AGN populations in GOODS-N through eMERGE ultra-deep JVLA observations

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and
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I. McHardy (School of Physics and Astronomy, University of Southampton),
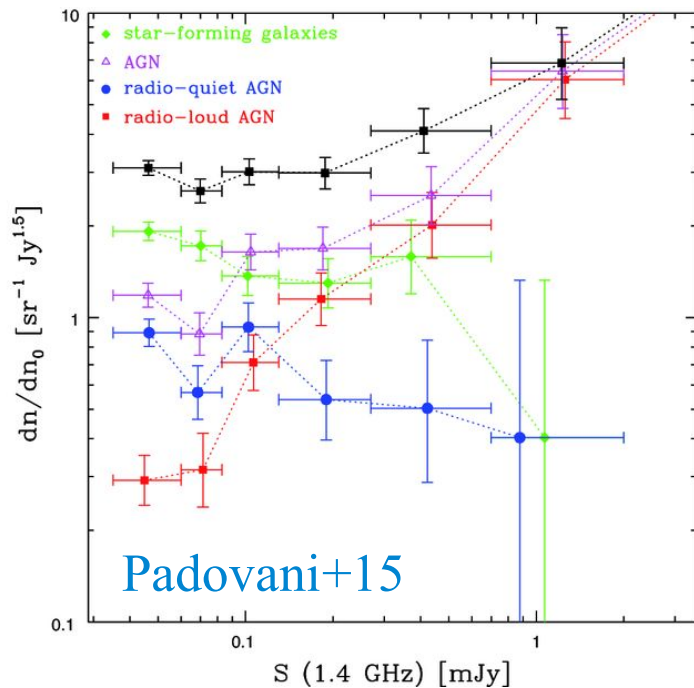R. Ivison (Institute for Astronomy, Univ. of Edinburgh, Royal Observatory)
And the eMERGE collaboration

Garching, June 30, 2016

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

Padovani+15

Composite sub-mJy radio source population

RQ AGNs start to appear at µJy levels in deep radio Fields (e.g. Seymour+08,Padovani+09,+11,+15 Bonzini+13)

1.4 GHz MERLIN on HST ACS i band
Star formation
Z~2
8 kpc
5.5 GHz 0.2 arcsec
-> radio AGN core   (Guidetti+15)

Ultra-deep radio obs. (~µJy 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 kpc)
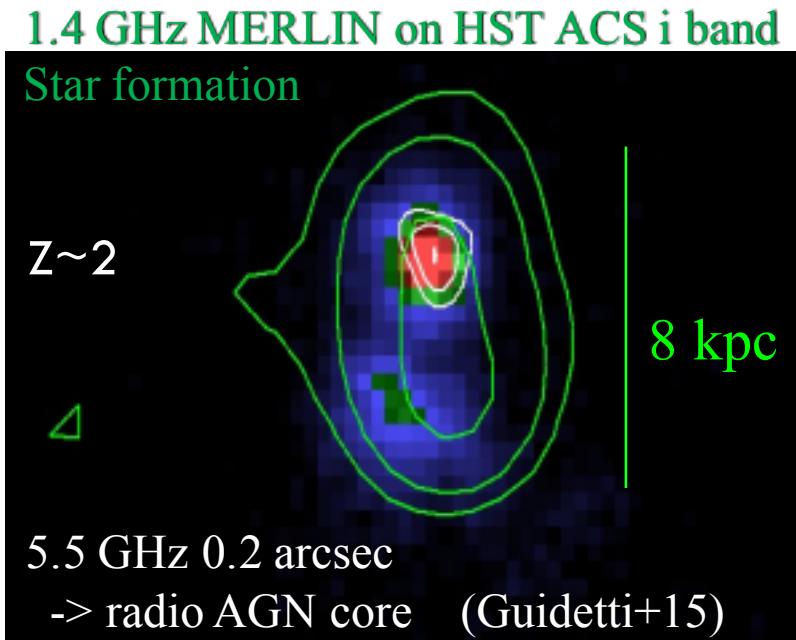
The eMERGE survey *eMERLIN Galaxy Evolution survey*

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

A very deep directed survey of the μJy radio source population in GOODS-N

Goal

- morphologically and spectrally identification of AGNs & SFgs up to z~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 μJy/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, ~1 µJy rms at center (1 sigma)

