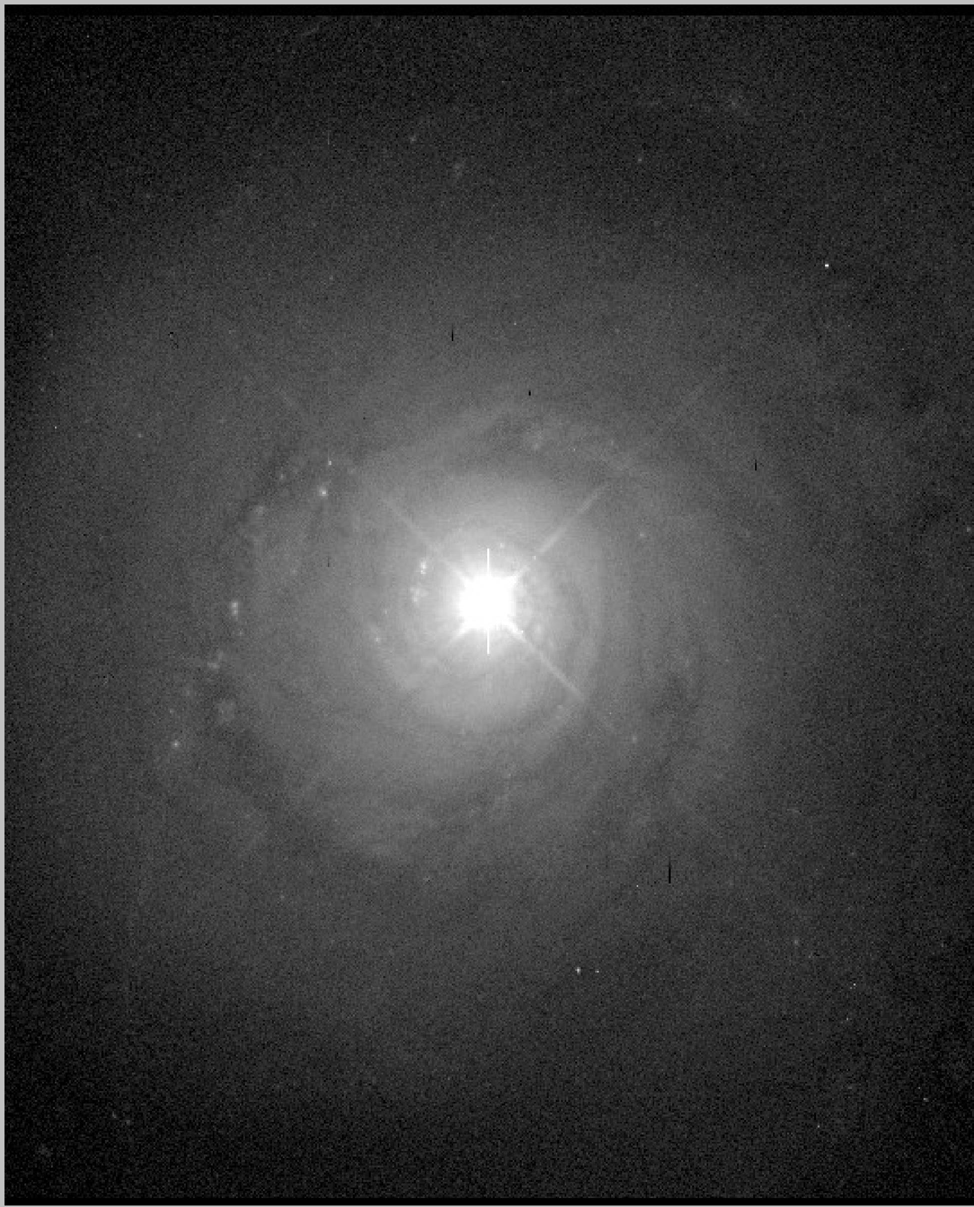
Active Galactic Nuclei

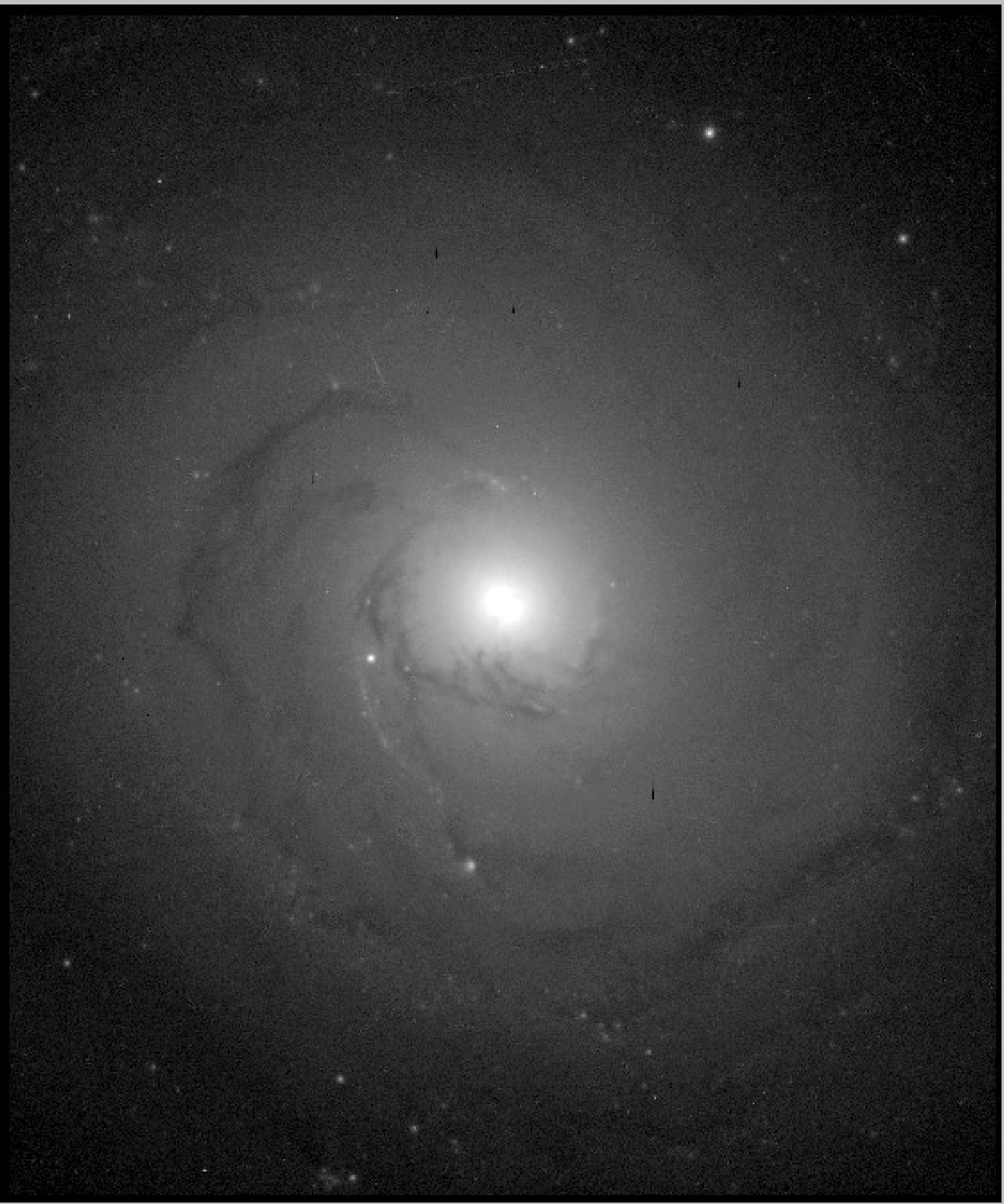
- First noted by Fath at Lick Observatory in 1908 who was taking spectra of the nuclei of “spiral nebulae” and noted that NGC 1068 had strong emission lines
- Slipher obtained a higher quality spectrum at Lowell in 1917, noted the lines were similar to planetary nebulae
- In 1926, Hubble noted 3 galaxies with strong emission lines: NGC 1068, NGC 4051, NGC 4151
- In 1943 (~30 years later!), Carl Seyfert recognized that there was a class of galaxies (now known as Seyfert galaxies), with strong, broad high-ionization emission lines and bright nuclei
- Seyfert nuclei are found in spiral galaxies

Active Galactic Nuclei cont.

- Seyferts emit only moderately in the radio.
  - $L_{radio} \sim 10^{40}$ erg/s
- Seyferts have strong x-ray emission
  - $L_{X\text{-ray}} > 10^{42}$ erg/s
- Two types of Seyfert galaxies
  - Seyfert 1
    - permitted recombination lines are broader than forbidden lines
  - Seyfert 2
    - permitted ***and*** forbidden lines are broad
- ~10% of Sa and Sb's are Seyferts
  - does a galaxy spend ~10% of its life as a Seyfert
  - or are ~10% of spirals Seyferts?

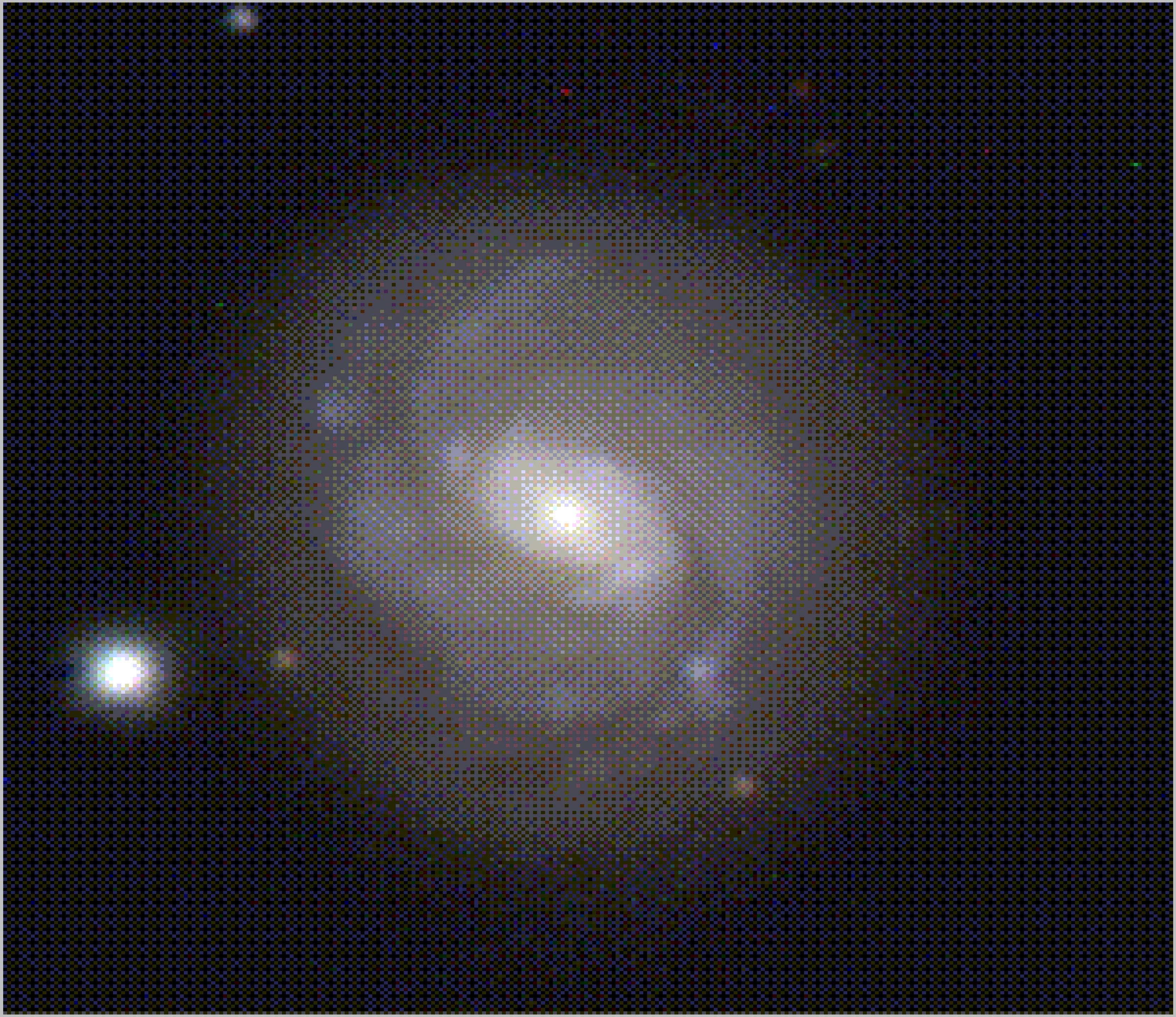


NGC 5548 Seyfert 1

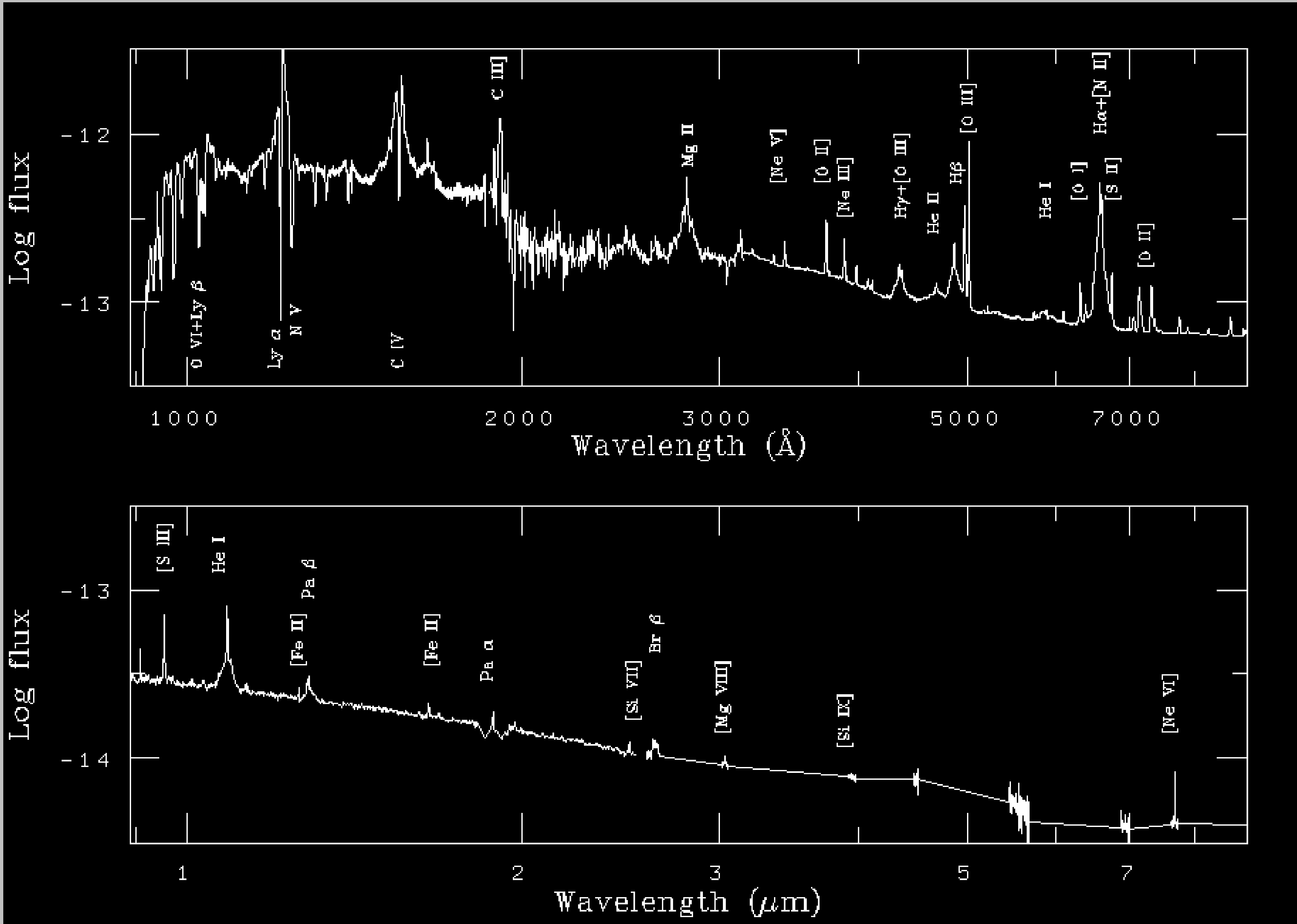


NGC 3027 normal galaxy

Images from University of Alabama (Keel)



NGC 1068 Seyfert 2



The spectrum of NGC 4151 a Seyfert 1

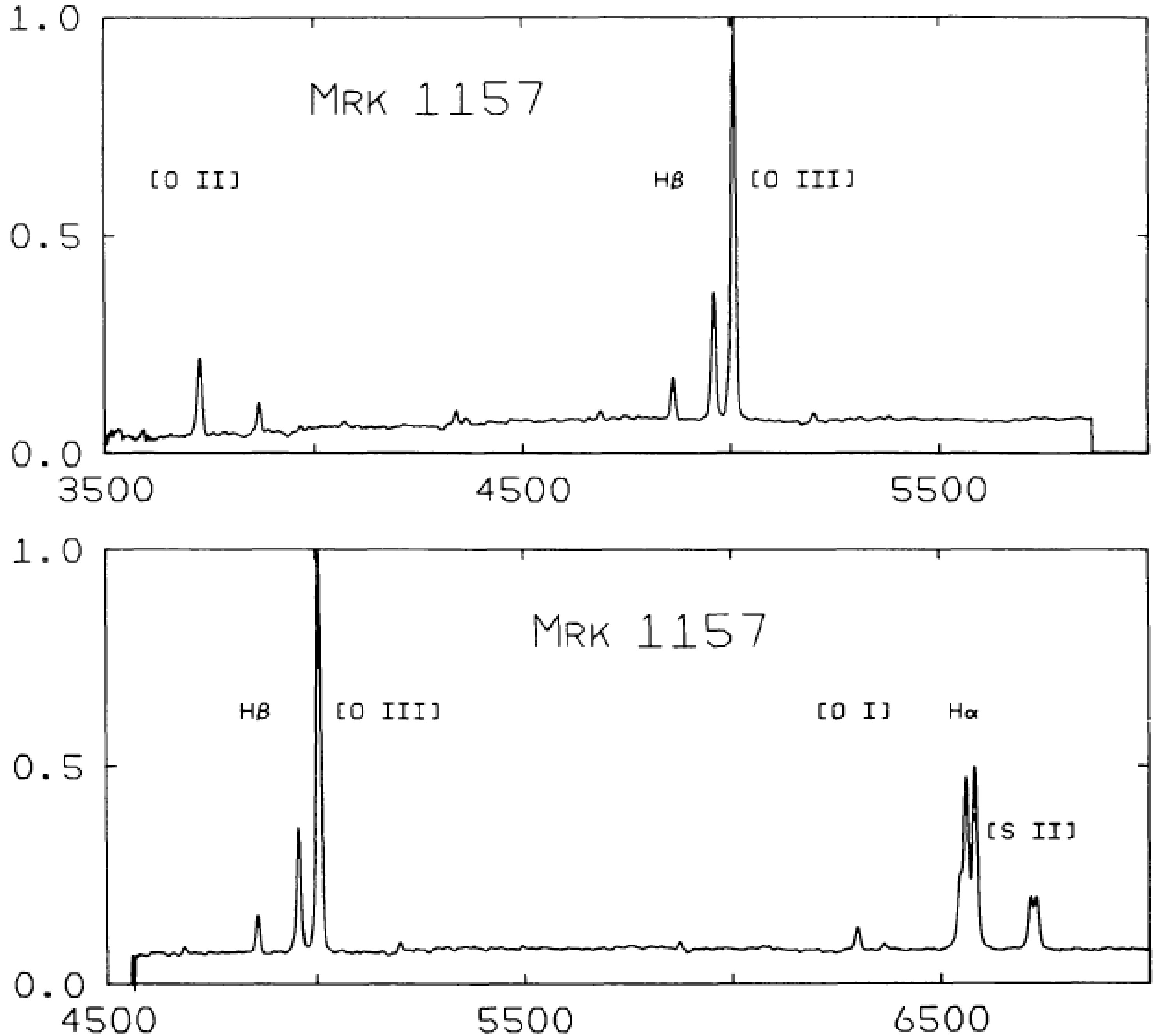


FIG. 2. Spectrum of Seyfert 2 galaxy Mrk 1157, scales and units as in Fig. 1.

