Ultra-deep sub-arcsec 5 GHz JVLA observations of GOODS-N: the nature of the radio emission in the faint radio source population

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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

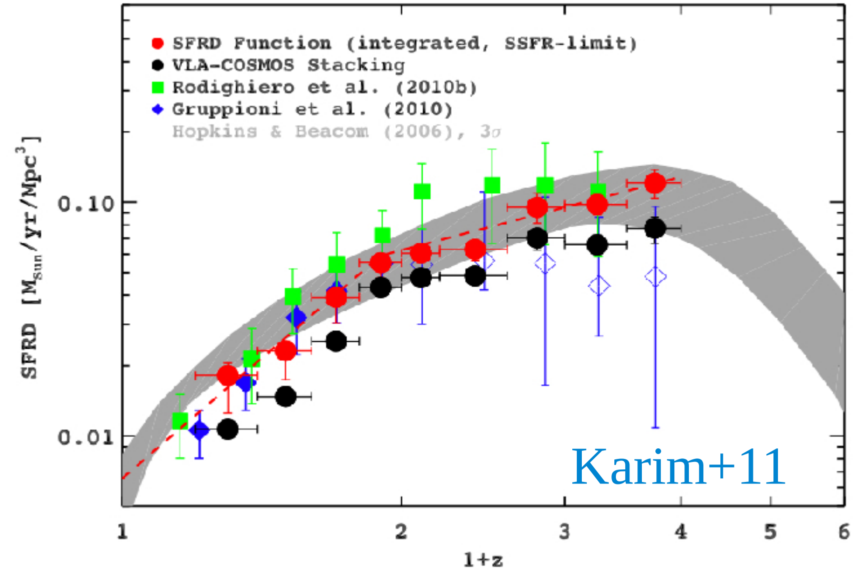
BOLOGNA, 21 OCTOBER 2015

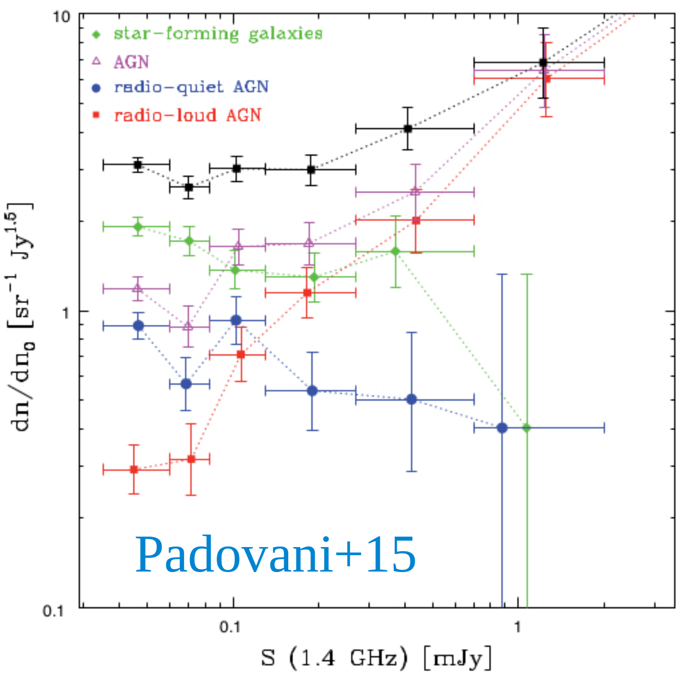
Outline

- Scientific context
- eMERGE Legacy Project
- Typical scientific case based on 5 GHz eMERLIN commissioning data in GOODS-N
- Ultra deep & sub-arcsec catalogue of GOODS-N at 5.5 GHz (JVLA)
- First IR & radio spectral analysis

Context

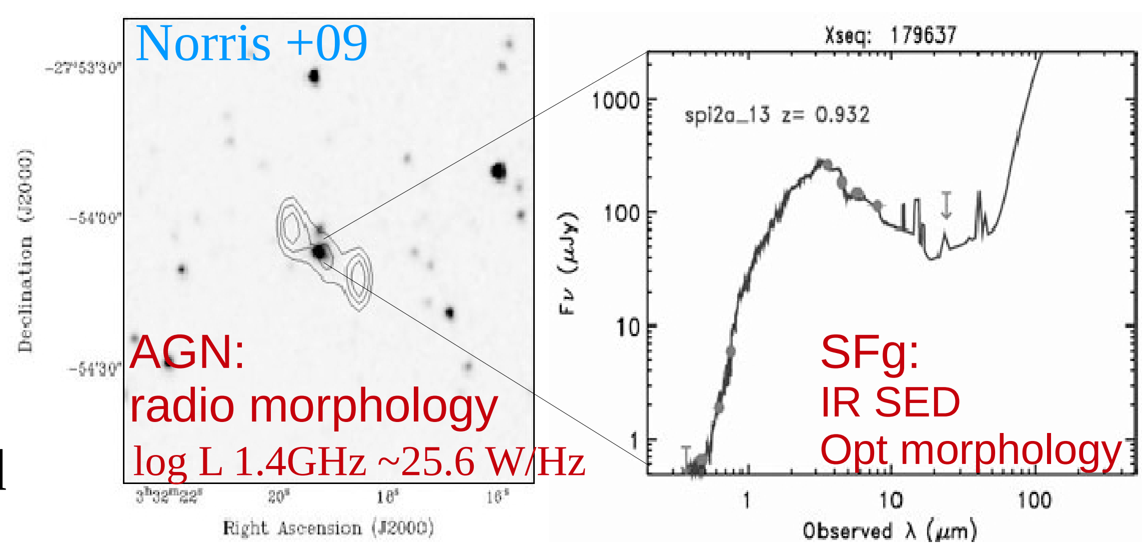
- Dust-unbiased cosmic star formation history → from radio survey





- 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)

- Evidence for hydrid AGN/SF systems @ high z (e.g. Alexander +05,08; Norris +09)



- Separation of the AGN-/SF- related emissions is the major point

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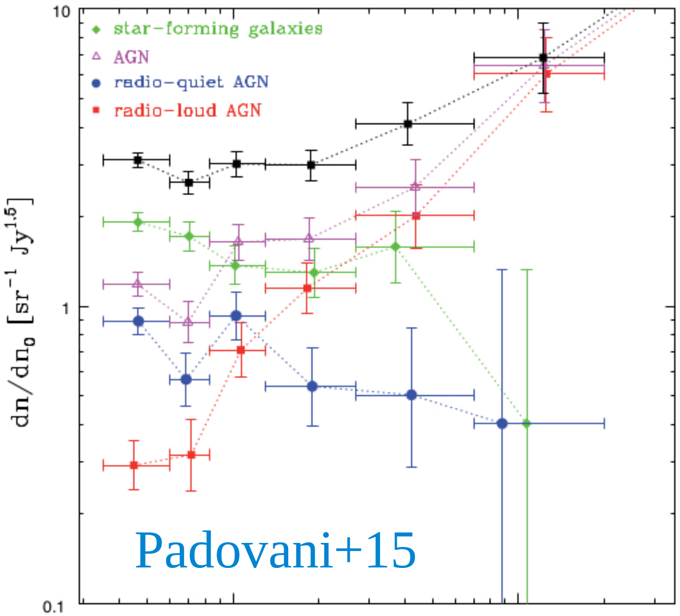

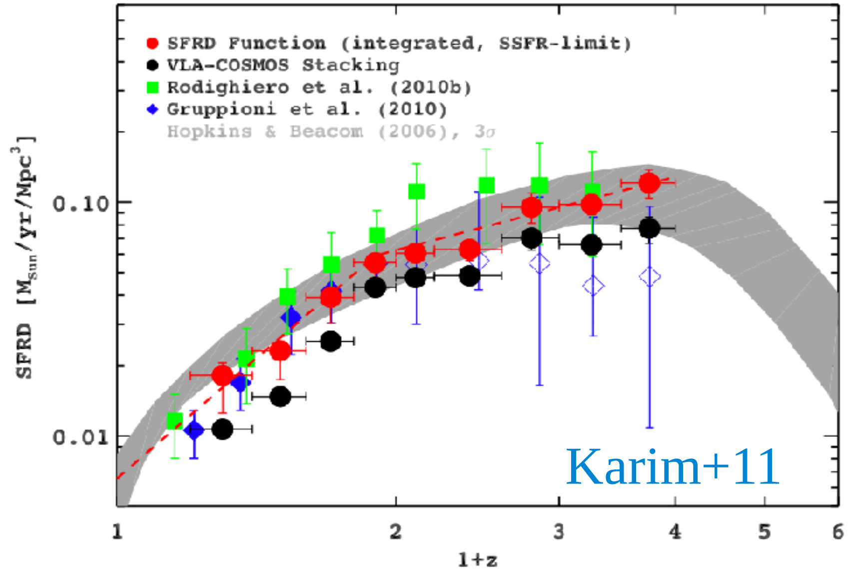

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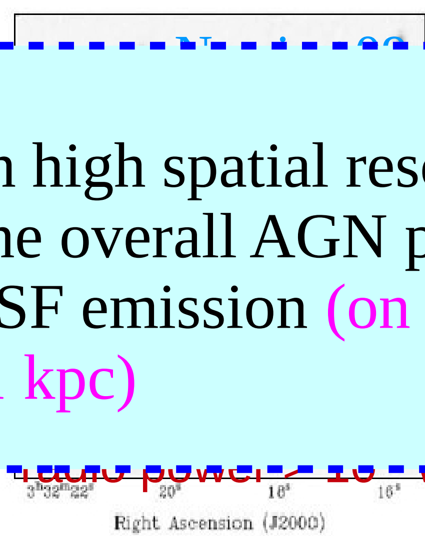
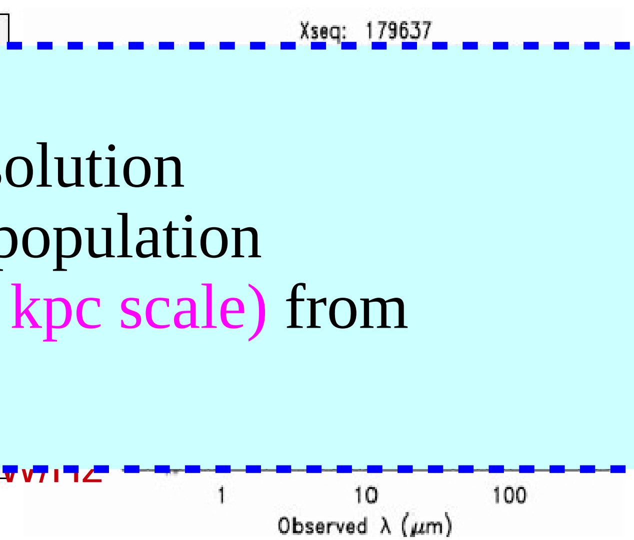
- RQ AGNs start to appear at μJy levels in deep radio fields (e.g. Seymour+08,Padovani+09,+11,+15 Bonzini+13)

