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

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On behalf of:

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I. McHardy, R. Ivison
and the eMERGE collaboration**



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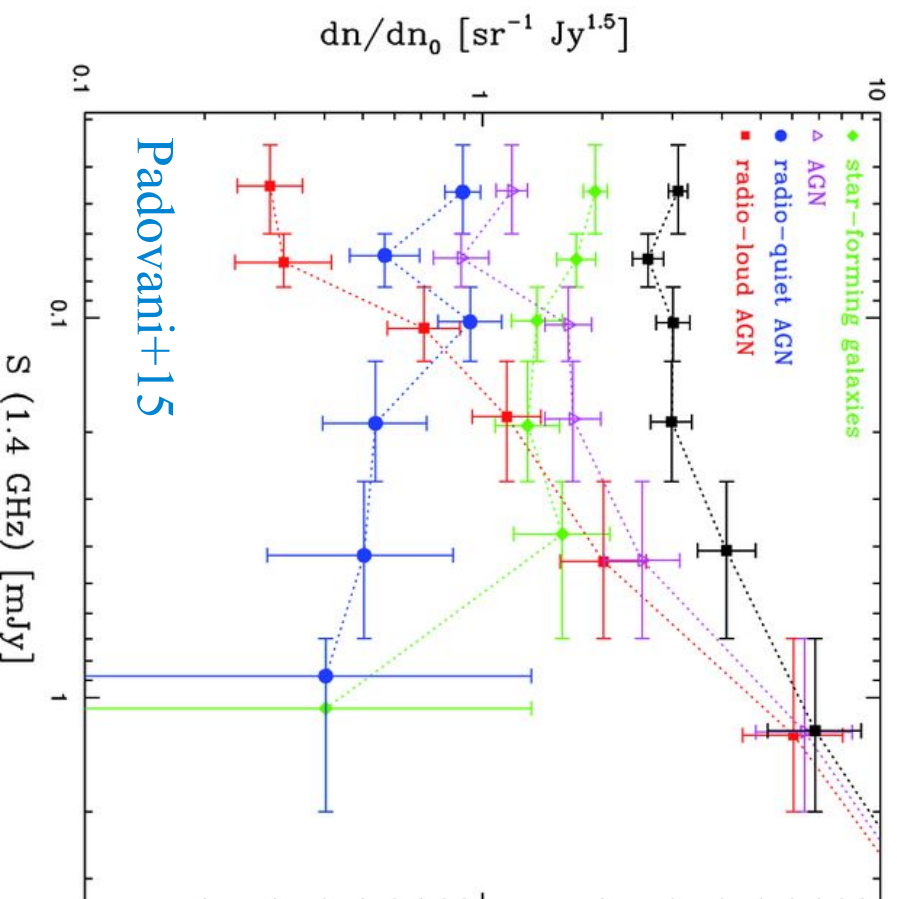
AGN 12, Napoli, 26-29 September, 2016

Faint radio source population

- Multi- λ studies of deep radio fields show a composite faint radio source population
→ star forming galaxies, AGNs (radio loud & radio quiet)

- For $S_{1.4\text{ GHz}} < 100\text{ }\mu\text{Jy}$ → star forming galaxies begin to dominate (e.g. Muxlow+05, Seymour+08, Mainieri+08, Smolčić+09, Padovani+09,+11,+15 Bonzini+13...)

- many RQ AGNs at μJy flux density levels



- Ultra-deep high resolution radio imaging (extinction free) important for a complete census of all AGNs

- Ancillary data are crucial for classifying radio source as AGN/star forming galaxies

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

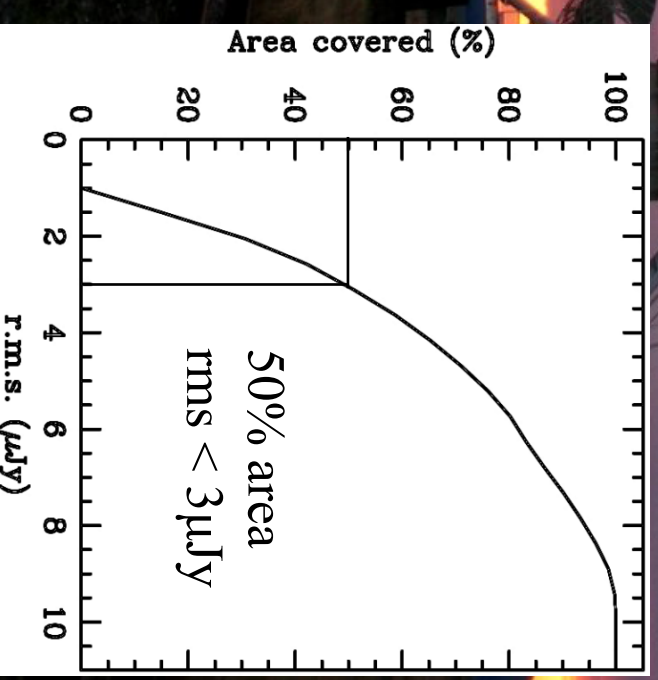
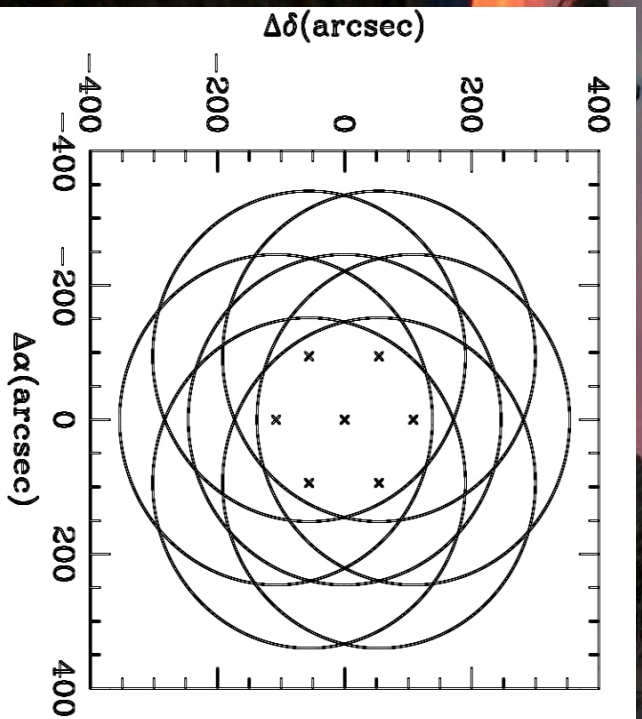
- 400 hrs eMERLIN+ JVLA @ 1.4 GHz
- 378 hrs eMERLIN+JVLA @ 5 GHz (PI Prandoni)
- resolution 50-2000 mas (0.5-tens of kpc at $z > 1$) with 0.5-1 μ Jy/b rms
- ancillary coverage of GOODS-N from radio to X-ray

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 (Q1 2017)

