Oxford Physics: Part C Major Option Astrophysics

High-Energy Astrophysics

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Today's lecture

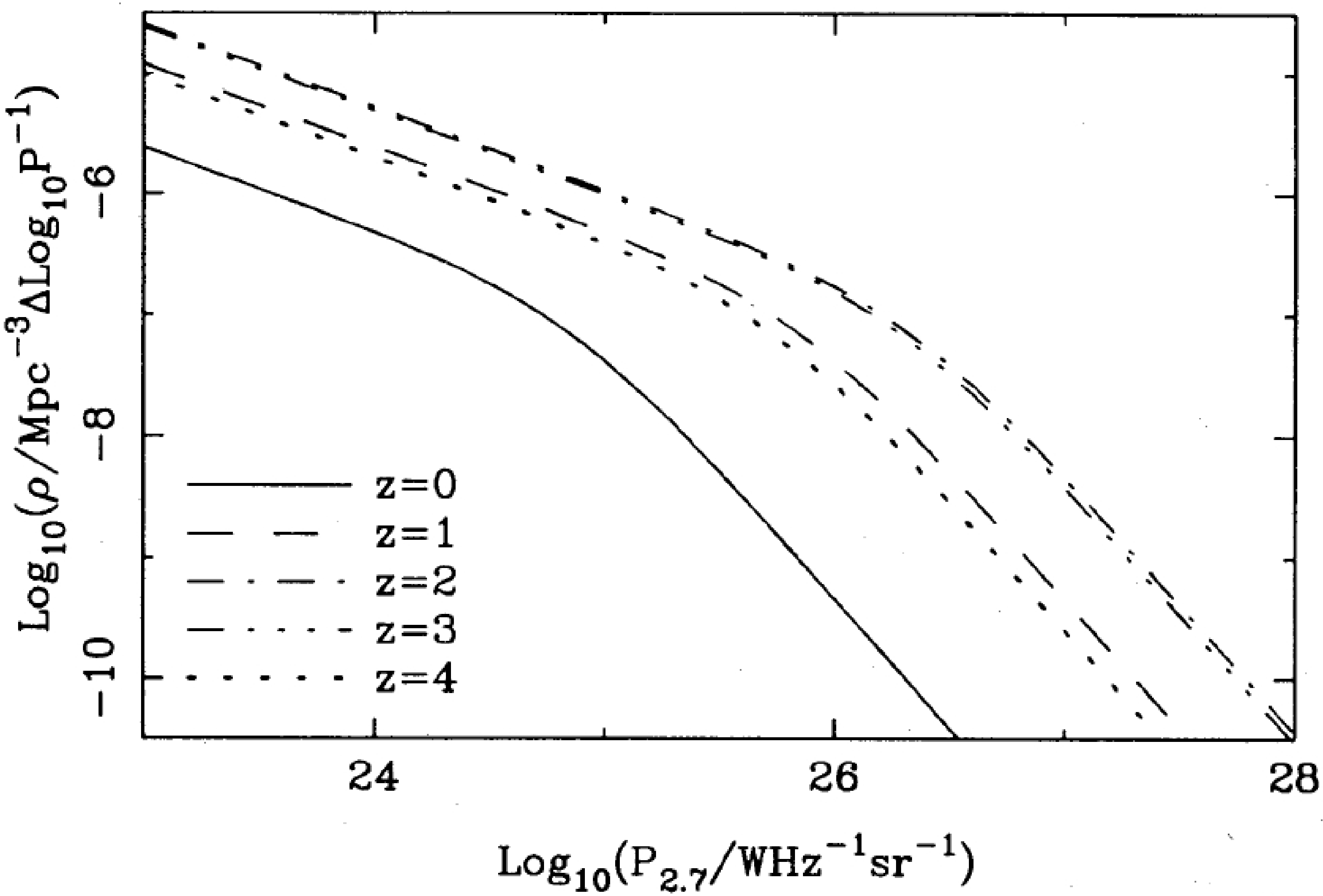
- AGN luminosity functions and their evolution.
- AGN accretion history and quiescent black holes today.
- The radio-loud/radio-quiet "dichotomy"

The radio luminosity function

Just as in the case of the stellar luminosities of quiescent galaxies, the radio-loud AGN can be described by a *radio luminosity function*. Observationally at low redshift this is well described as a two-power-law function:

$$\rho = \rho_0 \left[\left(\frac{P}{P_\mathrm{C}} \right)^\alpha + \left(\frac{P}{P_\mathrm{C}} \right)^\beta \right]^{-1}$$

Here ρ is the number of sources per unit volume per unit luminosity; P is luminosity; P_C and ρ_0 are characteristic luminosities and densities; and α and β are the two power-law indices.

