ACTIVE GALAXIES

Part VIII

- Supermassive black holes
  - Evidence for their existence
  - How to measure mass
  - The link with galaxy evolution
- Active Galactic nuclei
  - Different kinds of AGN
  - How black holes grow and how they affect the environment
  - Black holes at high redshift

Two or Three Types of Black Holes?

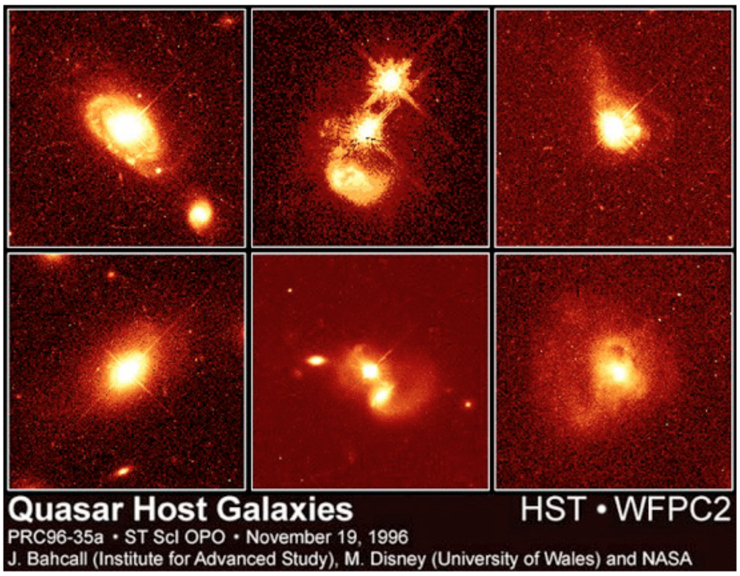
- Stellar Mass Black Holes: 3-100 times the mass of our Sun
- (Controversial) Intermediate mass Black Holes: 1,000 to 100,000 times the mass of our Sun
- Supermassive black holes: Millions to billions of times the mass of our Sun; found at the cores of galaxies

Schwarzschild radius

Size of a black hole

Mass	$R_S = 3\left(\frac{M}{M_\oplus}\right)$ km
1 Earth mass	2 cm
1 Solar mass	3 km
10 Solar masses	30 km
1 million Solar masses	3 million km ~ 4 x Solar radius!

Supermassive Black holes live in galaxy centres

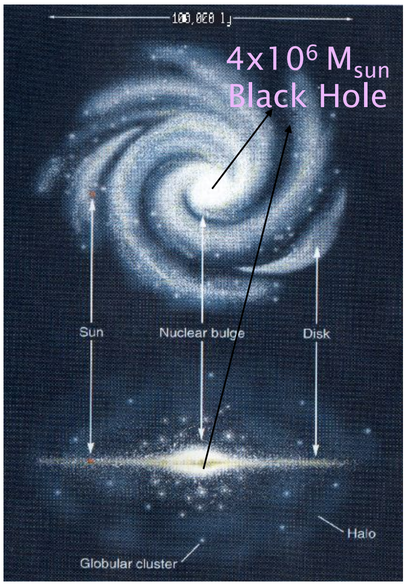


To establish the existence of supermassive black holes

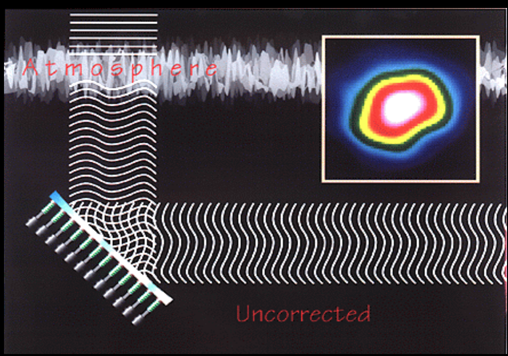
- Can measure the mass of supermassive black holes (SMBHs) by a variety of techniques, e.g.
  - Direct imaging of stars orbiting the SMBH (Galactic Centre only)
  - Imaging+spectroscopy of central gas disks (HST; radio-observations of “mega-masers”)
  - Reverberation mapping for AGN

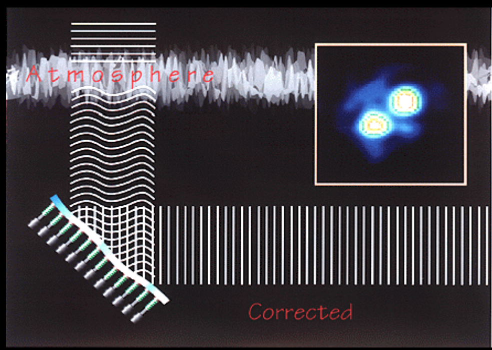
- Then establish that the object can only be a black hole
  - Size
  - Absence of surface

The Milky Way Galaxy has a supermassive black hole at its centre



Use adaptive optics to compensate for image degradation due to atmospheric turbulence





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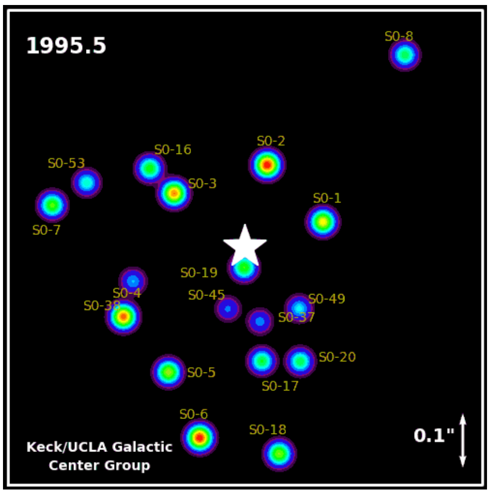
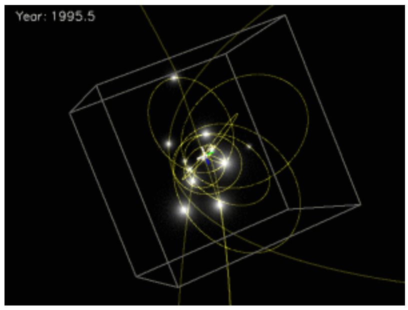
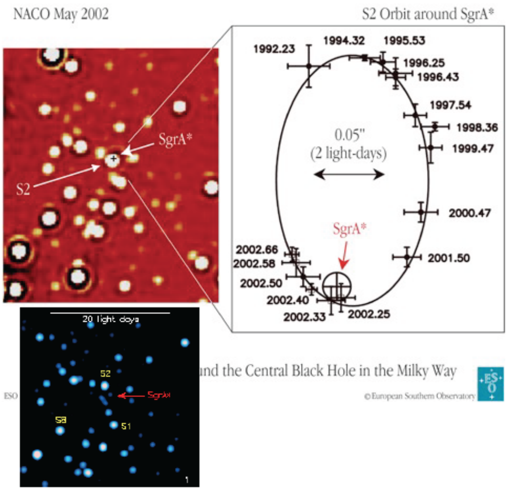
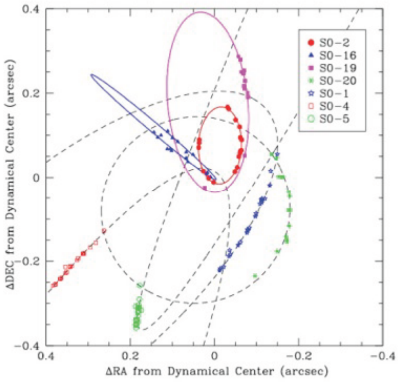
S-stars around the Galactic centre



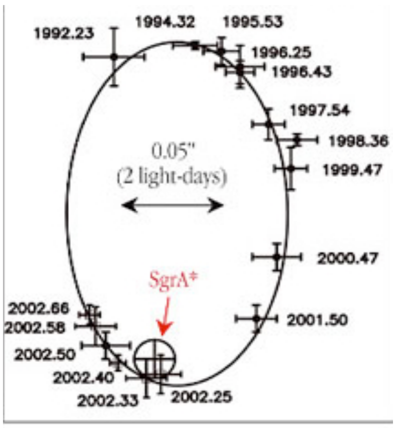


Centre of the Milky Way





S2: star with orbital period 15.2 yr



- For S2, Eccentricity =0.87
- Perigalacticon distance = 120 AU
  r_p = 120 x 1.5 x 10^8 km

$$a = \frac{r_p}{1-e} = 1.4 \times 10^{14} \text{ m}$$

- From Kepler 3,

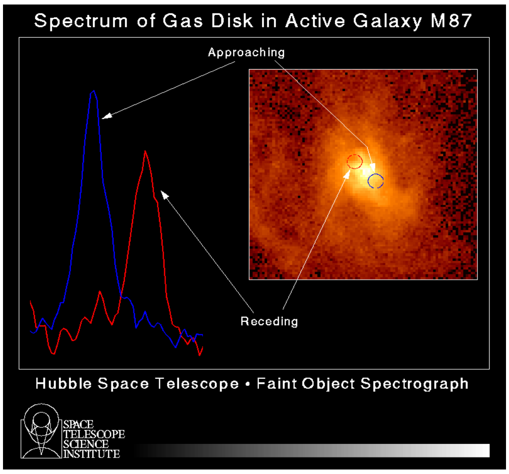
$$\frac{4\pi^2 a^3}{GP^2} \simeq 7 \times 10^{36} \text{ kg} = 3.5 \times 10^6 M_\odot.$$

- Schwarzschild radius=

$$R_S = \frac{2GM_{BH}}{c^2} = 4.2 \times 10^{-7} \text{ pc} = 0.08 \text{ AU} = 15 R_\odot.$$

M87 (nearby elliptical galaxy)

- Early HST target
  - Rotating gas disk at centre of galaxy
  - Measured disk rotation implies central object of 3×10^9 solar masses!
  - Mass cannot be due to normal stars at centre… there isn't enough light there.
- Good evidence for 3×10^9 solar mass black hole.

