The spectral age problem:
A VLA study of two powerful radio galaxies

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with Martin Hardcastle
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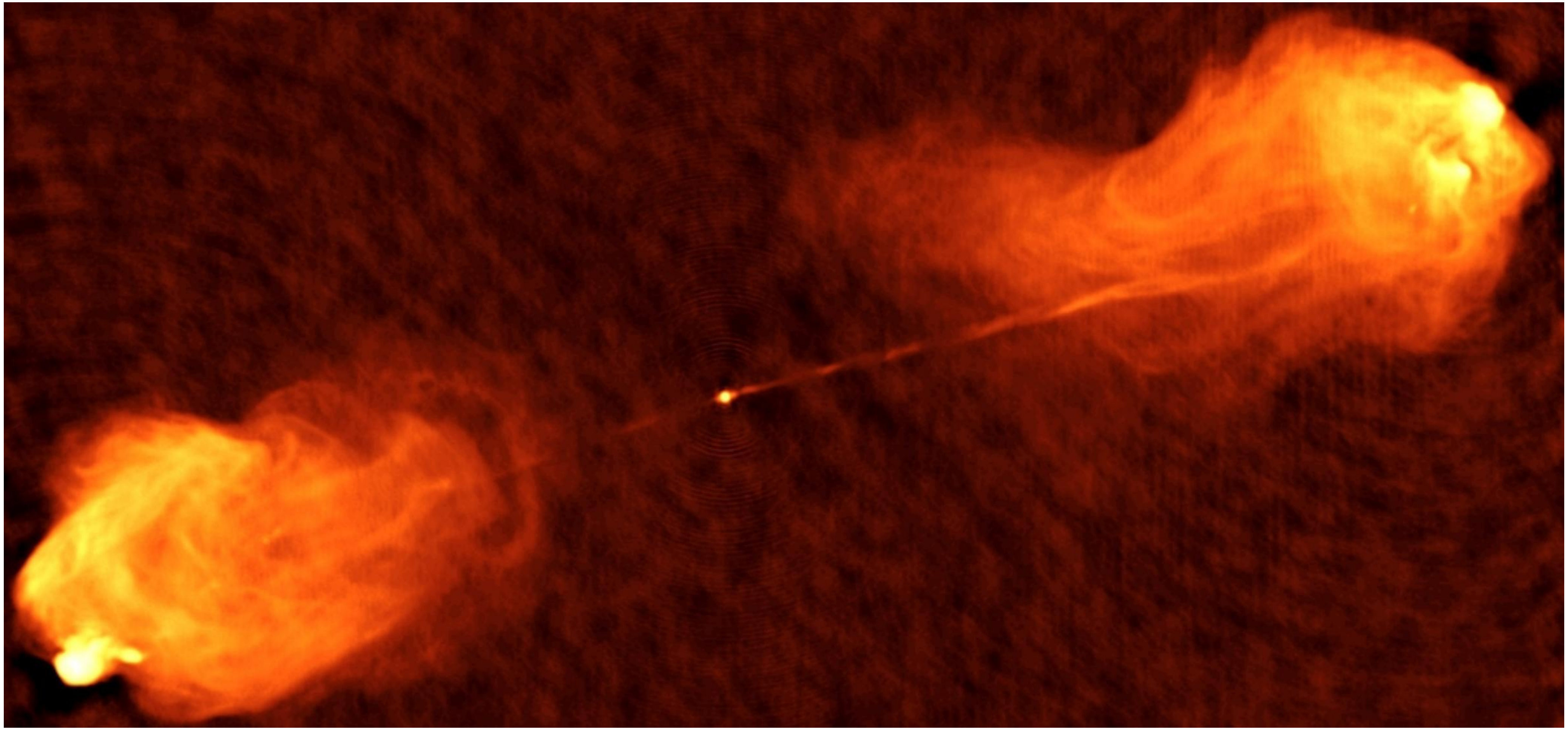
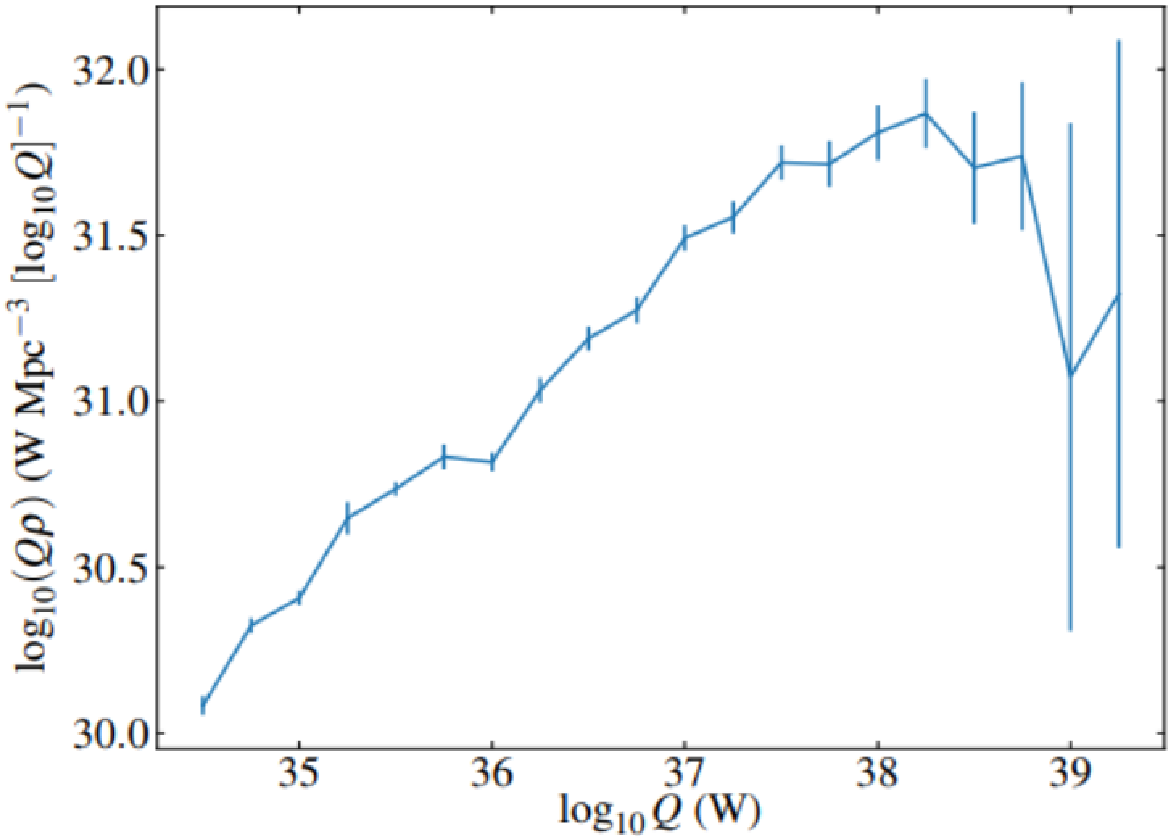
(+ LOFAR surveys team)

Background – the structure of a powerful radio galaxy (Cygnus A)



Credit: NRAO

Jet-driven AGN can overcome radiative losses

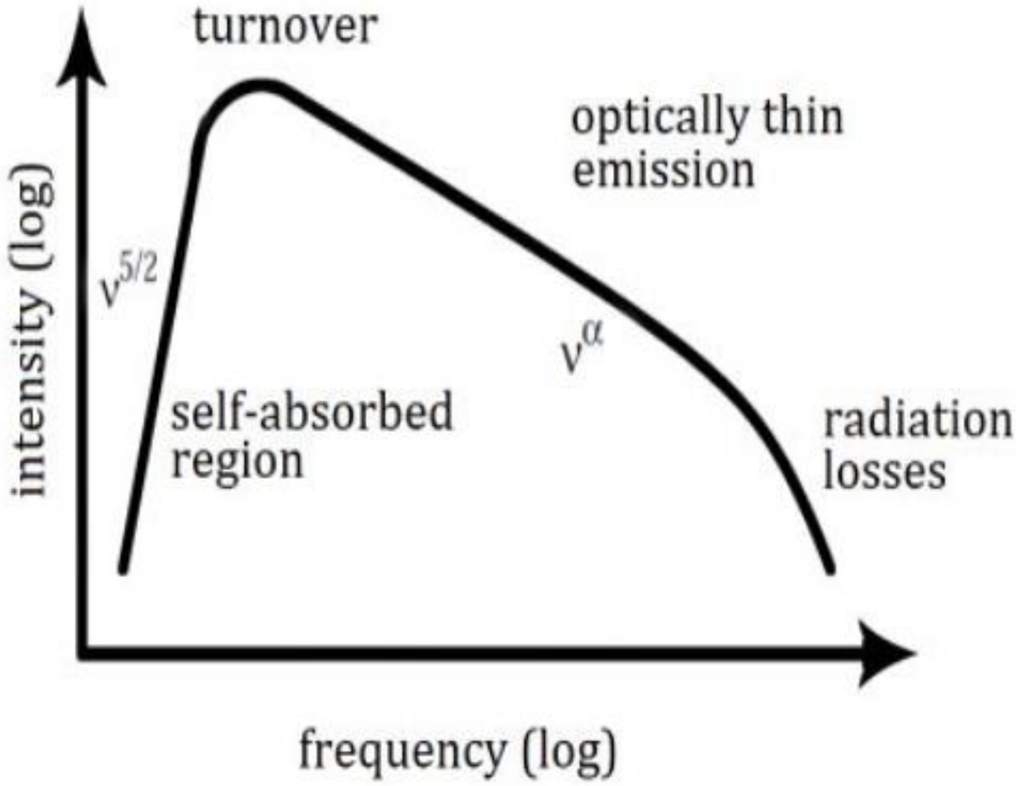


Hardcastle et al. (2019)

- Jet kinetic luminosity function based on bulk inference of jet powers of radio AGN observed in LoTSS DR1 (Hardcastle et al. 2019)
- Total kinetic power >= group/cluster cooling luminosity

