CAASTRO
ARC CENTRE OF EXCELLENCE
FOR ALL-SKY ASTROPHYSICS

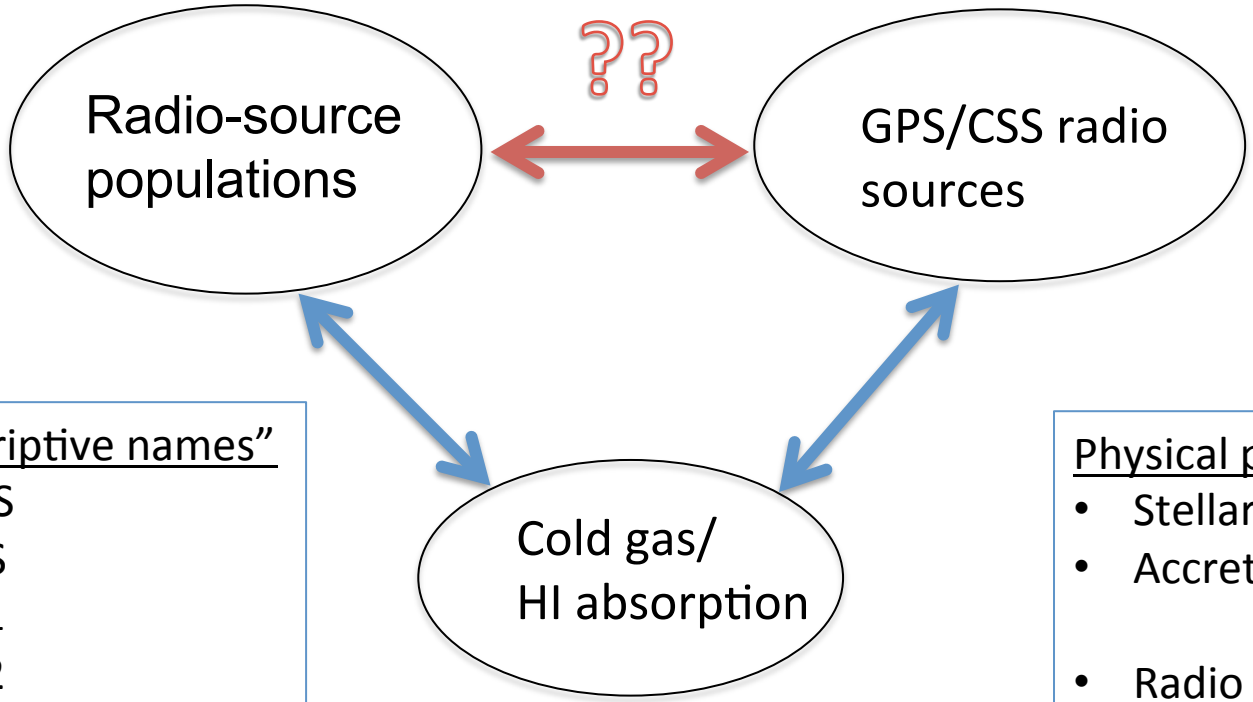
THE UNIVERSITY OF
SYDNEY

GPS/CSS radio sources and their relation to other AGN

Elaine M. Sadler
University of Sydney, Australia

Scope of this talk

"..attempt to place the GPS and CSS sources in a larger context..."



"Descriptive names"
- GPS
- CSS
- Sy1
- Sy2
- NLSy1
- BAL QSO

Geometry/orientation

Physical properties
- Stellar/BH mass
- Accretion rate
- Radio luminosity
- Radio source size/age

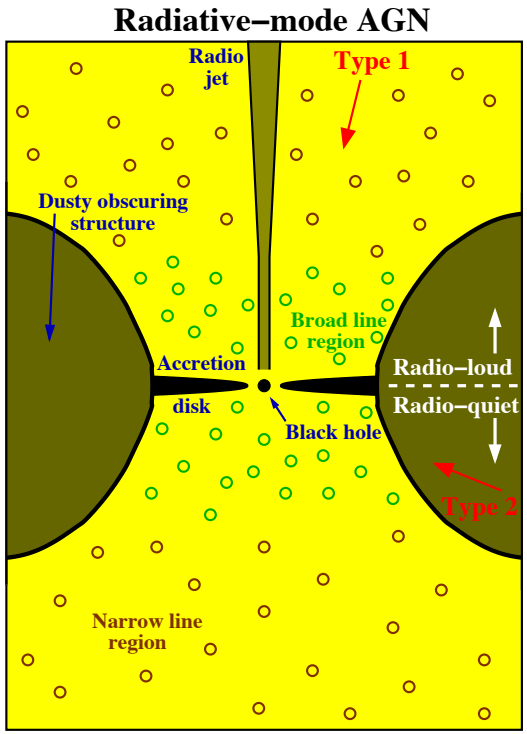
What I'll talk about

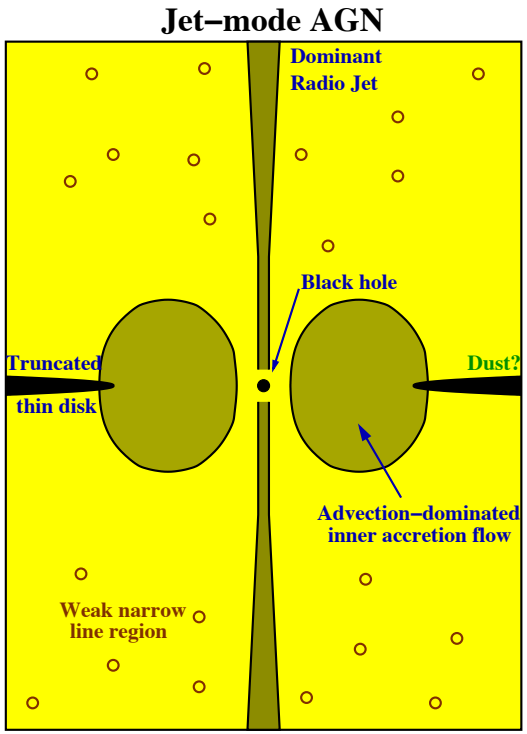
- Mainly **local** (z < 0.2) radio-source populations
- New era of sensitive **multi-frequency radio surveys,** and their impact.
- Some useful diagnostic plots for characterizing physical properties of large samples
- How do GPS/CSS sources relate to the overall radio AGN population? Are there low-luminosity GPS sources?
- Radio sources in clusters
- Open questions and next steps.

Two distinct kinds of radio AGN

High–excitation/"Radiative mode"

- Classical accretion disk
- Strong emission lines, high-excitation optical spectrum
- Central dusty torus
- Unified models apply





(Heckman & Best 2014)

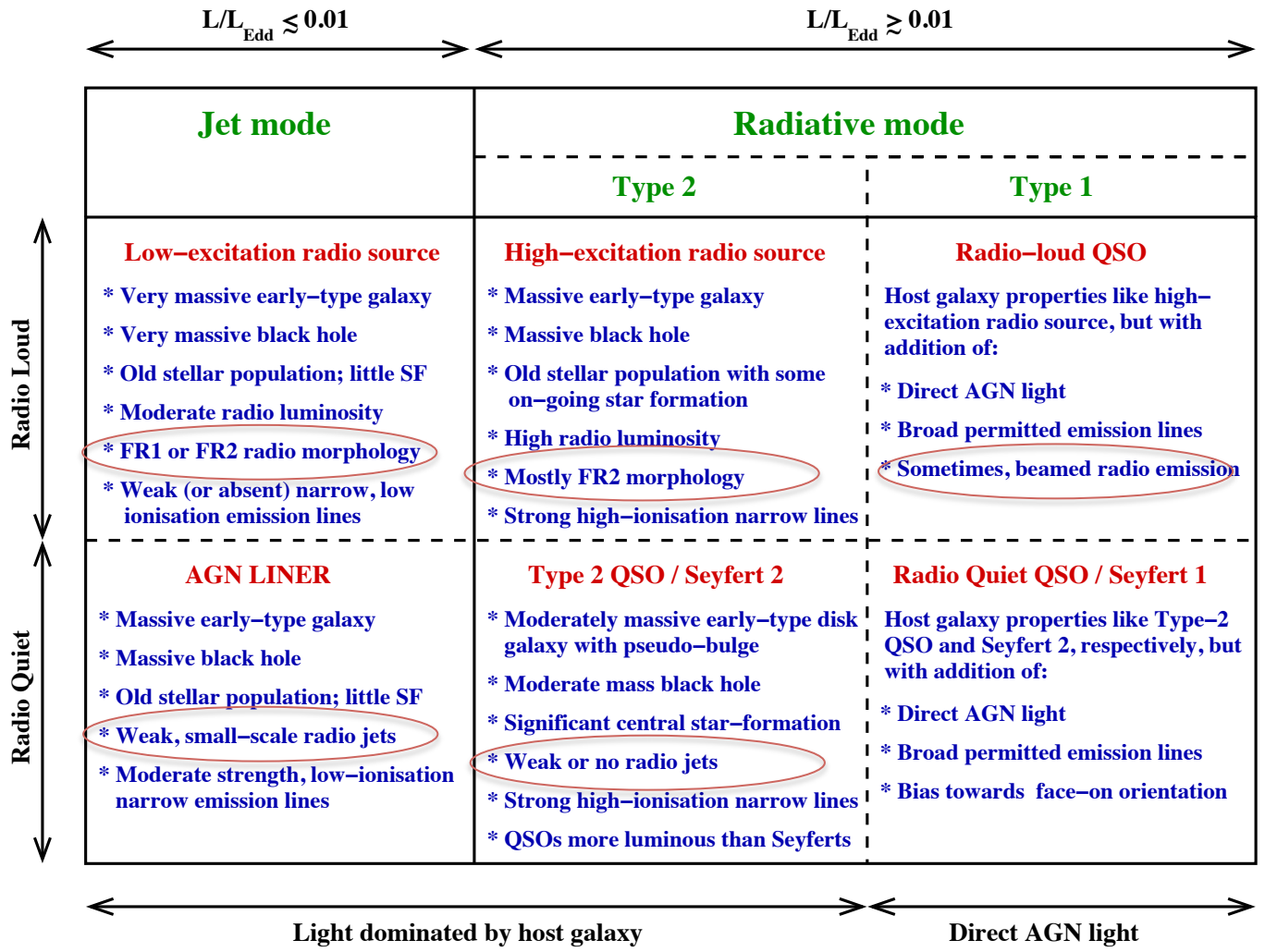
Low-excitation/"Jet mode"

- Inefficient accretion
- Weak or no optical emission lines
- No central dusty torus
- Jet can regulate/ inhibit SF in host galaxy

The current picture

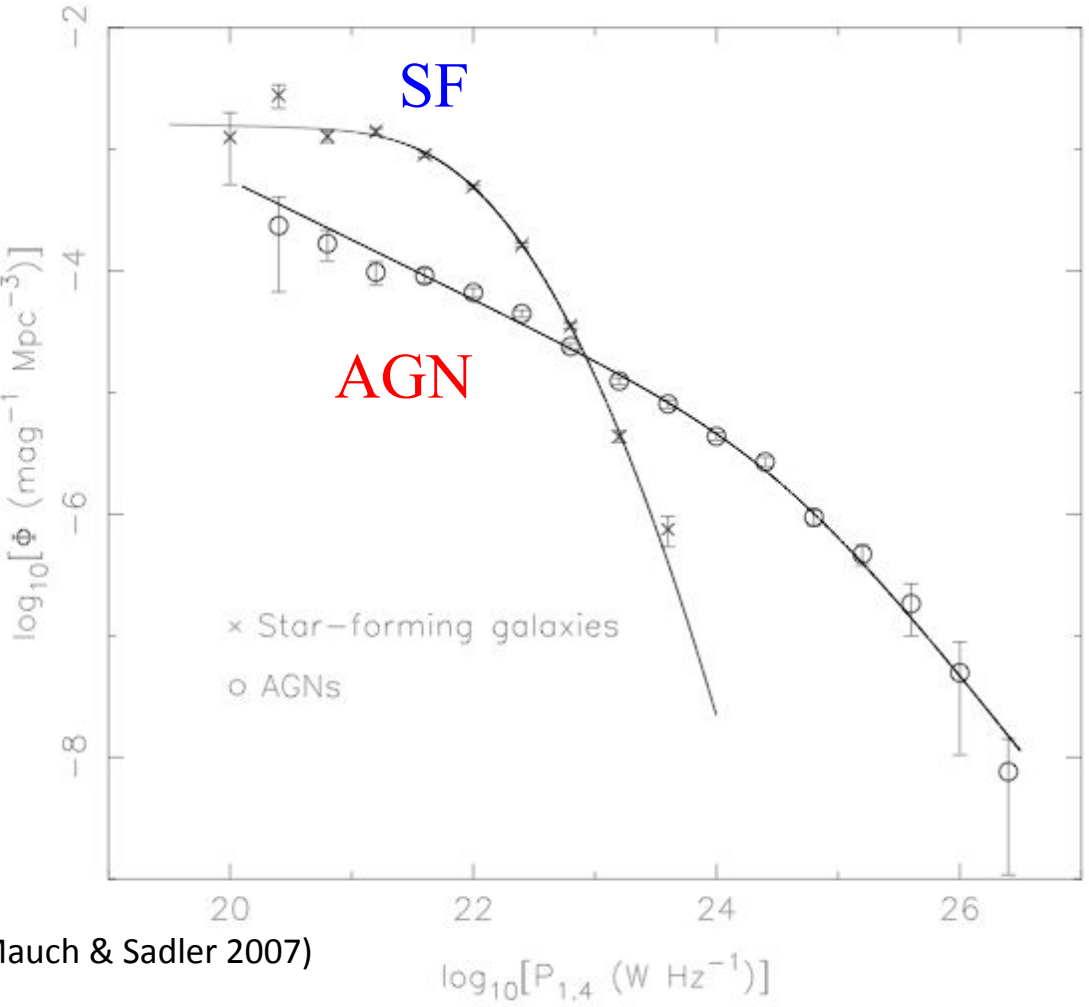
(Mainly from 1.4 GHz radio surveys at z~0)

Where do GPS/CSS sources fit in?



