Deep and sharp imaging with LOFAR: revealing the evolution of AGN

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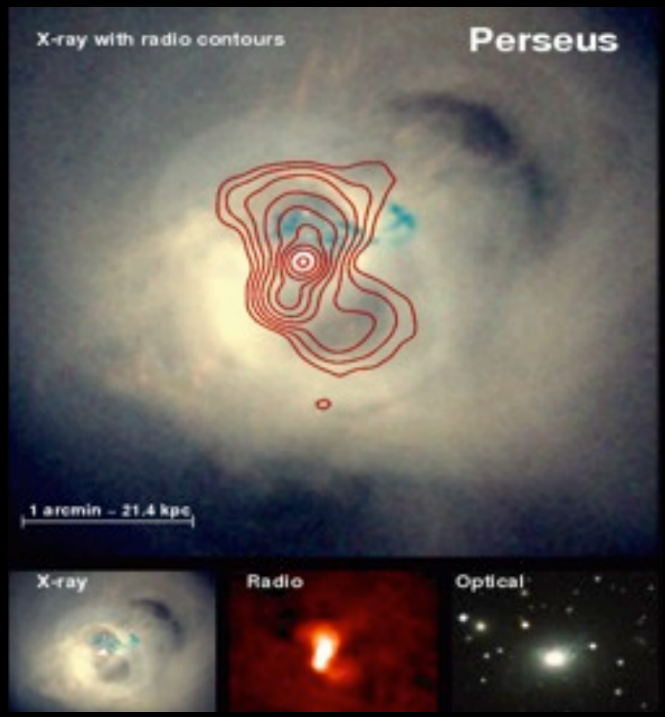
University of Hertfordshire

motivation

e.g. Croton+ 2006

Important for galaxy formation and evolution

- Heating from radio jets provides a means to balance cooling of the hot halo gas
- Stops star formation
- Self-regulating feedback

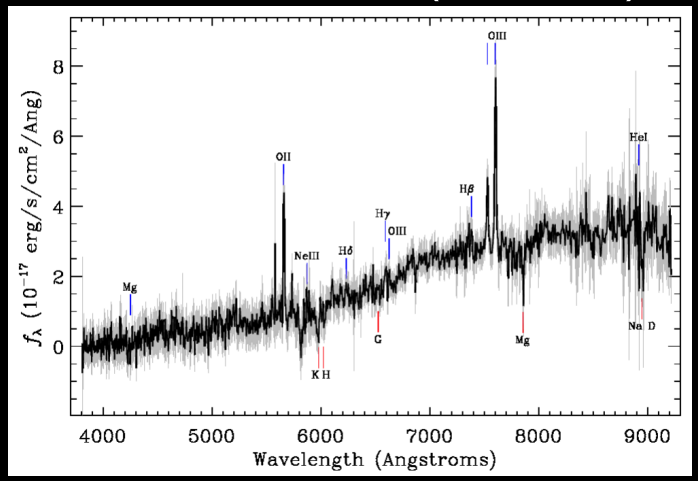


2 types of radio agn

Hine & Longair 1979

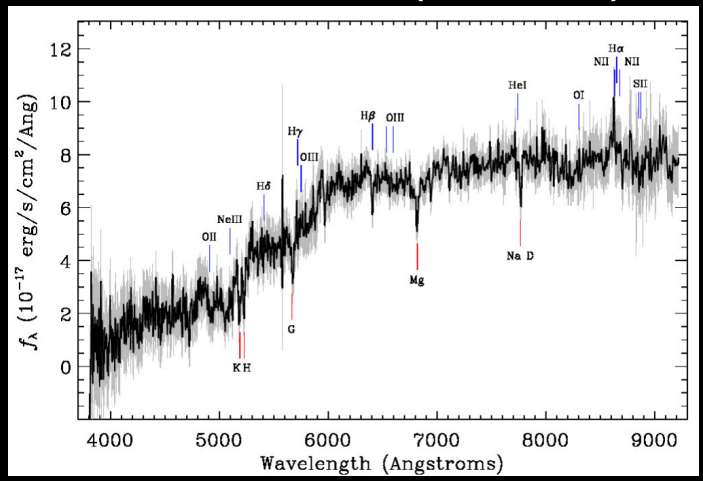
Laing+ 1994

High Excitation (HERGs)



- Typical AGN
  - With an accretion disk
  - Strong emission lines
  - X-ray
  - IR/sub-mm dusty torus
- cold/radiative mode

Low Excitation (LERGS)

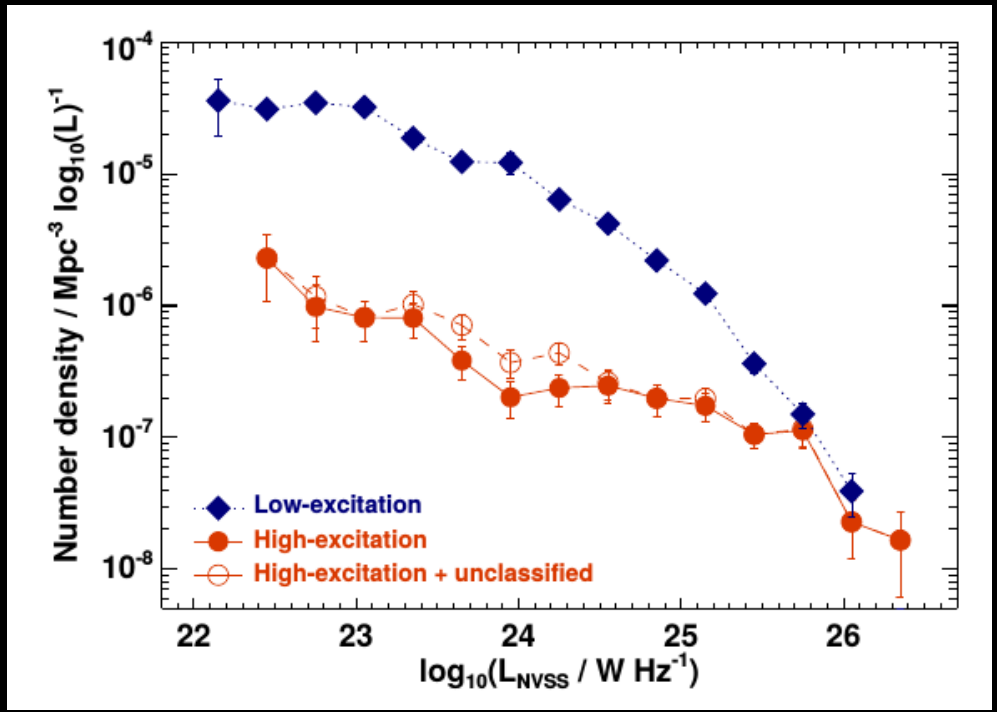


- Atypical
  - Missing all the emission associated with an accretion disk
  - Accretion of hot gas...
- hot/jet mode

the local population

Best & Heckman 2012

- SDSS DR7 + NVSS/FIRST
  - $> 18,000$ radio sources
- Both HERGs & LERGs are found over most of the range of luminosities
- LERGs dominate at low powers



what don't we know

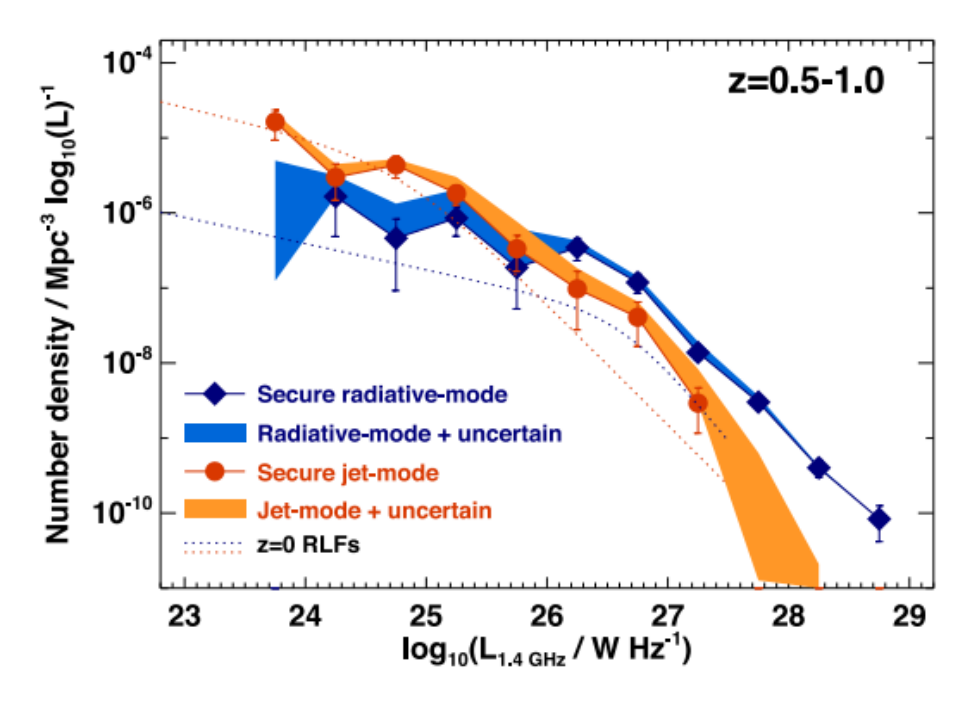
- How important are the different accretion modes in terms of galaxy evolution?
- How do they evolve with redshift?
- How efficient is the feedback?
- We can look at how the radio-loudness depends on:
  - Mass
  - Star formation
  - Galaxy type (e.g. colour)
  - Ionisation state

...All over cosmic time

the population at higher z

Best+ 2014

also Pracy+ 2015

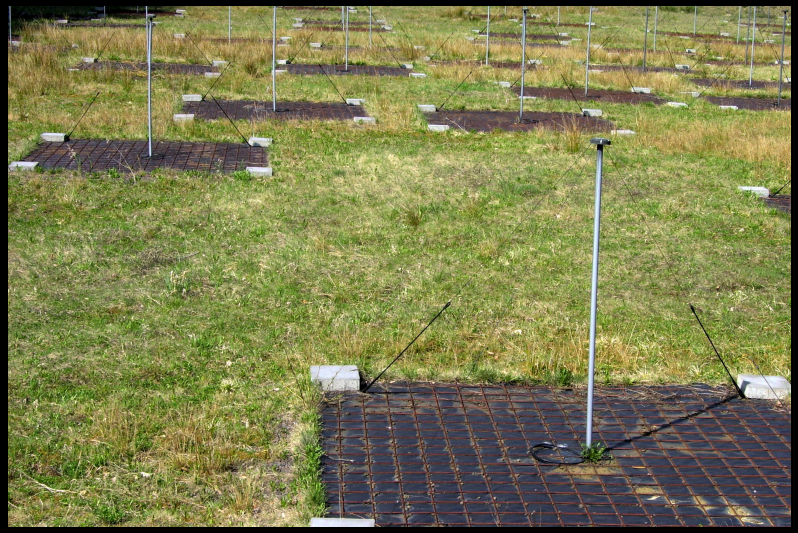


HERGs evolve strongly

LERGs are only weakly evolving

what do we need?

