About Radio Outflows in Radio-Quiet AGN

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Radio-Quiet AGN

>80% of AGN are RQ

Useful definition by *Kellermann+ 1989*
$R \equiv S_{6\ cm}/S_{4400\ Å} < 10$

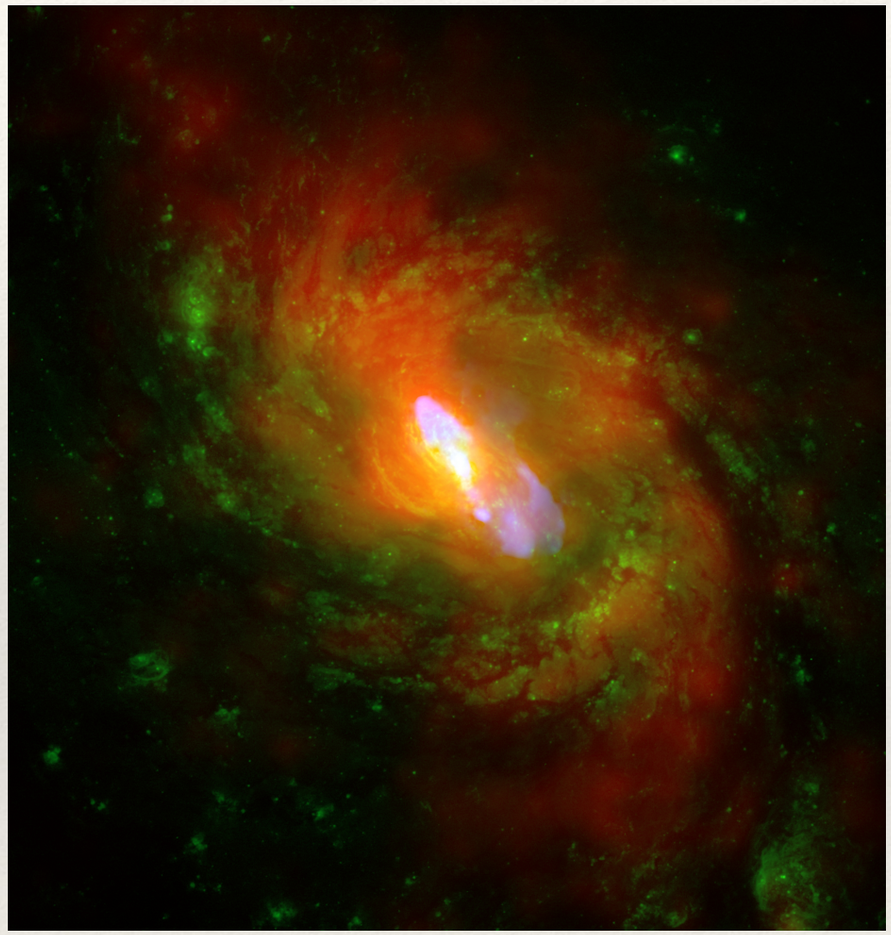
Seyfert galaxies, LINERs, RQQs

10 - 100 pc — 10 - 20 kpc radio outflows (*Ulvestad+ 1981, Baum+ 1993, Thean+ 2000, Gallimore+ 2006*)

Differences from the Radio-Loud AGN class ascribed to differences in BH masses, BH spins, accretion rates, jet-ISM interaction, etc. (*Blandford 1990, Wilson & Colbert 1995, Sikora+ 2007*)

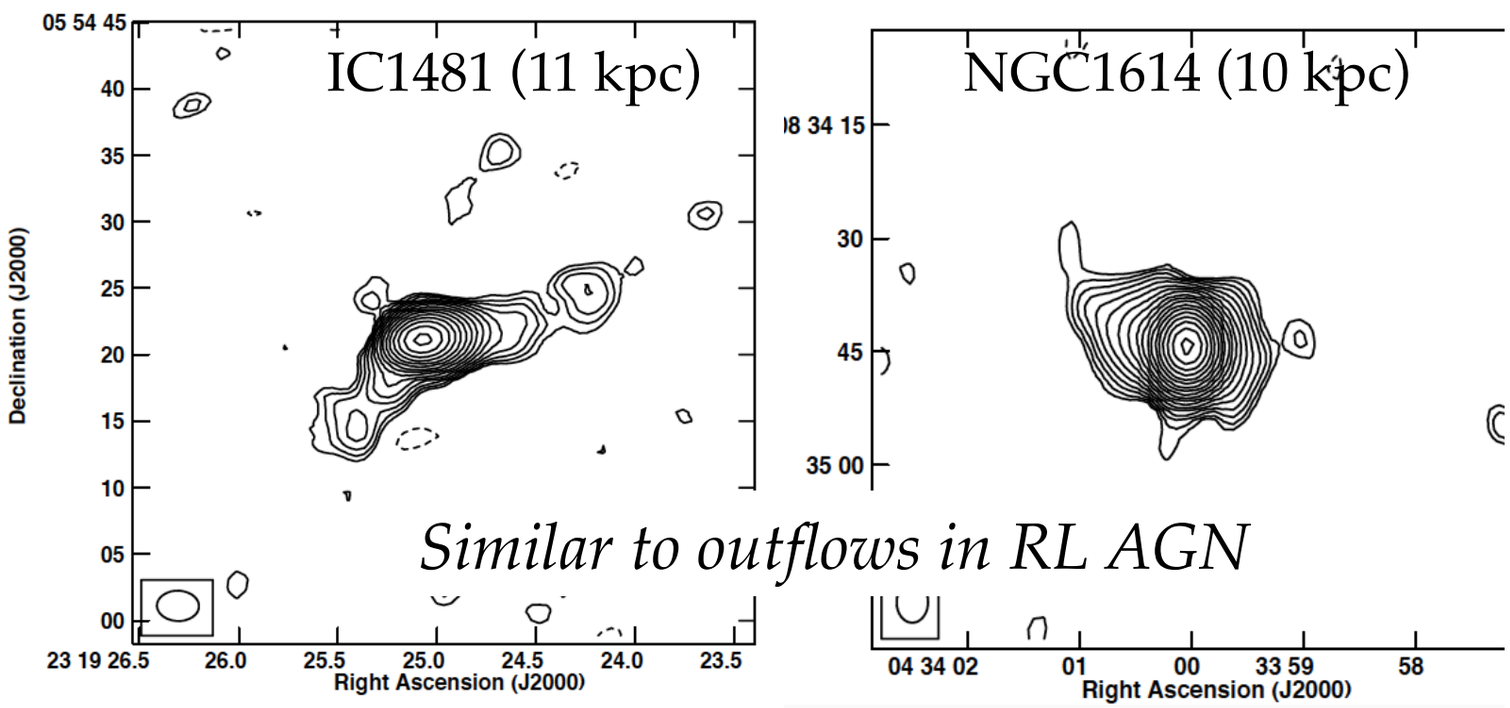
Contamination from stellar processes confuses the origin of radio emission: Disentanglement becomes important.