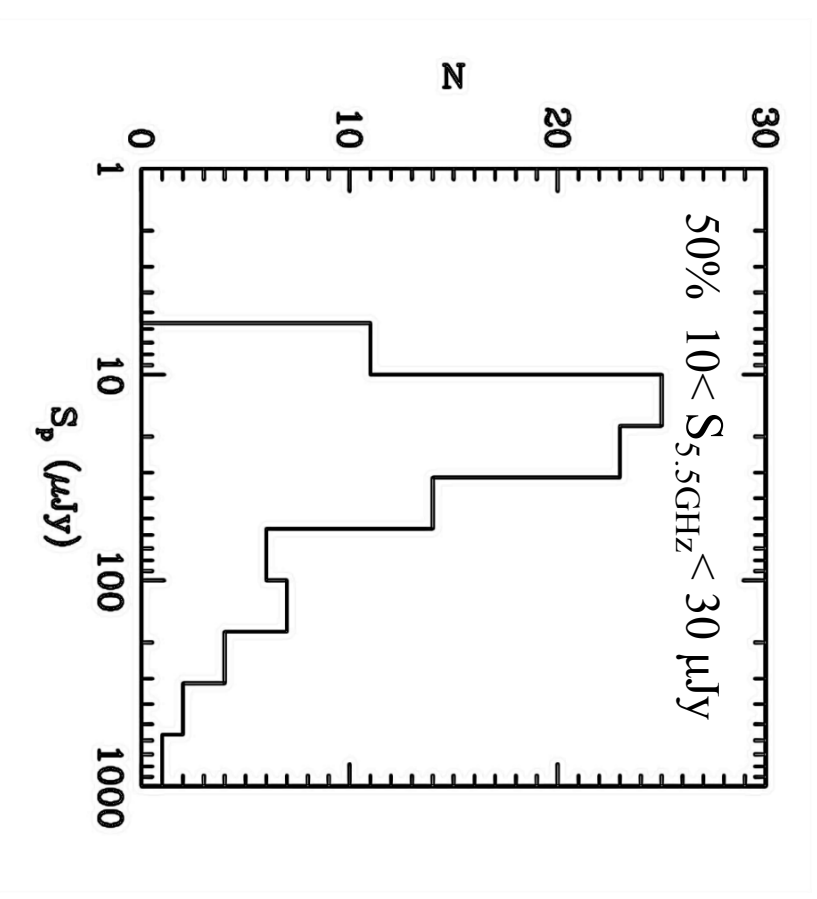
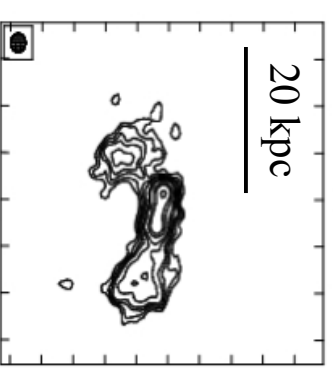
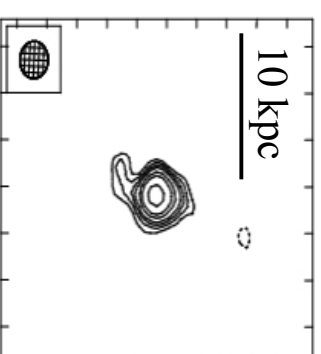
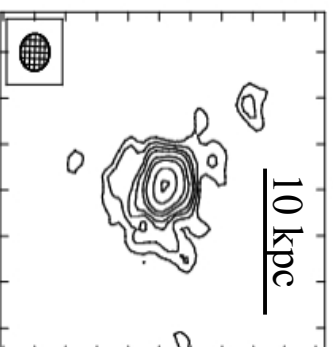
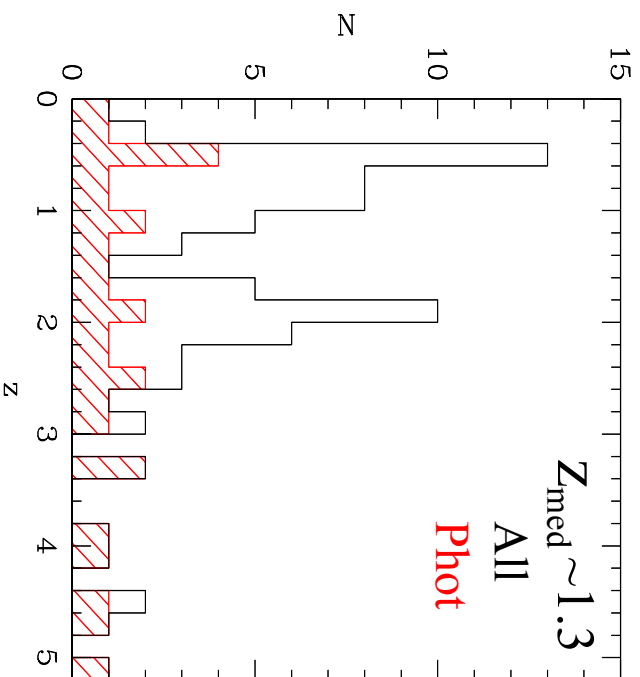
GOODS-N 5.5 GHz JVLA MOSAIC

- 7-pointing mosaic in GOODS-N (matching the 5 GHz e-MERLIN FoV)
→ 15 arcmin diameter field
- 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)



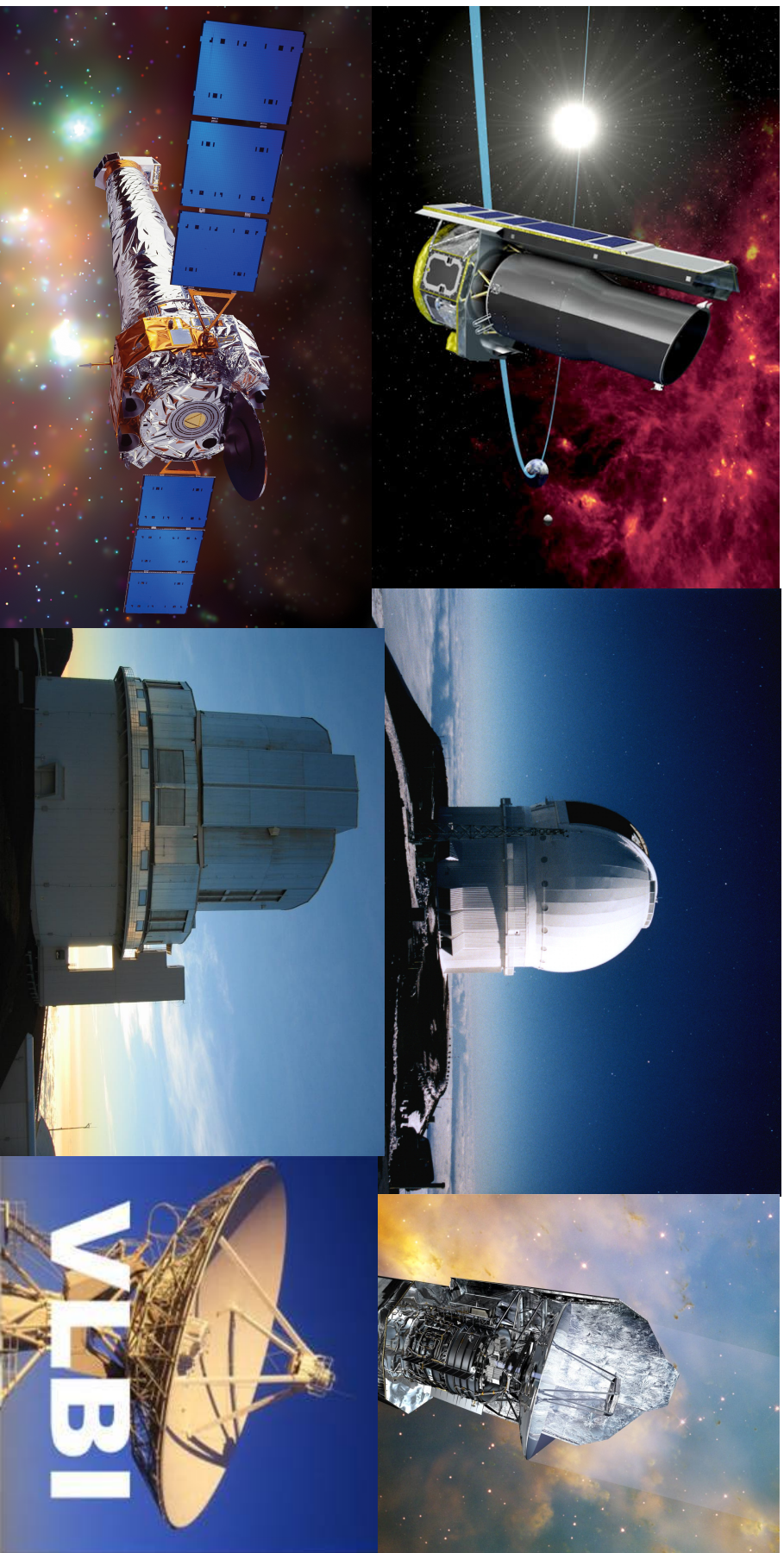
5.5 GHz catalogue

- 94 sources ($S/N > 5$) at $d < 7$ arcmin
- $S_{5.5\text{GHz}} > 6 \mu\text{Jy}$
- 88% secure NIR counterparts within $< 0.5''$
(< 24.45 Ks, AB mag, Wang+10)
- 95% with redshifts (e.g. Momcheva+16, Skelton+14)
- median size ~ 0.4 arcsec (~ 3 kpc at $z = 1.3$)



First contour @ 3σ

Ancillary GOODS-N data



Radio: 1.4 GHz VLA (Morrison+10), 1.6 GHz VLBI (Chi+13, Radcliffe+15)

Far-IR: Herschel PACS & SPIRE (Elbaz+11, Magnelli+13)

Mid-IR: Spitzer IRAC & MIPS (Wang+10, Magnelli+11,+13)

NIR: CFHT/ Subaru (Wang+10, Kajisawa+11)

X-ray: Chandra (Xue+16)

Multi- λ classification of 5.5 GHz sources

Look for nuclear activity in the 5.5 GHz sources, by applying multi- λ AGN selection criteria: **4 IR colour colour plots, X-ray luminosity, radio excess**

