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<b>Authors</b>	GUIDETTI, DARIA, BONDI, MARCO, PRANDONI, ISABELLA, Beswick, R. J., Muxlow, T. W. B., Wrigley, N., Smail, I. R., McHardy, I., Ivison, R., eMERGE Collaboration
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# AGN populations in GOODS-N through eMERGE ultra-deep JVLA observations

Daria Guidetti

Istituto di Radioastronomia-INAF, Bologna

and

M. Bondi, I.Prandoni (IRA-INAF, Bologna)

R.J. Beswick, T.W.B. Muxlow, N. Wrigley (Jodrell Bank Observatory, Univ. of Manchester), I.R. Smail (Institute for Computational Cosmology, Durham Univ.),

I. McHardy (School of Physics and Astronomy, University of Southampton),

R. Ivison (Institute for Astronomy, Univ. of Edinburgh, Royal Observatory)

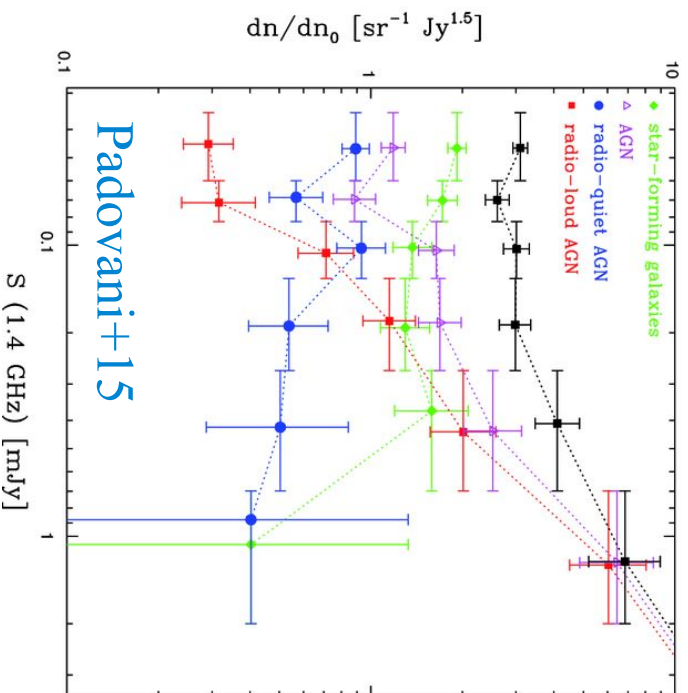
And the eMERGE collaboration



# Context

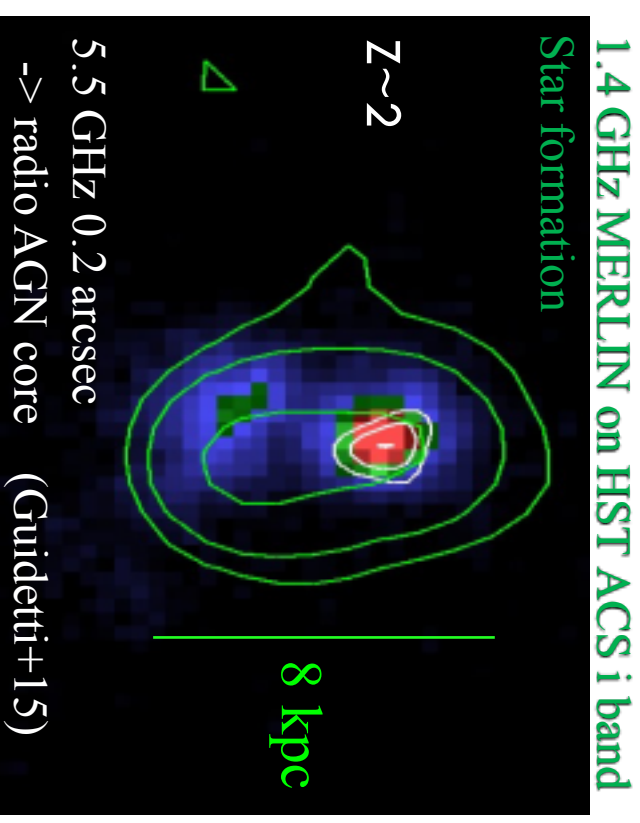
A complete census of faint AGNs in distant galaxies is crucial to understand AGN feedback, accretion regime and possible co-evolution with SF processes

Radio surveys increasingly important → unbiased and resolved view of AGNs & SF



- Composite sub-mJy radio source population
- RQ AGNs start to appear at  $\mu\text{Jy}$  levels in deep radio fields (e.g. Seymour+08, Padovani+09, +11, +15 Bonzini+13)

Ultra-deep radio obs. ( $\sim\mu\text{Jy rms}$ ) with high spatial resolution (sub-kpc → kpc) allow us to study the overall AGN population and distinguish extended kpc scale SF emission from more compact AGN components ( $<1\text{ kpc}$ )



