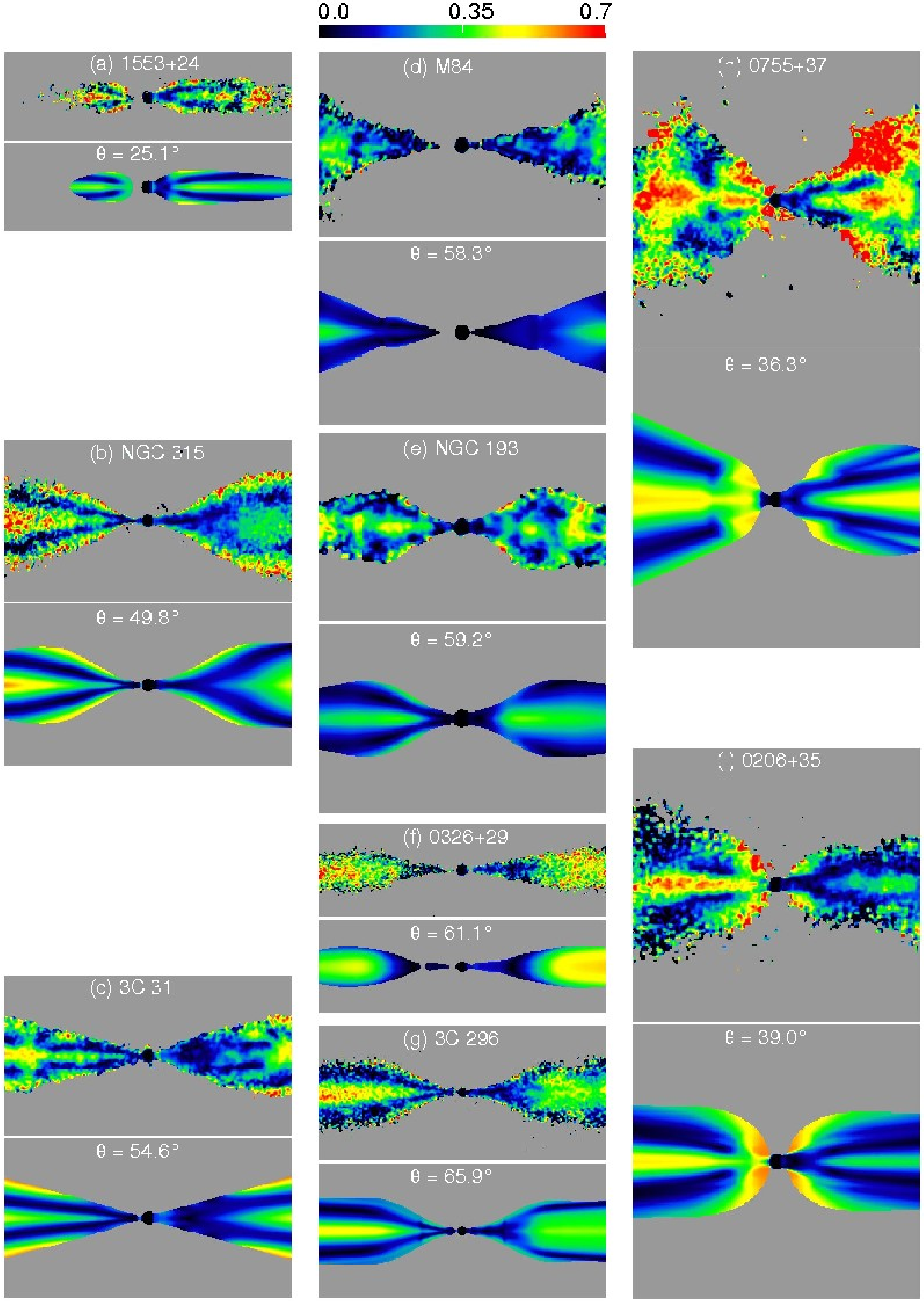


Top: data
Bottom: model

Colour I

Vector length
$p = (Q^2 + U^2)^{1/2}/I$

Vector direction along apparent magnetic field (perpendicular to **E**-vector direction corrected for Faraday rotation)



Degree of polarization
$p = (Q^2 + U^2)^{1/2}/I$

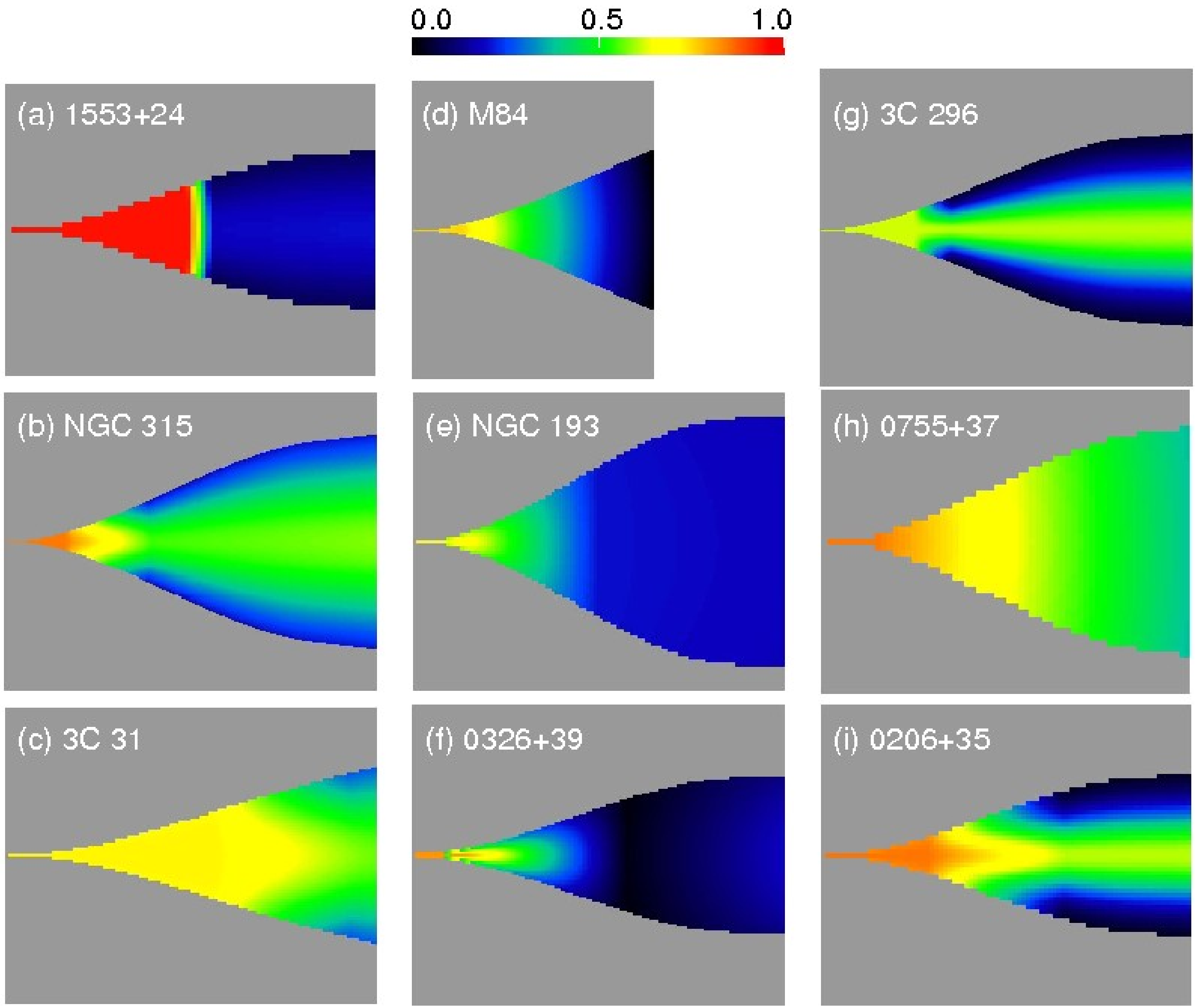
Same order as I fits

Note the asymmetry: approaching jet has minimum in p close to the nucleus

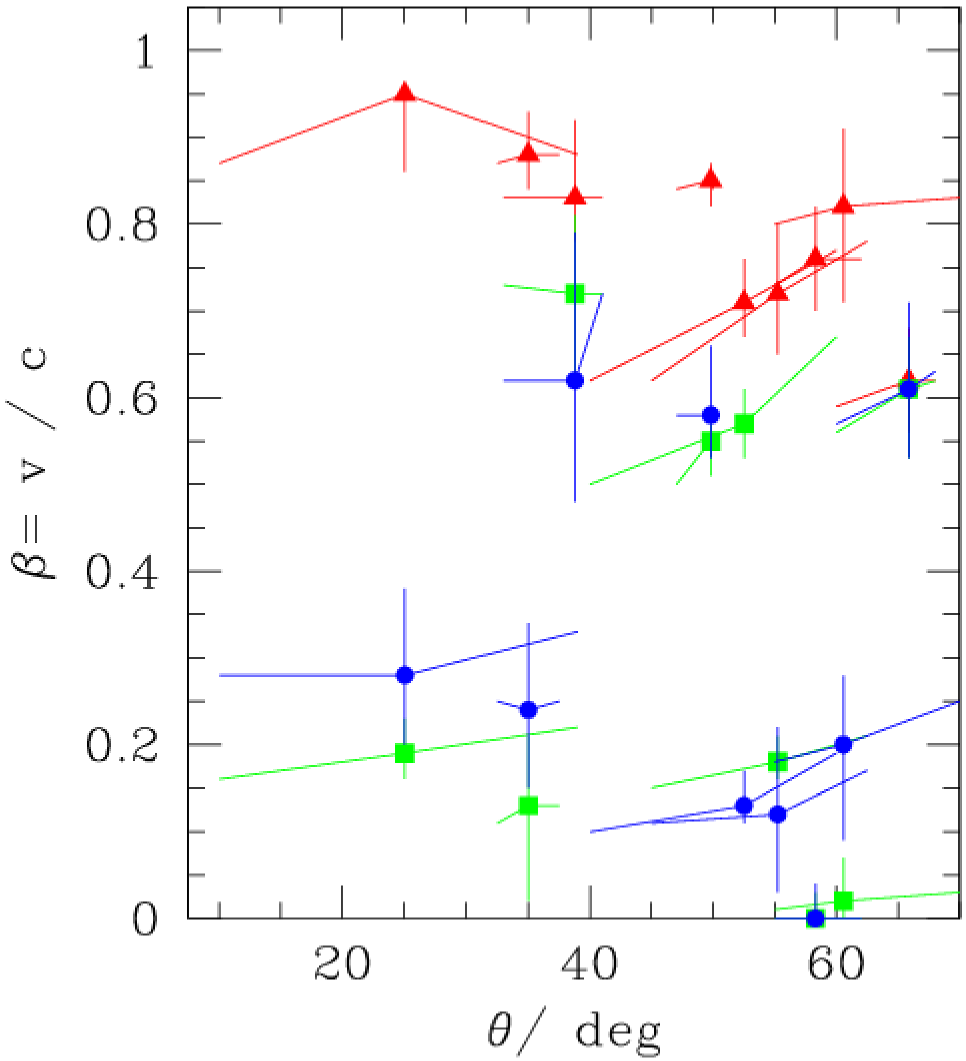
This is the key to solving for velocity and angle

