The Dynamics & Energetics of Radio-loud AGN

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Credit: NRAO

Radio-loud AGN

- Large scale radio jets
- Kinetic power large fraction of bolometric luminosity (>10^8 L_{Sun})
- Strongly polarised synchrotron radiation
- Elliptical hosts
- FRI---core-brightened
- FRII---edge-brightened

Key Questions

- Environmental Impact
  - Feedback/regulating galaxy growth
  - Shock heating in the intracluster medium
- Fundamental dichotomy
  - Physical parameters governing jet power
  - Why do some RG's form FRIs and some FRIIs?
  - Is there an evolutionary track (FRI → FRII)?
  - High/Low Excitation Radio Galaxies
- Dynamical Evolution
  - Spherical vs elongated lobes
  - Spectral age/dynamical age discrepancy
- Cosmological Impact
  - Why are more powerful sources found at higher redshift?
- **Jet power (E_{TOTAL}/T_{AGE})**
  - **Spectral age/Dynamical age discrepancy**

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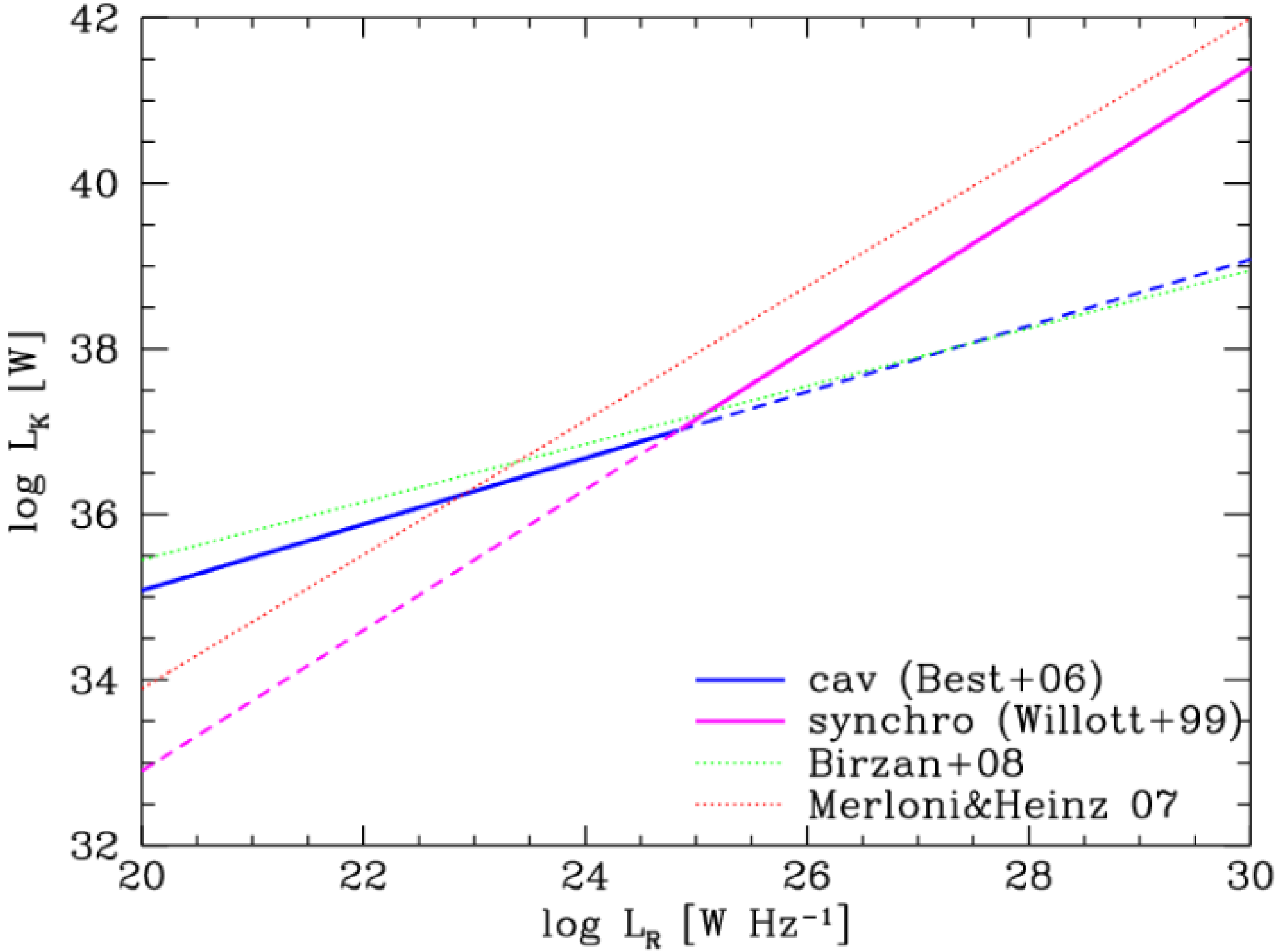
Kinetic Luminosity function



Credit: La Franca et al. (2010)