1. LARGE SAMPLES of Radio Galaxies
    - Going out to higher z
    - LOFAR
        - Steep spectra
        - Live longer
        - High sensitivity and resolution (0.1 mJy, 5" @ 150 MHz)
        - Wide field of view



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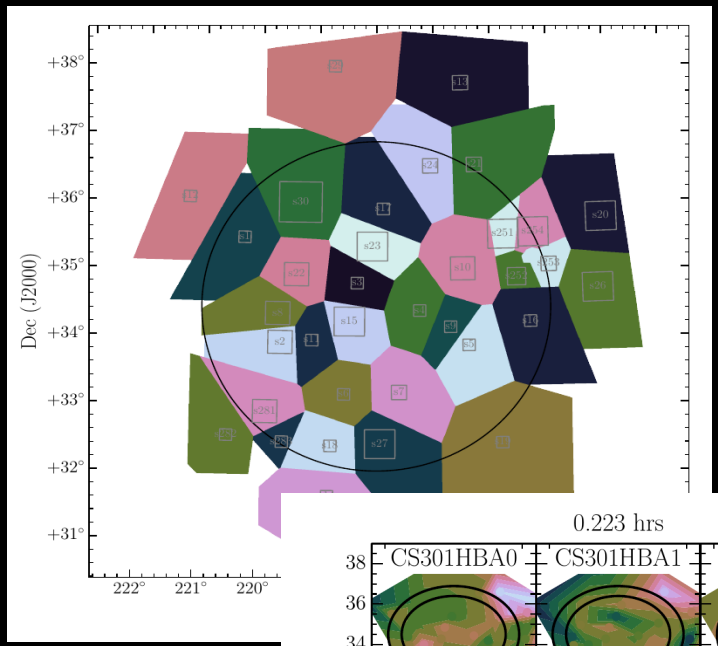
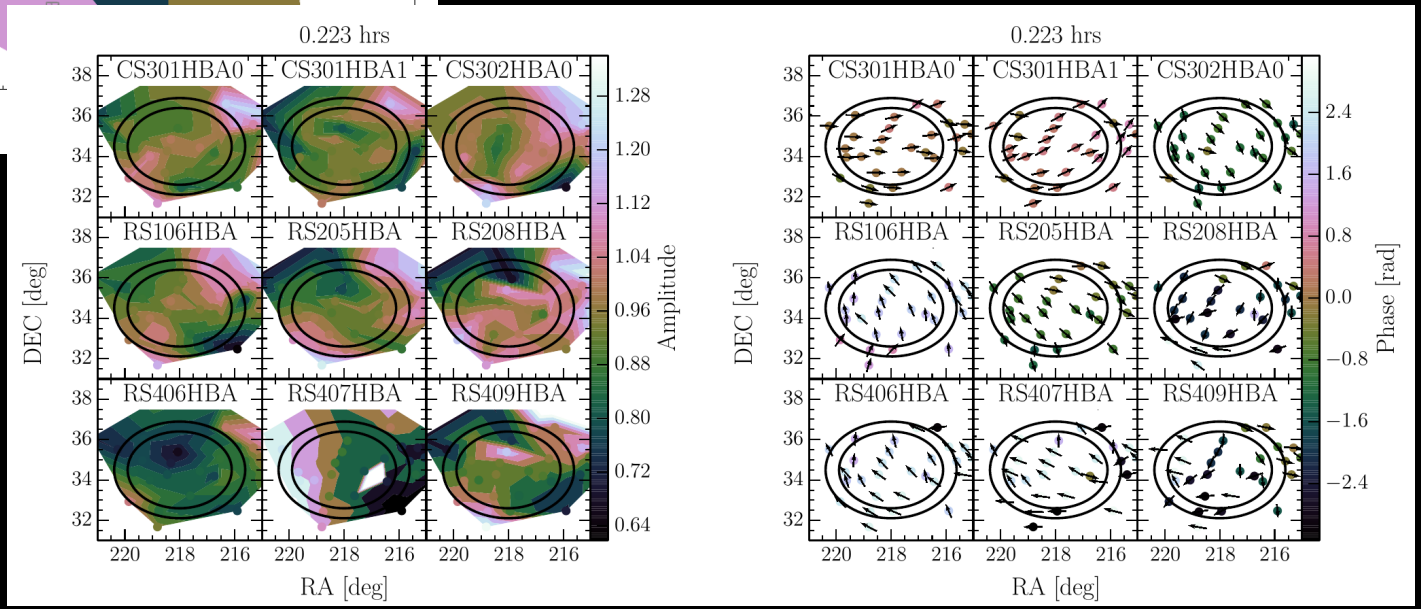
2. Matched to excellent multi-wavelength data
    - z, mass, SFR,... from photometry
    - Excitation state... from spectroscopy(?)
    - Famous extra-galactic deep fields

direction-dependent ionospheric calibration



"Facet"-based direction-dependent calibration

van Weeren, WLW+ 2016



LOFAR Boötes HBA image

WLW+ 2016

"Facet"-based direction-dependent calibration

150 MHz

40 MHz bandwidth

8 hr observation

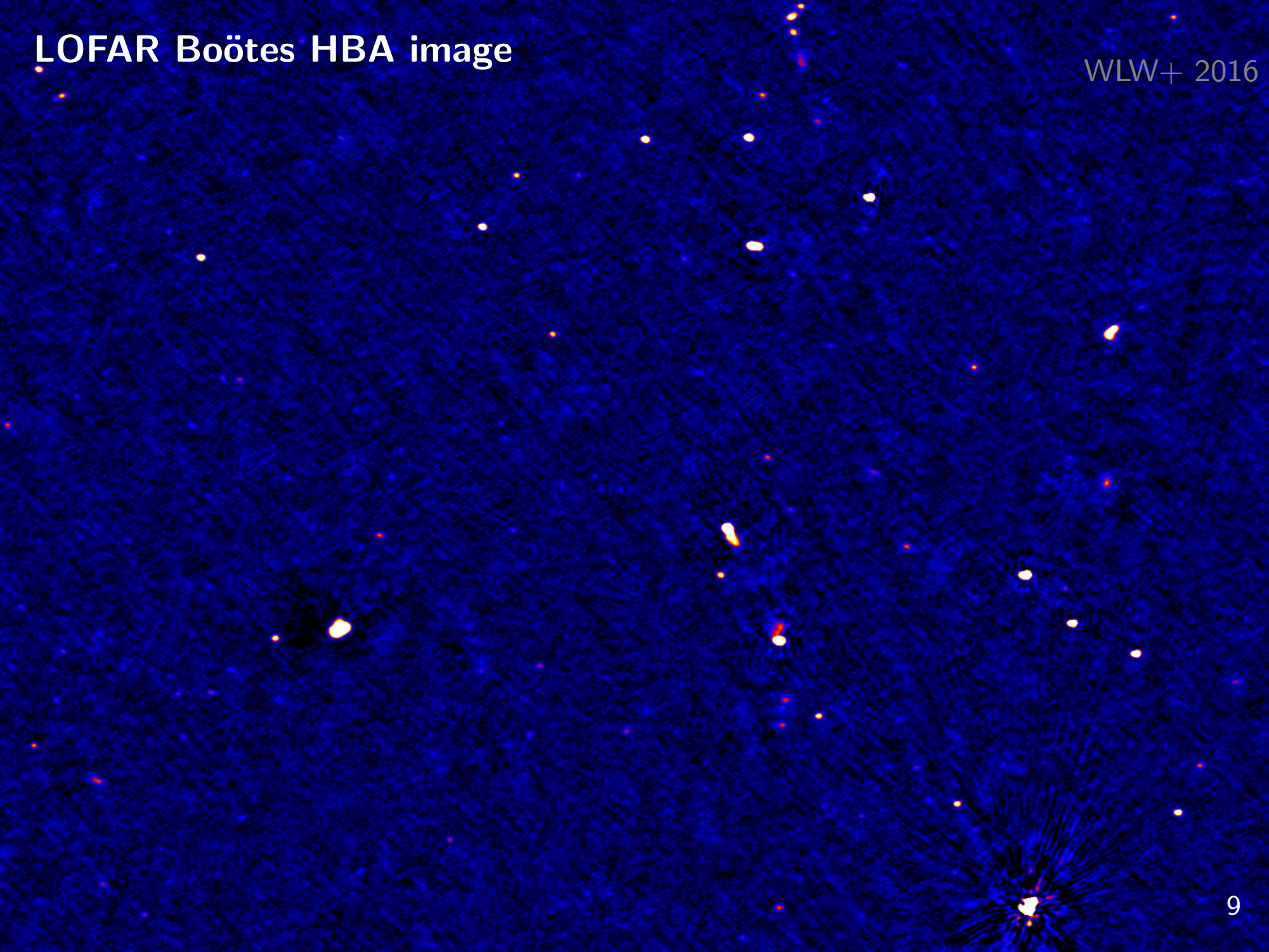
5.6x7.4″

$\sim$ 120 μJy/beam

2.44 deg radius

$\sim$ 19 deg^2

LOFAR Boötes HBA image



WLW+ 2016

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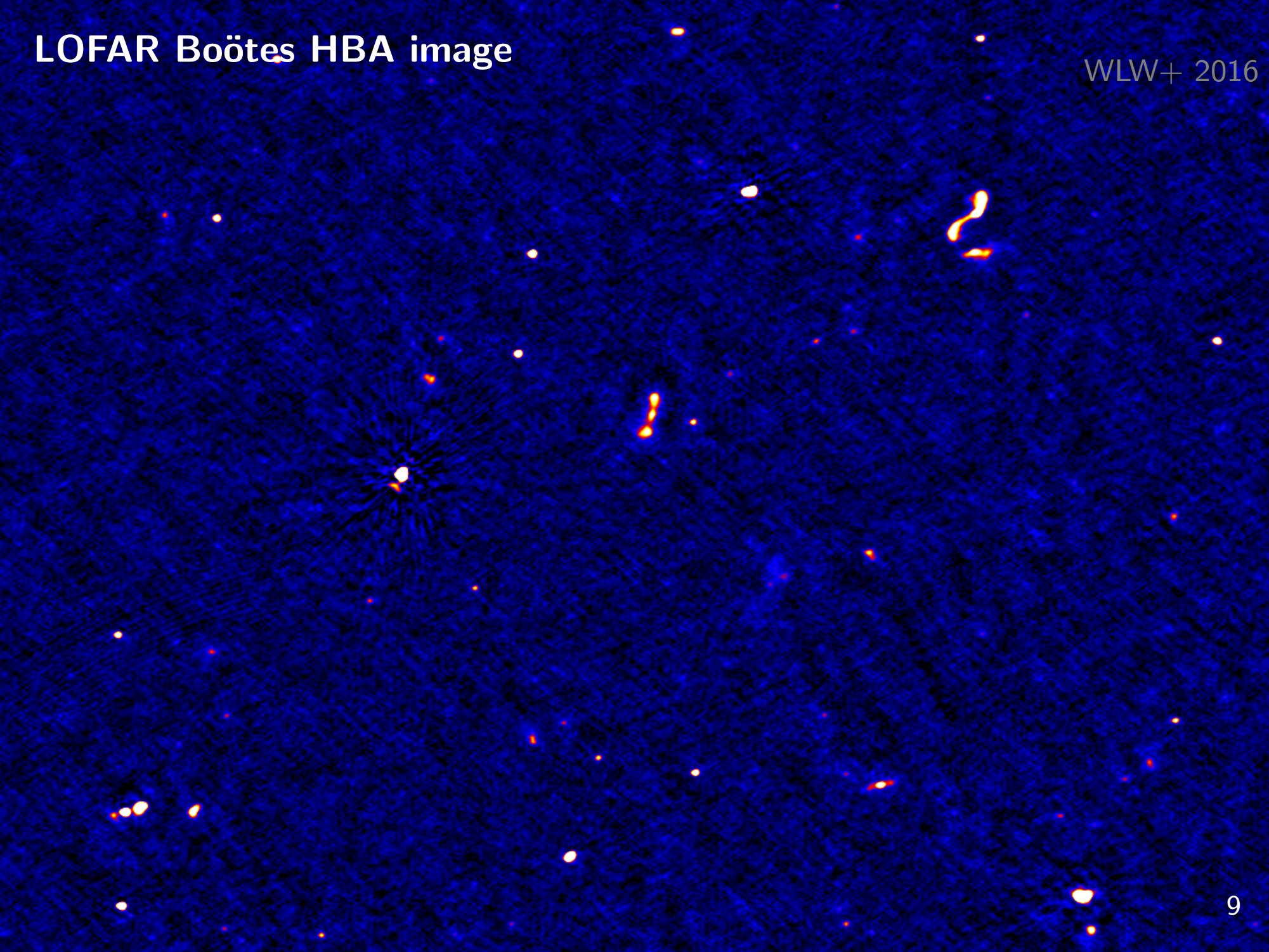