50% area
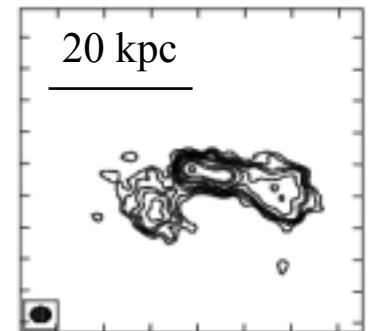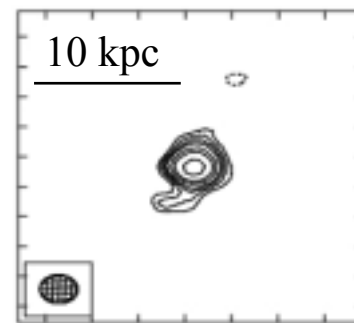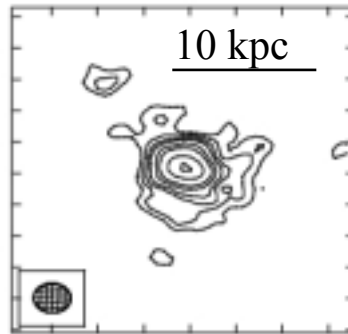rms < 3µJy
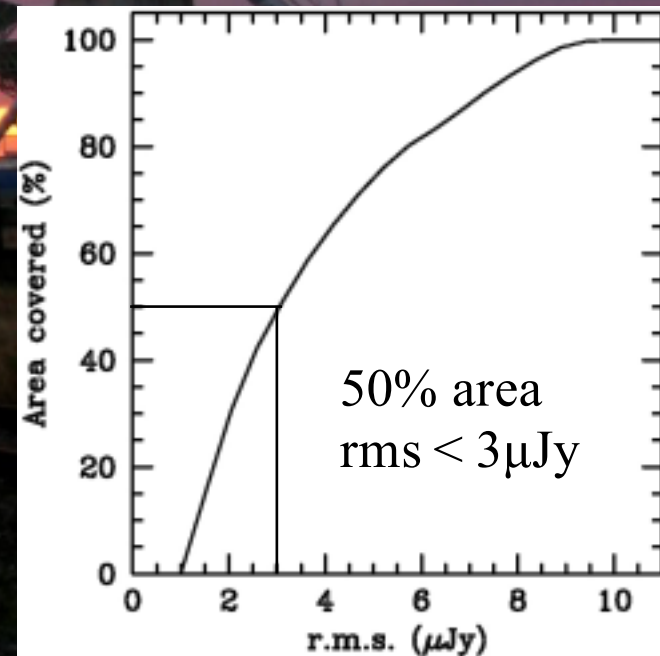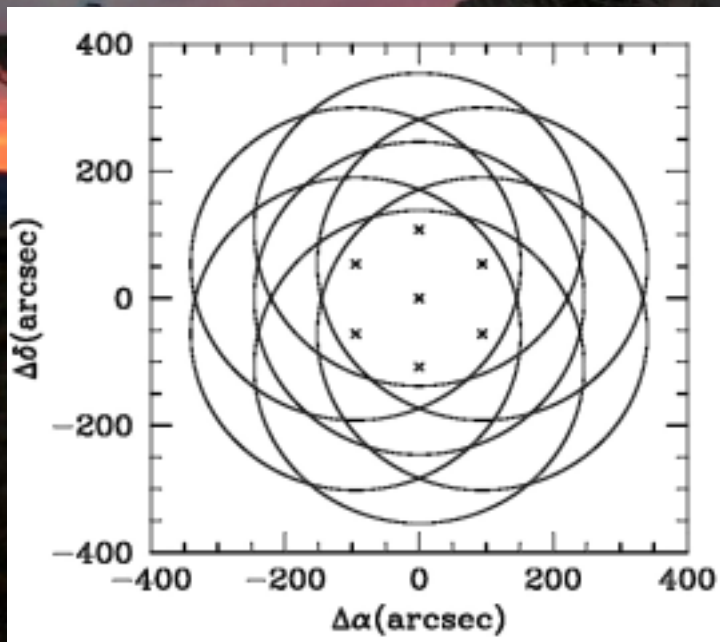
5.5 GHz catalogue

- 94 sources (S/N>5),   at <7 arcmin from the centre

- $S_{5.5GHz} > 6$ μJy, 50% with $S_{5.5GHz} < 30$ μJy

- 88% (83/94) secure Ks indentifications within <0.5"
  (WIRCam, 5σ depth of Ks, AB=24.45, Wang+10)

- 95% (79/83) with redshift (51 spec 28 phot)
  (Cowie+01,Wirth+04,Barger+08, Kajisawa+10, Momcheva+15)

