Technion
Israel Institute of Technology

Nuclear and host properies of local and distant radio galaxies (FR0-FRI-FRII): similarities and differences

Ranieri D. Baldi

A. Capetti, M. Chiaberge, A. Celotti,
E. Behar, A. Laor, and A. Horesh

INAF
Osservatorio Astronomico
di Torino

ma per seguir virtute e canoscenza
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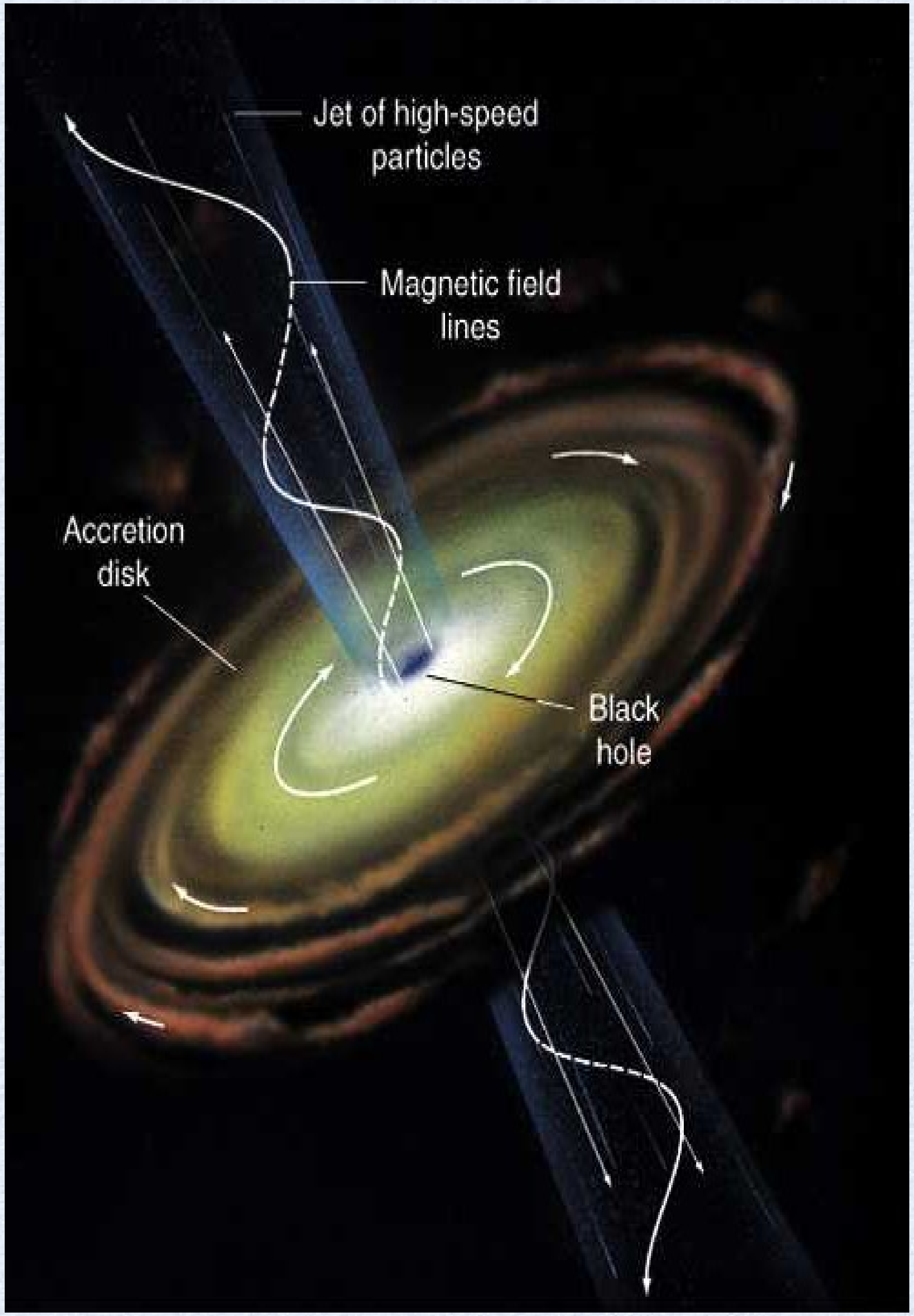
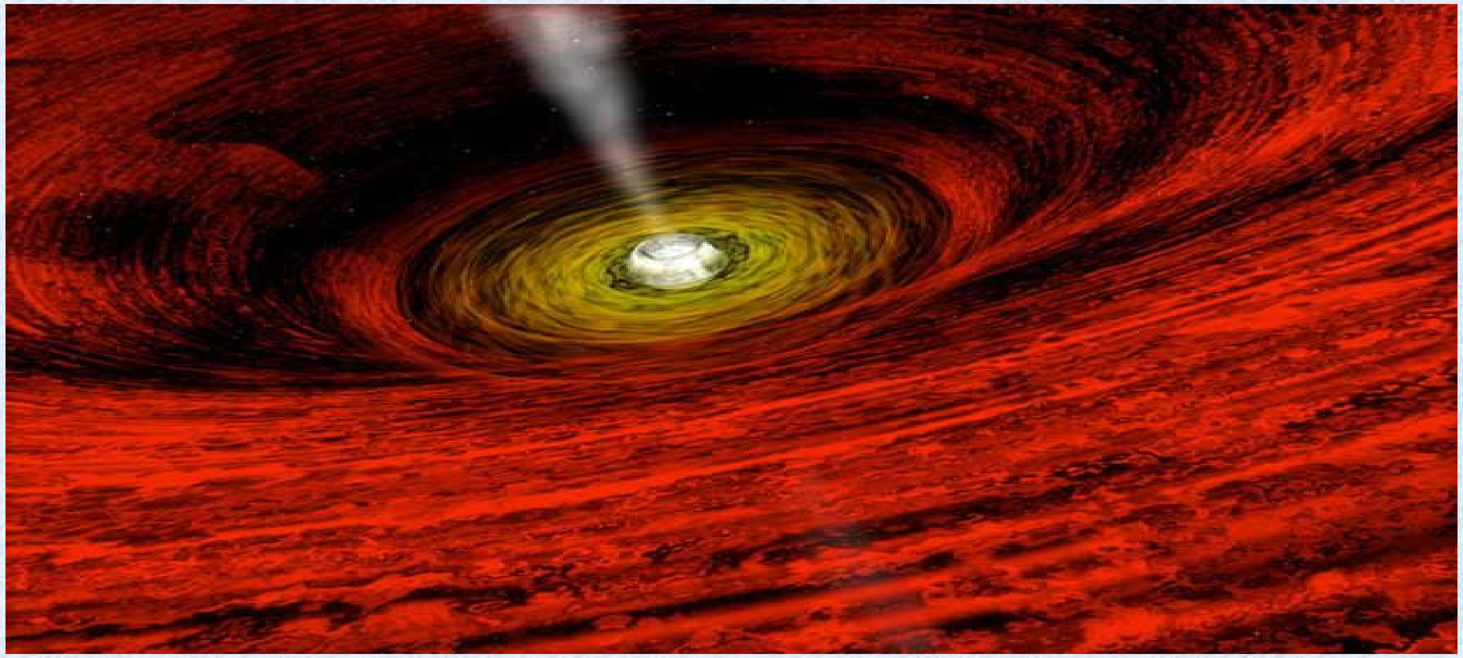
OUTLINE

1. Introduction on AGN and radio galaxies.
2. Radio galaxies in the local (**$z < 0.3$**) Universe.
3. Properties of local radio galaxies: nuclei, host, and star formation.
4. New radio-loud AGN population: FR0, dominant class in the local Universe?
5. Distant radio galaxies (**$z < 0.7$**) in the COSMOS field: host and AGN properties
6. Similarities and differences between local and distant RG
7. Conclusions and future perspectives.

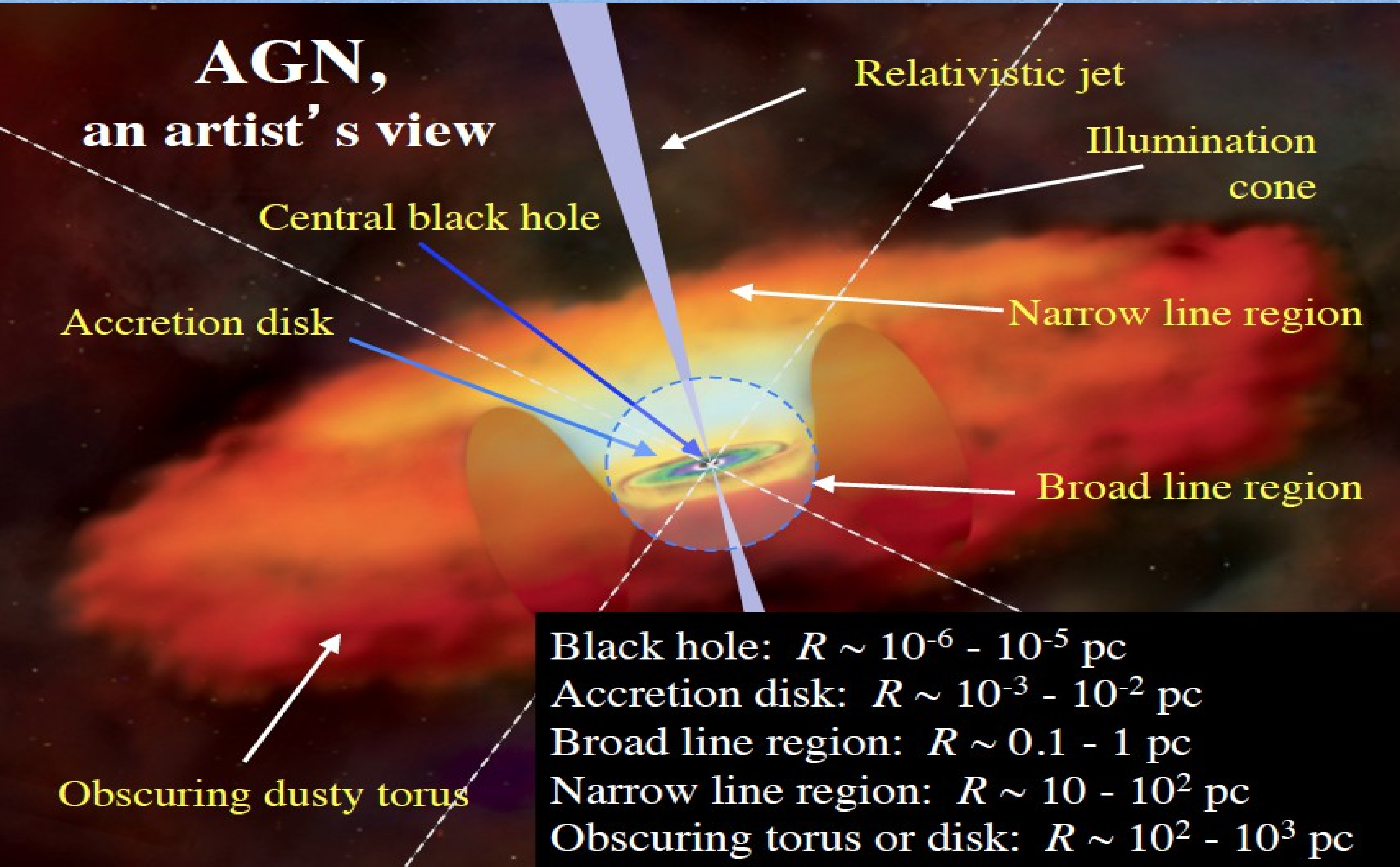
Black Hole & Active Galactic Nuclei



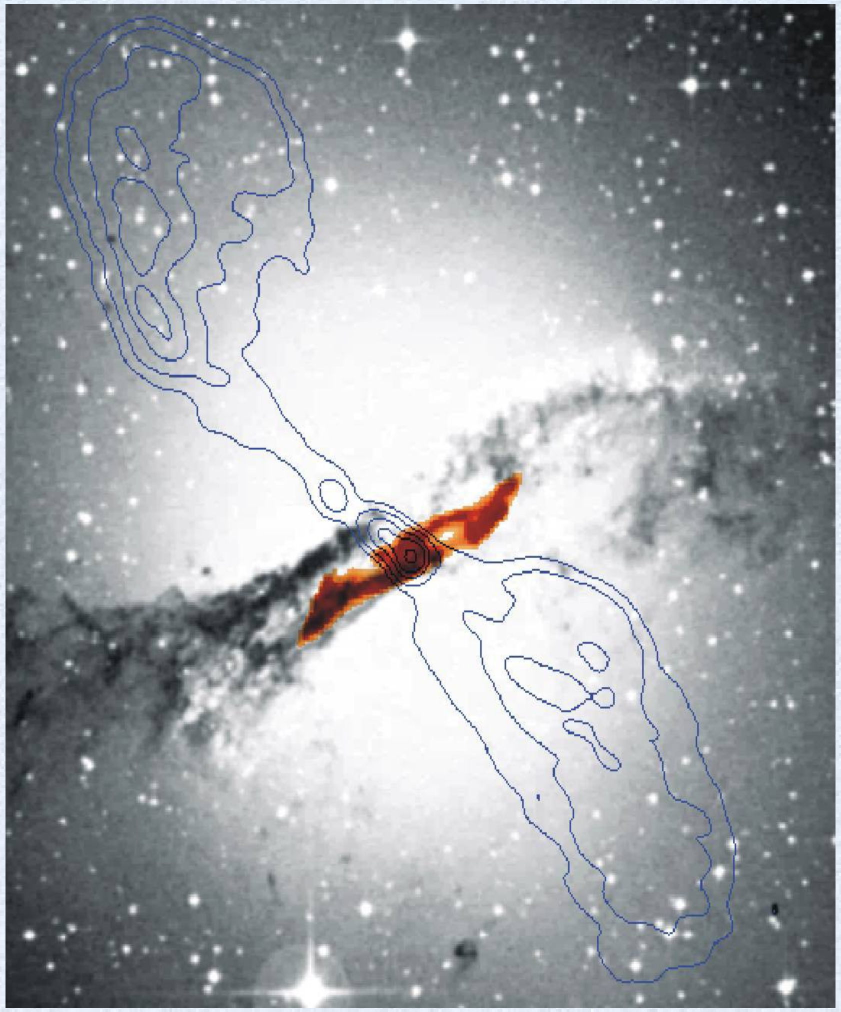
We now know that almost all galaxy bulges harbour black holes (BH) in their nuclei.
Most are quiet/silent and are detectable only via near-nuclear orbital dynamics.
A few are accreting gas which makes them visible through the release of potential energy.
Such nuclei are called **Active Galactic Nuclei** (**AGN**) and their hosts are called Active Galaxies.



Structure of AGN

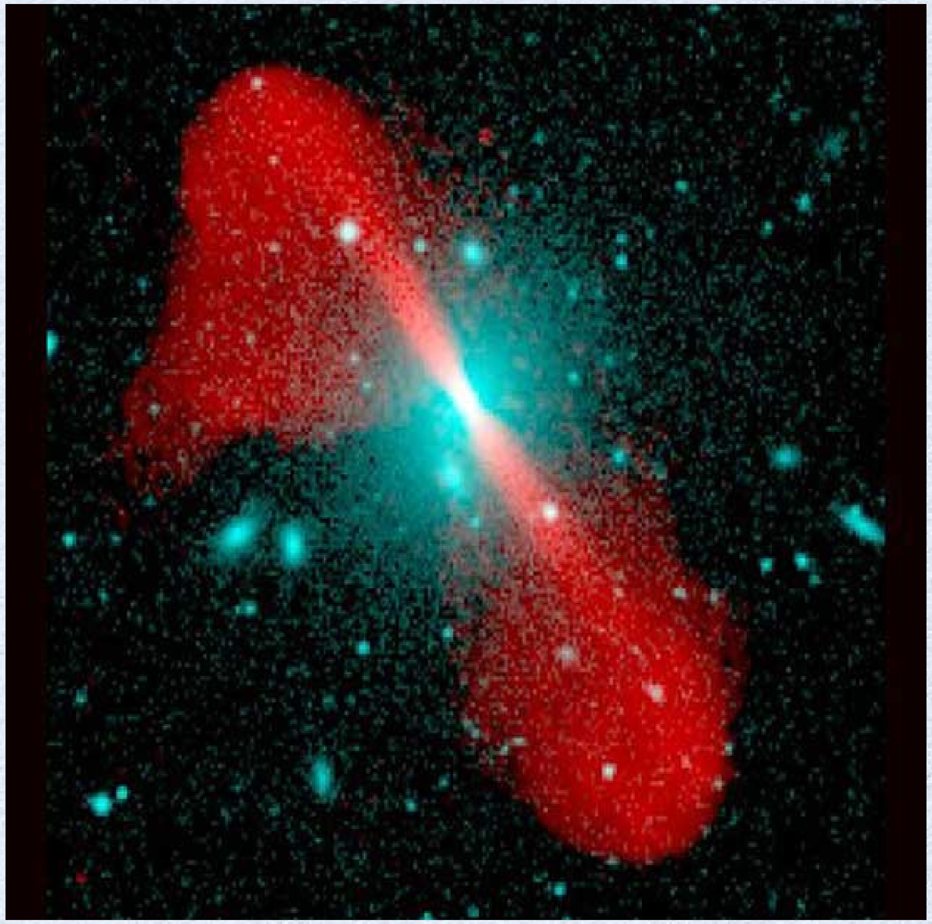


The radio-loud / radio-quiet dichotomy



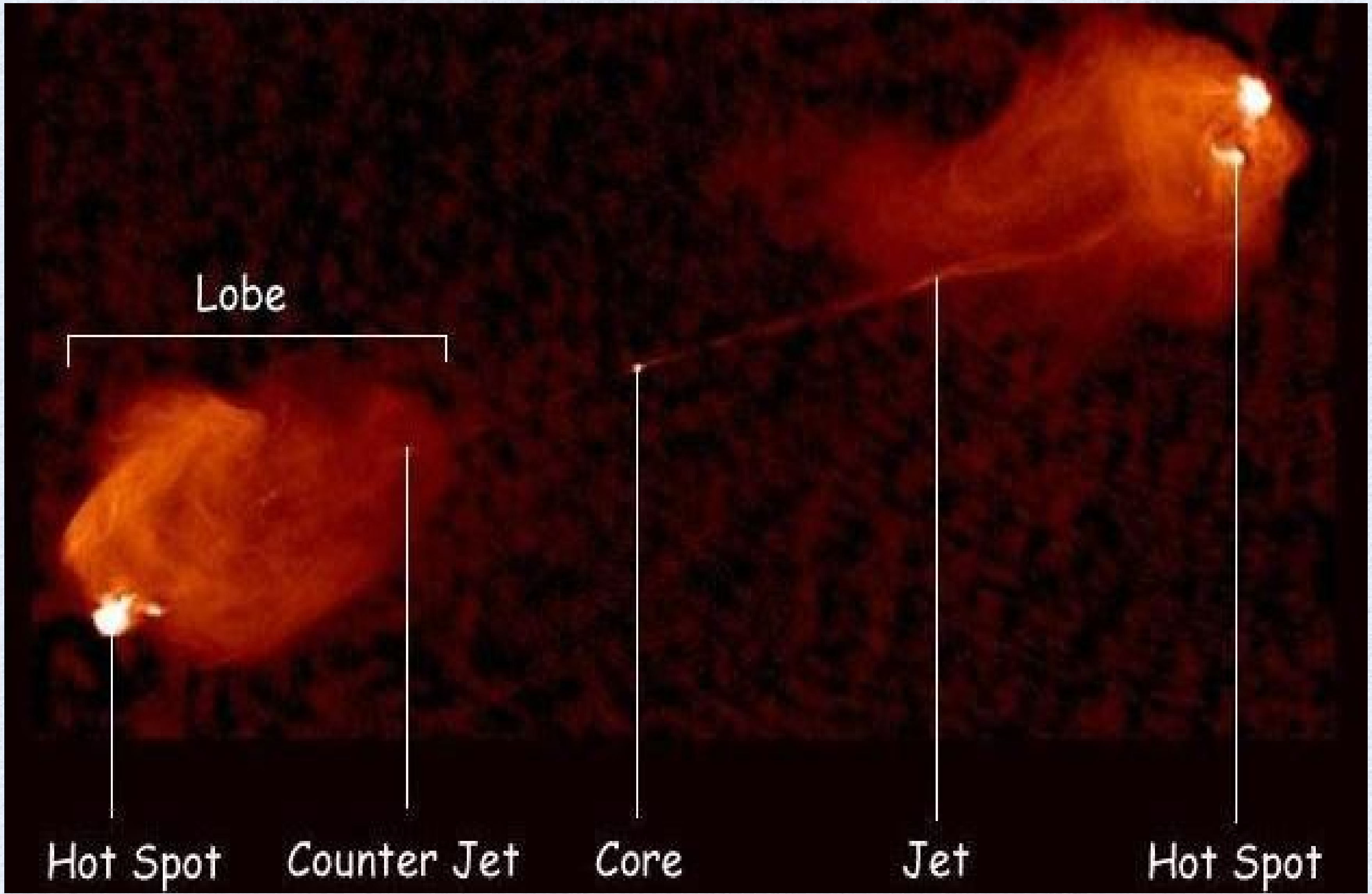
Among the many differences distinguishing AGN one of the best known and studied effect is the presence of two populations of AGN, which can be separated on the basis of their radio luminosity with respect to the light emitted in the optical band.

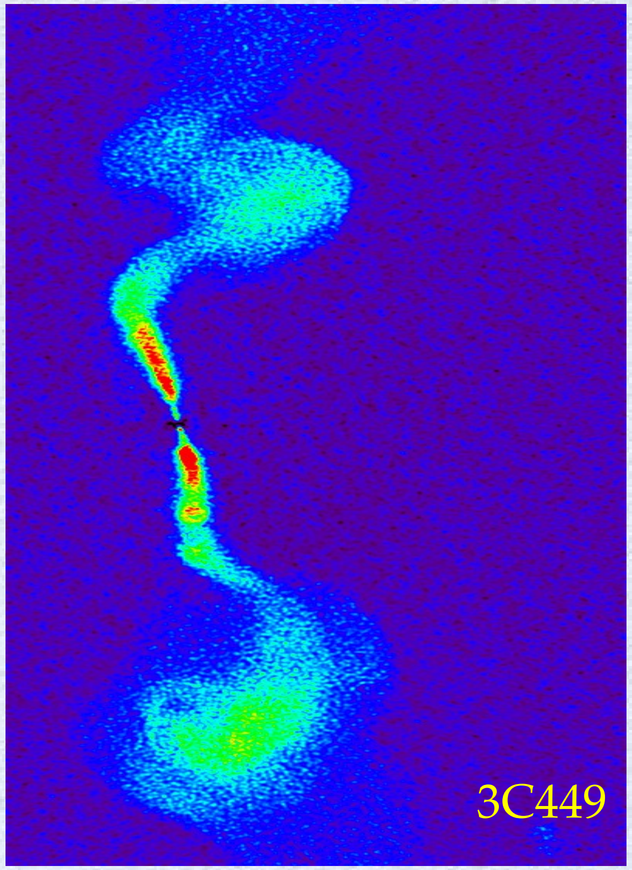
The dichotomy can be parametrized numerically, with a threshold of $L_{radio}/L_o = 10$ (Kellerman + 97) or in X-ray (Terashima & Wilson 03), but in most cases radio-loud AGN can be recognized by the presence of very extended radio-structures clearly associated to large scale jets.

