A Multi-scale Study of Outflows from Low Luminosity AGN

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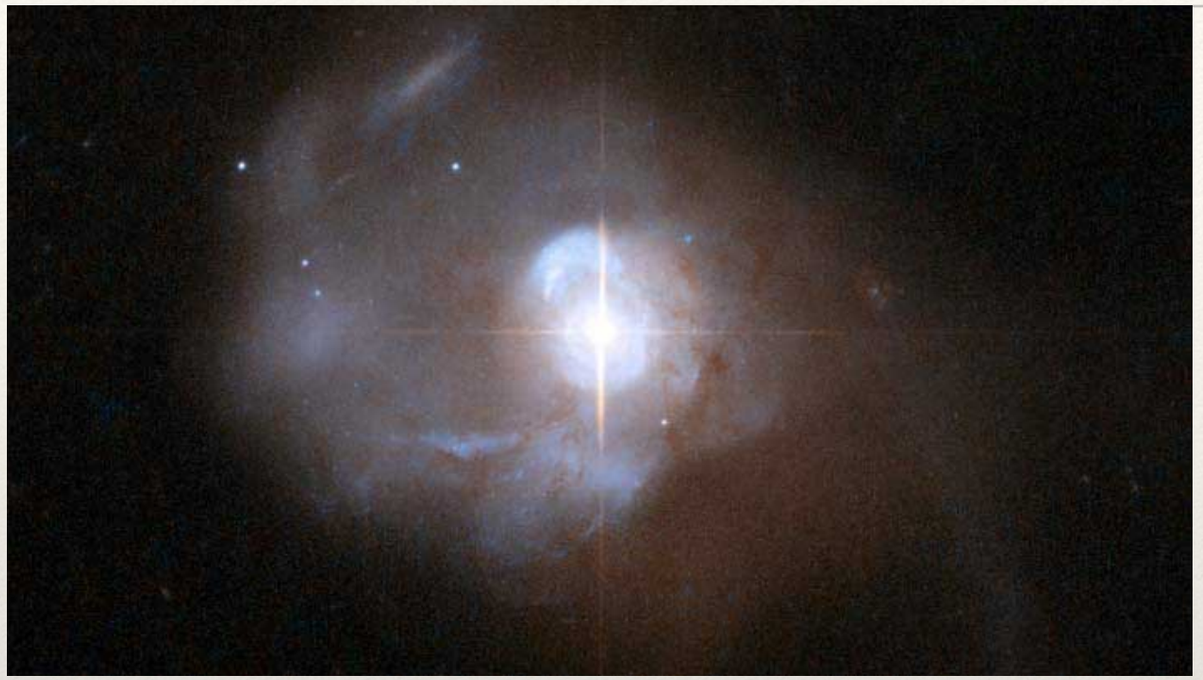
Low Luminosity AGN (LLAGN)

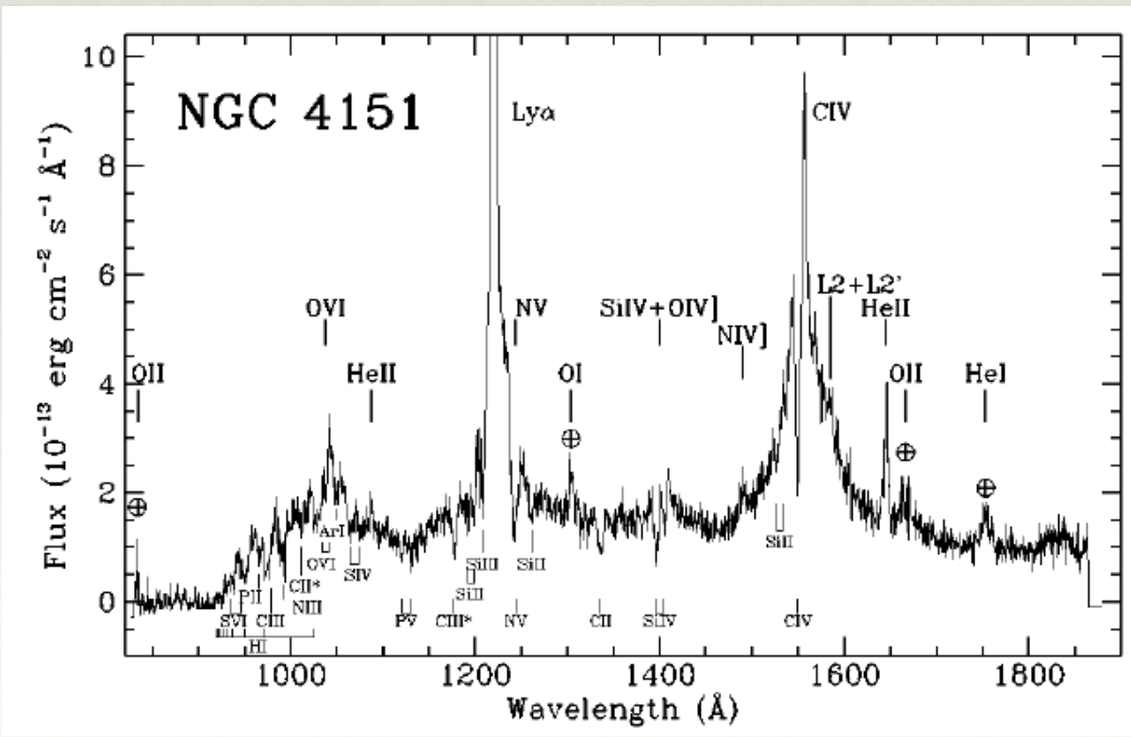
- $L_X < 10^{42}$ ergs/s (Ptak 1999)
- $L_{H\alpha} < 10^{40}$ ergs/s (Ho+ 1997)
- Seyfert galaxies
- Low Ionization Nuclear Emission-line Regions (LINERs) - spectra like Seyferts but low ionisation lines
- “Transition” sources - spectra between LINER/HII regions

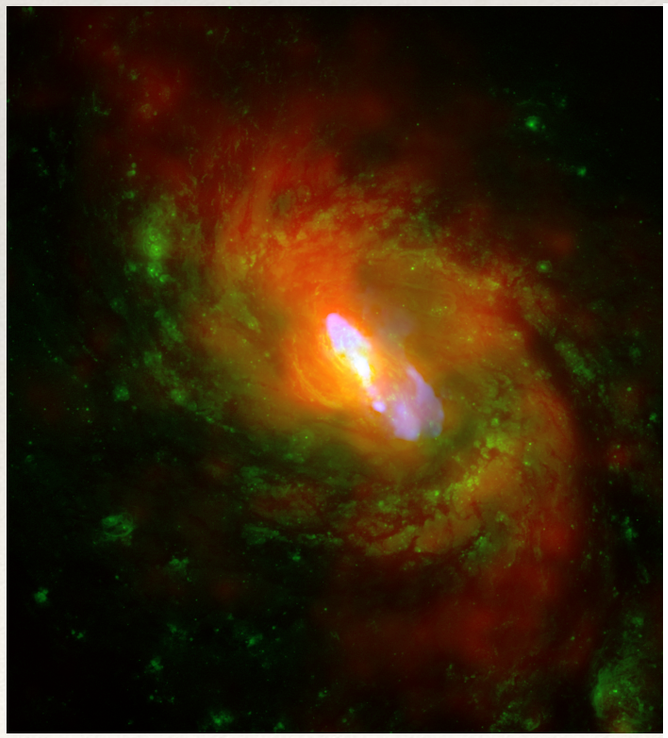
Seyfert Galaxies



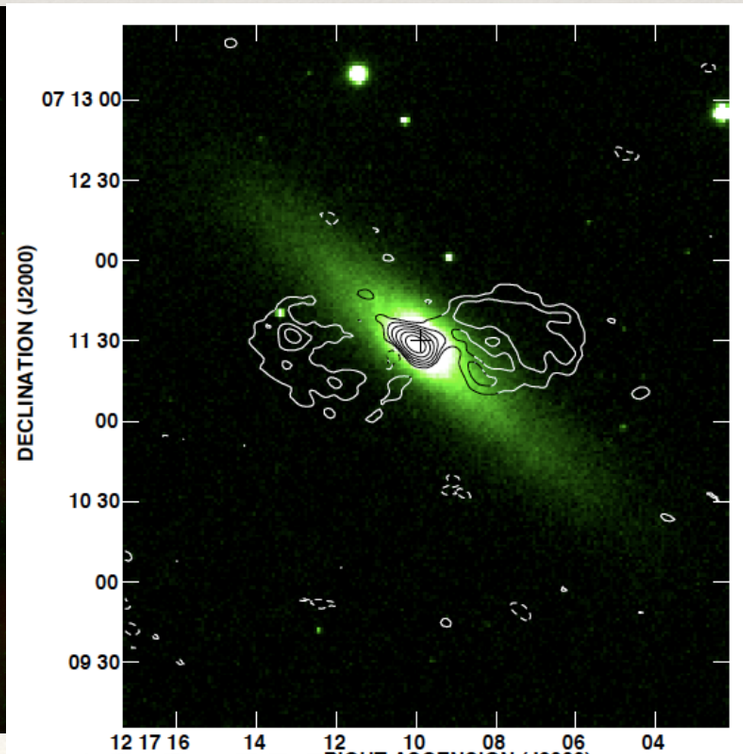
Carl Seyfert (1943)

- Spirals with bright star-like nuclei
- Peculiar emission line spectrum
- 10-100 pc – 10-20 kpc radio outflows
  (Baum+ 1993, Thean+ 2000,
  Gallimore+ 2006, Kharb+ 2016, …)



