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

Daria Guidetti
Istituto di Radioastronomia-INAF, Bologna

On behalf of:
M. Bondi, I. Prandoni, R.J. Beswick, T.W.B. Muxlow, N. Wrigley, I.R. Smail, I. McHardy, R. Ivison
and the eMERGE collaboration

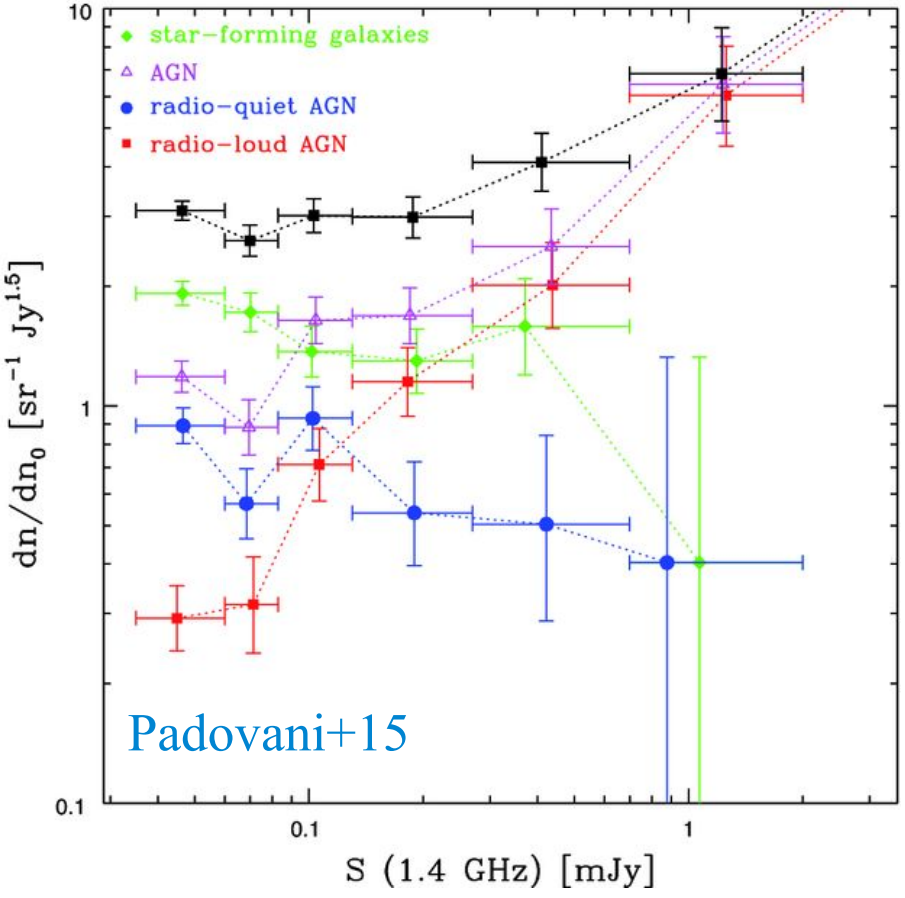
AGN 12, Napoli, 26-29 September, 2016

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 $S_{1.4\,GHz} < 100$ μJy → 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 μJy radio source population in GOODS-N

Goal

- morphologically and spectrally identification of AGNs & SFgs up to z~5

How

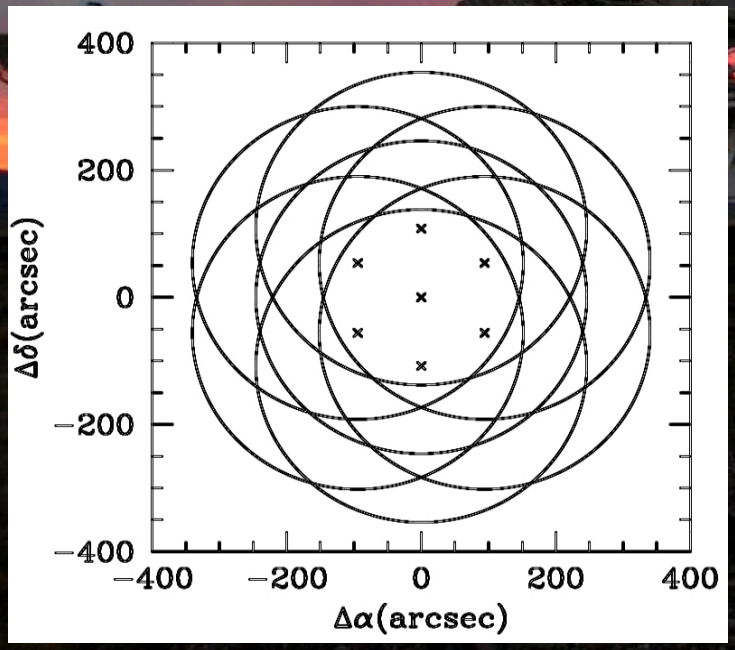
- 400 hrs eMERLIN+ JVLA @ 1.4 GHz
- 378 hrs eMERLIN +JVLA @ 5 GHz (PI Prandoni)
- resolution 50-2000 mas (0.5-tens of kpc at z >1) with 0.5-1 μJy/b rms
- ancillary coverage of GOODS-N from radio to X-ray

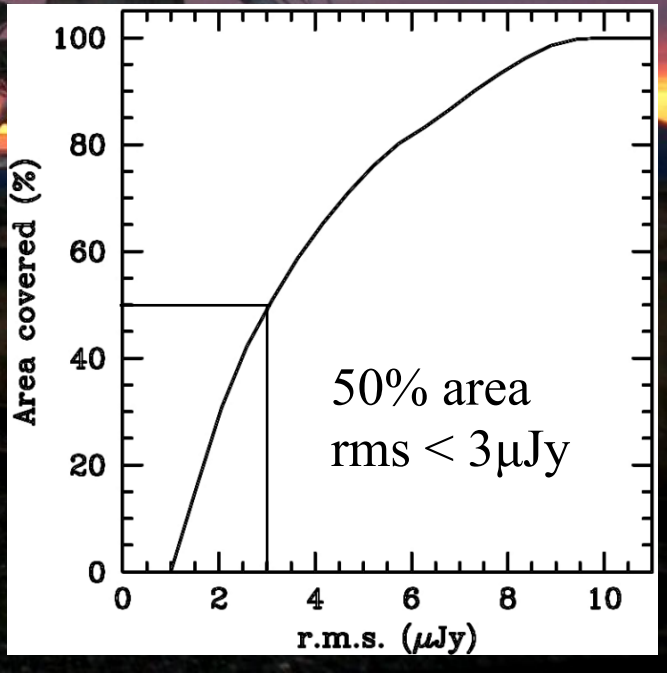
Status

- 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 (Q1 2017)