→ classification as RE AGNs, RI AGNs, star forming galaxies

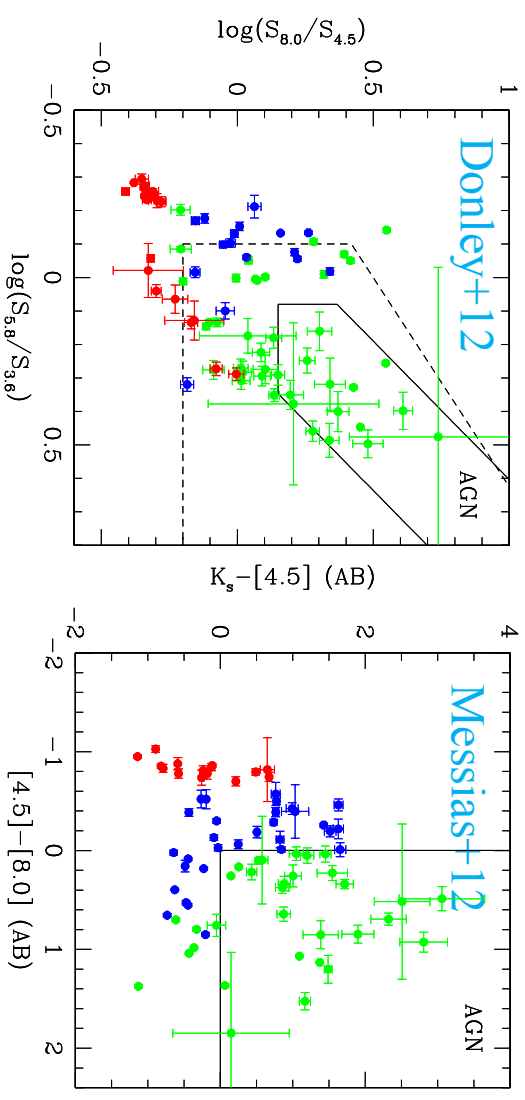
Multi- λ classification of 5.5 GHz sources

RE AGNs $\rightarrow$ #44 ●

at least by 1 of the IR cc plots

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

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

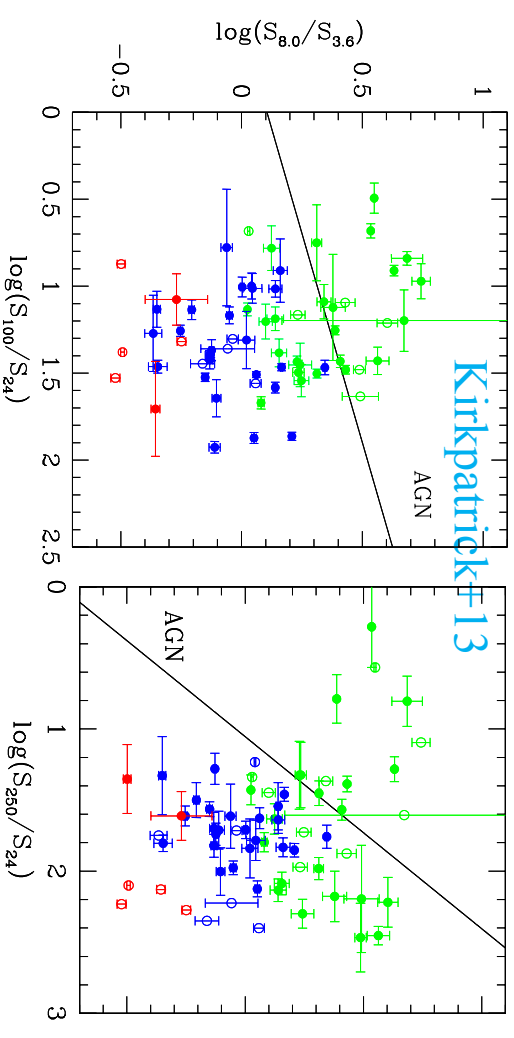


RI AGNs $\rightarrow$ #16 ●

MIR colours of red passive galaxies

Radio excess

q₁₀₀ ($\log [S_{100\mu\text{m}}/S_{1.4\text{GHz}}] < 1.5$ (Del Moro+13)
 $S_{100\mu\text{m}} = 1 \text{ mJy}$ (3 sigma) for upper limits



SFgs $\rightarrow$ #17 ●

Sources not selected as AGN by any criteria

44 RE AGNs
16 RI AGNs
17 SFgs

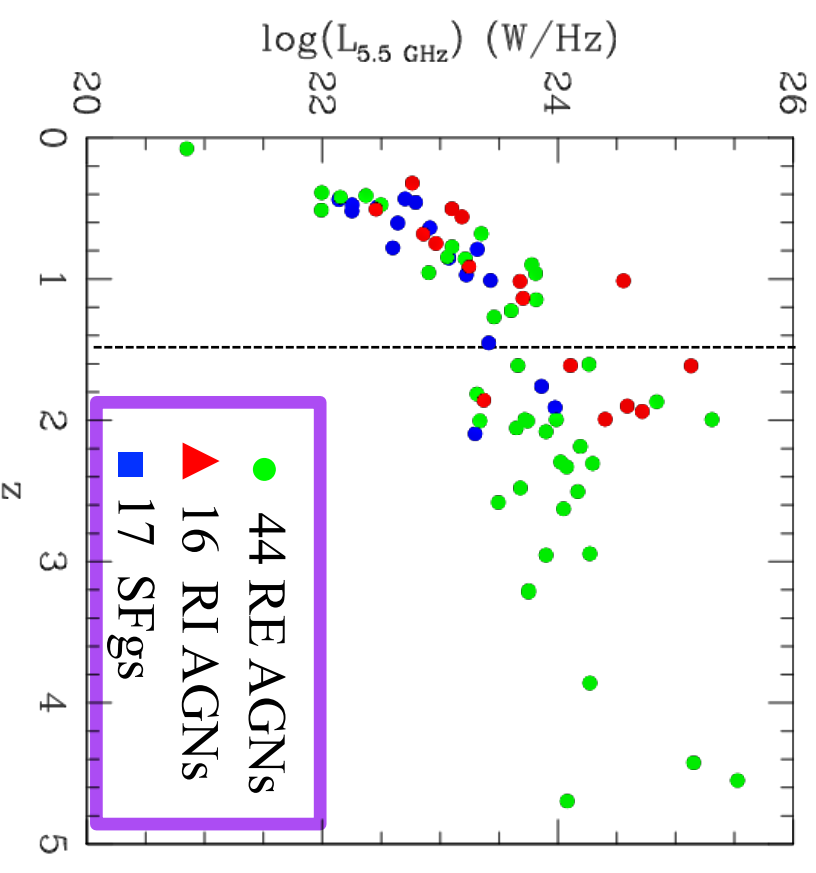
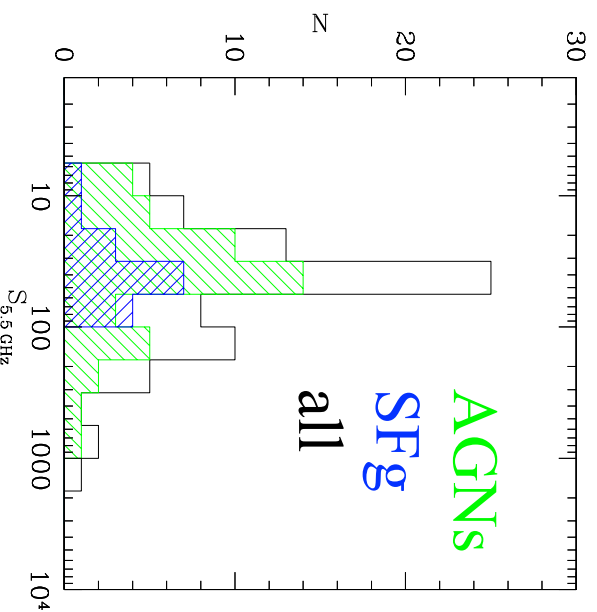
AGN content in the 5.5 GOODS-N catalogue

78% of the classified μ Jy radio sources are radio AGNs! **90% at $z > 1.5$!!**

Reliability: How many AGNs are real?

