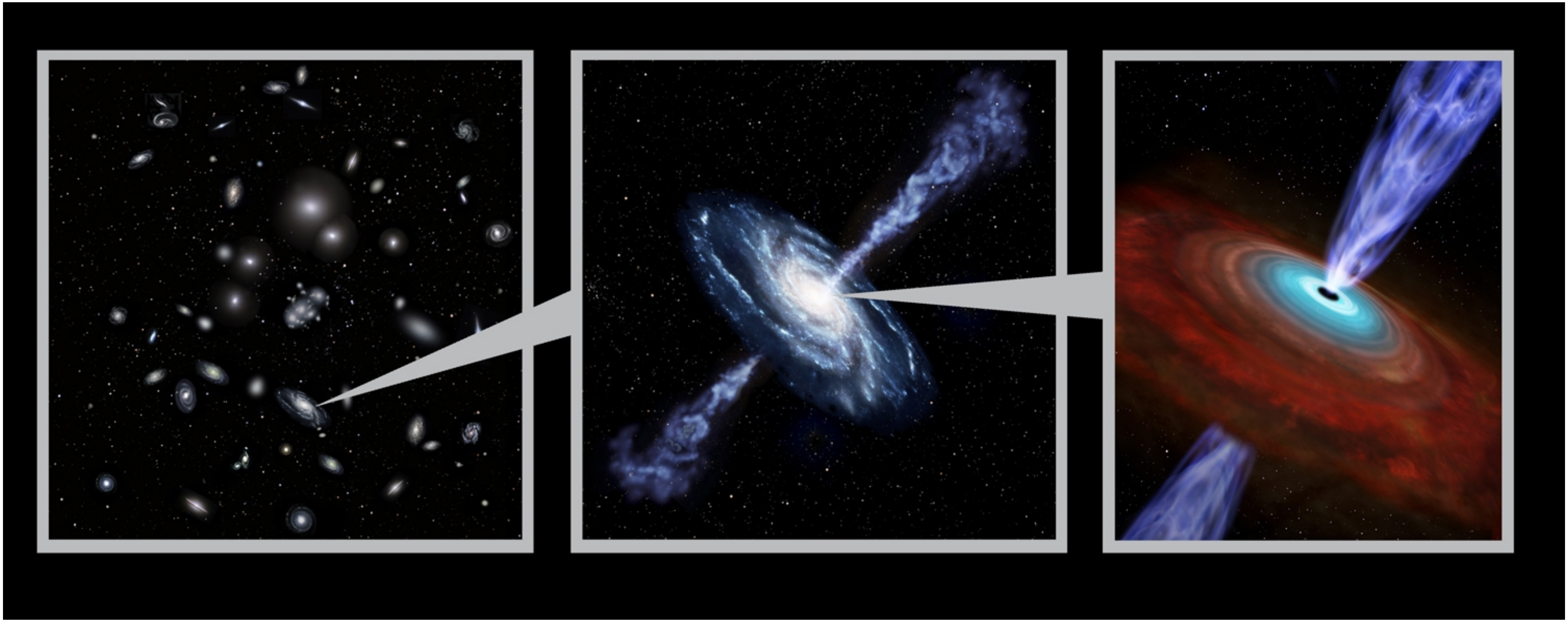
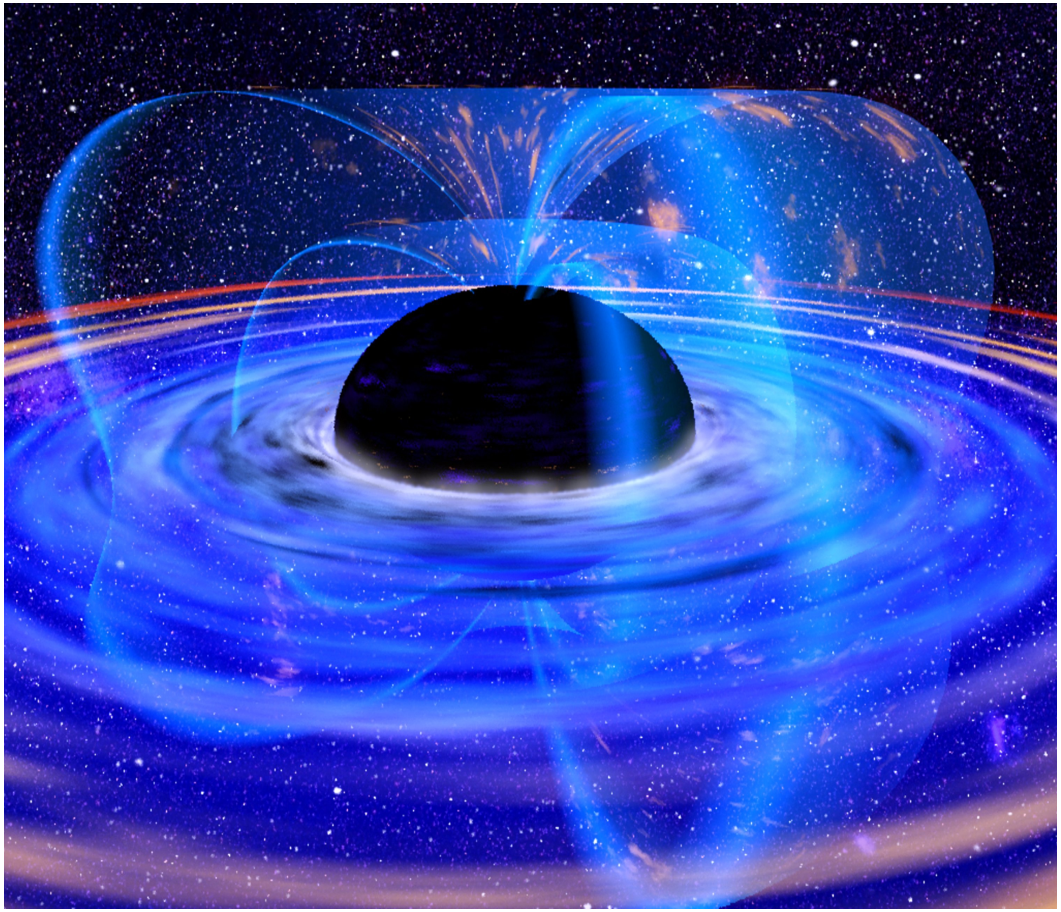
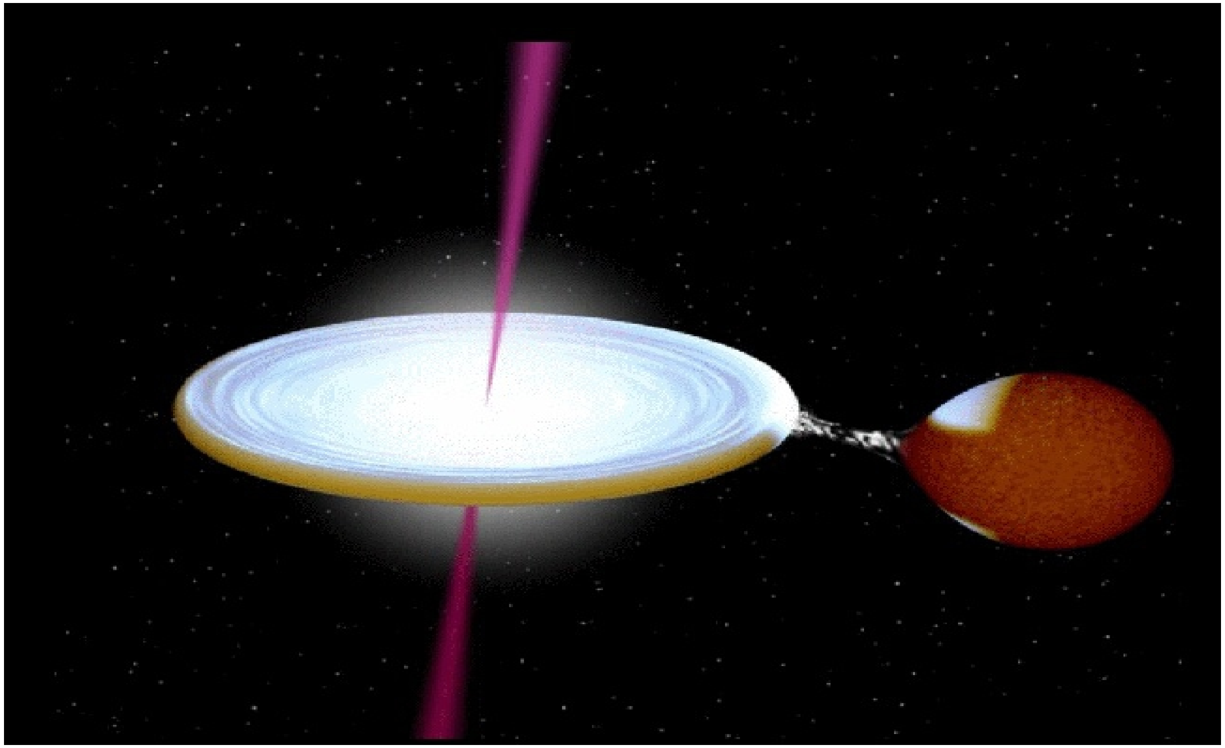
Black Holes and Active Galactic Nuclei





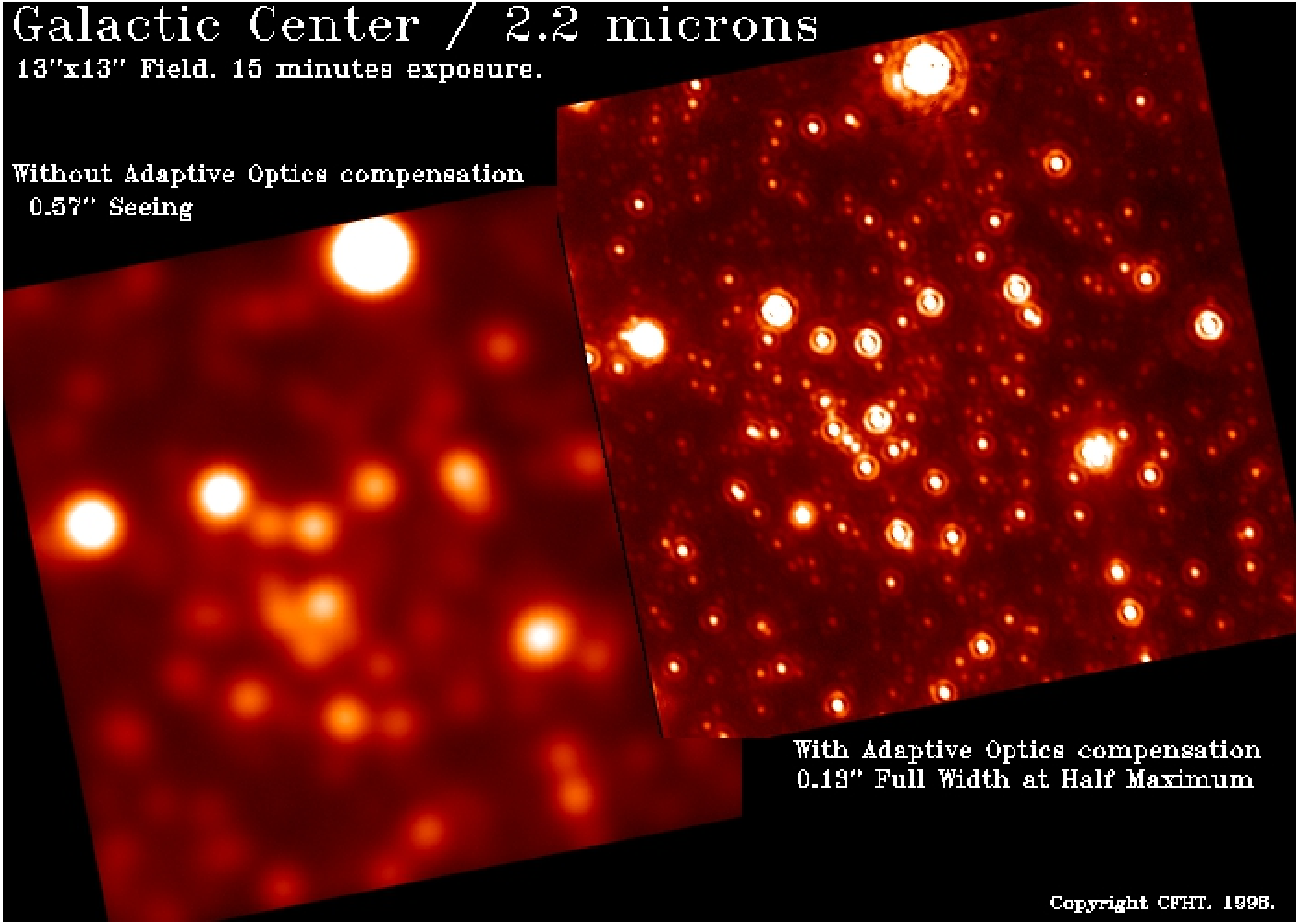
A black hole is a region of spacetime from which gravity prevents anything, including light, from escaping. The theory of general relativity predicts that a sufficiently compact mass will deform space-time to form a black hole. Around a black hole, there is a mathematically defined surface called an event horizon that marks the point of no return. The hole is called "black" because it absorbs all the light that hits the horizon.

Evidence for Black Holes in the Real Universe



X-ray binaries are a class of binary stars that are luminous in X-rays. The X-rays are produced by matter falling from one component, called the donor (usually a relatively normal star) to the other component, called the accretor, which is compact: a white dwarf, neutron star, or black hole. The infalling matter releases gravitational potential energy, up to several tenths of its rest mass, as X-rays. (Hydrogen fusion releases only about 0.7 percent of rest mass.)

THE GALACTIC CENTER



Galactic Center / 2.2 microns

13"x13" Field. 15 minutes exposure.

