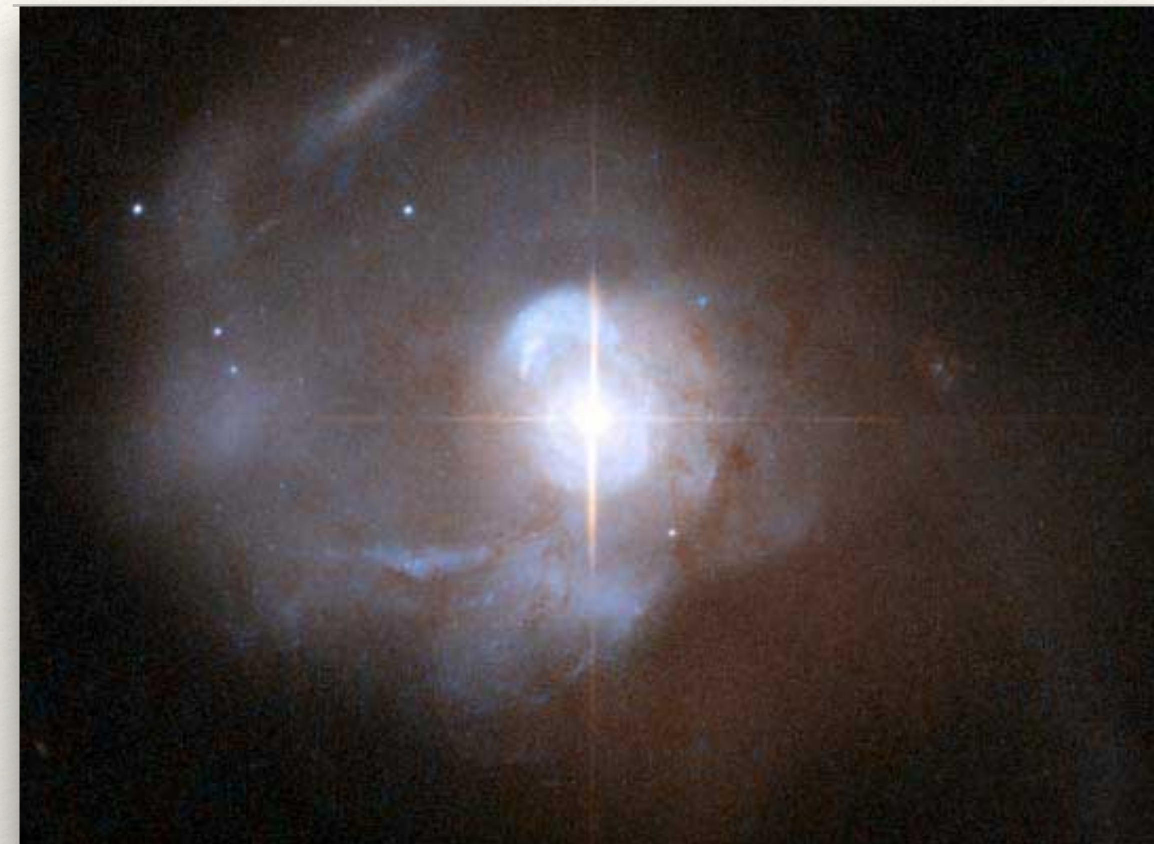
A Close Look at Samples of Radio Quiet AGN with the VLBA, VLA and GMRT

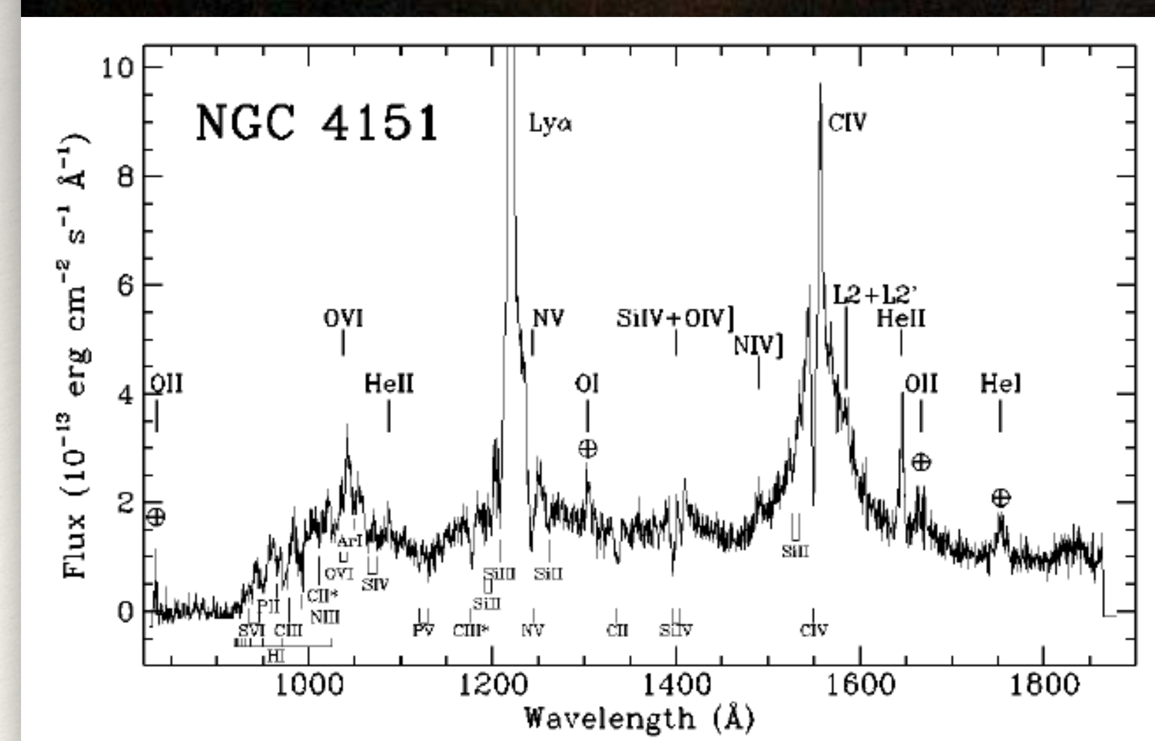
Preeti Kharb

National Centre for Radio Astrophysics (NCRA) - Tata Institute of Fundamental Research (TIFR), India

NCRA • TIFR

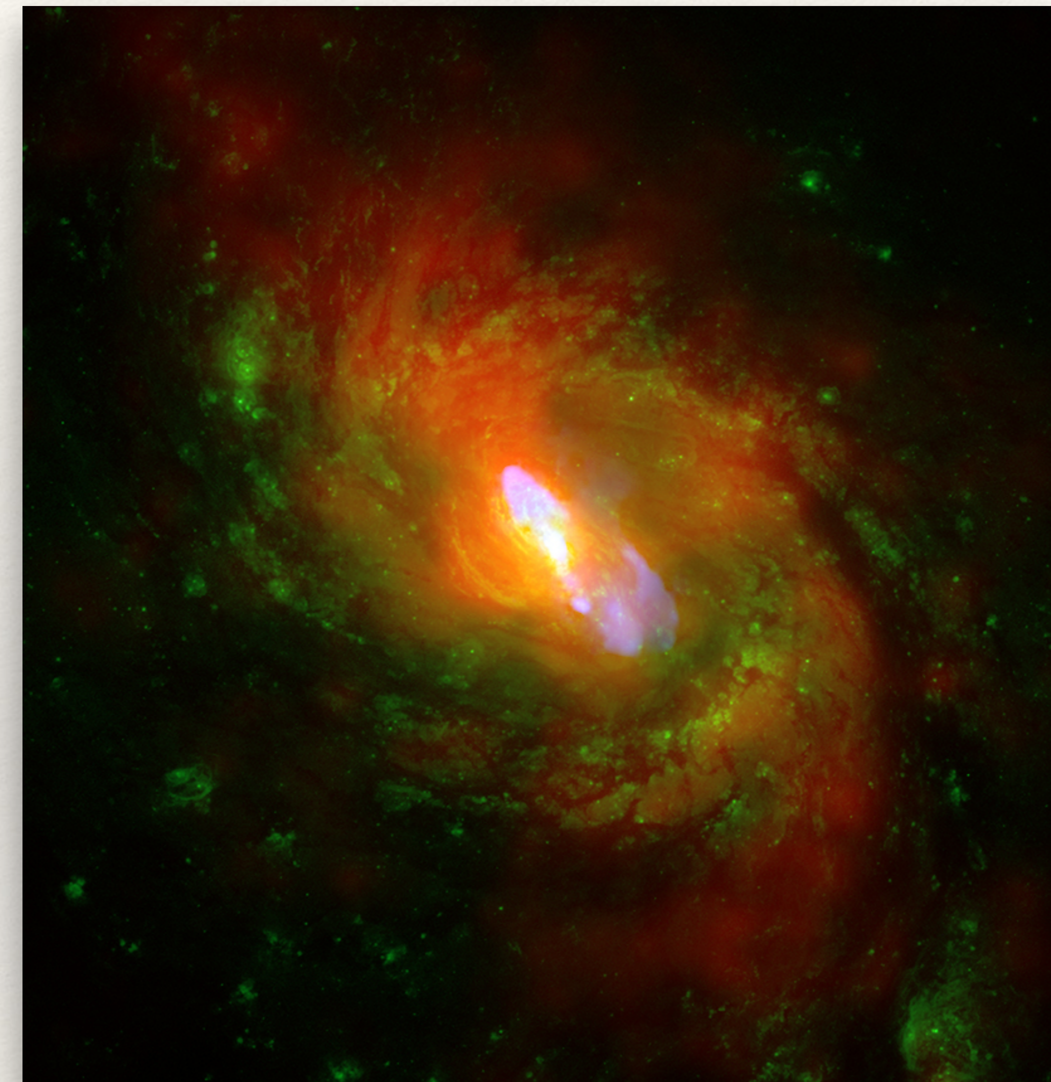
Active Galactic Nuclei (AGN)

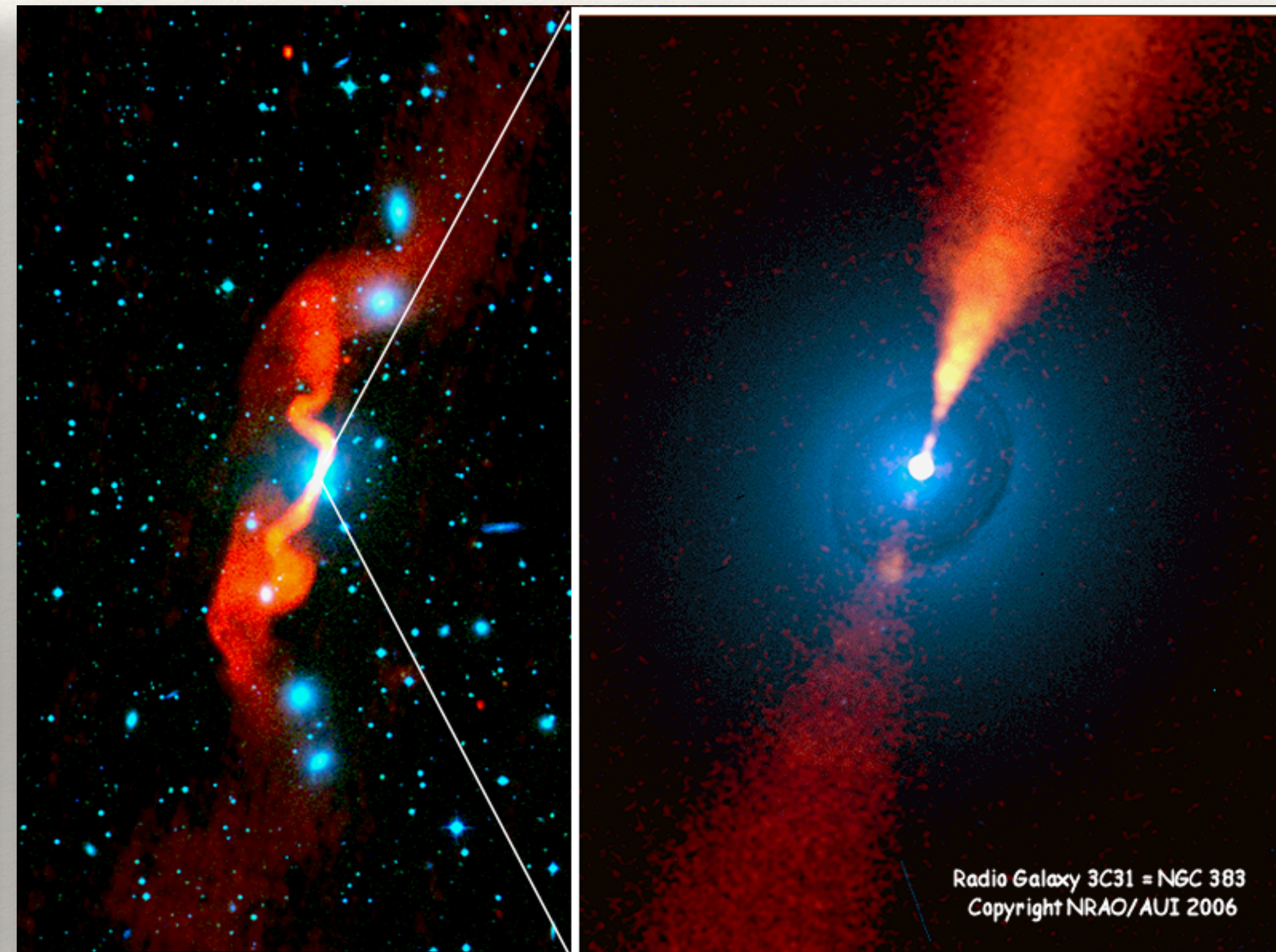




- *Carl Seyfert (1943)*
- Spiral or lenticular galaxies
- Bright star-like nucleus
- Peculiar spectrum with prominent emission lines.
- Type 1 & Type 2
- Orientation + Obscuration by Torus (*Antonucci 1993*)

