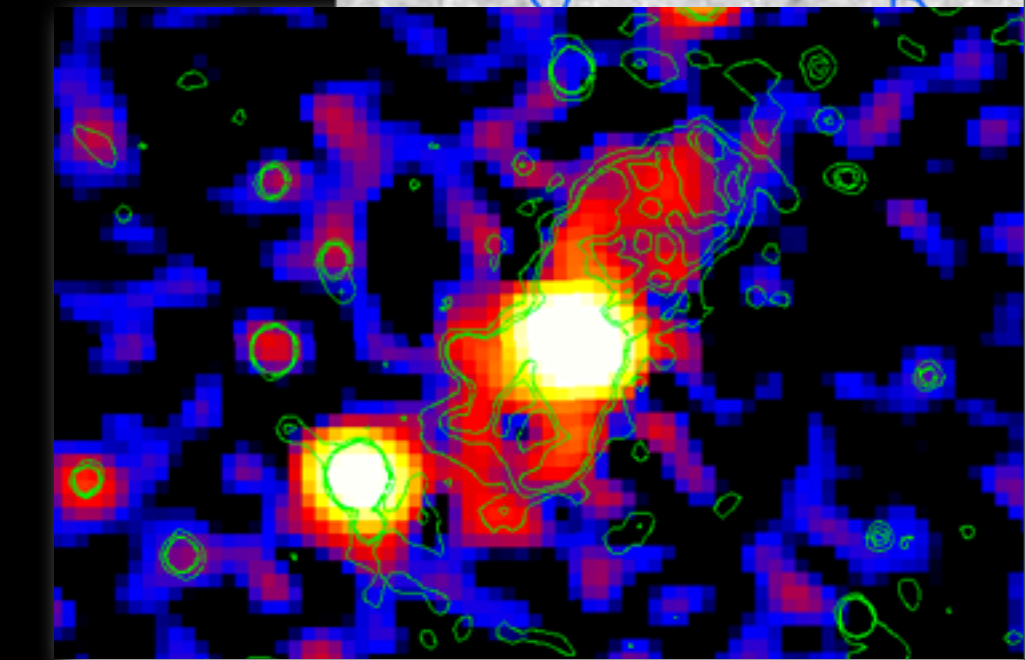
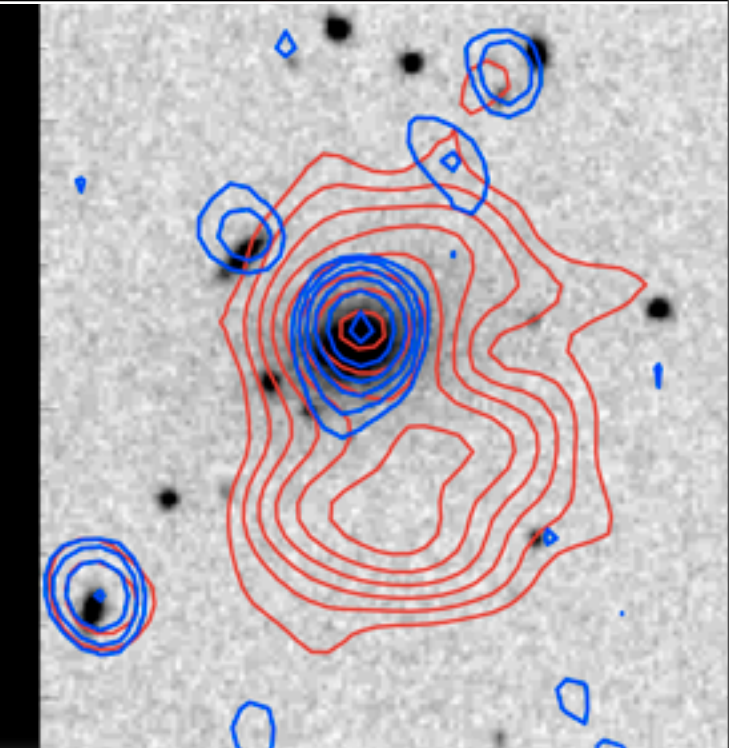
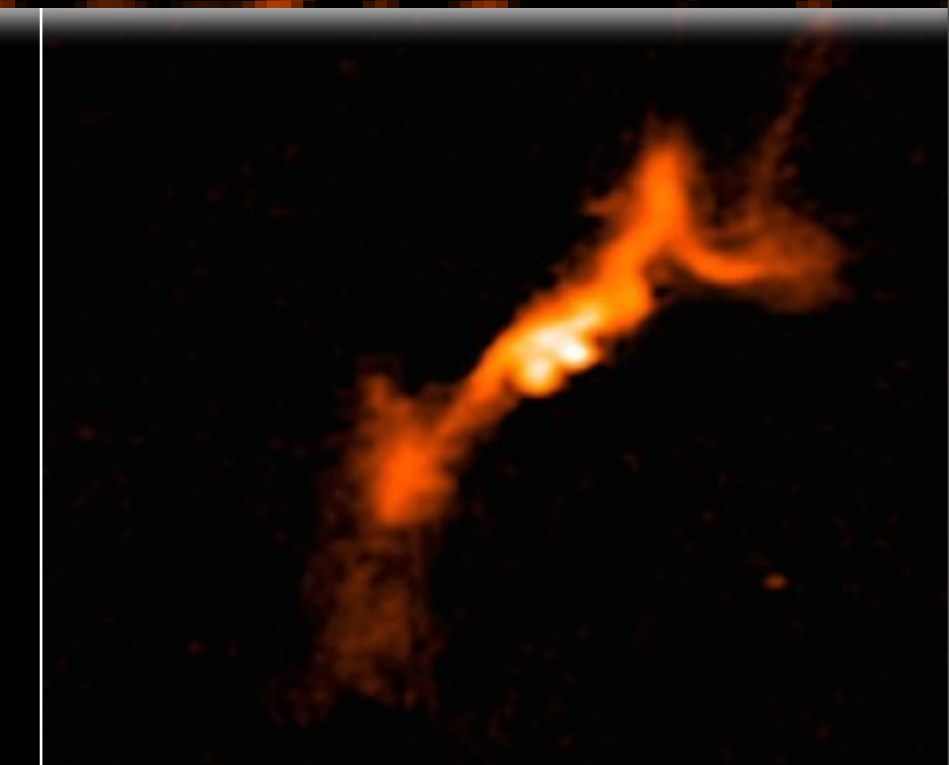
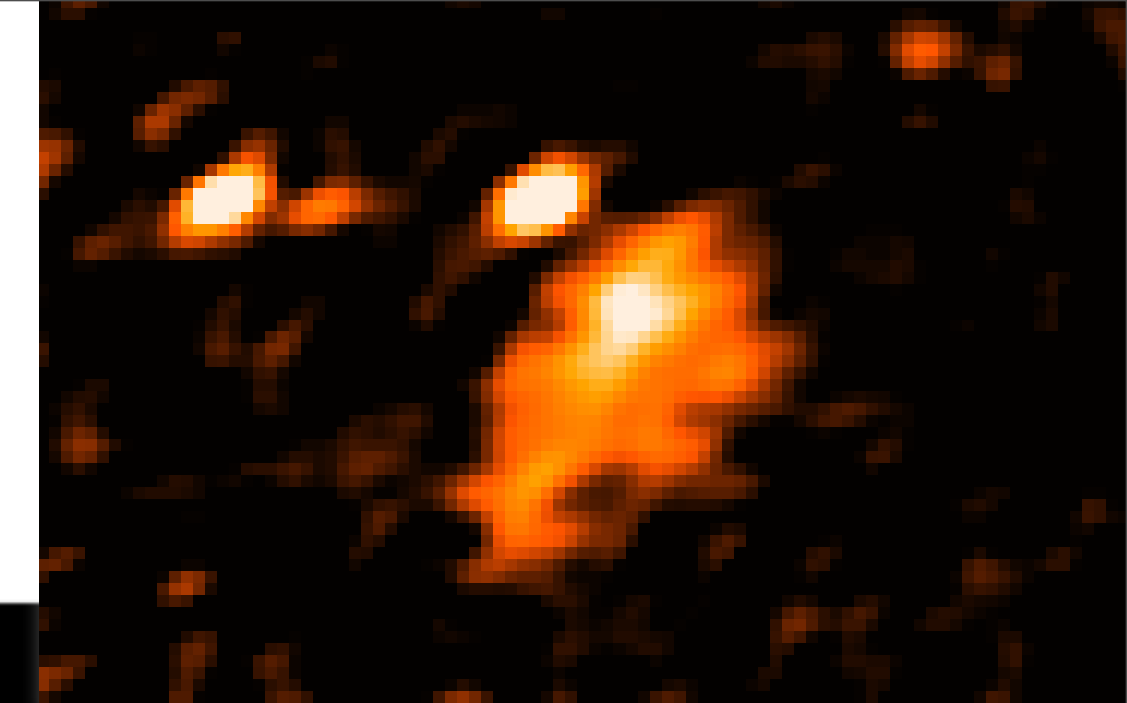