(Heckman & Best 2014)

Radio luminosity functions

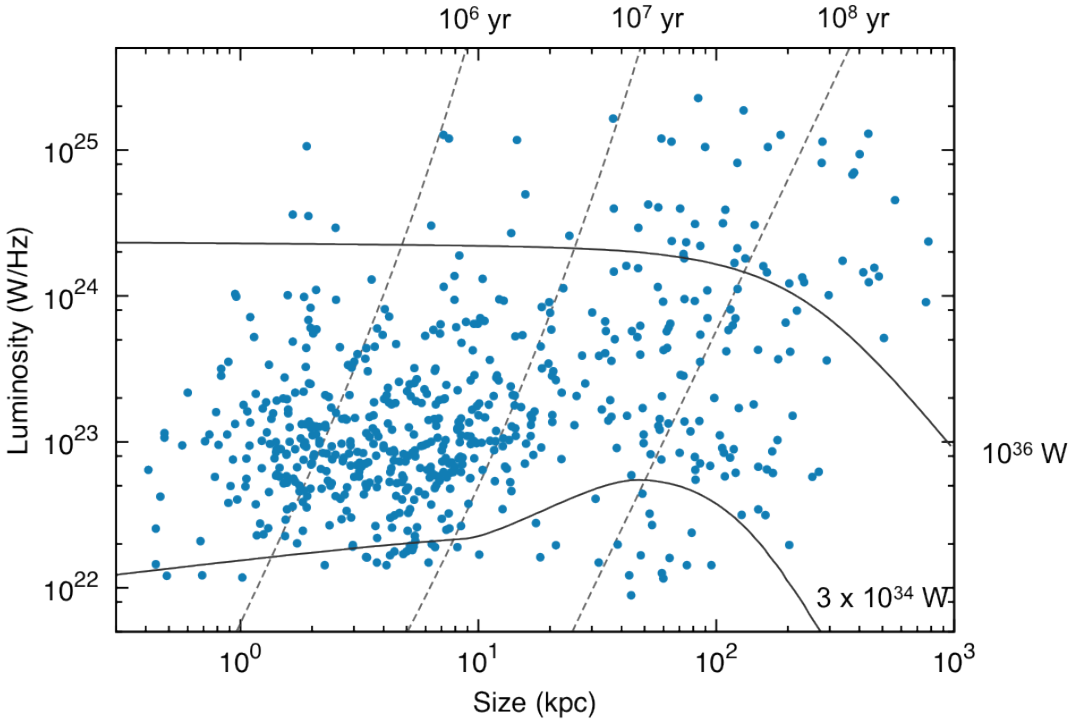


(Mauch & Sadler 2007)

At 1.4 GHz, local ($z < 0.2$) radio LFs for AGN and star-forming galaxies can now be measured over factors of $>10^6$ in radio power

Radio LF for local AGN is **broad,** but shows *no evidence for bimodality* (though AGN/SF can be hard to separate below 10^{23} W/Hz)

Local radio AGN at 1.4 GHz

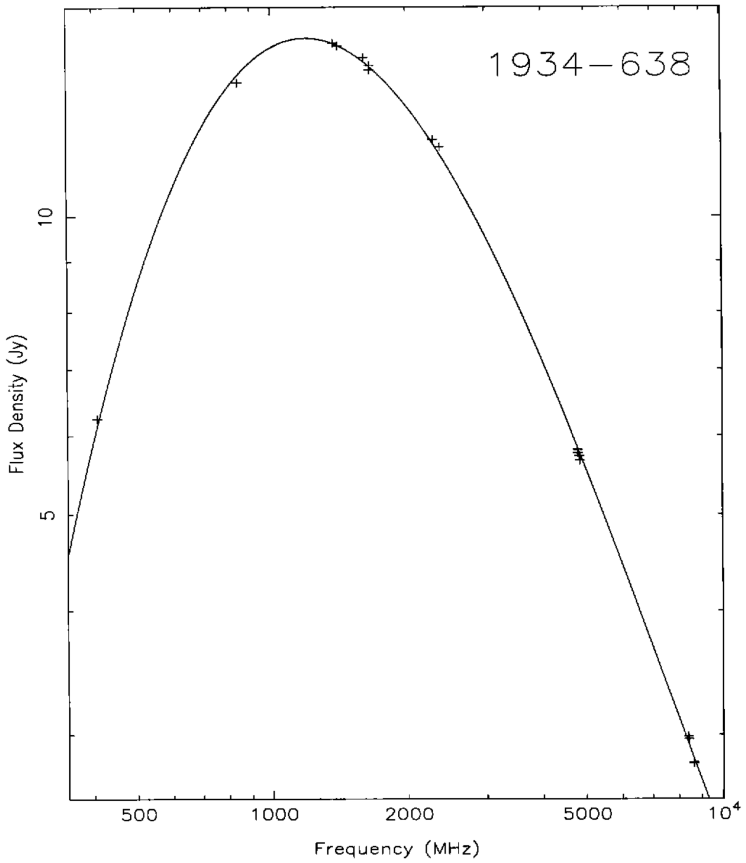


[data points: Shabala et al. 2008,
model tracks: Turner & Shabala 2015]

- *Excess* of compact, low-luminosity sources compared to extended sources.
- Suggests that not all compact sources will evolve into large-scale FR1/FR2 radio galaxies?

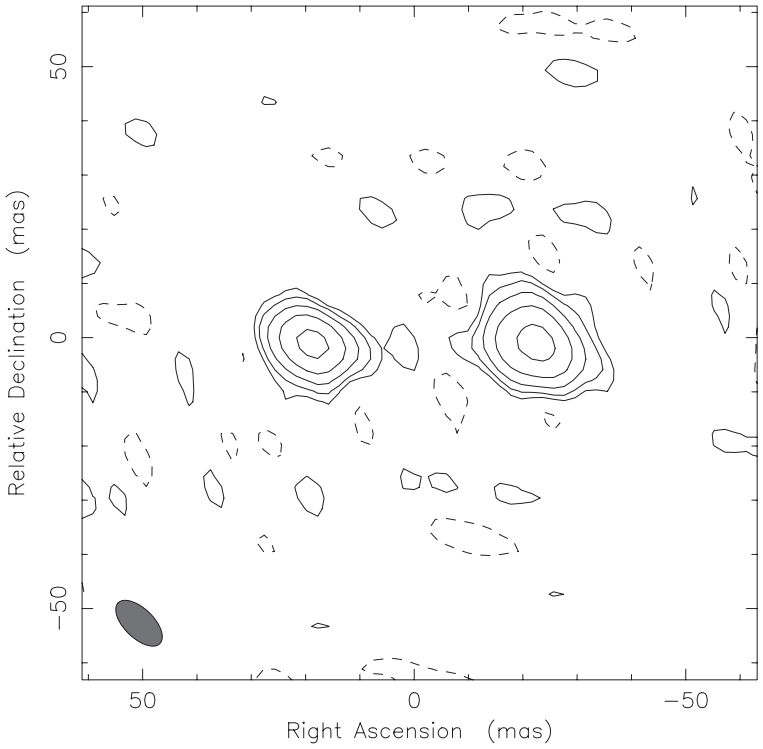
A canonical GPS source: PKS 1934-638

Radio: SED peak at 1.4 GHz



(Reynolds 1994)

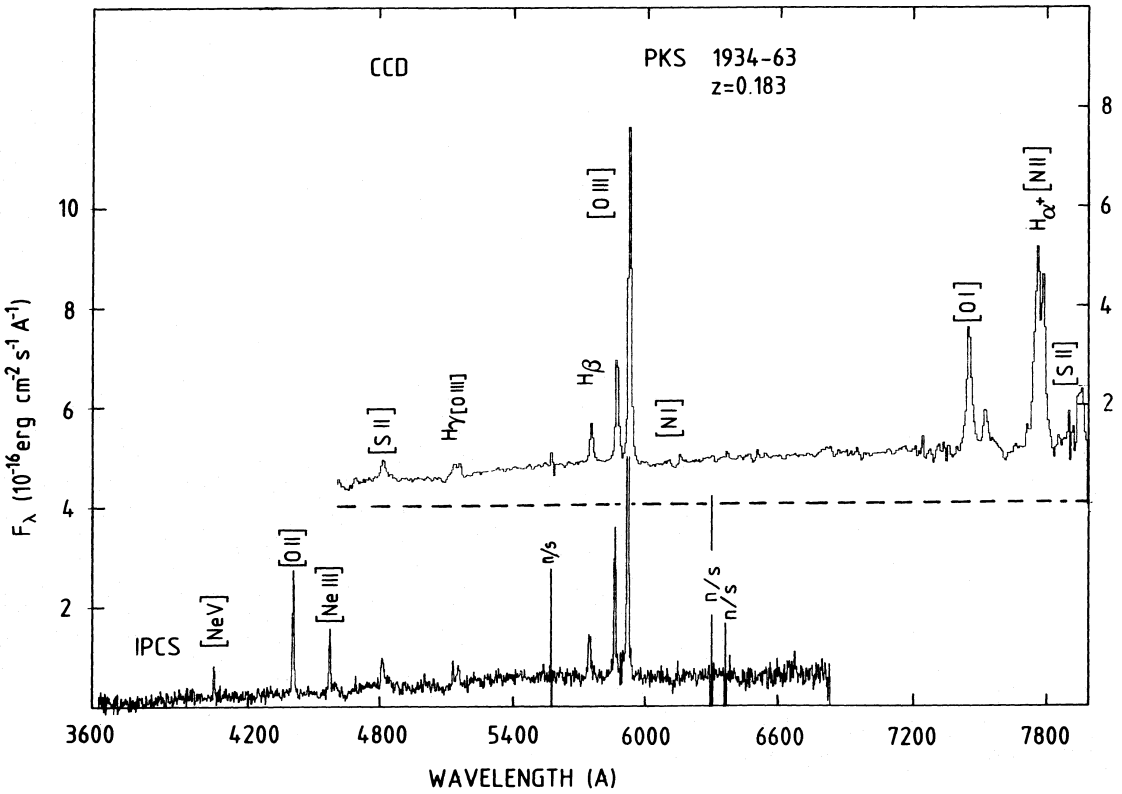
VLBI double (42 mas separation)



(Tzioumis+ 2010)

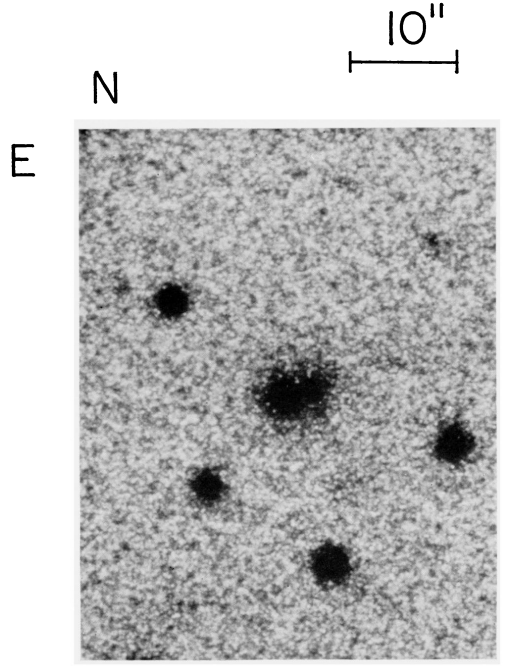
PKS 1934-638: optical

Optical: z=0.181 AGN (Sy2)



(Fosbury+ 1987)

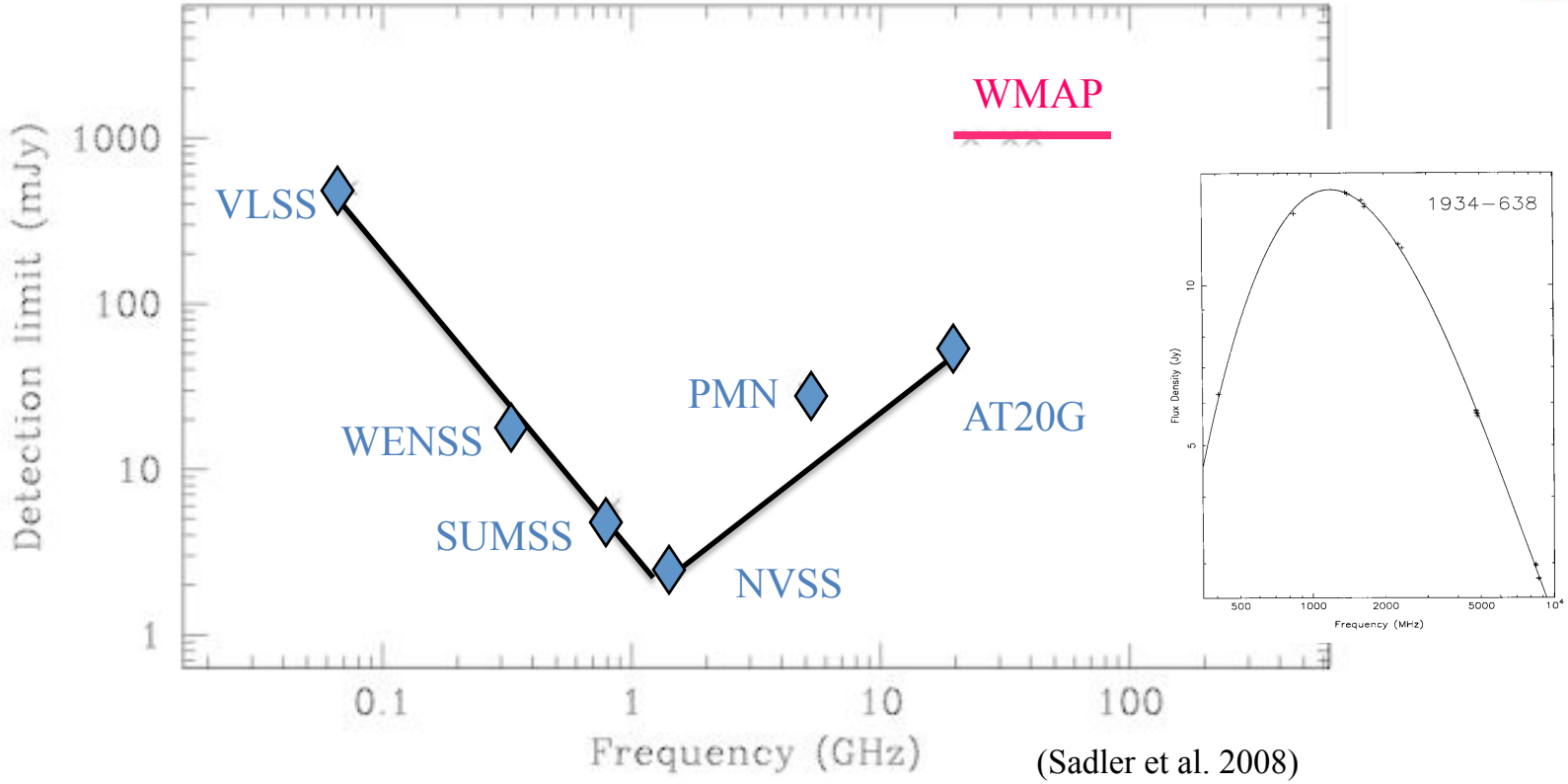
Host galaxy: Dust-lane elliptical?



PKS 1934-63

(Penston & Fosbury 1978)

Large-area radio continuum surveys

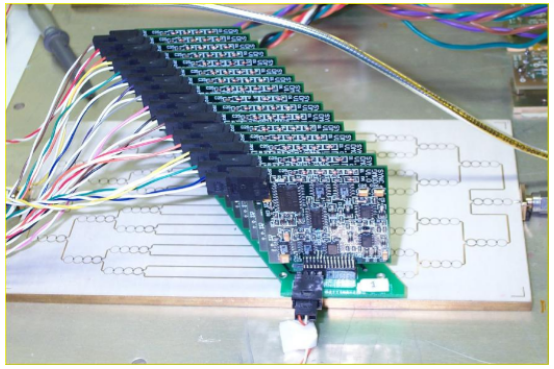


(Sadler et al. 2008)

Detection limits of some large-area (>10,000 deg^2) radio surveys

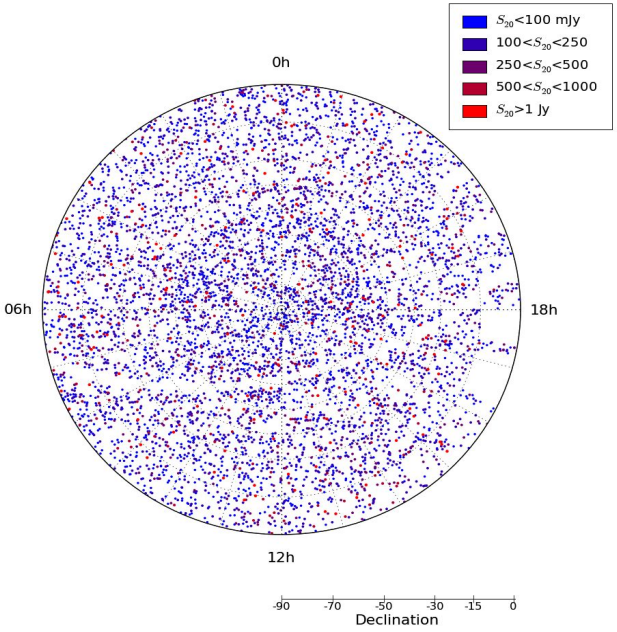
Now/near future: More sensitive surveys over larger frequency range (LOFAR, MWA, ASKAP, VLASS,…

The AT20G survey



2004-2008: Wide-band analogue correlator on ATCA, 2.4 arcmin FoV, fast scanning at 15 deg/min, 54ms sampling.

