Deep LOFAR imaging and AGN evolution

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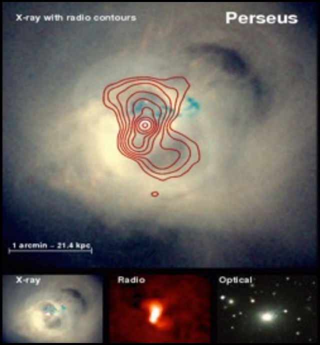
Broad Impact of Low Frequency Observing – Bologna, Italy
June 2017

University of Hertfordshire UH

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

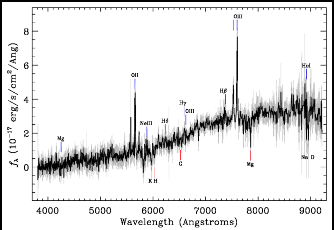


2 types of radio agn

Hine & Longair 1979

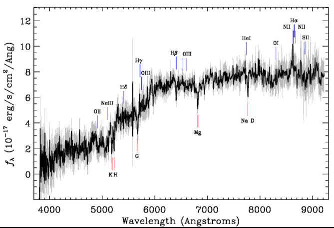
Laing+ 1994

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)

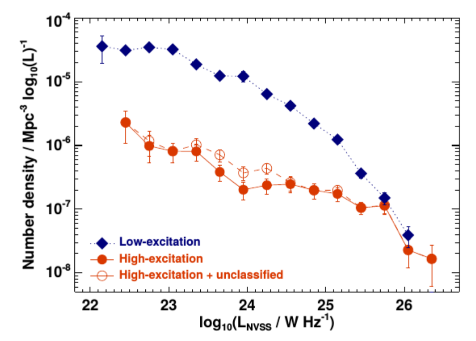


- Atypical
  - Missing all the emission associated with an accretion disk
  - Accretion of hot gas...
- hot/jet mode

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

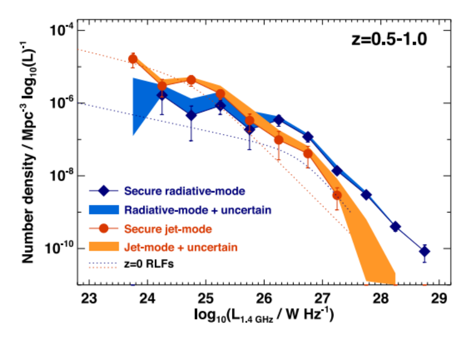
- How important are the different accretion modes in terms of galaxy evolution?
- How do they evolve with redshift?
- How efficient is the feedback?
- We can look at how the radio-loudness depends on:
  - Mass
  - Star formation
  - Galaxy type (e.g. colour)
  - Ionisation state

...All over cosmic time

the population at higher z

Best+ 2014

also Pracy+ 2015

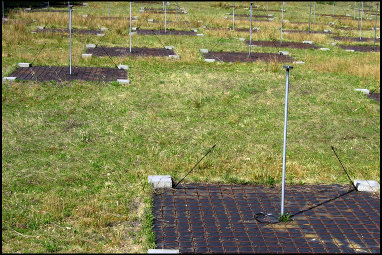


HERGs evolve strongly

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



what do we need?

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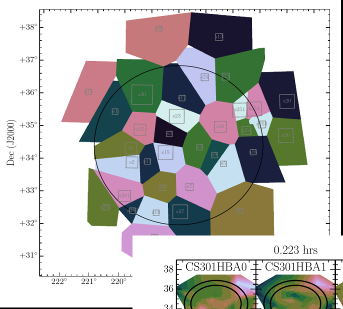
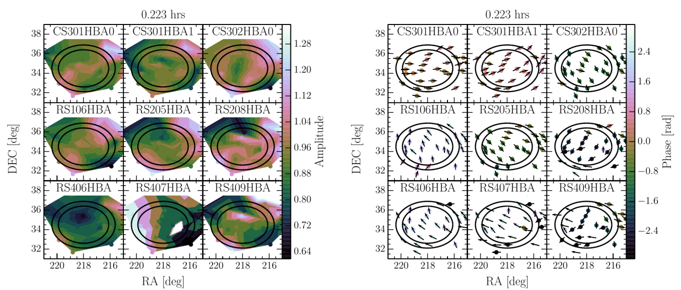
        - Wide field of view
2. Matched to excellent multi-wavelength data
    - z, mass, SFR,... from photometry
    - Excitation state... from spectroscopy(?)
    - Famous extra-galactic deep fields

