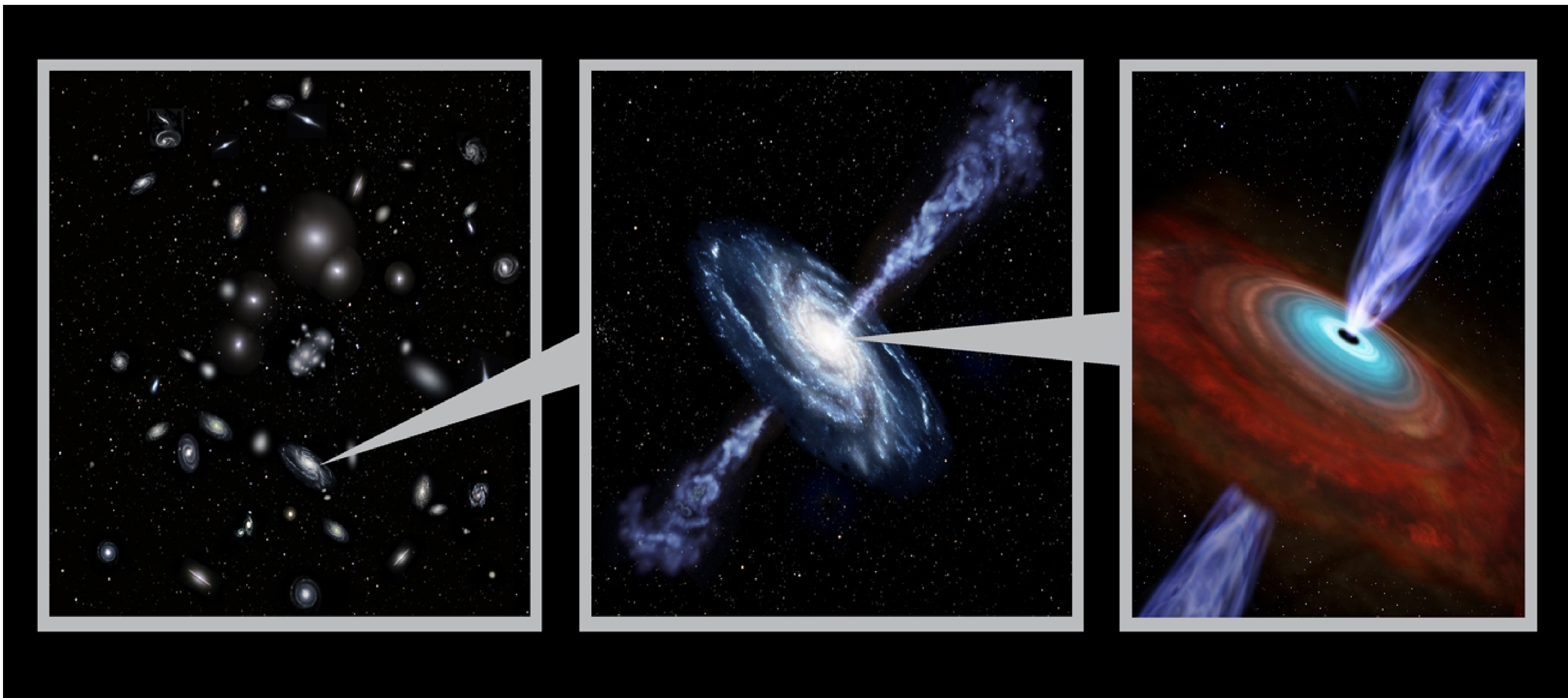
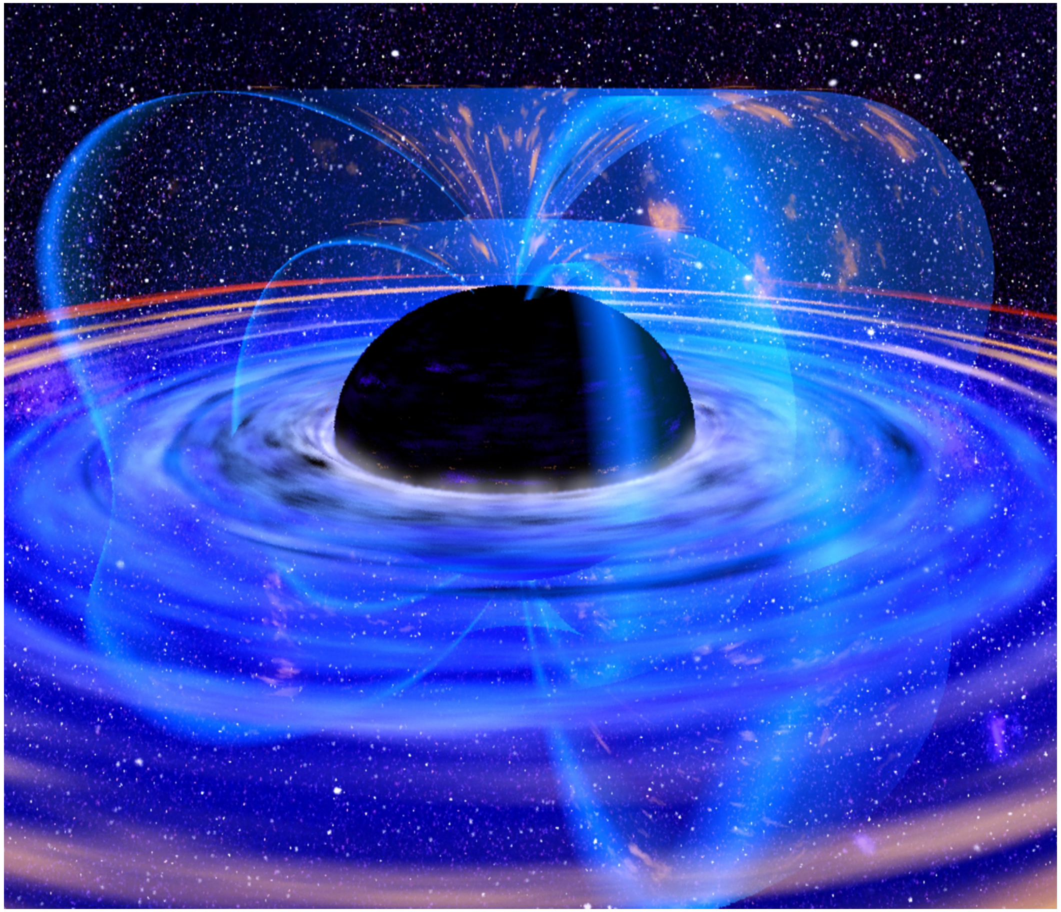
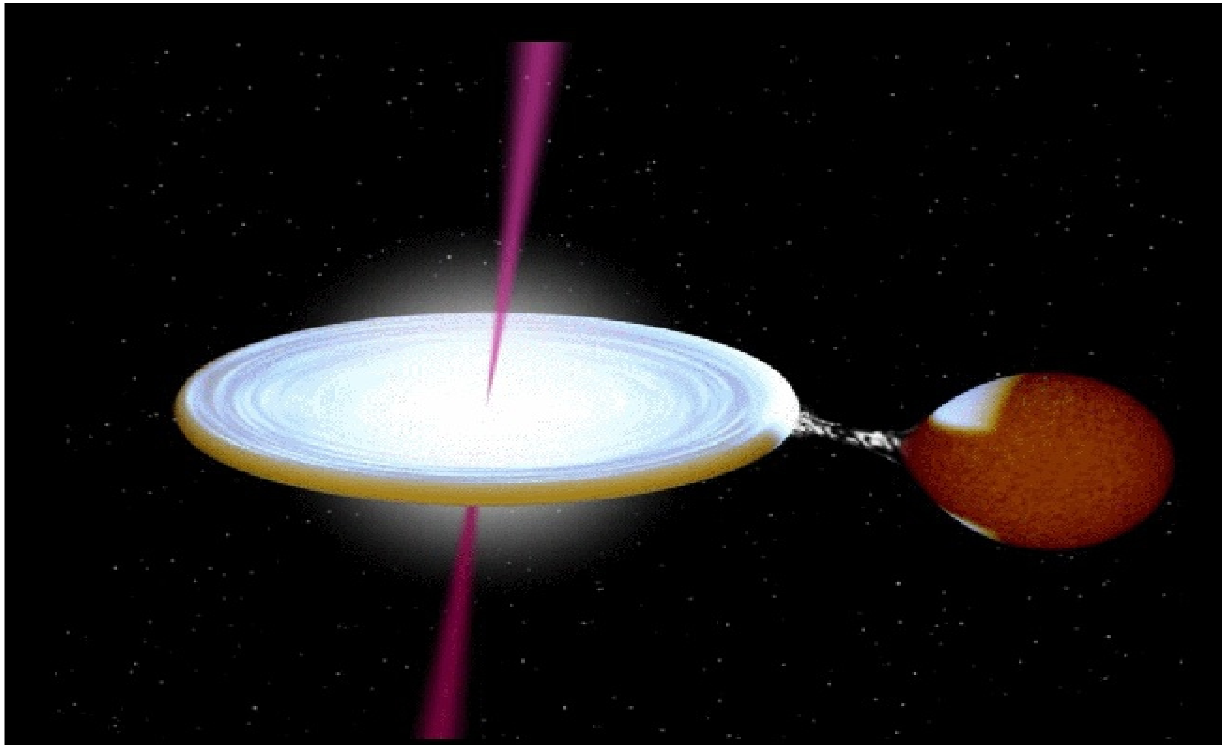
Supermassive Black Holes and their Galaxies



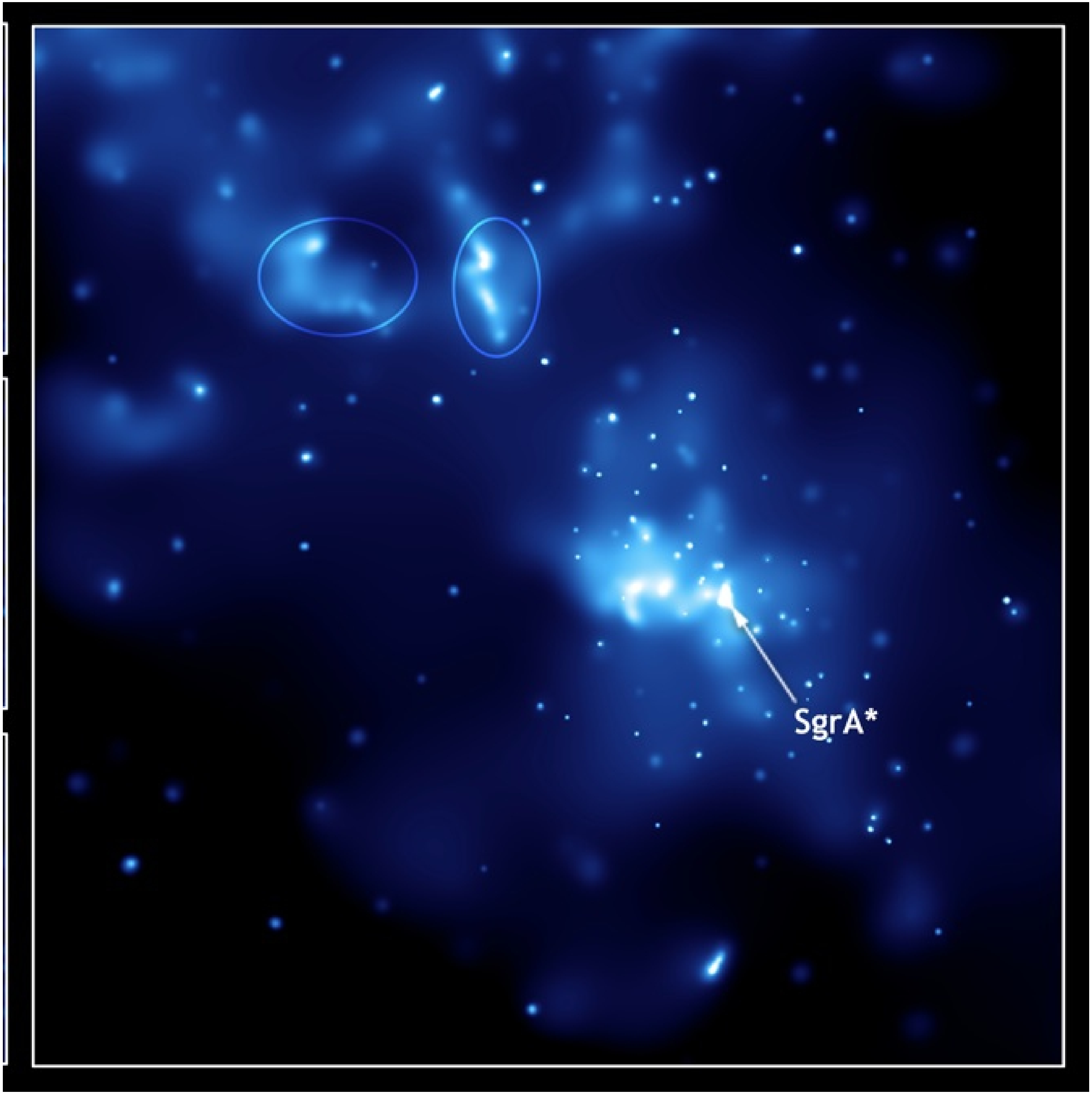


A black hole is a region of space time from which gravity prevents anything, including light, from escaping. The theory of general relativity predicts that a sufficiently compact mass will deform space-time to form a black hole.

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.

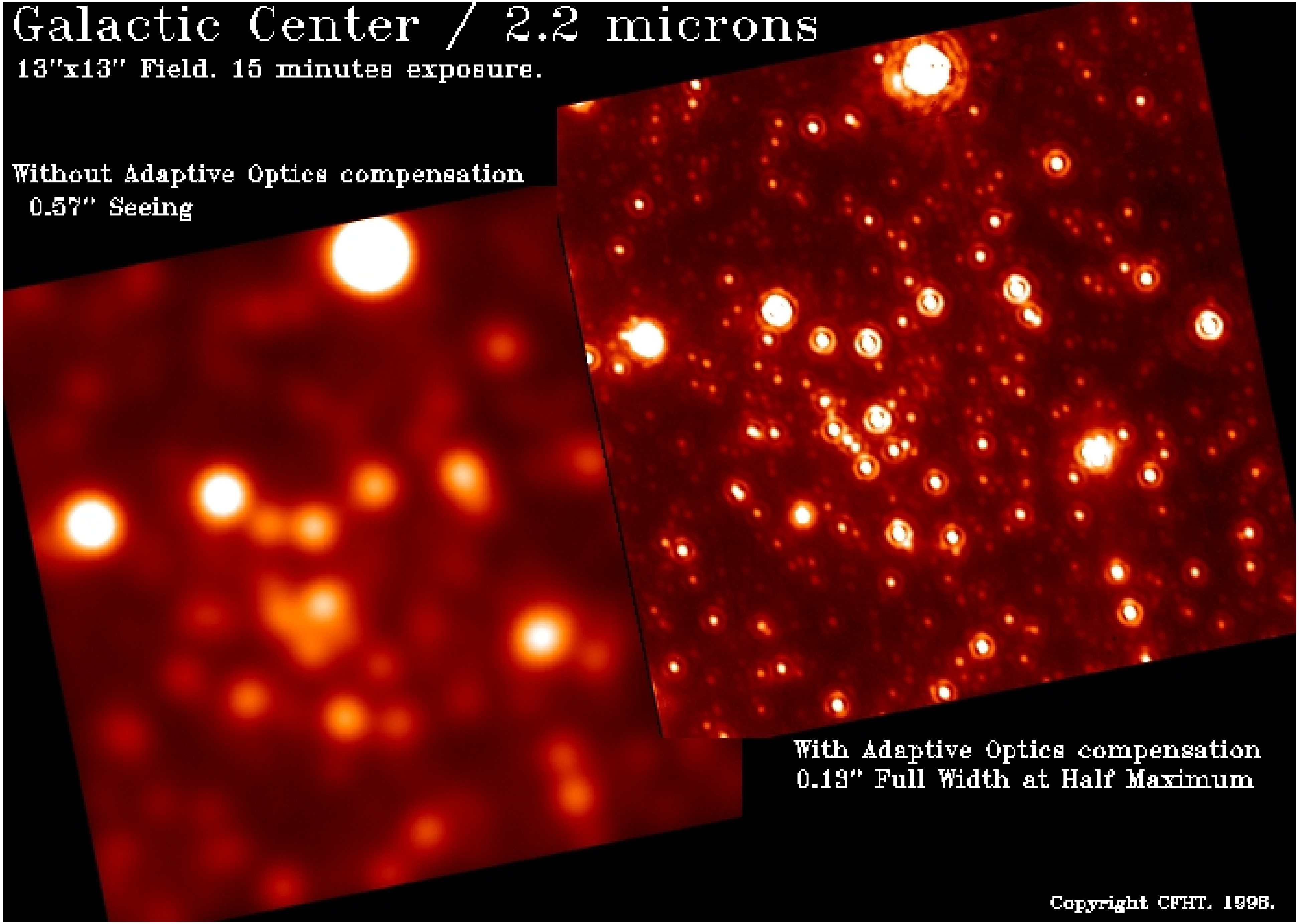


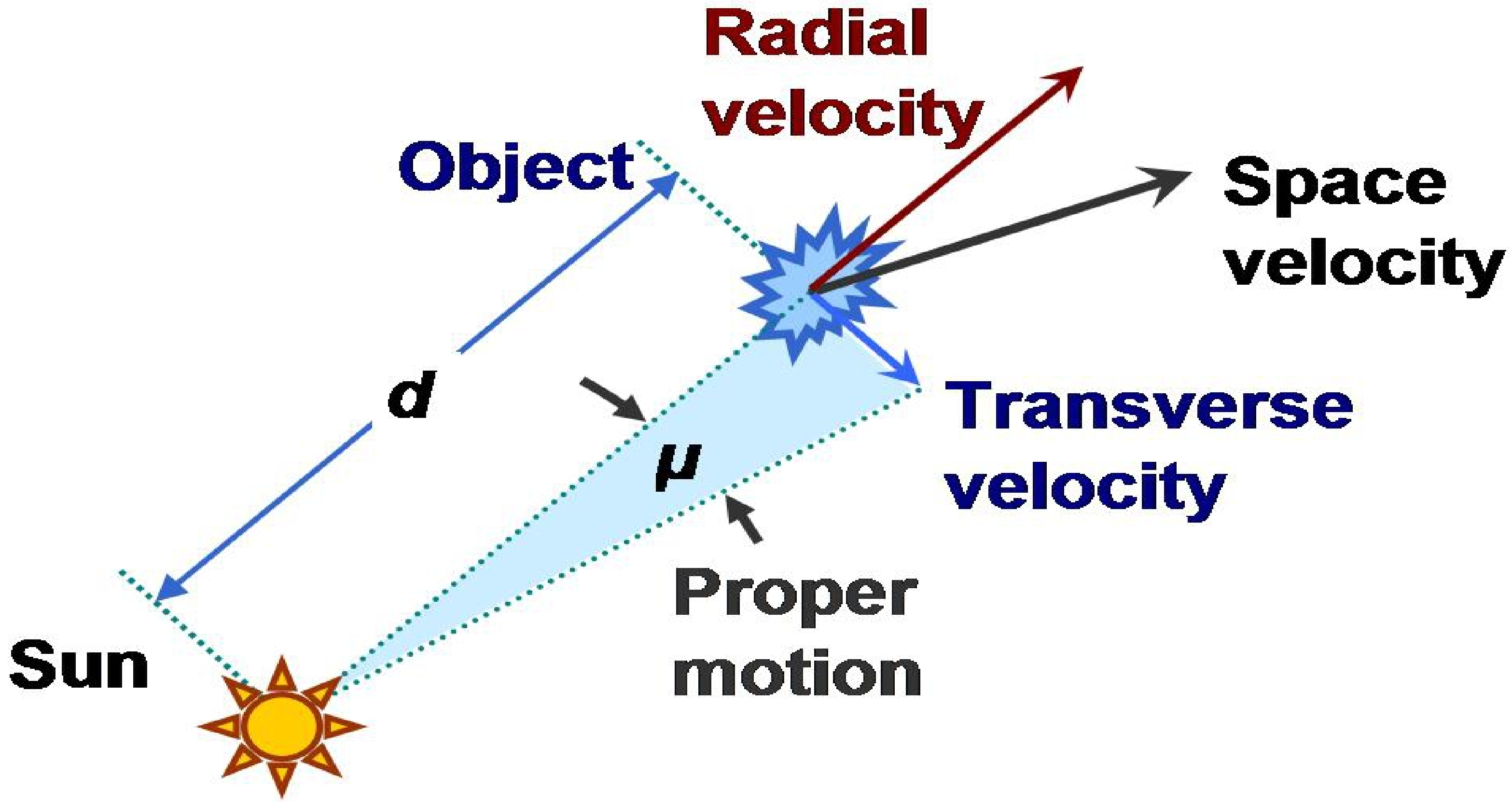
THE GALACTIC CENTER

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

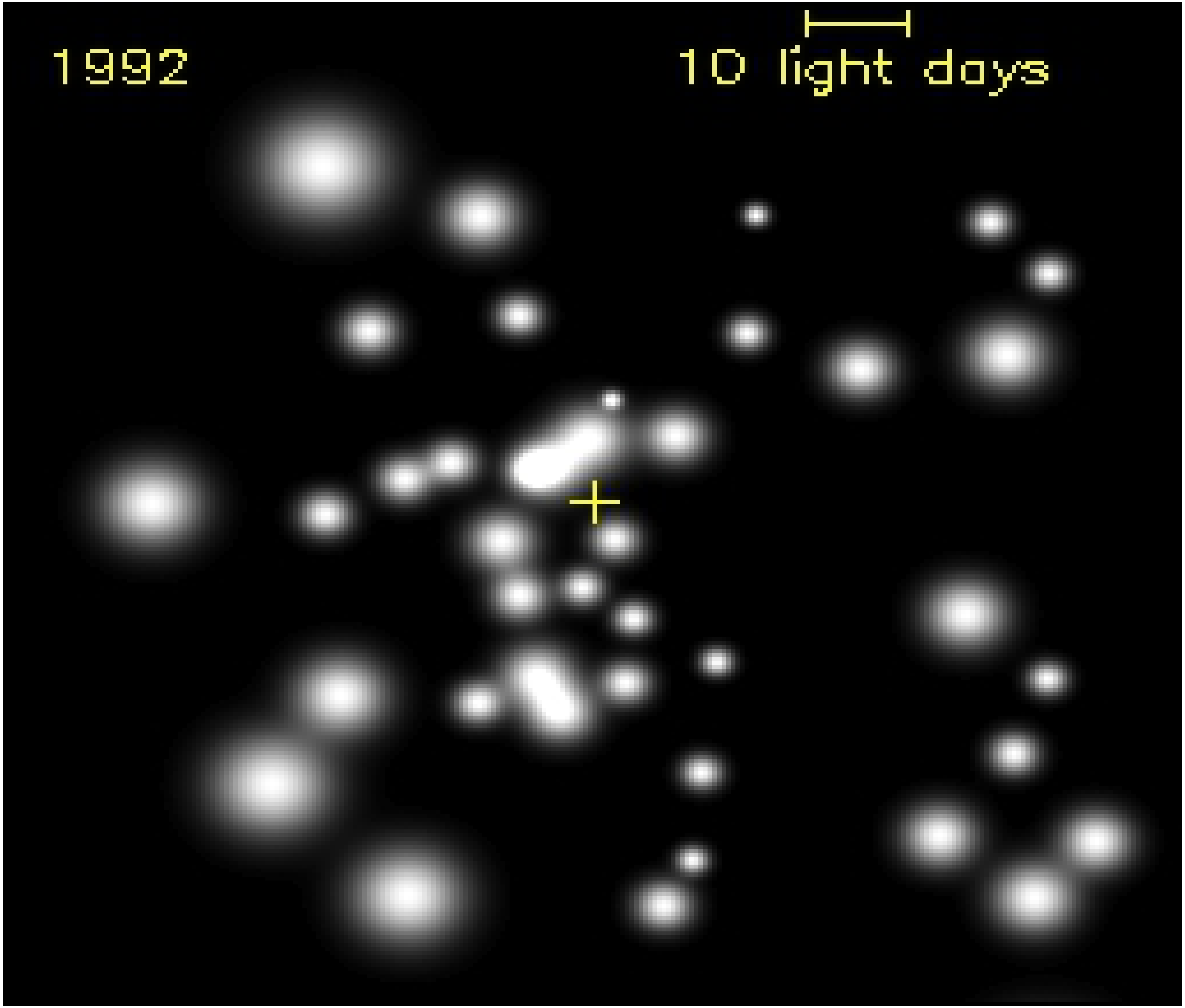
Sgr A* was discovered in1974, by astronomers Bruce Balick and Robert Brown using the baseline interferometer of the National Radio Astronomy Observatory.

THE GALACTIC CENTER





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.


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 4.4×10^6 $M_\odot$ 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 4.6×10^6 $M_\odot$ (Ghez et al. 2003,

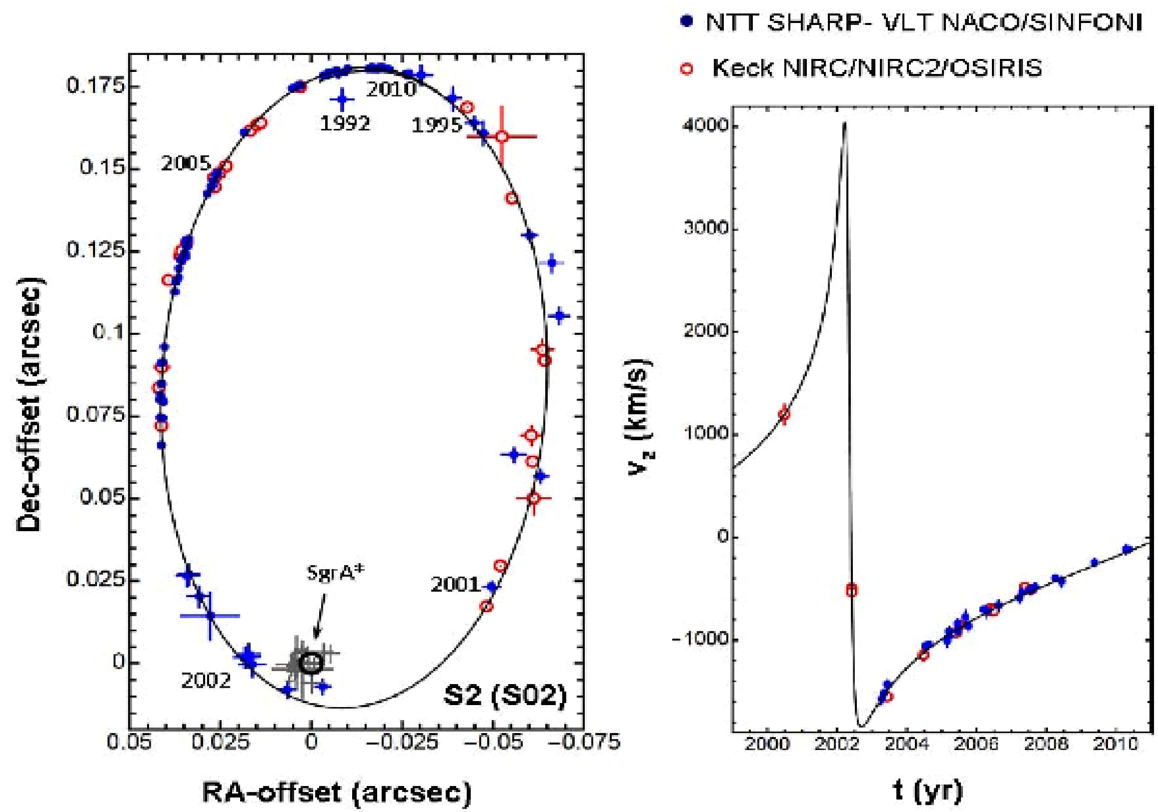
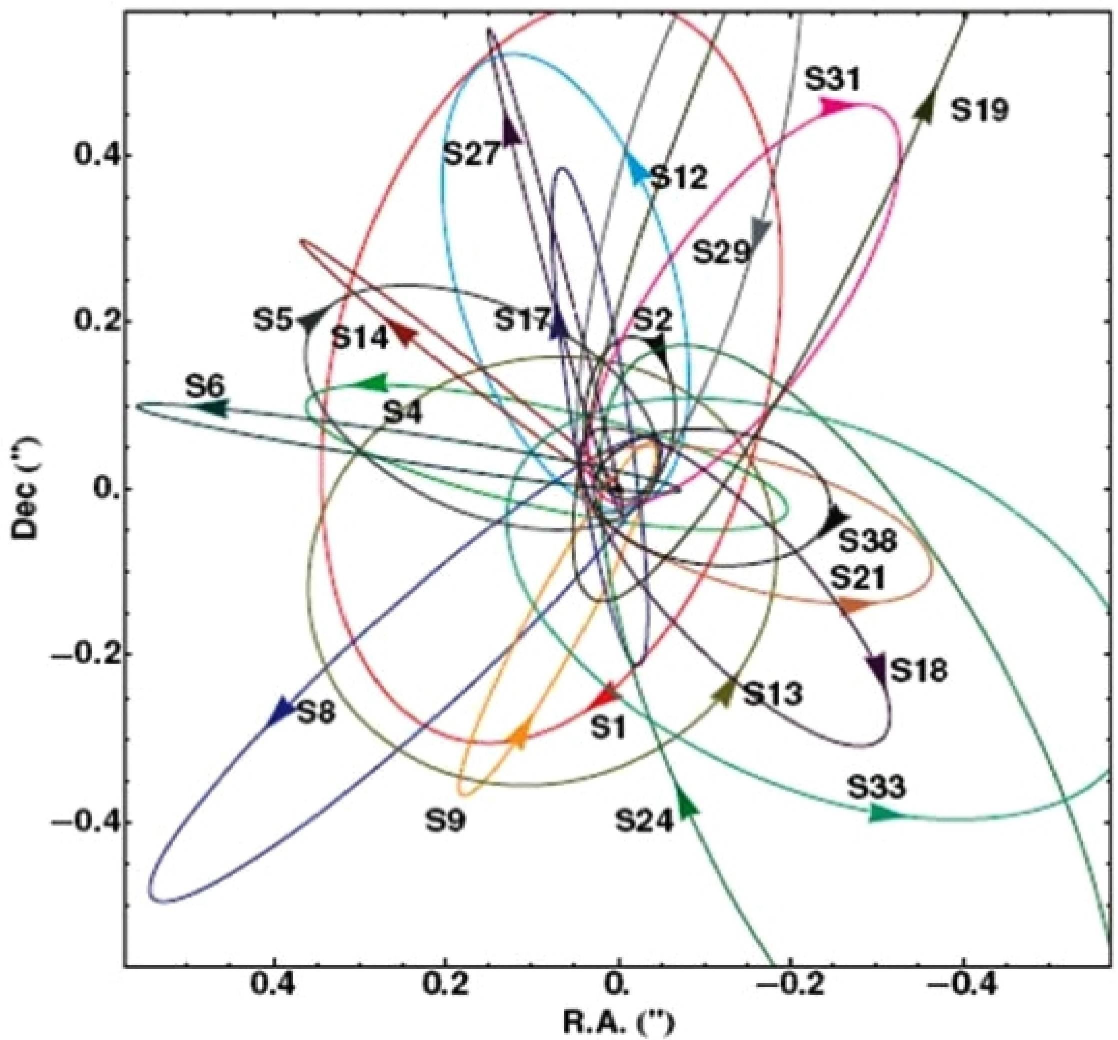


Figure 4.3.1. Orbit of the star S2 (S02) on the sky (left panel) and in radial velocity (right panel). Blue, filled circles denote the NTT/VLT points of Gillessen et al. (2009a,b, updated to 2010), and open and filled red circles are the Keck data of Ghez et al. (2008) corrected for the difference in 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 $5 \times 10^{15}\ M_{\odot} pc^{-3}$. 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***.