Without Adaptive Optics compensation
0.57" Seeing

With Adaptive Optics compensation
0.13" Full Width at Half Maximum

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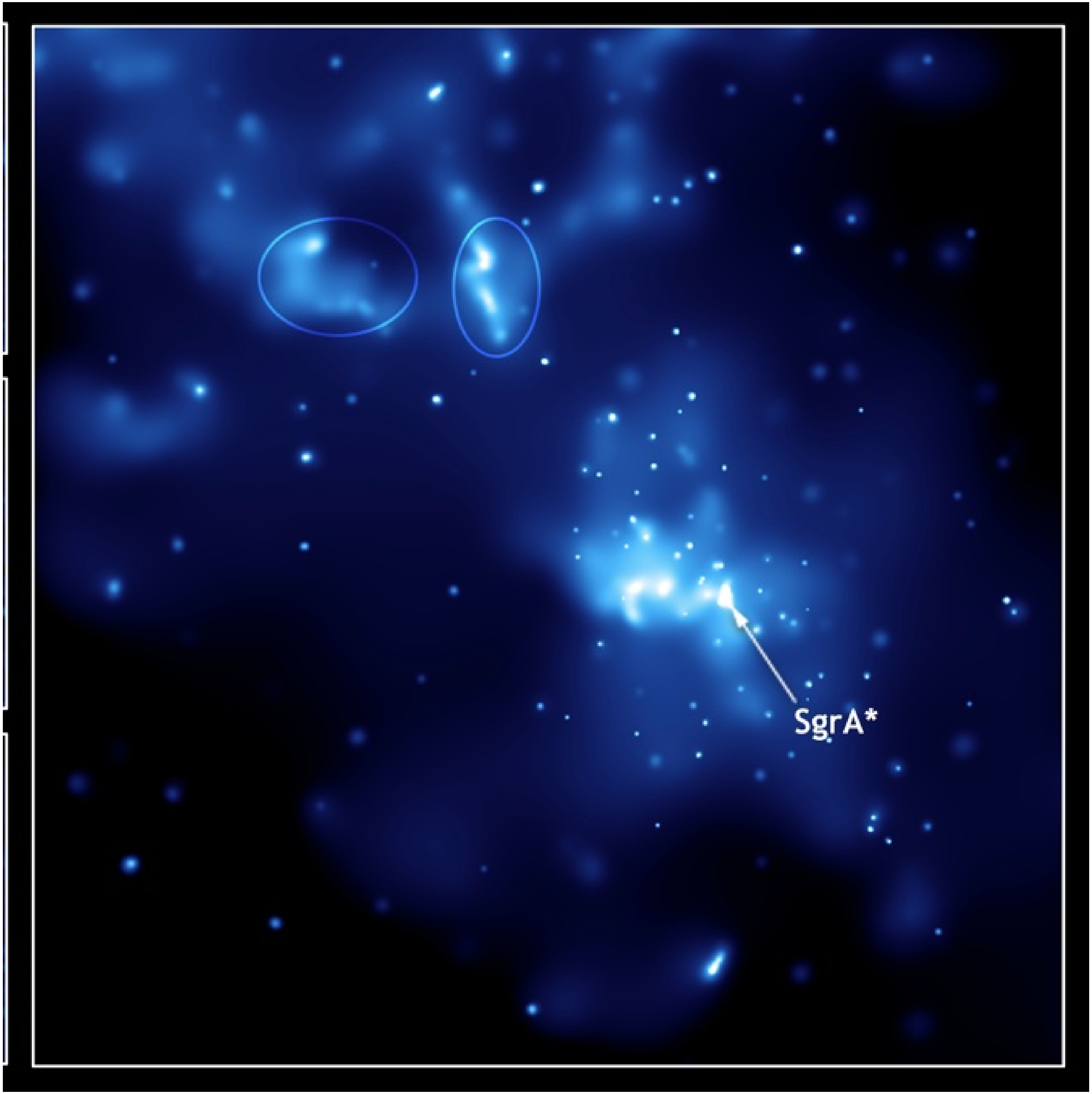
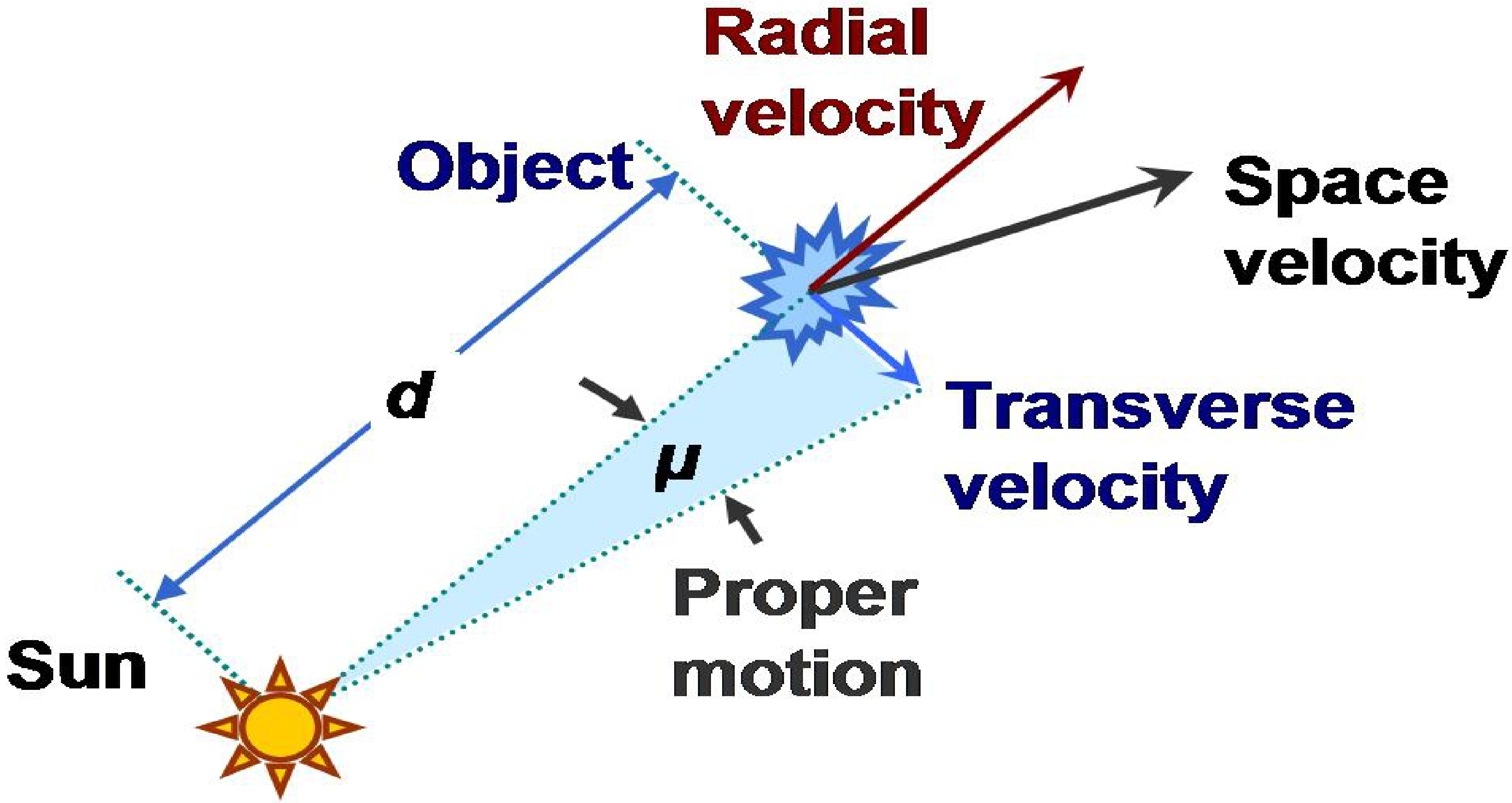
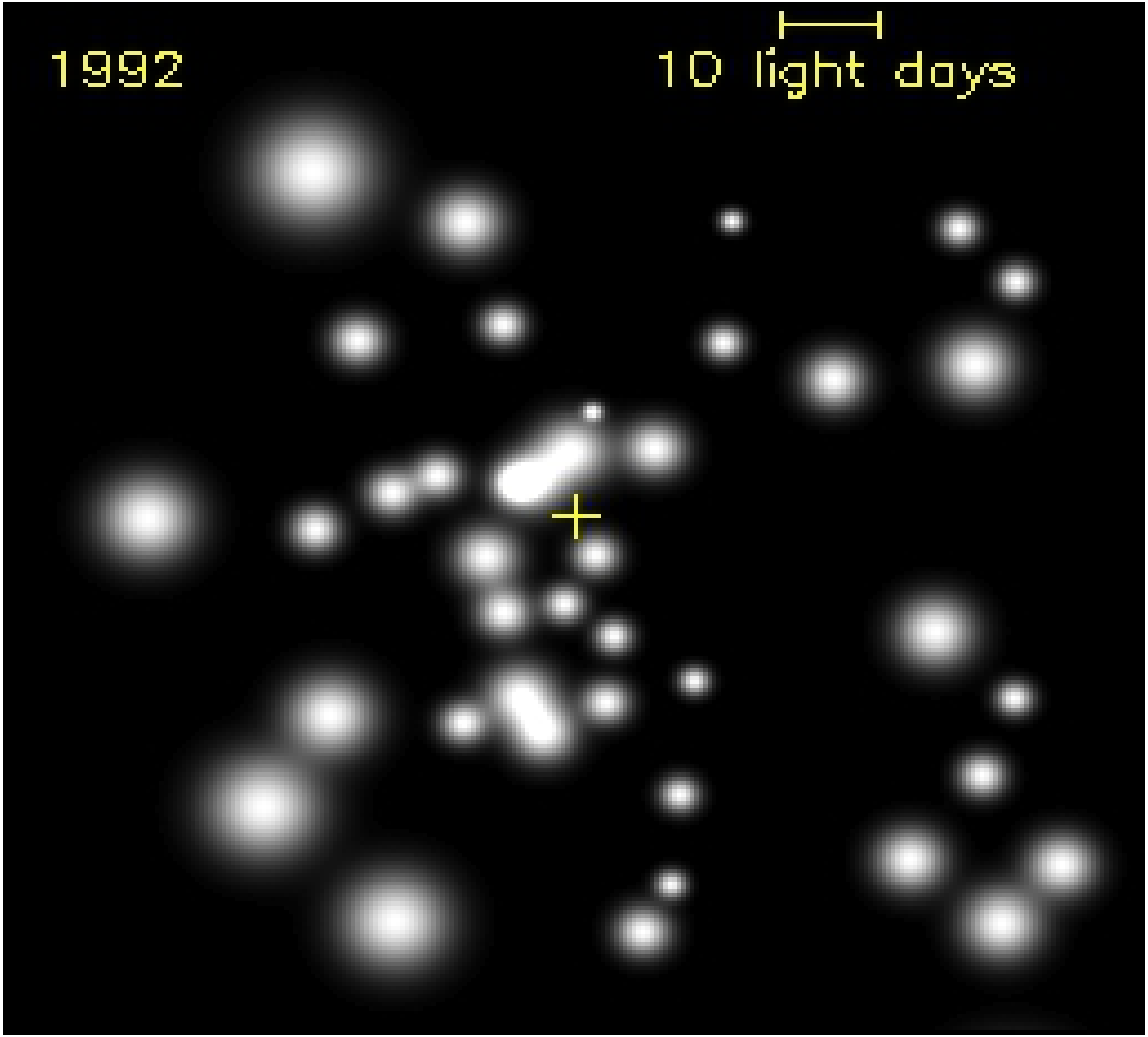


Sagittarius A* is a bright and very compact astronomical radio source at the center of the Milky Way galaxy,

Sgr A* was discovered in1974, by astronomers Bruce Balick and Robert Brown using the baseline interferometer of the National Radio Astronomy Observatory.



The proper motion of a star is its rate of angular change in position over time, as observed from the center of mass of the Solar System] It is measured in seconds of arc per year, arcsec/yr, where 3600 arcseconds equal one degree. This contrasts with radial velocity, which is the time rate of change in distance toward or away from the viewer, usually measured by Doppler shift of received radiation. The proper motion is not entirely "proper" (that is, intrinsic to the star) because it includes a component due to the motion of the solar system itself.


1992
10 light days

. Since S2 is on a highly elliptical orbit with $e = 0.88$, its peri-center distance from Sgr A* in spring 2002 was a mere 17 light hours, or 1400 R_S for a $4.4 \times 10^6\, M_\odot$ black hole (Figure 4.3.1). The data from the NTT/VLT and Keck telescopes agreed very well: the first orbital analyses gave 4.1×10^6 (Schödel et al. 2002) and $4.6 \times 10^6\, M_\odot$ (Ghez et al. 2003,

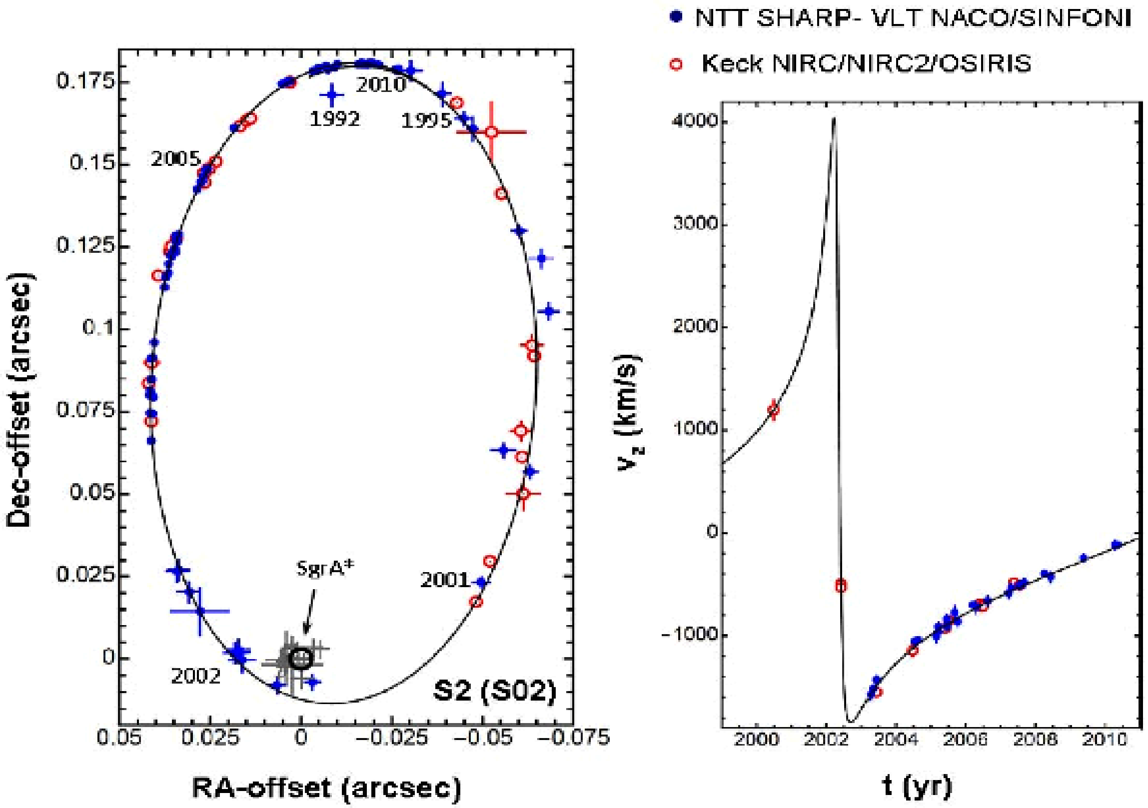
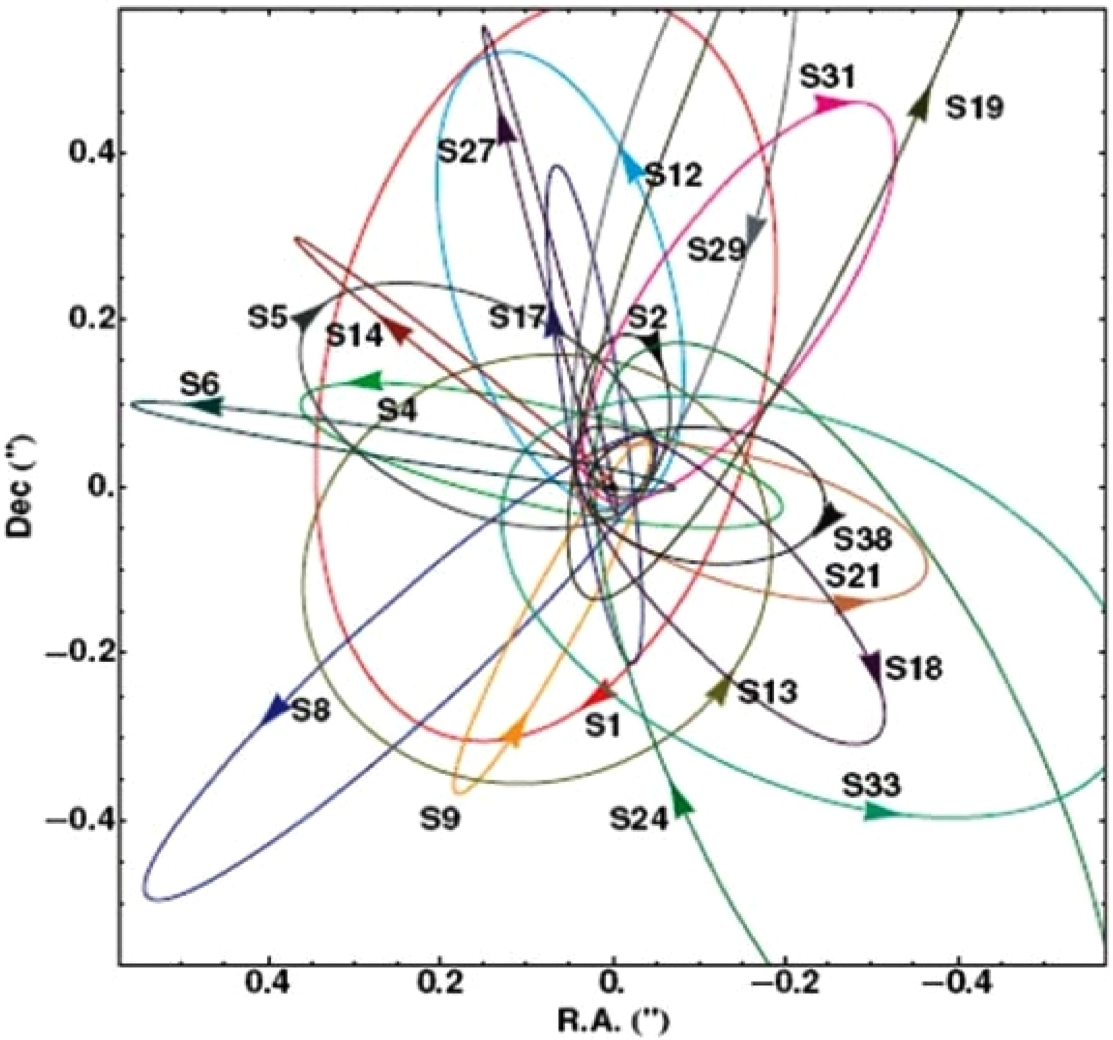
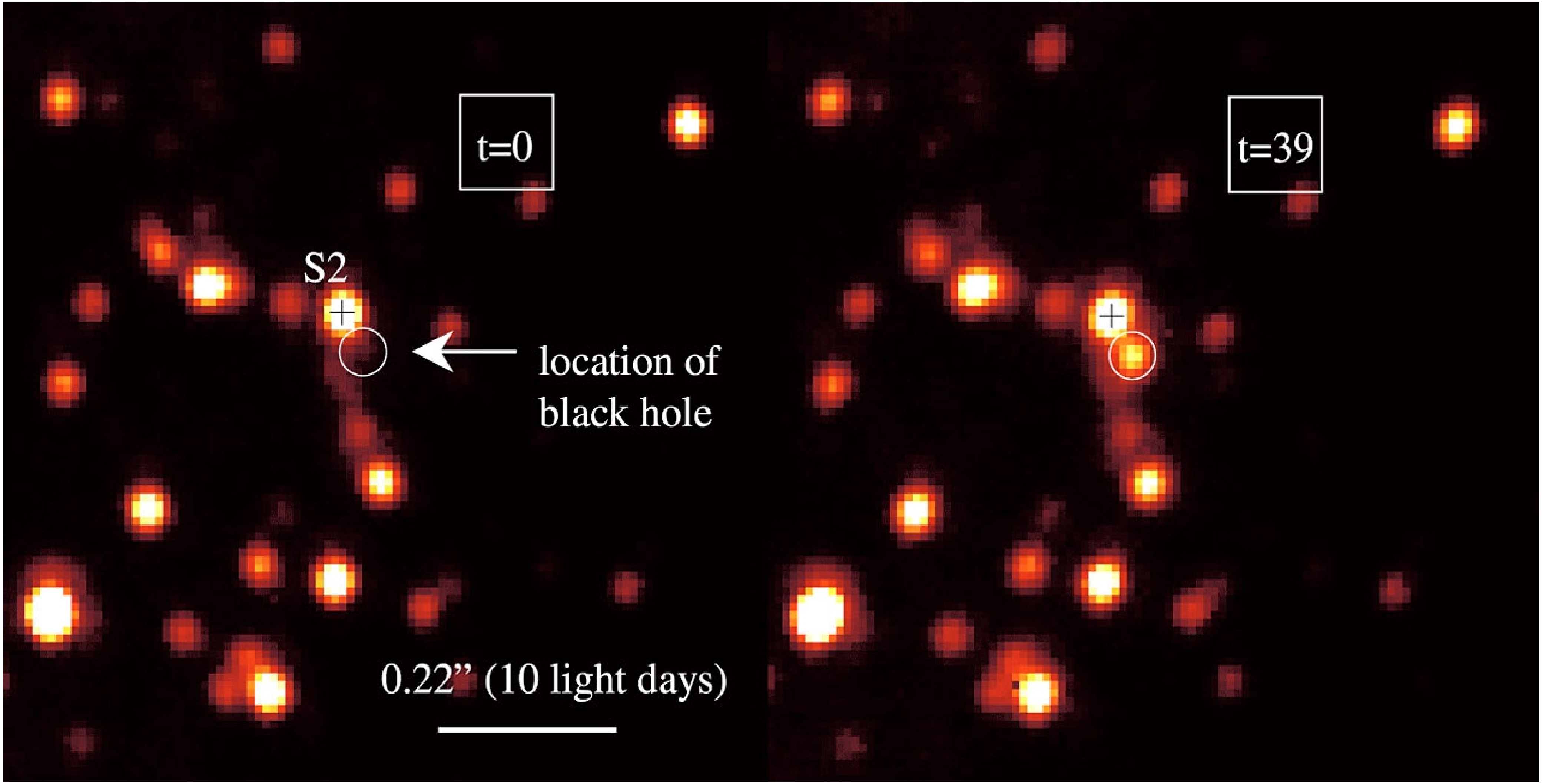


Figure 4.3.1. Orbit of the star S2 (S02) on the sky (left panel) and in radial velocity (right panel). Blue, filled circles denote the NTT/VLT points of Gillessen et al. (2009a,b, updated to 2010), and open and filled red circles are the Keck data of Ghez et al. (2008) corrected for the difference in coordinate system definition (Gillessen et al. 2009a). The positions are relative to the radio position of Sgr A* (black circle). The grey crosses are the positions of various Sgr A* IR-flares (§ 7). The center of mass as deduced from the orbit lies within the black circle. The orbit figure is not a closed ellipse since the best fitting model ascribes a small proper motion to the point mass, which is consistent with the uncertainties of the current IR-

In summary, from the stellar orbits it is now established that the Galactic Center contains a highly concentrated mass of ~ 4 million solar masses within the peri-center of S2, i.e. within 125 AU. This requires a minimum density of $5 \times 10^{15}\ M_\odot \mathrm{pc}^{-3}$. The mass centroid lies within ± 2 mas at the position of the compact radio source Sgr A*, which itself has an apparent size of < 1 AU only (Shen et al. 2005, Bower et al. 2006, Doeleman et al. 2008). Taken together, this makes the ***Galactic Center Black Hole the currently best case for the existence of astrophysical black holes***.




t=0
t=39
S2
location of
black hole
0.22" (10 light days)