Outstanding question: Jet powers of individual sources

- Require robust and accurate value for observed RLAGN
- Q = Total instantaneous energy injected/age
- `Spectral ages' – Synchrotron losses can be used to determine the loss time scale of electron populations in radio lobes.
- Radio observations could be enough to determine jet powers



$$t_{spec} = 2.6 \times 10^4 \frac{B^{1/2}}{B^2 + B_{CMB}^2} ((1+z)\nu_b)^{-1/2}$$

Problems with spectral ageing

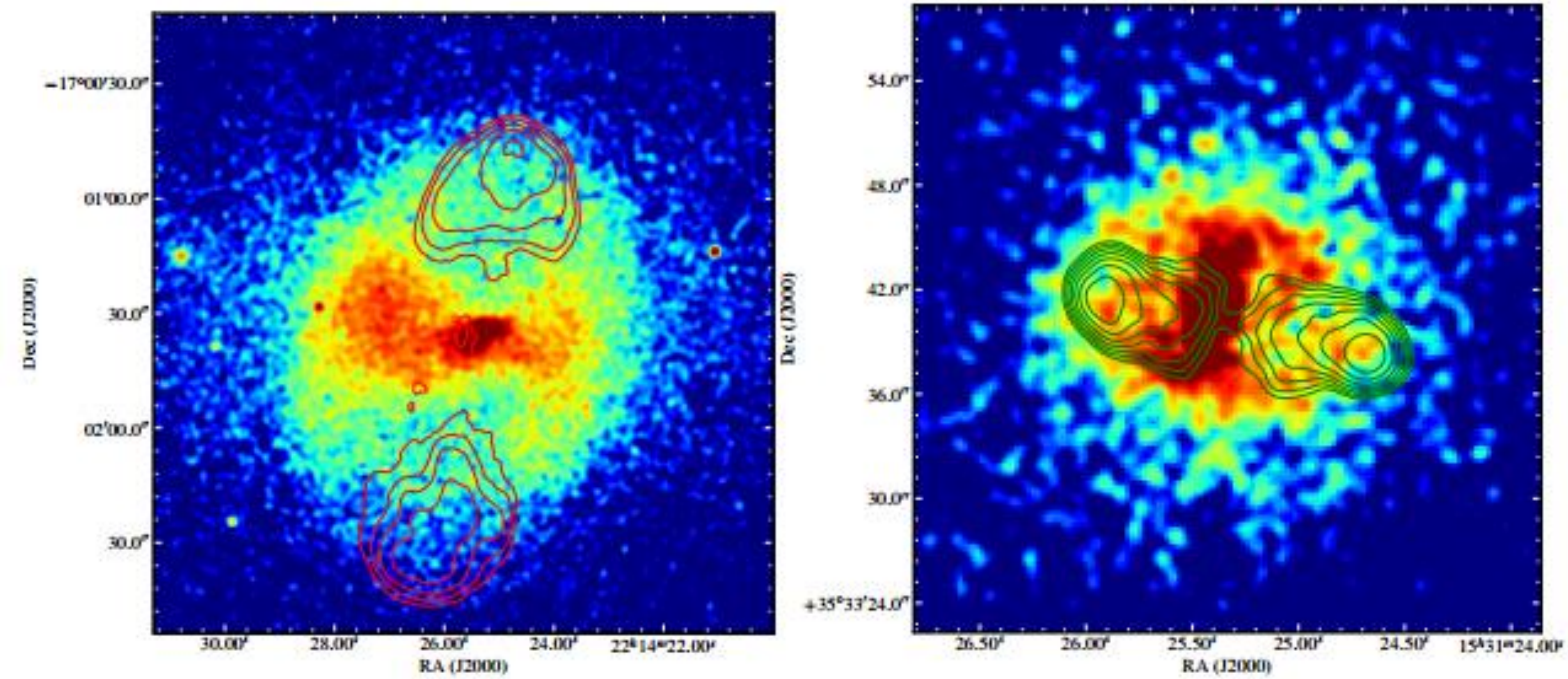
- Spectral ages *always* underestimated relative to jet dynamical lifetime

- Uncertain magnetic field strength – need inverse-Compton detections in radio lobes with X-ray
- Lack of broad-band maps at GHz frequencies – upgraded VLA
- High resolution maps showing all structure – upgraded VLA
- Electron mixing – factor of two underestimation of age (Turner 2017)

- BUT – we need spectral ages to work for upcoming radio surveys..

VLA study of 3C320 and 3C444

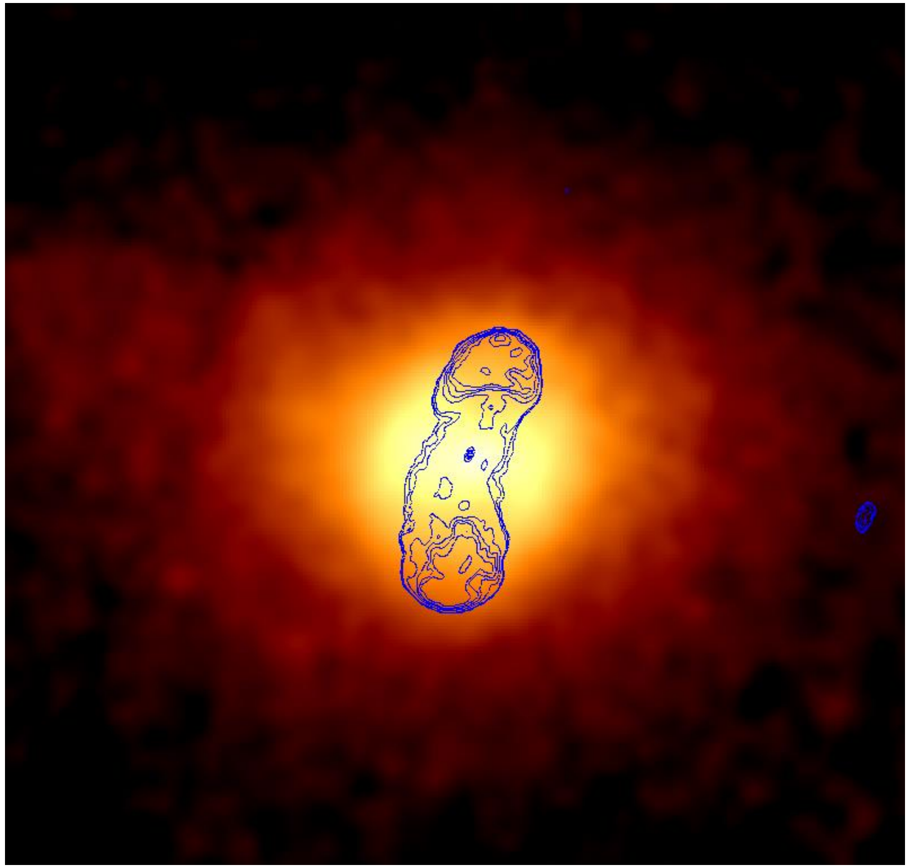
Source	z	Cluster kT (keV)	L_{178} $(W/Hz/sr)$	LAS (arcsec)	Size (kpc)
3C444	0.153	3.5	1×10^{26}	120	320
3C320	0.342	3.3	3×10^{26}	20	100



Croston et al. (2011)

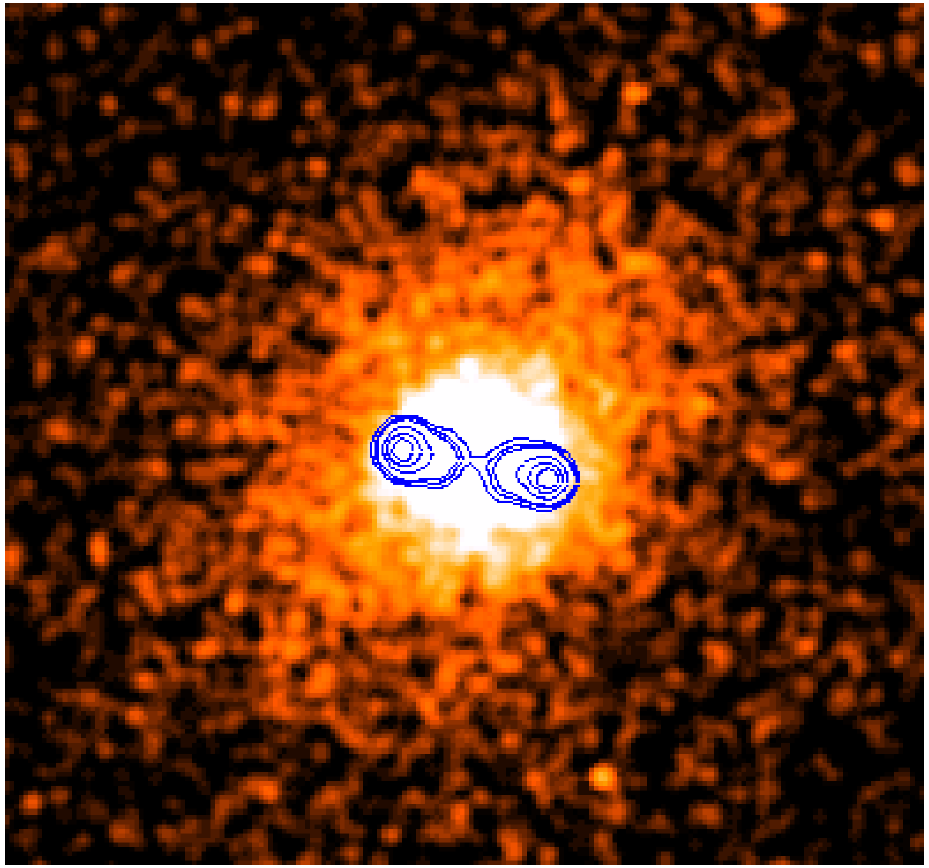
Mahatma et al. (in prep)