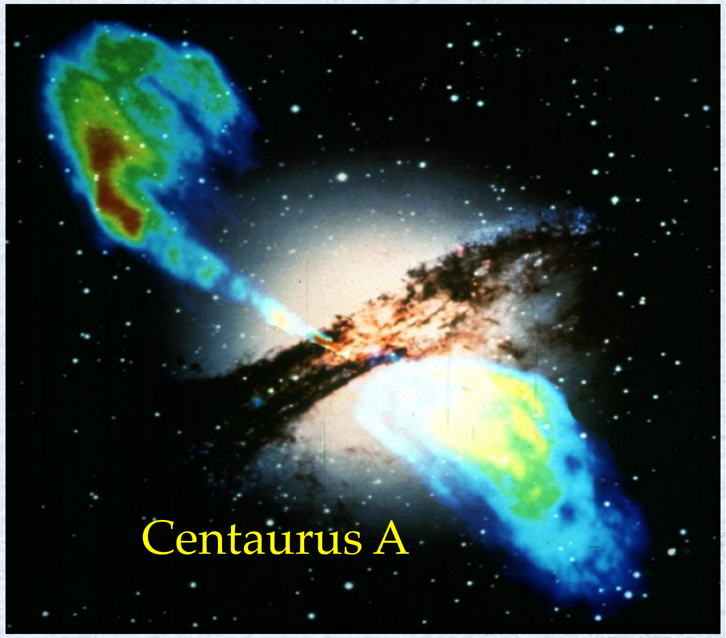


Radio Galaxies

- **Radio Galaxies** are RL AGNs with $L_r = 10^{39}$ up to 10^{46} erg s^{-1}.
- Morphologies of extended radio galaxies from pc to Mpc
- Collimated jets connecting the optical galaxy and the extended lobes
- Associated with elliptical galaxies and $M_{BH} > 10^8\ M_\odot$

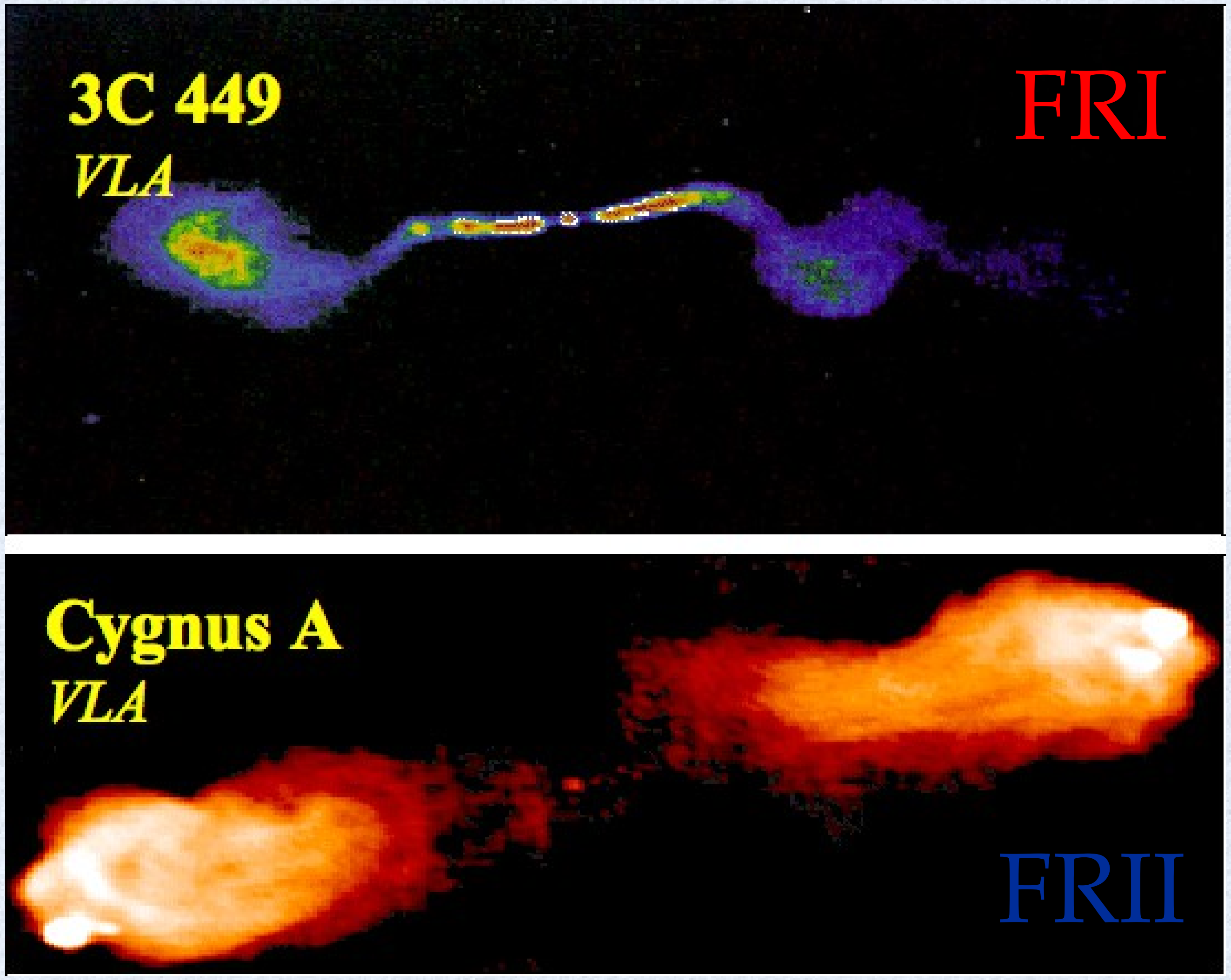




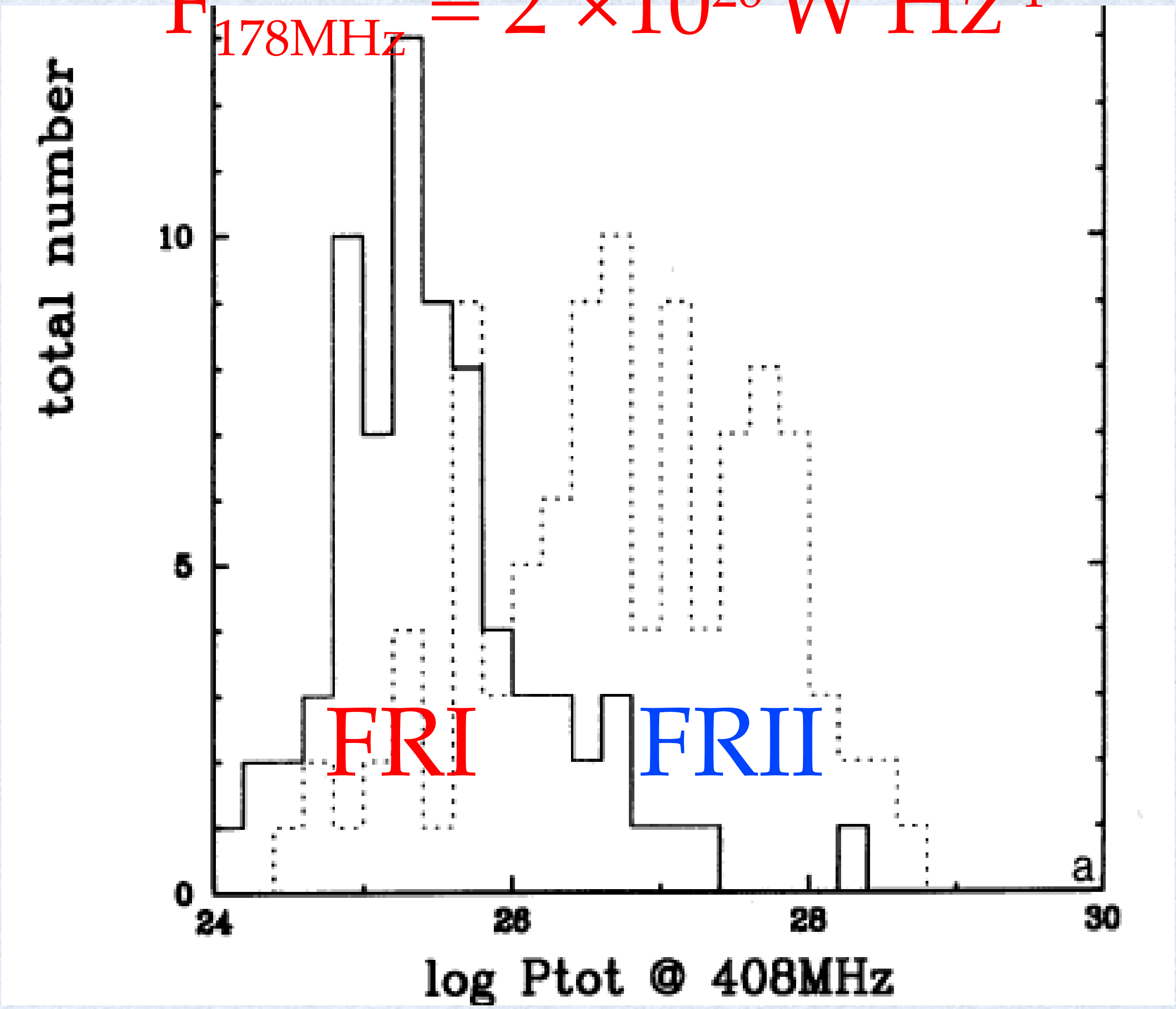


Radio Morphology Classification

Fanaroff & Riley (1974)



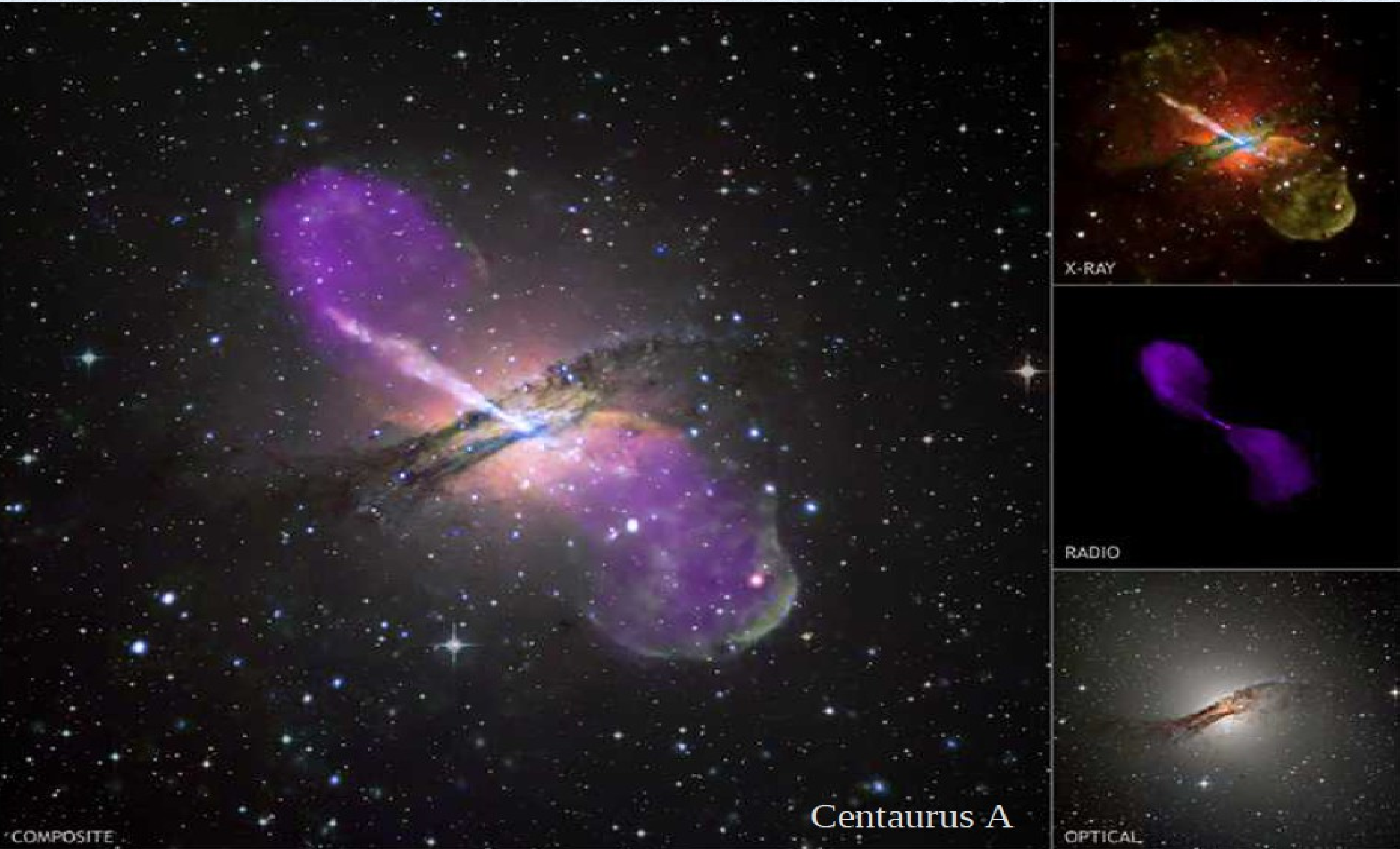
$F_{178MHz} = 2 \times 10^{26}$ W Hz^{-1}



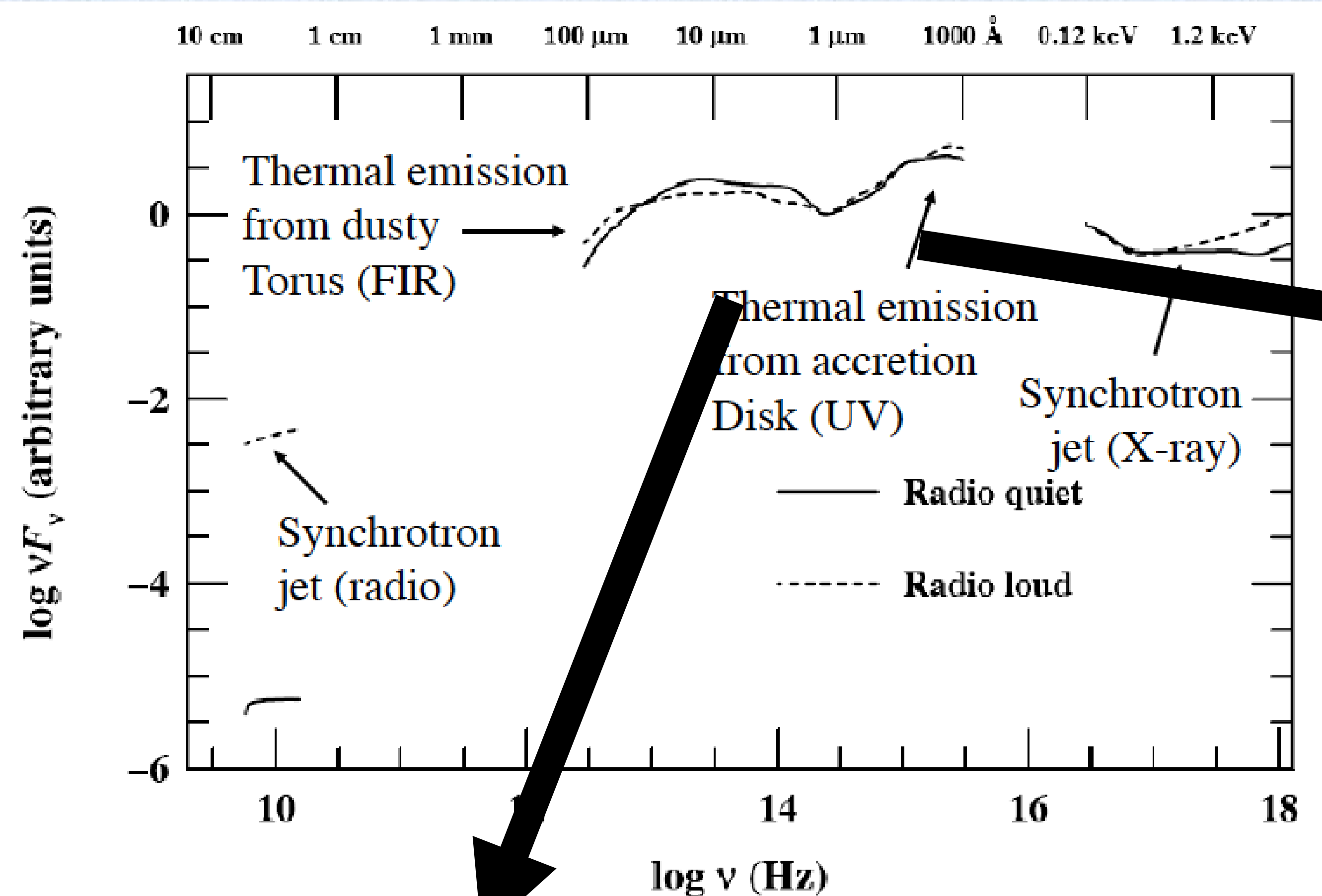
Zirbel & Baum 95

- Massive Early-type galaxies host RG
- FRI in rich environment, FRII in galaxy group

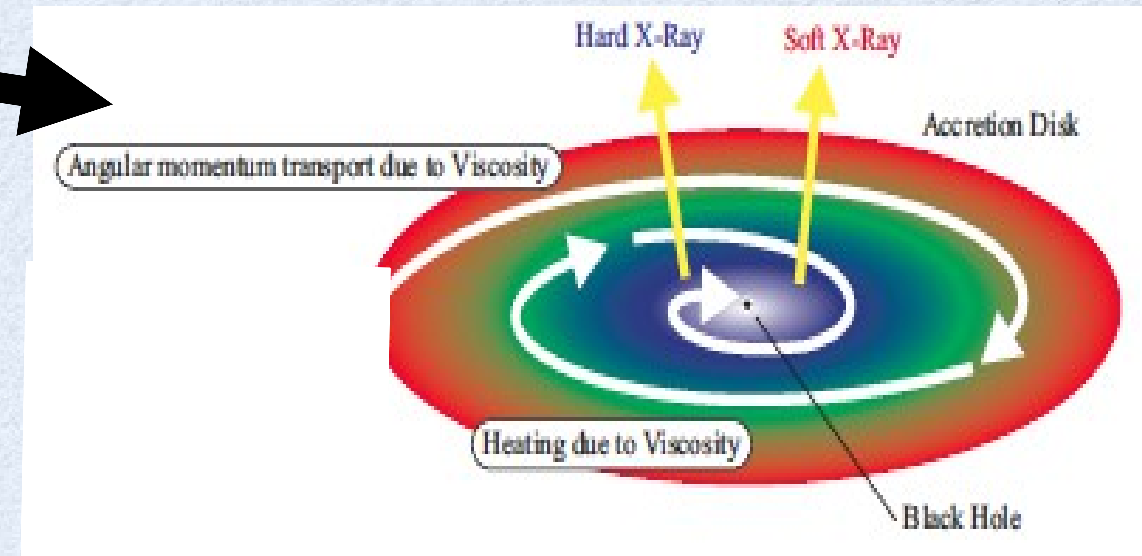
Multi-wavelength approach



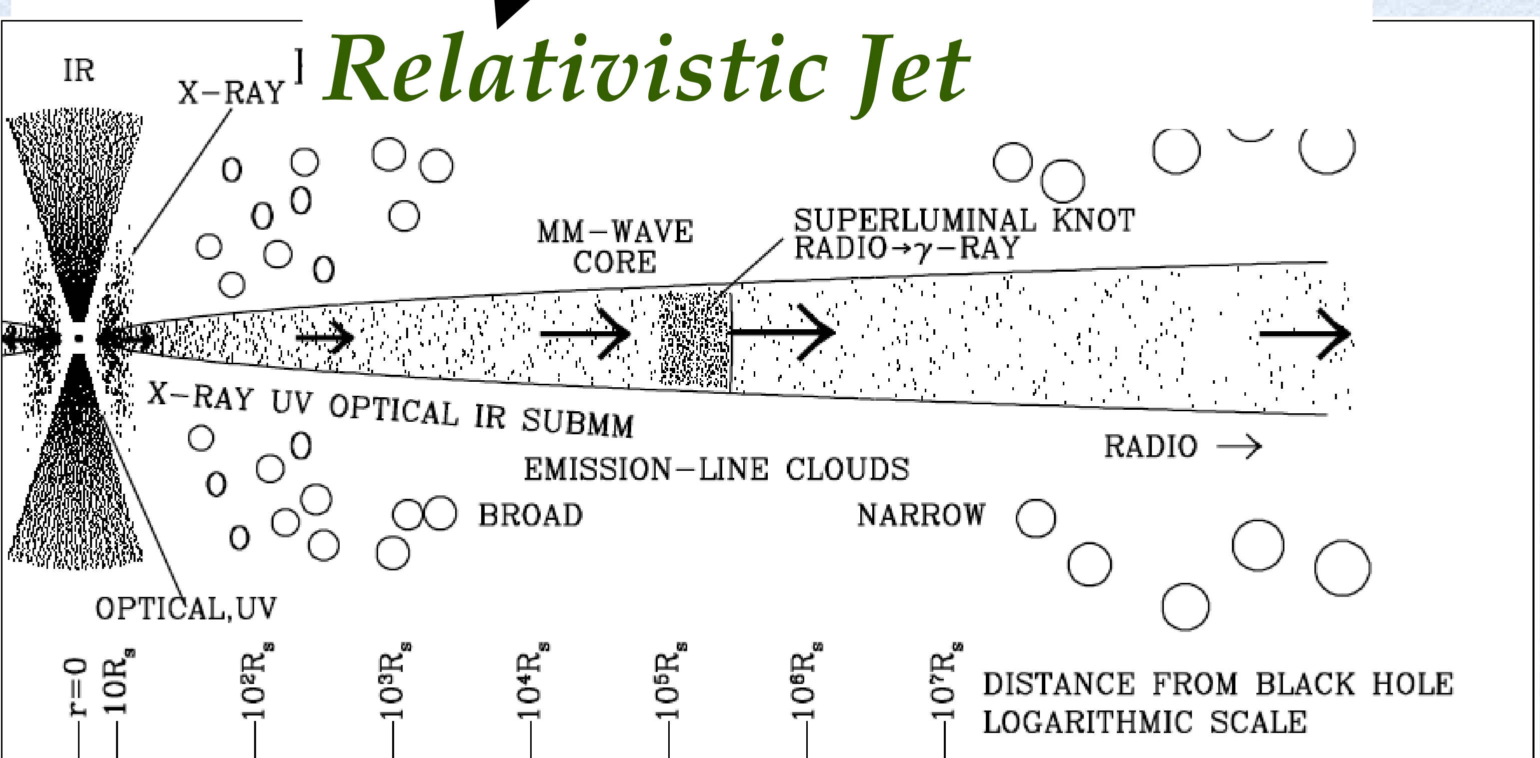
Spectral Energy Distribution



Standard disk / ADAF-RIAF

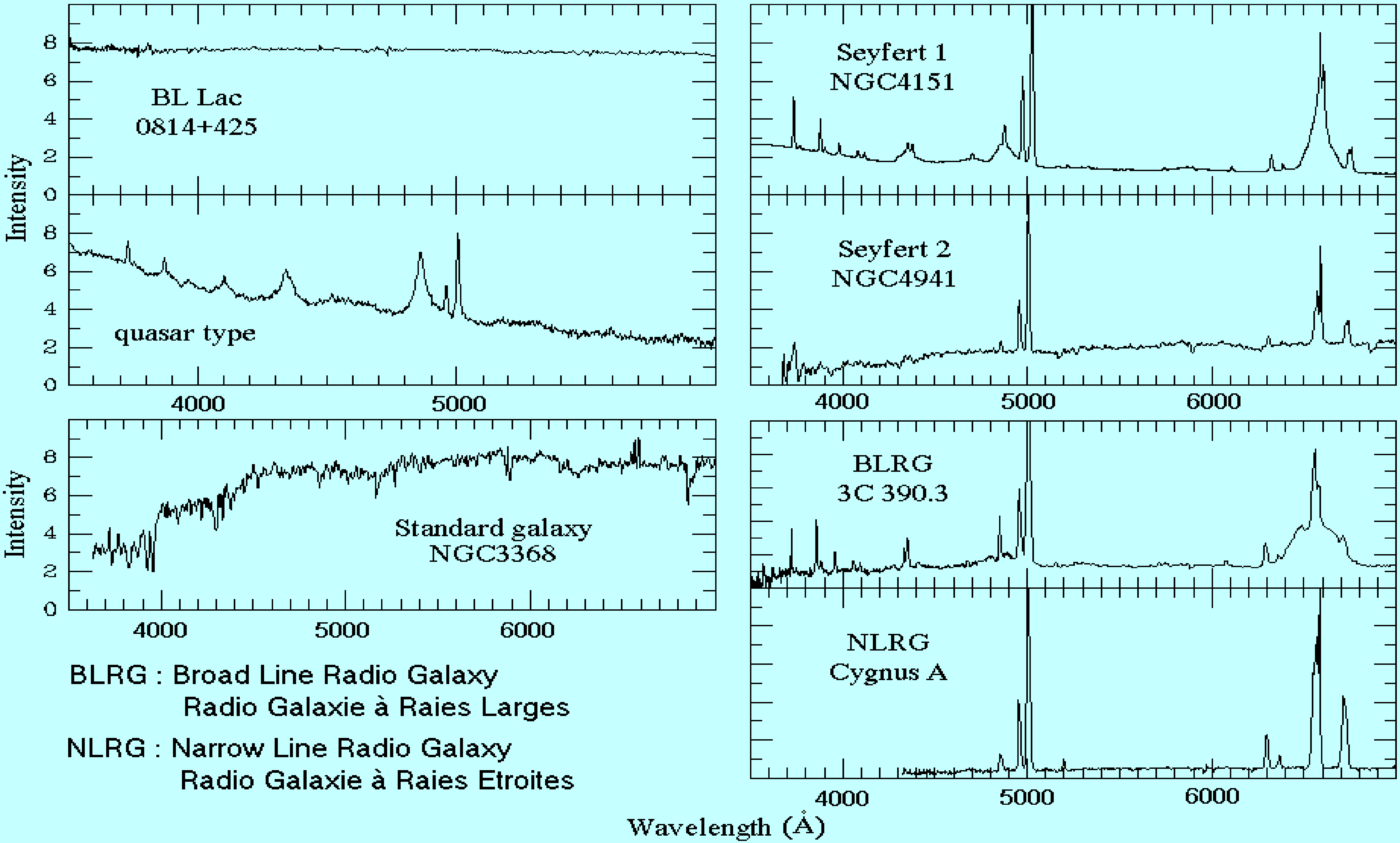


Relativistic Jet



Type of AGN (1)	L_{bol} [a] (ergs s^{-1}) (2)	Typical $\dot{M}_{bh}$ [b] ($M_\odot$ yr^{-1}) (4)
Standard disk	10^{46}–10^{48}	10–100
	10^{40}–10^{45}	10^{-3}–10^{-2}
RIAF	10^{39}–$10^{43.5}$	10^{-5}–10^{-4}