SPACE TELESCOPE IMAGING SPECTROGRAPH

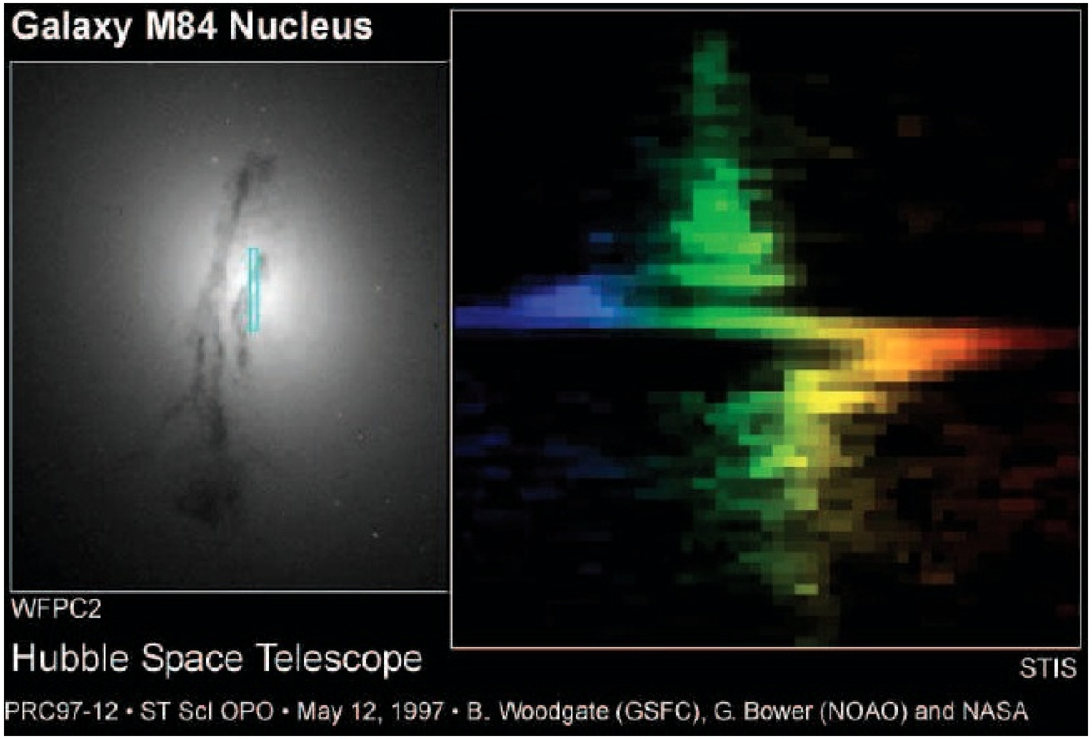
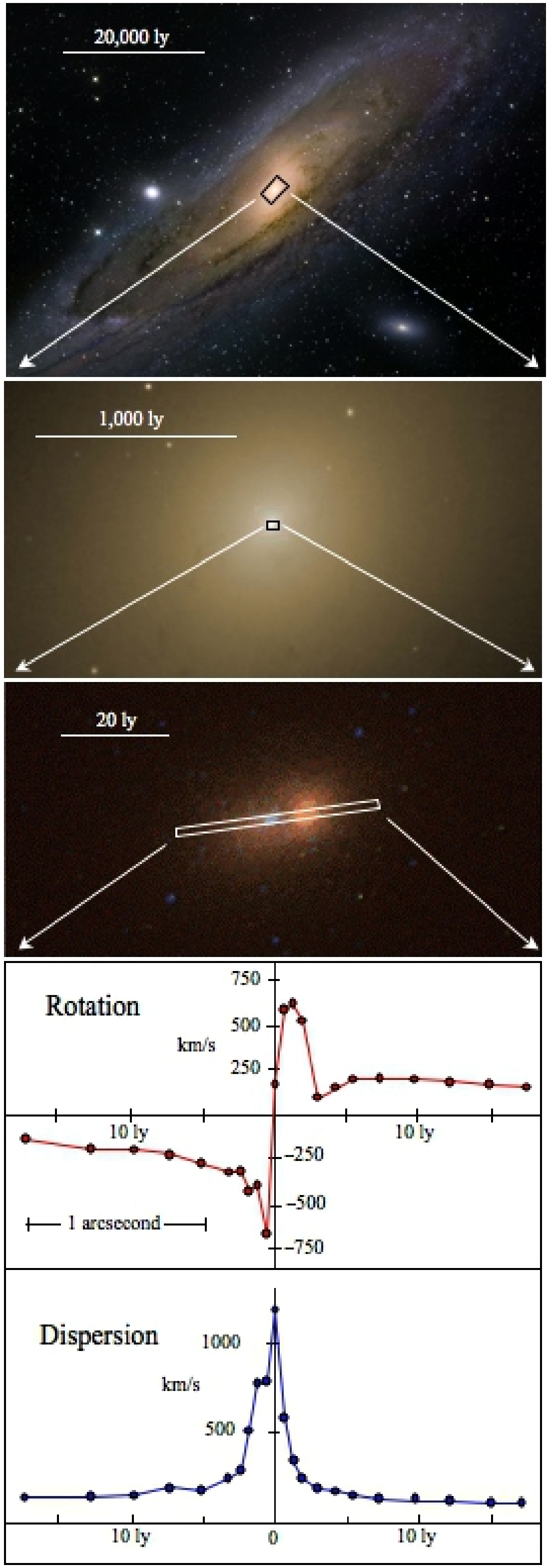
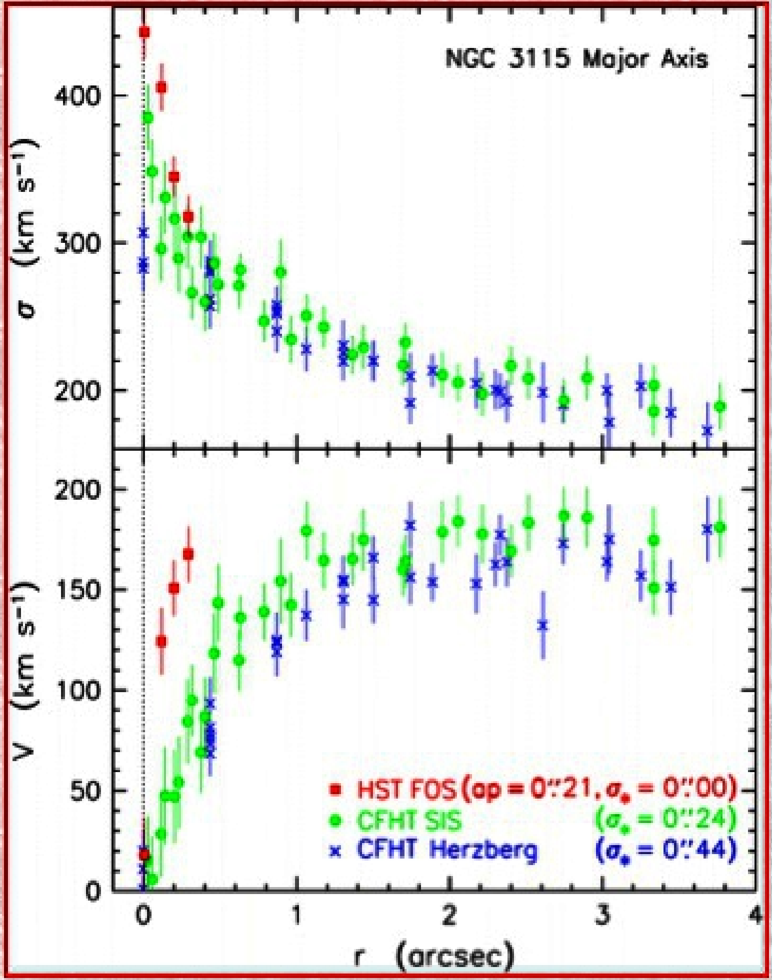


Fig. 50. Left: Image of M84; Right: Velocity profile across the nucleus of M84 taken with STIS aboard the HST. The estimated black hole mass is about 300 million solar masses.

The galaxy M31 , our nearest spiral neighbour

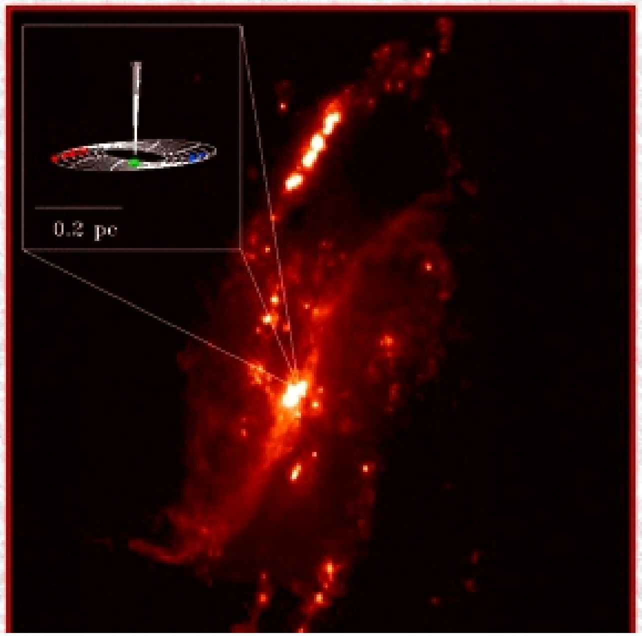


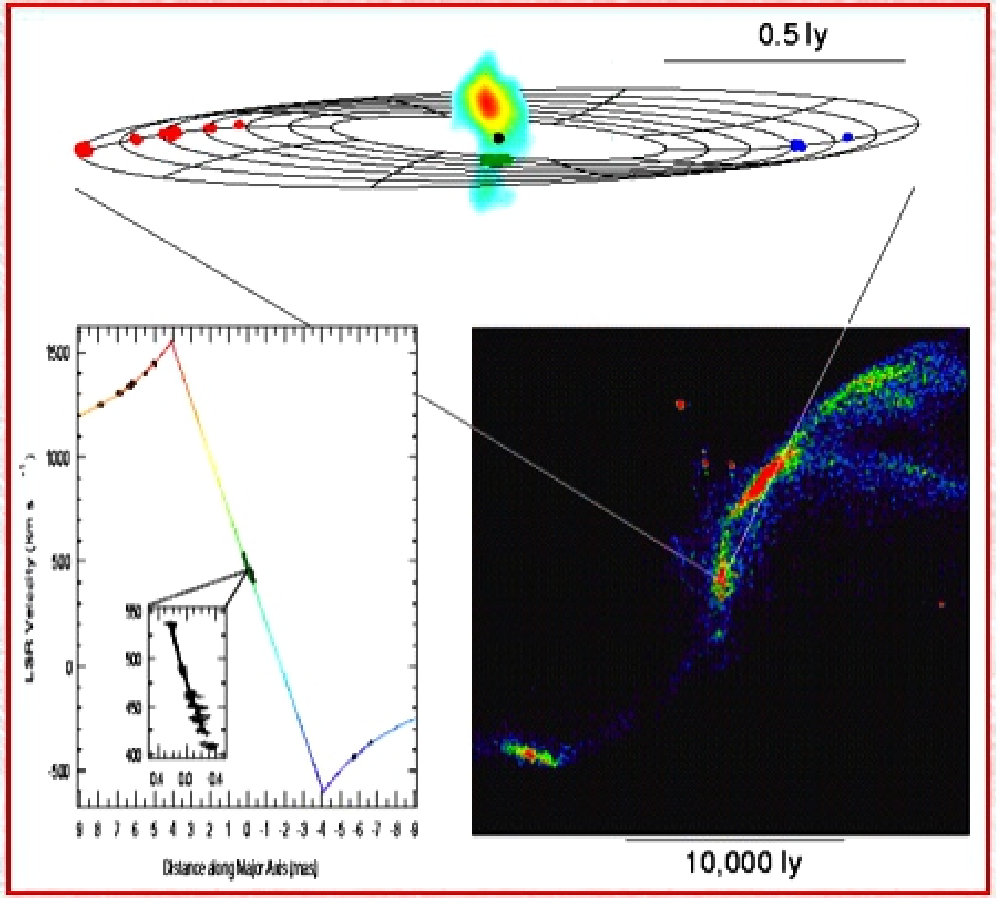
NGC 3115 Black Hole



NGC 4258 Black Hole

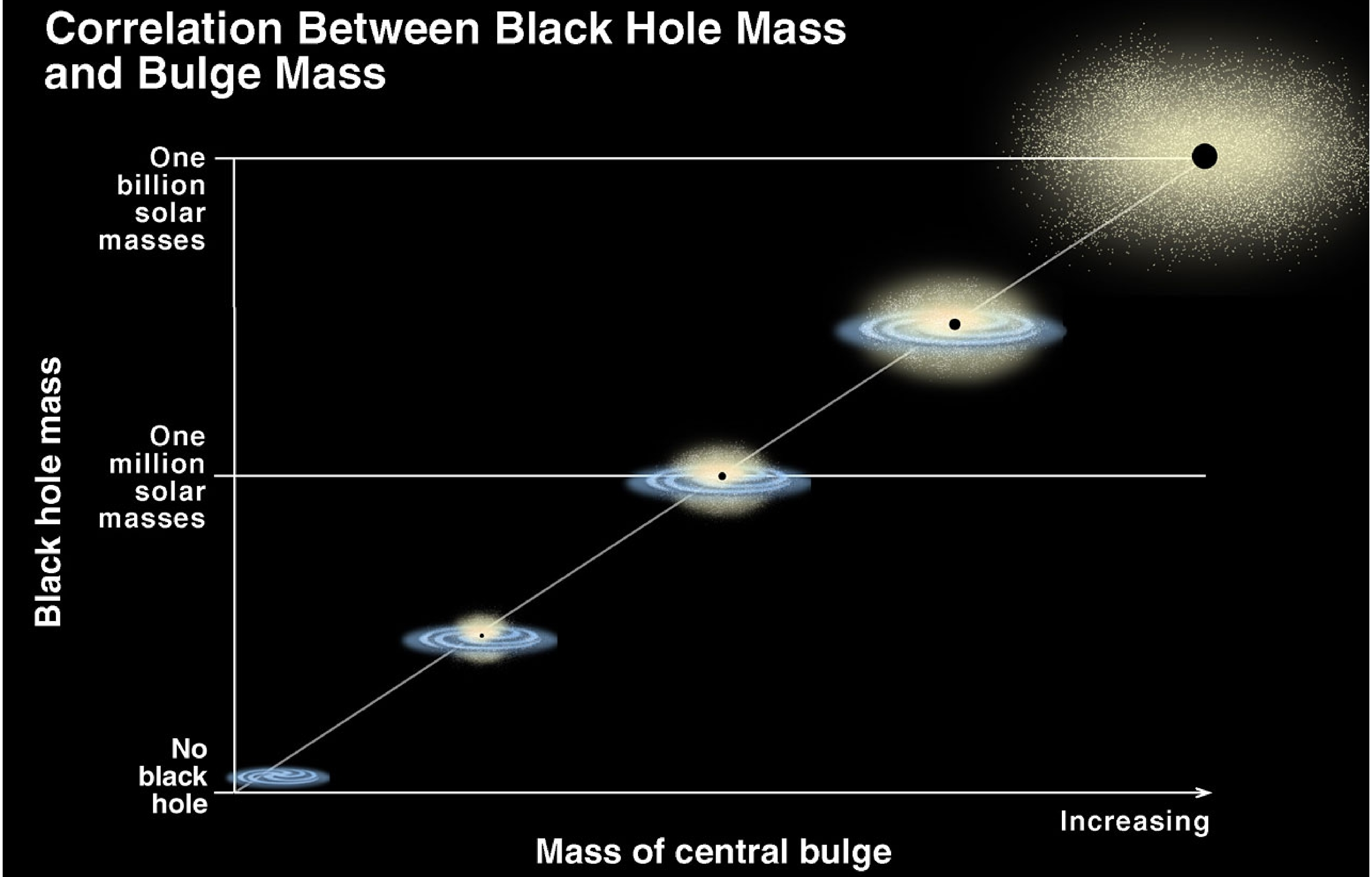
Water molecules in star-forming regions can undergo a population inversion and emit radiation at about 22.0 GHz, creating the brightest spectral line in the radio universe.

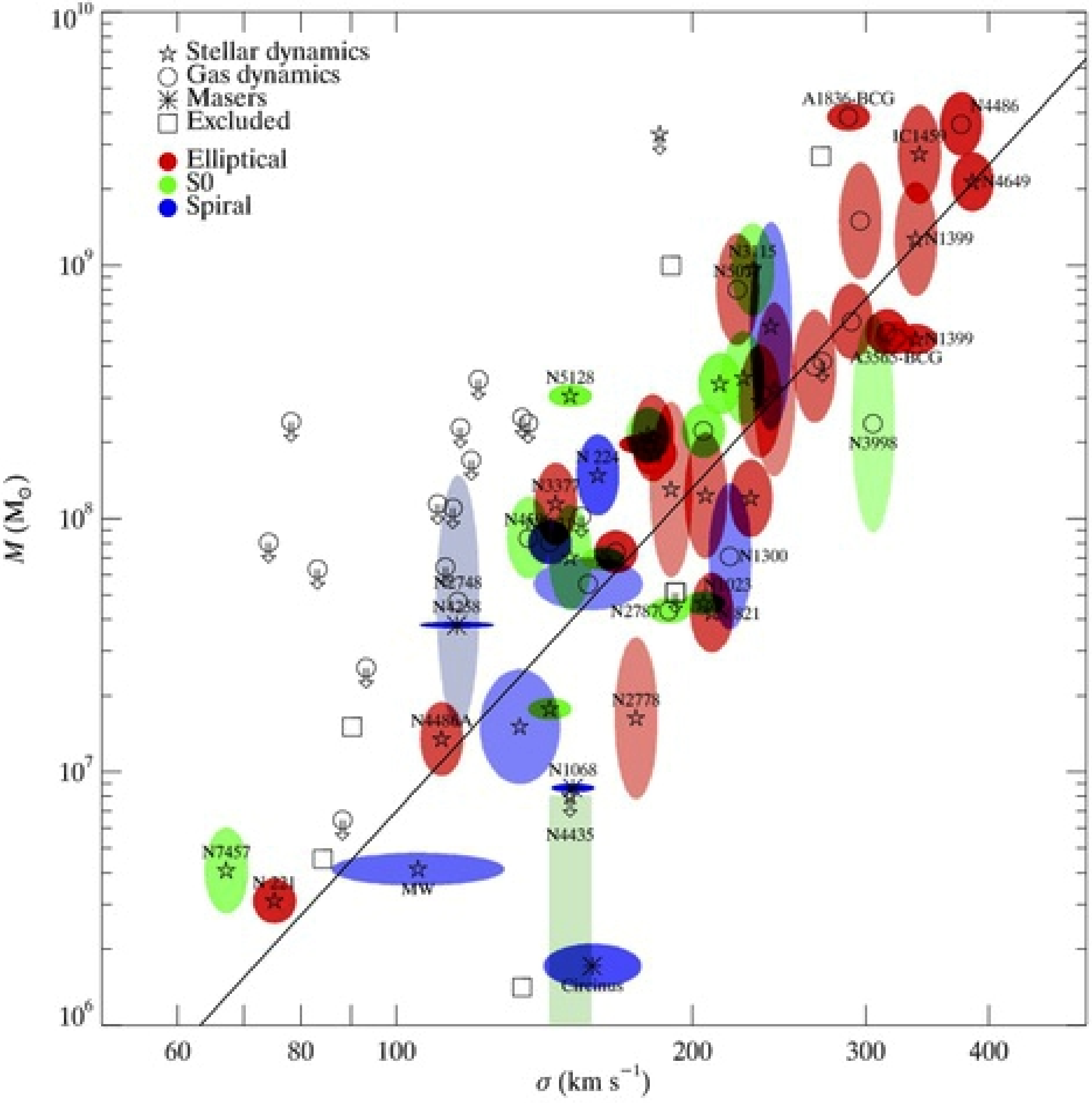




Nuclear gas disk with masers giving doppler velocities and proper motions.