Deep radio surveys (~μJy level) with high spatial resolution (sub-kpc → kpc) allow us to study the overall AGN population (RL&RQ) and distinguish extended SF emission (on kpc scale) from more compact AGN components (<1 kpc)

- Separate AGN-/SF- related emissions





The eMERGE survey *eMERLIN Galaxy Evolution survey*

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

See Beswick &Radclife talks

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

Goal

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

How

- 400 hrs eMERLIN+JVLA (Array A) @ 1.4 GHz
- 378 hrs eMERLIN + JVLA (Array A, B) @ 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

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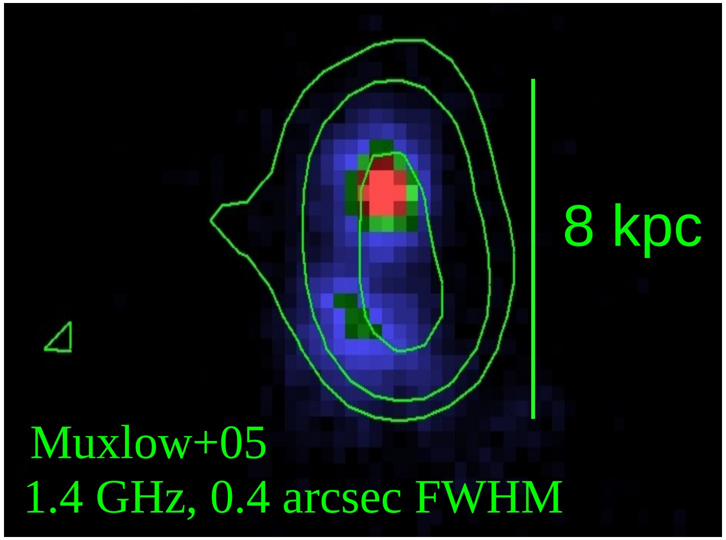
The hybrid system J123649+620737

potential hot ULIRG at z~2.2
(Casey+09)



1.4 GHz MERLIN contours on HST ACS i band image

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

The hybrid system J123649+620737: eMERLIN view @ 5 GHz

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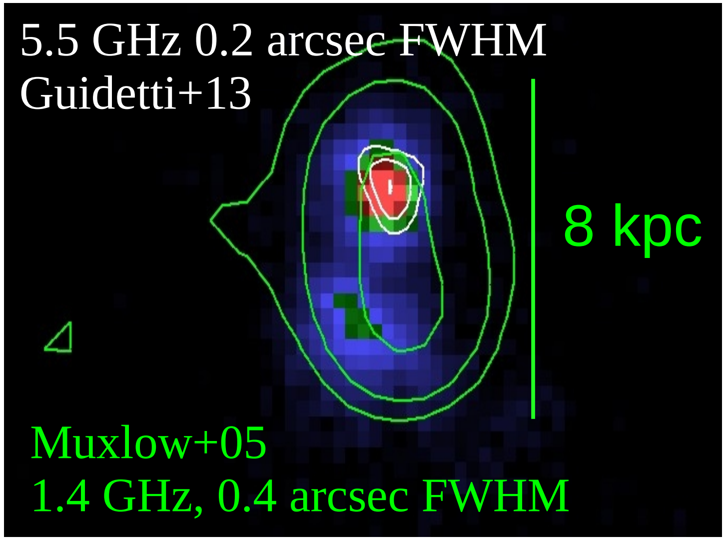

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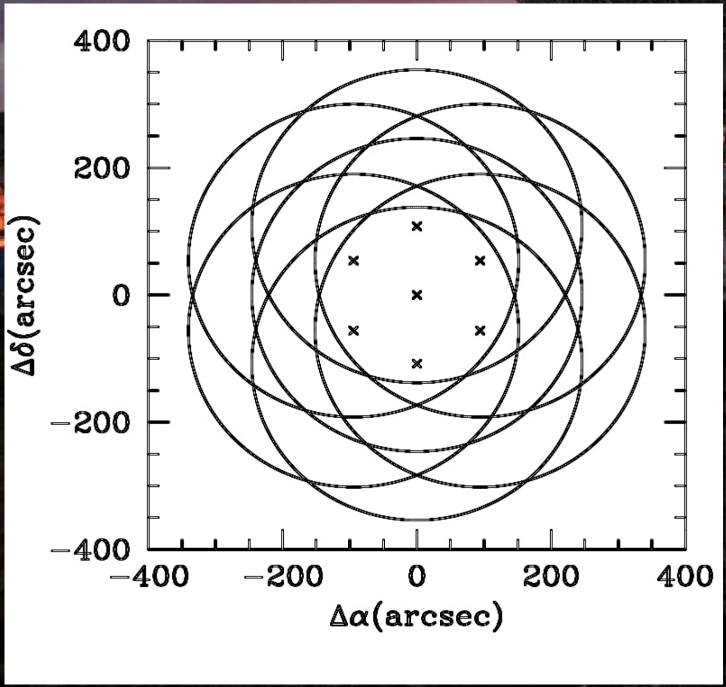
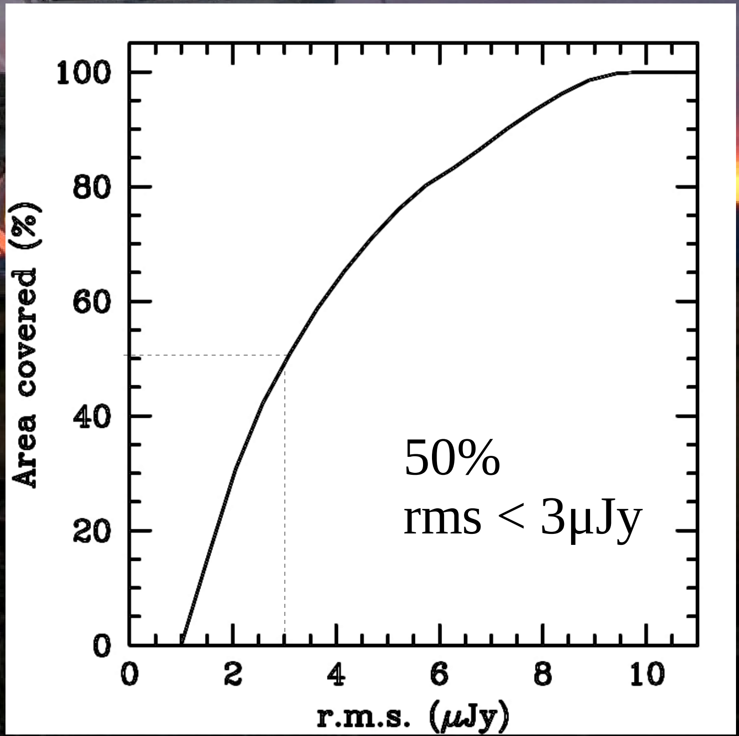
We found that AGN accounts at least for 60% for the total radio flux
→ SFR < 2800 $M_\odot$/year from our eMERLIN flux density

5.5 GHz JVLA mosaic

Guidetti+ in prep (I)

- 7-pointing mosaic in GOODS-N (matching the 5 GHz e-MERLIN one)
- Array A (14 h) & B (2.5 h) [PI: Muxlow] (Oct 2012 & Oct. 2013)
- Central frequency 5.5 GHz
- 2 GHz bandwidth (16 IFs, 64 channels of 2 MHz each)
- 0.5 arcsec resolution (A+B arrays); 1.4 μJy rms at center



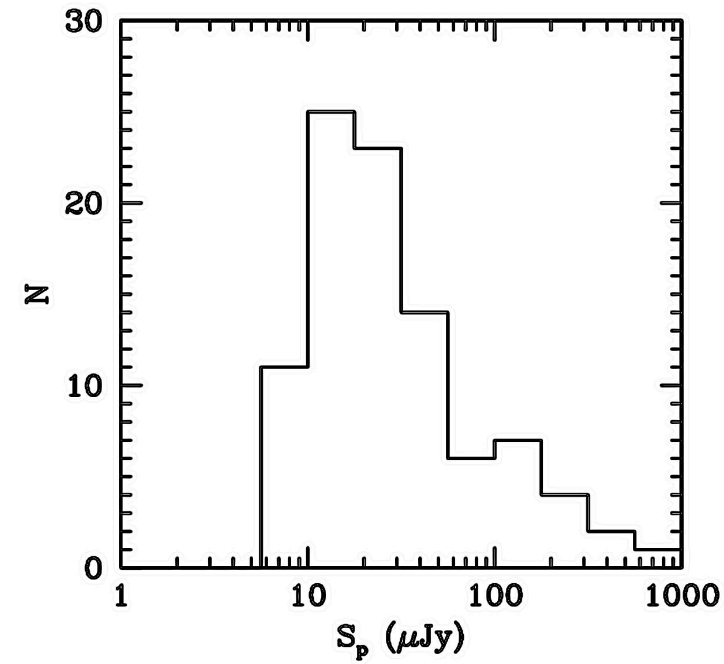


5.5 GHz catalogue & NIR counterparts

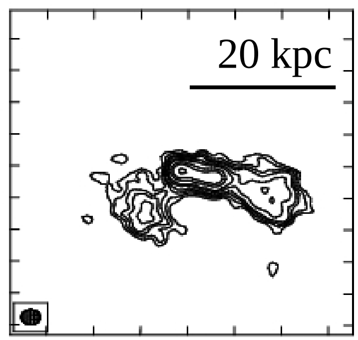
- 94 sources with S/N>5 at <7 arcmin from the centre

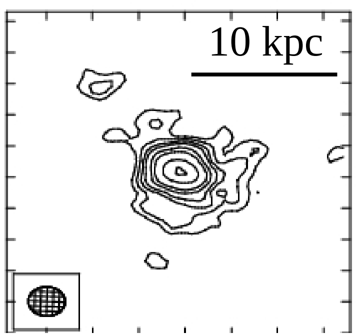
- S> 6 μJy, 50% with 10<S<30 μJy

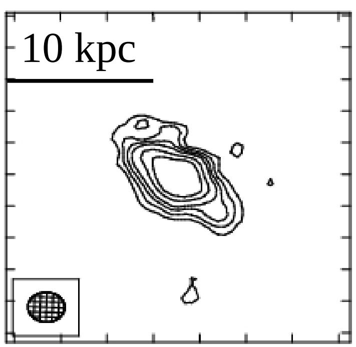
- <size> ~0.4 arcsec (~3 kpc at z=1)