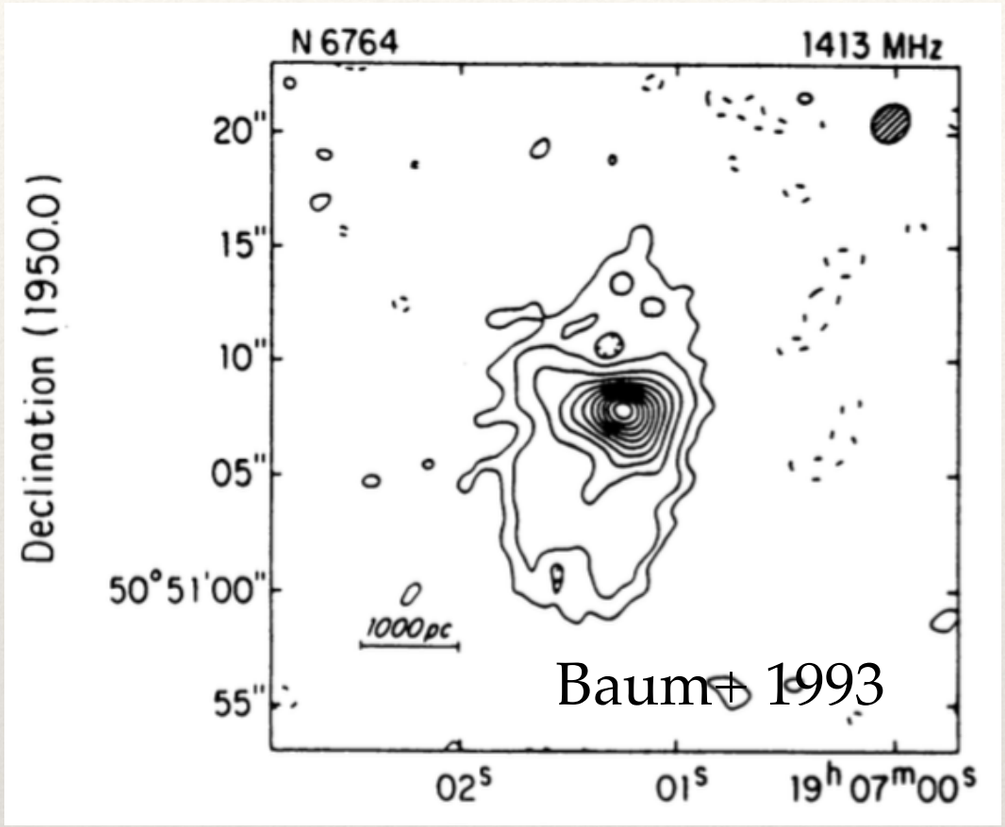


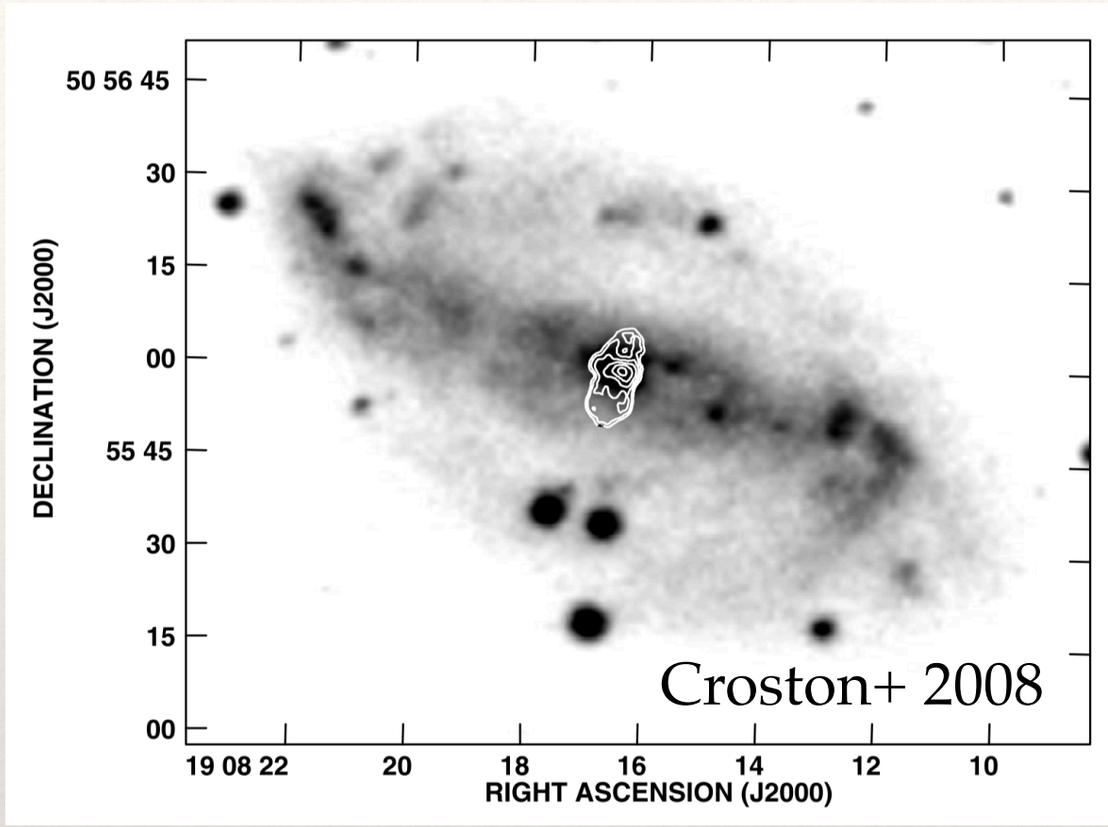
NGC1068



NGC4235

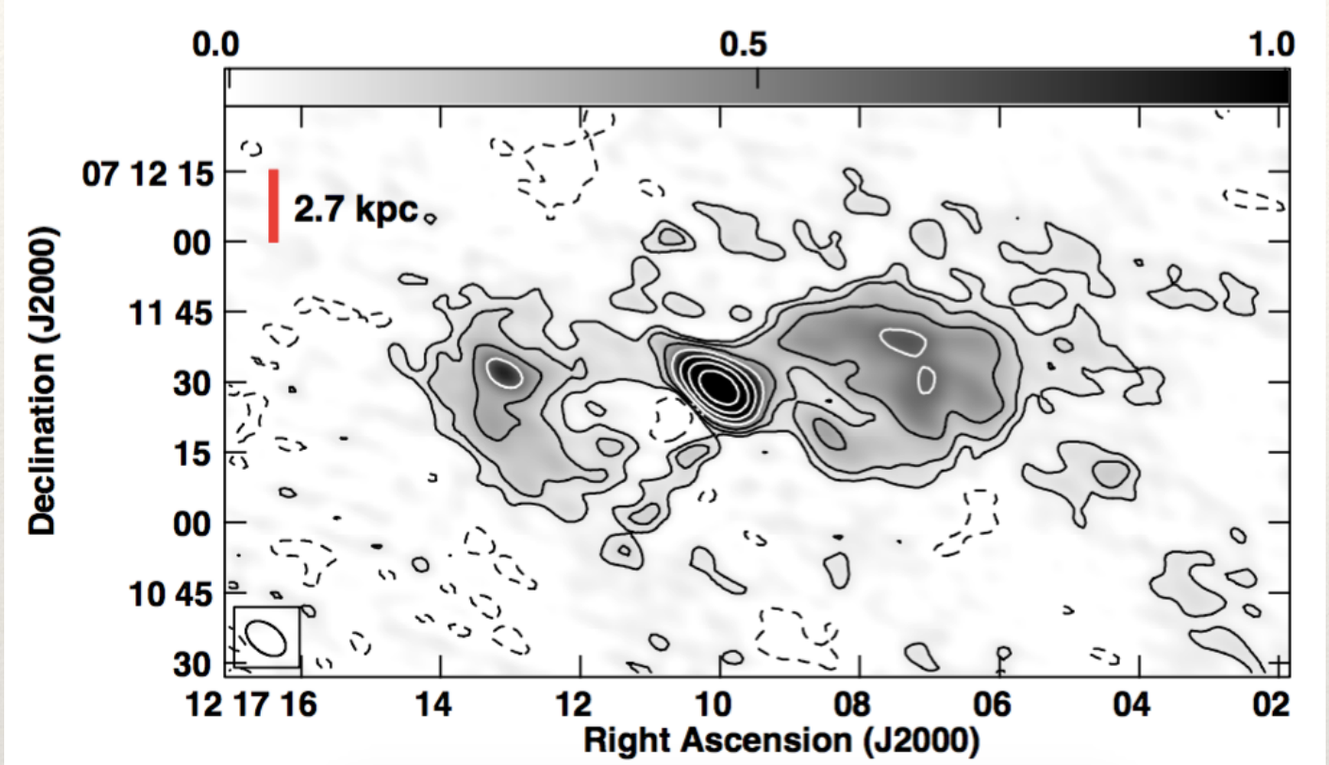
The Origin of Kiloparsec-scale Radio Structures (KSRs)

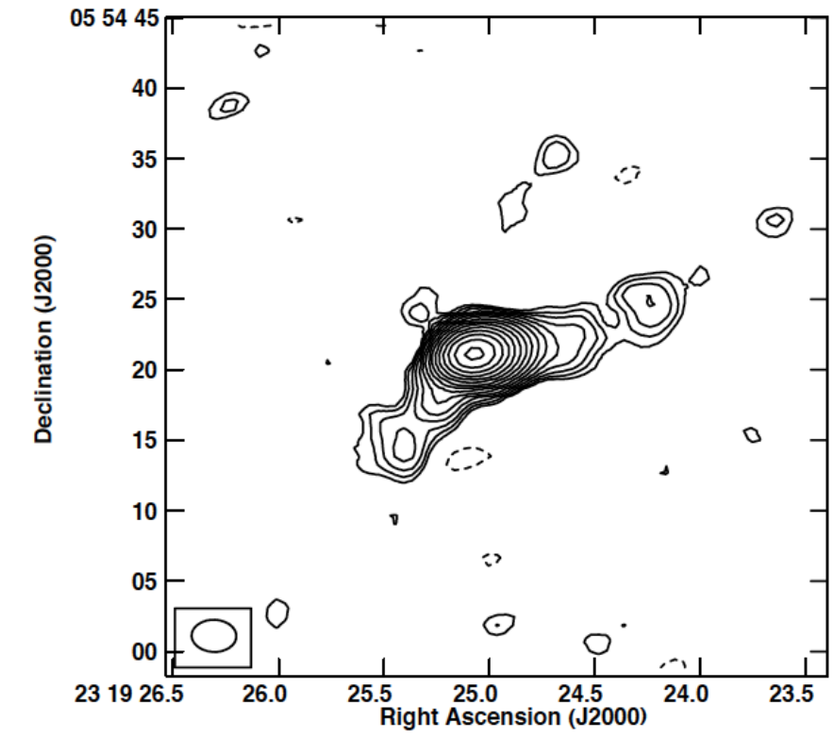


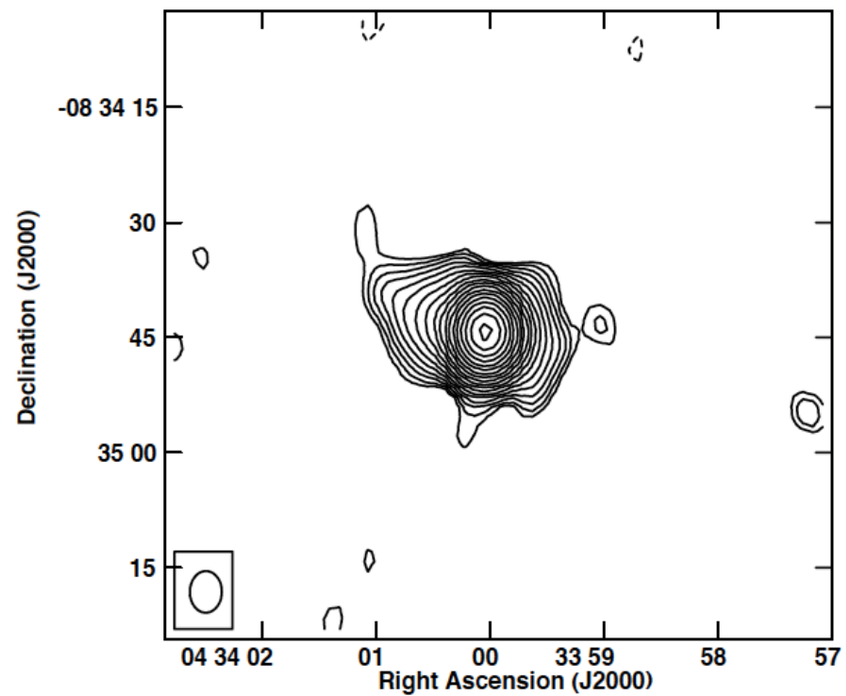


- Baum+ 1993, KSRs are starburst superwinds
- Colbert+ 1996, KSRs in Seyferts differ from starbursts. Seyfert KSRs are AGN-driven
- Gallimore+ 2006, KSRs mostly AGN-driven, but starburst winds cannot be ruled out

A KSR Study with the GMRT

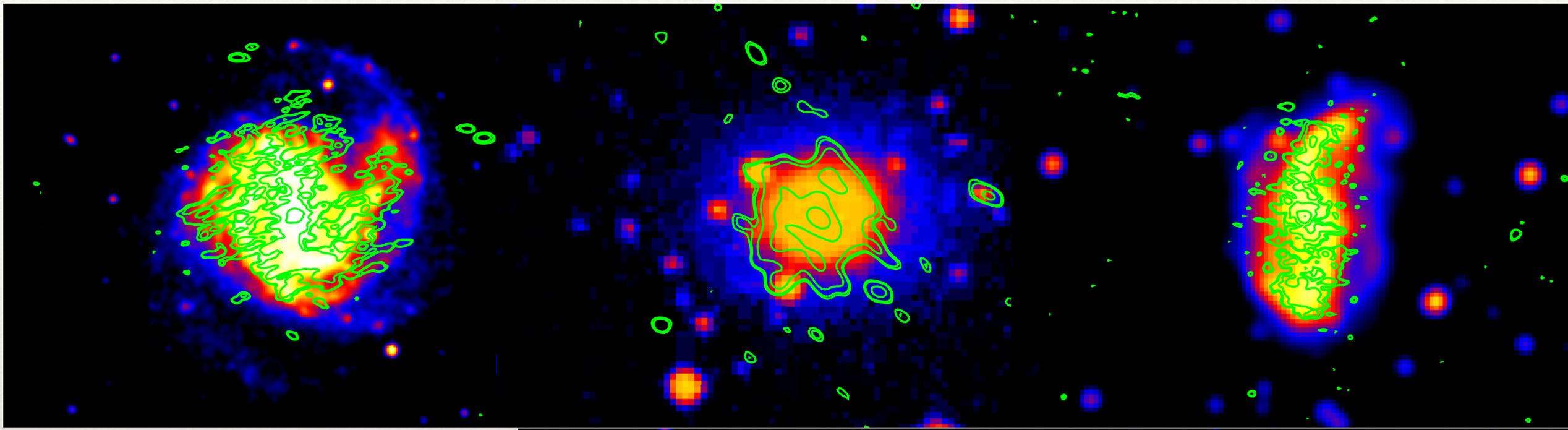






- ~70 Seyferts+LINERs with GMRT at 325, 610, 1390 MHz. $\boldsymbol{\theta}$ ~ 2″, 5″, 10″
- >50% show KSRs (44% in 5 GHz VLA study of Gallimore+ 2006)
- NGC4235 @610 MHz (24 kpc), IC1481 (11 kpc) & NGC1614 @1.4 GHz (10 kpc)

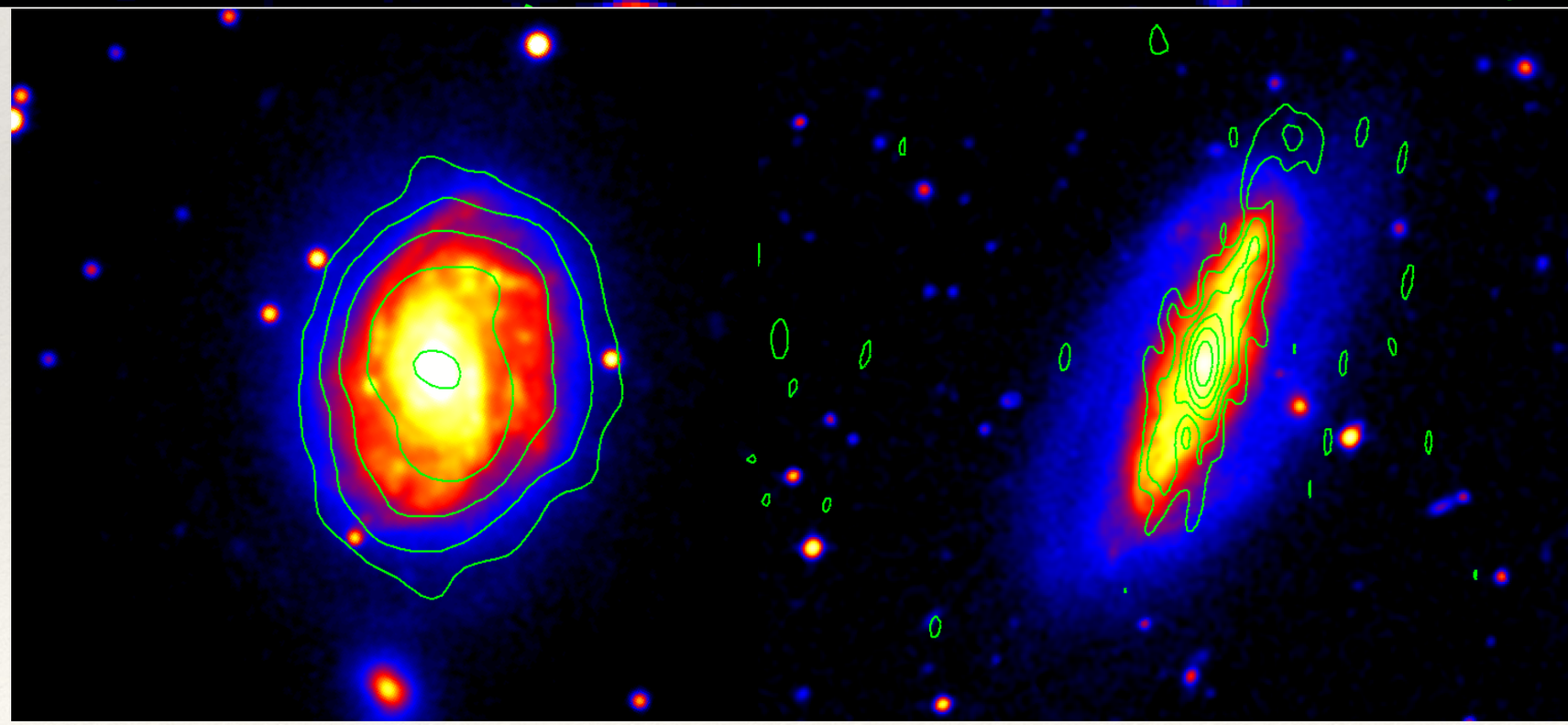
Emission from Host Galaxies



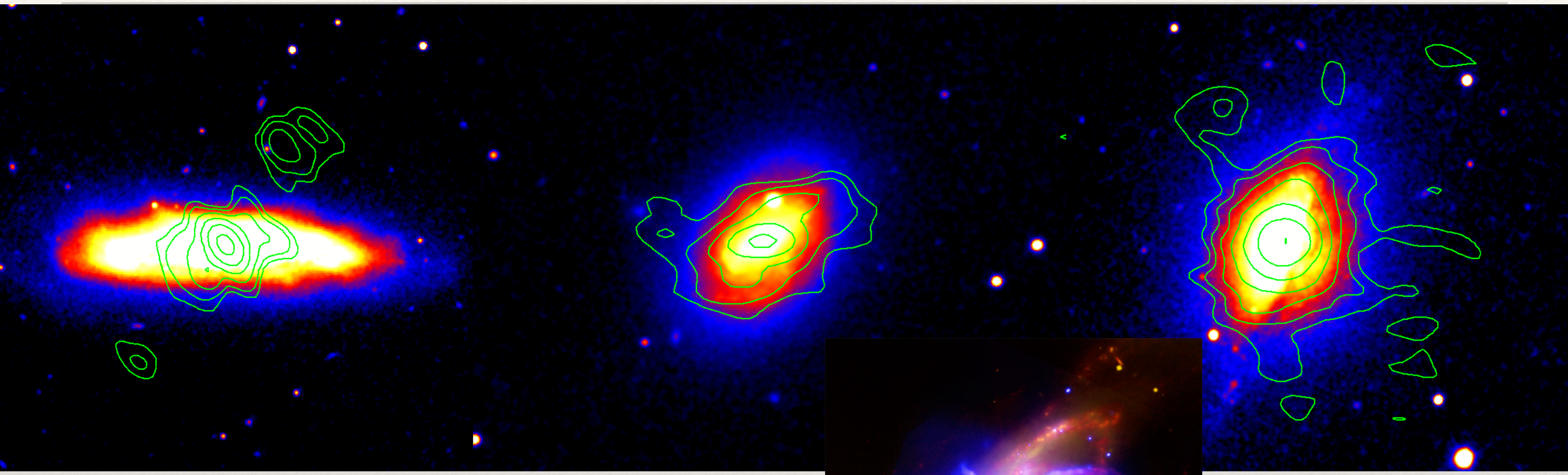
Galaxy emission in ~25% of sources at 1.4 GHz (also VLA, Edelson 1987)

