Extra-galactic Radio Sky

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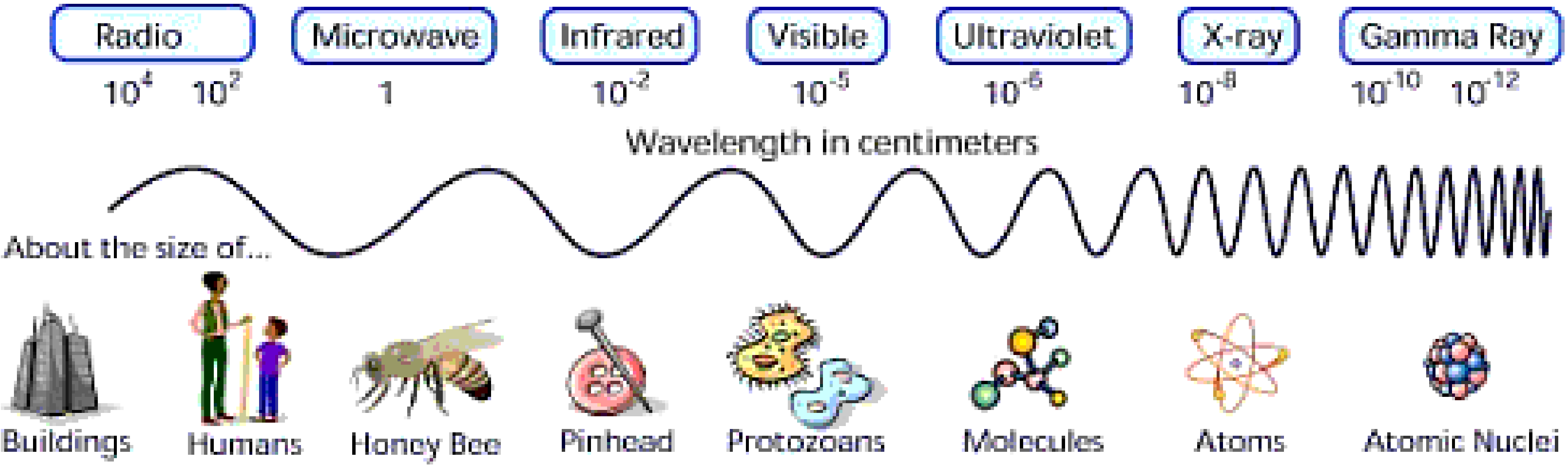
PUNE

Astronomy is ...

Astronomy is the study of planets, stars, galaxies, and other astronomical objects using the ***light*** they emit

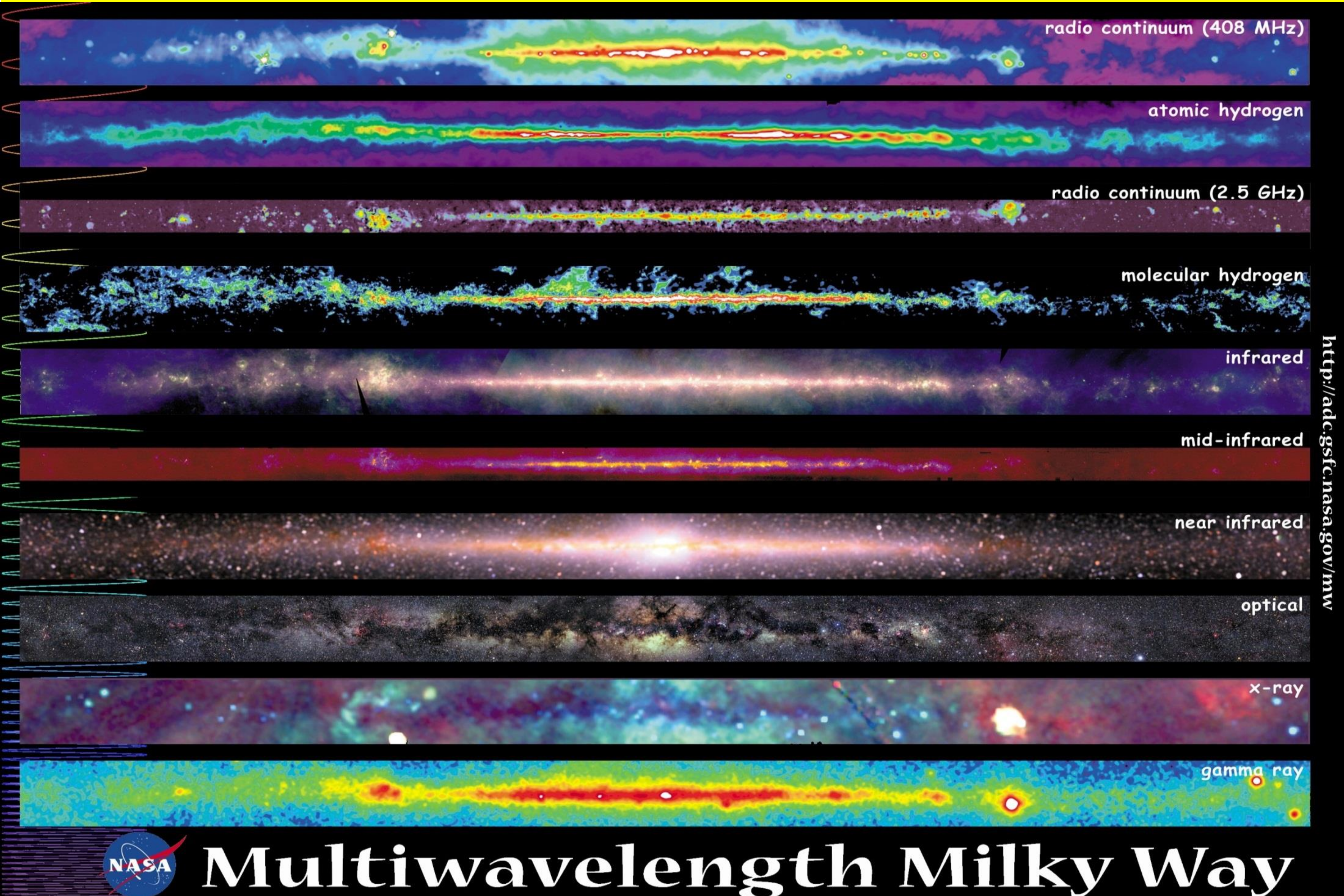
Lab Science vs Astronomy.



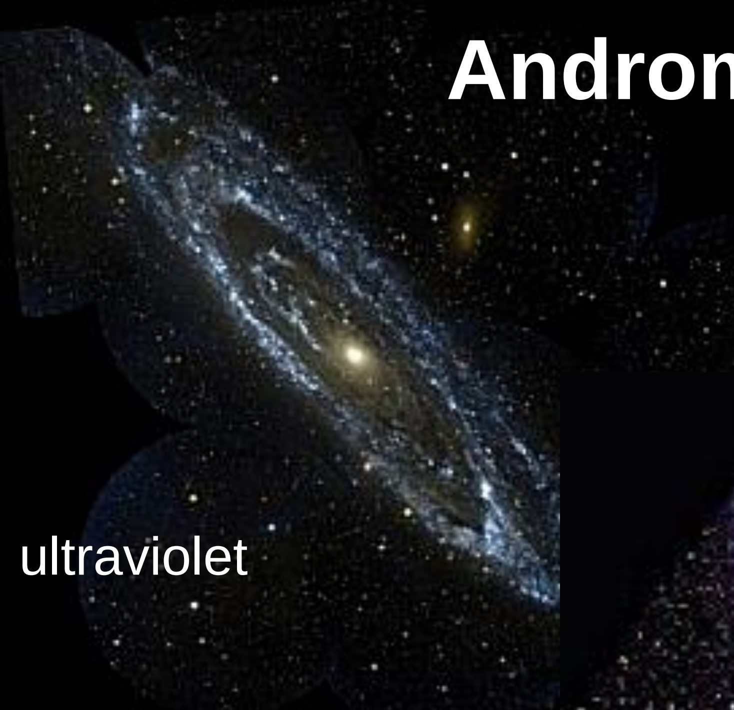
Different branches of astronomy as per branch of EM
Different observables in each band

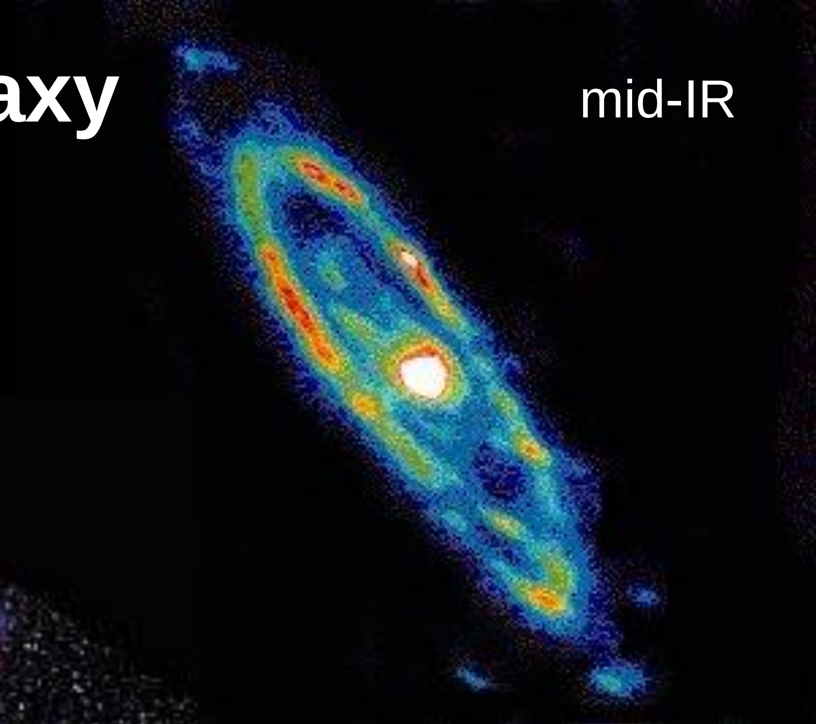
Consolidated picture from multi-wavelength data

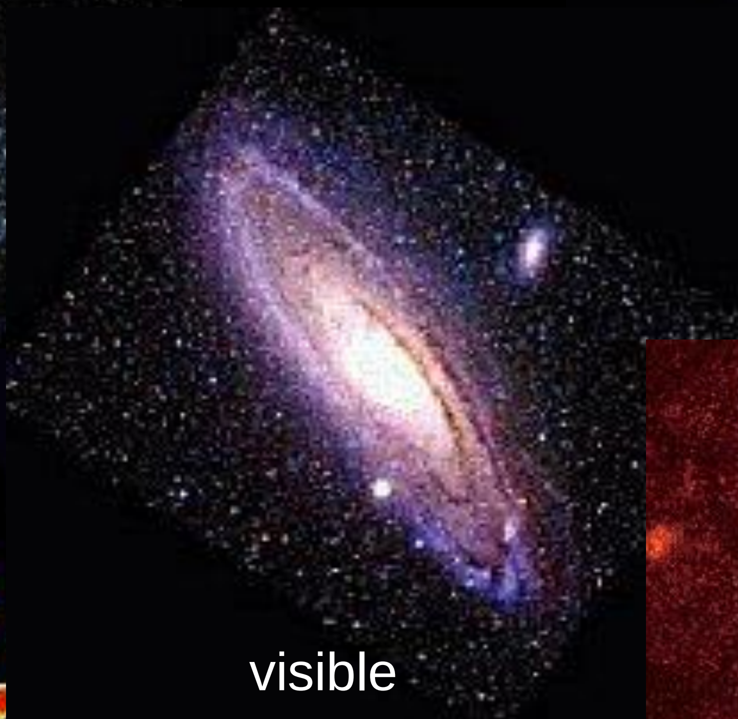
Multiwavelength Milky Way

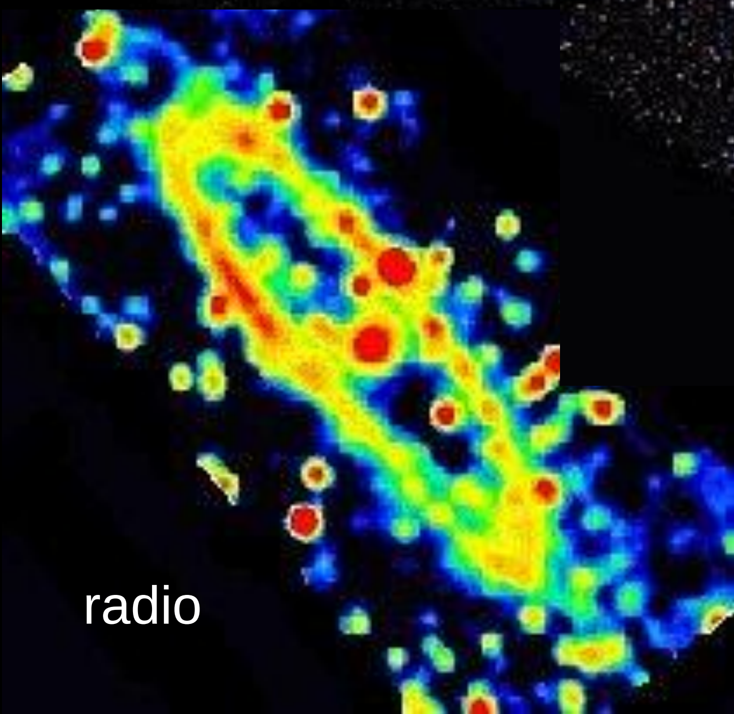


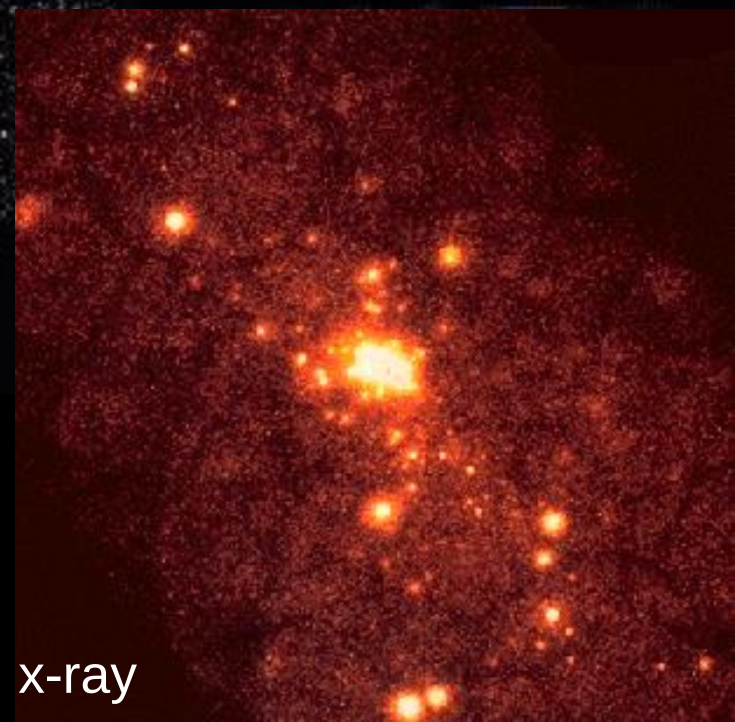
Andromeda Galaxy


ultraviolet


mid-IR


visible


radio


x-ray

Outline of the talk

- ✓ Multi-wavelength sky
- ✓ Normal galaxies; radio emission from Normal Galaxies
- ✓ Active galaxies; radio emission from Active Galaxies
- ✓ Emission processes
- ✓ Some interesting examples
- ✓ Discovery space using GMRT like low frequency telescopes.

Normal Galaxies

Galaxies are gravitationally bound systems of stars, mass up to 10^{12} solar mass, size upto tens of kpc

Hubble's observation that M31 is a separate galaxy is the birth of Extragalactic Astronomy.

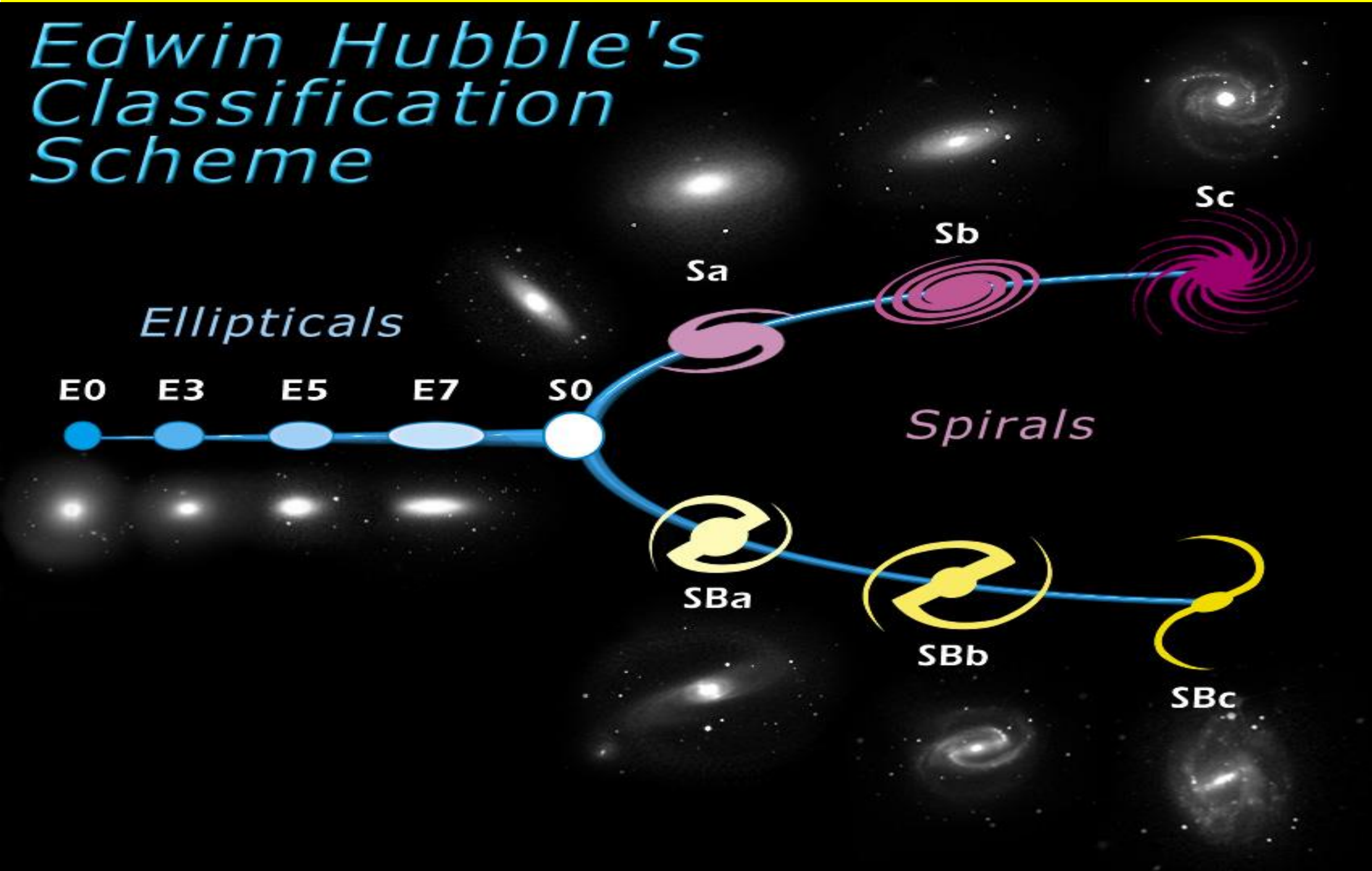
Dwarfs to spirals to Giant Ellipticals; range of morphologies and range of mass (a factor of 10,000) – Hubble Tuning fork diagram

Are the properties same for all range of galaxies?

What are their properties in different branch of EM spectrum?



Normal Galaxies



Radio Emission from Normal Galaxies

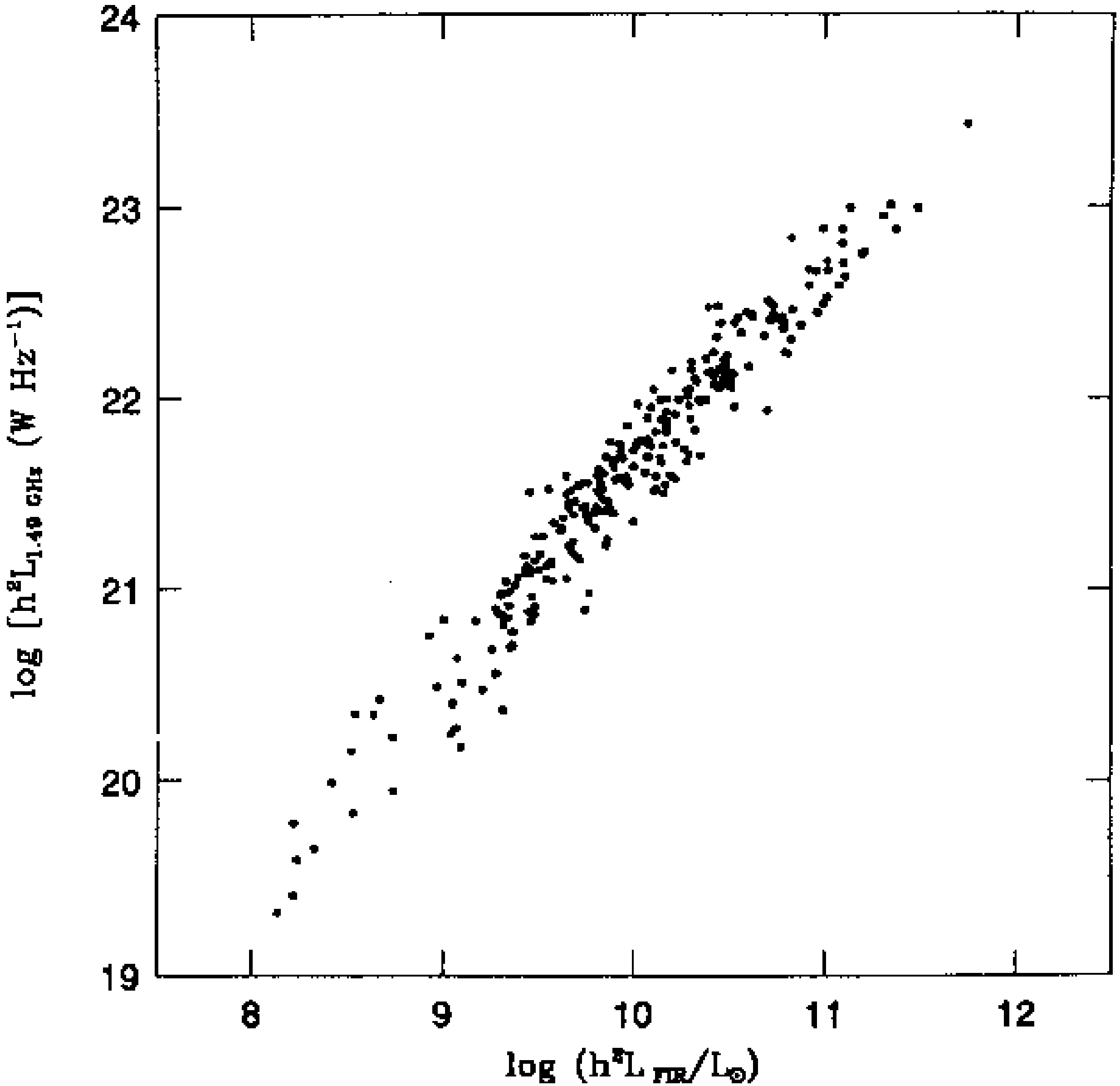
Normal galaxies dominate in the UV-optical-IR band of EM spectrum, powered by stellar processes..

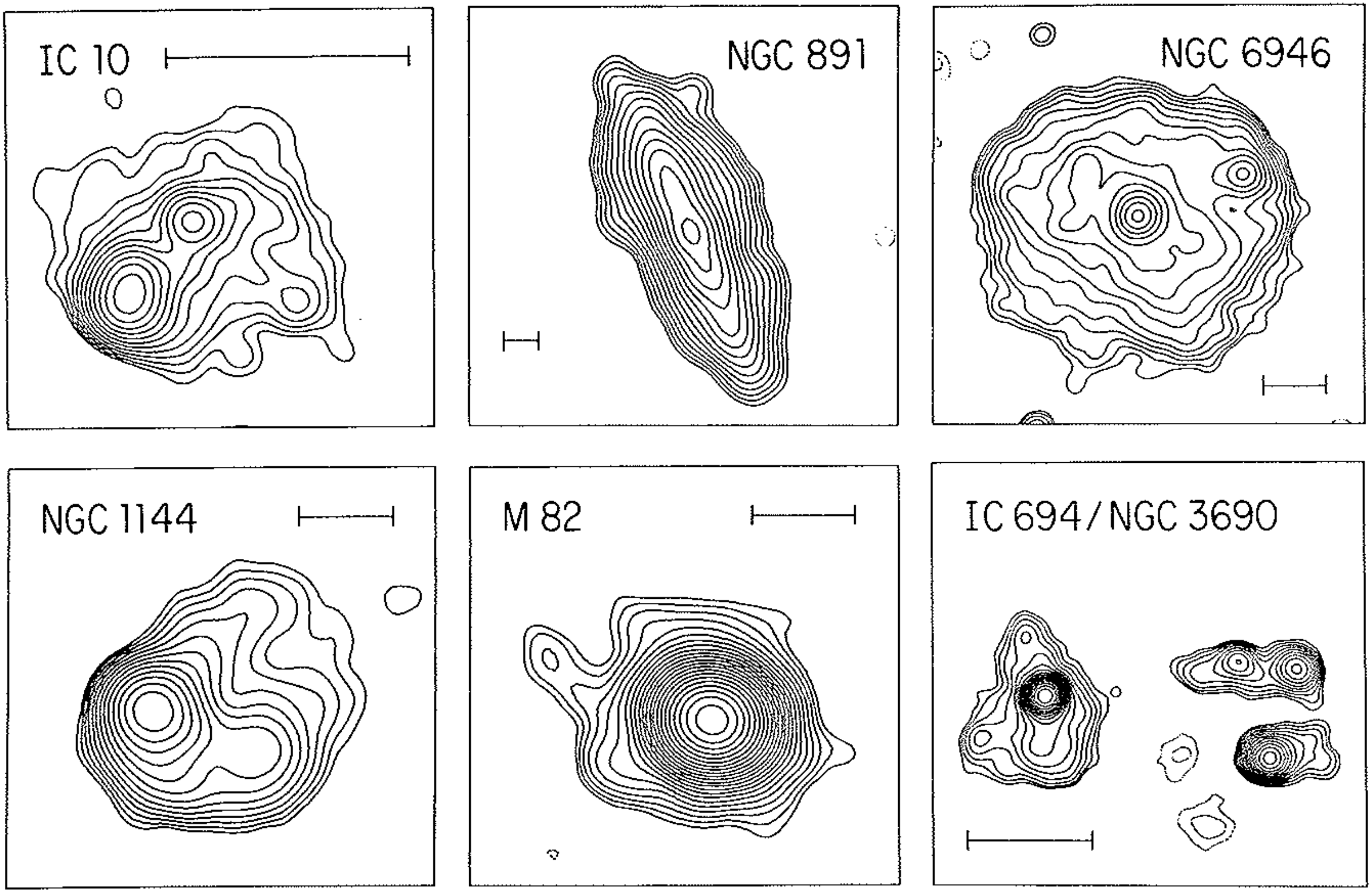
(if it has powerful emission in high-energy band, it won't be called "Normal") !