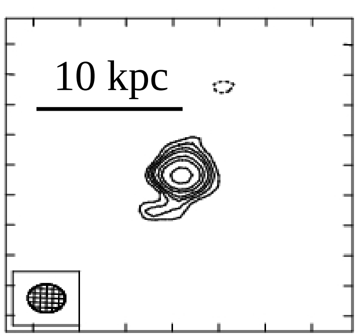


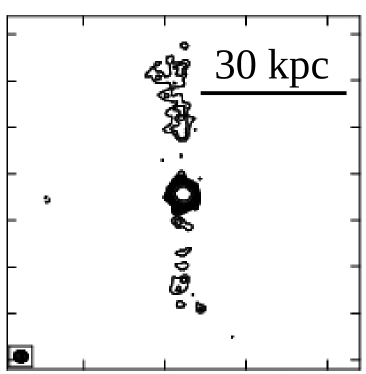
Some examples...
First contour @ 3σ











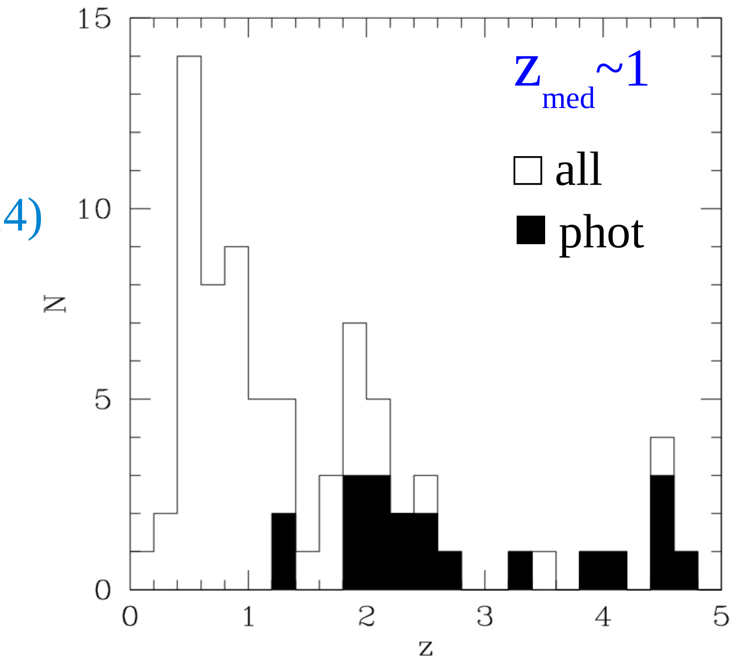
- 87% (82/94) secure Ks indentifications within <0.5”
  ultra-deep Ks-band catalogue by Wang+10
  (WIRCam, 5σ depth of Ks, AB=24.45)

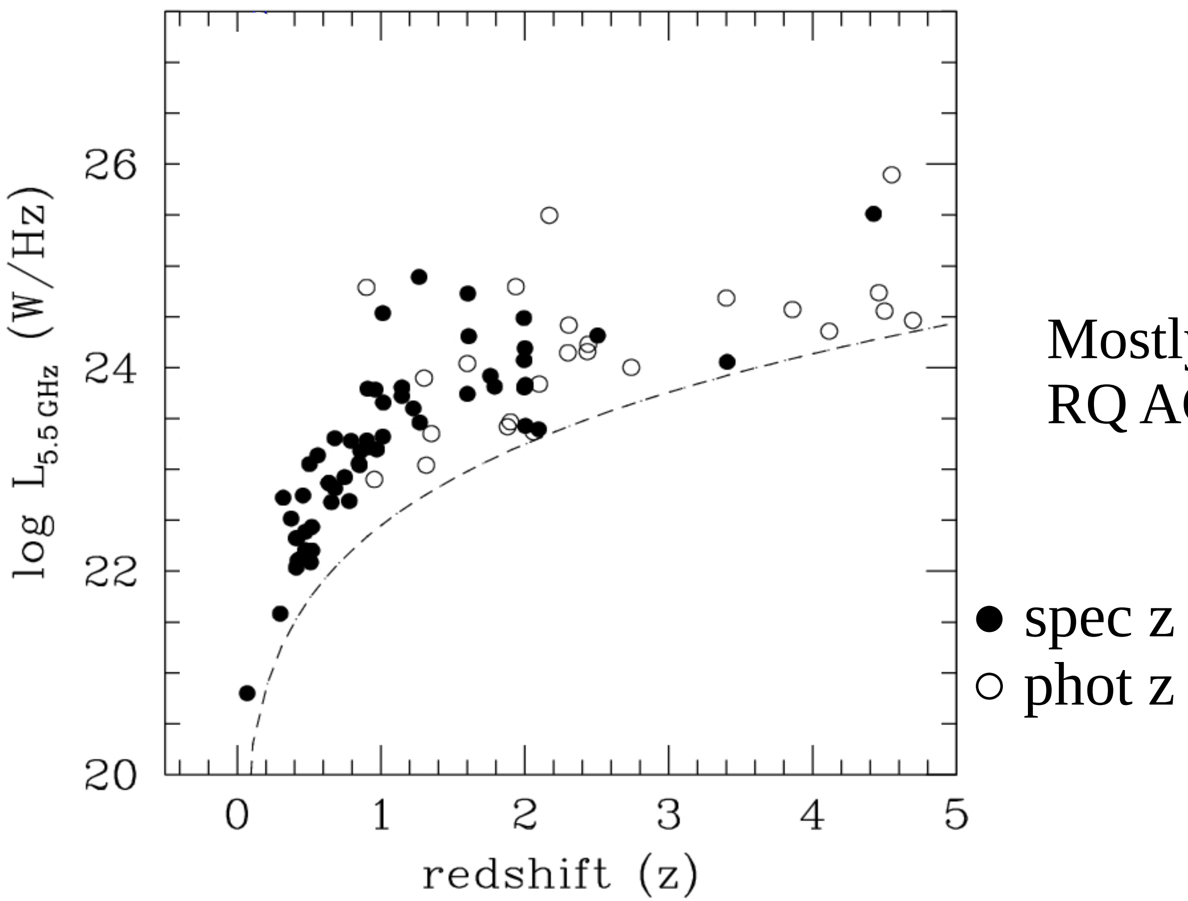
- 13% (12/94) no observed Ks counterpart:
  - Ks faint/distant/obscured sources
  - spurious? 10 with 5<S/N<5.5

Redshift and radio luminosity distribution

- 91% (75/82) with redshift (55 spec. 20 phot.)
  (from Cowie+01,Wirth+04,Barger+08, Kajisawa+10, Skelton+14)

- L= $10^{21\text{-}26}$ W/Hz

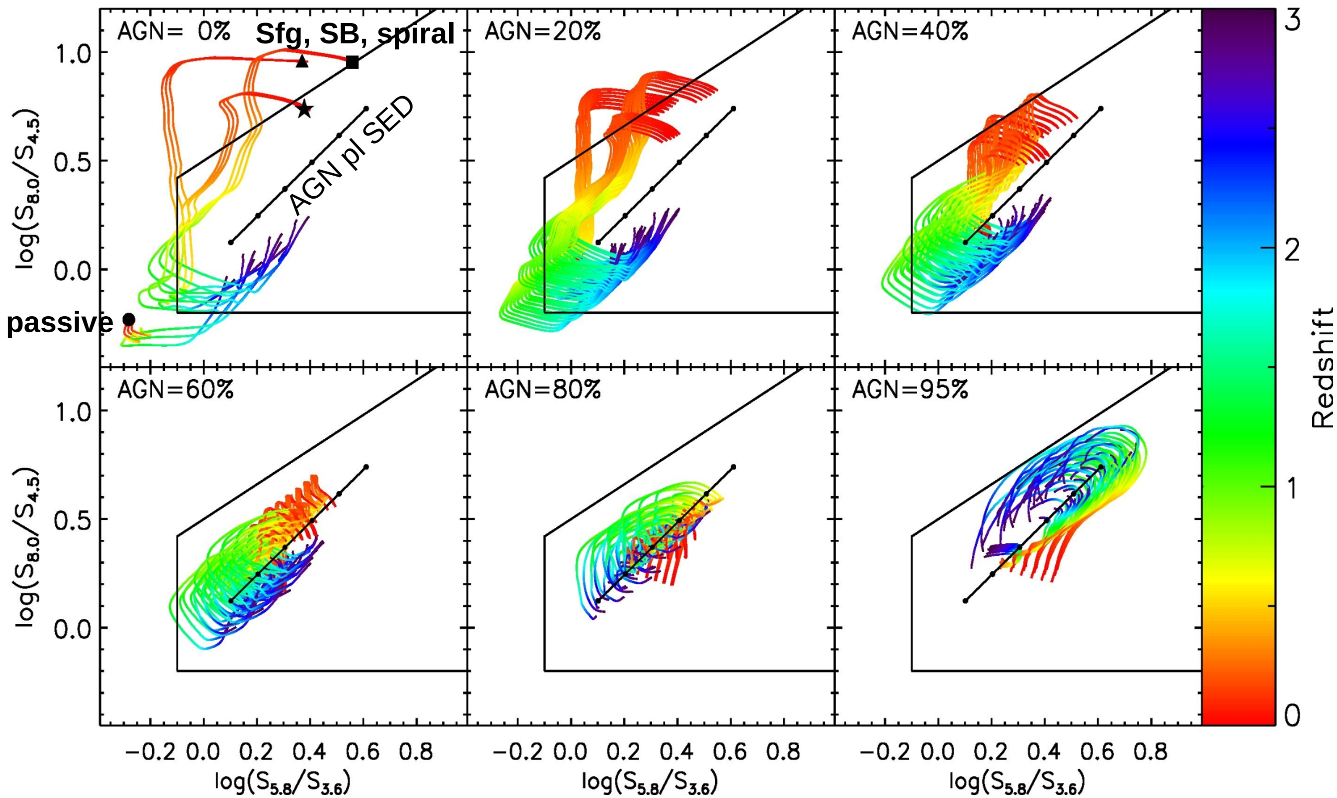




Mostly low luminosity RL AGNs
RQ AGNs, SFgs

IR classification of the 5.5 GHz sources

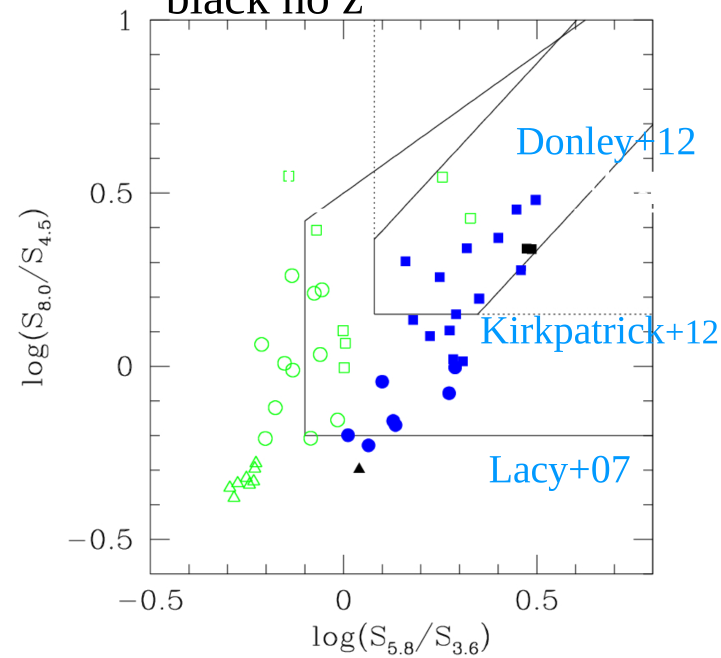
Donley+12



Guidetti+ in prep (I)