# The eMERGGE survey

*eMERLIN Galaxy Evolution survey*

PI Muxlow, Smail & McHardy and 60 CO-is from 9 countries

A very deep directed survey of the  $\mu$ Jy radio source population in GOODS-N

## Goal

- morphologically and spectrally identification of AGNs & SFGs up to  $z \sim 5$

## How

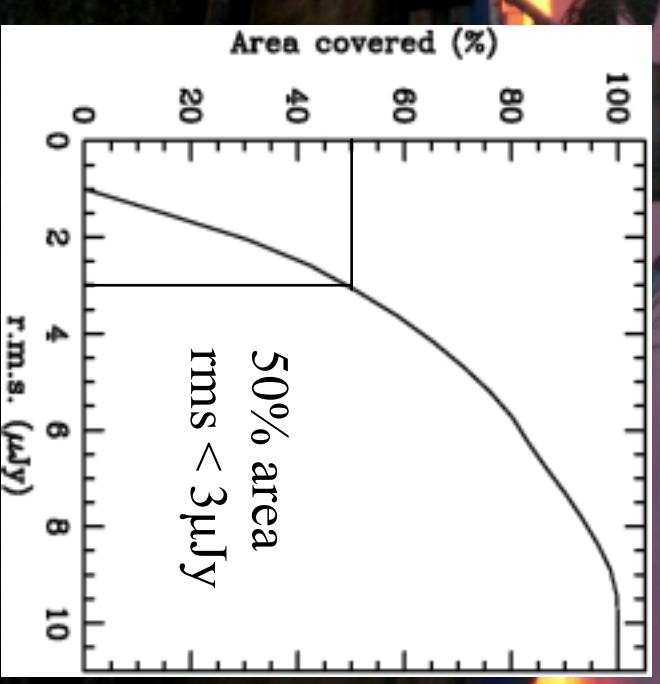
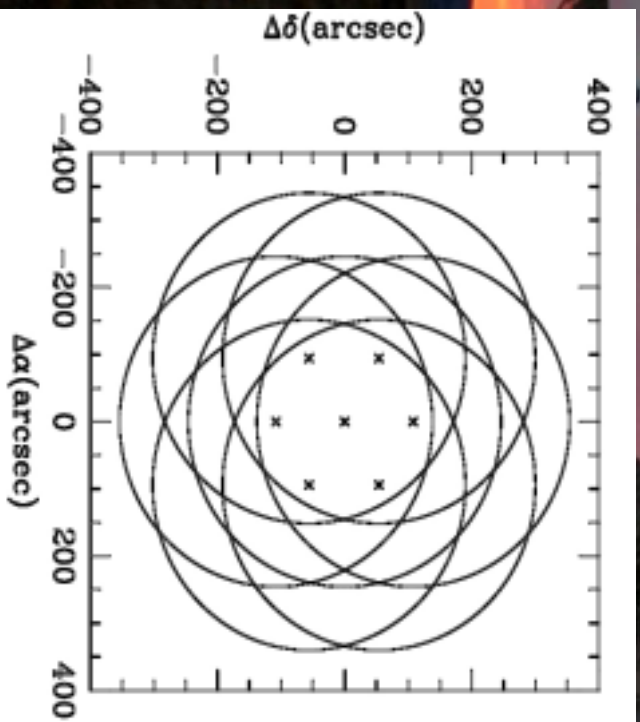
- 400 hrs eMERLIN+ JVLA @ 1.4 GHz
- 378 hrs eMERLIN +JVLA @ 5 GHz (PI Prandoni)
- resolution 50-2000 mas (0.5-tens of kpc at  $z > 1$ ) with 0.5-1  $\mu$ Jy/b rms
- ancillary coverage of GOODS-N from radio to X-ray

## Status

- 5 GHz JVLA A/B survey [complete] (Guidetti+ I & II in prep)
- 1.4 GHz JVLA-A (39 hrs) [complete] (Owen+in prep)
- 1.4 GHz (20 days, 15% data reduced) & 5 GHz eMERLIN (Q2->2016)

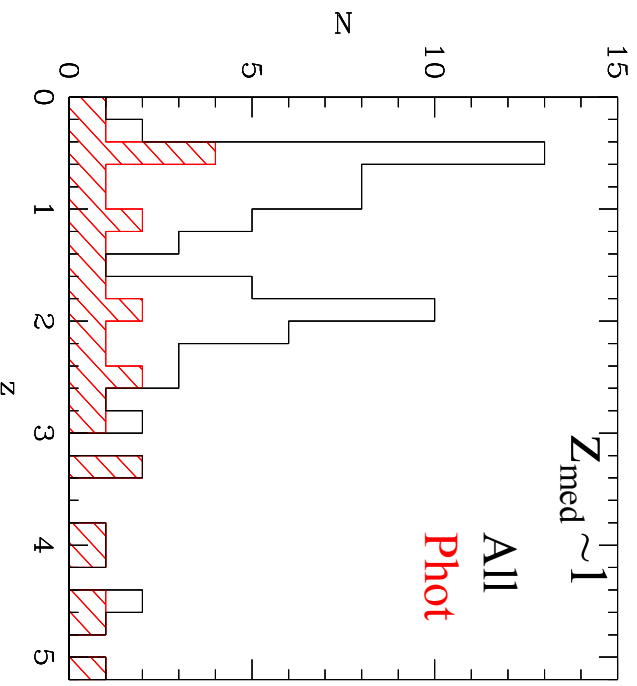
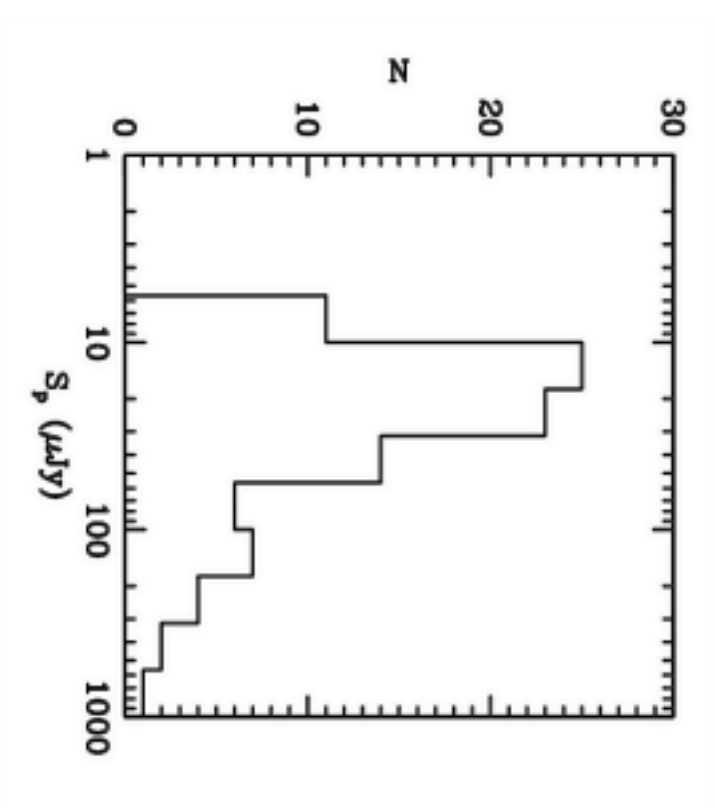
# 5.5 GHz JVLA MOSAIC