Radio-Loud/Radio-Quiet Divide





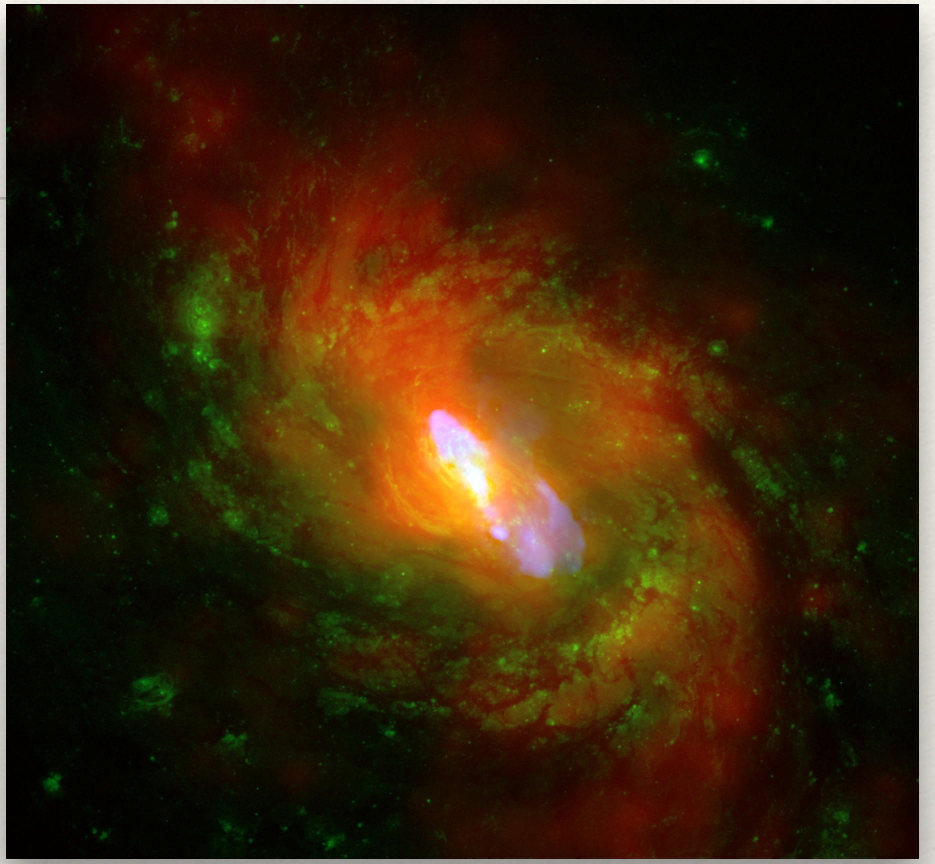
Seyfert galaxy NGC 1068

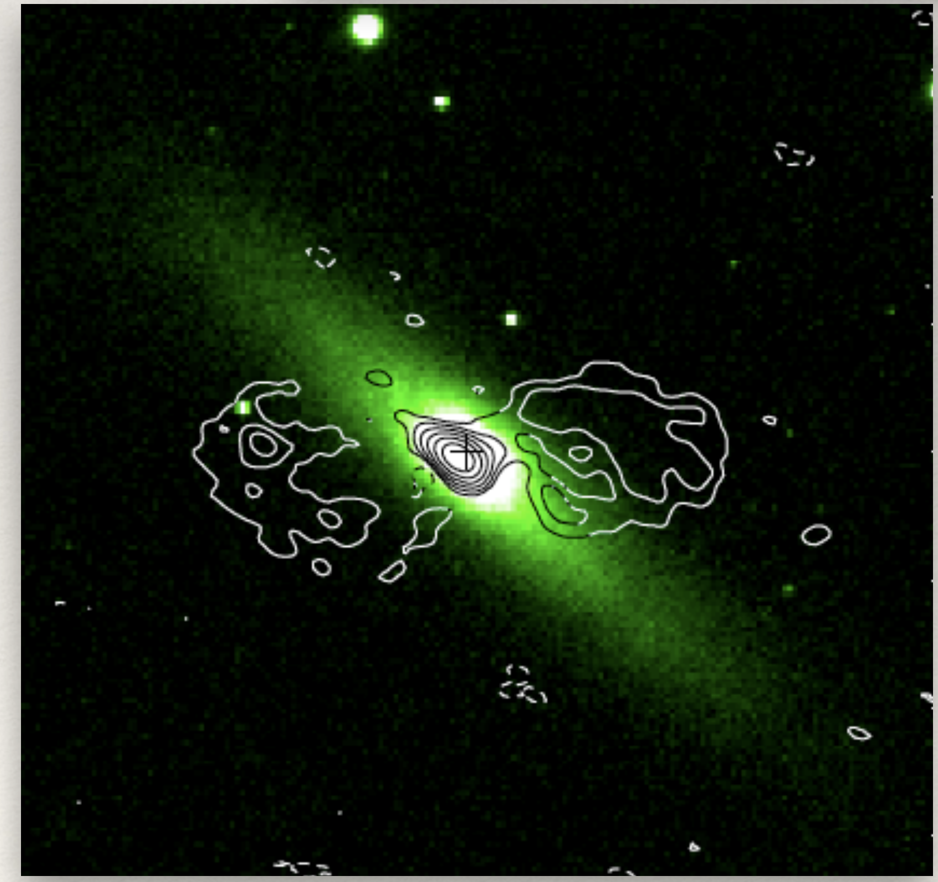
Radio galaxy 3C 31

Kellermann+ 1989

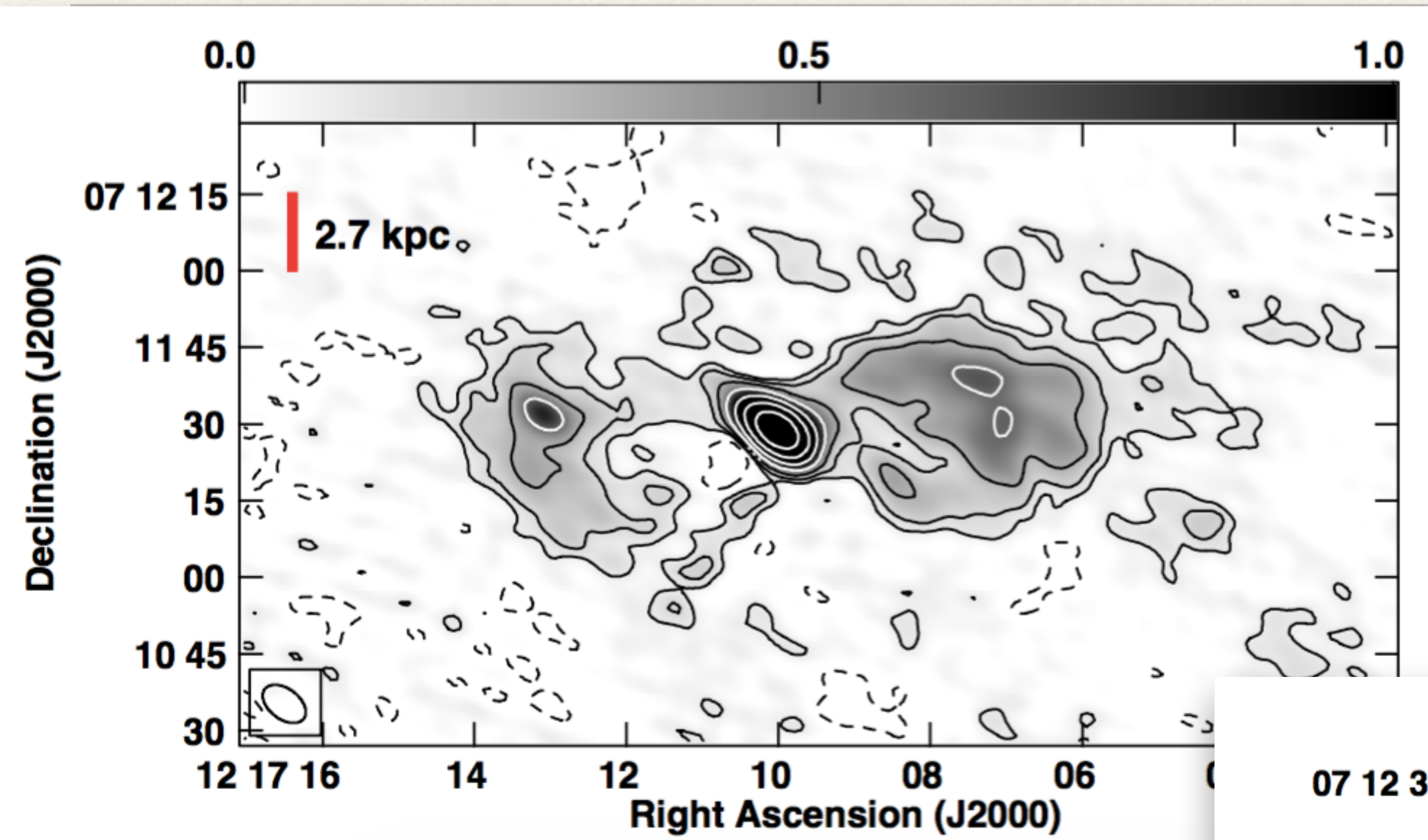
Radio Emission in RQAGN

- 10-100 pc – 10 kpc radio outflows
- Origin of kpc-scale radio structures (KSRs) debated
- *Baum+ 1993*, KSRs with WSRT, starburst superwinds
- *Colbert+ 1996*, KSRs in Seyferts different from KSRs in starbursts
- *Gallimore+ 2006*, AGN+starbursts contribute





RQAGN on Kpc-scales with the GMRT

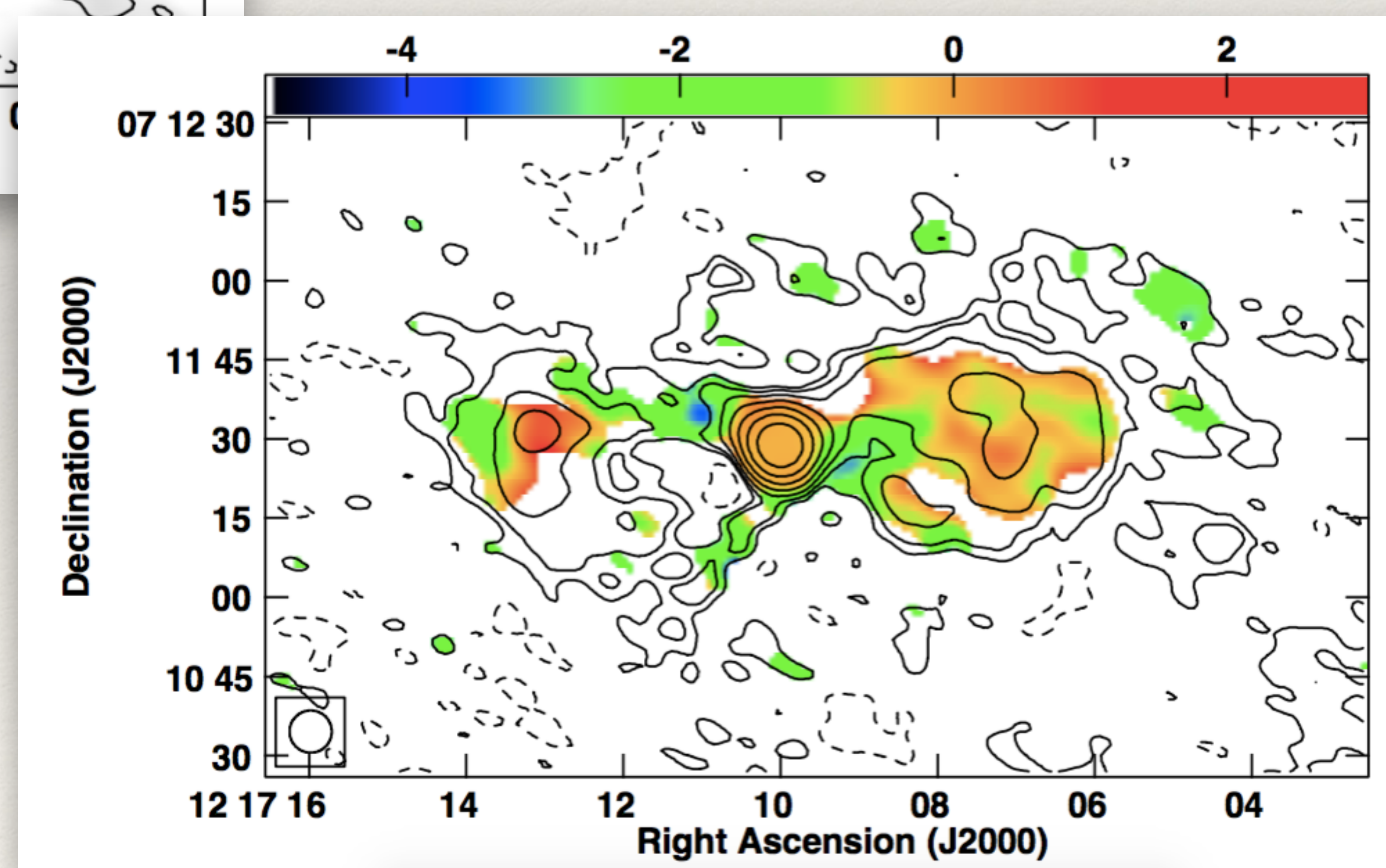


NGC4235: 610 MHz with GMRT

325 – 610 MHz spectral index

Lobe $\boldsymbol{\alpha} = -0.6 \pm 0.2$

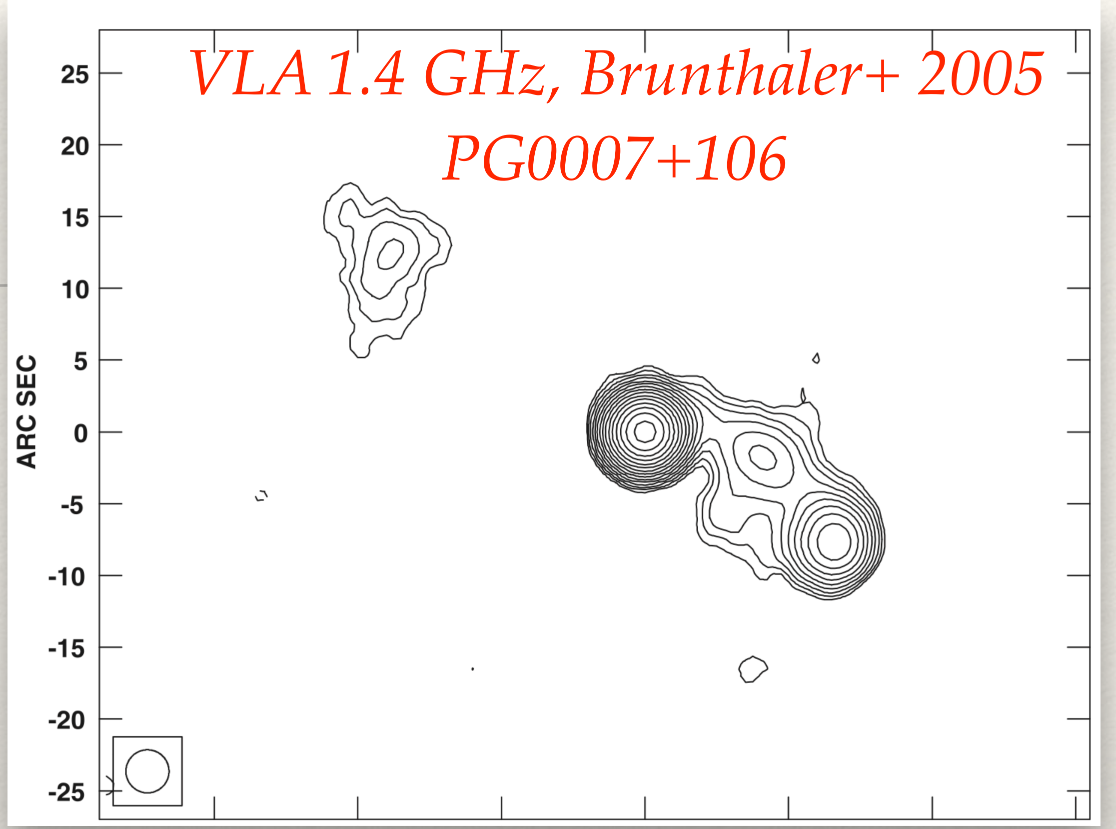
Relic Lobe $\boldsymbol{\alpha} = -1.8 \pm 0.2$