Searching for remnants of radio AGN with LOFAR

Raffaella Morganti

ASTRON (NL) and Kapteyn Institute (Groningen)

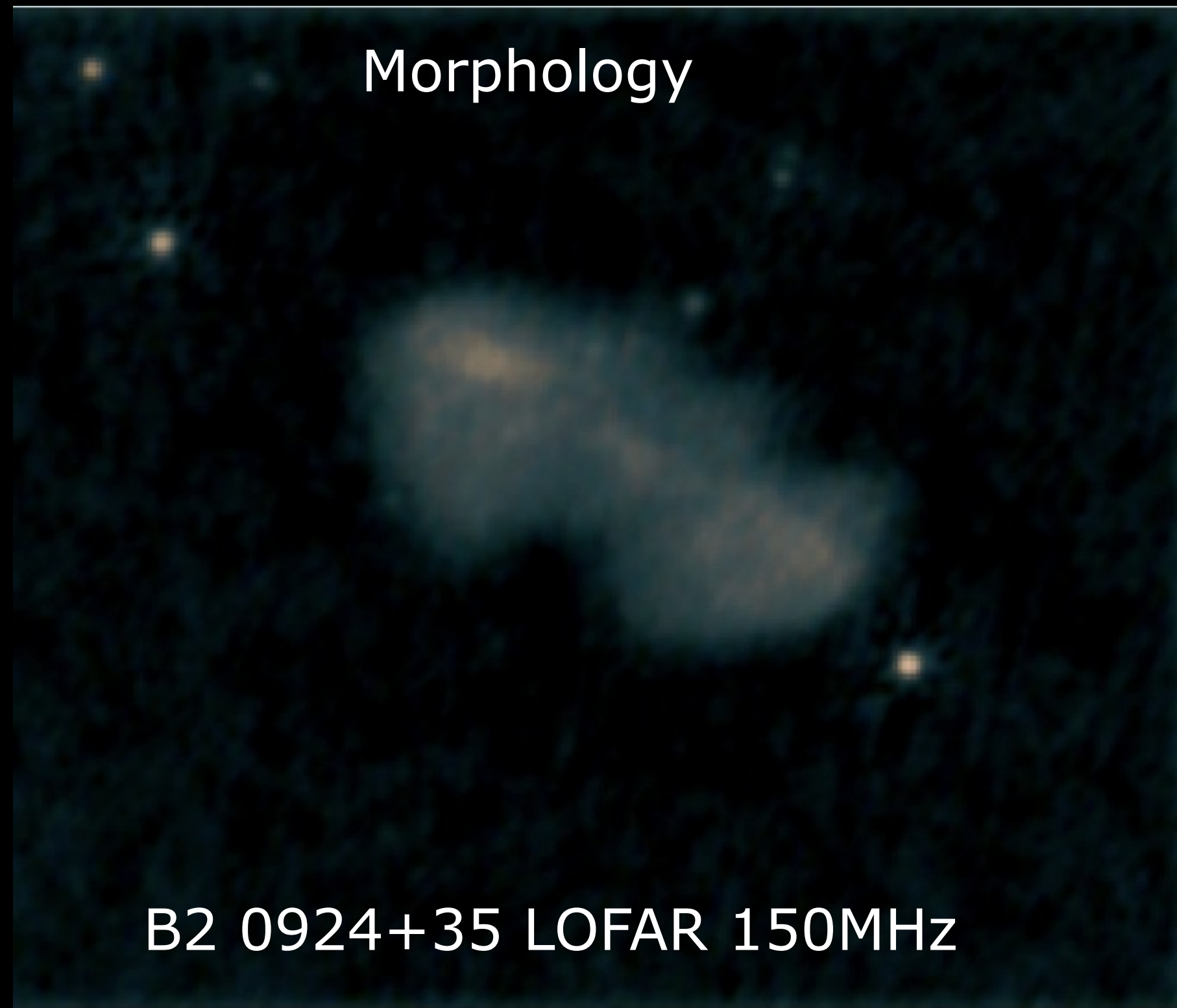
**Marisa Brienza, Elizabeth Mahony, Aleksandar Shulevski,
Leith Godfrey, Jeremy Harwood, Nicolas Vilchez**



Variety of diagnostics offered by LOFAR → quantify life-cycle of radio galaxies → relevant for impact on galaxy evolution

