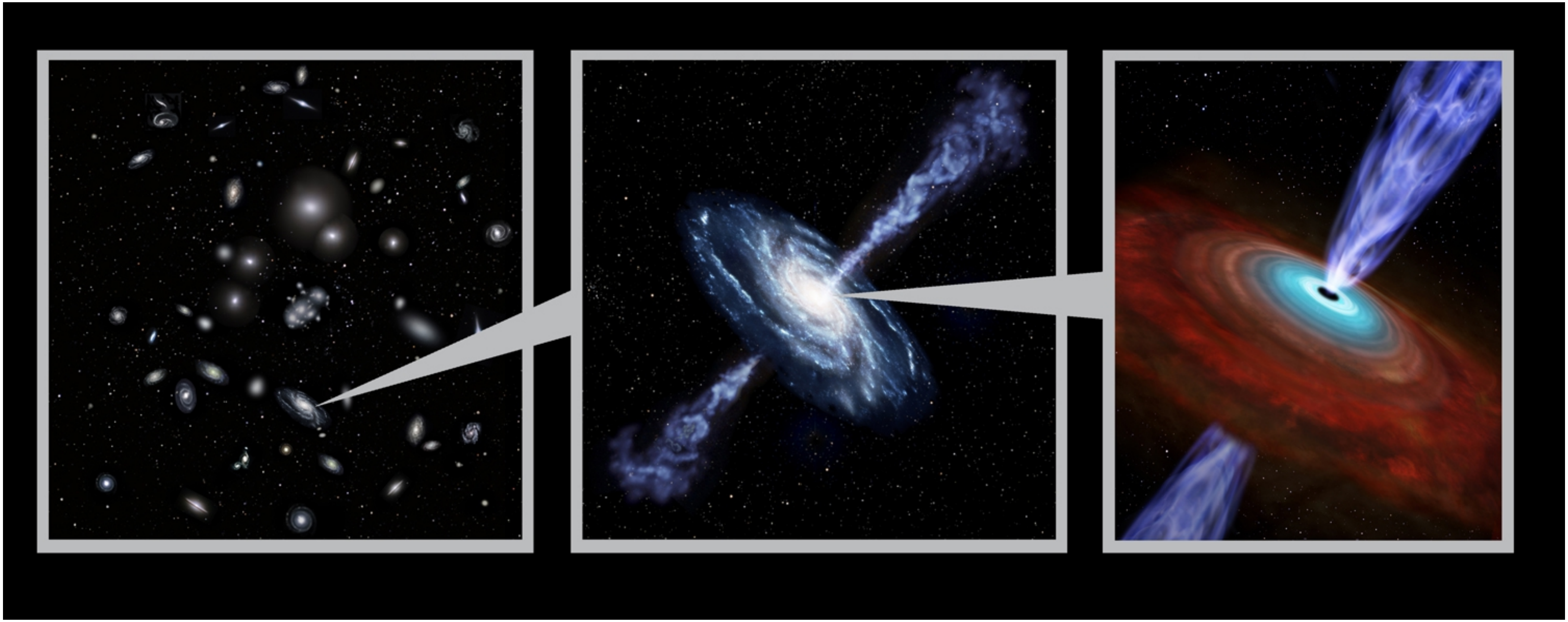
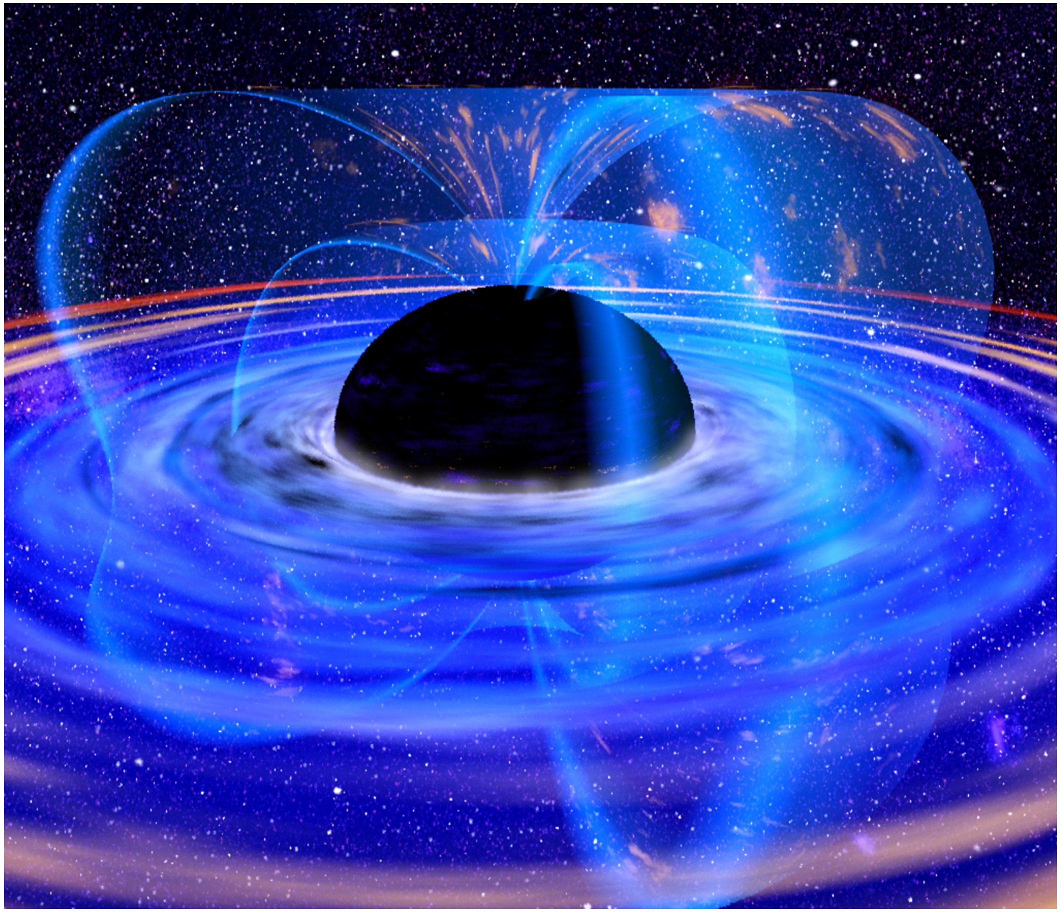
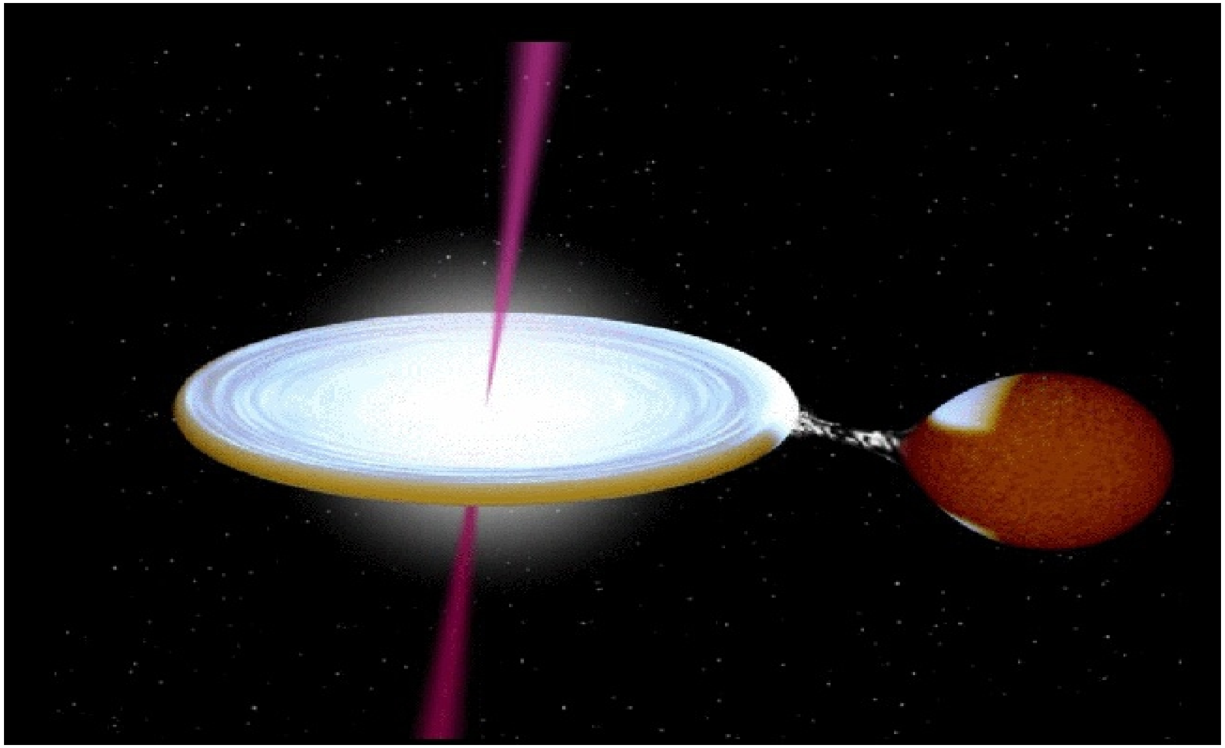
Black Holes and Active Galactic Nuclei





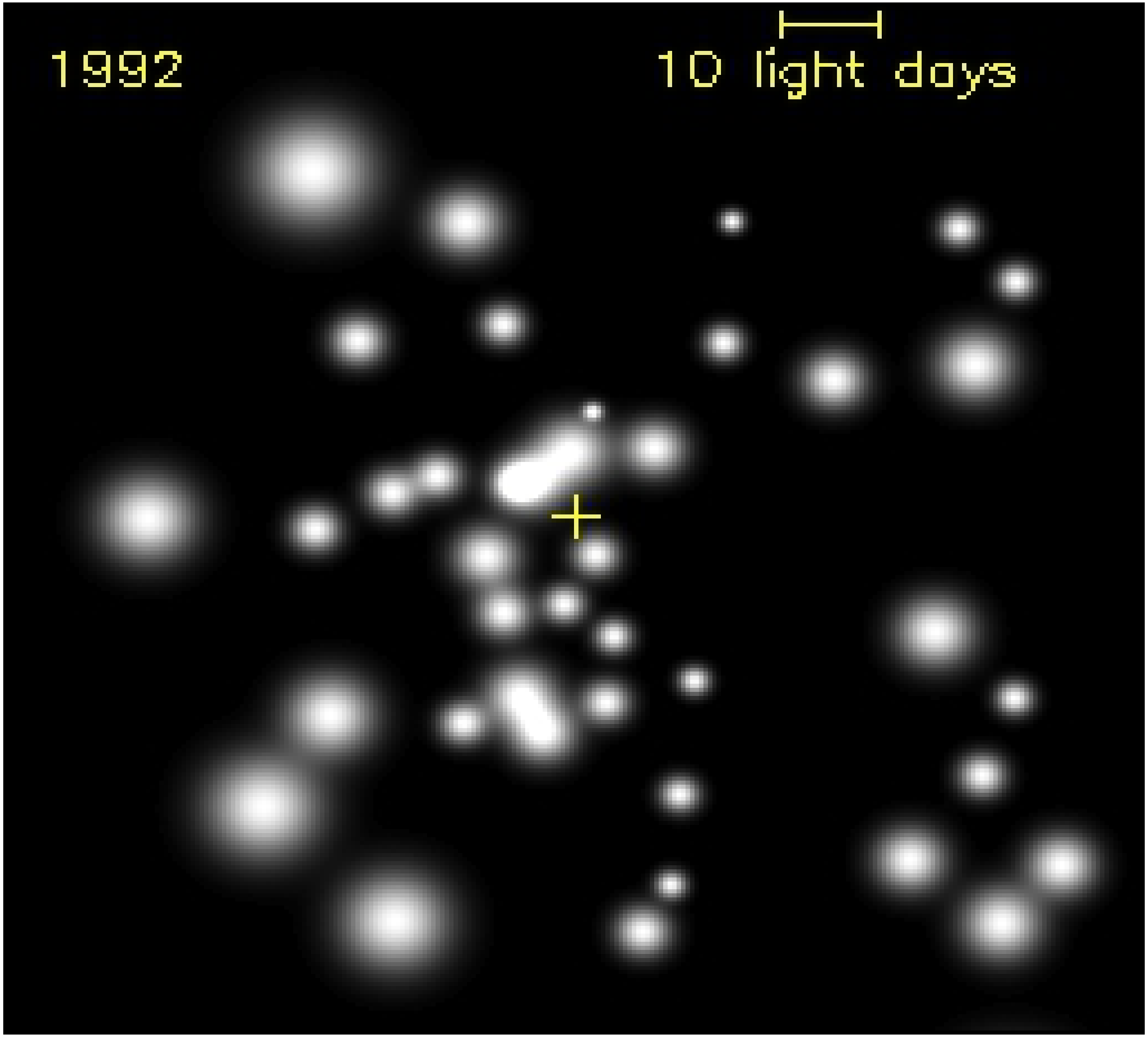
A black hole is a region of spacetime from which gravity prevents anything, including light, from escaping. The theory of general relativity predicts that a sufficiently compact mass will deform space-time to form a black hole. Around a black hole, there is a mathematically defined surface called an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

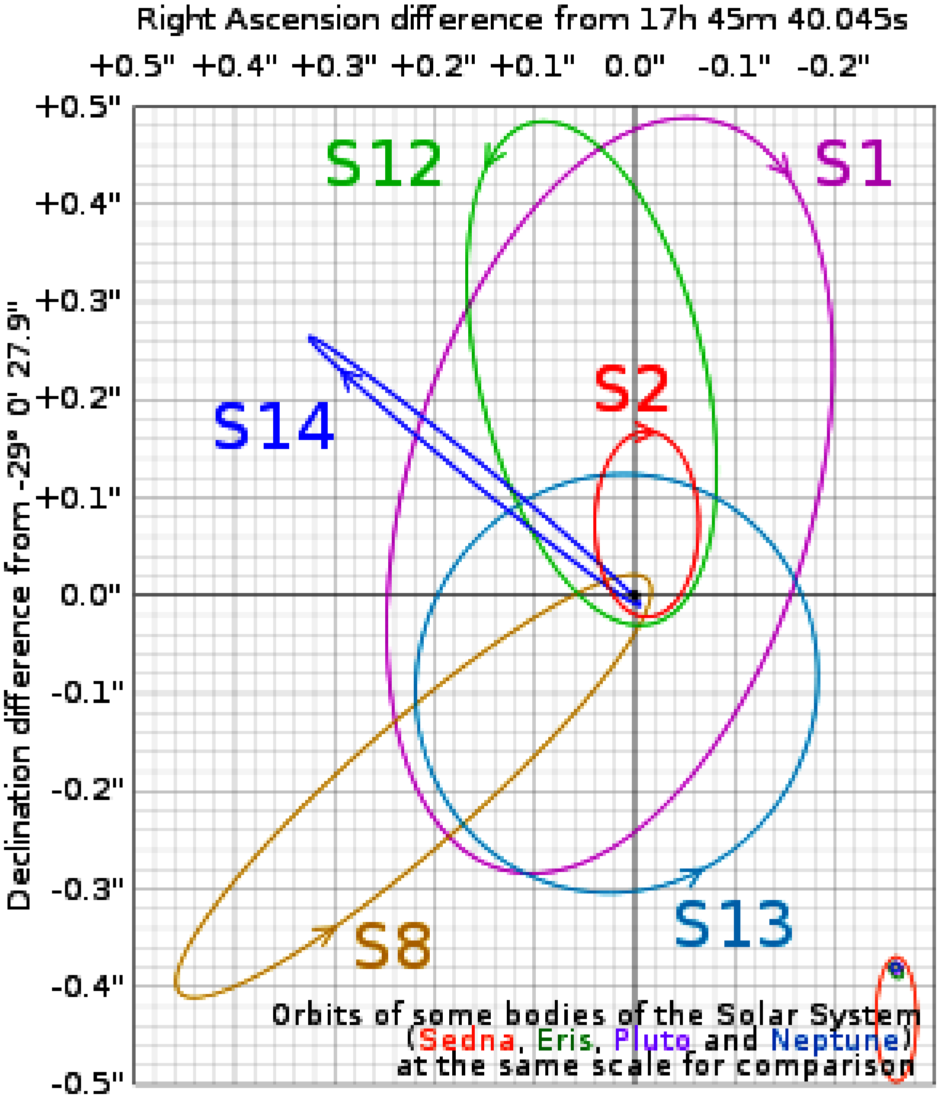
Evidence for Black Holes in the Real Universe

