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

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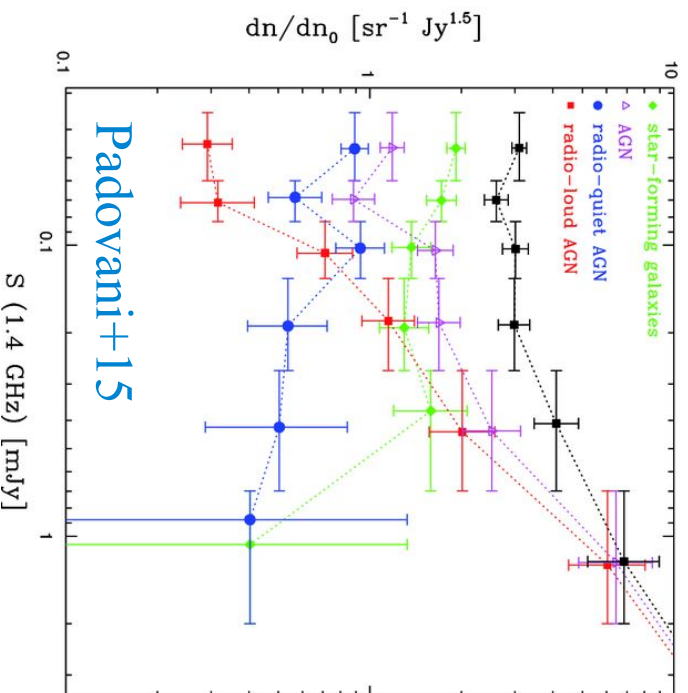
And the eMERGE collaboration



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

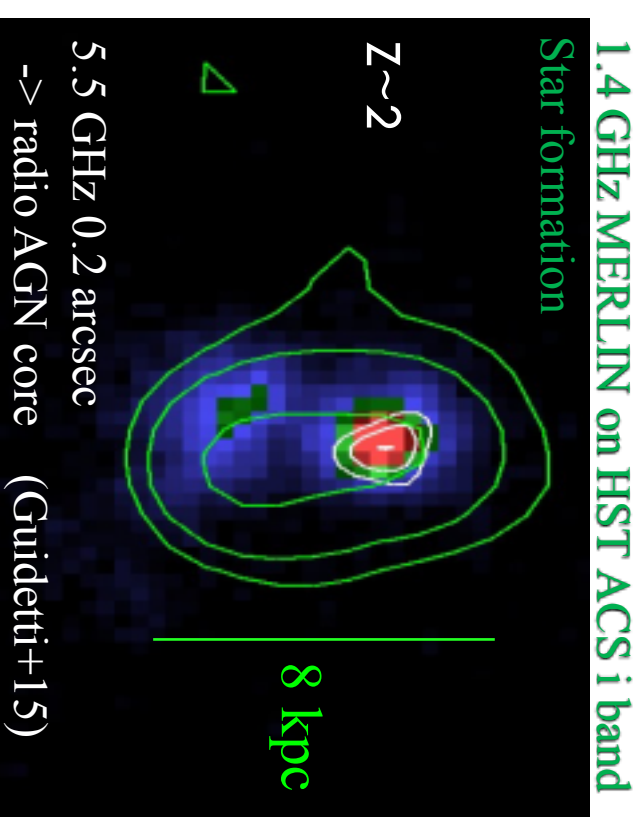
Radio surveys increasingly important → unbiased and resolved view of AGNs & SF



Composite sub-mJy radio source population

RQ AGNs start to appear at μJy 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 ($\text{sub-kpc} \rightarrow \text{kpc}$) allow us to study the overall AGN population and distinguish extended kpc scale SF emission from more compact AGN components ($< 1 \text{ kpc}$)



