CAASTRO
ARC CENTRE OF EXCELLENCE
FOR ALL-SKY ASTROPHYSICS

THE UNIVERSITY OF
SYDNEY

Radio AGN populations and their cosmic evolution

Elaine M. Sadler
CAASTRO/University of Sydney

www.caastro.org

Overview

What I'll (mainly) talk about:

Results from large-area surveys

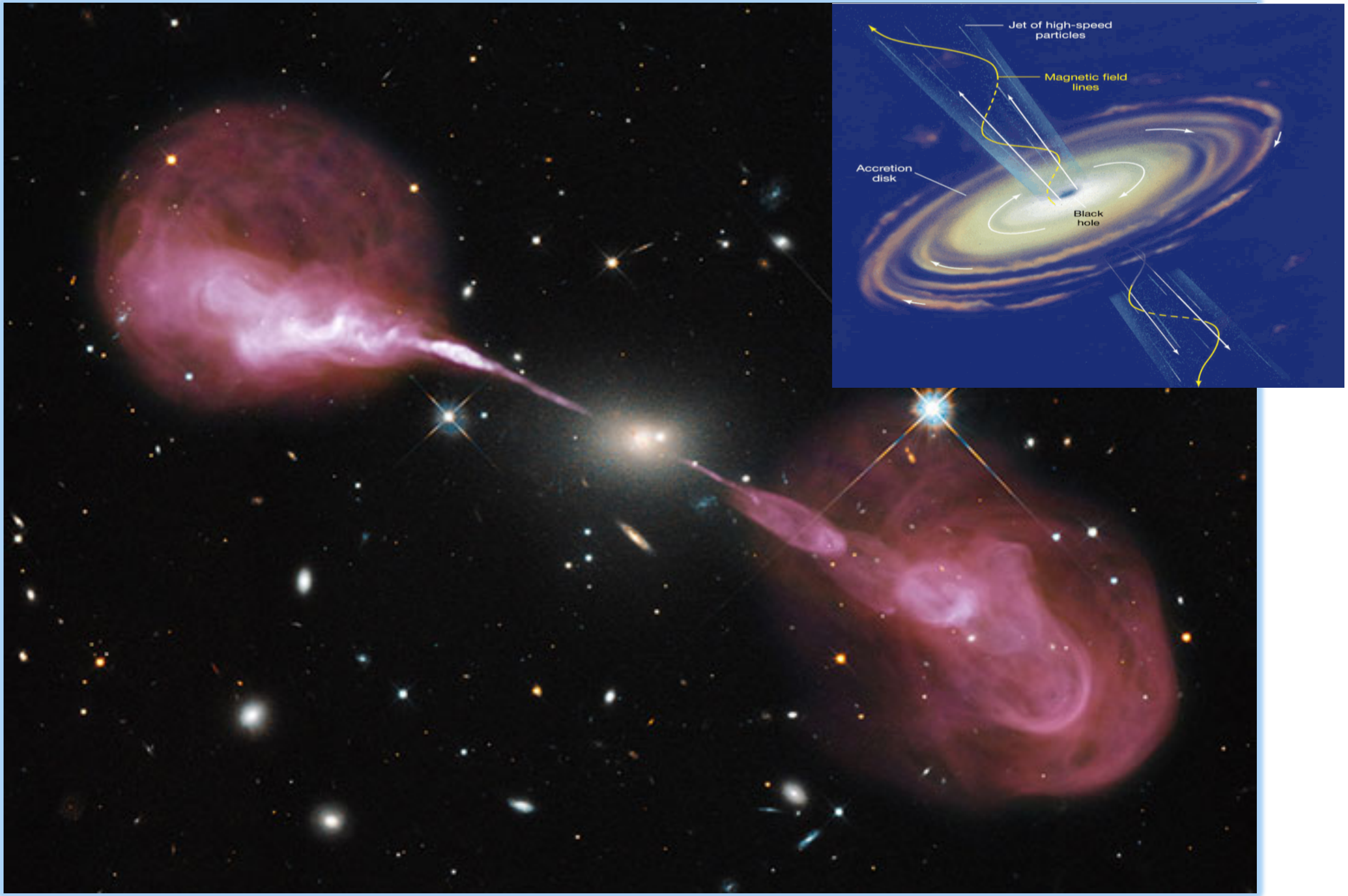
- Local radio-source populations and demographics
- Radio spectra and SEDs
- The AGN radio luminosity function and its evolution
- Searches for high-redshift radio galaxies at z > 5

Collaborators in this research include:

James Allison, Joe Callingham, Russell Cannon, John Ching, Rajan Chhetri, Scott Croom, Stephen Curran, Ron Ekers, Marcin Glowacki, Paul Hancock, Martin Hardcastle, Matt Jarvis, Helen Johnston, Elizabeth Mahony, Marcella Massardi, Tom Mauch, John Morgan, Raffaela Morganti, Vanessa Moss, Tara Murphy, Michael Pracy, Stas Shabala, David Wake

and members of the 6dFGS, 2dFGRS, 2SLAQ, WiggleZ, GAMA, AT20G, SUMSS and MWA GLEAM survey teams

Black holes and galaxy evolution

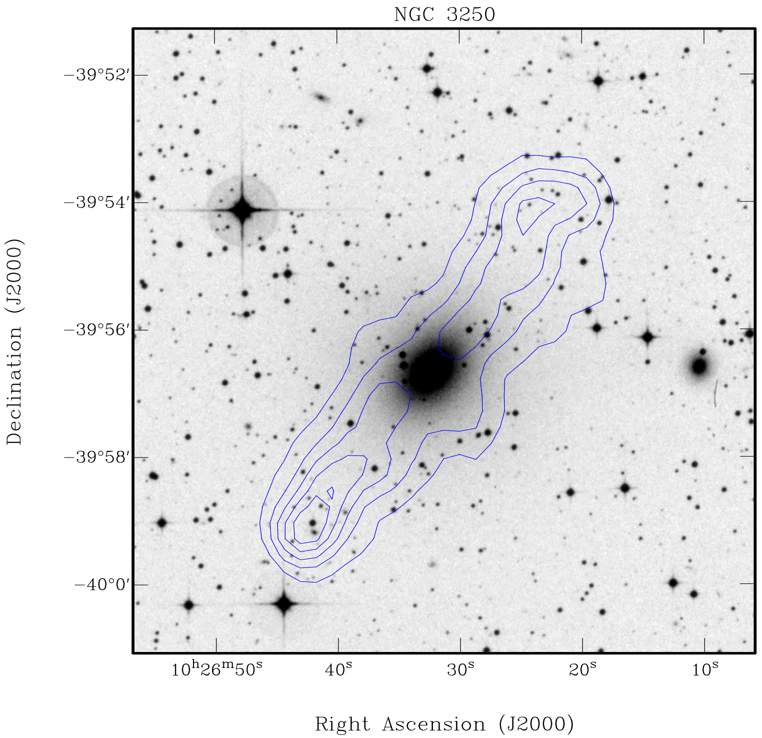


Hercules A: NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA)

Radio jets and galaxy evolution

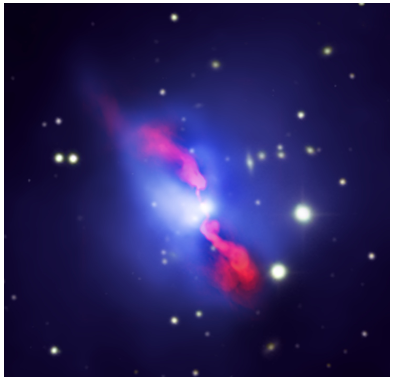
Radio jets are currently invoked both:

- to **trigger** star formation in galaxies (*"jet-induced star formation"*) and
- to **inhibit** star formation in massive galaxies (*"radio-mode feedback"*)



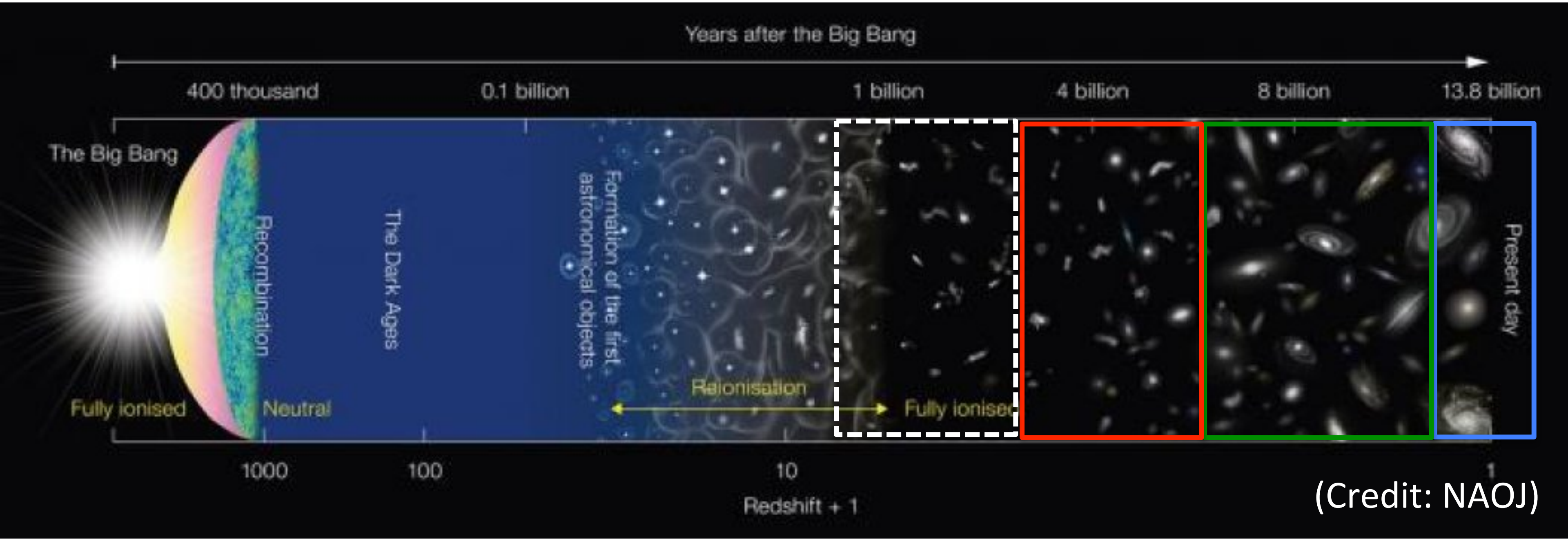
Relative importance of these two mechanisms is likely to depend on environment, ISM and redshift

Minkowski's object:
W. van Breugel/NRAO



MCS 0735.6+7421
B. McNamara/NASA/ESA/NRAO

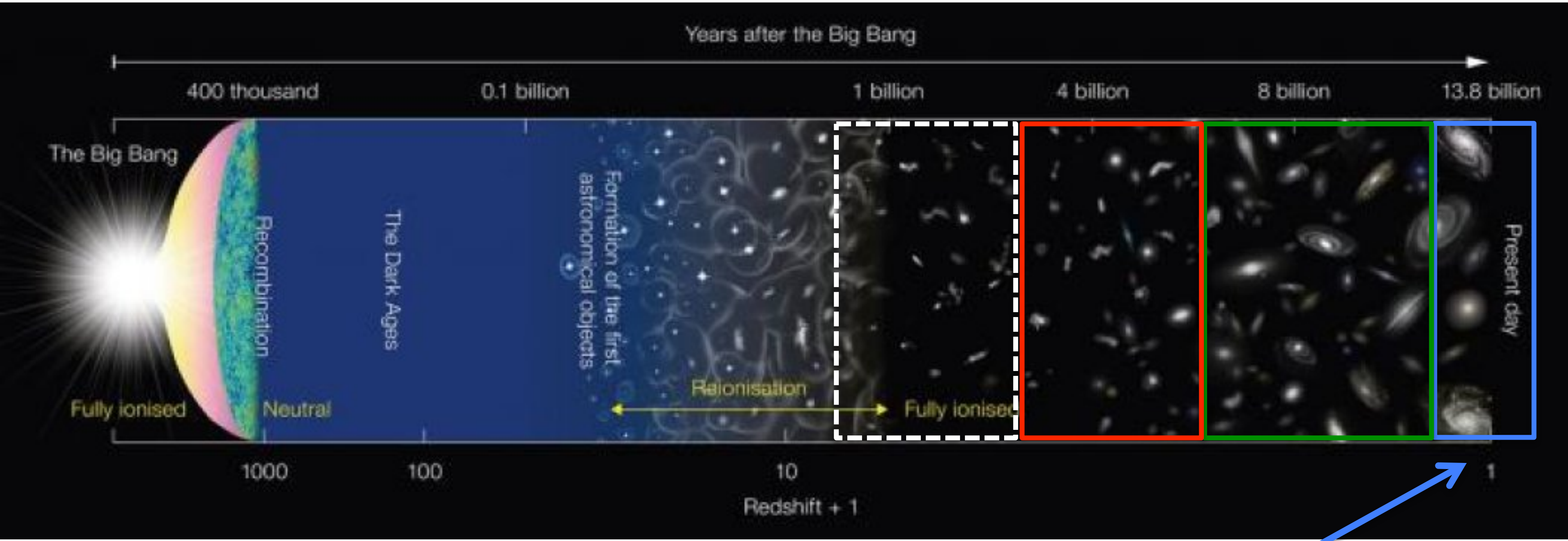
Radio AGN and their evolution



(Credit: NAOJ)

Redshift range	Lookback time	Technique
0.0 to 0.2	< 2.5 Gyr	Large-area radio and optical surveys
0.2 to 0.8	2.5 - 7 Gyr	Medium-area radio and optical surveys
0.8 to 3	7 - 11.5 Gyr	Small area surveys/ large-area data mining
3 to 6	11.5 - 12.8 Gyr	Large-area data mining

Radio AGN and their evolution



(Credit: NAOJ)

1) Local radio AGN populations at $z < 0.2$

Local radio-source populations

- Well-constrained at 1.4 GHz, now starting to be mapped out at frequencies from 100 MHz to 100 GHz
- Large samples (10,000+ objects) from combination of large-area optical and radio surveys over the past decade:

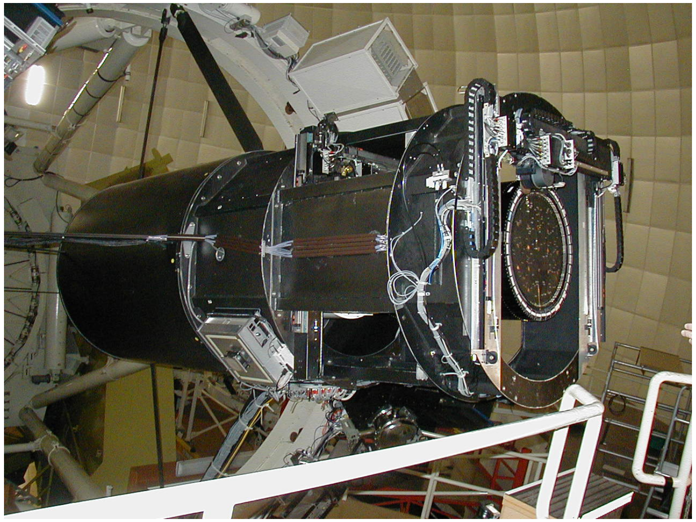
Large studies include:

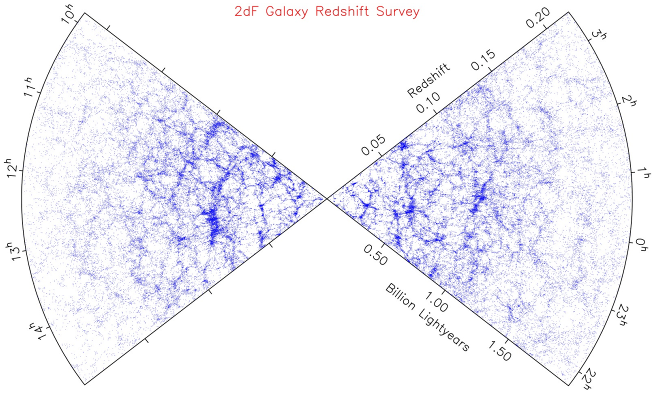
North
- NVSS/FIRST – SDSS (Best et al. 2005, 2012, 2014)