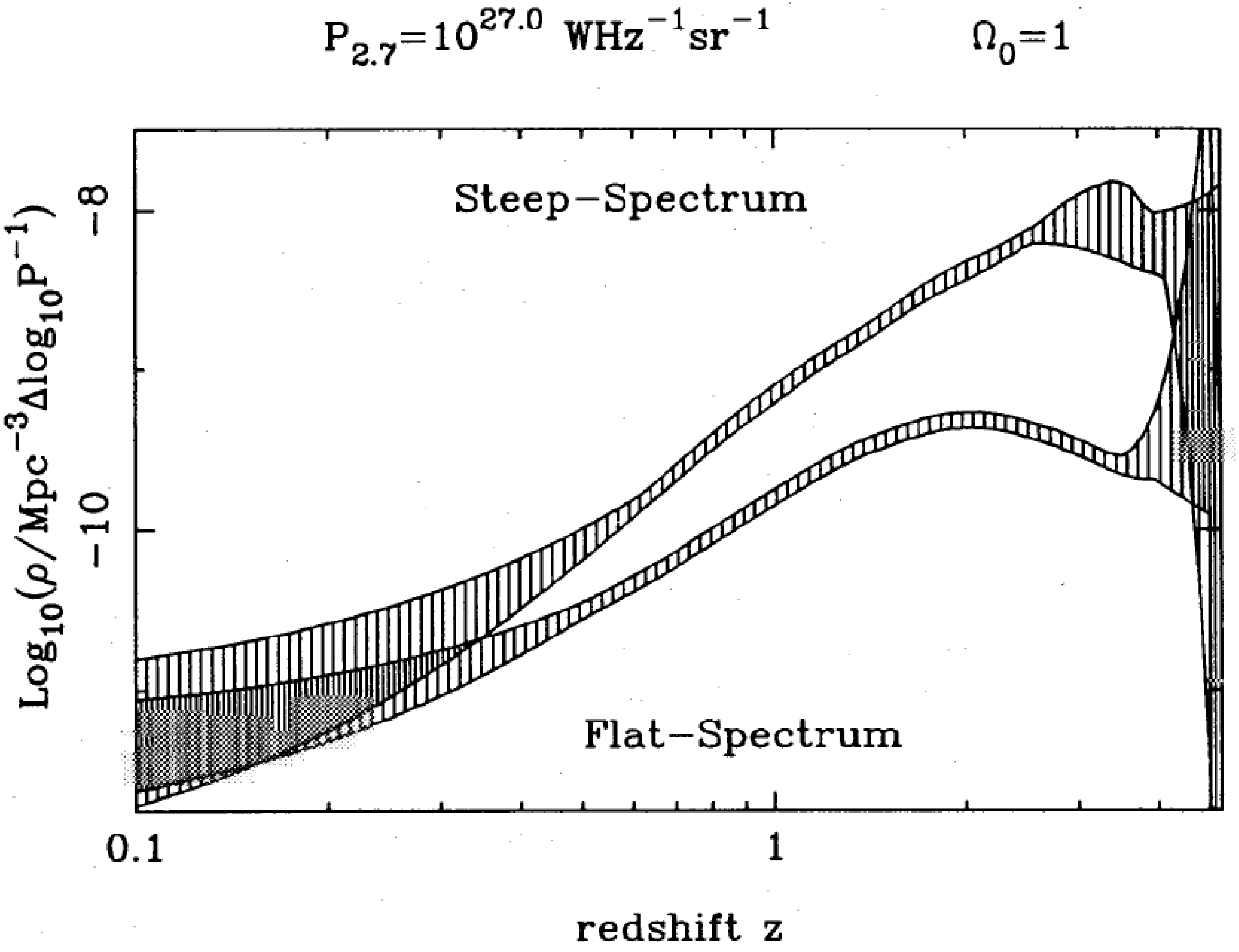


Log10(ρ/Mpc^-3 ΔLog10P^-1)
-6
-8
-10
z=0
z=1
z=2
z=3
z=4
24
26
28
Log10(P2.7/WHz^-1sr^-1)

Evolution of the RLF

We have alluded in earlier lectures to the fact that AGN activity was more common in the past. From redshift surveys of radiosources at cosmological distances, we measure an evolution in the *luminosity density*, i.e. the integral under the RLF. This scales roughly as $(1+z)^3$ between $z=0$ and $z \approx 2$, with conflicting evidence as to the presence, or steepness, of a turnover at high redshift.