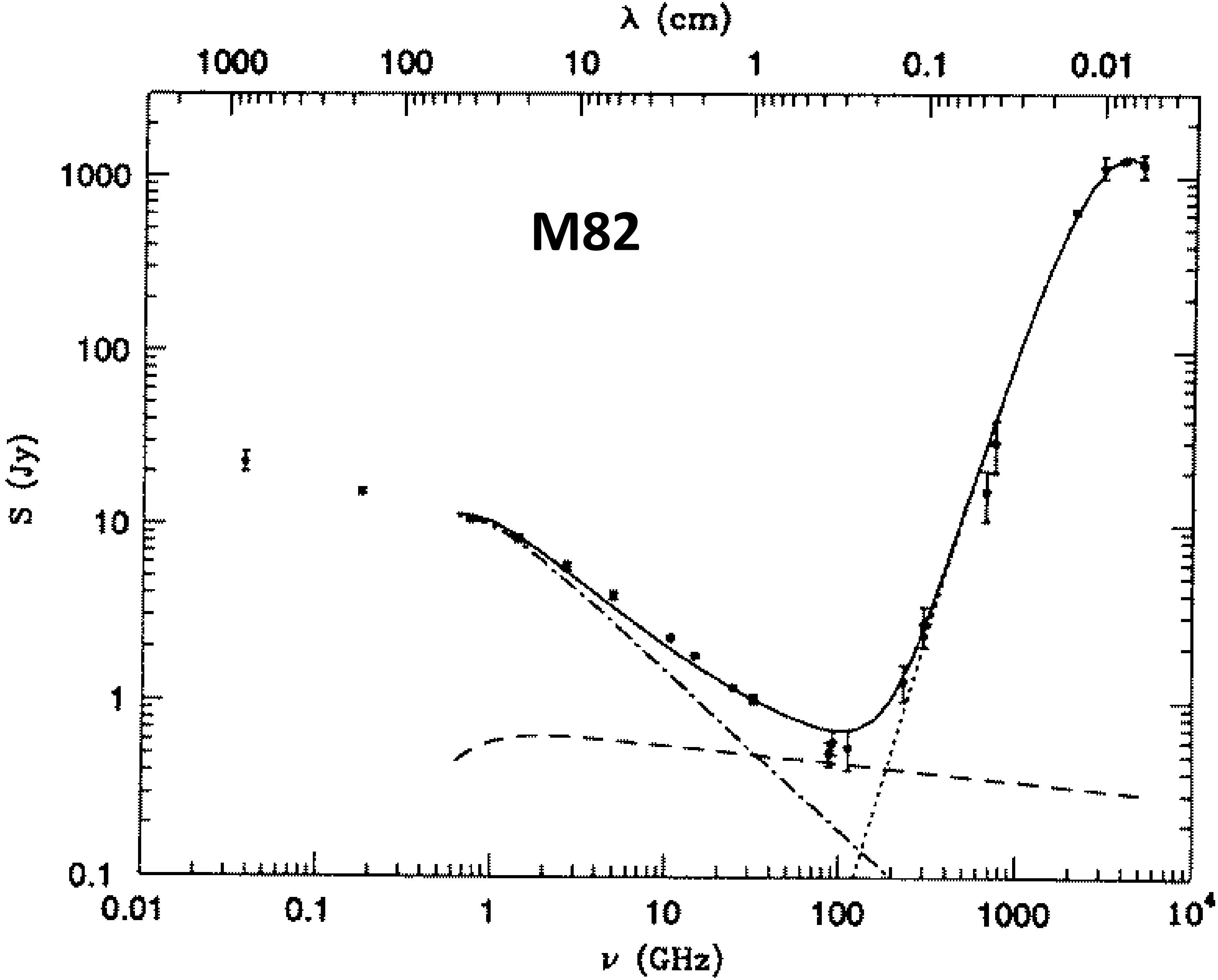
Radio Emission from Normal galaxies is due to Supernova remnants, HII regions, cosmic rays in ISM, etc – this means tight correlation with star-formation activity, hence IR..

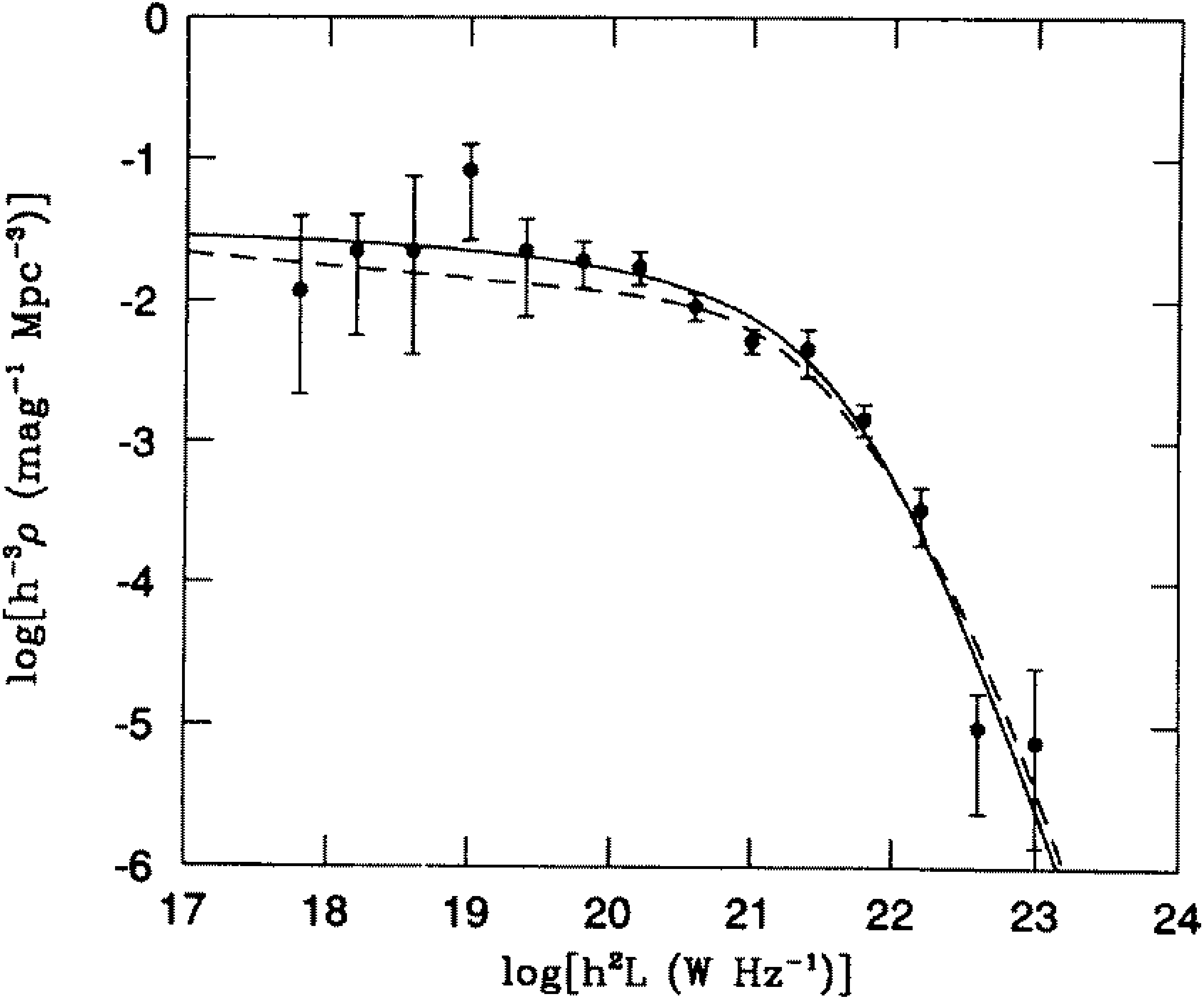
Condon, Annual Review of Astron. and Astrophy. - 1992

Radio – FIR correlation




IC 10
NGC 891
NGC 6946
NGC 1144
M 82
IC 694/NGC 3690


λ (cm)
1000
100
10
1
0.1
0.01
M82
S (Jy)
1000
100
10
1
0.1
0.01
0.1
1
10
100
1000
10⁴
ν (GHz)



0
-1
-2
-3
-4
-5
-6
17
18
19
20
21
22
23
24
log[h⁻³ρ (mag⁻¹ Mpc⁻³)]
log[h²L (W Hz⁻¹)]

Line Emission from Galaxies

In addition to continuum, there are also several spectral lines – prominent among them are neutral hydrogen (HI), deuterium (DI), OH, many transitions of CO, etc.

HI to trace dark matter and hydrogen content.

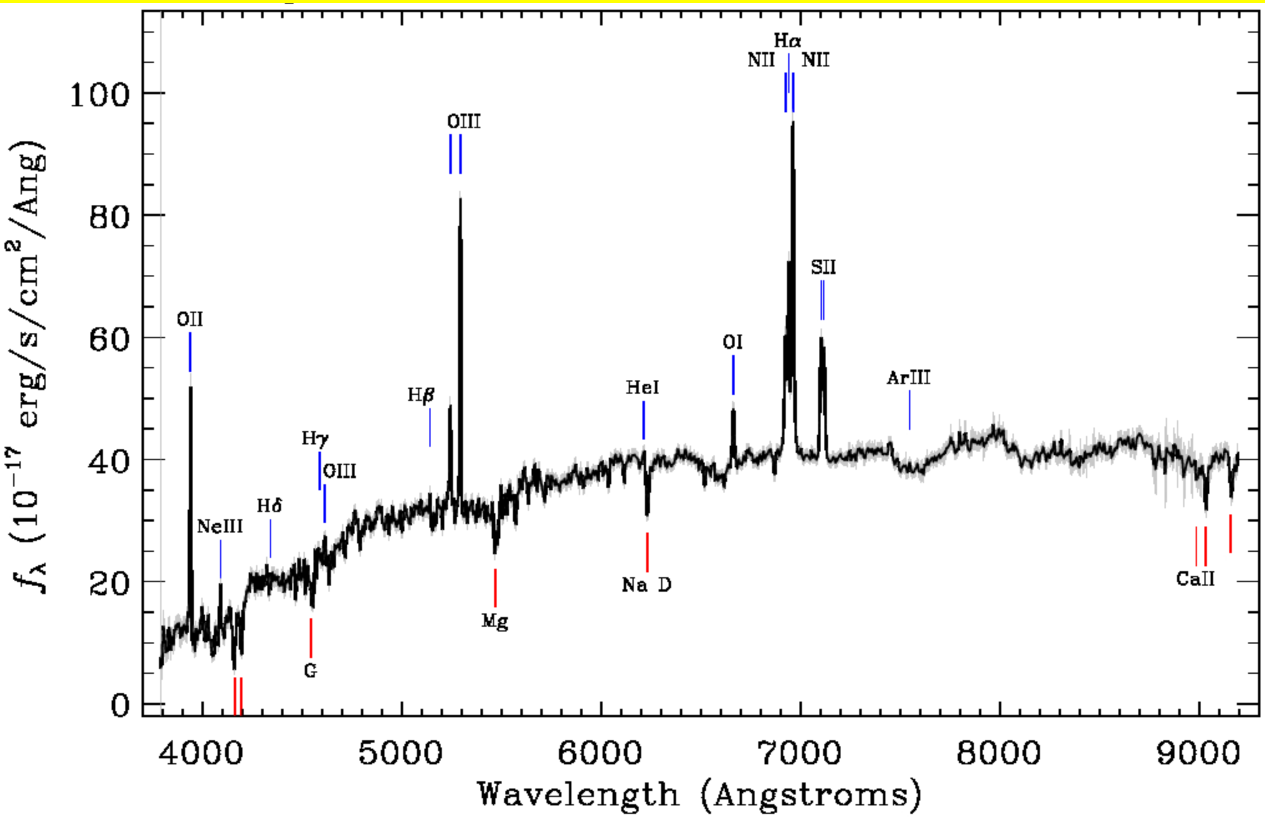
ALMA has revolutionised spectral line observations in Radio Astronomy

Due to sensitivity limitation, lines are observed in emission from nearby objects; but can be observed at all distances in absorption.

New phenomena in Galaxies noticed…

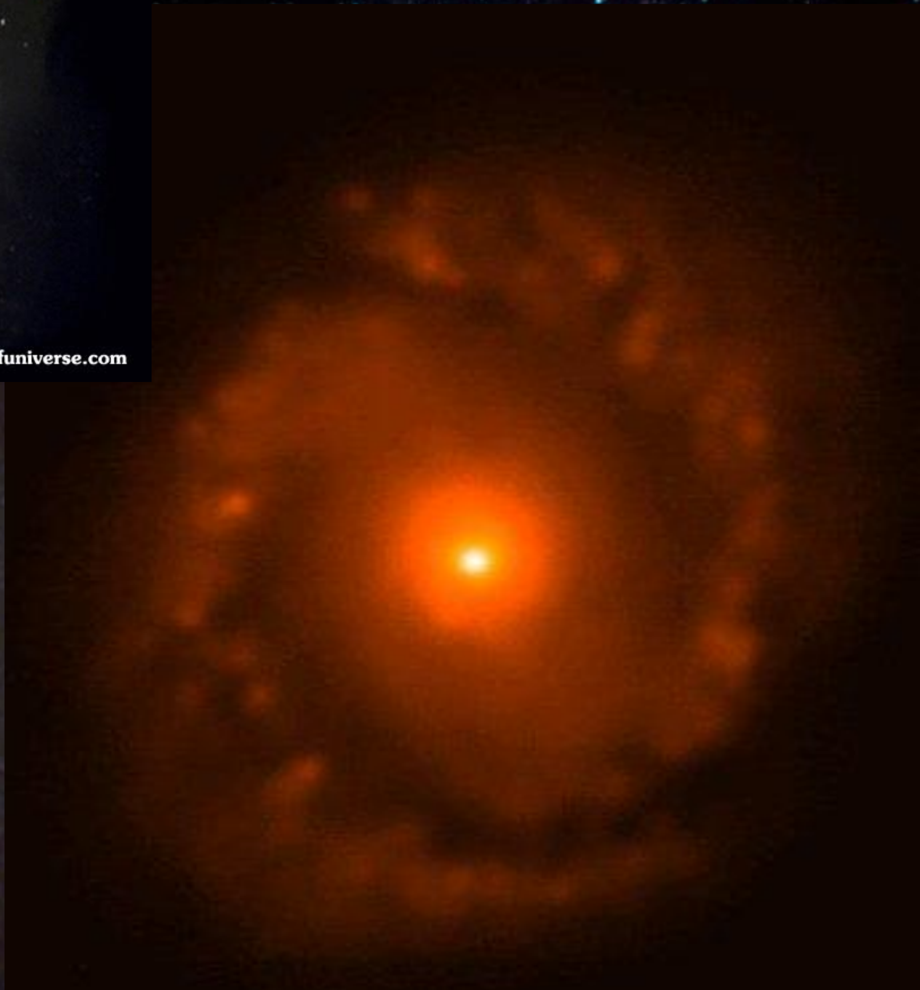
Early Days: In 1908, the spectra of nearby spiral galaxy, NGC1068 showed strong emission lines with large widths – Very different than collective starlight.

New phenomena in Galaxies noticed…



Carl Seyfert, in 1943 noticed that many spiral galaxies has very bright and compact nucleus, appearing like bright star at the center!!


www.creationofuniverse.com

New phenomena in Galaxies noticed…

The spectra dominated by high excitation nuclear emission lines. Many of them broad, with widths close to 10,000 km/s, seen near the centre. Among many lines, hydrogen lines were more broad as compared to other lines.

Why only some spiral galaxies have this peculiar property at the centre?

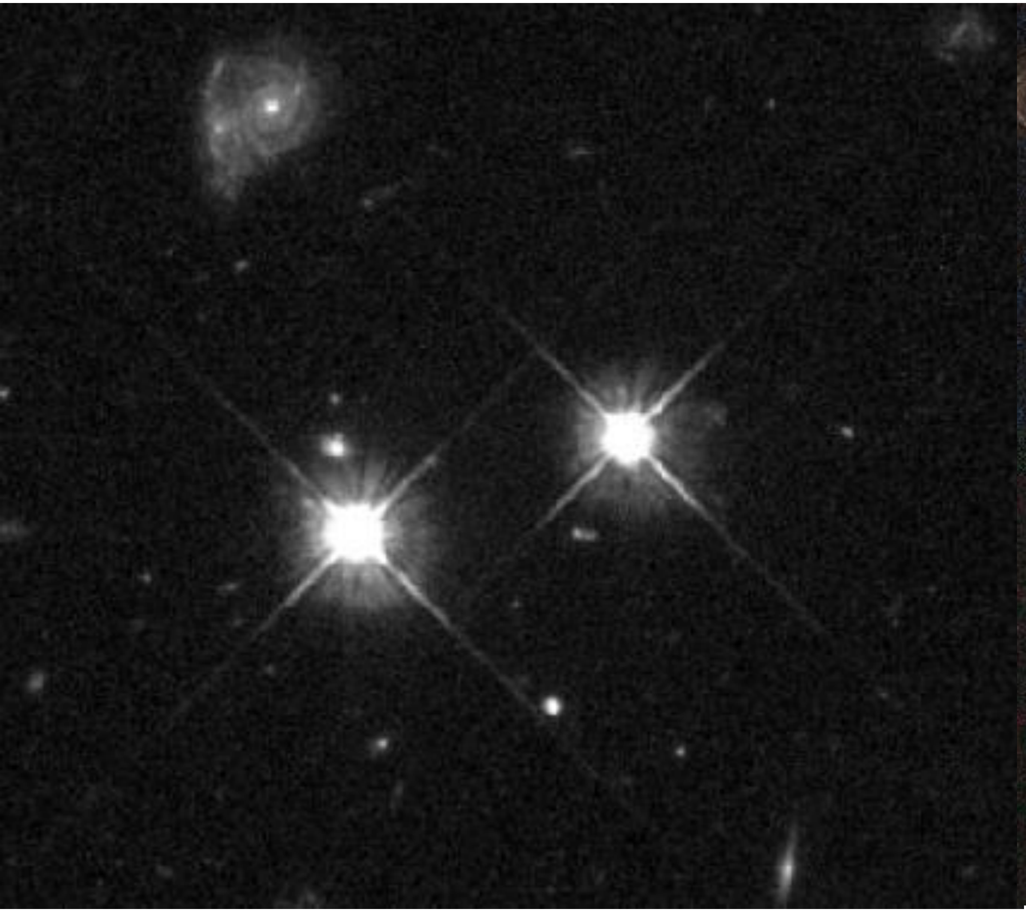
What is the source of this extraordinary energetic phenomena?

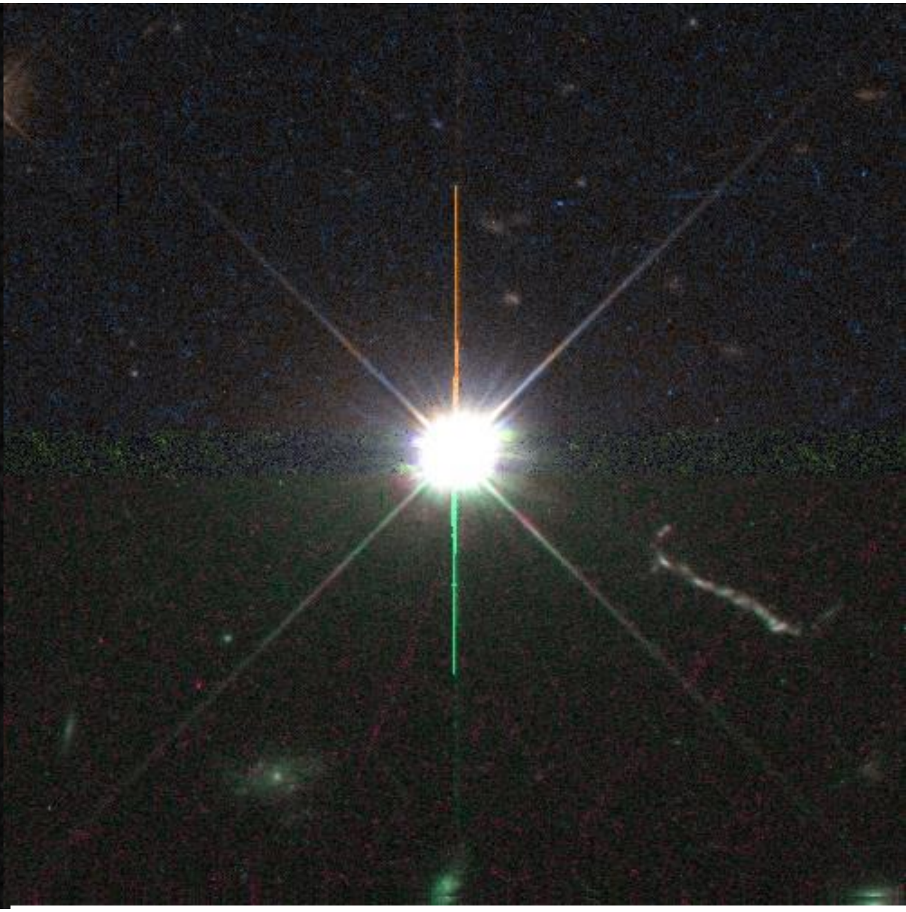
Mysterious “Radio Stars”

In late 50’s; about 200 radio sources were known (3C survey). Some were identified with galaxies, some with bright “stars” and some remained unidentified.

They are named as “Quasi Stellar Radio Sources”; or **QUASARS**; originally discovered in RADIO, but the name QUASARS are used even for those which do not emit radio.

One of them had strange spectra, not matching with any known elements till then.

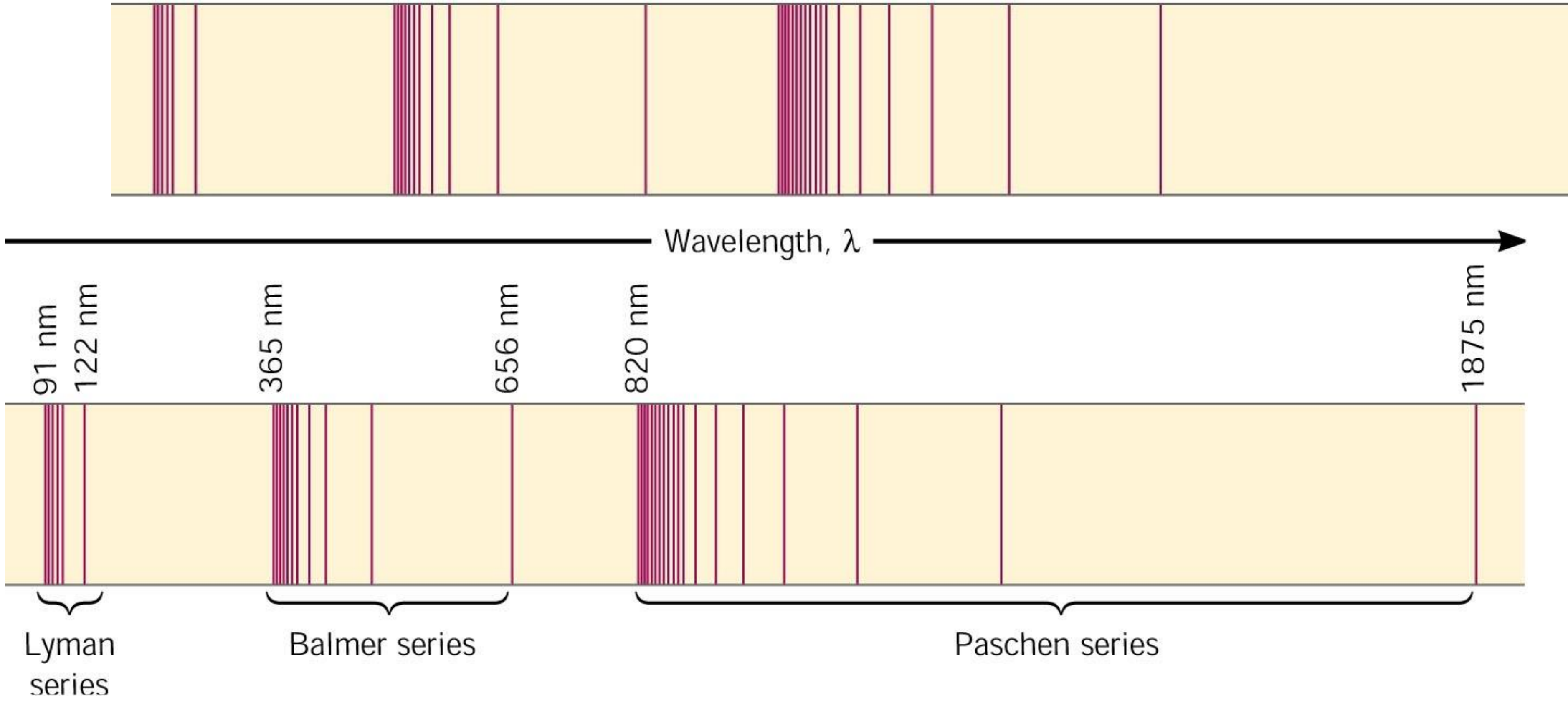




Mystery Solved!