- 7-pointing mosaic in GOODS-N (matching the 5 GHz e-MERLIN FoV)
- 14+2 hours in Array A & B [PI: Muxlow] (Oct 2012 & Oct. 2013)
- Central frequency 5.5 GHz, 2 GHz bandwidth
- 0.5 arcsec resolution,  $\sim 1 \mu\text{Jy}$  rms at center (1 sigma)

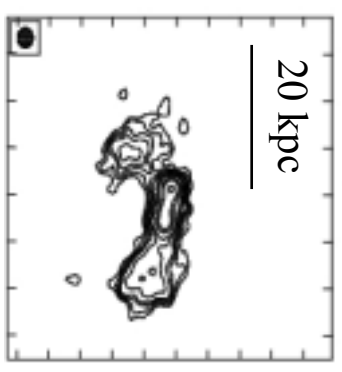
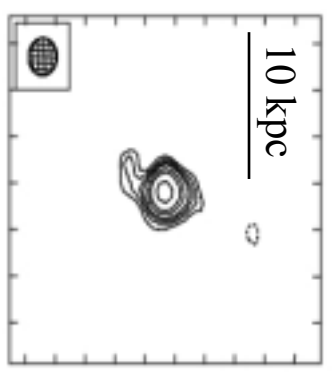
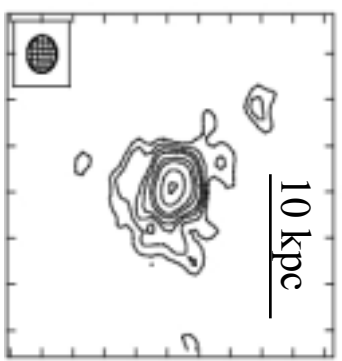


# 5.5 GHz catalogue

- 94 sources ( $S/N > 5$ ), at  $< 7$  arcmin from the centre
- $S_{5.5\text{GHz}} > 6 \mu\text{Jy}$ , 50% with  $S_{5.5\text{GHz}} < 30 \mu\text{Jy}$
- 88% (83/94) secure Ks identifications within  $< 0.5''$  (WIRCam,  $5\sigma$  depth of Ks,  $A_B = 24.45$ , Wang+10)
- 95% (79/83) with redshift (51 spec 28 phot) (Cowie+01, With+04, Barger+08, Kajisawa+10, Momcheva+15)



$\langle \text{size} \rangle \sim 0.4$  arcsec ( $\sim 3$  kpc at  $z=1$ )



First contour @  $3\sigma$

# Multi- $\lambda$ classification of the 5.5 GHz sources

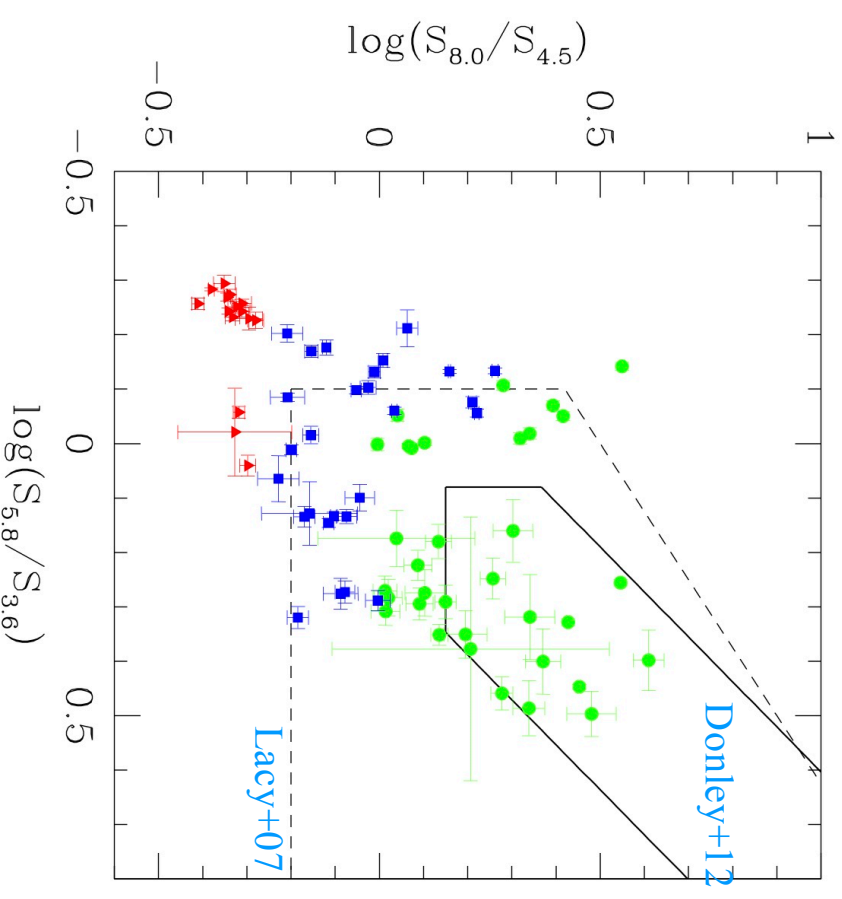
- 5 IR colour-colour plots (NIR-> FIR) → quasar mode AGNs, passive (radio mode), star forming galaxies
- L<sub>X-ray</sub> → quasar mode AGNs
- radio excess sources (Del Moro+13) → radio AGN (RM&QM)
- VLBI detections → radio AGN (RM&QM)



Samples of quasar/radio mode AGNs  
and star forming galaxies

# IR classification of the 5.5 GHz sources

- 93% (77/83) of the Ks-identified sources with 4-IRAC bands data (Wang+10)
- 78% (65/83) MIR, FIR Herschel+PEP data (Elbaz+11, Magnelli+13)
- 5 IR CC criteria
  - Stern+05 (IRAC), Donley+12 (IRAC)
  - Kirkpatrick+12 (IRAC, 24 $\mu$ m, 100 $\mu$ m, 250 $\mu$ m)
  - Messias+12 (Ks-band, IRAC)
  - 3 account for redshift evolution
  - 94% (77/83) IR- classified sources