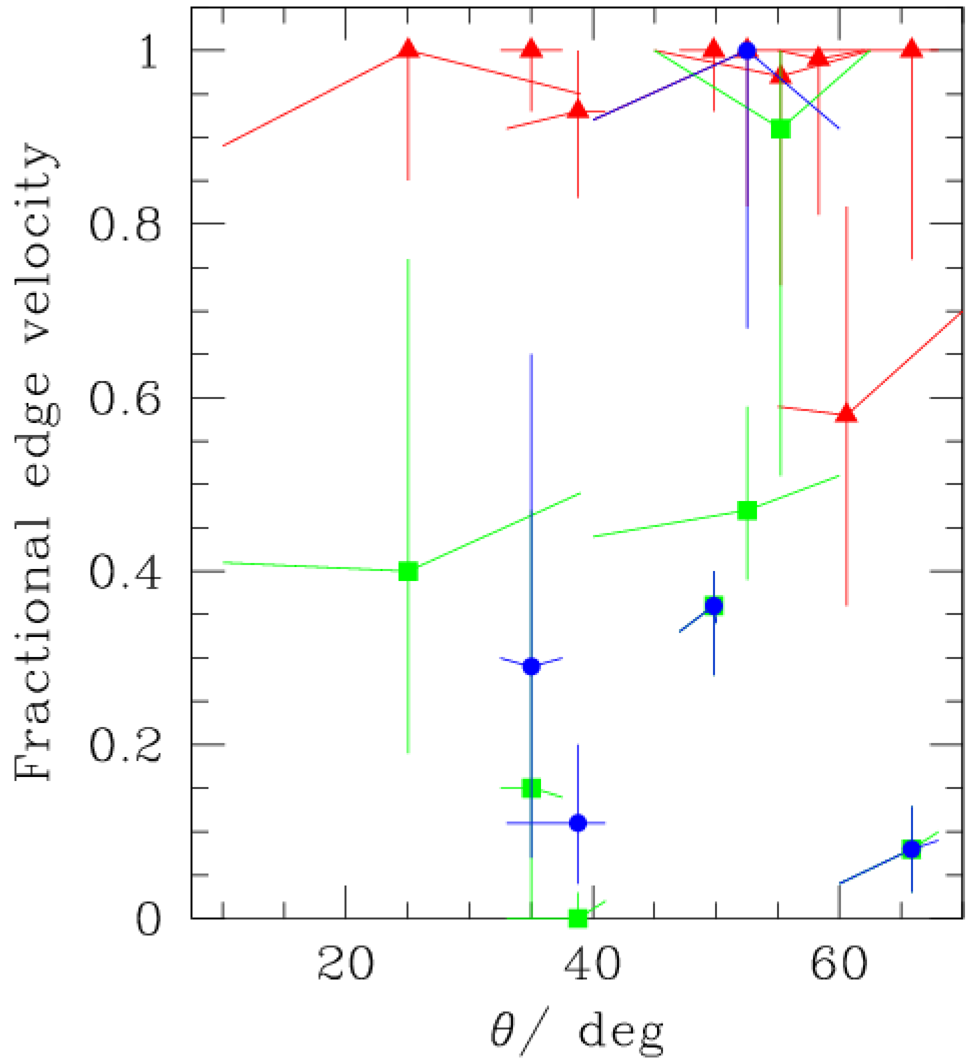
Basic field structure has longitudinal + toroidal components

Velocity fields



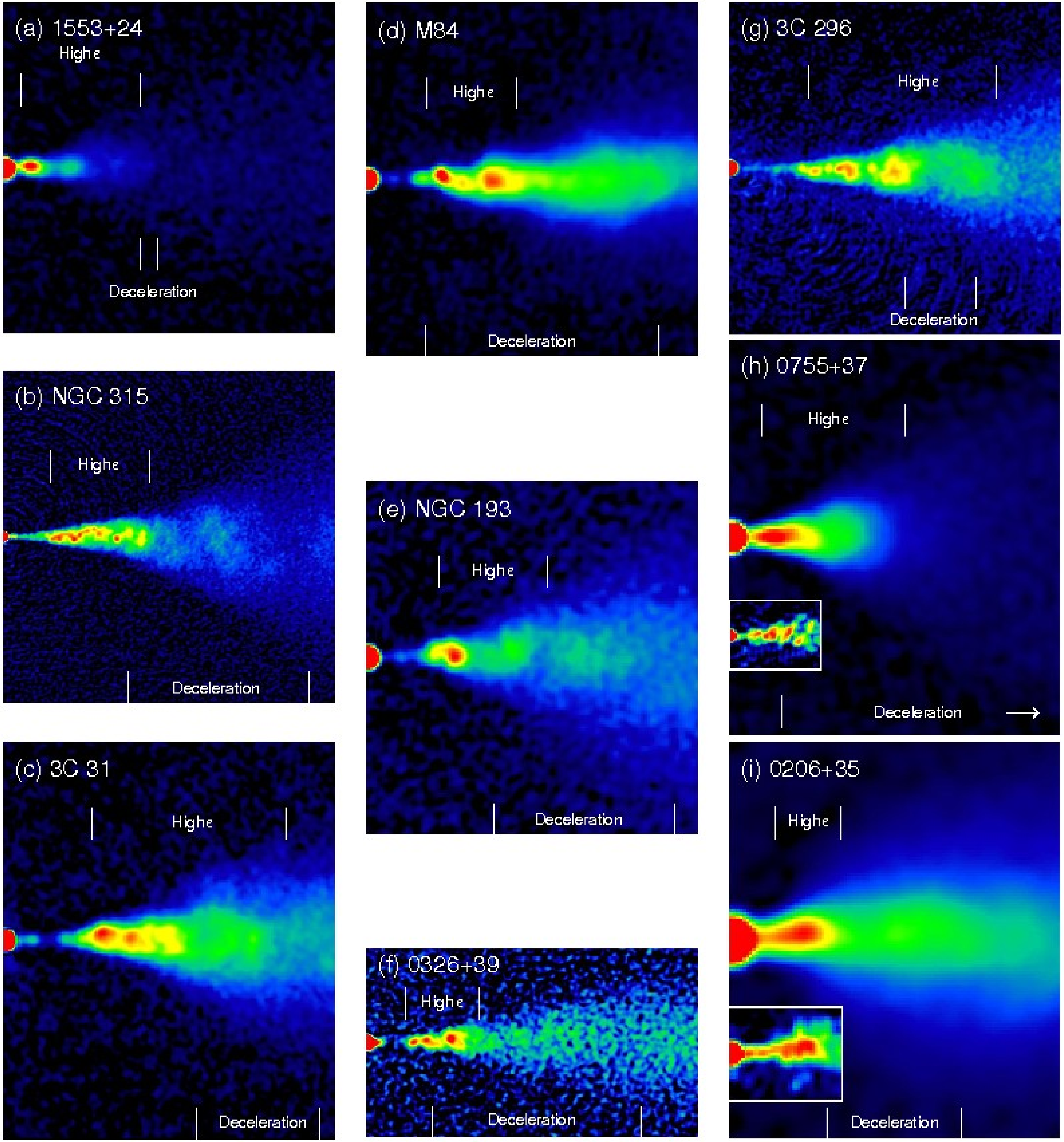
Velocity systematics





Velocity, spines, shear layers and all that

- $\beta \approx 0.8$ where the jets first brighten
- All of the jets decelerate rapidly in the flaring region, but starting and finishing at different distances from the nucleus
- At larger distances, most have roughly constant velocities in the range $\beta \approx 0.1 - 0.4$ and one (3C 31) decelerates slowly
- Evolution in the velocity profiles from ~top-hat to centrally peaked (→ boundary-layer entrainment) in the rapid deceleration zone
- Velocity profiles are smooth (~truncated Gaussian) at large distances. The whole jet is a shear flow - there is no discrete "spine"



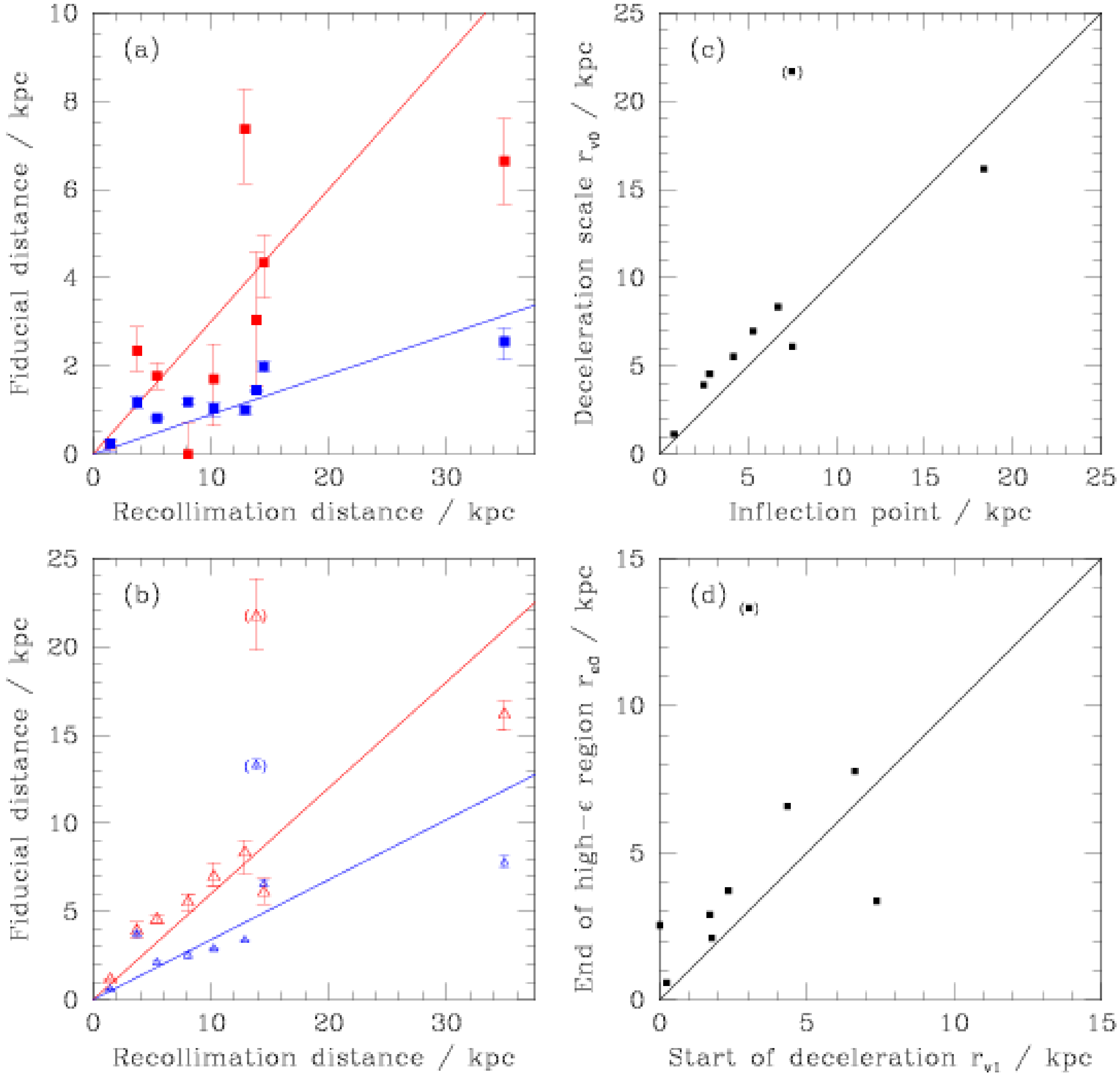
I images at high resolution

Well-defined flaring point

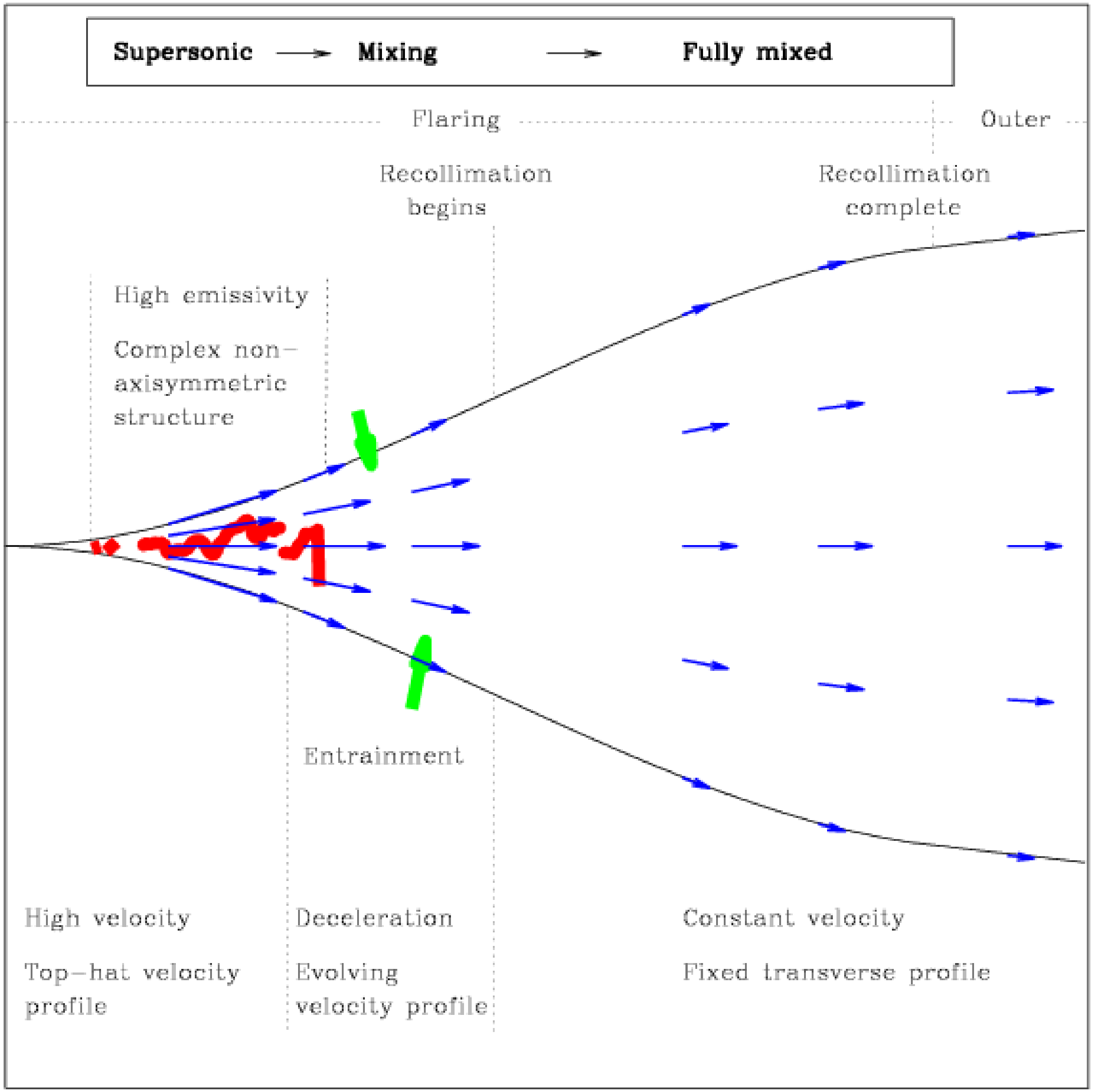
Complex, non-axisymmetric , structure with high proper emissivity near the jet axis