green z<1.5 blue z>1.5

black no z



- 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

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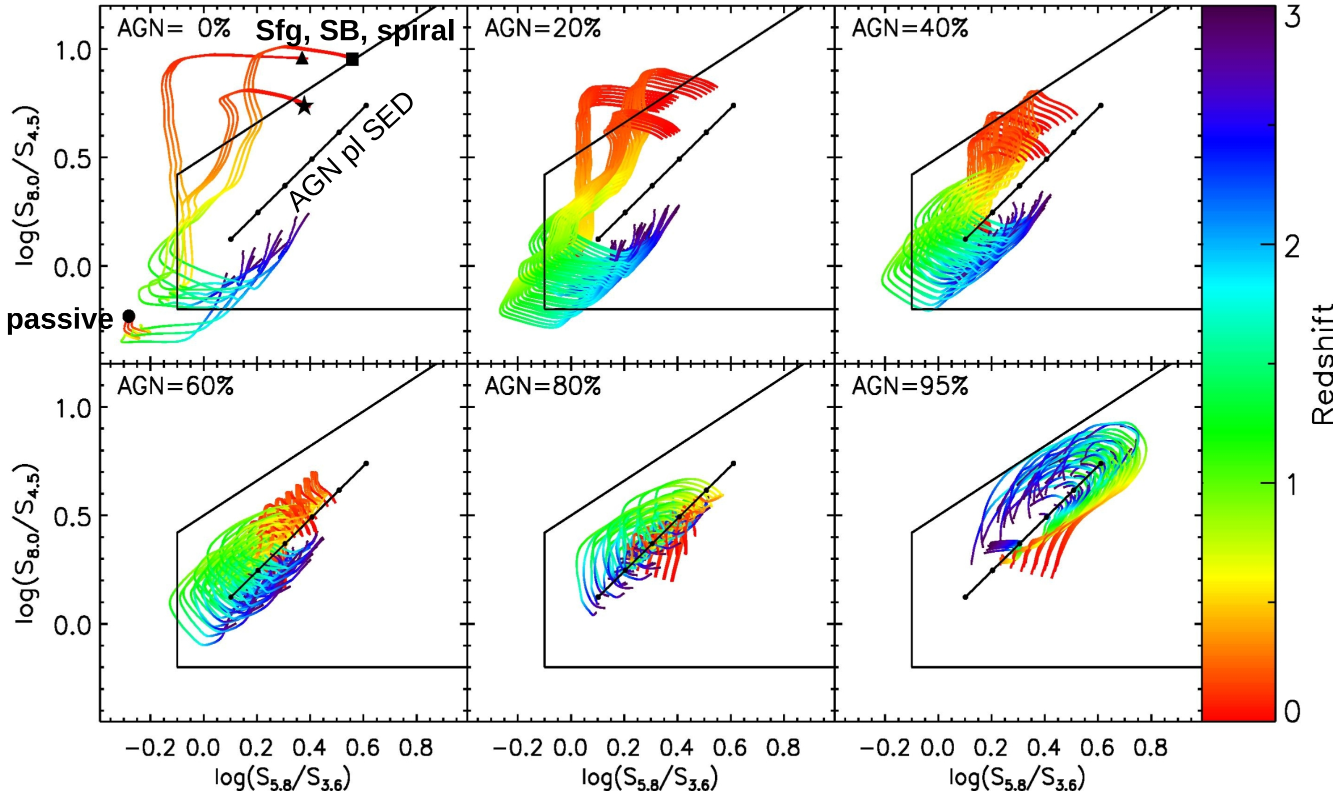

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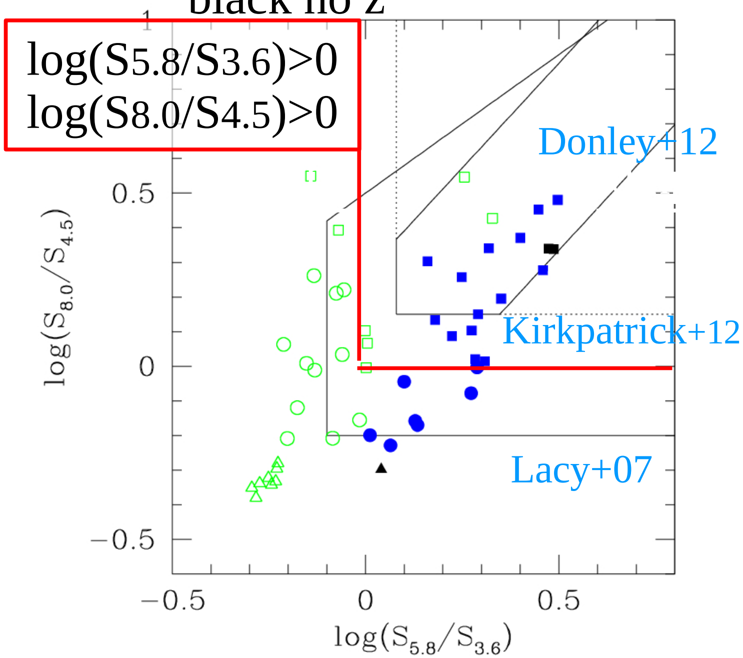

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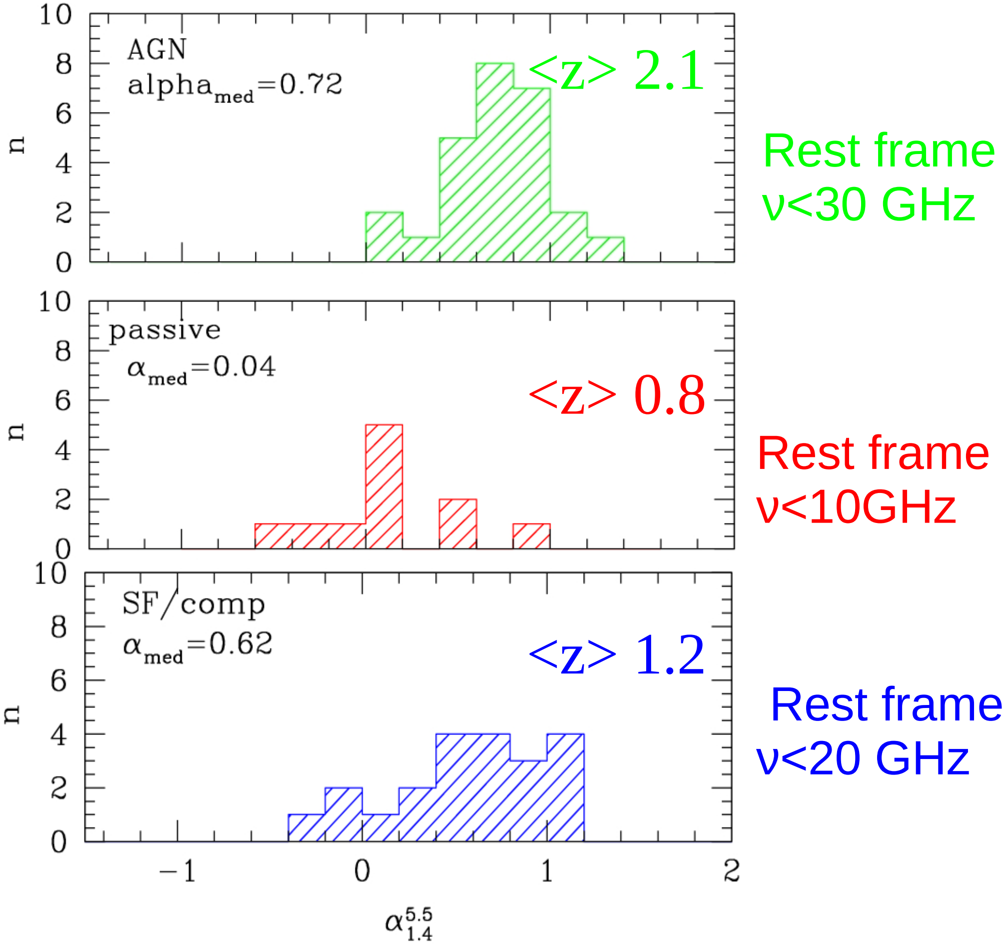
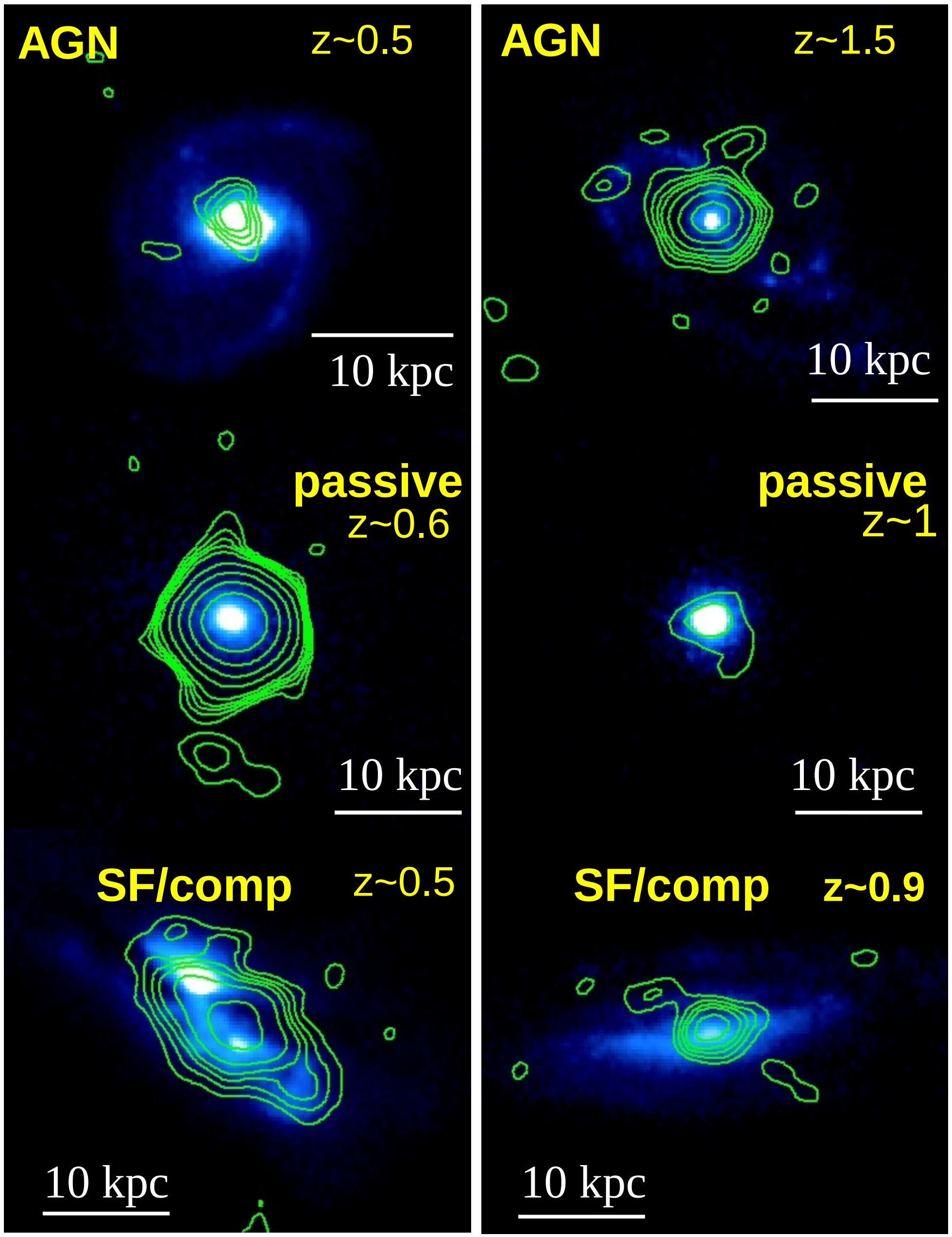
1.4-5.5 GHz spectral index

