ACTIVE GALACTIC NUCLEI

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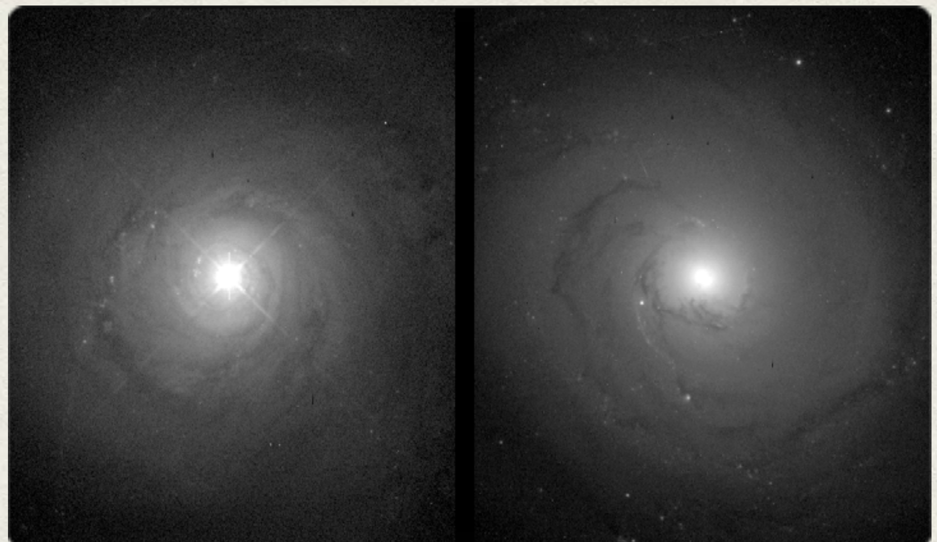
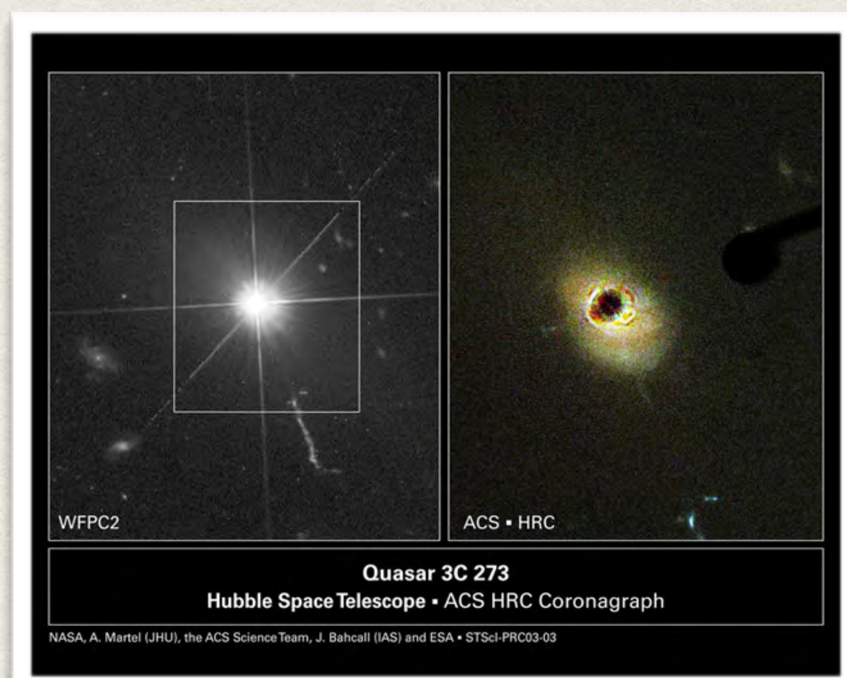
AGN

- C. Seyfert (1943): Star-like nuclei + peculiar emission-line spectra in spirals (NGC5548 vs. NGC3277)
- M. Schmidt (1963): Quasar 3C273 at z=0.158 discovered





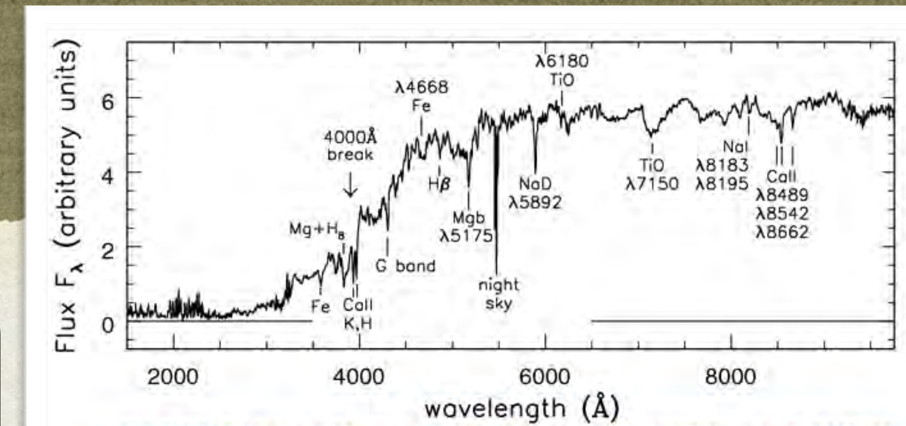
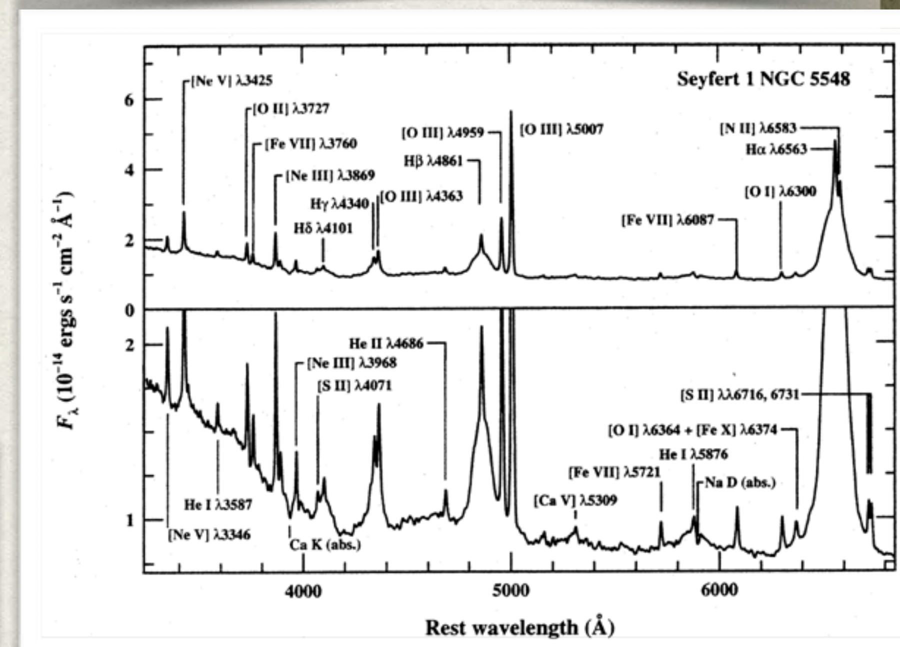
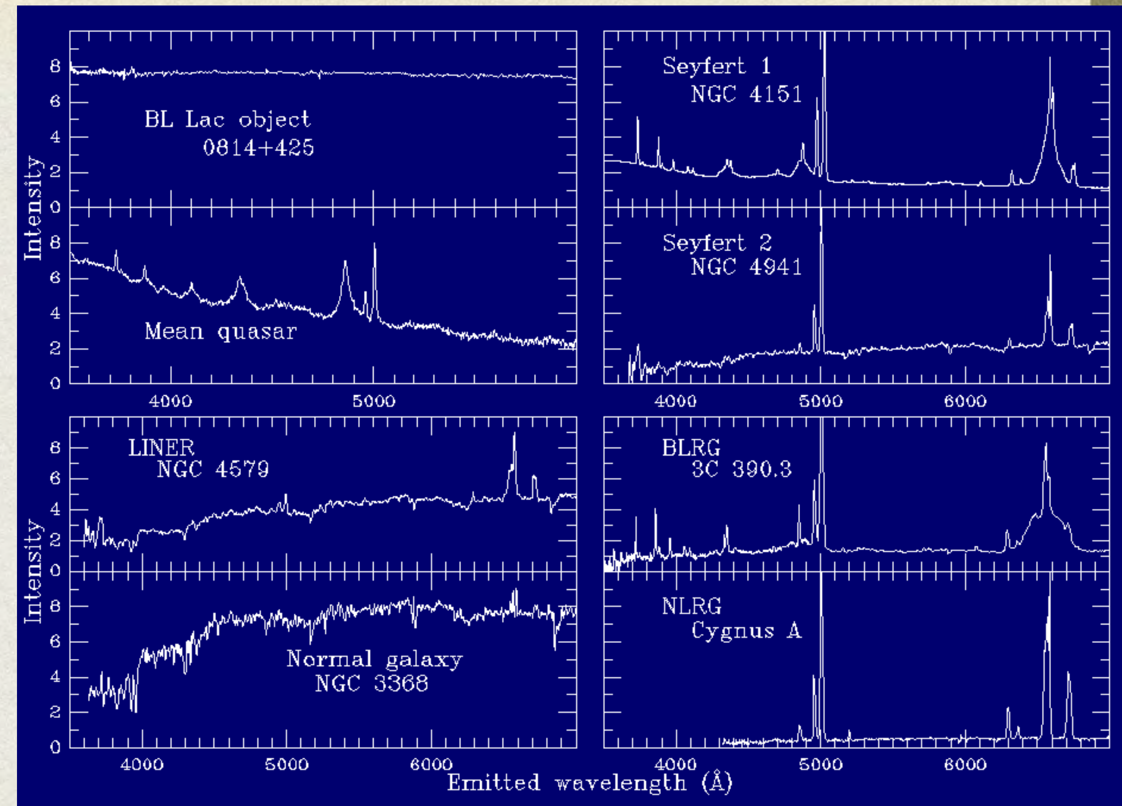


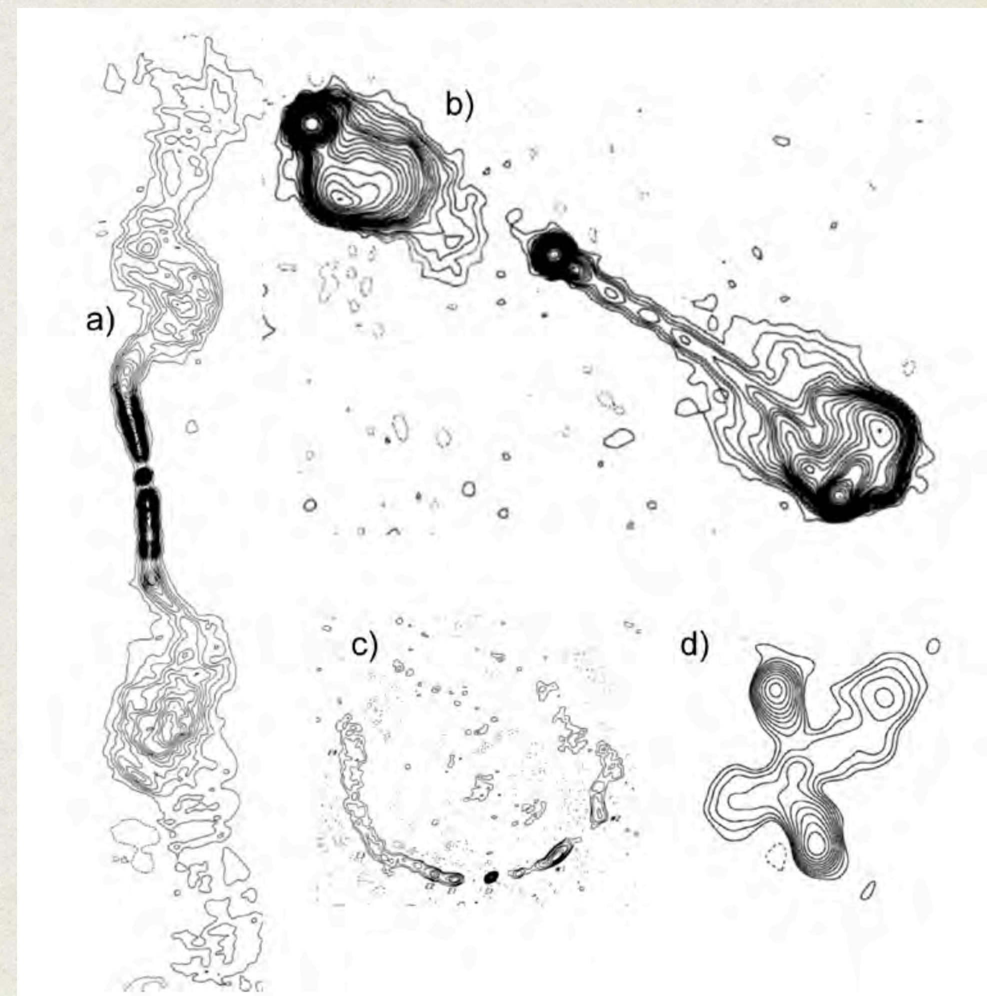
Fig 6.17 (A. Kinney) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007



The AGN zoo: list of AGN classes.

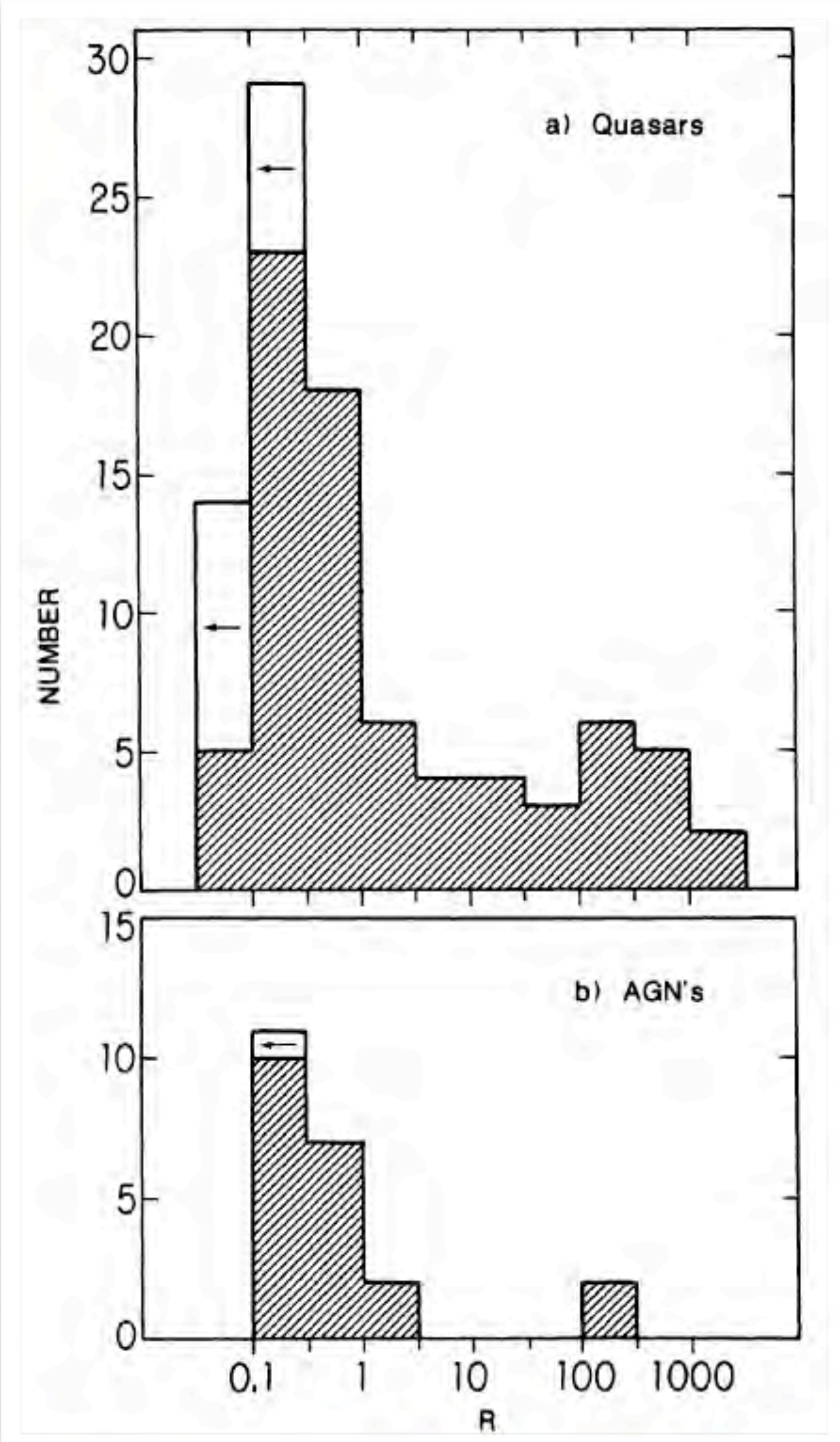
Class/Acronym	Meaning	Main properties/reference
Quasar	Quasi-stellar radio source (originally)	Radio detection no longer required
Sey1	Seyfert 1	FWHM $\gtrsim 1,000$ km s^{-1}
Sey2	Seyfert 2	FWHM $\lesssim 1,000$ km s^{-1}
QSO	Quasi-stellar object	Quasar-like, non-radio source
QSO2	Quasi-stellar object 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, $f_{\rm core} \geq f_{\rm ext}$ (same as FSRQ)
CSS	Compact steep spectrum radio source	core dominated, $\alpha_{\rm r} > 0.5$
CT	Compton-thick	$N_{\rm H} \geq 1.5 \times 10^{24}$ cm^{-2}
FR 0	Fanaroff-Riley class 0 radio source	ref. 5
FSRQ	Flat-spectrum radio quasar	RL AGN, $\alpha_{\rm r} \leq 0.5$
GPS	Gigahertz-peaked radio source	see ref. 6
HBL/HSP	High-energy cutoff BL Lac/blazar	$\nu_{\rm synch\ peak} \geq 10^{15}$ Hz (ref. 7)
HEG	High-excitation galaxy	ref. 8
HPQ	High polarization quasar	$P_{\rm opt} \geq 3\%$ (same as FSRQ)
Jet-mode		$L_{\rm kin} \gg L_{\rm rad}$ (same as LERG); see ref. 9
IBL/ISP	Intermediate-energy cutoff BL Lac/blazar	$10^{14} \leq \nu_{\rm synch\ peak} \leq 10^{15}$ 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	$\nu_{\rm synch\ peak} < 10^{14}$ Hz (ref. 7)
LDQ	Lobe-dominated quasar	RL AGN, $f_{\rm core} < f_{\rm ext}$
LEG	Low-excitation galaxy	ref. 8
LPQ	Low polarization quasar	$P_{\rm opt} < 3\%$
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, $\alpha_{\rm r} > 0.5$
USS	Ultra-steep spectrum source	RL AGN, $\alpha_{\rm r} > 1.0$
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