Deceleration starts in the high-emissivity region

Flaring region: homologous

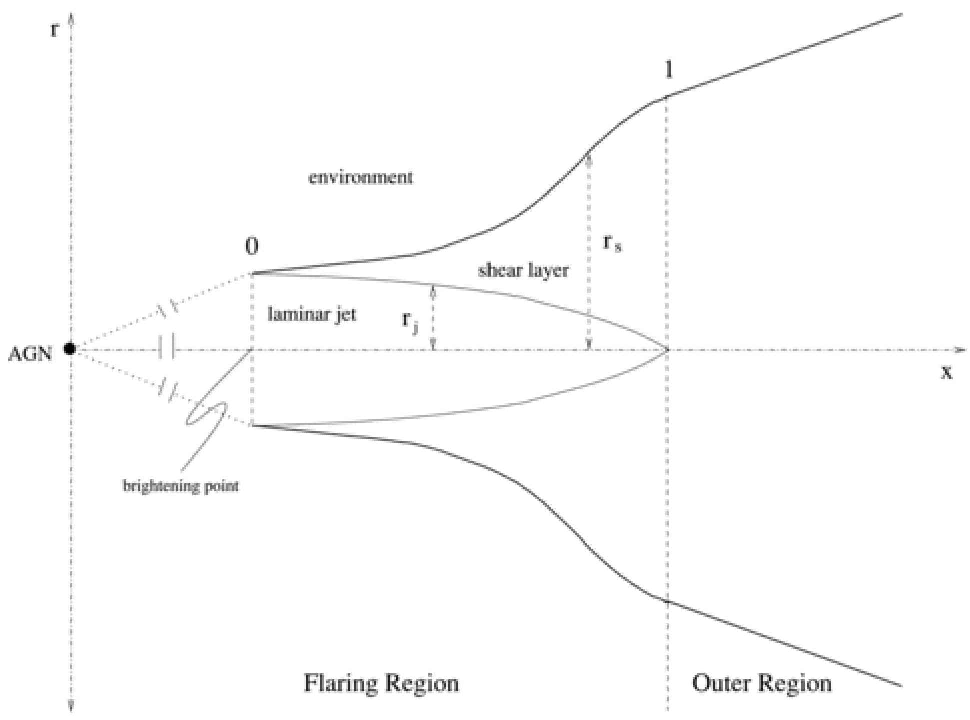


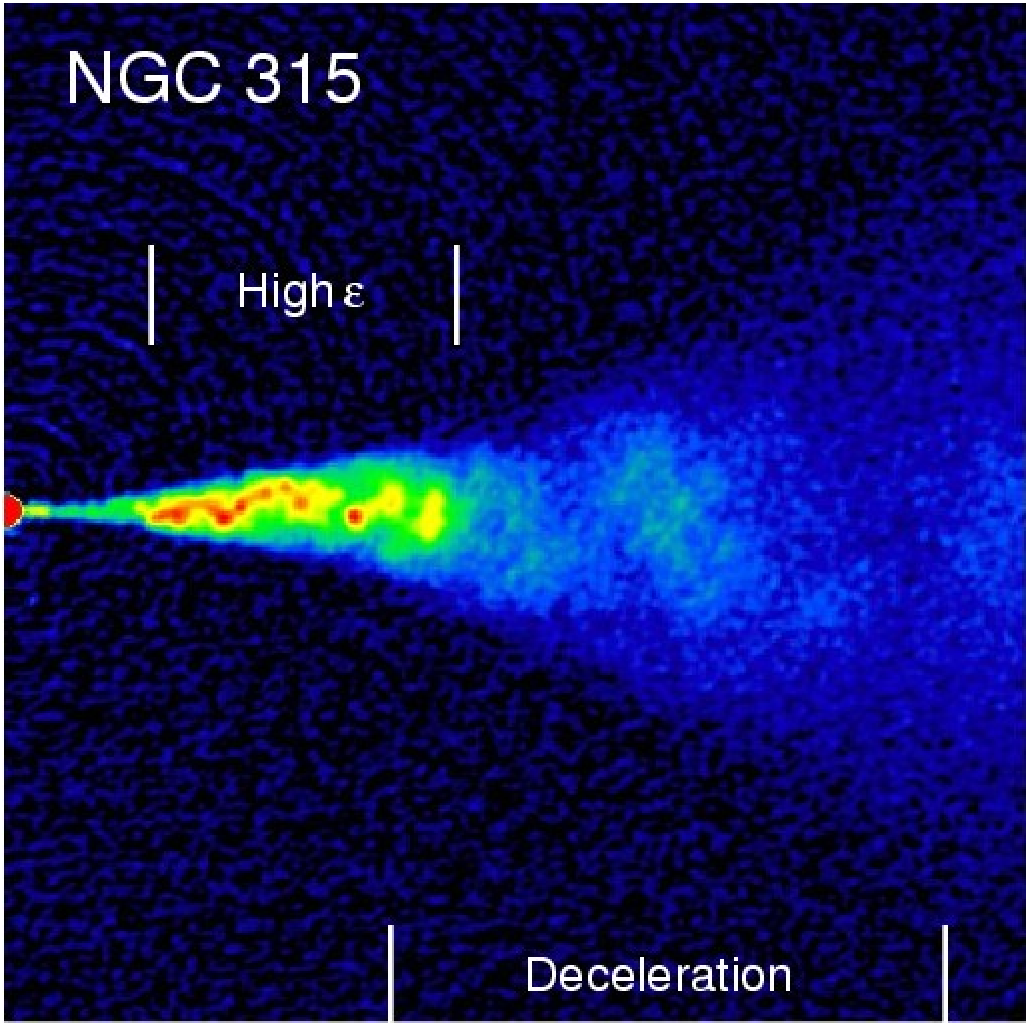
Cartoon



Supersonic → Mixing → Fully mixed
Flaring
Outer
Recollimation begins
Recollimation complete
High emissivity
Complex non-axisymmetric structure
Entrainment
High velocity
Top-hat velocity profile
Deceleration
Evolving velocity profile
Constant velocity
Fixed transverse profile

Mixing-layer model?



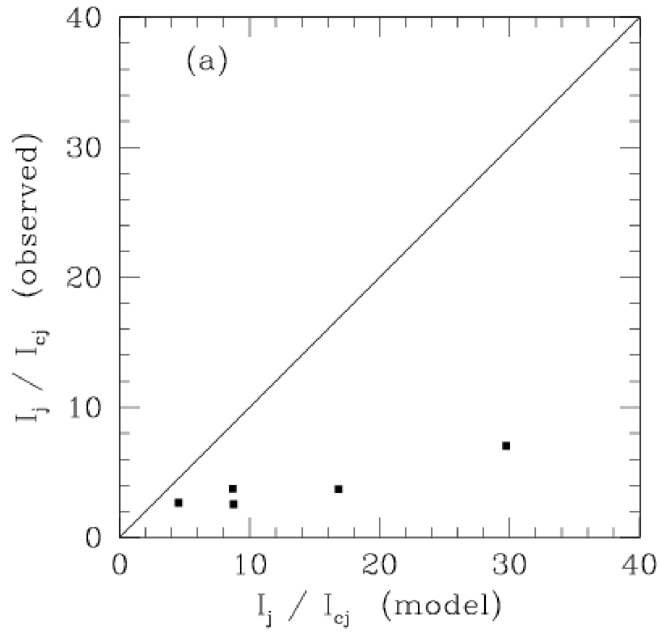


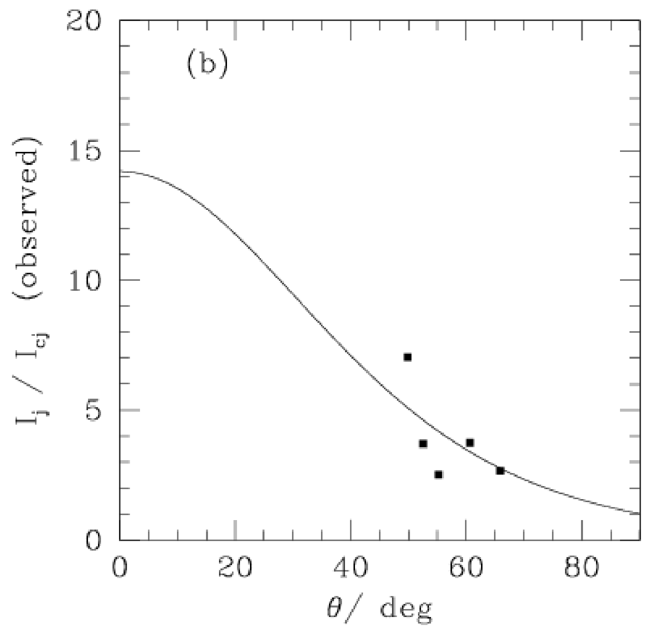
Wang, Kaiser, RL et al. (2009)

A qualitative picture

- Entrainment requires the onset of turbulence, eddies, weak shocks etc. → non-axisymmetric structures, enhanced emissivity, particle acceleration.
- Once significant mixing has occurred, the jet starts to slow down, initially at the edges, and to widen. It eventually becomes fully turbulent. This is the end of the high-emissivity region.
- Entrainment is drastically reduced:
  - when the external gas density becomes low or
  - when the jet reaches the shelter of a radio lobe (in which the plasma is mostly relativistic and light)
- After the mixing episode is complete, the jet recollimates (opening angle depends on residual entrainment rate)