GOODS-N 5.5 GHz JVLA MOSAIC

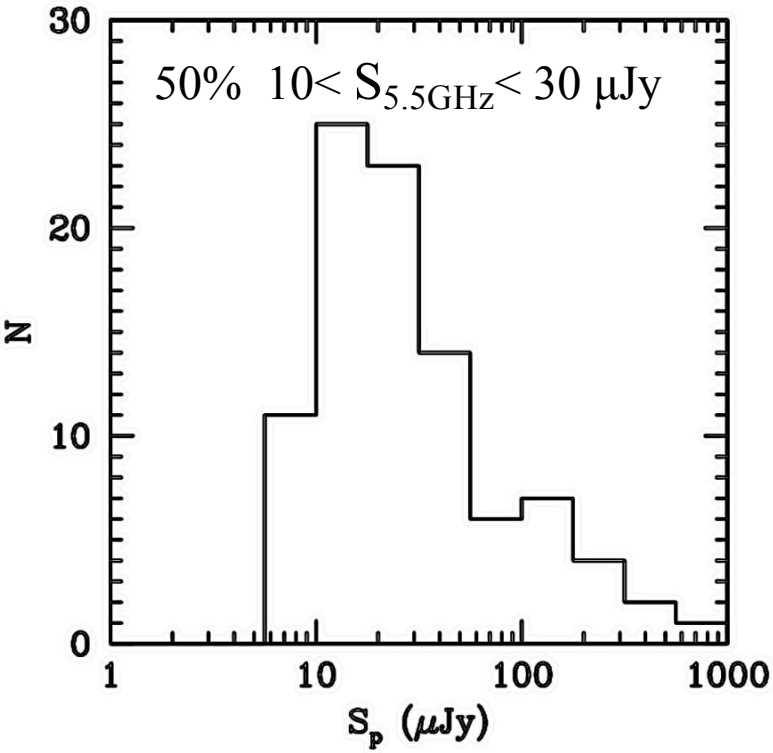
- 7-pointing mosaic in GOODS-N (matching the 5 GHz e-MERLIN FoV)
  → 15 arcmin diameter field
- 14+2 hours in Array A & B [PI: Muxlow] (Oct 2012 & Oct. 2013)
- Central frequency 5.5 GHz , 2 GHz bandwidth
- 0.5 arcsec resolution, ~1 μJy rms at center (1 sigma)

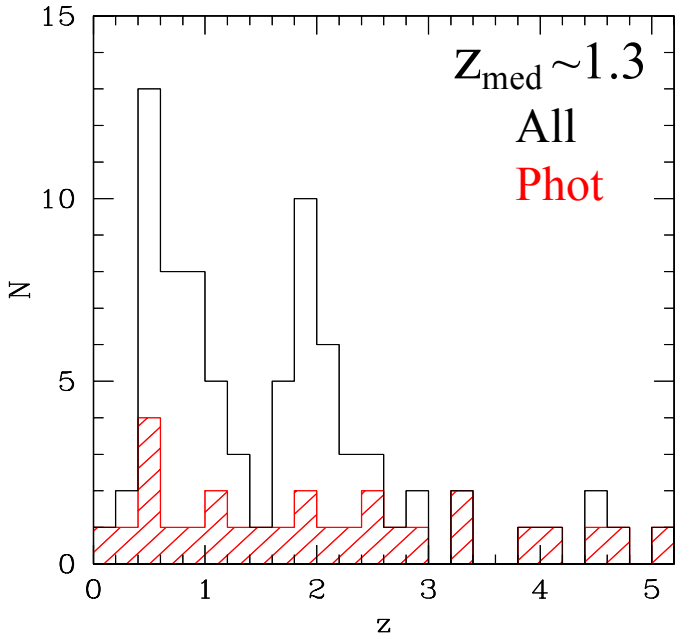


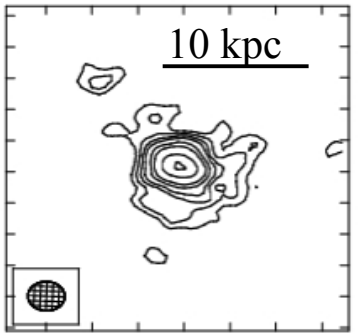


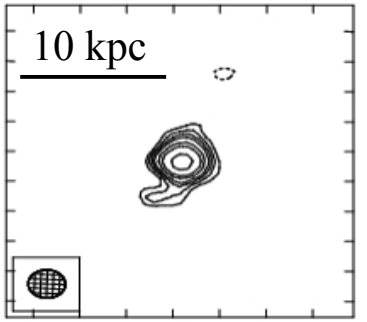
5.5 GHz catalogue

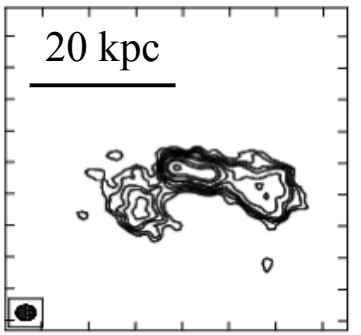
- 94 sources (S/N>5) at d <7 arcmin
- $S_{5.5GHz}$> 6 μJy
- 88% secure NIR counterparts within <0.5”
  (< 24.45 Ks, AB mag, Wang+10)
- 95% with redshifts (e.g. Momcheva+16, Skelton+14)
- median size ~ 0.4 arcsec (~3 kpc at z =1.3)











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**

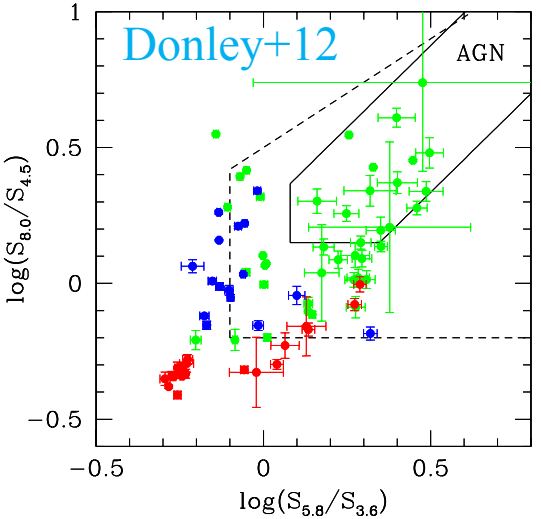
→ classification as RE AGNs, RI AGNs, star forming galaxies

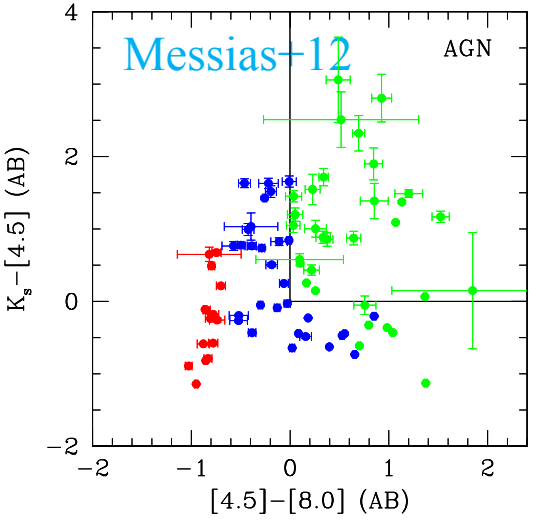
Multi-λ classification of 5.5 GHz sources

RE AGNs →#44 ●

- at least by 1 of the IR cc plots
- Lx [2-7 keV] > 10^{42} erg/s

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

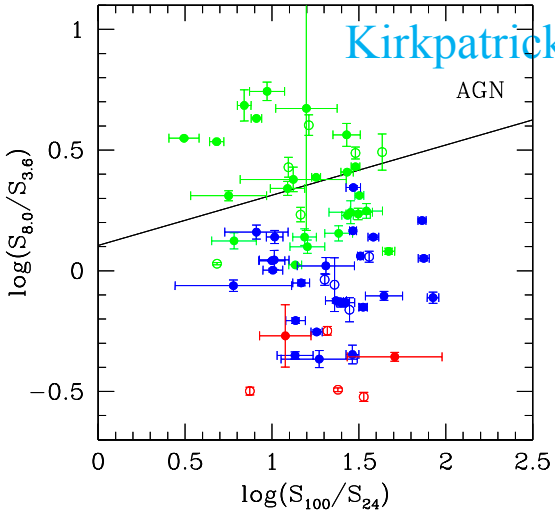


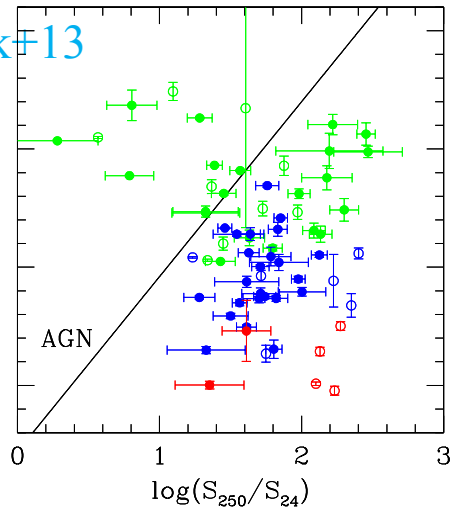


RI AGNs → #16 ●

- MIR colours of red passive galaxies
- Radio excess

  q_{100} (log [$S_{100\mu m}$/S1.4GHz]) <1.5 (Del Moro+13)
  $S_{100\mu m}$=1mJy (3 sigma) for upper limits