SPACE TELESCOPE IMAGING SPECTROGRAPH

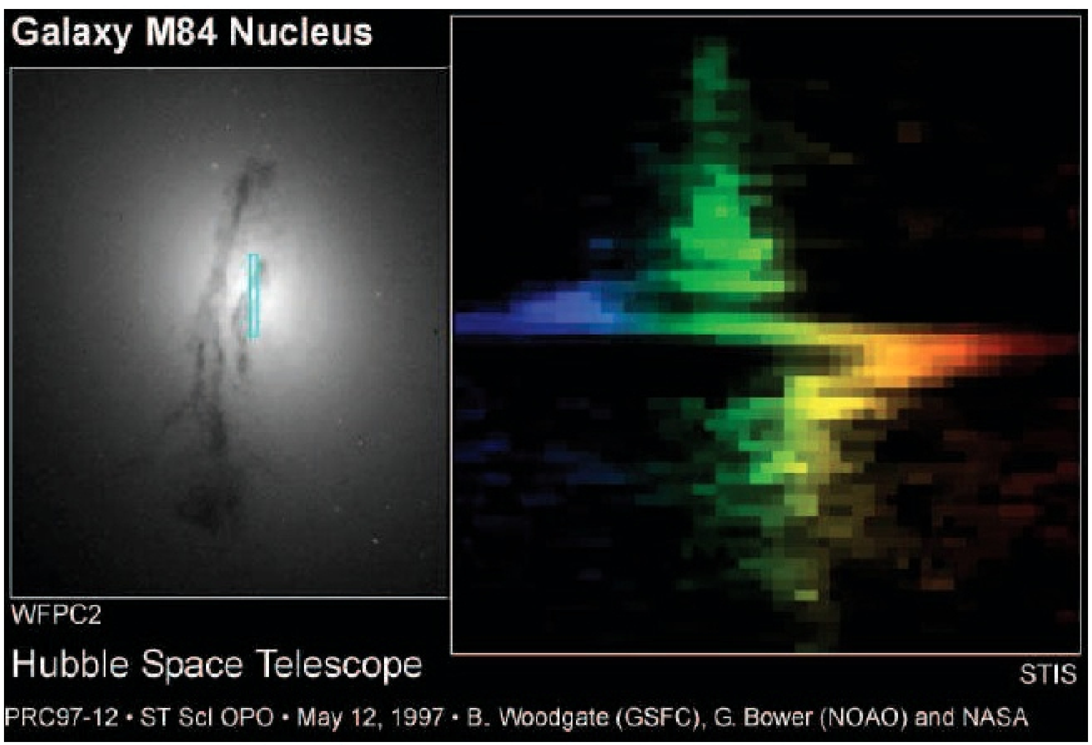
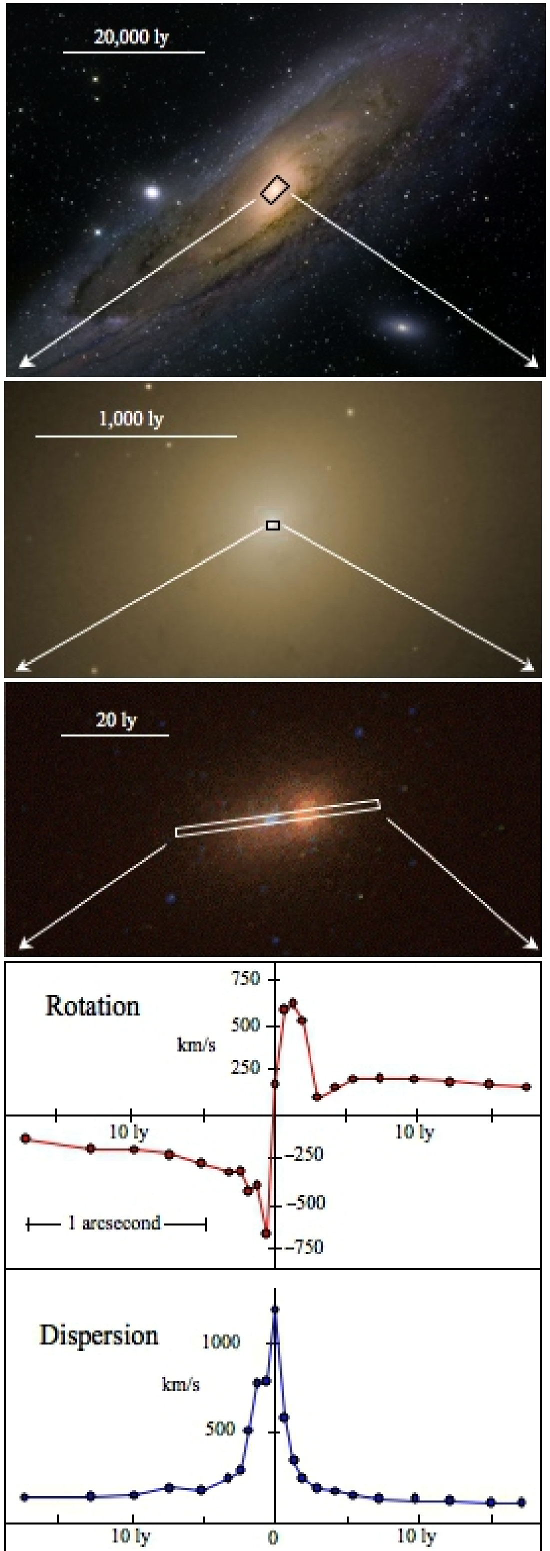


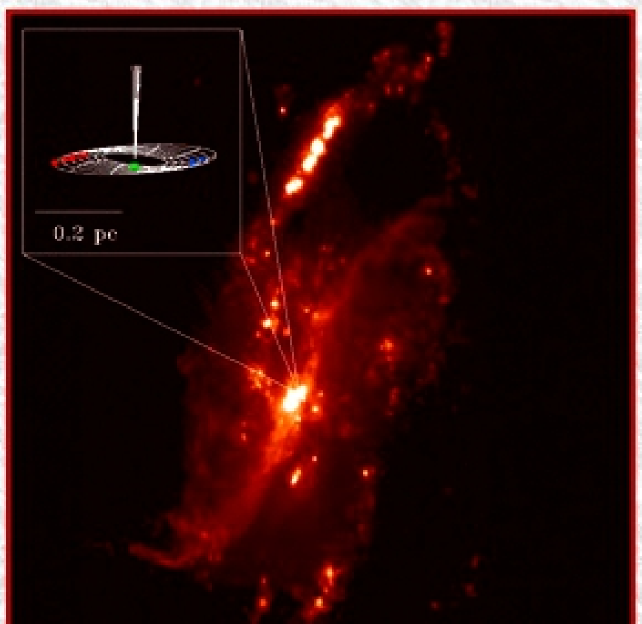
Fig. 50. Left: Image of M84; Right: Velocity profile across the nucleus of M84 taken with STIS aboard the HST. The estimated black hole mass is about 300 million solar masses.

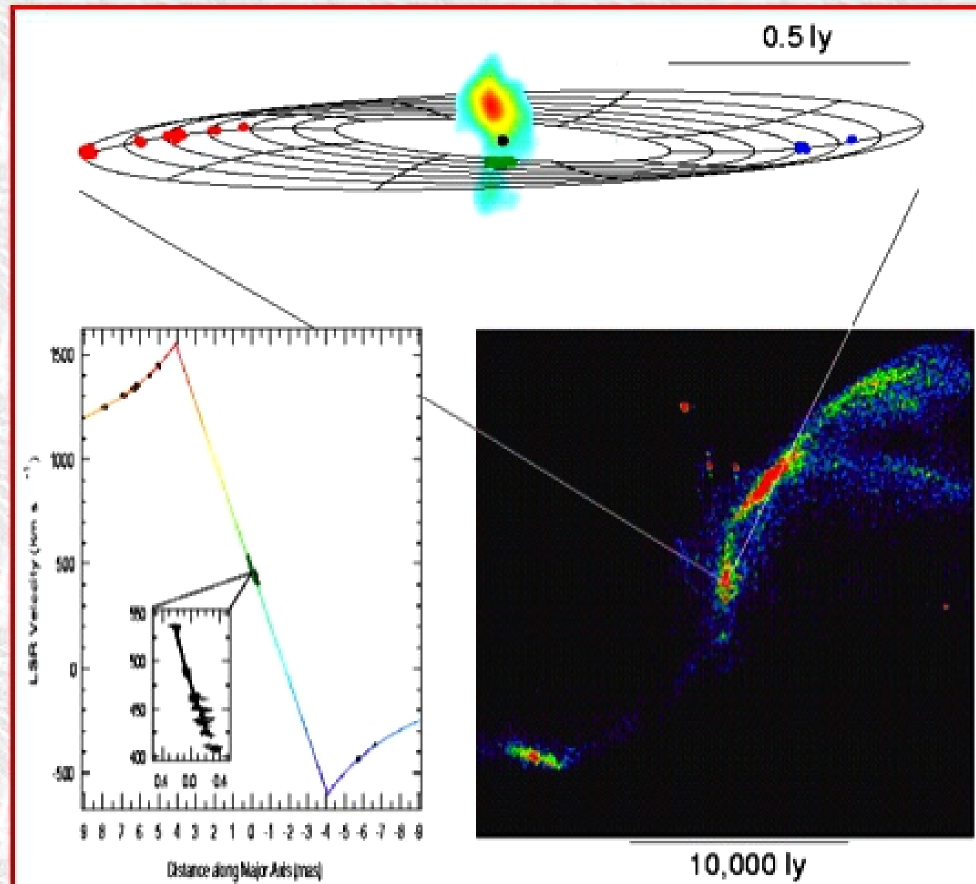
The galaxy M31 , our nearest spiral neighbour



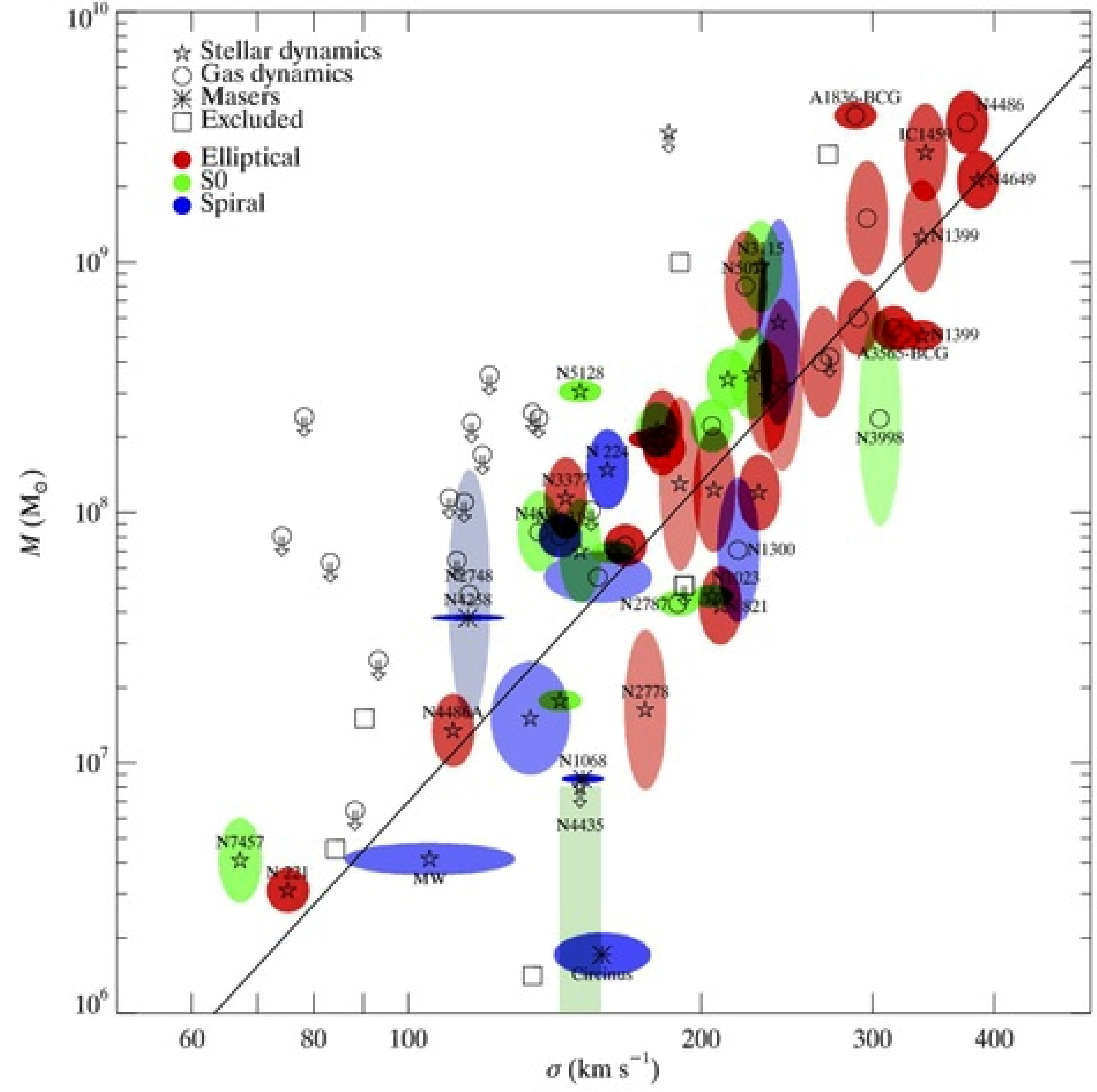
NGC 4258 Black Hole

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.



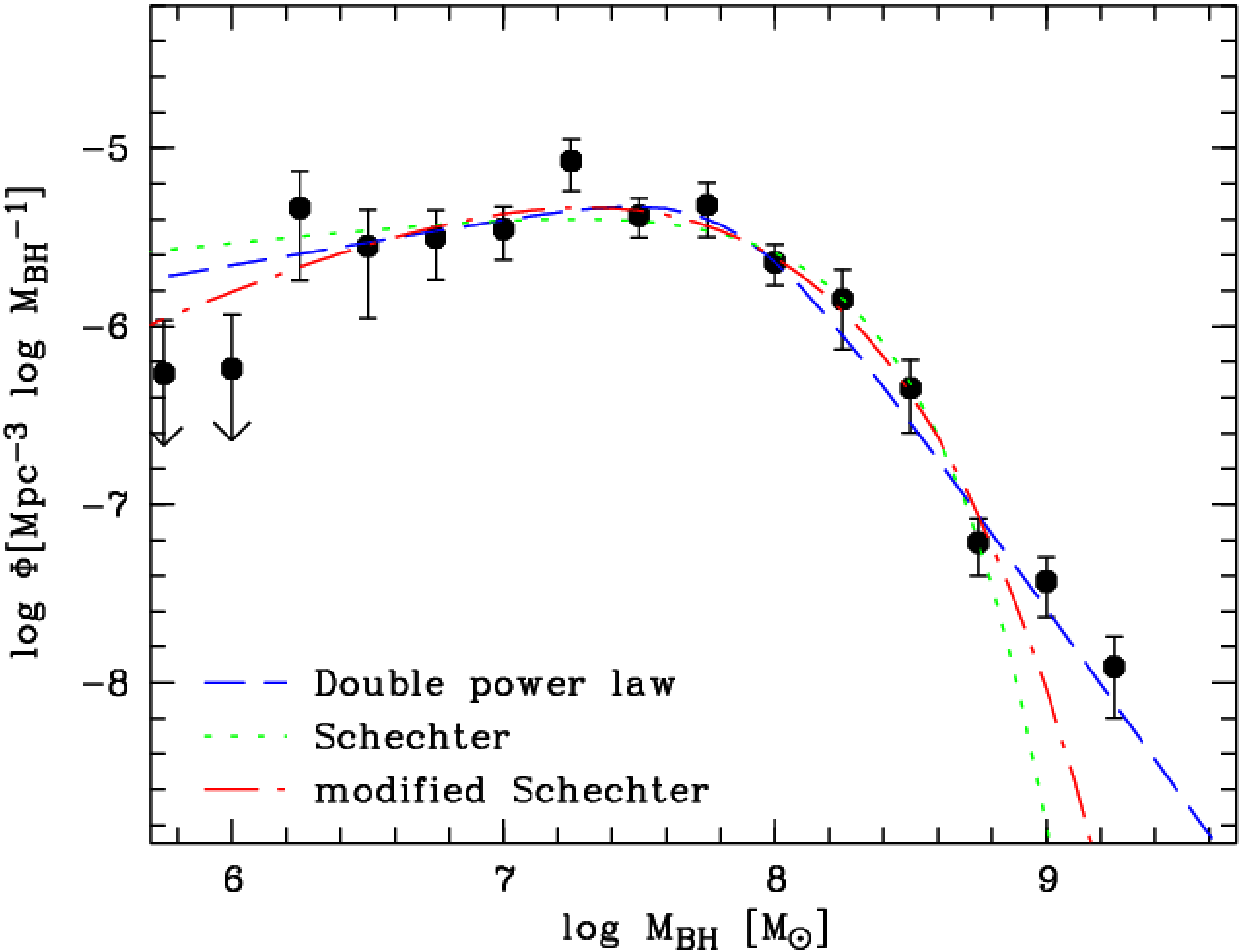


Nuclear gas disk with masers giving doppler velocities and proper motions.



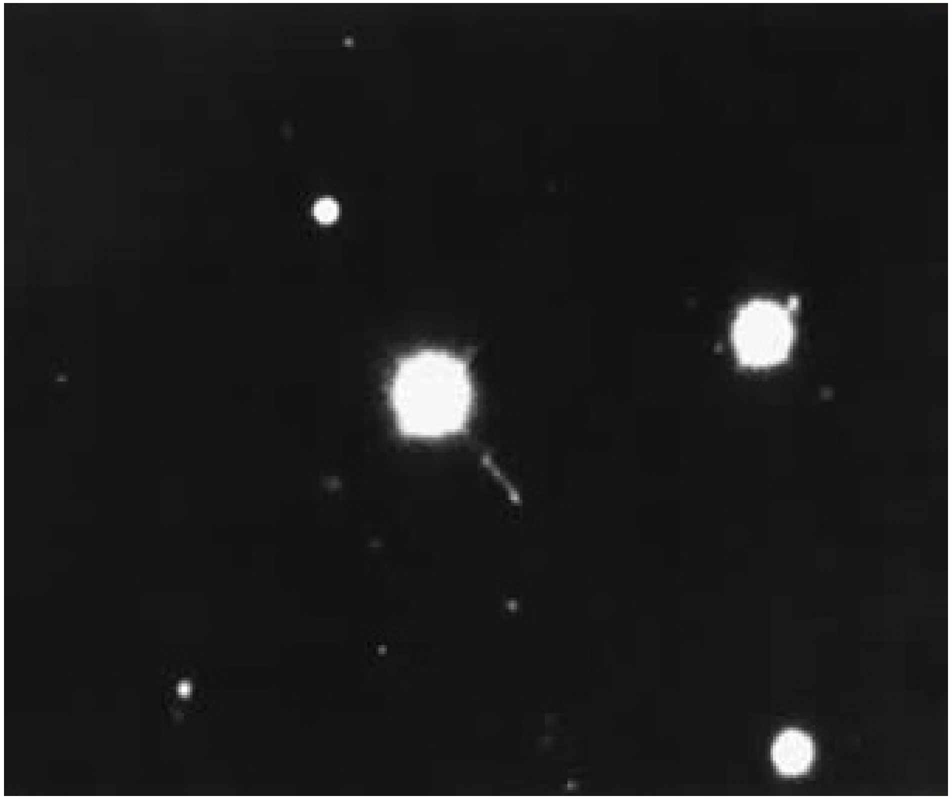
Stellar dynamics
Gas dynamics
Masers
Excluded
Elliptical
S0
Spiral
A1836-BCG
N4486
IC1459
N4649
N1399
N3115
N5077
A3565-BCG
N5128
N3998
N 224
N3377
N1300
N2748
N4258
N1023
N2787
N3821
N2778
N4486A
N1068
N4435
N7457
MW
Circinus
M ($M_\odot$)
σ (km s^{-1})
10^{10}
10^9
10^8
10^7
10^6
60
80
100
200
300
400

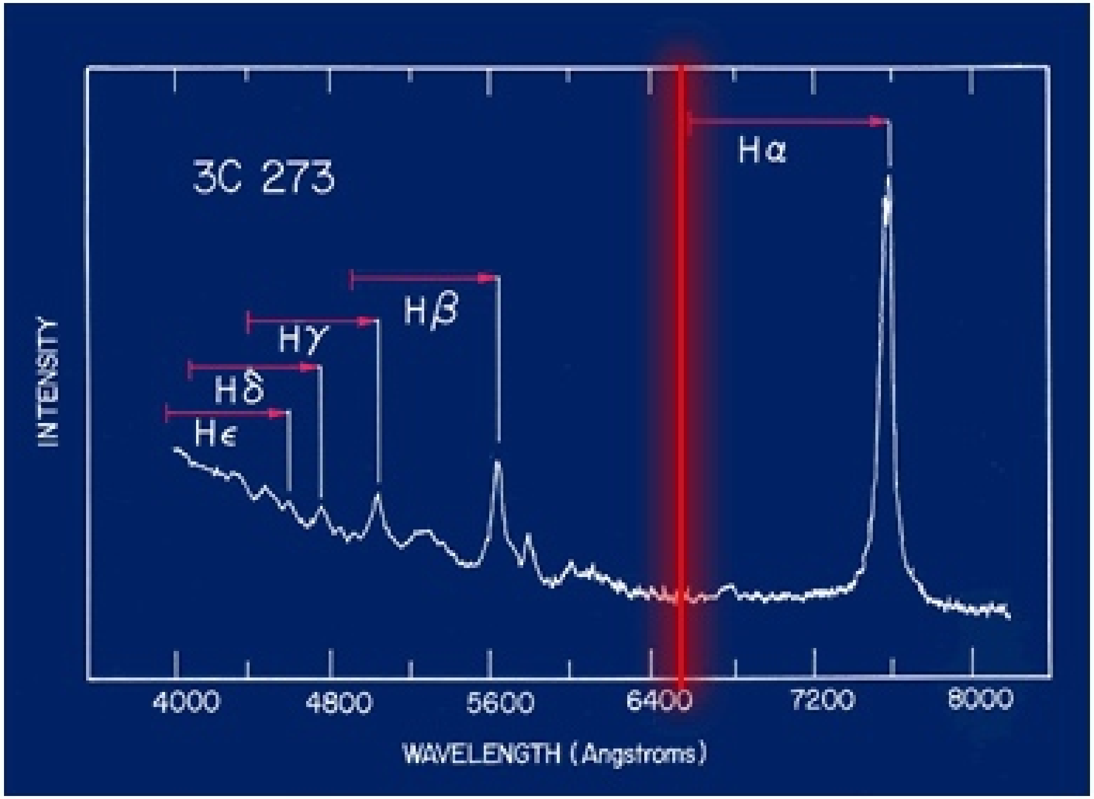
Black hole mass function (local Universe)

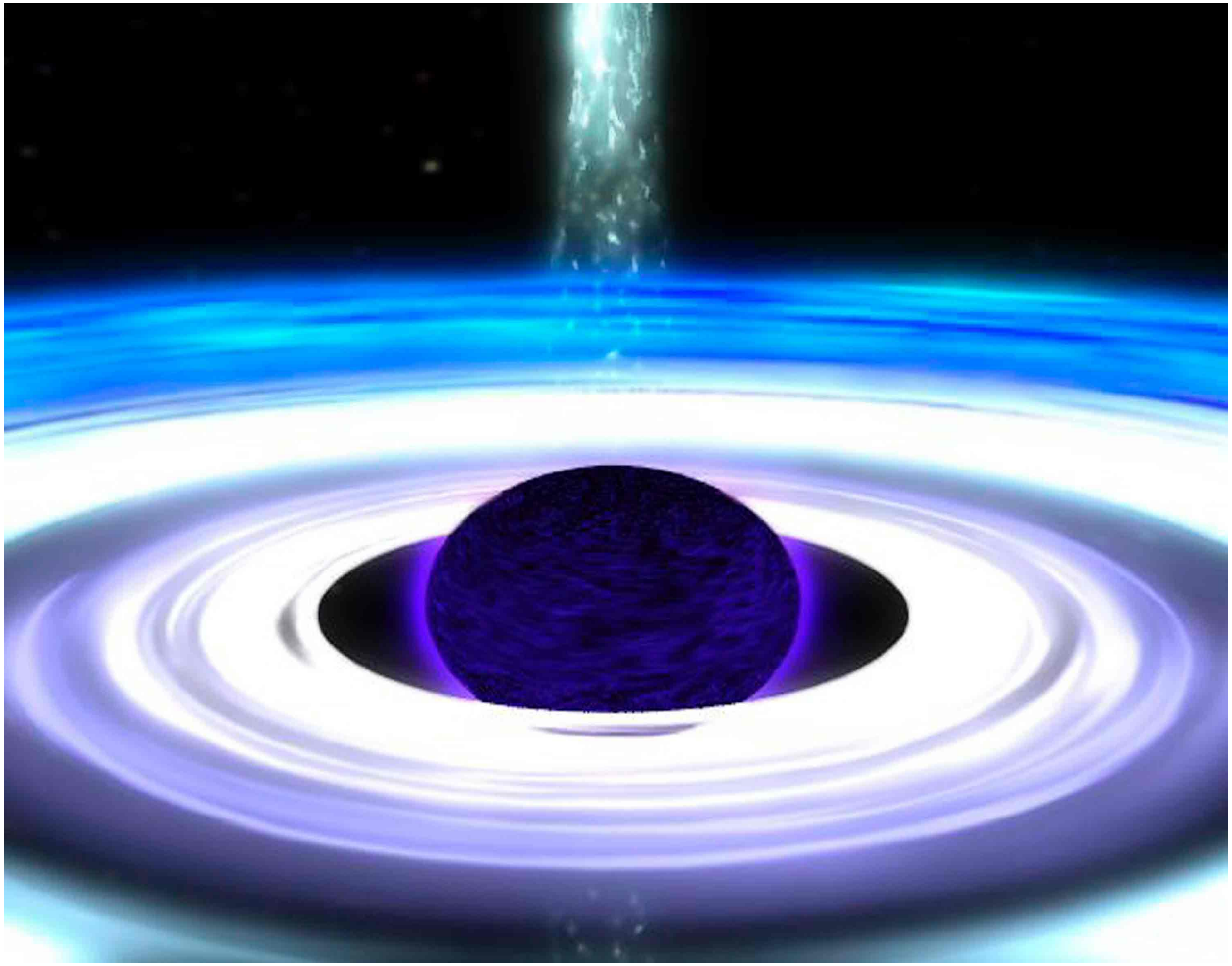


Accretion onto Black Holes

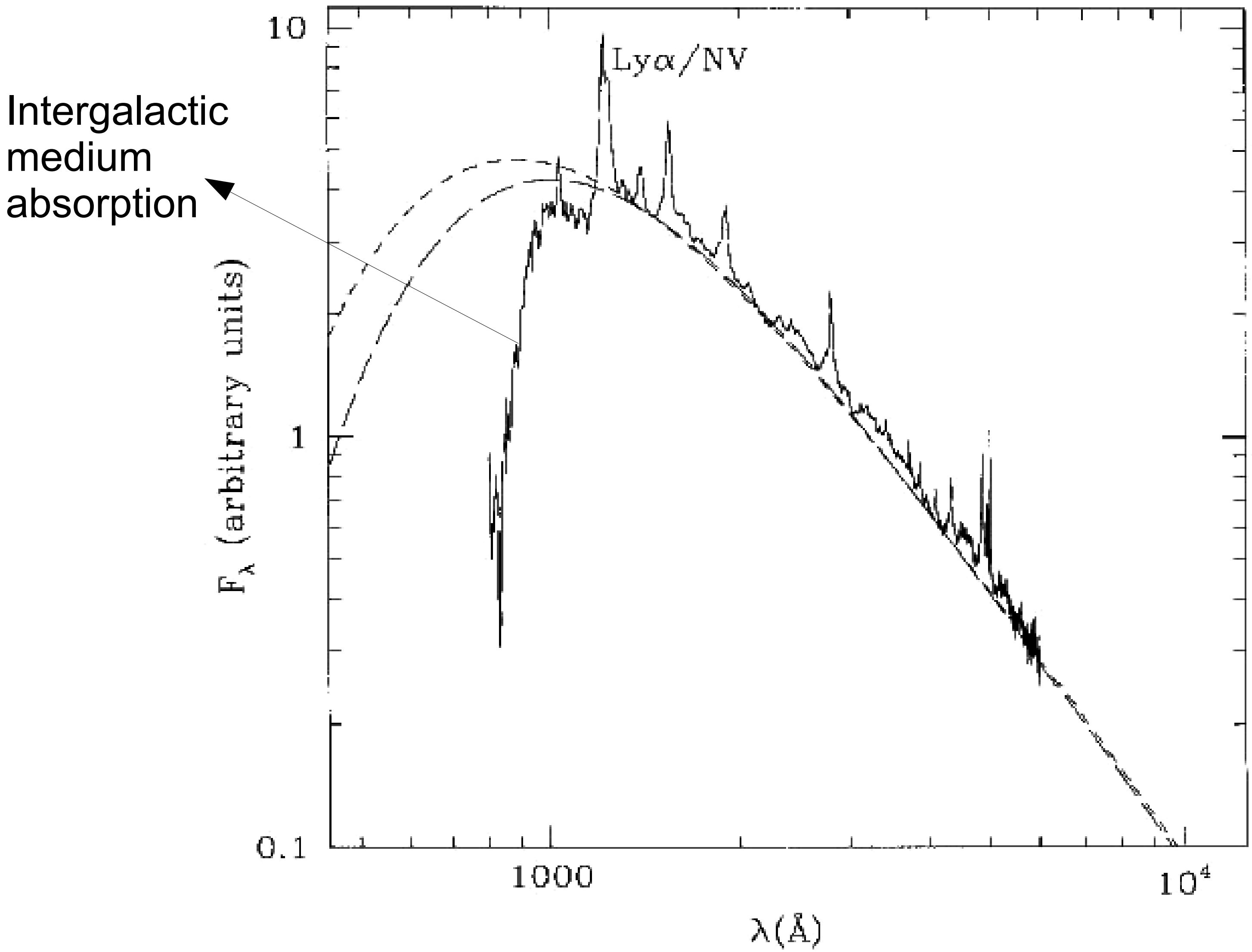
1963 M. Schmidt discovers that the radio source 3C273 can be identified with an optical point source (stellar) with a jet. The spectrum shows broad emission lines $H_{\beta,\gamma,\delta...}$, MgII, OIII ... which are redshifted by $z = 0.158 \Rightarrow v_r ad = 47400\frac{km}{s}$. So, the object was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







