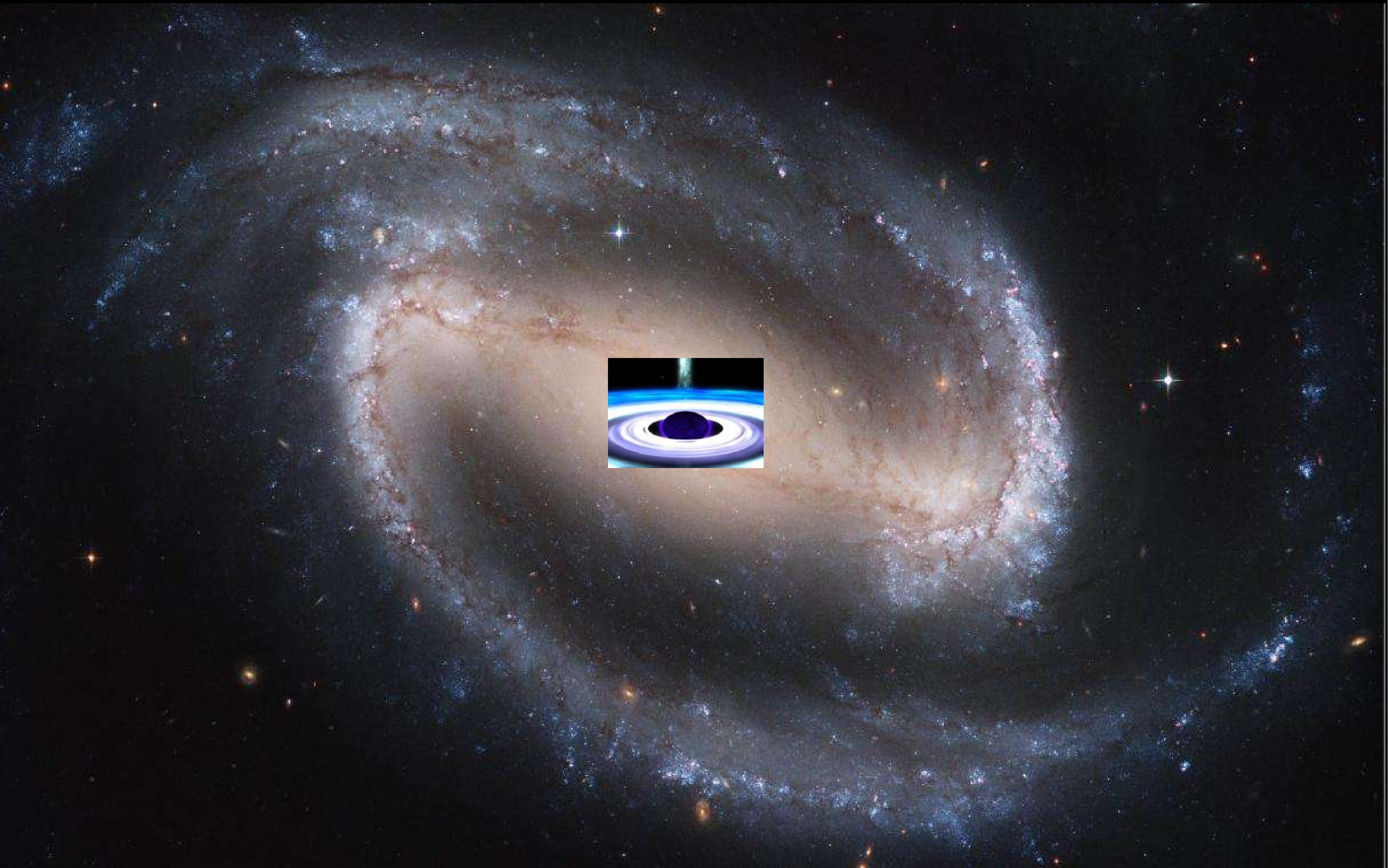
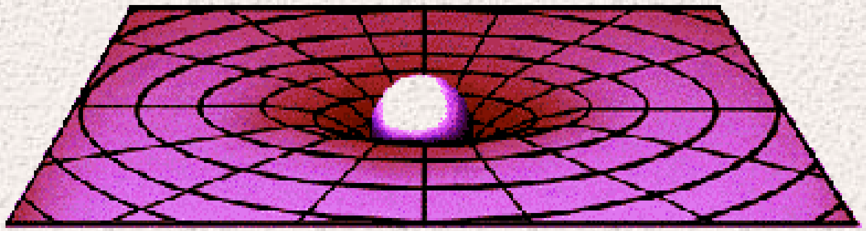
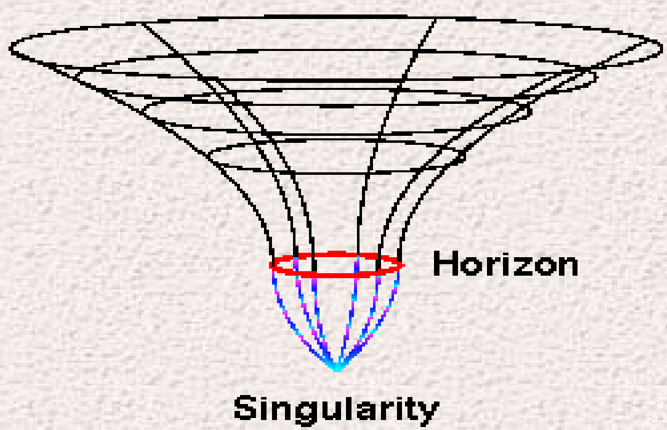
The Co-evolution of Galaxies and their Supermassive Black Holes



BLACK HOLES



The Curvature of Space caused by a Massive Object.



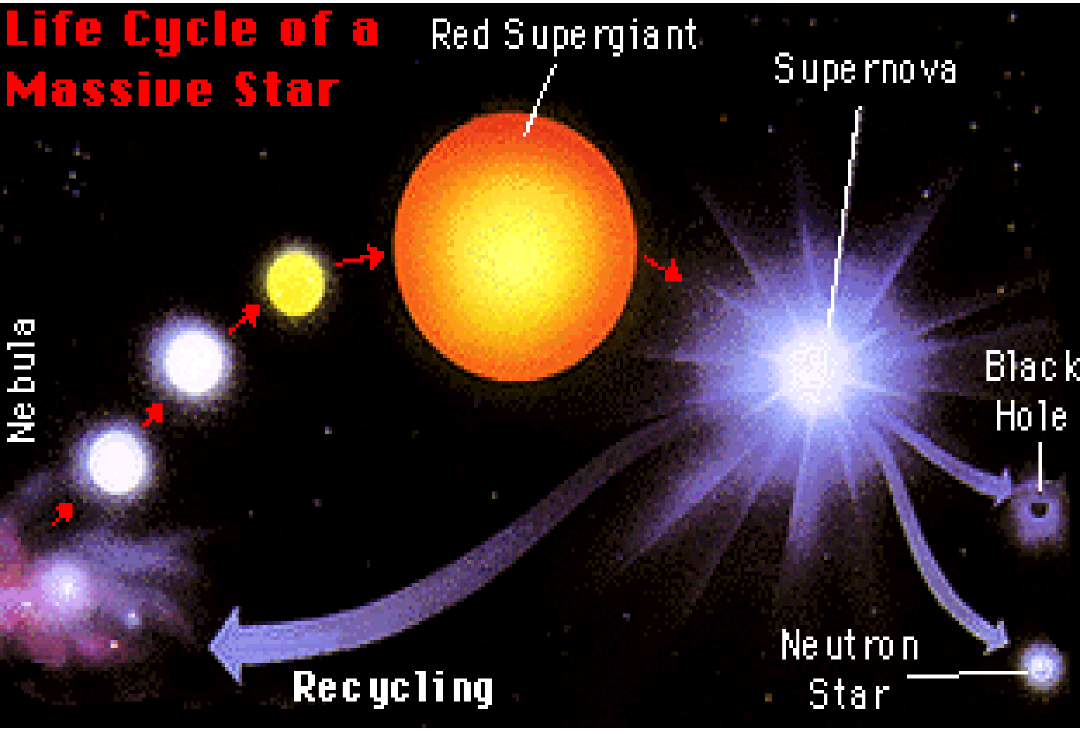
Curved Spacetime around a Black Hole. Inside the *horizon or gravitational radius* space is so strongly curved that nothing can escape.

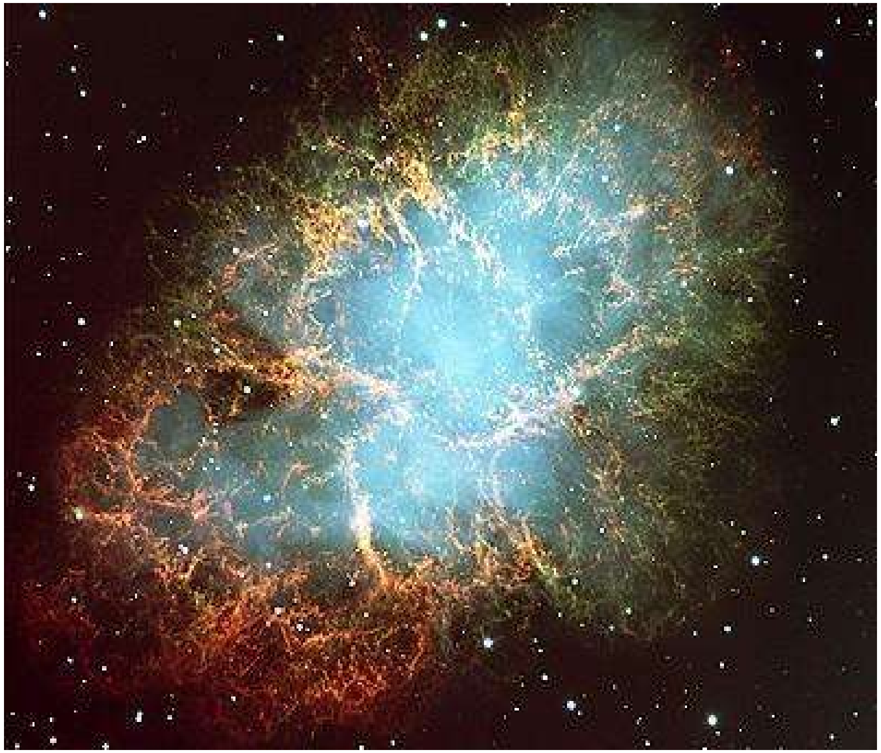
The French mathematician Laplace first speculated about the existence of an object so compact that the escape speed would be greater than the speed of light.

The first relativistic calculation was performed by Karl Schwarzschild (1916), shortly after Einstein published his theory.

$$R_{horizon} = 2\ G\ M/\ c^2$$

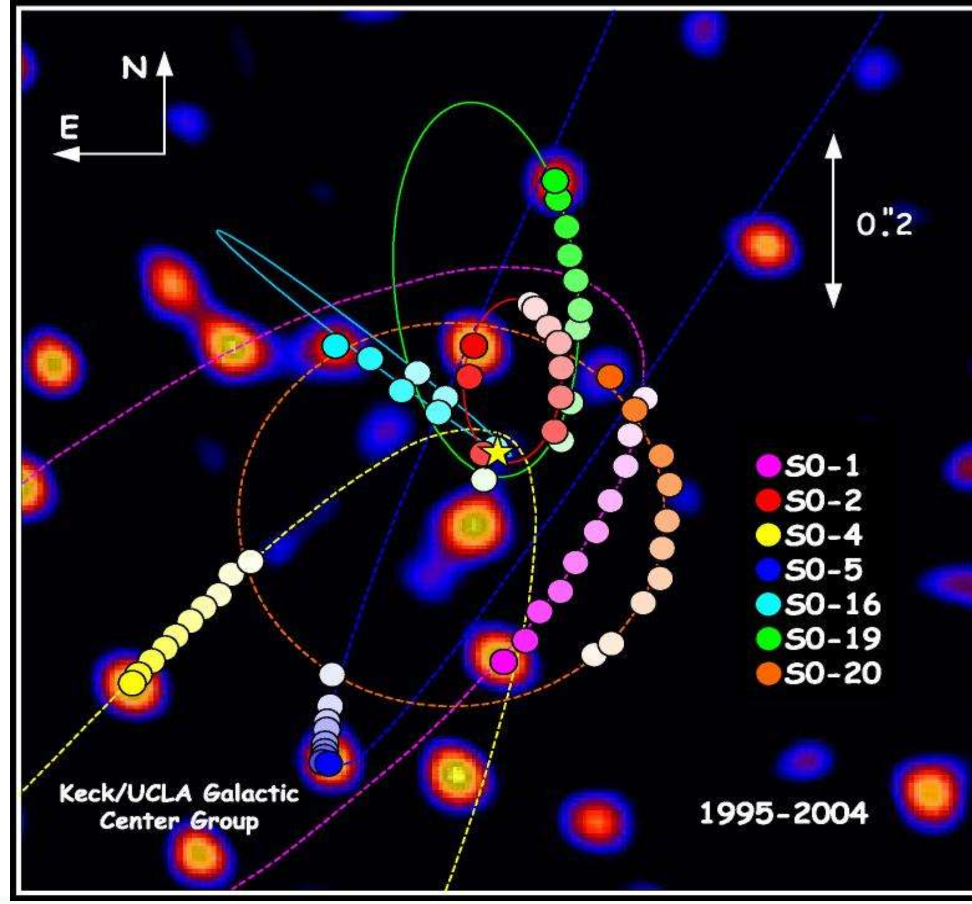
In 1939, J. Robert Oppenheimer and H. Snyder (a graduate student) described a mechanism by which black holes may be created in the real Universe.
A star that has exhausted all its nuclear fuel can no longer support itself against gravity. A star whose remnant core exceeds a critical limit following a supernova explosion will form a **black hole.**

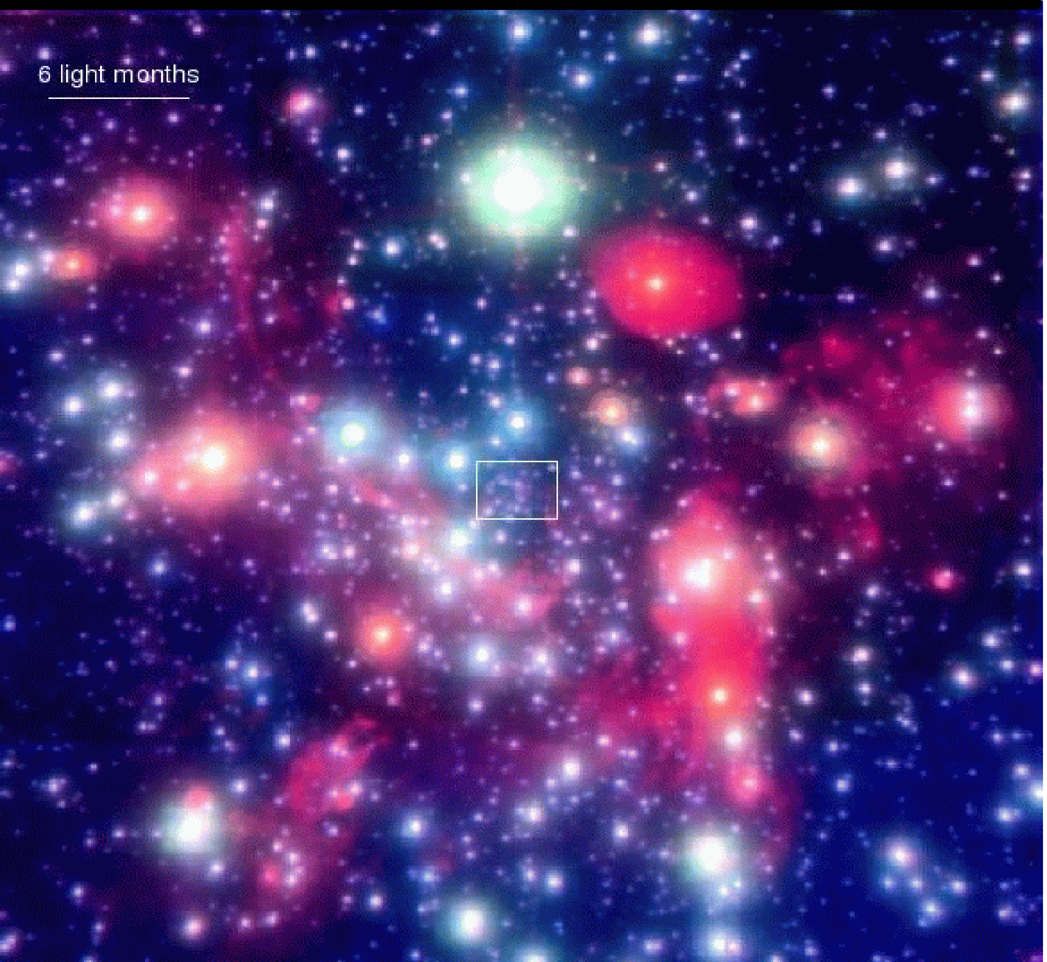


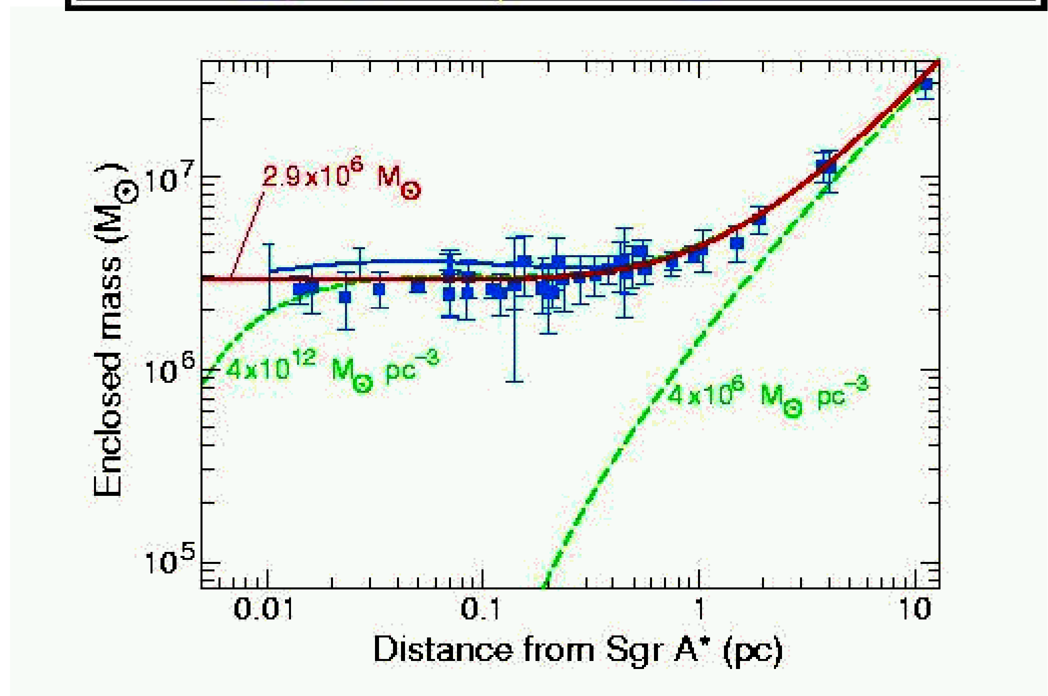


More than two dozen stellar black hole candidates have been indentified in the Milky Way, all of them part of binary systems in which the other component is a visible star. They have highly variable x-ray emission, thought to be coming from an **accretion disk** surrounding the black hole.

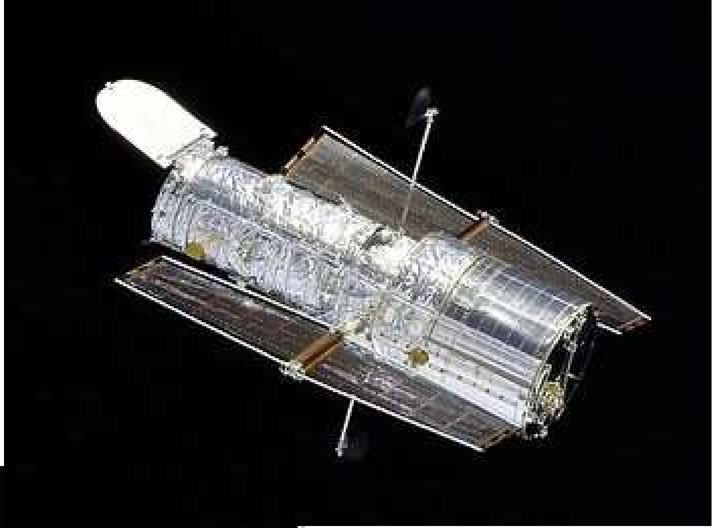
The Supermassive Black Hole at the Centre of the Milky Way