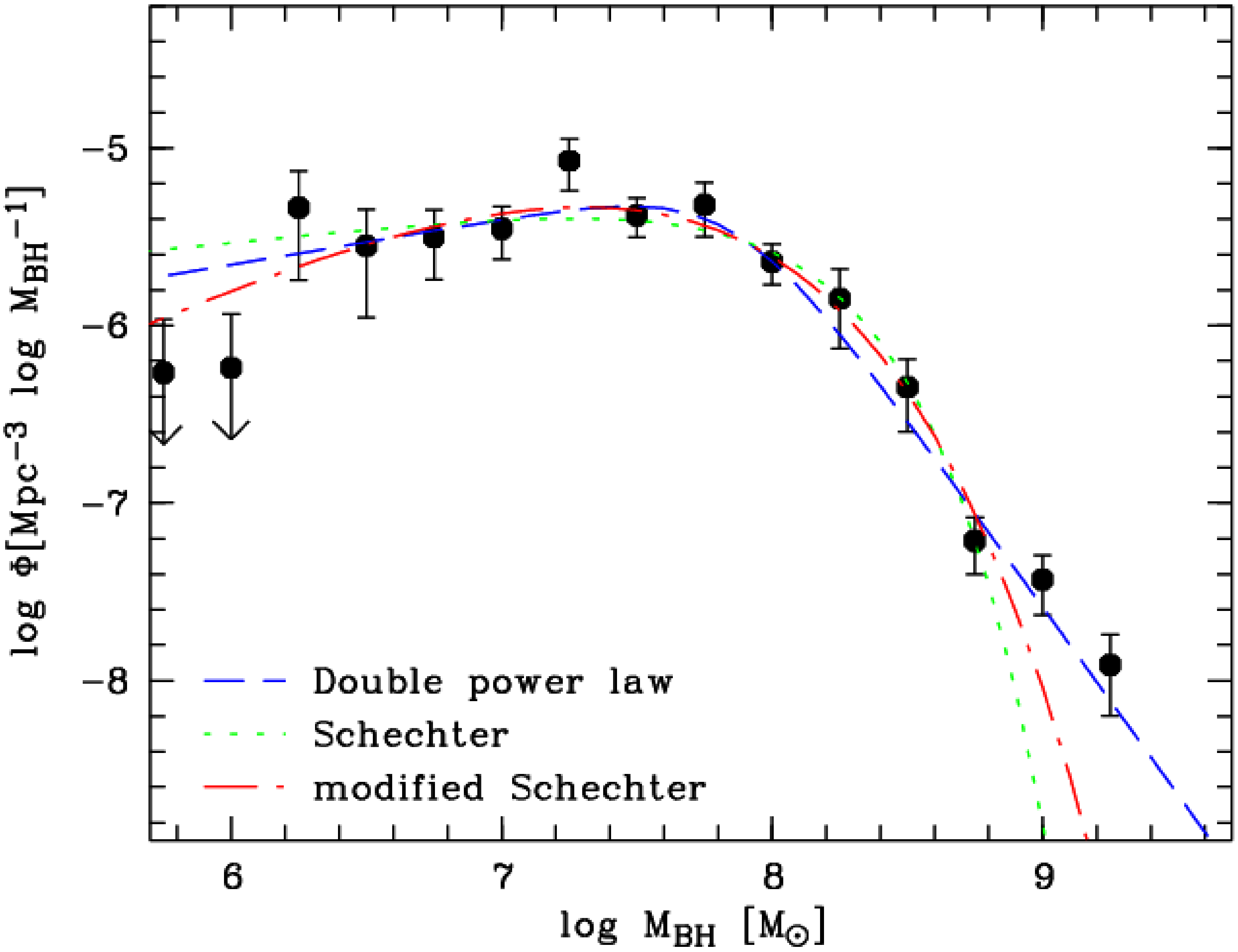
Correlation Between Black Hole Mass and Bulge Mass





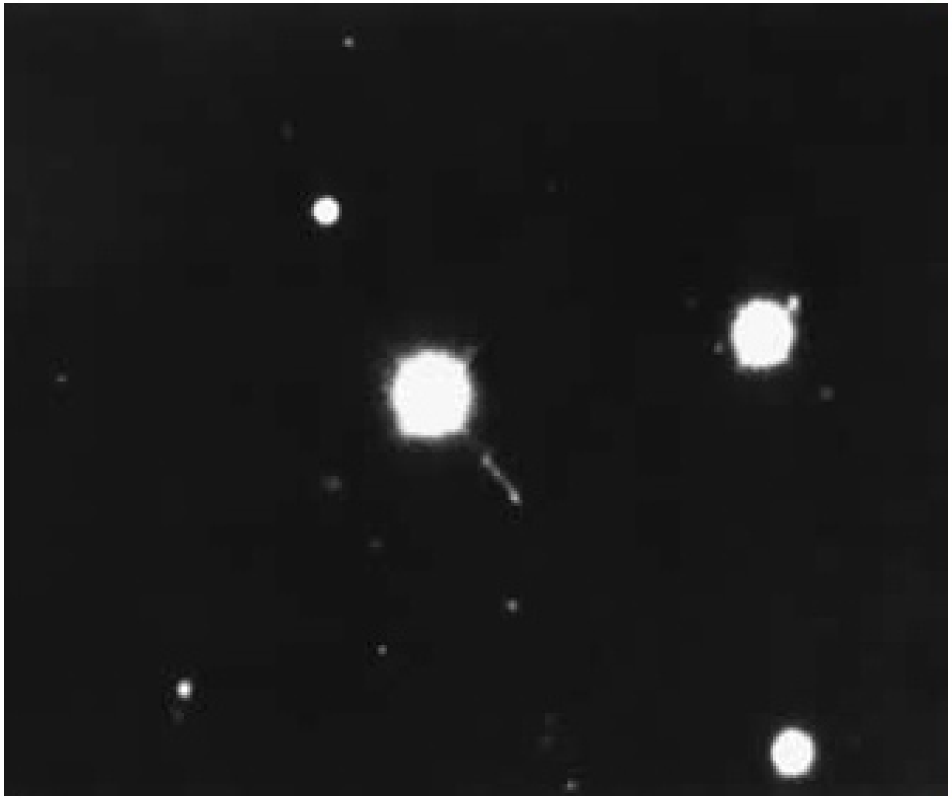
Stellar dynamics
Gas dynamics
Masers
Excluded
Elliptical
S0
Spiral
M ($M_\odot$)
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
σ (km s^{-1})
60
80
100
200
300
400
A1836-BCG
N4486
IC1459
N4649
N1399
N3115
N5077
N1399
A3565-BCG
N5128
N3998
N 224
N3377
N4459
N1300
N2748
N4258
N1023
N2787
N821
N2778
N4486A
N1068
N4435
N7457
N221
MW
Circinus

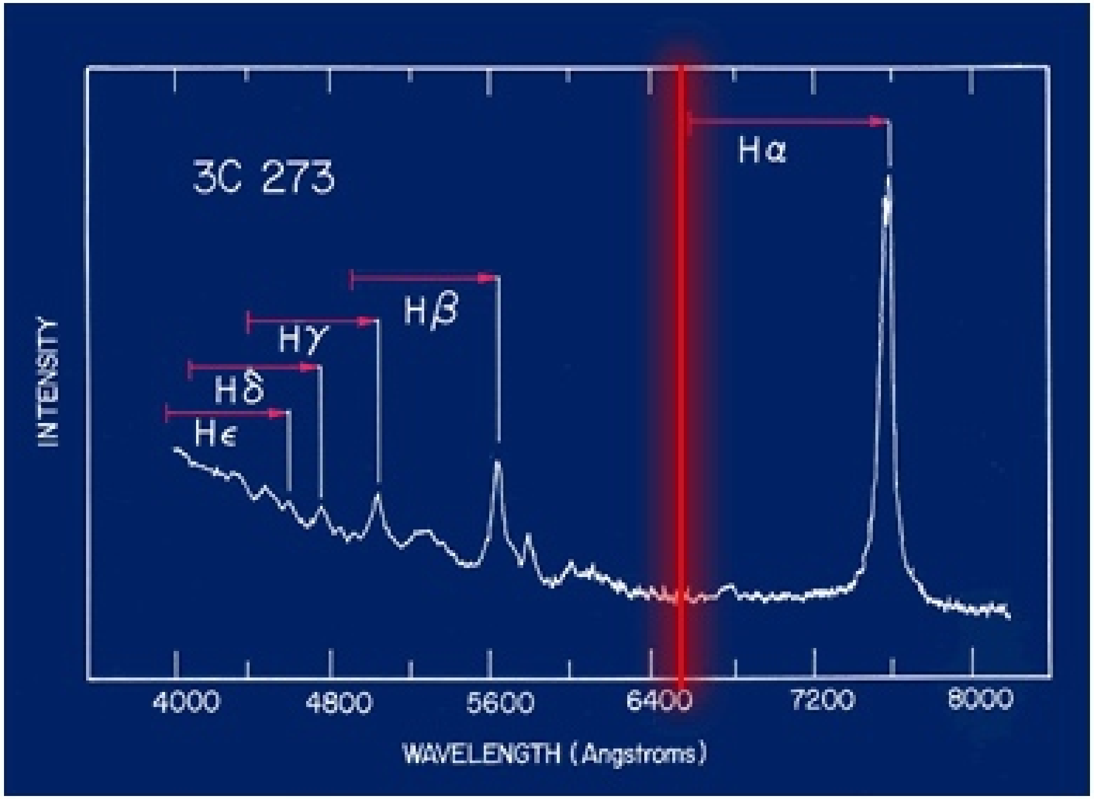
Black hole mass function
(local Universe)



Accretion onto Black Holes

1963 M. Schmidt discovers that the radio source 3C273 can be identified with an optical point source (stellar) with a jet. The spectrum shows broad emission lines $H_{\beta,\gamma,\delta\ldots}$, MgII, OIII …which are redshifted by $z = 0.158 \Rightarrow v_rad = 47400\frac{km}{s}$. So, the object was called a **QUAsi StellAr Radio source** → QUASAR.

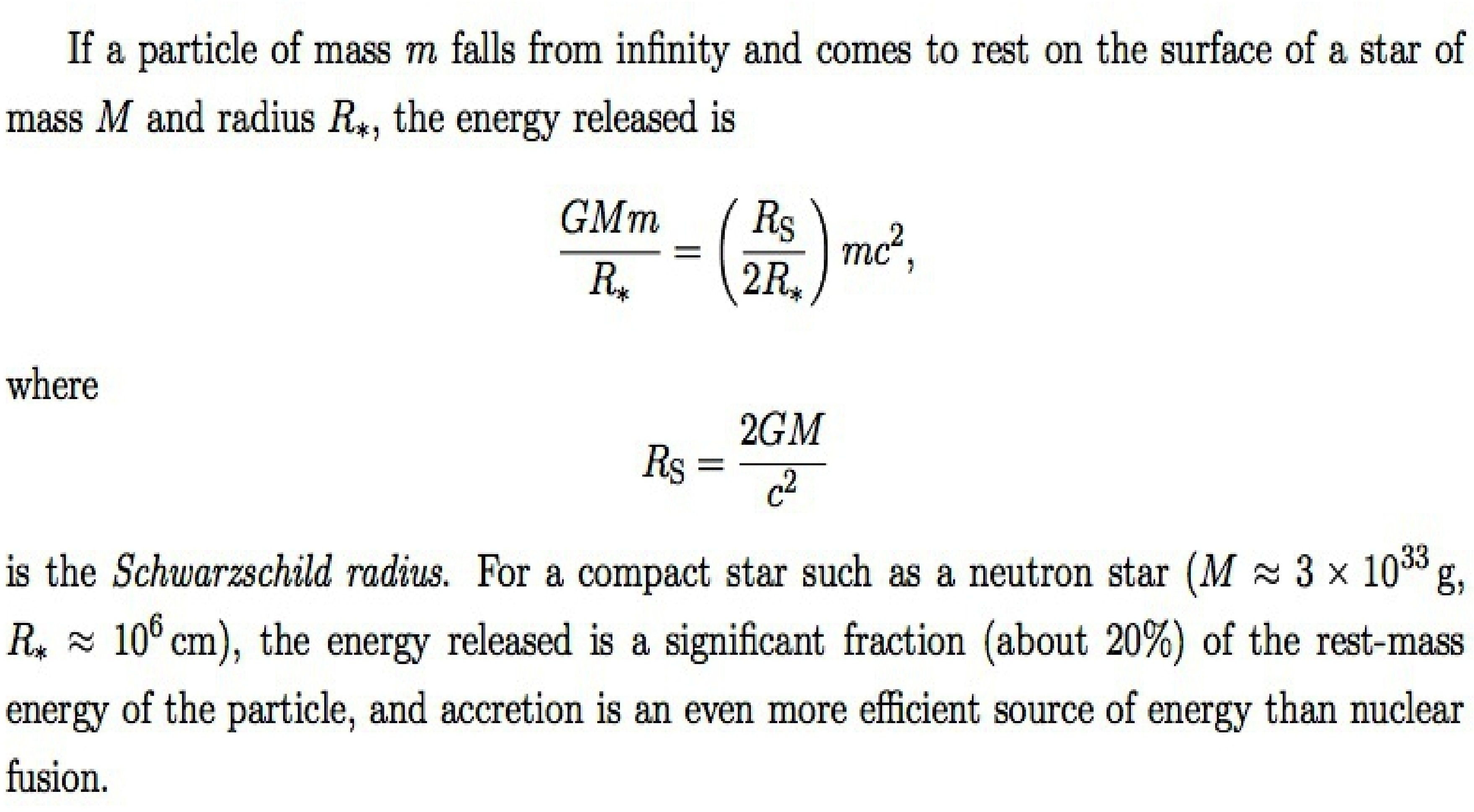




- Bright, unresolved nuclei of galaxies, at 10^{48} erg/s they can outshine their host galaxy by x100
- Continuum: not black-body
- Broad lines: ~3000km/s
- Found at redshifts z~0…6.5, with a peak at z~2 → phenomenon more common in the past
- Phenomenon rare or common but short-lived phase:

$$n_{galaxy} \sim 100 - 10.000\ n_{QSO}$$

Energy release by matter falling onto a compact object, such as a neutron star or black hole



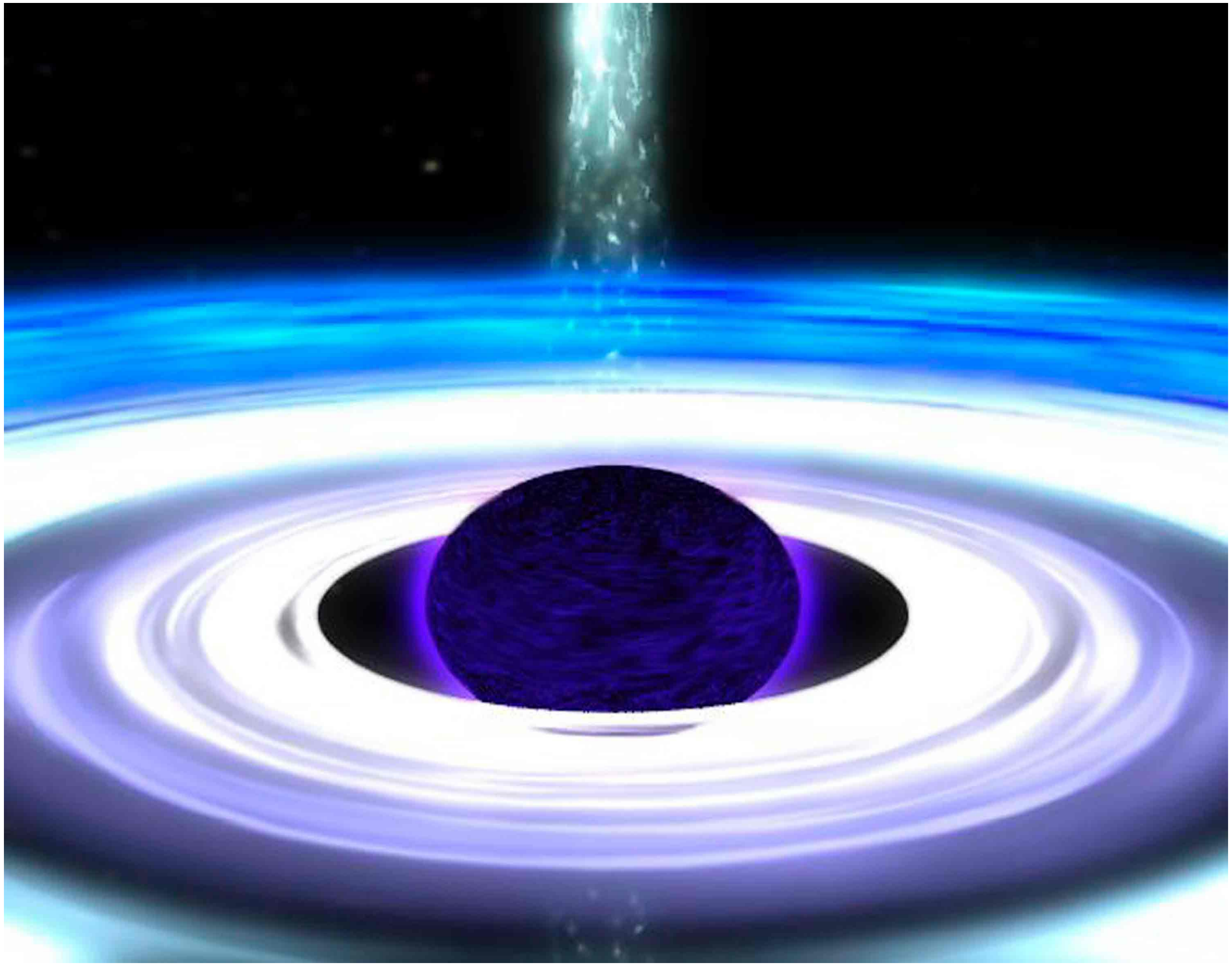
If a particle of mass m falls from infinity and comes to rest on the surface of a star of mass M and radius R_*, the energy released is

$$\frac{GMm}{R_*} = \left(\frac{R_S}{2R_*}\right) mc^2,$$

where

$$R_S = \frac{2GM}{c^2}$$

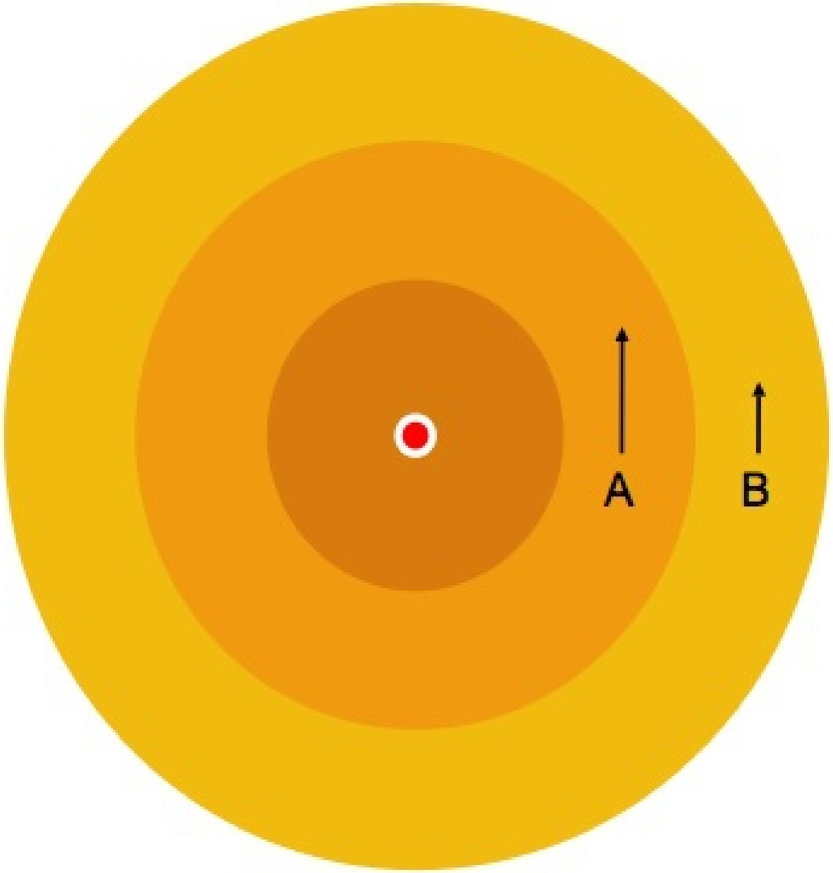
is the *Schwarzschild radius*. For a compact star such as a neutron star ($M \approx 3 \times 10^{33}$ g, $R_* \approx 10^6$ cm), the energy released is a significant fraction (about 20%) of the rest-mass energy of the particle, and accretion is an even more efficient source of energy than nuclear fusion.



