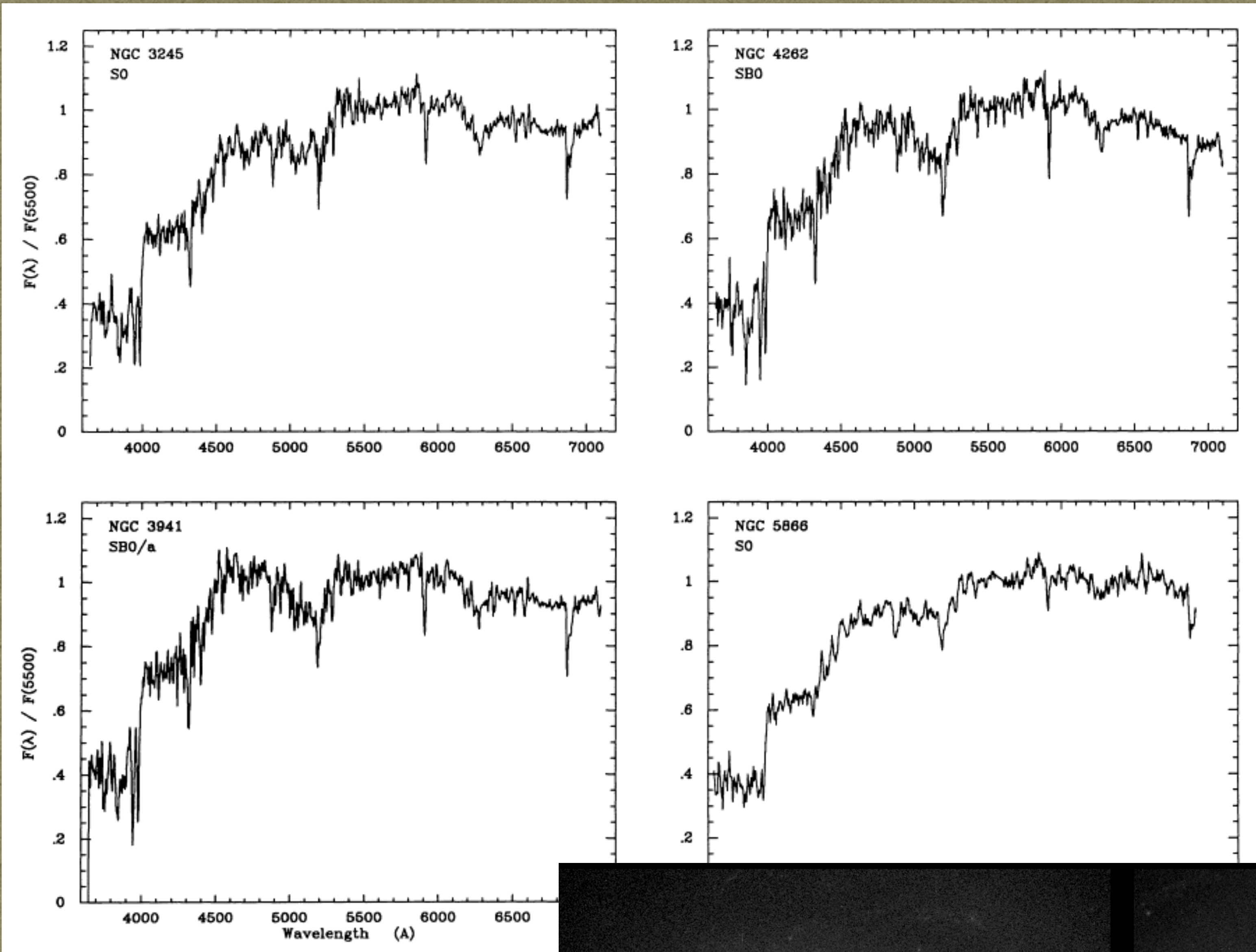
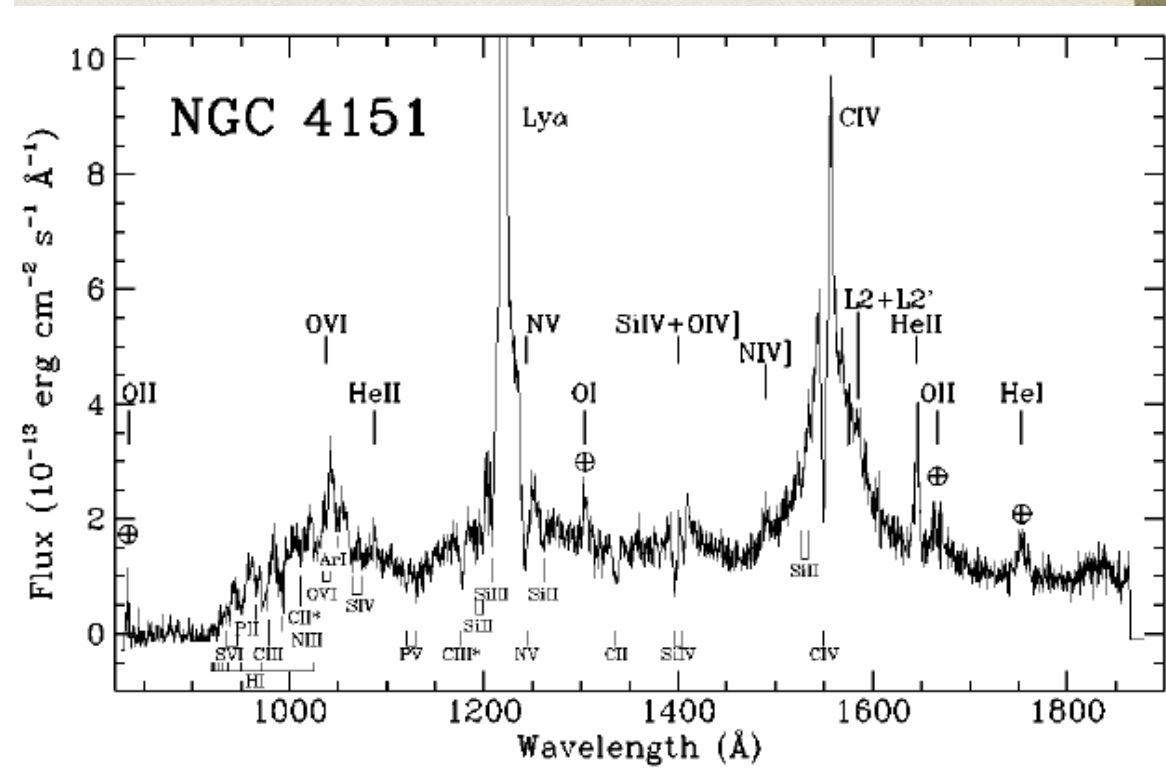
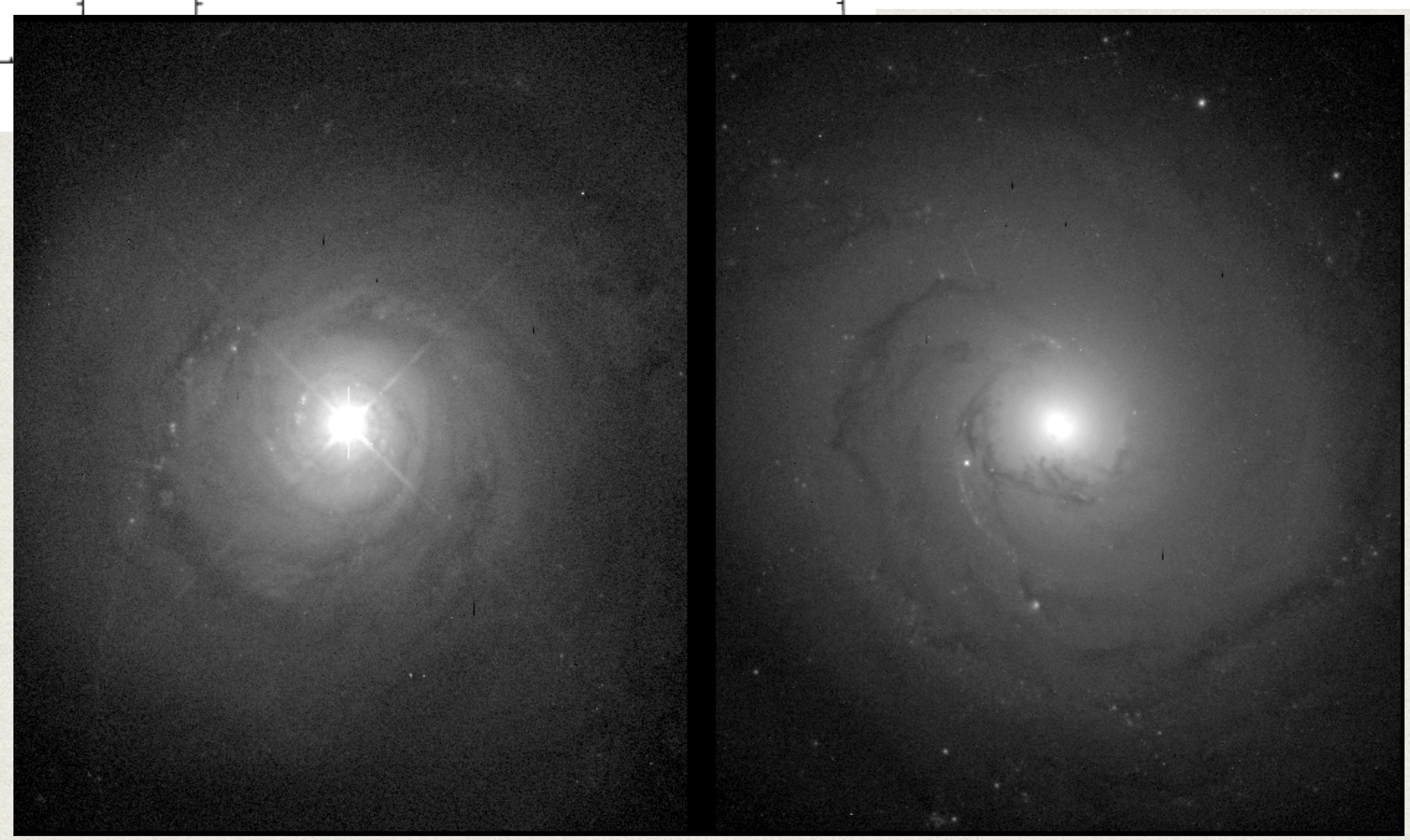
ACTIVE GALACTIC NUCLEI

Preeti Kharb
National Centre for Radio Astrophysics - Tata Institute of Fundamental Research



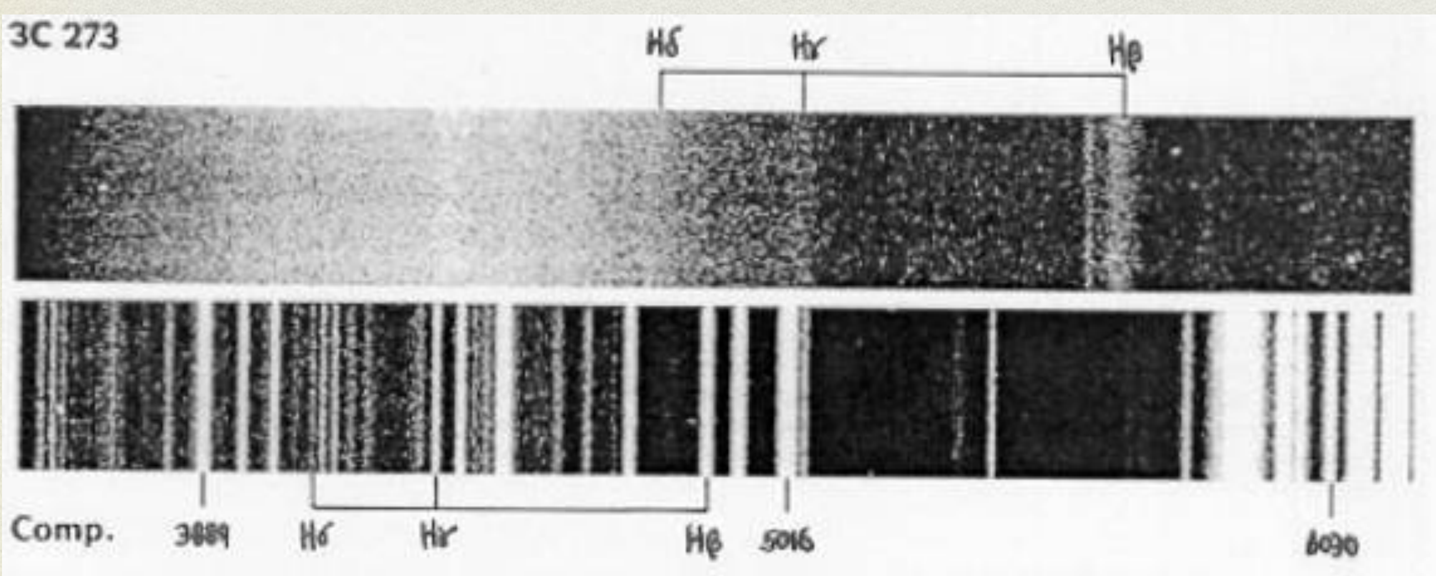


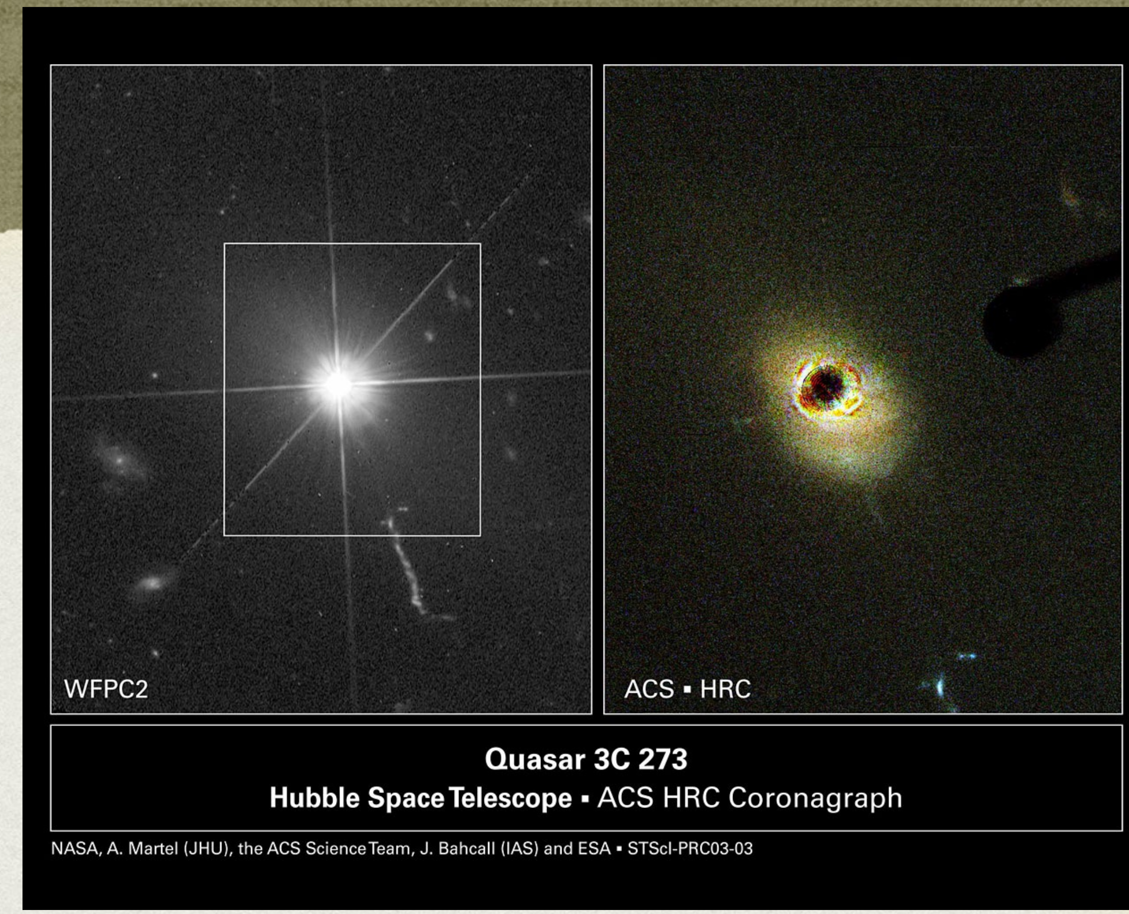


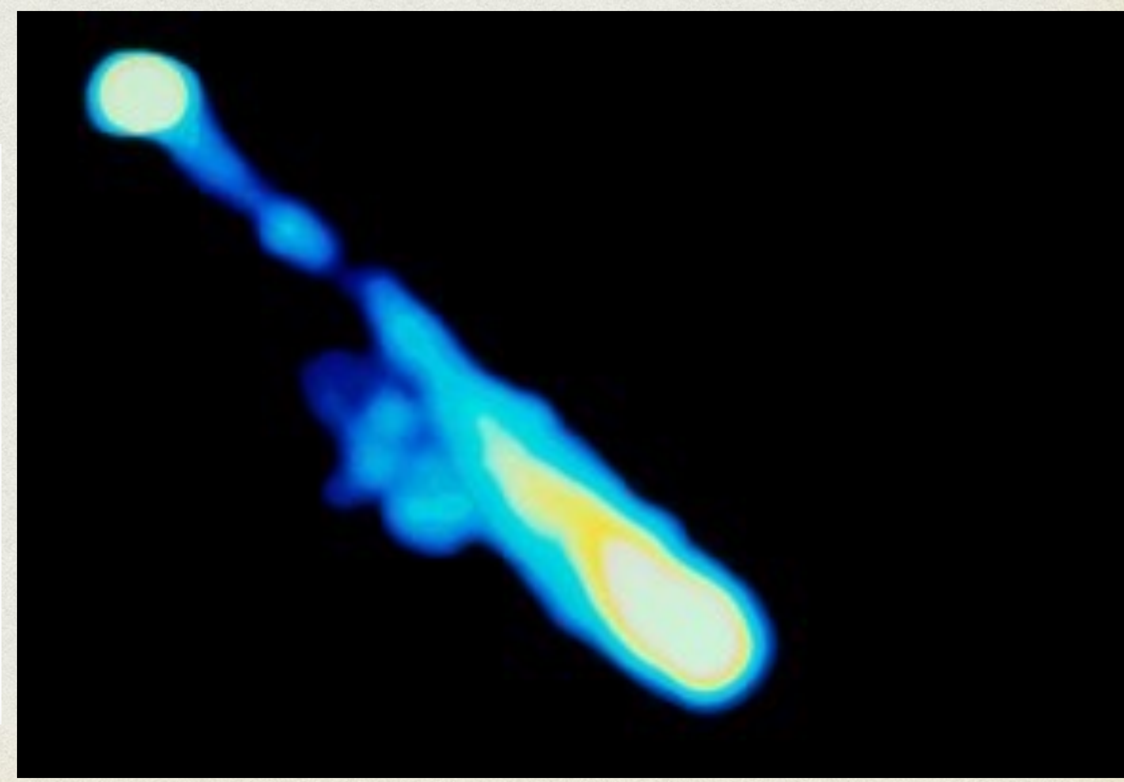
(NGC5548 vs. NGC3277 — Carl Seyfert)