- 9 RE AGNs on the basis of the LX only
- LIR from IR SED fitting ([Guidetti+, paper II in prep](#)) + LX-LIR for SFgs by [Symeonidis+14](#)
- SF accounts just for a few % of the X-ray emission in RE-AGNs

→ no significant contamination from SFgs in the AGN fraction

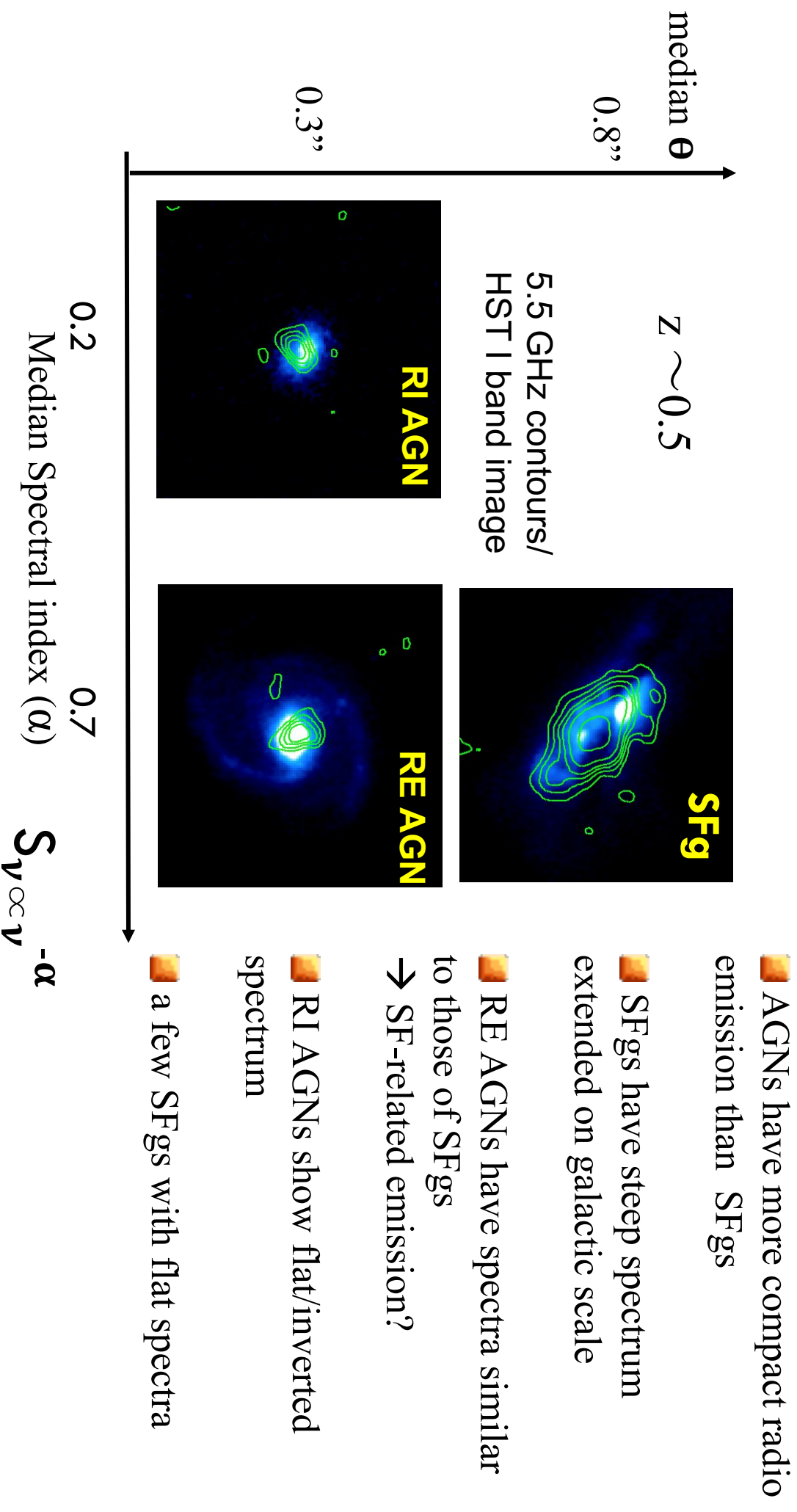


■ AGNs at all flux densities, redshifts, and 5.5 GHz luminosities

■ 3 SFgs at $z > 1.5$ are identified as sub-mm galaxies by [Barger+12](#)

Radio properties: angular size and spectral index

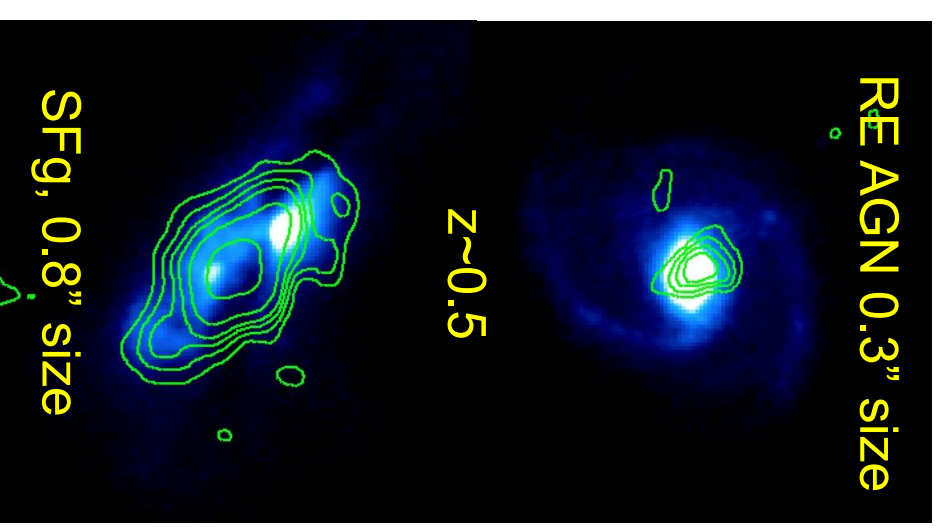
- 5.5 GHz angular size for $z < 1.5$ sources
- 1.4-5.5 GHz spectral analysis (1.4 GHz from VLA data, [Morrison et al. 2010](#)) limited to sources with size < 1 arcsec (#61)



Selection effects?

Very large presence of AGNs in our GOODS-N catalogue of the μ Jy radio source population

- ❑ $<->$ 1.4 GHz selected samples by e.g. Seymour +08 Padovani+11, 13, +15 etc, with similar multi- λ analysis
- ❑ Selection effects due to our sub-arcsec resolution & high frequency observations?
→ Are we favouring compact AGN sources and missing diffuse and extended arcsec scale emission of SFgs?
- ❑ Analysis of radio selected samples with multiple frequency & resolution but comparable depth in GOODS-N ([Guidetti+, paper II in prep](#))