Must be done before understanding the nature of outflows

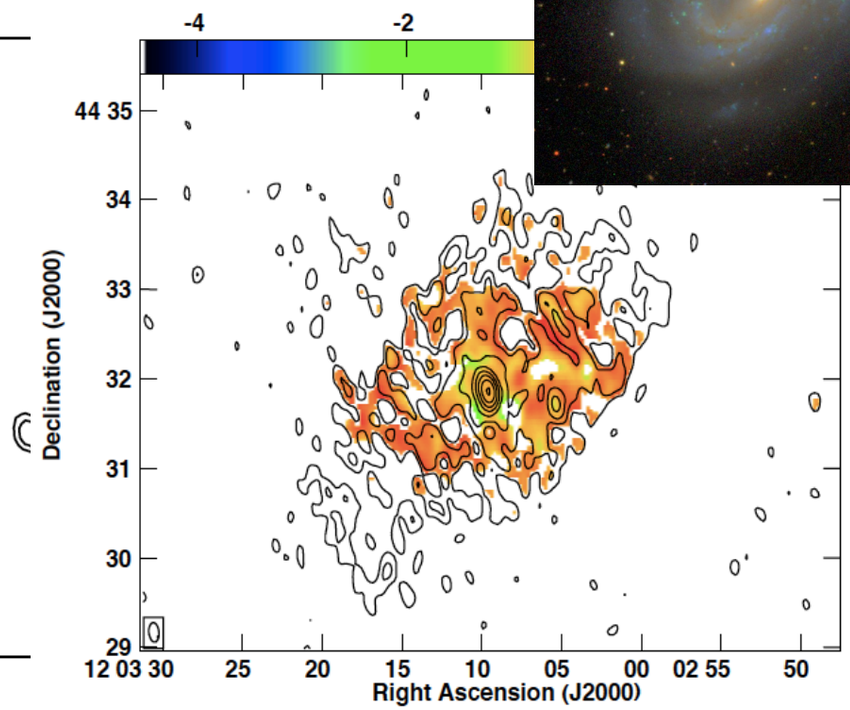


NGC1068

Studying RQ AGN Outflows with the GMRT



Similar to outflows in RL AGN



70 RQ AGN with GMRT at 325, 610, 1400 MHz. $\boldsymbol{\theta} \sim 2''$, $5''$, $10''$

While >50% show AGN-related outflows, galactic emission prominent at low $\boldsymbol{\nu}$

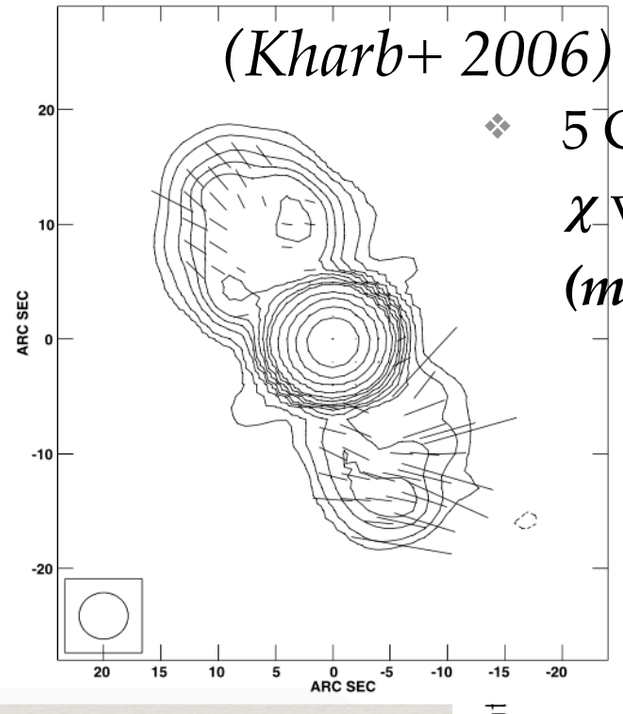
NGC4051: Radio jet [325-1400 MHz] $\boldsymbol{\alpha} = -0.6 \pm 0.1$ consistent with synchrotron.
Galactic Disk emission $\boldsymbol{\alpha} = -0.12 \pm 0.06$, consistent with free-free emission

Others: Galactic Disk + Continuum Halo $\boldsymbol{\alpha} = -0.9 \pm 0.1$. Impossible to identify AGN