SFgs → #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

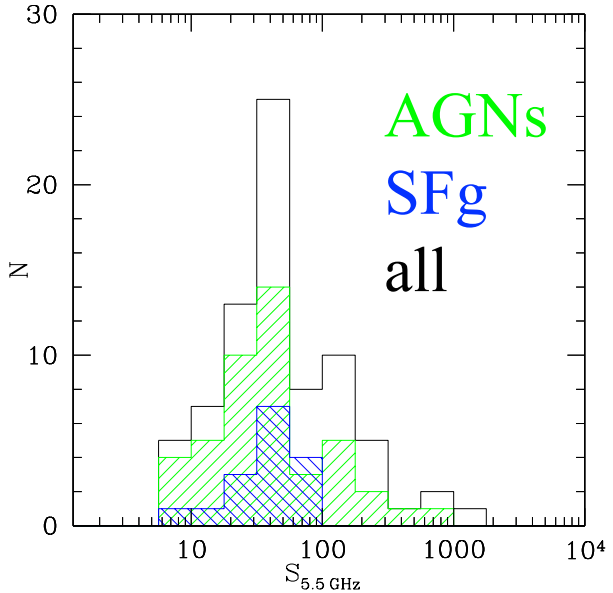
78% of the classified μJy radio sources are radio AGNs! **90% at z>1.5 !!**

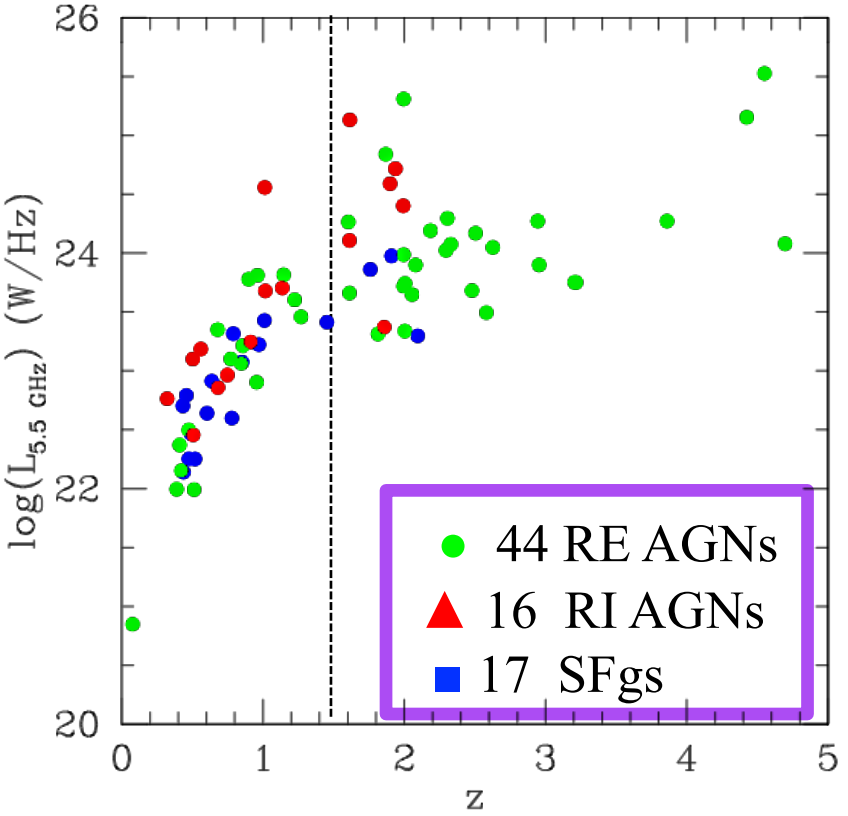
Reliability: How many AGNs are real?

- 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

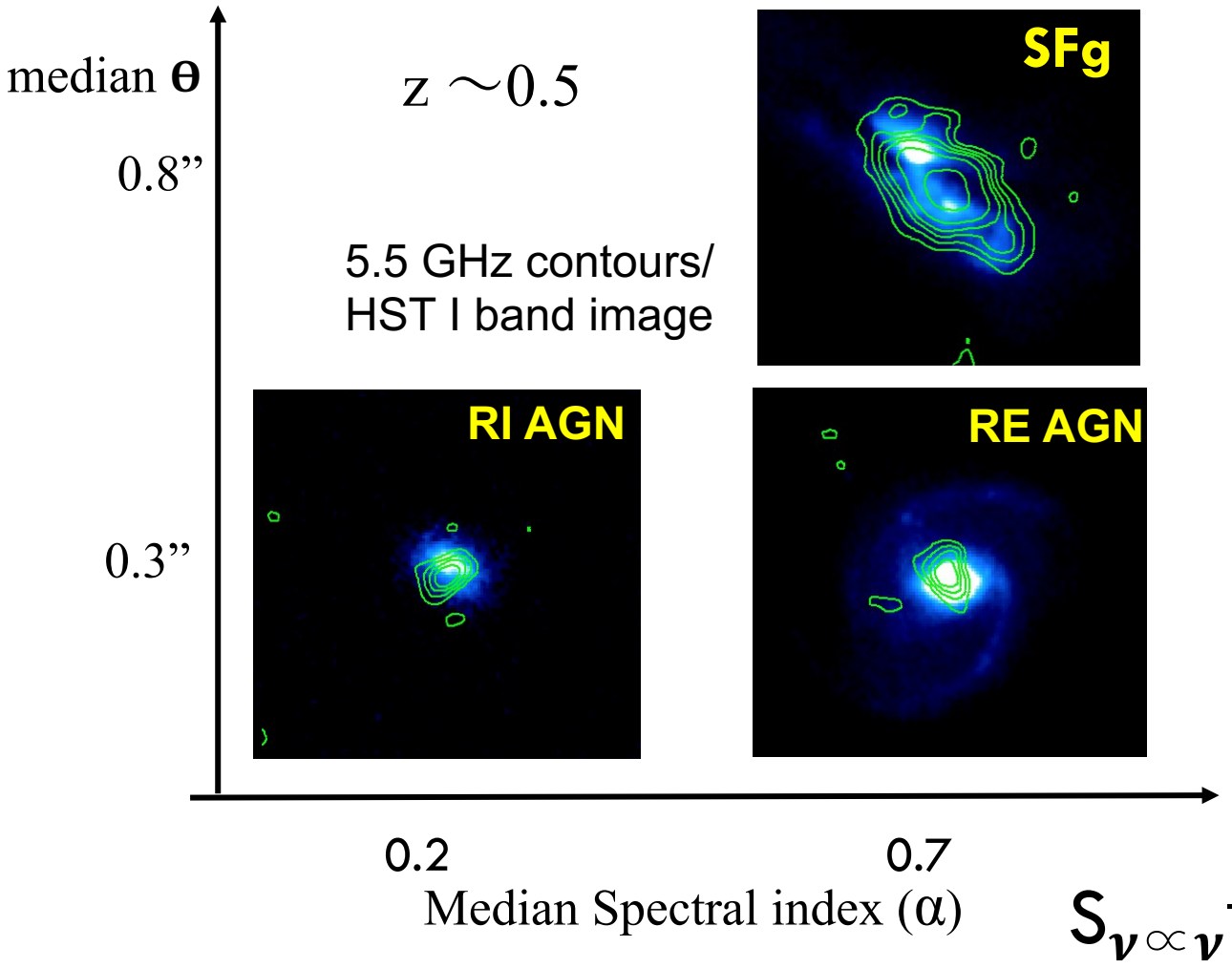




- AGNs at all flux densities, redshifts, and 5.5 GHz luminosities
- 3 SFgs at z>1.5 are identified as sub-mm galaxies by Barger+12