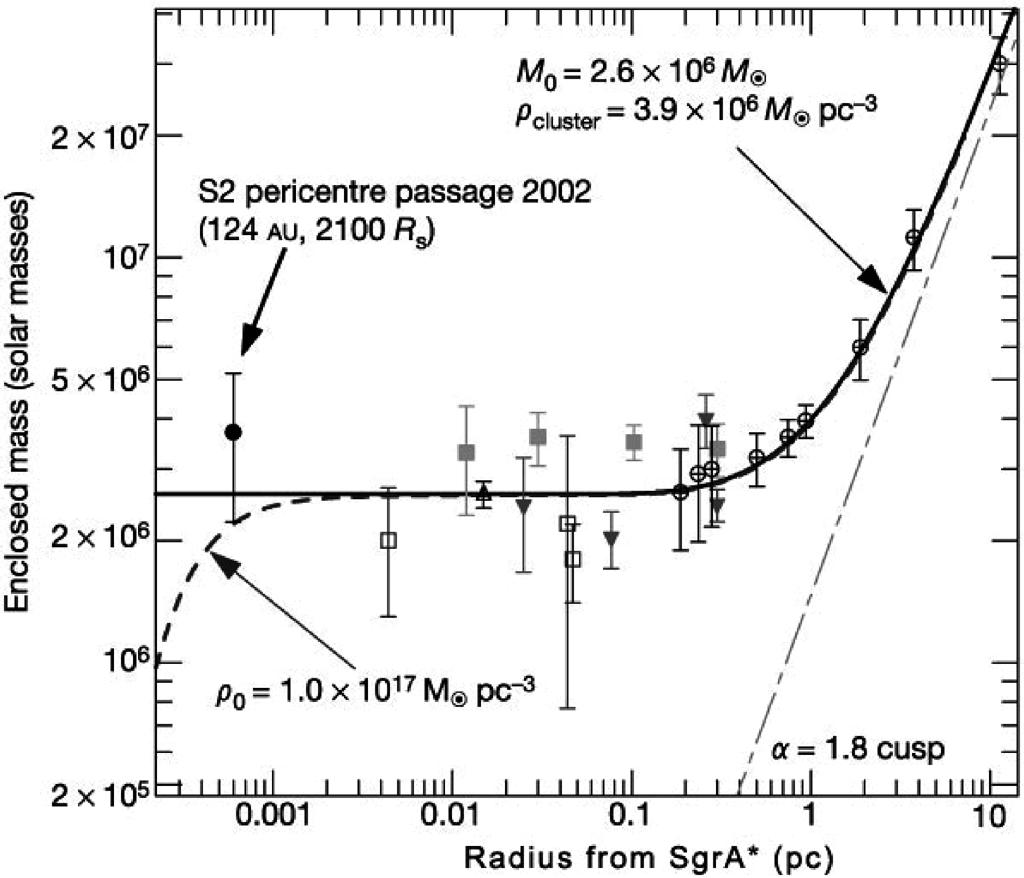


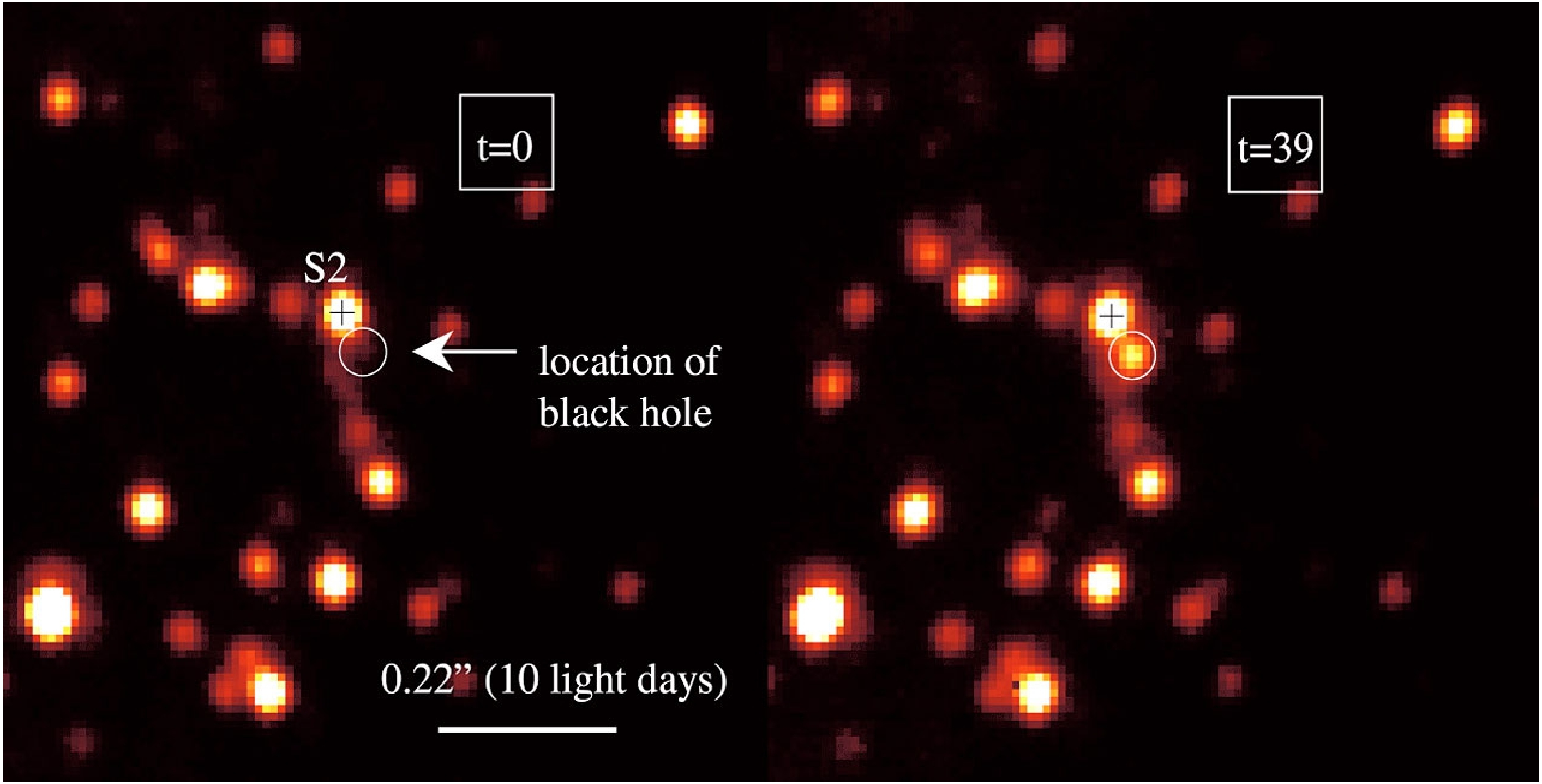
X-ray binaries are a class of binary stars that are luminous in X-rays. The X-rays are produced by matter falling from one component, called the donor (usually a relatively normal star) to the other component, called the accretor, which is compact: a white dwarf, neutron star, or black hole. The infalling 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


1992
10 light days


Right Ascension difference from 17h 45m 40.045s
+0.5" +0.4" +0.3" +0.2" +0.1" 0.0" -0.1" -0.2"
Declination difference from -29° 0' 27.9"
+0.5" +0.4" +0.3" +0.2" +0.1" 0.0" -0.1" -0.2" -0.3" -0.4" -0.5"
S12
S1
S14
S2
S13
S8
Orbits of some bodies of the Solar System
(Sedna, Eris, Pluto and Neptune)
at the same scale for comparison


$M_0 = 2.6 \times 10^6 M_\odot$
$\rho_{\mathrm{cluster}} = 3.9 \times 10^6 M_\odot \mathrm{pc}^{-3}$
S2 pericentre passage 2002
(124 AU, 2100 R_s)
$\rho_0 = 1.0 \times 10^{17} M_\odot \mathrm{pc}^{-3}$
$\alpha = 1.8$ cusp
Enclosed mass (solar masses)
2×10^7
10^7
5×10^6
2×10^6
10^6
2×10^5
0.001
0.01
0.1
1
10
Radius from SgrA* (pc)


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

SPACE TELESCOPE IMAGING SPECTROGRAPH

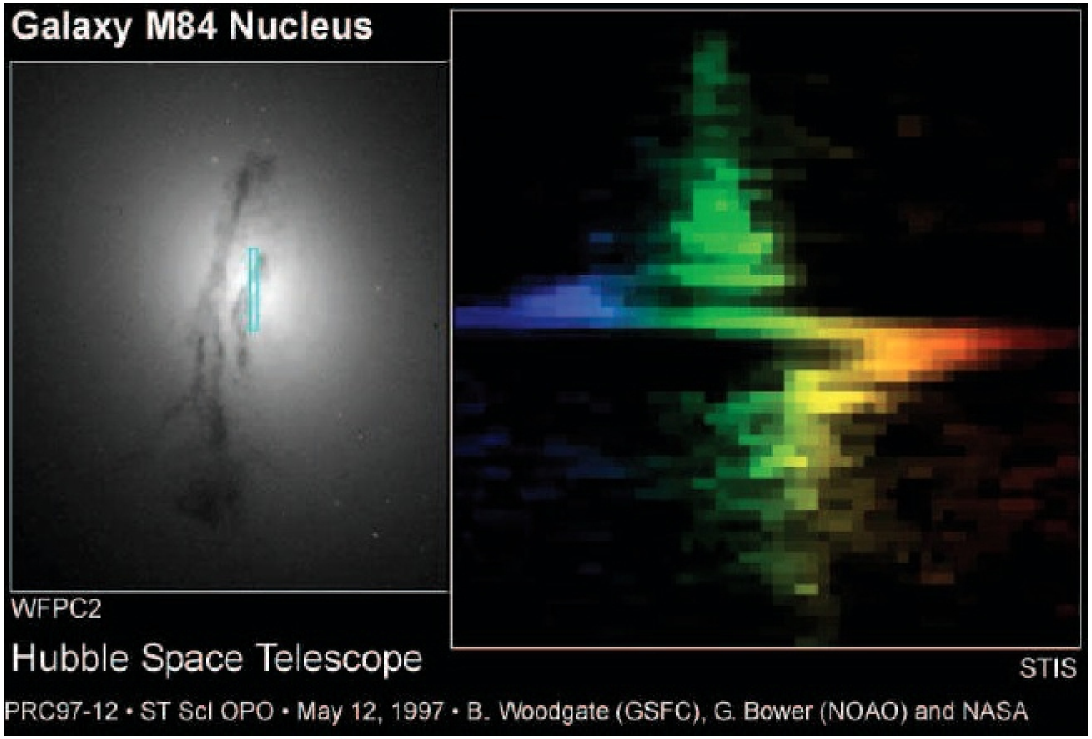
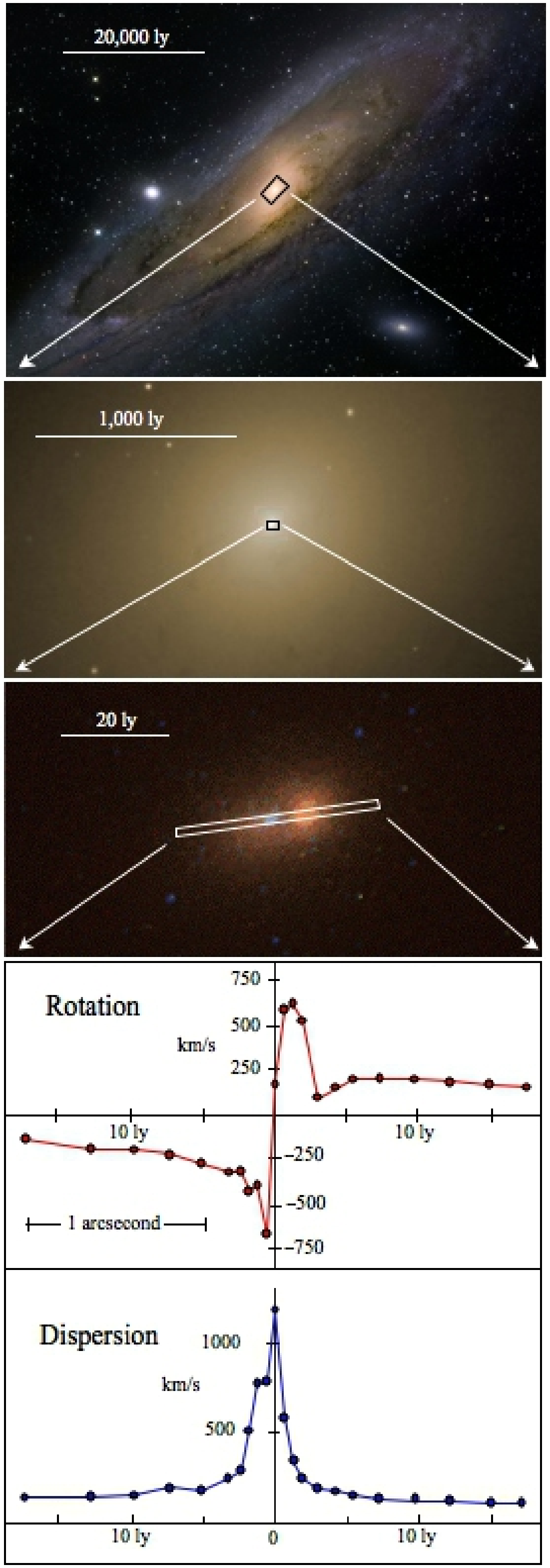
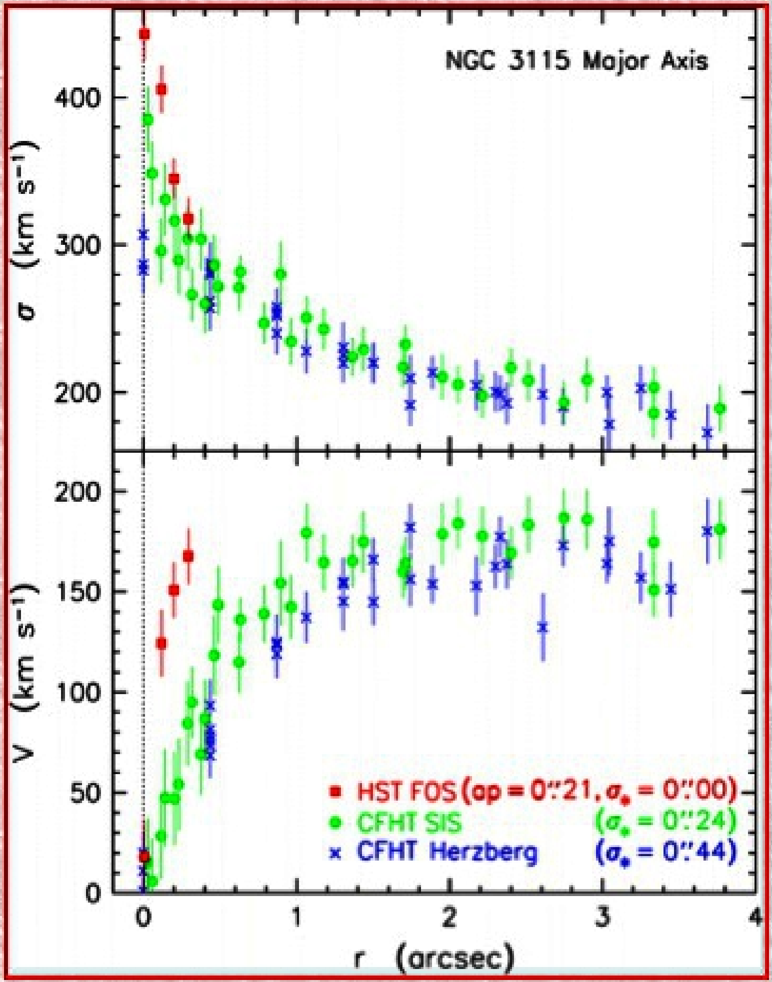


Fig. 50. Left: Image of M84; Right: Velocity profile across the nucleus of M84 taken with STIS aboard the HST. The estimated black hole mass is about 300 million solar masses.



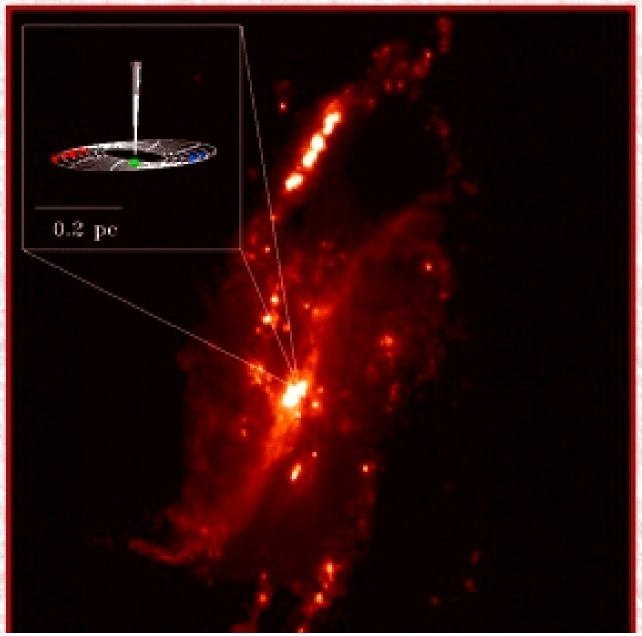
The galaxy M31 , our nearest spiral neighbour

