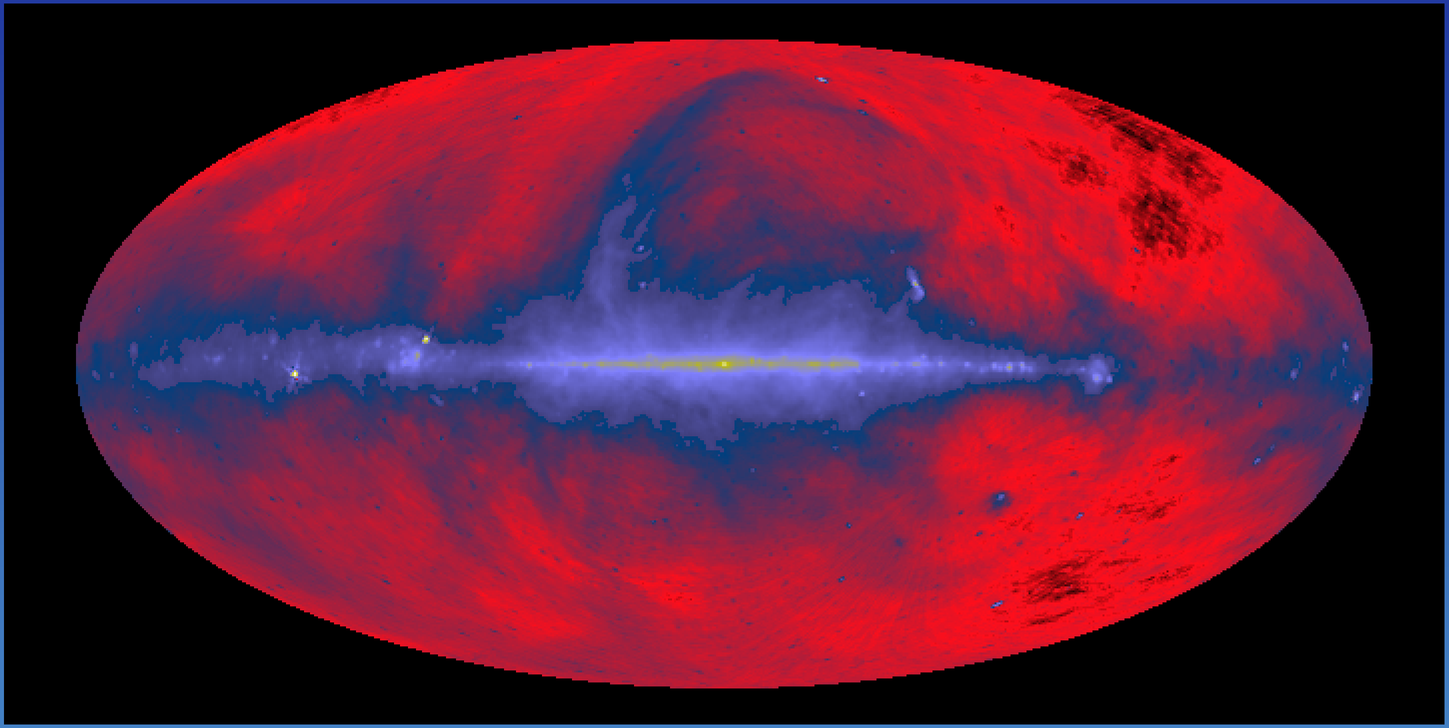
The Most Luminous Radio Galaxies

- The physics of radio galaxies and quasars
- The origin of their strong cosmological evolution
- Where they fit into the scheme of galaxy formation and evolution
- How does it all fit together

The Radio Sky



The radio sky is dominated by the diffuse emission from our Galaxy but, away from the Galactic Plane, there is a huge population of extragalactic radio sources.

The 3CR Radio Sources

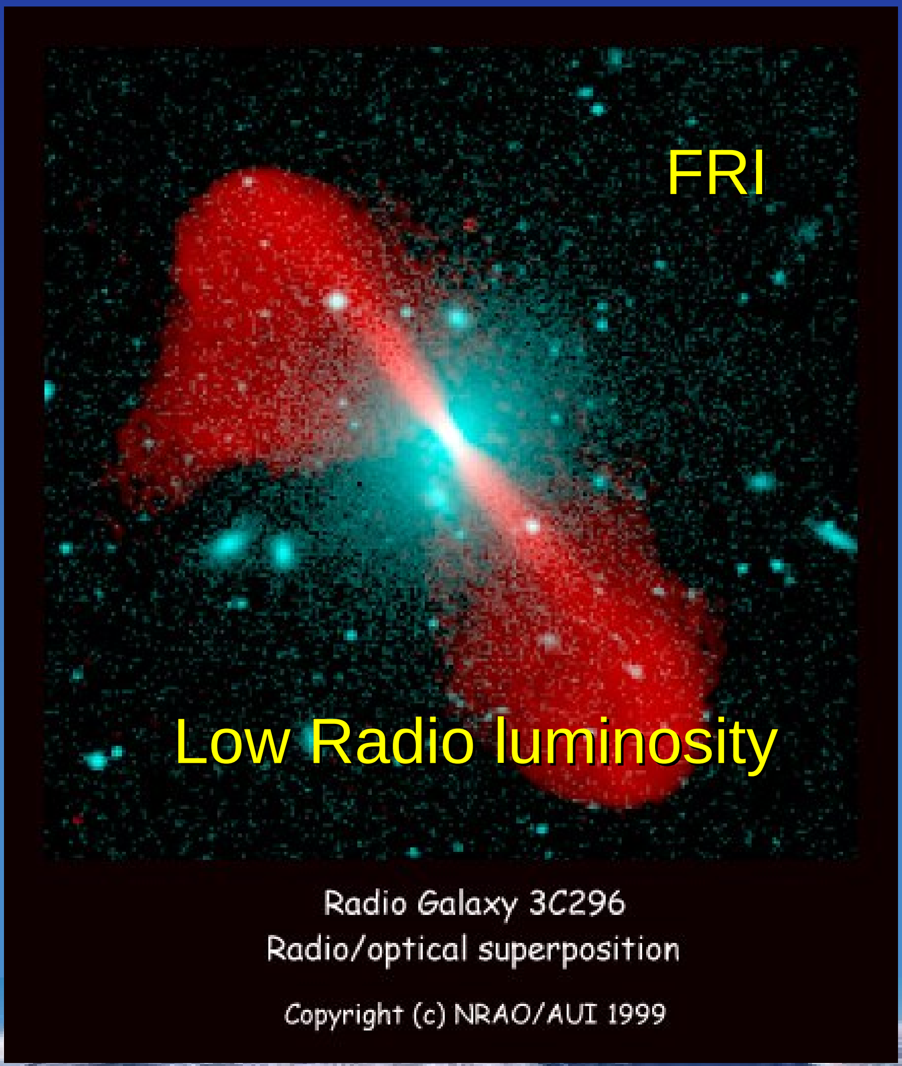
The brightest radio sources in the northern sky are contained in the Third Cambridge Catalogue of Radio Source, as revised by Andrew Bennett in 1962 - the 3CR catalogue. It contains 328 radio sources. Most of those at low galactic latitudes are galactic objects; virtually all of them at $|b|>10^{o}$ are distant extragalactic objects.

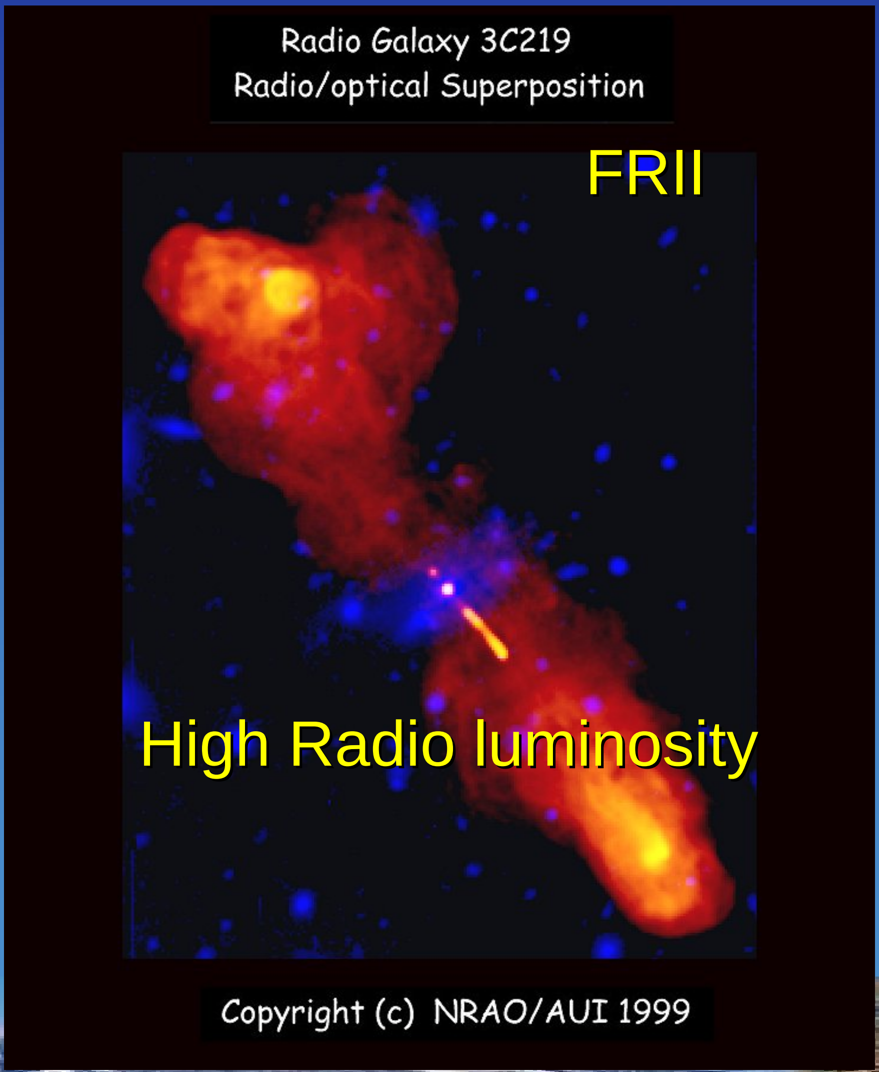
The 3CR Radio Sources

The sample is flux-density limited at S = 10 Jy at 178 MHz and so contains a mixture of nearby low radio luminosity objects and luminous distant objects.

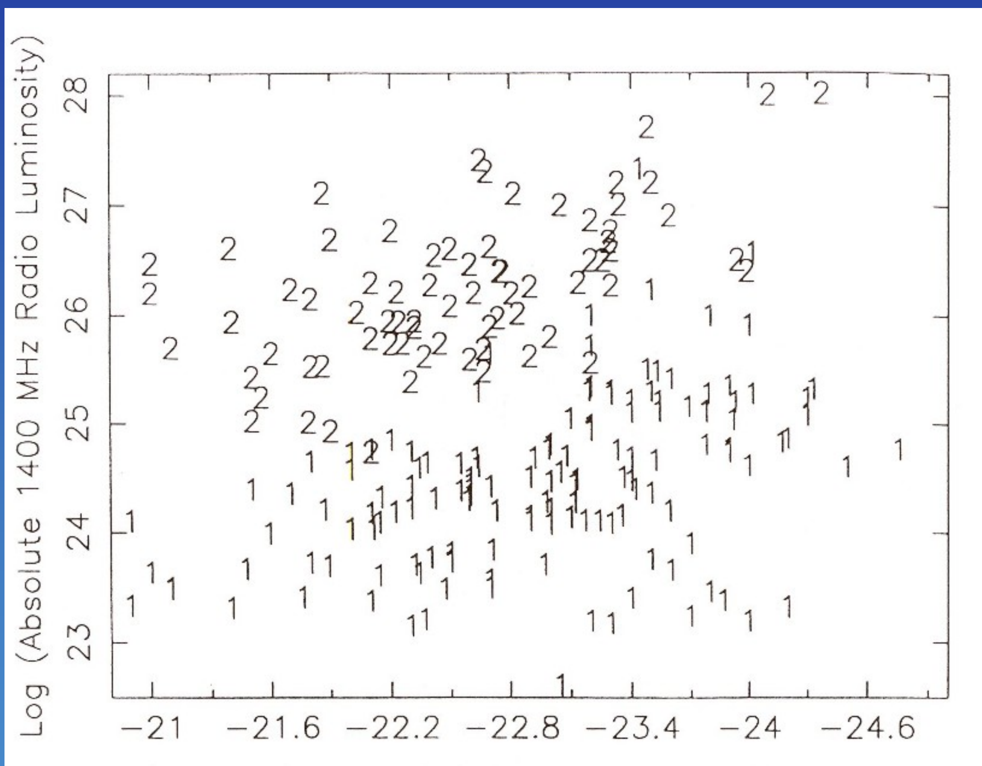
The radio structures of these sources were measured by aperture synthesis radio telescopes. There are significant differences between the extragalactic sources as a function of radio luminosity – the Fanaroff-Riley effect.

Fanaroff-Riley Classes I and II





Fanaroff-Riley Classes I and II

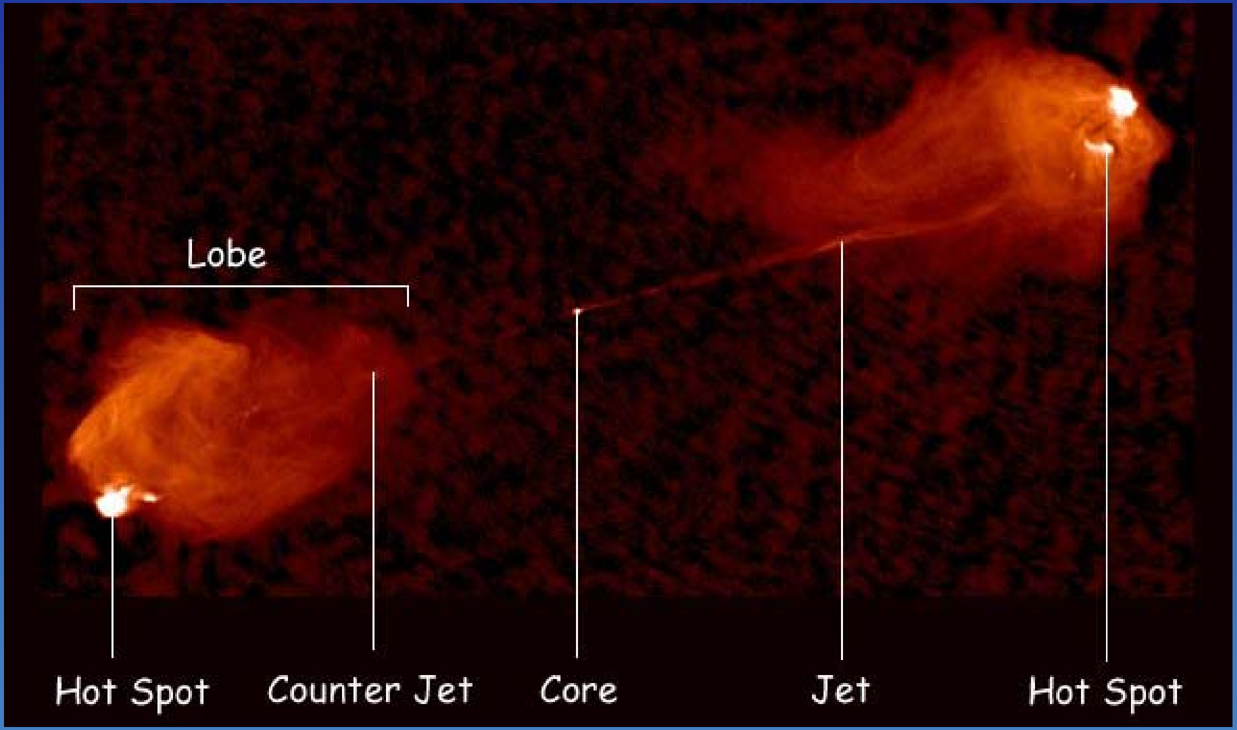


Optical Absolute Magnitude

There is a very marked transition between FRI and FRII as a function of radio luminosity.

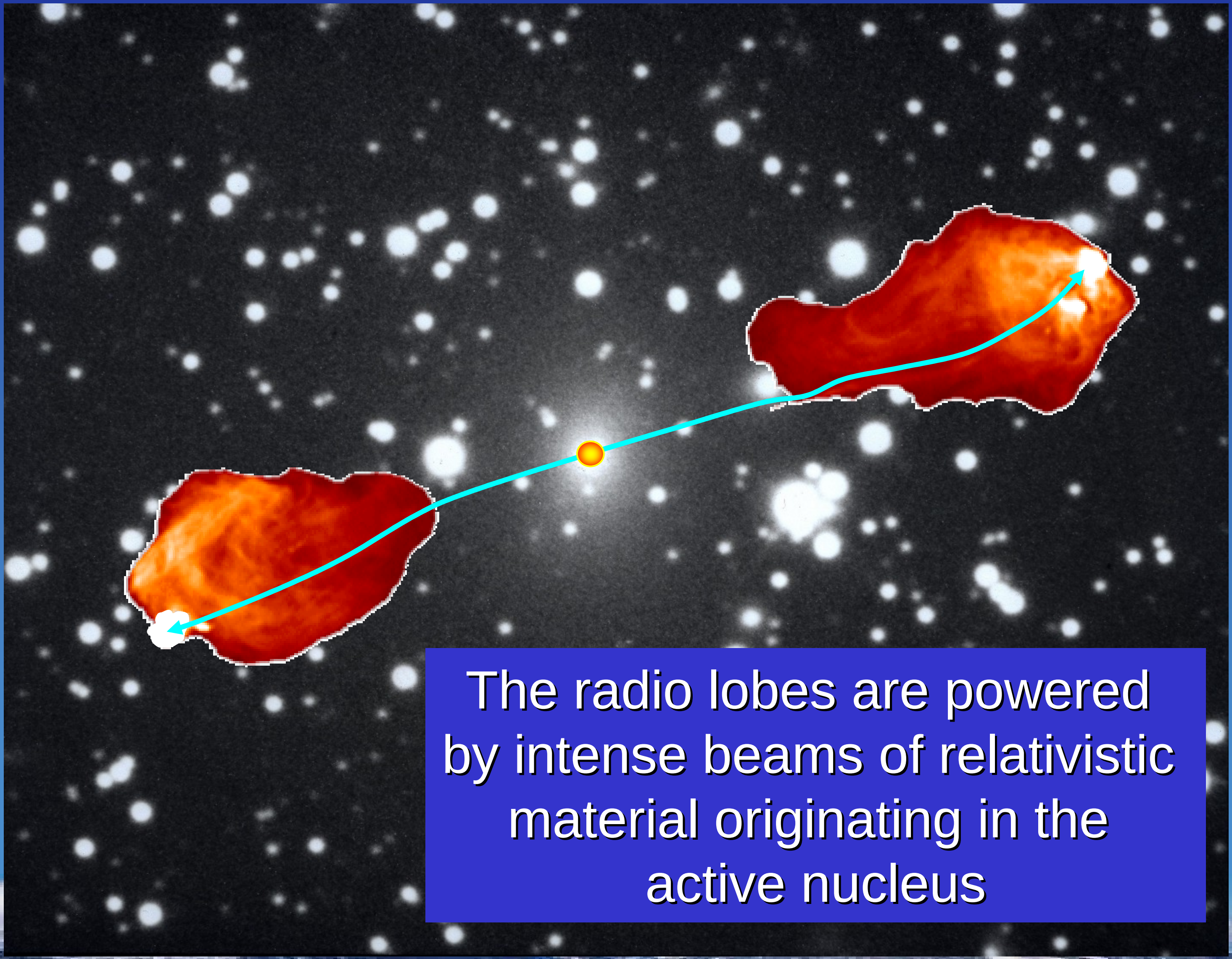
We will be almost exclusively concerned with the FRII sources which are the most luminous radio galaxies.

The Nature of the Radio Emission



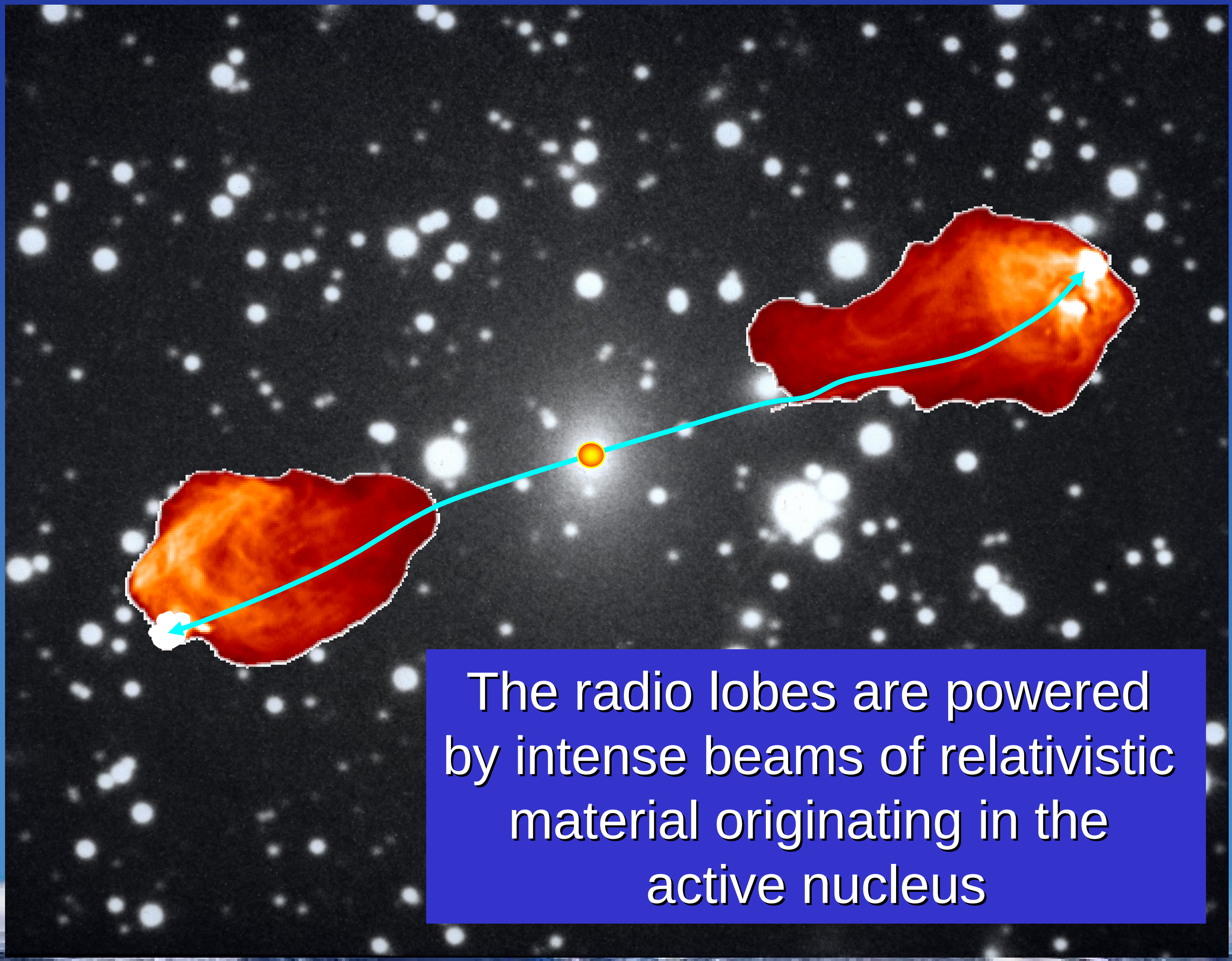
The radio emission is synchrotron radiation, the emission of extremely high energy electrons gyrating in a magnetic field. The electrons are produced by jets of relativistic material ejected from the active galactic nucleus.

The Radio Galaxy Cygnus A



The radio lobes are powered by intense beams of relativistic material originating in the active nucleus

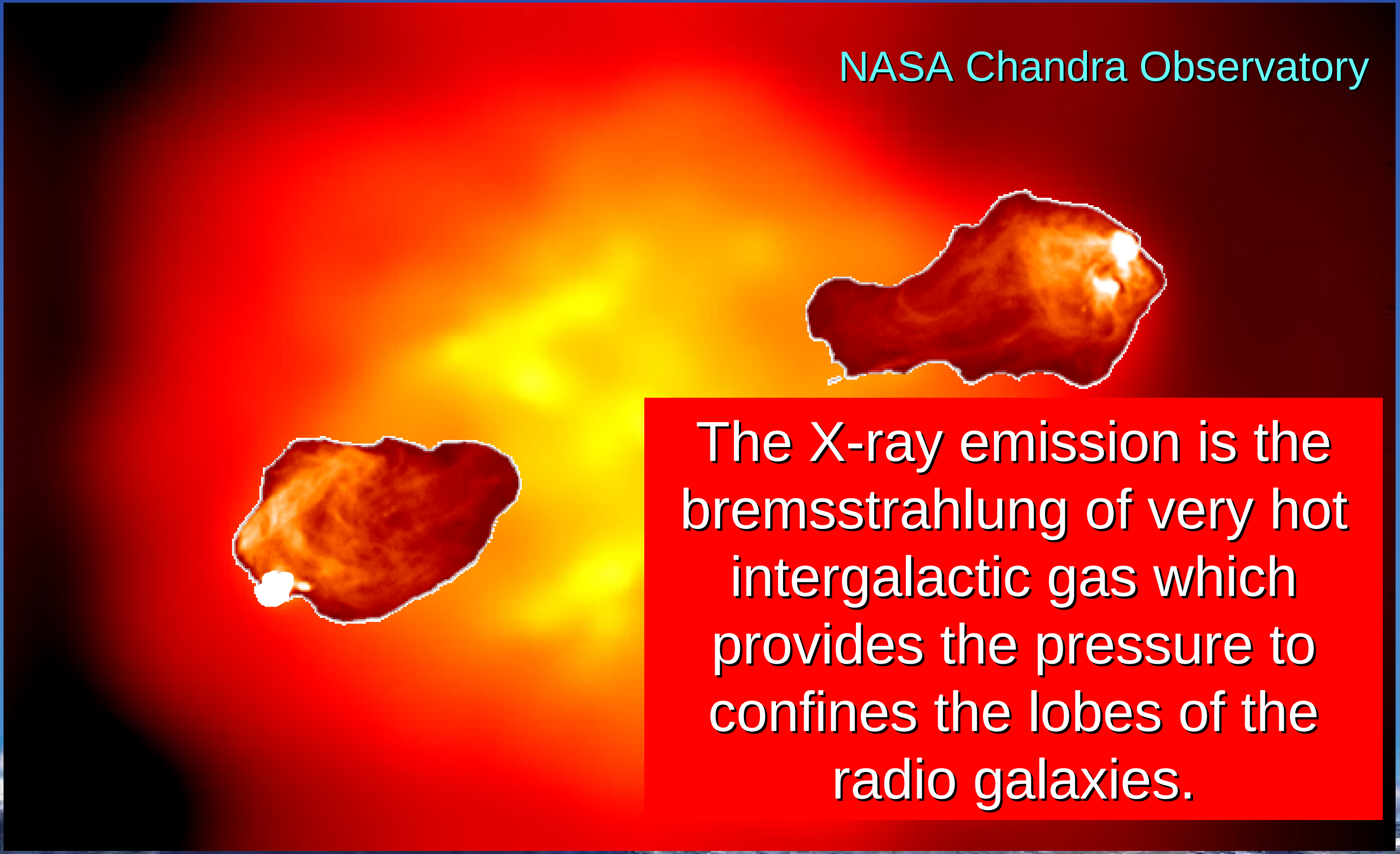
The Radio Galaxy Cygnus A



The radio lobes are powered by intense beams of relativistic material originating in the active nucleus

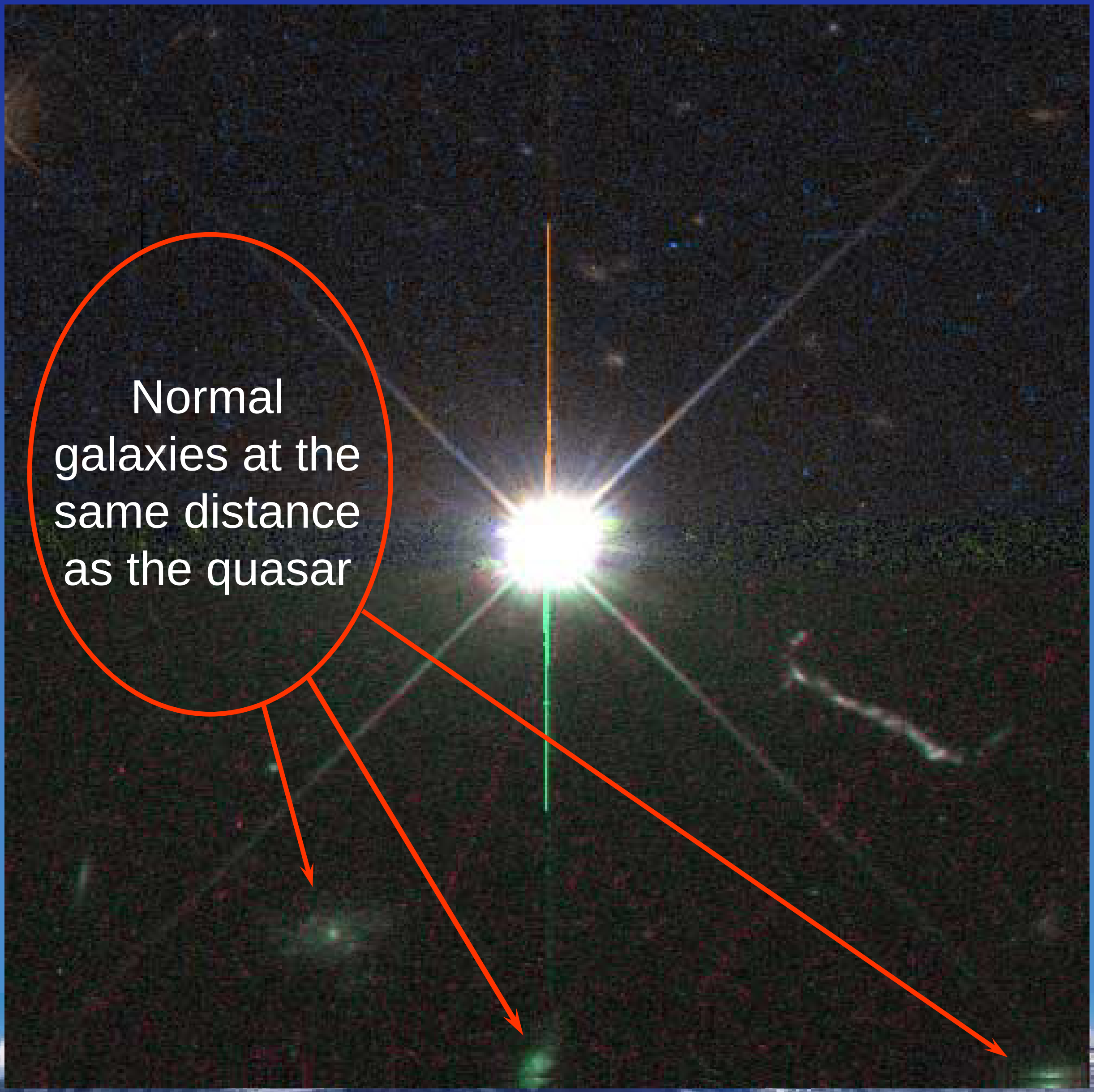
Cygnus A – X-ray image

The image shows the distribution of hot intergalactic gas surrounding the radio source.