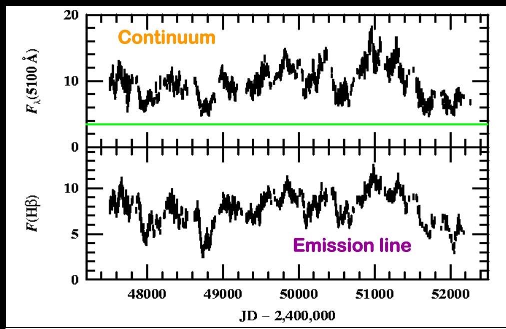


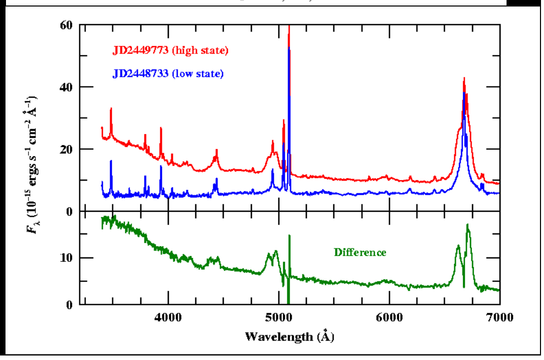
M106 (nearby spiral galaxy)

- M106 (NGC 4268)
- Contains central gas disk
- Disk produces naturally occurring MASER emission
- **Radio telescopes** can measure position & velocity of MASERs to great accuracy.
- Velocity changes with radius precisely as expected if all mass is concentrated at centre!
- 3×10^7 solar mass black hole

Reverberation Mapping

- Powerful probe of the broad-line region structure and kinematics
- Measure the emission-line response to continuum variations
- Need good enough time sampling to derive time lags between continuum and emission line variations unambiguously
- Emission lines respond to changes in the continuum flux with a “lag” corresponding to the light travel time from the ionizing source to the BLR

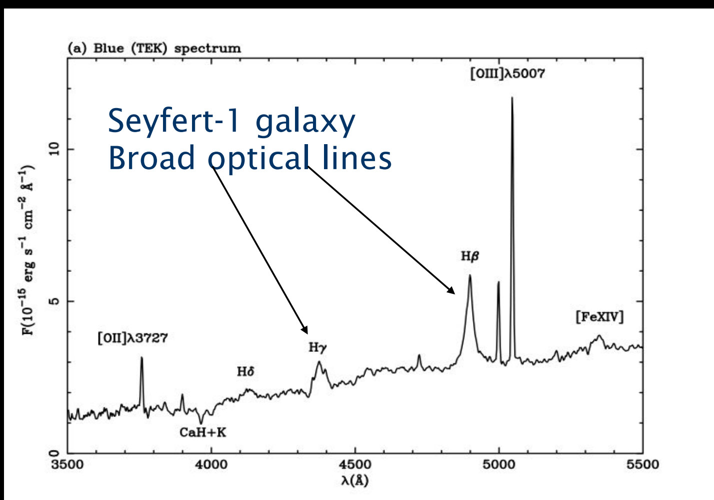




Reverberation mapping to measure mass of SMBH

Broad lines from matter moving in SMBH potential. They respond to changes in the UV continuum emission of the AGN

$$M \sim \frac{cv^2 \Delta t}{G}$$

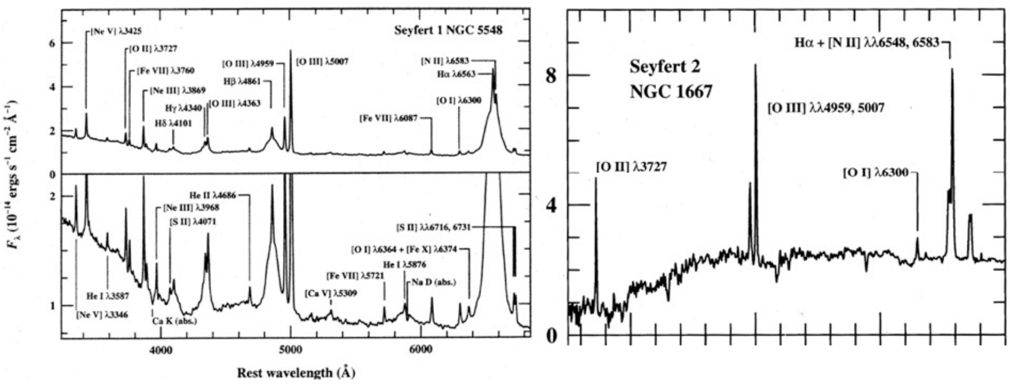


To establish the existence of SMBHs

- Stellar kinematics in the core of the galaxy
- Optical spectra: the width of the spectral line from broad emission lines
- X-ray spectra: The iron Kα line is seen is clearly seen in some AGN spectra
- The bolometric luminosities of the central regions of some galaxies are very high
- Variability in X-rays: Causality demands that the scale of variability corresponds to an upper limit to the light-travel time

Doppler width of optical spectral lines

- Broad lines $\Delta\lambda/\lambda = \Delta v/c \Rightarrow \Delta v$=8000 kms^{-1}.



Also GR effects- gravitational broadening

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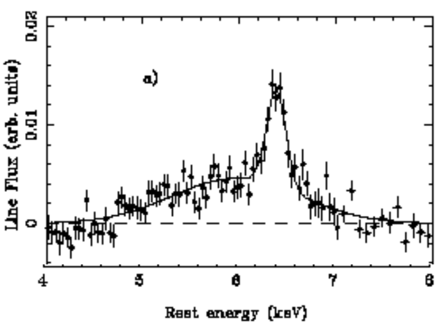
Proving the Existence of Black Hole X-ray spectra: the Fe K line

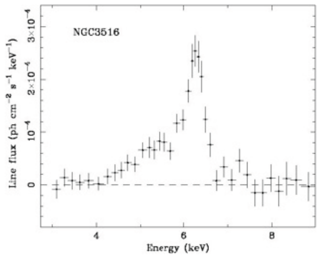
- X-ray spectroscopy of AGN reveals an Fe K-line (transition in tightly bound electrons of Iron). Its rest-energy varies between 6.4 and 6.7 keV depending upon the ionisation state.

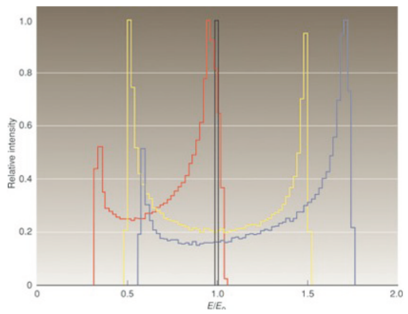


X-ray spectra: the Fe K line

- Iron line at 6.35 keV (Fe K-line, transition in tightly bound electrons) is distorted: combination of Doppler effect in the accretion disk and strong gravitational field of the black hole.

- Very broad (50.000km/s) line-profiles, offset to the red + gravitational redshift





black: intrinsic energy of Fe line (6.35 KeV)

yellow: double horned profile due to rotation

blue: shift due to relativistic Doppler effect and relativistic aberration

red: gravitational redshift effect (photons climb out of gravitational well)

the red line is what's observed

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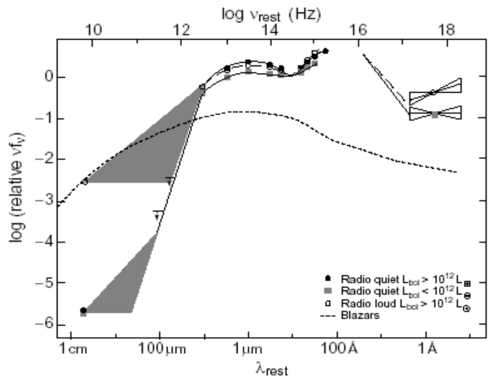
The “Broadband” emission



- Comparable power emitted across ~seven orders of magnitude in photon energy

Central Engine: Why a Black Hole? Energetic Considerations

- very large extents of jets, up to >1 Mpc, so lifetime is at at least 10^7 yr (assuming expansion speed c)
- $L_{bol} = 10^{47}$ erg/s. Multiply this by 10^7 yr gives 3 10^{61} erg
- can vary luminosity dramatically, by 50% in one day, so central source must be smaller than one light-day (<<3 10^{15} cm)
- burning hydrogen into Fe (nucleus w/ highest binding energy) releases 8MeV/nucleon, or 0.008 m_pc^2 per nucleon (i.e., efficiency 0.8%)
- to create 3 10^{61} erg one this needs $m=E/c^2/0.008 \sim 2\ 10^9\ M_{sun}$

To establish the existence of SMBHs

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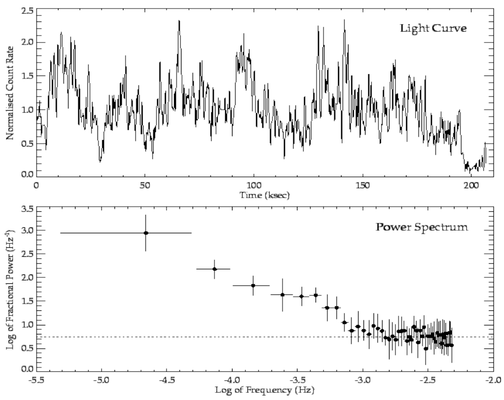
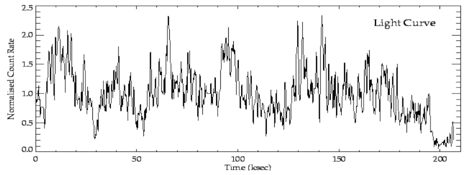
Variability: Size of emitting volume



- Light travel time argument: a source that varies significantly in time Δt must have size $R < c\Delta t$
- Here the source varies on a timescale of, say, an hour. So the emitting volume must be less than a light-hour across.