AGN

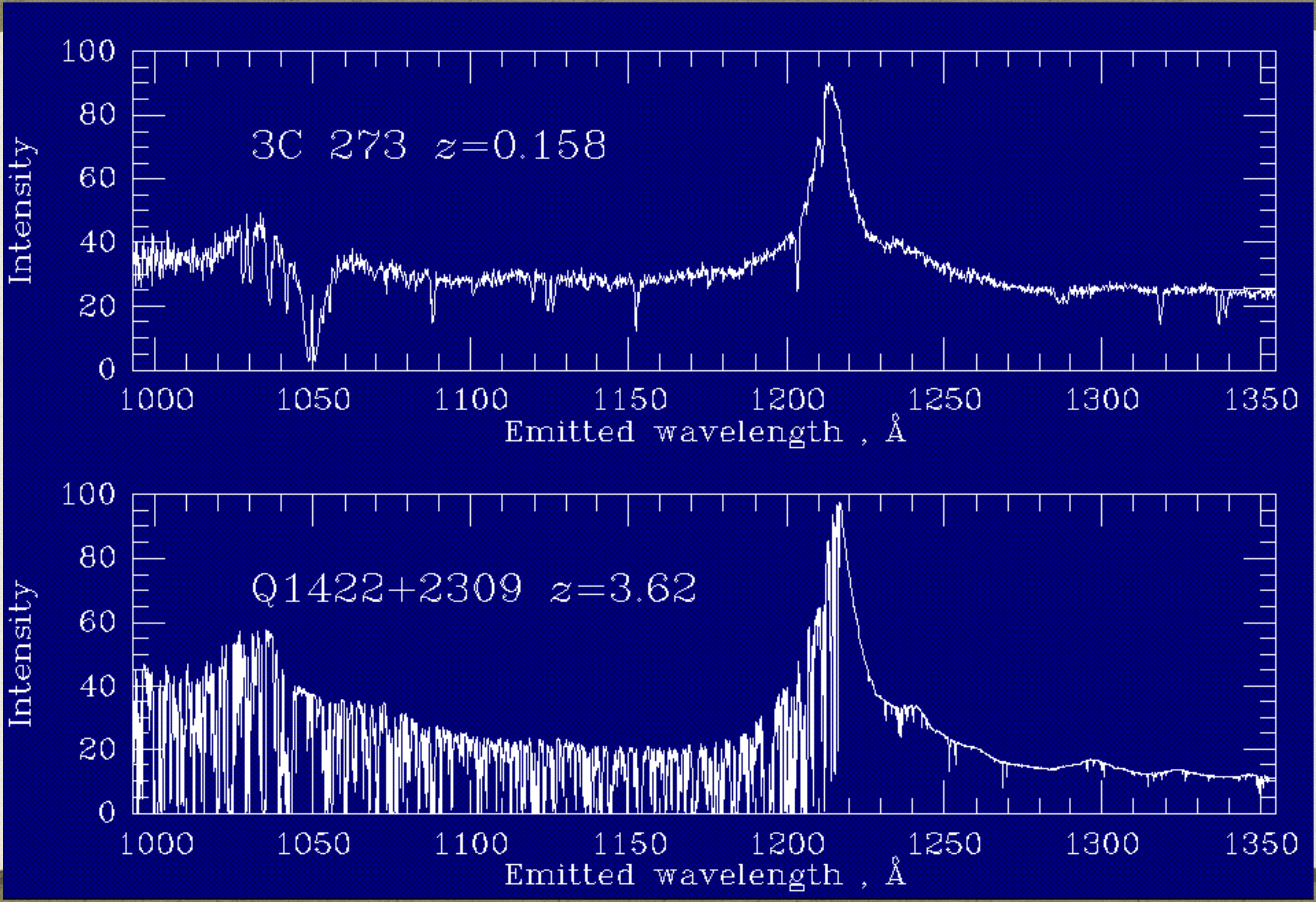
- Seyfert (1943): Star-like nuclei + peculiar emission-line spectra in spirals (NGC5548 vs. NGC3277)
- Schmidt (1963): Quasar 3C273 at z=0.158 discovered

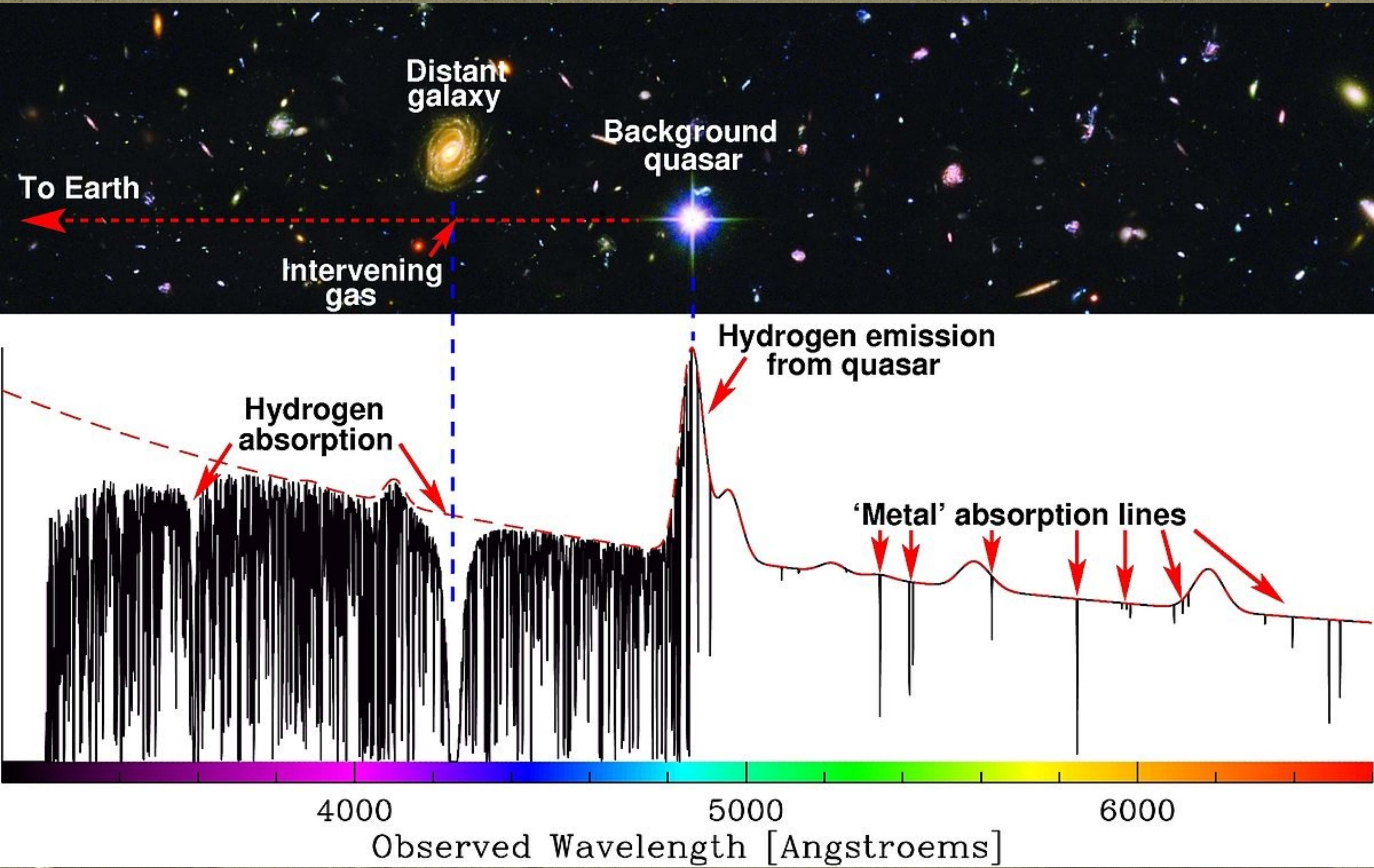






QUASAR ABSORPTION SPECTRA



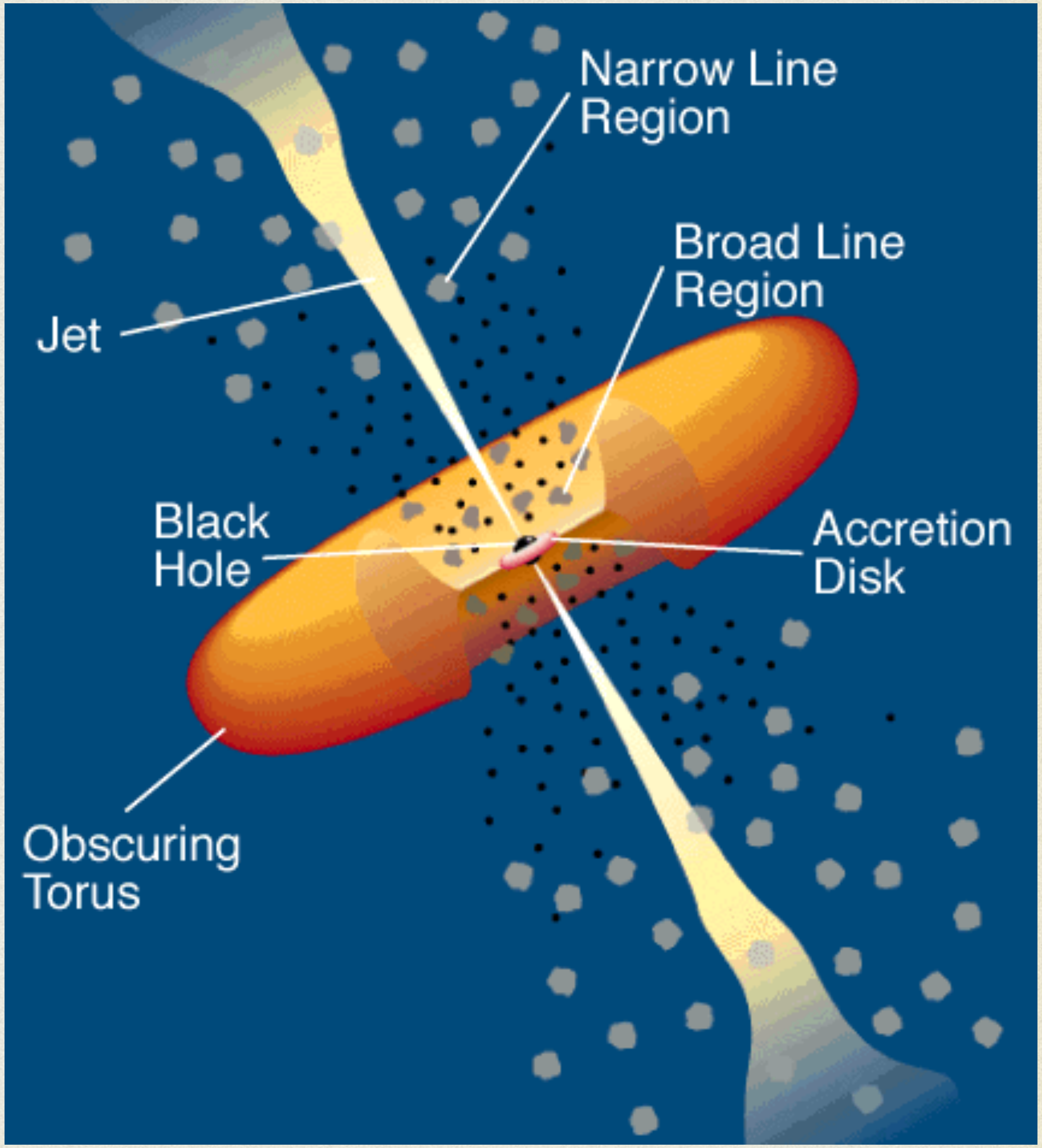

Distant galaxy
Background quasar
To Earth
Intervening gas
Hydrogen emission from quasar
Hydrogen absorption
'Metal' absorption lines
4000
5000
6000
Observed Wavelength [Angstroems]

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
- Relativistic Jets launched from Accretion disk - SMBH interface

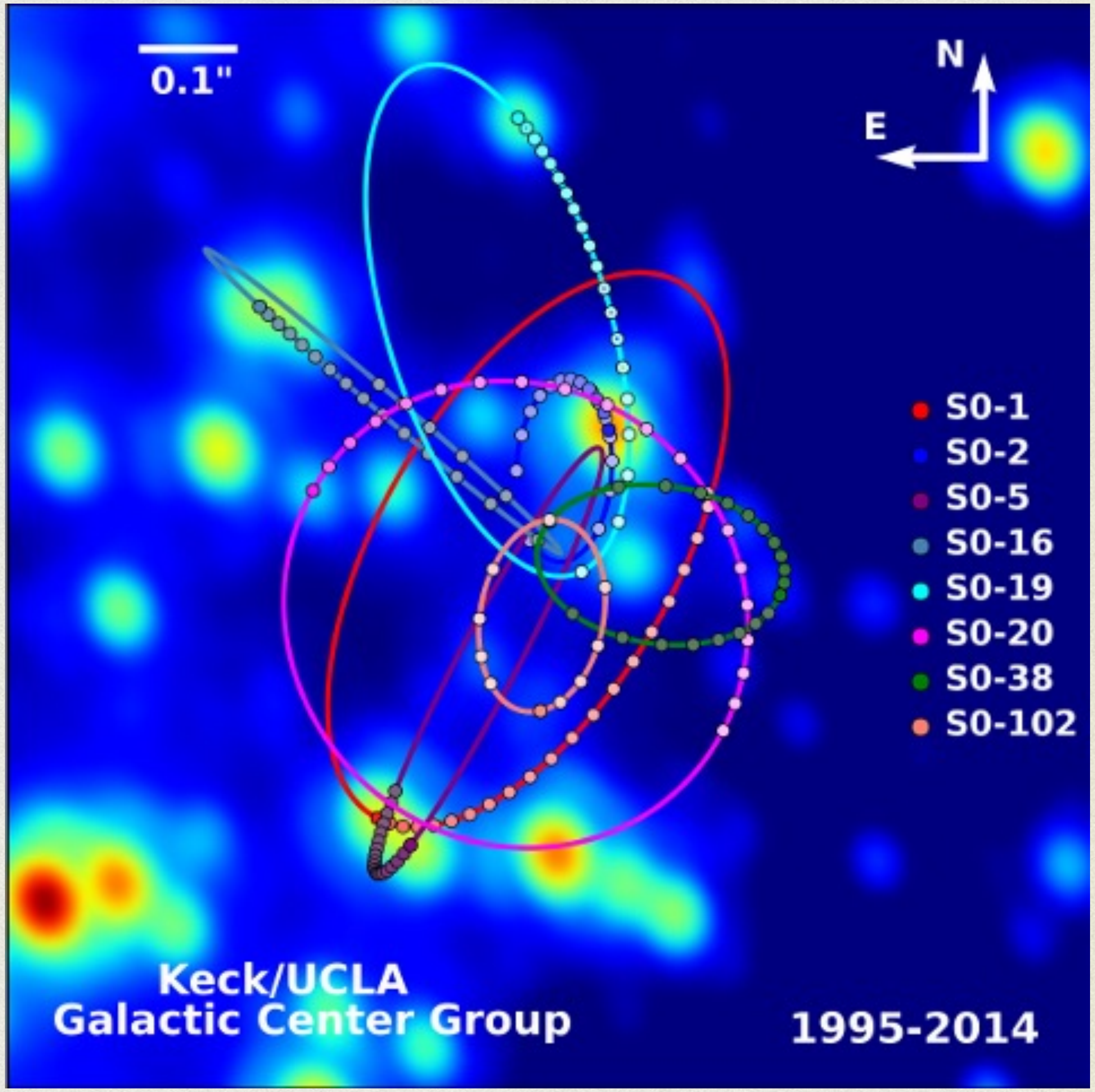
Type 1s & 2s differ by orientation

Unification (Antonucci 1993)

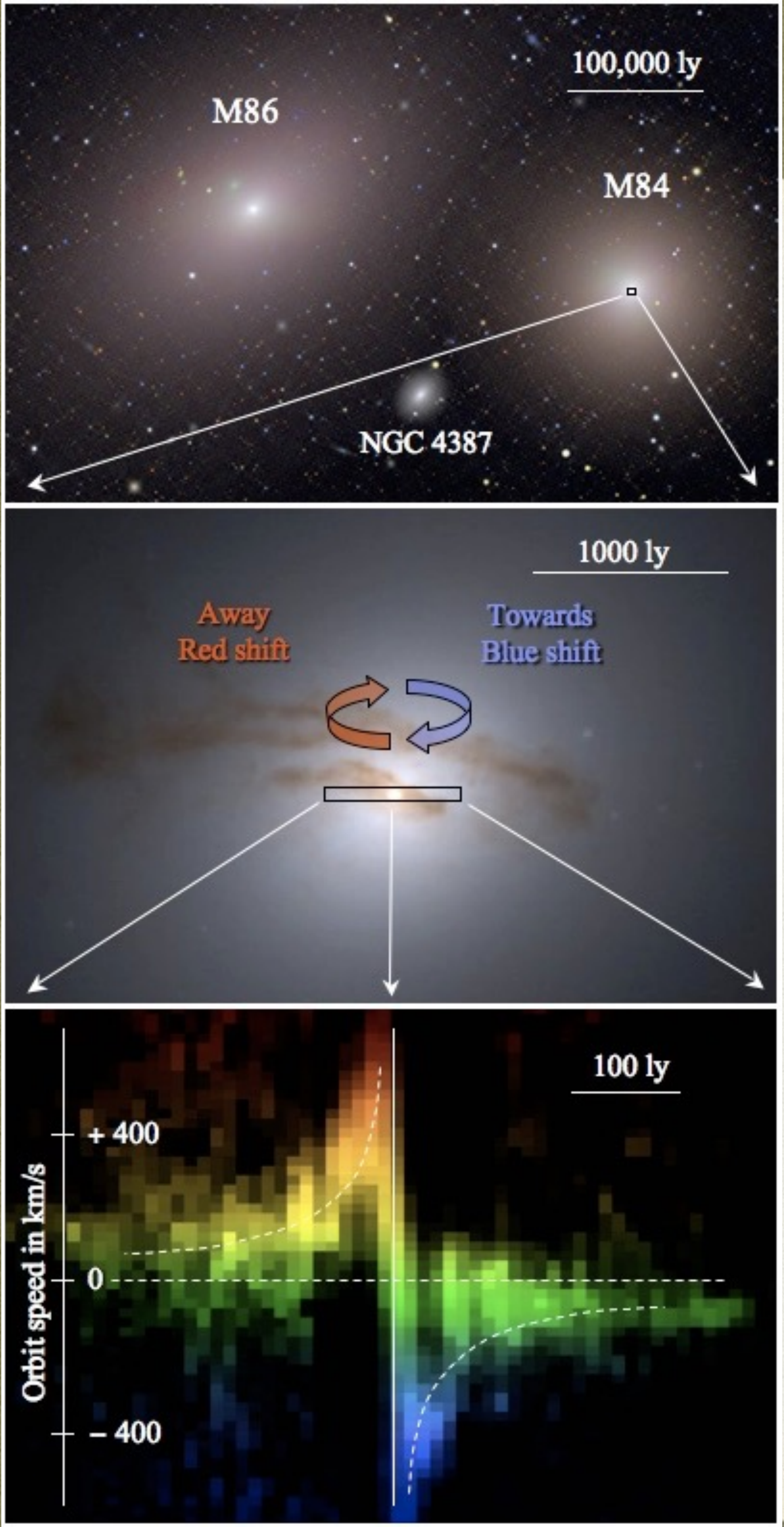


SUPERMASSIVE BLACK HOLE (SMBH) IN THE MILKY WAY

- All large galaxies have a supermassive black hole in their centres
- Newton's form of Kepler's 3rd law (equating gravitational force with centripetal force)
- $M = v_2 \cdot r/G$
- v = orbital velocity
- r = average orbital separation
- G = Gravitational constant
- Milky Way SMBH ~4.5×10^6 M⊙

