RADIO VIEW ON AGN

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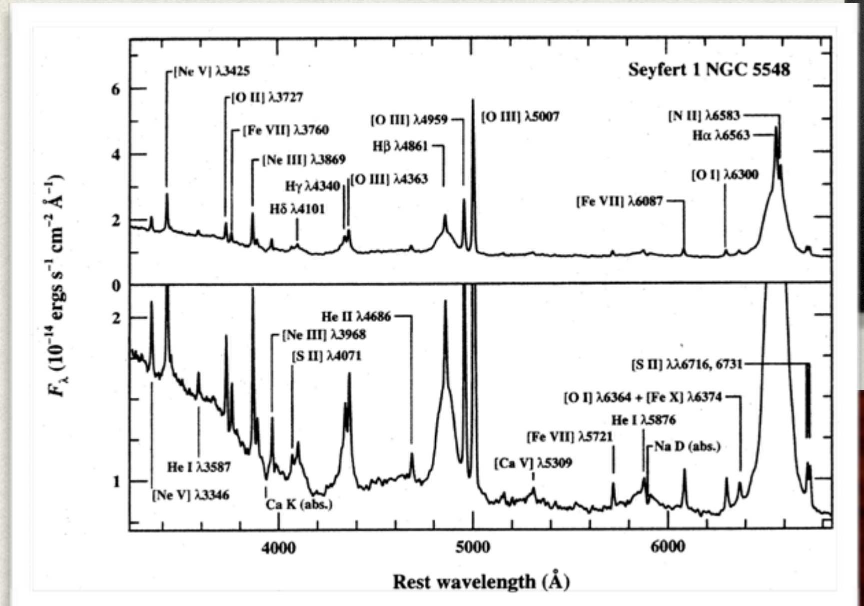
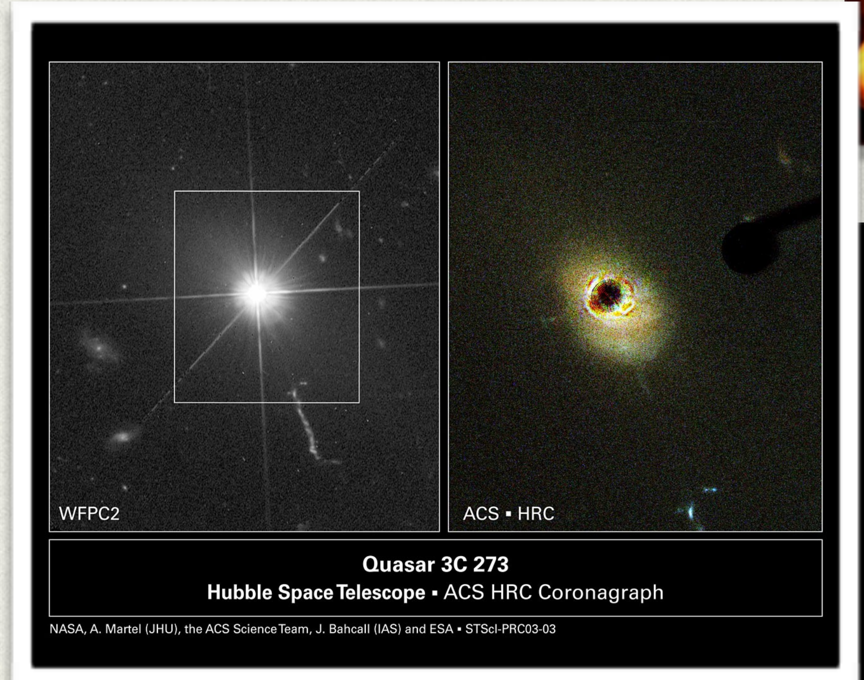
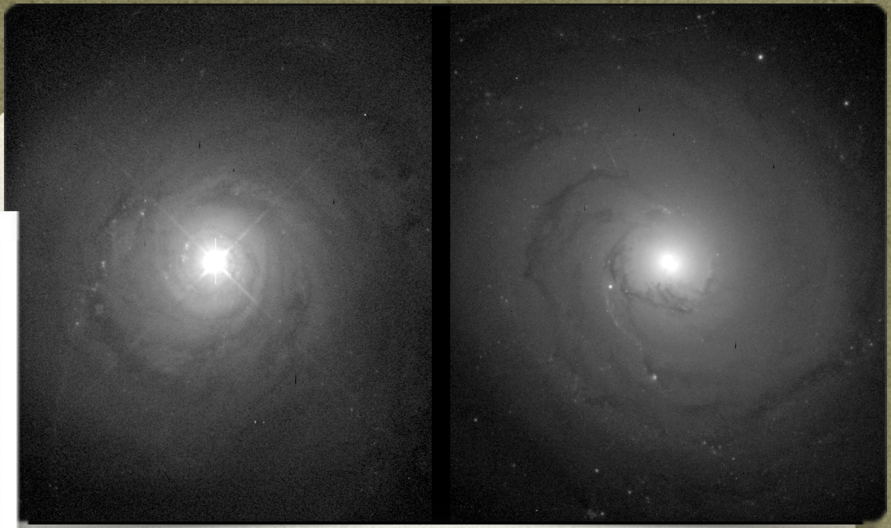
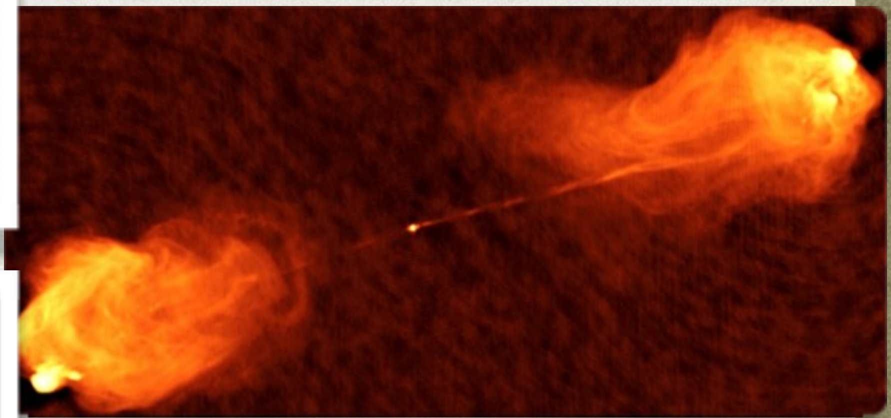
AGN

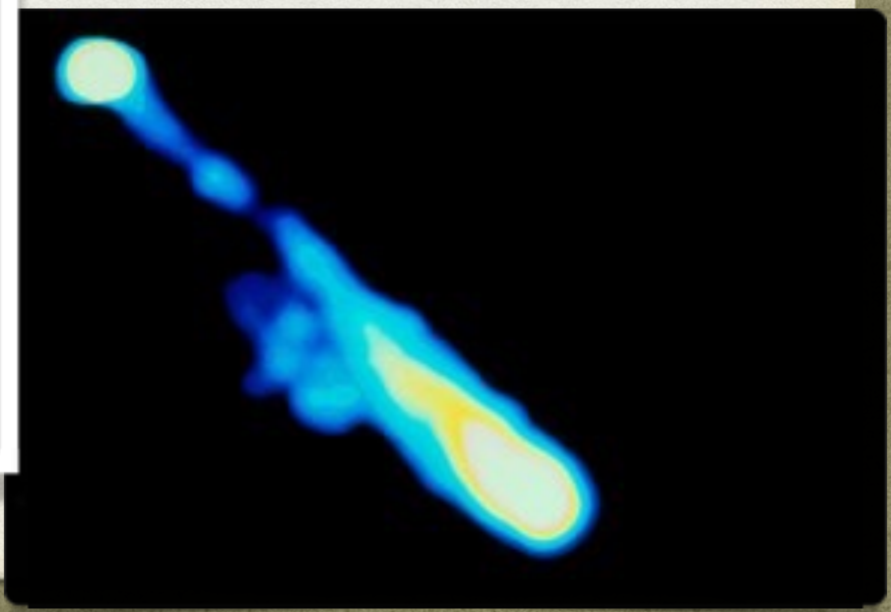
- Seyfert (1943): Star-like nuclei + peculiar emission-line spectra in spirals (NGC 1068, NGC 4151)
- Baade & Minkowski (1954): Cygnus A radio source has Seyfert-like spectra
- Schmidt (1963): Quasar 3C 273 at z=0.158 discovered





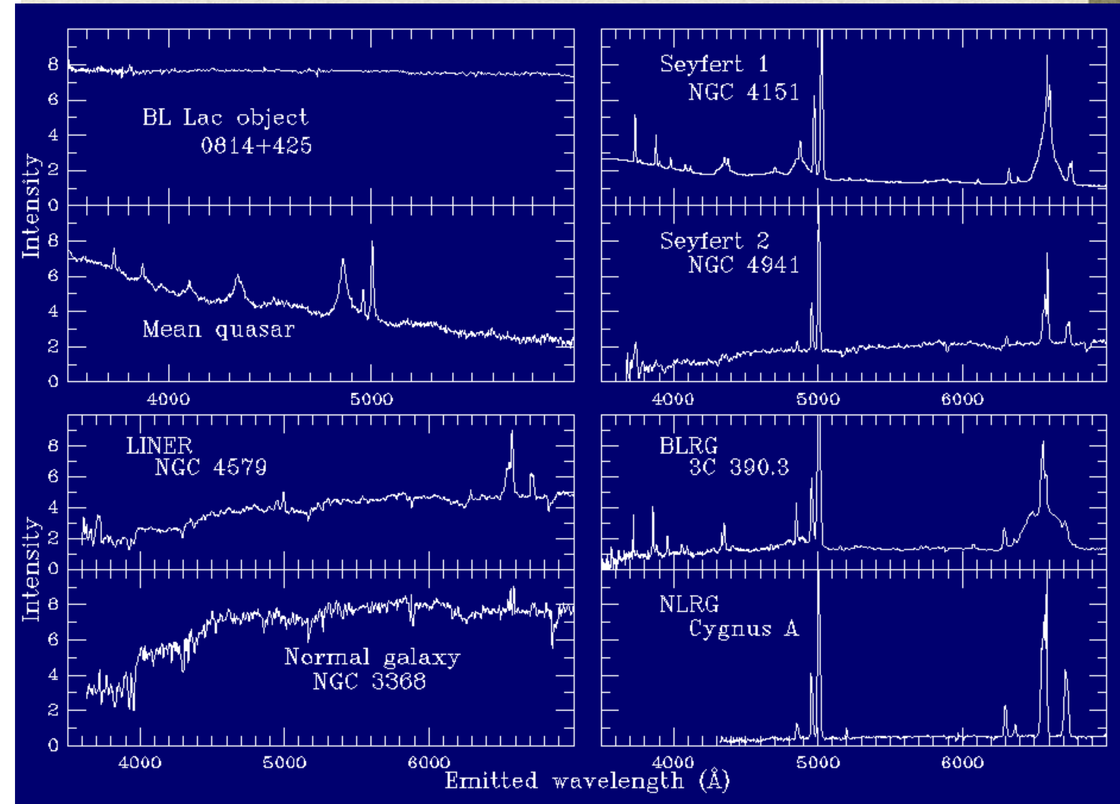


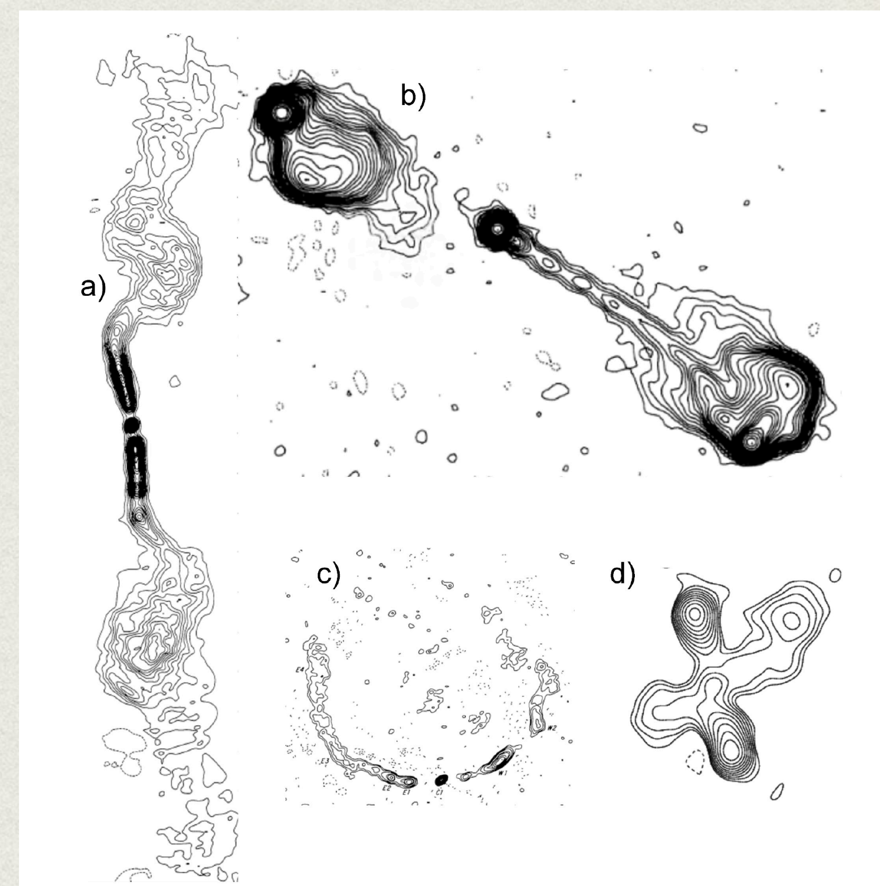




The AGN zoo: list of AGN classes.