$z_{med} \sim 1$

All
Phot
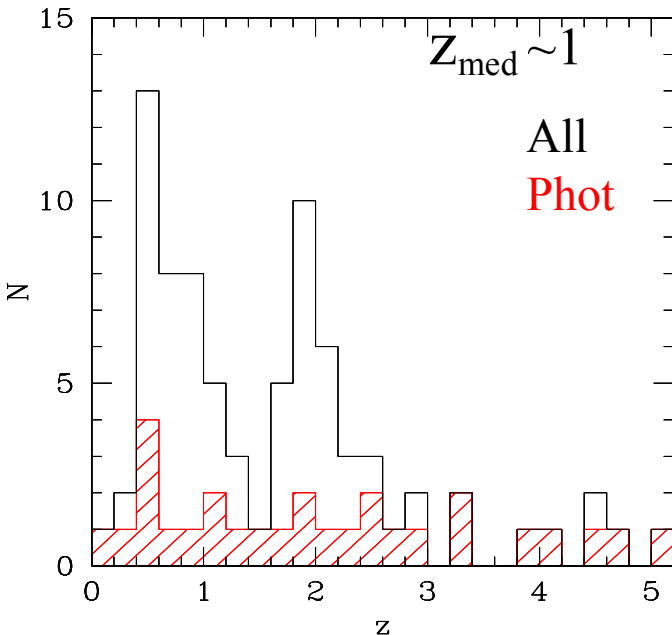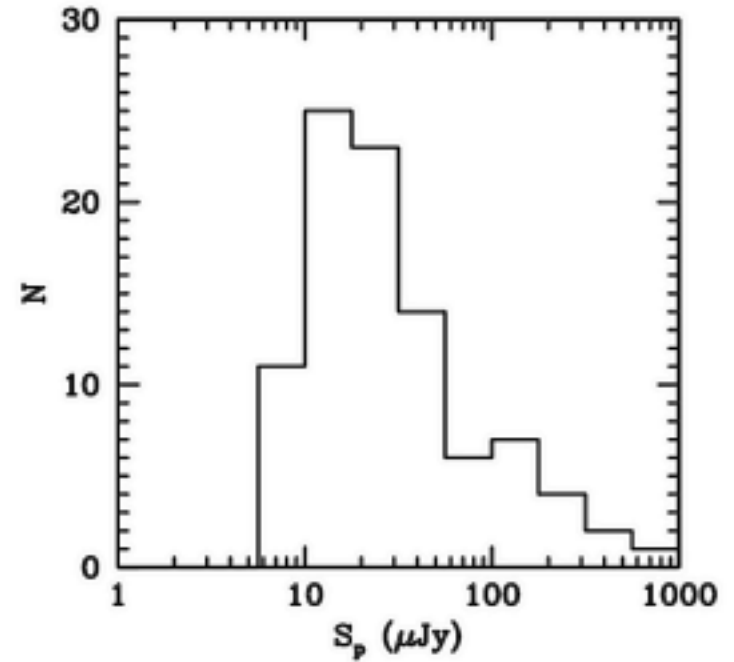
- <size> ~ 0.4 arcsec (~3 kpc at z =1)

10 kpc

10 kpc

20 kpc

First contour @ 3σ

Multi-λ classification of the 5.5 GHz sources

■ 5 IR colour-colour plots (NIR-> FIR) ➜ quasar mode AGNs, passive (radio mode), star forming galaxies

■ L_{x-ray} ➜ 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, 24μm, 100μm, 250μm)
- Messias+12 (Ks-band, IRAC)
- 3 account for redshift evolution
- 94% (77/83) IR- classified sources
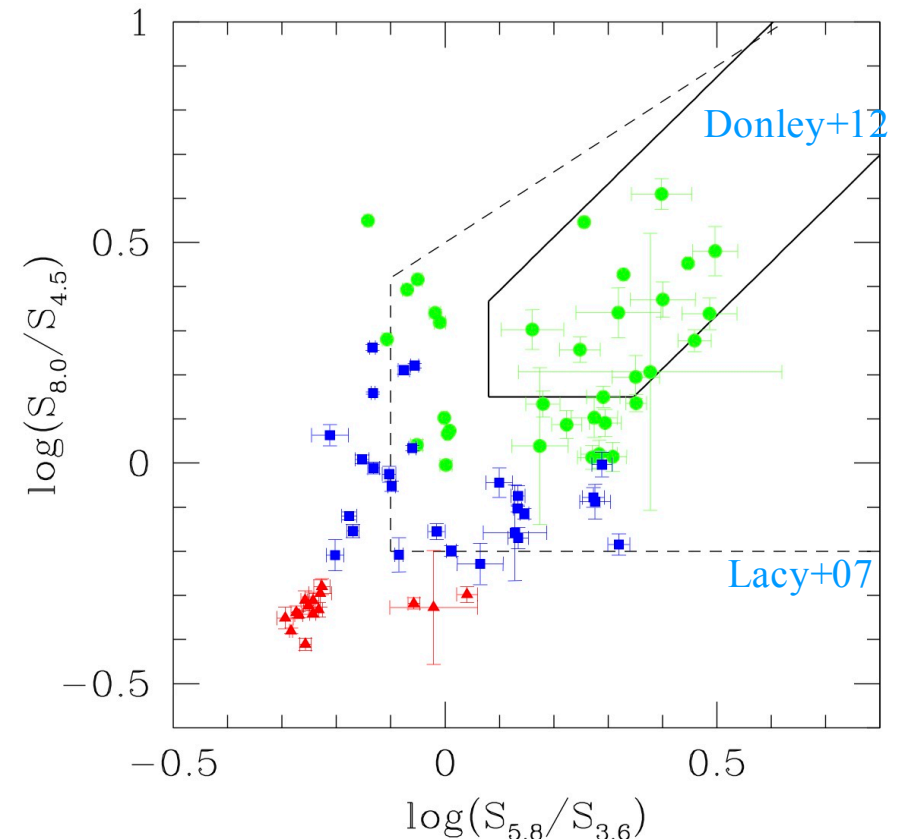
■ 35 AGNs (quasar mode)	45%
▲ 15 passive galaxies	20%
● 27 SF/hyb systems	35%

X-ray & radio AGNs

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

🟧 QM AGNs if :

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

Lx [0.2-7 keV] $>3\times10^{42}$ erg/s (for upp limits)

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

🟧 radio excess sources if:

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

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

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

🟧 1.6 GHz VLBI ➡ 18 sources (~10% not IR RM AGNs)
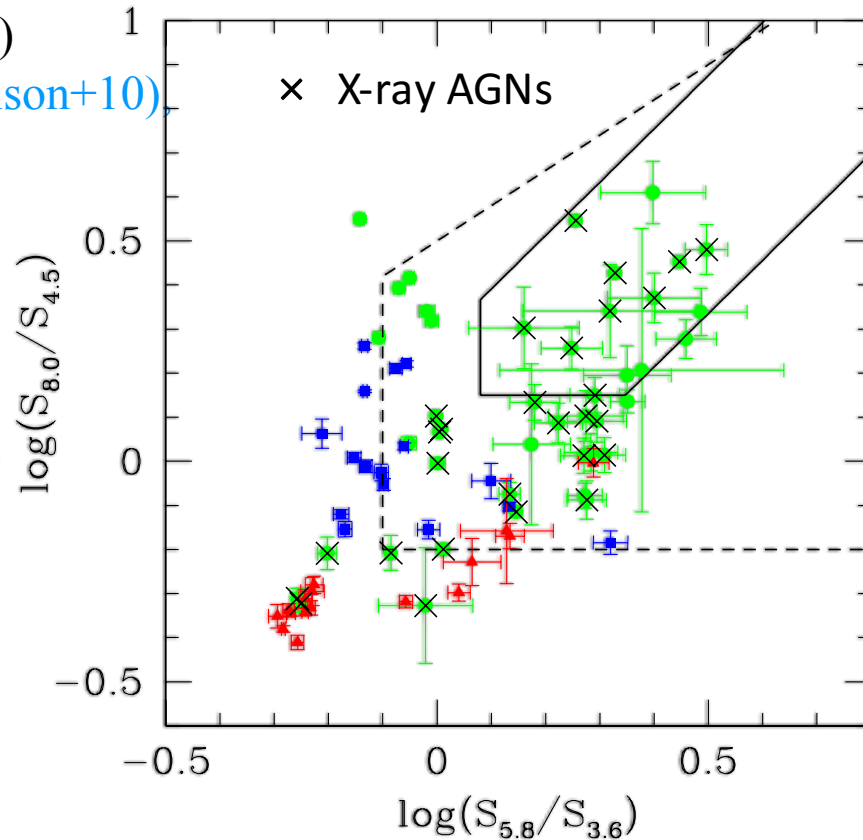
| ■ 35 QM AGNs |
| ▲ 15 RM AGNs |
| ● 27 SF/hyb |

➡

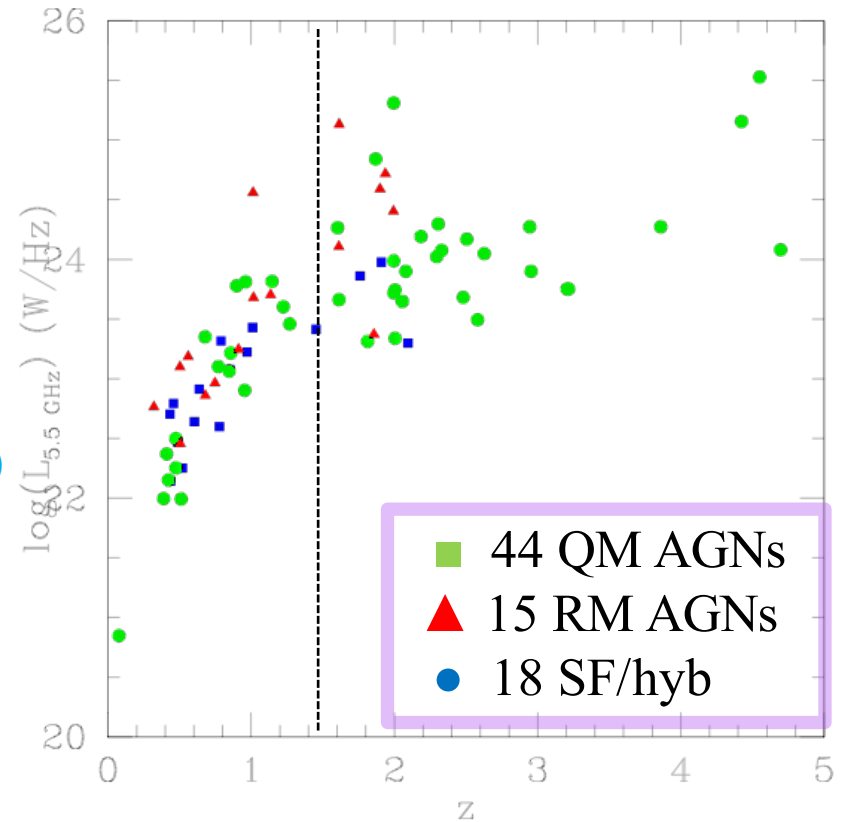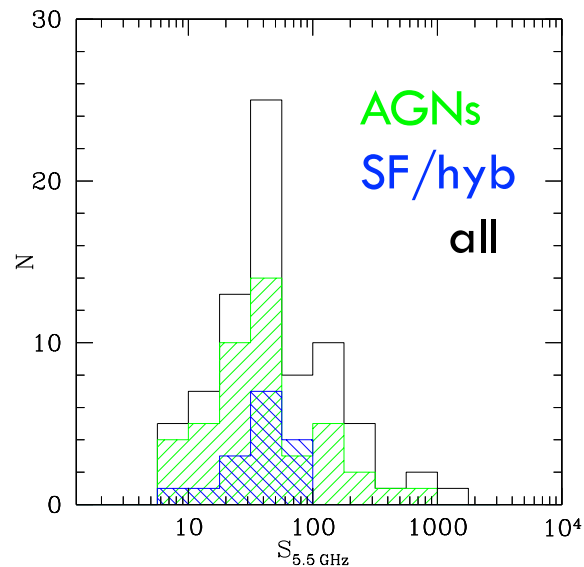| ■ 44 QM AGNs | 57% |
| ▲ 15 RM AGNs | 20% |
| ● 18 SF/hyb | 23% |

