Radio galaxies: main classes

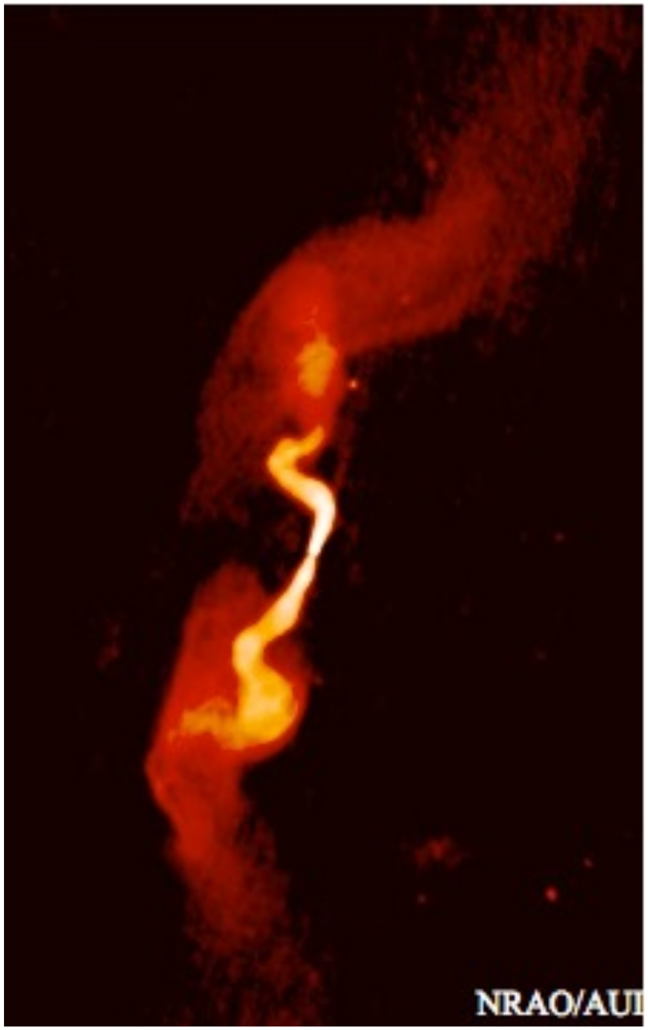
Large radio galaxies with lobes are divided into two types called *Fanaroff-Riley* (1974) type I and II:

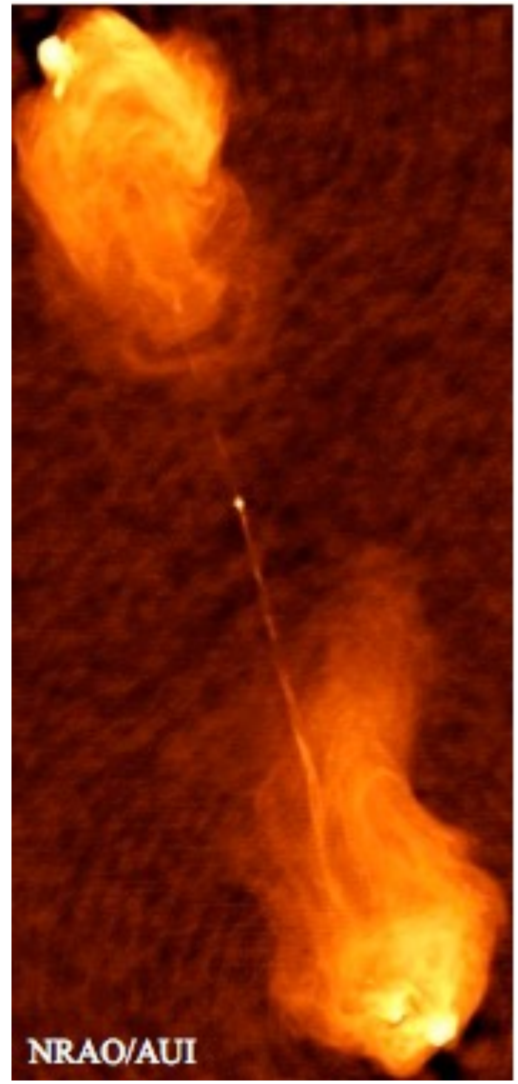
FRI: weaker radio sources that are bright in the center and fainter towards edge of lobes.

FRII: stronger radio sources that are brighter towards the limbs.

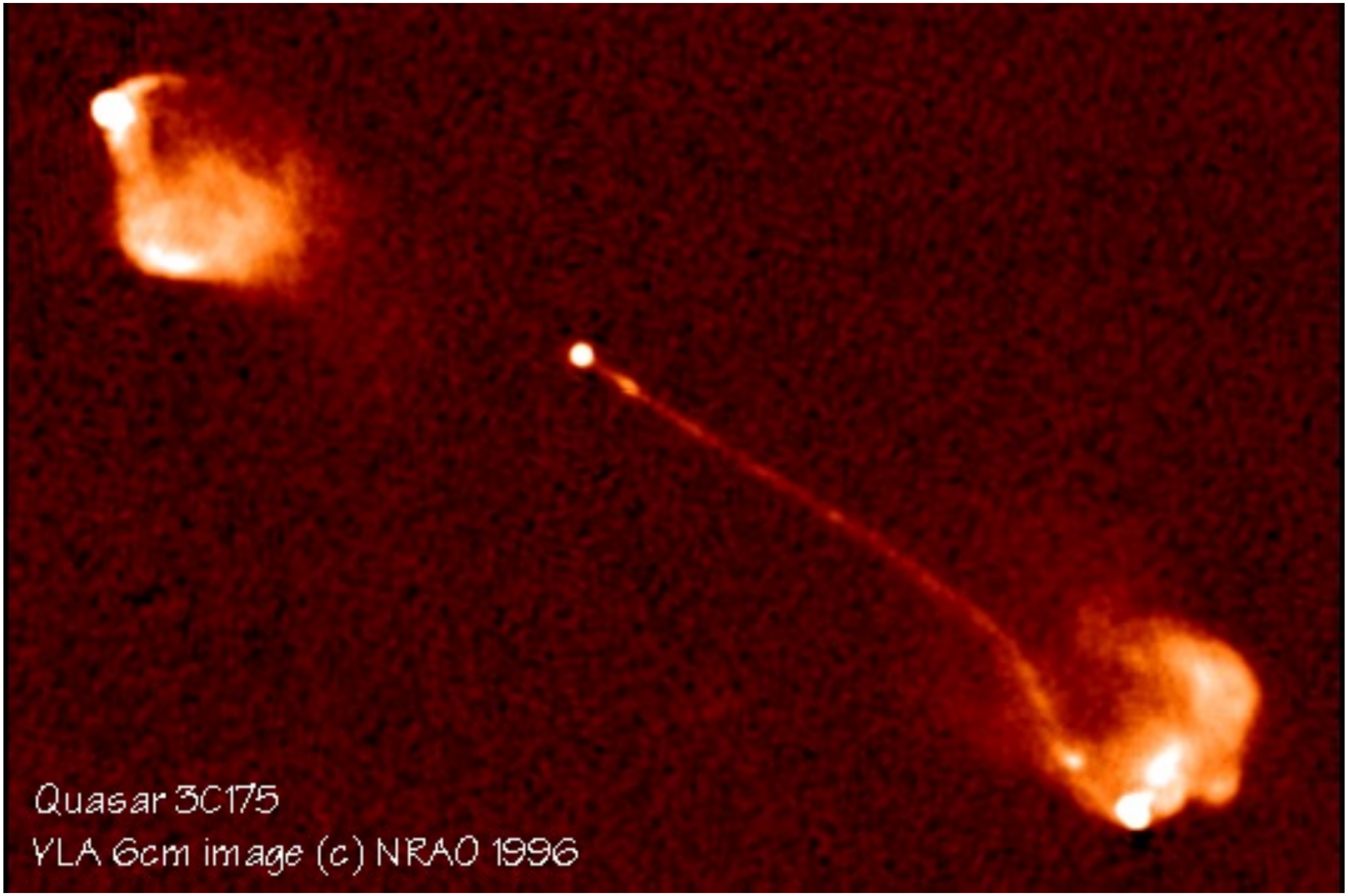
Luminosity transition around $L_{1.4GHz}=10^{25}$ Jy/s/Hz

Example FRI and FRII morphologies:

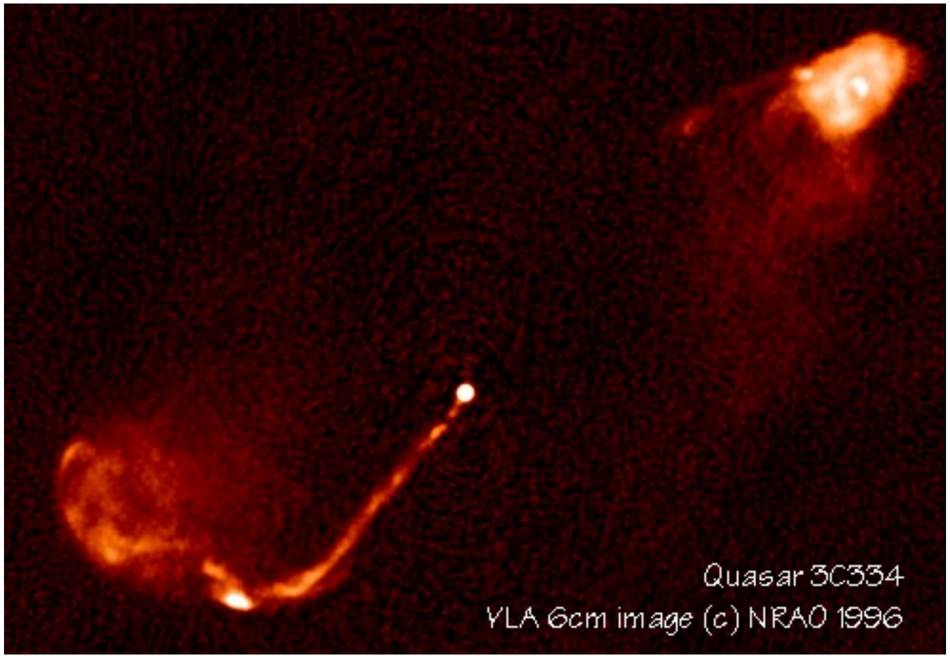




Quasars resemble High Power (FR II) radio galaxies



More quasars



More quasars

Vintage Quasar Model Gx3621...

$71.99

Used

eBay

Quasar Gx3604 Cassette Radio...

$67.46

Used

eBay

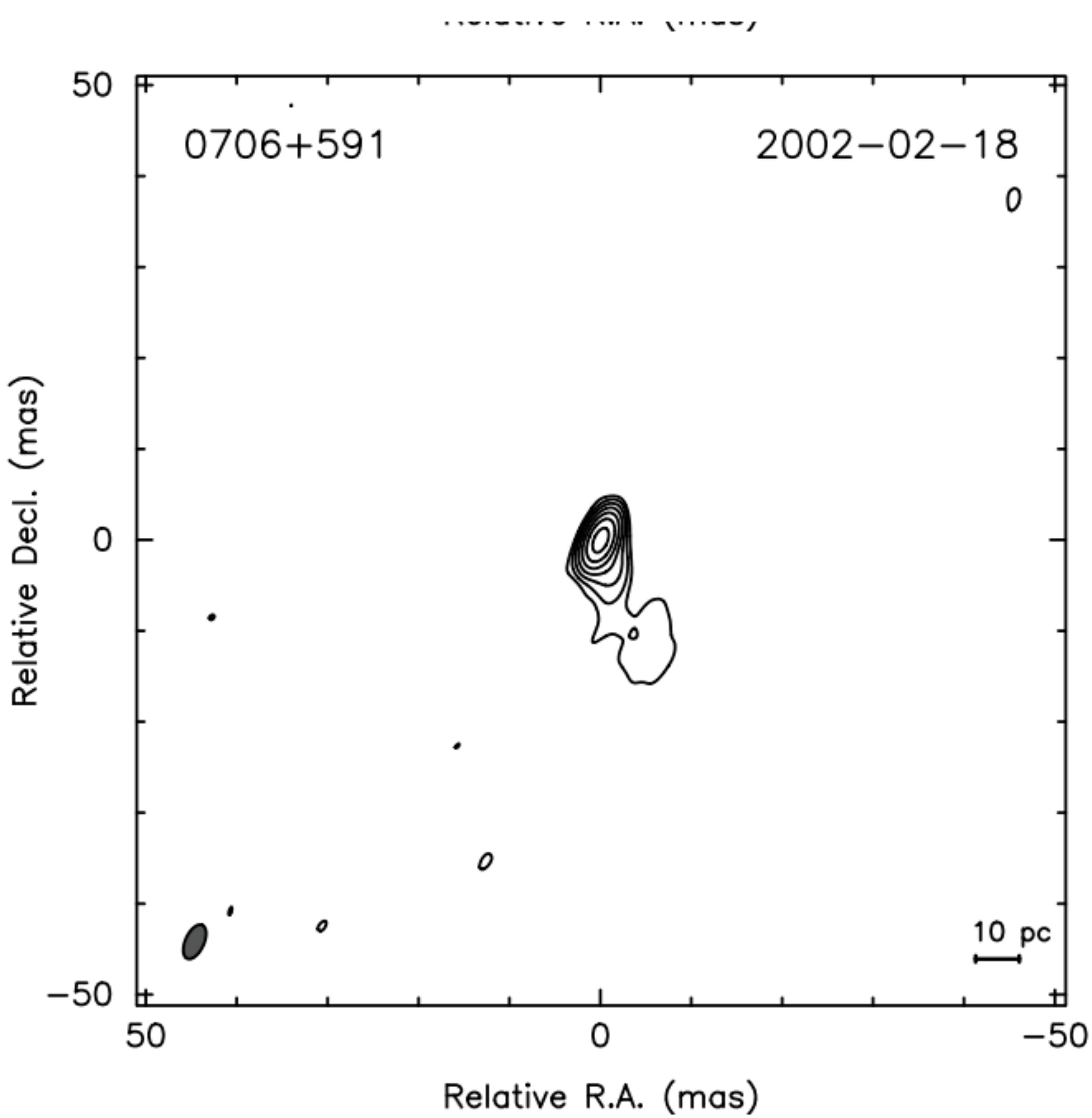
Vintage Quasar Gx-3611 Boombox...

