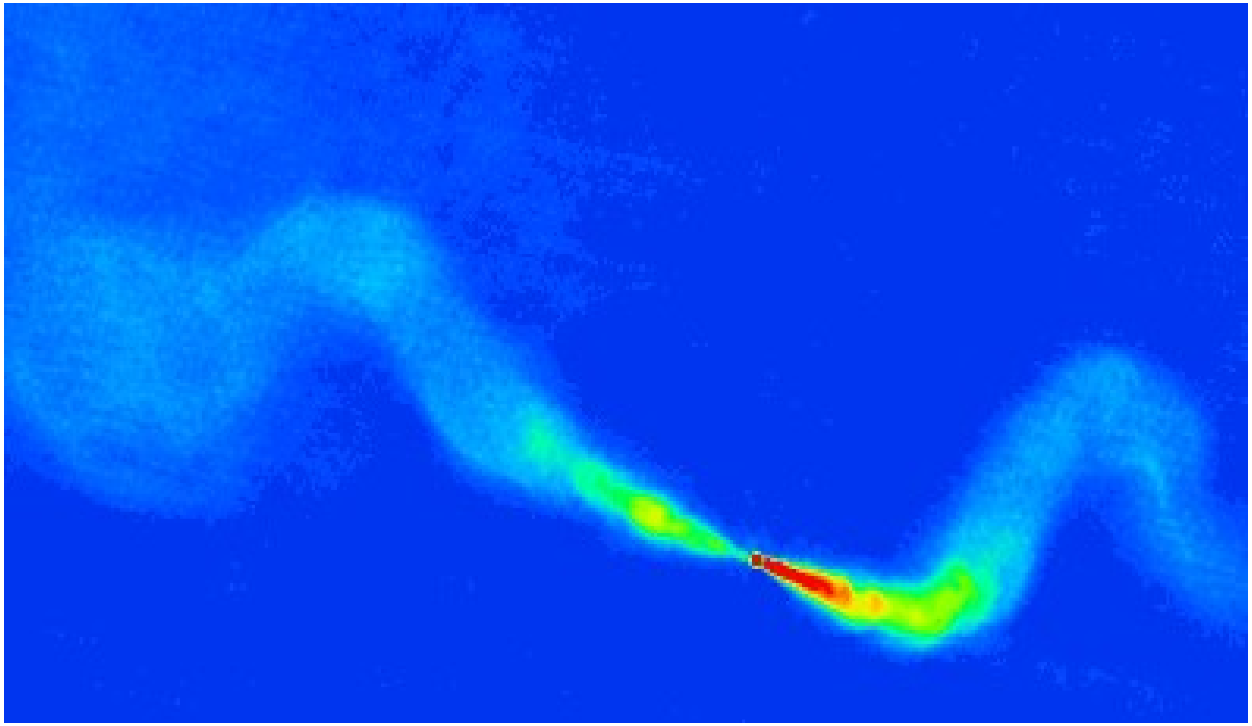
Resolving Key Questions in Extragalactic Jet Physics

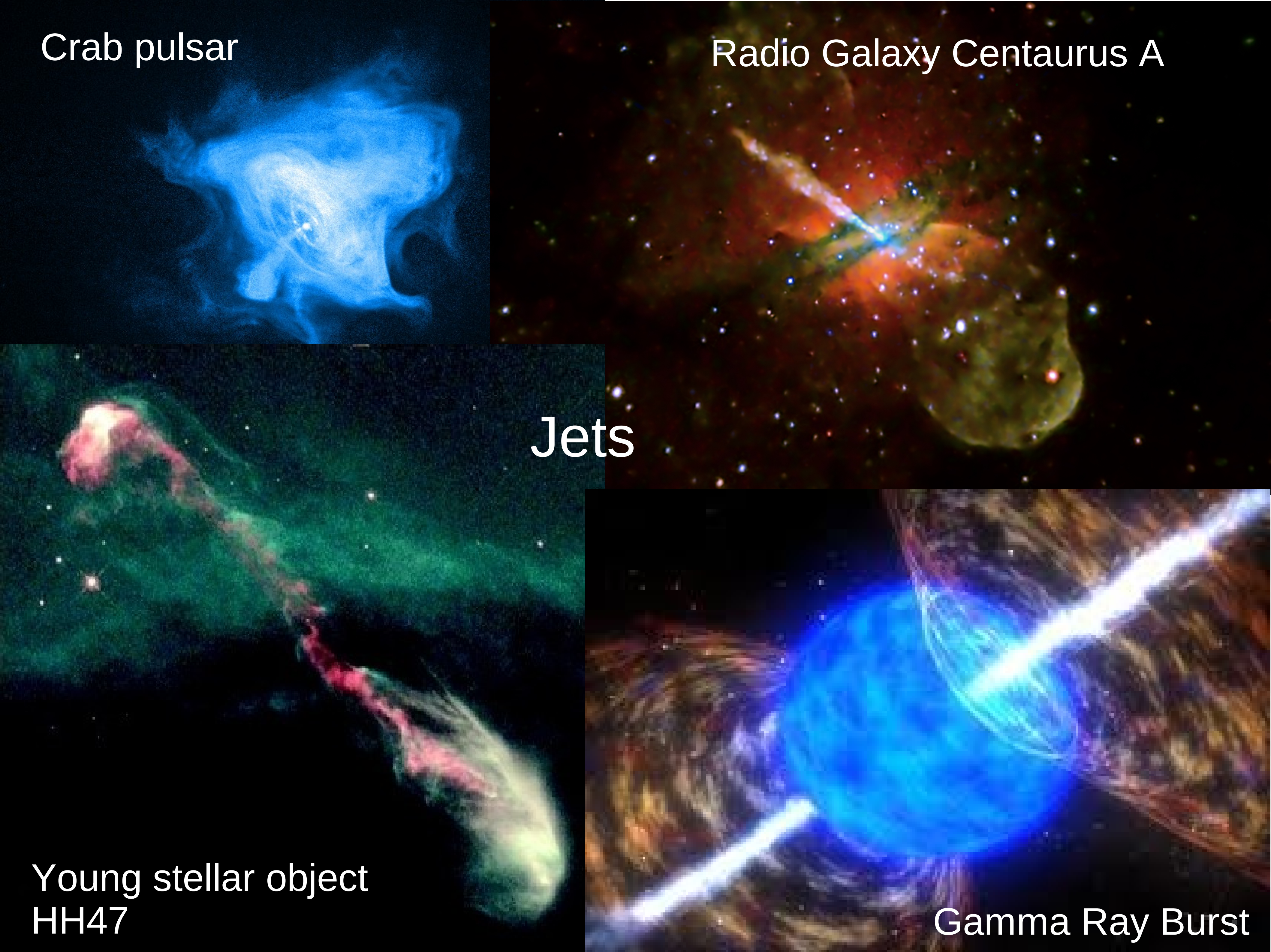
Robert Laing (ESO)

on behalf of Martin Hardcastle (U Herts)
and the rest of the Legacy Team

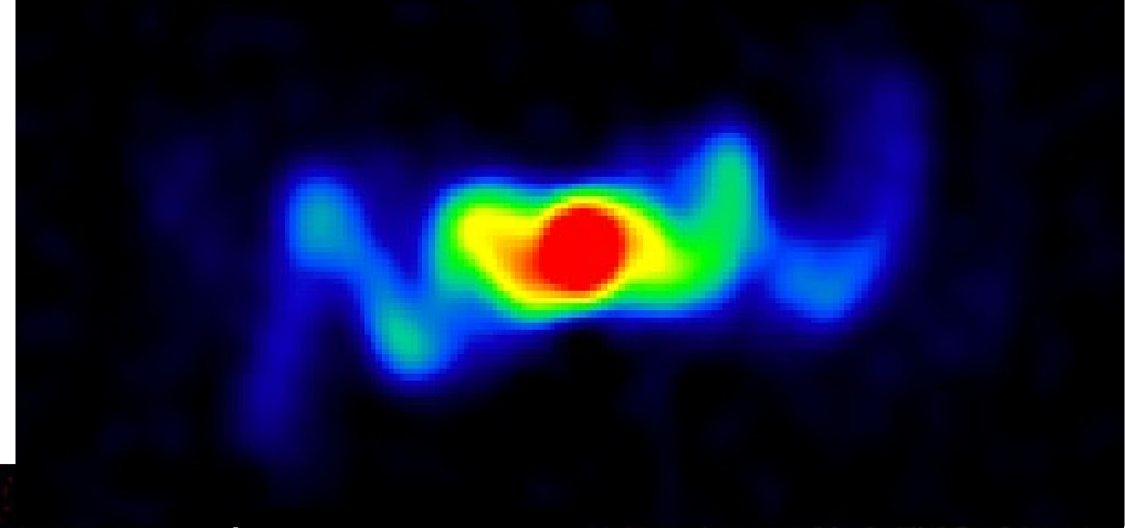


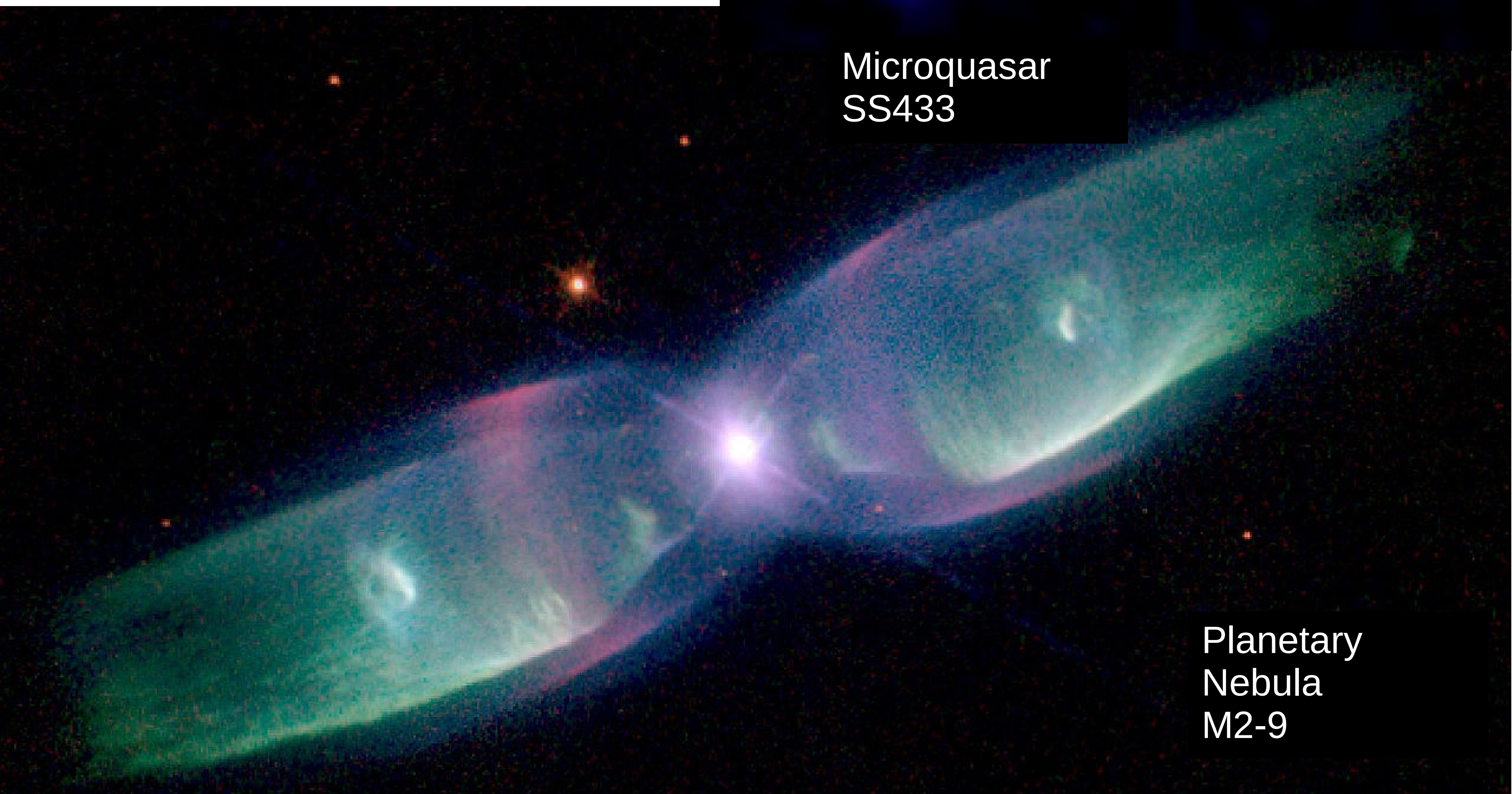
Outline

- Why study jets?
  - Jets and compact objects
  - Particle accelerators – electrons, cosmic rays, photons
  - Feedback
- The story so far
  - Relativistic flow
  - Weak jets and deceleration
  - Powerful jets
- Why e-MERLIN?
  - Transverse resolution
  - What starts deceleration?
  - How fast are powerful jets?
- Initial results


Crab pulsar
Radio Galaxy Centaurus A
Jets
Young stellar object
HH47
Gamma Ray Burst