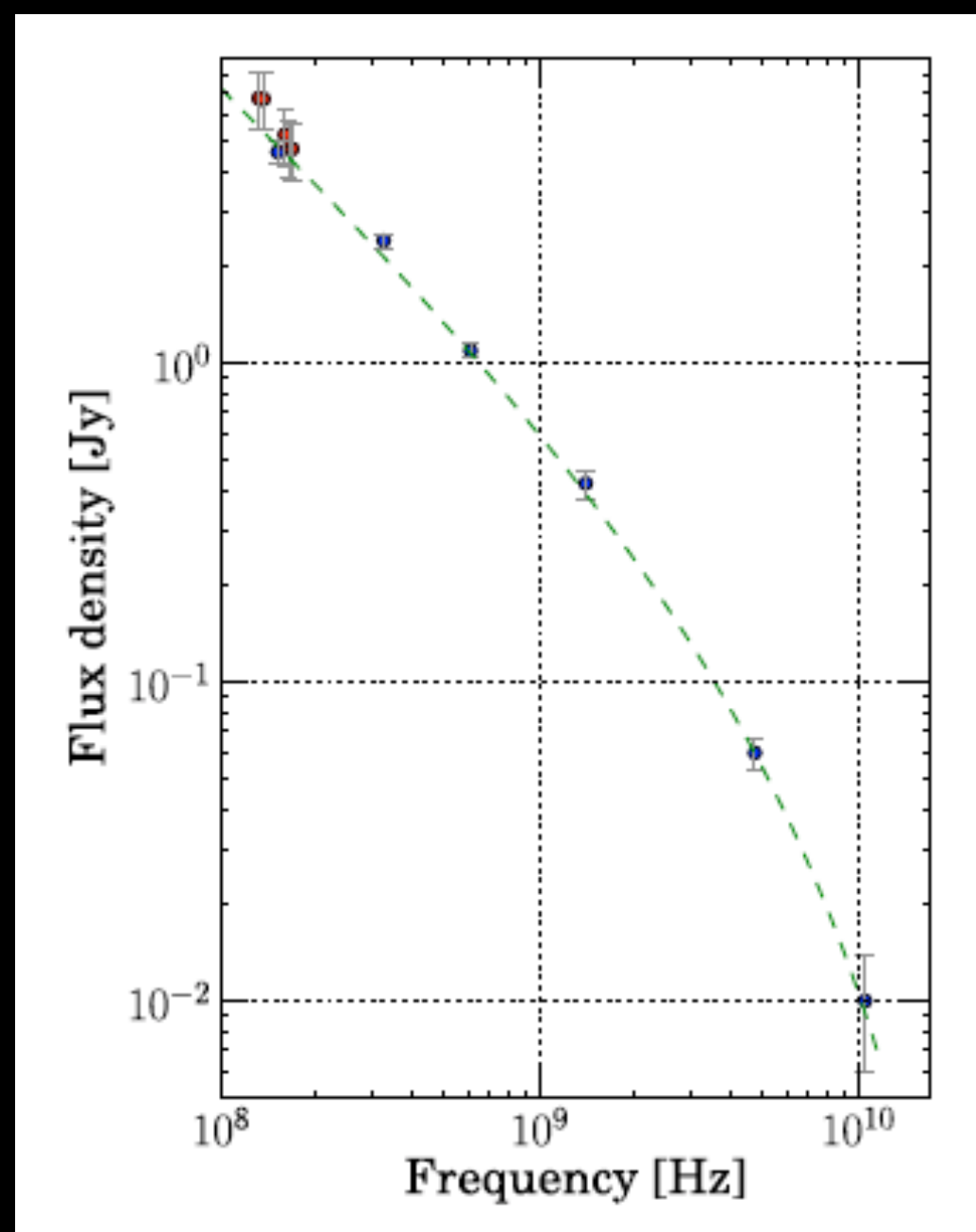
Our project: focus on remnant/restarted phase of radio galaxies

Morphology



B2 0924+35 LOFAR 150MHz

Spectral characteristics



Statistics (rare objects)



Shulevski et al. in prep

Selection of samples so far: remnant/dying/restarted radio AGN

Double-double radio galaxies

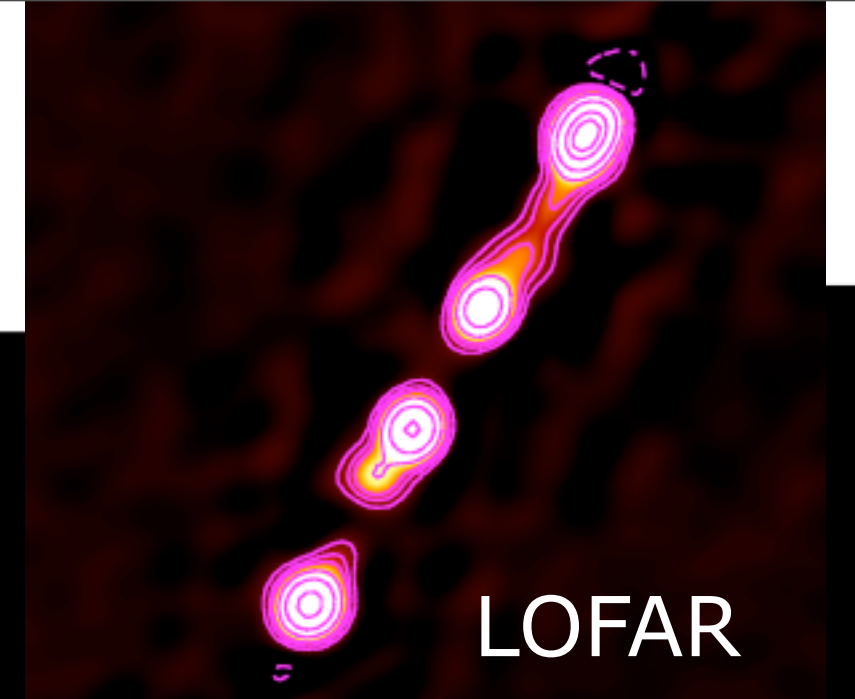
→ selected from morphology → fast cycle (e.g. 20 Myr ON a few Myr OFF, *Konar & Hardcastle 2013, Schoenmakers et al.*)

Remnant/dying

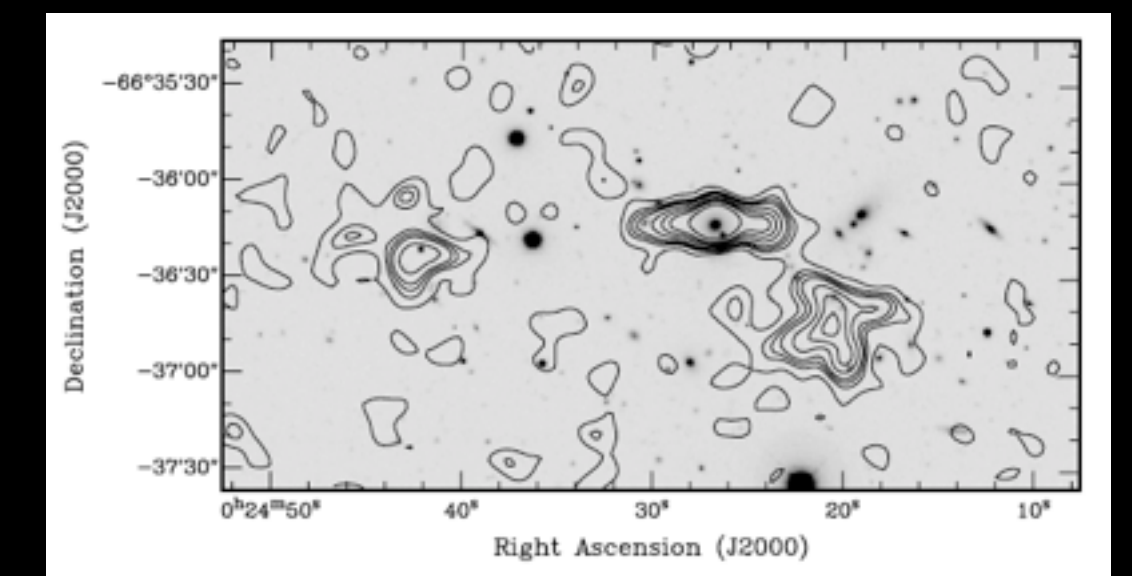
→ Results from morphology (no spectral info available): e.g. *Saripalli et al.*