Optical Spectra

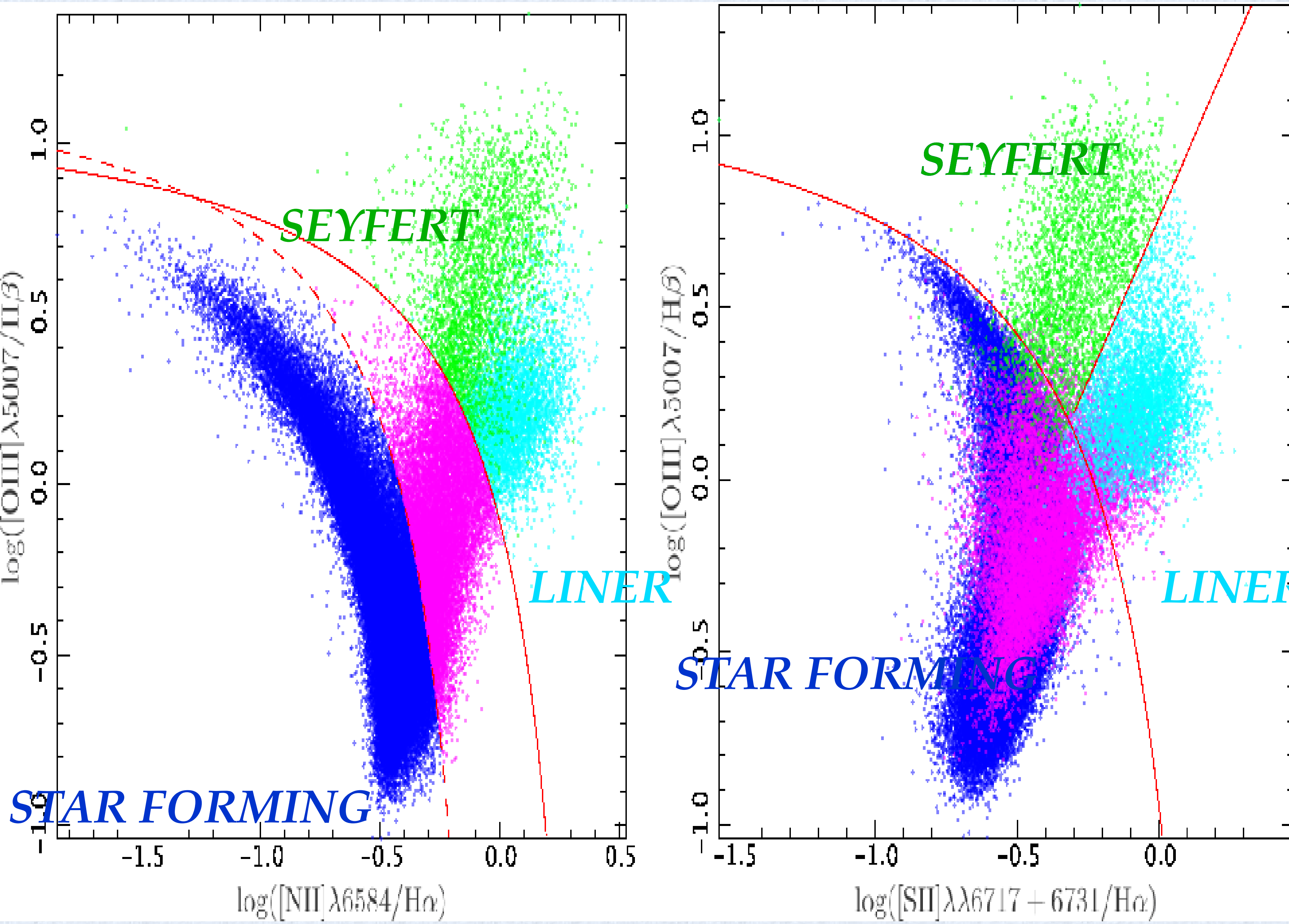


BLRG : Broad Line Radio Galaxy
Radio Galaxie à Raies Larges

NLRG : Narrow Line Radio Galaxy
Radio Galaxie à Raies Etroites

OPTICAL CLASSIFICATION

AGN can be classified on the basis of the emission line ratios.



HIGH EXCITATION GALAXIES (HEG e BLO)

(FRII)

Narrow and brod EL

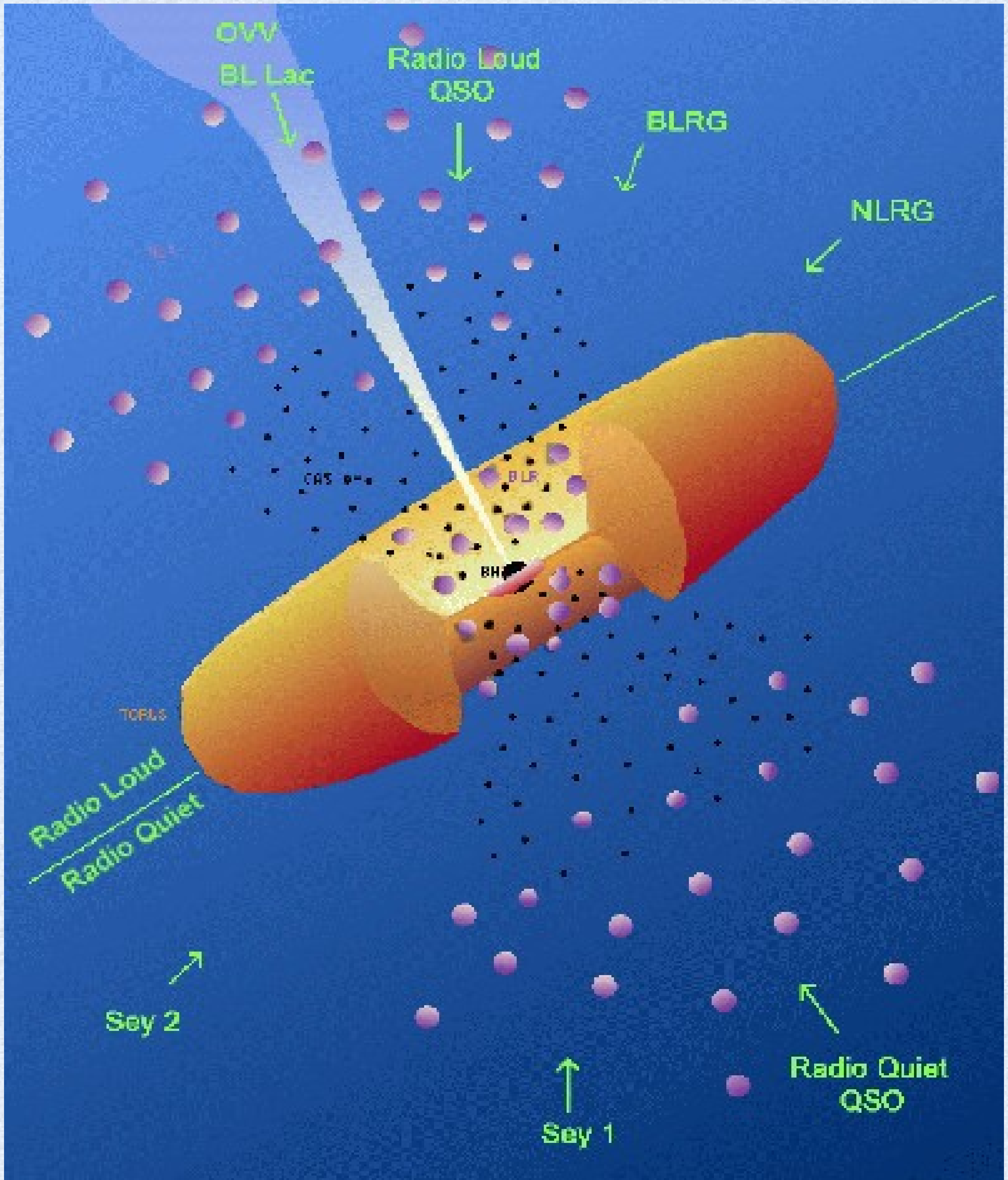
LOW EXCITATION GALAXIES (LEG)

(FRI-FRII)

Narrow EL

BPT: Baldwin+81, Kewley+06, Buttiglione+10

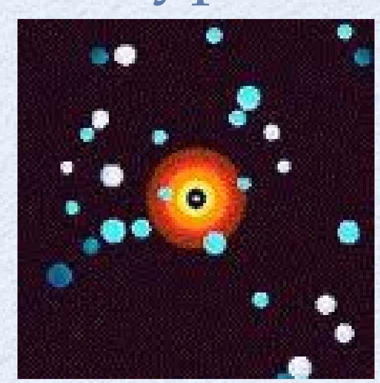
Unification Model



The simple principle of the Unification mode which try to explain the AGN phenomenology is that the differences among various types of AGN arise from orientation dependence.

RL AGN: Urry & Padovani 95
RQ AGN :Antonucci & Miller 85

Type I



Type II

The narrowed-line HEGs are the obscured counterpart of BLOs

Questions

The fundamental questions:

- ***what sets the level of activity of local radio galaxies?***
- ***Which are the properties of the hosts of local radio galaxies?***
- ***Which is the link between star formation and nuclear activity?***
- ***Which are the merger histories of local radio galaxies?***

10^{43} erg/s

FRII

HEG

LEG

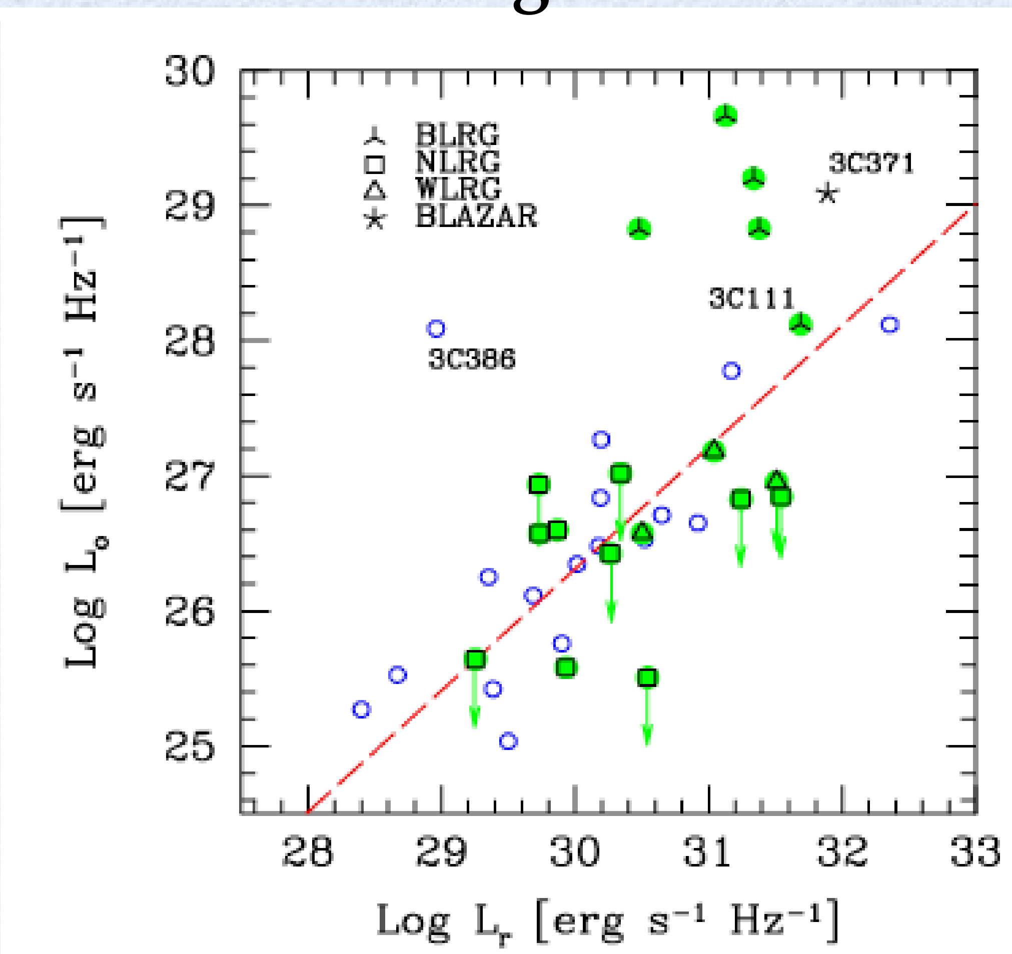
FRI

10^{38} erg/s

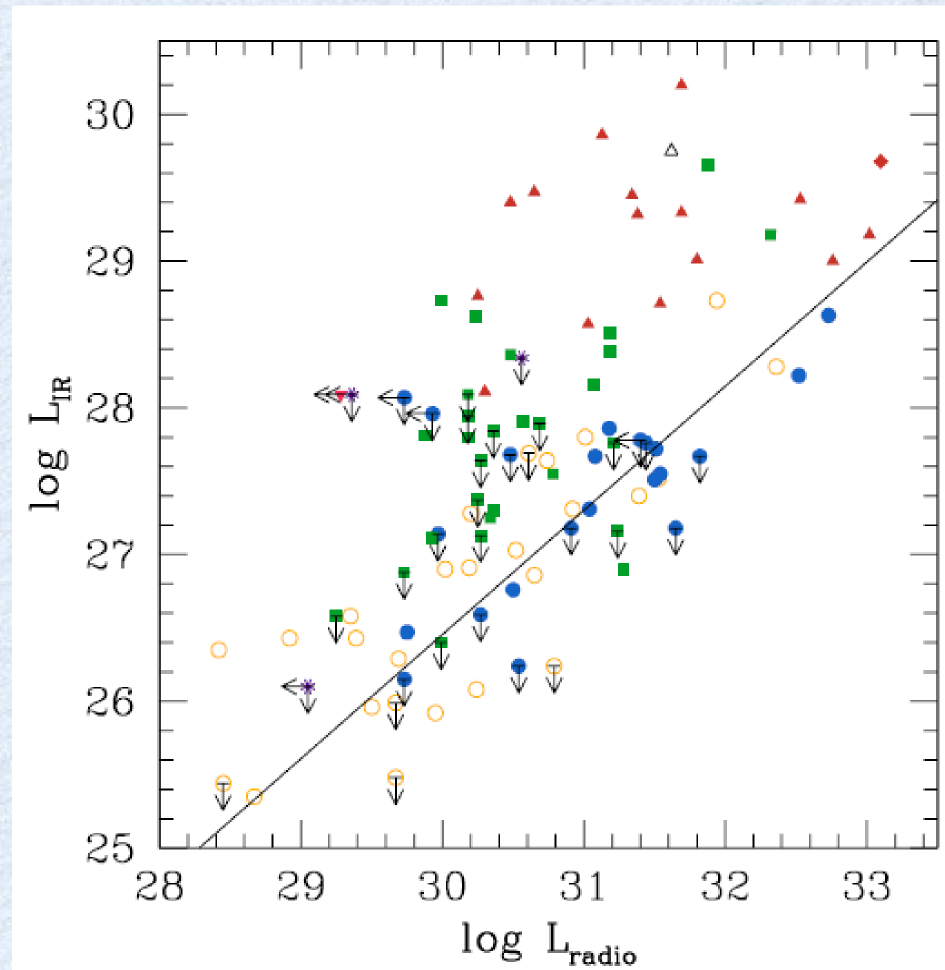
Radio Core Power

NUCLEI: LEG

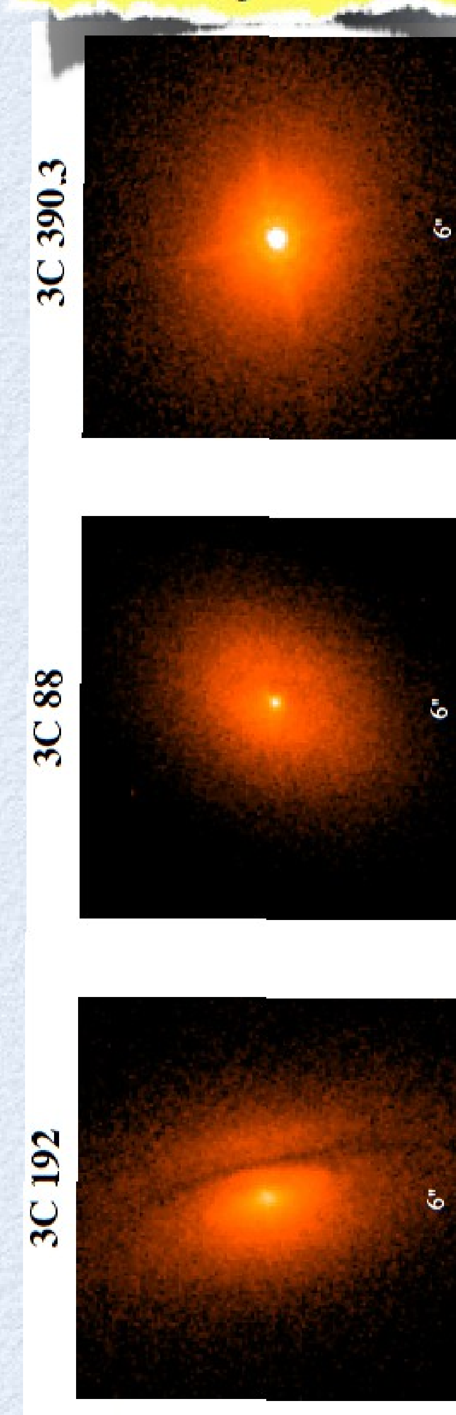
Chiaberge + 99



Baldi + 10



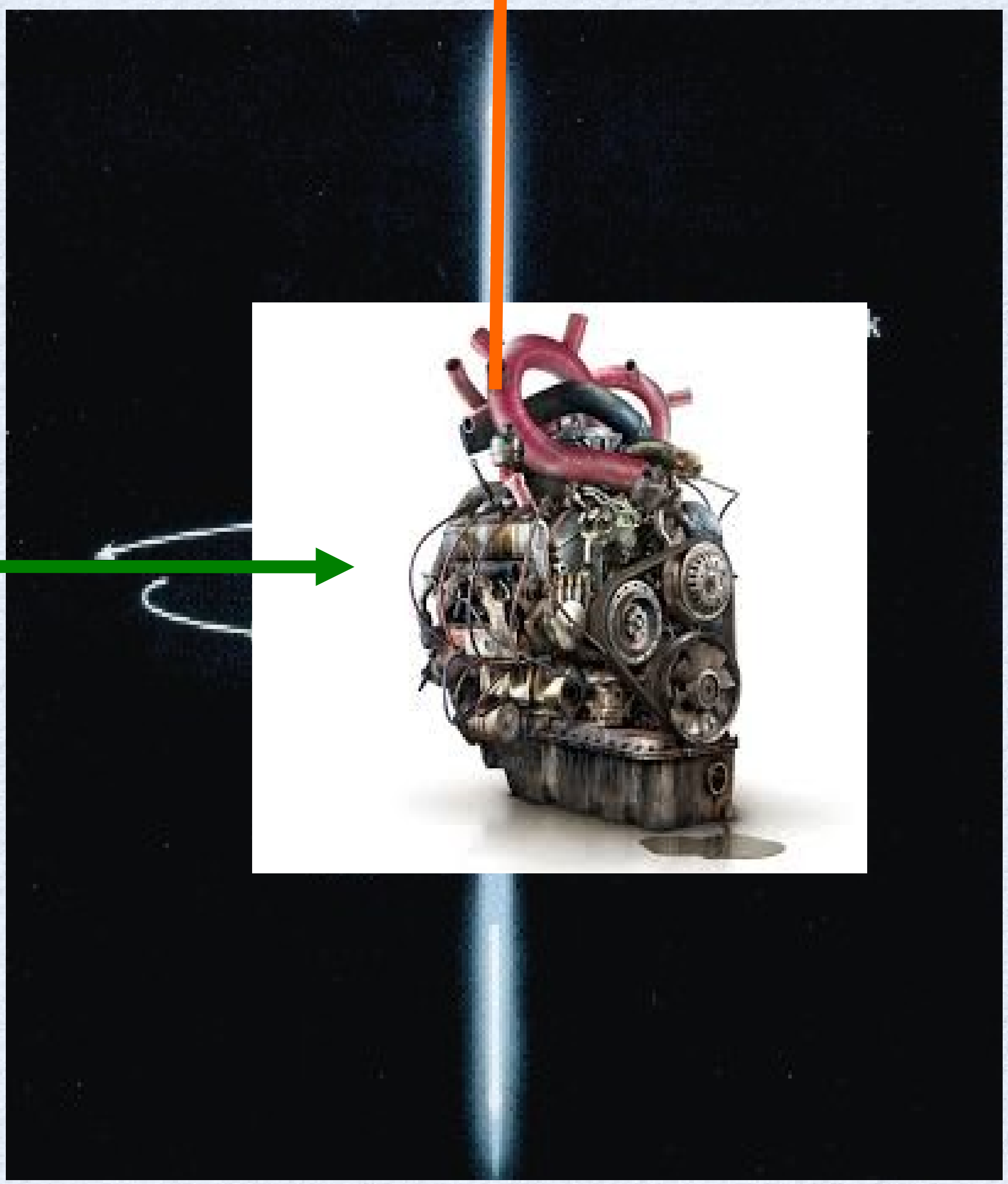
HST/ACS



- Radio-optical-infrared-Xray correlation: Synchrotron-dominated nuclei
- Sub-Eddington, low radiatively efficient disk
- No torus (for FRI)