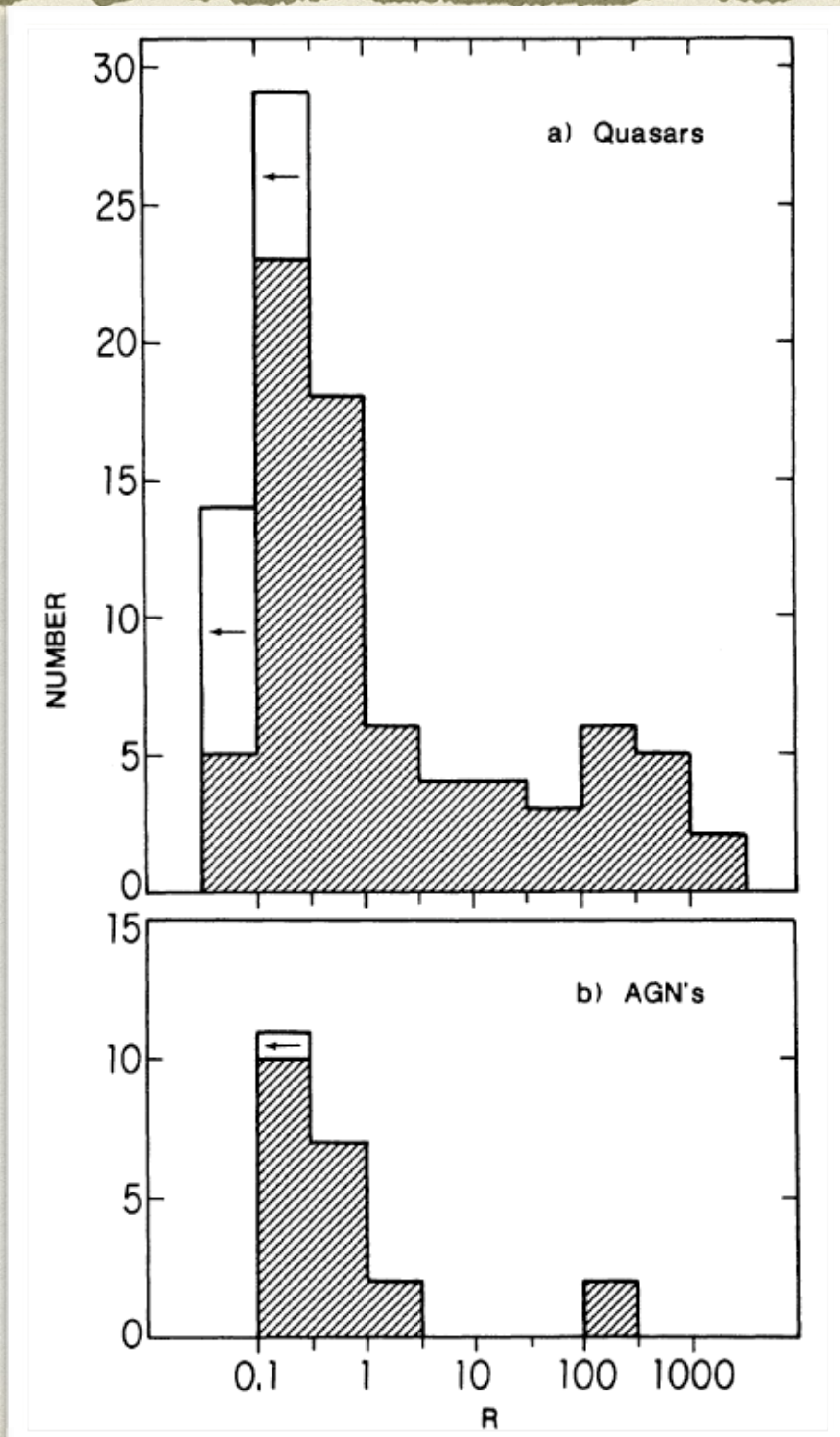
Class/Acronym	Meaning	Main properties/reference
Quasar	Quasi-stellar radio source (originally)	Radio detection no longer required
Sey1	Seyfert 1	FWHM $\gtrsim 1,000$ km s^{-1}
Sey2	Seyfert 2	FWHM $\lesssim 1,000$ km s^{-1}
QSO	Quasi-stellar object	Quasar-like, non-radio source
QSO2	Quasi-stellar object 2	High power Sey2
RQ AGN	Radio-quiet AGN	see ref. 1
RL AGN	Radio-loud AGN	see ref. 1
Jetted AGN		with strong relativistic jets; see ref. 1
Non-jetted AGN		without strong relativistic jets; see ref. 1
Type 1		Sey1 and quasars
Type 2		Sey2 and QSO2
FR I	Fanaroff-Riley class I radio source	radio core-brightened (ref. 2)
FR II	Fanaroff-Riley class II radio source	radio edge-brightened (ref. 2)
BL Lac	BL Lacertae object	see ref. 3
Blazar	BL Lac and quasar	BL Lacs and FSRQs
BAL	Broad absorption line (quasar)	ref. 4
BLO	Broad-line object	FWHM $\gtrsim 1,000$ km s^{-1}
BLAGN	Broad-line AGN	FWHM $\gtrsim 1,000$ km s^{-1}
BLRG	Broad-line radio galaxy	RL Sey1
CDQ	Core-dominated quasar	RL AGN, $f_{core} \geq f_{ext}$ (same as FSRQ)
CSS	Compact steep spectrum radio source	core dominated, $\alpha_r > 0.5$
CT	Compton-thick	$N_H \geq 1.5 \times 10^{24}$ cm^{-2}
FR 0	Fanaroff-Riley class 0 radio source	ref. 5
FSRQ	Flat-spectrum radio quasar	RL AGN, $\alpha_r \leq 0.5$
GPS	Gigahertz-peaked radio source	see ref. 6
HBL/HSP	High-energy cutoff BL Lac/blazar	$\nu_{synch\ peak} \geq 10^{15}$ Hz (ref. 7)
HEG	High-excitation galaxy	ref. 8
HPQ	High polarization quasar	$P_{opt} \geq 3\%$ (same as FSRQ)
Jet-mode		$L_{kin} \gg L_{rad}$ (same as LERG); see ref. 9
IBL/ISP	Intermediate-energy cutoff BL Lac/blazar	$10^{14} \leq \nu_{synch\ peak} \leq 10^{15}$ Hz (ref. 7)
LINER	Low-ionization nuclear emission-line regions	see ref. 9
LLAGN	Low-luminosity AGN	see ref. 10
LBL/LSP	Low-energy cutoff BL Lac/blazar	$\nu_{synch\ peak} < 10^{14}$ Hz (ref. 7)
LDQ	Lobe-dominated quasar	RL AGN, $f_{core} < f_{ext}$
LEG	Low-excitation galaxy	ref. 8
LPQ	Low polarization quasar	$P_{opt} < 3\%$
NLAGN	Narrow-line AGN	FWHM $\lesssim 1,000$ km s^{-1}
NLRG	Narrow-line radio galaxy	RL Sey2
NLS1	Narrow-line Seyfert 1	ref. 11
OVV	Optically violently variable (quasar)	(same as FSRQ)
Population A		ref. 12
Population B		ref. 12
Radiative-mode		Seyferts and quasars; see ref. 9
RBL	Radio-selected BL Lac	BL Lac selected in the radio band
Sey1.5	Seyfert 1.5	ref. 13
Sey1.8	Seyfert 1.8	ref. 13
Sey1.9	Seyfert 1.9	ref. 13
SSRQ	Steep-spectrum radio quasar	RL AGN, $\alpha_r > 0.5$
USS	Ultra-steep spectrum source	RL AGN, $\alpha_r > 1.0$
XBL	X-ray-selected BL Lac	BL Lac selected in the X-ray band
XBONG	X-ray bright optically normal galaxy	AGN only in the X-ray band/weak lined AGN





Padovani+ 2017, A&A Review

THE RL-RQ DICHOTOMY



Palomar Bright Quasar Survey
Kellermann+ 1989

Radio-loud / Radio-quiet AGN

$\mathbf{R} = S_{5\ \mathrm{GHz}}/S_{\mathrm{B\text{-}band}} \geq 10$

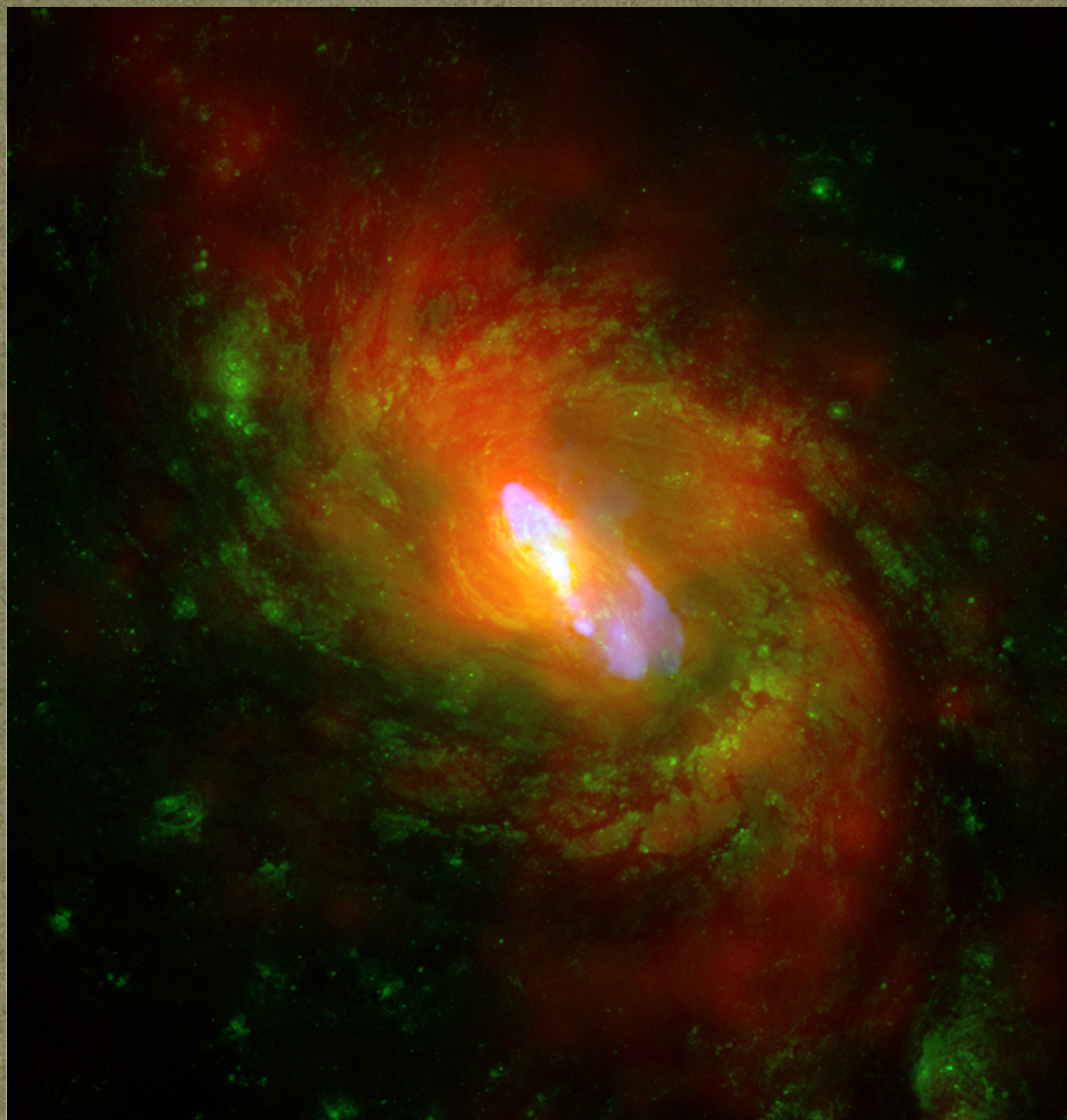
Bimodality observed

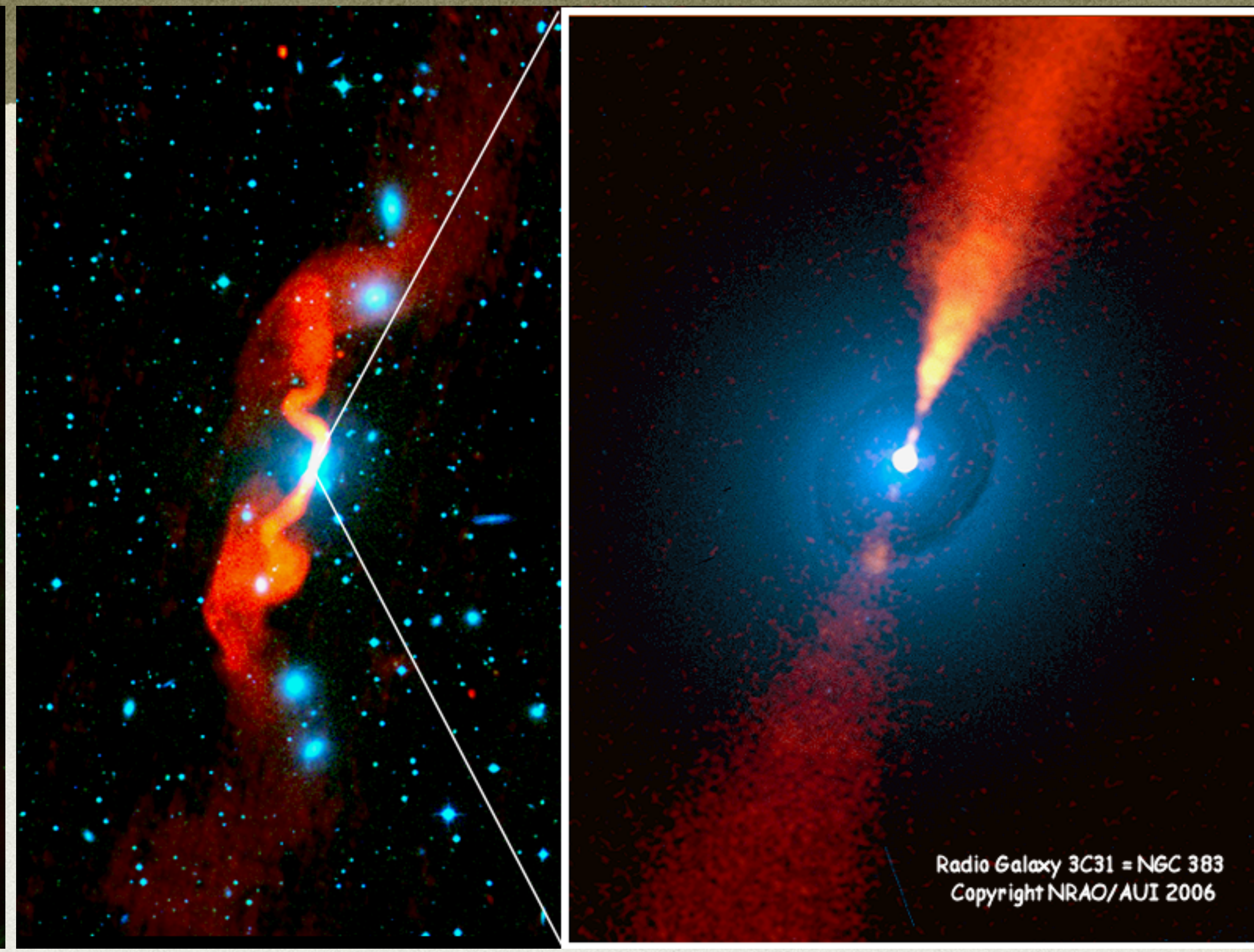
Quasars $M_B < -23$
"AGNs" $M_B > -23$

~15% sources "radio-loud"

Jetted (<1%) versus Non-jetted
(Padovani+ 2017, A&A Review)

RADIO EMISSION IN AGN





Seyfert galaxy NGC1068

Radio galaxy 3C31

Radio-Loud AGN typically reside in elliptical galaxies, Radio-Quiet AGN typically in spiral galaxies

AGN MODEL

Supermassive black hole (SMBH) ~10^6–10^9 $M_\odot$

Broad-line region (BLR) line widths ~1000 – 10,000 km/s, $n_e > 10^9$ cm^{-3}

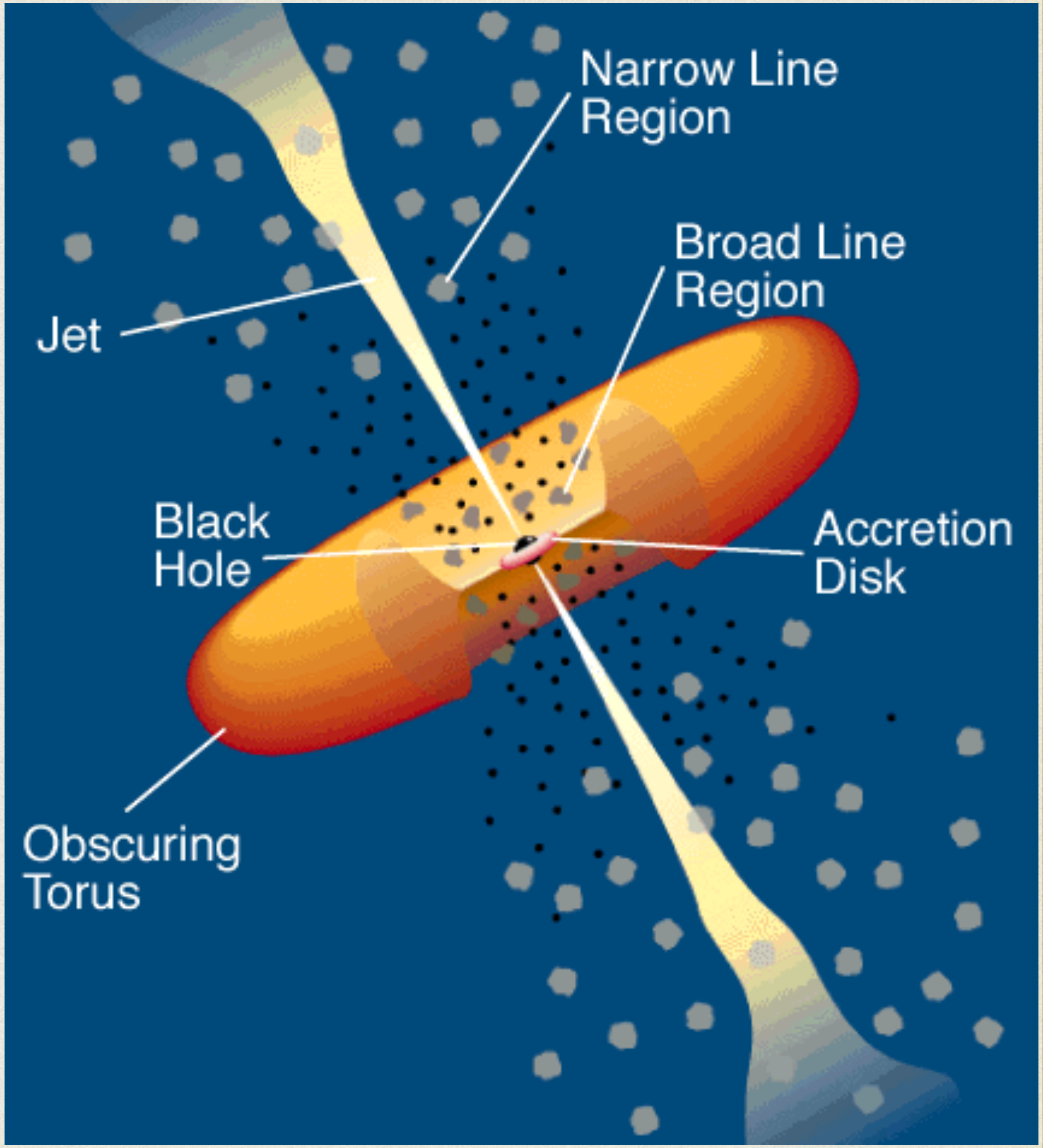
Narrow-line region (NLR) line widths ≤ 500 km/s, $n_e \sim 10^3$ cm^{-3}