- 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)



5.5 GHz contours/ HST I band image

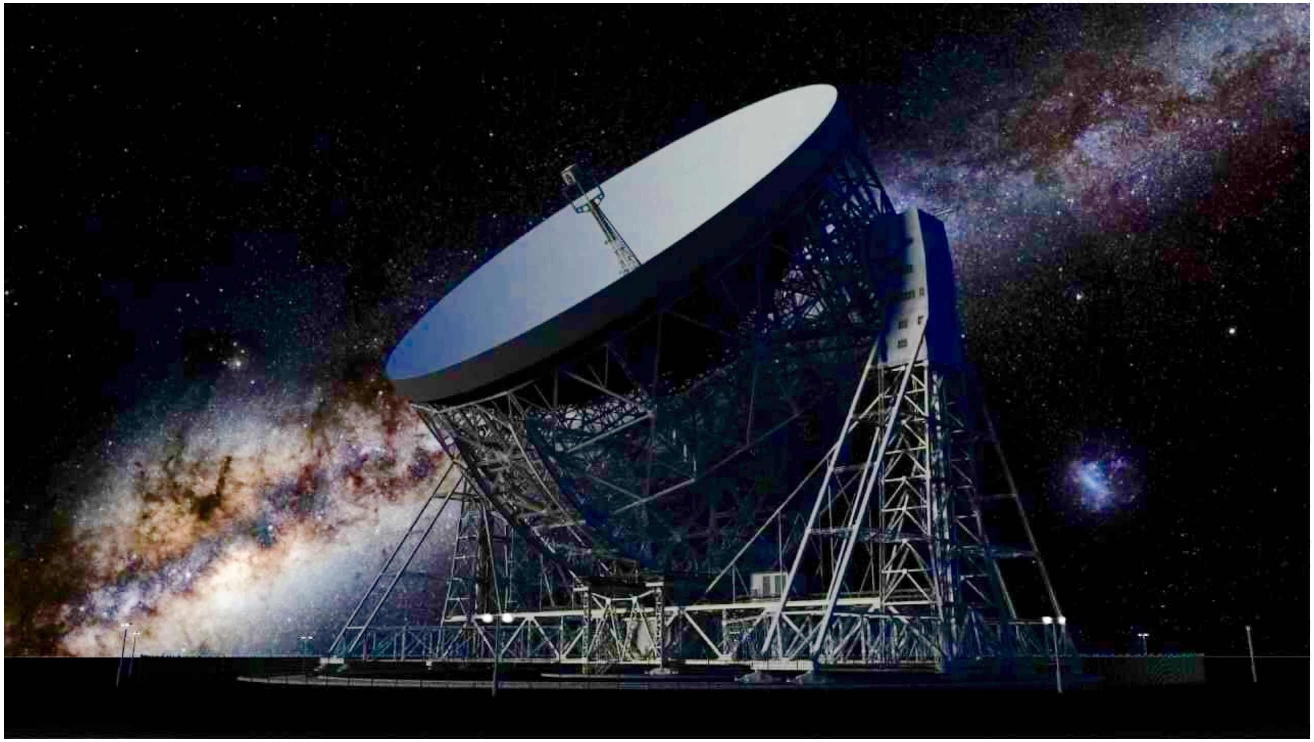


What next

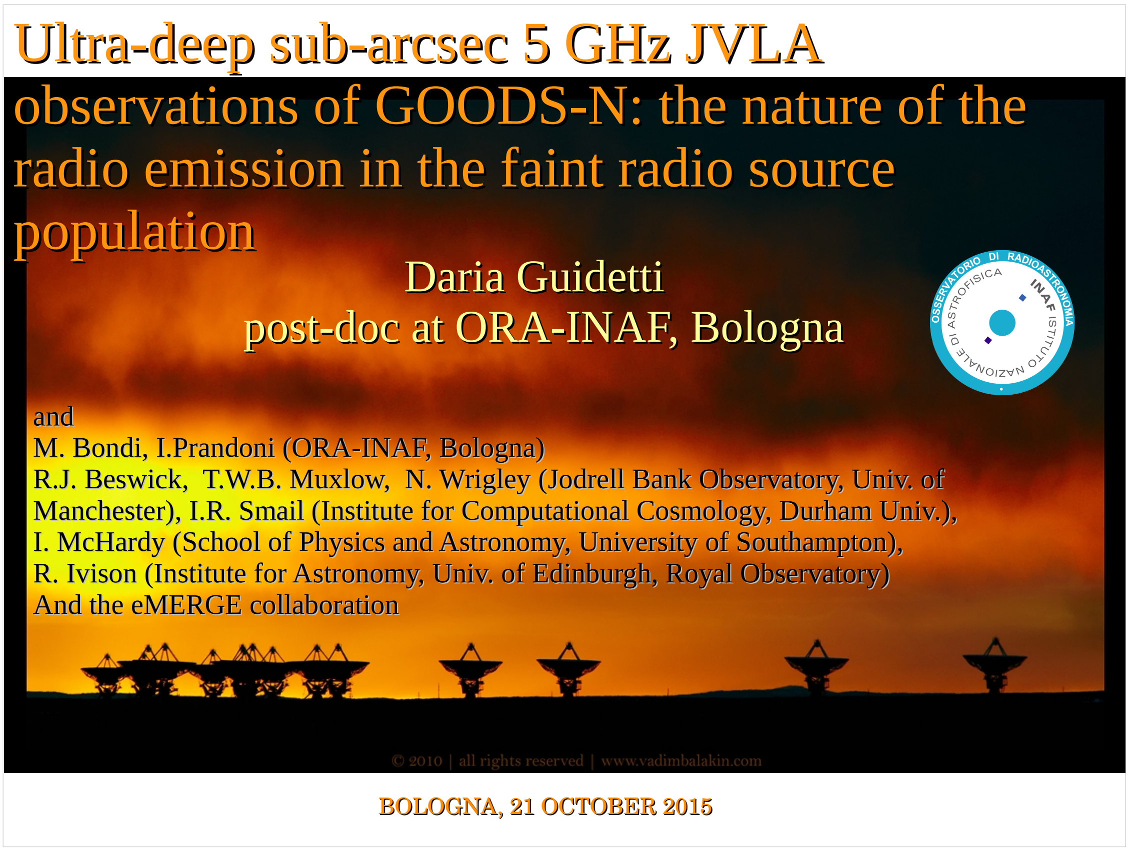
- Same analysis for a 1.4 GHz selected sample (300 sources with S>20 μJy in our mosaiced area, Morrison+10) +other multiwavelength AGN diagnostics (X-ray, q24, optical colors) (Guidetti+ in prep II)

- 5 GHz VLBI observations (18 hrs) of 5 radio excess GOODS-N sources (S>200-900 μJy @ 1.4 GHz, 3 of them have IR SED of Sfg) (PI Guidetti)

- Looking forward for 5.5 GHz eMERLIN data (Lovell included!)



Lovell telescope at Jodrell Bank Observatory (UK)



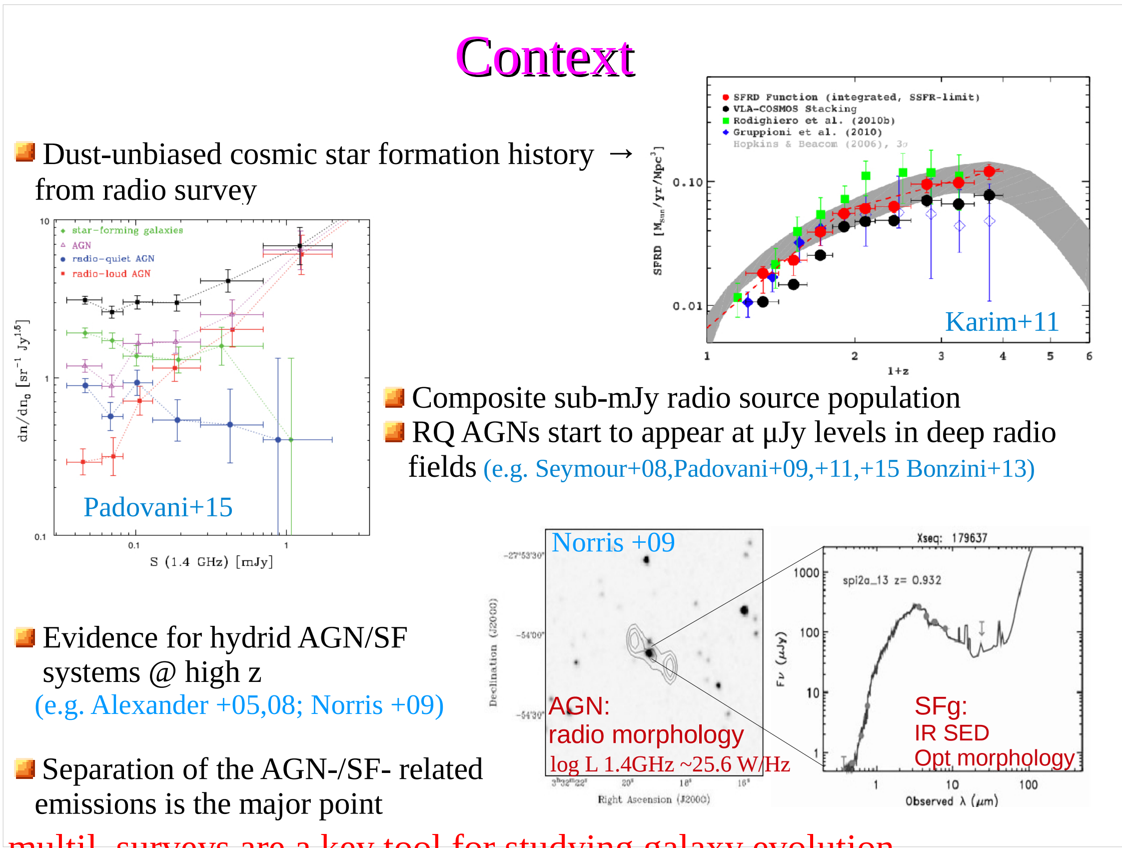
Hi all, I'm a post-doc at Ora,where I work with I. Prandoni and Marco Bondi and these are the others collaborators.