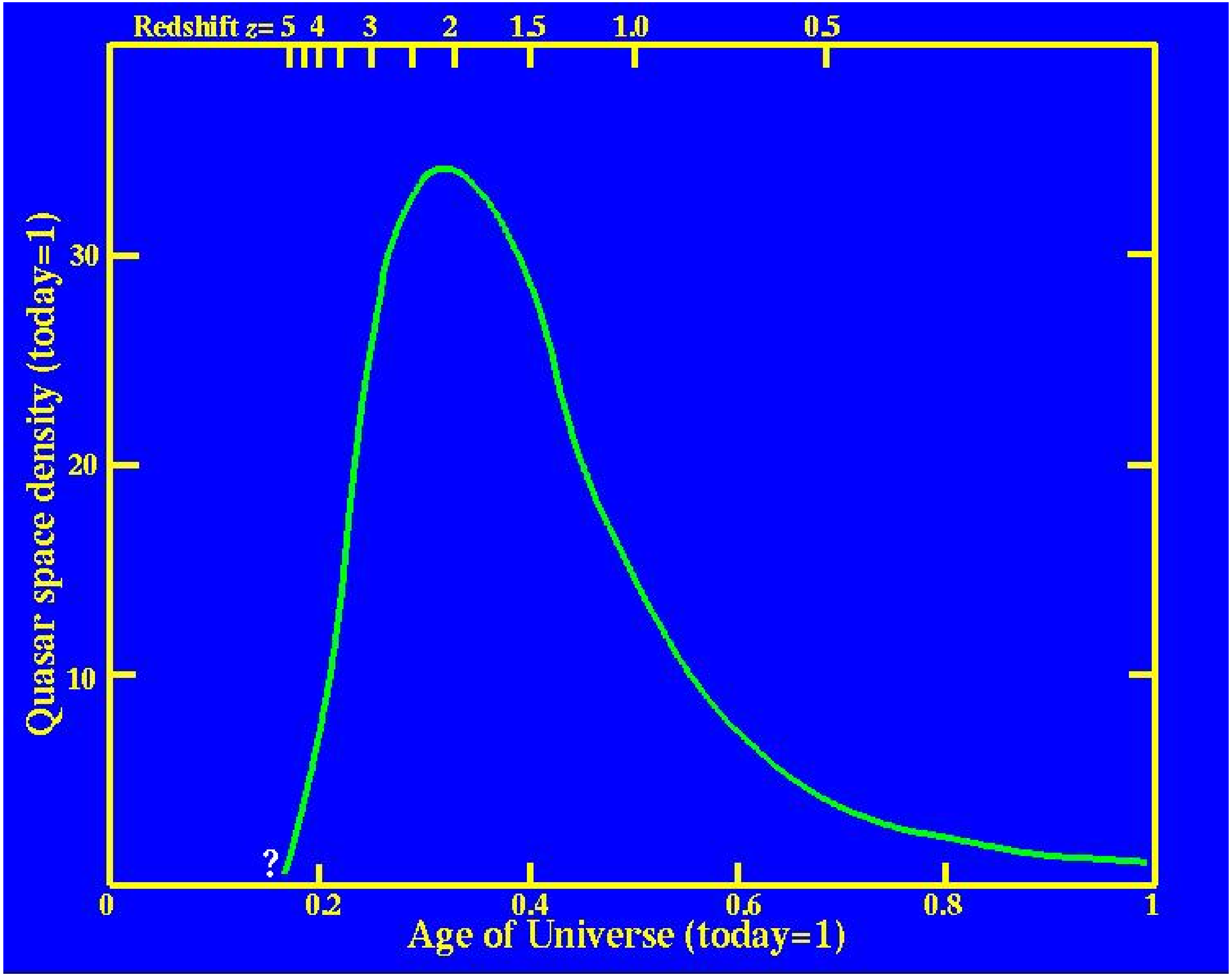
This evolution could be *luminosity evolution* or *density evolution*