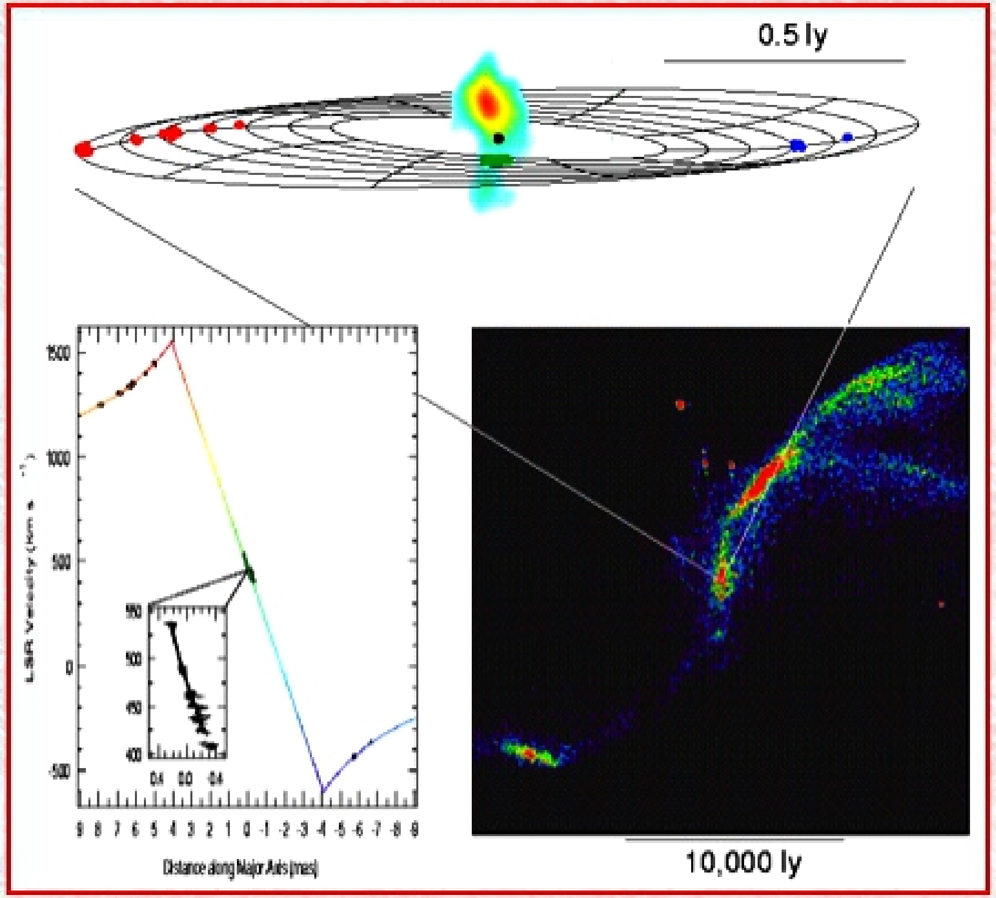
NGC 3115 Black Hole



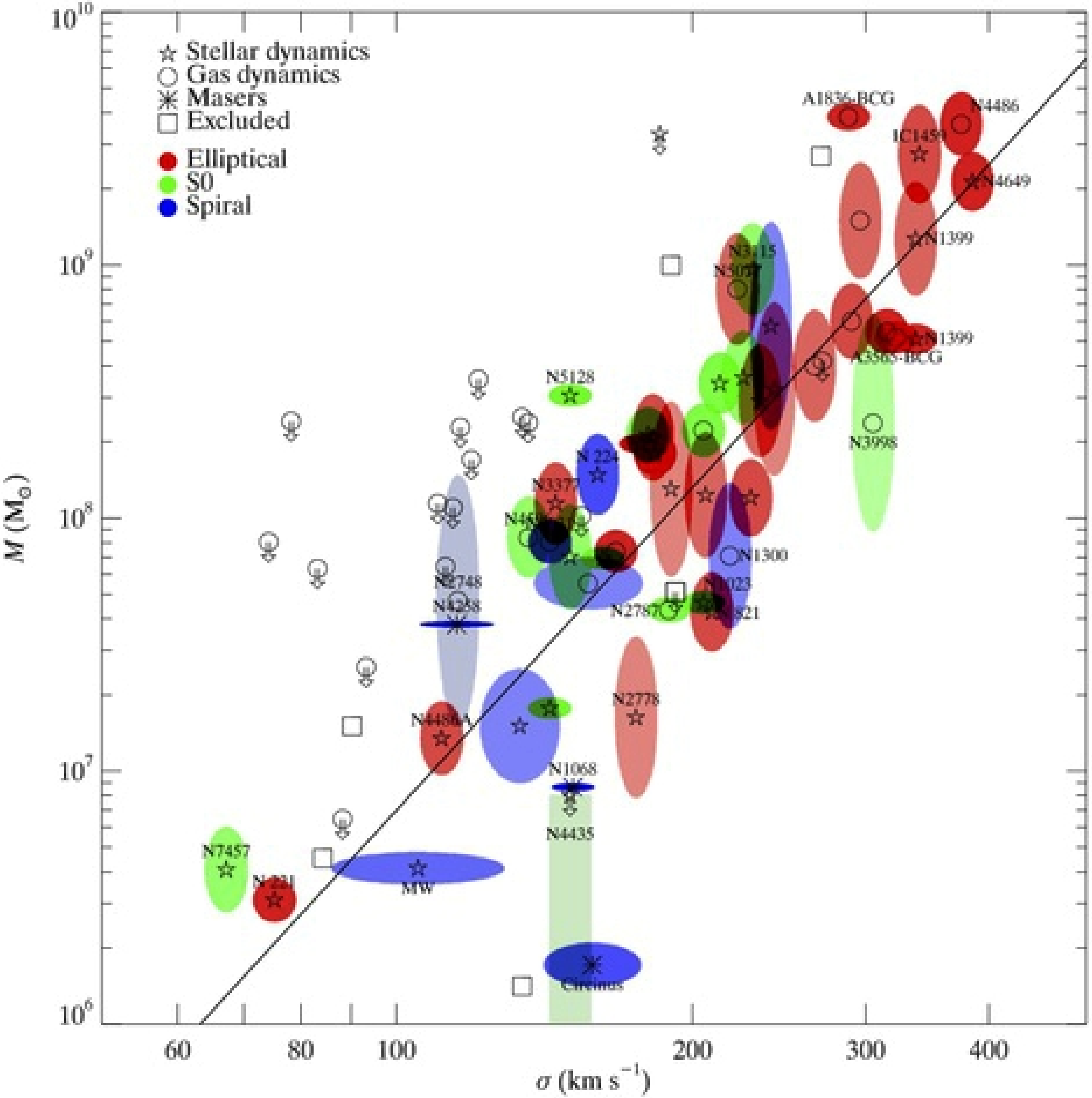
NGC 4258 Black Hole

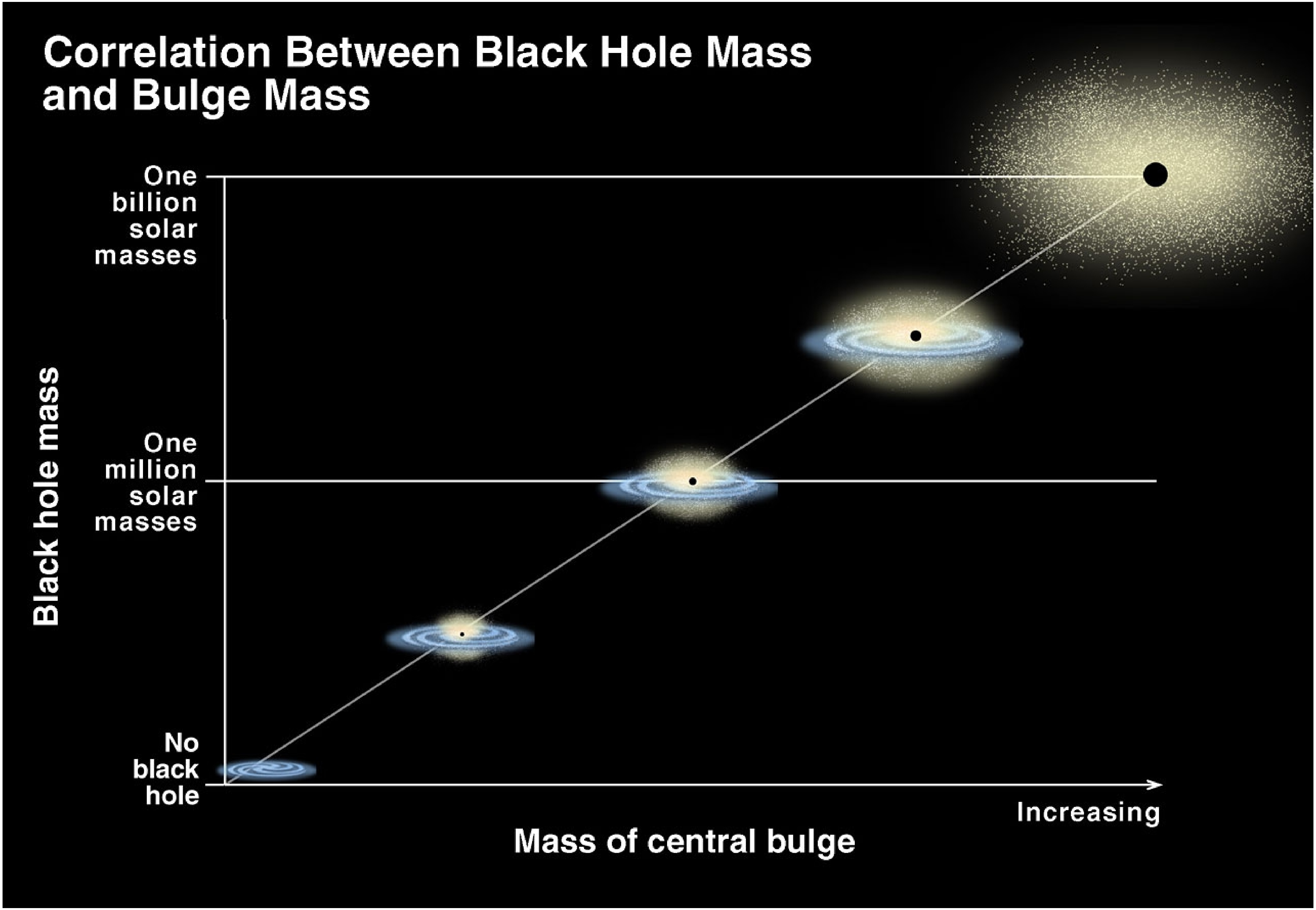
Water molecules in star-forming regions can undergo a population inversion and emit radiation at about 22.0 GHz, creating the brightest spectral line in the radio universe.





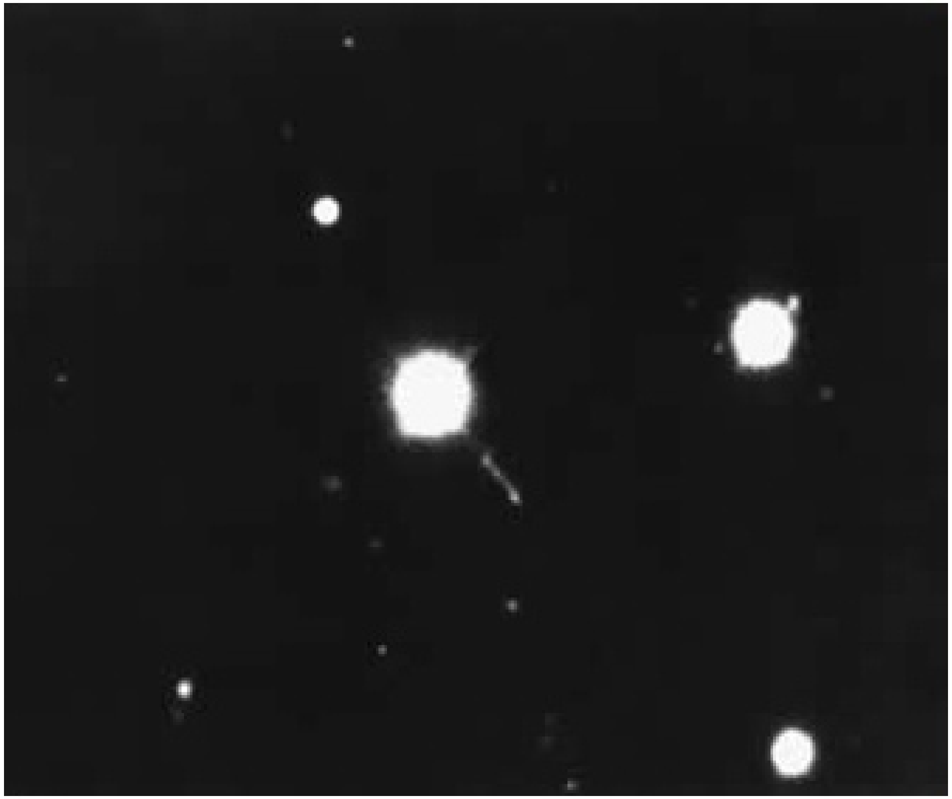
Nuclear gas disk with masers giving doppler velocities and proper motions.

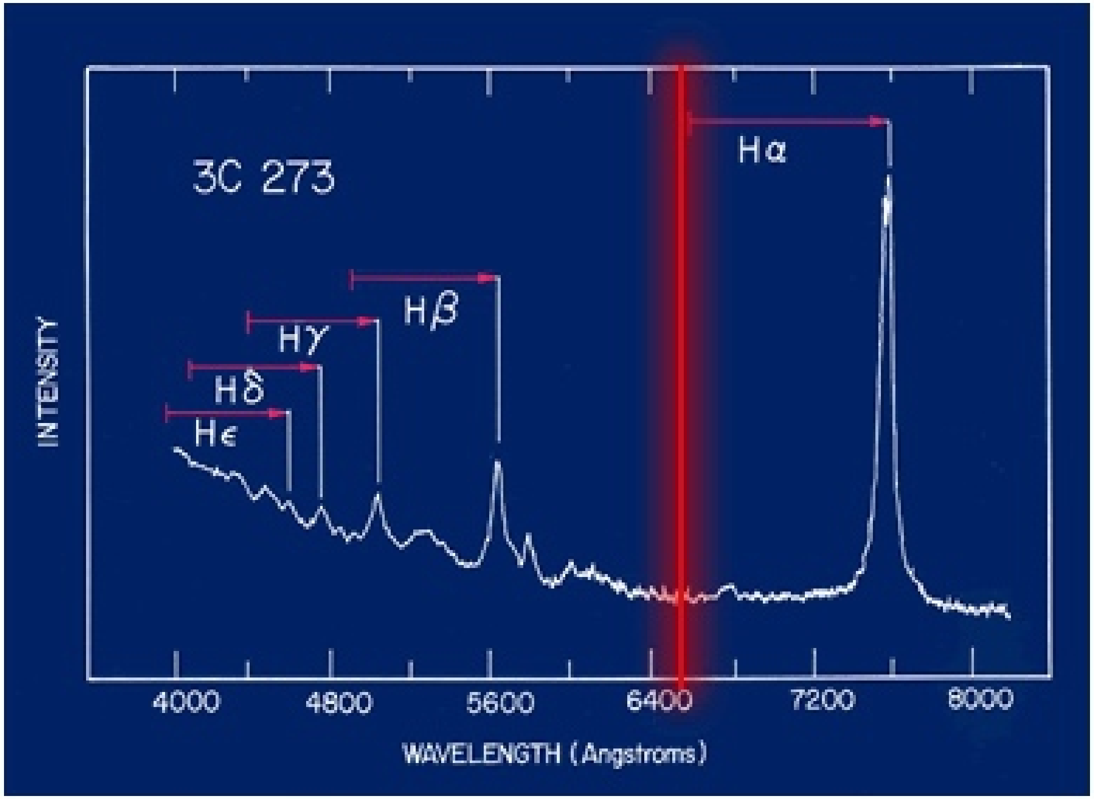
Stellar dynamics
Gas dynamics
Masers
Excluded
Elliptical
S0
Spiral
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
M ($M_\odot$)
60
80
100
200
300
400
σ (km s^{-1})
A1836-BCG
N4486
IC1459
N4649
N1399
N3115
N5077
N1399
A3565-BCG
N3998
N5128
N 224
N3377
N1300
N2748
N4258
N2787
N2778
N4486A
N1068
N4435
N7457
MW
Circinus



Correlation Between Black Hole Mass and Bulge Mass

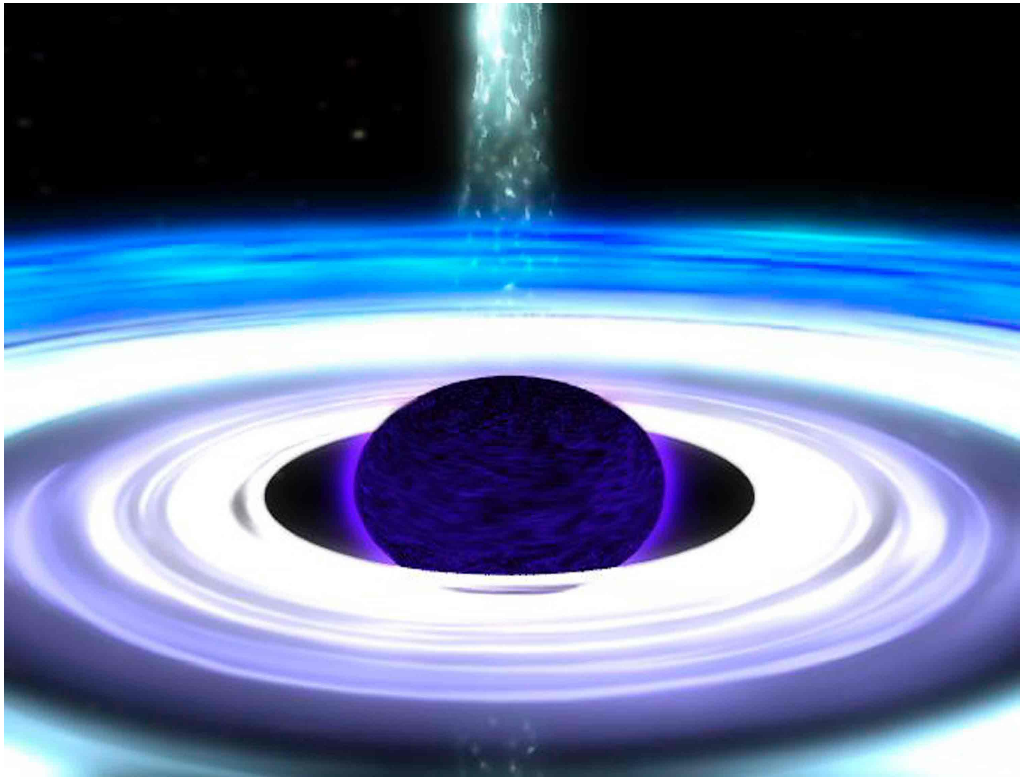
1963 M. Schmidt discovers that the radio source 3C273 can be identified with an optical point source (stellar) with a jet. The spectrum shows broad emission lines $H_{\beta,\gamma,\delta,...}$, MgII, OIII ...which are redshifted by $z = 0.158 \Rightarrow v_rad = 47400\frac{km}{s}$. So, the object was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

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



The orbital period of the gas in an **accretion disk** will change with radius, just like the orbital periods of the planets in the solar system. This implies that adjacent rings of gas will rub against each other and be subject to friction which will allow the gas to move toward the black hole.

This frictional force is responsible for heating the gas in the disk which can then radiate. The source of the radiant energy is ultimately gravitational and up to about 10^{20} erg of energy may be released for every gram of gas that is accreted onto a black hole. (This is several hundred times more efficient than the nuclear processes occurring in stars.) Most of this energy will be released fairly close to the black hole, within a radius of typically 10^{15} cm for massive black hole in a quasar. In order to fuel a bright quasar, gas must accrete at a rate of up to 10 M_sun yr-1.

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. They radiate in all wavebands from the radio through to the gamma-ray range via the synchrotron and the inverse-Compton scattering process.

10.6. 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: $L_\odot = 4 \cdot 10^{26}\,\mathrm{W}$. 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 $\dot{M} \approx 2\mathrm{M}_\odot/\mathrm{yr}$.

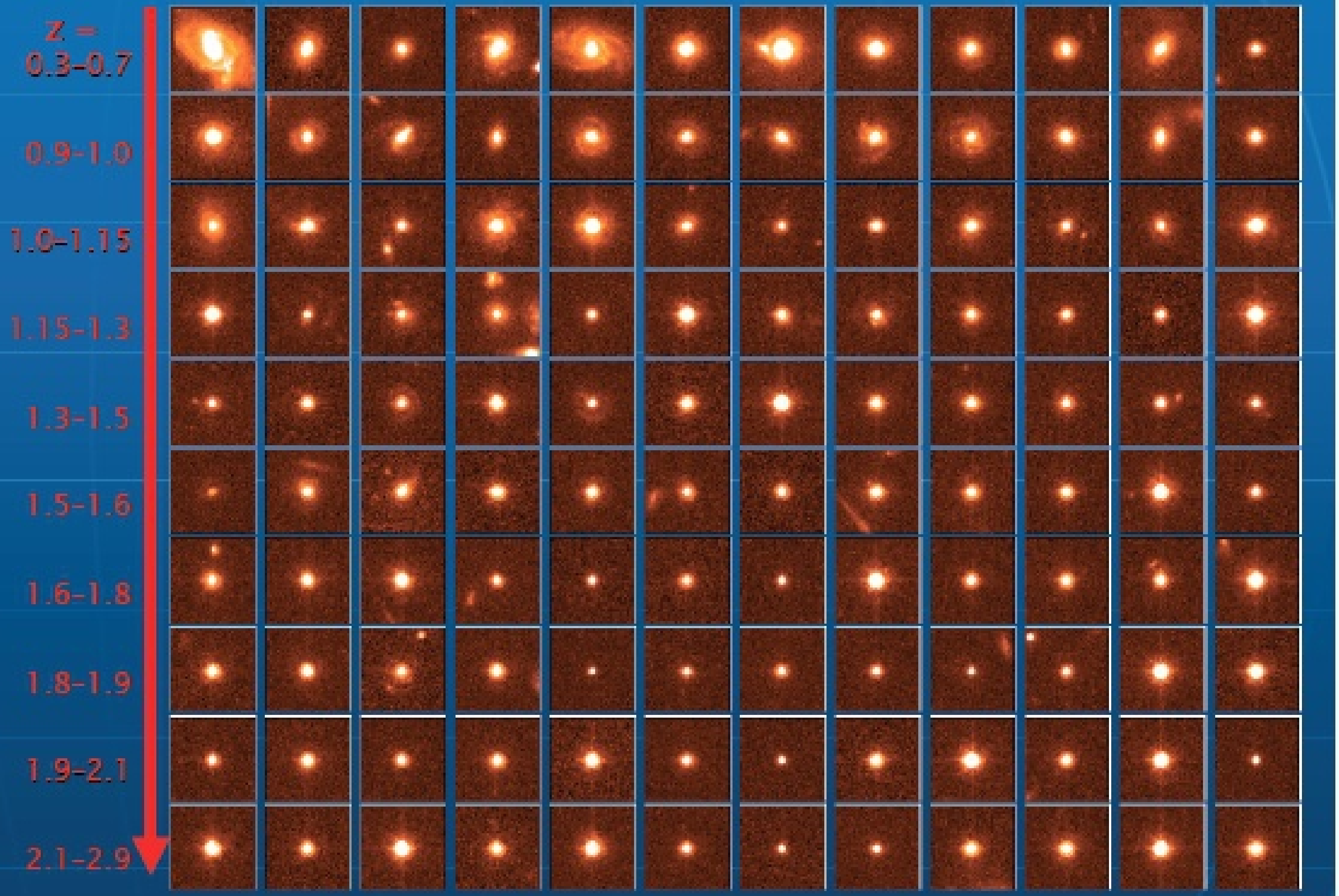
One can use this to determine the Eddington Limit, i.e. the maximum accretion rate onto the central object for a given black hole mass. This calculates to:

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

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

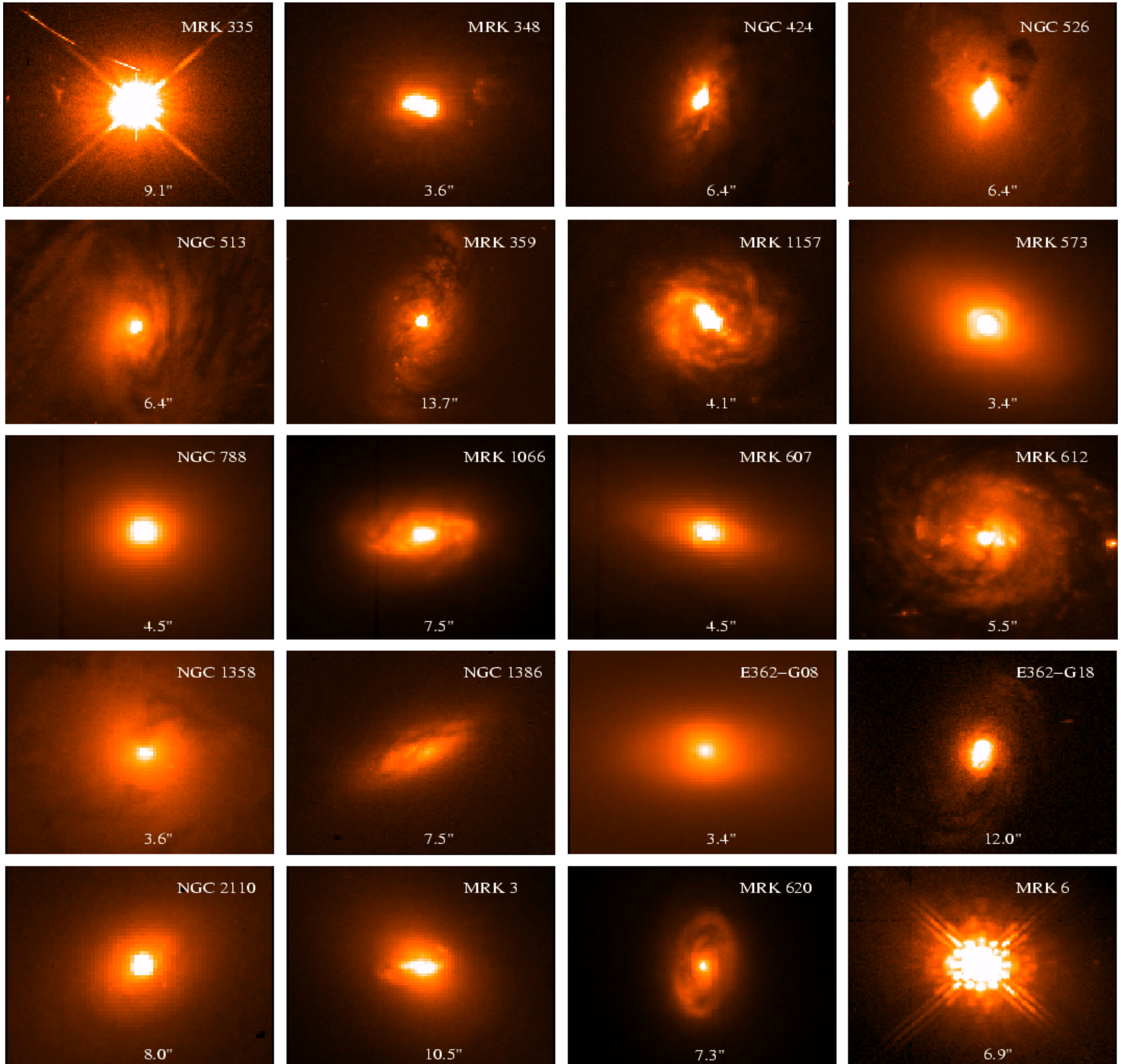
Answer:

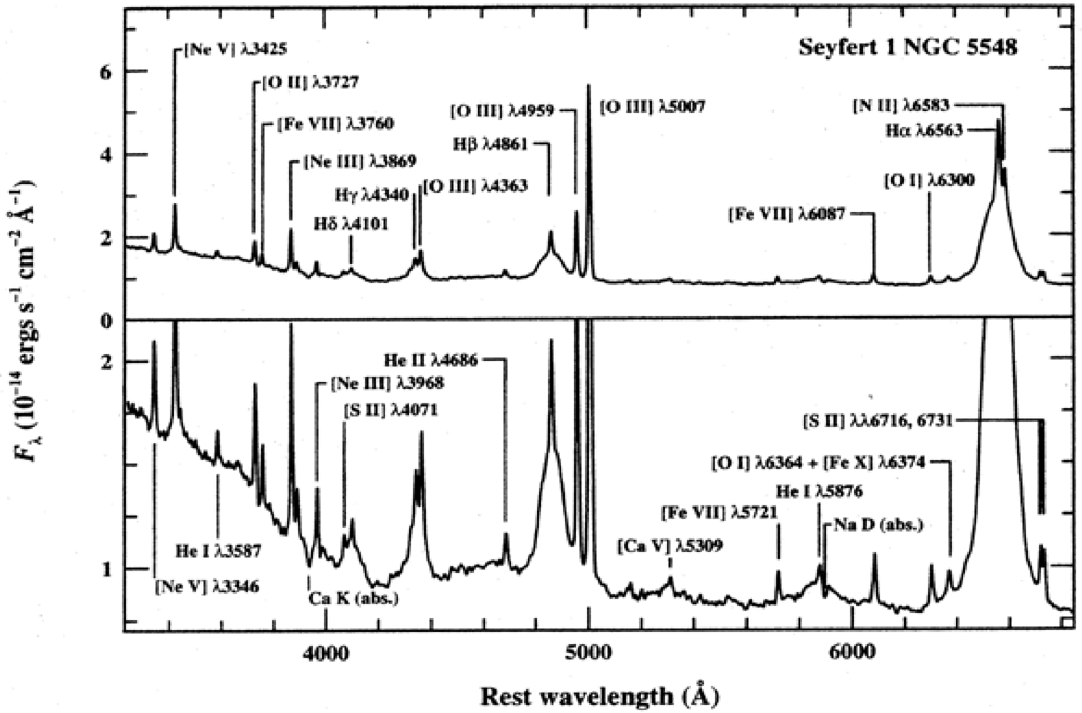
whenever on ‘has a chance’ to see a ‘host galaxy’ one does see one



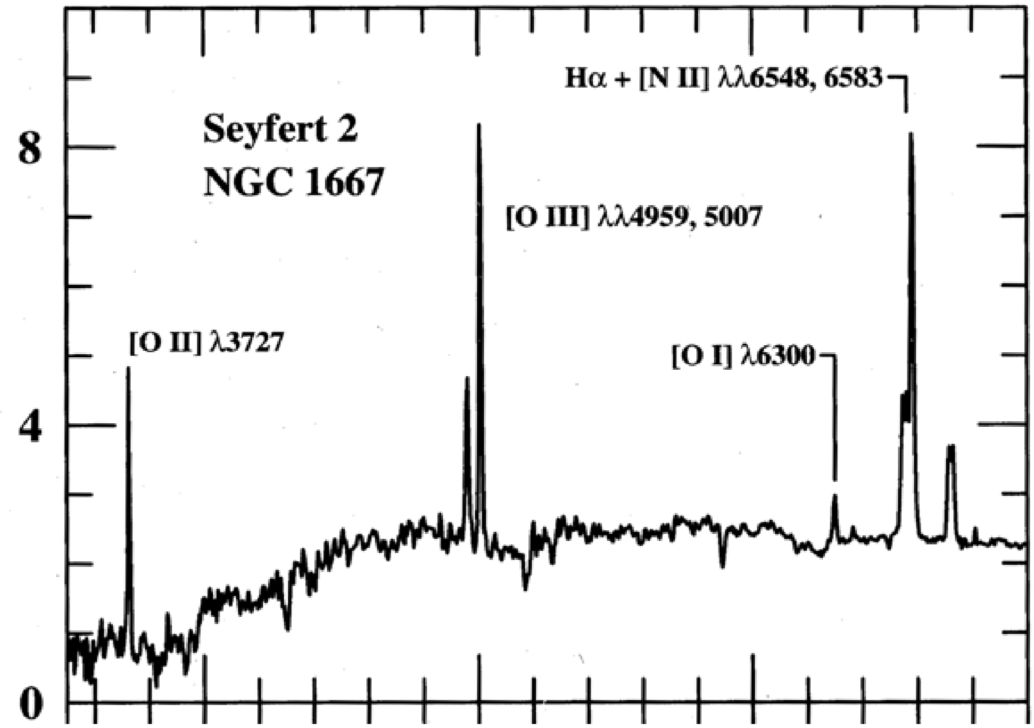
HST imaging COSMOS: Jahnke et al 2007/8

Seyfert Galaxies: fainter versions of quasars

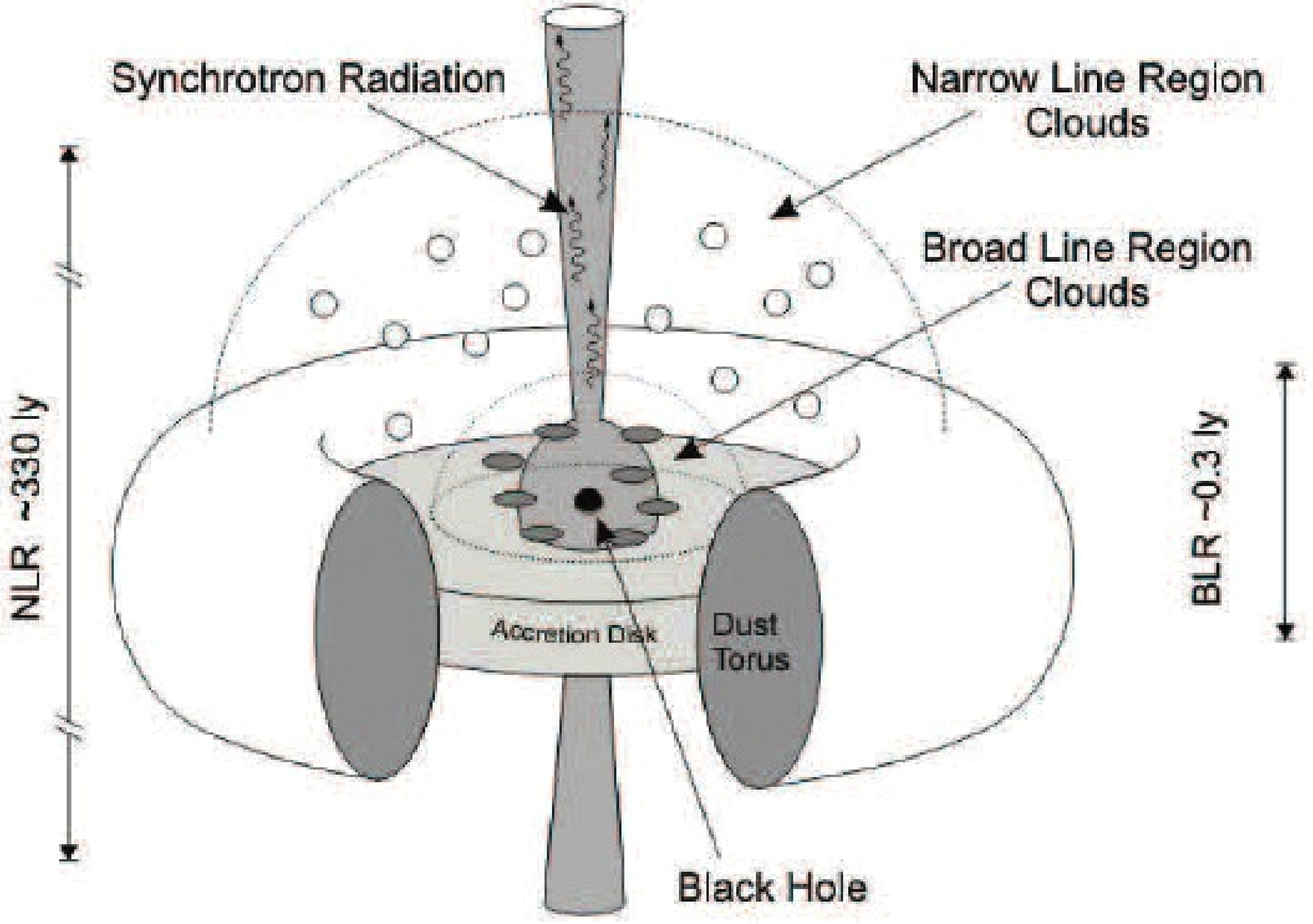




Seyfert Is have spectra with broad emission lines and there are clear point-like central nuclei in the images of the host galaxy.



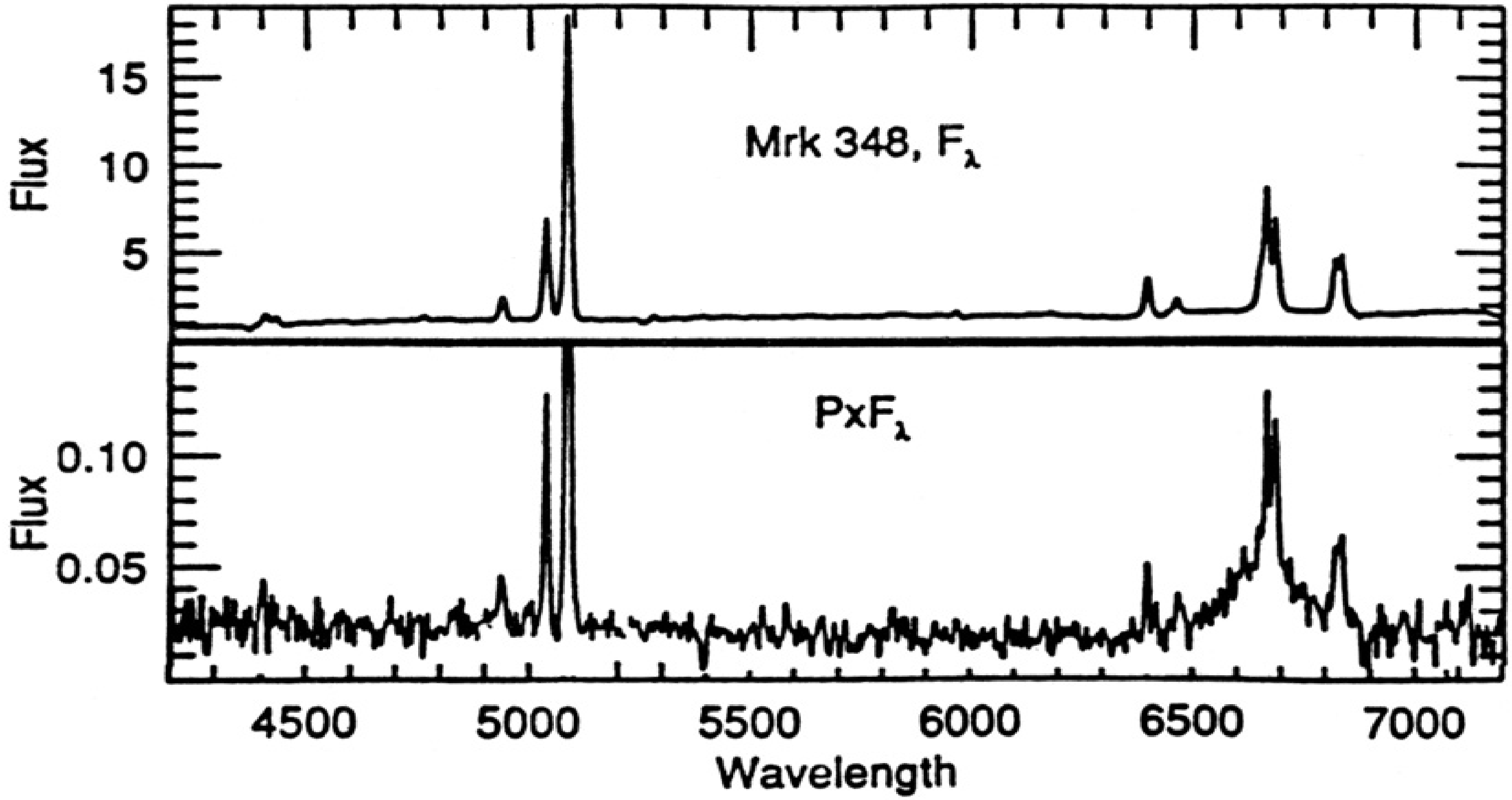
In Seyfert Is, there is no point-like nucleus. The spectro show strong HIGH IONIZATION POTENTIAL emission lines



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.