The purpose of my talk is to present the first 5 GHz catalogue of GOODS-N which falls within the context of the eMERge legacy project

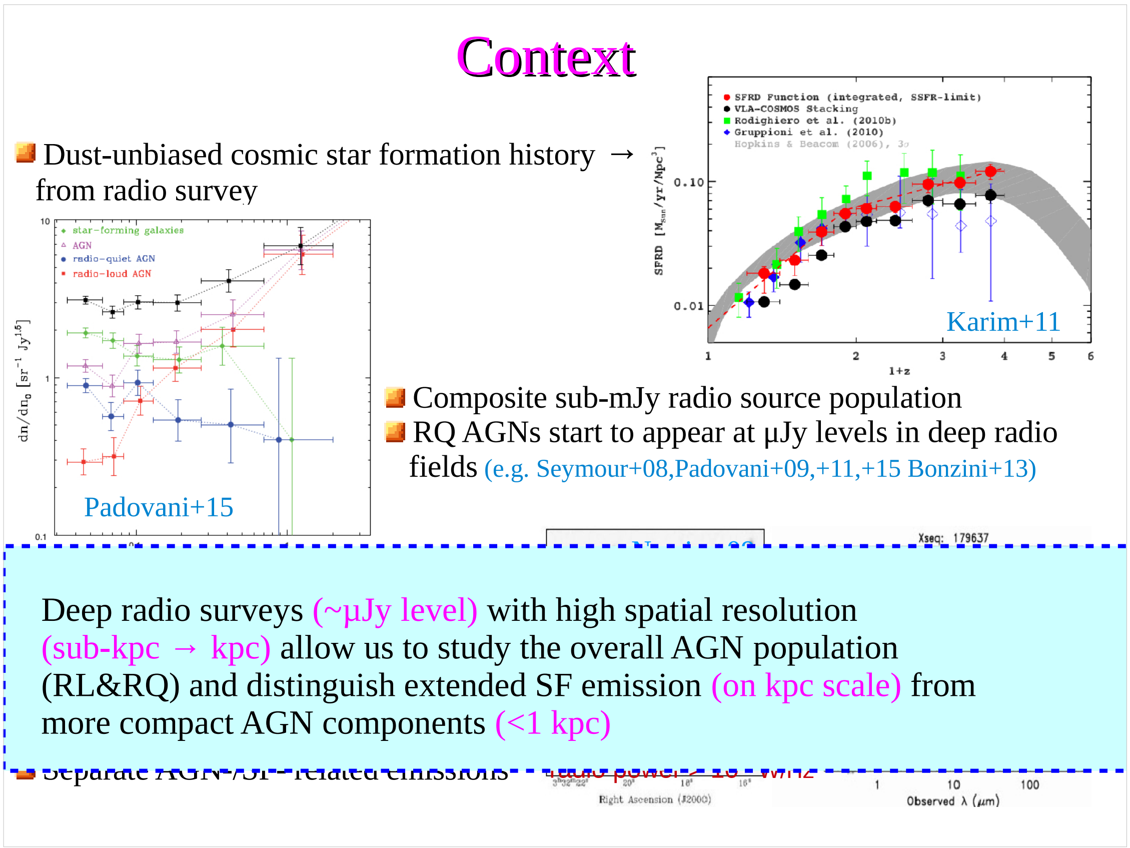
Outline

- Scientific context
- eMERGE Legacy Project
- Typical scientific case based on 5 GHz eMERLIN commissioning data in GOODS-N
- Ultra deep & sub-arcsec catalogue of GOODS-N at 5.5 GHz (JVLA)
- First IR & radio spectral analysis

To start with I will spend just a few words on the scientific context, I will briefly describe the legacy project eMERGE and summarize a pilot study carried out with eMERLIN coom. data,
Then I'll present our 5 GHz catalogue of GOODS-N based on JVLA obs. with sub-arcsec res and microJy sensititivt and finally I'll show the first analysis of the IR properties of the 5 GHz sources and their radio spectral index.



Deep multil surveys are a key tool for studying galaxy evolution.
Radio surveys are becoming increasingly important in the context of galaxy evolution because of their increasing sensitivities, because provide a powerful tool for measuring both SF & AGN activities in a way which is unbiased by dust obscuration and gas absorption and they have high ang resol. thanks to the inferferoemtry techinque..
With the help of multil info, which is fundamental, deep radio surveys allowed for example to derive the extinxtion free integrated SF history (not affected by dust obs.).
The
AGNs traditionally probed by radio surveys are the RL ones, which however represents only the 10% of the overall AGN population. Neverthless
And to investigate the composition of the radio surce population, down to the sub-mJy where it appears to be a mixture of star-forming galaxies and AGNs, including the RQ component at microJy levels.   the lowest flux densities (S < 100 μJy) and and interestengly with a significance presence of radio-quiet AGNs around microJy levels, . (RQ AGNs, by definition, are radio faint, share many multiwavelength properties with Sf galaxies,radio luminosities included and therefore it might be difficult to distinguish from Sf galaxies)
2) However, there is growing evidence for the
presence of embedded AGNs in star forming galaxies, especially at high z so hybrid systems where the twophenomena co-exist (in particular around z~2, eg Alexander et al. 2005, 2008). So, the key point is not anymore to assign...
Separate the two relative emissions is the key point.
Deep radio surveys (sensitivity at sub-microJy level) with spatial resolution on a wide range of scales (from sub-kpc up to tens of kpc) give us the possibility to study the overall AGN population (RL&RQ) and to properly map and distinguish diffuse emission associated with SF from more compact AGN components, up to high z.
Caso ibrido di Norris:This source has the radio morphology
of an AGN, but the SED of a star-forming galaxy.
 flux density of 9 mJy at a photometric redshift of 0.932, it is too faint at optical wavelengths for the Sky Survey AGN buried deeply inside a dusty star-forming galaxy.



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All of these requirements will be met by the eMERGE survey,

Which stands for emerlin galaxy evolution survey, a huge legacy project

whose goal is to obtain a complete sampling of the radio source population up to high z, and morphologically and spectrally identify and distinguish AGNs cores from Sfg in the field GOODS-N. To do that the survey is based on the combination of ultra deep eMERLIN and JVLA observations at 1.4 and 5 GHz, and when ultimated will provide angular resolution on a wide range of scales, going from 50 mas up to some arcsec (corresponding to thise spatial scales at high z), together with sub-microJy sensitivity, everything with the precious help of the plenty of multiwavelenght data that GOODS-N possesses. Bologna has the leadership for the 5 GHz survey,

Today I will present as I said the JVLA observations

The eMERLIN observations will be completed next year and today I will report on the 5 GHz JVLA observations.

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The status of the other eMERge observations was described yesterady by Beswikck

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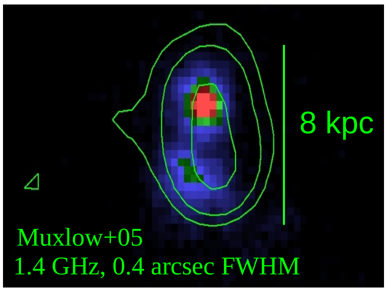
(Casey+09)

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



1.4 GHz MERLIN contours on HST ACS i band image

AGN
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- Optical compact core
- Radio excess source

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)**

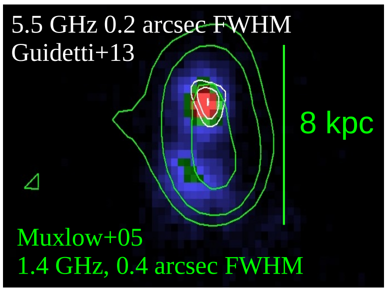
Just as hint of what will be possible to do with this survey, I will show you an interesting case of hybrid system at a z~2 which was studied in detail by Casey09. Multil observations suggest the presence of both SF and AGN activities: the galaxy has optical/NIR spectra with features that are consistent with a starburst at z~2.2 and does not exhibit AGN spectral features at all (e.g. no CIV l 1549 absorption). These are the contours of the emission seen by MERLIN at 1.4 Ghz with these ang resolution overlaid onto the HST image, the radio emission is extended over 8 kpc, a bit more than the optical counterpart, and there is no evidence for a compact radio core. Despite these info, the presence of an AGN is suggested by: the strong X-ray luminosity the very brigth and compact nucleus and the fact
It is a radio excess source (..). Casey+09 used this MERLIN data to quantify the SFR after removing the possible AGN contribution to the overall radio emission and derived a SFR of ~4000 solar masses per year.

SB spectrum: robust interstellar absorption lines which would be heavily diluted/undetected if an AGN dominated the UV con- tinuum emission;

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



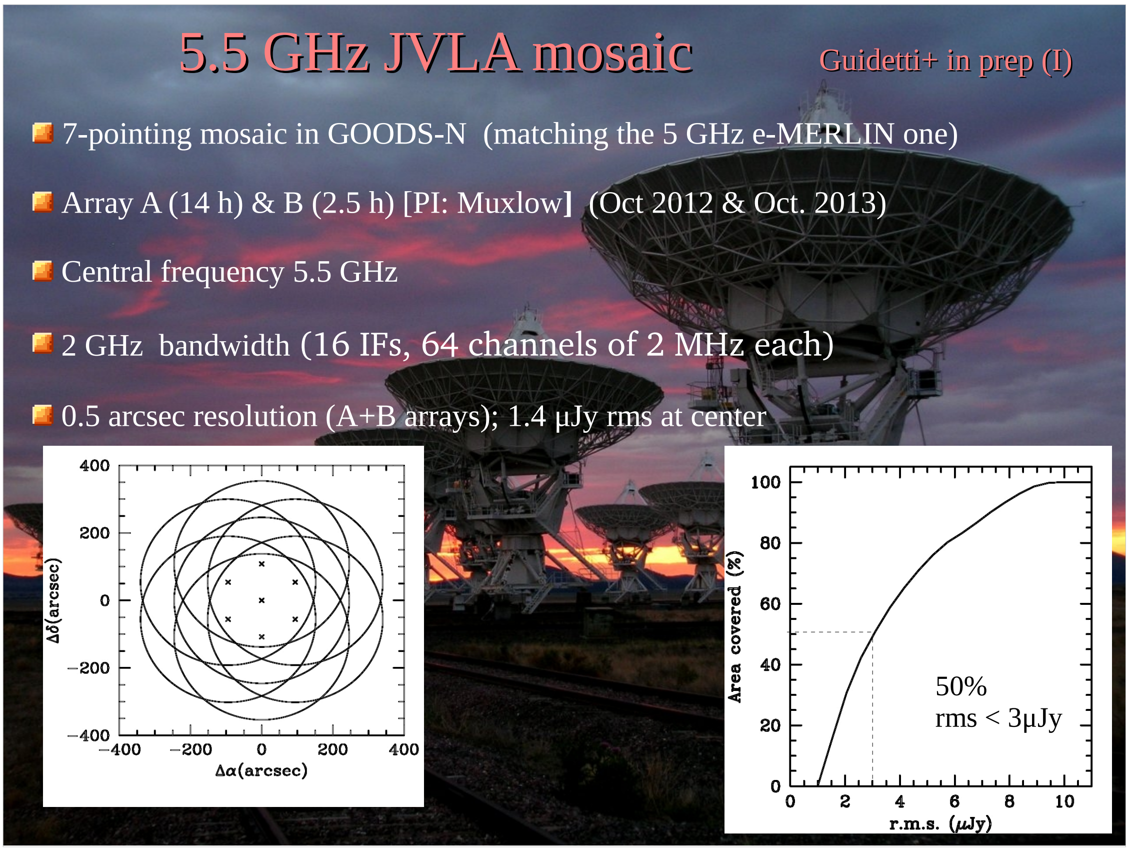
1.4 GHz MERLIN contours on HST ACS i band image