The black holes in quasars are believed to be surrounded by an **accretion disk** of matter spiraling into the black hole.

Outward angular momentum transport

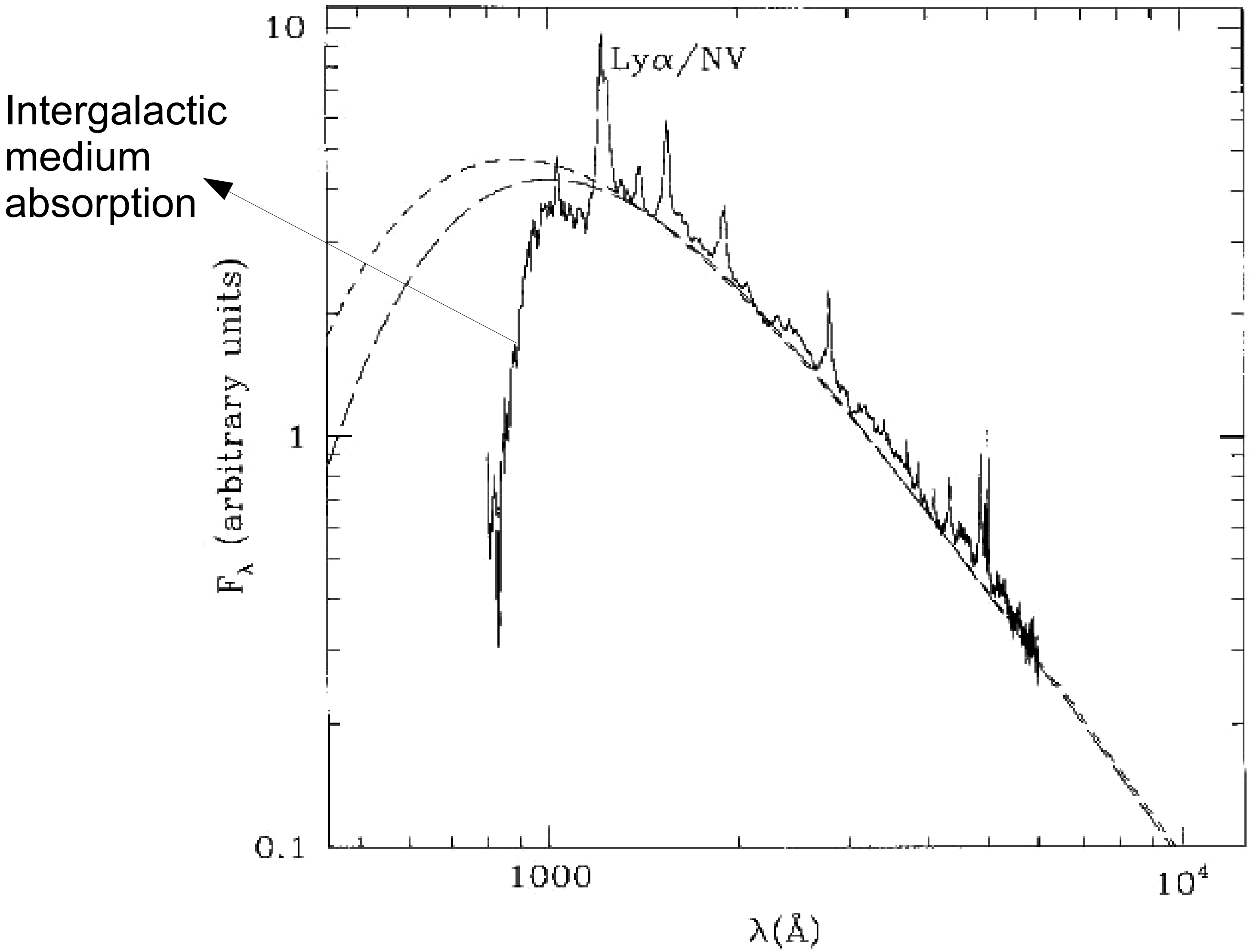
Ring A moves faster than ring B. Friction between the two will try to slow down A and speed up B. This means: angular momentum is transferred from A to B.



Specific angular momentum for a Keplerian disk:

$$l = rv_{\phi} = r^2\Omega_K = \sqrt{GM_* r}$$

So if ring A looses angular momentum, but is forced to remain on a Kepler orbit, it must move inward! Ring B moves outward, unless it, too, has friction (with a ring C, which has friction with D, etc.).



Intergalactic medium absorption

Best-fit blackbody accretion disk spectra to the line-free continuum windows of the composite quasar spectrum of Francis et al. (1991). The solid curve shows the composite spectrum; the short-dashed curve, a disk model around a Schwarzschild hole; and the long-dashed curve, a disk model around a Kerr hole with a = 0.98M.

Eddington Limit

If we consider a parcel of atomic hydrogen gas at a distance r from a source of luminosity L, then the flux at the position of the parcel of gas is $F = L/(4 \cdot \pi \cdot r^2)$ if we assume there is no opacity along the line of sight from the source of L to the gas.

The photon pressure onto the parcel of gas from the the central source is then

$$P = \frac{F}{c} = \frac{L}{4 \cdot \pi \cdot c \cdot r^2} \tag{128}$$

In general the opacity along the line of sight can be determined as the Thompson cross section, i.e.

$$\sigma_e = \frac{8 \cdot \pi}{3} \cdot \left(\frac{e^2}{m_e \cdot c^2} \right)^2 \tag{129}$$

were e is the charge of the electron, m_e the mass of the electron, and c the speed of light. (Thompson scattering on electrons is the main source of scattering in this area).

Hence, in order for material to be able to accrete onto the central black hole, the radiation pressure has to be lower than the gravity, i.e. in order to accrete we need:

$$F_{rad} = \sigma_e \cdot \frac{L}{4 \cdot \pi \cdot c \cdot r^2} \leq \frac{G \cdot M \cdot m_p}{r^2} \tag{130}$$

with m_p the proton mass. Since both, radiation pressure and gravity are proportional to r^{-2}, there is no equilibrium distance were the two are in balance. We can hence determine the Eddington limit: the maximum luminosity of an AGN for a given black hole mass.

$$L \leq \frac{4 \cdot \pi \cdot G \cdot m_p}{\sigma_e} \cdot M = L_E \tag{131}$$

which is in physical units:

$$L_E = 3.2 \cdot 10^4 \cdot \left(\frac{M}{M_\odot}\right) \cdot L_\odot \tag{132}$$

One can also determine the minimum mass (Eddington Mass) for the central black hole for a given luminosity:

$$M_E = 8 \cdot 10^5 \cdot \left(\frac{L}{10^{37}\mathrm{W}}\right) \cdot M_\odot \tag{133}$$

Note: $L_\odot = 4 \cdot 10^{26}$ W. With these we get Eddington masses for Seyfert galaxies in the order of 10^6 $\mathrm{M}_\odot$ and for quasars we obtain 10^8 $\mathrm{M}_\odot$!!!!

The luminosity of the quasar is due to mass accretion, i.e. conversion of gravitational potential energy into kinetic energy. I.e. the luminosity is

$$L = \eta \cdot \dot{M} \cdot c^2 \tag{134}$$

were η is the efficiency of the conversion. Models predict that $\eta \approx 0.1$, which compares to the efficiency of hydrogen fusion of only $\eta = 0.007$!!!. With these numbers it is easy to calculate that a typical QSO with $L \approx 10^{39}$ W needs mass accretion rates of $\dot{M} \approx 2\mathrm{M}_\odot/\mathrm{yr}$.

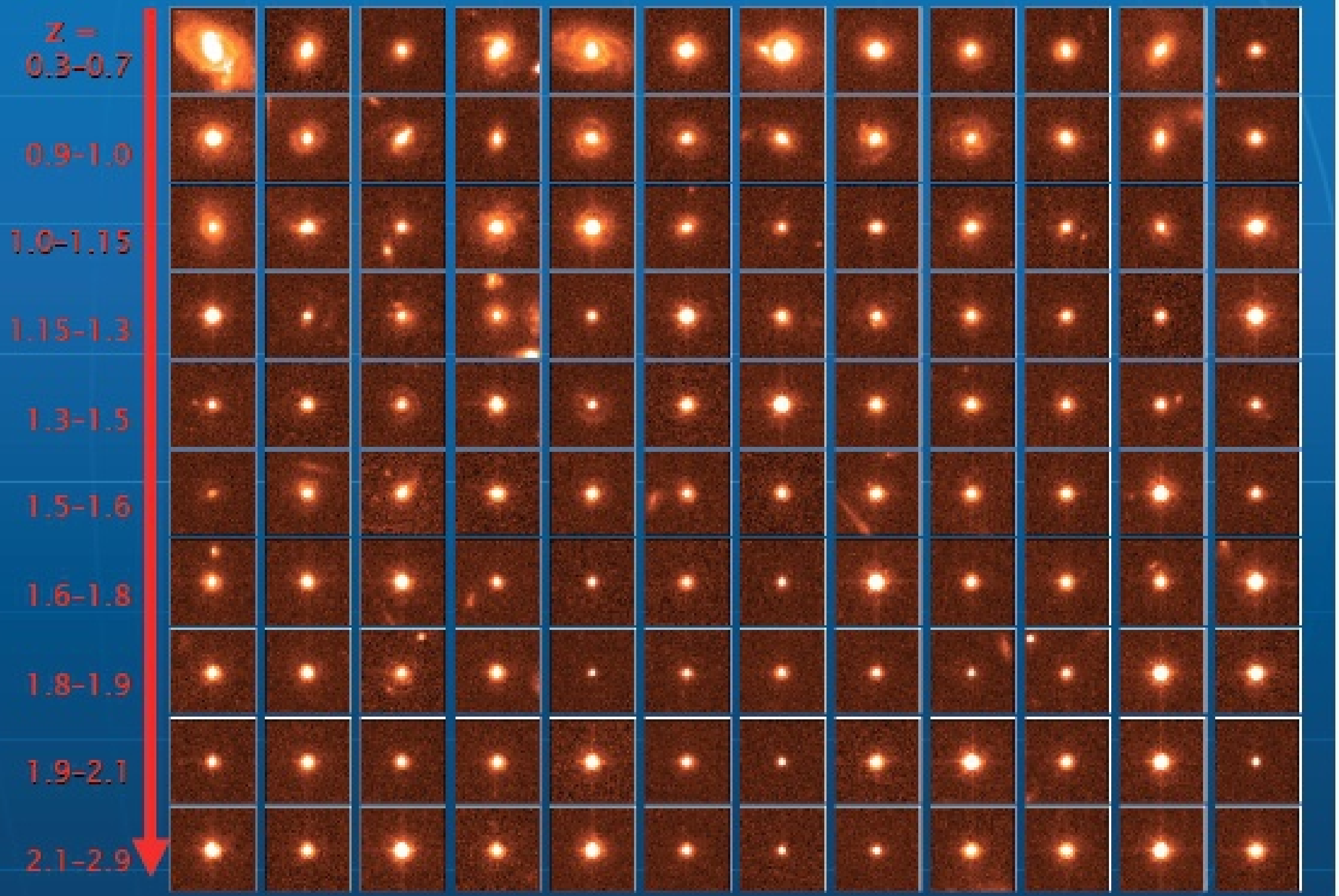
One can use this to determine the Eddington Limit, i.e. the maximum accretion rate onto the central object for a given black hole mass. This calculates to:

$$\dot{M}_E = \frac{L}{\eta \cdot c^2} = 2.2 \cdot \left(\frac{M}{10^8 M_\odot} \right) M_\odot / yr \tag{135}$$

Are QSOs actually active galactic nuclei? (i.e. live in galaxy center)

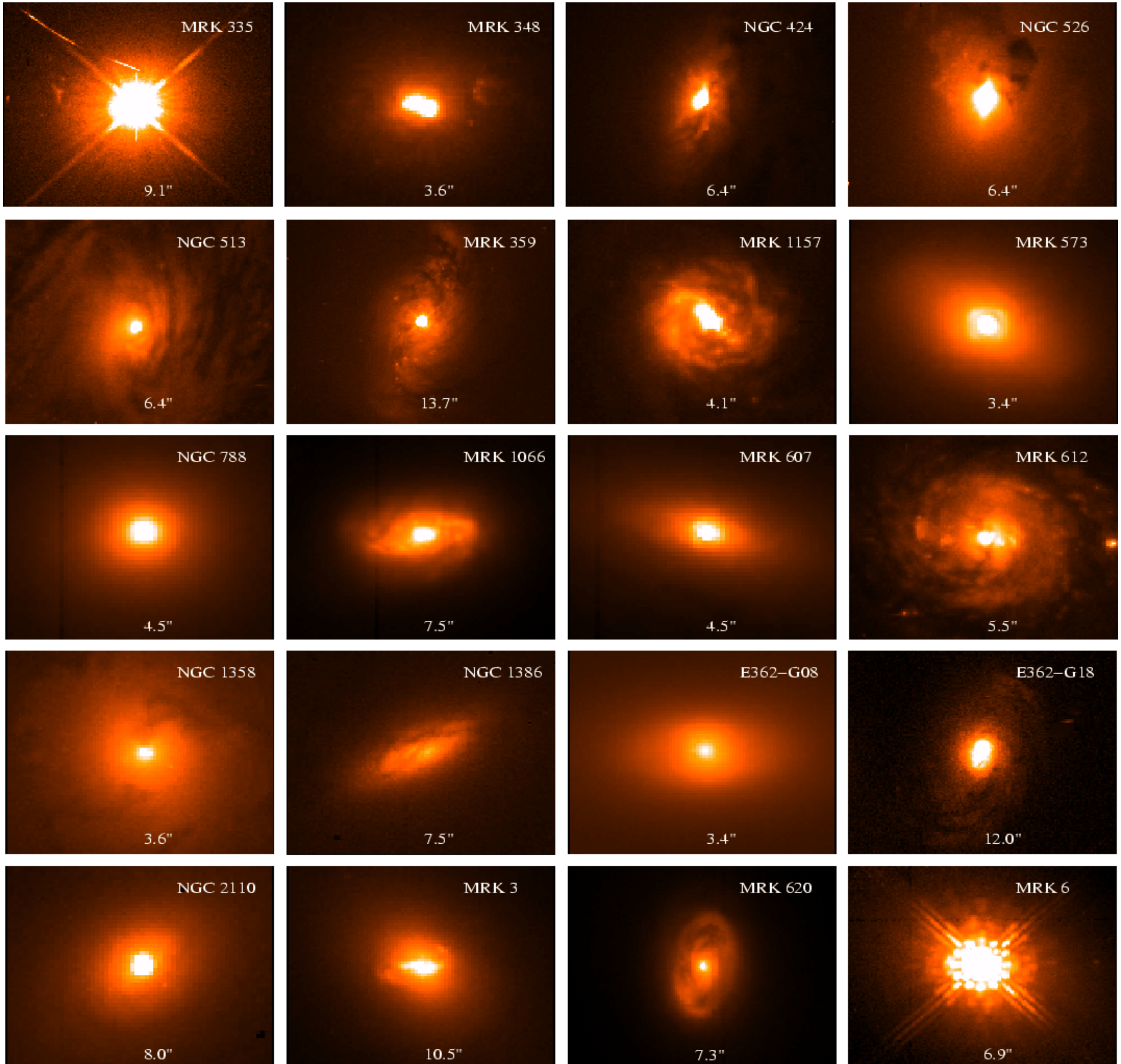
Answer:

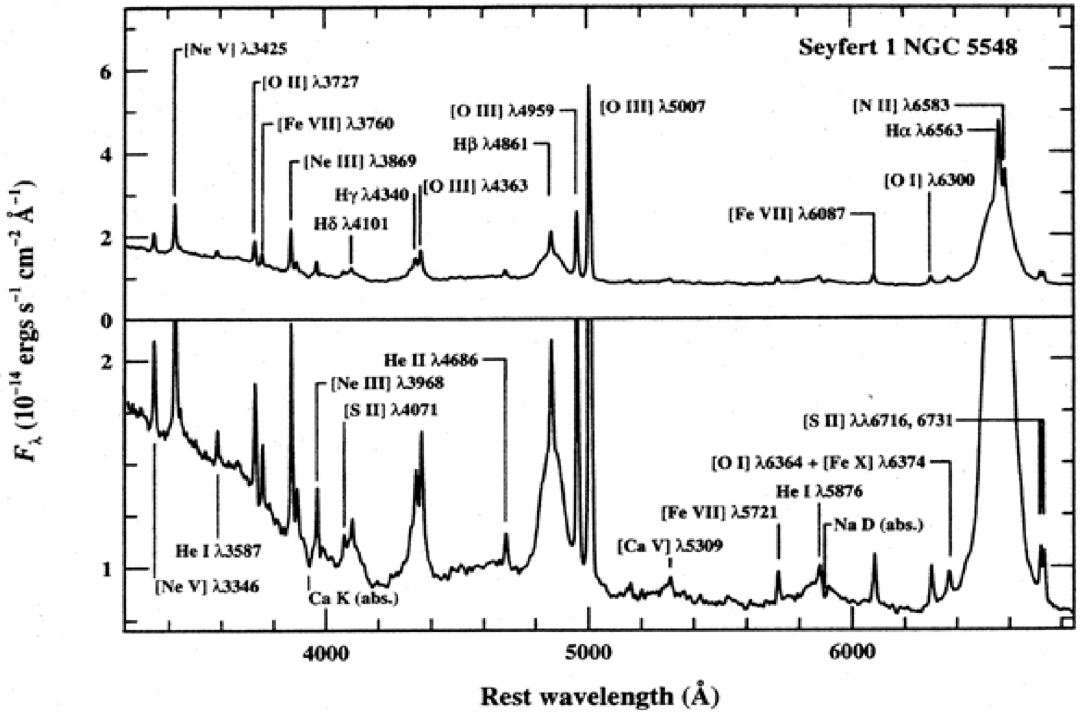
whenever on 'has a chance' to see a 'host galaxy' one does see one