→ episodic activity: active phase followed by a brief dying phase and restarting activity → *remnants rare, restarted not so rare*

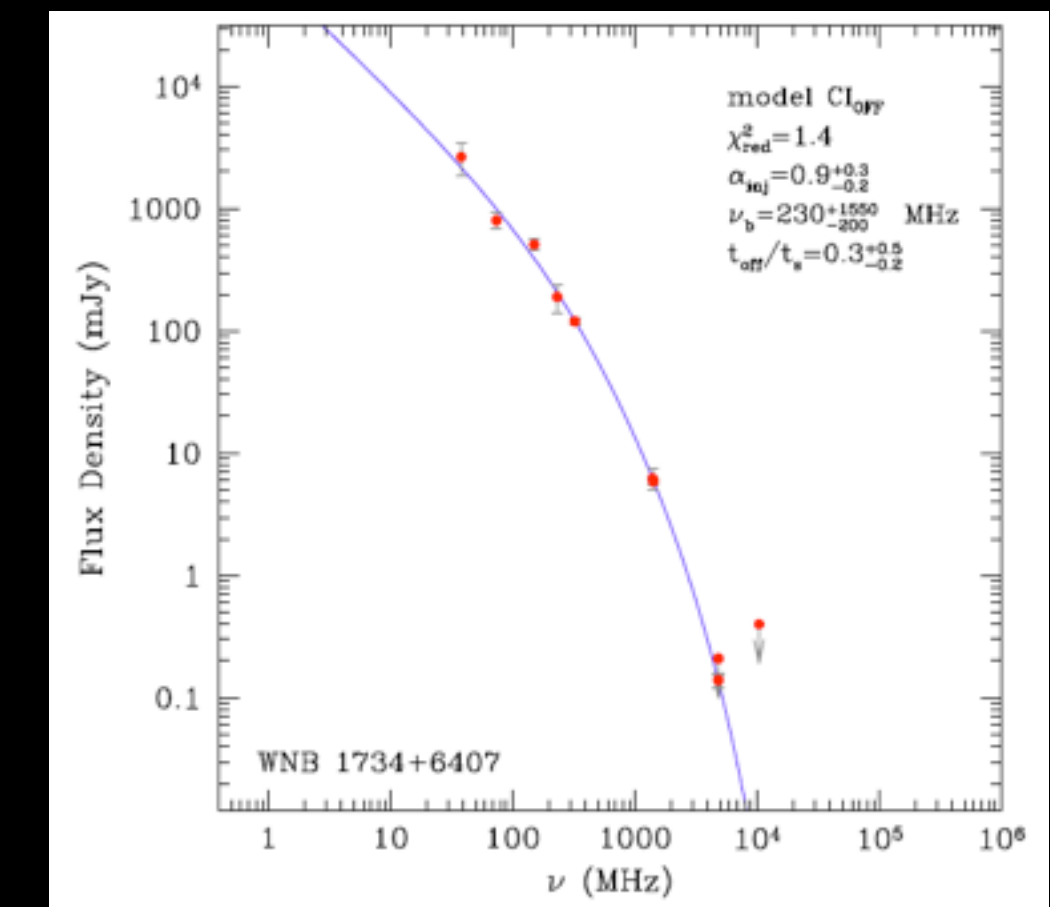
→ Results from selection on steep spectrum (spectral curvature) → minority outside clusters → remnant phase short or similar to active phase (*Parma et al. 2007, Dwaraknath & Kale 2009, van Weeren et al. 2011, Murgia et al. 2011*)



Orru` et al. 2015 submitted

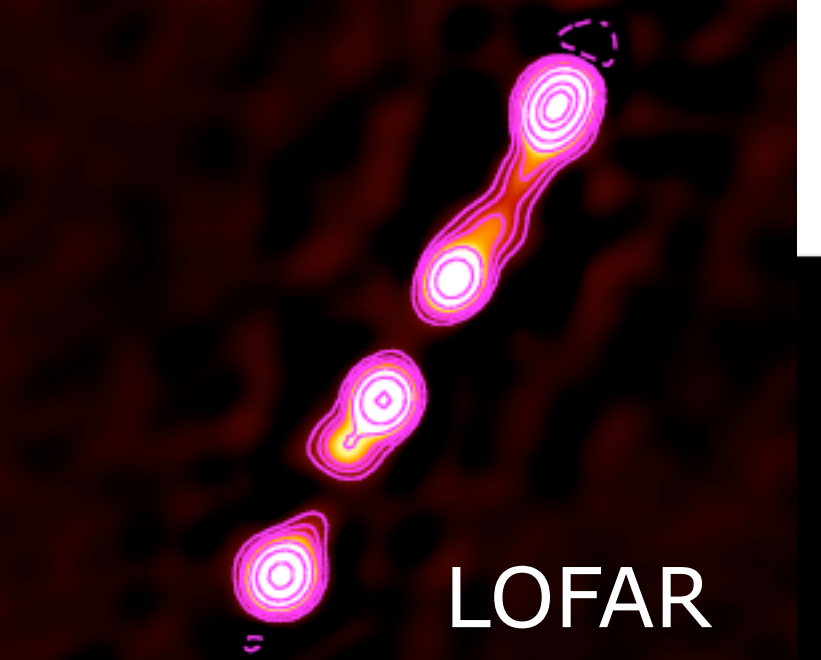


Saripalli et al.