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 & $L_{5.5GHz}$

- 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 μJy (most QM)

■ 44 QM AGNs
▲ 15 RM AGNs
● 18 SF/hyb

AGNs
SF/hyb
all

1.4-5.5 GHz spectral index & optical images

■ 1.4 GHz information from VLA catalogue (1.7" FWHM Morrison et al. 2010)
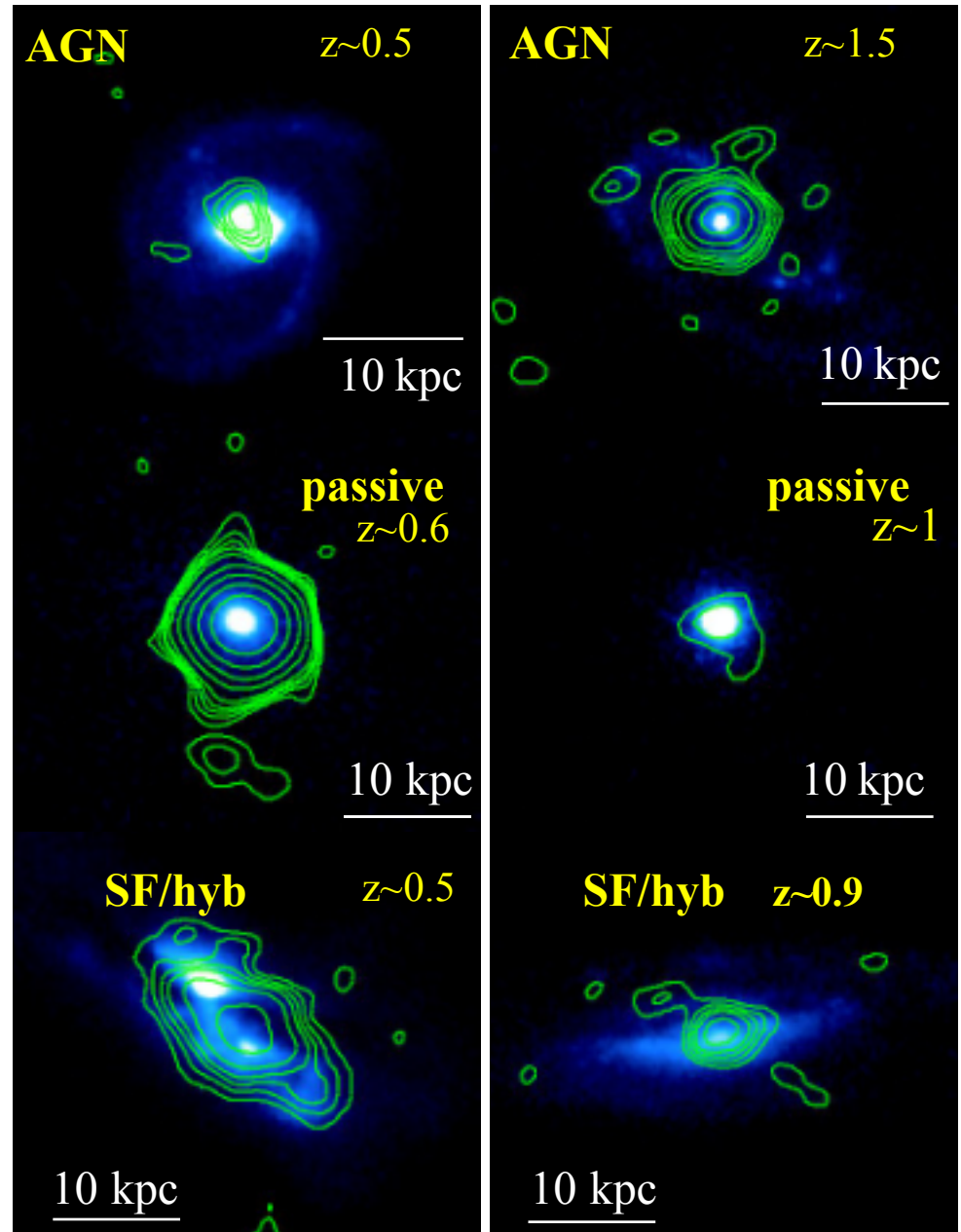
■ Spectral analysis limited to compact sources:
61 with size <1 arcsec
(~ 8 kpc @ z=1)

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

- ■ 31 QM AGNs α_{med} ~ 0.73
- ▲ 14 RM AGN   ~ 0.40
- ● 16 SF/hyb systems   ~ 0.72