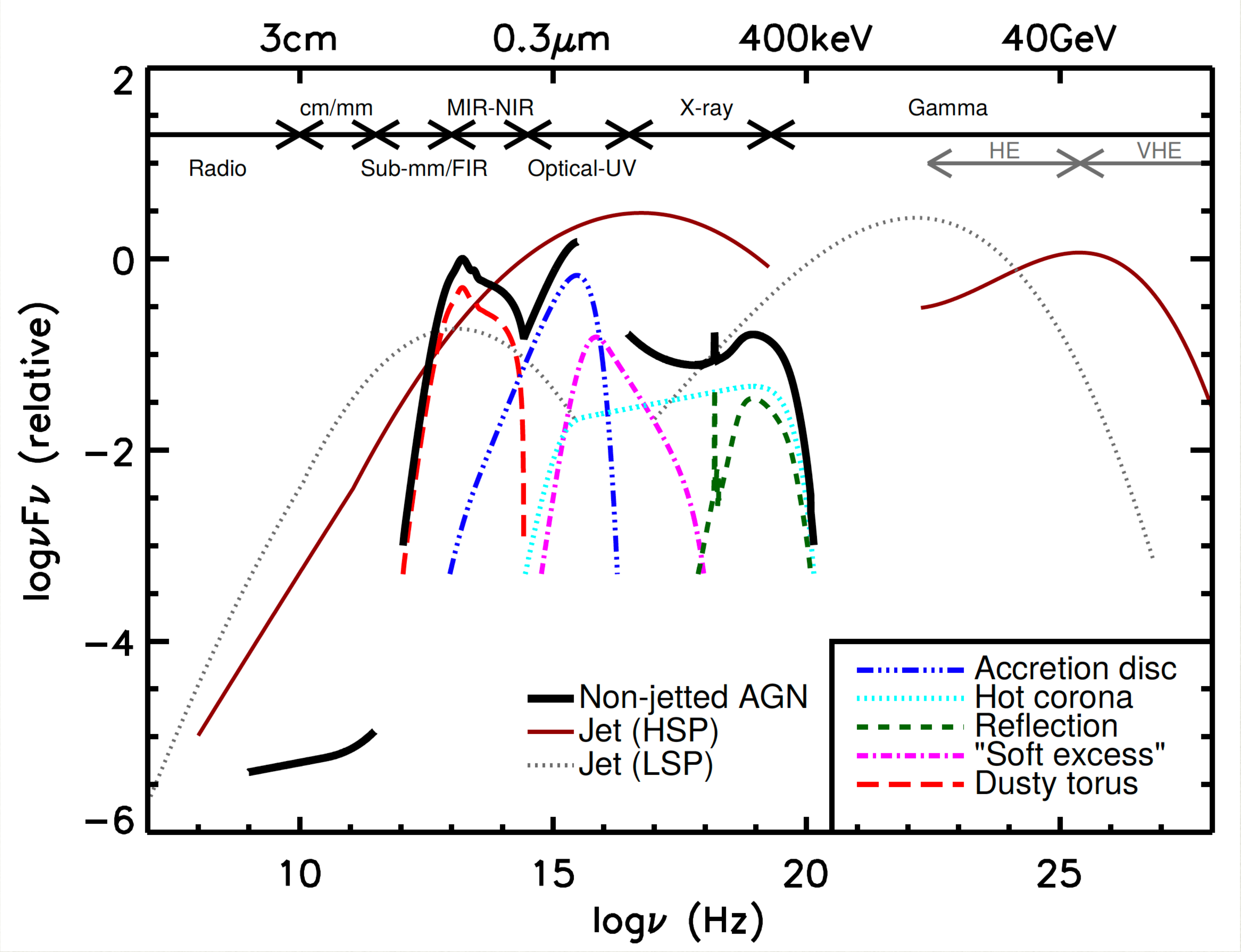
Dusty torus shields the BLR from some lines of sight

Jets launched from Accretion disk-SMBH interface

Type 1s & 2s differ by orientation

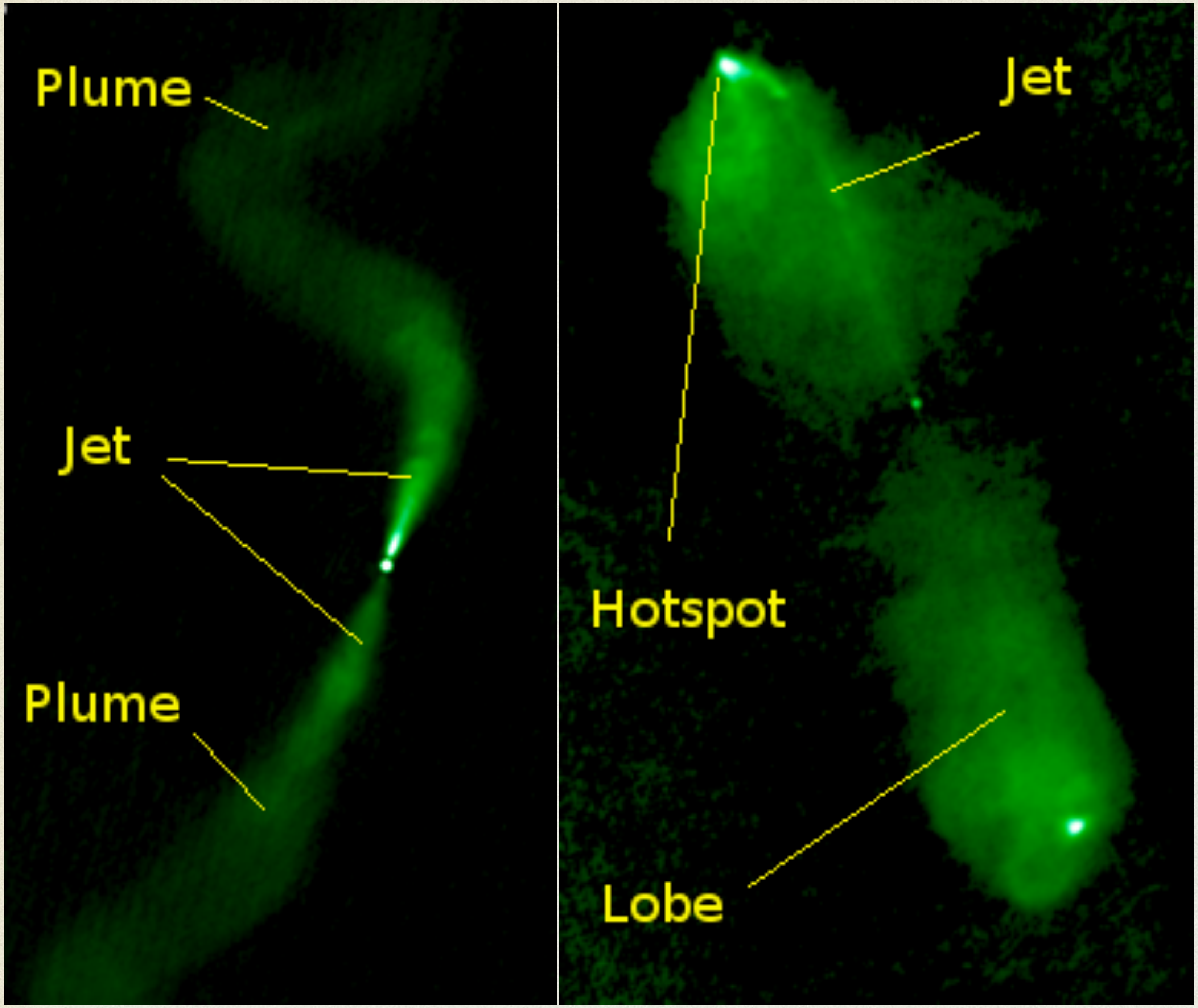
Unification (Antonucci 1993)





Padovani+ 2017, A&A Review

RADIO-LOUD AGN: FANAROFF-RILEY DICHOTOMY

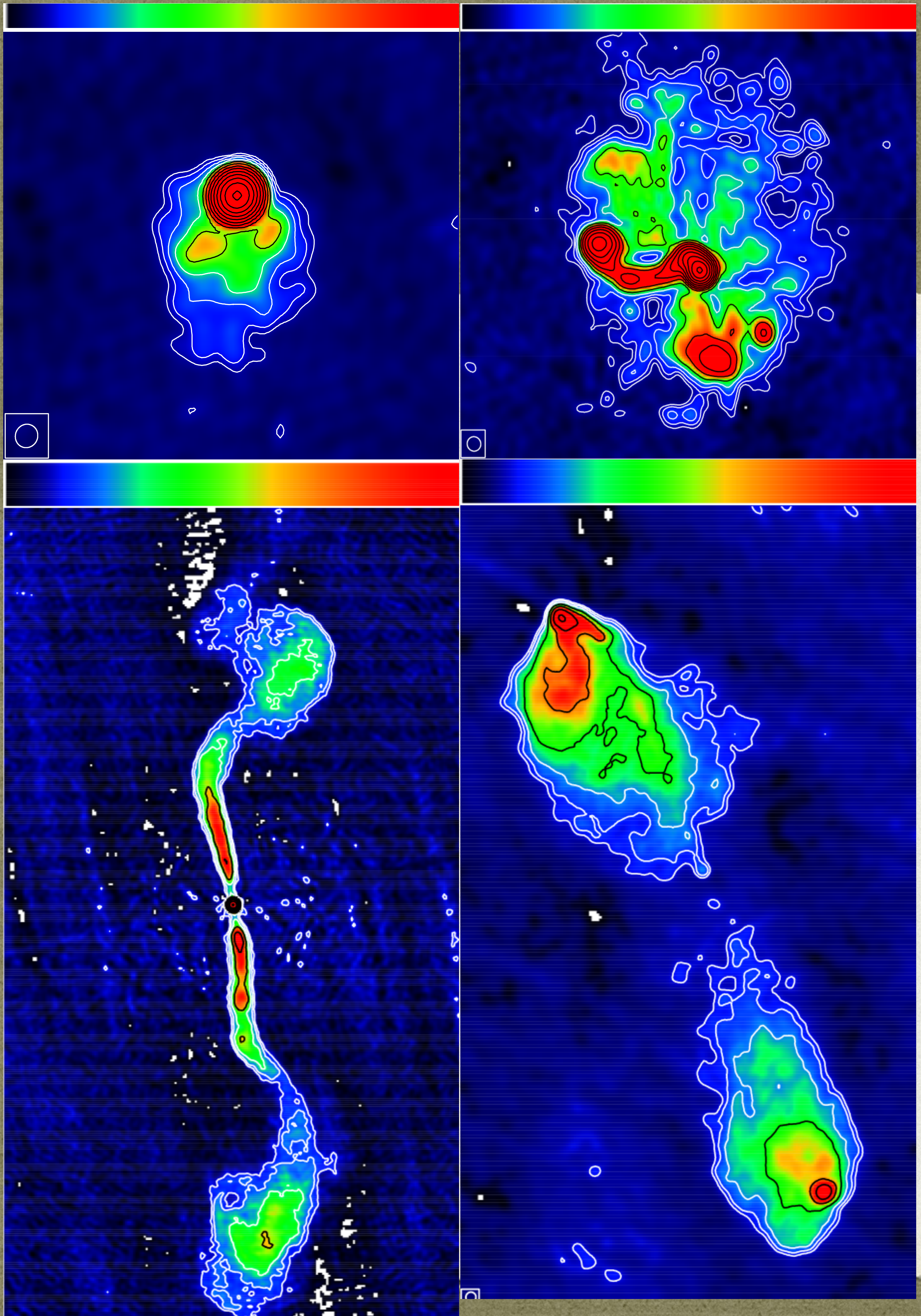


Fanaroff-Riley type I (FRI) & type II (FRII)

$L_{178} \approx 2 \times 10^{25}$ W/Hz (Fanaroff & Riley, 1974)

Break depends on host galaxy magnitude (Owen & Ledlow, 1994)

Hybrid radio morphology sources (Gopal-Krishna & Wiita, 2000)



RADIO-LOUD UNIFICATION

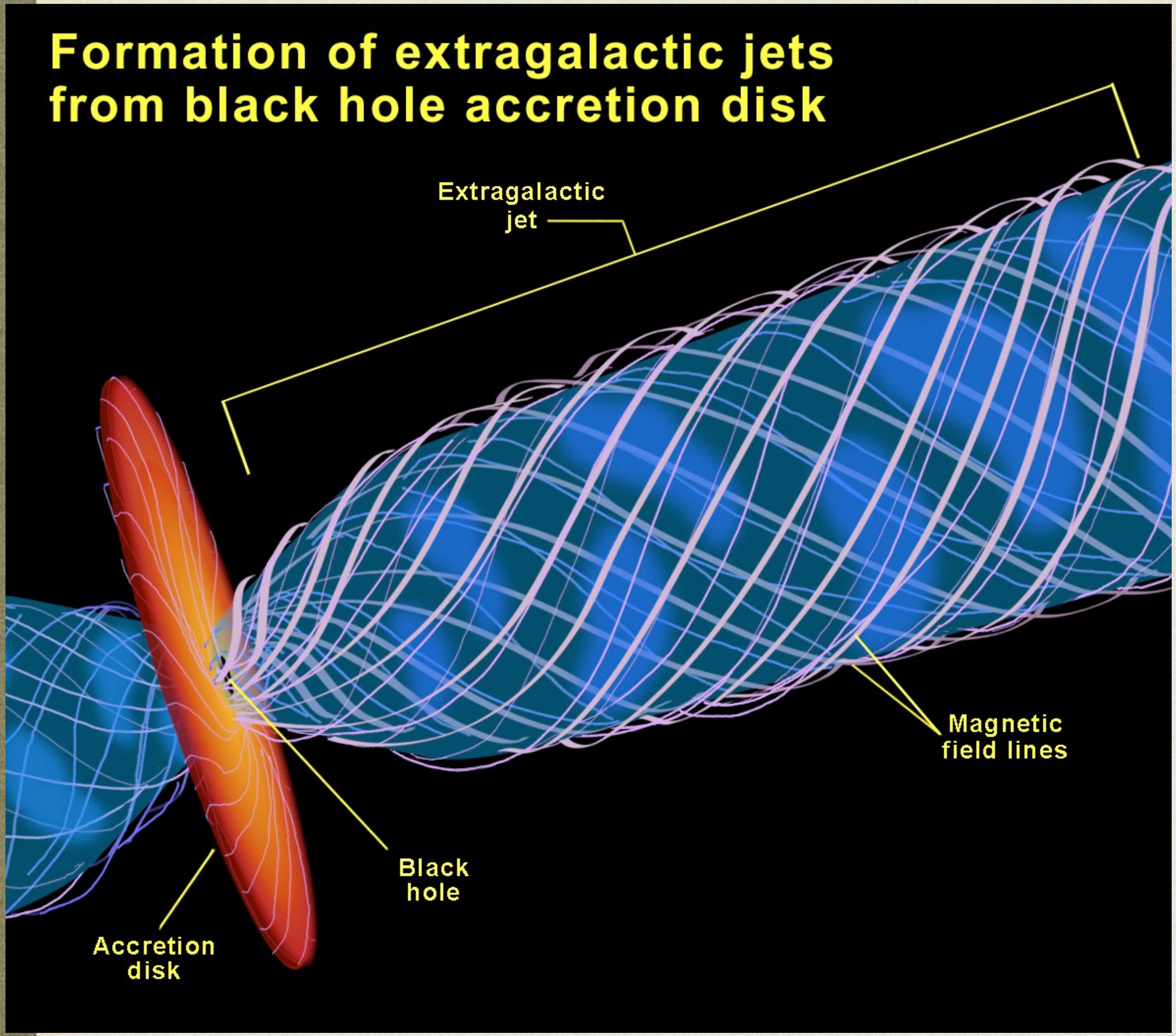
Pole-on FRIs = BL Lac objects

Pole-on FRIIs = Quasars

(Urry & Padovani 1995)

- Formation, collimation and propagation of jets ?
- Jet composition ?
- Jet stability: is there a large-scale magnetic field ?
- Interaction with the surrounding medium ?

JET FORMATION IN AGN



Blandford & Znajek (1977)

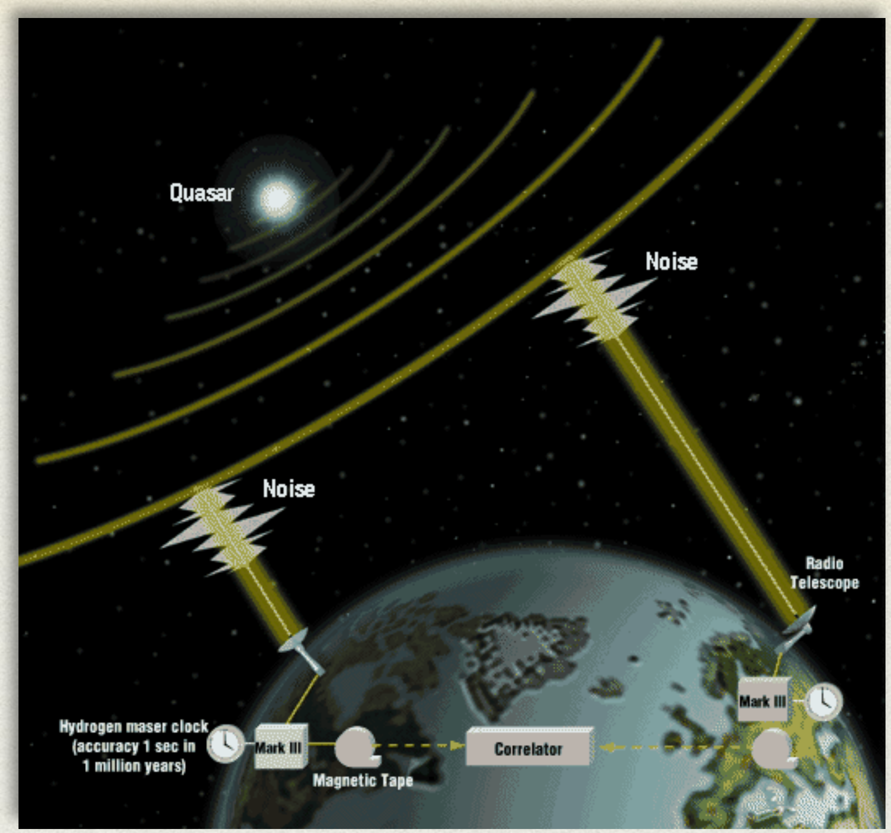
Energy & angular momentum extraction from a spinning black hole.