Murgia et al. 2011

Selection of samples so far: remnant/dying/restarted radio AGN



Orru` et al. 2015 submitted

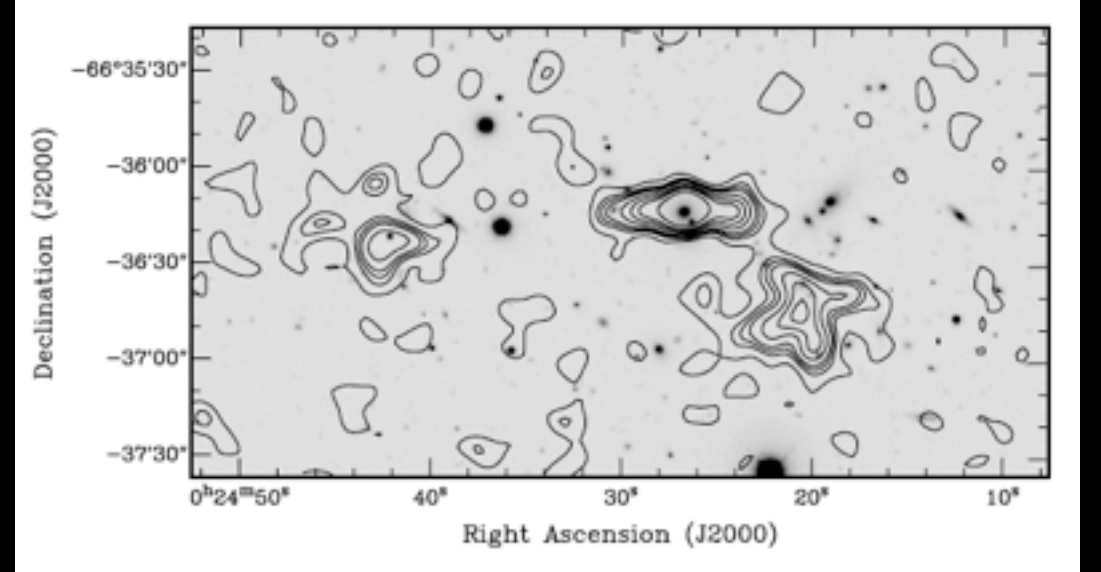
Double-double radio galaxies

→ selected from morphology → fast cycle (e.g. 20 Myr ON a few Myr OFF, Konar & Hardcastle 2013, Schoenmakers et al.)

Remnant/dying

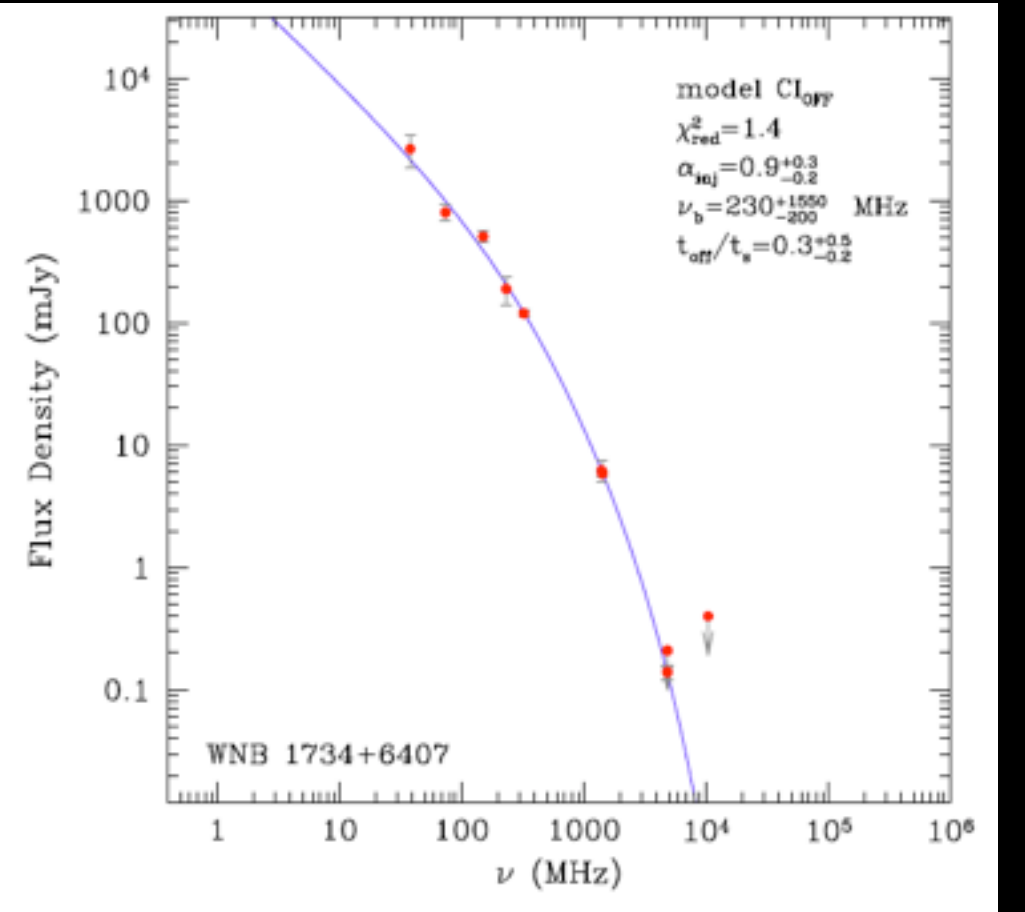
→ Results from morphology (no spectral info available): e.g. Saripalli et al.
→ episodic activity: active phase followed by a brief dying phase and restarting activity → *remnants rare, restarted not so rare*

→ Results from selection on steep spectrum (spectral curvature) → minority outside clusters → remnant phase short or similar to active phase (Parma et al. 2007, Dwaraknath & Kale 2009, van Weeren et al. 2011, Murgia et al. 2011)



Saripalli et al.

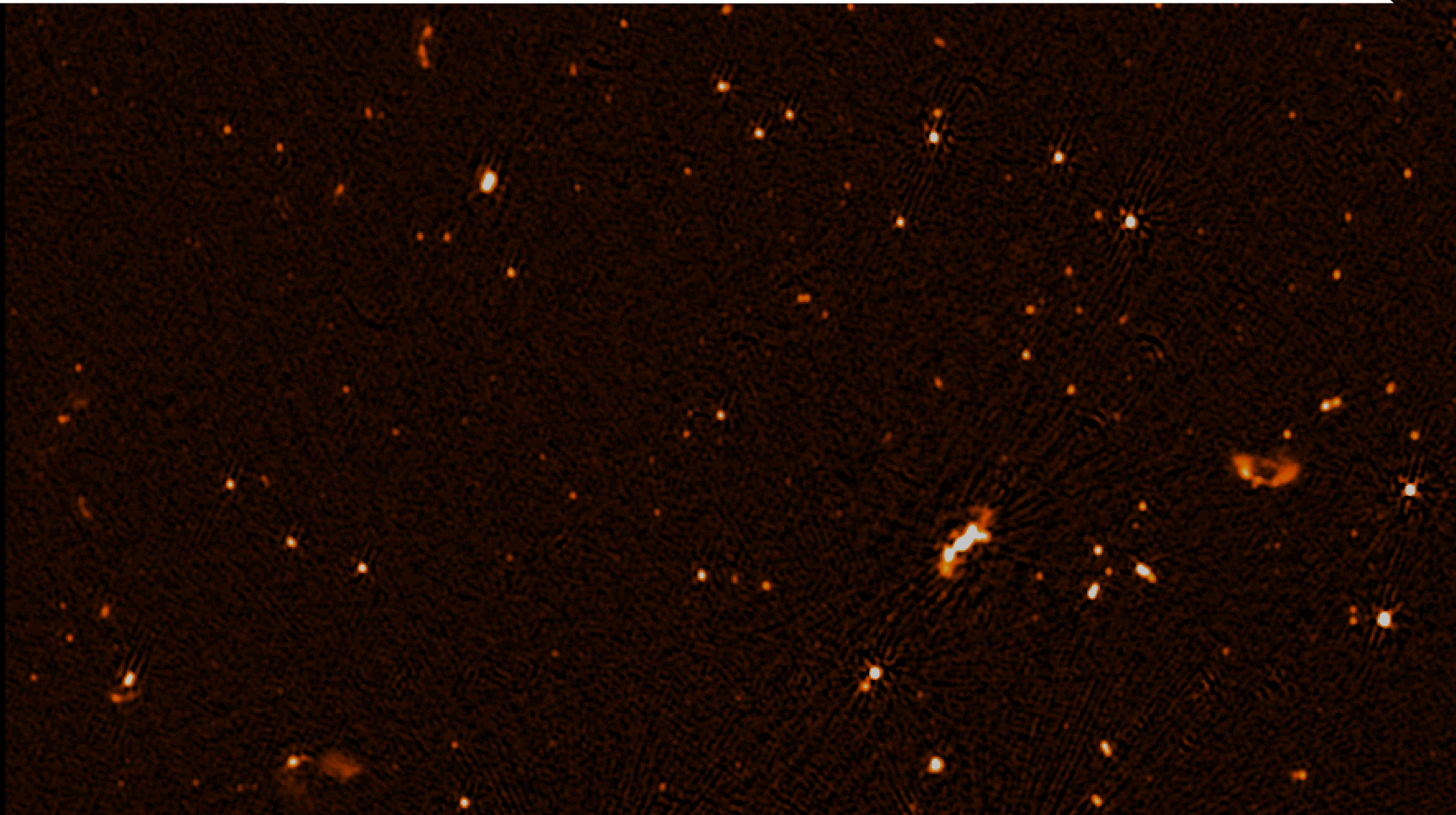
There is a broad expectation that deep low frequency radio surveys will reveal an abundance of steep spectrum remnant radio galaxies
Is this expectation well founded?