More jets

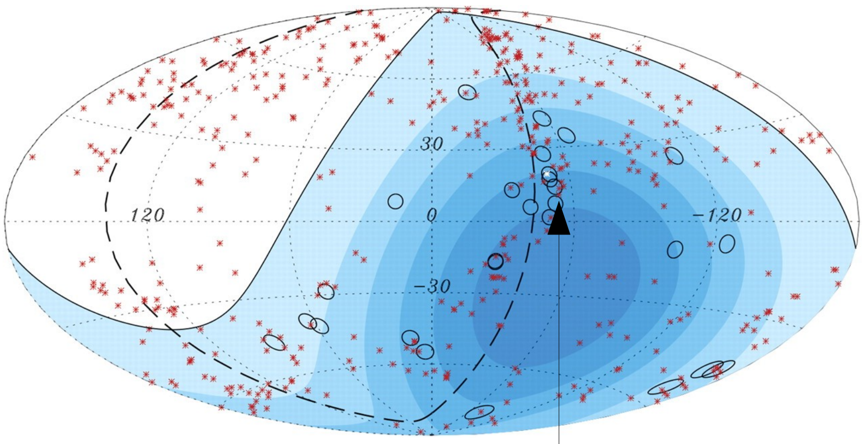




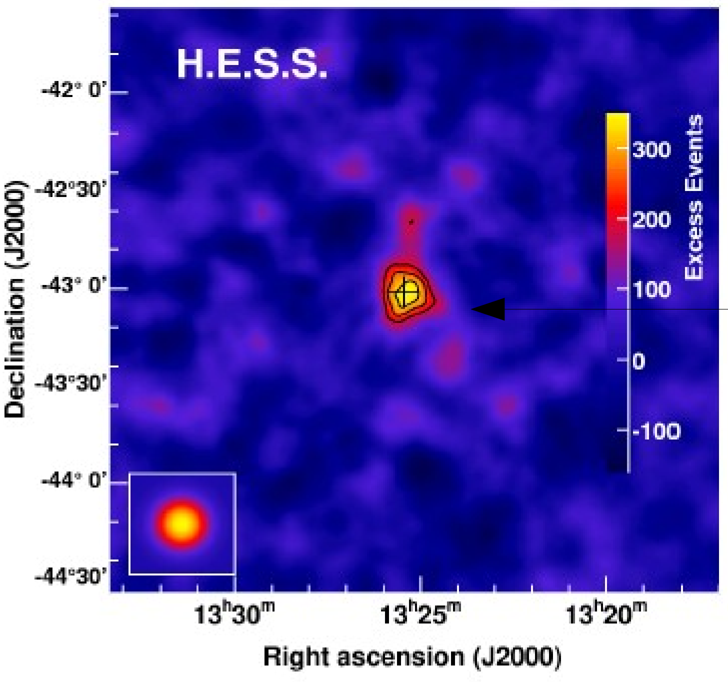
Jets as particle accelerators: Cen A

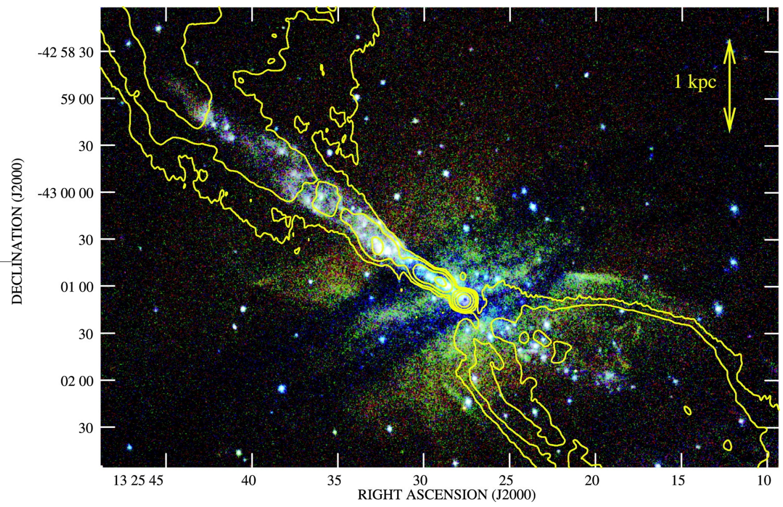
10^{20} eV protons
(or maybe not)

Auger (Abraham et al. 2007)



10^{13} eV photons



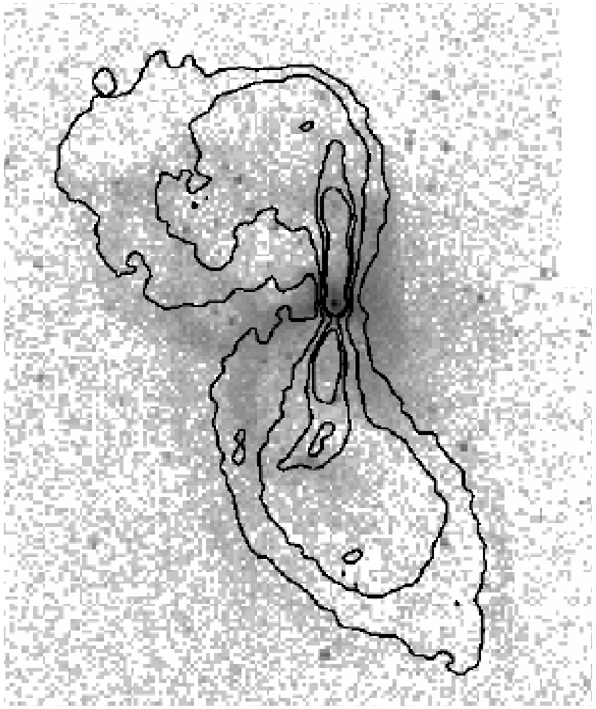


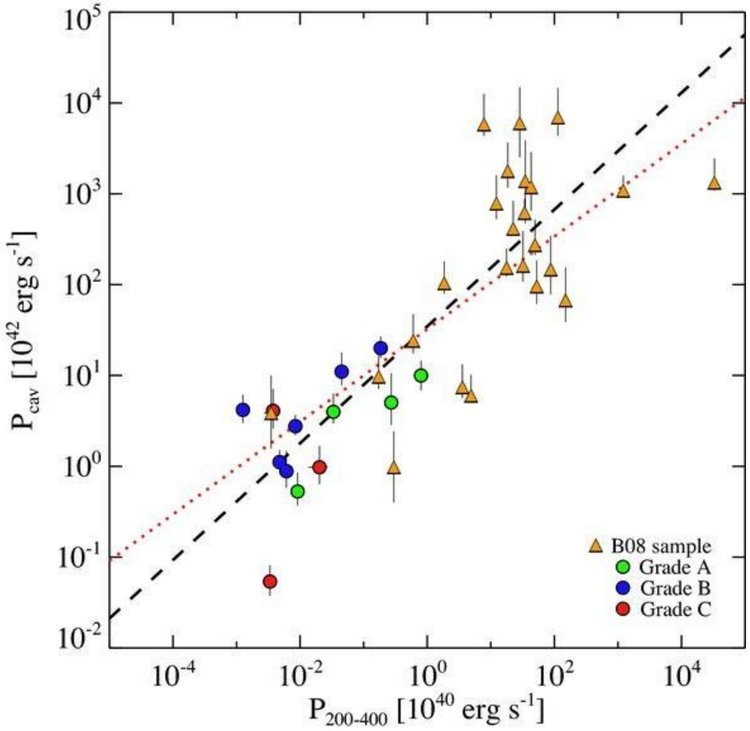
HESS (Aharonian et al. 2009)

Feedback in galaxies, groups and clusters

M84

(Finoguenov et al. 2008)
Grey-scale soft X-rays;
contours radio

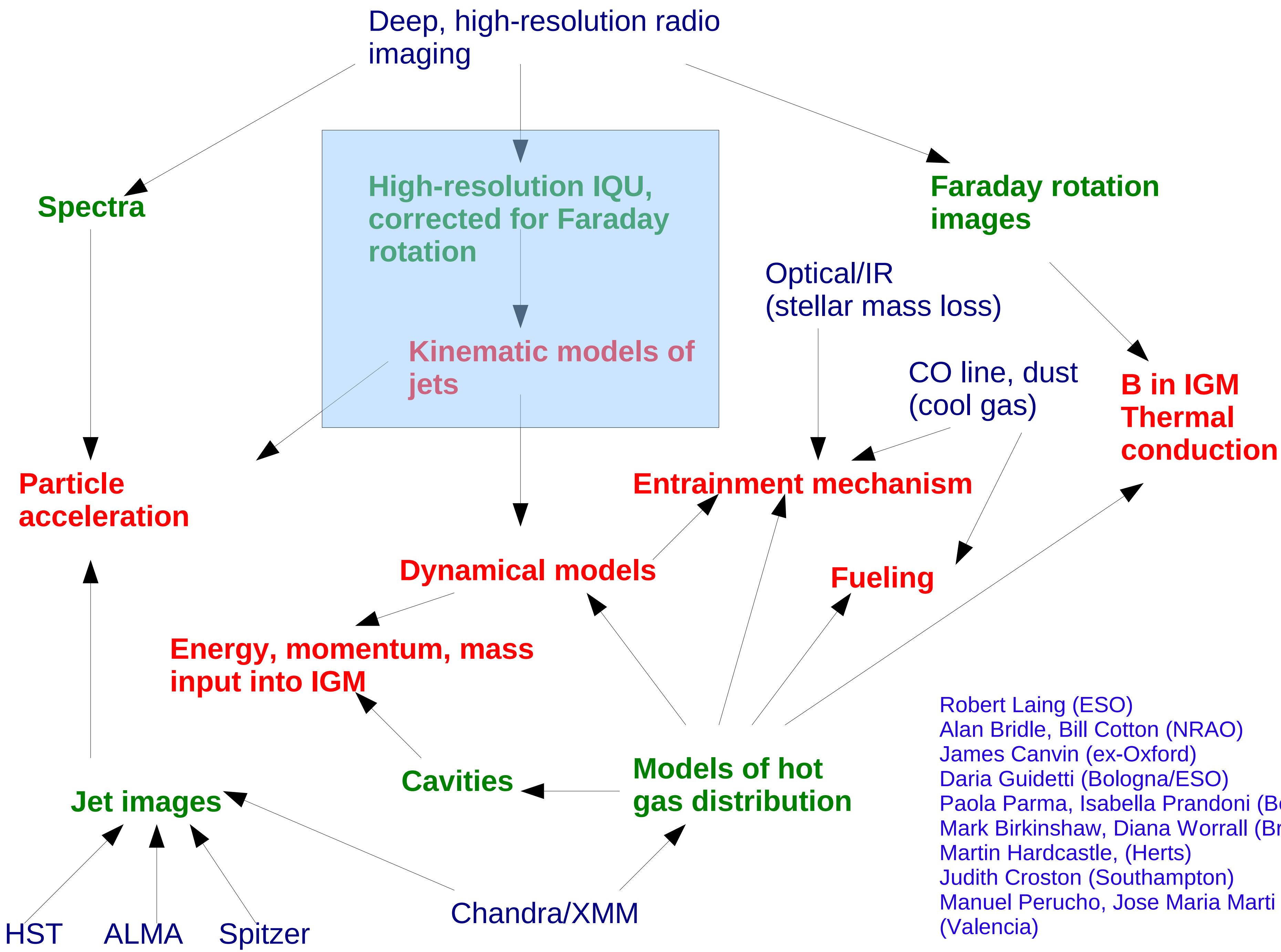




Cavagnolo et al.

Hydra A

McNamara et al.