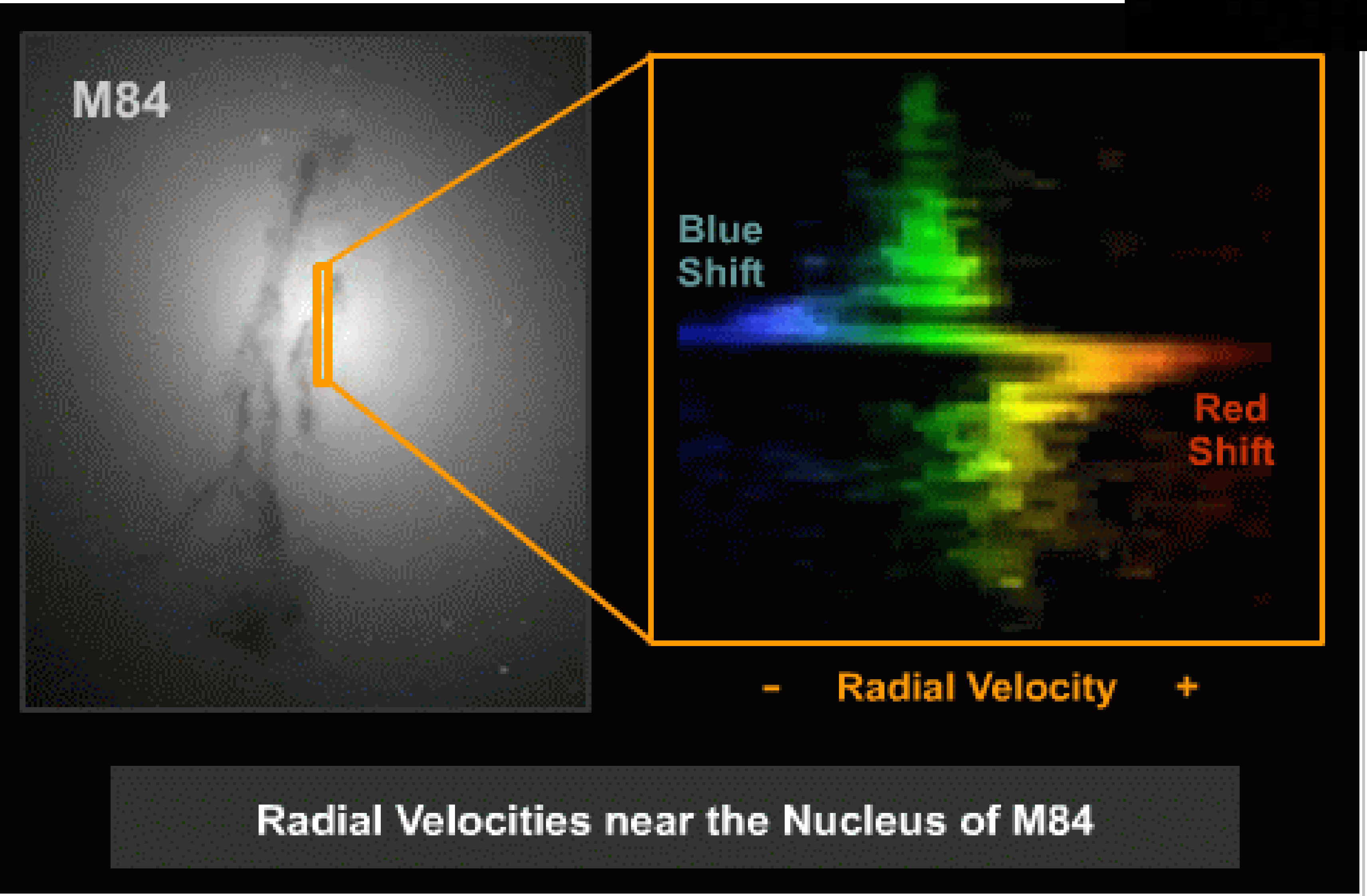






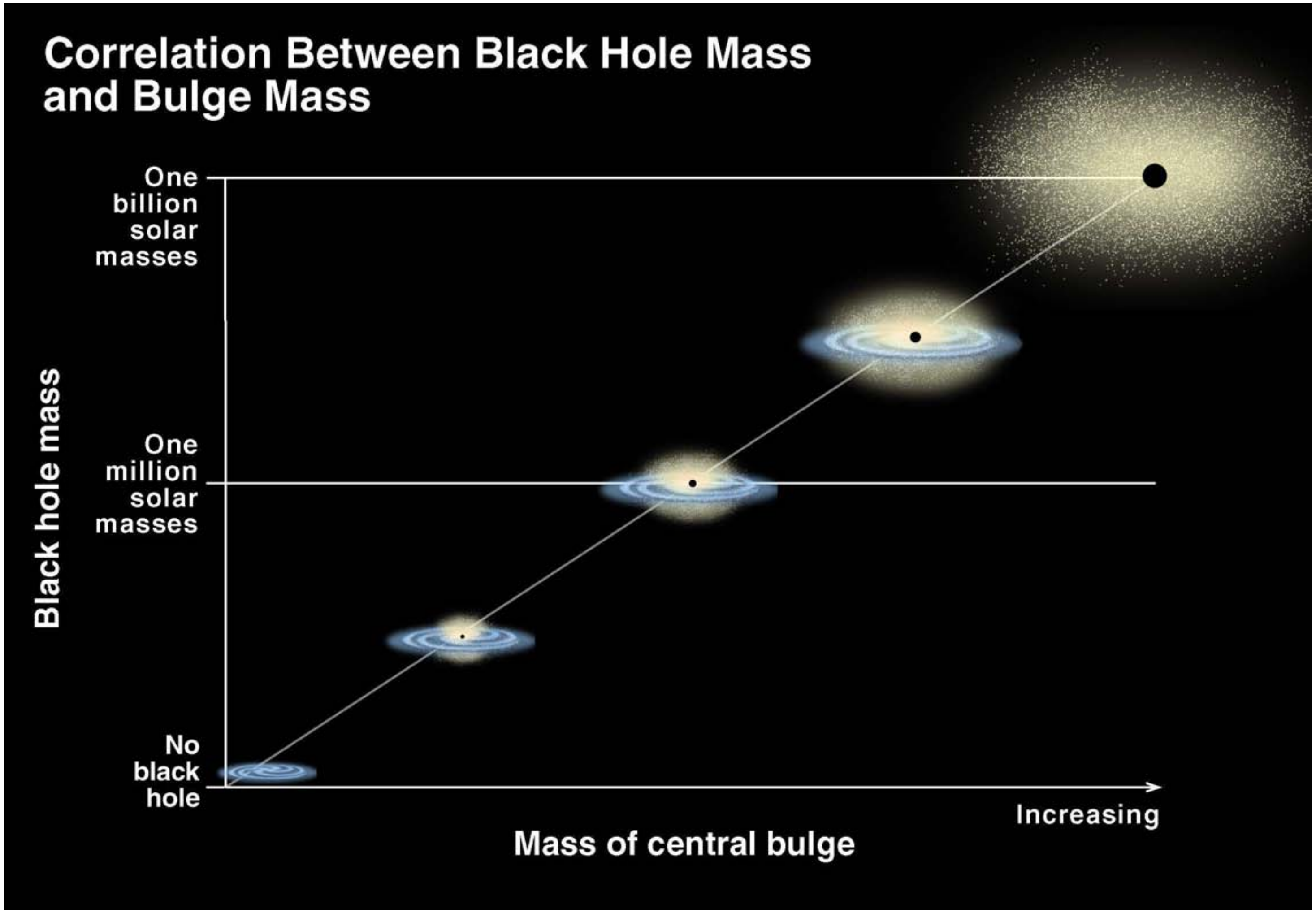
Evidence for Supermassive Black Holes in Other Galaxies



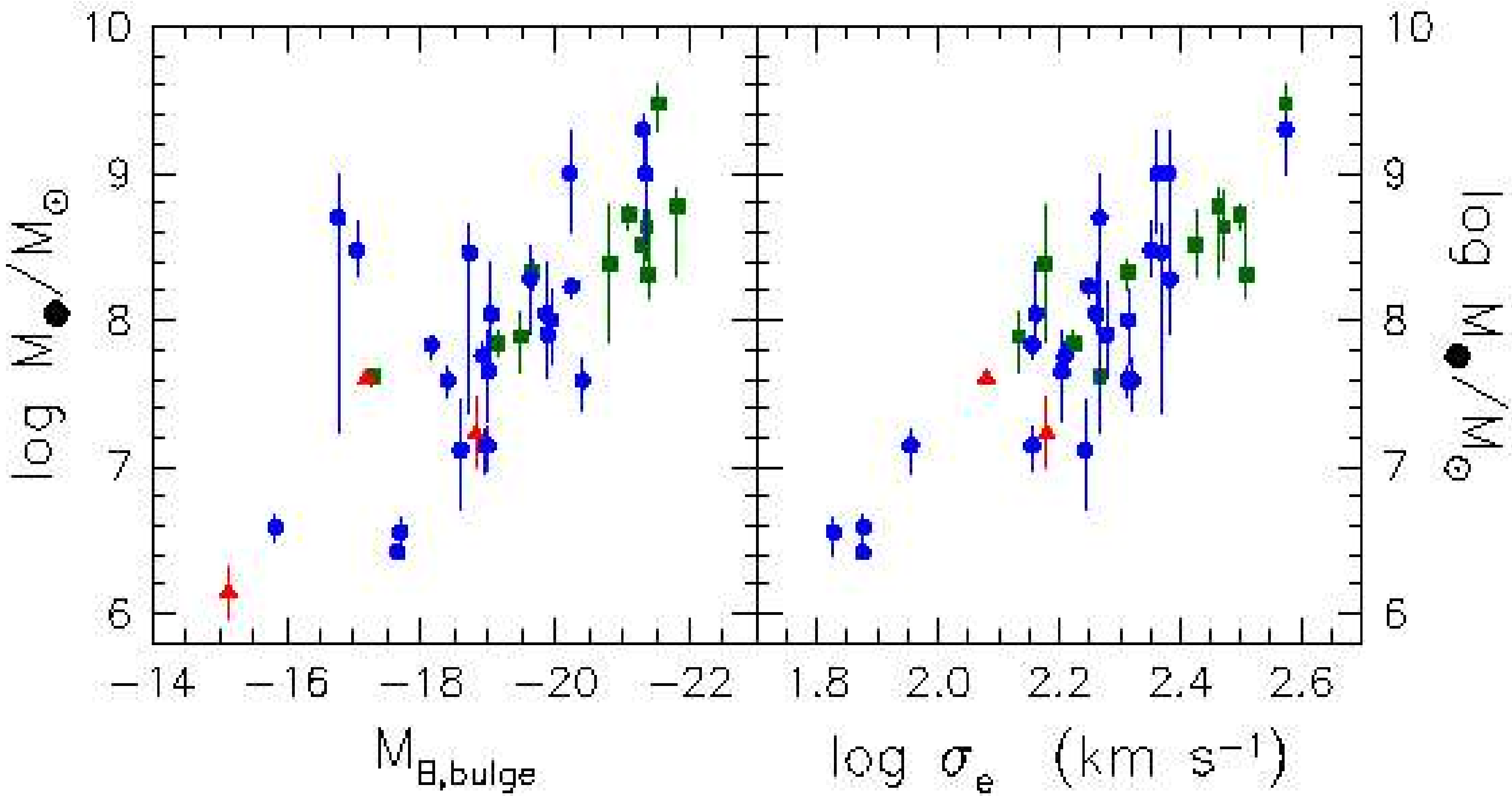


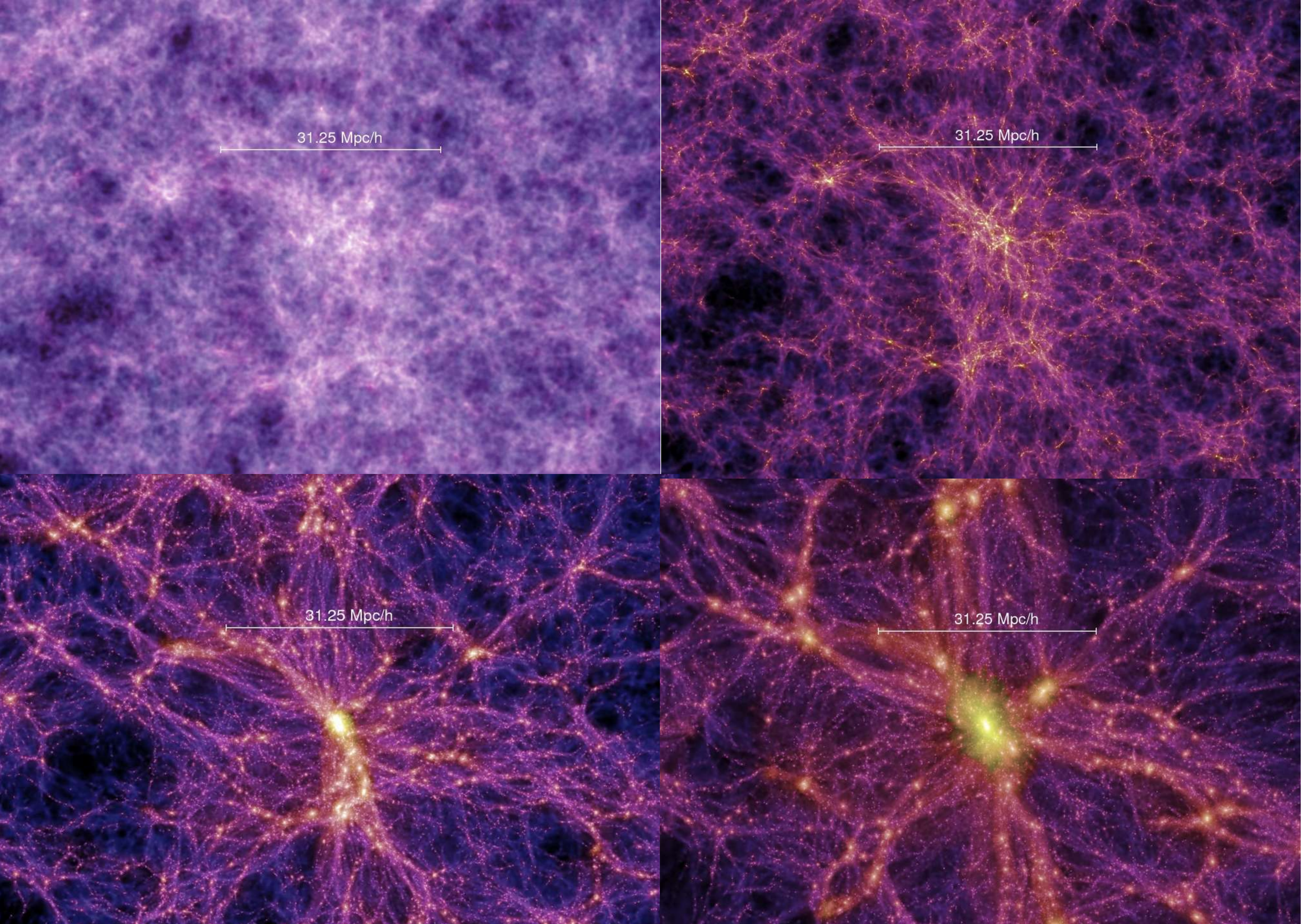
Revolution in in our understanding of galaxy formation:

1) All galaxy bulges contain supermassive black holes
2) The massof the black hole is tightly correlated with the mass of the bulge.



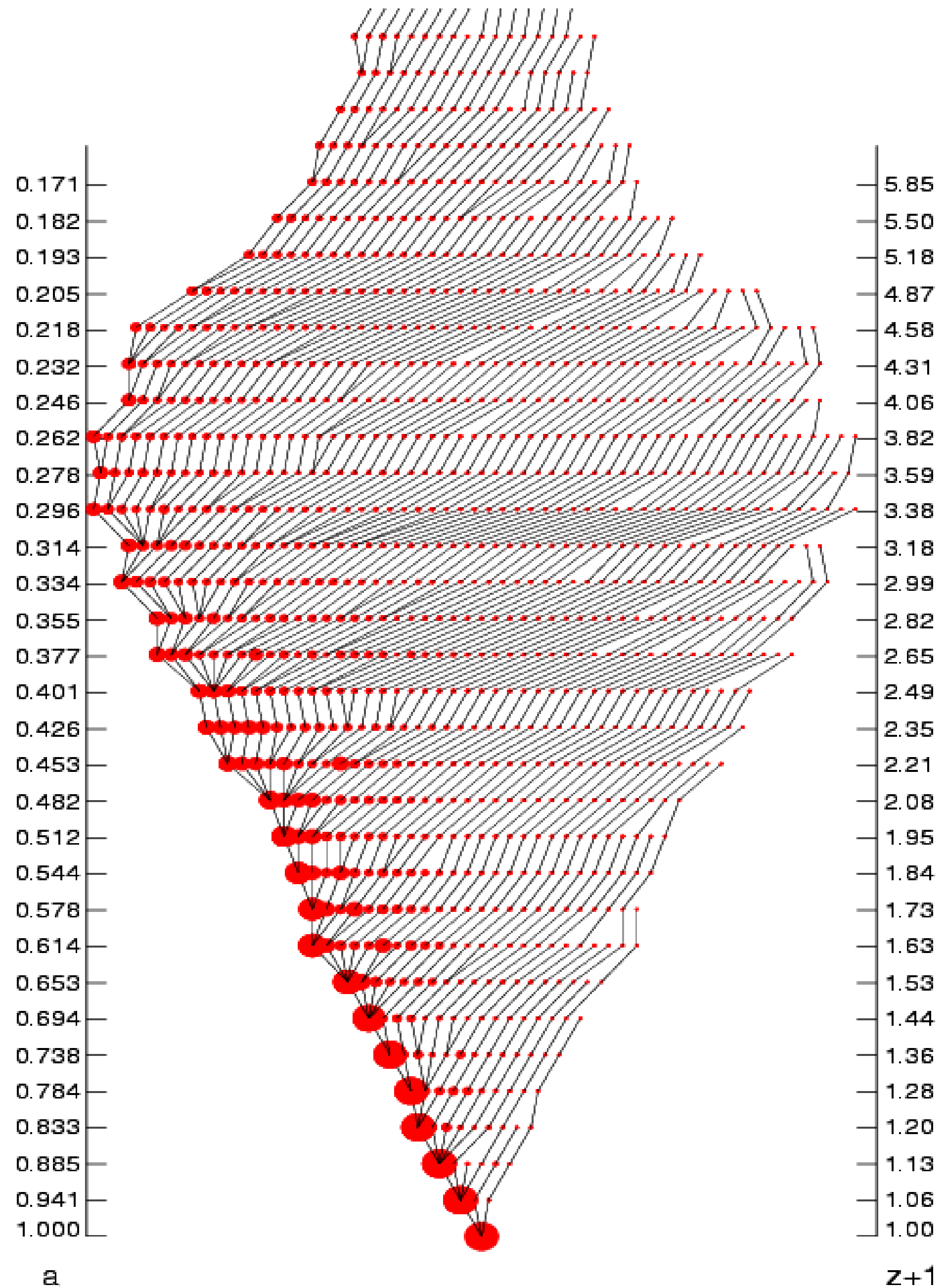
From John Kormendy



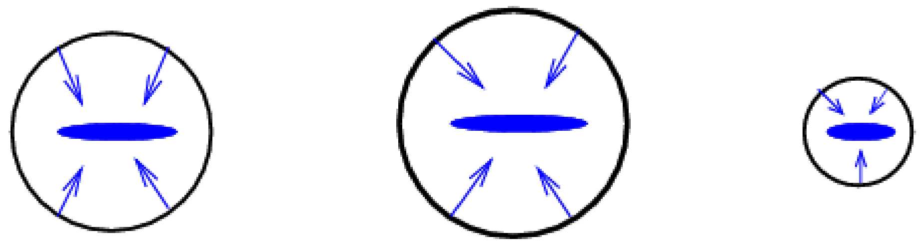


Standard paradigm for structure formation in the Universe

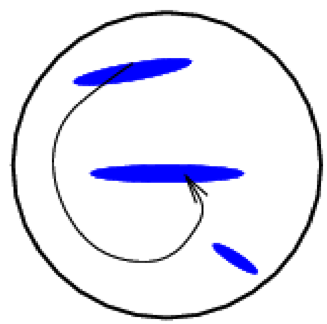
STRUCTURE FORMS HIERARCHICALLY



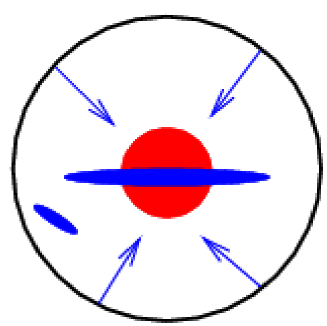
Galaxies are believed to form through two processes: gas accretion and merging



Gas cools and forms a rotationally–supported disk

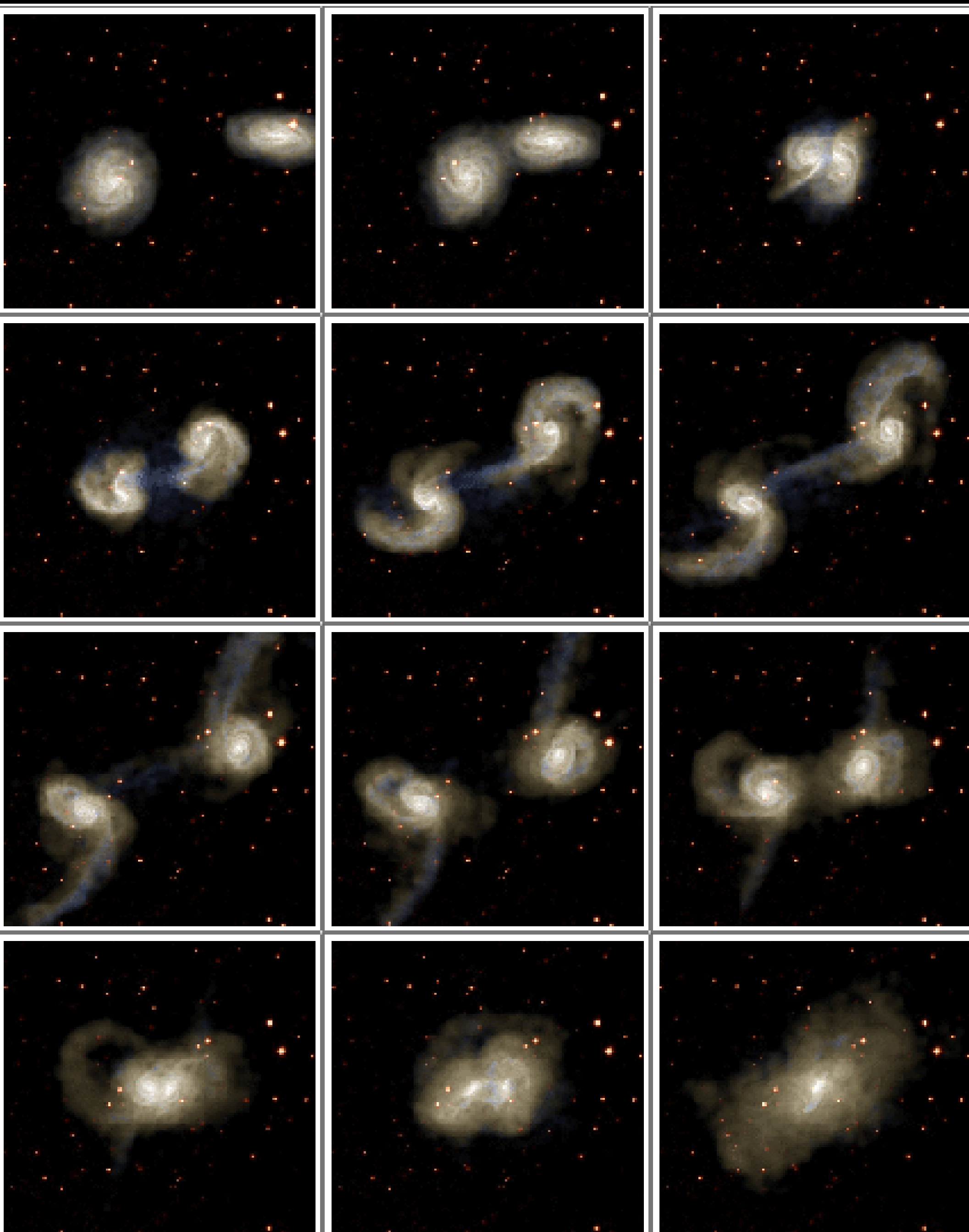


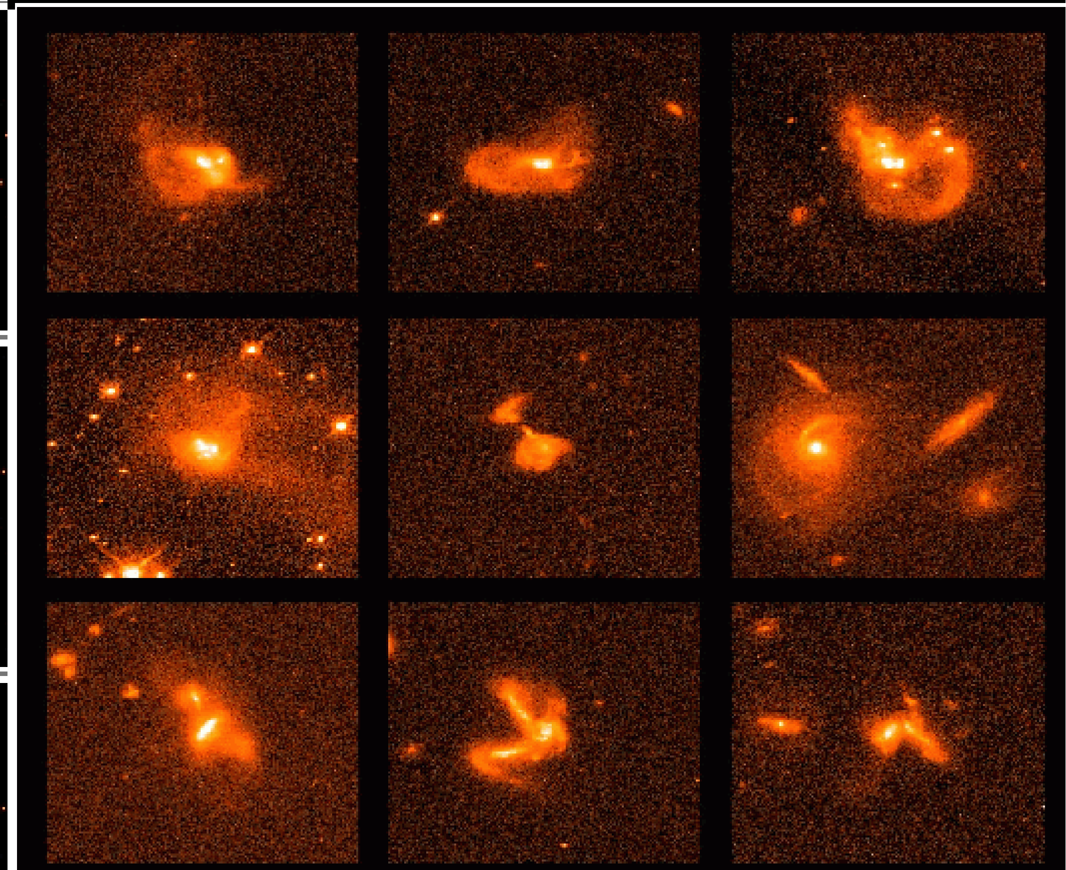
Galaxies merge on a dynamical friction time–scale