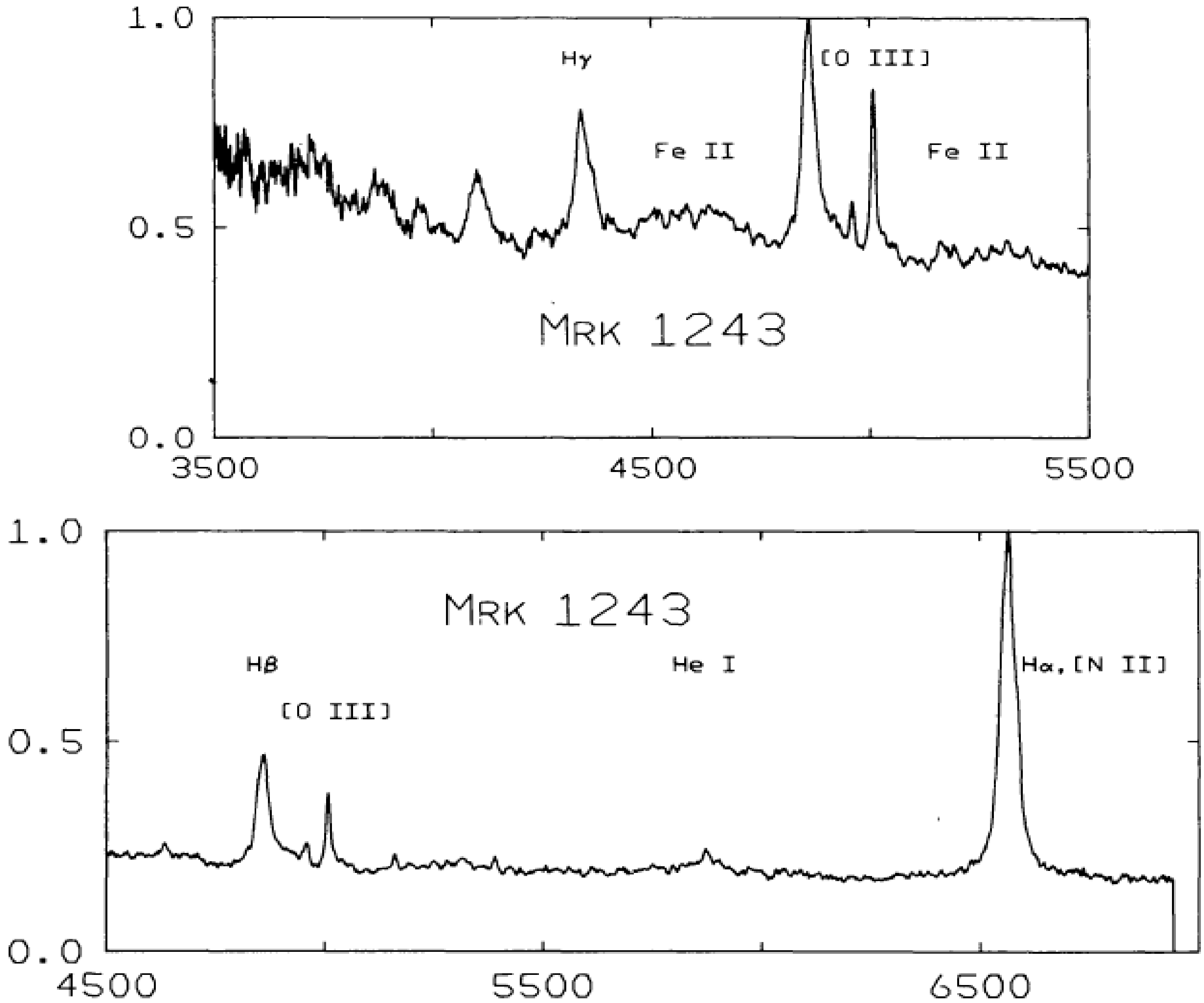
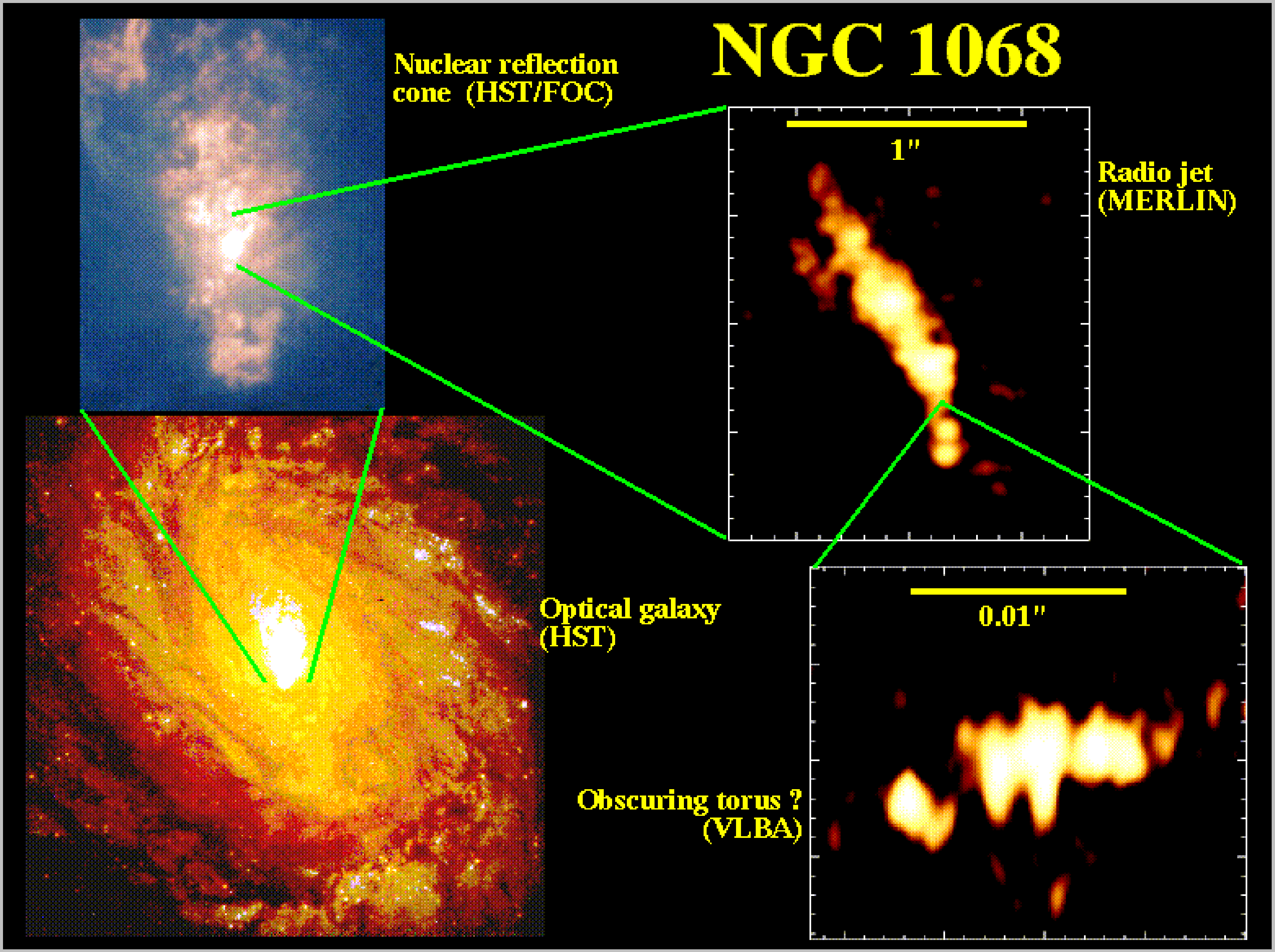
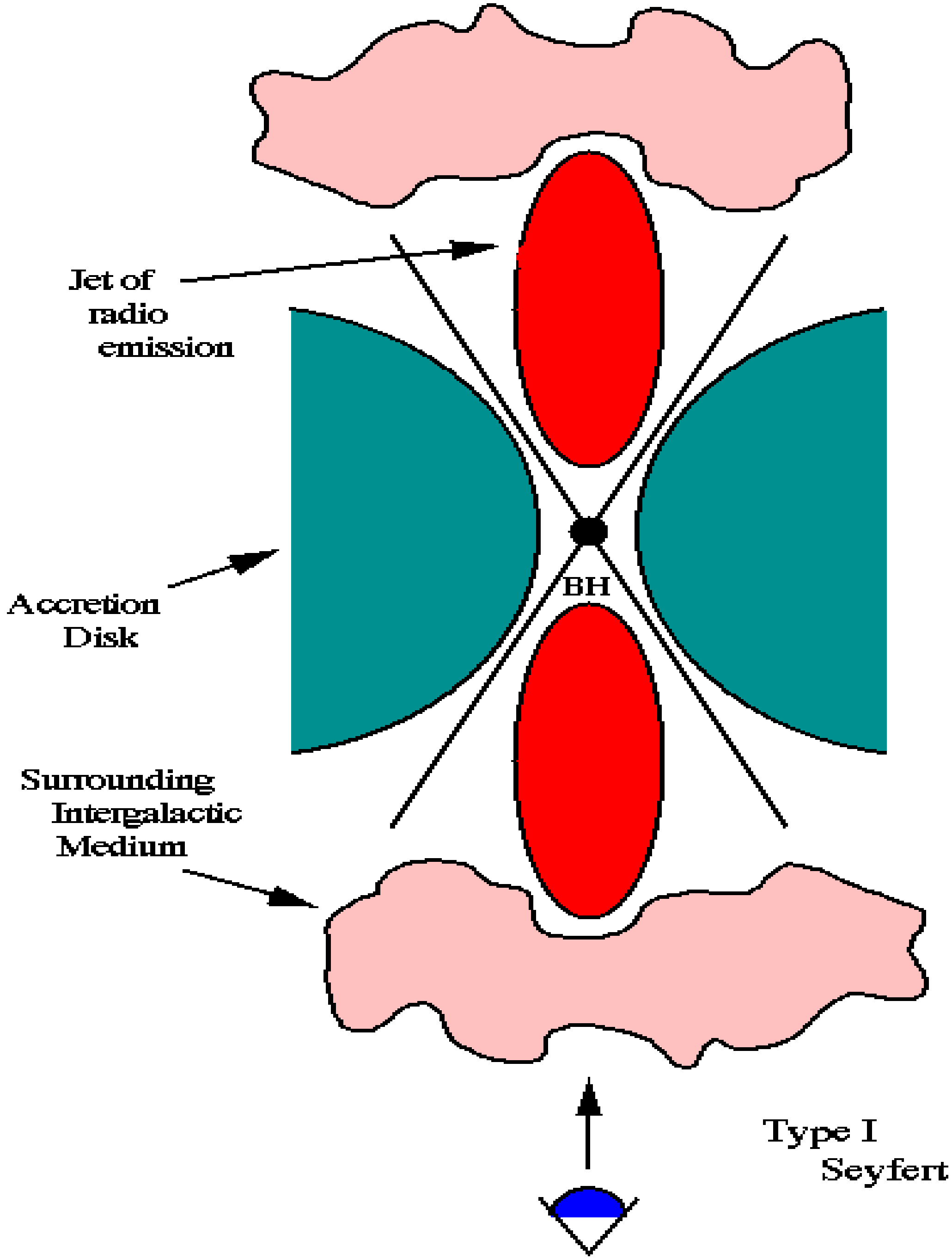


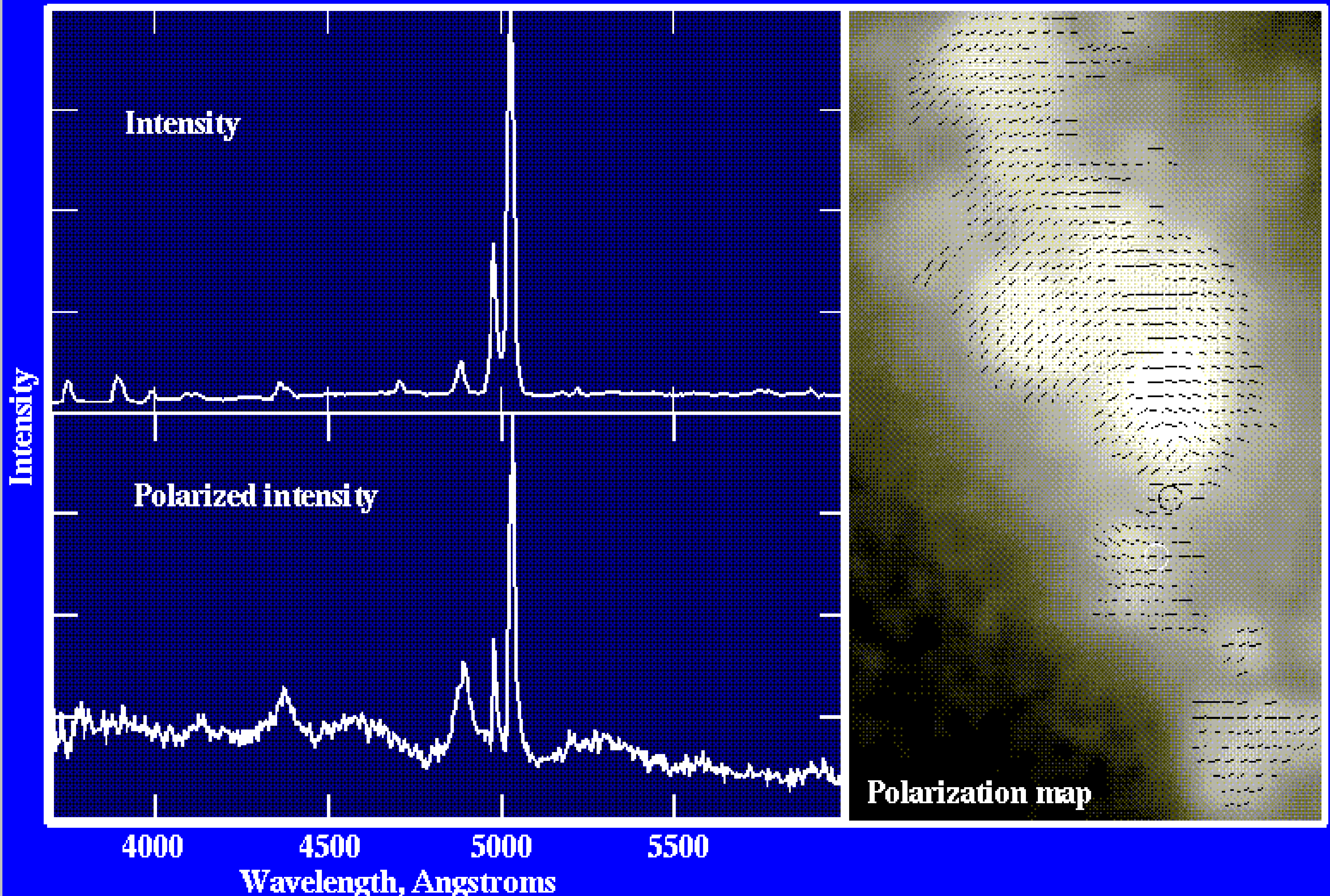
FIG. 1. Spectrum of Seyfert 1 galaxy Mrk 1243, *above*, λλ3500–5500; *below*, λλ4500–7000 in the rest system of the object. *Vertical scale*, relative energy flux in flux units per unit wavelength interval, *horizontal scale*, wavelength in Angstrom units.

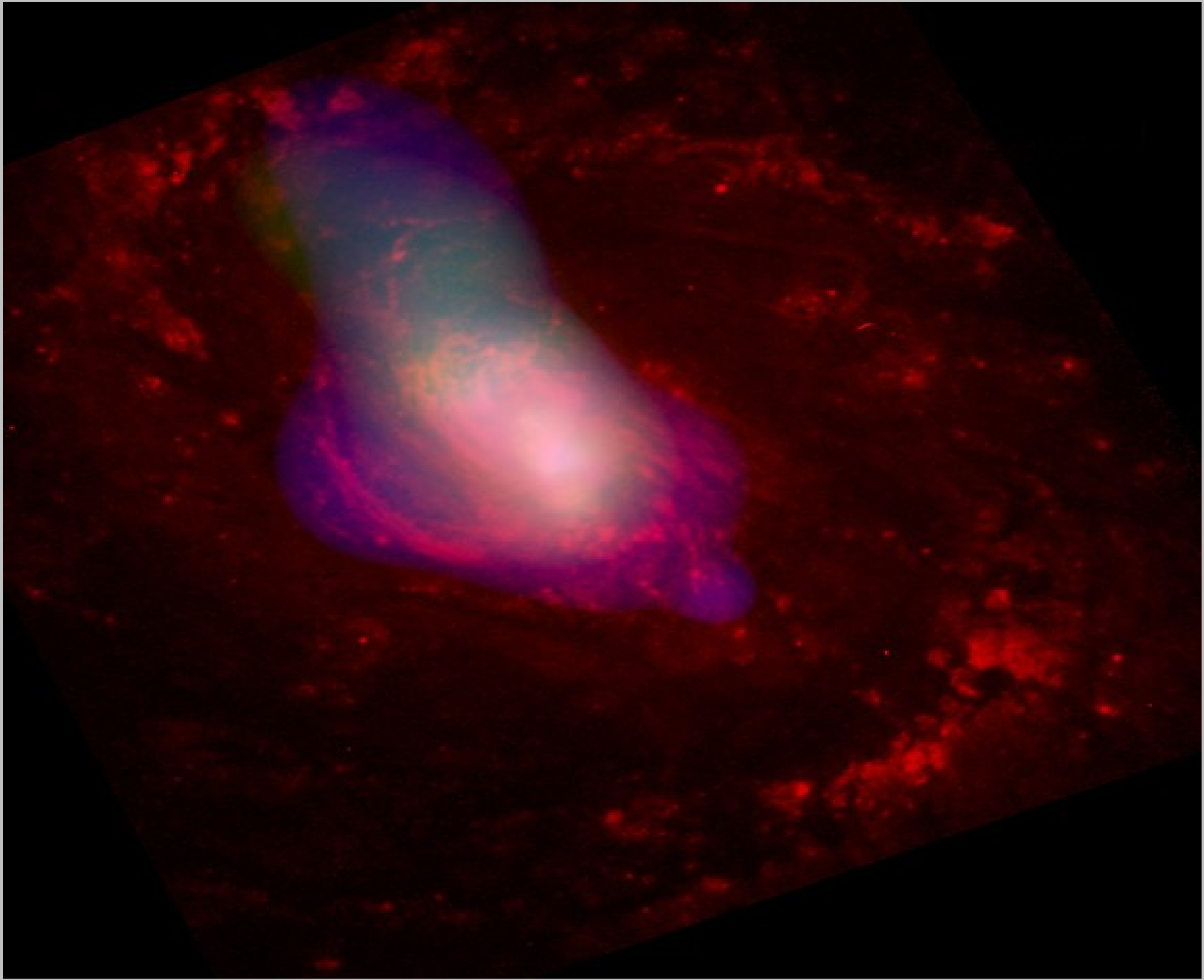

NGC 1068
Nuclear reflection cone (HST/FOC)
1"
Radio jet (MERLIN)
Optical galaxy (HST)
0.01"
Obscuring torus ? (VLBA)