- |   |                       |     |
|---|-----------------------|-----|
| ■ | 35 AGNs (quasar mode) | 45% |
| ▲ | 15 passive galaxies   | 20% |
| ● | 27 SF/hyb systems     | 35% |

# X-ray & radio AGNs

X-ray for 63% (52/83) (Xue+16), 100 $\mu$ m for 63% (52/83) (Elbaz+11, Magnelli+13), 1.4 GHz VLA for 100% (Morrison+10) 1.6 GHz VLBI (Chi+13, Radcliffe+15)

QM AGNs if :

$L_x [2-7 \text{ keV}] > 10^{42} \text{ erg/s}$

$L_x [0.2-7 \text{ keV}] > 3 \times 10^{42} \text{ erg/s}$  (for upp limits)

→ 29 X-ray QM AGN (30% not IR QM AGNs)

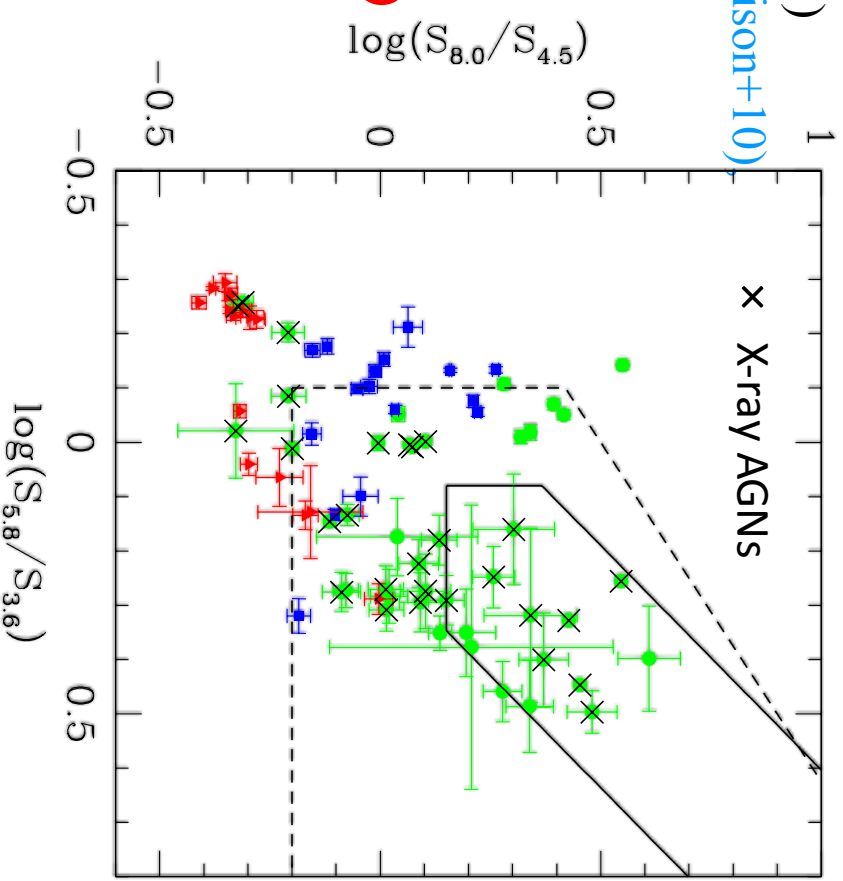
radio excess sources if:

$q_{100} (\log [S_{100\mu\text{m}}/S_{1.4\text{GHz}}]) < 1.5$  (Del Moro+13)

$S_{100\mu\text{m}} = 1 \text{ mJy}$  (3 sigma) for upper limits

→ 31 radio excess (~10% not IR RM AGN)

1.6 GHz VLBI → 18 sources (~10% not IR RM AGNs)



35 QM AGNs  
15 RM AGNs  
27 SF/hyb

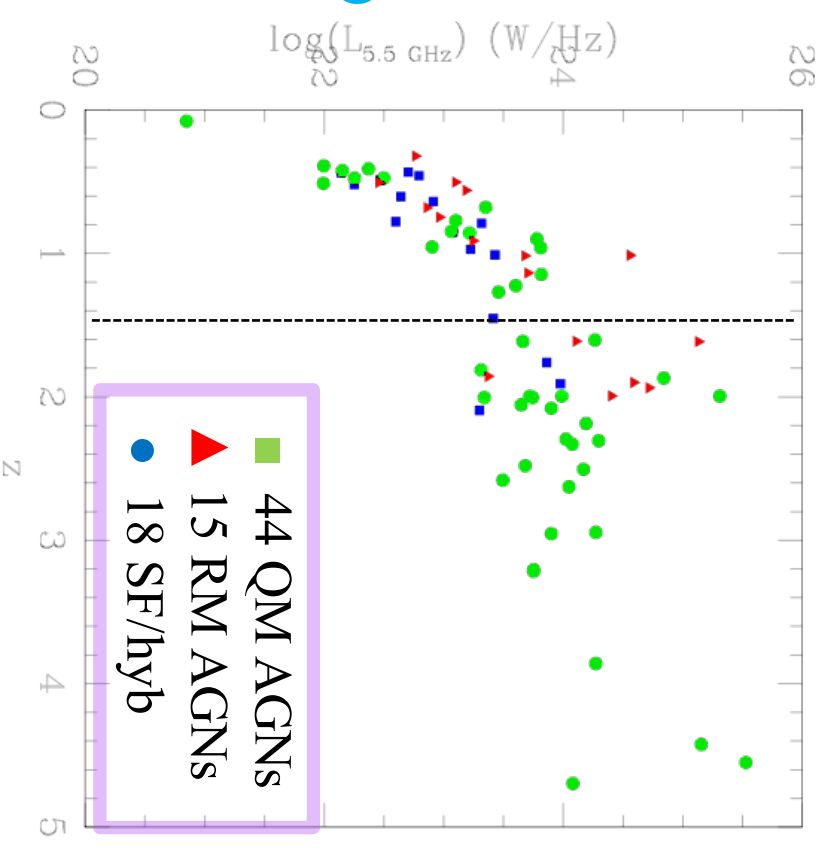
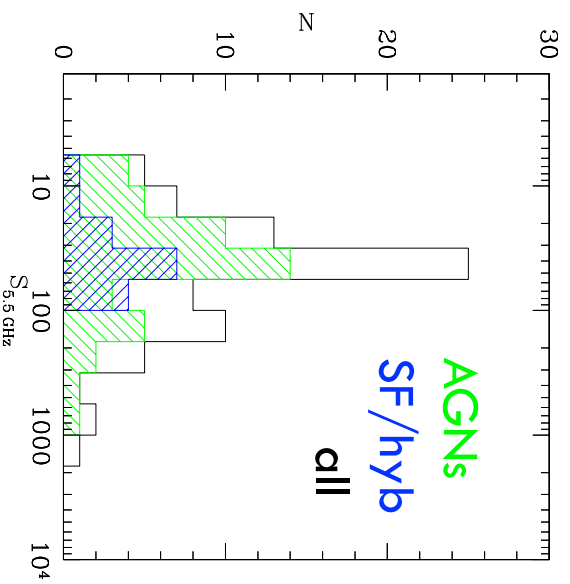