Major merger leads to formation of bulge; new disk forms when gas cools again

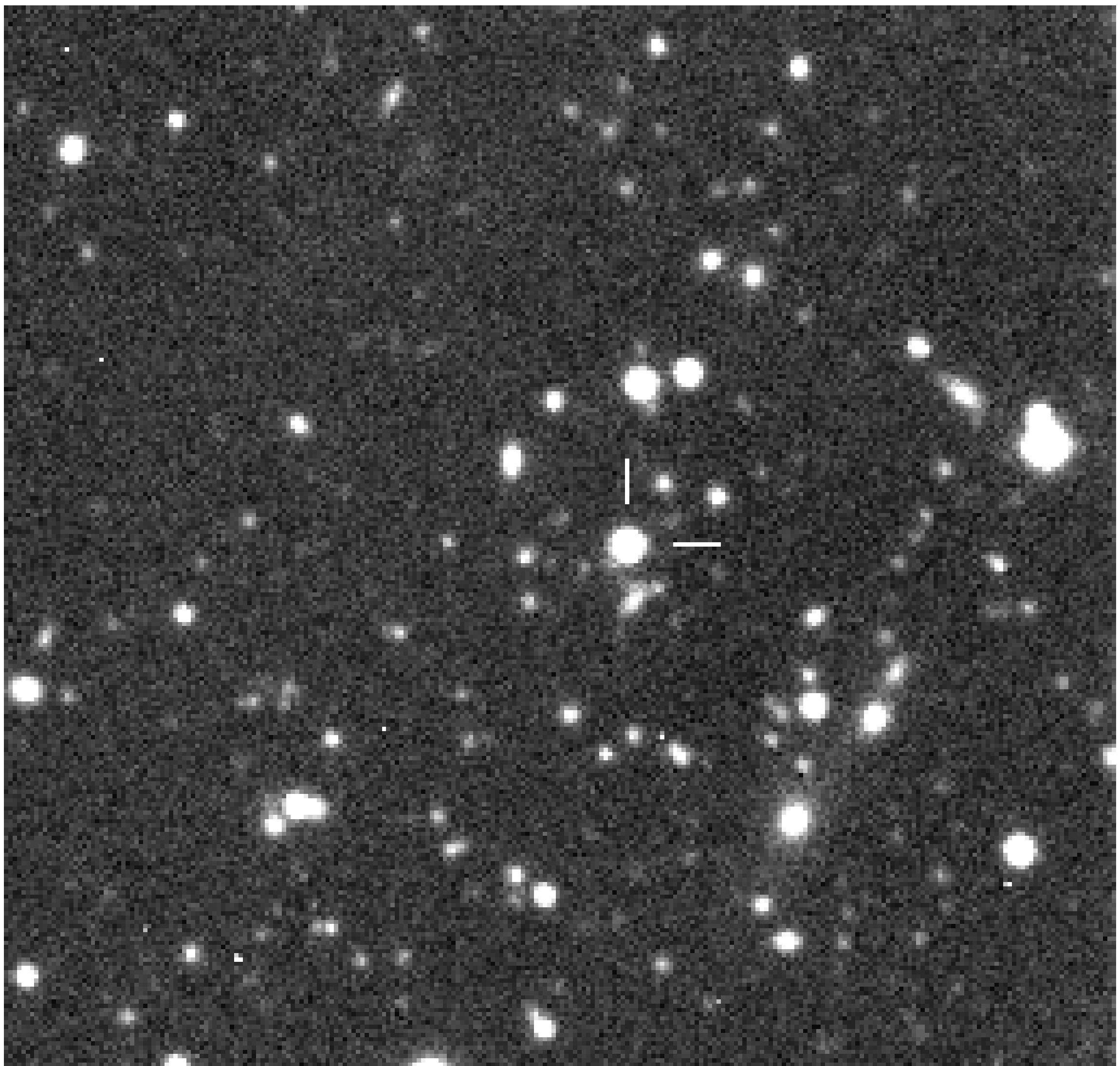
Mergers between galaxies are also well-documented



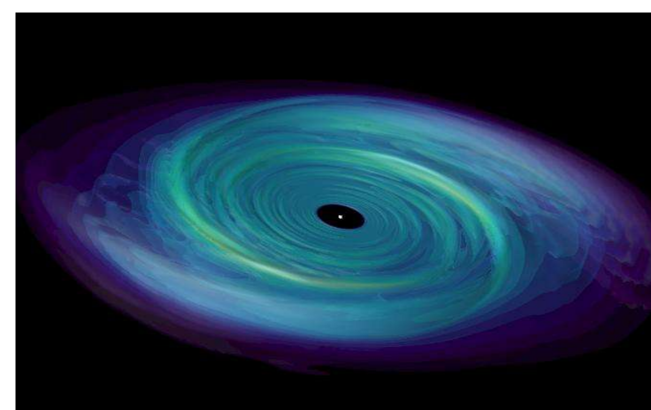


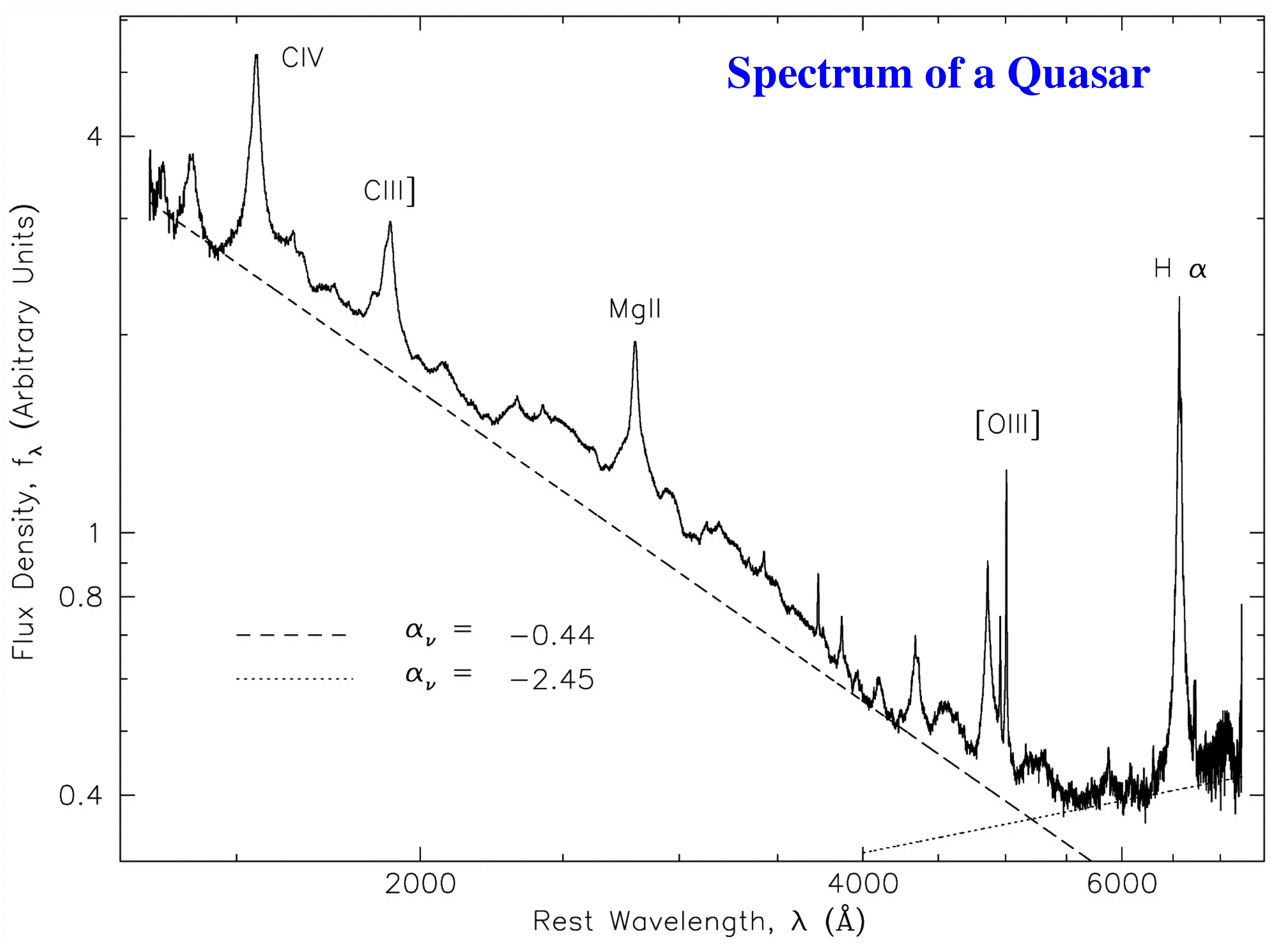
A new frontier in astrophysics:
what happens when the black holes in these galaxies merge?

Quasars (quasi-stellar objects) have apparent brightnesses comparable to stars in our galaxy, yet they are at cosmological distances.



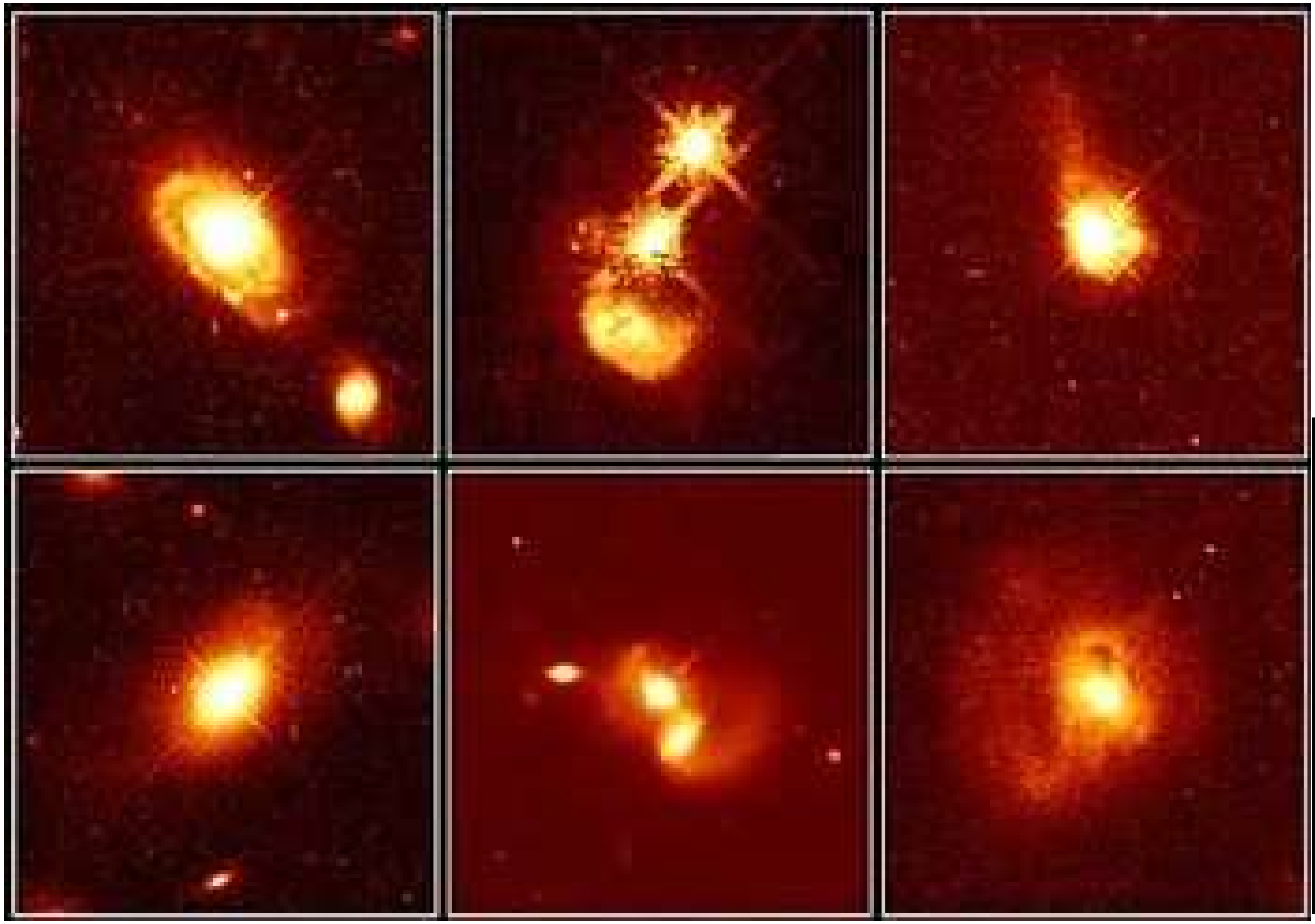
Only possible source of energy: accretion disks surrounding supermassive black holes. Frictional heating in the disk can convert 10% of the rest mass energy on the infalling material into radiation.

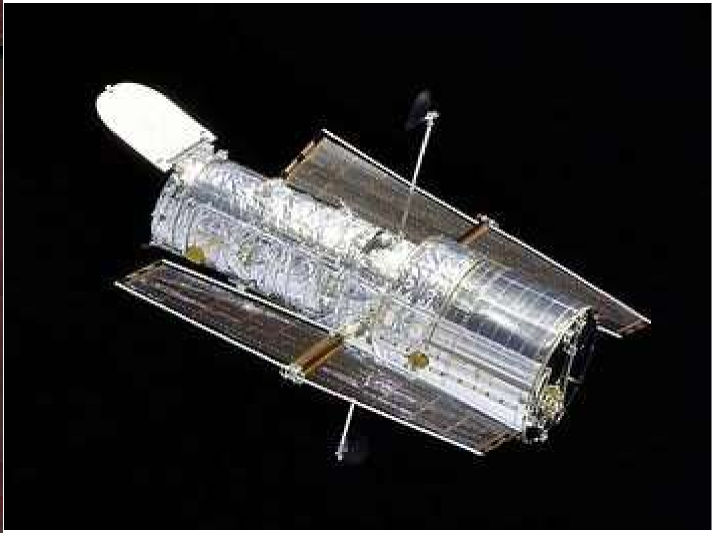


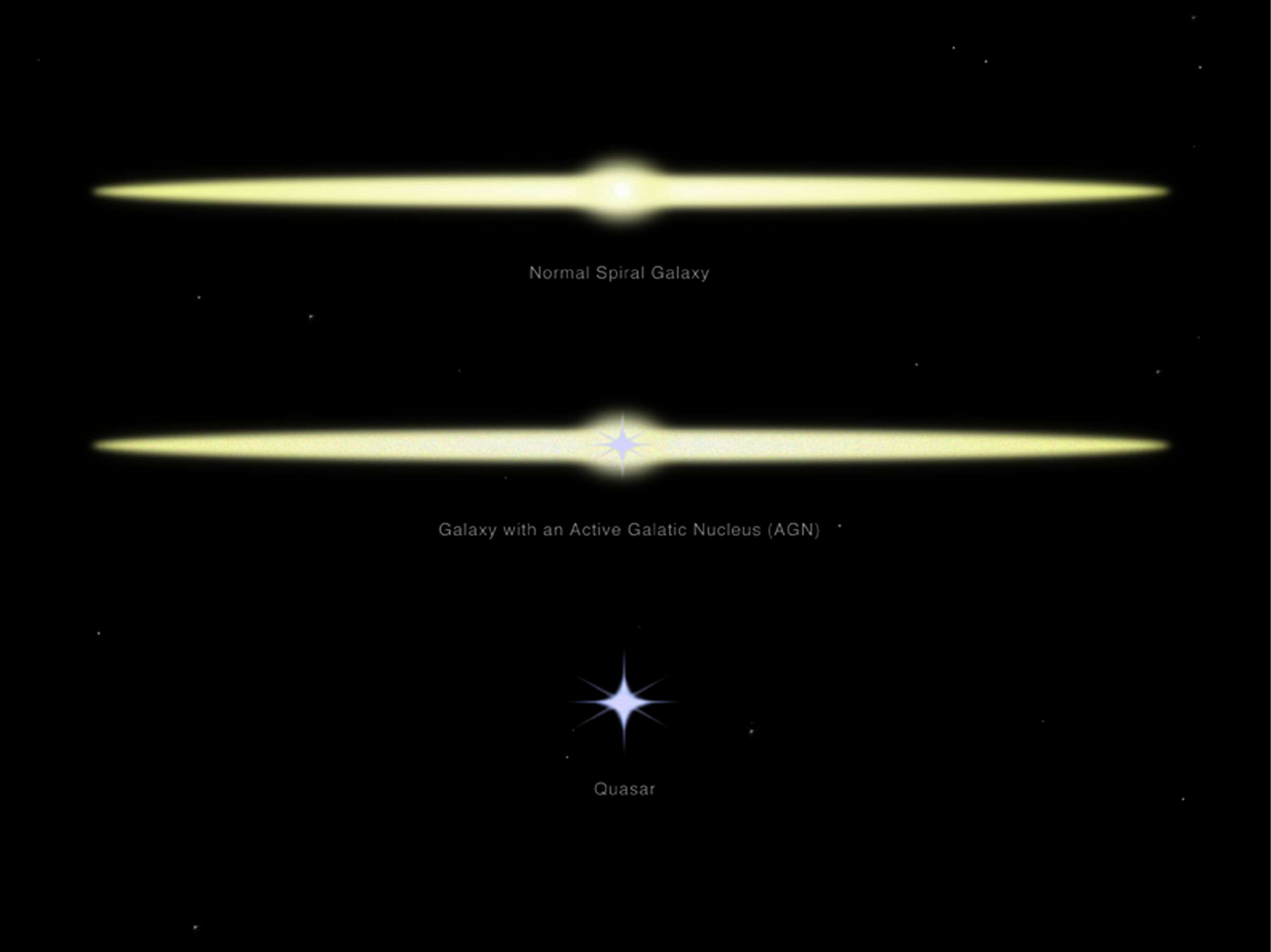


Spectrum of a Quasar
CIV
CIII]
MgII
[OIII]
H α
4
1
0.8
0.4
α_ν = −0.44
α_ν = −2.45
2000
4000
6000
Rest Wavelength, λ (Å)
Flux Density, f_λ (Arbitrary Units)

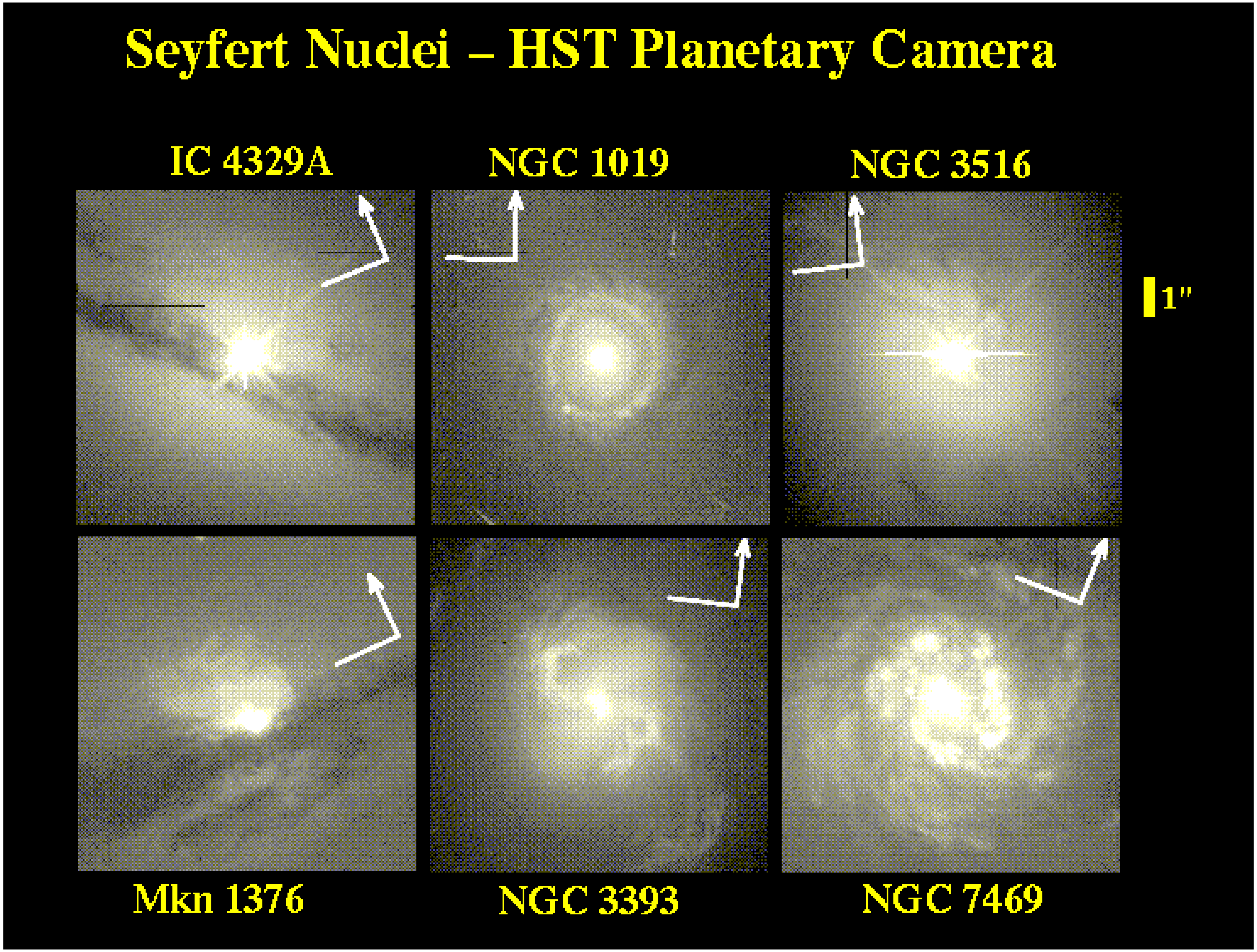
Only after the advent of the Hubble Space Telescope, did it become clear that quasars reside within galaxies. Some show disturbed morphologies.