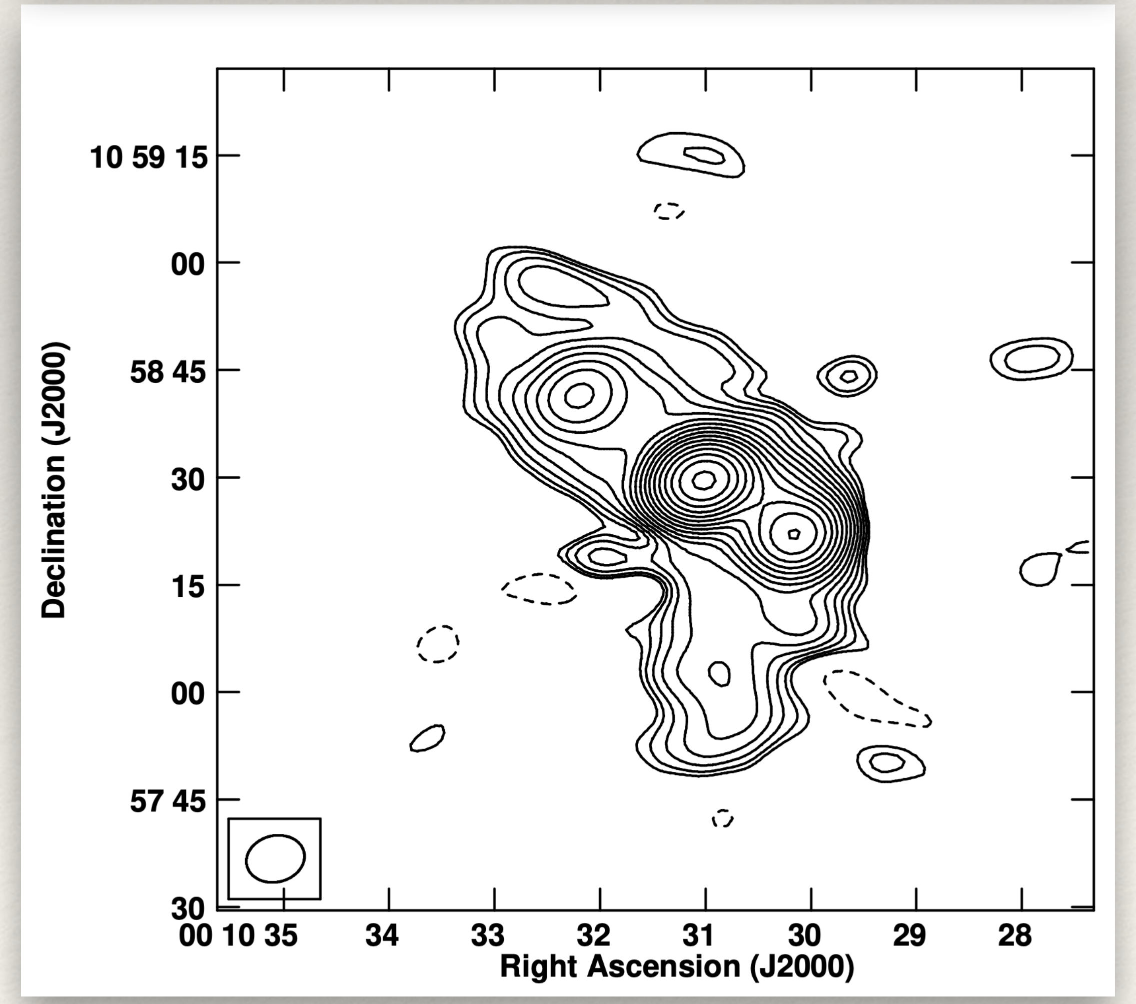


Kharb, Srivastava, Singh+ 2016

RQAGN on Kpc-scales

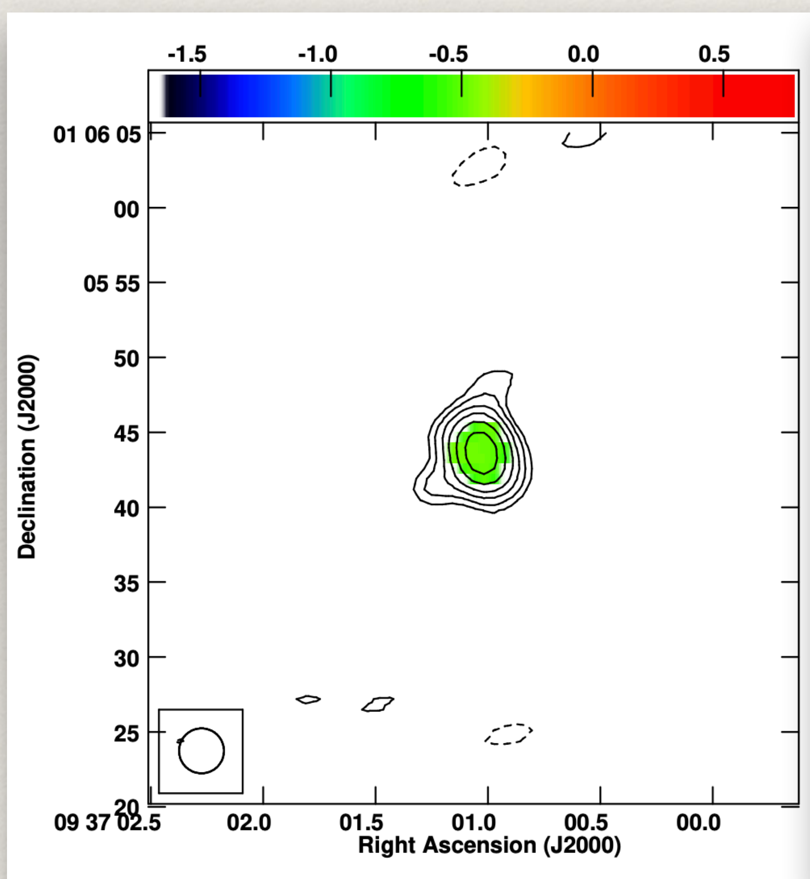
- A 685 MHz GMRT study of 22 (of 87) Palomar Green (*Green+ 1986*) QSOs: *Silpa, Kharb, Ho+ 2020*
- (Remaining sources observed now)
- ~3″ – 5″ resolution
- PG0007+106 = IIIZw2
- GMRT-VLA spectral indices: Relic emission (**α** steeper than −1.5) in IIIZw2 and other sources
- Inverted / flat to steep core spectra

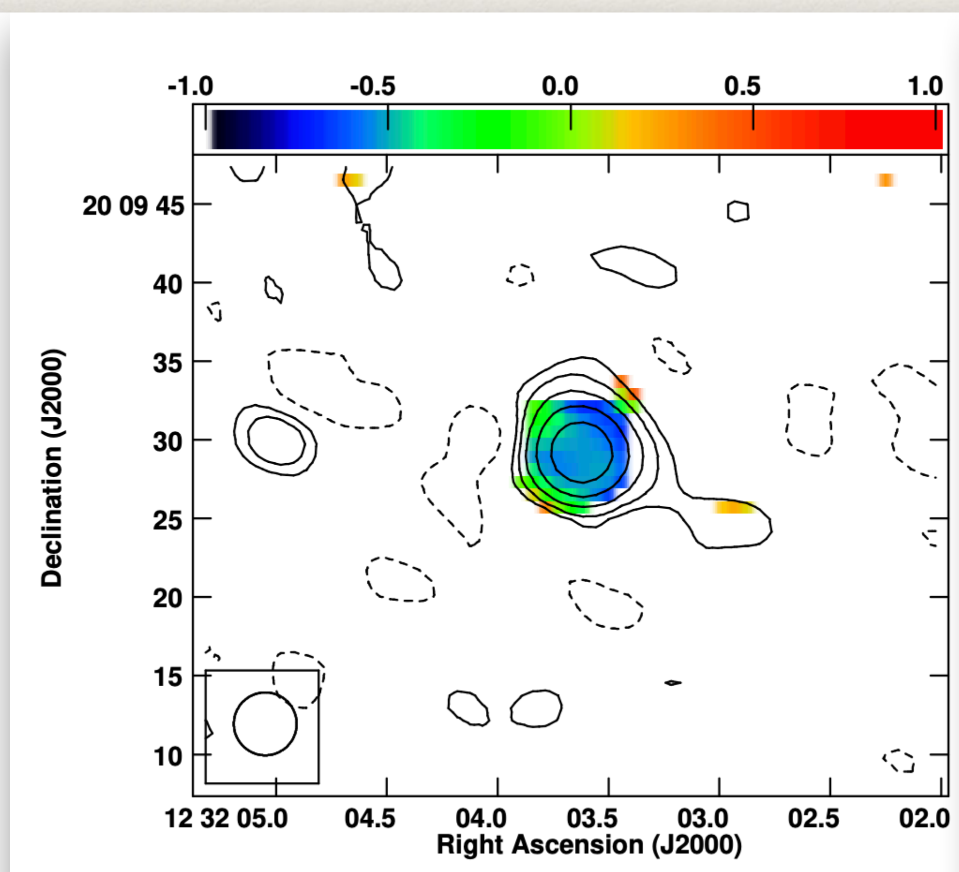


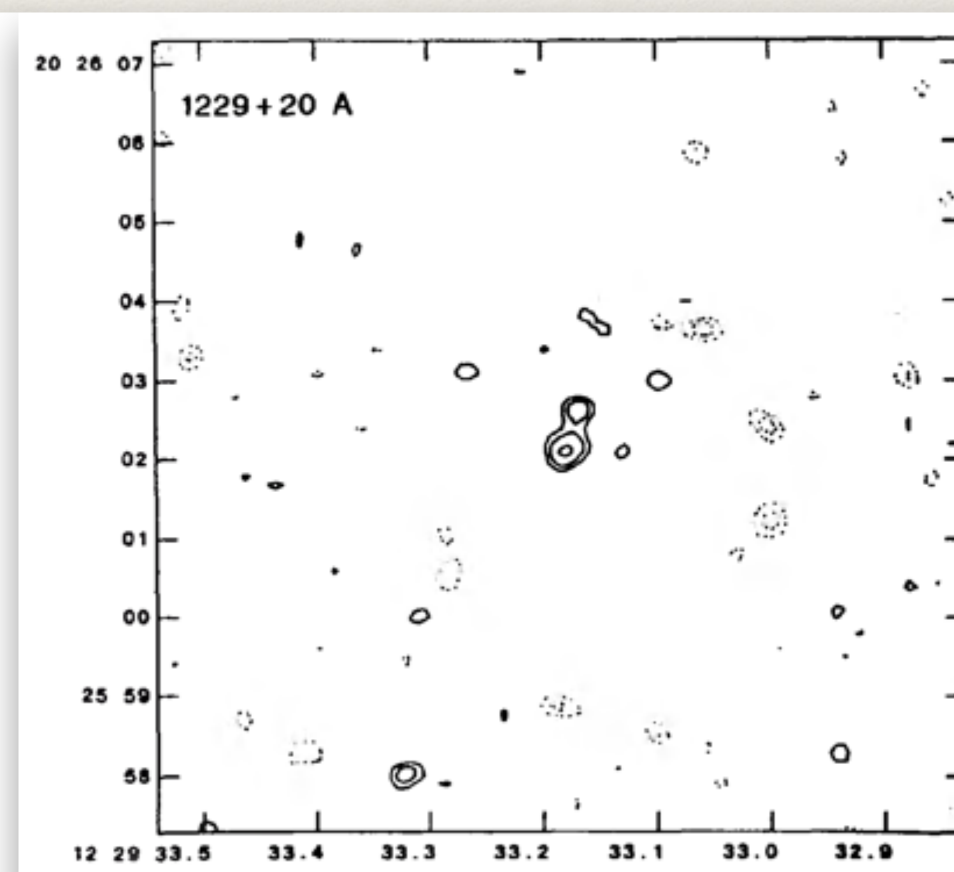


RQAGN on Kpc-scales

- Unresolved in GMRT ~3″ – 5″ resolution observations
- Steep spectrum sources are unresolved jets / lobes (1229+20, *Kellermann+ 1994*)
- New ~1″ resolution VLA images currently being acquired (PI: Silpa S.)