4σ detections imaged at 5, 8 and 20 GHz with full ATCA

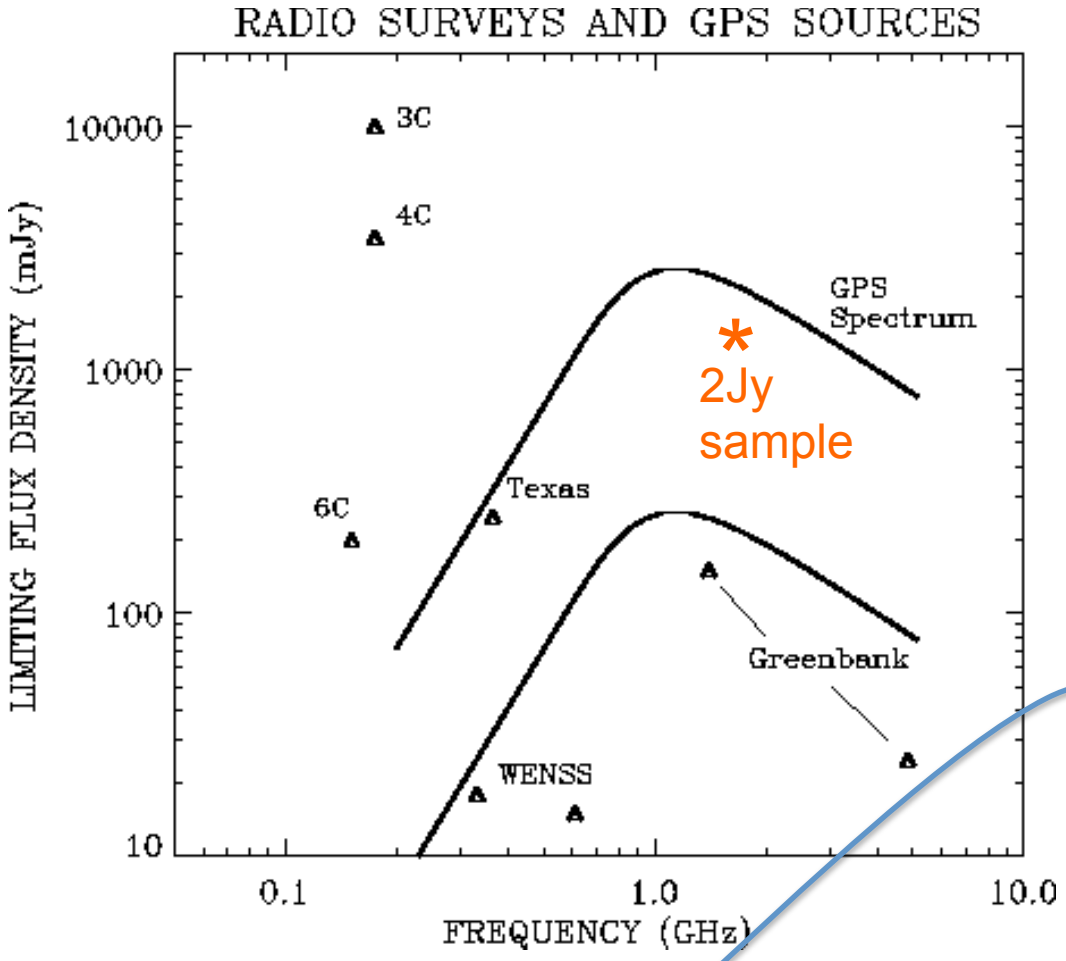


Public data releases:

- Bright Source Sample (Massardi et al. 2008)
- Main AT20G catalogue (Murphy et al. 2010)
- Optical IDs and redshifts for AT20G sources (Mahony et al. 2011)
- 20 GHz scanning survey catalogue (Hancock 2012)
- AT20G High-resolution catalogue (Chhetri et al. 2013)

+ some smaller follow-up data sets (deep 20 GHz, 95 GHz, HI absorption,...)

Why a 20 GHz survey?

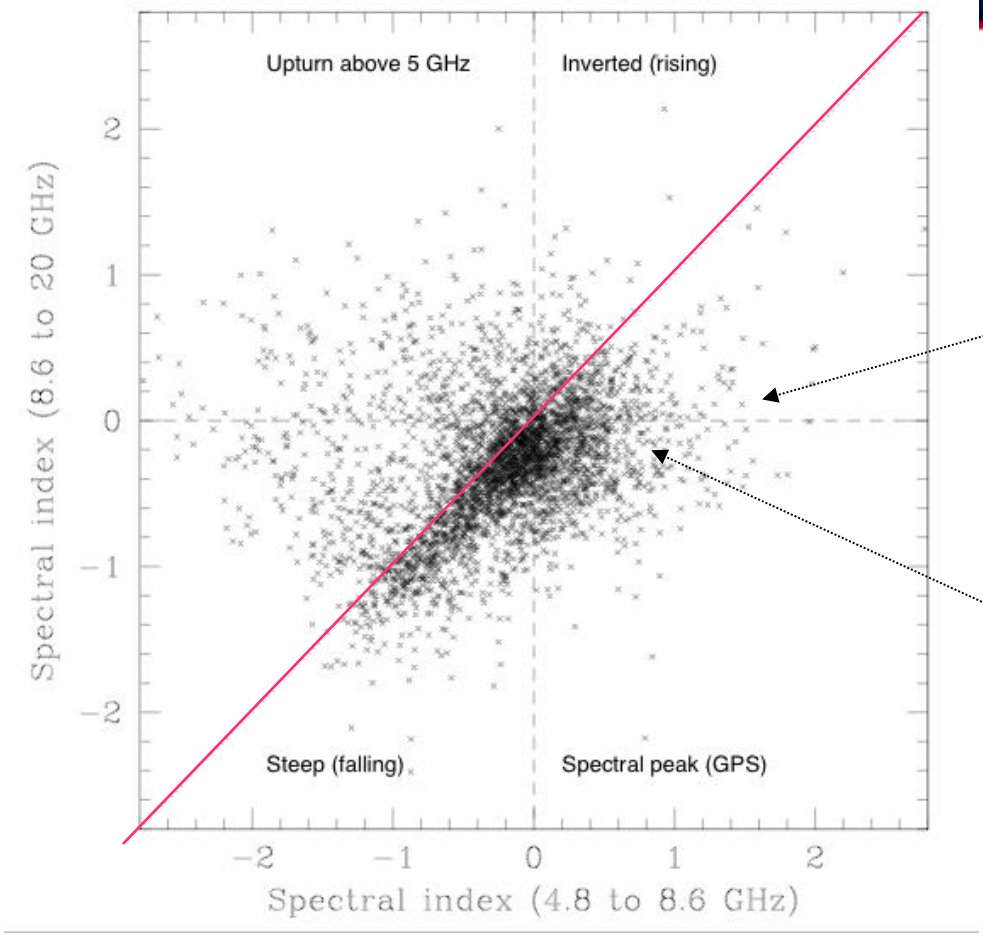


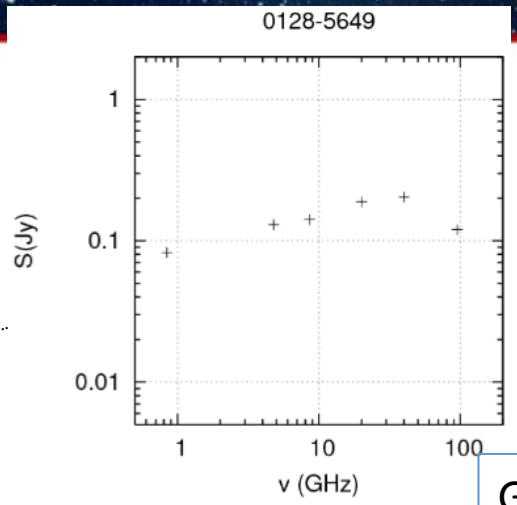
(Snellen et al. 1998)

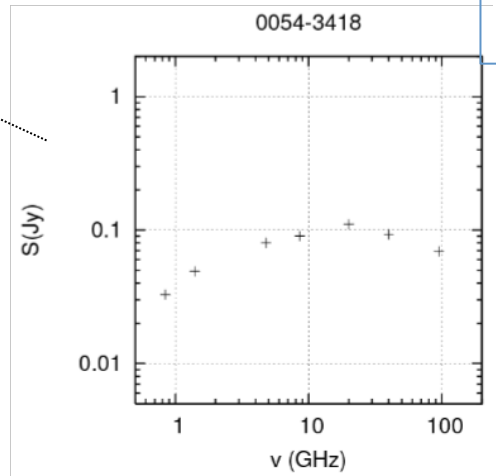
New parameter space:

Selection at 20 GHz (with near-simultaneous data at 5, 8 GHz) should allow us to identify faint, nearby sources with spectral peaks well above 1 GHz.

The 20 GHz source population





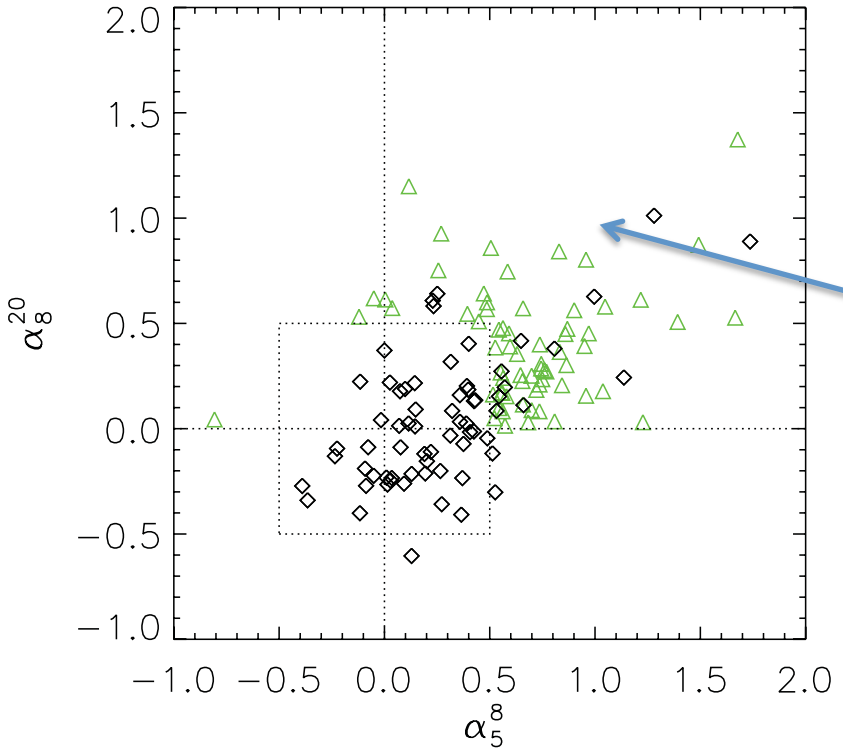


GPS sources?
Blazars?

AT20G, radio two-colour diagram: 65% QSOs & BL Lacs, 25% galaxies, 10% faint/blank.

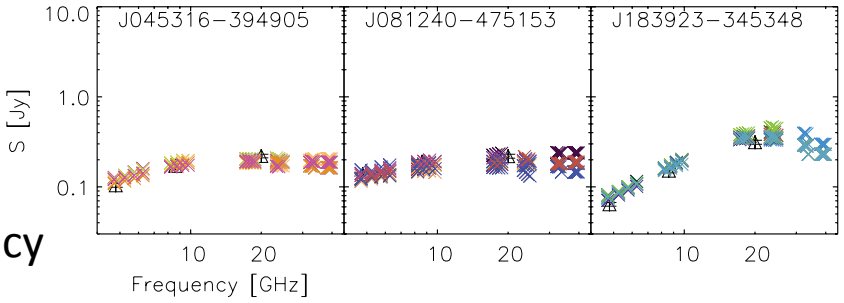
(Murphy et al. 2010; Mahony et al. 2011)

‘Inverted spectrum’ sources



Bonaldi et al. (2013): Multifrequency monitoring of AT20G ‘inverted spectrum’ sources above 200 mJy at 20 GHz

Most sources in this quadrant are *flaring blazars*, but some are genuine (non-varying) peaked sources with a spectra peak above 20 GHz.



The HFP sources studied by Bonaldi et al. (2013) show a decrease of the peak frequency with time at a mean rate of −3 ± 2 GHz/year

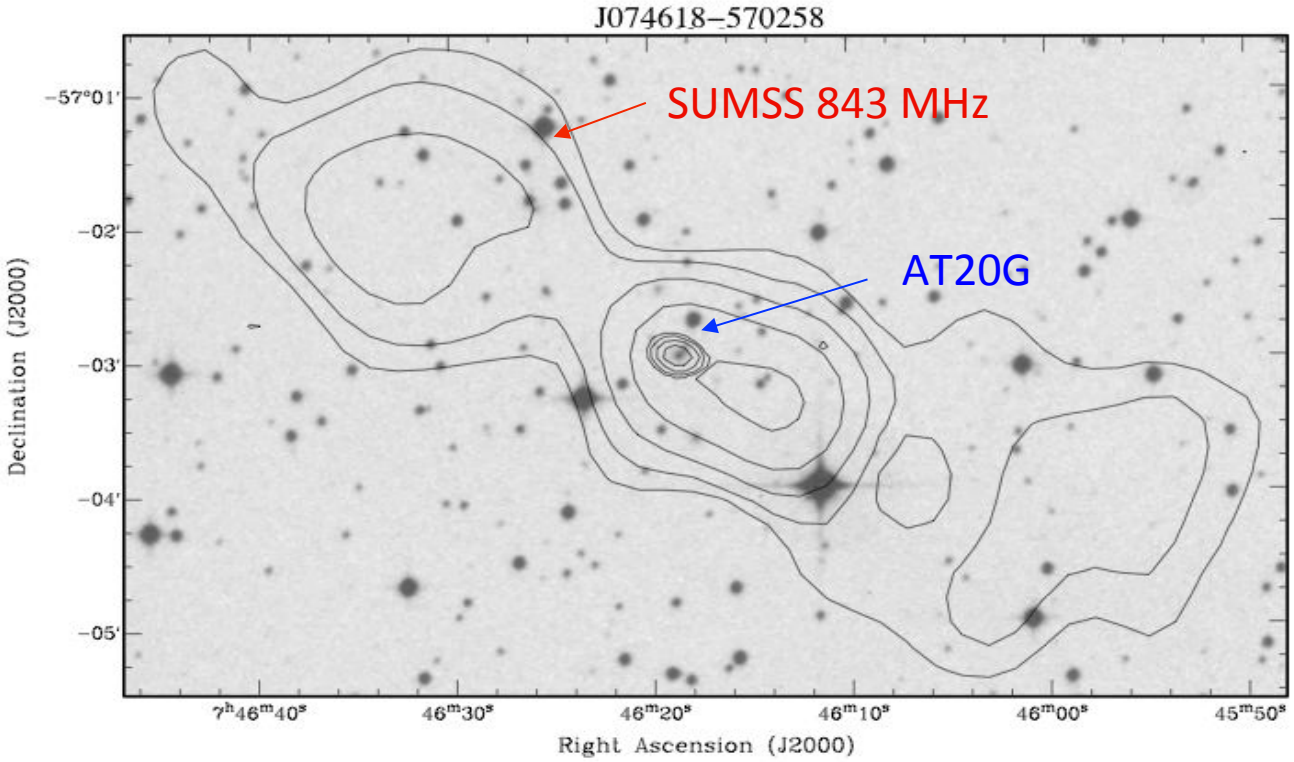
AT20G 'candidate GPS' sources

	O'Dea (1998)	AT20G Sample
Typical Peak Freq	1 GHz	8-15 GHz
Number of sources	31	688
Galaxy/QSO fraction	50% / 50%	23% / 77%
Median z	0.5 / 1.6	0.2 / 1.2
Median Log(P_5)	27 / 28 W/Hz	25 / 27 W/Hz

Paul Hancock (2009 PhD thesis): Complete sample of 688 candidate GPS sources from AT20G with spectral peaks above 5GHz. Majority are QSOs/blazars, but also a population of >100 candidate GPS galaxies.

VLBI data for a subset (Hancock 2010) imply source sizes typically < 100 pc at 5 GHz.