Martin Schmidt just “redshifted” the spectra by z=0.158 and the lines were Hydrogen lines and other known lines..

Mystery Solved!



$$z = (\lambda_{obs} - \lambda_{rest}) / \lambda_{rest}; \quad \textbf{\textit{OR}} \quad \lambda_{obs} = (1 + z)\,\lambda_{rest}$$

Mystery Solved!

Martin Schmidt just “redshifted” the spectra by z=0.158 and the lines were Hydrogen lines and other known lines..

“Stars” are much farther compared to normal Galaxies!

Scientists were quick to realise that these objects can be used as tool to study distant universe, because they are very powerful.

Hoyle and Fowler (1963) and Zel’dovich and Novikov (1964) proposed that black holes must be involved in such extra-ordinary phenomena;

Blackhole physics, implications to galaxy formation, and probing large distance made Quasars mode demanding.

Properties of Active Galaxies

- Compact, star-like bright nucleus, size < 100 pc
- Broad emission lines: If material is gravitationally bound, the mass of the nucleus is very high applying virial theorem (M ~ v2.r/G; v ~ 10,000 km/s; r < 100 pc).
- Simple arguments on balance (outward radiation pressure vs self-gravity) indicates that the central mass has to be more than 10^8 to 10^9 for quasars.

In any case, something extra-ordinary is happening.

What are Active Galaxies?

The "**active**" central part of the (***otherwise normal***) galaxy, is known as "Active Galactic Nuclei", or AGN

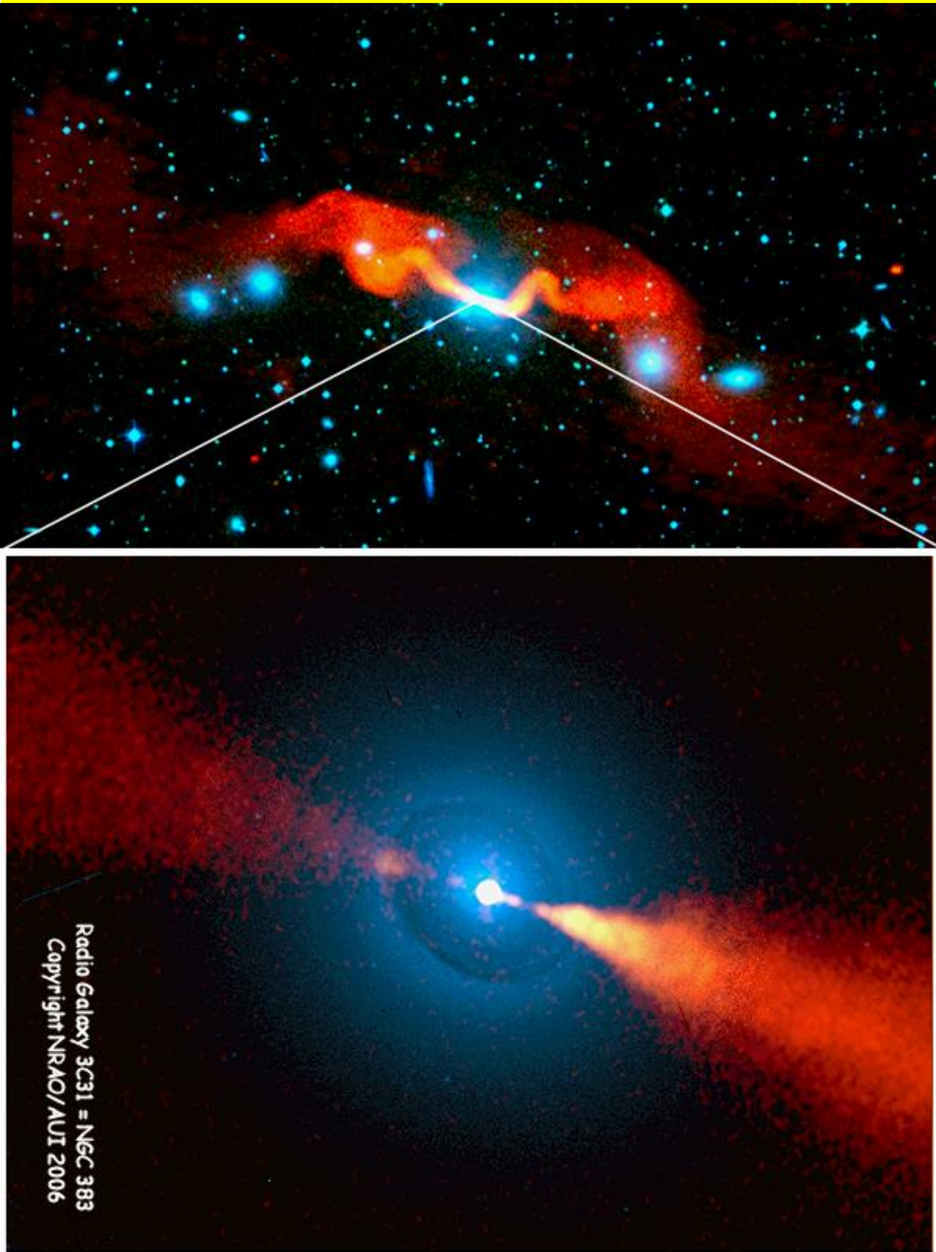
Seyferts - lower luminosity among AGNs, further narrow and broad based on line width

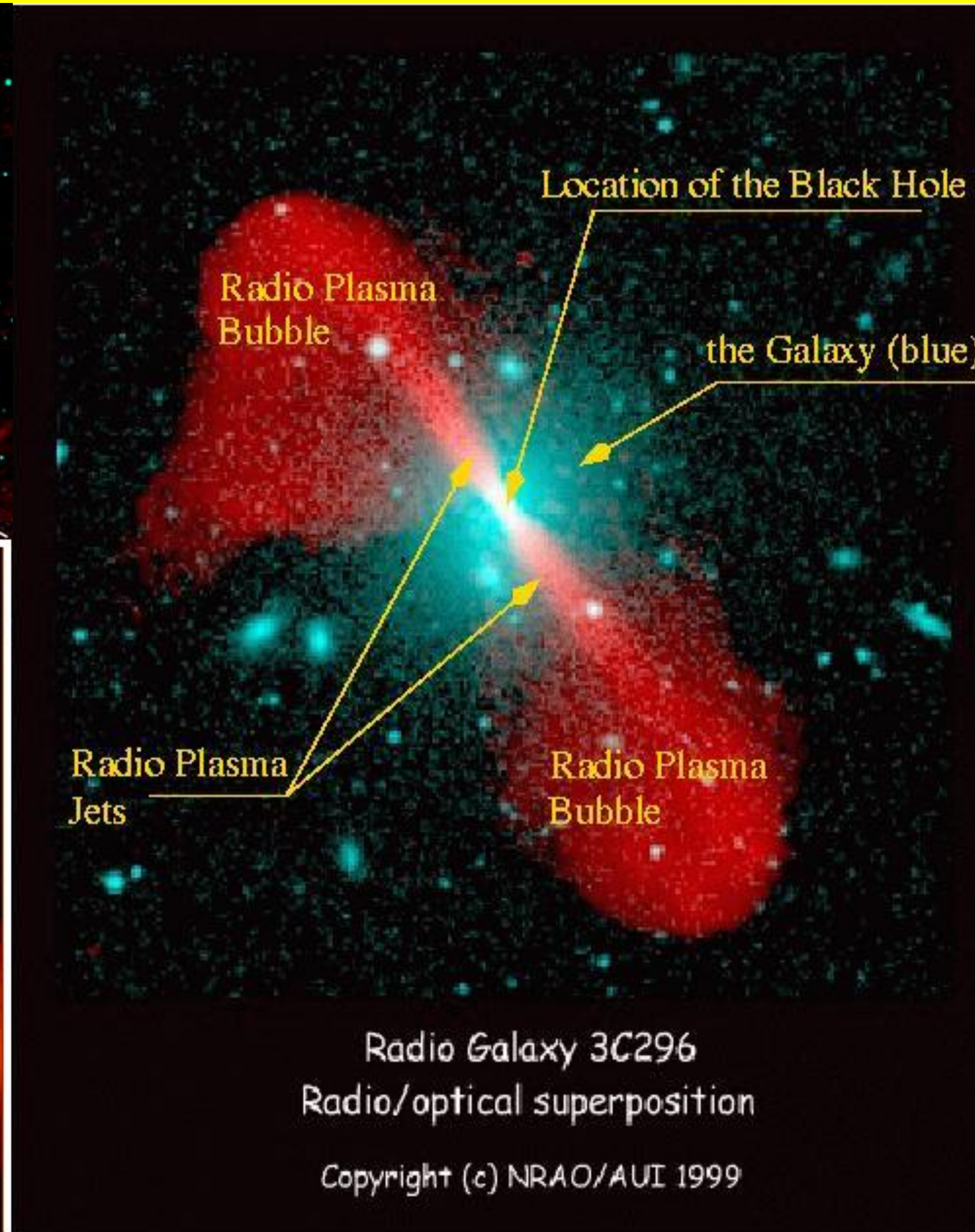
Quasars - The most luminous among the AGNs, radio loud and quiet

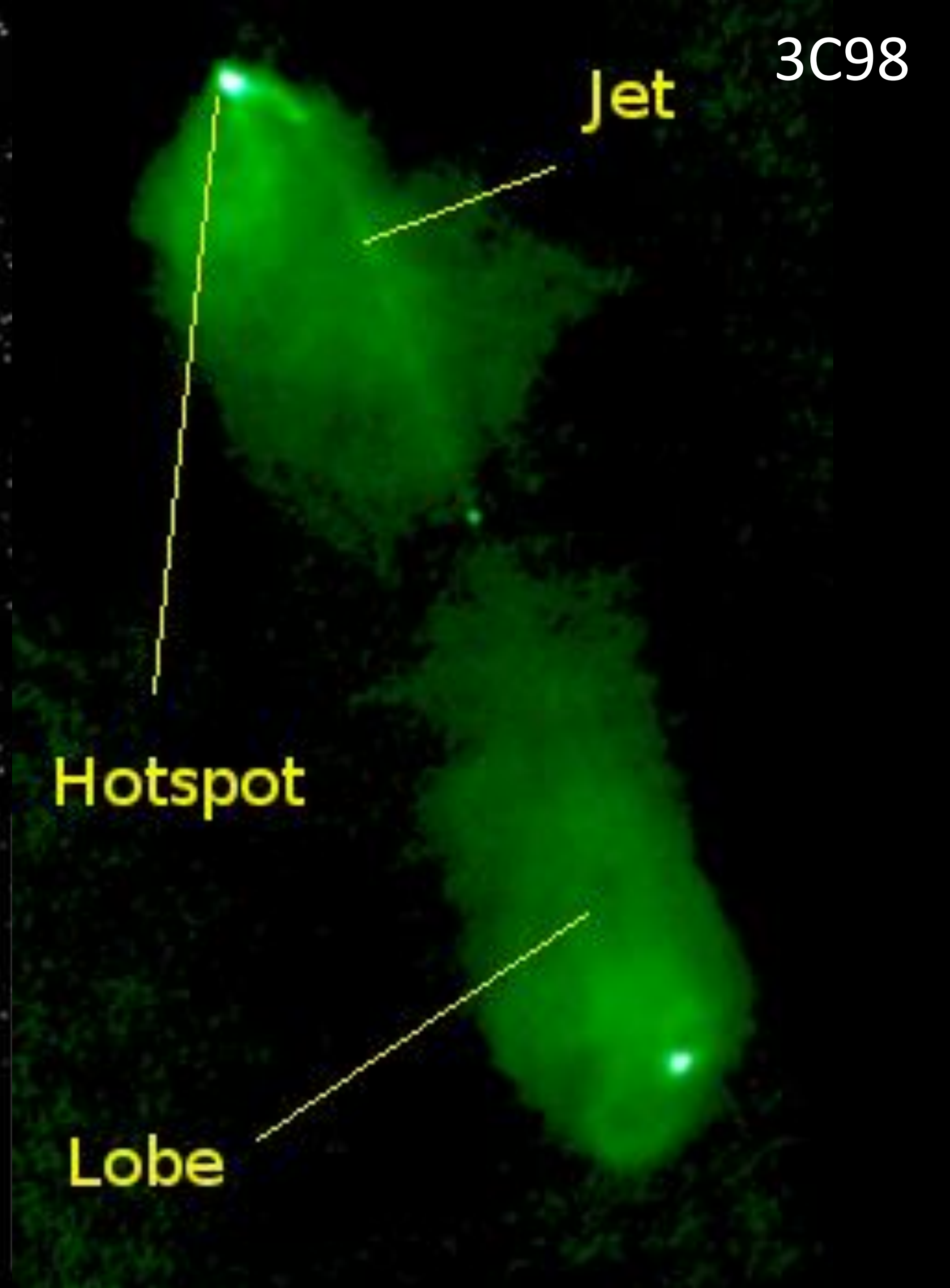
Radio Galaxies - Otherwise an ordinary giant elliptical, but "quasar like" center, radio loud

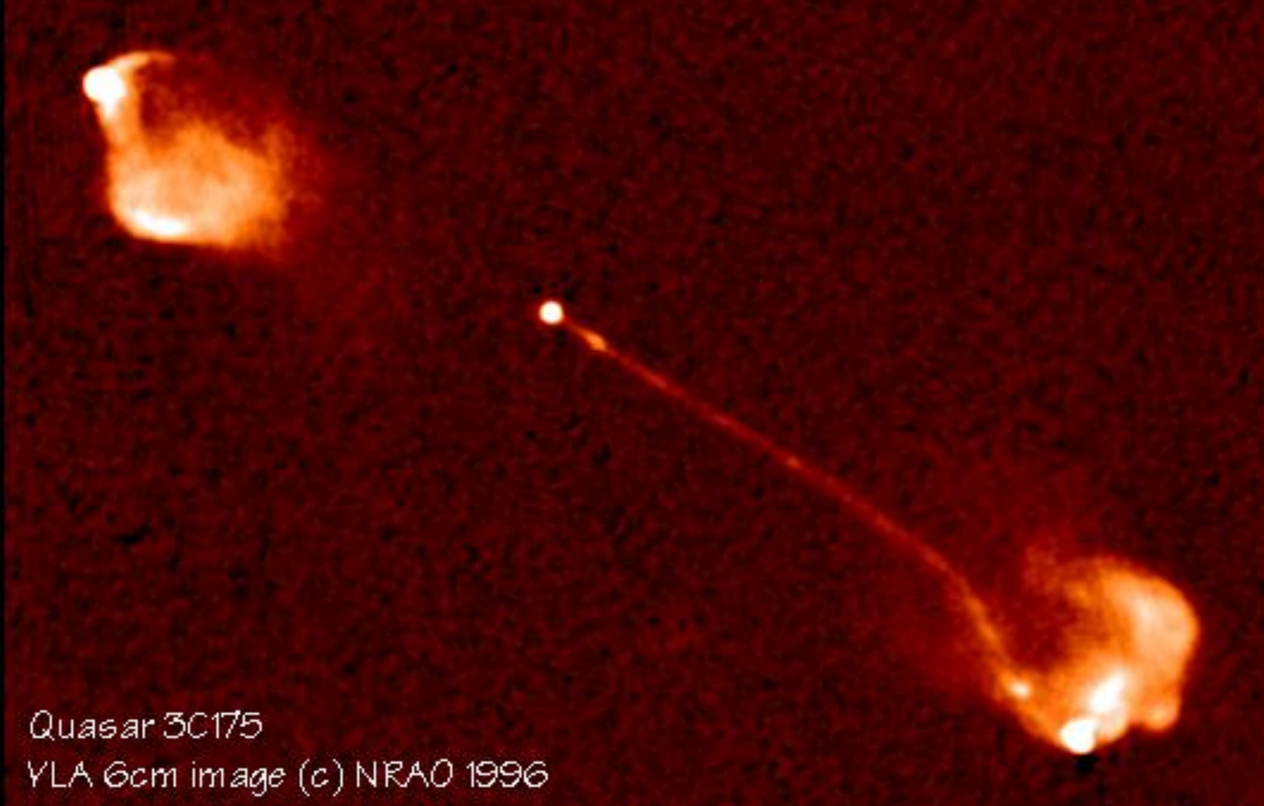
BL-Lacs , OVVs - Absence of strong emission lines, violently variable.