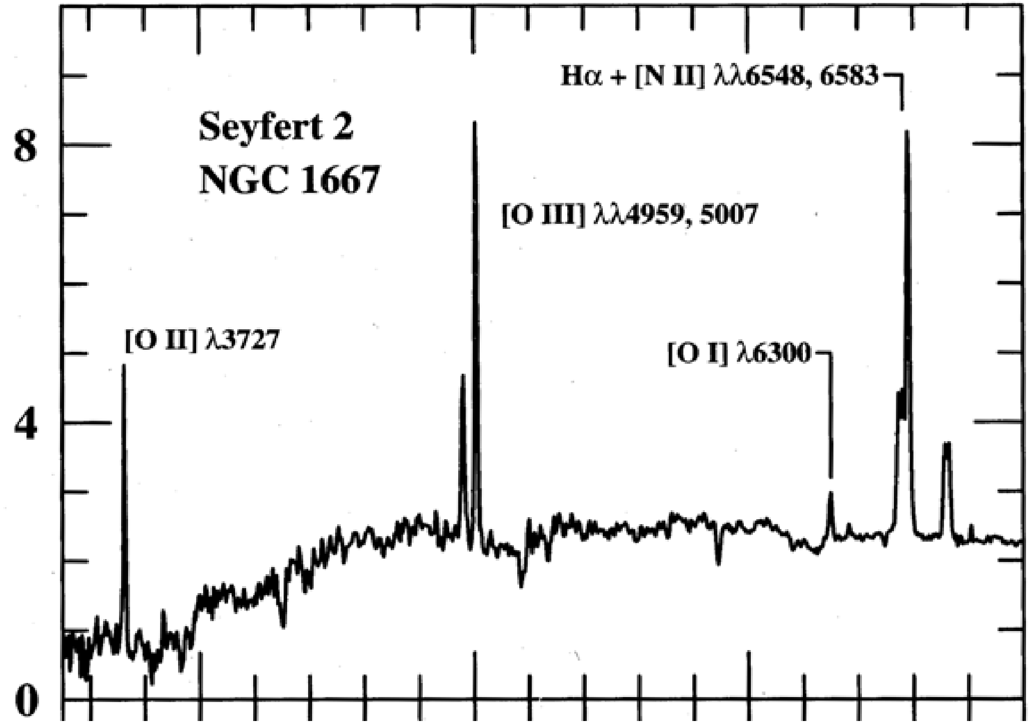
HST imaging COSMOS: Jahnke et al 2007/8

Seyfert Galaxies: fainter versions of quasars

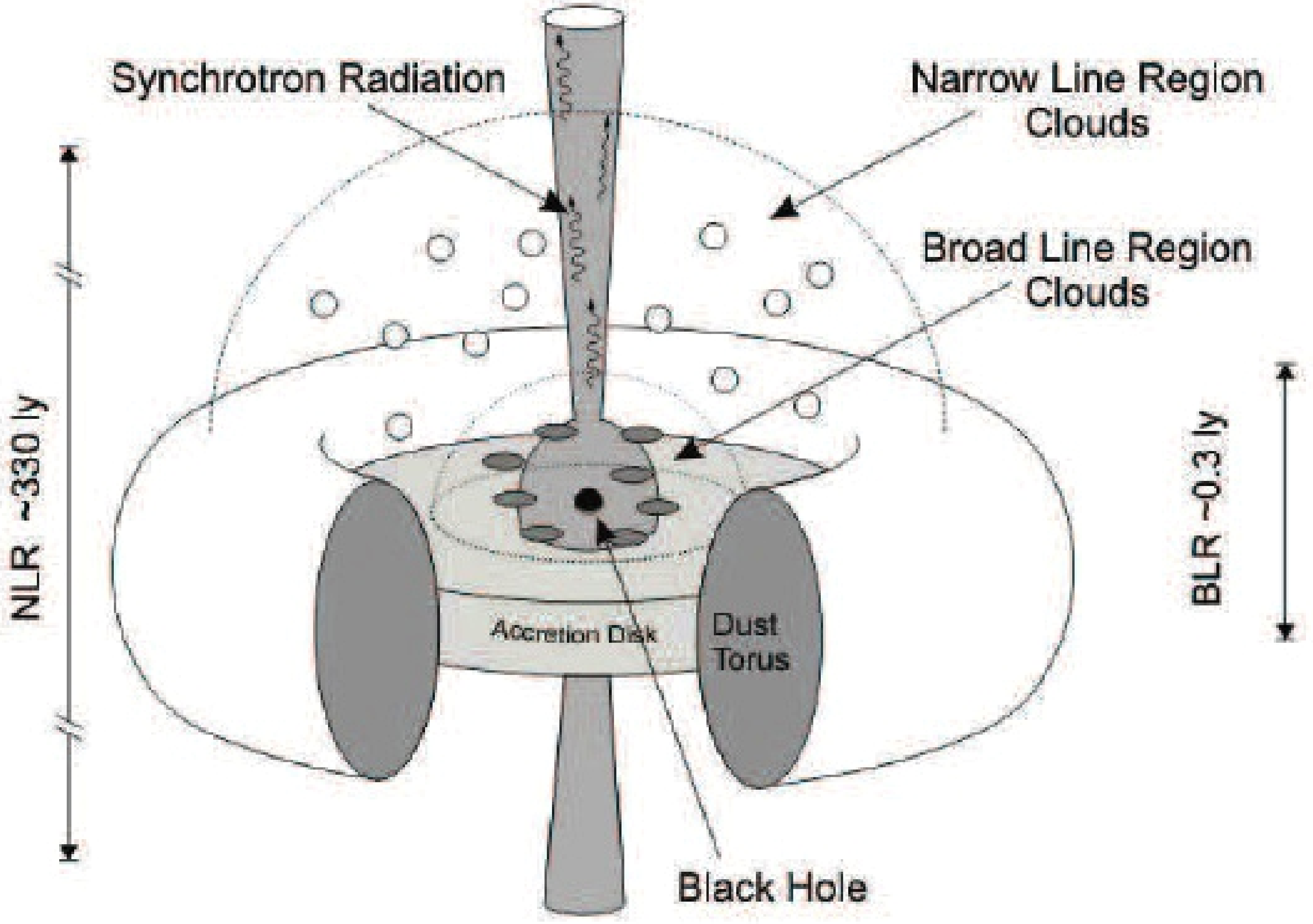




Seyfert Is have spectra with broad emission lines and there are clear point-like central nuclei in the images of the host galaxy.

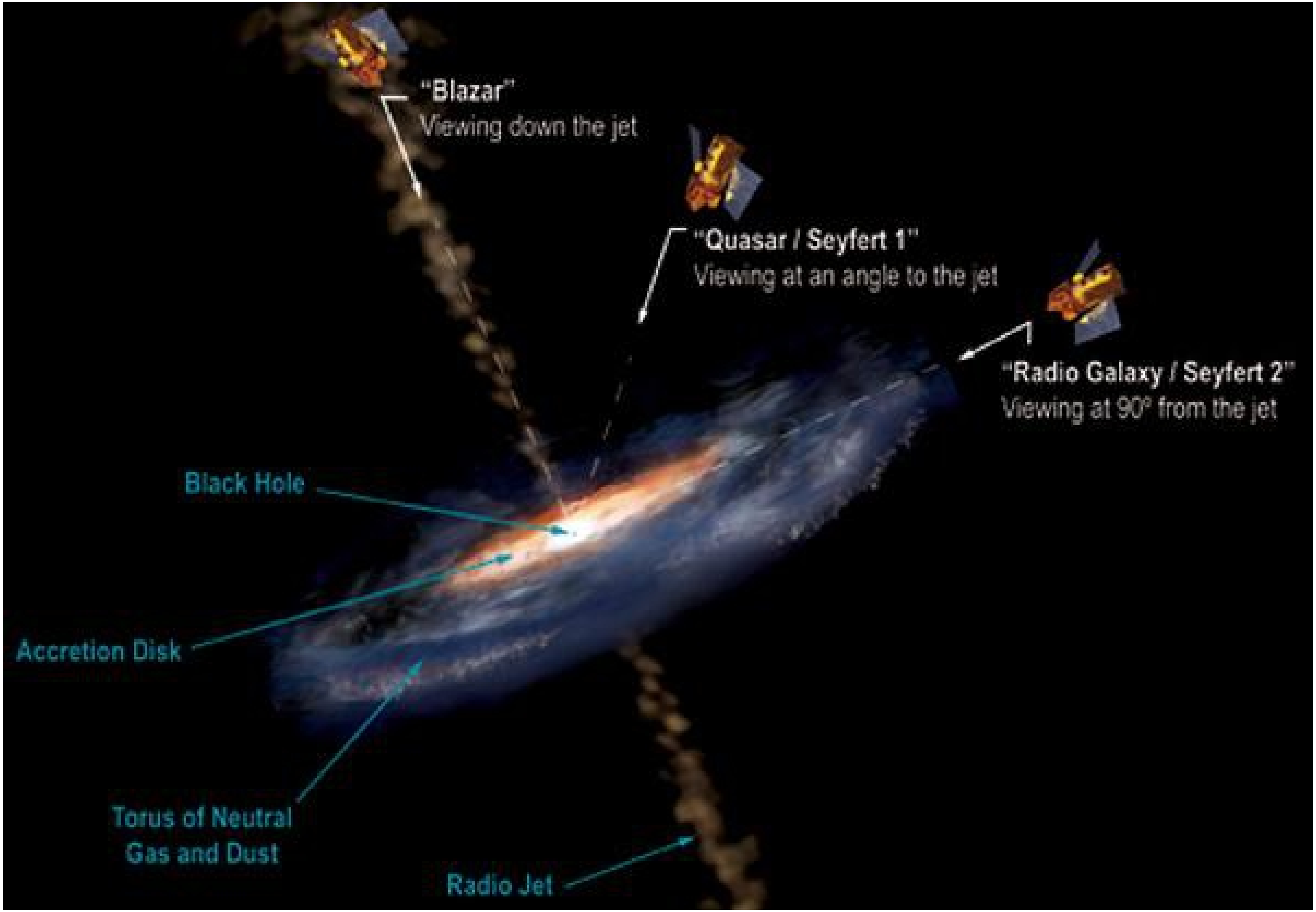


In Seyfer 2s, there is no point-like nucleus. The spectro show strong HIGH IONIZATION POTENTIAL emission lines

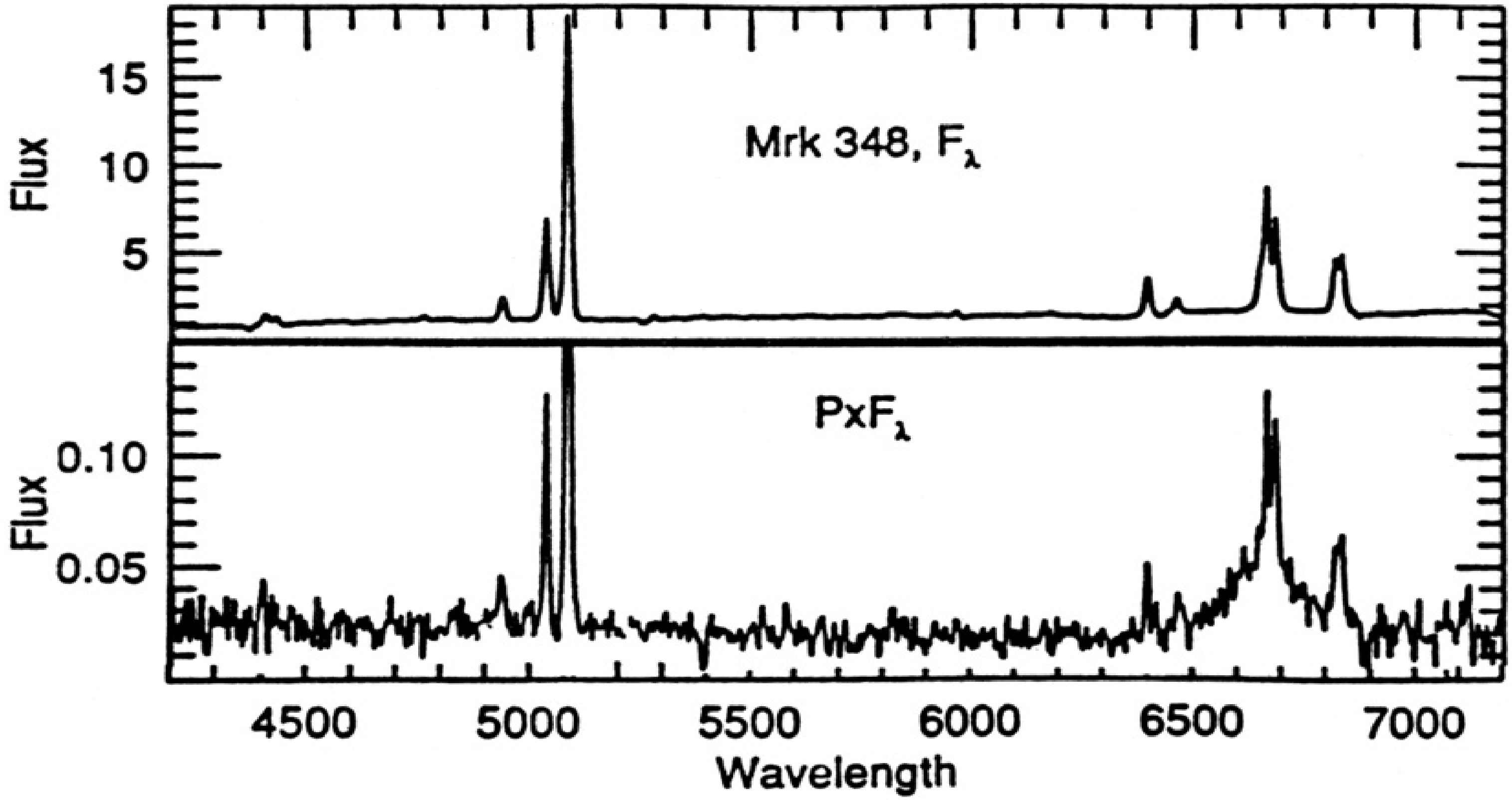


The Unified Model

All known classes of AGN are thought to be explainable by the above scheme. Depending on the viewing angle the observed spectra will look different, leading to a different classification of the object.


"Blazar"
Viewing down the jet
"Quasar / Seyfert 1"
Viewing at an angle to the jet
"Radio Galaxy / Seyfert 2"
Viewing at 90° from the jet
Black Hole
Accretion Disk
Torus of Neutral Gas and Dust
Radio Jet