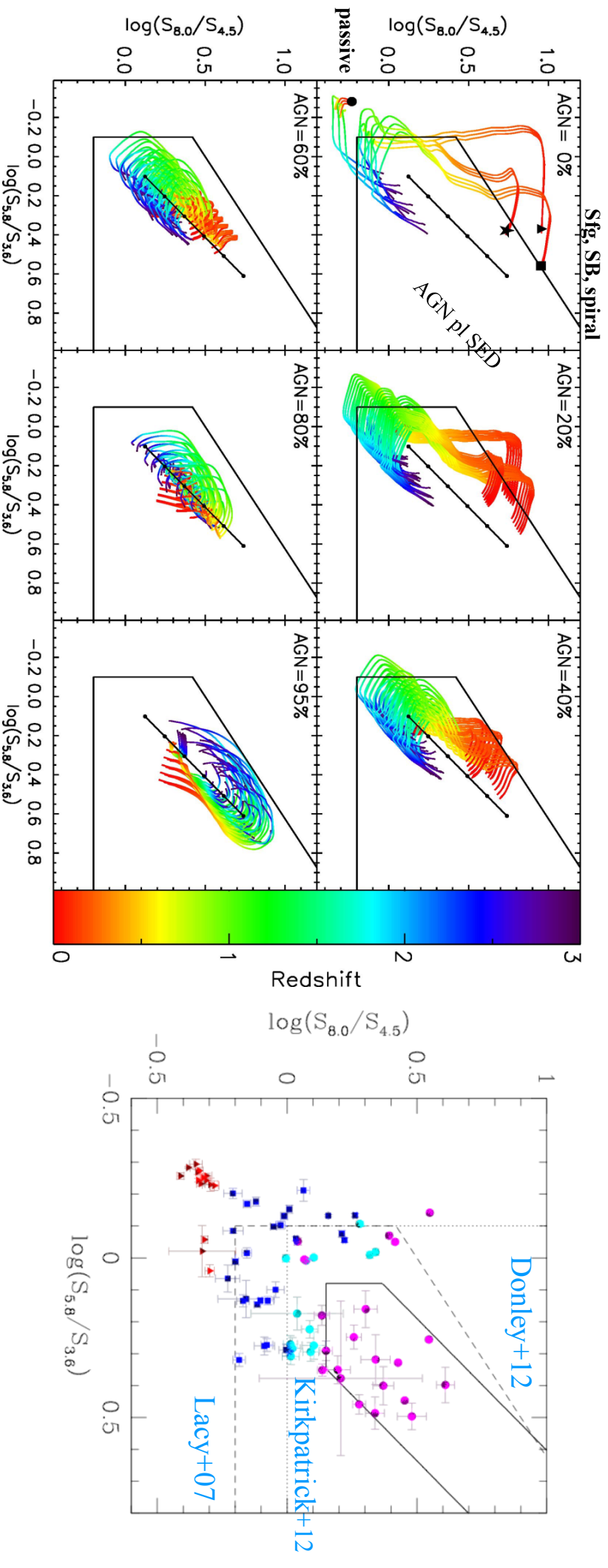
5.5 GHz contours/
HST I band image

Summary

- Ultra-deep GOODS-N catalogue at 5.5 GHz with sub-arcsec resolution
- Multi-band AGN diagnostic to quantify the AGN content
- AGNs dominate the radio source catalogue (80%) at all flux densities and redshifts
- RE & RI AGNs have more compact radio emission than SFgs
- RE AGNs and SFgs have similar steep radio spectra, RI AGNs have flat/inverted spectra
- 30% RE AGNs with radio excess, 15% VLBI detected
- Comparative analysis of radio selected samples with multiple frequency & resolution but comparable depth is needed ([guidetti+](#), [paper II in prep](#))
- path for planned SKA & precursors surveys with comparable depth over much extended areas

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

1.4 GHz selected sample

from VLA catalogue (1.7" FWHM Morrison+10)

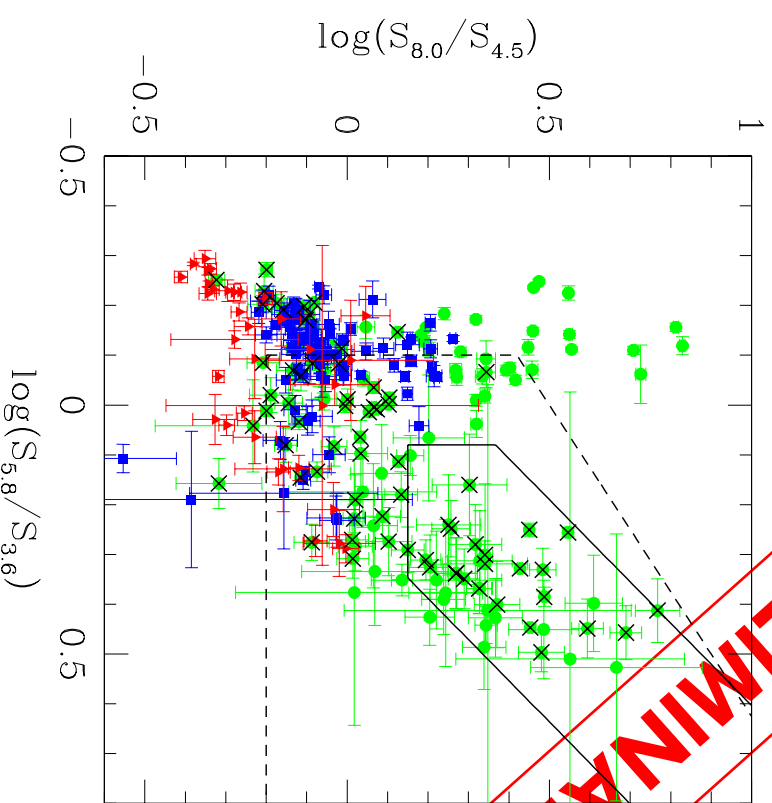
300 1.4 GHz sources selected in the same area of our 5.5GHz mosaic (99% $20\mu\text{Jy} > S_{1.4\text{GHz}} > 1\text{mJy}$)

1.4 GHz selected sources

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

5.5GHz selected sources

- 44 RE AGNs
- 15 RI 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

AGN content of the 5.5 GHz catalogue

- 4 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)

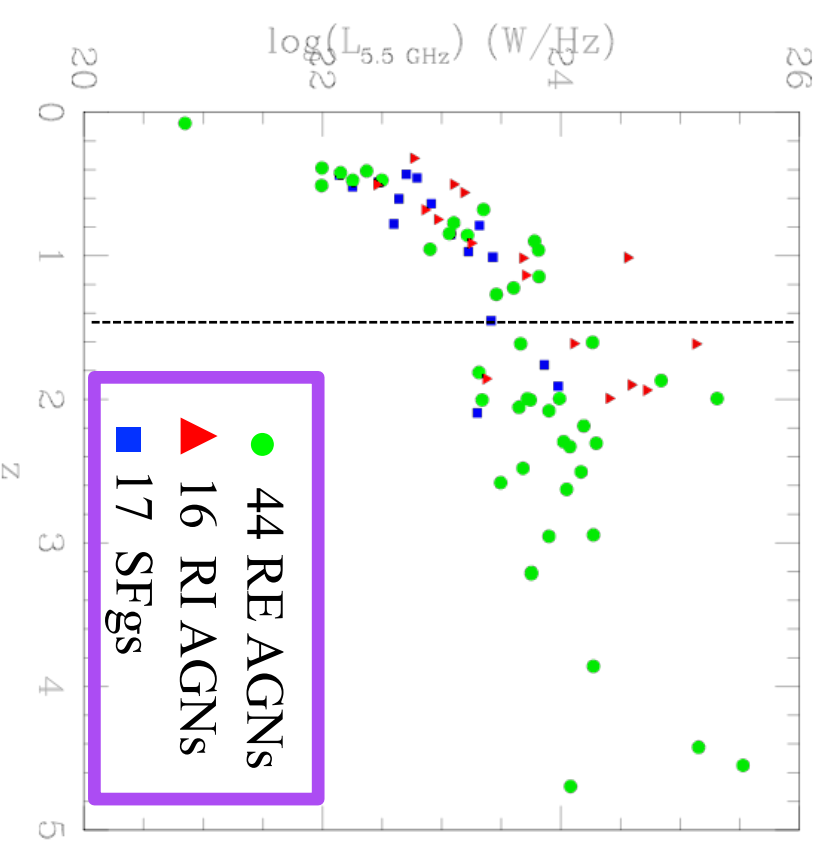
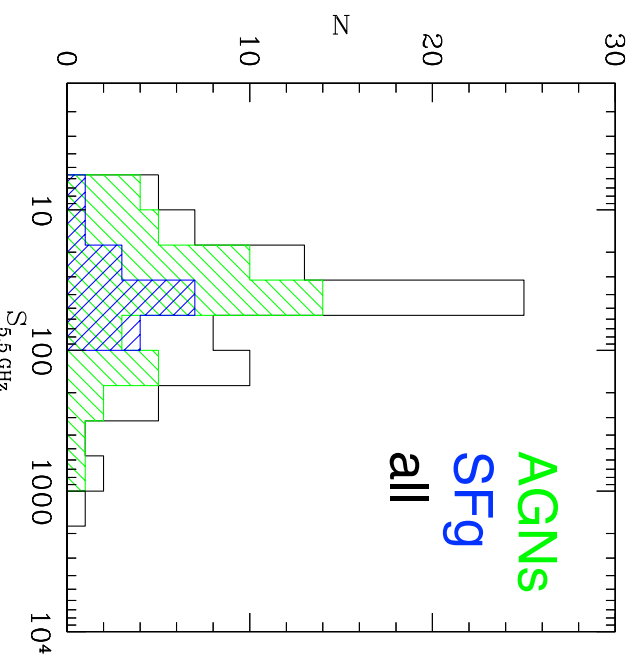


Samples of quasar/radio mode AGNs
and star forming galaxies

AGN content in the 5.5 GOODS-N catalogue

78% of the classified μ Jy radio sources are radio AGNs! **90% at $z > 1.5$!!**

no significant contamination from SFgs in the AGN fraction
 $\rightarrow$ just a few % of SF related X-ray emission, via X-ray/optical ratio & Lx-LIR for SFgs (Symeonidis+14)