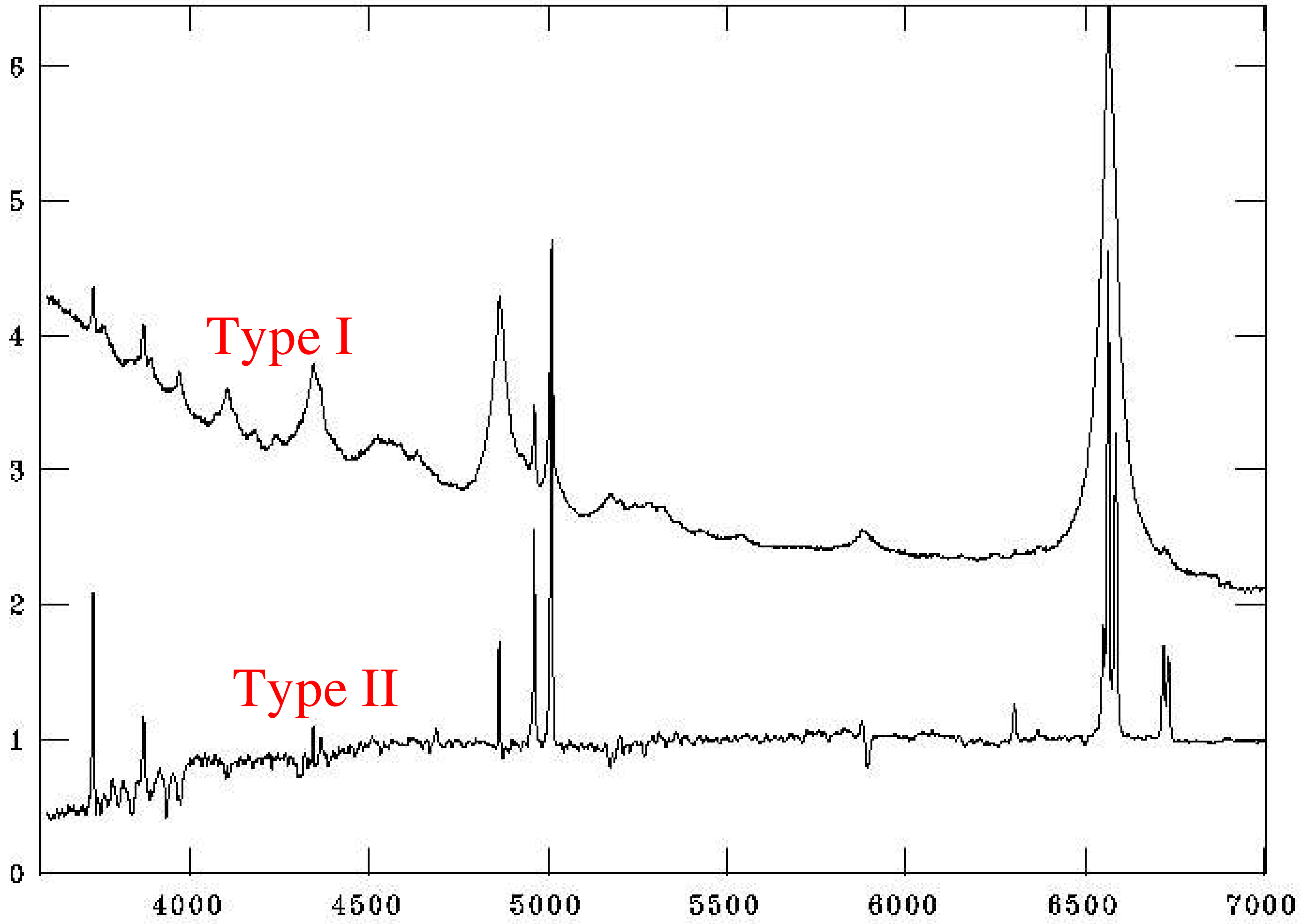



Normal Spiral Galaxy
Galaxy with an Active Galatic Nucleus (AGN)
Quasar

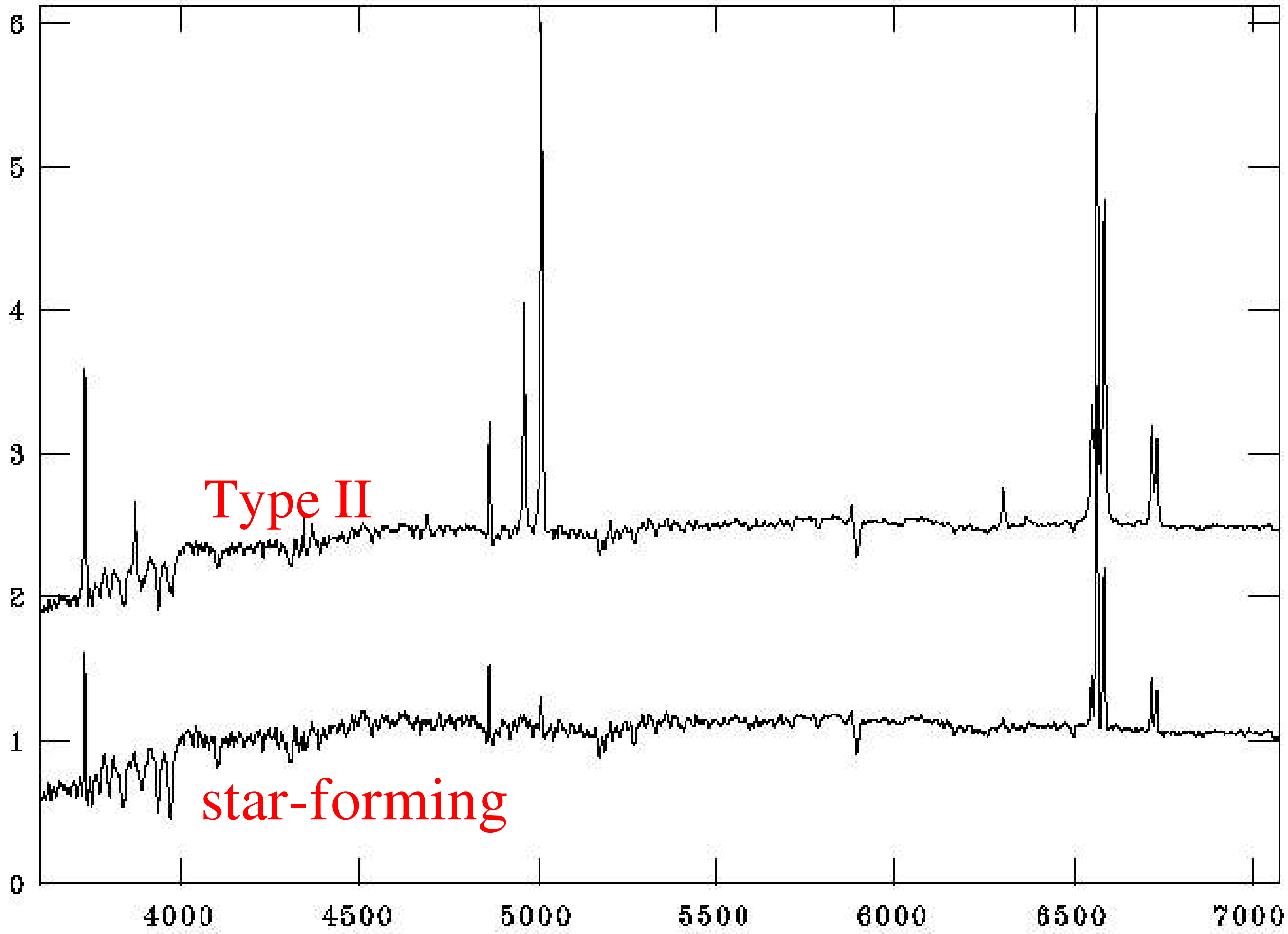
Seyfert galaxies are names for Carl K. Seyfert who in 1943 described them as gaving peculiar spectra with notable emission lines. They sometimes, but not always, have bright point-like nuclei.

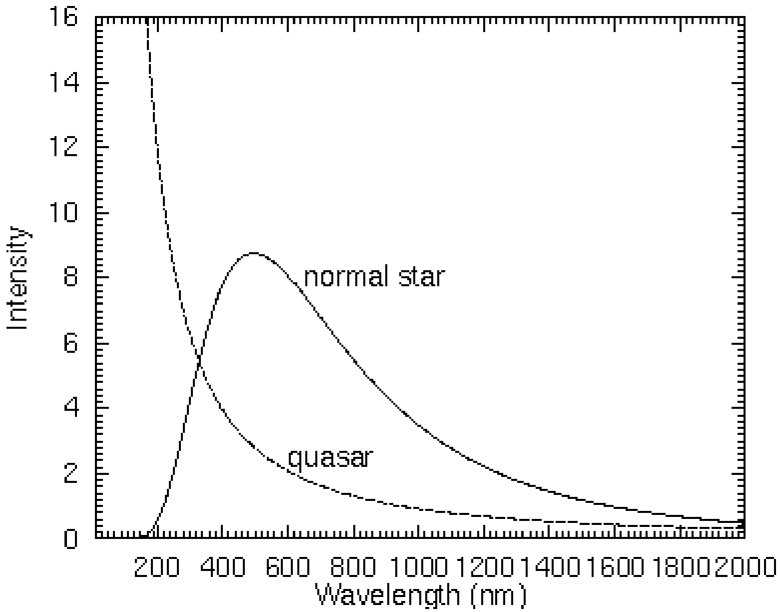


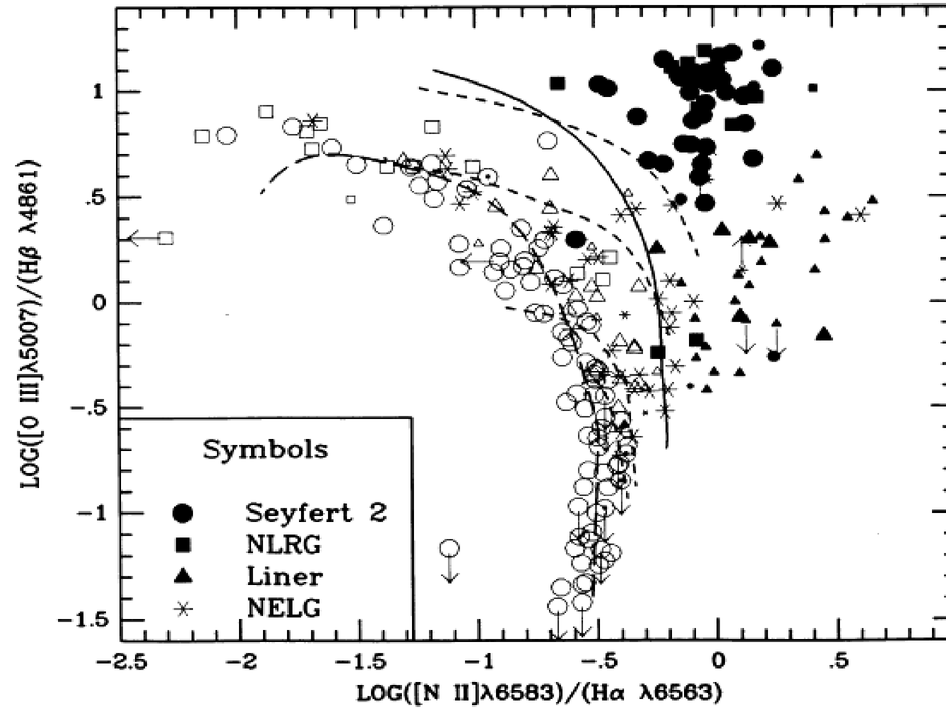
Two types of Seyfert galaxies: Type I and Type II.

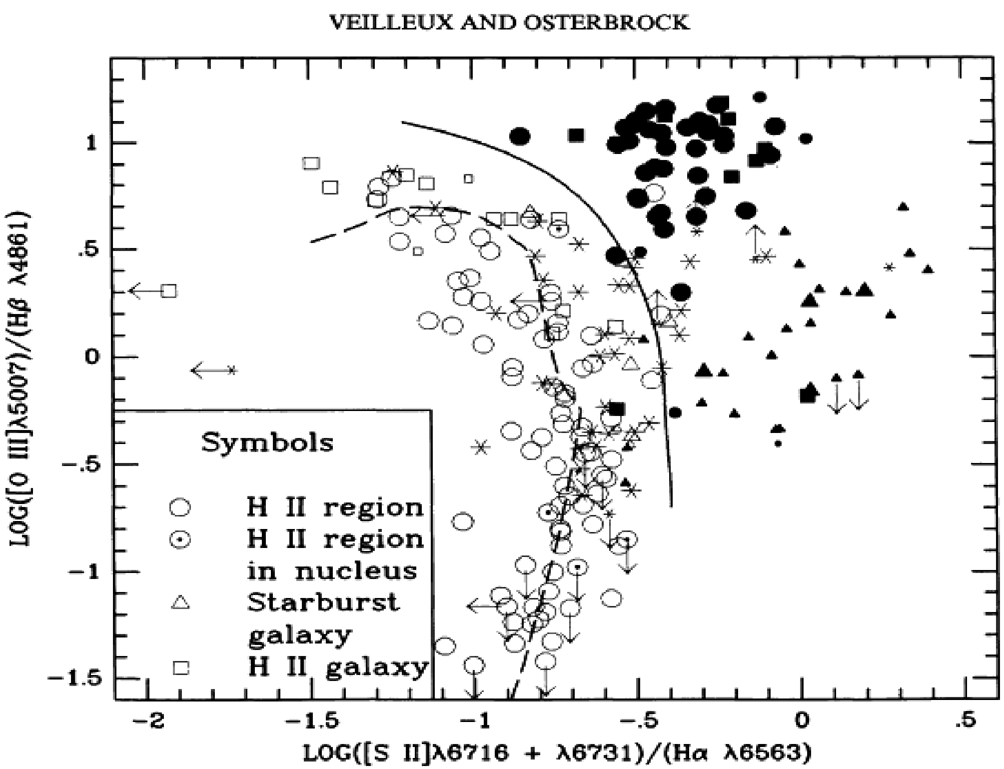


A Type II Seyfert compared to a normal star-forming galaxy



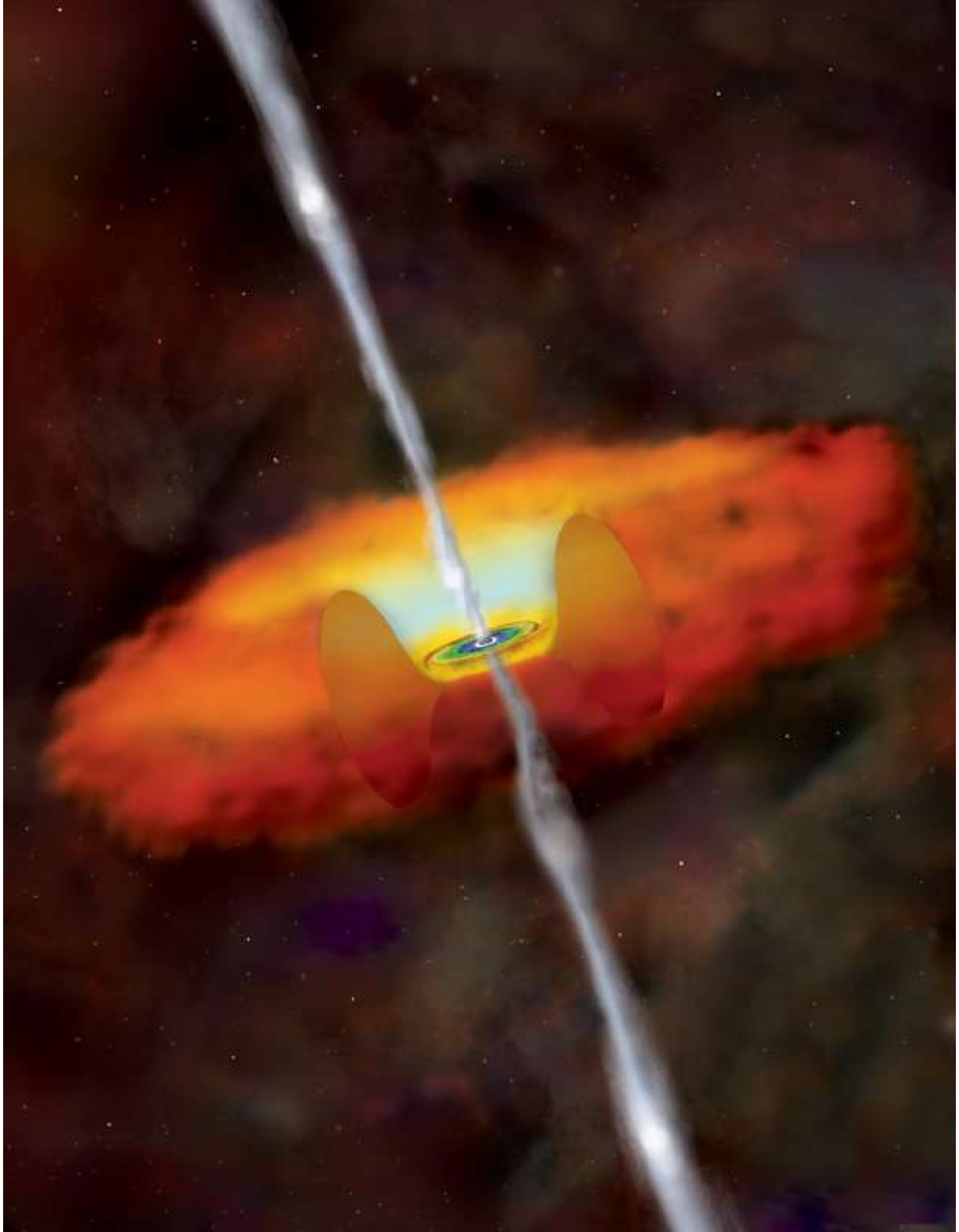






The peculiar line ratios in a Type II Seyfert spectrum can be understood if the source of ionizing radiation is not massive stars, but a source with a much “harder” spectrum.

But why do Seyfert II's not exhibit broad emission lines??



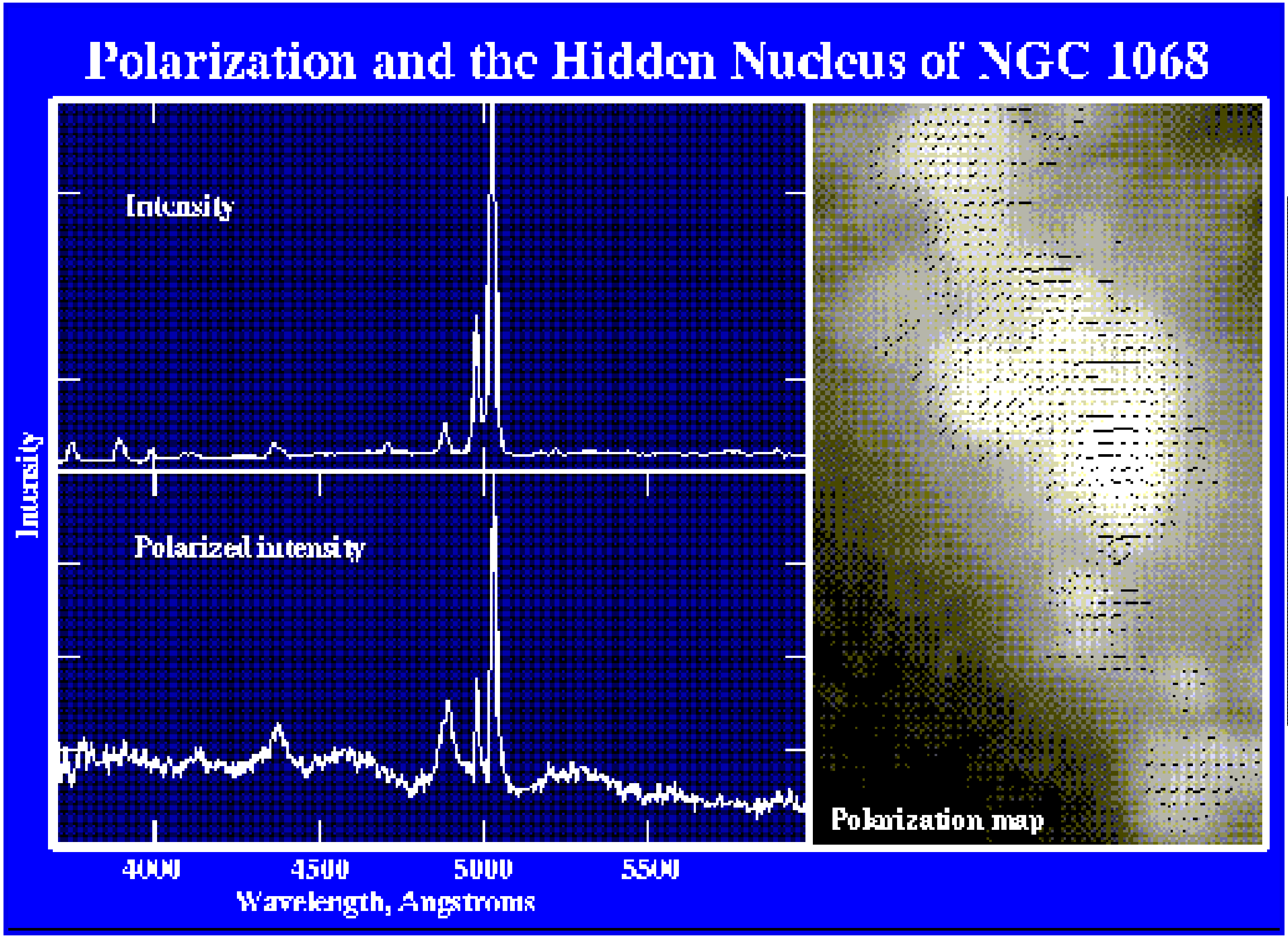
PROPOSED GEOMETRY

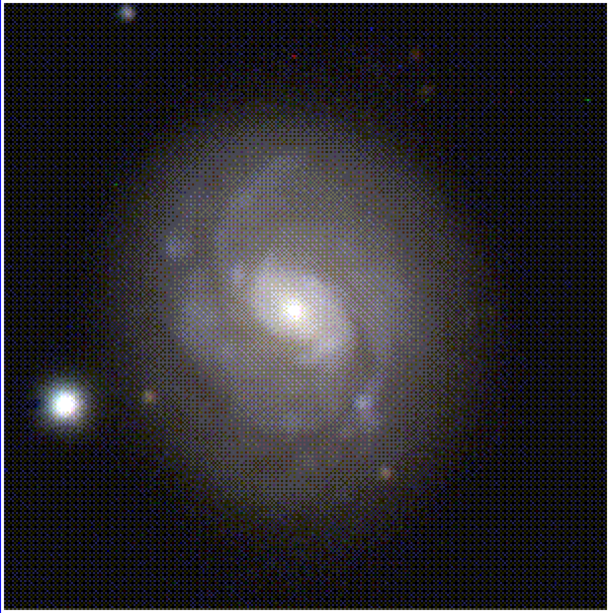
The accretion disk is surrounded by a dusty obscuring “torus”.

One sees a Type II AGN when the torus is oriented perpendicular to the line-of-sight, so that the accretion disk is obscured.

One sees a Type I AGN when one looks at the system face-on.

PROOF: Detection of the "hidden" broad line component in polarized light in NGC1068 by Antonucci & Miller in 1985.



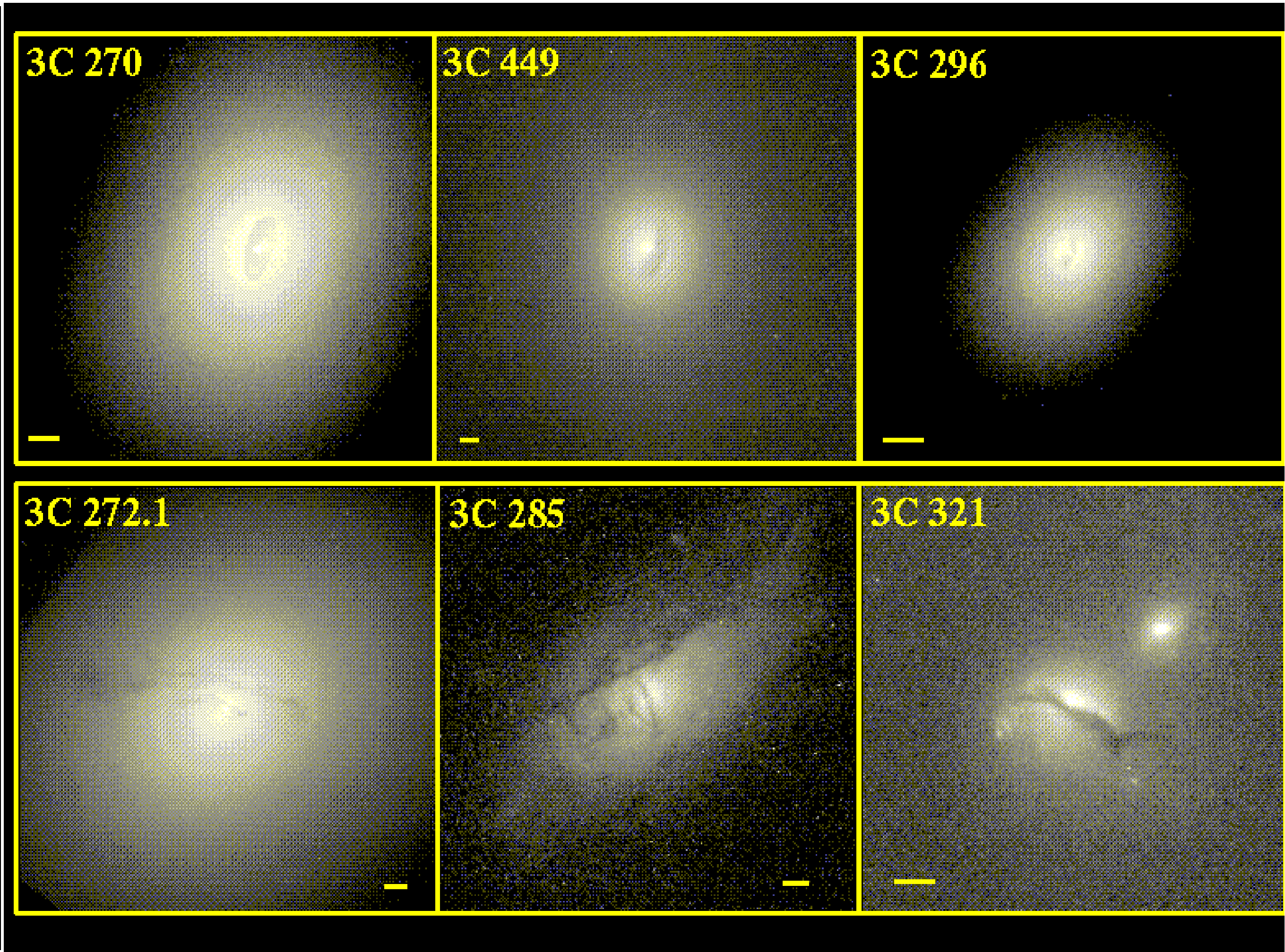


AGN "Unification"