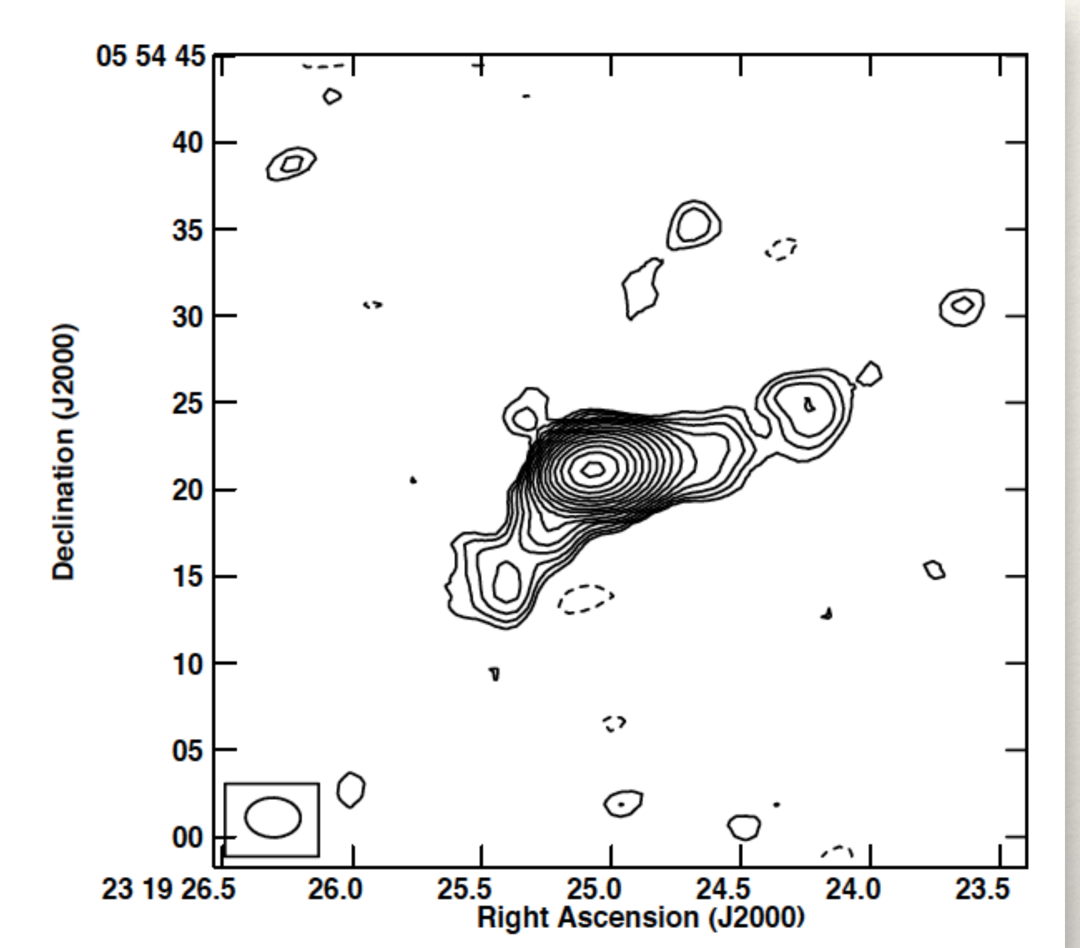


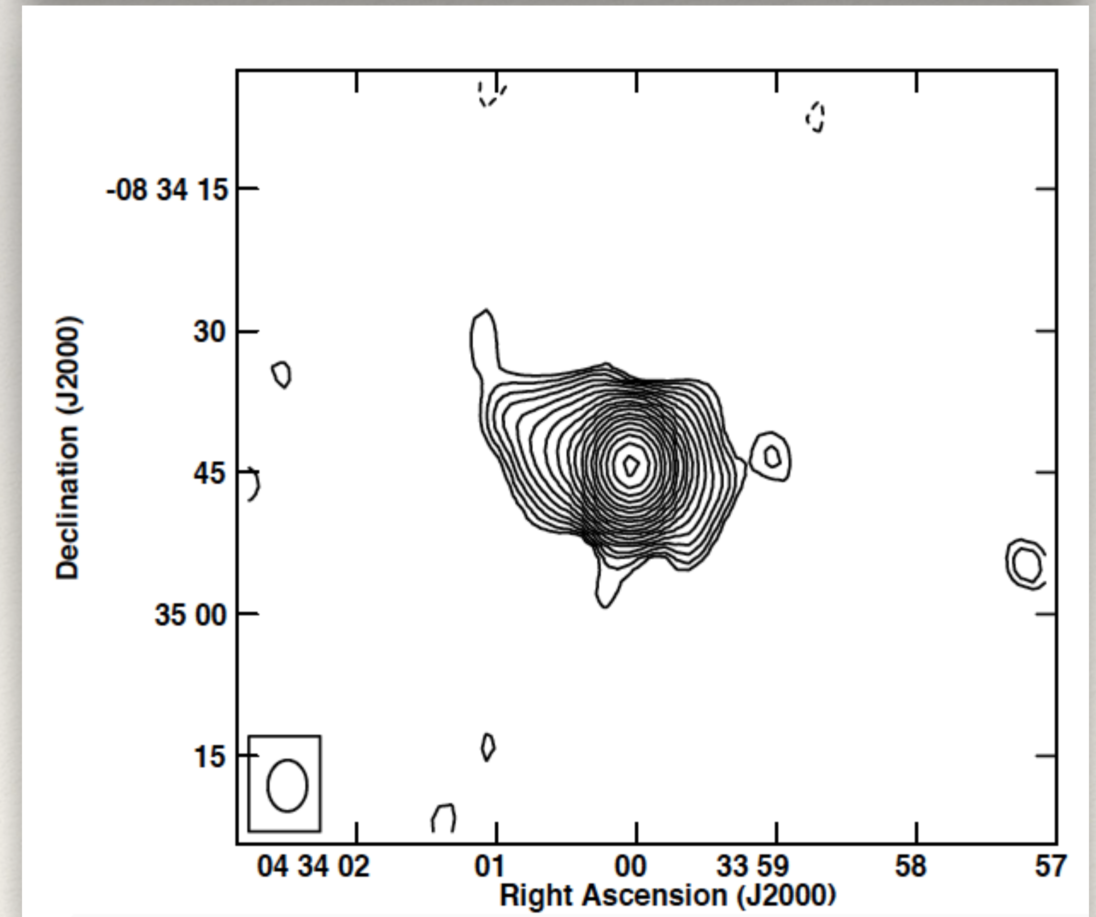




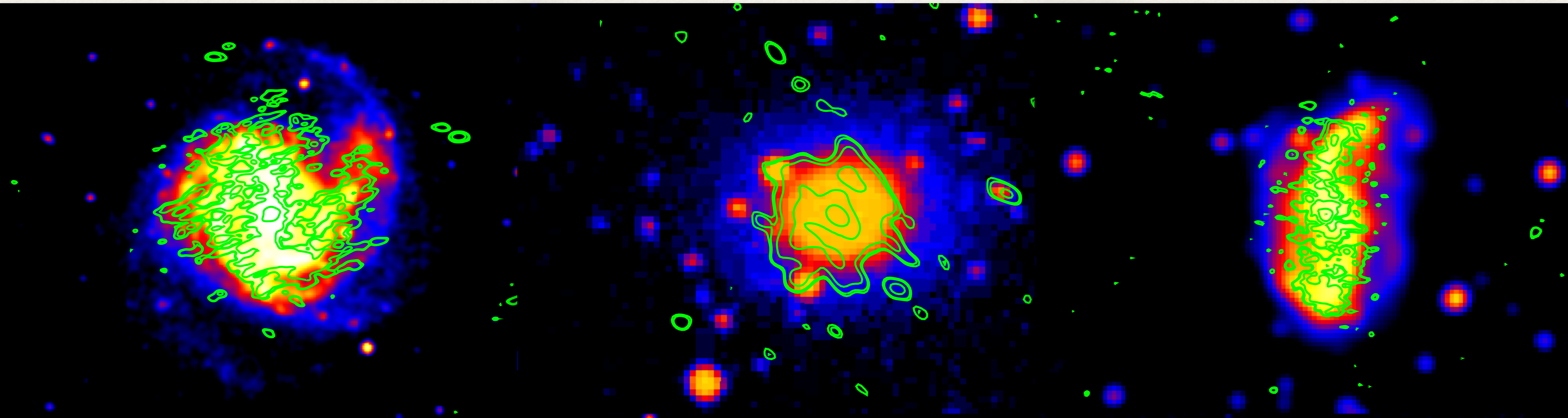
RQAGN on Kpc-scales

- Seyfert galaxies from **S7** (*Dopita+ 2014*)
- 610 MHz, 1.4 GHz with the GMRT
- IC 1481 (11 kpc), $\boldsymbol{\alpha} \sim -0.8 \pm 0.1$
- NGC5506 (10 kpc), $\boldsymbol{\alpha} \sim -0.69 \pm 0.04$
- Optically thin synchrotron emission
- *Nandi, Rubinur + in prep.*
- *S7: Siding Spring Southern Seyfert Spectroscopic Snapshot Survey*



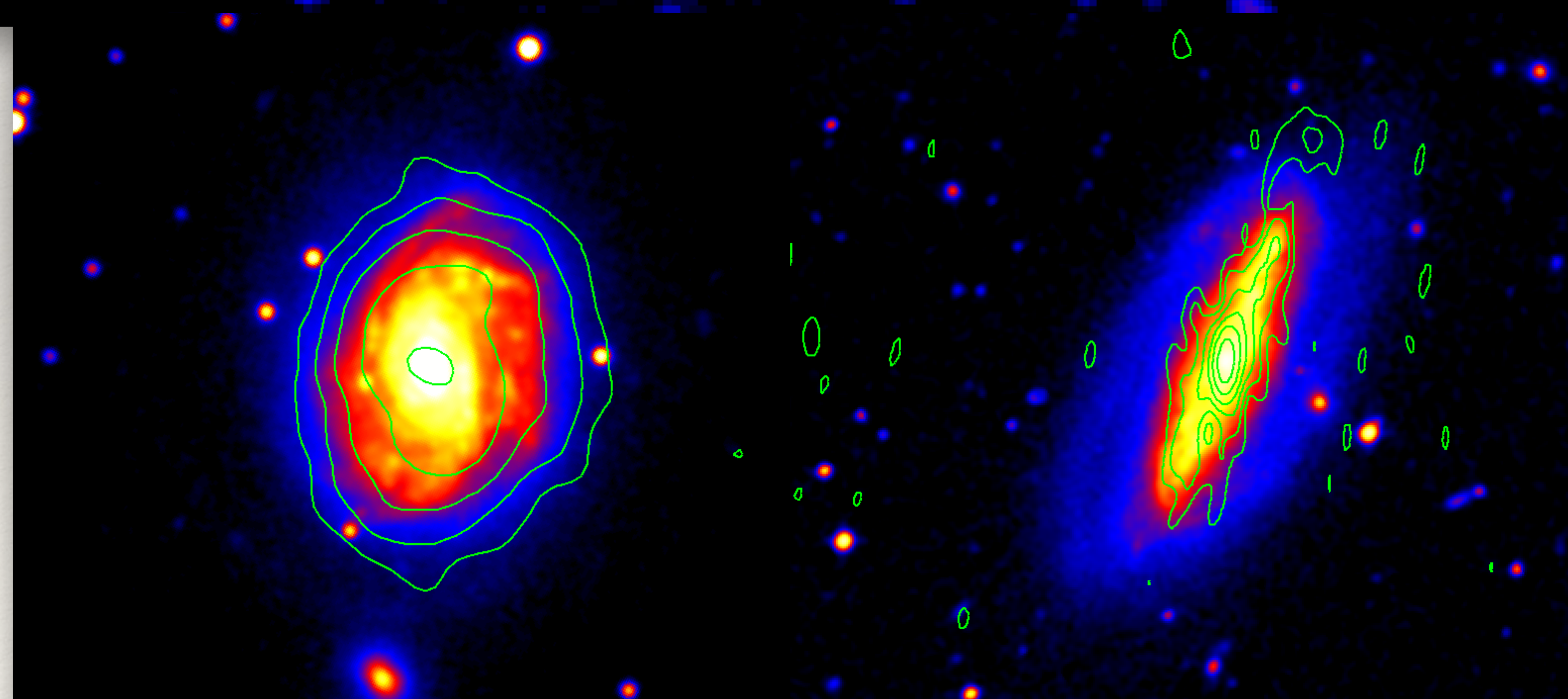


Host Galaxy/Stellar Emission

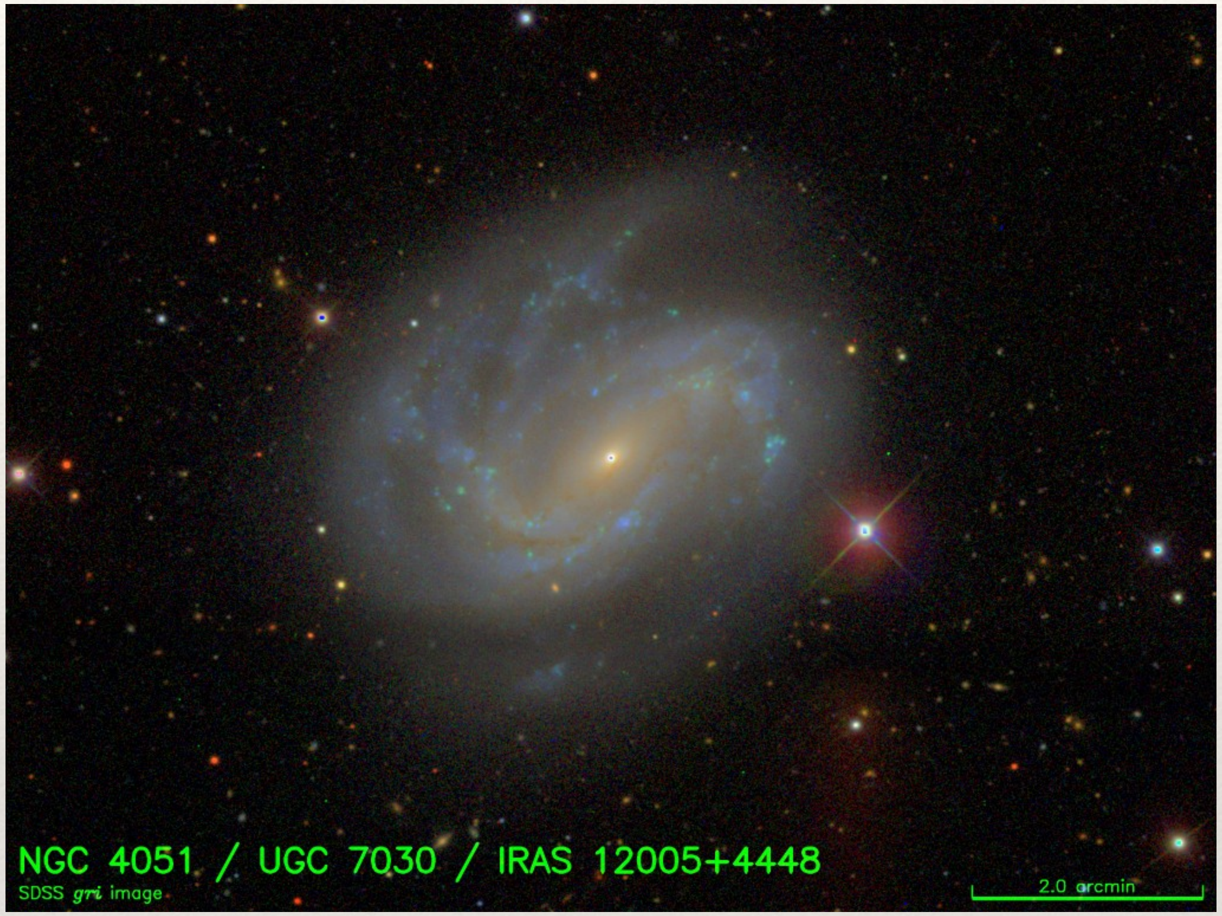


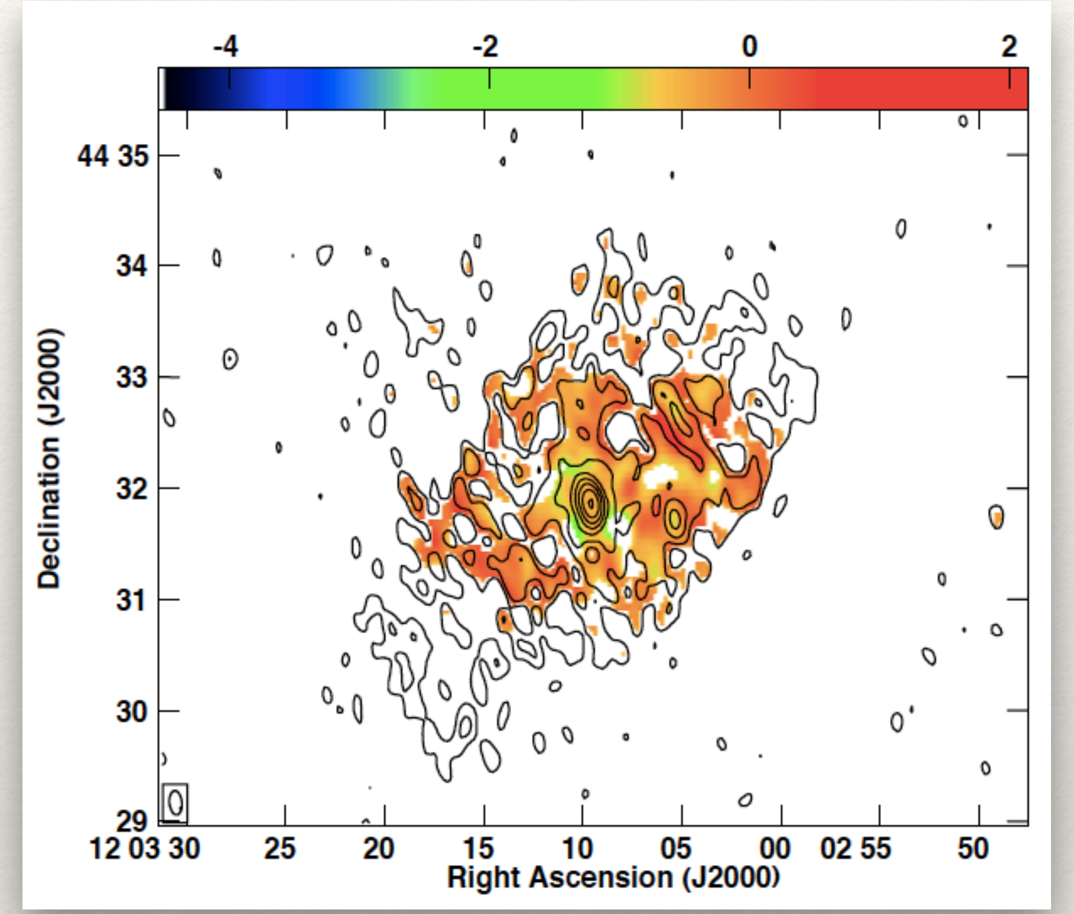
Host galaxy emission in 25% of sources at 1.4 GHz