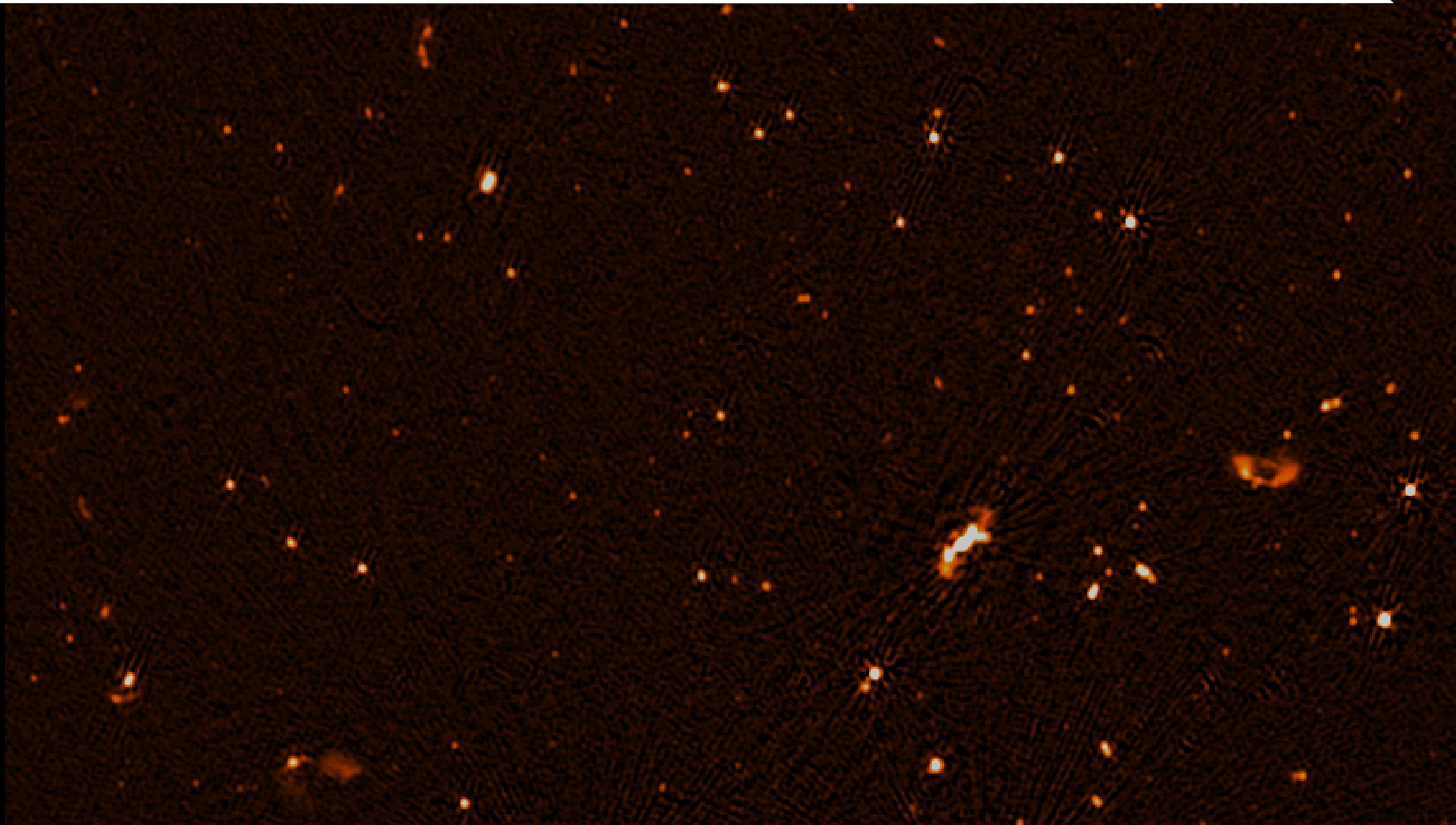
Murgia et al. 2011

Selecting from the radio morphology
First results already very interesting...

Some images are reaching the required quality ...