$79.99

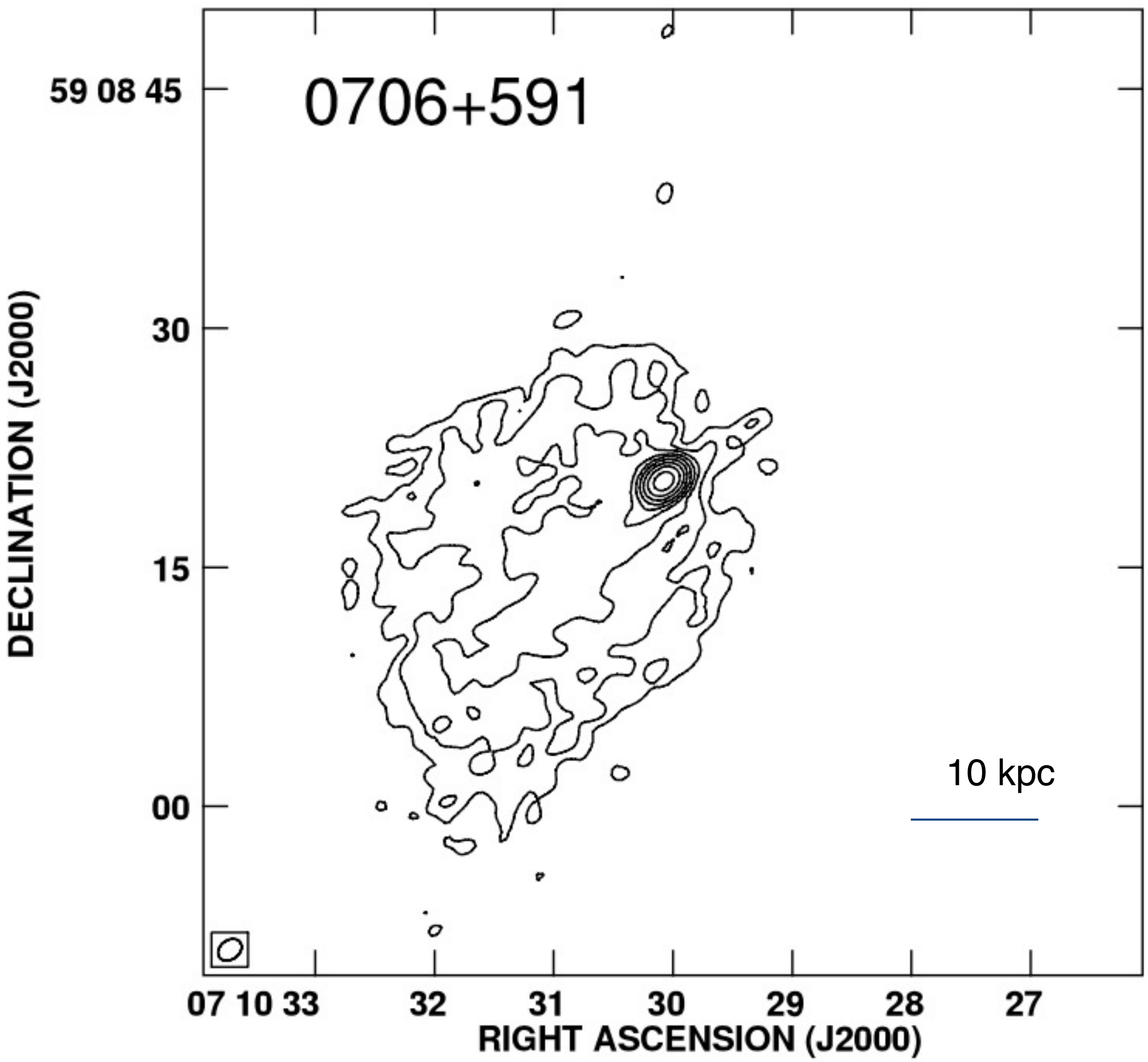
Used

eBay

Nearby Blazar 0706+591



Nearby Blazar 0706+591

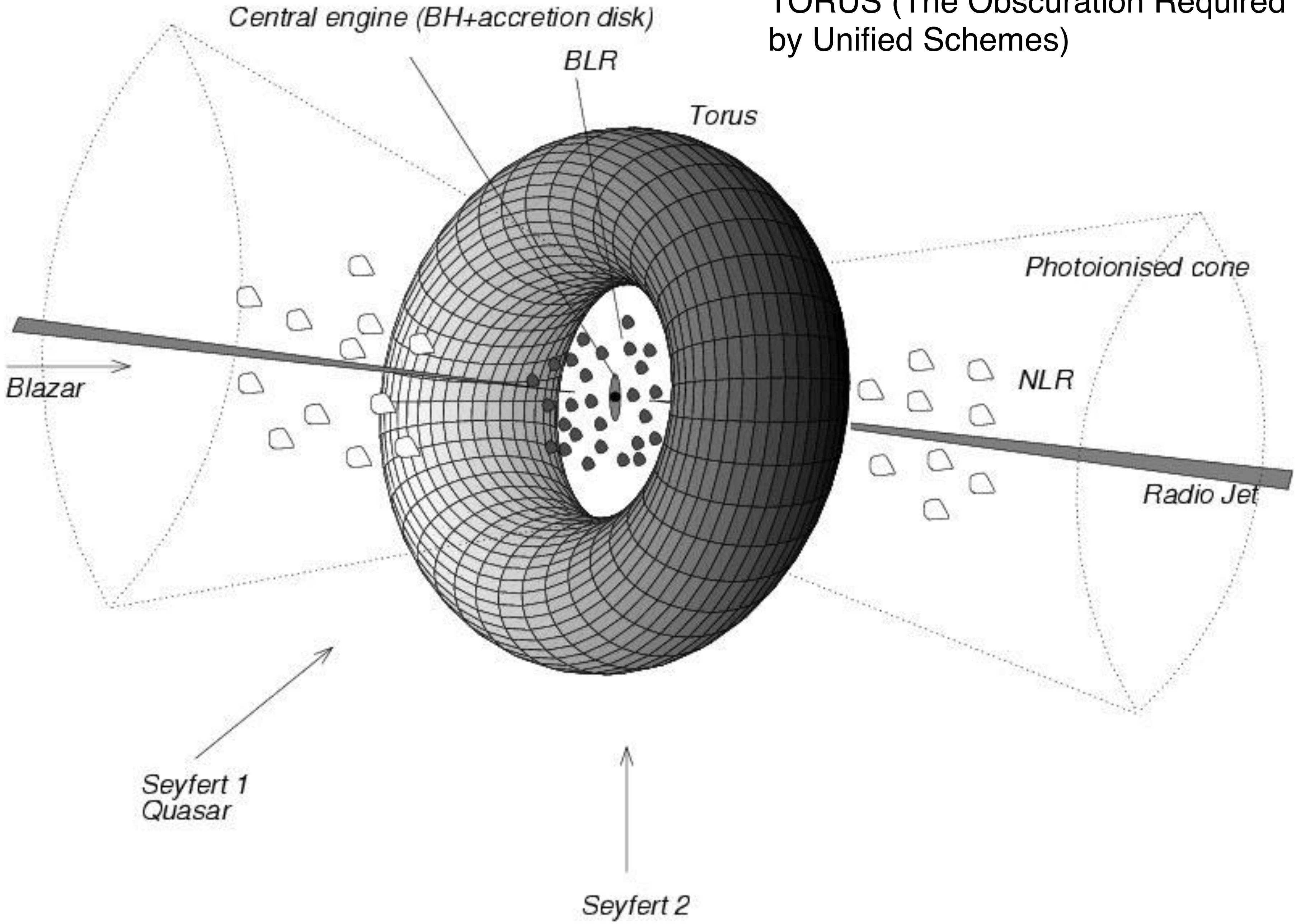


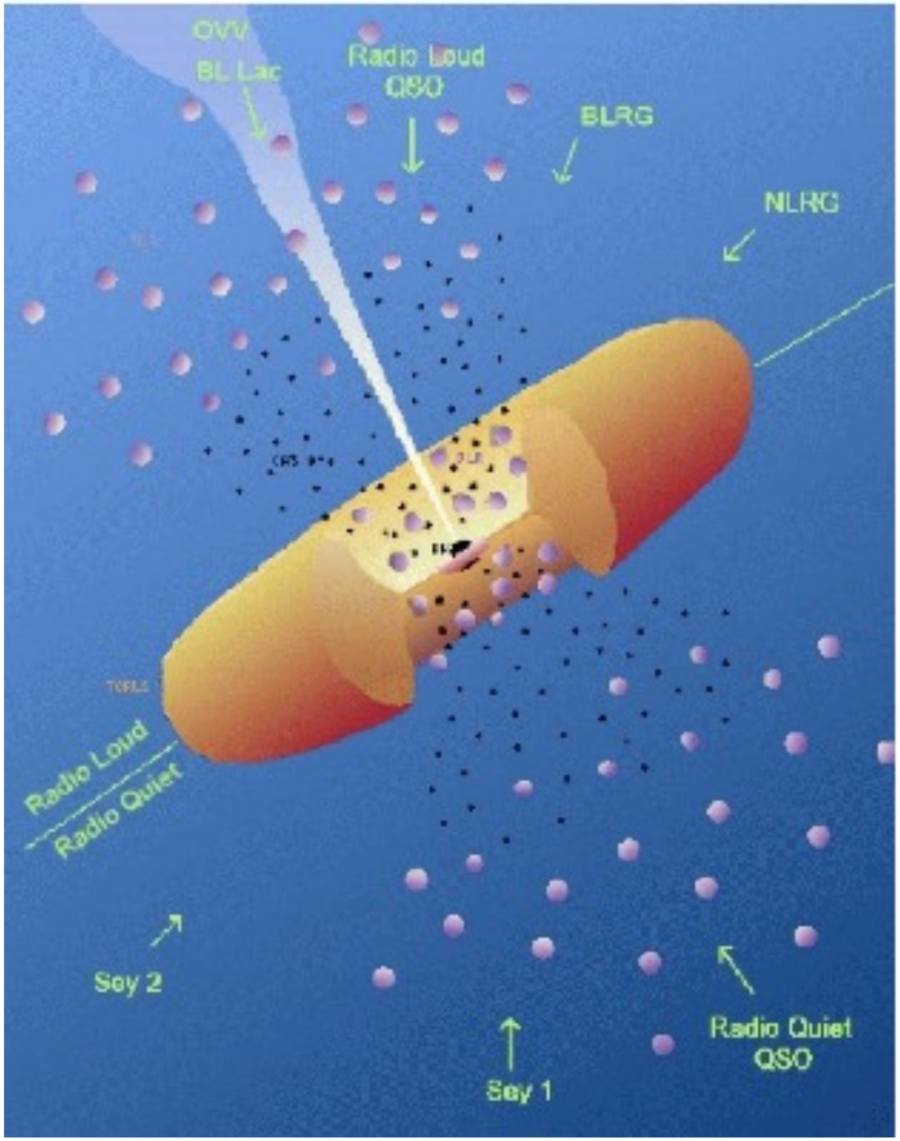
AGN classification

	Narrow Lines	Broad lines	Synchrotron	
	Type 2	*Type 1*	*Type 0*	*Optical Spectral Type*
Radio-quiet	**Seyfert 2**	**Seyfert 1**		
		Radio-quiet Quasars		
Radio-loud	**Narrow Line Radio Galaxies FRI**	**Broad Line Radio Galaxies FRII**	**Blazars**	
	NLRG FRII	**Lobe-dominated Quasars FRII**	**Core-dominated Quasars HPQ, OVV FSRQ**	

Luminosity

TORUS (The Obscuration Required by Unified Schemes)

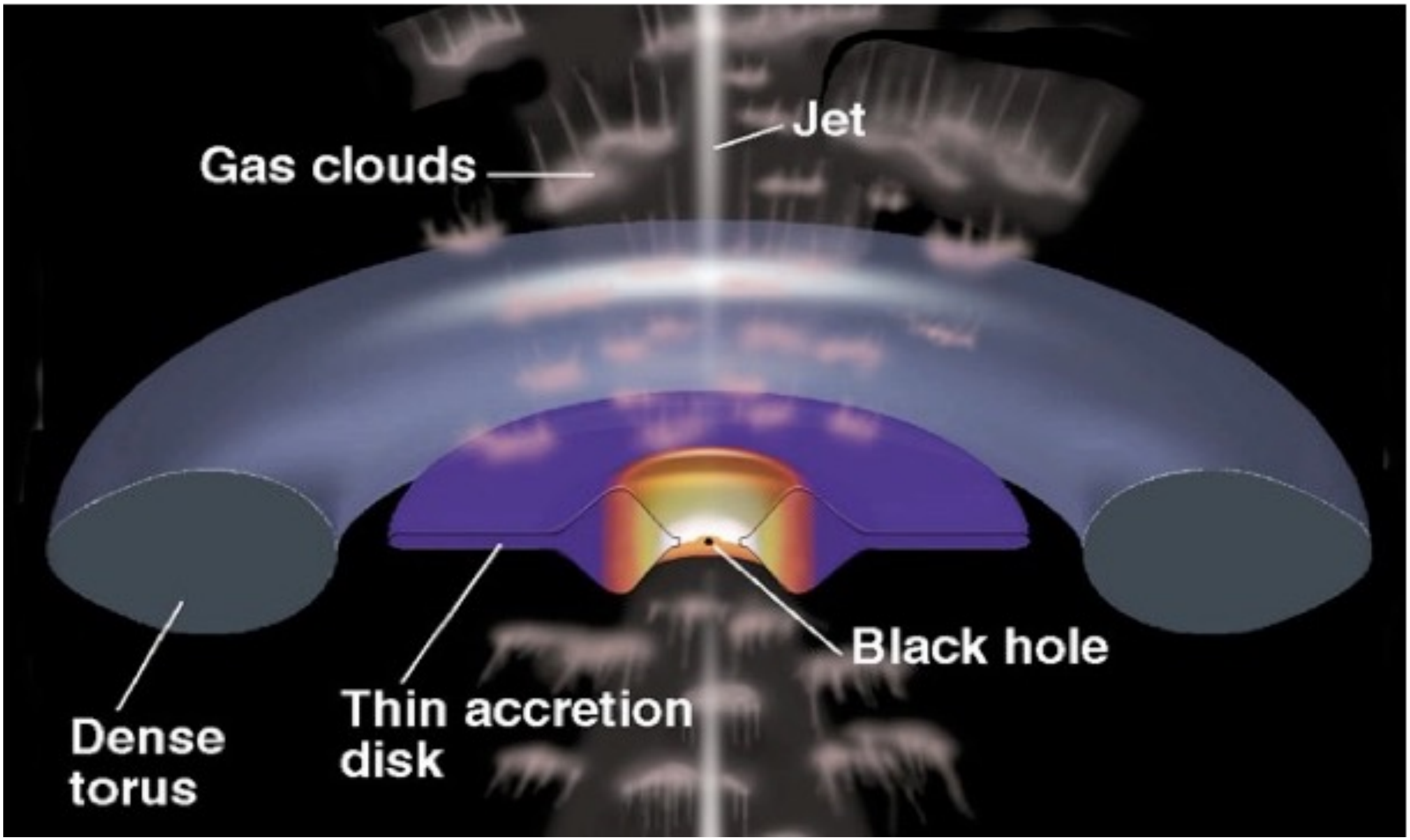




	Face-on	Edge-on
Radio-quiet	Sy1	Sy2
	QSO	
Radio-loud	BL Lac	FRI
	BLRG	NLRG
	Quasar	FRII