The X-ray emission is the bremsstrahlung of very hot intergalactic gas which provides the pressure to confines the lobes of the radio galaxies.

The Quasar 3C 273



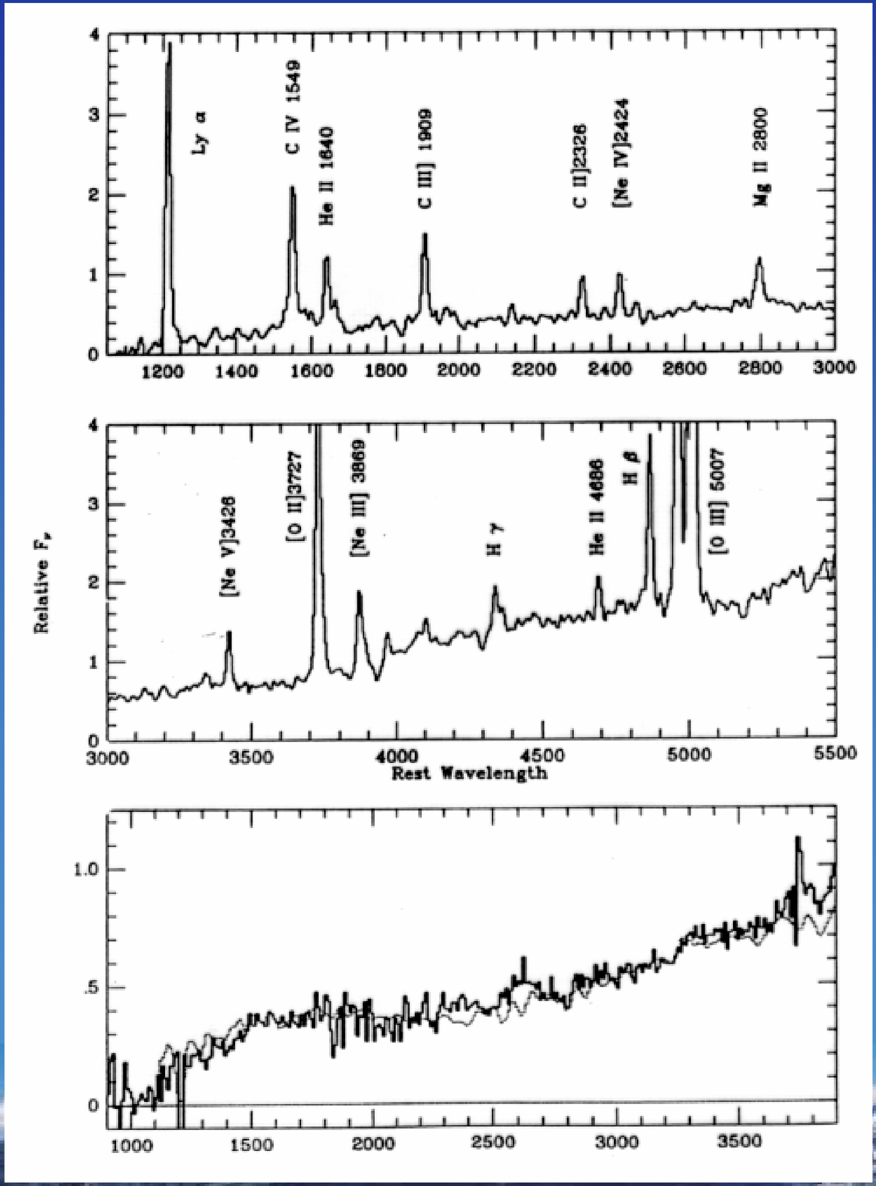
In 1963, 3C 273, the first quasar, was discovered. They can be up to 1000 more luminous than the massive host galaxy.

The 3CR quasars are all FRII radio sources when selected at low radio frequencies.

The Spectra and Redshifts of the 3CR Radio Galaxies

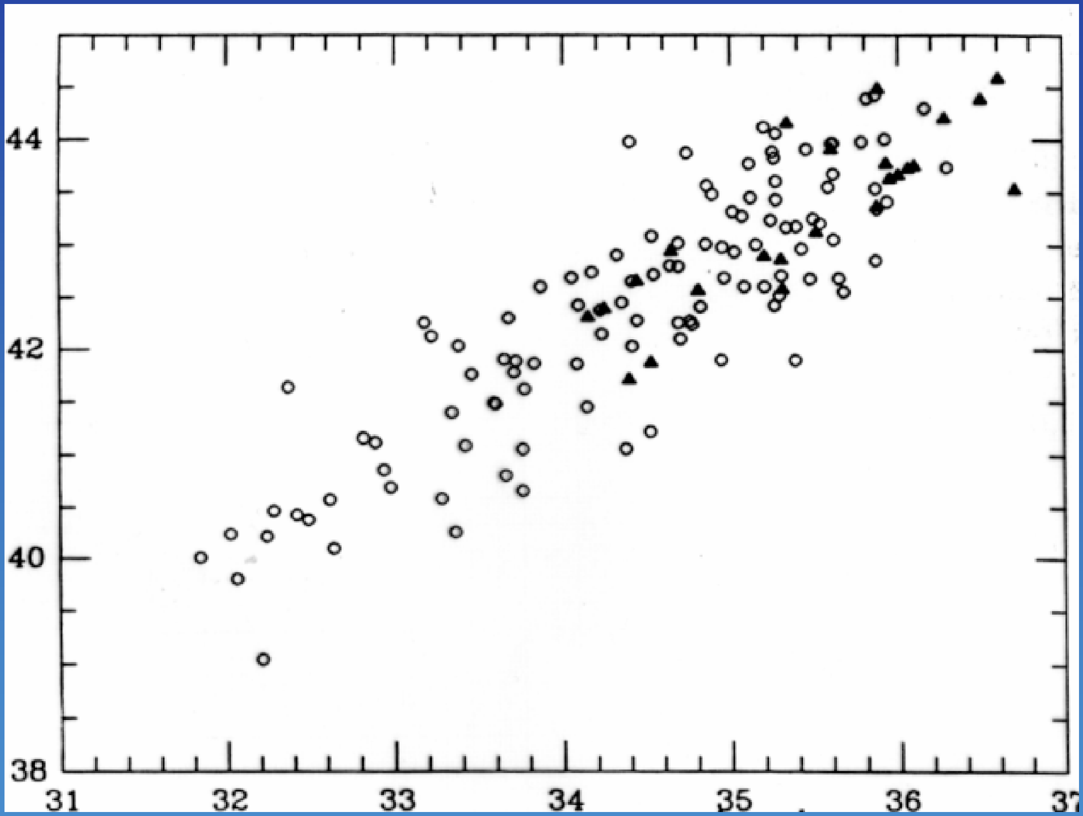
- By great good fortune, the optical spectra of many of the very faint radio galaxies contained strong, narrow emission lines.
- Spinrad and his colleagues were able to measure redshifts for most of the faint radio galaxies in the 3CR sample by the early 1980s.

Spectra of the 3CR Radio Galaxies



Composite spectra for two large redshift 3CR radio galaxies. The lines are strong and narrow, allowing the underlying stellar continuum to be observed.

Spectra of the 3CR Radio Galaxies

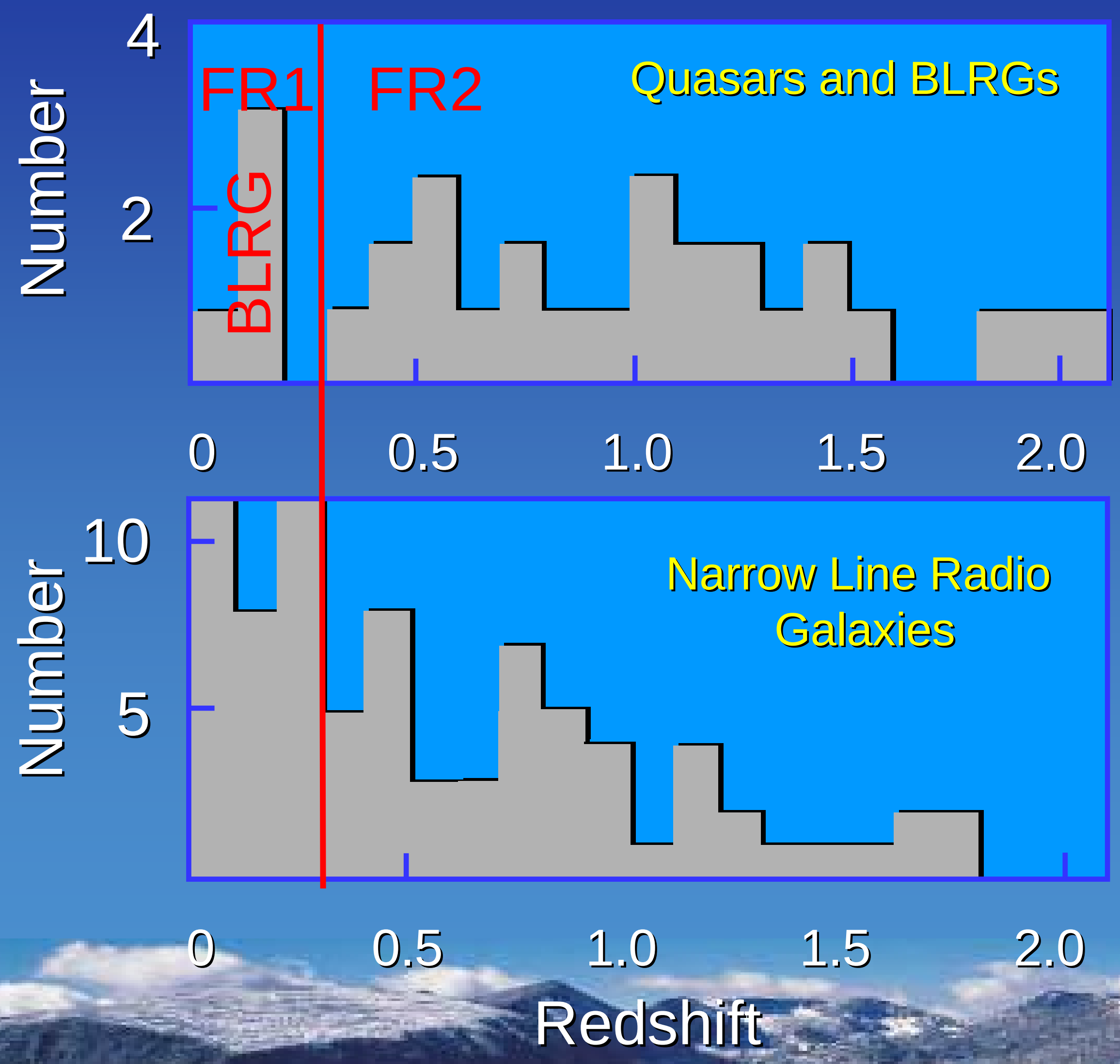


$\log_{10}$ (OII luminosity/erg s^{-1})

log(Radio luminosity/W Hz^{-1})

By good fortune, the strengths of the emission lines were correlated with radio luminosity.

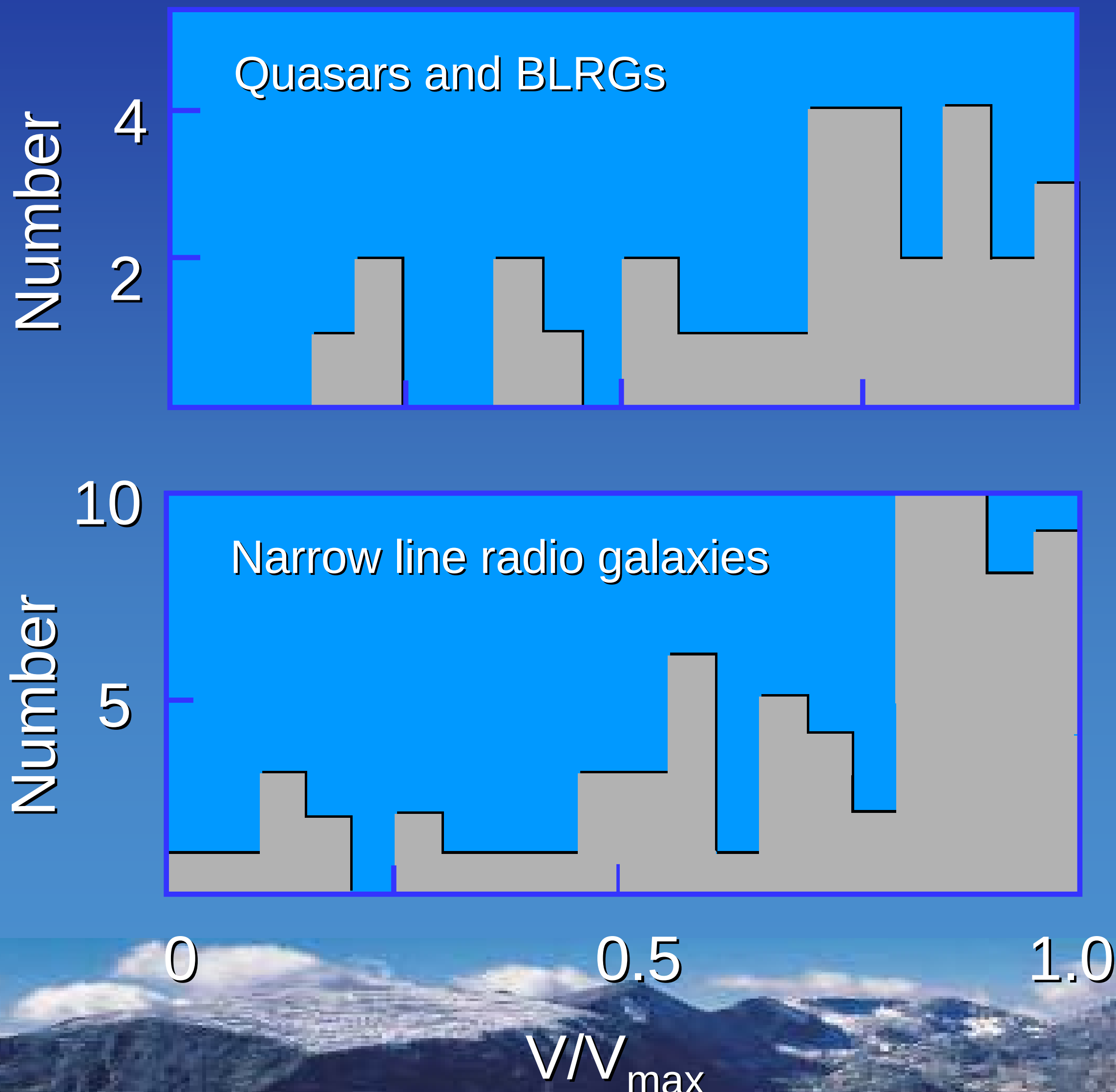
Redshift distributions for 3CR radio galaxies and quasars – a complete sample



Note that the radio galaxies and quasars span the same range of redshift.

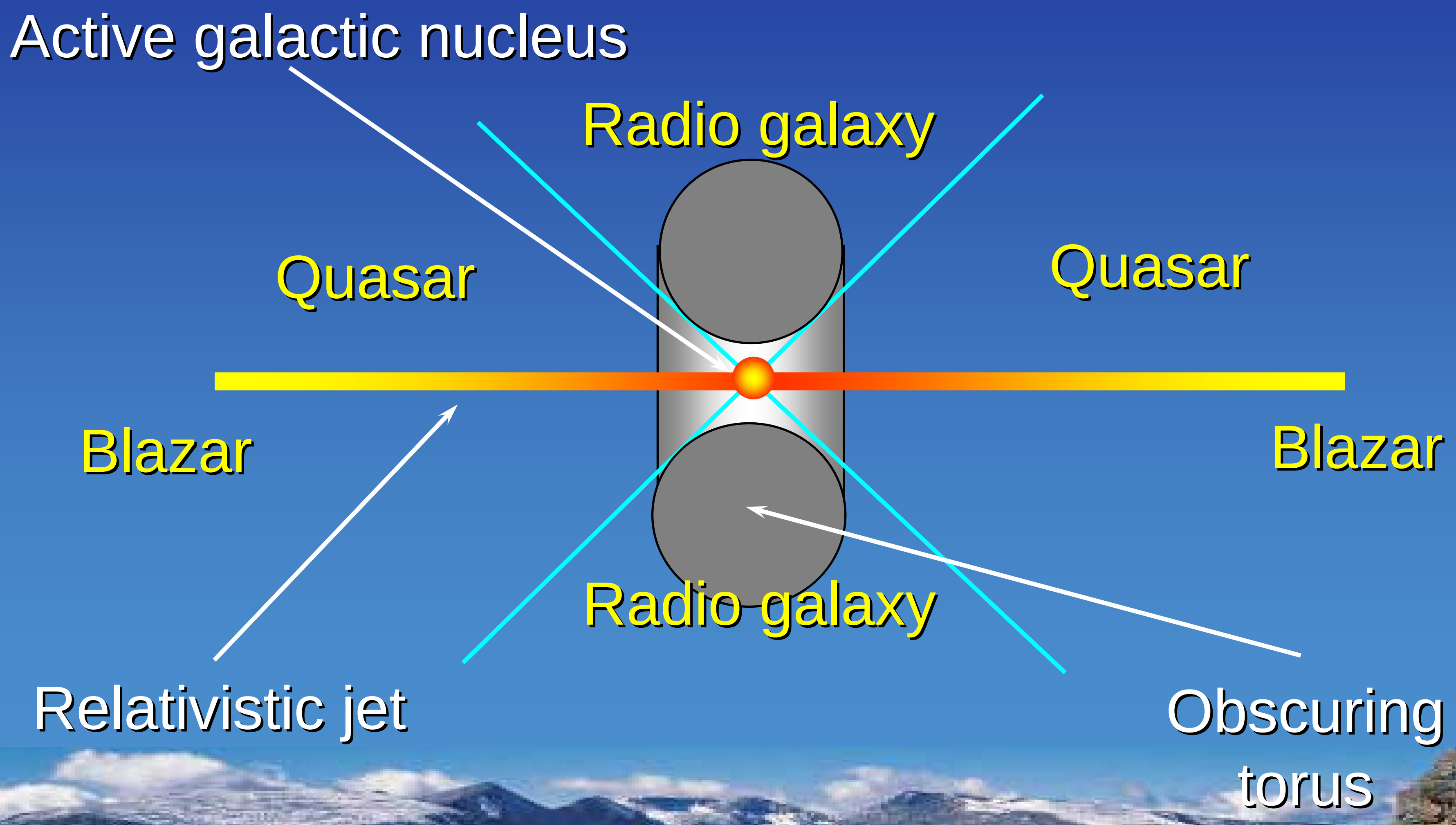
For the FR2 sources, the distributions are the same.

The V/V$_{max}$ Test

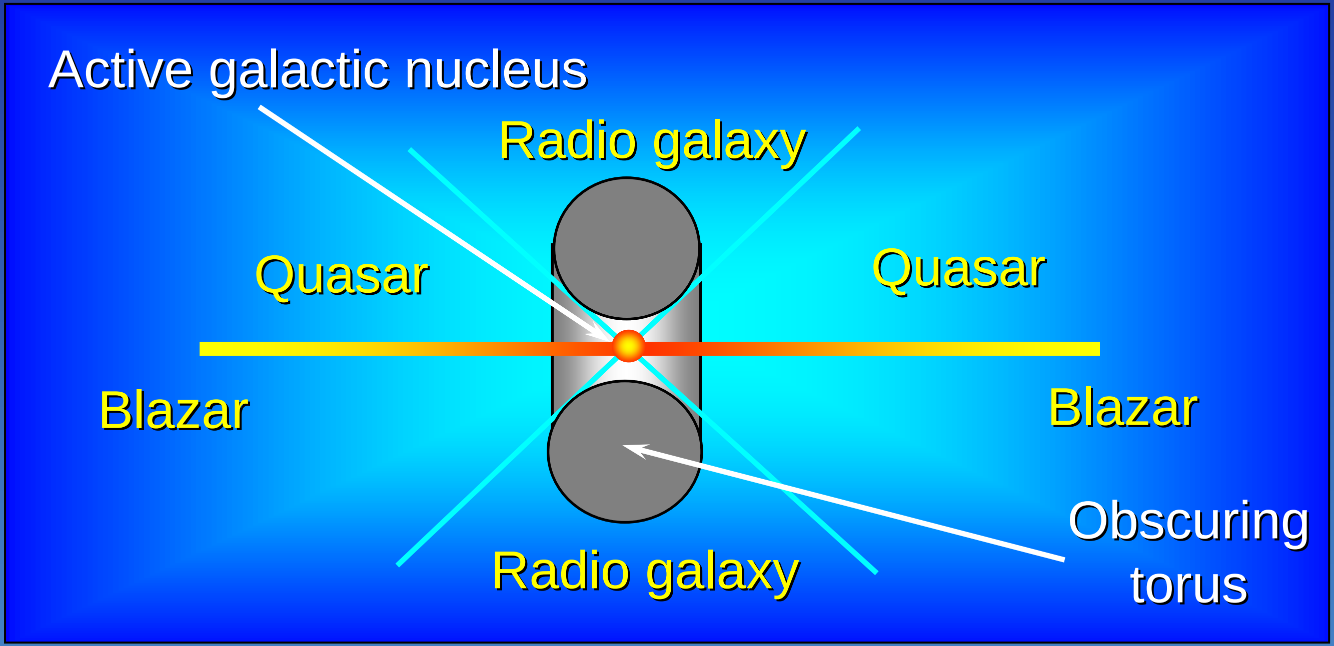


The test shows that the radio galaxies and quasars are piled up towards the limits of their observable volumes. This is direct evidence for the strong evolution of these populations with cosmic epoch.

The Orientation-based Unification Scheme for 3CR Radio Galaxies and Quasars



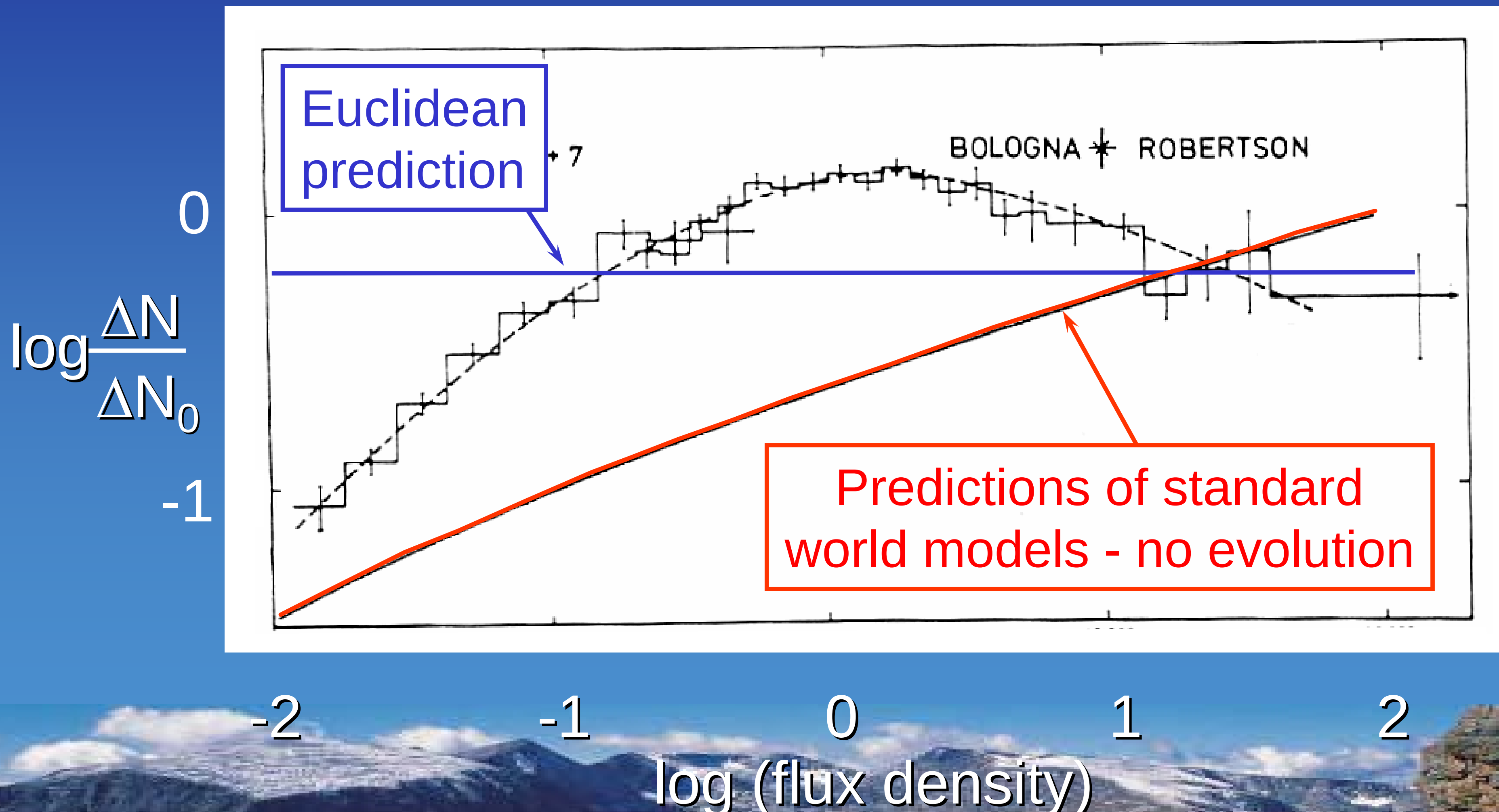
The Orientation-based Unification Scheme for 3CR Radio Galaxies and Quasars



- For the 3CR sample and others, orientation-based unification schemes are remarkably successful.
- Cosmological evolution, statistics of numbers and sizes, asymmetries, presence of one/two sided jets.
- The host galaxies of radio quasars are the radio galaxies.