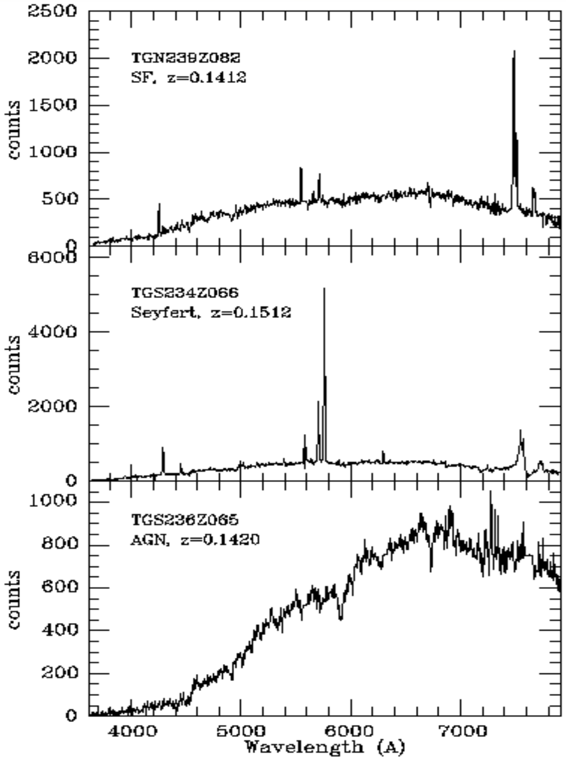
South
- NVSS- 2dFGRS (Sadler et al. 2002)
- NVSS – 6dFGS (Mauch & Sadler 2007)
- AT20G – 6dFGS (Sadler et al. 2014)

Equatorial
- FIRST – GAMA/WiggleZ (Pracy et al. 2016, Ching et al. 2017)

Local radio-source populations







Star-forming galaxy

Emission-line AGN (HERG)

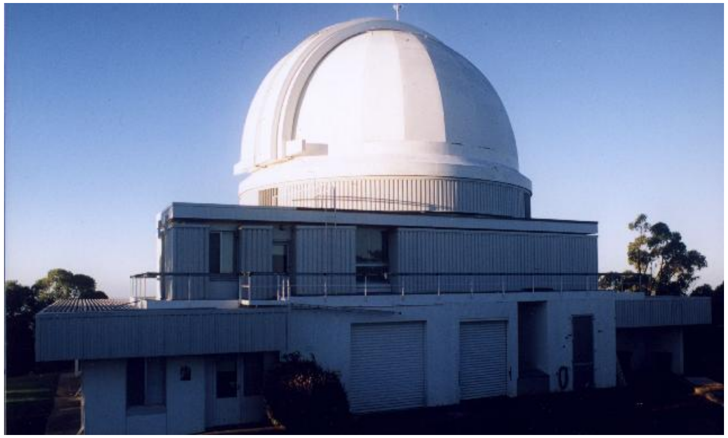
Absorption-line AGN (LERG)

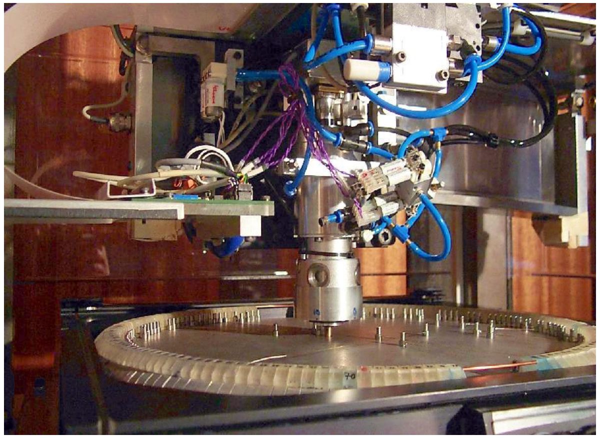
(Sadler et al. 2002)

Match with large-area optical surveys: spectra can usually distinguish starbursts from AGN unambiguously.

The 6dF Galaxy Survey

(Jones et al. 2004, 2009)





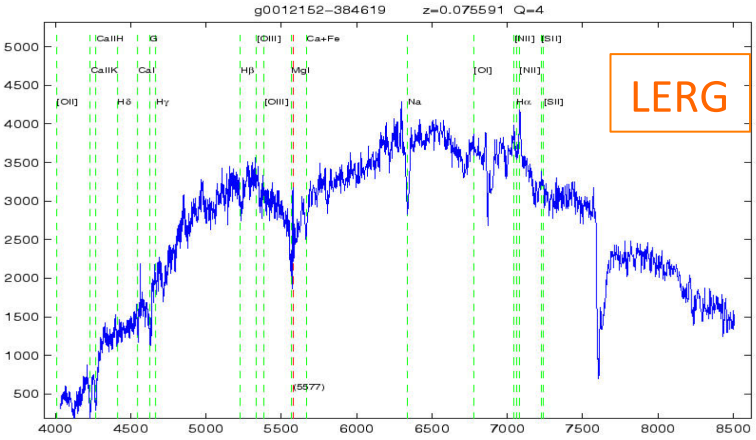
Redshifts and spectra for a K-band selected sample (K < 12.75 mag) of 150,000 galaxies (plus additional targets) over the whole southern sky at dec < 0 deg.

New 6dF Taipan survey starts late 2017

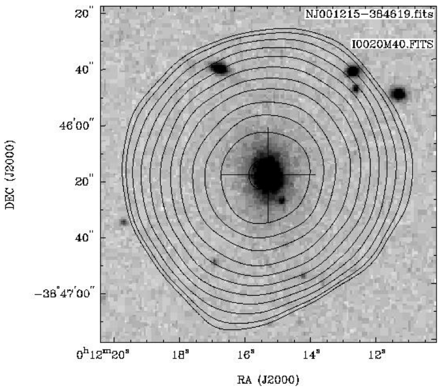
Median redshift z ~ 0.05, allows us to study local radio-source populations within the context of their host population

6dFGS radio sources

NVSS 1.4 GHz

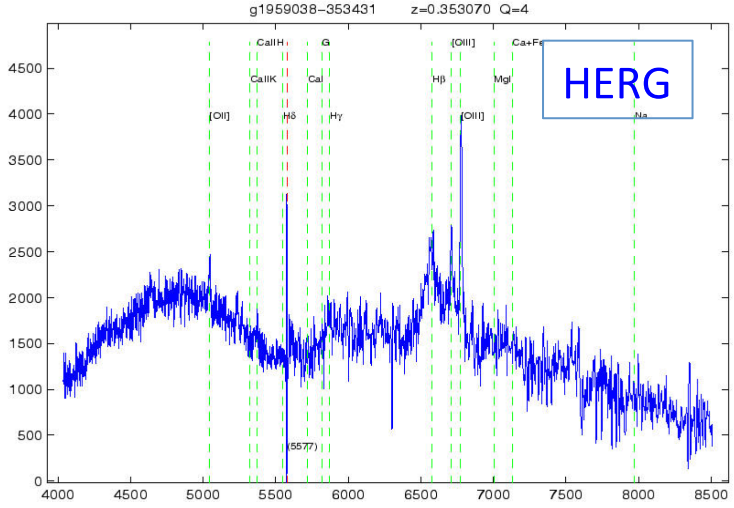


LERG

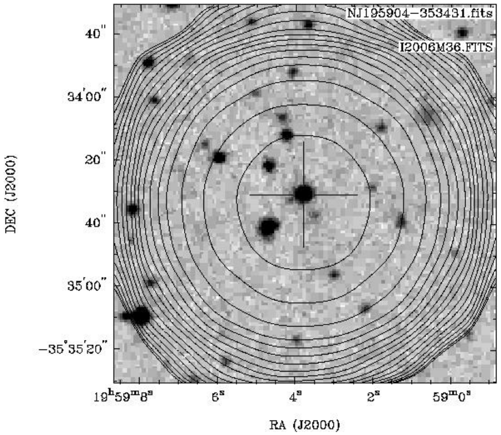


6dFGS provided spectra of 10,000+ radio AGN and starburst galaxies

Definitive local benchmark for studying the evolution of radio-source populations

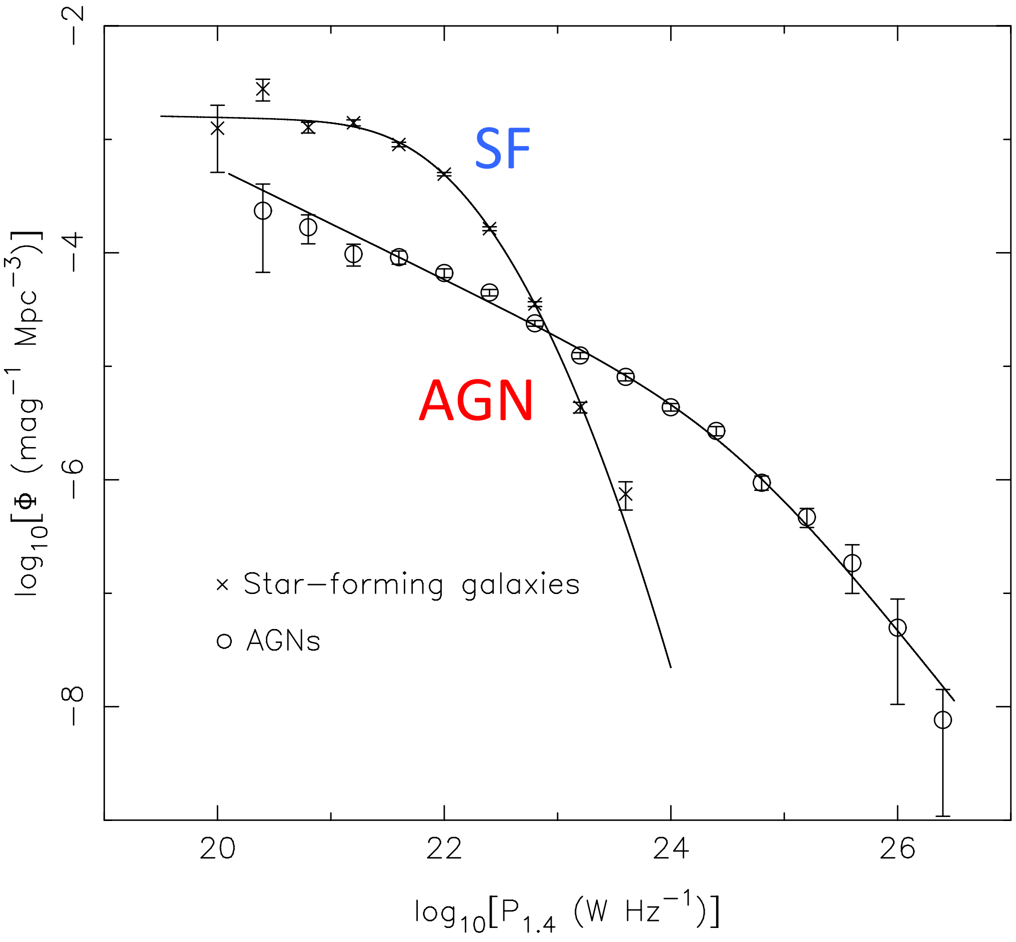


HERG



6dFGS spectra of radio AGN

Local radio luminosity functions



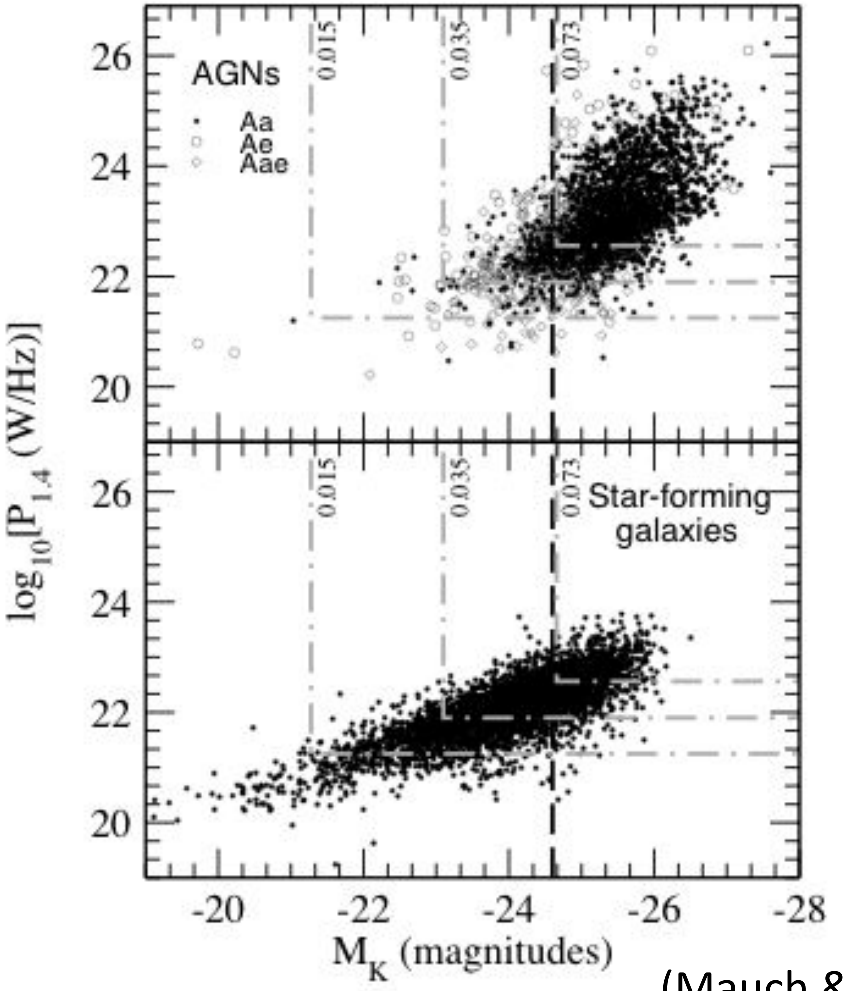
(Mauch & Sadler 2007)

At 1.4 GHz:

Local (z~0) radio LFs for AGN and star-forming galaxies accurately measured over six orders of magnitude.

There is a **wide overlap** in the radio luminosities of AGN and star-forming galaxies – need to have tools for distinguishing them.

Radio-source host galaxies (6dFGS)



(Mauch & Sadler 2007)

Radio-loud AGN (radio galaxies) have a wide range in radio luminosity, but are only found in the most luminous/ massive optical galaxies.

Star-forming galaxies span a much wider range in stellar mass.

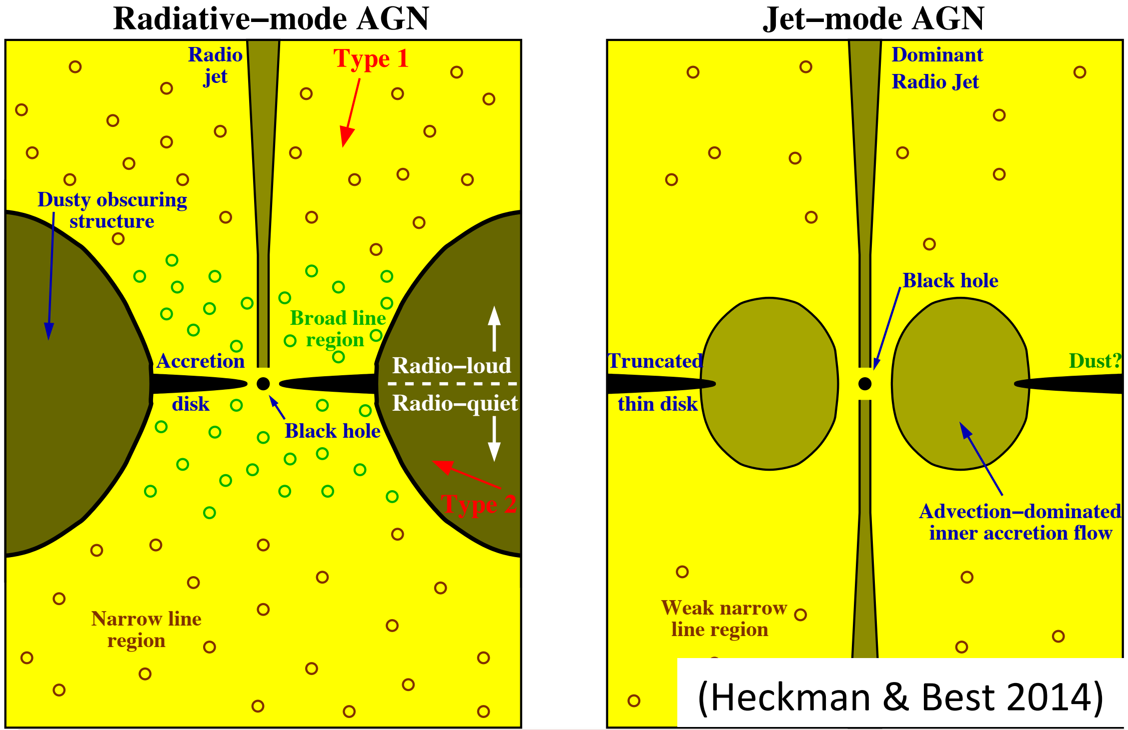
- *Fraction* of galaxies hosting radio-loud AGN increases with galaxy stellar mass (Auriemma et al. 1977, Sadler et al. 1989, Best et al. 2005)