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

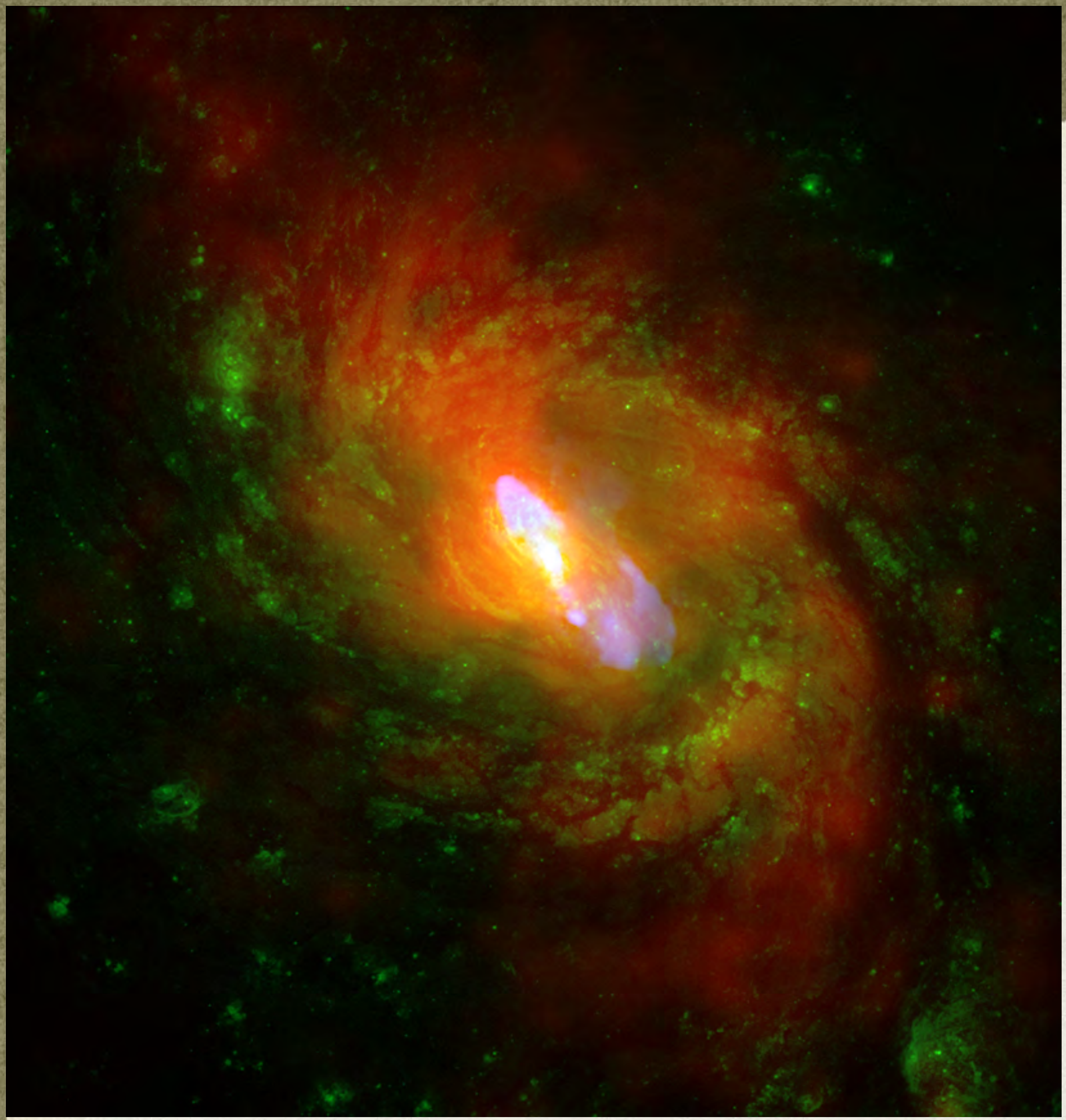
Bimodality observed

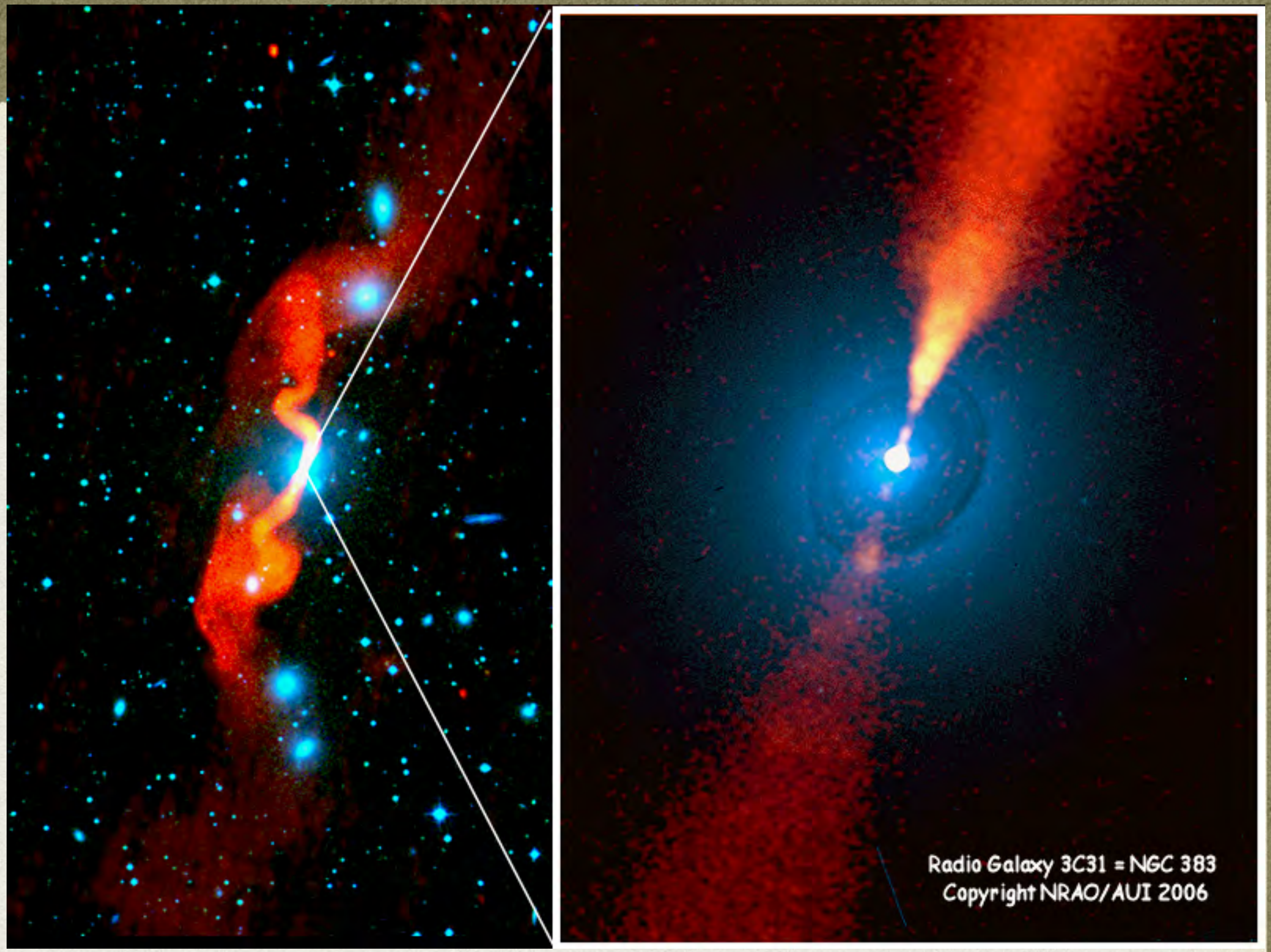
Quasars $M_B < -23$
"AGNs" $M_B > -23$

~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 ~10^6–10^9 $M_\odot$

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

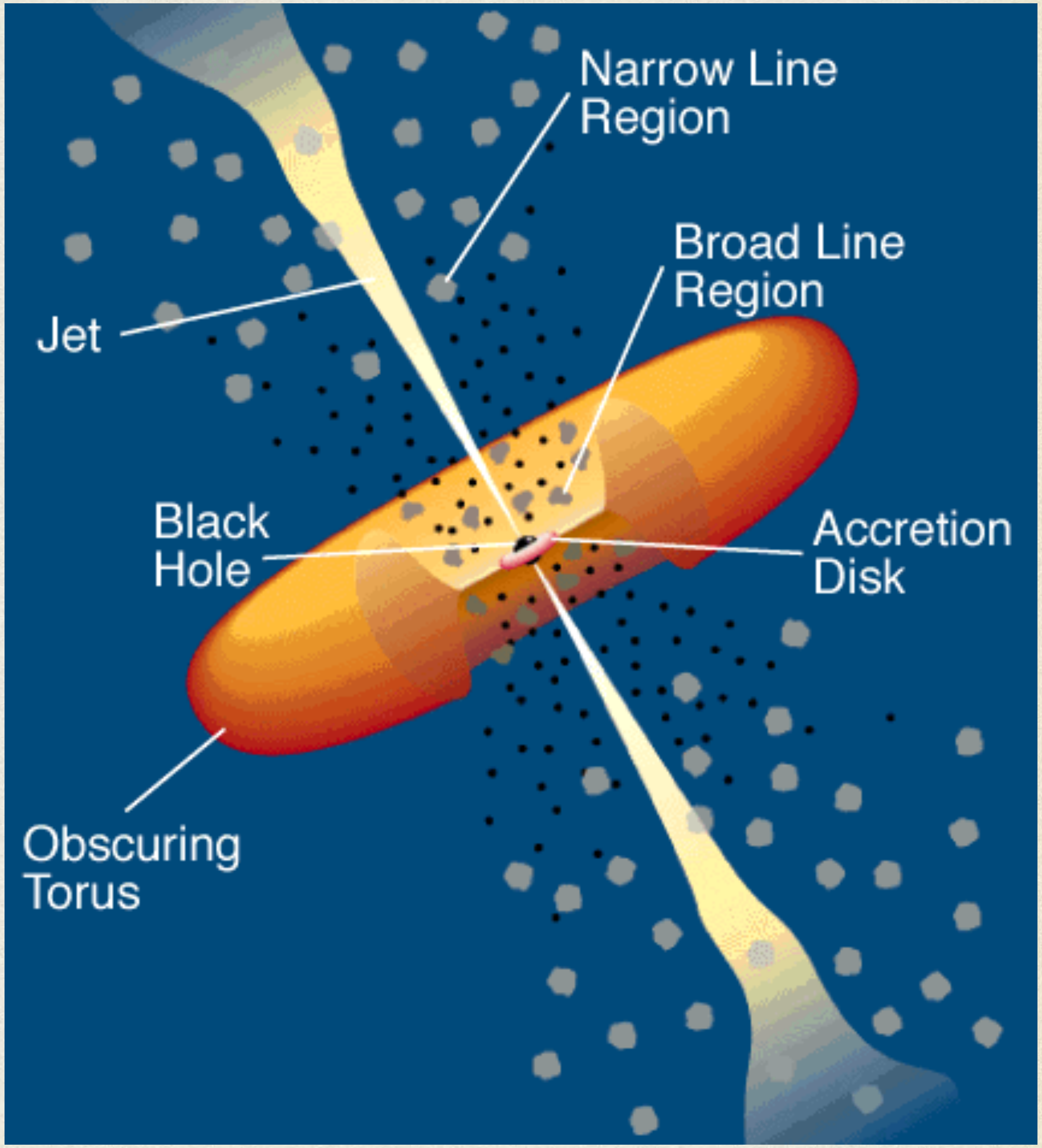
Narrow-line region (NLR) line widths ≤ 500 km/s, n_e~10^3 cm^{-3}

Dusty torus shields the BLR from some lines of sight

Type 1s & 2s differ by orientation

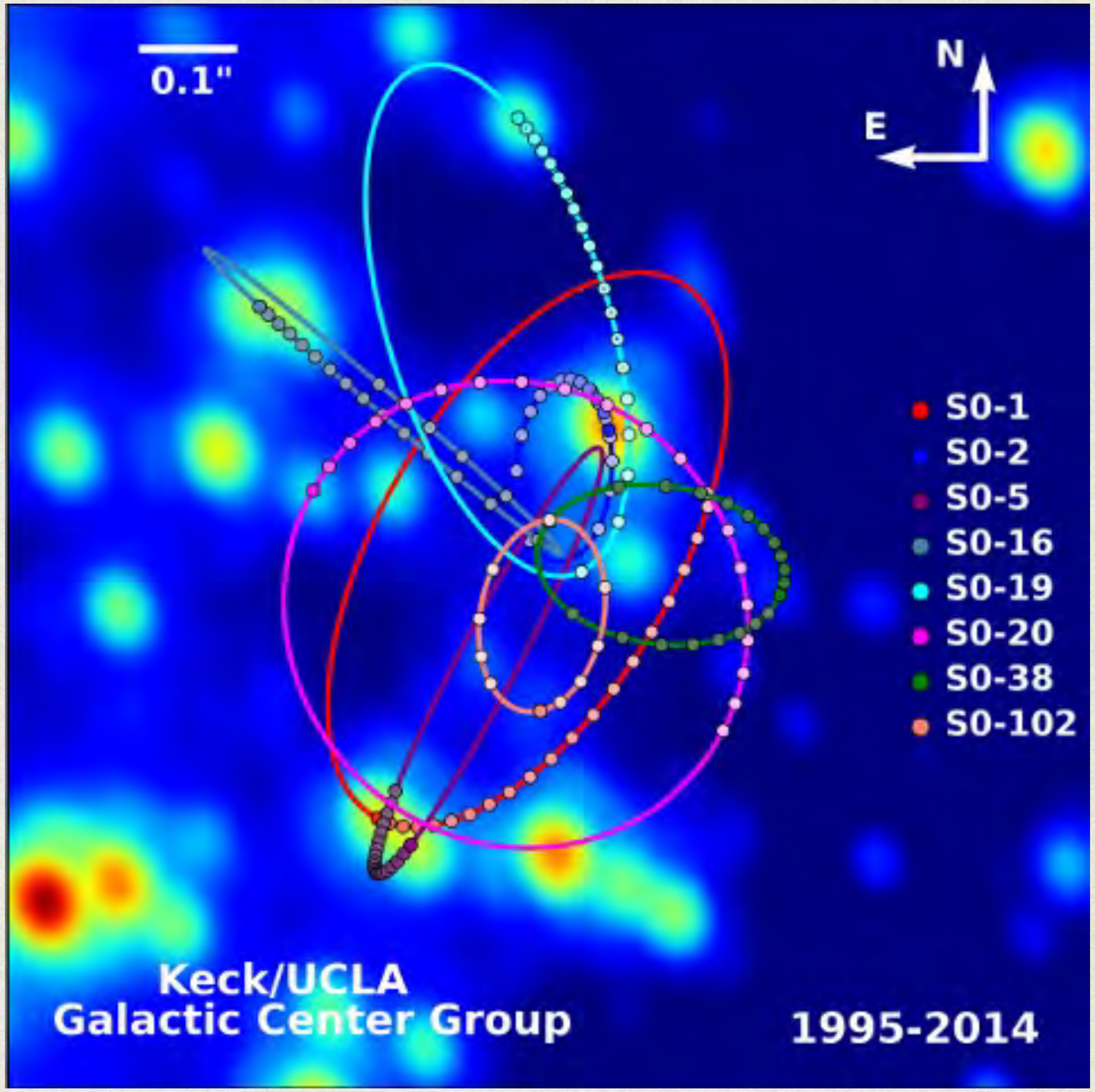
Unification (Antonucci 1993)