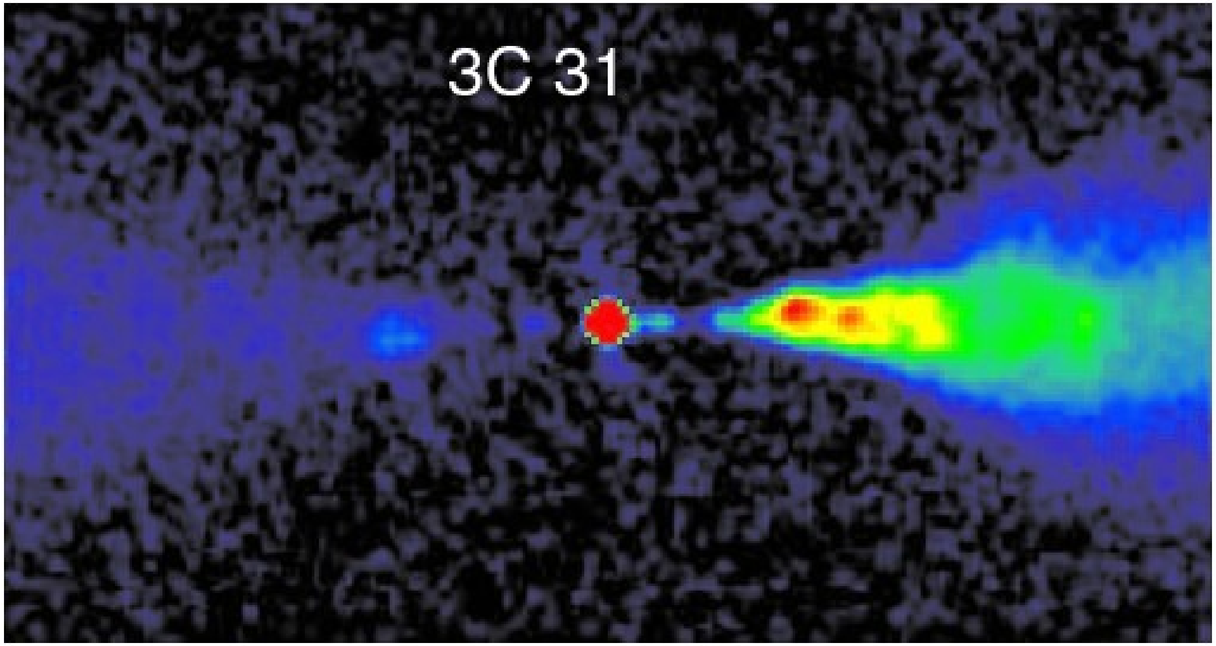
Velocity in the inner jet





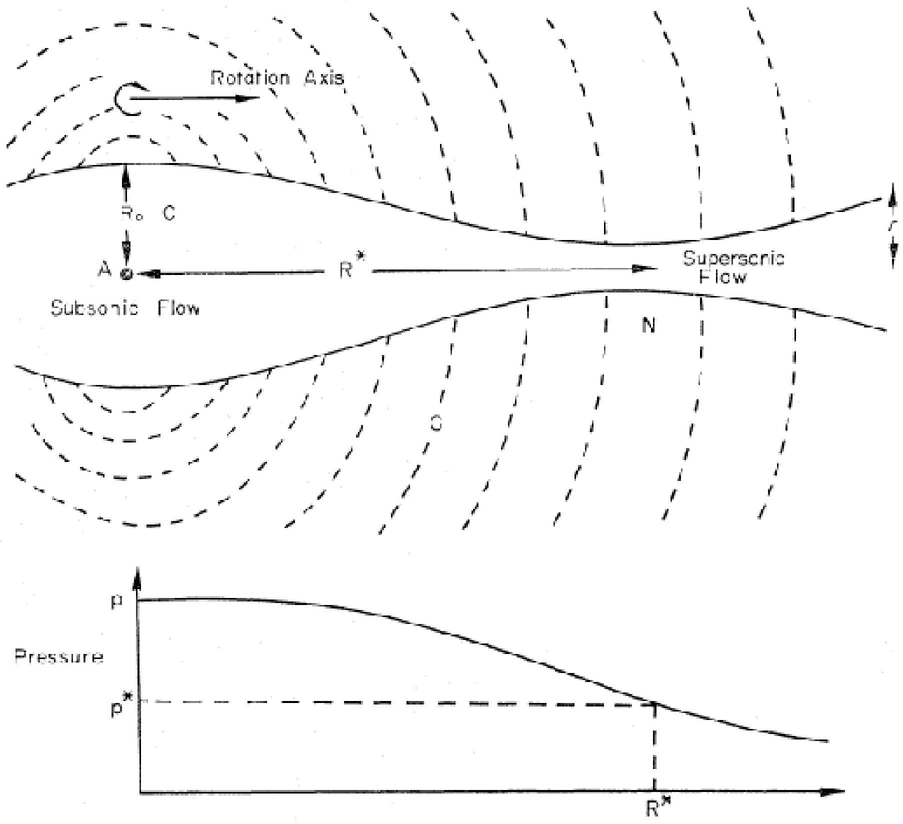
Sidedness ratios in the inner jets are lower than after the flaring points.

Slow boundary layer?
or
Low bulk velocity?

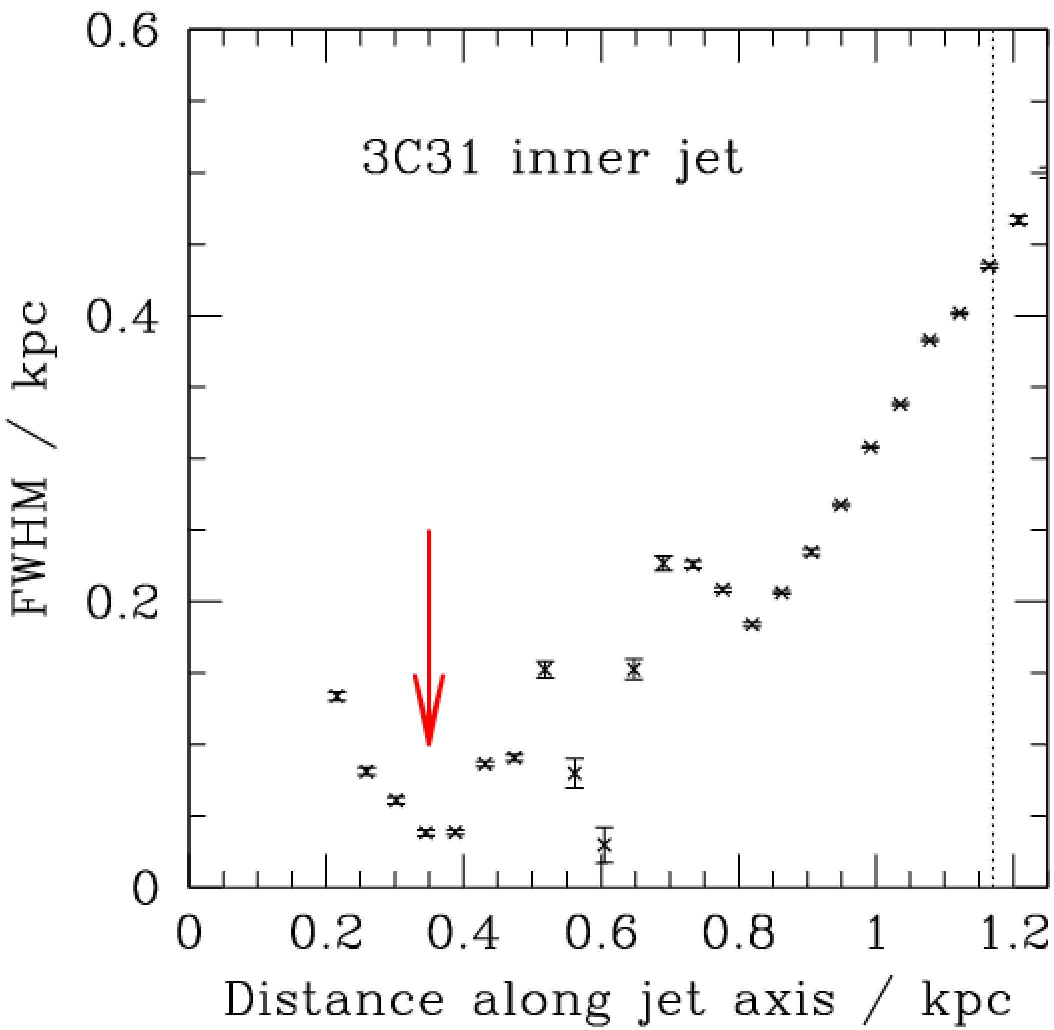


Return of the Twin Exhaust

- All of the twin-jet sources have coronae of hot plasma with $p/p_0 \approx$ ½ on typical scales ≈ 1 kpc
- Jets could accelerate from β ≈ 0.5 to β ≈ 0.8 via the twin-exhaust mechanism (Blandford & Rees 1974).



Can we locate the nozzle?



Maybe, in this case

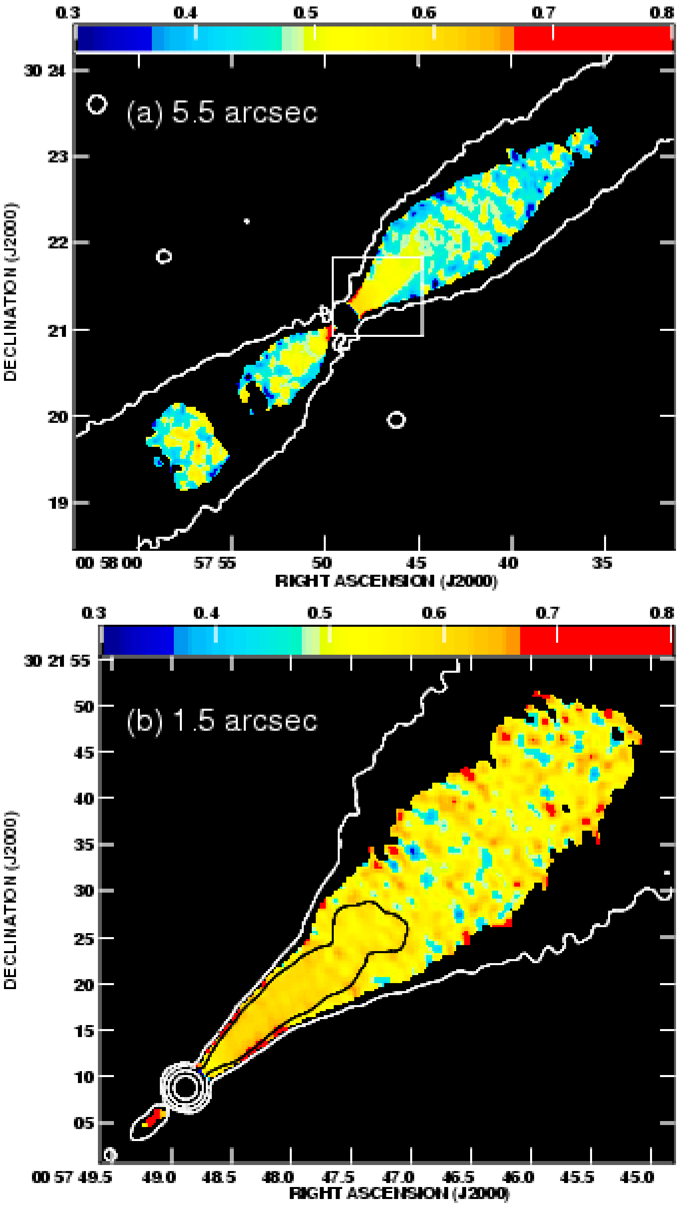
Sonic point and nozzle at 0.3 kpc from nucleus

Acceleration to $\beta \approx 0.8$ ($M \approx 2$) at 1.2 kpc

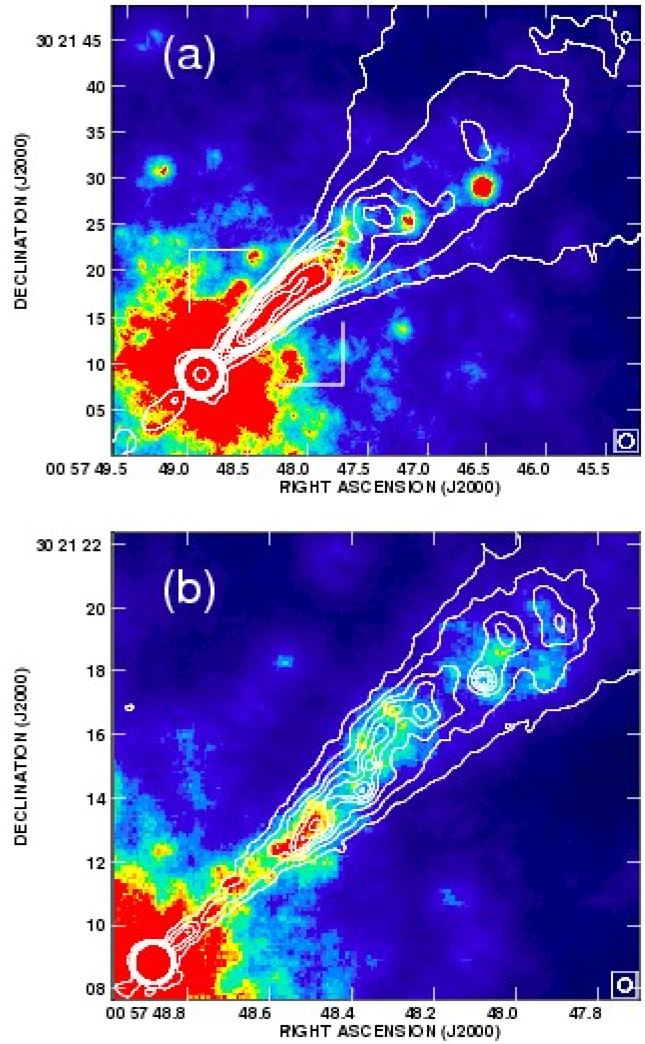
New picture

- Faint, well-collimated inner jets are internally subsonic (but still highly supersonic with respect to the external medium).
- They are accelerated to mildly supersonic speeds by the external pressure gradient of the dense, central IGM.
- The high-emissivity region corresponds to transonic flow ($M \approx 2$)
- This region ends when the jet again becomes subsonic, shortly after the start of significant boundary-layer entrainment.
- Open question: what triggers the start of boundary-layer entrainment?