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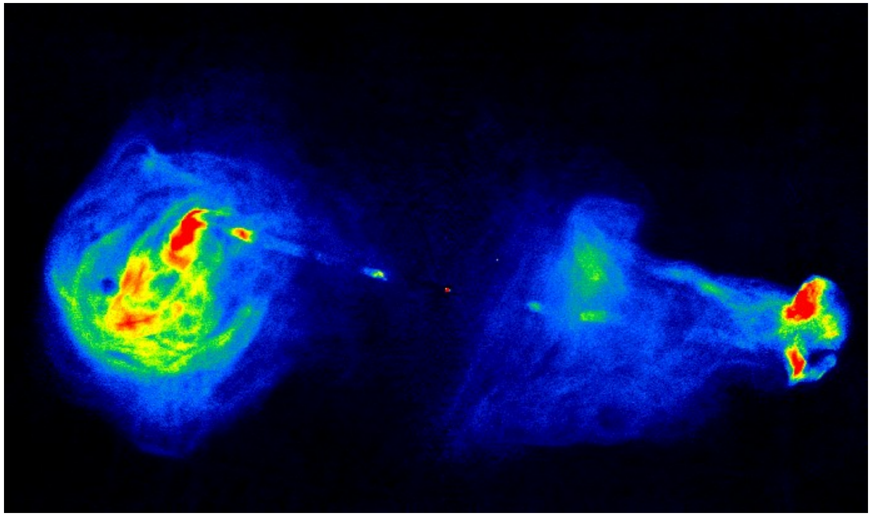
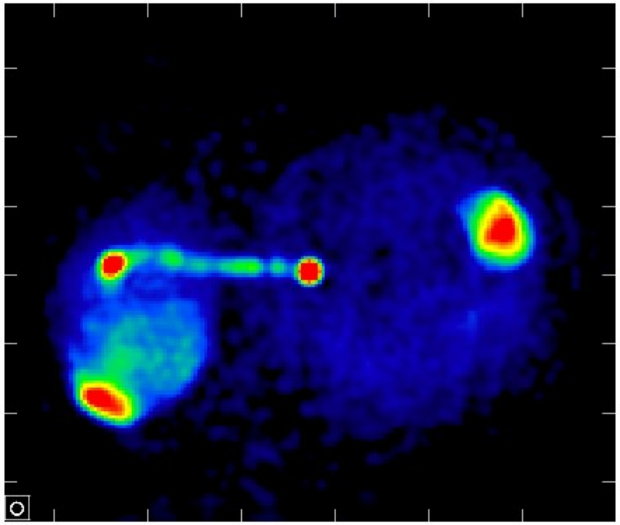
Fanaroff-Riley (FR) classes and jet flavours

3C353
Swain, Bridle &
Baum

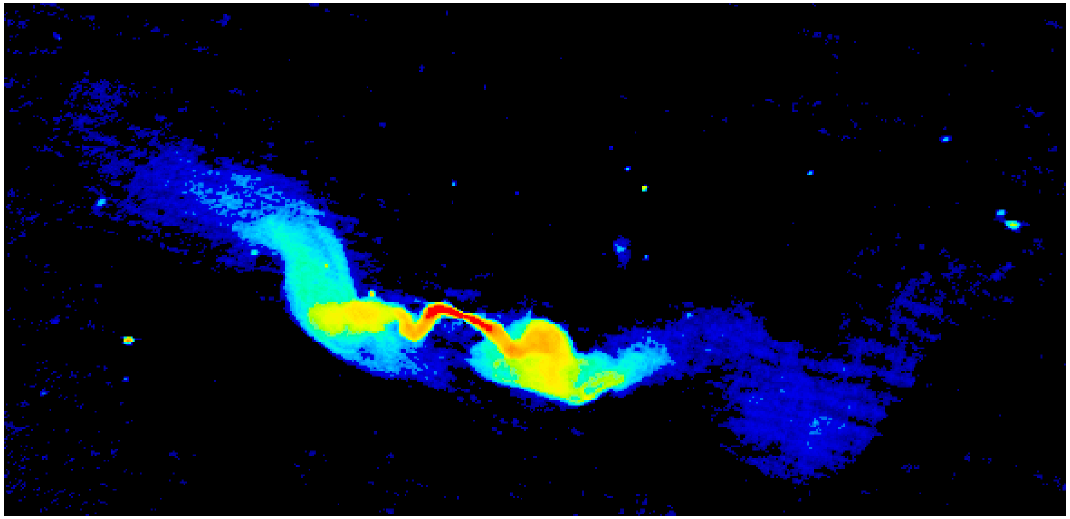


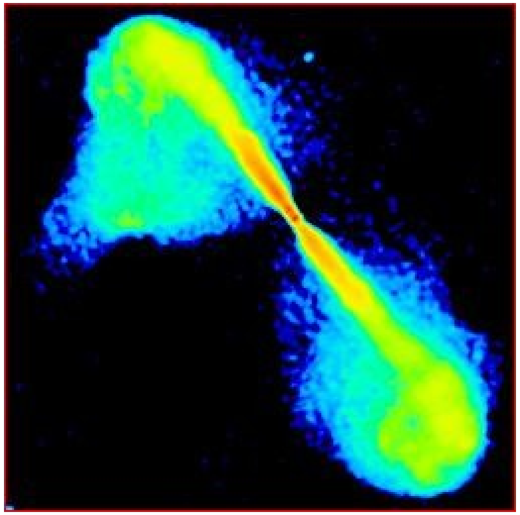


3C133
Floyd et al.

FRII – high power, narrow jets, hot-spots

3C31
RL et al.





3C296
Leahy & Perley
RL et al.

FRI – low power, broad jets, no hot-spots

Relativistic effects in jets

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

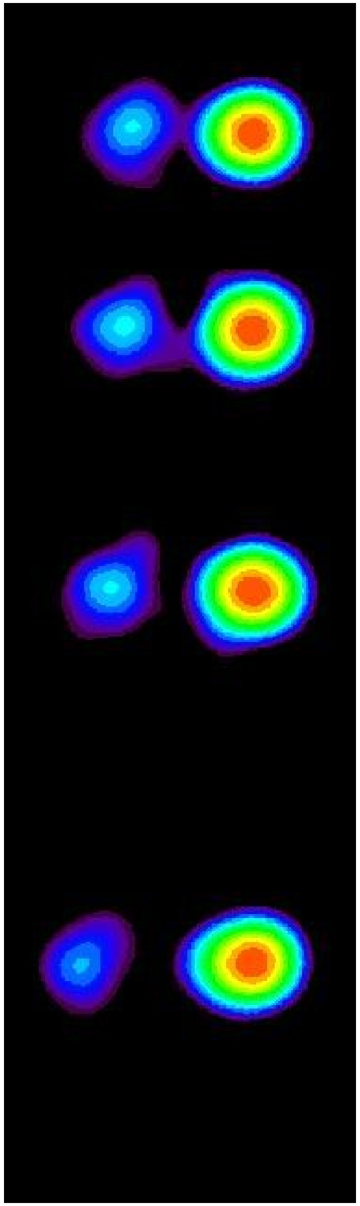
$$S(\nu) = D^{2+\alpha}S_0(\nu)$$ Doppler boosting

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

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

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

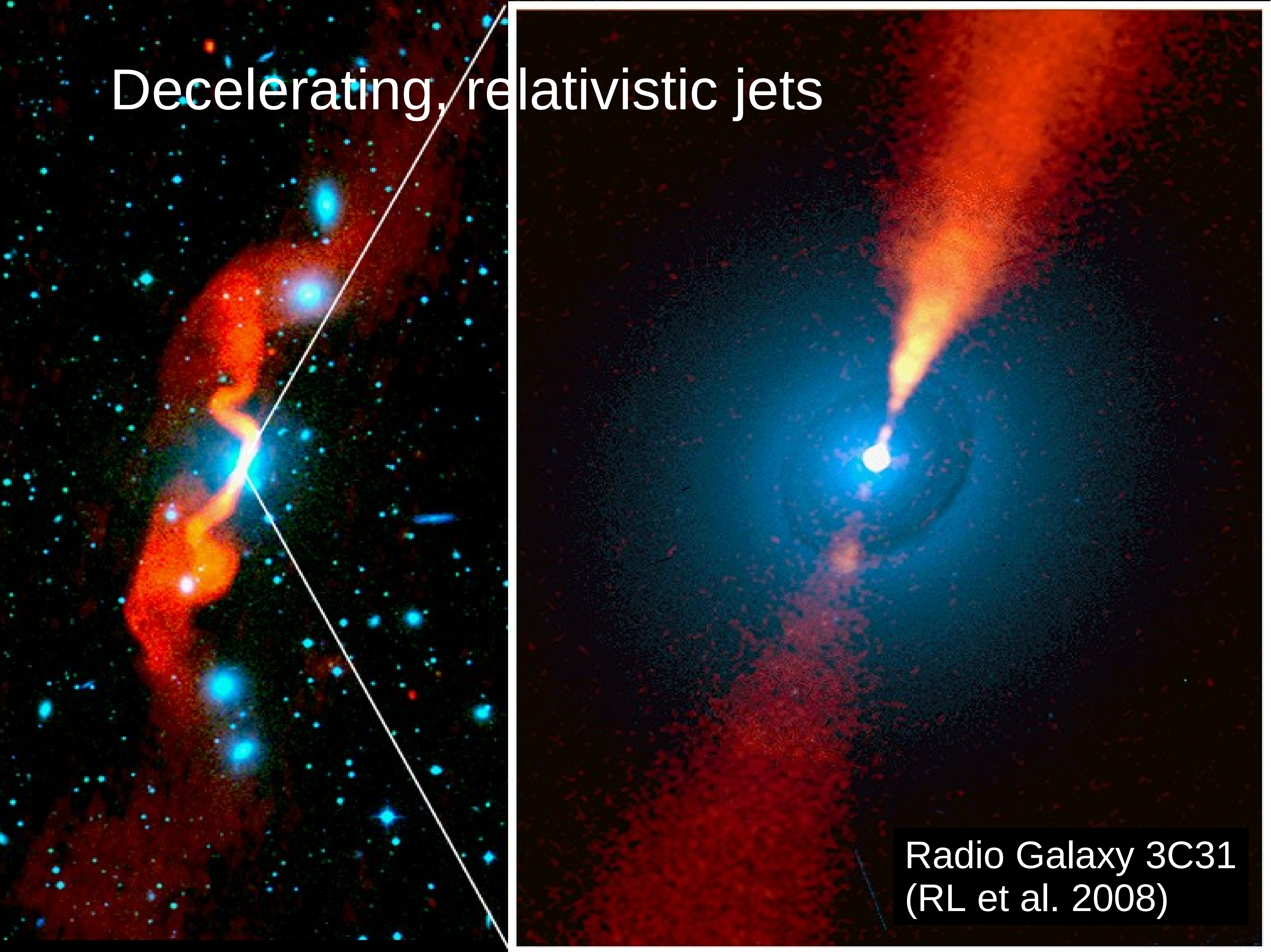
Superluminal motion →



3C279: $v_{app} = 30c$

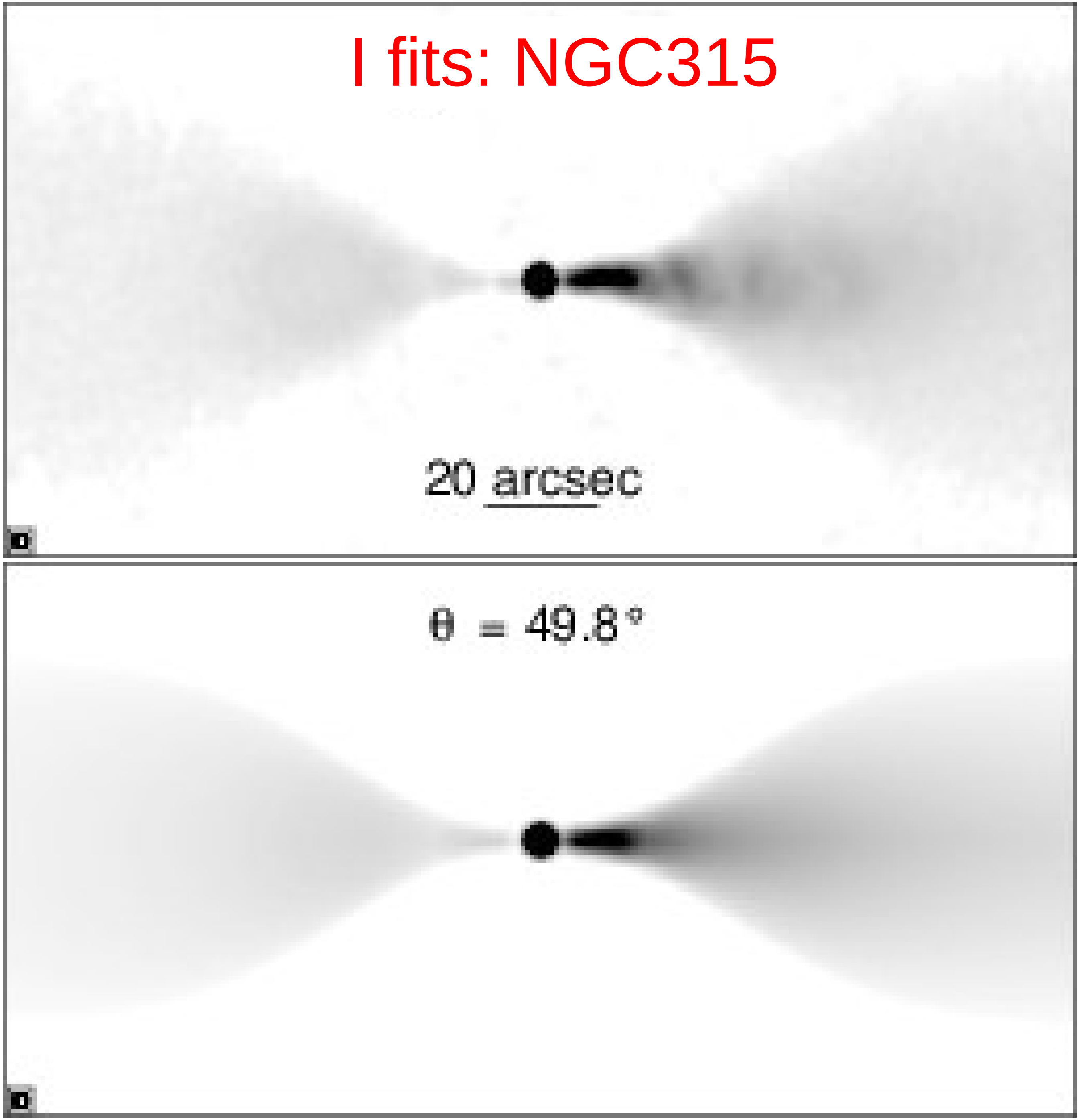
Assume intrinsic symmetry
Model geometry, velocity field, emissivity and **B**
Use linear polarization to decouple β and θ