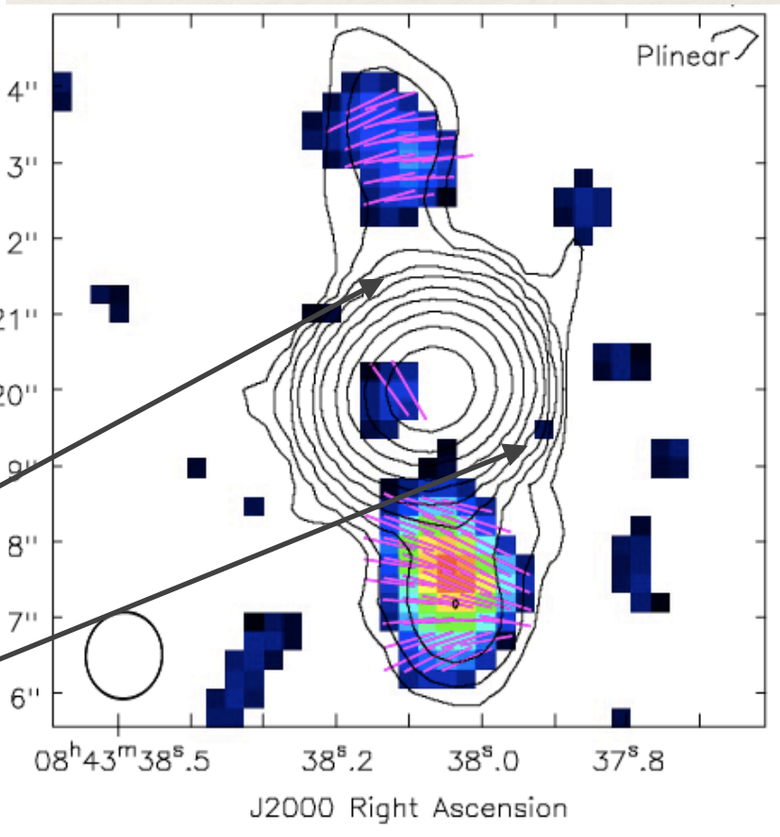
Disentangle AGN & Galactic Contributions via Polarimetry

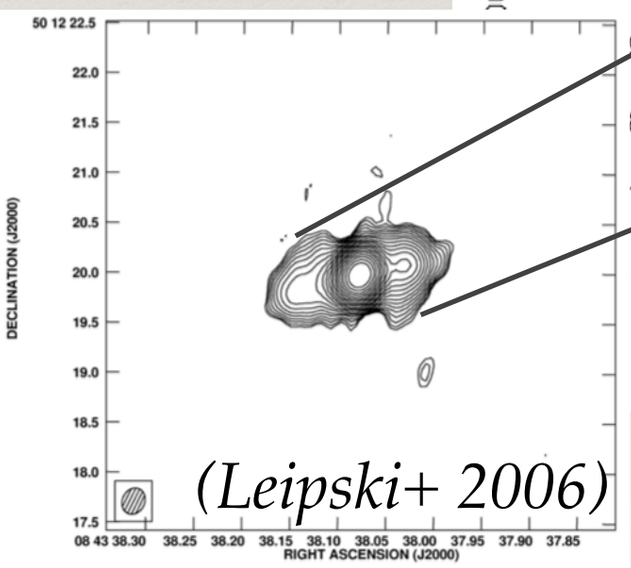
- *EXPECTATIONS from POLARIMETRY*
- More organized magnetic fields in AGN outflows. Galactic emission a mixture of non-thermal synchrotron + thermal free-free - ***m*** lower
- 10 Seyferts + 8 SB with EVLA at 1.4 and 5 GHz
- Detected the presence of secondary misaligned radio lobes in polarized light in NGC2639
- *Check out Biny Sebastian's Poster*

(Kharb+ 2006)



- 5 GHz VLA image of Mrk6 with χ vectors. Fractional polarization ***(m)*** a few % to 50% at edges