direction-dependent ionospheric calibration



"Facet"-based direction-dependent calibration

van Weeren, WLW+ 2016

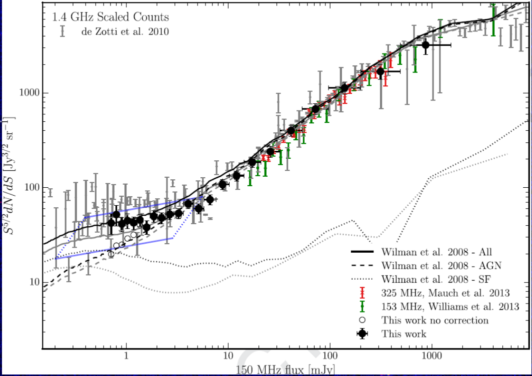


LOFAR Boötes HBA image

"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

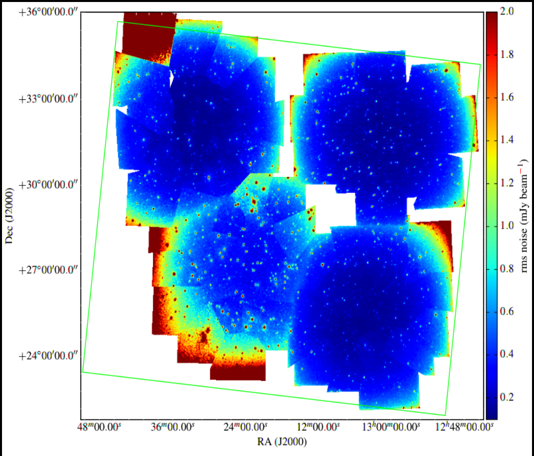


Hardcastle+ 2016

"Facet"-based direction-dependent calibration

150 MHz
48 MHz bandwidth
4×8 hr observations

5.6x7.4″
$\sim$ 100 μJy/beam
$\sim$ 142 deg^2
$>$ 17 000 sources

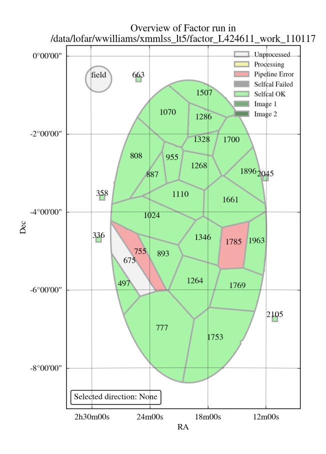


factor

David Rafferty, Andreas Horneffer, CITT

facet calibration pipeline

- `https://github.com/lofar-astron/factor`
- user friendly
- built on the LOFAR generic pipeline framework
- can run across multiple compute nodes
- can process multiple observations
- significant optimisation of the original scripts
- uses latest wsclean (Offringa+), dysco compression (Offringa+)
- can routinely produce science-ready images