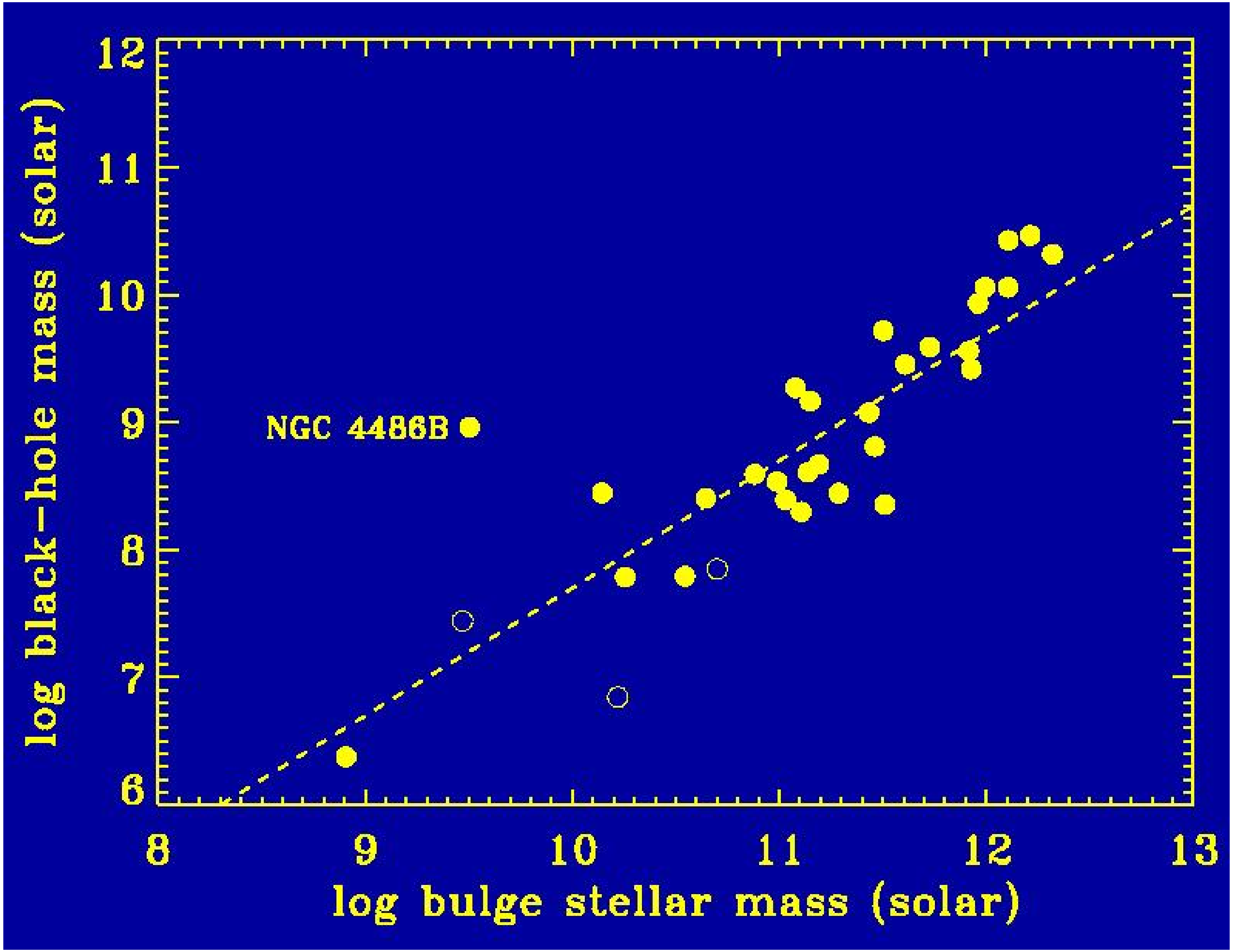


$P_{2.7}=10^{27.0}$ WHz^{-1}sr^{-1}
$\Omega_0=1$
Steep-Spectrum
Flat-Spectrum
$\mathrm{Log}_{10}(\rho/\mathrm{Mpc}^{-3}\Delta\log_{10}P^{-1})$
−8
−10
0.1
1
redshift z

Accretion history and remnant black holes today

From the known lifetimes of radiosources and the Eddington mass-doubling time for SMBH accretion, we expect that an individual AGN episode is only a short fraction of the lifetime of an individual galaxy. Hence we now have a picture in which most massive galaxies underwent an AGN phase early in their history. This implies that there are *relic* quiescent SMBH's in the centre of most galaxies today.


Redshift z= 5 4 3 2 1.5 1.0 0.5
Quasar space density (today=1)
30
20
10
?
0
0.2
0.4
0.6
0.8
1
Age of Universe (today=1)