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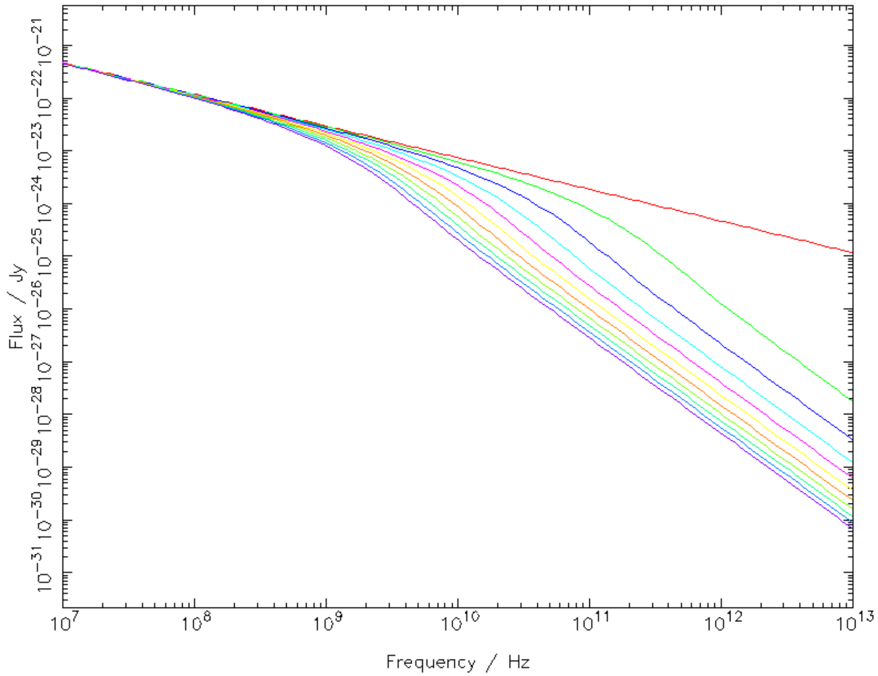
Spectral vs Dynamical age

- Synchrotron cooling in the lobes of radio galaxies has a steepening effect on the radio spectrum (Spectral ageing.
- Age of electron population in lobes is a function of `break' frequency and lobe magnetic field
- Dynamical ages given by a model of the lobe advance speed and an estimate of source size.
- Spectral ages always underestimated…
  - Lack of broad-bandwidth radio data?
  - Wrong magnetic field estimates?
  - Substantial mixing of electron population?
  - Dynamical ages are wrong...



Harwood et al. (2013)

Spectral Ageing

- Steepening of radio spectra at high-frequencies is a function of source age and B-field.
- JVLA 1.4 GHz and 6 GHz observations of two cluster-centre FRII radio galaxies.
- Fit synchrotron ageing models to observed spectra (BRATS – Harwood et al. 2013)
- Compare with dynamical age

$$J(\nu) \propto N_0 \nu^{-\frac{(p-1)}{2}} B^{\frac{p+1}{2}}$$

$$-\left(\frac{dE}{dt}\right) = 2\sigma_T c U_{mag} \gamma^2 \sin^2 \alpha$$

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

Longair (2010)

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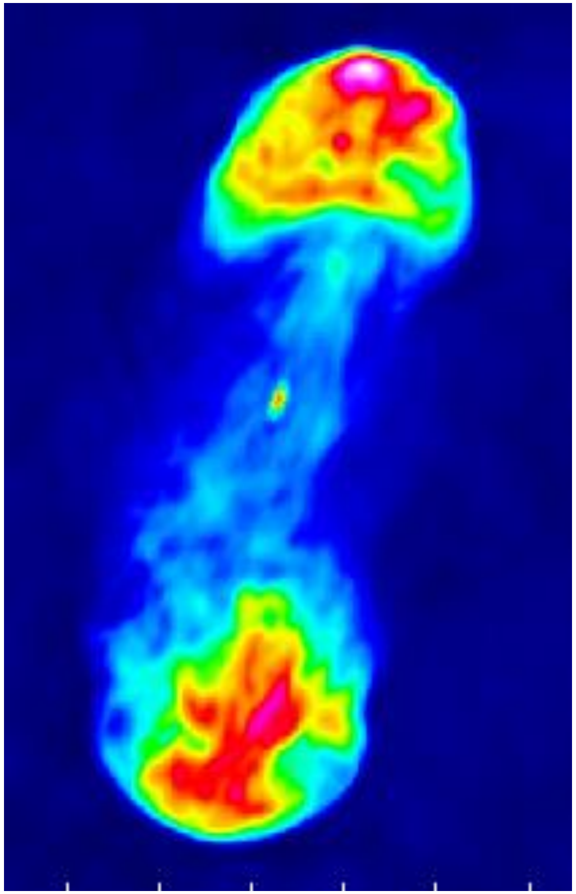
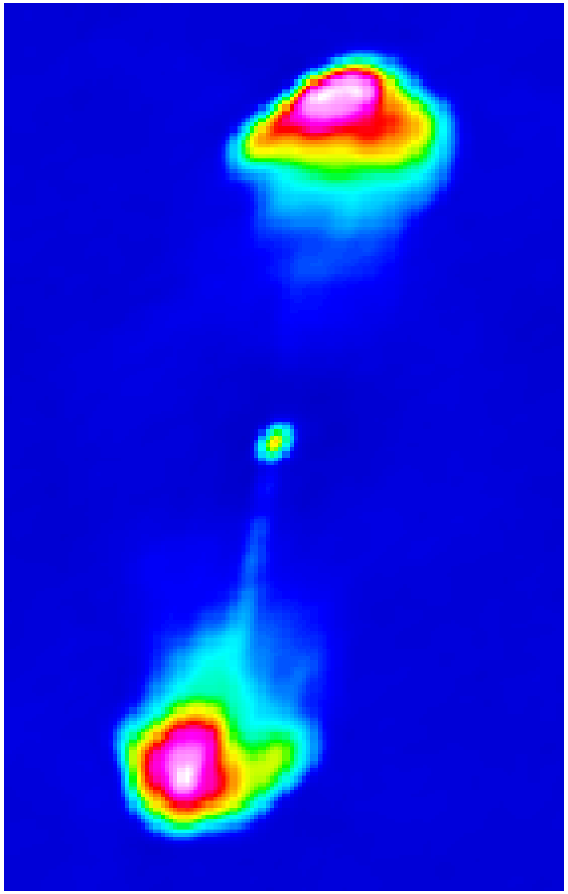
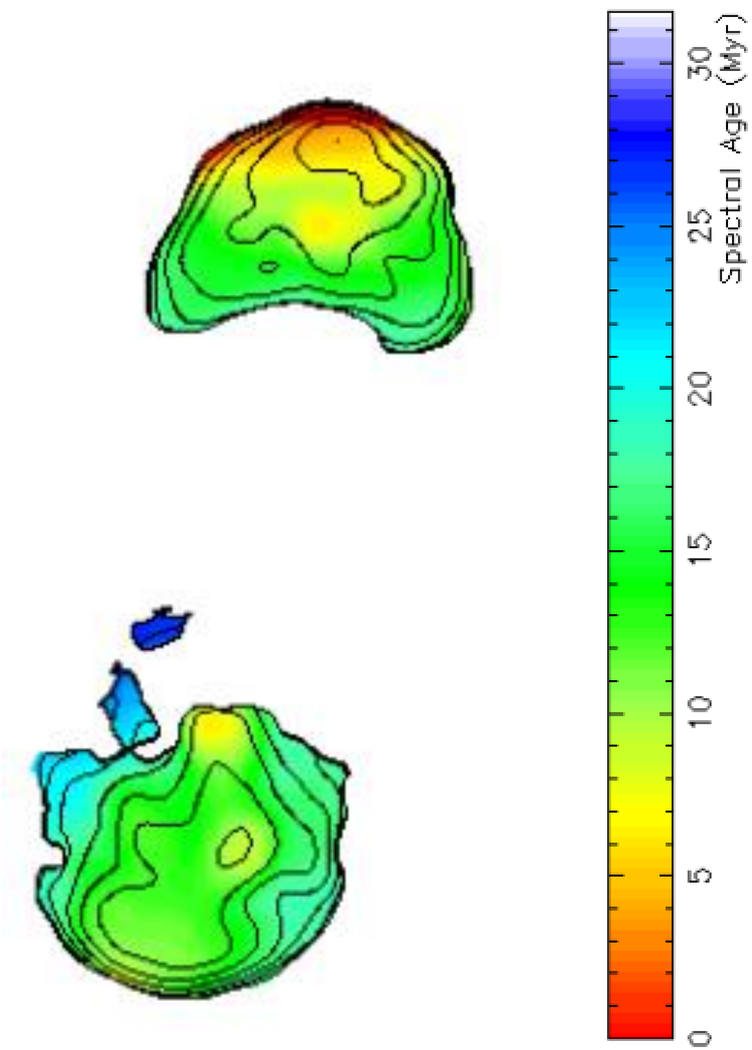
Source	z	Cluster kT (keV)	L_{178} $(W/Hz/sr)$	LAS (arcsec)	Size (kpc)
3C444	0.153	3.5	1×10^{26}	120	320
3C320	0.342	3.3	3×10^{26}	20	100