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)

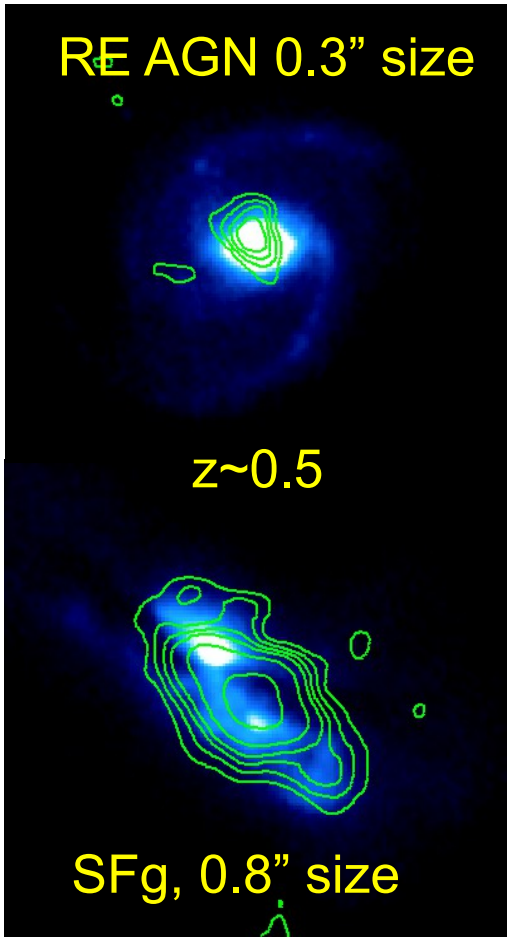


- AGNs have more compact radio emission than SFgs
- SFgs have steep spectrum extended on galactic scale
- RE AGNs have spectra similar to those of SFgs
  → SF-related emission?
- RI AGNs show flat/inverted spectrum
- a few SFgs with flat spectra

Selection effects?

Very large presence of AGNs in our GOODS-N catalogue of the μJy 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)