Relativistic Jets launched from Accretion disk - SMBH interface

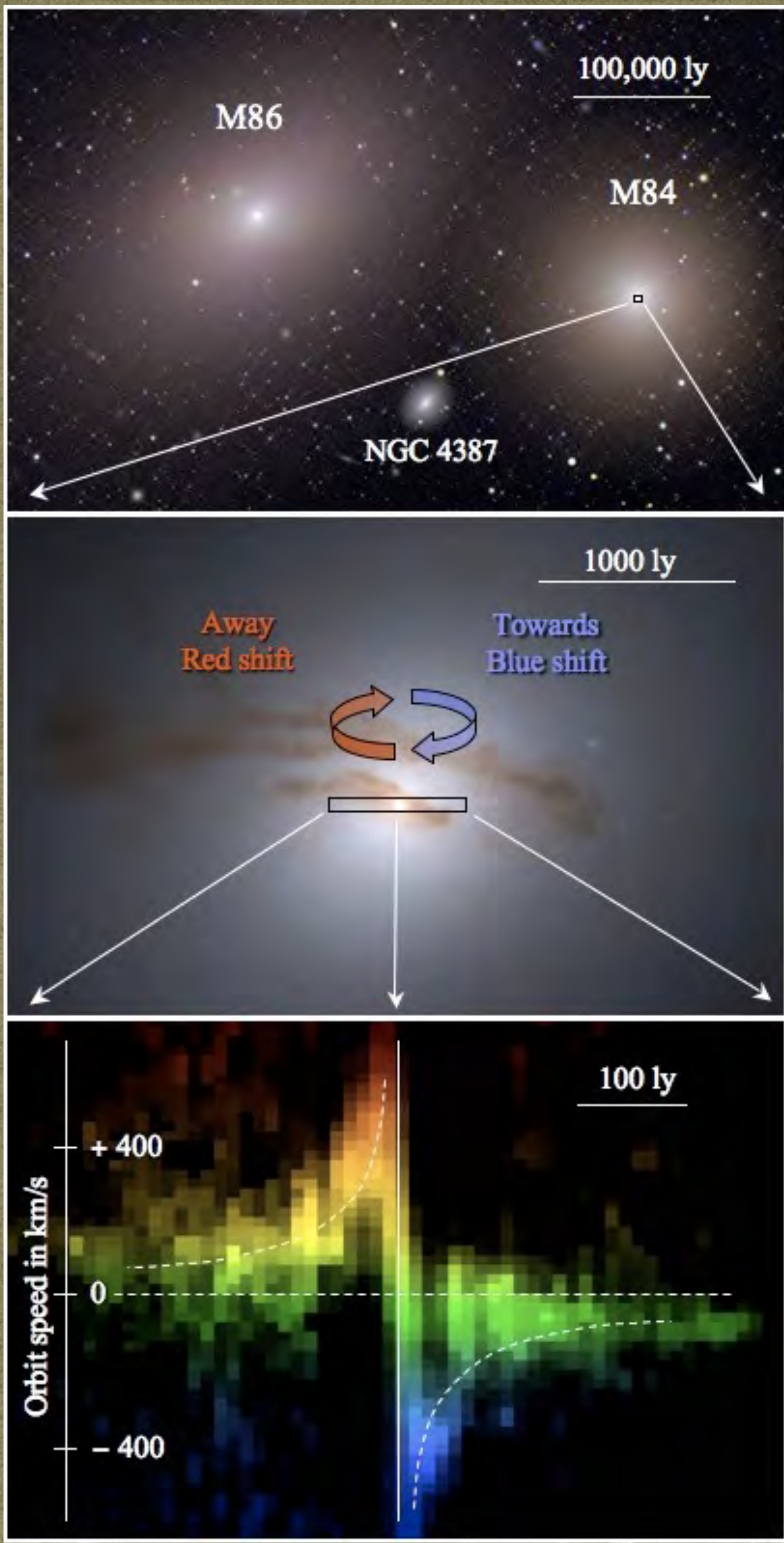


SUPERMASSIVE BLACK HOLE (SMBH) IN THE MILKY WAY

- All large galaxies have a supermassive black hole in their centres
- Measure mass from orbital period and average distance of stars in orbit around the central mass
- From Newton's form of Kepler's Third law (equating gravitational force with centripetal force)
- $M = v_2 . r/G$
- v = orbital velocity
- r = average orbital separation
- G = Gravitational constant
- Milky Way SMBH ~$4.5 \times 10^6 M_\odot$



SMBH IN EXTERNAL GALAXIES



HST/STIS observations of the nuclear gas disk in M84. The approximately Keplerian velocity suggests a black hole mass of ~3×10^8 solar masses

Top Right: The radio (red) and X-ray (blue) emission from M84

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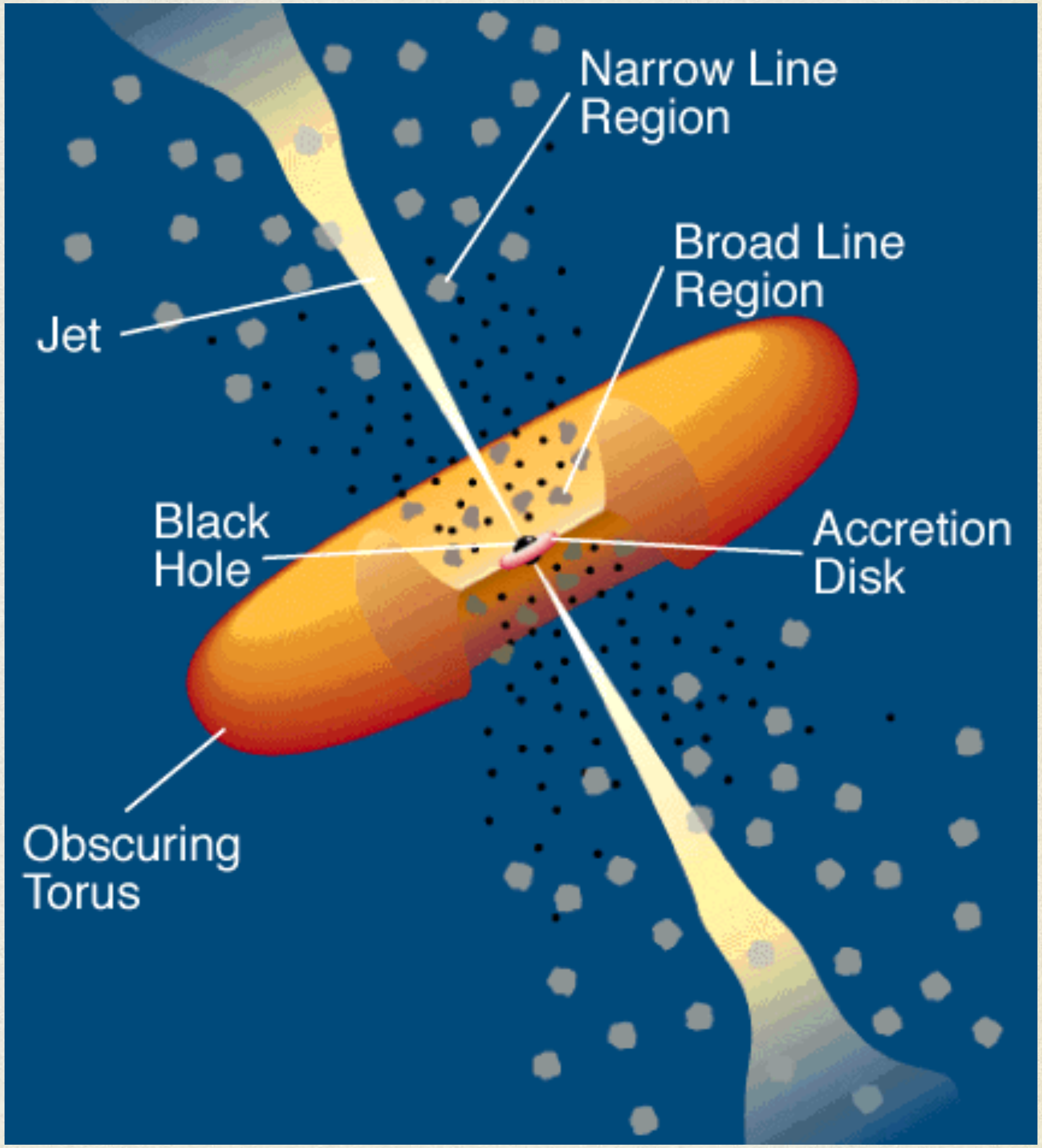


Observed Luminosity versus Intrinsic Luminosity

$$L_{obs} = \delta^{3+\alpha} L_{int}$$

Jet-to-Counterjet Intensity Ratio

$$R = \left(\frac{1 + \beta cos\theta}{1 - \beta cos\theta}\right)^{3+\alpha}$$

Apparent Speed of Jet

$$\beta_{app} = \frac{\beta sin\theta}{1 - \beta cos\theta}$$

where,

Beta, $\beta = v/c$

Doppler factor, $\delta = \frac{1}{\gamma(1-\beta cos\theta)}$

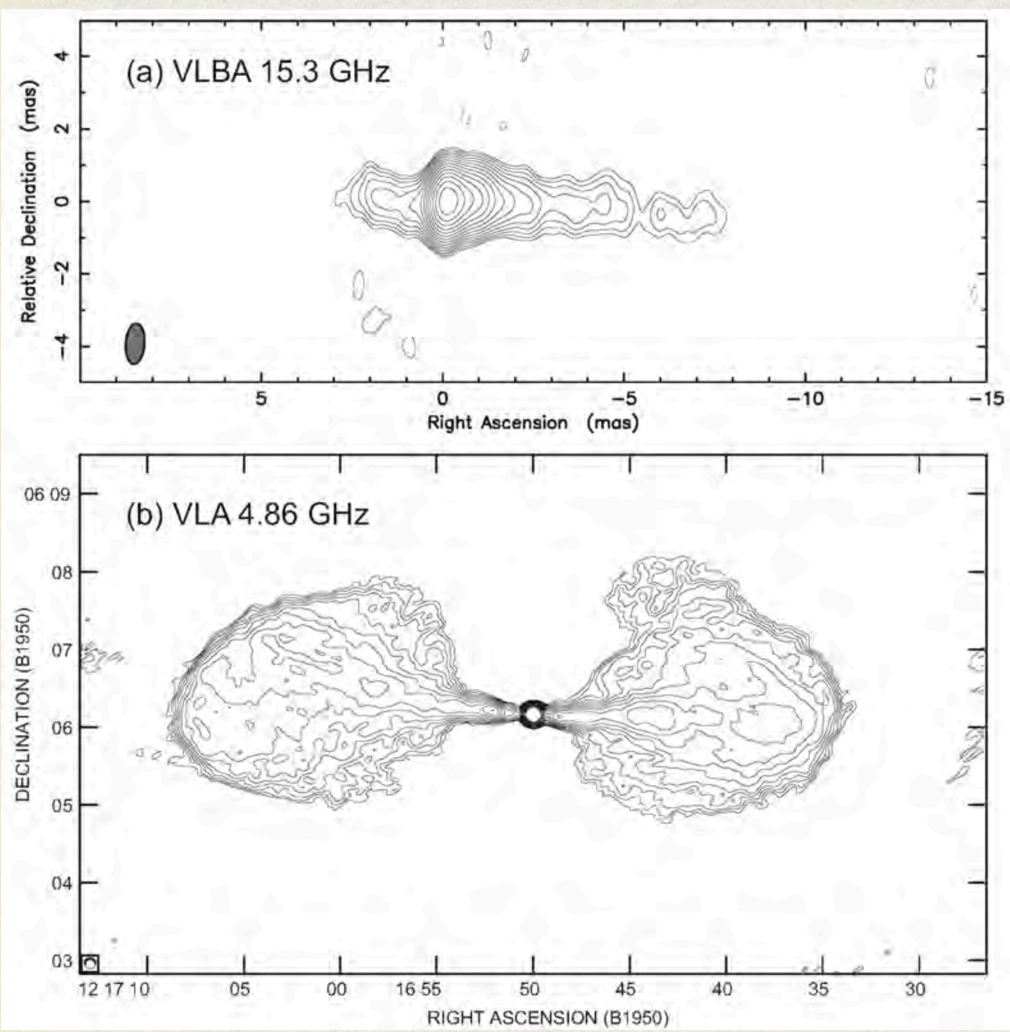
Lorentz factor, $\gamma = \frac{1}{\sqrt{1-\beta^2}}$

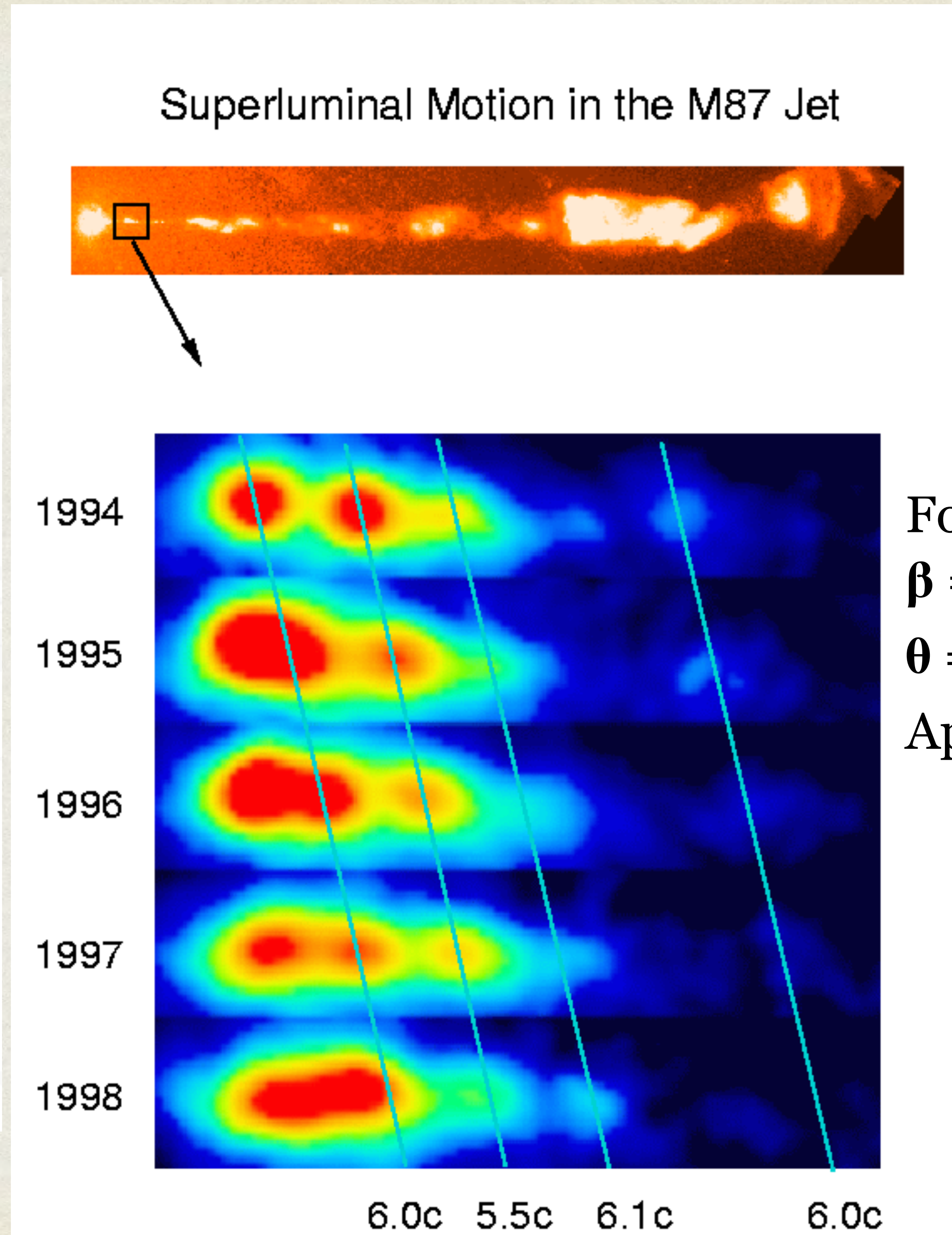
θ = angle of Jet with respect to line of sight