Observations: X-ray



3C444

XMM-Newton 0.3-7 keV



3C320

Chandra 0.5-5 keV

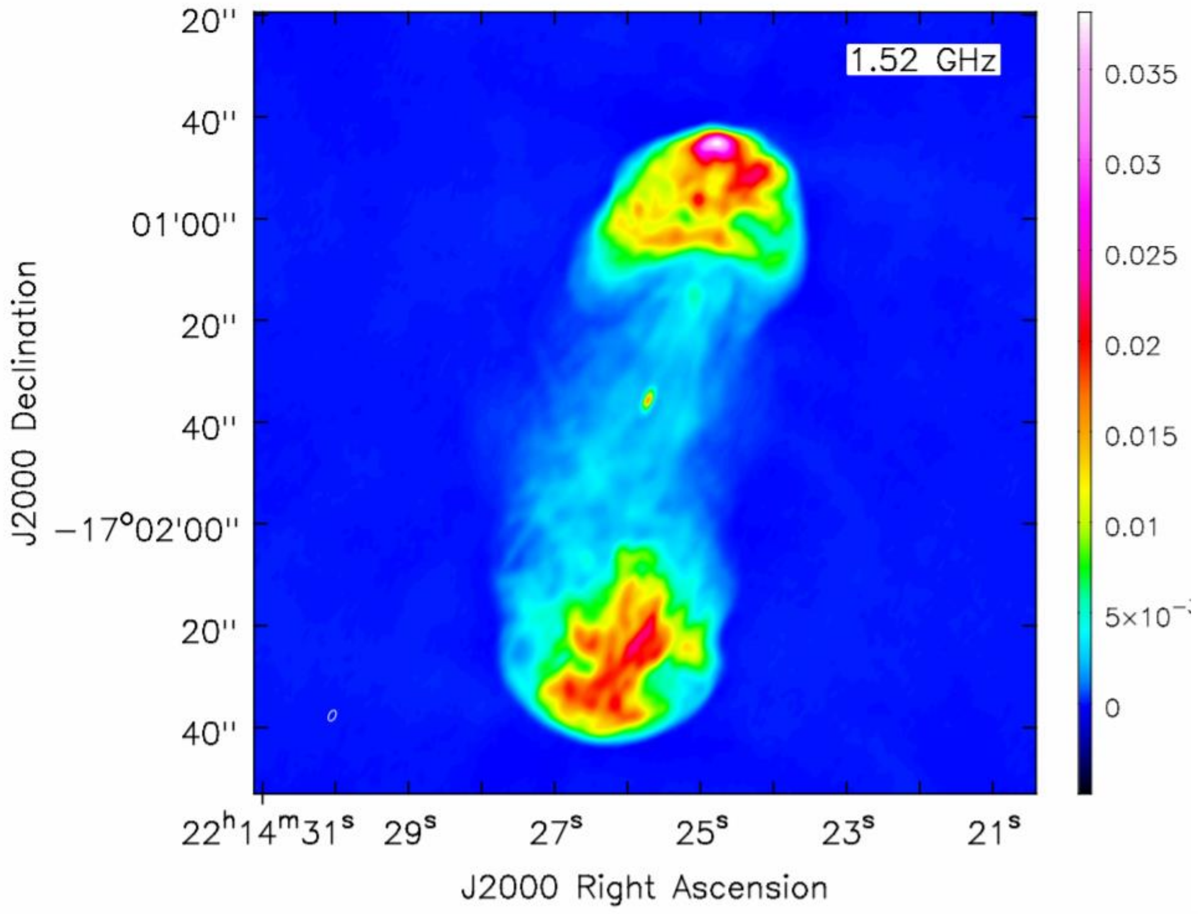
Mahatma et al. (in prep)

Observations: VLA

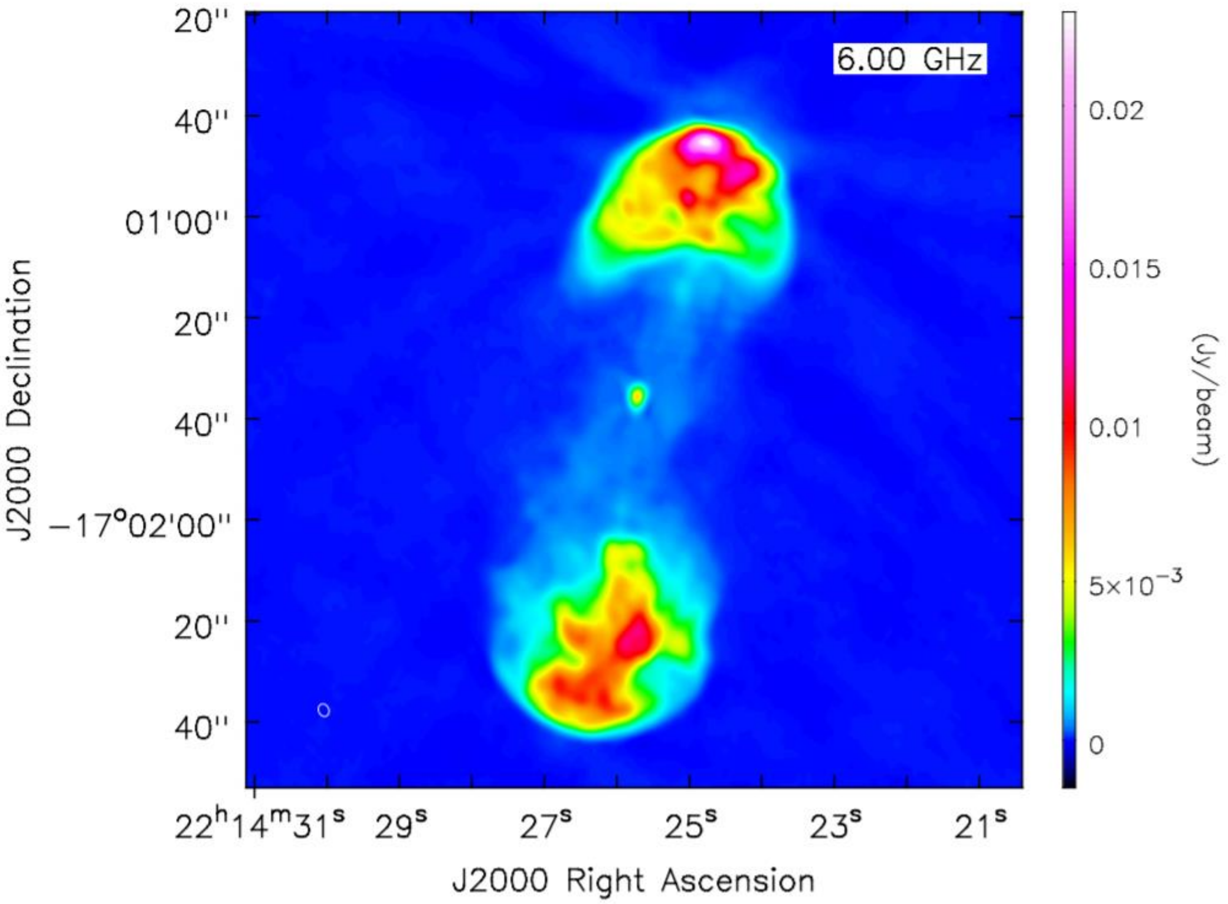
Source	Project ID	Array	Frequency band (GHz)	Observation date	Duration (hrs)	Flux Calibrator
3C320	15A-420	A	L, C	01/08/15	4	3C286
		B	C	15/02/15	1.5	
	CY4223	Mk2,Pi,Da, Kn,De,Cm	L	22/03/18	6.5	3C286
3C444	15A-420	A	L	18/06/15	3.5	3C48
		B	L, C	07/02/15	4	
		C	C	31/01/16	1.5	

Mahatma et al. (in prep)

Observations: VLA (3C444)