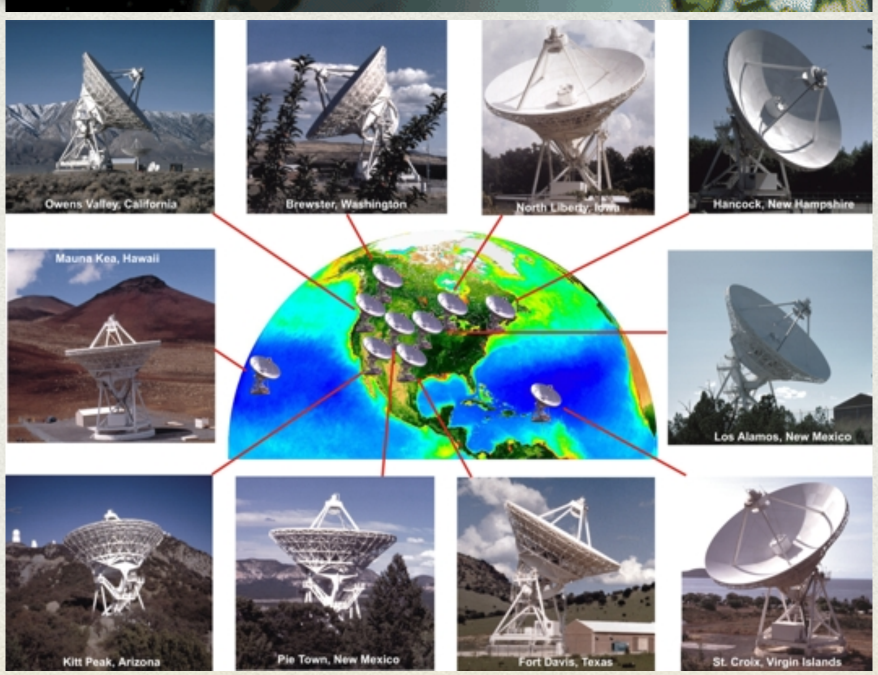
Strong poloidal magnetic field needed

Power extracted is proportional to B^2 & ω^2

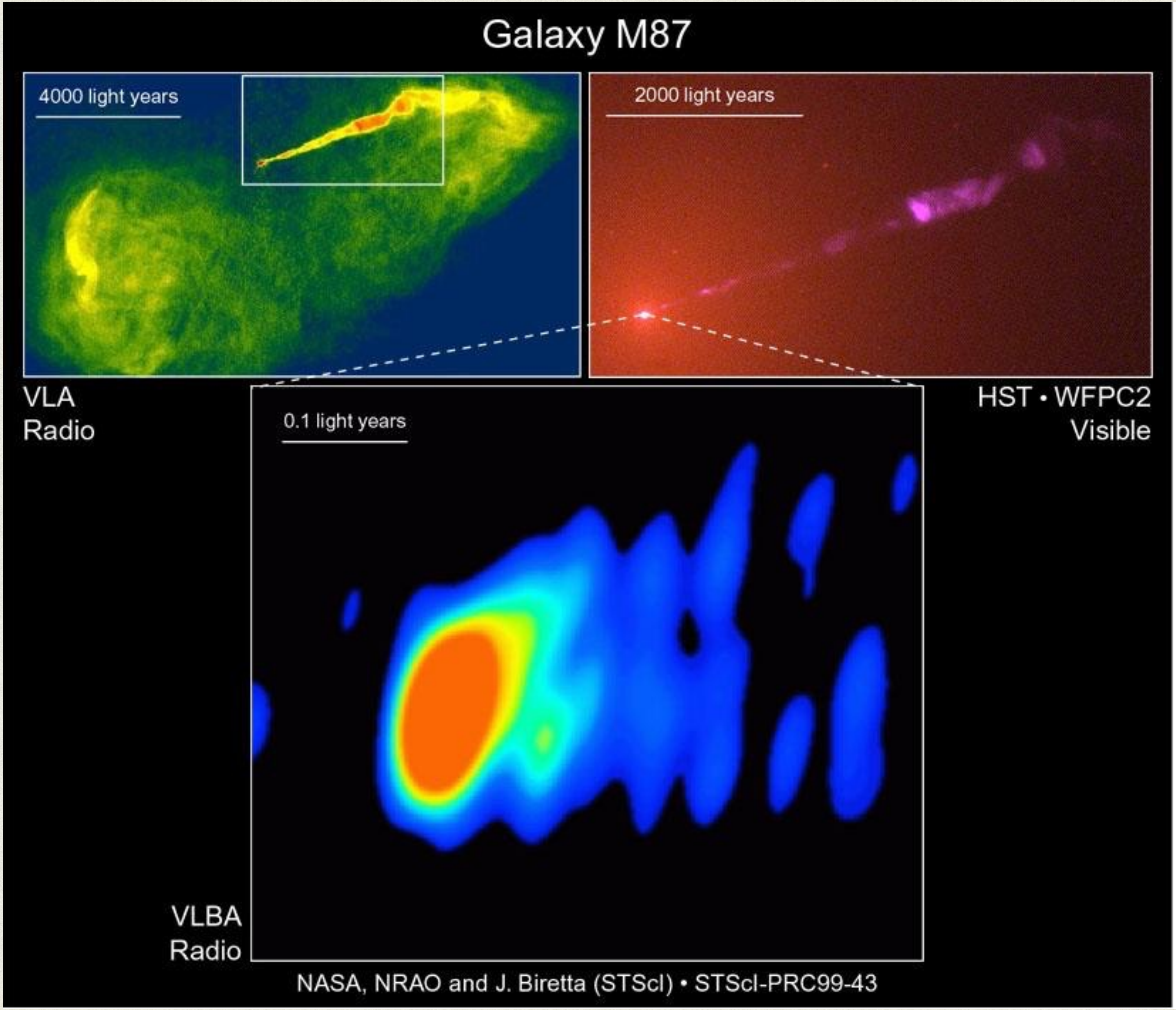
B = magnetic field strength
ω = angular velocity

VERY LONG BASELINE INTERFEROMETRY (VLBI)



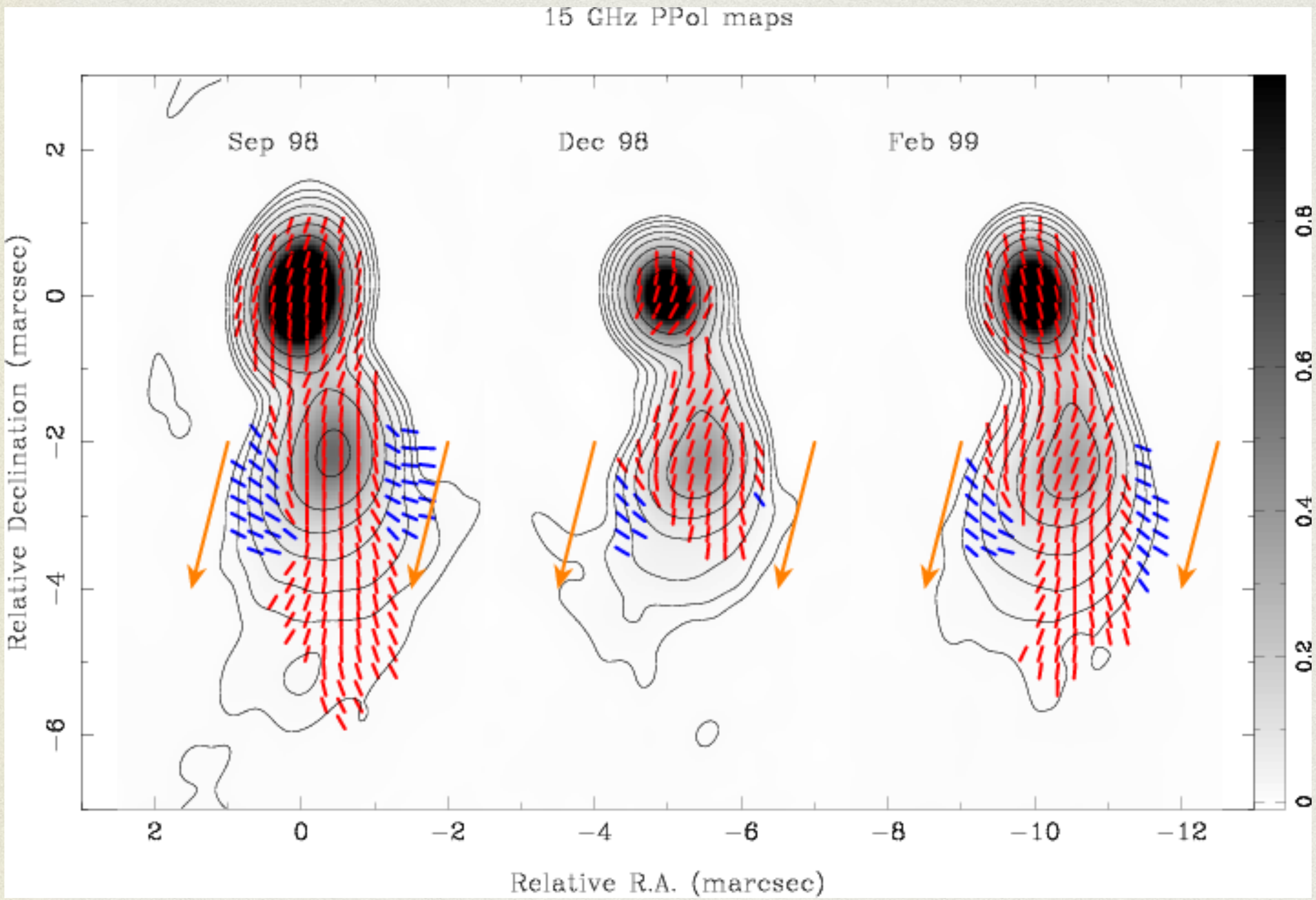


- Widely separated antennas not connected by cables (Unlike VLA, GMRT)
- Data recorded on magnetic tapes
- Recorded data is time-stamped by atomic clocks (e.g., hydrogen maser)
- Later, the tapes are played back with accurate time-stamps and correlated in a central location


Galaxy M87
4000 light years
2000 light years
VLA
Radio
HST • WFPC2
Visible
0.1 light years
VLBA
Radio
NASA, NRAO and J. Biretta (STScI) • STScI-PRC99-43

VLBI POLARIZATION

Synchrotron emission is highly linearly polarized (as much as 75% for optically thin radio emission and highly ordered magnetic field)



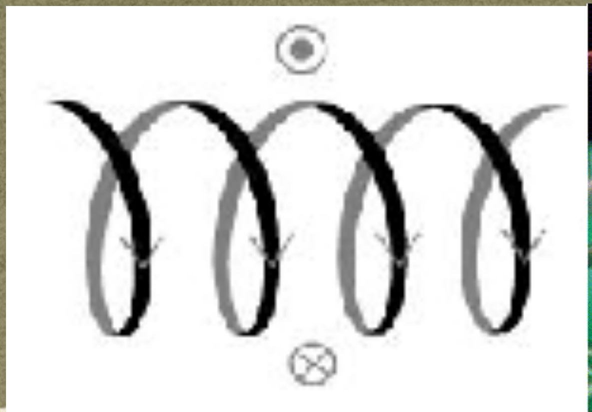
Electric vectors (χ) - Plane of polarisation

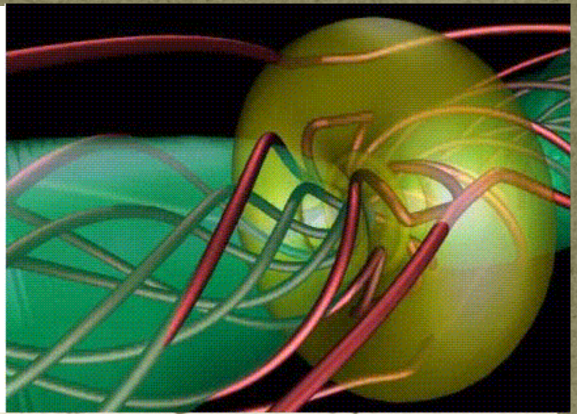
Magnetic field orientation is perpendicular to χ vectors for optically thin emission

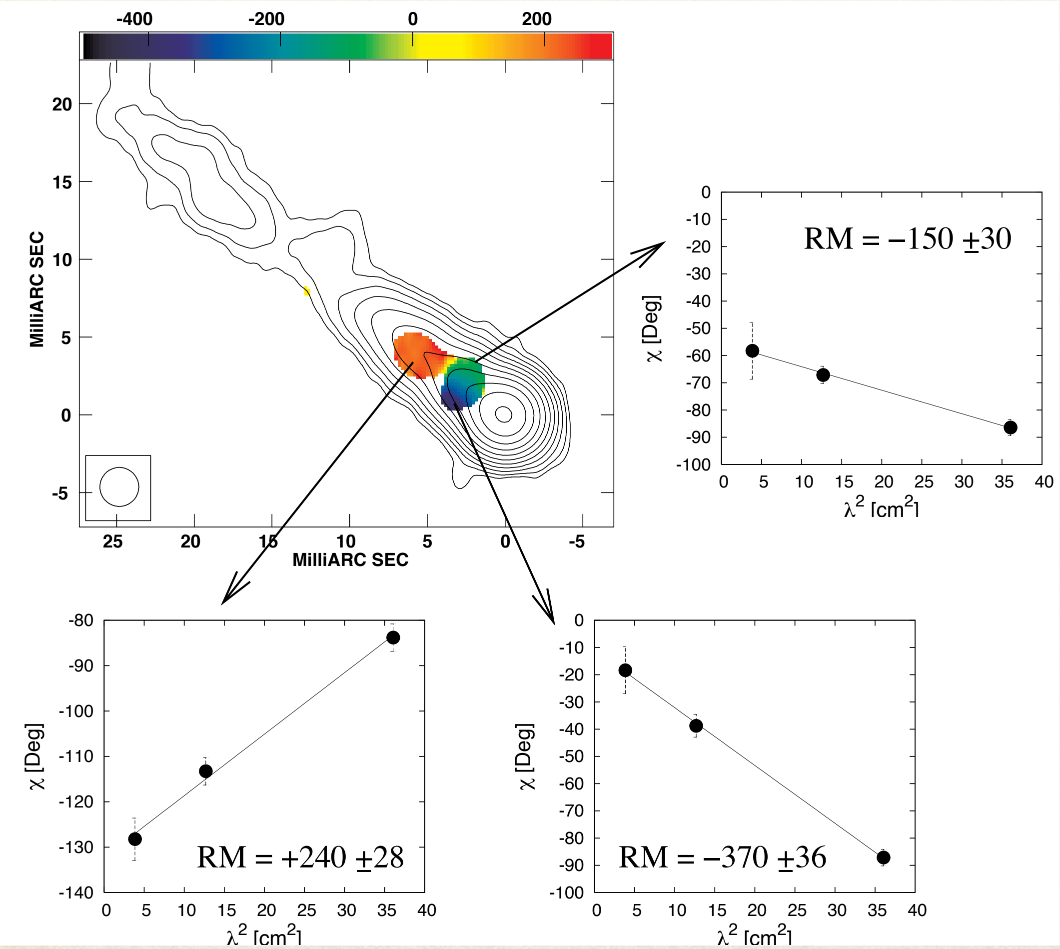
“Spine-Sheath” (Marscher+ 2002, Gabuzda 2003)

Helical magnetic fields (Lyutikov+ 2005)