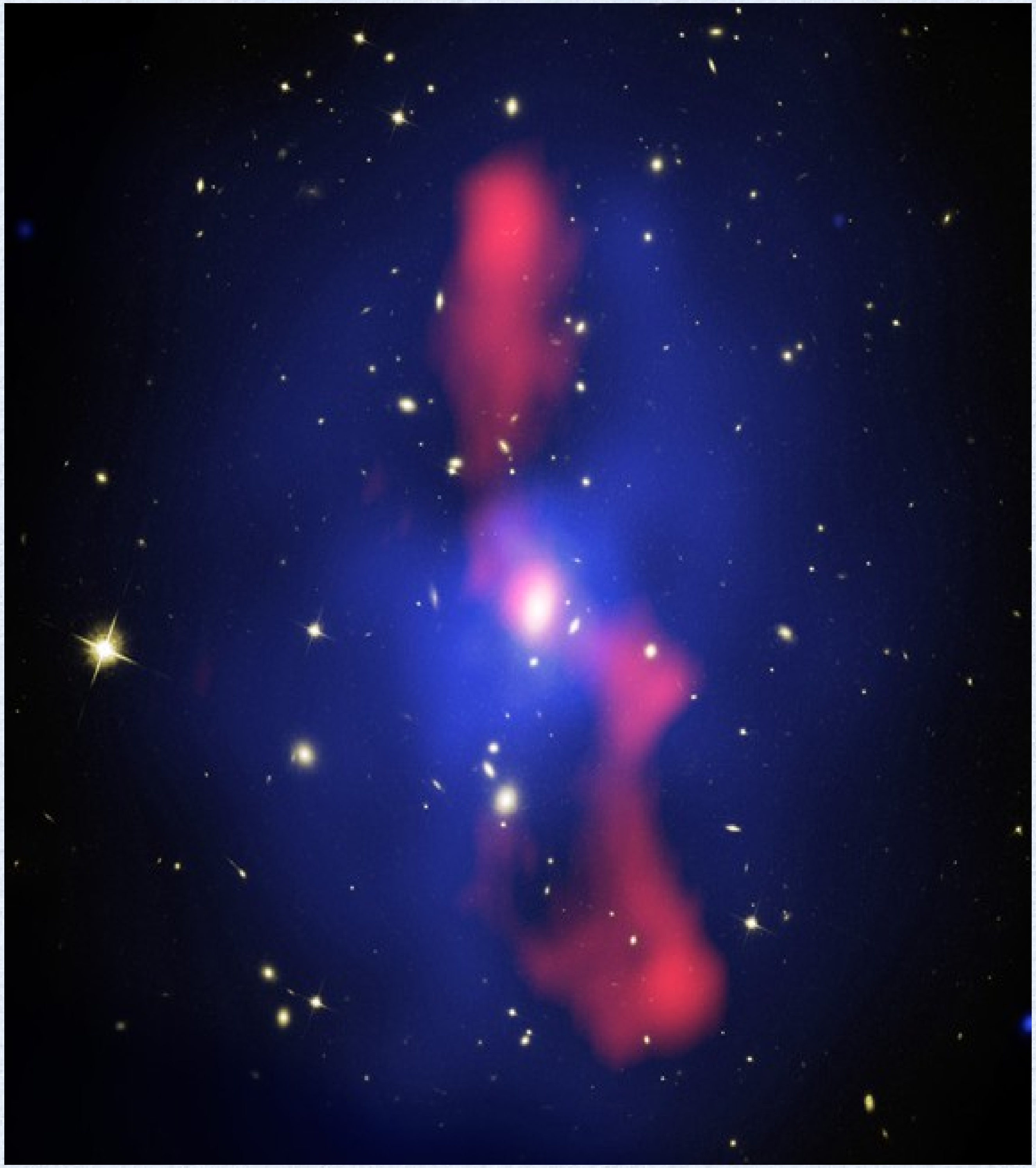
Accretion-Jet

Energy Output

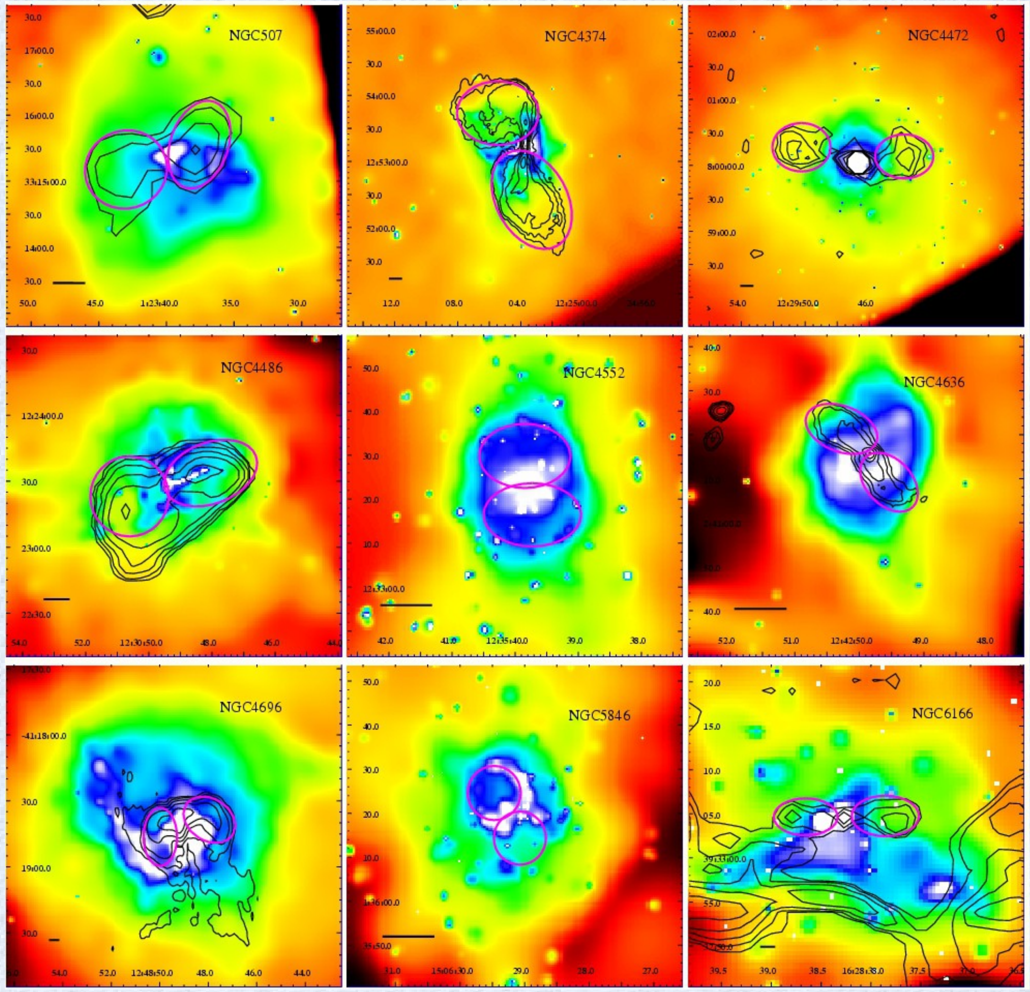


Energy Input

FRI Nuclei: Accretion



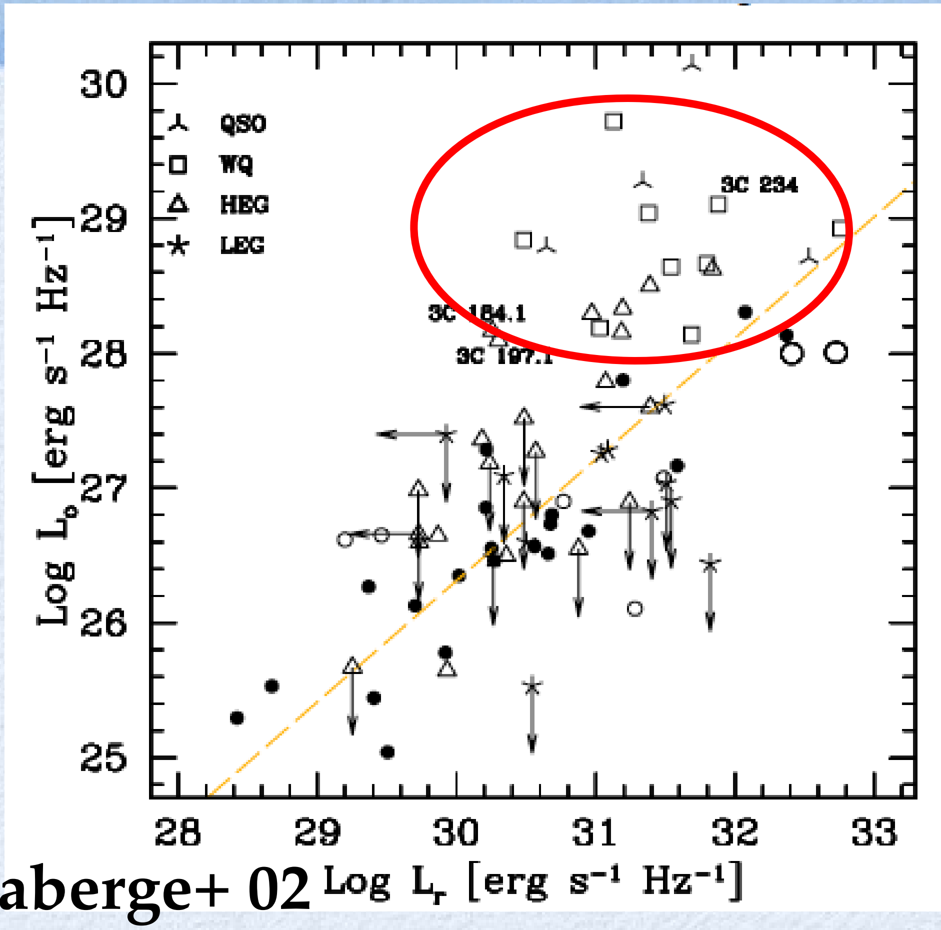
X-ray cavities



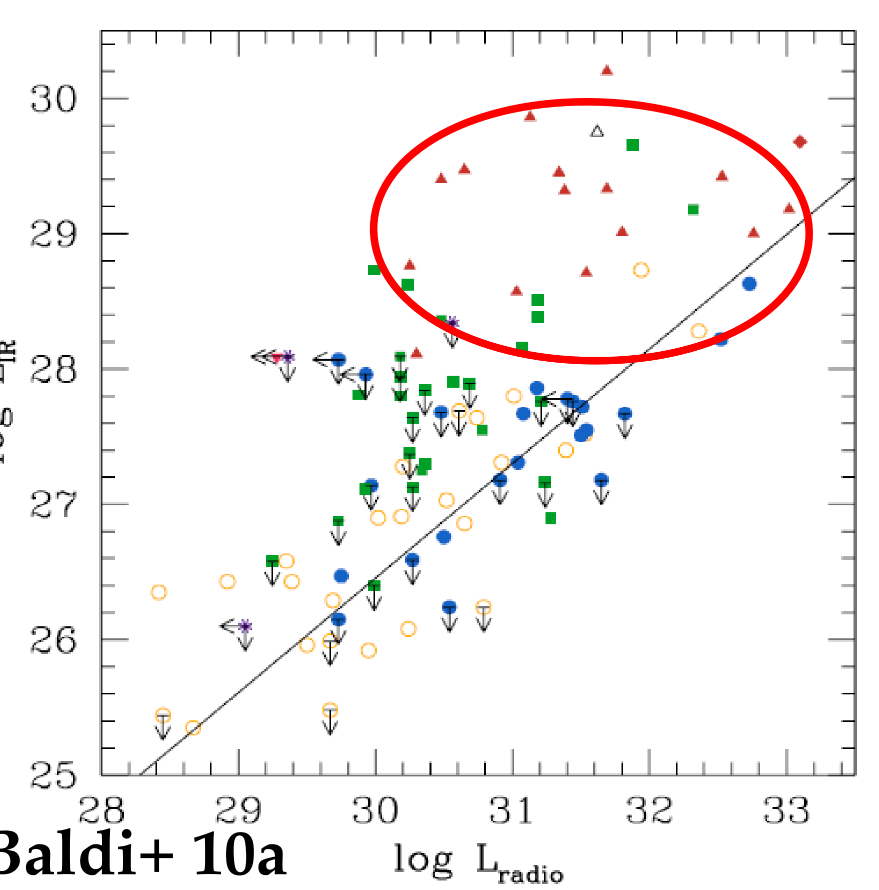
Balmaverde, Baldi & Capetti 08
Allen+ 06, Nemmen & Tchekhovskoy 14

Secular hot gas accretion sets the level of nuclear activity.

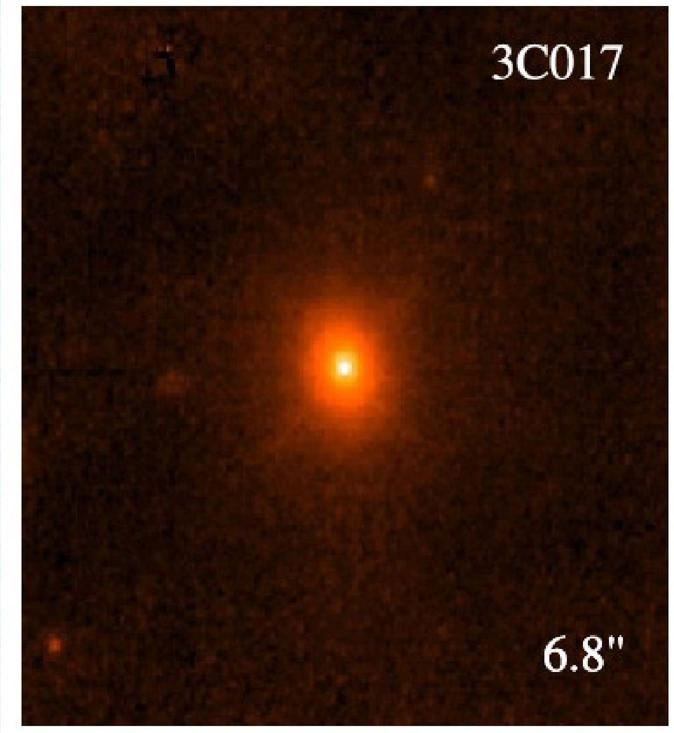
NUCLEI: HEG



Chiaberge+ 02

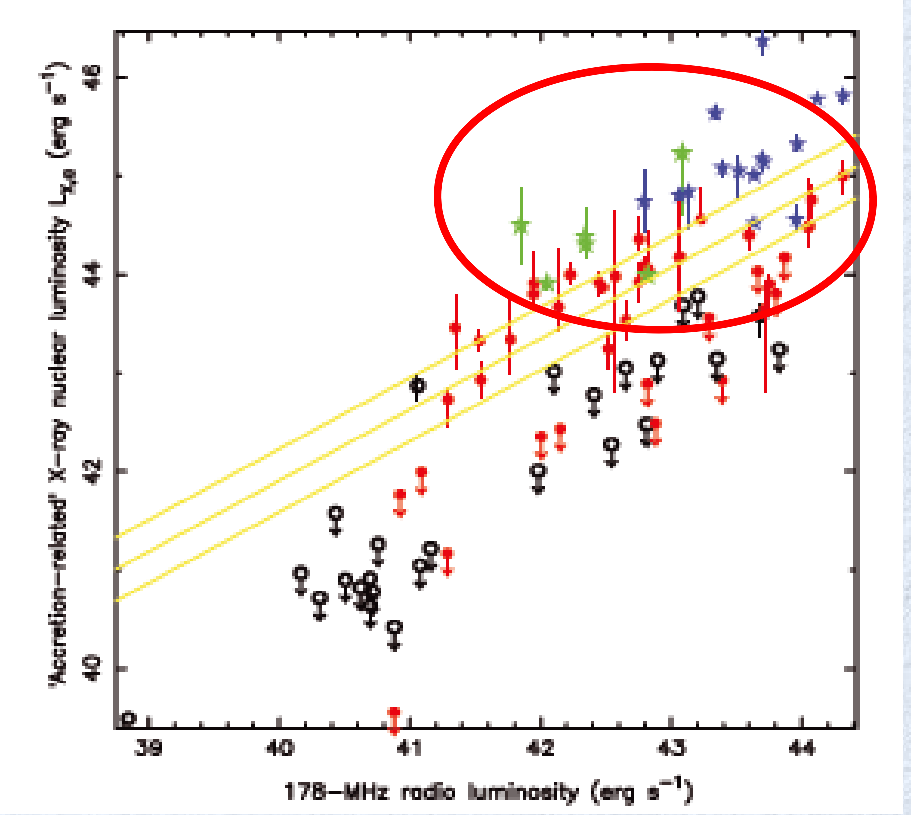


Baldi+ 10a

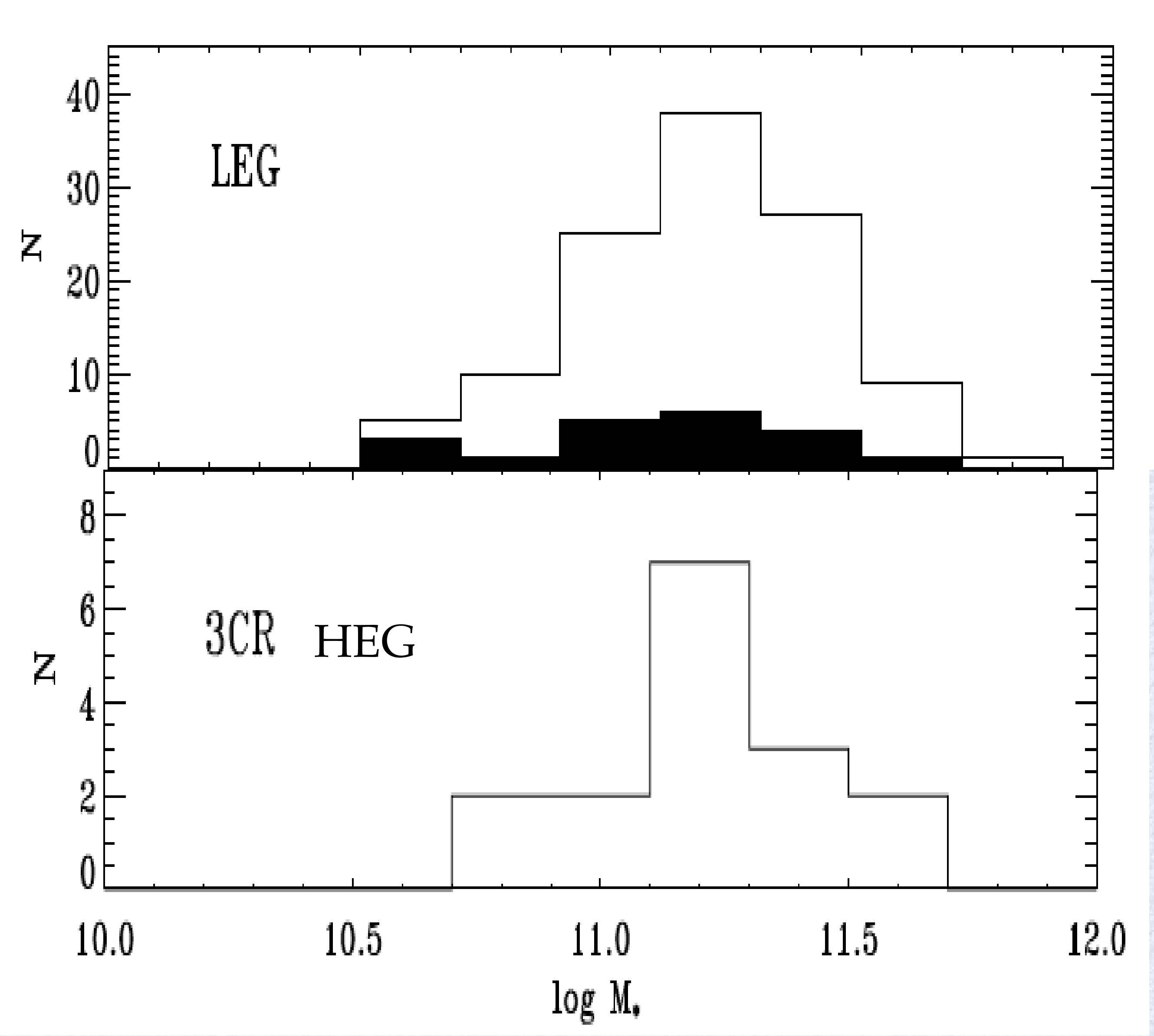


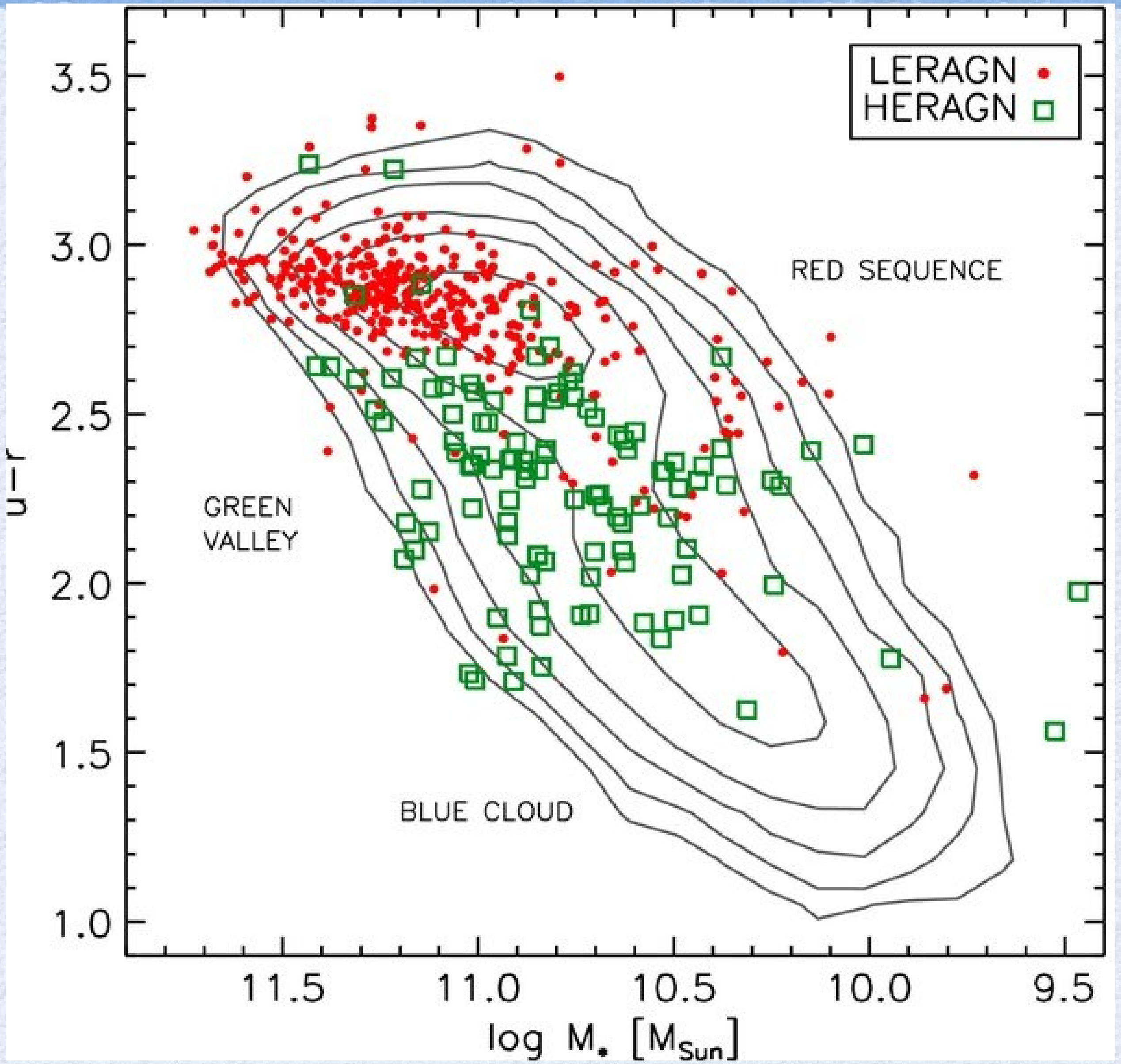
Hardcastle+ 09

- No correlation between radio and IR nuclei: no synchrotron origin
- SED analysis: IR origin from the torus and disk.
- ~fraction of Eddington rate, high radiatively efficient disk (standard thin disk)
- Torus (49.7° Baldi+13)



HOST





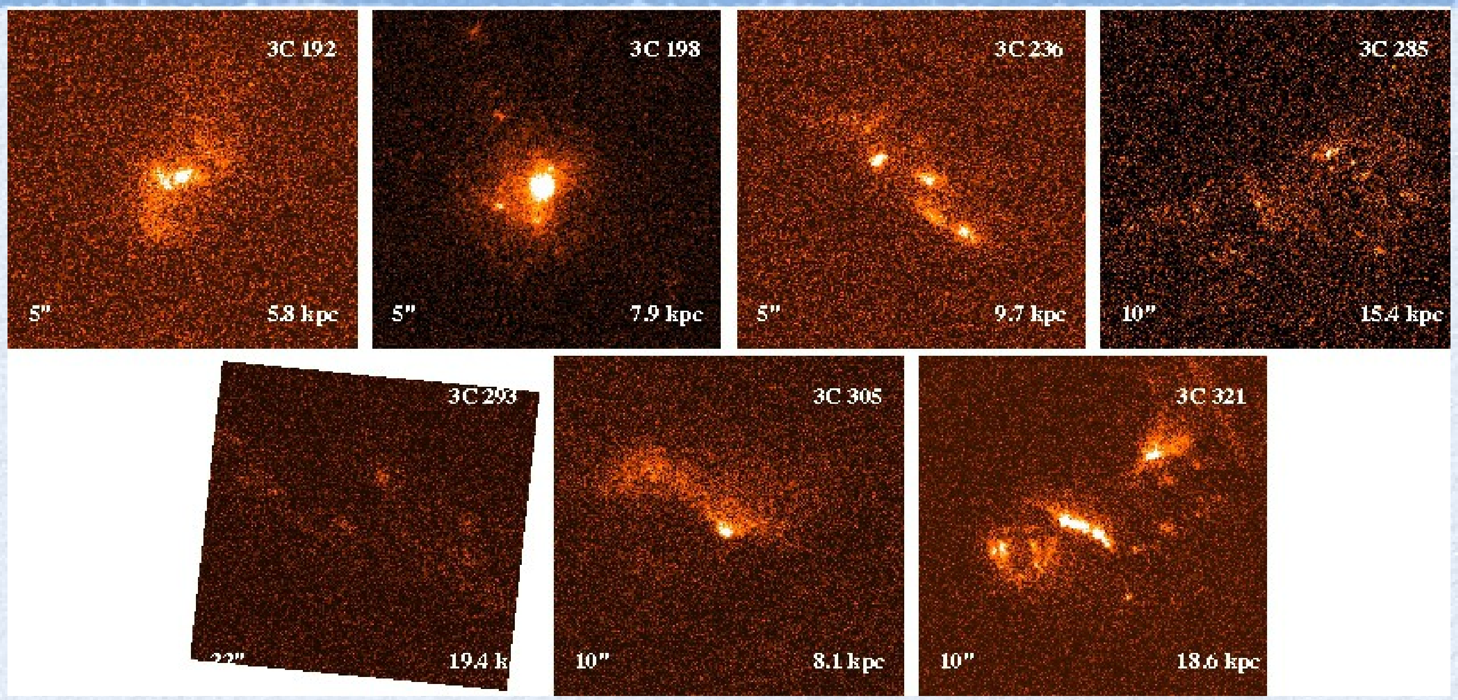
Baldi & Capetti 10b

Smolcic+ 09, Baldi & Capetti 08, 10b

Radio-loud AGN are in massive host galaxies (~$10^{10.5}$ – $10^{11.5}$ $M_\odot$)

FRI ETG are on average brighter (massive) ~0.5 mag than FRII

Star formation

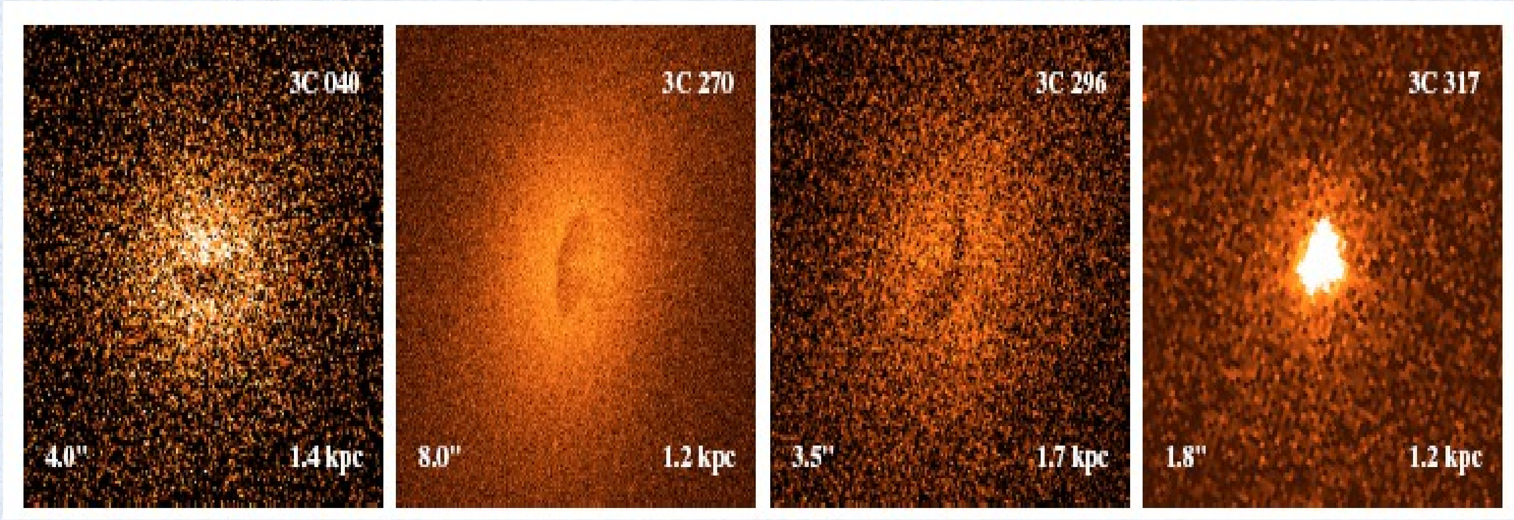


HEG: extended star formation

AGN activity triggered by a recent "wet" (gas rich) merger.