Two distinct populations of radio AGN

High–excitation/"Radiative mode"

HERG

- **High** accretion rate, classical accretion disk
- Strong emission lines, high-excitation optical spectrum
- Central dusty torus
- Unified models apply



(Heckman & Best 2014)

Low-excitation/"Jet mode"

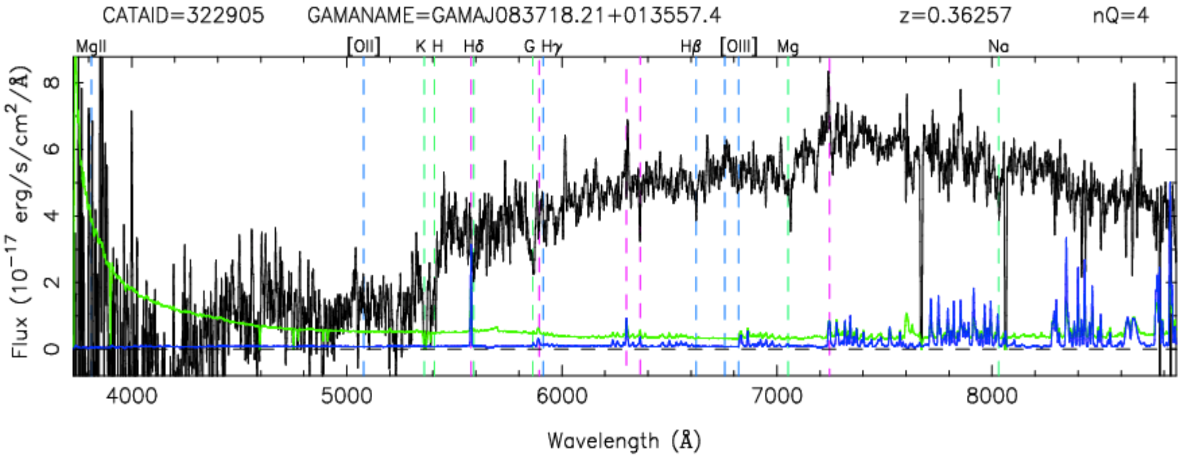
LERG

- **Low** accretion rate, inefficient accretion
- Weak or no optical emission lines
- No central dusty torus
- Jet can inhibit SF in host galaxy

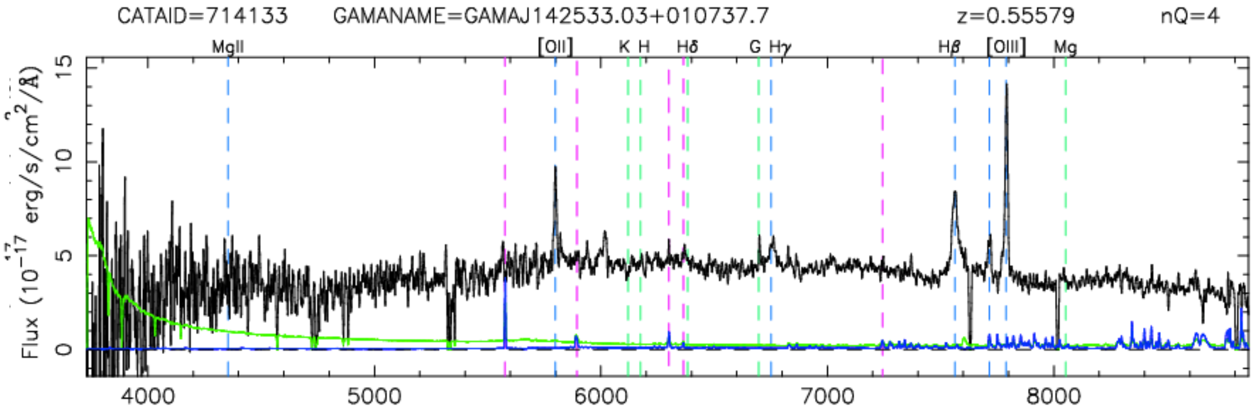
> "..accretion of the hot phase of the IGM is sufficient to power *all* low-excitation radio sources, while high-excitation sources are powered by accretion of cold gas " (Hardcastle et al. 2007)

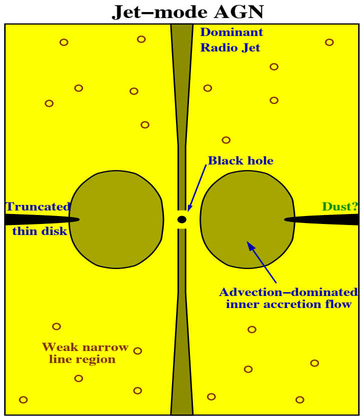
Radio AGN: Spectral classifications

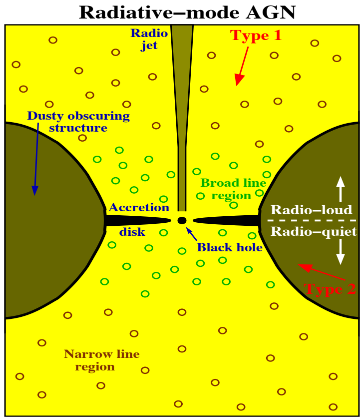
LERG (weak/no emission lines)



HERG/QSO (strong emission lines)



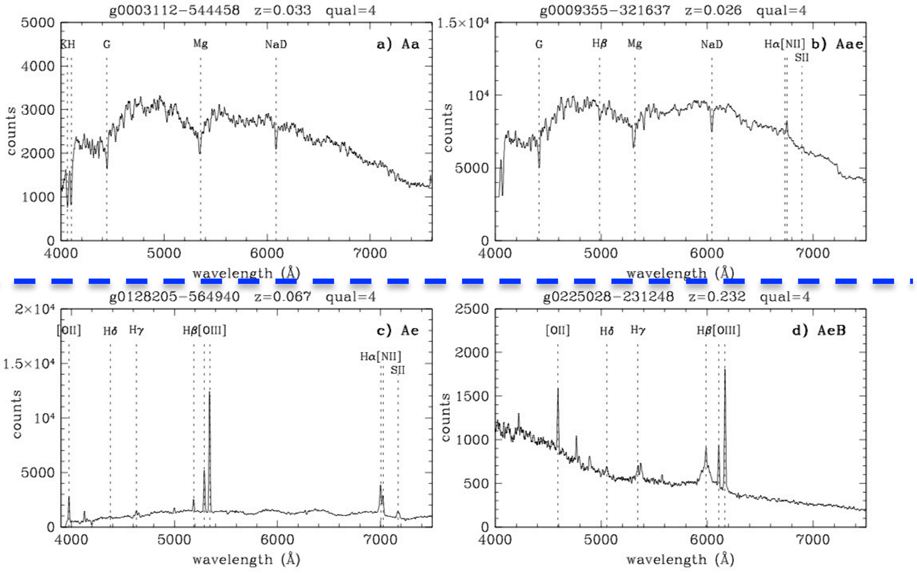




Objects with broad emission lines (QSOs) identified visually.

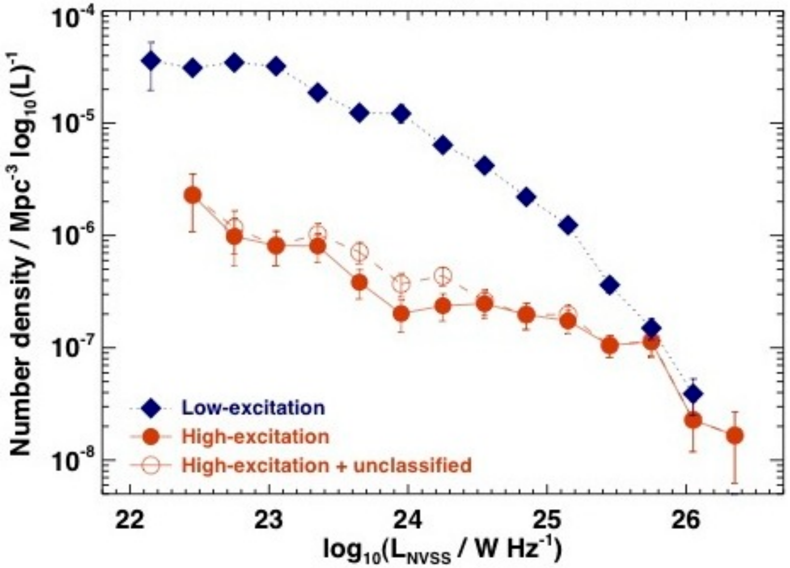
Local radio LF for LERGs and HERGs

LERG



HERG

6dFGS spectra

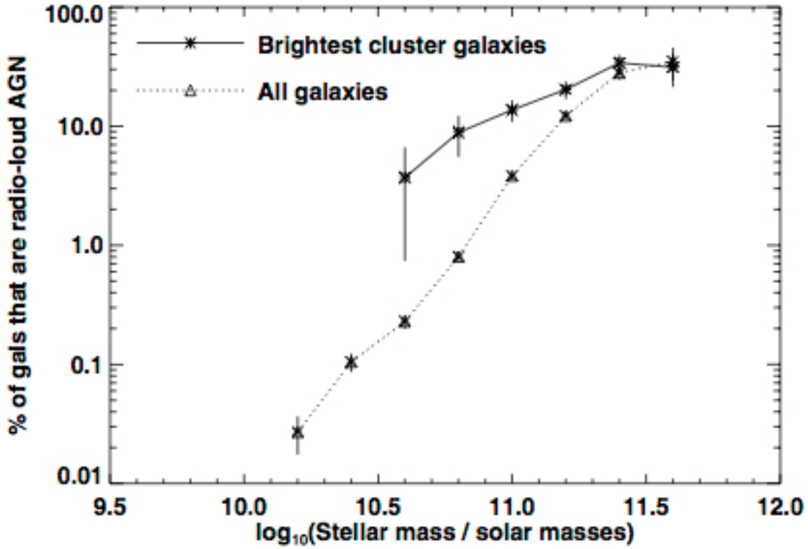


(Best et al. 2012)

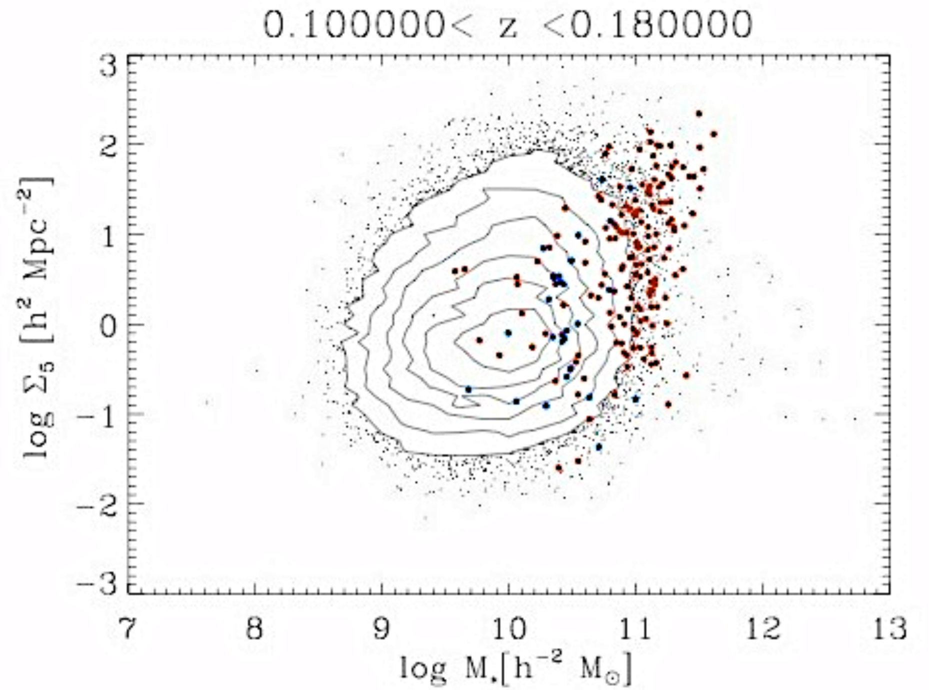
Both LERG and HERG systems are found over a wide range in radio luminosity (Best et al. 2012), but **>95% of local radio AGN are LERGs**

Radio-source clustering

Locally, radio AGN are preferentially found in **massive** galaxies in **clustered environments**



(Best et al. 2007)



(Ching et al. 2017b)

CAASTRO
ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

The AT 20 GHz Survey (AT20G)

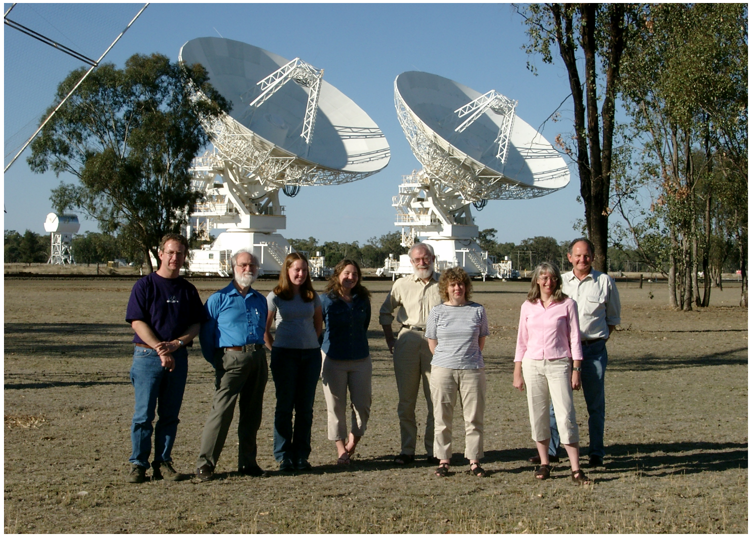
Survey description: Murphy et al. (2010), Hancock et al. (2011)

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

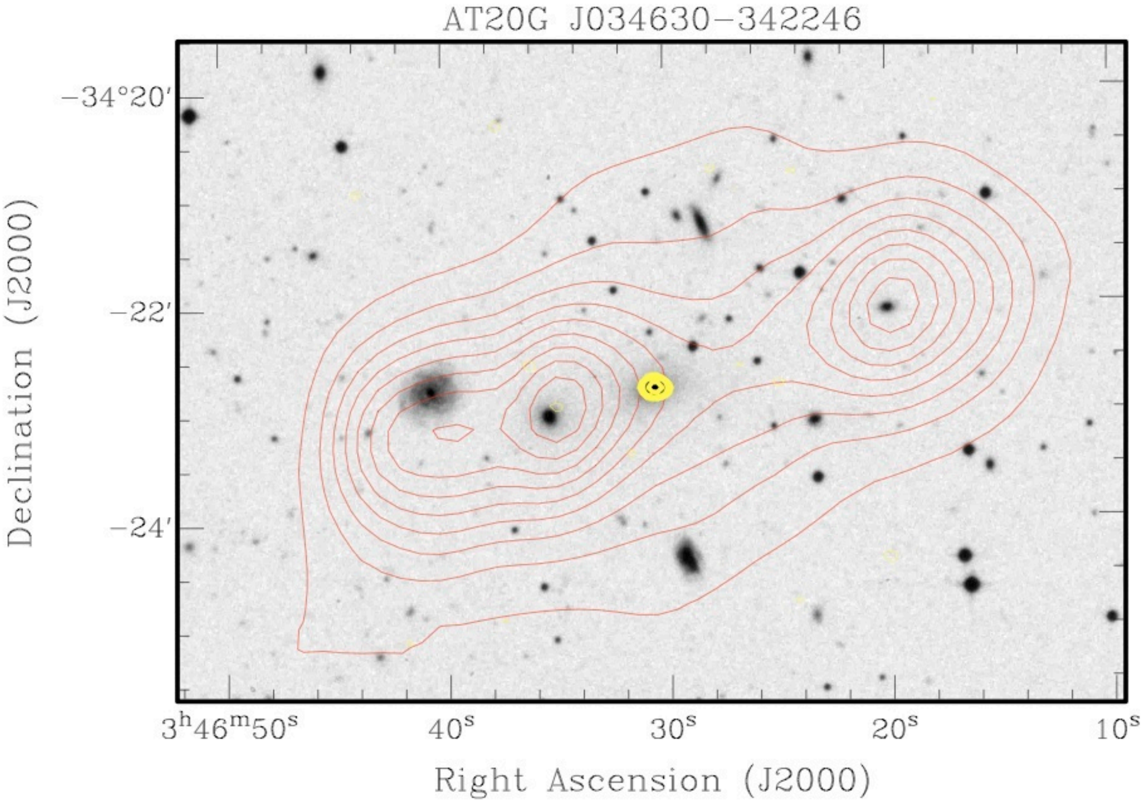
4σ detections imaged at 5, 8 and 20 GHz with full ATCA hybrid array