Variability: Size of emitting volume



- Light travel time argument: a source that varies significantly in time Δt must have size $R < c\Delta t$
- Here the source varies on a timescale of, say, an hour. So the emitting volume must be less than a light-hour across.
- Now imagine this galaxy is at a redshift z=3. We have to take into account cosmic time dilation. This makes events at high z appear slower by a factor (1+z). What we see as 1 hr is therefore, in the rest frame of the galaxy, only 0.25 hr.

i.e. $\Delta t_{\rm rest} = \Delta t_{\rm measured} \div (1+z)$.

Does every galaxy have a supermassive black hole?

CMO=Central Massive Object

$>10^6$ Msun- most probably BH. Milky way at the lowest end

Others could be dense star clusters

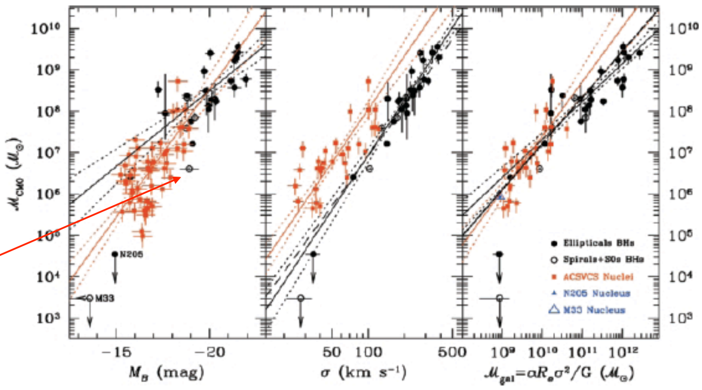
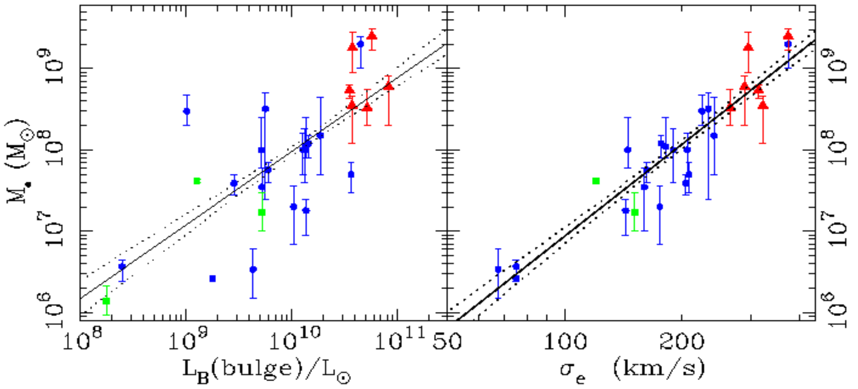


FIG. 2.—*Left panel:* Mass of the CMO plotted against absolute blue magnitude of the host galaxy (or bulge for spiral galaxies). Nuclei from the ACSVCS are shown as red squares. The SBHs in early-type and spiral galaxies are shown as filled and open circles, respectively. *Middle panel:* CMO mass as a function of the velocity dispersion of the host galaxy, measured within R_e. *Right panel:* CMO mass plotted against galaxy mass, defined as $\mathcal{M}_{\rm gal} \equiv \alpha R_e \sigma^2/G$ with $\alpha = 5$. In

Ferrarese et al 2006

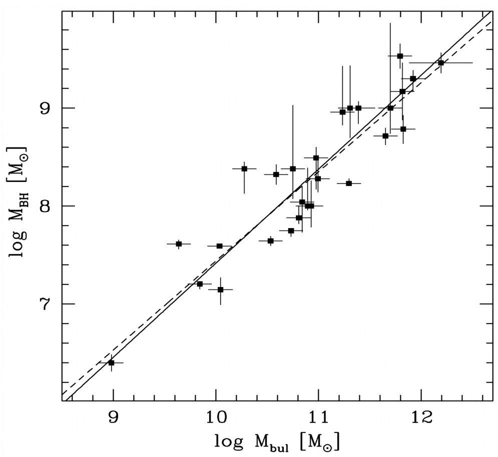
Black hole mass is strongly linked to host properties

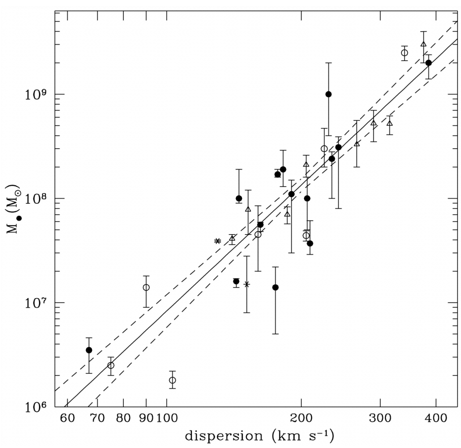
The “M-sigma relation”



- Plot mass of black hole against luminosity (left) and velocity dispersion (right) of galactic bulge

Black hole mass is strongly linked to host properties

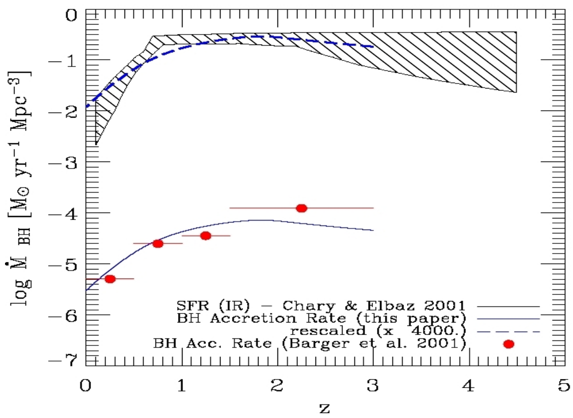




Marconi & Hunt

Tremaine et al.

The Co-evolution Of Galaxies & Black Holes



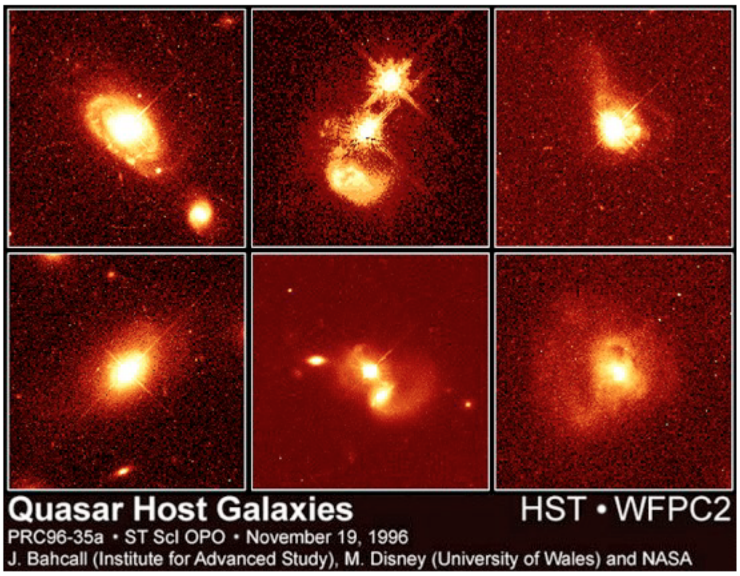
The rate at which black holes grew via accretion (as AGN) was very much higher in the early universe

A similar trend is seen in rate at which galaxies grew via star formation

The Connection is to the Bulge Component of Galaxies

Black holes and galaxy formation

- Find that black hole mass is correlated strongly with the velocity dispersion of the bulge (and, more weakly, with the luminosity of the bulge)
- Velocity dispersion is a better indicator of the mass of the galactic bulge
- **Extremely important result!** Shows that black hole growth "knows" about the properties of the galaxy (or maybe galaxy formation knows about the black hole?)



Nuclear Activity in galaxies

- The (geometric) centres of galaxies (few pc) exhibit local properties which cannot be found anywhere in the rest of the galaxy.
- It turns out that many of these phenomena are related to the bottom of the potential well and black holes.

- compact, very bright centers, $R_{nucl} \simeq 3pc$
- spectra with strong emission lines
- ultraviolet-excess
- X-ray emission
- jets and double radio sources with $R_{jet} \sim kpc - Mpc$
- variability over the whole spectrum on short timescales: $t_{var} \sim minutes... \sim days$
- AGN luminosities:

$$L_{nuc} = 10^{45} - 10^{48} \frac{erg}{s} \simeq 10^{12} - 10^{15} L_{\odot}$$

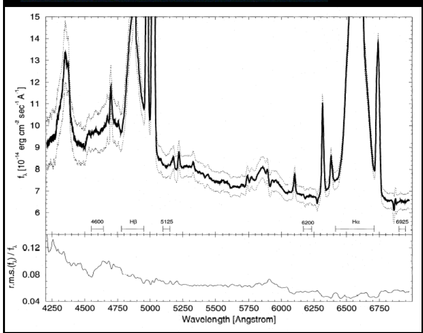
AGN Types
1. Radio Galaxies

The M87 Jet

- Radio emission comes from lobes 0.1-0.5Mpc
- Radiation is synchrotron emission
- $L_{radio} \sim 10^{8-10}$ $L_o \sim 10^{42}$-10^{44} erg/s
- Reside almost exclusively in massive galaxies
- Particle acceleration to $>10^{12}$ MeV

- **Note:** all ‘radio AGN’ show other signs of nuclear activity, but not all AGN have radio jets/lobes