5.5 GHz contours/ HST I band image

AGN   z~0.5
10 kpc

AGN   z~1.5
10 kpc

passive
z~0.6
10 kpc

passive
z~1
10 kpc

SF/hyb   z~0.5
10 kpc

SF/hyb   z~0.9
10 kpc
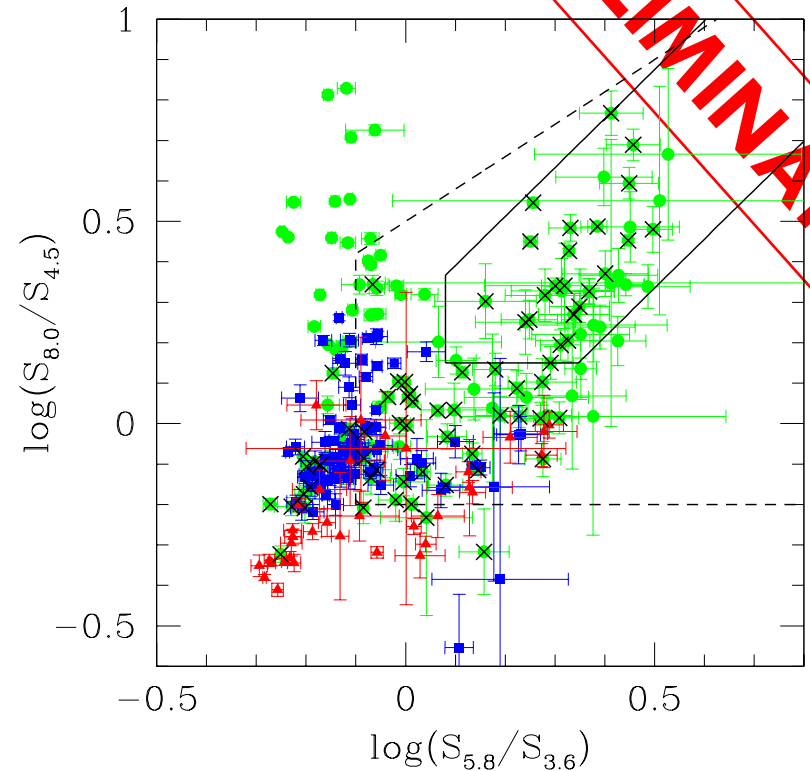
1.4 GHz selected sample

from VLA catalogue (1.7" FWHM Morrison+10)

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

1.4 GHz selected sources

- ■ 142 QM AGNs ⎤
- ▲ 34 RM AGNs ⎦ ➜ ~65%
- ● 86 SF/hyb systems ➜ ~35%

5.5GHz selected sources

- ■ 44 QM AGNs ⎤
- ▲ 15 RM AGN ⎦ ➜ ~80%
- ● 18 SF/hyb systems ➜ ~20%

a larger fraction of SF/Hyb and steep spectra (84% ⟵➝ 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 JVLA 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 µJy

◾ 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 µJy & sub-Jy sky
with ~ 50 mas resolution → truly resolved & unbiased
view of AGN & SF processes up to high redshifts
in GOODS-N

76m Lovell
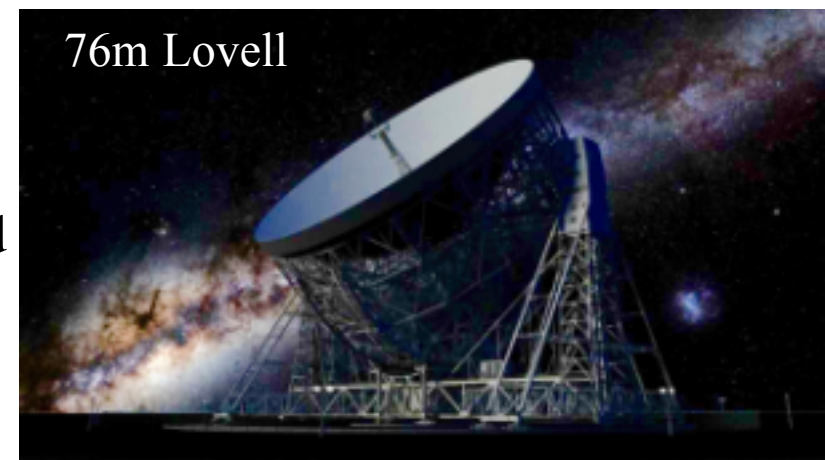
X-ray AGNs

- X-ray for **63%** (52/82) (Xue+16)

  (20 AGNs, 9 pas, 15 SF/hyb)