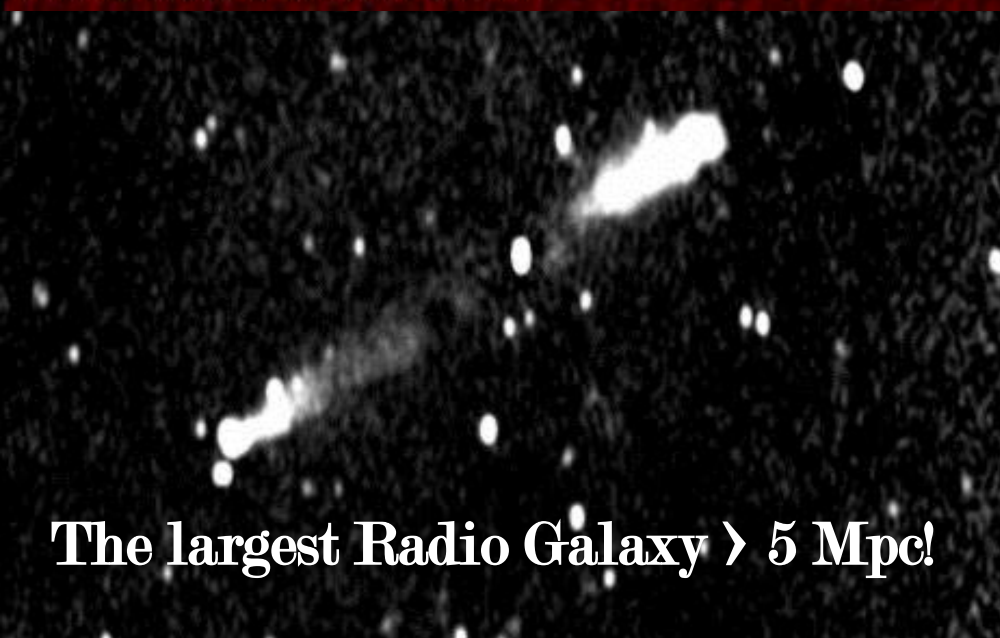
Radio Sources with Active Galaxies

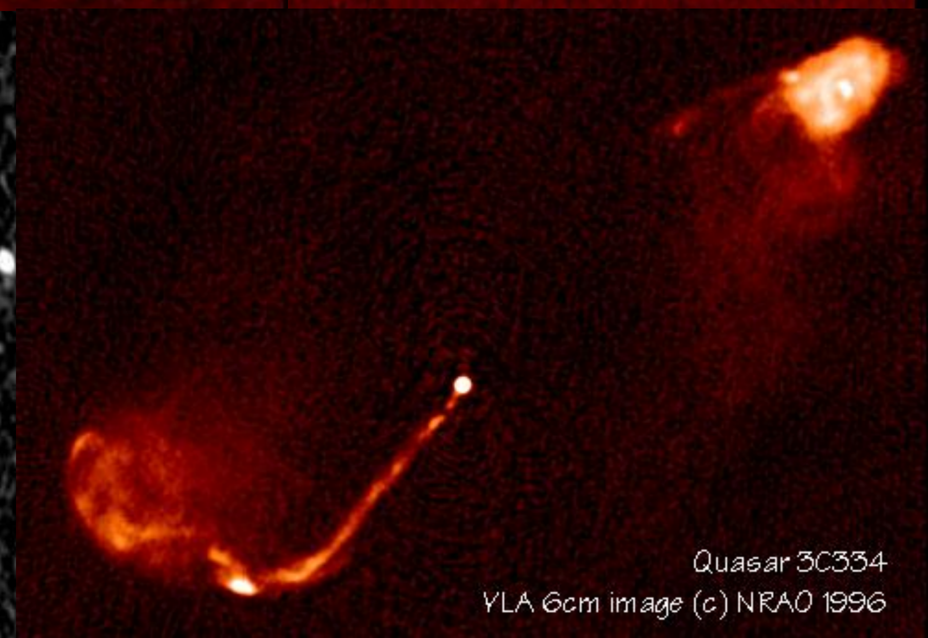


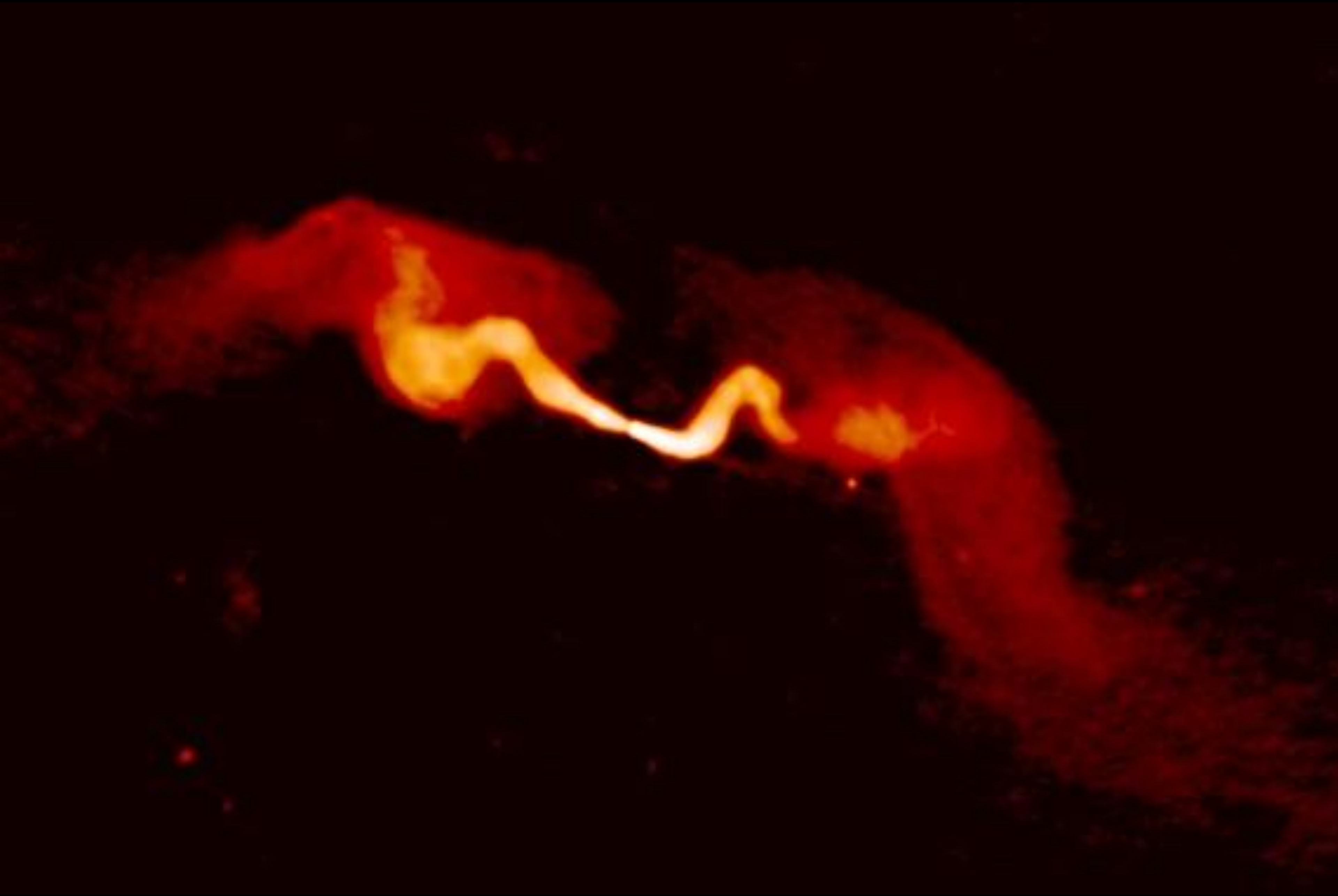


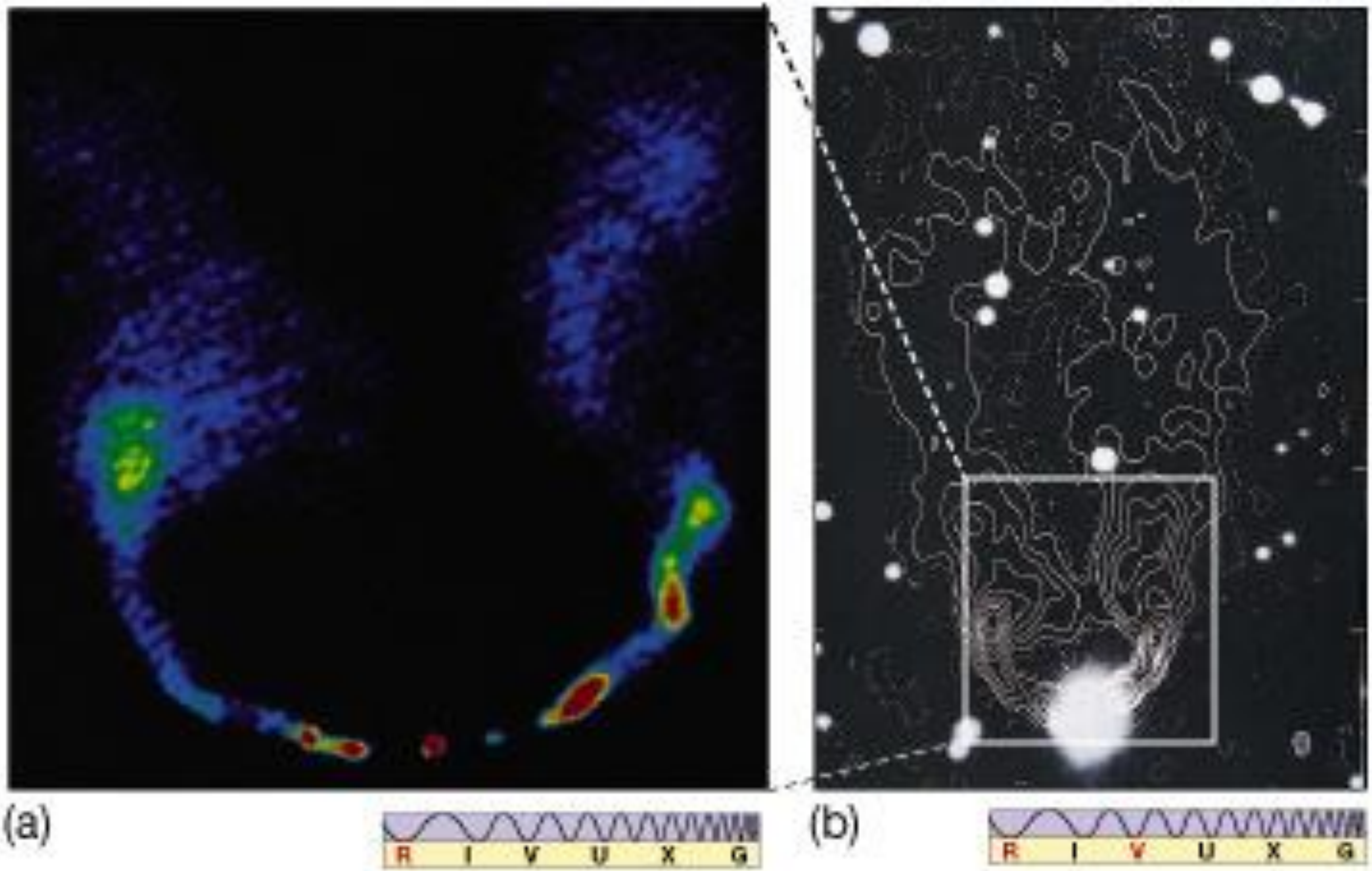

Centaurus - A

3C98
Jet
Hotspot
Lobe

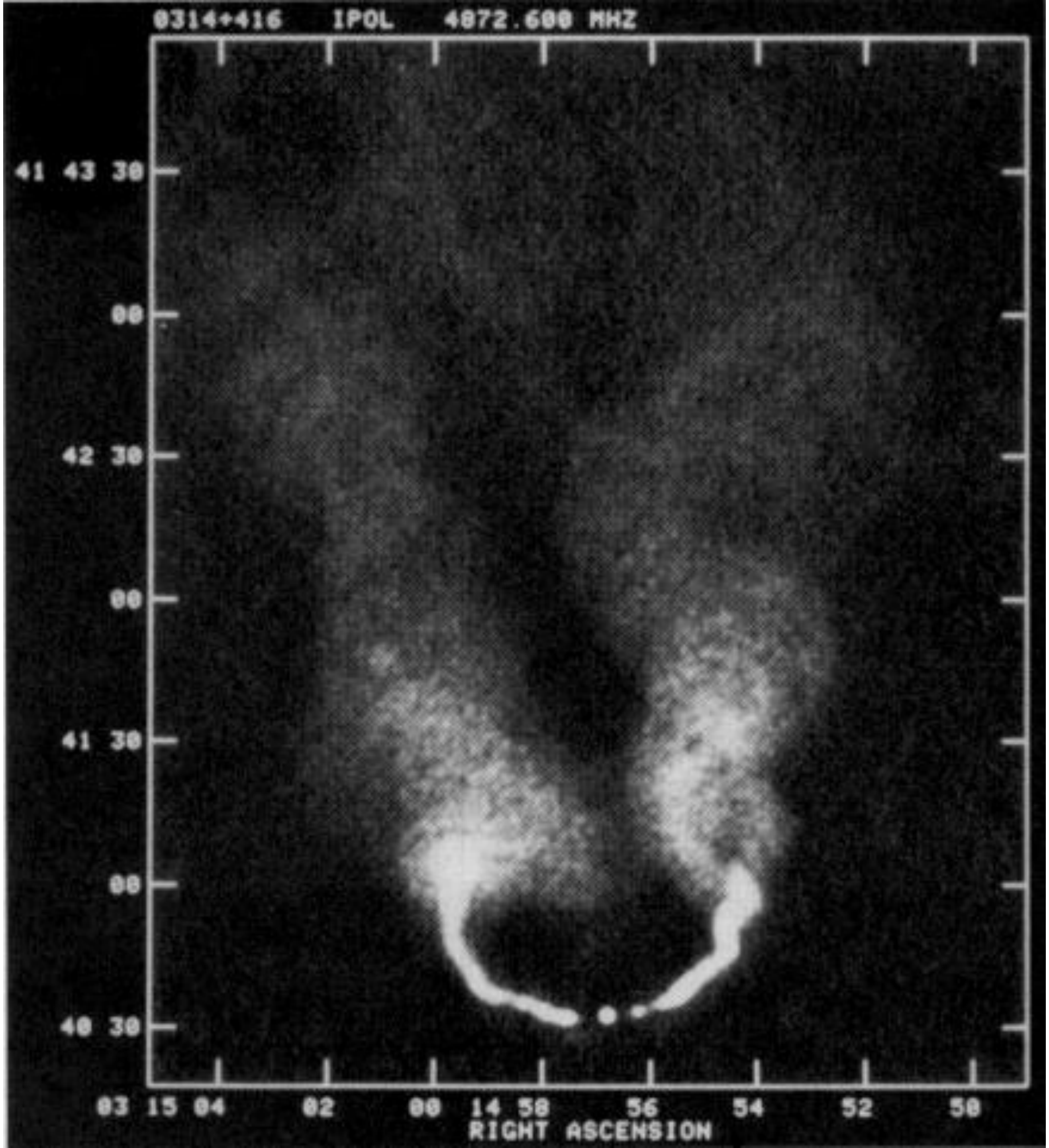

Quasar 3C175
VLA 6cm image (c) NRAO 1996


The largest Radio Galaxy › 5 Mpc!

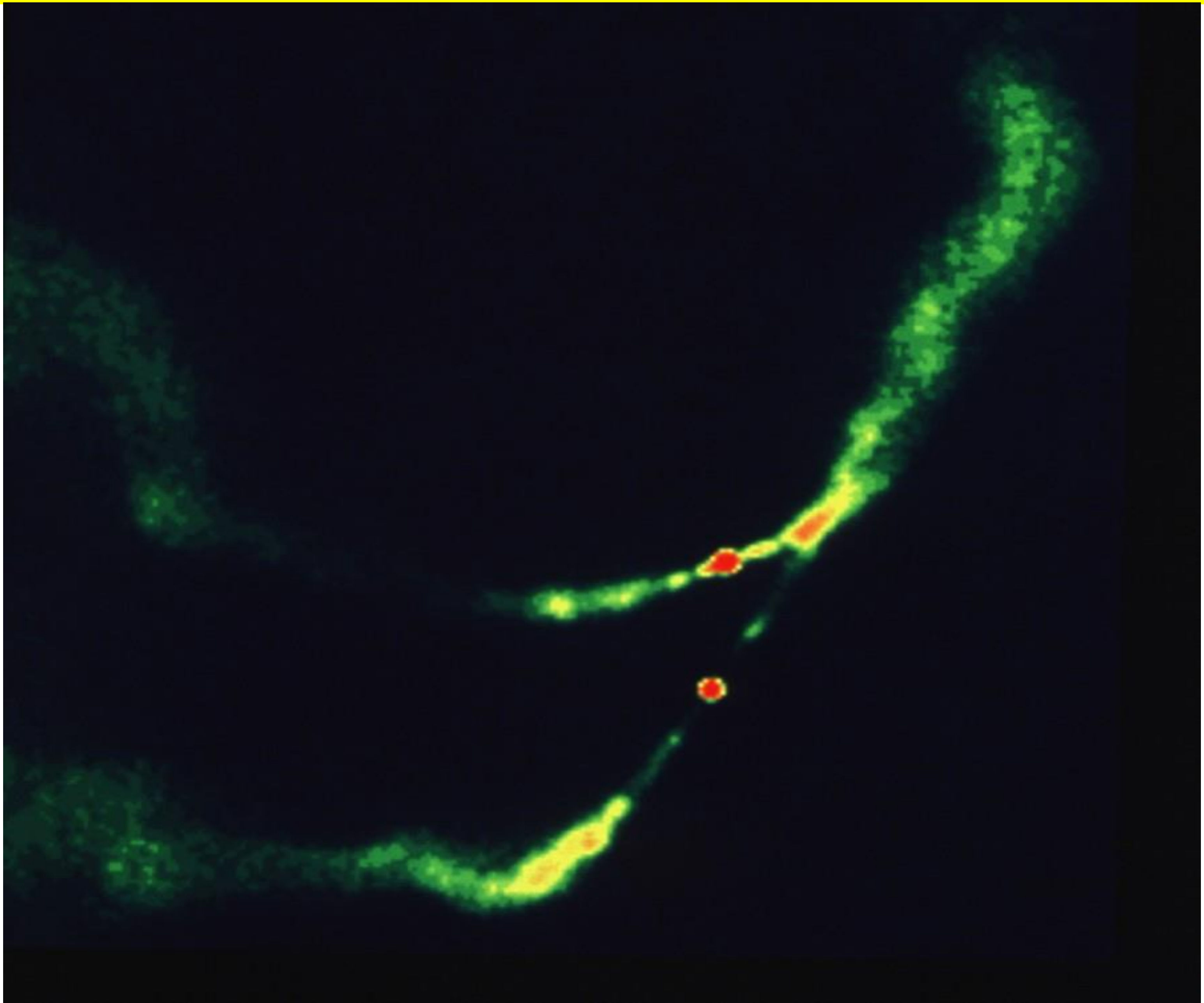

Quasar 3C334
VLA 6cm image (c) NRAO 1996



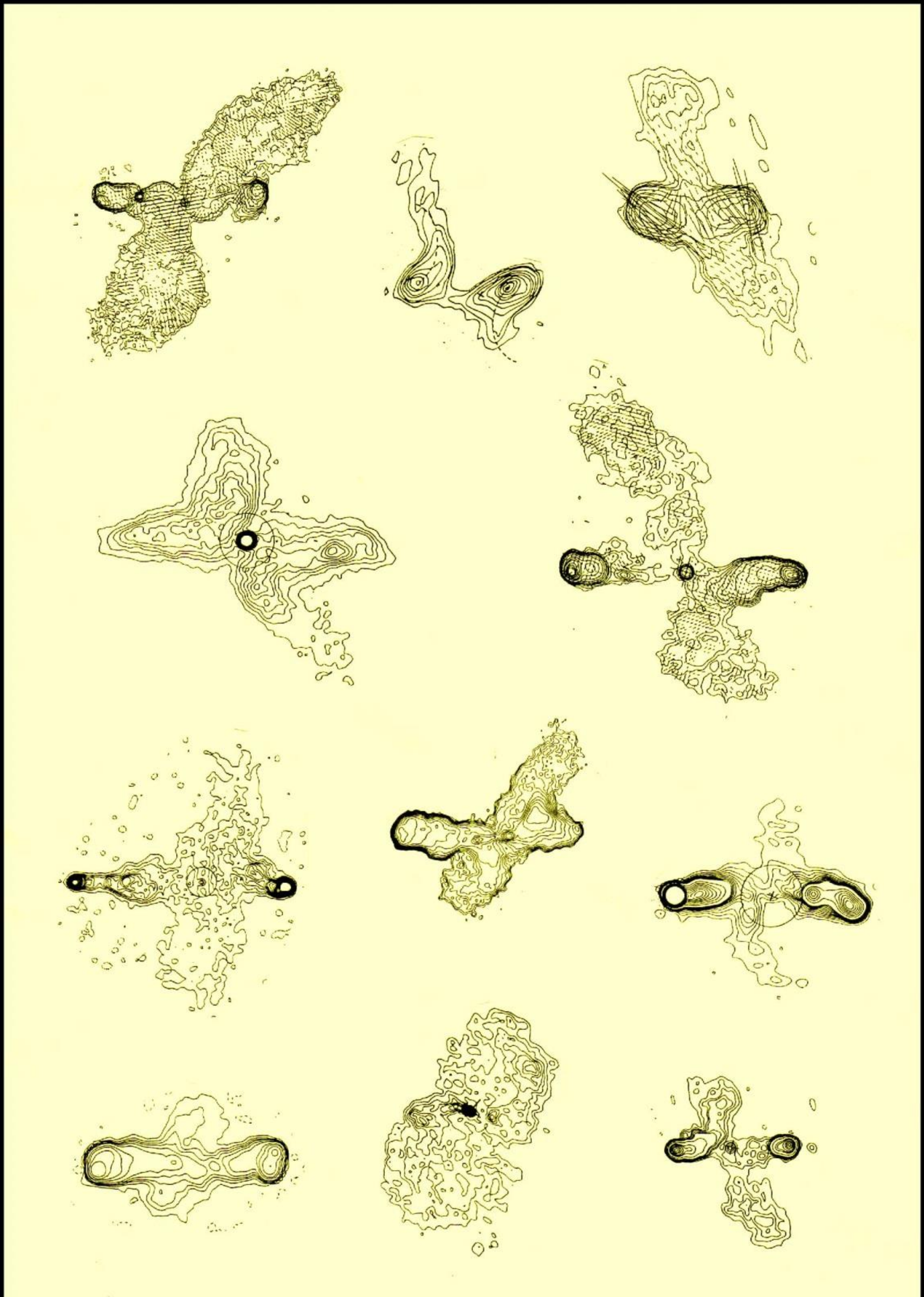

(a)
R I V U X G
(b)
R I V U X G

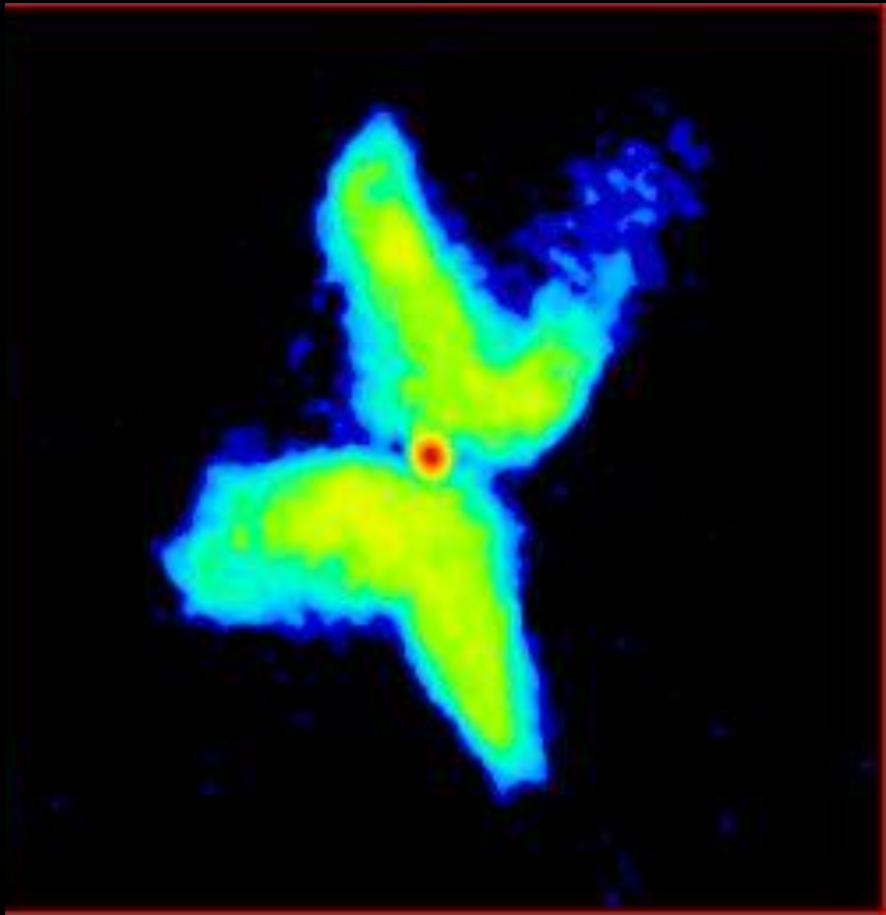

0314+416 IPOL 4872.600 MHZ
41 43 30
00
42 30
00
41 30
00
40 30
03 15 04
02
00
14 58
56
54
52
50
RIGHT ASCENSION

Interesting case of twin blackhole system (3C75/Abell 400)



X-Shaped radio galaxies





What are Radio Galaxies/Quasars?

They are the largest single object in the universe, with a powerful central engine spewing jets in both directions (which may not be visible always) producing strong radio emission at the end of jet

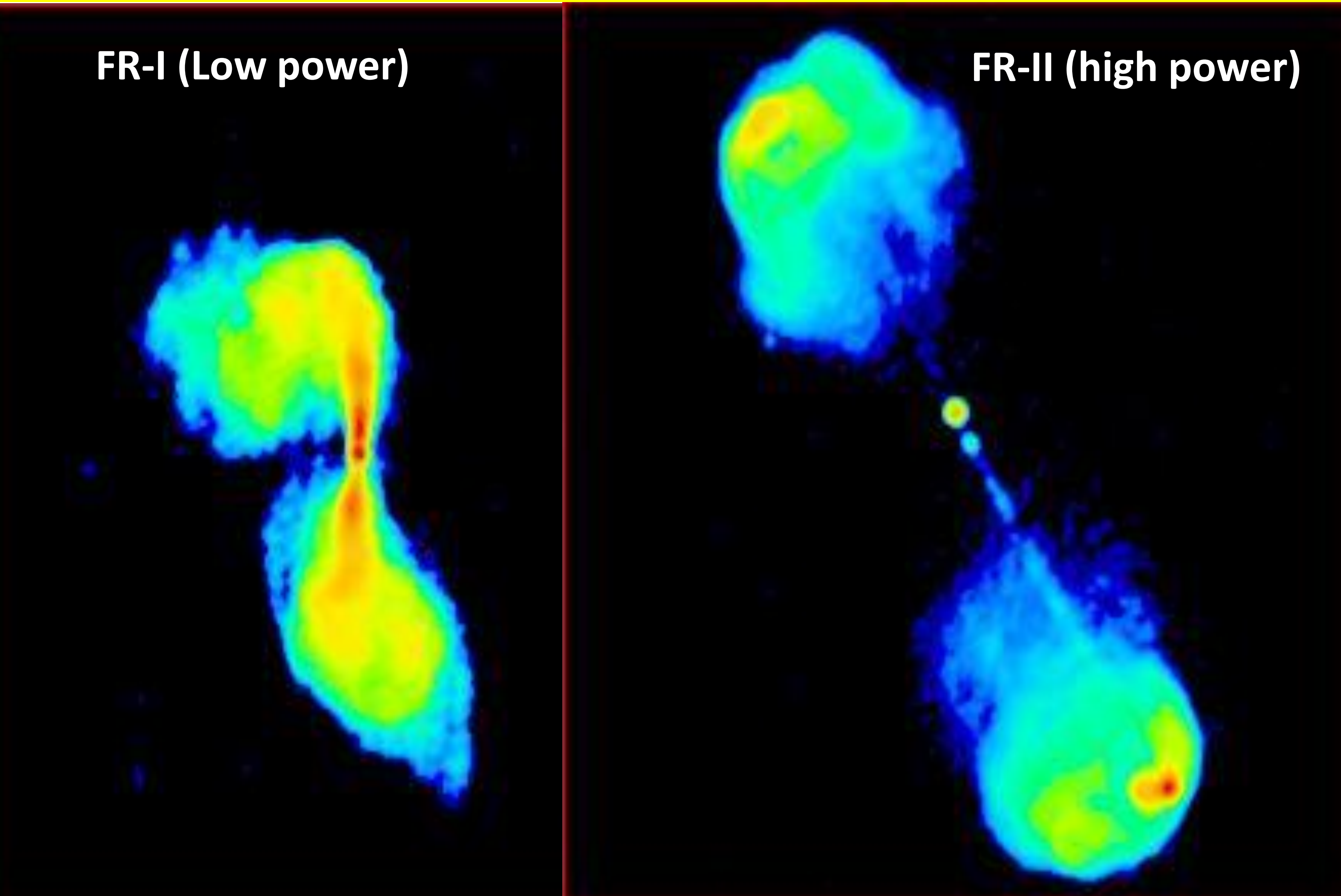
Remember water jet used for washing the car

The hosts of the central engine – or the Active Galactic Nuclei – is usually elliptical (giant elliptical if the radio galaxy is most powerful)

The radio luminosities more than 10 times the optical, upto 10^{29} W/Hz at 1.4 GHz

AGN is a must, but not all AGNs are radio loud.

Two broad class – FRI & FRII



Models of AGN

1. Compact Star Clusters (NO BH):

Supernovae outshines the galaxy for a short duration.

PROBLEMS:

The poison statistics would imply, less luminous AGN to have less SN and large variability. The ‘connected SN activity’ is needed to maintain steady luminosity.

Can’t explain how radio components move in a fixed direction (jets and hotspots)

The lifetime of such massive cluster is < 10^7 years, through random encounters, small stars will escape and massive stars will fall into center and evolve to a BH.

Models of AGN

2. Supermassive stars:

In principle, a star can have mass up to 10^8 $M_{\odot}$, without violating Eddington limit.

PROBLEMS:

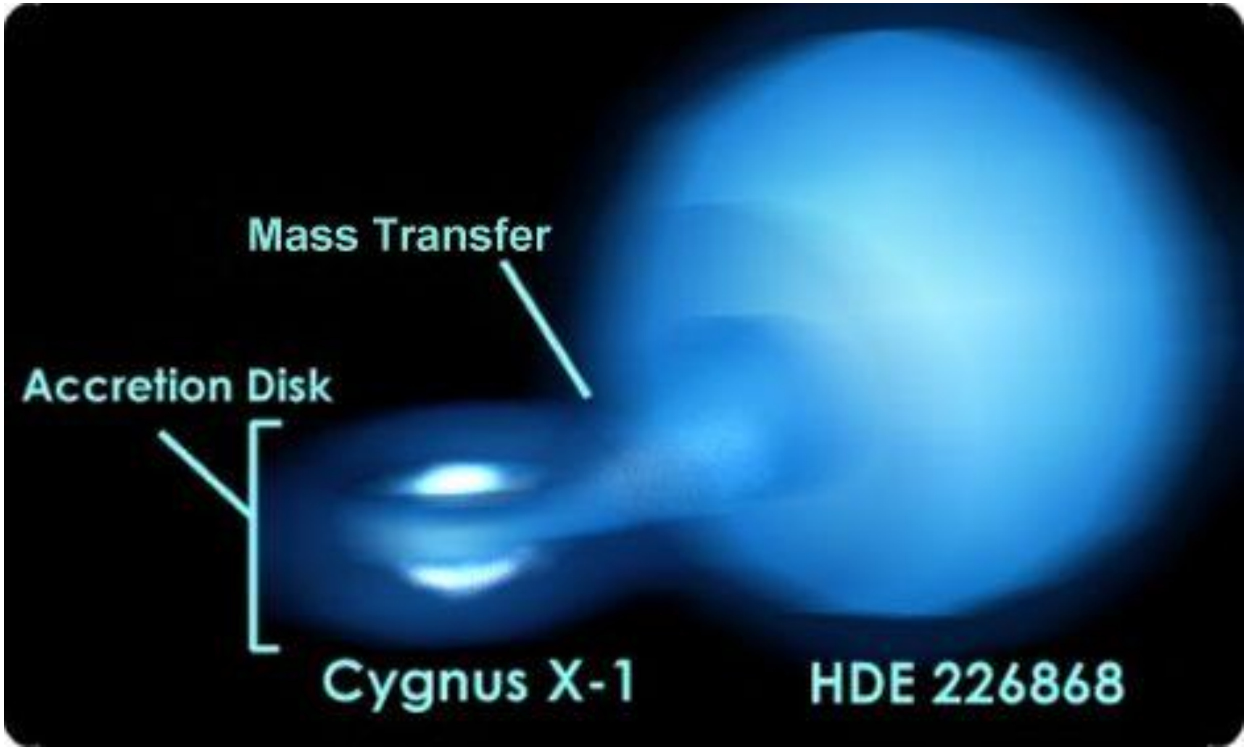
(a) Can not be supported by gas pressure for long and becomes unstable in $< 10^7$ yrs.

(b) How to produce collimated radio jets travelling at relativistic speeds to millions of pc.