44 QM AGNs 57%  
15 RM AGNs 20%  
18 SF/hyb 23%

77% of the classified sources are AGNs!!

# AGN content in the 5.5 GOODS-N catalogue

- ~ 78% of the sources host an AGN (RM+QM)
- AGNs over all  $z$  &  $L_{5.5\text{GHz}}$
- at  $z > 1.5$  >90% (34/37 sources) are AGNs
- 3 SF/hyb at  $z > 1.5$  are sub-mm galaxies (Barger+12)
- AGNs dominate down to few  $\mu\text{Jy}$  (most QM)



# 1.4-5.5 GHz spectral index & optical images

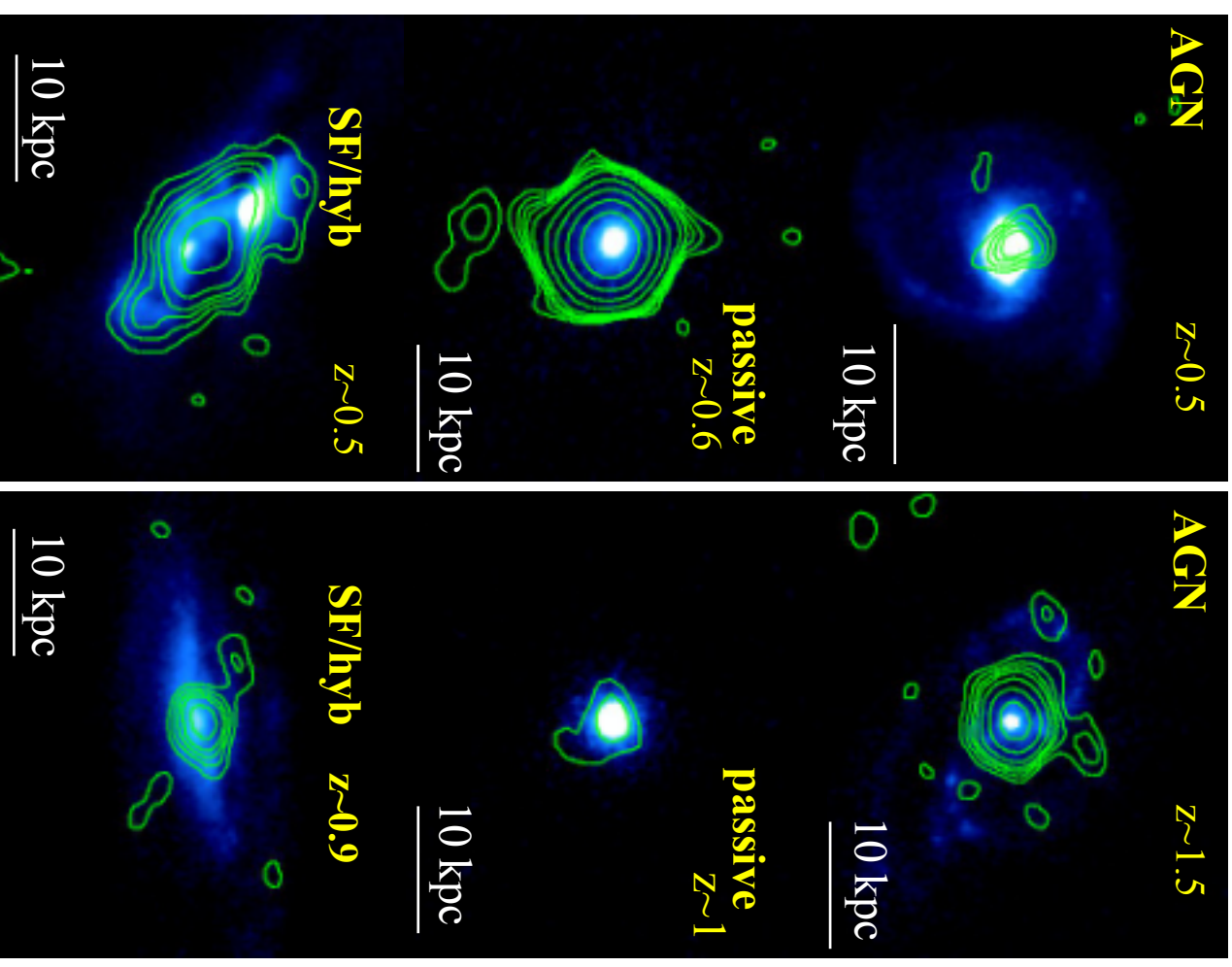
1.4 GHz information from VLA catalogue (1.7" FWHM [Morrison et al. 2010](#))

Spectral analysis limited to compact sources:  
61 with size < 1 arcsec  
(~ 8 kpc @ z=1)

$$S_{\nu} \propto \nu^{-\alpha}$$

- 31 QM AGNs  $\alpha_{\text{med}} \sim 0.73$
- ▲ 14 RM AGN  $\sim 0.40$
- 16 SF/hyb systems  $\sim 0.72$

5.5 GHz contours/ HST I band image



# 1.4 GHz selected sample

from VLA catalogue (1.7" FWHM Morrison+10)