The freshly acquired gas form stars (SFR up to ~30 $M_{\odot}yr^{-1}$) and power the AGN.

LEG and FRI: no star formation



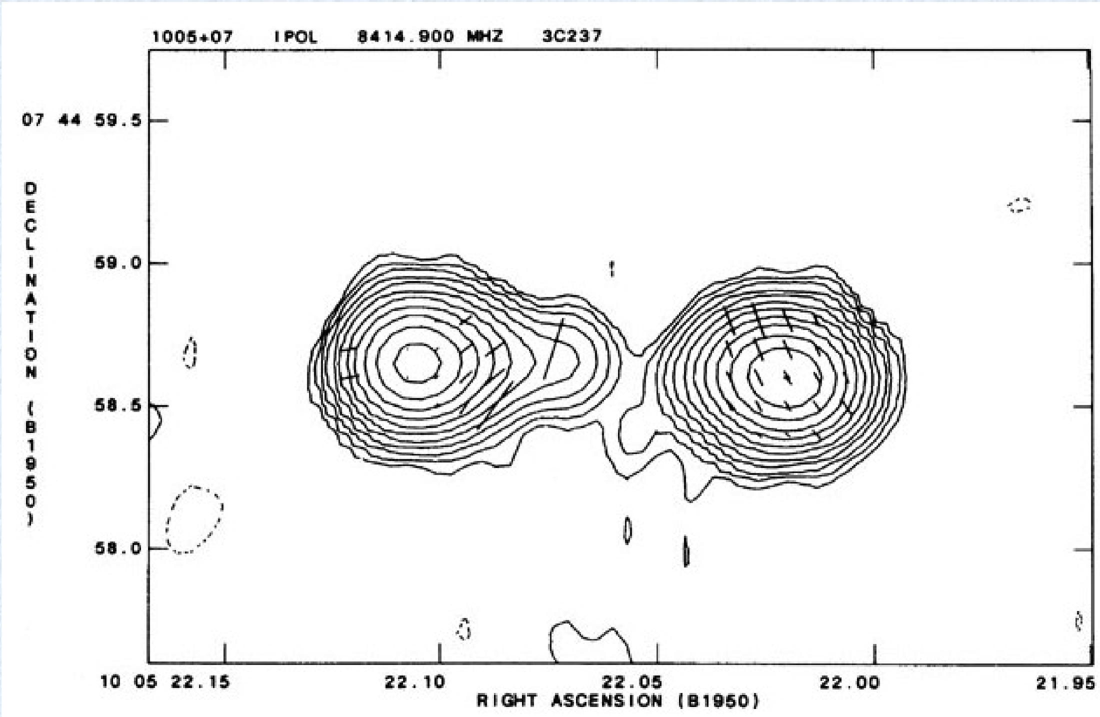
No link between AGN and mergers.

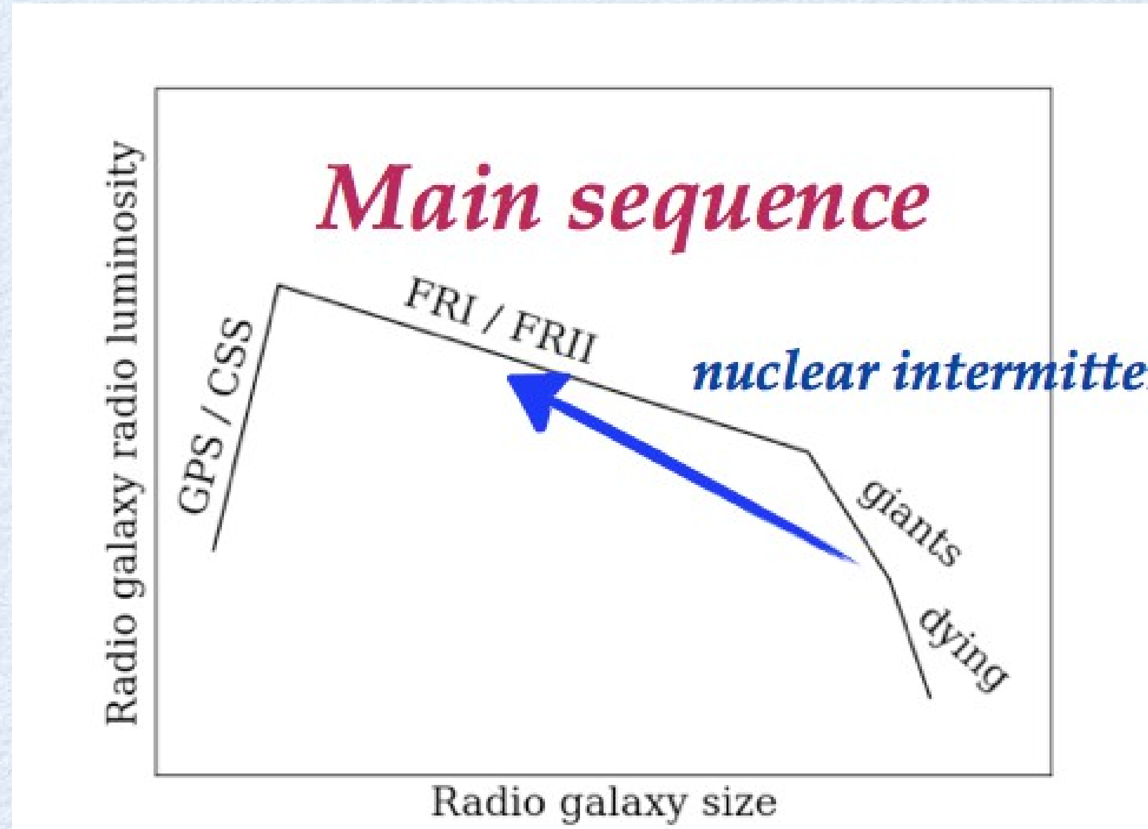
No merger or "dry" (gas poor) merger.

Read and dead host galaxies (SFR ~ few $M_{\odot}yr^{-1}$)

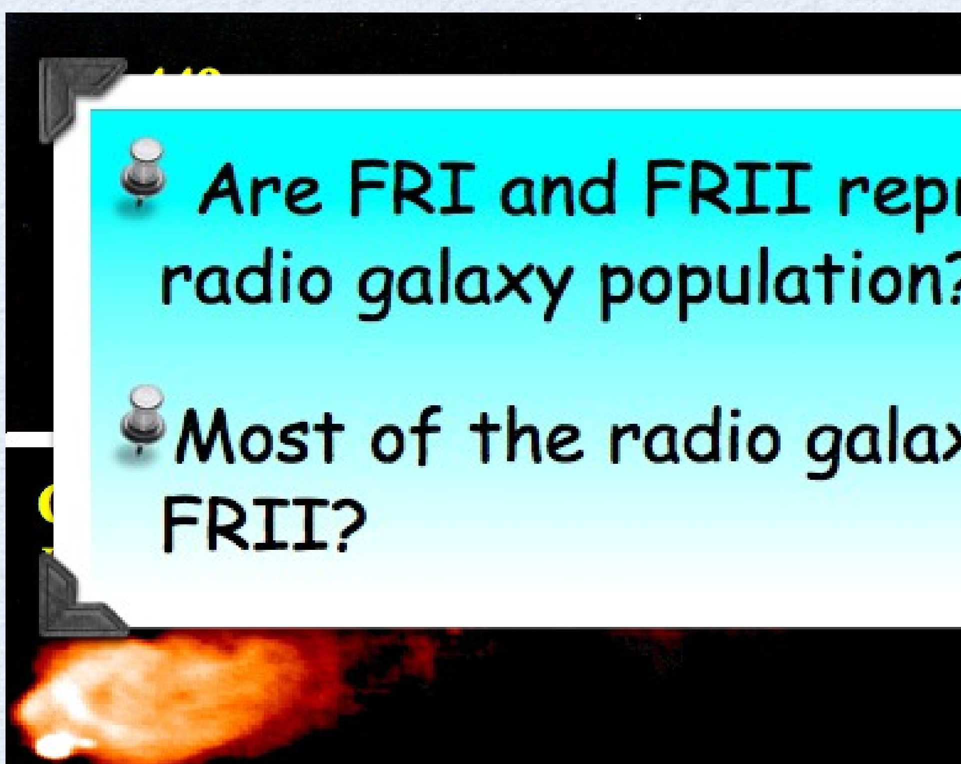
Baldi & Capetti 08

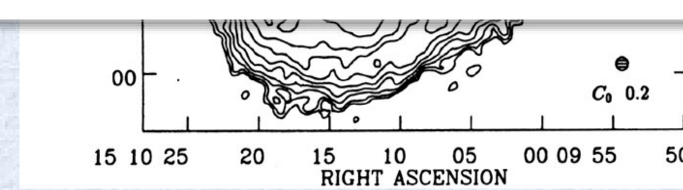
Radio Galaxy evolution





Kapinska & Kaiser 09, Snellen+ 00,
Kunert-Bajraszewska+ 10, An & Baan 12

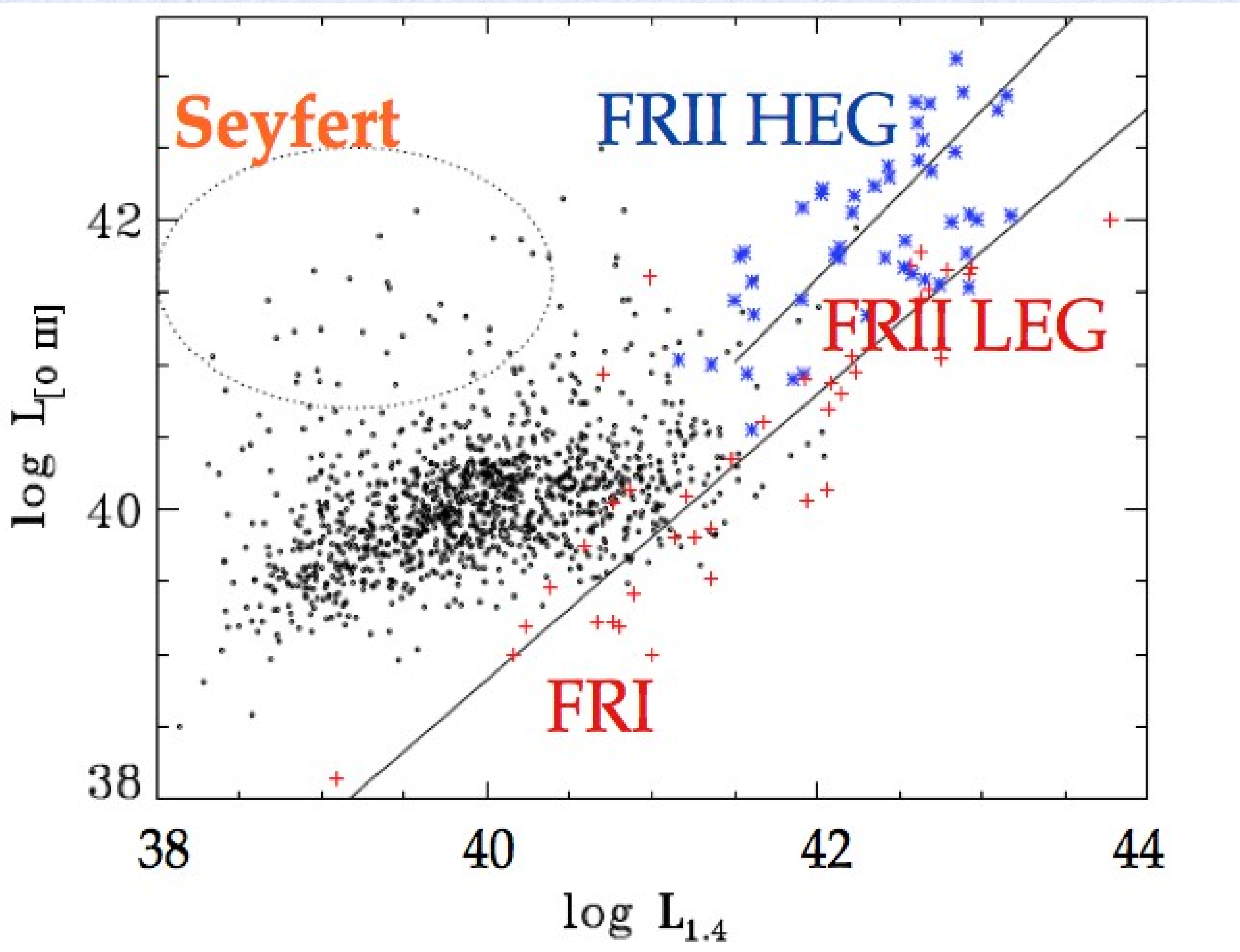




- Are FRI and FRII representative of the “main sequence” radio galaxy population?
- Most of the radio galaxies in the (local) Universe are FRI or FRII?

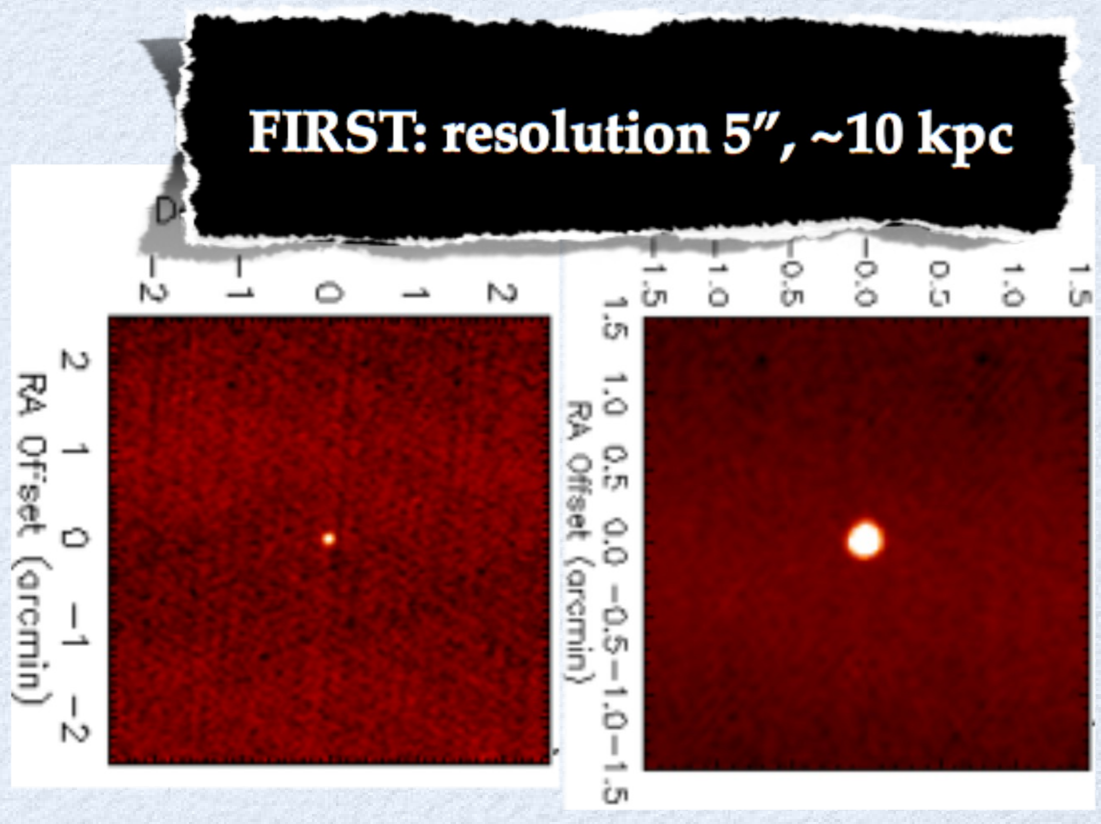
Local RL AGN population

Best et al (2005) select 2215 low-luminosity radio-loud AGN (F > 5mJy) cross-matching SDSS (DR2) and NVSS and FIRST in the local Universe (z < 0.3)



Baldi & Capetti 10b

Most of the Best el al. sample shows a clear deficit in total radio emission with respect the classical radio galaxies FRI and FRII.



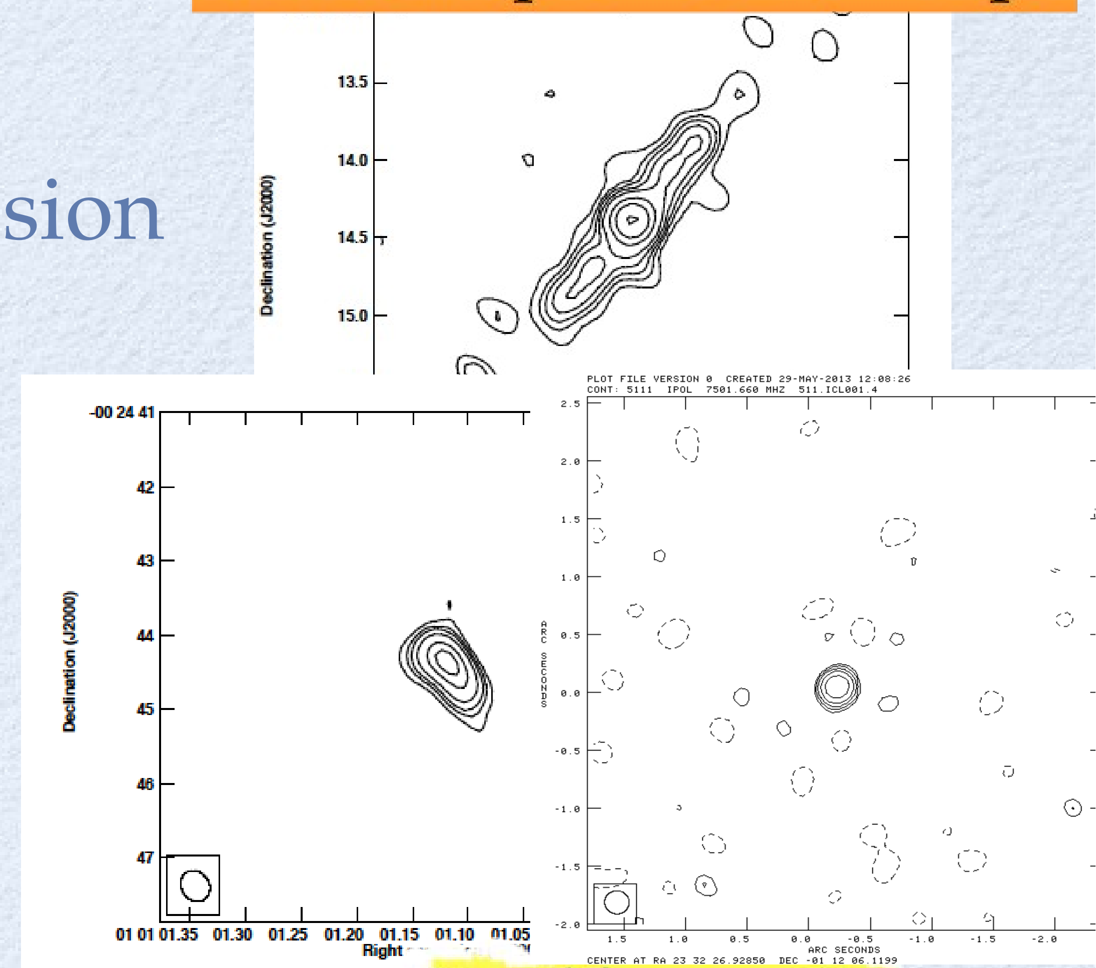
FR 0 radio galaxies

Baldi & Capetti 09; Baldi, Capetti, Giovannini 15

- Compact radio morph < some kpc
- Lack of substantial extended radio emission
- High core dominance
- Nuclear luminosity ~10^{40} erg/s similar to FRI → **hot gas accretion**
- LEG spectrum
- Red (elliptical) hosts
- Dominant radio class of the radio-loud AGN population

} FRI

Radio maps: < 0.2″, < 3kpc



Sadler+ 14

Compact FR0 are the dominant source population at 20 GHz (AT20G-6dFGS sample)