A recently restarted radio galaxy?



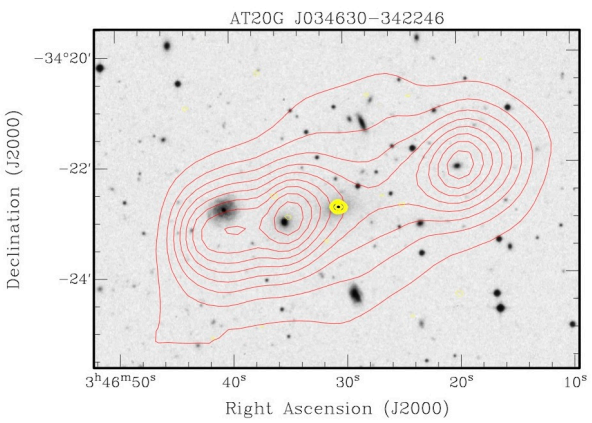
AT20G J074618-570258: z=0.13, passive early-type galaxy. FRI Giant radio galaxy at 843 MHz (Saripalli et al. 2005), extreme GPS source with peak above 20 GHz (Hancock et al. 2009)

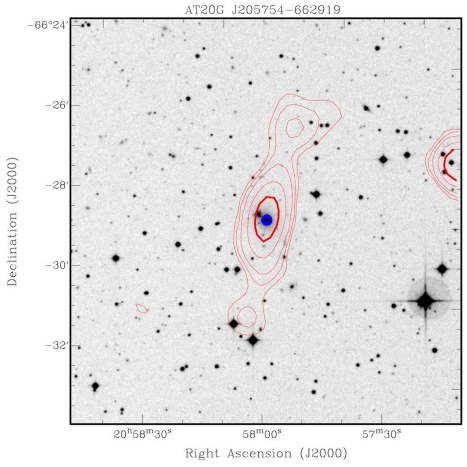
A local radio-galaxy sample selected at 20 GHz

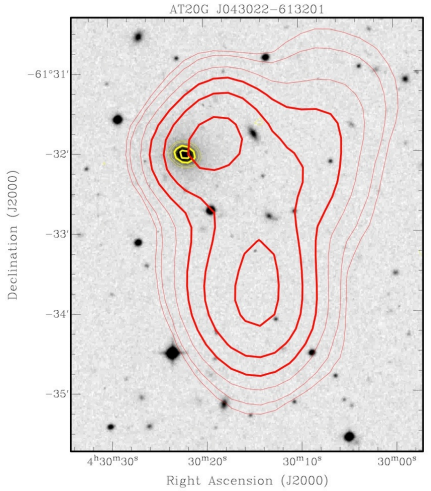
By observing a 20 GHz-selected sample:

- Work at a frequency where AGN emission dominates
- Aim to detect the youngest and most powerful local radio galaxies
- Local benchmark for high-redshift radio surveys: e.g. at z ~3, observed frequencies of 1.4 and 5 GHz correspond to rest-frame 6 and 20 GHz

How do local GPS/CSS sources relate to the wider AGN population?

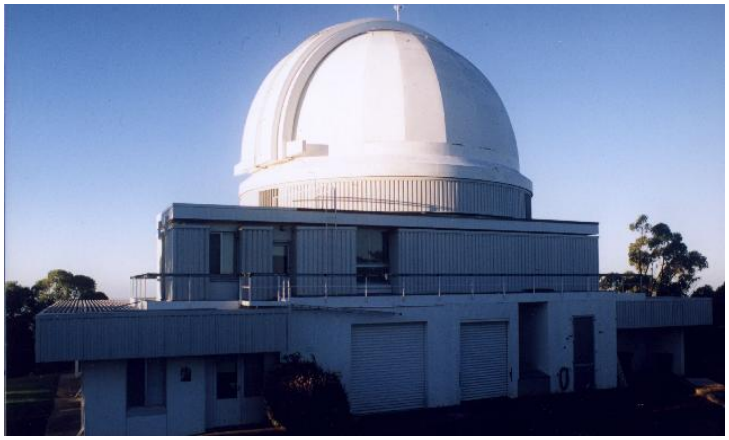


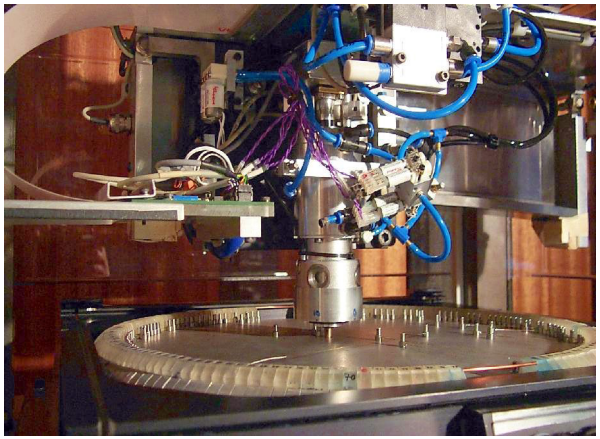




The 6dF Galaxy Survey

(Jones et al. 2004, 2009)

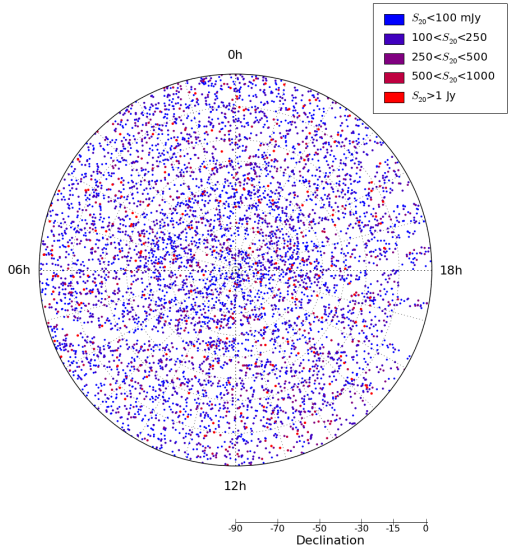


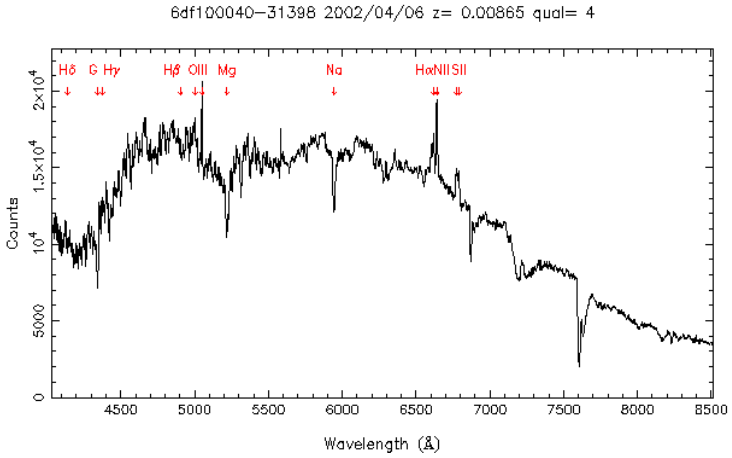


Redshifts and spectra for a K-band selected sample (K < 12.75 mag) of 150,000 galaxies (plus additional targets) over the whole southern sky.

Median redshift z ~ 0.05, allows us to study local radio-source populations within the context of their host population

AT20G-6dFGS galaxy sample





Radio: 20 GHz flux density above 40 mJy from AT20G catalogue (Murphy et al. 2010)

Optical/IR: In 6dFGS main galaxy sample (Jones et al. 2009),K <12.75 mag.

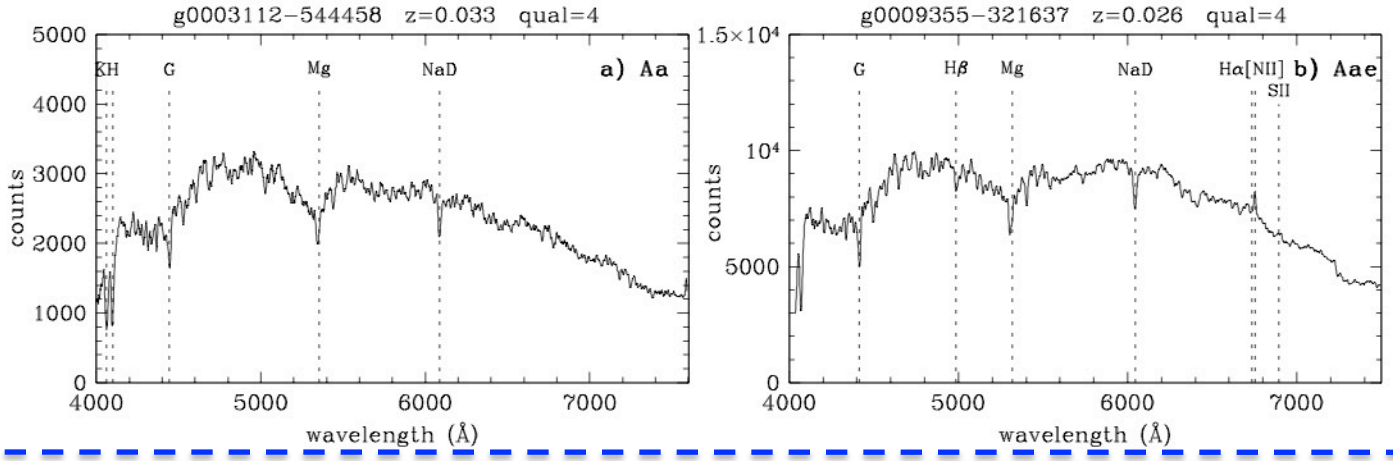
Final 'AT20G Local' sample:

- 202 galaxies (201 AGN)
- *Median redshift z = 0.058*
- Optical spectra (LERG/HERG)
- Radio spectral index measurements (1-20 GHz)

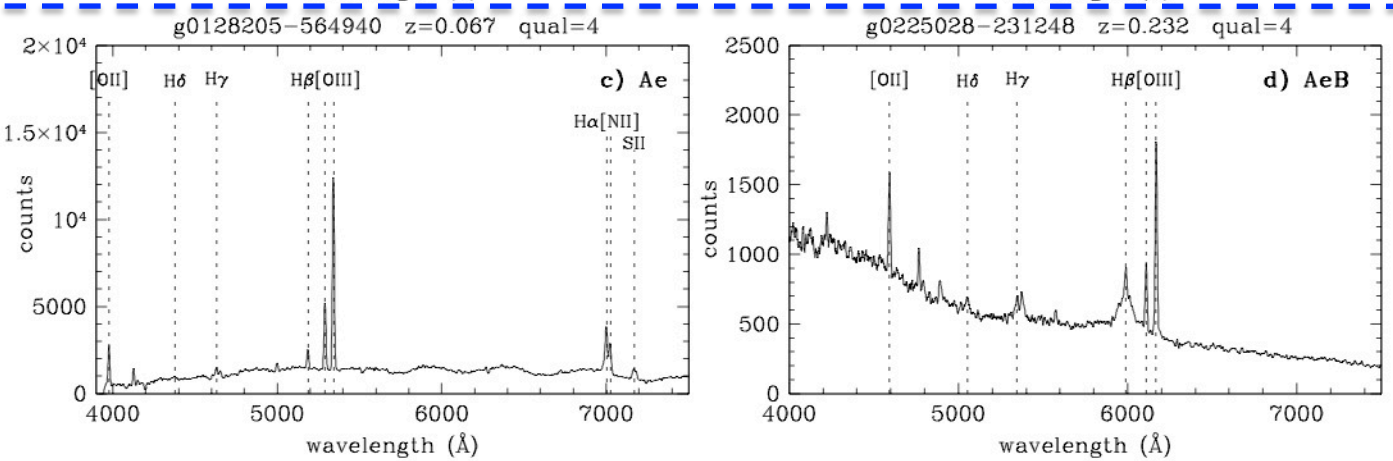
(Sadler et al. 2014)

6dFGS spectra

LERG



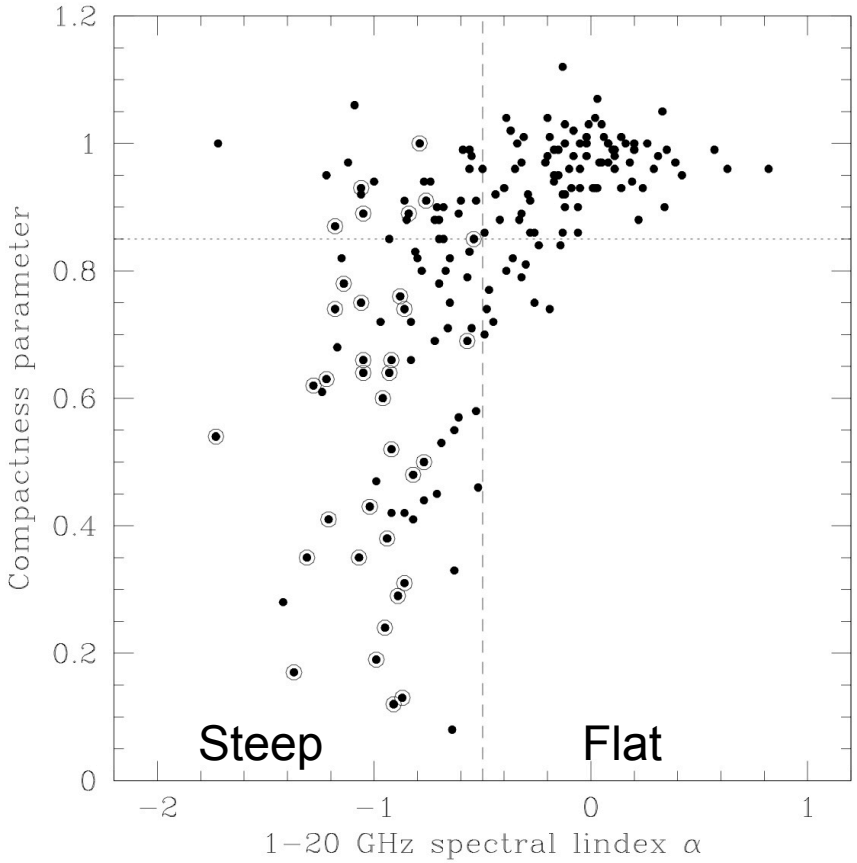
HERG



Source sizes at 20 GHz

Ratio of 20 GHz visibilities on long and short baselines (Chhetri et al. 2013)

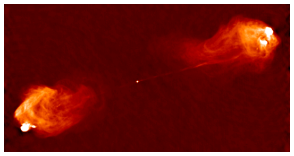
Source size



At 20 GHz, almost 50% of the sources are very compact (<0.2 arcsec in size, i.e. smaller than 500pc at z~0.05) and have 'flat' radio spectra

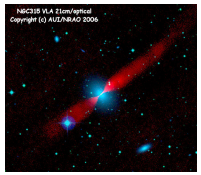
Radio structure at 1 GHz

FR-2
8%



16/201 (8%) have FR-2 morphology at 1 GHz. Most of these objects are also double or triple sources at 20 GHz.

FR-1
24%



49/201 (24%) have FR-1 morphology at 1 GHz. Most of these are also extended sources at 20GHz.