>50% at 610/325 MHz



Disentangling AGN & Stellar Contributions

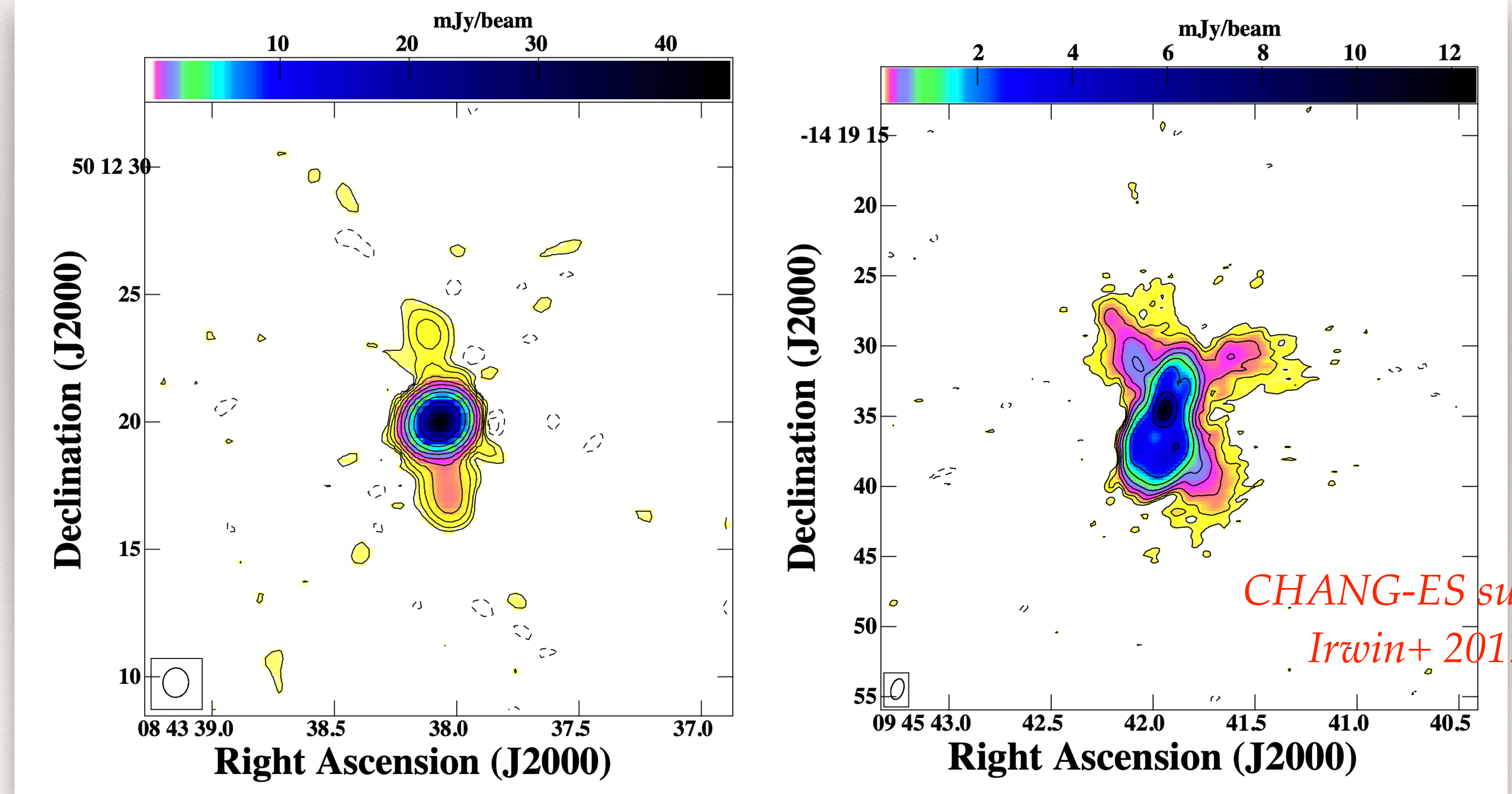


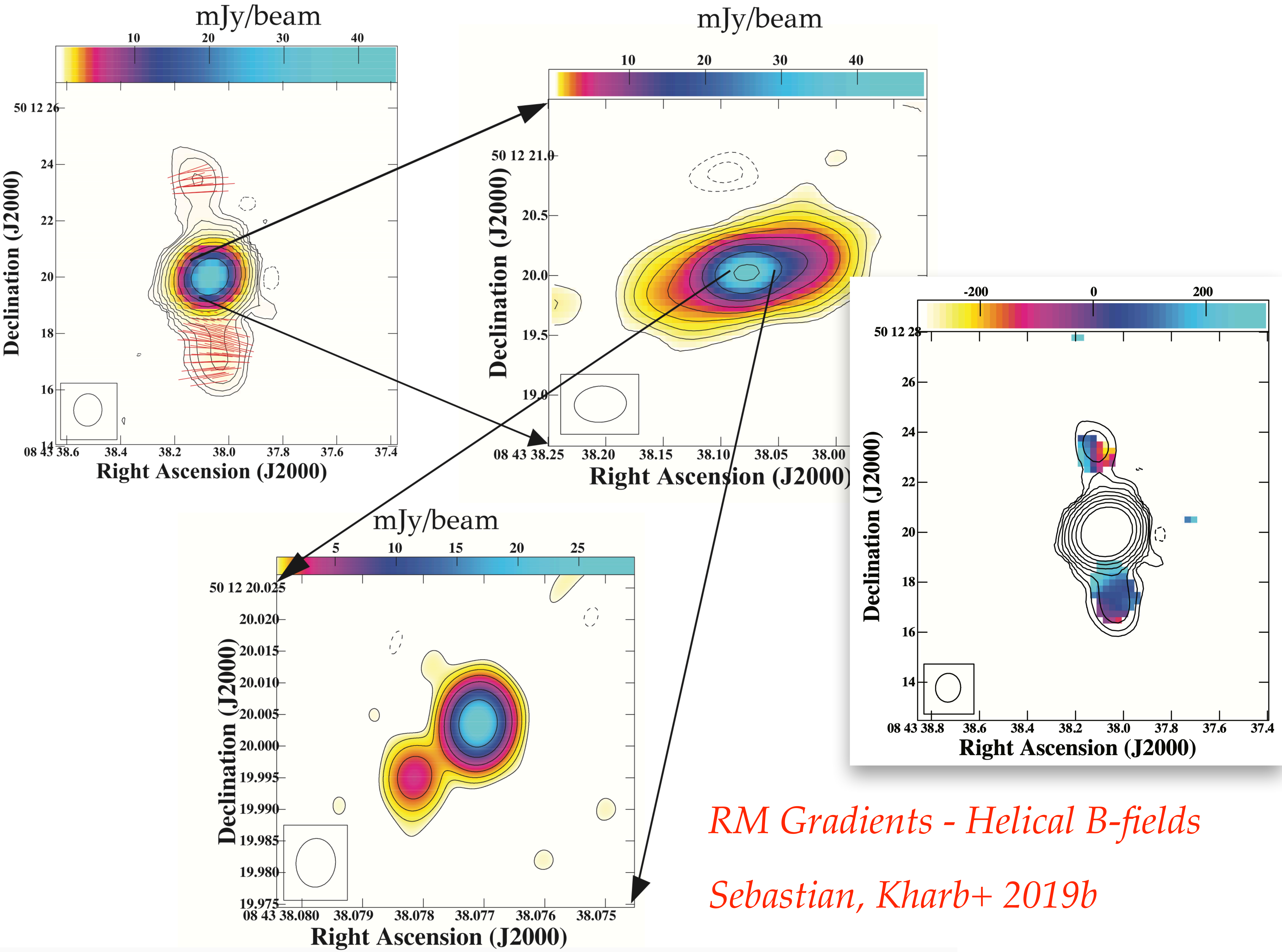


- NGC4051: Spectral index from GMRT (325 MHz) and VLA (1425 MHz)
- Galactic emission $\boldsymbol{\alpha} = -0.12 \pm 0.06$, consistent with free-free emission
- Core $\boldsymbol{\alpha} \sim -0.63 \pm 0.08$, consistent with synchrotron emission

RQAGN with the VLA

- A polarization-sensitive 5.5 GHz VLA study (1″- 2″ resolution)
- *Sebastian, Kharb+ 2019a, 2019b, 2020*





RM Gradients - Helical B-fields

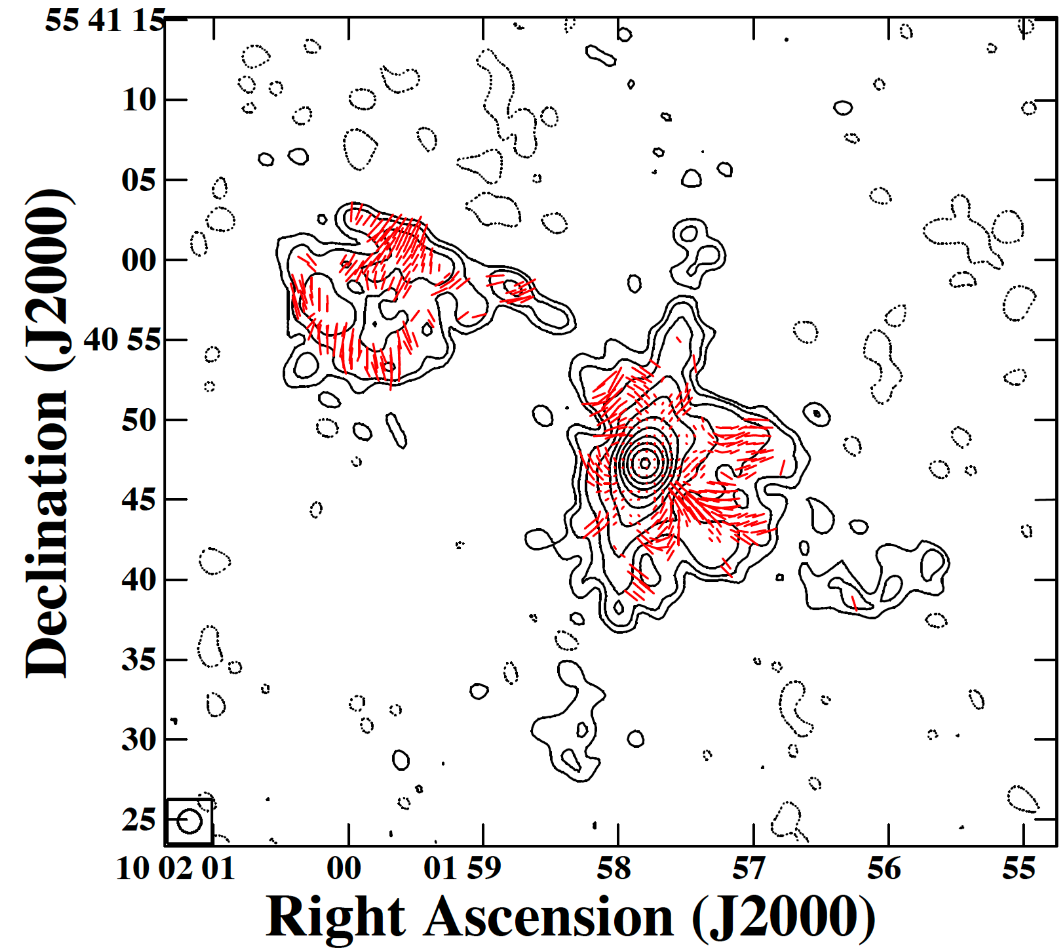
Sebastian, Kharb+ 2019b

Polarized Emission

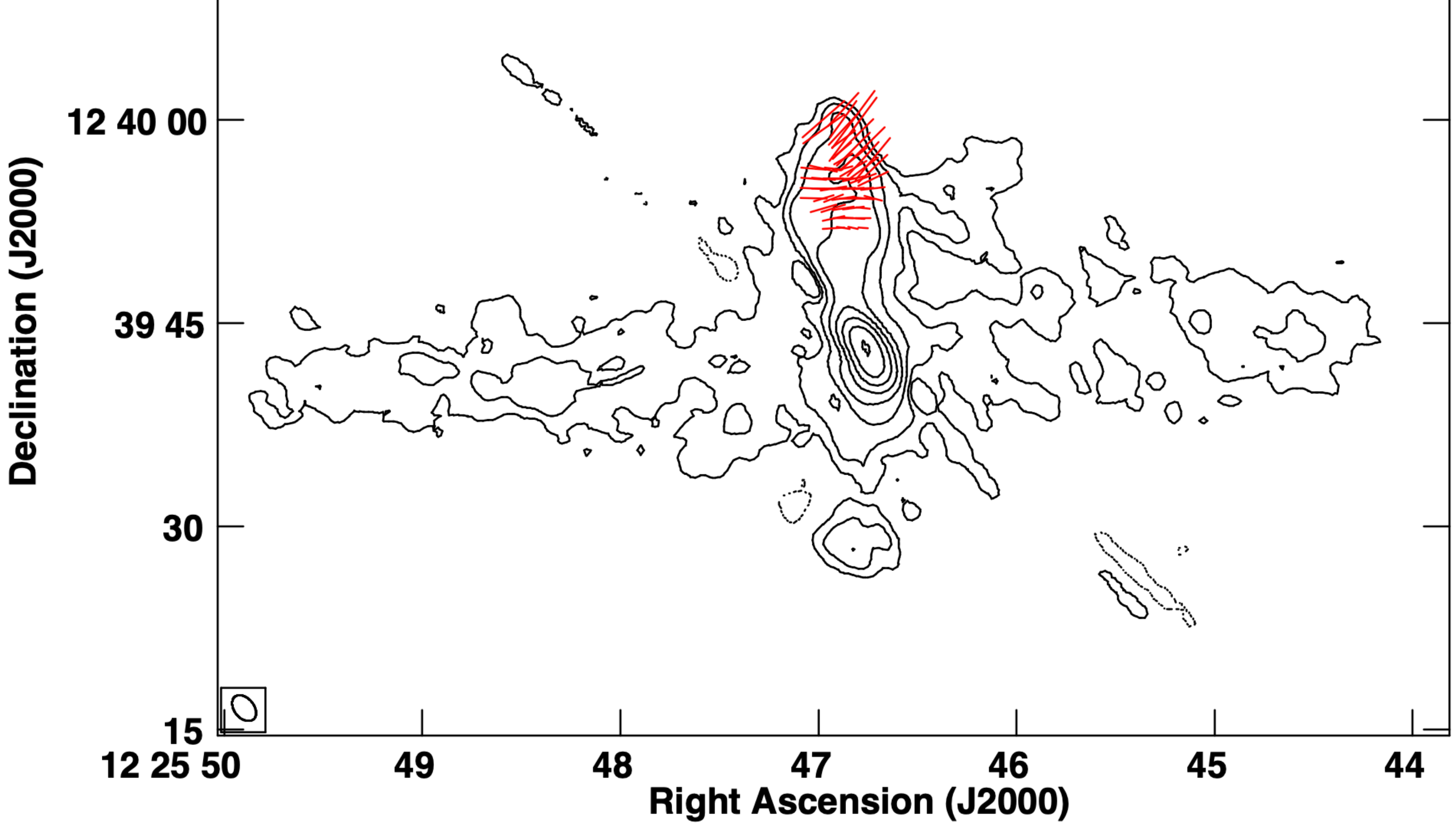
Fractional polarization: few % – 40% at edges