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

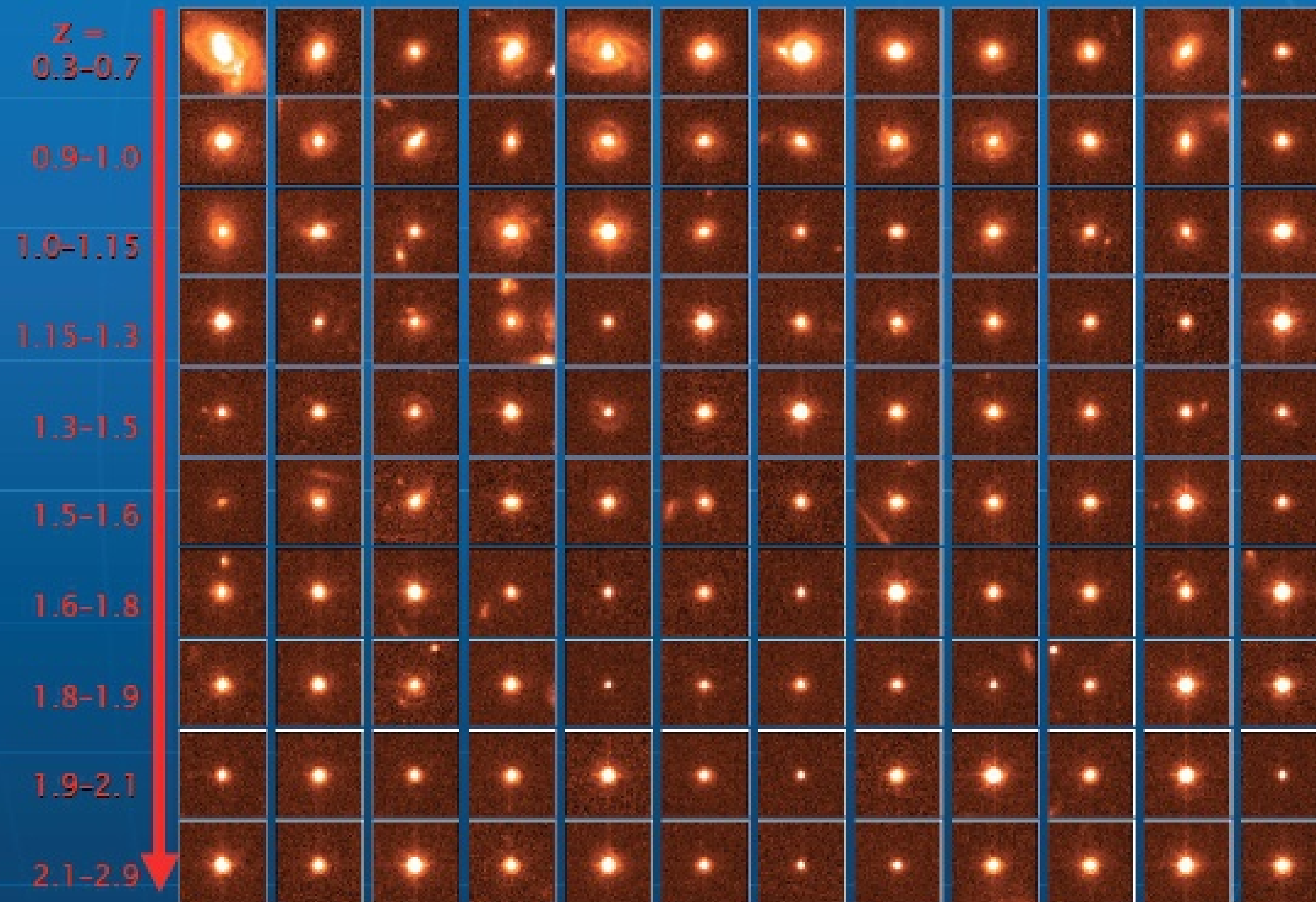


Best-fit blackbody accretion disk spectra to the line-free continuum windows of the composite quasar spectrum of Francis et al. (1991). The solid curve shows the composite spectrum; the short-dashed curve, a disk model around a Schwarzschild hole; and the long-dashed curve, a disk model around a Kerr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

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

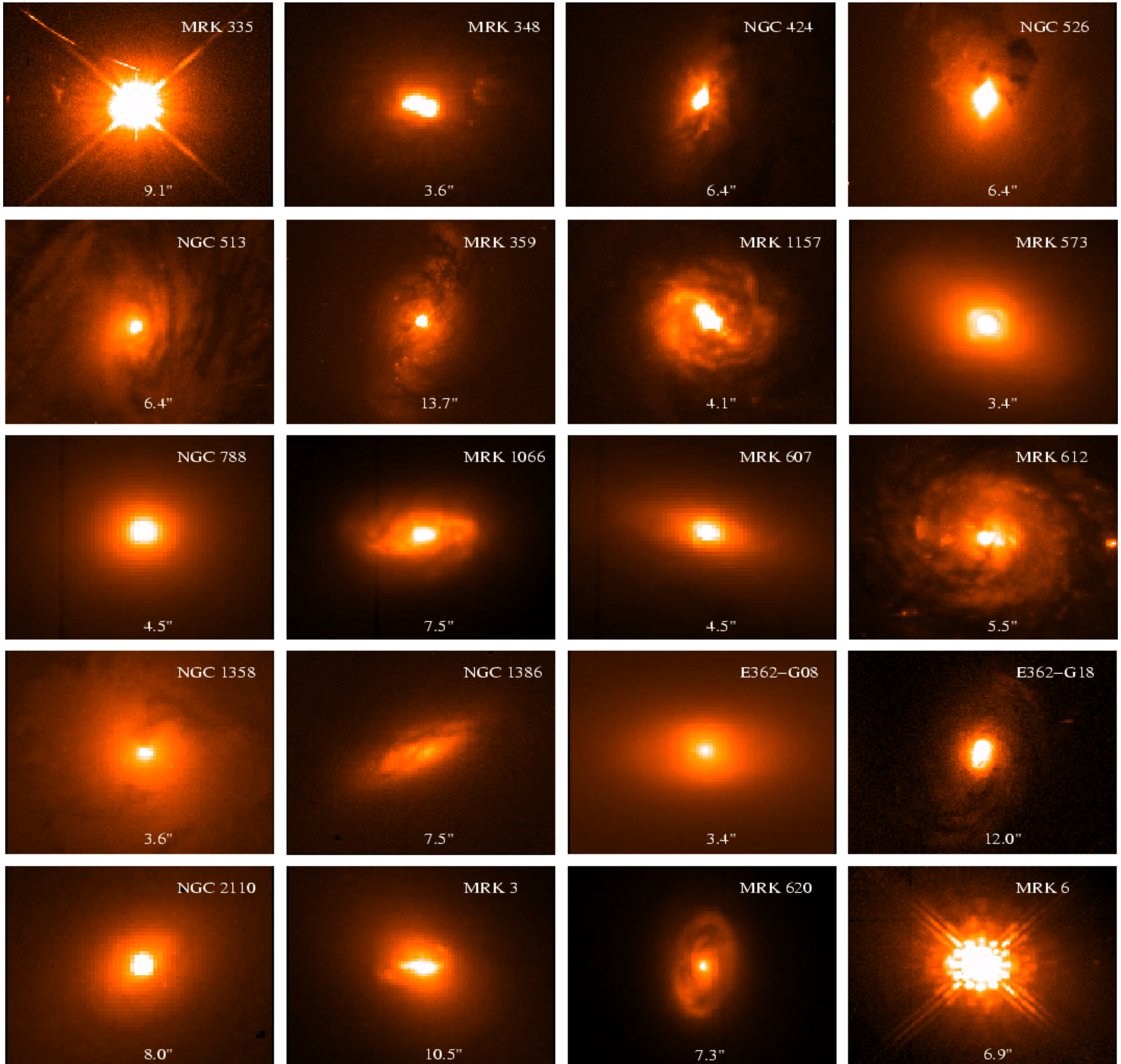
Answer:

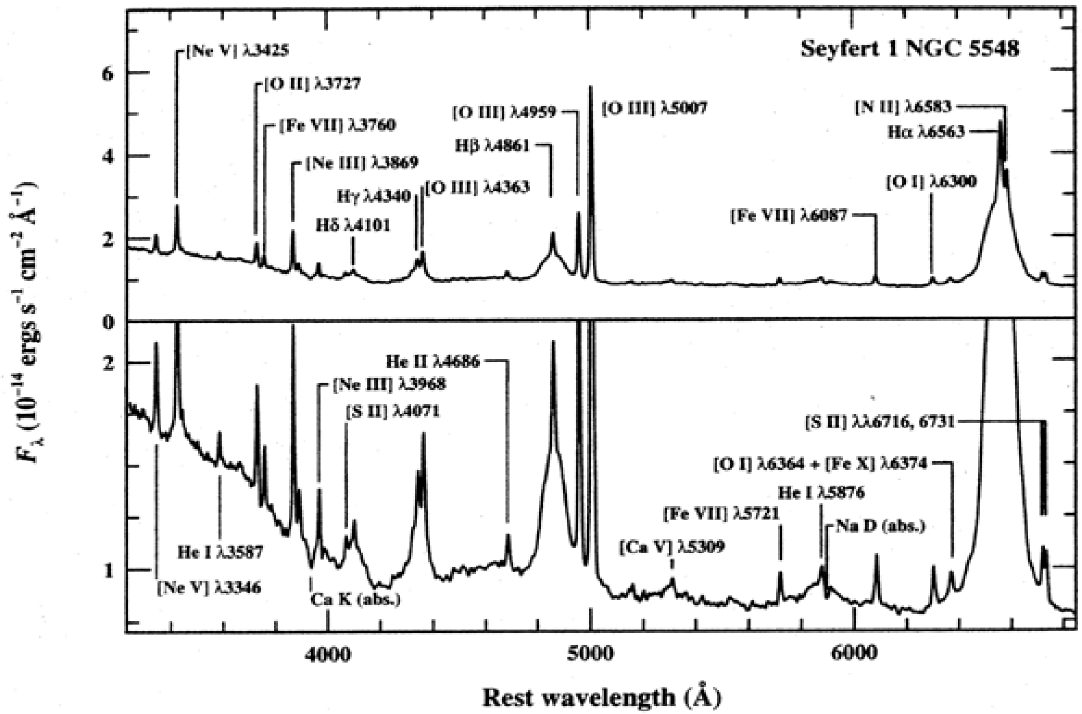
whenever on 'has a chance' to see a 'host galaxy' one does see one



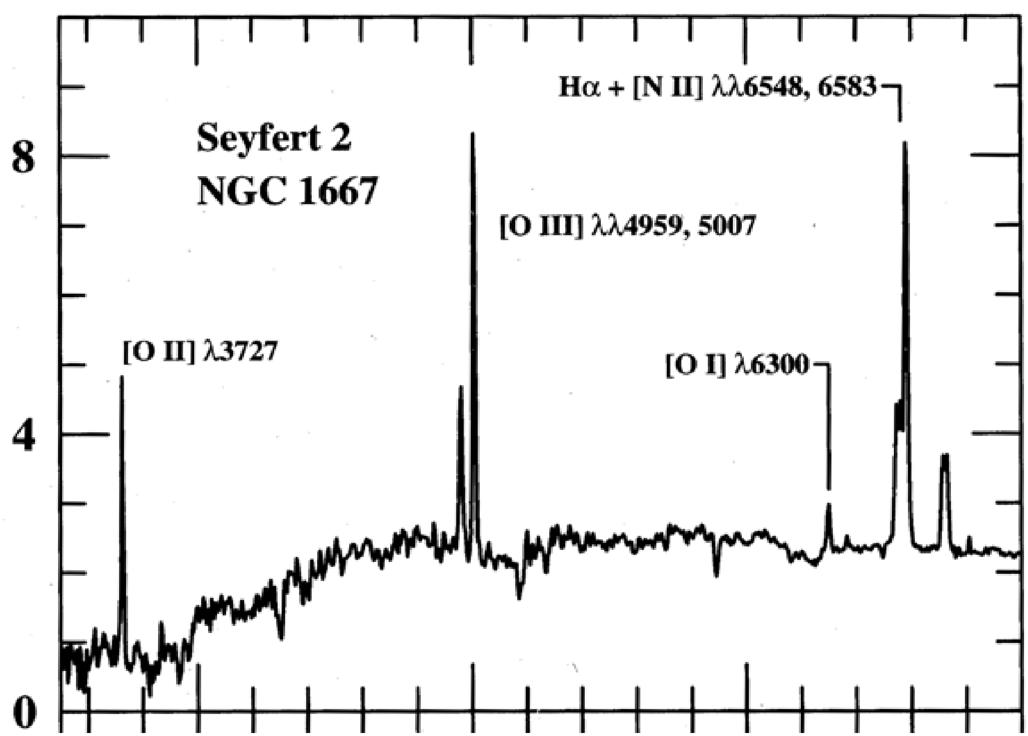
HST imaging COSMOS: Jahnke et al 2007/8

Seyfert Galaxies: fainter versions of quasars

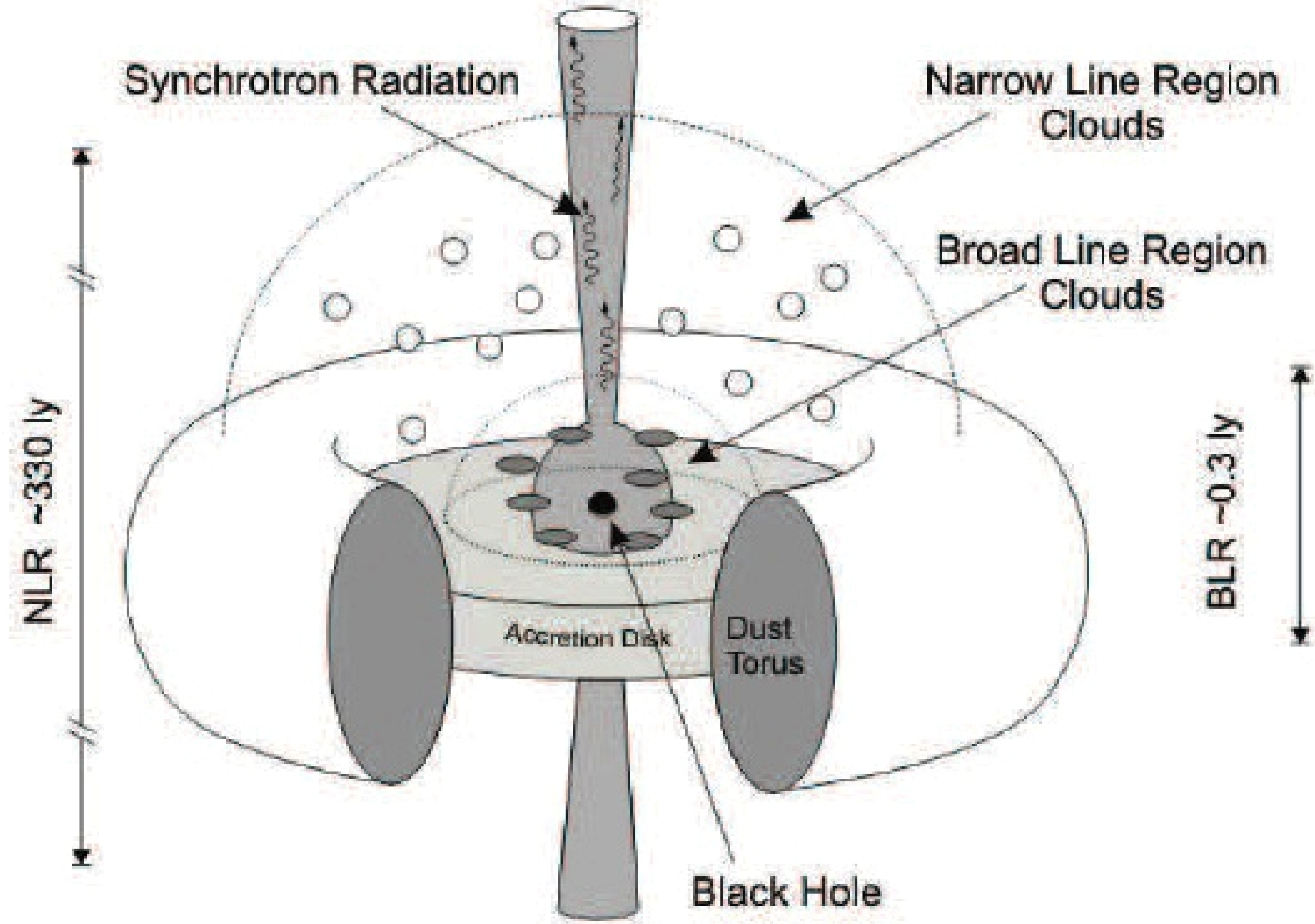




Seyfert Is have spectra with broad emission lines and there are clear point-like central nuclei in the images of the host galaxy.

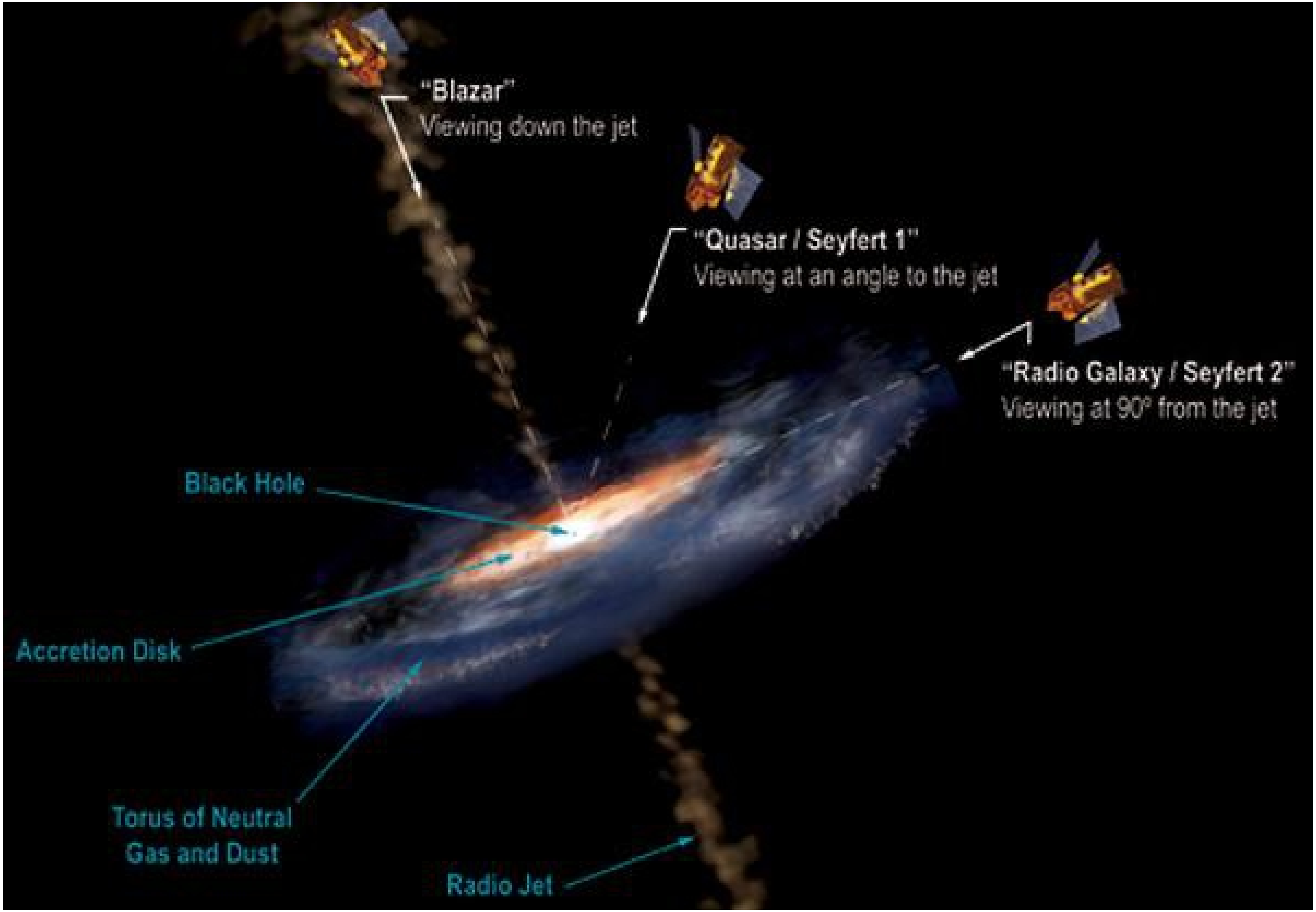


In Seyfert 2s, there is no point-like nucleus. The spectro show strong HIGH IONIZATION POTENTIAL emission lines

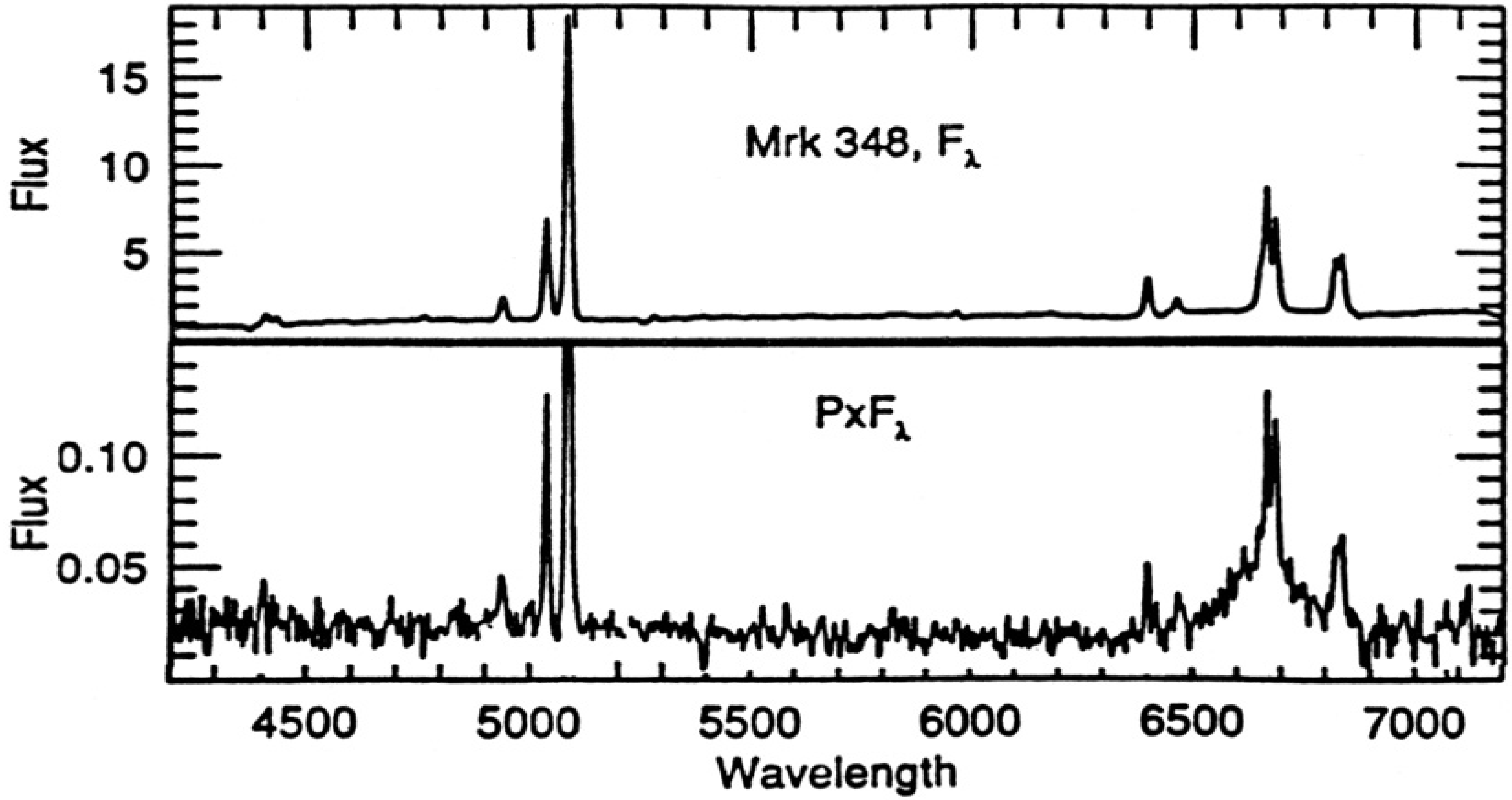


The Unified Model

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

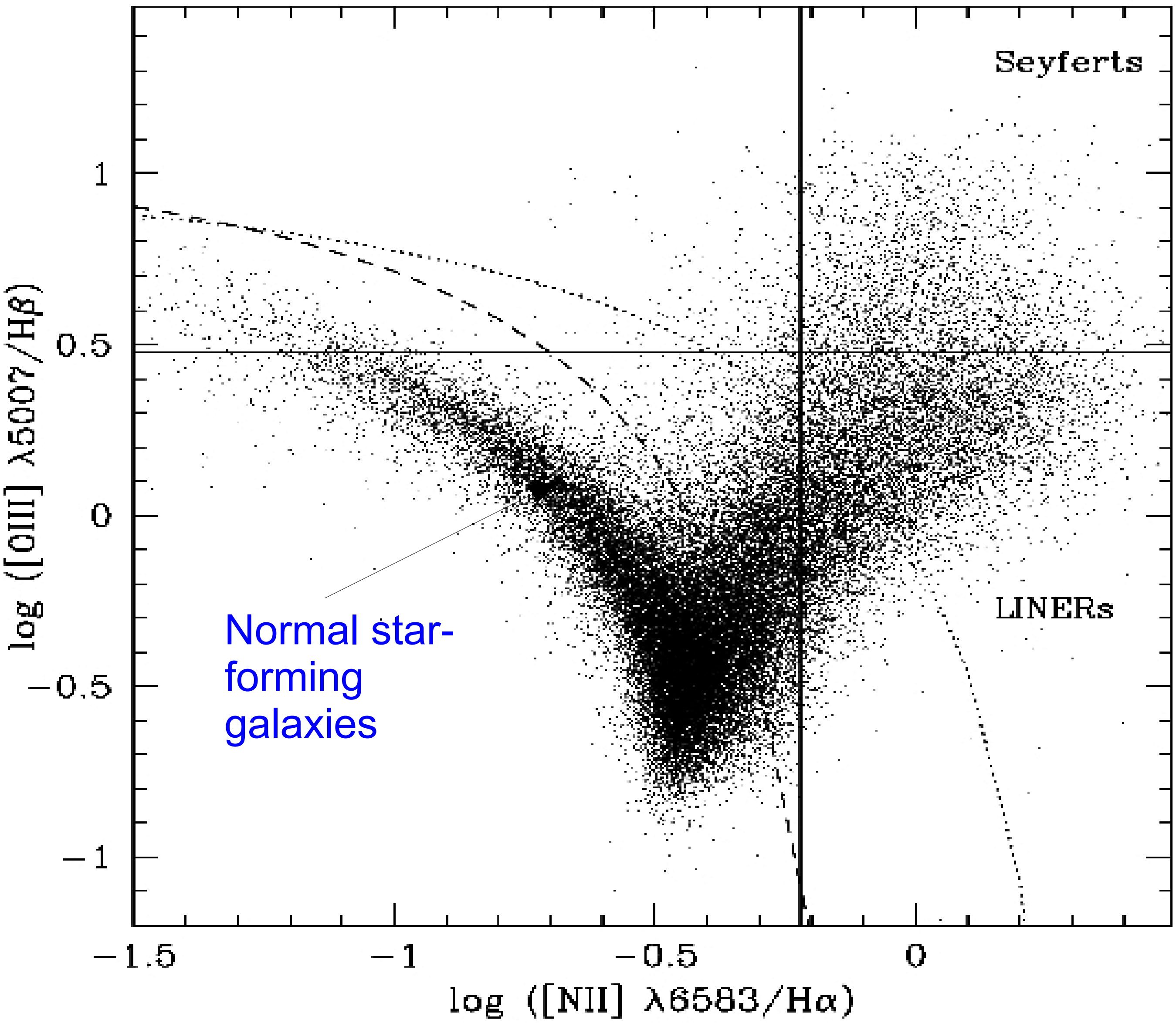
Evidence for the Unified Model



Type II AGN

Spectrum in polarized light showing broad lines

Emission-line diagnostic diagrams for identifying Type 2 AGN

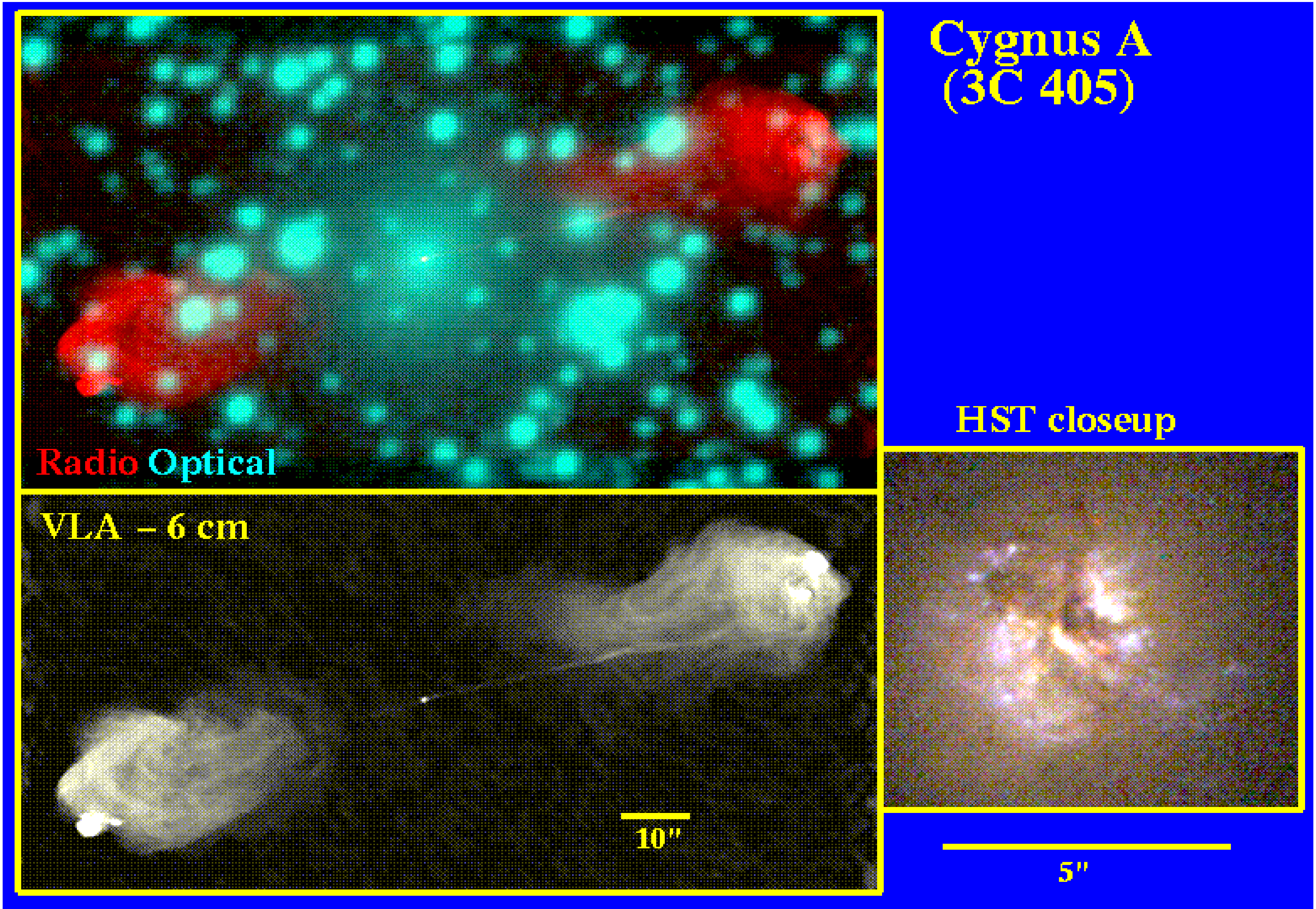


Some accretion discs produce jets of twin, highly collimated, and fast outflows that emerge in opposite directions from close to the disc. The direction of the jet ejection is determined either by the angular momentum axis of the accretion disc or the spin axis of the black hole.