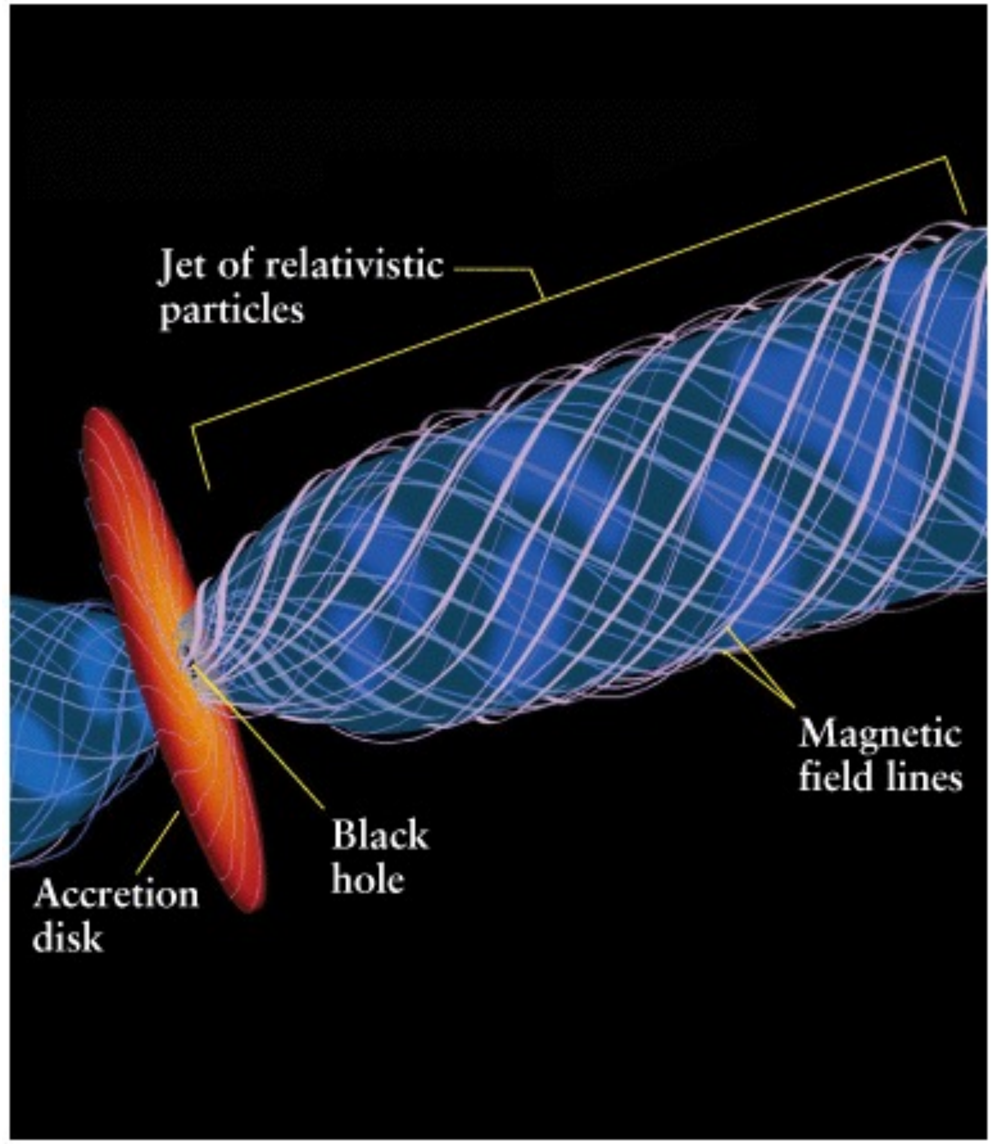
Proposed by Rowan-Robinson in 1977, and became a popular model in the mid-80s.

Model for the central region: SMBH, surrounded by accretion disk containing infalling material. If conditions are right, the AGN may possess a magnetically confined jet (the source of radio emission).



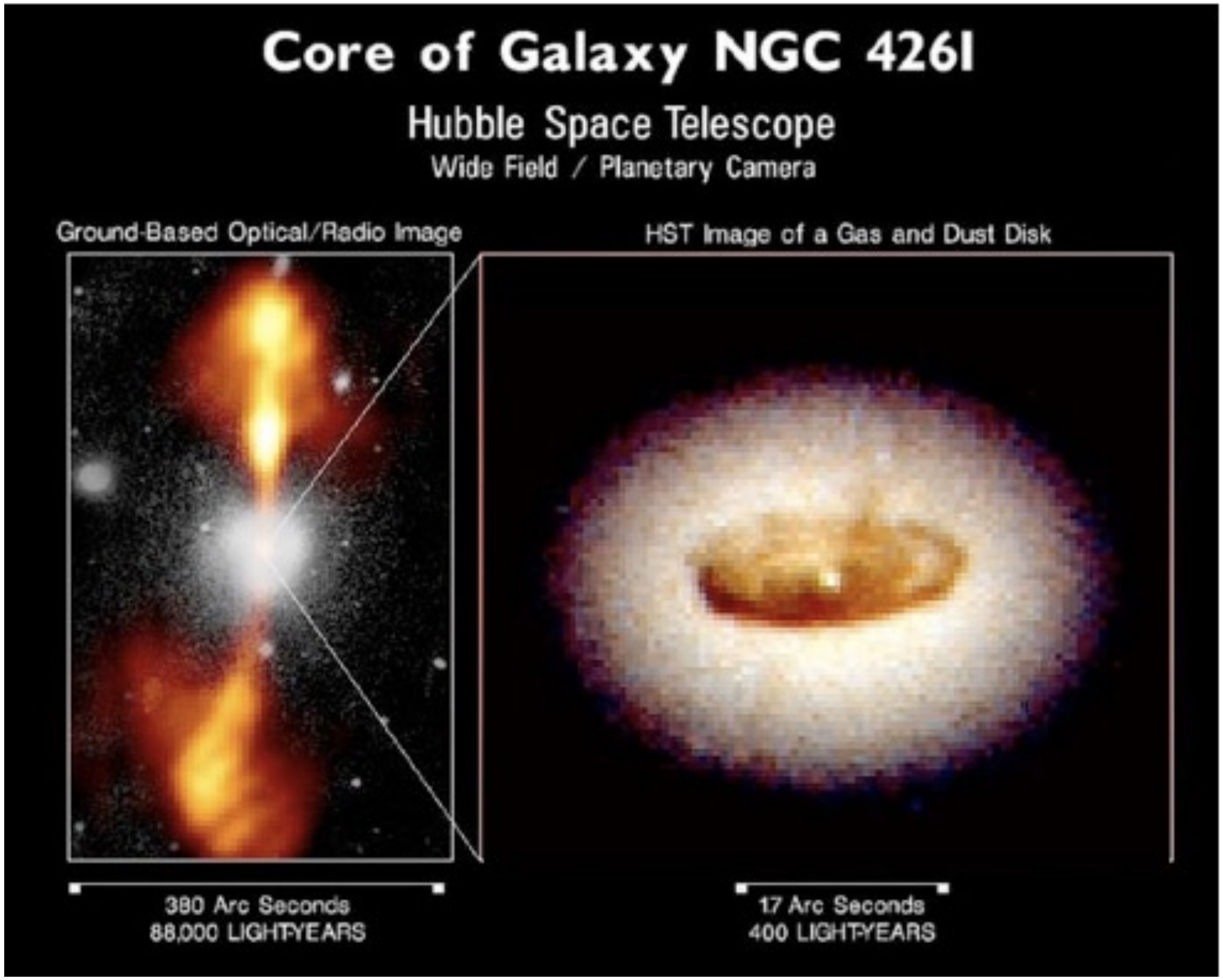
Gas pressures and temps get very high in inner accretion disk – matter can be expelled away from disk in 2 jets.

Jets kept narrow by magnetic fields.

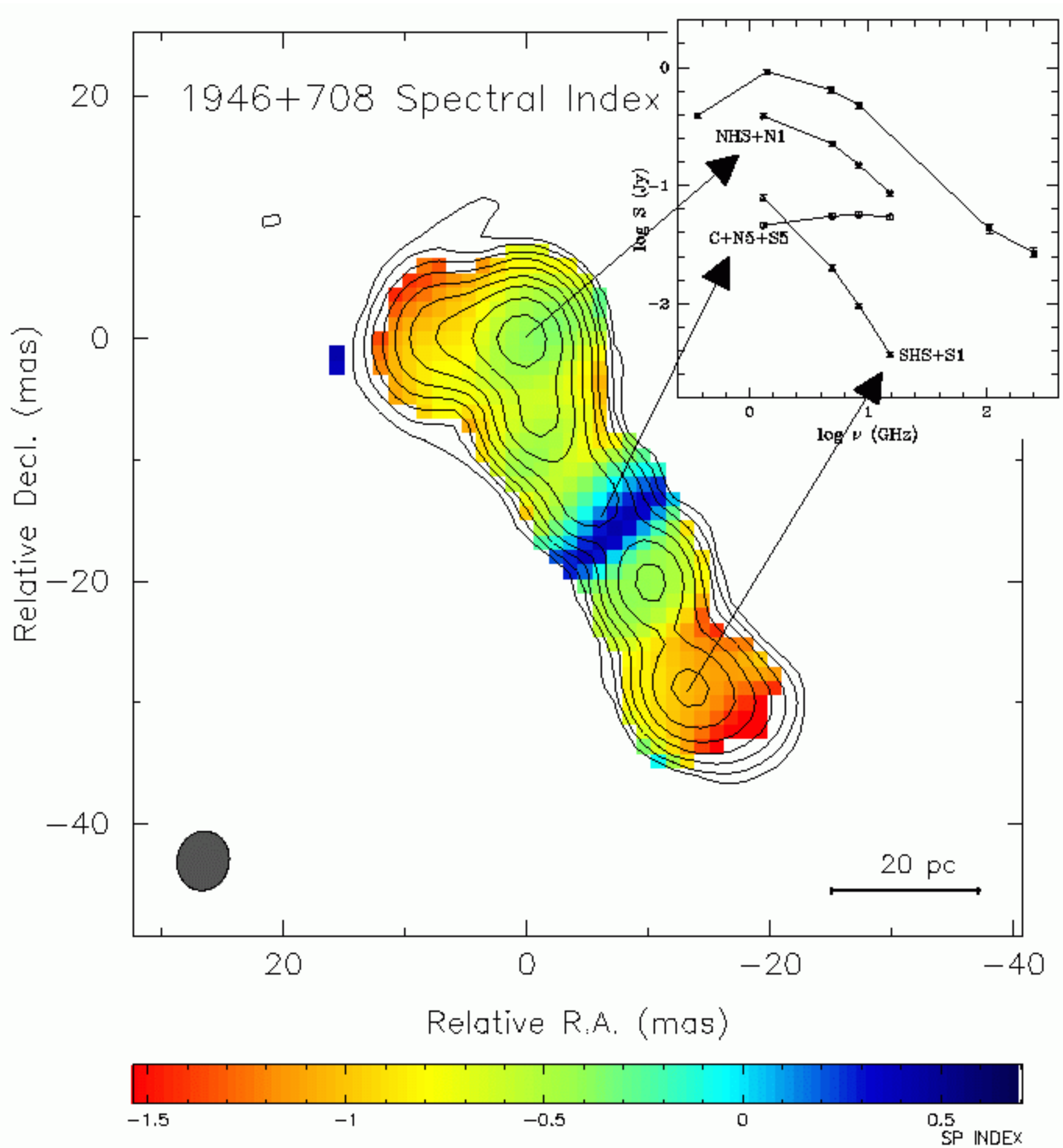


Support for unification:

Direct imaging of torus



Free-free absorption in 1946+708



Peck & Taylor (2001)

Spectral index map from 1.3/5 GHz VLBI observations

Energy source

- AGN power output truly huge.

- Comes from release of potential energy as gas falls toward black hole.

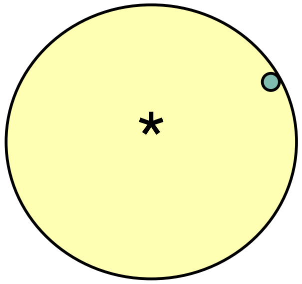
$$PE = -Gm_{gas}M_{bh}/r$$

- Energy released when a particle falls toward a black hole is the difference between its potential energy when $r = \infty$ and when $r \Rightarrow R_s$

- Change in energy $= -Gm_{gas}M_{bh}/\infty + Gm_{gas}M_{bh}/r$

$$= 0 + \text{very large number!}$$

Bondi Accretion



$$v = (2GM/R)^{1/2}$$

$$= c\,(R_g/R)^{1/2}$$

$$L = 0.5\ \dot{M}\, c^2\ (Rg/R)$$

$$L = \varepsilon\, \dot{M}\, c^2$$

and $\dot{M} = \pi R_b^2 \rho v$

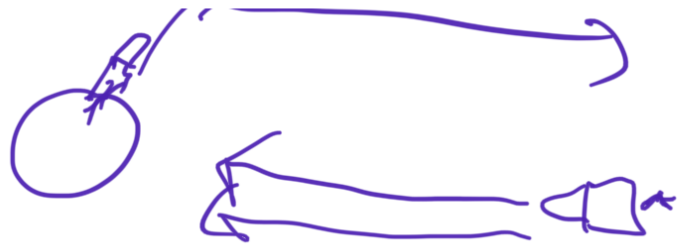
c = speed of light
v = velocity
R = object radius
R_g = gravitational radius
ε = efficiency

$\varepsilon = 3 \times 10^{-4}$ for accretion onto a white dwarf, 0.15 for a neutron star
ε up to 0.5 for a rotating black hole

Compared to 7×10^{-3} for hydrogen fusion, or 10^{-9} for chemical reactions

Accretion is a very efficient energy source

Energy source



$$v_{esc} = \sqrt{\frac{2GM}{R}}$$

$$P.E = -\cancel{\frac{GmM_{BH}}{r_\infty}}^{\,0} + \frac{GmM_{BH}}{r_s} \qquad r_s = \frac{2GM}{c^2}$$

$$K.E. = P.E \approx \frac{GmM_{BH}}{\frac{2GM_{BH}}{c^2}} = \frac{1}{2}c^2 m_{gas} \qquad E = mc^2$$

$$\frac{1}{2}mv^2 = P.E = E = \frac{1}{2}m_{gas}c^2$$

$$E/s = \frac{1}{2}\dot{m}c^2$$

$$L = \frac{1}{2}\dot{m}c^2 \approx \varepsilon \dot{m}c^2$$

How much luminosity can an AGN make?