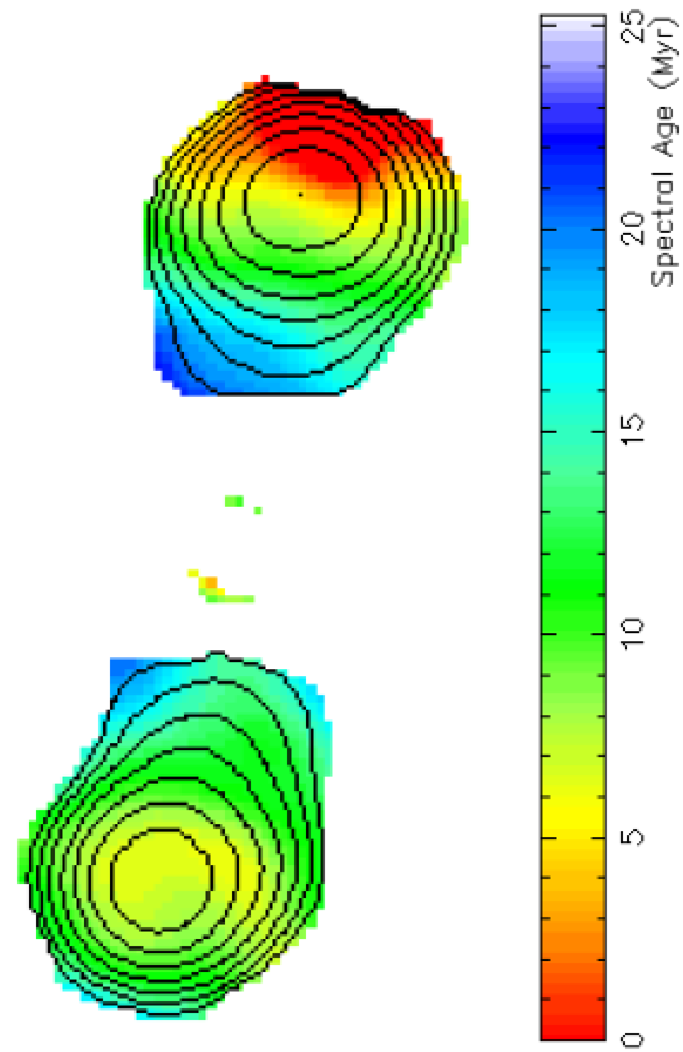




Mahatma et al. (in prep)



$30.10^{+0.10}_{-0.23}$ Myrs



$25.10^{+0.31}_{-0.23}$ Myrs

Mahatma et al. (in prep)

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Dynamical ages

- Ratio of source length and lobe advance speed
- Use ICM shock driven by radio galaxy as a proxy for radio jet advance
- Model ICM shock using Rankine-Hugoniot jump conditions

$$\frac{\rho_2}{\rho_1} = \frac{\Gamma+1}{\Gamma-1+2/\mathscr{M}^2}$$

$$v_{shock} = a_{sound}\mathscr{M}$$

$$\frac{p_2}{p_1} = \frac{2\Gamma\mathscr{M}^2+(1-\Gamma)}{\Gamma+1}$$

$$\frac{T_2}{T_1} = \frac{\left[2\Gamma\mathscr{M}^2+(1-\Gamma)\right]\left[\Gamma-1+2/\mathscr{M}^2\right]}{(\Gamma+1)^2}$$