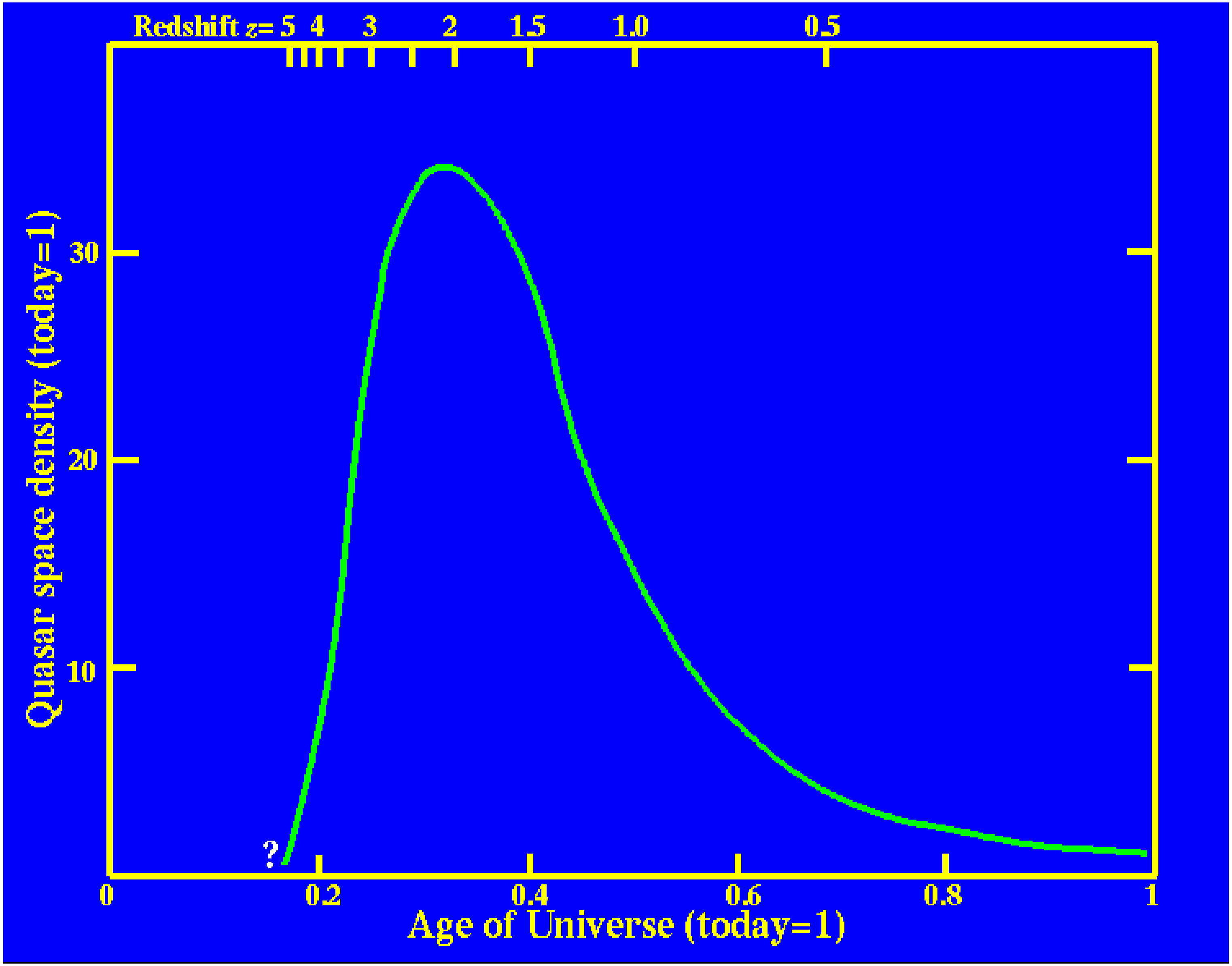
	Accretion disk Obscured	**Accretion disk Unobscured**
Low accretion rate	Seyfert II	Seyfert I
High accretion rate	Type 2 quasars	Classical quasars

Radio galaxies are usually giant elliptical galaxies. They often exhibit jet structure from a compact nucleus. They typically exhibit two lobes of radio frequency emission that are aligned with the jets visible in the optical. The jets may extend over hundreds of kiloparsecs. Their nuclear optical spectra are similar to that of very low power Seyfert galaxies.

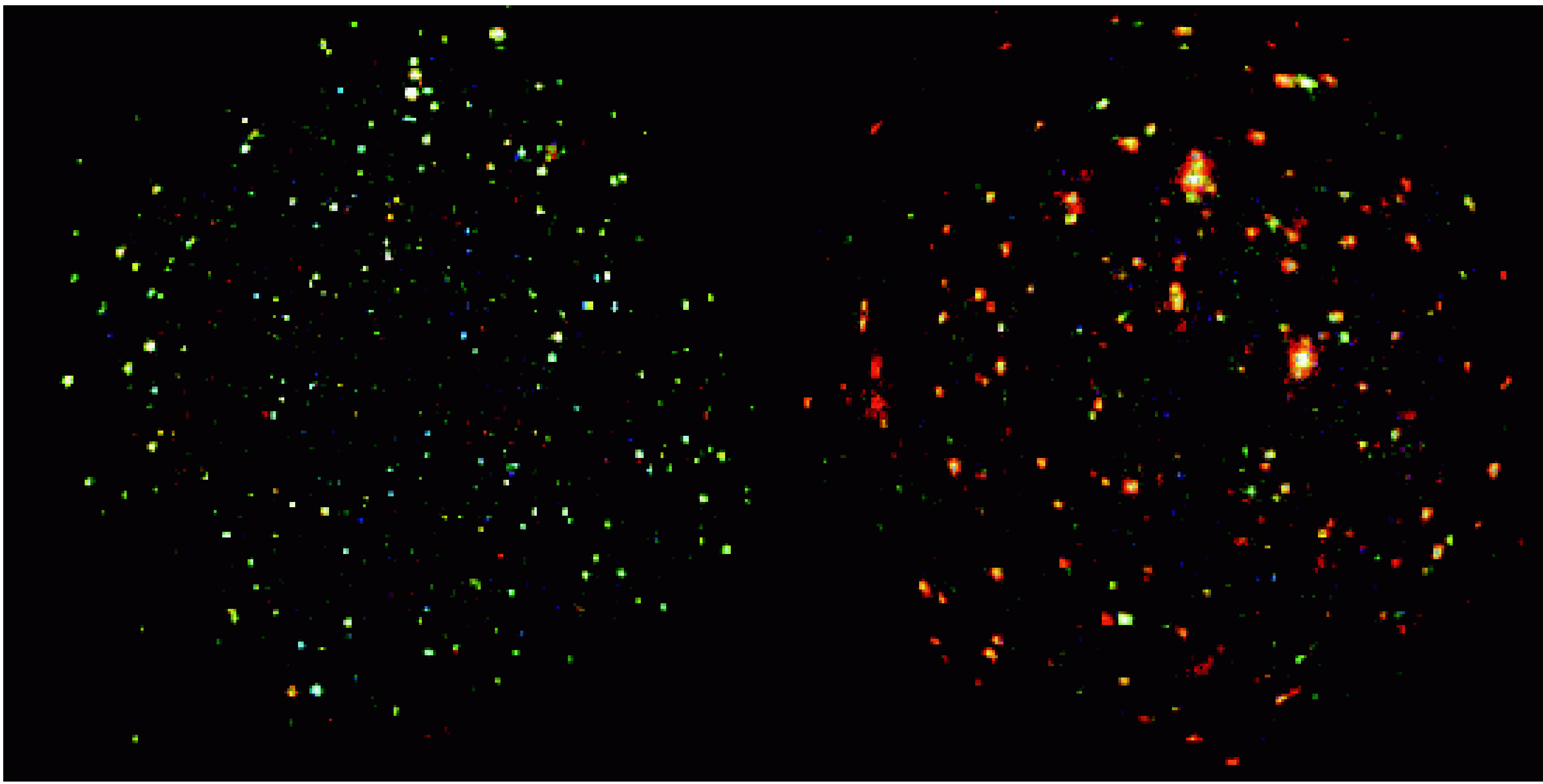
Radio Galaxy 3C288
VLA 4cm image



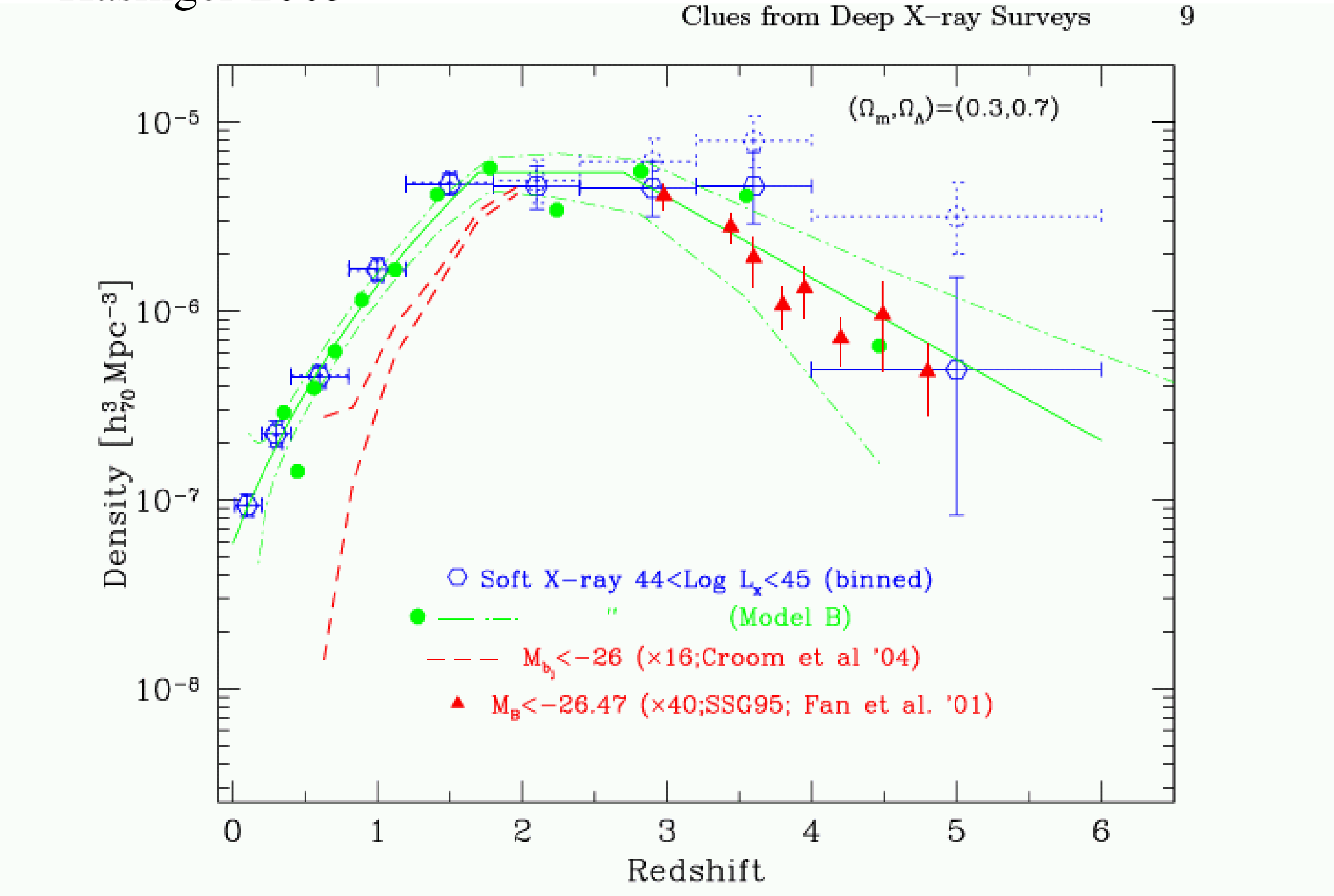
The number density of AGN has evolved very strongly as function of cosmological time...



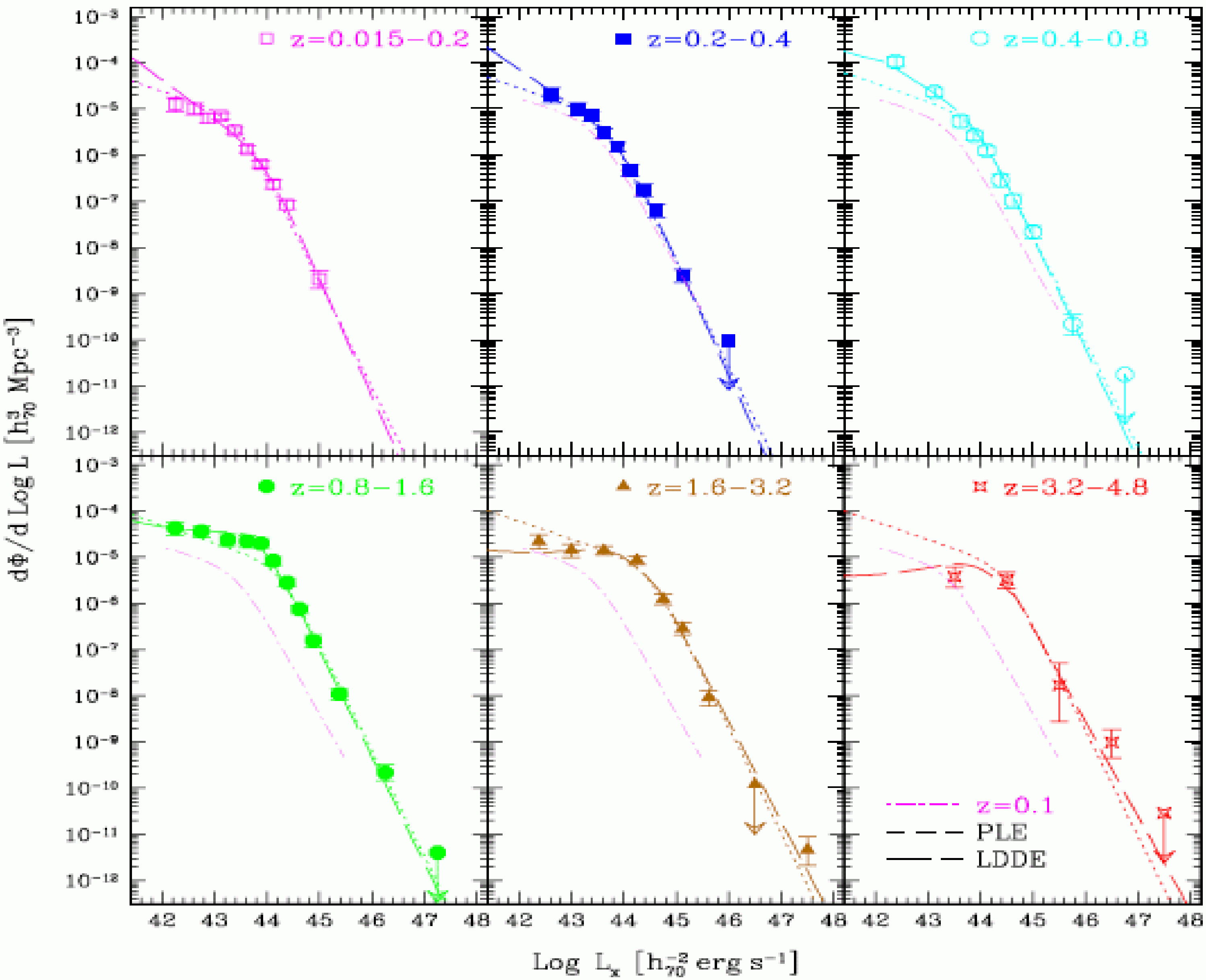
New very deep X-ray surveys are probing the space density of Type II “obscured” quasars and seyferts out to cosmological distances.....



Hasinger 2005



Convert luminosity in seen in AGN to the amount of mass being accreted by black holes. Does this produce the black holes seen today? : **Answer:** yes, roughly.


z=0.015–0.2
z=0.2–0.4
z=0.4–0.8
z=0.8–1.6
z=1.6–3.2
z=3.2–4.8
z=0.1
PLE
LDDE
dΦ/d Log L [h_{70}^3 Mpc^{-3}]
Log L_x [h_{70}^{-2} erg s^{-1}]

Models for the joint evolution of galaxies, quasars and supermassive black holes

Assumption: Black holes are formed and fuelled during the same merging events that destroy disks and make galaxy bulges.
Assumption: Some fraction of the gas present in the galaxy is added to the black hole and fuels the quasar.

Kauffmann & Haehnelt 2000
Cattaneo 2001
Granato et al 2001
Volunteri et al 2003
Di Matteo et al 2003
Bromley et al 2004
Croton et al 2006
Cattaneo et al 2006
Hopkins et al 2005,2006

Figure 5 The mass function of black holes as a function of epoch. Solid, dotted, short-dashed, long-dashed, short dashed-dotted and long dashed-dotted show results at z=0, 0.5, 1, 2, 3.1 and 3.8 respectively.

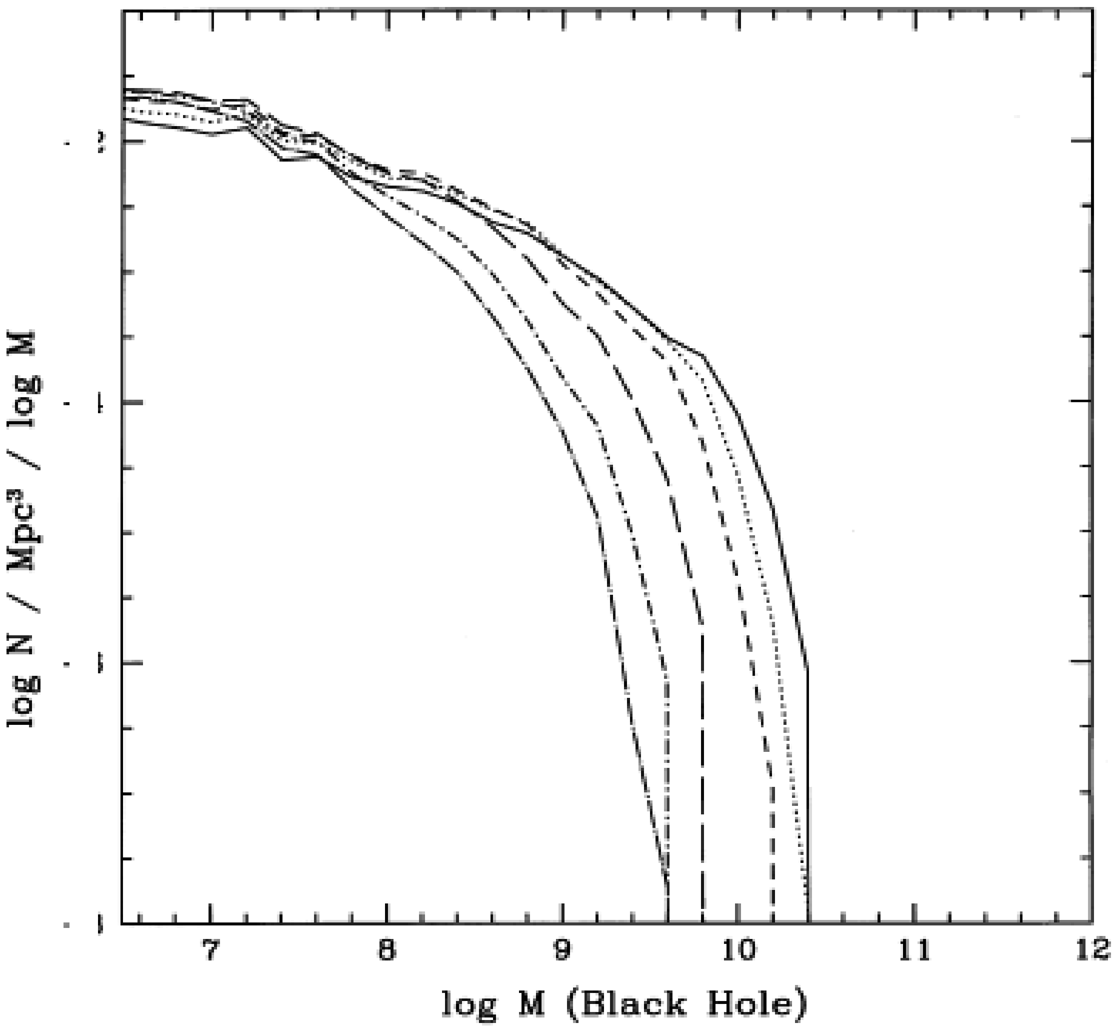
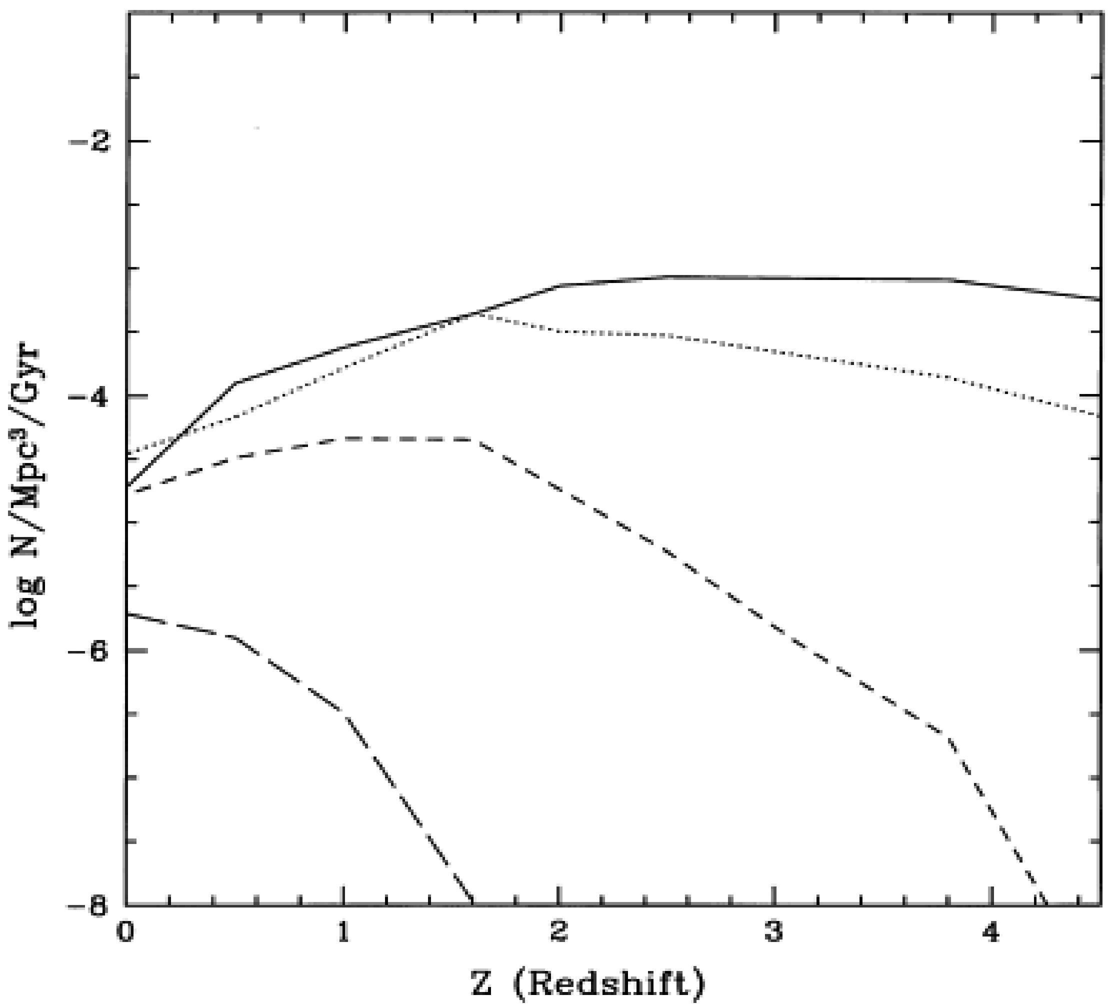


Figure 6 The evolution of the number of major mergers per Gyr and per comoving cubic Mpc which produce black holes of different mass. Solid, dotted, short-dashed and long-dashed lines show results for merged galaxies containing black holes with 10^7, 10^8, 10^9 and 10^{10} M respectively.