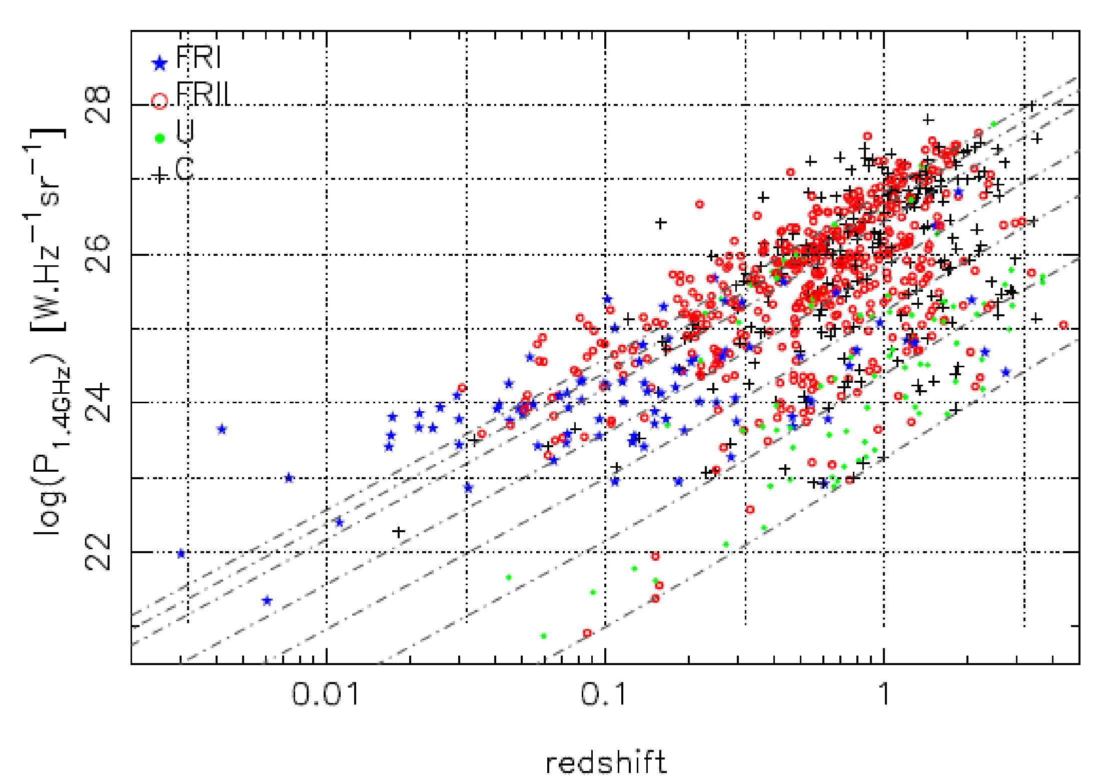
Local radio galaxies

LOW-POWER RG → *RED HOST*
HOT GAS ACCRETION MODE

HIGH-POWER RG → *BLUE HOST*
COLD GAS ACCRETION MODE

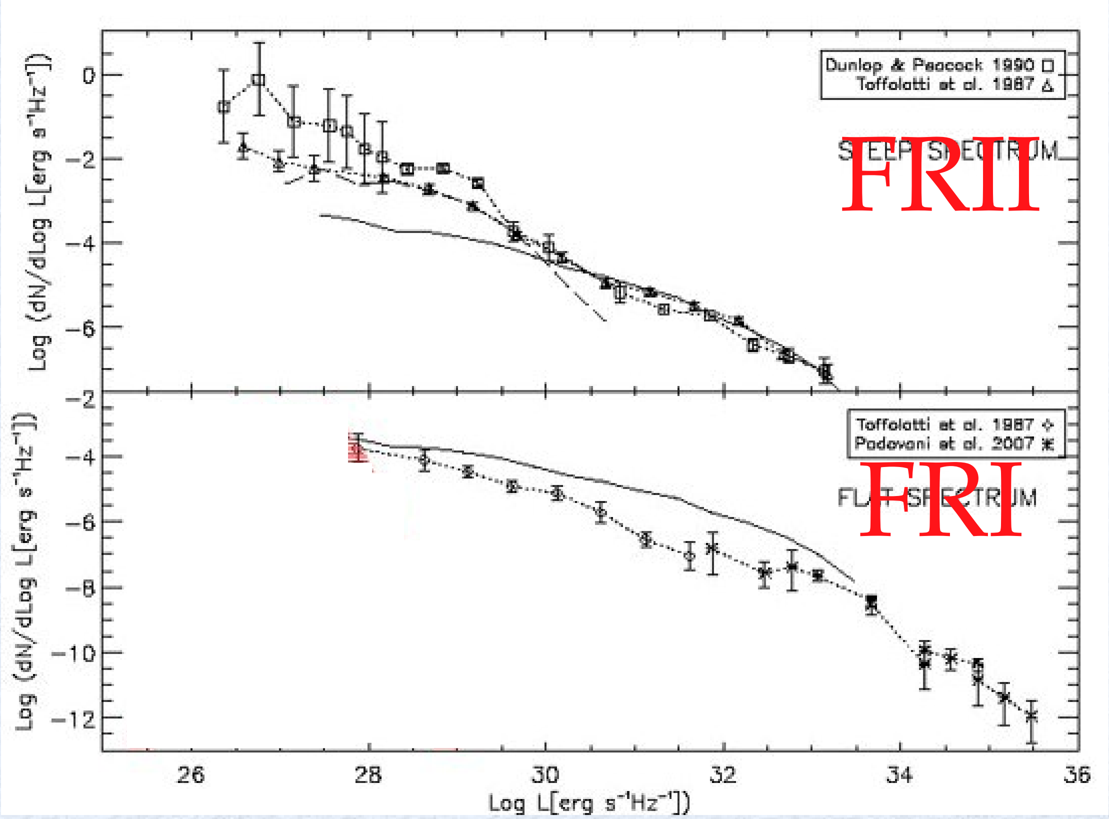
High-z Radio Galaxies

- Our knowledge of RG at high z is exclusively based on studies of FRII



Gendre, Best, Wall 10

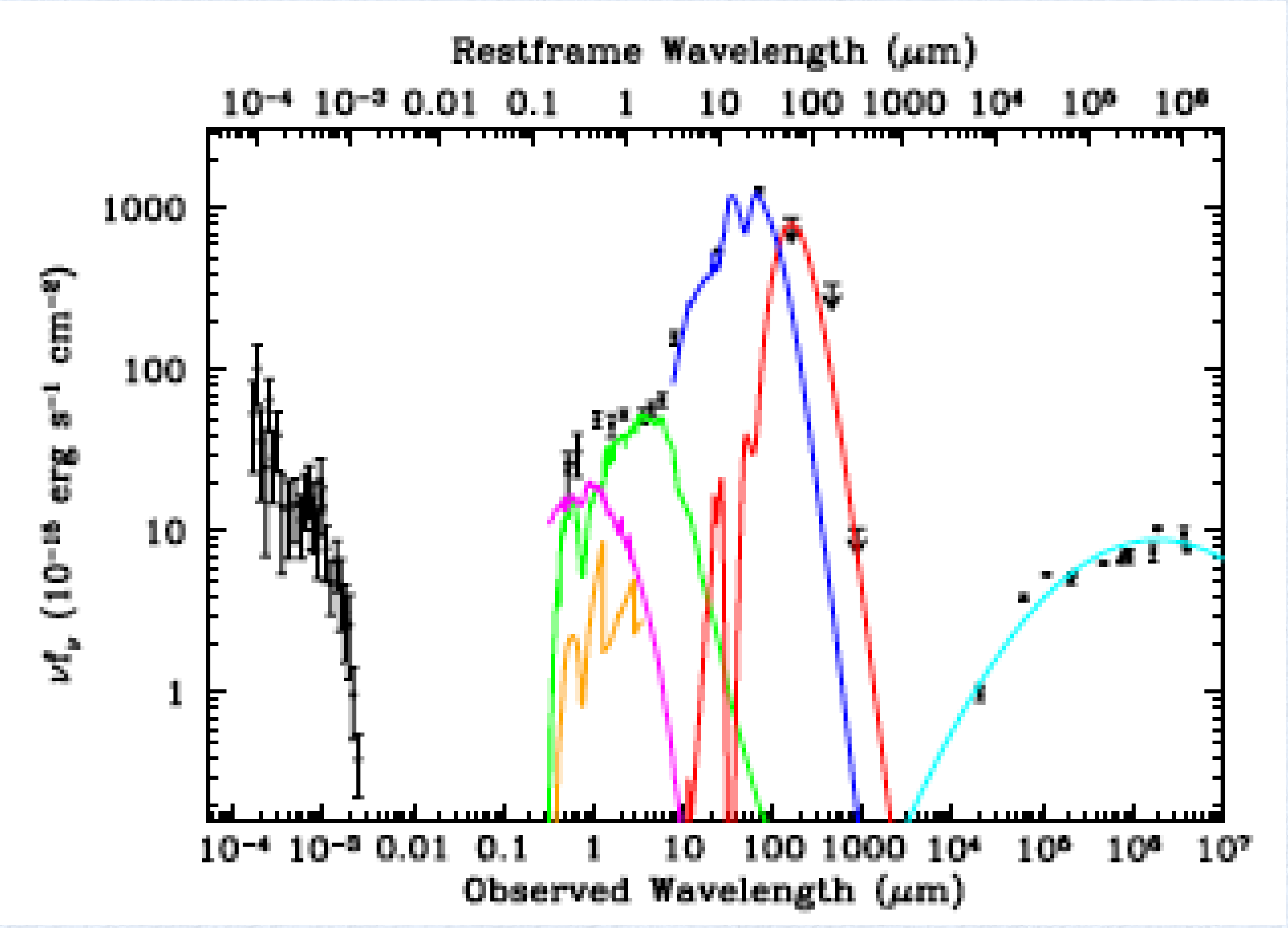
Dunlop & Peacock 90, Condon+ 02,



- The missing piece of the puzzle? study of FRI at high z.

HIGH-Z RADIO GALAXY

QUASAR

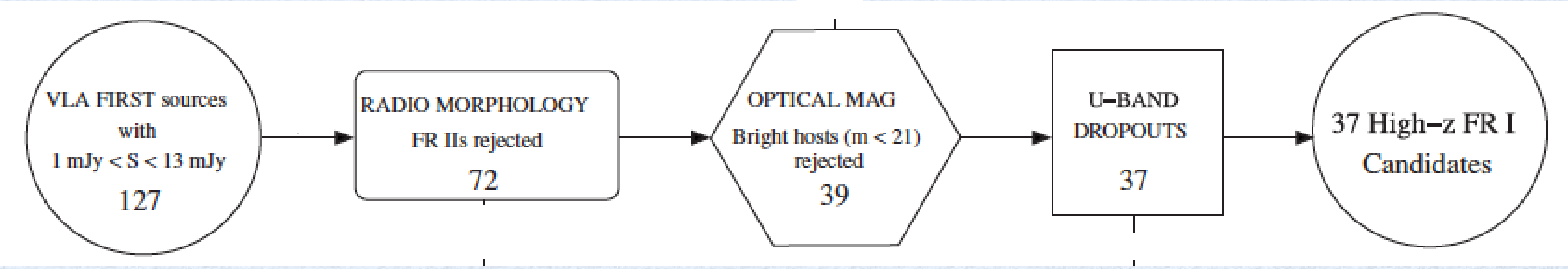


High-z radio galaxies usually associated with Massive galaxies, (obscured) quasar, high star formation, (proto-) cluster (e.g., review from Miley & De Breuck 08)

Constituent	Observable	Typical Diagnostics	Refs.	Mass ($M_\odot$)
Relativistic plasma	Radio continuum	Magnetic field, age, energetics, pressure, particle acceleration. Jet collimation and propagation	1,2	
	X-ray continuum	Magnetic field, equipartition, pressures	3,4,1	
Hot ionized gas $T_e \sim 10^7$–10^8K $n_e \sim 10^{-1.5}$cm^{-3}	Radio (de)polarisation	Density, magnetic field,	1	10^{11-12}
	X-rays	Temperature, density mass		
Warm ionized gas $T_e \sim 10^4$–10^5K $n_e \sim 10^{0.5-1.5}$cm^{-3}	UV-optical emission lines	Temperature, density, kinematics, mass, ionisation, metallicity, filling factor	5,6,7,8	$10^{9-10.5}$
	Nebular continuum	SED contamination	9,10	
Cool atomic gas $T_s \sim 10^3$K n(HI) $\sim 10^1$cm^{-3}	HI absorption	Kinematics, column densities, spin temperature, sizes, mass	11,8	10^{7-8}
	UV-optical absorption lines	Kinematics, mass, column densities, metallicity	8,12 13,14	
Molecular gas T ~ 50 - 500K $n(H_2) > 10^2$ cm^{-3}	(Sub)millimeter lines	Temperature, density, mass	15	10^{10-11}
Dust T ~ 50 - 500K	UV-optical polarisation	Dust composition, scattering, mass, hidden quasar	16 17	10^{8-9}
	(Sub)millimeter continuum	Temperature, mass, heating source	18	
Old stars t > 1 Gyr	Optical to near IR continuum	Age, mass, formation epoch	19	10^{11-12}
Young stars t <0.5 Gyr	UV-optical	Star formation rates, ages	20,8	10^{9-10}
	Lyα	Star formation rate	20	
Quasar (hidden or dormant)	UV-optical polarisation broad lines	Luminosity	21,22	
Supermassive black hole	Extended radio, Quasar	Formation, evolution	23,24	$\sim 10^9$

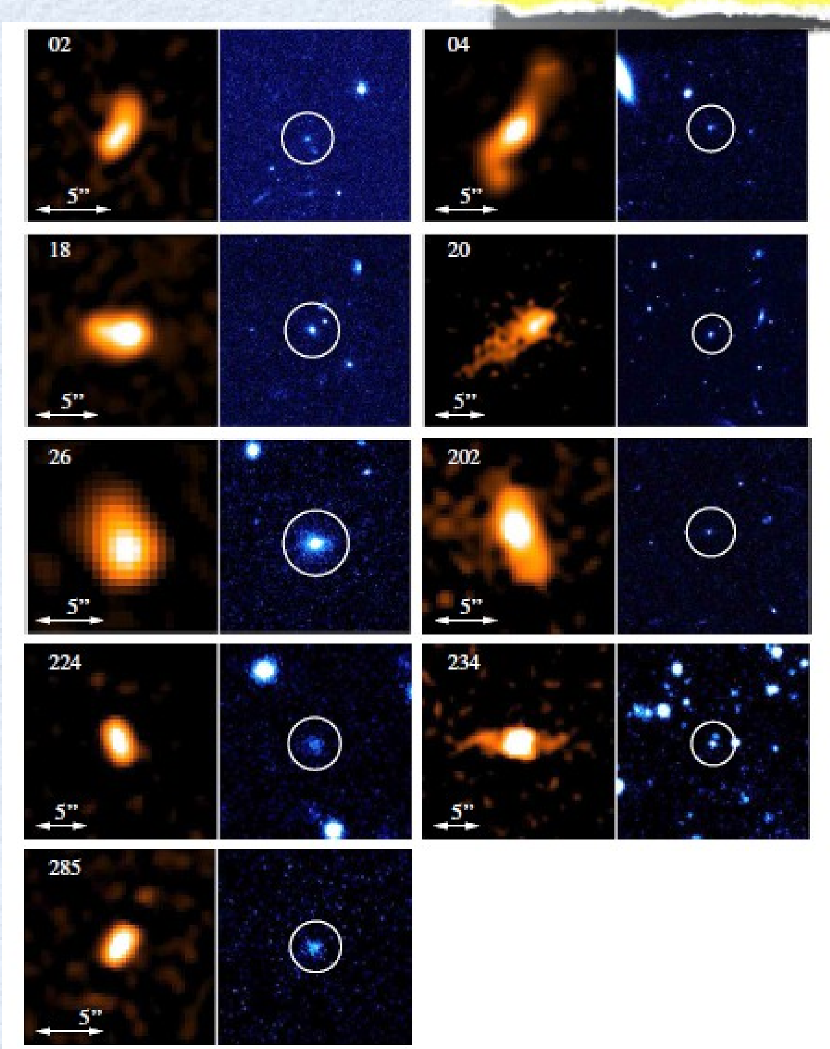
FRI AT HIGH Z

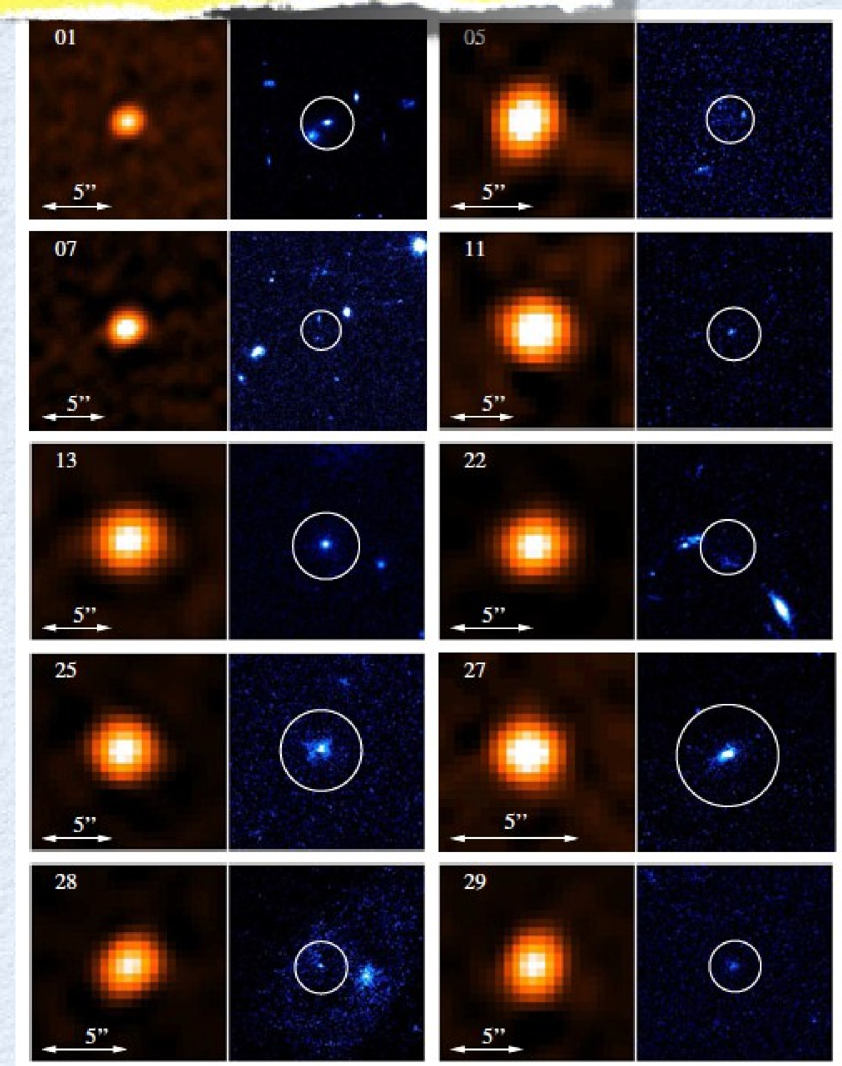
- a few FRI in 7C sample (Heywood + 07) and two possible FRI in HDF (Snellen & Best 01)
- Chiaberge + 09 selected the first sizeable sample of 37 FRI candidates at z≳1 in the COSMOS field.
- 4-steps selection criteria: radio ($1 < F < 13$ mJy), optical ($m_i > 21$), no FRII, independent of photo-z



FRI candidates

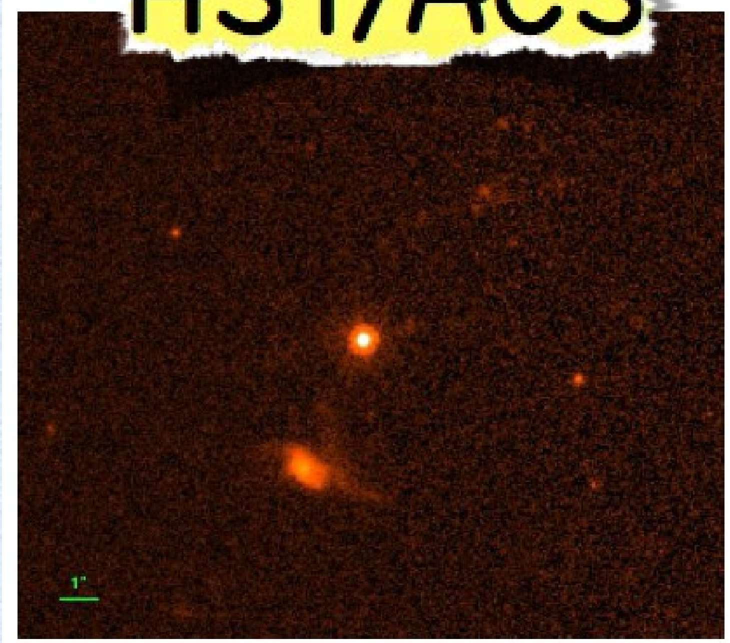
VLA-COSMOS





5″-> ~40 kpc @ z=1.5
~ 1.5'' resolution

HST/ACS



- Extended and compact radio sources
- 1< z < 2 , Ilbert + 09, Mobasher + 07
- Host: no clear spirals and one QSO (Prescott + 06)

FR0???

COSMOS SURVEY

- COSMOS survey provides multi-wavelength imaging and spectroscopy from radio to X-ray, covering a 2 deg^2.
- It includes HST, Subaru, GALEX, Spitzer data

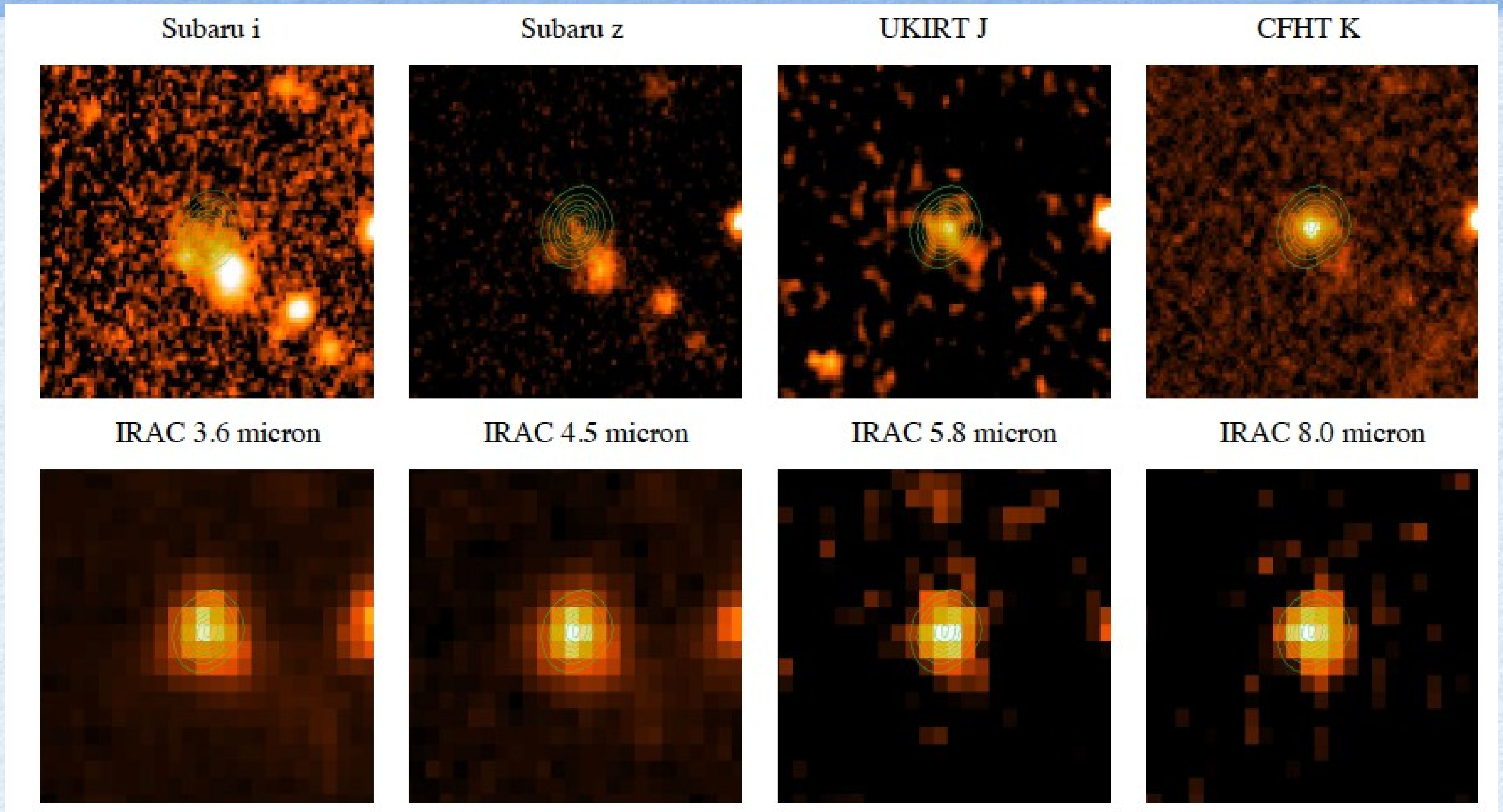
COSMOS catalog: i < 25

COSMOS BROAD BANDS AND THEIR PROPERTIES.

Filter	Telescope	λ_{eff}	FWHM	sensitivity
FUV	GALEX	1538.6Å	230.8Å	25.7
NUV	GALEX	2315.7Å	789.1Å	26.0
u^*	CFHT	3911.0Å	538.0Å	26.5
B_J	Subaru	4439.6Å	806.7Å	27.0
g^+	Subaru	4728.3Å	1162.9Å	27.0
V_J	Subaru	5448.9Å	934.8Å	26.6
r^+	Subaru	6231.8Å	1348.8Å	26.8
i^*	CFHT	7628.9Å	1460.0Å	24.0
i^+	Subaru	7629.1Å	1489.4Å	26.2
$F814W$	HST	8037.2Å	1539.0Å	27.2
z^+	Subaru	9021.6Å	9021.6Å	25.2
J	UKIRT	12444.1Å	1558.0Å	23.7
K_S	NOAO	21434.8Å	3115.0Å	21.6
K	CFHT	21480.2Å	3250.0Å	23.7
IRAC1	Spitzer	35262.5Å	7412.0Å	23.9
IRAC2	Spitzer	44606.7Å	10113.0Å	23.3
IRAC3	Spitzer	56764.4Å	13499.0Å	21.3
IRAC4	Spitzer	77030.1Å	28397.0Å	21.0
MIPS1	Spitzer	23.68μm	4.7μm	29.6

Capak+ 07, 08, Taniguchi+ 08
Koekemoer + 07, Sanders + 07

Counterpart identification

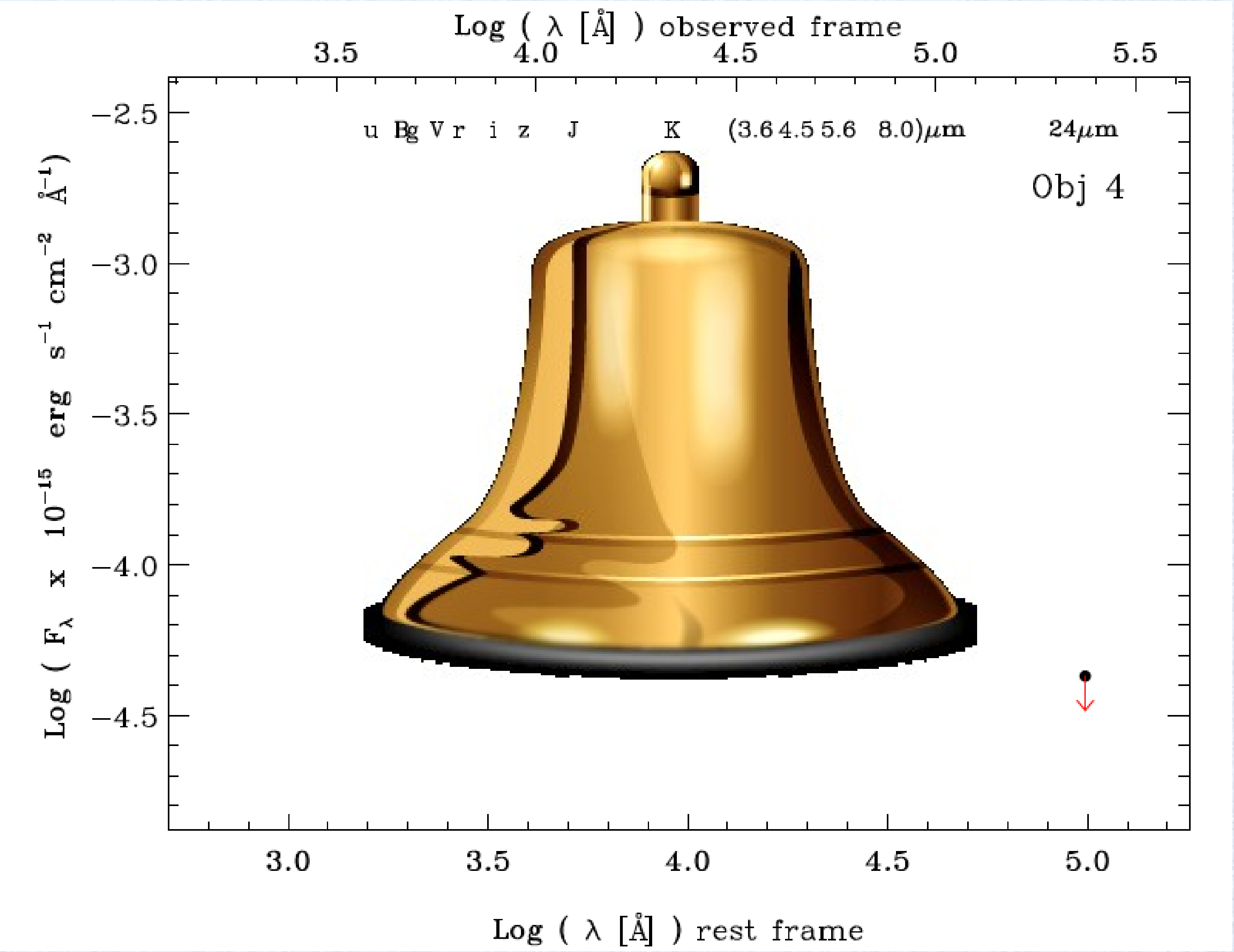


- Counterpart identification: 29 correctly identified in i band.
- We perform our 3″-aperture photometry on the mis-identified counterparts.