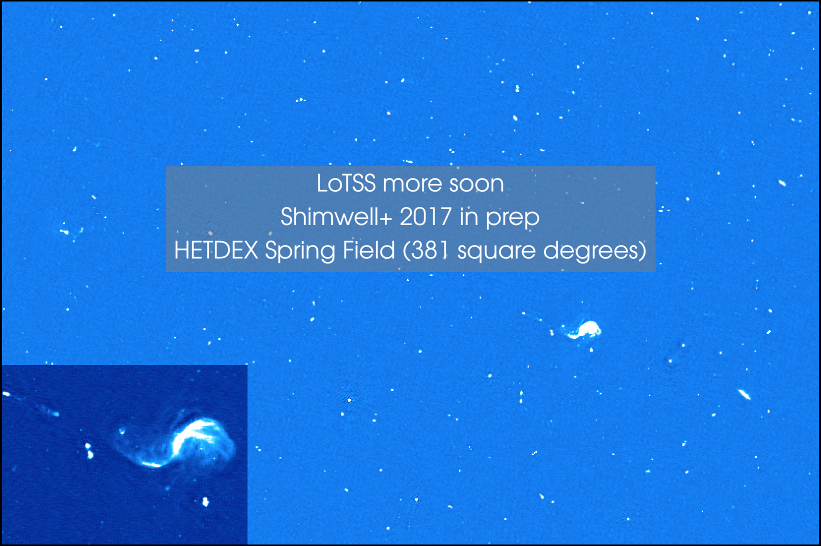
XMM-LSS: Catherine Hale, WLW

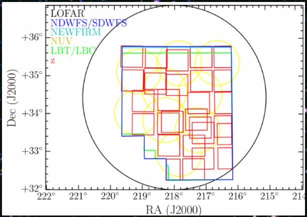
Other fields:

- Toothbrush cluster (van Weeren+ 2016)
- Bootes (WLW+ 2016)
- H-ATLAS (Hardcastle+ 2106)
- A2034 (Shimwell+ 2016)
- ELAIS-N (Sabater+)
- Lockman Hole (Mandal+)
- XMM-LSS (Hale, WLW+)
- + many others

realising lotss

Shimwell+





- 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

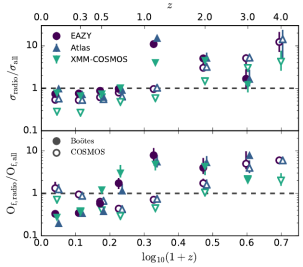
NOAO

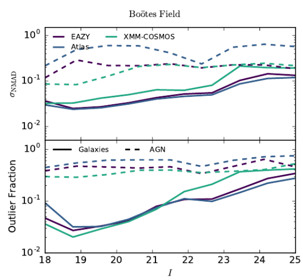
AURA

NSF

Duncan+ submitted

- 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)



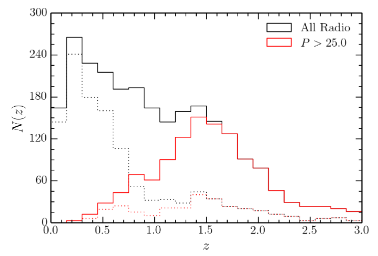


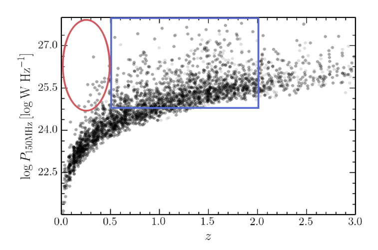
NOAO Deep Wide - Field Survey

boötes sample

Select LOFAR sample

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



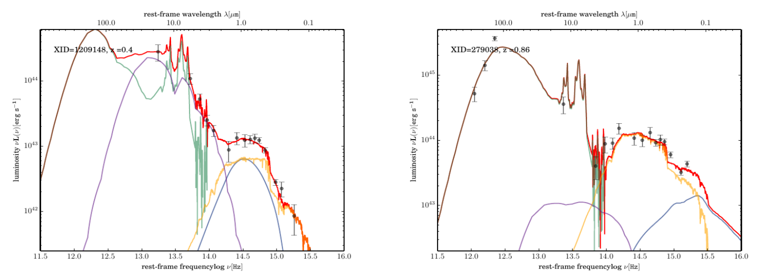


agn accretion modes from sed fitting

Calistro Rivera+ arXiv:1606.05648

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

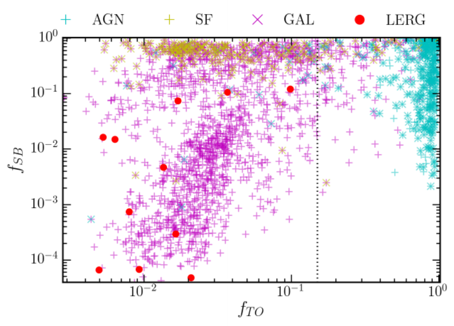
- Including FIR Herschel data from HERMES
- Components
  - Galaxy & starburst
  - IR torus & accretion disk