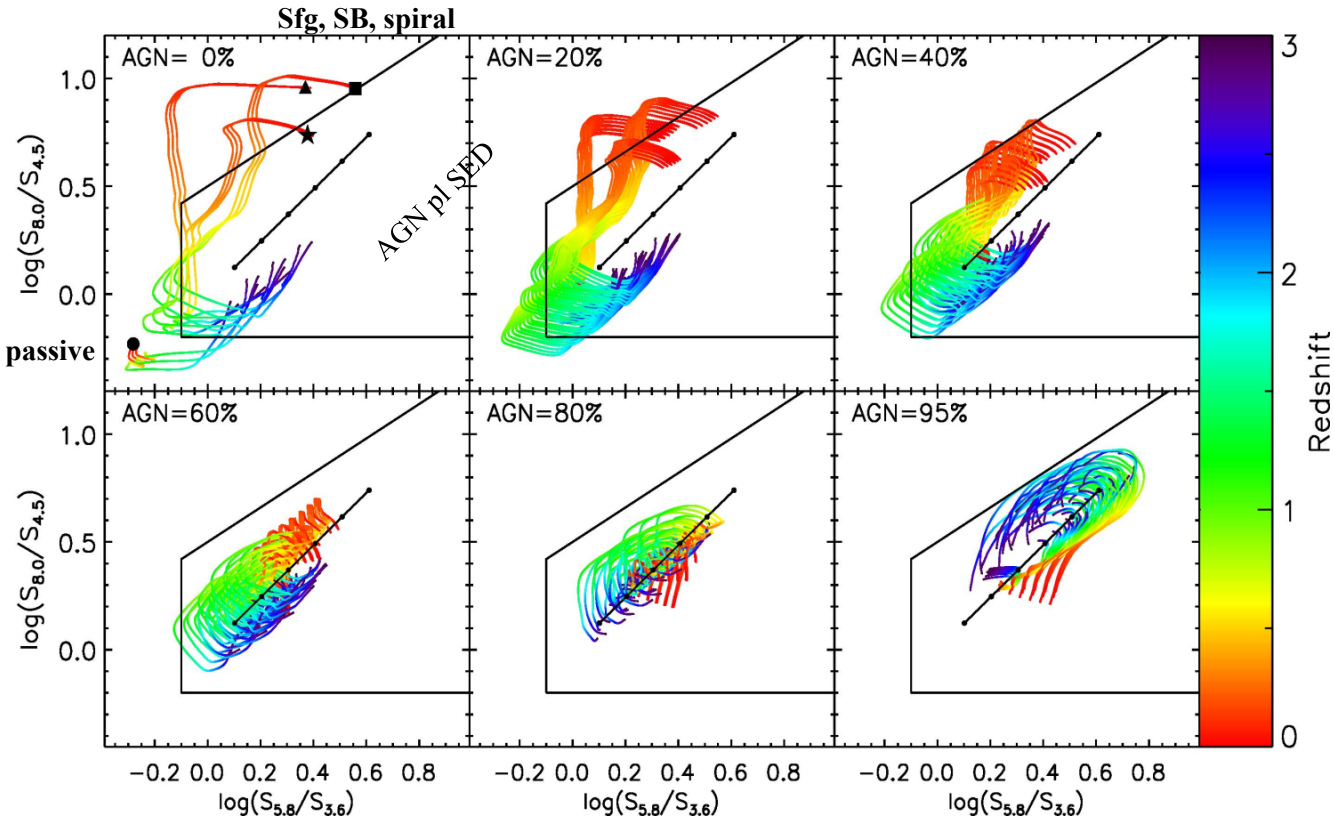
5.5 GHz contours/
HST I band image

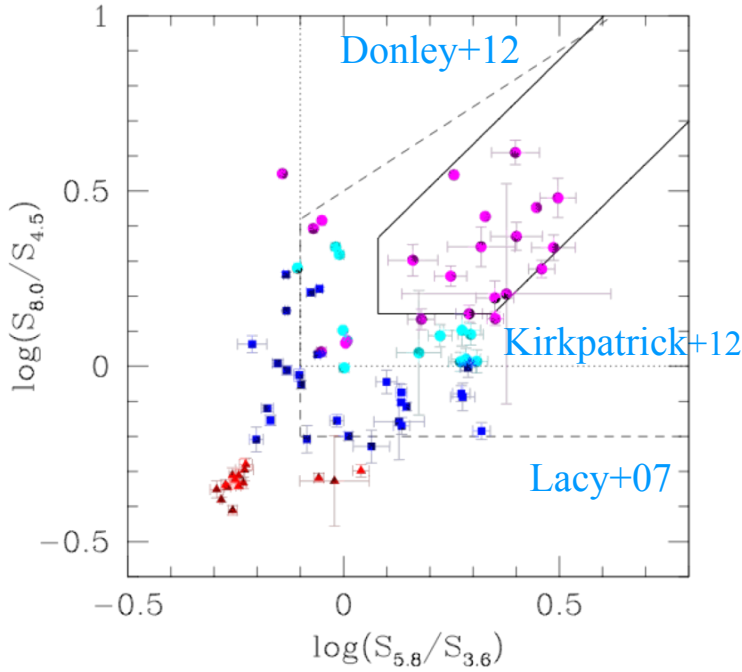
Summary

- 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





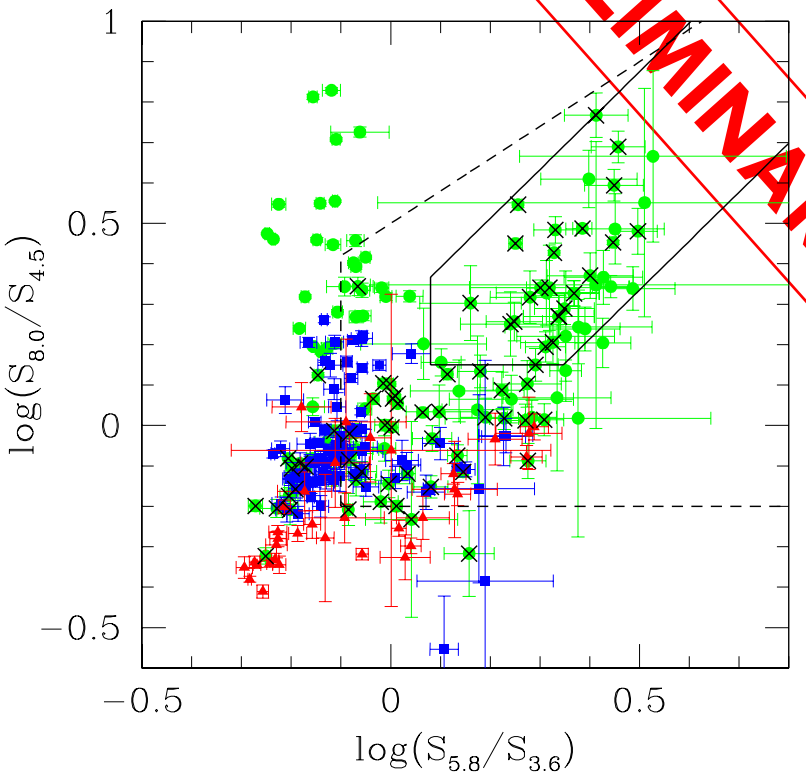
- 5 IR CC criteria by Stern+05 (IRAC), Donley+12 (IRAC), Kirkpatrick+12 (IRAC, Far-IR), Messias+12 (Ks, IRAC)
- 4-IRAC bands photometry for 90% (74/82) of the Ks-identified sources (Wang+10)
- Far-IR Herschel photometry for 79% (65/82) (Elbaz+11)

- ■ 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% 20μJy>$S_{1.4GHz}$>1mJy)



1.4 GHz selected sources

- 142 RE AGNs
- 34 RI AGNs

] ➜ ~65%

- 86 SF/hyb systems ➜ ~35%

5.5GHz selected sources

- 44 RE AGNs
- 15 RI 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

AGN content of the 5.5 GHz catalogue

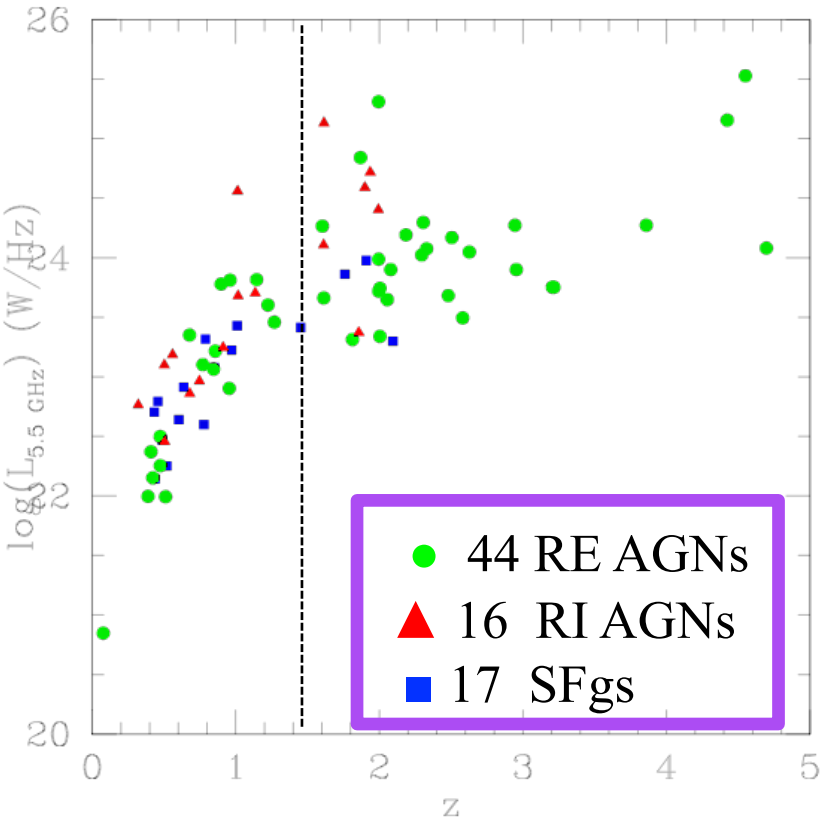
- 4 IR colour-colour plots (NIR-> FIR) ➜ quasar mode AGNs, passive (radio mode), star forming galaxies
- $L_{x\text{-}ray}$ ➜ quasar mode AGNs
- radio excess sources (Del Moro+13) ➜ radio AGN (RM&QM)
- VLBI detections ➜ radio AGN (RM&QM)

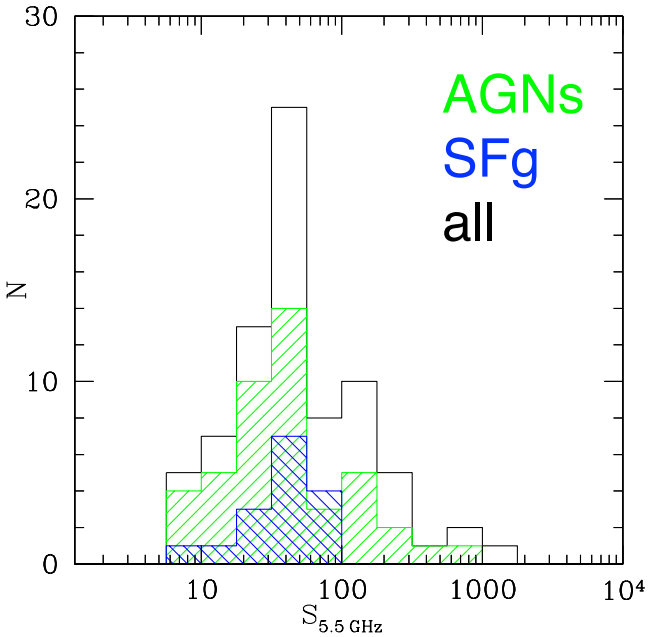
Samples of quasar/radio mode AGNs and star forming galaxies

AGN content in the 5.5 GOODS-N catalogue

- **78%** of the classified μJy radio sources are radio AGNs! **90% at z>1.5 !!**