WLW+ 2016

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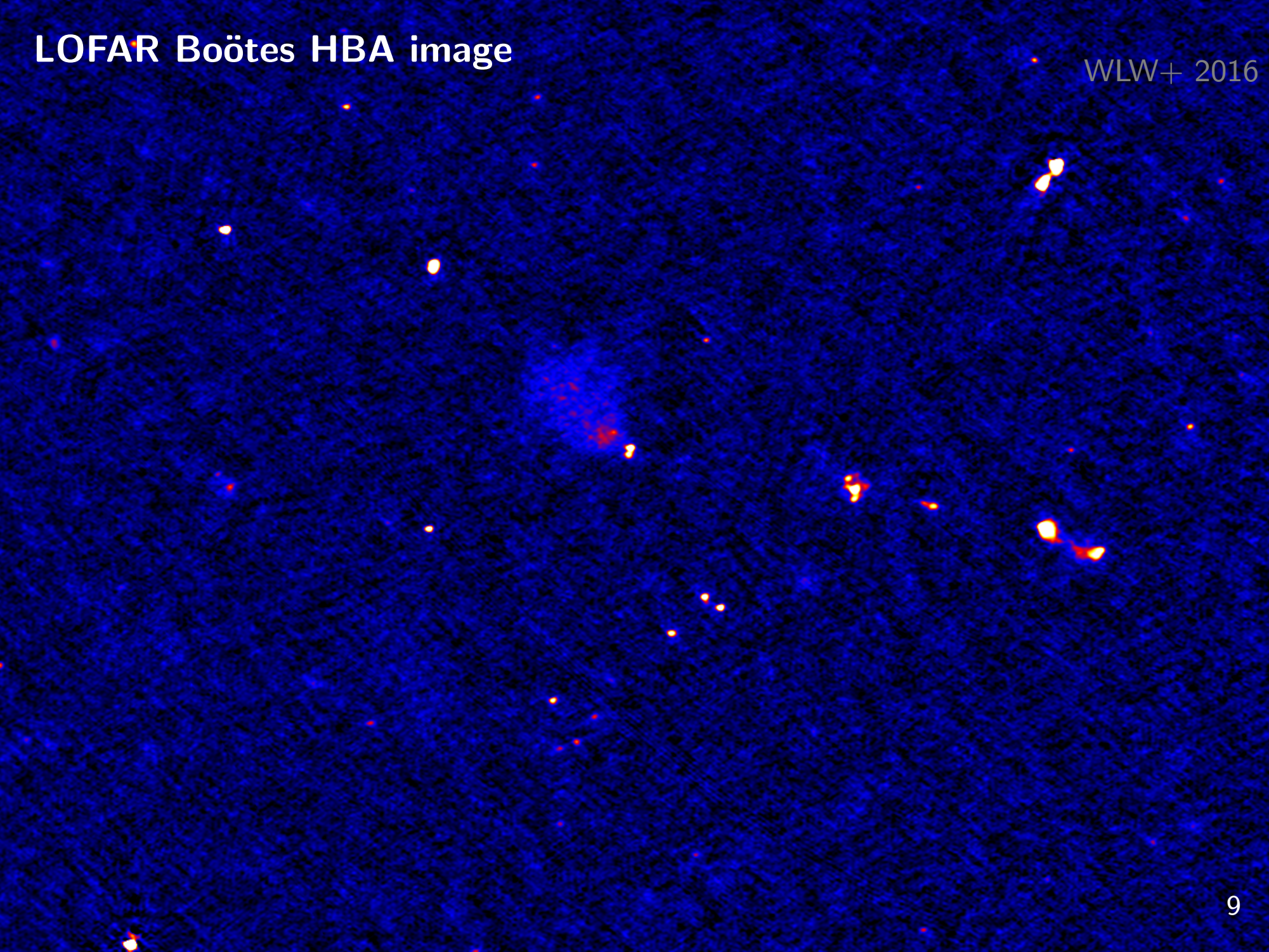

WLW+ 2016

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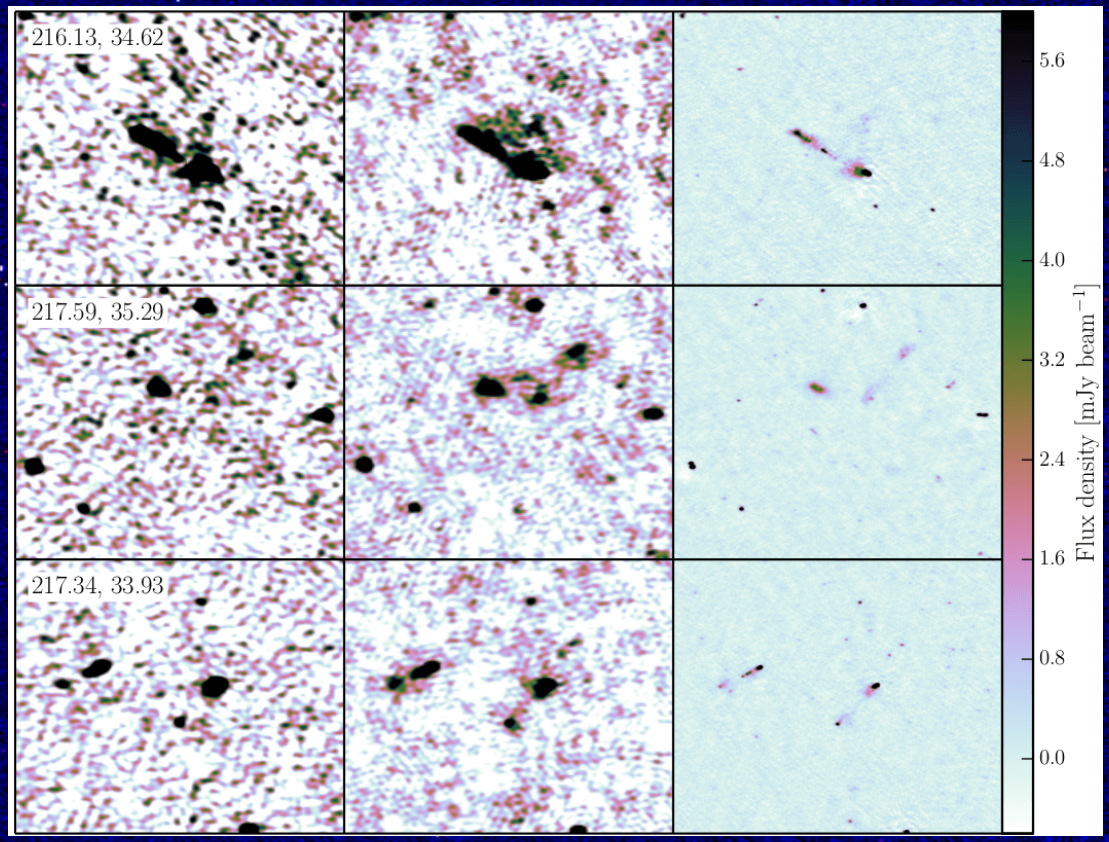

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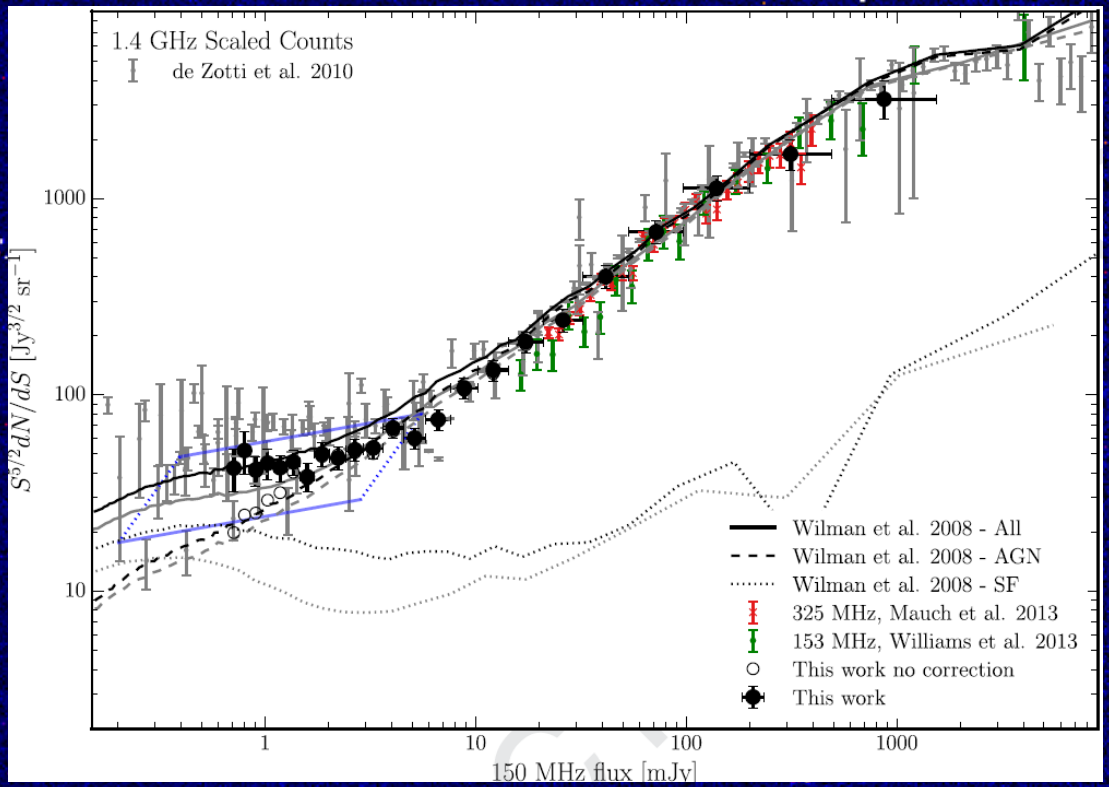
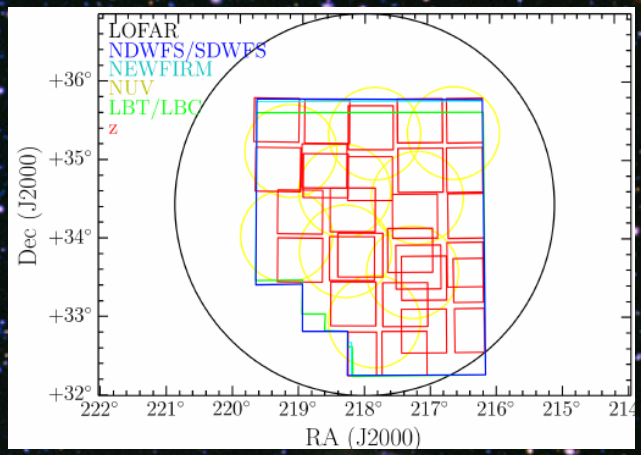
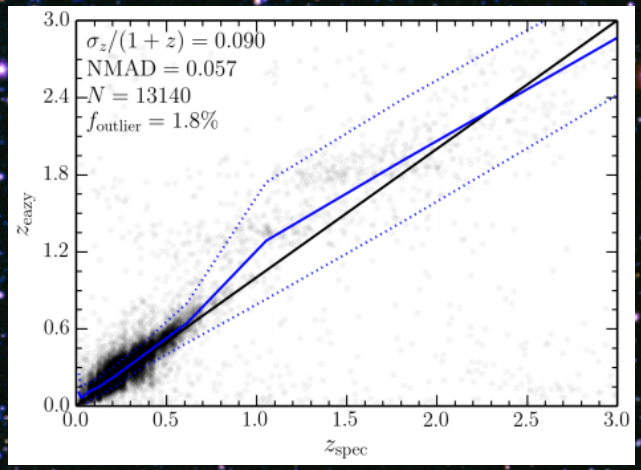