The eMERGE survey *eMERLIN Galaxy Evolution survey*

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

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

Goal

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

How

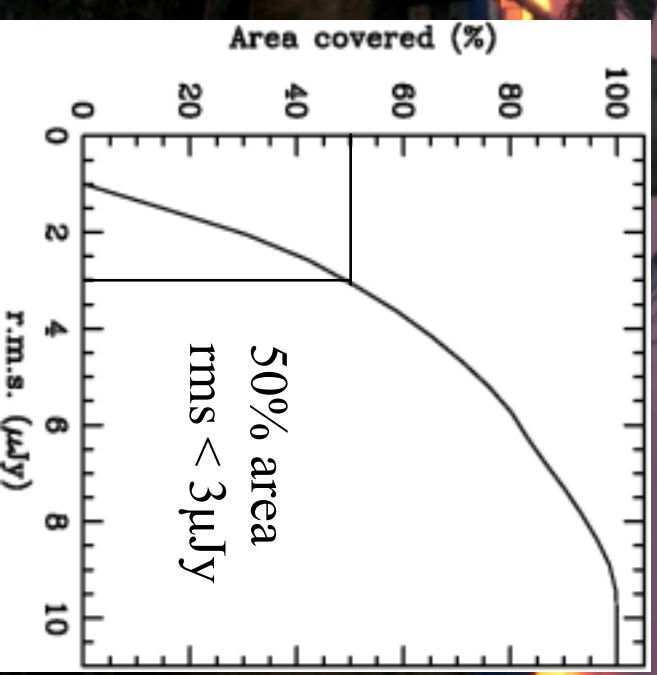
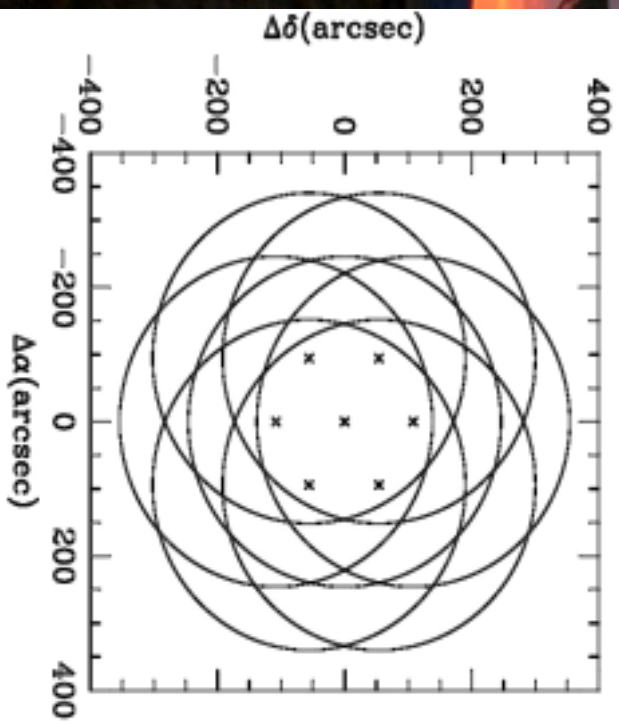
- 400 hrs eMERLIN+ JVLA @ 1.4 GHz
- 378 hrs eMERLIN + JVLA @ 5 GHz (PI Prandoni)
- resolution 50-2000 mas (0.5-tens of kpc at $z > 1$) with 0.5-1 μ Jy/b rms
- ancillary coverage of GOODS-N from radio to X-ray

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)

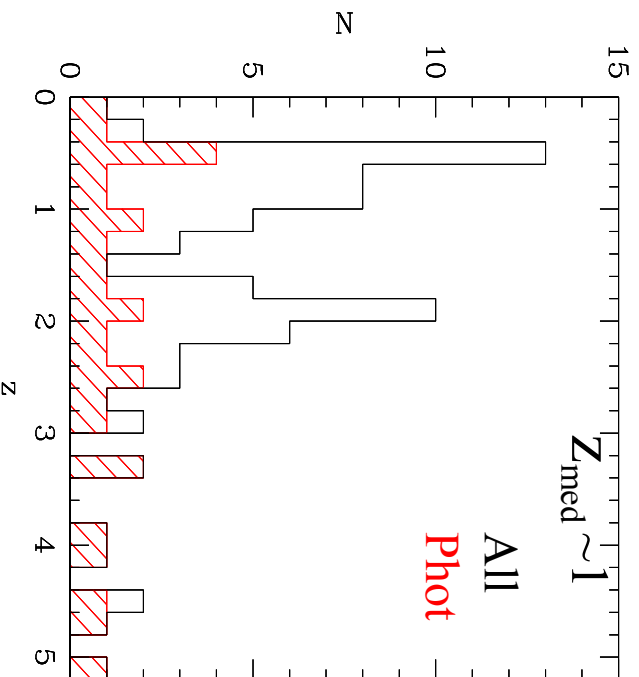
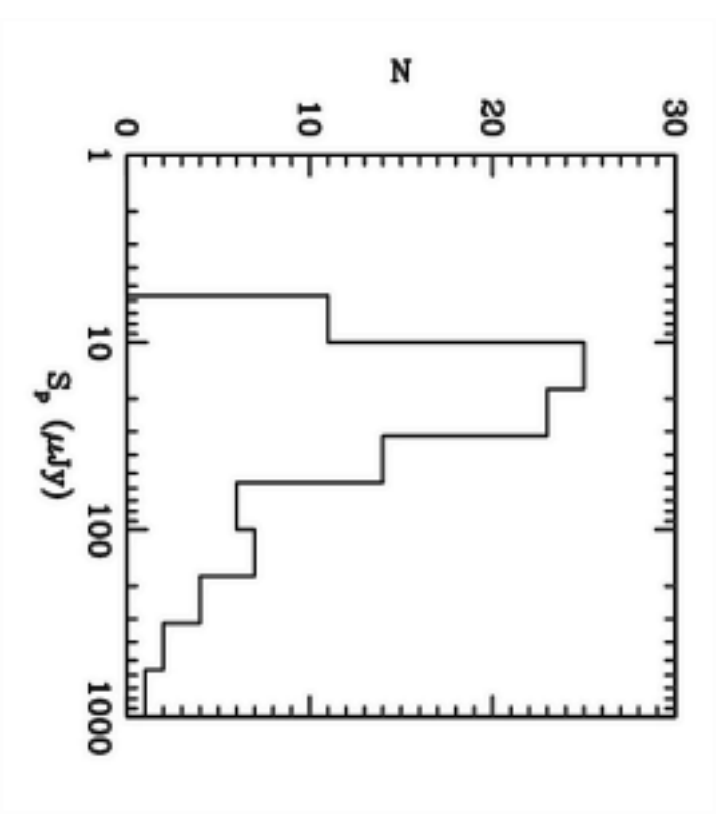
5.5 GHz JVLA MOSAIC