Decelerating, relativistic jets



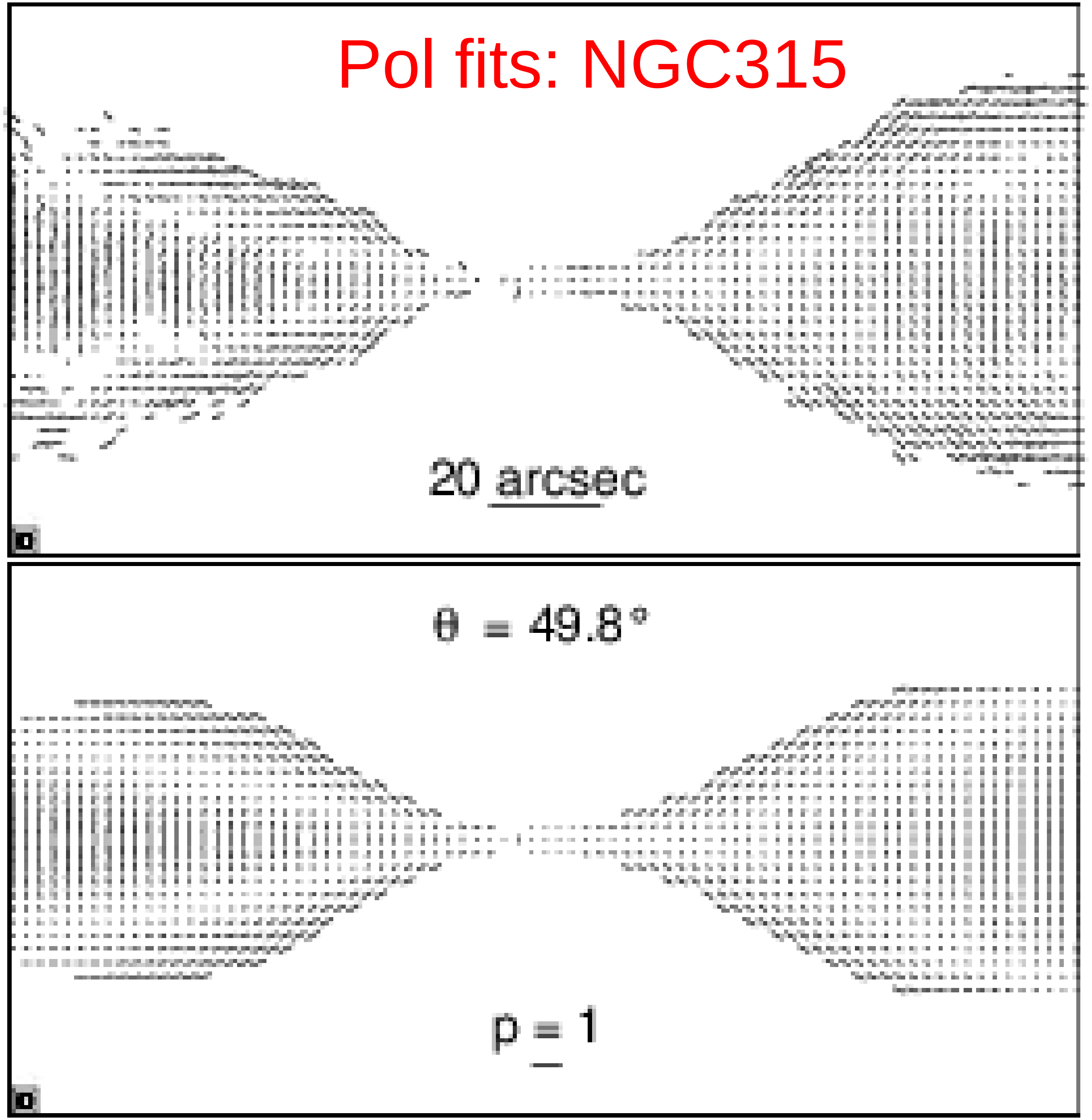
Radio Galaxy 3C31
(RL et al. 2008)