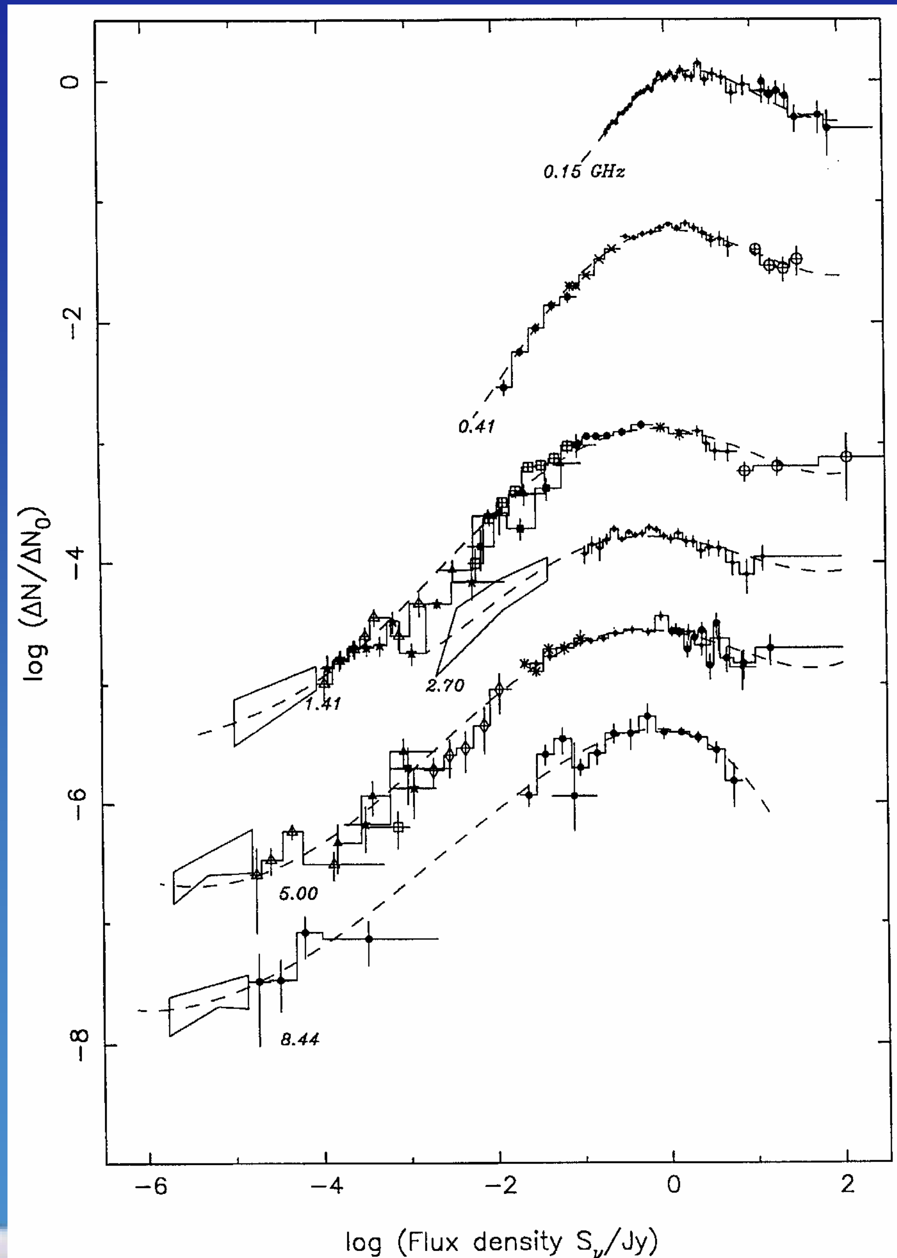
The Radio Source Counts

The counts of radio sources had shown that there is a large excess of faint radio galaxies and quasars.



Radio source counts at a wide range of frequencies (Wall 1977)

$\log \frac{\Delta N}{\Delta N_0}$



log (flux density)

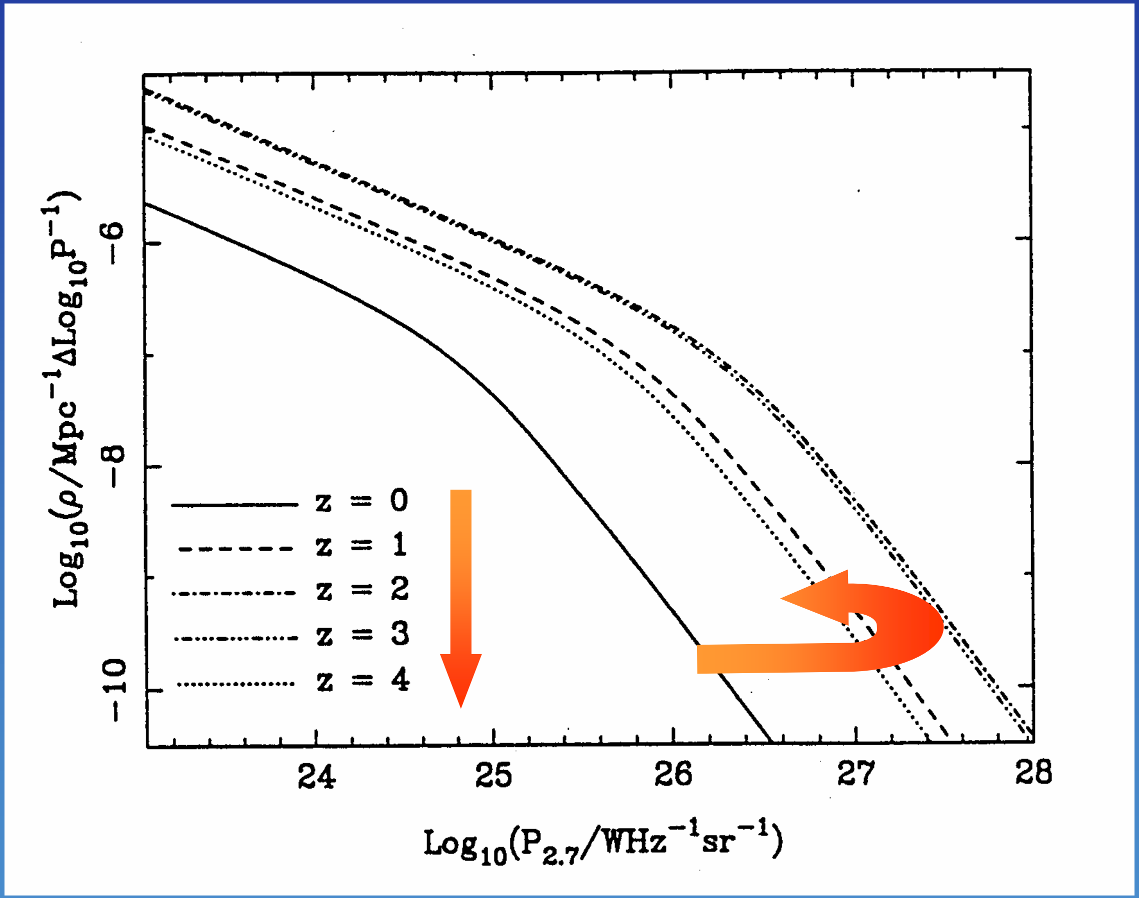
All show the same generic features

The Evolution of the Radio Source Populations

These data suggested that there had been an enormous increase in the numbers of radio sources at large redshifts.

It turns out that the radio quasars and the radio galaxies exhibit precisely the same form of evolution with cosmic epoch (or redshift).

Determining the Evolution Function

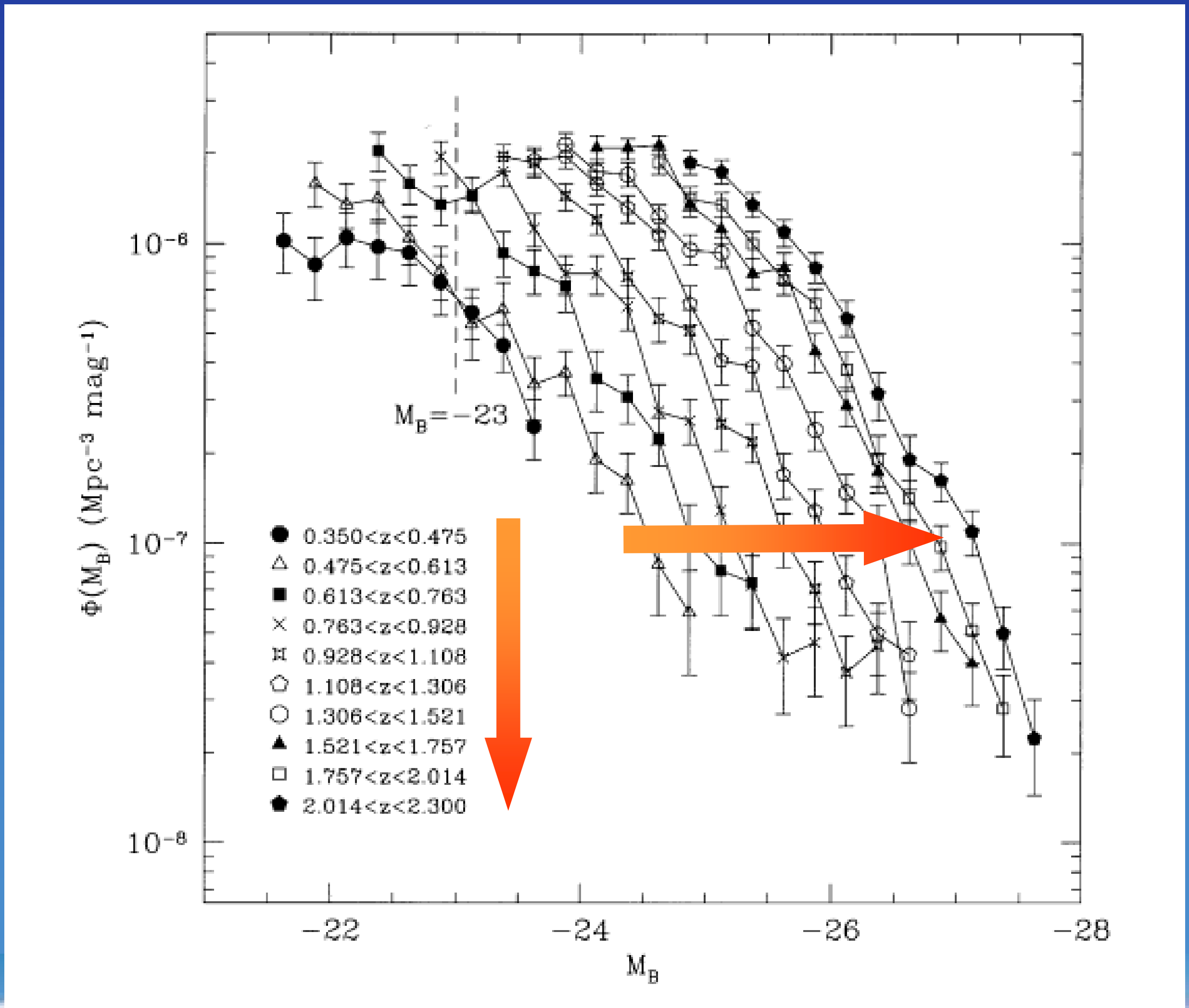


Dunlop and Peacock 1990

Pure luminosity evolution

Deep radio surveys confirm the decrease in the comoving number density of radio sources at large redshifts

Radio-Quiet Quasar Statistics

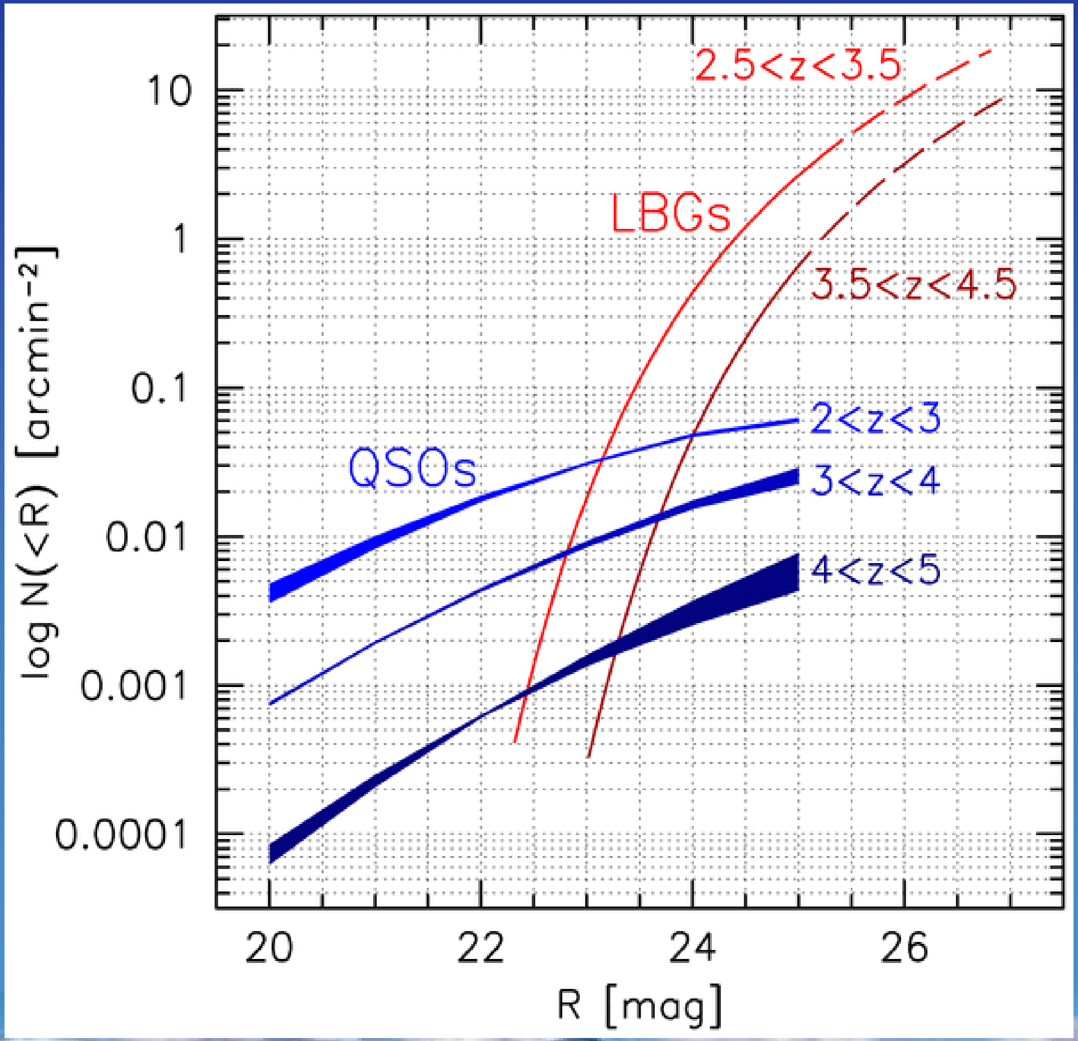


AAO 2dF quasar survey (2000)

Evolving luminosity function 7000 quasars. The observed changes are consistent with luminosity evolution.

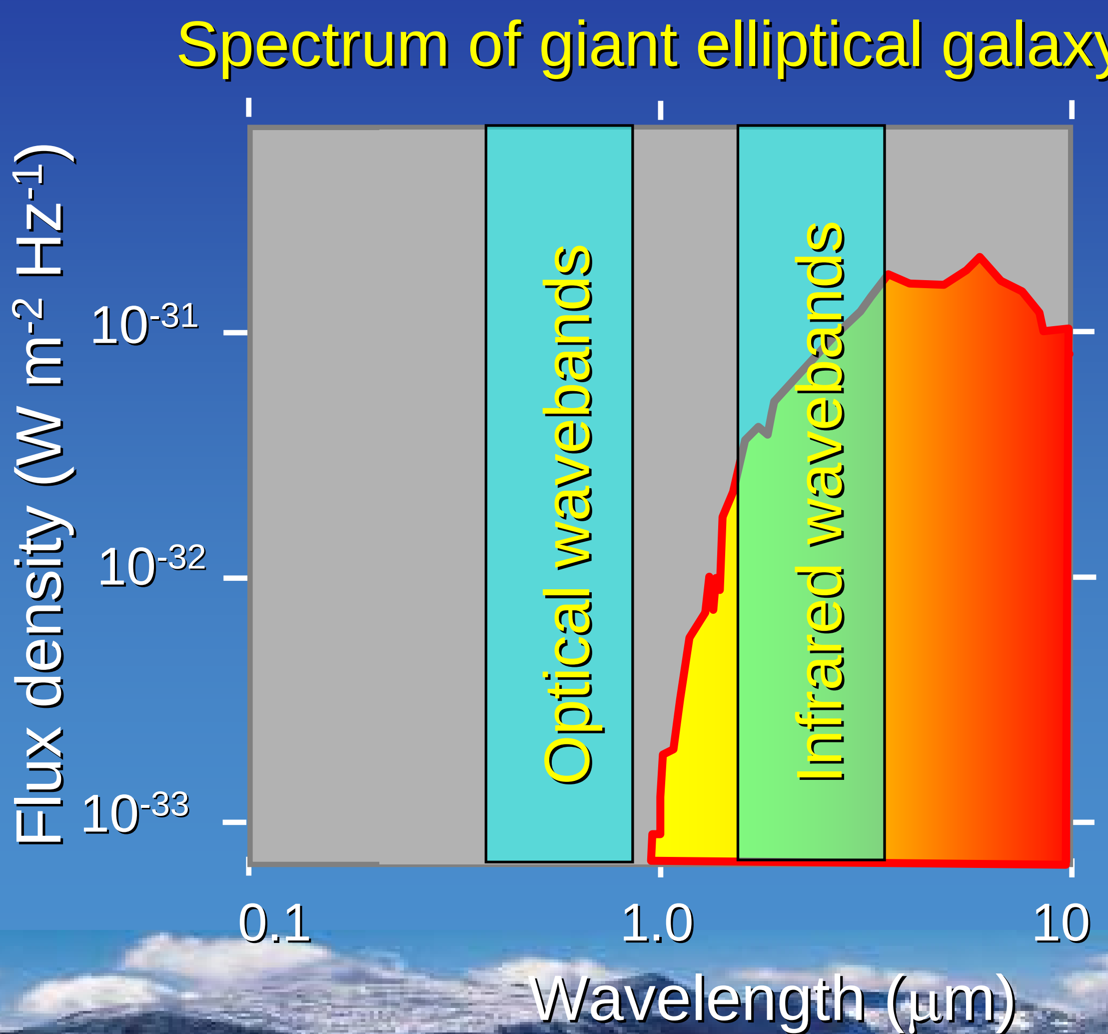
Boyle et al 2000

Quasar Statistics



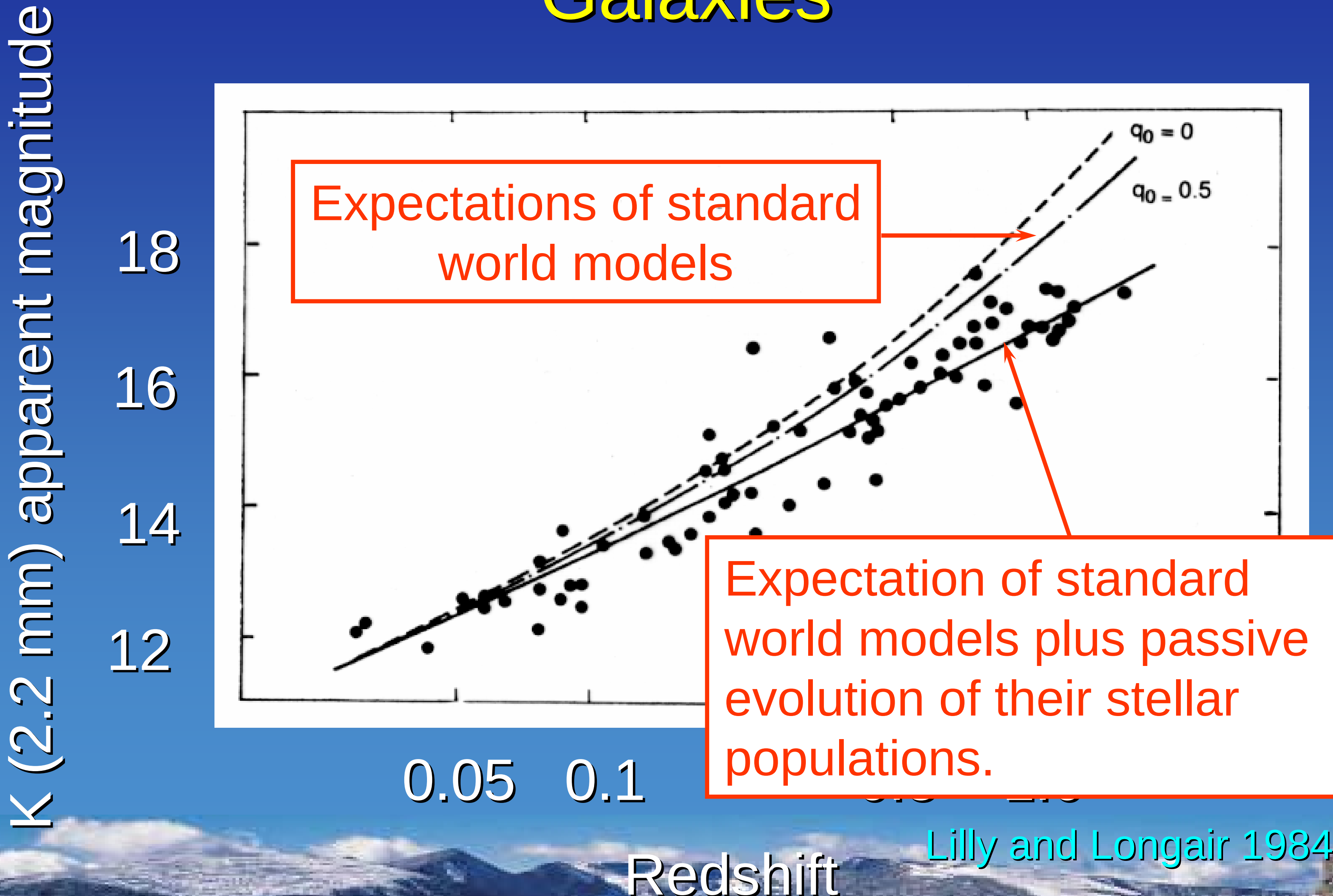
Continuing decrease of quasar populations at faint magnitudes. Contrast this wth the numbers of Lyman Break Galaxies

Infrared Observations of Galaxies



Galaxies are relatively brighter in the near infrared K waveband (2.2 μm) as compared with the optical waveband. This is especially true of galaxies at large redshifts.

The K-z Relation for 3CR Radio Galaxies



Lilly and Longair 1984

Good News and Bad News

- We planned a number of surveys to pin down the evolution of the optical, infrared and radio properties of the radio source population. The K-z relation held out to z ~ 2.

But

- in 1987, Chambers *et al.* and McCarthy *et al.* discovered that the optical images of the radio galaxies were aligned with their radio axes. The radio source activity was influencing the optical, and possibly, infrared images.

The Hubble Space Telescope

Observations of the 28 brightest 3CR radio galaxies in the northern sky in the redshift interval $0.6 < z < 1.8$. These should contain clues to the origin of the strong cosmological evolutionary effects.

Optical HST images : θ = 0.1 arcsec
Infrared UKIRT images : θ = 1 arcsec
Radio VLA images : θ = 0.18 arcsec