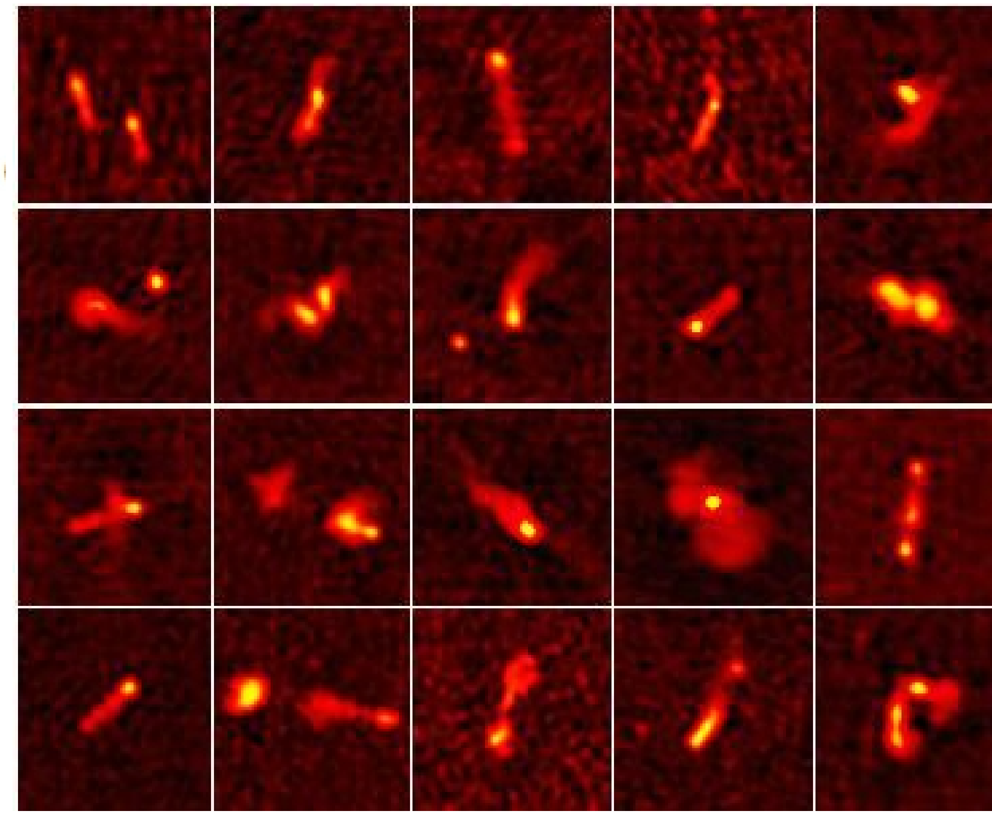
Rotating black hole as energy source:

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)

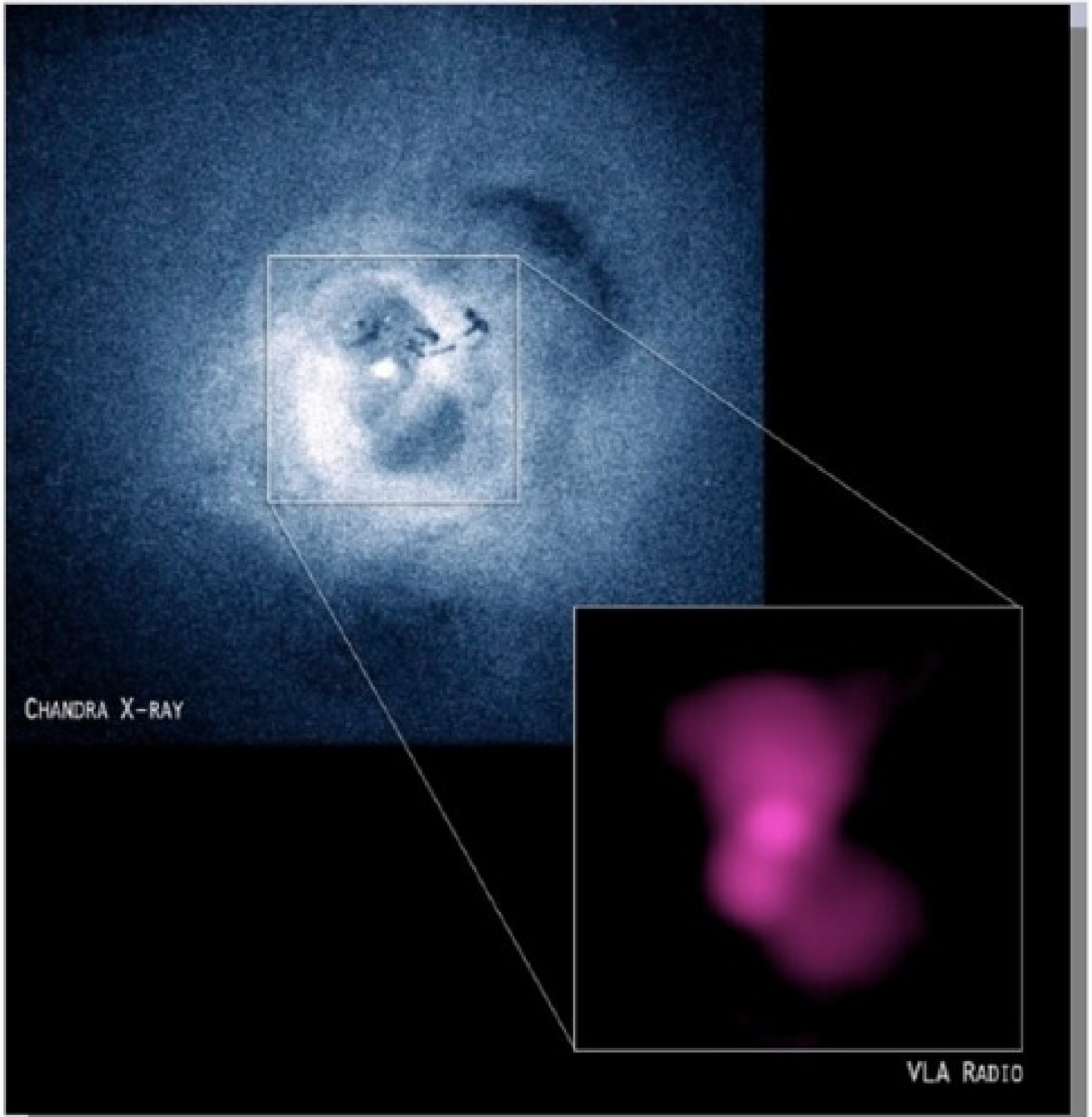
Cygnus A - the prototype high-powered radio galaxy



Low-powered radio galaxies

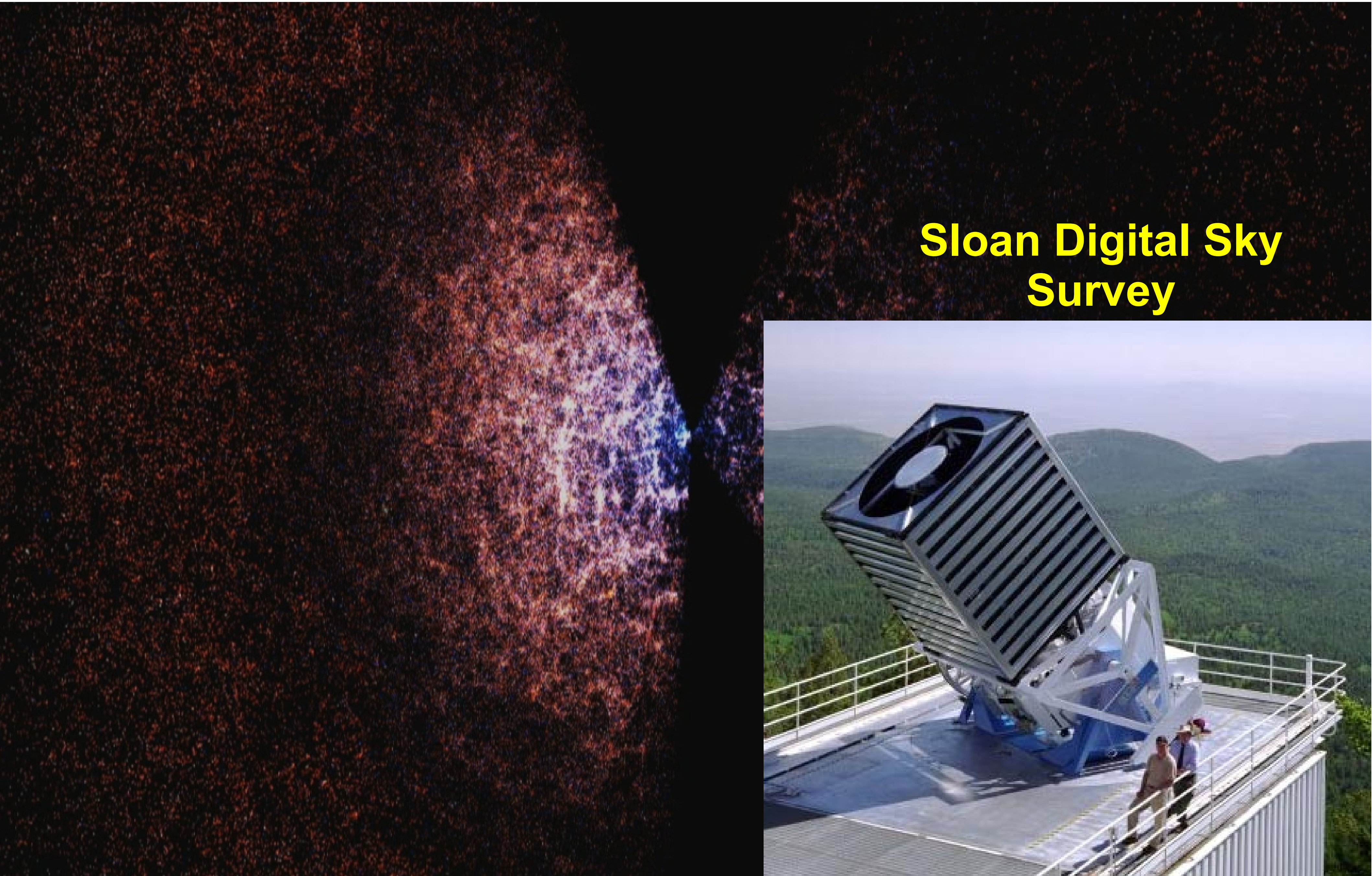


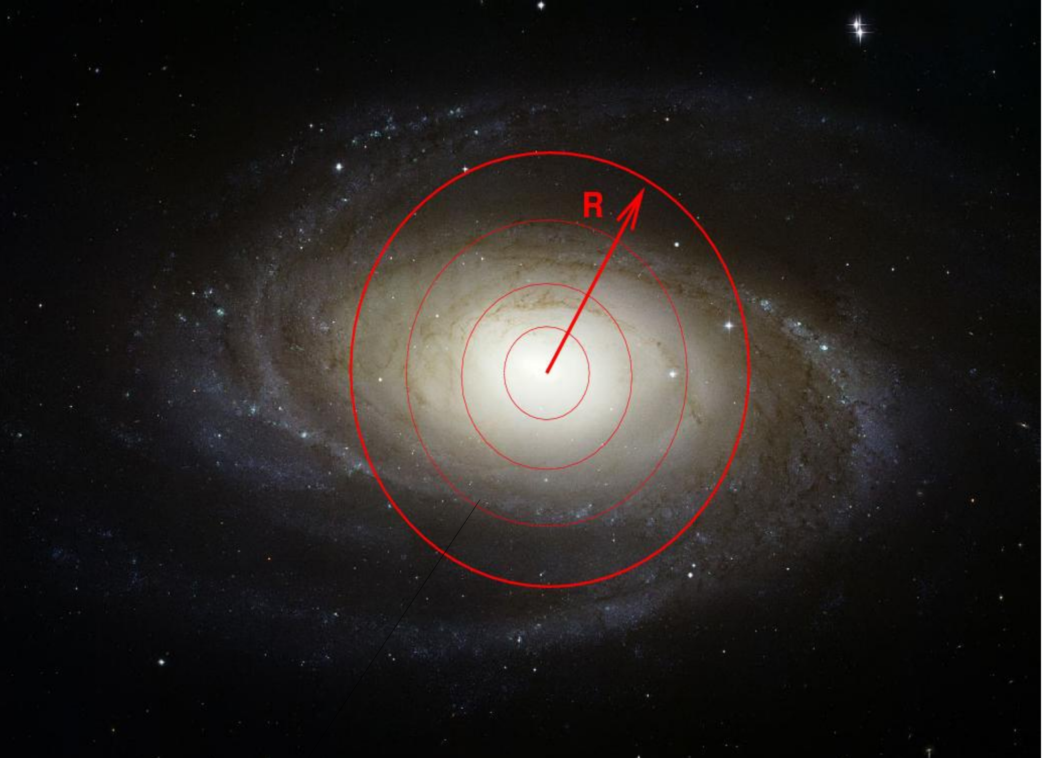
Clear evidence that radio-loud AGN influence their gaseous environment



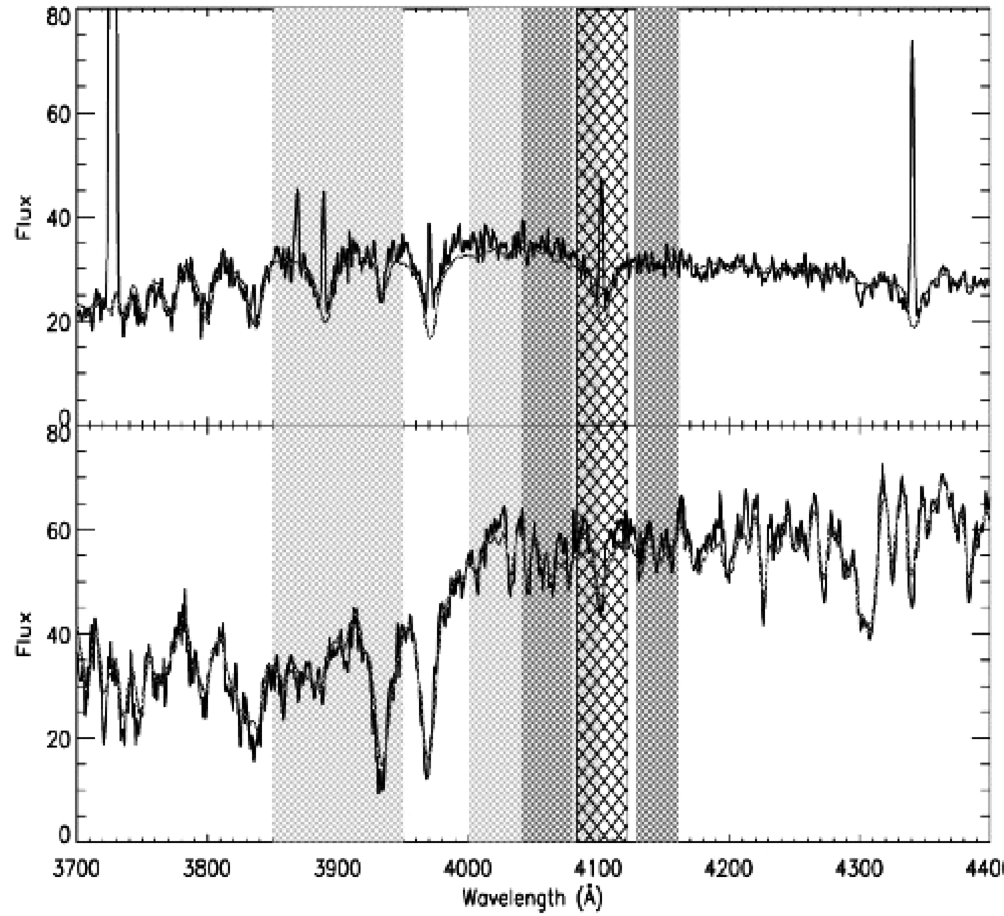
Feedback of radio-loud AGN into the surrounding IGM (seen through X-ray here).

The link between black hole growth and galaxy formation: clues from large spectroscopic surveys





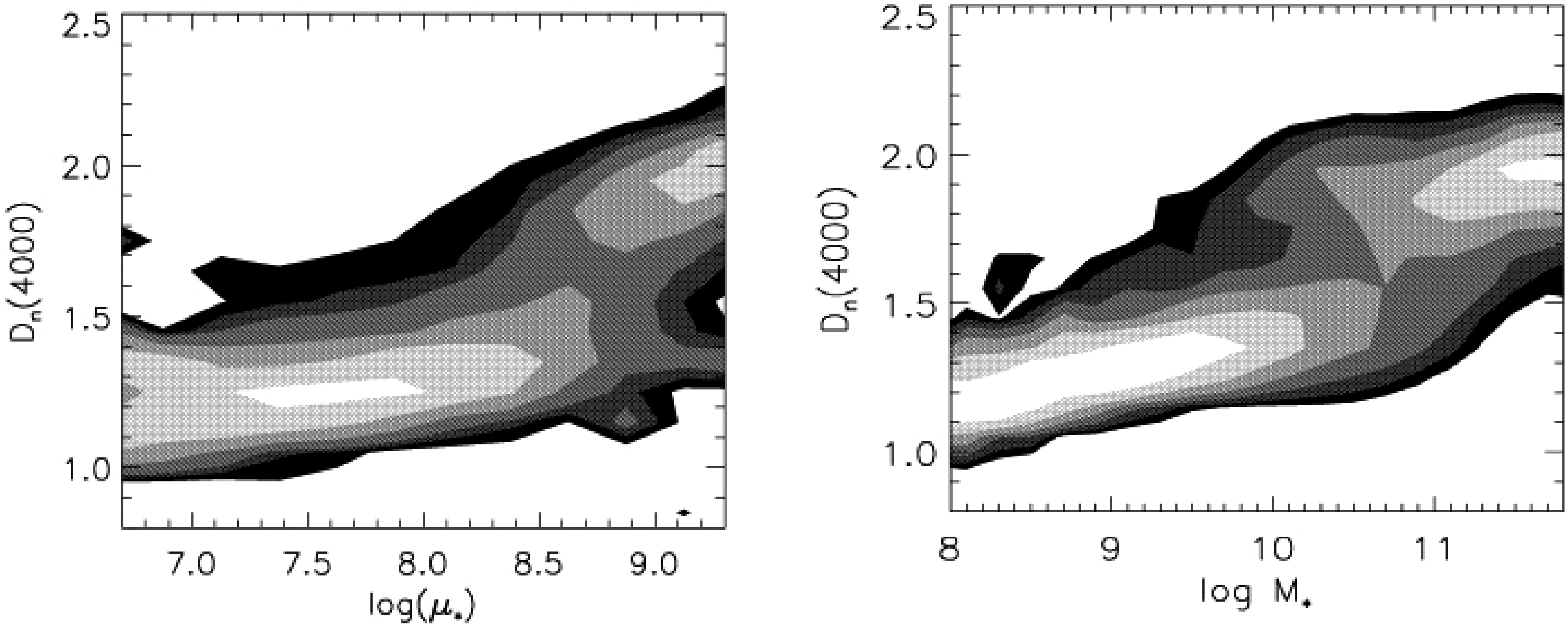
R50—radius enclosing half the light



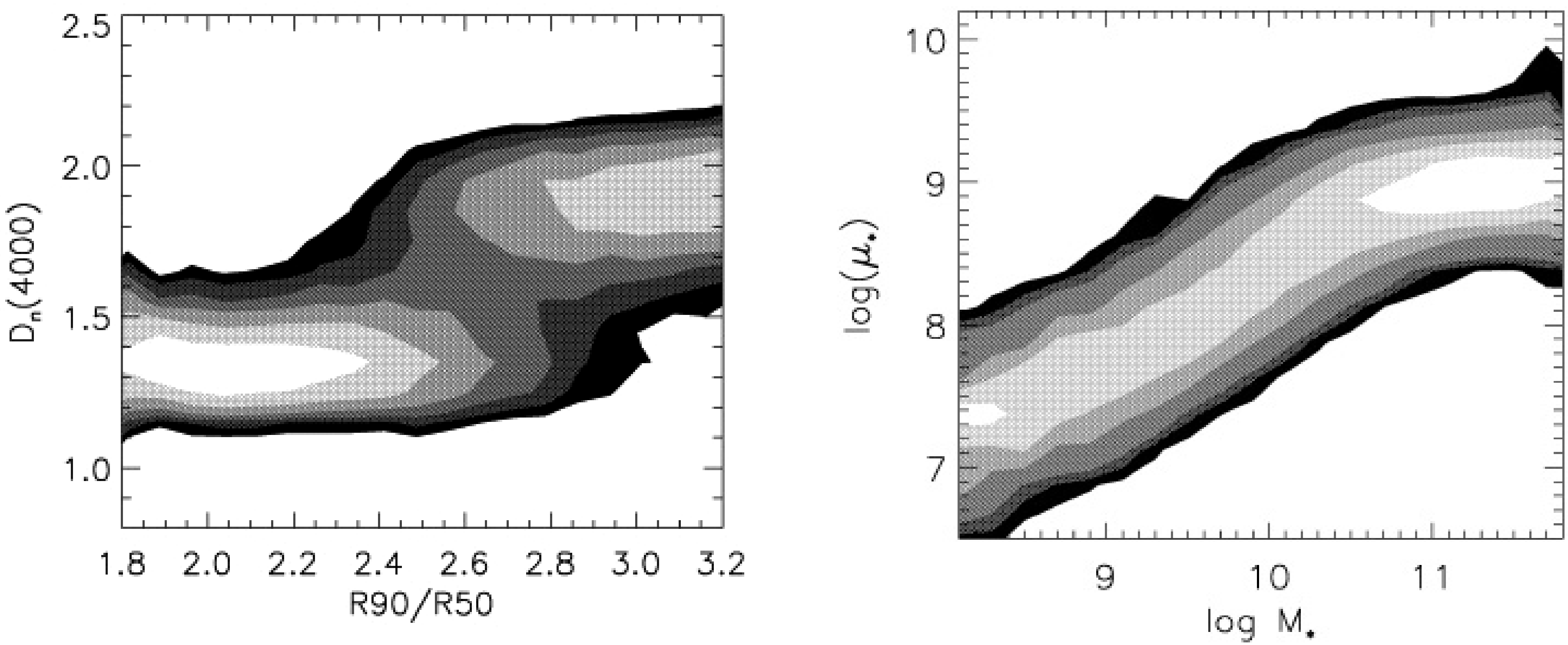
Concentration index (C) = R90/R50

Stellar surface mass density ($\mu^* = 0.5\ M_*/R50^2$)

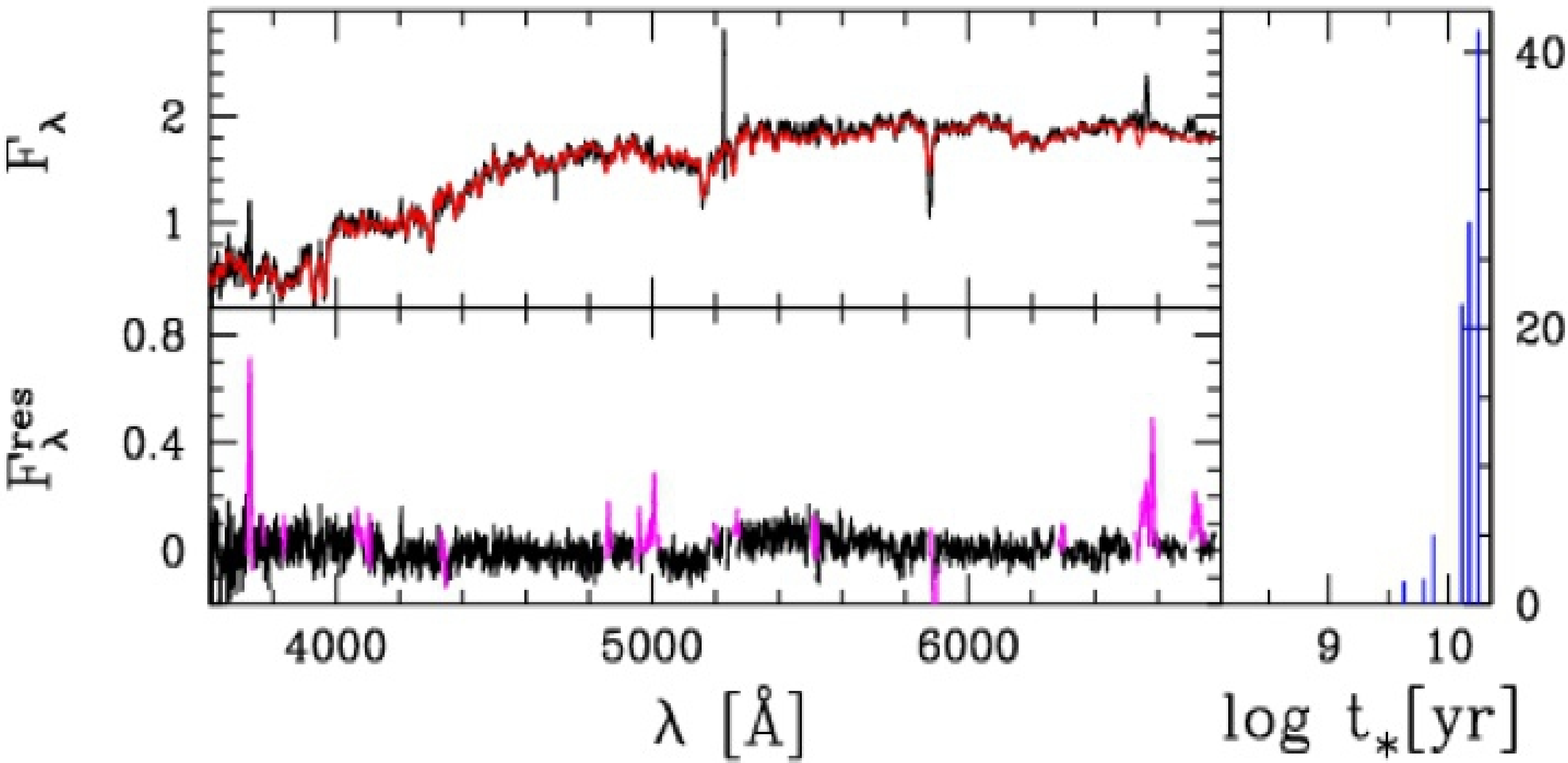
Stellar age parametrized by the 4000 Ā break: ratio of flux bluewards and redwards of the break in the spectrum



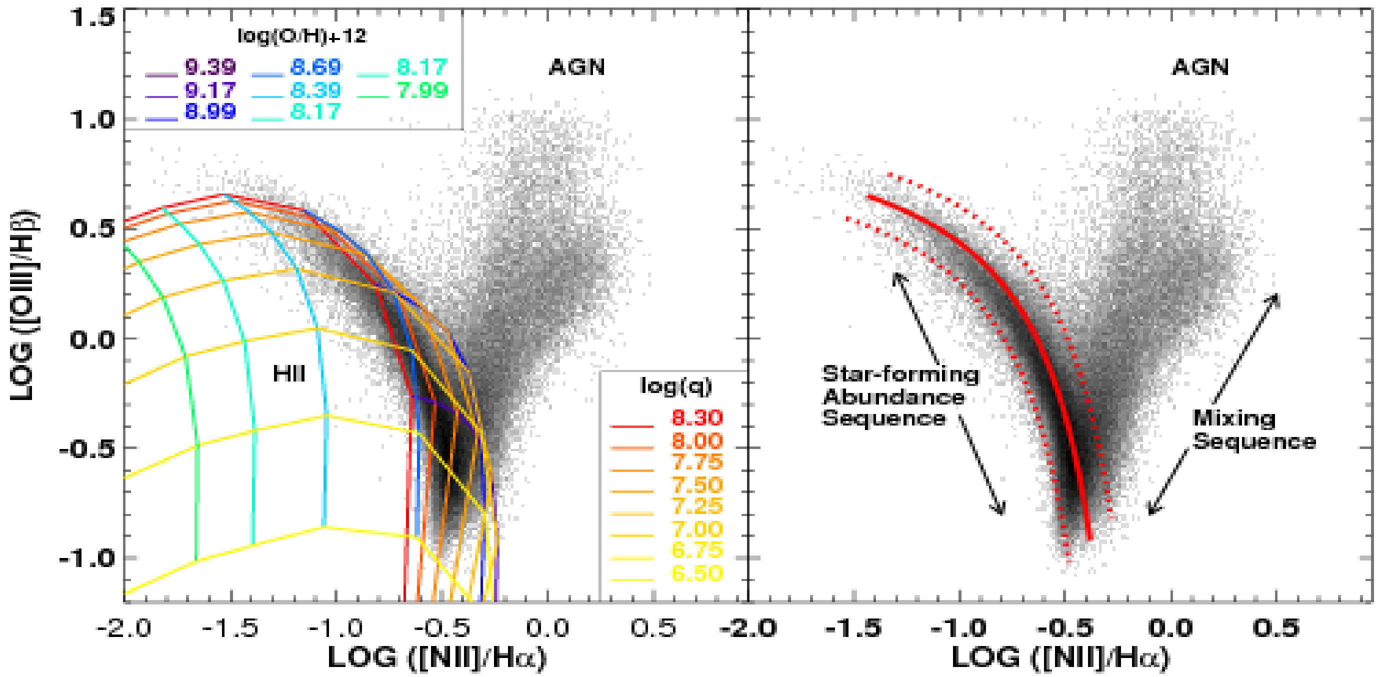
Scaling relations for normal galaxies

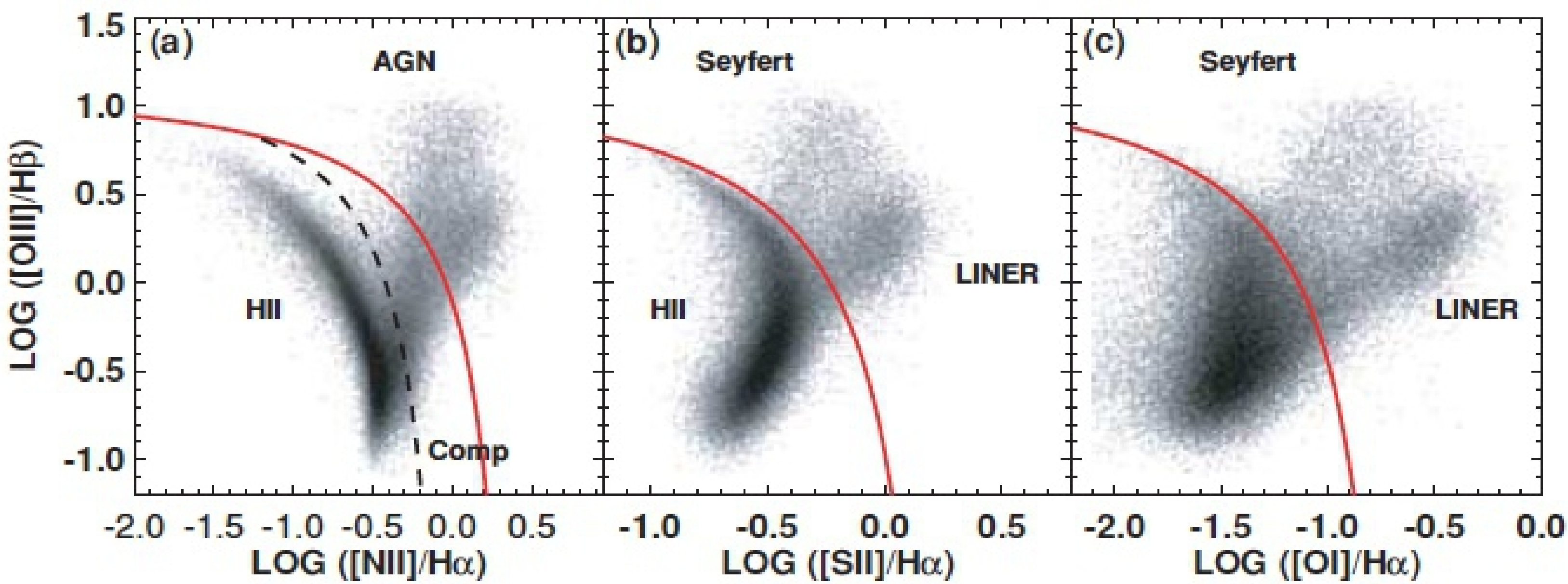


Fit the stellar absorption line spectrum with a superposition of stellar templates of different ages/metallicities, subtract, then measure emission lines from the residual spectrum.