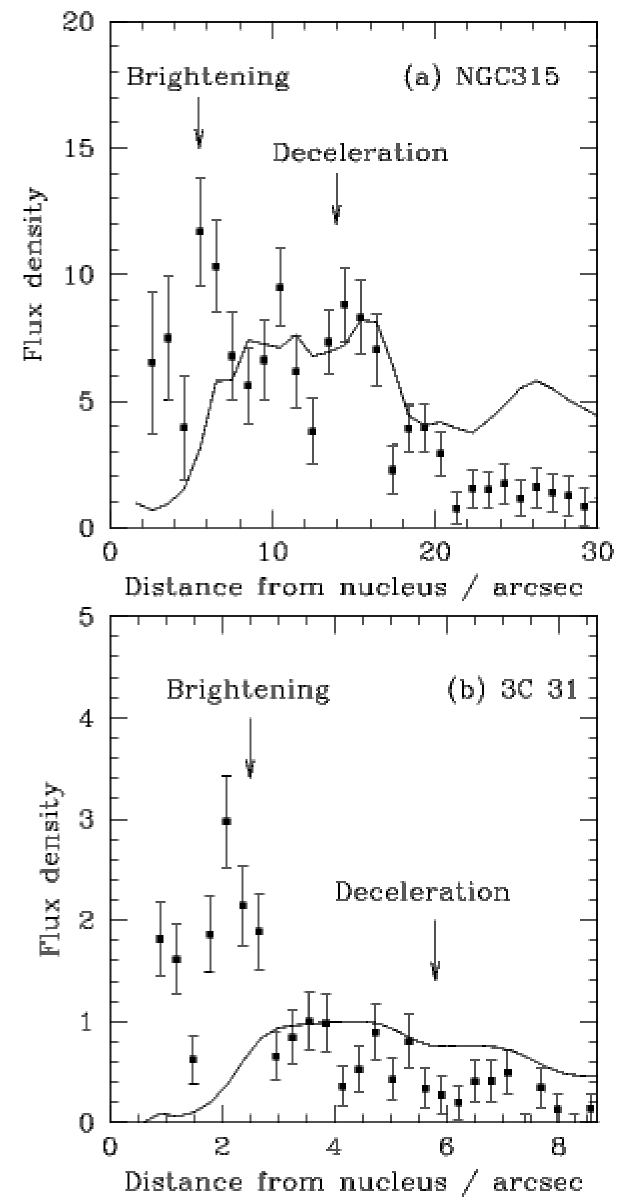
Particle acceleration in jet bases

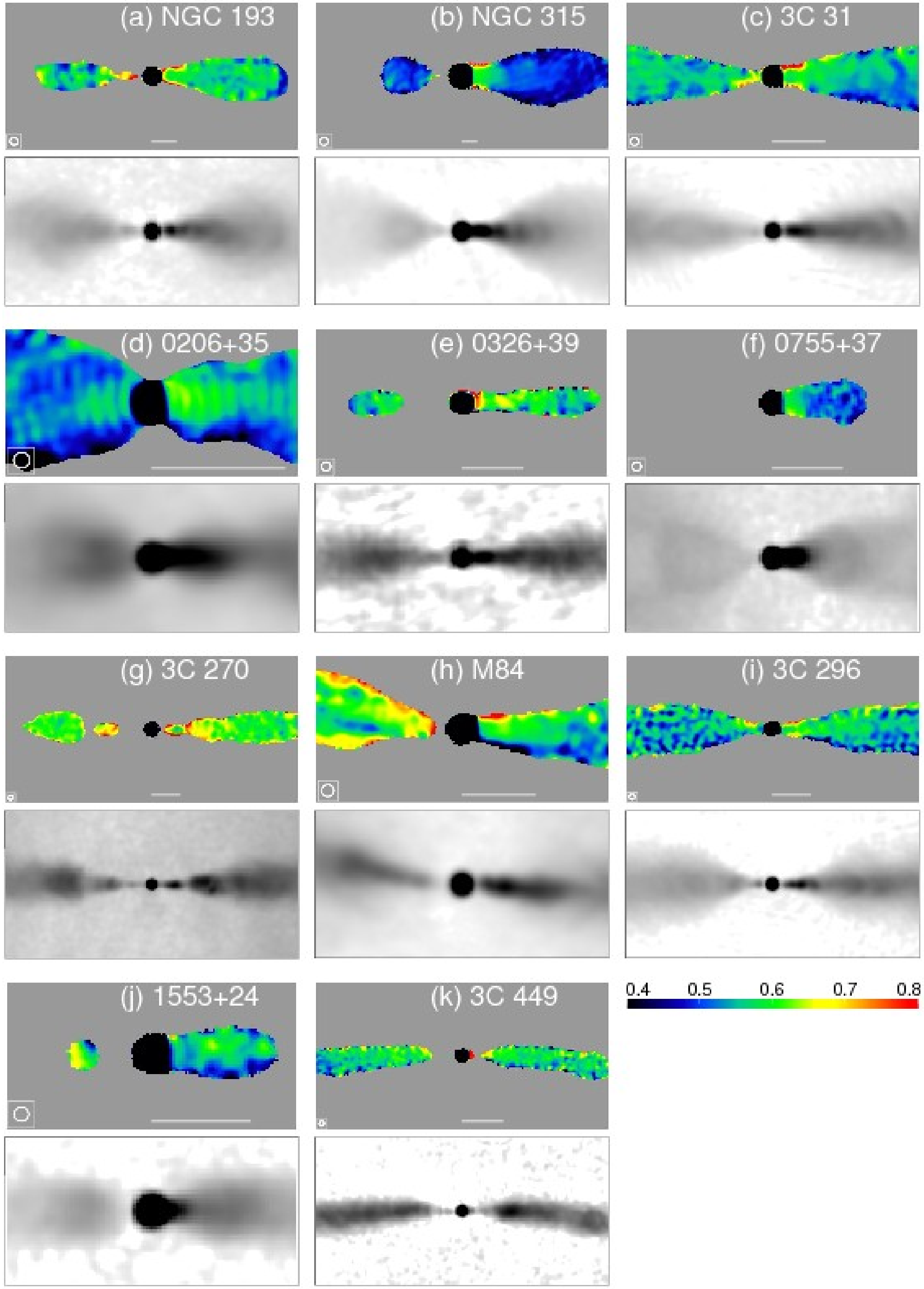


Spectral index
(RL et al. 2006)

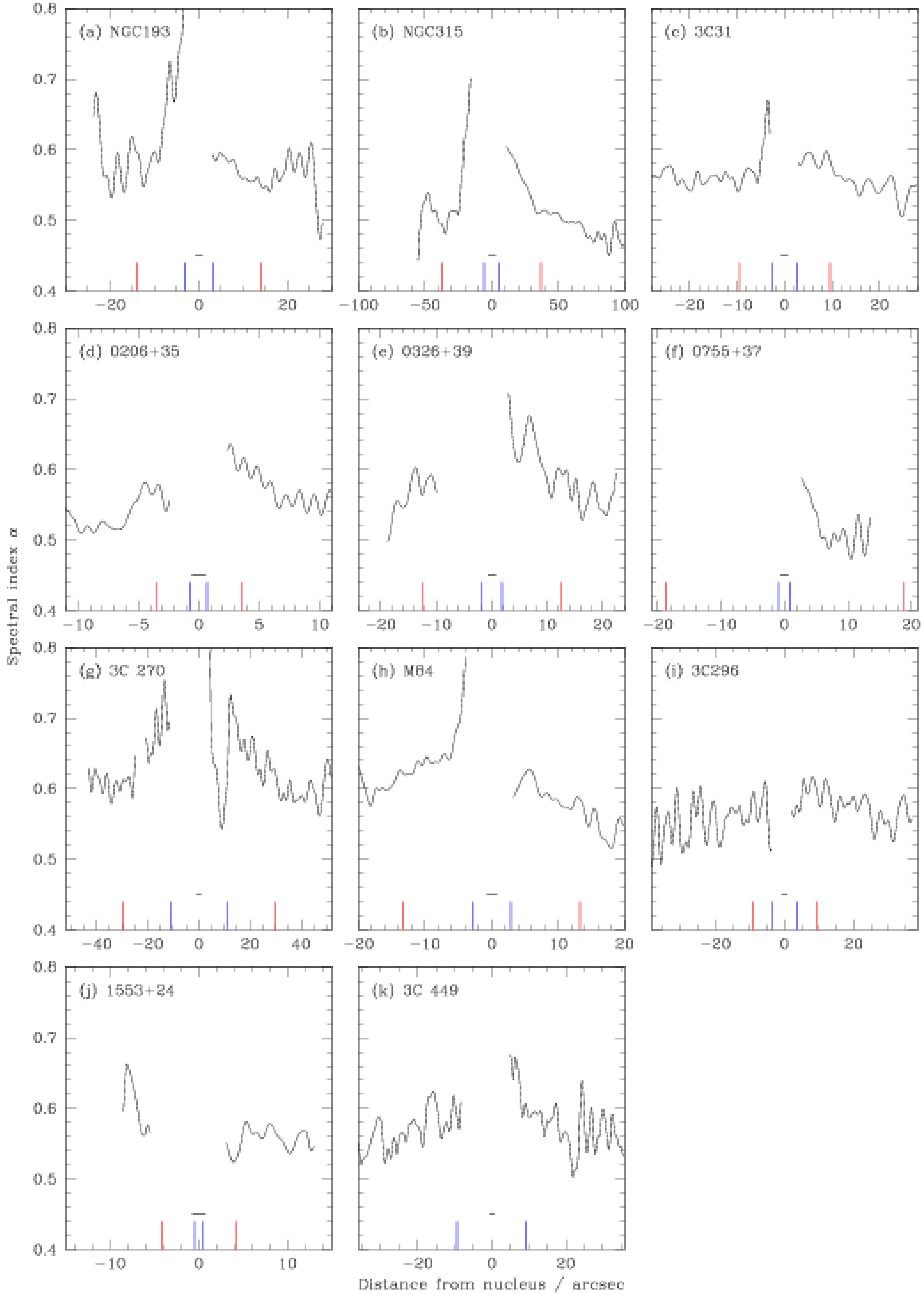


Radio/X-ray
(Worrall et al. 2007)





(a) NGC 193
(b) NGC 315
(c) 3C 31
(d) 0206+35
(e) 0326+39
(f) 0755+37
(g) 3C 270
(h) M84
(i) 3C 296
(j) 1553+24
(k) 3C 449
0.4
0.5
0.6
0.7
0.8



Spectral index in the high-emissivity region has a remarkably low dispersion around a mean value of 0.61