AGN Types
2. Seyfert galaxies

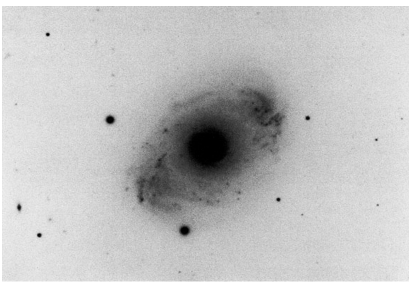


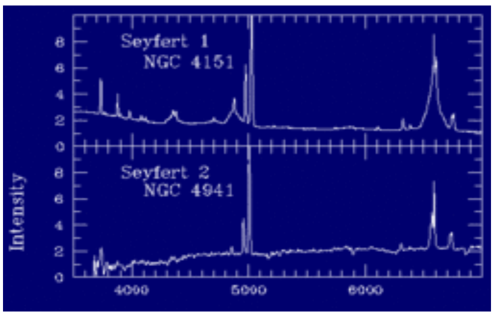
- Spirals with bright, unresolved nuclei with $L \sim 10^{45}$ erg/s
- Forbidden emission lines narrow (300km/s)
- Permitted emission lines (in Seyfert 1) broad: ~3000km/s
- Line ratios exclude photo-ionization by hot stars
- From variability studies (light travel time continuum → broad lines) it follows that $R_{\text{broad-lines}} \sim 0.01\text{-}1\,\text{pc}$

Seyfert I and Seyfert II galaxies

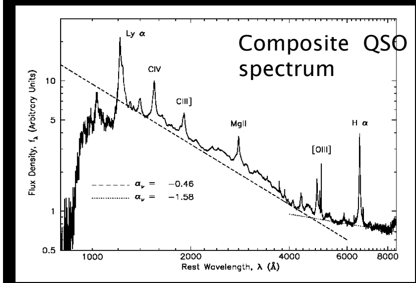
The nuclei of Seyfert I galaxies are bright in the infrared, optical and ultraviolet. They show broad and narrow emission lines.

Seyfert II nuclei are fainter in the UV and the optical but have similar luminosities to Seyfert Is in the IR. Their spectra have only narrow emission lines, not broad ones.





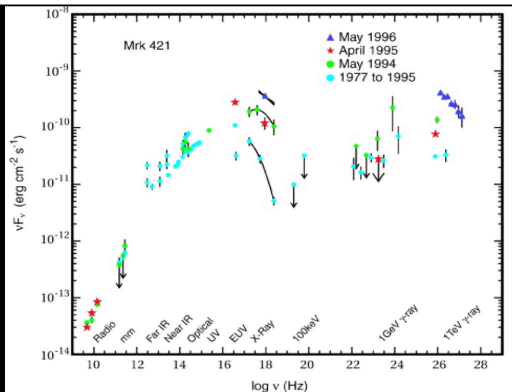
AGN Types:
3. Luminous Quasars (QSO)



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

$n_{galaxy} \sim 100 - 10{,}000 \times n_{QSO}$

AGN Emission Across the Energy Spectrum



It turns out that to explain emission across such a vast range of energy, one needs a combination of:

- accretion disk (multiple black-bodies)
- Relativistic particle acceleration (including jets)
- Dust (at 50K), heated by the radiation from the accretion disk

Orientation effects (jets, relativistic beaming) must play a role

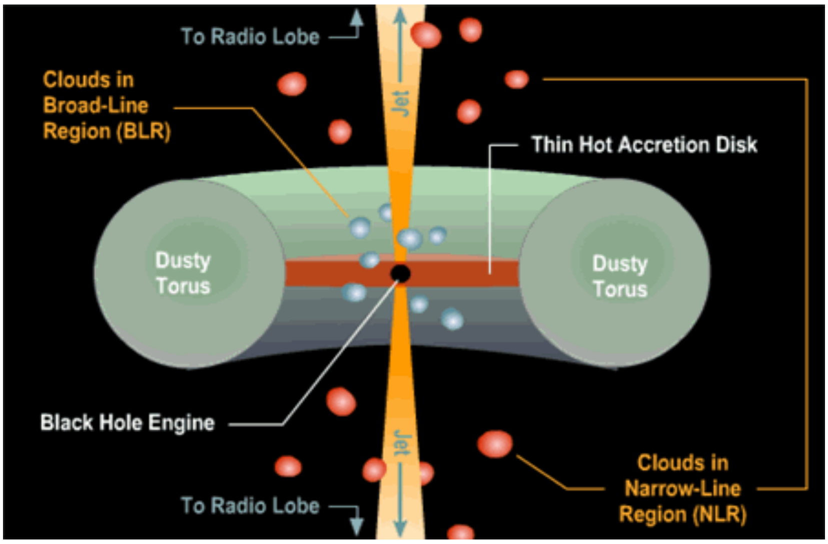
What powers most AGN?

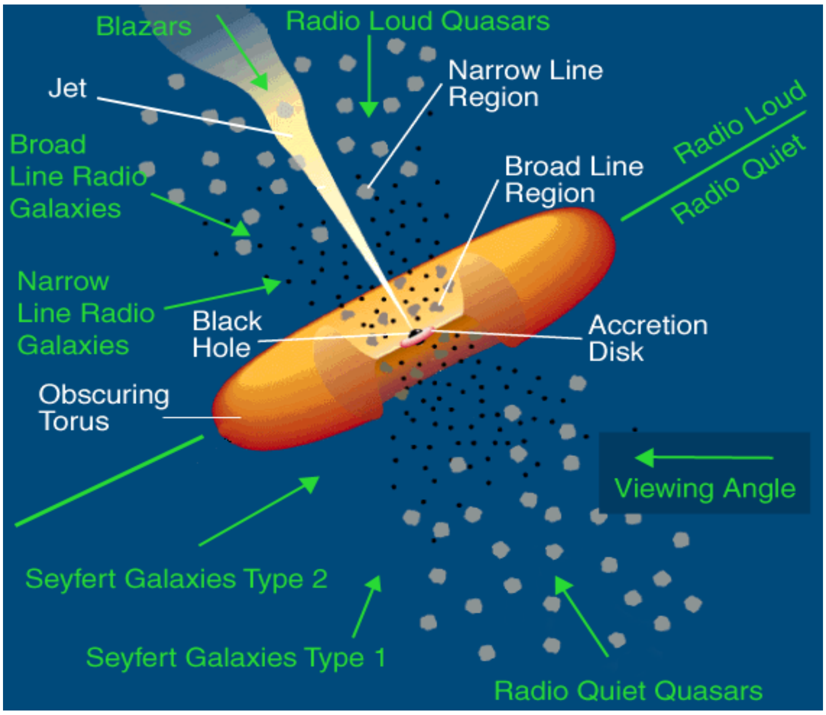
- From what region does the activity emerge?
- AGN vary at many wavelengths
- More rapid variability for higher energy radiation
- Size < c x $t_{variability}$

radio/optical	$\Delta t_{obs} \simeq 10d$	$\Rightarrow$	$l_{emis} \simeq 0.01pc$
radio/optical	$\Delta t_{obs} \simeq 1d$	$\Rightarrow$	$l_{emis} \simeq 10^{-3}pc$
TeV	$\Delta t_{obs} \simeq 1h$	$\Rightarrow$	$l_{emis} \simeq 10^{-5}pc$

The (Now) Standard Picture:

AGN are Powered by Accretion onto Black Holes





Energetics of accretion onto a black hole

- As material drops towards the black hole, its potential energy is converted into kinetic energy.
- If that kinetic energy is converted into thermal energy (dissipation) then it will be radiated away

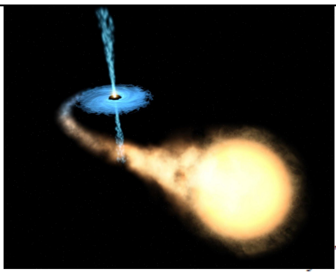
$$\boxed{L_{Acc} \simeq \frac{1}{16} \dot{m} c^2} \qquad 1g \rightarrow 10^6\ kWh$$

efficiency of hydrogen burning is:

$$\boxed{L_{H-burn} \simeq 0.007 \dot{m} c^2}$$

- Such luminous accretion of an ionized plasma has a natural upper limit, the Eddington limit:
  - Gravitational pull on proton = radiation pressure on electron (Thompson cross section)

$$L_{Edd} = \frac{4\pi c G M_{BH} m_p}{\sigma_{Te^-}}$$



Black hole accretion

Consider a black hole accreting matter due to its gravitational pull, in a spherically symmetric way

The large luminosity itself can stop the accretion by the outward pressure the light exerts on infalling material.

- ❑ So accretion will be able to take place steadily only if the force of gravity the black hole exerts on the infalling material exceeds the force from radiation pressure.
- ❑ Thus the more massive the black hole, the larger the luminosity it's capable of emitting by accretion.
- ❑ The maximum luminosity via accretion, called the **Eddington luminosity**, is that for which the forces of gravity and radiation pressure balance.

We shall now derive a formula for the Eddington luminosity to see what it has to say about quasar black holes.

The Eddington luminosity: derivation

Photons per unit time incident on electron:

$$\dot{n} = \frac{P_{\text{intercepted}}}{h\nu} = \frac{L}{4\pi R^2}\frac{\sigma_e}{h\nu}$$

Cross-sectional area of electron, for light scattering

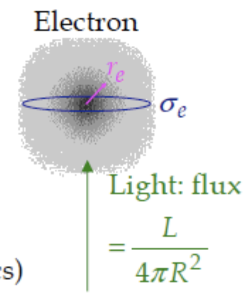
Distance from BH

"Classical radius of electron:" assume its rest energy comes from electrostatic potential energy.

$$m_e c^2 = \frac{e^2}{r_e} \quad \Rightarrow \quad r_e = \frac{e^2}{m_e c^2} = 2.8 \times 10^{-15}\ \text{m}$$

$$\sigma_e = \frac{8\pi r_e^2}{3}$$

Thomson cross section
(8/3, not 1: quantum mechanics)



The Eddington luminosity: derivation (continued)

- Momentum per incident photon: $p_{\text{photon}} = h/\lambda = h\nu/c$
- Since the electron radius is so much smaller than the wavelength of light, light will scatter from the electron **isotropically** (uniformly in all directions). The scattered light therefore has **zero momentum** on the average.
- Thus **all the incident photon momentum is transferred to the electron**, resulting in an outward force of

$$F_{\text{rad},\,e} = \frac{dp}{dt} = p_{\text{photon}}\dot{n} = \frac{h\nu}{c}\frac{L\sigma_e}{4\pi R^2 h\nu} = \frac{2r_e^2 L}{3cR^2} = \frac{2e^4 L}{3m_e^2 c^5 R^2}$$

- Similarly, there is a force on the proton, but since the proton radius is so small, $r_p = e^2/m_p c^2 = 1.5\times10^{-16}$ cm, this force is negligible compared to that on the electron.