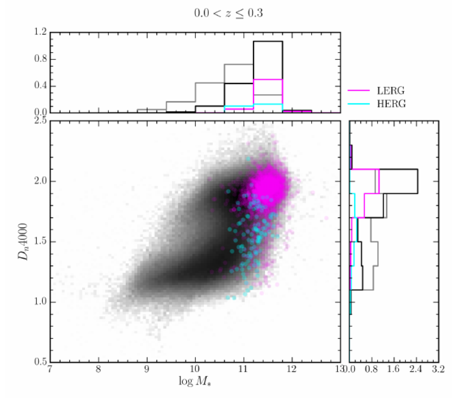
agn accretion modes from sed fitting

- Classify SF vs AGN
- Classify HERG vs LERG
- AGN torus fraction
  - Fraction of IR light from torus relative to Galaxy

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



host galaxies of radio agn at moderate *z*

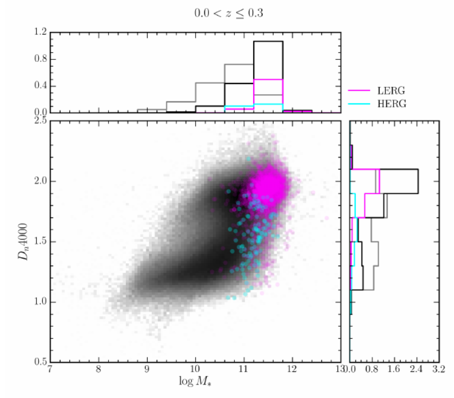


WLW+ in prep

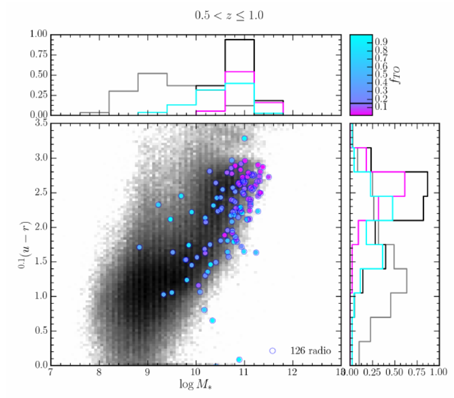
Local sample – SDSS
Colour vs mass
HERGs/LERGs classified spectroscopically

host galaxies of radio agn at moderate z

WLW+ in prep



LOFAR sample
Colour vs mass
HERGs/LERGs classified photometrically



host galaxies of radio agn at moderate *z*

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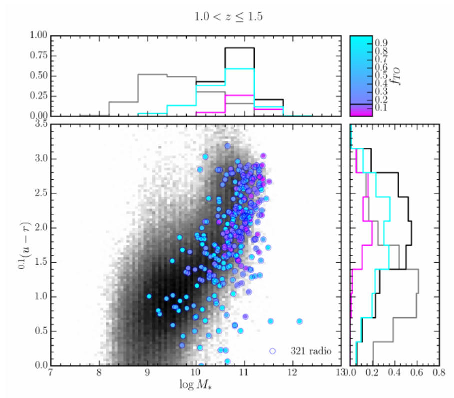
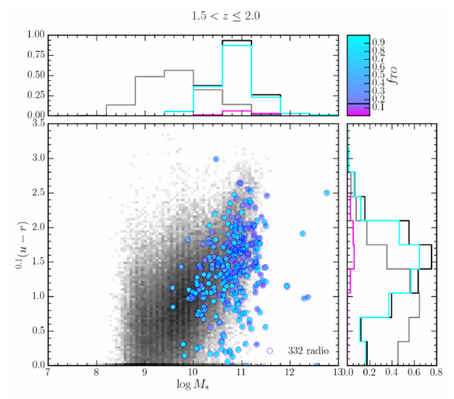
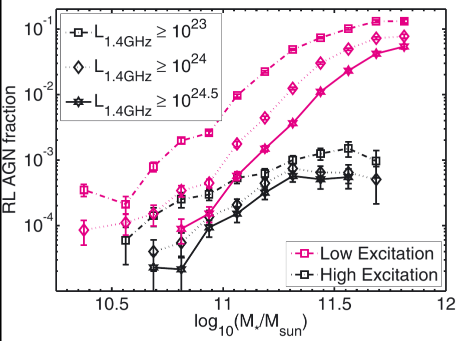