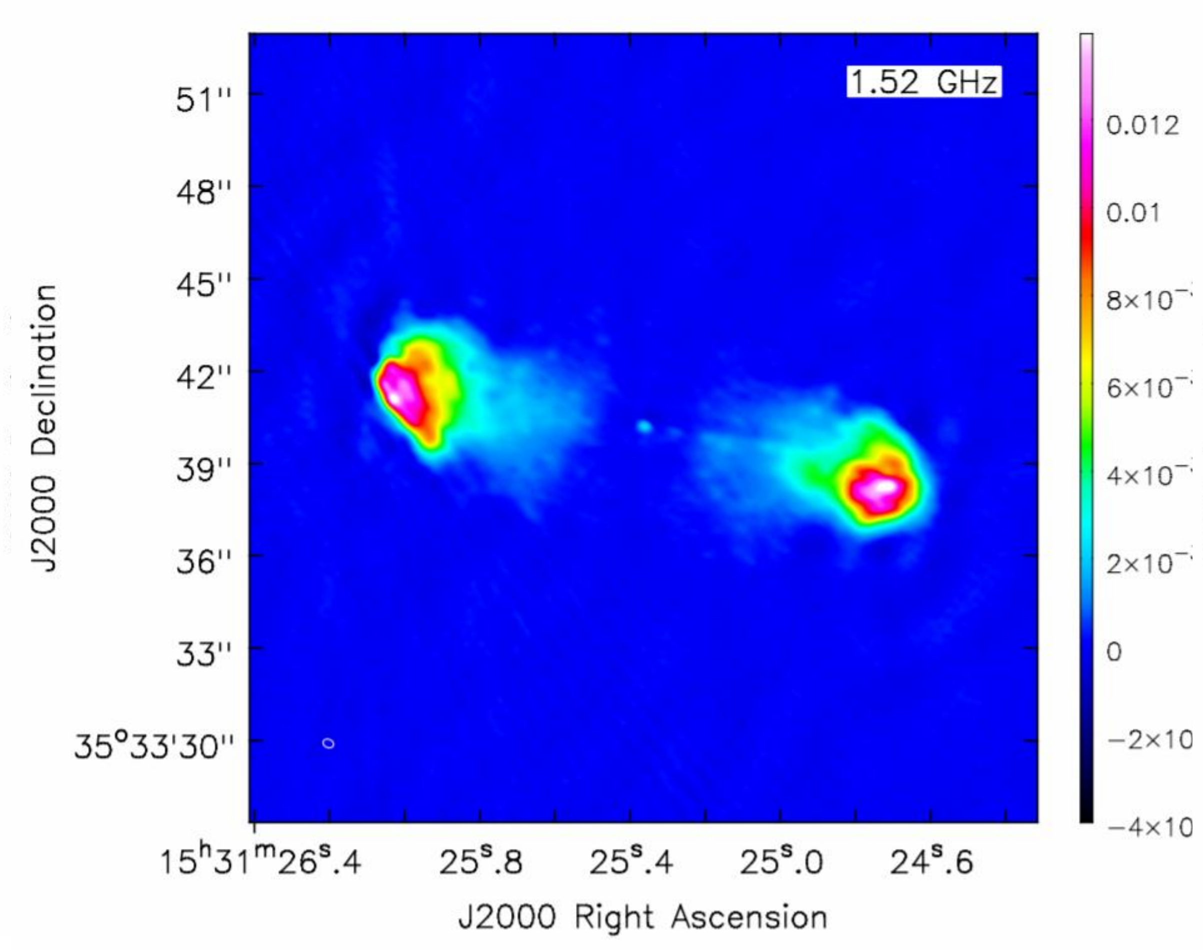
L-band



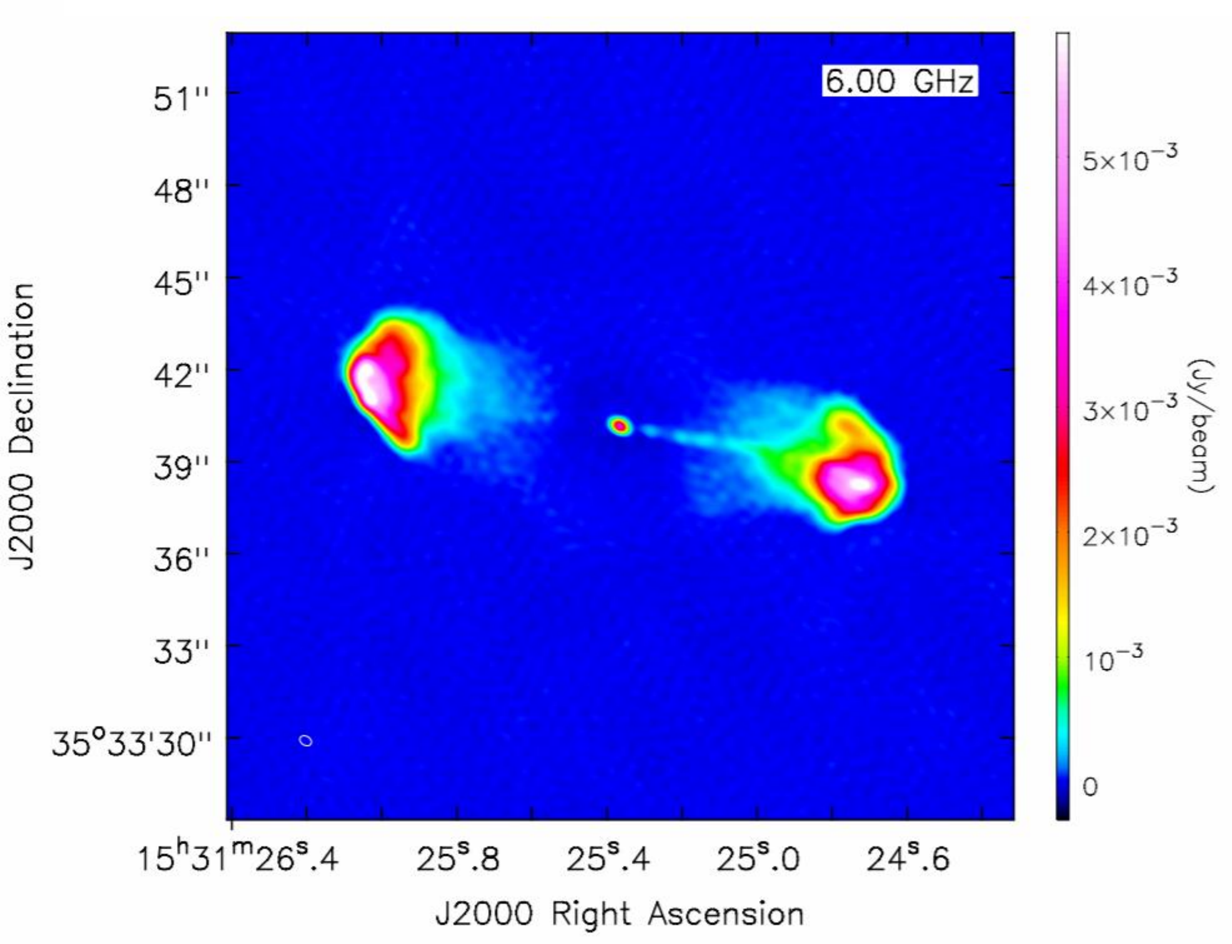
C-band

Mahatma et al. (in prep)

Observations: VLA (3C320)