>50% at 610 MHz (top)

>70% at 325 MHz (bottom)



Both AGN & Galactic Contributions

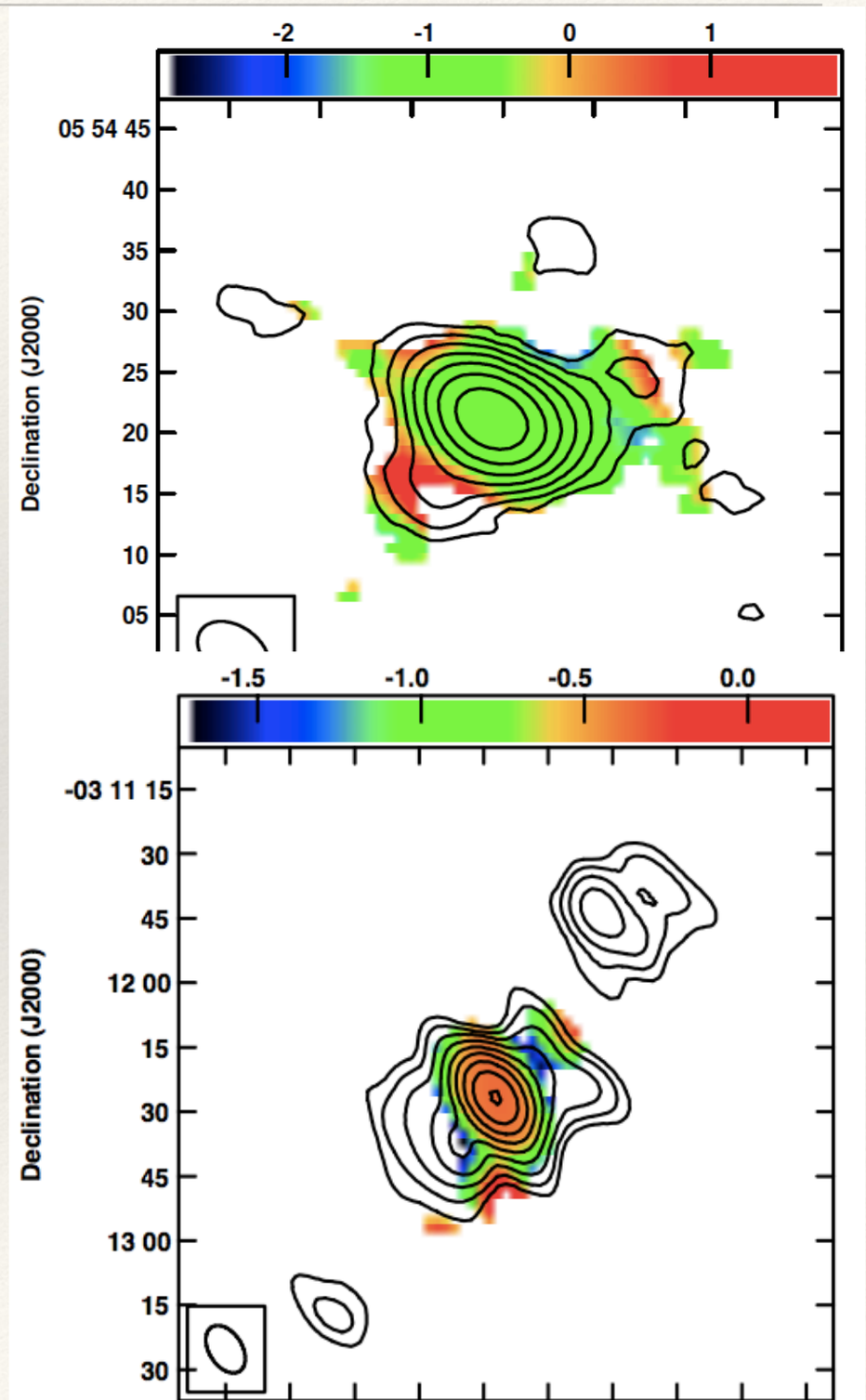


The “anomalous arms” of NGC4258

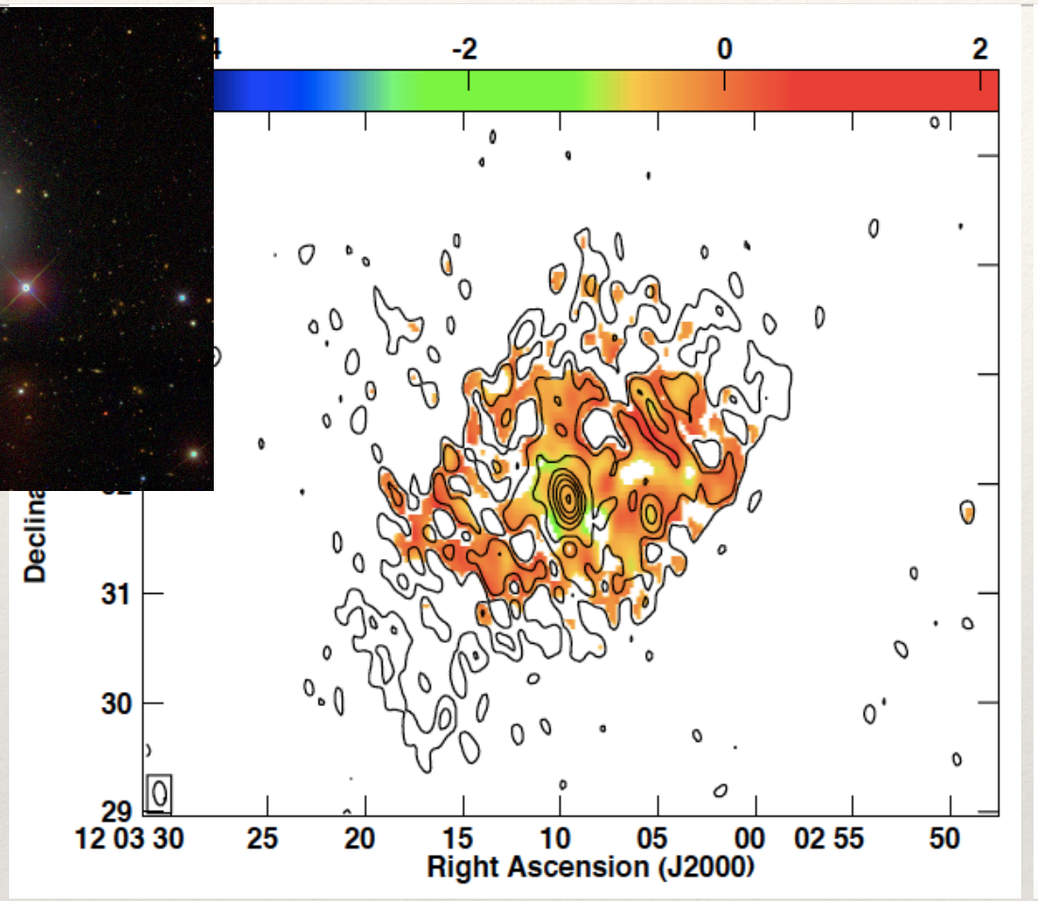
- How to disentangle the AGN and stellar contributions ?

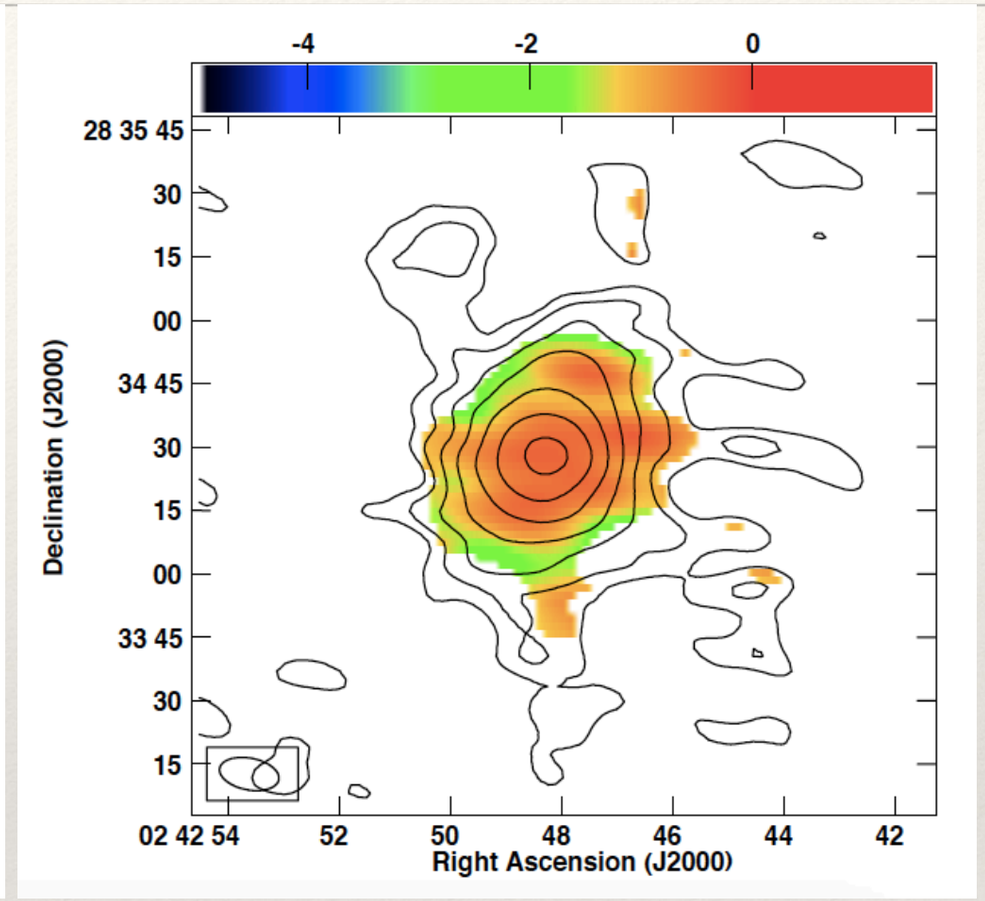
Spectral Indices of KSRs

- KSRs: steep-spectrum radio cores, jets
- IC 1481, $\alpha \sim -0.8 \pm 0.1$ (GMRT 610 - 1390 MHz)
- NGC5506, $\alpha \sim -0.69 \pm 0.04$ (GMRT 325 MHz - VLA 4.9 GHz)
- Consistent with optically thin synchrotron emission



Disentangling AGN & Galactic Contributions



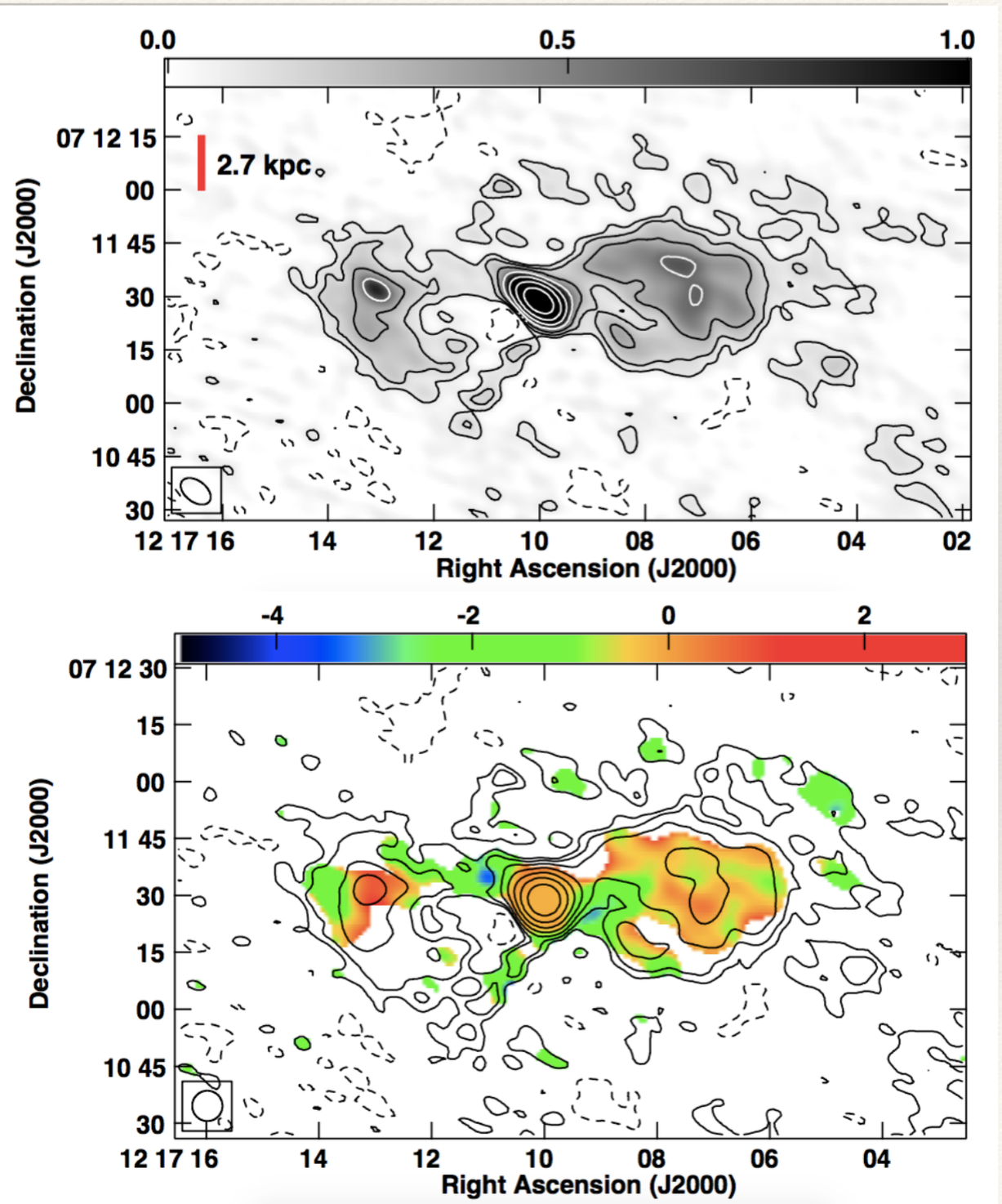


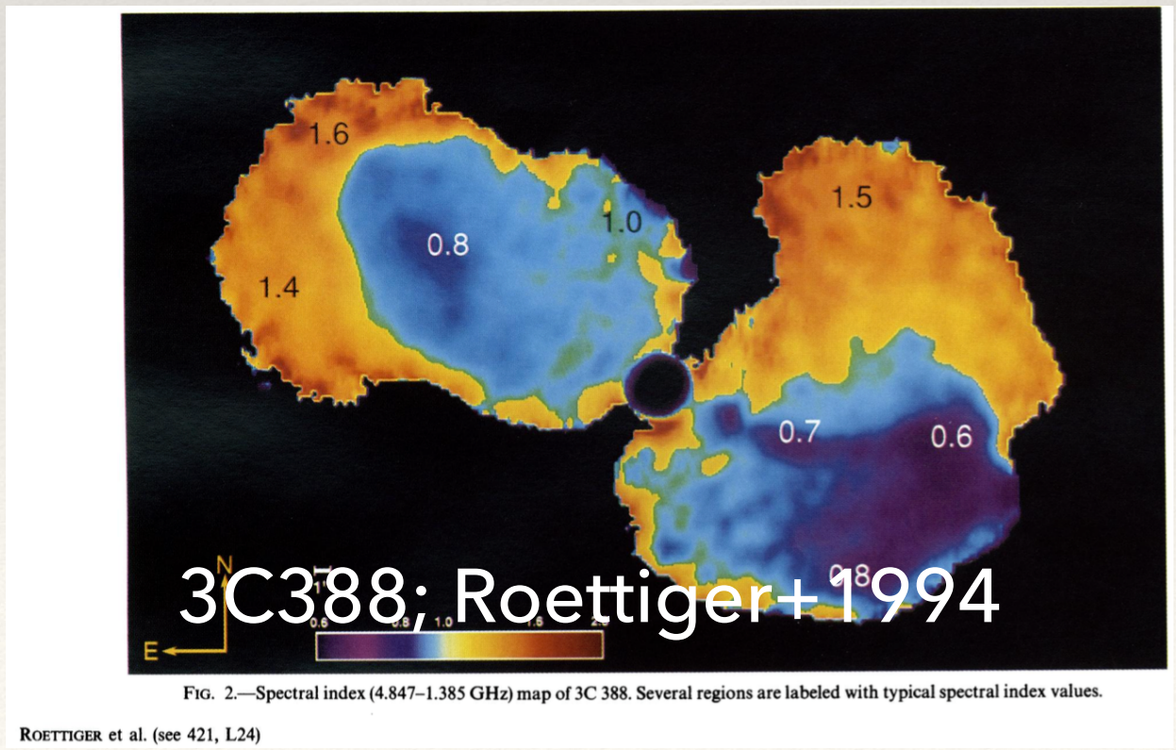
Spectral index from GMRT (325 MHz) & VLA (1425 MHz) $S \propto \nu^{\alpha}$

- **NGC4051**: Radio jet $\boldsymbol{\alpha} = -0.63 \pm 0.08$, consistent with synchrotron emission
- Galactic Disk emission $\boldsymbol{\alpha} = -0.12 \pm 0.06$, consistent with free-free emission
- **NGC1056**: Galactic Disk $\boldsymbol{\alpha} = -0.95 \pm 0.10$, consistent with synchrotron emission; Disk + Radio Continuum Halo **MIXED RESULTS**

Relic Lobes (?)