Spectral index, α, defined such that Flux density, $S_\nu \propto \nu^\alpha$

ONE-SIDED JETS, SUPERLUMINAL MOTION

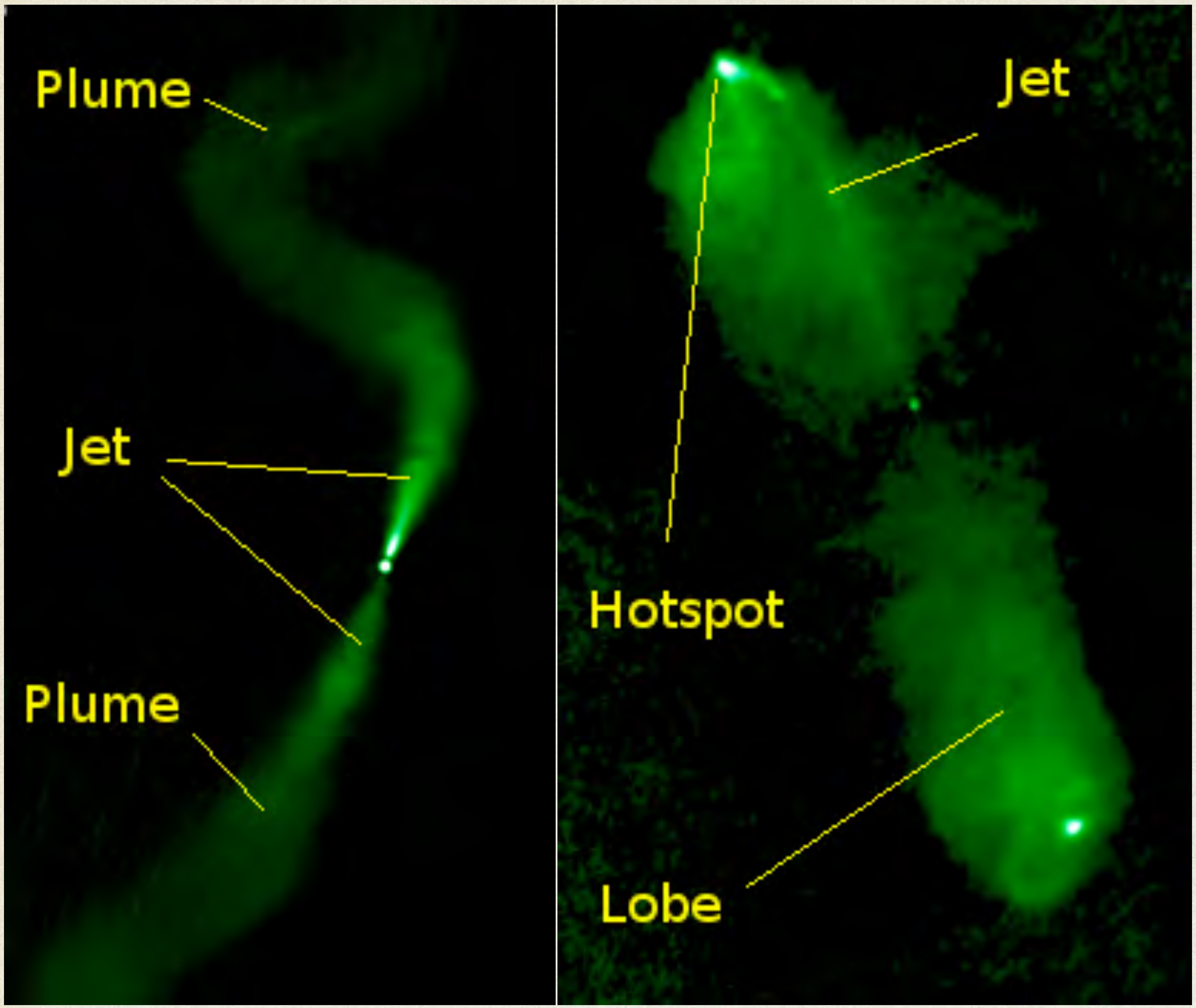
Brightness asymmetry in Jets





For
β = 0.99,
θ = 10 degrees
Apparent **β** = 6.9

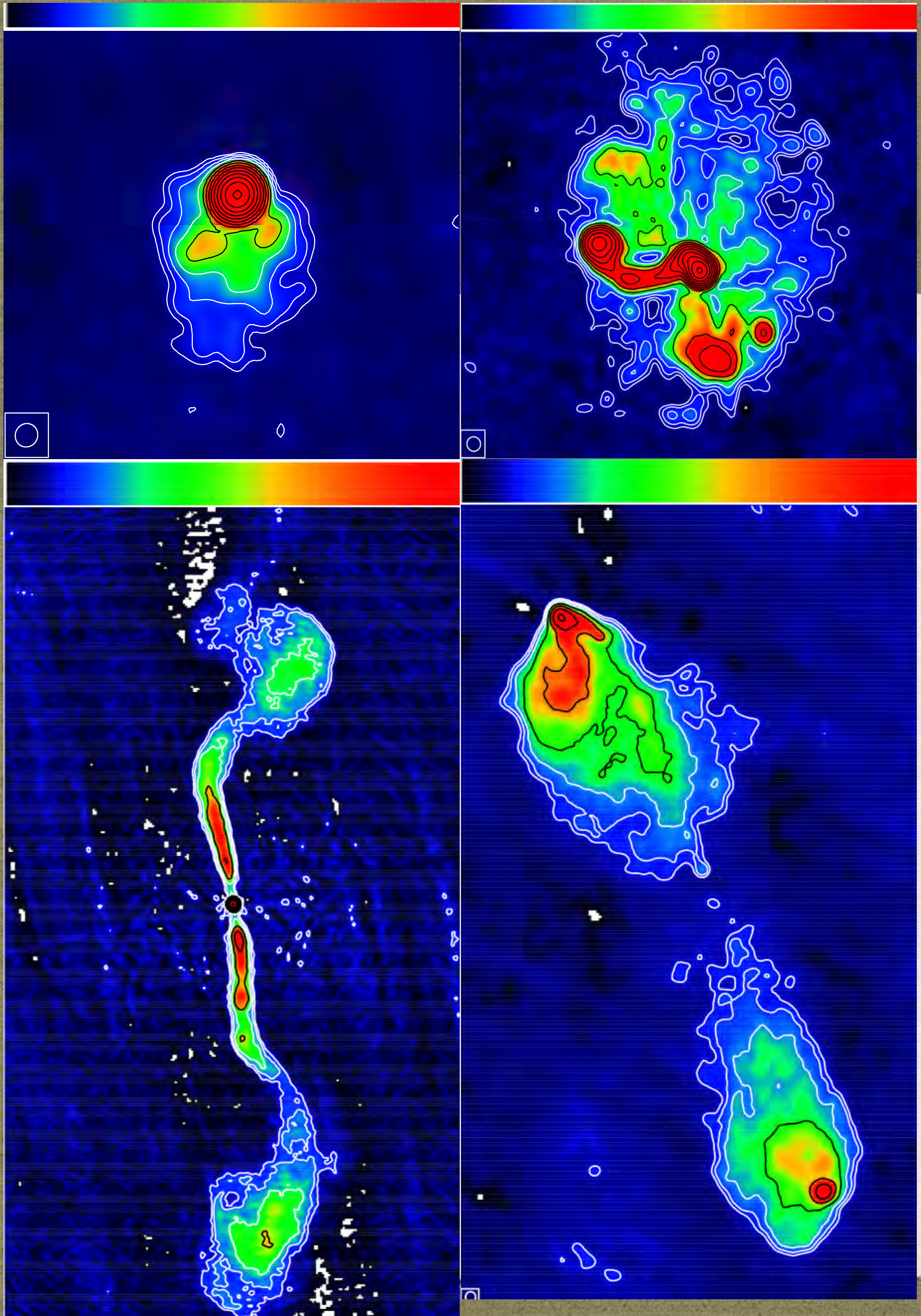
RADIO-LOUD AGN: FANAROFF-RILEY DICHOTOMY



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)



RADIO-LOUD UNIFICATION

Pole-on FRIs = BL Lac objects

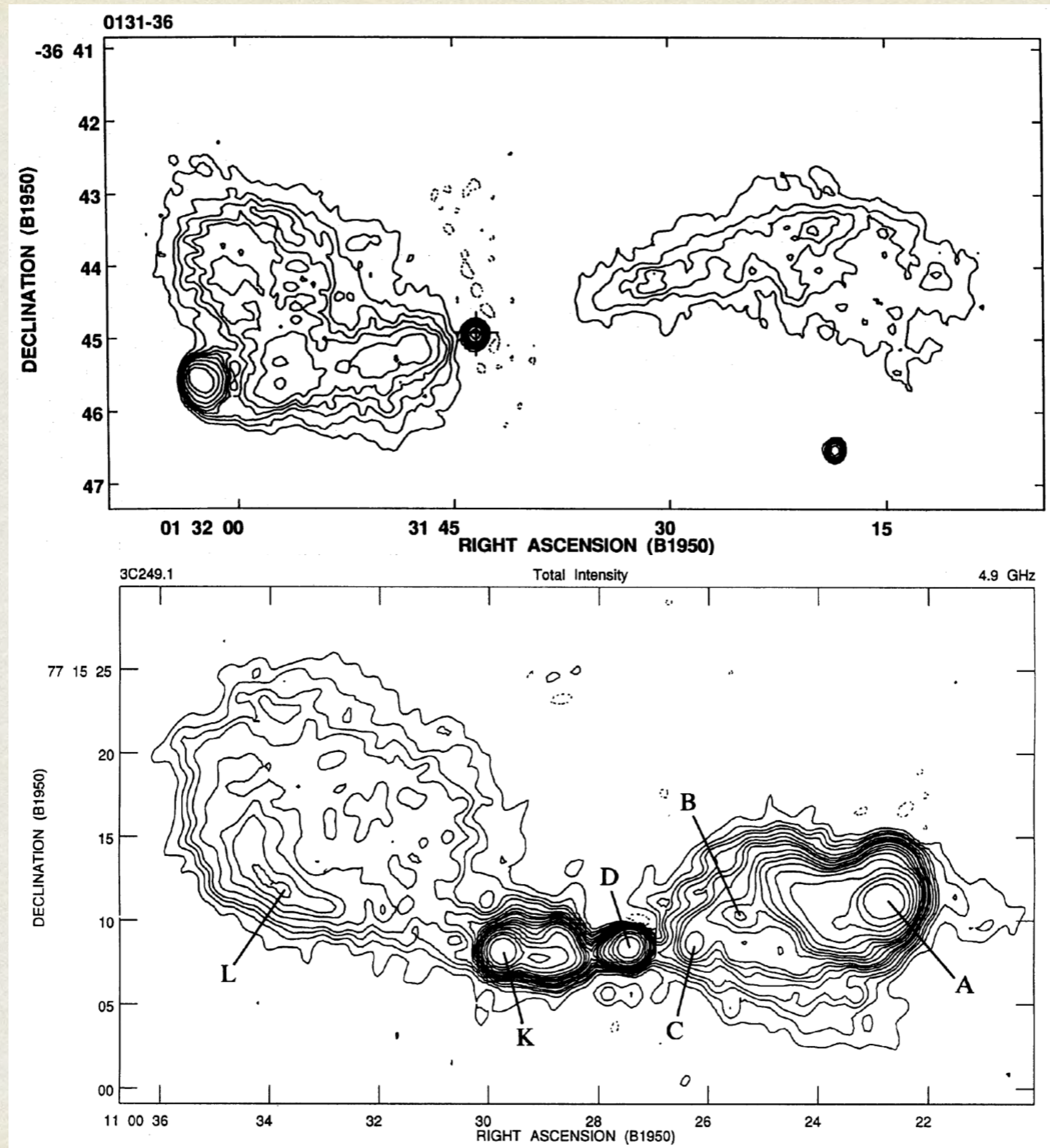
Pole-on FRIIs = Quasars

(Urry & Padovani 1995)