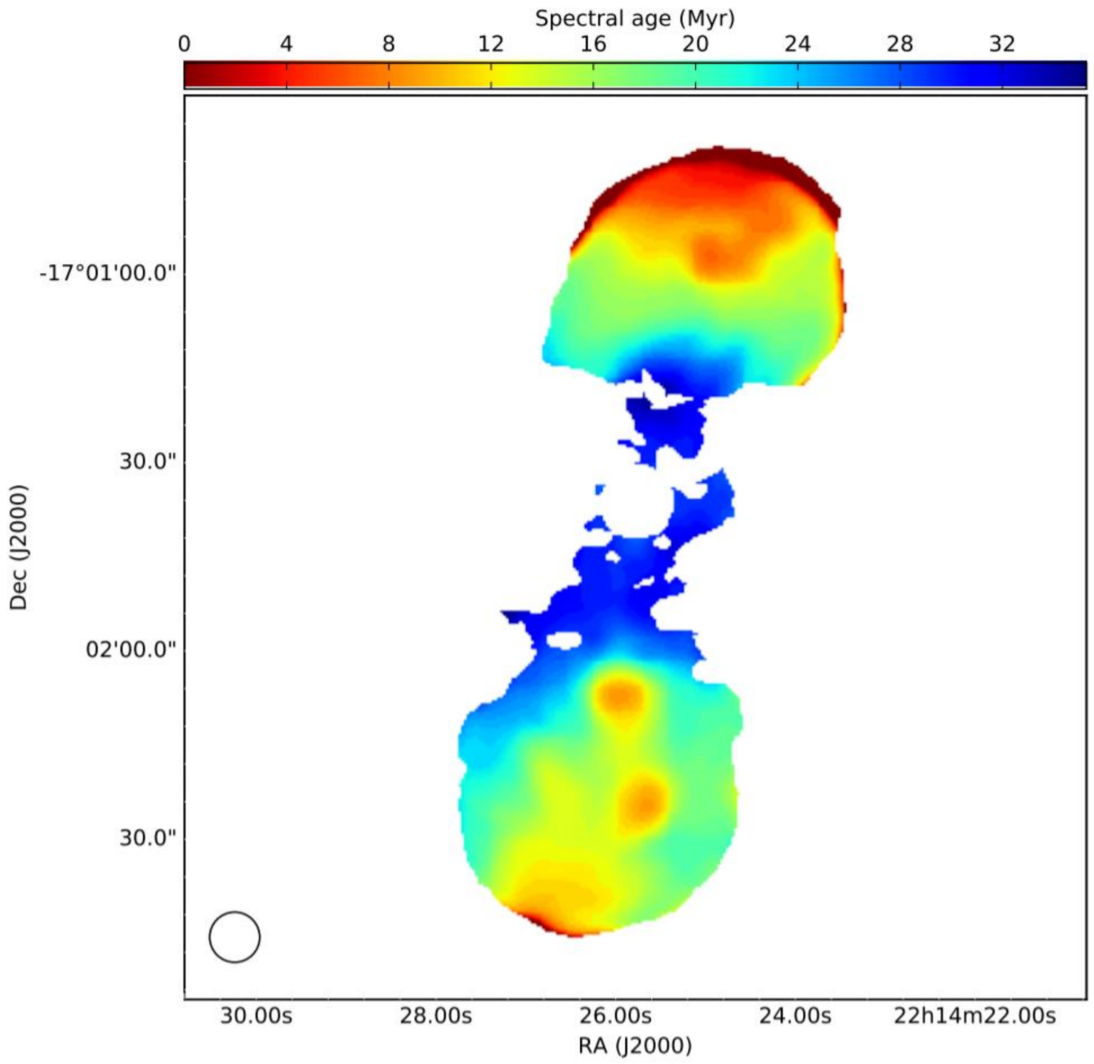
L-band

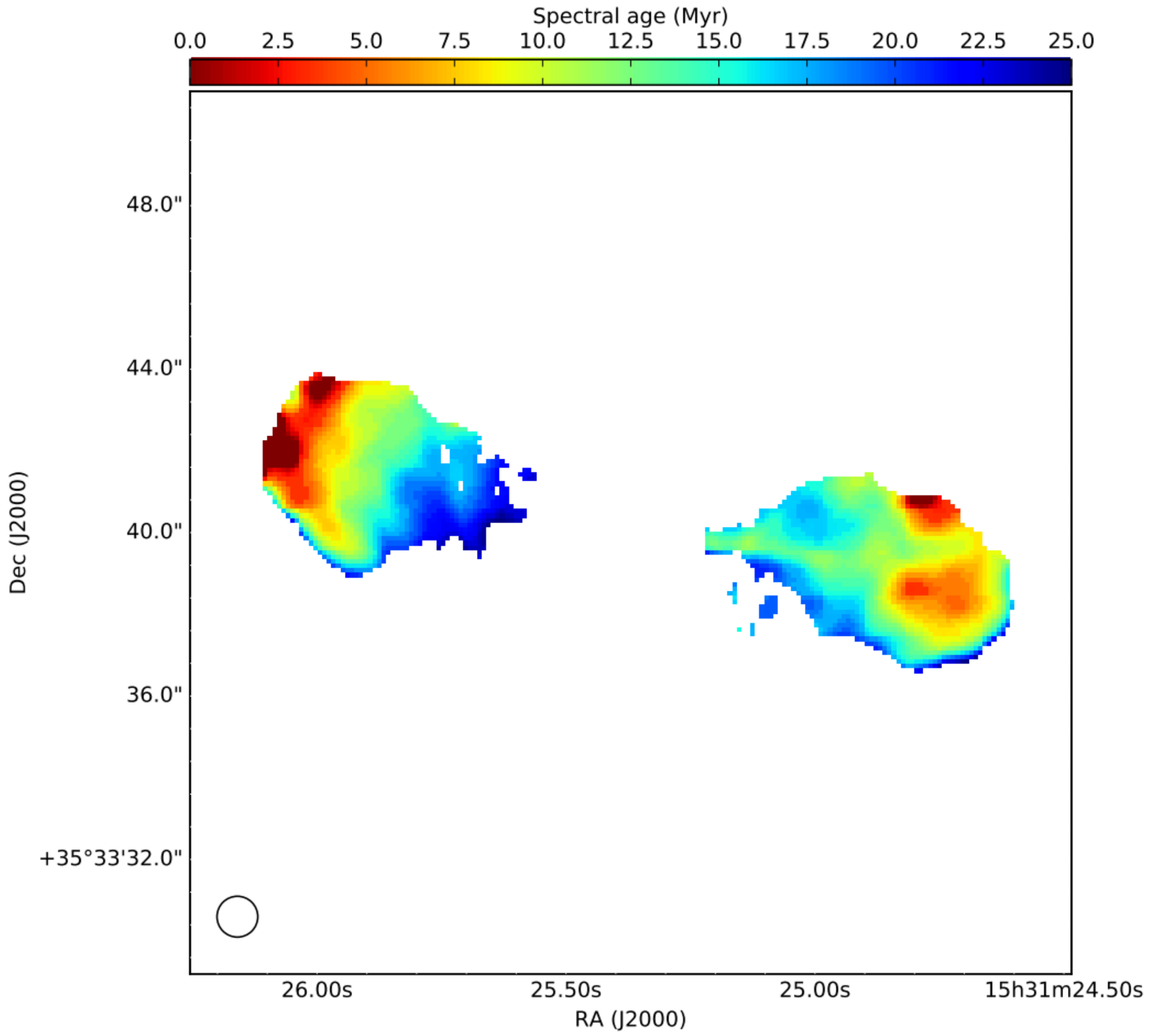


C-band

Mahatma et al. (in prep)

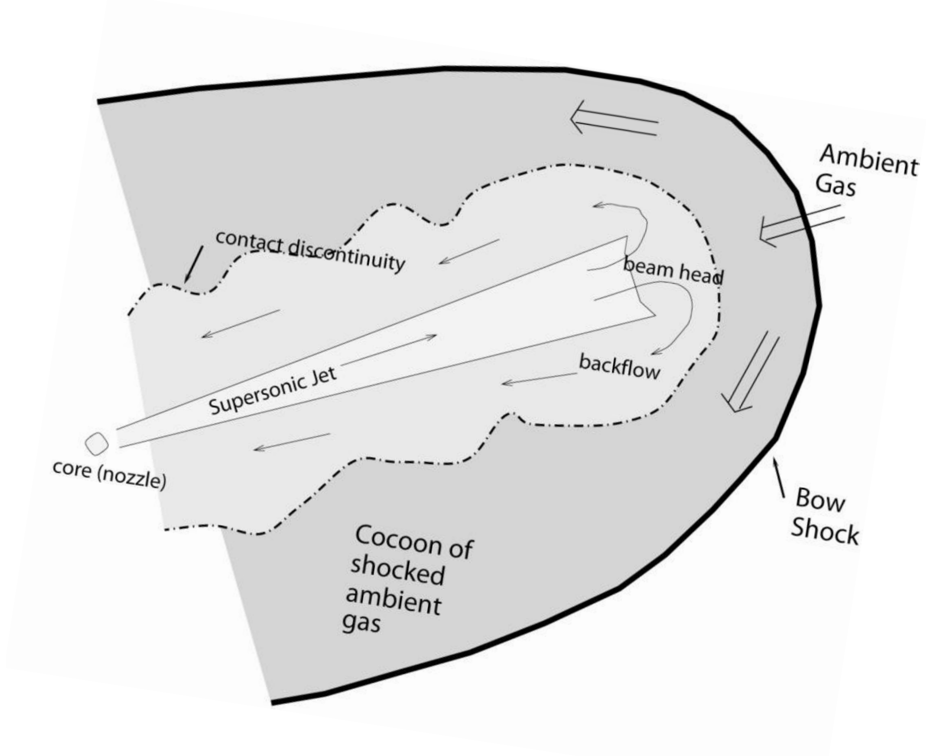
Spectral ageing maps (BRATS: Harwood et al. 2013)





Analytic model (Hardcastle 2018)

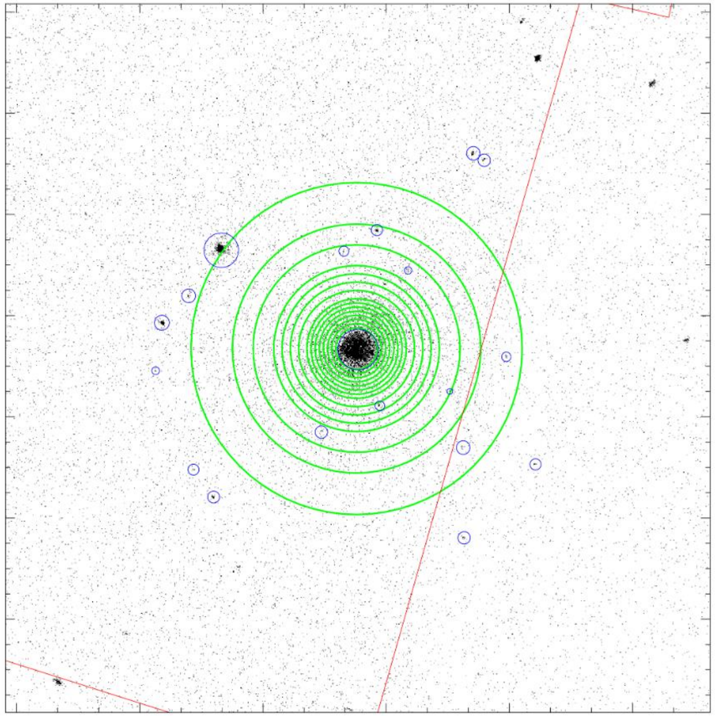
- Evolves the shocked shell around a radio galaxy in a given environment with a given jet power.
- Numerically computes energetics at each time step: dynamical ages

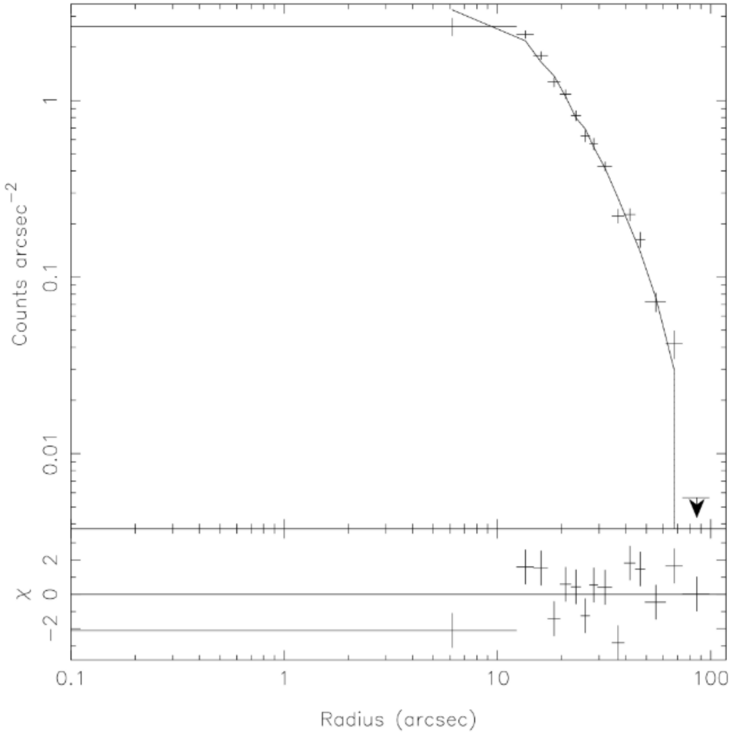


Mahatma et al. (in prep)

Environmental prediction

- Require model of environment before AGN switched on
- Fitted beta model to X-ray radial profile excluding central shock





Source	Parameter	Value
3C320	β	$0.67^{+0.038}_{-0.042}$
	kT	$3.91^{+0.44}_{-0.42}$ keV
	p_0	$1.53^{+0.098}_{-0.13}$ Pa
	r_c	$82.06^{+5.35}_{-5.94}$ kpc
	q	2.0
	z	0.342
	ζ	$0-1$
	$Q_{\rm jet}$	$10^{36}-10^{38}$ W
	θ	$45^\circ-90^\circ$

Mahatma et al. (in prep)

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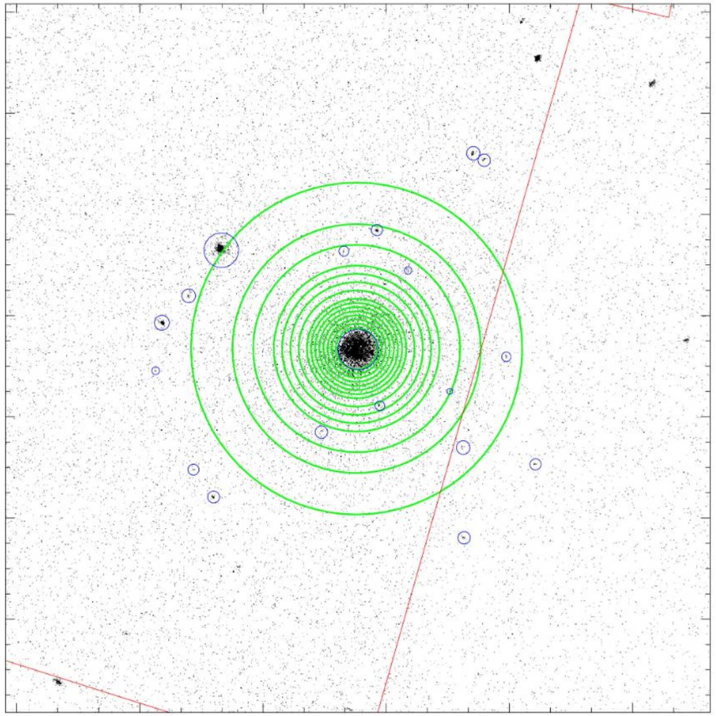