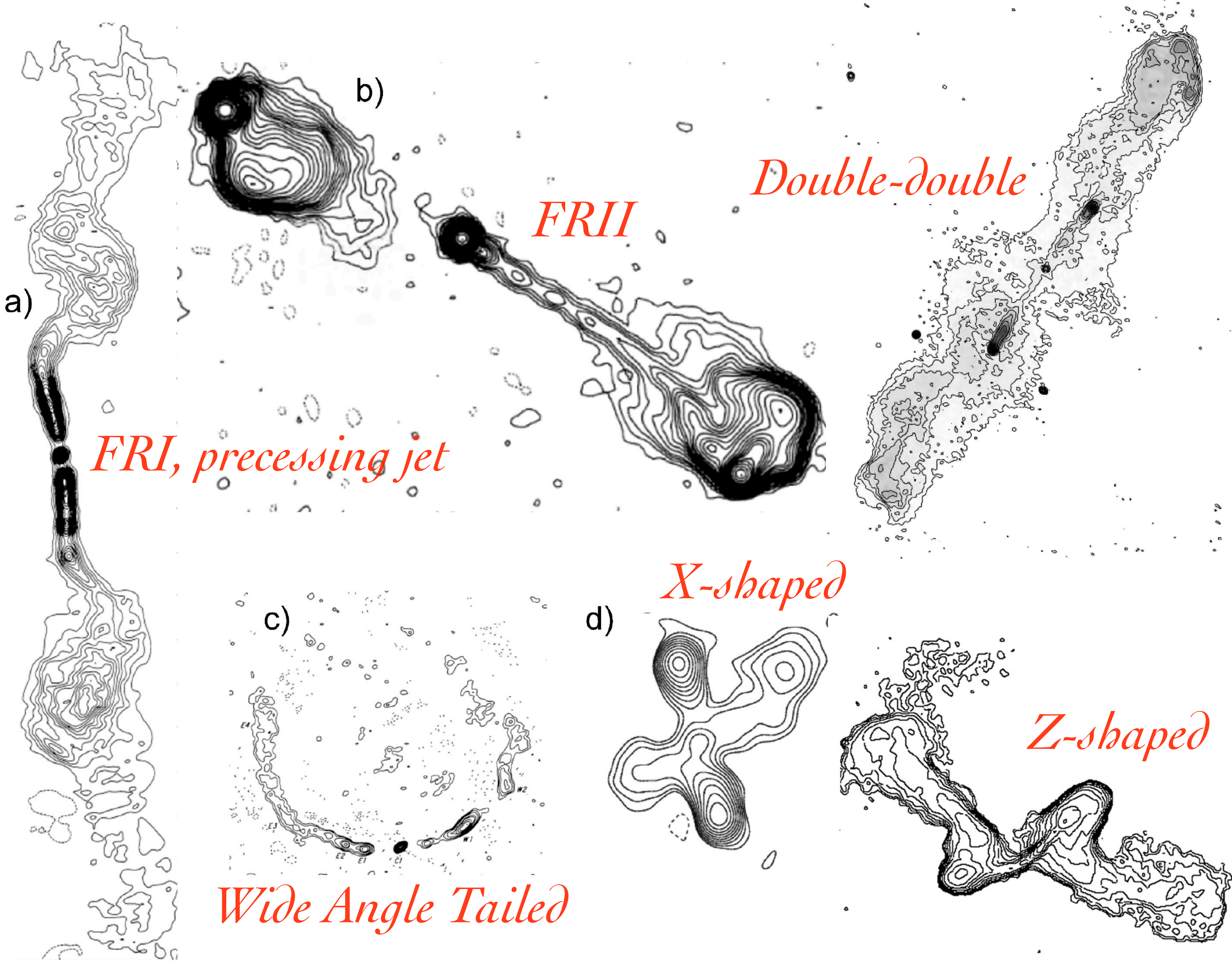


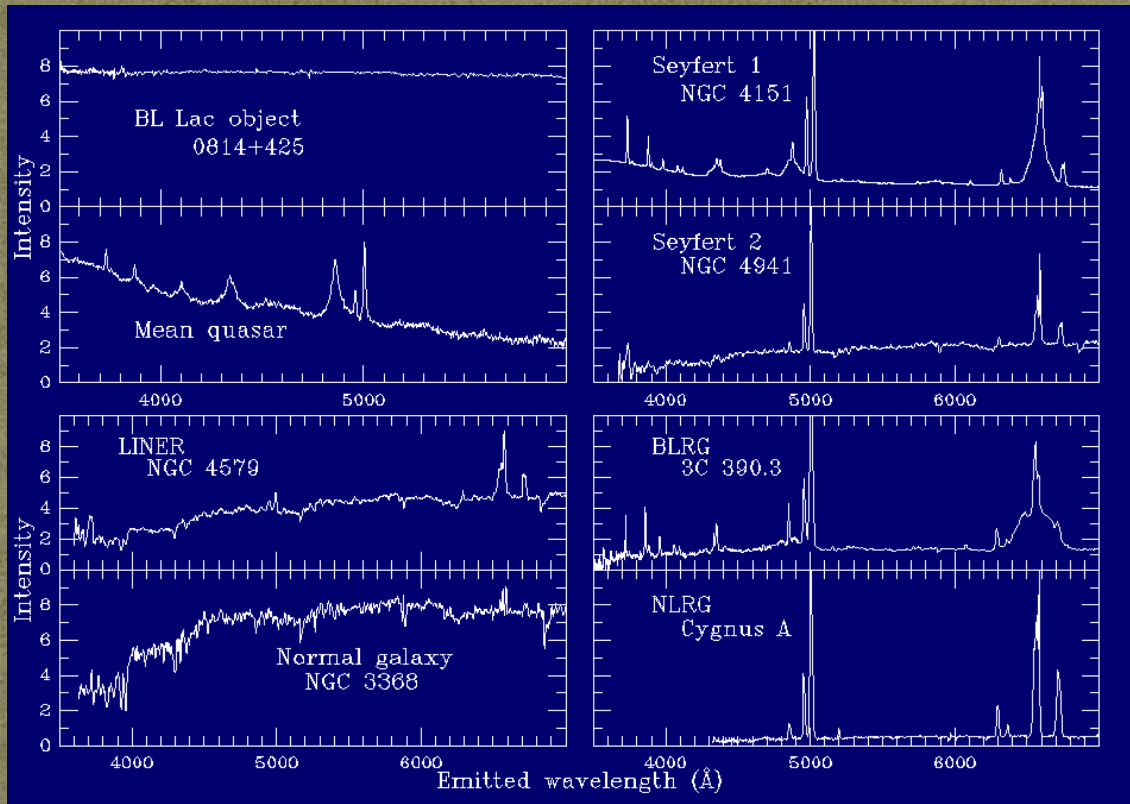
SMBH IN EXTERNAL GALAXIES

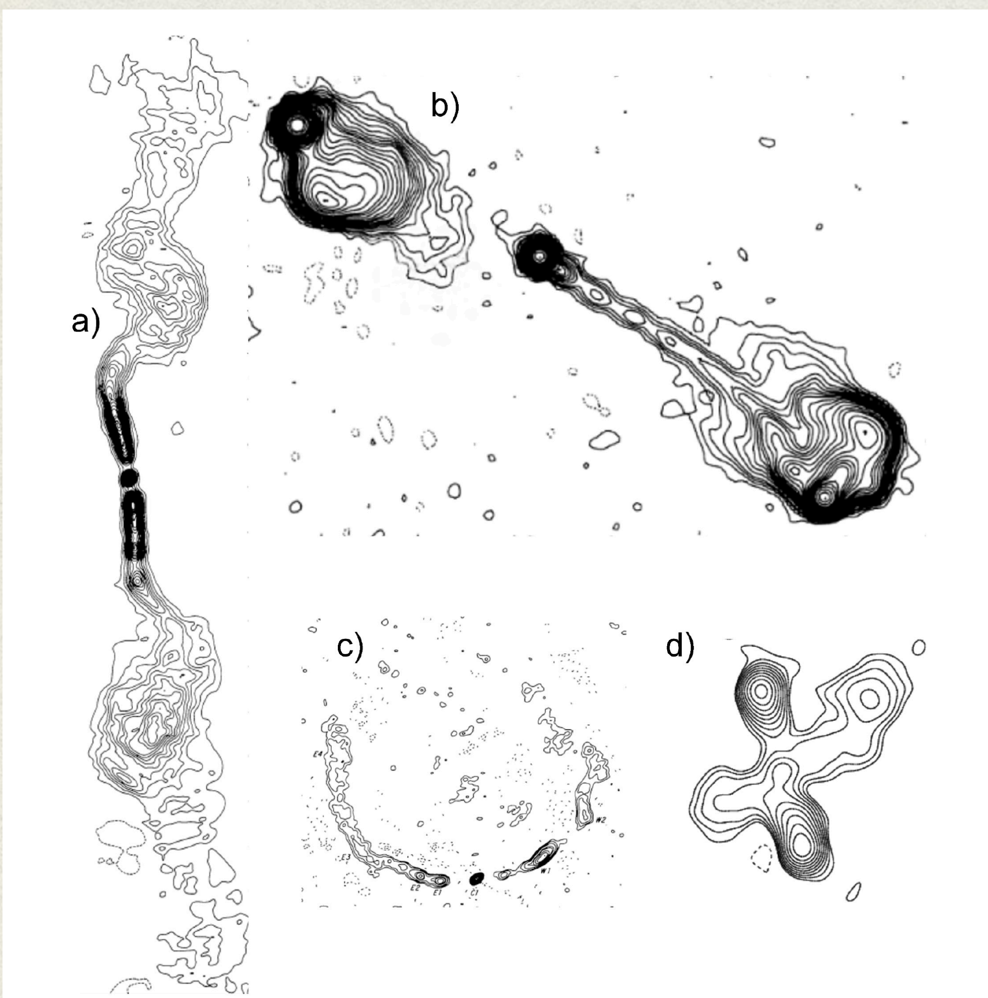


HST/STIS observations of nuclear gas disk in M84. Keplerian velocity suggests a BH mass of ~$3 \times 10^8 M_\odot$

Top right: Radio (red) and X-ray (blue) emission from M84


a)
FRI, precessing jet
b)
FRII
Double-double
c)
Wide Angle Tailed
d)
X-shaped
Z-shaped