ROTATION MEASURE GRADIENTS





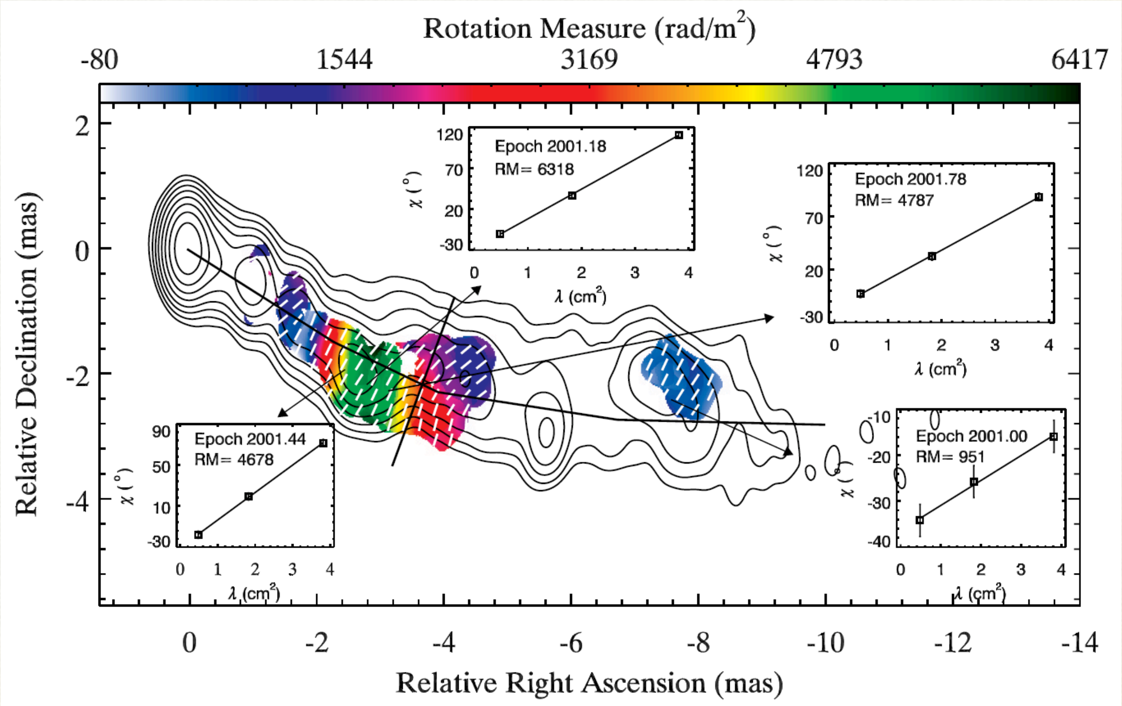


$$RM = \frac{e^3}{2\pi m_e^2 c^4} \int_L n_e \boldsymbol{B} \cdot d\boldsymbol{s}$$

$$\chi(\lambda^2) = \chi_0 + \lambda^2\, \mathrm{RM},$$

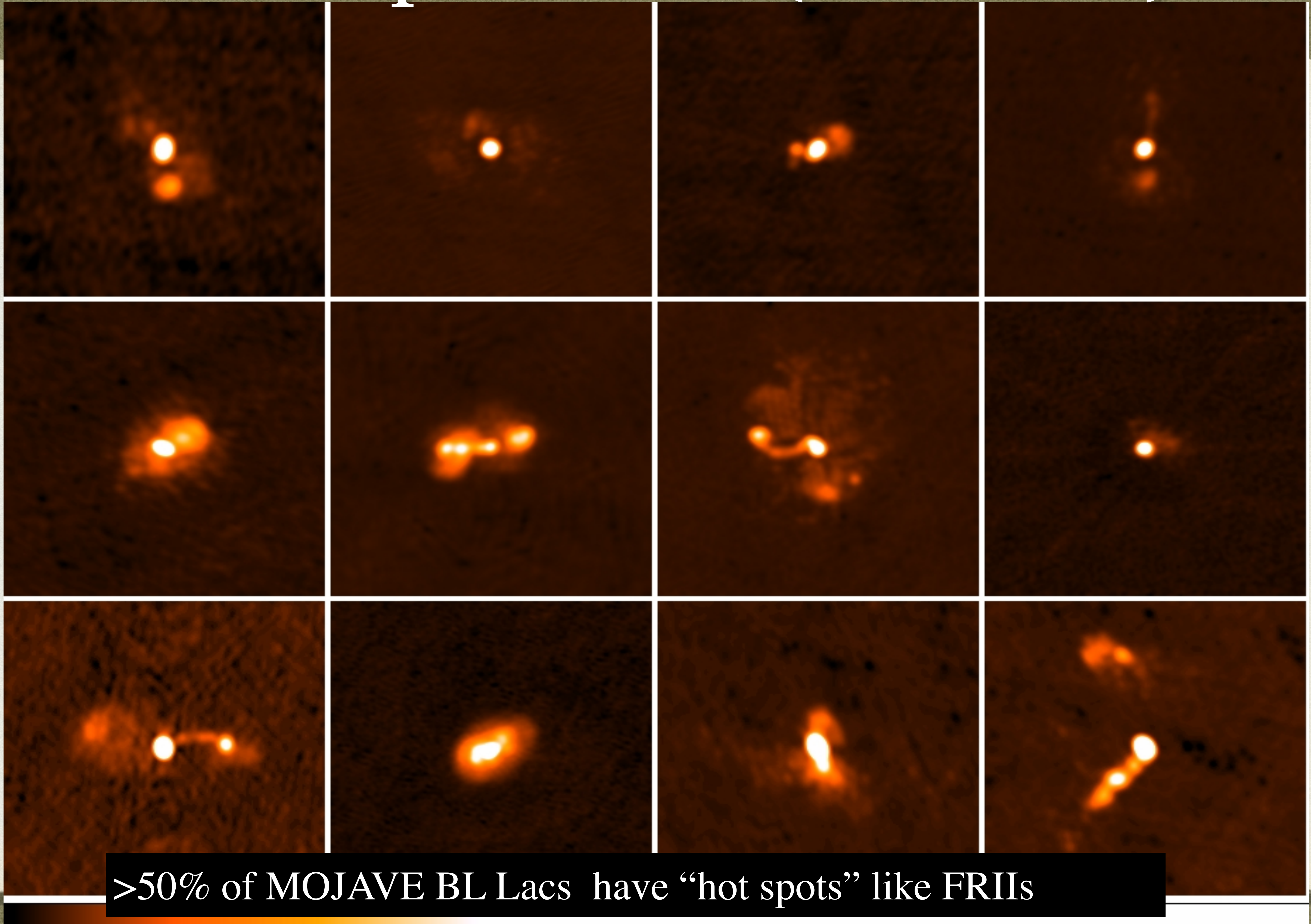
Signature of helical magnetic fields wrapping the jets (Blandford 1993)

3C78 – VLBI @ 5, 8, 15 GHz (Kharb+ 2009)



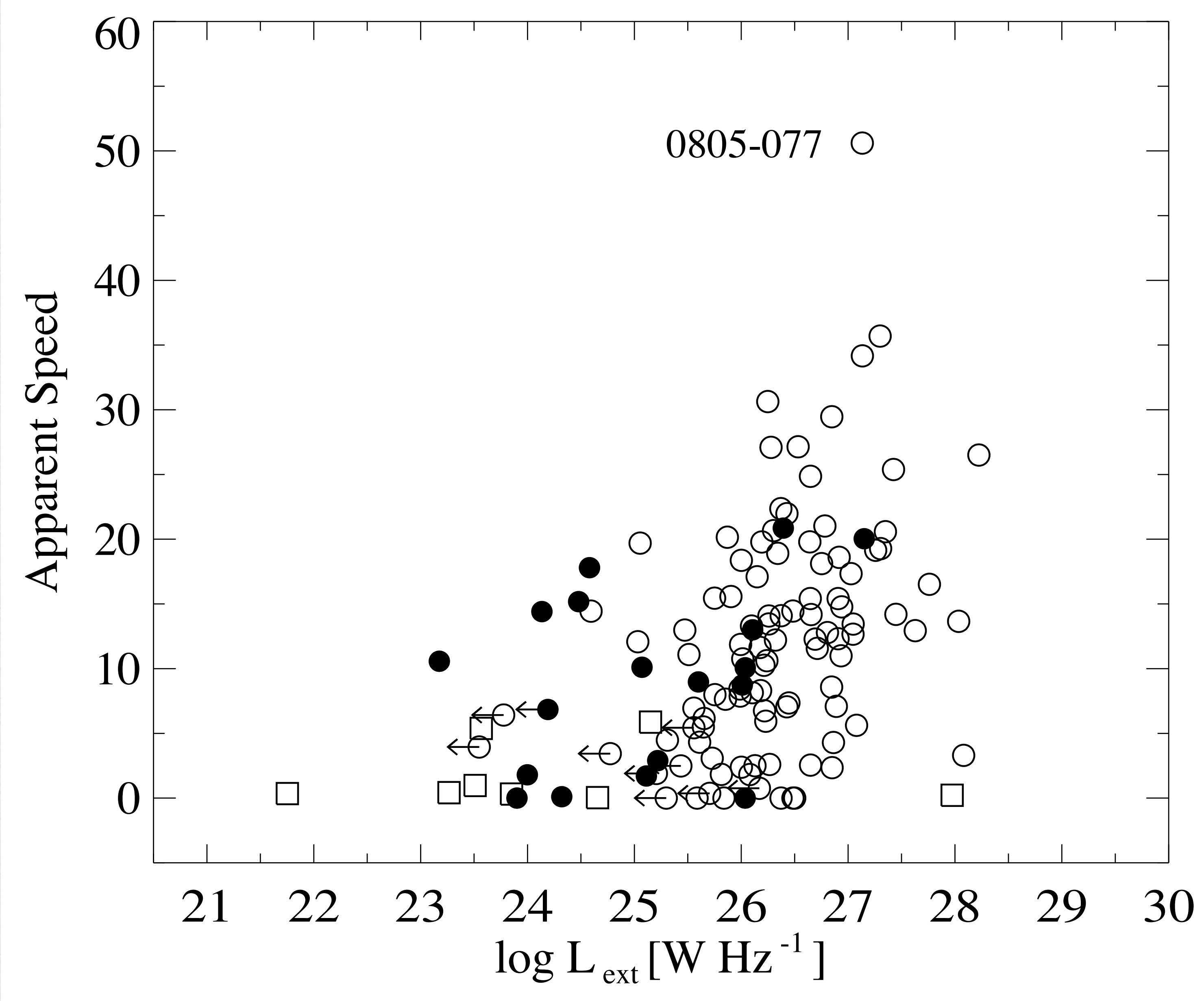
3C120 – VLBA @ 15, 22, 43 GHz (Gómez+ 2008)

Monitoring of Jets in AGN with VLBA Experiments (MOJAVE)



>50% of MOJAVE BL Lacs have “hot spots” like FRIIs

RELATING THE PC-SCALE TO THE KPC-SCALE



Faster parsec-scale jets have more radio-powerful lobes

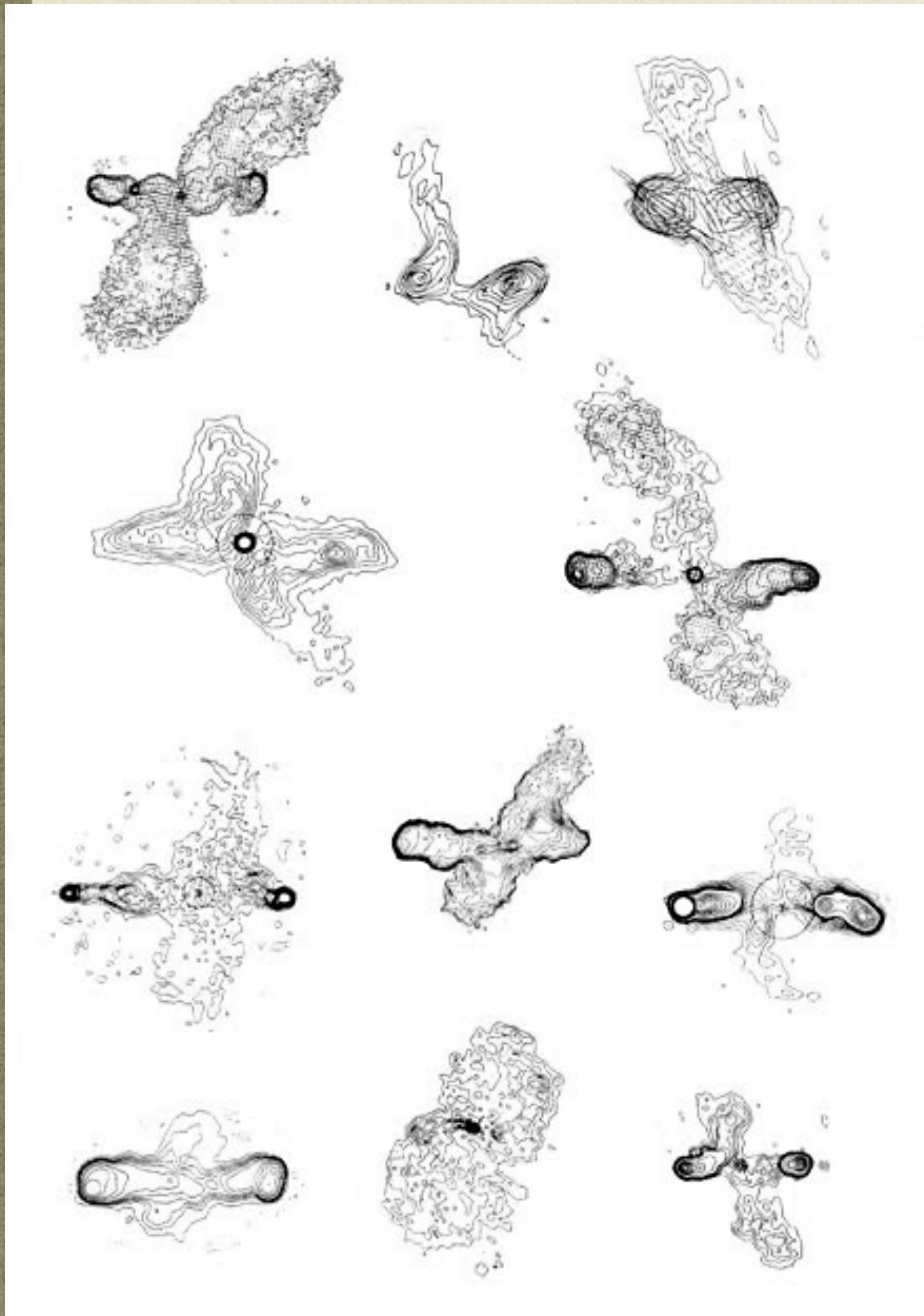
(Spearman rank correlation test results: p=5e-7
Partial regression w/ effects of luminosity distance removed: p=0.0028
Partial regression w/ effects of core luminosity removed: p=0.0075)

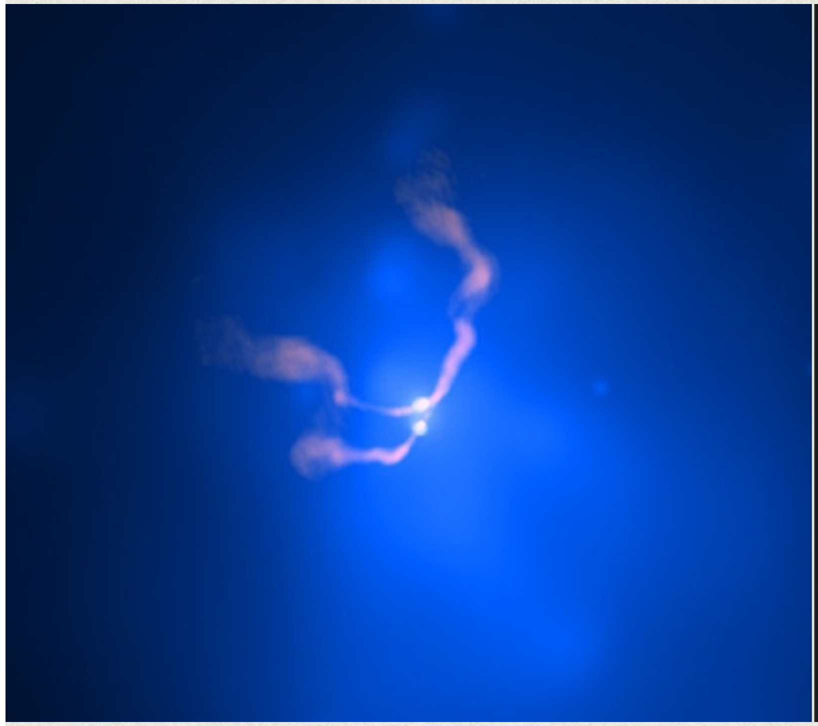
Undermines the role of the environment on jet/lobe emission