- NGC4235: 325 - 610 MHz spectral index
- Lobe $\alpha = -0.6 \pm 0.2$
- Relic Lobe $\alpha = -1.8 \pm 0.2$
- (Kharb+ 2016)





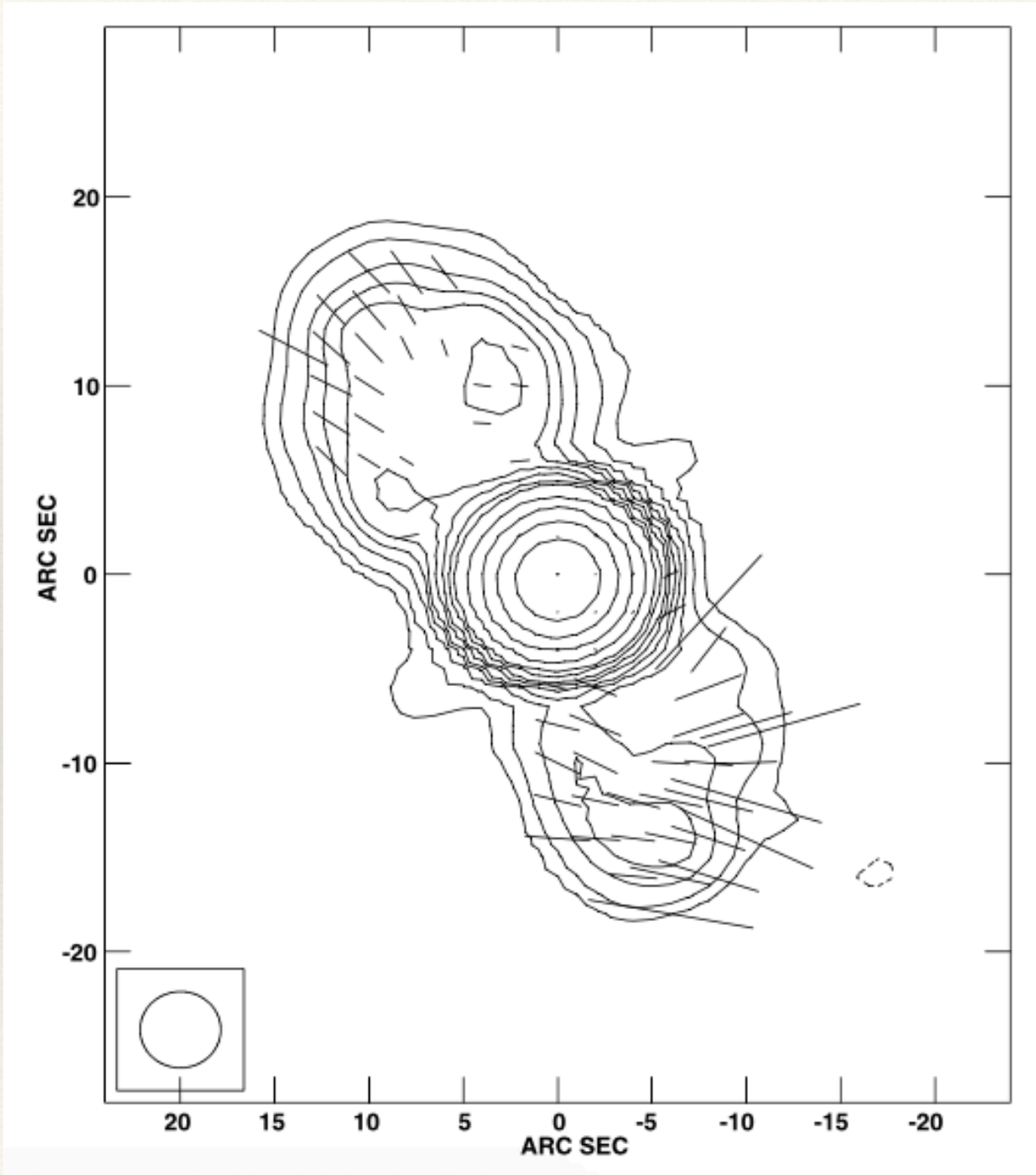
3C388; Roettiger+1994

FIG. 2.—Spectral index (4.847–1.385 GHz) map of 3C 388. Several regions are labeled with typical spectral index values.

ROETTIGER et al. (see 421, L24)

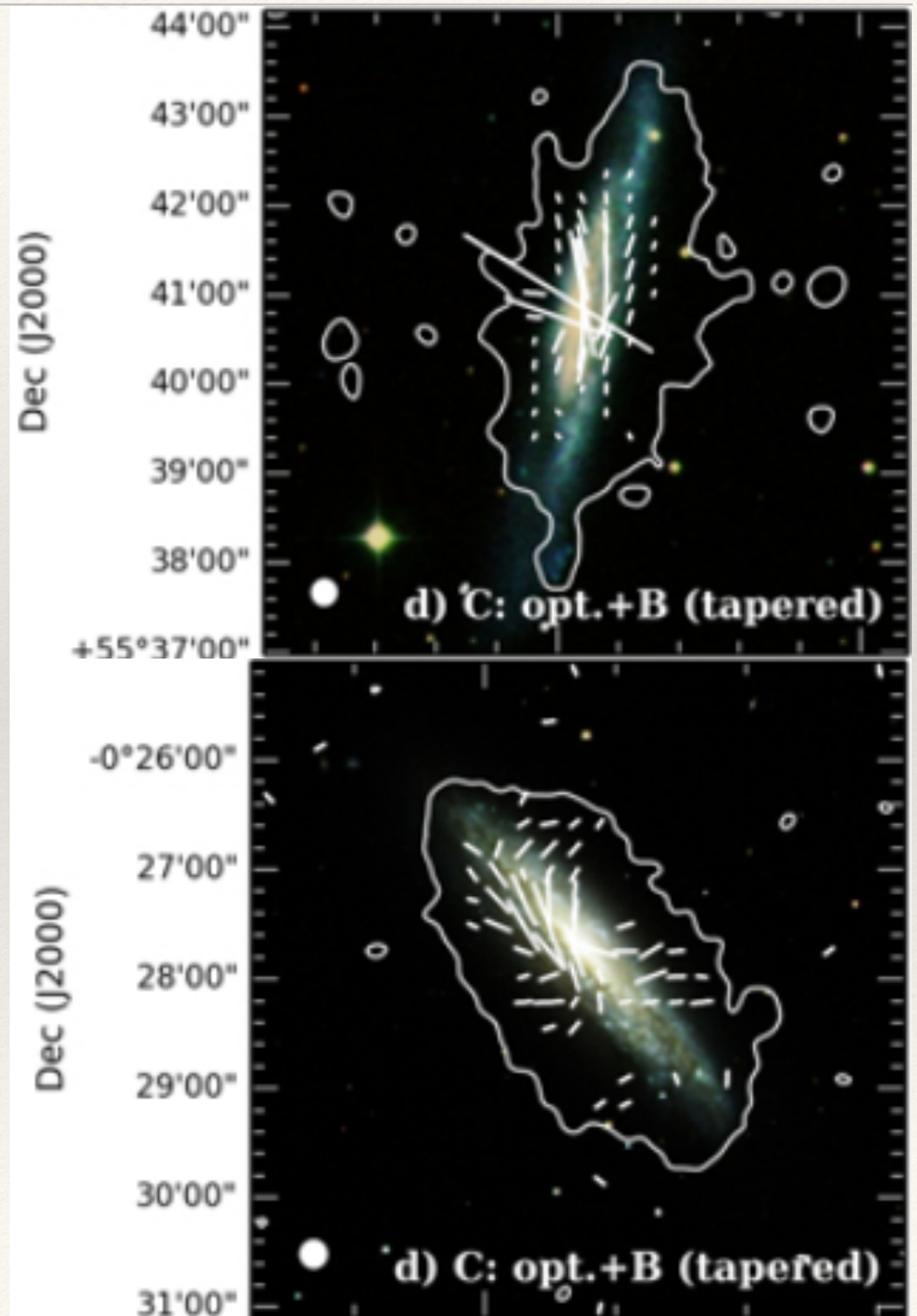
Disentangle AGN & Galactic contributions via Polarimetry

- 5 GHz VLA image of Mrk6 with polarization vectors (Kharb+ 2006)
- Fractional polarization - a few % to 50% at edges
- EXPECTATIONS from POLARIMETRY
- More organized magnetic fields in AGN outflows
- Galactic emission a mixture of non-thermal synchrotron + thermal free-free - Degree of polarization lower

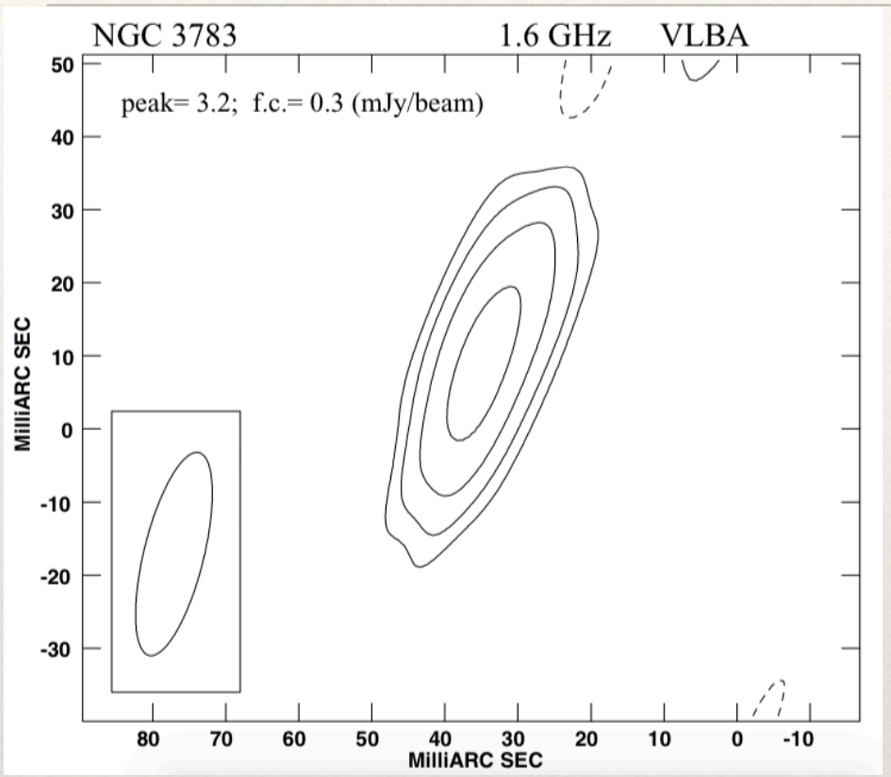


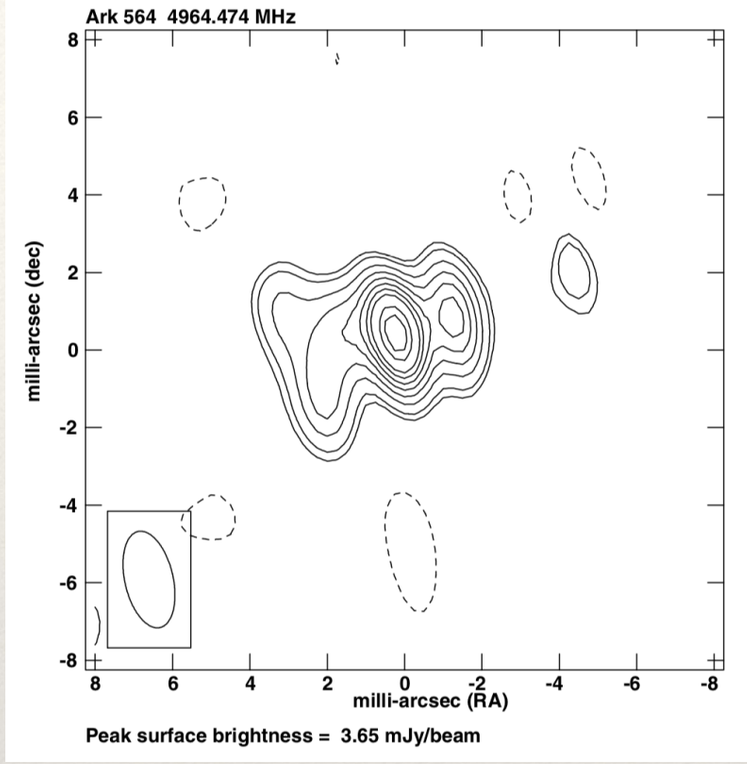
Disentangle AGN & Galactic Contributions via Polarimetry