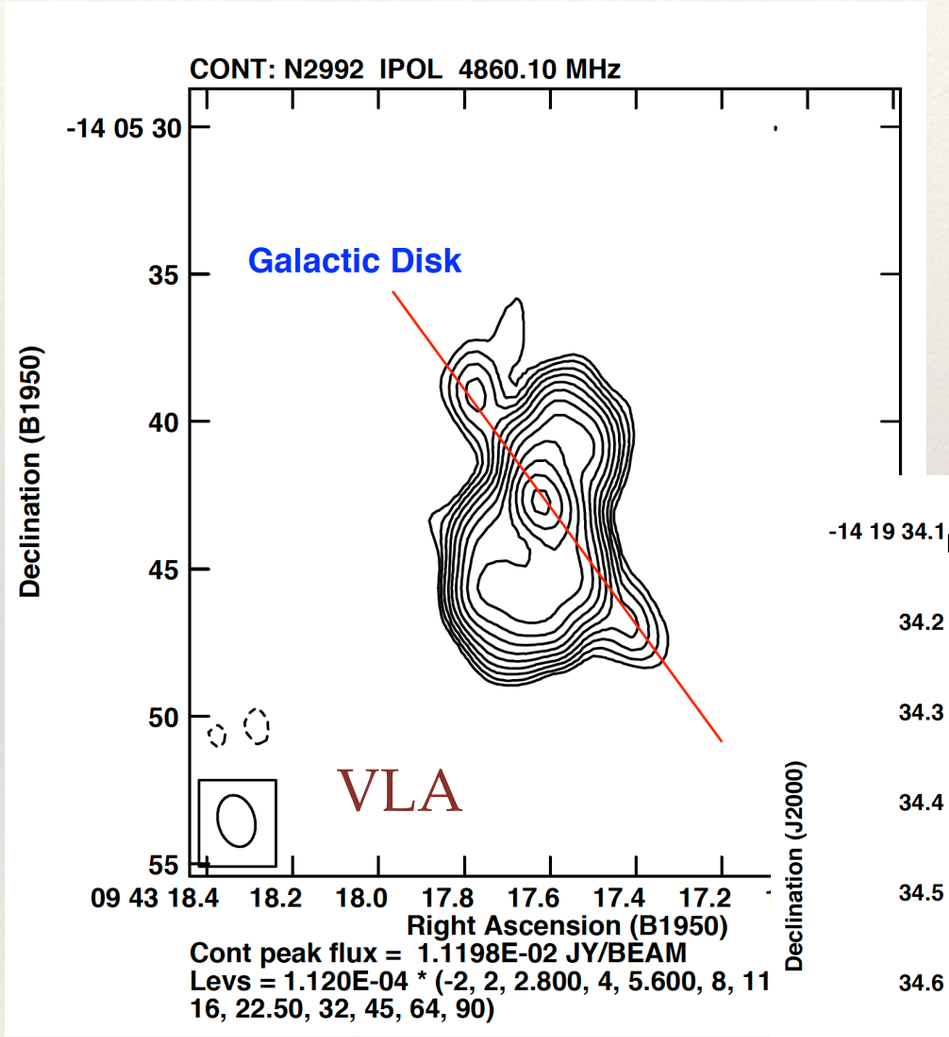


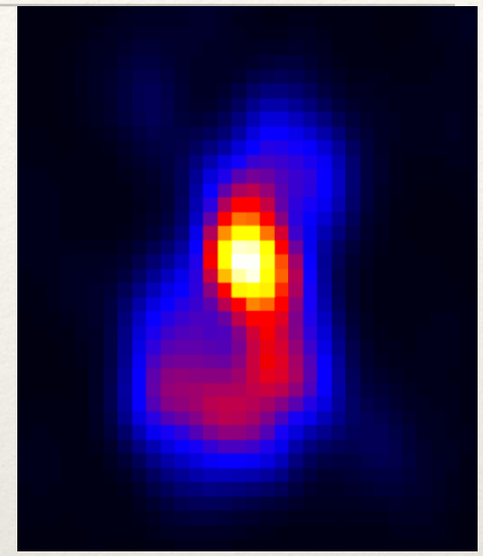


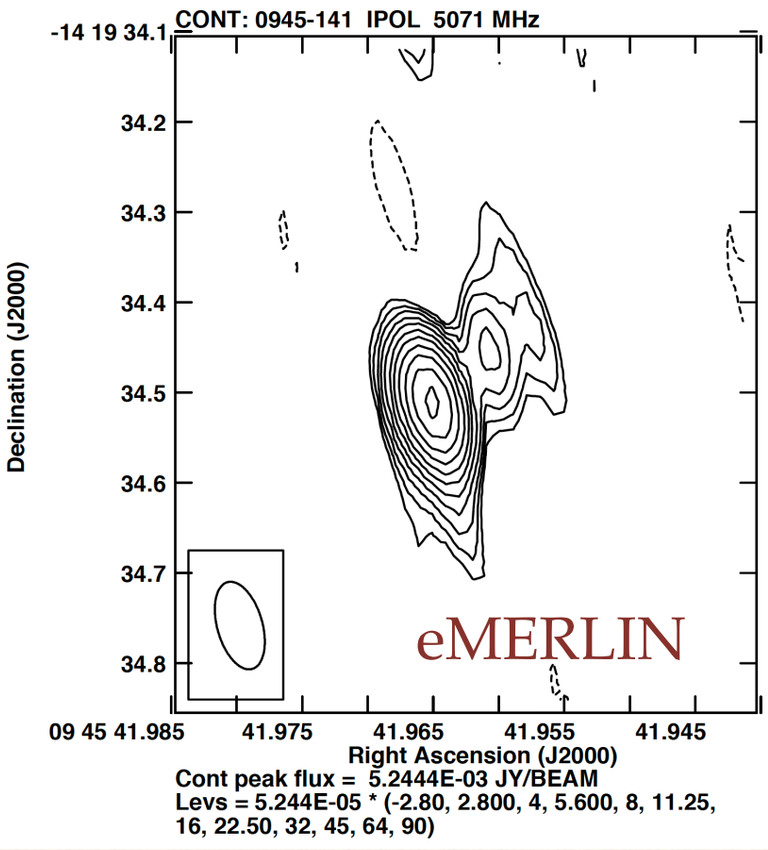
(Leipski+ 2006)