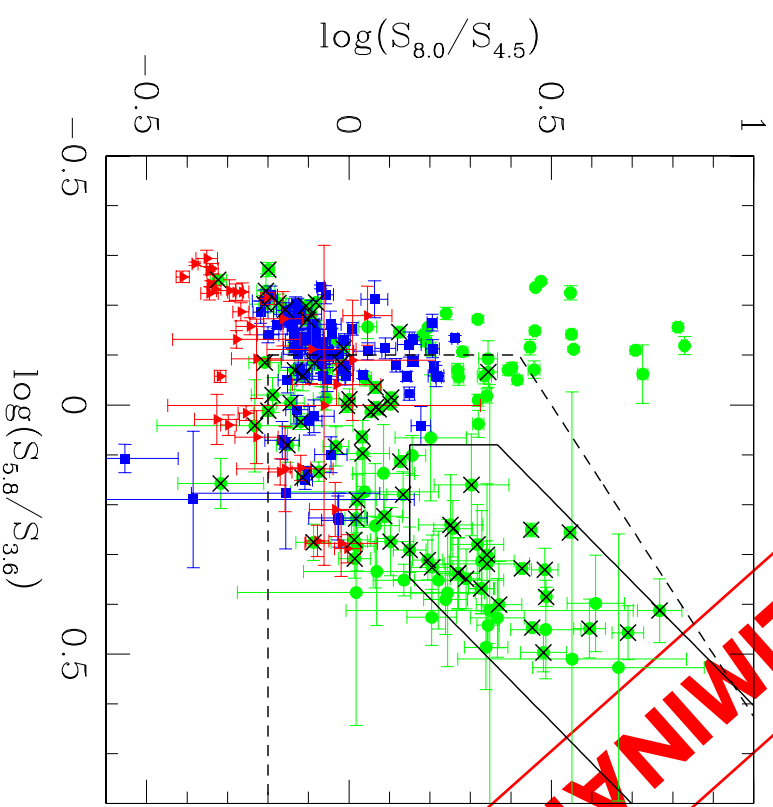
300 1.4 GHz sources selected in the same area of our 5.5GHz mosaic (99%  $20\mu\text{Jy} > S_{1.4\text{GHz}} > 1\text{mJy}$ )

## 1.4 GHz selected sources

- 142 QM AGNs  $\rightarrow \sim 65\%$
- 34 RM AGNs
- 86 SF/hyb systems  $\rightarrow \sim 35\%$

## 5.5GHz selected sources

- 44 QM AGNs  $\rightarrow \sim 80\%$
- 15 RM AGN
- 18 SF/hyb systems  $\rightarrow \sim 20\%$

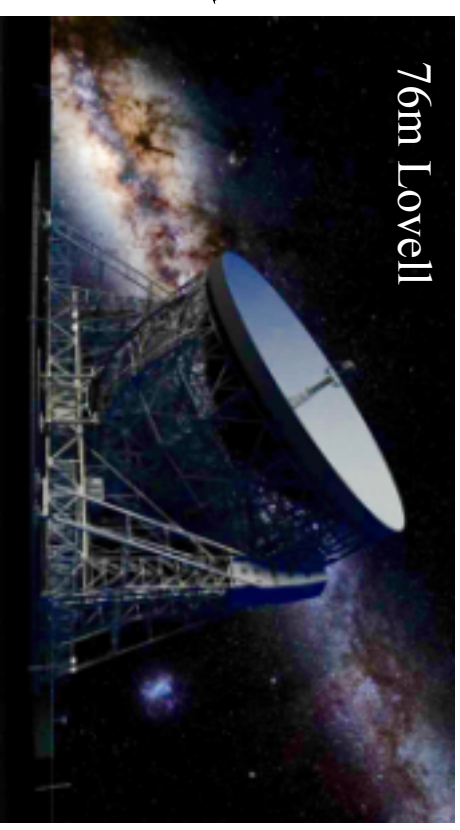


a larger fraction of SF/Hyb and steep spectra (84%  $\leftarrow \rightarrow$  49% at 5.5 GHz) but AGNs still dominate

# Summary

- First catalogue of radio sources in GOODS-N at 5.5 GHz based on ultra-deep VLA data with sub-arcsec resolution
- Analysis of the AGN/SFG content in the 5.5 GHz catalogue via 5 IR cc plots, hard X-ray luminosity,  $q_{100}$  radio excess and VLBI detections
- The majority of the sources are AGN related (mostly quasar mode) down to a few  $\mu\text{Jy}$
- 30% of quasar mode AGNs show a radio excess, 15% VLBI detected
- quasar mode AGNs and SF/hyb have similar steep radio spectra, radio mode AGNs flat/inverted spectra
- In the same sky area, a 1.4GHz selected sample at arcsec resolution contains a larger fraction of SF/hyb and steep spectra, but AGNs still dominate
- Looking forward for eMERLIN data  
(Lovell included) to explore the  $\mu\text{Jy}$  & sub-Jy sky  
with  $\sim 50$  mas resolution  $\rightarrow$  truly resolved & unbiased  
view of AGN & SF processes up to high redshifts  
in GOODS-N

76m Lovell



# X-ray AGNs

- X-ray for **63%** (52/82) (Xue+16)  
 (20 AGNs, 9 pas, 15 SF/hyb)

X-ray AGN if:

- $L_x [2-7 \text{ keV}] > 10^{42} \text{ erg/s}$
- $L_x [0.2-7 \text{ keV}] > 3 \times 10^{42} \text{ erg/s}$  (for upp limits)