- 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)

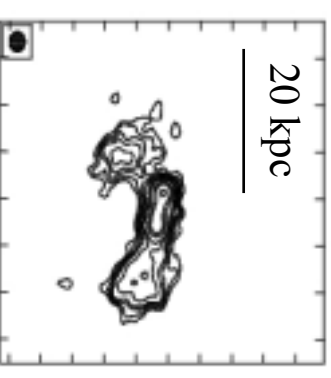
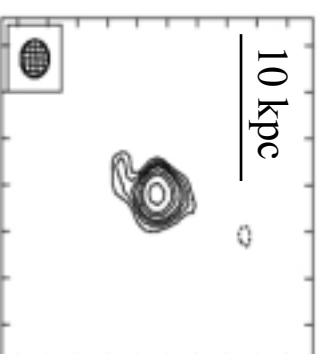
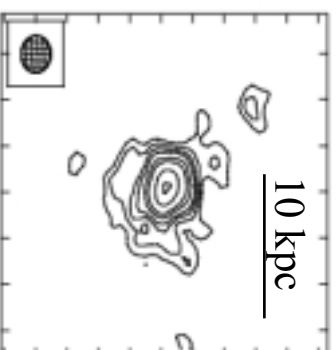


5.5 GHz catalogue

- 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, 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)



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



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)



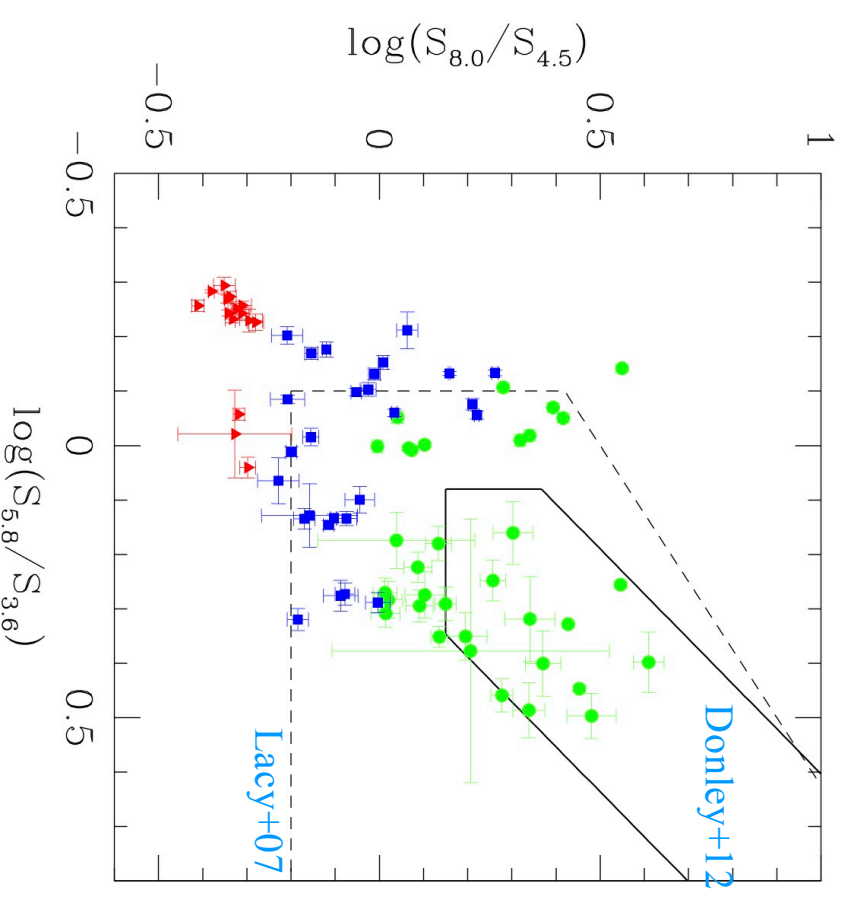
Samples of quasar/radio mode AGNs
and star forming galaxies