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

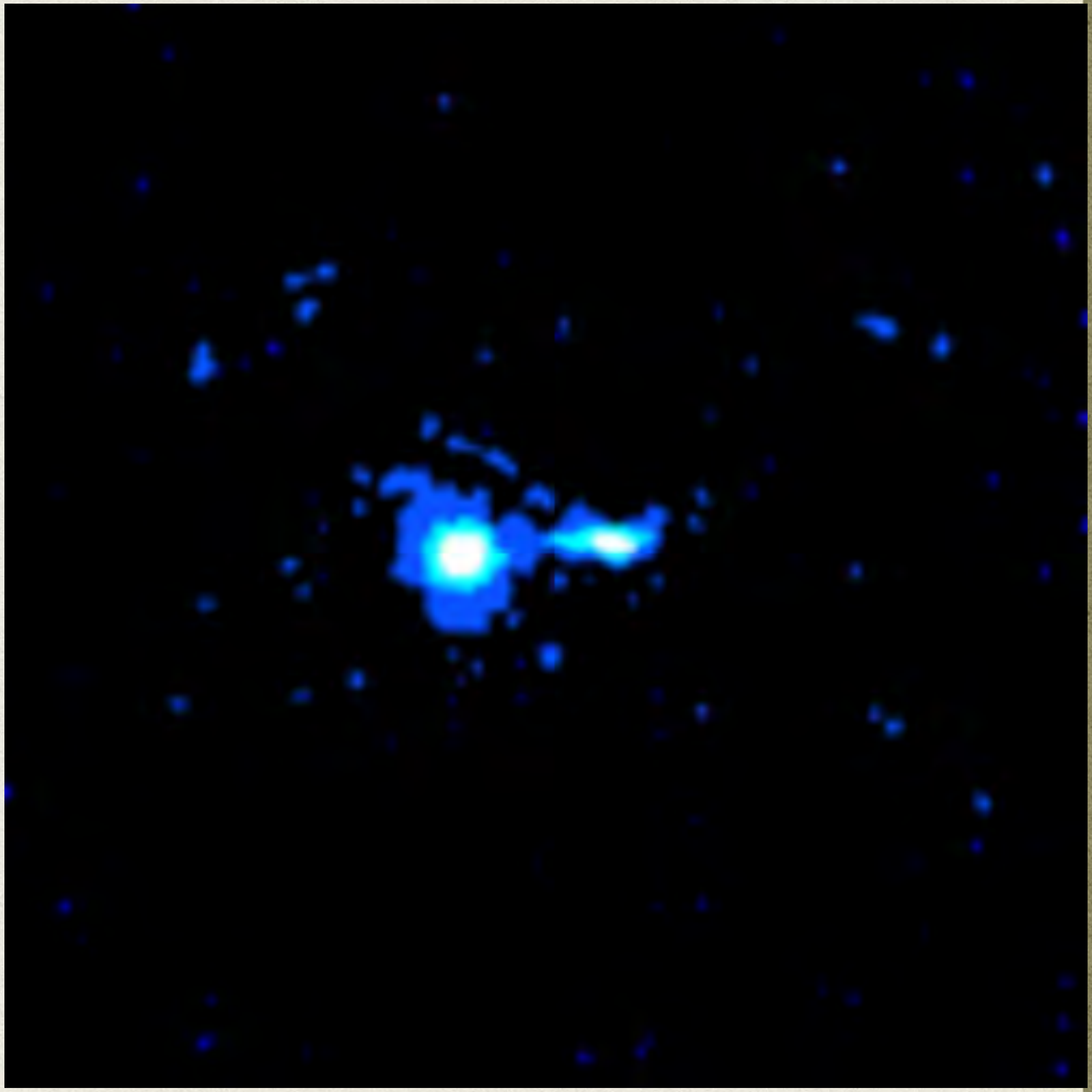
HYBRID / INTERMEDIATE SOURCES

- Bridle et al. 1994
- Morganti 1993

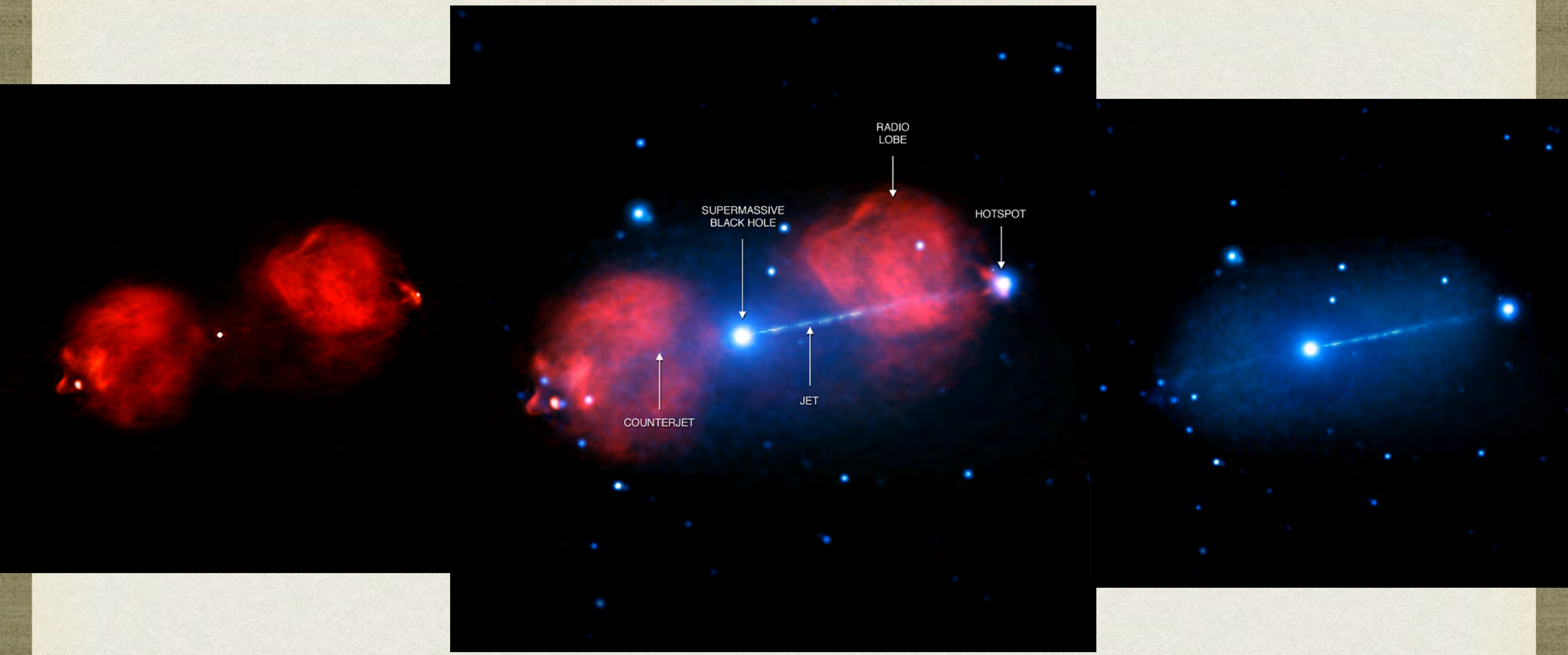


CHANDRA'S FIRST LOOK: X-RAY JETS

- In August 1999 Chandra ACIS observed its first celestial target PKS 0637-752 during the initial focusing of the telescope
- High z (0.654) Quasar
- 100 kpc X-ray Jet (Schwartz+ 2000)



X-RAYS FROM AGN JETS



Pictor A

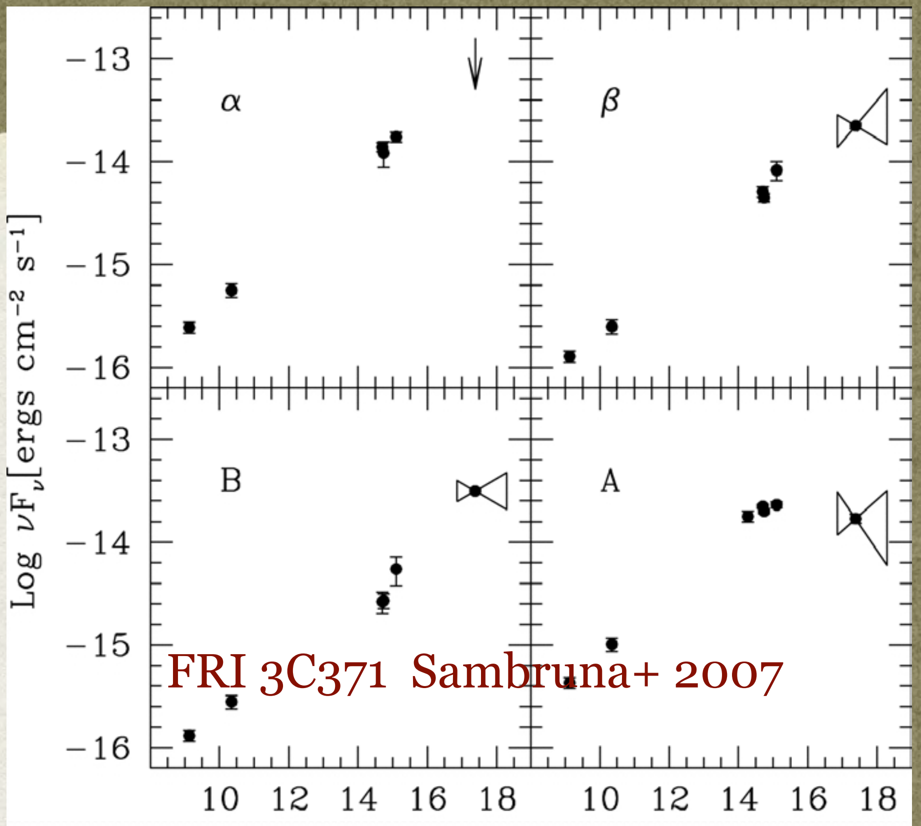
X-RAY EMISSION MECHANISMS

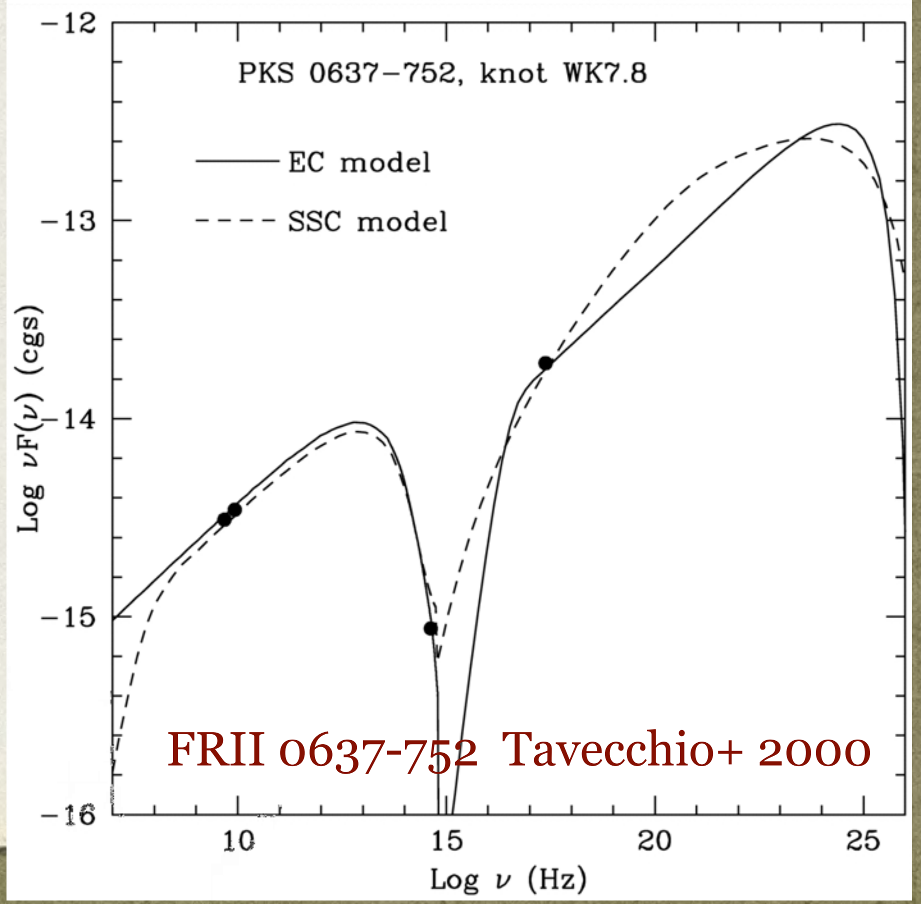
- **Thermal Bremsstrahlung**: predicted n_e is > n_e upper limit from Faraday RM values — Ruled out for AGN jets

- **Synchrotron**: $\gamma > 10^7$ needed + *in situ* acceleration as electron lifetimes are of the order of 10 yrs for Equipartition B-field B_{eq} — works in FRI Jets

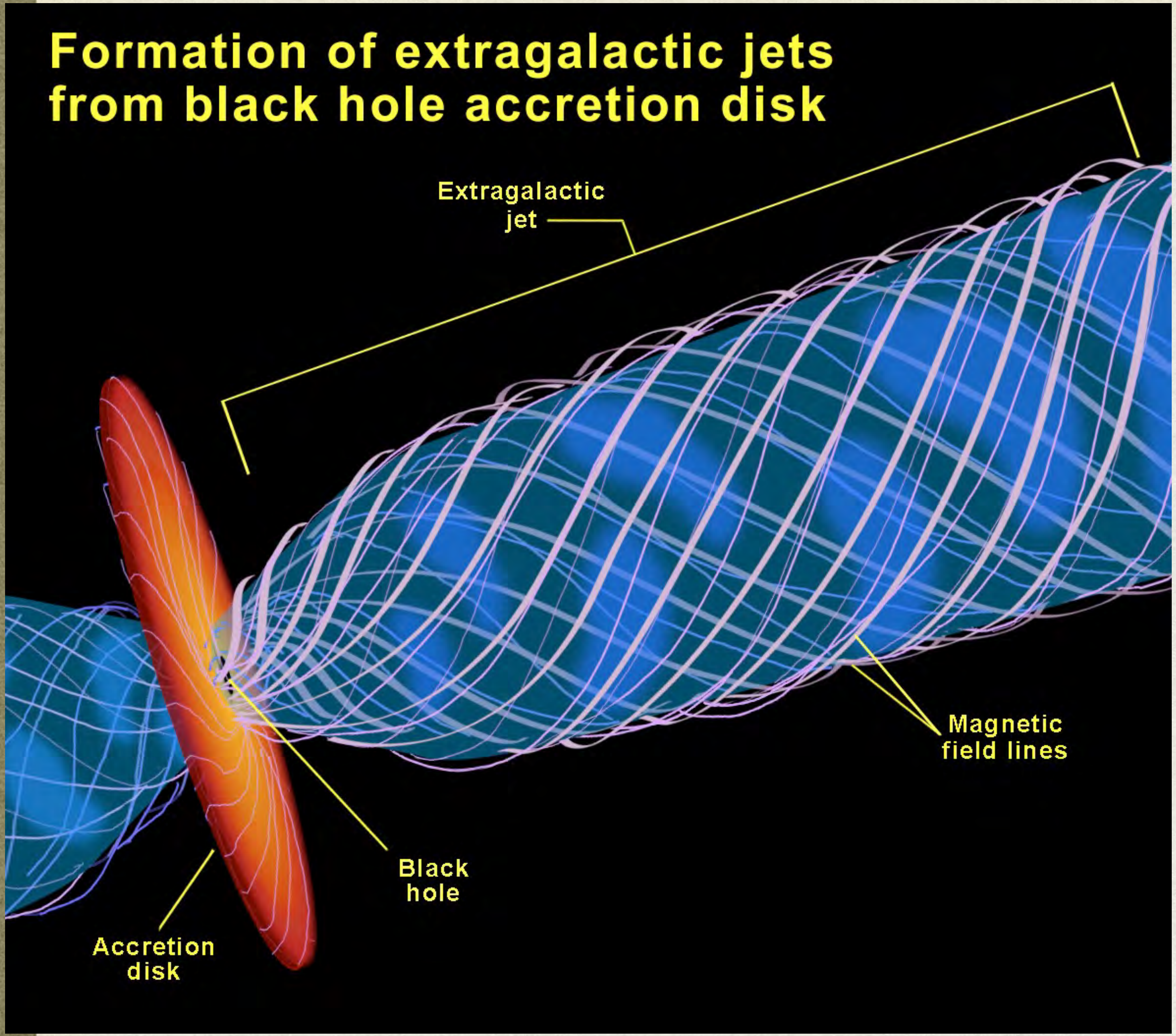
- **Synchrotron-self-Compton**: need B fields far from B_{eq}. Large energy budget — works in some hotspots but not in Jets

- **IC/CMB**: need highly relativistic kpc-scale jets (Γ~10) at small angles to line of sight — works in FRII Jets although radio data (indirectly) suggest Γ~2. Does not work in some blazar jets with Fermi gamma-ray detection





JET FORMATION IN AGN



Blandford & Znajek (1977)

Energy & angular momentum extraction from a spinning black hole.

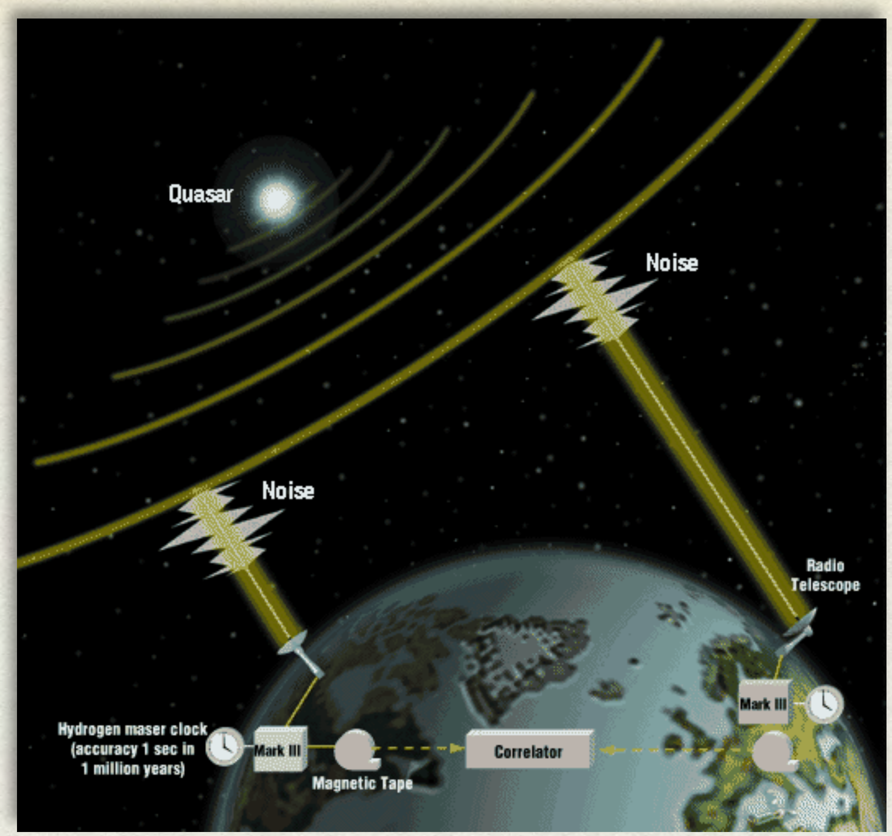
Strong poloidal magnetic field needed

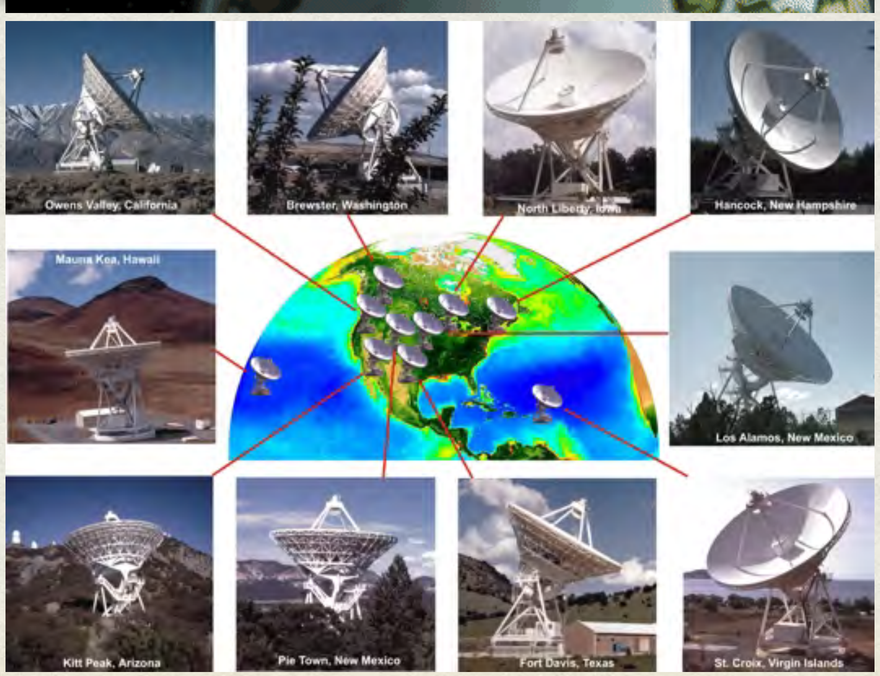
Power extracted is proportional to B^2 & ω^2