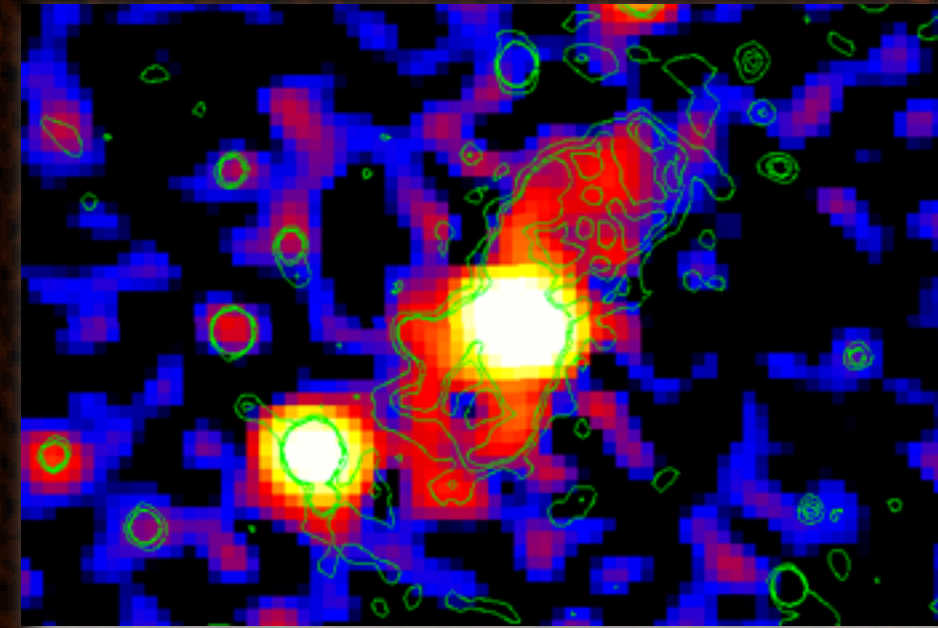
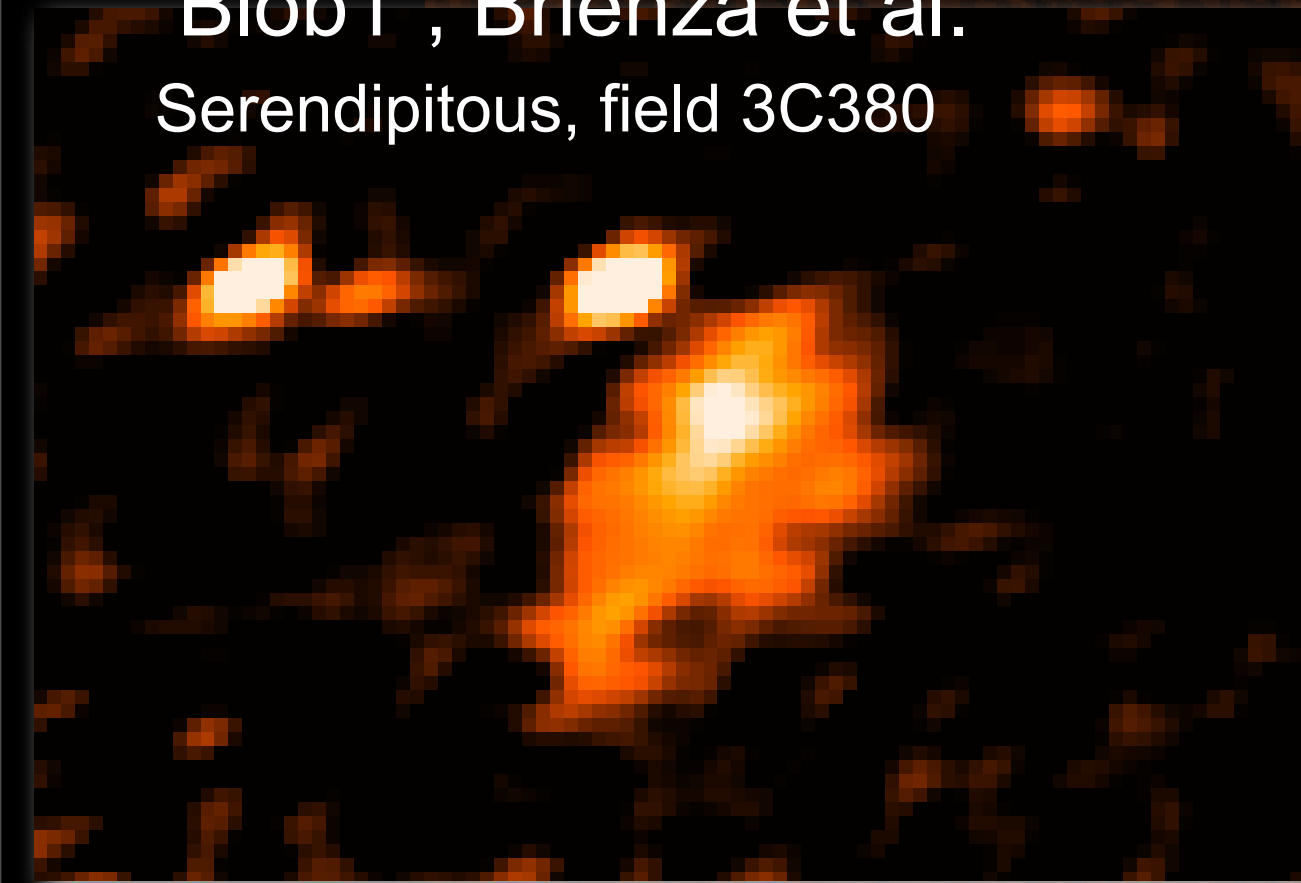