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, 24 μ m, 100 μ m, 250 μ 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 μ 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)

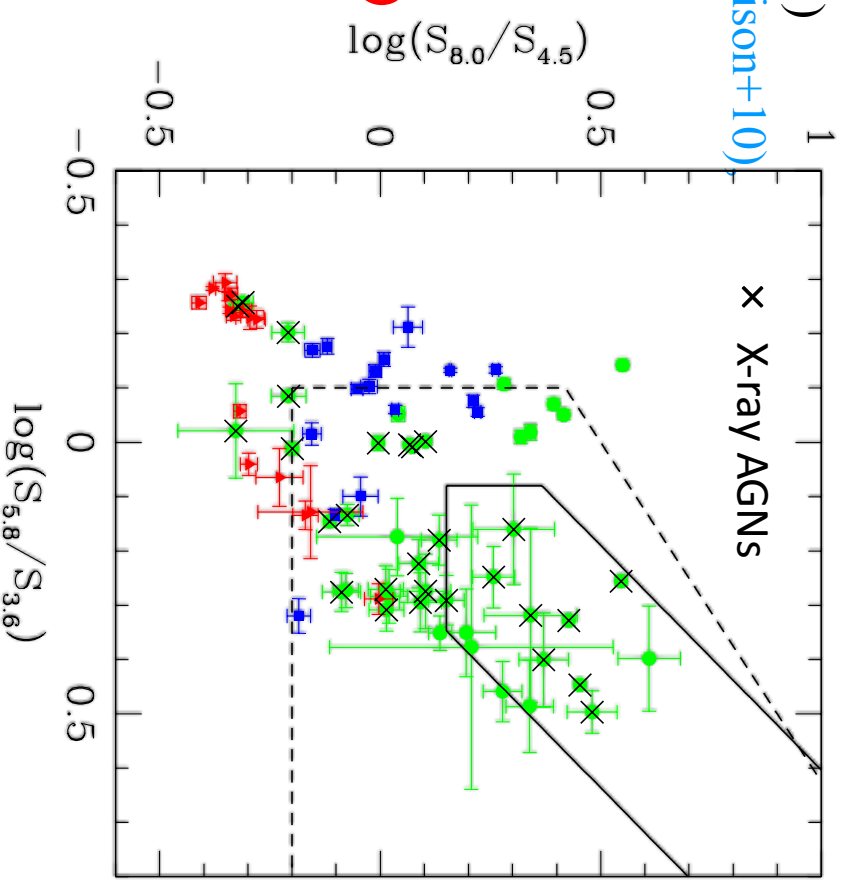
radio excess sources if:

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

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

→ 31 radio excess ($\sim 10\%$ not IR RM AGN)