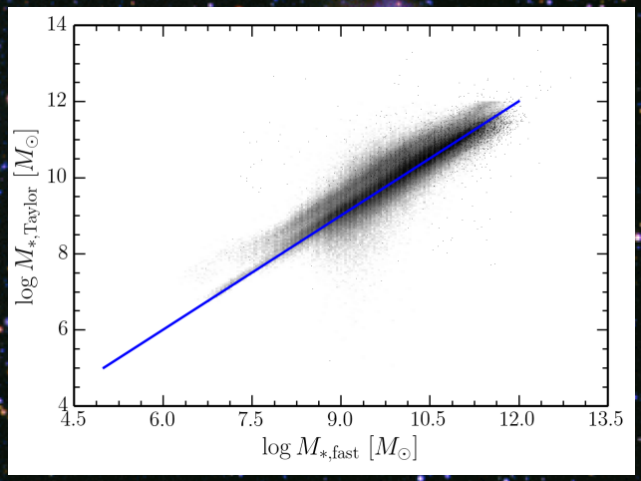
- NDWFS – B_W, R, I – 9.3 deg^2
- zBoötes – z'
- FLAMEX – J, K_s
- SDWFS – irac 3.6, 4.5, 5.8, 8.0 μm
- MAGES – mips 24 μm
- GALEX – NUV, FUV
- Chandra xBoötes – X-Ray
- *Herschel* HerMES – 250, 350, 500 μm



NOAO Deep Wide - Field Survey

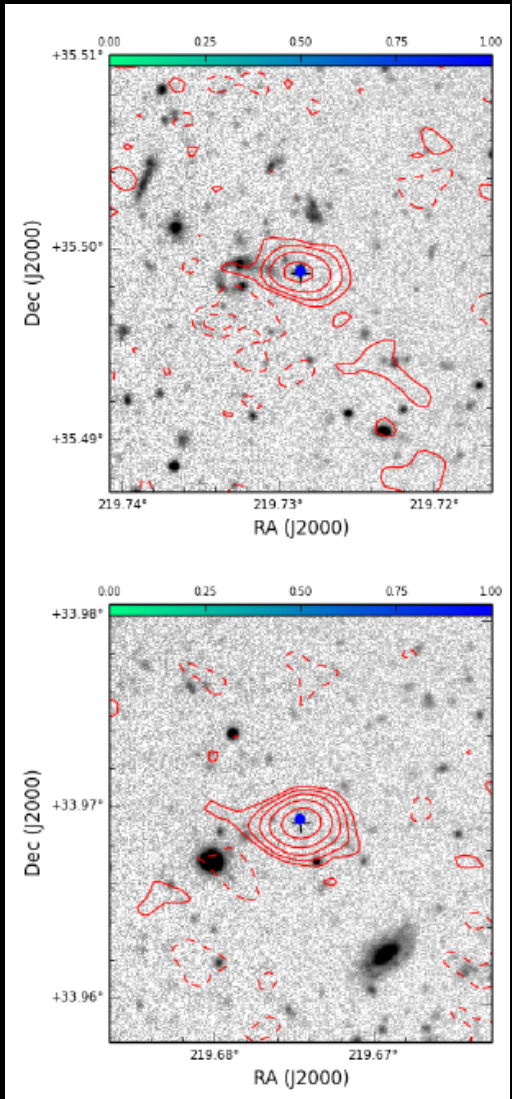
- Spec-z (AGES)
  - $m_I < 21$ mag
  - incomplete beyond $z > 1$
- For $\sim 900,000$ sources
  - $m_I < 24$ mag
  - Photo-z's (EAZY)
  - Stellar masses, star formation rates (FAST)
  - Rest-frame colours (InterRest)

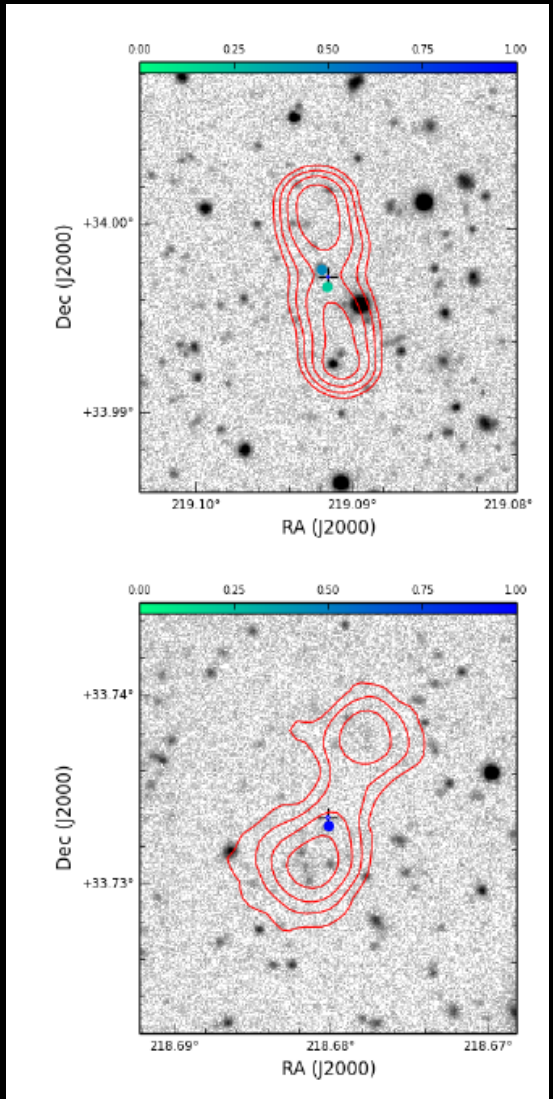




NOAO Deep Wide - Field Survey

radio-optical matching





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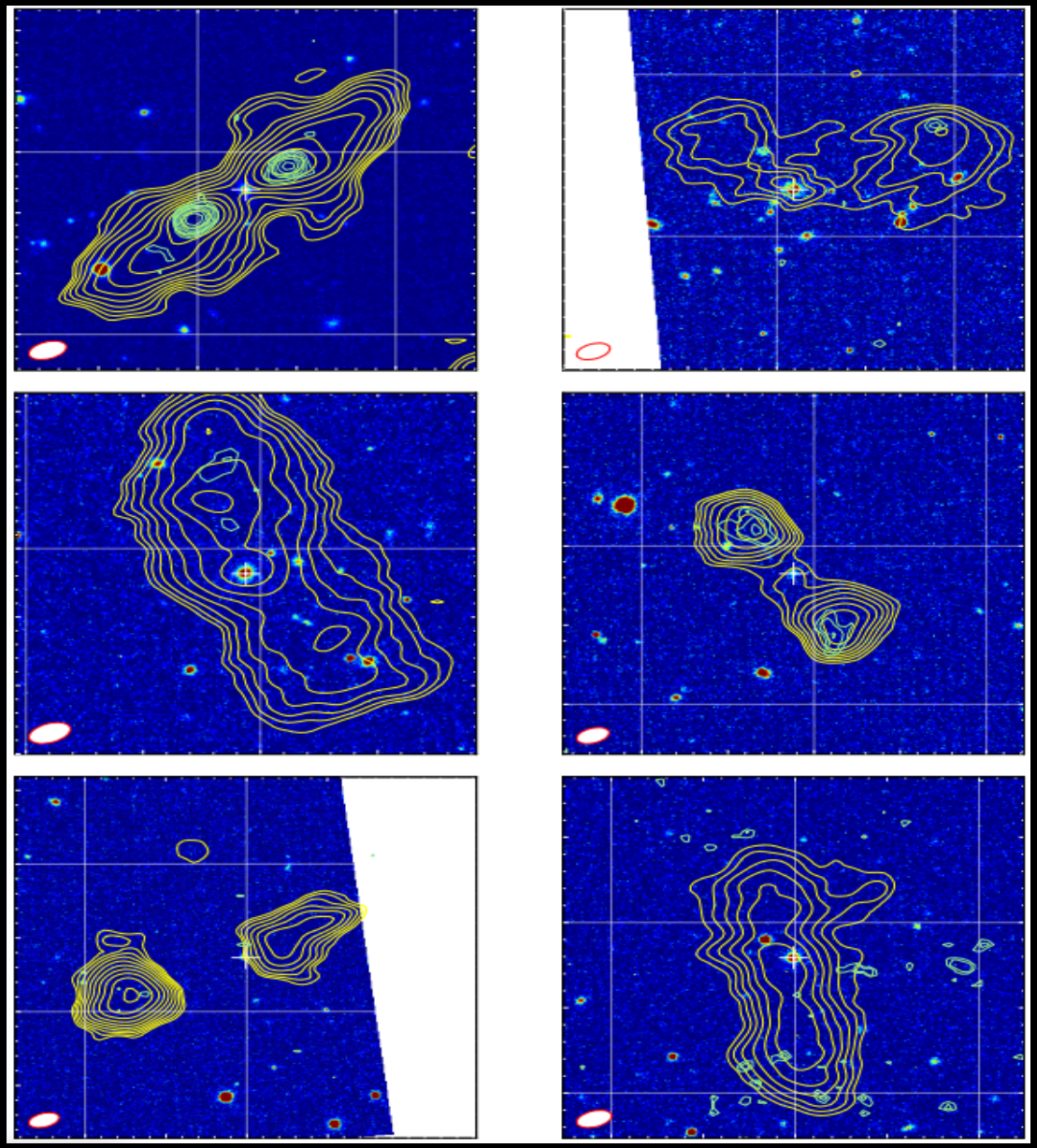
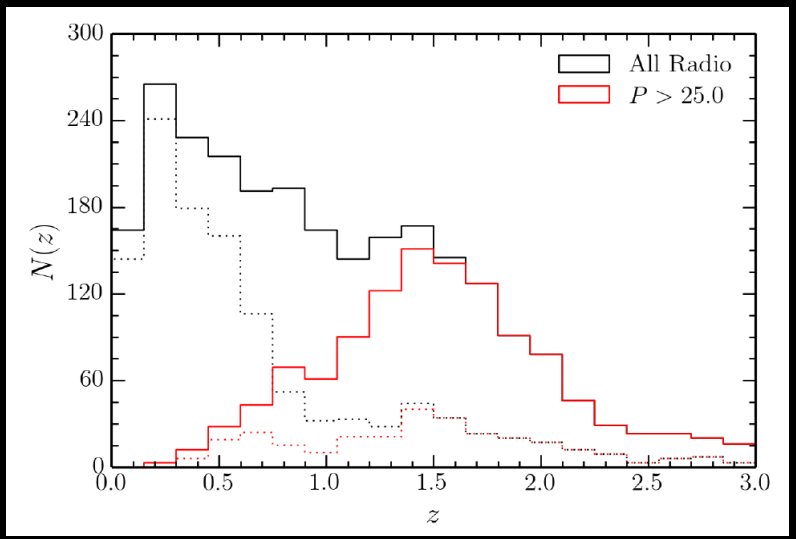
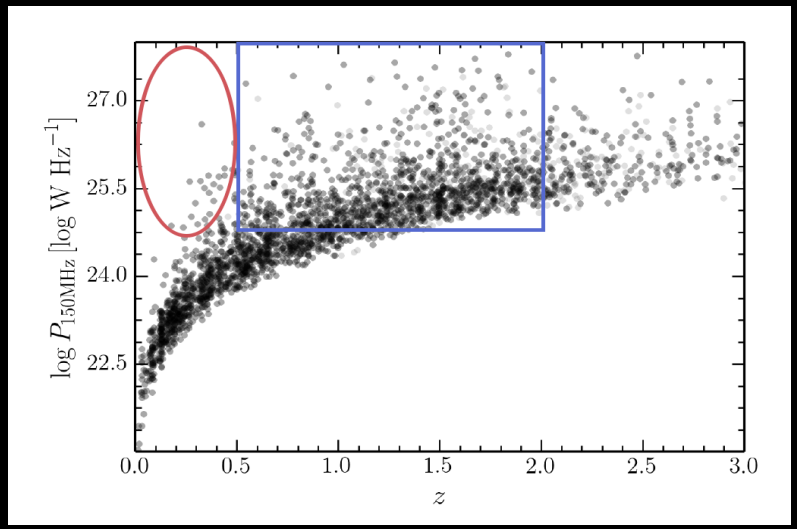