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

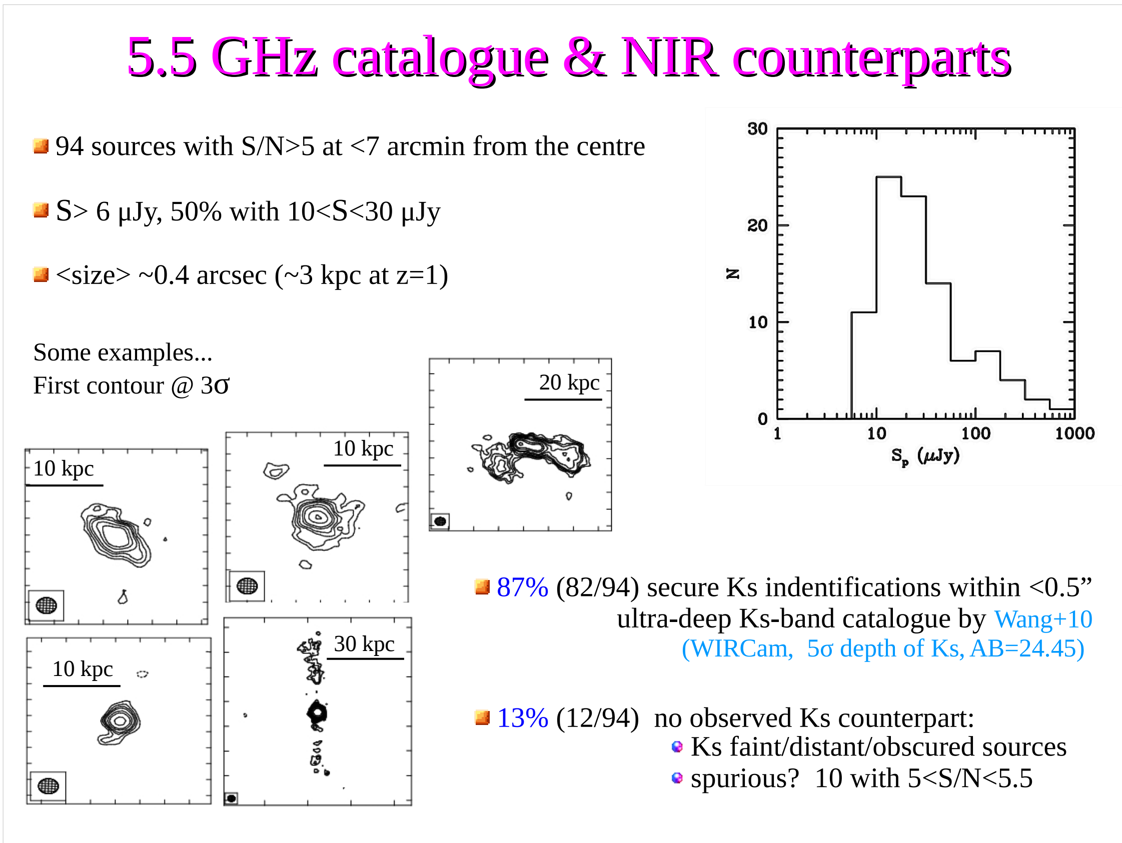
AGN flux density ~130 μJy assuming a radio core of 0.4 arcsec (MERLIN)
Radio emission: ~40% AGN + 60% SF → **SFR ~ 4000 $M_{\odot}$/year** (Casey+09)

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

Now let's add the cntrs of the emission detected by our eMERLIN data at 5 GHz, shown in white. As you can see we better identify the compact core of the AGN which overlays the bright optical nucleus and therefore we better disentangle the AGN-related emission from the presumably SF component. We found that Casey et al have underestimated the AGN flux denisity by at least the 30%, and therefore overestimated the SFR by the same amount. With our eMERLIN data , we got this value for the SFR, still high but based on a more accurate AGN flux determination.



Now I will present you the JVLA obs at 5 GHz, they consist of a mosaic of 7 pointings, very close to each other , whose geometry is optimized for eMERLIN) ,
have 2 GHz of BW and provide an angular resolution of 0.5 arcsec. This isthe visibility function of our mosaic which shows its
excellent sensitivity: the 50% of the mapped area is characterized by a rms noise lower than 3 microJy, and the whole field has a noise <10 microJy.
This makes our survey the most sensitive one at this freq, and moreover coupled with a subarcsec resolution.



We built a catalogue of 94 sources above a local S/N of 5, in a circular region of radius 7 arcmin around the mosaic centre whose peaks are brighter than 5 times the local noise.

The peak brightness distribution here shows that half of the sources fall bewteen 10 and 30 microJy. Their mean radio angualr size is 0.4 arcsec which corresponds to ~ 3 kpc at the median z of the catalogue, (and I will show the z distirbution in the next slide). This means that the majority of our sources are extended on galactic-sub galactic scale, and hence mostly AGN systems have core / core-jet morphologies.

The 87% of our catalogue have a secure Ks band counterpart in the ultra deep catalogue by Wang+10, characterzised by this sensitivity depth (in the Vega system).

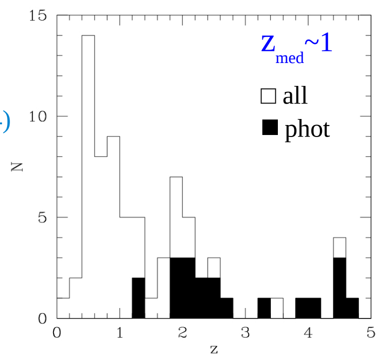
The continum histo shows the distribution of the offset between the radio and the nir poisitions.

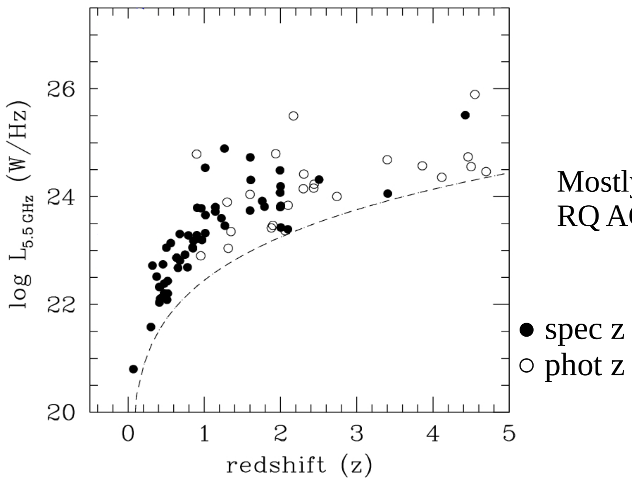
12 sources have no Ks counterpart , so they could be either spurius radio sources, and they have low S/N ratios in our mosaic,

Or more intringuing, they could be intrinsecally faint also in the NIR or obscured.

Redshift and radio luminosity distribution

- 91% (75/82) with redshift (55 spec.   20 phot.)
  (from Cowie+01,Wirth+04,Barger+08, Kajisawa+10, Skelton+14)
- L= $10^{21\text{-}26}$ W/Hz





Mostly low luminosity RL AGNs
RQ AGNs, SFgs

In this slide I show the z and radio luminosity disitrbution of our catalgue.

More than 90% of the Nir identified radio sources possess a z: mostly are spec and these are essentially available up to a z of ~ 2. The solid histogram is the distribution of all z,

And displays one peak aournd 0.6 and a secondary peak aournd 2, and has a median of ~1, We have checked that when a source possesses both spectroscopic & photometric z, these are well in agreement, (therefore we consider quite reliable the phot measurements by Kajisawa also for the highest z object) Here I plotted the rest-frame radio luminosities against z,

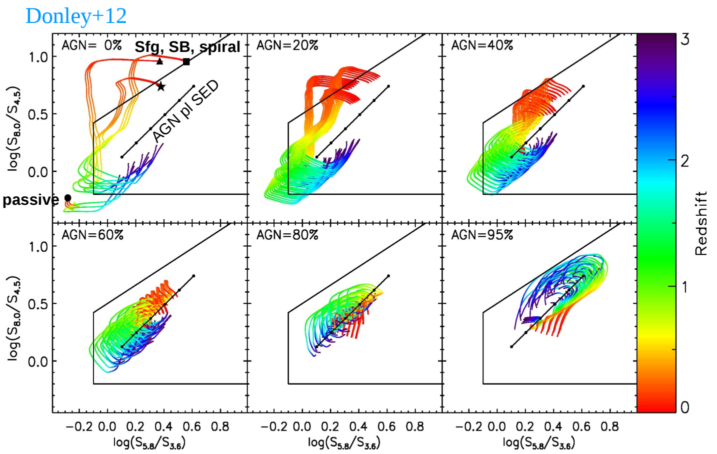
together with some well known local radio sources of different types (Sfg, AGNs) our 5 sigma detection threshold is plotted as dashed line assuming assuming an average radio spix of 0.7, which is the typical value for extragalactic radio sources, You can see that we are sensitive to objects with radio luminosities as faint as 10 **22 up to z of about 1, so we are selecting quite low Lr, typically found in sources characterized by moderate star formation processes (SFR ~ 9 Mstar/year). Essentially with these obs. which are not completed yet, I recall,   we have increased the sensitivity by almost an order of magnitude wrt the previous deep radio surveys.

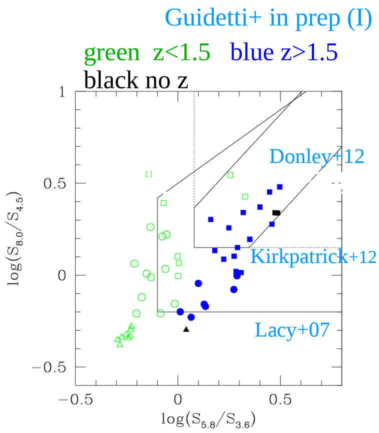
In general our objects are more powerful than M82, and their Lr are similar to those of FRI radio galaxies like M84, Virgo A, and significantly lower than those of FR II and powerful quasars

After all, GOODS-N whas chosen as a field free of strong radio emitters
we are selecting radio sources which

may include RQ, RL AGNS, passive galaxies and Sfg as well.