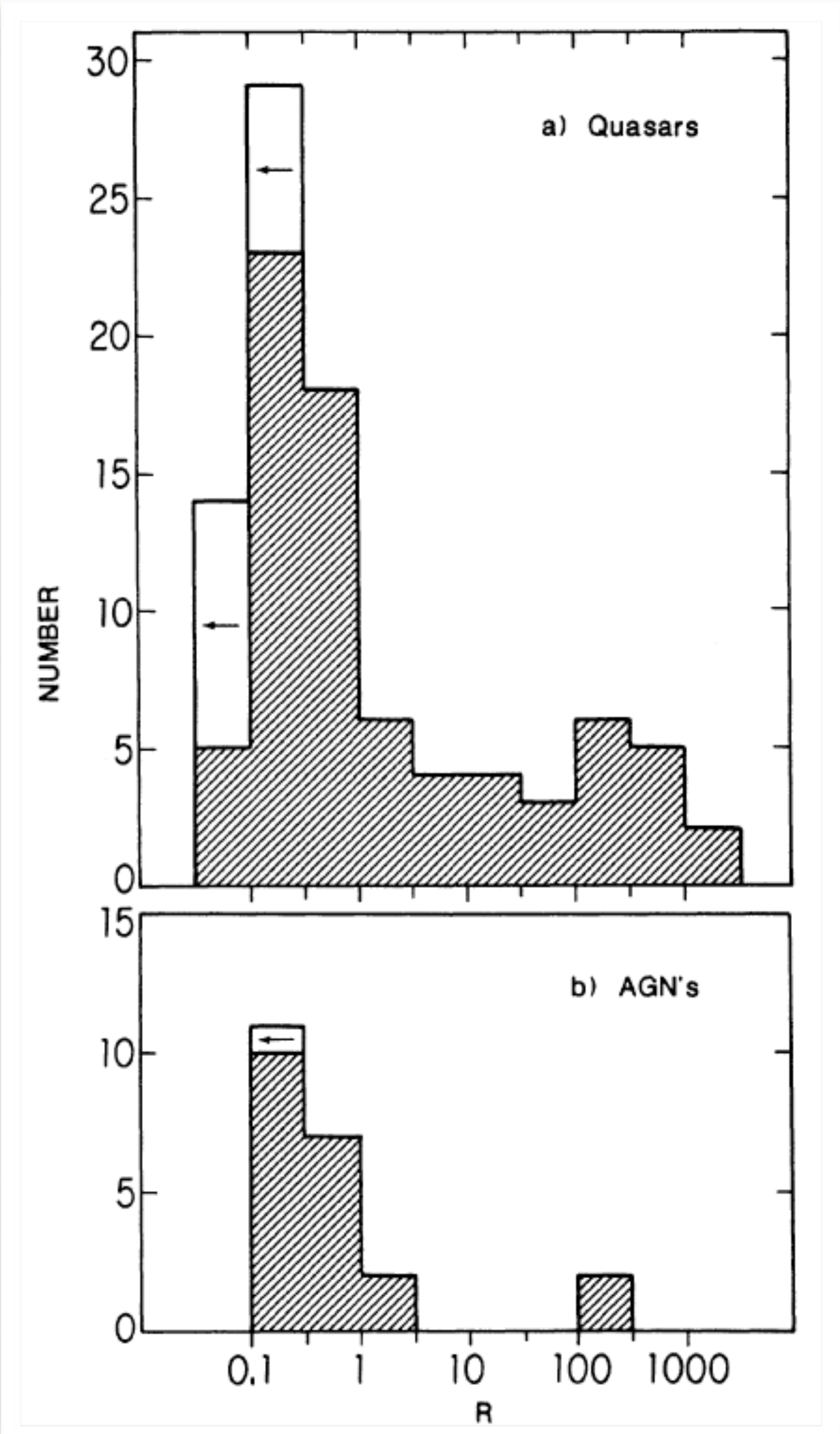


Padovani+ 2017, A&A Review

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

THE RL-RQ DICHOTOMY



Palomar Bright Quasar Survey
Kellermann+ 1989

Radio-loud / Radio-quiet AGN

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

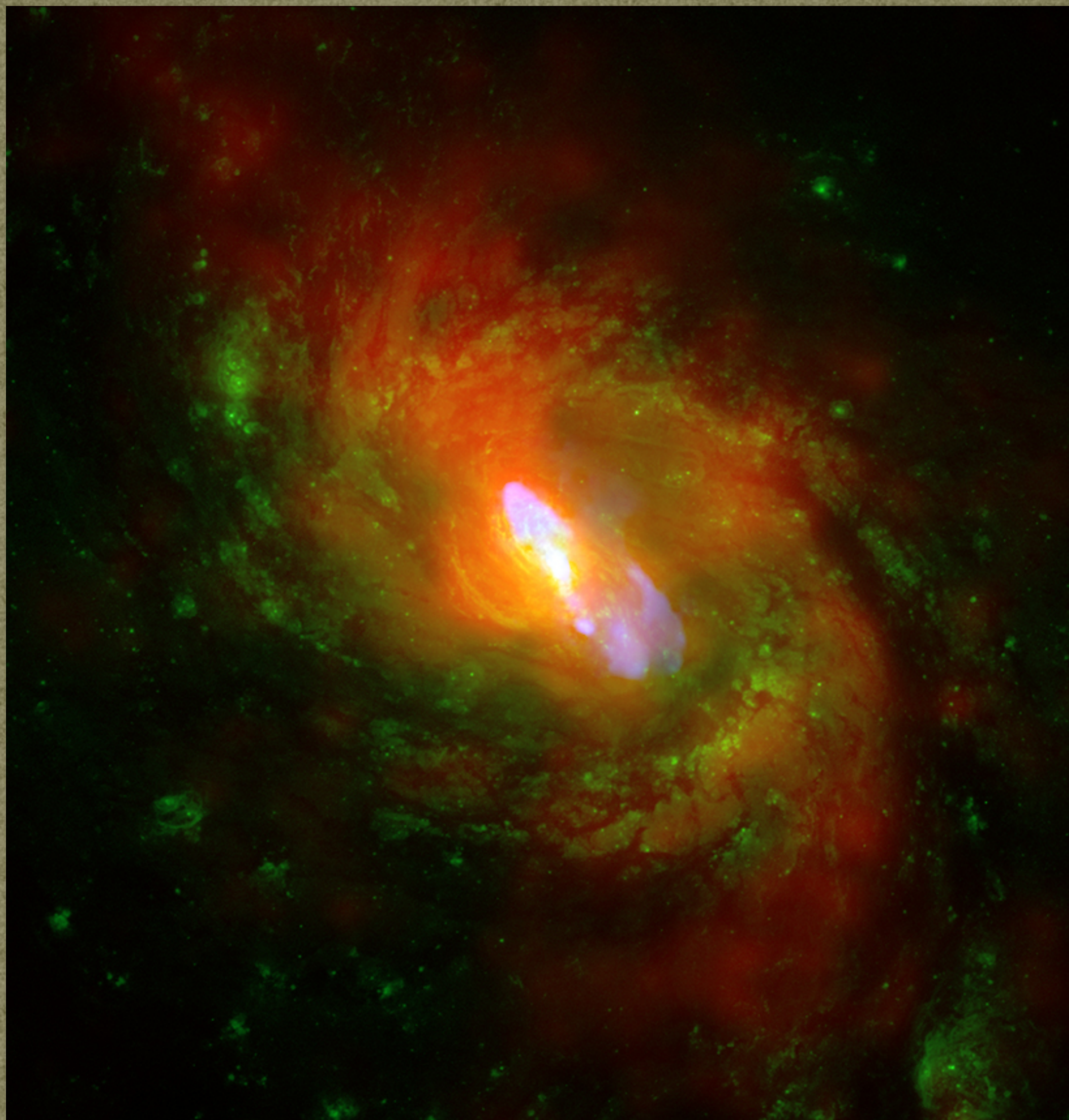
Bimodality observed

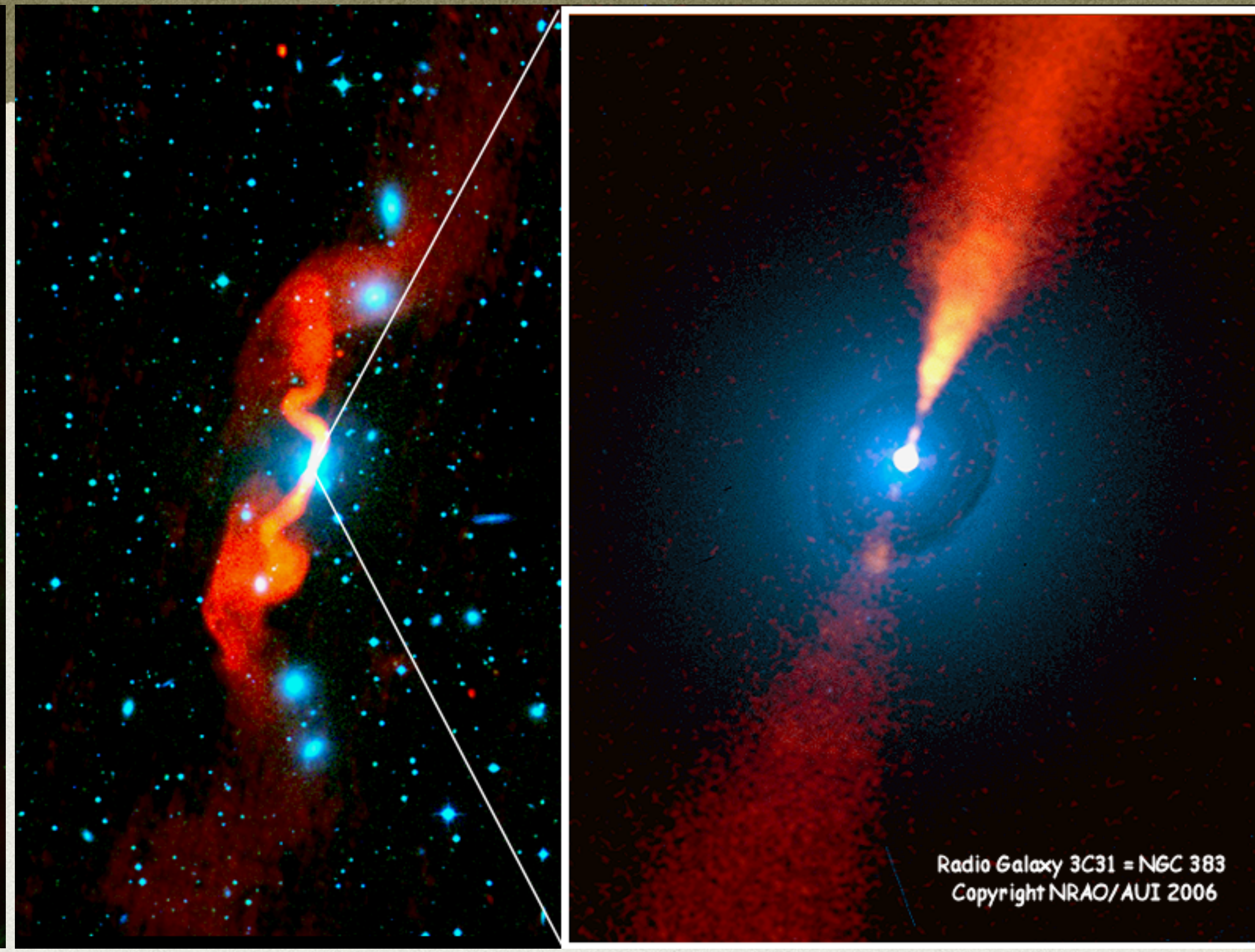
Quasars $M_B < -23$
"AGNs" $M_B > -23$

~15% sources "radio-loud"

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

RADIO EMISSION IN AGN

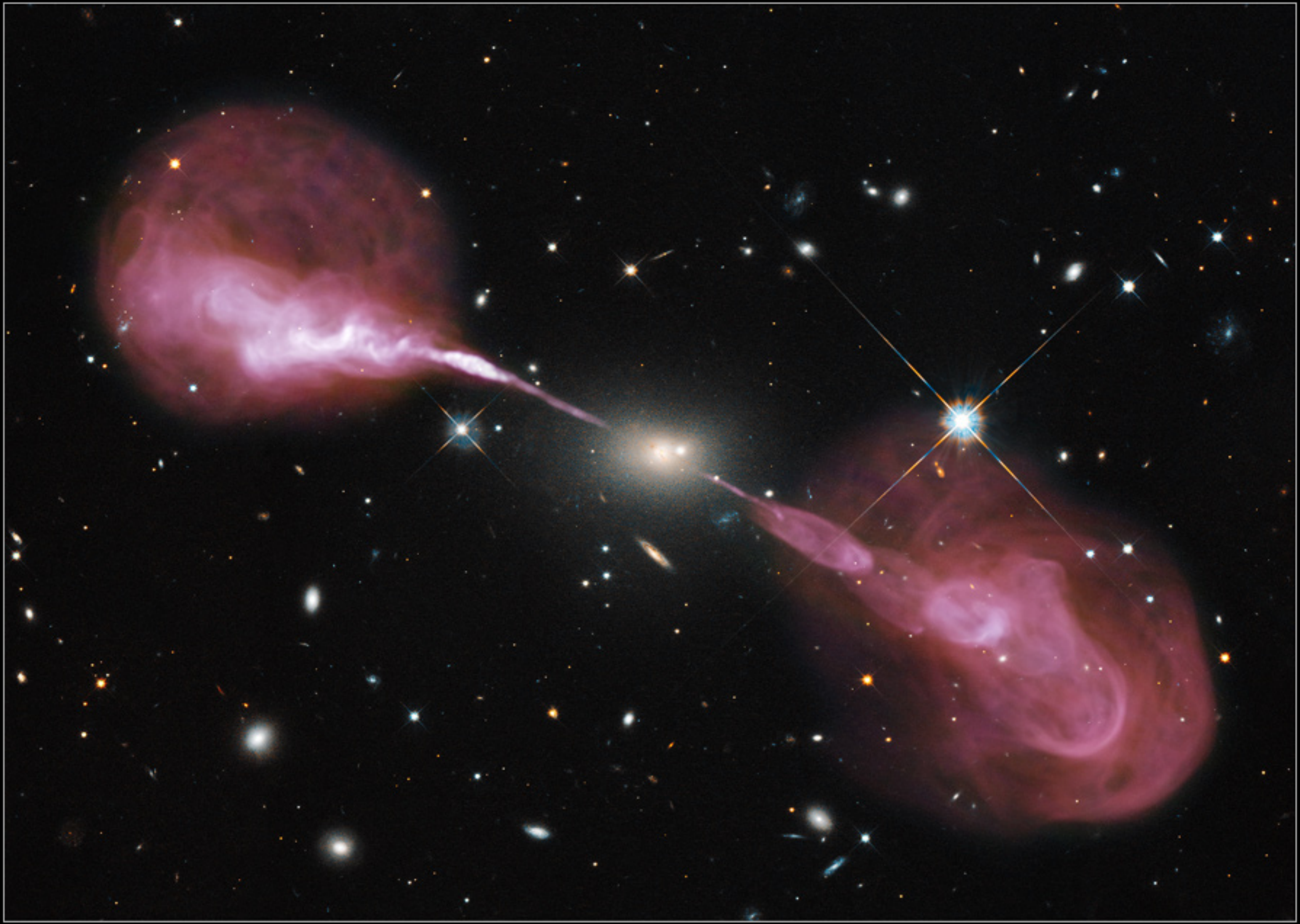




Seyfert galaxy NGC1068 Radio galaxy 3C31

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

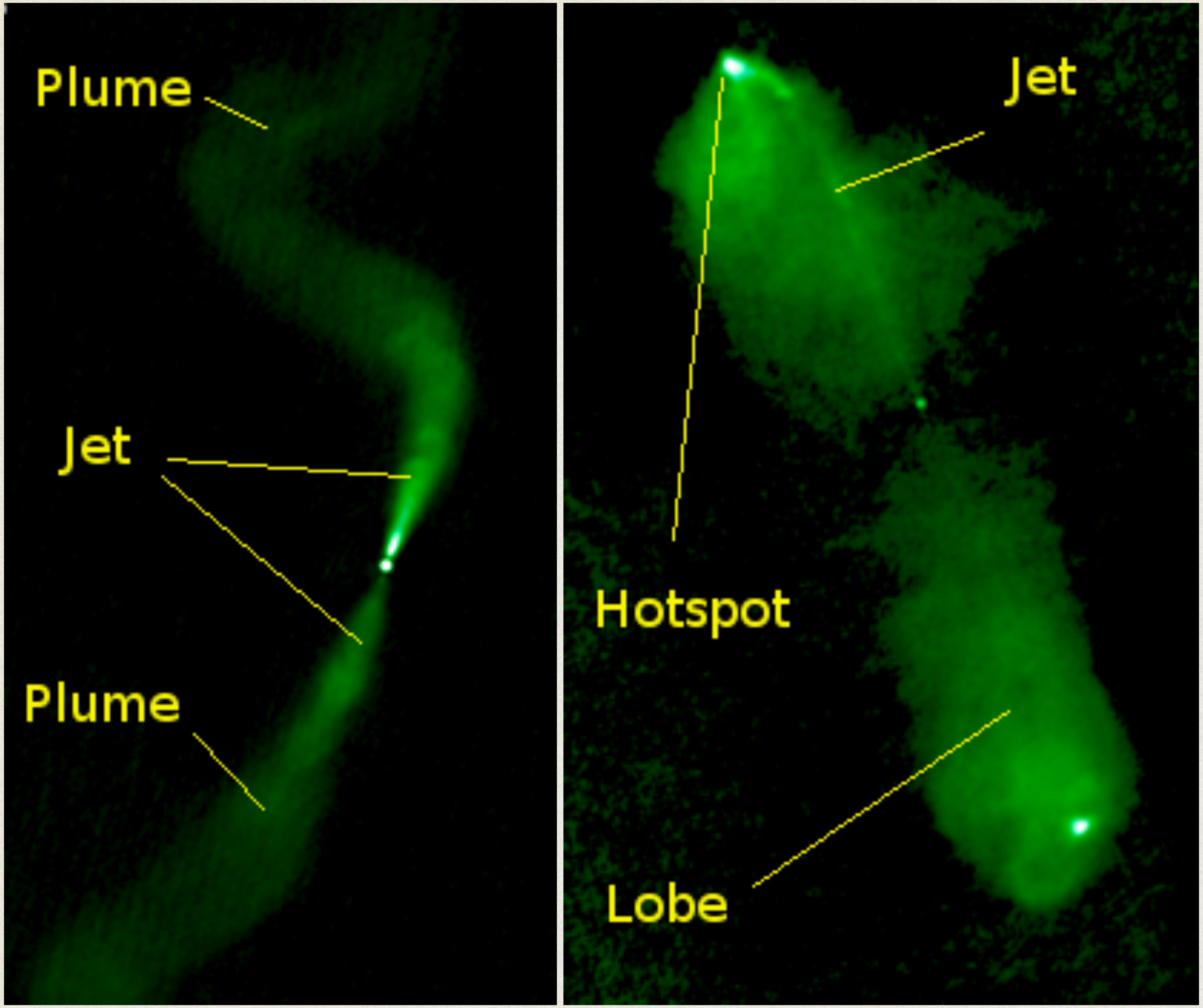
Radio Galaxy Hercules A



Hubble Heritage

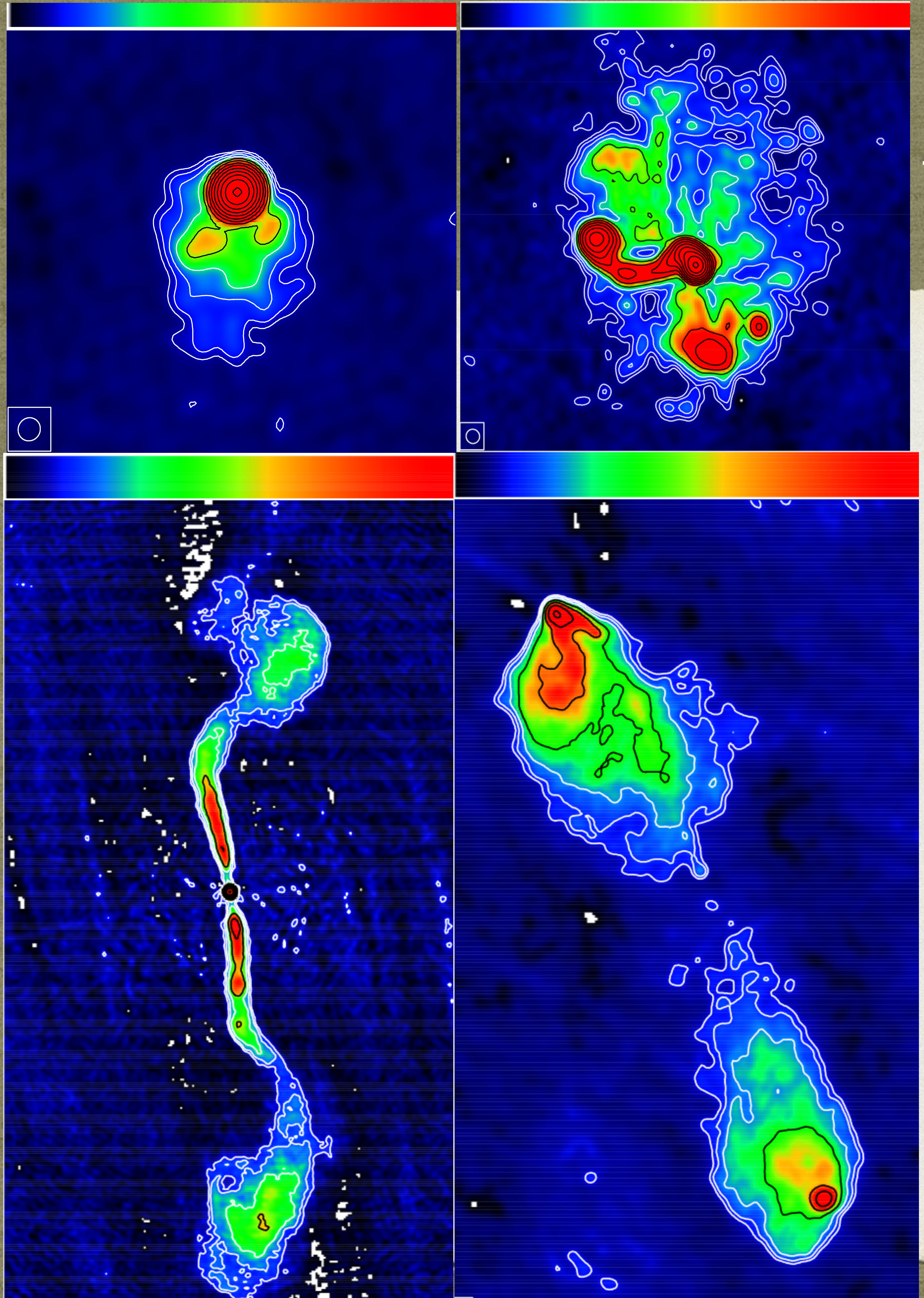
NASA, ESA, NRAO • *HST* WFC3/UVIS • VLA • STScI-PRC12-47

RADIO-LOUD AGN: FANAROFF-RILEY DICHOTOMY



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

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



RADIO-LOUD UNIFICATION

Based on **orientation-independent properties** like radio lobe morphology + luminosity, emission-line spectra, galaxy types and environments

FRIs are parent population of BL Lac objects

FRIIs are parent population of radio-loud quasars

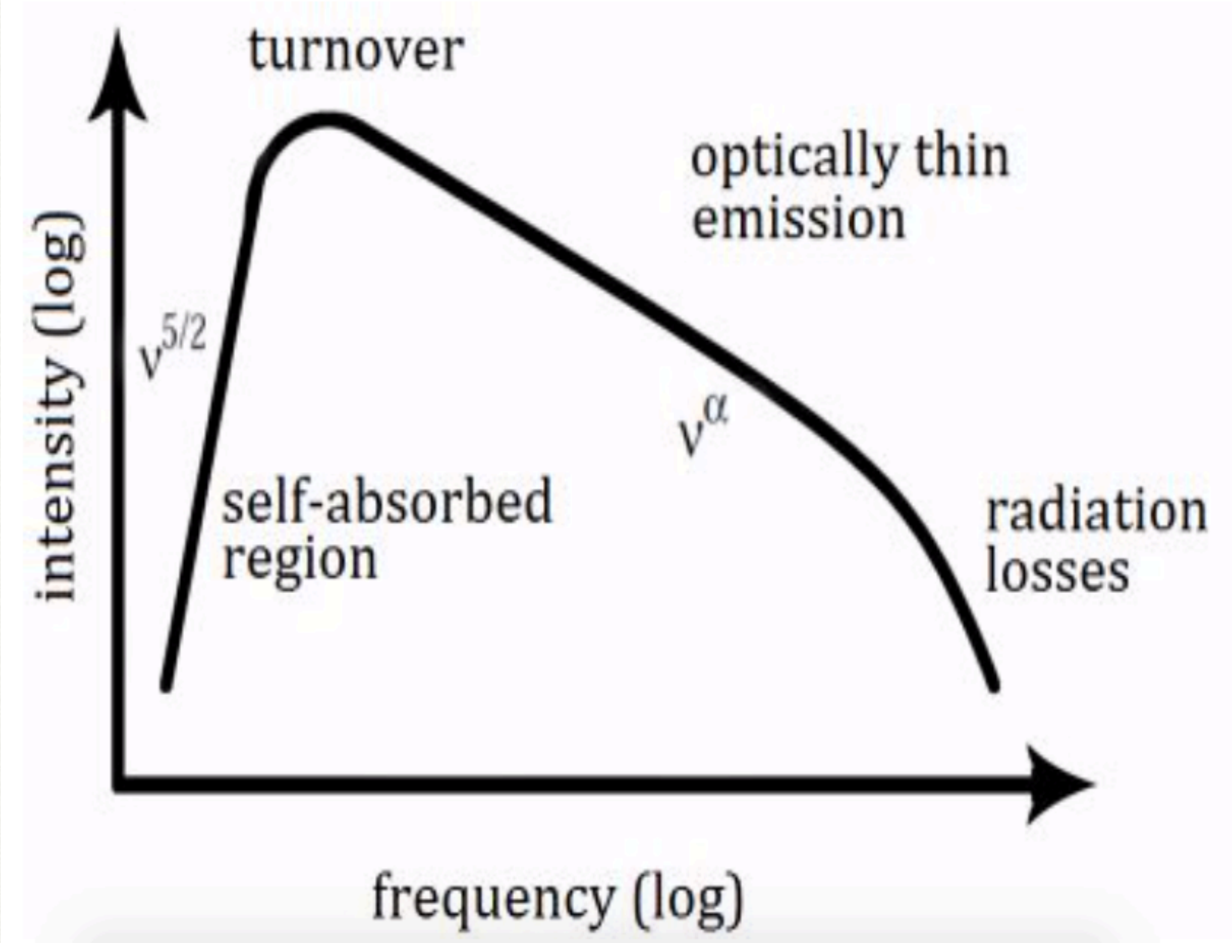
(Blandford & Rees 1978, Urry & Padovani 1995)