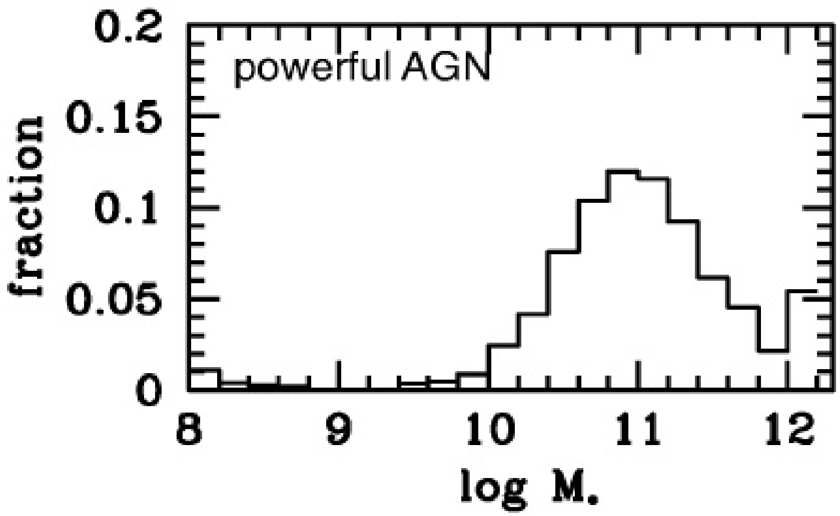


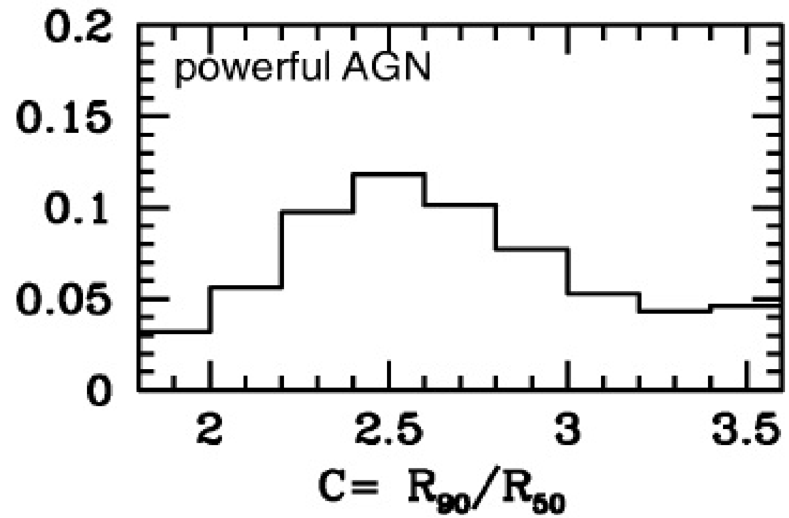
Emission line diagnostic diagrams for identification of AGN through emission-line ratios





Fraction of AGN as a function of Mass/Concentration





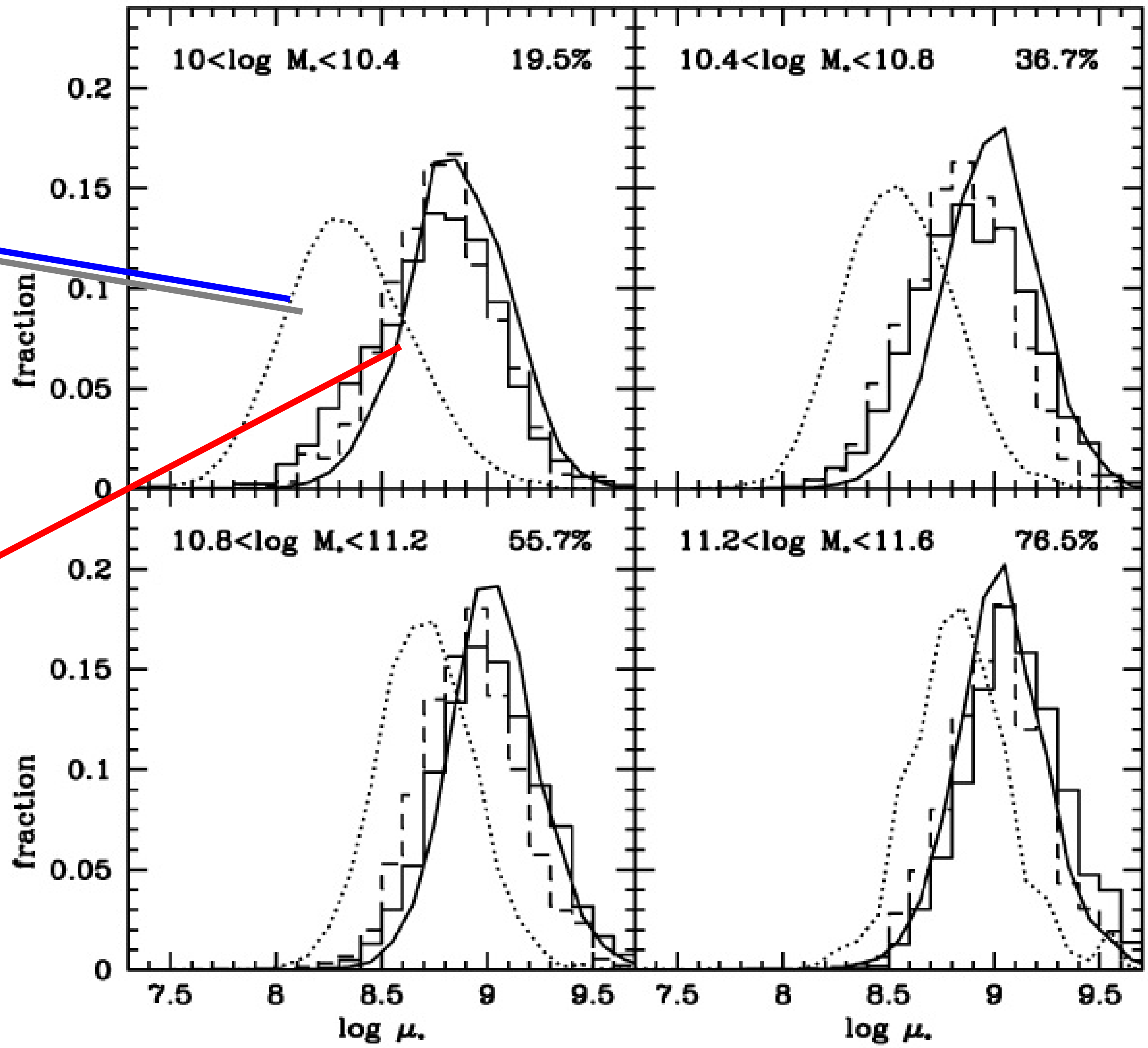
AGN are found only in massive galaxies with significant bulge component

No AGN and no evidence for black holes in galaxies like these.

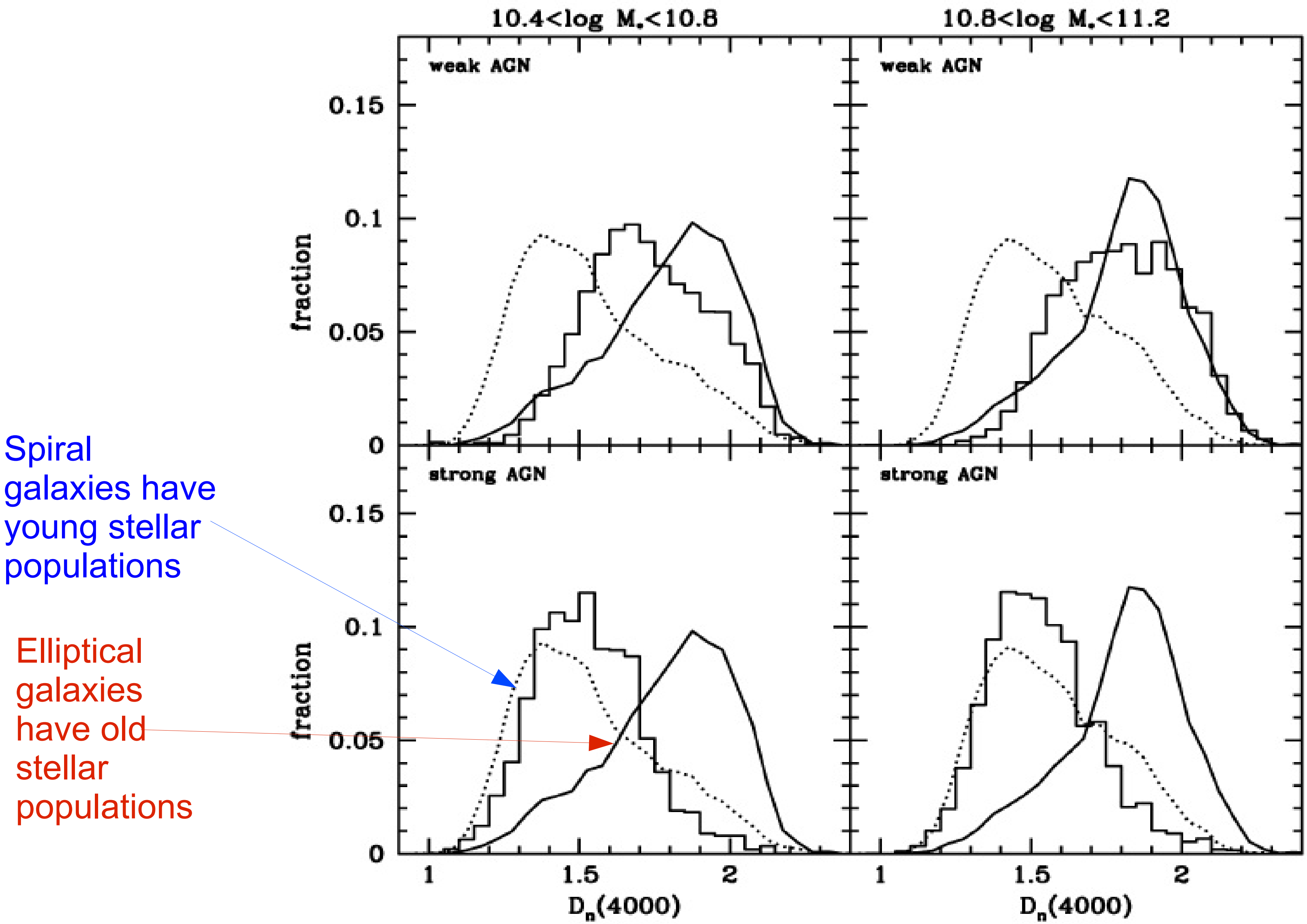
The stellar structure of the host galaxies of AGN is closest to early-type (elliptical)

Spiral galaxies have low densities

Elliptical galaxies have high densities

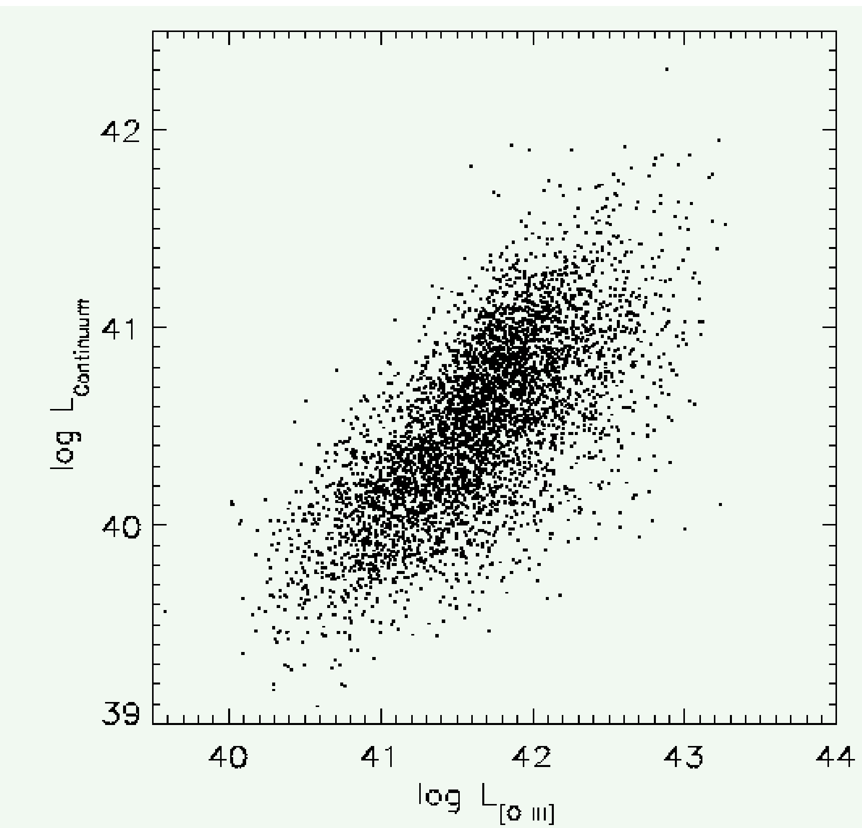


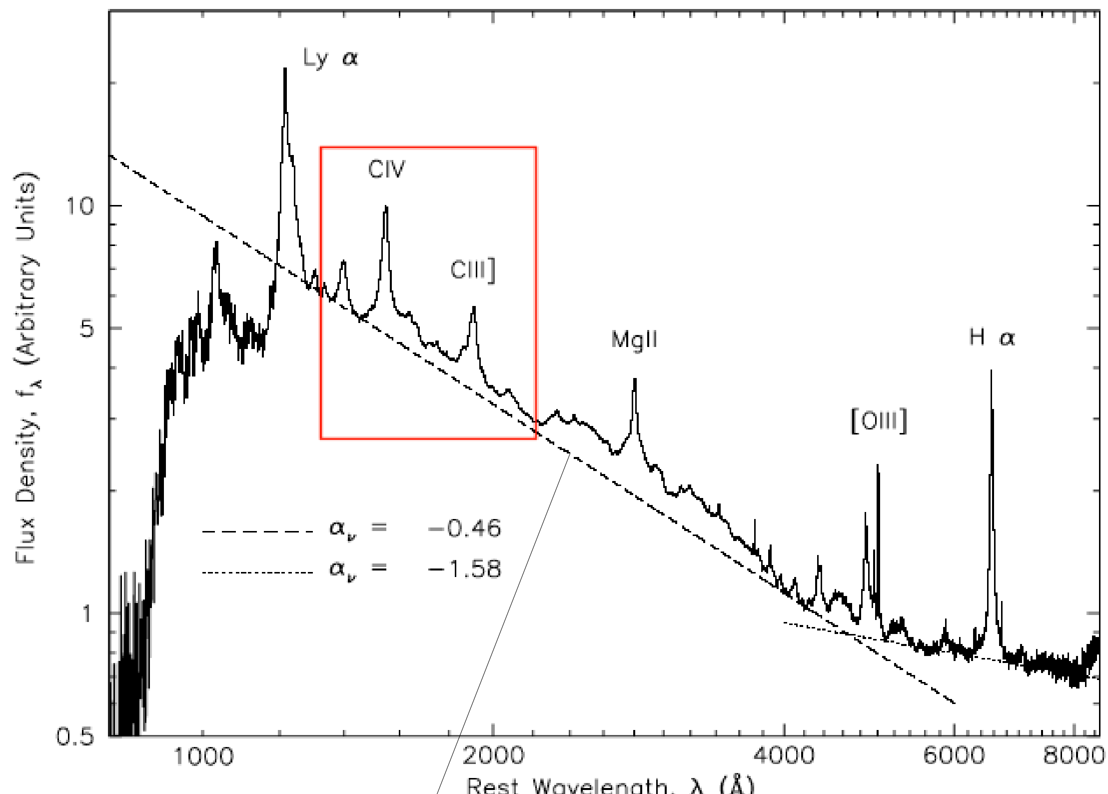
The stellar populations of the host galaxies of strong AGN are closest to late-type (spiral)



Accretion

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





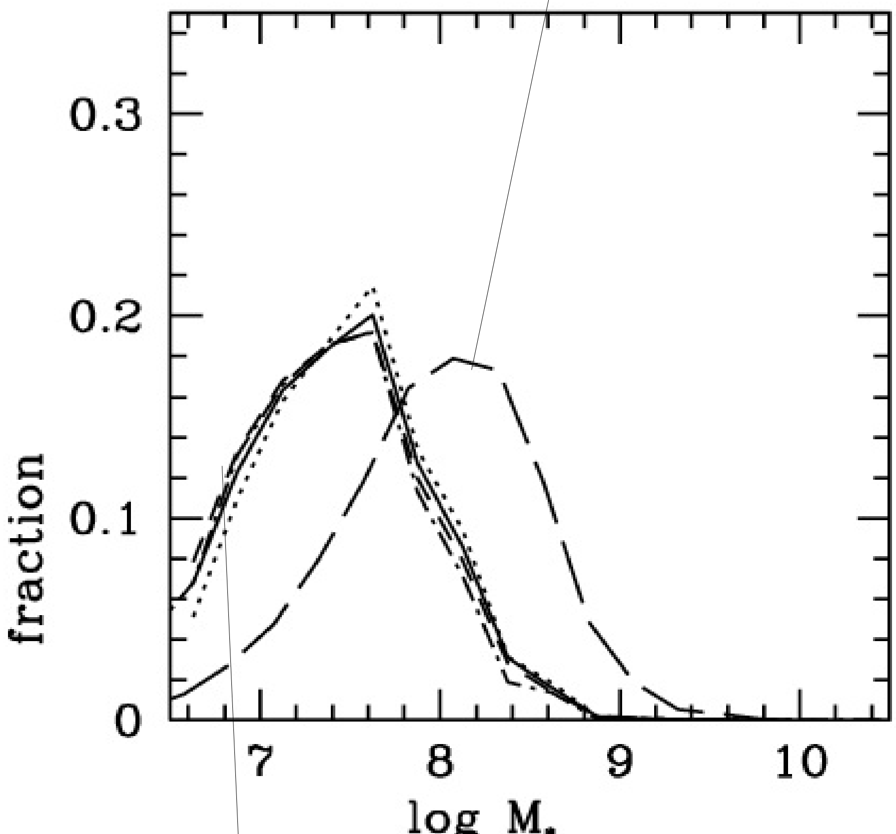
Correlation of [OIII] luminosity with bolomertic continuum luminosity for Type 1 AGN

Continuum is from accretion disk

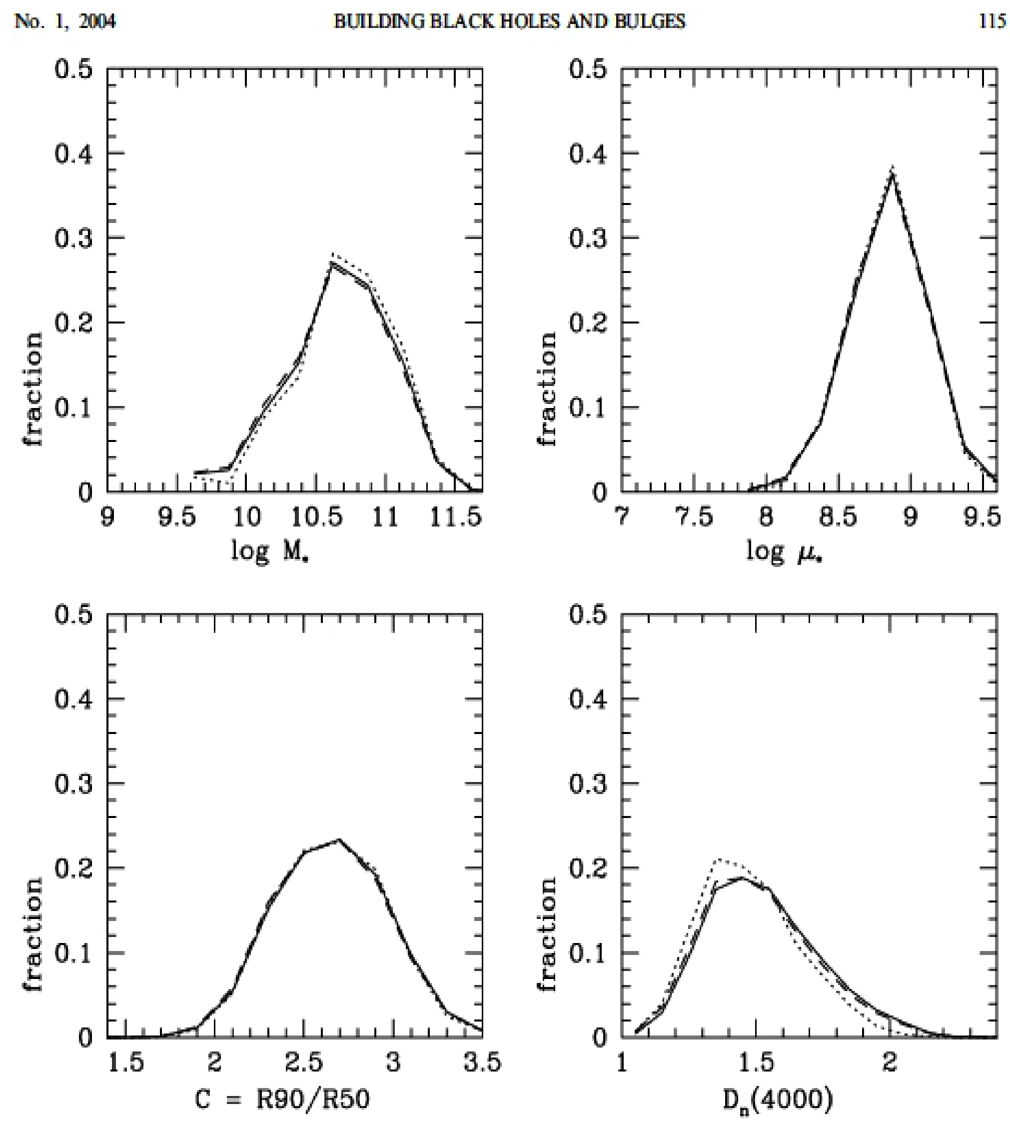
Which black holes and galaxies are currently accreting?

Distribution of Σ L[OIII] as a function of galaxy properties

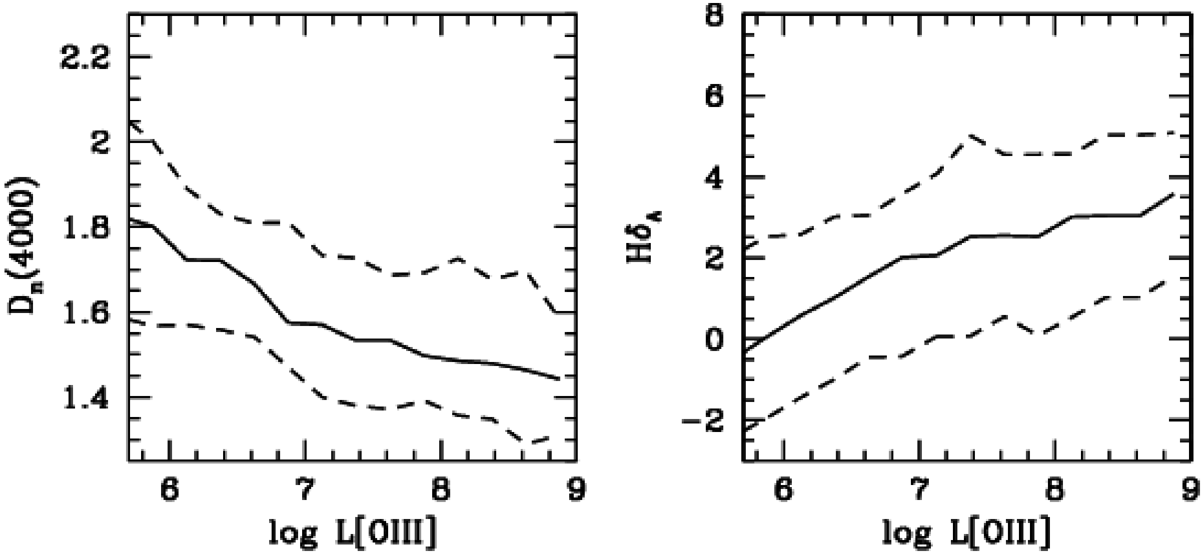
Distribution of $\Sigma M_{\text{black hole}}$



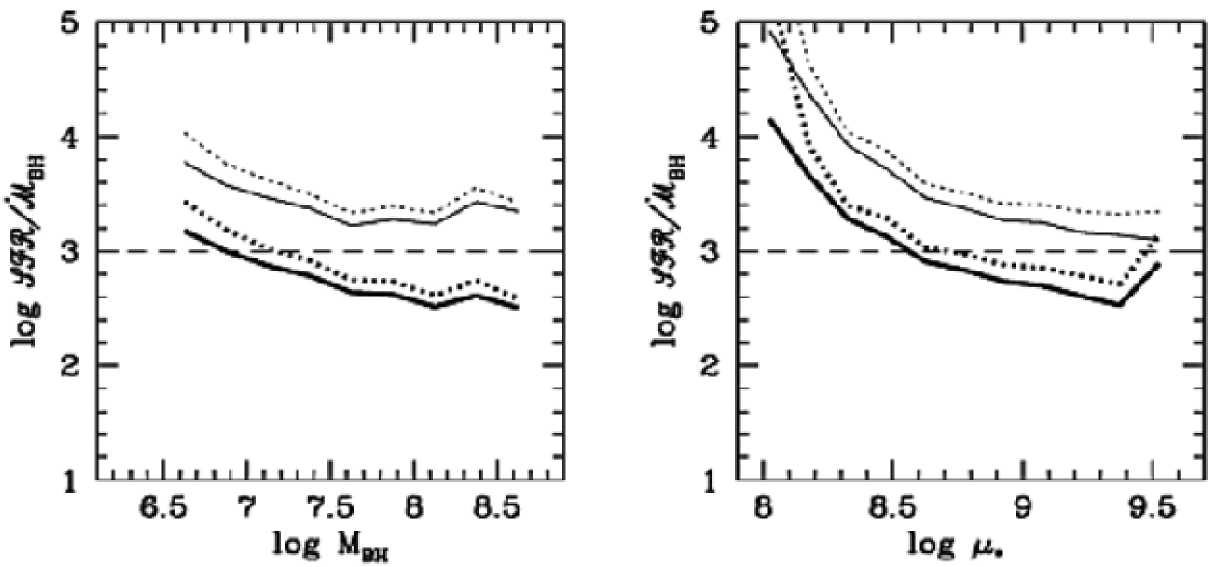
Distribution of Σ L[OIII] as a function of $M_{\text{black hole}}$