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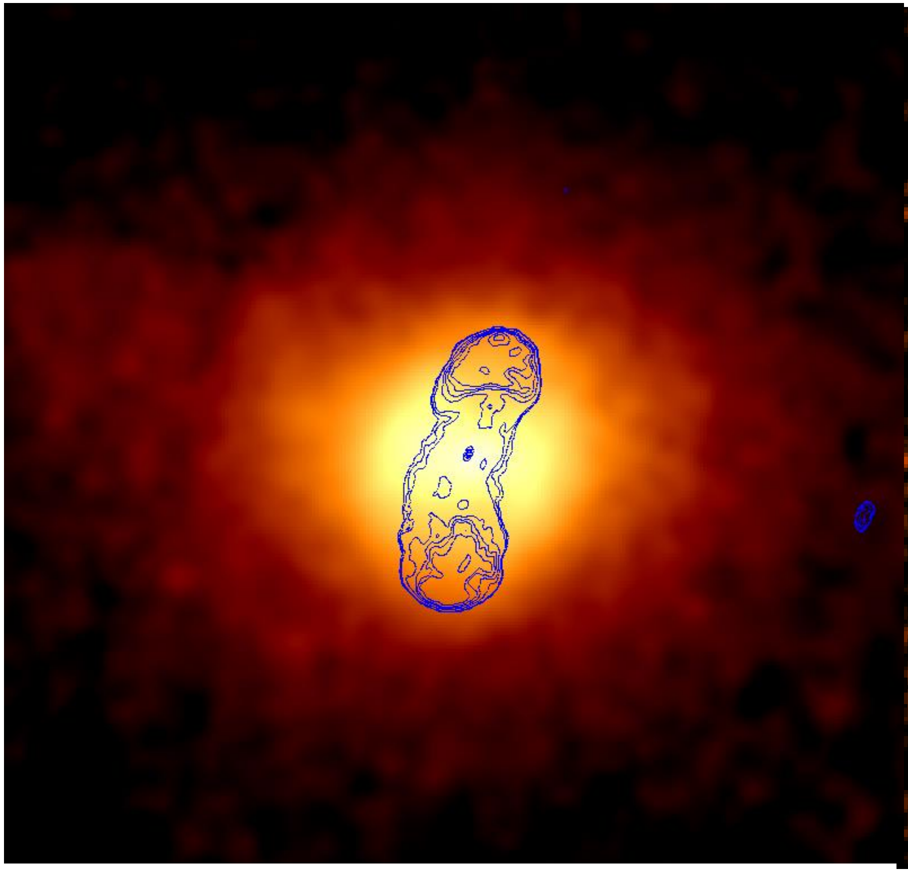
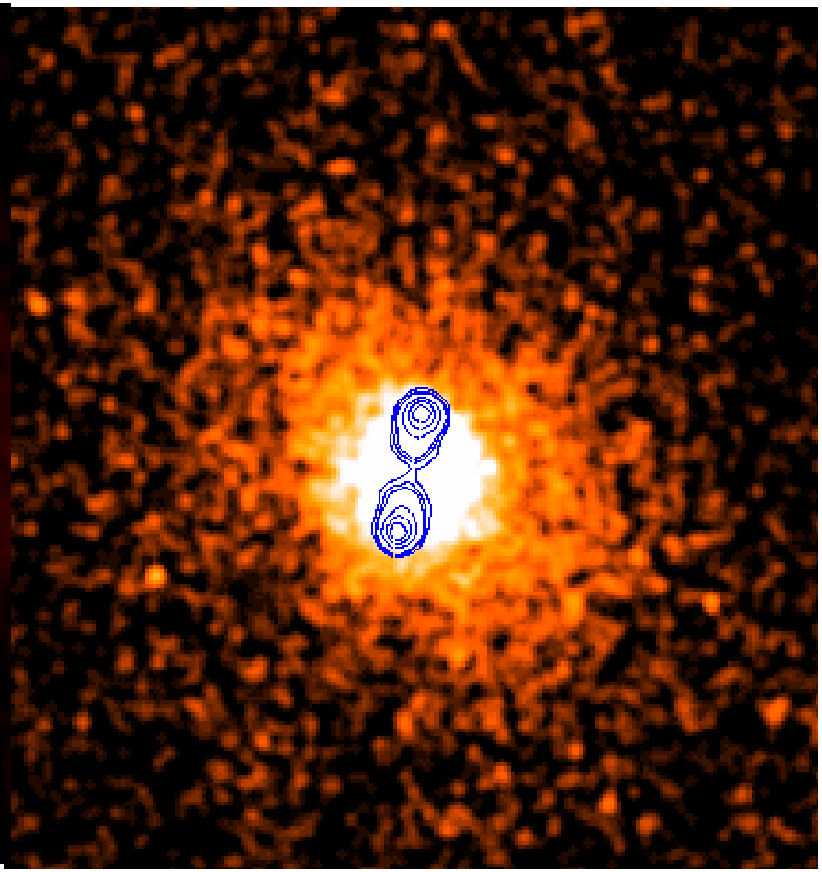
New XMM



T_{dyn}~90 Myrs

Croston et al. (2011)

Chandra



T_{dyn}~25 Myrs

Mahatma et al. (in prep)

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Results and Conclusions

- Agreement between spectral and dynamical ages for 3C320, not for 3C444(!)
- Spectral age analysis requires broad-bandwidth observations and strong B-field constraints
- Temperature measurements may not be reliable to measure shock properties
- Density ratio more direct proxy for shock strength
- Radio lobes are not in equipartition between B-field and electron energies.
- Lobe plasma of cluster-centre FR-II radio galaxies do not require a significant population of protons for dynamical evolution