Critical aspect of the model: galaxies are more gas rich at higher redshift

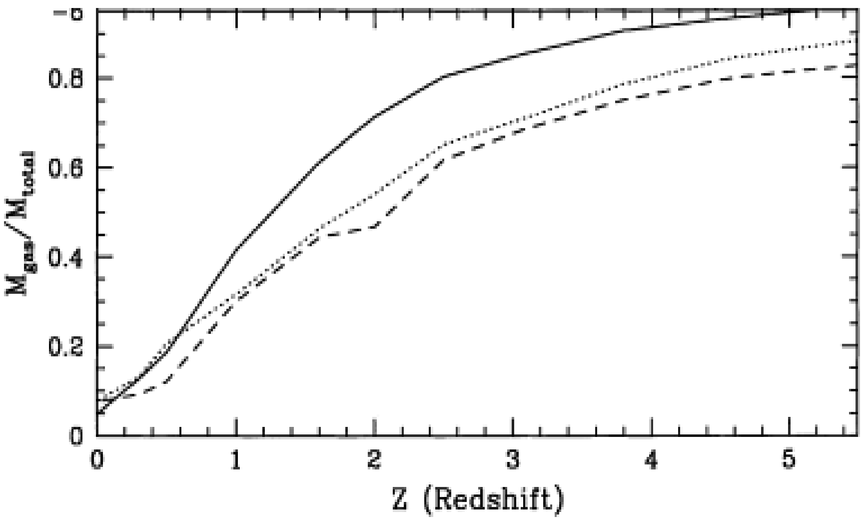


Figure 17 Top: the evolution of the space density of quasars with M_B<-26 f
Bottom: the same for quasars with M_B<24.

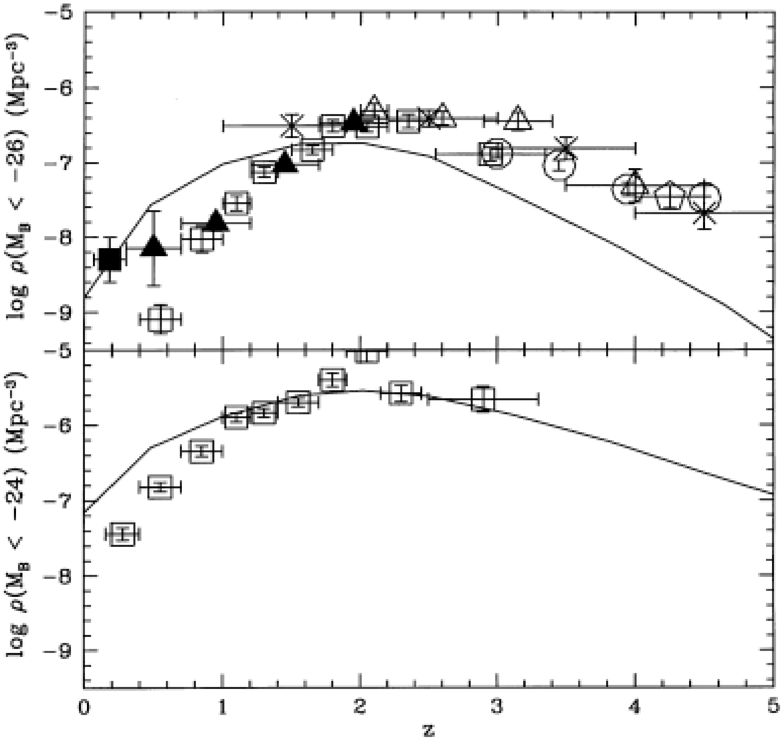
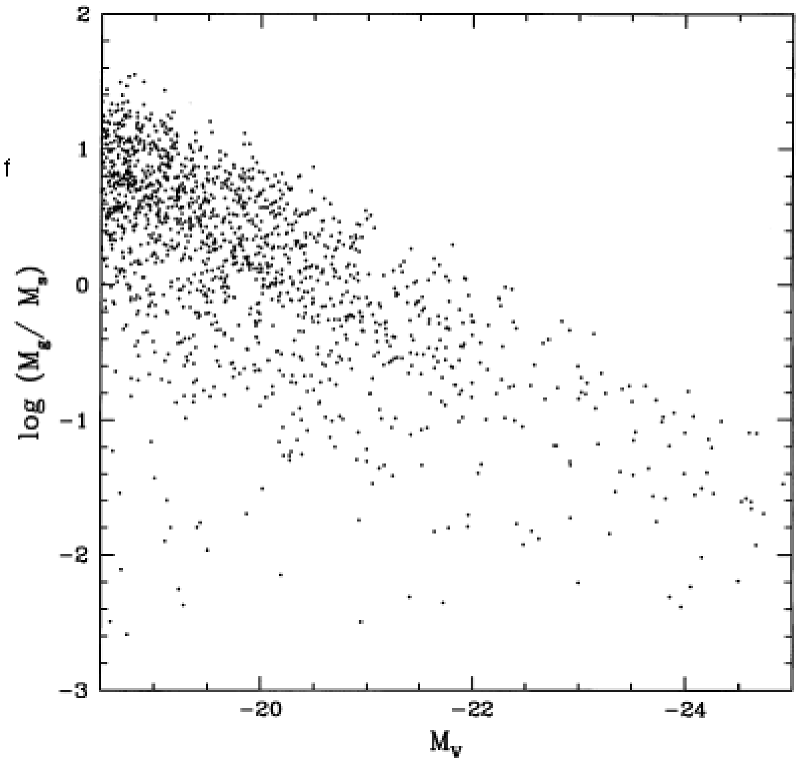
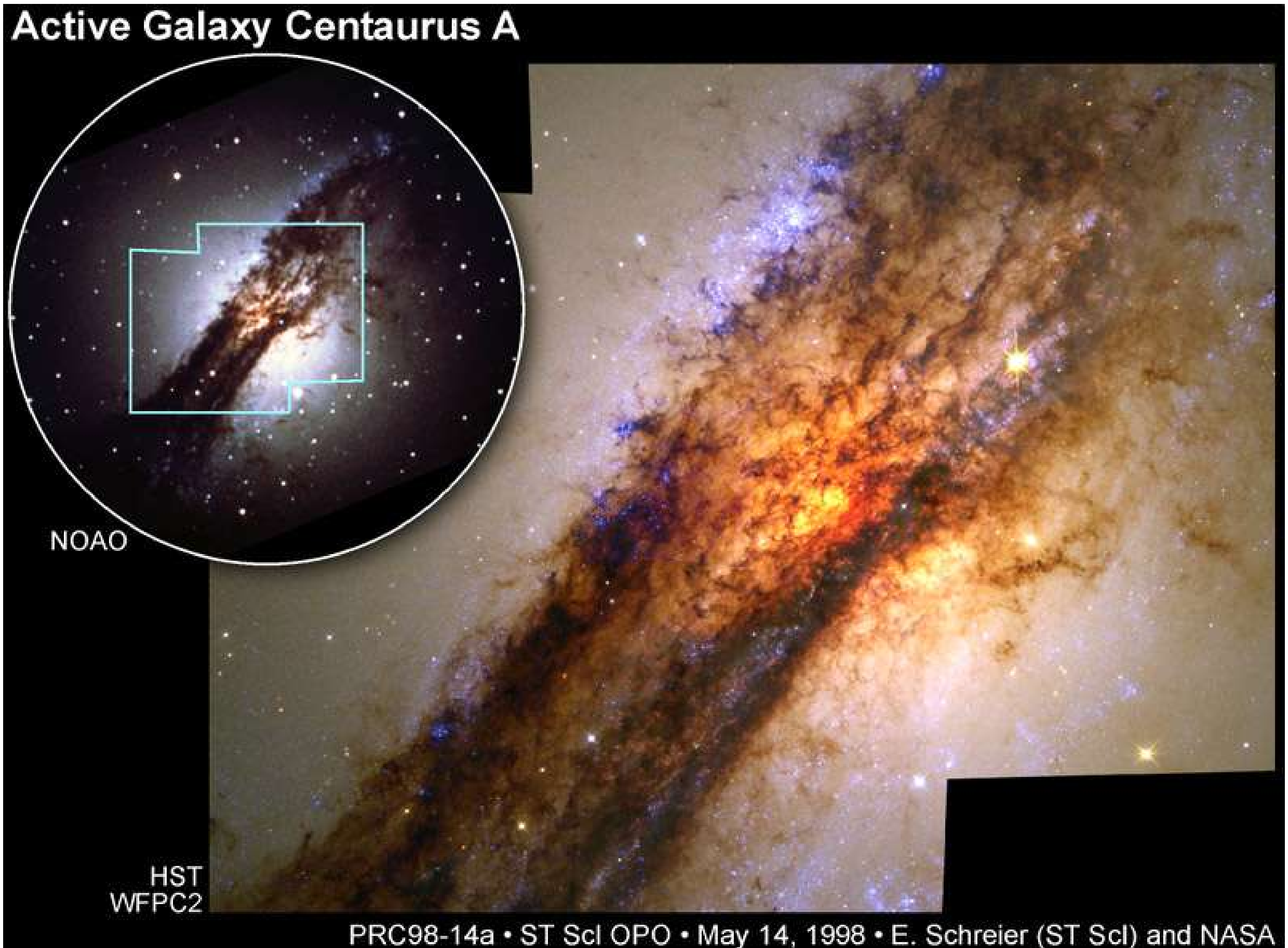


Figure 14 The ratio of gas mass to stellar mass present during the last major merger of an elliptical galaxy of present-day magnitude M_V

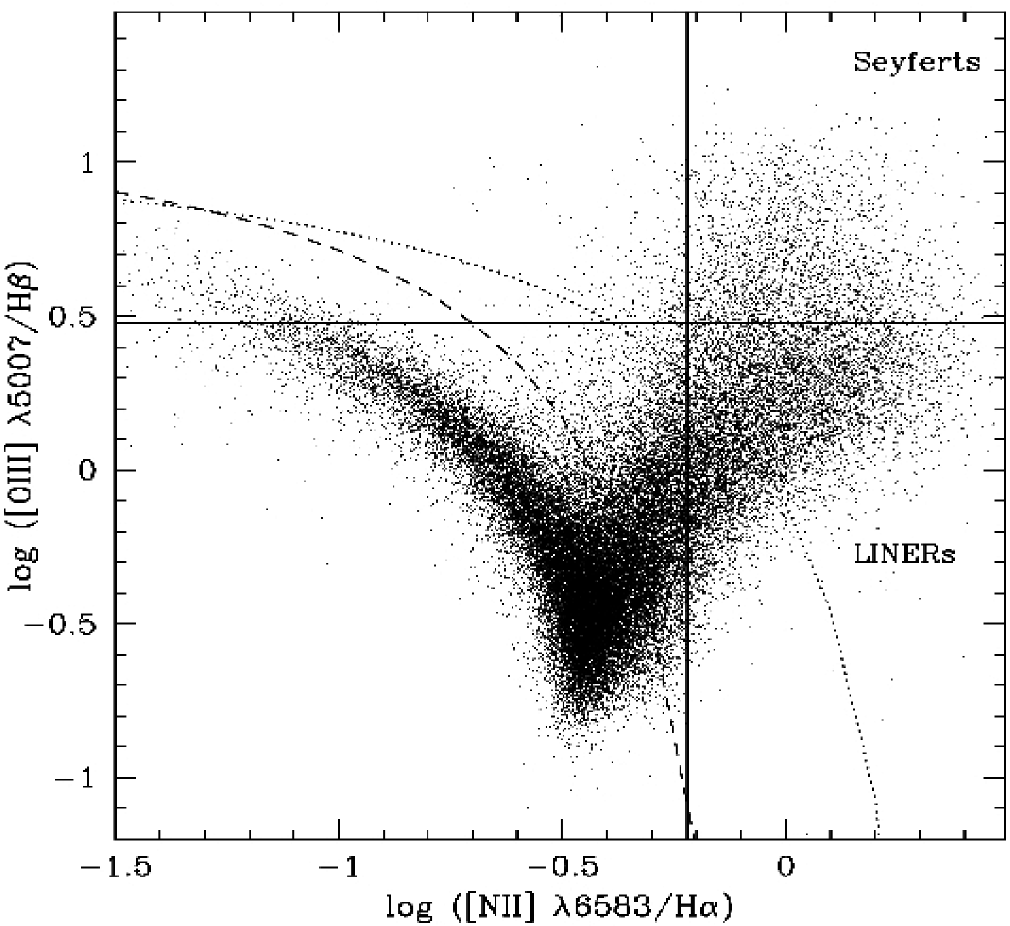


What is the observational evidence that AGN are signposts of "bulges-in-formation"?



Surveys of Type II AGN at Low Redshifts from SDSS

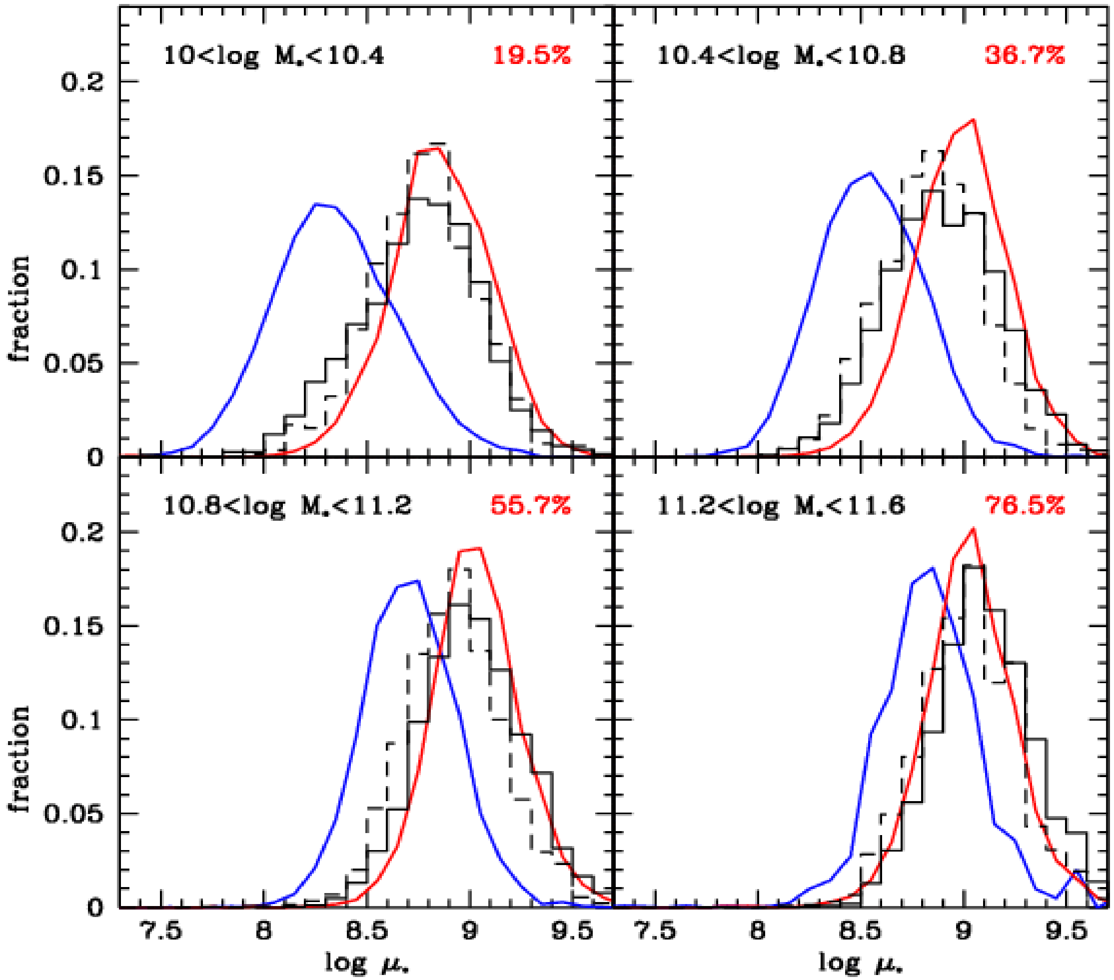
(for detailed analysis of host galaxy properties)



Kauffmann et al 2003

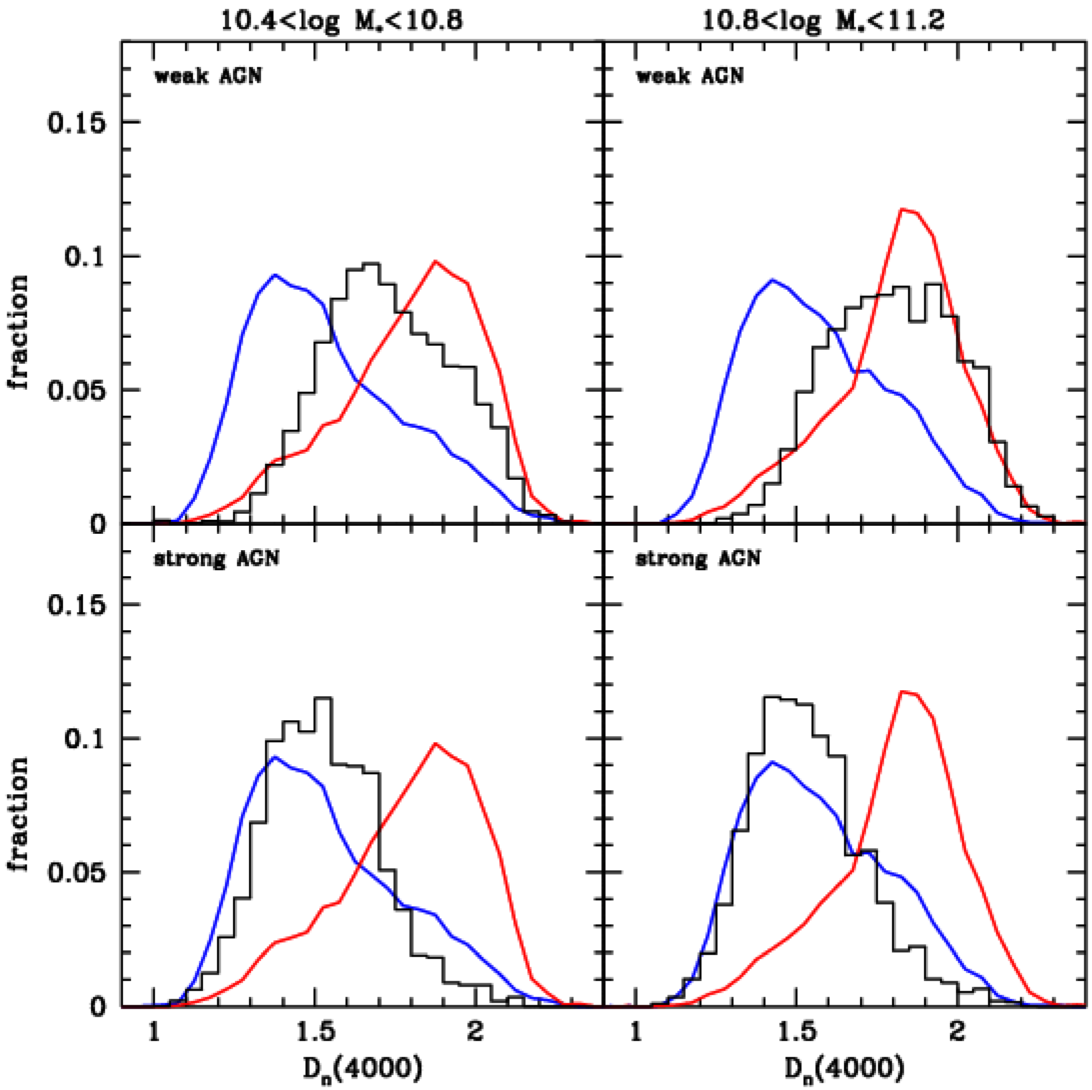
Star formation in bulges:

The structural properties of AGN compared to early- and late-type galaxies: low redshifts

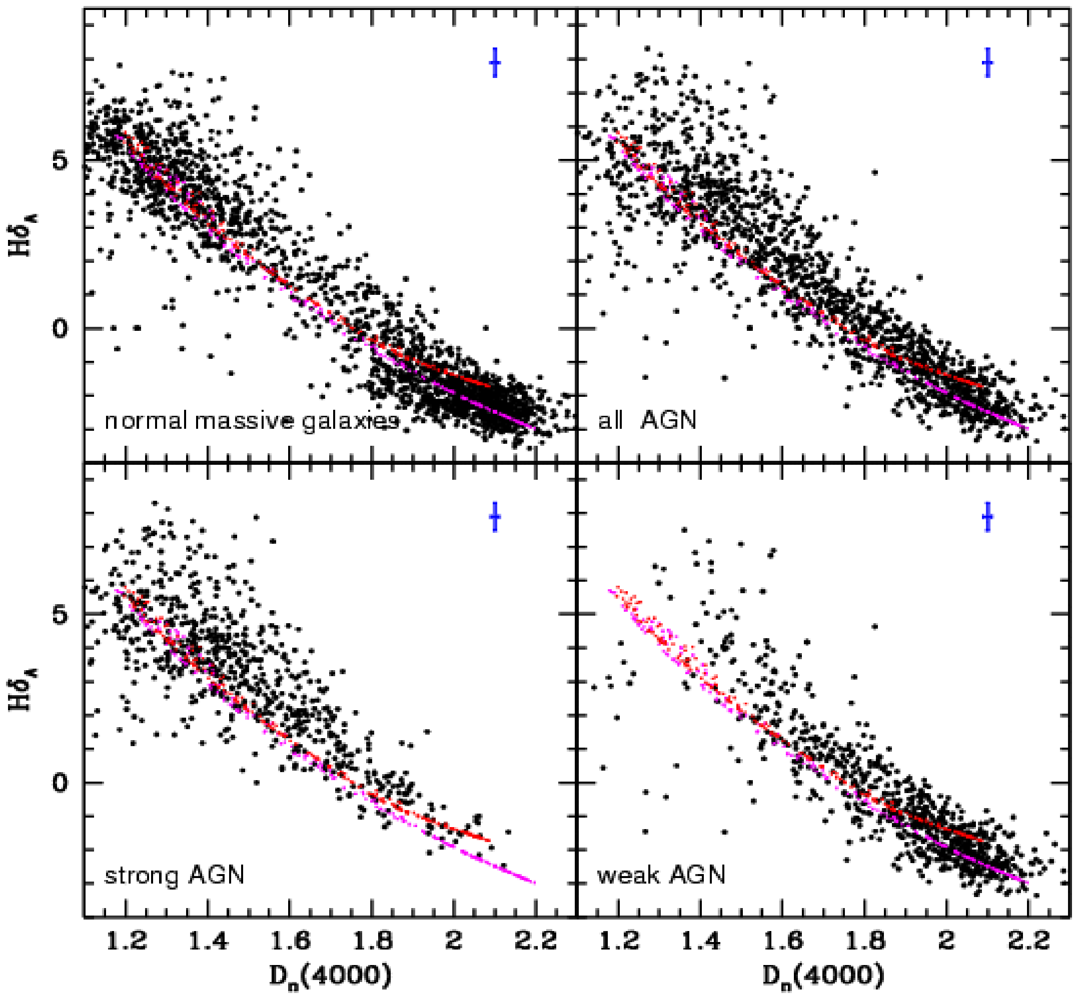


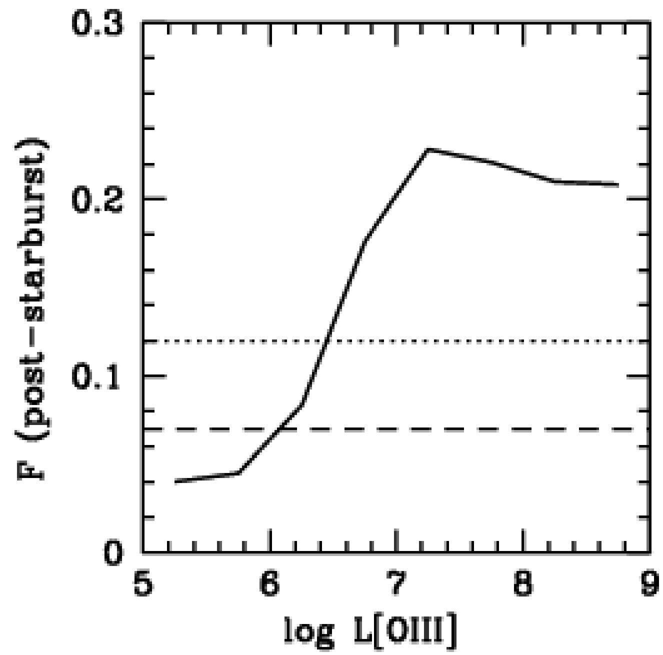
Kauffmann et al 2003

Mean stellar ages of AGN compared to late- and early-type galaxies



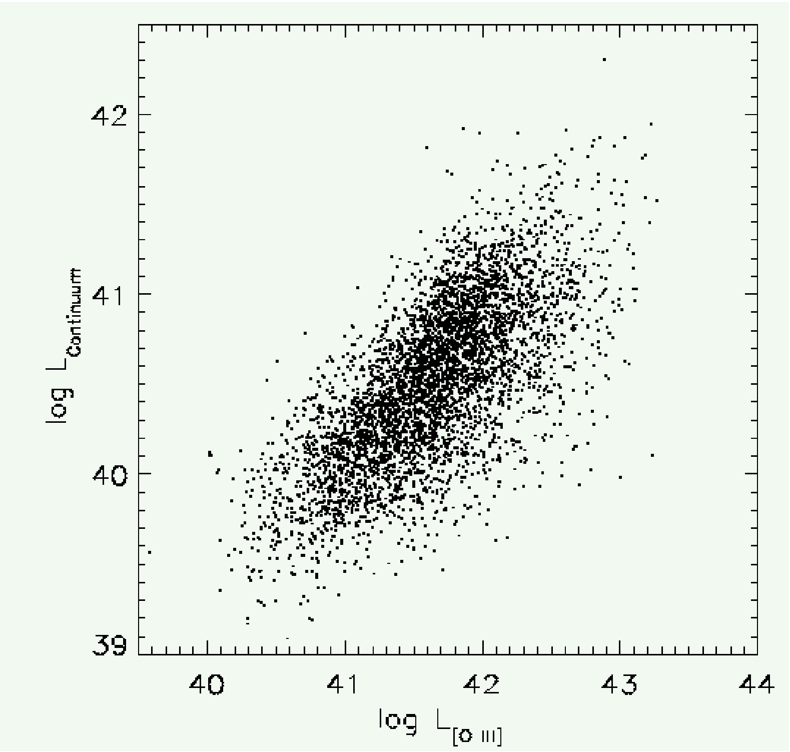
We see evidence that powerful AGN have experienced recent **STARBURSTS...**