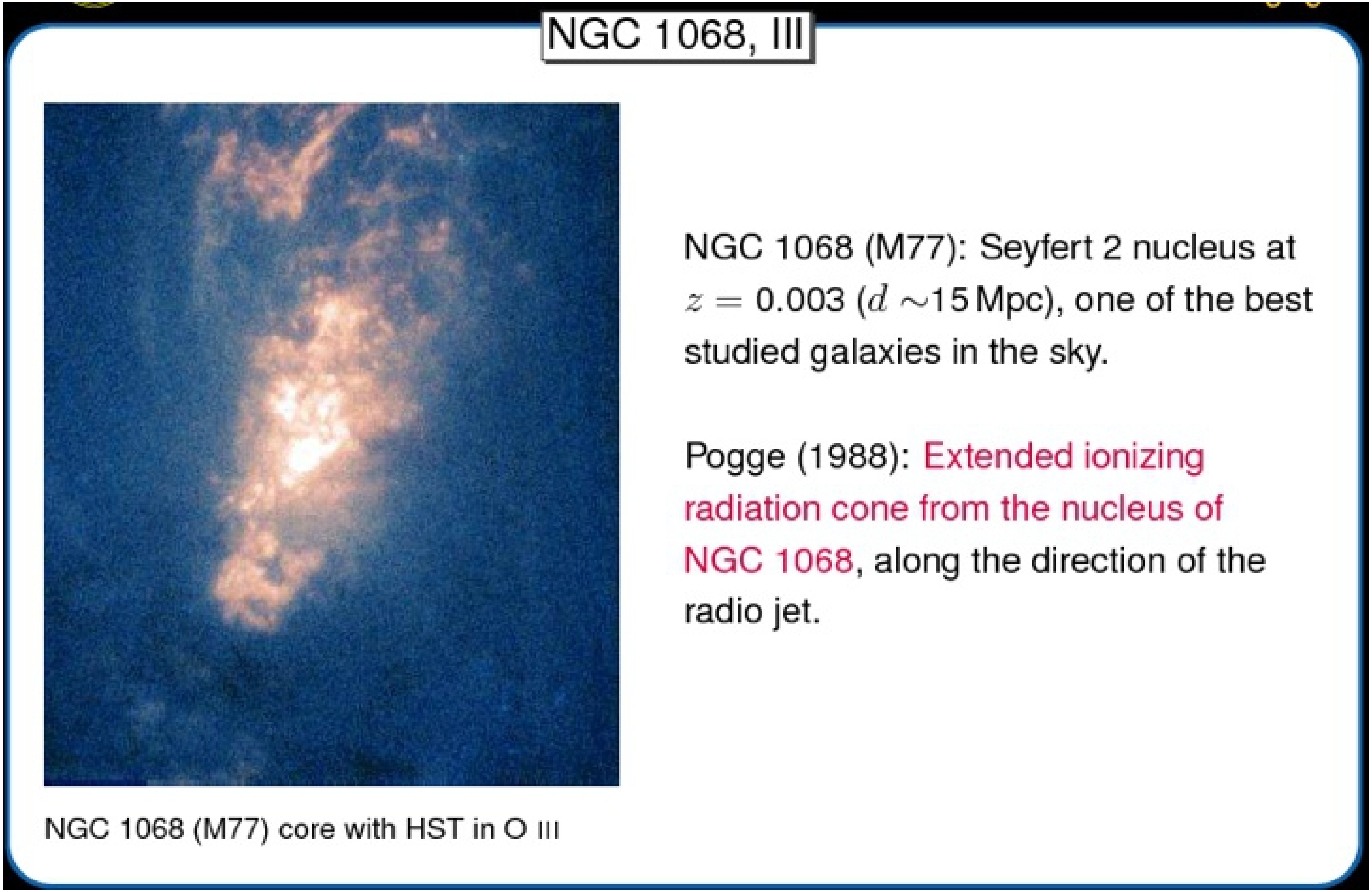
Evidence for the Unified Model



Type II AGN

Spectrum in polarized light showing broad lines

The Narrow Line Region



NGC 1068, III

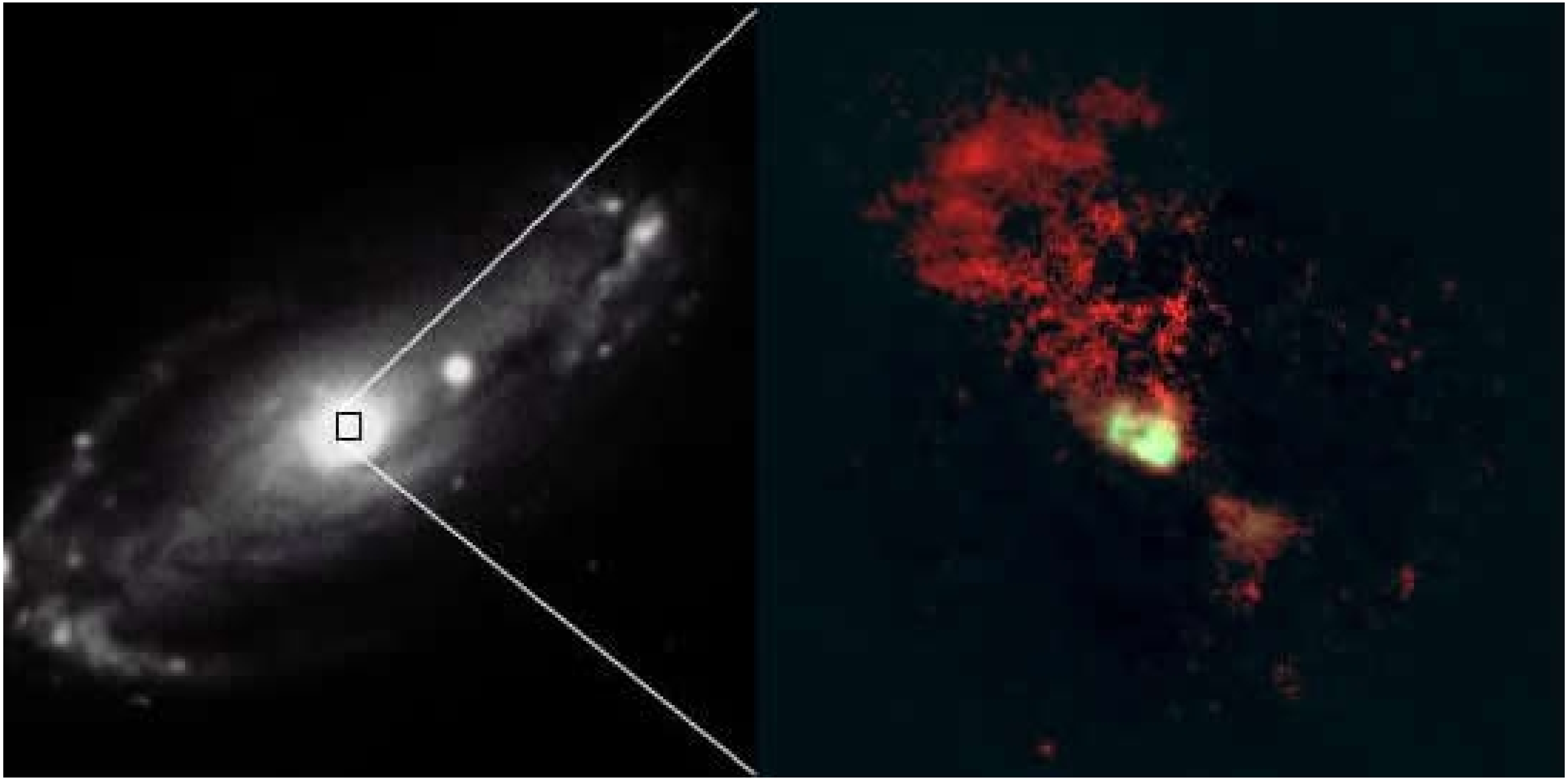
NGC 1068 (M77): Seyfert 2 nucleus at $z = 0.003$ ($d \sim 15\,\mathrm{Mpc}$), one of the best studied galaxies in the sky.

Pogge (1988): Extended ionizing radiation cone from the nucleus of NGC 1068, along the direction of the radio jet.

NGC 1068 (M77) core with HST in O III

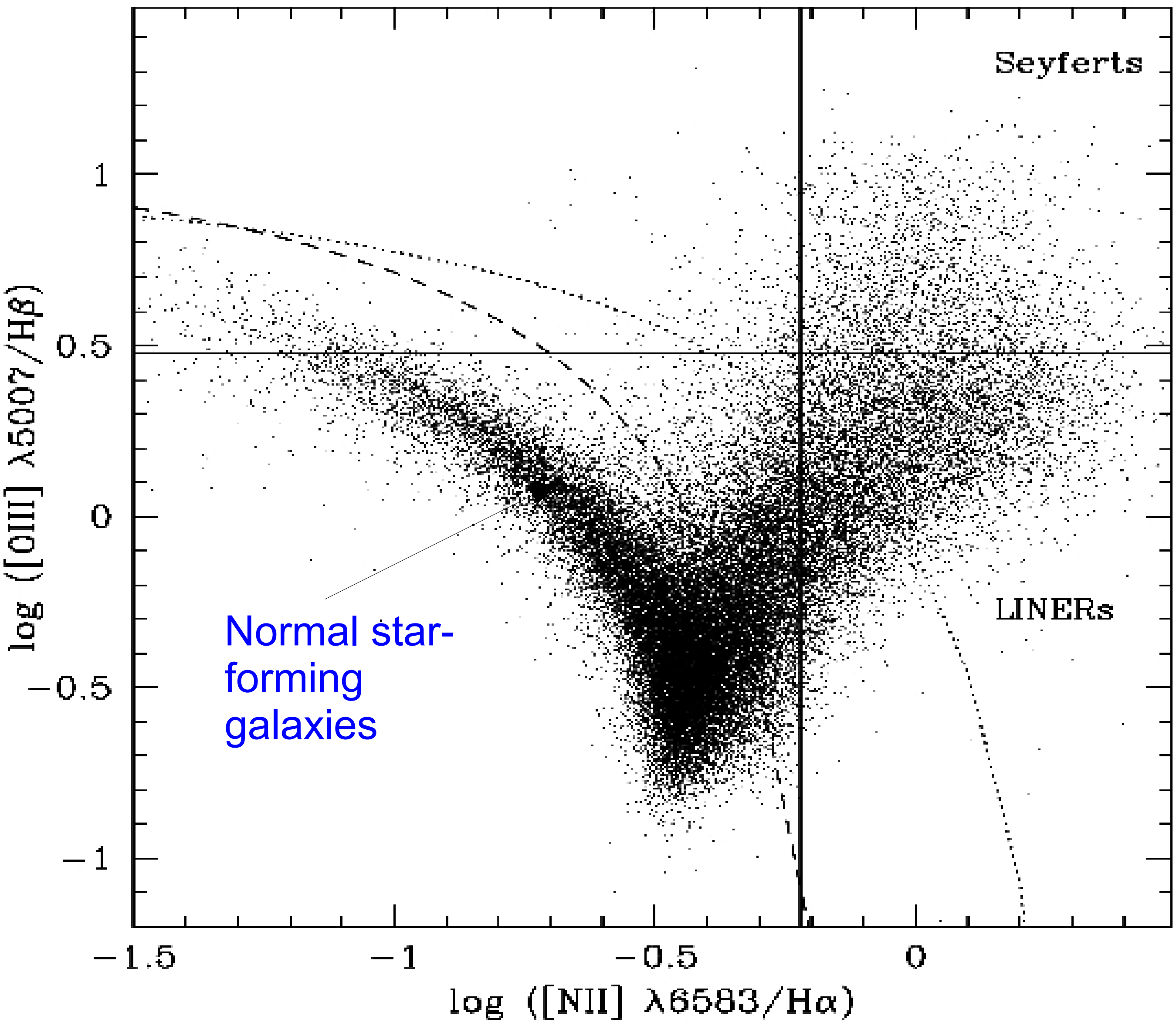
The Seyfert Galaxy NGC 5728

Photoionisation must be caused by AGN itself: hot stars do not produce the high-energy photons to excite the highest-ionization lines.



HST image of area in box

Emission-line diagnostic diagrams for identifying Type 2 AGN



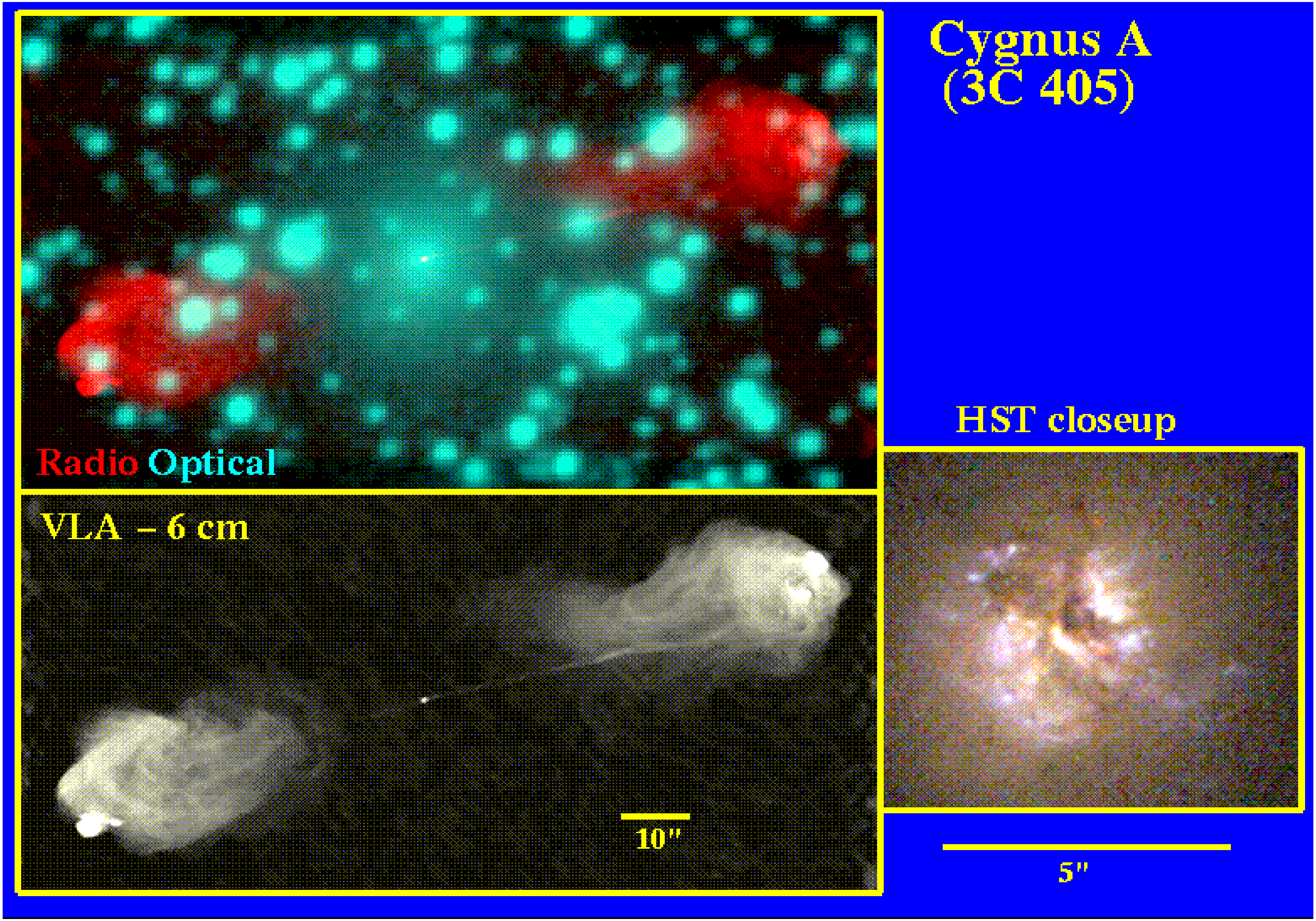
Normal star-forming galaxies

Some accretion discs produce jets of twin, highly collimated, and fast outflows that emerge in opposite directions from close to the disc. The direction of the jet ejection is determined either by the angular momentum axis of the accretion disc or the spin axis of the black hole.

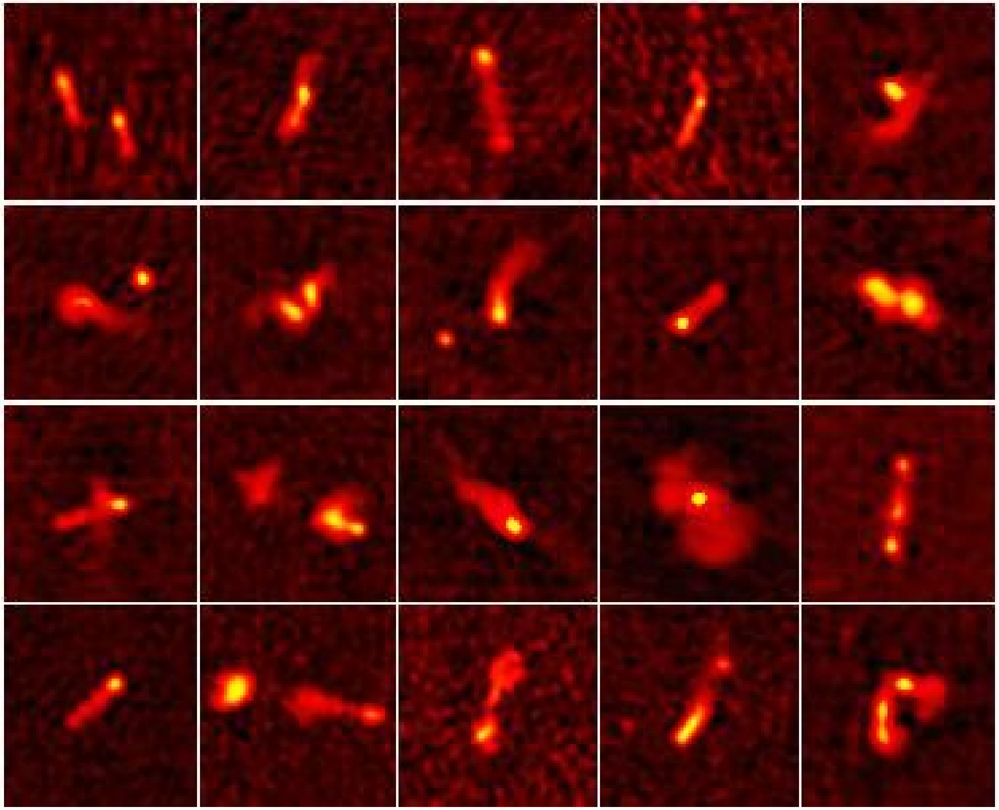
Rotating black hole as energy source:

The magnetic fields around the accretion disk are dragged by the spin of the black hole. The relativistic material is possibly launched by the tightening of the field lines (Blandford-Znajek process)

Cygnus A - the prototype high-powered radio galaxy



Low-powered radio galaxies



Fanaroff-Riley classification

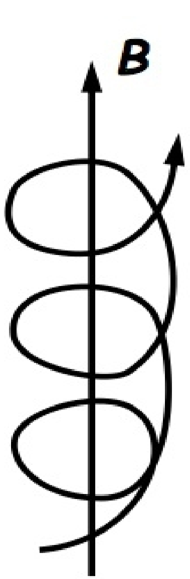
- FR1 radio galaxies have the brightest emitting region less than half of the distance from the core to the extremity of the radio source (e.g. 3C31)
- FR2 radio galaxies have the brightest emitting region more than half of the distance from the core to the extremity of the radio source (e.g. PKS2356-61)

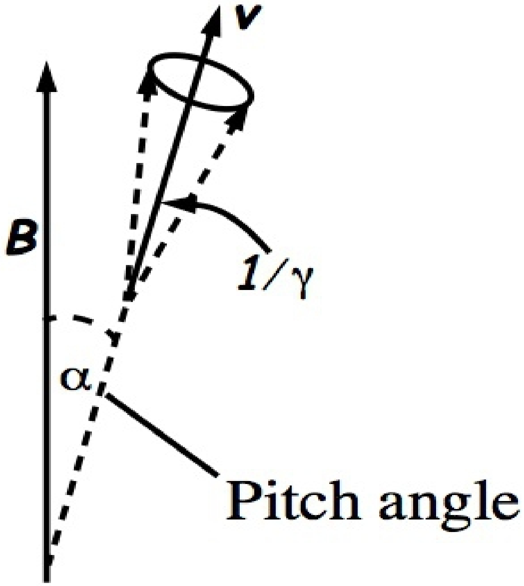
Optical morphology

- Almost all radio galaxies are elliptical or S0 galaxies
- Some powerful galaxies have associated emission line gas possibly associated with a merger in the recent past

2 Emission mechanism

Radio emission results from the synchrotron mechanism, involving highly relativistic particles in a magnetic field





Non-thermal distributions of electrons

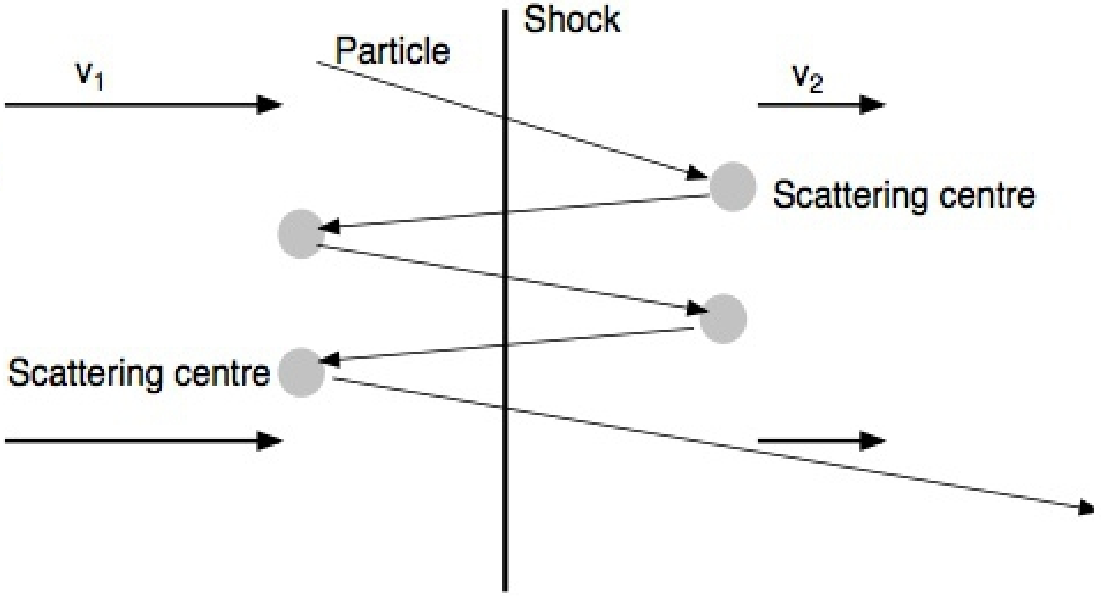
The "zeroth order" spectrum for a distribution of electrons is frequently represented as a power-law

$$N(\gamma)\,d\gamma = \begin{array}{c}\textit{No. density of particles in the}\\ \textit{interval}\ \gamma \rightarrow \gamma + d\gamma\end{array} = K\gamma^{-a}d\gamma$$

Origin of particle spectrum

- Shock waves in relativistic plasma give rise to power-law distribution of electrons

- Repeated scatterings of electrons across the shock front. At each scattering the particle gains energy