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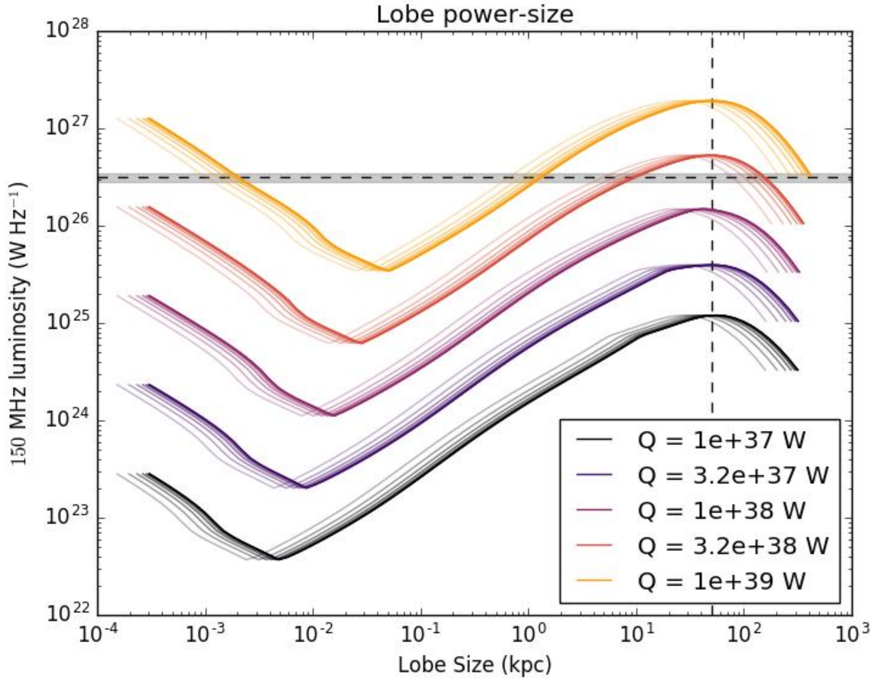
Analytic modelling

- Semi-analytic model of Hardcastle (2018)
- Describes the dynamics of the ‘shocked shell’ around radio galaxy based on environment and jet power