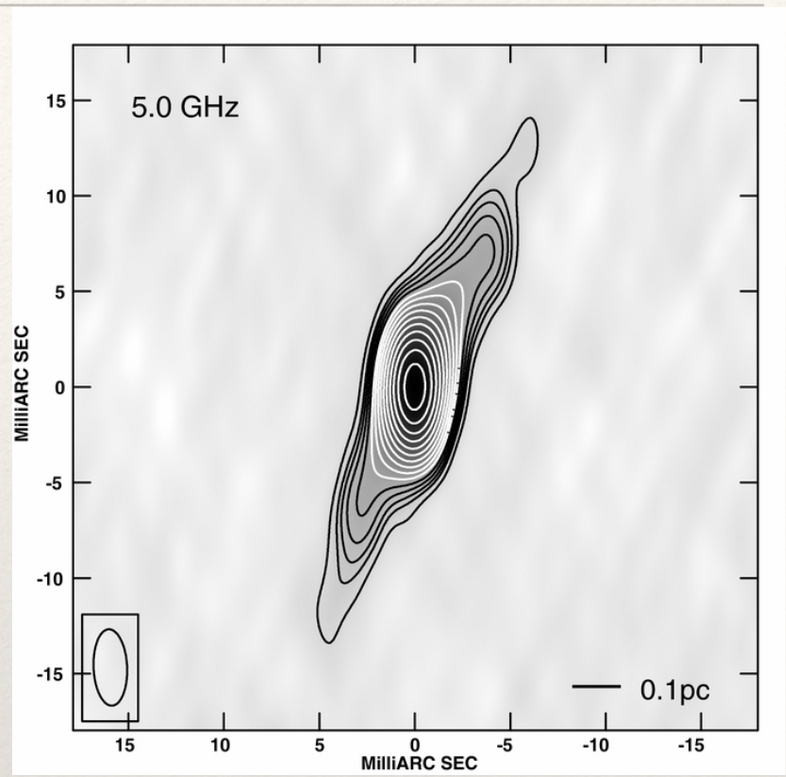
- CHANG-ES: 6 GHz EVLA D-array study of 35 edge-on spiral galaxies for Galactic Halos (Wiegert+ 2015)
- NGC3079 & NGC4666 with B-field vectors (POLN vectors rotated by 90 deg)
  - NGC3079 with a well-known KSR shows high polarization aligned with KSR PA
  - EVLA B-array at 1.5 & 6 GHz for polarimetry of 10 Seyferts w/ KSRs & 8 edge-on Starburst galaxies (PI: Kharb)



Parsec-scale Radio Emission in Seyferts



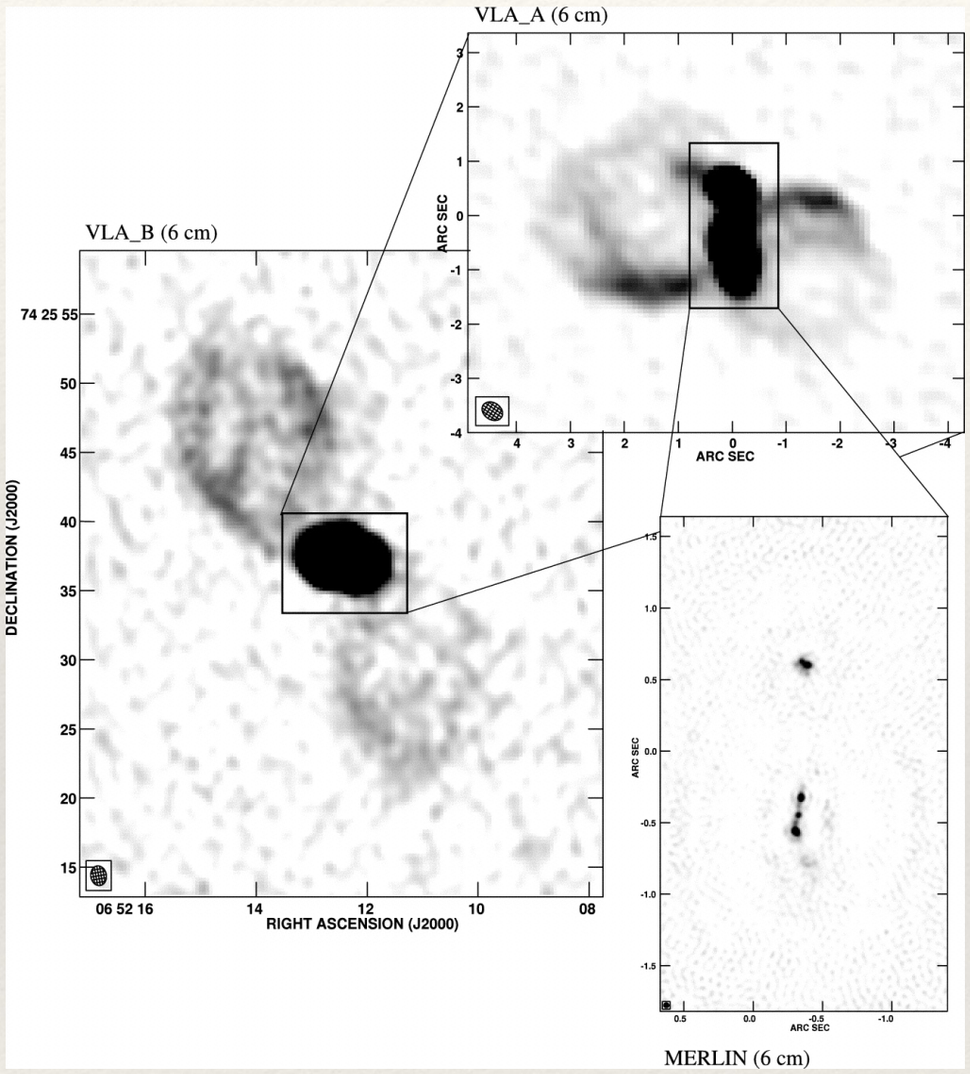




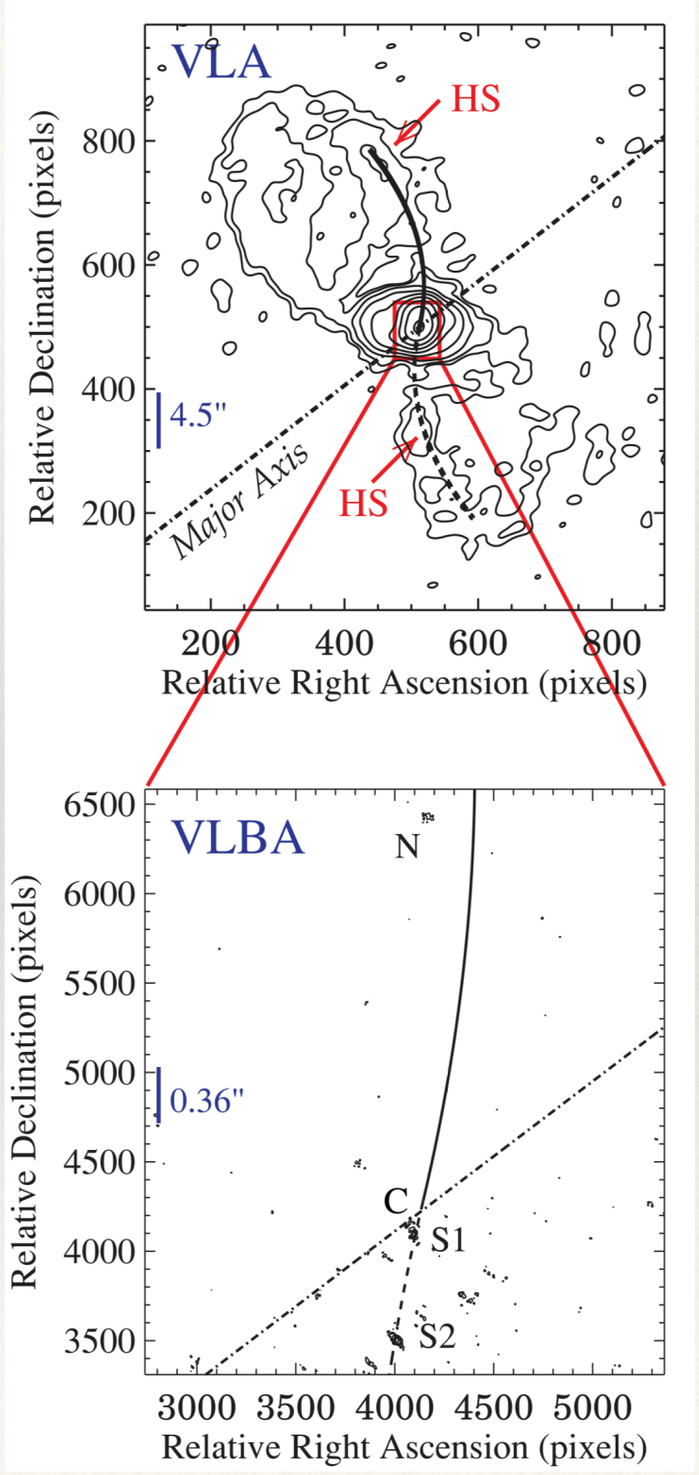
NGC3783 (Orienti+ 2010) Ark564 (Lal+ 2004) NGC4594 (Hada+ 2013)

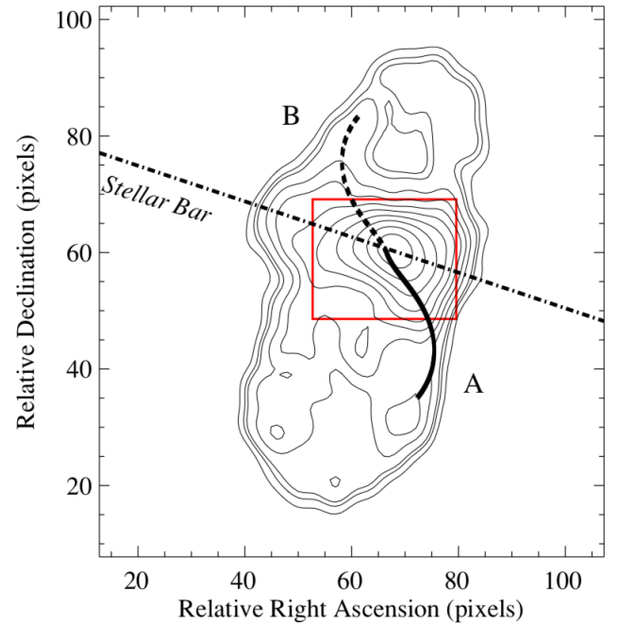
- Faint cores, wiggly jets. Accretion-disk warping or jet instabilities
- Cores have $T_B \sim 10^6$ - 10^8 K. Flat or inverted spectral indices. Weak AGN (Middelberg+ 2005, 2007, Giroletti+ 2009, Panessa+ 2013, others)

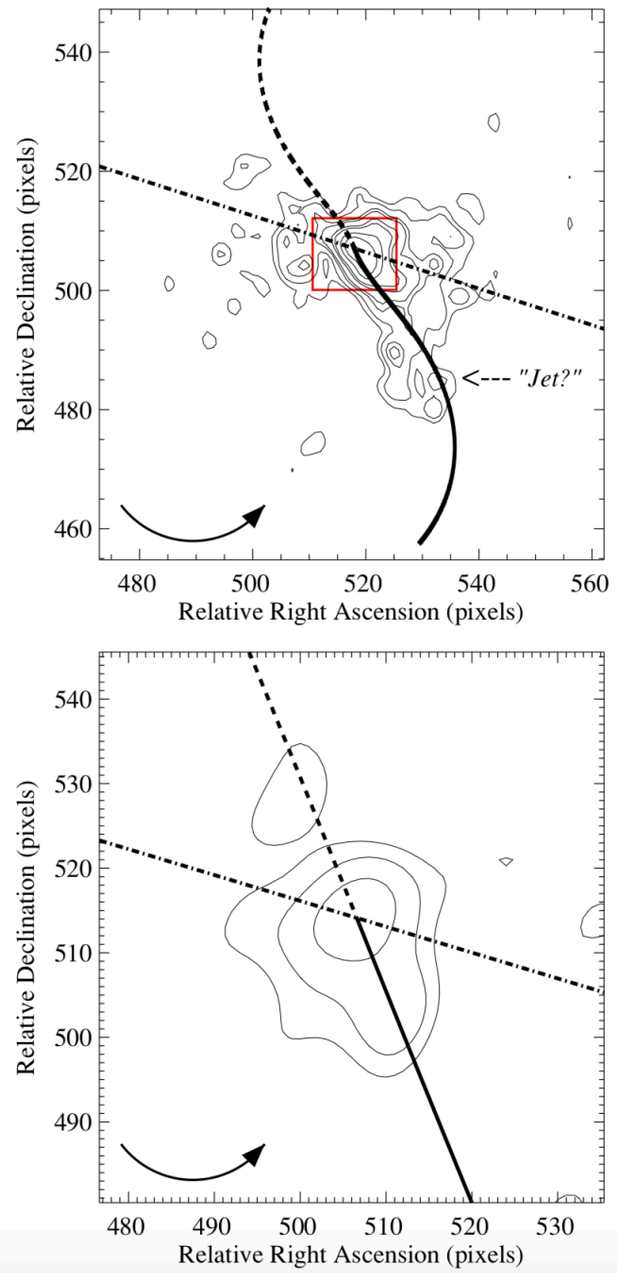
Parsec to Kiloparsec-Scales



- Frequent misalignment: jet precession or pressure gradients + jet-ISM interaction (Middelberg+ 2005)
- Mrk6 (Kharb+ 2006, 2014)
- NGC6764 (Kharb+ 2010)