The Eddington luminosity: derivation (continued)

- Each electron will drag a proton with it, whether these particles are bound in an atom or reside in ionized gas, because matter on macroscopic scales has equal numbers of positive and negative charges and the electrostatic force between them is strong.
- Similarly, each proton will drag an electron with it. The gravitational force exerted by the black hole on each proton is of course much larger than that on an electron.
- Accretion takes place if $F_{\text{grav},\,p} + F_{\text{grav},\,e} > F_{\text{rad},\,p} + F_{\text{rad},\,e}$

  or, to good approximation, $F_{\text{grav},\,p} > F_{\text{rad},\,e}$

The Eddington luminosity: derivation (continued)

Thus in order to accrete at luminosity L, the black hole mass M must be such that

$$\frac{GMm_p}{R^2} > \frac{2e^4L}{3m_e^2c^5R^2}$$

$$\frac{M}{L} > \frac{2e^4}{3Gm_pm_e^2c^5} = 1.6 \times 10^{-15} \text{ kg s J}^{-1} = 3\times10^{-5} M_\odot L_\odot^{-1}$$

$$\text{Given } M: \quad L < \boxed{L_E = \frac{3GMm_pm_e^2c^5}{2e^4}}$$ **Eddington luminosity**

$$\text{Given } L: \quad M > \frac{2e^4L}{3Gm_pm_e^2c^5}$$

Eddington luminosity

At the Eddington limit

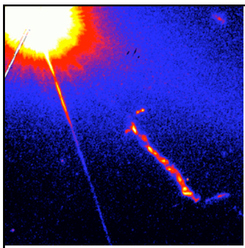
$$L_E = \frac{3GMm_Hc}{2r_e^2}$$

where the classical radius of the electron

$$r_e \equiv \frac{e^2}{m_ec^2} = 2.8 \times 10^{-15}\ m$$

So if L=10^{39} W, and the BH is radiating at the 0.1 x the Eddington limit, then

$$M_{BH} = \frac{(2r_e^2)(0.1L)}{3Gm_Hc} = 7.7M_\odot \text{ X } 10^6$$



Quasar black holes have to be supermassive

The Eddington luminosity is the maximum luminosity that a body with mass M can produce by accretion.

Now consider a typical quasar like 3C 273, with $L = 10^{12} L_\odot$.

$$M > \frac{2e^4 L}{3Gm_p m_e^2 c^5} = 3\times 10^7 M_\odot$$

Supermassive black hole required!

- There are quasars with luminosities as large as $L = 10^{14} L_\odot$; thus we should expect to find central black holes well in excess of $10^9 M_\odot$: equivalent to the mass of a good-size galaxy.
- The event-horizon radius of the minimum-mass black hole that would power 3C273: $R_{Sch} = 2GM/c^2 = 0.6\text{AU}$.

Energetics of accretion onto a black hole

$$L_{\text{Edd}} \sim 1.3 \times 10^{38}\ \text{erg/s}$$

This implies

$$M_{BH} \geq 10^7 M_\odot$$

for Seyfert galaxies, and

$$M_{BH} \simeq 10^9 M_\odot$$

for quasars. Using

$$L_{Acc} \simeq \frac{1}{16}\dot{m}c^2 = L_{Edd}$$

yields the corresponding maximum accretion rate:

$$\dot{m}_{Edd} \simeq 5 \cdot 10^{-10} \frac{M_{BH}}{M_\odot} \left[\frac{M_\odot}{yrs}\right]$$

NB:

In an accretion disk it is assumed that the conversion of energies E_{pot} → $E_{thermal}$ (→ $E_{radiation}$ black body) happens locally and much faster than the inflow

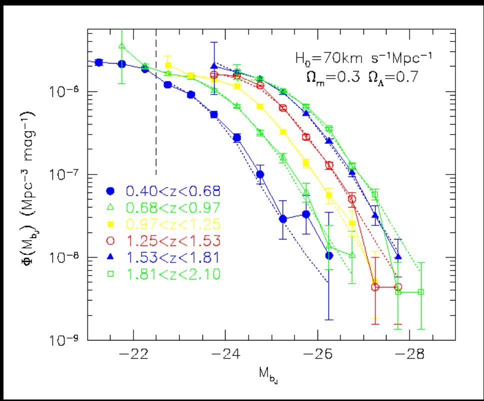
→ gravitational energy is instantly exploited.

This need not be the case. There is an old puzzle why some galaxy centers are so 'dark', despite the presence of BHs and gas at galaxy centers (e.g. Galactic center)

→ 'advection dominated' accretion (ADAF) → no radiation

Cosmic Evolution of the AGN Activity

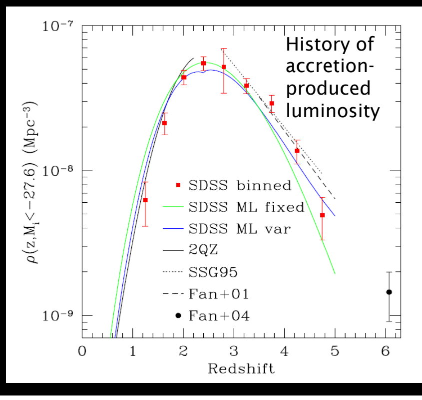
- Describe the distribution of accretion luminosities at different cosmic epochs by the “quasar-luminosity-function” at different redshifts



2DF Survey: Croom et al 2004

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

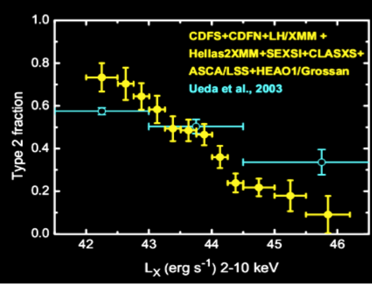
(e.g. SDSS Richards et al 2006)

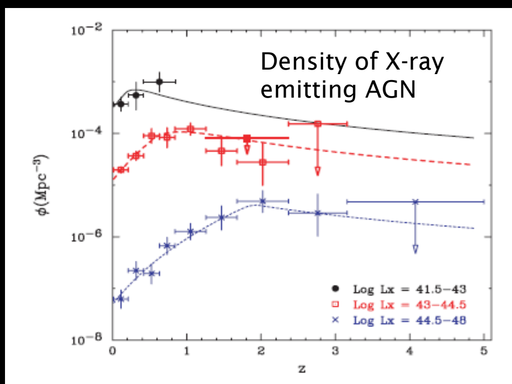


Note the ‘Cosmic Evolution’ for less luminous AGN looks different (‘downsizing’)

- If AGN luminosity is less drastic, not all material may get blown out → obscured AGN → still detectable in X-rays or mid-IR
- Density of X-ray AGN accretion

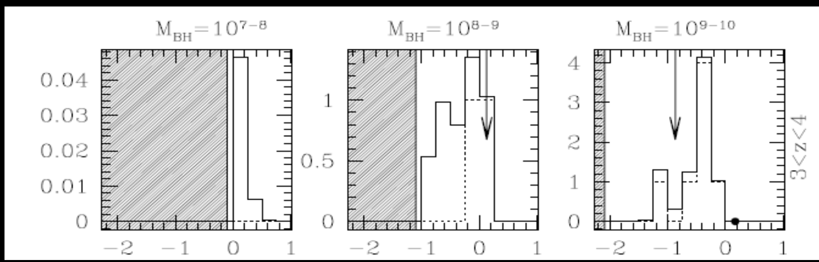
Ueda et al 2003





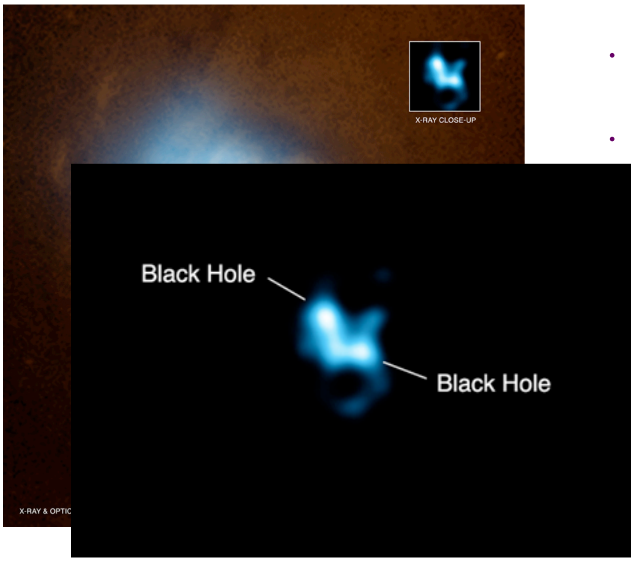
How do BHs grow?

- Long-ish phases of $L \ll L_{Eddington}$?
- Is most of the growth at $L \sim L_{eddington}$ in spurts, turned off in between? (it seems that this is the case..)



- If galaxies merge then their central black holes should merge, too….
  - Importance of this effect not known (yet)
  - Can BHs get ejected before merging?

Two black holes in one galaxy?



- NGC 3393- 50 Mpc away
- Spiral galaxy with two SMBHs at its core

Separated by 150 pc=490 ly

Found by the Chandra X-ray observatory

Believed to be the result of a merger

Fabbiano et al 2011

When galaxies merge, their SMBHs merge too

Does the observed BH accretion match the present-day black hole density?