10-100 pc to Kpc: NGC2992

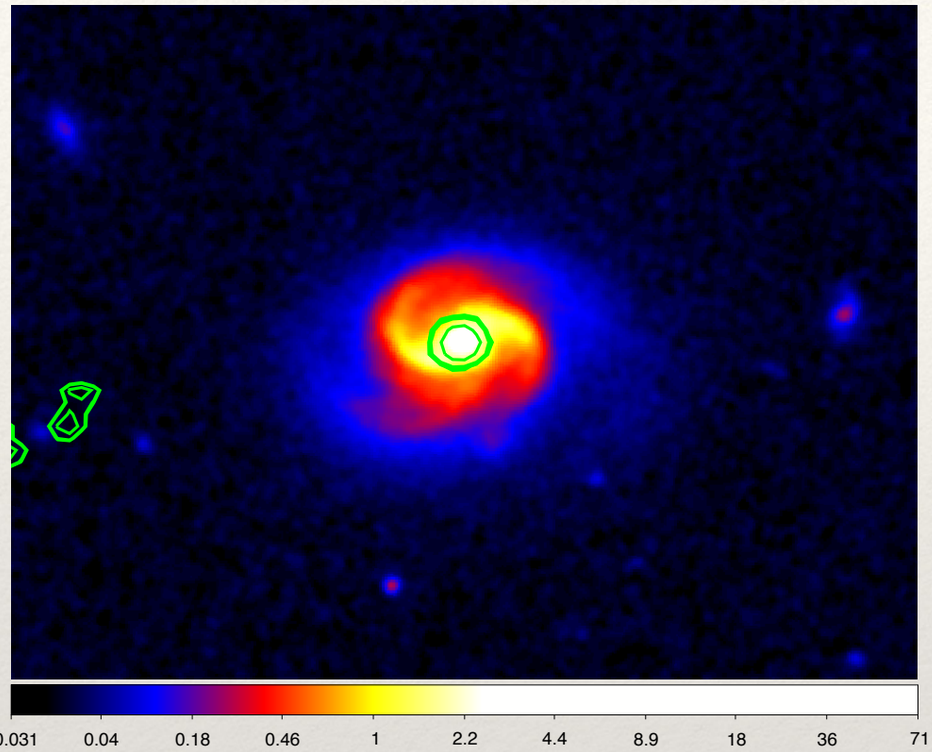
- Sy2 at z=0.0077
- 2 kpc VLA lobes at 5 GHz
- 40 pc eMERLIN one-sided jet at 5 GHz
- Curved jets from pc - sub-kpc - kpc-scales imply a connection from AGN to lobes
- Secondary lobes revealed in NGC2992 from polarimetry (CHANGES, *Irwin+ 2017*)
- Supports a jet origin for the lobes