The Australia Telescope Compact Array

© D.Smyth, CSIRO



A different view of the radio sky…



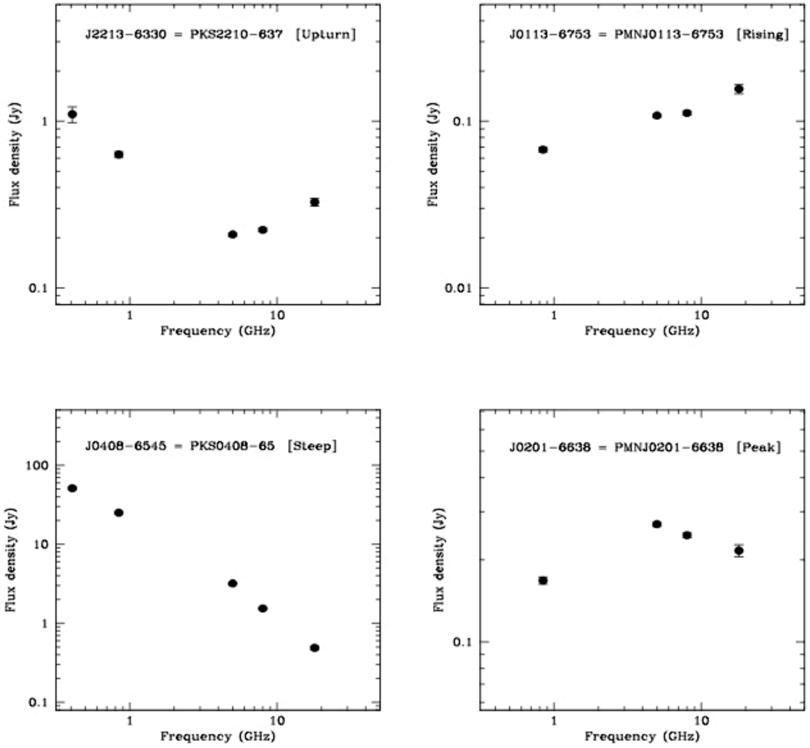
Nearby radio galaxy PKS 0344-34, z=0.0535

20 GHz image pinpoints **recent** AGN activity; lower-frequency image reflects activity on much **longer timescales**

Red: NVSS 1.4 GHz
Yellow: AT20G 20 GHz

CAASTRO
ARC CENTRE OF EXCELLENCE
FOR ALL-SKY ASTROPHYSICS

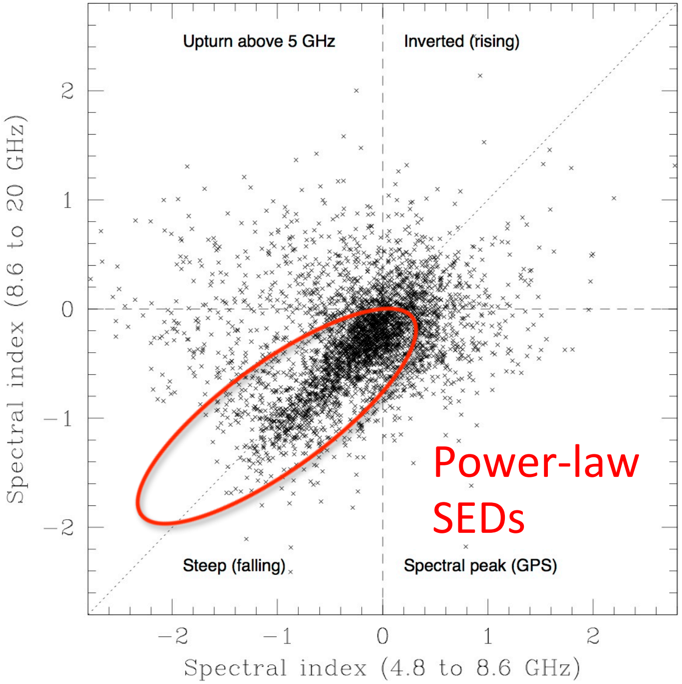
Radio SEDs at 1-20 GHz



(Sadler et al. 2006; Murphy et al. 2010)

AT20G: Near-simultaneous data at 5, 8, 20 GHz

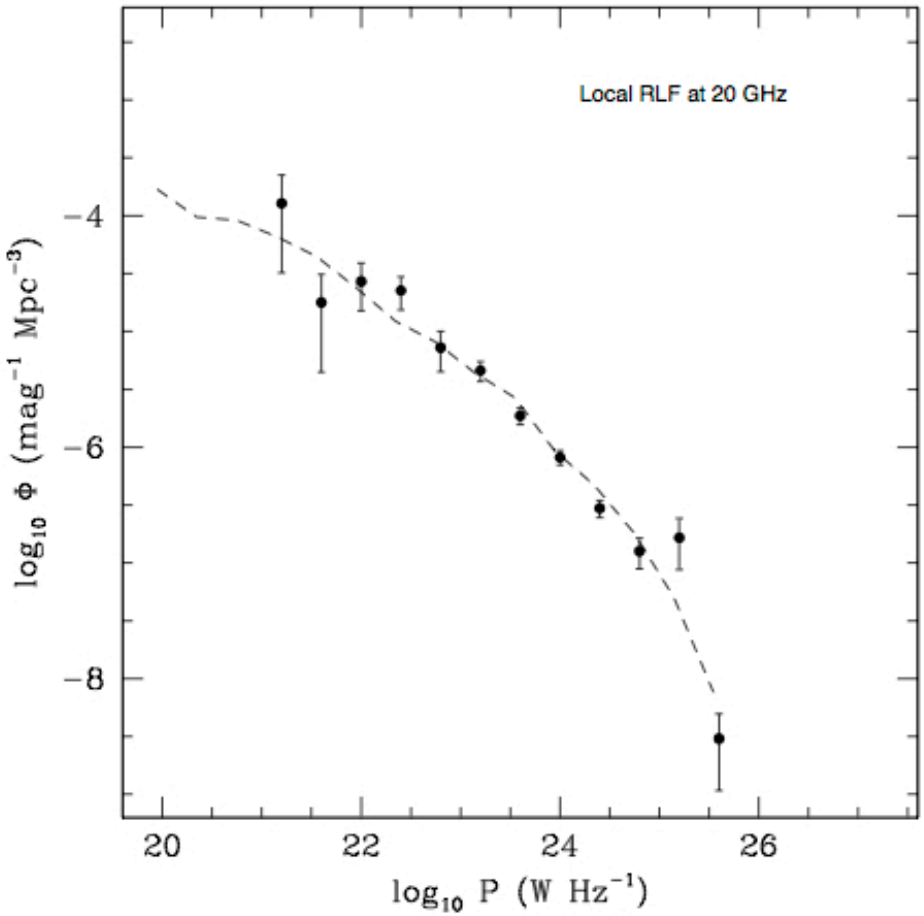
Radio two-colour plot



Power-law SEDs

Local RLF for AGN at 20 GHz

AT20G-6dFGS local radio AGN

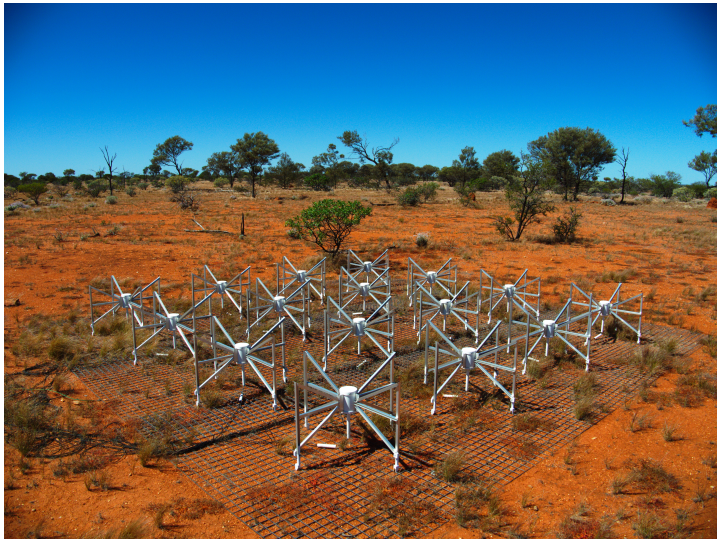


(Sadler et al. 2014)

Local radio LF for AGN at 20 GHz is well-fitted by the 1.4 GHz RLF shifted in radio power with a constant 1.4–20 GHz spectral index of −0.74.

i.e. Radio AGN population shows a diversity of SEDs, but **population as a whole** behaves in a predictable way, consistent with a simple power-law SED

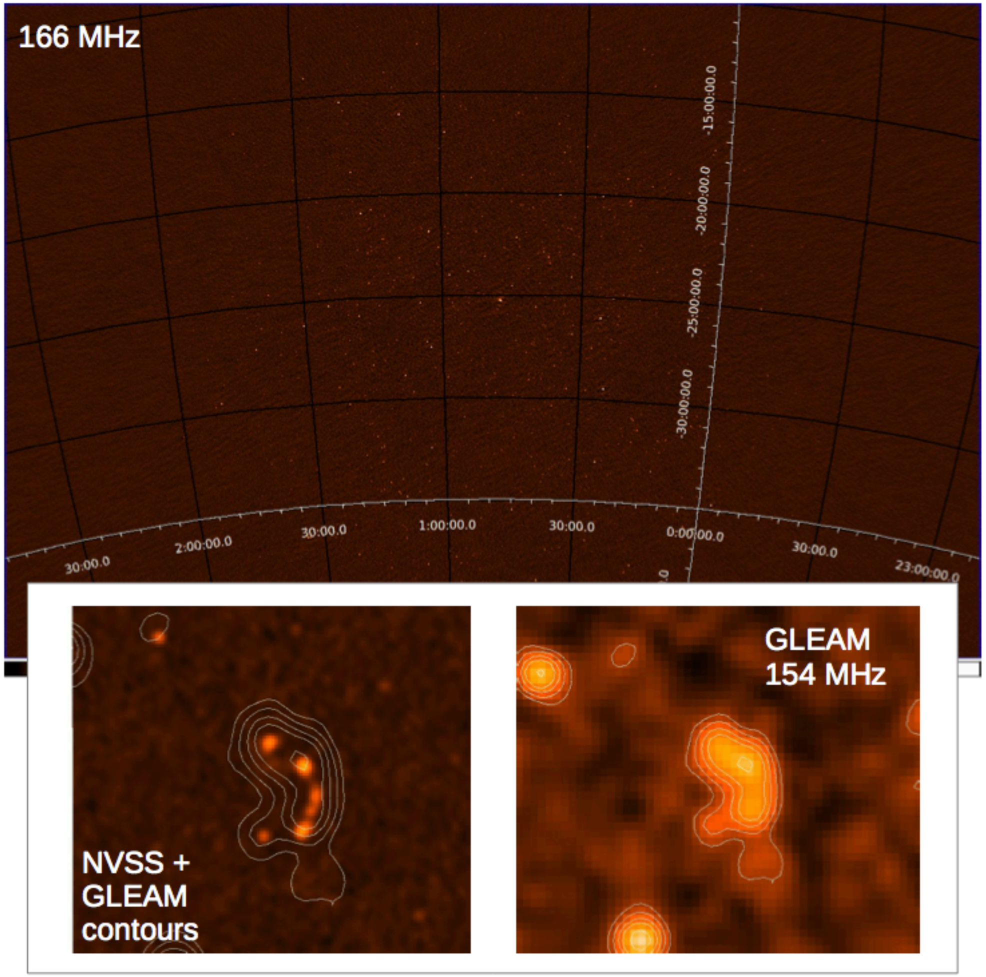
Low-frequency: MWA GLEAM



Murchison Widefield Array (MWA)

GLEAM survey: > 28,000 deg^2 of sky at 72-231 MHz (dec < +30, |b|<10), complete to ~170 mJy.

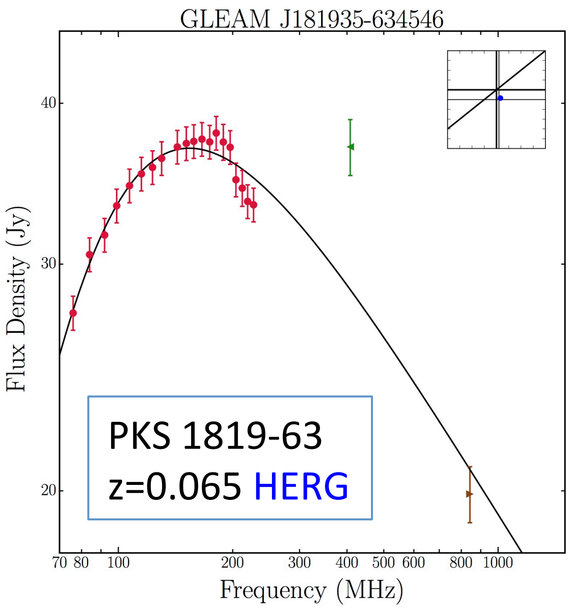
(Hurley-Walker et al. 2017)



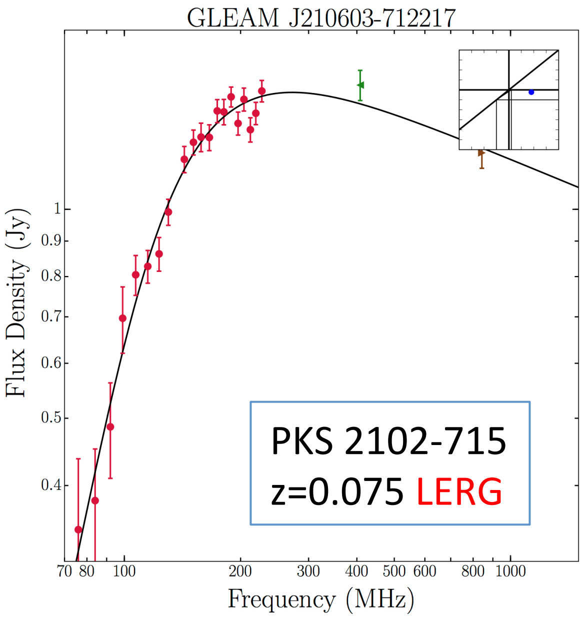
(image from Lister Staveley-Smith)

CAASTRO
ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

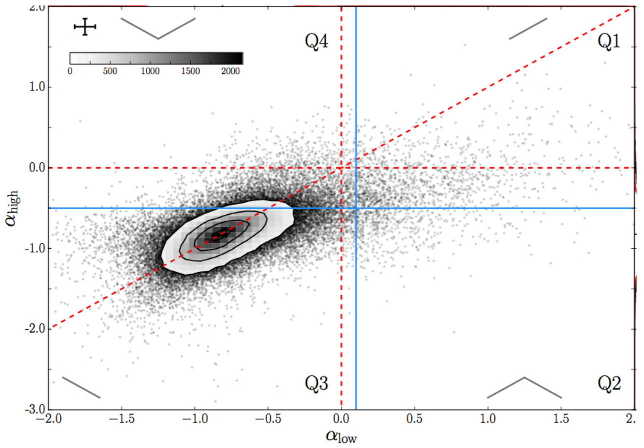
MWA GLEAM peaked-spectrum sources



PKS 1819-63
z=0.065 HERG



PKS 2102-715
z=0.075 LERG

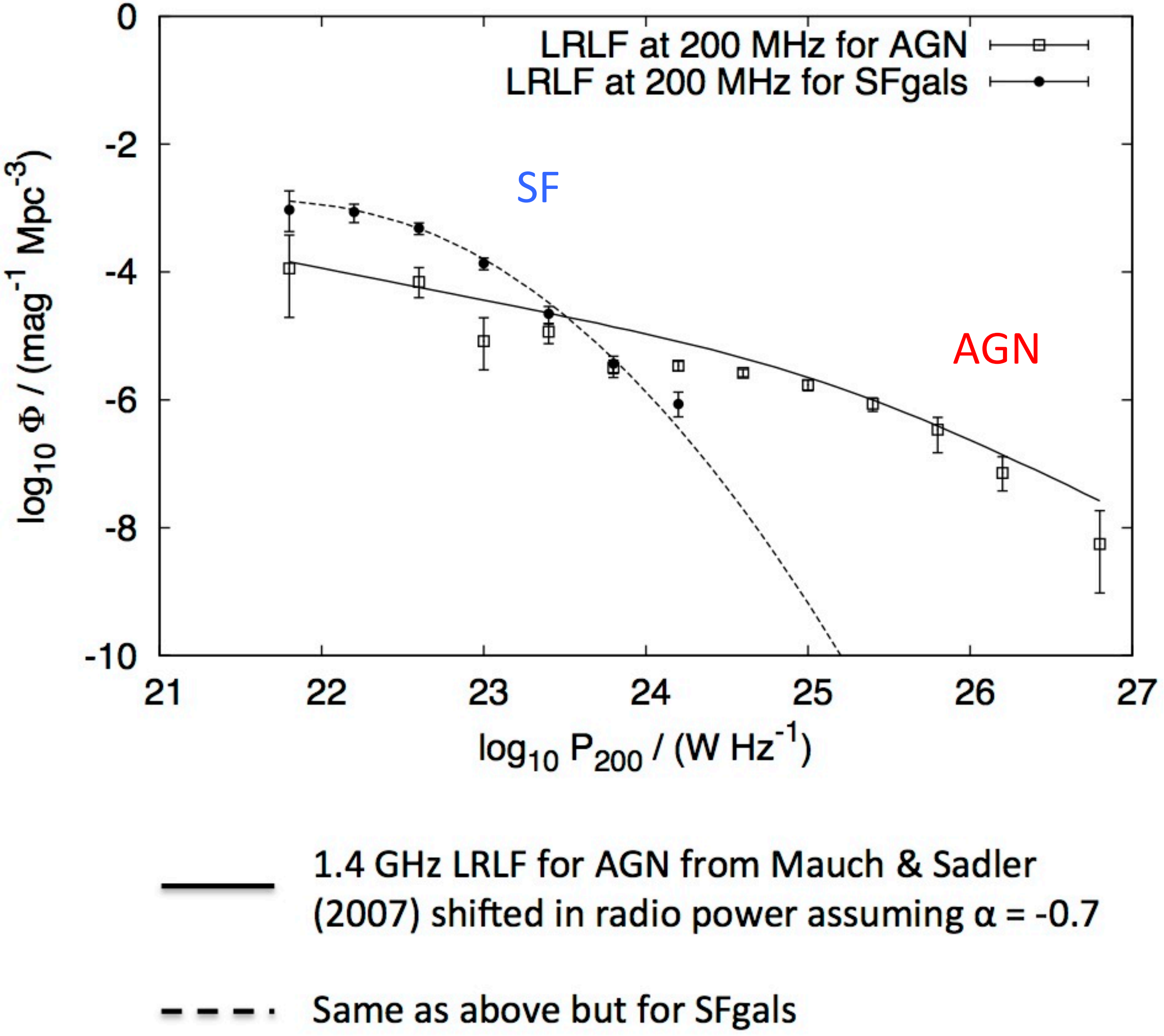


GLEAM two-colour plot

Joe Callingham PhD thesis (Callingham et al. 2017)