- Taking the M_{BH}-σ relation and using the stellar velocity dispersion measured by SDSS, one gets the present epoch density of (mostly dormant) black holes:

$$\rho_{\bullet,L}(z=0) \simeq 2.9 \times 10^5\ M_\odot\ \mathrm{Mpc}^{-3}$$

- Integrating the (emitted) energy from AGNs, assuming

$$L_{rad}(\mathrm{optical}) \approx \varepsilon \frac{\dot{M}_{BH} c^2}{2} \quad \text{with } \varepsilon \sim 0.1$$

yields consistency!

(Yu and Tremaine 2002)

→ Do we 'see' most accretion?

→ Picture does 'hang together'?

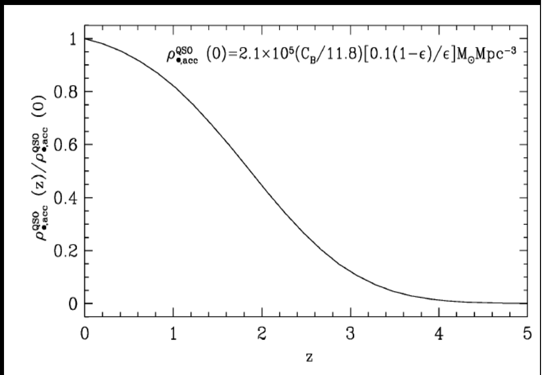


Figure 1. The history of the comoving massive BH mass density due to accretion during optically bright QSO phases. The QSO luminosity function

'Duty Cycle' and Lifetime of Luminous Accretion Phases

Duty cycle

If 1 galaxy ←→ 1 black hole

f ~ $n_{AGN}(>L|z)$ / $n_{Gal}(>M|z)$)~10^{-3}

•Find corresponding galaxies and AGN

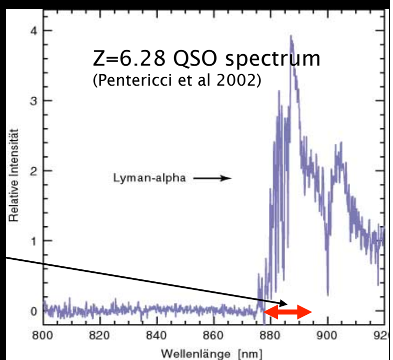
Lifetime (of individual luminous phase)

- indirect arguments suggest few x 10^7 yrs
- Direct: measure size of 'over-ionized' sphere around high-z QSO

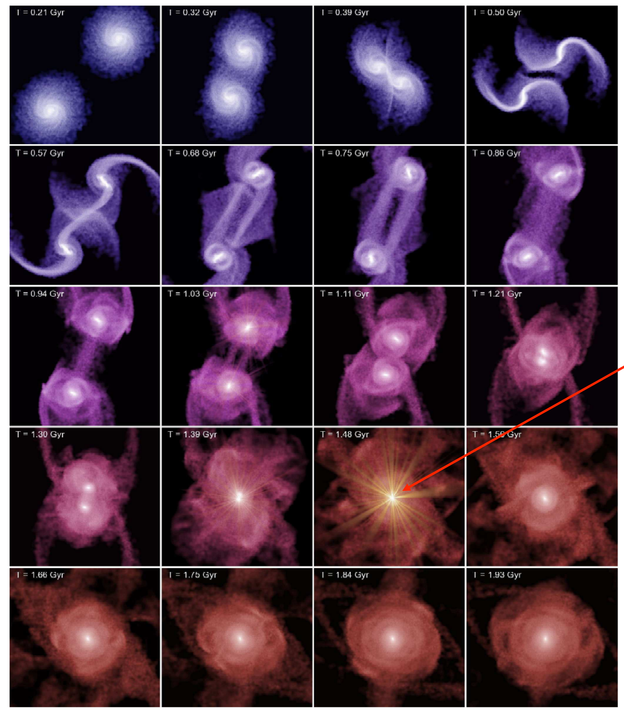
$$t_{\text{UV-bright lifetime}} > \frac{r_{\text{ionized}}}{c} = 2\times10^7\ \text{yrs}$$

- Compare to e-folding time

$$t_{\text{Salpeter}} \approx \frac{M_{BH}}{\dot{M}_{BH}} = 4\times10^7 \left[\frac{\varepsilon}{0.1}\right] \text{yrs} \quad \text{at Eddington rate}$$



→ M_{BH} may e-fold in one QSO phase!

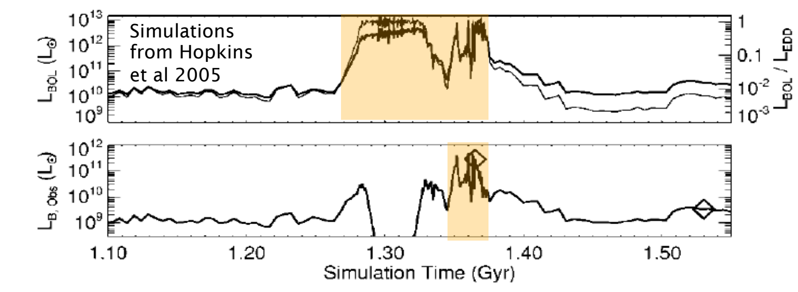


- QSO/AGN phases as shortlived stages of a galaxy merger where gas is being funneled to the center
- Hydrodynamical simulations by Hopkins and Springel

How black holes grow

Scenarios emerging from these simulations:
Merger of gas rich galaxies
→ gas to the centre → (dust-enshrouded) star-burst
→ black hole accretion → whose energy output blows out gas

total accretion phase is longer than 'optically bright' QSO phase



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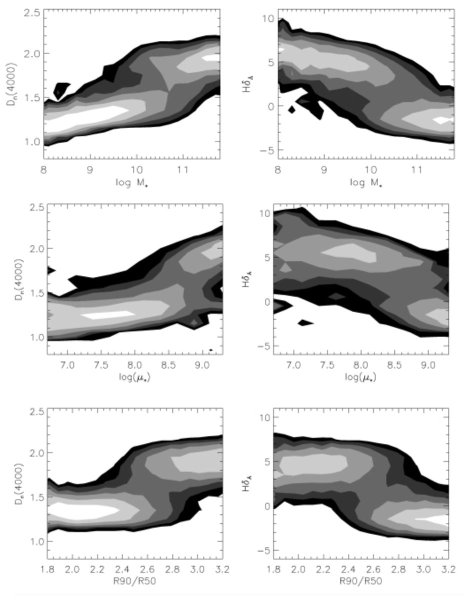
The Local Galaxy “Landscape”

THE BIMODAL SDSS GALAXY POPULATION

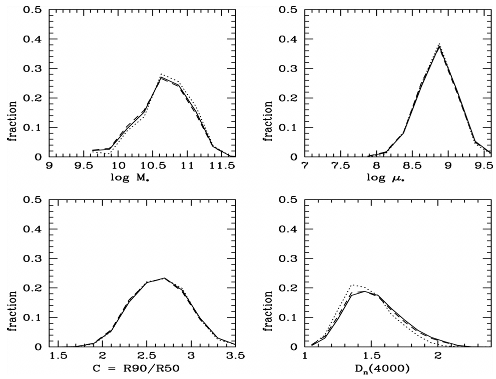
Characteristic scales for transition from old to young:

- $\mathbf{M_* \sim 3 \times 10^{10}\ M_\odot}$
- **Low mass galaxies are young, high mass galaxies are old**
- $\mu_* \sim 3 \times 10^8\ \mathbf{M_\odot}/kpc^2$
- **Low density galaxies are young, high density galaxies are old**
- **C ~ 2.6**
- **Low-concentration (late-type) galaxies are young**

  High-concentration (early-type) galaxies are old
- **Black Holes: the domain of massive, dense, high-concentration galaxies (big bulges)**

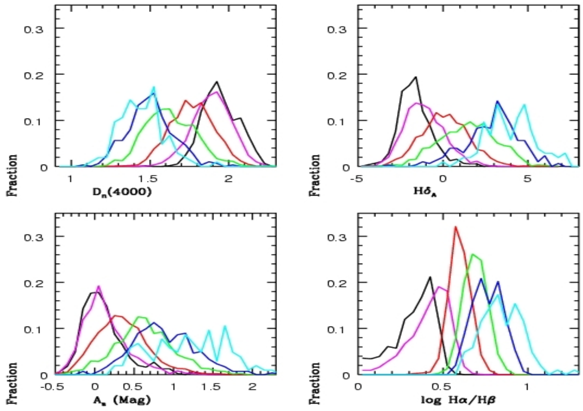


Where do they live?