radio loud fraction in the local universe

Best+ 2005

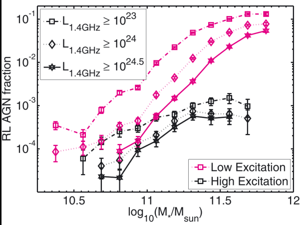
Janssen+ 2013

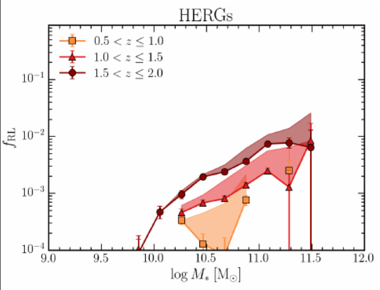


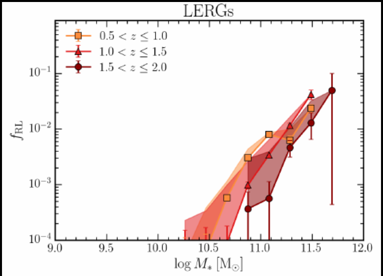
- Radio-loud fraction for **HERGs** is weakly mass-dependent $\propto M^{1.5}$
- For LERGs it is strongly mass dependent $\propto M^{2.5}$

radio-loud fraction

WLW+ in prep

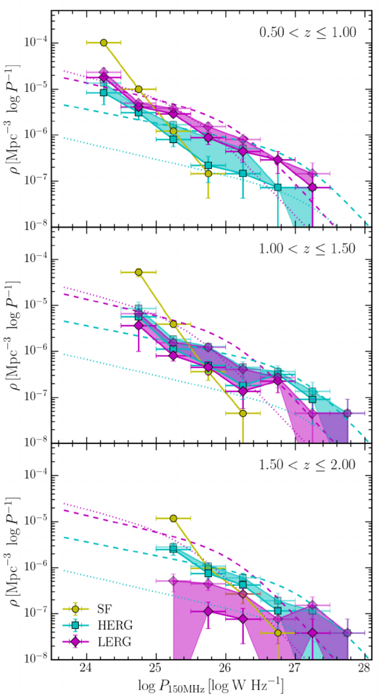






WLW+ submitted

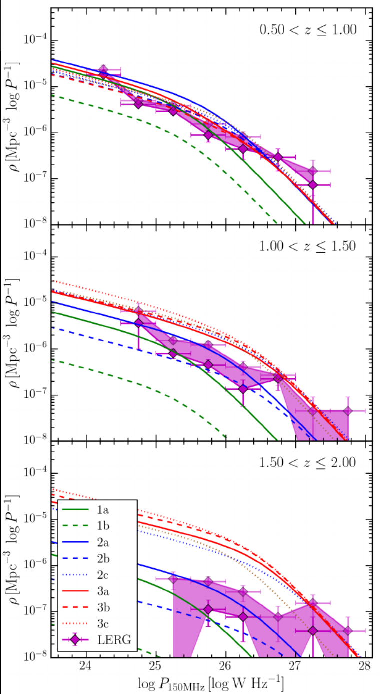
HERG LF's evolve very slowly
Space density of the highest power sources peaks at $z \sim 1$



evolving rlf's

WLW+ submitted

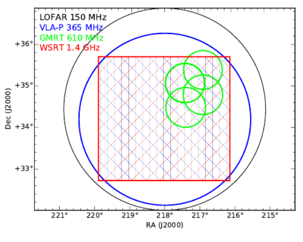
LERG LF's decline strongly
models suggest LERGs density and luminosity evolution
following the evolution of massive quiescent galaxies
(with a delay in between radio activity and quiescent galaxy formation)
(Best+ 2014)