- ~1500 GLEAM sources with spectral peaks between 72 MHz and 1.4 GHz
- Allows uniform identification of GPS radio galaxies – **detailed studies possible at low redshift**

Local RLF at 200 MHz



1.4 GHz LRLF for AGN from Mauch & Sadler (2007) shifted in radio power assuming α = -0.7

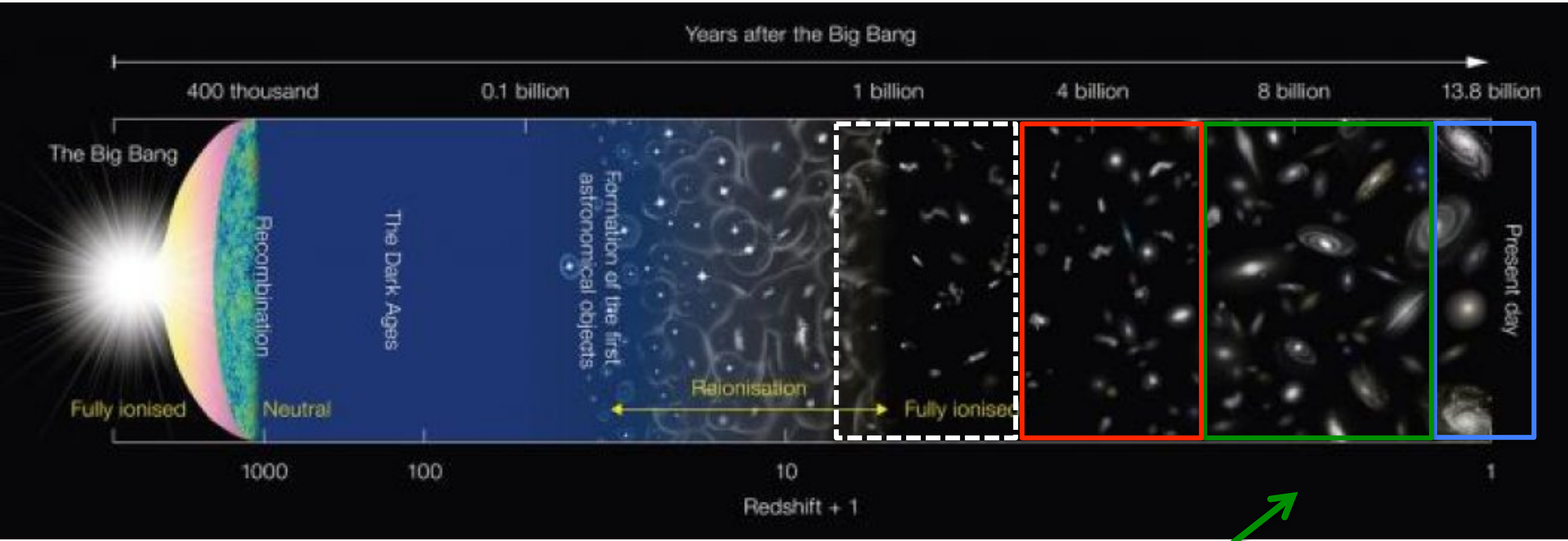
Same as above but for SFgals

As at 20 GHz, radio AGN population shows a diversity of SEDs, but RLF for **population as a whole** is again consistent with a simple power-law SED shifted by alpha = -0.7

MWA GLEAM
(T.Franzen 2017, in prep)

Similar results found at 325 MHz by Prescott et al. (2016)

Radio AGN and their evolution



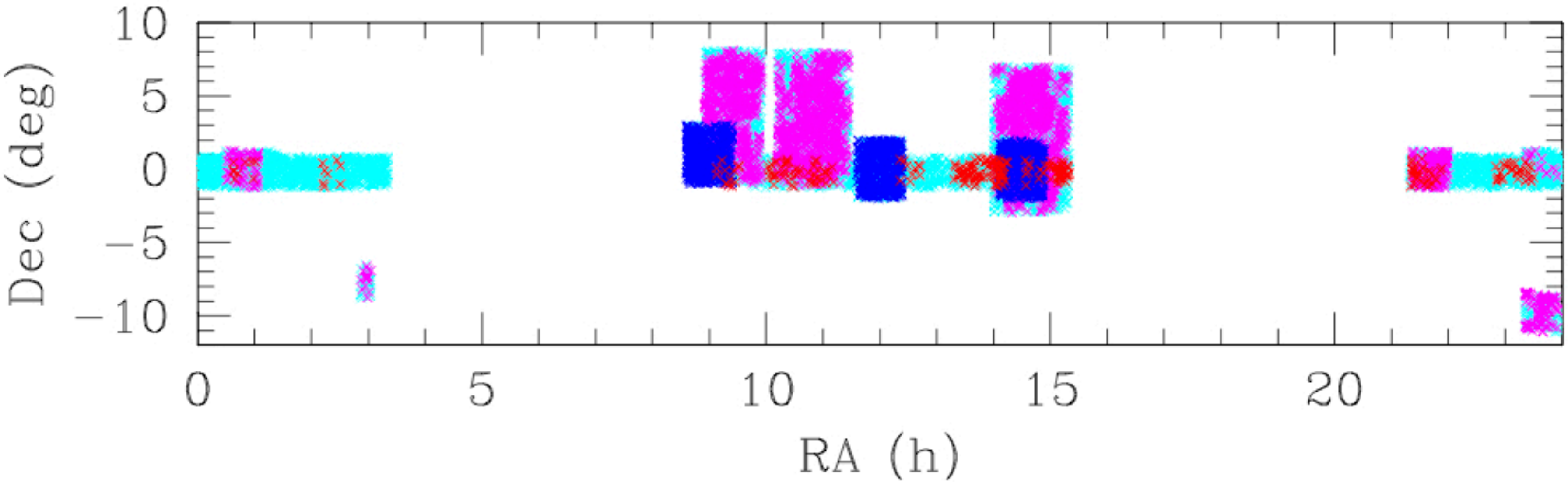
(Credit: NAOJ)

2) Radio AGN populations at $0.2 < z < 0.8$

Radio sources in GAMA/WiggleZ

Goal: Measure evolution of radio-source populations to z ~0.8, environments of radio galaxies and QSOs

Ching et al. (2017a)

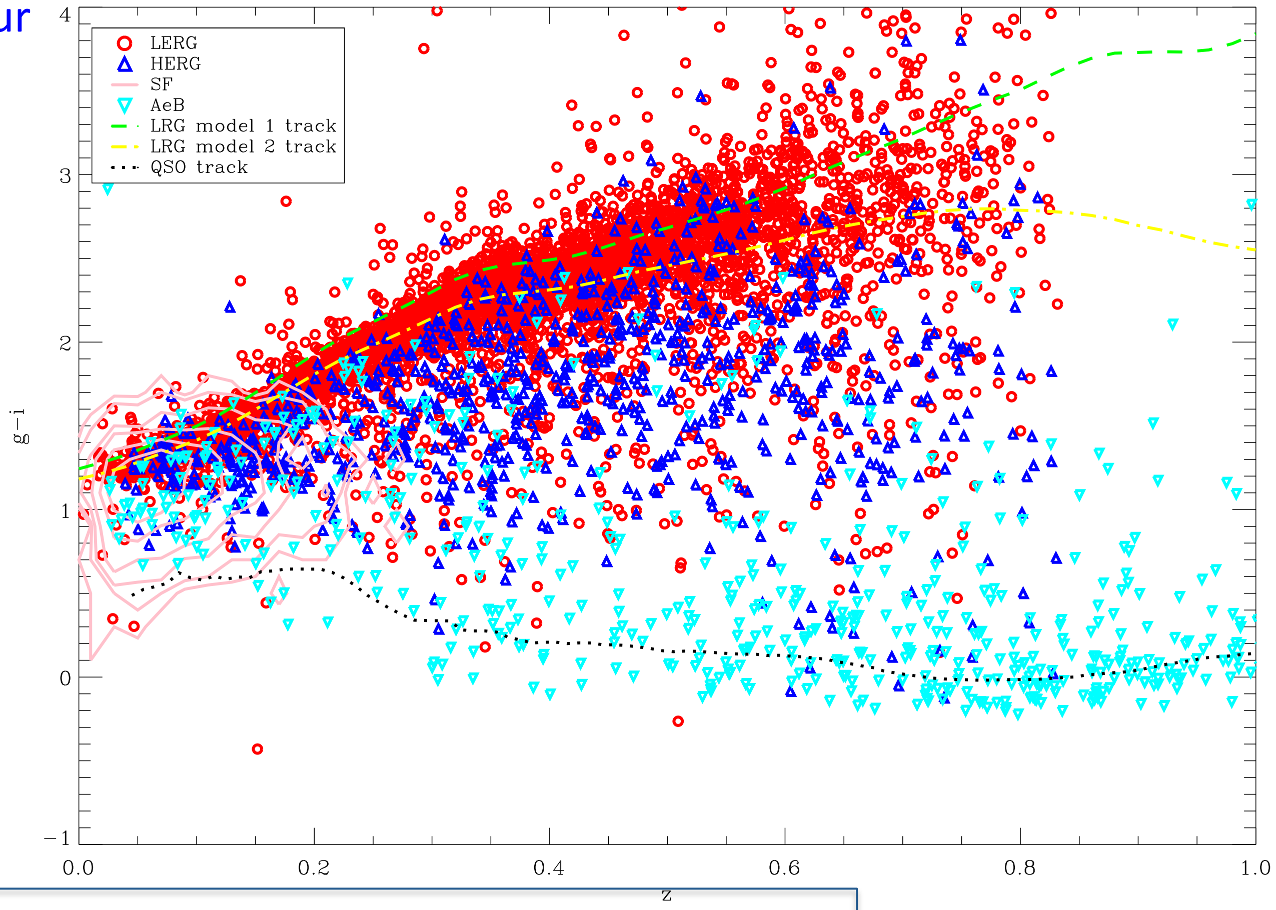


Spectroscopic observations (SDSS, 2SLAQ, WiggleZ, GAMA):

- Input catalogue of 19,000 SDSS radio-source IDs (i < 20.5 mag)
- No colour selection, includes QSOs as well as galaxies
- ‘Piggyback’ additional spectroscopy targets (faint galaxies, QSOs)

Radio AGN hosts to z = 0.8 at 1.4 GHz

g-i colour



Catalogue: Ching et al. 2017a, MNRAS 464, 1306

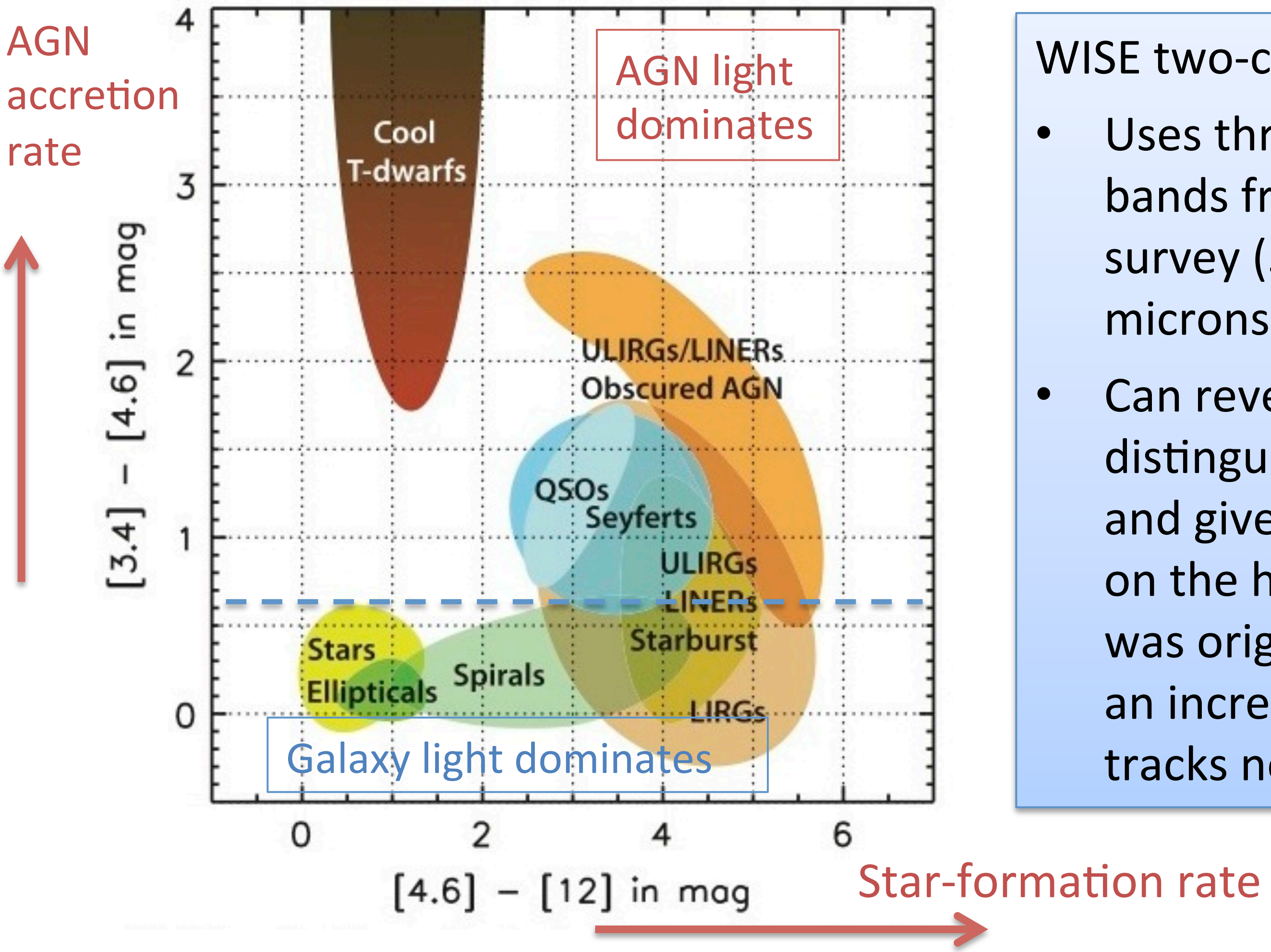
Radio LFs to z=0.8: Pracy et al. 2016, MNRAS 460,2

1.4 GHz: 10,000+ radio AGN with optical spectra

Redshift

WISE mid-IR colours

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

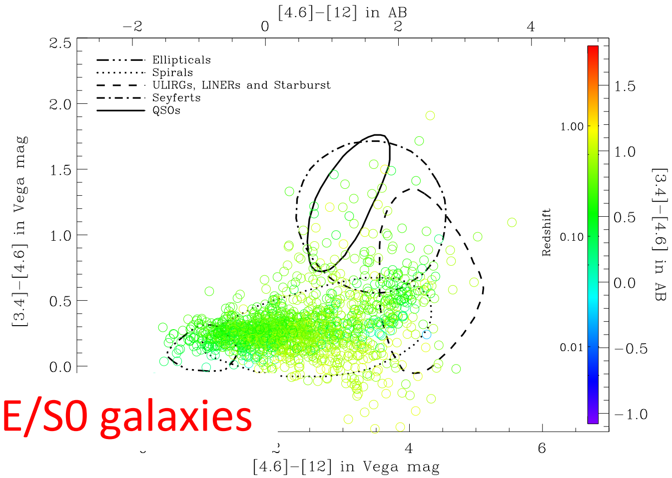


WISE two-colour plot:

- 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.