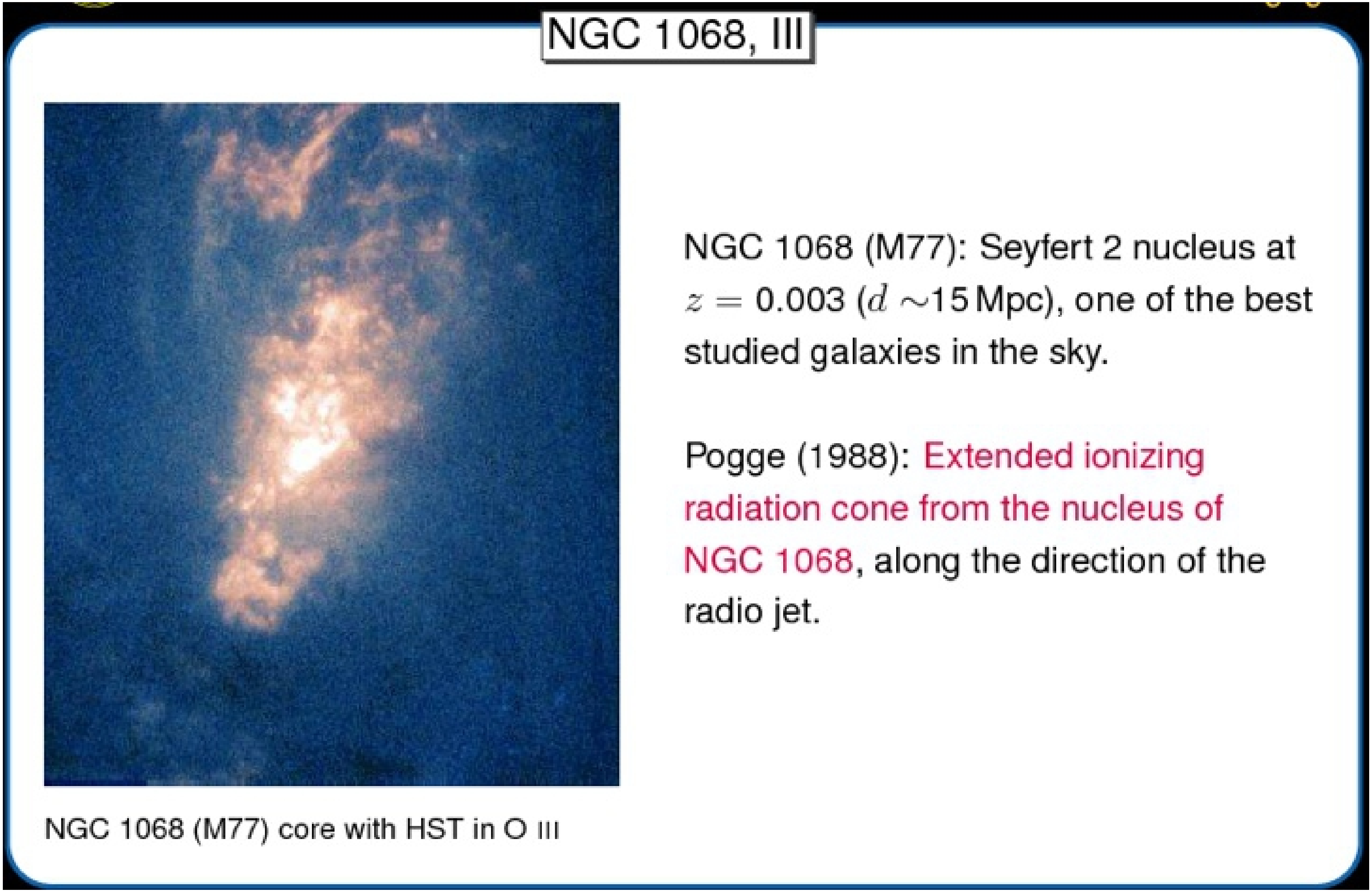
Evidence for the Unified Model



Type II AGN

Spectrum in polarized light showing broad lines

The Narrow Line Region



NGC 1068, III

NGC 1068 (M77) core with HST in O III

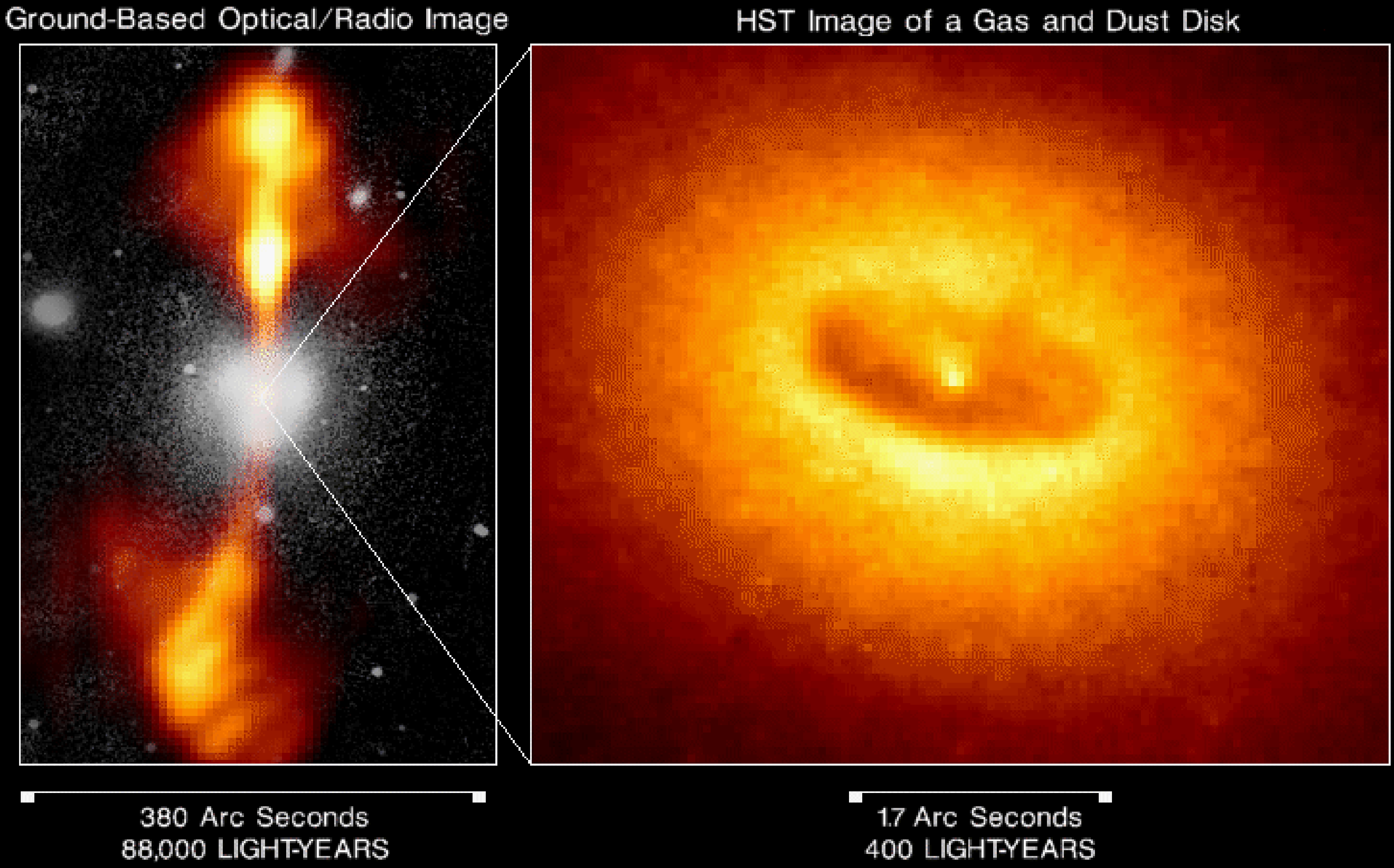
NGC 1068 (M77): Seyfert 2 nucleus at $z = 0.003$ ($d \sim 15\,\mathrm{Mpc}$), one of the best studied galaxies in the sky.

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

Core of Galaxy NGC 4261

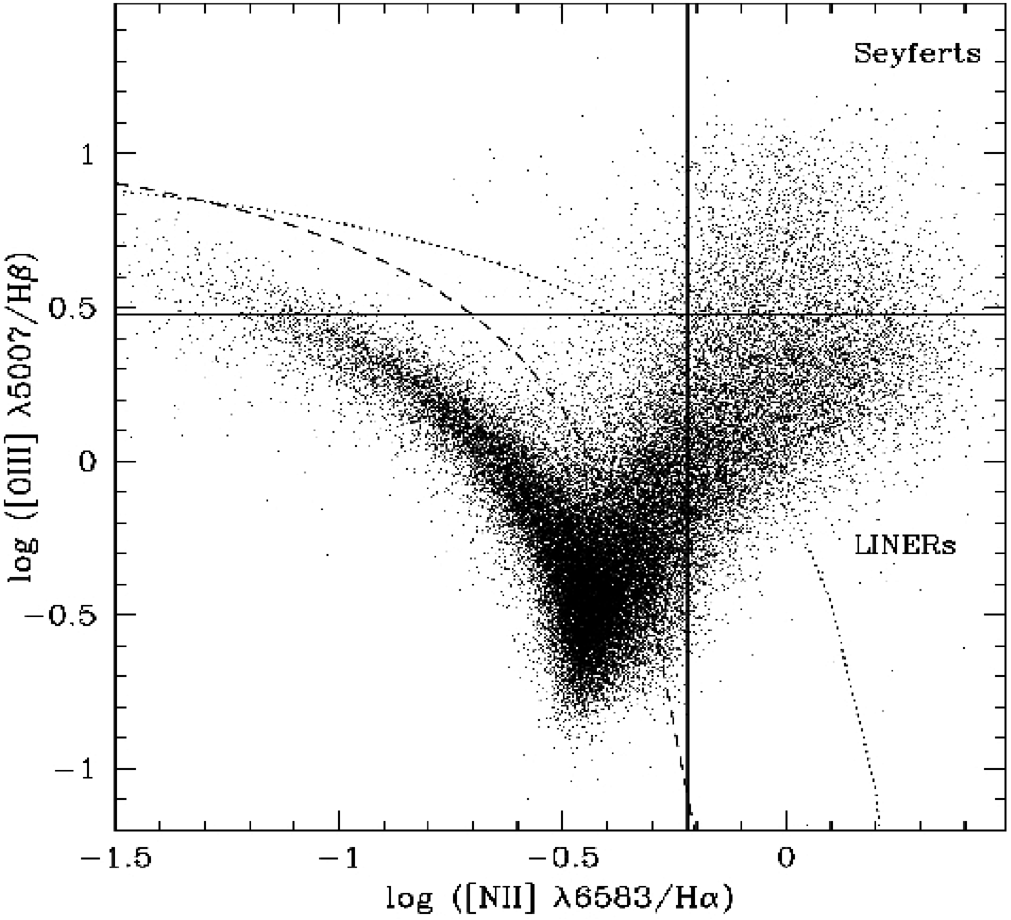
Hubble Space Telescope

Wide Field / Planetary Camera



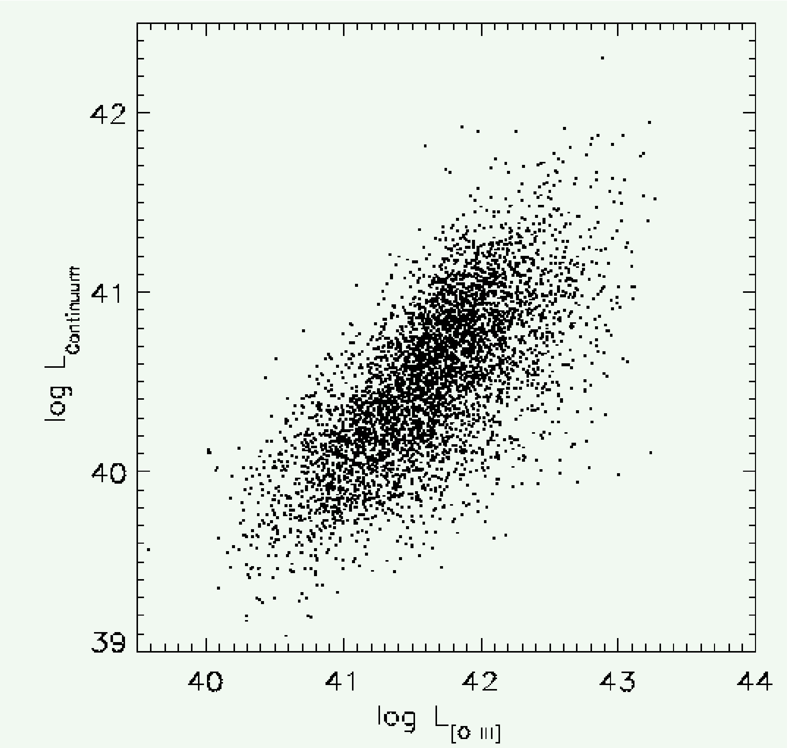
Surveys of Type II AGN at Low Redshifts from SDSS

(for detailed analysis of host galaxy properties)

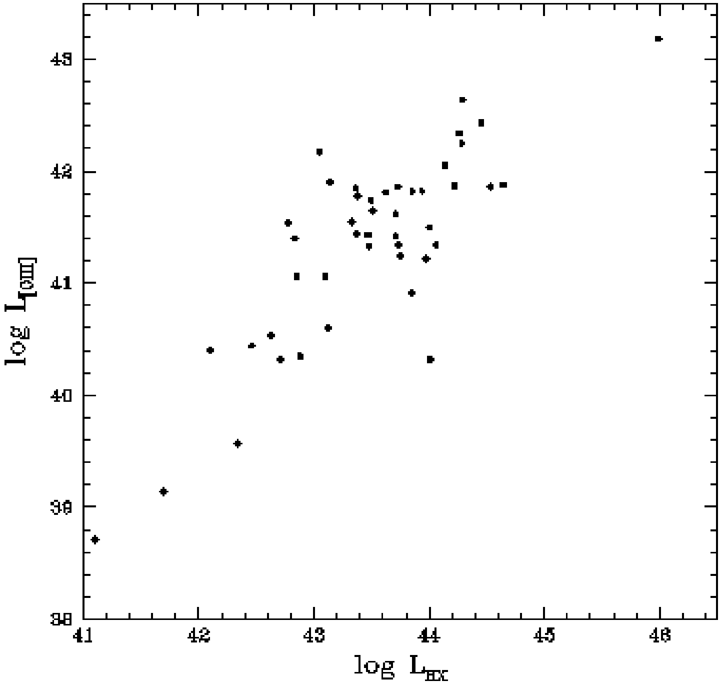


Accretion

The [OIII] Line Luminosity as a Black Hole Accretion rate Indicator

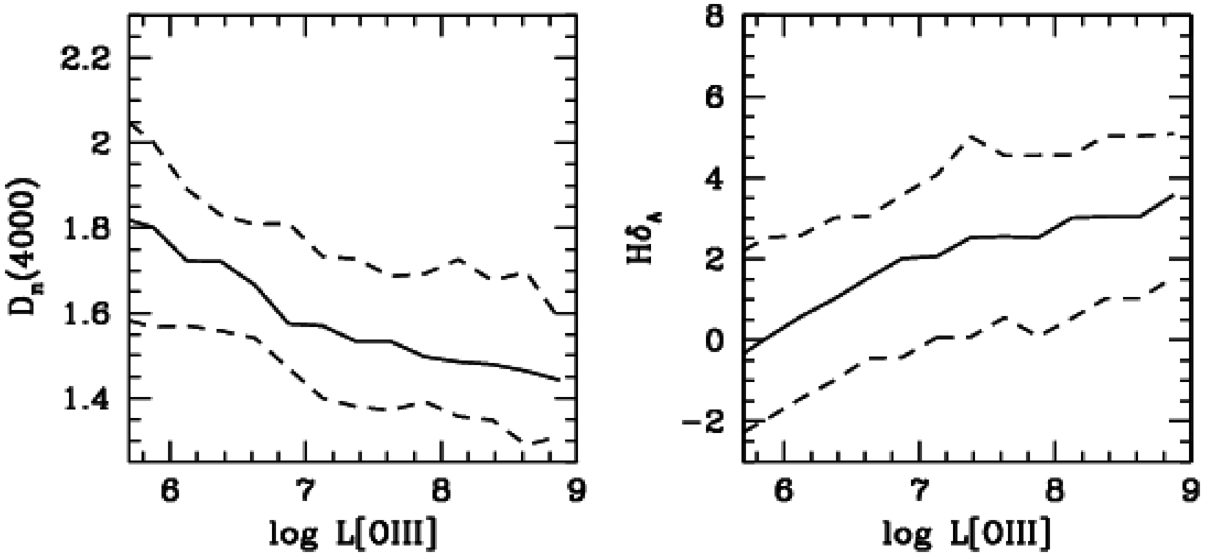


Correlation of [OIII] luminosity with continuum luminosity for Type 1 AGN

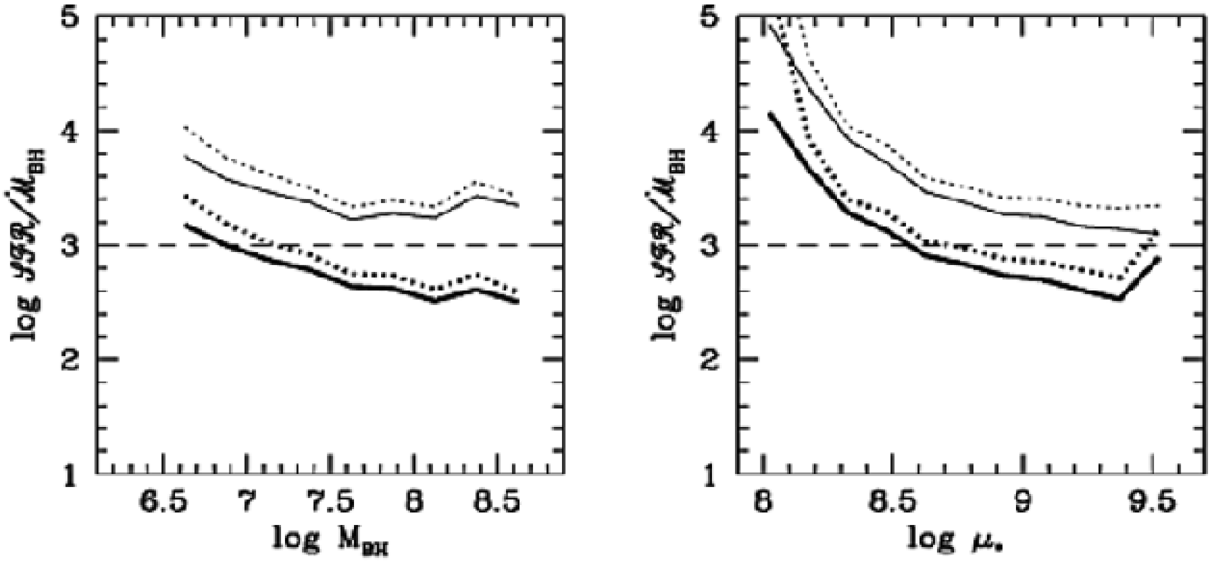


Correlation of [OIII] luminosity with hard x-ray luminosity

The Starburst-AGN Connection

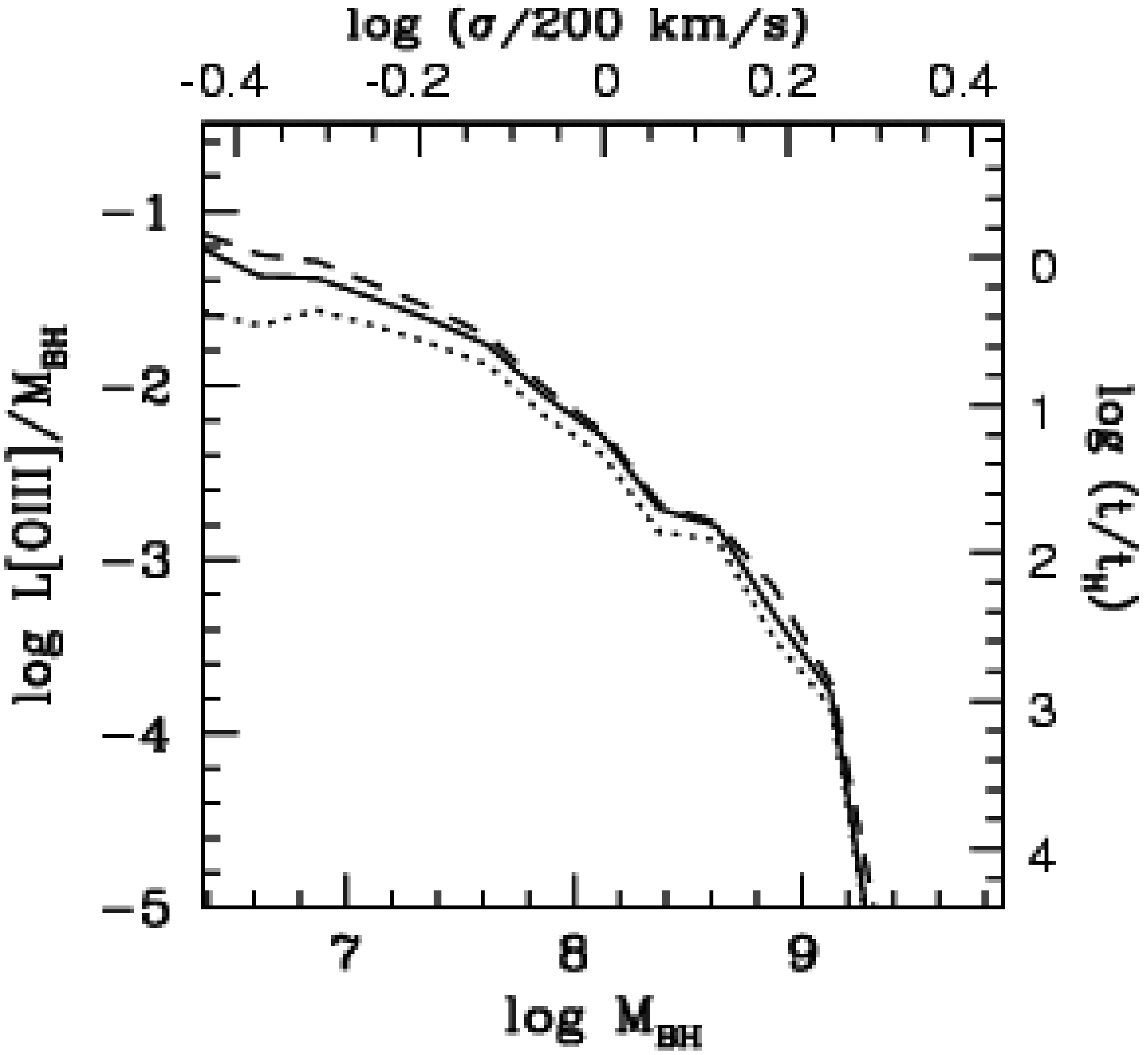


More strongly accreting AGN have younger stellar populations



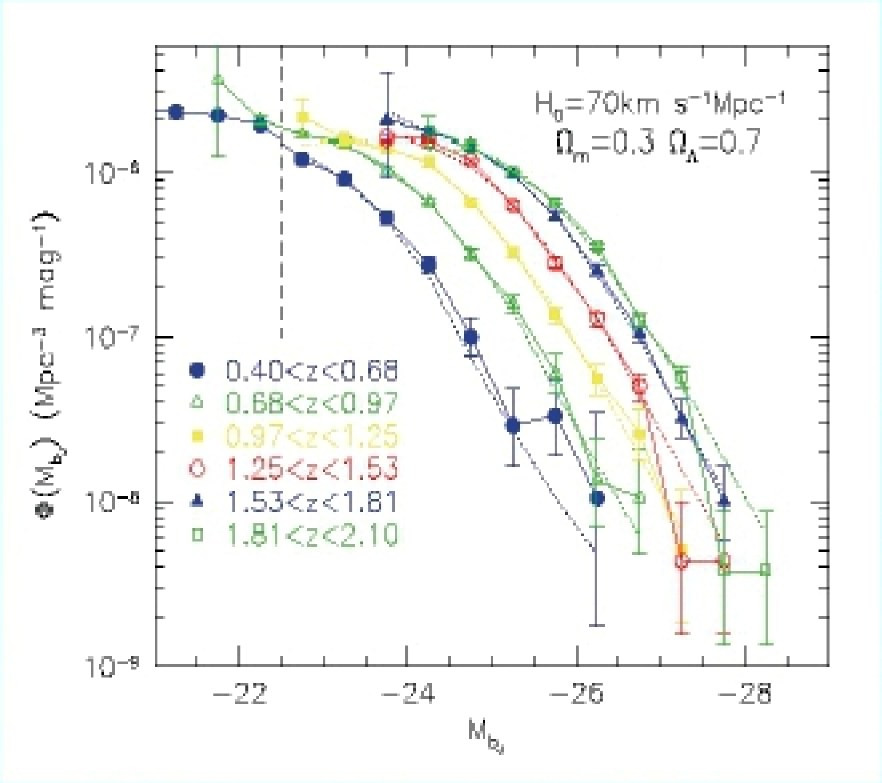
The average ratio between the star formation rate in the bulge and the accretion rate onto the black hole is 1000 – remarkably close to the ratio of bulge mass to black hole mass.