The Starburst-AGN Connection

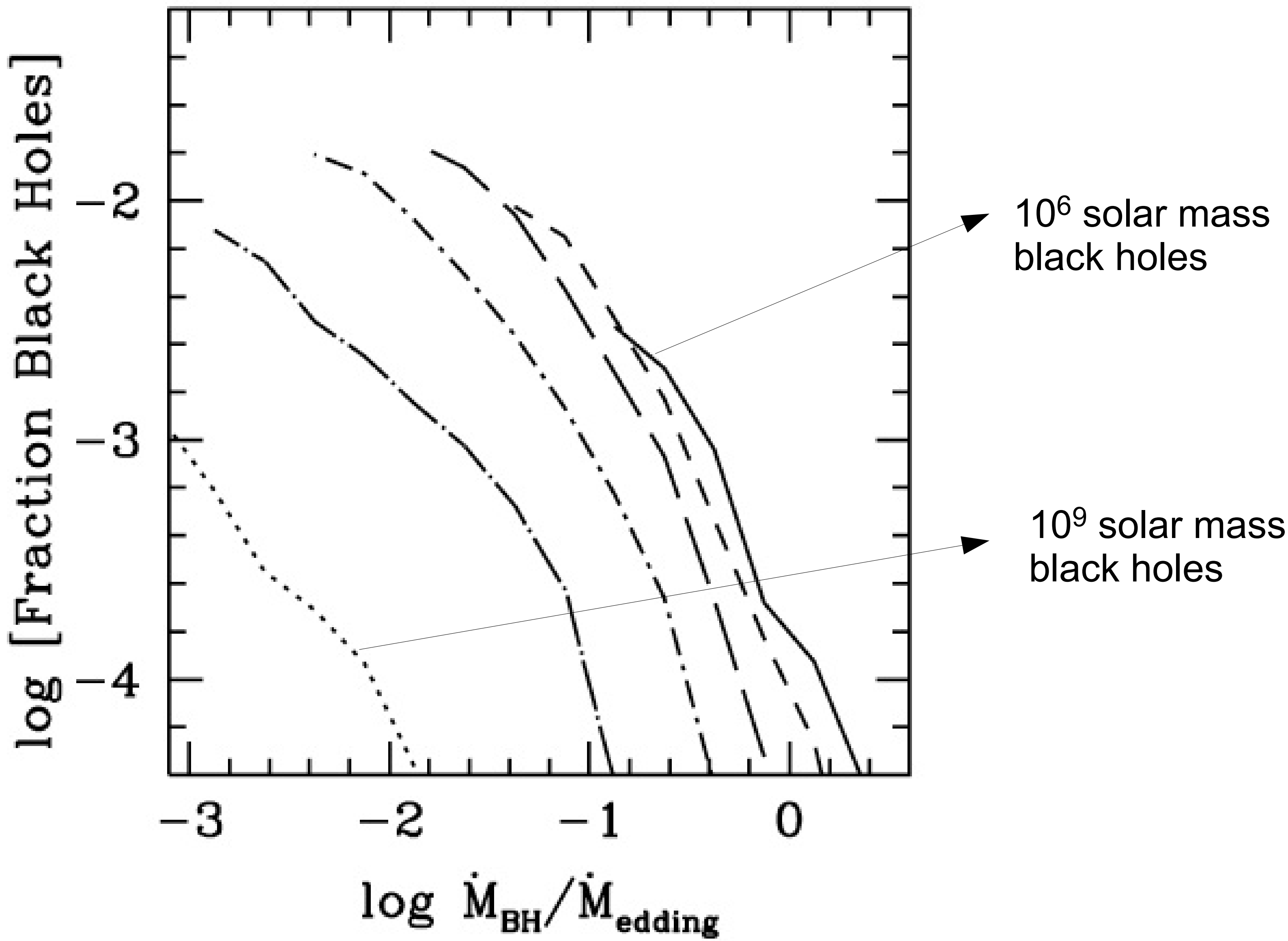


More strongly accreting AGN have younger stellar populations

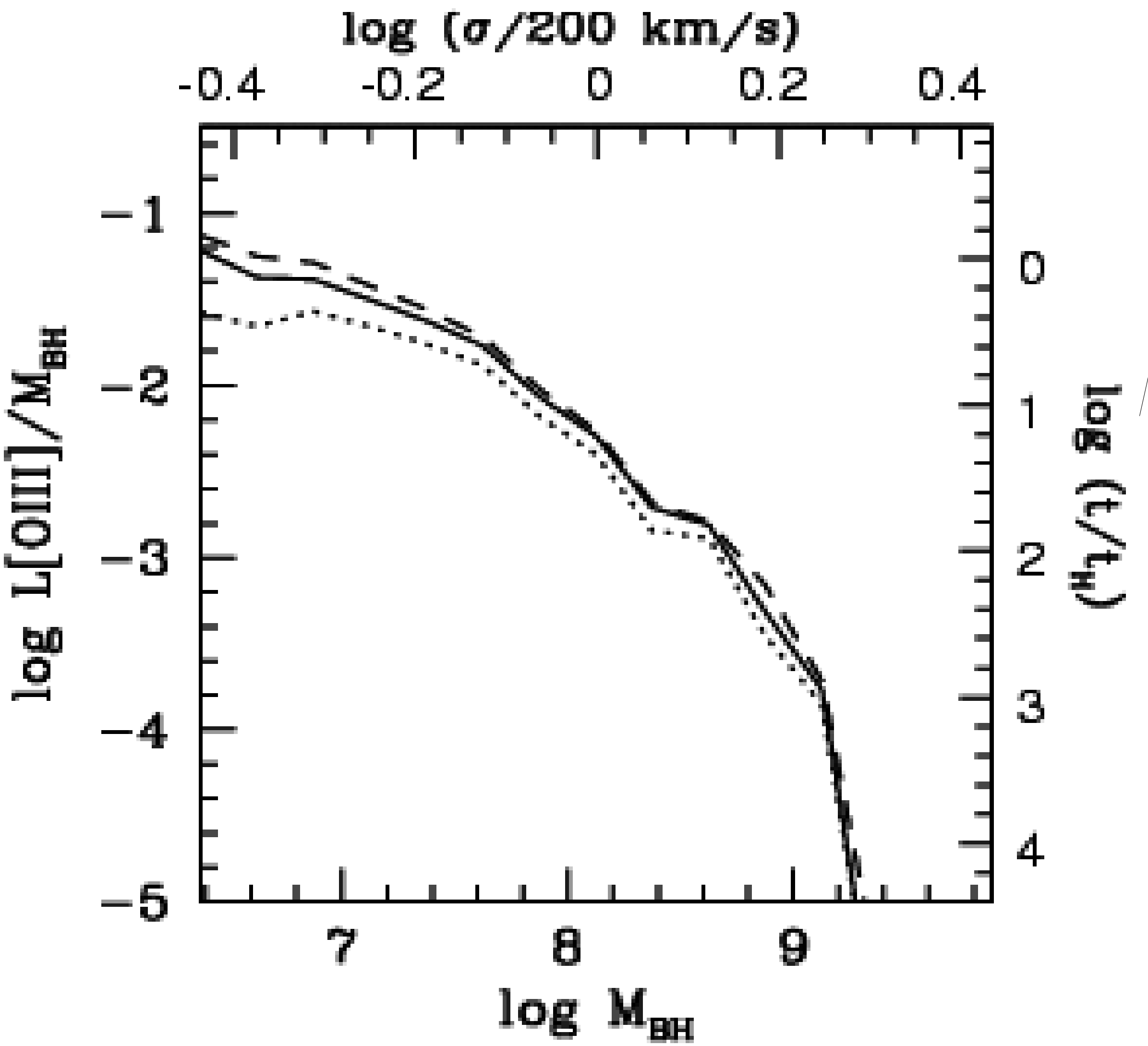


The average ratio between the star formation rate in the bulge and the accretion rate onto the black hole is 1000 – remarkably close to the ratio of bulge mass to black hole mass.

Distribution of accretion rates (in units of the Eddington accretion rate) for black holes of different mass

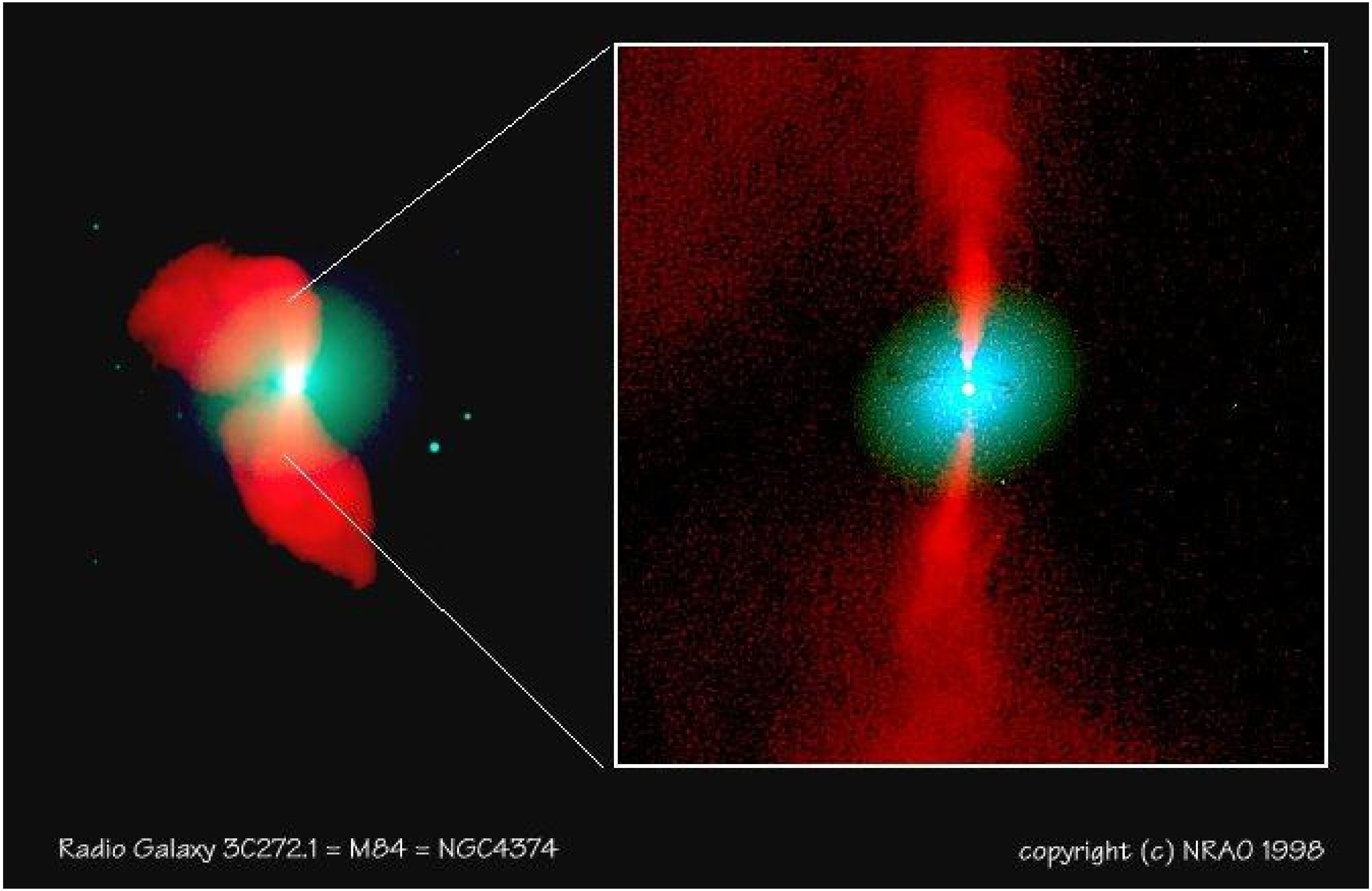


Most of the accretion today is occurring onto low mass black holes in galaxies like our own Milky Way ==> Massive black holes formed early on in the Universe and then stopped growing

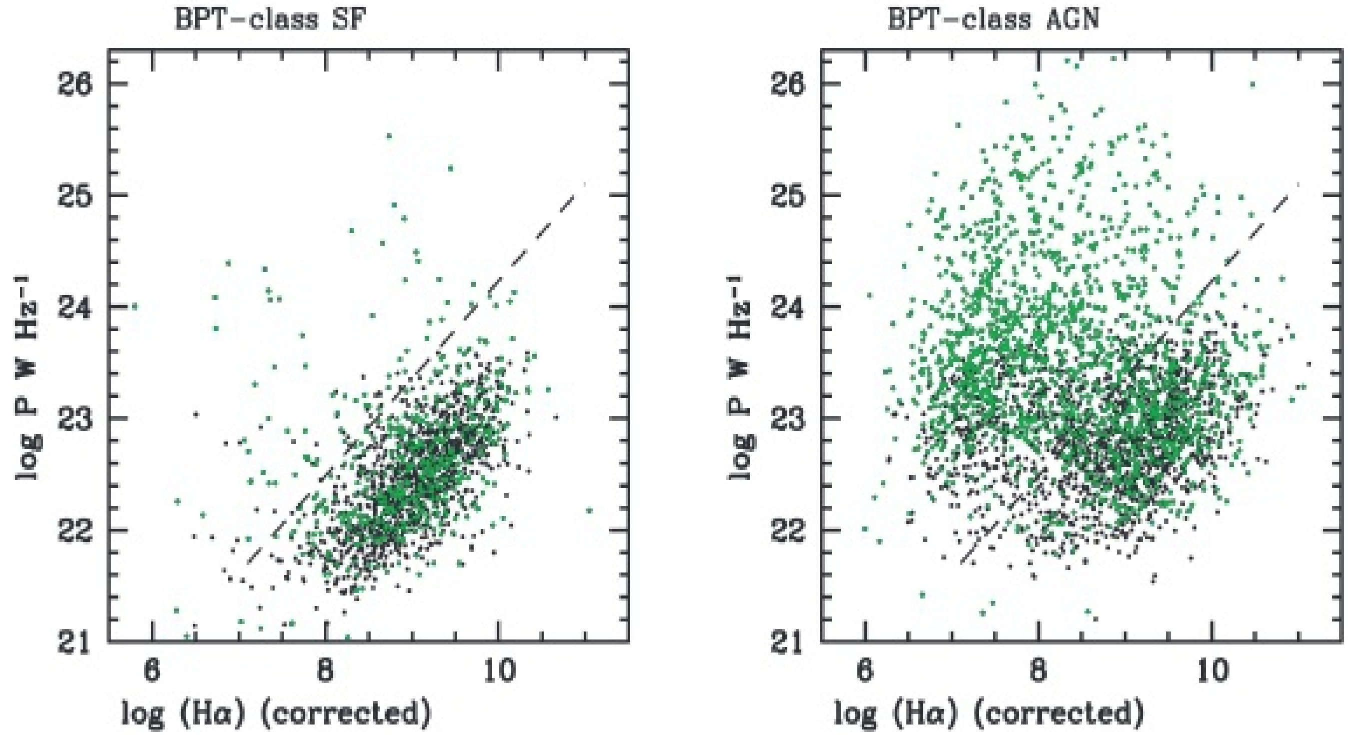


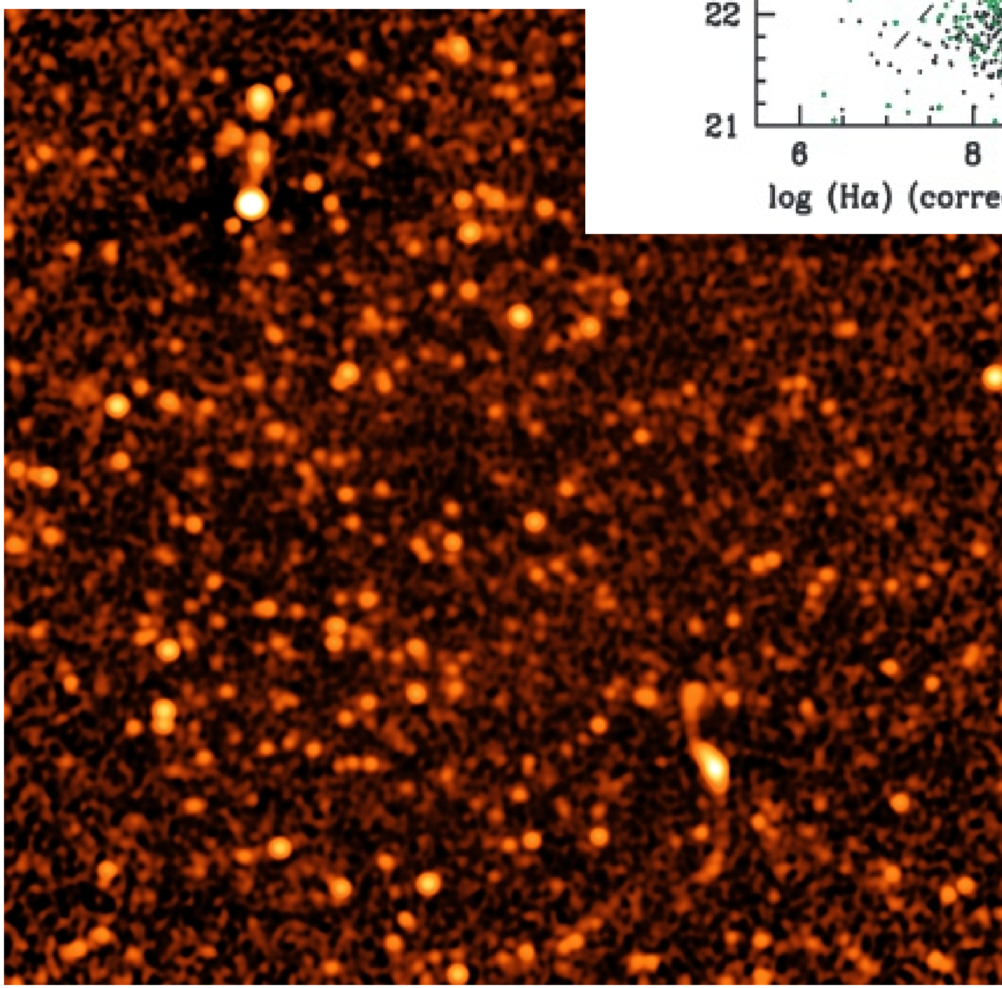
Growth time of black hole in units of the Hubble time

What about radio-loud AGN?



Deep wide-field radio surveys can be cross-correlated with SDSS optical surveys

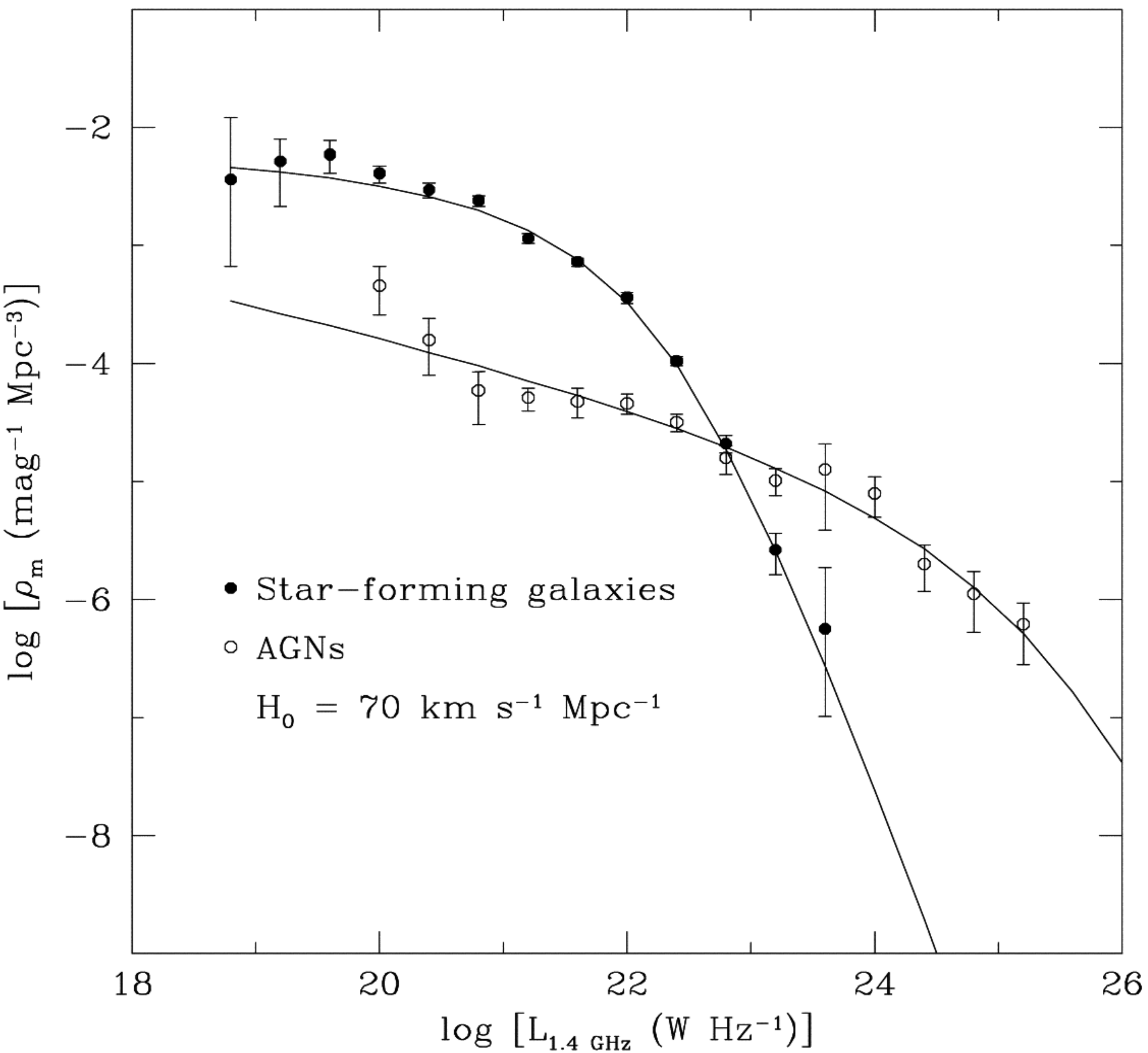


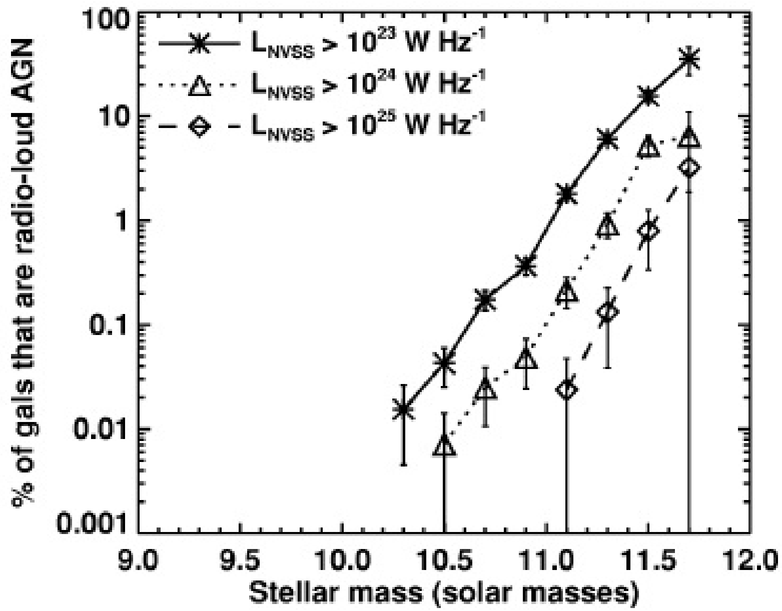


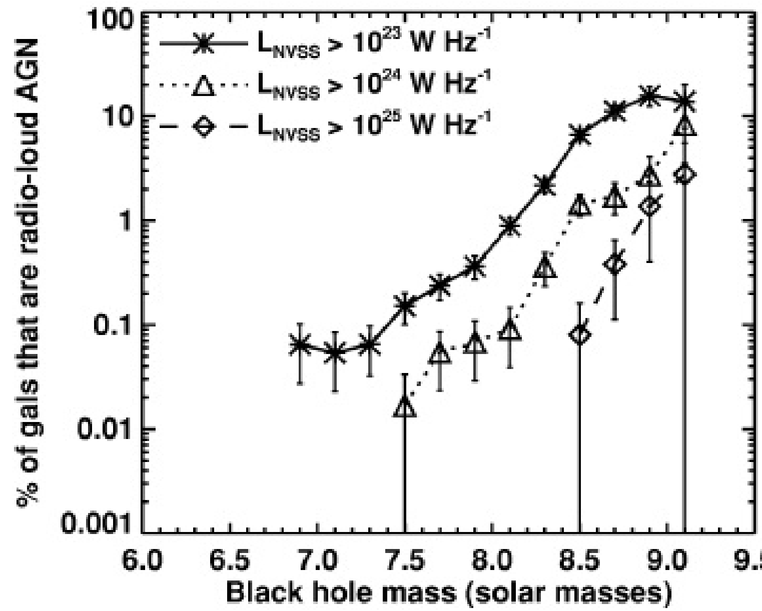
Radio synchrotron emission arises from electrons accelerated in supernovae shocks: correlation between radio emission and star formation rate as measured by Halpha emission

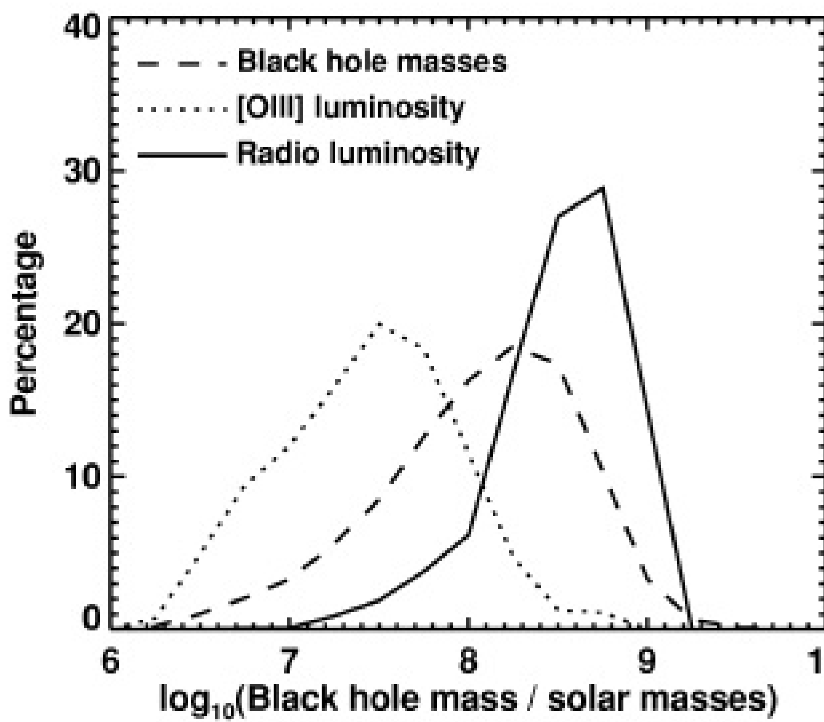
Radio AGN can be identified by their excess radio luminosity with respect to this correlation

Radio luminosity function for star-forming galaxies and radio AGN







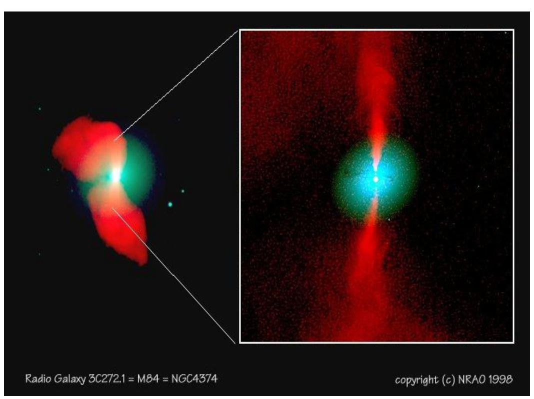


Radio AGN are found most frequently in the very most massive galaxies: **more massive than the hosts of optical AGN**

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

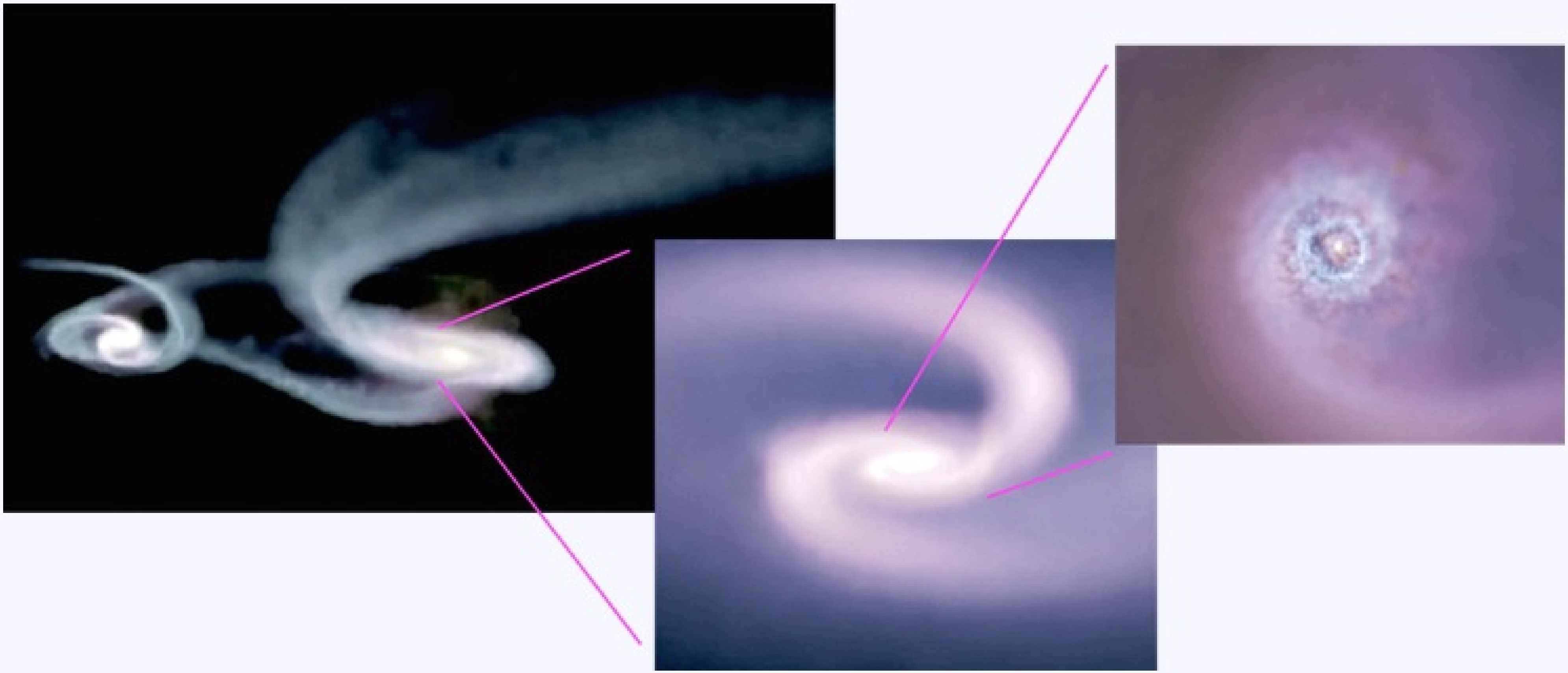


Present-day Optical Radio-AGN activity is linked to:

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

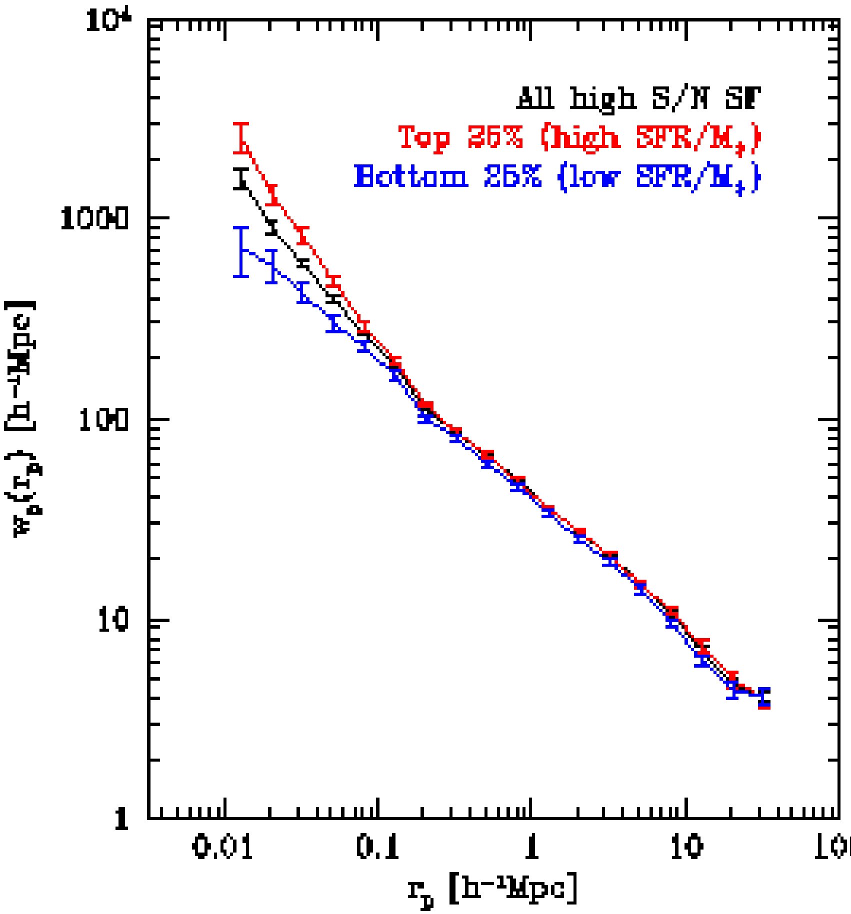
HOW ARE AGN FUELLED?