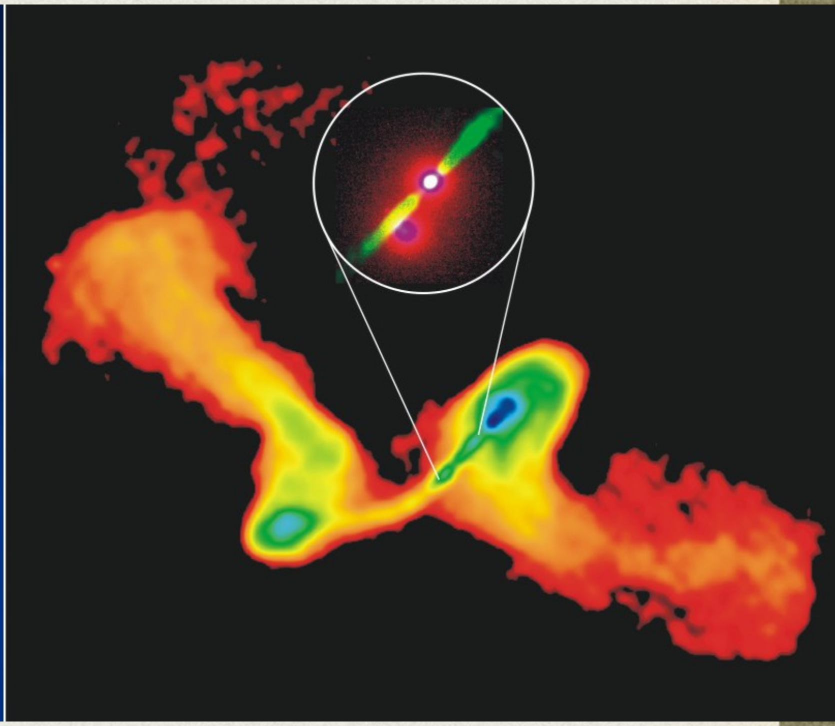
Continuum in properties between BL Lacs and Quasars

Kharb, Lister, Cooper, 2010

JET DIRECTION CHANGES



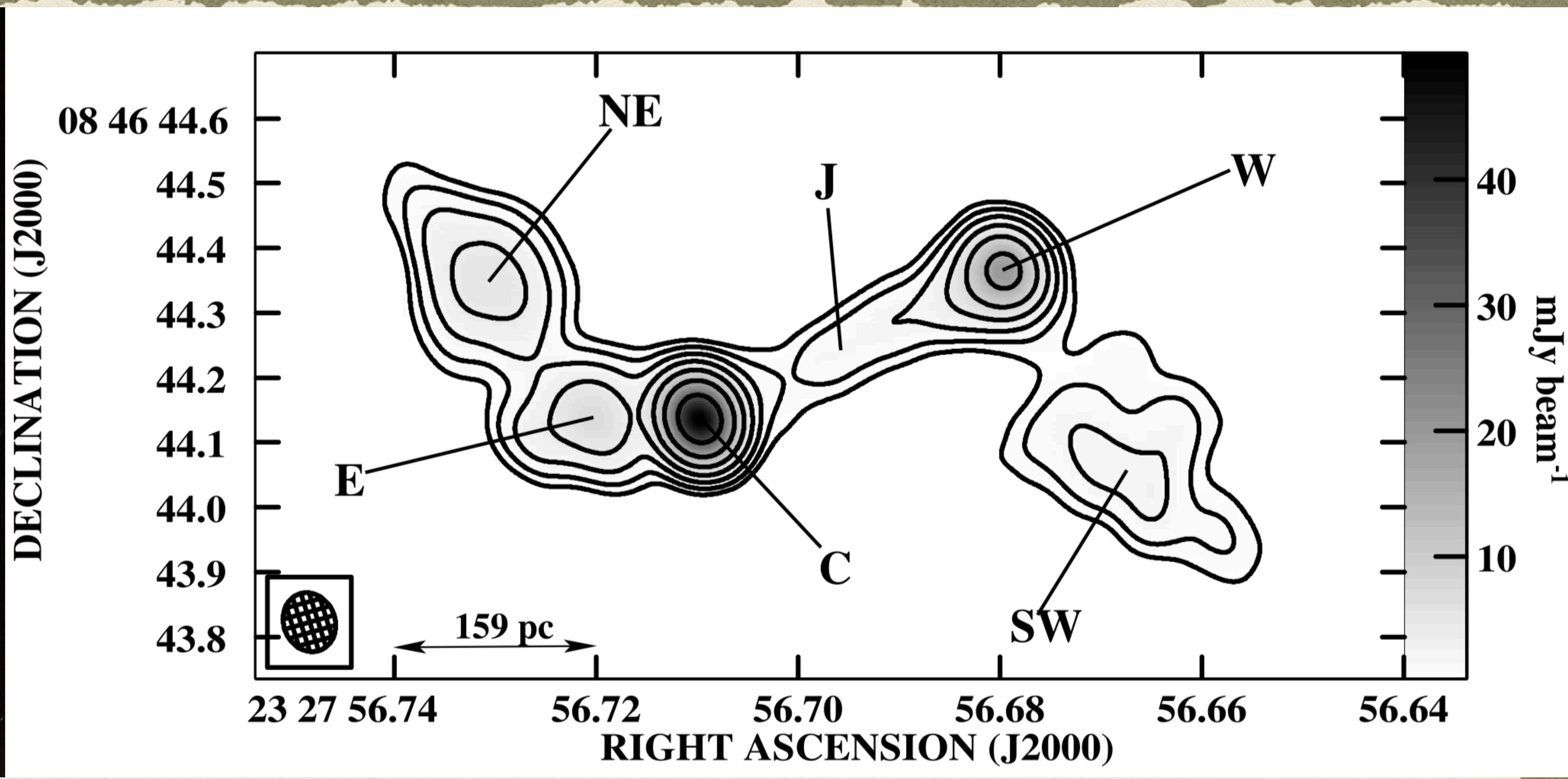




X-shaped, Z-shaped Radio Galaxies

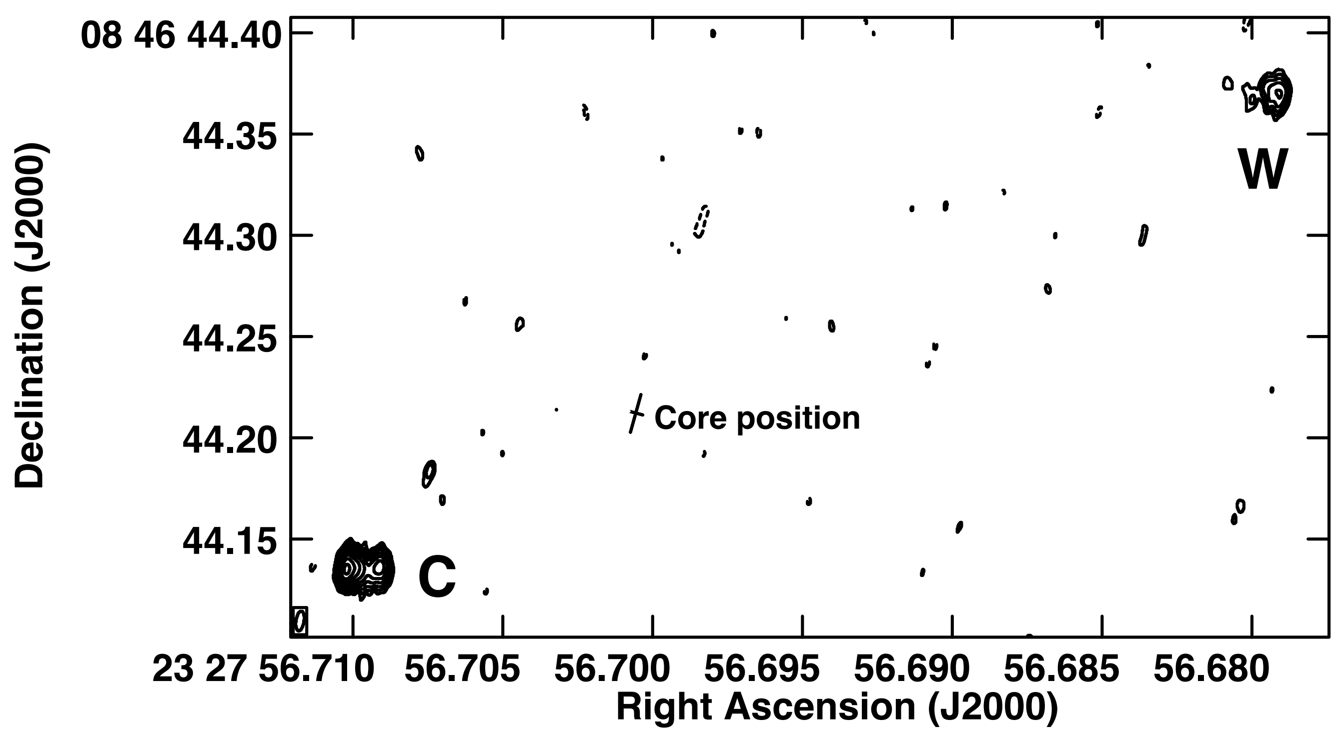
Jet Realignment due to Binary Black Holes?

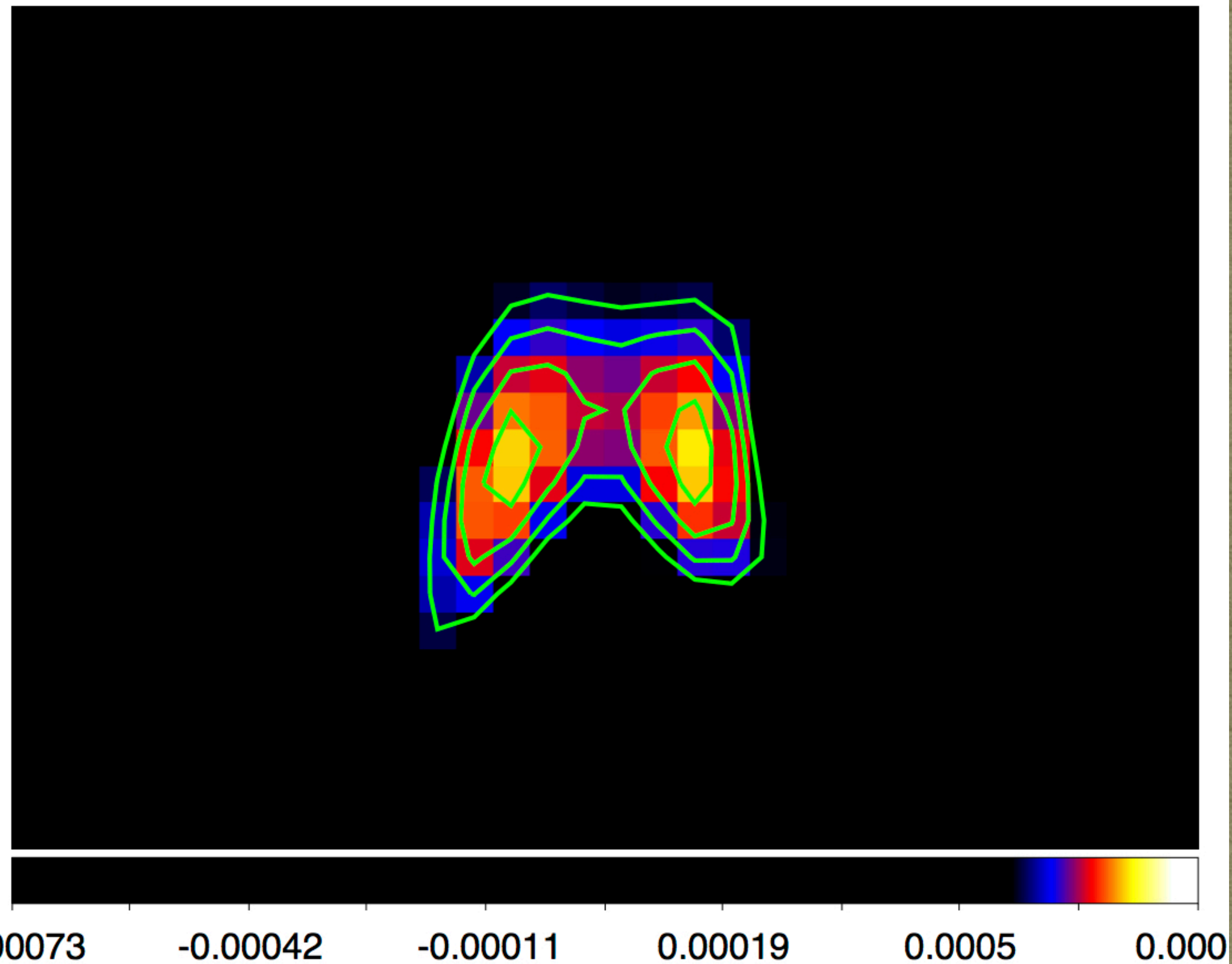
NGC 7674



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

NGC 7674

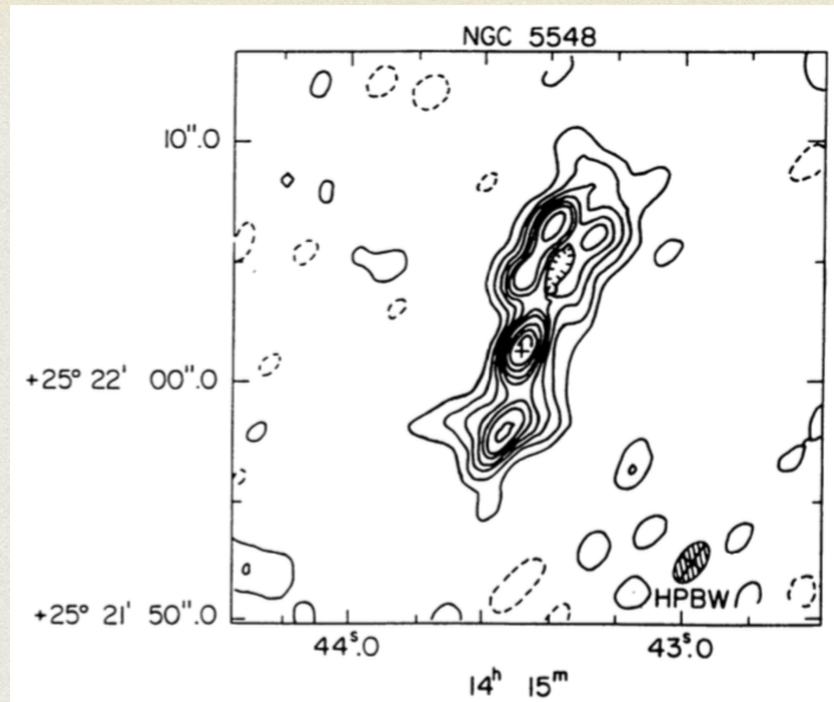


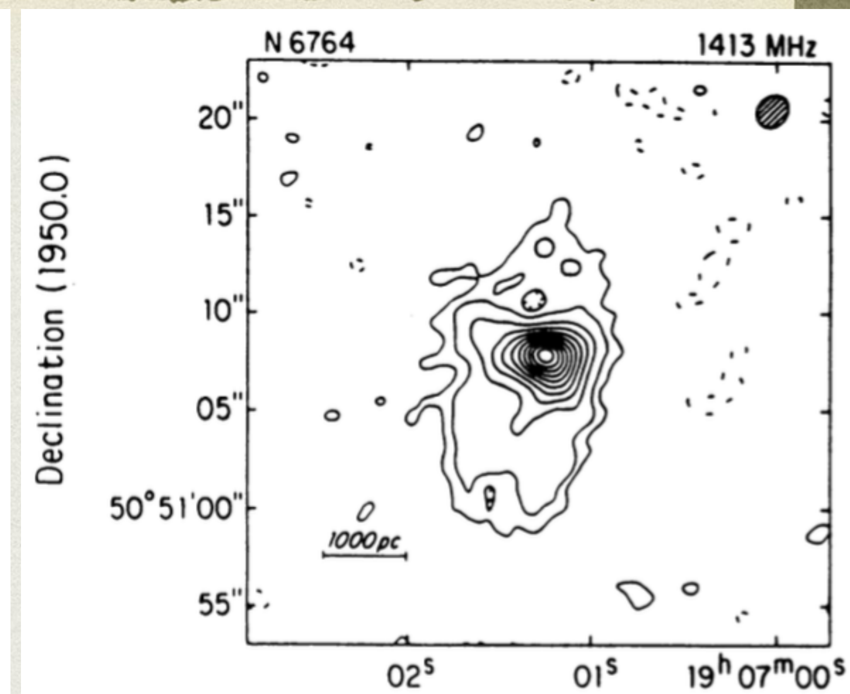


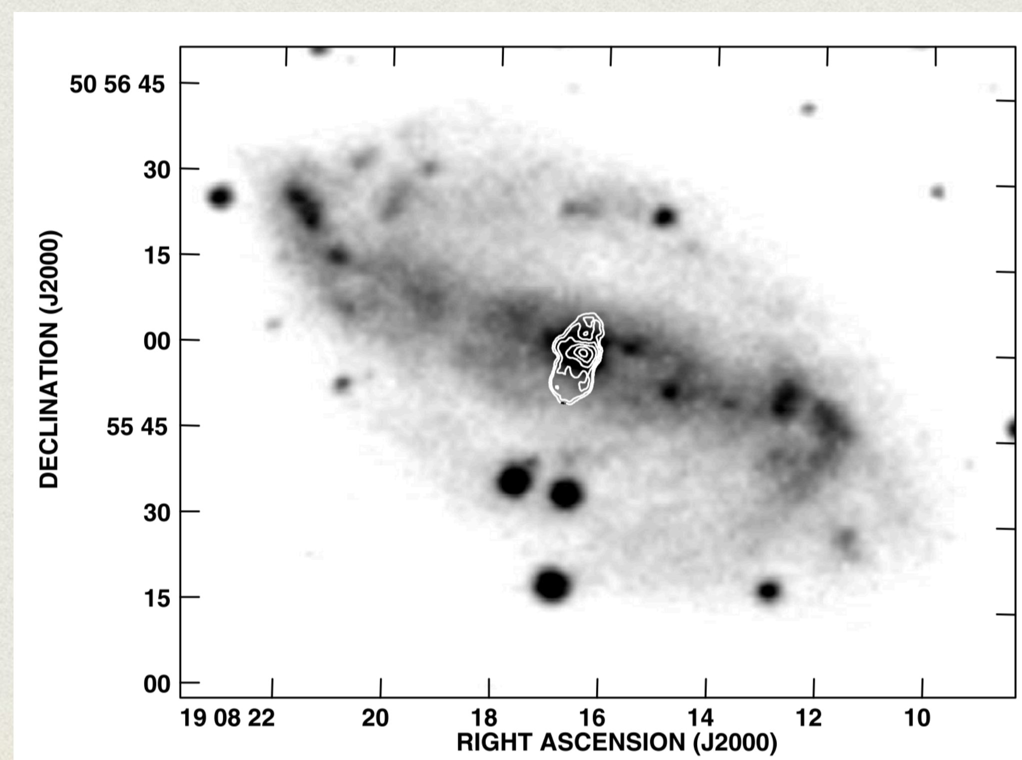
- VLBA at 2, 5, 8, 15 GHz
- $T_B > 5 \times 10^6$ K. Inverted spectral indices.
- Core projected separation = 0.65 mas = 0.35 parsec. ***Closest SMBH binary!***
- Kharb, Lal & Merritt 2017, Nature Astronomy