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





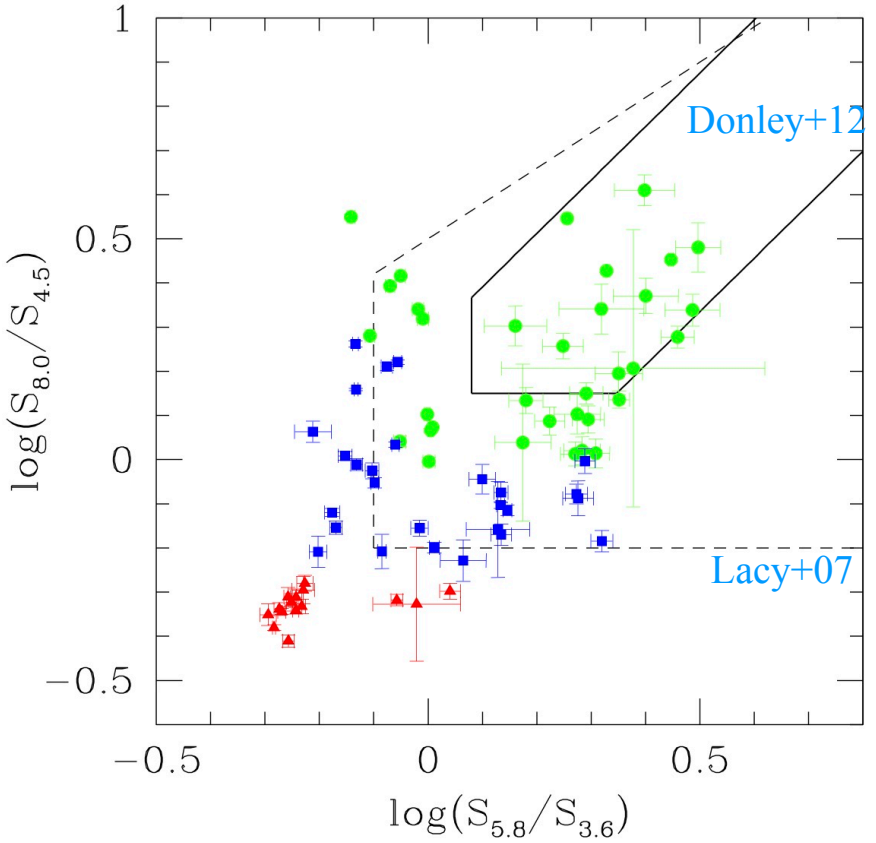
- AGNs dominate at all flux densities, redshifts and $L_{5.5GHz}$
- 3 SFgs at z>1.5 are sub-mm galaxies (Barger+12)

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

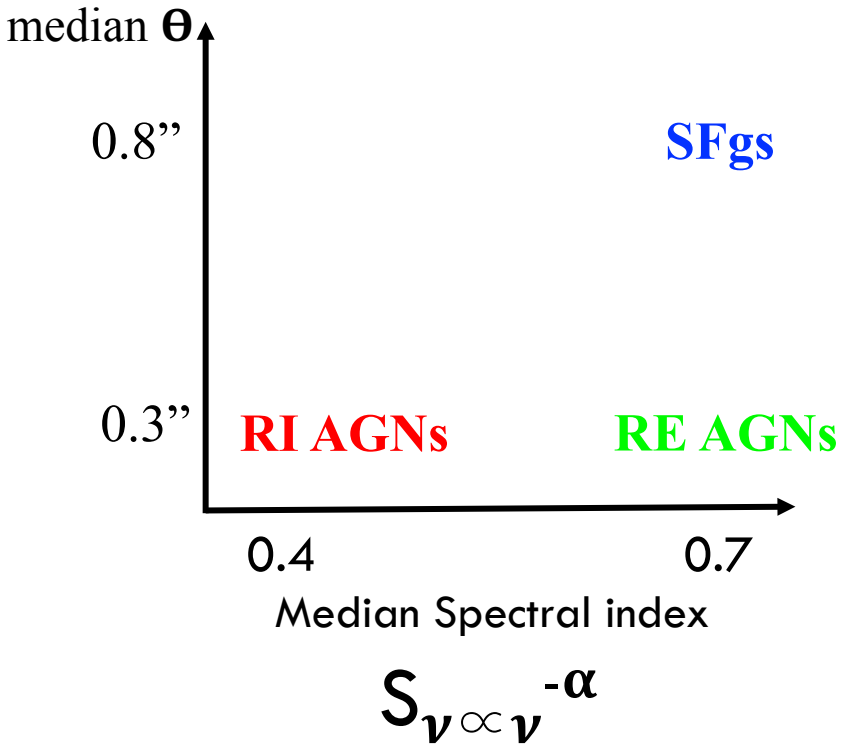


- 35 RE AGNs (45%)
- 15 passive -> RI AGNs (20%)
- 27 SF/hyb systems 35%

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 → SF related emission?