The Eddington luminosity is the maximum possible luminosity that can be radiated without blowing away the accreting gas (via radiation pressure)

$$L_{edd}=3x10^{4}\ (M/M_{sun})\ L_{sun}$$

M = black hole mass

Worksheet 15

Worksheet 15 solution

a) $L_{edd} = 3\times10^{4} \cdot 10^{9}\ L_\odot$

$= 3\times10^{13}\ L_\odot = \varepsilon \dot{m} c^2$

b) $3\times10^{13}\ L_\odot = \frac{1}{2}\dot{m}c^2$

c) $\dot{m} = \frac{2 \cdot 3\times10^{13}\ L_\odot}{c^2} = \frac{6\times10^{13}\ L_\odot \cdot \frac{3.84\times10^{26}\ W}{1\ L_\odot}}{\cancel{0.5}\ (3\times10^{8}\ m/s)^2}$

$= 2.56\times10^{23}\ \frac{kg}{s} \cdot \frac{1\ M_\odot}{2\times10^{30}\ kg}$

$= 1.28\times10^{-7}\ \frac{M_\odot}{s} \cdot \frac{3.14\times10^{7}\ s}{yr}$

$= 4\ M_\odot/yr$

Presentation Schedule (RH114)

Dec 3 11:00-12:15

- Dean Montroy (ASU)
- Giovanna Cartagena (MIT)
- Franco Uribe Lavalle (Stanford)
- Olwyn Hagerty (UCLA)
- Alex Robinson (Caltech)
- Mason Winner (UA)
- Charles Dana (NAU)

Powerpoint talk
Length = 7 min + 2 min Q&A

Send slides to me the day before and I will put them on a presentation laptop (mac).

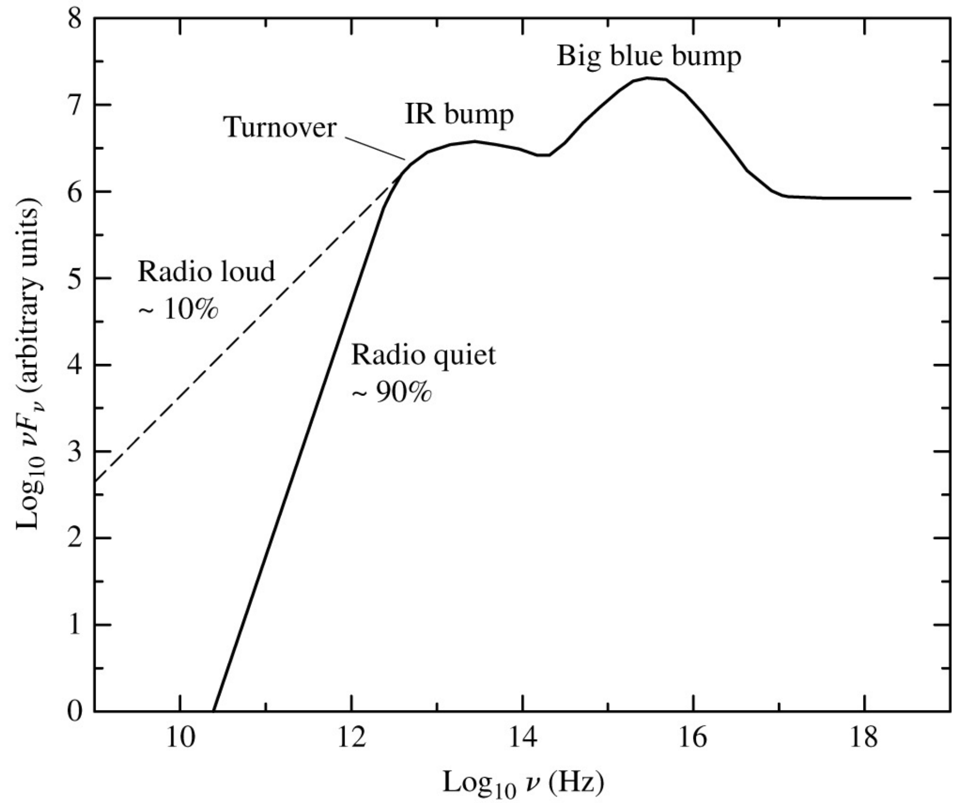
Dec 5 11:00-12:15

- Govind Sarraf (UNM)
- Elizabeth Shields (NMSU)
- Madeline Ayling (UA)
- Sara Pezzaili (Harvard)
- Aniketh Sarkar (JHU)
- Emma Barney (UC Boulder)
- Louis Jencka (UC Boulder)

Dec 10 12:30-2:30

- Jacky Privette (Berkeley)
- Viktoria Aivaliotis (Caltech)
- Stephanie Paiva-Flynn (ASU)
- Juaquin Sanchez (UCLA)
- Santiago Armijo (Berkeley)
- Arnel Oczon (TTU)

Spectral Energy Distributions (SEDs) for AGN



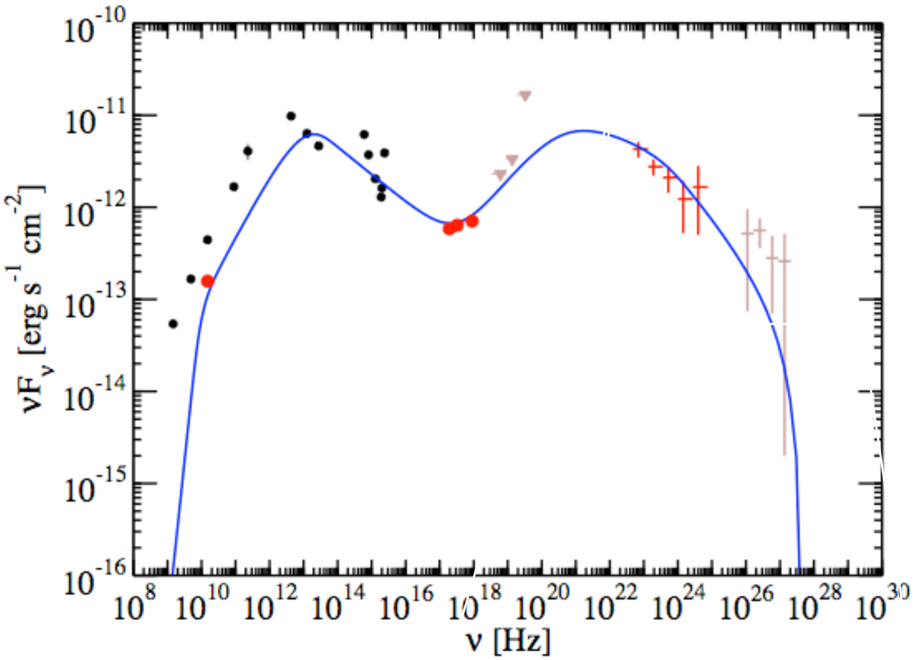
L_{IR} contains up to 1/3 of the bolometric luminosity

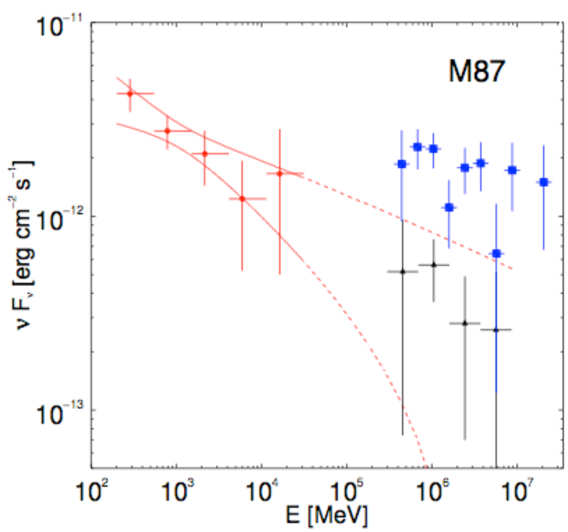
L_{BBB} contains a large fraction of L_{bol} as well