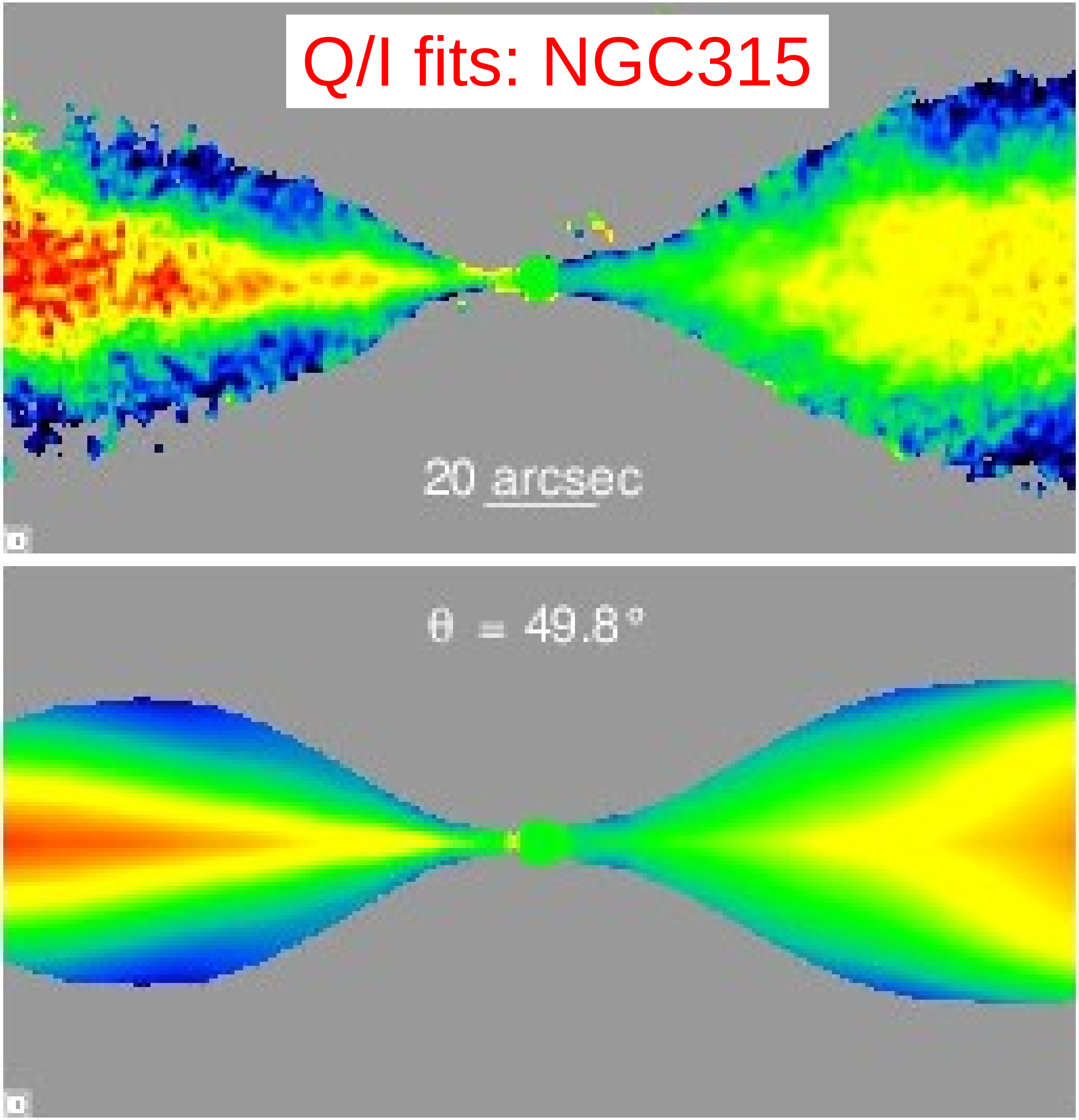
I fits: NGC315

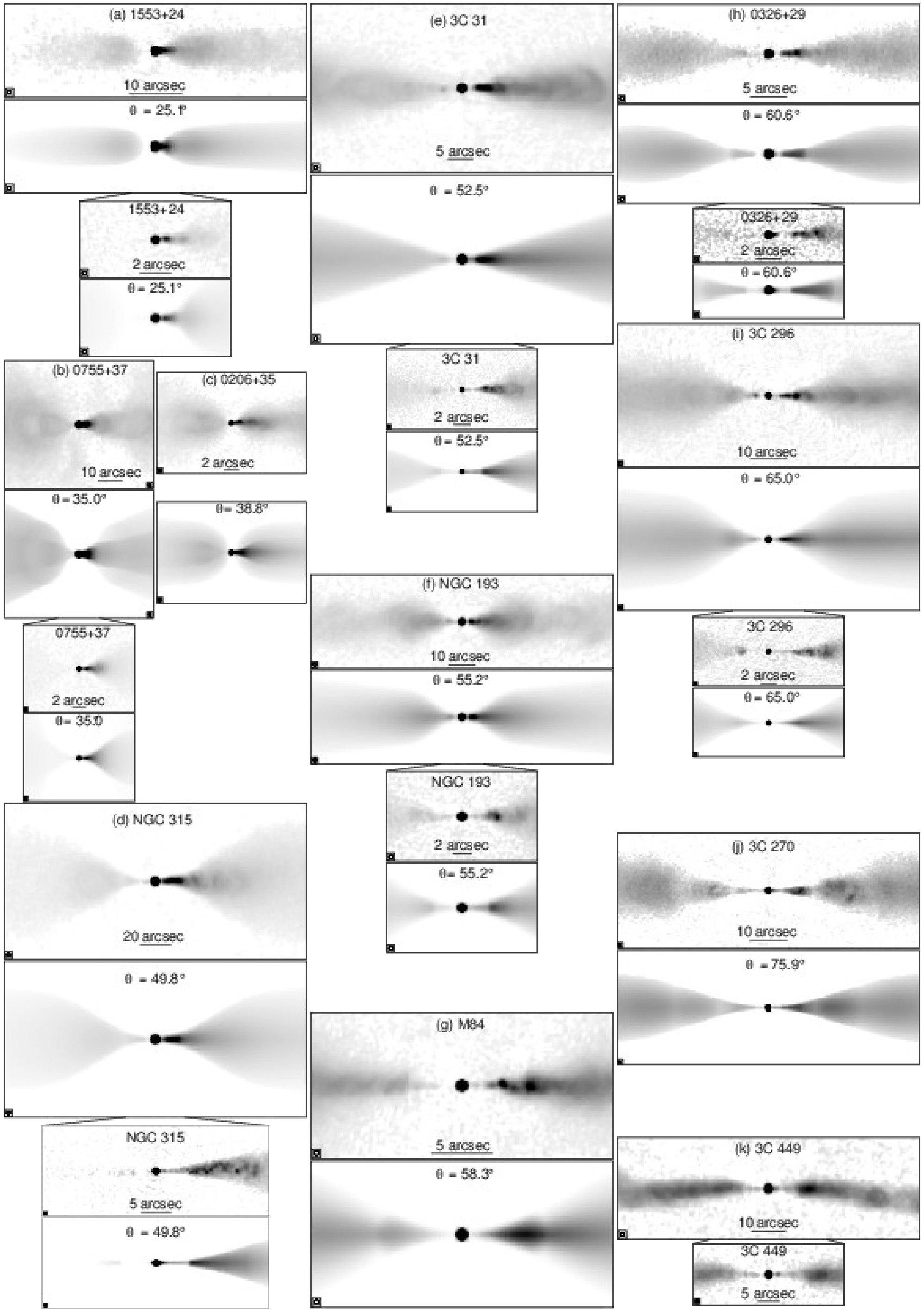


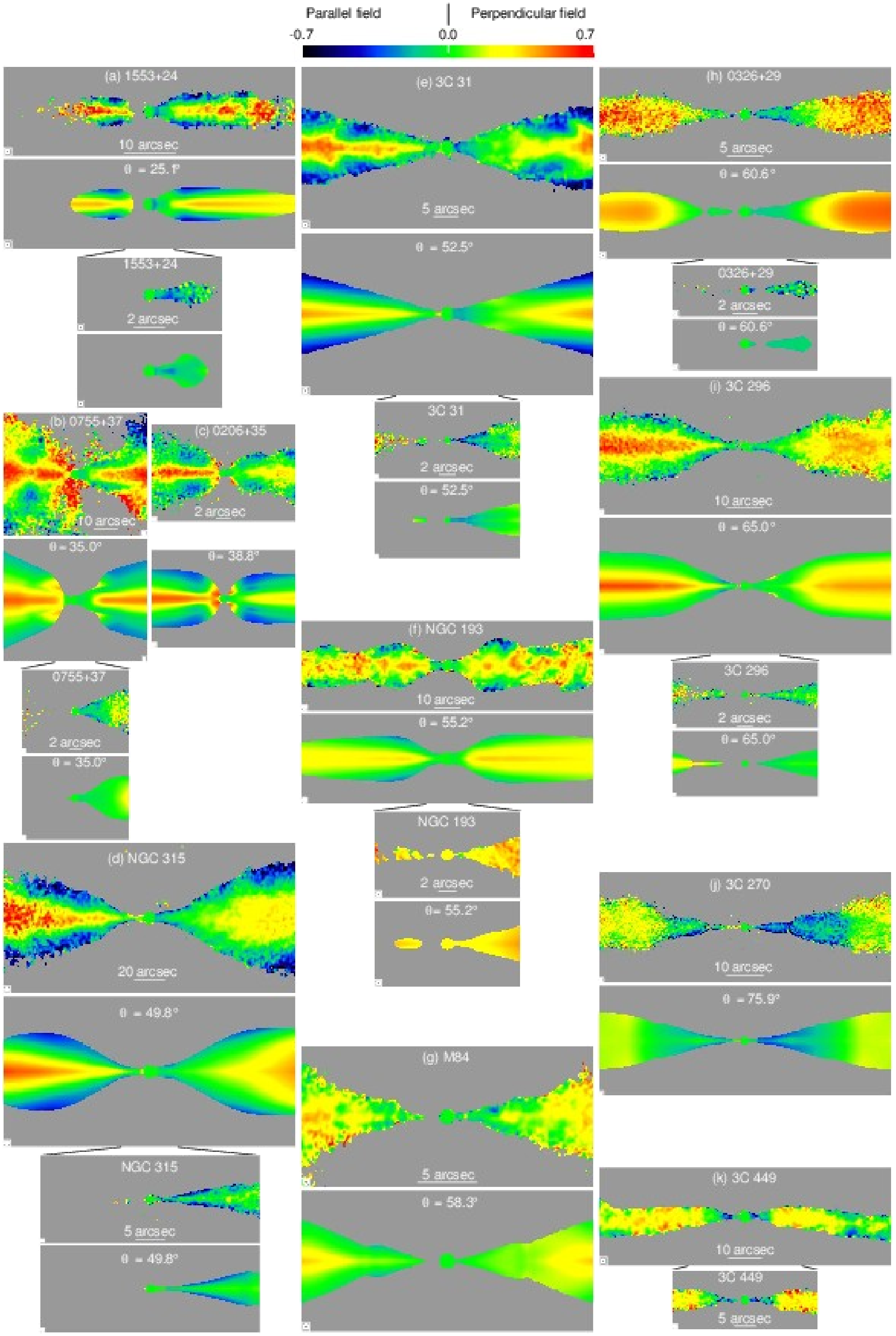
Laing & Bridle (2014)

Pol fits: NGC315




Q/I fits: NGC315
20 arcsec
θ = 49.8°


(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


Parallel field
Perpendicular field
-0.7
0.0
0.7
(a) 1553+24
10 arcsec
θ = 25.1°
1553+24
2 arcsec
(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
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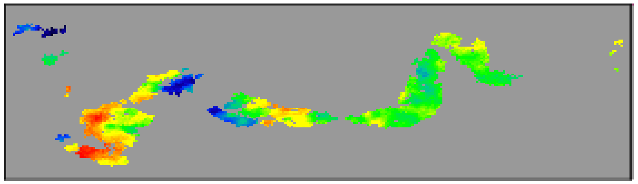
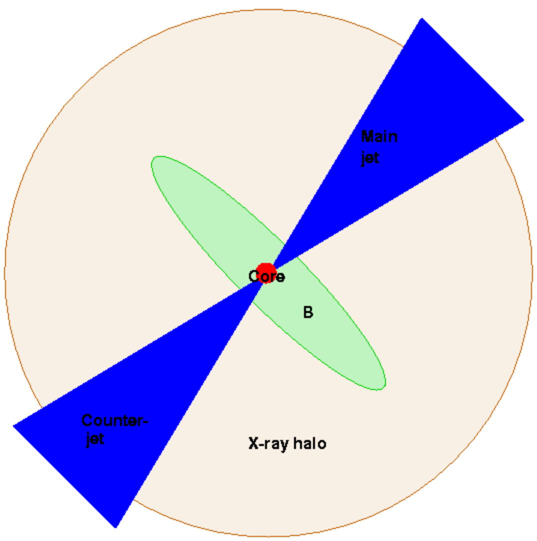
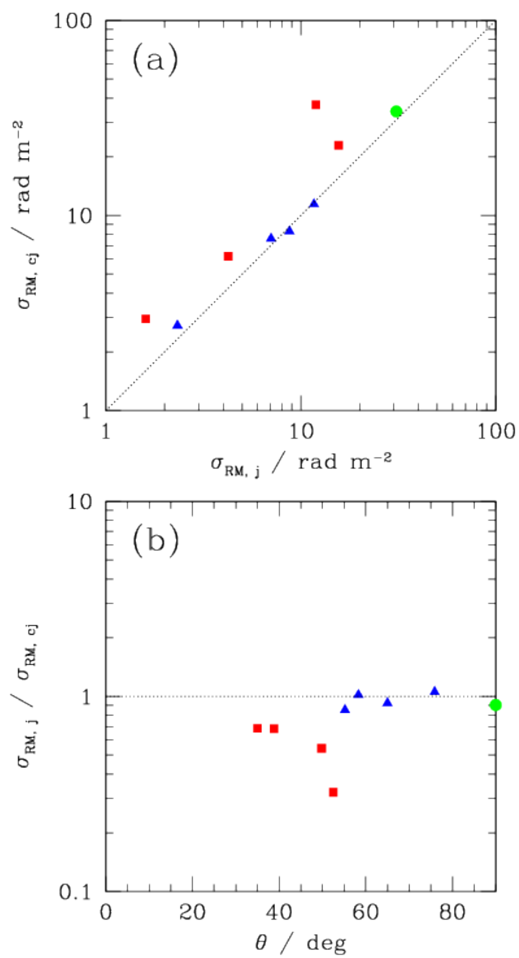
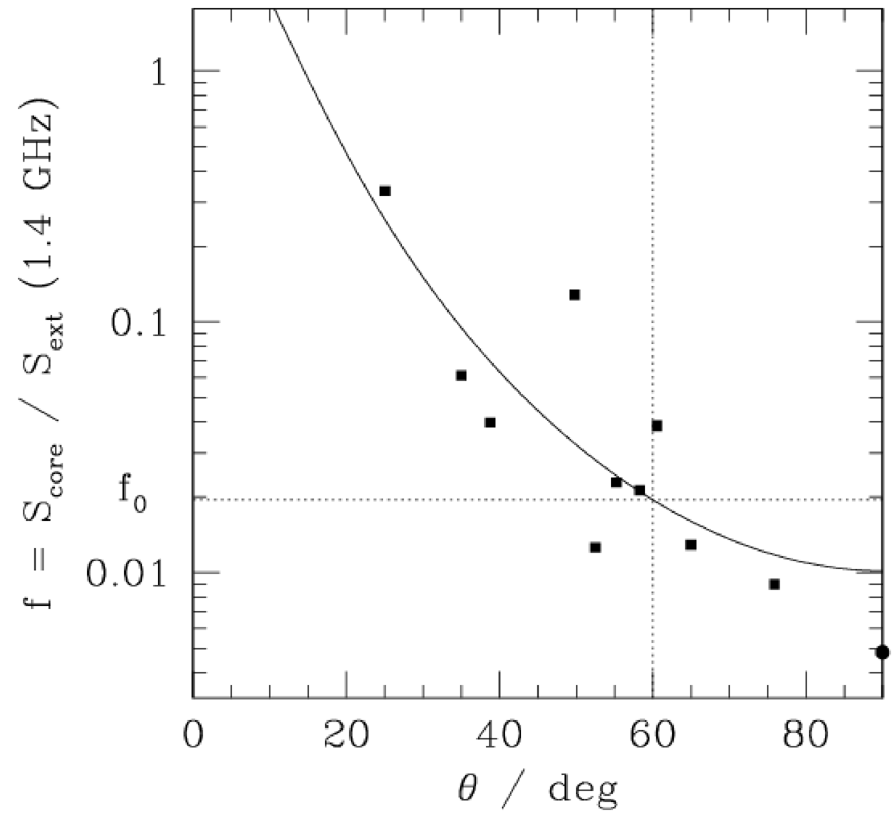
3C 296
2 arcsec
θ = 65.0°
(j) 3C 270
10 arcsec
θ = 75.9°
(k) 3C 449
10 arcsec
3C 449
5 arcsec