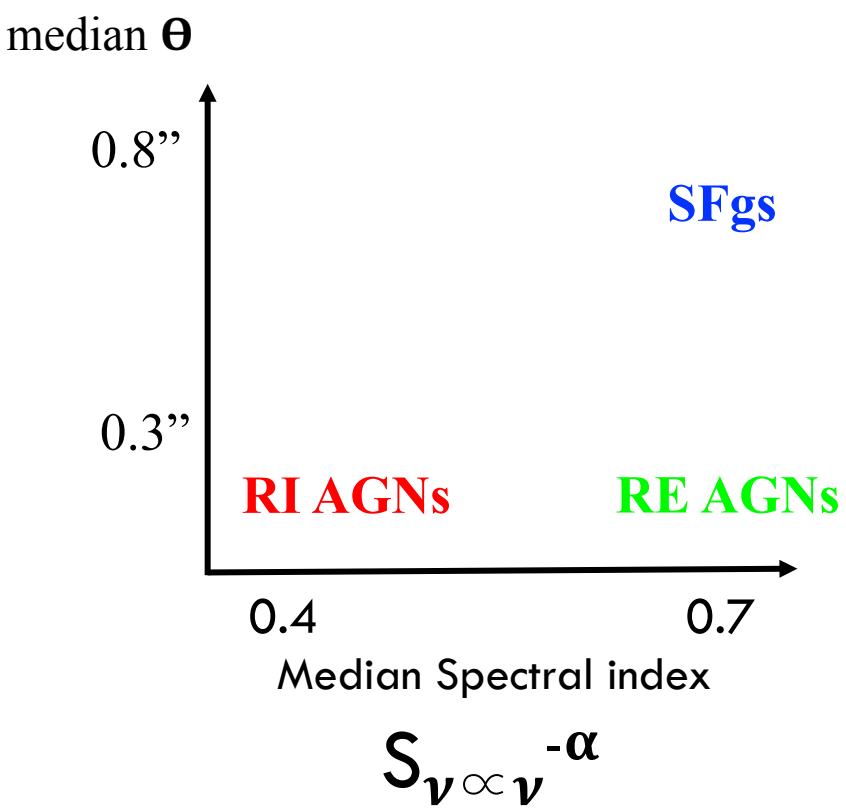
- RI AGNs many flat/inverted spectra

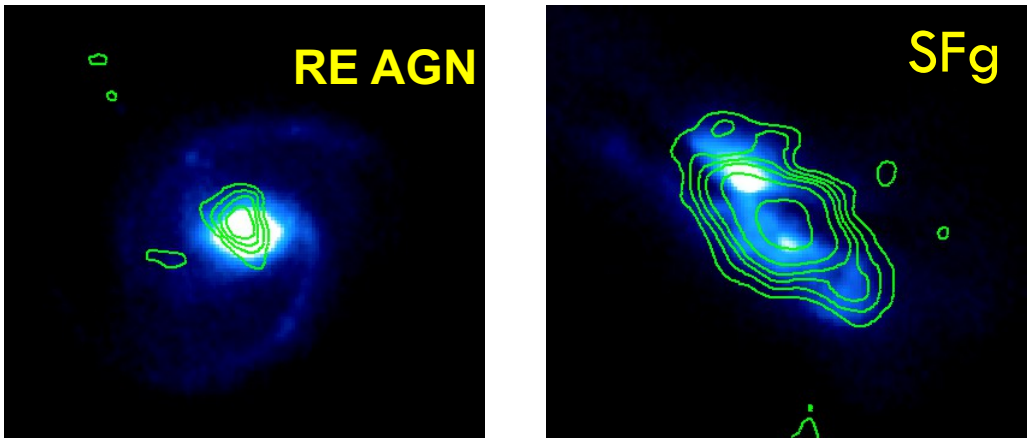
- Few SFgs with flat spectra (hybrid sources?)

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 (#61)
  (~ 8 kpc @ z=1)





- More compact radio emission in RE & RI AGNs than in SFgs

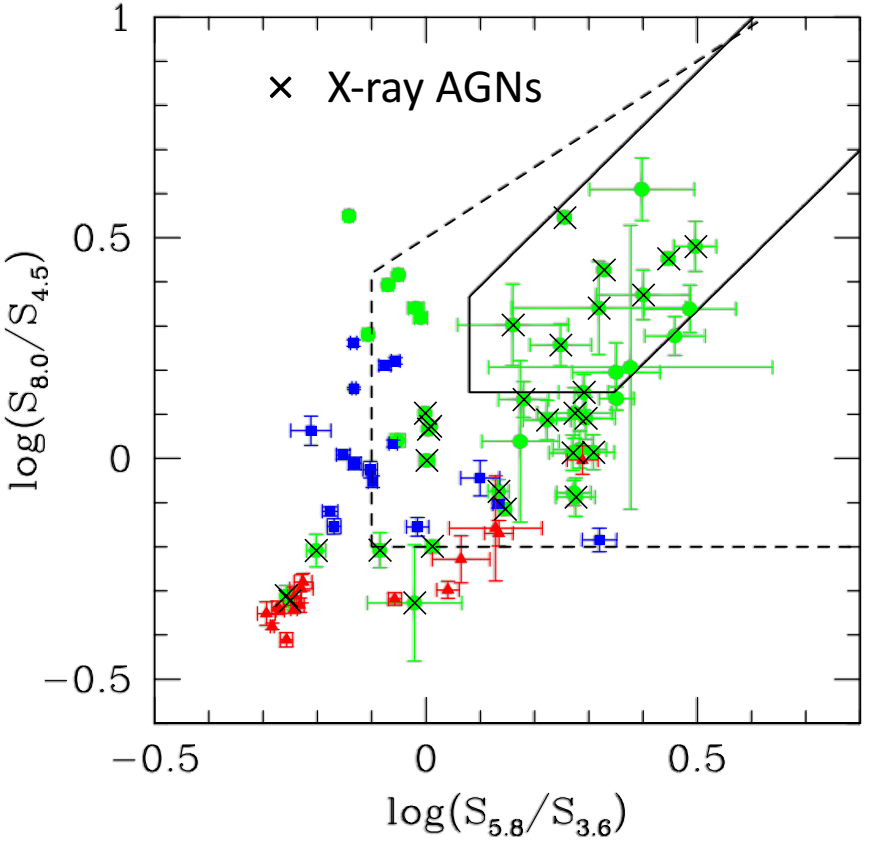
- RE AGNs and SFgs have similar steep radio spectra → SF related emission?

- RI AGNs many flat/inverted spectra

- Few SFgs with flat spectra (hybrid sources?)

X-ray luminosity

- RE AGNs if :
  Lx [2-7 keV] $> 10^{42}$ erg/s
  Lx [0.2-7 keV] $>3\times10^{42}$ erg/s (for X-ray upp limits)
  ➜ 29 X-ray RE AGN



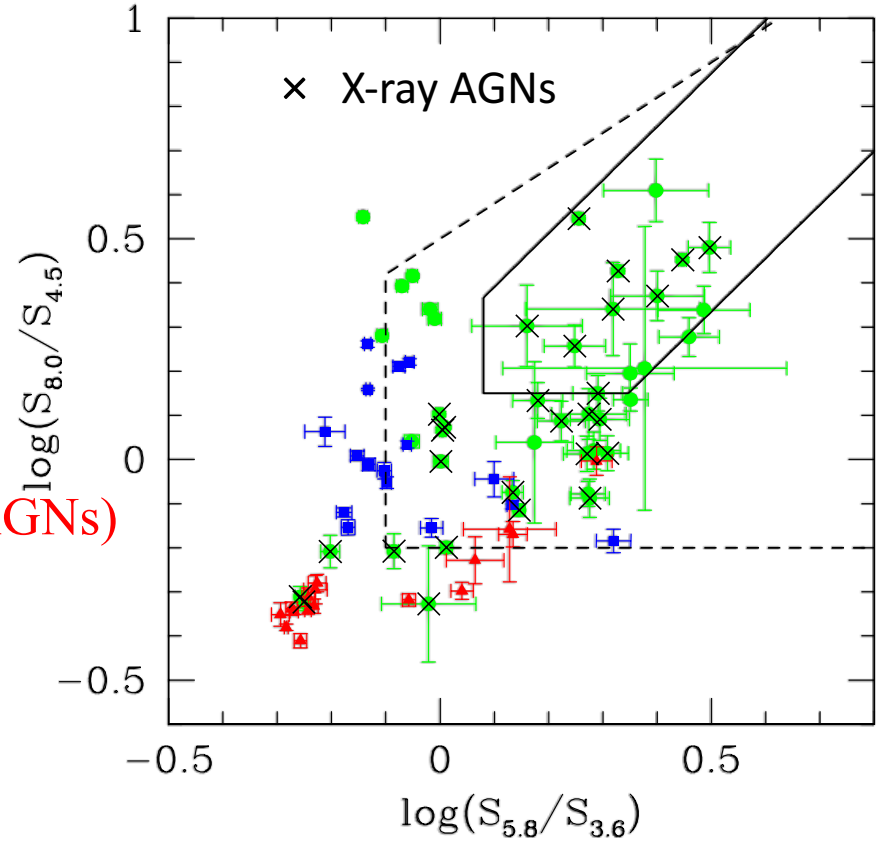
■ 35 RE AGNs	■ 44 RE AGNs 57%
▲ 15 RI AGNs	▲ 15 RI AGNs 20%
● 27 SF/hyb	● 18 SF/hyb 23%

77% of the classified sources are AGNs!!

radio

- 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 RI AGN)

- 1.6 GHz VLBI ➜ 18 sources (~10% not IR RI AGNs)



■ 35 RE AGNs	■ 44 RE AGNs 57%
▲ 15 RI AGNs	▲ 15 RI AGNs 20%
● 27 SF/hyb	● 18 SF/hyb 23%