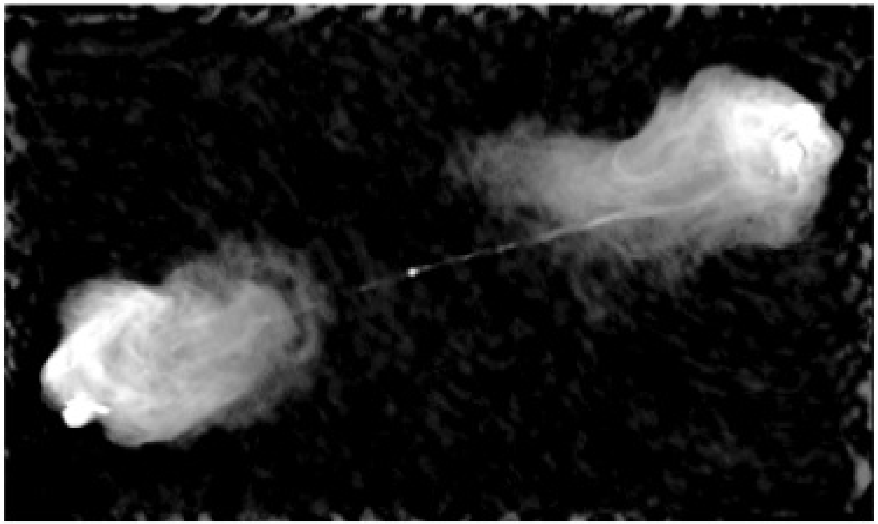
- Particles with the most scatterings gain the most energy

- There is a finite probability, in the post-shock region that a particle will escape downstream

- The combination of scatterings plus escape leads to power-law in energy

3 The energy involved in radio galaxies

- Measurements of the emission from an astrophysical object involve the flux density:



$F_\nu = \mathit{Watts}\ m^{-2}\ Hz^{-1}$ *at telescope*

- For optically thin emission, this is related to the emissivity and the luminosity distance of the source by:

$$F_\nu = \frac{1}{D_L^2} \int_V j_\nu \, dV$$

- The emissivity is defined as

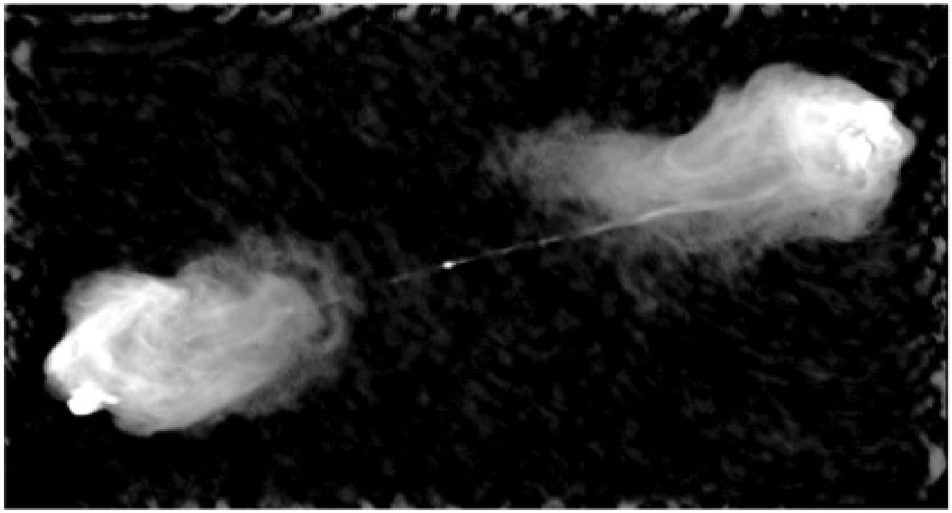
$$j_\nu = \frac{\text{Power emitted per unit volume}}{\text{per unit frequency per steradian}}$$

- In the case of synchrotron emission

$$j_\nu \propto \varepsilon_e B^{\frac{a+1}{2}} \nu^{-\left(\frac{a-1}{2}\right)}$$

ε_e = Energy density of electrons B = Magnetic field

Characteristic values of minimum energy parameters



Cygnus A:

$$B_{min} = 9\times10^{-9}\,T = 9\times10^{-5}\,G$$

$$\varepsilon_{e,min} = 4\times10^{-11}\,J\,m^{-3}$$

$$E_{min} \approx 3\times10^{52}\,J$$

4 Radio galaxies - the smoking gun for black holes

What can we learn from the minimum energy?

$$\dot{M}_{acc} = \text{Mass accretion rate}$$

$$\text{Power released from accretion onto black hole} = \alpha \dot{M}_{acc} c^2$$

$$\alpha \sim 0.1$$

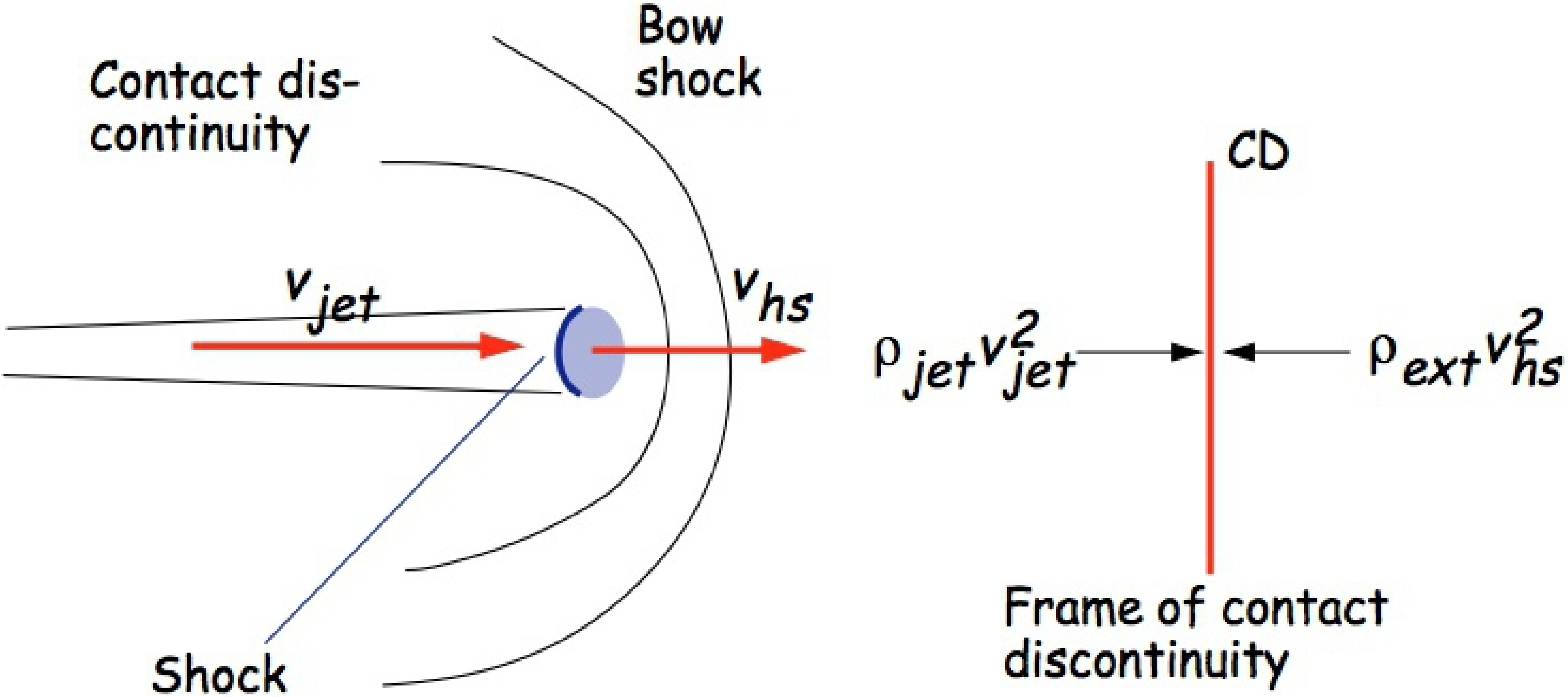
$$\text{Total energy released} = E_{tot} = \alpha M_{acc} c^2$$

$$M_{acc} = \frac{E_{tot}}{\alpha c^2} = 5.6\times10^6 \left(\frac{E}{10^{53}\ J}\right)\left(\frac{\alpha}{0.1}\right)^{-1} \text{solar masses}$$

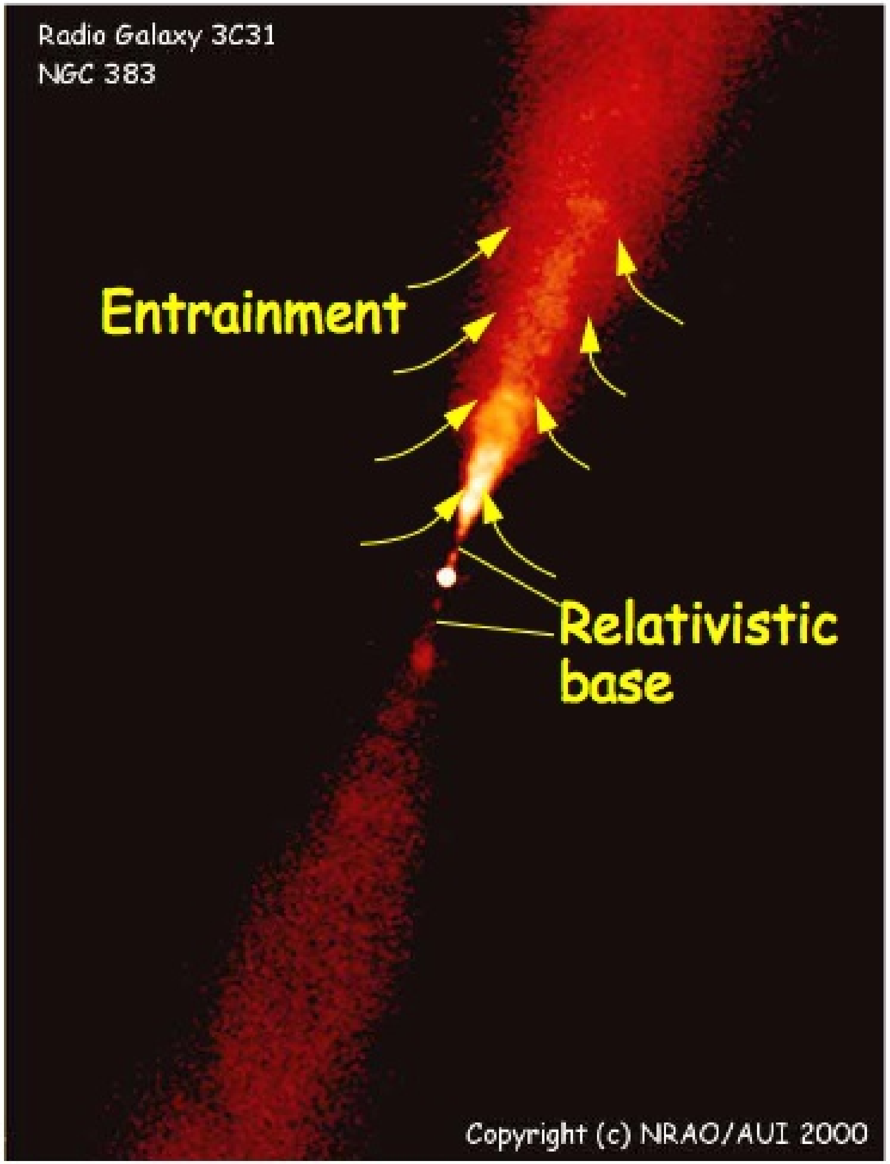
Of order 2×10^6 solar masses has to be accreted

7 FR2 jets - hot spot dynamics

Non-relativistic calculation for hot-spot advance



8 FR1 jets

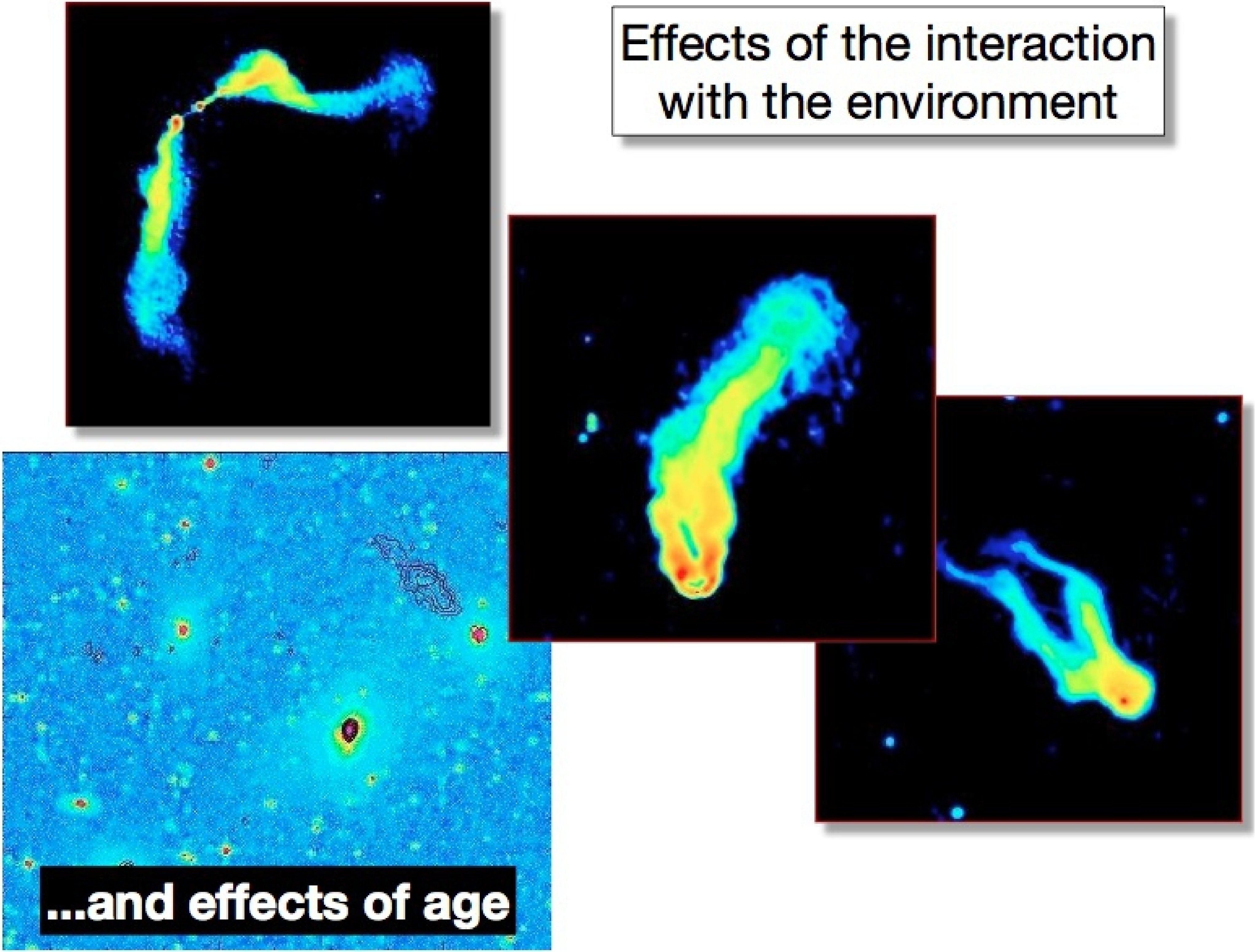


The prototype FR2 radio source 3C 31 is used to illustrate some of the important features of jets in low-powered radio galaxies.

Entrainment is responsible for the spreading of jets with distance from the core and for a high surface brightness

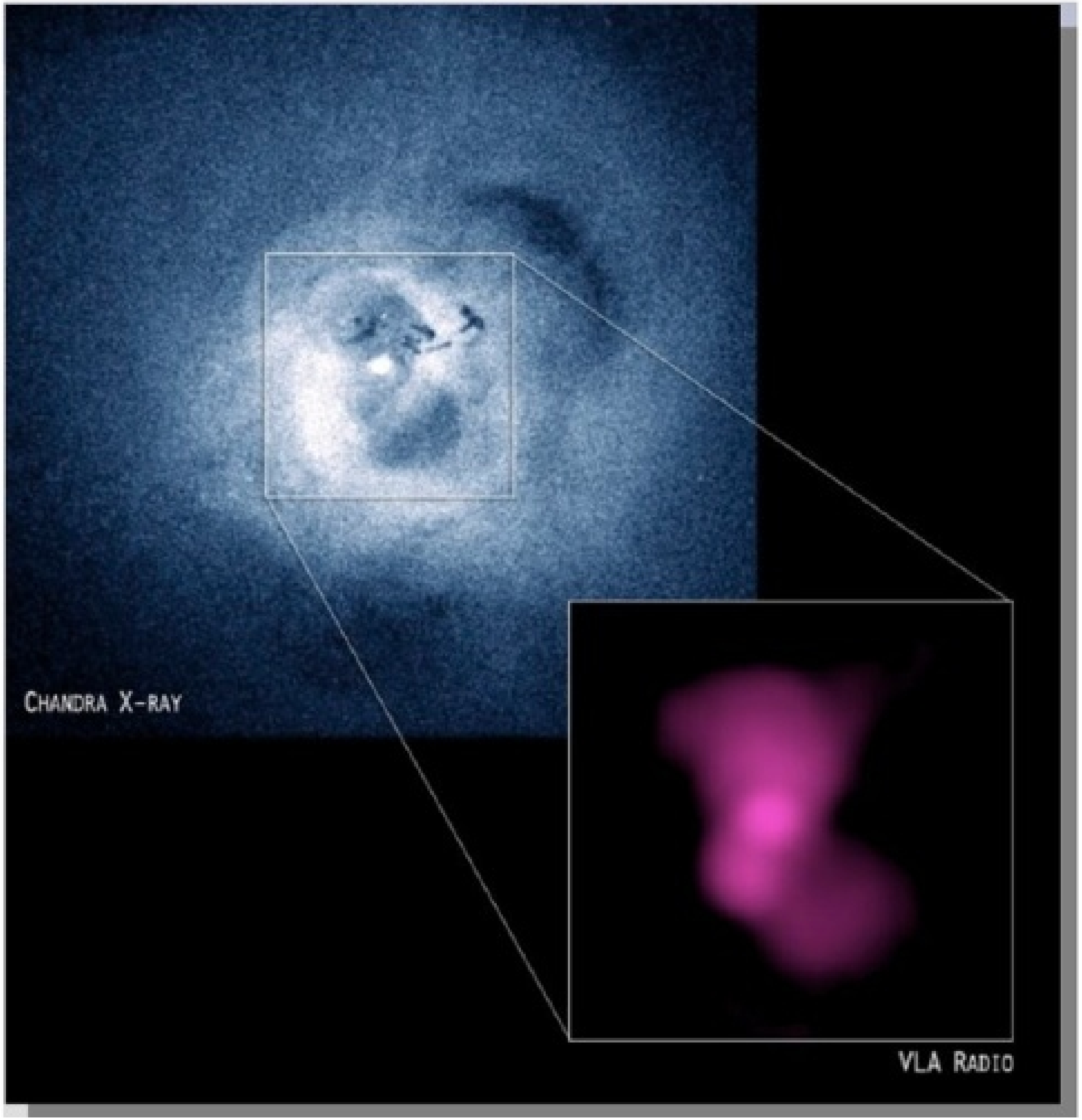
The jets are relativistic near the base and show a surface brightness asymmetry resulting from relativistic beaming

Effects of the interaction with the environment



...and effects of age

Why study radio-loud AGN?



Feedback of radio-loud AGN into the surrounding IGM (seen through X-ray here).