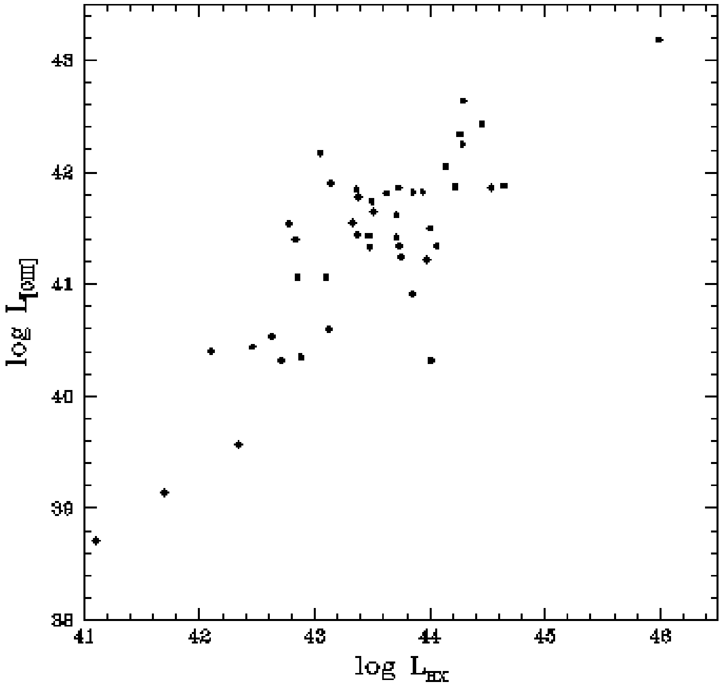


Accretion

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

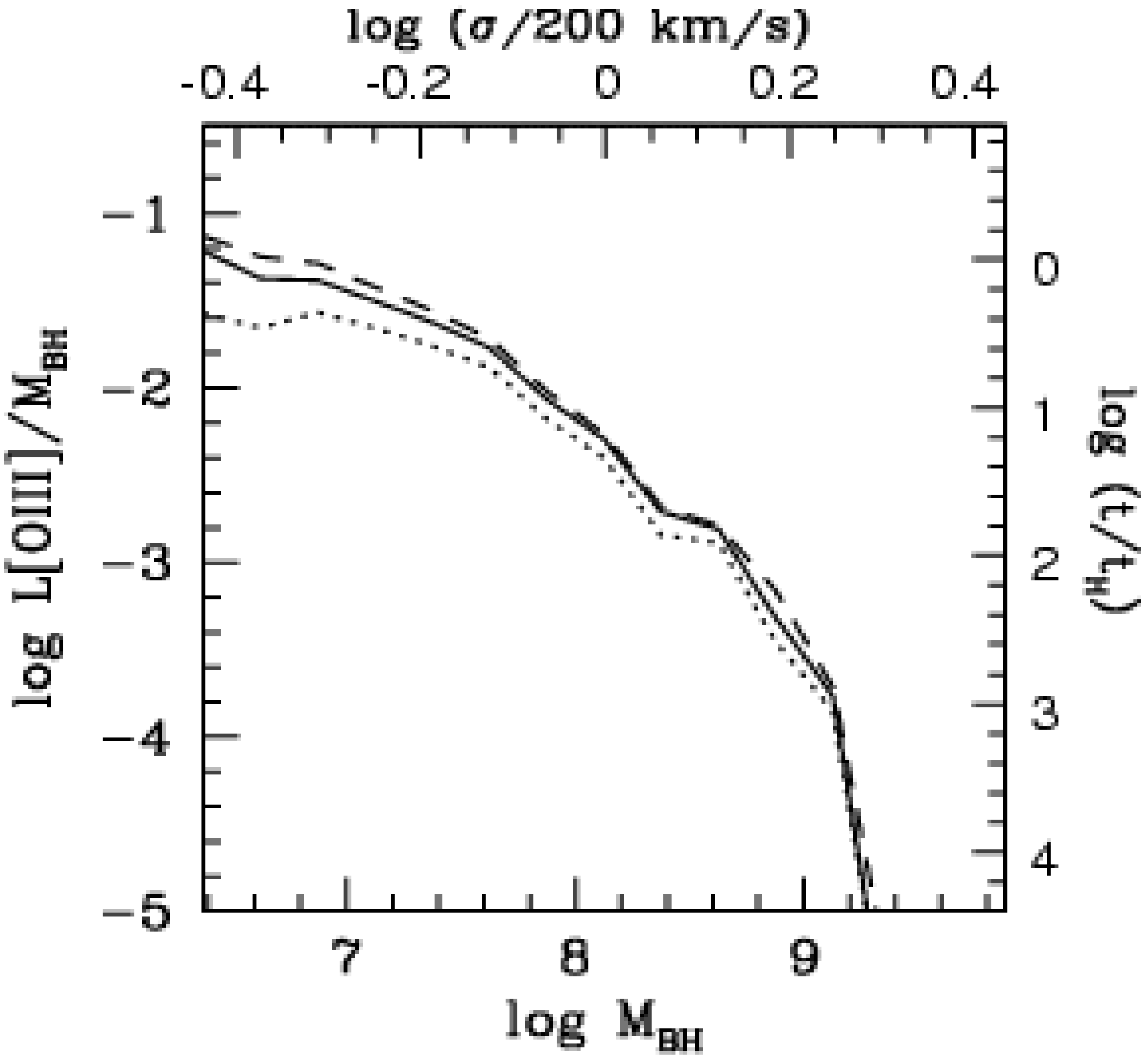


Correlation of [OIII] luminosity with continuum luminosity for Type 1 AGN (Zakamska et al 2003)



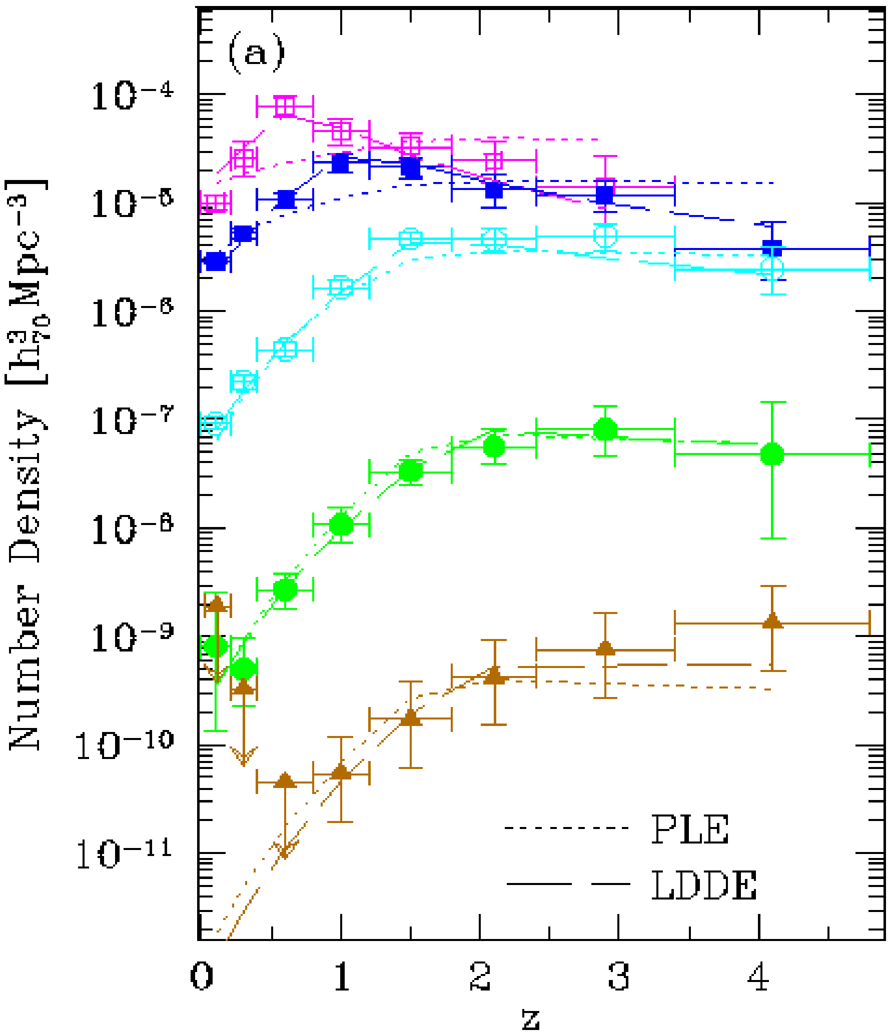
Correlation of [OIII] luminosity with hard x-ray luminosity (Heckman et al 2005)

Most of the accretion today is occurring onto low mass black holes.

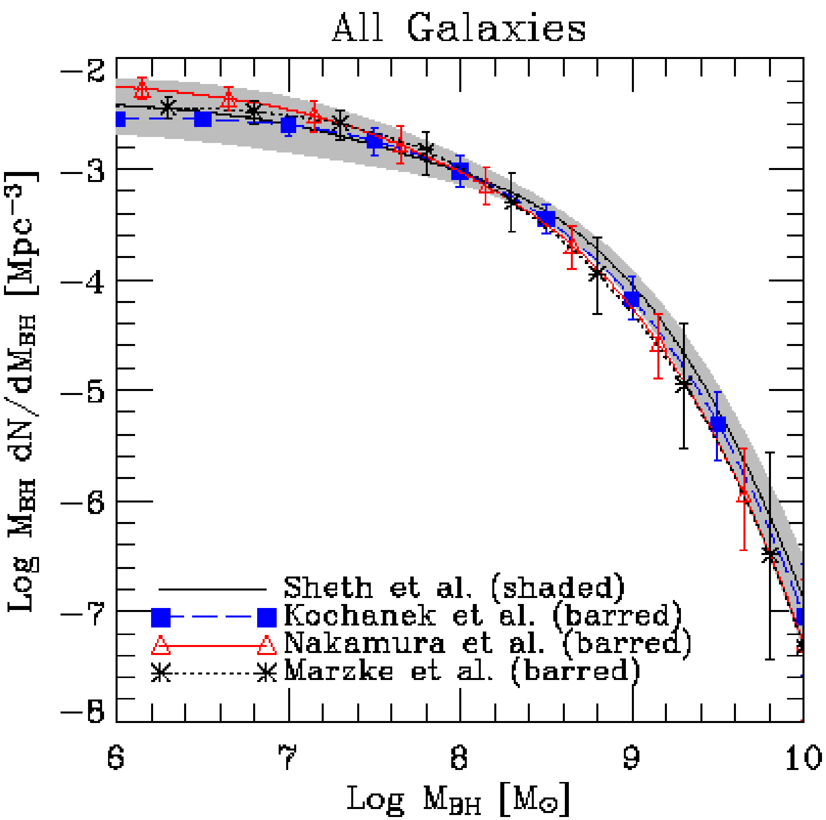


Heckman et al 2004

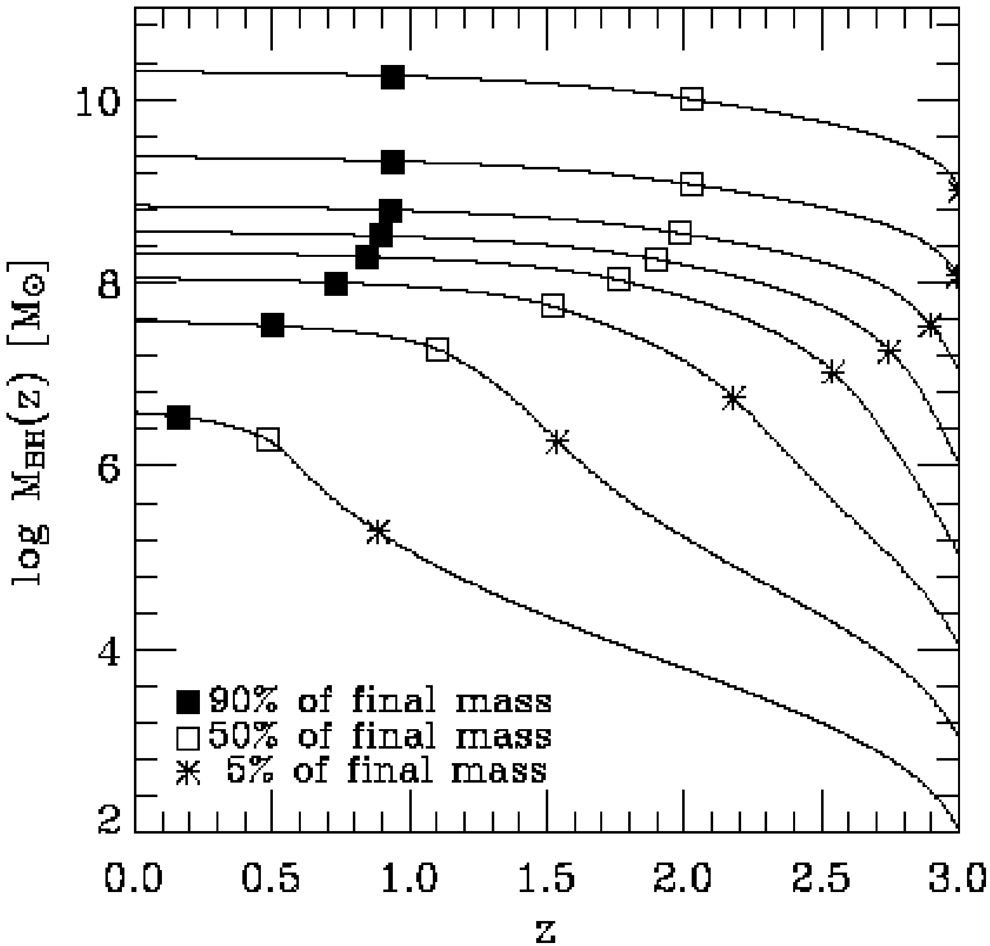
The history of accretion:



Hasinger et al 2005

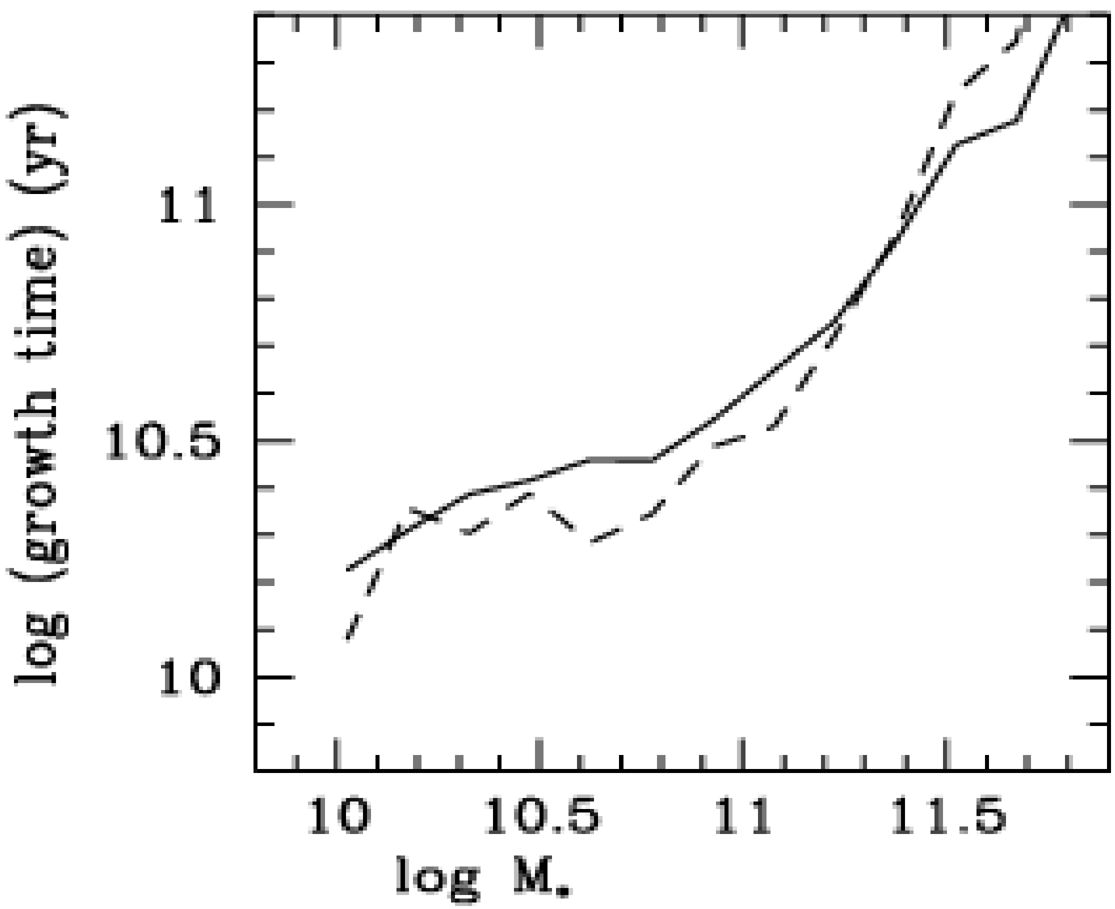


Downsizing: The characteristic mass of actively accreting black holes is getting smaller at lower redshifts.
A consistent picture!



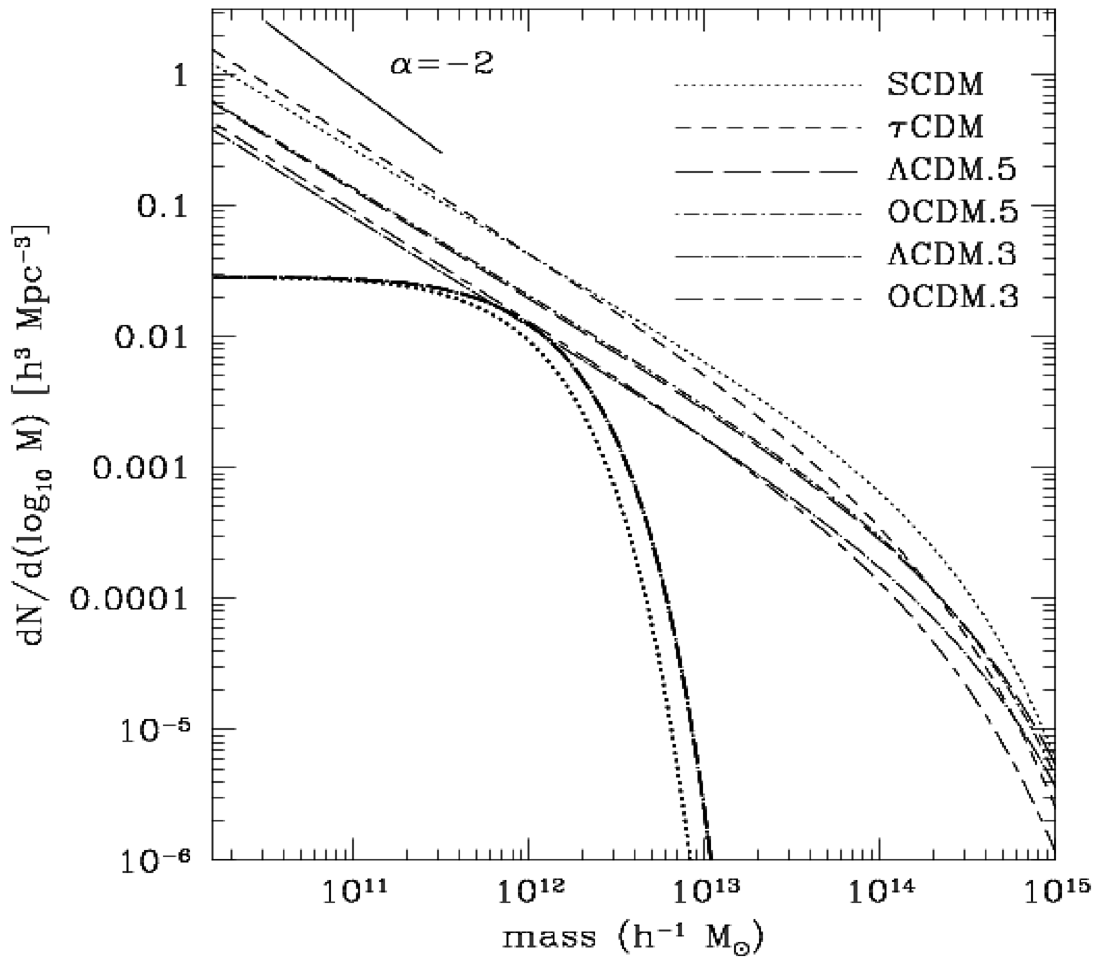
Marconi et al 2004

The estimated growth time of the bulge through star formation is the same as the growth time of the black hole .



3) Does AGN feedback help resolve some long-standing problems in galaxy formation?

Why does the galaxy luminosity function have a Schechter form?