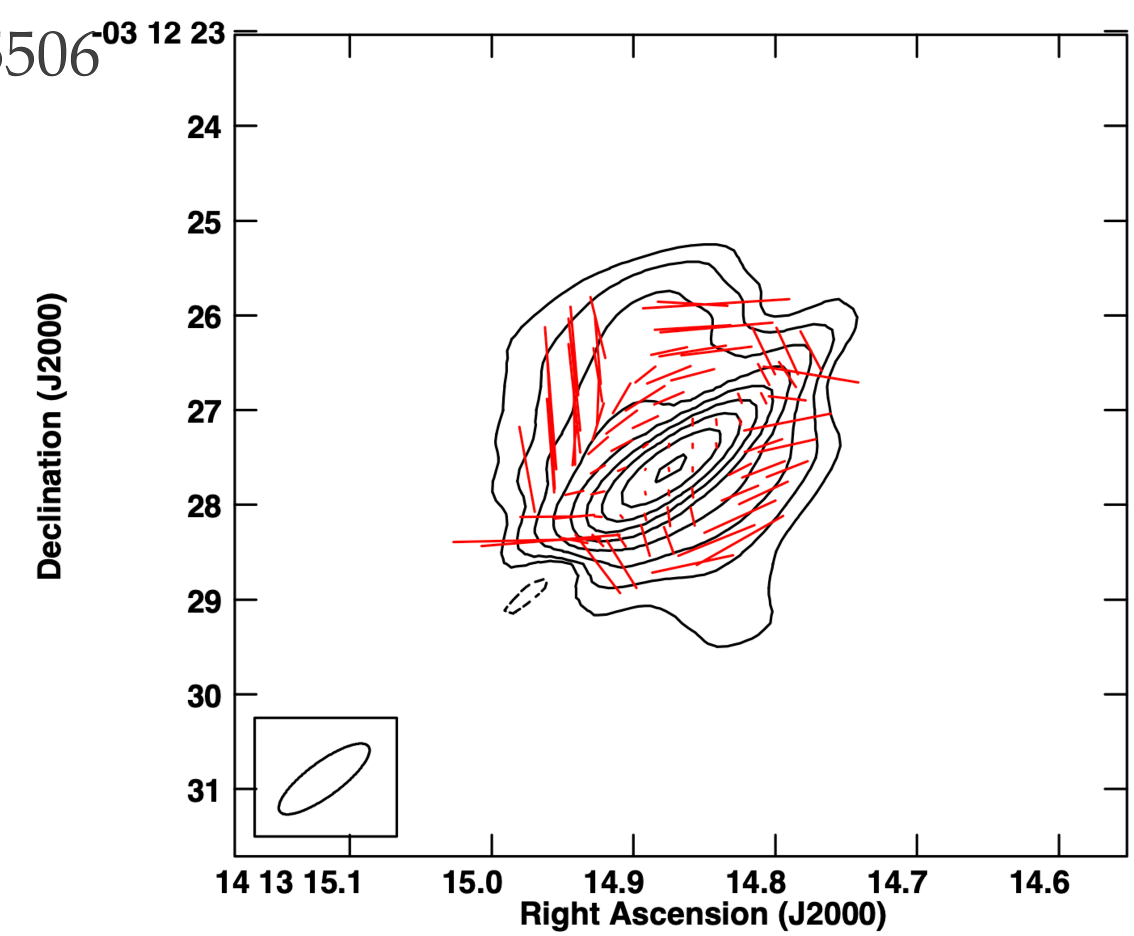
B-fields aligned at the edges, poloidal inside

Sebastian, Kharb+ 2020, MNRAS

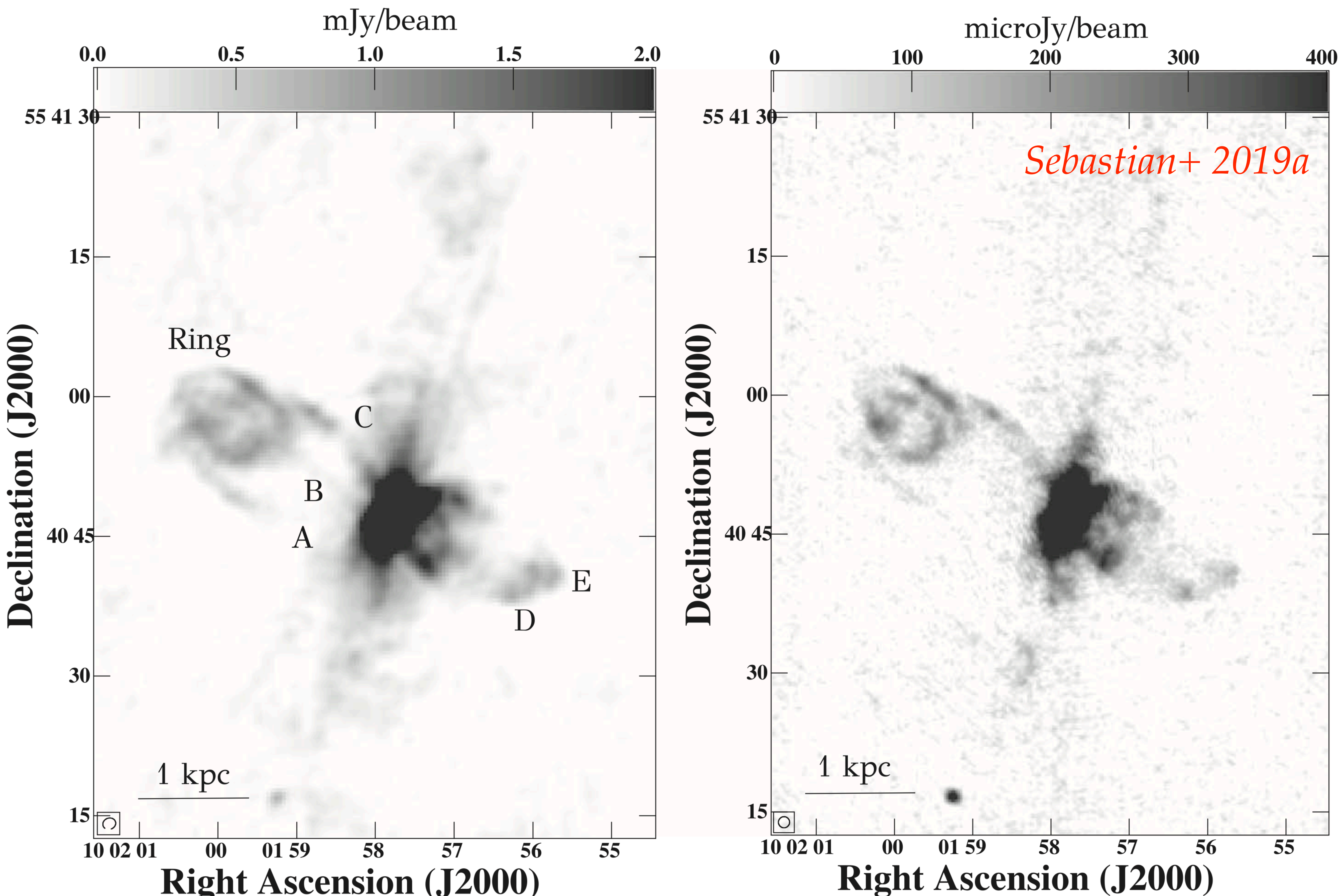


Top: NGC3079   Left: NGC4388   Right: NGC5506

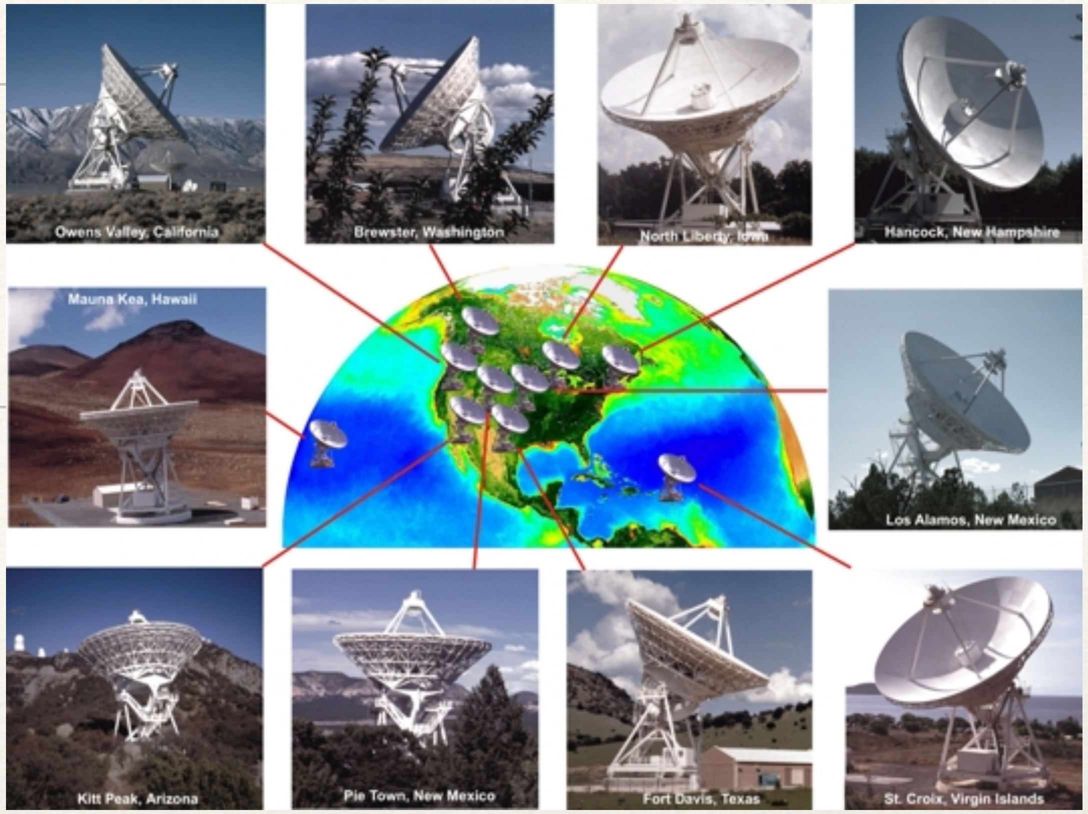




The Filamentary Radio Lobes of NGC 3079



RQAGN on Pc-scales

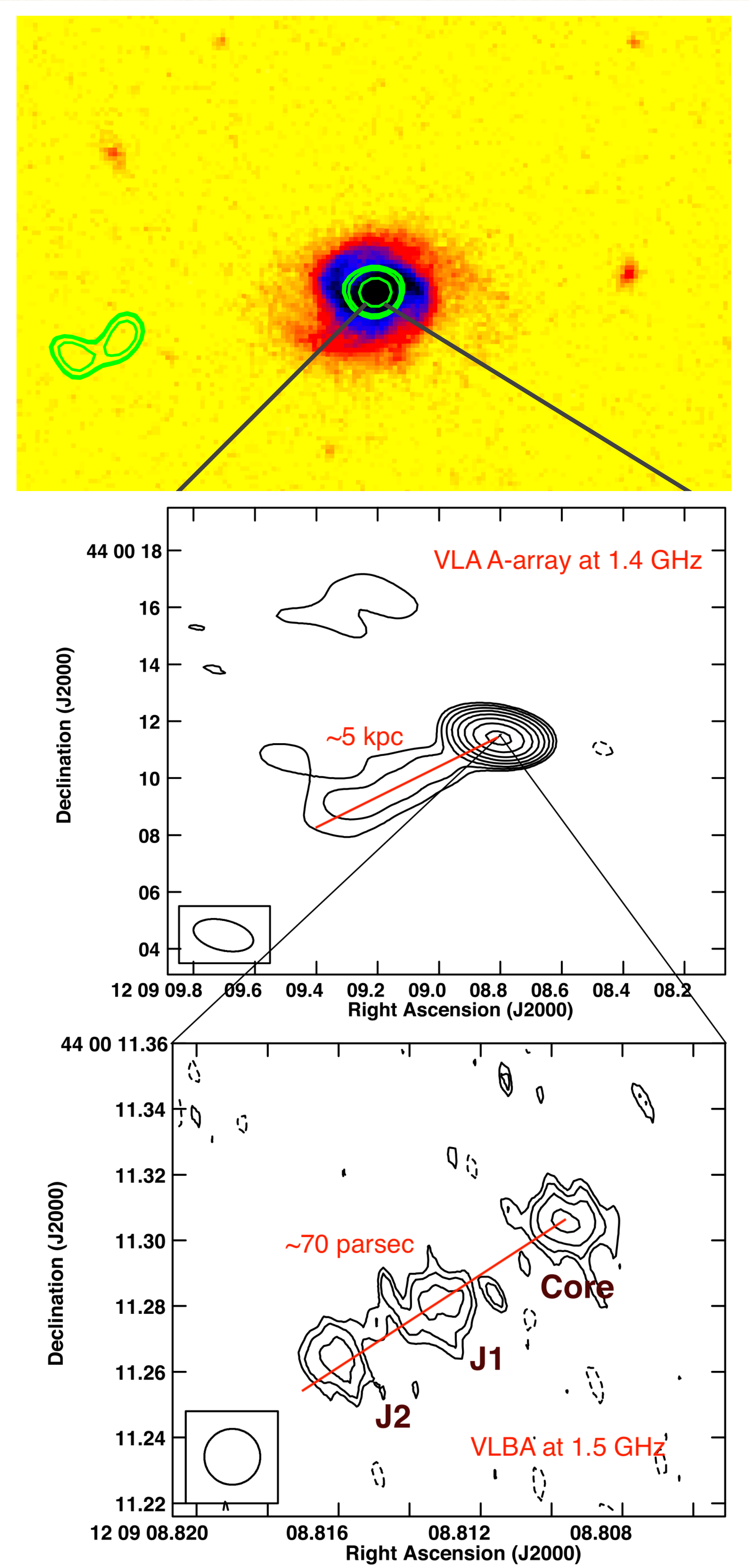


- KPNO Internal Spectroscopic Red Survey, KISSR (*Salzer+ 2000*)
- Chose sources with double-peak emission lines + VLA FIRST (5.4″ resolution @1.4 GHz) detections
- 1.5 + 5 GHz VLBI observations of 9 Type 2 Seyferts & LINERs

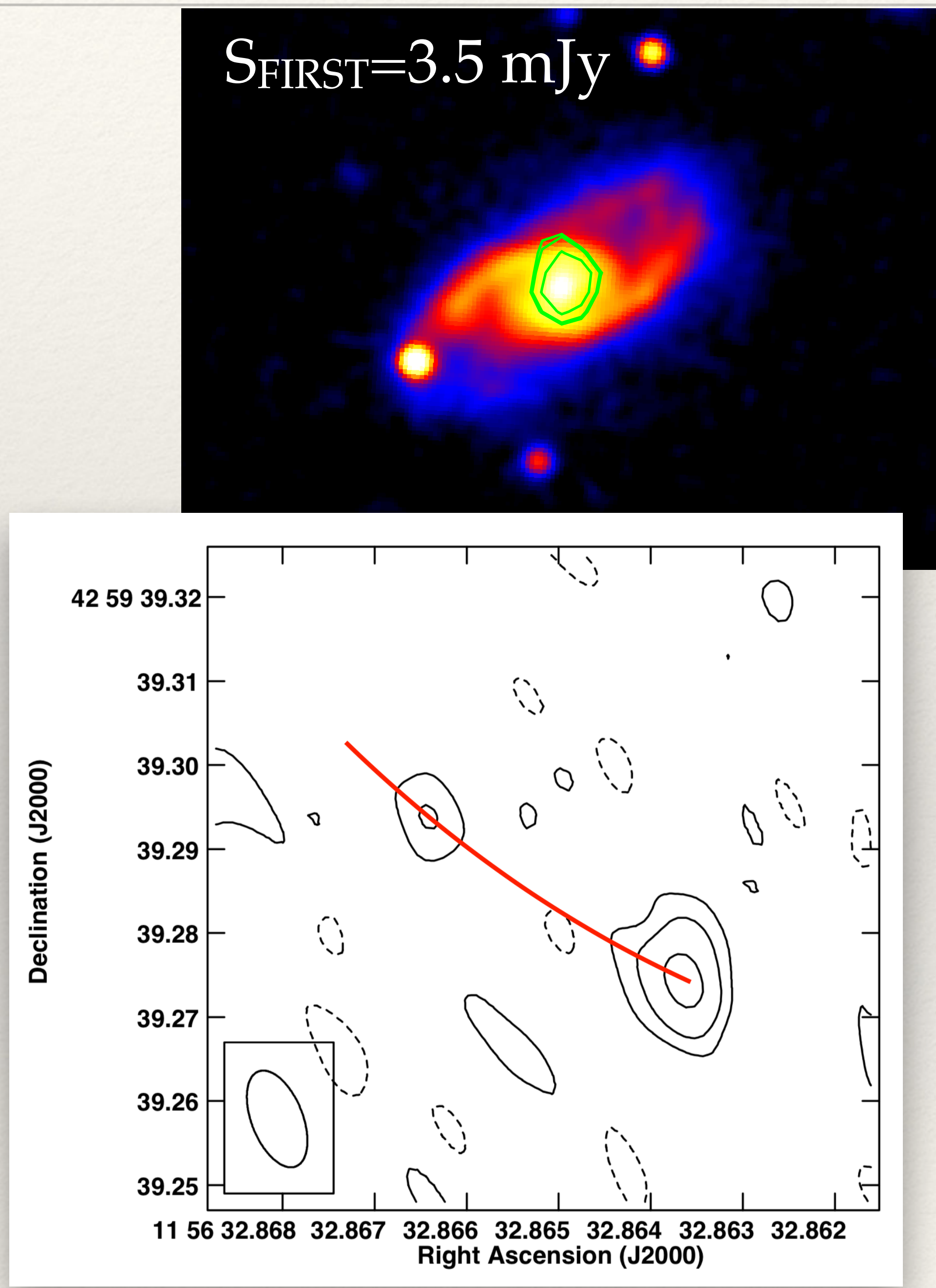
RQAGN on Pc-scales

- KISSR 1219, S_{FIRST} = 6 mJy
- VLA ~5 kpc jet, VLBA ~70 pc jet @1.5 GHz
- $\alpha < -1.0$ for core and jet features
- FFA or Doppler boosting?
- Jet-to-counterjet I ratio for $\theta > 50^{\circ}$ (Sy 2)
- v $\gtrsim$ 0.55c to $\gtrsim$ 0.25c from pc to kpc-scales. Deceleration!