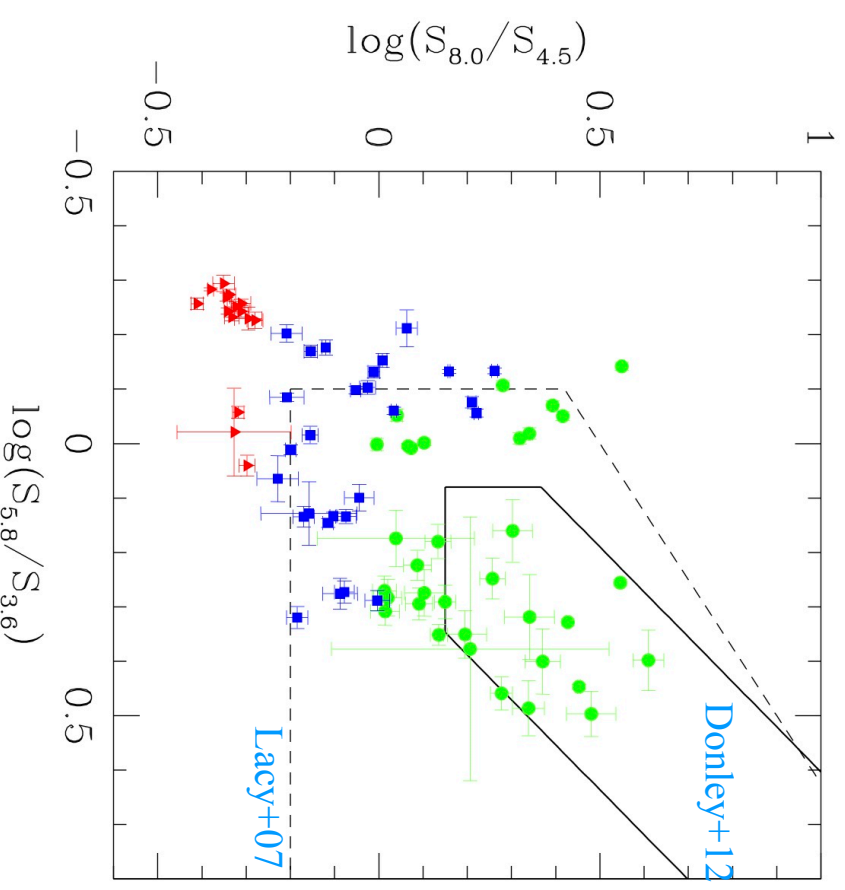
AGNs dominate at all flux densities, redshifts and L5.5GHz
 3 SFgs at $z > 1.5$ are sub-mm galaxies (Barger+12)

IR classification of the 5.5 GHz sources

- 93% (77/83) of the NIR-identified sources with 4-IRAC bands data (Wang+10)
- 78% (65/83) MIR, FIR Herschel+PEP data (Elbaz+11, Magnelli+13)

4 IR CC criteria

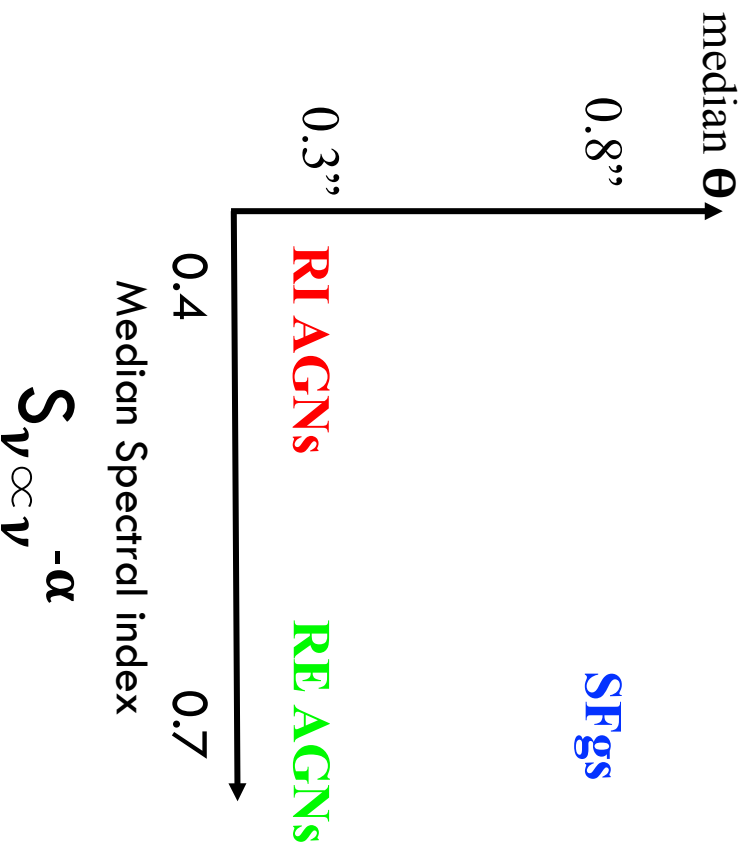
- Donley+12 (IRAC)
- Kirkpatrick+12 (IRAC, 24 μ m, 100 μ m, 250 μ m)
- Messias+12 (Ks-band, IRAC)
- 3 account for redshift evolution
- 94% (77/83) IR- classified sources



- 35 RE AGNs (45%)
- 15 passive -> RI AGNs (20%)
- 27 SF/hyb systems 35%

Radio properties: angular size and spectral index

- 5.5 GHz angular size for $z < 1.5$ sources
- 1.4-5.5 GHz spectral analysis (1.4 GHz from VLA data, [Morrison et al. 2010](#))
- Spectral analysis limited to sources with size < 1 arcsec (#61)
(~ 8 kpc @ $z=1$)

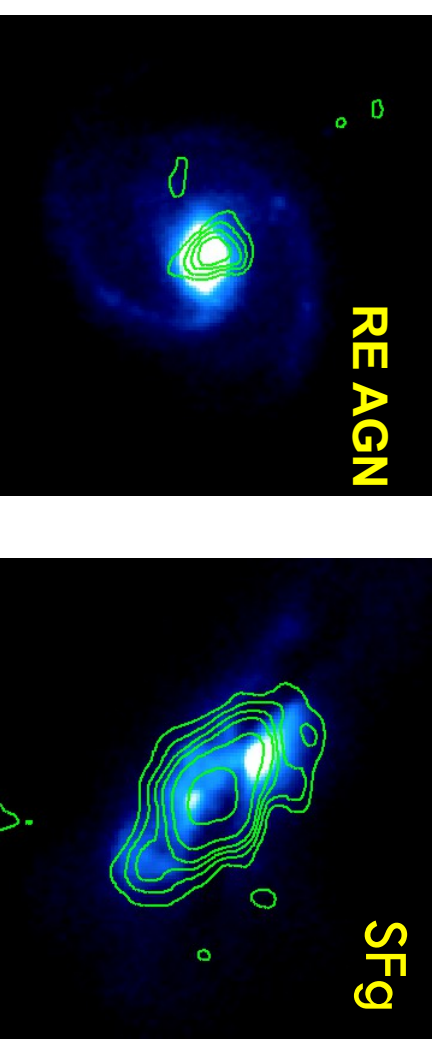
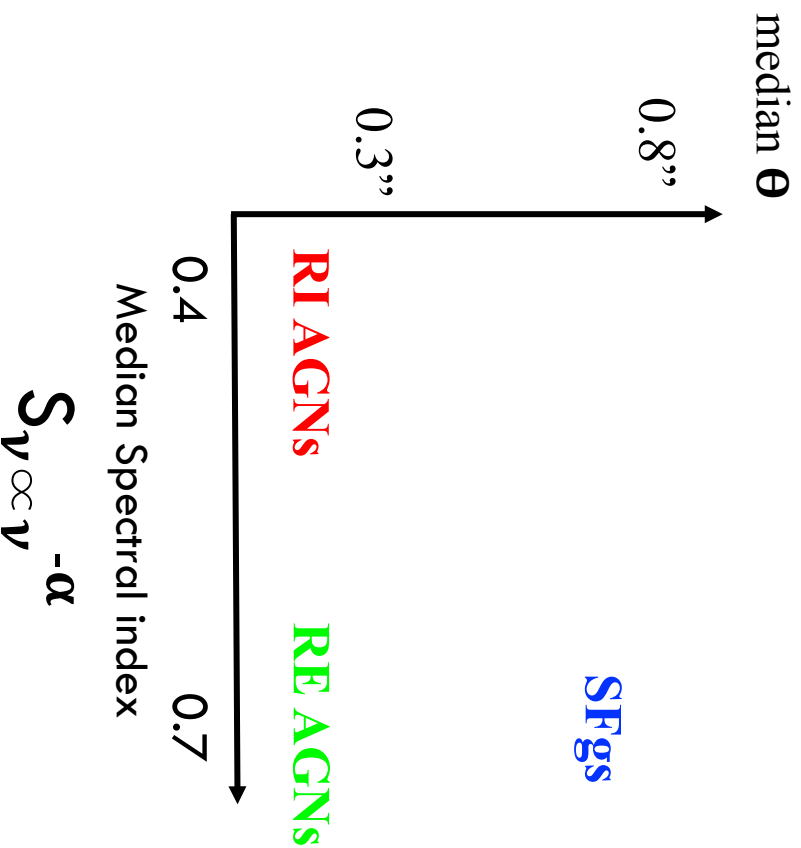


- More compact radio emission in RE & RI AGNs than in SFgs
- RE AGNs and SFgs have similar steep radio spectra $\rightarrow$ SF related emission?
- RI AGNs many flat/inverted spectra
- Few SFgs with flat spectra (hybrid sources?)