(c) GTR predicts such systems will eventually form BH

The case for Blackhole

In 70s, the black-hole accretion disk theory successfully explained galactic X-Ray sources.



For AGNs, the phenomena has to be scaled up by several orders of magnitude.

Basic properties of BH

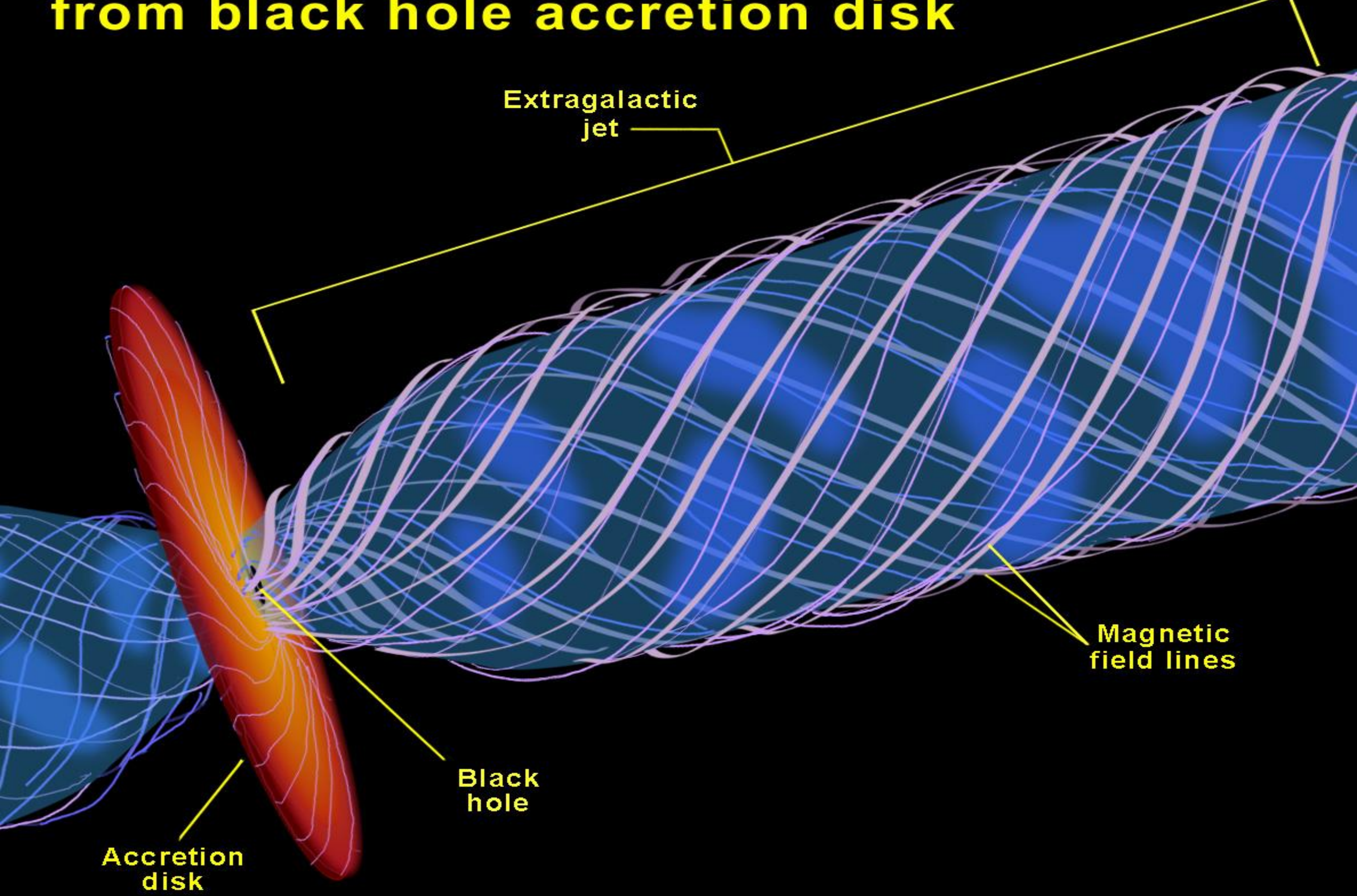
The schwarzschild radius is Rs = $2GM/c^2$; for Sun, Rs ~ 3 km.

The spin and the mass of BH can convert gravitational energy into KE of particle.

The region between Rs and 'static radius' where everything has to rotate with BH is called 'ergosphere'. The particle can escape from this region with huge energy (Penrose process) – this is one way to extract the energy.

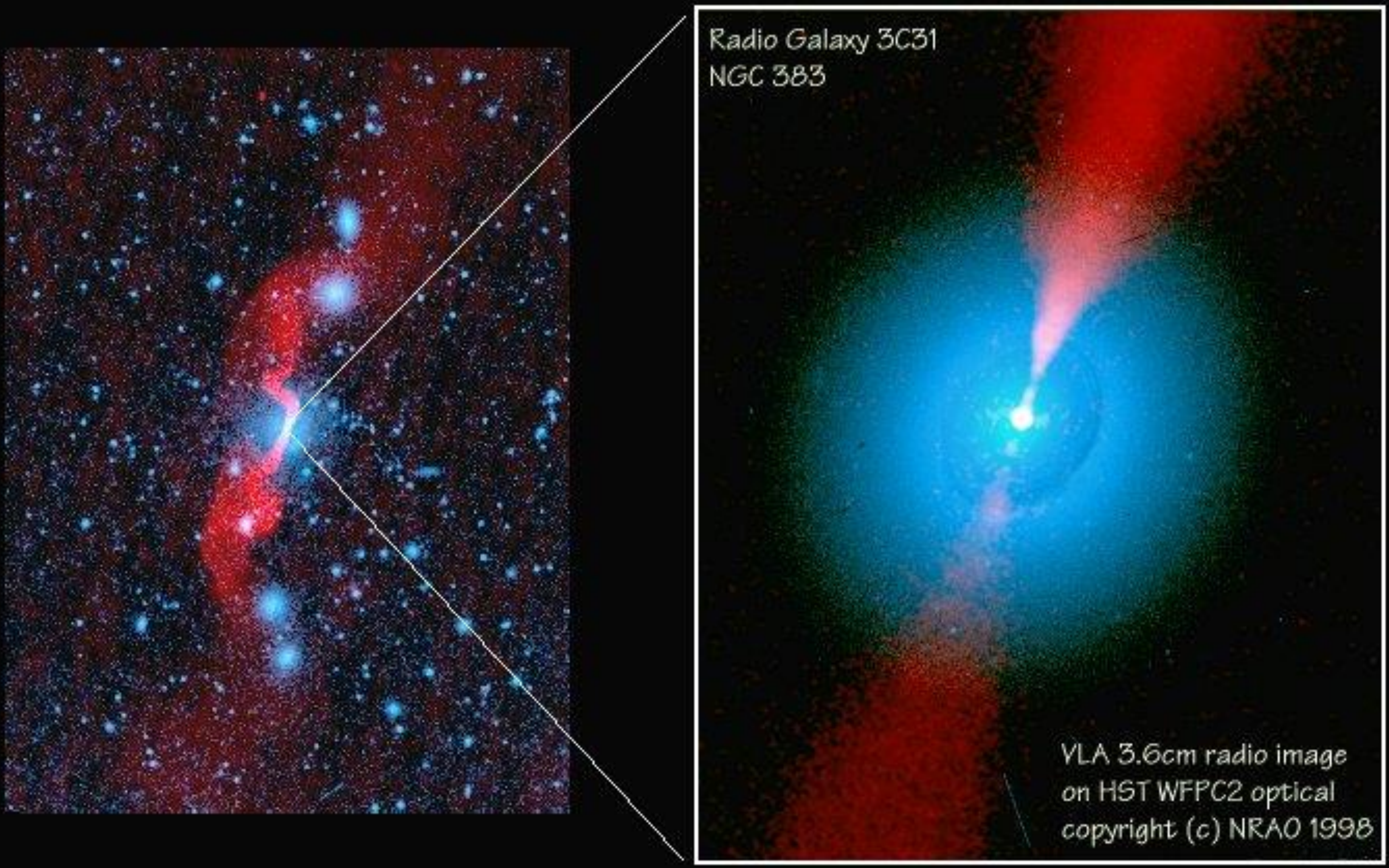
The best evidence for BH comes from galactic X-Ray binaries.

Formation of extragalactic jets from black hole accretion disk




HARDY

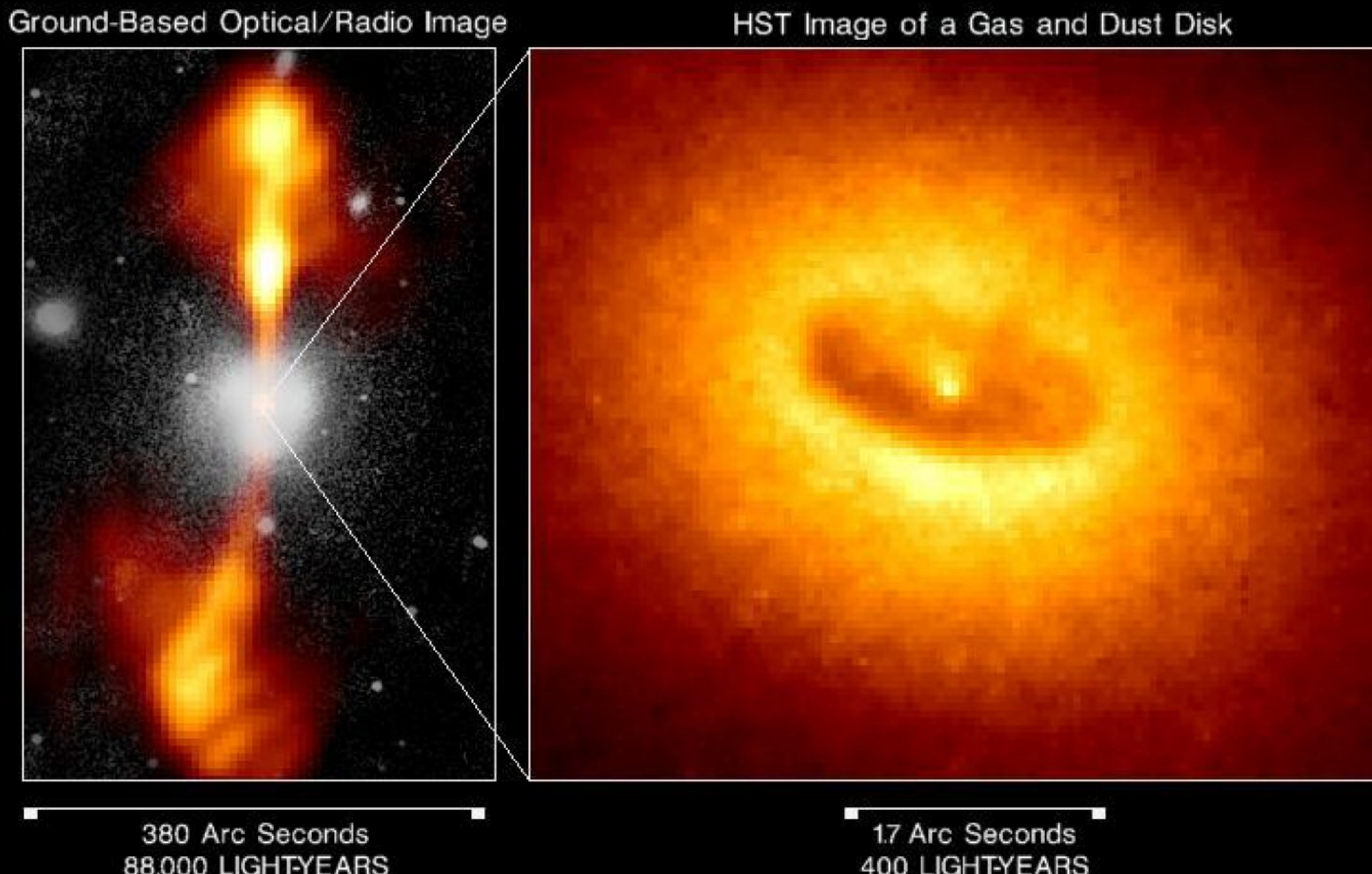
An Example: 3C31

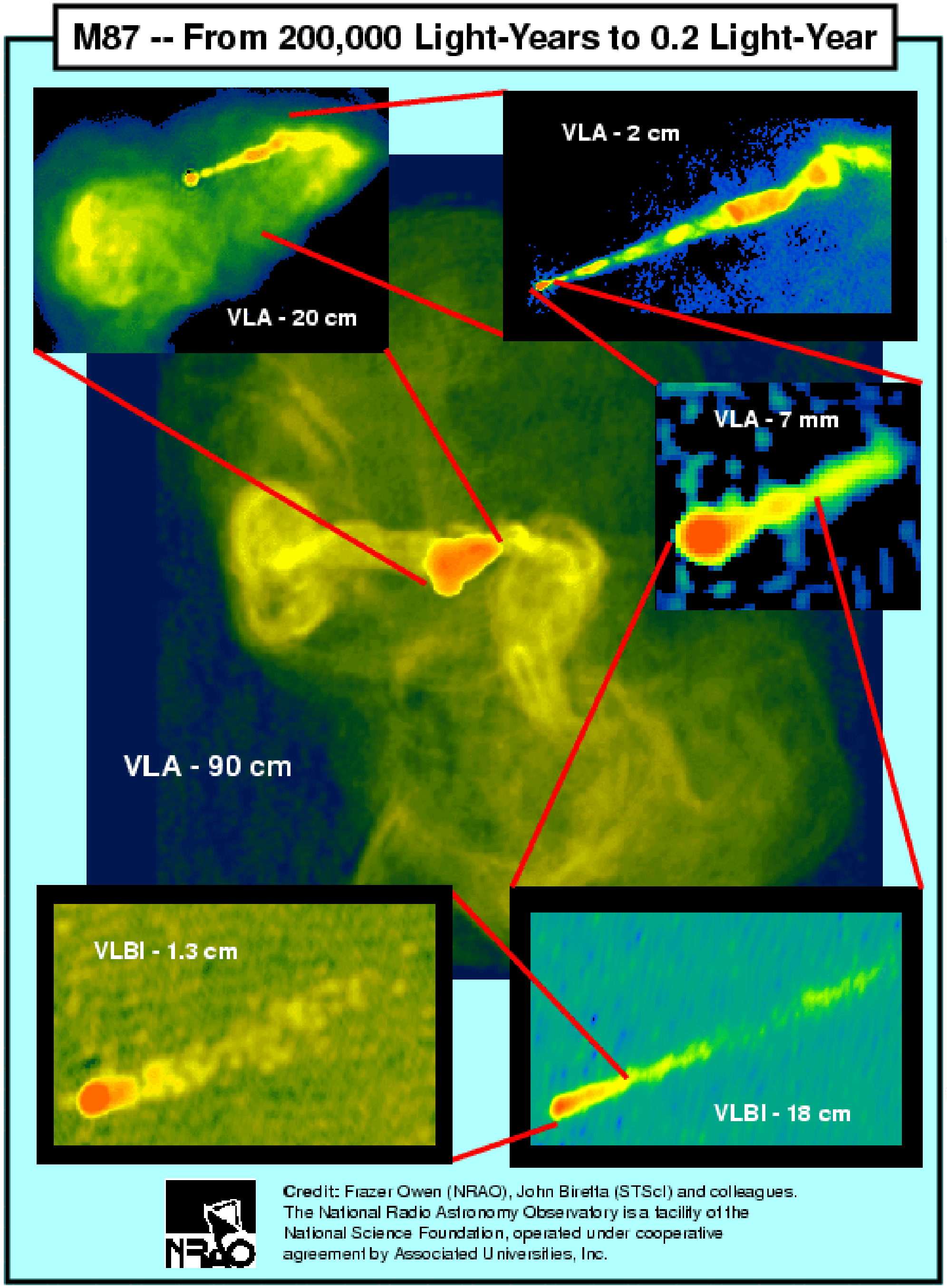


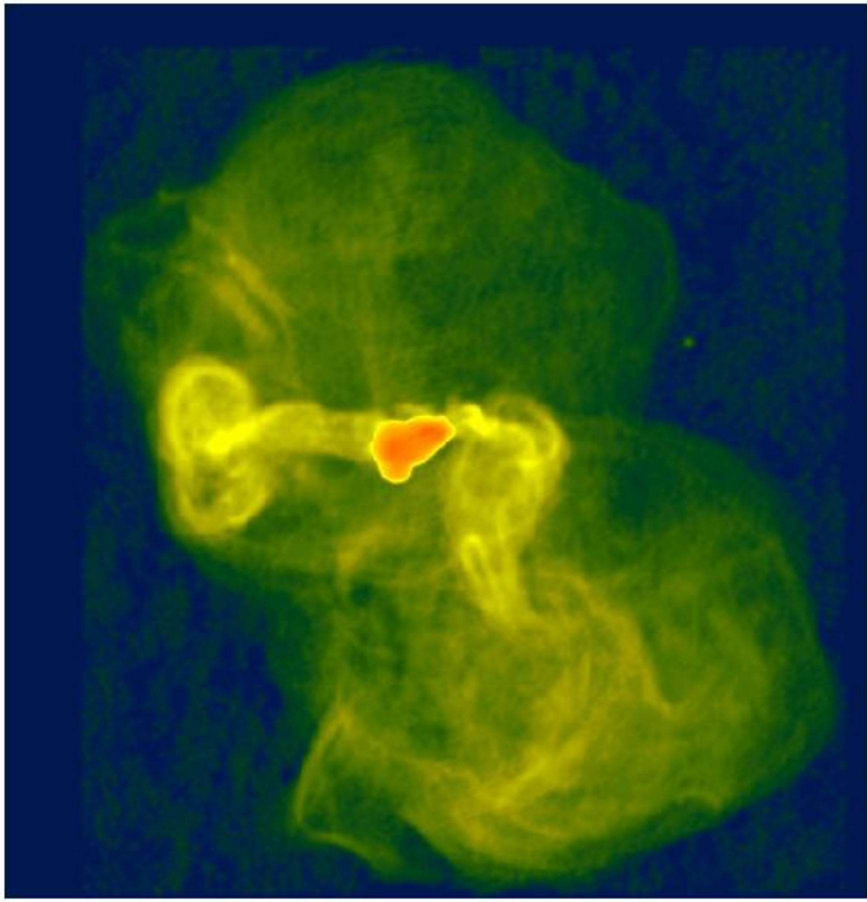
Core of Galaxy NGC 4261

Hubble Space Telescope

Wide Field / Planetary Camera




M87 -- From 200,000 Light-Years to 0.2 Light-Year
VLA - 20 cm
VLA - 2 cm
VLA - 7 mm
VLA - 90 cm
VLBI - 1.3 cm
VLBI - 18 cm
NRAO
Credit: Frazer Owen (NRAO), John Biretta (STScI) and colleagues.
The National Radio Astronomy Observatory is a facility of the
National Science Foundation, operated under cooperative
agreement by Associated Universities, Inc.



Radiation from AGNs

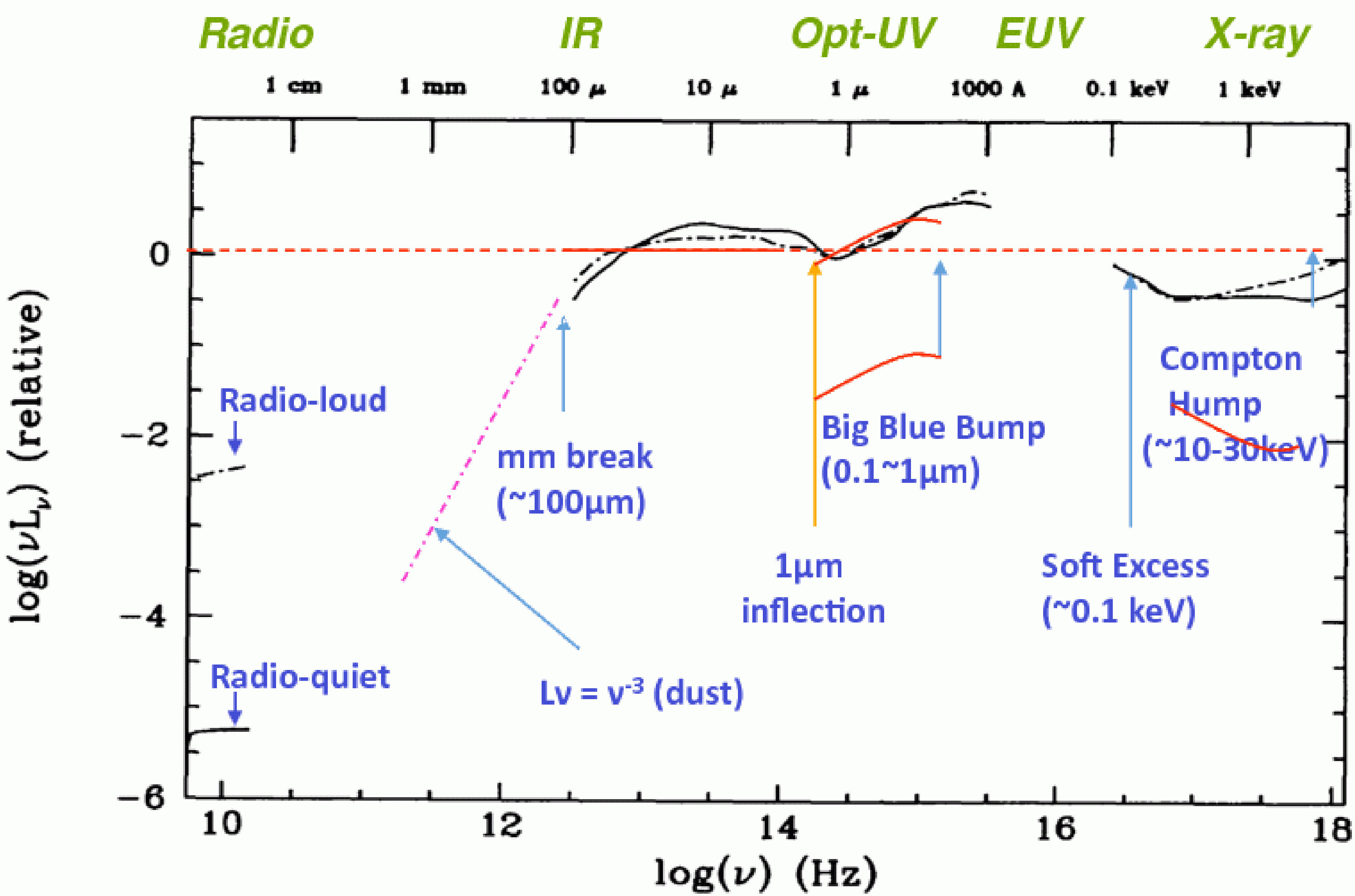
Most luminous "central engine", also drive secondary radiation (like I/C; re-radiated IR).

The spectral energy distribution of AGN is by power-law.

$\underline{F_\nu = C\nu^{-\alpha}}$ *OR* $\underline{\nu F_\nu \approx \textbf{Constant}}$ for $\alpha \approx 1$

Where F_ν is the observed flux per unit frequency interval, C, the proportionality constant, α is the power-law index (or the spectral index).

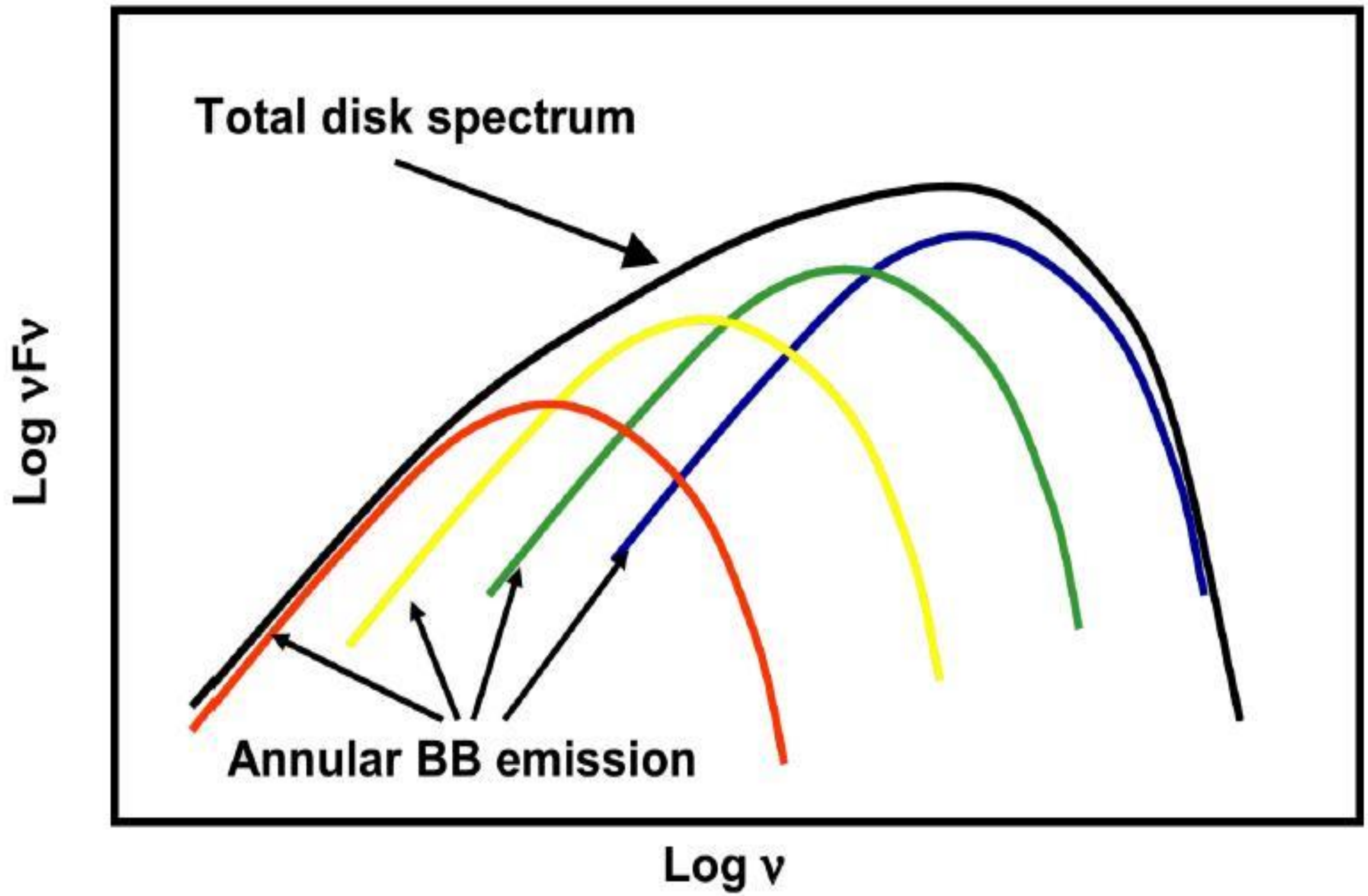
AGN exhibits strong emission from TeV to Radio band, <u>a factor of 10^{20}!</u>



Elvis et al., 1994, ApJS, 95, 1

UV-Optical Continuum

The superposition of these BB spectra will thus look like:



IR Continuum

The IR continuum is produced by dust (thermal) and/or synchrotron radiation (non-thermal).