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

→ 29 sources $\Big[$ 20/35 in QM AGNs
3/15 in RM AGNs
6/27 in SF/hyb
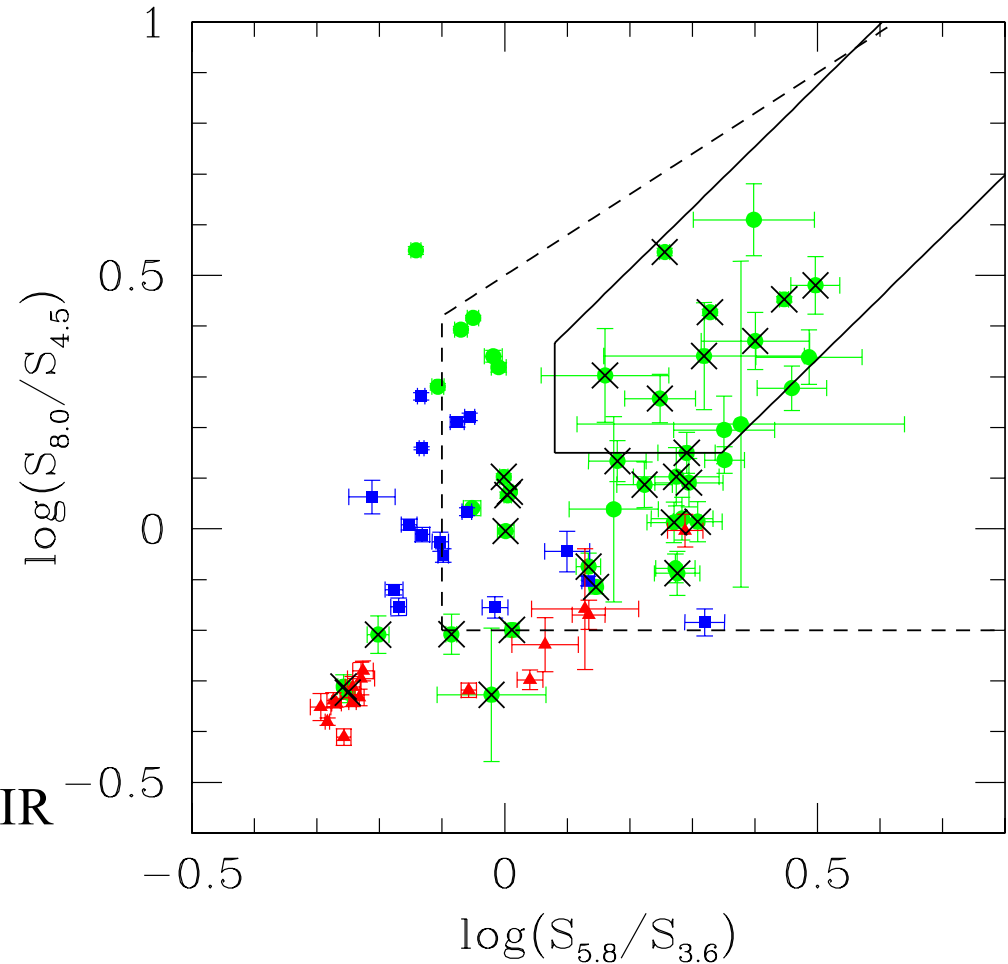
- 22% of SF/hyb contains an AGN not seen in IR

- AGN brightest X-ray sources
  $L_{x_{med}} \sim 5 \times 10^{43}$ erg/s
  $L_{x_{med}} \sim 1.7 \times 10^{41}$ erg/s
  for pas & SF/hyb

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

Radio active AGNs

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

- 100μm for 63% (52/82) (Magnelli+13,+15)
- $S_{100\mu m}$=1mJy (3 sigma) for upper limits
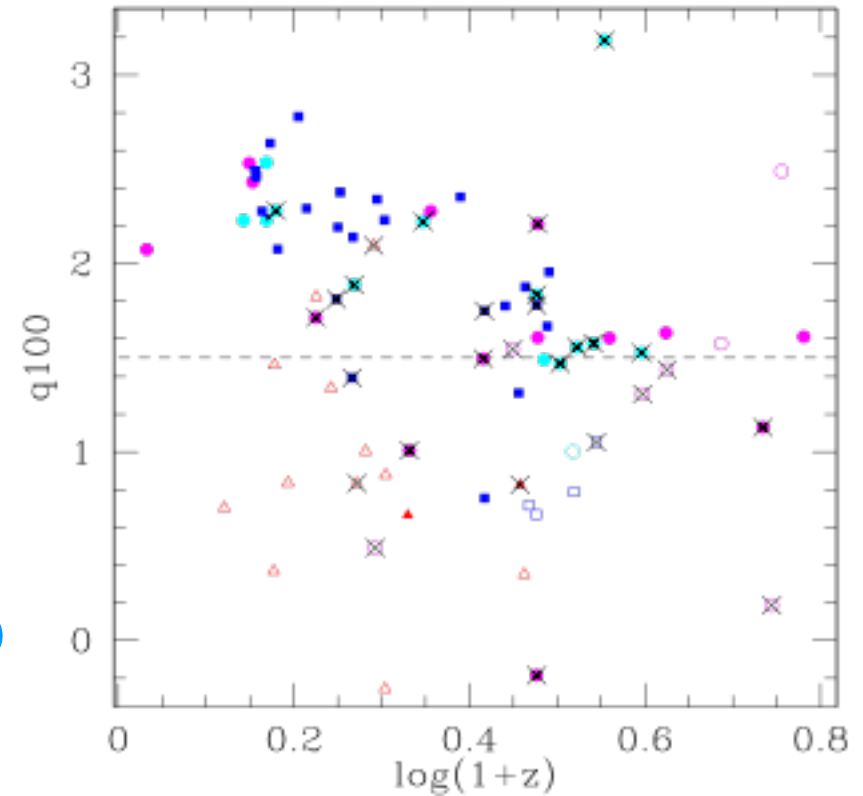- 1.4 GHz VLA for (82/82) (Morrison+10)

Radio excess if:

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

➡ 31 radio excess sources:

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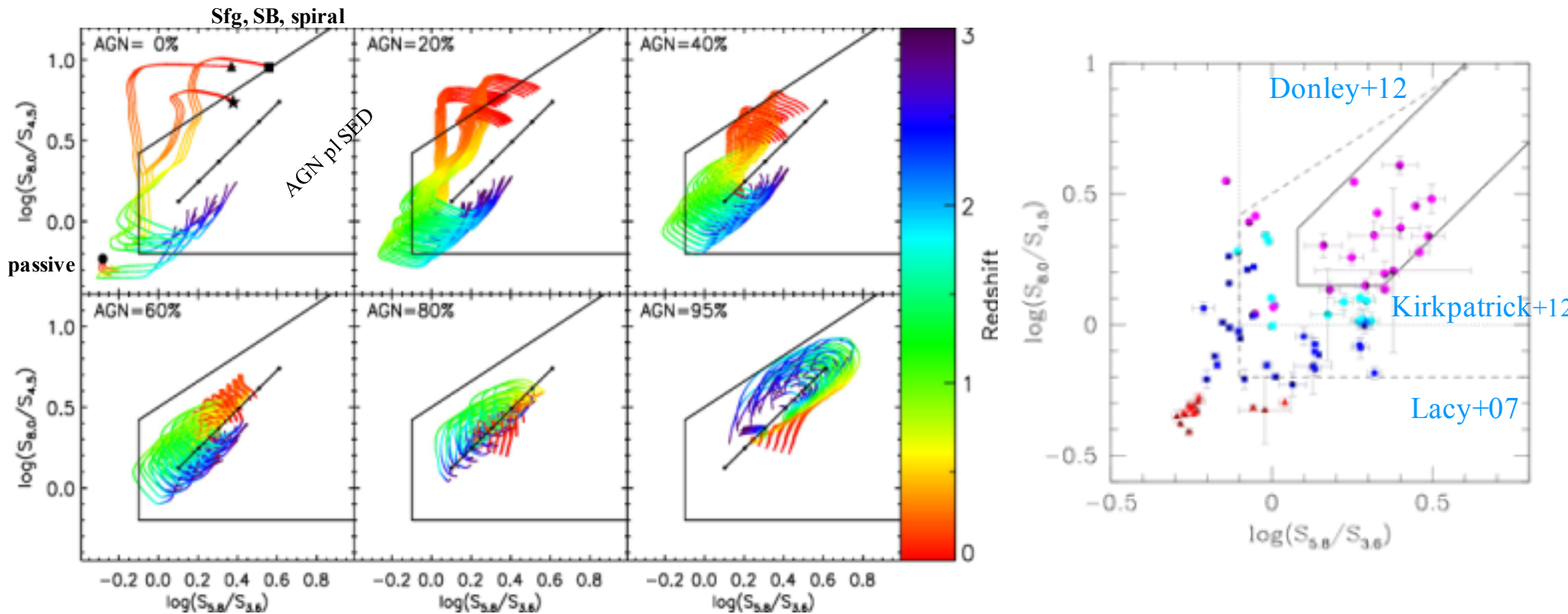- 6 /27 AGN in SF/hyb
  ➡ AGNs which only appear in radio

1.4 GHz VLBI (Chi+13, Radclife+15)
  ➡ 13 sources (all radio excess)

IR classification of the 5.5 GHz sources

- 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~2.2
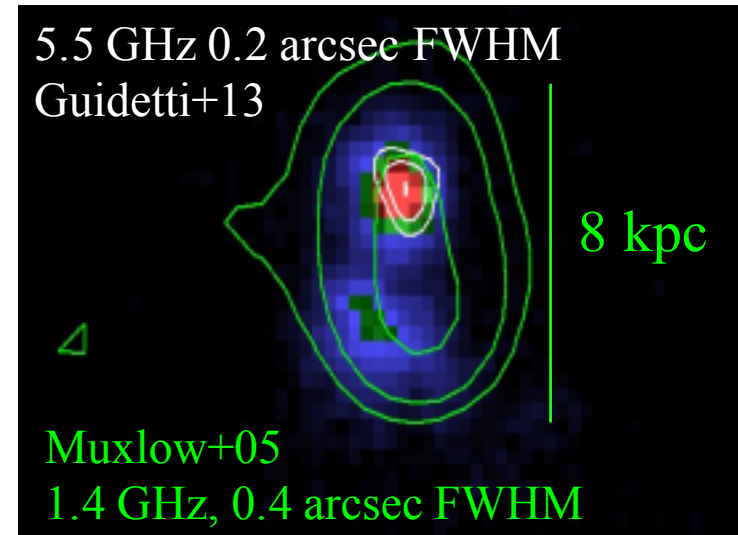(Casey+09)

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 1.3×10^{45} erg/s
- Optical compact core
- Radio excess source

5.5 GHz 0.2 arcsec FWHM
Guidetti+13

8 kpc

Muxlow+05
1.4 GHz, 0.4 arcsec FWHM

1.4 GHz MERLIN contours on HST
ACS i band image

- AGN flux density ~130 µJy assuming a radio core of 0.4 arcsec (MERLIN)
Radio emission: ~40% AGN + 60% SF → **SFR ~ 4000 M$_\odot$/year** (Casey+09)

We found that AGN accounts at least for 60% for the total radio flux
→ SFR < 2800 M$_\odot$/year from our eMERLIN flux density