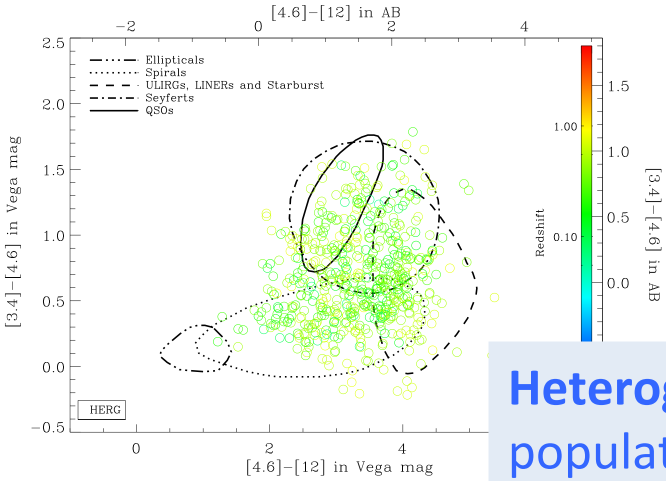
Radio populations in WISE

LERG



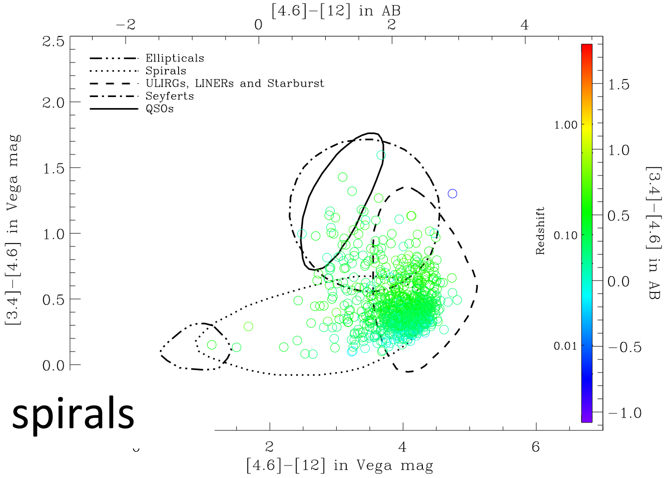
Normal E/S0 galaxies

HERG



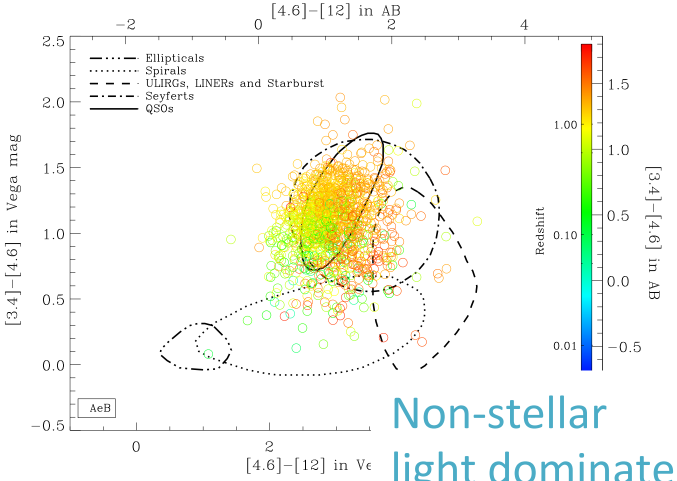
Heterogeneous population

Star-
forming



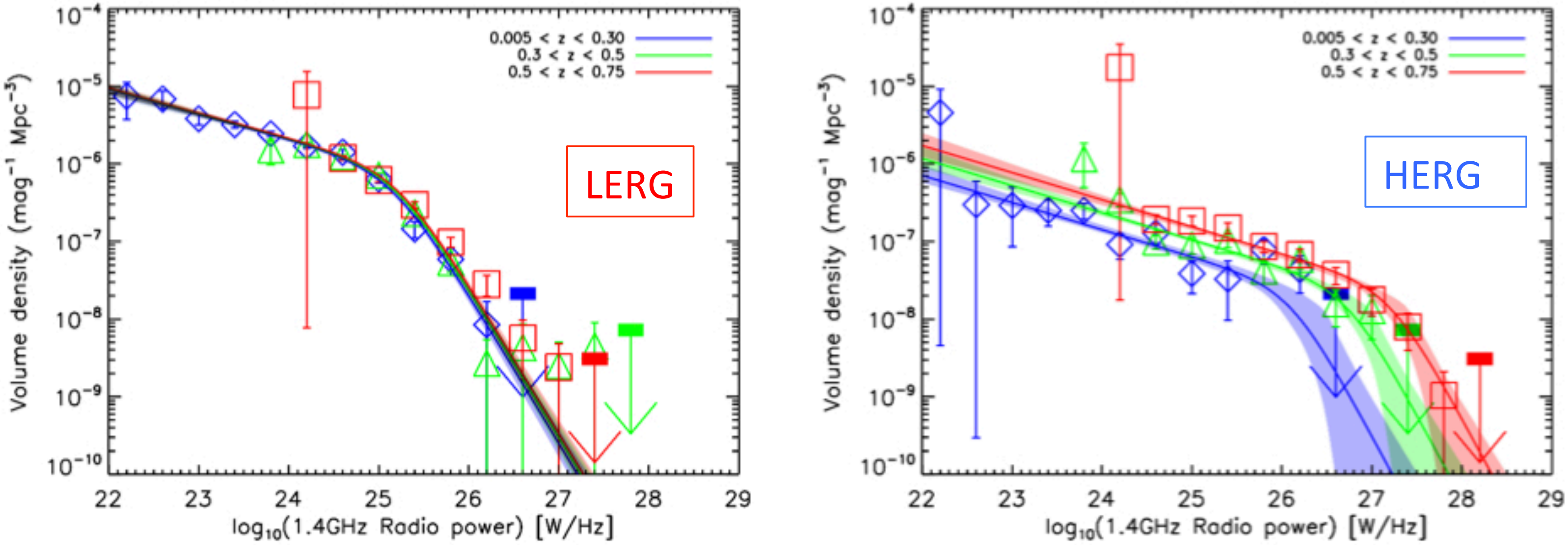
Normal spirals

QSO



Non-stellar light dominates

Redshift evolution to z = 0.75

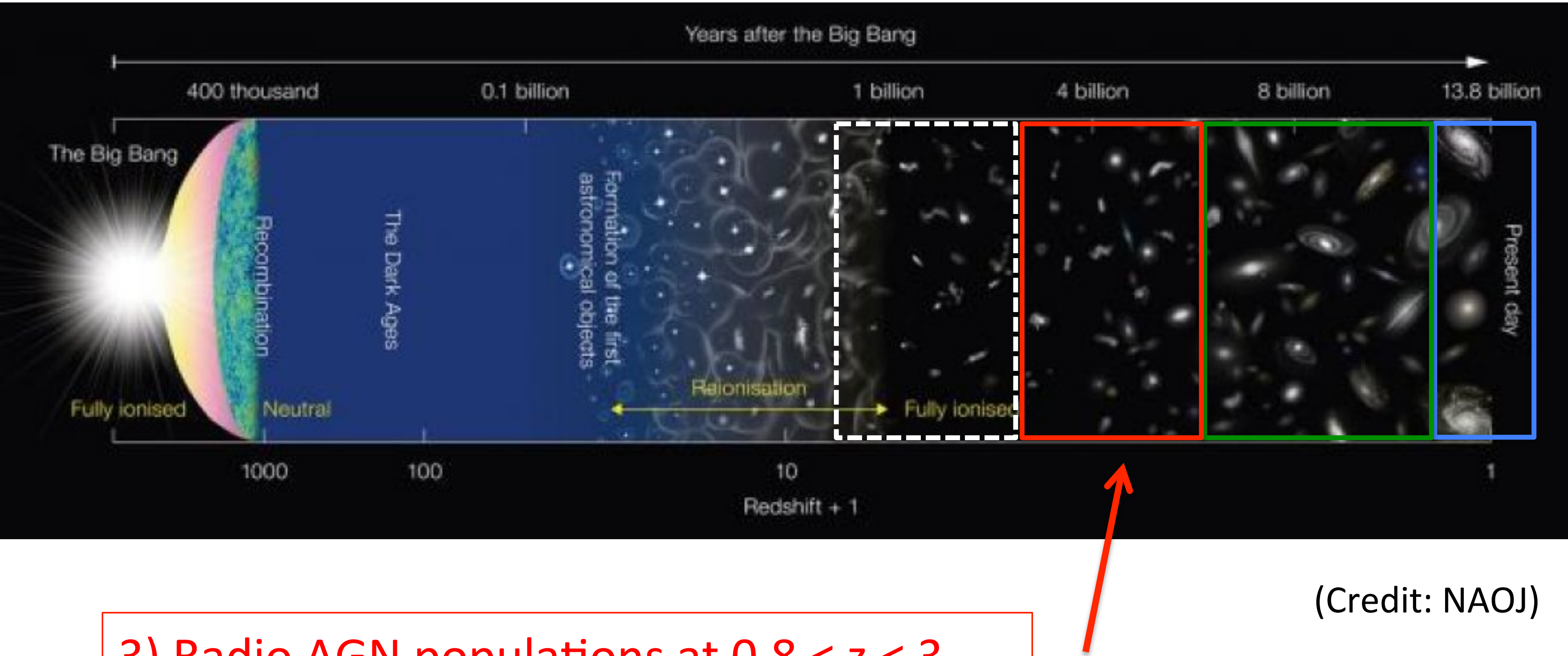


(Pracy et al. 2016)

Radio LF in three redshift bins to z=0.75

- LERGs - little or no evolution over past 6.5 Gyr
- HERGs – **rapid** evolution (up to ~ $(1+z)^7$ for PLE, $(1+z)^3$ for PDE), similar to that seen for bright QSOs in this redshift range

Radio AGN and their evolution



(Credit: NAOJ)

3) Radio AGN populations at 0.8 < z < 3

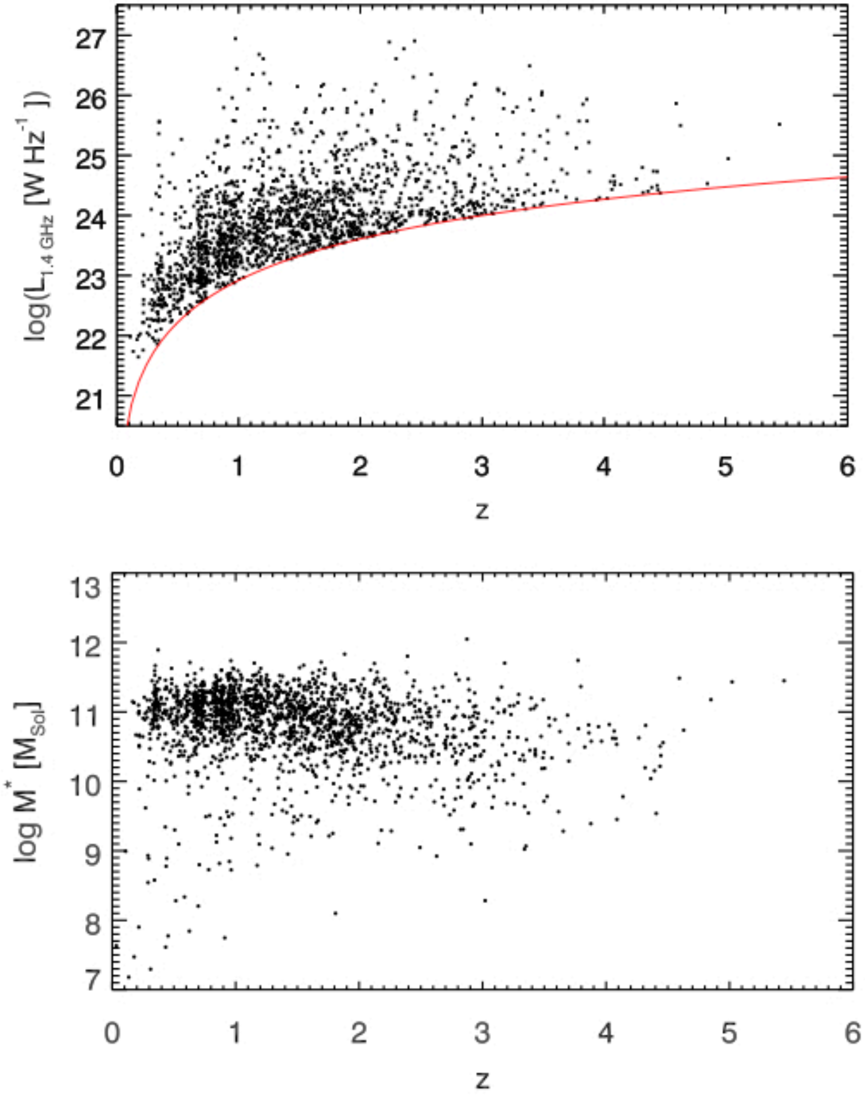
Radio AGN at $z > 1$ from COSMOS

Deep optical/radio imaging

- 2 deg^2 COSMOS field
- Deep radio imaging at 3 GHz
- Photometric redshift estimates
- AGN/SF separation via ratio of radio and NIR flux densities
- No HERG/LERG separation
- 1814 radio AGN at $0 < z < 5.5$, most at $0.5 < z < 2.5$
- Total sample volume ~ 0.05 Gpc^3

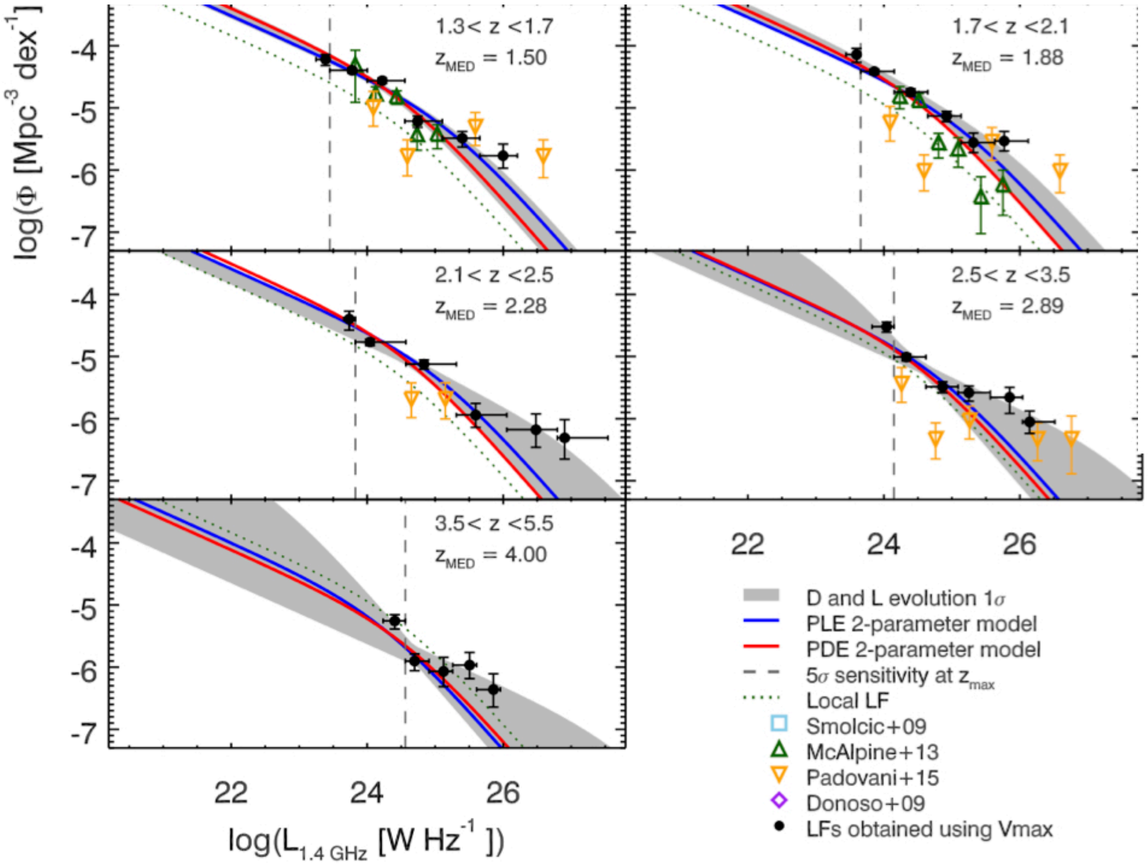
(vs 0.3 to 0.5 Gpc^3 for $z < 1$ samples) means the most powerful radio galaxies are not well sampled