Radio properties: angular size and spectral index

- 5.5 GHz angular size for $z < 1.5$ sources
- 1.4-5.5 GHz spectral analysis (1.4 GHz from VLA data, [Morrison et al. 2010](#))

- Spectral analysis limited to sources with size < 1 arcsec (~ 8 kpc @ $z=1$)



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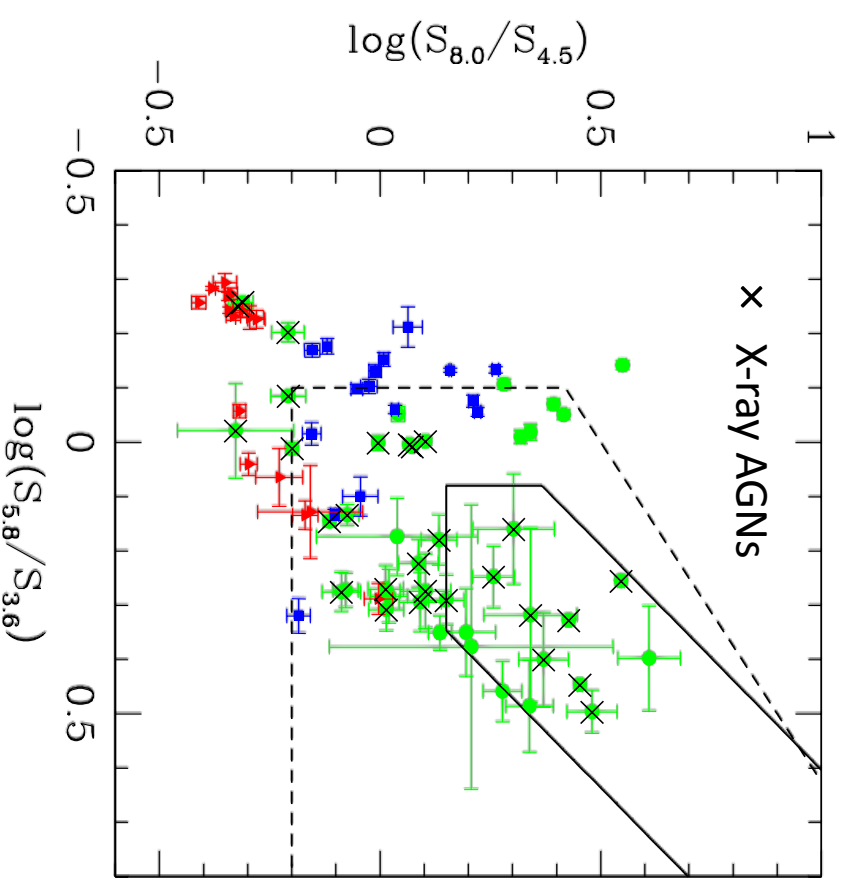
X-ray luminosity

RE 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 X-ray upp limits)

→ 29 X-ray RE AGN



35 RE AGNs

15 RI AGNs

27 SF/hyb



44 RE AGNs 57%

15 RI AGNs 20%

18 SF/hyb 23%

77% of the classified
sources are AGNs!!

radio

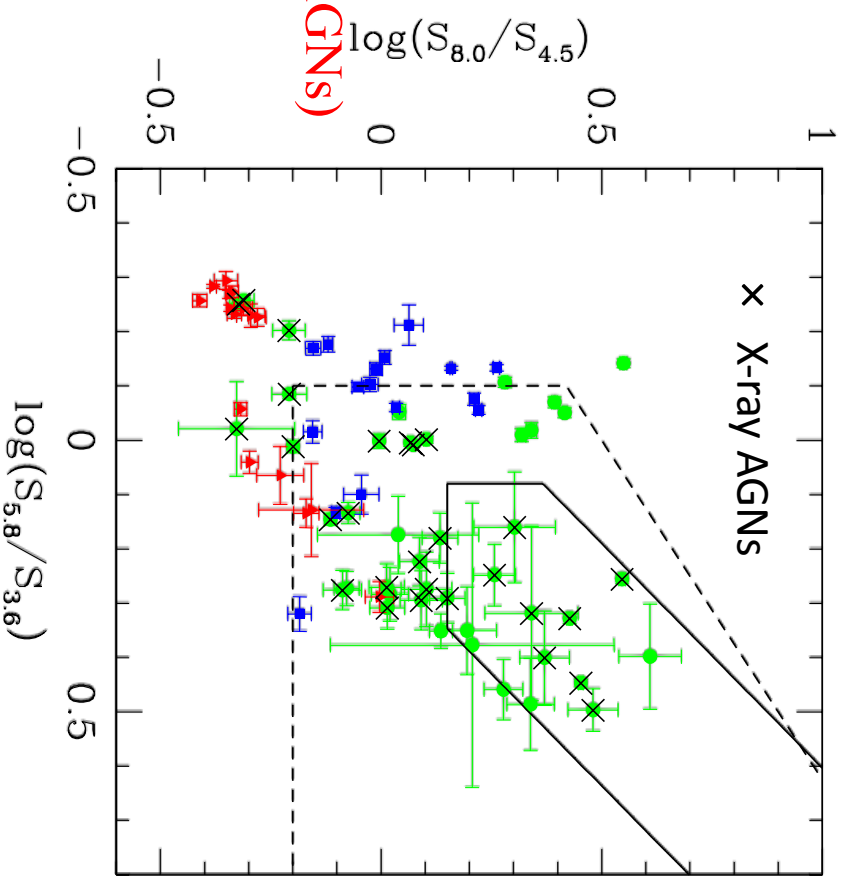
radio excess sources if:

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

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

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

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



35 RE AGNs

15 RI AGNs

27 SF/hyb



44 RE AGNs 57%

15 RI AGNs 20%

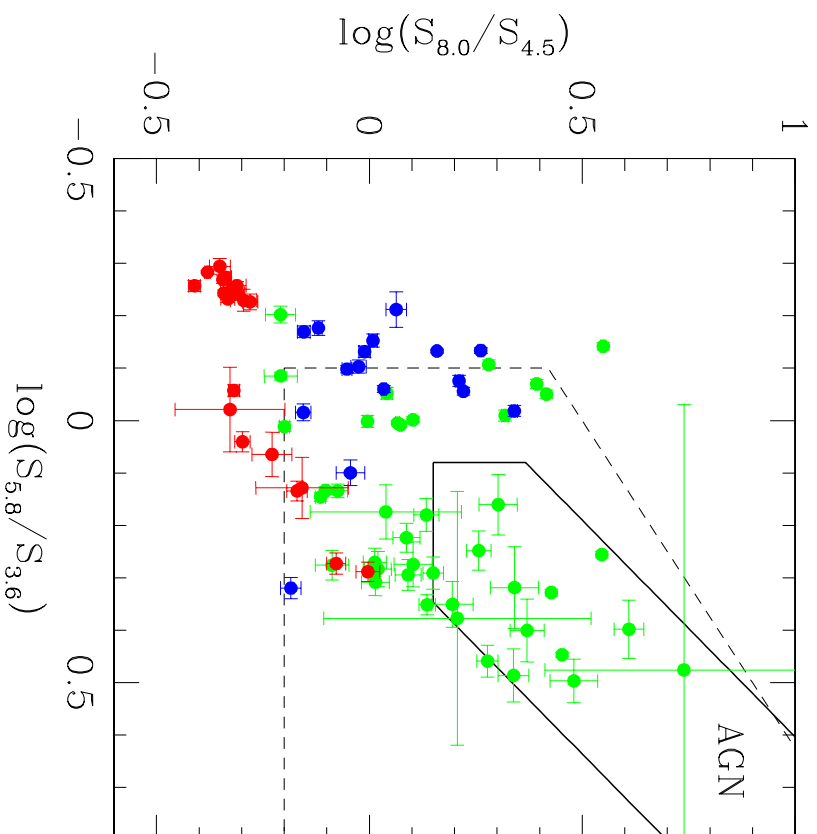
18 SF/hyb 23%

77% of the classified
sources are AGNs!!