B = magnetic field strength
ω = angular velocity

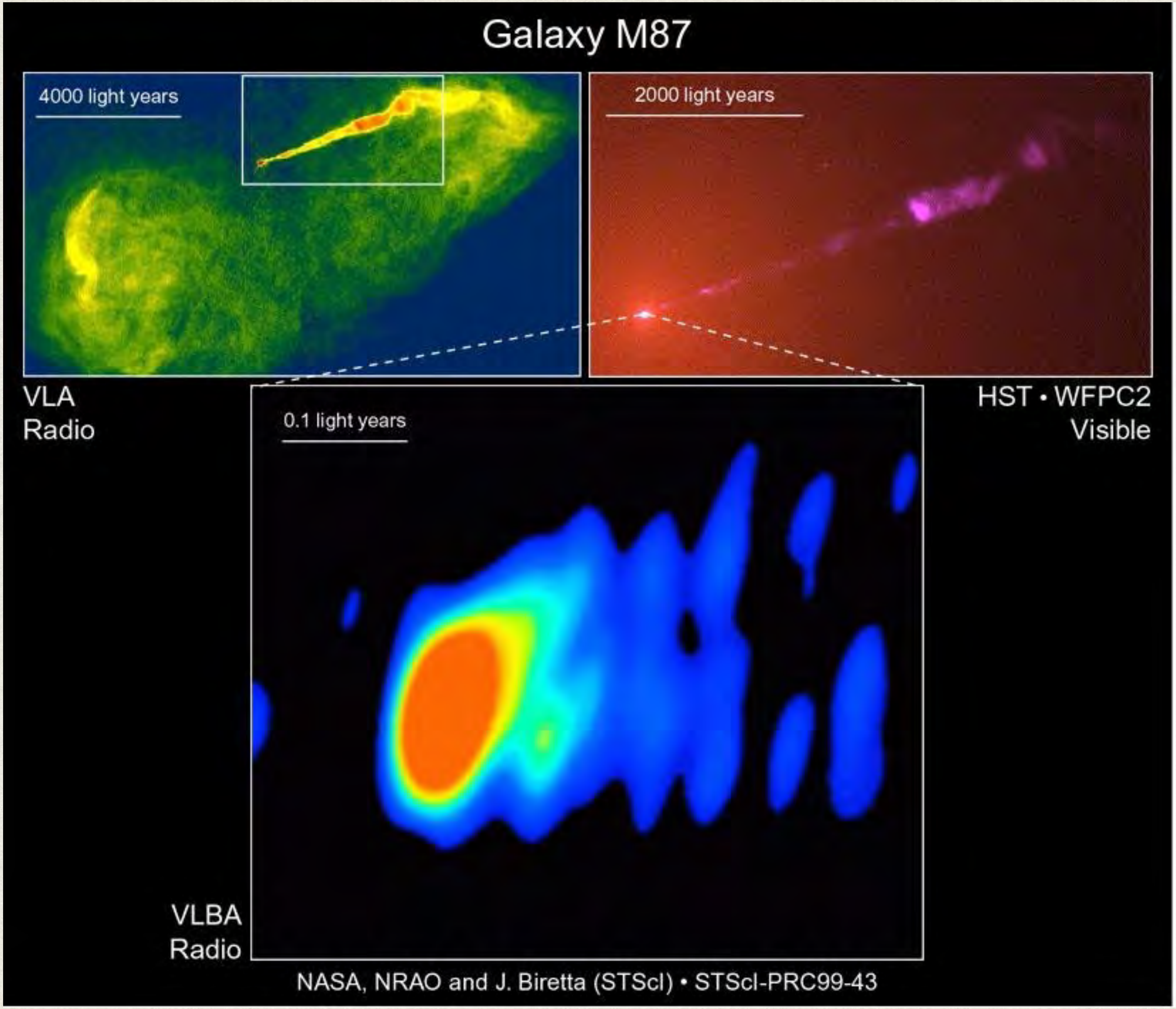
VLBI Polarisation needed

VERY LONG BASELINE INTERFEROMETRY (VLBI)



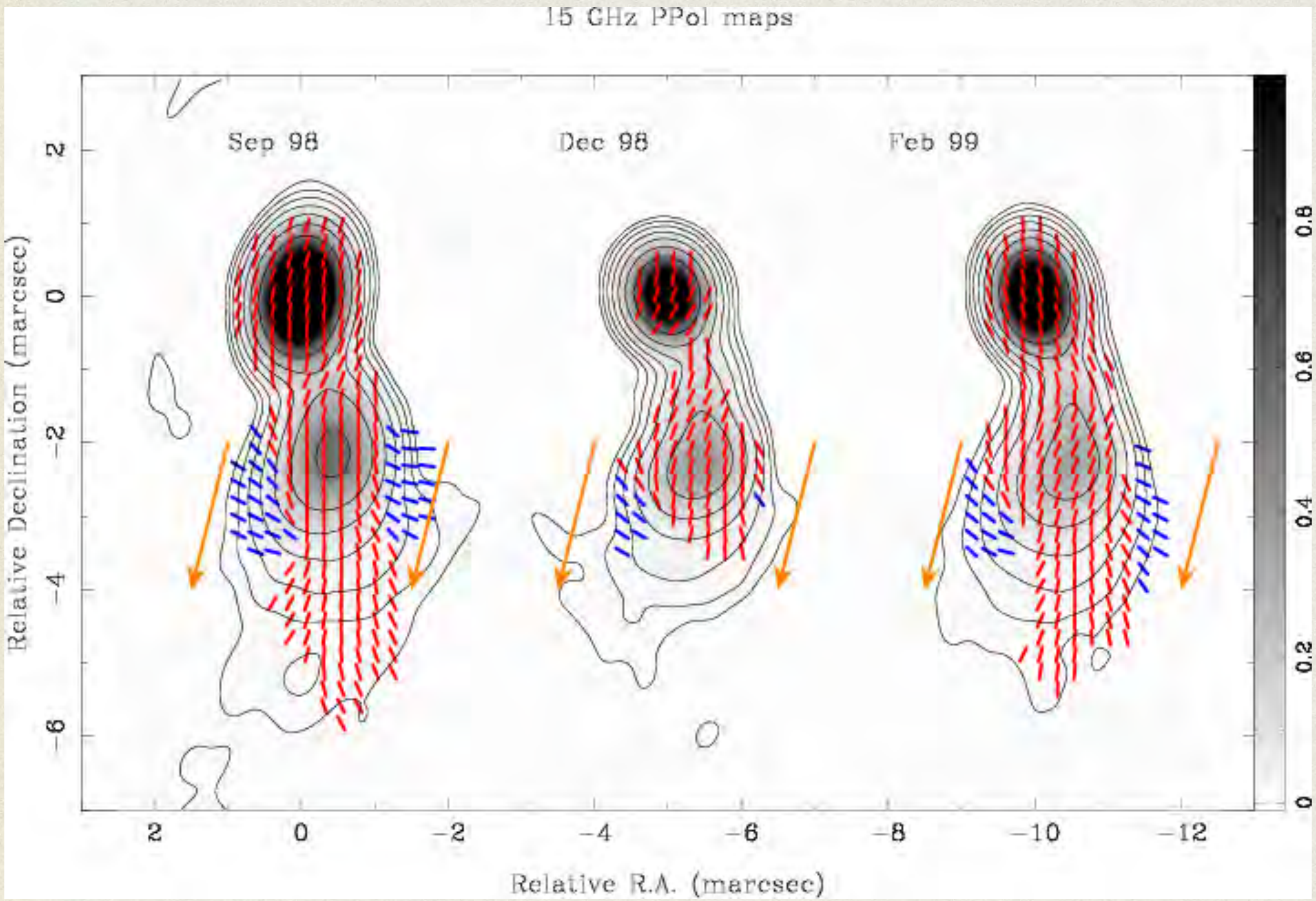


- Widely separated antennas not connected by cables (Unlike VLA, GMRT)
- Data recorded on magnetic tapes
- Recorded data is time-stamped by atomic clocks (e.g., hydrogen maser)
- Later, the tapes are played back with accurate time-stamps and correlated in a central location


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

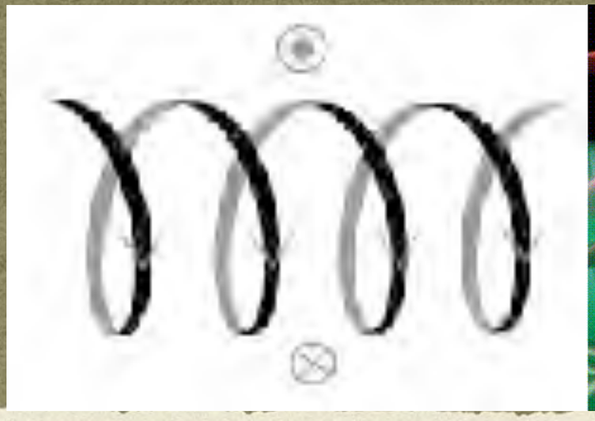
Magnetic field orientation is perpendicular to χ vectors for optically thin emission

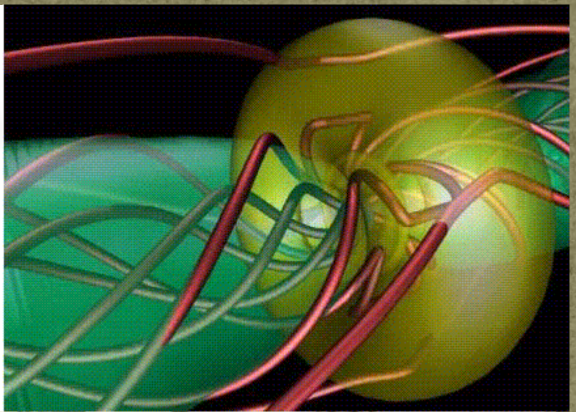
"Spine-Sheath" (Marscher+ 2002, Gabuzda 2003)

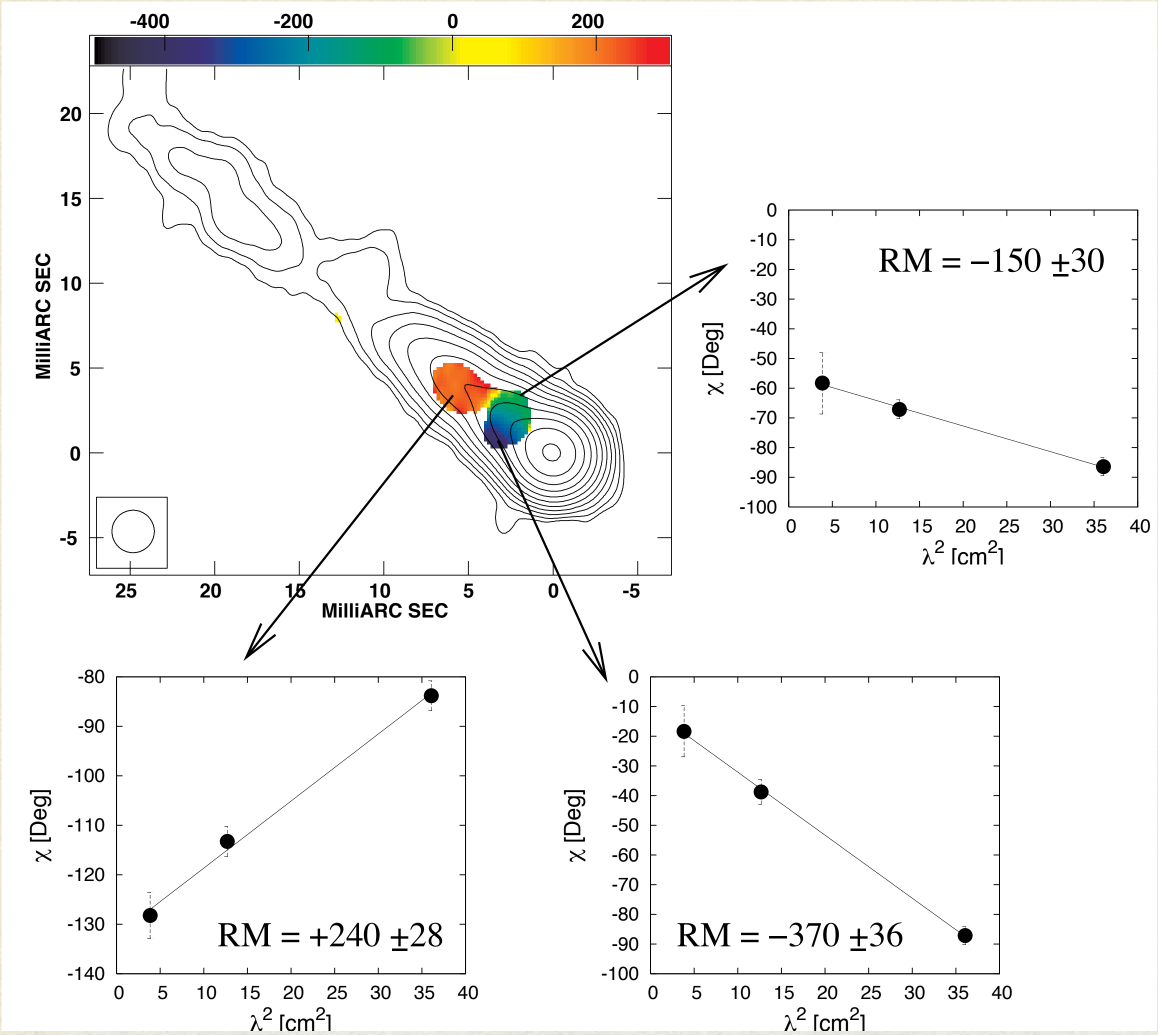
Helical magnetic fields (Lyutikov+ 2005)

Or Jet-Medium Interaction (Laing 1993)