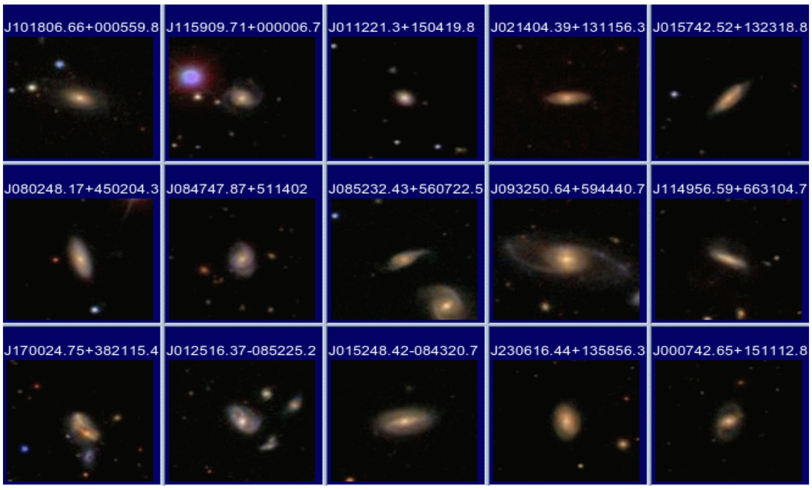
- They live in “hybrid” galaxies
- Near the boundaries between the bimodal population
- Structures/masses similar to early-type galaxies
- Bulges: young stellar population

Luminosity Dependence



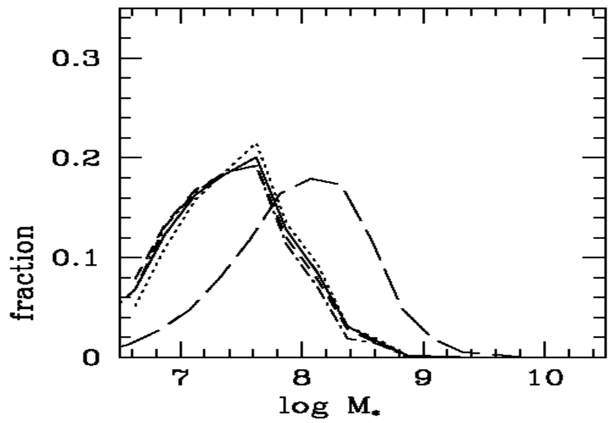
- As the AGN luminosity increases the stellar population in the bulge becomes younger
- And the amount of dust/cold-gas increases

Trigger: Morphology



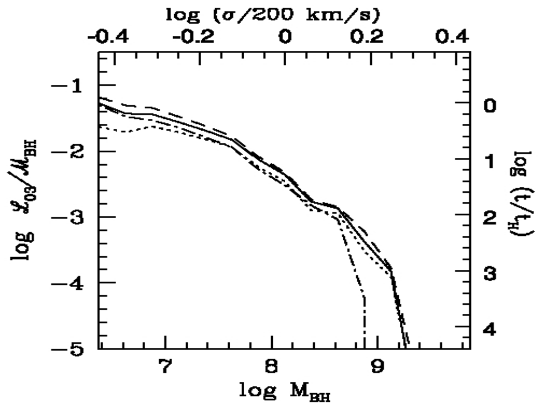
- Usually ~normal early-type disk galaxies

WHICH BLACK HOLES ARE GROWING?



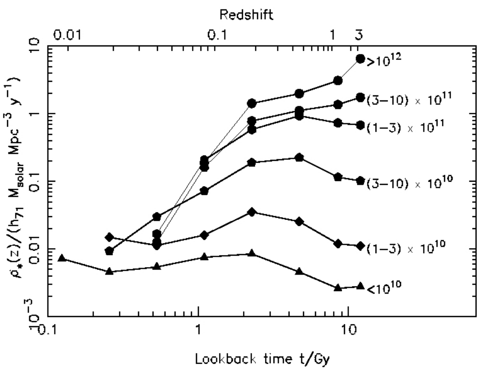
- Mass resides in the more massive black holes
- Growth dominated by less massive ones

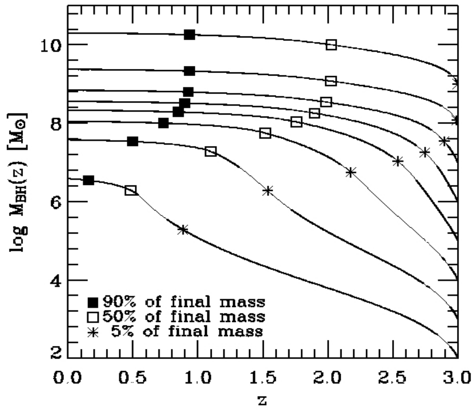
MASS-DOUBLING TIMES



- Only ~ Hubble Time for lower mass black holes
- Orders-of-magnitude longer for the most massive black holes ("dead quasars")

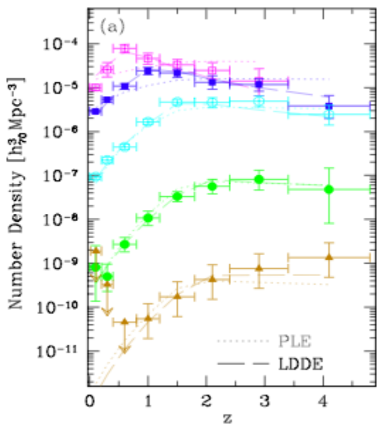
DOWNSIZING



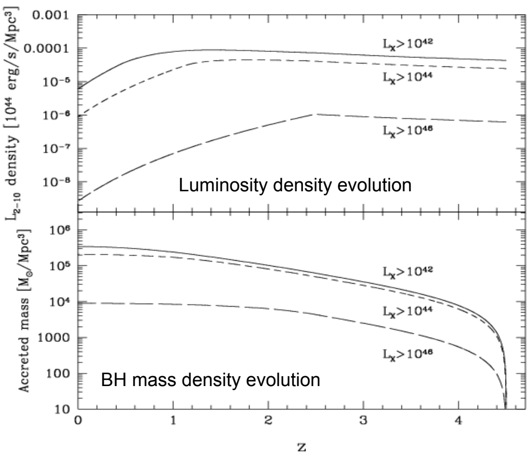


The characteristic mass scales of the populations of rapidly growing black holes and galaxies have decreased with time in the universe. The most massive form earliest.

AGN EVOLVE



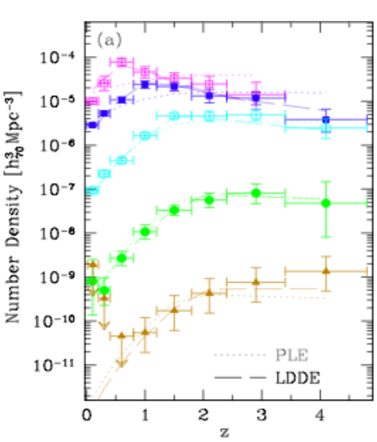
Hasinger et al. (2005)
Also Ueda et al. 2003



La Franca et al. 2005

Typical BH mass or accretion rate reduces with *z*?

AGN EVOLVE



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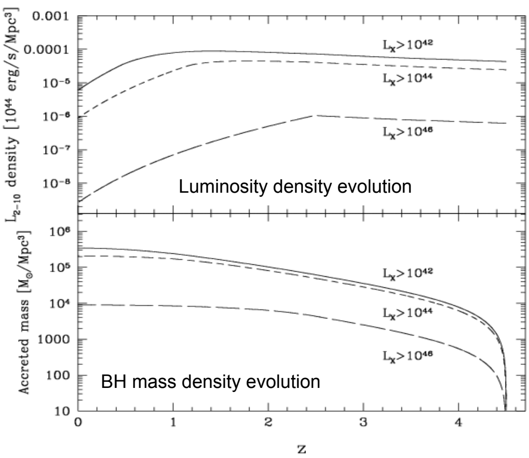
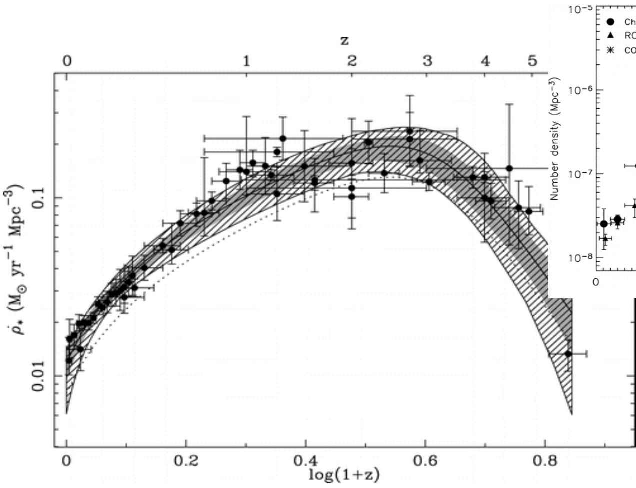


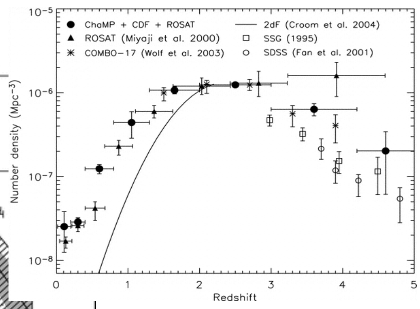
La Franca et al. 2005

Typical BH mass or accretion rate reduces with *z*?

K. Nandra: AGN/Galaxy Coevolution
Columbia Warm/Hot Universe

GALAXIES EVOLVE



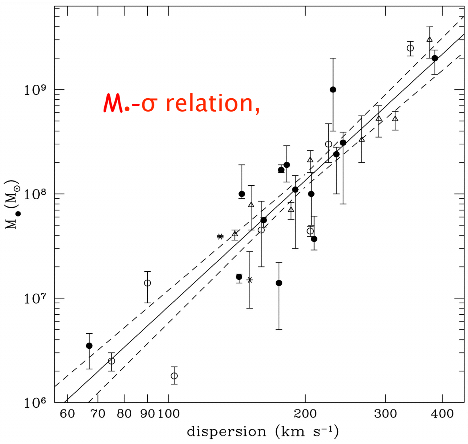


AGN number density:
Silverman et al. (2005)

SFRD: Hopkins & Beacom (2006)

Similar evolution:
Boyle & Terlevich 1998

GALAXIES AND AGN CO-EVOLVE



Black hole mass correlated to host galaxy bulge mass.

↓

Formation of bulge and growth of black hole are related.