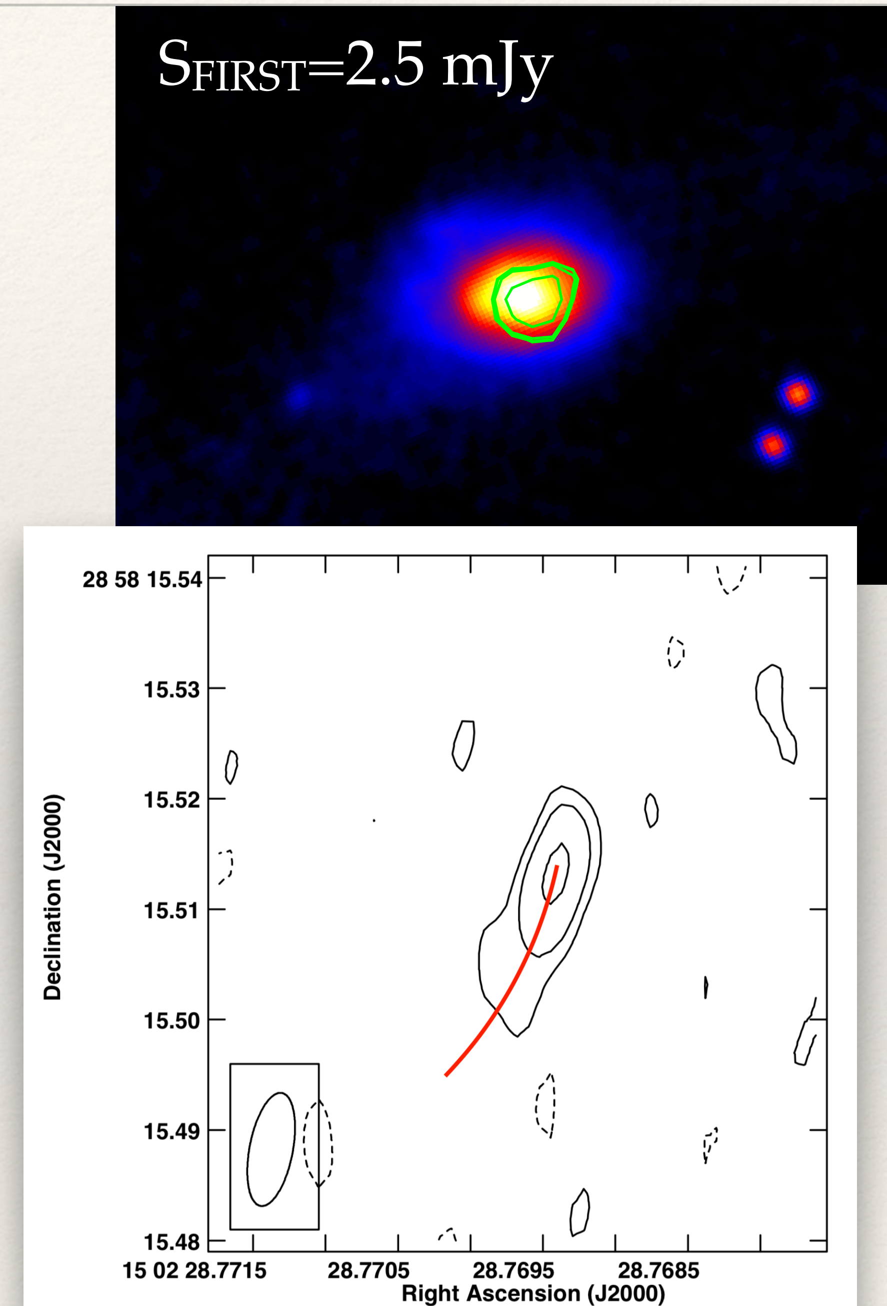
Kharb, Subramanian, Vaddi+ 2017



RQAGN on Pc-scales



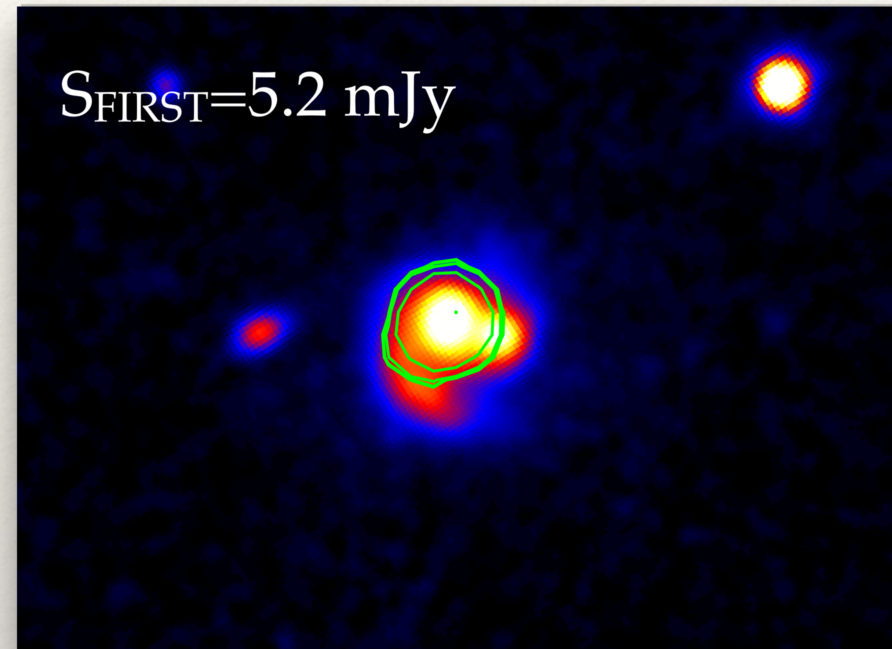
KISSR 1154 (~50 pc)



KISSR 618 (~30 pc)

No detections at 5 GHz. Steep radio spectrum. *Kharb+ in prep.*

RQAGN on Pc-scales

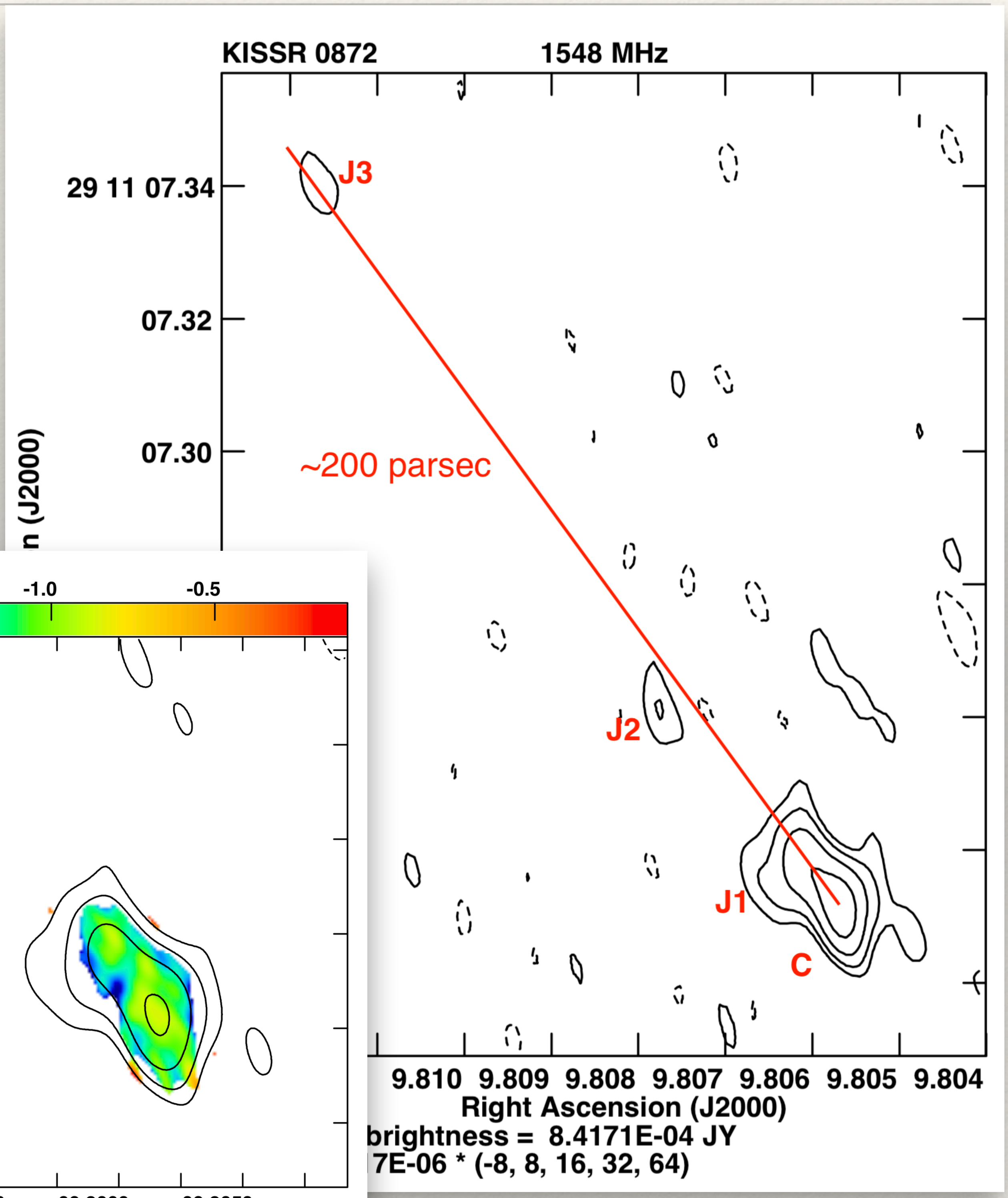


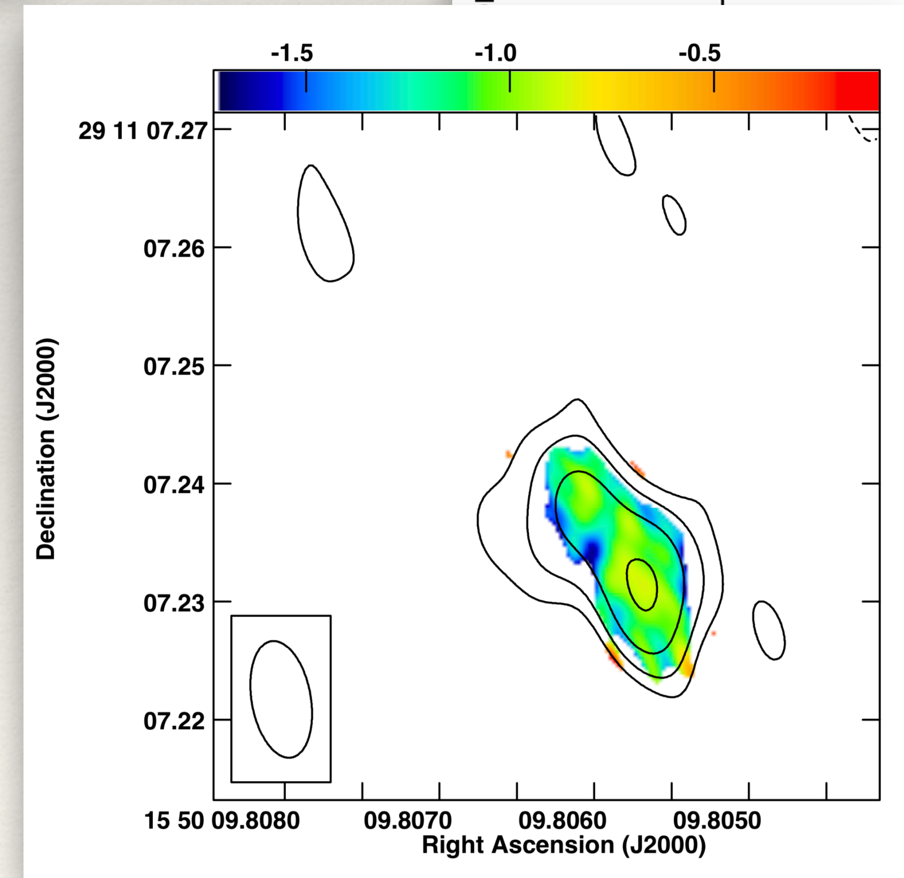
KISSR 872

~200 pc long jet

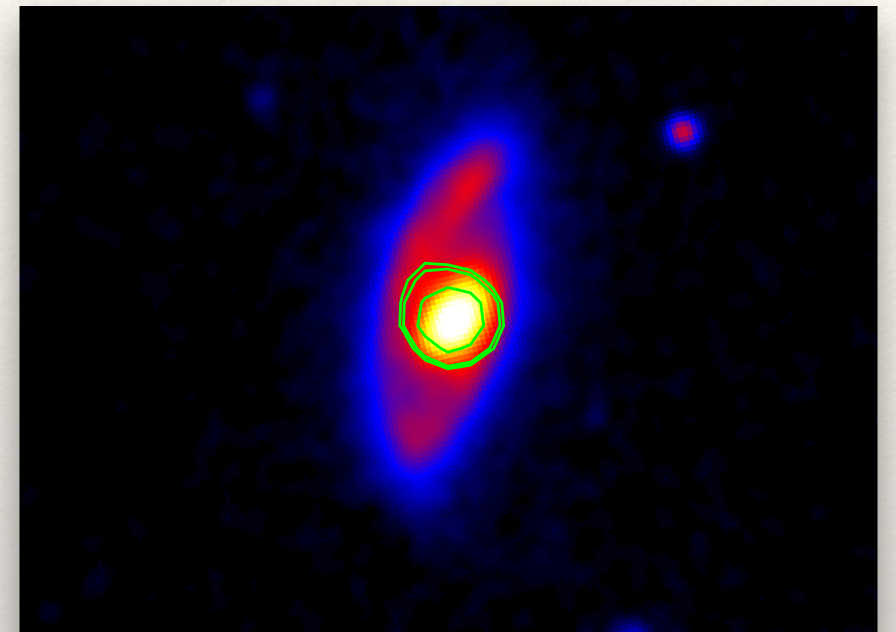
α varies from -0.90 ± 0.07 to -1.22 ± 0.19