Spectral Energy Distribution

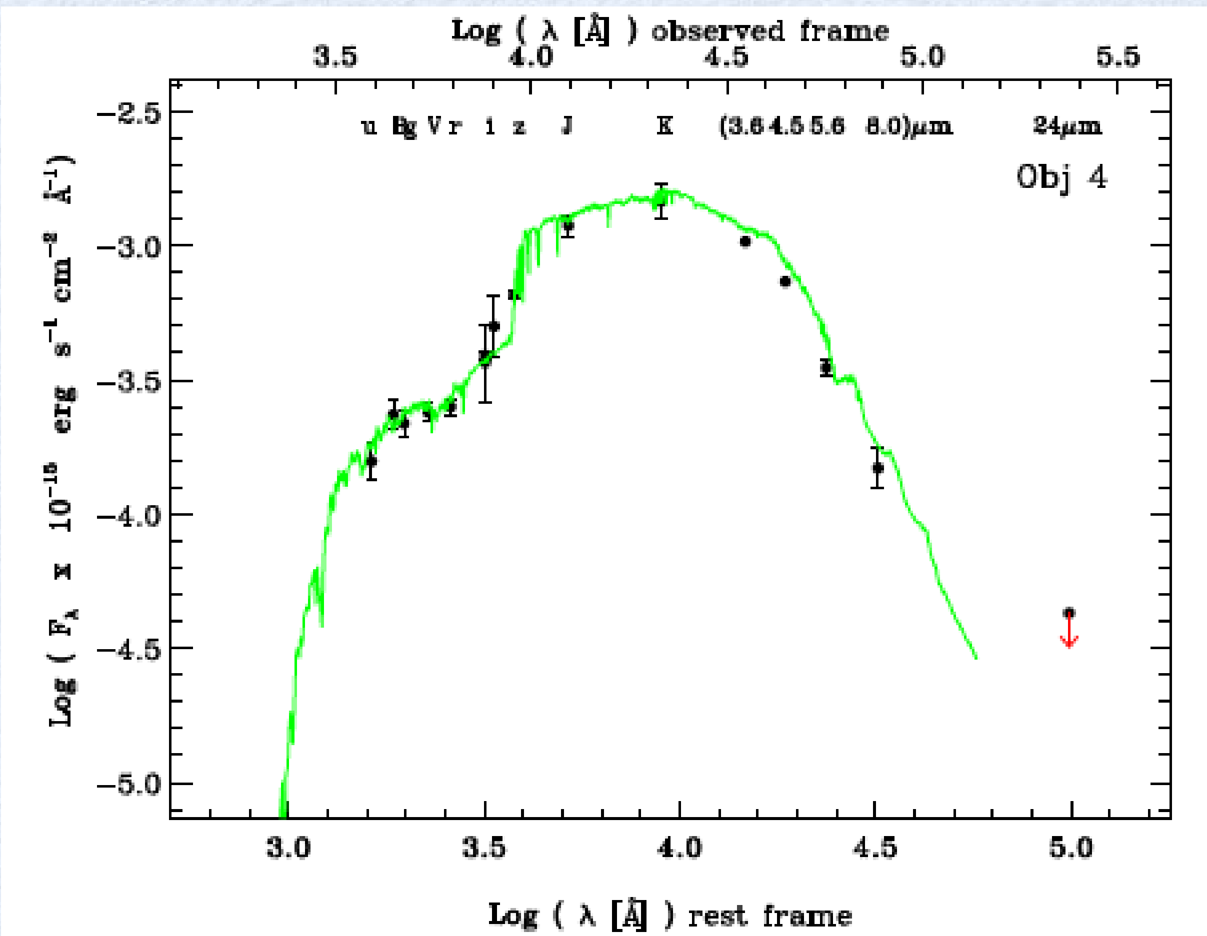
Baldi + 13

- SEDs from FUV to MIR bands.
- Stellar Templates: Bruzual & Charlot 03, 09 and Maraston+ 05
- E(B-V)=0-3



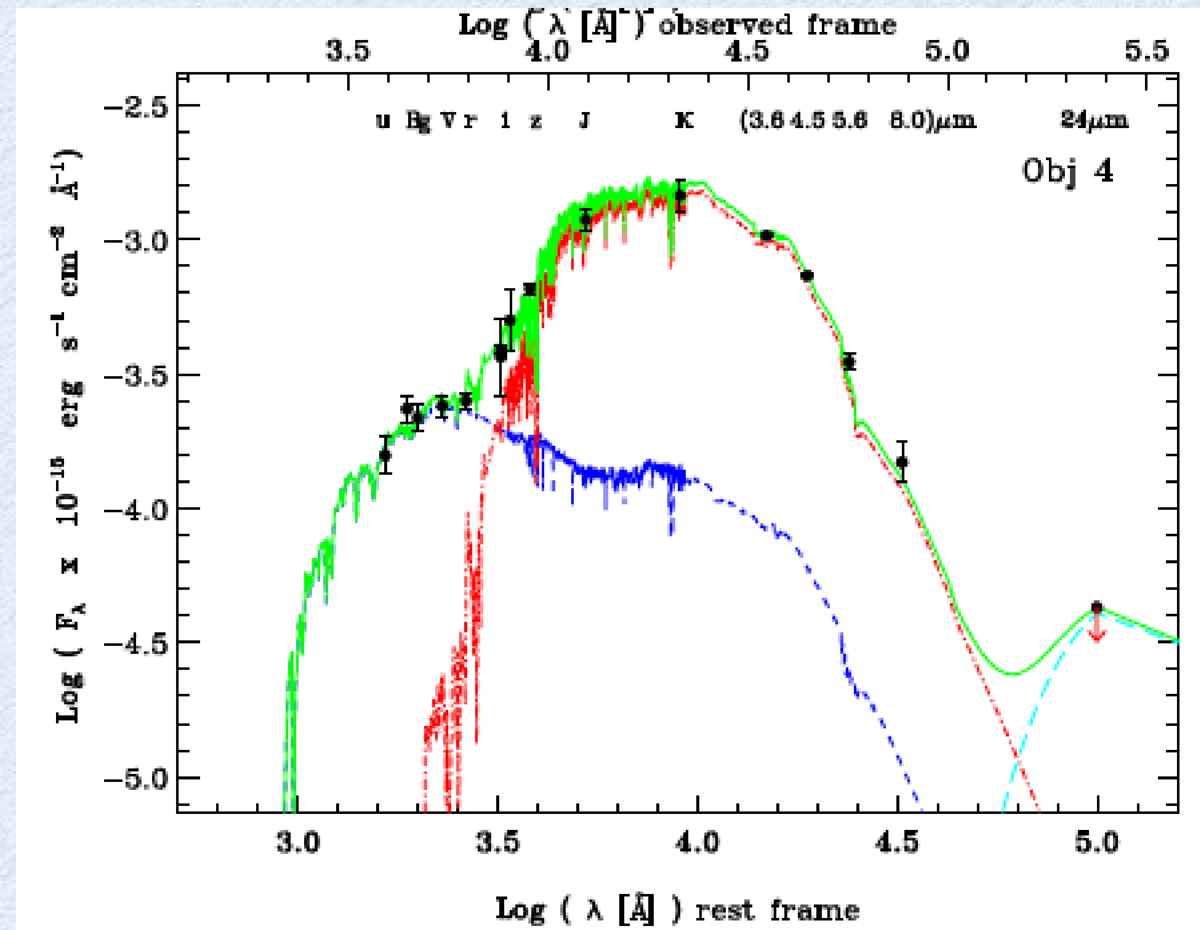
SED FITTING

Hyperz (Bolzonella+ 00)



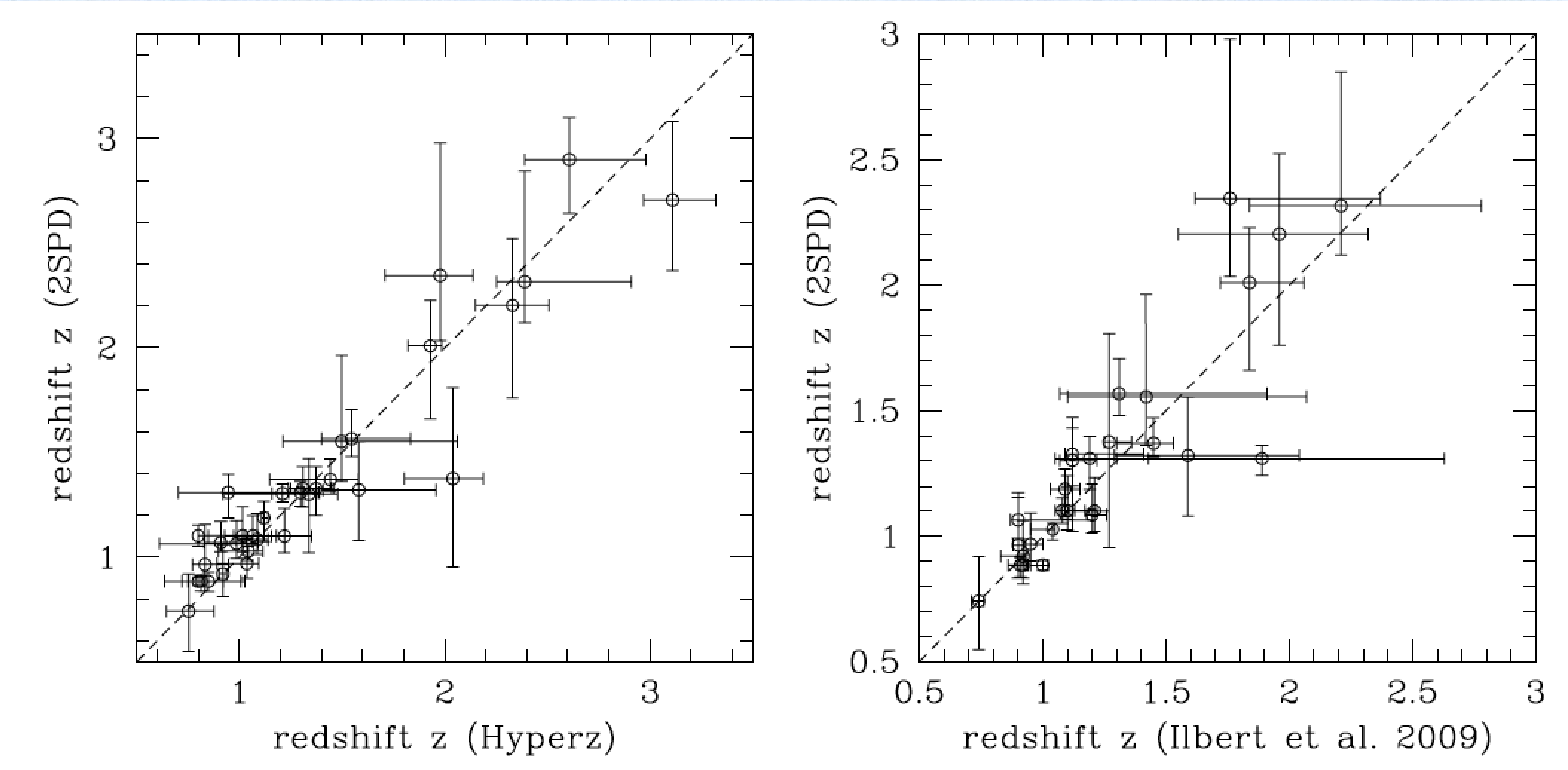
composite stellar population with single SF history

2SPD



Two stellar population (OSP and YSP) and dust component(s)

Results: photo-z

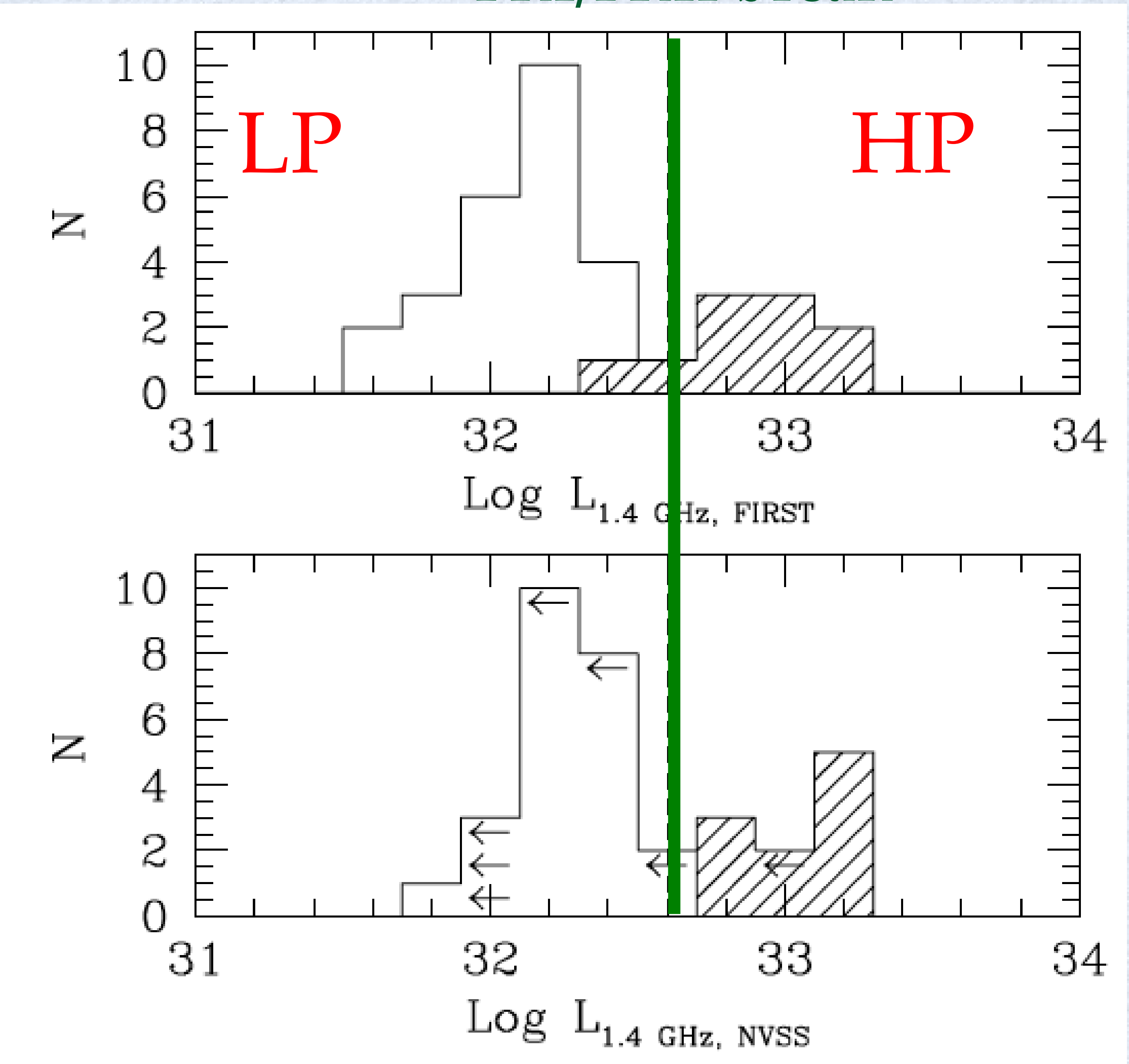


- The photo-z of the sample range from 0.7 to 3.
- Agreement with previous photo-z derivation and spectro-z (Ilbert+09, Lilly + 07, Trump + 07).

Results: Radio Distribution

- K-corrected Radio distribution straddling the FRI/FRII break: LP and HP sources
- $L_{FIRST} \sim 10^{40.7\text{-}42.3}$ erg/s

FRI/FRII break



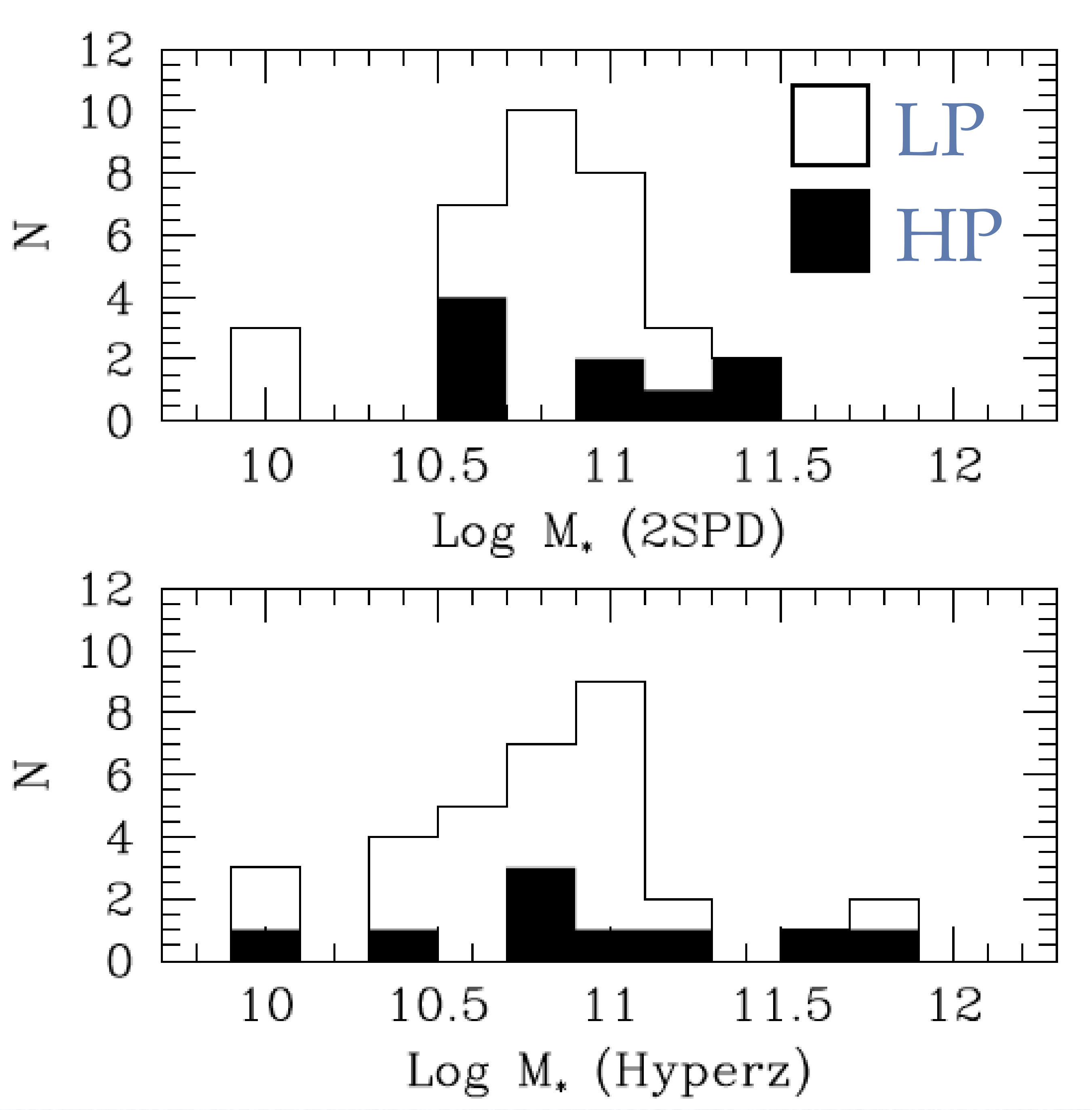
erg/s/Hz

Baldi+ 13, 14

Results: Stellar Pop

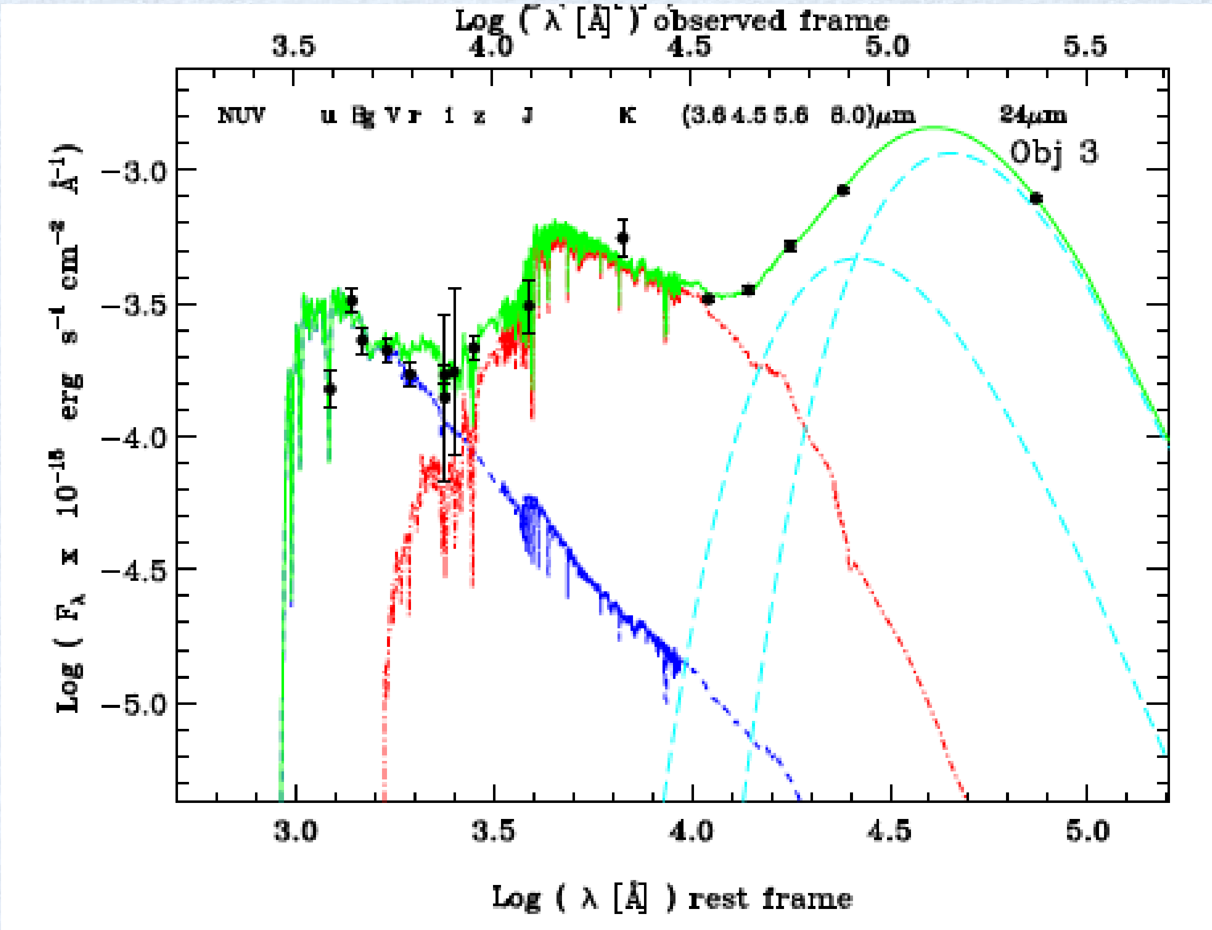
- Stellar masses: $10^{10.5\text{-}11.5}$ $M_\odot$.
- SEDs are red and dominated by OSPs.
- OSP: $1\text{-}3 \times 10^9$ yr.
- YSP: 1-30 Myr and $\lesssim$1% mass contribution.