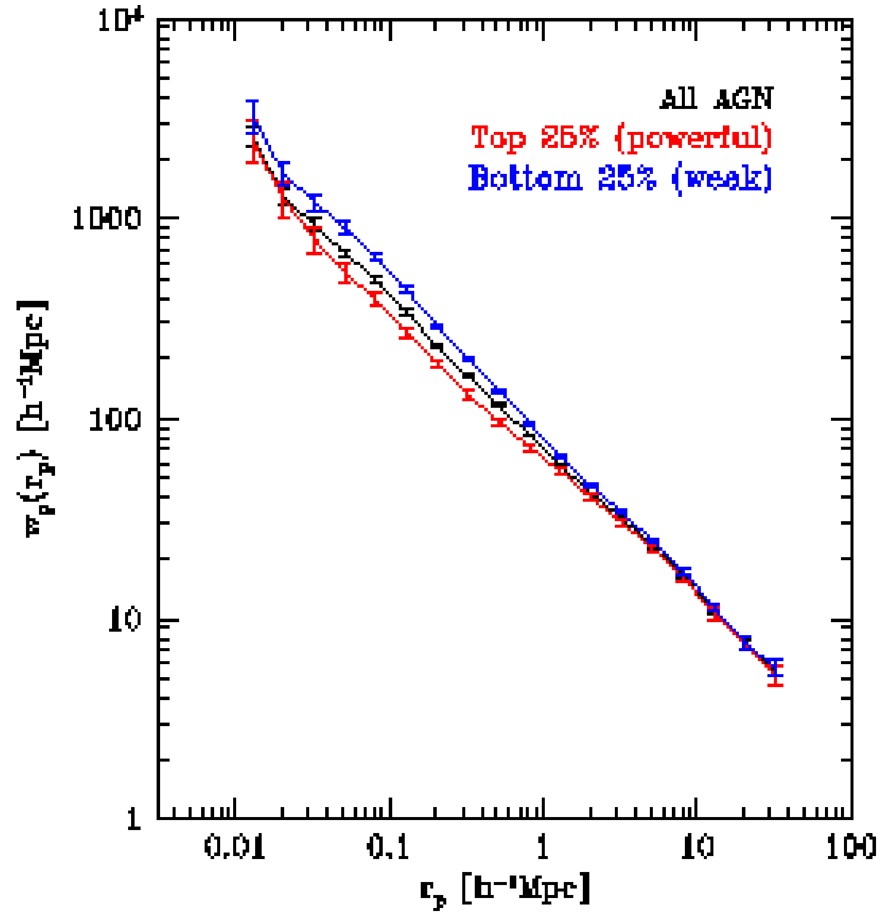
AGN Fueling: Movies



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

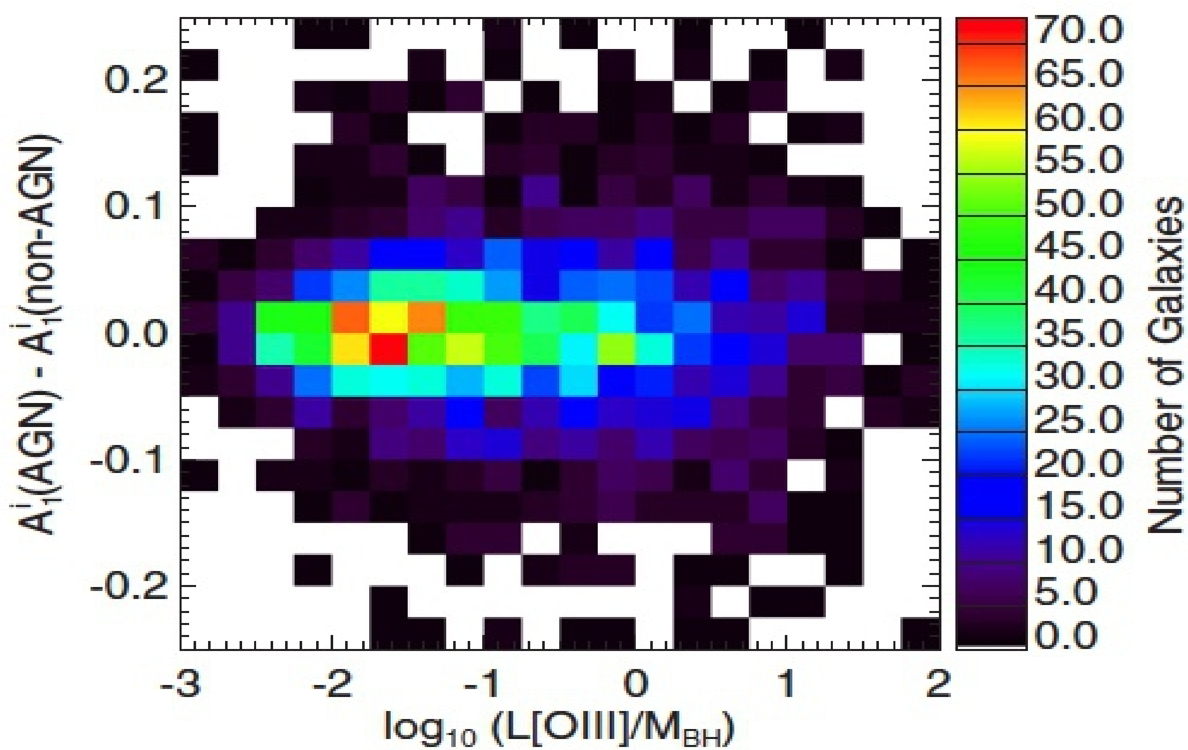
The cross-correlation function star-forming galaxies compared to AGN.





Lopsided galaxy

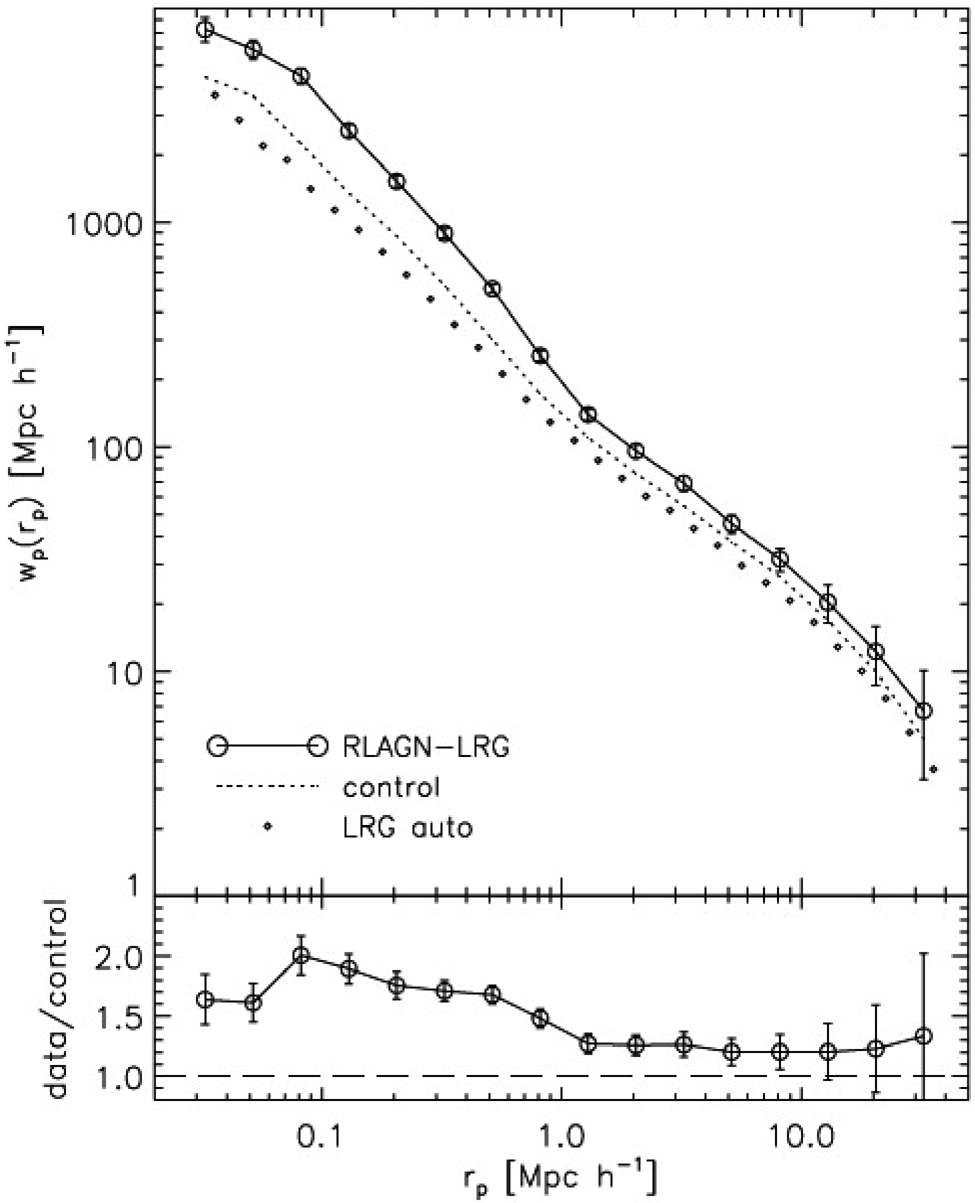
Symmetric galaxy

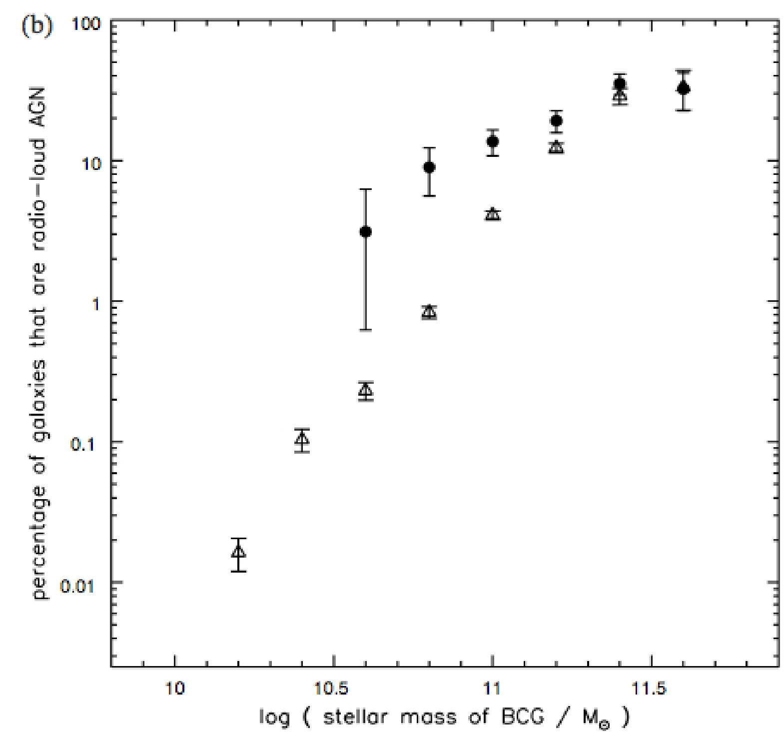


No evidence for excess of lopsided AGN hosts compared to matched control samples of non-AGN

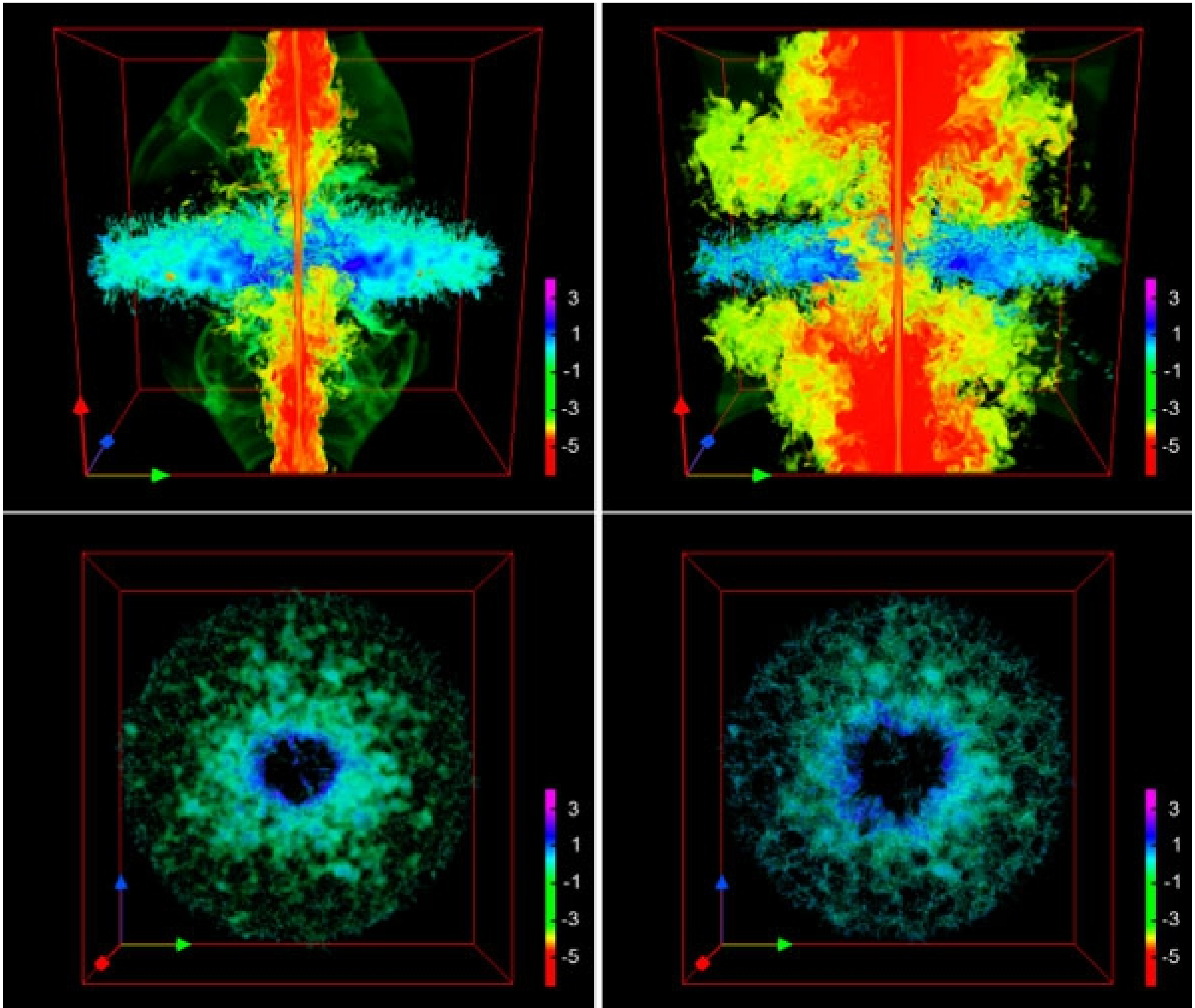
Processes very close to the black hole likely to be the key to understanding black hole fuelling. New technology needed.

Radio-loud AGN are more strongly clustered than control samples – frequently found in the BCG (brightest cluster galaxy)

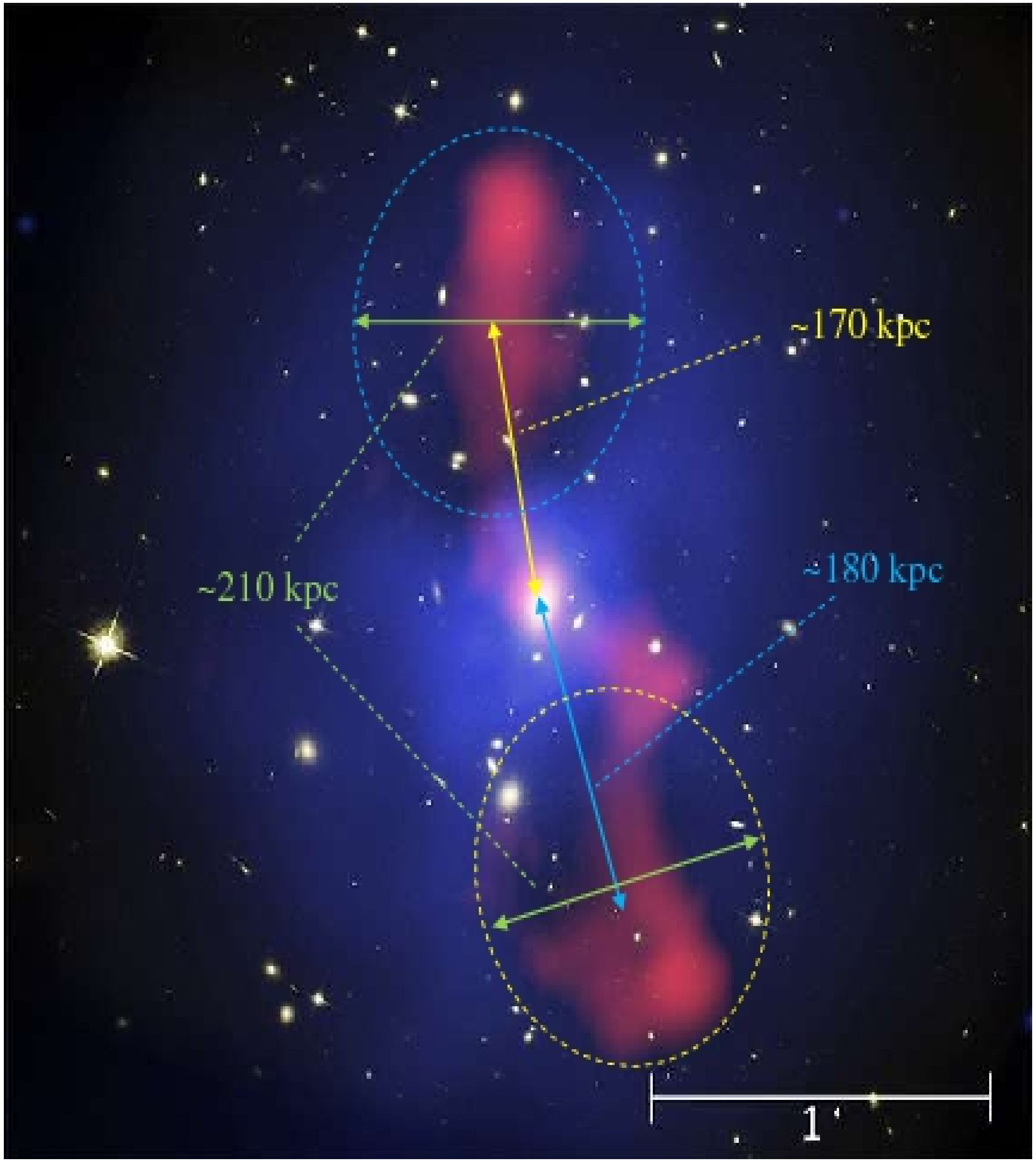




AGN “Feedback” : Impact on Galaxy Formation



More examples of cavities in X-ray emission filled in with radio synchrotron emitting plasma



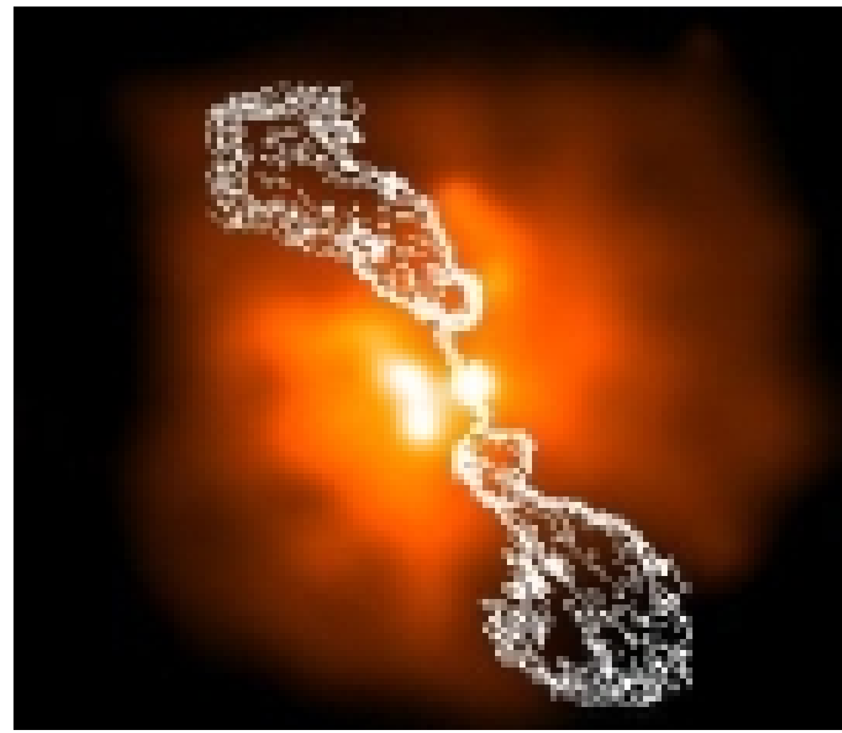
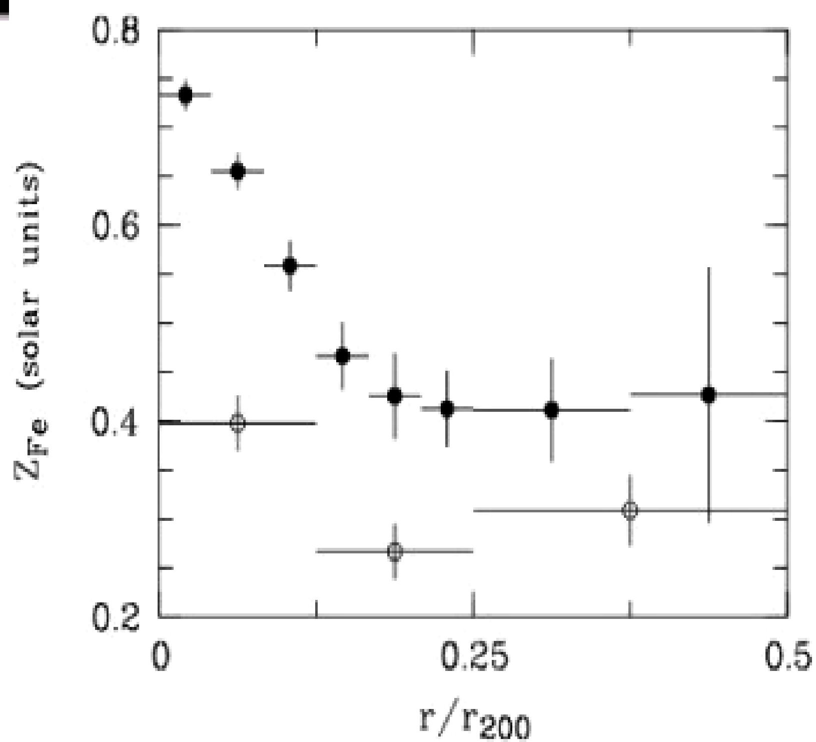
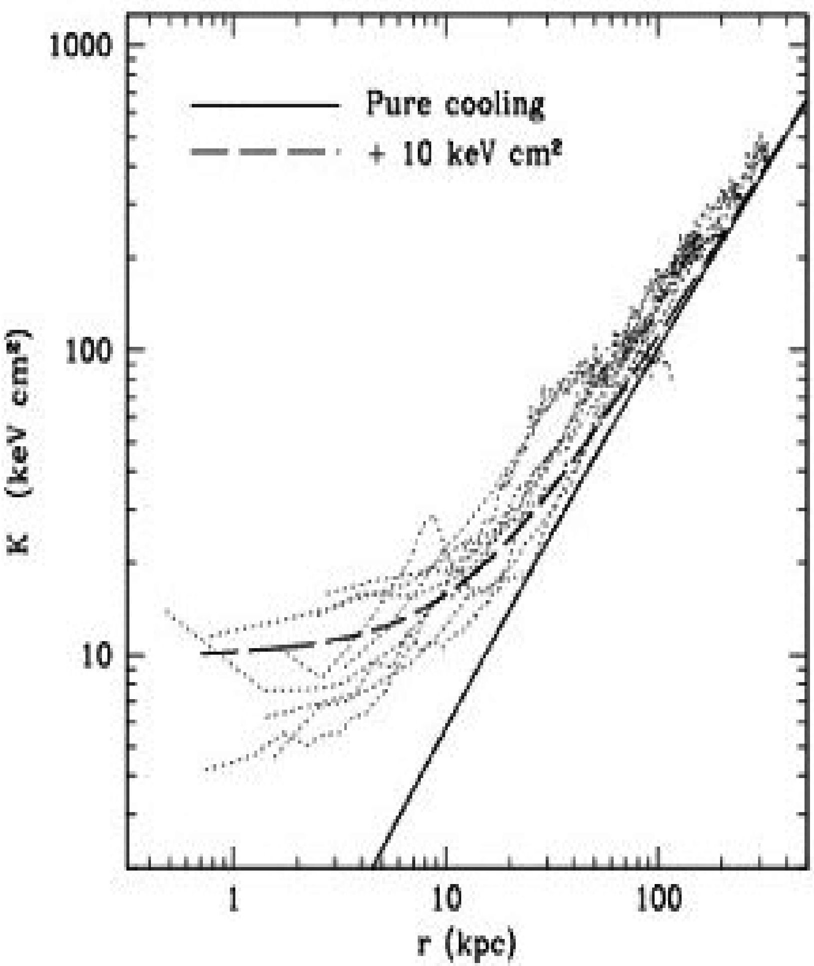


Figure 7 from B R McNamara and P E J Nulsen 2012 New J. Phys. 14 055023

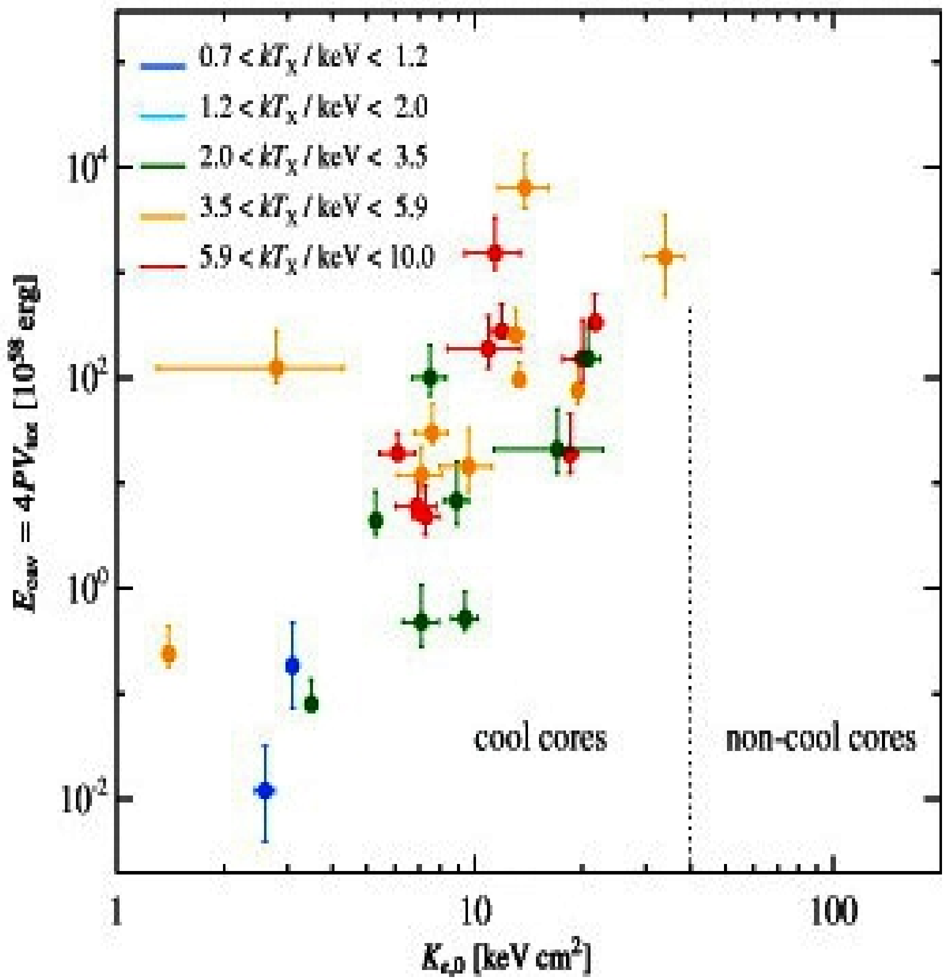
Figure 6 from B R McNamara and P E J Nulsen 2012 New J. Phys. 14 055023