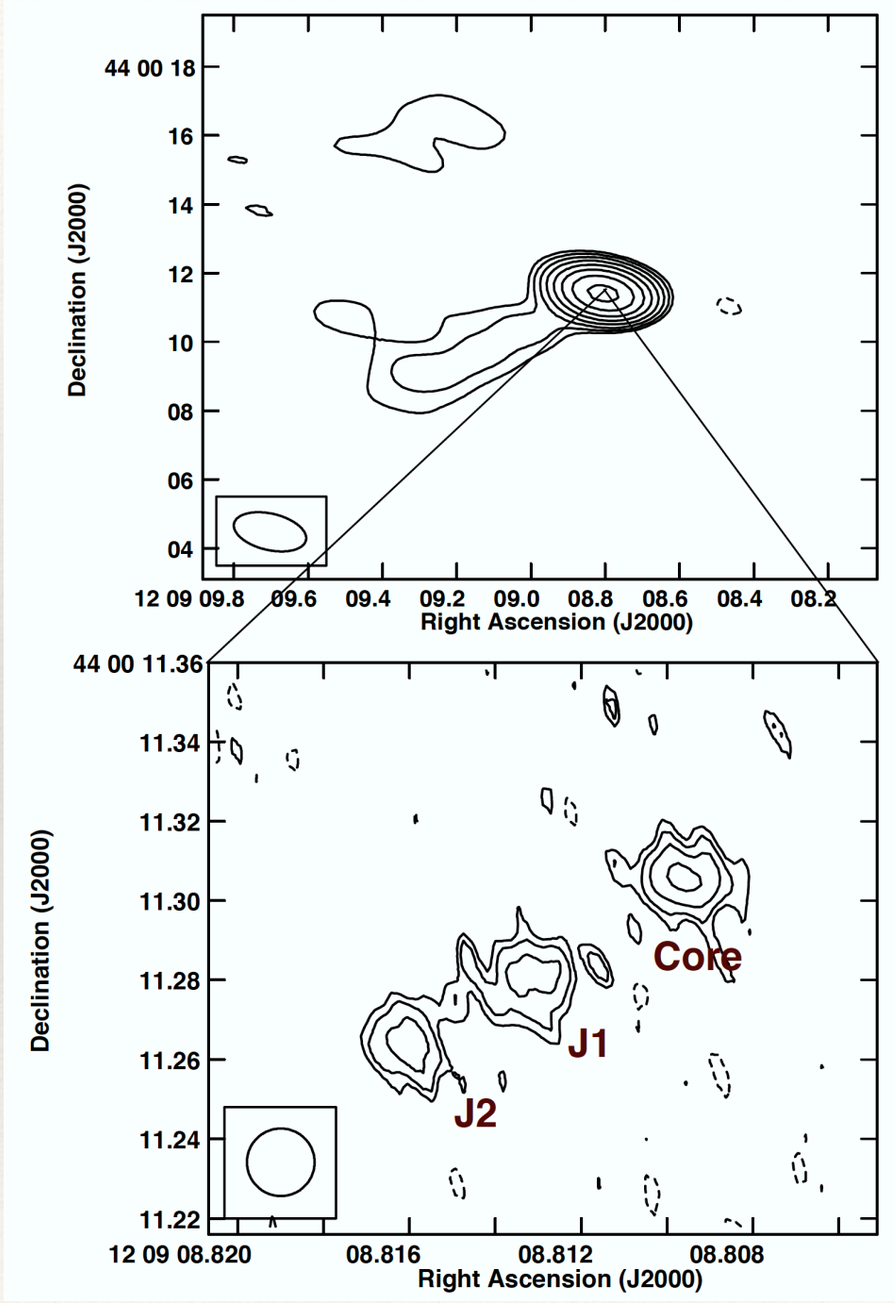






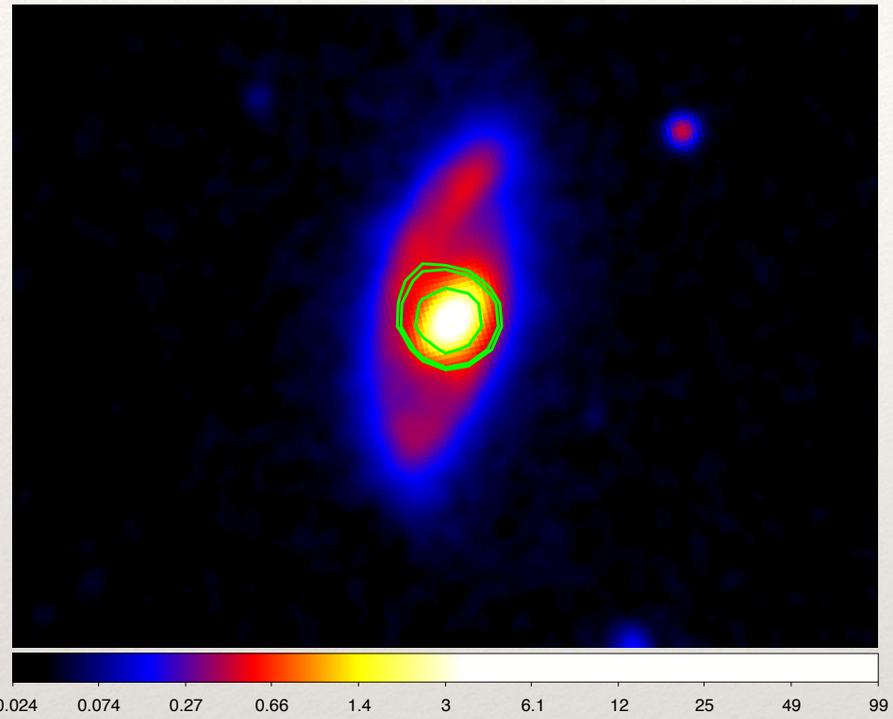
Seyferts on Parsec-scales: KISSR1219

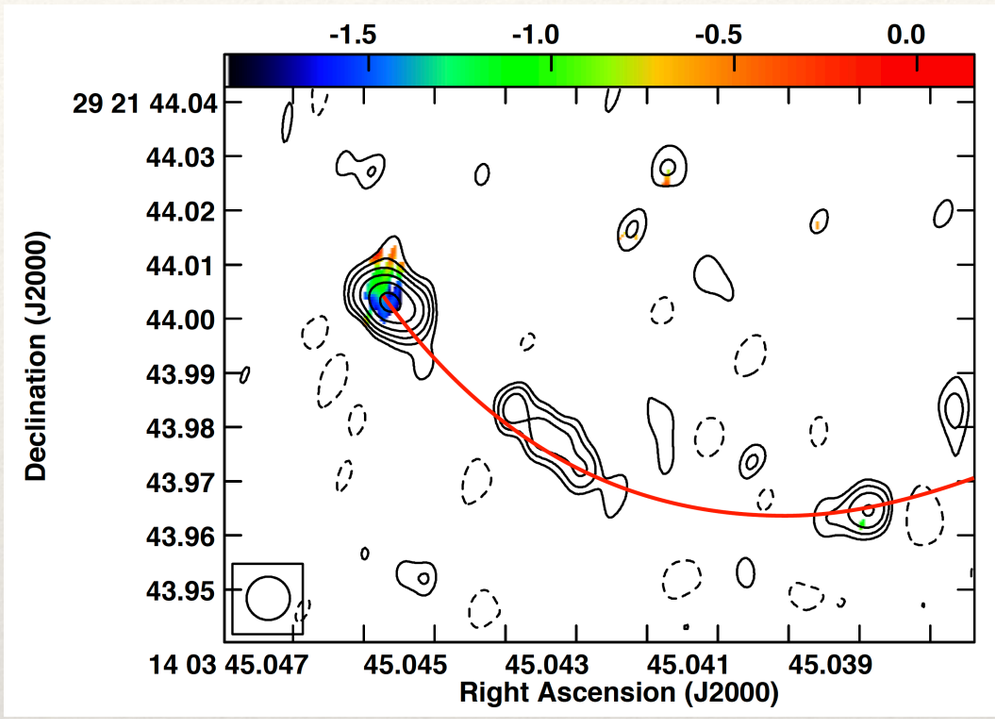




- Seyfert 2 at z = 0.0375
- FIRST flux density, S_{FIRST}~6 mJy
- Steep spectrum 5 kpc jet with EVLA, 70 pc jet with VLBA at 1.5 GHz
- (*Kharb+ 2017*)