ROTATION MEASURE GRADIENTS







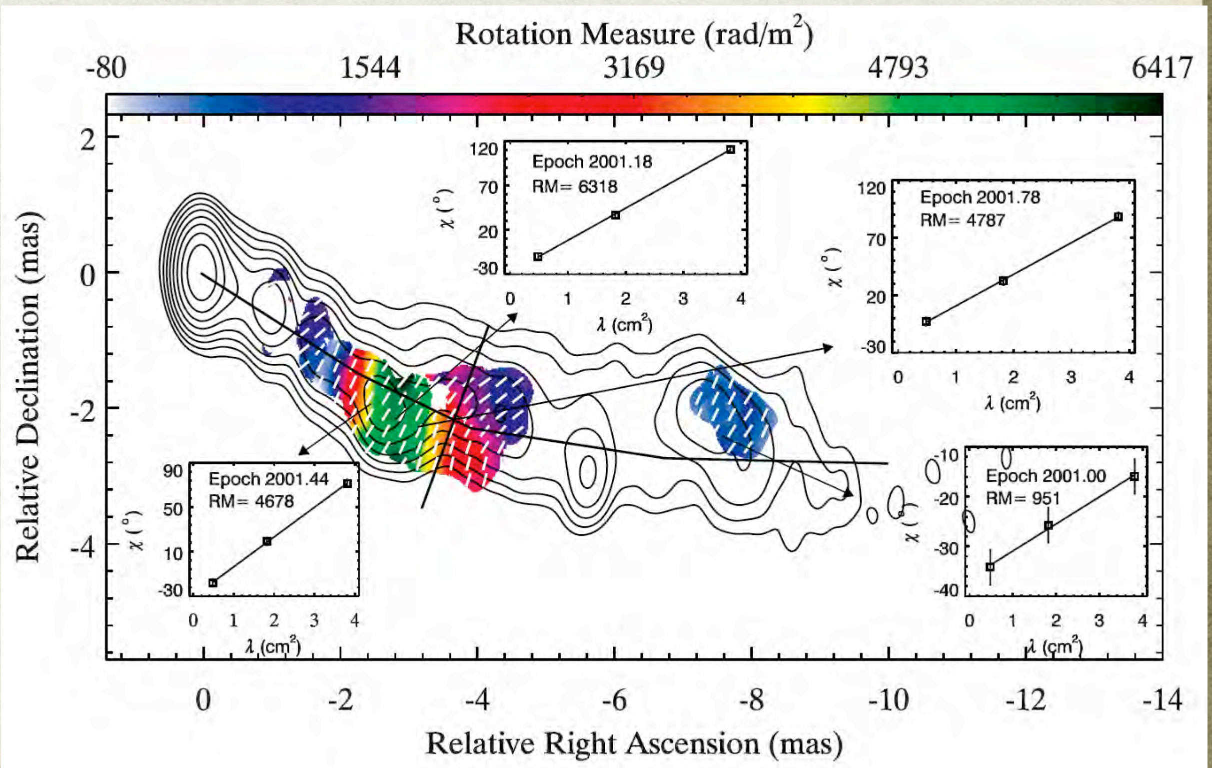
$$\mathrm{RM} = \frac{e^3}{2\pi m_e^2 c^4} \int_L n_e \boldsymbol{B} \cdot d\boldsymbol{s}$$

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

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

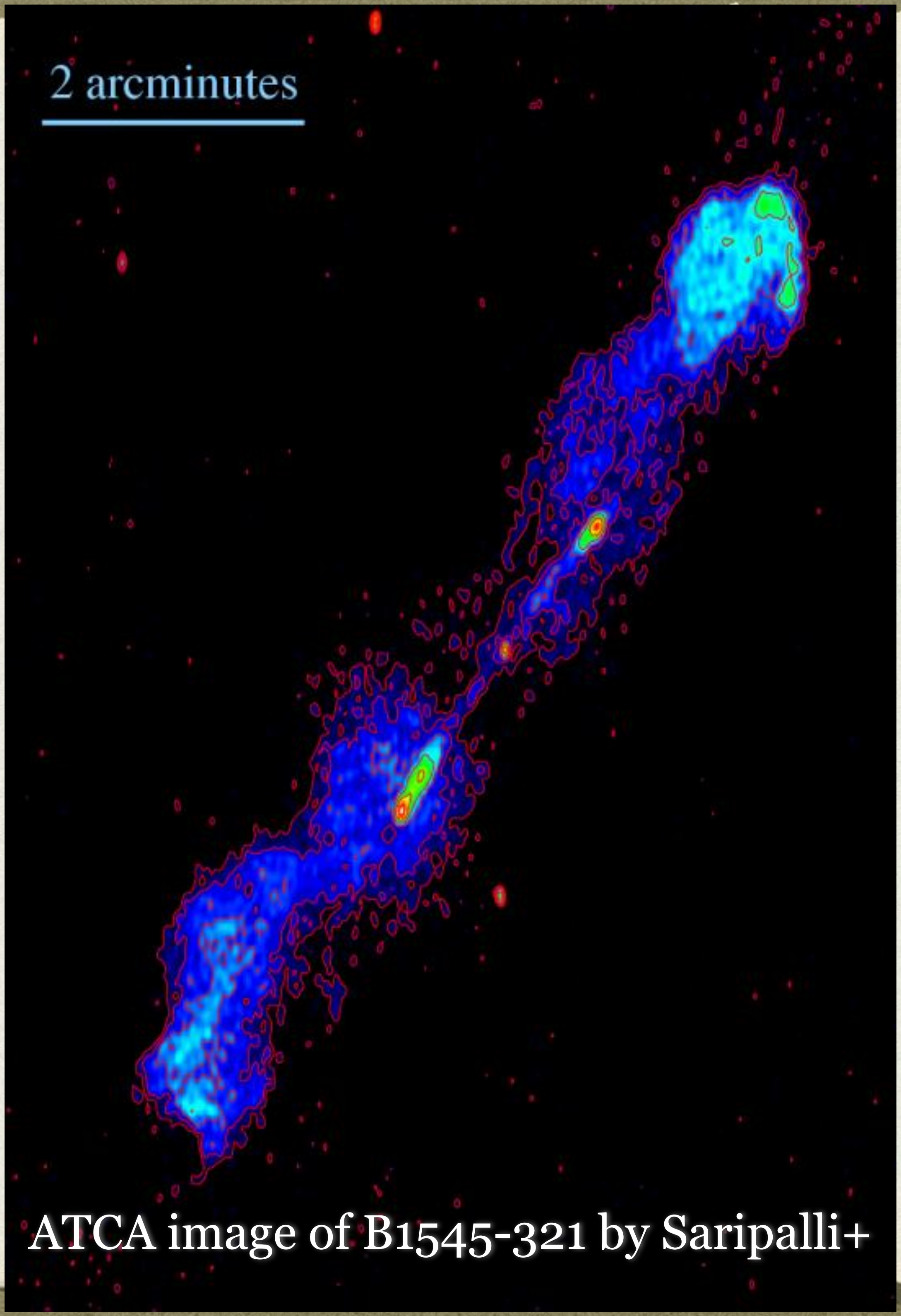
3C78 – VLBI @ 5, 8, 15 GHz (Kharb+ 2009)

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



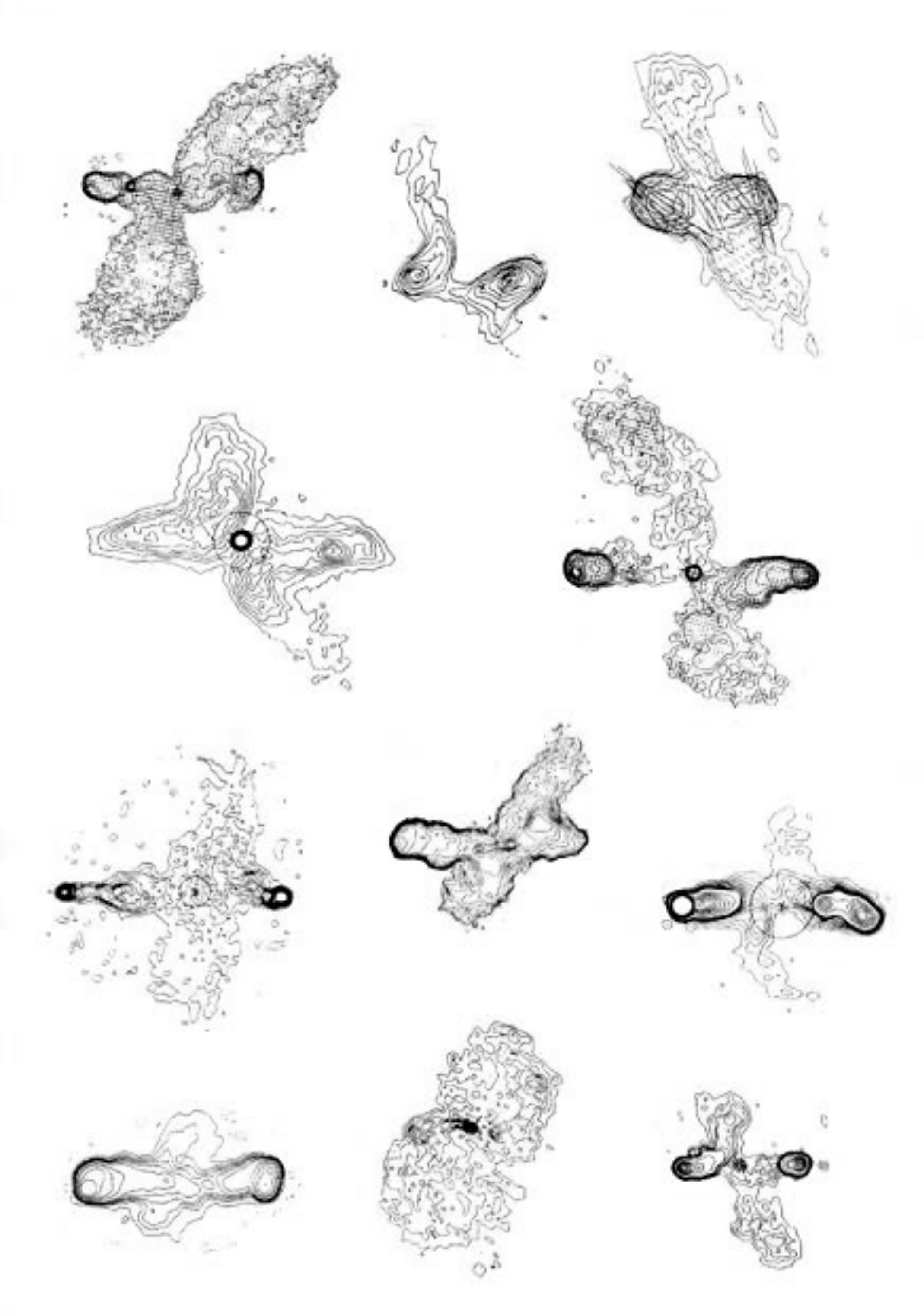
EPISODIC ACTIVITY

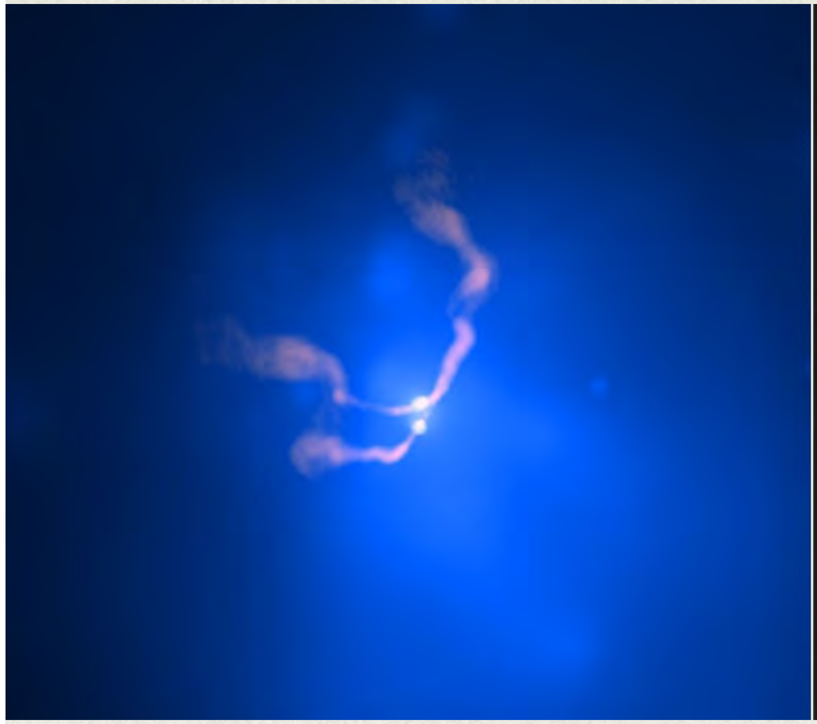
- Giant radio galaxies ≳1 Mpc
- Double-double radio galaxies
- AGN activity is episodic
- "Relic" steep-spectrum (synchrotron ageing) lobes