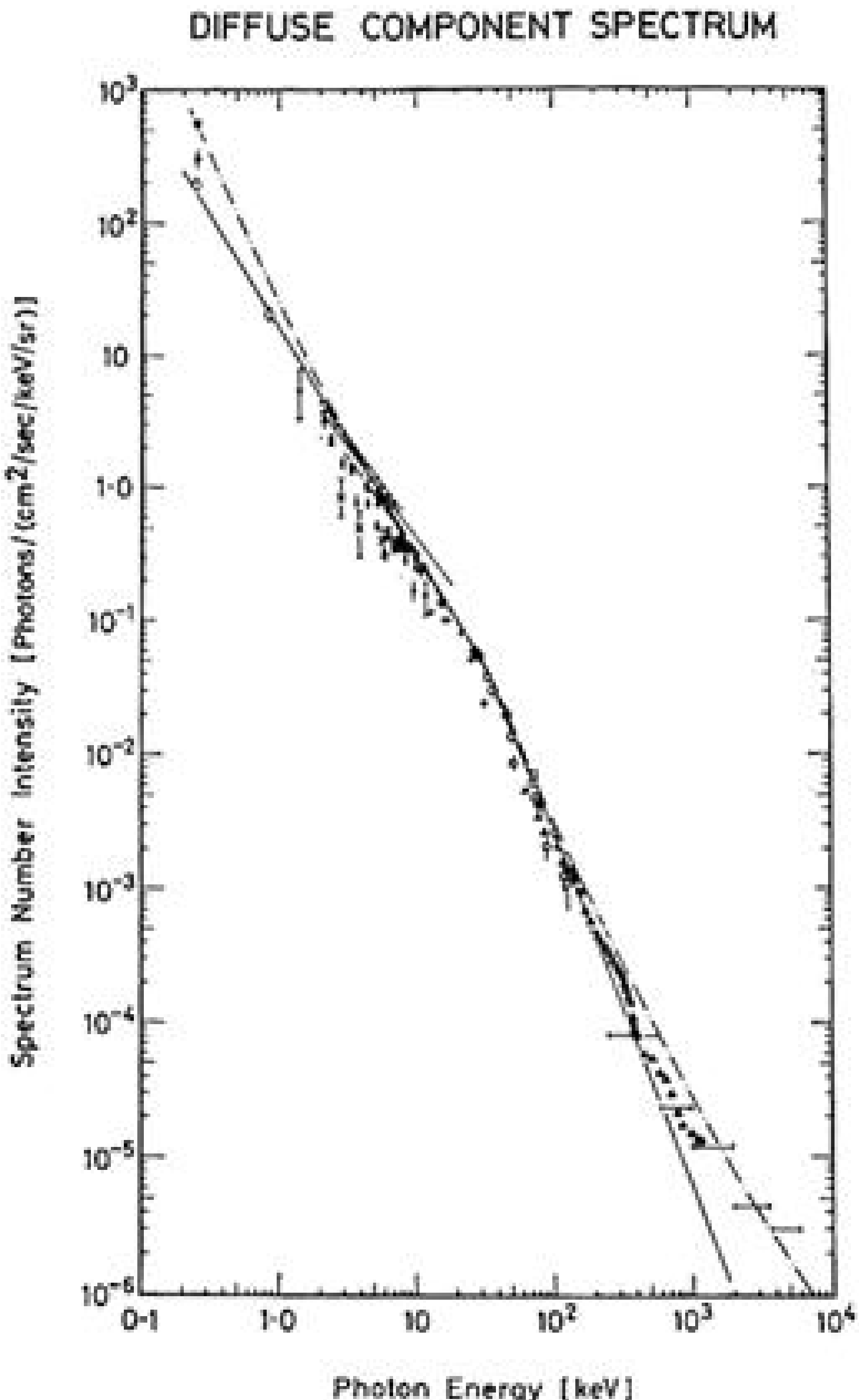


log black-hole mass (solar)
log bulge stellar mass (solar)
NGC 4486B
12
11
10
9
8
7
6
8
9
10
11
12
13

Accretion history contd.

That the quiescent black holes in today's galaxies are the relics of AGN activity in the past can be shown by considering the *diffuse high-energy background* as measured by satellite, at energies ranging from UV upwards.

The background high-energy flux which we observe across the sky is dominated by the individual contributions from AGN emitting at the epoch of their peak activity, at around $z \approx 2$–3.



DIFFUSE COMPONENT SPECTRUM
Spectrum Number Intensity [Photons/(cm2/sec/keV/sr)]
Photon Energy [keV]

Accretion history contd.

If we integrate under the X-ray background spectrum, we find that there is a mean energy density in the local Universe $\epsilon \approx 10^{-16}$Jm^{-3}.

Let us approximate that this energy was all released at $z = 2$. Radiation energy density scales as $(1 + z)^4$ so this implies an energy density at the peak of the quasar era of 81ϵ.

Using our standard accretion efficiency of 10%, this implies that there was a *mass* density in recently-fed black holes of $810\epsilon/c^2$ at $z = 2$. Now, as the Universe expands mass density scales as $(1 + z)^3$, which means that there will be a mass density in black holes at the present day equal to $30\epsilon/c^2$.

Accretion history contd.

Now let us use our numbers: $\epsilon \approx 10^{-16}$Jm^{-3}.

This gives us a present-day mass density in relic black holes of about 3×10^{-32} kg m^{-3}.

If we take the mean number density of galaxies today (0.01 Mpc^{-3}) and allow one black hole to inhabit each galaxy, we find a mean black hole mass per galaxy of $5 \times 10^{7} M_{\odot}$.

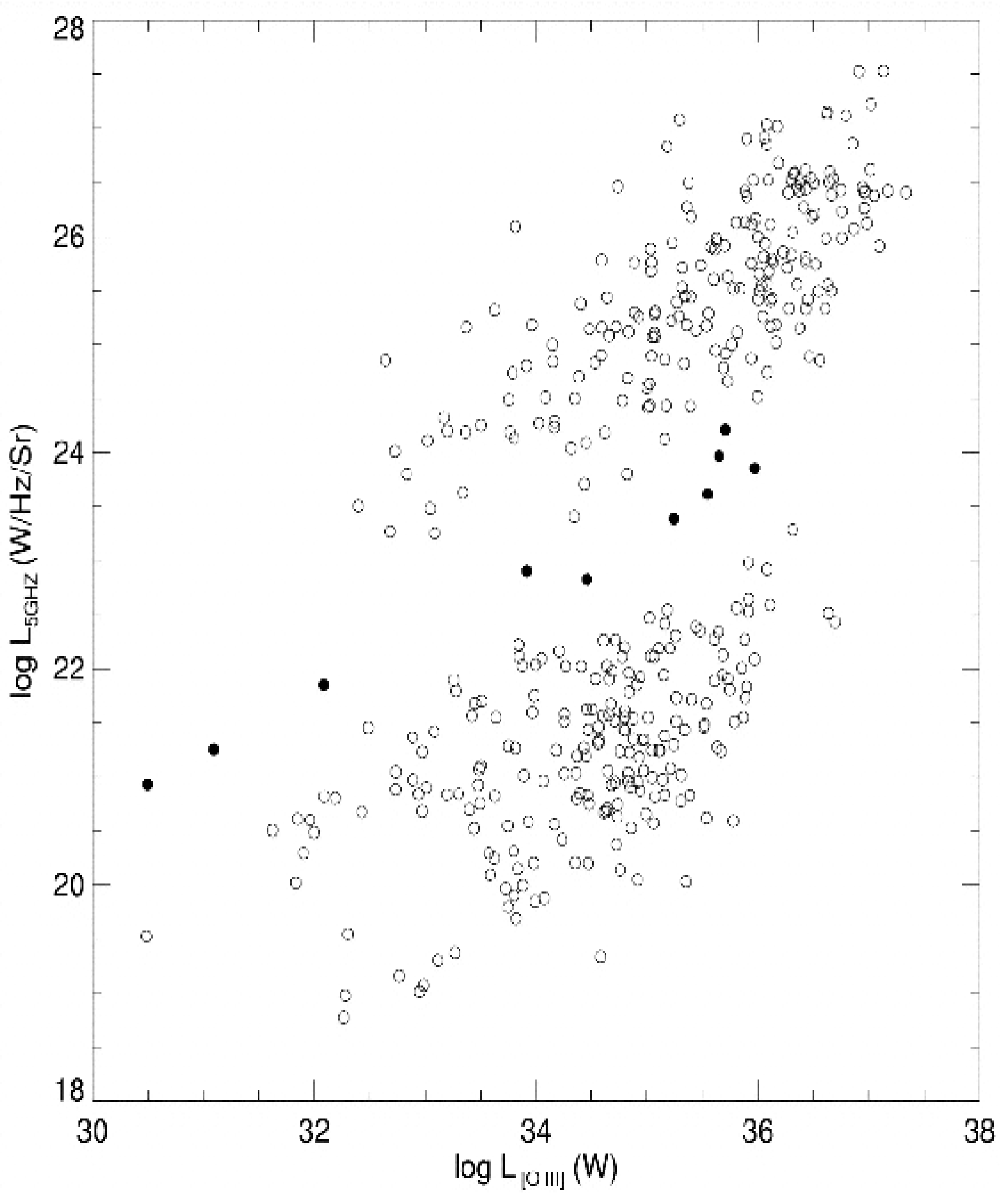
Can we see why this is an underestimate?