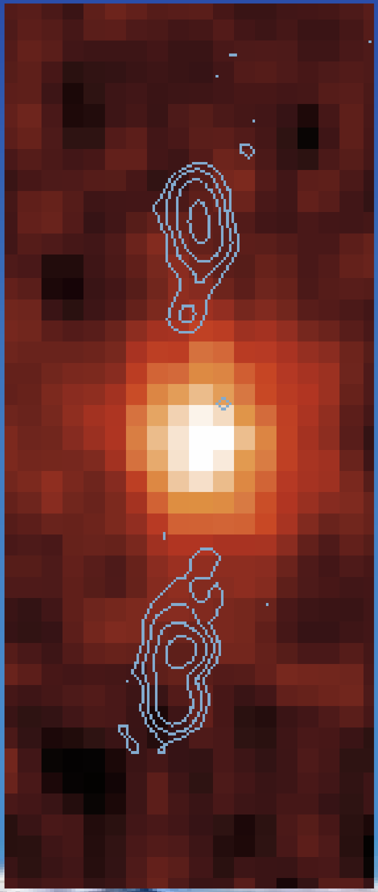
θ = angular resolution

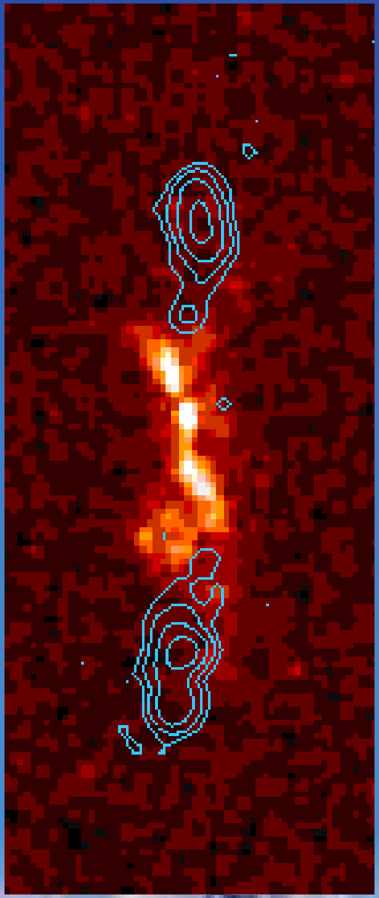
3C 266   z = 1.272

Blue lines are the contours of radio emission

Infrared image
UKIRT
2.2 microns

Old stars



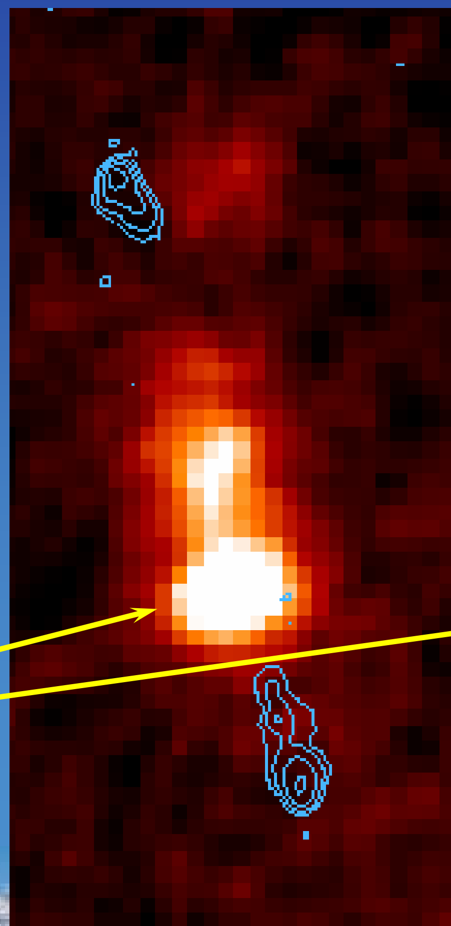


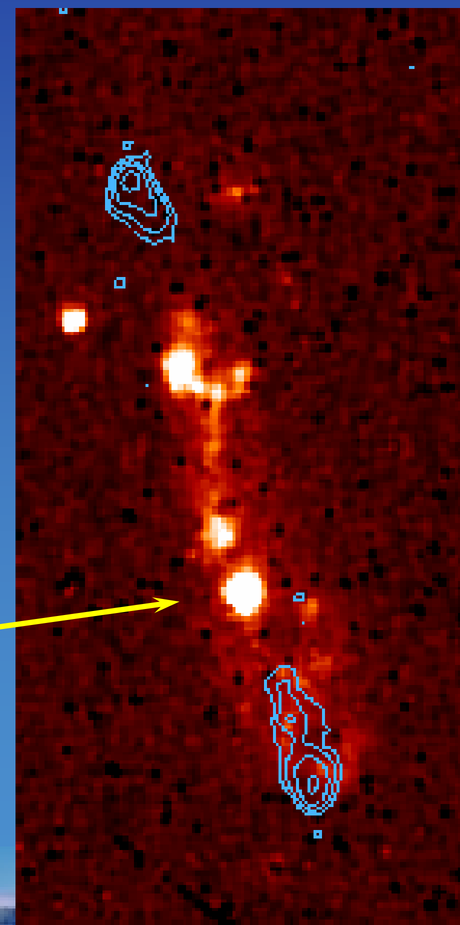
HST optical
image
0.8 microns

3C 368 z = 1.132

Blue lines are the contours of radio emission

Infrared image
UKIRT
2.2 microns





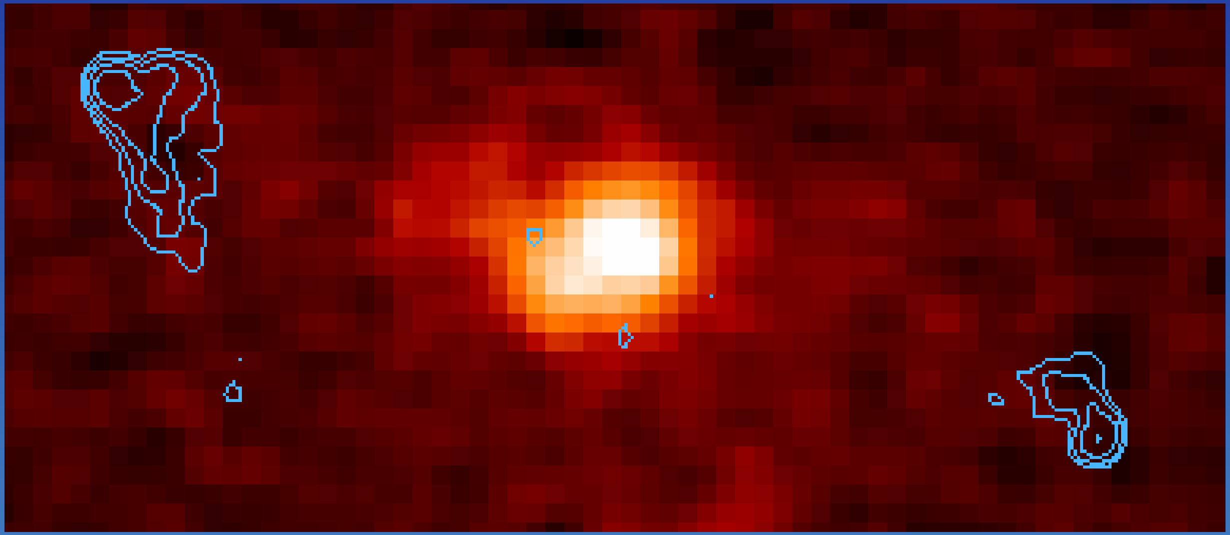
HST optical
image
0.8 microns

Unrelated
foreground
star

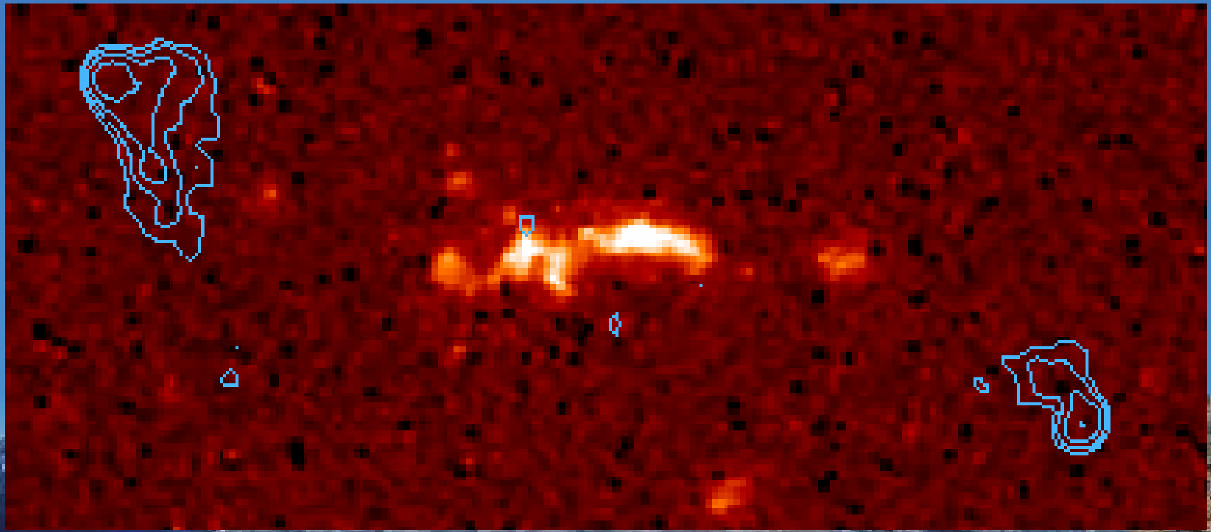
3C 324   z = 1.207

Blue lines are the contours of radio emission

Infrared image
UKIRT
2.2 microns



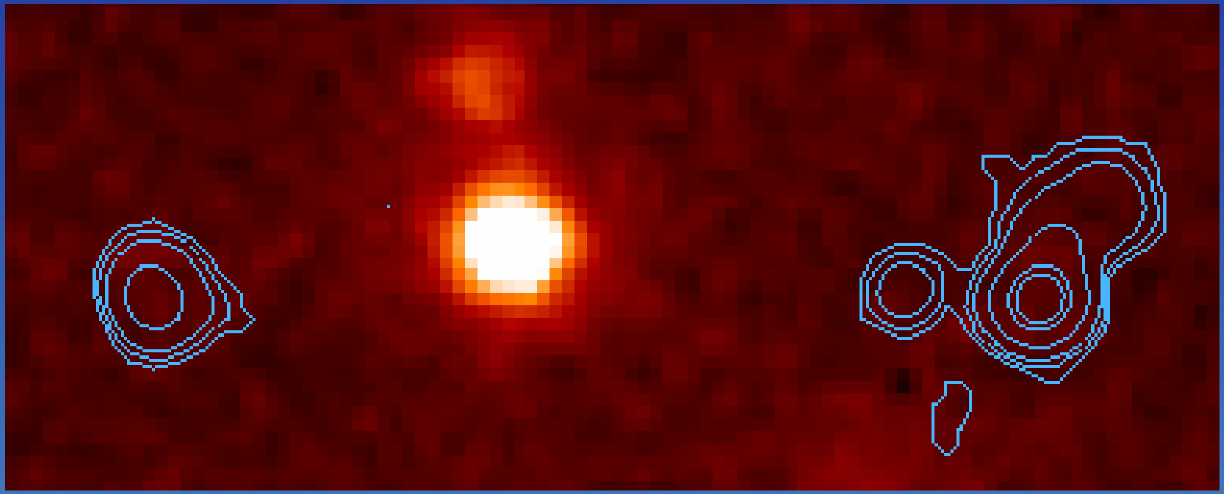
HST optical
image
0.8 microns



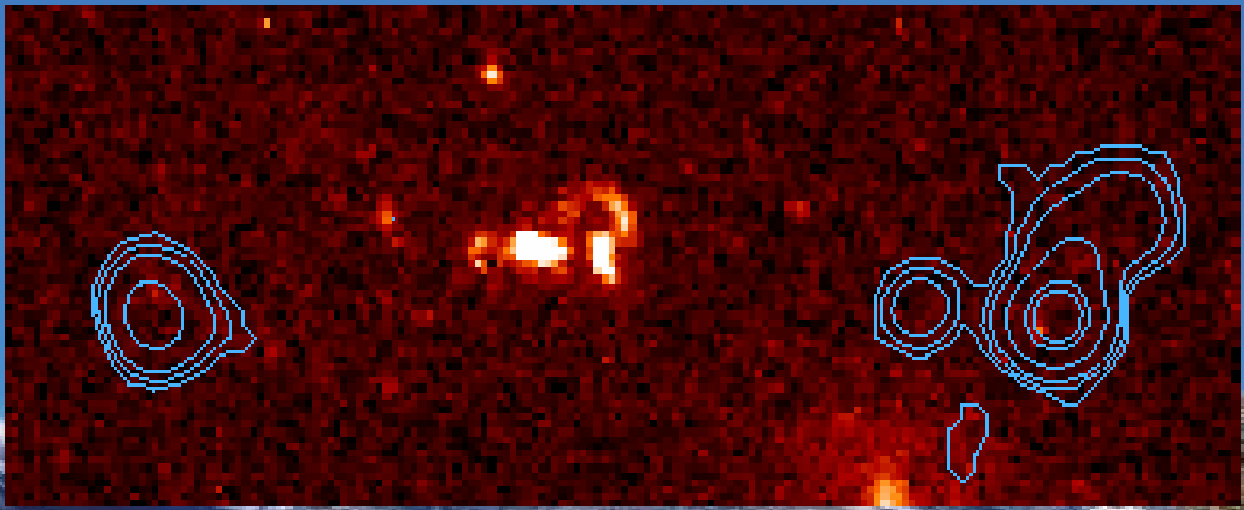
3C 280 z = 0.996

Blue lines are the contours of radio emission

Infrared image
UKIRT
2.2 microns



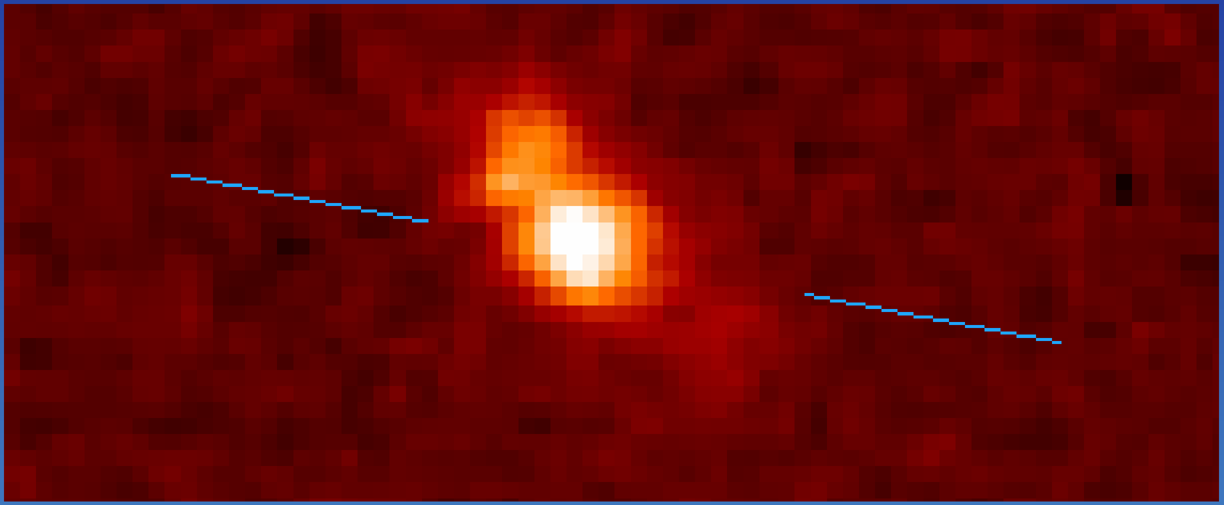
HST optical
image
0.8 microns



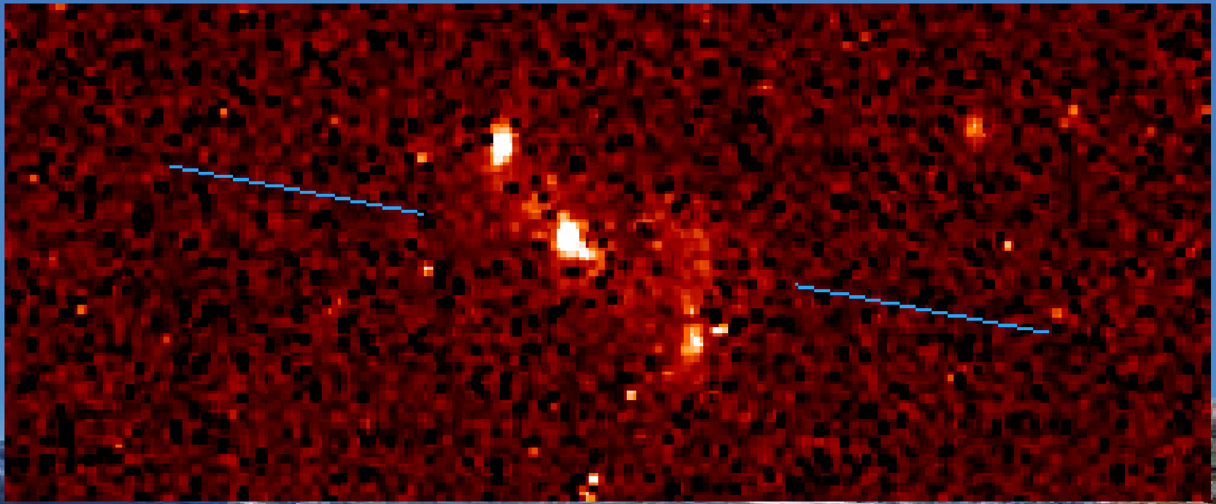
3C 267 z = 1.144

Blue lines are the contours of radio emission

Infrared image
UKIRT
2.2 microns

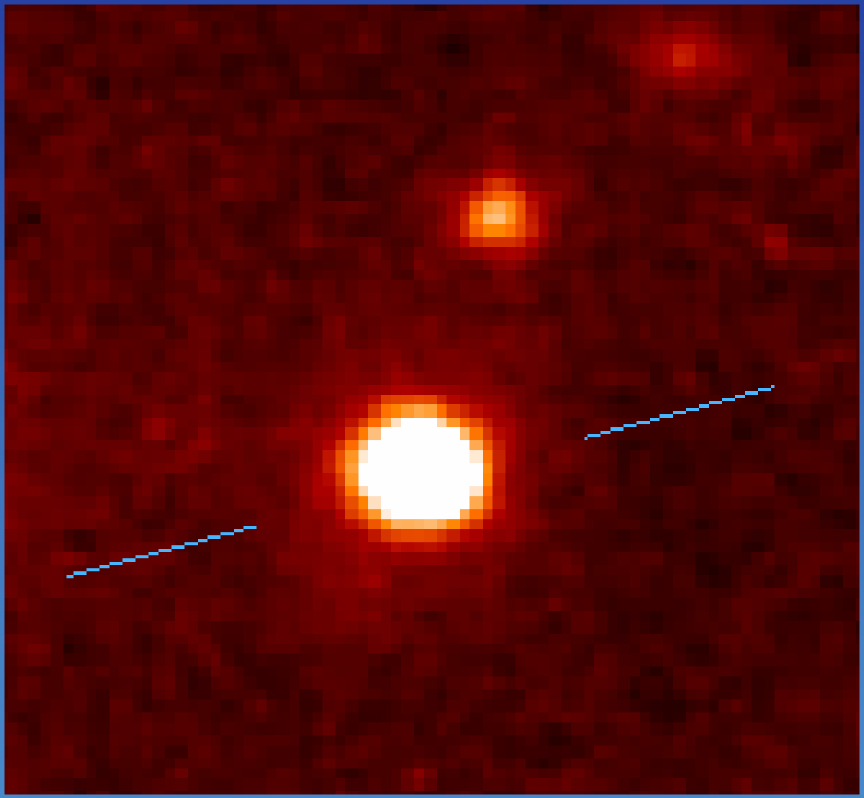


HST optical
image
0.8 microns

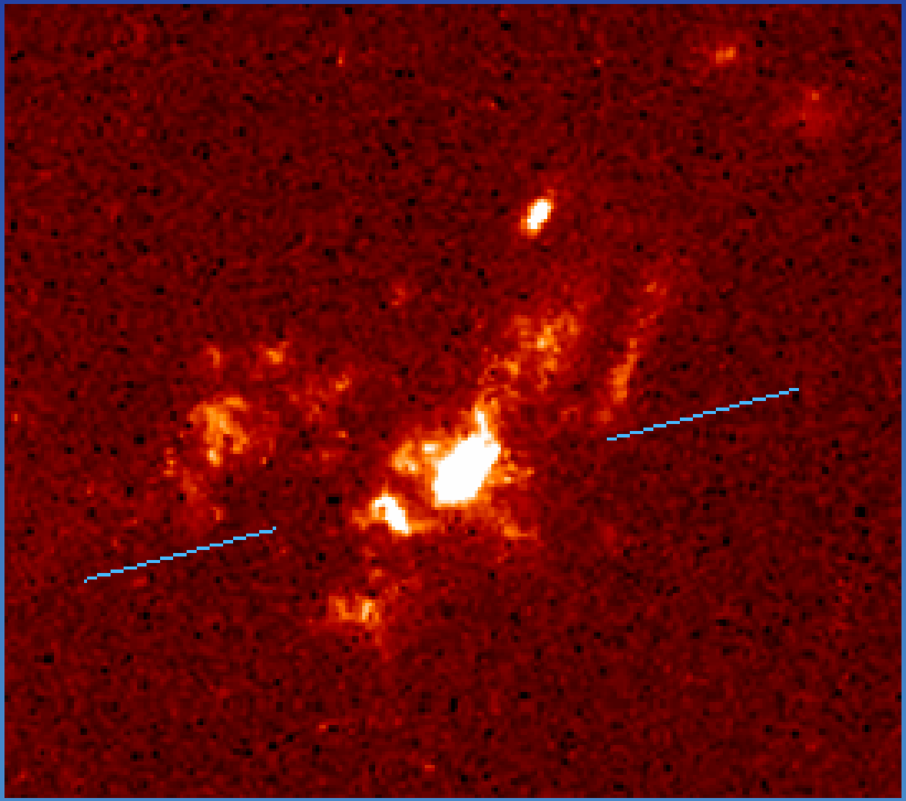


3C 265   z = 0.811

Blue lines are the contours of radio emission



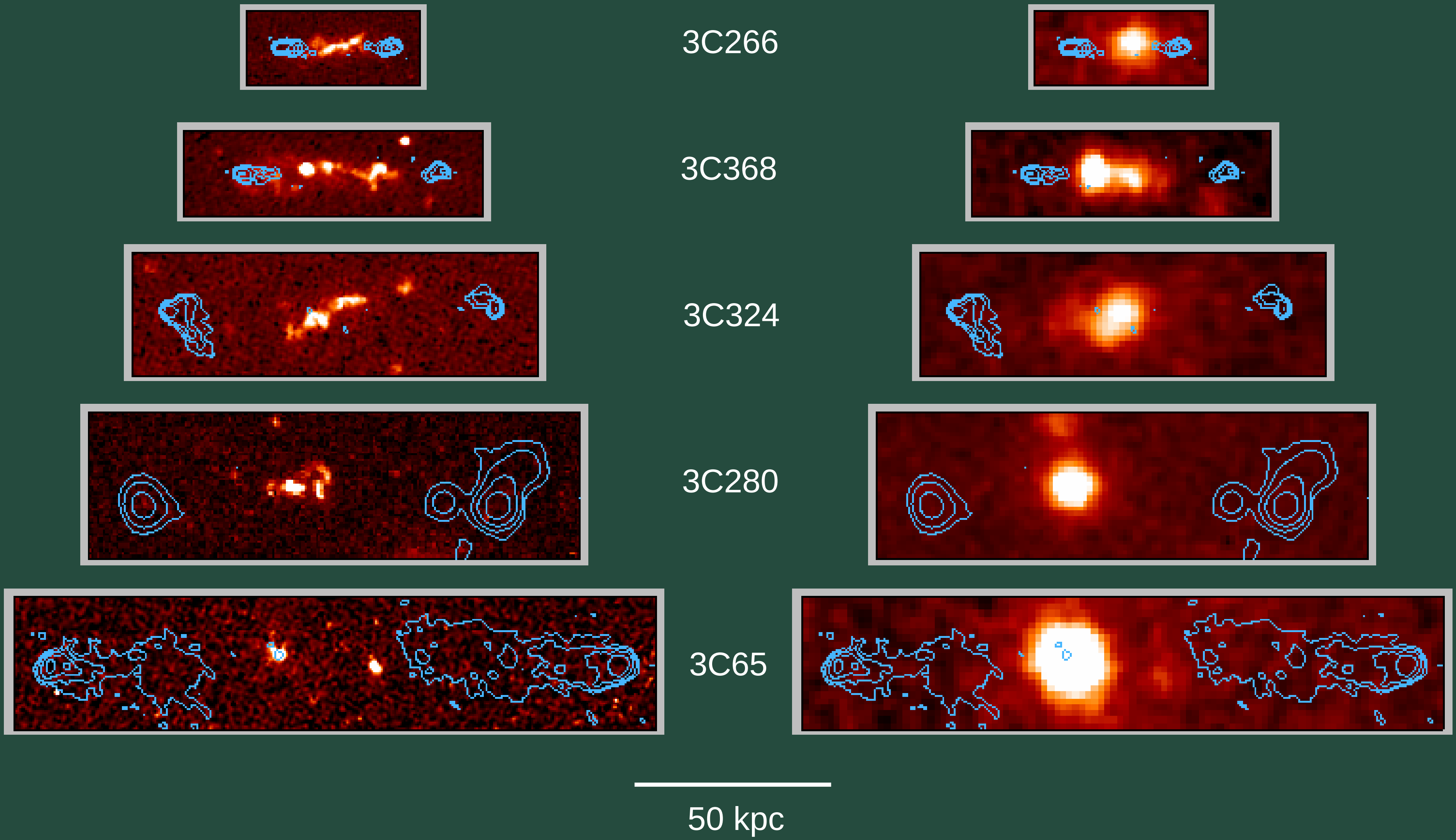
Infrared image
UKIRT
2.2 microns

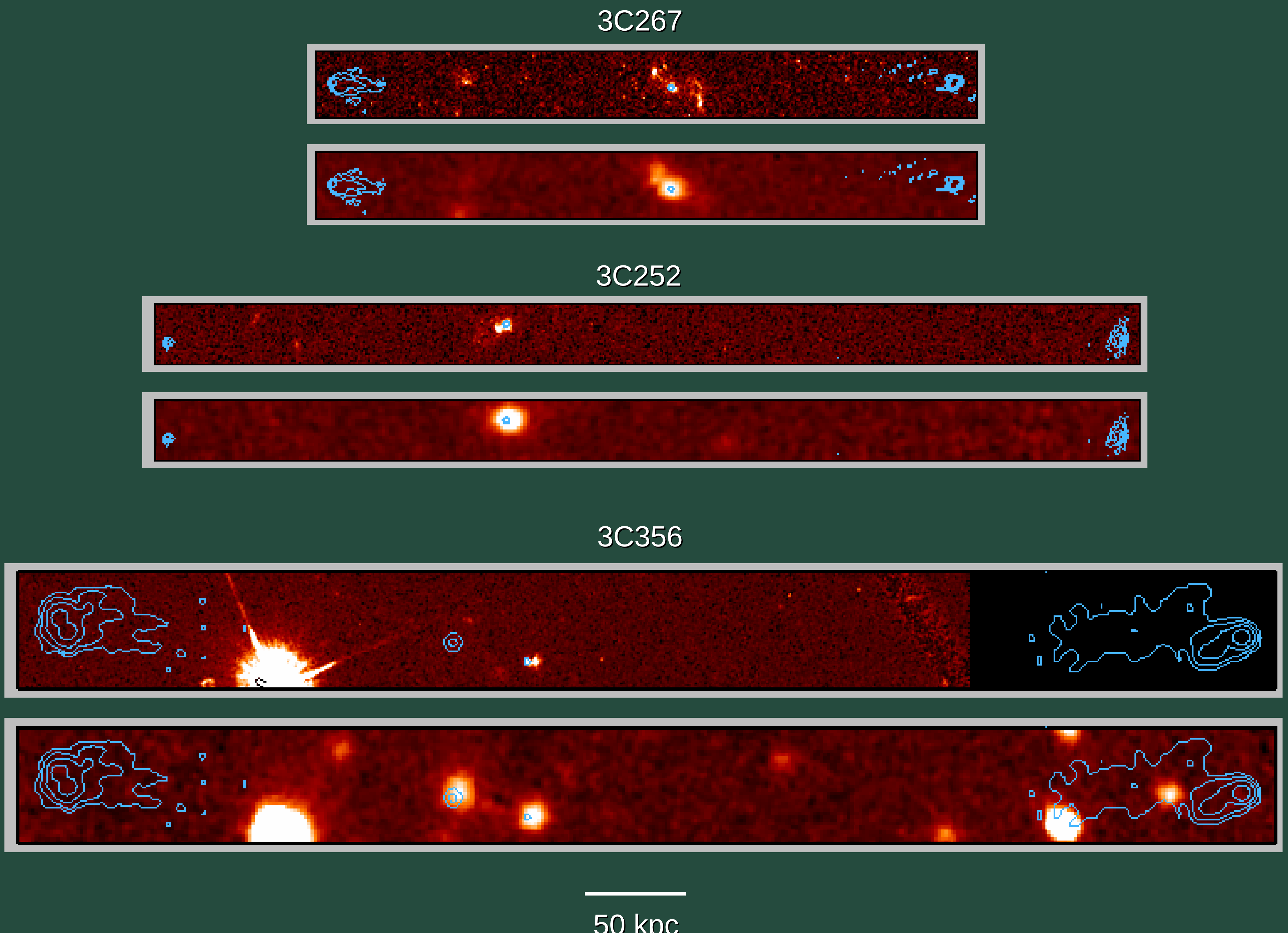


HST optical
image
0.8 microns

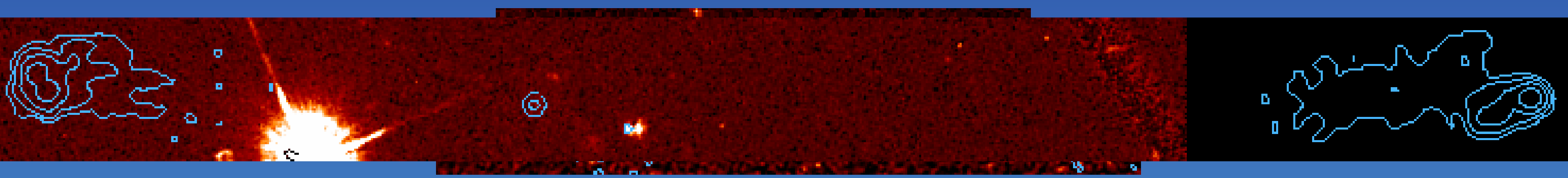
The radio galaxies in the redshift interval $1 < z < 1.3$

- There are 8 radio galaxies in the sample in the redshift interval 1 to 1.3, when the Universe was about a third its present age.
- They all have roughly the same intrinsic radio luminosity.
- Their relative luminosities and sizes are independent of the cosmological model.
- They all display a strong alignment effect.


3C266
3C368
3C324
3C280
3C65
50 kpc


3C267
3C252
3C356
50 kpc

Evolution of Powerful Radio Galaxies - the optical movie



100 kpc

All images on the same physical scale

Understanding the Alignment Effect

Possible causes

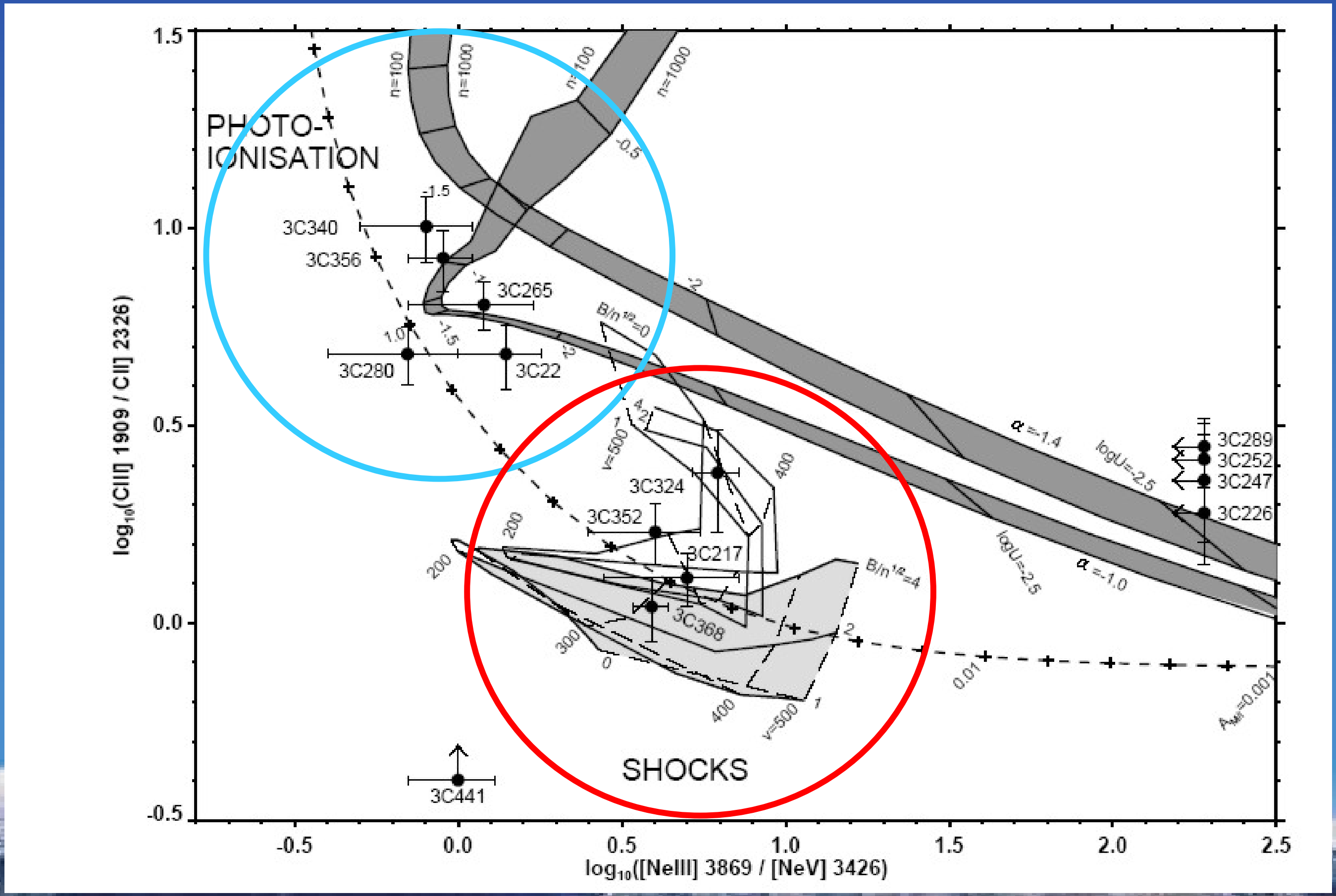
- Jet-induced star formation
- Scattering of the light of an obscured nucleus - unification schemes for active galaxies
- ‘nebular emission’/shocks induced by the passage of the radio jet

Understanding the Alignment Effect

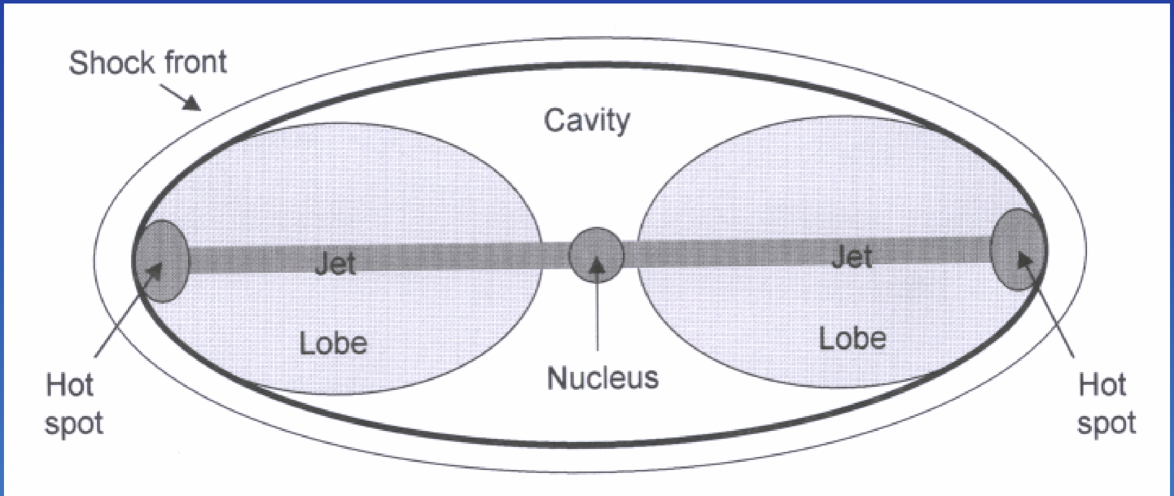
Philip Best, Huub Rottgering and I began a long campaign of 2-d imaging optical spectroscopy to understand the excitation mechanisms of the aligned emission.