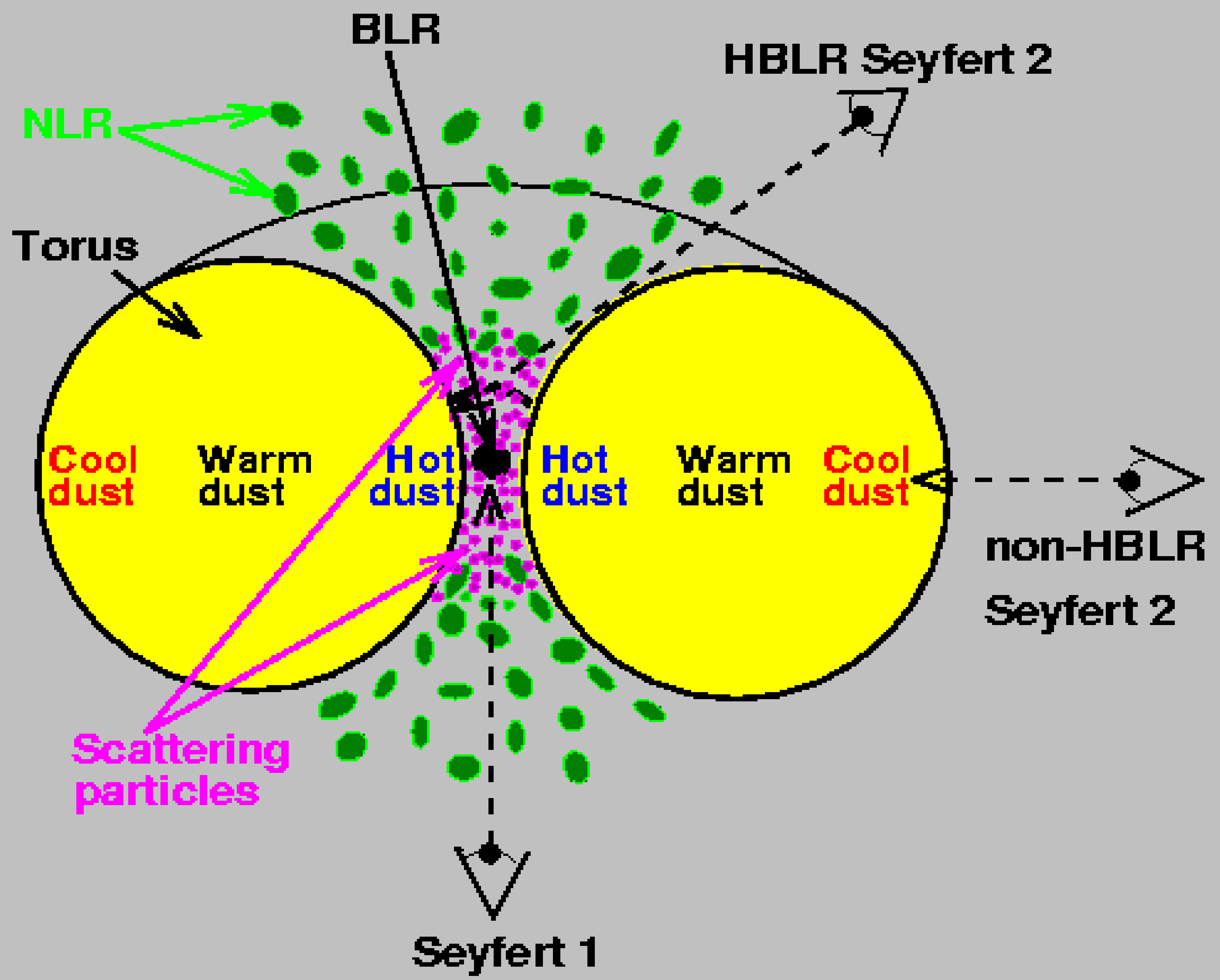
Note: this is an edge–on view of a "slice" of the system. In 3 dimensions, the accretion disk would look like a donut which came out of the page (towards you) and extended into the page (on the other side).

Polarization and the Hidden Nucleus of NGC 1068





An X-ray + optical image of NGC 1068 a Seyfert 2



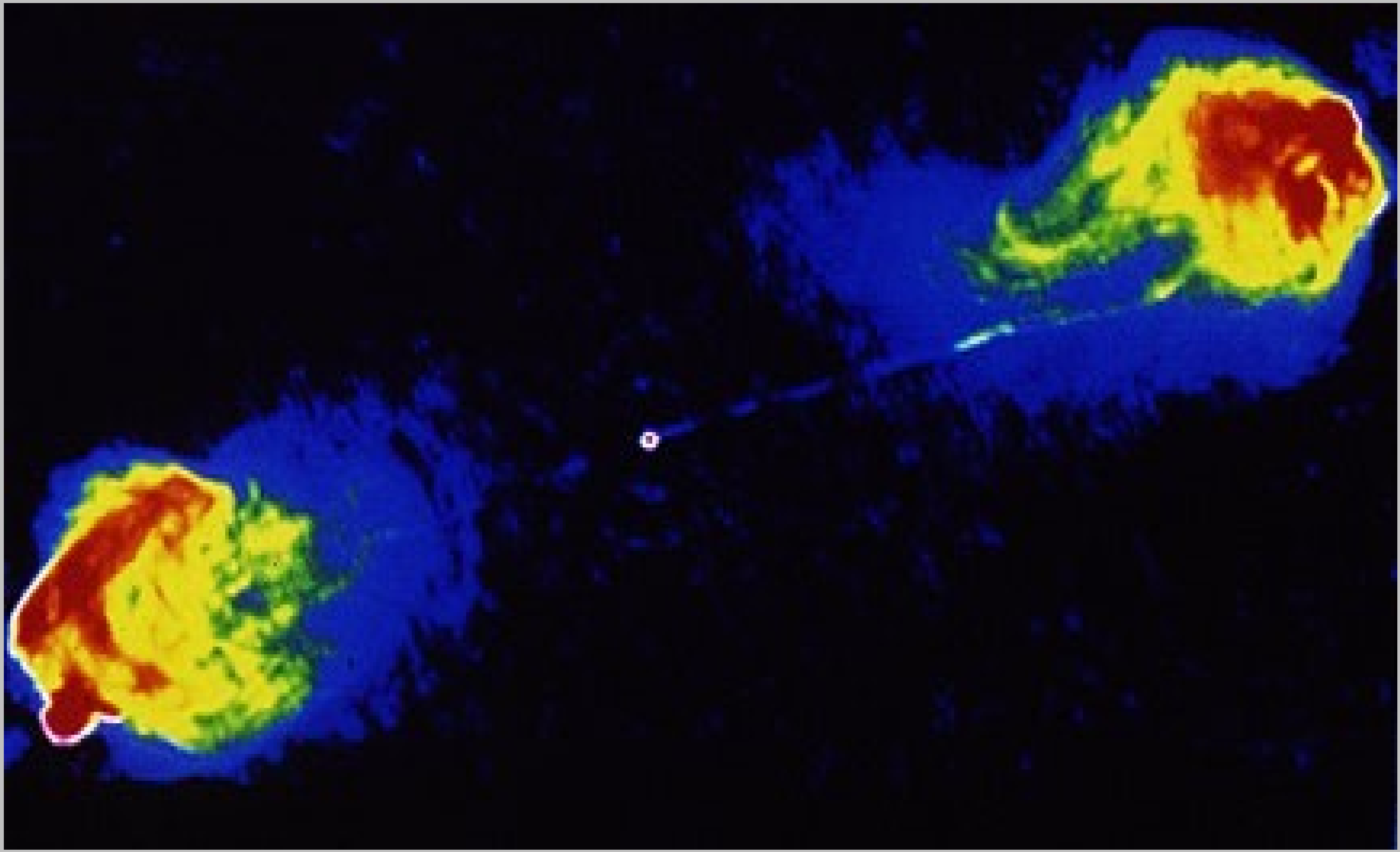
Heisler, PASA (1998)

Active Galactic Nuclei
Radio Galaxies

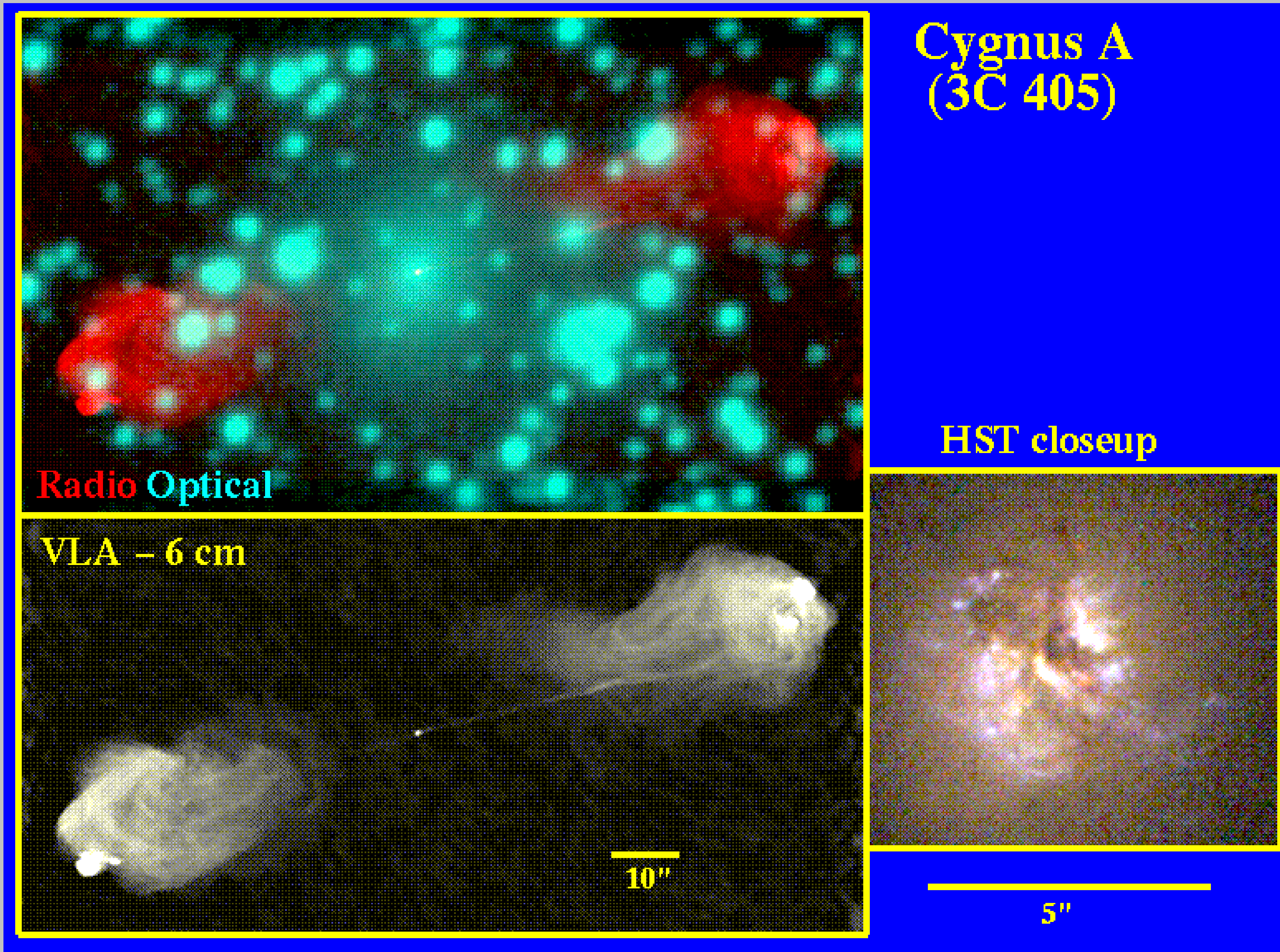
- In the 1950s advances in radio astronomy led to the discovery of radio galaxies
  - Cygnus A with a redshift of z=0.057
- Many such galaxies have been found using radio surveys e.g. the third Cambridge (3C, 1959), fourth Cambridge (4C, 1965), and PKS (Parkes, 1969) surveys
- The emission-line spectra of radio galaxies are similar to Seyfert galaxies
  - Broad line radio galaxies (BLRG). Like Seyfert 1's
  - Narrow line radio galaxies (NLRG). Like Seyfert 2's
- Radio galaxies are typically found in elliptical galaxies, with extended (100kpc – 10Mpc) jets, unlike Seyferts!

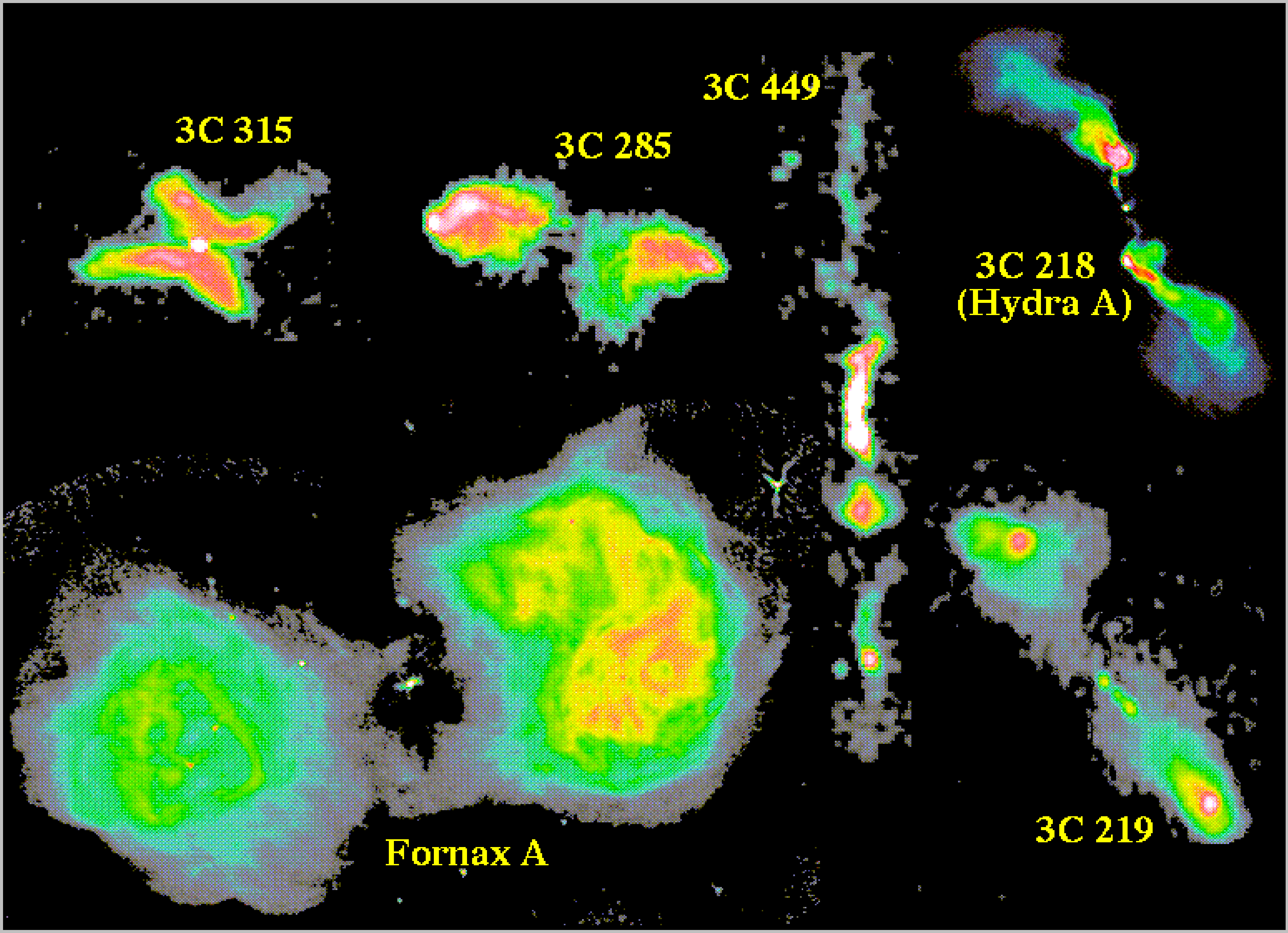
Active Galactic Nuclei
Radio Galaxies cont.