Consistency tests





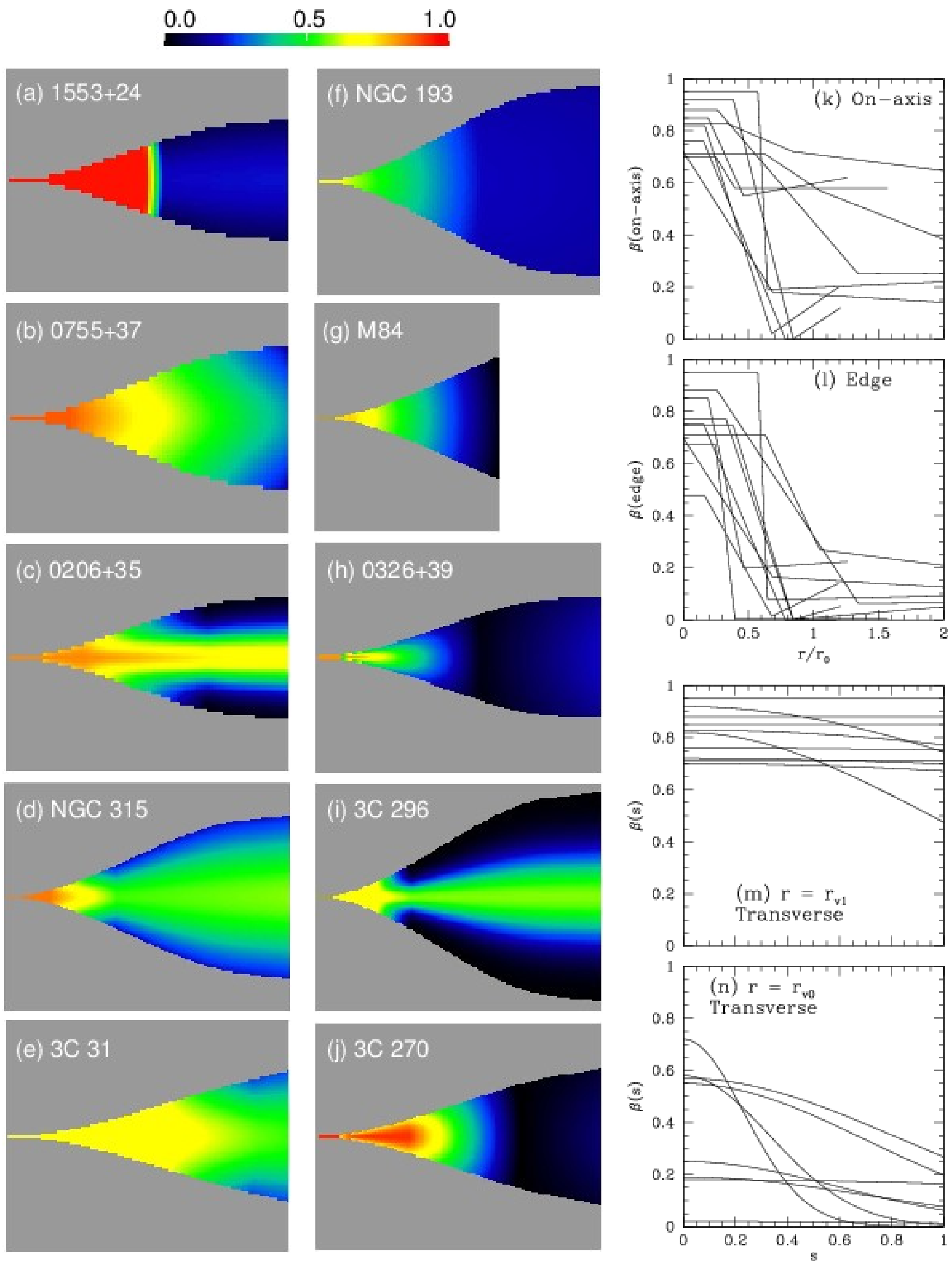




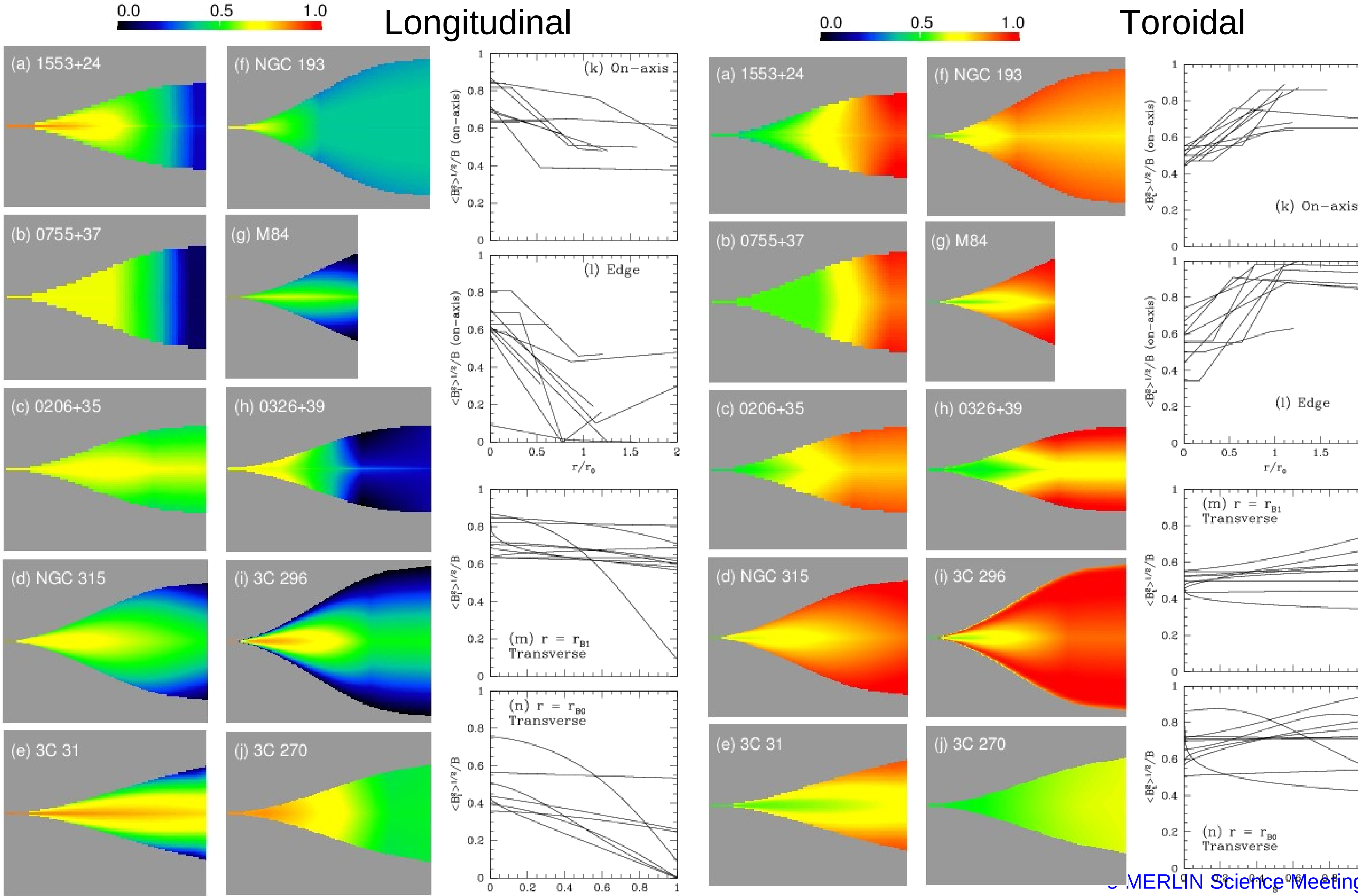
Asymmetries in Faraday rotation: near side shows lower RM dispersion. Symmetrical for θ > 55°; asymmetrical at smaller inclinations.

Fractional core flux density anticorrelated with θ in the expected way.

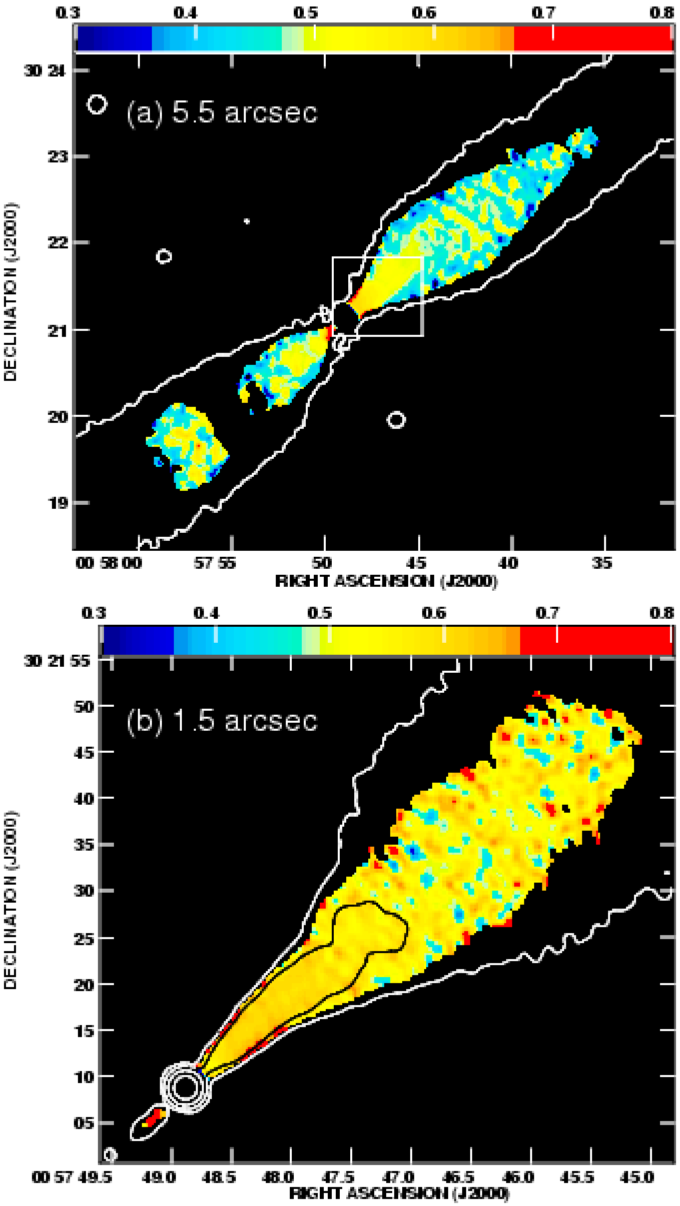
Velocity Field



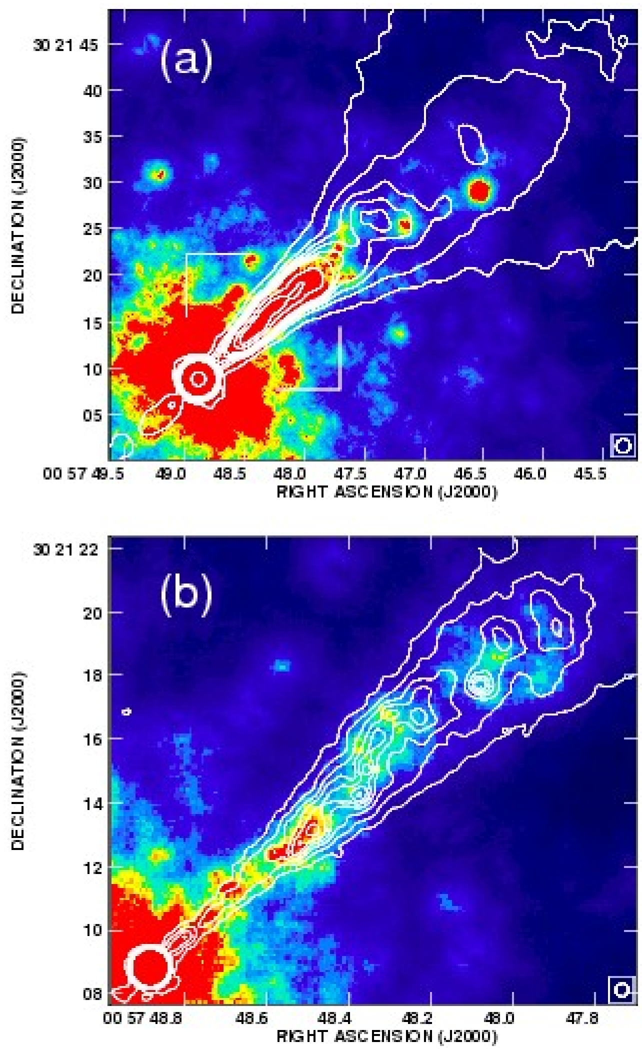
Magnetic Field Geometry

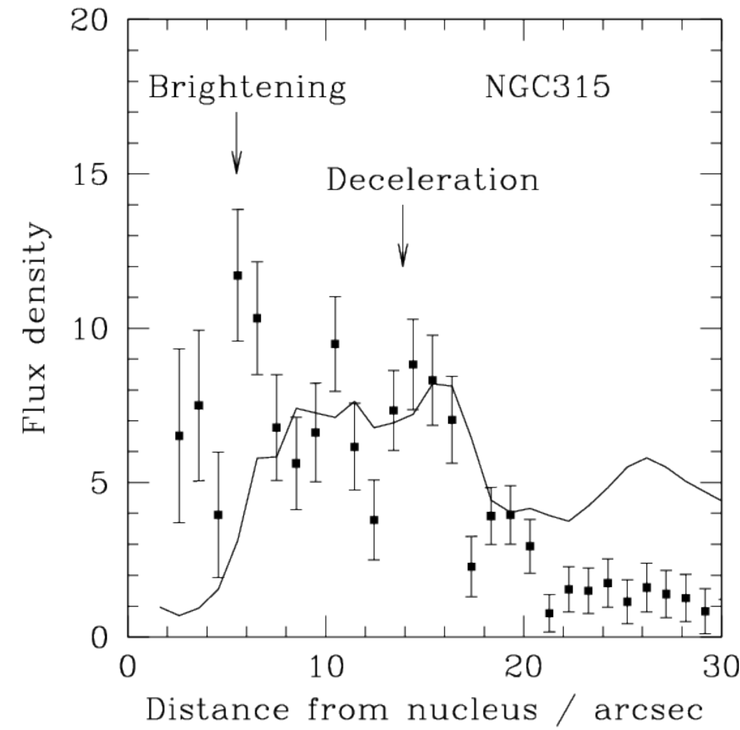


Particle Acceleration



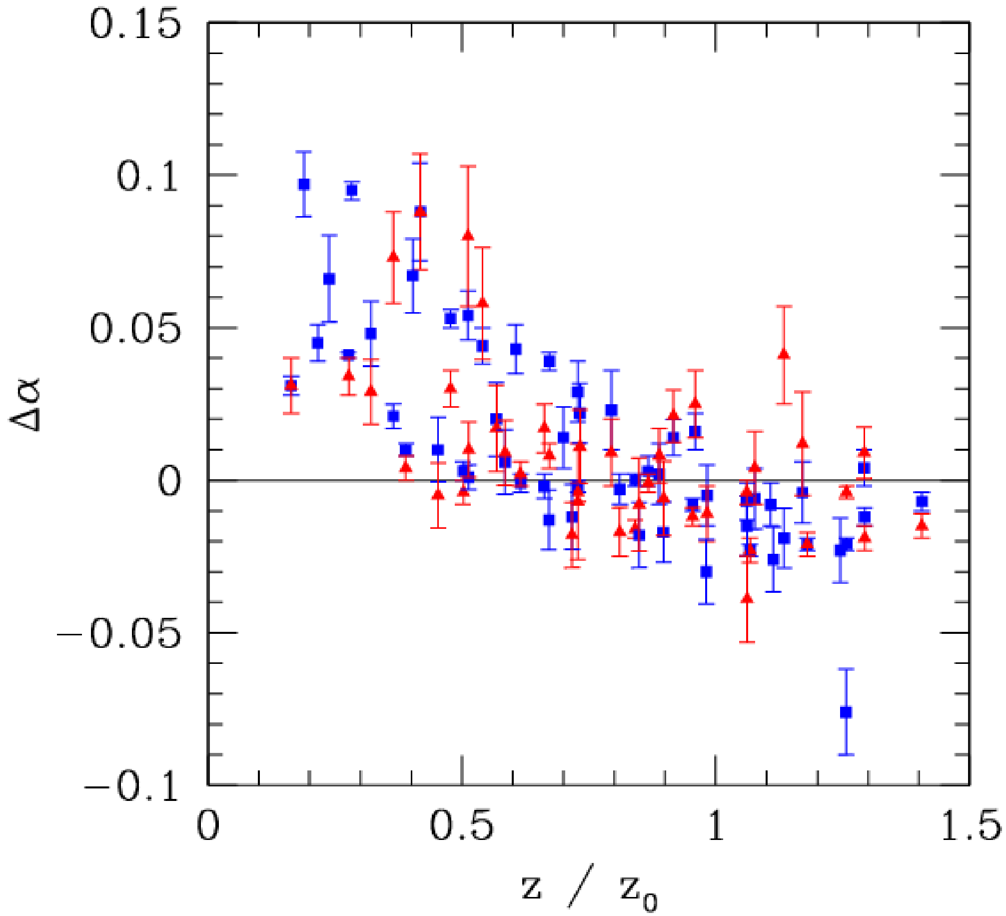
Spectral index
(RL et al. 2006)