The radio-loud/radio-quiet dichotomy

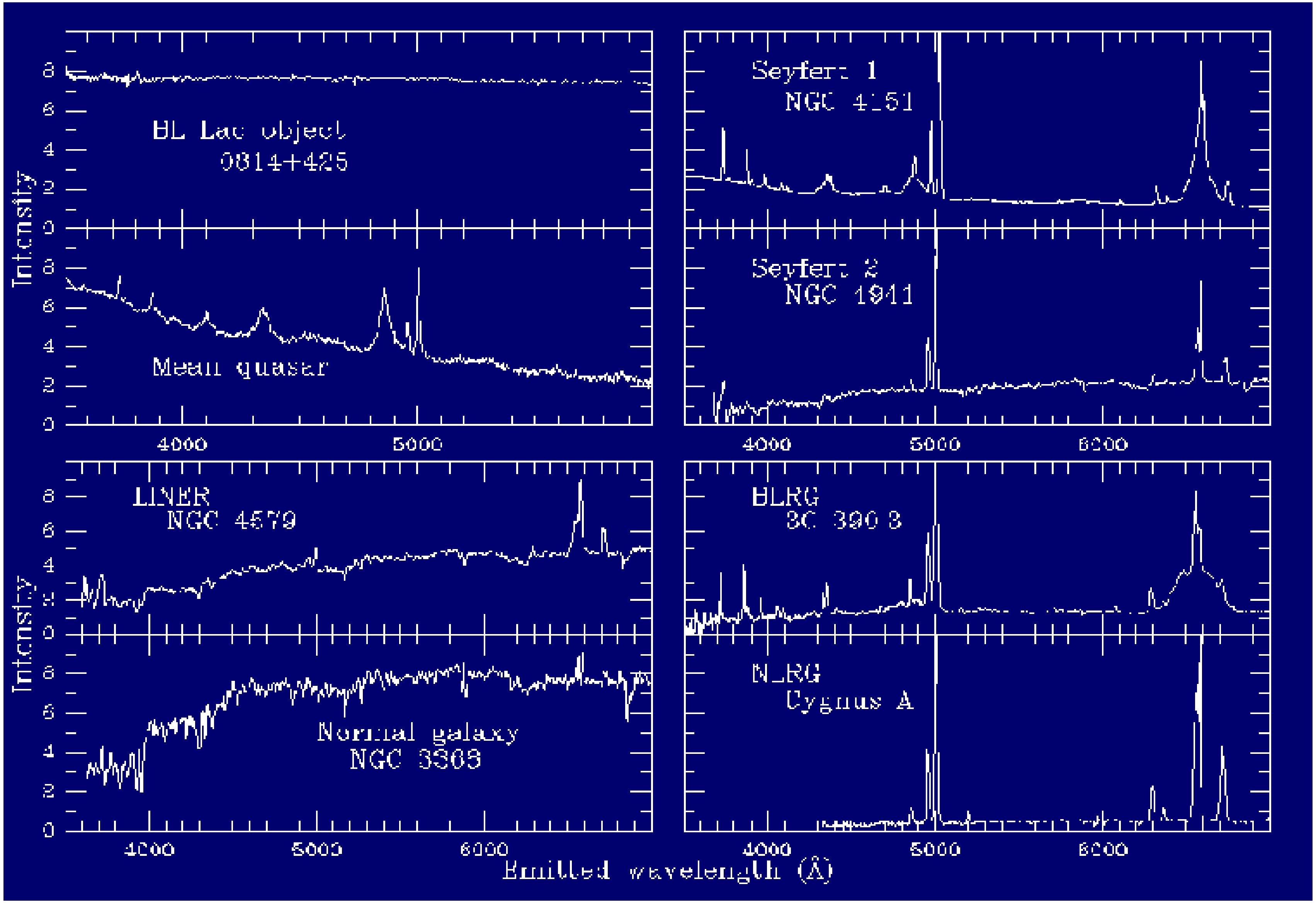
Although we now know that even low-luminosity AGN such as Seyferts have jets, the extraordinarily powerful jets of the most luminous sources gives rise to a traditional breakdown of AGN into “radio loud” and “radio quiet” categories.