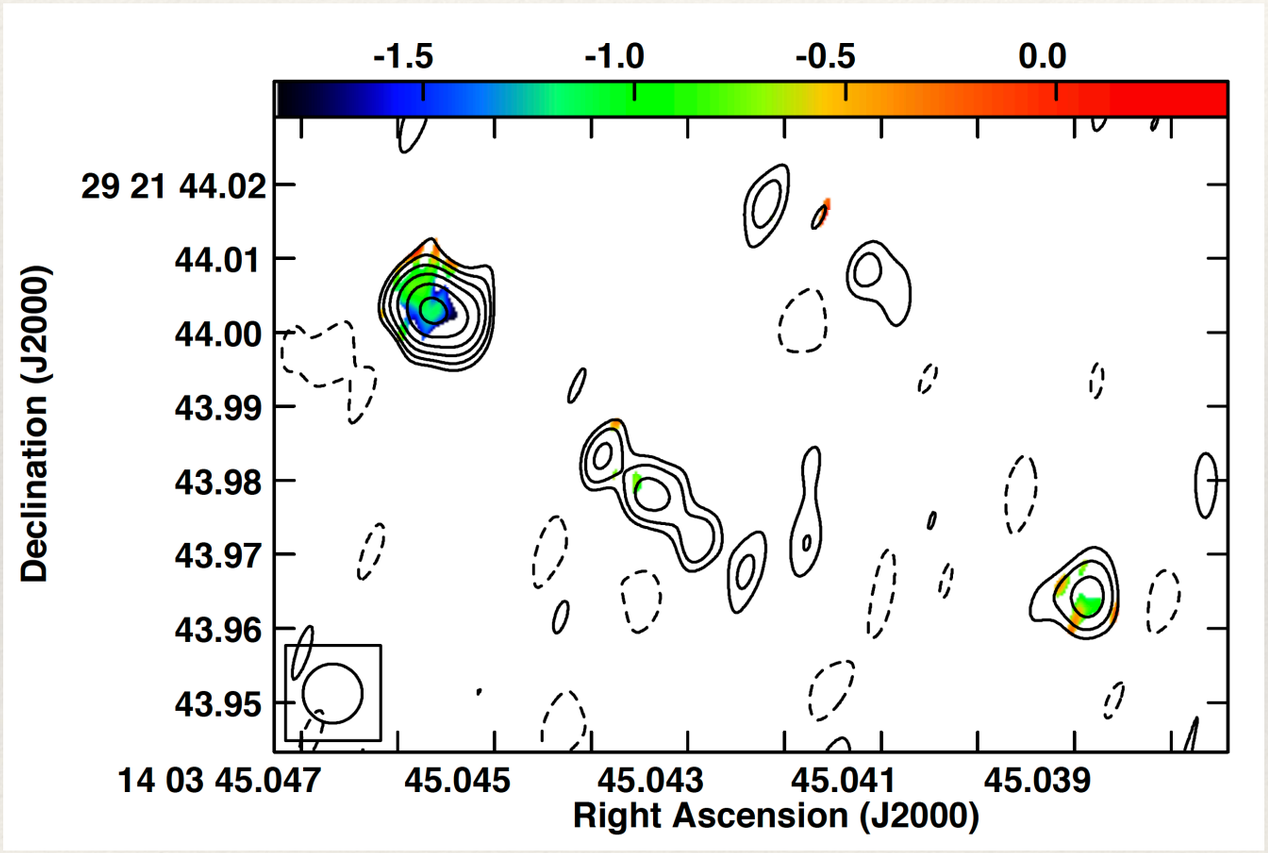
Seyferts on Parsec-scales: KISSR434





- Seyfert 2 at z=0.0641
- S_{FIRST} ~6 mJy
- 150 parsec VLBA jet at 1.4 GHz (*Kharb+ 2019*)

Jet One Sidedness



- (*Kharb+ 2019*)

Jet-to-counterjet surface brightness ratio

$$J=\left(\frac{1+\beta\cos\theta}{1-\beta\cos\theta}\right)^{p}$$

Observed J ≥ 21

Sy 2 with torus half opening angle ~ 50 deg (Simpson+ 1996)

Jet inclination ≥ 50 deg

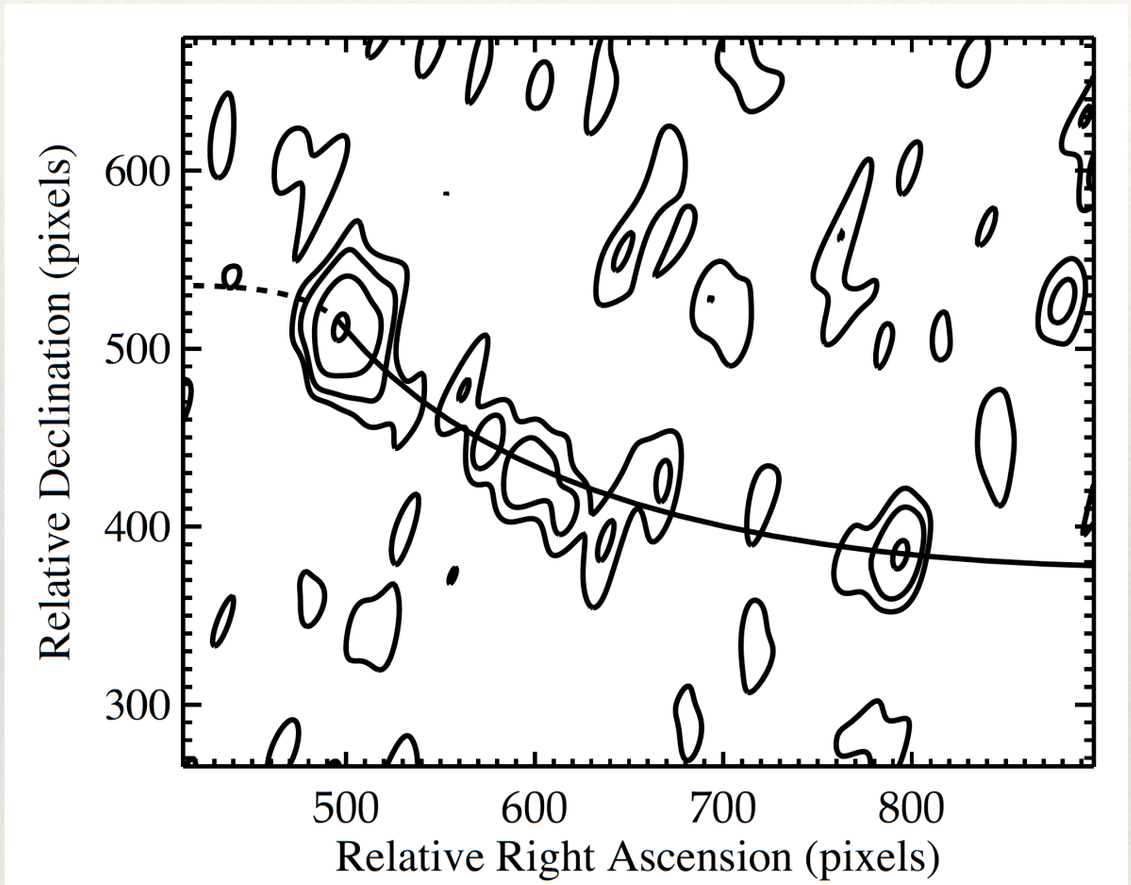
For p = 2+$\boldsymbol{\alpha}$ = 3

Jet speed ≥ *0.75c*

(*v = 0.9c* in III Zw 2; *Brunthaler+ 2000*)

In KISSR1219, Jet speed ≥ *0.55c* to ≥ *0.25c* from parsec to kpc-scales for jet inclination ≥ 50 deg

Jet Bending - Rotating ISM?