The Ionisation Diagnostic Diagram

The large sources have emission line spectra consistent with photoionisation. The smaller sources are consistent with shock excitation.



Shock Excitation of Ambient Cool Gas Clouds



Ingredients of the model:

- Kaiser and Alexander model of the evolution of the shock front
- Dopita and Sutherland model of shock excitation of cool gas clouds
- Mendoza analysis of shock waves entering cool clouds

Shock Excitation of Ambient Cool Gas Clouds

A self-consistent set of parameters can be found to account for the structures in terms of the shock wave associated with the radio cocoon exciting and heating compact cool clouds.

Typical parameters:

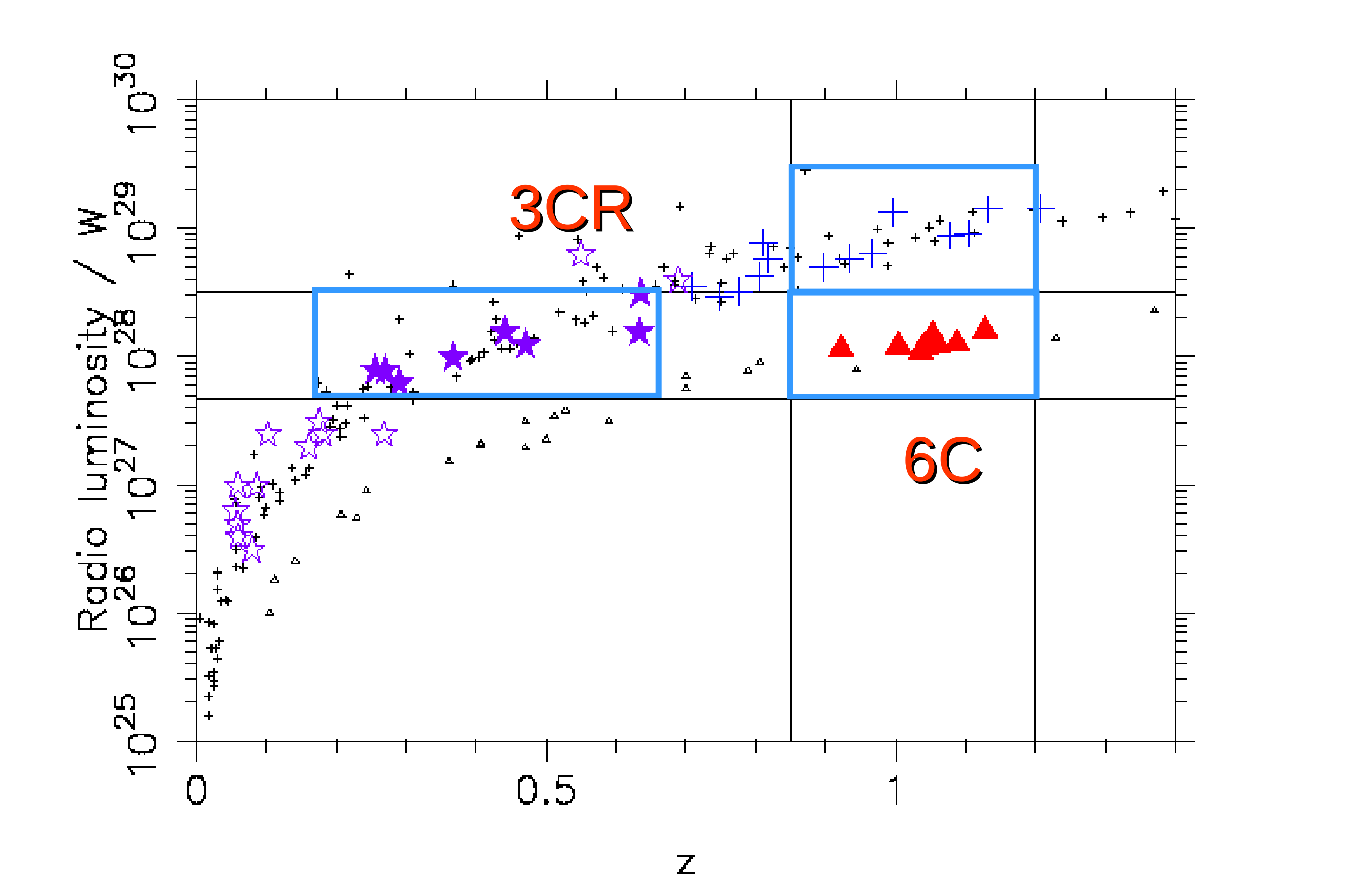
Particle density in IGM	0.03 cm^{-3}
Particle density in clouds	10^2 cm^{-3}
Filling factor	10^{-6}
Velocity of shock in IGM	0.02 c
Velocity of shock in cloud	200 km s^{-1}

The 6C sample

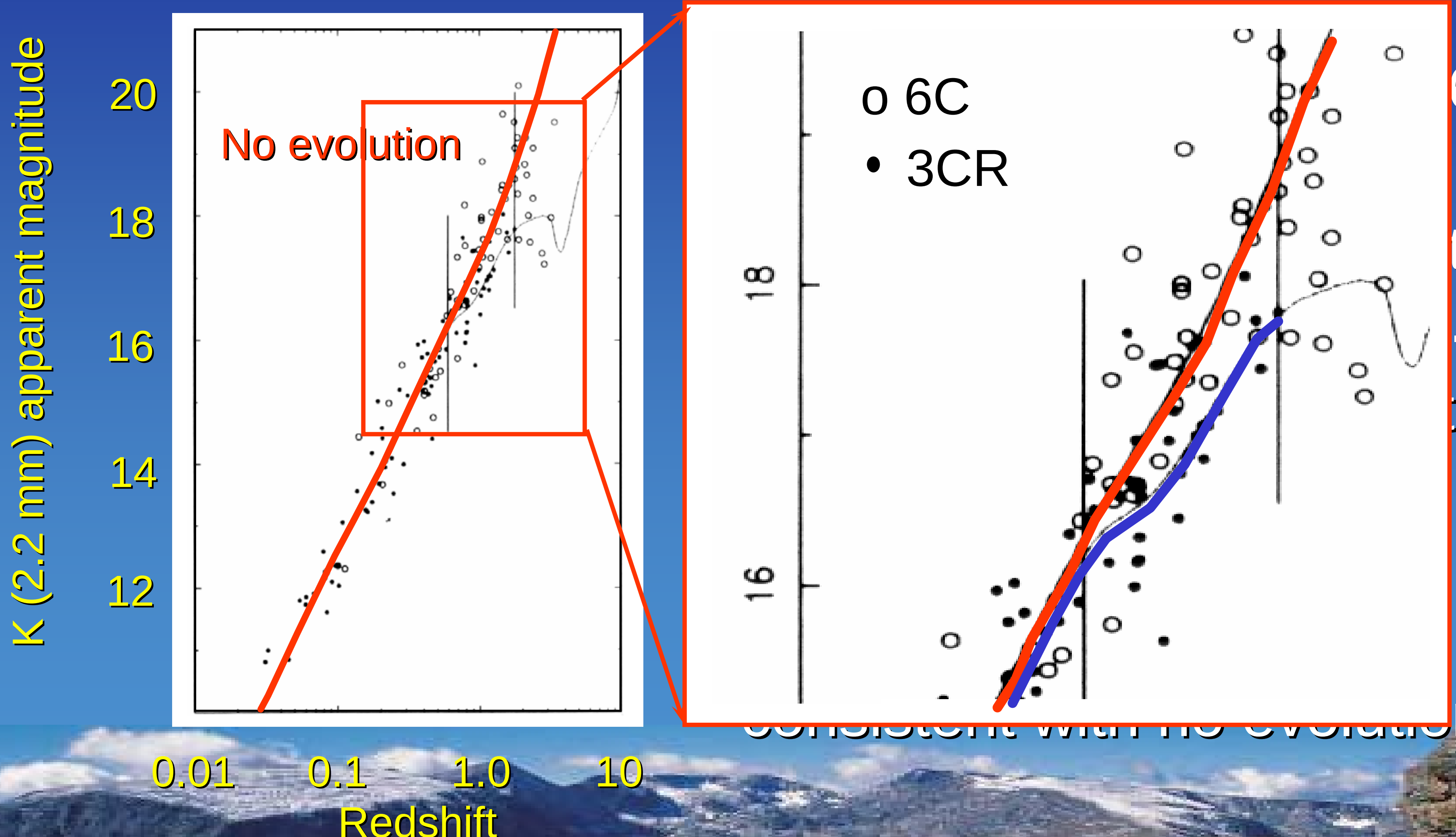
- The next step was to apply the same techniques to fainter samples of radio sources – the 6C sample selected by Rawlings and Eales.
- The sample is about a factor of six fainter than the 3CR sample.
- The analysis was carried out with Katherine Inskip and Philip Best and there were two motivations.

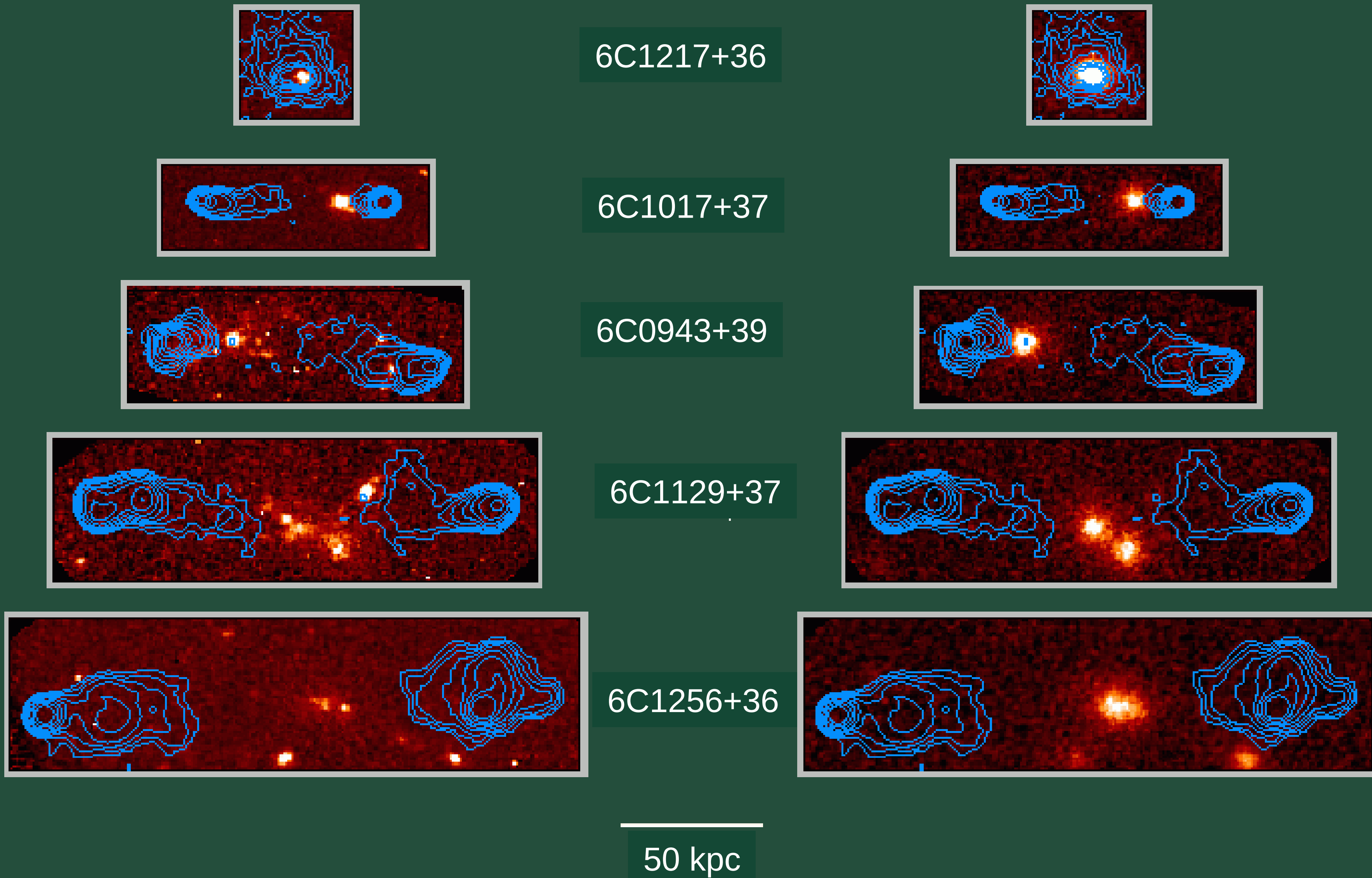
Separating radio luminosity from redshift changes

The 6C sample is about 6 times fainter than the 3CR sample



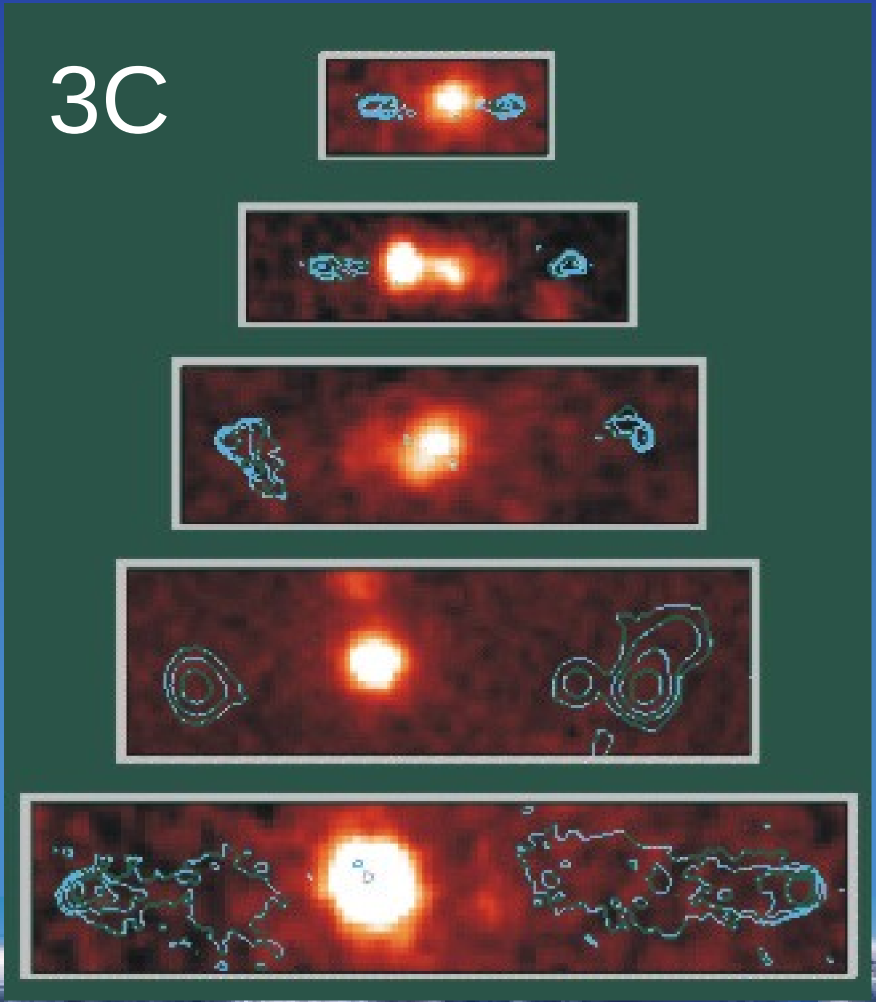
The K-z Relation for 6C Radio Galaxies - Eales and Rawlings

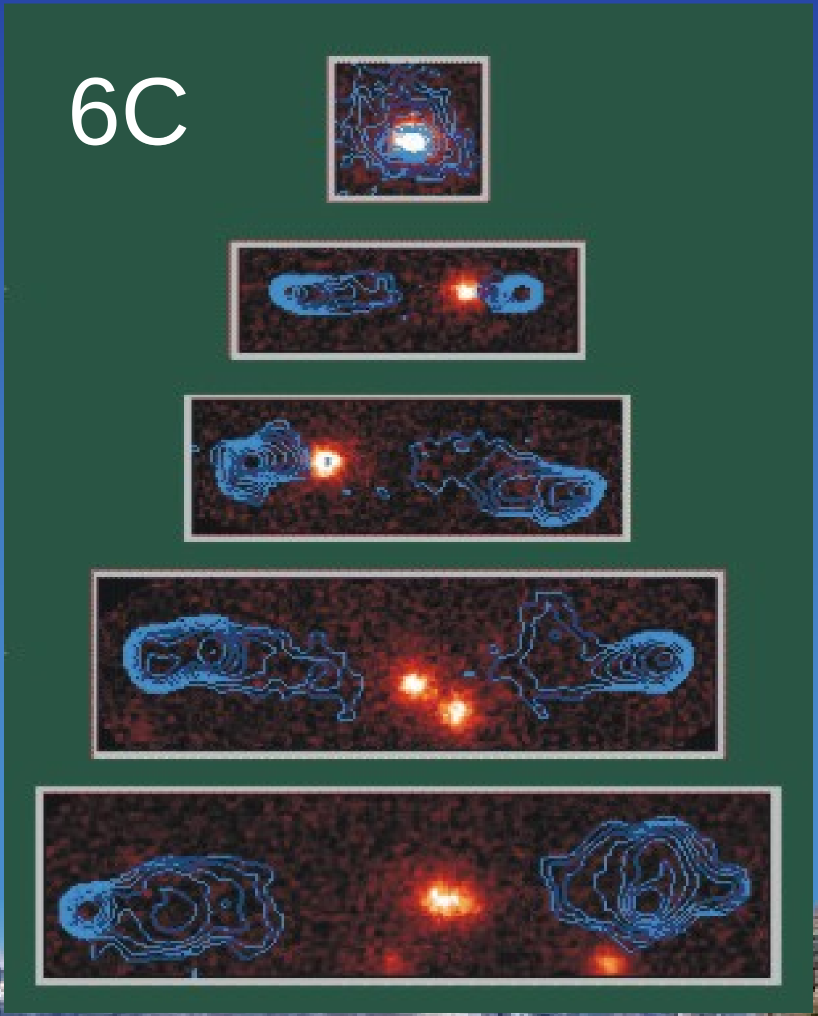



6C1217+36
6C1017+37
6C0943+39
6C1129+37
6C1256+36
50 kpc

Comparison of the 3C and 6C Galaxies

The 6C galaxies are less luminous and smaller than the 3C galaxies





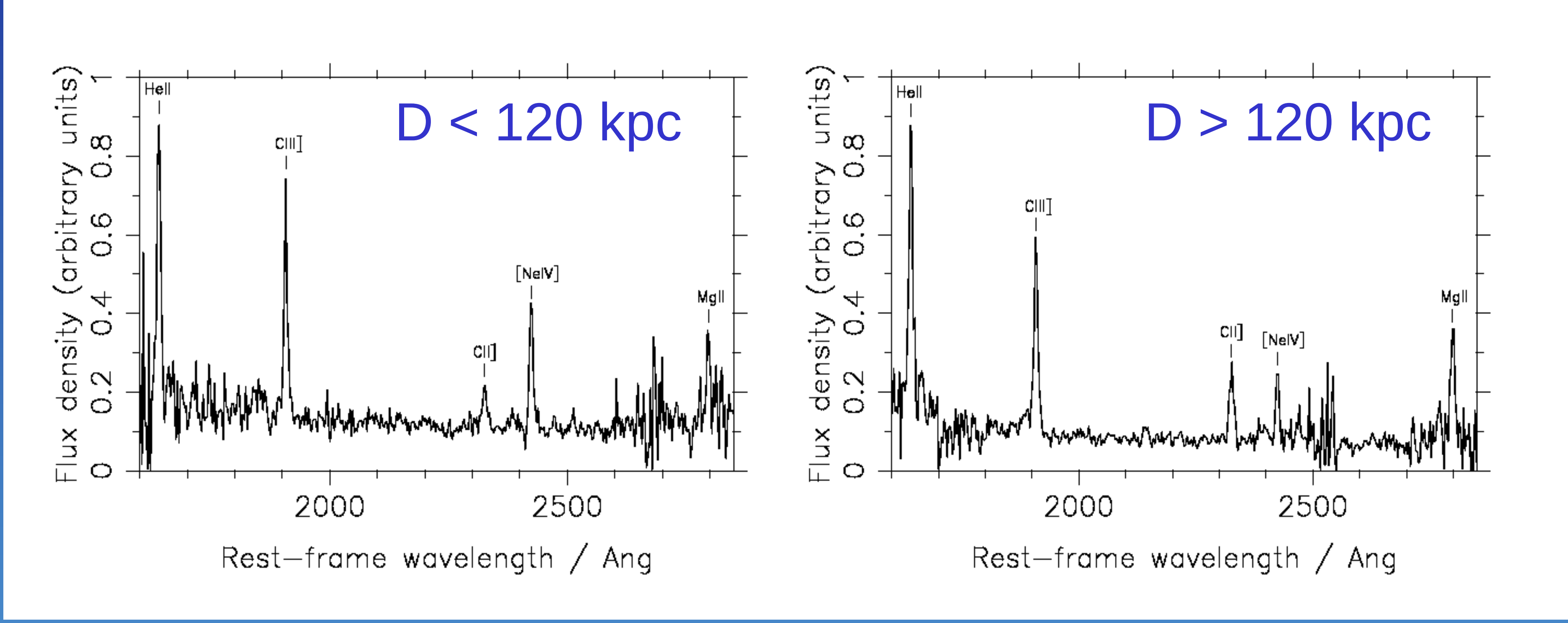
Spectroscopic Surveys of the Aligned Structures

We have completed deep two-dimensional optical spectroscopic observations of all the z ~ 1 radio galaxies in the 3CR and 6C samples.

These enable the physics of these phenomena to be understood in some detail and related to the dynamics of the radio sources.

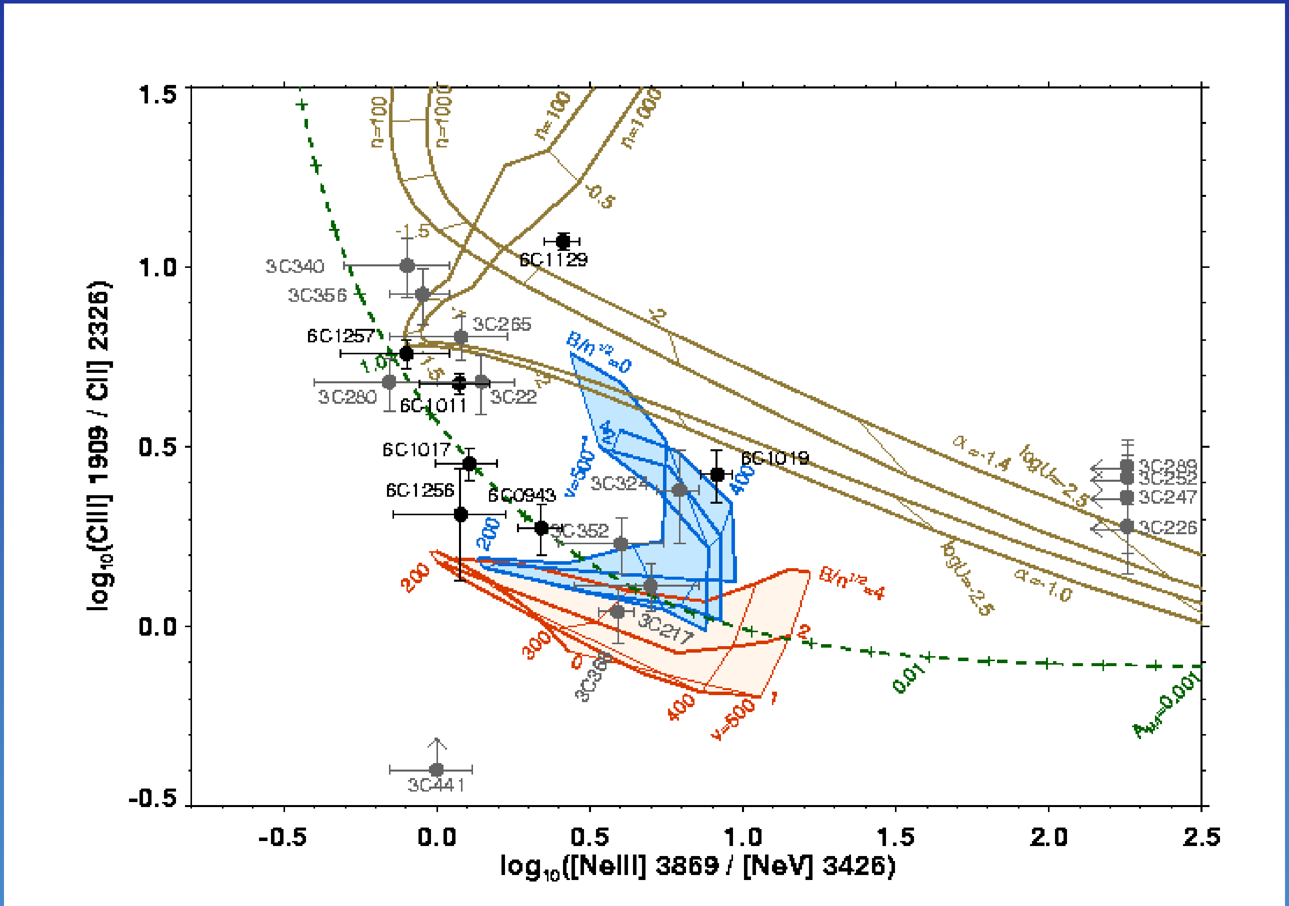
Work of Katherine Inskip, Philip Best, Huub Rottgering, Steve Rawlings, Garret Cotter and MSL

Composite spectra for large and small radio sources (short wavelength)