boötes sample

Select LOFAR sample

- Photo-z's
- $0.5 < z < 2.0$
- $P_{150} > 10^{25}$ W/Hz
- $\sim$ 1000 sources



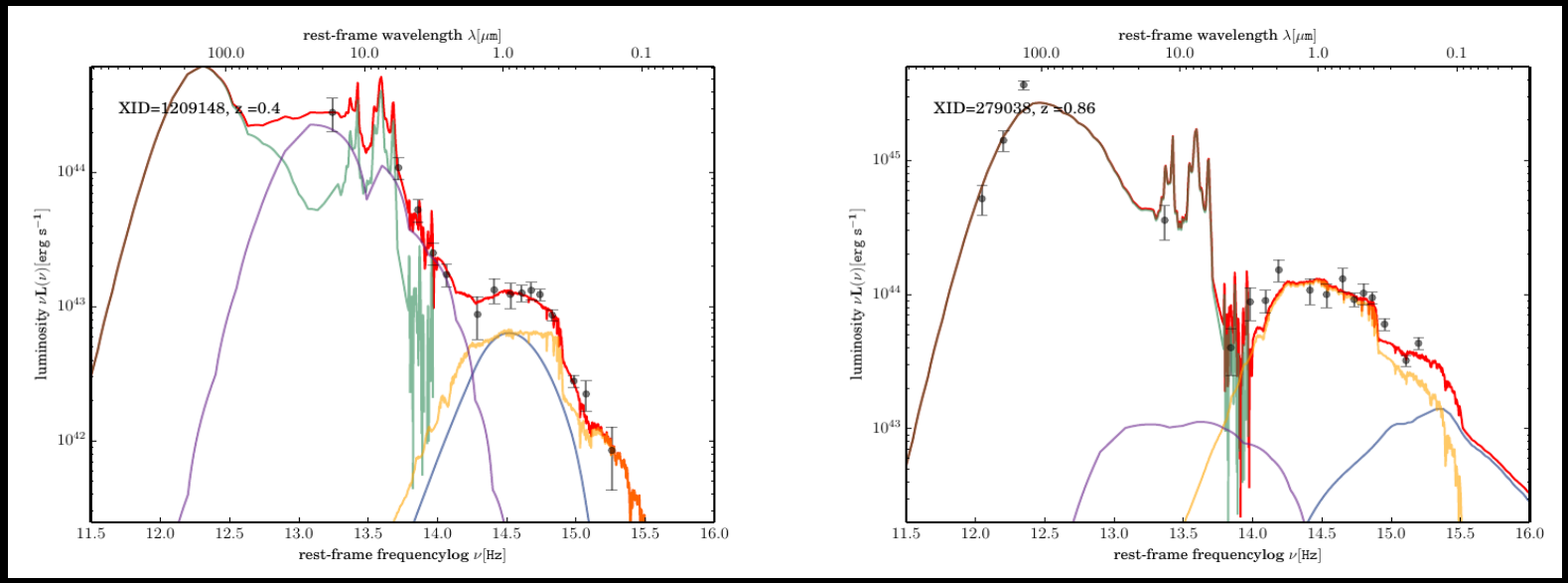


agn accretion modes from sed fitting

Calistro Rivera+ arXiv:1606.05648

AGNfitter `https://github.com/GabrielaCR/AGNfitter`

- Including FIR Herschel data from HERMES
- Components
  - Galaxy & starburst
  - IR torus & accretion disk

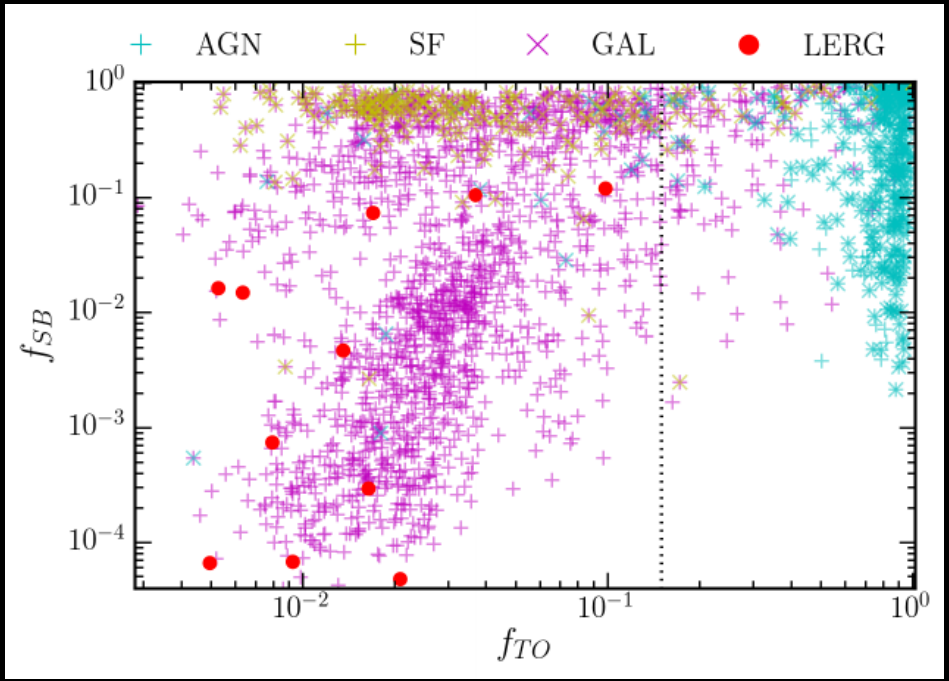


agn accretion modes from sed fitting

- AGN torus fraction
  - Fraction of IR light from torus relative to Galaxy

$$f_{TO} = \frac{L_{TO}}{L_{TO} + L_{GA}}$$

- Classify cold- vs hot-mode (HERG vs LERG)