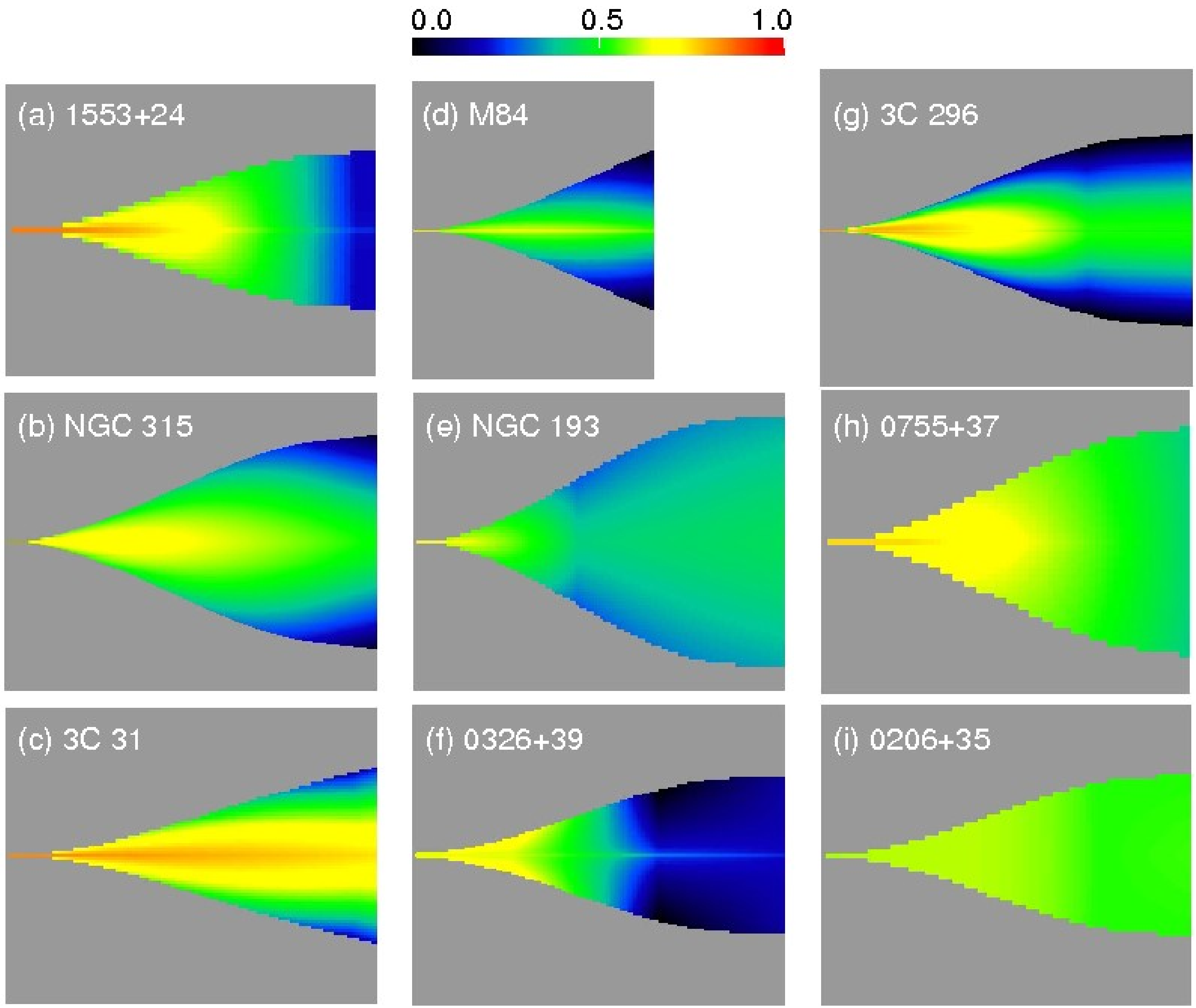
Spectrum flattens with increasing distance from the nucleus

Transverse structure in NGC315

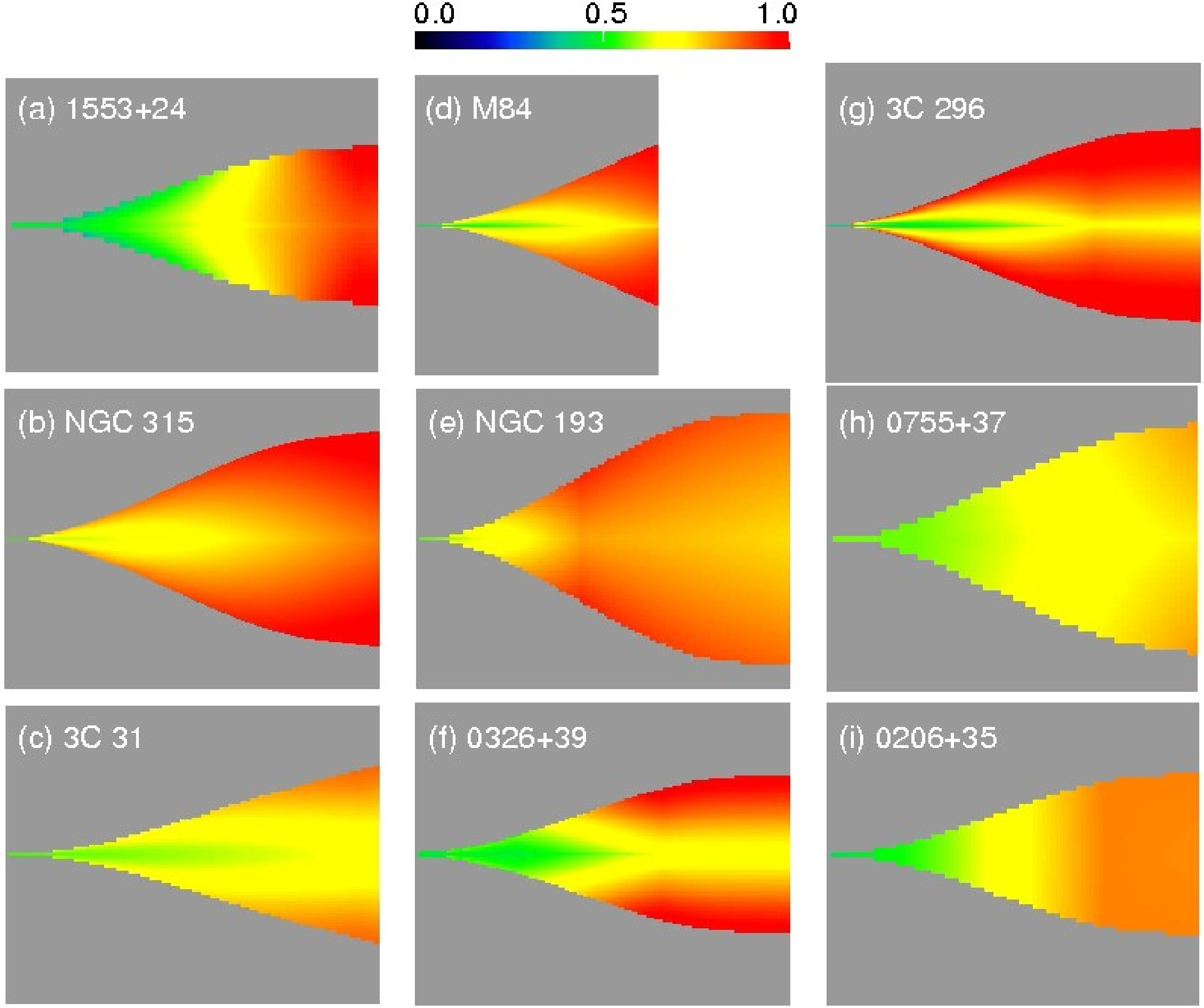
Spectrum and particle acceleration

- Radio - X-ray emission is consistent with synchrotron emission from a single electron population with a broken power-law spectrum.
- Very short synchrotron lifetime requires local particle acceleration
- Adiabatic compression due to deceleration is not enough to match radio emissivity profile
- Characteristic spectral index of 0.61 in the high-emissivity part of the jet base, flattening outwards and at jet edges: different acceleration mechanisms: shocks + shear?

Longitudinal field component



Toroidal field component



Magnetic field structure

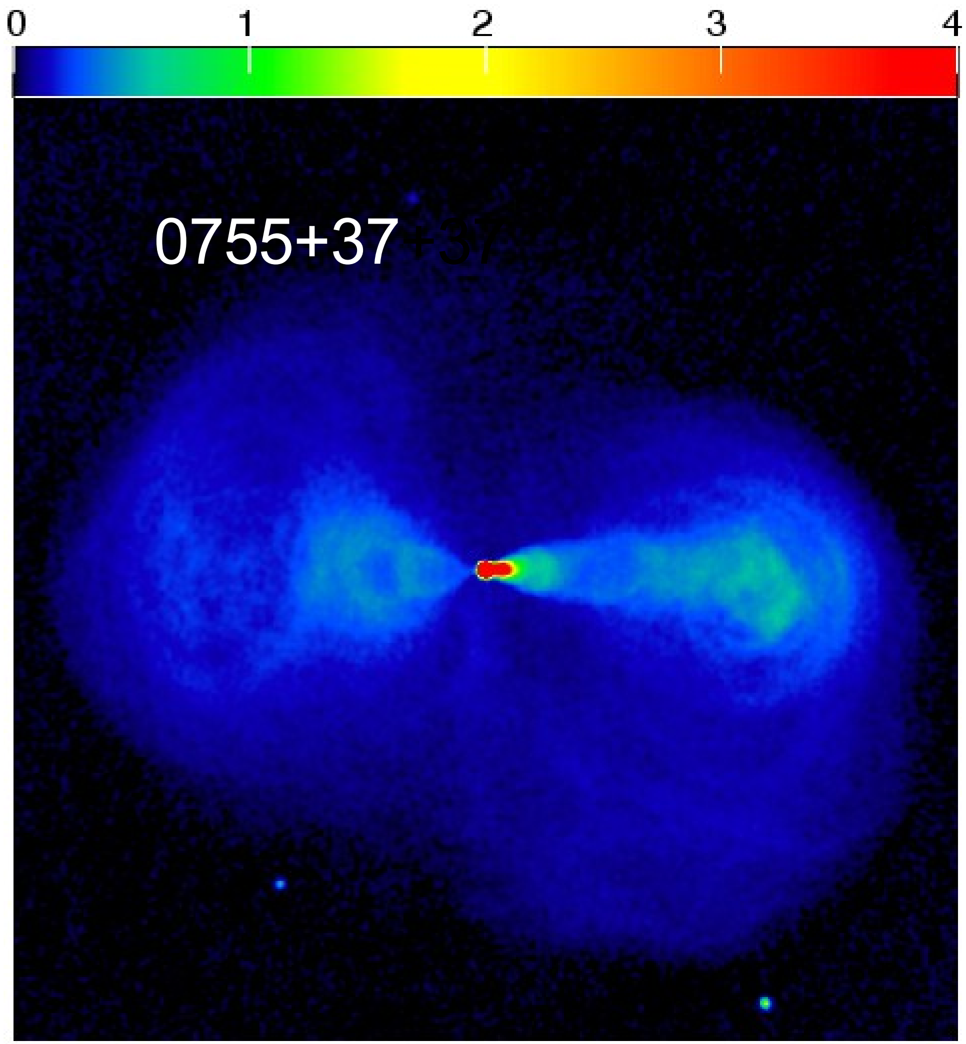
- Initial field is dominated by longitudinal component
- Longitudinal component relatively stronger on-axis (in the knots of the high-emissivity region)
- Evolution to mainly toroidal field
- Qualitatively as expected from flux-freezing

$B_t \propto (\Gamma\beta r)^{-1}$

$B_l \propto r^{-2}$

- Simple, but quantitative models including shear do not work (Laing & Bridle 2004)
- Toroidal component may be a leftover from the collimating field on small scales

Backflow?

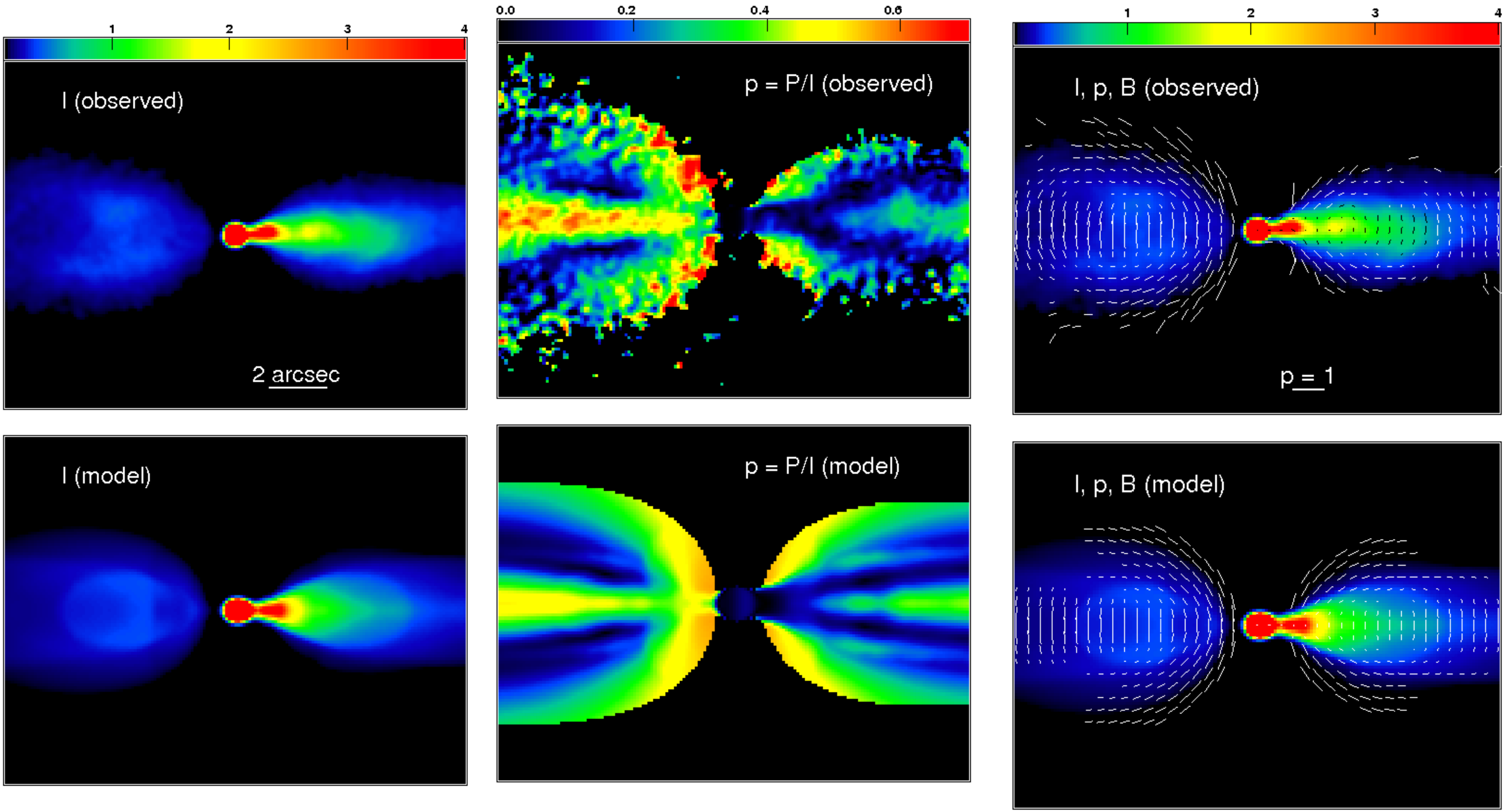


Is one jet intrinsically wider?