FR-0
68%

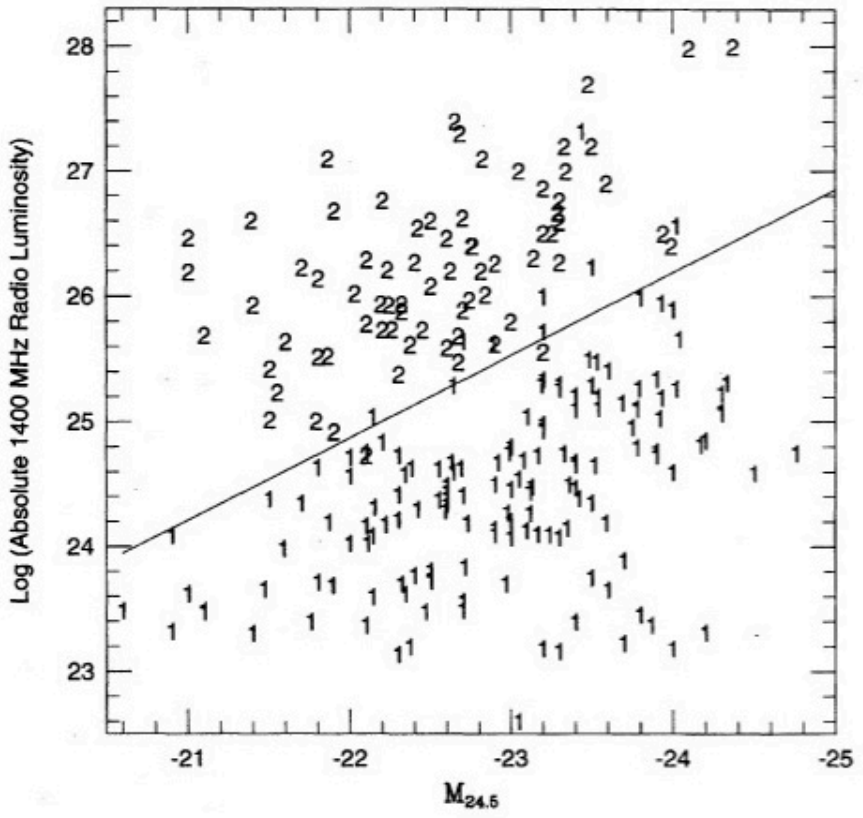
Most (136/201, 68%) are unresolved at 1 GHz (source size < 20 arcsec, < 15 kpc at z~0.05)

Estimate that 6 to 30% of these 'FR0s' are beamed sources, most are NOT beamed

Ghisellini 2011: "*The 'FR 0' radio ellipticals are a new population of radio sources (Baldi et al. 2009) having the same core radio luminosity of FR Is, but hundreds of times less power in the extended emission.*"

Two useful plots

1. The "Ledlow-Owen diagram" (Ledlow & Owen 1996)

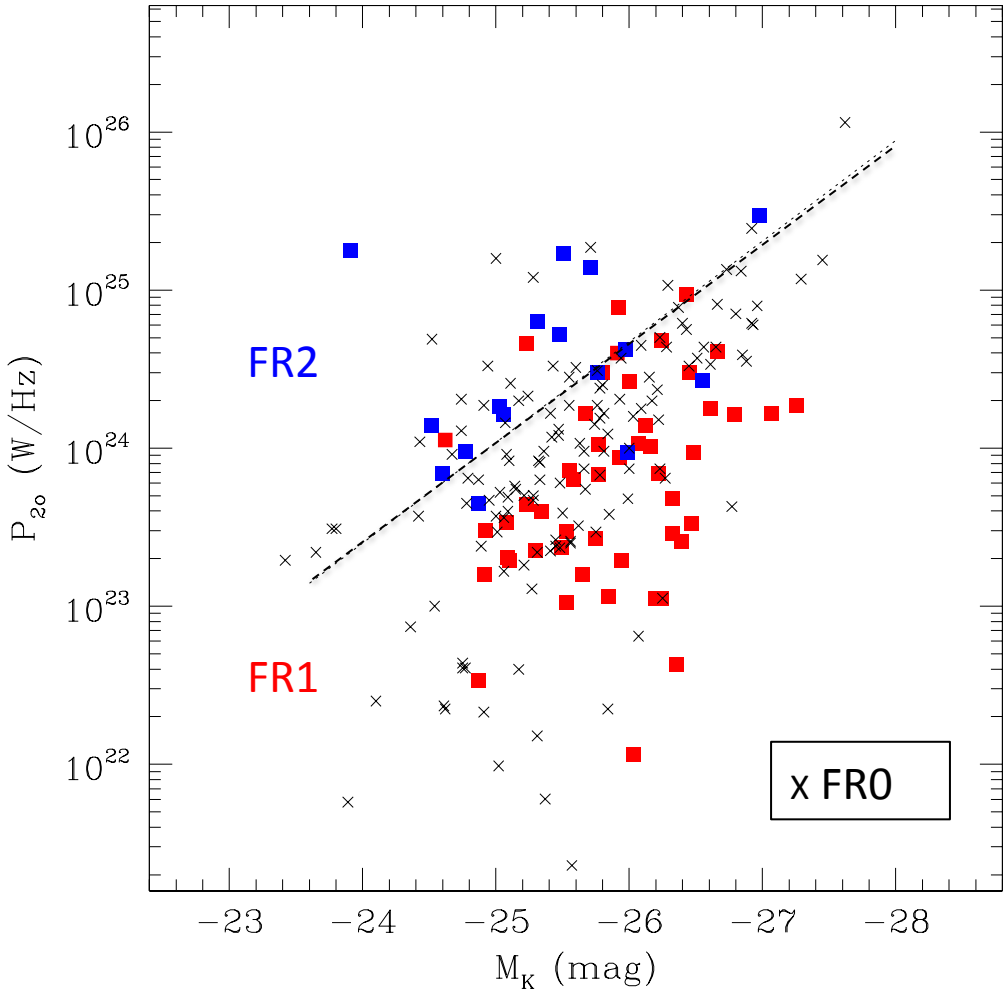


Radio luminosity

Galaxy stellar mass

- Nearby cluster galaxies at 1.4 GHz
- Distinct FR1-FR2 break, which shifts with galaxy stellar mass
- But *is it real??* A range of selection effects at play in both this and subsequent studies (e.g. Best et al. 2008; Gendre et al. 2013)

Ledlow-Owen plot at 20 GHz

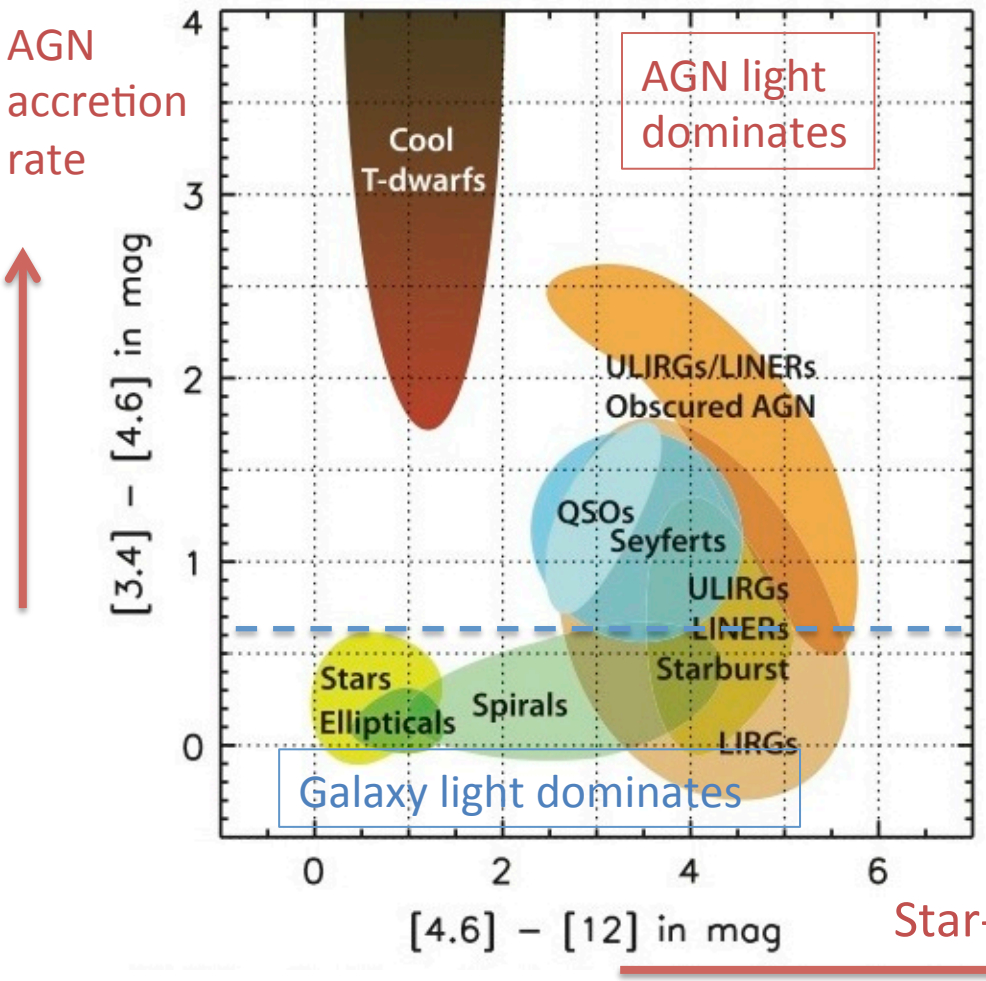


All data points come from the same radio survey AND the same optical sample: L-O relation does appear to hold!

20 GHz luminosity essentially measures the core power. Note that the large number of FR0 galaxies overlap in radio power with the FR1/FR2 systems.

Two useful plots

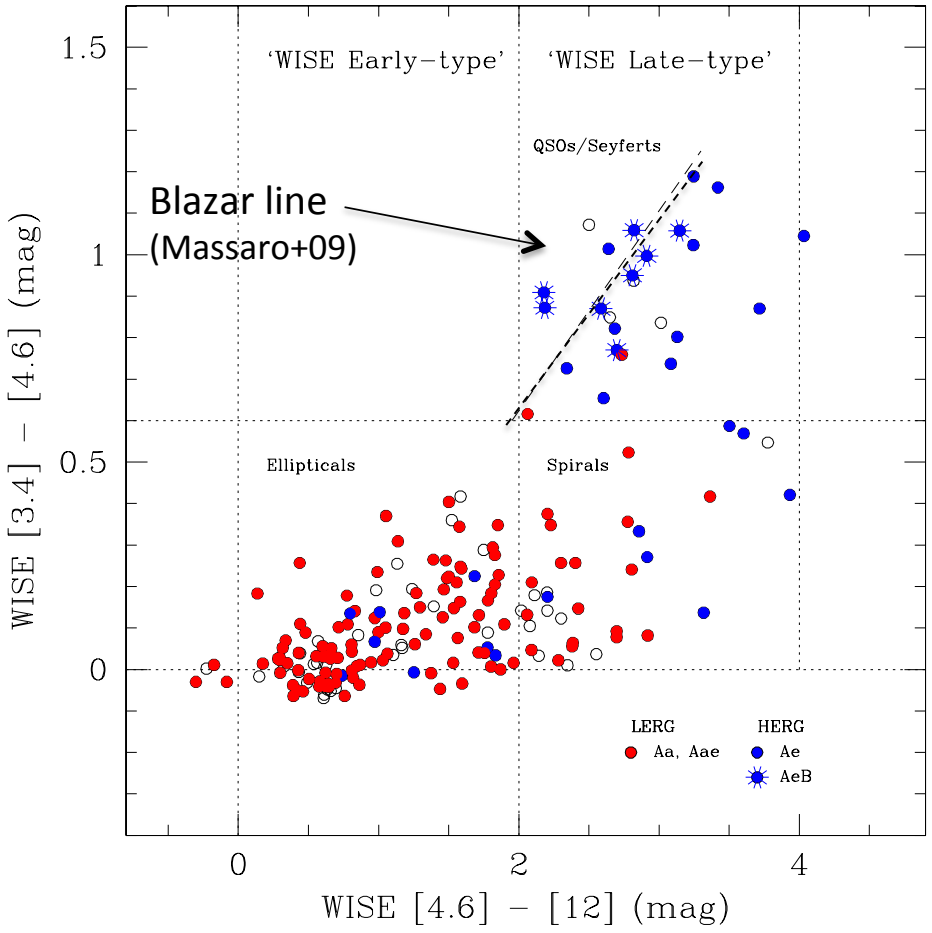
2. The WISE two-colour plot (Wright et al. 2010)



- Uses three of the four mid-IR bands from the all-sky WISE survey (3.4, 4.6 and 12 microns).
- Can reveal obscured AGN, distinguish HERG and LERG and give some information on the host galaxy. Diagram was originally empirical, but an increasing range of model tracks now being developed.

The WISE 2col plot at 20 GHz (1)

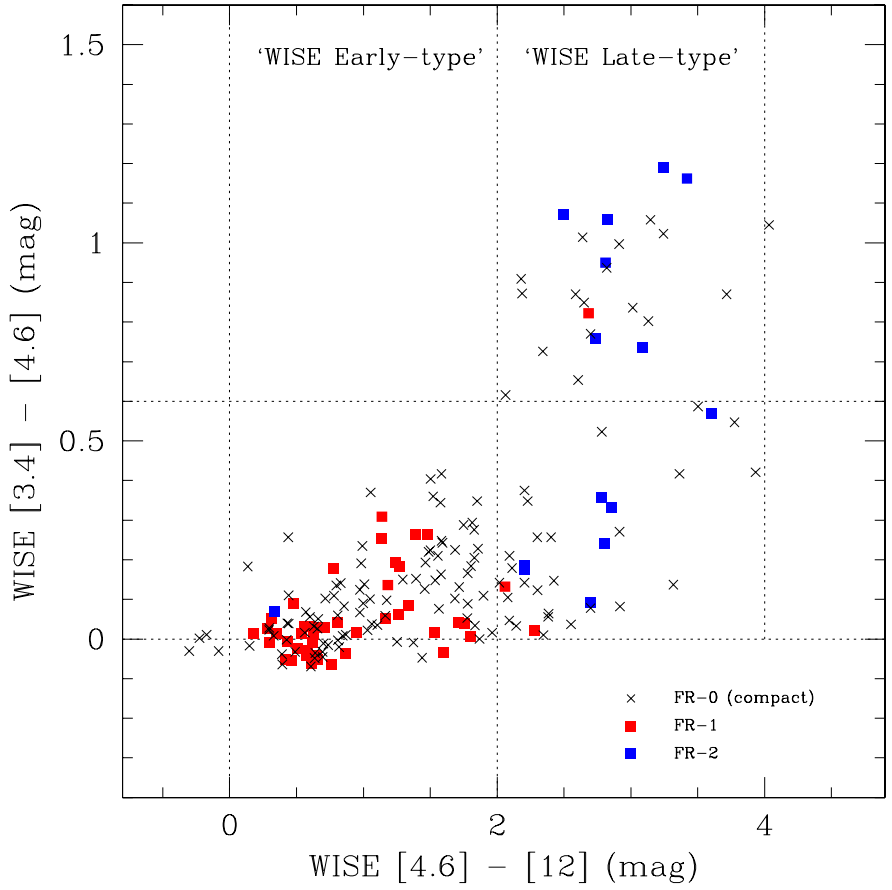
Optical spectroscopic classification (HERG/LERG/QSO)



- Good agreement between spectroscopic and WISE classifications of HERGs and LERGs
- Objects with Sy1 spectra all lie close to the 'blazar line'
- *~30% of host galaxies are spiral/star-forming* (agrees with optical classification)

The WISE 2col plot at 20 GHz (2)