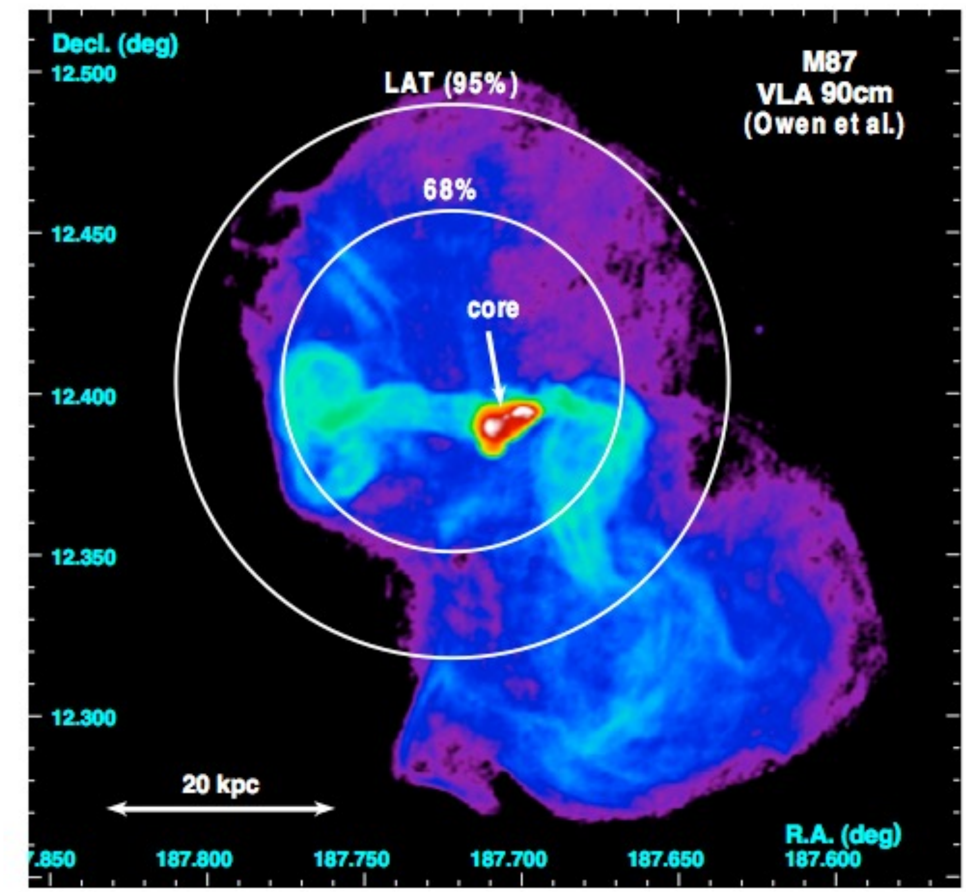
IR bump due to dust reradiation

BBB due to blackbody emission from accretion disk

M87

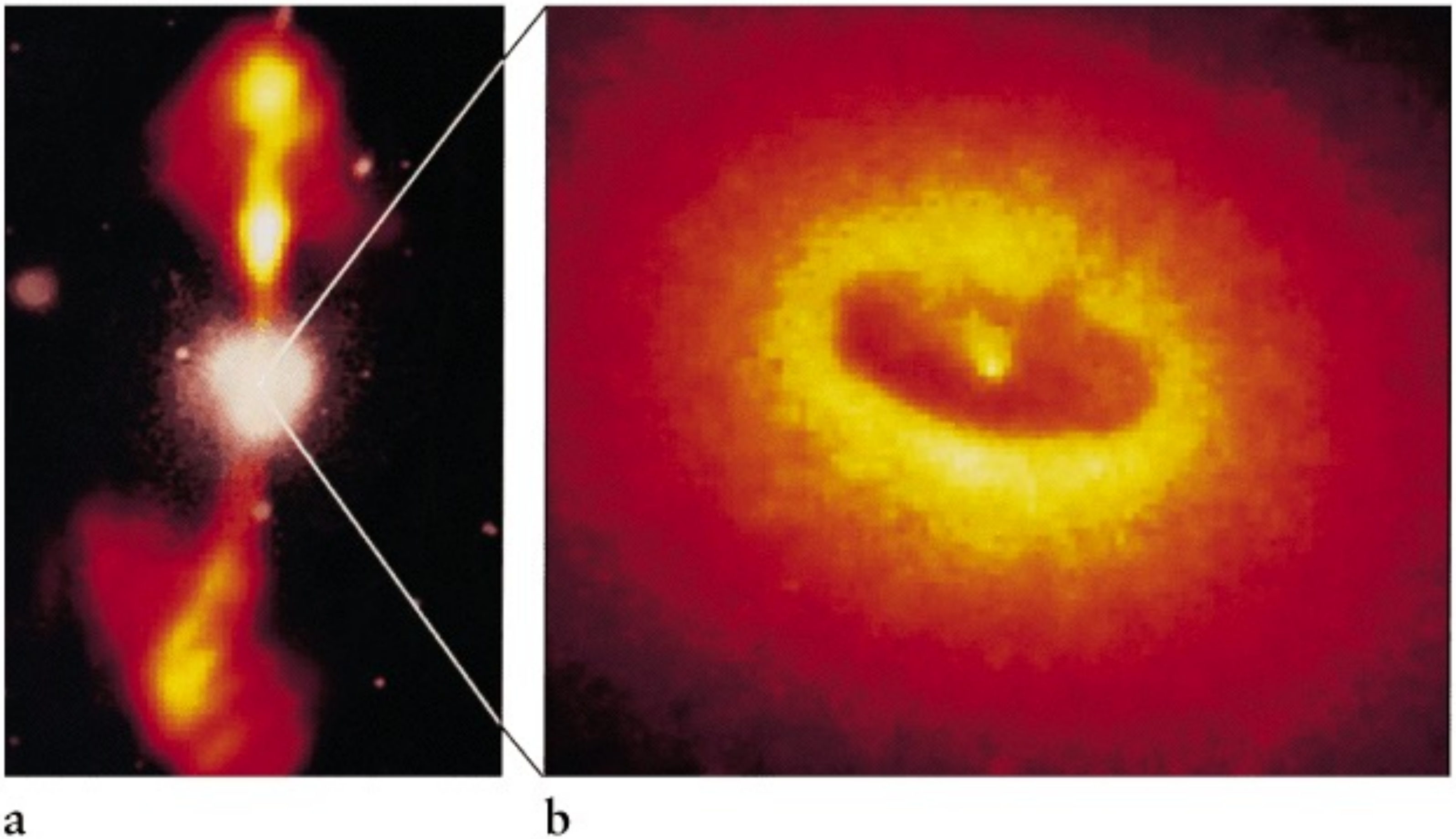


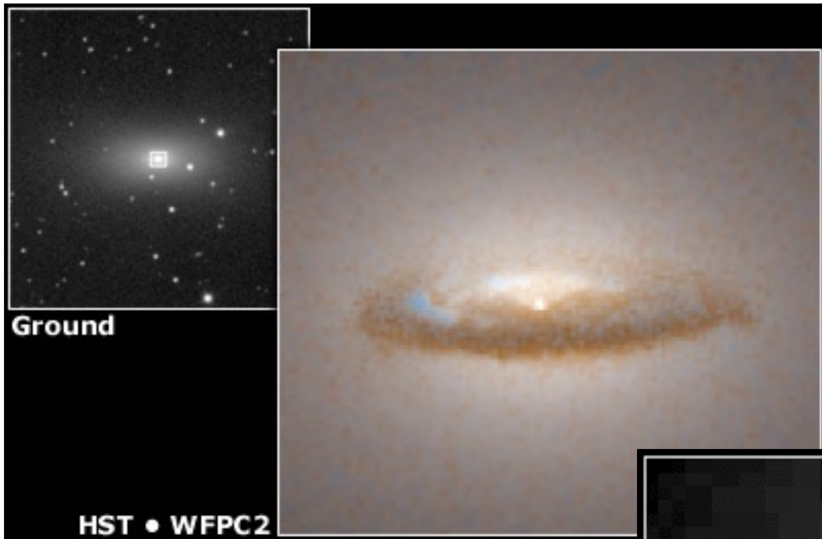


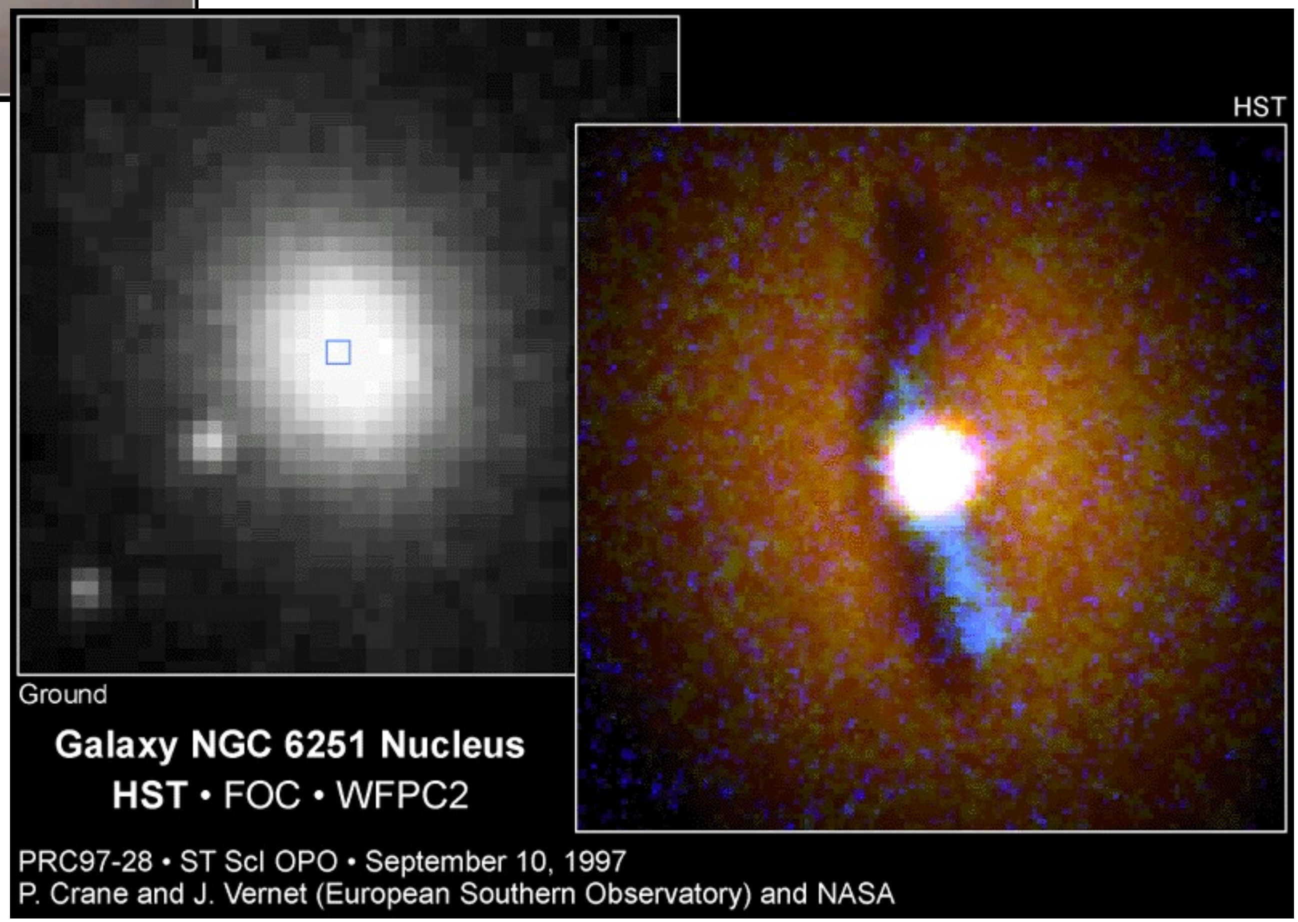


Abdo et al. (2009)

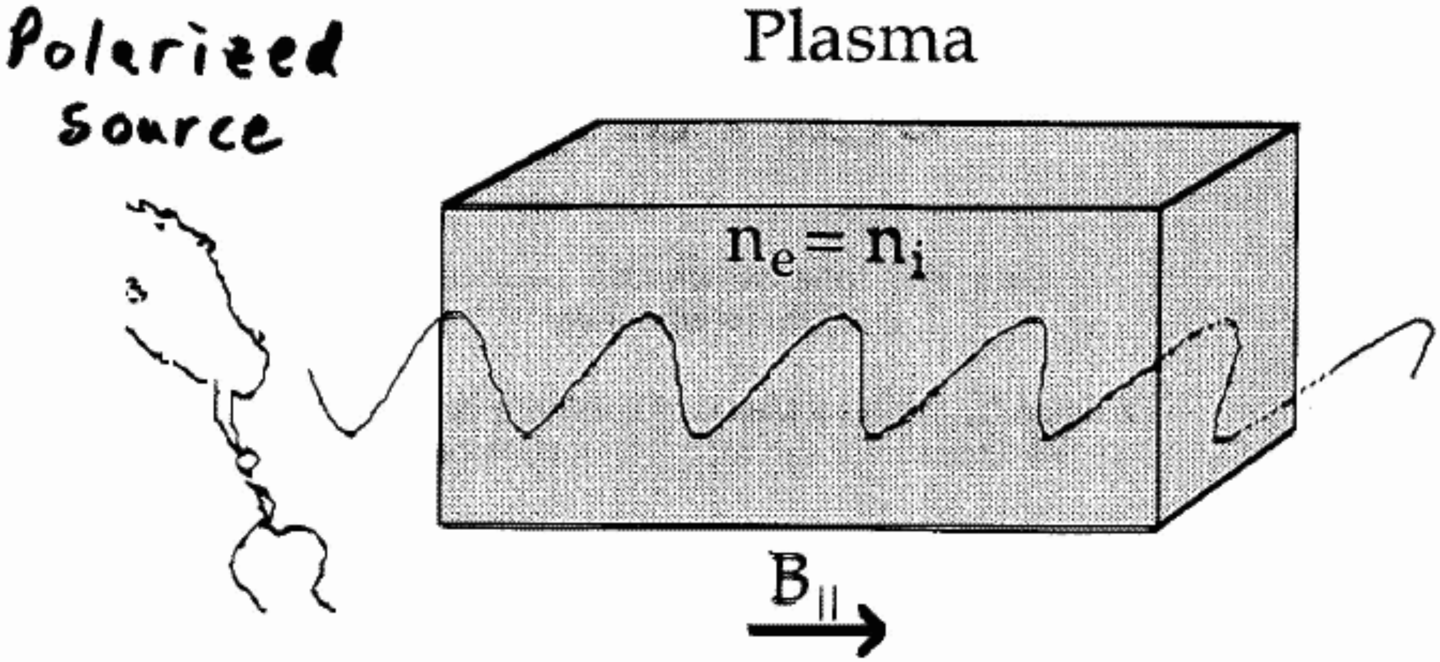
The accretion disk around a black hole in NGC 4261




Ground
HST • WFPC2


HST
Ground
Galaxy NGC 6251 Nucleus
HST • FOC • WFPC2
PRC97-28 • ST ScI OPO • September 10, 1997
P. Crane and J. Vernet (European Southern Observatory) and NASA

Faraday Rotation

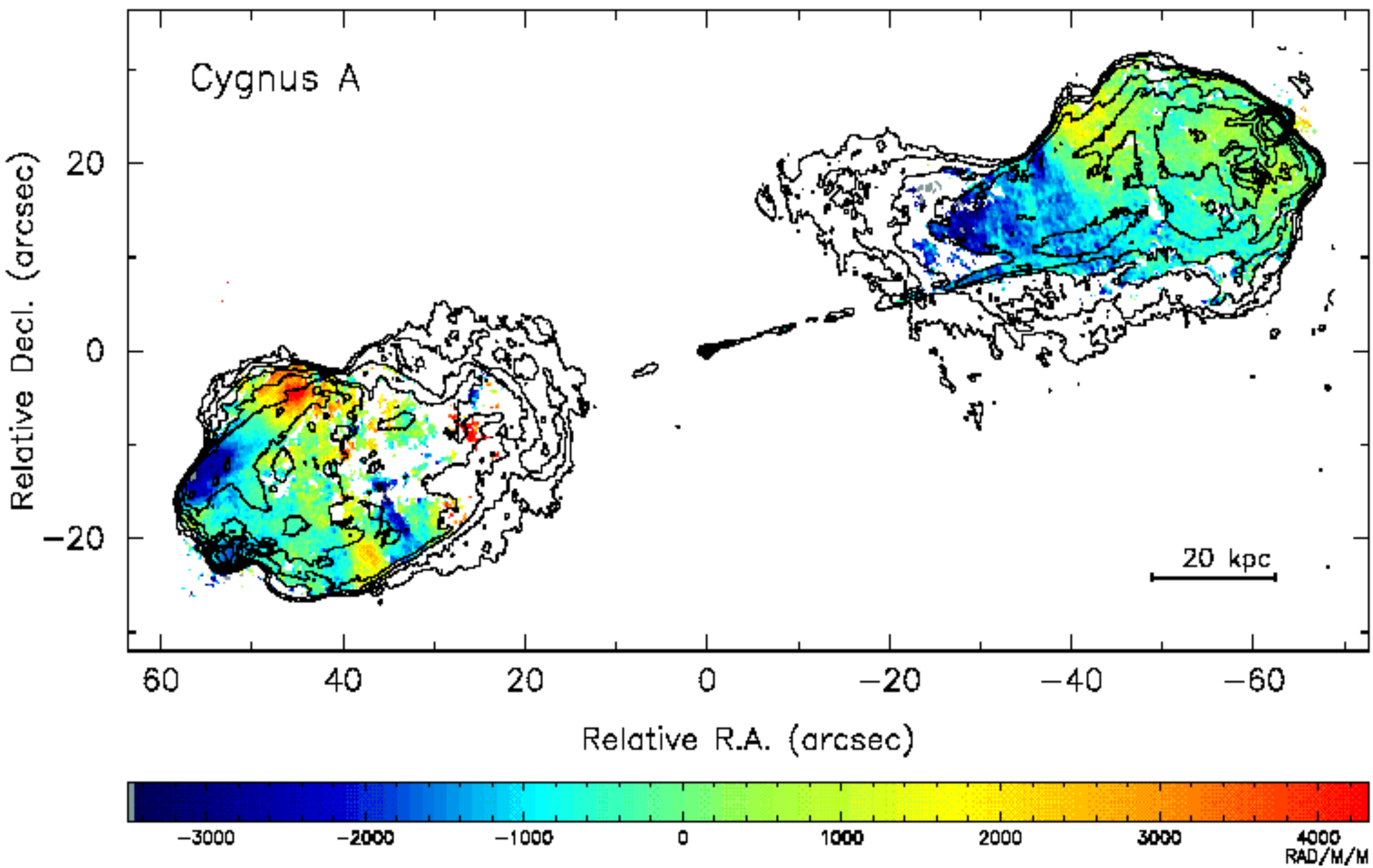


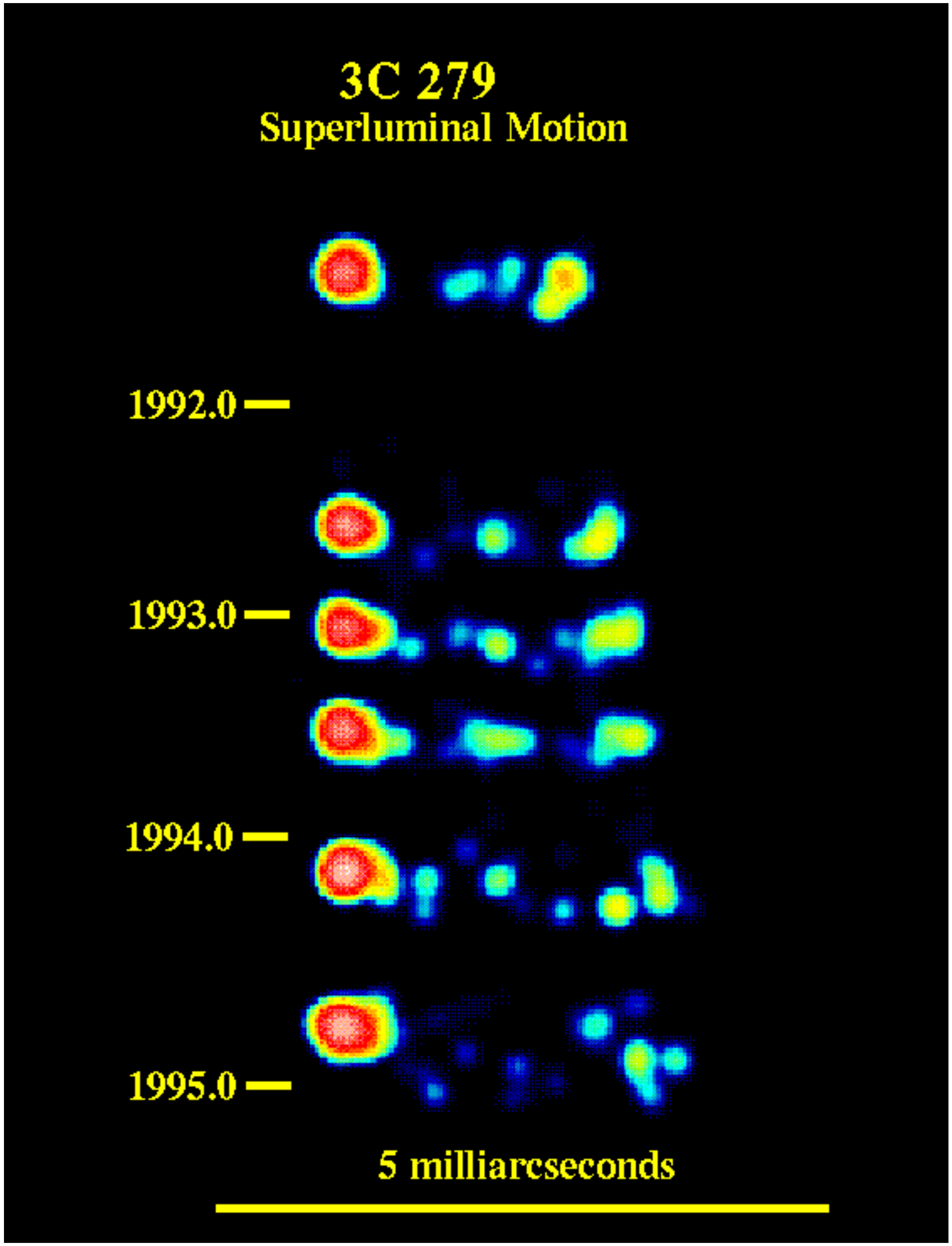
$$\Psi = \Psi_o + \mathrm{RM}\,\lambda^2$$