- Assumptions based on insights of numerical simulations (Hardcastle & Krause 2013; English et al. 2016)
- Describes radio lobe luminosity evolution and lobe dynamics



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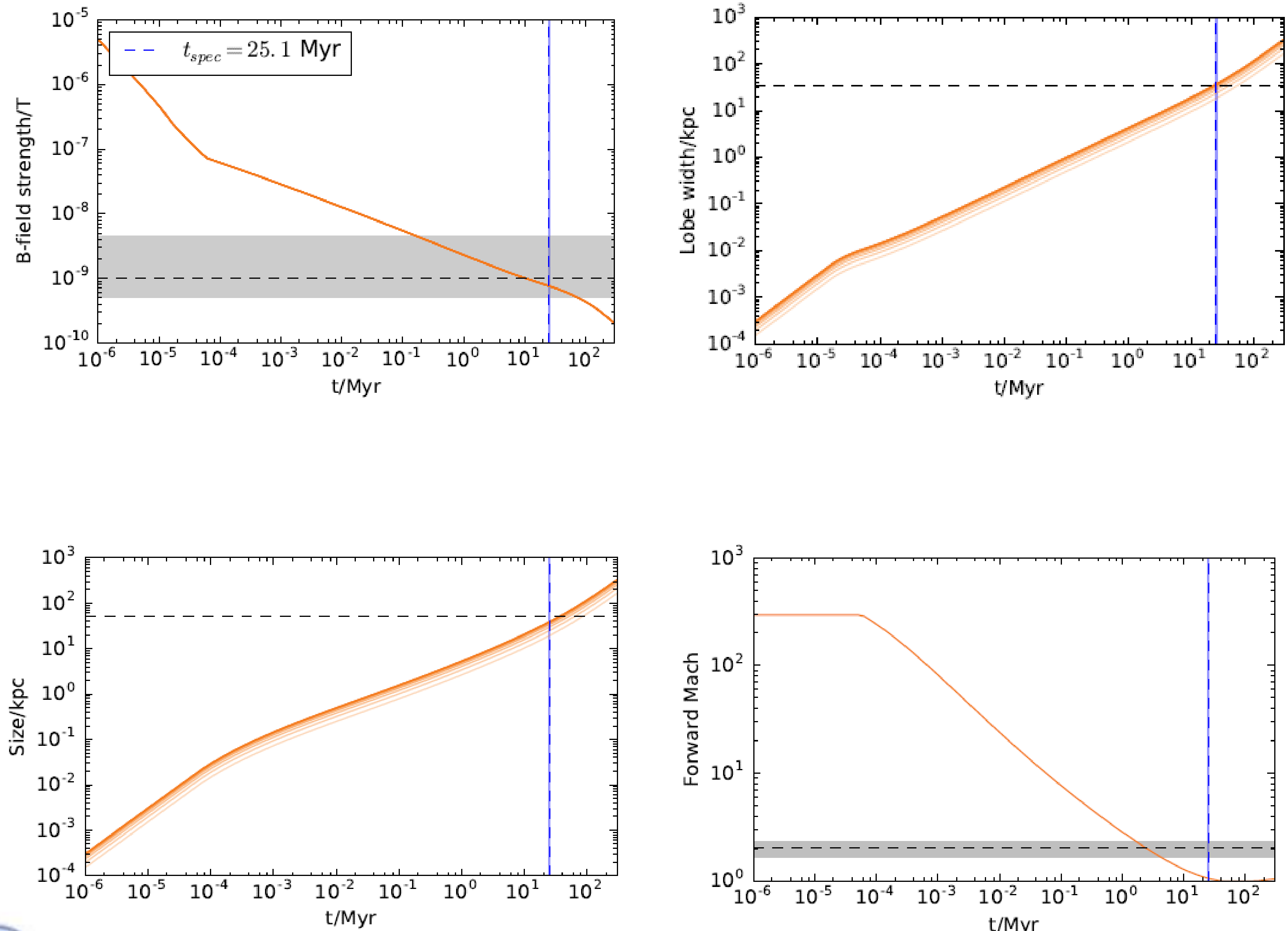
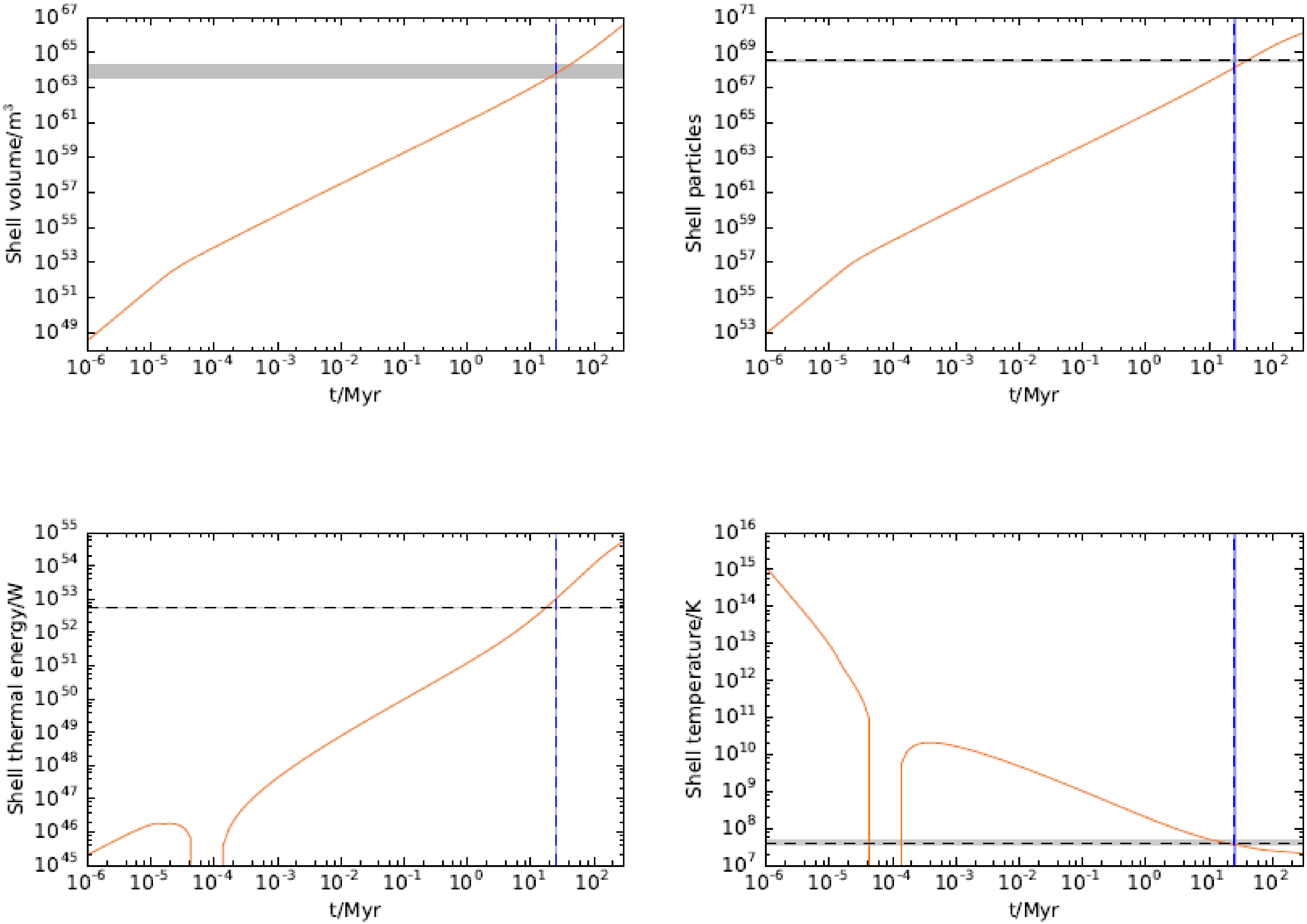