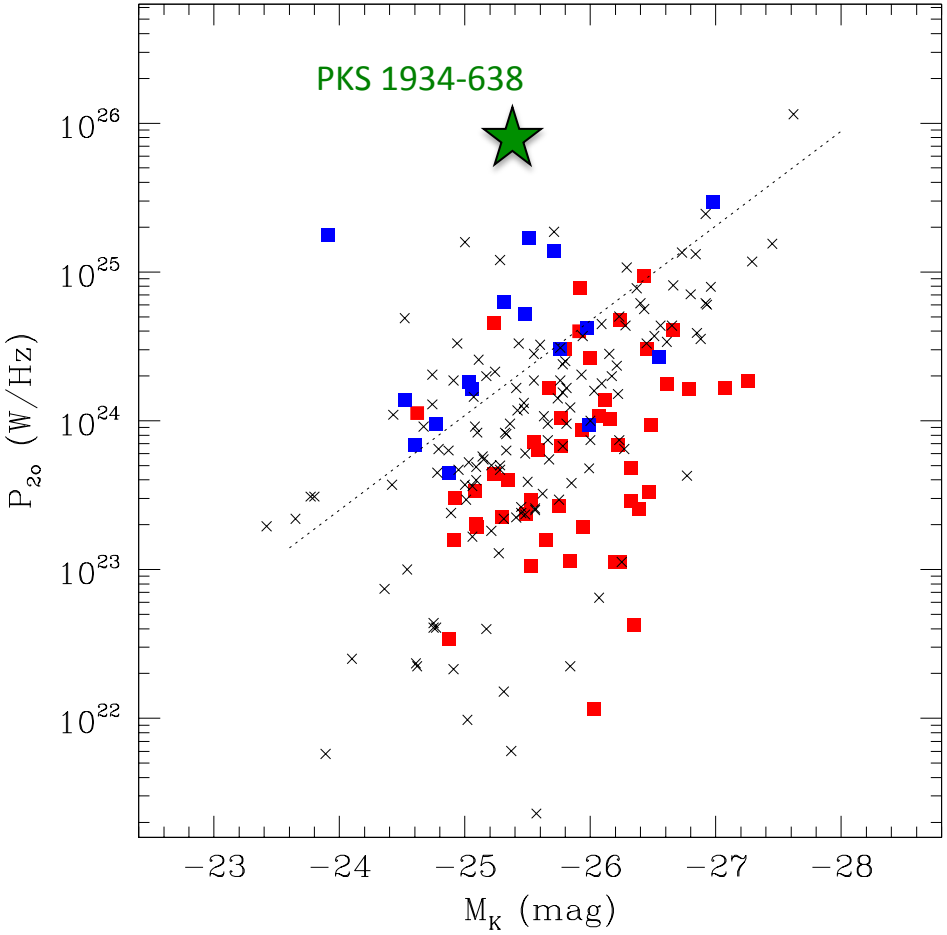
Radio morphology classification (FR0/FR1/FR2)

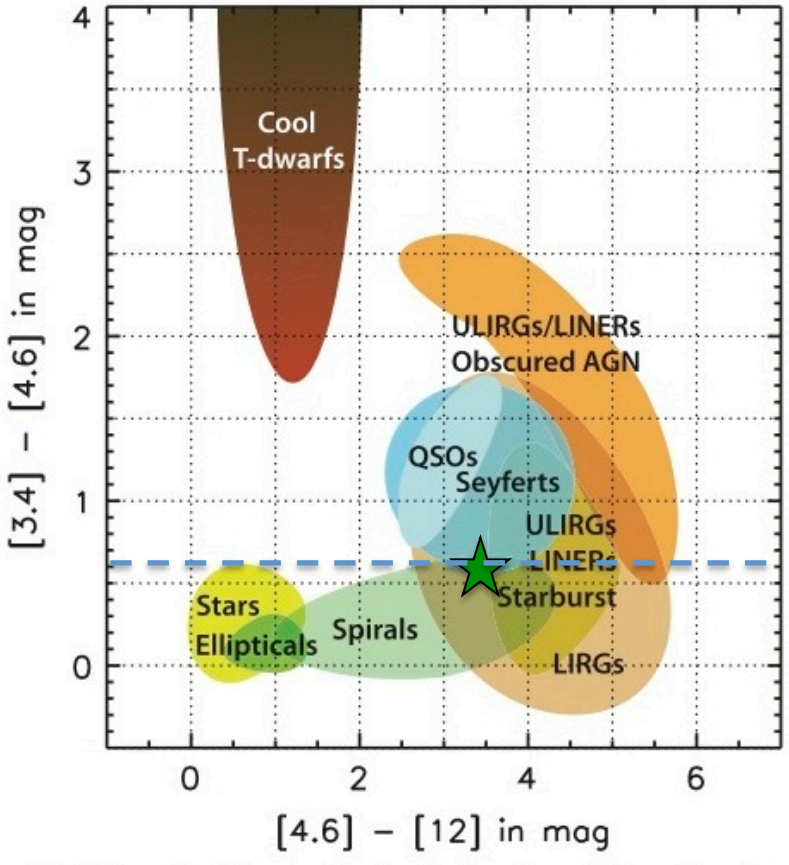


There is a *remarkably clean split* in the host galaxies of FR1 and FR2 radio sources. For the 59 FR1 and FR2 galaxies with reliable WISE photometry:

- 93% (41/44) of FR-1 hosts are in WISE early-type galaxies
- 93% (14/15) of FR-2 hosts are in WISE late-type galaxies

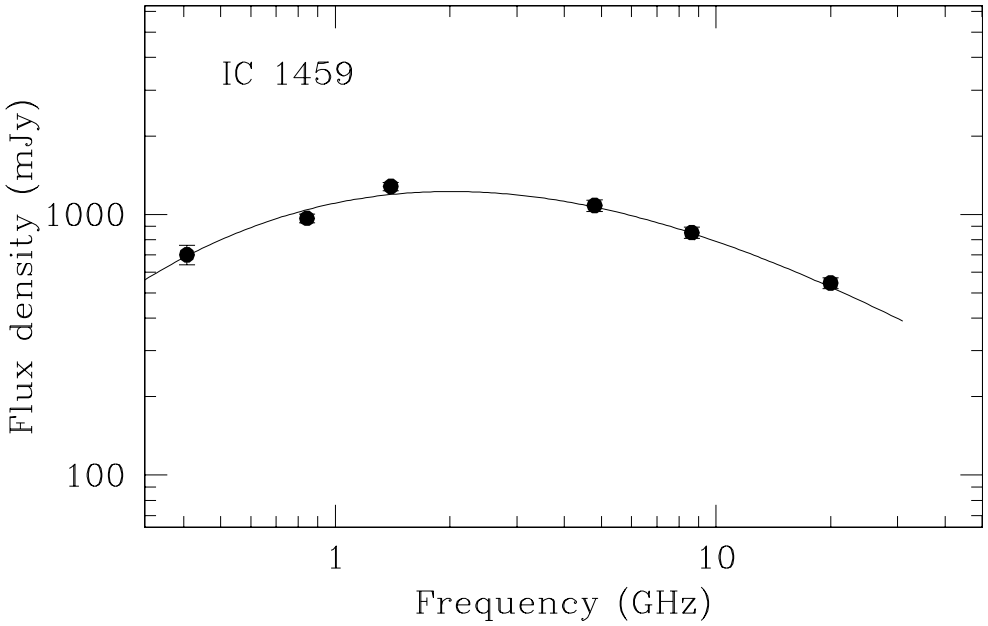
GPS source PKS 1934-638



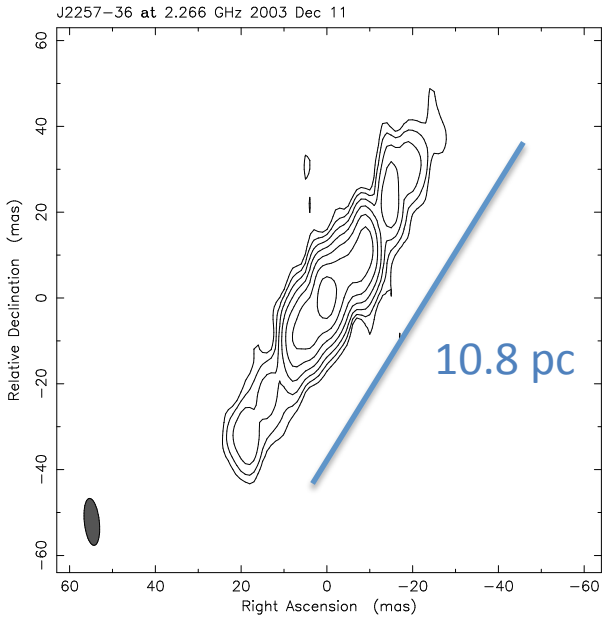


Low-luminosity GPS sources

IC 1459: the closest GPS radio galaxy?



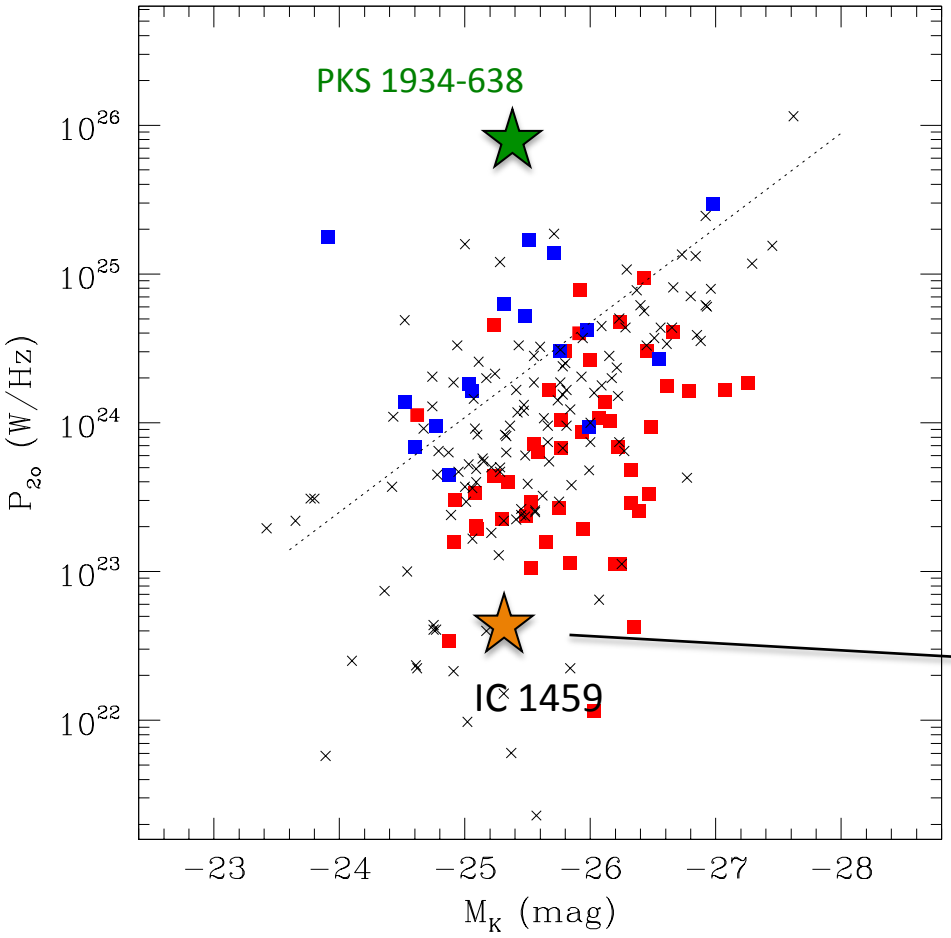
VLBI: Tingay & Edwards 2014

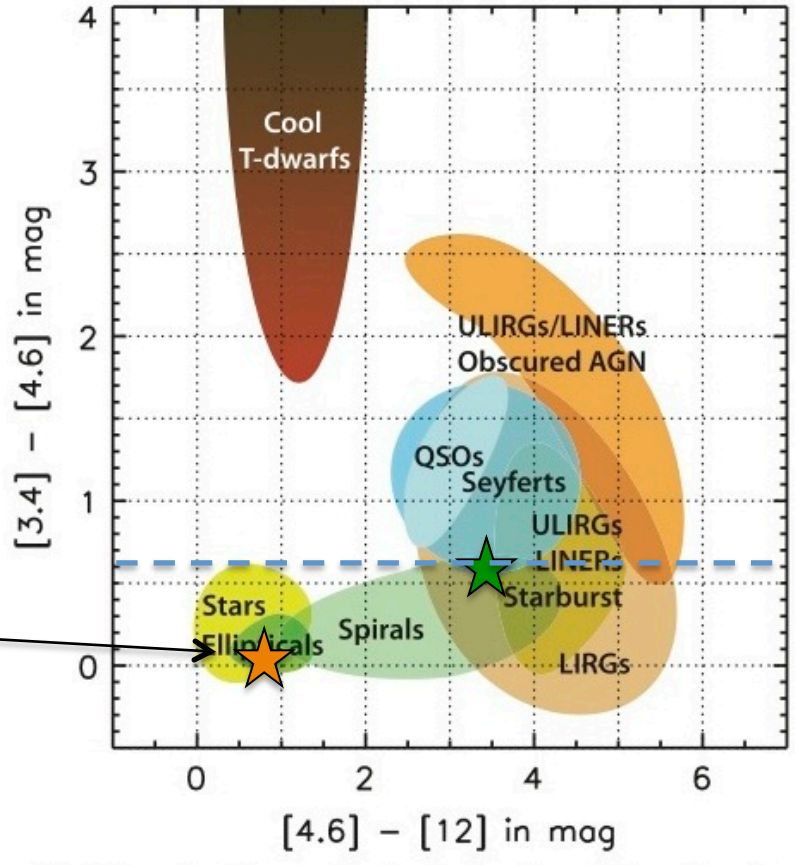


Early-type galaxy at z = 0.006 (d=23 Mpc)
Radio luminosity at 1.4 GHz: $10^{23.0}$ W/Hz

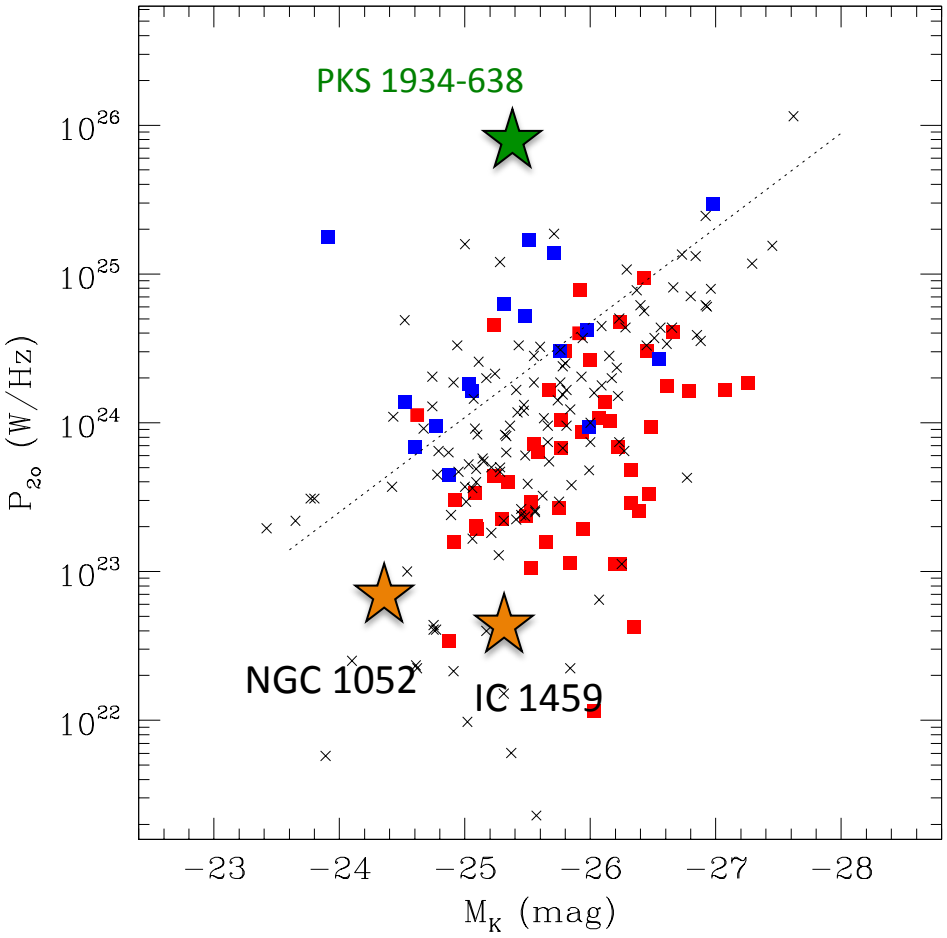
VLBI morphology is FR1-like, rather than double