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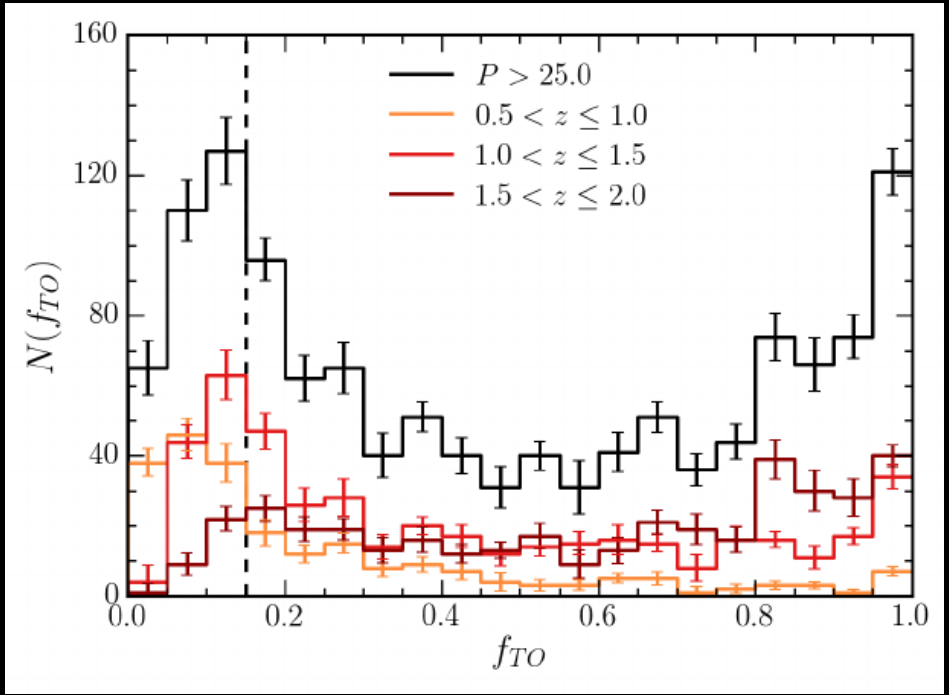
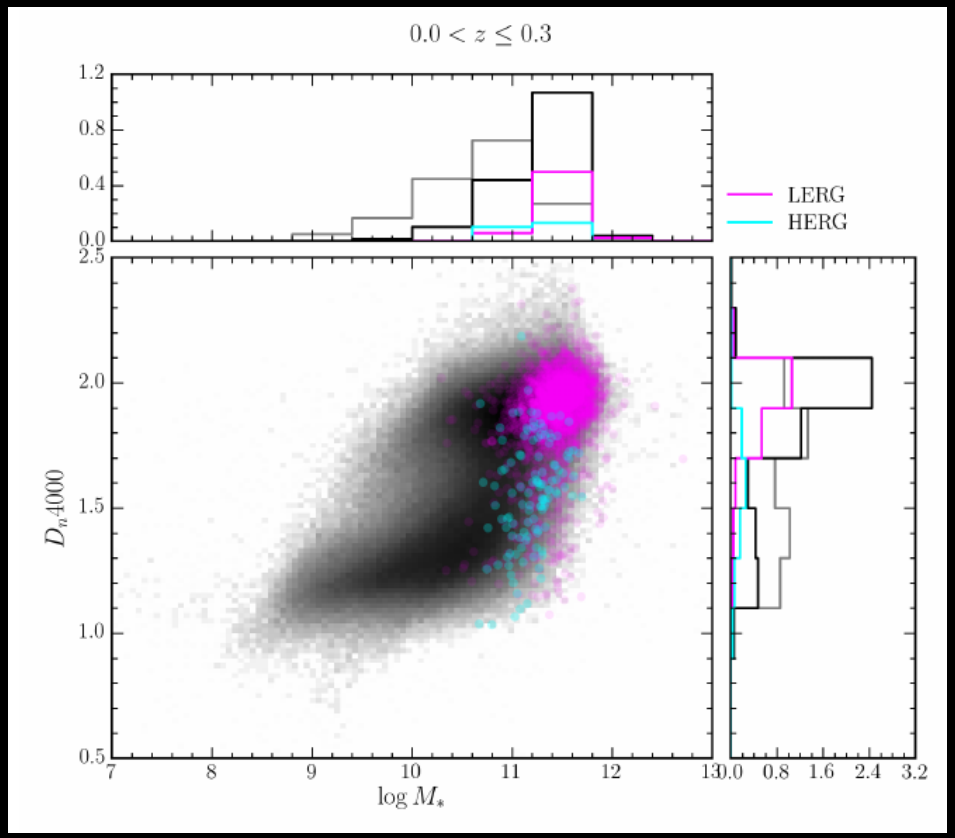