No: we see evidence for narrow structures on both sides of the nucleus – but sometimes as **minima** on the counter-jet side.

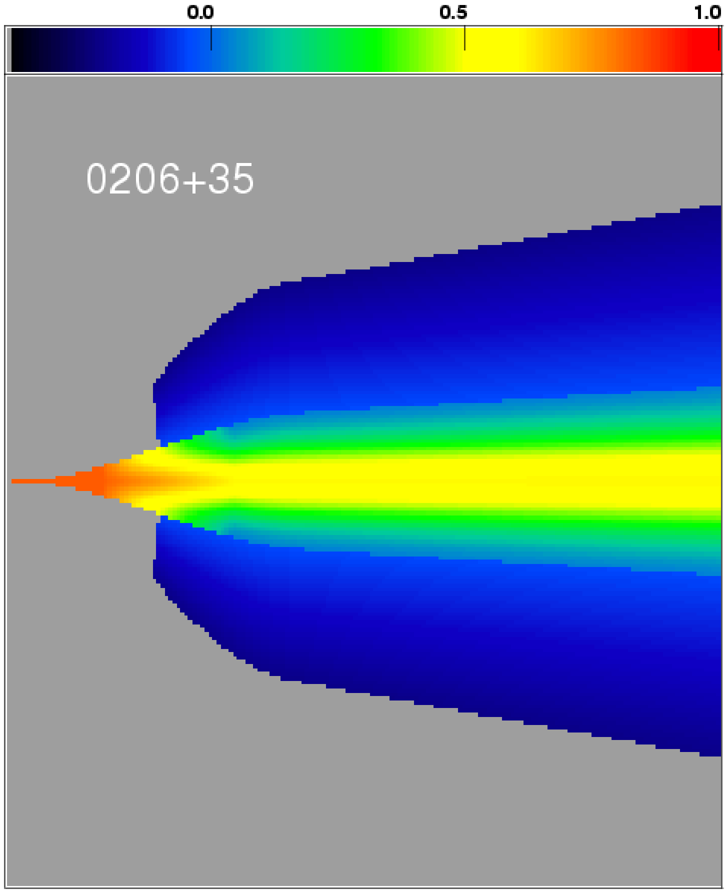
What if there is mildly relativistic backflow in the material immediately surrounding the jets?

Data-model comparisons (0206+35)



$\theta = 39^{o}$

Velocity field (v/c)

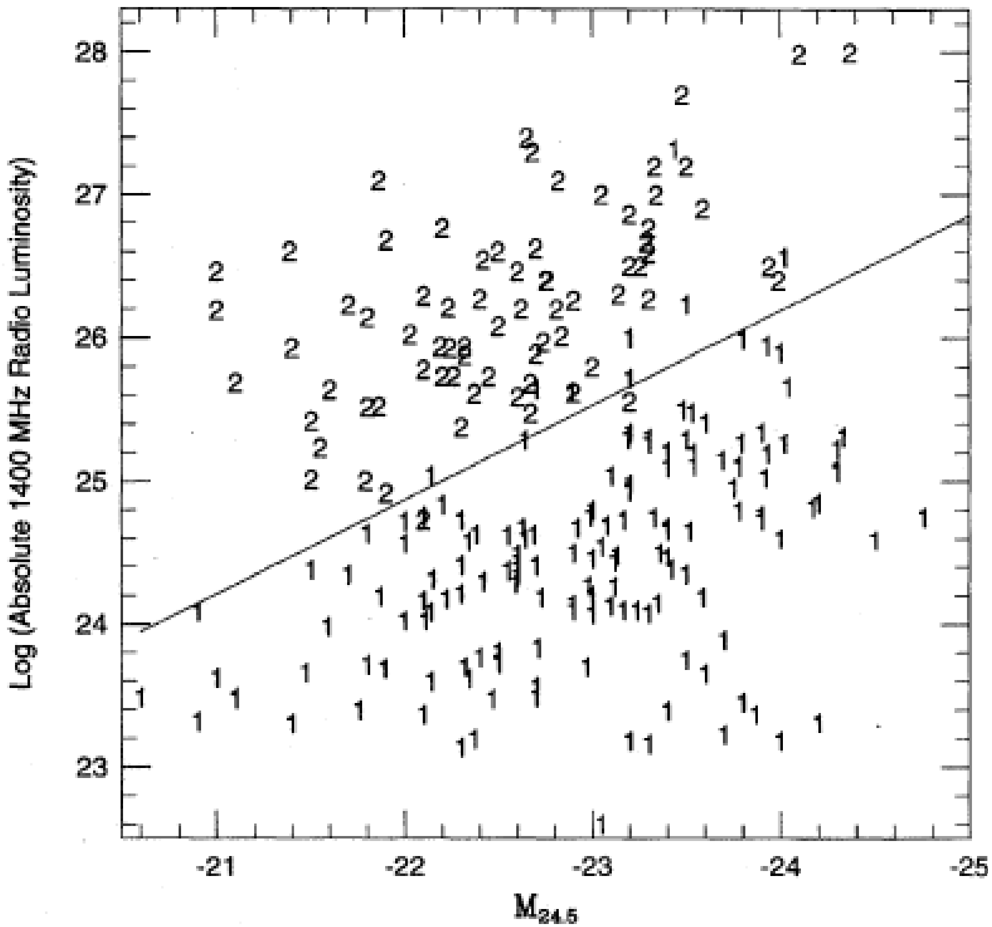


?

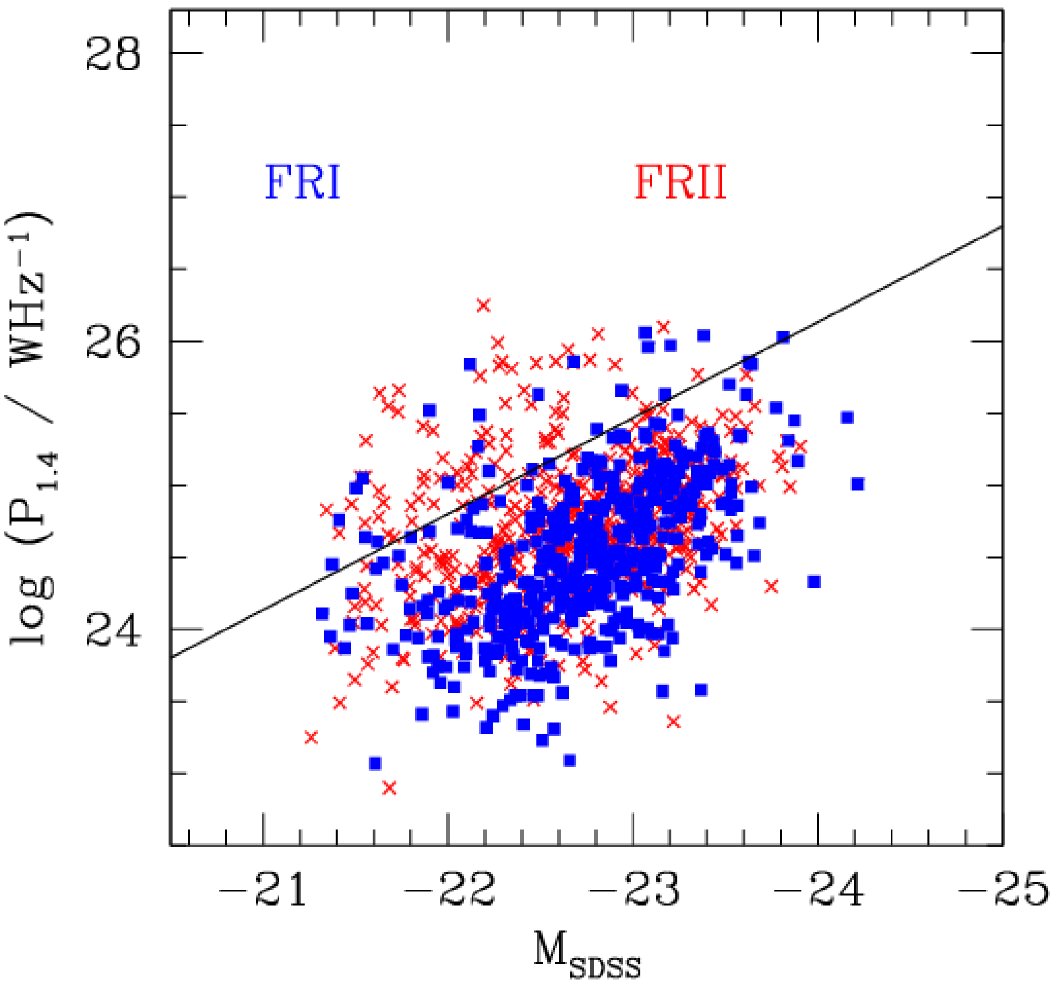
Summary

- Kinematic models of relativistic jets for FRI jets – now 9 examples
- Excellent fits
- 3D models of velocity, proper emissivity, field ordering
- Evidence for acceleration from subsonic before jets brighten
- Bright region where $\beta \approx 0.8$ ($M \approx 2$)
- Boundary-layer entrainment starts (why?); transverse velocity profile evolves.
- Entrainment stops when the jet enters a lobe, or the surroundings become too tenuous
- Field evolution longitudinal $\rightarrow$ toroidal
- Dynamics: energy and mass flux, entrainment rate from conservation laws + mixing-layer approximation