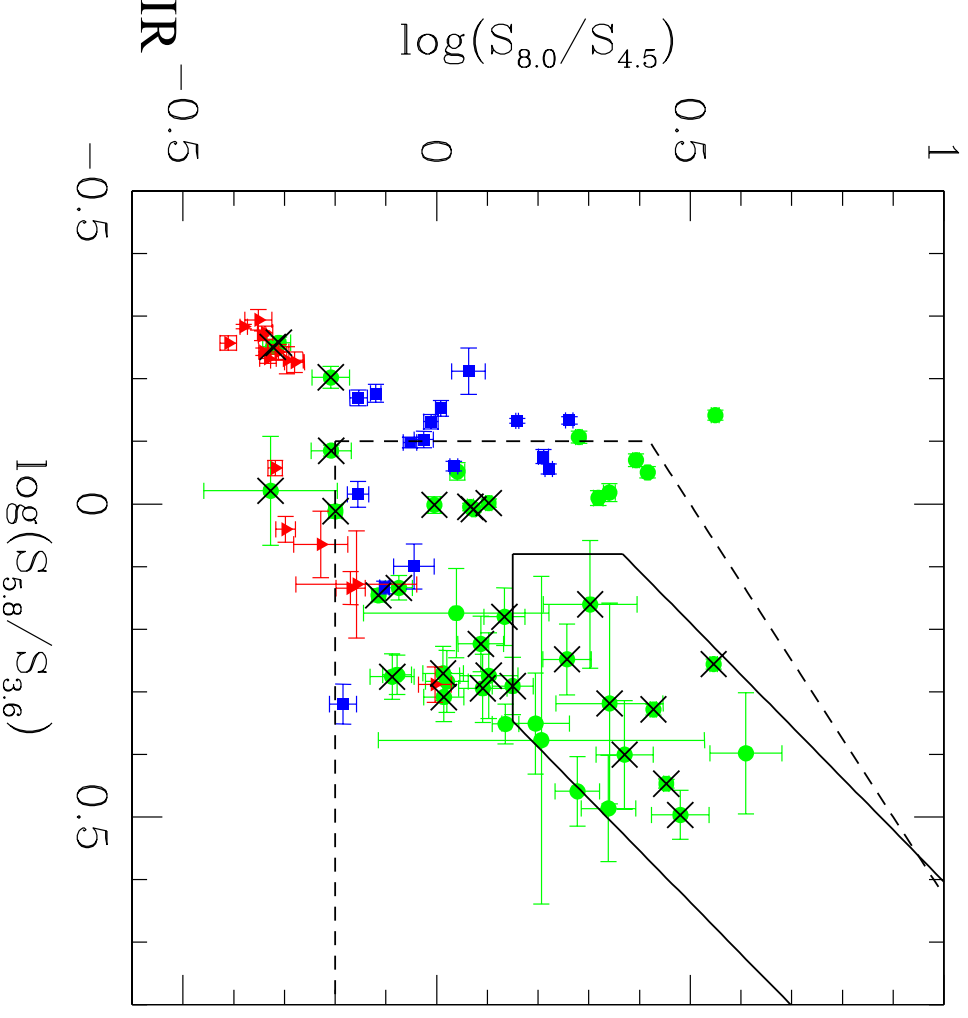
→ 29 sources

[
 20/35 in QM AGNs  
 3/15 in RM AGNs  
 6/27 in SF/hyb

- 22% of SF/hyb contains an AGN not seen in IR

- AGN brightest X-ray sources

$L_{X_{\text{med}}} \sim 5 \times 10^{43} \text{ erg/s}$   
 $L_{X_{\text{med}}} \sim 1.7 \times 10^{41} \text{ erg/s}$   
 for pas & SF/hyb



■ 44 QM AGNs  
▲ RM AGN  
● SF/hyb systems

# Radio active AGNs

Rifare con nuovi colori  
Aggiungere le VLBI

Radio AGN revealed by a radio excess wrt what expected from star formation (from FIR/radio..) & by VLBI detections

- 100 $\mu$ m for 63% (52/82) (Magnelli+13,+15)
- S<sub>100 $\mu$ m</sub>=1mJy (3 sigma) for upper limits
- 1.4 GHz VLA for (82/82) (Morrison+10)

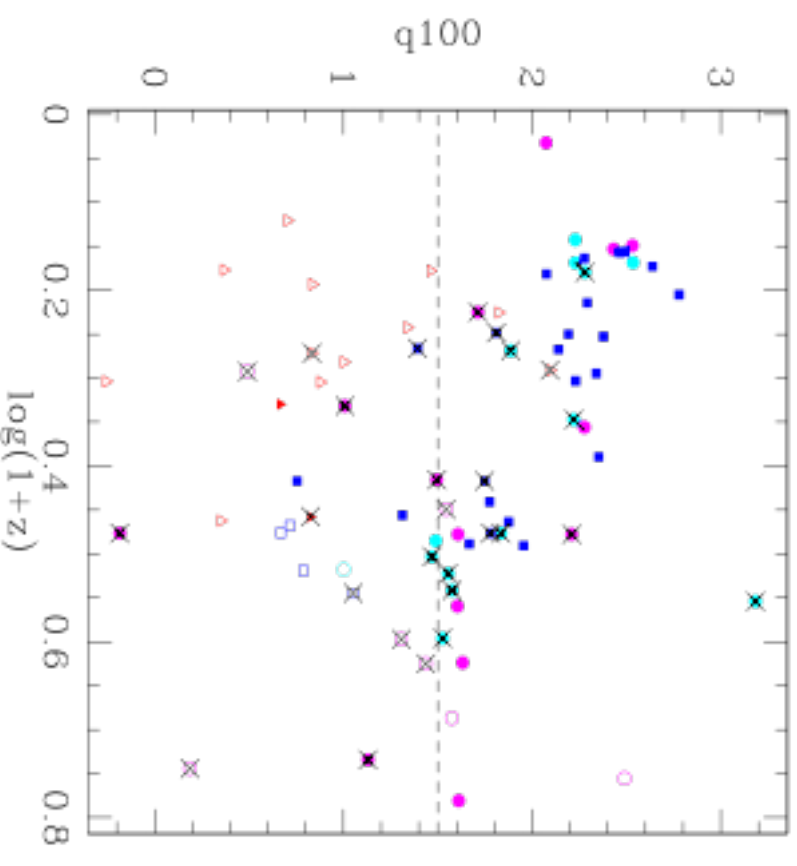
Radio excess if:

$$q100 (\log [S_{100\mu\text{m}}/S_{1.4\text{GHz}}]) < 1.5 \text{ (Del Moro+13)}$$

→ 31 radio excess sources:

- 13/15 passive
- 12/36 ? QM AGNs -> AGN-related radio emission
- 6 /27 AGN in SF/hyb