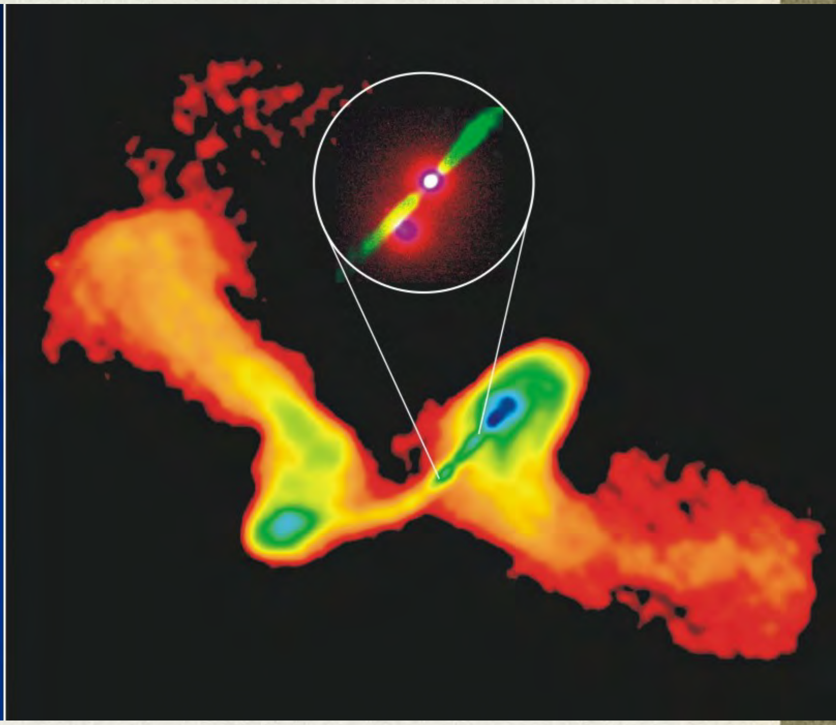


ATCA image of B1545-321 by Saripalli+

JET DIRECTION CHANGES





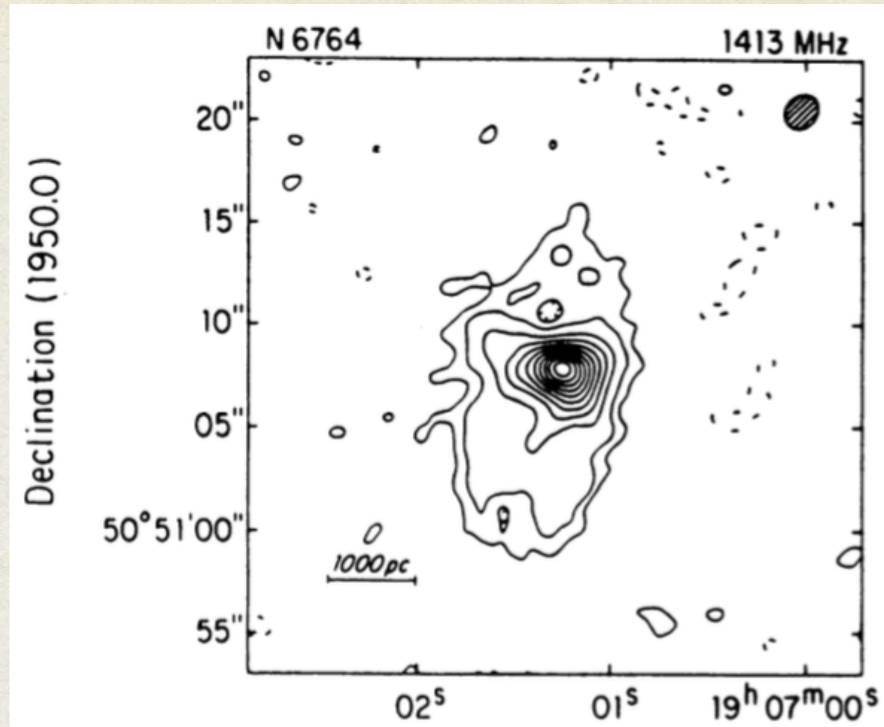


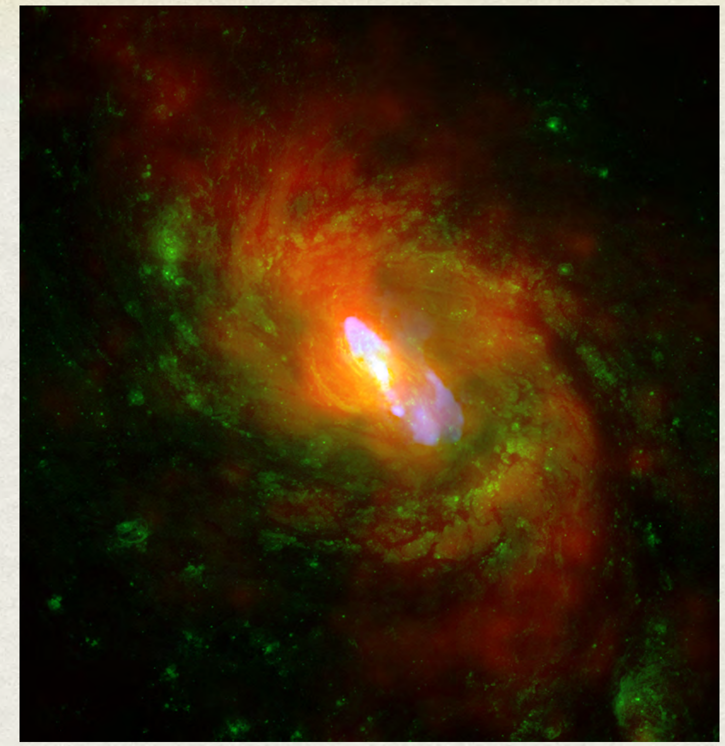
X-shaped, Z-shaped Radio Galaxies

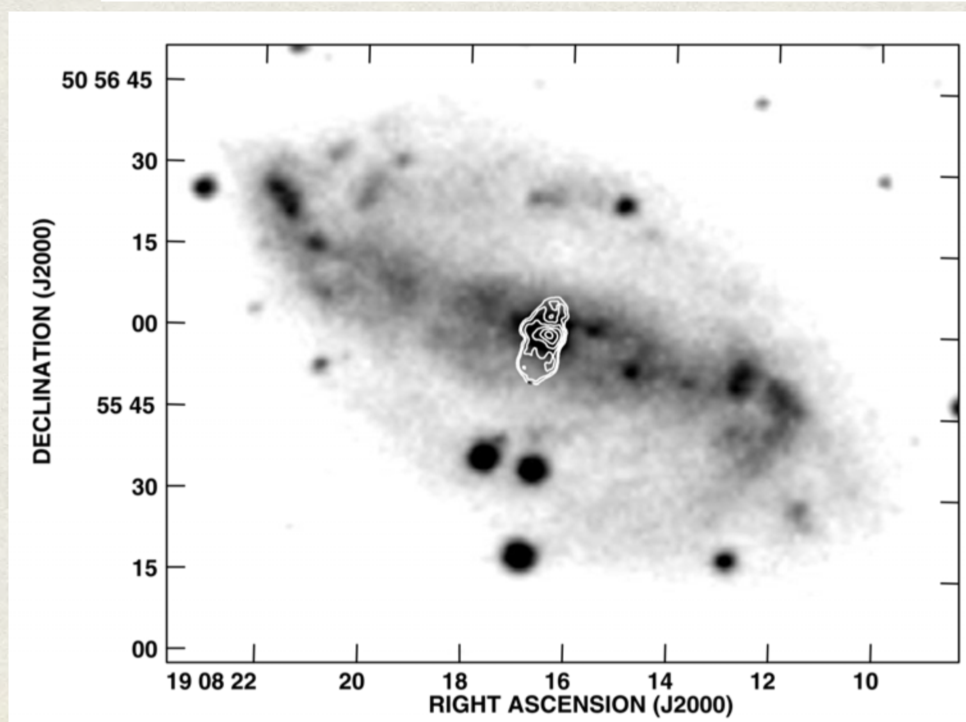
Jet Realignment due to Binary Black Holes?

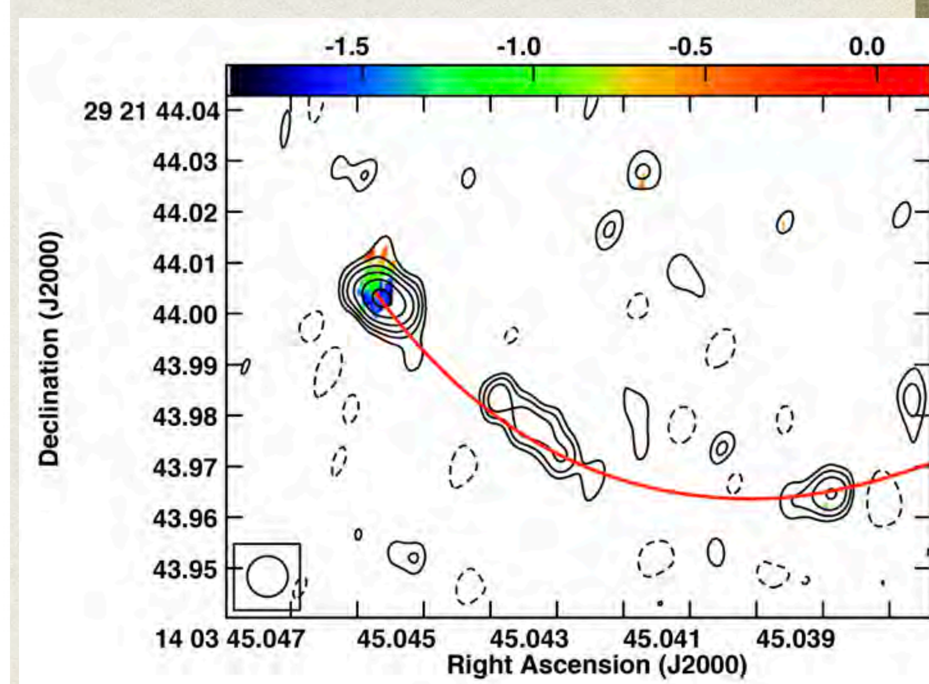
RADIO EMISSION IN RQ AGN

- Kiloparsec-scale Radio Lobes
- Are they starburst-driven winds (Wilson 1988; Baum+ 1993) or AGN Jet-driven (Colbert+ 1996) ?
- VLBI reveals 10-100 parsec-scale jets









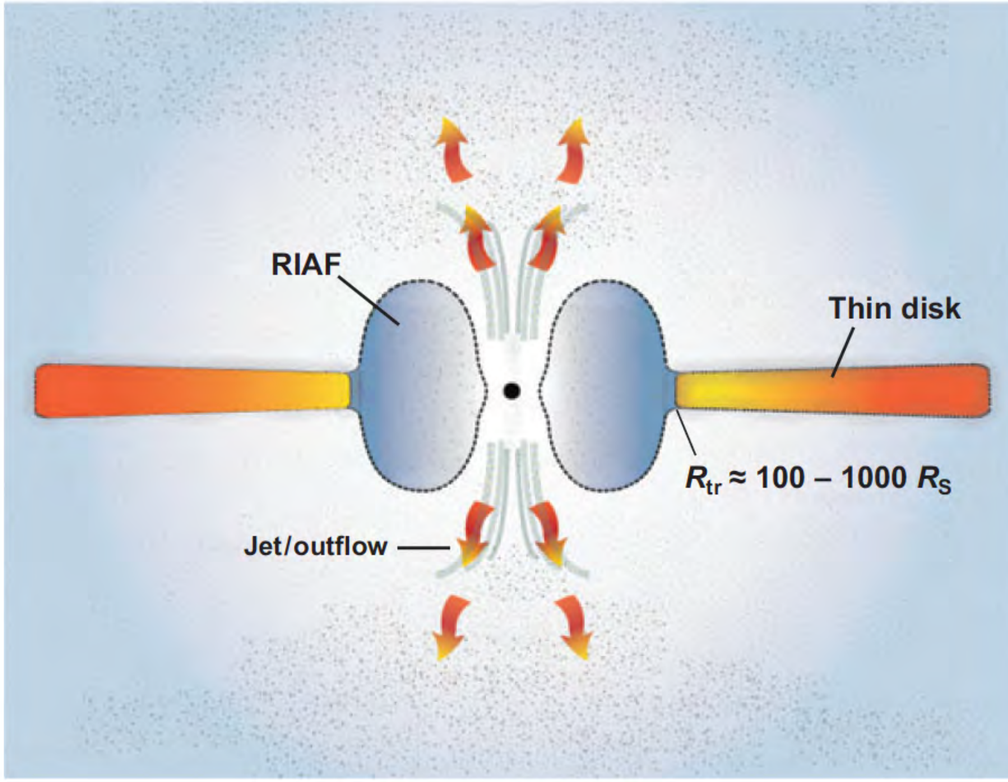
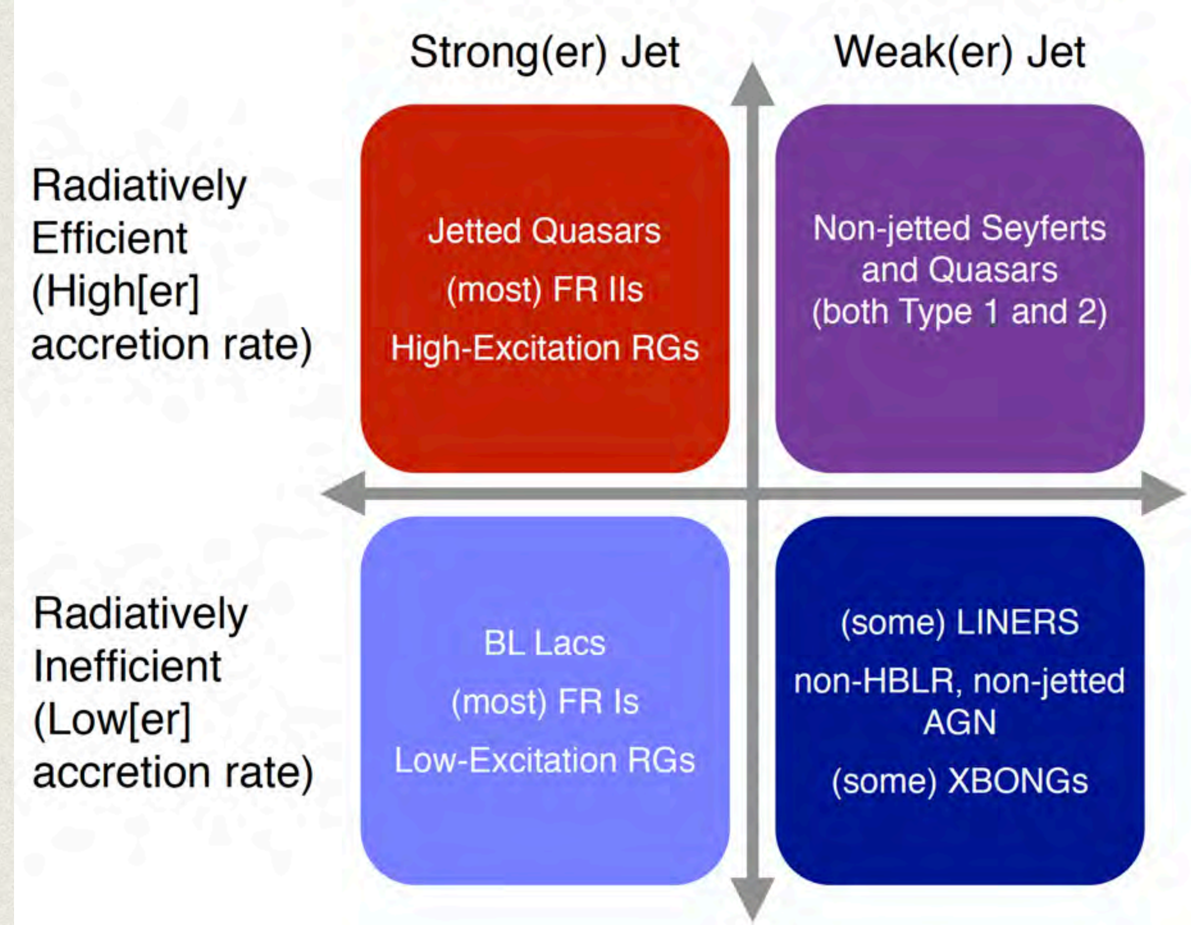


Figure 13

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 = $\lambda = L_{bol}/L_{Edd}$

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

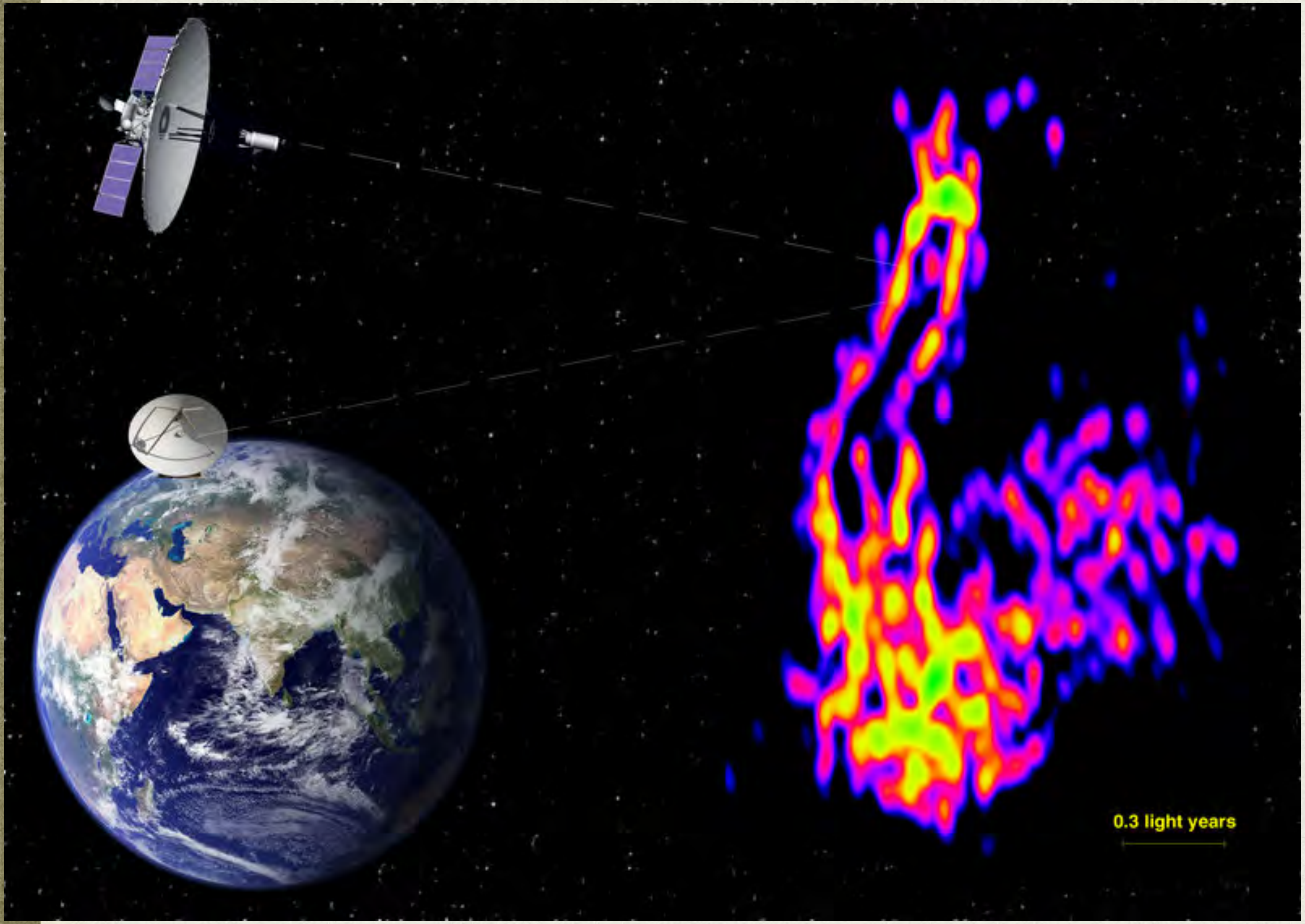
when $\lambda < 0.01$

Radiatively Inefficient Accretion Flow (RIAF)

else "standard" geometrically thin, optical thick disk

Padovani+ 2017, A&A Review

SPACE VLBI



First mission (1997-2003)

HALCA 8m dish
Best resolution ≈ 0.1 mas

Freq: 1.6 & 5 GHz

New mission (2011)

RadioAstron - 10m dish
Max. Baseline = 350,000 km

Freq: 0.325, 1.6, 5, 22 GHz

Perseus A with ~50 microarsec resolution

EVENT HORIZON TELESCOPE (EHT)

- mm-wave VLBI
- Milky Way SMBH gravitational radius ~ 10 microarcsec
- Resolution <60 microarcsec at 230 - 450 GHz
- Also look at M87
- Data acquired in April 2017 - being analysed