$t_{spec} = 25.1$ Myr
B-field strength/T
Lobe width/kpc
Size/kpc
Forward Mach
t/Myr
t/Myr
t/Myr
t/Myr


Shell volume/m³
t/Myr
Shell particles
t/Myr
Shell thermal energy/W
t/Myr
Shell temperature/K
t/Myr

Results and Conclusions

- Semi-analytic model can approximately reproduce source properties, given only jet power and environment
- Shocked shell Mach number varies rapidly with time – RH conditions do not apply to time-averaged quantities.
- Spectral ages can estimate source age IF we have the correct magnetic field.
- Need to determine effective B-field that has aged the oldest electron population
- Ratio of energy densities change with time?
- Apply model to larger samples of sources for quick determination of energetics

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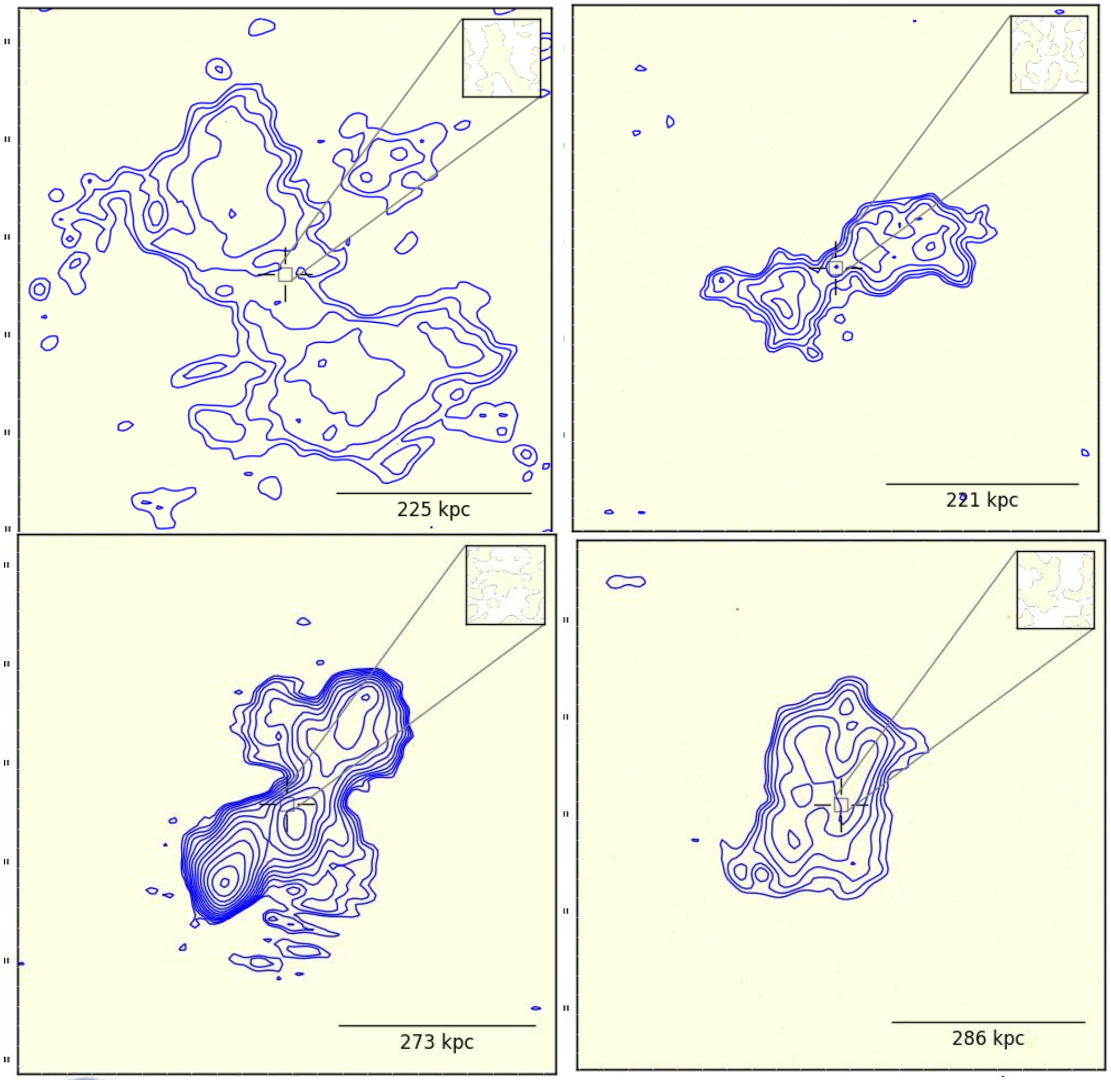
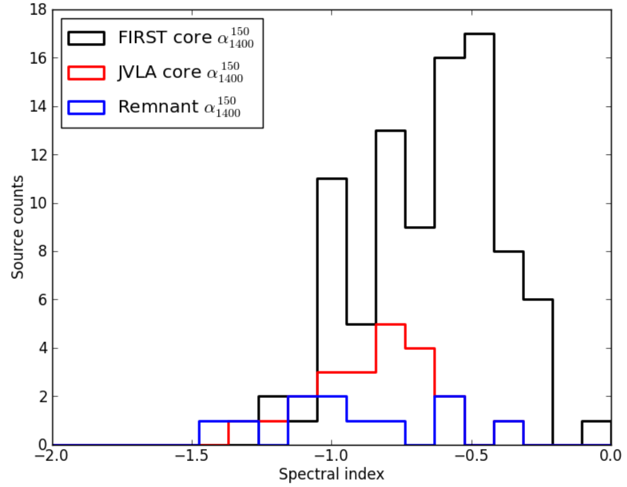
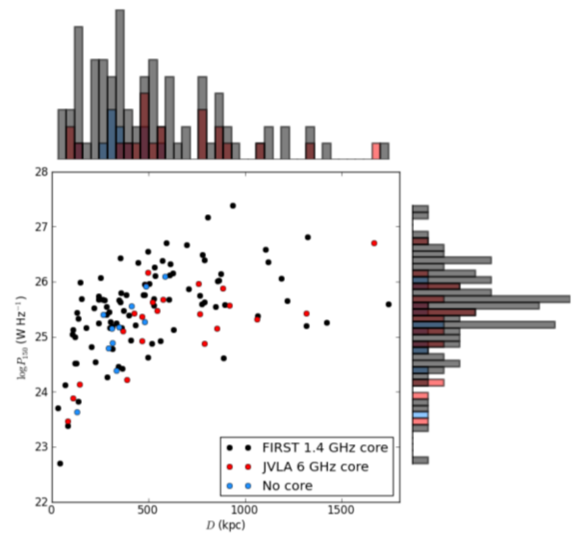
Remnant radio galaxies (LOFAR H-ATLAS)