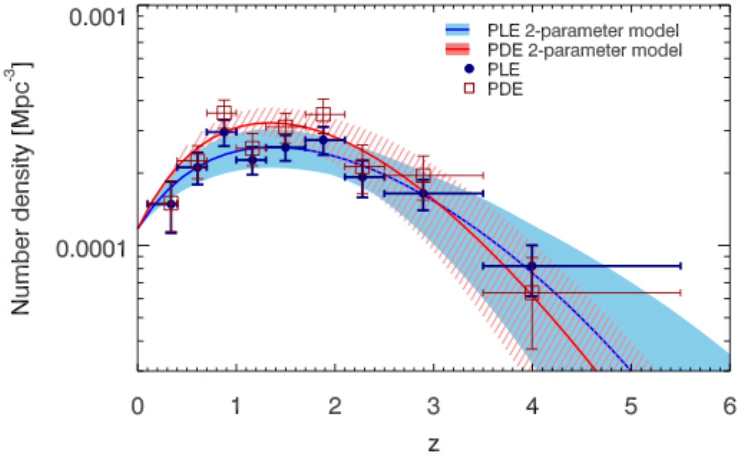
(Smolcic et al. 2017)



Radio LF at $z > 1$ (COSMOS field)

Radio luminosity functions for AGN in the COSMOS field



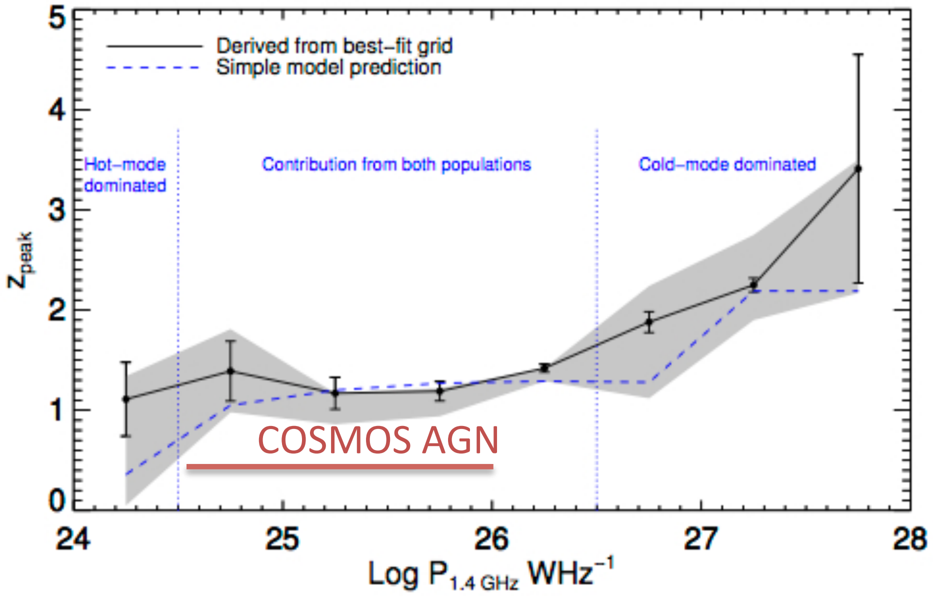


Moderate evolution in the number density of radio AGN at $0.5 < z < 3$, turnover at $z \sim 1.5$?

(Smolcic et al. 2017)

Redshift evolution at $z > 1$

Dunlop & Peacock (1990): “Redshift cutoff” for powerful radio AGN, with comoving density dropping by a **factor of five** from redshift 2 to 4

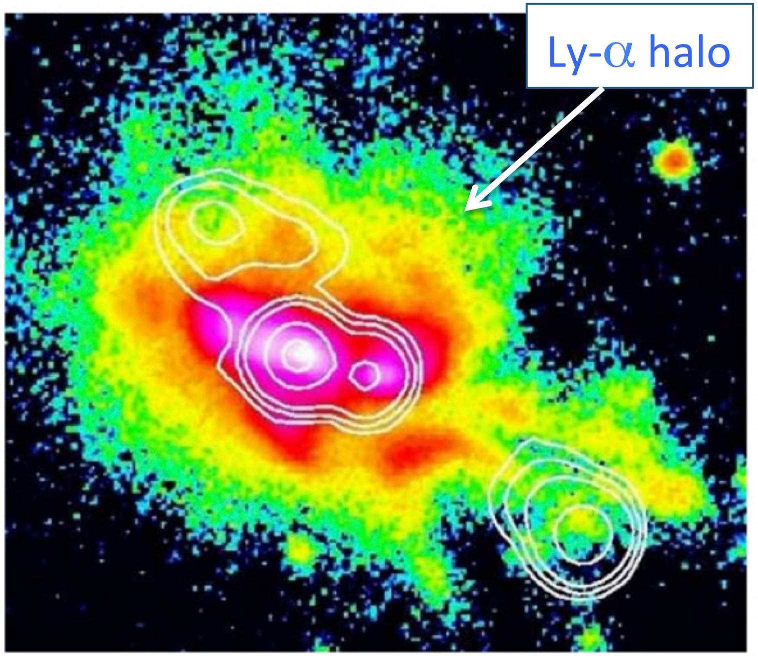


Recent progress: Combination of models and deep optical/radio observations

Rigby et al. (2015): ‘Cosmic downsizing’, with lower-power radio AGN peaking at lower redshift

Powerful radio galaxies at z > 2

Surface density of very powerful radio galaxies is low – need large-area surveys to find them (at all redshifts)



(Miley & De Breuck 2008)

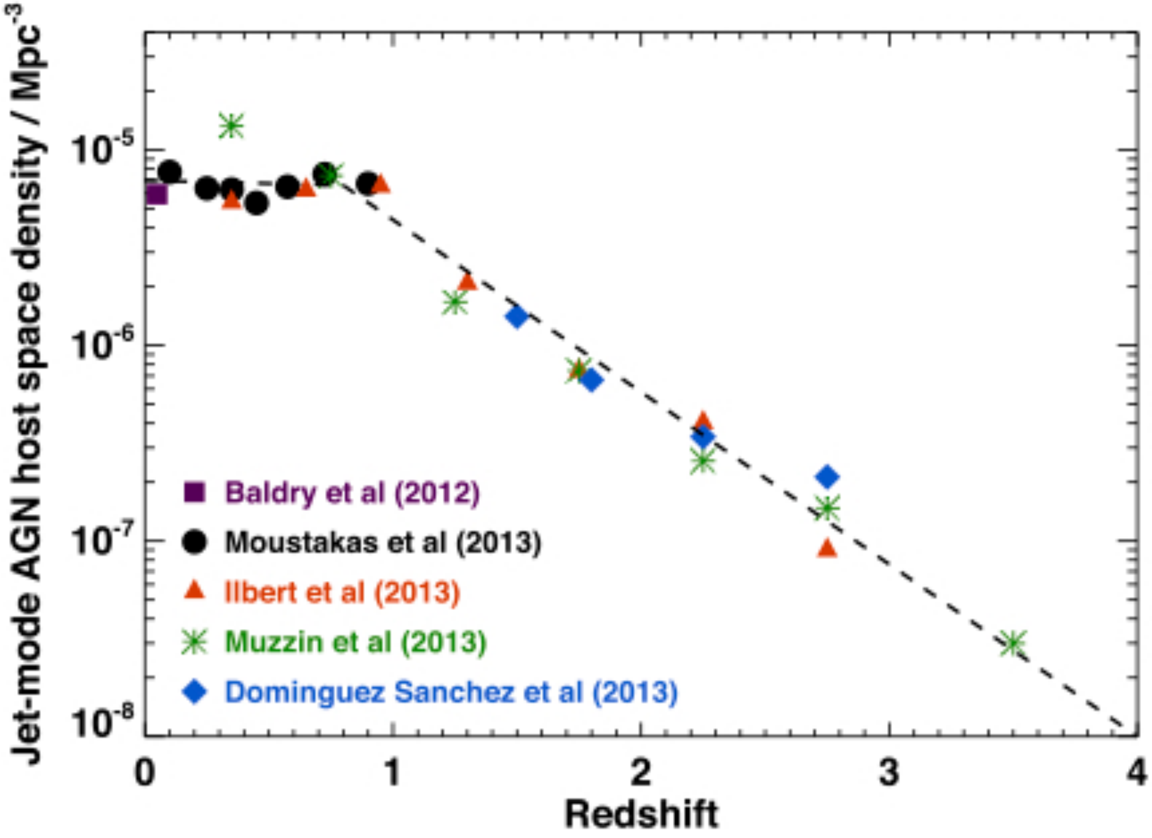
4C 41.17 at z = 3.8

At z > 2, many powerful radio galaxies are gas-rich, vigorously star-forming and trace the location of early gaseous 'proto-clusters'

Peak of activity for luminous radio AGN corresponds to the **emergence of the 'red sequence'** of massive galaxies in proto-clusters at 2 < z < 3 (Kodama et al. 2007)

CAASTRO
ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

Predicted evolution of LERGs at z > 1

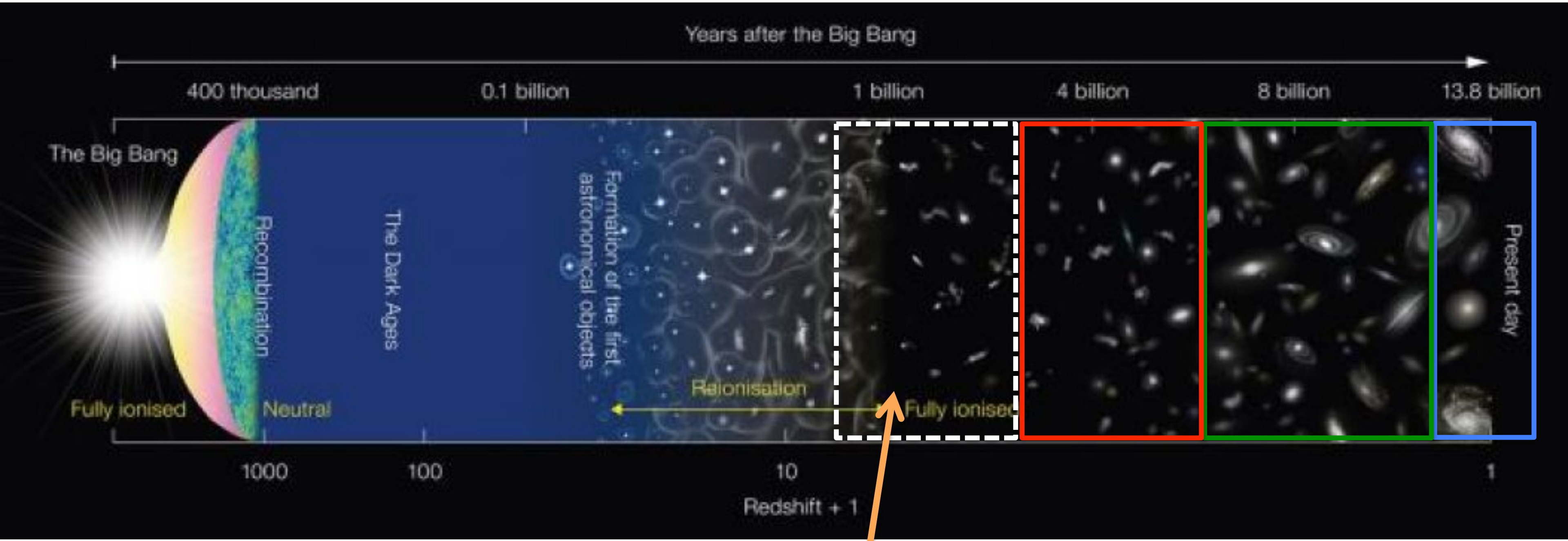


(Best et al.2014)

Space density of LERGs expected to decrease at z > 1 based on decline in ‘red’ host galaxies

Complex evolution of radio AGN populations at z > 1, details still to be worked out

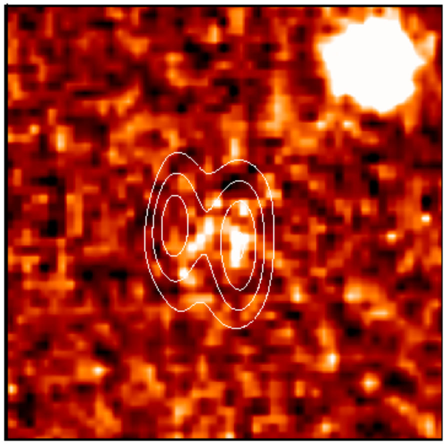
Radio AGN and their evolution



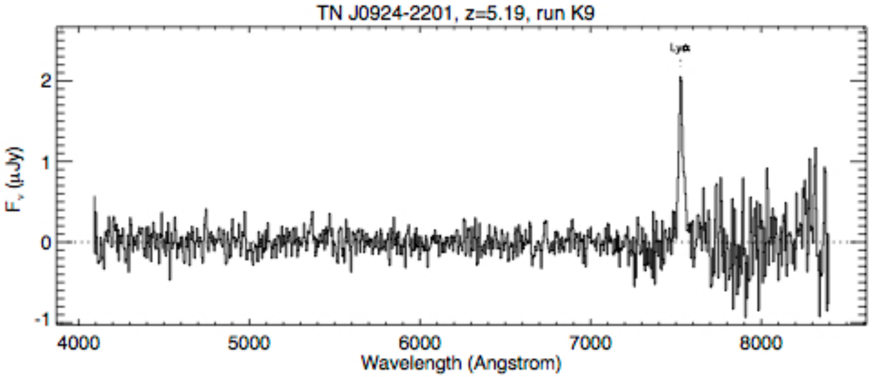
(Credit: NAOJ)

4) Radio AGN populations at z > 3

Radio galaxy TN 0924-2201 at z = 5.2

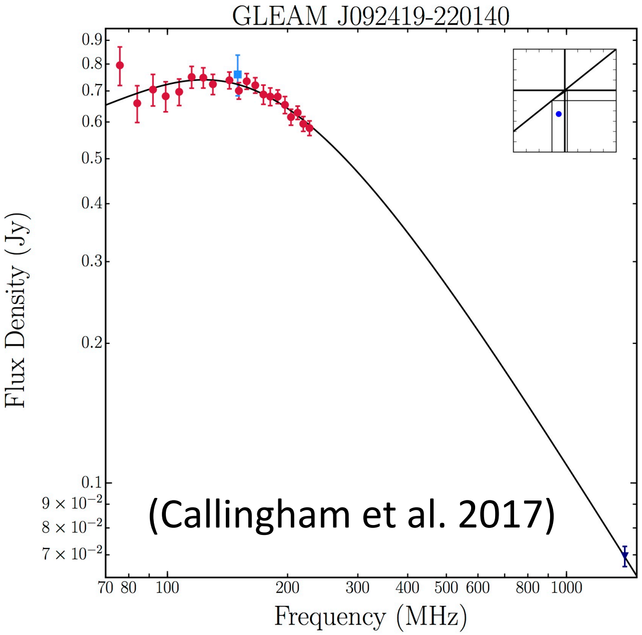


(van Breugel et al. 1999)



(De Breuck et al. 2001)

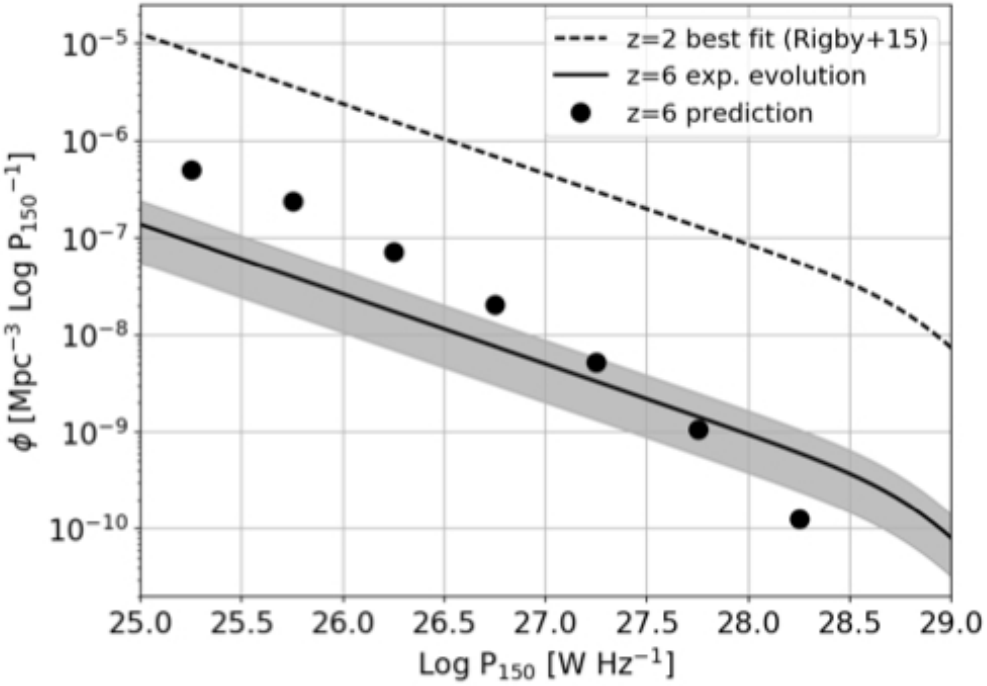
- Selected as an Ultra-Steep Spectrum (USS) radio source, α = -1.6 at 325-1400 MHz (van Breugel et al. 1999)
- MWA spectrum shows a peak near 120 MHz, flux density 0.8 Jy



(Callingham et al. 2017)

How many radio AGN at z > 6?