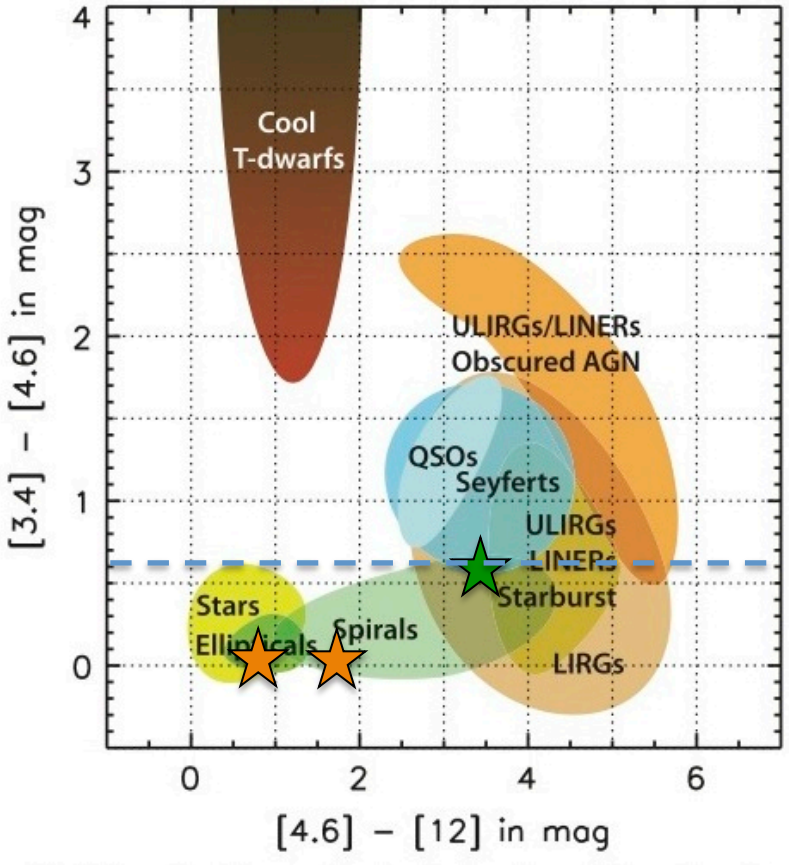
Low-power GPS sources



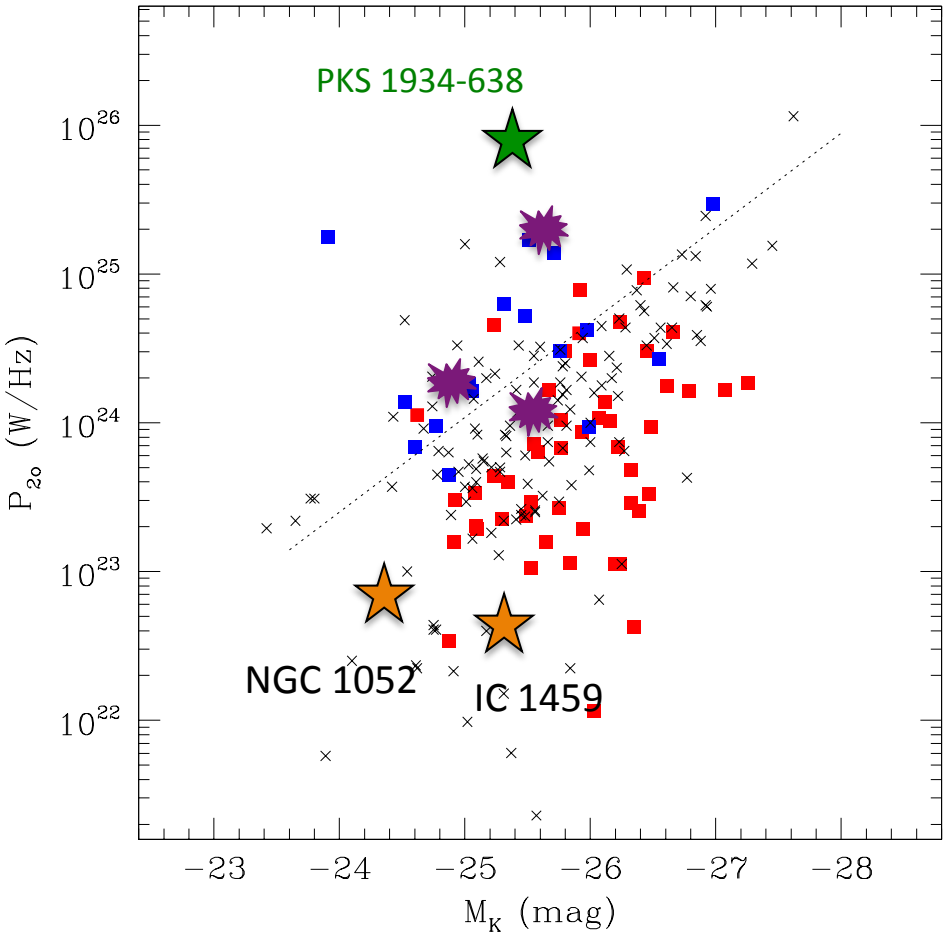


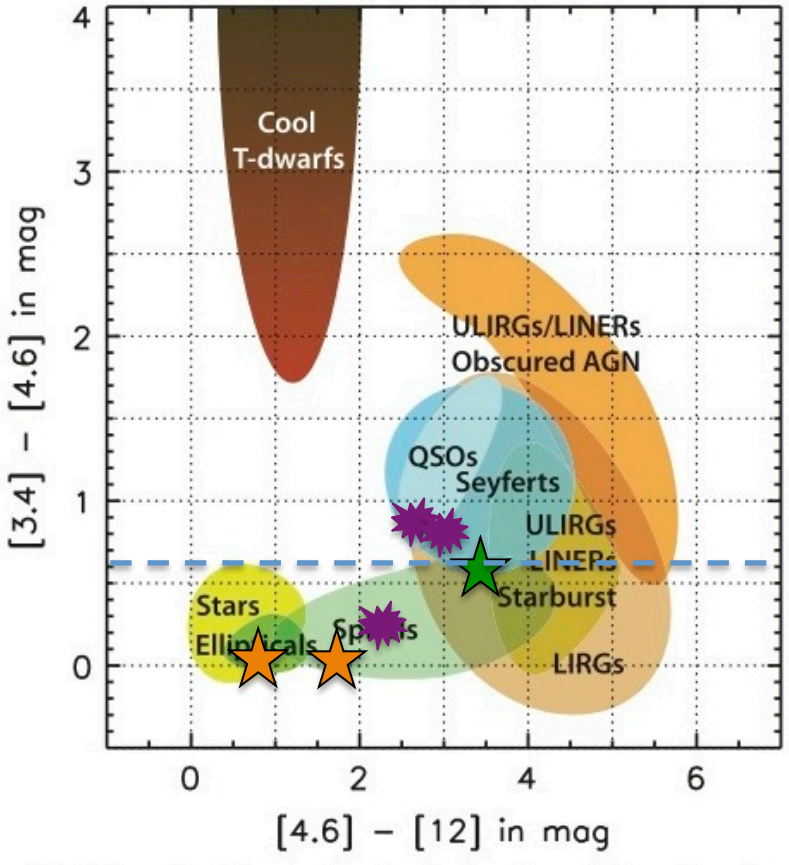
Low-power GPS sources





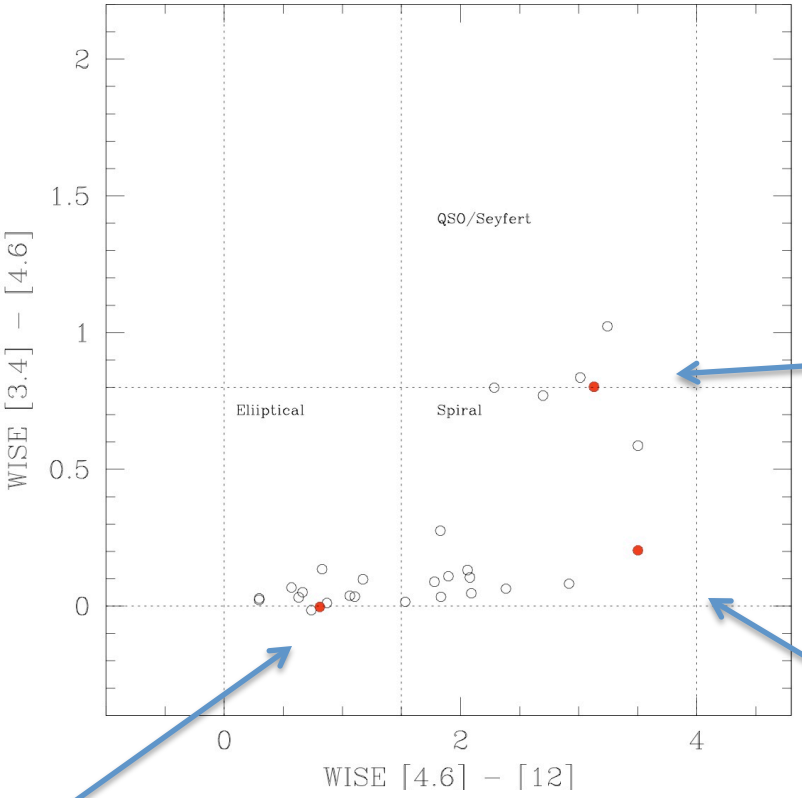
Fermi-detected sources

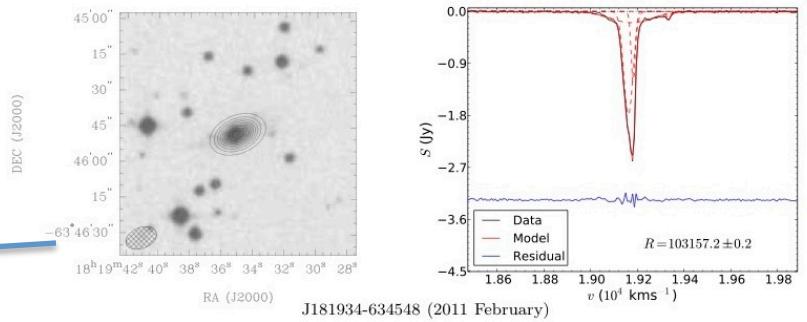




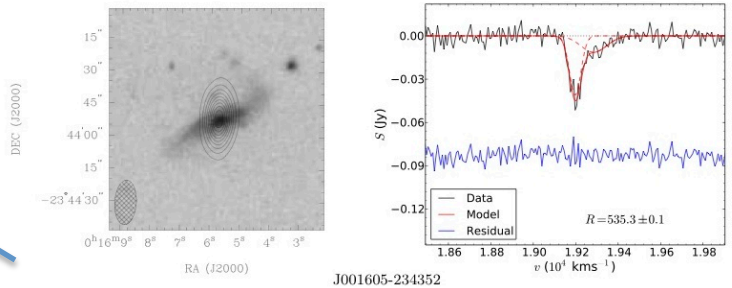
HI absorption-line studies

(Allison et al. 2012)

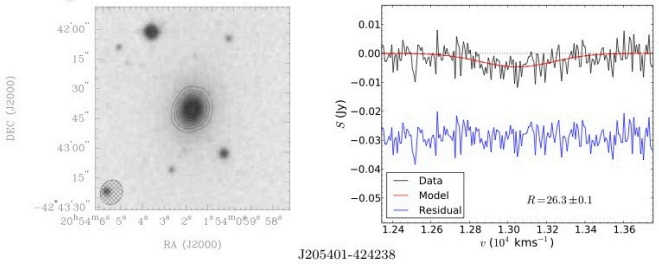




J181934-634548 (2011 February)



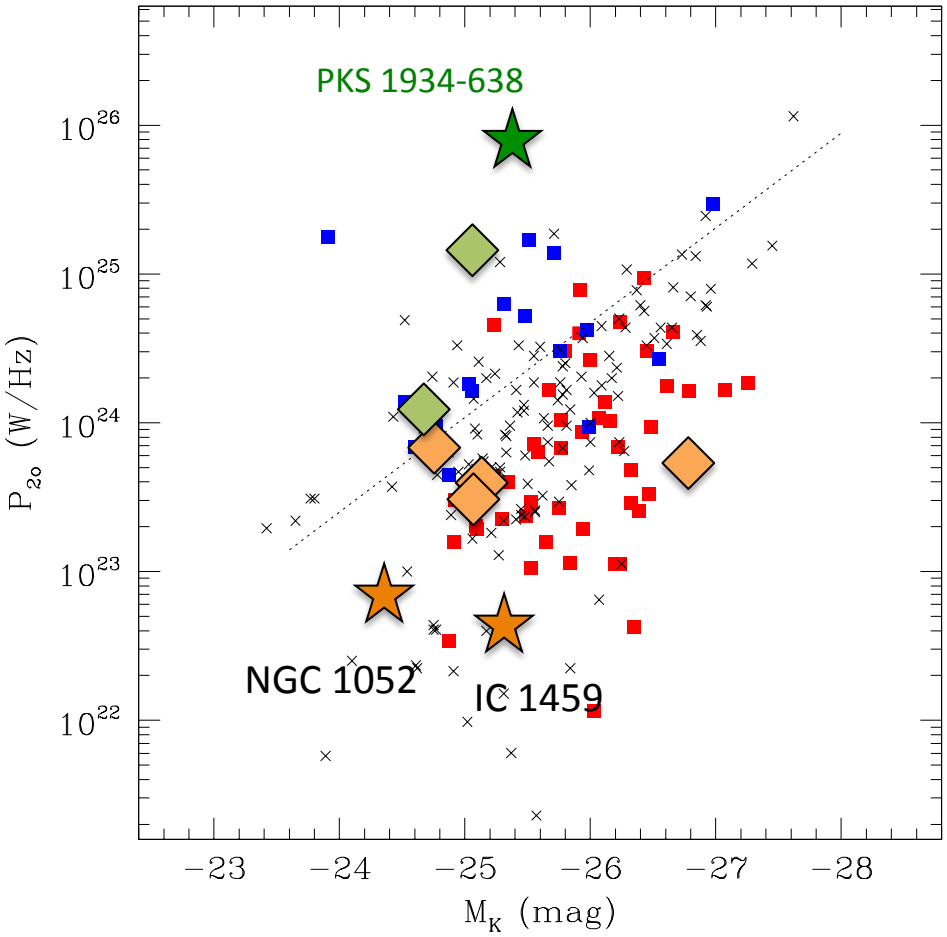
J001605-234352

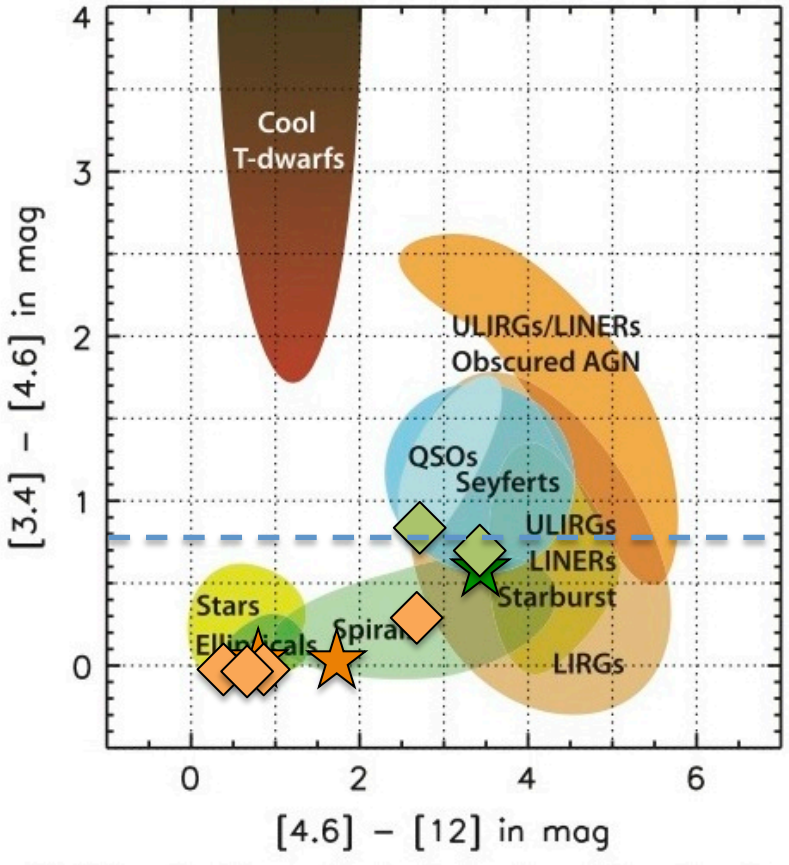


J205401-424238

HI absorption (and emission) results imply that both LERGs and HERGs in our sample sometimes contain cold neutral gas.