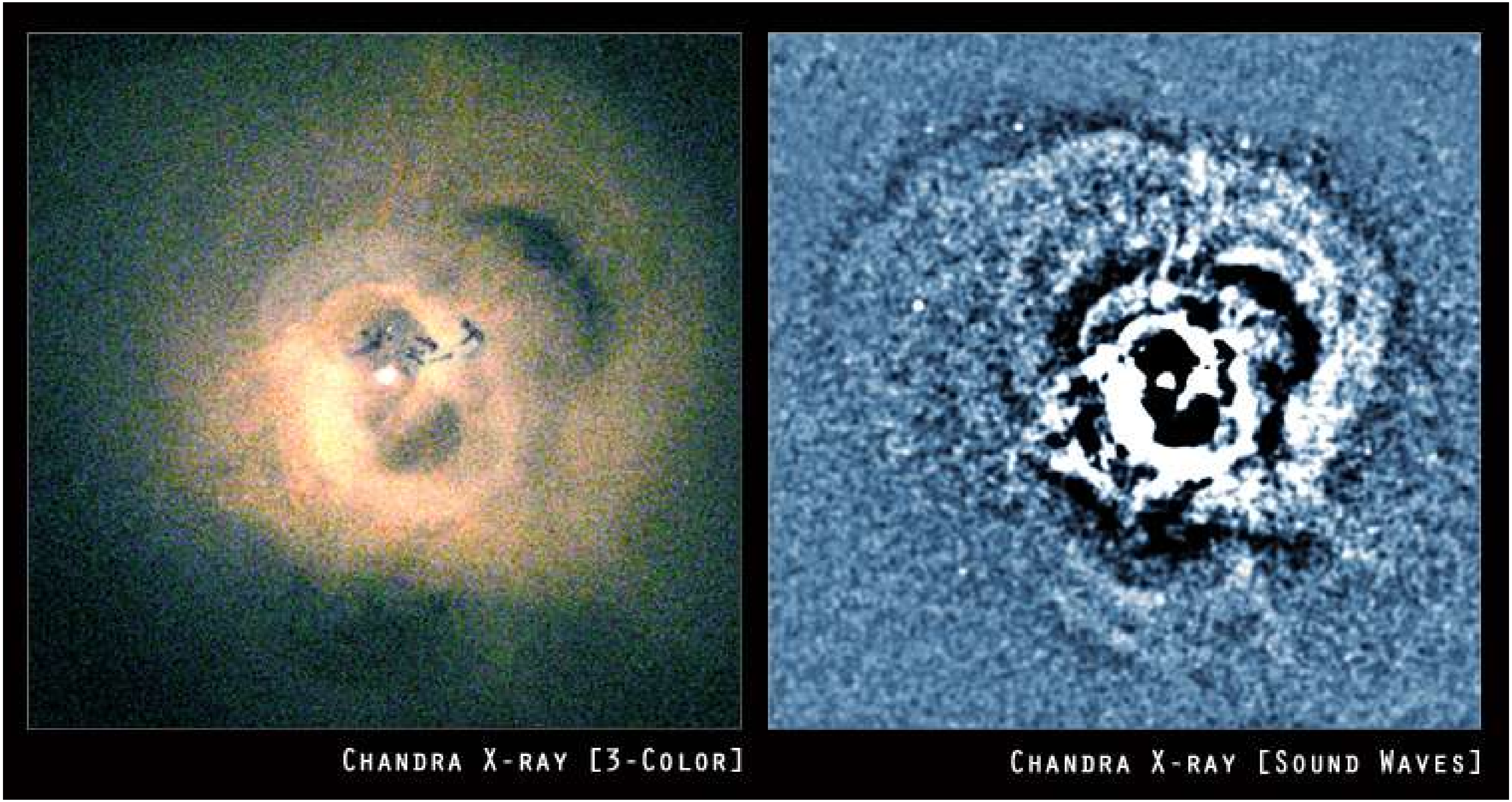
Somerville & Primack 2001

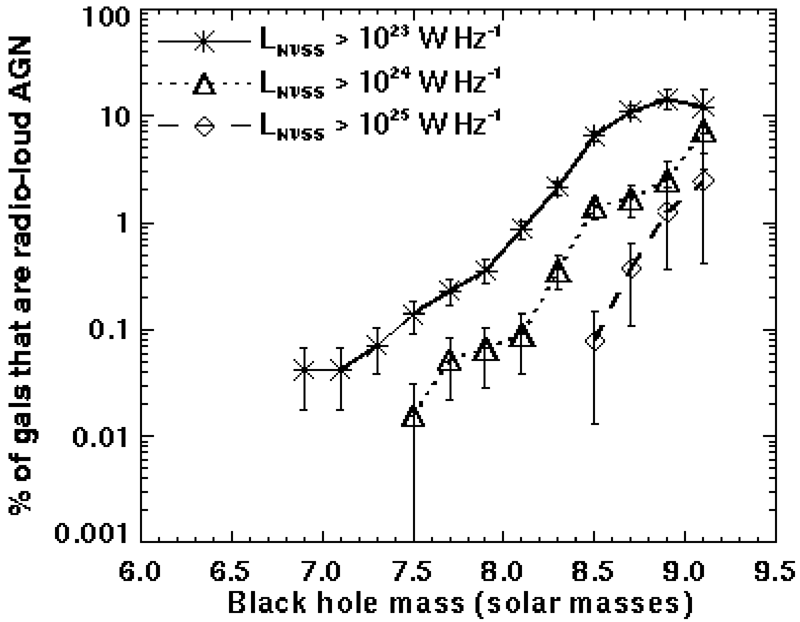
In order to prevent the formation of too many very massive galaxies, one must reduce the efficiency with which gas is able to cool in dark matter halos with very large masses.

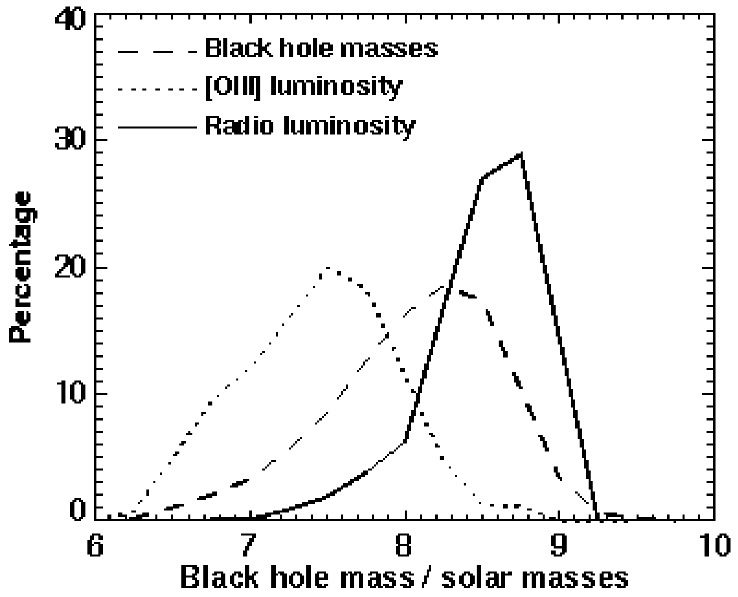
However, massive galaxies found in the massive halos are **RED** with very little ongoing star formation. We therefore require a source of feedback that is **NOT RELATED TO STAR FORMATION.** As we have seen, optical AGN activity is closely linked with strong star formation events in a galaxy.

Candidate: Radio -loud AGN.

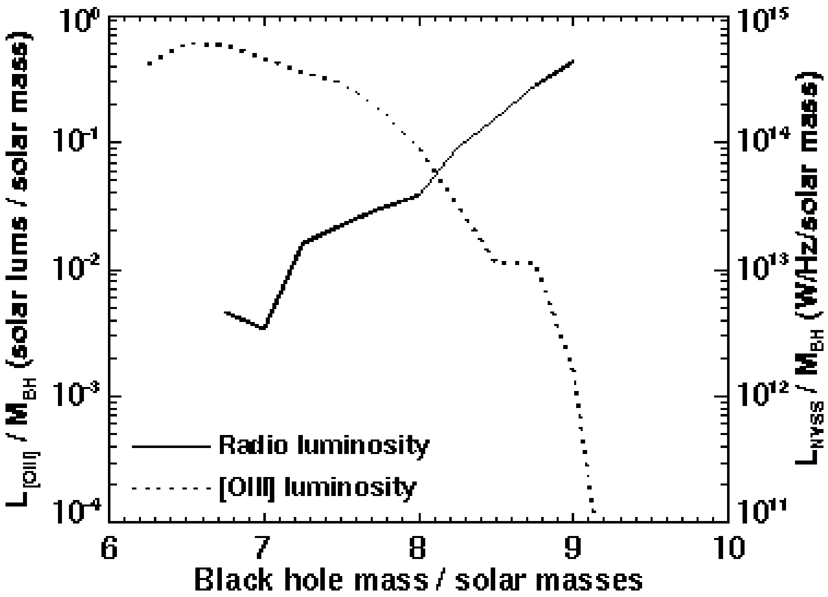
In clusters, there is evidence that radio galaxies may be regulating gas cooling onto the central cluster galaxy.







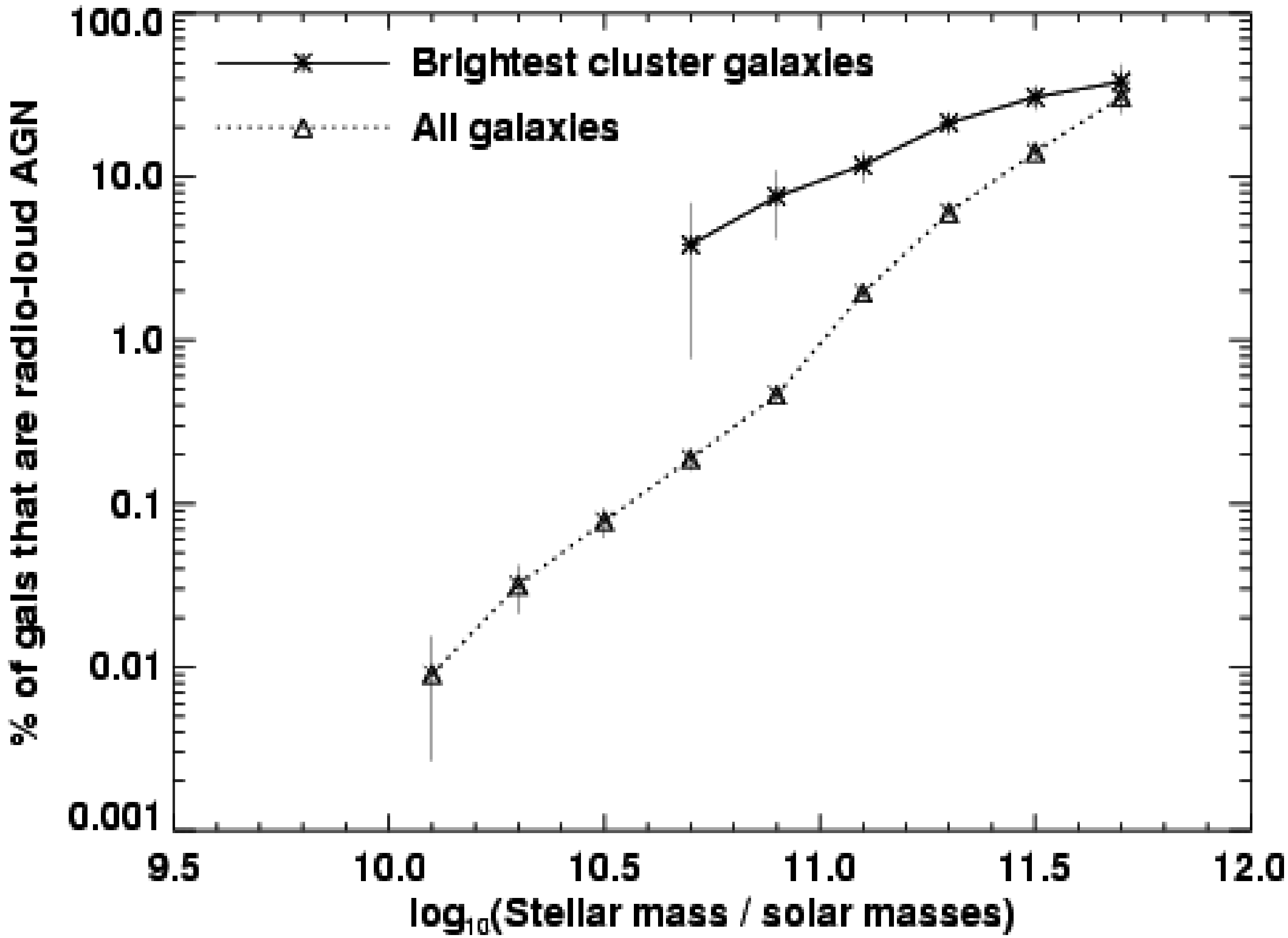
Radio galaxies are strongly biased towards high mass galaxies that contain massive black holes.



Best et al 2005

Radio-loud fraction is significant boosted in the central galaxies in clusters and groups.

Van der Linden, in preparation



In the local Universe, radio AGN are located in the "right places" to solve the over-cooling problem for large galaxies.

New work by Croton et al 2005

Ingredients for a model for the joint evolution of galaxies and their black holes.

The "quasar" mode

In the quasar mode, super-massive black holes grow through merging events where black holes coalesce and cold disk gas is driven onto the central black hole.

$$\dot{m}_{BH,Q} = \frac{f_{BH} m_{cold}}{1 + (280\mathrm{kms}^{-1}/\mathrm{V}_{\mathrm{vir}})^2}$$

This is the primary mode of black hole growth

(Kauffmann & Haehnelt 2000)

Ingredients

The "radio" mode

In the radio mode, quiescent hot gas accretes onto the central super-massive black hole. This ongoing accretion comes from the surrounding hot halo, where we capture the mean behavior with an empirical equation.

$$\dot{m}_{BH,R} = \kappa_{\rm AGN} \left(\frac{m_{BH}}{10^7 M_\odot} \right) \left(\frac{V_{vir}}{200 {\rm kms}^{-1}} \right)^3$$

This accretion is typically well below the Eddington rate

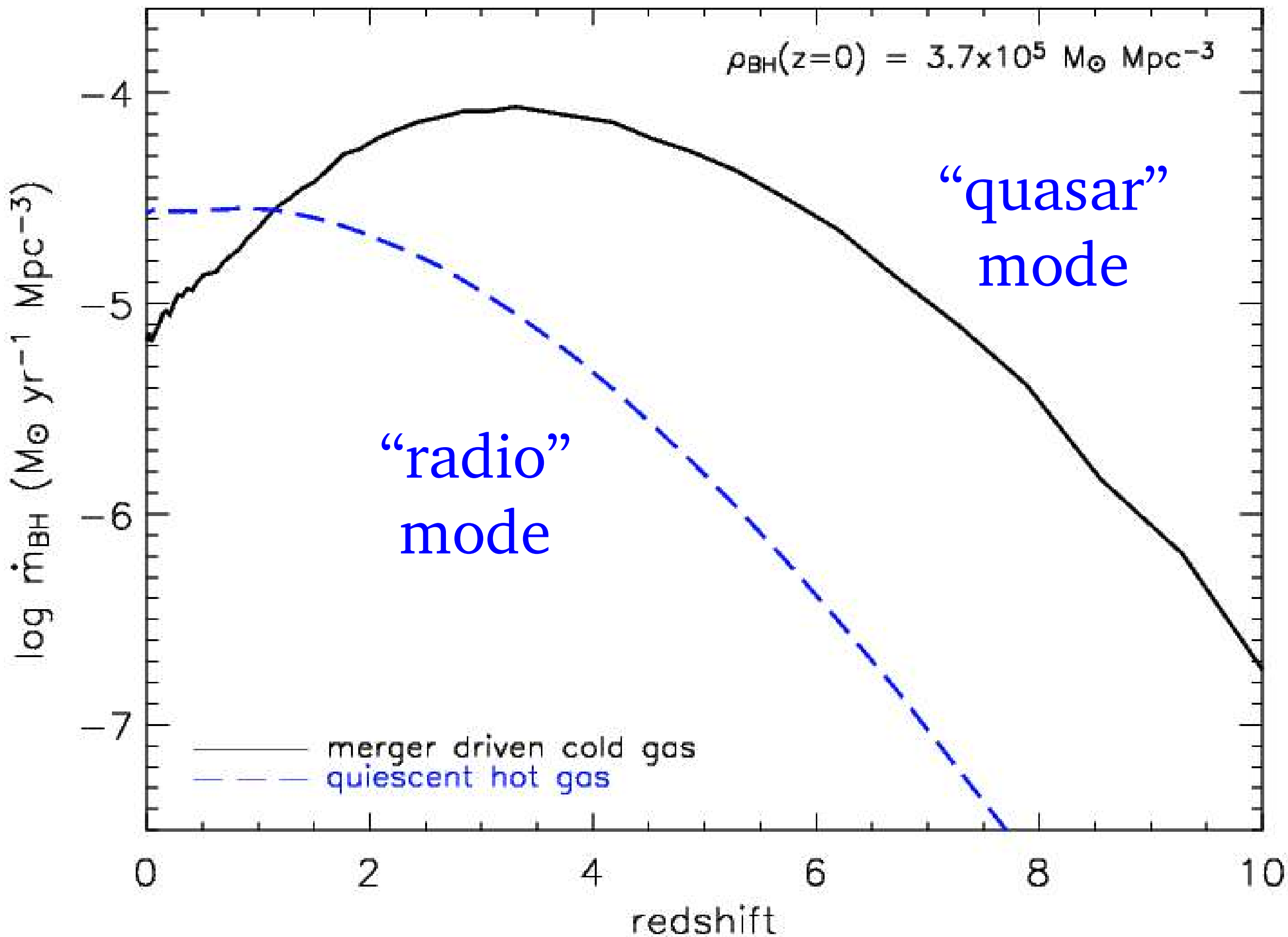
Results – BH growth

Black hole mass accretion history

Black hole mass density at z=0

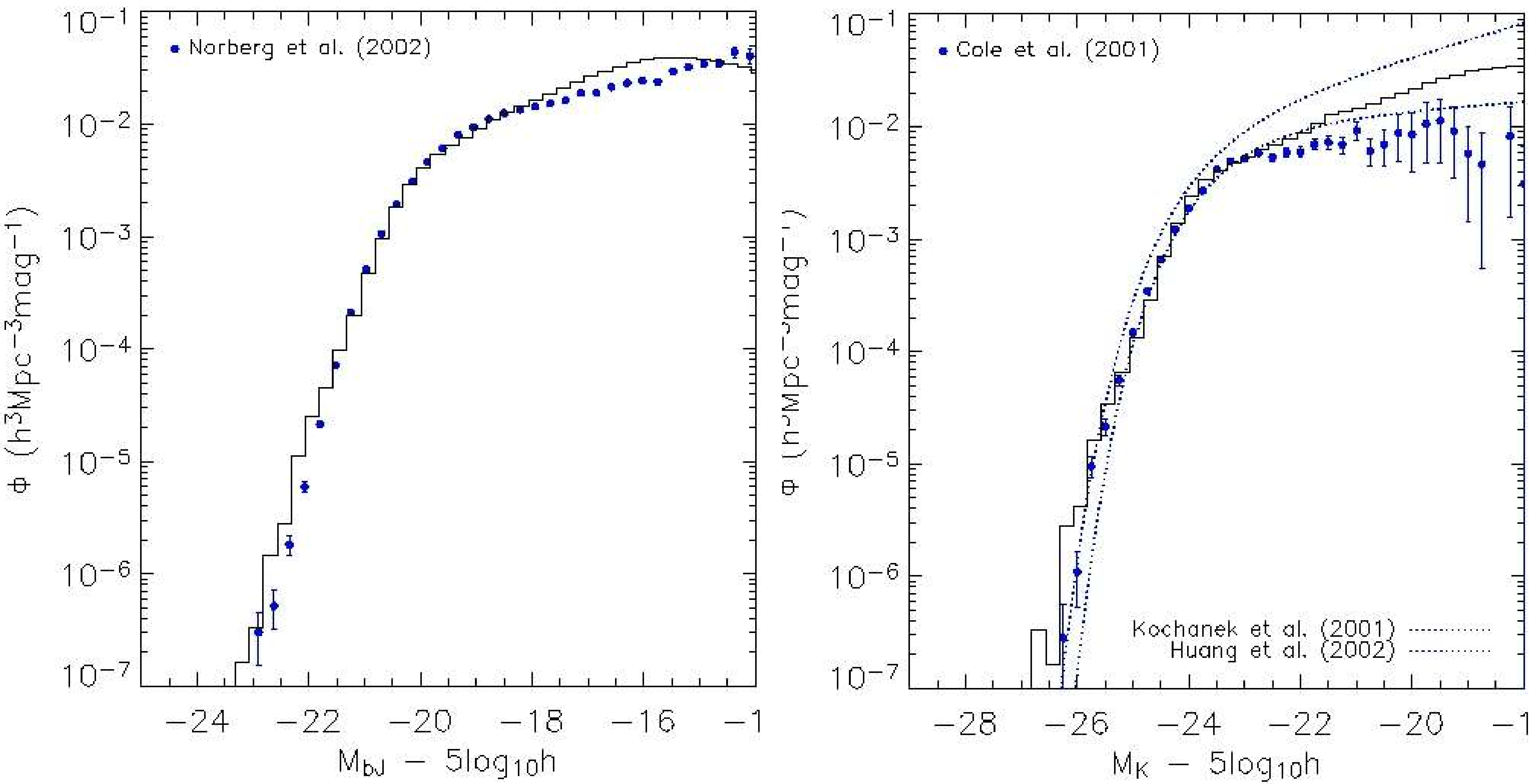
2-5 x 10^5 Msun Mpc^{-3}

(Merloni 2004)



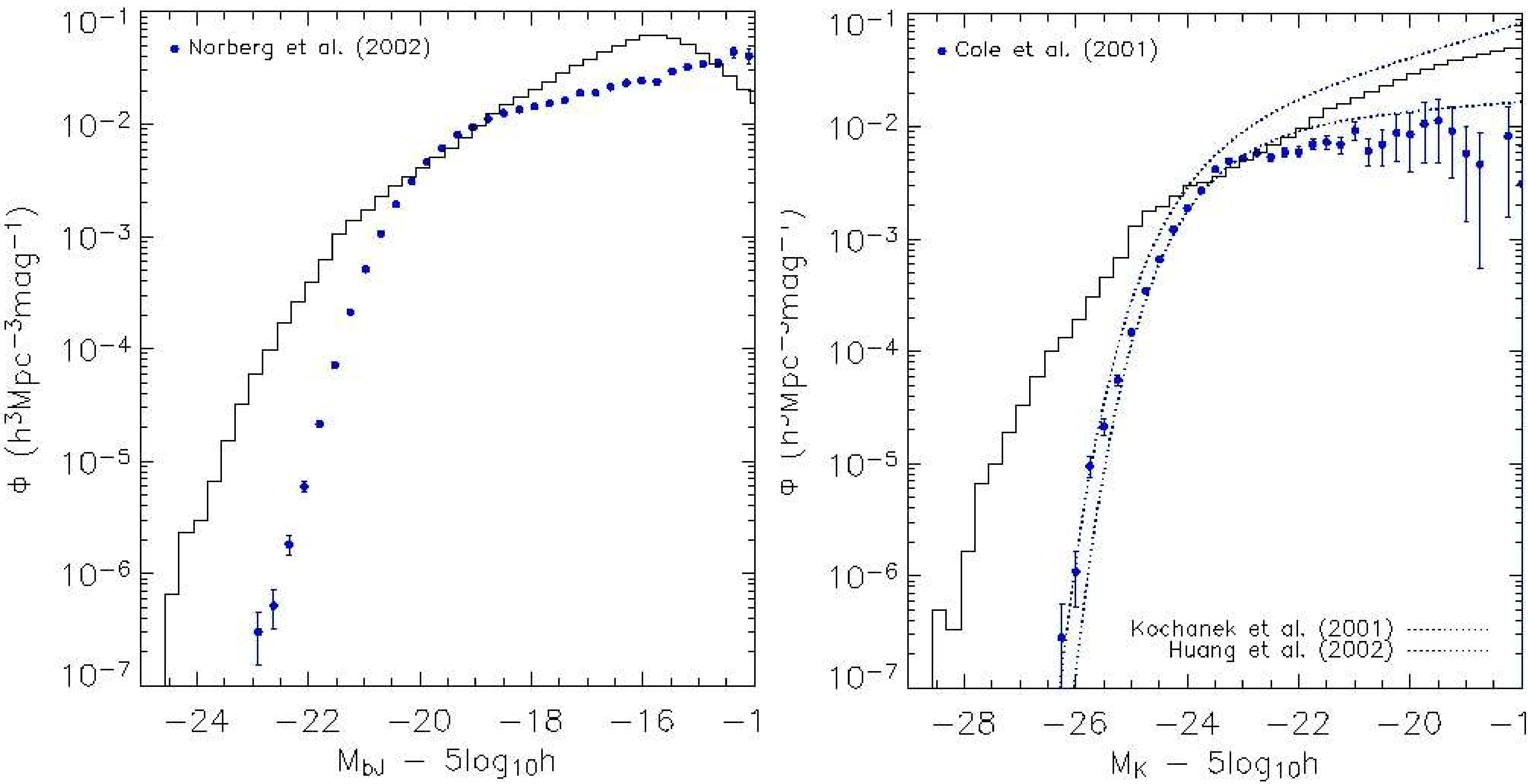
Quasar mode dominates the BH mass history

Effect of feedback on the Luminosity Function



Full model with reionisation, AGN and SN feedback Croton et al 2005

Effect of radio AGN feedback on the Luminosity Function



Full model with ~~reionisation~~, ~~AGN~~ and SN feedback

Croton et al 2005

MANY open questions in this field of research!

How did the first supermassive black holes form?

Is the relation between black hole mass and bulge mass different at high redshift or is it truly “Universal”?

When galaxies merge, how long does it take for their supermassive black holes to merge? Will these mergers produce gravitational waves that we can detect?

Why is there such a tight relation between black hole mass and bulge mass? Does this imply that the black hole is regulating the star formation in the bulge or vice versa?

Why do some black holes produce powerful jets and become radio loud? What is the influence of these jets on the long-term evolution of the galaxy? Do these processes change at higher redshifts?