Predicted RLF at z=6



(Saxena et al. 2017)

Saxena et al. (2017): Predictions for the number of z ~ 6 radio sources in GLEAM and LOFAR surveys:

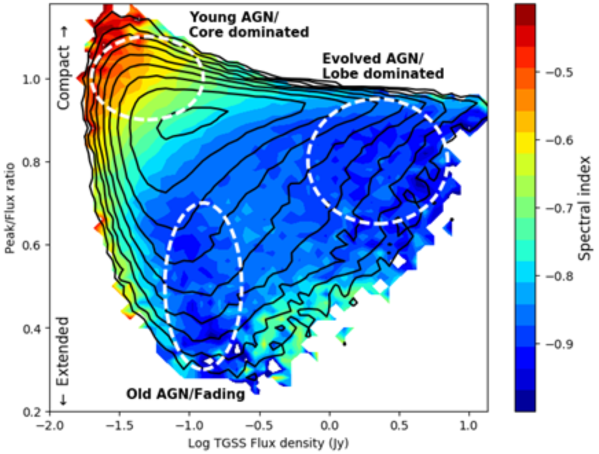
31 in GLEAM
92 in TGSS
Several thousand (0.6/deg^2) in LOFAR LoTSS!

Surface density:
0.6/deg^2 at 0.01 mJy
0.001/deg^2 at 5 mJy

Finding z > 5 radio sources

USS selection (Miley & De Breuck 2008):

1. *Radio:* Filter out suitable candidates ('Ultra-steep' radio spectrum, small angular size)
2. *Optical/IR:* Remove objects with bright (nearby) counterparts
3. *Radio:* Refine radio positions for remaining candidates, use deep optical/IR as first-order redshift estimate
4. *Optical:* Spectroscopy with 8m-class telescopes to measure redshifts



(TGSS-NVSS spectral indices: de Gasperin et al. 2017)

Are there some shortcuts we could take with large-enough samples?

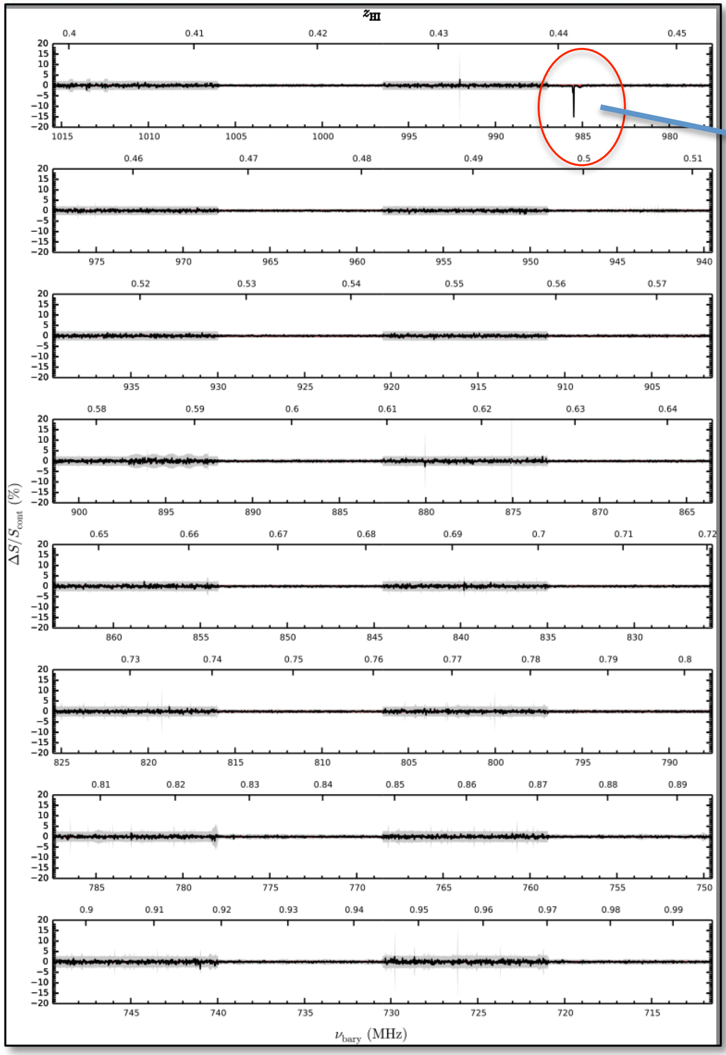
- Redshift information from 21cm HI absorption
- Peaked spectrum sources as (compact) high-z candidates

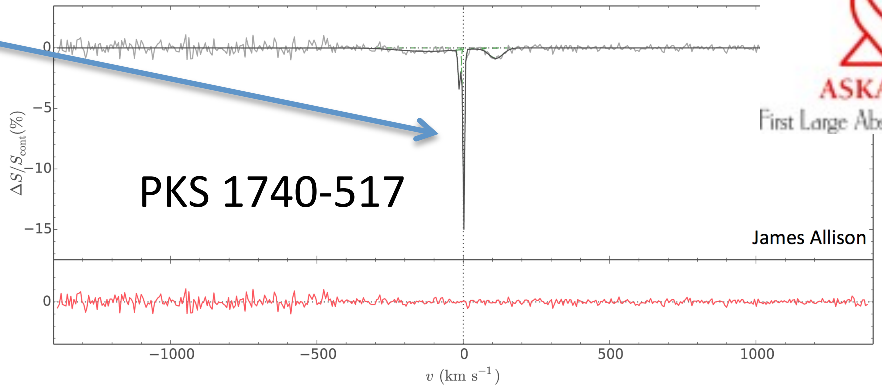
CAASTRO
ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

ASKAP: Redshifts from 21cm absorption

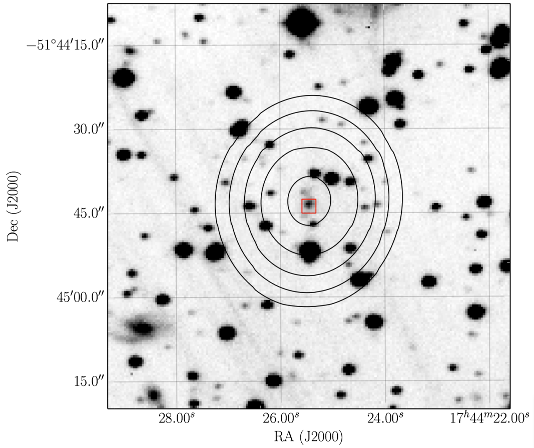
Commissioning data 2015-16

ASKAP-FLASH
First Large Absorption Survey in HI





PKS 1740-517

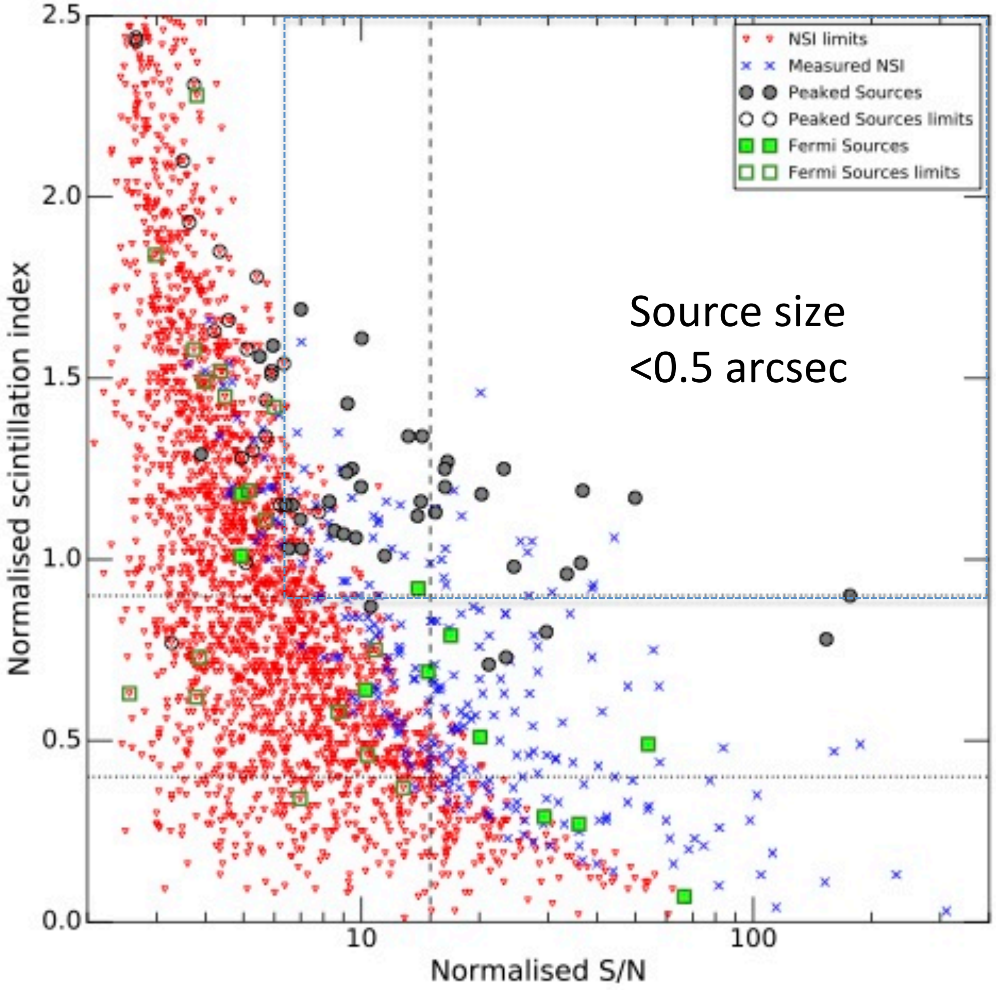


(Allison et al. 2015)

Detection of neutral hydrogen within a young radio galaxy at z=0.44

*** See James Allison's talk for MWA HI pilot study at z > 5*

MWA IPS results



Source size
<0.5 arcsec

(Chhetri et al. 2017)

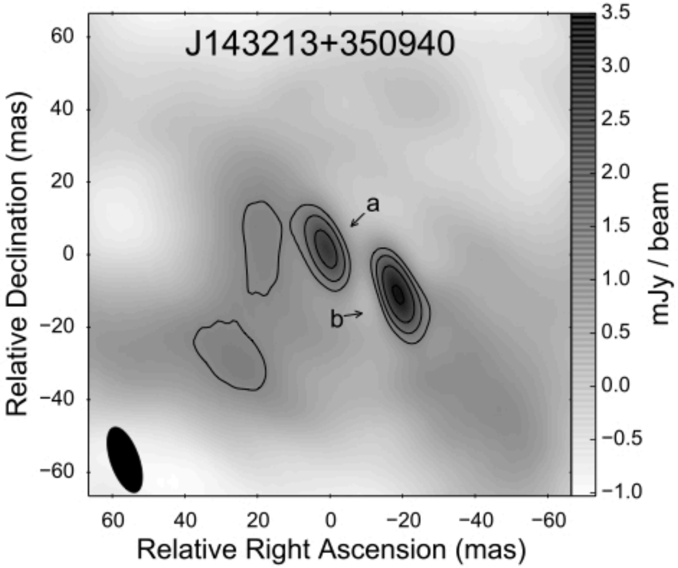
Work by Morgan et al. (2017) and Chhetri et al.(2017), *** see also Friday's talk by J-P Macquart*

- Peaked-spectrum sources appear to be the **dominant population of compact sources** at low radio frequencies
- At least out to z ~1, many also show HI absorption
- Could be good candidates for high-z radio AGN?
- Future HI absorption studies with SKA1-Low

VLBI structure of peaked sources

Coppejans et al. (2016):
EVN VLBI observations of eleven sources with **MHz-peaked spectra**, *flux densities of a few mJy*

Results:
High VLBI detection rate (82%), all detected sources are compact (<1.1 kpc in size)



Phot. redshift z ~ 1.0

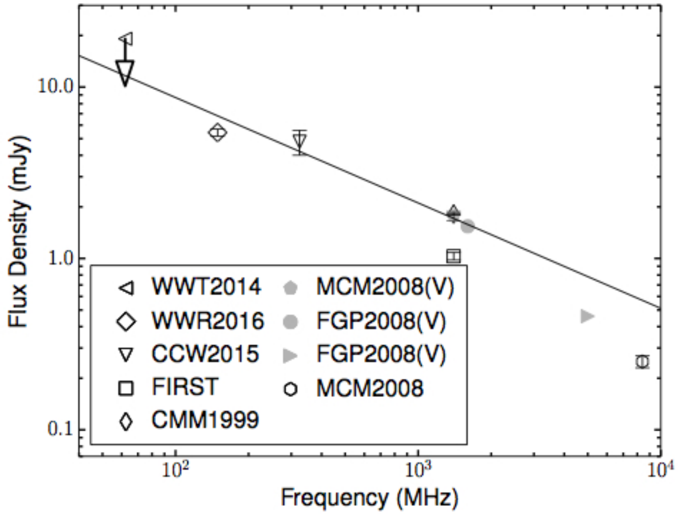
"Low frequency colour-colour diagrams are an easy and efficient way of selecting small AGN"

The way forward at z > 5?

Radio SEDs at z > 4.5

Coppejans et al. (2017) :
Radio spectra of 30 radio AGN at z > 4.5 that were also observed with VLBI

Result:
Roughly equal numbers of steep, peaked and flat radio spectra

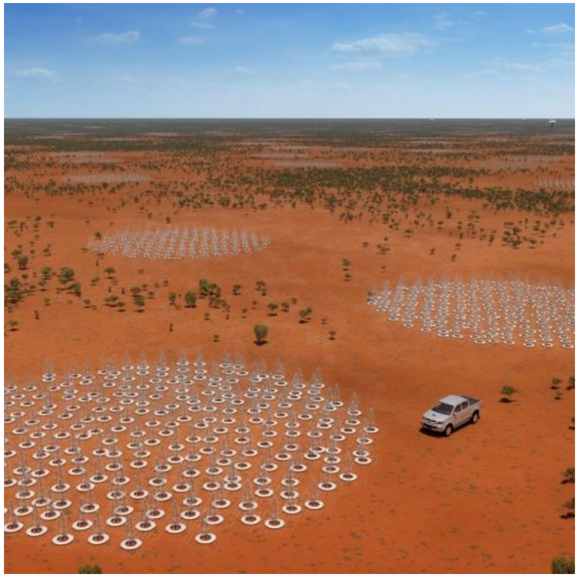


J11427+3312: z = 6.12, α = -0.6

"More effective methods are necessary to reliably identify complete samples of high-redshift sources based on radio data"

Summary and next steps

- At 0 < z < 1, AGN populations and demographics well mapped out from large-area surveys (at 1.4 GHz, and soon at 150 MHz)
- At 1 < z < 5, new deep radio and optical surveys are starting to provide samples of 1000+ objects, map out evolution
- At z > 5, **new data mining challenges** to identify and study the full range of high-z radio AGN



- <u>Great opportunities</u> in the near future, with new wide-band, large-area radio surveys from ASKAP, MWA, VLA, LOFAR
- <u>Enormous potential</u> for next-generation low-frequency surveys to provide a new perspective on many aspects of radio AGN and their cosmic evolution