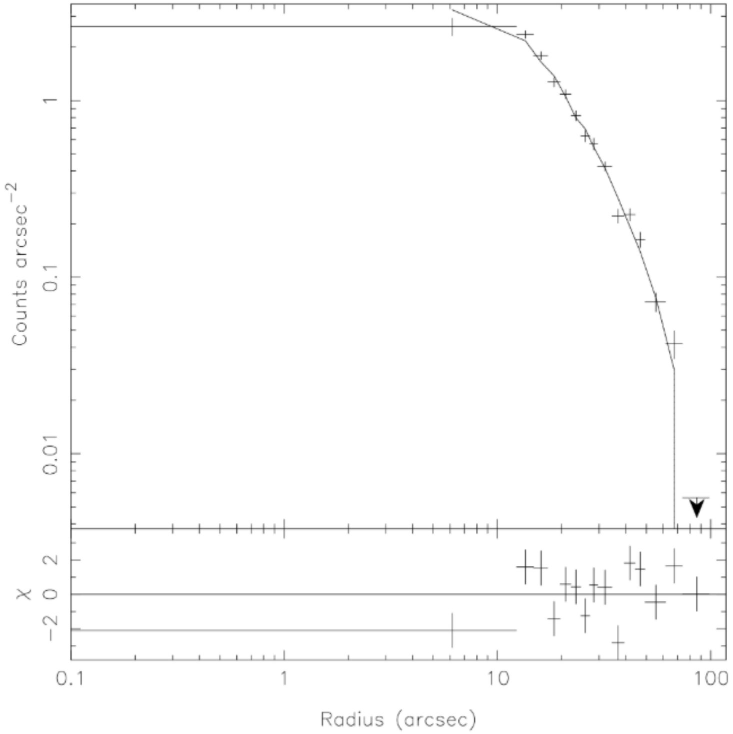

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Dynamical ages: Model of Hardcastle (2018)

- Known parameters
  - Environment central pressure, isothermal temperature, core radius, beta index, redshift, low frequency injection index
- Unknown parameters
  - Jet power
  - Zeta = Ub/Ue (=1 for equipartition)
  - Source inclination angle

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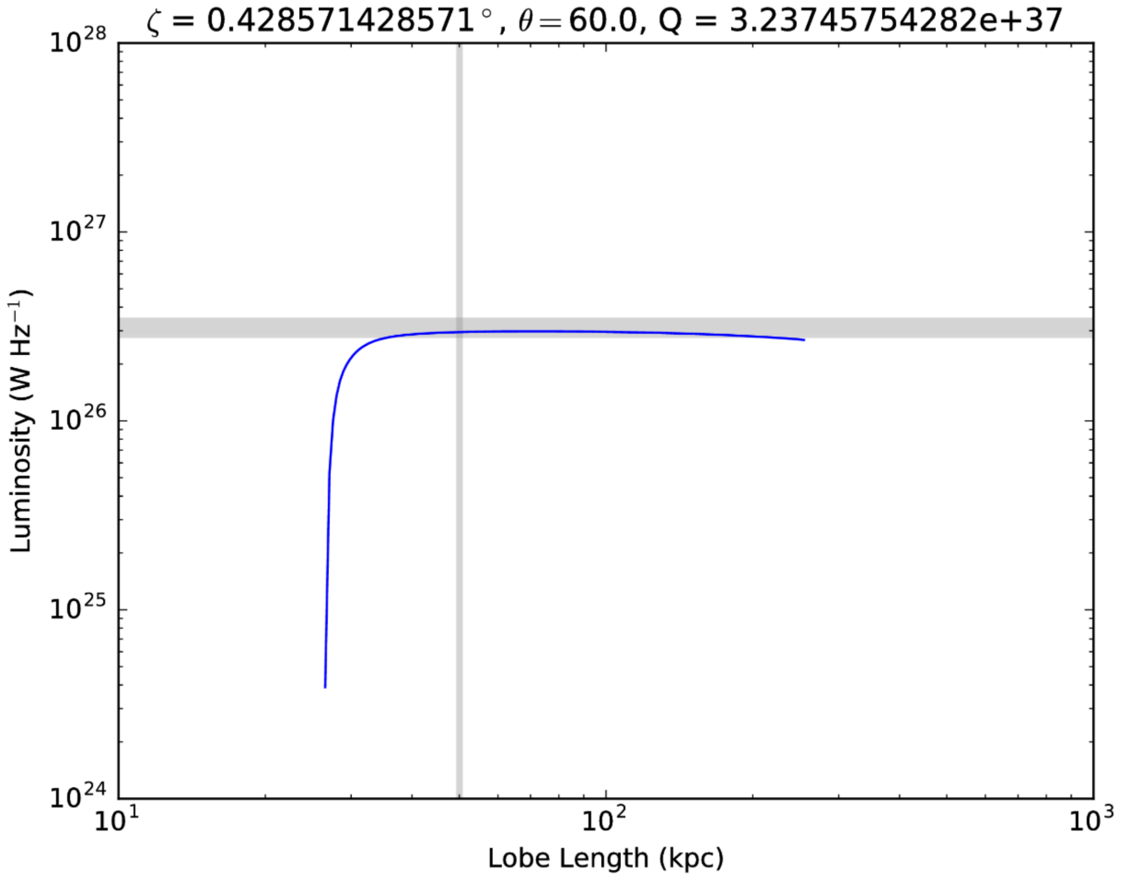
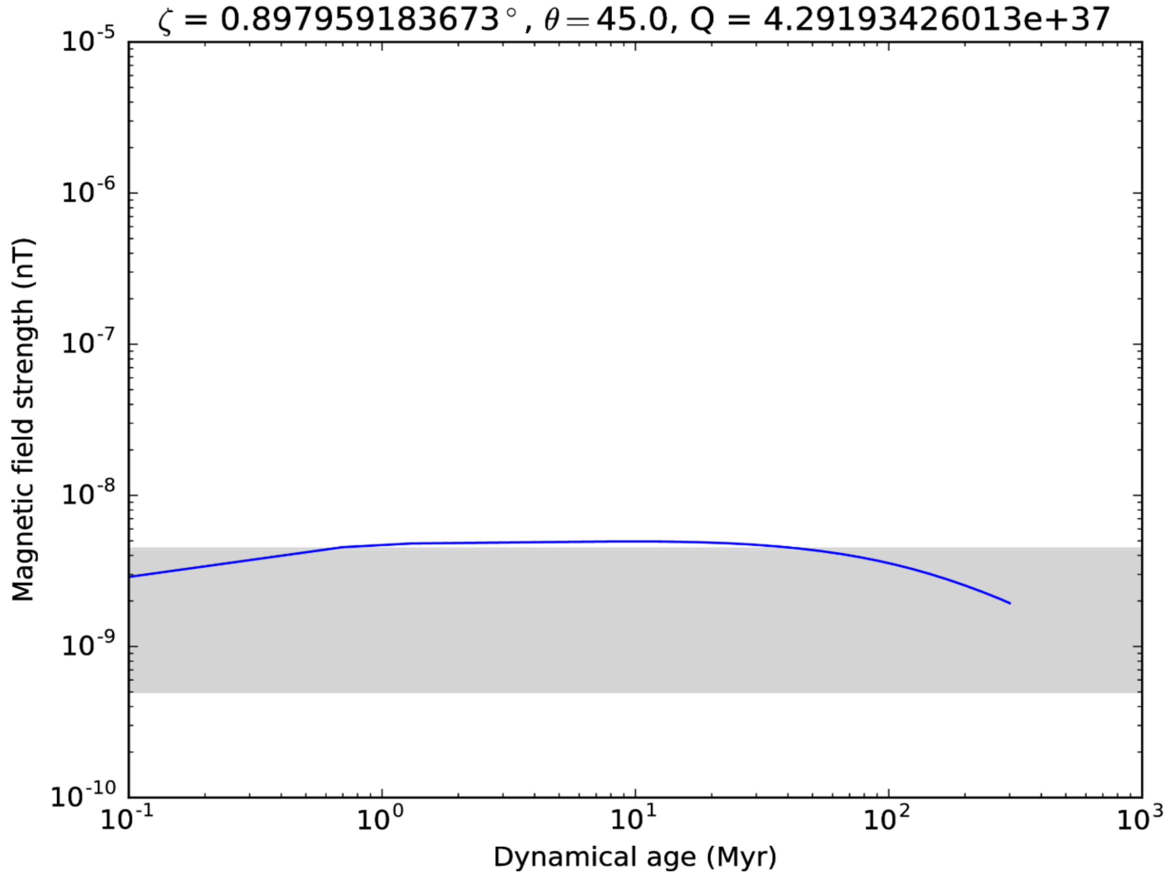
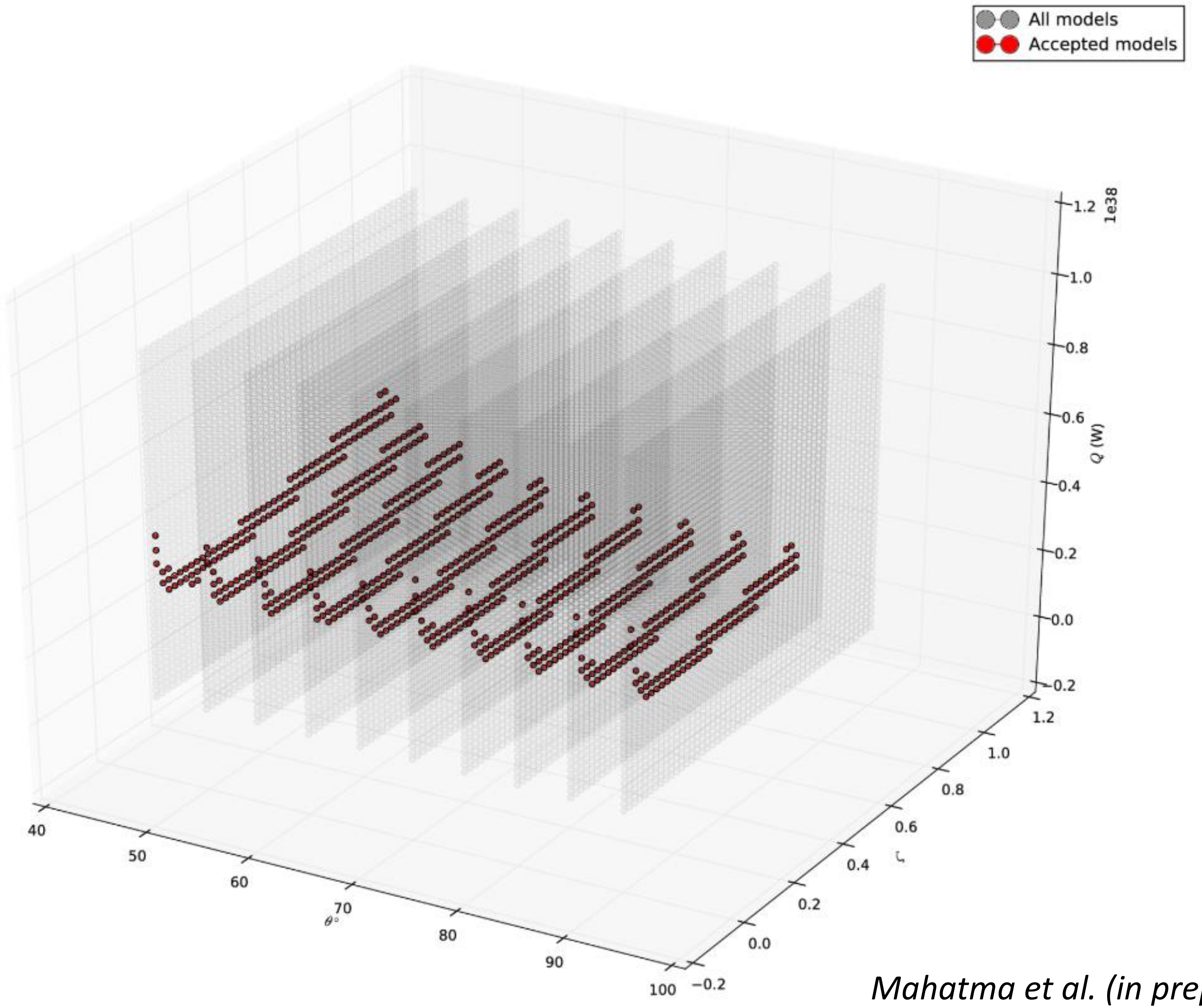
Mahatma et al. (in prep)