Compact sources with HI absorption (GPS/CSS candidates)





What are the AT20G 'FR-0' radio galaxies?

• Heterogeneous population in terms of both host-galaxy morphology (75% in WISE early-type galaxies, 25% in WISE spirals) and optical spectra (75% LERG, 25% HERG).

• Overall radio properties match those expected for young (CSS/ GPS) radio galaxies (40% GPS, 60% CSS) – if so, this represents the largest and most complete sample of young radio galaxies in the local universe.

Open questions:

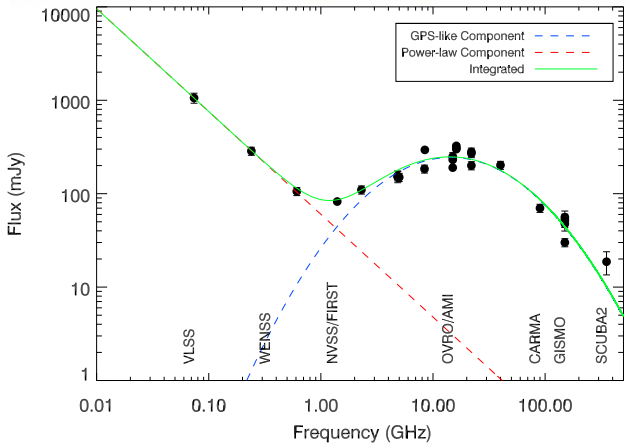
• Small-scale structure – VLBI observations in progress
• Demographics/modelling – early phase of classical radio galaxies, or short-lived episodic activity?
• Gas supply and fuelling?
• Effects of environment – are they really young, or are there faint, extended jets and lobes which we just don't see?

Radio cores in local BCGs

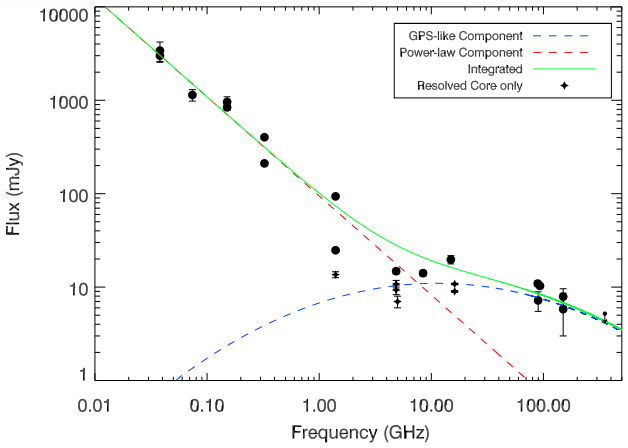
Recent work by M. Hogan et al. (2015)

- Measured high radio frequency (15 GHz - 353 GHz) properties and variability of 35 Brightest Cluster Galaxies (BCGs).
- These are the most core-dominated sources drawn from a parent sample of more than 700 X-ray selected clusters, so results can be related back to the general population.
- At least 6% of the parent cluster sample (and >15% of cool-core clusters) contain a radio-source at 150 GHz of at least 3mJy ($\approx 10^{23}$ W/Hz at the median redshift of $z \approx 0.13$).
- >3.4% of the BCGs (and >8.5% of cool core clusters) in the parent sample show a GPS component in their spectra that peaks above 2 GHz

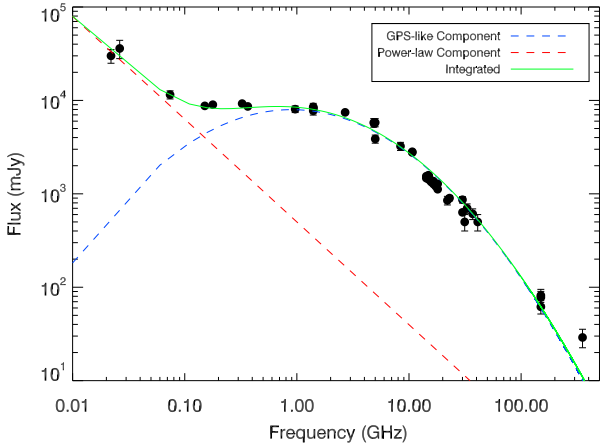
Radio spectra of BCGs



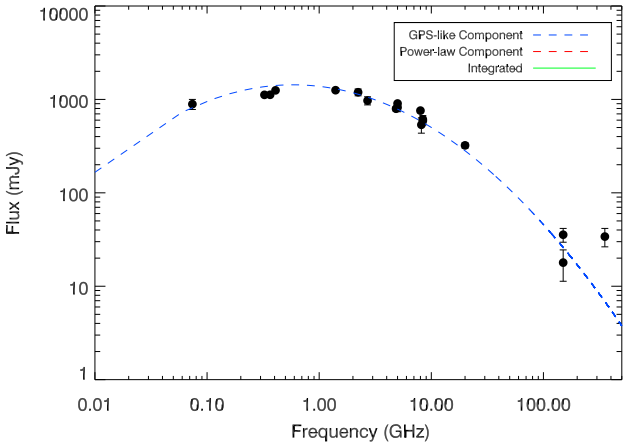
(a) *R0439+05*



(b) *E1821+644*



(c) *4C+55.16*



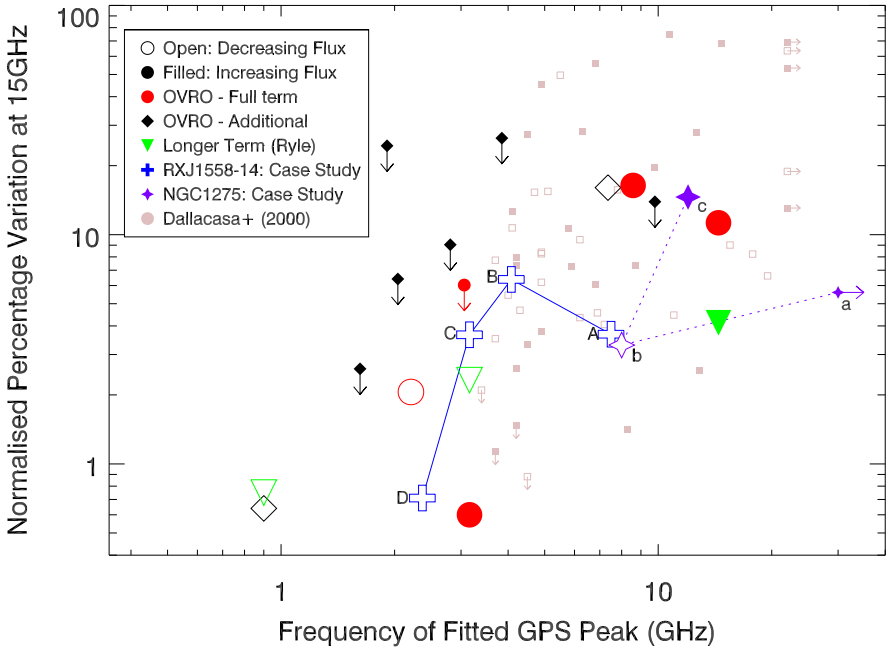
(d) *MACS0242-21*

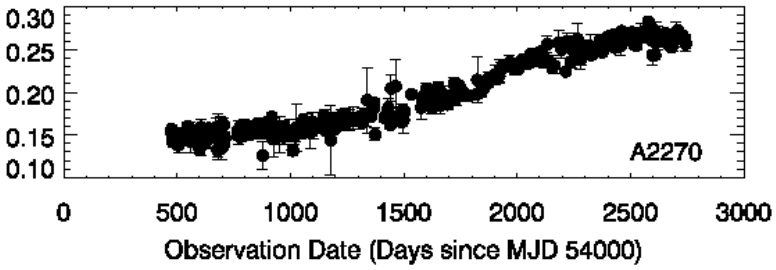
BCGs are an excellent population to put the GPS fraction into the context of a population of sources that are active 100% of the time (at least in cool core clusters).

(Hogan et al. 2015)

Radio variability in BCGs

(Hogan et al. 2015)





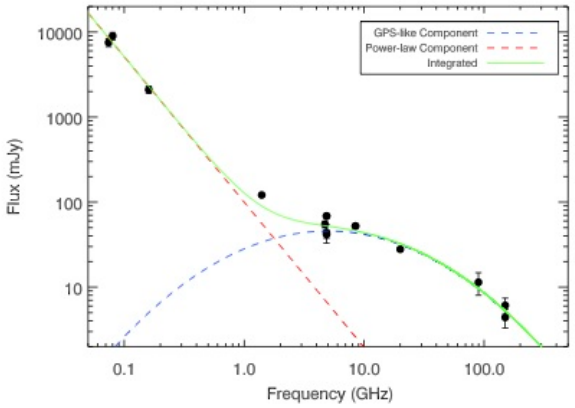
- General trend for higher-peaking sources to be more variable
- BCG GPS-like components show similar 15 GHz variability properties to the Dallacase et al. (2000) HFP sample.

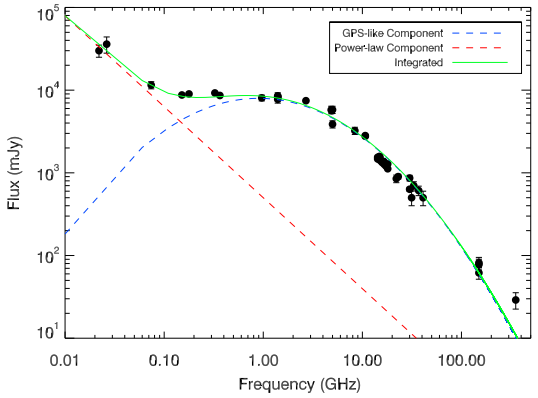
GPS sources as ‘waves of activity’

Alastair Edge:

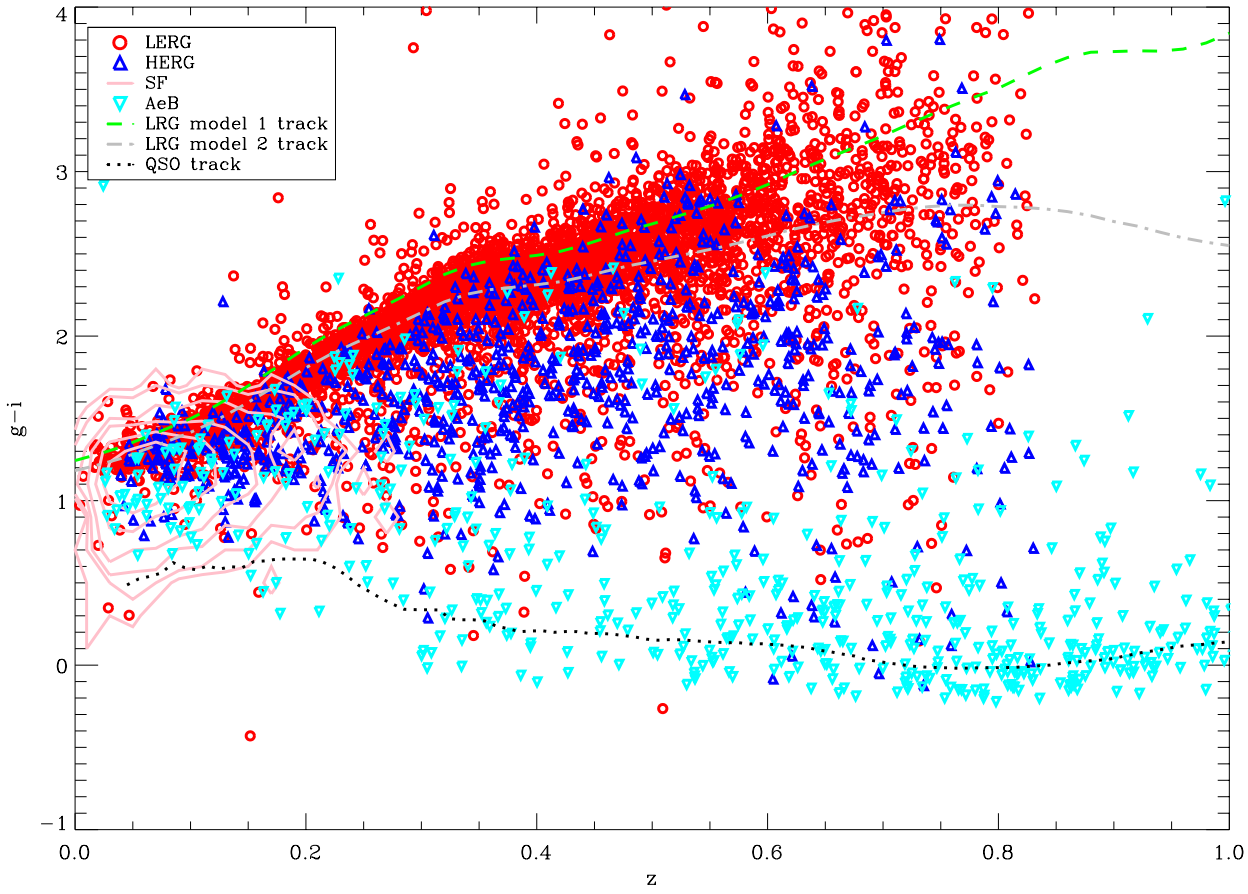
“I am keen to confront the "GPS sources are young/restarted" view with the argument that the GPS phenomenon should be viewed as *waves of AGN activity "lapping the shores of Rimini"* - we just spot them as they crest and break.

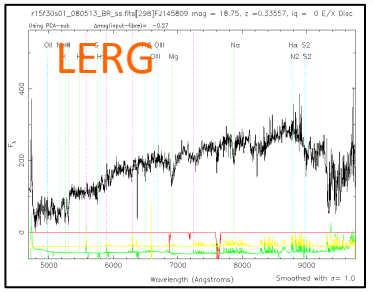
The waves come regularly not individually so seeing a strong GPS can't be used to argue that a source is "young" as we can’t know how many waves have come before it from the presence of a GPS component alone.

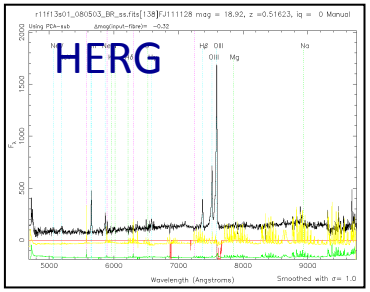


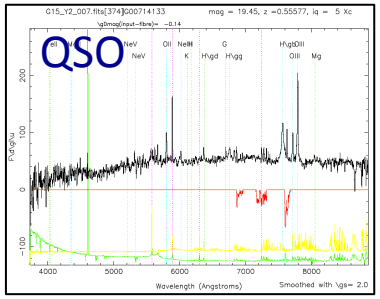


Next steps: radio-source populations to z ~1









(J. Ching, 2014 PhD thesis)

1.4 GHz 10,000+ radio AGN with optical spectra

Summary

- 'Classical' GPS and CSS radio sources tend to be powerful radio sources ($P > 10^{25}$ W/Hz) with compact double morphology.
- Is this largely a selection effect? *I think so!*
- We can now start to find lower-power CSS/GPS candidates, including (i) objects with FR1-like morphology on parsec scales and (ii) high-frequency GPS-like peaked components embedded within low-frequency extended emission (especially in cluster galaxies).
- Future wide-band surveys to mJy flux levels should tell us much more!
- Need WIDE coverage (100 MHz to 100 GHz!).