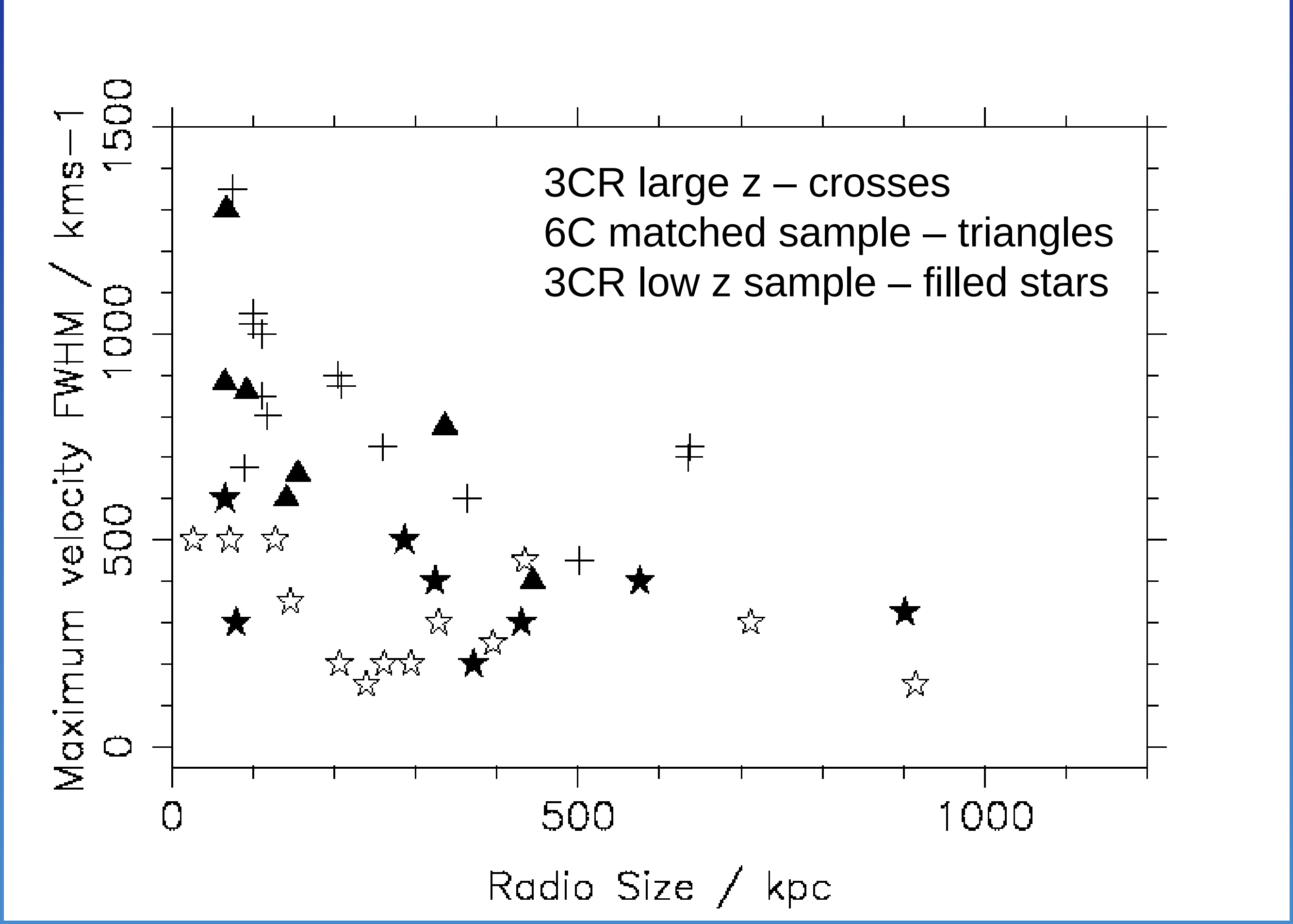
The ionisation state of the emission line gas is strongly correlated with radio size. Smaller sources exist in a lower ionization state

The Ionisation Diagnostic Diagram



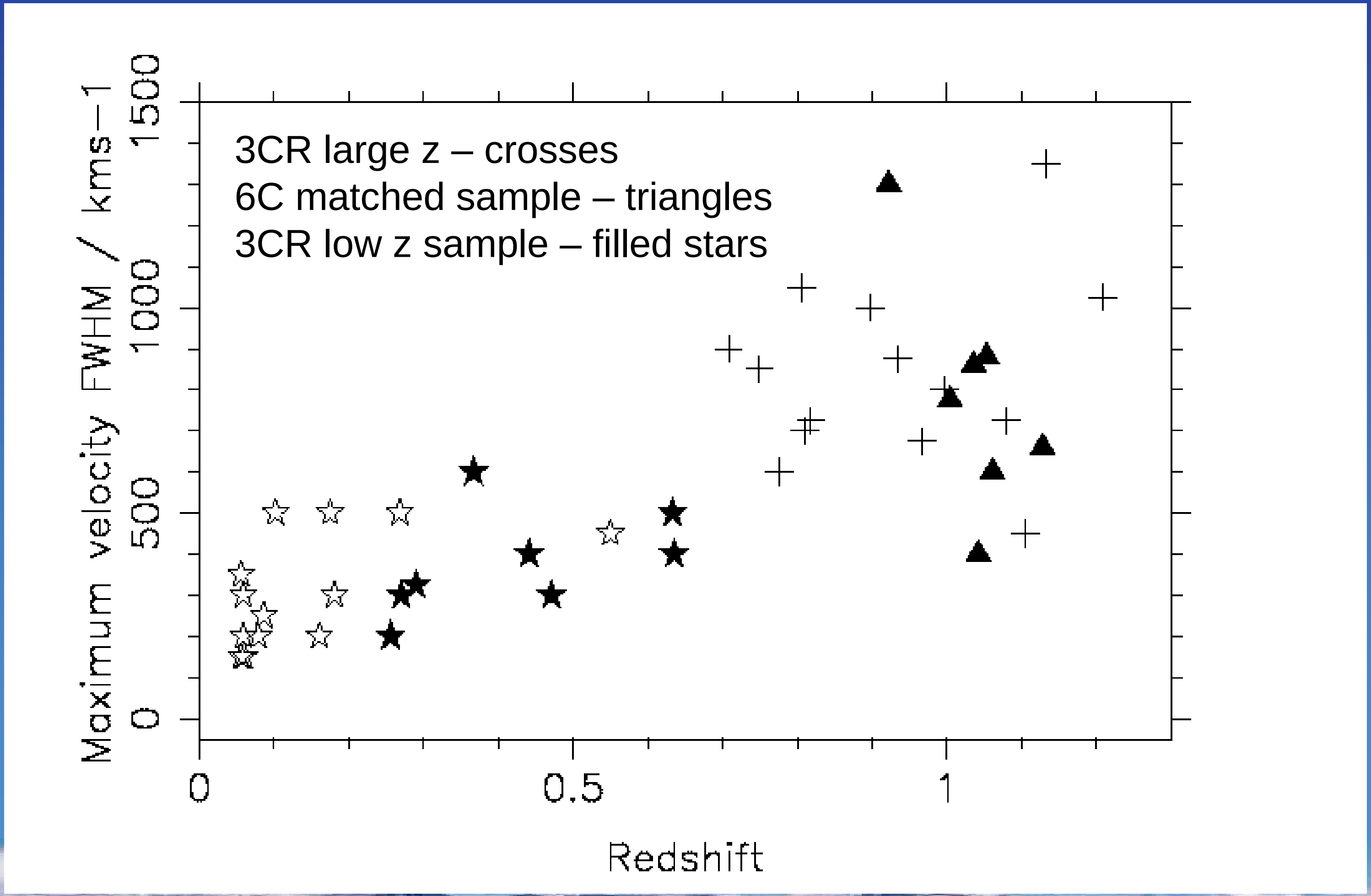
The large sources have emission line spectra consistent with photoionisation. The smaller sources are consistent with shock excitation.

Kinematics and Radio Size

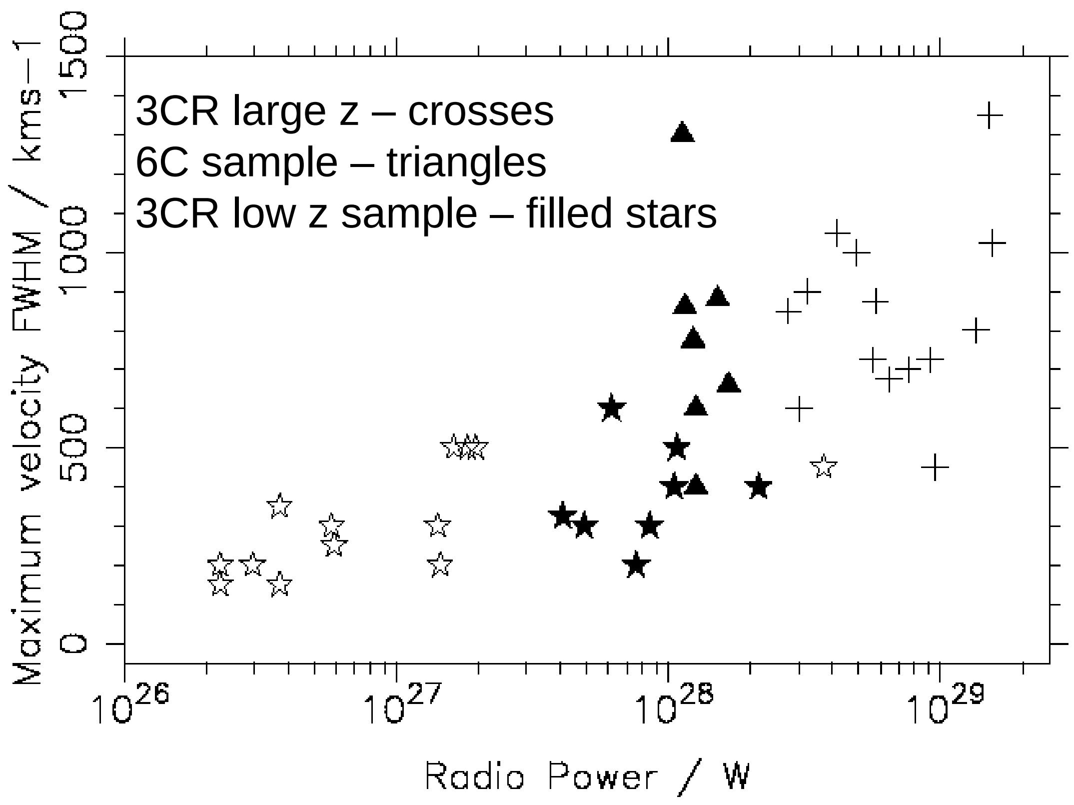


The conclusion is in agreement with the broad range of velocities and velocity components present in the small sources.

Kinematics versus Redshift



Kinematics versus Radio Power



Evolution of the host galaxy and/or environment

- Significant evolution of the host galaxy properties with redshift is required to explain the kinematics of the extended emission line regions.

- Other observational evidence for evolution
  - High-z radio sources often belong to richer cluster environments.
  - The alignment effect is less extreme at low-z.

- These suggest that:
  - The distribution and density of gas clouds varies with z
  - Interactions between the IGM and the radio jets are less important at low-z.

Influence of the radio source on the IGM

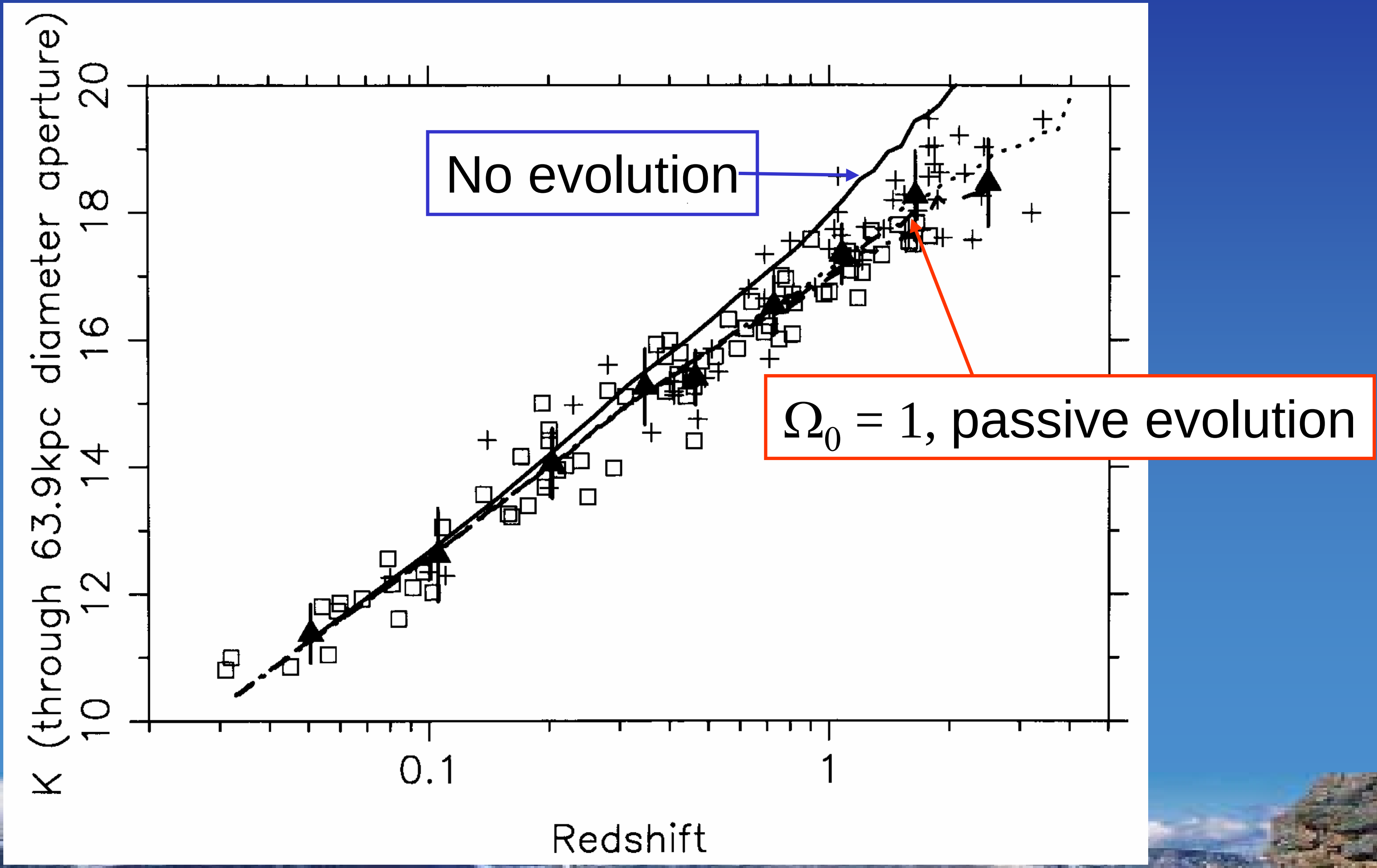
- Gas kinematics are clearly influenced by the power of the radio source.

- Expanding radio source may alter the distribution of cool gas clouds in the IGM, and the extent of the observed aligned emission.

- Shocks associated with the radio source may trigger star formation.

The K-z Relation for Radio Galaxies

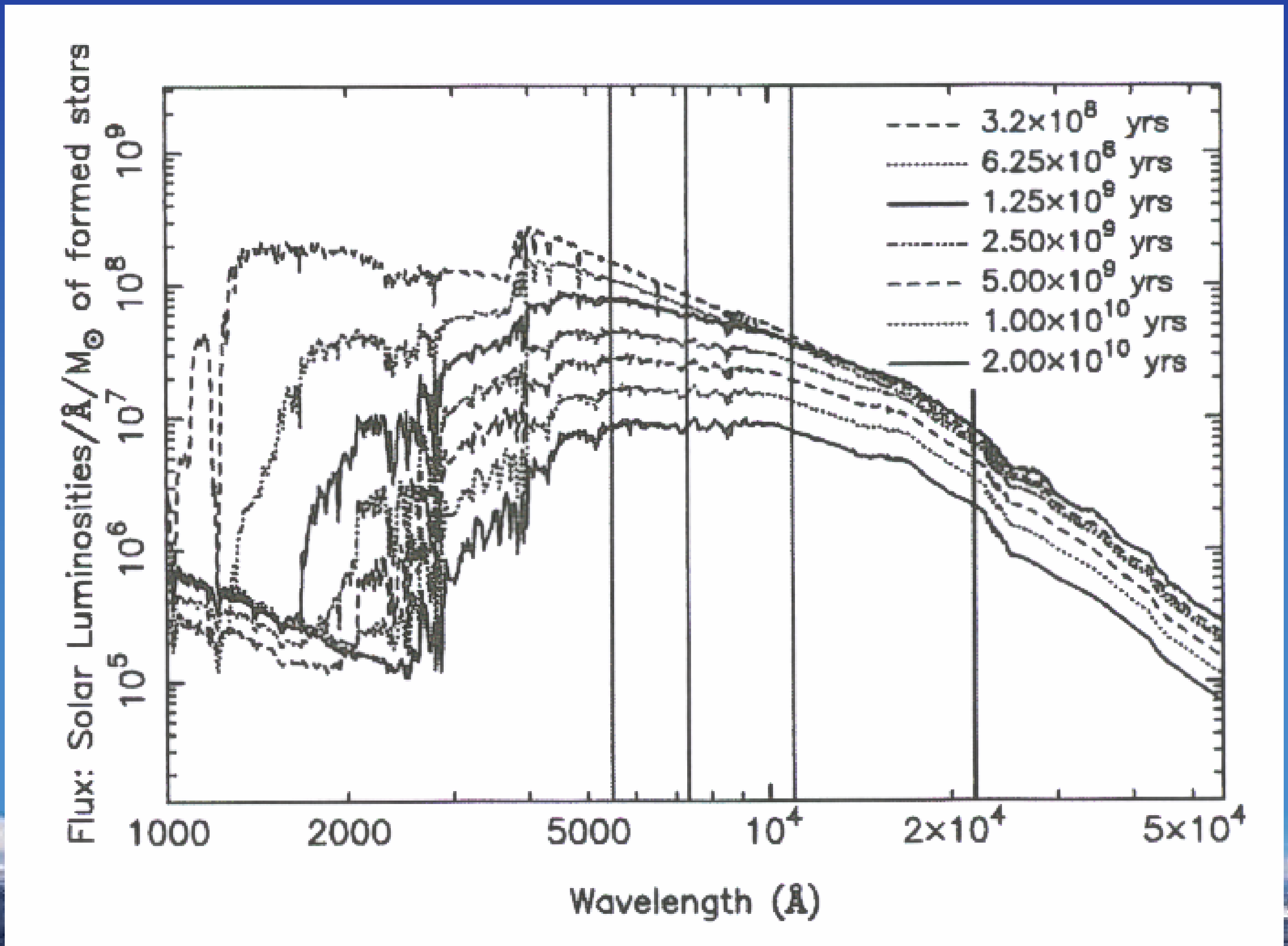
A new analysis for a wide range of world models



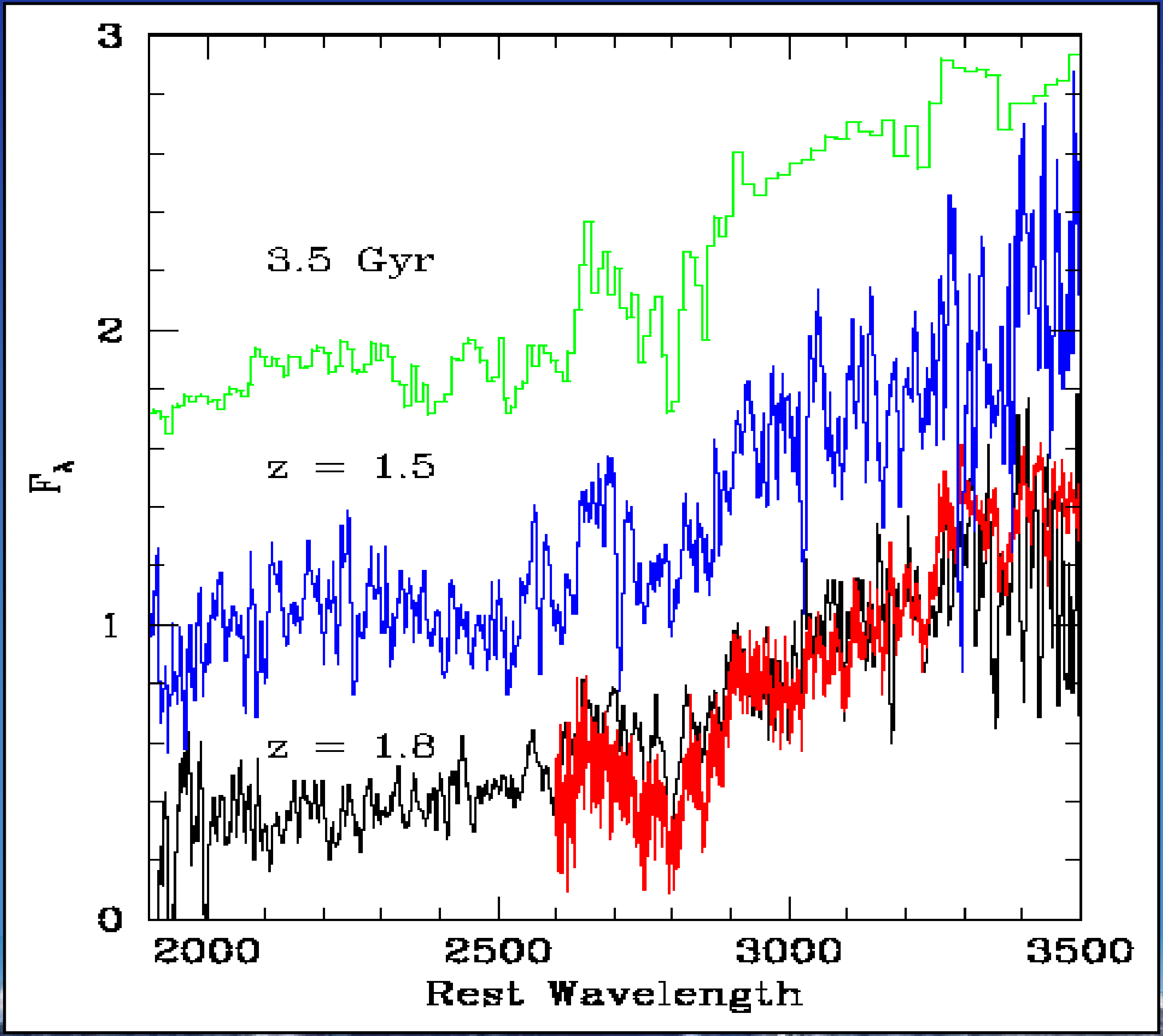
Features of the New Analysis
(Katherine Inskip,Philip Best + MSL)

- Analyses repeated using wider range of cosmological models.
- Use of the latest galaxy evolution codes of Bruzual and Charlot (GISSEL).
- Variation of parameters
  - Epoch of star formation.
  - Metallicity.
  - Starbursts associated with the radio source events.

Bruzual and Charlot GISSEL Galaxy Evolution Models



The Oldest Galaxies

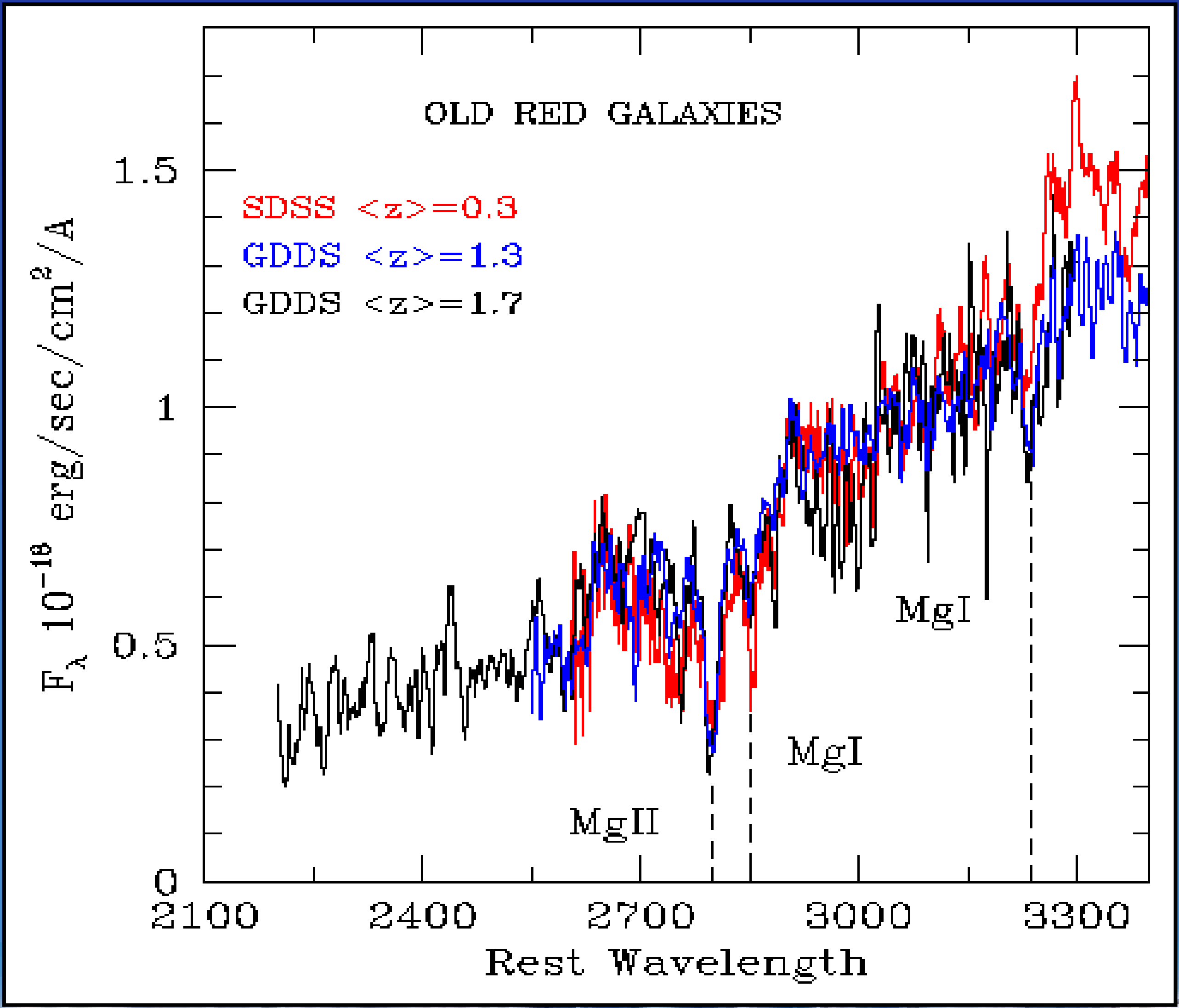


Evolved stars dominate the red objects to z ~ 2

Little evolution in spectral shapes over ~ 7 Gyr in look Back-Time

McCarthy 2005

The Oldest Galaxies



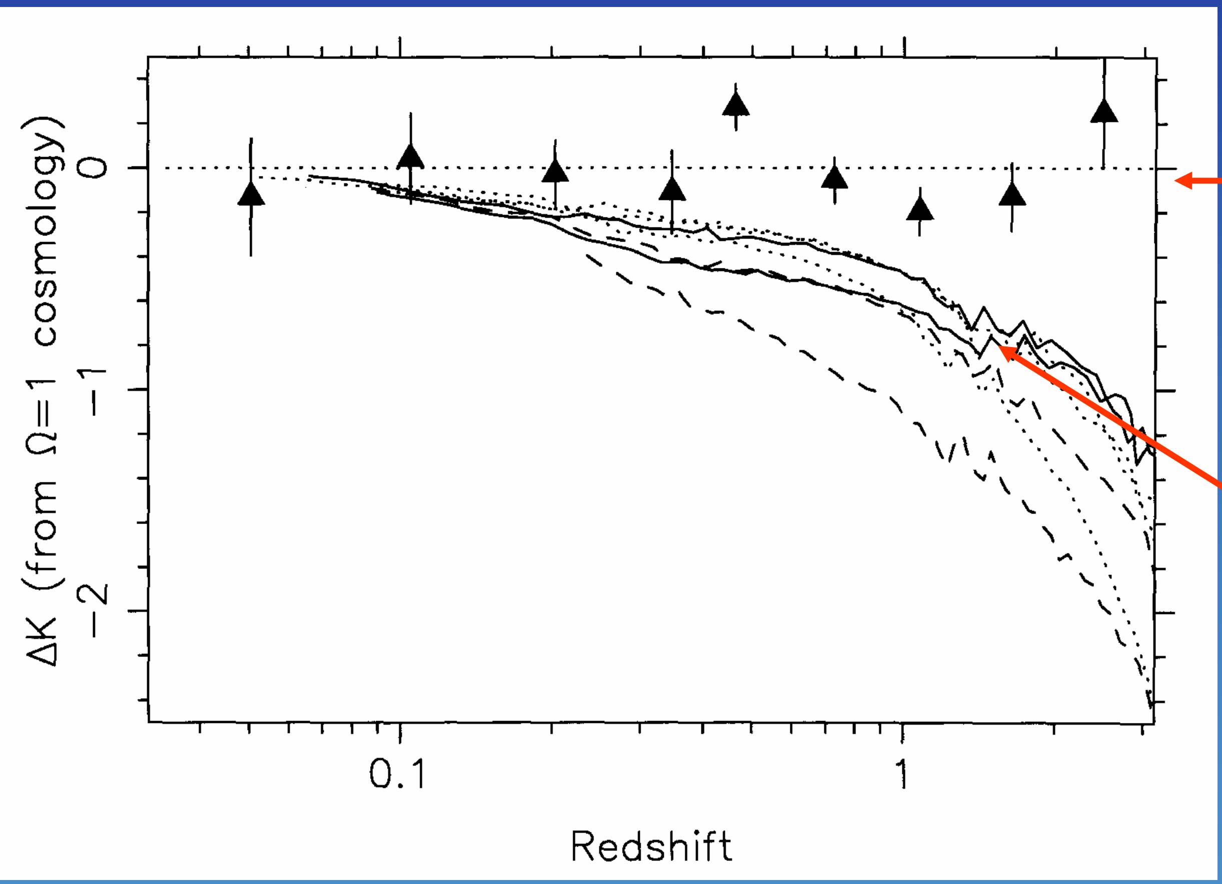
Modest evolution in the spectra of the massive red galaxies from z = 1.8 to the present