KILOPARSEC RADIO STRUCTURES

- Systematic studies w/ VLA and Westerbork at 5 & 1.4 GHz
- Diffuse radio emission by starburst-driven winds (Wilson 1988; Baum+ 1993)
- Colbert et al. 1996 suggested AGN-driven based on non-spherical morphology and skewed orientations w.r.t. galactic disks

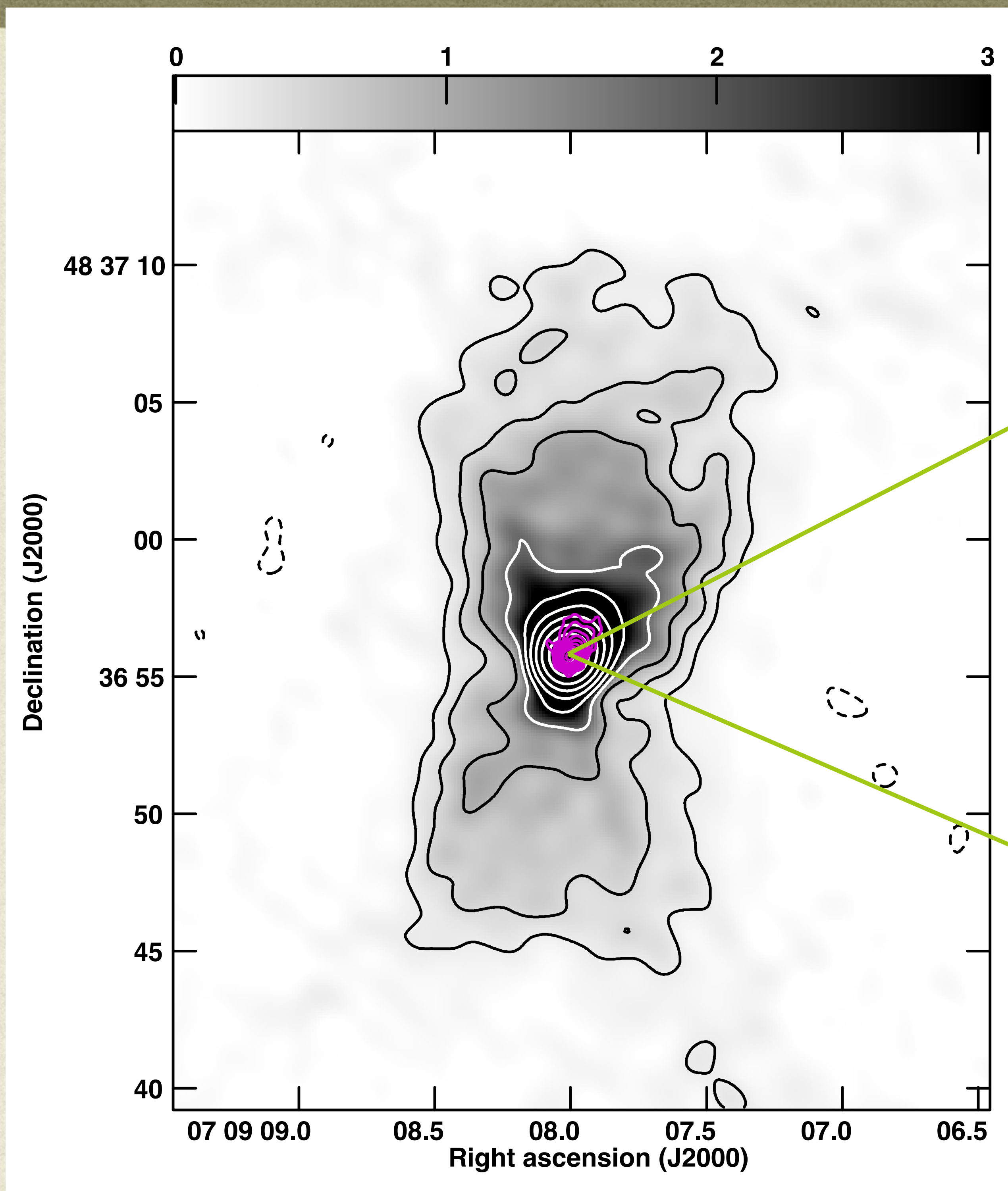


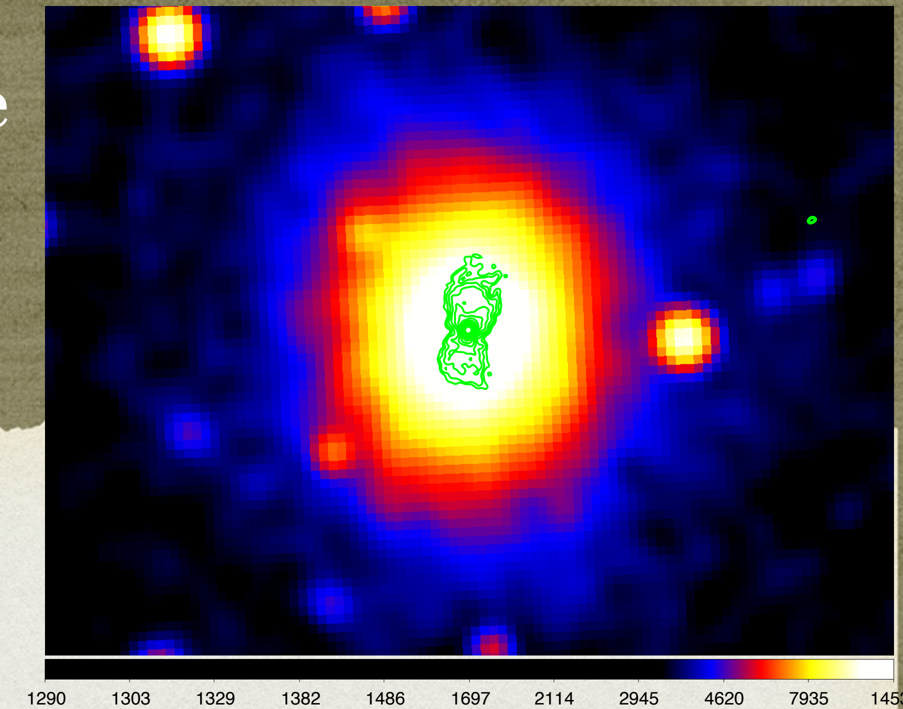


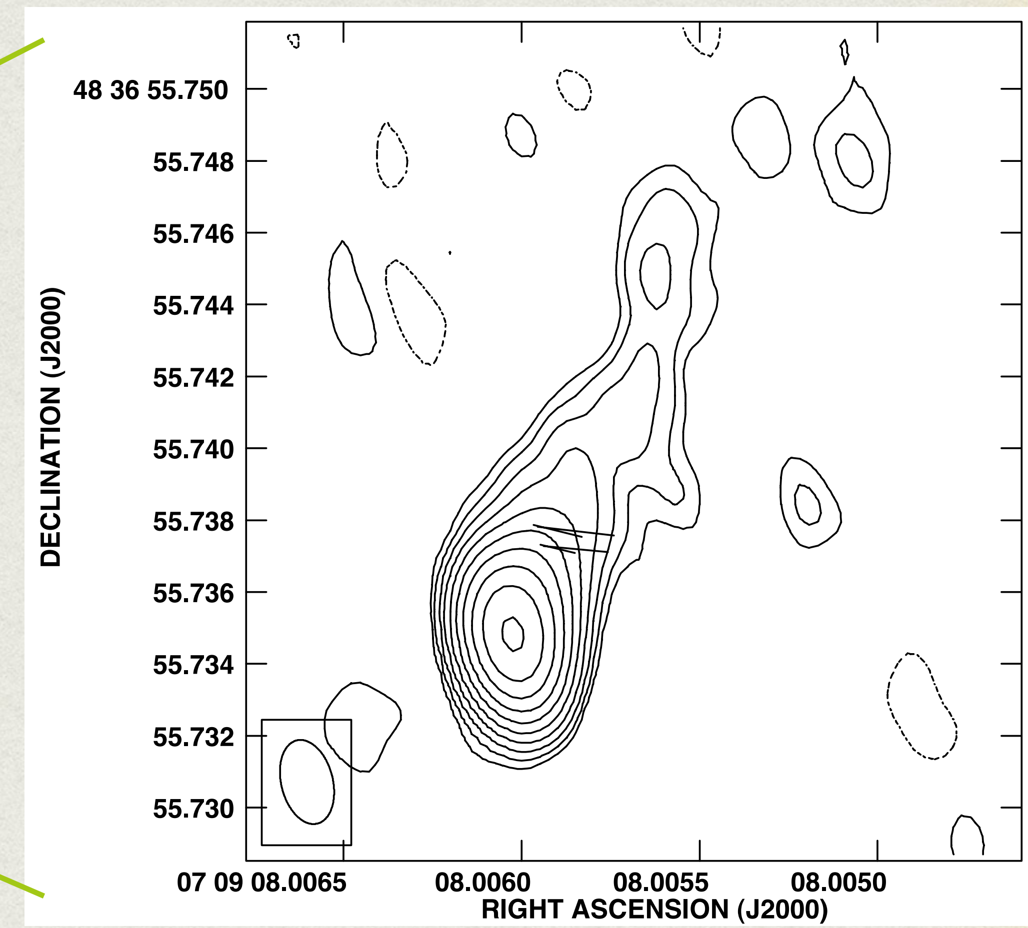


UGC 3695: FRI radio galaxy with lowest "**R**" in sample of Seyferts & FRIs (Kharb+ 2014)

Radio Lobe Extent ≥10 kpc, E-S0 galaxy





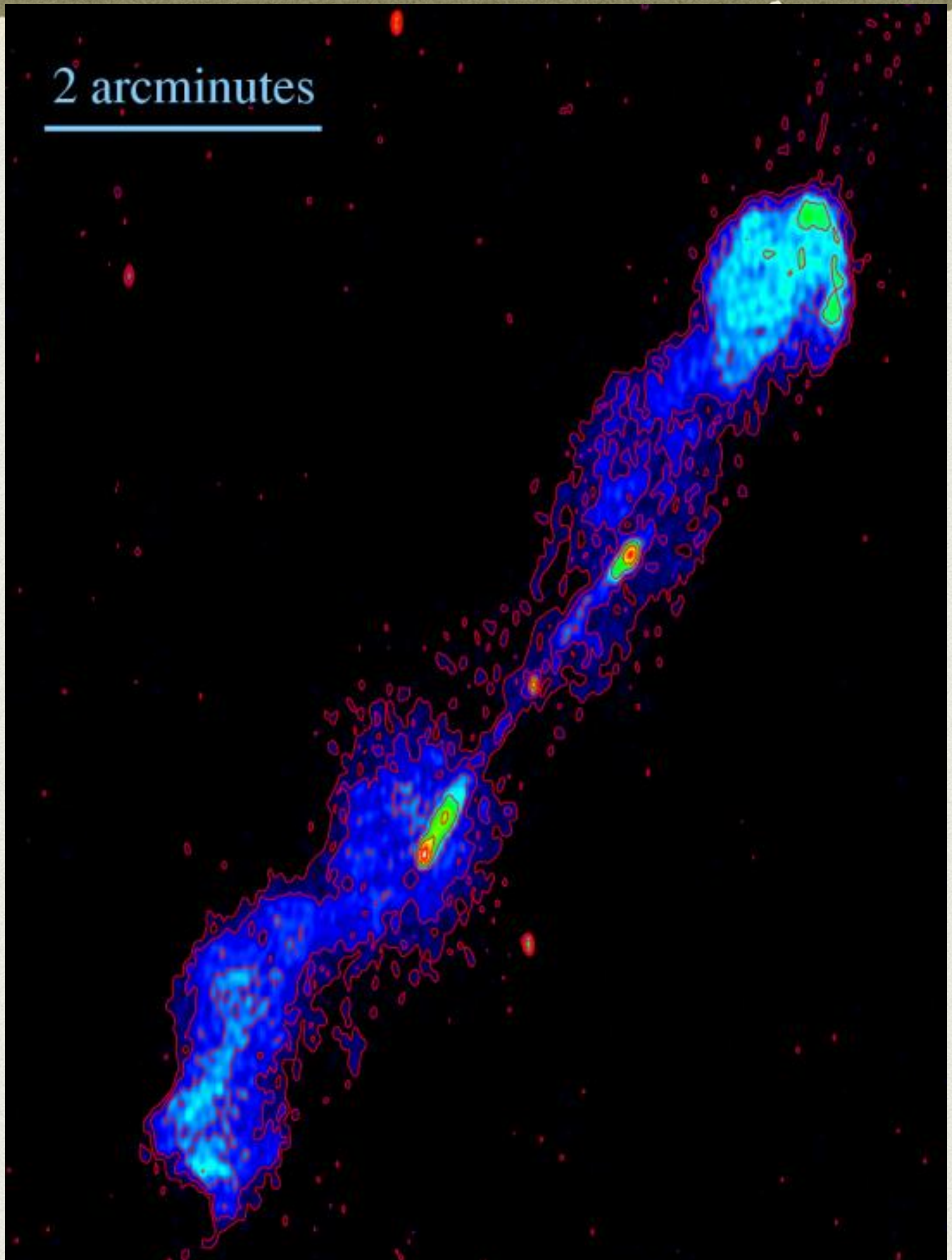


VLBI image from Kharb+ 2012

FRI - Jetted Seyferts/LINERs (Baldi+ 2018)

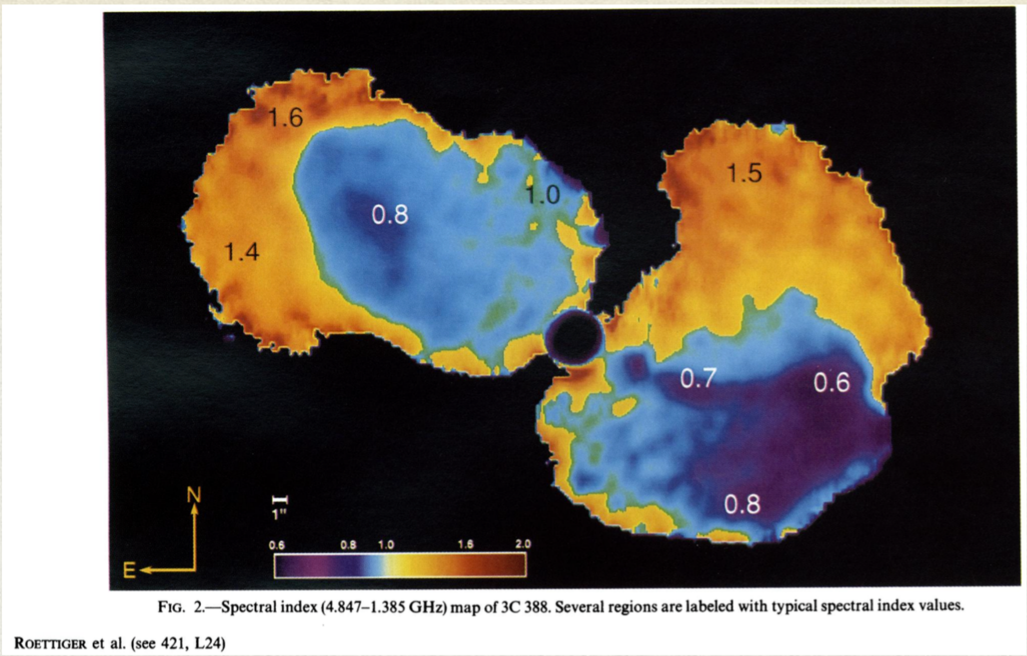
EPISODIC ACTIVITY

- Giant radio galaxies ≳1 Mpc
- Double-double radio galaxies
- AGN activity is episodic
- "Relic" steep-spectrum (synchrotron ageing) lobes