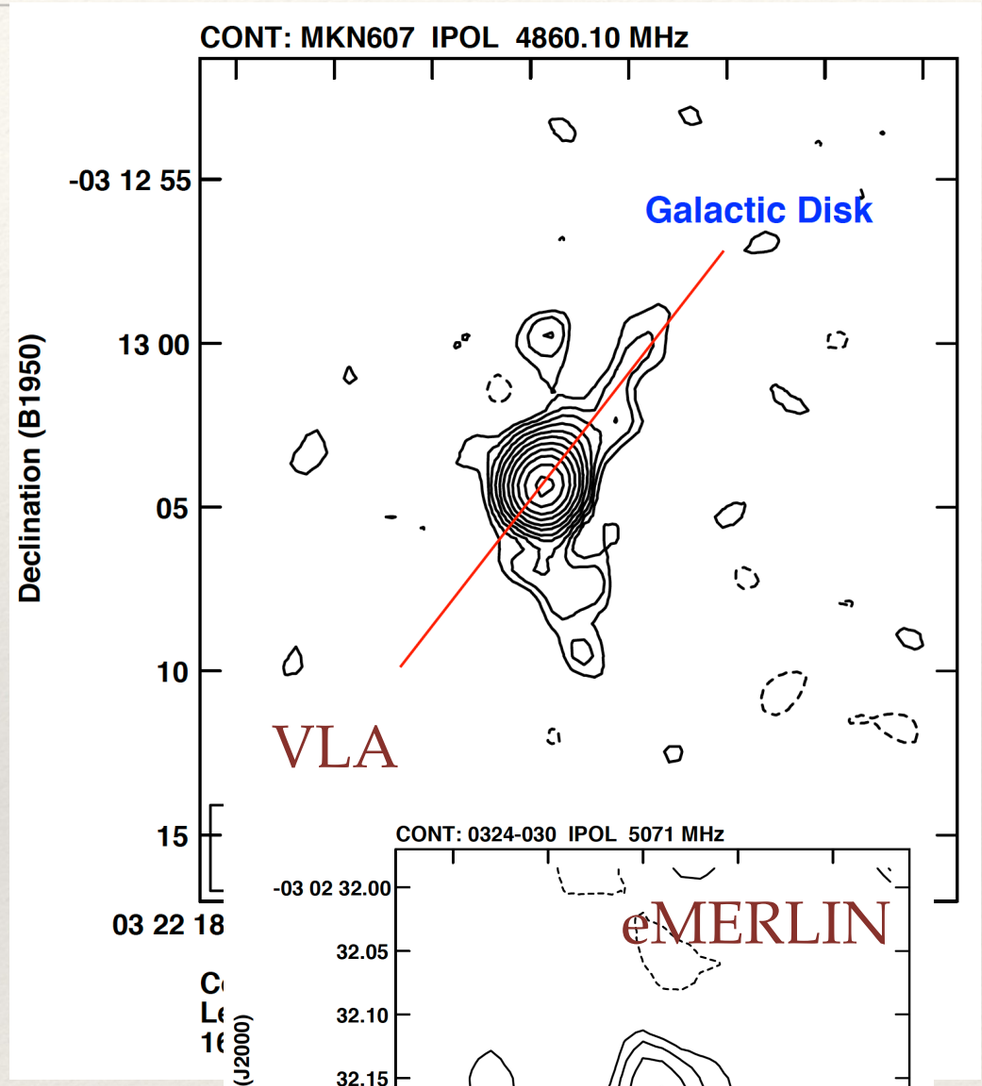






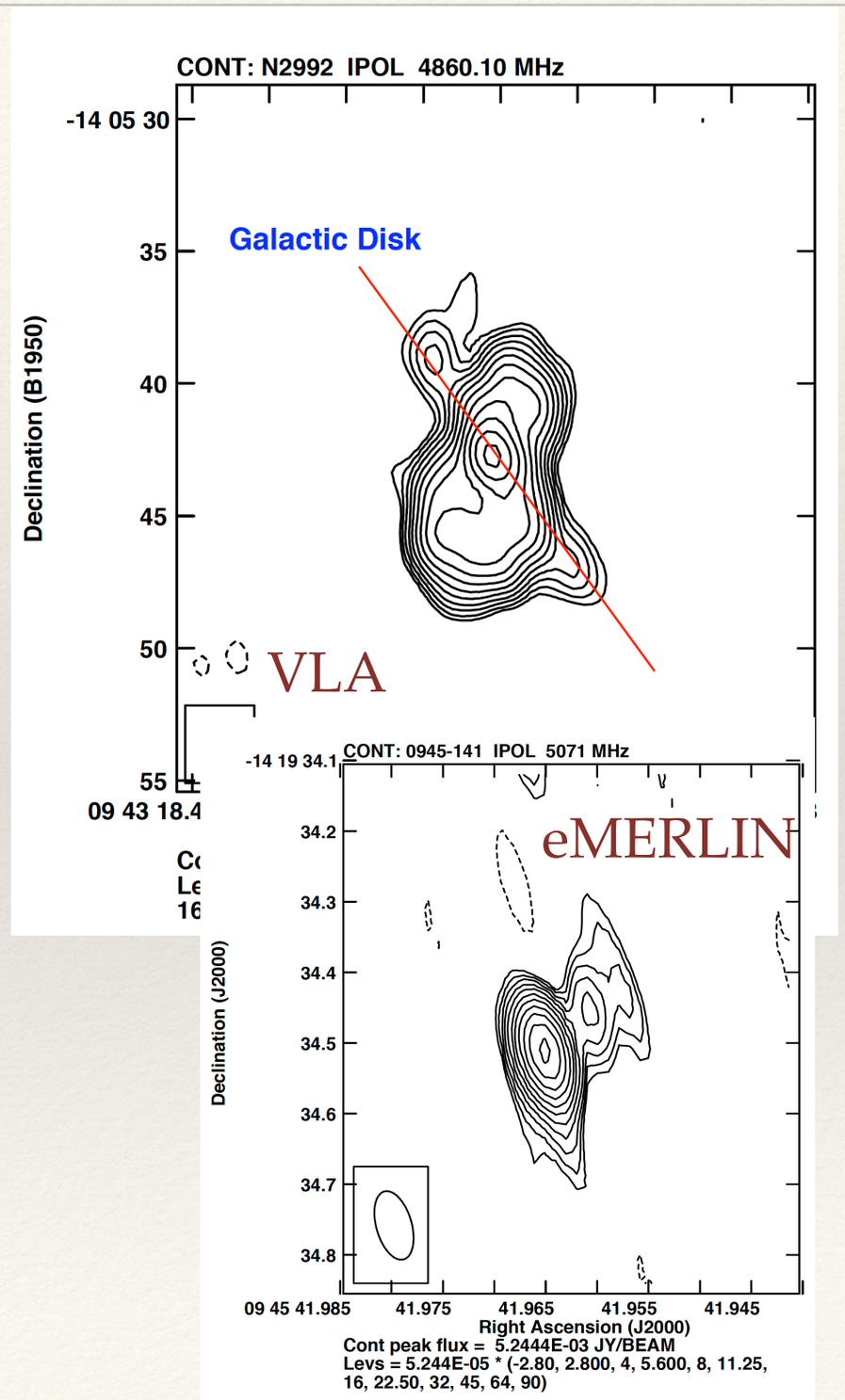
10-100 pc to Kpc: NGC1320

- Seyfert 2 galaxy at z=0.0088
- 1.5 kpc KSR with VLA at 5 GHz
- 17 parsec core-jet structure with eMERLIN at 5 GHz
- Almost 90 degrees misaligned

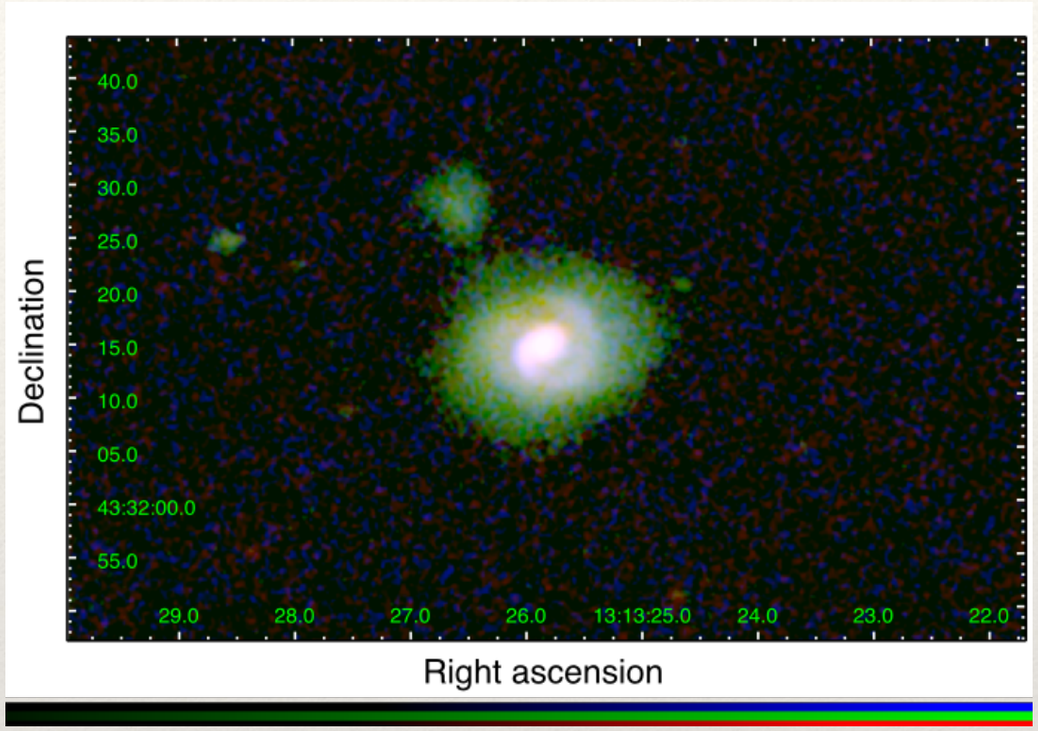


10-100 pc to Kpc: NGC2992

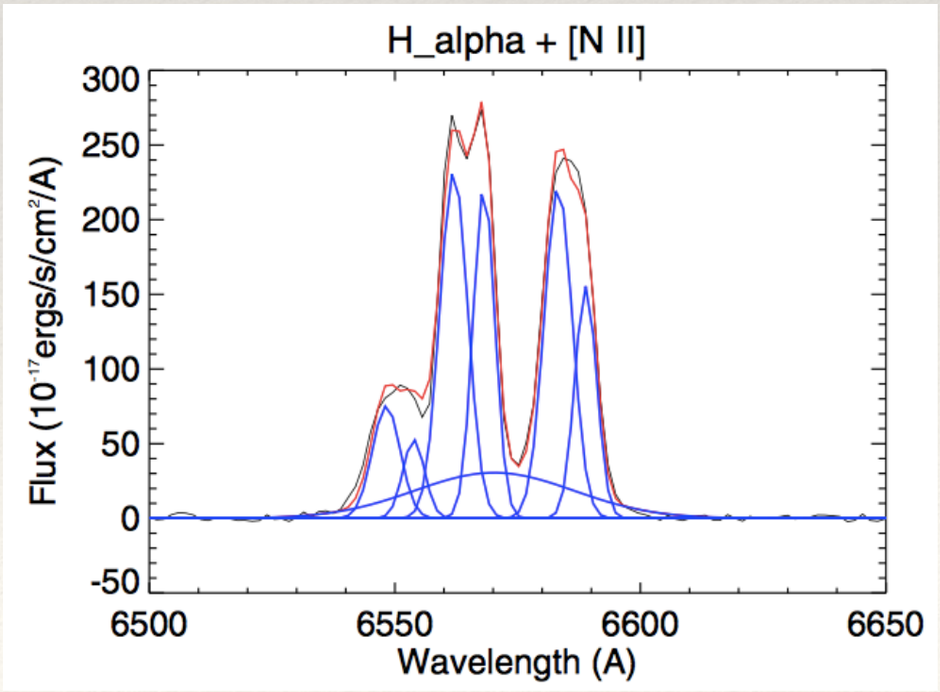
- Unobscured Seyfert 2 at z=0.0077
- 1.9 kpc VLA KSR at 5 GHz
- 38 parsec eMERLIN one-sided jet at 5 GHz
- Leading into the NW edge of the Northern lobe
- <u>Kpc - Sub-kpc - Parsec-scale</u> connection implies that the AGN jet is powering the KSR in several (all?) Seyferts



Seyferts with VLBI: KISSR1494



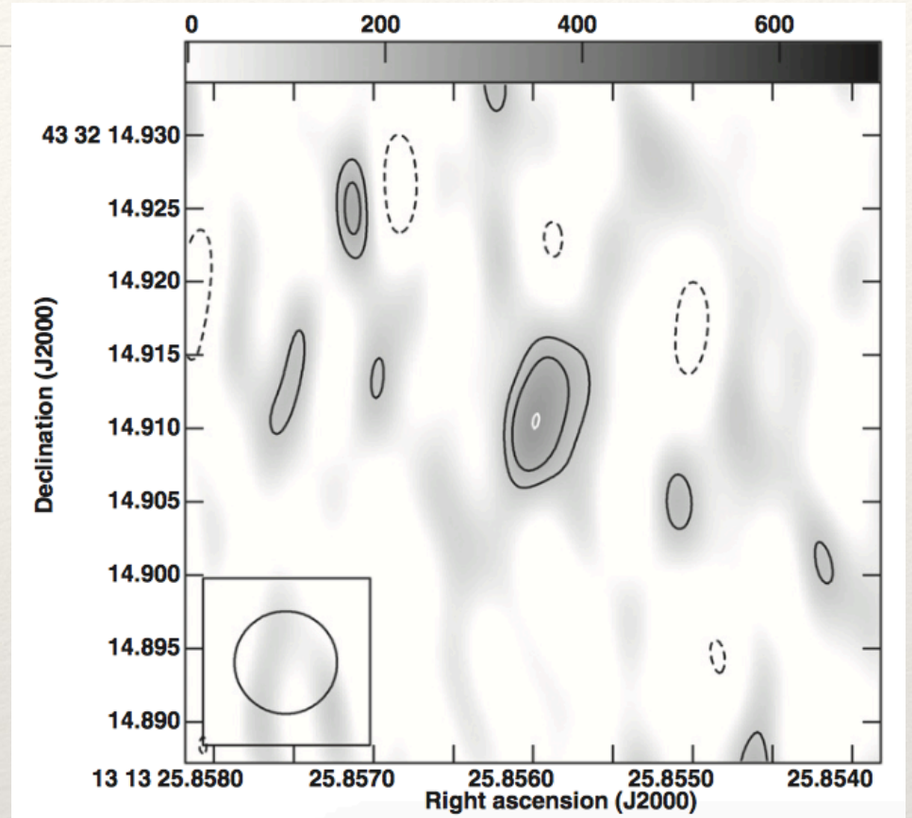
- *KISSR = KPNO Internal Spectroscopic Survey - Red (Wegner+ 2003)*
- Seyfert 2 at z = 0.0574
- Double-peaked emission lines in SDSS spectra = DPAGN

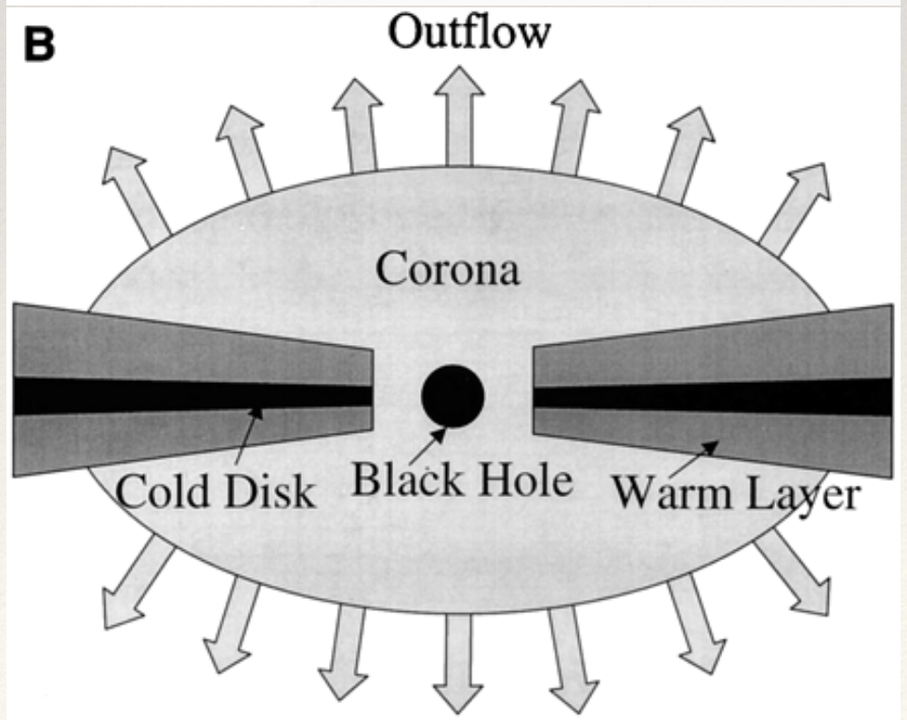


Outflowing Corona (?)