- The radio emission is non-thermal
  - Synchrotron radiation from relativistic particles in a magnetic field
- Radio galaxies are separated into two types based on the morphology of the jet
  - Fanaroff-Riley Type I (FRI) – edge darkened radio jets, slower jet speeds, $L_{radio} < 10^{42}$ erg/s
  - Fanaroff-Riley Type II (FRII) – edge brightened radio jets, fast jet speeds ~0.1c, $L_{radio} > 10^{42}$ erg/s

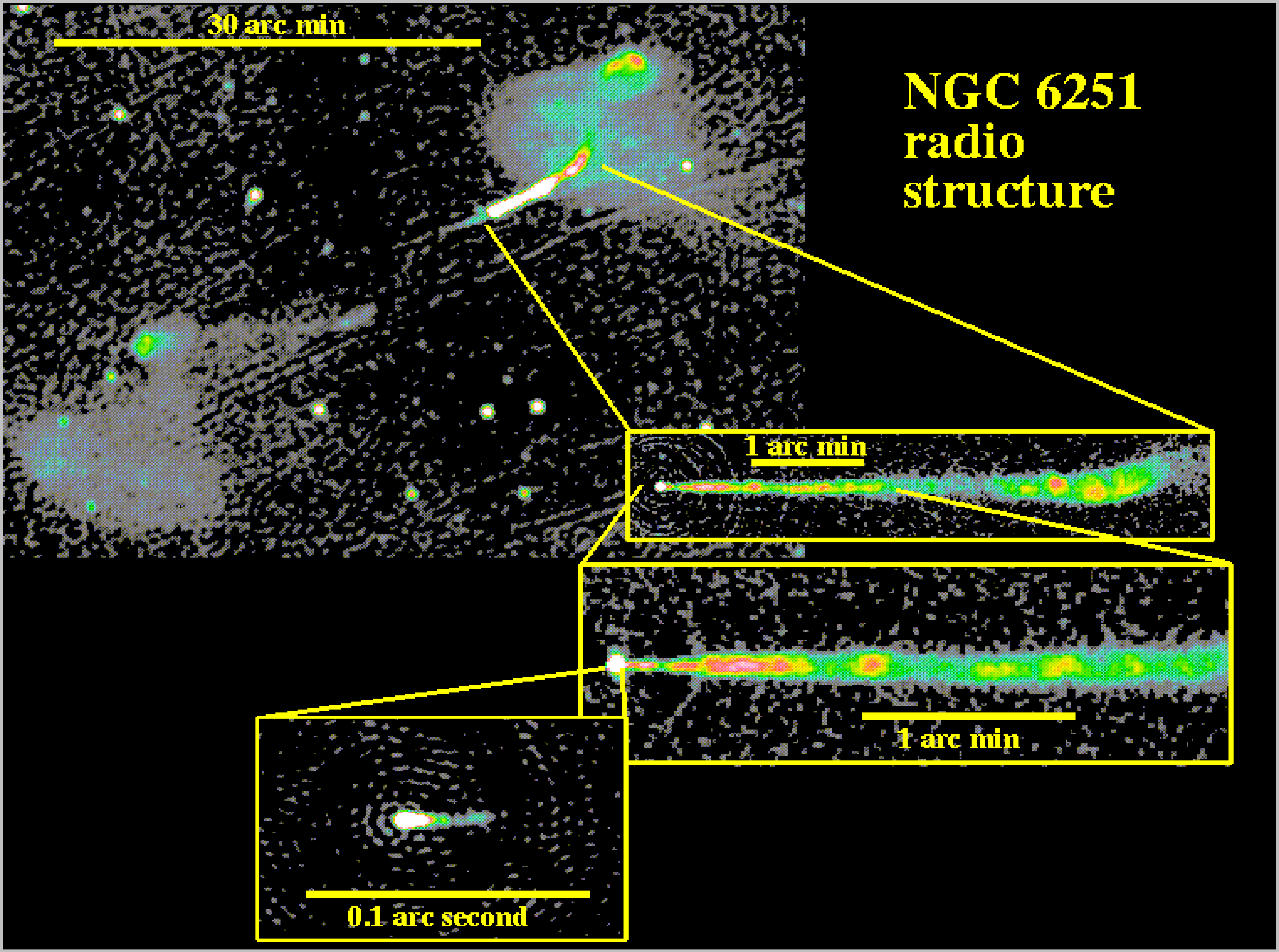


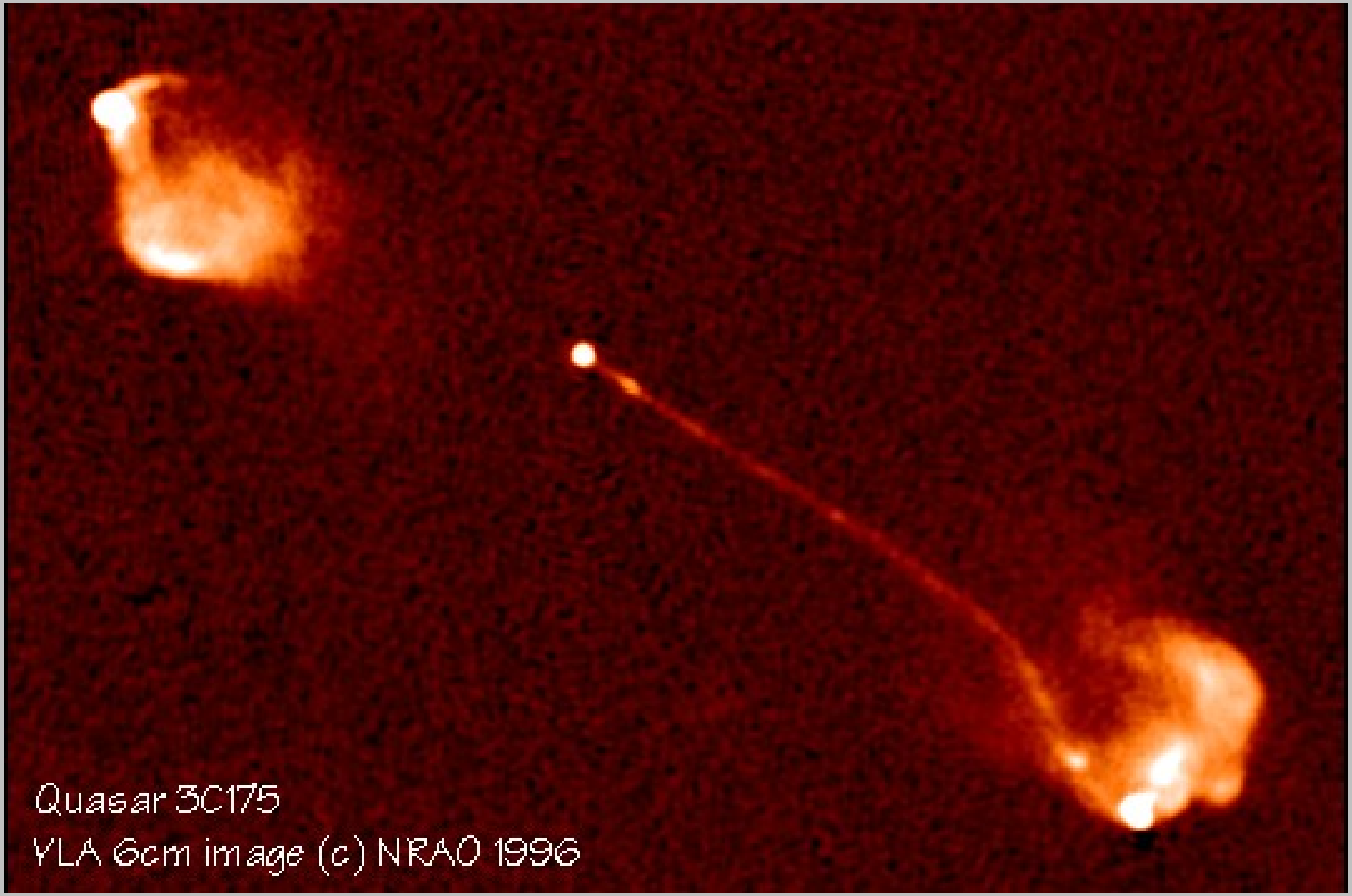
Radio image of Cygnus A, Perley & Dreher
Courtesy NRAO/ AUI


Cygnus A
(3C 405)
Radio Optical
VLA – 6 cm
10″
HST closeup
5″

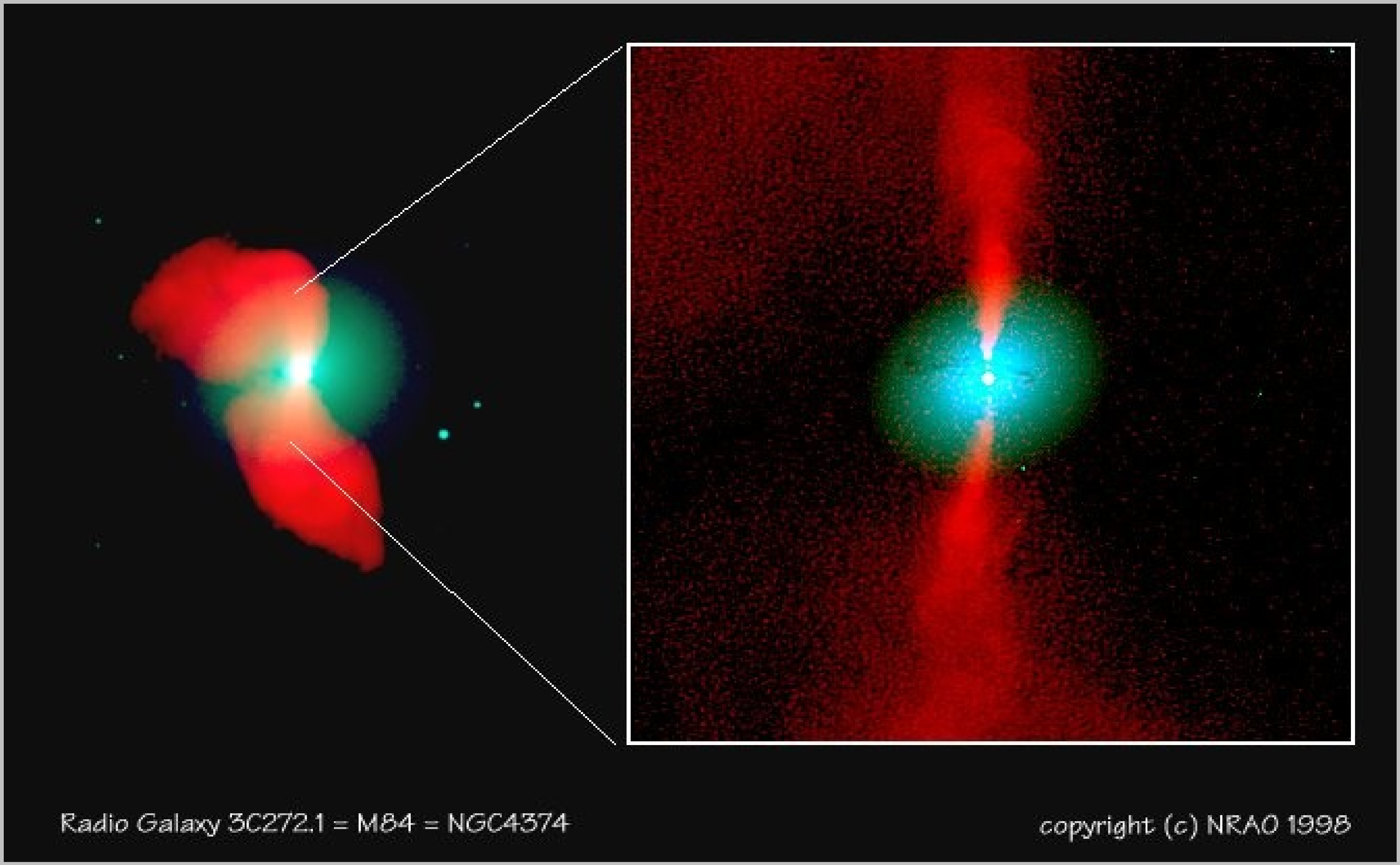


Radio Galaxies gallery

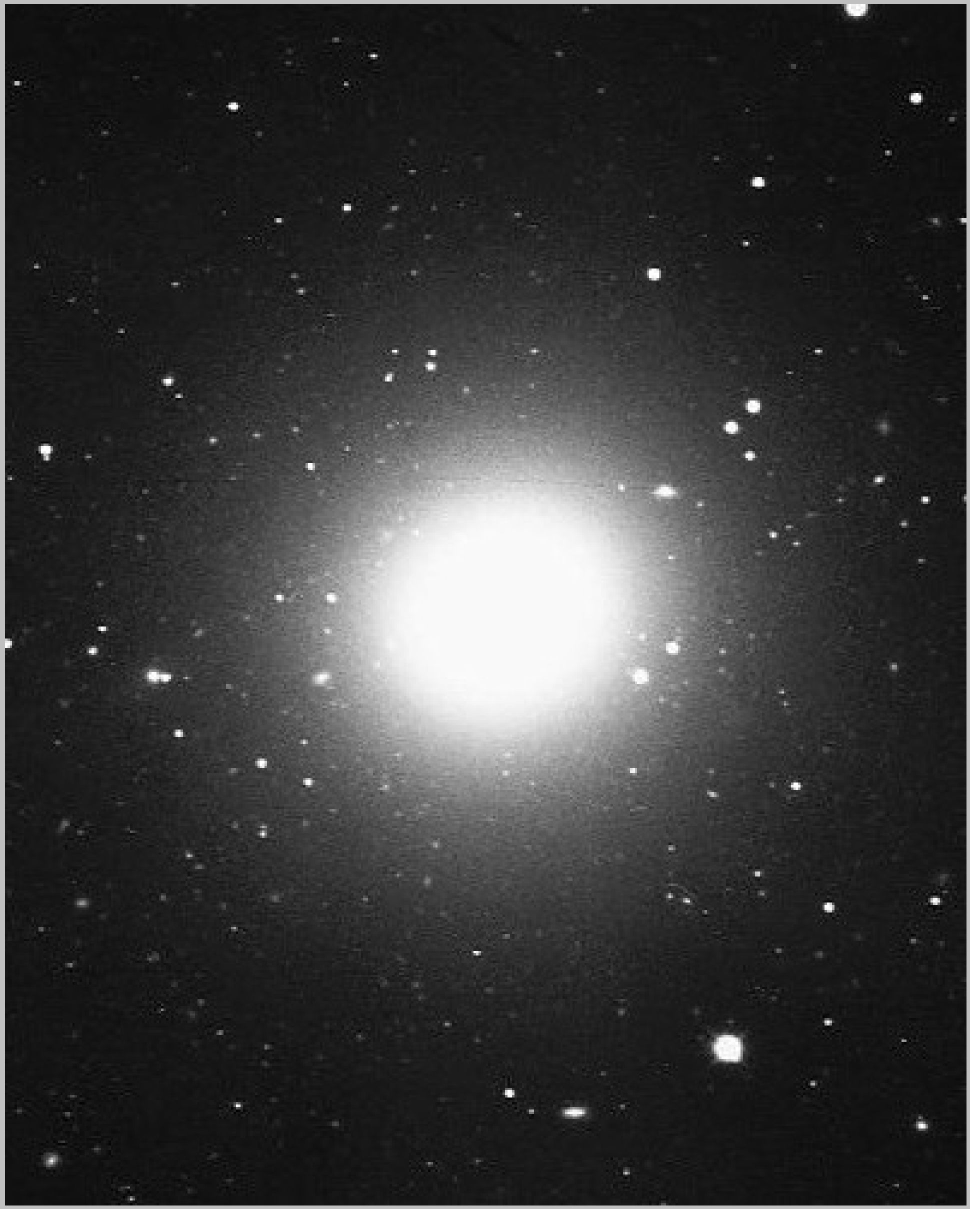

30 arc min
NGC 6251
radio
structure
1 arc min
1 arc min
0.1 arc second



3C 175 FR II radio galaxy

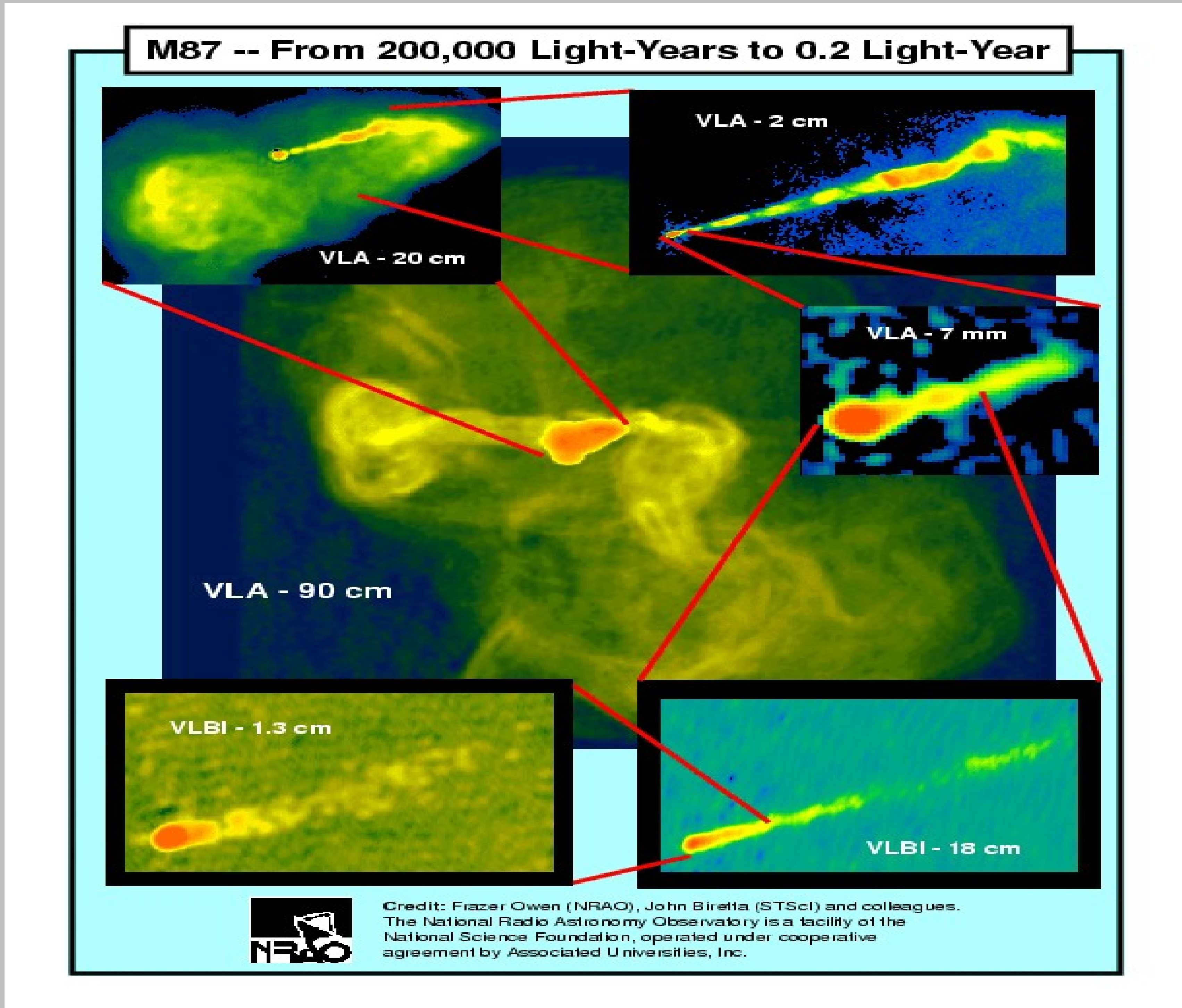


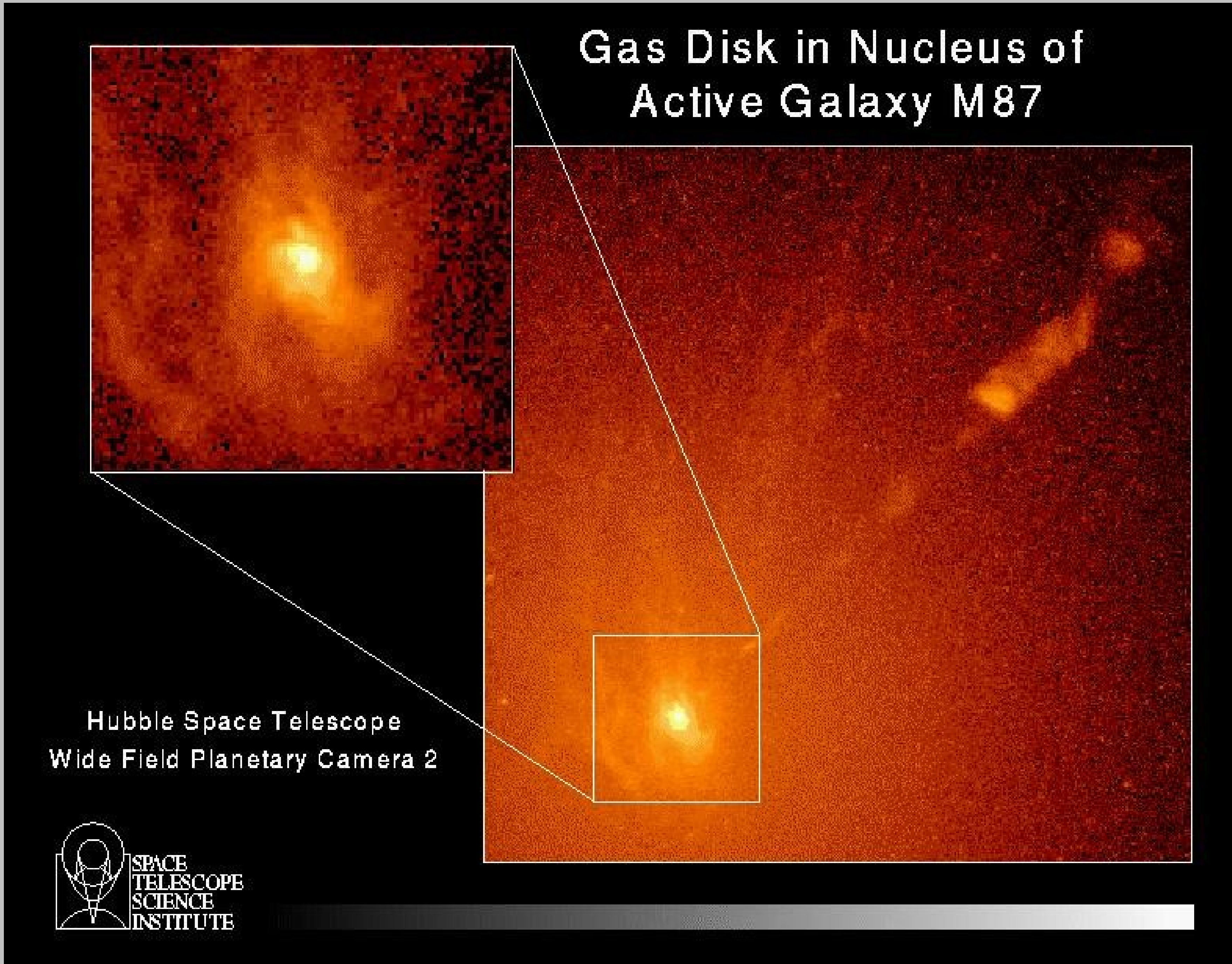
M84 FR I radio galaxy



M84 S0

M87


M87 -- From 200,000 Light-Years to 0.2 Light-Year
VLA - 20 cm
VLA - 2 cm
VLA - 7 mm
VLA - 90 cm
VLBI - 1.3 cm
VLBI - 18 cm
NRAO
Credit: Frazer Owen (NRAO), John Biretta (STScI) and colleagues.
The National Radio Astronomy Observatory is a facility of the
National Science Foundation, operated under cooperative
agreement by Associated Universities, Inc.