Single model run: 3C320





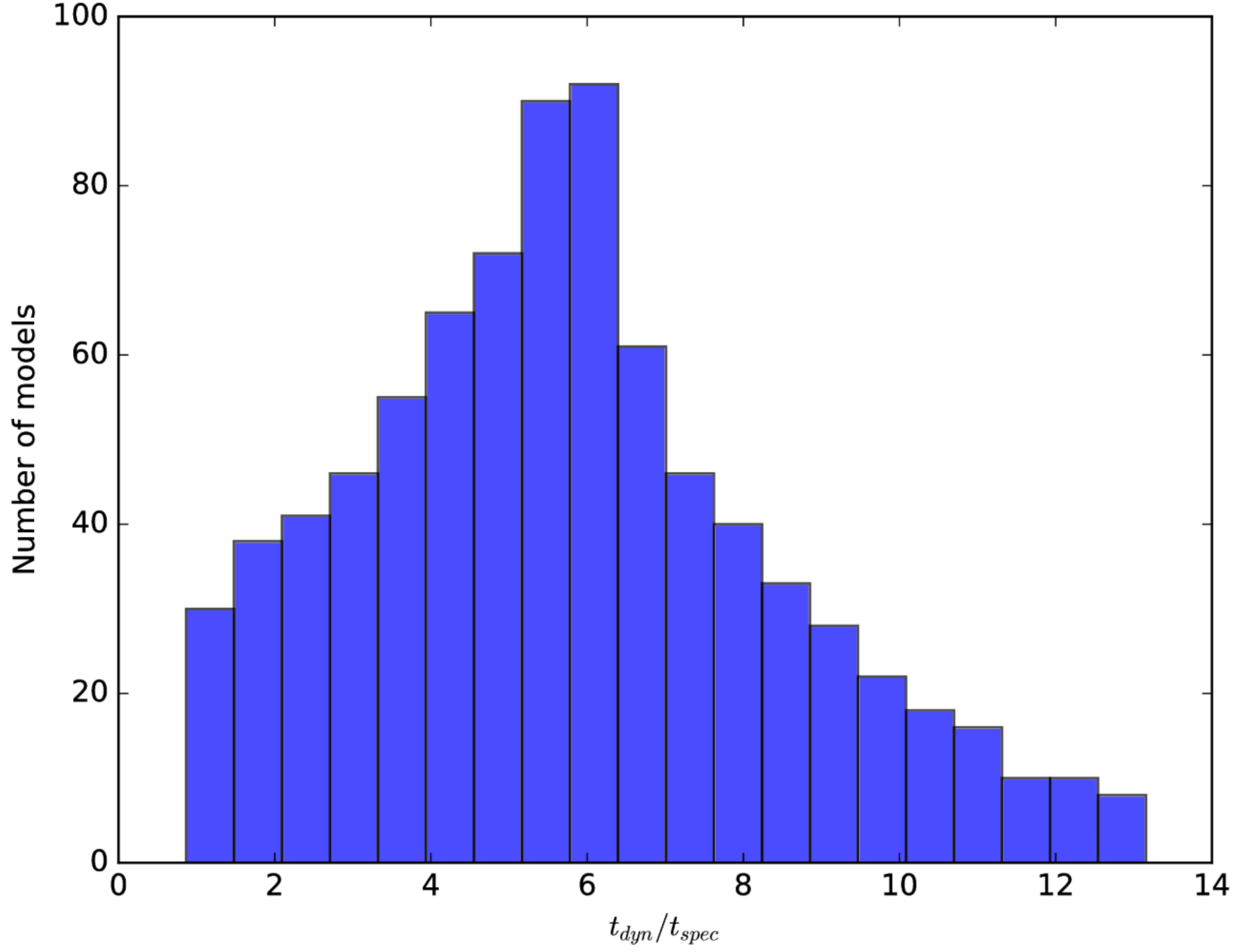
All model runs: 3C320



Mahatma et al. (in prep)

Mahatma et al. (in prep)

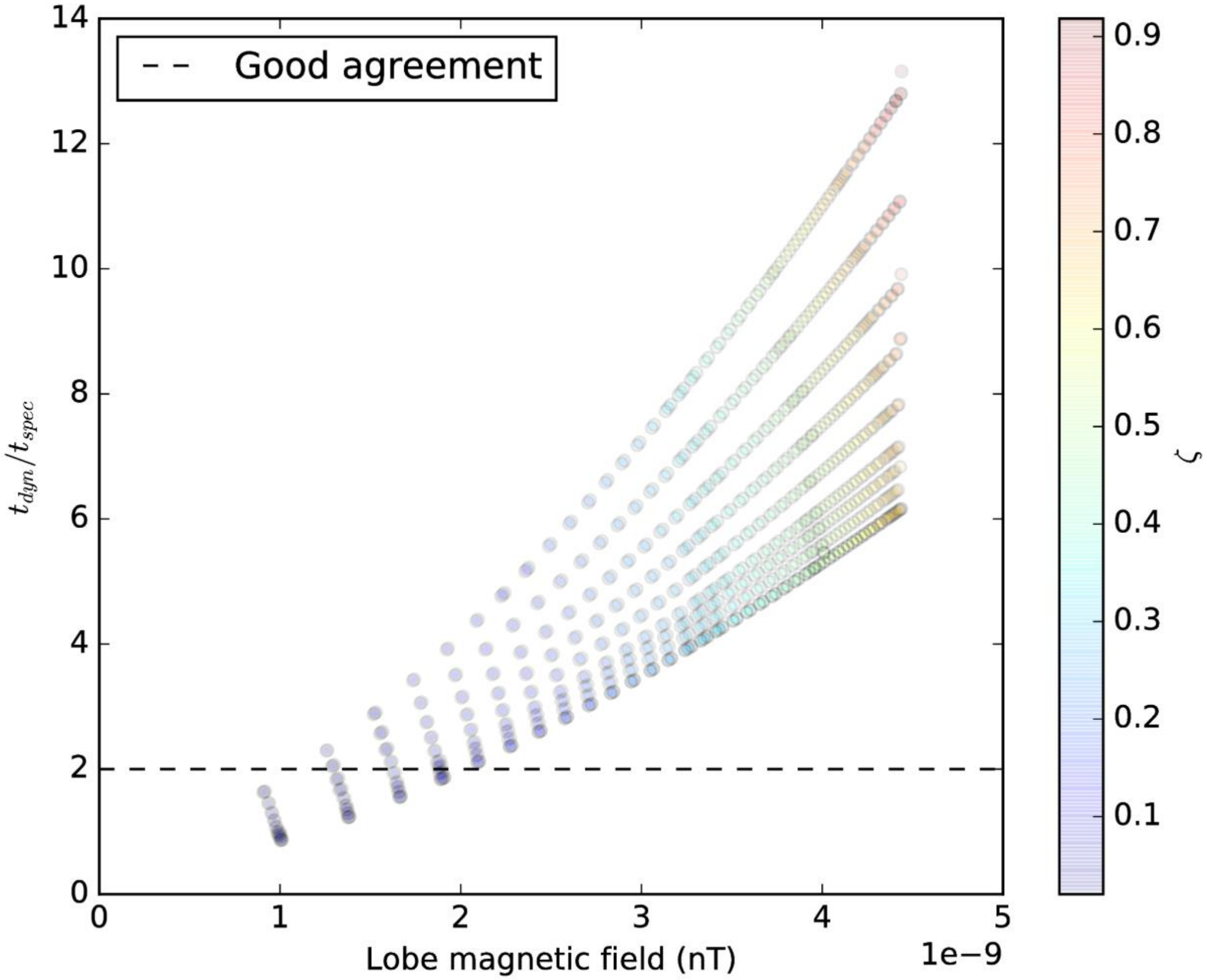
New robust spectral and dynamical ages (3C320)