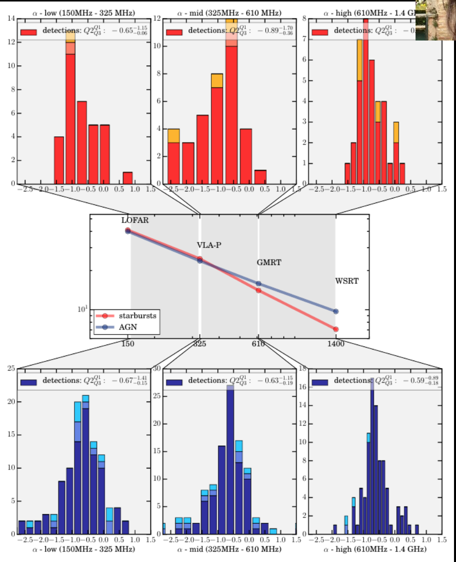


agn multi-frequency spectral properties

Calistro Rivera+ 2017

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

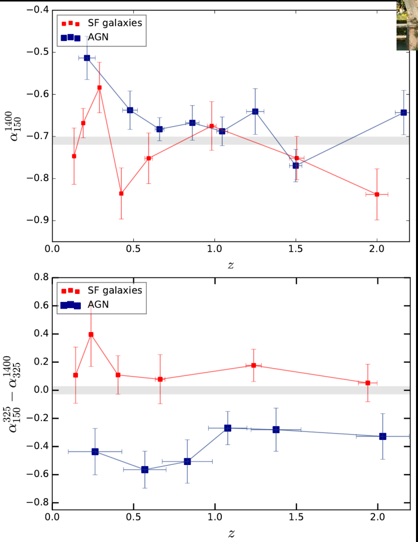




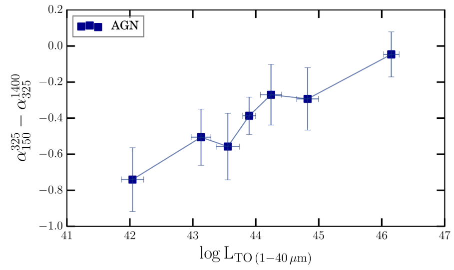
agn multi-frequency spectral properties

Calistro Rivera+ 2017

no significant z dependence
or dependence on SFR



but a connection between AGN luminosity and spectral curvature – more powerful AGN are straighter

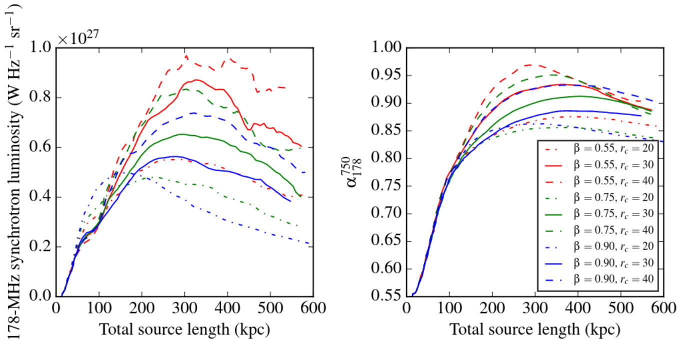


understanding cosmological feedback

- Estimate total feedback power in the local universe (as function of galaxy mass, environment etc) from observations
- Radio luminosity is a poor proxy for jet power – depends also on environment, time, etc

Hardcastle & Krause 2014

- Numerical models predict tracks in power-size-spectral index space for a single source
- but are very expensive

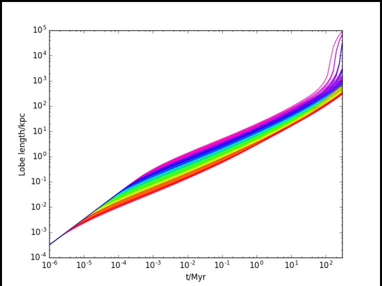


towards jet kinetic luminosity functions

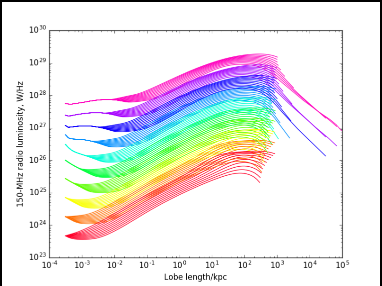
Hardcastle in prep

- 'Simpler' anaytical model
- quickly cover parameter space
- for different jet powers (colours; red → magenta)
- ... and environments