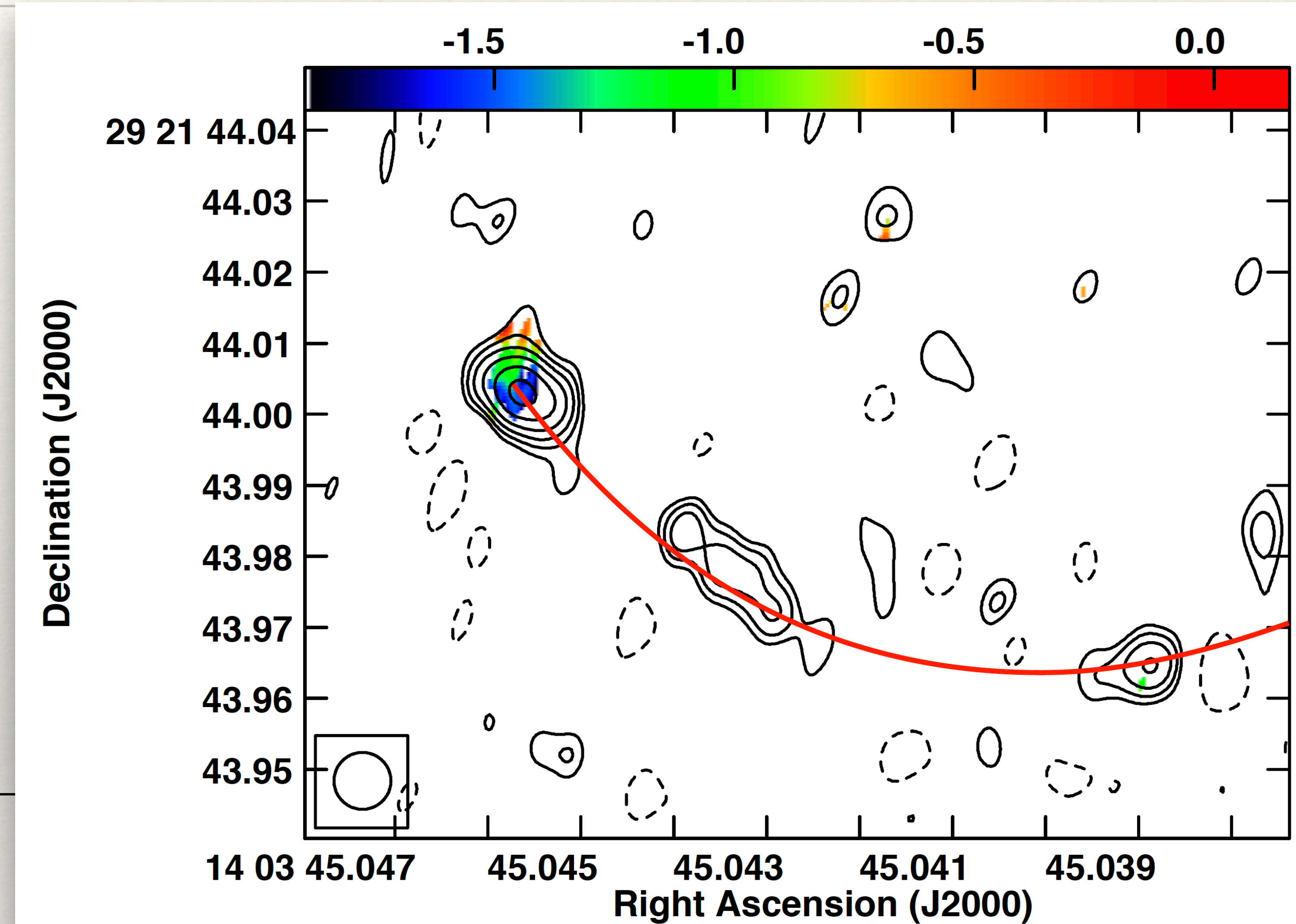
Kharb+ in prep.





RQAGN on Pc-scales





- KISSR 434, S_{FIRST} ~4 mJy
- 150 parsec curved VLBI jet at 1.5 GHz. Inner 10 parsec at 5 GHz
- Steep-spectrum ($\alpha \sim -1.0$), relativistic ($v \sim 0.75c$ for $\theta > 50^{\circ}$), curved jet [*v ~ 1.25c in III Zw 2, Brunthaler+ 2000*] *Kharb+ 2019*

Jet Bending - Precession?

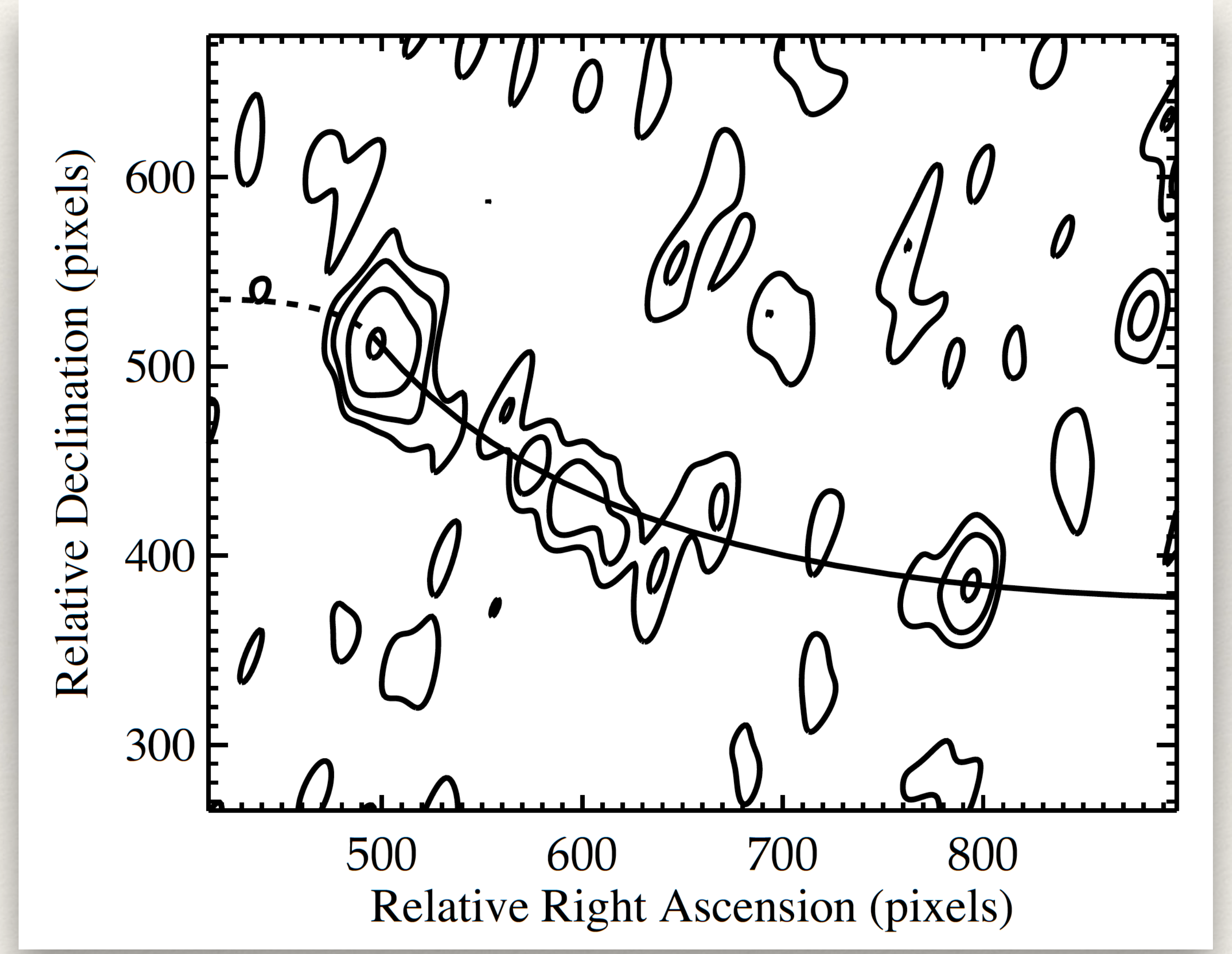
Precessing Jet model (*Hjellming & Johnston 1981* for SS433) best-fit parameters

Jet inclination = 50° (fixed)

Jet Speed = 0.75c (fixed)

Precession cone half-opening angle = 40°

Precession Period = 1.8×10^{4} yr



Precession due to BBHs?

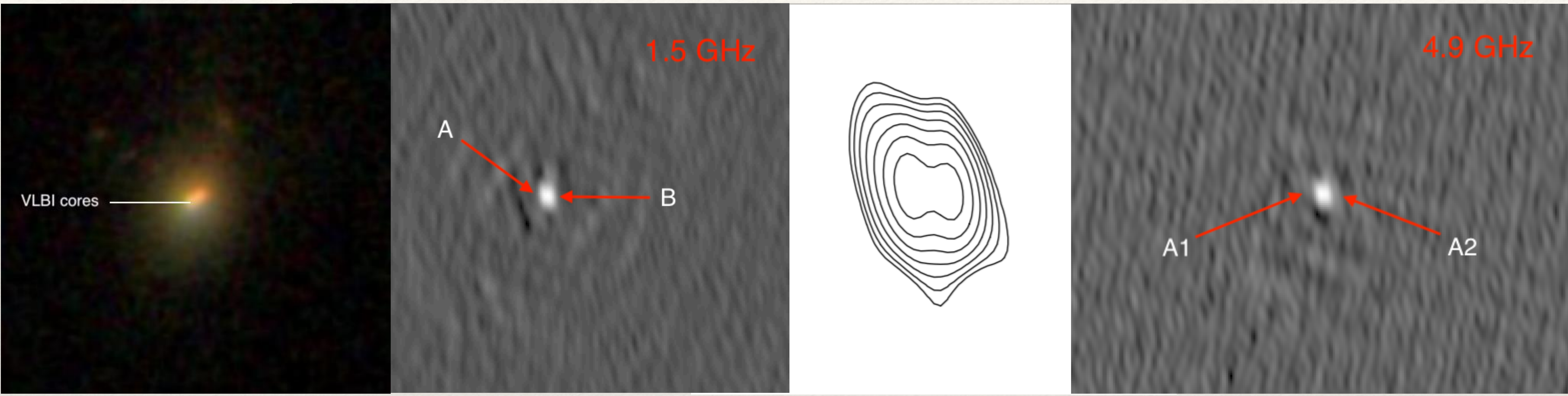
- Geodetic precession period of massive BH "M" orbited by smaller BH "m" (*Begelman+1980*)

$$P_{prec} \sim 600\, r_{16}^{5/2}\, (M/m)\, M_8^{-3/2}\ yr$$

- An equal mass binary BH with a separation (r_{16} in units of 10^{16} cm) of 0.015±0.005 pc needed to match jet precession period. Cannot be ruled out by present data.

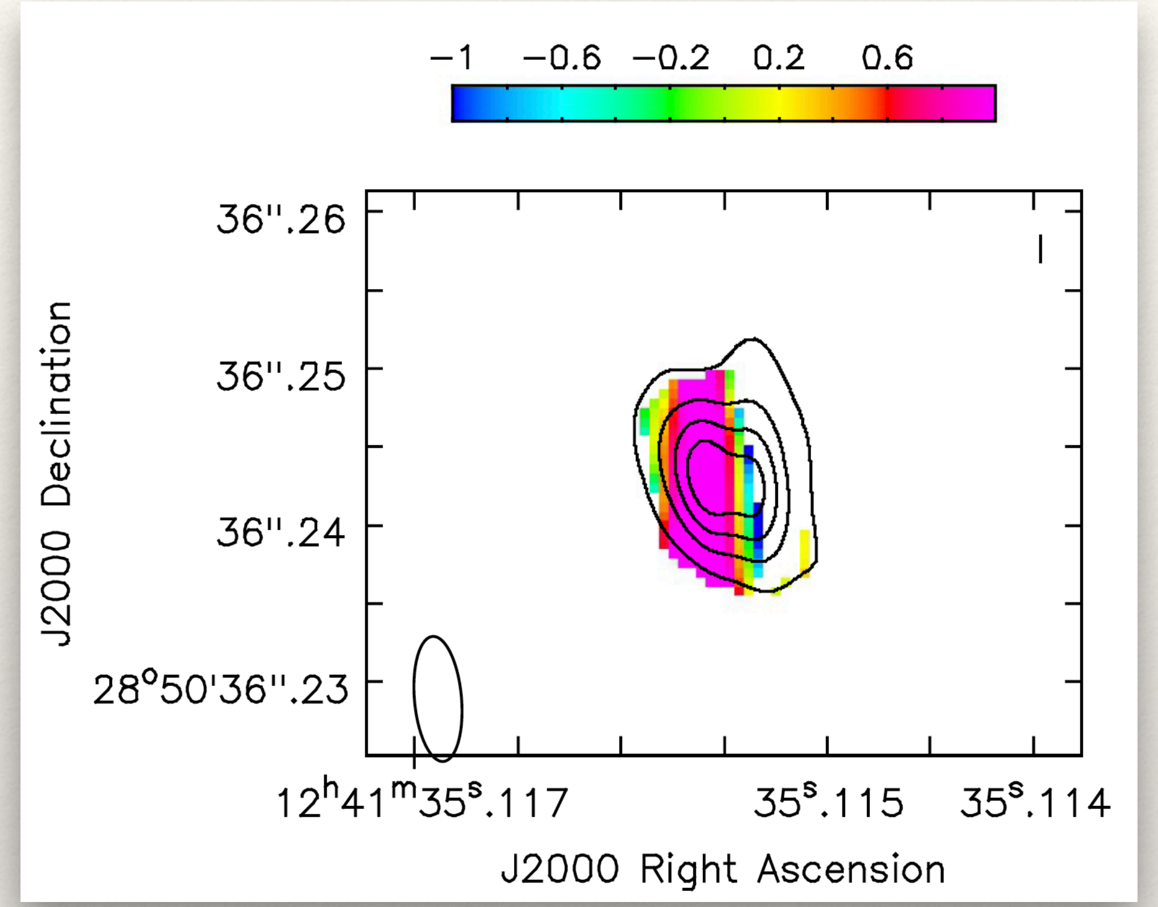
- *Krause+ 2019* for radio-loud AGN

The Intriguing Case of KISSR 102



- LINER galaxy with two optical nuclei
- "Offset" AGN: AGN emission lines offset from galactic absorption lines by ~200 km s^{-1} (*Comerford & Greene 2014*)
- A & B sepn. = 4.8 parsec,   A1 & A2 sepn. = 1.7 parsec
- Inverted spectral index for A, $\alpha = +0.61 \pm 0.08$, steep spectrum for B, $\alpha < -1.6$

KISSR 102



- Sharp change in **α** values between A & B. Inconsistent with a "core-jet" structure from a single AGN. Or else, strong jet-medium interaction!
- End result of a 3-body interaction involving 3 SMBHs? (Total BH mass from M-**σ** relation ~$1.7 \times 10^9\ M_\odot$) *Kharb, Lena, Paragi+ 2020*

Overall

- RQAGN have jets - “Jetted AGN”
- RQAGN show episodic AGN activity. Radio lobes with different spectral indices at different orientations
- RQAGN radio lobes highly polarized. No “significant” mixing of thermal plasma with synchrotron plasma?
- Inferred magnetic fields aligned at lobe edges, but poloidal inside the outflows. RM gradients - helical / complex magnetic field structures
- One-sided jets on pc-scales. Could they be Doppler-boosted?
- Are curved pc-scale jets precessing? Sub-pc binary BHs cannot be ruled out at present
- Overall, RQAGN appear to be scaled-down versions of RLAGN