1.6 GHz VLBI → 18 sources ($\sim 10\%$ not IR RM AGNs)



35 QM AGNs

15 RM AGNs

27 SF/hyb



44 QM AGNs

15 RM AGNs

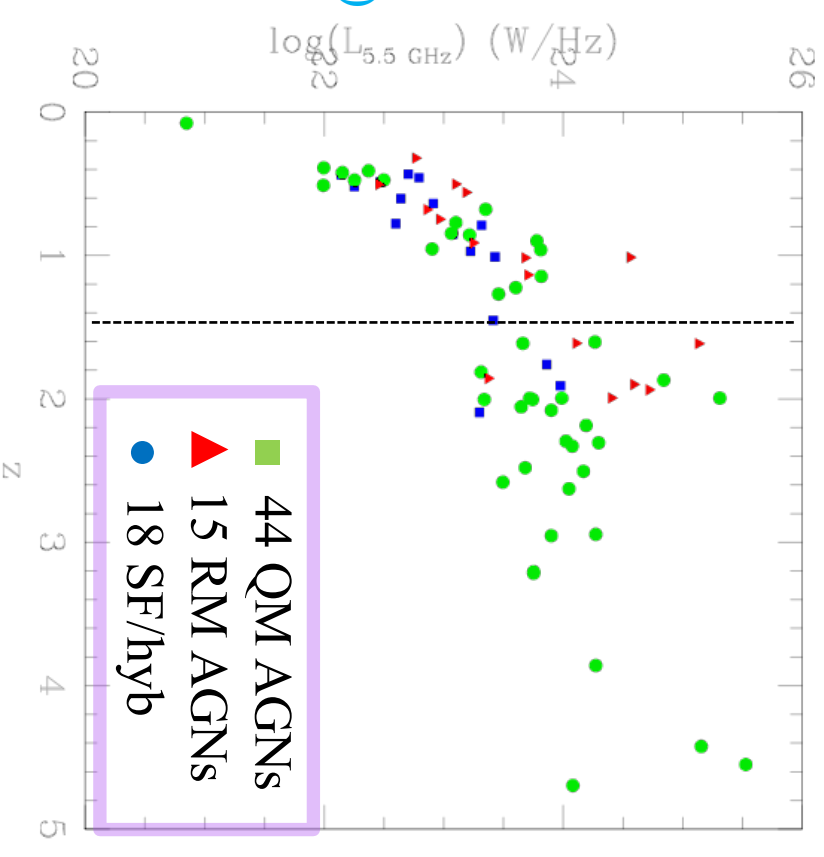
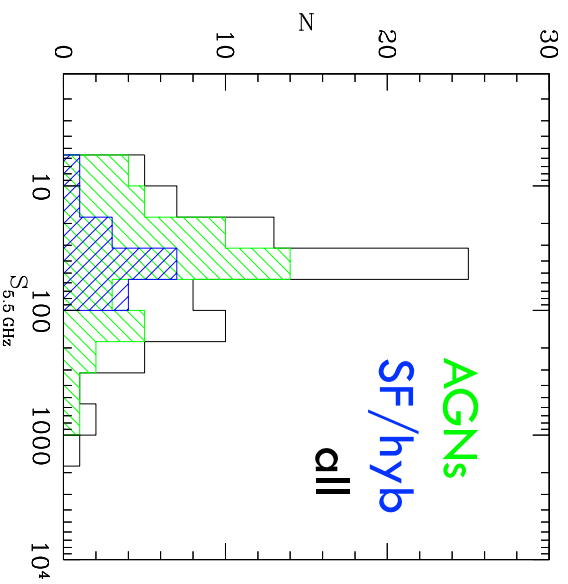
18 SF/hyb

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 μJy (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](#))

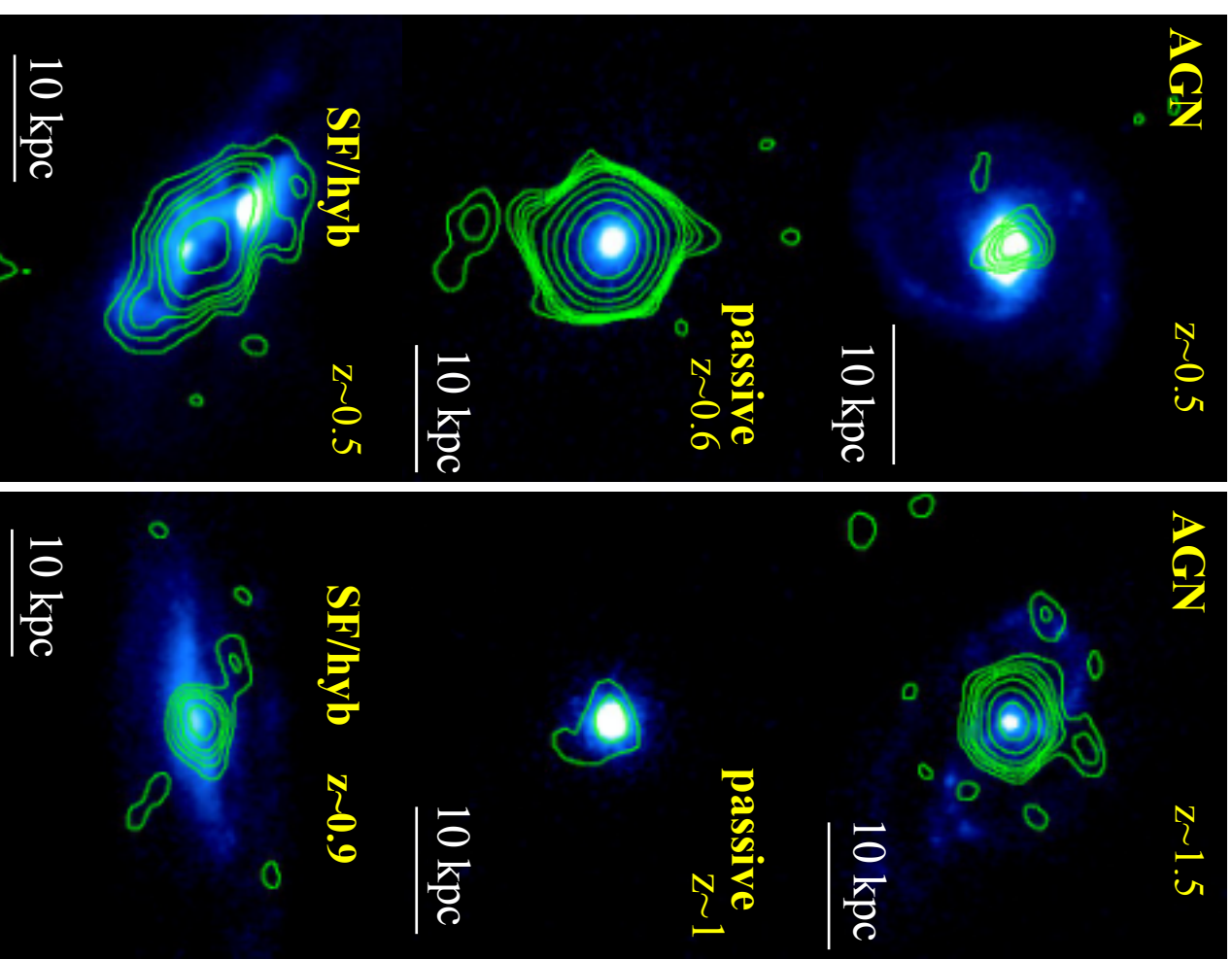
Spectral analysis limited to compact sources:

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	~ 0.40
●	16 SF/hyb systems	~ 0.72

5.5 GHz contours/ HST I band image



1.4 GHz selected sample

from VLA catalogue (1.7" FWHM Morrison+10)

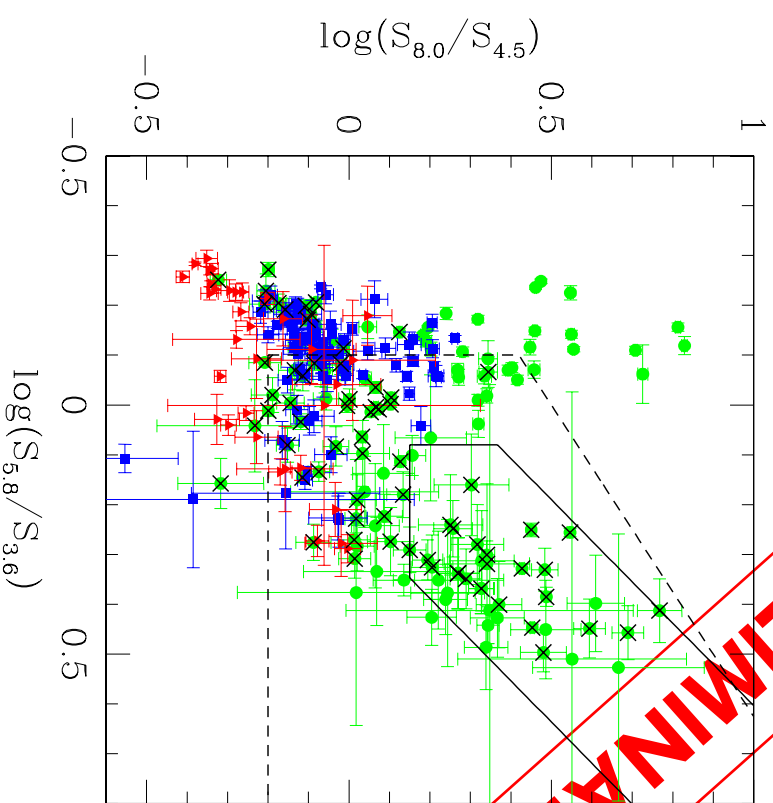
300 1.4 GHz sources selected in the same area of our 5.5GHz mosaic (99% $20\mu\text{Jy} > S_{1.4\text{GHz}} > 1\text{mJy}$)

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 $\rightarrow \sim 20\%$



PRELIMINARY

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 JVA 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 μ 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 μ Jy & sub-Jy sky with ~ 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 keV] > 10⁴² erg/s
- L_x[0.2-7 keV] > 3 × 10⁴² erg/s (for upp limits)