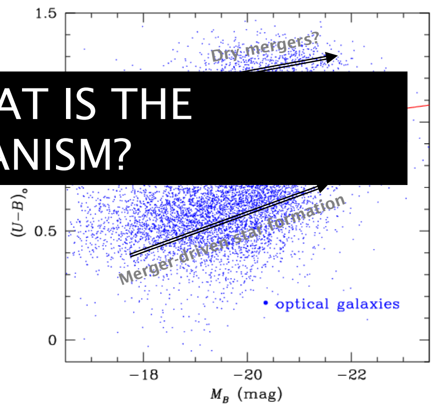
↓

AGN play a significant role in the evolution of galaxies

Magorrian et al. 1988; Gebhardt et al. 2000; Ferrarese & Merrit 2000; Tremaine et al. 2002

GALAXIES EVOLVE (2)

DEEP2 survey, 0.4<*z*<1.4; Willmer et al. 2006



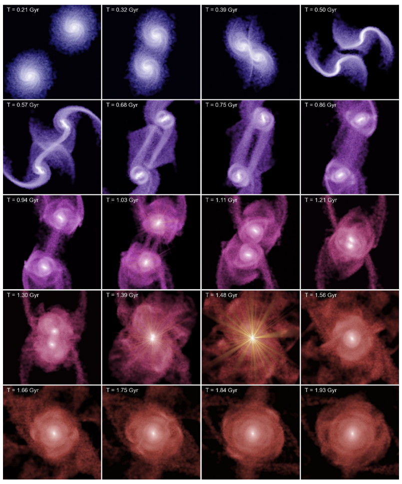
- Colour bimodality:
  - Blue cloud: active star-forming

KEY QUESTION: WHAT IS THE QUENCHING MECHANISM?

via mergers in blue cloud
- Rapid quenching to red sequence. Mechanism?
- Further red sequence growth via "dry mergers"?

e.g. Strateva et al 2001; Bell et al 2004; Faber et al 2008

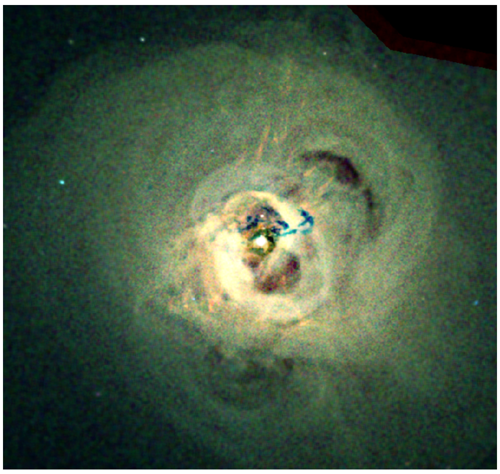
QSO MODE FEEDBACK

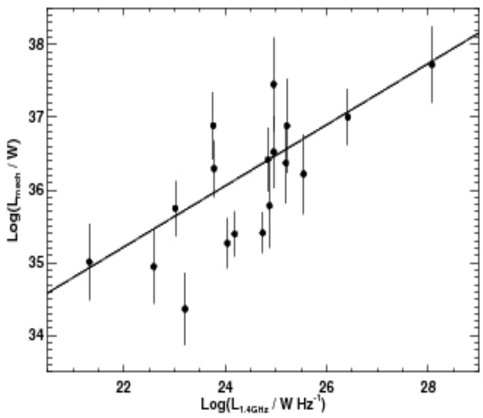


- Gas rich major merger
- Inflows trigger BH accretion & starbursts
- Dust/gas clouds obscure AGN
- AGN wind sweeps away gas, quenching SF and BH accretion.

Hernquist (1989)
Springel et al. (2005)
Hopkins et al. (2006)

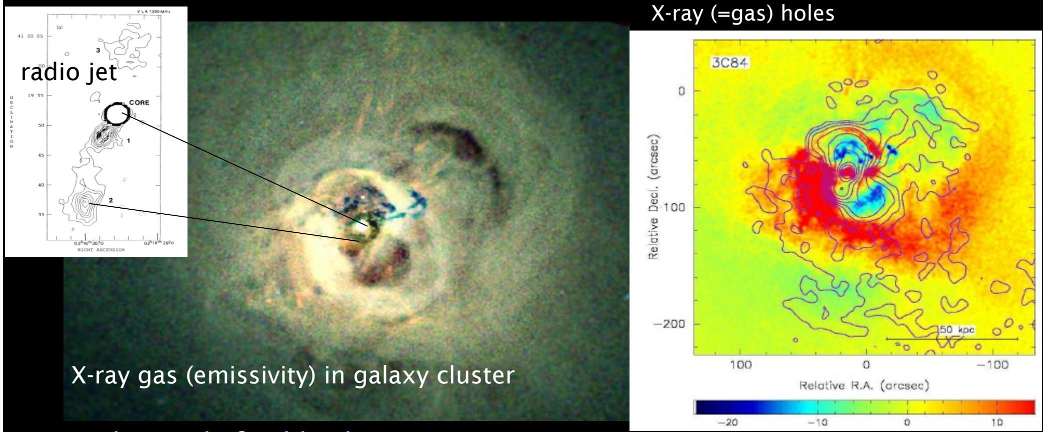
Radio Jets: Energetics based on cavities inflated in the hot ICM





The Impact of AGNs on their Host Galaxies
Case study: radio AGN in the Perseus cluster
(e.g. Fabian et al 2003)

radio emission (relativistic particles)
X-ray (=gas) holes



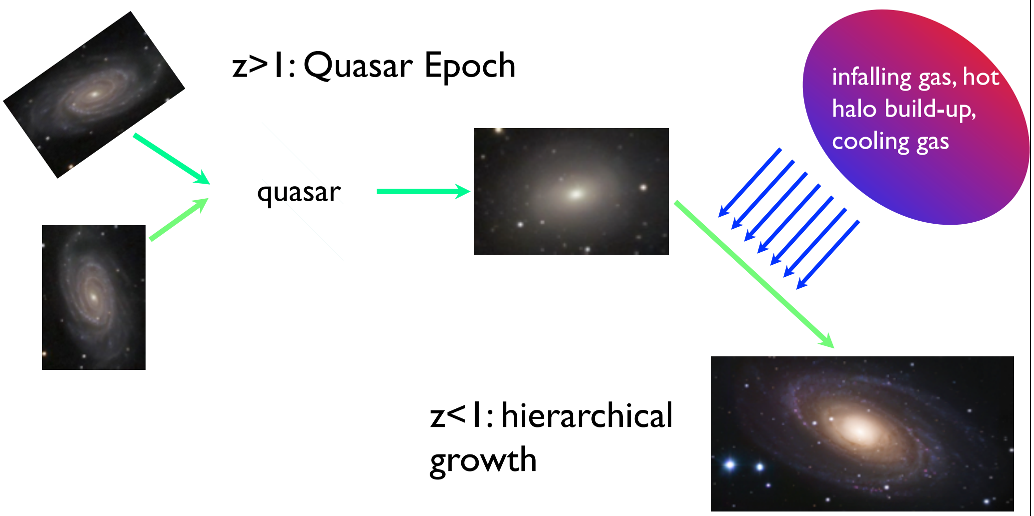
Radio-mode feed-back (e.g. Croton et al 2006)

- only effective in (massive) halos that have 'hot' X-ray atmosphere
- energetic feed-back that requires no star-formation itself
- Efficiency increases with M_{BH} →? only effective after the BH has grown?

→ explanation of why massive galaxies no longer form stars?

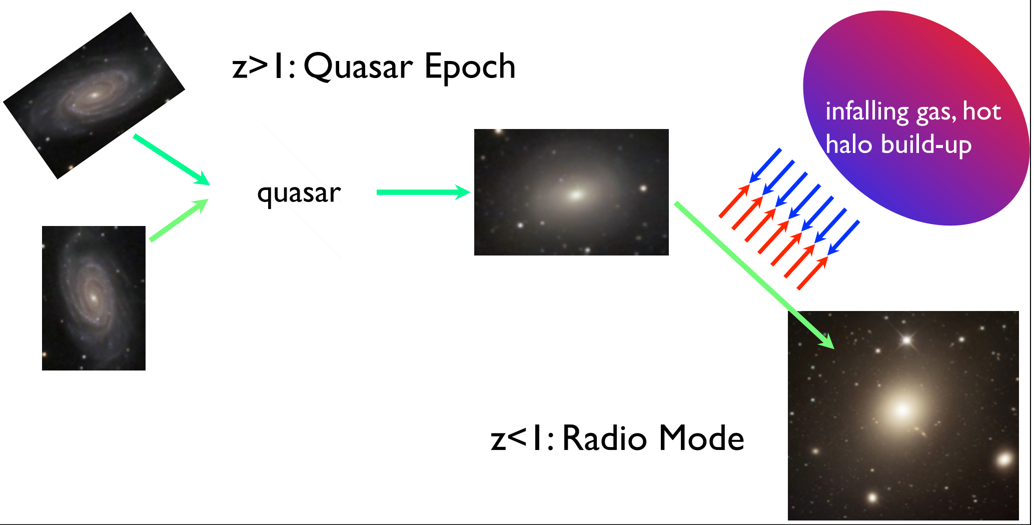
RADIO MODE FEEDBACK

Croton et al. 2006



RADIO MODE FEEDBACK

Croton et al. 2006



AGN FEEDBACK

	When?	Trigger?	Feeding?	Consequence?
Quasar Mode	at early times	gas rich mergers	cold gas	BH growth, sets properties of ellipticals
Radio Mode	at late times	BH & hot halo large enough?	hot gas? stellar winds?	suppresses cooling gas, shuts down SF

A complete picture of galaxy evolution probably needs both

Final Thoughts

AGN are important for several reasons:

> They have produced ~10% of all the luminous energy since the Big Bang

> They are unique laboratories for studying physics under extreme conditions

> They played a major role in the evolution of the baryonic component of the universe (galaxies and the inter-galactic medium)

Summary

- A wide range of energetic phenomena at the cores of galaxies can be best explained by material accreting onto supermassive black holes.
- Dynamical/observational evidence for black holes is very strong in many galaxies
- Black holes are (nearly?) ubiquitous in the centers of nearby massive galaxies.
  - M_{Bh} correlates (surprisingly?) well with σ_* or M_*, indicating a strong link with galaxy formation
- AGNs (quasars, etc,…) are *shortlived* phases in the lives of *normal* galaxies