Most of the accretion today is occurring onto low mass black holes in galaxies like our own Milky Way ==> Massive black holes formed early on in the Universe and then stopped growing



Cosmic Evolution of the AGN Activity

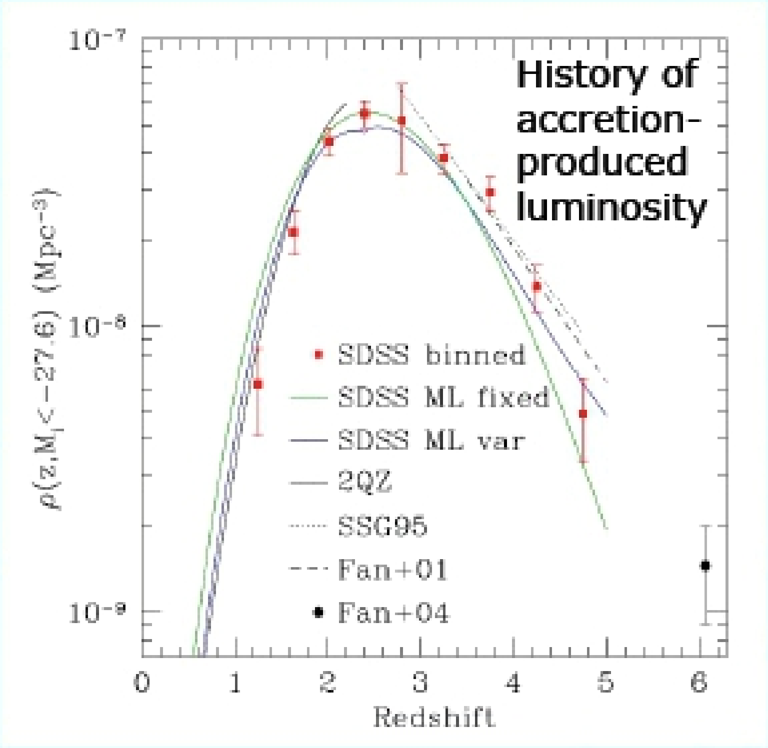
- Describe the distribution of accretion luminosities at different cosmic epochs by the "quasar-luminosity-function" at different redshifts



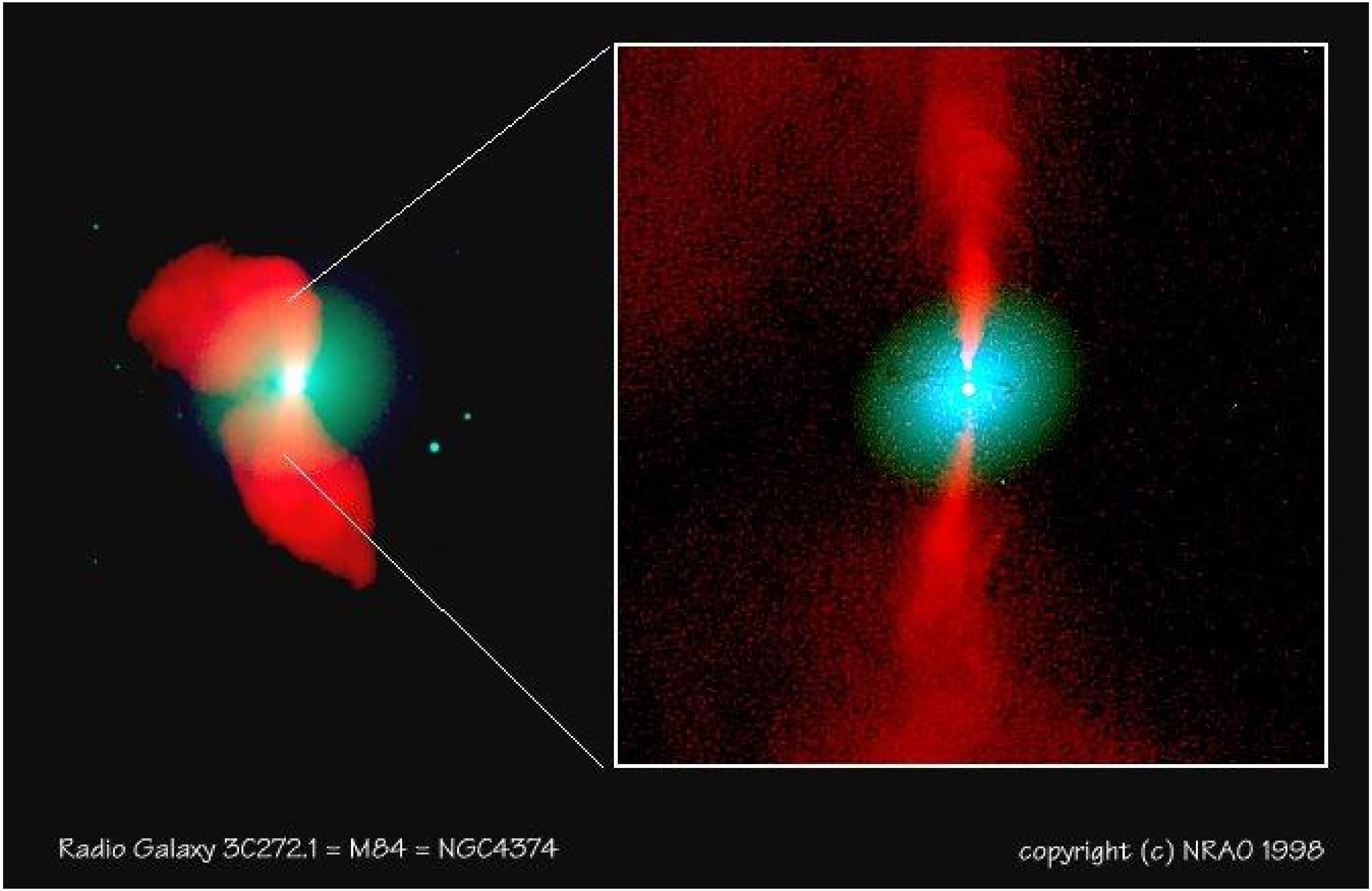
2DF Survey: Croom et al 2004

Abundance of luminous QSOs has decreased by 2 orders of magnitude since early epochs!

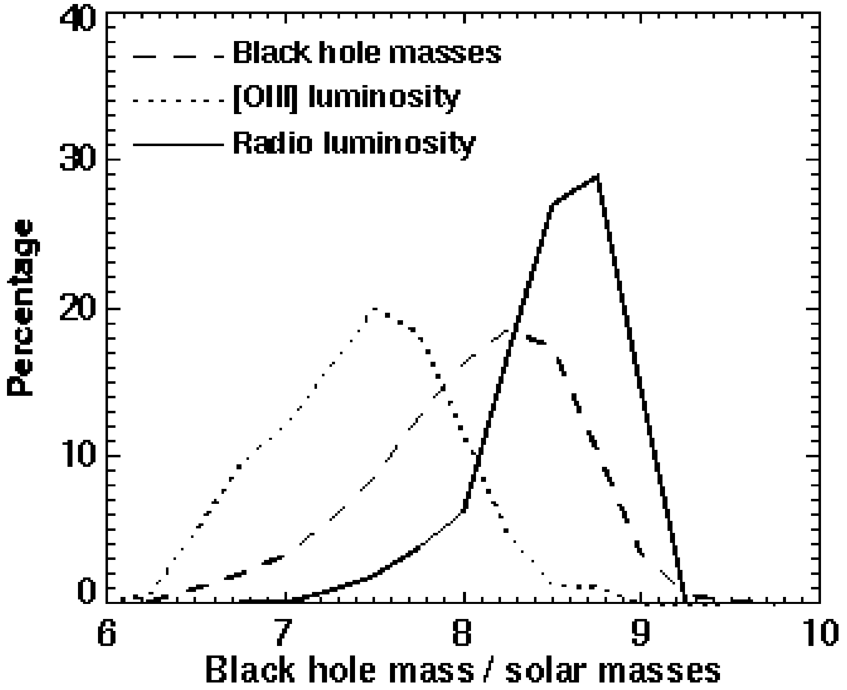
(e.g. SDSS Richards et al 2006)

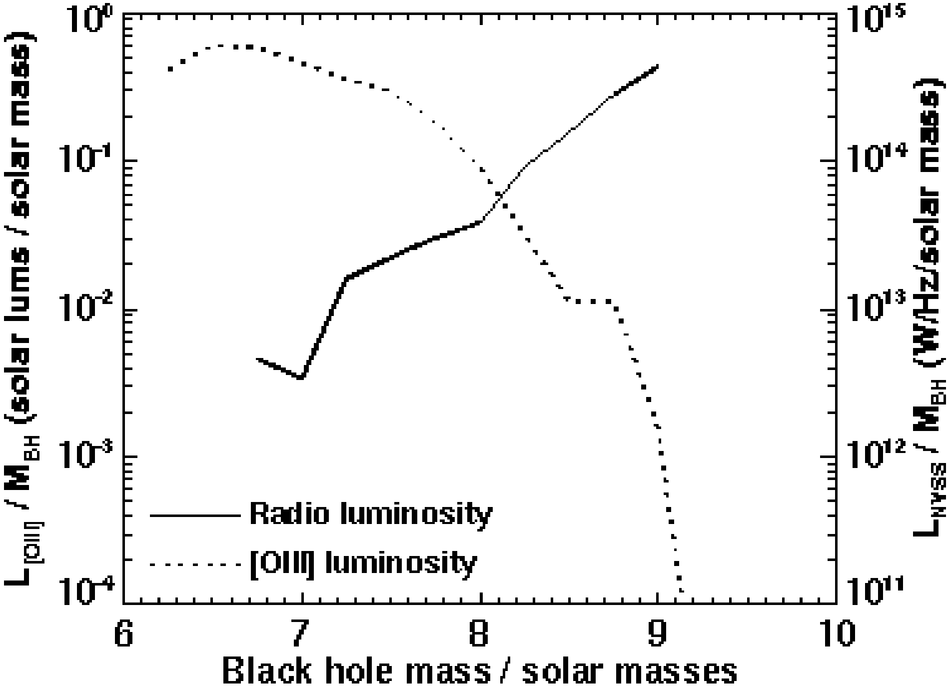

History of accretion-produced luminosity

What about radio-loud AGN?



Radio galaxies are strongly biased towards high mass galaxies that contain massive black holes.

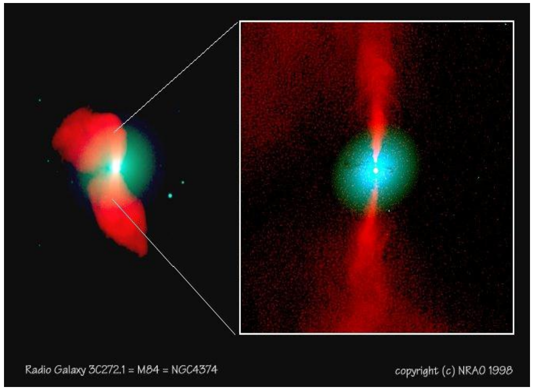




CONCLUSIONS FROM STUDYING HOST GALAXIES

Present-day Optical (emission-line) AGN activity is linked to:

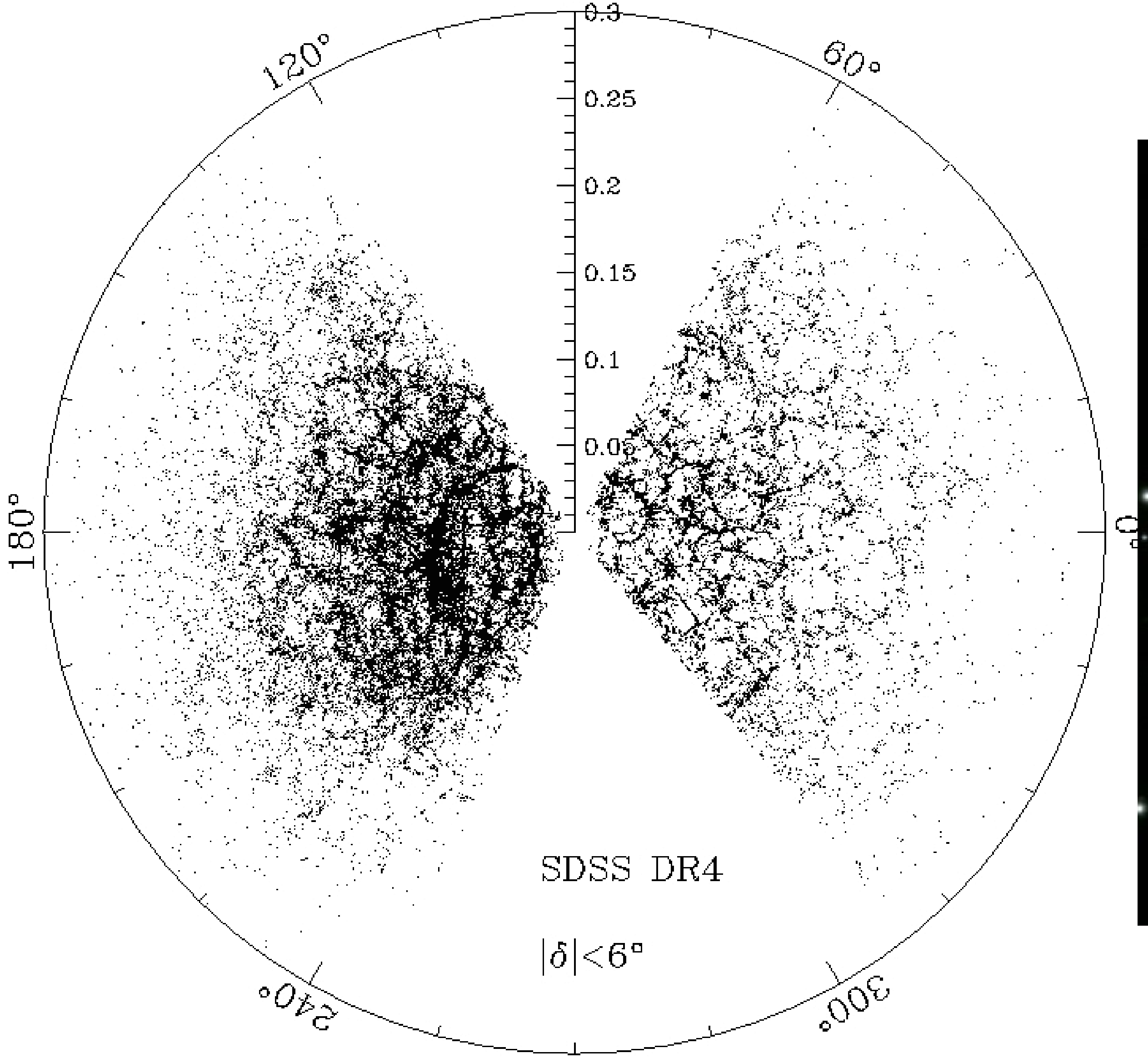
1) lower mass black holes
2) galaxies with low mass bulges
3) more powerful AGN found in galaxies with younger stellar populations

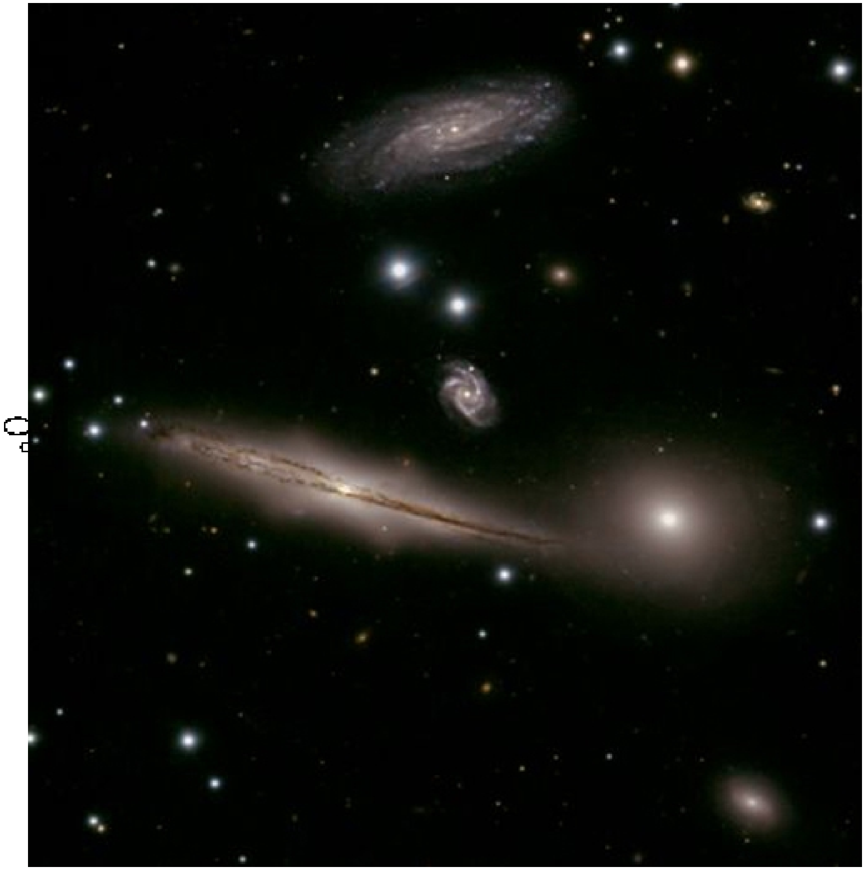


Present-day Optical Radio-AGN activity is linked to:

1) high mass black holes
2) galaxies with higher mass bulges
3) no apparent dependence on mean stellar age