8m @100 hrs

30% have $z_f > 5$

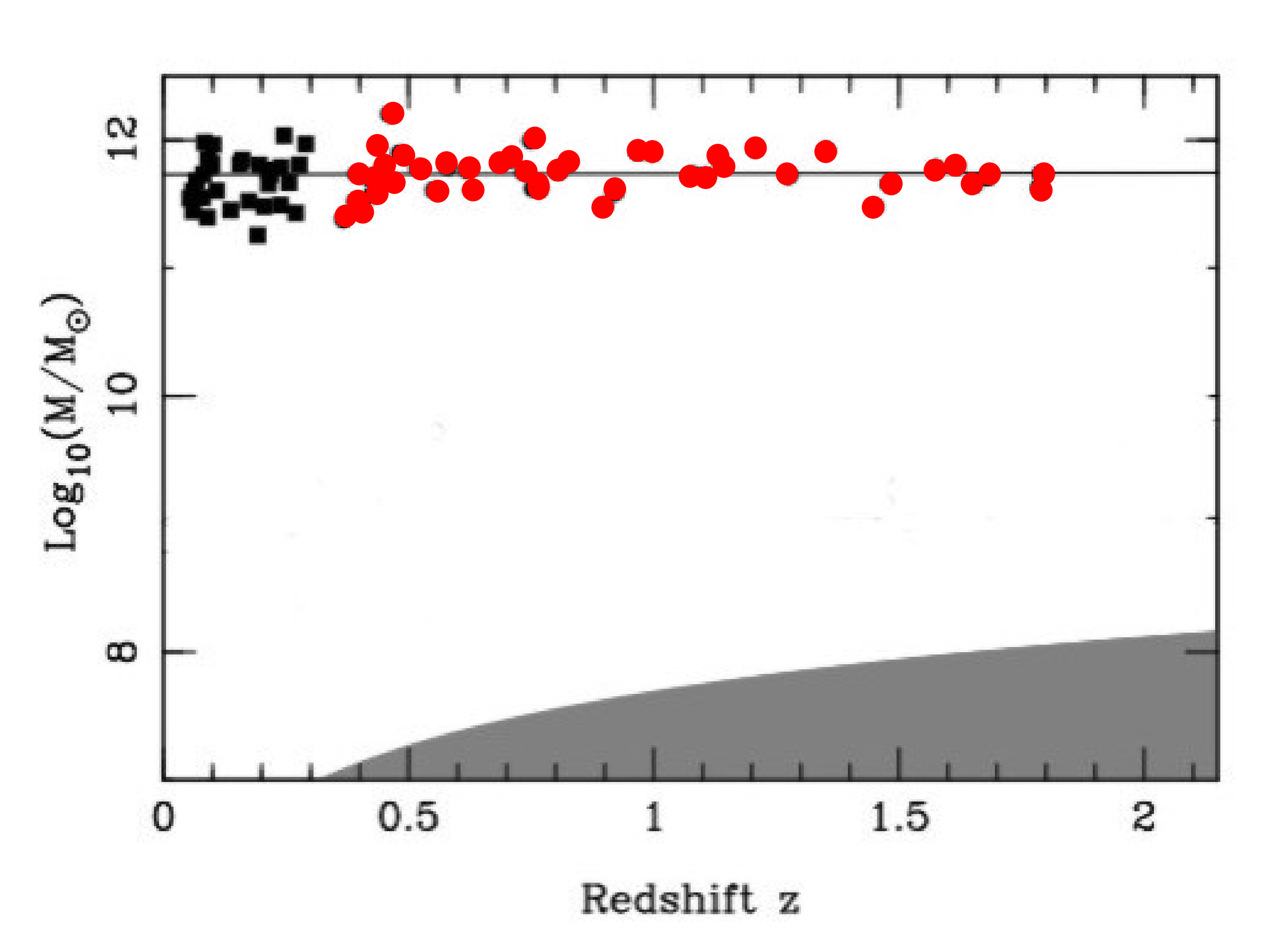
McCarthy 2005

Other world models, including passive evolution



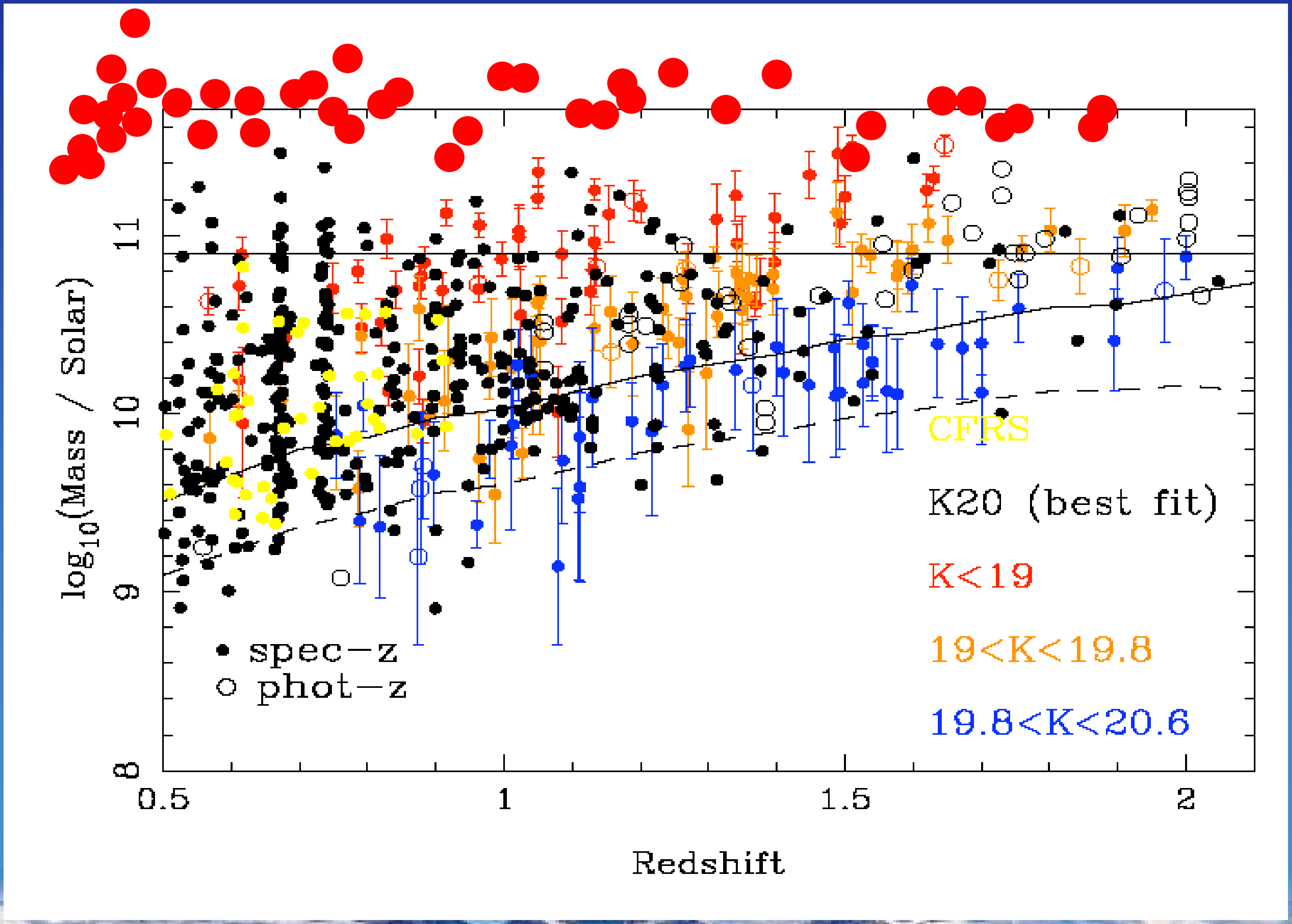
Ω_0	Ω_Λ
1.0	0.0
0.3	0.0
0.1	0.0
0.0	0.0
0.3	0.7
0.3	0.3
0.1	0.9
0.1	0.3

3CR Radio Galaxy Stellar Masses



McLure, Best et al 2005

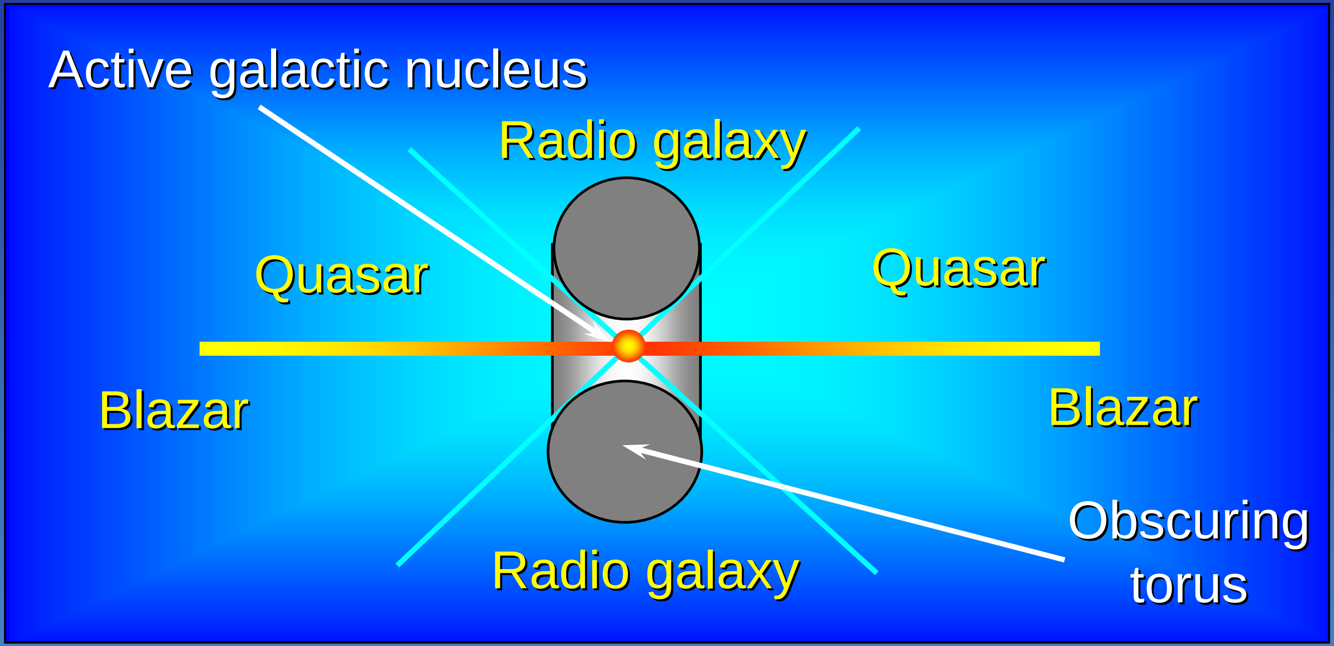
Galaxies in General versus Redshift



Glazebrook et al. 2005

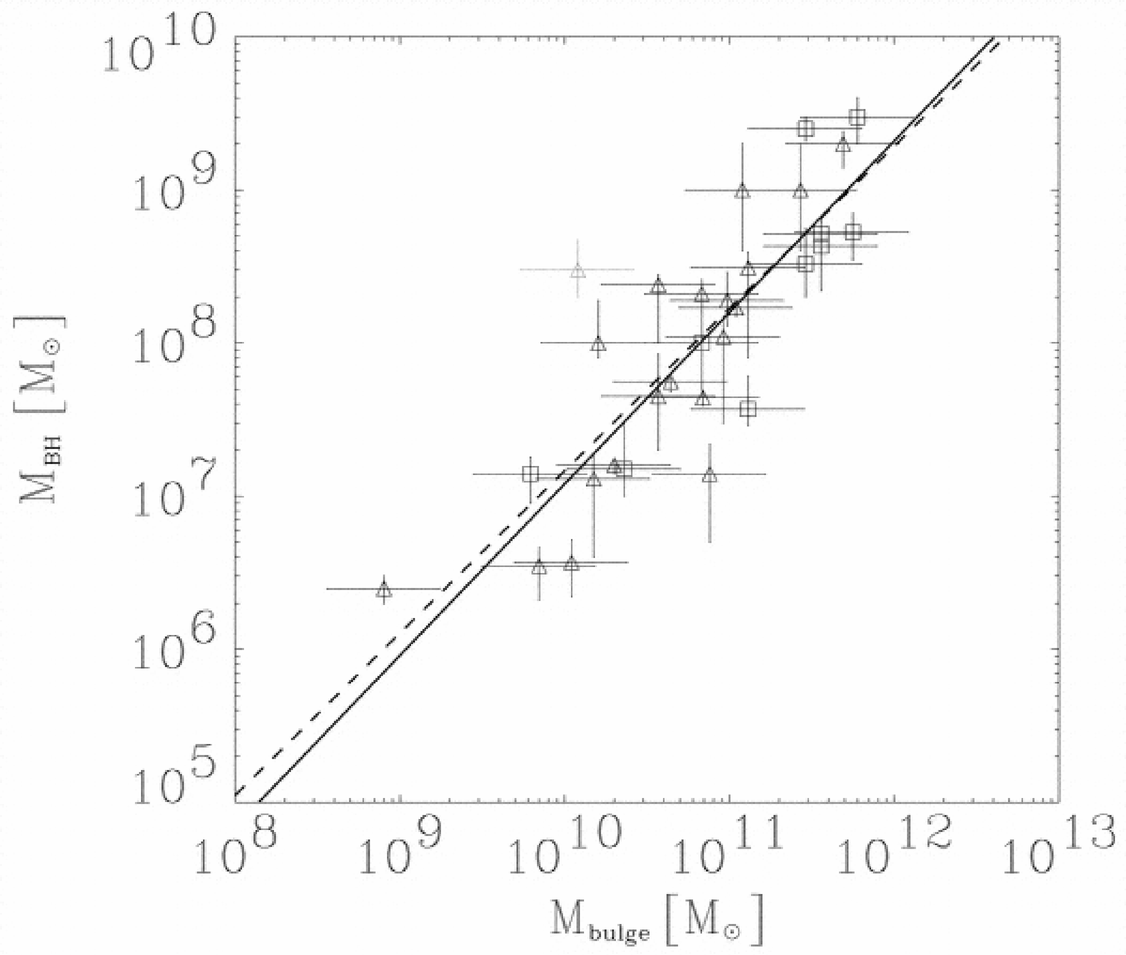
Gemini Deep Deep Survey + K20

The Orientation-based Unification Scheme for 3CR Radio Galaxies and Quasars



- For the 3CR sample and others, orientation-based unification schemes are remarkably successful.
- Cosmological evolution, statistics of numbers and sizes, asymmetries, presence of one/two sided jets.
- The host galaxies of radio quasars are the radio galaxies.

The Bulge-Black Hole Connection

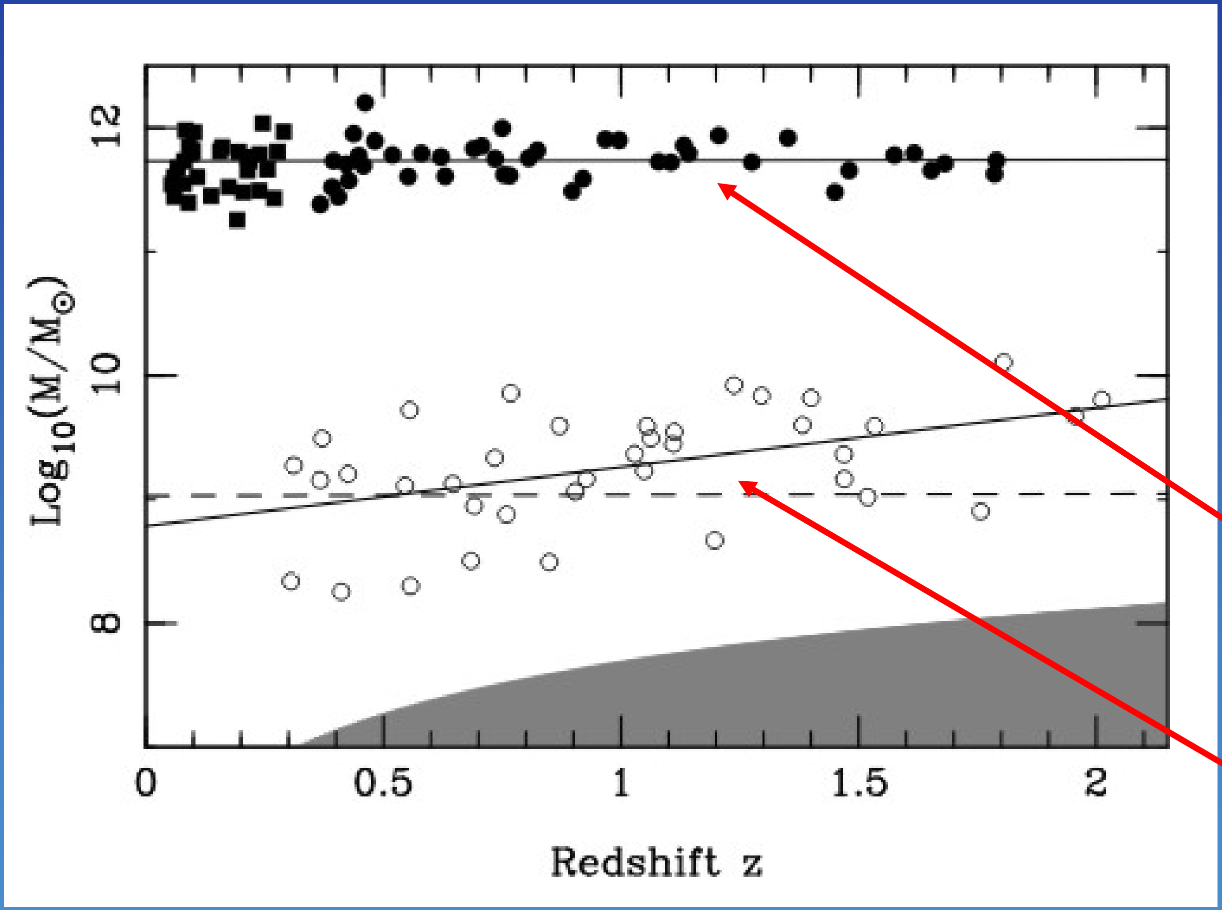


For nearby galaxies, there is a close linear relation between the masses of the central black holes and the mass of the bulge (or spheroid) of the galaxy. Typically it is found that

$M_{BH}/M_{sph} = 0.002$

Häring and Rix (2004)

The Bulge-Black Hole Connection for 3CR Radio Galaxies and Quasars

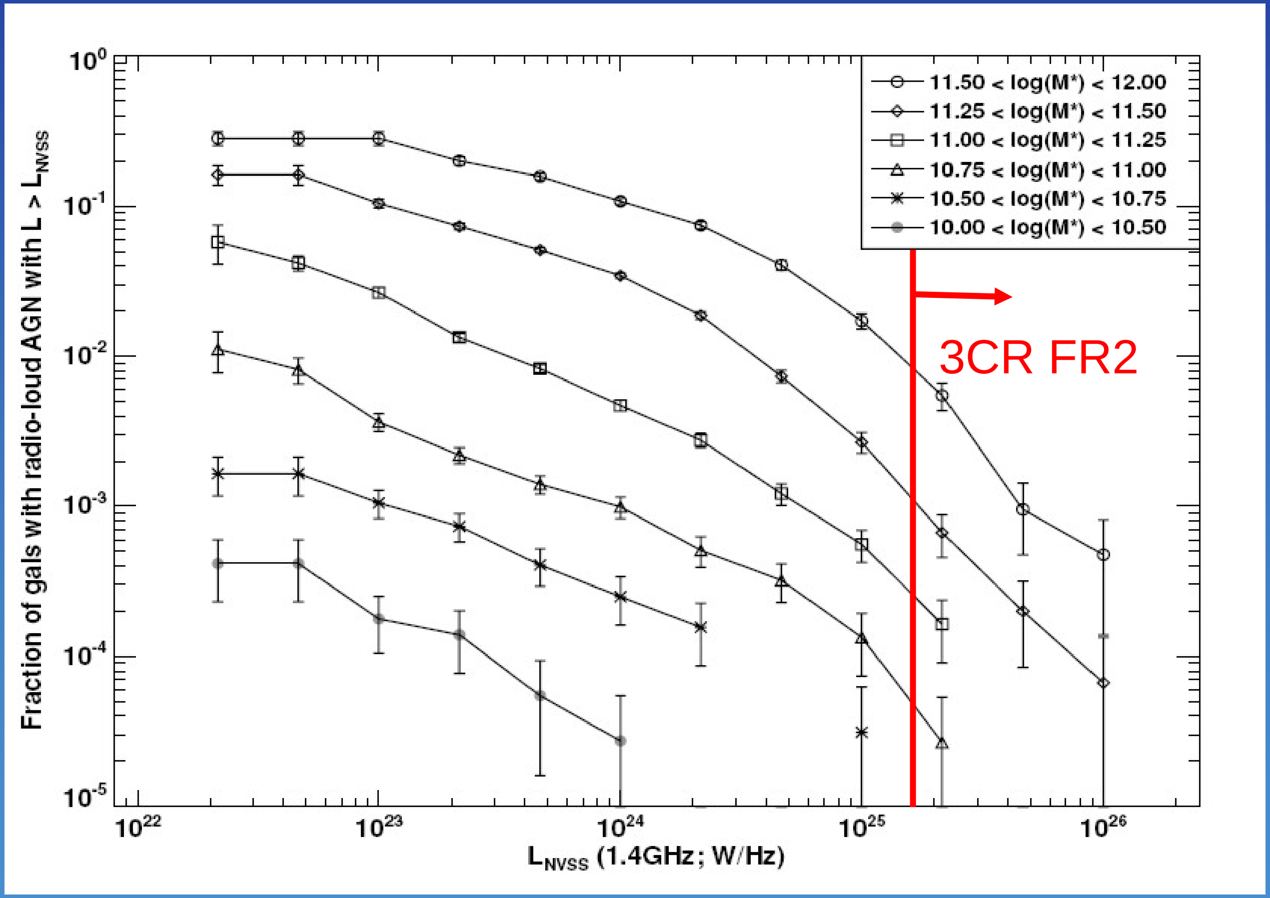


Because of the success of the orientation-based unification scheme, it is possible to derive:

- spheroid masses for the radio galaxies
- black hole masses for the quasars.

McLure *et al* (2005)

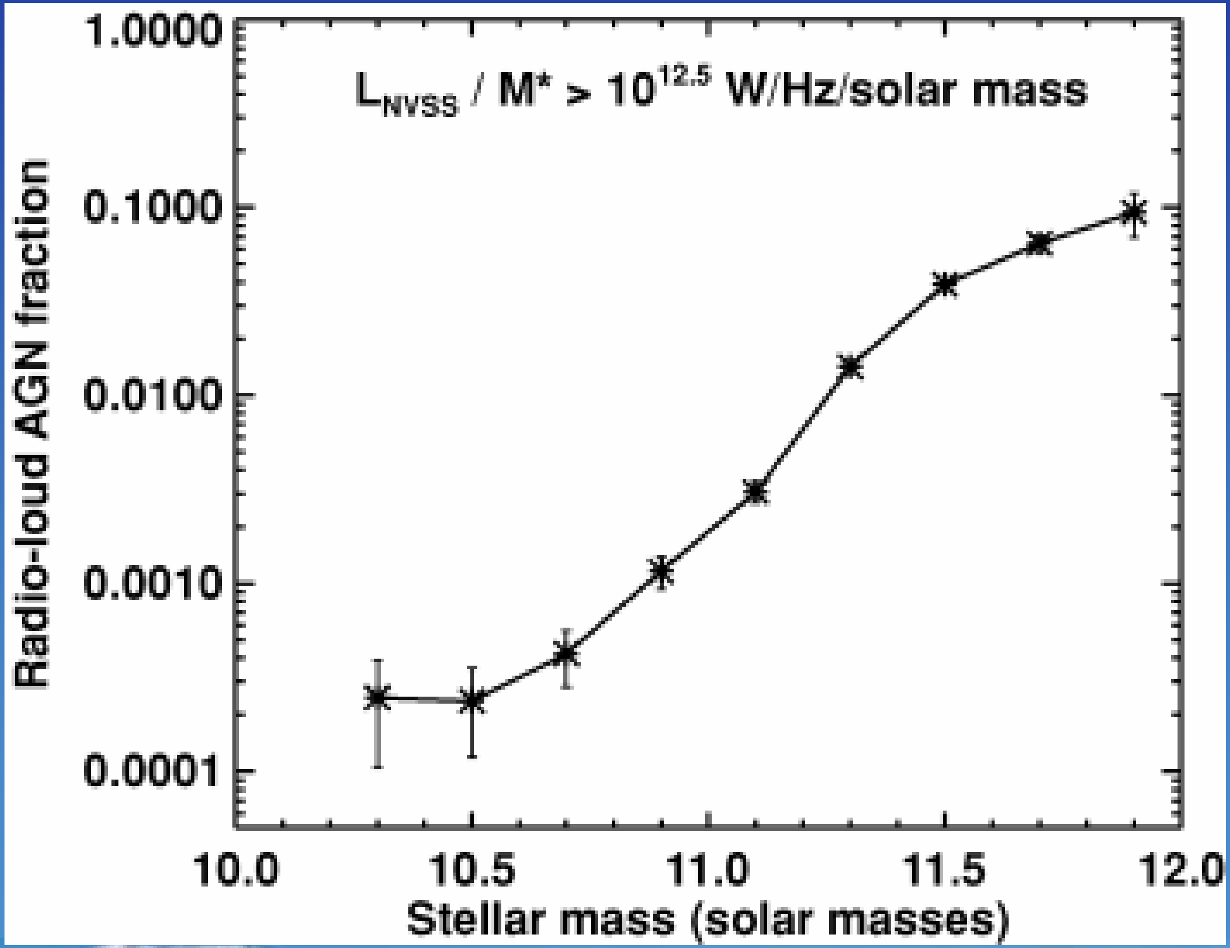
Probability of a Galaxy Becoming a Radio Galaxy from SDSS



Philip Best and his colleagues showed that the fraction of radio-loud active galaxies is a very strong function of the mass of the galaxies and consequently of their central black hole masses.