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

Many IR cc criteria are used to classify sources as AGNs, Sfg and passive galaxies, on the basis of their different SED across the IR band.

For samples characterized by sources spanning a wide range of z (as our catalogue) it is essential to take into account the color evolution with z to avoid misidentifiations. This is clearly shown by this figure from Donley+12 which displays the expected IRAC colors of different type of galaxies with varying AGN contribtuions and their evolution in z.

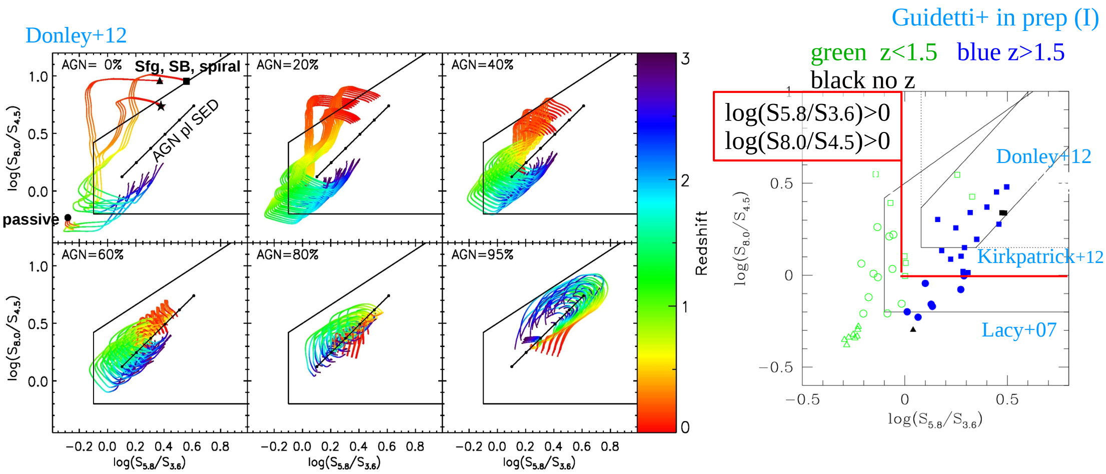
This is the orginal AGN selection region by Lacy+, this is the locus for luminous AGNs with IRAC power law SED. As the AGN contribution to the MIR emission increasis, the tracks move closer and redward to the power law locus. Pure star forming and passive at low z tend to stay here, but as z increasing they move inward the Lacy region, contaminating the AGN identifications. To our 5 GHz selected sources, we applied these 5 IR CC criteria, based on IRAC, Ks and FIR Herschel photometries..

here I just show the original CC plot by Lacy+ with their AGN selection wedges, and those revised by Donley+ and Kirkpatric+, and which summarised the classifications from all the IR AGN selection criteria used.

Squares symbols indicate sources which are classified as AGN candidates by at least one of these IR criteria, in total are 36 objects. The other criteria add these points which are clustered near the bottom left of the Donely+ wedge. So, as far as concerns our radio sample, widening the AGN selection region with these color cuts in red, would allow us to select all the AGN candidates.

Triangles indicate this cluster of sources with IRAC colors typical of passive galaxies at z<1 (still according to this study). Finally, the circles are the 24 sources which do not fit in the AGN selection region of any of these used colo color plots. Following the Donely tracks, they could be pure star forming galaxies, hybrids systems not AGN dominated, or early type gal. at high z.

IR classification of the 5.5 GHz sources



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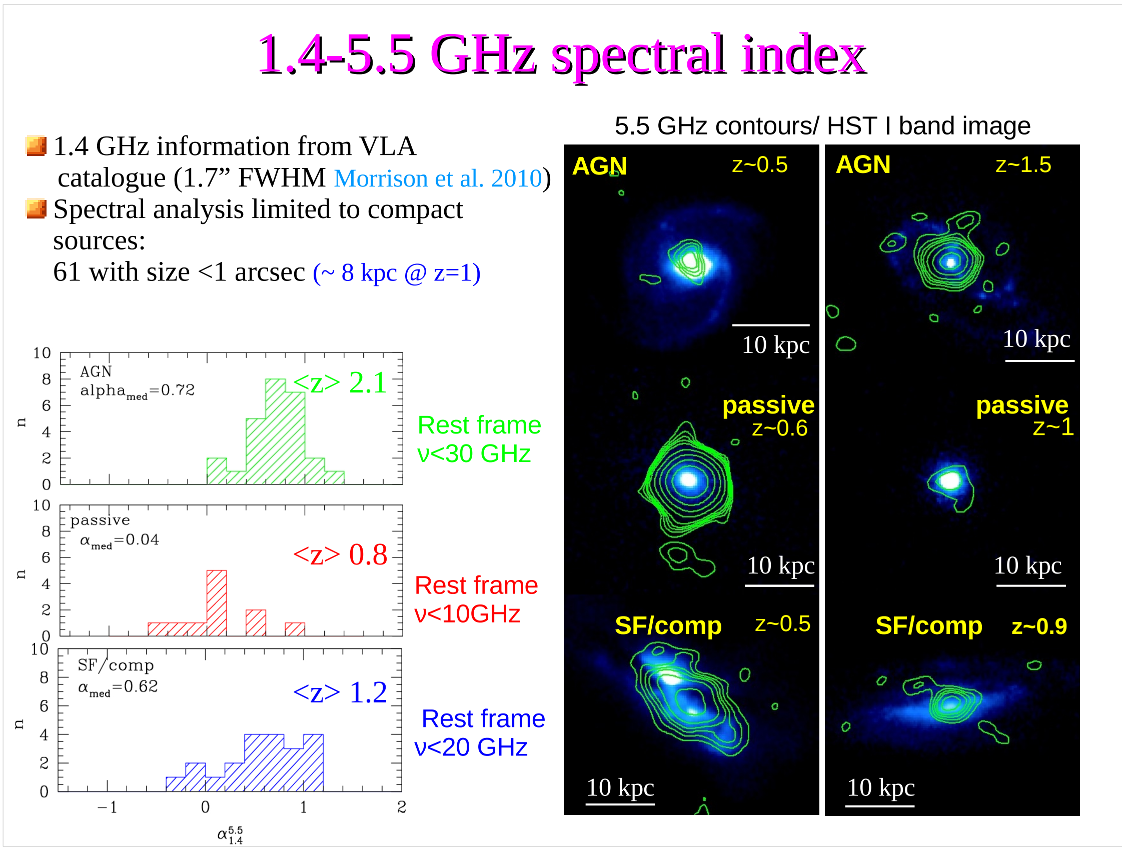


We derived radio spectral index by using the Morrison+ catalogue at 1.4 GHz.

and restricted the spectral analysis to a sub-sample of sources with size smaller than 1 arcsec, because this guarantees a similar surface brigthness sensitivities at the two radio frequencies and this essential to derive reliable spectral indeces. At the median z of our sample, 1 arcsec corresponds to 8 kpc, therefore we're selecting radio emission on galactic scale, as shown in these examples of radio contours overlaid on the HST images. which could be associated with SF, cores of RG, compact Quasars. At the rest-frame frequencies we are probing, a radio emission with flat/inverted spix is likely to be powered by an AGN (as free free emission/absorption are negligible at the rest frame freq.), so it can be used as a positive AGN diagnostic. However, our spectral indeces are global, I mean they refer to this overall emission on kpc scale, so they include contributions from the host galaxy and from possible AGNs cores and jets, and therefore we could miss flat-spectrum cores if these are not dominant. Now, the spectral distribution of the IRAC AGN candidates is characterized on average by steep spectra, indicating optically thin synctrorton emission, and this is consistent with what found in X-ray selected AGNs, and might suggest a radio emission, still on average, dominated by the host galaxy. In contrast, that of the passive galaxies is flatter suggesting a relative large fraction of self-absorbed radio AGN cores, as observed in many local FRI radiogalaxies (also on VLBI scale), so these passive sources should be the counterparts at high z and at low radio luminosity of FRI radiogalaxies. The distribution of the remainders is steep on average but does not show any particular peak. This is symptomatic of a mixture of radio emission processes, (SF,jets))somewhat expected considering the multiple possible IR classifications. Finally, the optical images seem to confirm the IRAC classifications: optically bright & compact cores are seen in the quasar mode AGNs, the coutnerparts of the passive galaxies are early types. I wish to add that in many of these sources, the host galaxies seem to have disturbed morphologies or ongoing mergers, which could enhance the SF and give raise to the steep spectra.

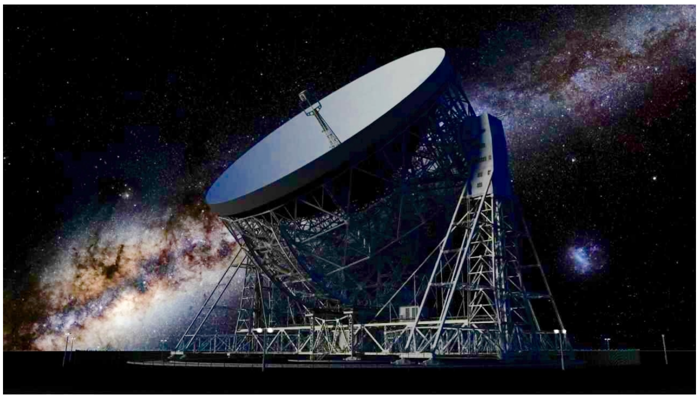
The spatial scales of the sampled emission is more or less the same, independently of z, As for such z values the conversion from angular to linear scales are similar..

What next

- Same analysis for a 1.4 GHz selected sample (300 sources with S>20 μJy in our mosaiced area, Morrison+10) +other multiwavelength AGN diagnostics (X-ray, q24, optical colors) (Guidetti+ in prep II)

- 5 GHz VLBI observations (18 hrs) of 5 radio excess GOODS-N sources (S>200-900 μJy @ 1.4 GHz, 3 of them have IR SED of Sfg) (PI Guidetti)

- Looking forward for 5.5 GHz eMERLIN data (Lovell included!)



Lovell telescope at Jodrell Bank Observatory (UK)

This is my last slide:
What we are doing
-we're performing a same analysis on a larger GOODS-N sample selected at 1.4 GHz in the area of our mosaic (300 sources) starting from Morrison+/Owen (in prep) observations by looking also at at other AGN activity indicators and the spectral analysis will be done in details

- start the calibration of new VLBI data of 5 radio excess sources where we hope to reveal compact radio cores.
However,
we're looking forward to having the 5 eMERLIN data which will allow us to explore the nanoJy sky at mas-subarcsec resolution

Obviously, the eMERge survey is a pathfinder for SKA surveys, MIGHTEE tier1 and SKA1 wide is expected to reach teh same sensitivity but over almos the all sky