- VLBA at 1.6 & 5 GHz
- 0.7 mJy core of size (8 × 6 pc) only at 1.6 GHz
- $T_b \sim 1.4 \times 10^7$ K
- $\alpha \sim -1.5 \pm 0.5$ *steep!*
- Optically thin synchrotron emission. *Not compact*
- Base of an outflowing coronal wind ?
- NLR clouds could be pushed out due to this outflow = double peaks

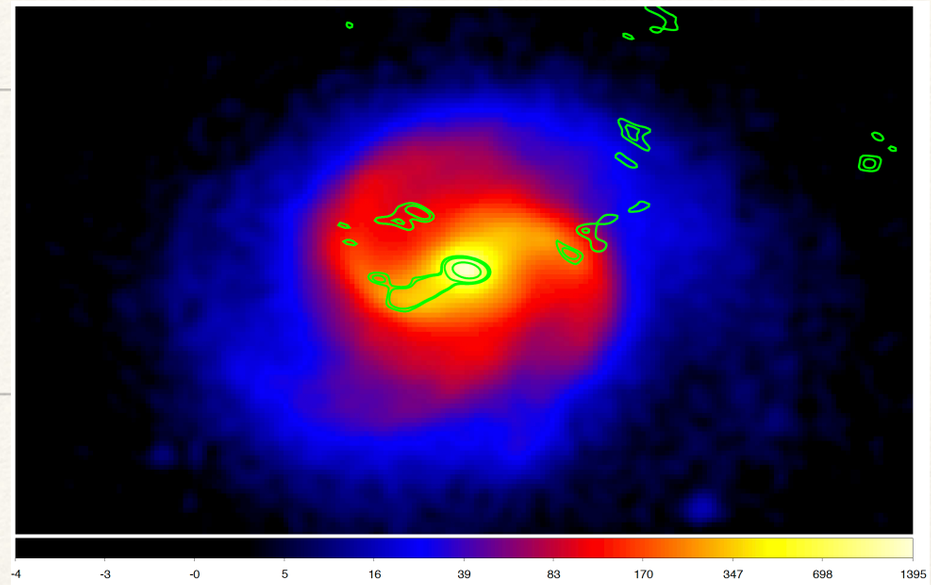
(Kharb, Das, Paragi+ 2015)

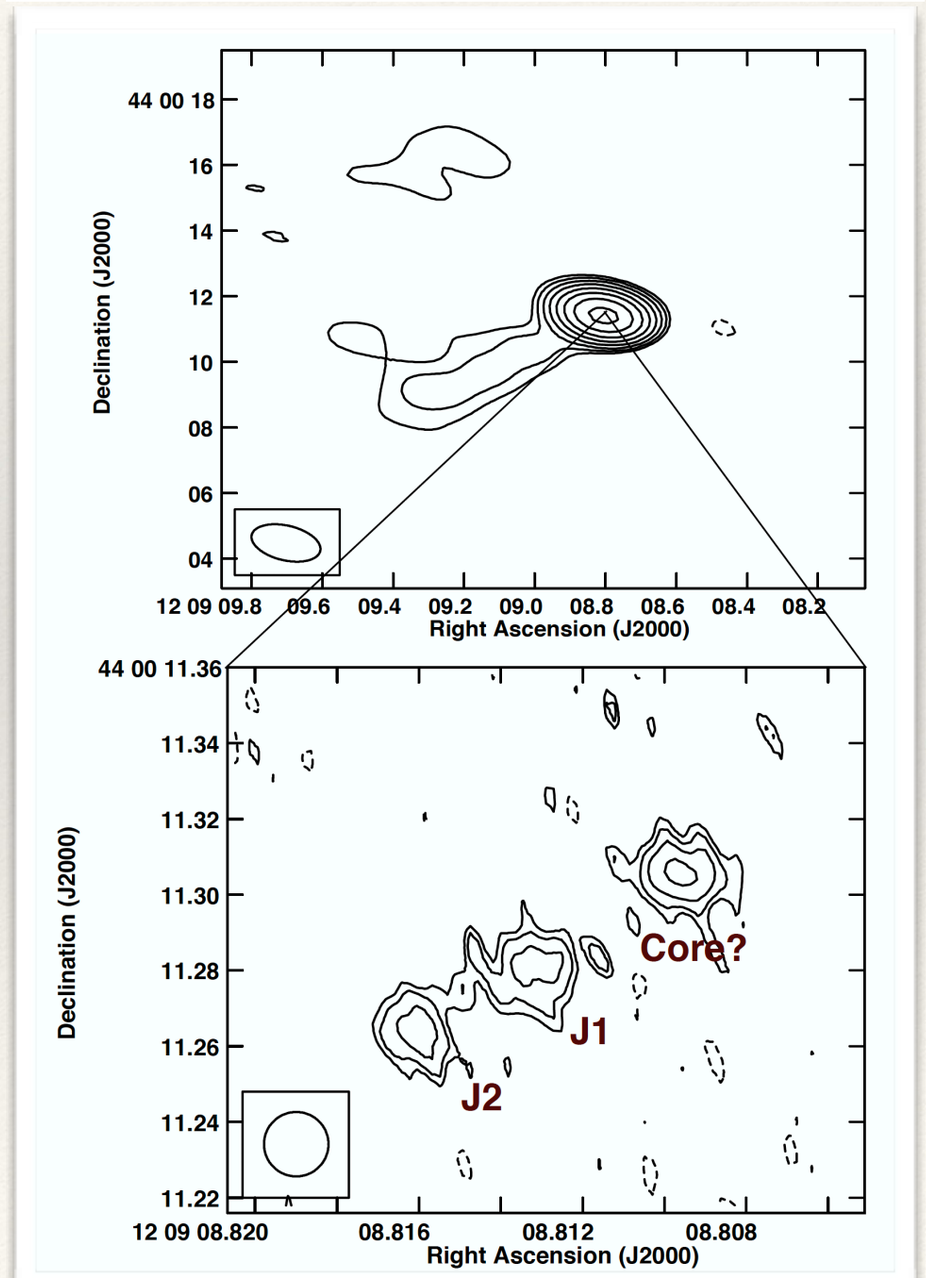




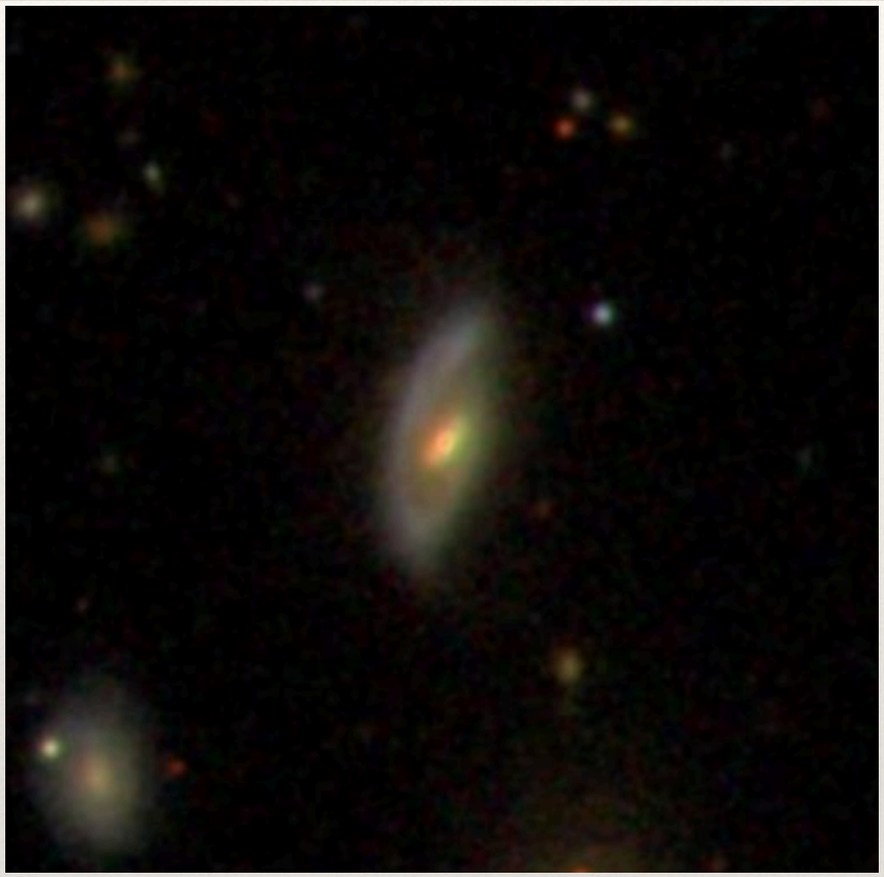
KISSR1219: One-sided Jet

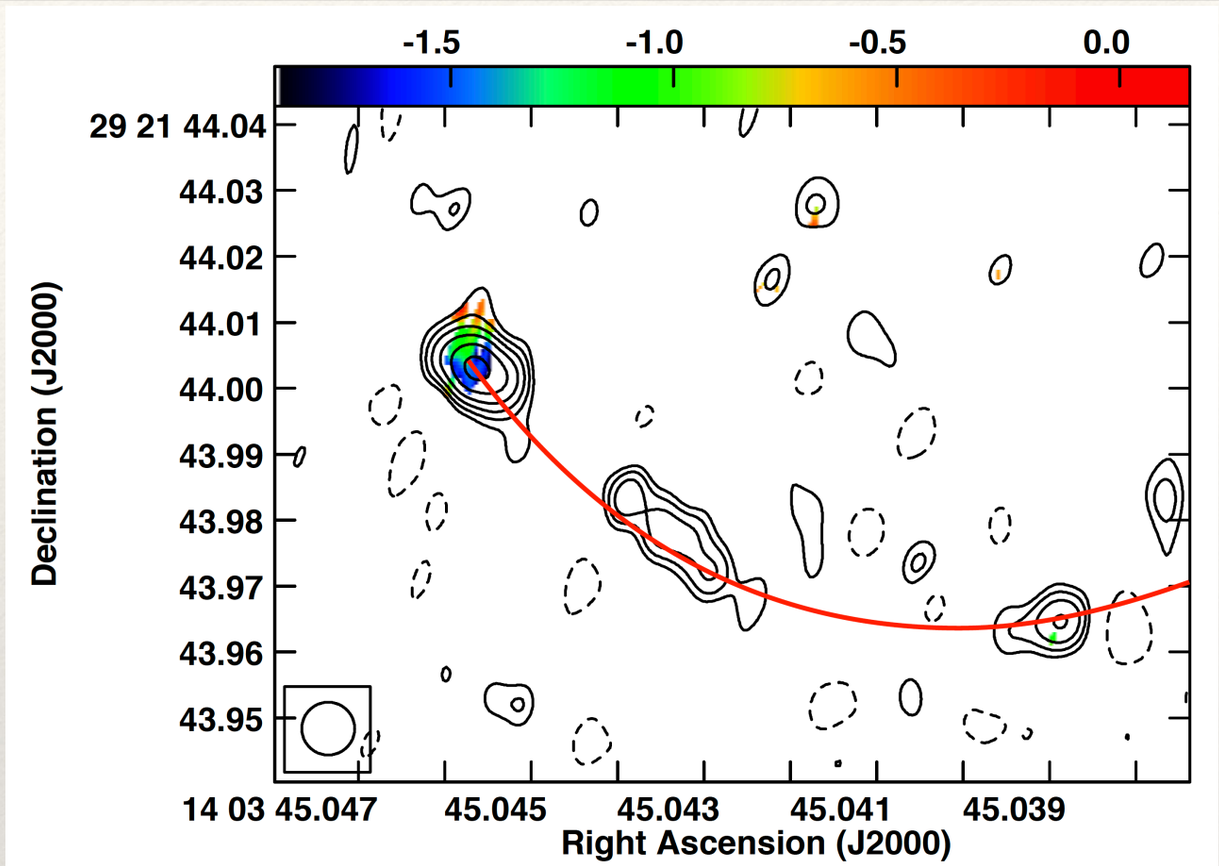
- Seyfert 2 at z=0.0375, DPAGN
- EVLA ~5 kpc jet
- VLBA ~70 pc jet at 1.6 GHz
- α <−1.0 for core & jet features
- Jet-to-counterjet I ratio for θ>50°
- v ≳ 0.55c - ≳ 0.25c from parsec to kpc-scales. Strong jet deceleration!
- NLR clouds pushed away by the outflow = double-peaks
- (Kharb, Subramanian, Vaddi, Das, Paragi, 2017)