IR emission from dust grains heated by optical and UV light from the nucleus is least disputed.

For Ultra-Luminous IR Galaxies, this can go considerably up. Dust mass can be upto 10^{10} $M_{\odot}$

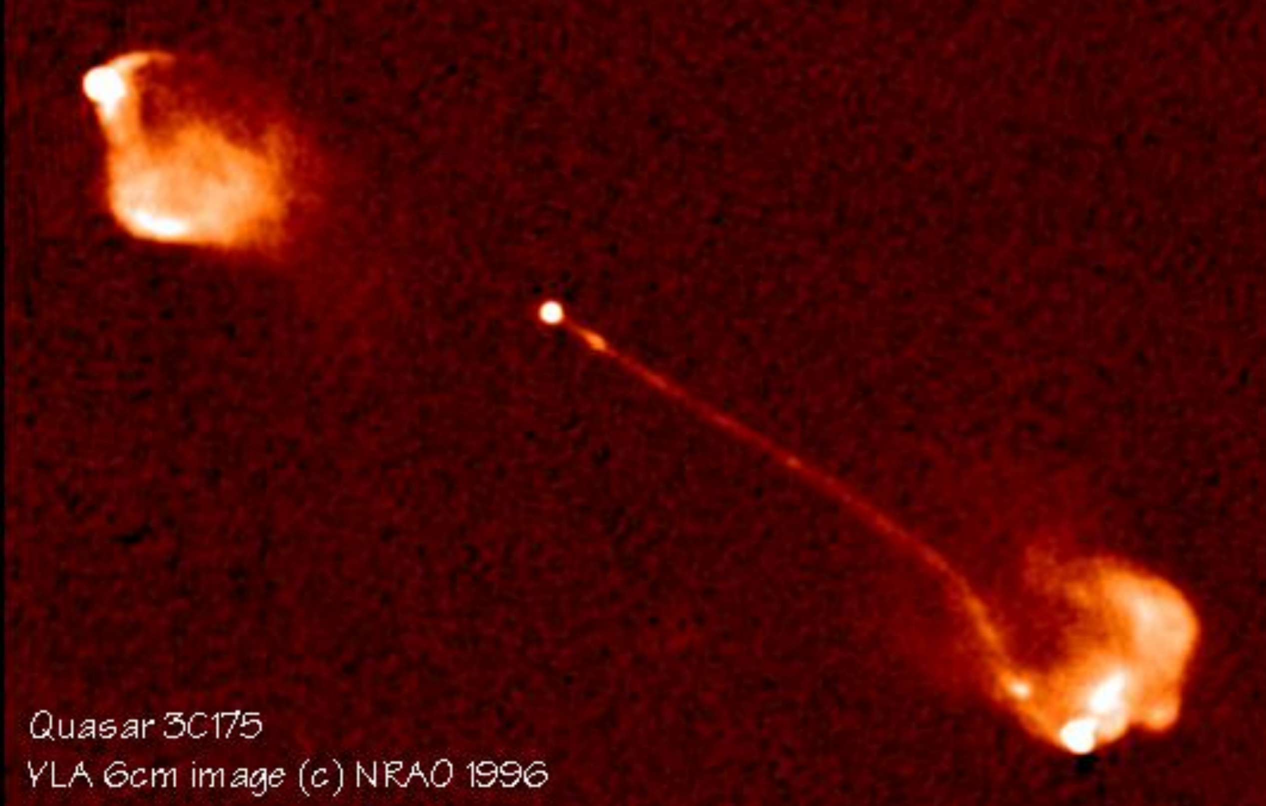
In radio loud AGNs, some fraction of IR was also found due to synchrotron radiation from jets.

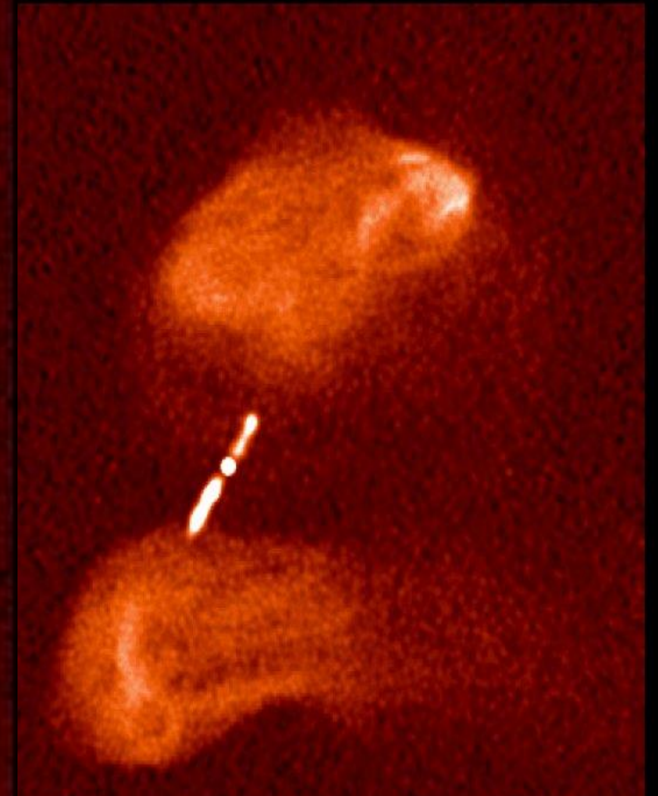
Radio Continuum

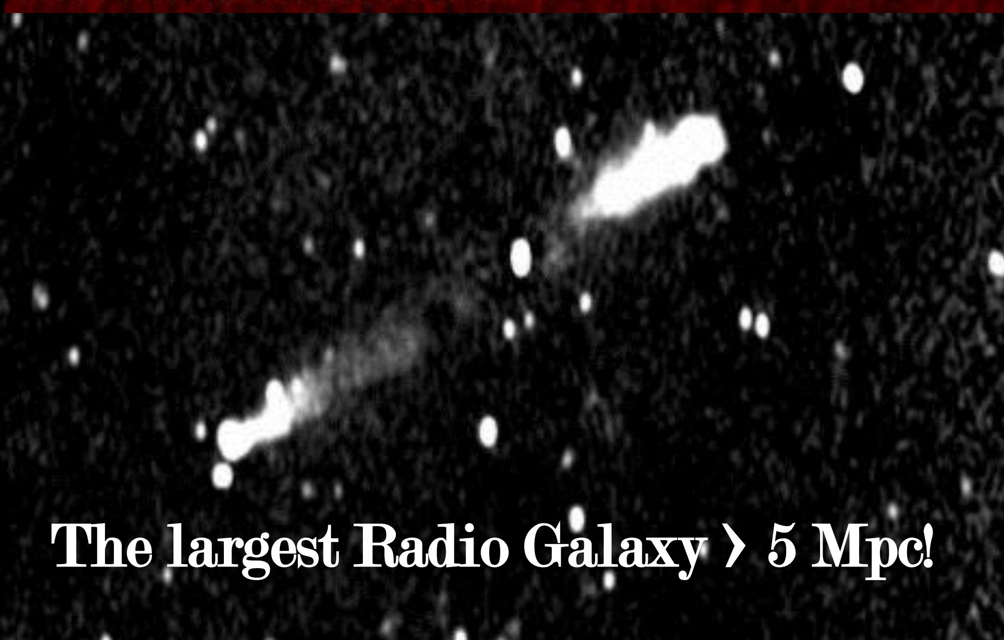
Strong radio emission (radio luminosity comparable or higher than optical luminosity) is seen from about 10% of AGNs.

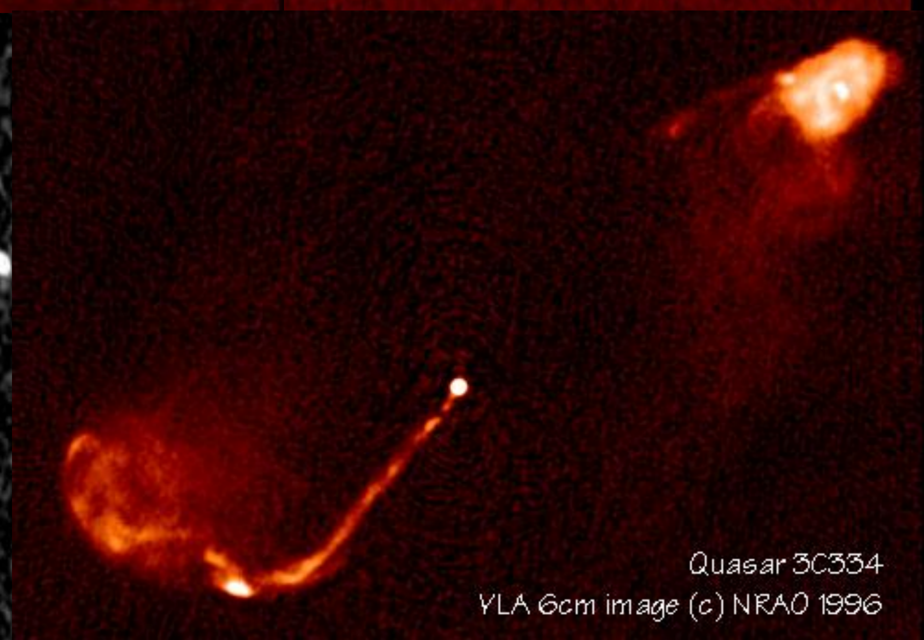
The most important difference is that the radio emission is well beyond the central engine, sometimes as far as a few million light years from the engine.

Historically, if Radio Luminosity at 5 GHz is > 10 times that at optical B-band; the object is called ***RADIO LOUD***

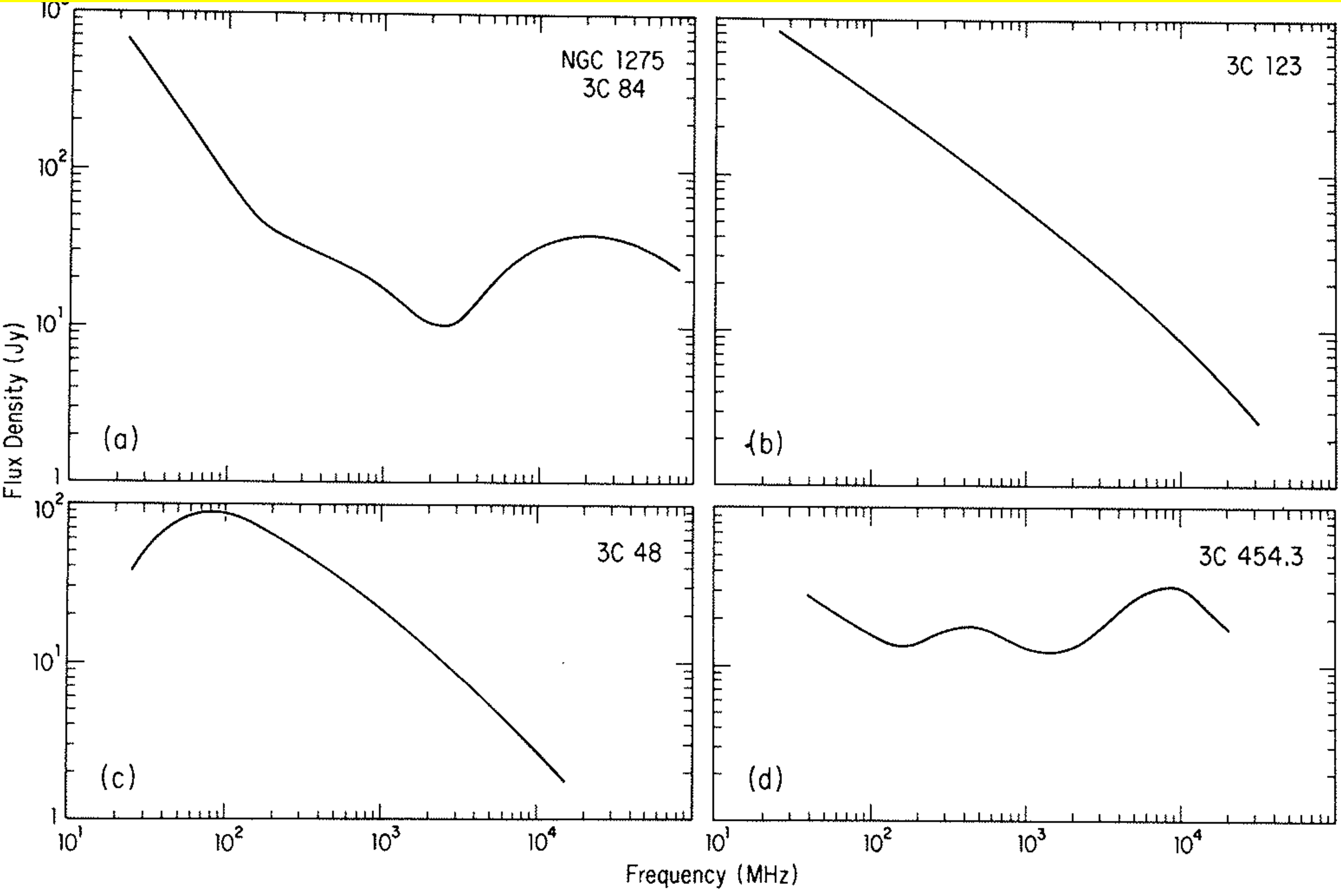

Quasar 3C175
YLA 6cm image (c) NRAO 1996




The largest Radio Galaxy > 5 Mpc!


Quasar 3C334
YLA 6cm image (c) NRAO 1996

Spectra (flux vs frequency)



How is the radiation produced? (Emission Mechanism)

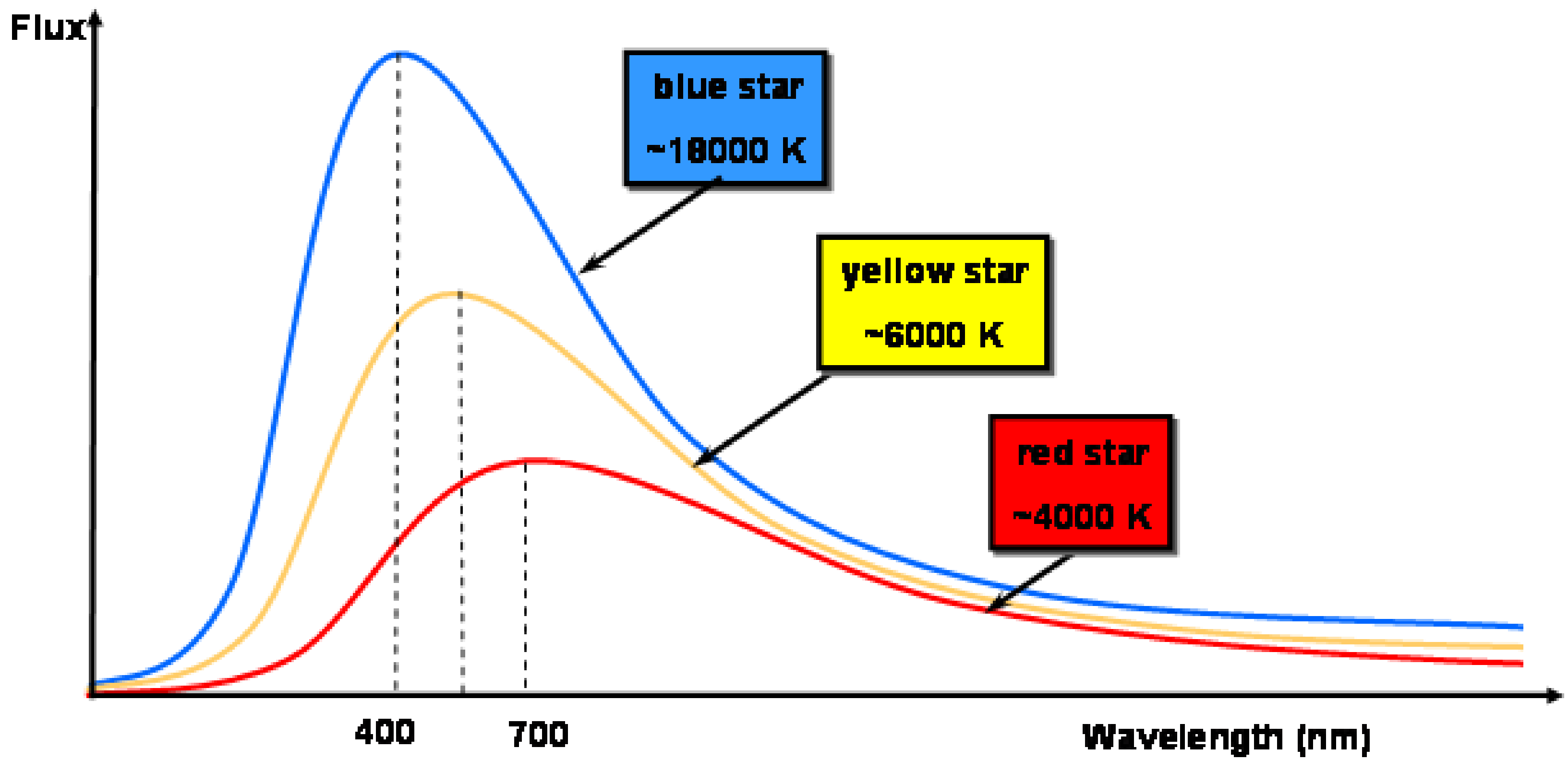
Continuum

- Blackbody
- Synchrotron
- Bremsstrahlung

Lines

- Hydrogen
- Maser lines

Blackbody Radiation



OK for UV and Optical. For RADIO, the Temp required is unrealistic; increase in power at other bands not seen

$$I(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1}$$

Bremsstrahlung Radiation

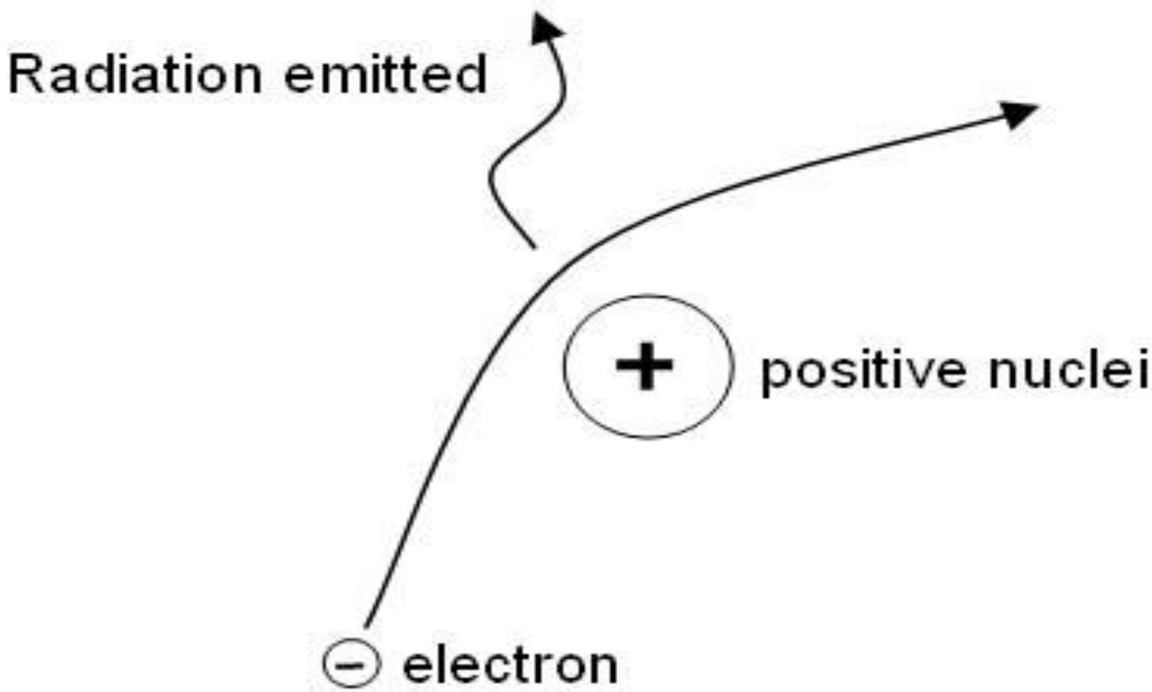
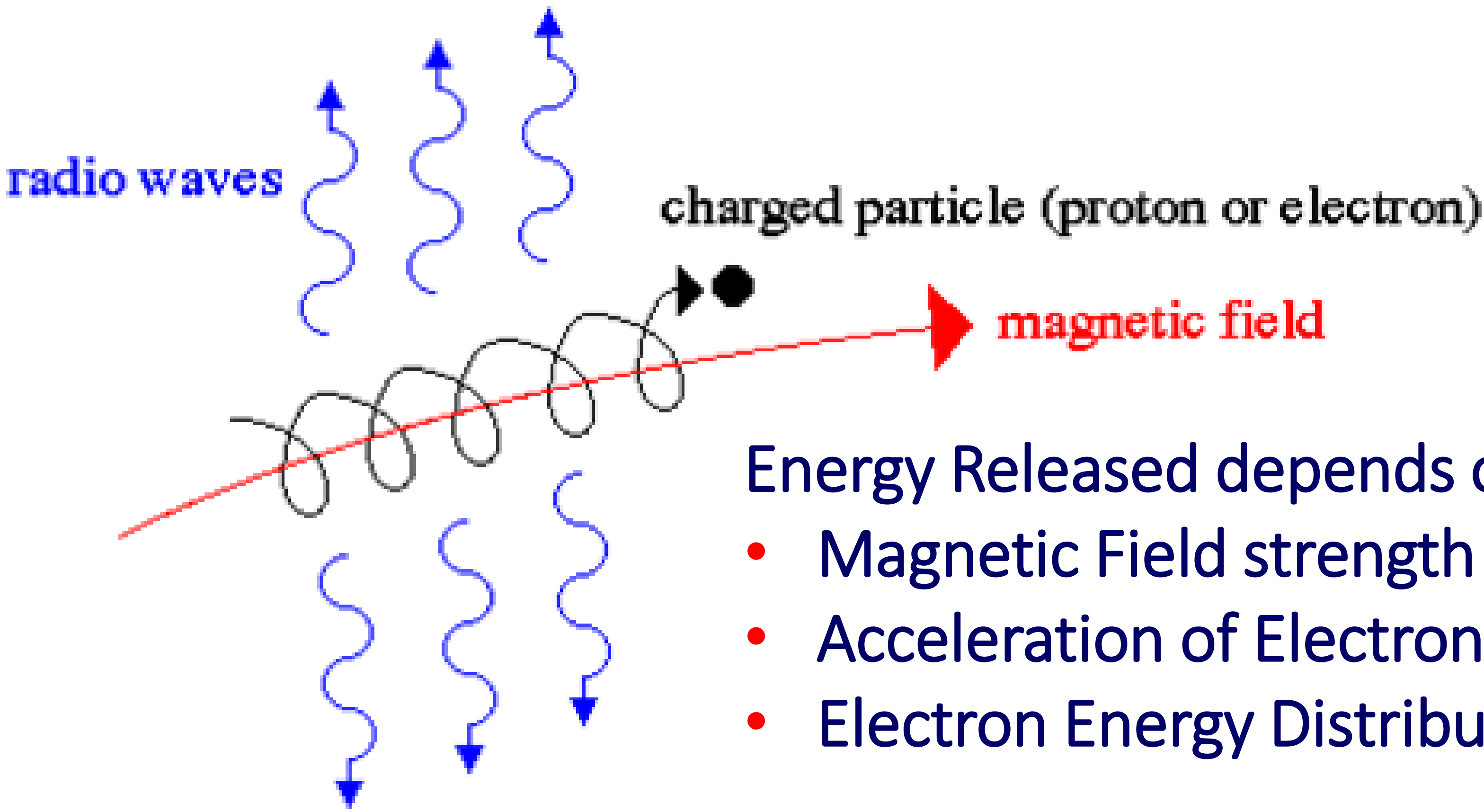


Figure 1: Bremsstrahlung (or 'braking') radiation is emitted when the path of a charged particle such as an electron is deviated by another charged particle. The acceleration of the electron causes it to emit a photon of light with an energy indicative of the electrons kinetic energy.