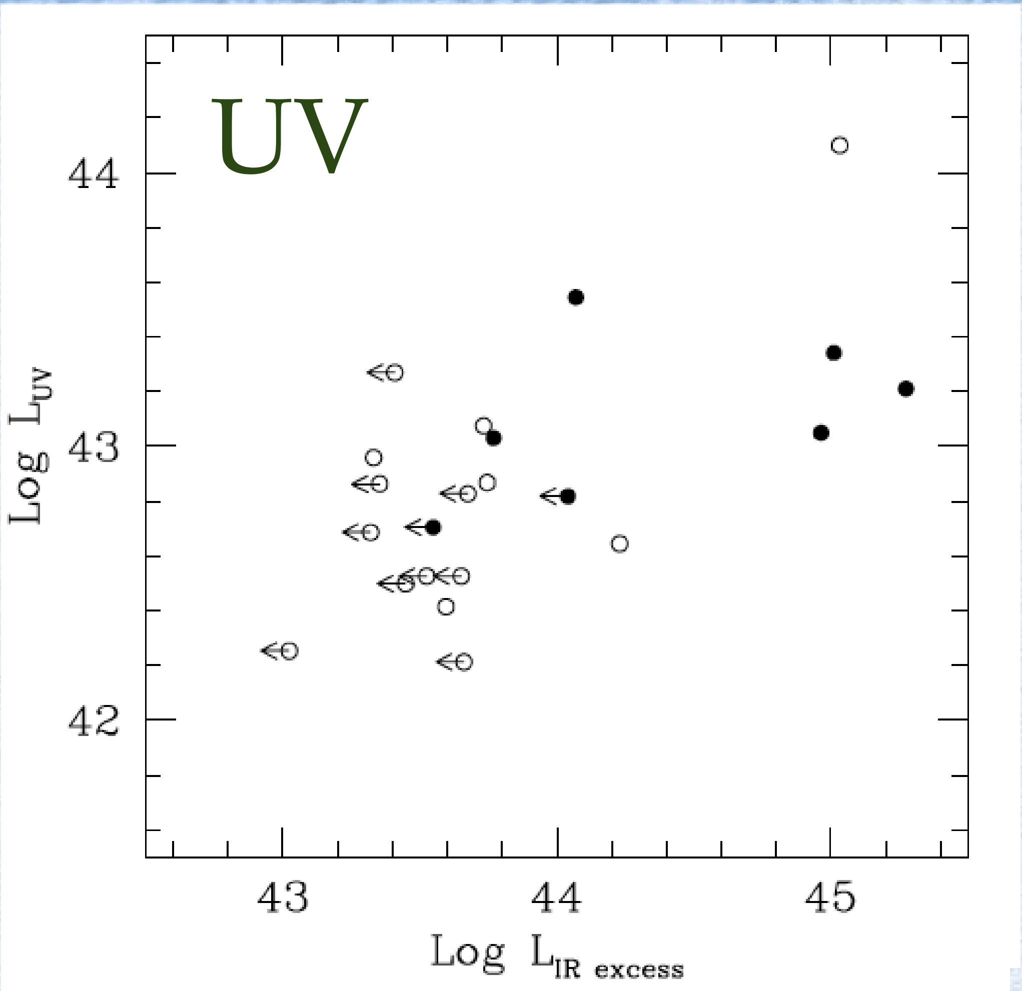
Baldi + 13, 14



Baldi+ 13

Results: MIR & UV



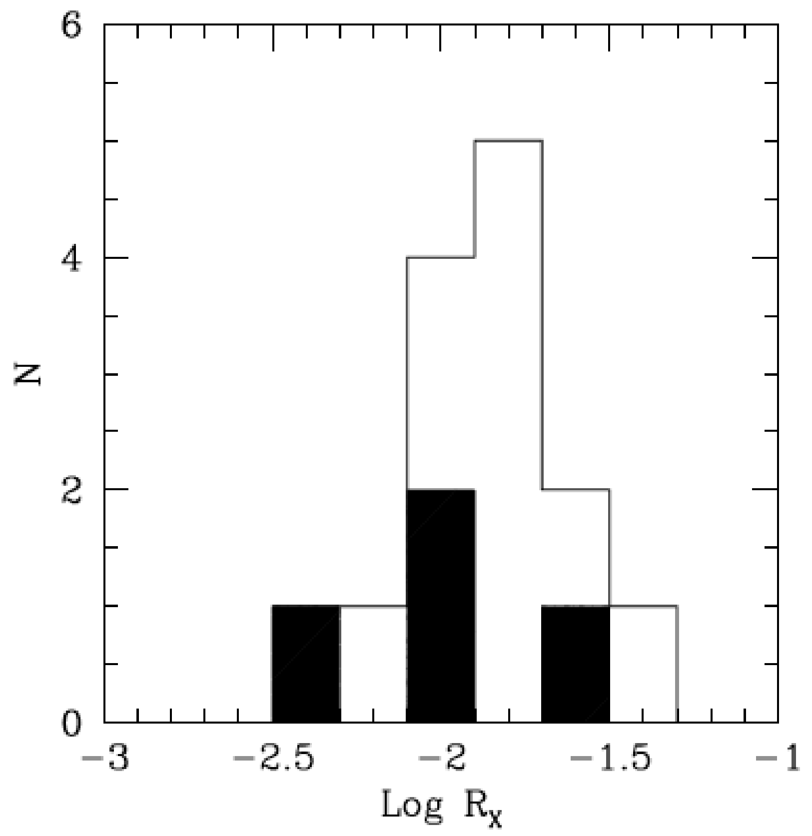


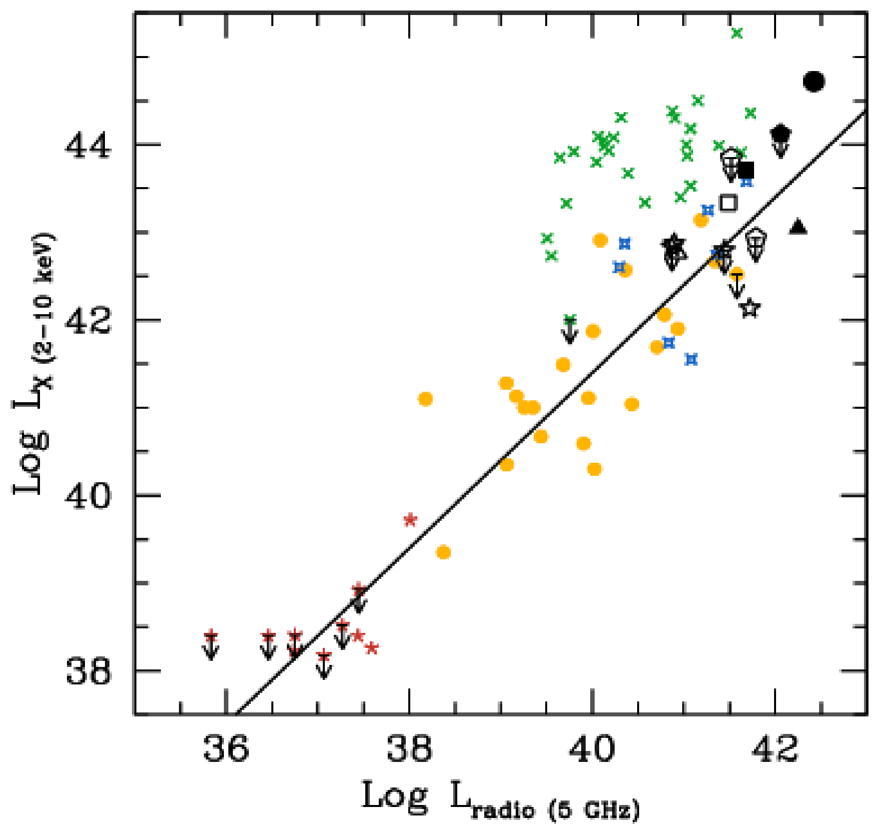
Baldi+ 13, 14

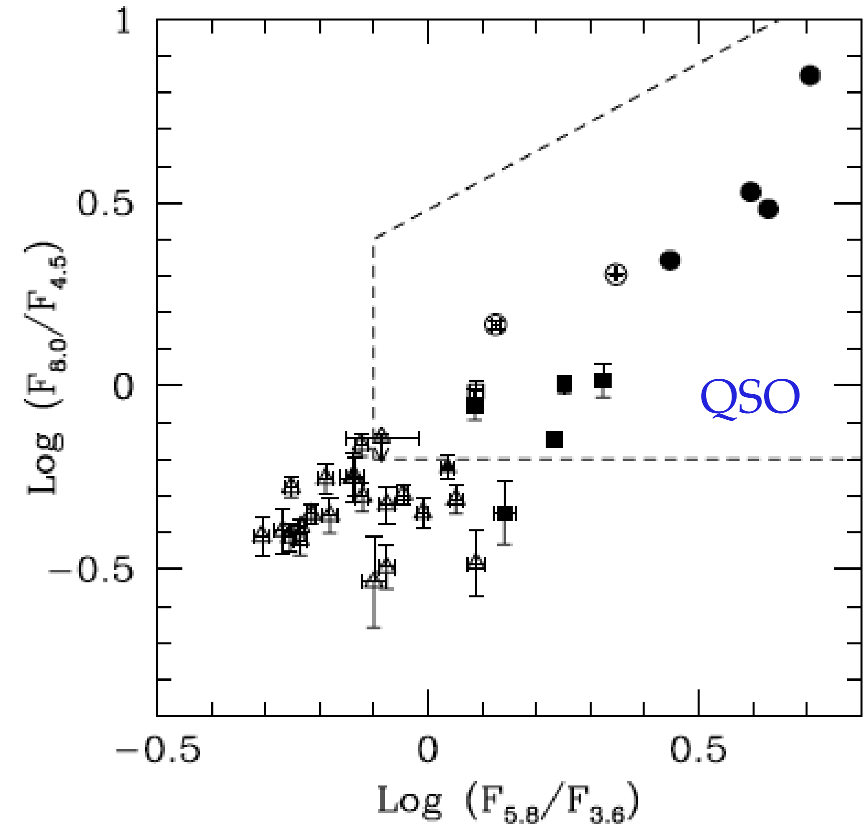
- T range ~300-850 K; radio-IR relation: AGN origin
- L_{dust} ~$10^{43.5-45.5}$ erg s^{-1}

- L_{UV} ~ 10^{42-44} erg s^{-1}
- radio-UV no relation, IR-UV relation: SF or AGN?

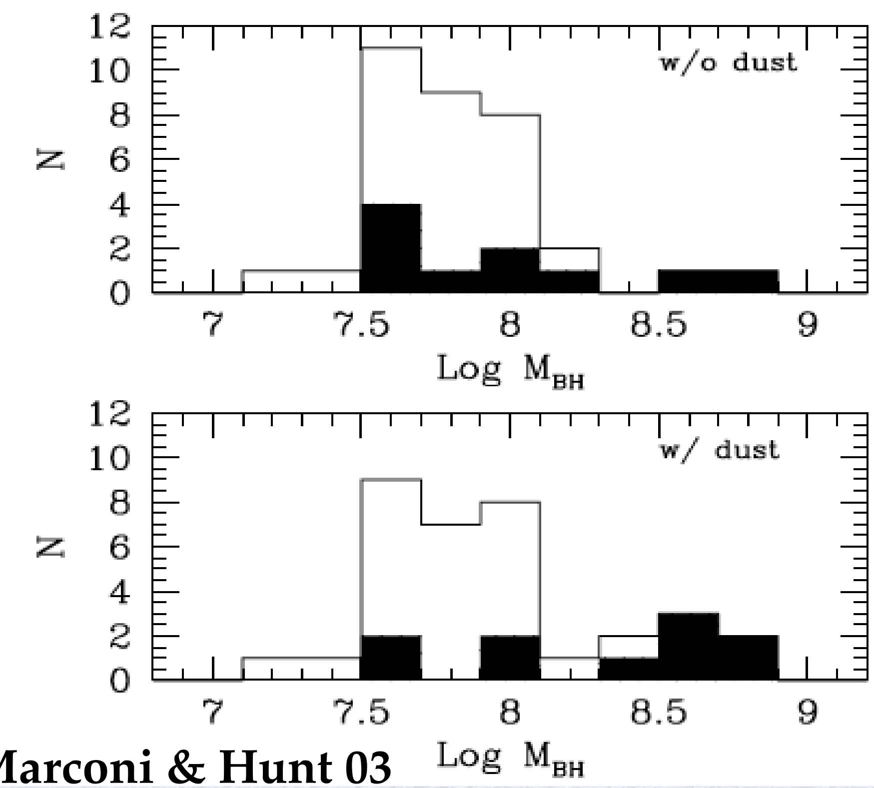
HIGH-Z RADIO GALAXY: AGN





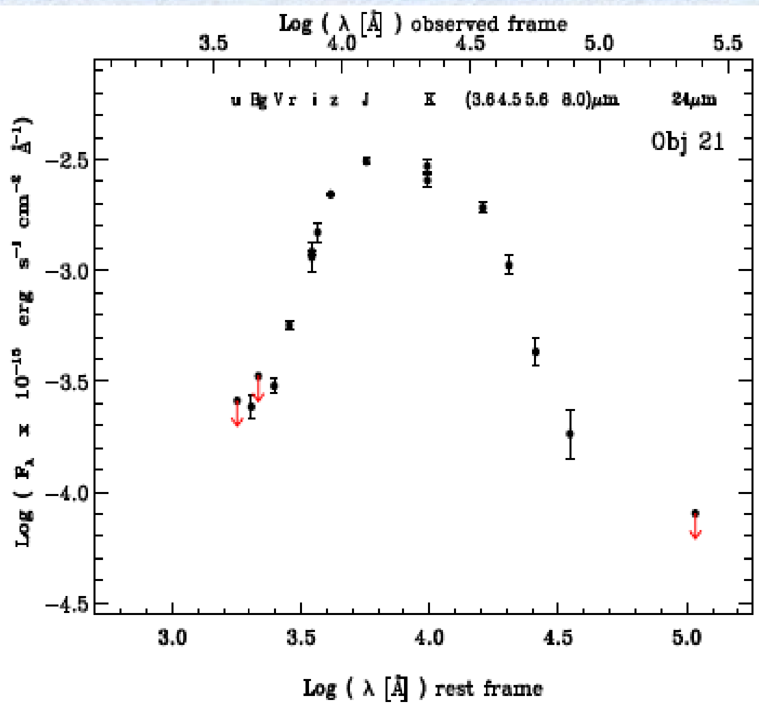


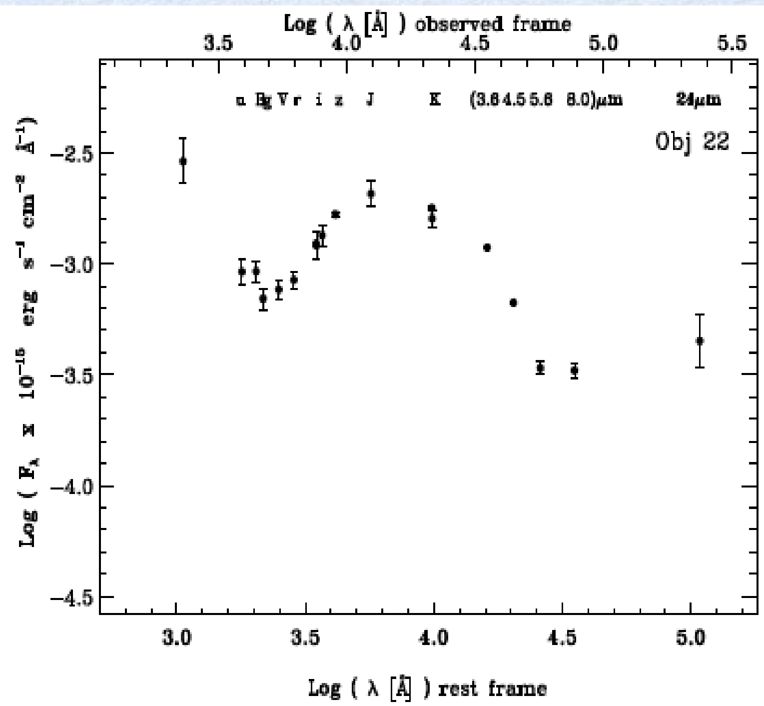
- Log R_x > - 4.5: radio loud
- X-ray- radio correlation: synchrotron nuclei?
- IRAC diagnostics: QSO?
- $M_{BH} > 10^8\ M_\odot$?



Marconi & Hunt 03

HIGH-Z RADIO POPULATION



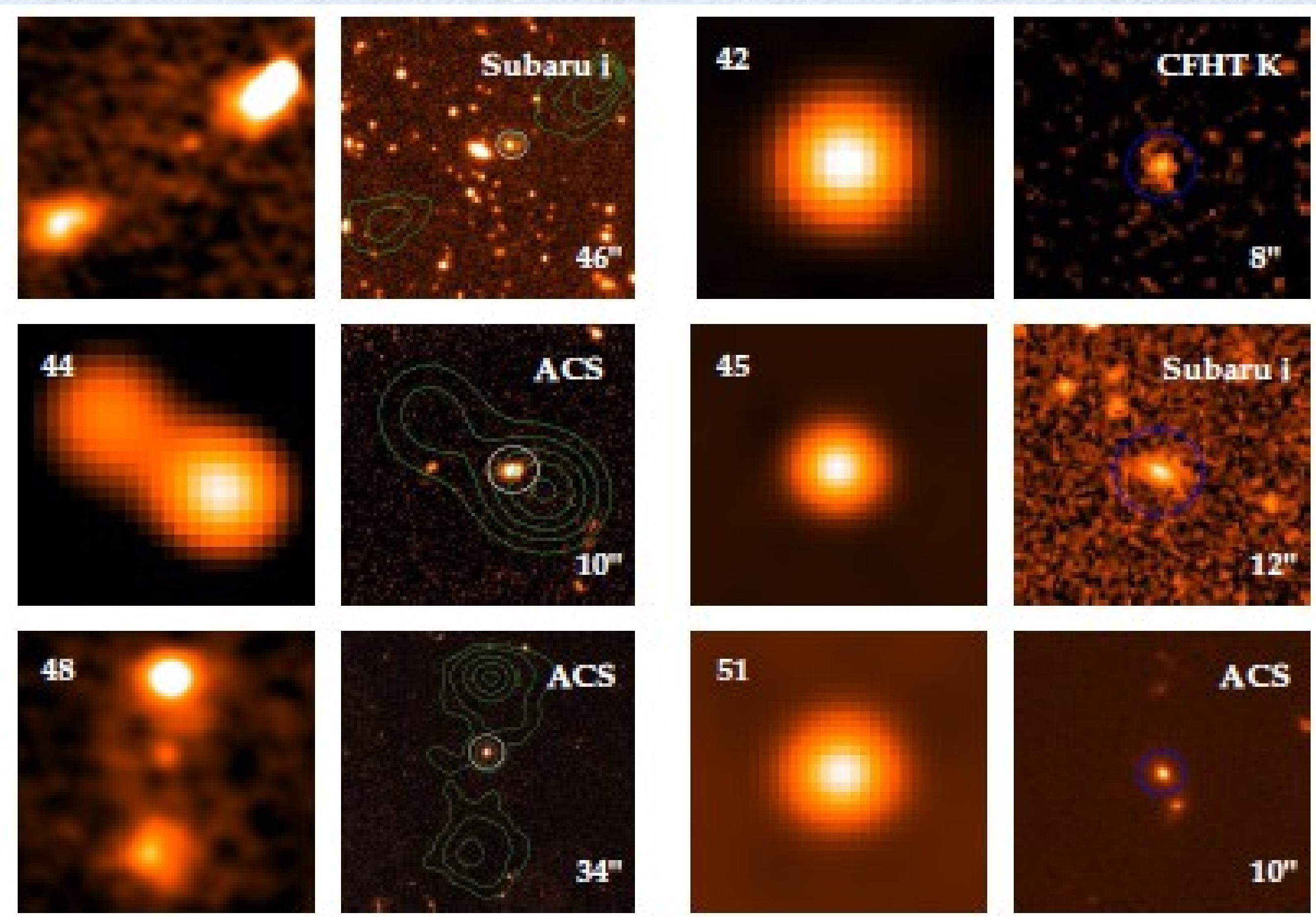


In COSMOS field

F_{FIRST} > 13 mJy

+ FRII

- FRI e FRII
- 0.7 < z < 3
- SED: most are OSP
- UV and MIR excess are typically in FRII



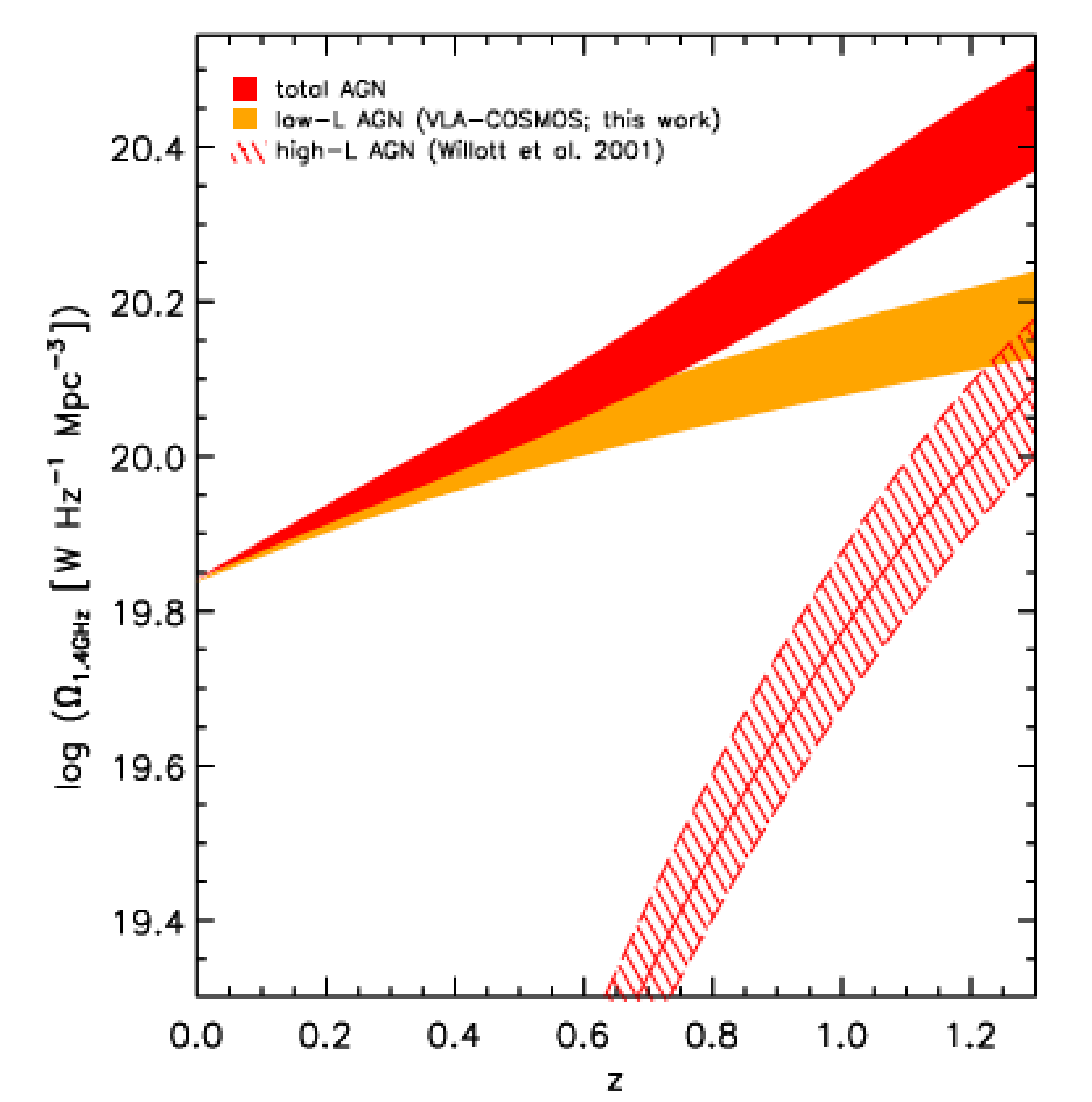
Comparison with local RG

- Radio distribution: LP-HP/LEG-HEG ✔
- Host mass: $\sim 10^{10.5} - 10^{11.5}\ M_{\odot}$ ✔
- Host color: LP red, HP bluer ✔
- Accretion: QSO vs RIAF ✔
- environment (Castignani et al 14) ✔
- MIR and UV excess in HP and not in LP ✔

LP/HP = FRI/FRII?
Possible progenitors?

COSMIC EVOLUTION

- Similar stellar masses
- Similar color vs radio power relation
- HP RG have a stronger evolution than LP RG



Smolcic+ 09, Best+ 14
Heckman & Best 14

LP RG occur in most massive galaxies at z~1 and quench cold gas accretion
HP RG undergo gas-rich merger which induces strong BH and galaxy growth

Conclusions

- **LP and HP radio galaxies in local Universe appear to have typically similar behavior to those in distant Universe: accretion, host properties, environment.**

- Future: study of the new population of FR0; optical spectra e radio morphology of distant radio galaxies


THANK YOU