Radio galaxies in the P - M plane

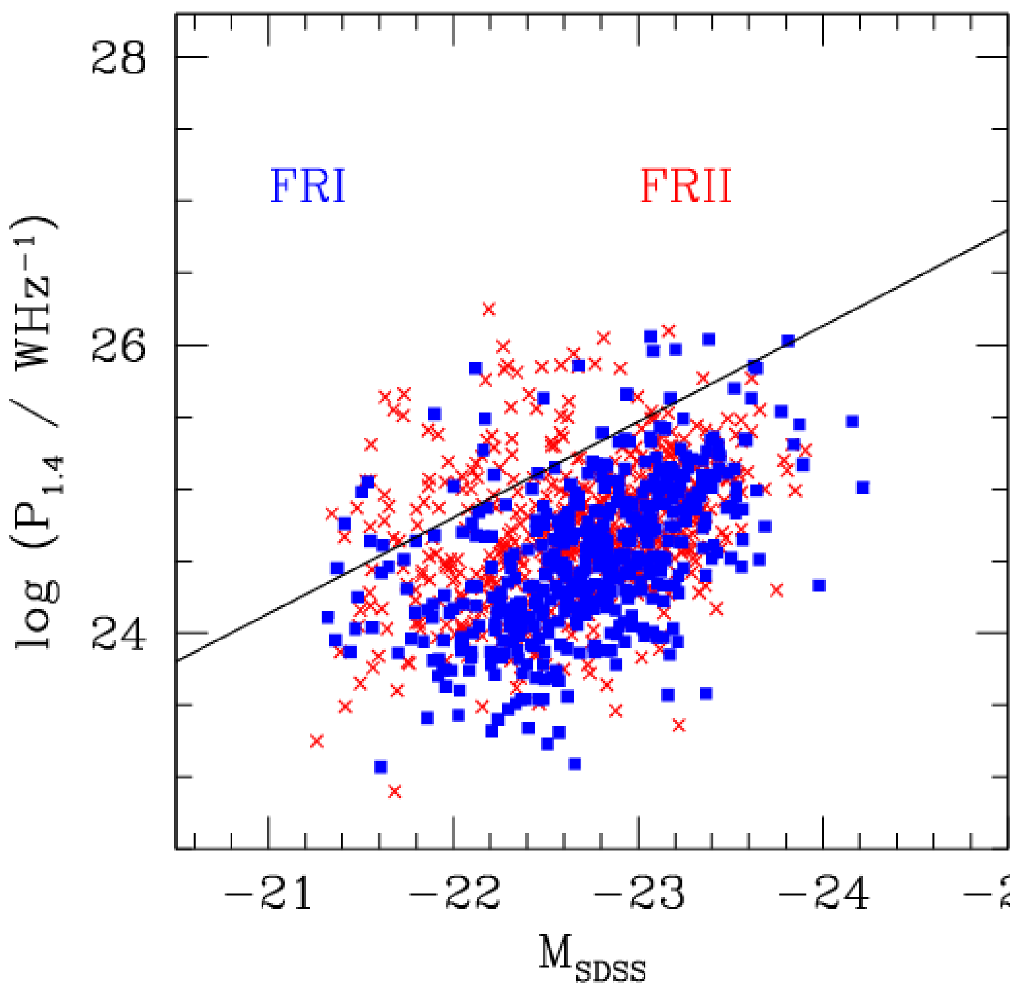


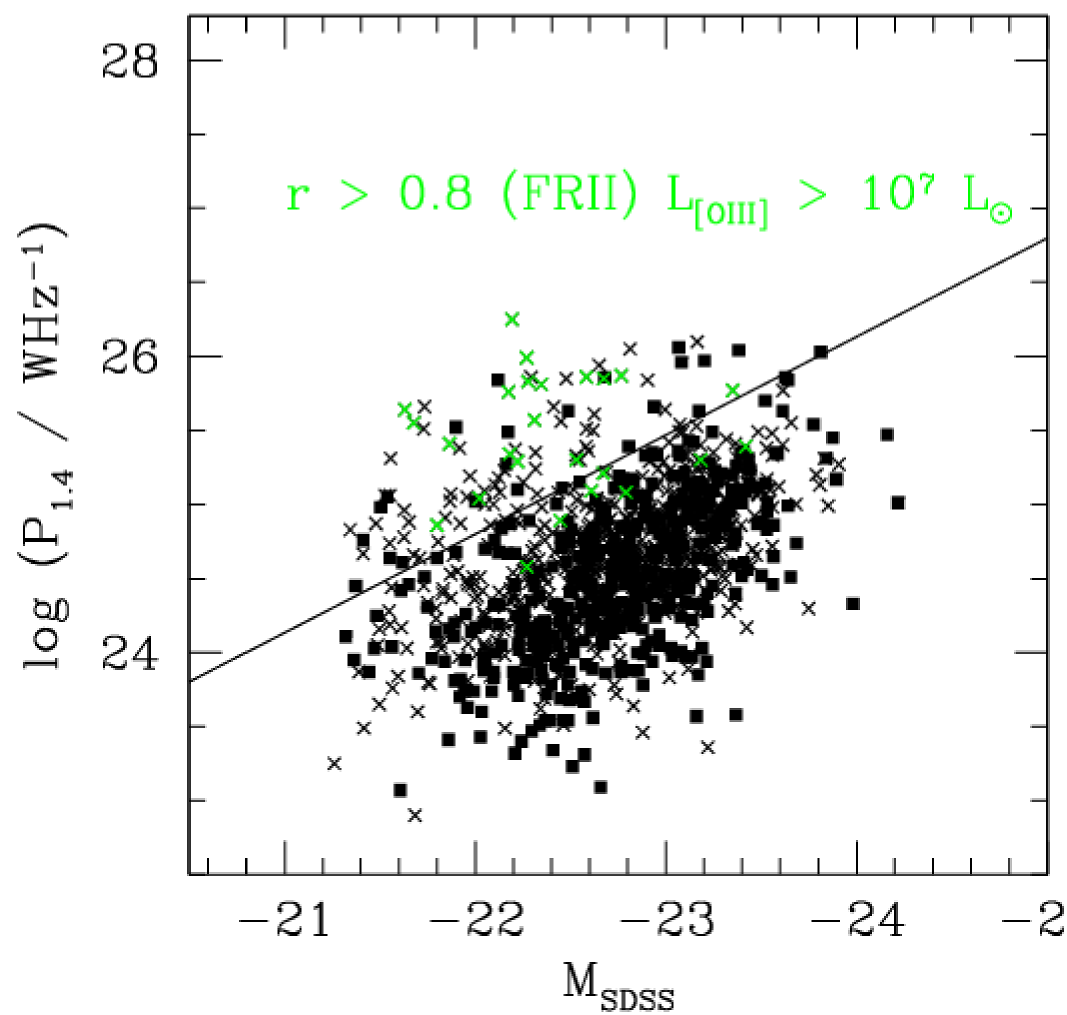
Ledlow & Owen 1994



Lin et al. (2010)

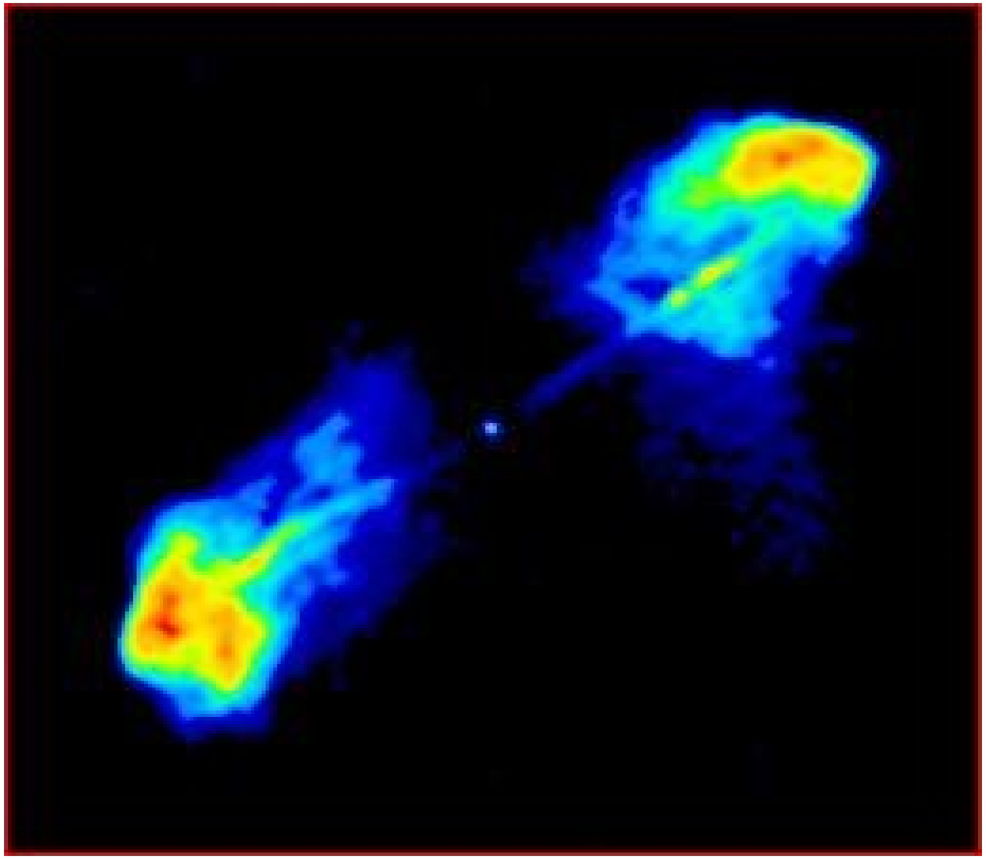
Radio galaxies in the P - M plane (2)

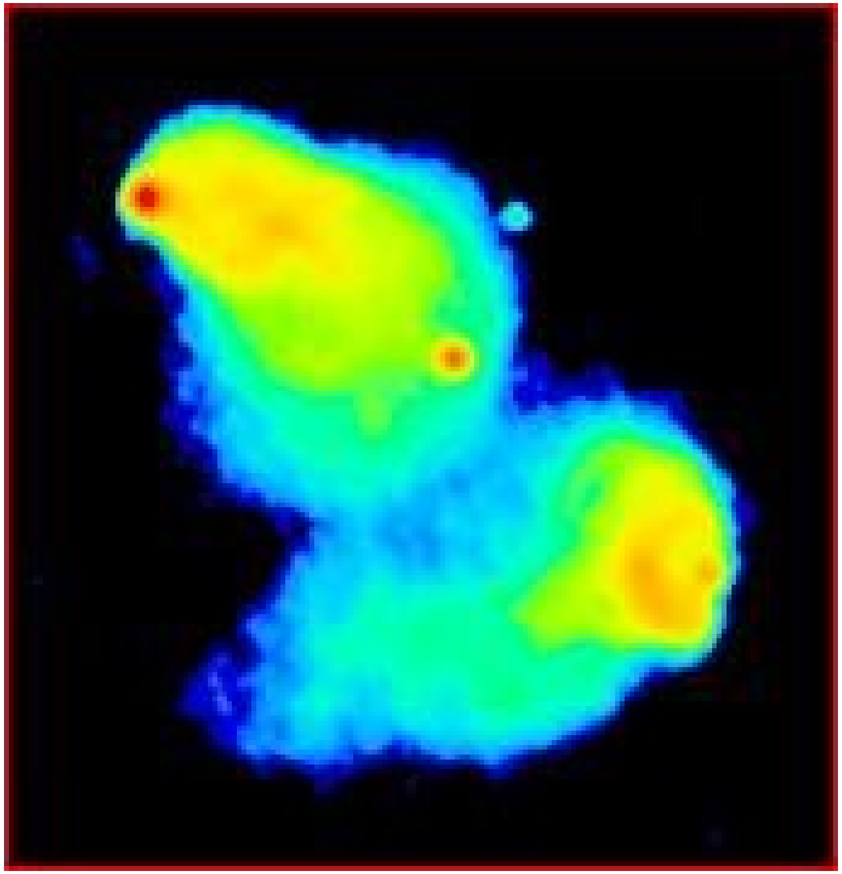




Lin et al. (2010)

FRII sources and hot-spots





3C438: no hot-spots, low-excitation spectrum, very dense environment

3C382: hot-spots, high-excitation spectrum, sparse environment

FR classes and the P - M plane

- Ledlow & Owen (1996): clean separation in the P-M plane.
- Recent work using samples selected by cross-matching SDSS optical and FIRST radio (Best 2009; Lin et al. 2010). Much more overlap.
- Both studies have biases:
  - L&O small, heterogeneous samples, selected to explore different types of source. Good radio imaging.
  - Lin et al.: much larger sample, well-defined selection, but limited by lack of sensitivity to extended radio structure.
- Lin et al. highlight a population of FRII sources with bright emission lines (probably most with hot-spots). These are very like the low-power FRII's in 3C. They have lower stellar masses and live in sparser environments than the rest.

Is there any connection between FR classes and accretion rate?

- High/low excitation optical spectra ↔ high/low accretion rate (Ghisellini & Celotti, Marchesini et al., Hardcastle et al....)
- Classical unified models equate FRII = high accretion rate and FRI = low accretion rate, but this cannot be precisely correct:
  - There are FRI sources with BLR (Lara et al., Blundell & Rawlings)
  - There are FRII sources with low-excitation spectra (although many do not have hot-spots)
- On the other hand, there is a distinct class of FRII sources with high accretion rate and well-defined hot-spots. Why are they different?

Speculation

- Jets from low-accretion rate AGN are “light”, in the sense that most of the energy is carried by relativistic particles (and field), rather than bulk KE of protons.
- Jets from high-accretion rate AGN are “heavy”, with most of the energy carried by proton KE.

cf. Reynolds et al. (1996)

Consequences

- Easy to decelerate light jets, so FRI jets are likely. Jets usually remain subsonic, so no hot-spots
- The most luminous light jets in very dense environments just remain supersonic → FRII (weak hot-spots?)
- Difficult to decelerate heavy jets, which remain supersonic. FRII sources form except perhaps in very dense/messy environments
- Low-luminosity blazars ↔ light ↔ SSC ↔ high-frequency peak
- High-luminosity blazars ↔ heavy ↔ EC ↔ low-frequency peak

Comments?