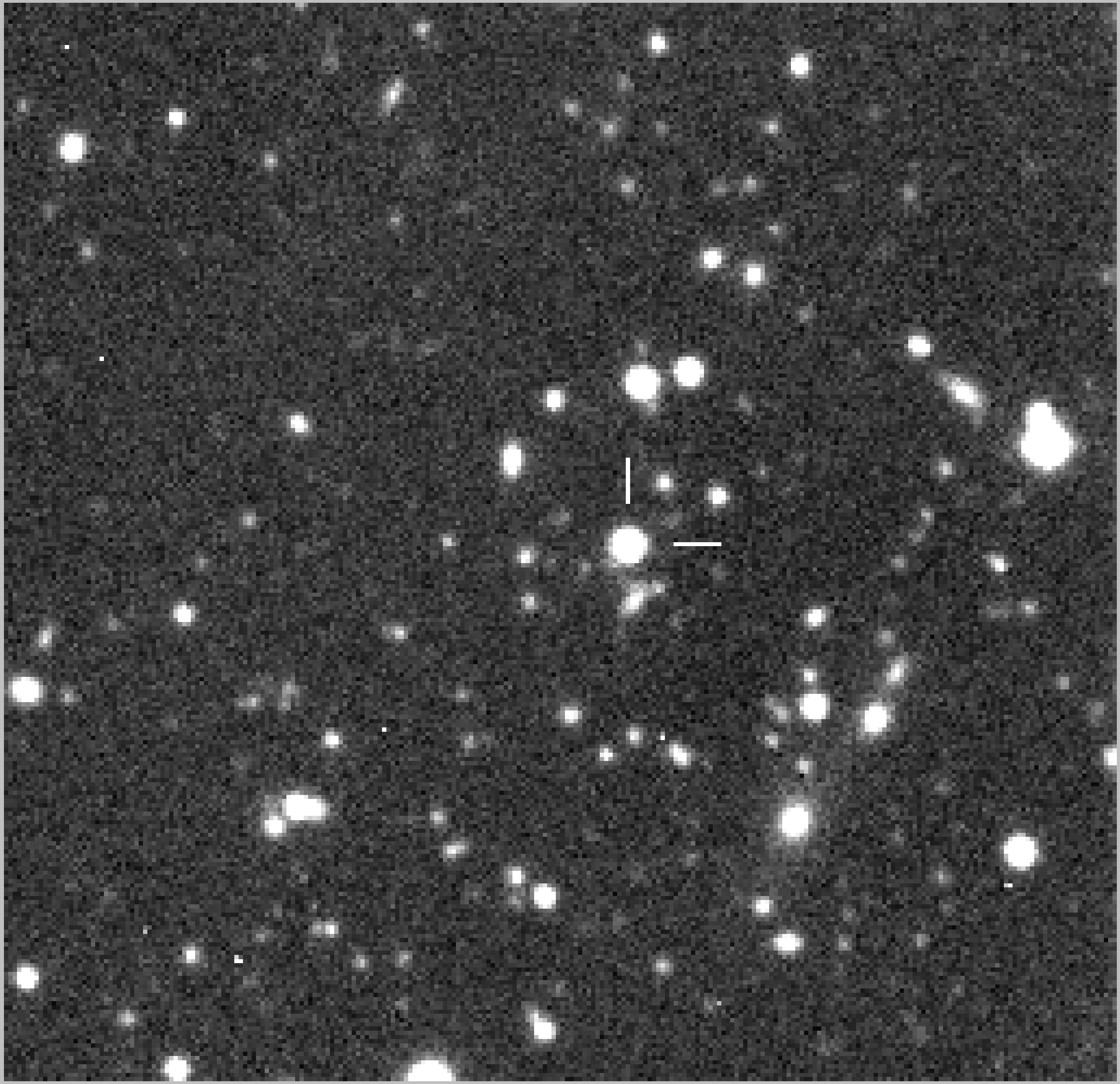
M87 Optical Jet

Active Galactic Nuclei
Quasars

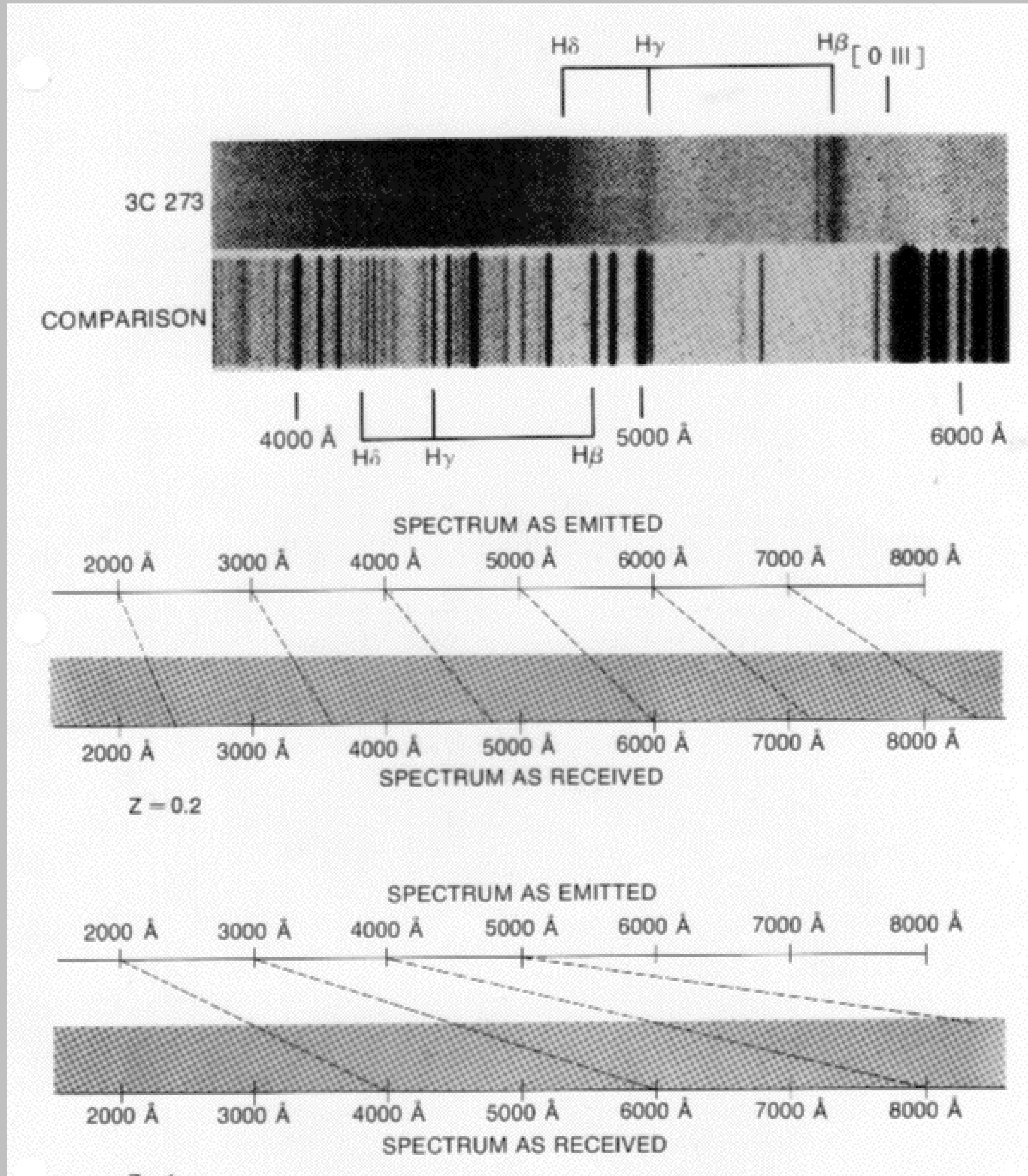
- Some radio sources were found to be associated with point-like (stellar) objects with no associated galaxy
  - Because of this these objects are known as quasars (quasi-stellar radio sources)
  - quasi-stellar objects (QSO's)
- M. Schmidt (1963) found that the spectrum of 3C273 had nebular emission lines at a redshift of $z=0.158$!
- Soon after it was discovered that 3C 45 had a redshift of $z=0.367$
  - This began the race for the highest redshift quasar!

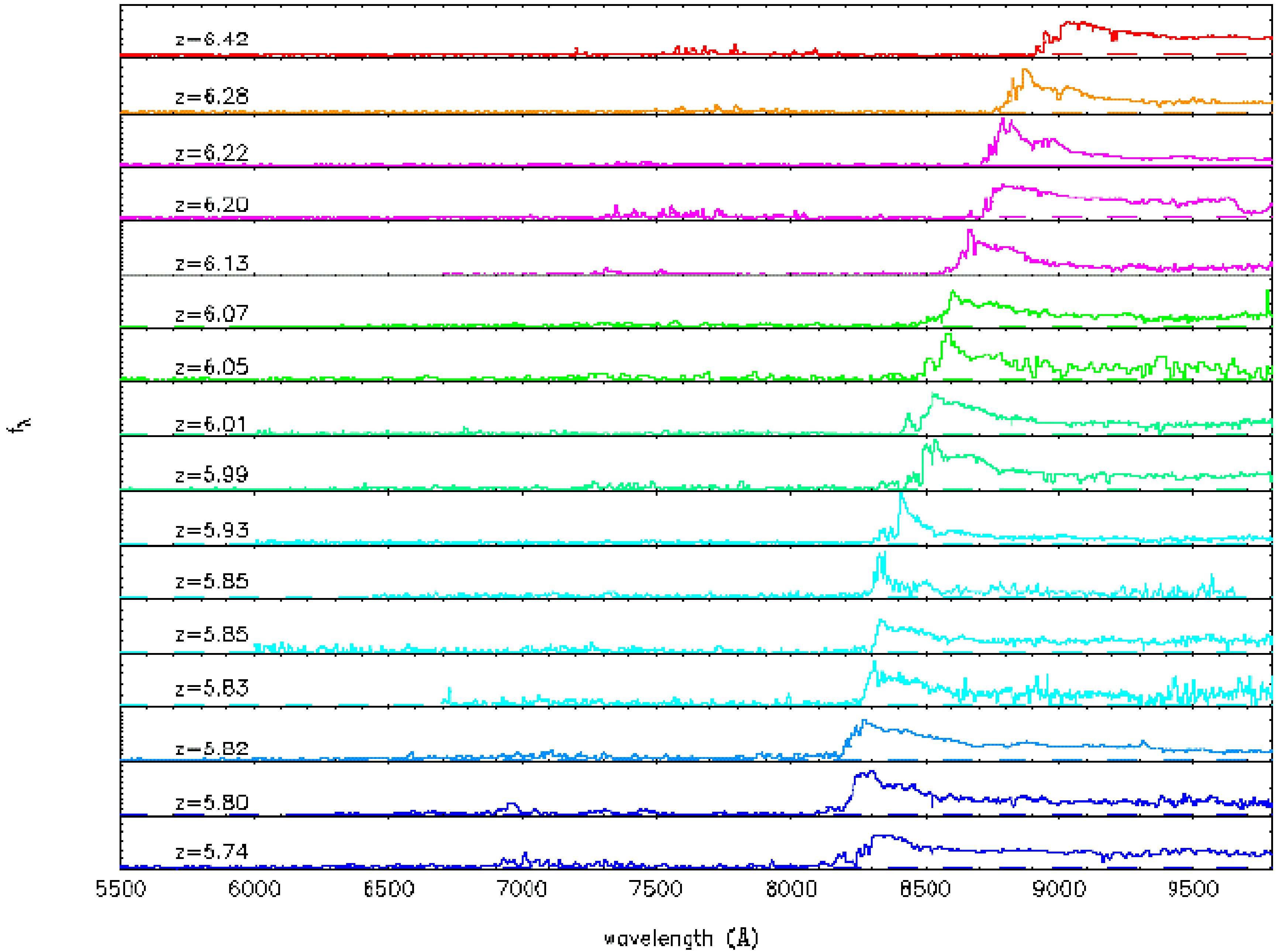
Active Galactic Nuclei
Quasars cont.

- Quasars are very luminous.
  - $L \sim 10^{13} - 10^{15}\ L_\odot$
- QSO's out number quasars by a factor of 10 – 30, but we often use the name quasar for both objects
- Quasars are variable
  - Variable on timescales of hours – days
- Current high redshift record is z=6.43 (SDSS)Schneider et al. (2002)