kpc μGauss

$$\mathrm{RM} = 812 \int_0^L n_e B_{||}\, dl \ \text{radians/m}^2$$

cm^{-3}

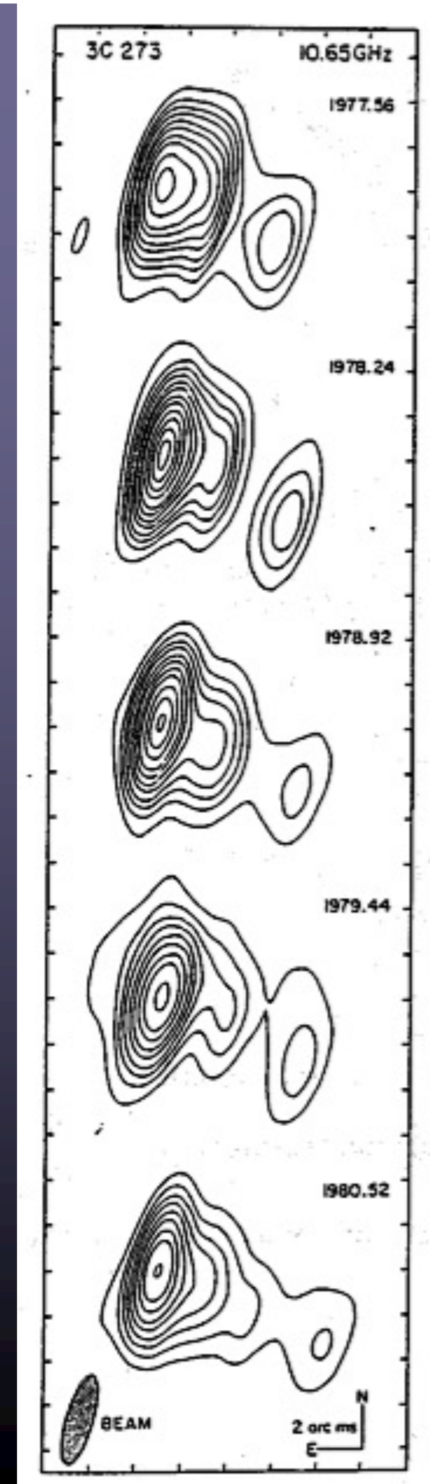

Cygnus A
Relative Decl. (arcsec)
20
0
−20
60
40
20
0
−20
−40
−60
Relative R.A. (arcsec)
20 kpc
−3000
−2000
−1000
0
1000
2000
3000
4000
RAD/M/M

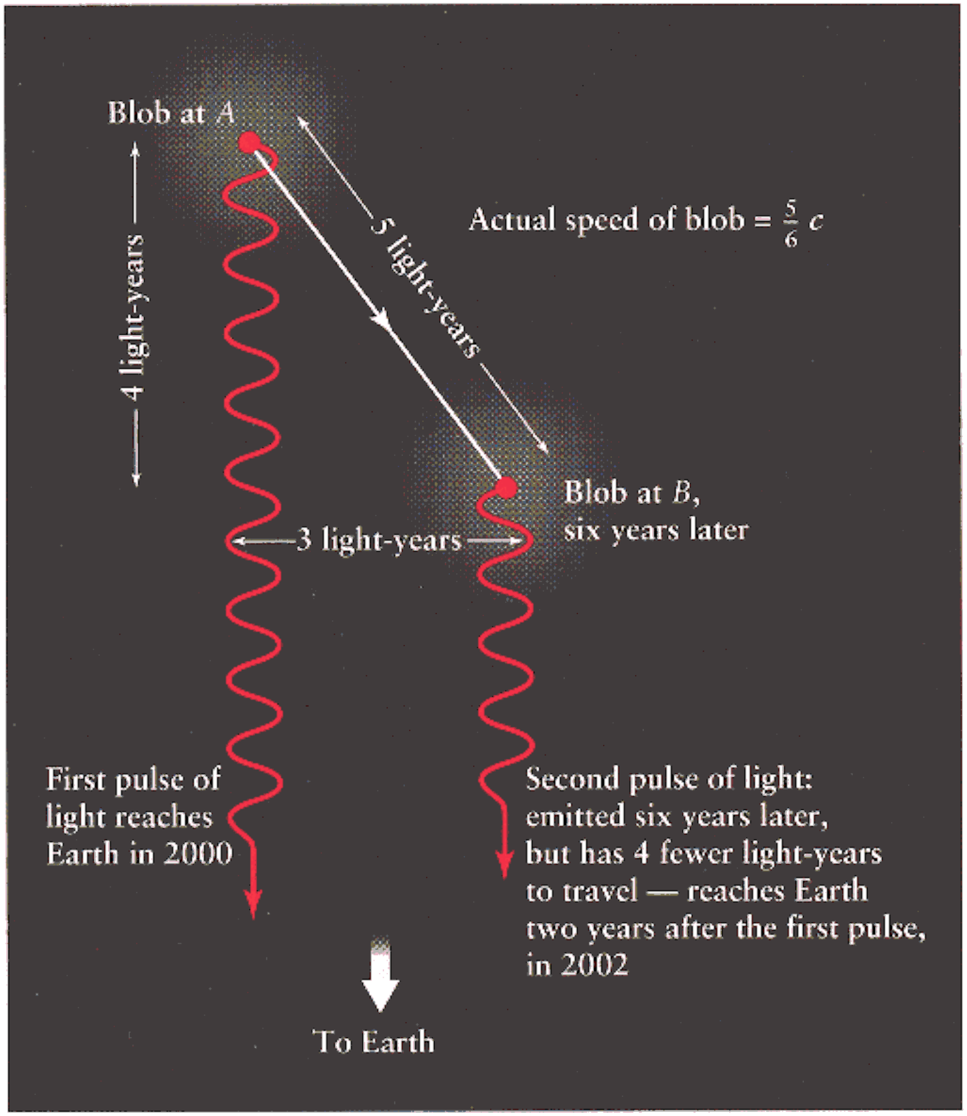

3C 279
Superluminal Motion
1992.0
1993.0
1994.0
1995.0
5 milliarcseconds

EXAMPLE 2
Superluminal motion

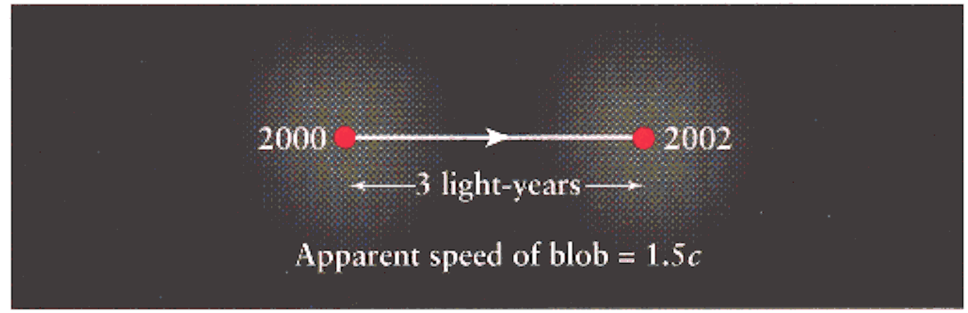
Pearson et al. 1981

constant expansion observed at
rate = $\Delta\theta$/year = 0.76 ± 0.04 mas/year
$z = 0.158$ so D = 940 Mpc
assuming $H_0 = 50$ km sec^{-1} Mpc^{-1}.
1 mas = 10^{-3} arcsec = 4.85×10^{-9} radians
d = D$\Delta\theta$ so the apparent transverse
velocity, or rate = d/year
= 10 lt-years/year
= 10 c [!!]





a View from above



b View from Earth

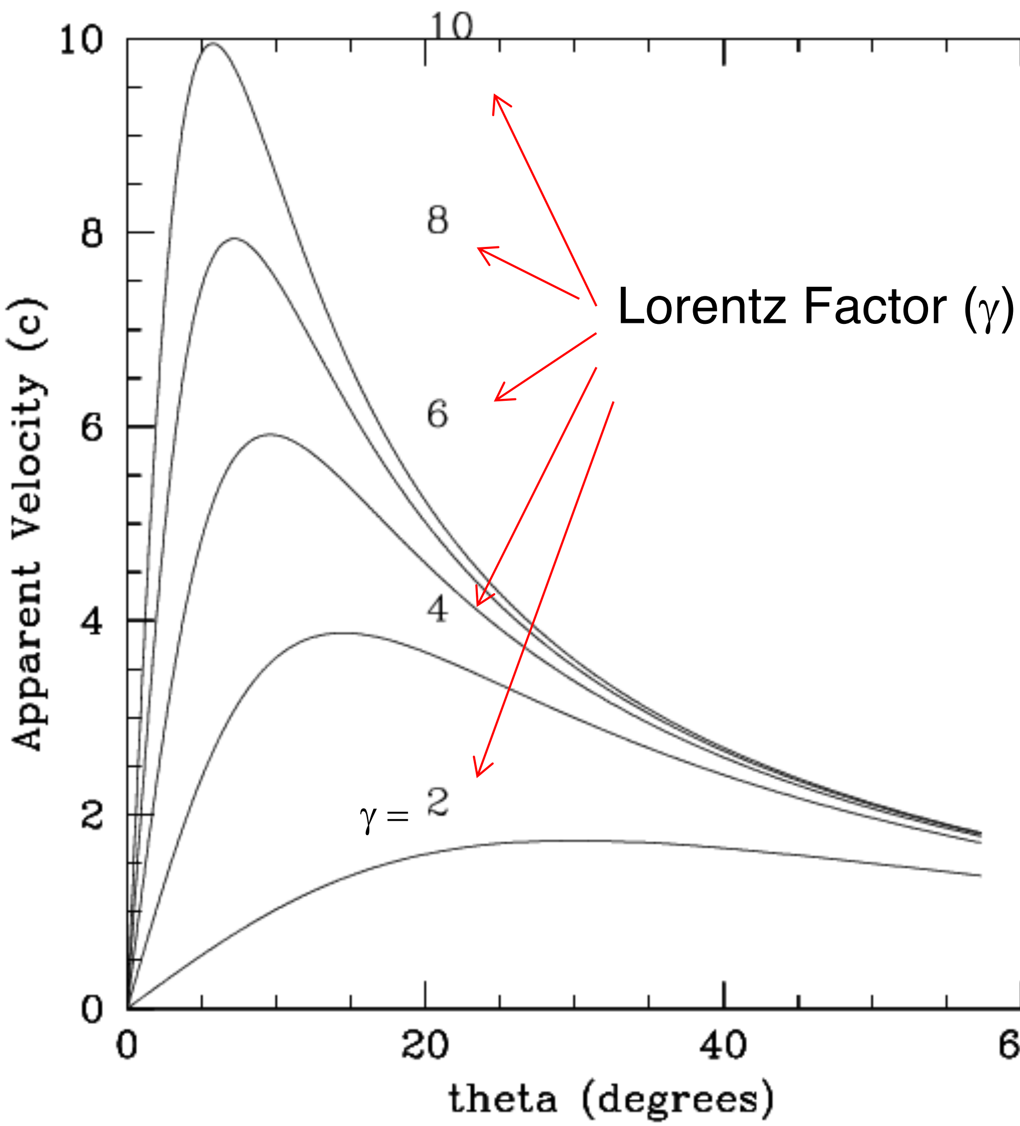
INTERACTIVE EXERCISE 27.2

Figure 27-18

An Explanation of Superluminal Motion An object moving almost directly toward the Earth at a high speed (but slower than light) can appear to be going faster than light. **(a)** If a blob of material ejected from a quasar moves at five-sixths of the speed of light, it covers the 5 light-years from point A to point B in six years. In the case shown here, it moves 4 light-years toward the Earth and 3 light-years in a transverse direction. The light emitted by the blob at A reaches us in 2000. The light emitted by the blob at B reaches us in 2002. The light left the blob at B six years later than the light from A but had four fewer light-years to travel to reach us. **(b)** From Earth we can see only the blob's transverse motion across the sky, as in Figure 27-18. It appears that the blob has traveled 3 light-years in just two years, so its apparent speed is $^3/_2$ of the speed of light, or 1.5 times c.

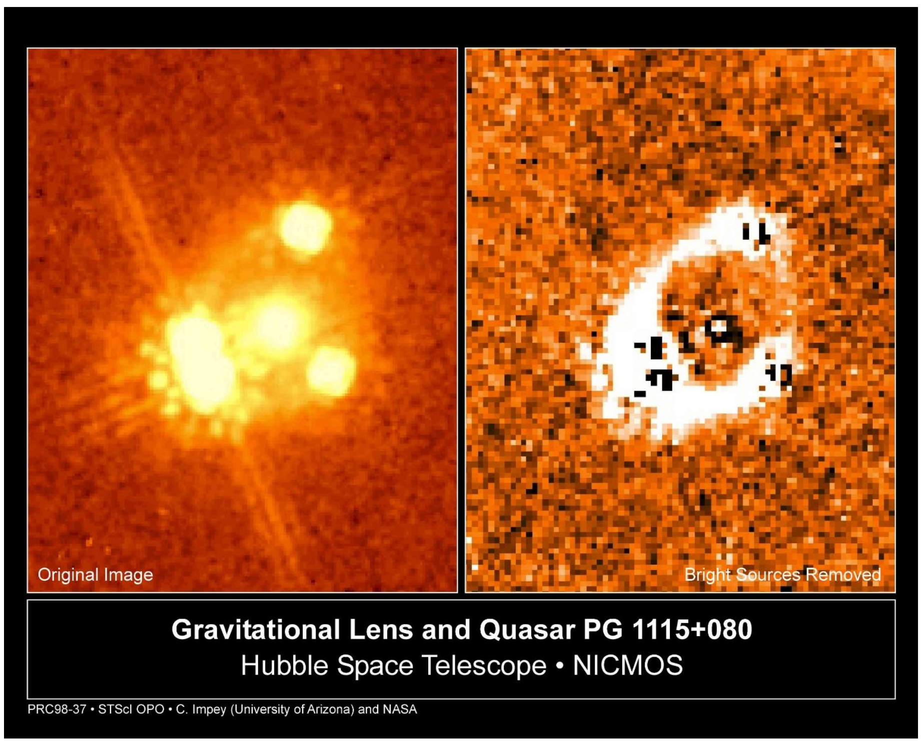
$$\beta\_app = \beta \sin(\theta) / (1 - \beta \cos(\theta))$$

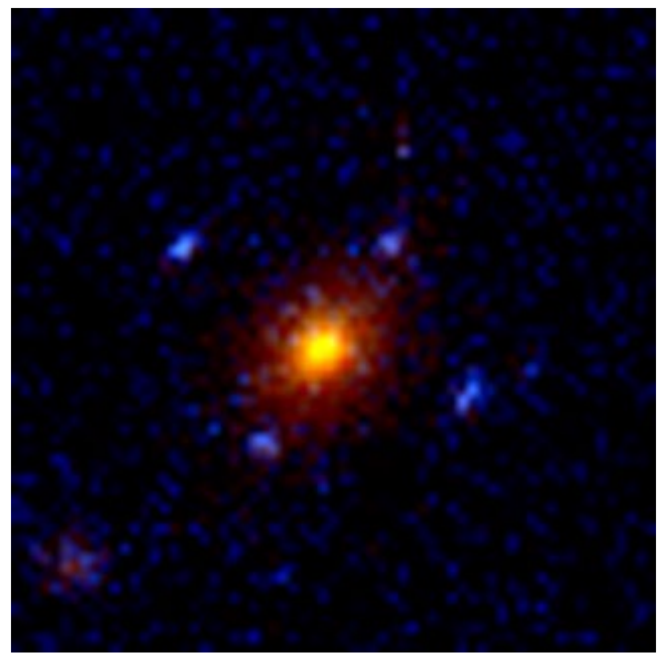
Apparent Velocity as a function of angle



Why are AGN interesting?