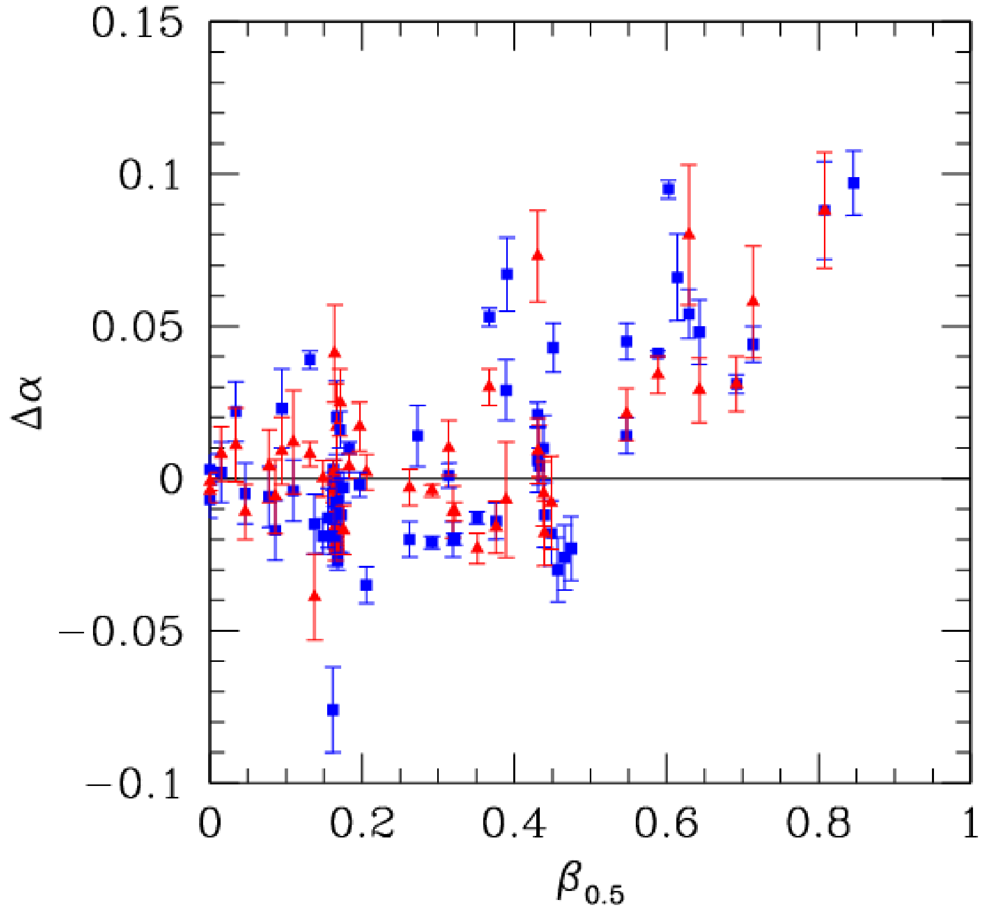




Radio/X-ray
(Worrall et al. 2007)

Spectrum and speed

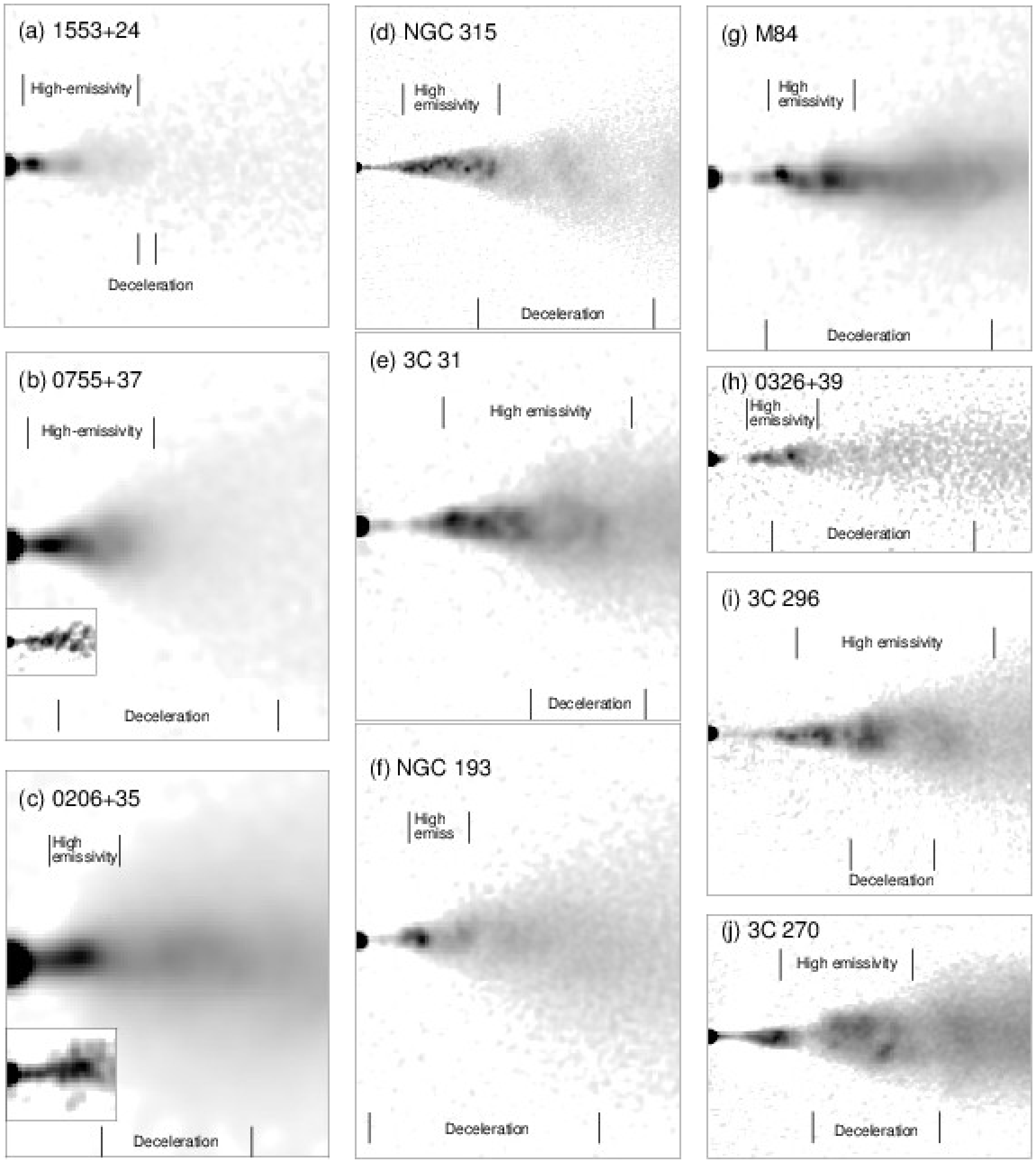


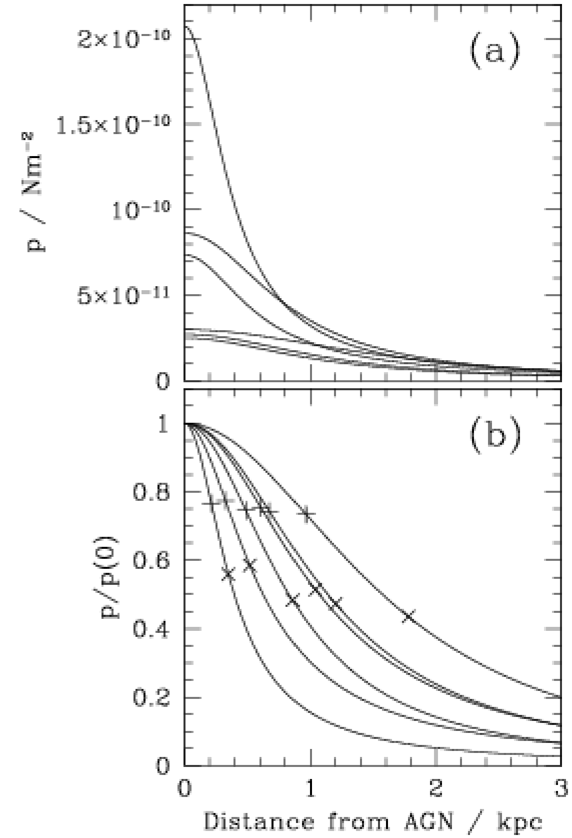


Spectrum becomes flatter with increasing distance from AGN
Opposite to effect of synchrotron losses
Velocity-dependent particle acceleration

Laing & Bridle (2013)

The onset of deceleration





Jets brighten and flare where the external pressure is falling rapidly

New questions

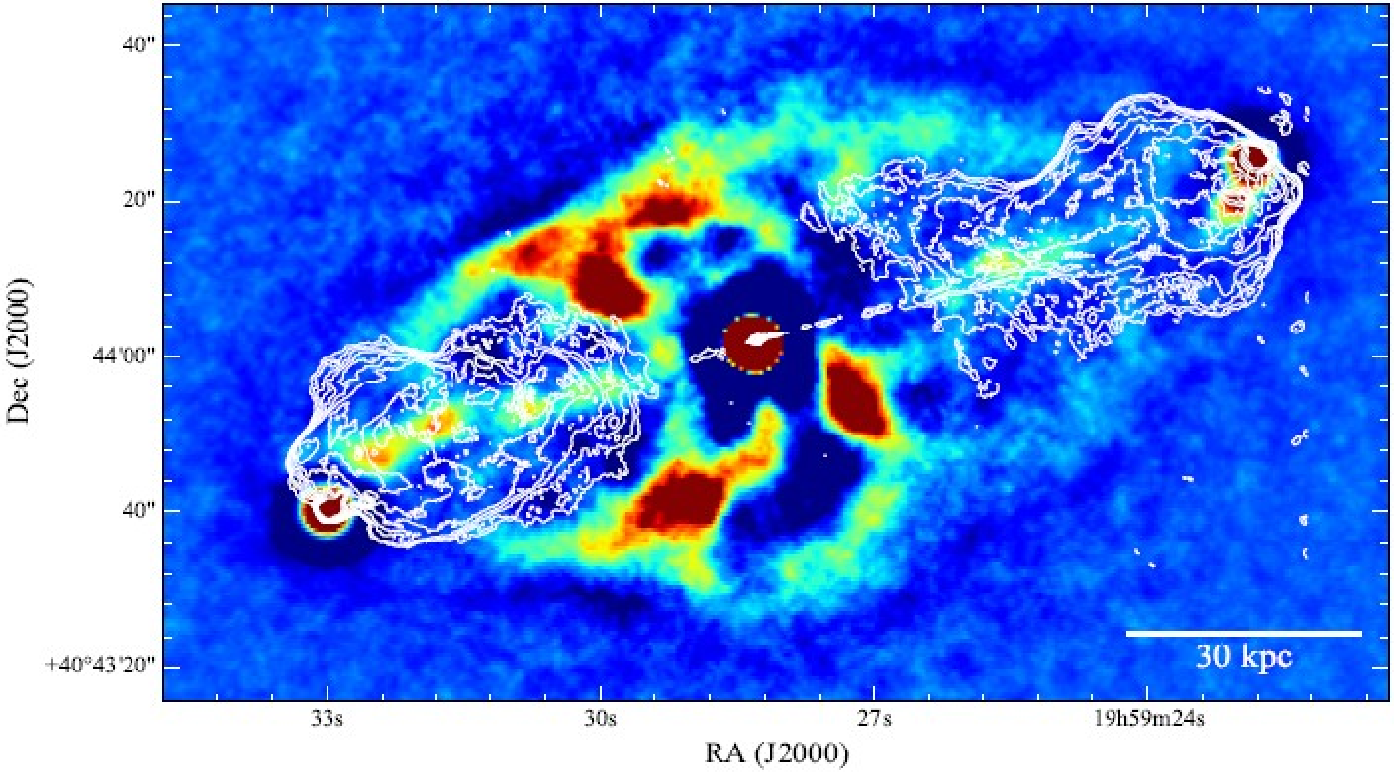
- Why is the sudden brightening followed by deceleration?
  - Jets become overpressured, expand rapidly, form shocks?
  - Growth of unstable Kelvin-Helmholtz modes?
  - Initial deceleration due to mass lost from stars in the jet volume (probably only at low power)?
  - All or none of the above?
- What is the velocity upstream of the flaring point?
  - Fast spine+thin, slow surface layer?
  - Acceleration in steep pressure gradient?
- Need higher resolution, particularly transverse to the jet axis
  - Jet-crossing features
  - Velocity profile

→ e-MERLIN

Powerful Jets

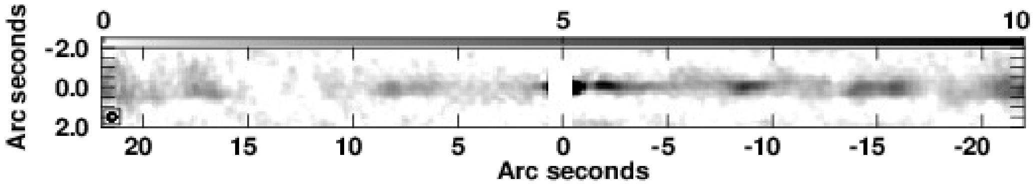
- Much less known
  - Fainter and narrower than the low-power jets
  - Often very asymmetrical, so counter-jets are very dim
- Key questions
  - Relativistic on kpc scales, but how fast?
  - Integrated jet sidedness ratios suggest $\beta \simeq 0.6 - 0.7$ (slower than the fast parts of low-power jets!), but may be misleading
  - If X-rays from extended quasar jets are due to beamed inverse Compton scattering of CMB photons, then the jets must have $\Gamma \sim 10$ **spines**, with the radio coming from much slower ($\Gamma \sim 2$) **shear layers**.
  - Too hard to resolve (often even detect) counter-jets, with one exception – **Cygnus A**
  - What can we learn from main (approaching) jets only?