RADIO EMISSION IN AGN

- Incoherent synchrotron emission

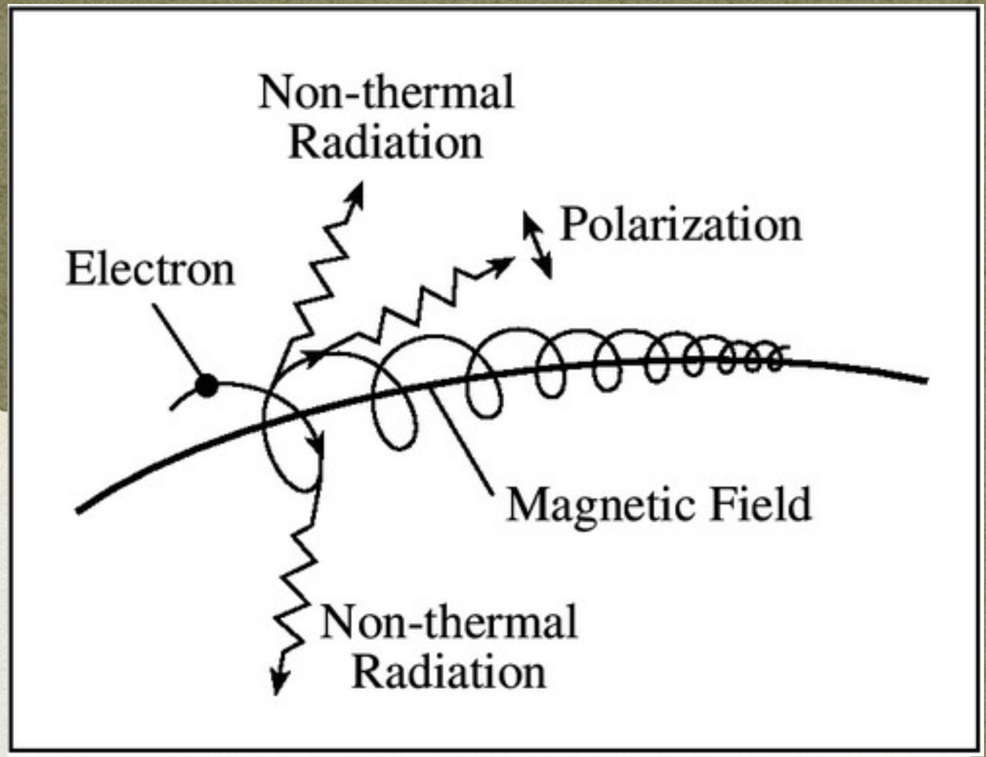
$$N(E)dE = N_0 E^{-s} dE$$

- $\alpha = (s-1)/2$
- Typically, $\alpha = 0.7$
- $s = 2.4$



- Electrons radiate at frequencies proportional to energy *E*; the rate of loss of energy is proportional to E^2

SYNCHROTRON RADIATION



Frequency of radiation proportional to frequency of gyration, ν_g

$\nu_g = Be/2\pi m_e$

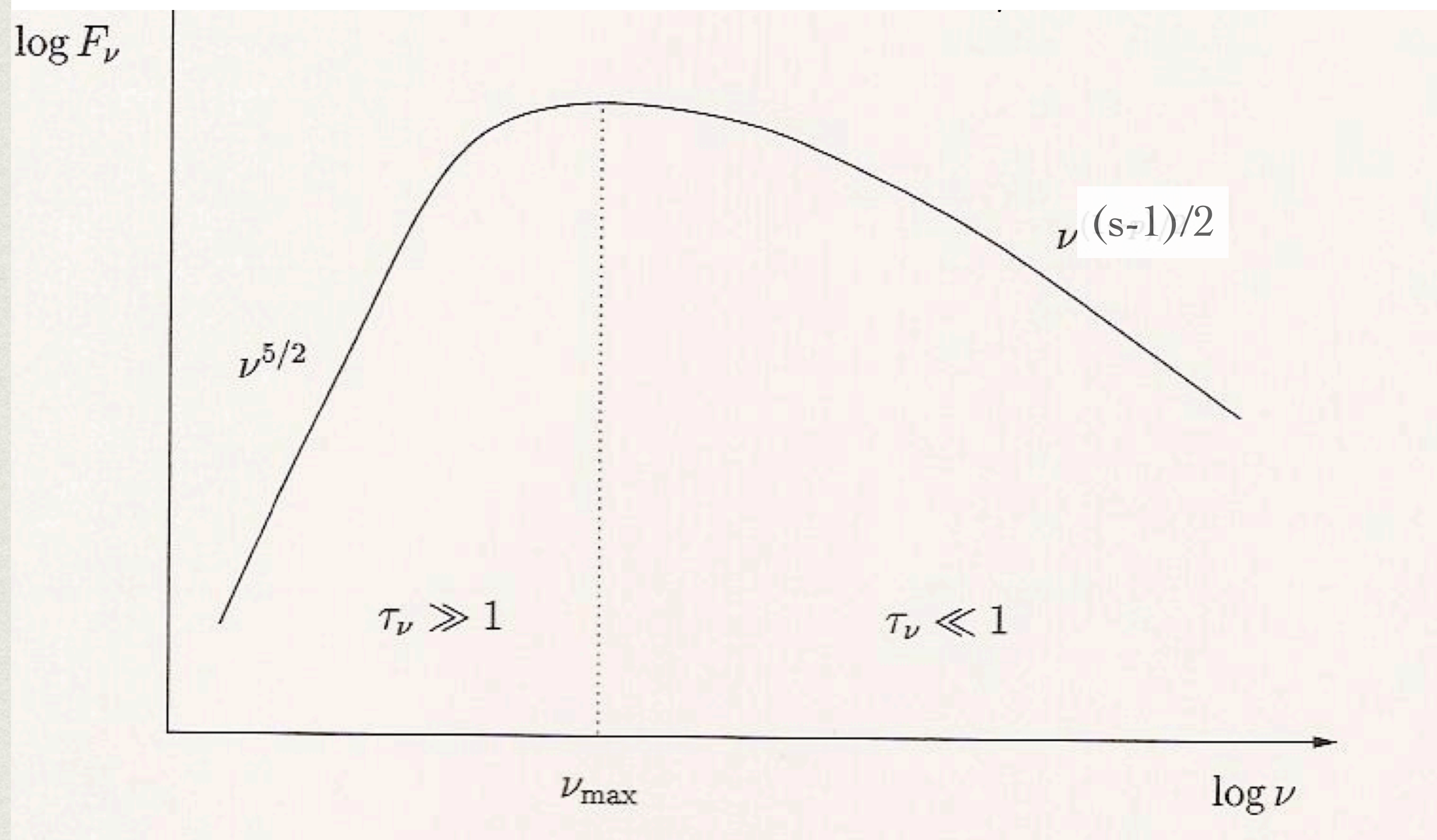
Relativistic electrons, $\nu_s = \gamma^2 . \nu_g$

where

γ = Lorentz factor = $1/(1-\beta^2)^{1/2}$

$\beta = v/c$

Spectral index, $\alpha = (s-1)/2$



the synchrotron spectrum of a source with a power law electron distribution $N(E) \propto E^{-s}$

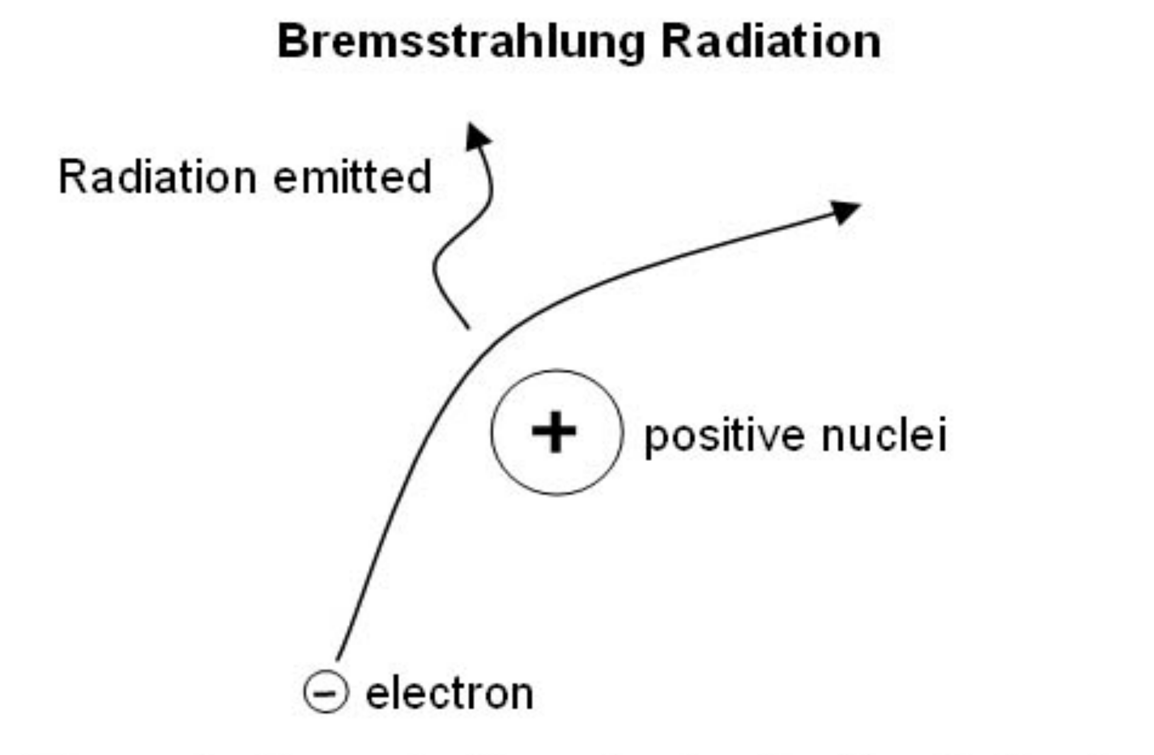
FREE-FREE EMISSION

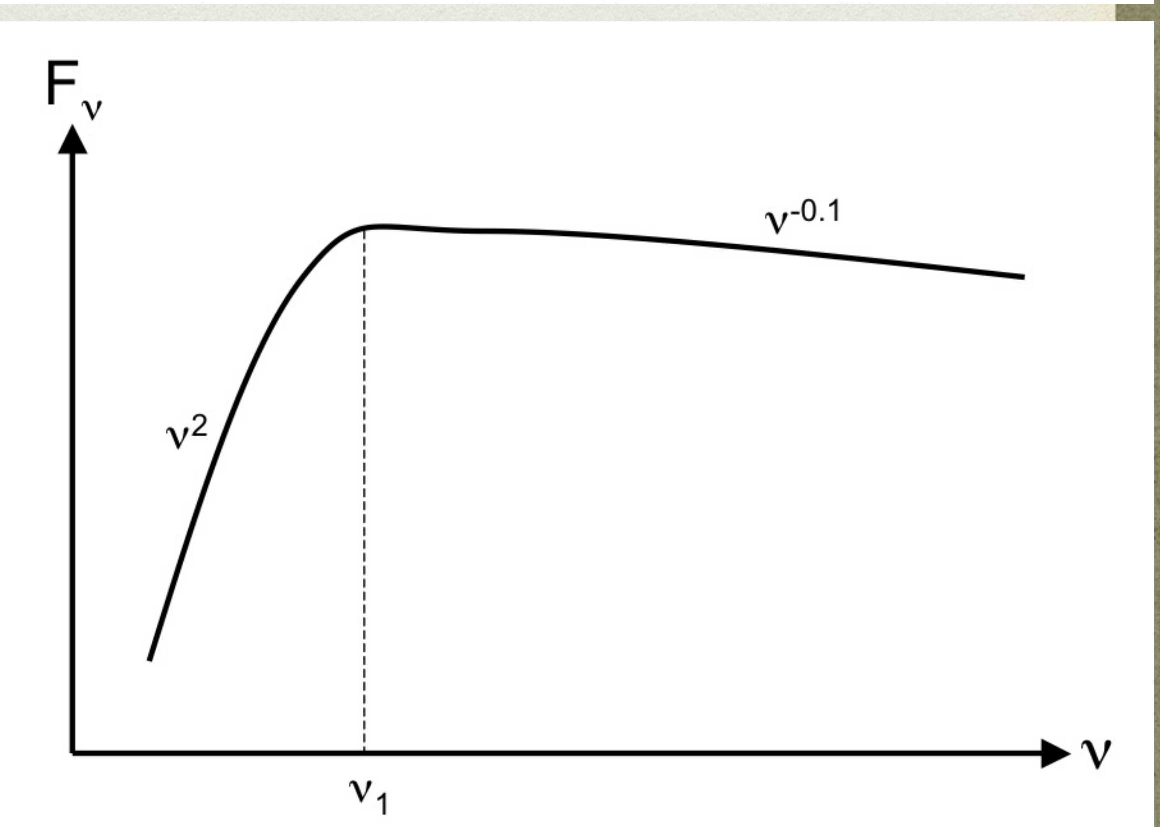
Flux density, $F_\nu \sim \nu^\alpha$

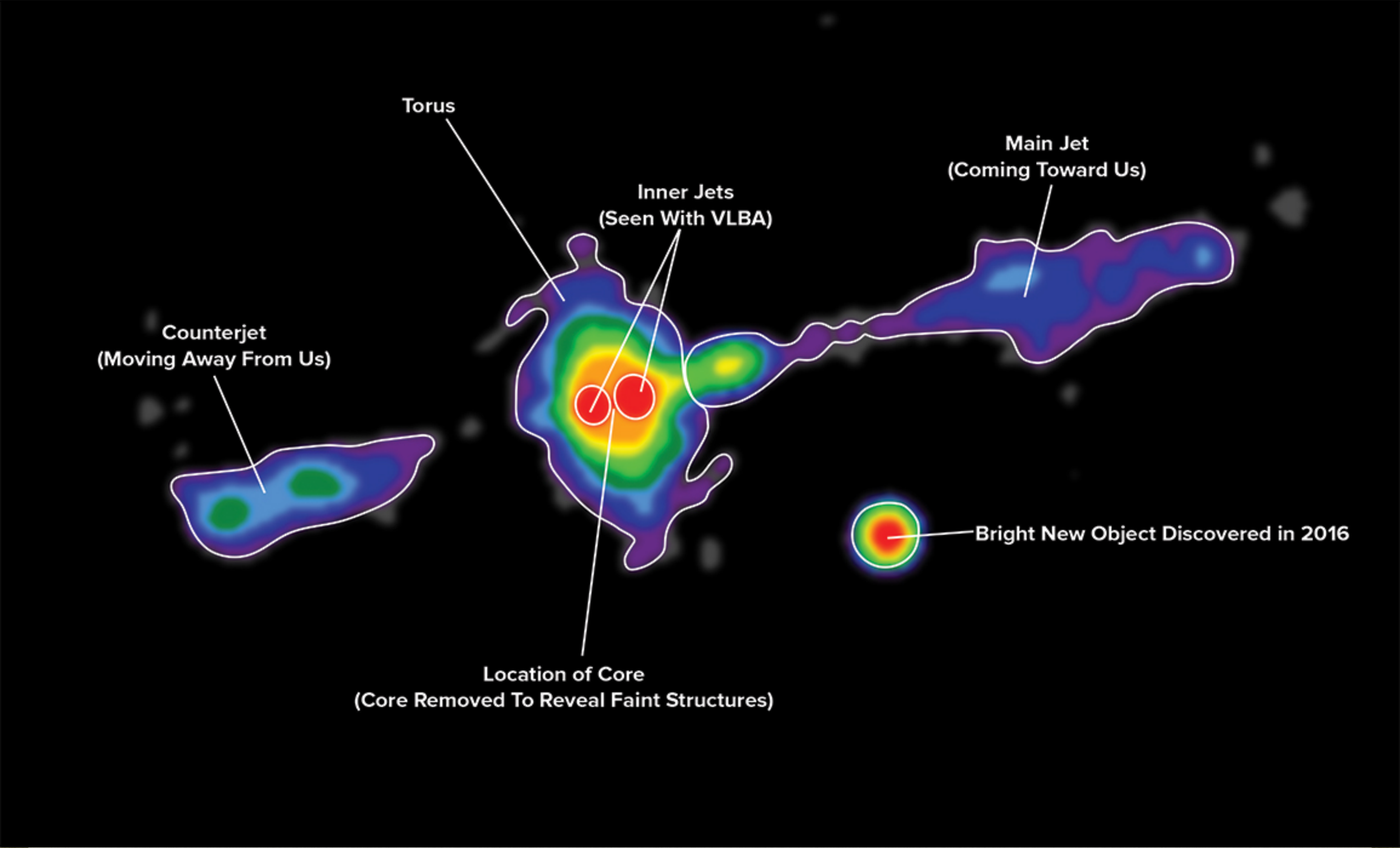
Optically thin, α=-0.1

Optically thick — self-absorption

α=+2



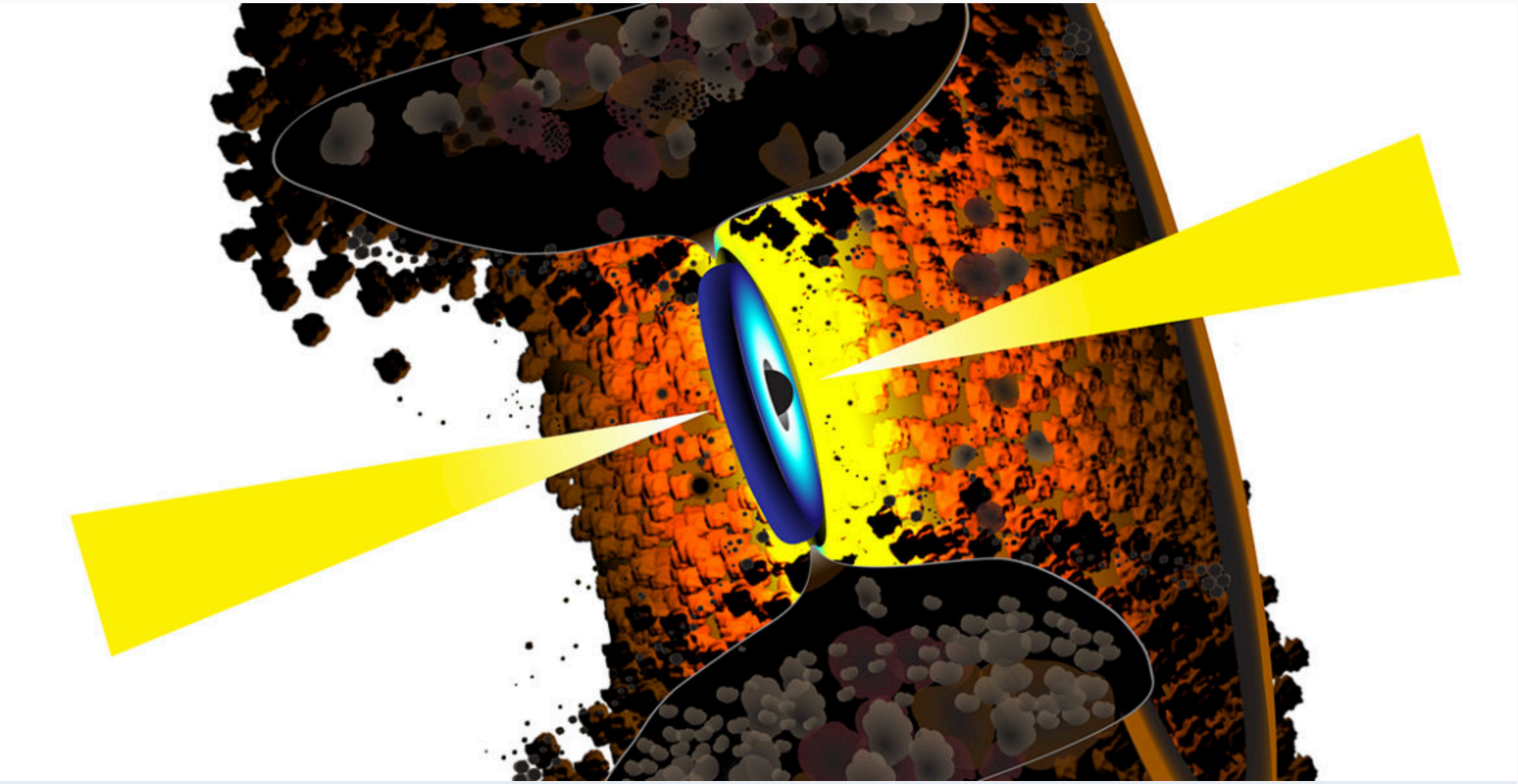




VLA at 18-48 GHz
Torus emission is optically thin free-free emission
Torus size 300 × 500 parsec (Carilli+ 2019)