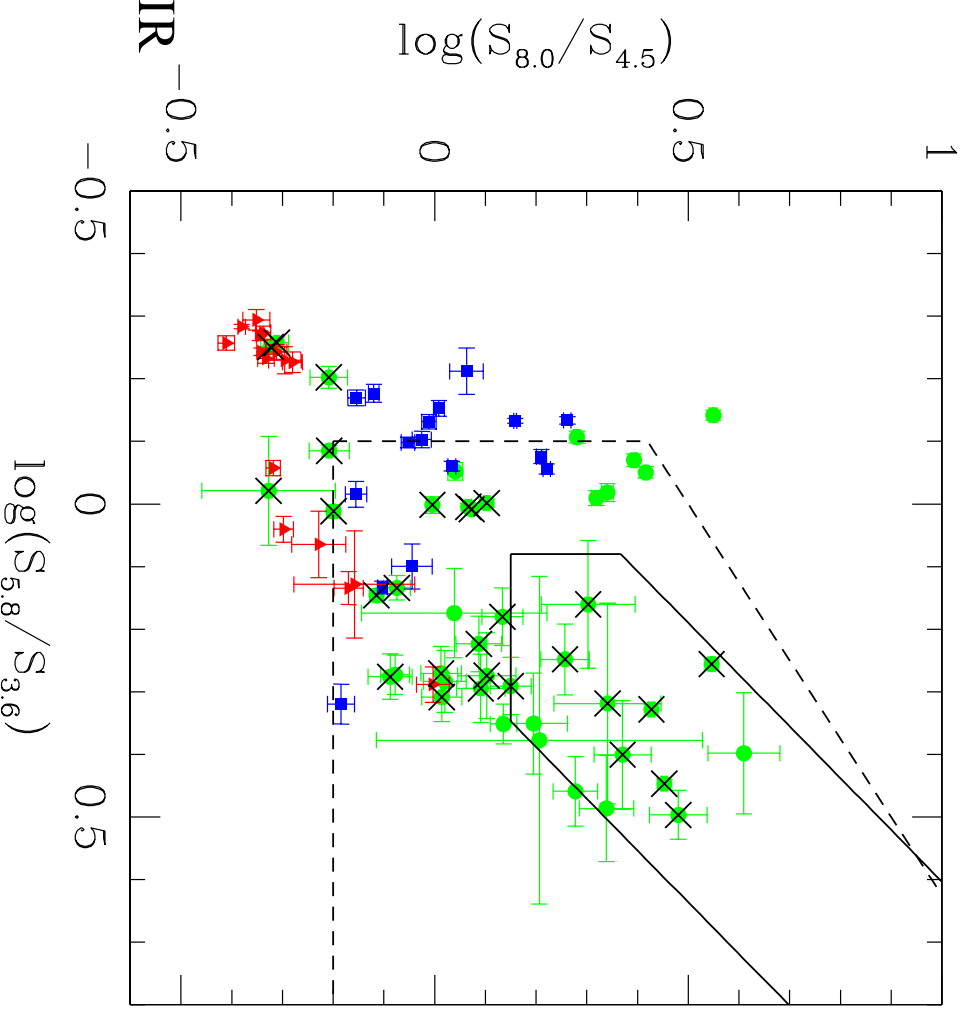
→ 29 sources

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,med} ∼ 5 × 10⁴³ erg/s
L_{X,med} ∼ 1.7 × 10⁴¹ 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 μ m for 63% (52/82) (Magnelli+13,+15)
- $S_{100\mu\text{m}}=1\text{mJy}$ (3 sigma) for upper limits
- 1.4 GHz VLA for (82/82) (Morrison+10)

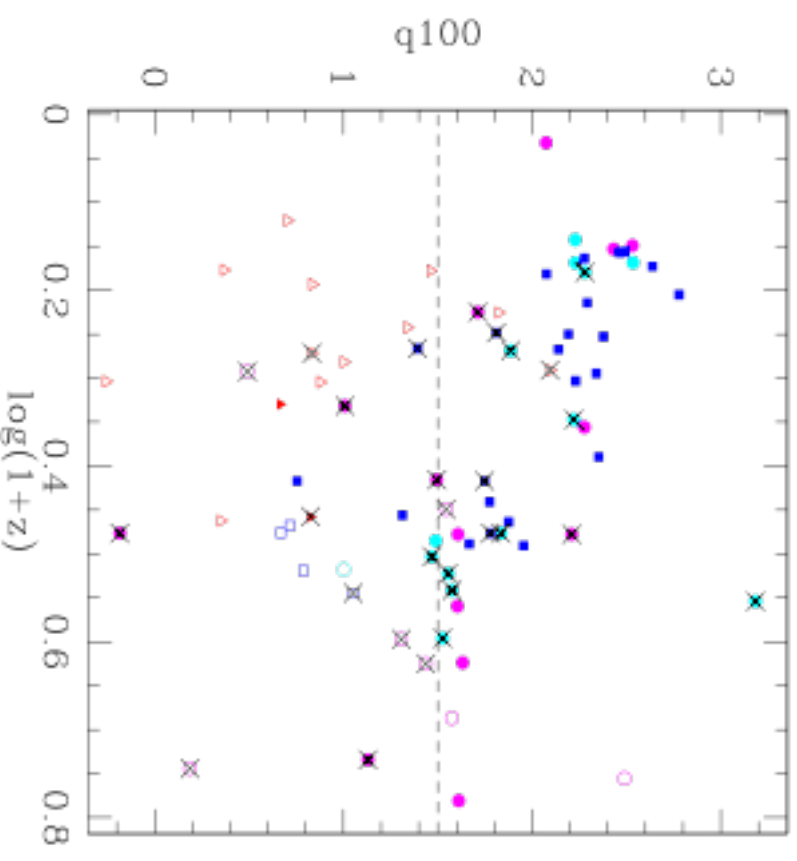
Radio excess if:

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

→ 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

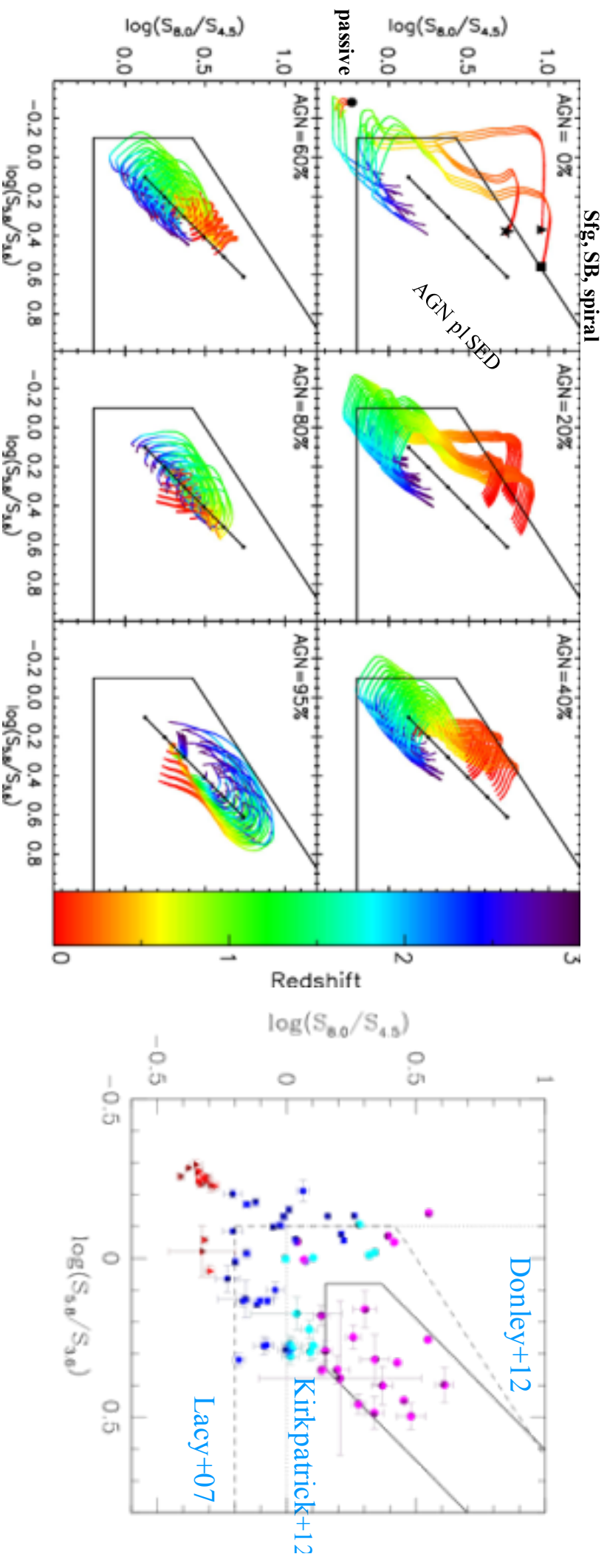


1.4 GHz VLBI (Chi+13, Radcliffe+15)

→ 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)

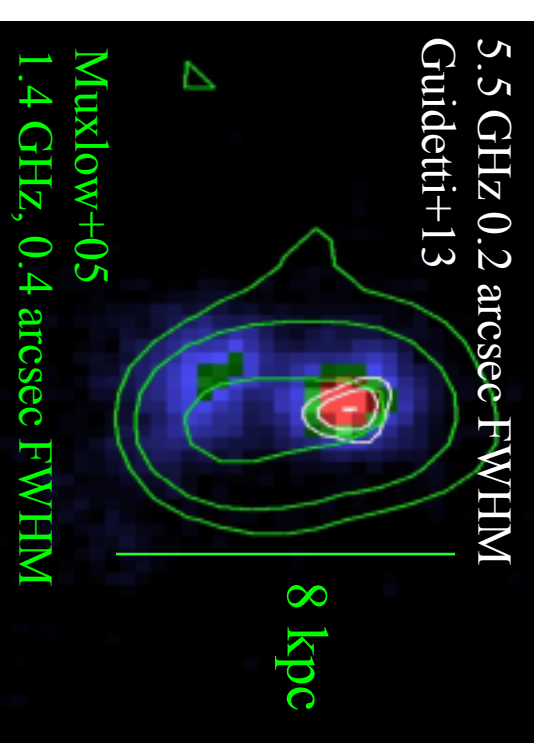
SF galaxy

- 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 1.3×10^{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