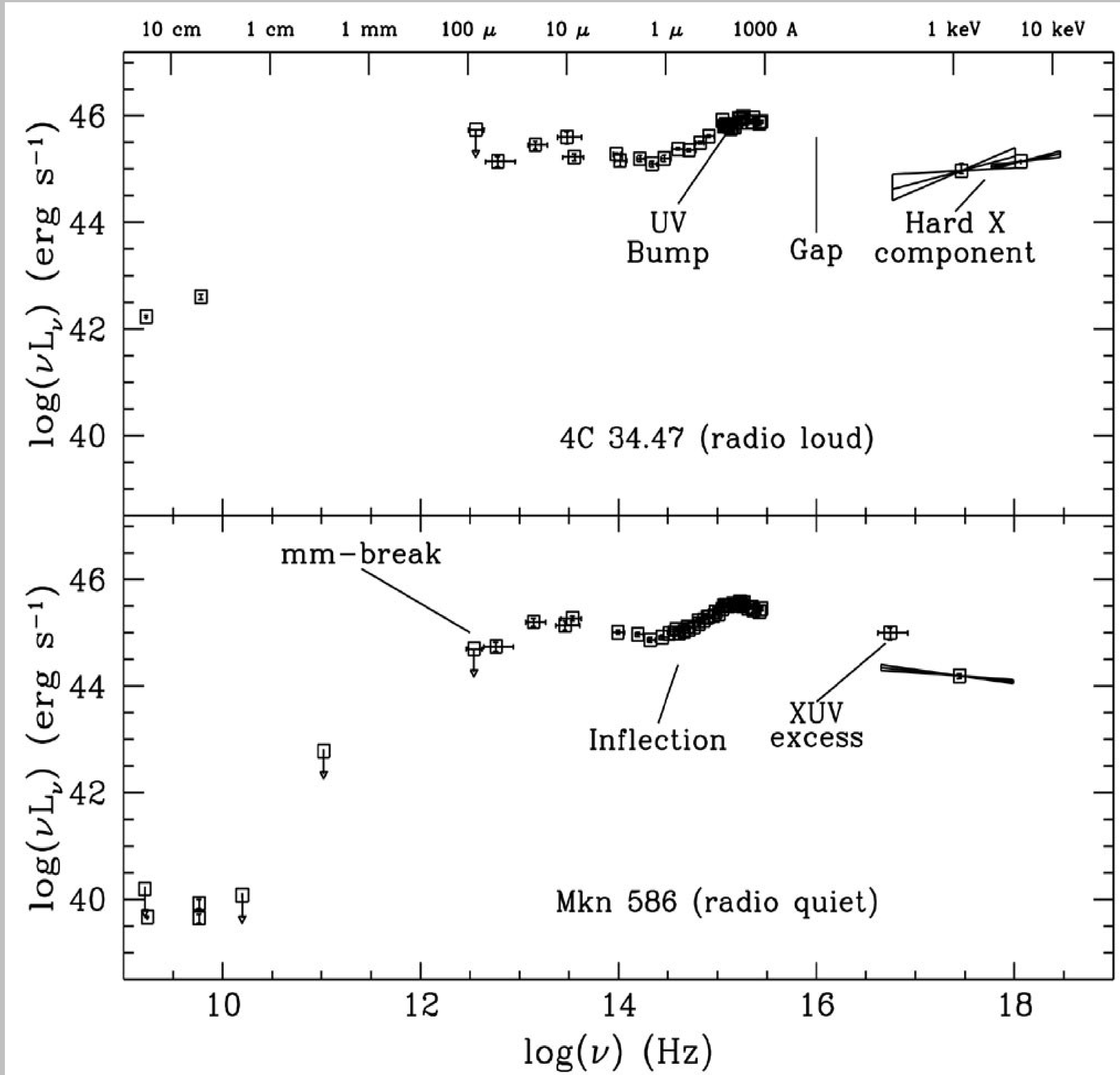


PKS 1117-248 z=0.466

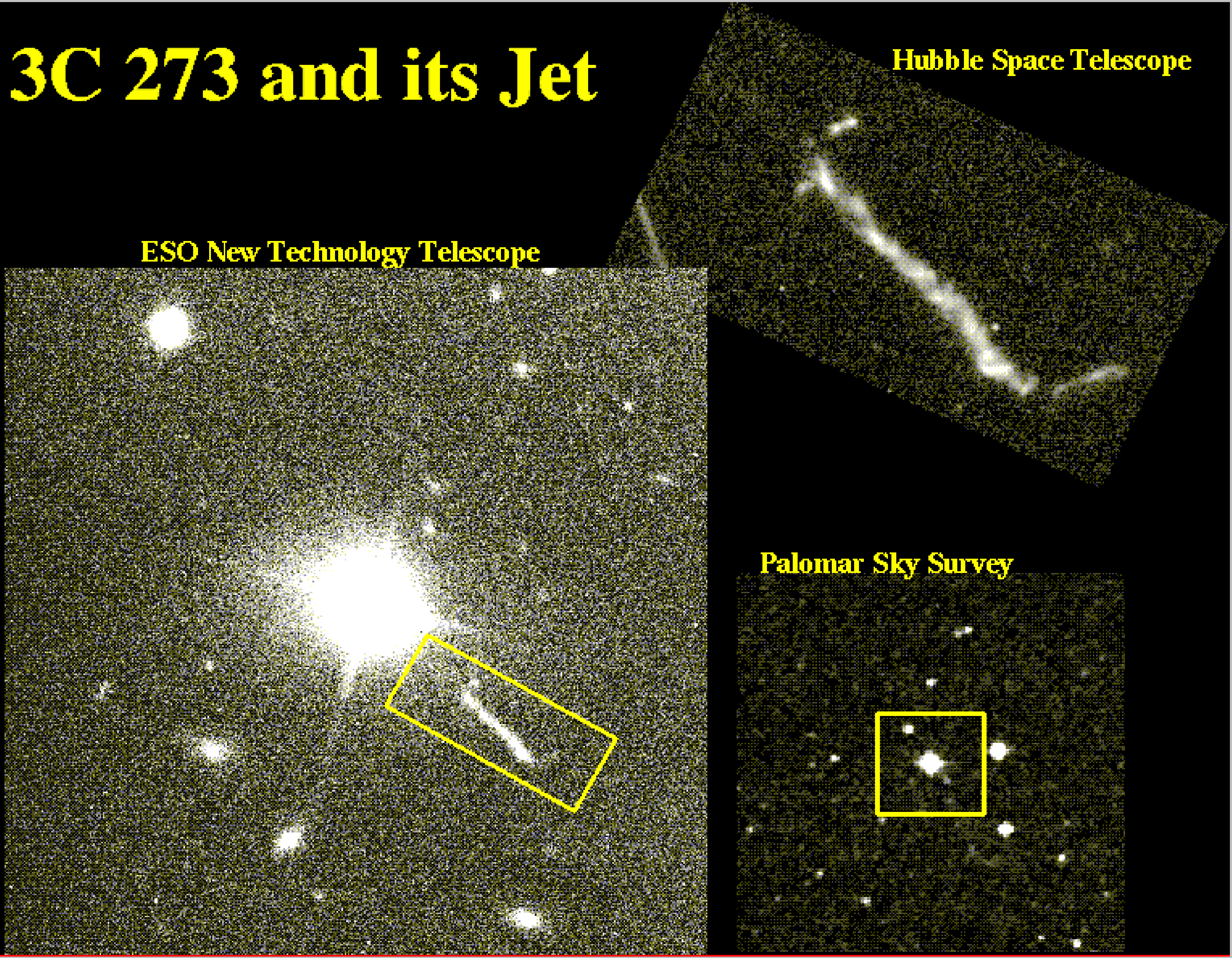

Hδ
Hγ
Hβ
[0 III]
3C 273
COMPARISON
4000 Å
Hδ
Hγ
Hβ
5000 Å
6000 Å
SPECTRUM AS EMITTED
2000 Å
3000 Å
4000 Å
5000 Å
6000 Å
7000 Å
8000 Å
2000 Å
3000 Å
4000 Å
5000 Å
6000 Å
7000 Å
8000 Å
SPECTRUM AS RECEIVED
Z = 0.2
SPECTRUM AS EMITTED
2000 Å
3000 Å
4000 Å
5000 Å
6000 Å
7000 Å
8000 Å
2000 Å
3000 Å
4000 Å
5000 Å
6000 Å
7000 Å
8000 Å
SPECTRUM AS RECEIVED



Quasars in the SDSS, Fan et al (2004)


10 cm
1 cm
1 mm
100 μ
10 μ
1 μ
1000 A
1 keV
10 keV
log(νL_ν) (erg s^-1)
UV
Bump
Gap
Hard X
component
4C 34.47 (radio loud)
mm-break
Inflection
XUV
excess
Mkn 586 (radio quiet)
log(ν) (Hz)

3C 273 and its Jet



Active Galactic Nuclei
Quasars cont.

- Hypothesis:
  - Quasars are powered by gas flowing toward a supermassive black hole
- Support
  - Quasars are bright at X-ray and gamma-ray wavelengths
  - Quasars are often located in merging galaxies
  - Quasars are very compact
    - A black hole with a mass of $10^9\ M_{\odot}$ Schwarzschild radius of only 20 AU (r< 3 light-hours)

Active Galactic Nuclei
Quasars cont.

- The brightest quasars have a luminosity of $L = 10^5\ L_{MW} = 10^{42}$ watts
- The amount of gas need to produce 10^{42} joules of energy is $M = E/c^2 = 10^{25}$ kilograms
- Every year, it must consume > 200 times the mass of the Sun
  - Most simulations show that the efficiency is only between 1 – 10 % so you need much more mass
- This is over two trillion solar masses during the age of the universe
  - Much more than the mass of any galaxy!
- So this phase must last only a short time!

Active Galactic Nuclei
Quasars cont.

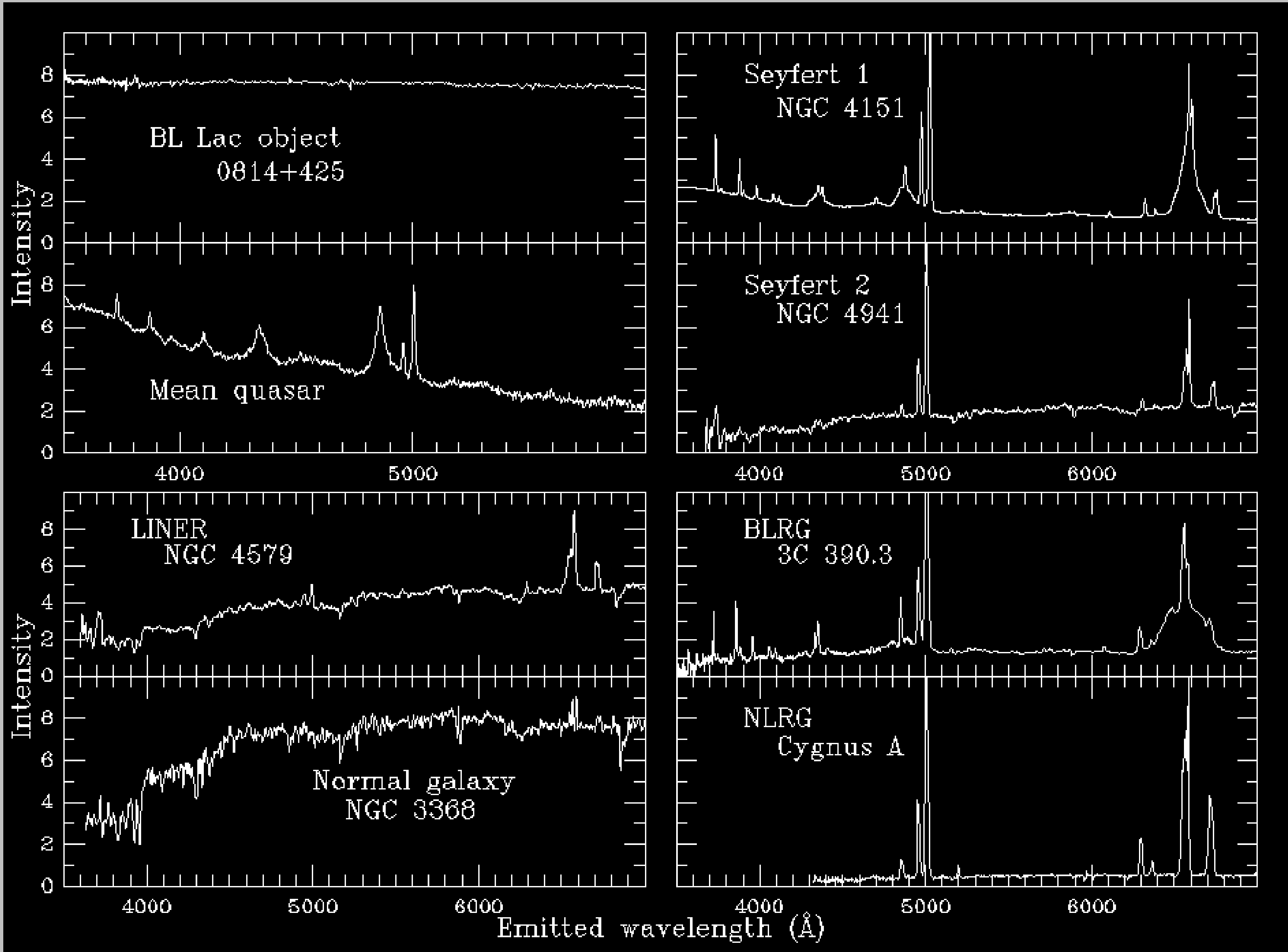
- This implies that Supermassive Black Holes existed in the early universe
  - Do galaxies form around BH's?
  - All galaxies have a black hole at their center?

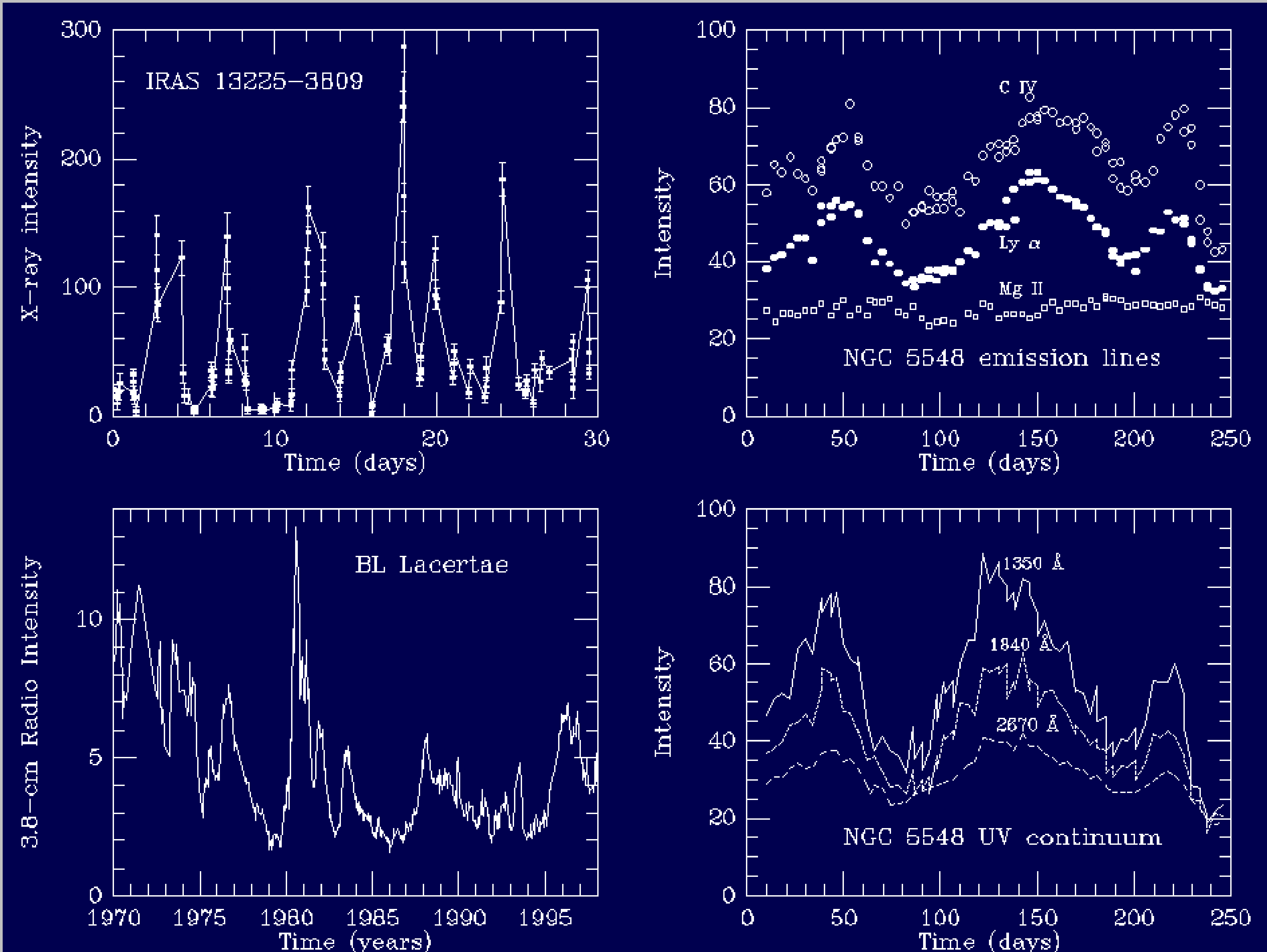
Active Galactic Nuclei
BL Lac's

- Cataloged as variable stars (e.g., BL Lacertae)
- Highly variable, highly polarized
- Variability occurs on the time scale of days
- Virtually featureless continuous spectra
- Also optically violent variables (OVV) quasars
- Collectively OVV’s and BL Lac’s are known as blazars

Active Galactic Nuclei
LINERs

- Low Ionization Nuclear Emission Line Region (LINERs)
- Low ionization spectrum, but difficult to make entirely with stars
- No evidence of non-thermal continuum
- ~50% of nearby spiral nuclei are LINERs
  - Perhaps ionized both by stars and an accretion disk?


BL Lac object
0814+425
Mean quasar
Seyfert 1
NGC 4151
Seyfert 2
NGC 4941
LINER
NGC 4579
Normal galaxy
NGC 3368
BLRG
3C 390.3
NLRG
Cygnus A
Intensity
Emitted wavelength (Å)

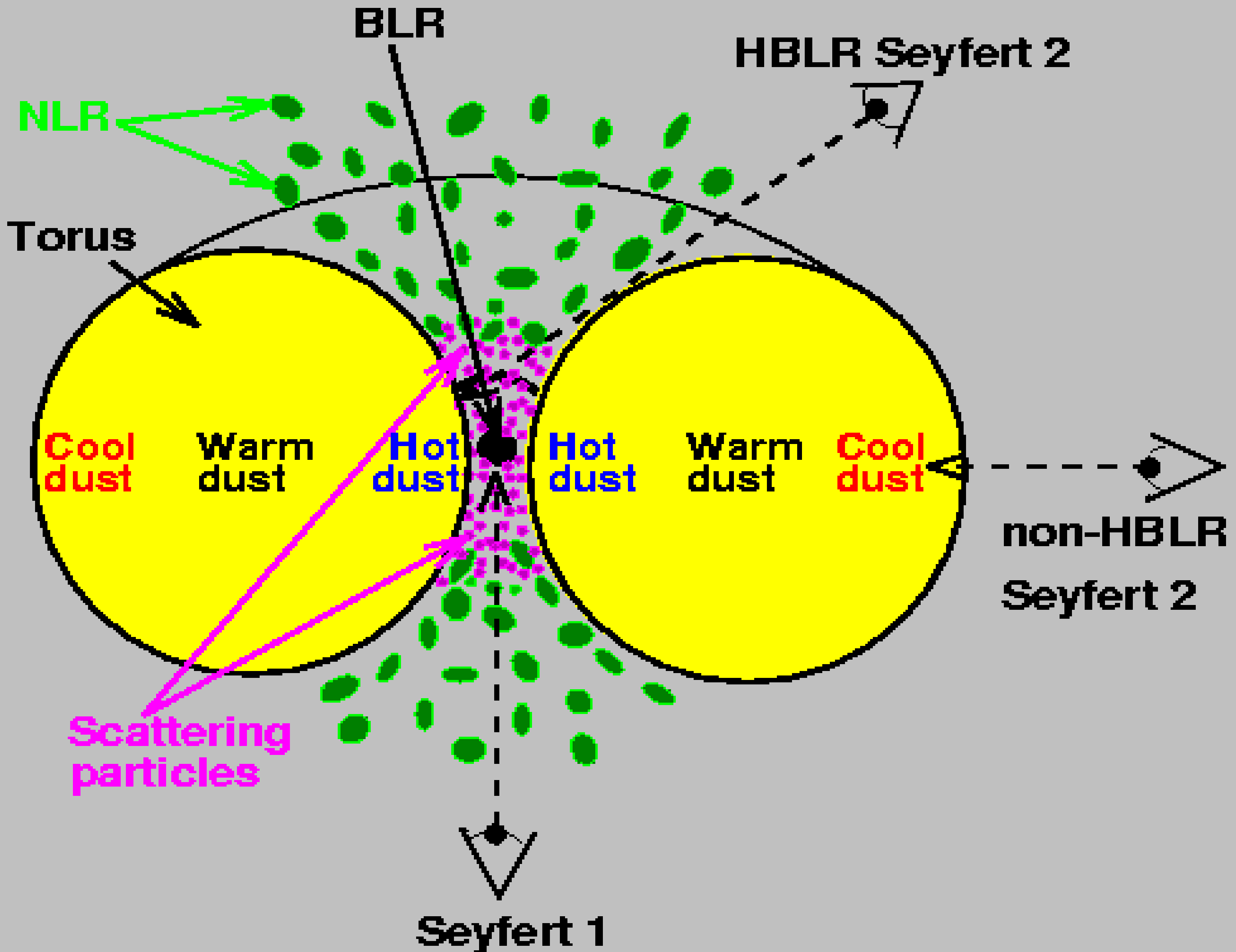

IRAS 13225−3809
X−ray intensity
Time (days)
NGC 5548 emission lines
C IV
Ly α
Mg II
Intensity
Time (days)
BL Lacertae
3.8−cm Radio Intensity
Time (years)
NGC 5548 UV continuum
1350 Å
1840 Å
2670 Å
Intensity
Time (days)

What do they have in common?

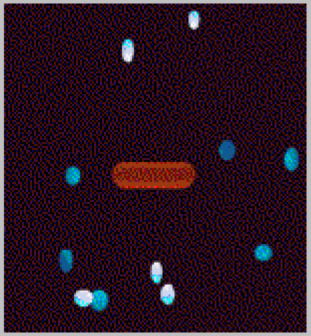
- Variability on short time scales implies a small emission region
  - $R = c\Delta t$ ~ 7-10 AU (for variability on the order of hours)
- Highly luminous!
- Most likely powered by a black hole
- Schwarzschild radius is the radius where the "escape velocity" equals the speed of light around a black hole of mass M:
  - $R_{Sch} = 2GM/c^2$
- Continuum emission powered by gas falling onto central black hole, losing potential energy, heating up and radiating
- Since gas has angular momentum it forms an accretion disk

Unified Model

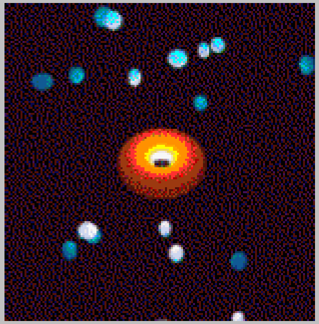
- Black hole with an accretion disk
- Material near the BH is ionized
- Close to the BH the clouds have high velocities (BRL)
  - $V > 2000$ km/s
- Further away from the BH lower velocity and narrow lines (NLR)
  - 500 km/s $< V <$ 1000 km/s
- Dust torus surrounds the central engine and BLR in the same plane as the accretion disk. The orientation of the dust torus relative to the line of sight affects the classification of the AGN.