Possible in certain special cases, but spectral shape not steep.
Require dense clouds of ionized gas

Synchrotron

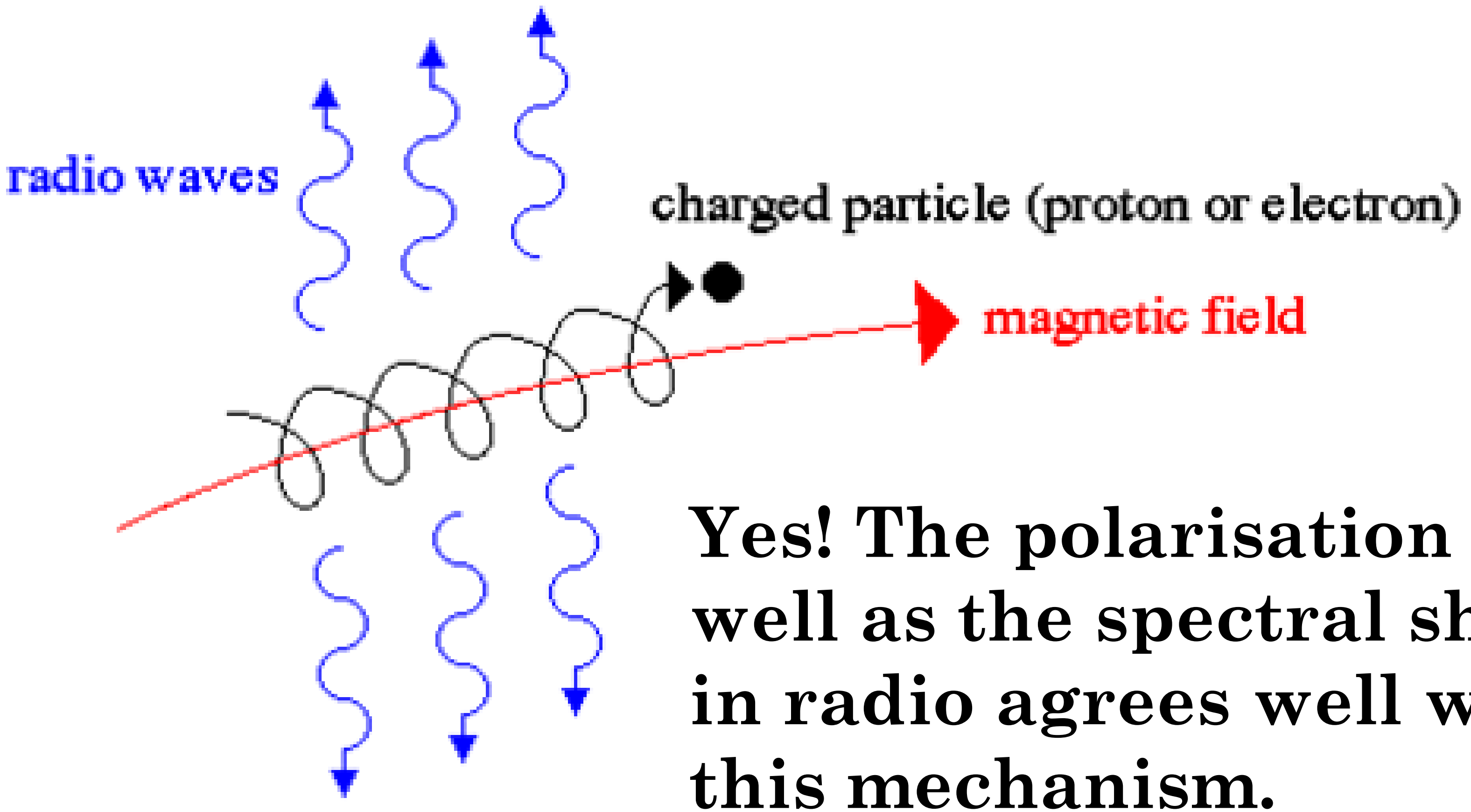


Energy Released depends on

- Magnetic Field strength
- Acceleration of Electron
- Electron Energy Distribution

synchrontron radiation occurs when a charged particle encounters a strong magnetic field – the particle is accelerated along a spiral path following the magnetic field and emitting radio waves in the process – the result is a distinct radio signature that reveals the strength of the magnetic field

Synchrotron

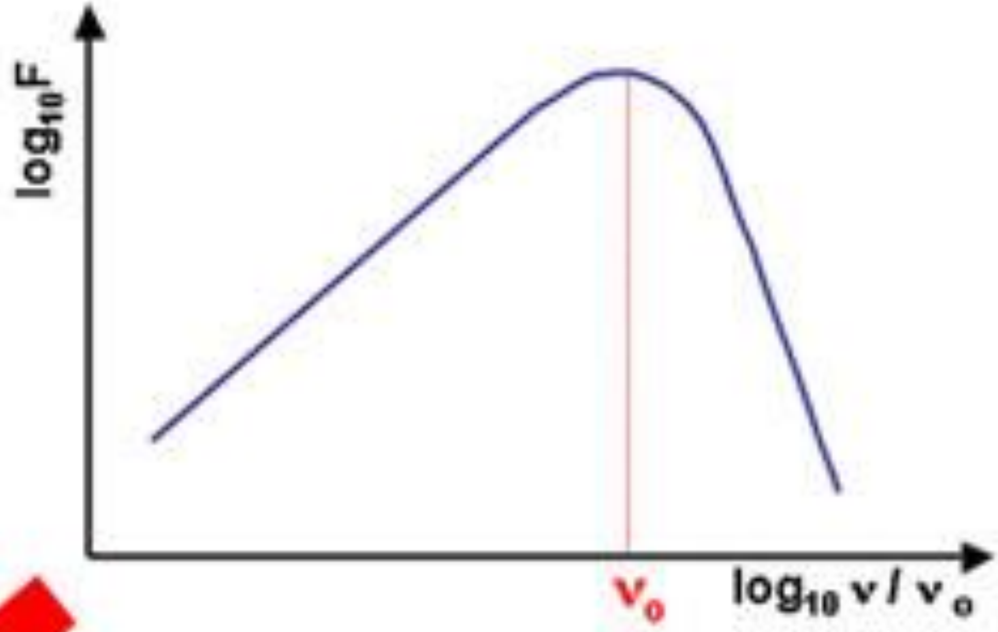


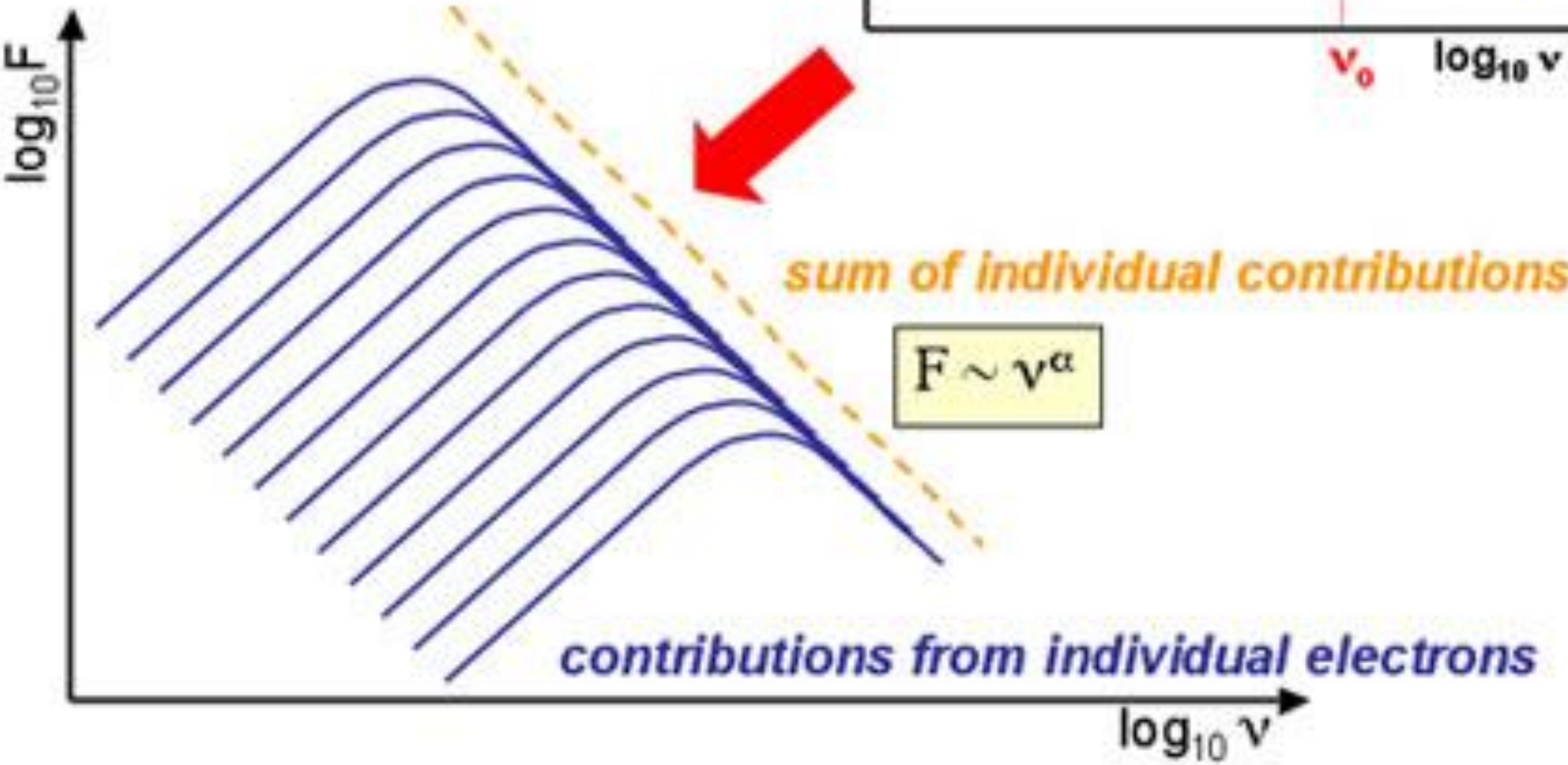
Yes! The polarisation as well as the spectral shape in radio agrees well with this mechanism.

synchrontron radiation occurs when a charged particle encounters a strong magnetic field – the particle is accelerated along a spiral path following the magnetic field and emitting radio waves in the process – the result is a distinct radio signature that reveals the strength of the magnetic field

Electron Distribution

$N(E) \propto E^{-p}$

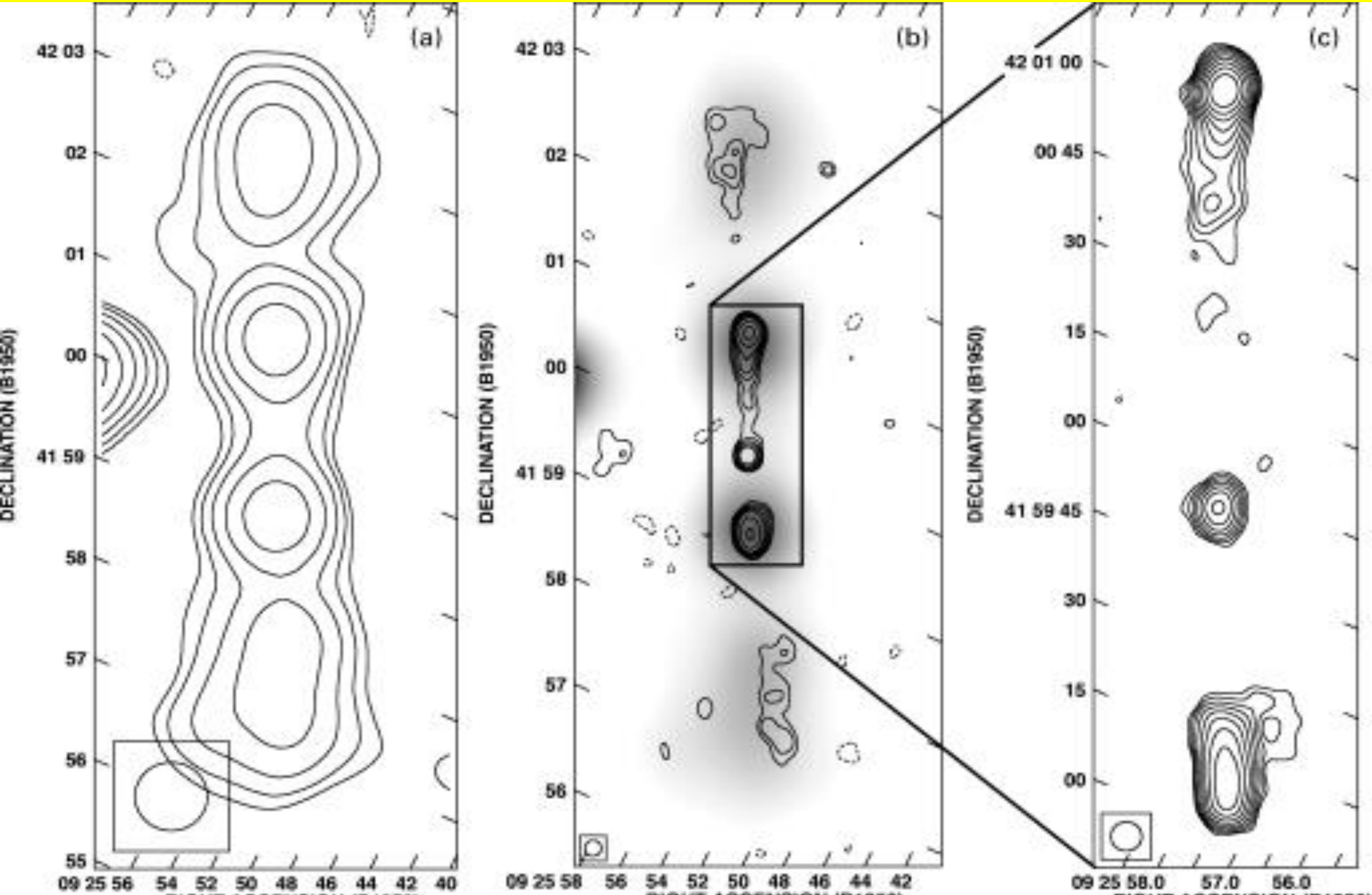




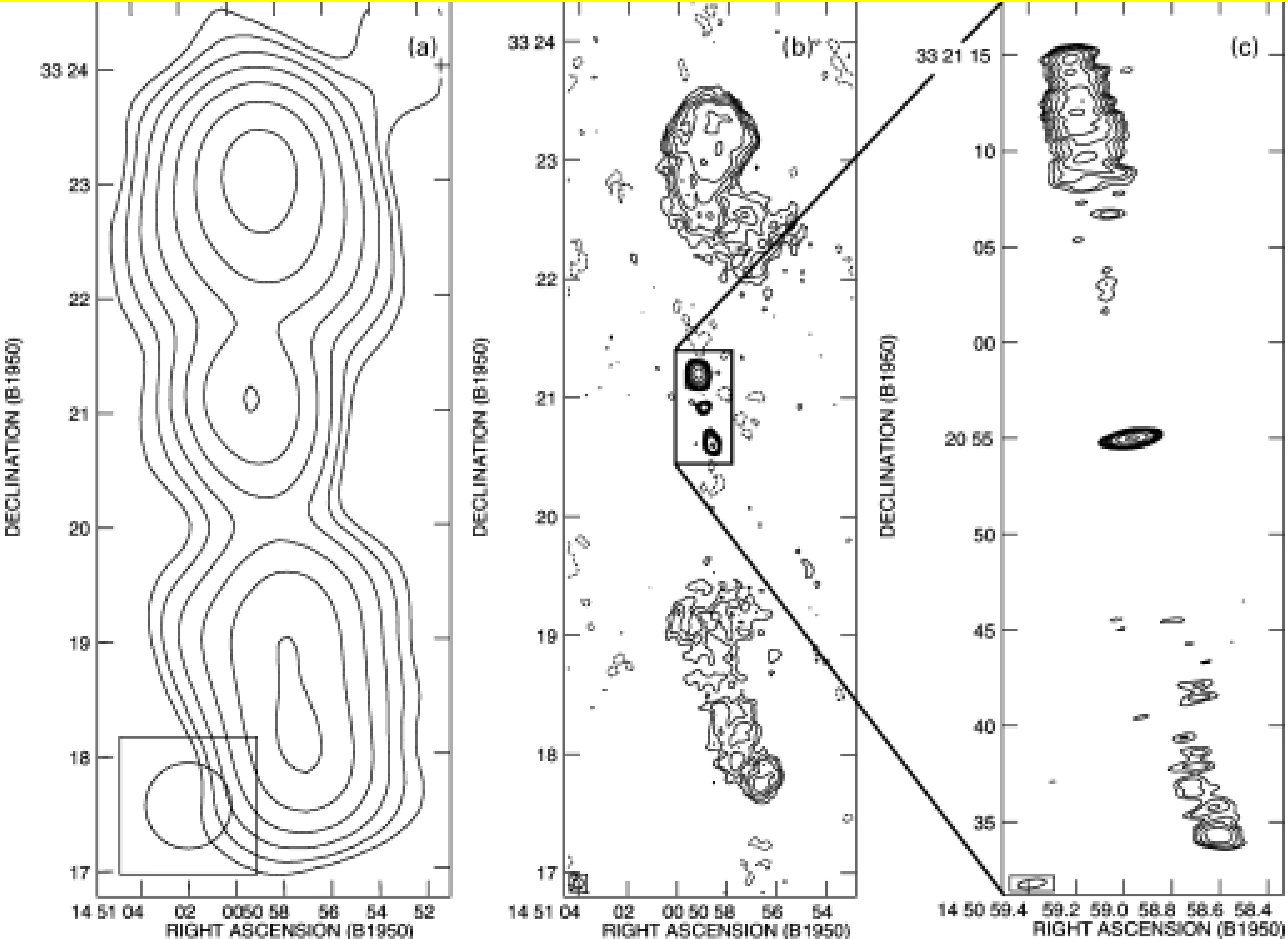
Summary till now

- Normal galaxies are weak radio emitters; it is related to SFR; hence tight radio – IR relation.
- Active Galaxies are subset among galaxies, exhibiting highly energetic phenomena at the center.
- Black-hole OR ultra-compact energy source is needed to explain this phenomena.
- The objects attain gigantic scales in radio.
- Radio sources are seen in clusters without host galaxies

Double-Double Radio Galaxies



Double-Double Radio Galaxies



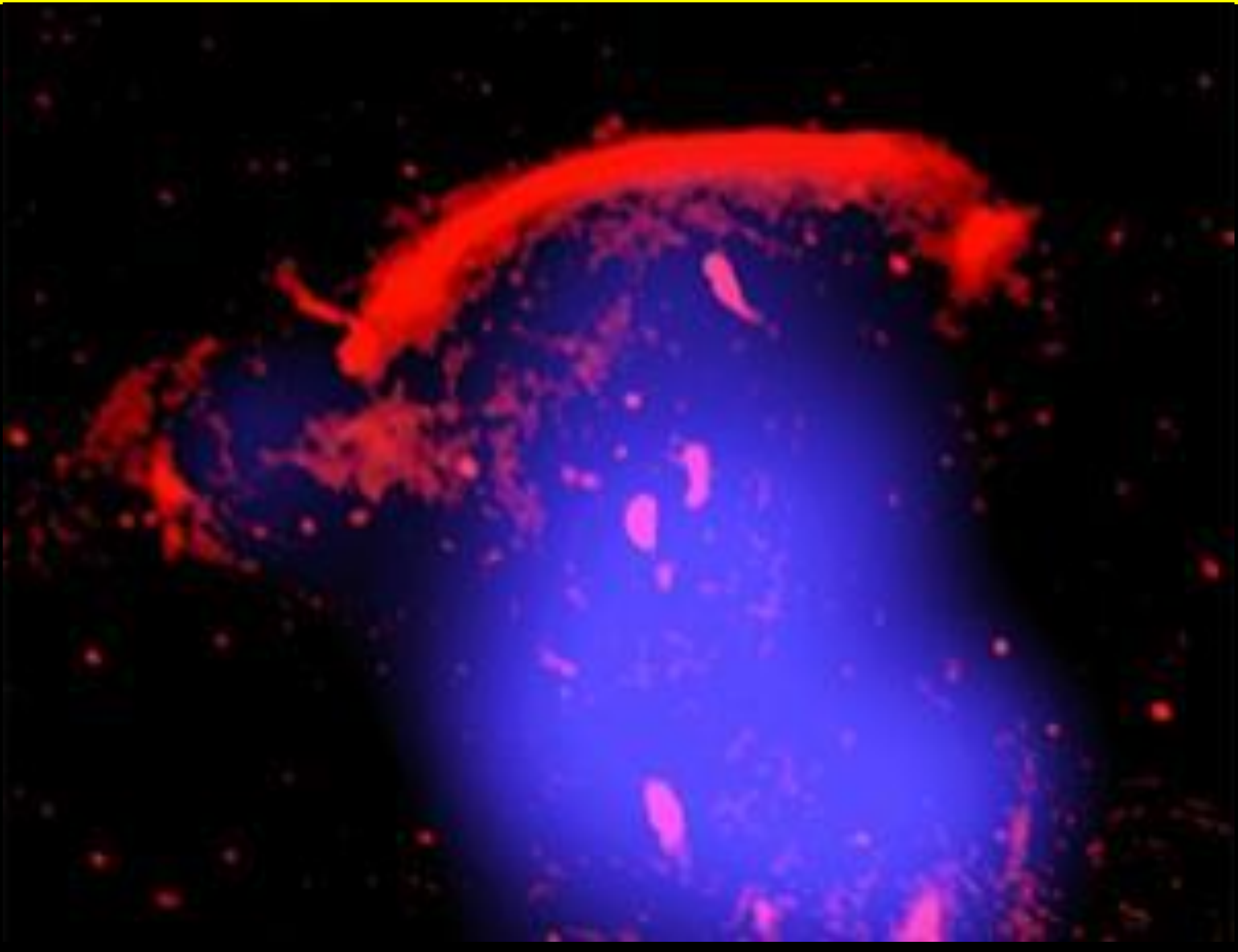
What does this say?

- The radio phenomena can stop and start
- What if the jet stops are does not restart?
- Does every AGN goes through radio phase ???

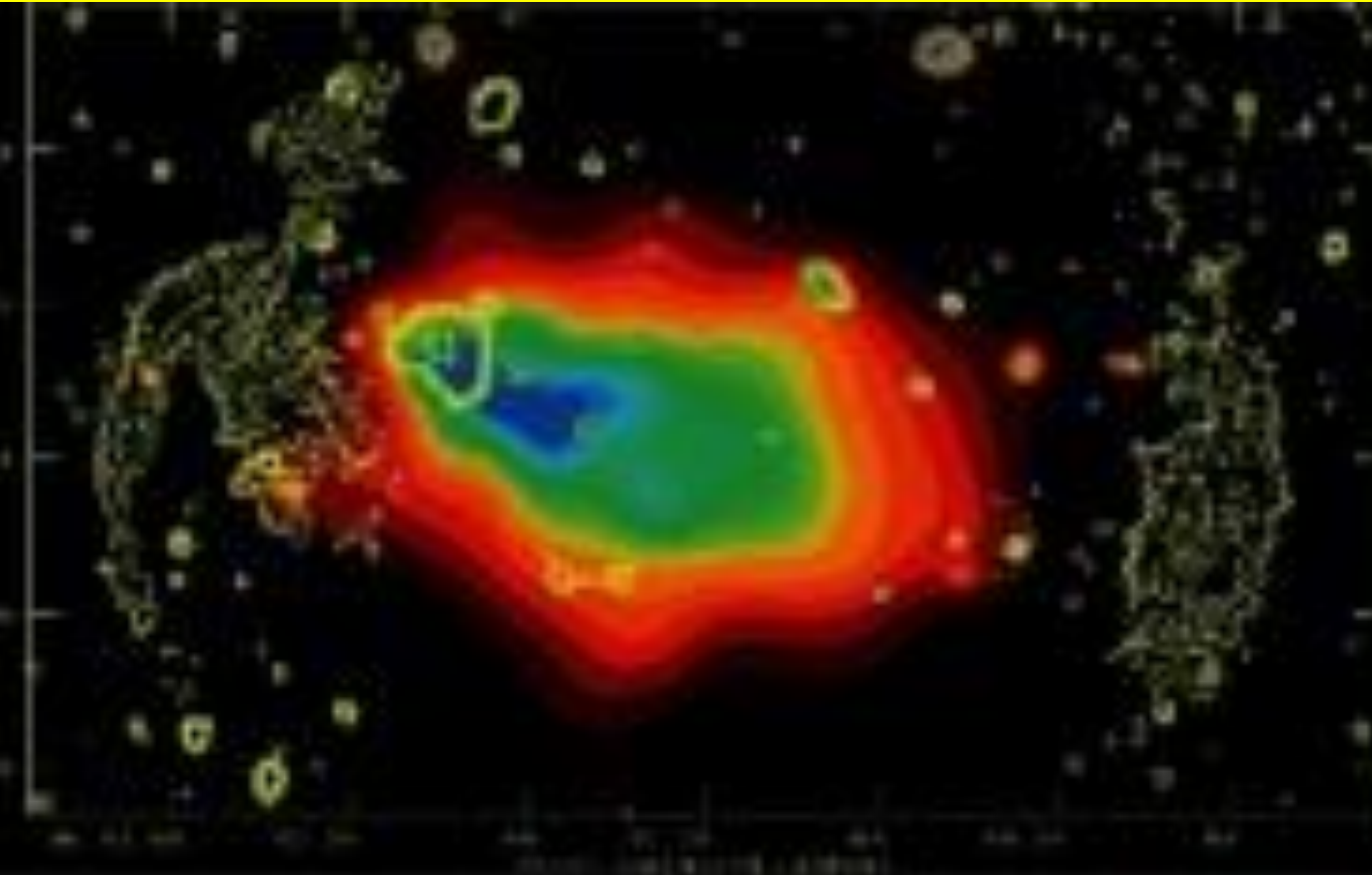
Radio Sources in Clusters

Cluster radio relics are diffuse radio sources in clusters of galaxies not associated with any active galaxy. The relativistic electrons in the relics are believed to be (re)accelerated by the merger shocks.