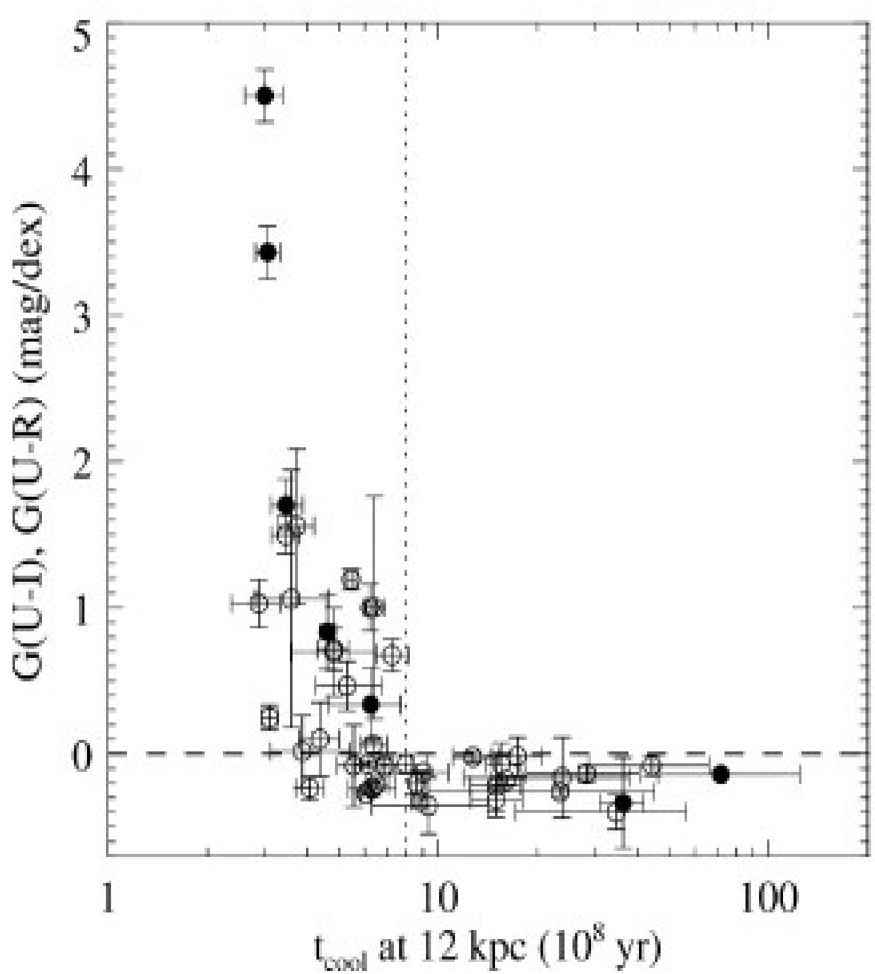
Entropy profiles of clusters

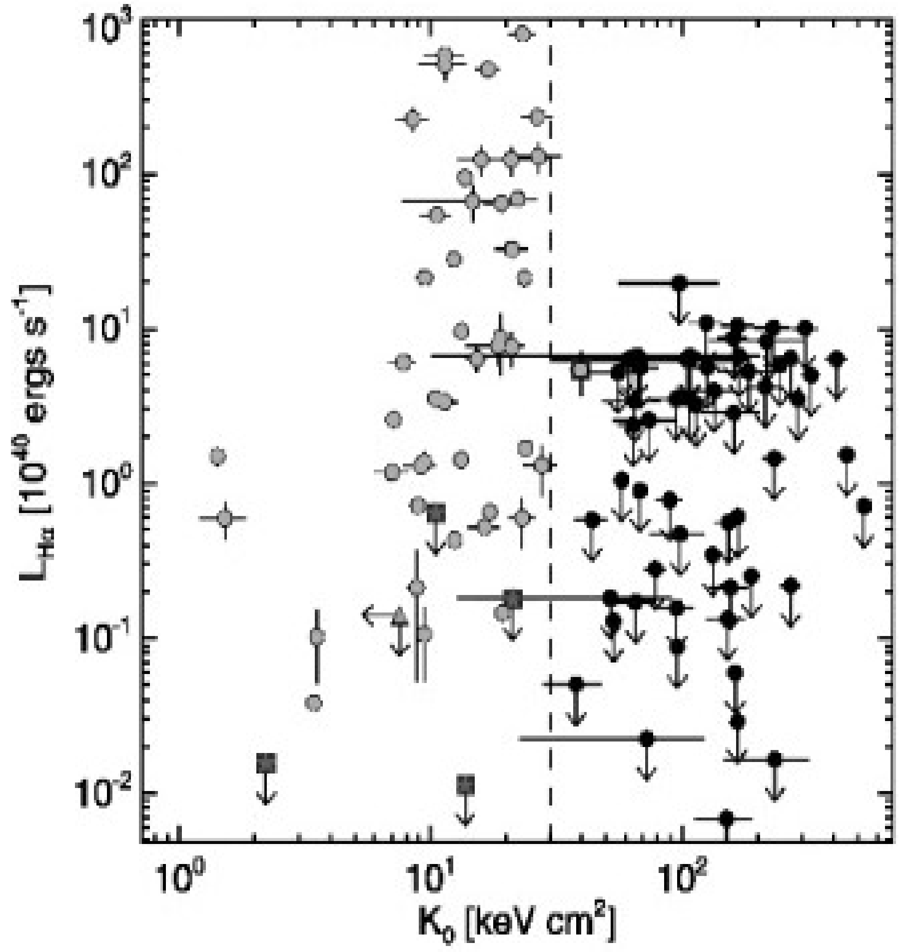


Central entropy versus radio power



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

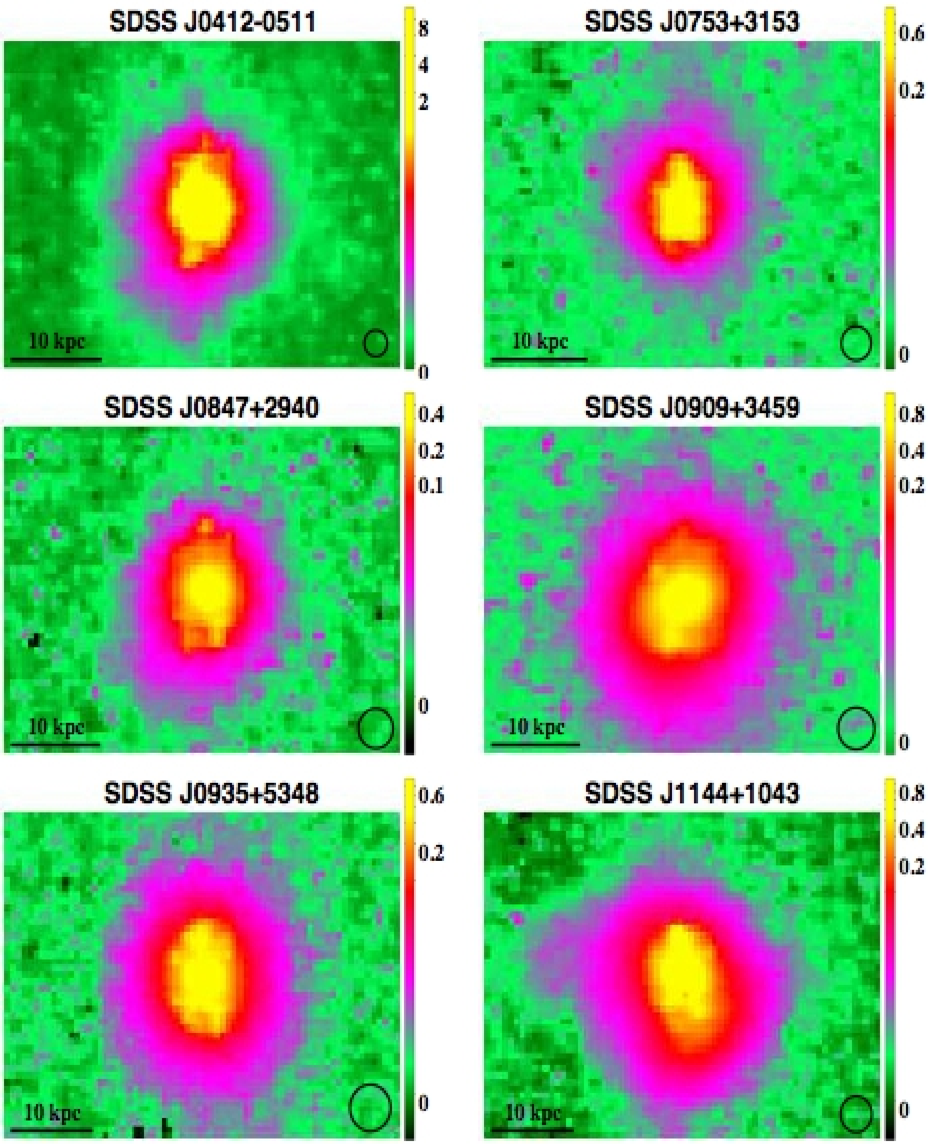


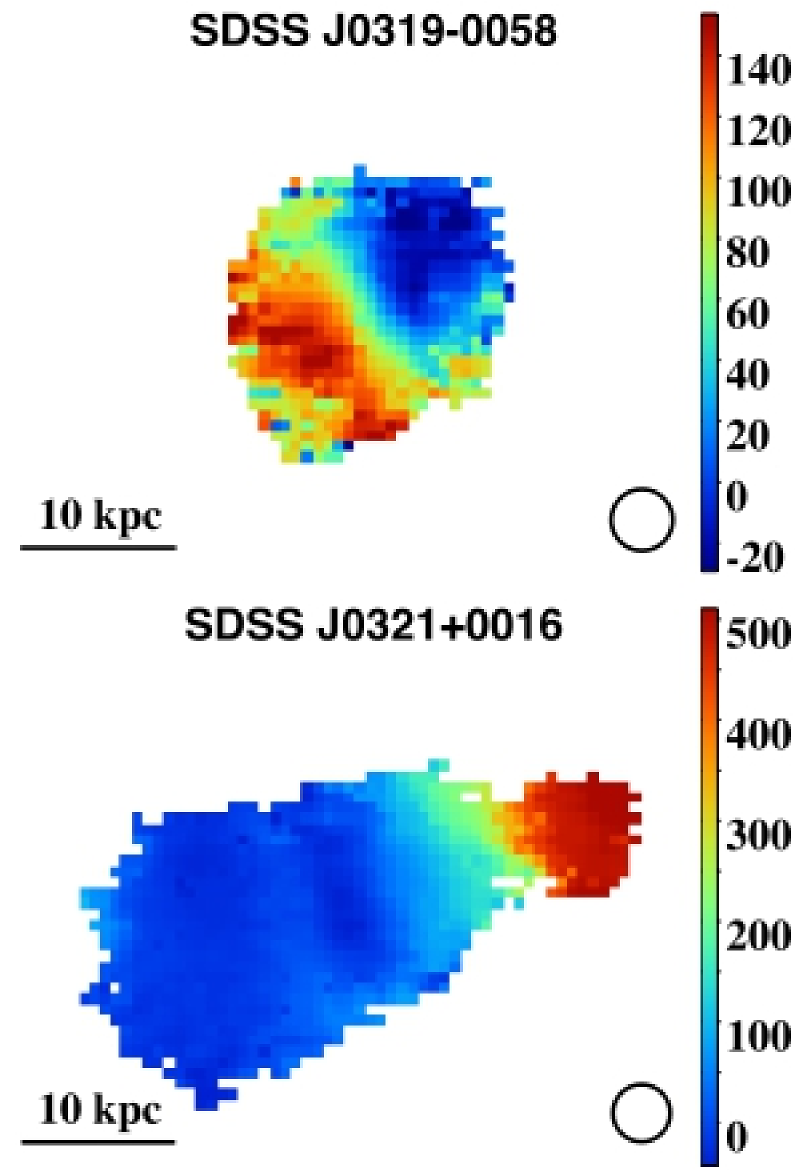


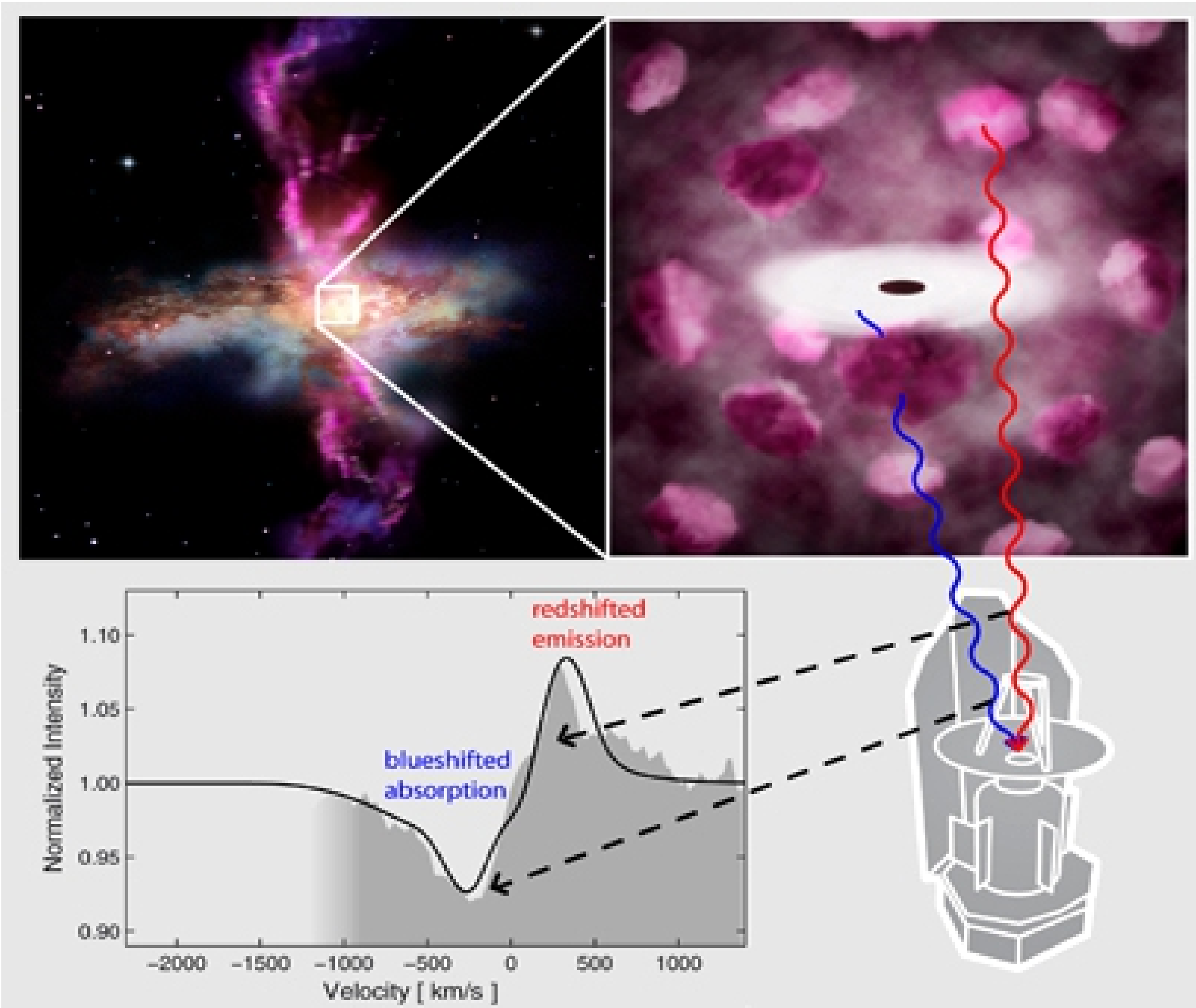
A possible picture is emerging from the data:

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.

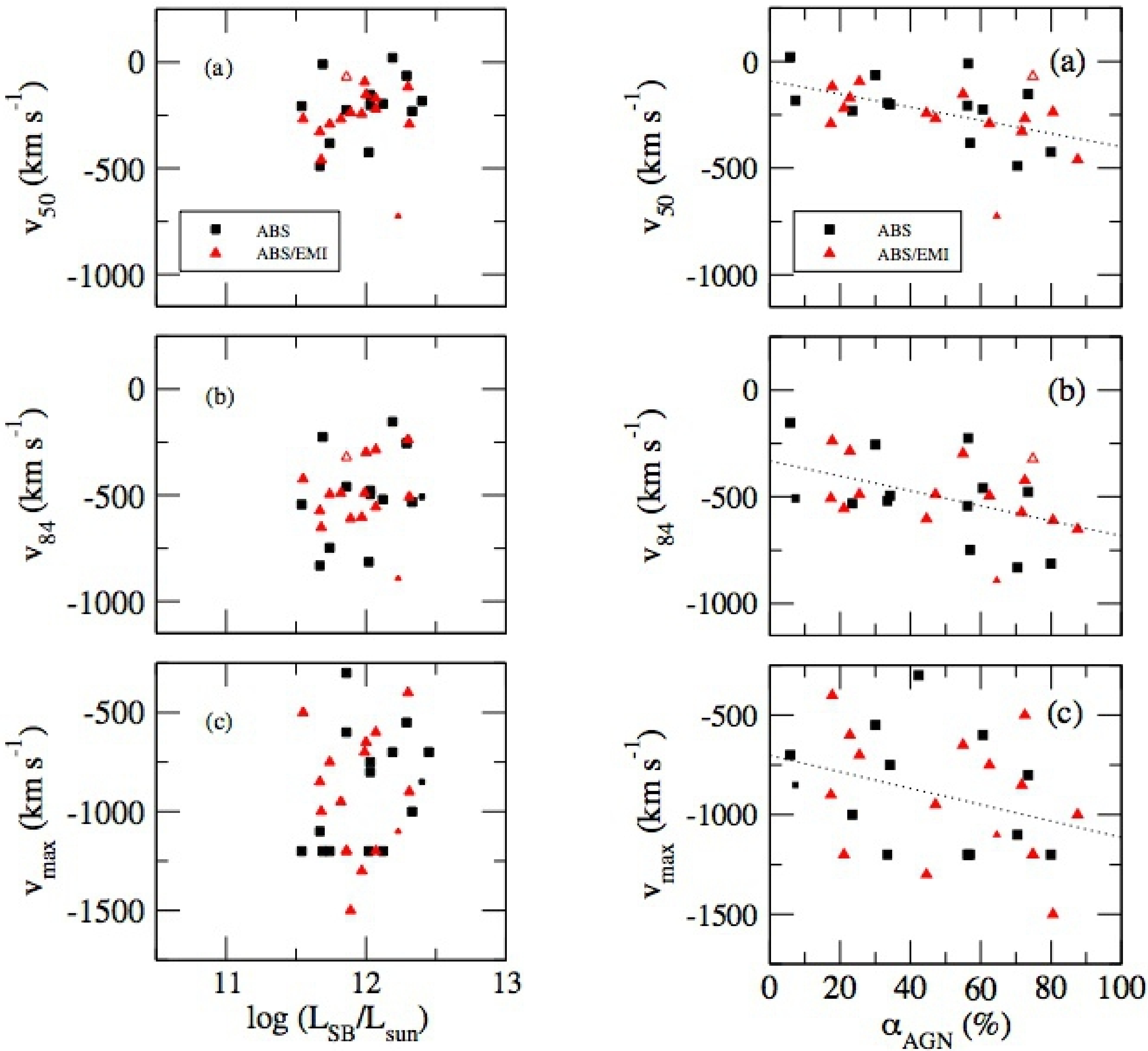
Outflows of ionized gas around Type II quasars also now seen. These ionized gas “halos” extend out to radii of 50 kpc and are very round in morphology. (Greene & Zakamska)







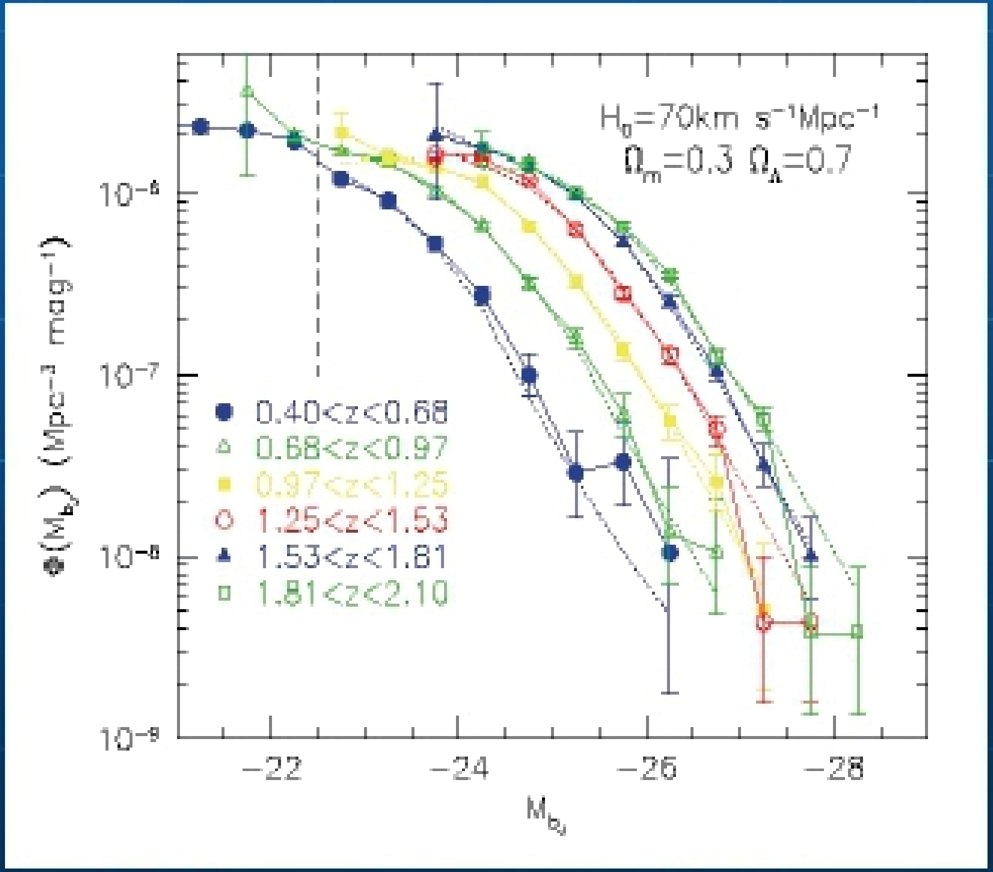
HERSCHEL observations of outflows of molecular gas in nearby quasars and AGN


(a)
(b)
(c)
ABS
ABS/EMI
v_{50} (km s^{-1})
v_{84} (km s^{-1})
v_{max} (km s^{-1})
0
-500
-1000
-1500
11
12
13
log (L_{SB}/L_{sun})
0
20
40
60
80
100
α_{AGN} (%)

ACTUAL IMPACT OF OUTLOWS FROM QUASARS ON SUBSEQUENT EVOLUTION OF GALAXY NEEDS TO BE BETTER UNDERSTOOD

Cosmic Evolution of the AGN Activity

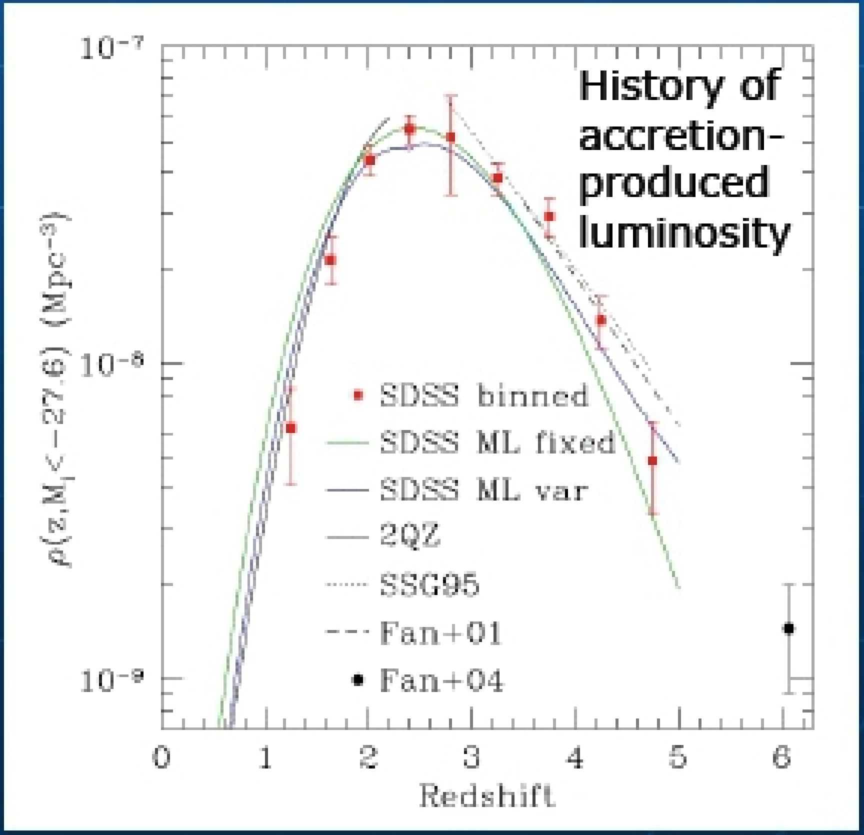
- Describe the distribution of accretion luminosities at different cosmic epochs by the "quasar-luminosity-function" at different redshifts



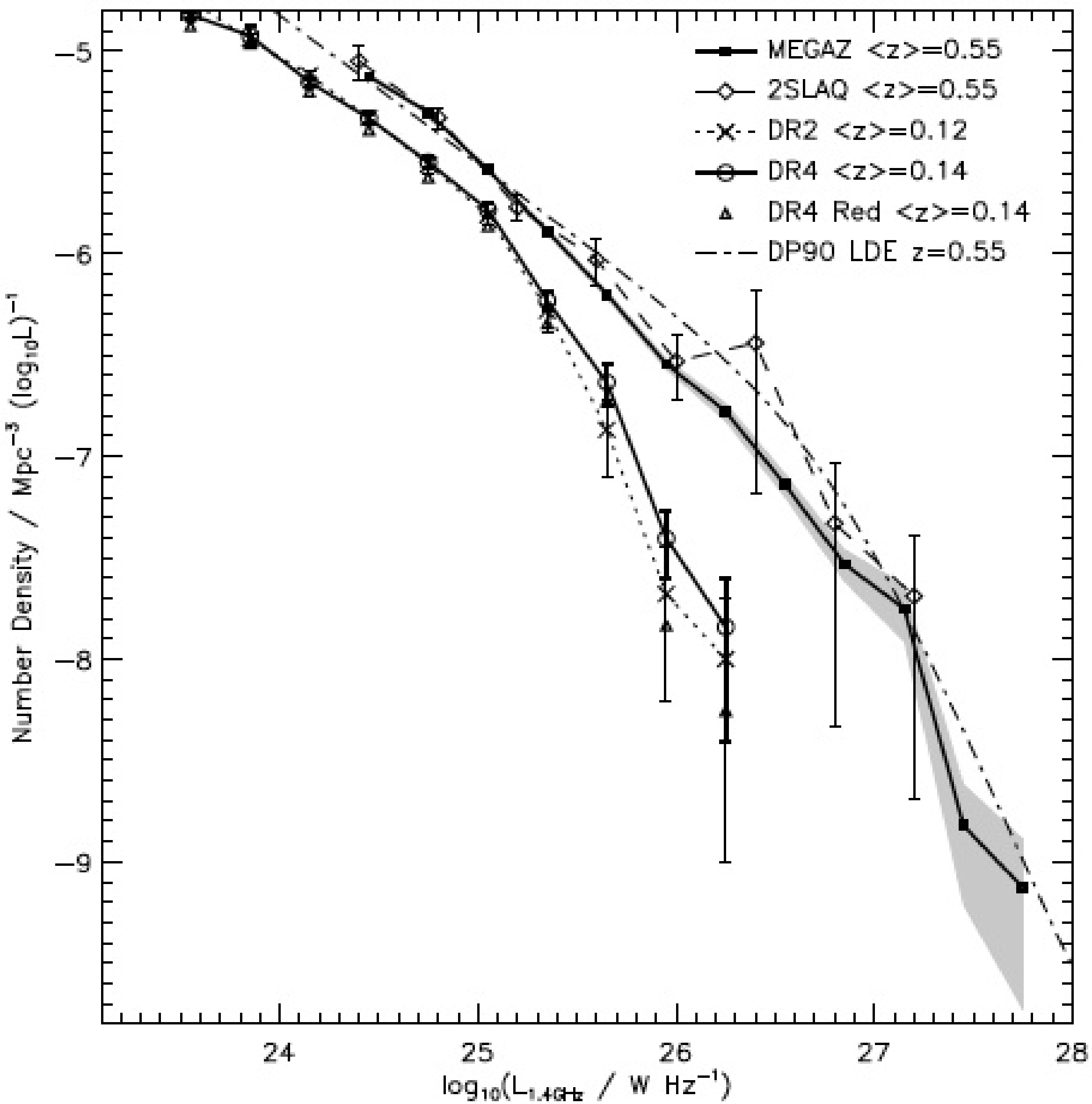
2DF Survey: Croom et al 2004

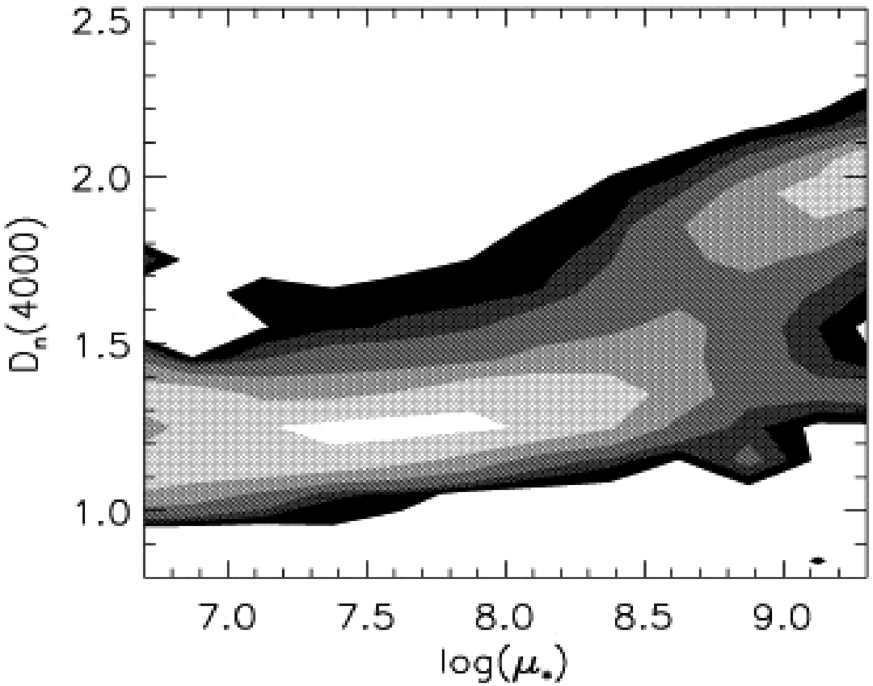
Abundance of luminous QSOs has decreased by 2 orders of magnitude since early epochs!

(e.g. SDSS Richards et al 2006)



Likewise radio AGN are more luminous at higher redshifts ==> Higher accretion rates onto the black holes





BEFORE WE ARE ABLE TO UNDERSTAND THE FULL PICTURE OF HOW AGN HAVE SHAPED THE FORMATION AND SUBSEQUENT EVOLUTION OF TODAY'S GALAXY POPULATION.