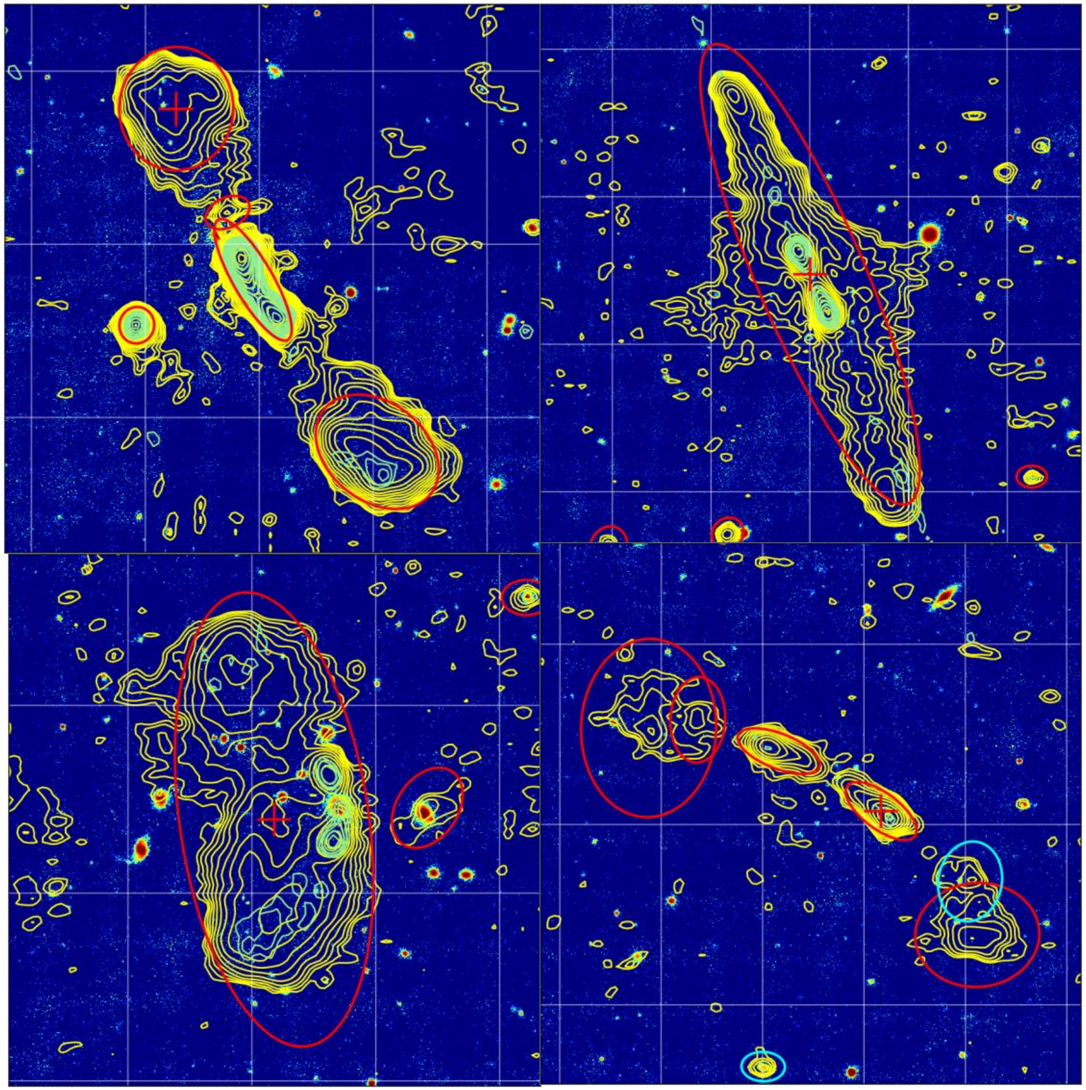


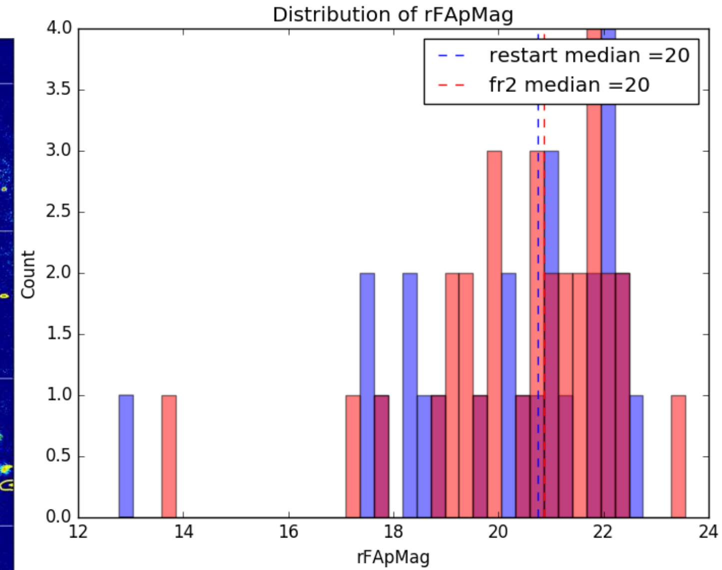


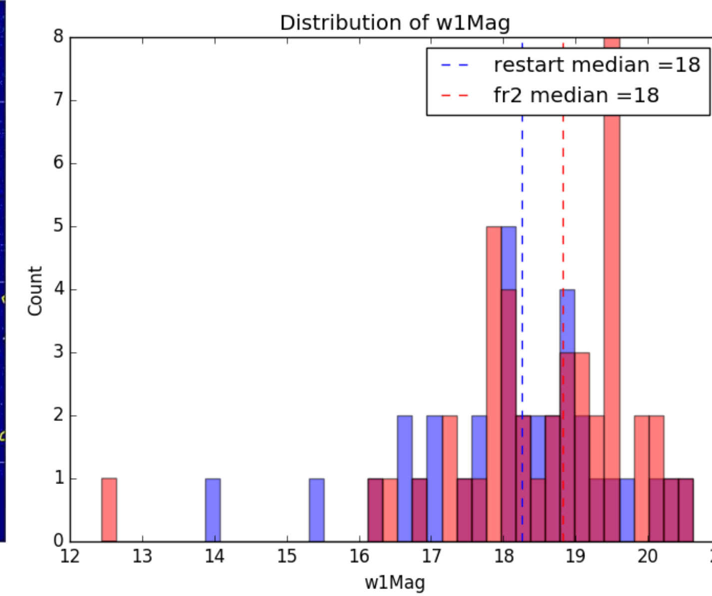


Mahatma et al. (2018)

Restarting radio galaxies (LoTSS HETDEX)







Mahatma et al. (in prep)

Results and Conclusions

- Now have a robust, systematic sample of candidate remnant radio-loud AGN (around 11 sources)
- Remnant fraction of 10% implies very rapid fading of synchrotron plasma
- Spectral index of switched off sources varies substantially
- Samples of restarting radio galaxies are now starting to be made with LOFAR (LOFAR Two-Metre Sky Survey – Shimwell (2017, and in prep)
- Global star-formation may not change significantly between AGN episodes – possibly require large multiples of outbursts

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