Best et al 2005

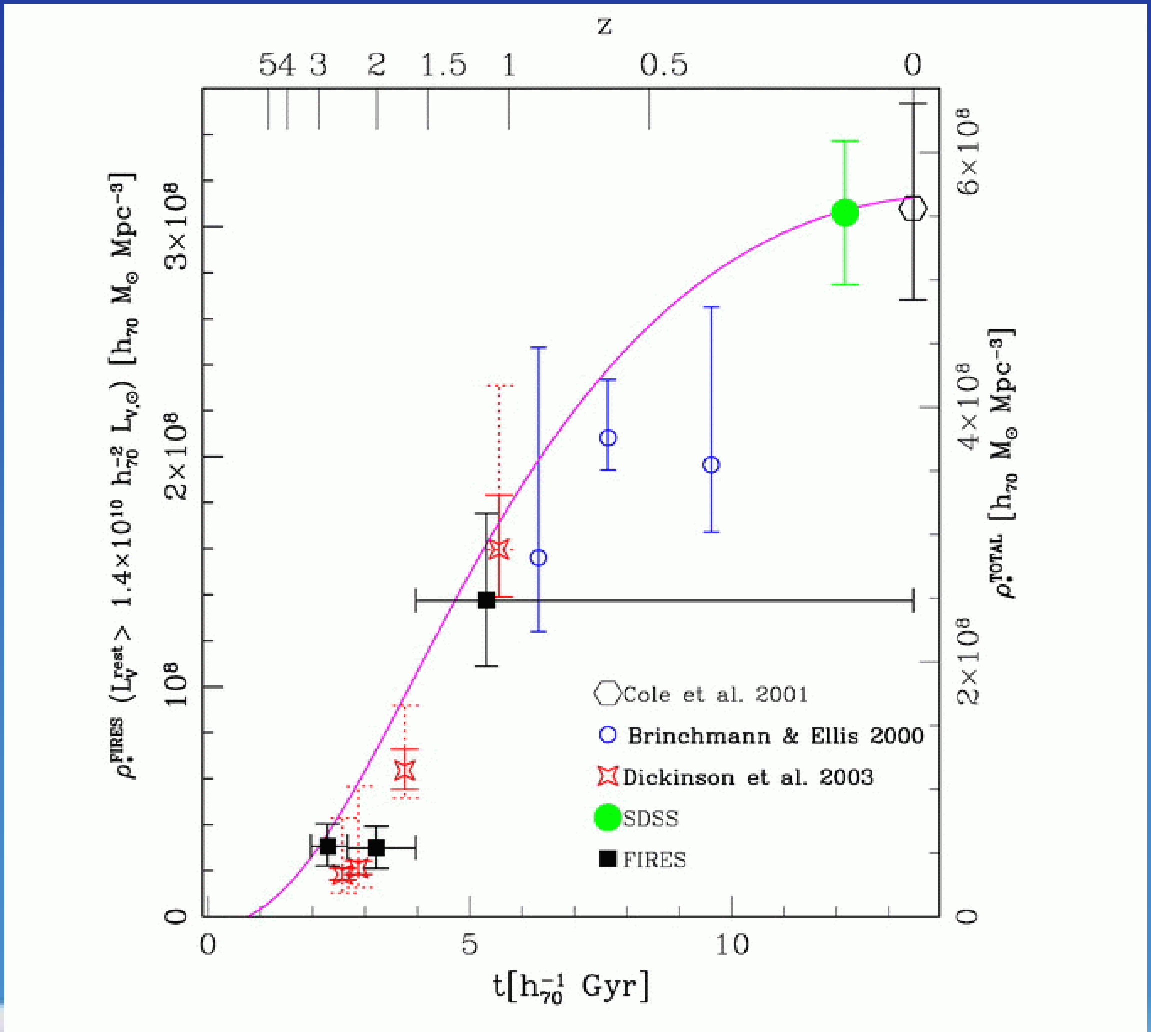
Probability of a Galaxy Becoming a Radio Galaxy from SDSS



Philip Best and his colleagues analysed the probability that a galaxy is a powerful radio galaxy as a function of galaxy mass using a very large sample of galaxies from the SDSS.

Best et al 2005

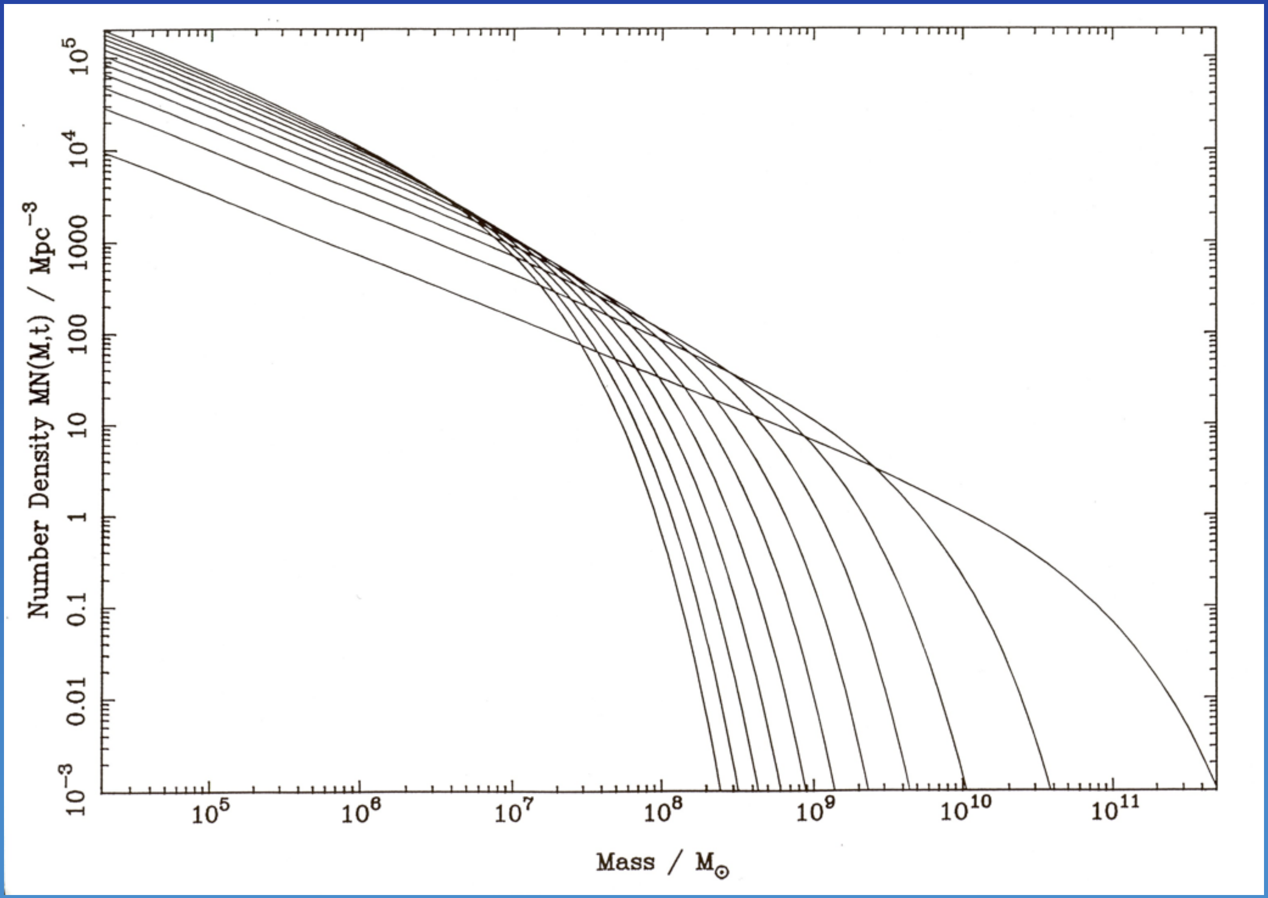
Global Evolution of Stellar Mass Density



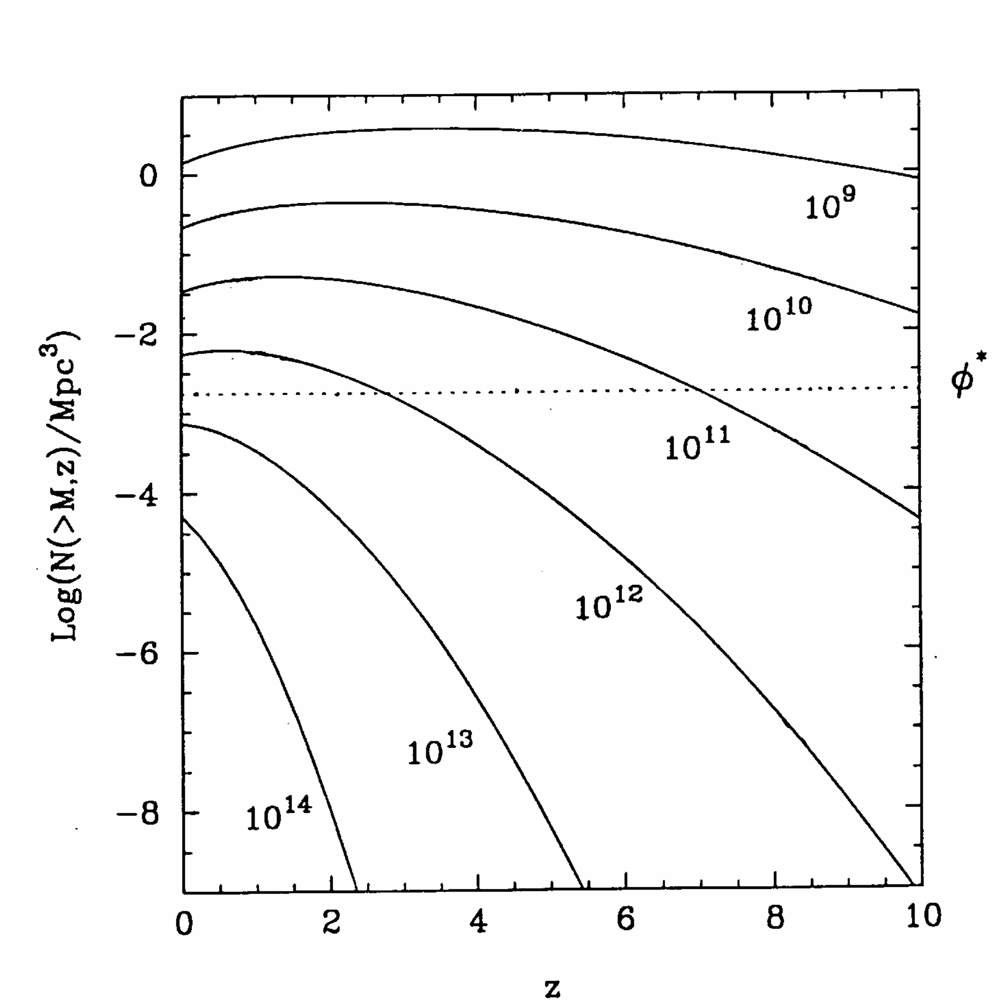
Rudnick et al. 2004

FIRES Program

The Evolution of the Press-Schechter Mass Function with Cosmic Epoch



The Evolution of the Mass Function of Bound Systems according to the Press-Schechter Formalism

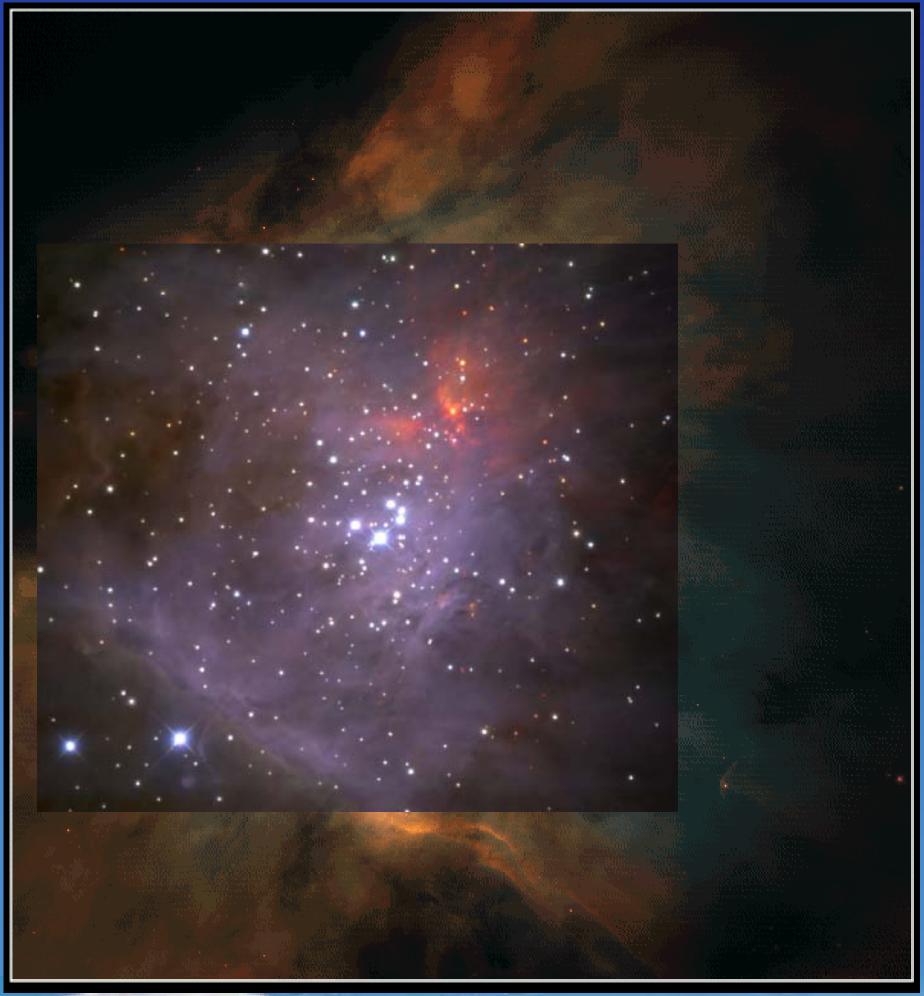


The massive galaxies which host super-massive black holes can barely have formed at the largest redshifts at which the powerful radio galaxies and quasars are observed.

Conclusions

- 2.2 μm is a very good archaeological waveband for understanding the global evolution of stellar populations out to z = 3.
- The choice of cosmological model is more important than the stellar evolution corrections for passively evolving giant elliptical galaxies.
- All models with significant longer ages, for example, $\Omega_0 = 0.3$, $\Omega_\Lambda = 0.7$, result in the more distant galaxies being more luminous than those nearby.
- Unlikely to be due to a combination of lower metallicity and star formation epoch occurring at relatively small redshift.

The Dust Problem



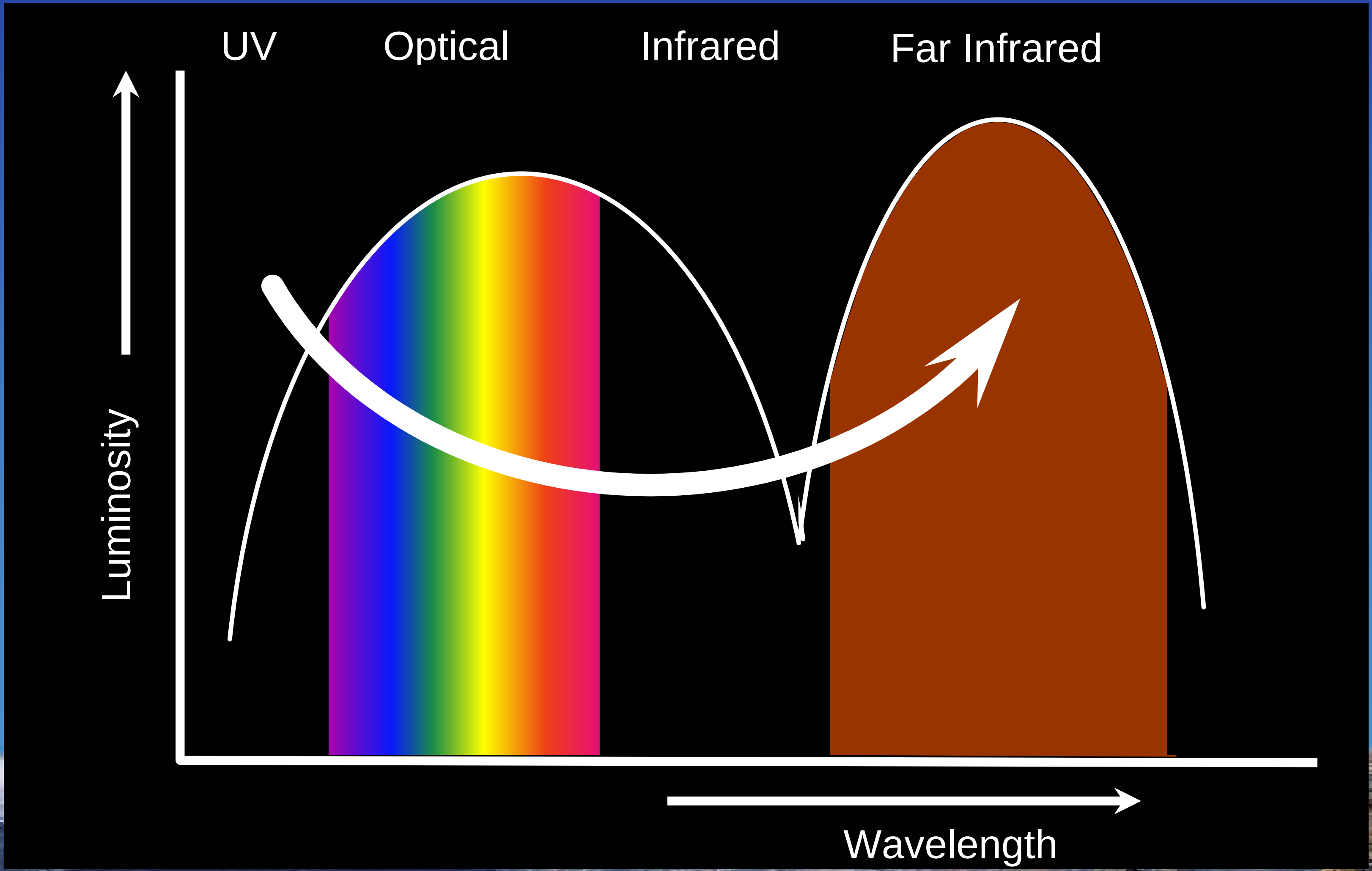
Calar Alto 3.5 m telescope, Spain – IR

- Wherever stars are forming, there are huge quantities of interstellar dust.

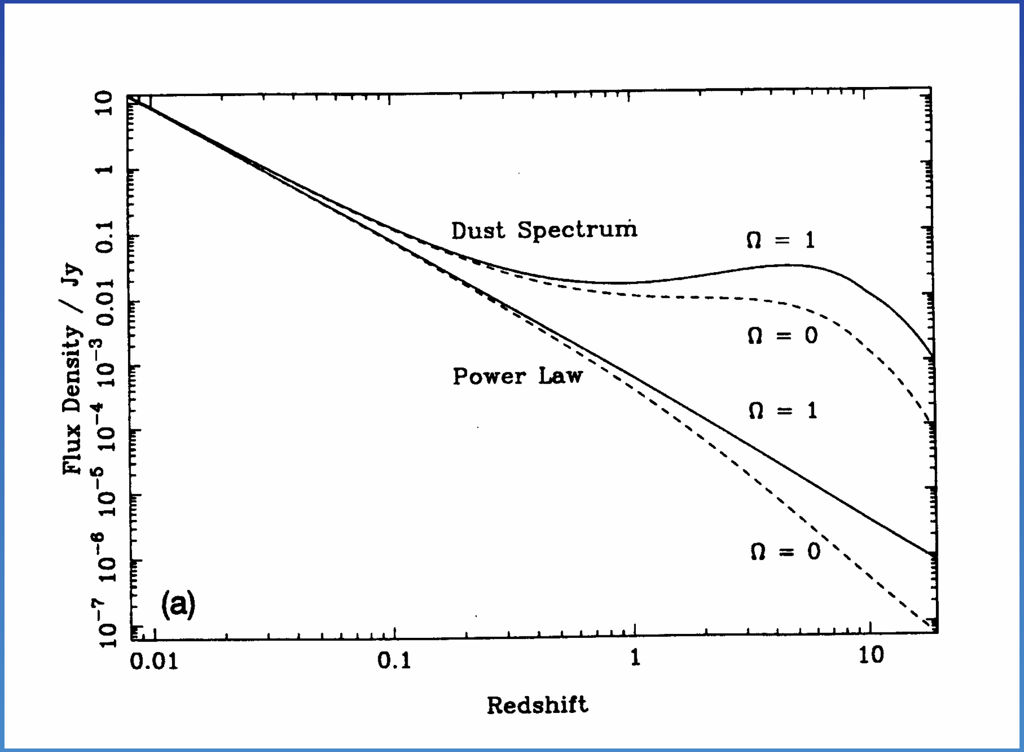
The Orion Nebula observed at optical and infrared wavelengths

The Role of Dust

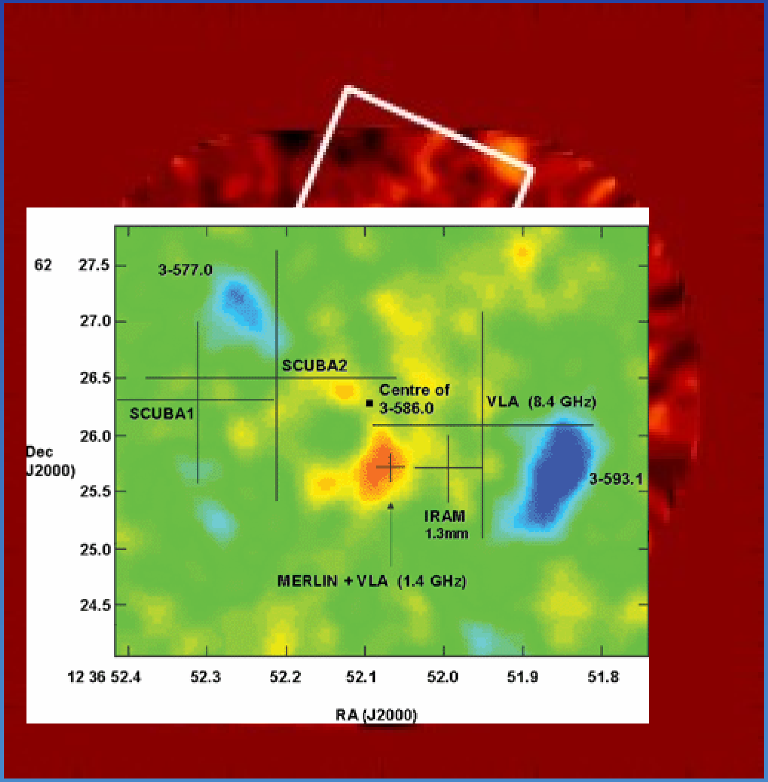
Optical and UV emission absorbed by dust and re-radiated in the far infrared waveband



Submillimetre Flux Density-Redshift Relation for a Starburst Galaxy

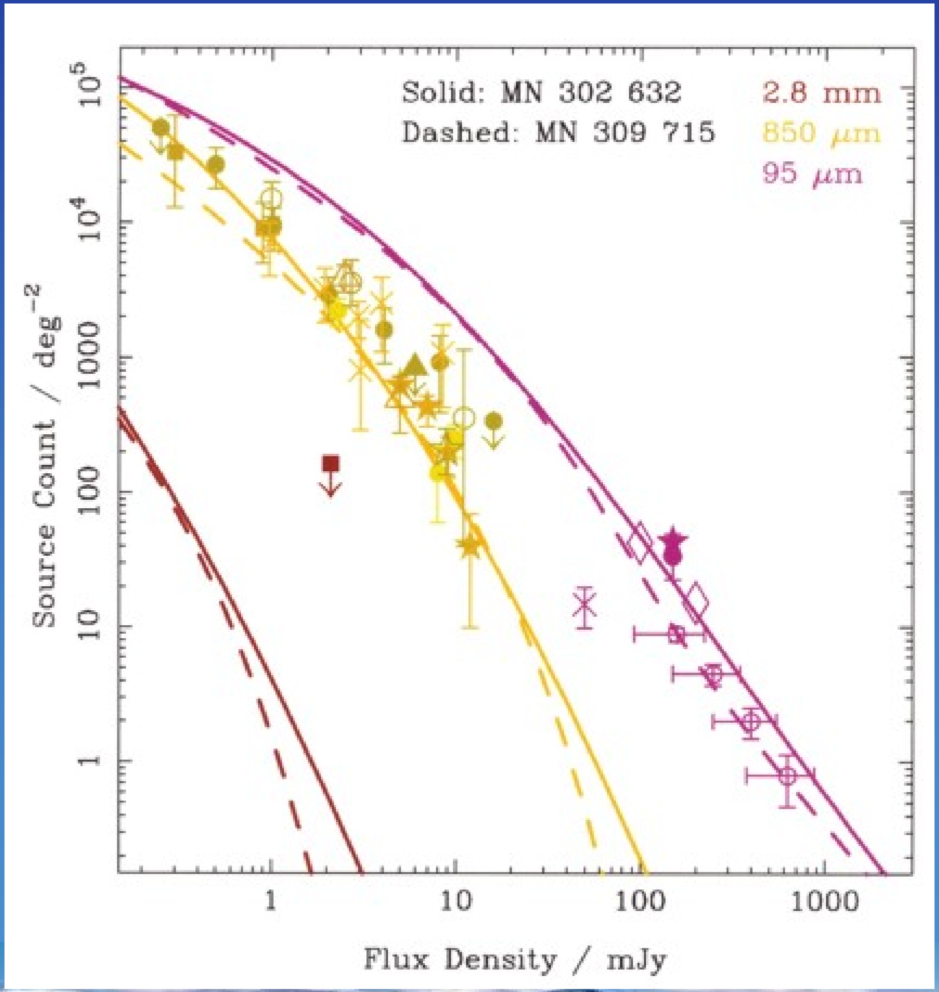


Blain and Longair 1993



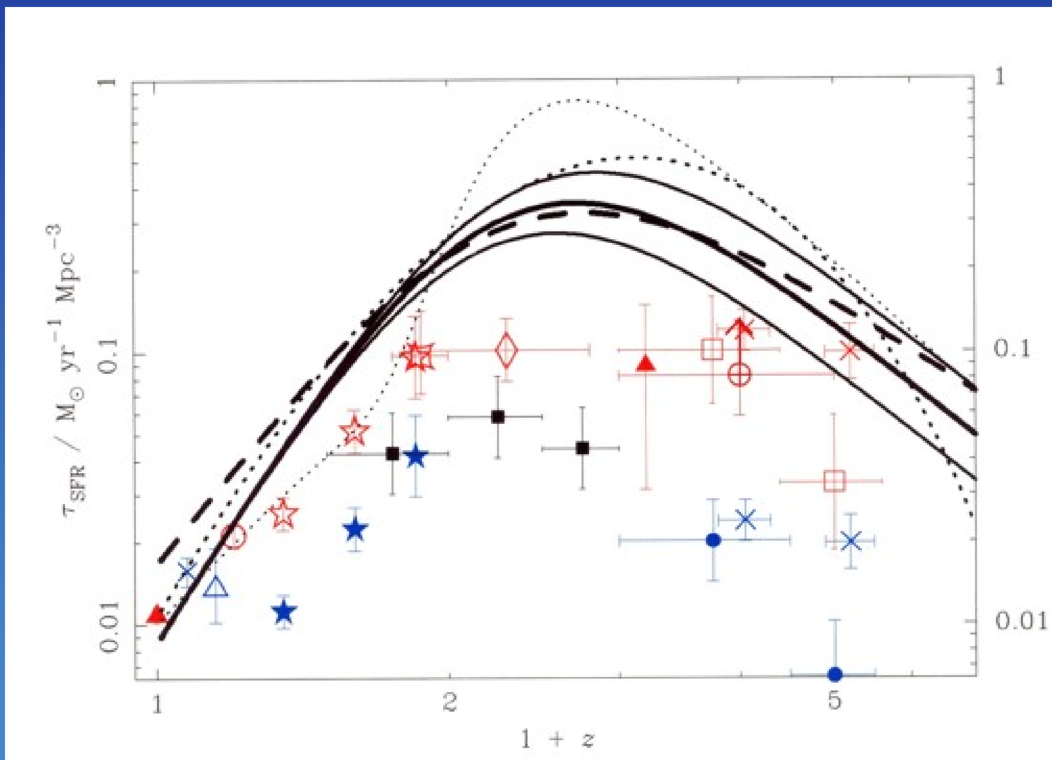
Hubble Deep Field

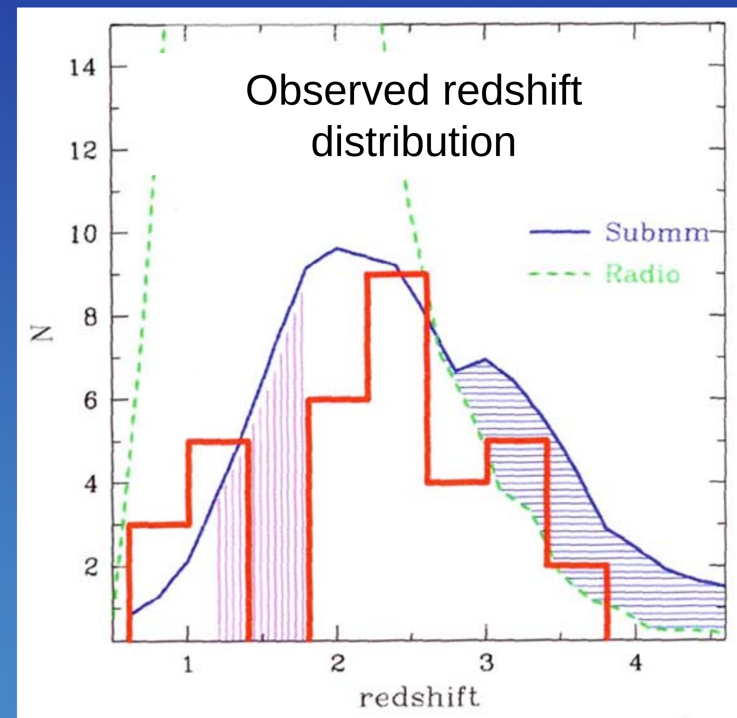
The Number Counts of Submiillimetre Galaxies



The number counts of faint infrared sources indicate a large excess of faint sources.

The Cosmic Rate of Star Formation





Putting togther all the data, we can determine the cosmic star formation rate from UV, optical and submillimetre observtions

How Does It All Hang Together?