- (*Kharb+ 2019*)

"Bending equation" from momentum transfer relation (*de Young 2000*):

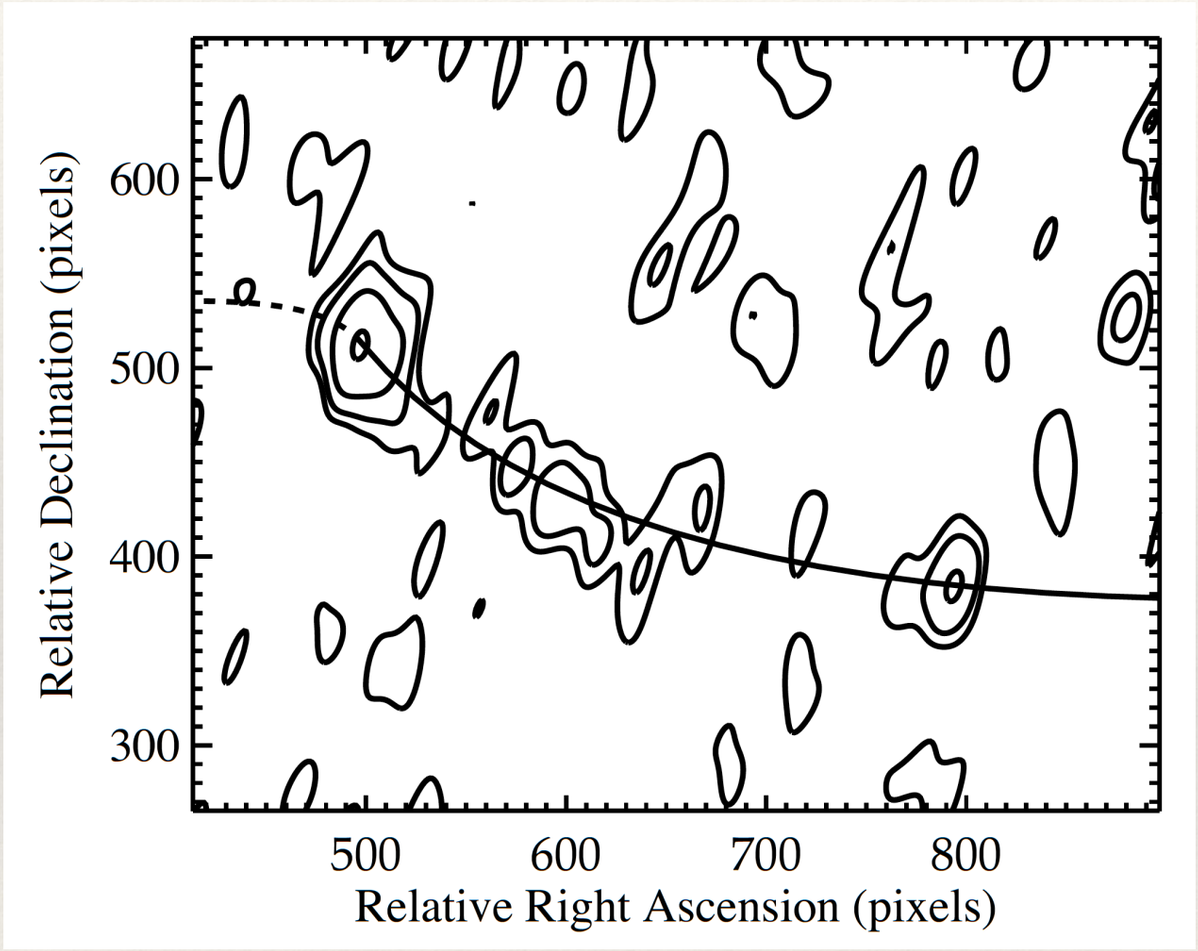
$$\rho_{jet}.v_{jet}^2/R_b = \rho_{ext}.v_{rel}^2/R_{sc}$$

$R_{sc} = R_{jet} = 10$ parsec, $R_b = 375$ parsec

$\eta = \rho_{jet}/\rho_{ext} = 0.01$ (light jet) ➡

$v_{rel} > 3600$ km/s. Too large!

Jet Bending - Precession?



- (*Kharb+ 2019*)

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

Jet inclination = 50 deg (fixed)

Jet Speed = 0.75c (fixed)

Precession cone half-opening angle = 40 deg

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.

- For radio powerful galaxies, BBH separations ~0.05 pc (*Krause+ 2019*)

Summary

- RQAGN exhibit radio outflows on scales of 10-100 pc to 10-20 kpc
- Low frequency observations with the GMRT detect a large fraction of radio lobes, but also more galactic emission
- Trying to disentangle AGN & Stellar contribution using Spectral Indices + Polarimetry
- VLBI reveals (one-sided!) AGN jets.
- Multiple misaligned Lobes + Curved jets appearing to connect to the lobes support an AGN jet origin for RQAGN lobes.