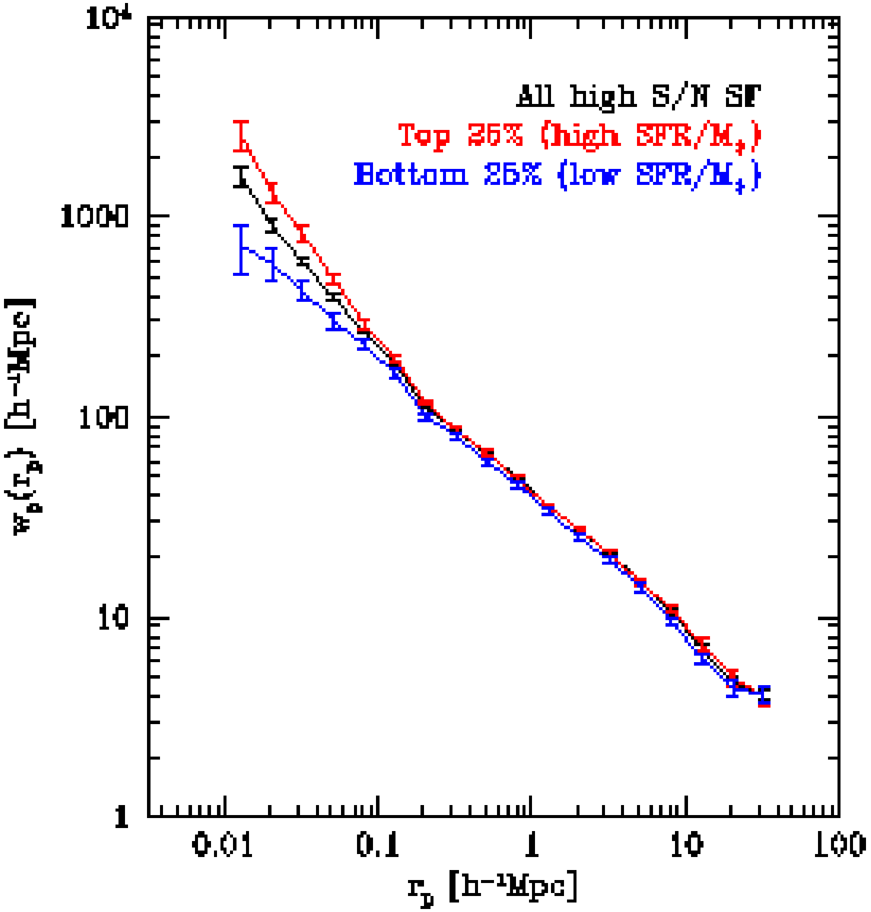
STUDYING THE ENVIRONMENTS OF AGN IN SDSS

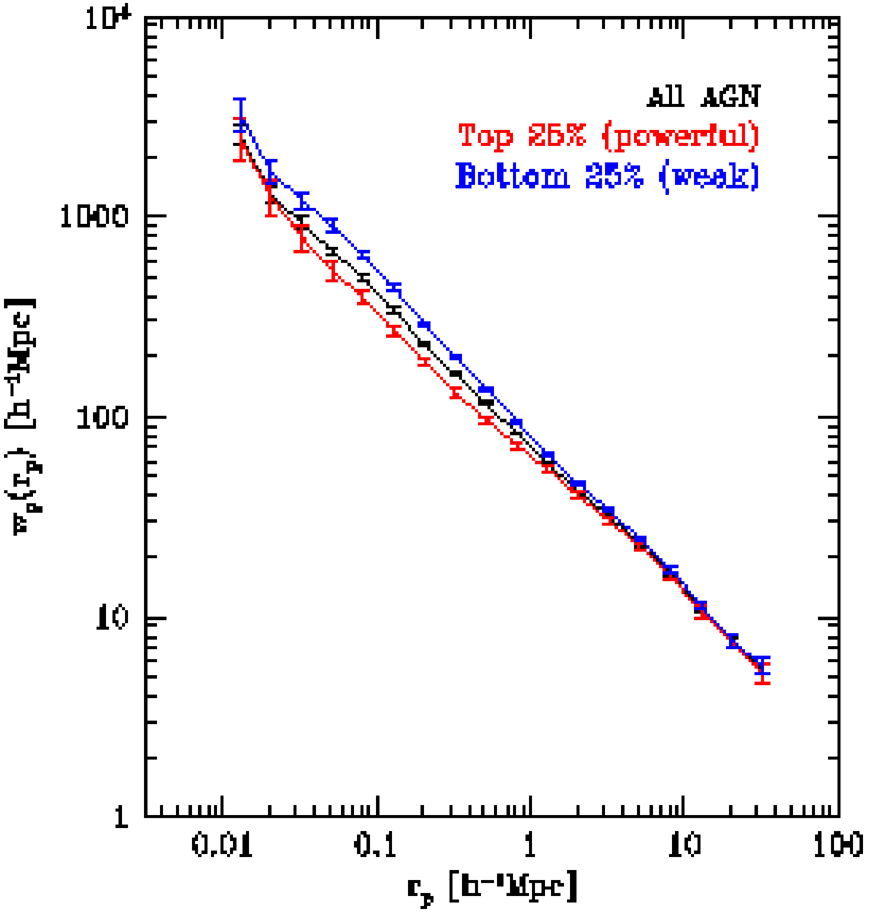




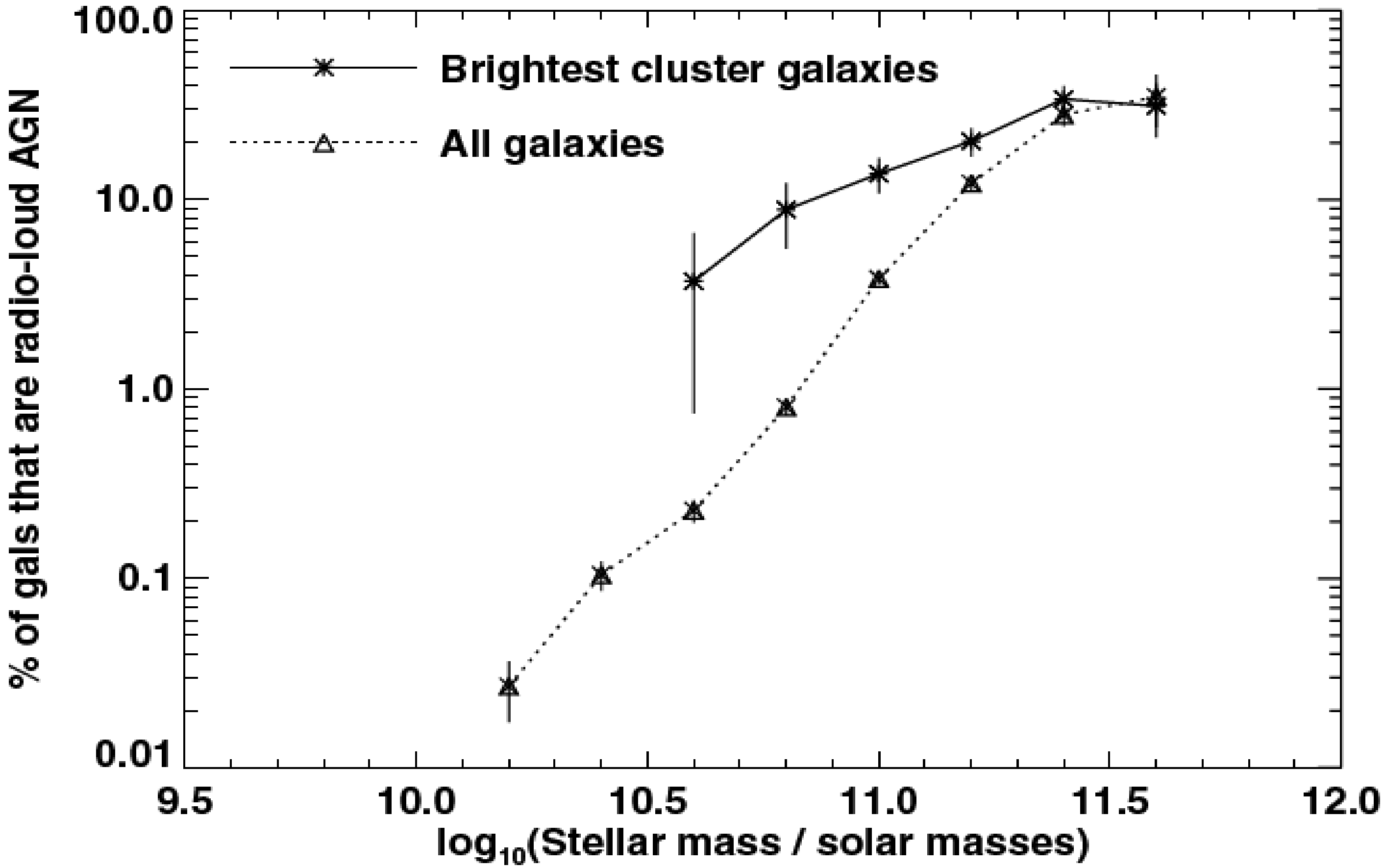
Galaxy interactions/mergers trigger more star formation, but apparently NOT more AGN activity

The cross-correlation function star-forming galaxies compared to AGN.

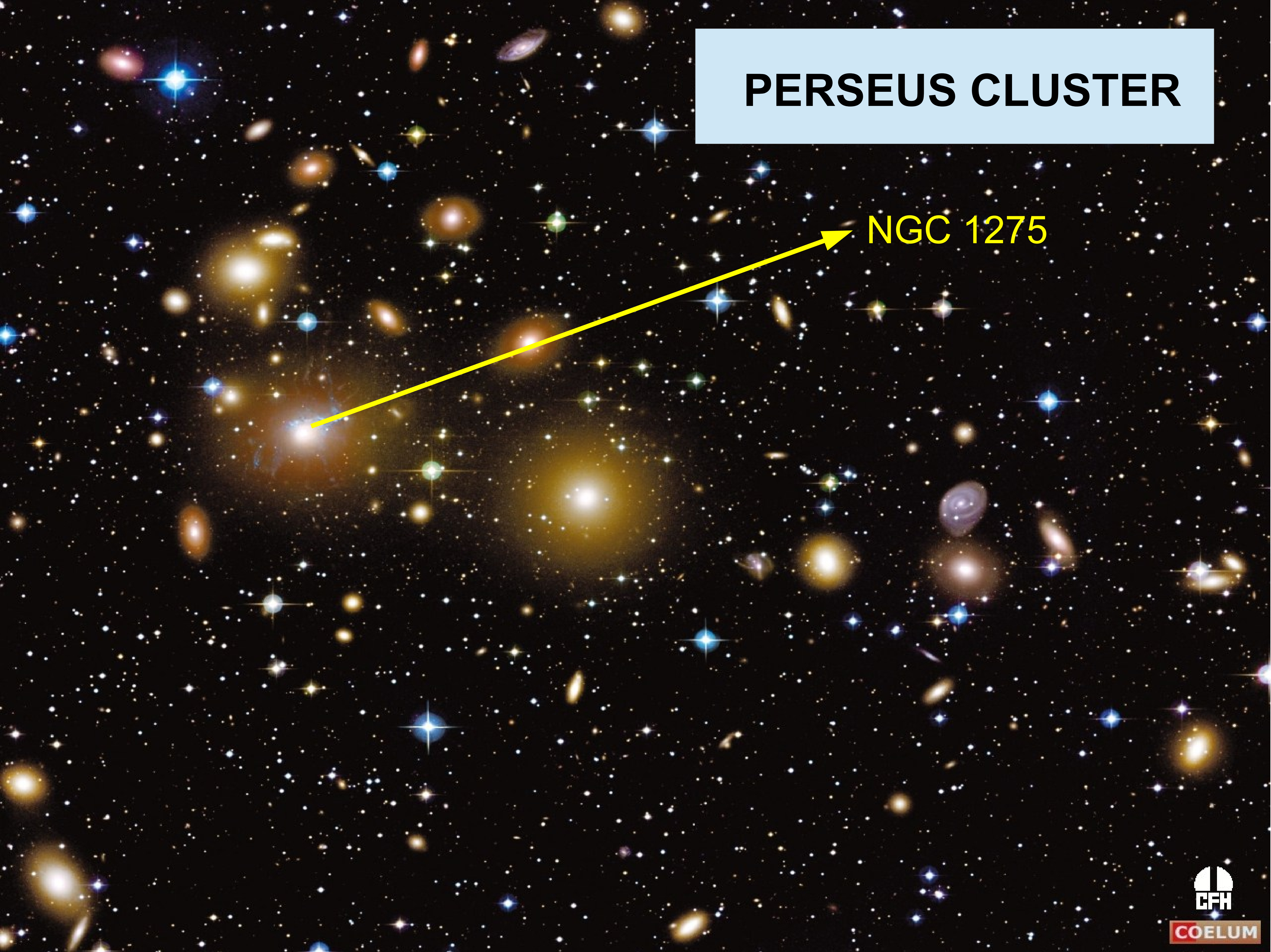


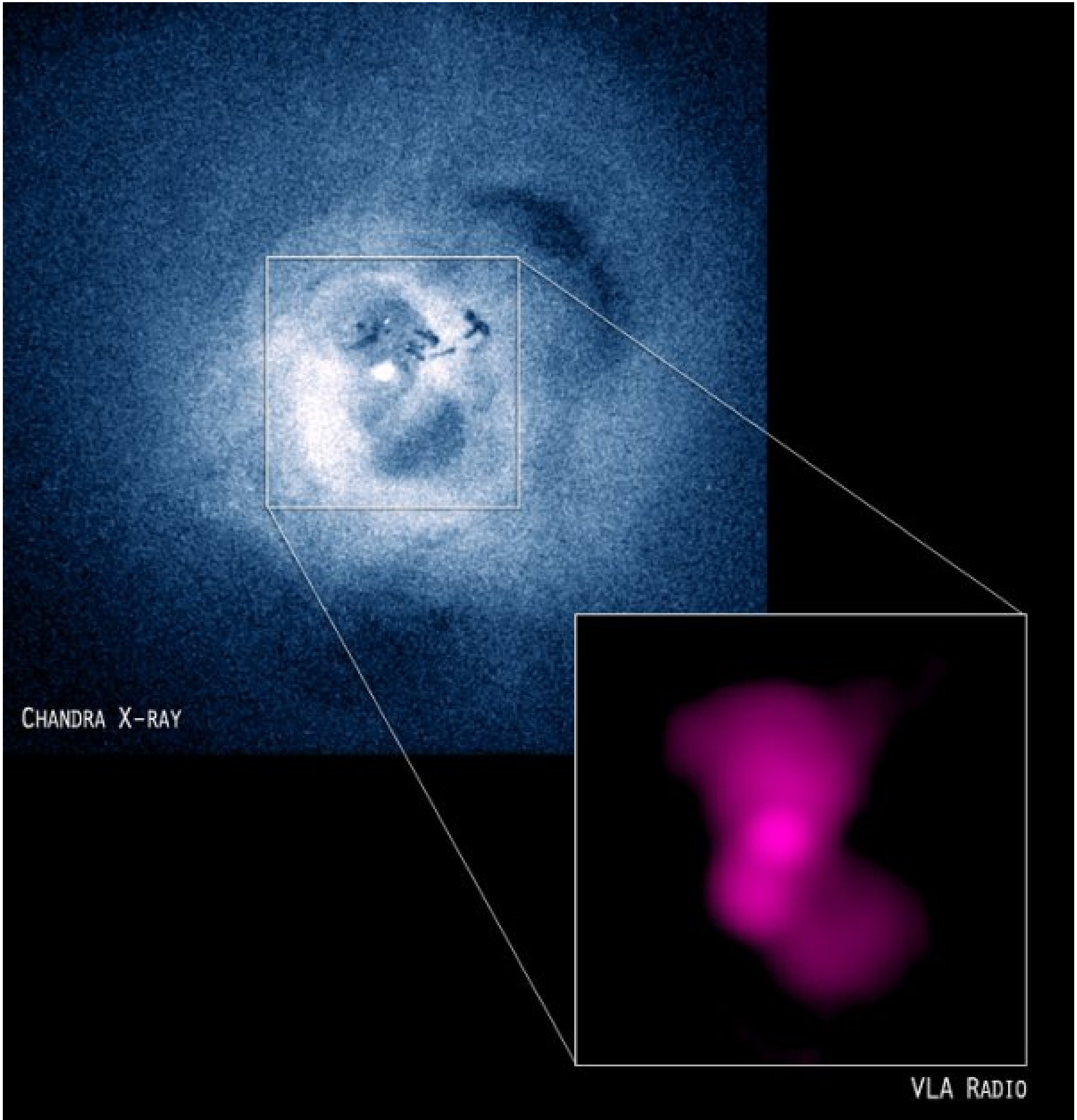


At fixed stellar mass, radio AGN activity is enhanced in galaxies that sit at the **centers** of groups and clusters.



PERSEUS CLUSTER



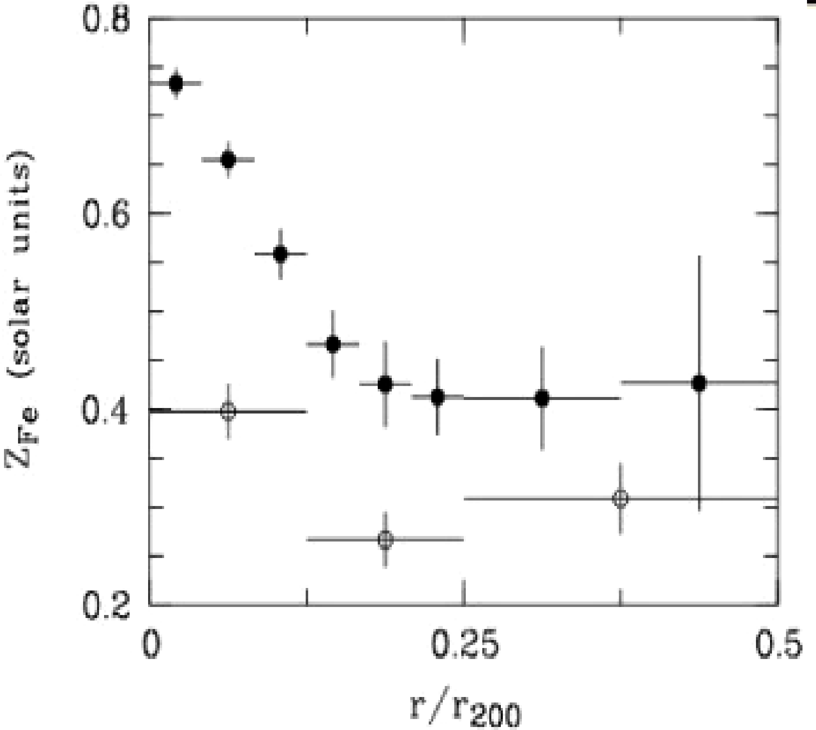


RADIO-AGN ACTIVITY INFLUENCING THE GAS IN THE PERSEUS CLUSTER

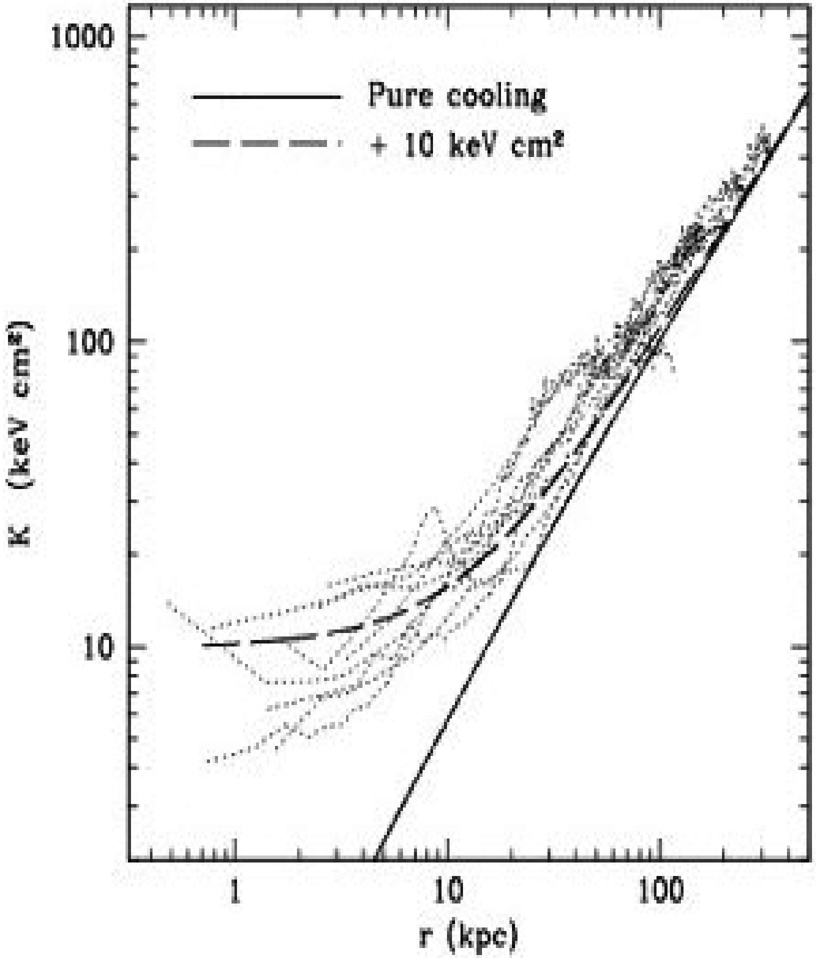
Hα emission traces filamentary structure of gas that have been “uplifted” from the central galaxy