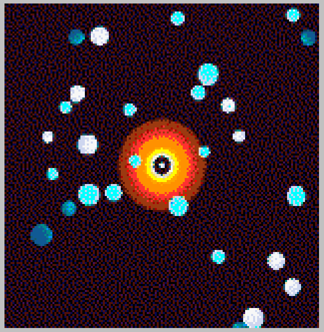
Unified Model



Type 2 objects:
Seyfert 2s, Narrow Line Radio Galaxies
and Type 2 Quasars



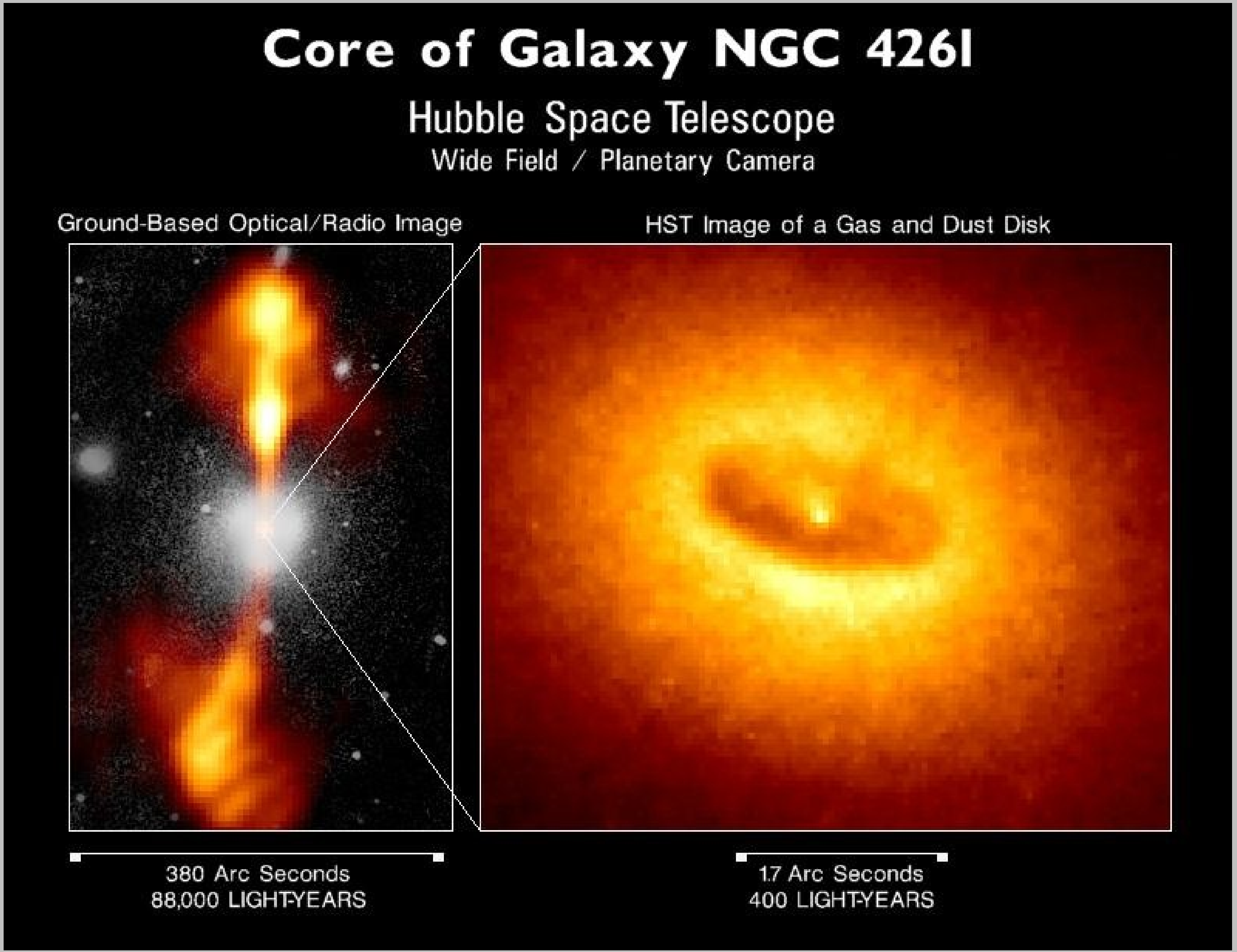
Type 1 objects:
Seyfert 1s, Broad Line Radio Galaxies
and (Type 1) Quasars



Blazars:
BL Lac Objects and
Optically-Violent Variables

Unified Model cont.

- Different wavelength light comes from different areas of the “central engine”
  - Gamma rays from the very inner accretion disk
  - X-ray and UV from next innermost parts of disk and jet
  - Radio from particles accelerated to relativistic energies in the jet (synchrotron radiation)
  - Visible light (continuum) from farther out in disk or jet
  - Visible light (emission lines) from BLR and NLR clouds
  - Infrared from radiation from surrounding dust grains, either in clouds or from the torus


Core of Galaxy NGC 4261
Hubble Space Telescope
Wide Field / Planetary Camera
Ground-Based Optical/Radio Image
HST Image of a Gas and Dust Disk
380 Arc Seconds
88,000 LIGHT-YEARS
1.7 Arc Seconds
400 LIGHT-YEARS

Maximum Luminosity

- For objects this bright radiation pressure is significant
- So we want to balance gravitational attraction with the outward radiation pressure

$$\frac{GM(m_e + m_p)}{r^2} = \frac{\sigma_T L}{4\pi r^2 c}$$

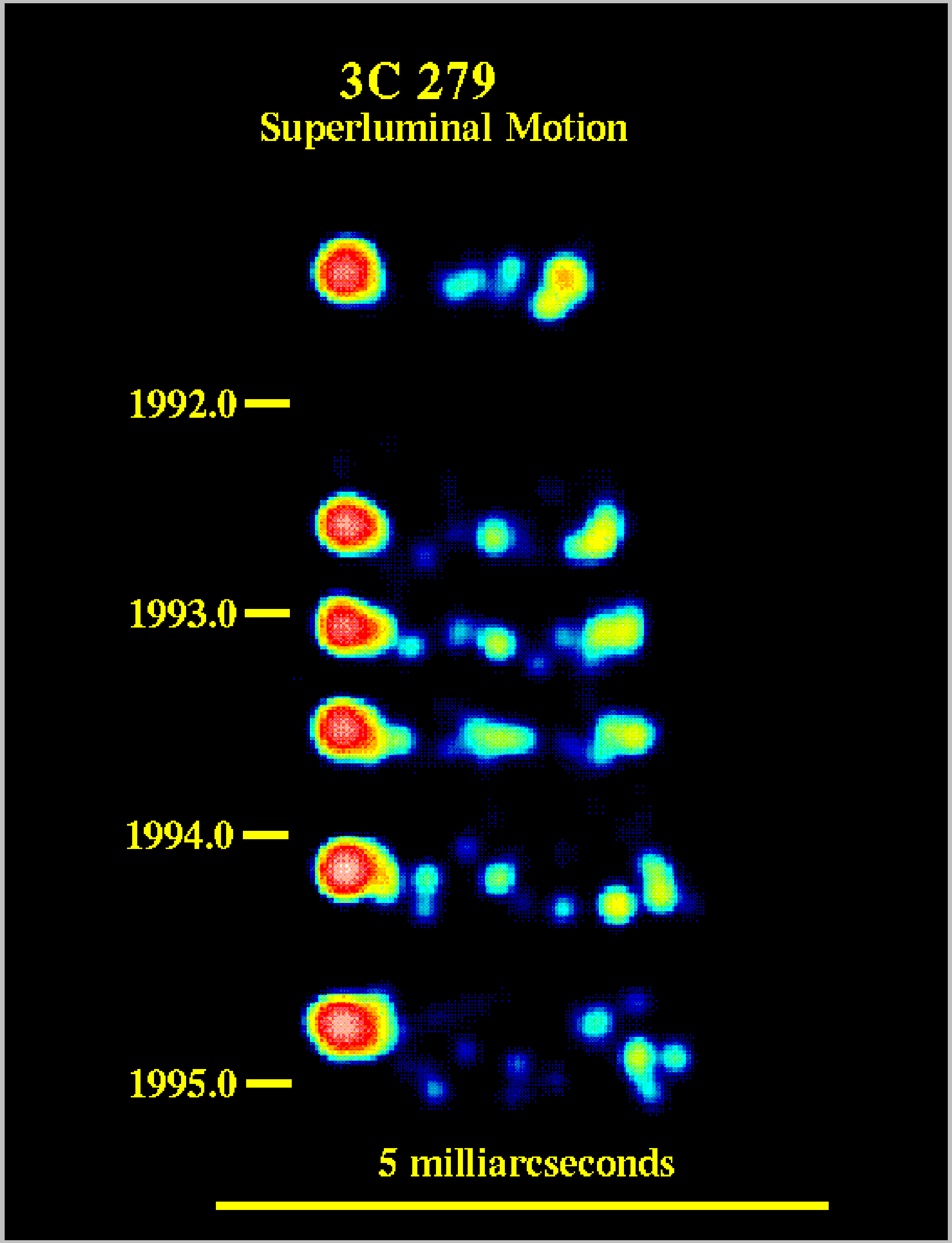
σ_T is the Thompson cross section: 6.652×10^{-25} cm^{-2} and since $M_p >> M_e$ we can rewrite this as

Maximum Luminosity cont.

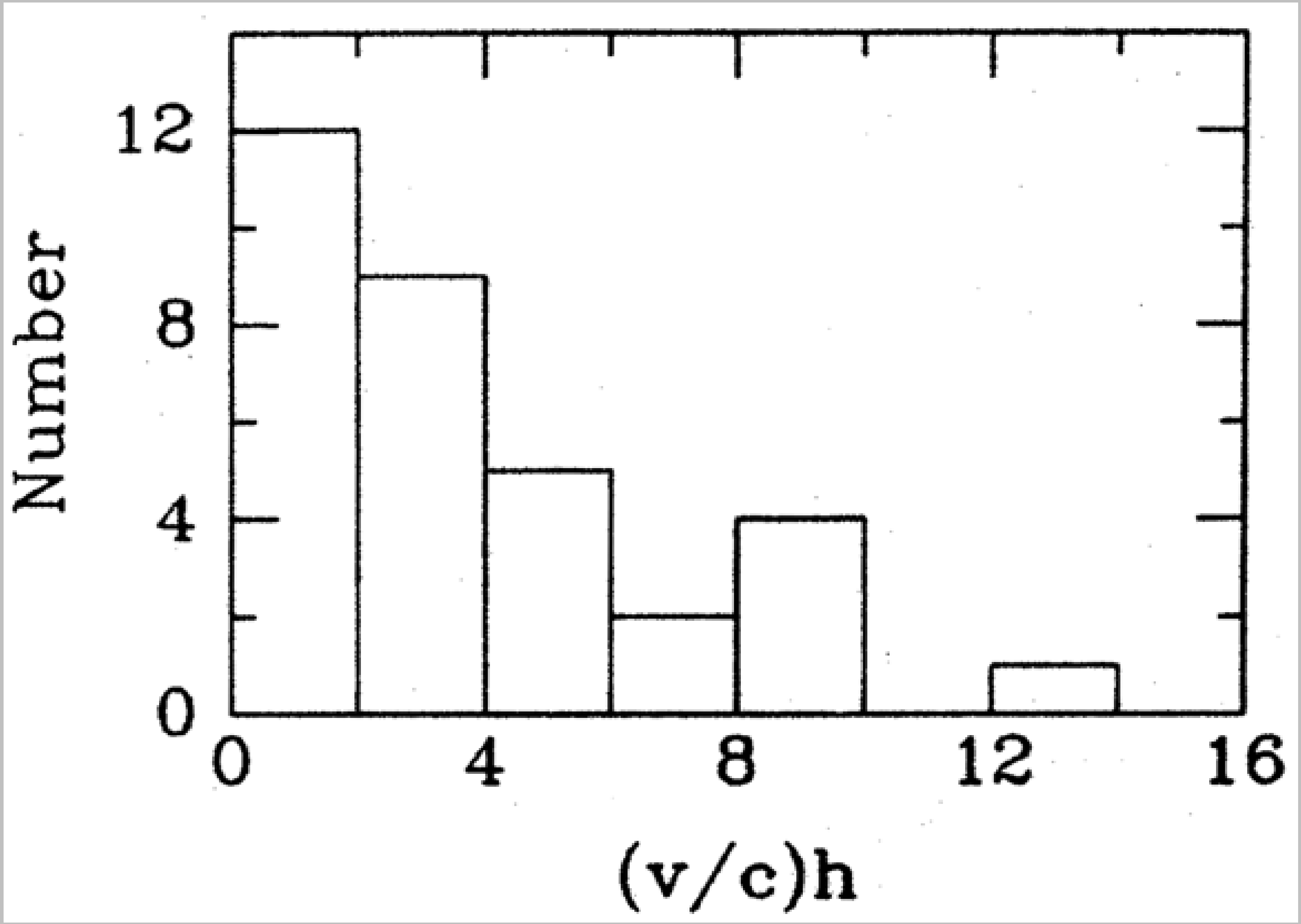
$$L_E = \frac{4\pi G M m_p c}{\sigma_T}$$

Where L_E is the Eddington Luminosity. Writing this in solar units $L_E \approx 1.3\text{x}10^{38}$ $(M/M_\odot)$ erg/s or $\approx$ $3\text{x}10^4$ $(M/M_\odot)$ $L_\odot$

So for a bright AGN $\sim 10^{11} L_\odot$, we would infer a mass of $\sim 3\text{x}10^6$ $M_\odot$.

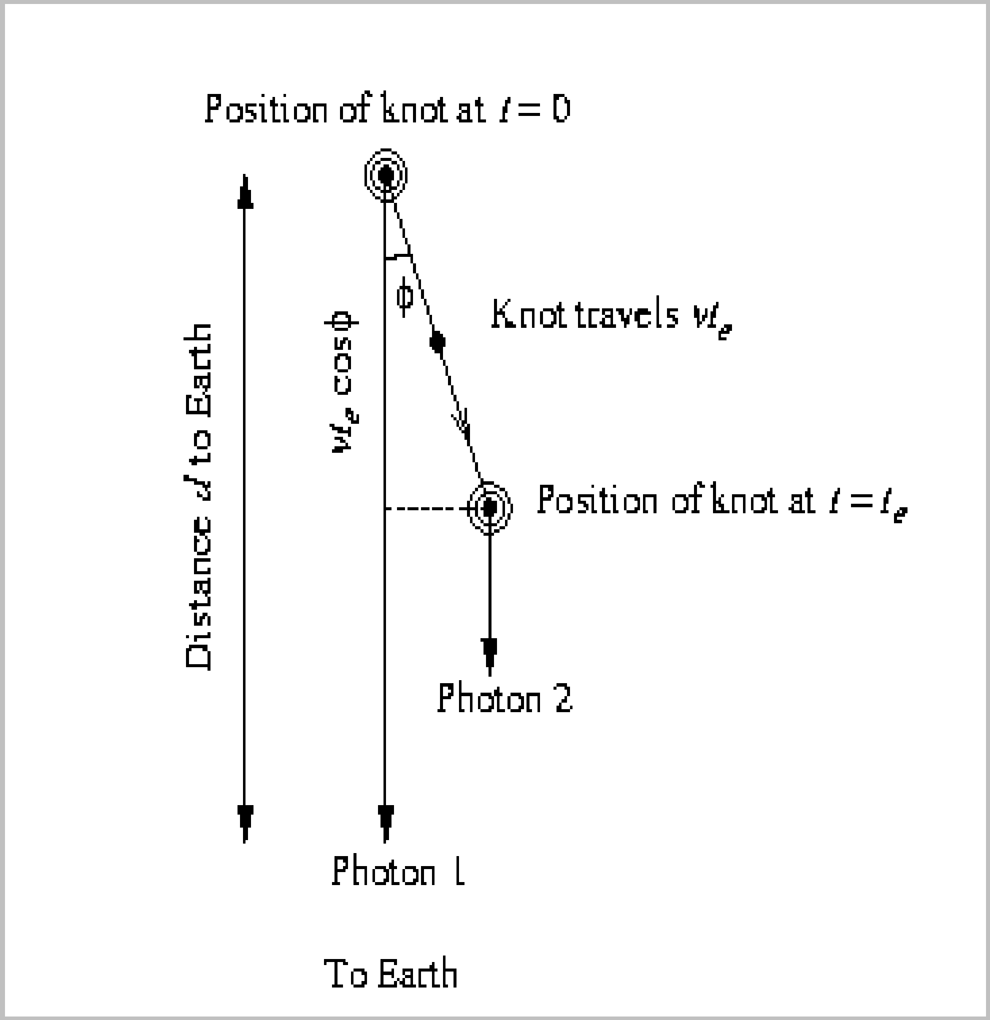


Measuring the apparent motion of the “blobs” gives you v ~ 4c
New Physics??



V/C for a sample of 33 jets

Superluminal Motion



The knots are moving towards us at an angle ϕ measured from the line of sight.

A photon emitted along the line of sight at time t=0, travels a distance d to us, taking a time t_1 to arrive:
$t_1 = d/c$

A second photon is emitted at a time t later, when the blob is a distance $d - vt\cos\phi$ away from us. The second photon arrives at $t_2 = t + (d - vt\cos\phi)/c$

The observed difference in the time of arrival from photon 1 & 2 is:
$\Delta t_{obs} = t_2 - t_1 = \Delta t\,(1 - v\cos\phi/c) < \Delta t$

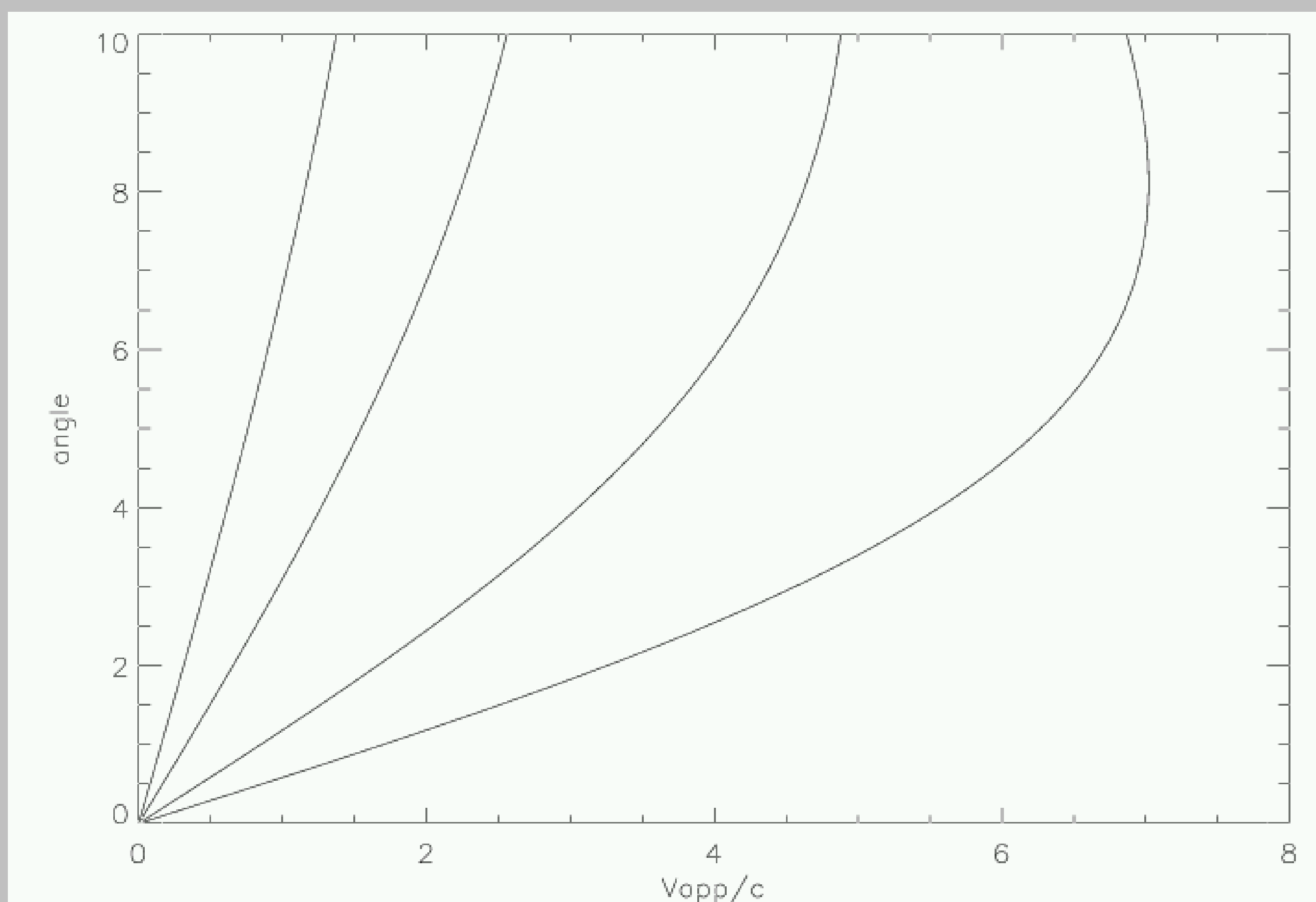
Superluminal Motion

The apparent transverse velocity is

$V_{app} = vT_e \sin(\phi) / \Delta t$

$= v \sin(\phi)/(1 - v\cos(\phi)/c)$ let $\beta = v/c$

$= \beta c \sin(\phi) / \{1 - \beta\cos(\phi)\}$



Superluminal Motion cont.