host galaxies of radio agn at moderate z



WLW+ in prep

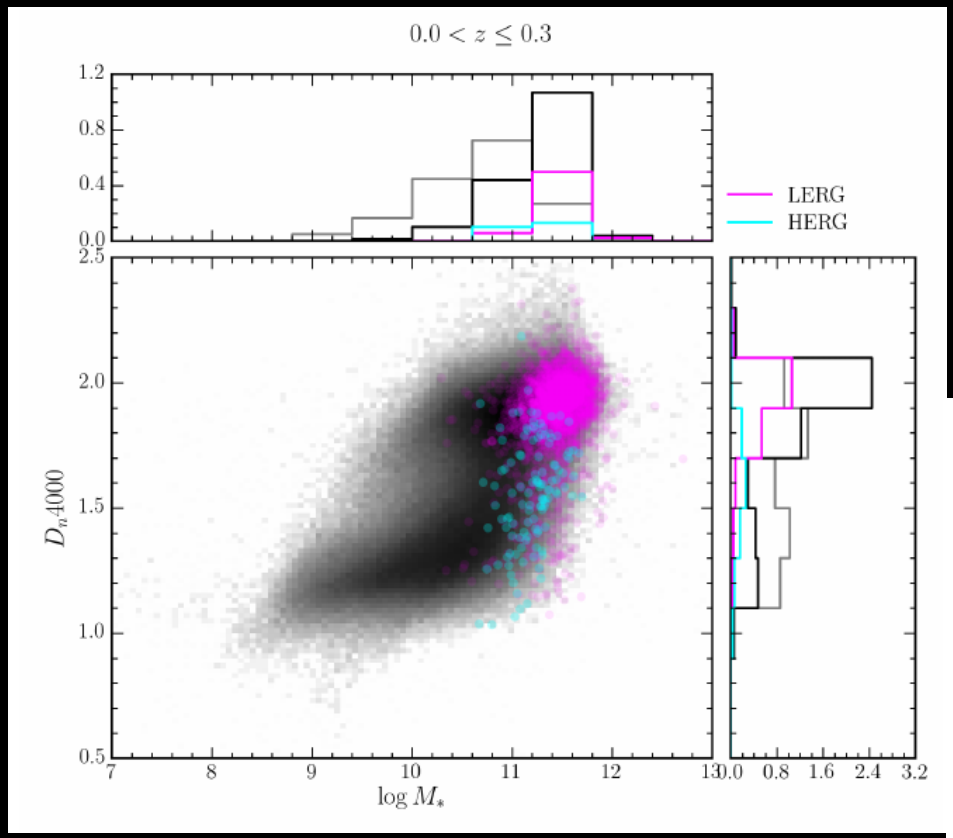
Local sample – SDSS

Colour vs mass

HERGs/LERGs classified spectroscopically

host galaxies of radio agn at moderate z

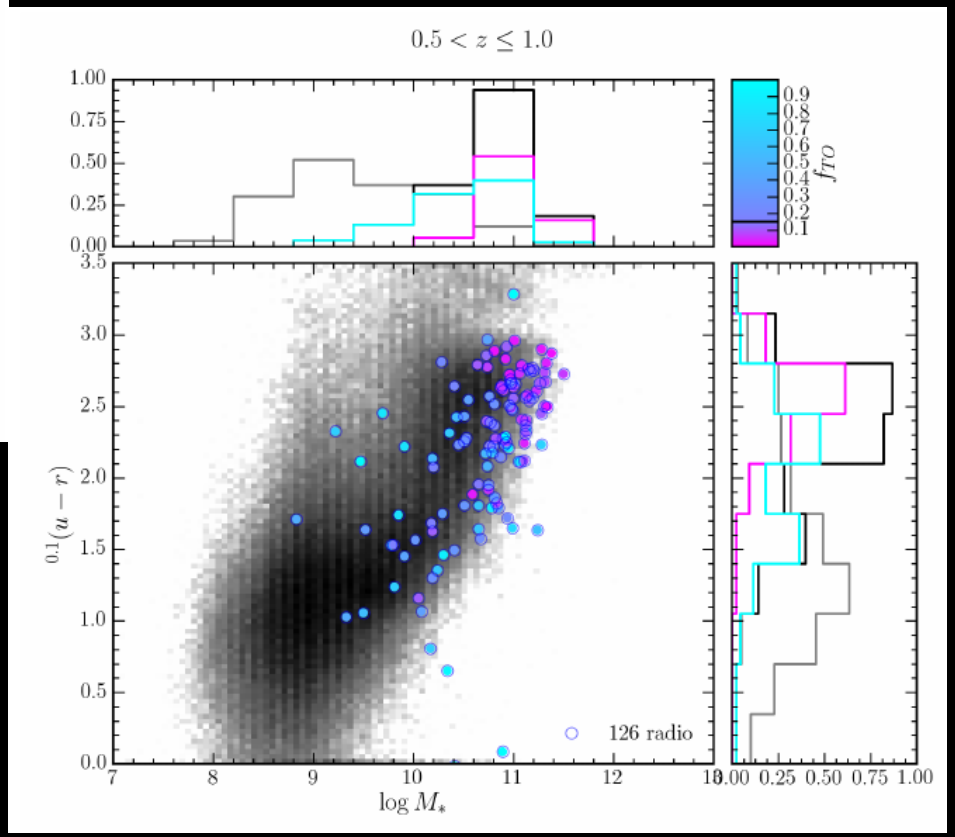
WLW+ in prep



LOFAR sample

Colour vs mass

HERGs/LERGs classified photometrically



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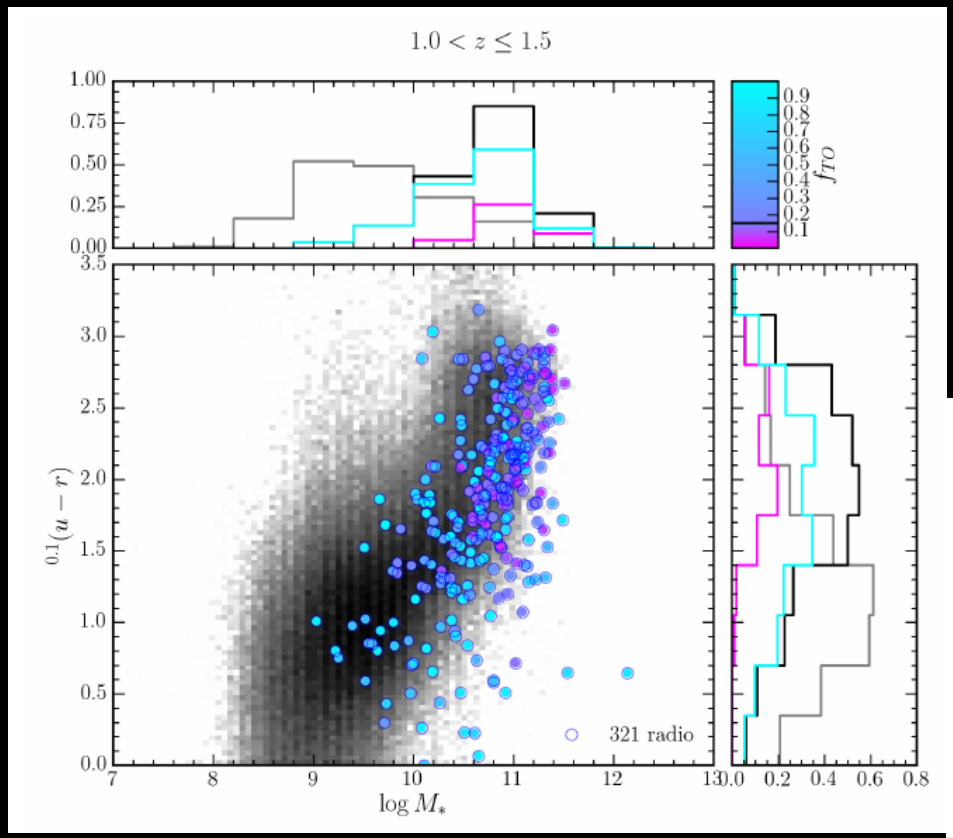
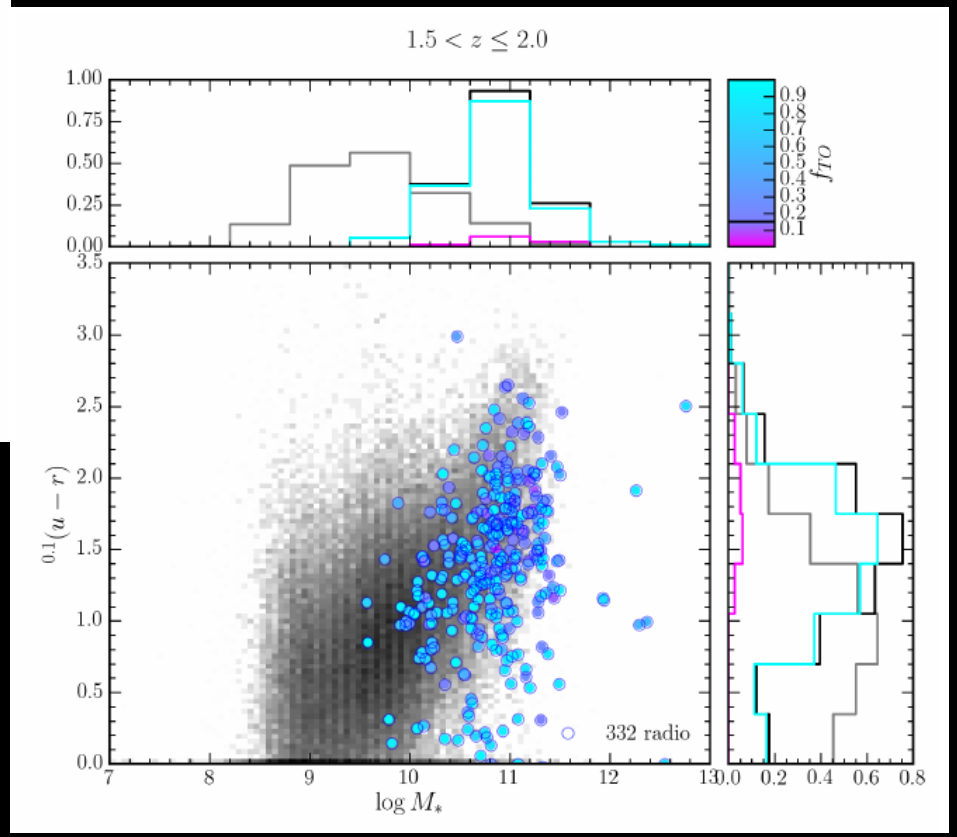
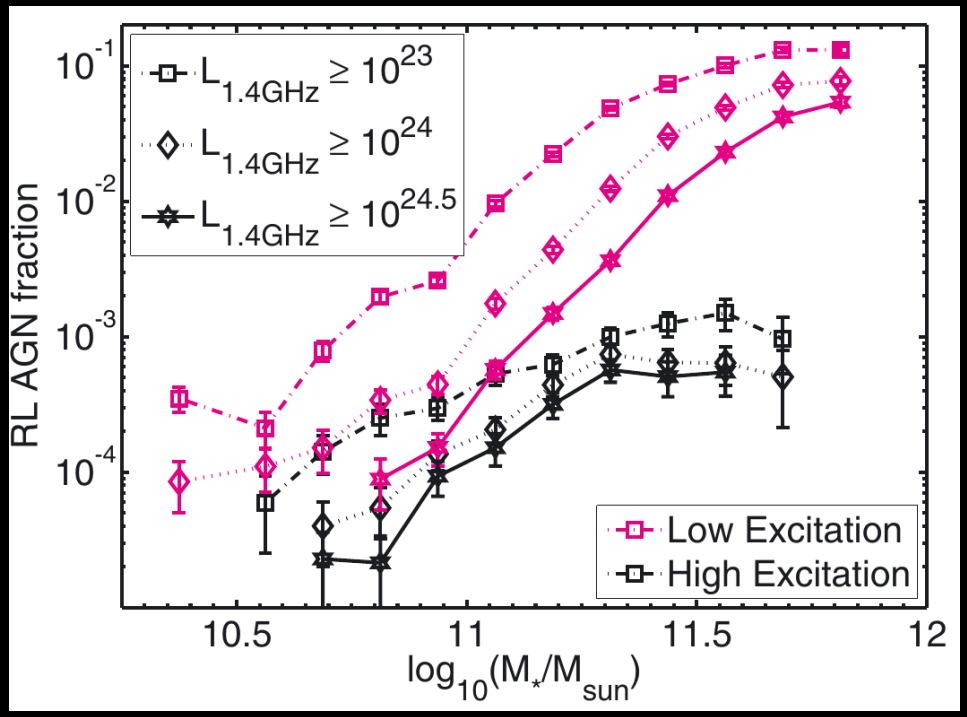




radio loud fraction in the local universe

Best+ 2005

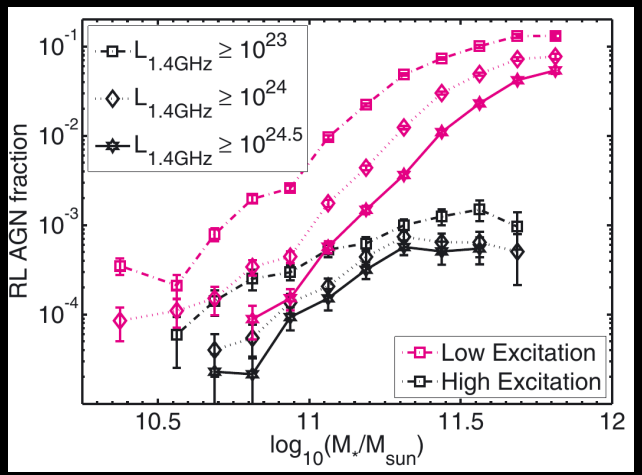
Janssen+ 2013

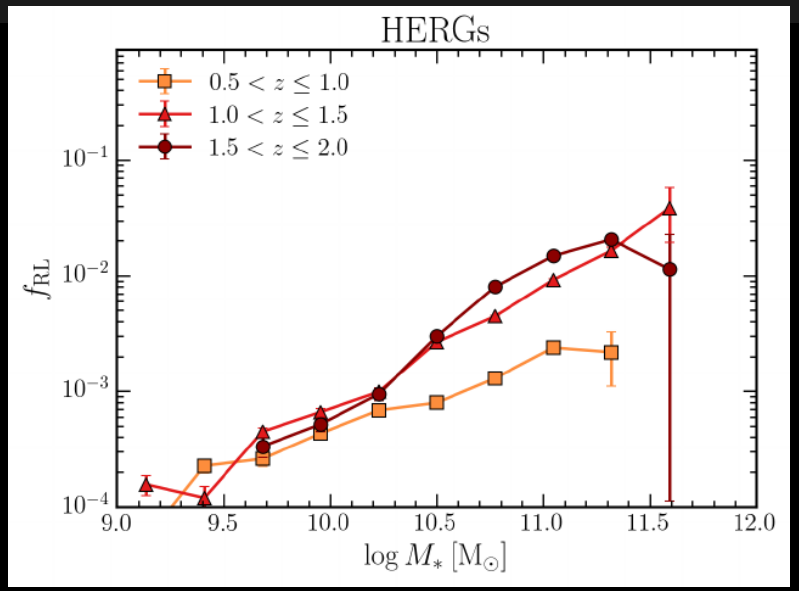


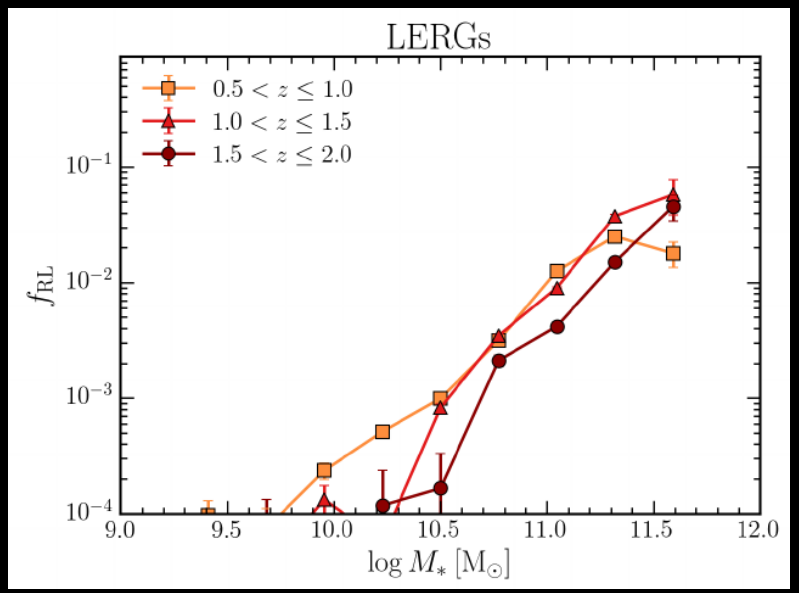
- Radio-loud fraction for **HERGs** is weakly mass-dependent $\propto M^{1.5}$
- For LERGs it is strongly mass dependent $\propto M^{2.5}$