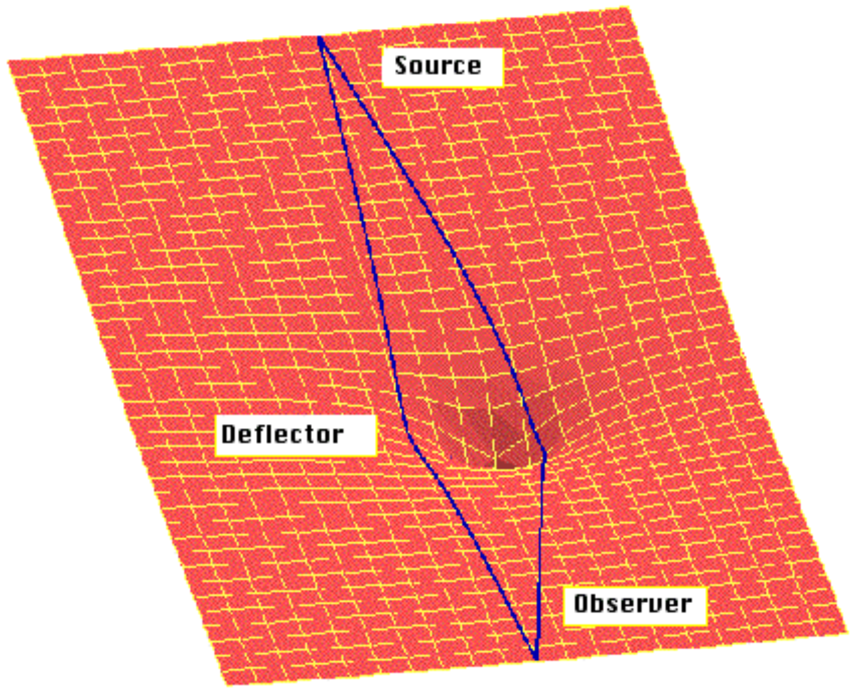
a) For studying black hole physics
b) Studying high energy physics
c) Background sources on cosmological scales
    a) Lyman alpha forest in optical spectra (absorbing gas in walls? IGM information)
    b) Gravitationally lensed by clusters, can get Hubble constant from time delay



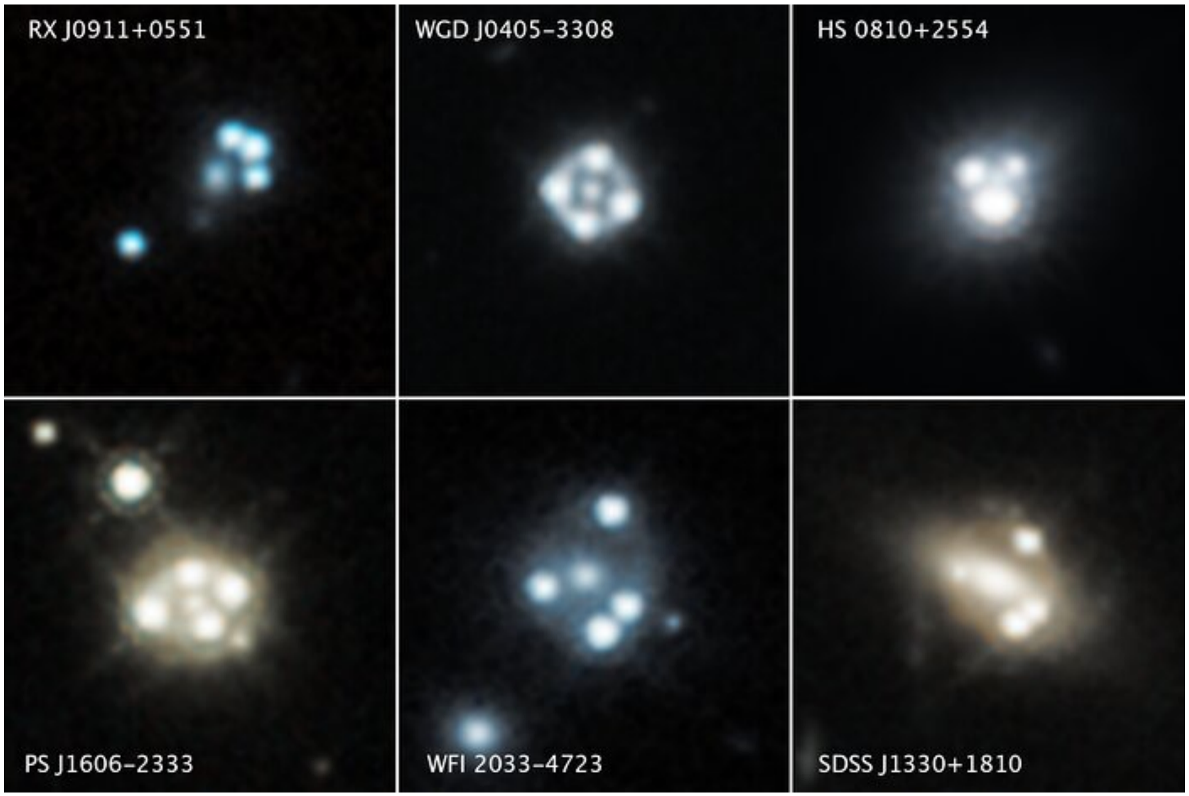


Gravitational lensing

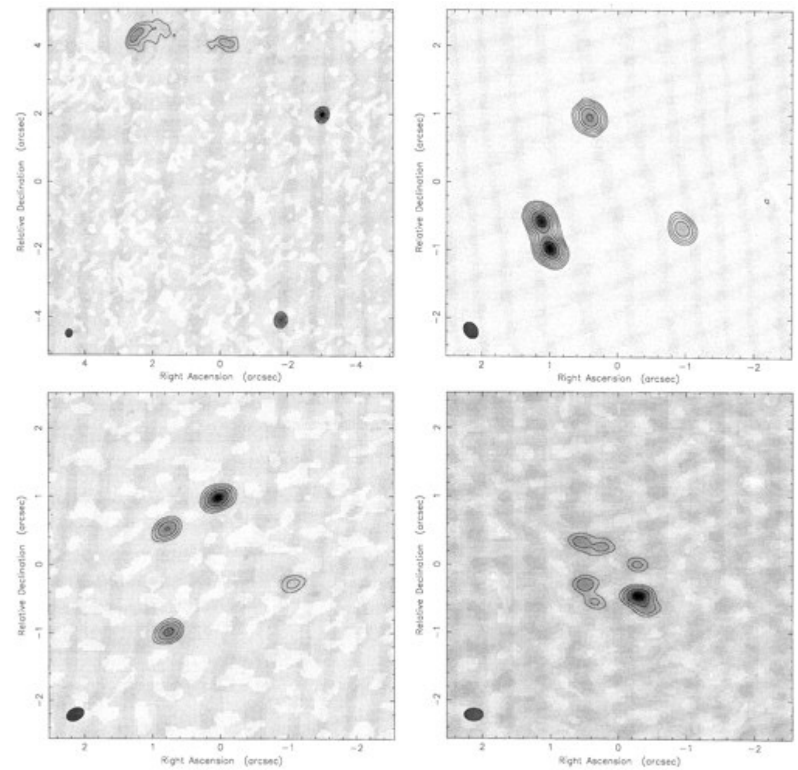
- The presence of matter distorts the path of the light.
- The distribution of matter determines how this distortion occurs.
- If we can measure the distortion, we can estimate the distribution of the matter!



Gravitational Lensing of Quasars



Optical with Hubble Space Telescope



Radio with VLA
Myers et al. 1999

c) background radiation to detect absorption lines in host galaxies at large redshifts

d) produce cosmic background radiation, e.g. X-ray wavelengths

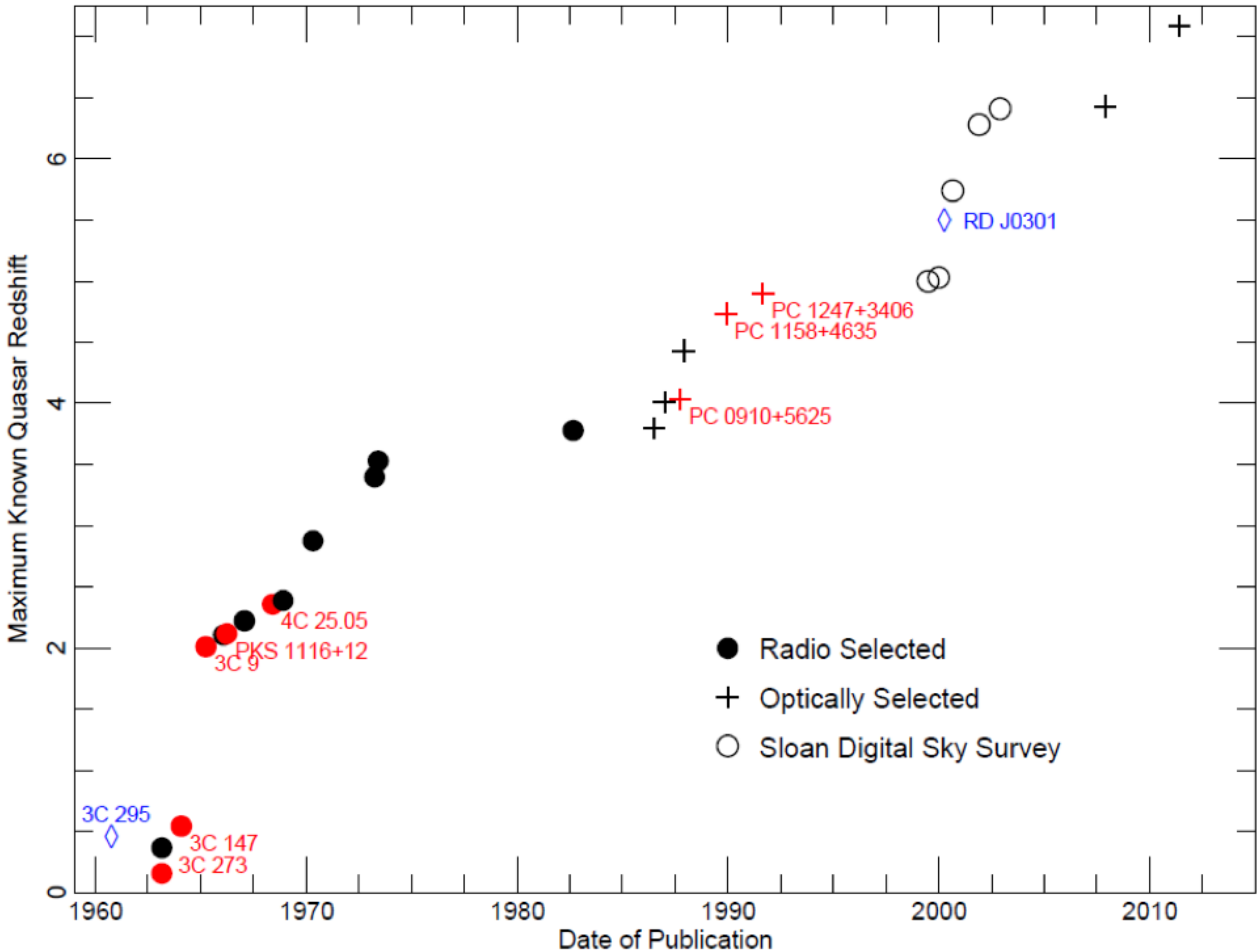
d) Use radio cores as cosmic reference points for fixed coordinate systems

e) History of the Milky Way: have all galaxies been an AGN at some point? Are they still?