The exception: Cygnus A



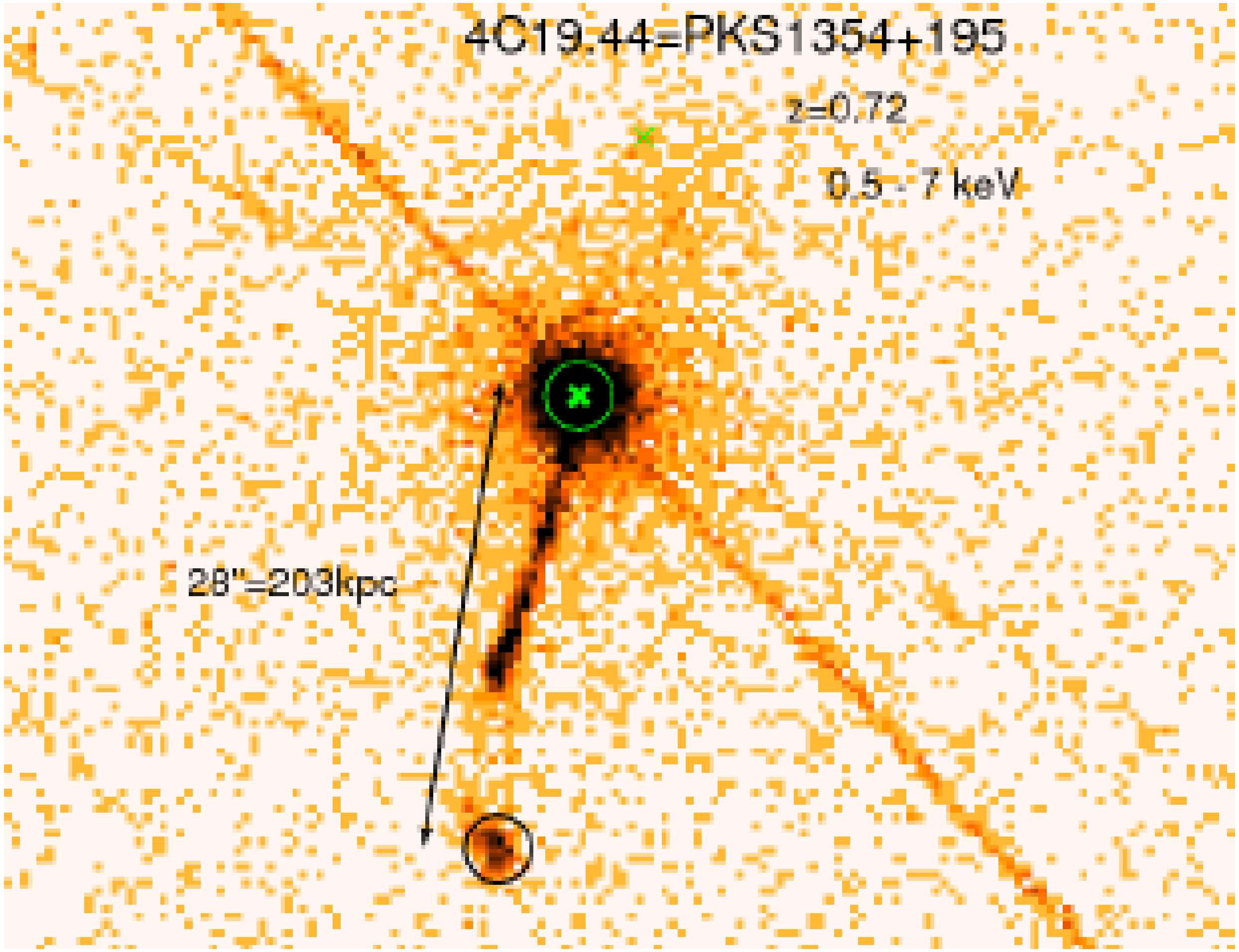
Radio contours
(0.4 arcsec, 5GHz)

Chandra colour
(Michael Wise)



Jets (lobe subtracted)

Beamed inverse Compton X-rays?



If X-ray emission is beamed inverse Compton scattering of CMB, then Γ ~ 10 (Tavecchio et al.; Celotti et al.)

Radio emission likely to be slower?

.... but this idea doesn't work in 3C273 (Meyer & Georganopoulos)

Chandra image of X-ray emission from radio quasar 4C19.44 (Schwartz 2008)

Speeds in Powerful Jets

- Transverse profiles of I and linear polarization
  - At lower inclinations, jets appear more centrally peaked (we see more of the spine)
  - Use fractional core flux f as an indicator of orientation
  - Look at transverse profiles at different f
  - End-on sources like 3C273 should provide a good test ...
  - ... but are really hard to image
- Again, we need resolution better than 0.1 arcsec

→ e-MERLIN

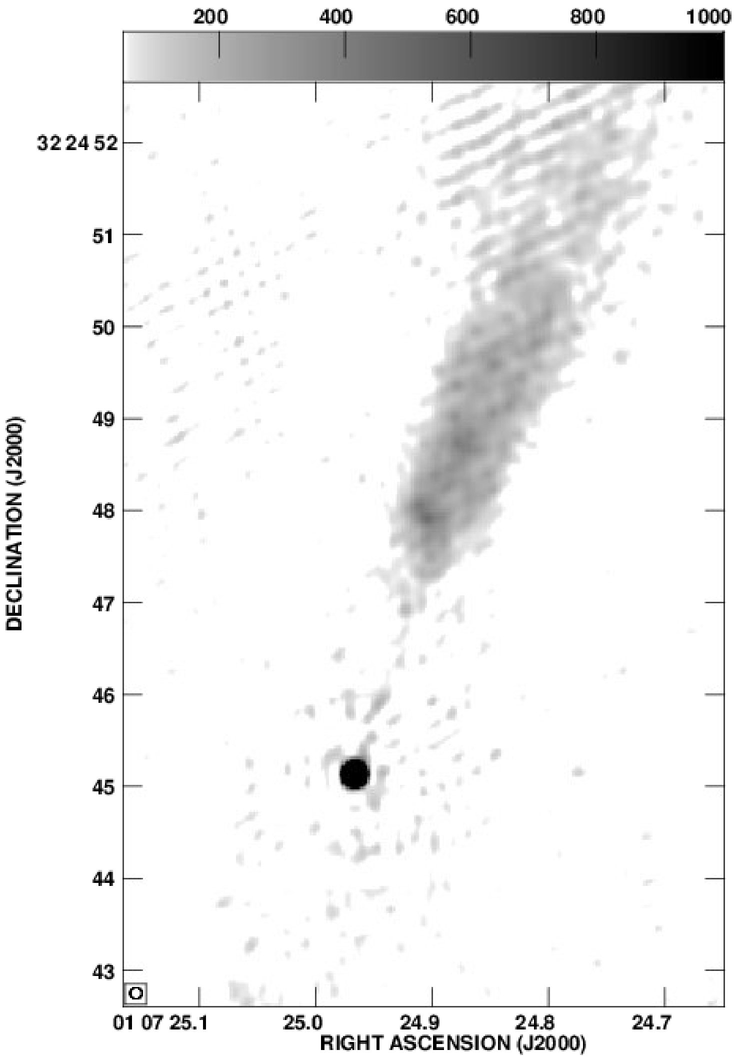
Legacy Proposal

- Two representative sub-samples of flux-limited 3CRR sample
  - Wealth of multifrequency data
  - Legacy value
- Weak (FRI) radio sources with twin jets, $z < 0.06$
  - 10 sources, L band
- Powerful (FRII) sources
  - 11, L and C bands
- 375 hours allocated
  - Image fidelity/dynamic range (need noise-limited imaging)
  - Accurate polarization calibration
  - Wide-band MFS (including polarization; RM synthesis)
  - Combination with (J)VLA, initially in different spectral configurations

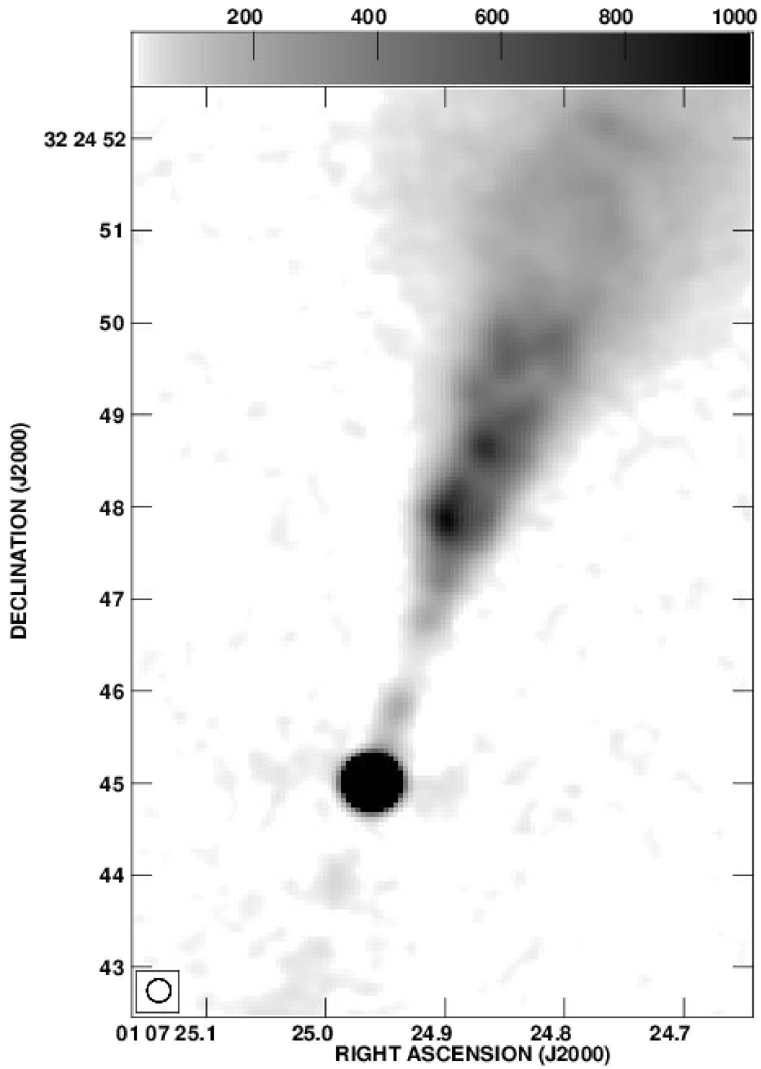
First Steps

- Commissioning observation
  - 3C31, L band
  - Parallel hands only; no linear polarization
  - No Lovell yet
  - Processing@home, so needed to install software
- Reduction
  - Mostly following Cookbook to a first approximation; lots of help from Anita
  - Most difficult step was flagging the phase reference and getting good gain solutions: point source calibrator and target were much easier
  - Imaging with ROBUST ≈ 0 and multi-scale CLEAN (3 scales)

Results so far



e-MERLIN, 6 IF's averaged
0.125 arcsec FWHM



VLA, 8.4 GHz, 100MHz bandwidth
ABCD, 0.25 arcsec FWHM
(RL et al. 2008)

Initial Image

- rms 23 µJy/beam (thermal noise 12 µJy/beam)
  - thermal noise may be underestimated because flagging not fully taken into account in estimate
- Artefacts: these are mostly multiplicative rather than additive
  - Symmetry suggests mostly amplitude errors remaining
- Peak 56 mJy/beam
  - ~75 mJy/beam from 1.5-arcsec resolution VLA observations at the same frequency
  - Need to check flux transfer, but some of this could be either variability or resolution
- Another obvious limitation is short-spacing coverage (large-scale ripple parallel to jet axis)
  - Need to add in VLA data (although the bandwidth is very different)
  - Weights?
  - Cross-calibration?

What did I learn that wasn't in the Cookbook?

- Installation of pipeline and SERPent autoflagger
  - Painless, with the exception of the Obit build: better to distribute Parseltongue binaries
- SERPent
  - Default parameters caused some overflagging on calibrator data
  - Works well on bandpass-calibrated target data (parameters tweaked)
- Imaging
  - For our purposes: robust = 0 works well; need multi-scale CLEAN
- Next steps
  - MFS imaging (CASA, with AIPS IMAGR in spectral mode as a check)
  - Most efficient way of tracking down remaining calibration errors and RFI?
  - Accuracy of flux transfer?

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