radio-loud fraction

WLW+ in prep

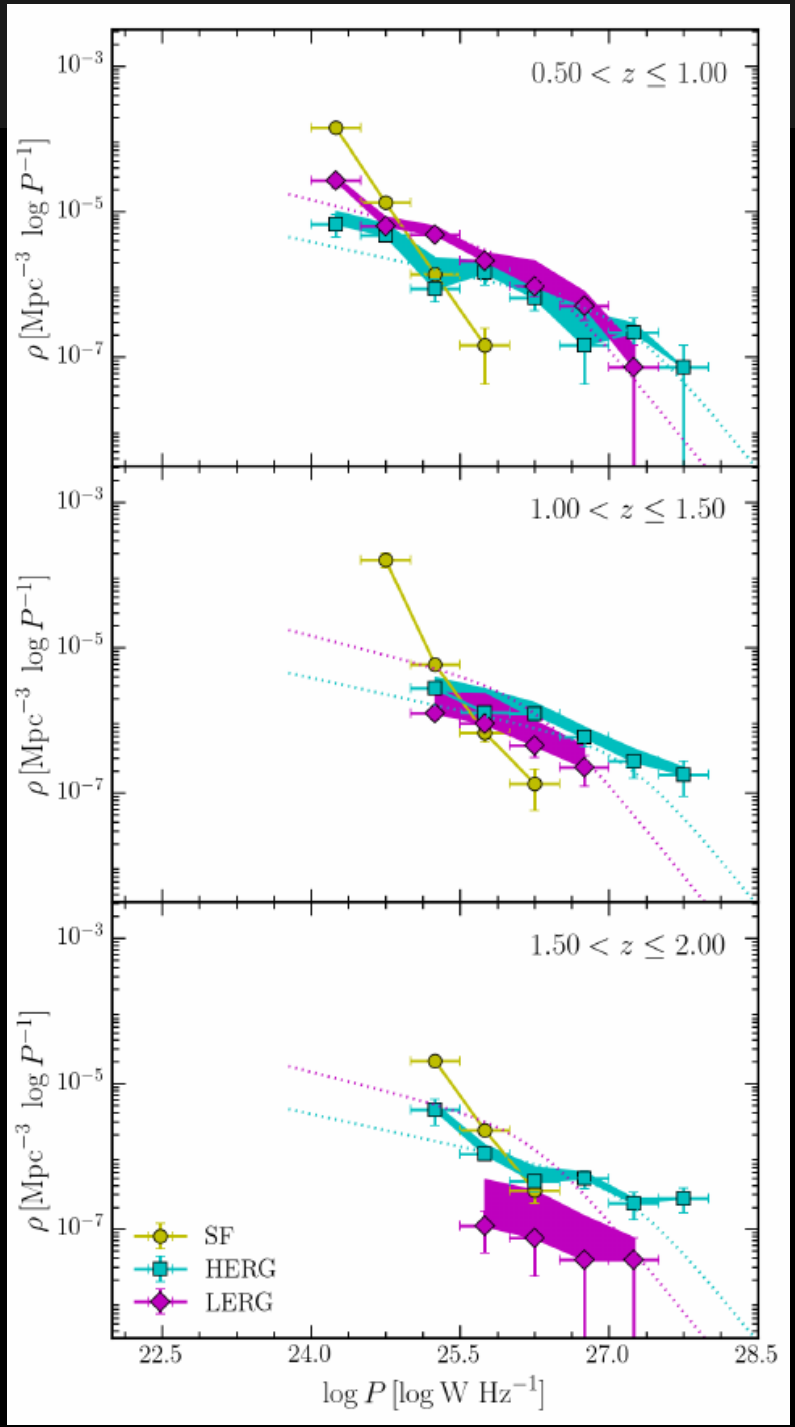






evolving RLFs

WLW+ in prep

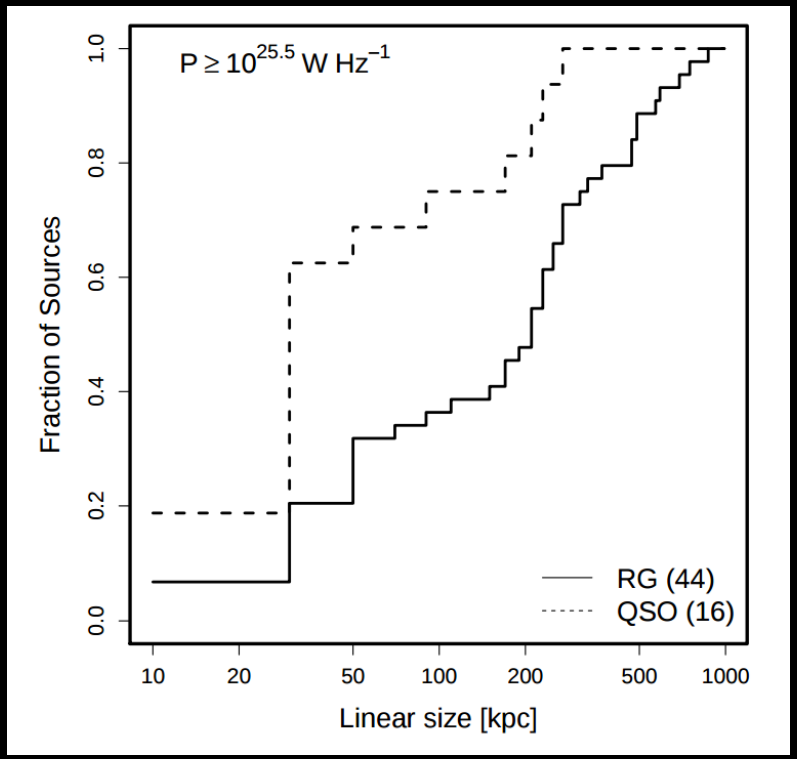


even more science

Morabito+ in prep

quasars are smaller than radio galaxies – AGN unification

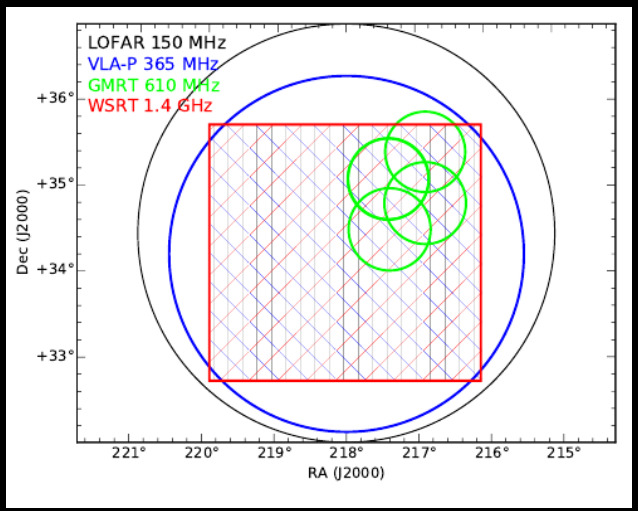
(cf. Barthel+ 89, Singal+ 14)

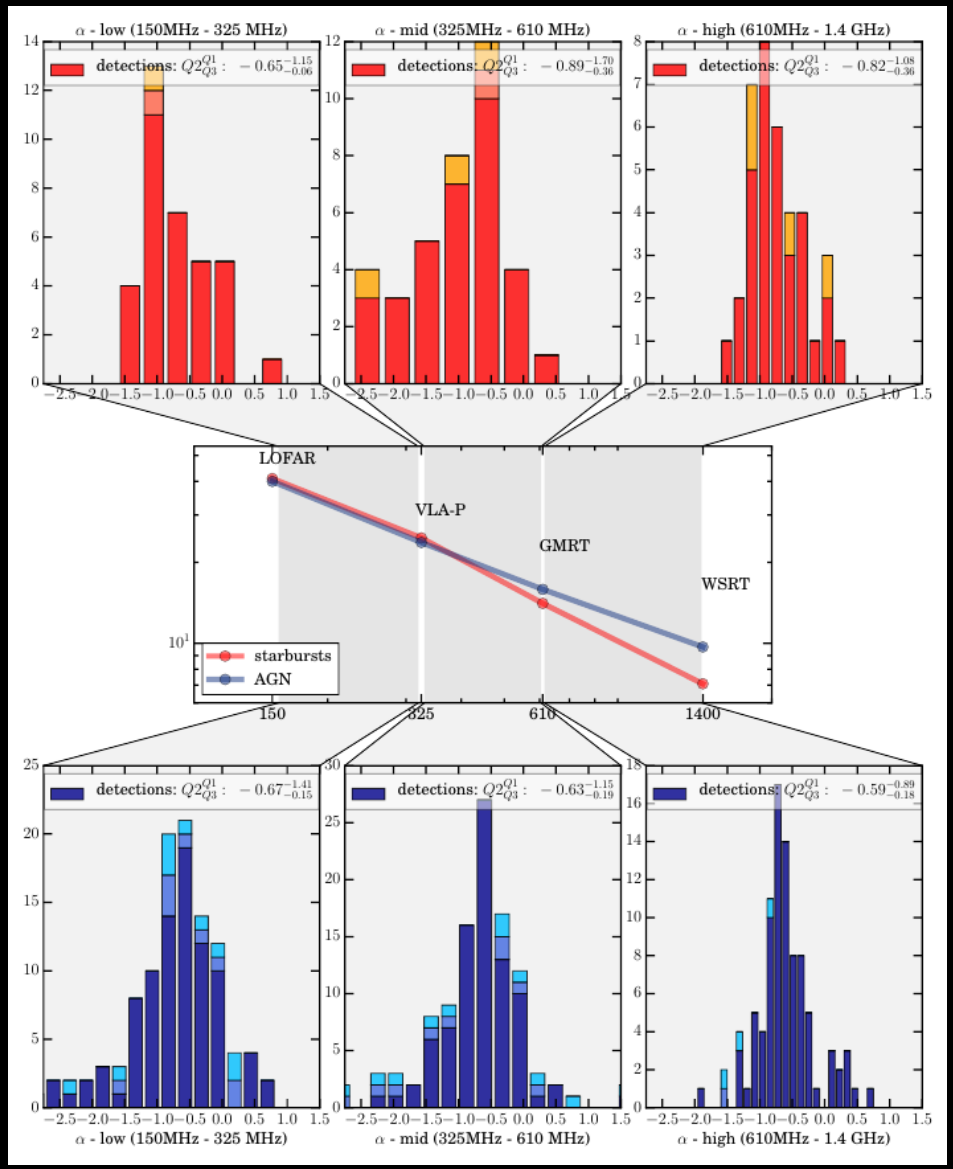


even more science

Calistro Rivera+ in prep

Low frequency spectra for AGN and starbursts – AGN steepen, starbursts flatten

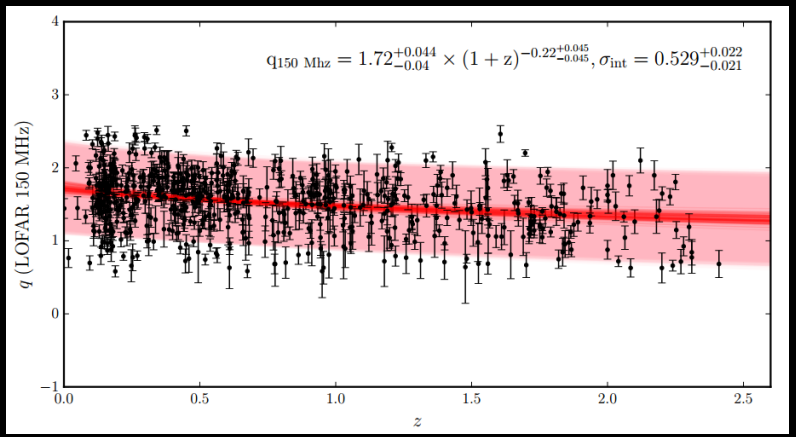


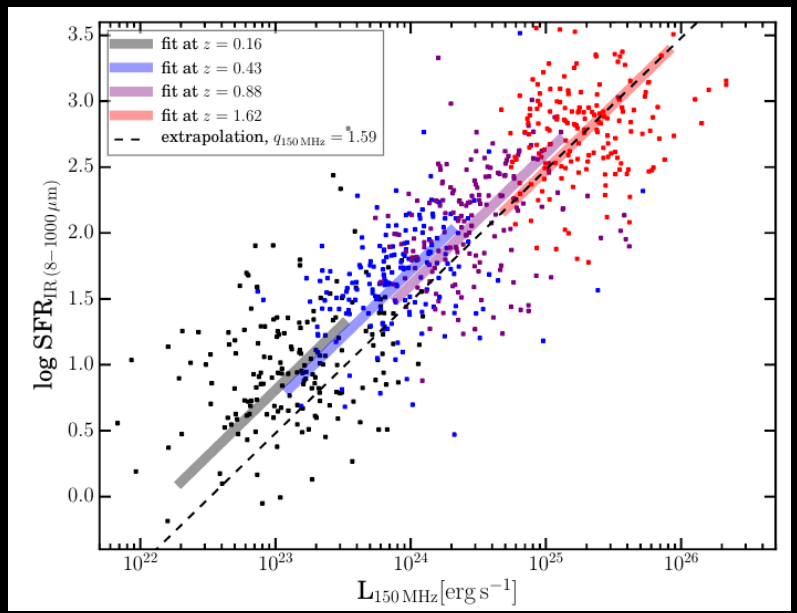


even more science

Calistro Rivera+ in prep

FIR-radio correlation at 150 MHz – calibrating radio SFRs





summary

- Combined with excellent multiwavelength data (LOFAR) Radio Surveys have an important role in understanding the AGN population
- LOFAR is now producing deep high-resolution images
  - LoTSS more soon...
- The LOFAR Boötes sample shows
  - Radio AGN hosts at higher z are bluer, less massive
  - Radiative mode accretion becomes dominant at $z >\sim 1$, LERGS begin to decline
  - Lots of exciting AGN/SF science in the works!