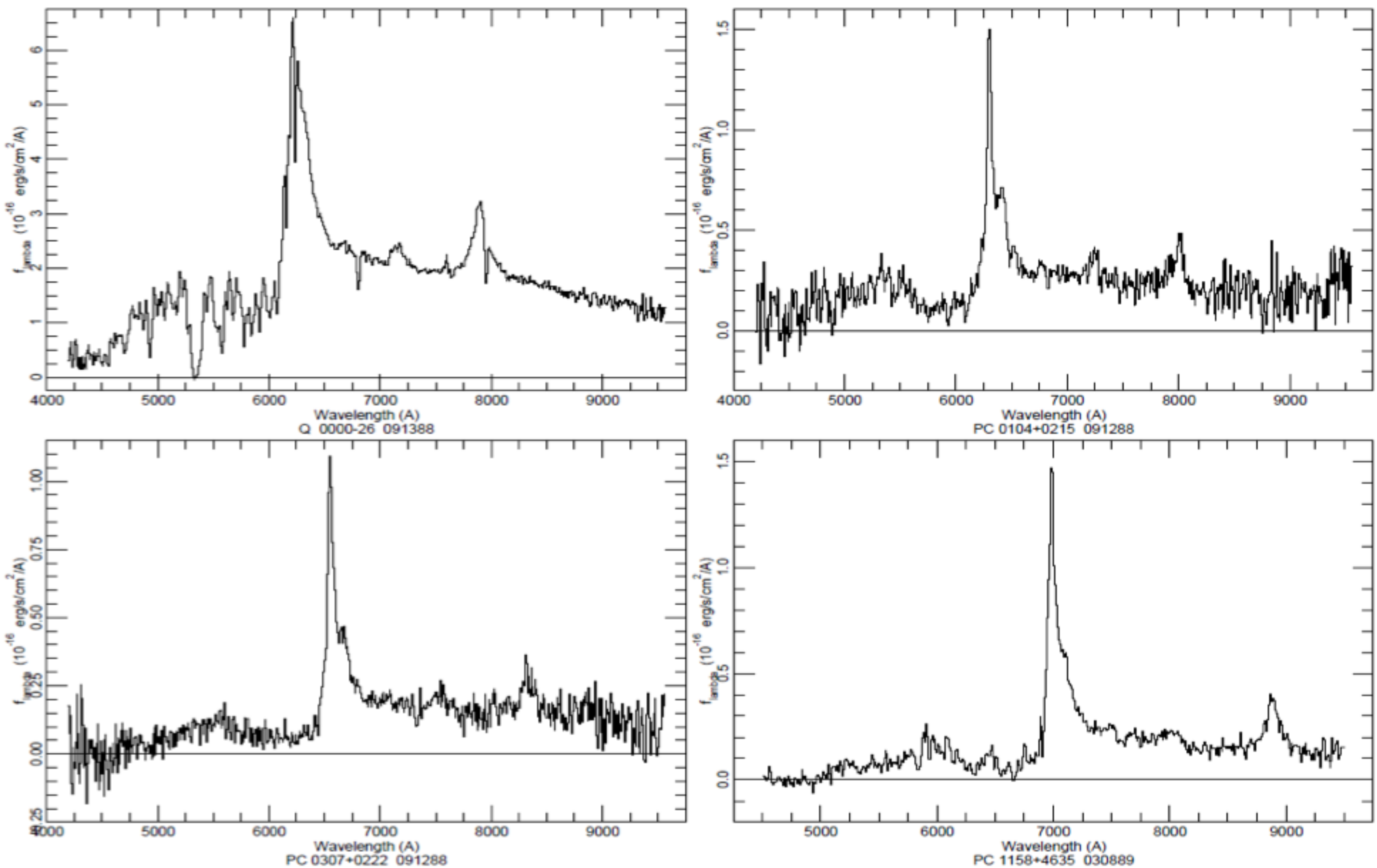
Questions

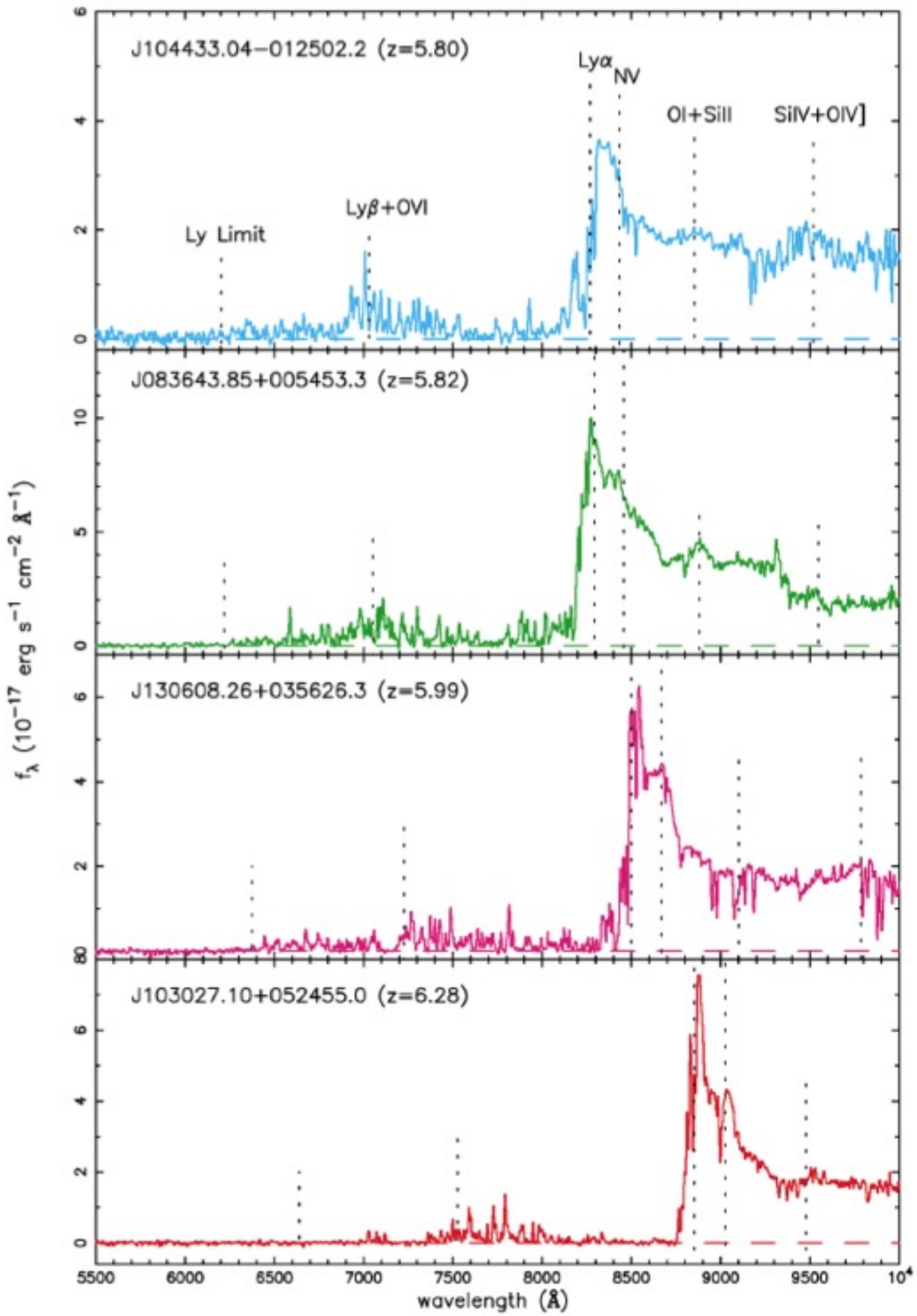
- How do supermassive black holes form?
  - formation and growth of supermassive black holes are tightly coupled to the formation of the bulge of a galaxy.
- How are they fueled?
  - Galaxy interactions might dump gas into the nuclear region
  - Stellar bars might be able to funnel gas into the nucleus from the disk
  - Cannibalism of a gas-rich dwarf?
- Do most galaxies have supermassive black holes?
  - Probably, growing amount of dynamical evidence for the presence of massive black holes in many nearby, but otherwise "inactive" galaxy nuclei (including our own Galaxy
- Where are all the dead quasars lurking?
  - There were many more AGNs in the distant past, but few today

High Redshift Quasars



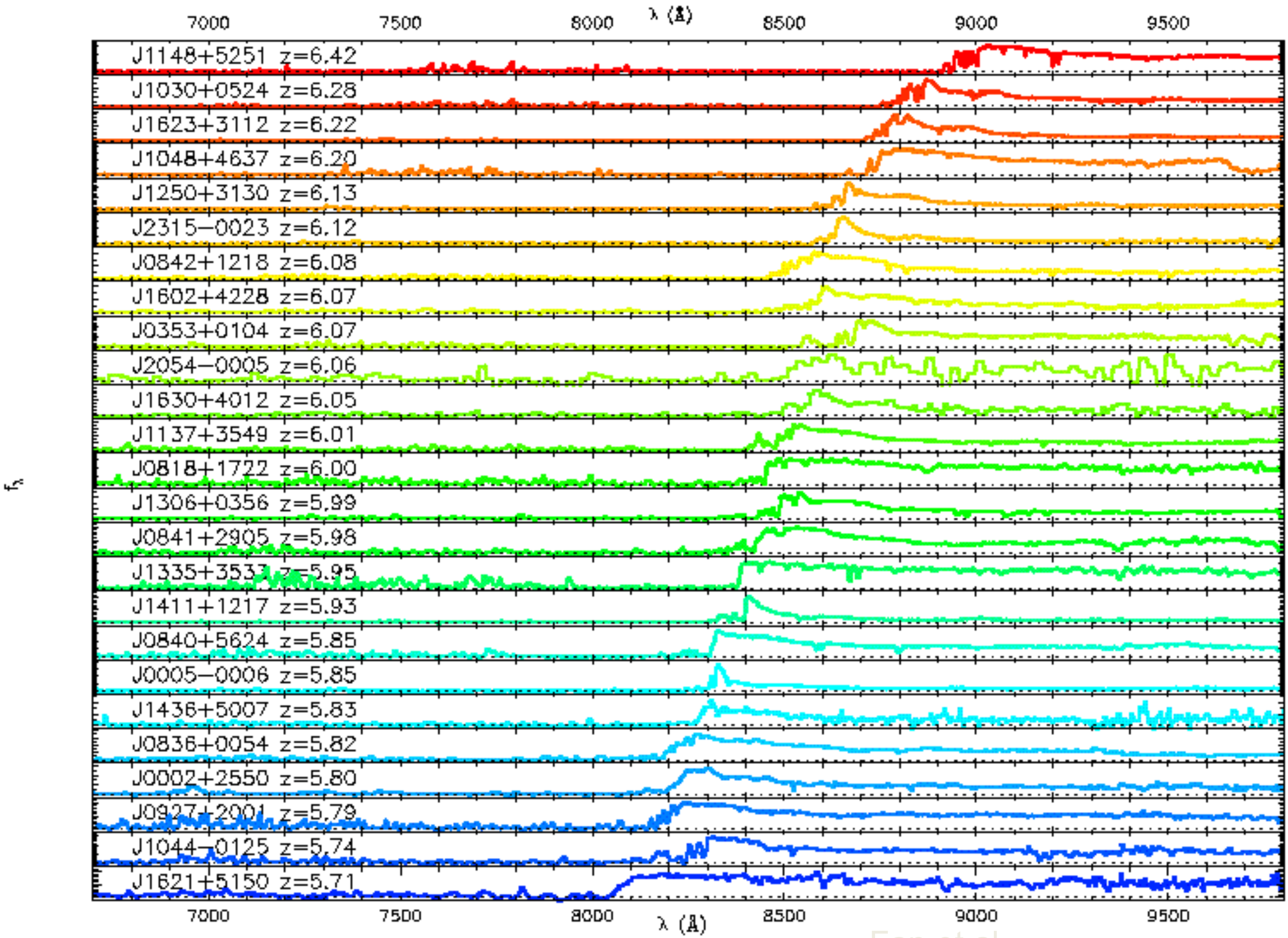
Indications of rapid increase of H I Opacity at z ~ 4





Detection of Gunn-Peterson Troughs in z ~ 6 Quasars in 2001

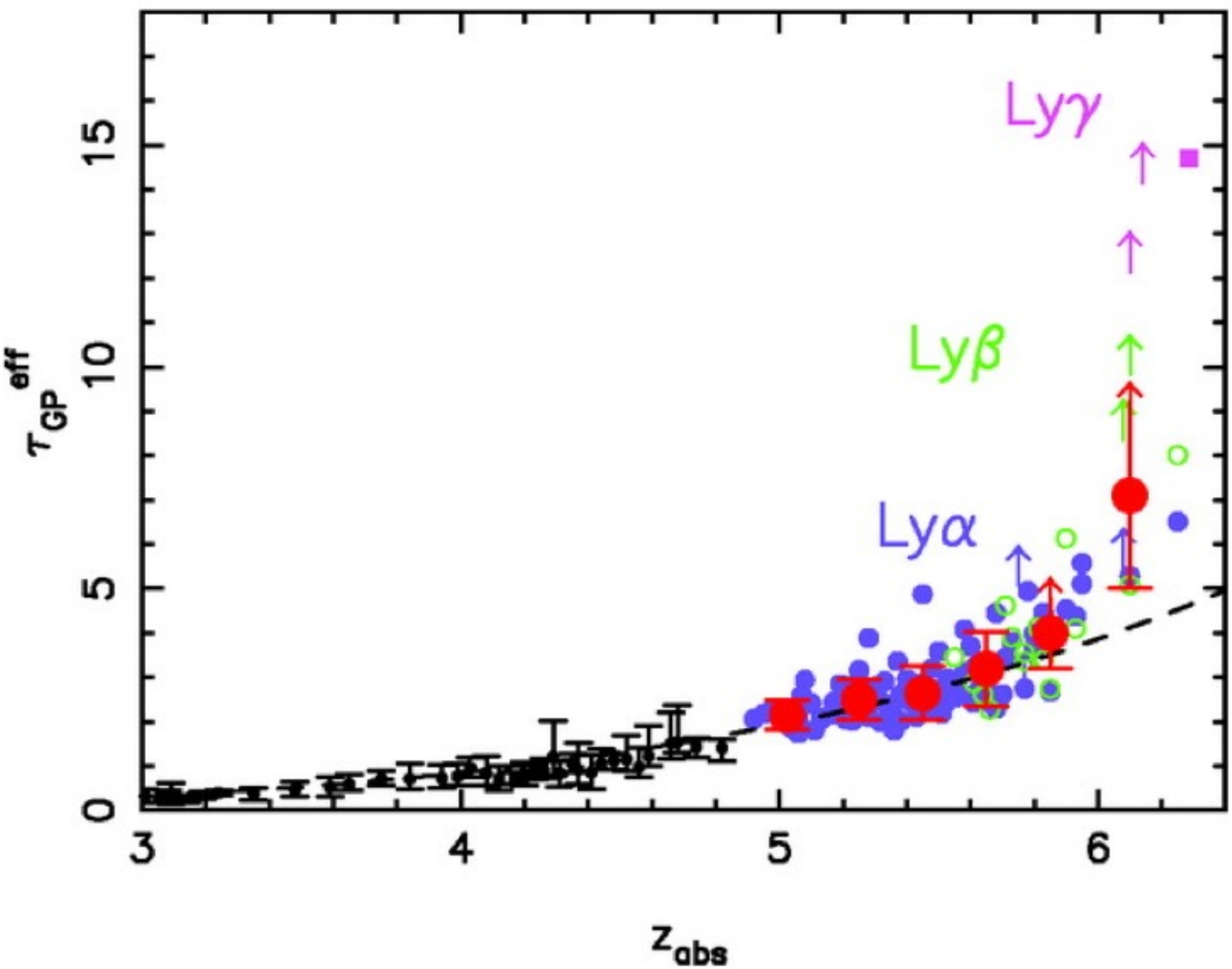
Becker et al (2001)



λ (Å)
7000
7500
8000
8500
9000
9500
J1148+5251 z=6.42
J1030+0524 z=6.28
J1623+3112 z=6.22
J1048+4637 z=6.20
J1250+3130 z=6.13
J2315−0023 z=6.12
J0842+1218 z=6.08
J1602+4228 z=6.07
J0353+0104 z=6.07
J2054−0005 z=6.06
J1630+4012 z=6.05
J1137+3549 z=6.01
J0818+1722 z=6.00
J1306+0356 z=5.99
J0841+2905 z=5.98
J1335+3533 z=5.95
J1411+1217 z=5.93
J0840+5624 z=5.85
J0005−0006 z=5.85
J1436+5007 z=5.83
J0836+0054 z=5.82
J0002+2550 z=5.80
J0927+2001 z=5.79
J1044−0125 z=5.74
J1621+5150 z=5.71
f_λ

Fan et al.

Rapid increase in H I Opacity at z ~ 6



Fan et al (2006)

What we have Learned

- The number density of quasars drops dramatically at $z > 3$
- Billion solar mass black holes can form within a billion years of the big bang
- The Epoch of Reionization (EoR) ends around $6 < z < 8$ after which the Universe is fully ionized (again)