5.5 GHz selected AGNs

RE AGNs

- at least by 1 IR cc plot
 - Lx [2-7 keV] $> 10^{42}$ erg/s **or**
Lx [0.2-7 keV] $> 3 \times 10^{42}$ erg/s
(for hard-X upp limits)
- #44 sources



● 44 RE AGNs

5.5 GHz selected AGNs

RE AGNs

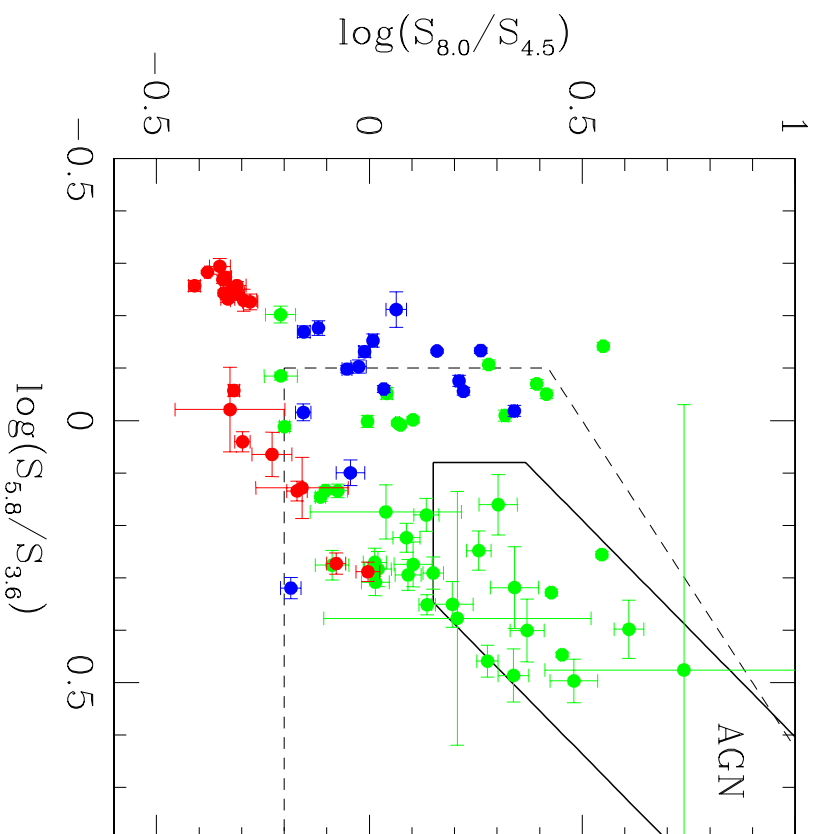
- at least by 1 IR cc plot
- Lx [2-7 keV] > 10^{42} erg/s **or** Lx [0.2-7 keV] > 3×10^{42} erg/s (for upp limits)

→ #44 sources

RI AGNs

- MIR colours of red passive galaxies (Donley+12)
- Radio excess
q100 ($\log [S_{100\mu\text{m}}/S_{1.4\text{GHz}}] < 1.5$ (Del Moro+13)
 $S_{100\mu\text{m}} = 1\text{mJy}$ (3 sigma) for upper limits

→ #16 sources



- 44 RE AGNs
- 16 RI AGNs

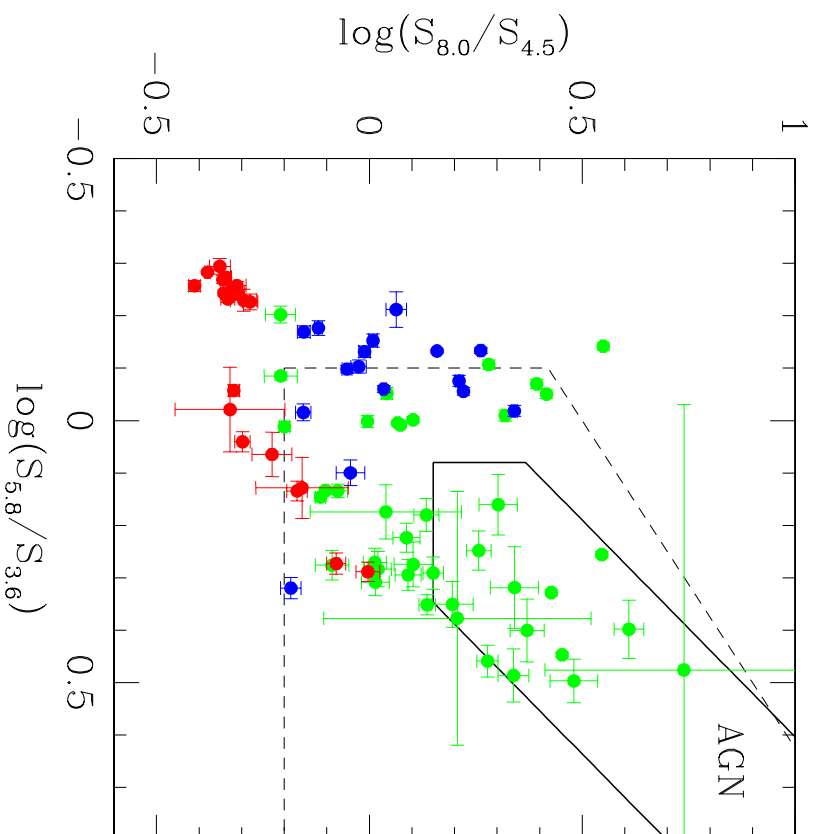
5.5 GHz selected AGNs

RE AGNs

- at least by 1 IR cc plot
- L_x [2-7 keV] > 10⁴² erg/s **or** L_x [0.2-7 keV] > 3 × 10⁴² erg/s (for upp limits)
- #44 sources

RI AGNs

- MIR colours of red passive galaxies (Donley+12)
- Radio excess
- q₁₀₀ (log [S_{100μm}/S_{1.4GHz}]) < 1.5 (Del Moro+13)
S_{100μm}=1mJy (3 sigma) for upper limits
- VLBI detections (1.4-1.6 GHz, Chi+13, Radcliffe+15)
- #16 sources



- 44 RE AGNs
- 16 RI AGNs
- 17 SFgs

5.5 GHz selected AGNs

4 IR colour colour plots → RE AGNs and

- [Donley+12](#) (IRAC), [Kirkpatrick+12](#) (IRAC, 24μm, 100μm, 250μm), [Messias+12](#) (Ks-band, IRAC)
- all account for redshift evolution

$L_X [2-7 \text{ keV}] > 10^{42} \text{ erg/s}$ **or** →

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

Radio excess

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

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

MIR colours of red passive galaxies ([Donley+12](#))

→ #44 sources

→ #16 sources

Multiwavelength AGN diagnostics

Search for evidence of nuclear activity in the 5.5 GHz sources, whatever the band via:

- 4 IR colour plots → **RE & RI AGNs**
 - Donley+12 (IRAC)
 - Kirkpatrick+12 (IRAC, 24μm, 100μm, 250μm)
 - Messias+12 (Ks-band, IRAC)
- strong X-ray sources → **RE AGNs**
- radio excess sources → **RI AGNs**

→ 5.5 GHz radio sources classified as RE & RI AGNs and star forming galaxies

Multiwavelength AGN diagnostics

Radio: 1.4 GHz VLA (Morrison+10), 1.6 GHz VLBI (Chi+13, Radcliffe+15)

Far-IR: Herschel PACS & SPIRE (Elbaz+11, Magnelli+13)

Mid-IR: Spitzer IRAC & MIPS

NIR: .. / Subaru (Wang+10, Kajisawa+11)

X-ray: Chandra (Xue+16)

→ Search for evidence of nuclear activity in the 5.5 GHz sources, whatever the band via:

 **4 IR colour colour plots → RE & RI AGNs**

- Donley+12 (IRAC)
- Kirkpatrick+12 (IRAC, 24μm, 100μm, 250μm)
- Messias+12 (Ks-band, IRAC)
- all account for redshift evolution

 **strong X-ray sources → RE AGNs**

 **radio excess sources → RI AGNs**

→ 5.5 GHz radio sources classified as RE & RI AGNs and star forming galaxies