VLA Makes First Direct Image of Key Feature of Powerful Radio Galaxies

Structure suggested by theorists decades ago



Credit: Bill Saxton, NRAO/AUI/NSF

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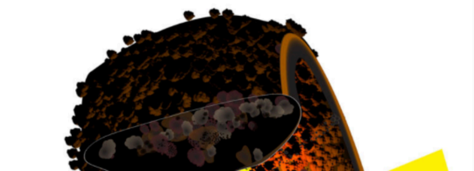
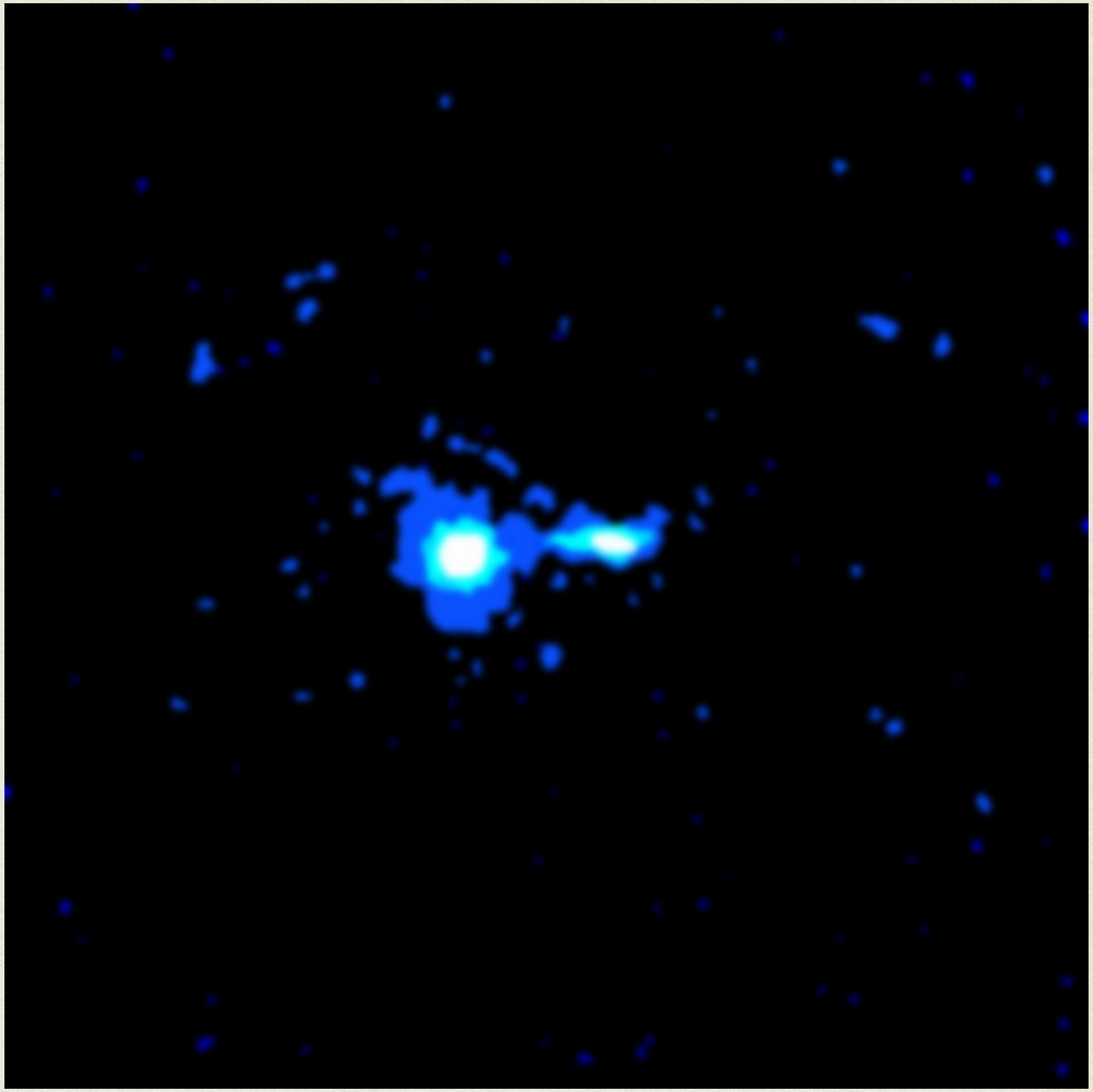
Astronomers used the National Science Foundation's Karl G. Jansky Very Large Array (VLA) to make the first direct image of a dusty, doughnut-shaped feature surrounding the supermassive black hole at the core of one of the most powerful radio galaxies in the Universe — a feature first postulated by theorists nearly four decades ago as an essential part of such objects.

Images & Videos

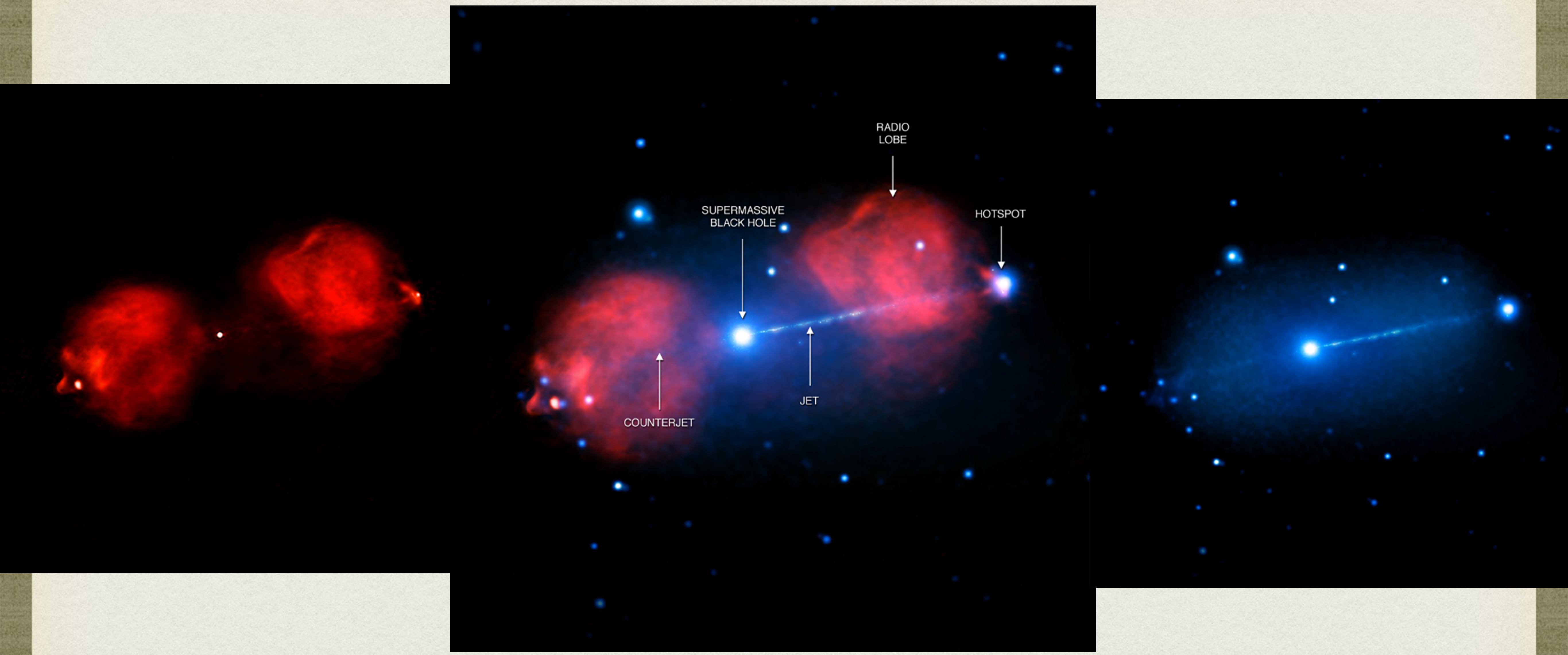


CHANDRA'S FIRST LOOK: X-RAY JETS

- In August 1999 Chandra ACIS (Advanced CCD Imaging Spectrometer) 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)
- But electron lifetimes ~10s of yrs for "equipartition" magnetic fields!



X-RAYS FROM AGN JETS



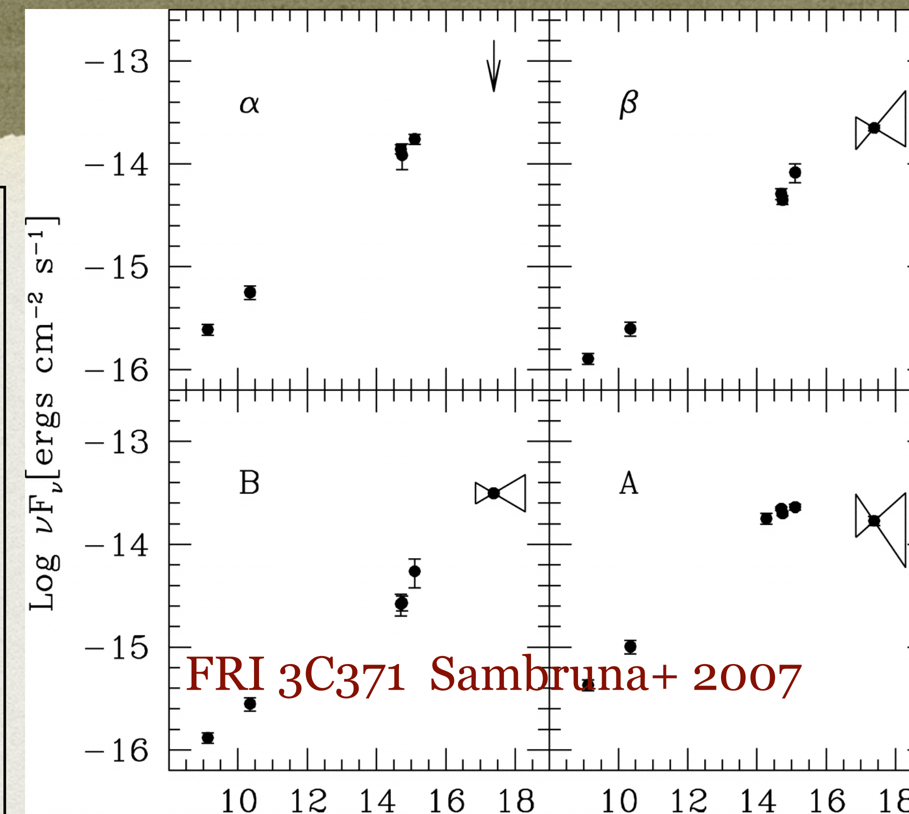
Pictor A

X-RAY EMISSION MECHANISMS

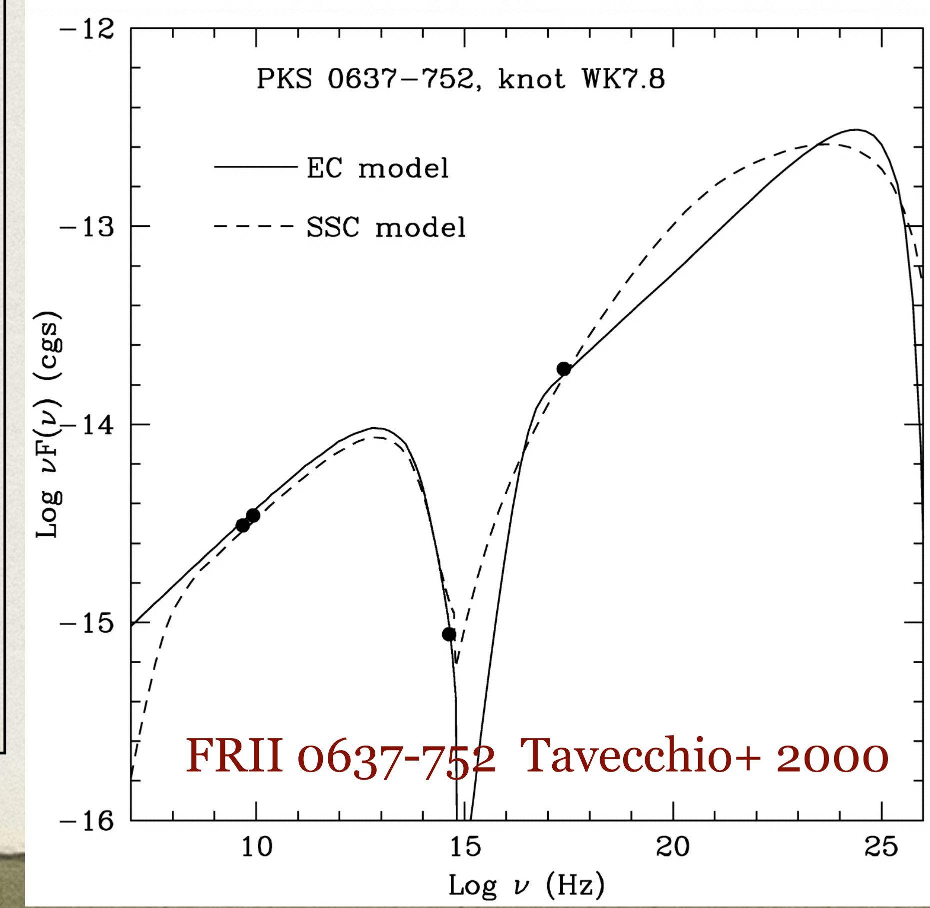
- **Synchrotron**: $\gamma > 10^7$ needed + *in situ* acceleration as electron lifetimes are of the order of 10 yrs for Equipartition B-field B_{eq} — works in FRI Jets

- **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

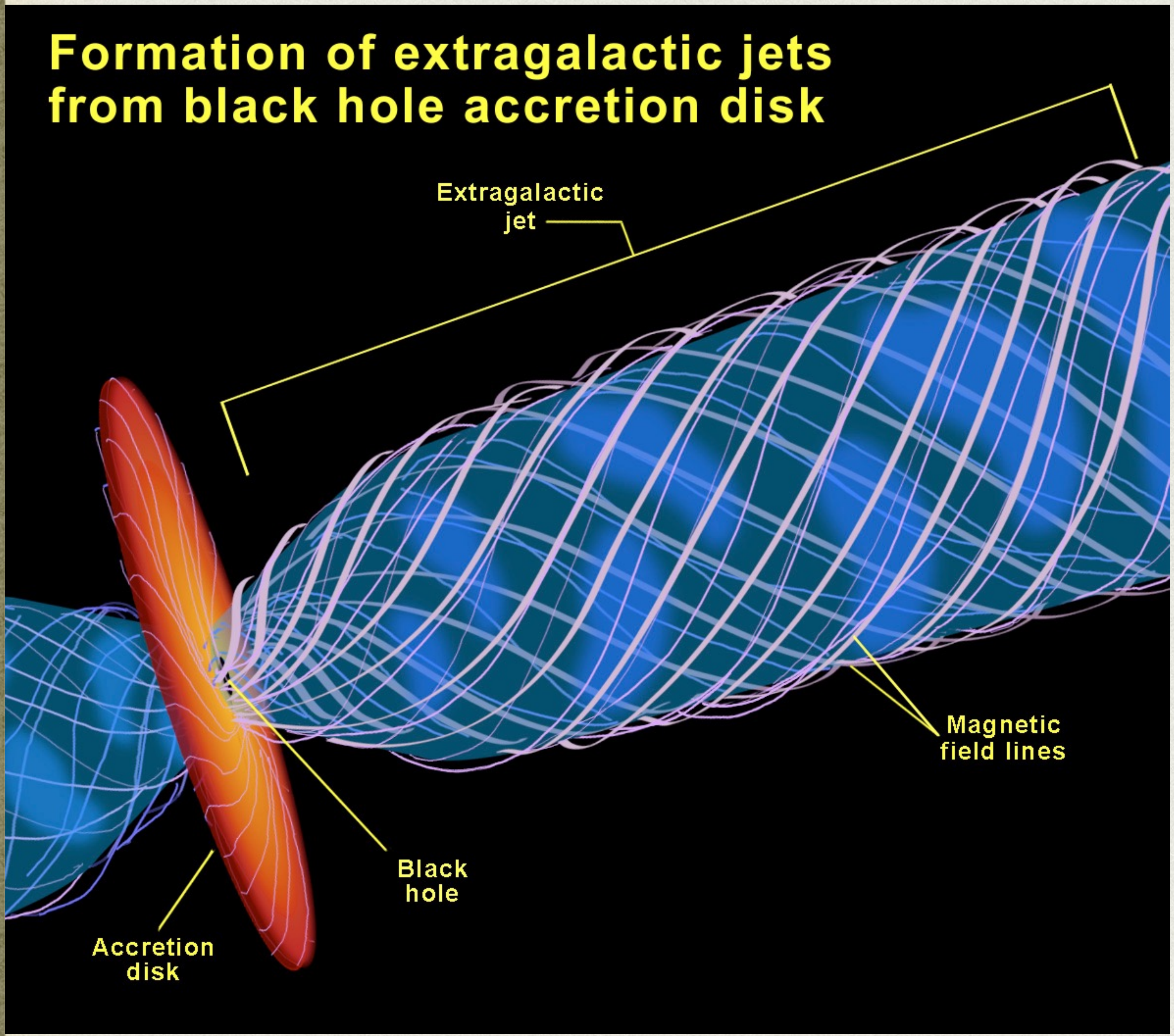


FRI 3C371 Sambruna+ 2007



FRII 0637-752 Tavecchio+ 2000

JET FORMATION IN AGN



Blandford & Znajek (1977)

Energy & angular momentum extraction from a spinning black hole.