→ AGNs which only appear in radio

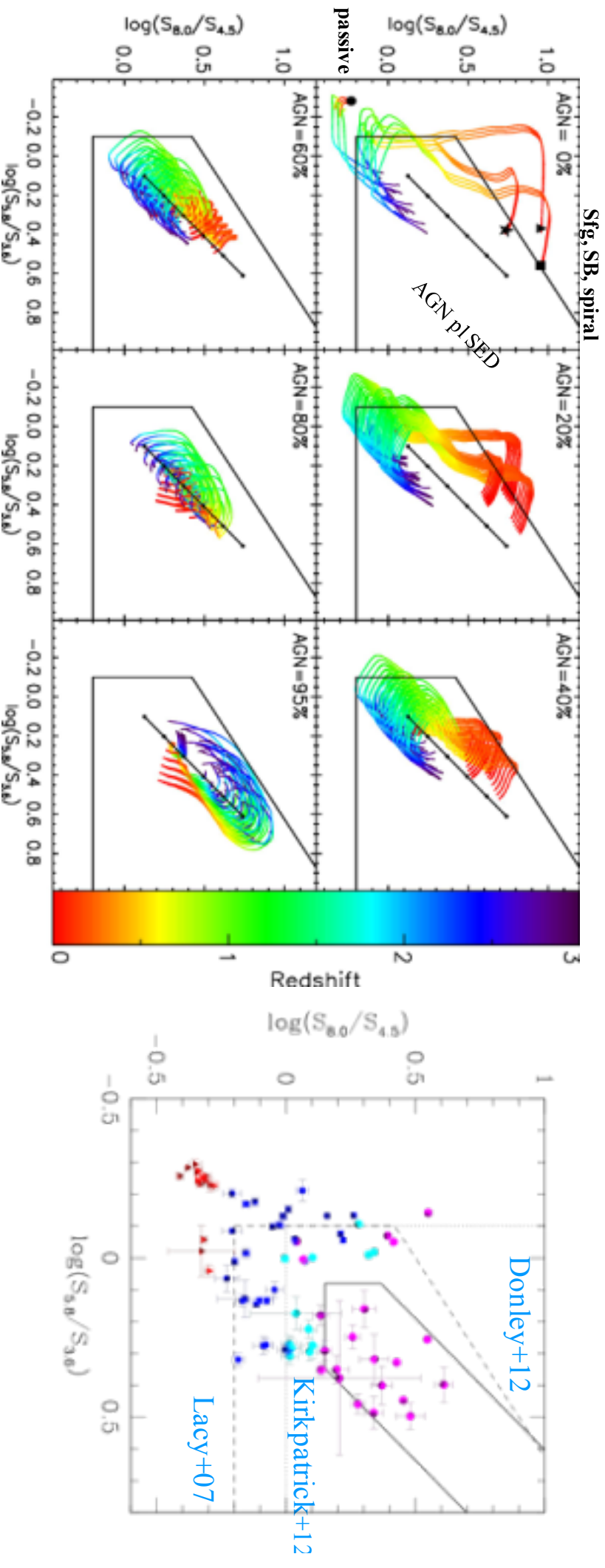


$$1.4 \text{ GHz VLBI (Chi+13, Radcliffe+15)}$$

→ 13 sources (all radio excess)

# IR classification of the 5.5 GHz sources

Donley+12



5 IR CC criteria by Stern+05 (IRAC), Donley+12 (IRAC), Kirkpatrick+12 (IRAC, Far-IR), Messias+12 (Ks, IRAC)

4-IRAC bands photometry for 90% (74/82) of the Ks-identified sources (Wang+10)

Far-IR Herschel photometry for 79% (65/82) (Elbaz+11)

- 36 AGN candidates (selected by at least 1 IR criterium)
- 14 candidate passive ellipticals
- 24 SF/comp systems

# THE HYBRID SYSTEM J123649+620737: EMERLIN VIEW @ 5 GHz

potential hot ULIRG at  $z \sim 2.2$   
(Casey+09)

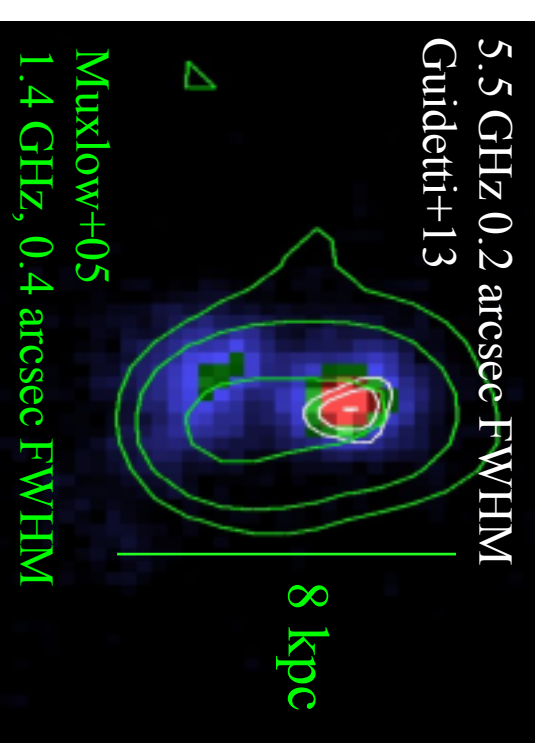
## SF galaxy

- Optical/near IR spectra
- No AGN spectral features
- No radio core in the 1.4 GHz MERLIN
- image at 0.4 arcsec FWHM

## AGN

- X-ray luminosity [2-10 keV] of  $1.3 \times 10^{45}$  erg/s
- Optical compact core
- Radio excess source

- AGN flux density  $\sim 130 \mu\text{Jy}$  assuming a radio core of 0.4 arcsec (MERLIN)
- Radio emission:  $\sim 40\%$  AGN +  $60\%$  SF  $\rightarrow$  **SFR  $\sim 4000 M_{\odot}/\text{year}$**  (Casey+09)



1.4 GHz MERLIN contours on HST  
ACS i band image

We found that AGN accounts at least for 60% for the total radio flux

$\rightarrow$  SFR  $< 2800 M_{\odot}/\text{year}$  from our eMERLIN flux density