Radio Sources in Clusters (Shock)



Radio Sources in Clusters (A3376)



TIFR GMRT Sky Survey (TGSS)

S. K. Sirothia , N. G. Kantharia, C. H. Ishwara-Chandra, Gopal-Krishna

NCRA-TIFR, Pune, India

The Survey

We propose to carry out an extragalactic radio continuum survey at 150 MHz, using the Giant Metrewave Radio Telescope (GMRT), covering about 32,000 sq. deg of the sky north of declination of -30 degrees and reaching an rms noise of 7-9 mJy/beam at an angular resolution of about 20 arcsec. (*The TGSS has been extended to southern declinations and will cover the entire sky observable with GMRT*.) When complete, the survey is expected to detect more than 2 million sources.

The above has become possible due to the development of AIPS++ based automated data analysis tools for GMRT data (Sirothia 2009, Ph.D. thesis) which can identify and remove data corrupted by radio frequency interference (RFI) and by other problems. We note that despite being a prime objective conceived for the GMRT, no major low-frequency survey has so far been undertaken with this telescope and this survey when completed will be the first of its kind from GMRT . **The proposed GMRT 150 MHz survey will result in more than 4 times improvement both in sensitivity and angular resolution over all existing surveys at this frequency.** Also it will be strategically placed in the frequency gap between the two existing prominent radio surveys, namely WENSS (325 MHz) and VLSS (74 MHz), each having only a modest angular resolution of ~1 arcmin. The survey proposed here is expected to fulfill a prominent goal of the GMRT and will prove to be a major database for multi-wavelength astronomy. We are proposing to complete these observations before the solar activity in the current solar cycle peaks around 2012. The analyzed data will be made available to the astronomy community in an expeditious manner (possibly on time scales of a few

News

We announce TGSS data release 5. All the images and catalogues released have been made with the modified pipeline and have better sensitivity to extended structure. *(30 November 2012)*

Apologies to all users who have been waiting for the next TGSS data release. We have not been able to have our October 2012 release. *(1 November 2012)*

Next data release has been delayed. There was a power cut at NCRA which resulted in a week's downtime for the TGSS computing lab which, in turn, resulted in an effective loss of about three weeks of analysis time. Release delayed to October 2012. *(6 September 2012)*

TGSS team has a new online book-keeping tool. As the number of imaged and released fields increase; the complexity of book-keeping is also increasing which this tool will help handle. *(6 September 2012)*

We announce TGSS data release 4 covering about 1 steradian of the southern sky. *(20 April 2012)*

The next TGSS data release is scheduled for April 2012. *(3 April 2012)*

All the observations at 150 MHz of the sky accessible to GMRT have been completed. Data analysis is in progress. The data analysis pipeline is being improved to increase sensitivity to faint extended structure. *(3 April 2012)*

New TGSS images as part of TGSS DR3 are released on 31 October 2011. *(31 October 2011)*

Overview of TGSS

TGSS is designed to carry out survey at 150 MHz with GMRT from dec of -55d to +90d, covering 90% of sky.

This will be the only counterpart to NVSS in metrewaves.

Superior resolution (20”) and noise (7 to 9 mJy/beam)

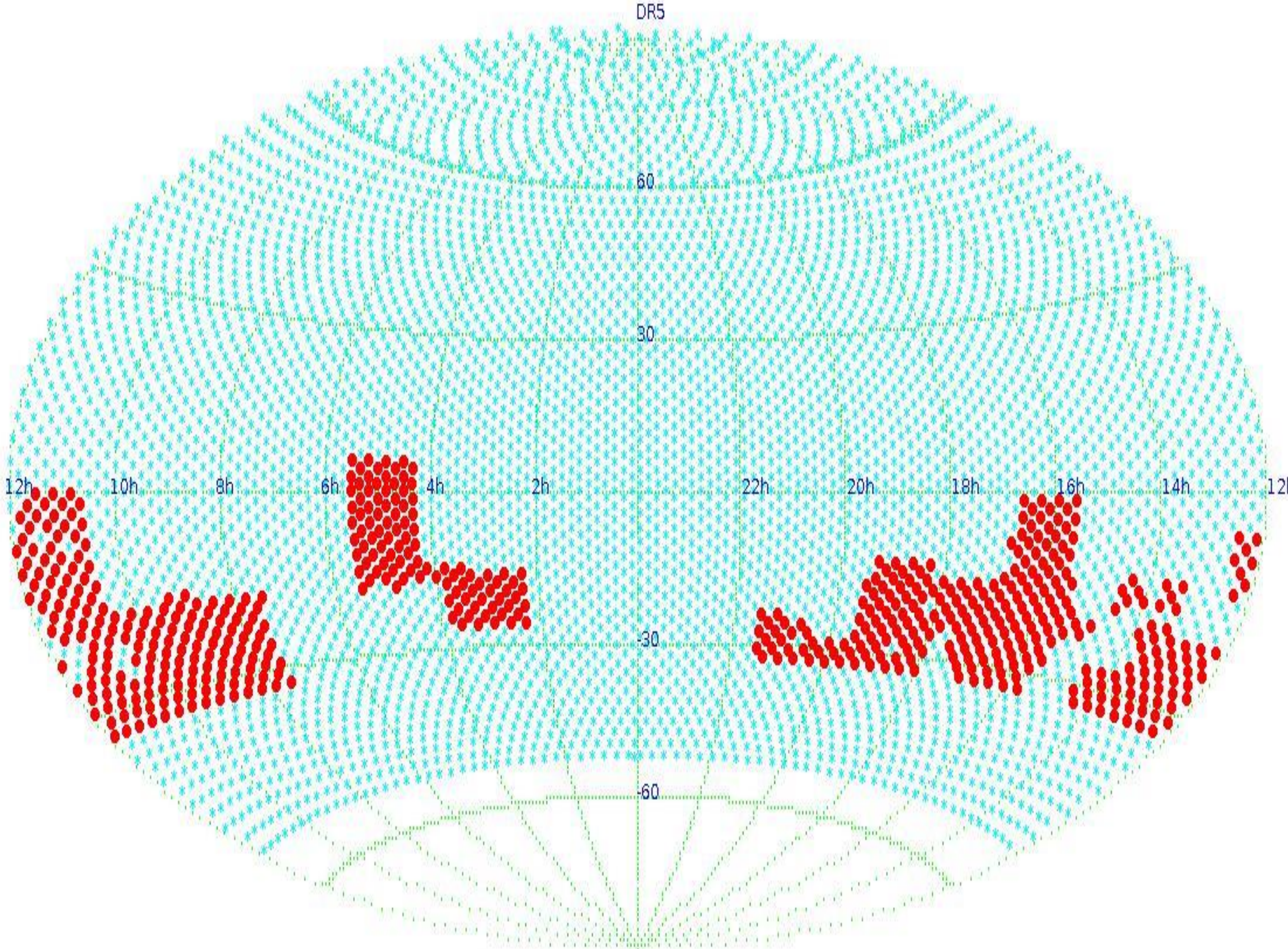
Observations started in 2010 and over in March 2012.

Dedicated computing facility running automated pipeline.

Expected to catalogue over a million sources down to completeness limit of 40 mJy

TGSS data products are available in tgss.ncra.tifr.res.in

About 1 sr of sky area is already released.



DR5
60
30
12h
10h
8h
6h
4h
2h
22h
20h
18h
16h
14h
12h
-30
-60

Some major radio surveys

Survey Name (Telescope)	Frequency Range (MHz)	Sensitivity (mJy/beam)	Angular resolution (arcsec)	Sky area (sq deg)
MSSS-LBA	30-74	≤15	≤100	20,000
VLSS (VLA)	74	100	80	30,000
MSSS-HBA	120-170	≤5	≤120	20,000
TGSS (GMRT)	140-156	7-9 **(6)**	20	**37,000**
WENSS (WSRT)	330	3.6	54	10,000
NVSS (VLA)	1400	0.45	45	35,000

Ref: LOFAR website   (LOFAR-MSSS not yet available)

Looking for distant AGNs

When did the universe born?

When did the FIRST star/galaxy born?

When did the FIRST AGN born?

Were they different than our neighbors?

How to detect them?

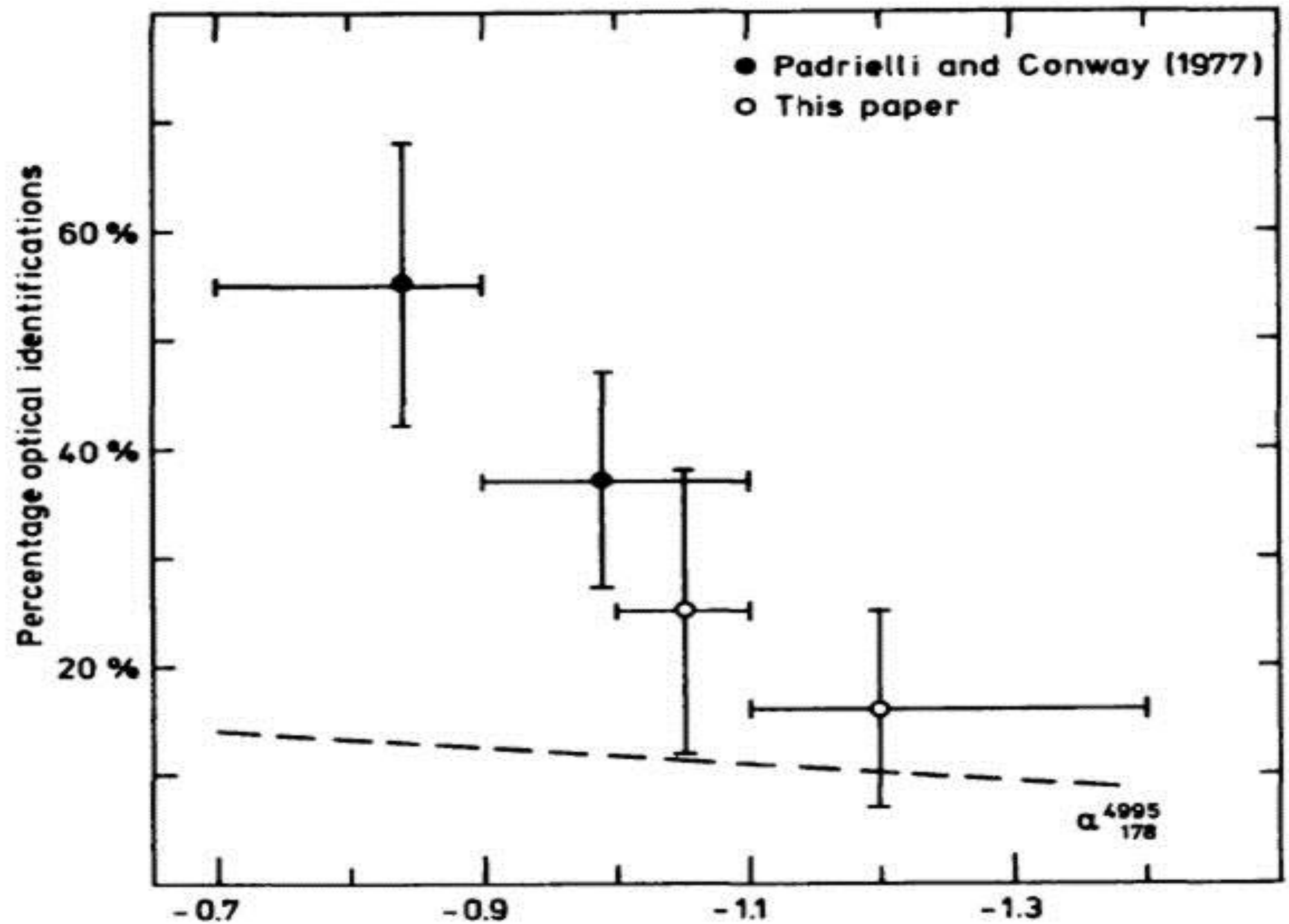
Radio Advantage: Dust obscuration not an issue

The AGN in host galaxy has strong emission lines which makes it easier to get redshift

The hosts are always **massive** ellipticals

Optical identification of RGs

- *It has been first noticed in early 80's that the fraction of 3C radio sources that can be optically identified are* ***3 times less*** *for those with radio spectral index steeper than 1 (stronger at lower radio frequencies).*



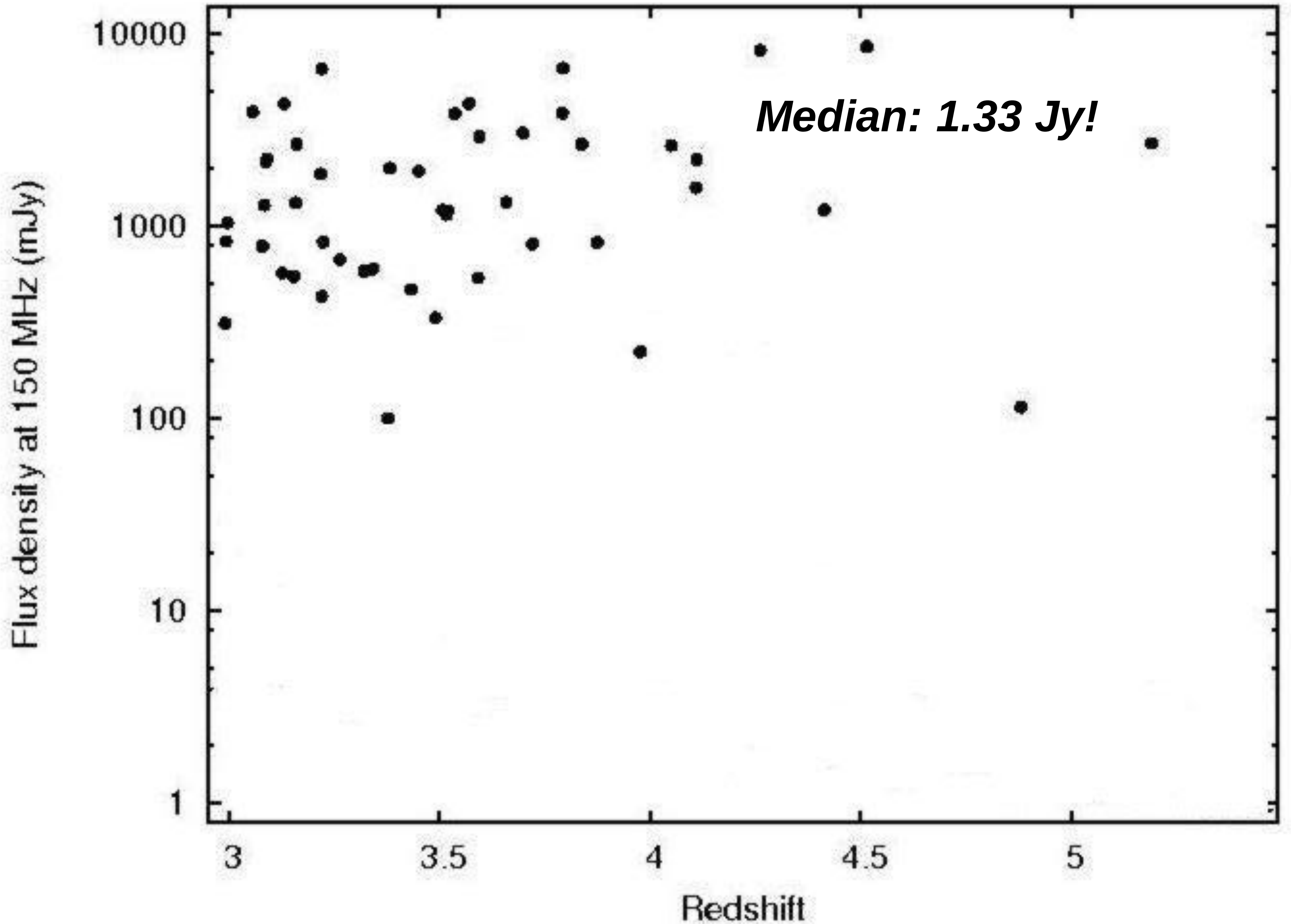
Radio Spectral Index between 178 MHz and 5 GHz

(The dashed line is the chance coincidence rate)

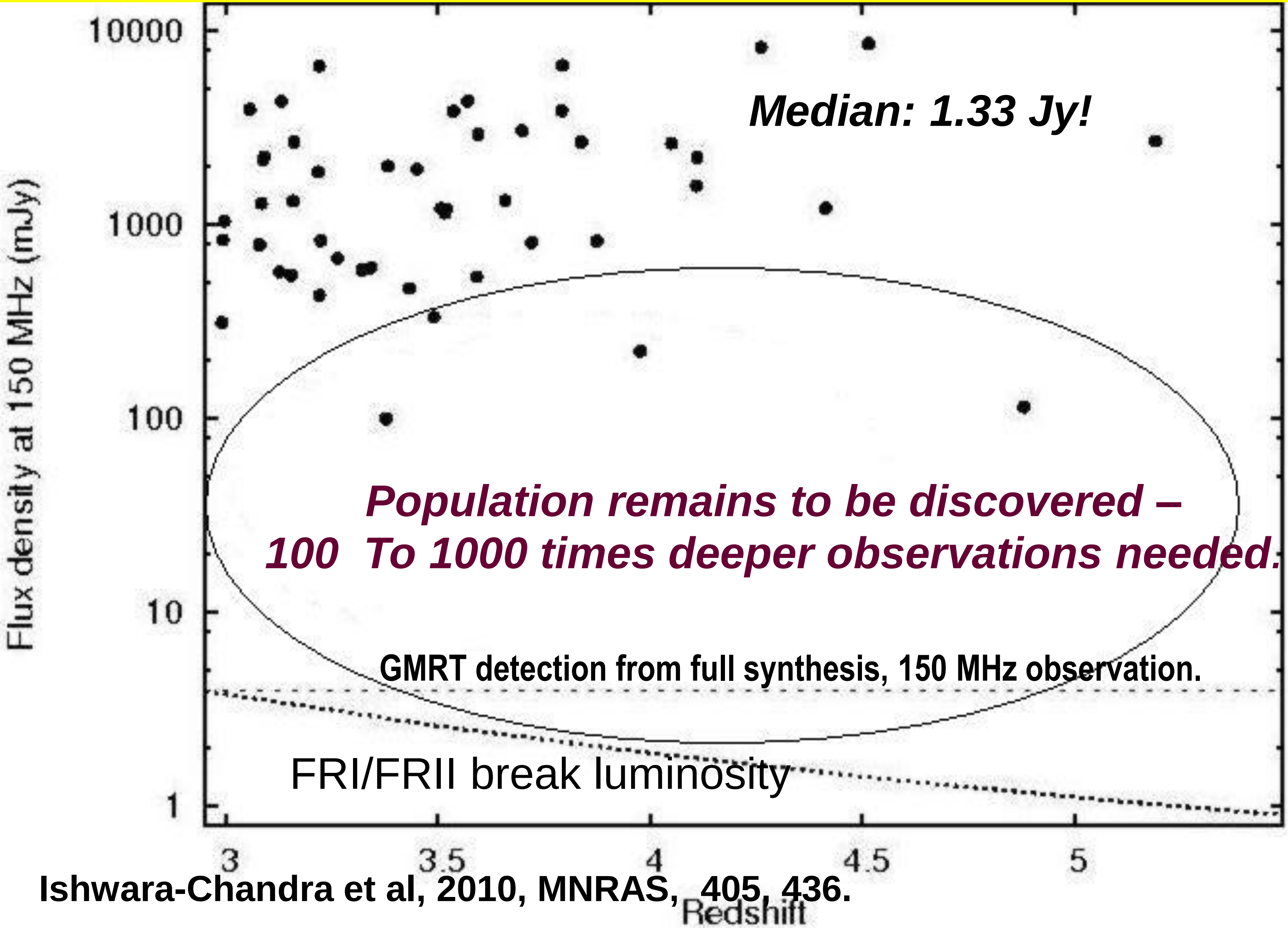
Optical identification of RGs

- *It has been first noticed in early 80's that the fraction of 3C radio sources that can be optically identified are* ***3 times less*** *for those with radio spectral index steeper than 1 (stronger at lower radio frequencies).*
- This finding that the steep spectrum sources are more distant as compared to the sources with normal spectra, has been exploited since then to find more high-redshift radio galaxies.
- *Most of the High-z radio galaxies known today (~ 45) are discovered using this correlation.*
- ***(Blumenthal and Miley, 1979, Tielens, Miley and Willis, 1979; Miley and de-Breuck, 2008 for review).***

Known HzRGs:- Tip of the iceberg?



Known HzRGs:- Tip of the iceberg?



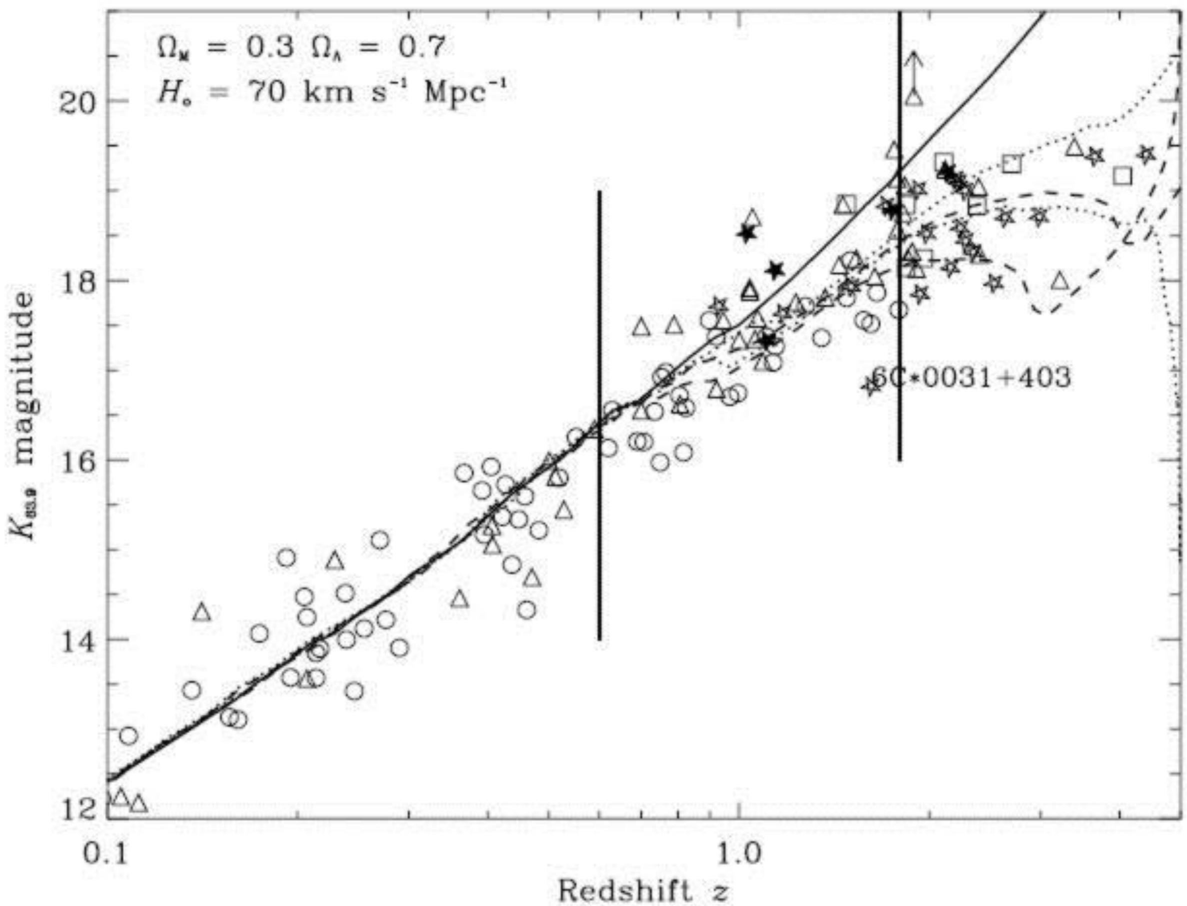
Ishwara-Chandra et al, 2010, MNRAS, 405, 436.

The GMRT Programme....

- To optmize the search, 'well known deep fields' are chosen for observing *at 150 MHz* for this purpose, most of which don't have much radio data below 1.4 GHz
  (in 'reverse' direction)
- **LBDS** – ***Ishwara-Chandra et al, 2010, MNRAS, 405, 436***
- **DEEP-II-1,2,3** (~2 deg X 0.5 deg/field & 50,000 spectra).
  - ***scrutiny underway – wealth of data from DEEP2 survey.***
- **VIRMOS-VLT** – (~ 4 $degree^2$ and 10,000 spectra)
- **VLA-COSMOS** - (~ 2 $degree^2$ and 40,000 spectra)
- **HDF/GOODS-N** – small field of view, but wealth of data .
- **TIFR-GMRT Sky Survey**

What next?

– First two steps are done, now the third step ***Deep K-Band imaging, for K – z relation to estimate redshift and then spectroscopy of z > 3 objects***.



Concluding Remarks

- ✓ Extra galactic Sky is dominated by Active Galaxies (sources stronger than a mJy)
- ✓ Extra galactic Sky is dominated by Star Burst Galaxies (sources fainter than a mJy)
- ✓ At low frequencies, we preferentially see steep spectrum and old objects
- ✓ Clusters often host sources without any host optical galaxy, this is to do with cluster mergers and re-accelaration of old plasma..
- ✓ TGSS can potentially discover many interesting sources at low radio frequencies..