length vs time



luminosity vs length



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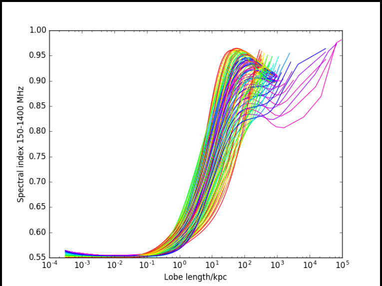
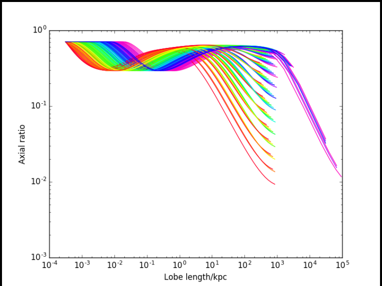
spectral index vs length



axis ratio vs length

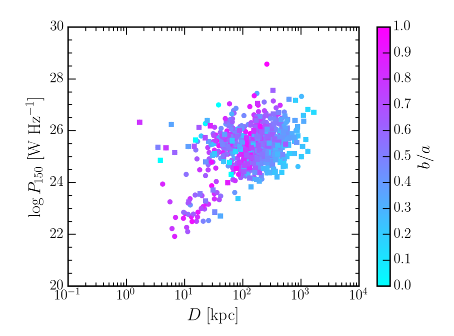


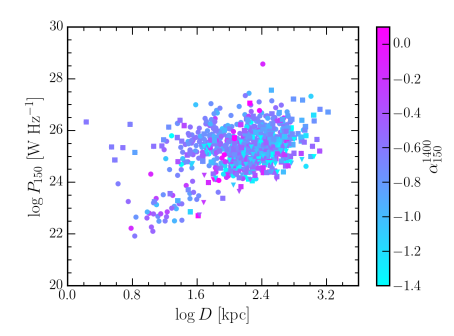
towards jet kinetic luminosity functions

PRELIMINARY

WLW+ in prep

- Bright local sample from Böotes & H-atlas
- Spectral indicies from LOFAR-NVSS
- Fluxes & shapes from the LOFAR images





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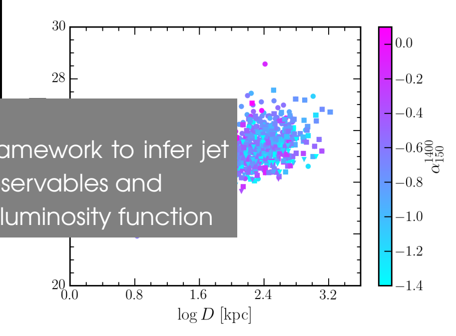
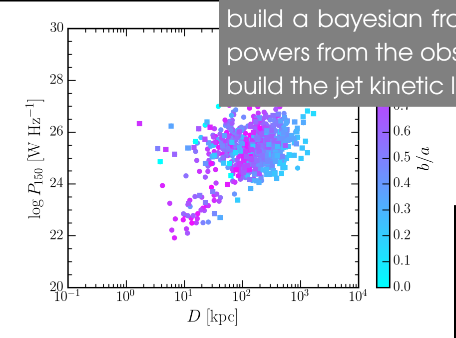


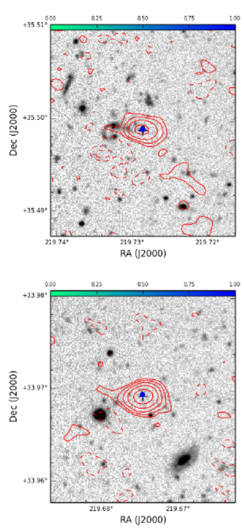
TO DO
build a bayesian framework to infer jet powers from the observables and
build the jet kinetic luminosity function

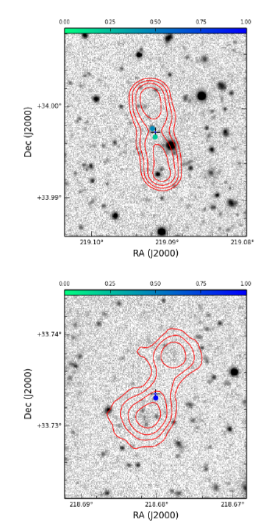


summary

- 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 and H-atlas samples show
  - Radio AGN hosts at higher z are bluer, less massive
  - Radiative mode accretion becomes dominant at $z >\sim 1$, LERGS begin to decline
  - LF spectral shapes of AGN/SF are different
  - Working towards jet kinetic luminosity functions
  - Lots of exciting AGN/SF science in the works!

radio-optical matching





radio-optical matching