Strong poloidal magnetic field needed

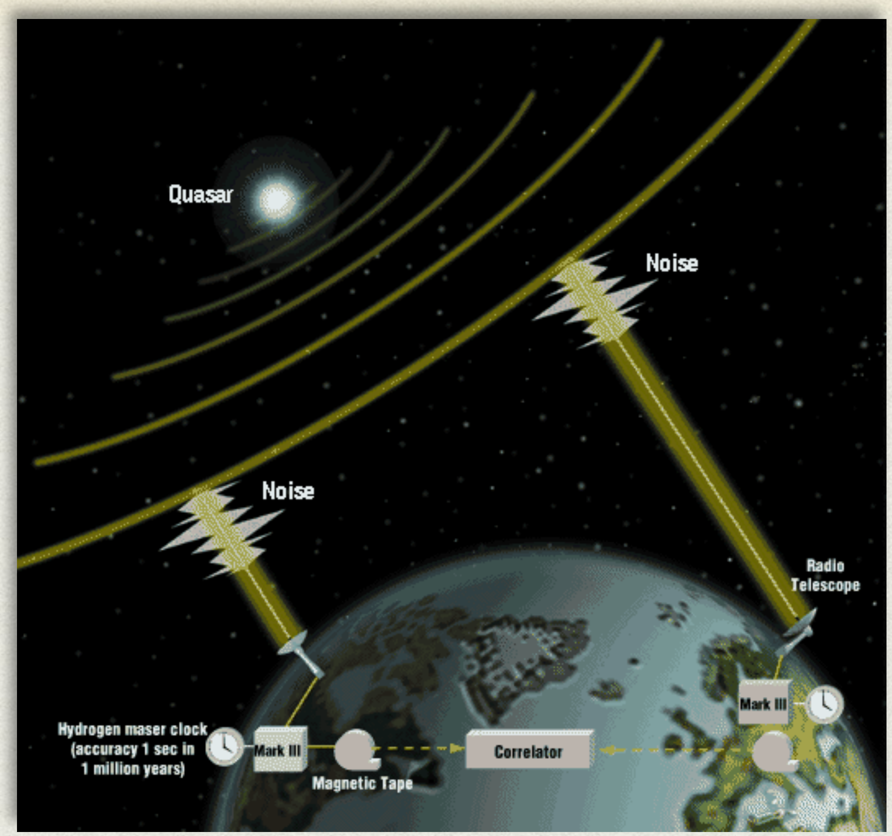
Power extracted is proportional to B^2 & ω^2

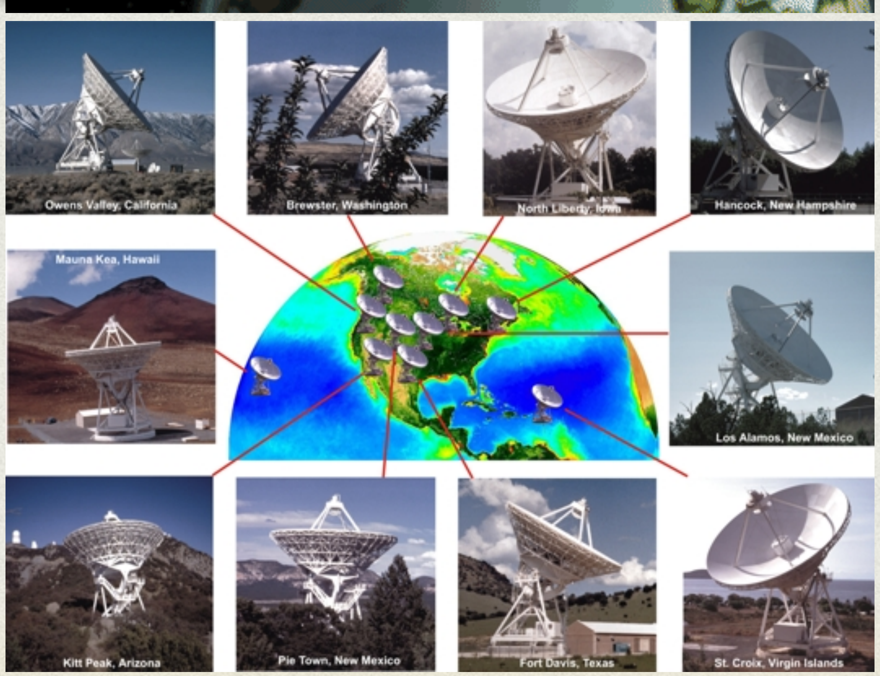
B = magnetic field strength

ω = angular velocity

Polarization-sensitive VLBI!

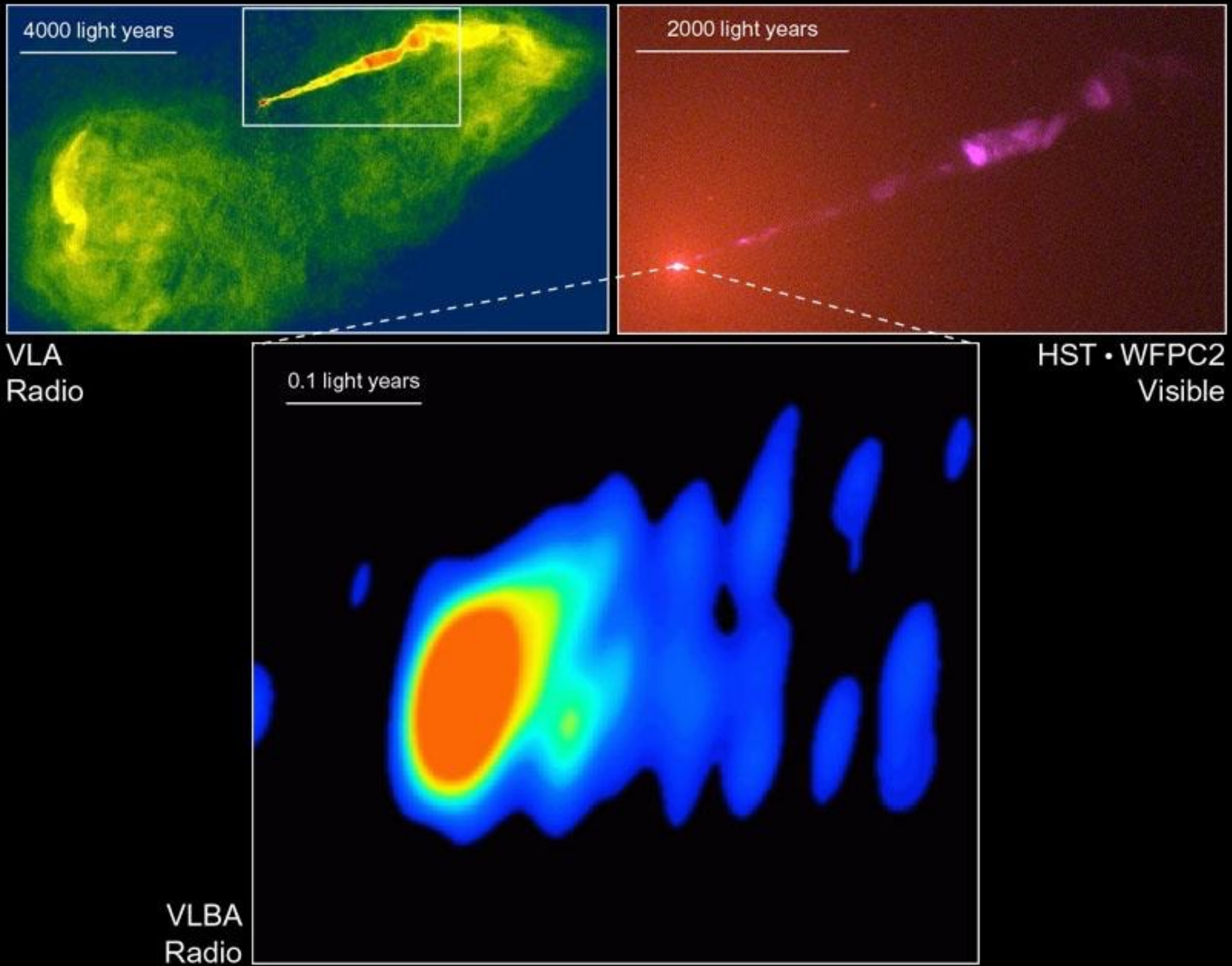
VERY LONG BASELINE INTERFEROMETRY (VLBI)





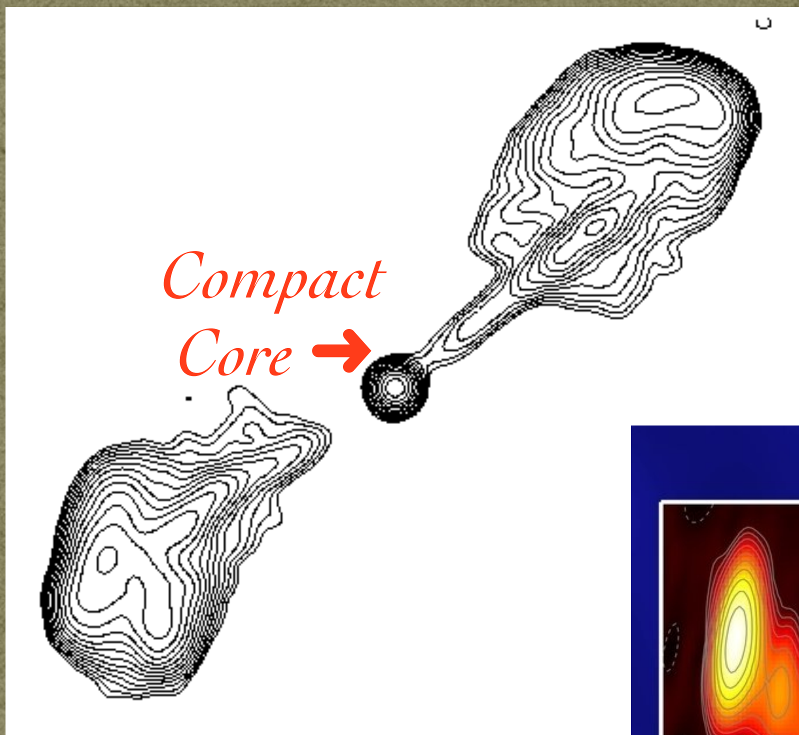
- Widely separated antennas not connected by cables (Unlike VLA, GMRT)
- Data recorded on magnetic tapes
- Recorded data is time-stamped by atomic clocks (e.g., hydrogen maser)
- Later, the tapes are played back with accurate time-stamps and correlated in a central location

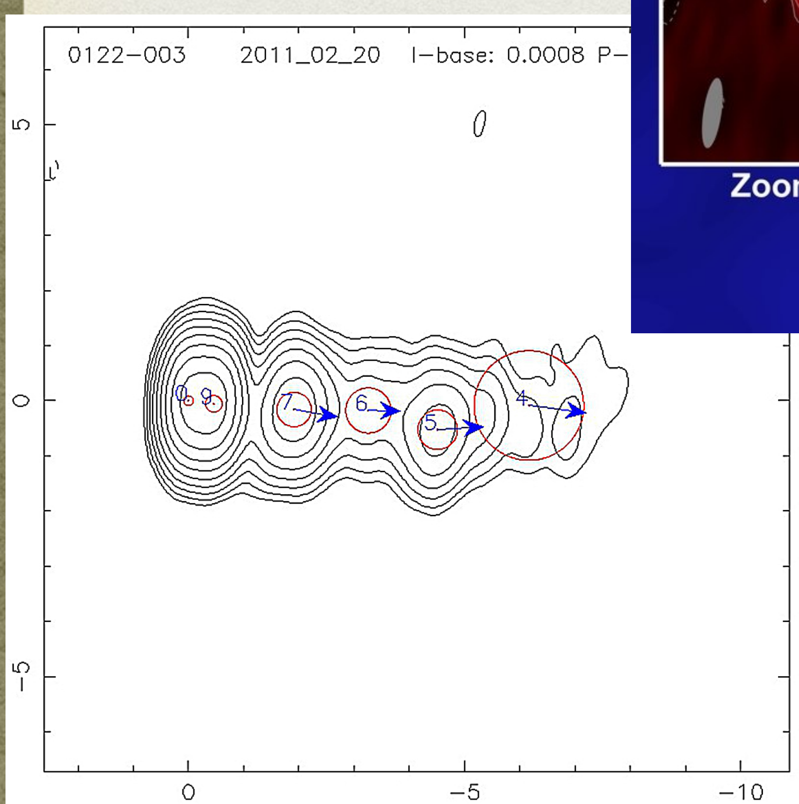
Galaxy M87

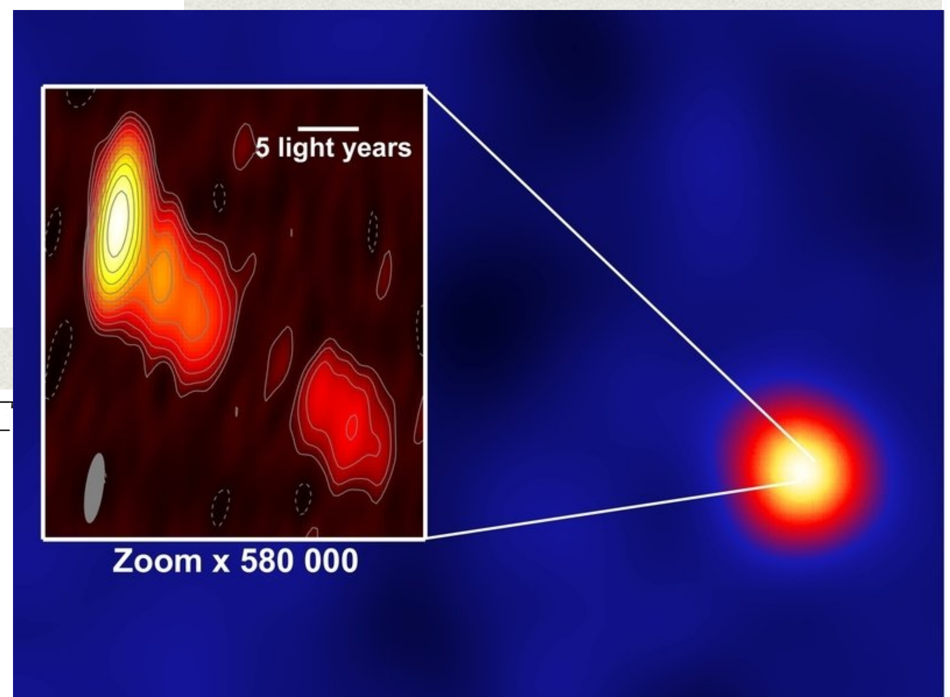


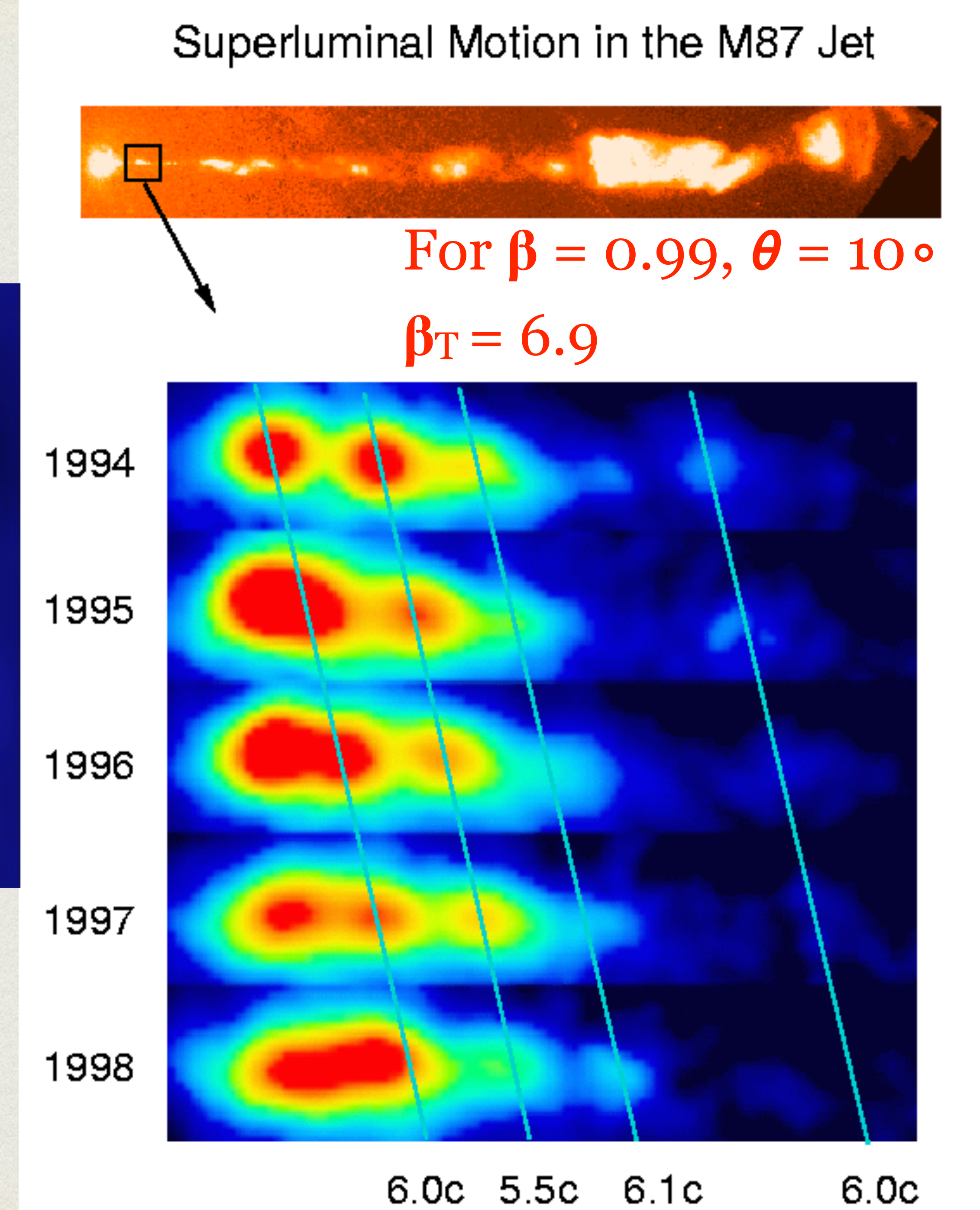
NASA, NRAO and J. Biretta (STScI) • STScI-PRC99-43