Figure 7 from B R McNamara and P E J Nulsen 2012 New J. Phys. 14 055023

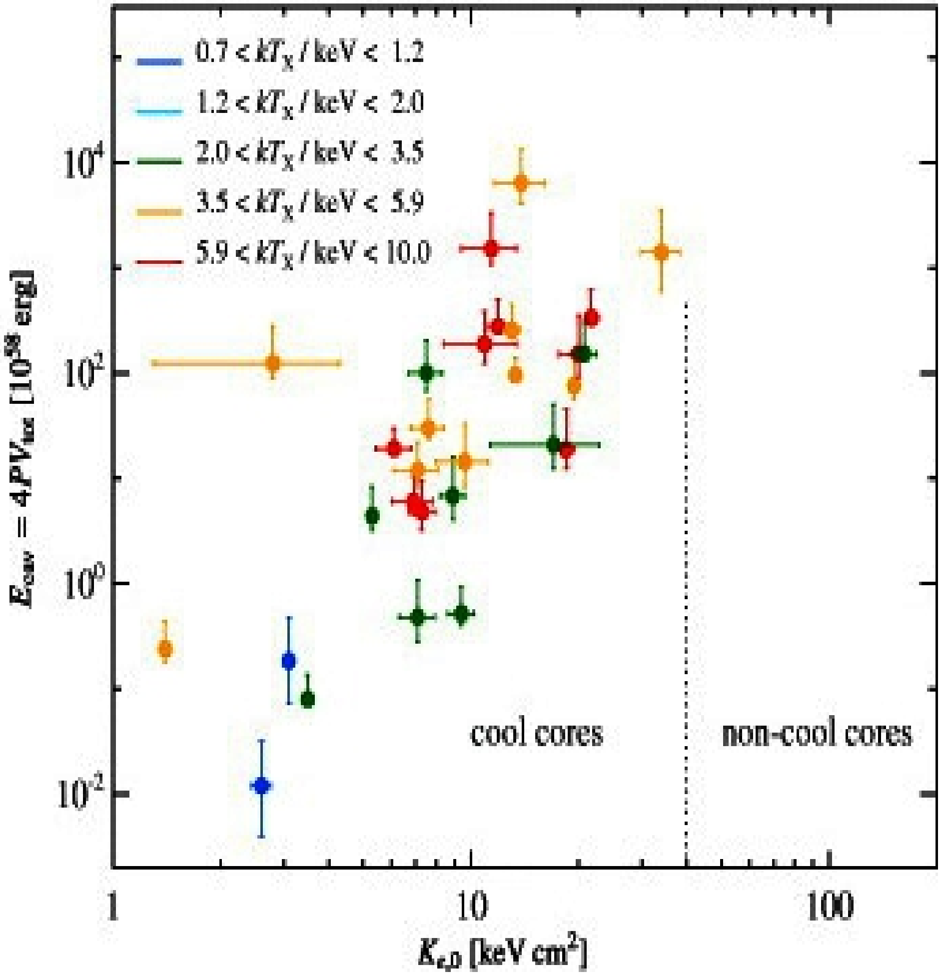
Figure 6 from B R McNamara and P E J Nulsen
2012 New J. Phys. 14 055023



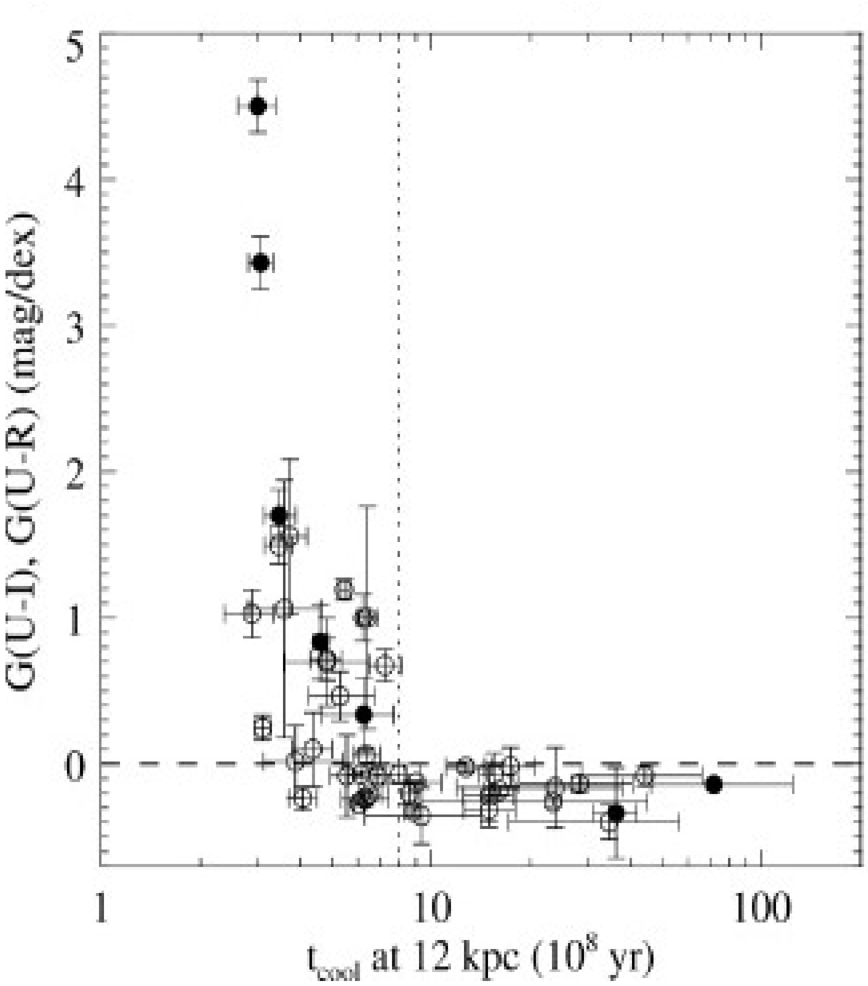
Entropy profiles of clusters

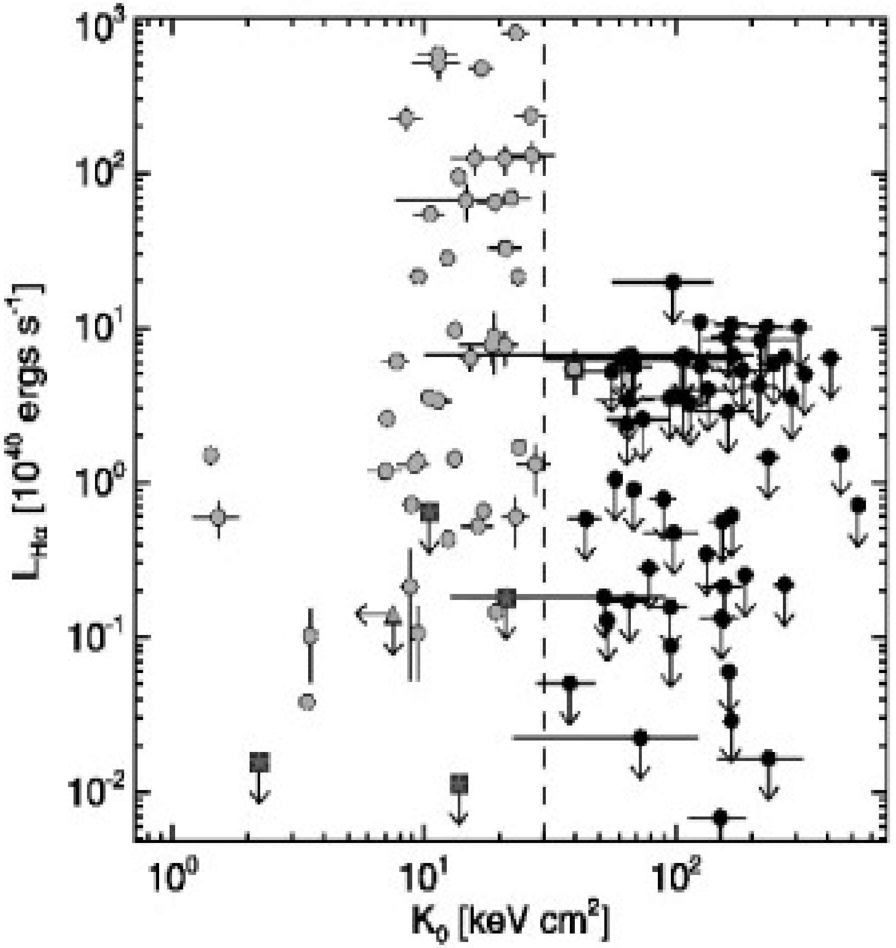


Central entropy versus radio power



Central entropy determines whether there is star formation in the central galaxy

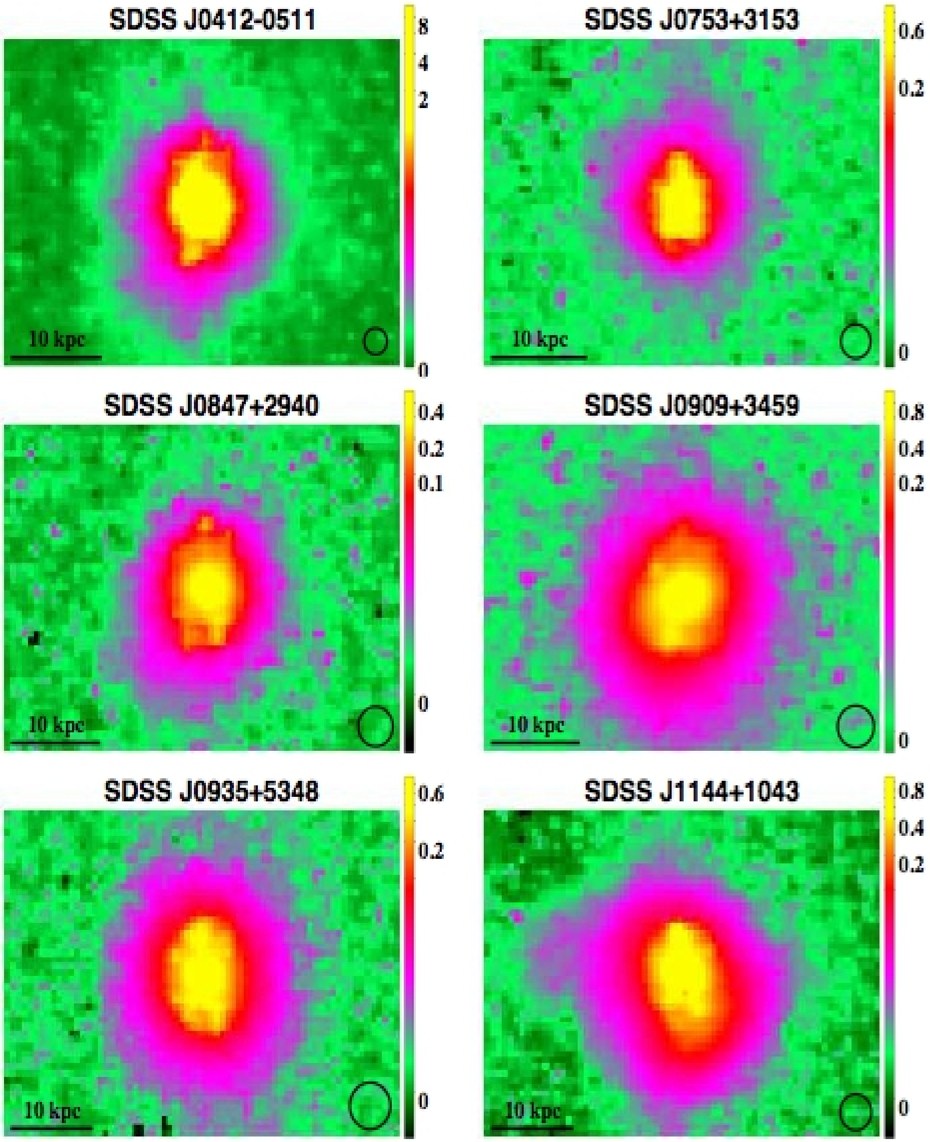


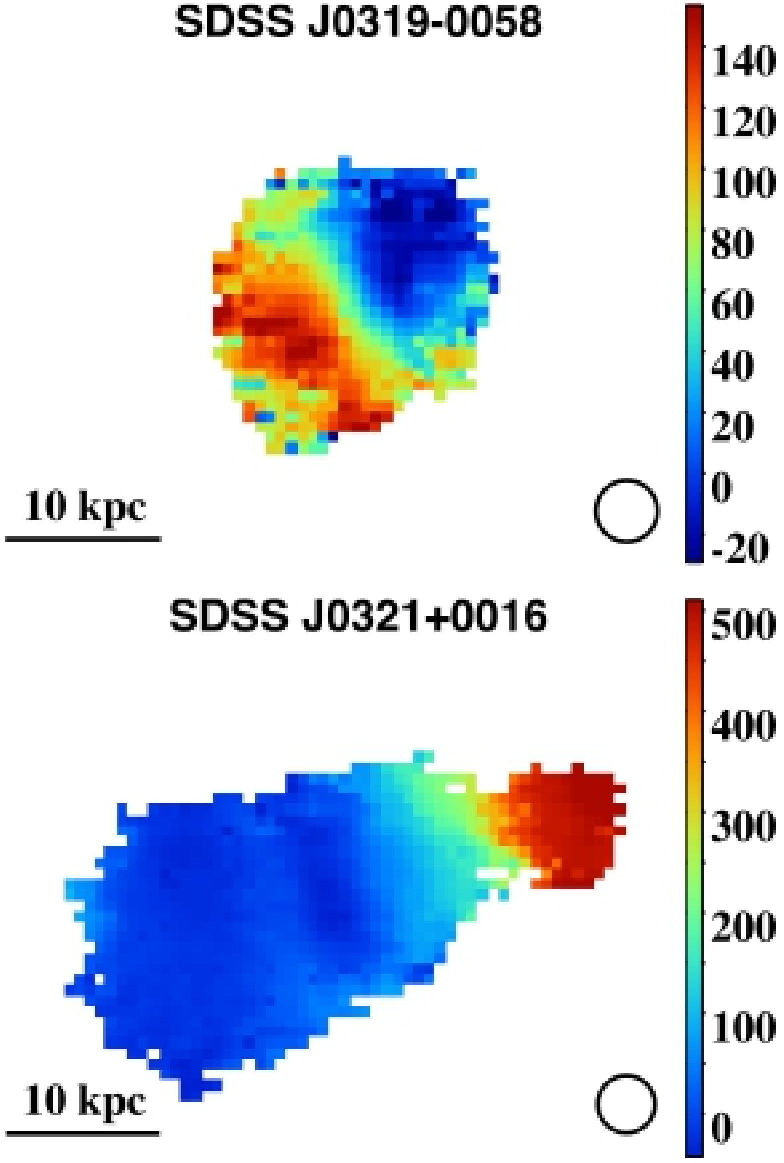


A possible picture is emerging from the data:

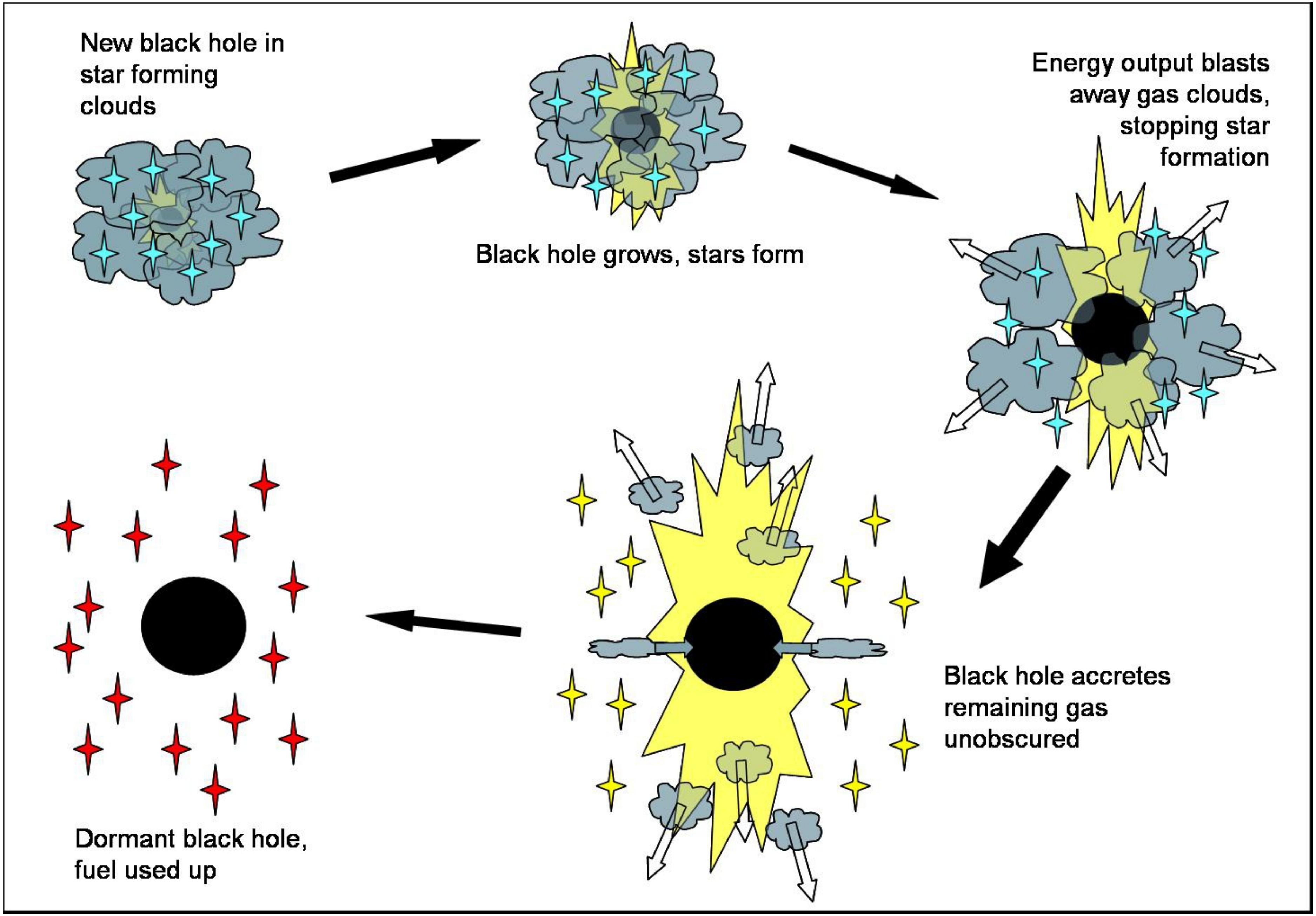
Jets from AGN (visible at radio wavelengths as a result of synchrotron emission) push gas and metals out of the central galaxy, and also heat the ambient gas, preventing from cooling and forming stars.

Outflows of ionized gas around Type II quasars also now seen. These ionized gas “halos” extend out to radii of 50 kpc and are very round in morphology. (Greene & Zakamska)





How do black holes form?



New black hole in star forming clouds

Black hole grows, stars form

Energy output blasts away gas clouds, stopping star formation

Black hole accretes remaining gas unobscured

Dormant black hole, fuel used up

OUTLOWS FROM QUASARS REMAIN POORLY UNDERSTOOD

(this is an artist's impression)