Let $\gamma = 1/(1- v^2/c^2)^{1/2}$, this is the Lorentz factor. Then: $v_{app} \leq \gamma v$ (the maximum observed velocity) which occurs when $\cos \phi = v/c$. We will only observe superluminal motion when the jets are pointed within an angle of $1/\gamma$ towards the line of sight.

This light will be beamed and brightened.

Superluminal Motion cont.

To a stationary observer, the "clocks" on the knot appear to run slow by a factor of γ, from before,

$\Delta t_{obs} = \Delta t\ (1 - v\cos\phi / c)$

$\Delta t_{obs} = \Delta t_e\, \gamma\, (1 - v\cos\phi / c)$

So the observed frequency of the light is

$\nu_{obs} = \nu_e [\gamma\, (1 - v\cos\phi / c)]^{-1}$

When $\gamma >> 1$, all the light is focused into a narrow cone of $\sin\phi = 1/\gamma \sim \phi$,

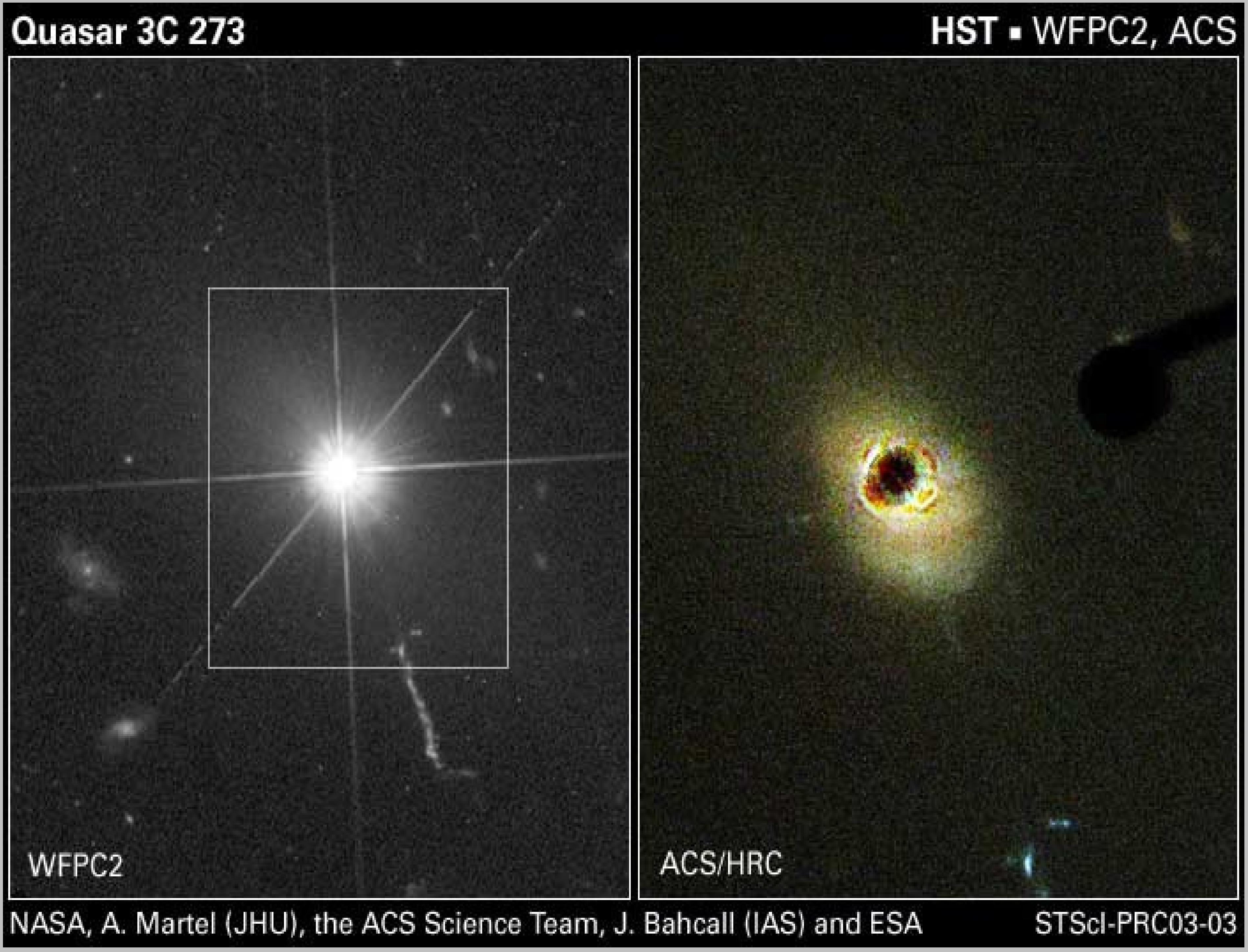
and compressed in time by $\Delta t_{obs} = \Delta t_e / 2\gamma$.

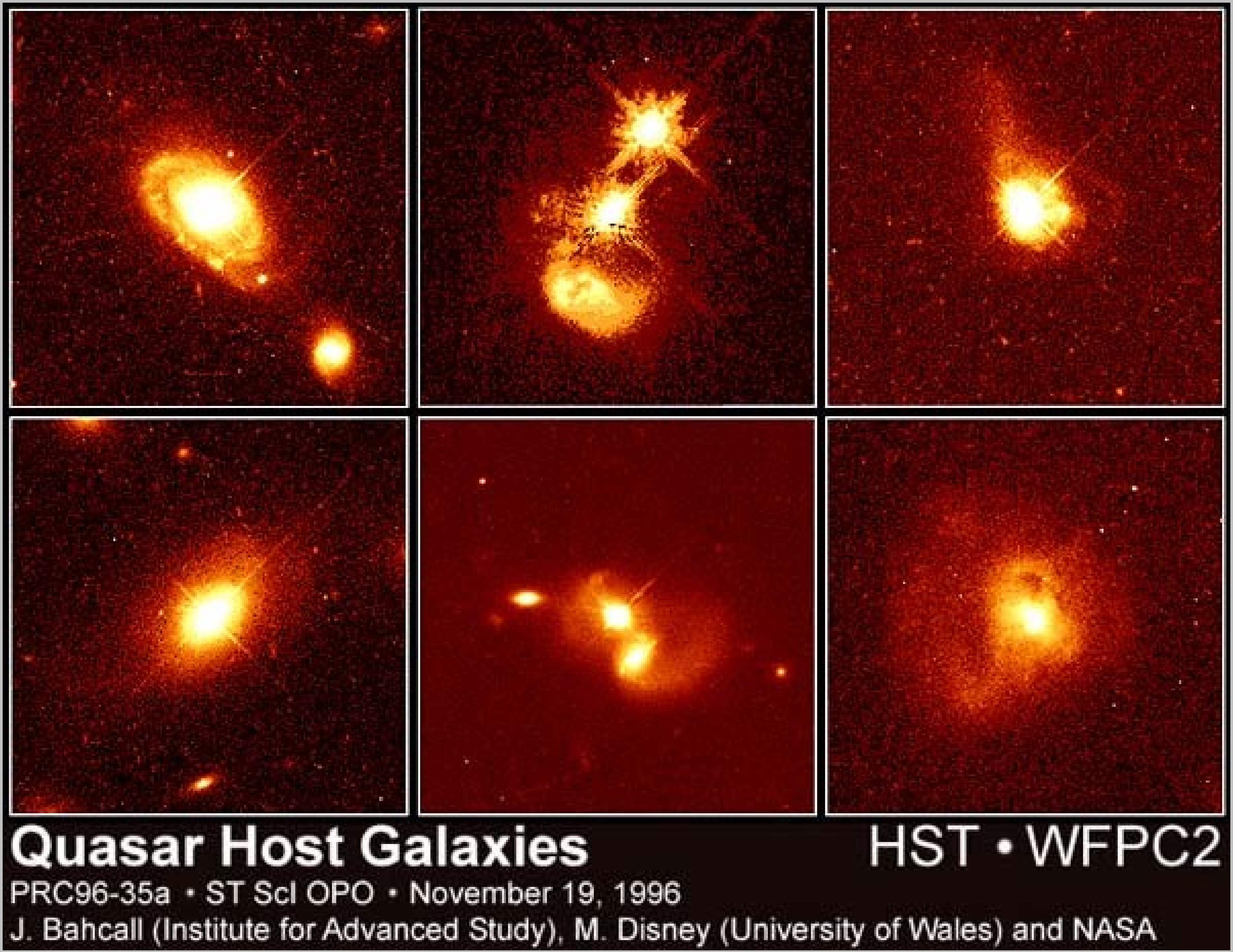
Thus the light will be brightened by a factor of $1/(2\gamma)^2$

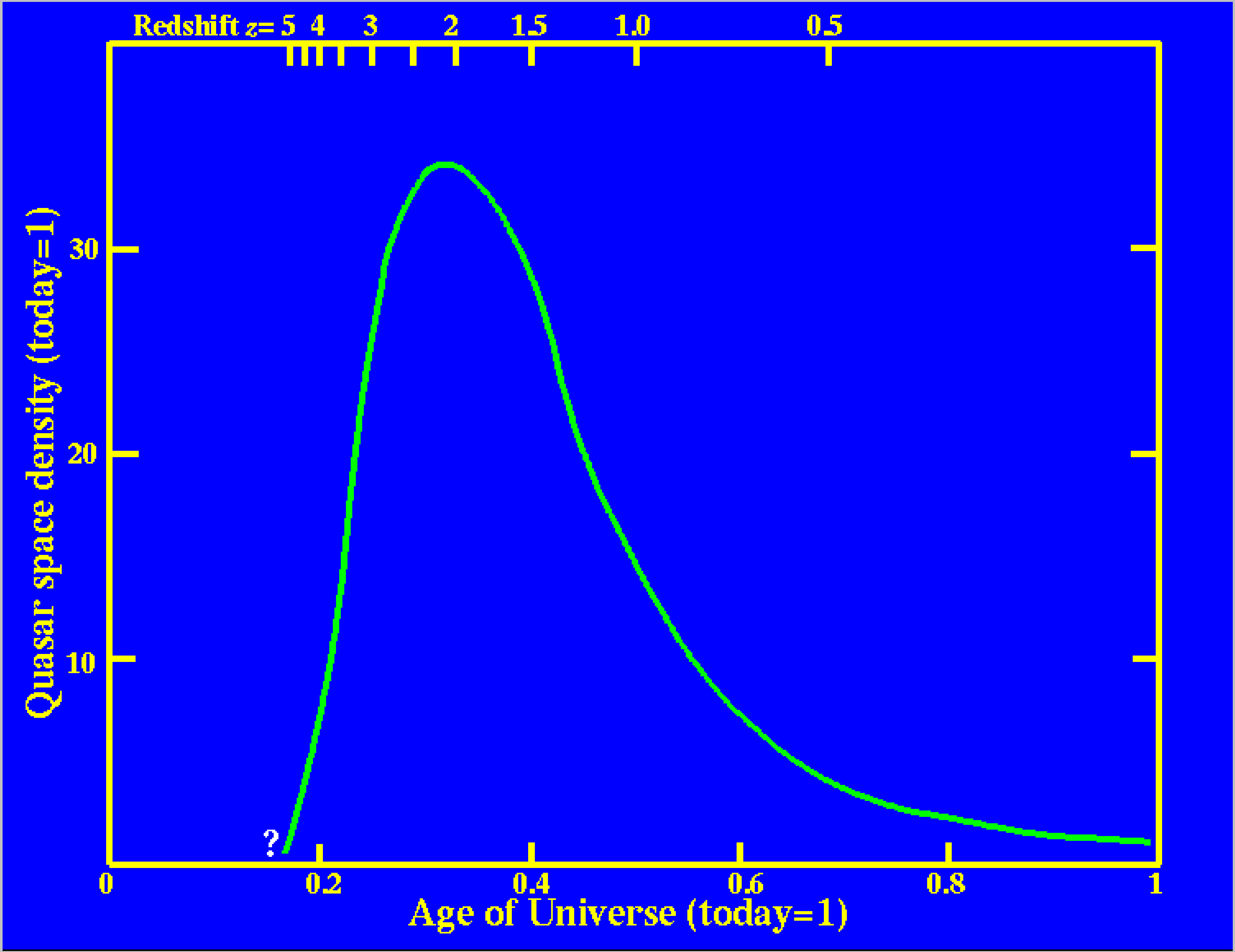
This explains why we usually only see one relativistic jet, the one being beamed towards us.

Quasar Host Galaxies

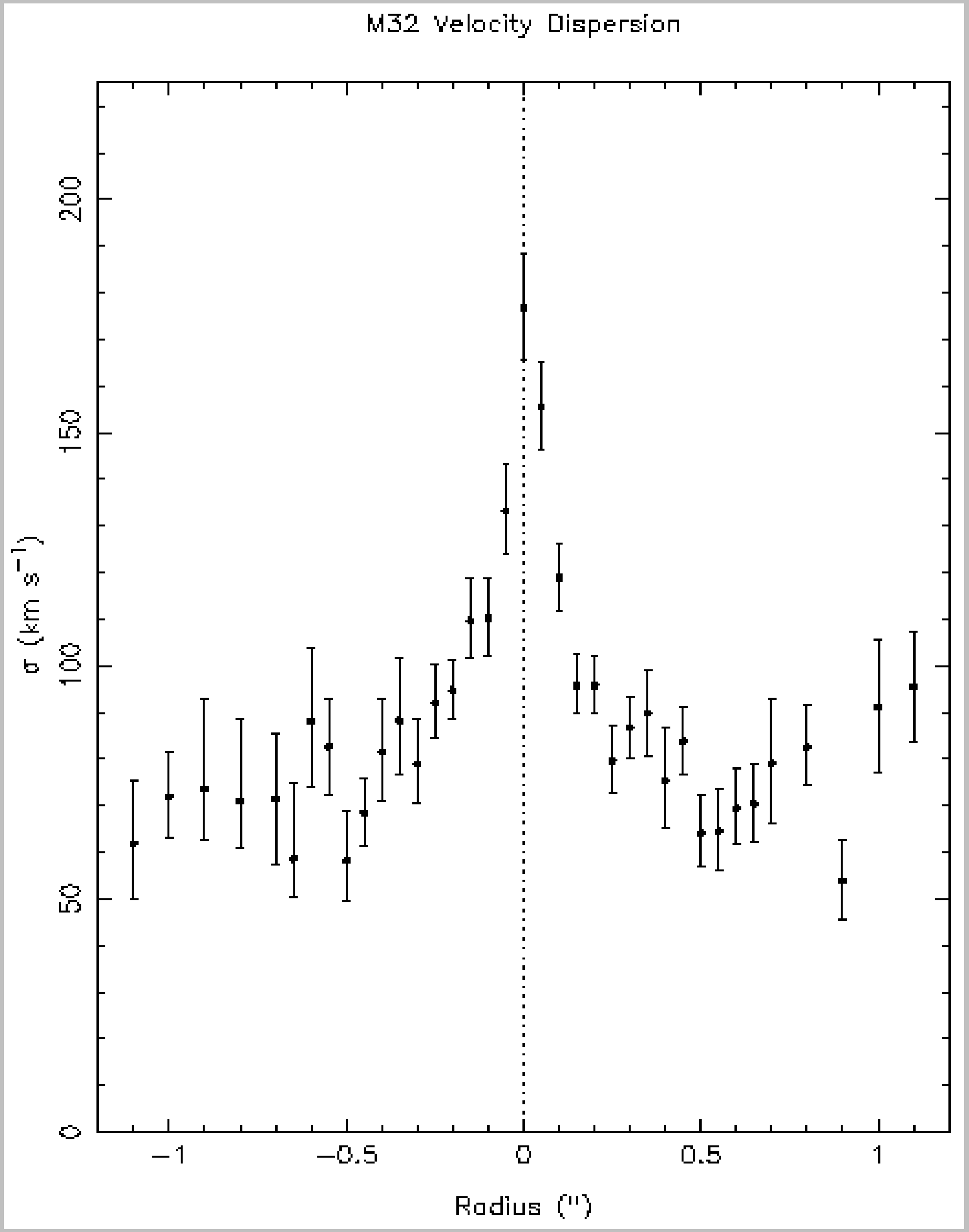
- With good telescopes (and some image processing) the quasar light can be subtracted and the host galaxy revealed
  - One can image quasar hosts with HST
  - Many are interacting – does interactions trigger AGN activity? Promote fueling gas into centers?
- Not all galaxies with SMBH are AGN (even the Milky Way)
- Quasars were much (~1000x) more numerous at z~3 than today
  - Is an AGN a requirement for galaxy formation? Does every galaxy have a SMBH?
  - More interactions in the past?
- Quasars were also much more luminous in the past
- There is probably some combination of luminosity and density evolution!


Quasar 3C 273
HST ▪ WFPC2, ACS
WFPC2
ACS/HRC
NASA, A. Martel (JHU), the ACS Science Team, J. Bahcall (IAS) and ESA
STScI-PRC03-03


Quasar Host Galaxies
HST • WFPC2
PRC96-35a • ST ScI OPO • November 19, 1996
J. Bahcall (Institute for Advanced Study), M. Disney (University of Wales) and NASA


Redshift z= 5 4 3 2 1.5 1.0 0.5
Quasar space density (today=1)
30
20
10
?
0 0.2 0.4 0.6 0.8 1
Age of Universe (today=1)

M32



There is evidence that most if not all galaxies have a BH in their center but many of these are quiet! Not being fed(?) so they are hard to detect