“ONE-SIDED” JETS, SUPERLUMINAL MOTION









For $\beta = 0.99$, $\theta = 10°$

$\beta_T = 6.9$

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,

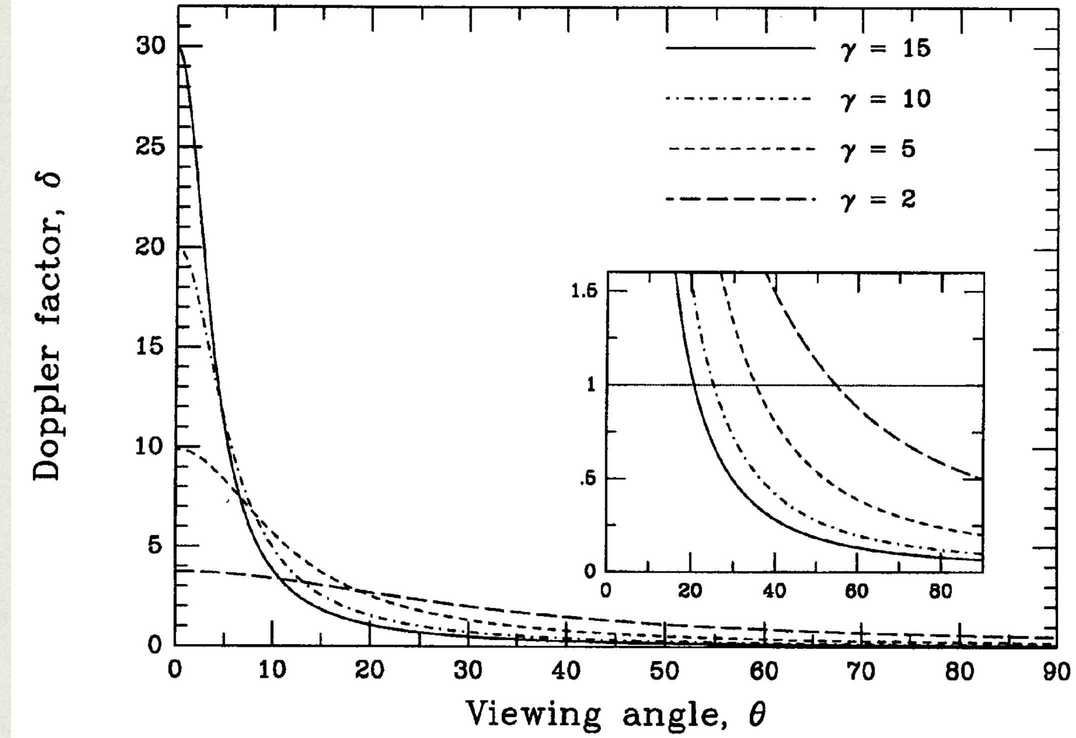
Beta, $\beta = v/c$

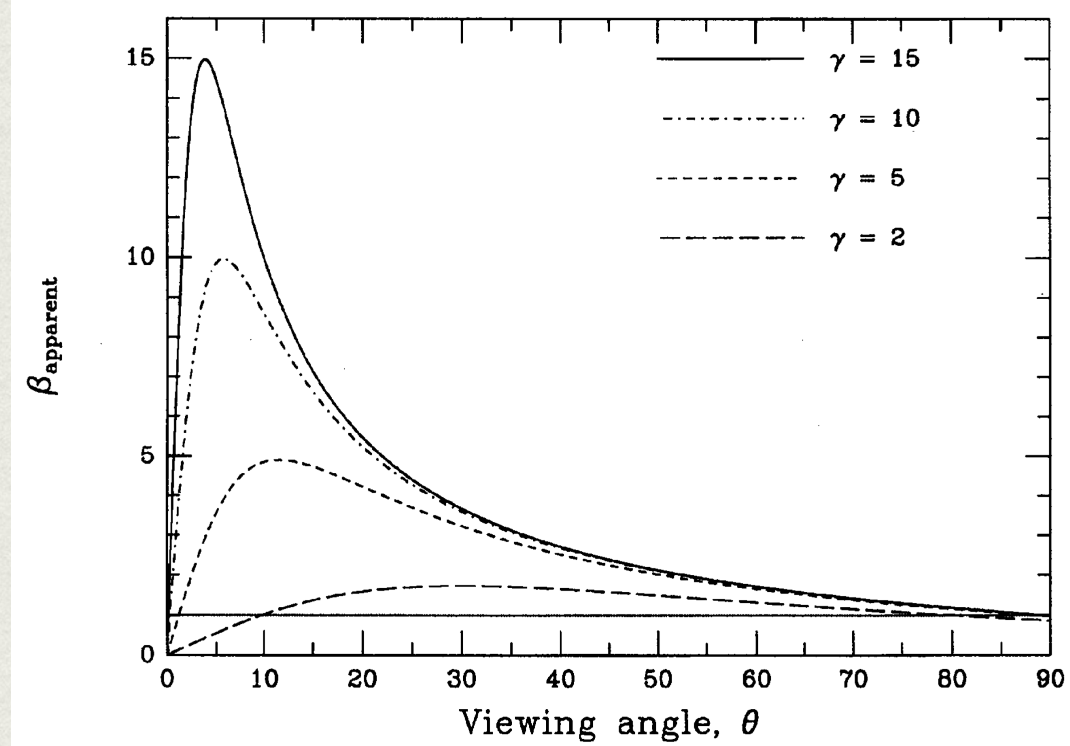
Doppler factor, $\delta = \frac{1}{\gamma(1-\beta cos\theta)}$

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, $S_\nu \propto \nu^\alpha$

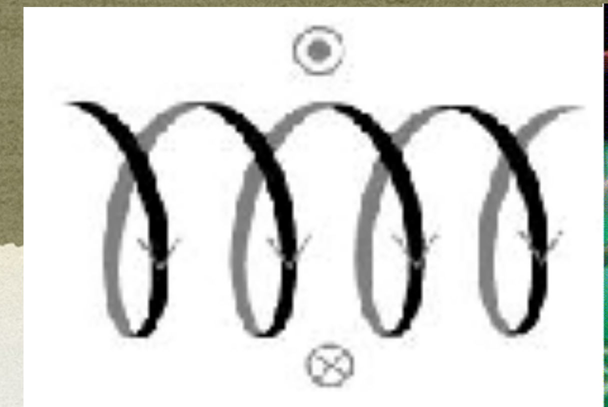


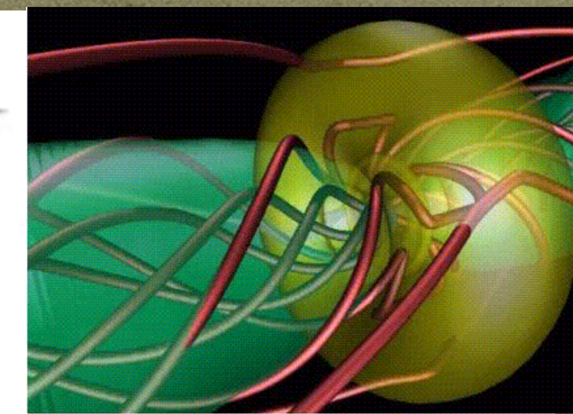


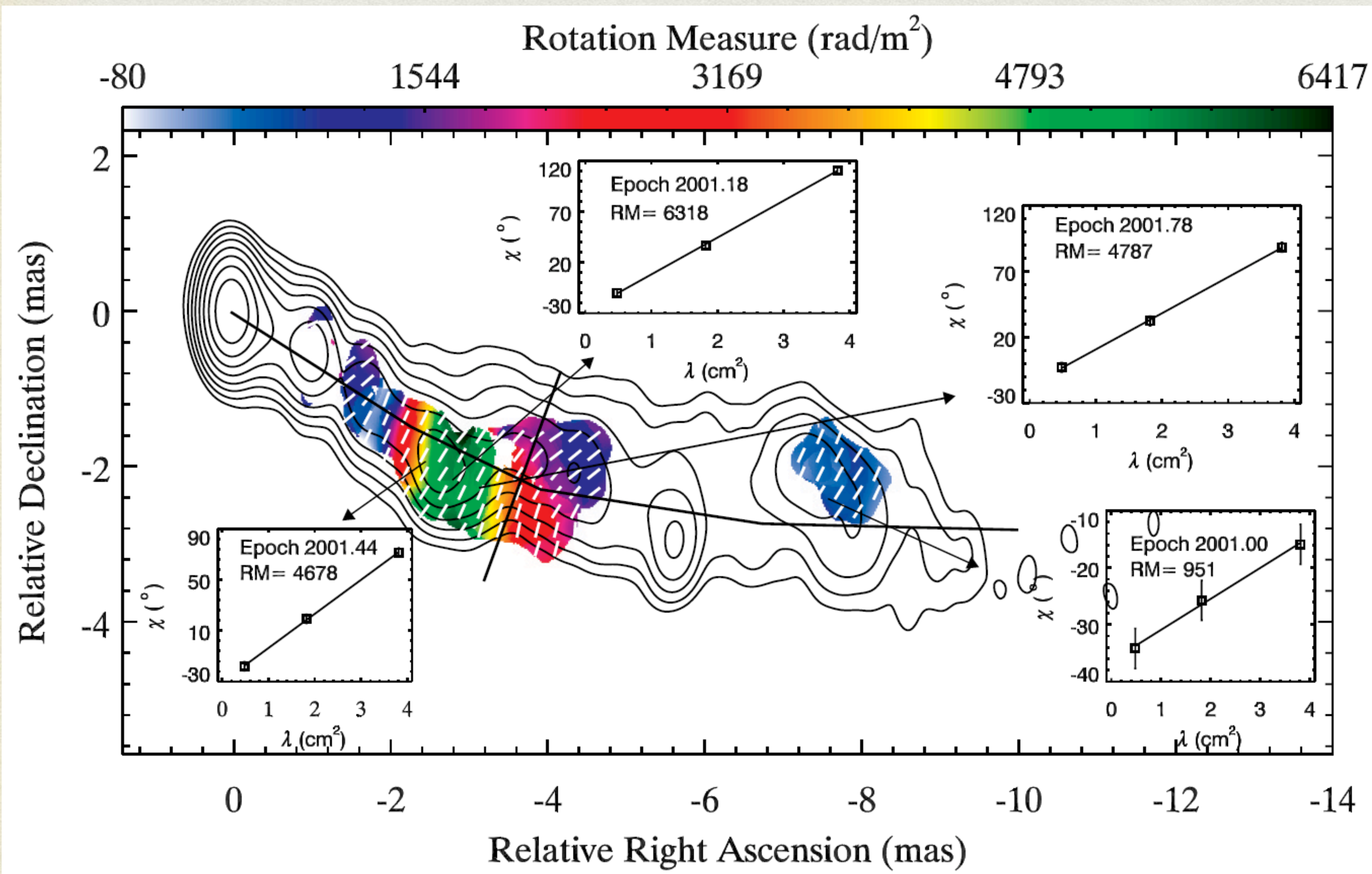
Rybicki - Lightman Book

https://ned.ipac.caltech.edu/level5/Urry1/UrryP_contents.html

ROTATION MEASURE GRADIENTS







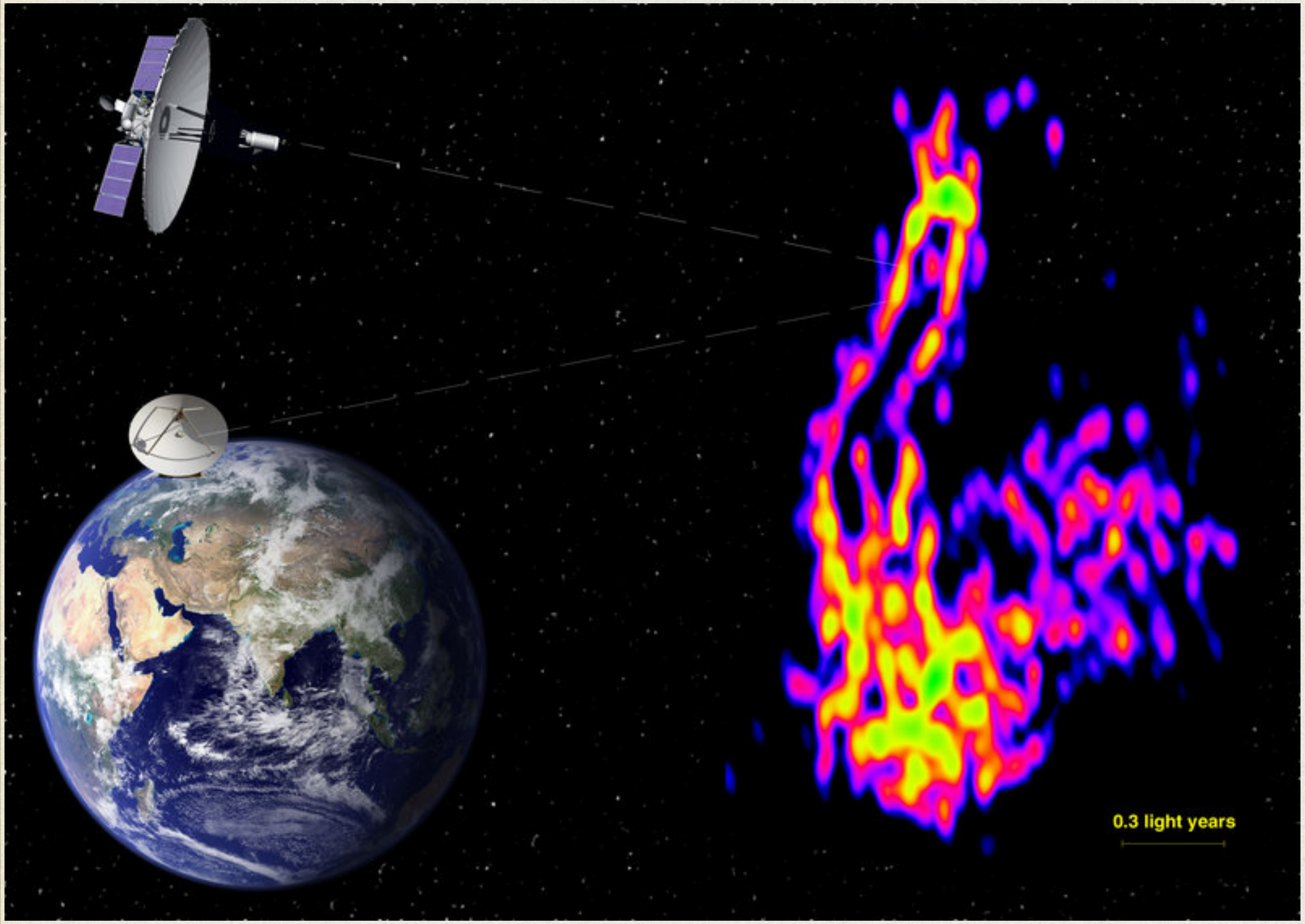
$$\chi(\lambda^2) = \chi_0 + \lambda^2 \,\mathrm{RM},$$

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

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

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

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 = 3C84 at ~50 **μ**as

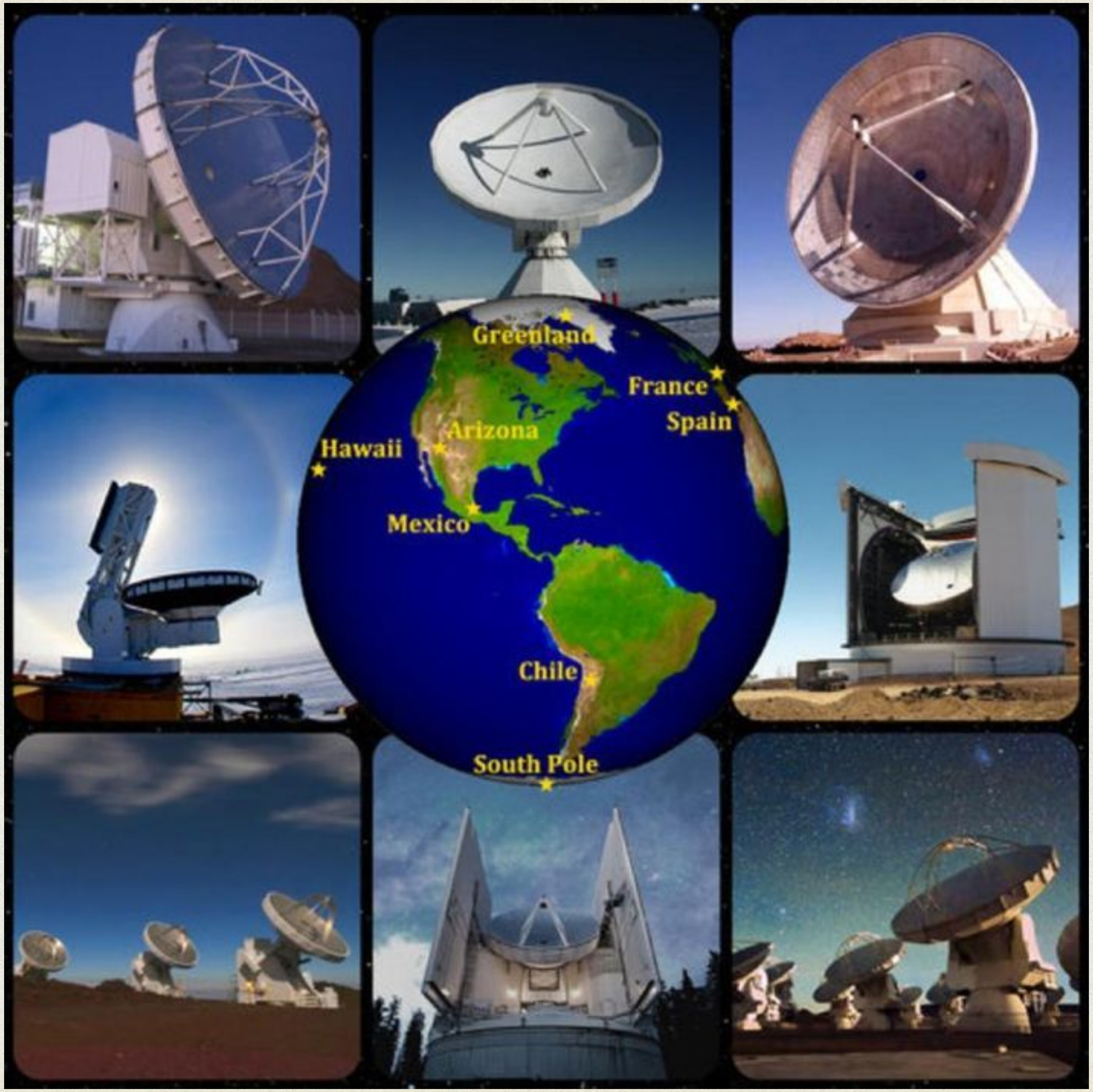
~10^2 - 10^4 r_g from black hole

≥250 r_g wide - from accretion disk

Giovannini+ 2018, Nature Astronomy

EVENT HORIZON TELESCOPE (EHT)

- mm-wave VLBI
- Milky Way SMBH gravitational radius ~ 10 µas
- Resolution <60 µas at 230 - 450 GHz
- Also look at M87
- Data from 8 telescopes acquired in April 2017 -
- Press Release April 2019



THE BLACKHOLE IN M87