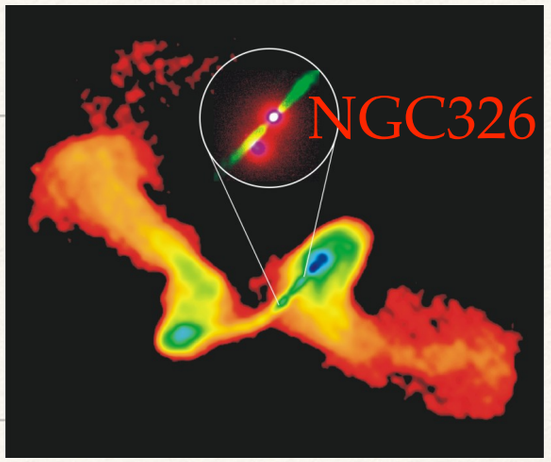
Seyferts with VLBI: KISSR434

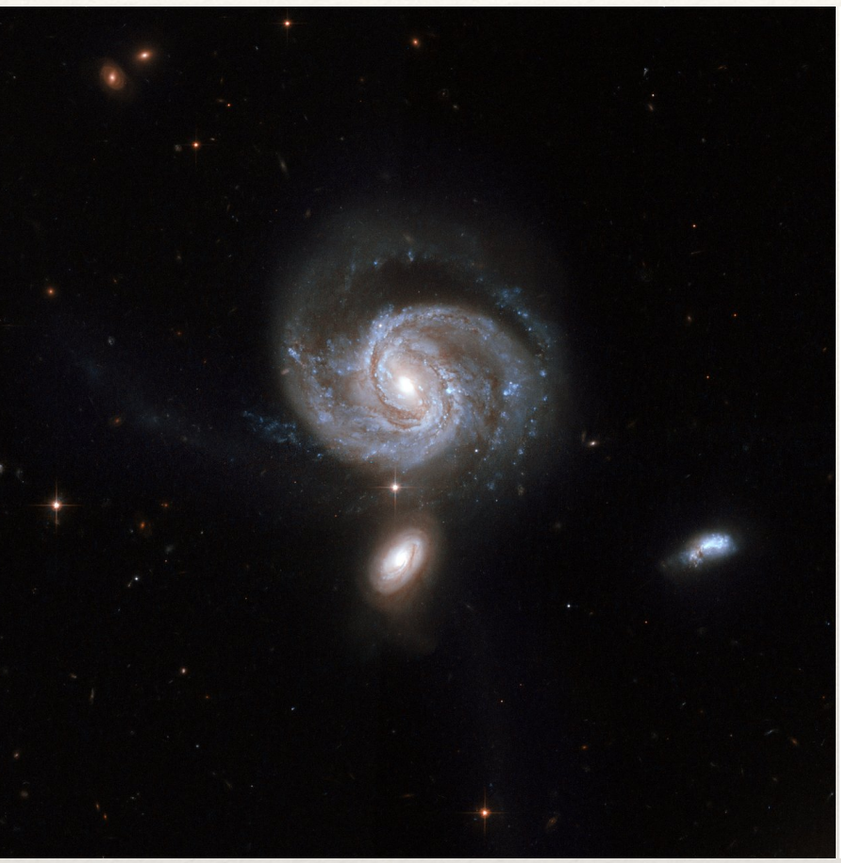


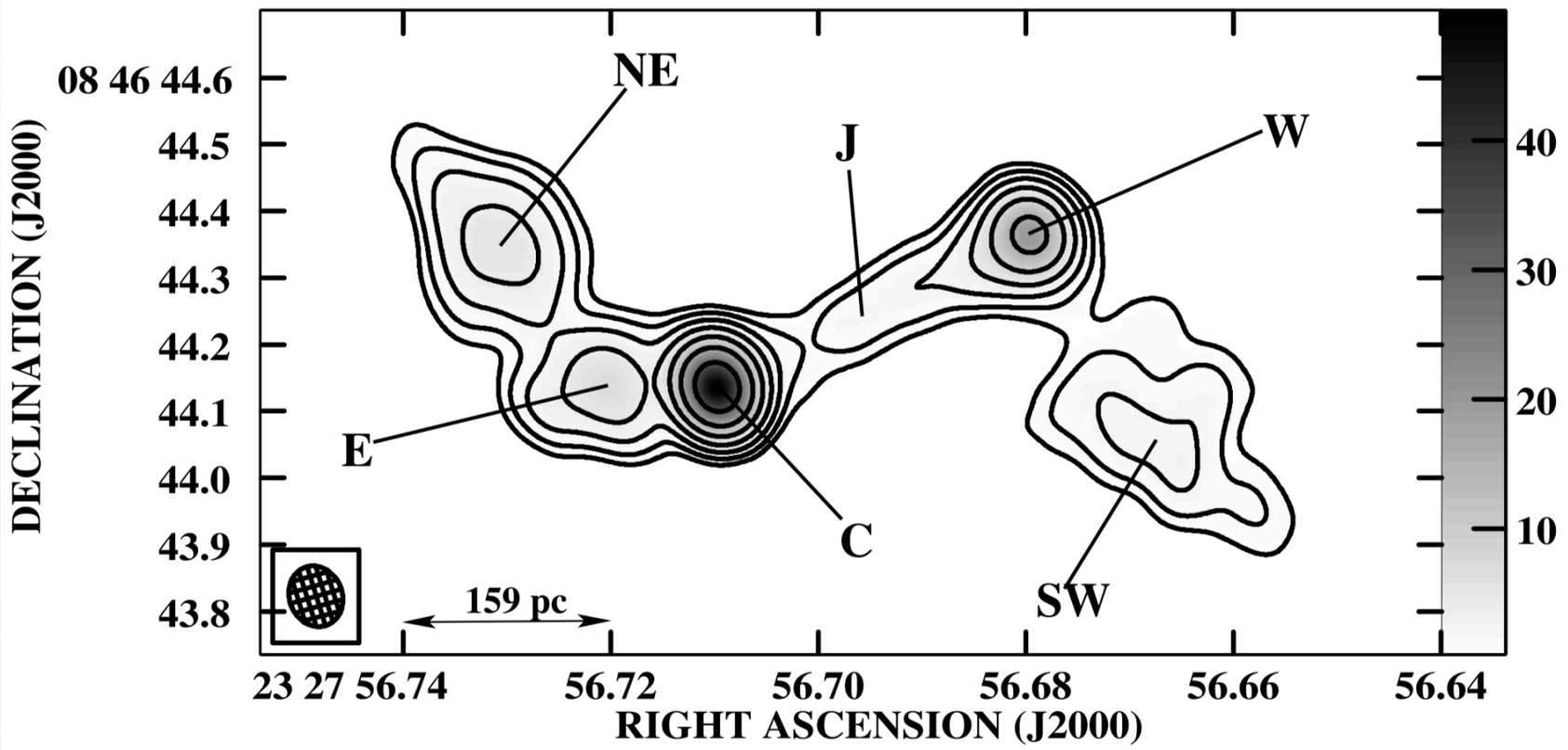


- Seyfert 2 at z=0.0641, DPAGN
- VLA FIRST image shows an unresolved source of size 5″ = 6 kpc. Upper limit of the size of the KSR.
- VLBA 1.5 & 5 GHz. Steep-spectrum precessing (?) jet
- (Kharb+ 2018, in prep.)

Seyferts with VLBI: NGC7674

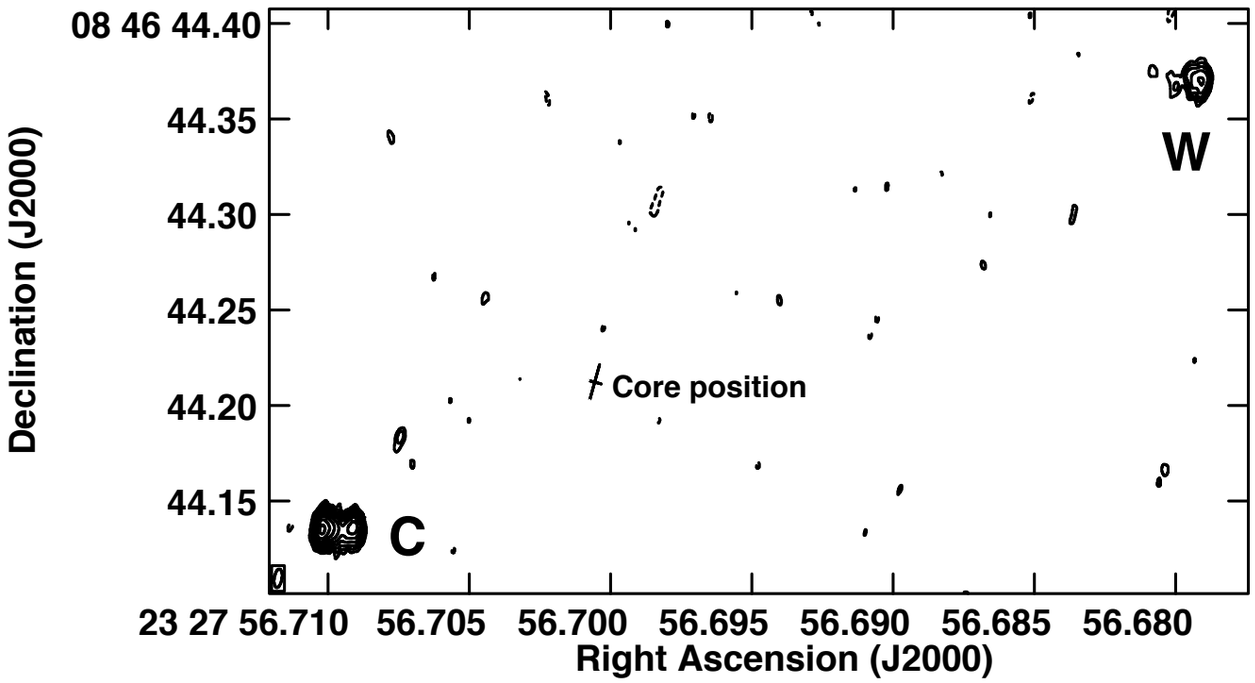


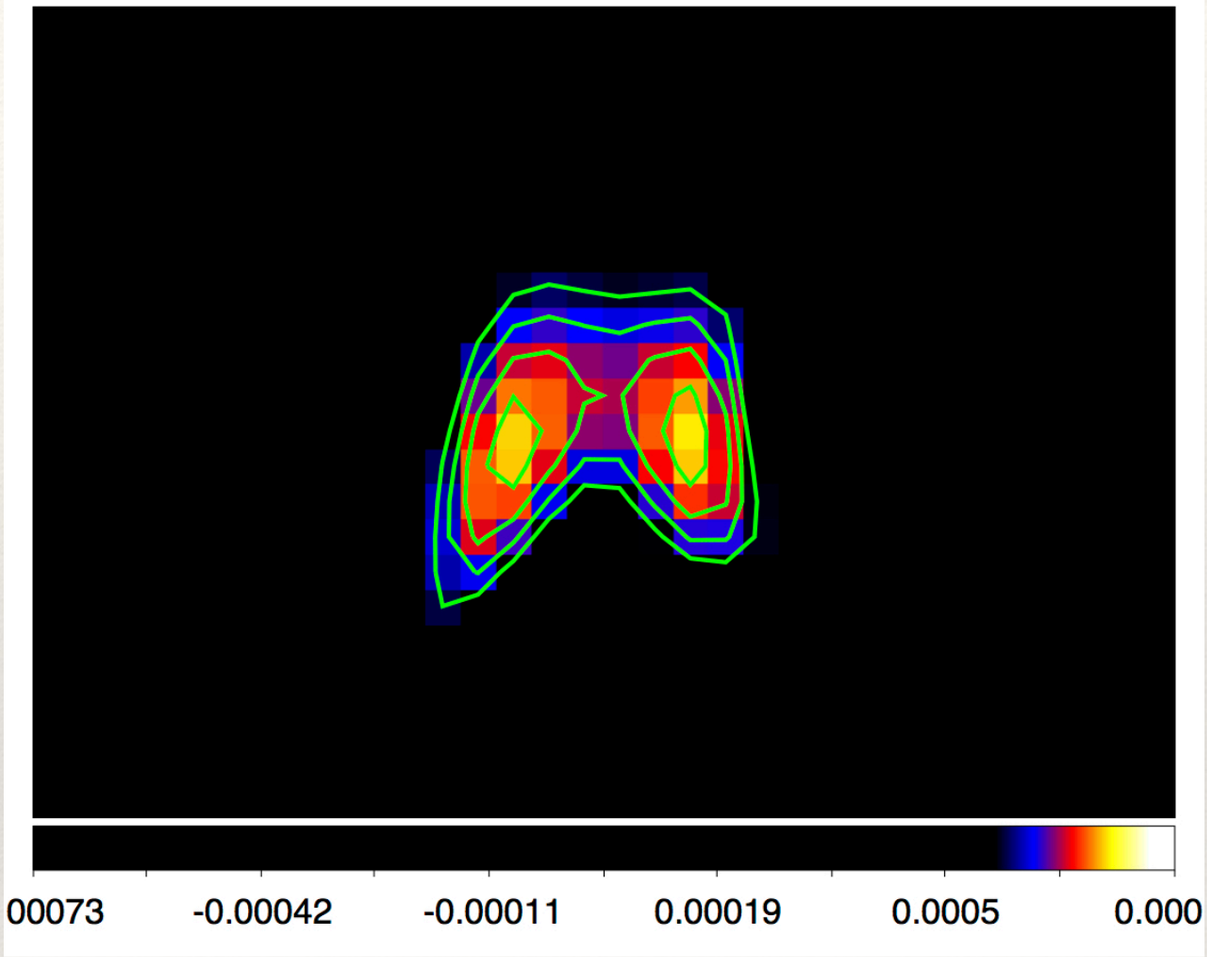




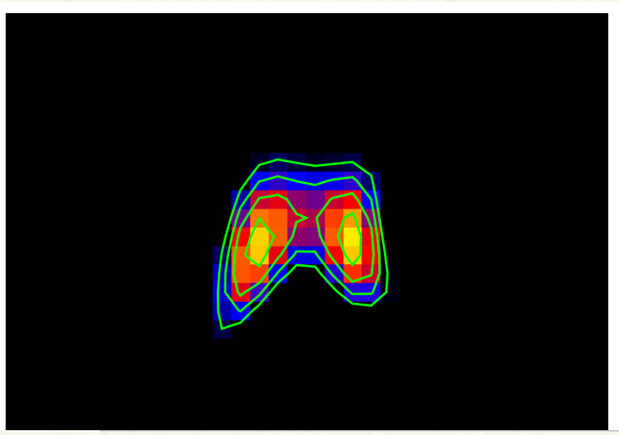
- Seyfert 2/LIRG at z=0.0289
- Z-shaped 0.7 kpc radio jet with the VLA (Momjian+ 2003)
- Core not detected at 1.4 GHz

Binary Black Holes (?)

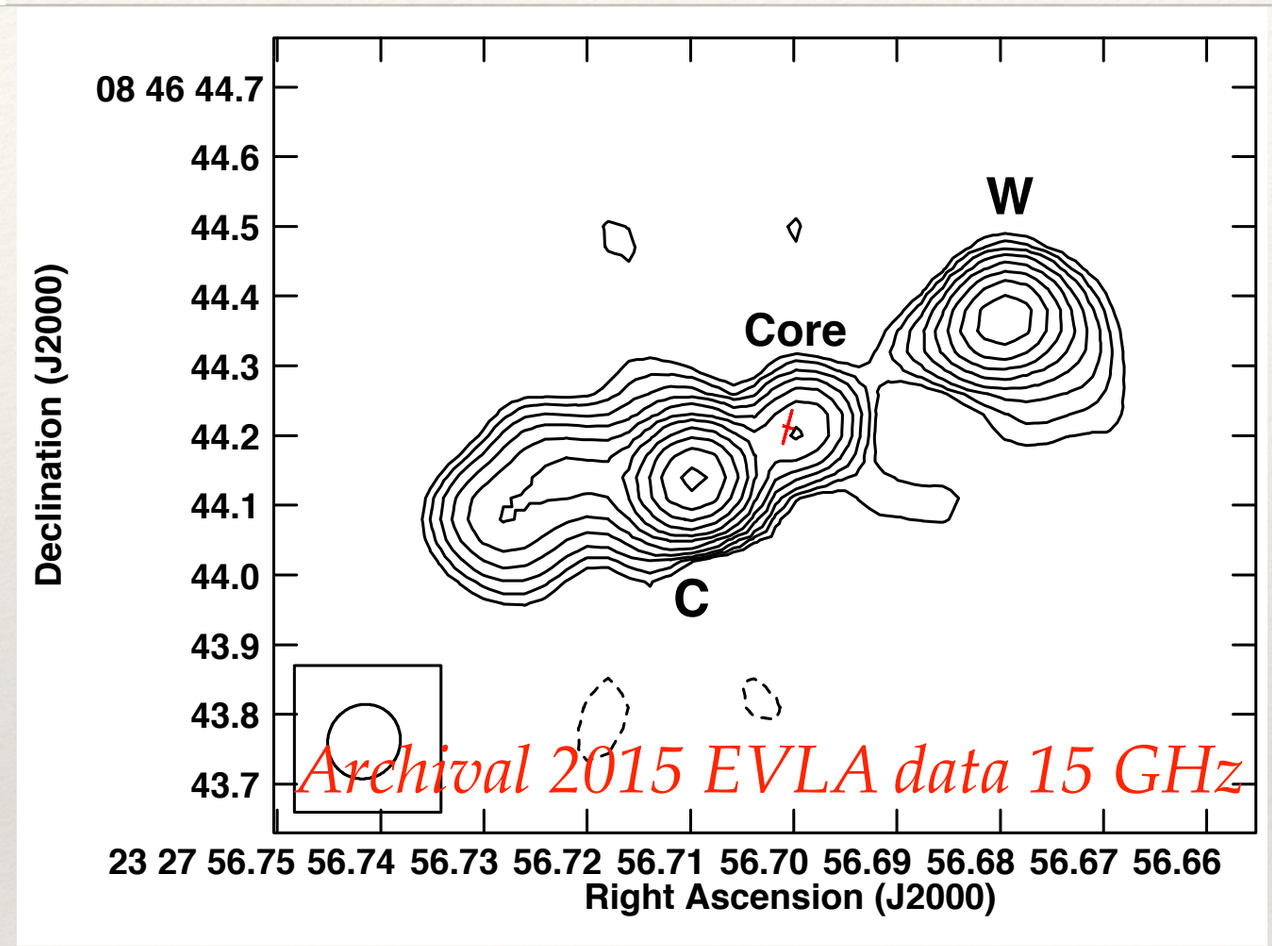




- VLBA observations at 2, 5, 8, 15 GHz
- Twin Cores with T_B ~2 - 6 x 10^7 K. Inverted spectral indices.



NGC7674



- Core projected separation = 0.65 mas = 0.35 parsec. ***Closest SMBH binary!***
- (Kharb, Lal & Merritt 2017, Nature Astronomy)

Summary

- 10-100 pc to 10-20 kpc radio outflows present in LLAGN. KSRs suggested to be AGN or starburst-wind driven
- Low frequency data with the GMRT and 325, 610, 1390 MHz detect larger fractions of KSRs, but also more galactic emission
- Trying to disentangle AGN & Stellar contribution using Spectral Indices - MIXED results. Trying to disentangle using Polarimetry - Results in the near future
- VLBI reveals coronae and jets that impact the emission-line gas. These jets appear to connect to the KSRs, supporting an AGN jet origin for the KSRs