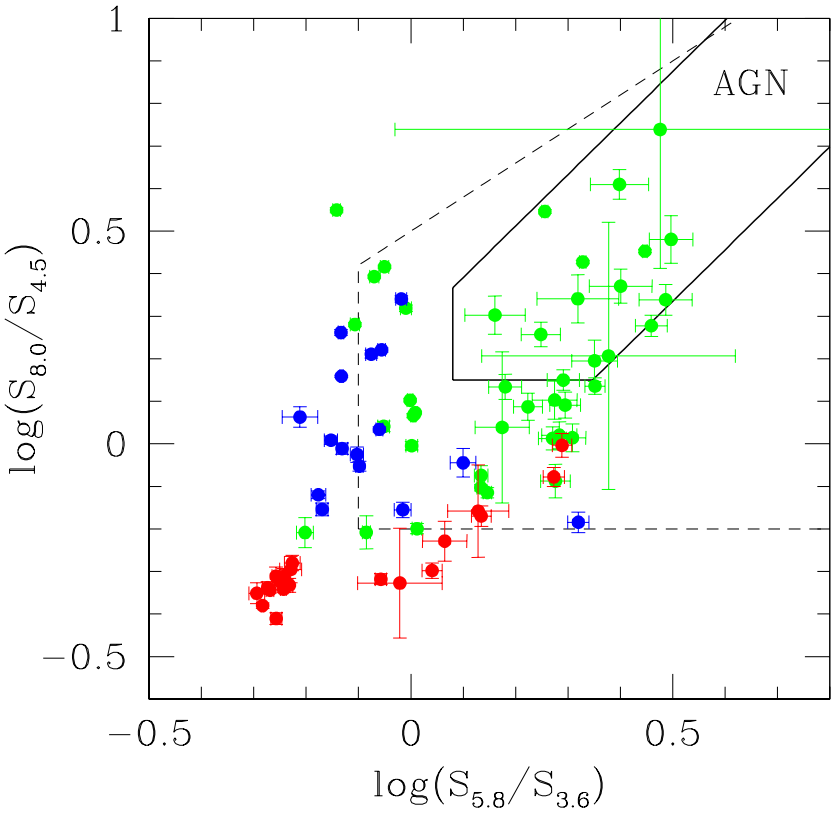
77% of the classified sources are AGNs!!

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] >3×10^{42} erg/s
  (for hard-X upp limits)

➜ #44 sources



- 44 RE AGNs

5.5 GHz selected AGNs

RE AGNs

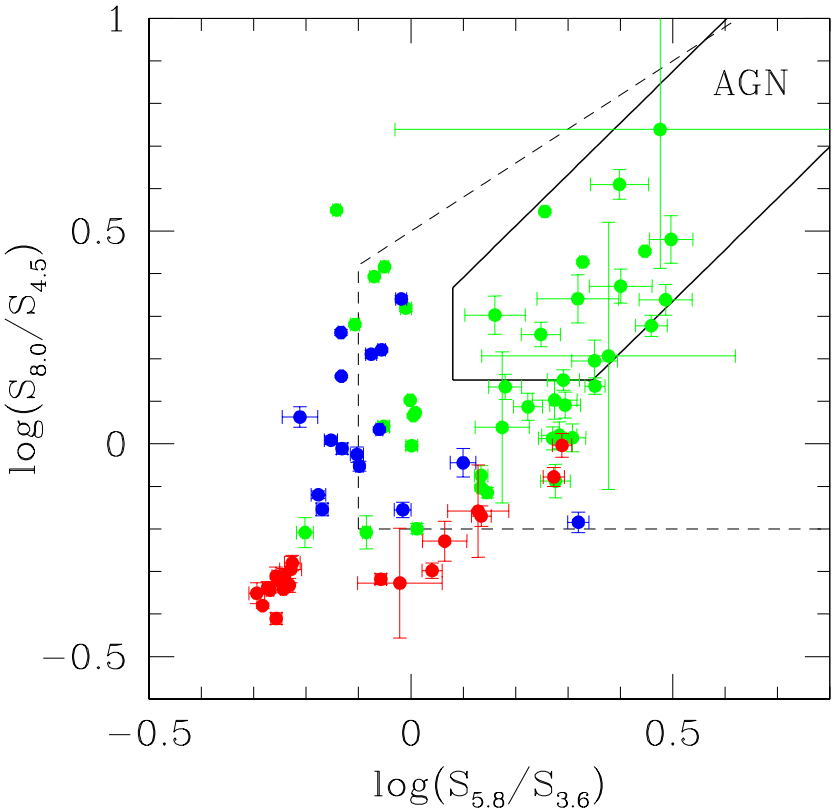
- at least by 1 IR cc plot
- Lx [2-7 keV] > 10^{42} erg/s **or** Lx [0.2-7 keV] >3×10^{42} erg/s (for upp limits)

➜ #44 sources

RI AGNs

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

➜ #16 sources



- 44 RE AGNs
- 16 RI AGNs

5.5 GHz selected AGNs

RE AGNs

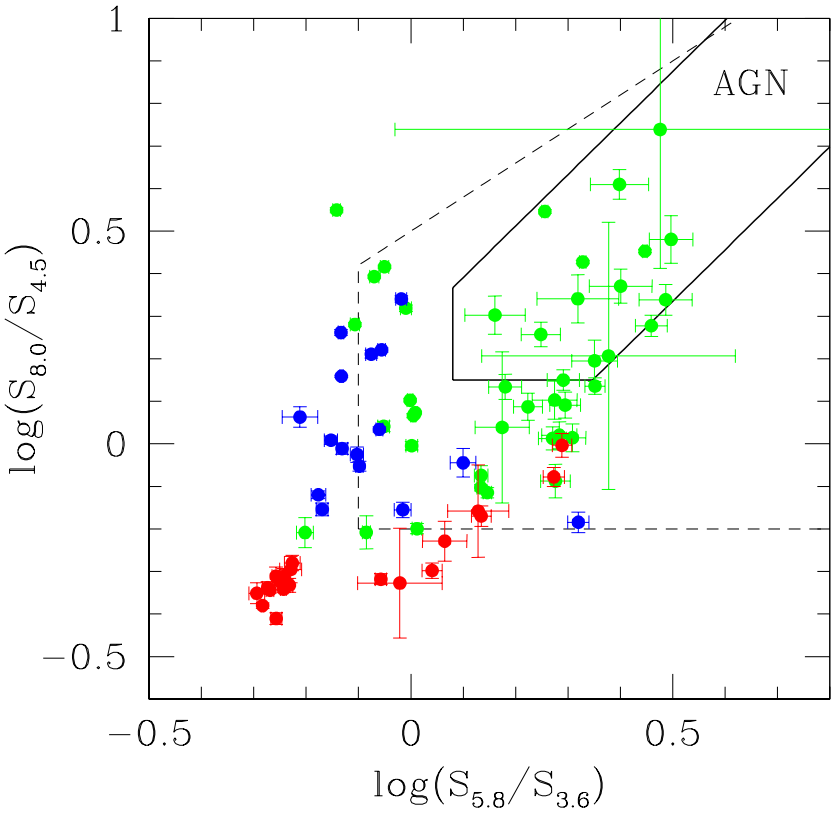
- at least by 1 IR cc plot
- Lx [2-7 keV] > 10^{42} erg/s **or** Lx [0.2-7 keV] >3×10^{42} erg/s (for upp limits)

➜ #44 sources

RI AGNs

- MIR colours of red passive galaxies (Donley+12)
- Radio excess
- q_{100} (log [$S_{100\mu m}/S_{1.4GHz}$]) <1.5 (Del Moro+13)
  $S_{100\mu m}$=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

- Lx [2-7 keV] > 10^{42} erg/s **or** →
  Lx [0.2-7 keV] >3×10^{42} erg/s
  (for upp limits)

- Radio excess
  q100 (log [$S_{100\mu m}/S_{1.4GHz}$]) <1.5 (Del Moro+13)
  $S_{100\mu m}$=1mJy (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 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