Mahatma et al. (in prep)

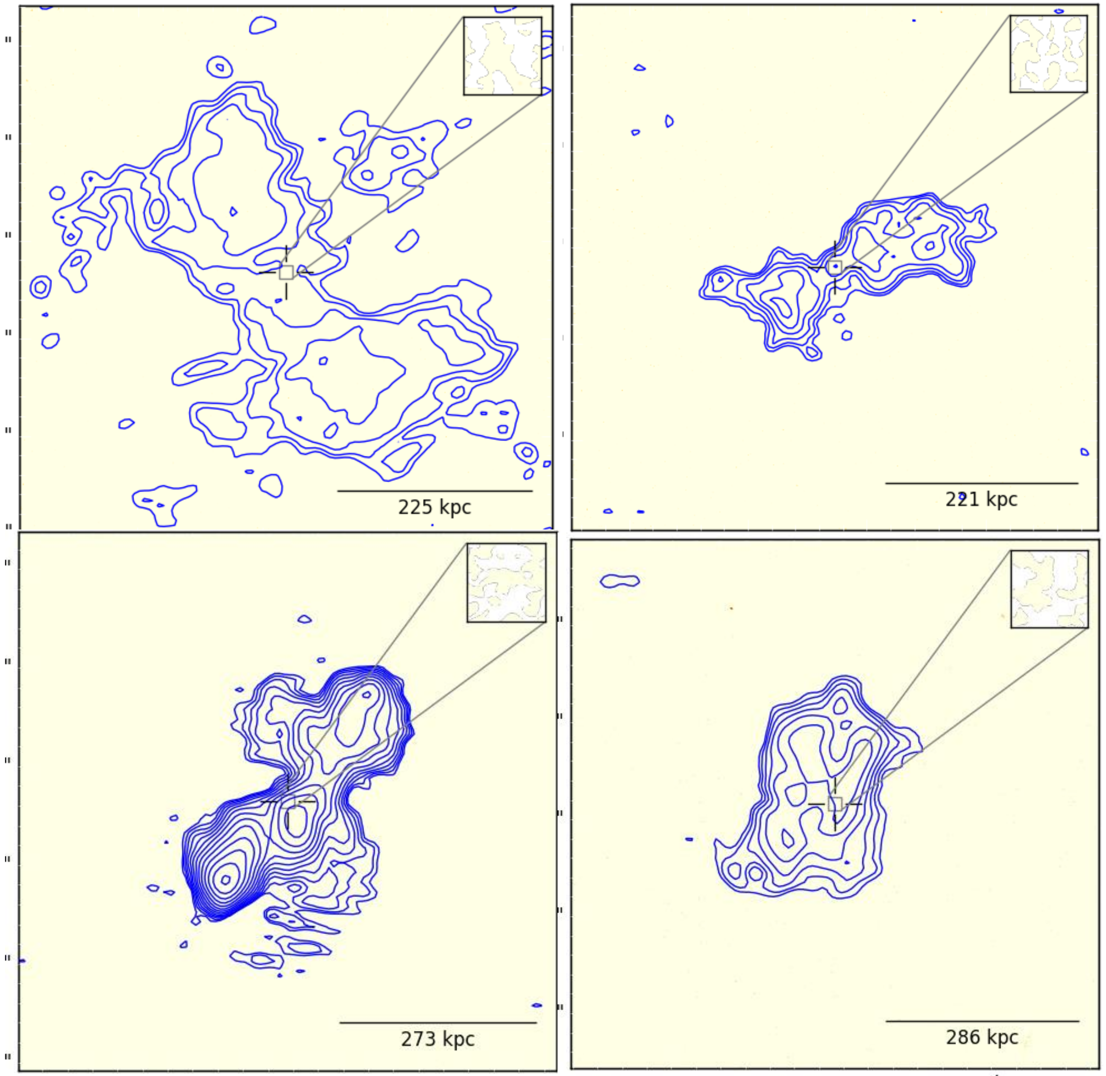
All model runs: 3C320

- Obtained agreement between dynamical and spectral ages
- Agreement favours low magnetic field/low zeta
- For this source, equipartition systematically underpredicts spectral age
- Inefficient distribution of jet energy to particles and field
- Factor of 2 discrepancy explained by mixing (Turner et al. 2017)



Mahatma et al. (2018;MNRAS)

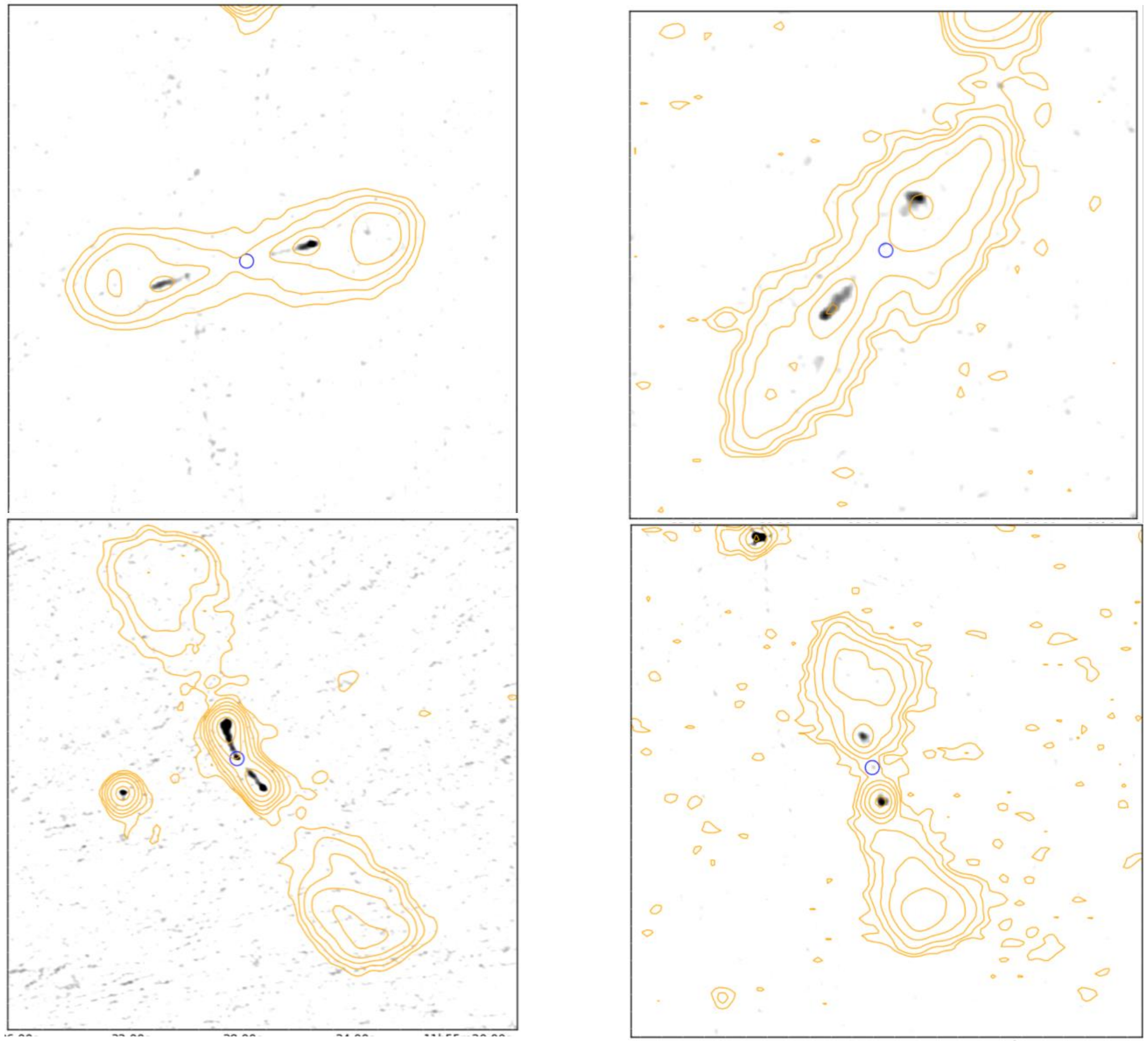
LOFAR results – Remnant radio galaxies



- Systematic sample of candidate remnant radio galaxies
- Upper limit remnant fraction of 10% (agrees with Godfrey 2017, Brienza et al 2017)
- Rapid cooling time once jet switches off

Mahatma et al. (2019, A&A Special Edition)

LoTSS DR1: Double-double radio galaxies



- Visually identified sample of 33 DDRGs – systematic samples coming (Jurlin et al, in prep.)
- Optical photometry shows that DDRGs have the same host galaxies as normal RLAGN
- Restarted activity for FR-IIs likely driven by small scale (accretion) events.
- Chaotic cold accretion?

Summary

- Spectral ages can be reconciled with dynamical ages using correct B-field and electron mixing factor
- Need larger sample to test robustness – streamline spectral ageing pipeline for large samples
- Rare classes of radio galaxies are now being found and sampled with LOFAR
- Remnants have a rapid fading timescale
- Restarting FR-IIs are a normal part in the life-cycle of RLAGN