The classical radiogalaxies and quasars are generally taken to fall into the radio-loud category, and lower luminosity objects such as the Seyferts fall into the radio-quiet class.

However the a complication arises in that there seem to be many objects with the same optical/UV/X-ray properties as the (radio-loud) quasars, but which lack strong radio jets. To avoid confusion we shall refer to these as radio-quiet quasars.



28
26
24
22
20
18
30
32
34
36
38
log L5GHZ (W/Hz/Sr)
log L[O III] (W)



BL Lac object
0814+425
Mean quasar
Seyfert 1
NGC 4151
Seyfert 2
NGC 1941
LINER
NGC 4579
Normal galaxy
NGC 3368
BLRG
3C 390.3
NLRG
Cygnus A
Intensity
Emitted wavelength (Å)

The radio-loud/radio-quiet dichotomy

- Dichotomy: Two separate populations with small number of intermediate cases.

- Correlations: Quasi-thermal emission from the accretion region and non-thermal emission correlated within each sub-class.

- Radio-quiet but not radio-silent: Radio-quiet objects do have jets. Superluminal motions have been detected in some Seyfert galaxies.

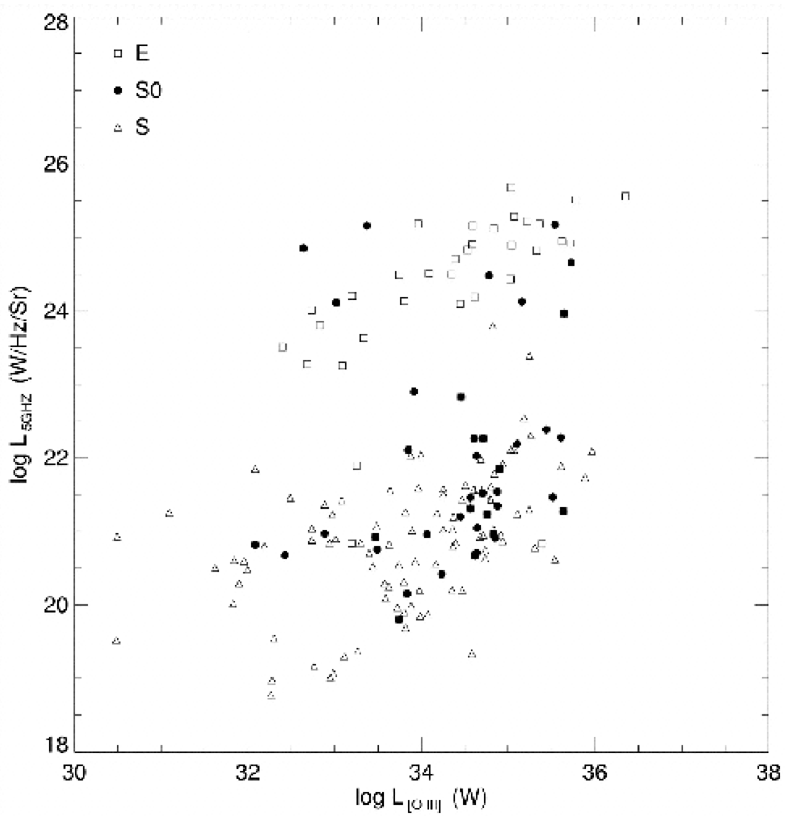
But is there really a dichotomy?

- Definitions of radio-loudness: total radio luminosity, extended radio luminosity; radio/optical flux ratio. All have problems.