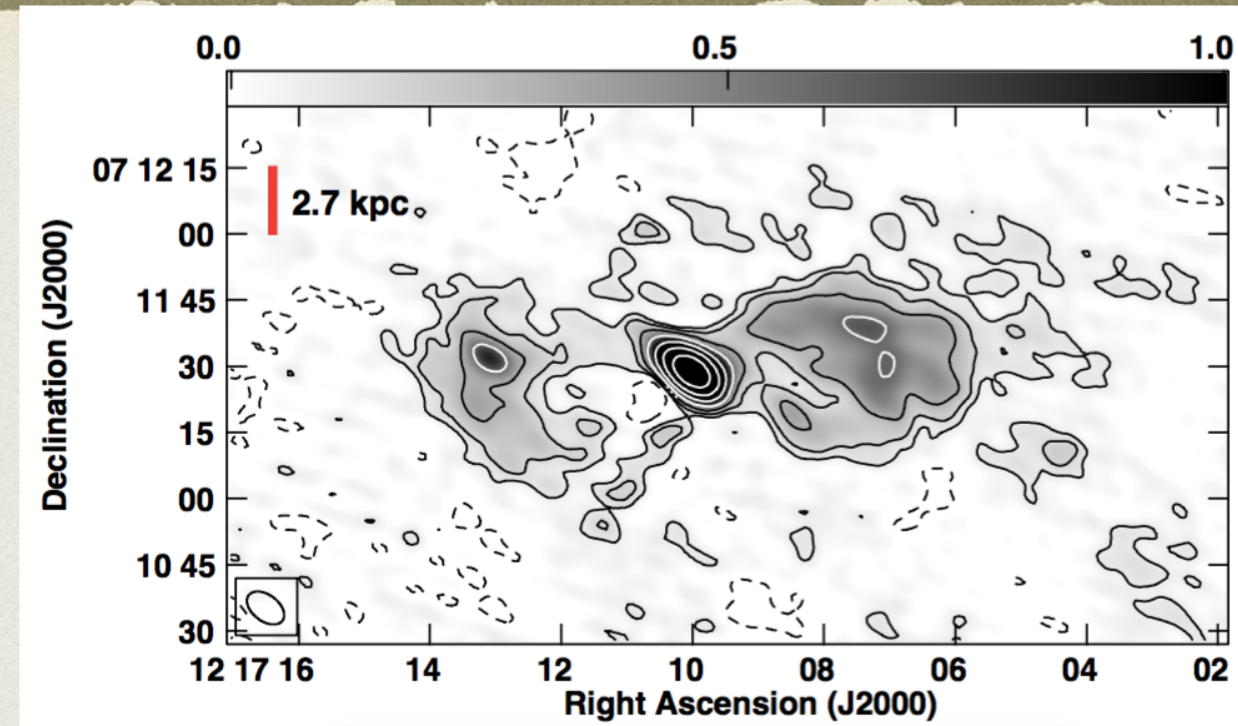


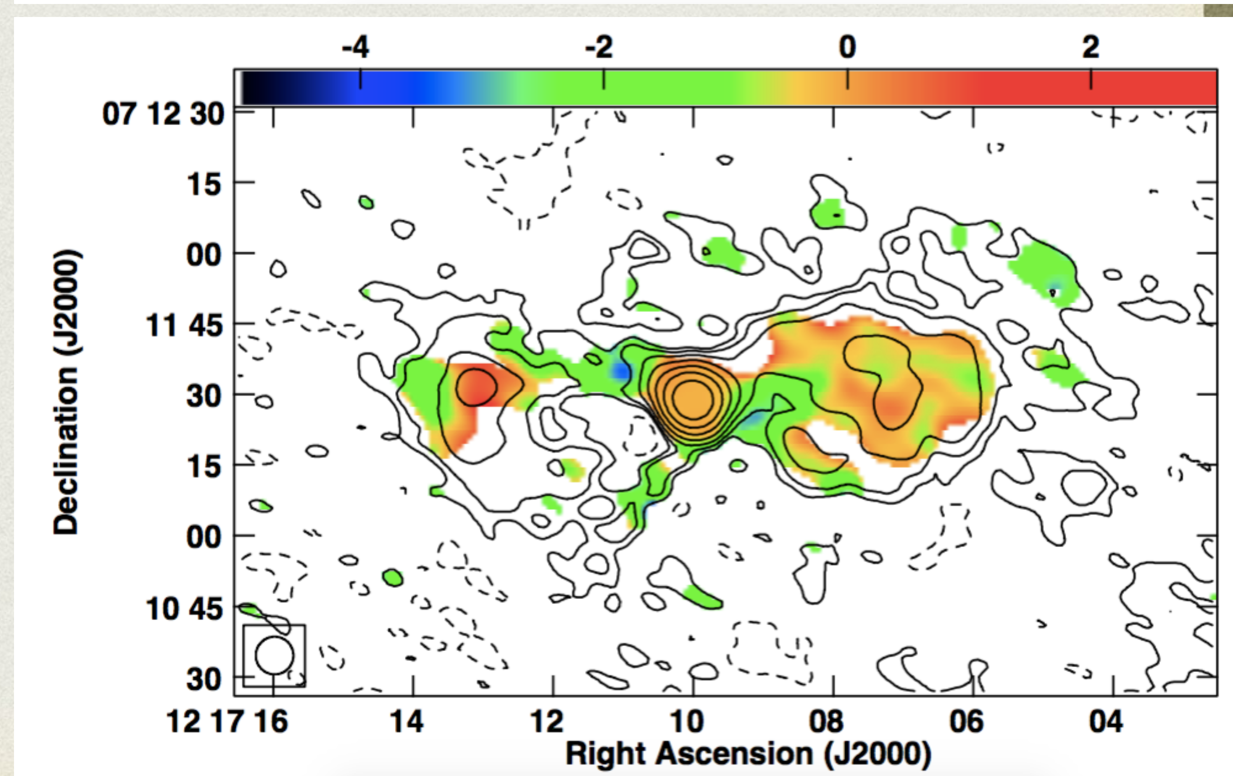
ATCA image of B1545-321 by Saripalli+

RELIC LOBES



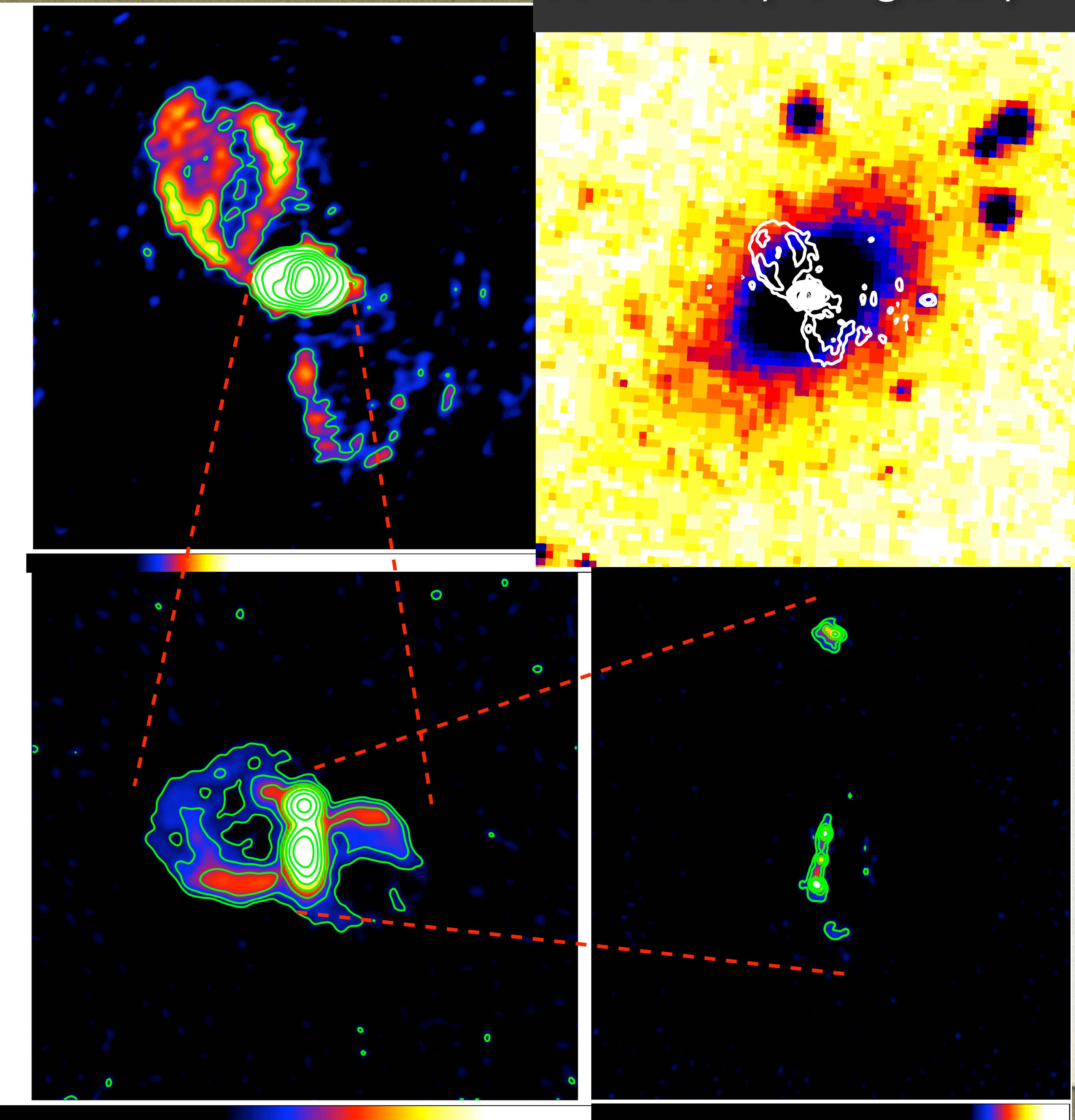
3C388; Roettiger+ 1994





- Seyfert 1 NGC 4235: GMRT 325 - 610 MHz spectral index, Lobe: -0.6+/-0.2, Relic: -1.8+/-0.2 (Kharb+ 2016)
- Myers & Spangler (1985) formalism: Relic lobe 2 times older

Jetted Seyfert galaxy Mrk 6

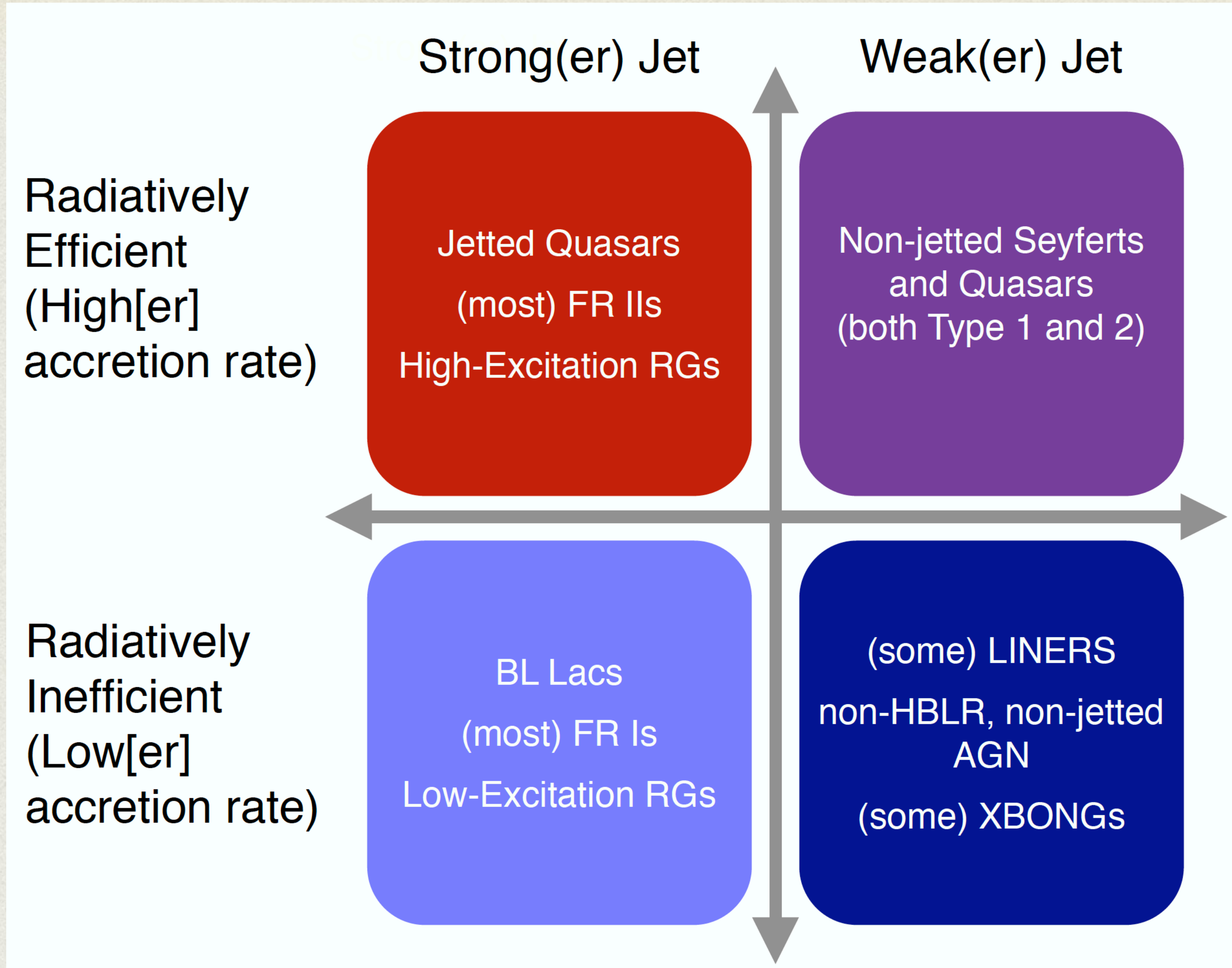


1.4 & 5 GHz - VLA A, B, C, D arrays

North-South ~12 kpc, East-West ~3 kpc, N-S ~1 kpc jet

SFR ~33 $M_{\odot}$/yr required (Kharb+ 2006)

Herschel (L250μm) SFR < 0.8 $M_{\odot}$/yr (Kharb+ 2014)



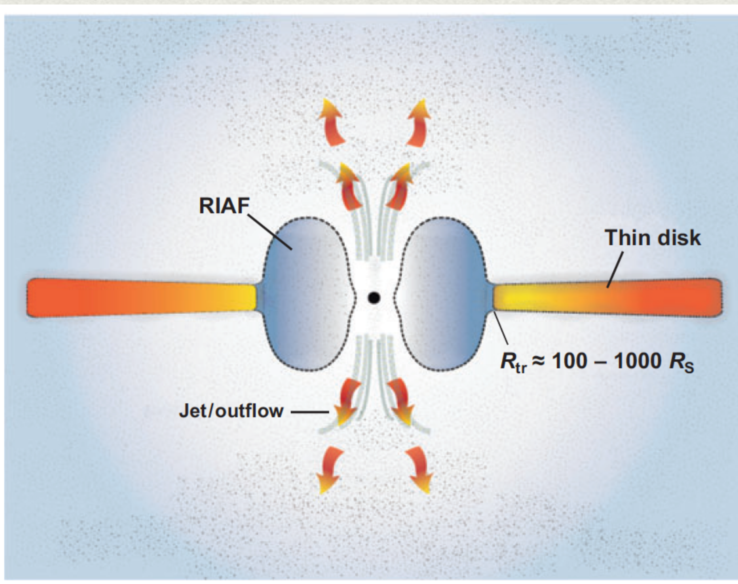


Figure 13
A diagram of the central engine of LLAGNs, consisting of three components: an inner, radiatively inefficient accretion flow (RIAF); an outer, truncated thin disk; and a jet or outflow. (Courtesy of S. Ho.)

Eddington rates = λ = L_{bol}/L_{Edd}

when λ <0.01 Radiatively Inefficient Accretion Flow
else "standard" geometrically thin, optical thick disk

Padovani+ 2017, A&A Review

$$L_{\rm Edd} = \frac{4\pi G M m_{\rm p} c}{\sigma_{\rm T}} \cong 1.26 \times 10^{31} \left(\frac{M}{M_\odot}\right) {\rm W} = 3.2 \times 10^4 \left(\frac{M}{M_\odot}\right) L_\odot$$

SUMMARY

- Magnetic fields (helical?) instrumental in jet launching, collimation, propagation
- Role of environment unsettled; also Jet composition
- Continuum in properties between FRIIs and FRIs
- Continuum in properties between FRIs and Jetted Seyferts/LINERs
- AGN classification may depend only on a few parameters: Orientation, Accretion-rate, Presence (or absence) of strong jets, Host galaxy and its environment
- SKA with large frequency coverage (50 MHz - 20 GHz) and nanoJy sensitivity will revolutionize the study of Radio AGN