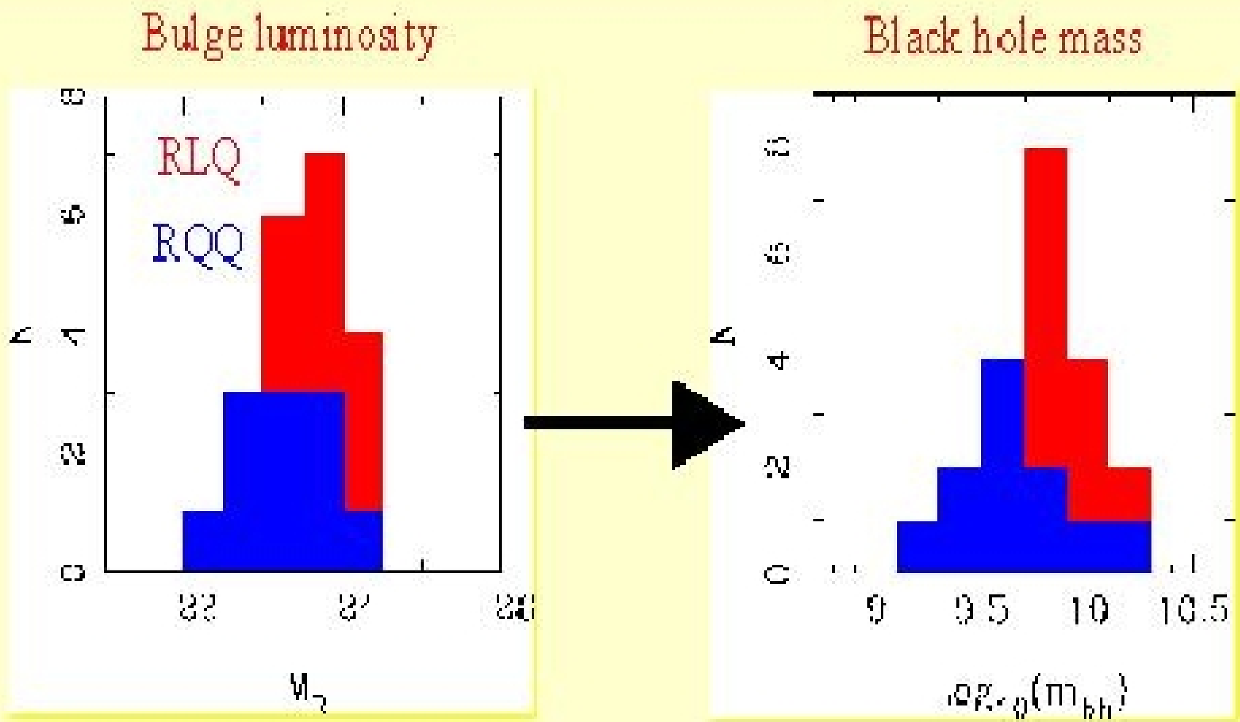
- Radio-quiet quasars do have radio emission, but this is difficult to detect/image at high redshift, and has been missed in surveys.

- Large, unbiased samples of spectroscopically-selected quasars now available (e.g. SDSS, 2DF).

- Perhaps a steep *luminosity* function for *jet power*.



Host galaxies of radio-loud and radio-quiet AGN



$M\,(bh) \sim 10^{9} - 10^{10}\ M_{0}$

Physics of radio-loudness

- BH mass? Radio-loud AGN seem to be associated with the most massive galaxies and therefore (via the bulge luminosity - BH mass correlation) the most massive black holes, but this cannot be the whole story. Why jets?

- Duty cycle? But never see very powerful jets in spiral hosts (do see radio-quiet quasars in spirals)

- Jet disruption in radio-quiets—but low-power jets are seen.

- BH spin may be required for efficient jet production and collimation (e.g via Blandford-Znajek). But no solid evidence yet on BH spin (e.g. from X-ray line profiles).

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BLACK HOLE SPIN AND THE RADIO LOUD/QUIET DICHOTOMY OF ACTIVE GALACTIC NUCLEI

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ABSTRACT

Radio loud active galactic nuclei (AGNs) are on average 1000 times brighter in the radio band compared to radio quiet AGNs. We investigate whether this radio loud/quiet dichotomy can be due to differences in the spin of the central black holes (BHs) that power the radio-emitting jets. Using general relativistic magnetohydrodynamic simulations, we construct steady state axisymmetric numerical models for a wide range of BH spins (dimensionless spin parameter $0.1 \leqslant a \leqslant 0.9999$) and a variety of jet geometries. We assume that the total magnetic flux through the BH horizon at radius $r_{\rm H}(a)$ is held constant. If the BH is surrounded by a thin accretion disk, we find that the total BH power output depends approximately quadratically on the angular frequency of the hole, $P \propto \Omega_{\rm H}^2 \propto (a/r_{\rm H})^2$. We conclude that, in this scenario, differences in the BH spin can produce power variations of only a few tens at most. However, if the disk is thick such that the jet subtends a narrow solid angle around the polar axis, then the power dependence becomes much steeper, $P \propto \Omega_{\rm H}^4$ or even $\propto \Omega_{\rm H}^6$. Power variations of 1000 are then possible for realistic BH spin distributions. We derive an analytic solution that accurately reproduces the steeper scaling of jet power with $\Omega_{\rm H}$ and we provide a numerical fitting formula that reproduces all our simulation results. We discuss other physical effects that might contribute to the observed radio loud/quiet dichotomy of AGNs.

Key words: accretion, accretion disks – black hole physics – galaxies: jets – galaxies: nuclei – magnetohydrodynamics (MHD) – quasars: general – relativistic processes

Online-only material: color figures