... and interesting objects start to appear

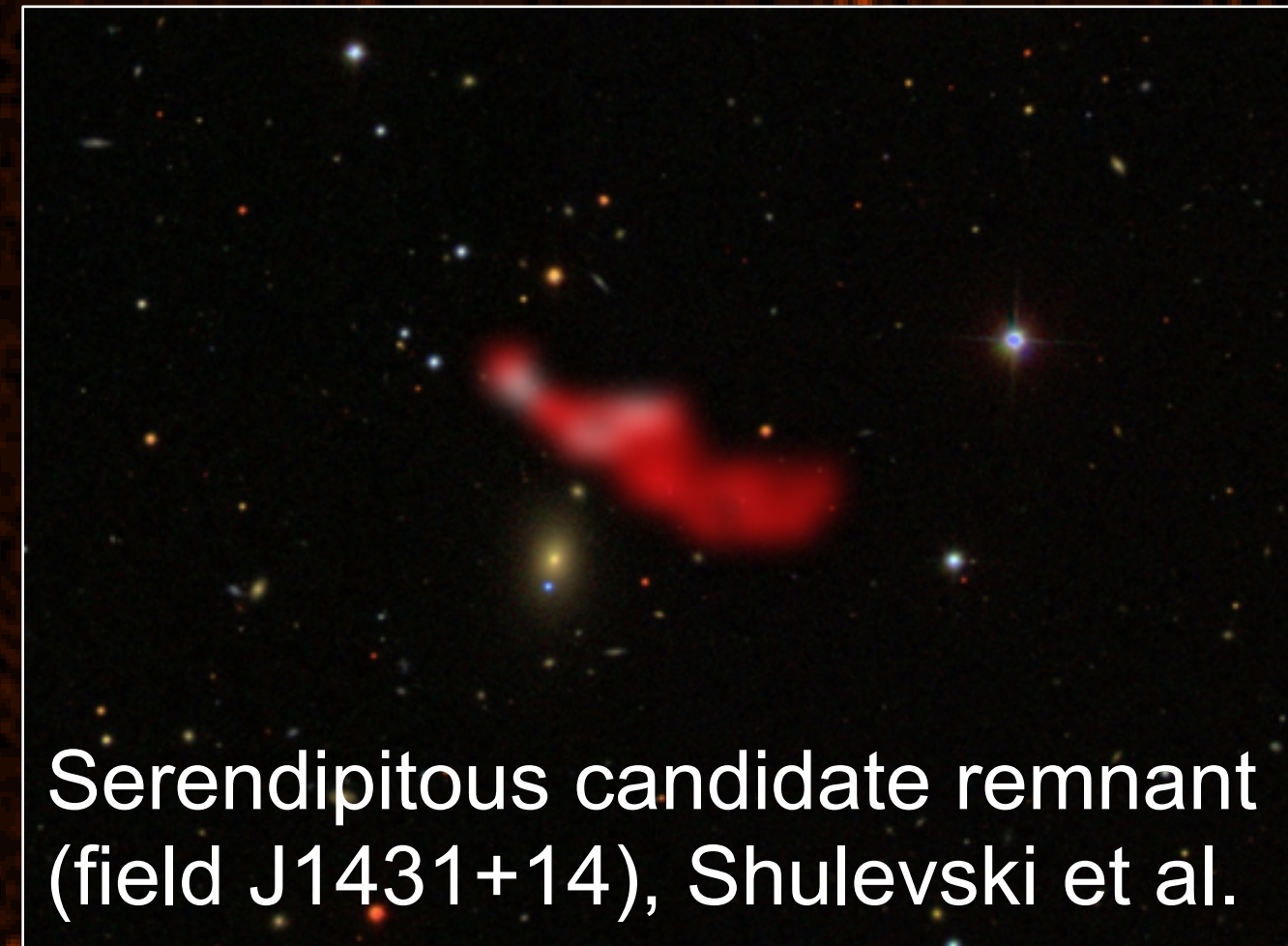


... and interesting objects start to appear

“Blob1”, Brienza et al.
Serendipitous, field 3C380



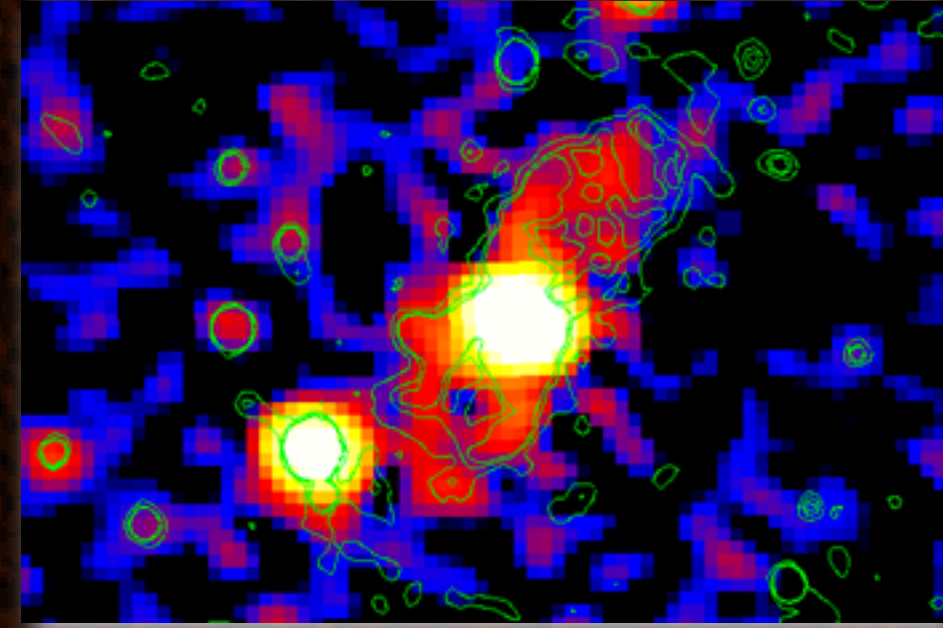
Candidate remnant around
B2 0258+35 - Brienza et al.



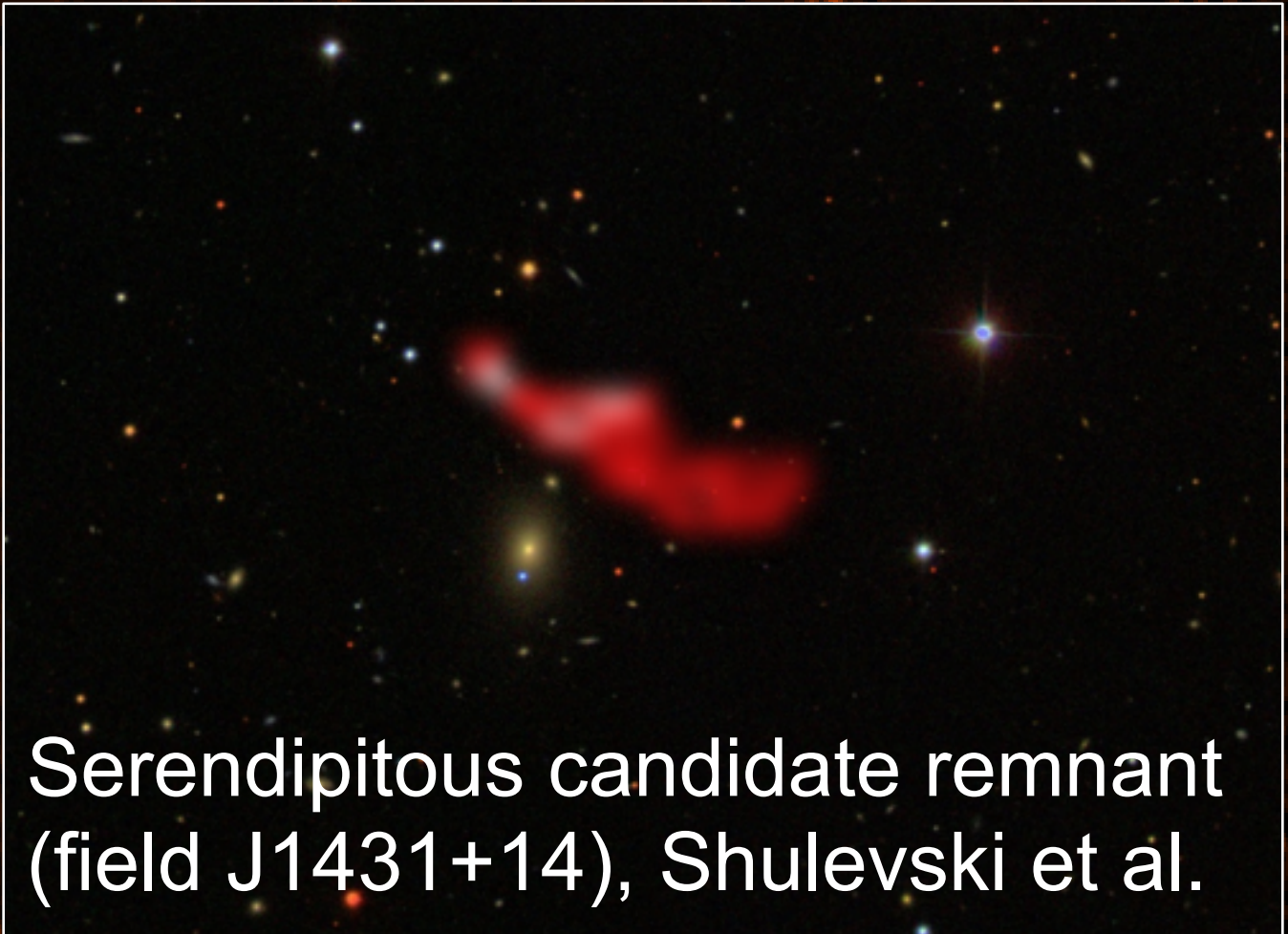
Serendipitous candidate remnant
(field J1431+14), Shulevski et al.

... and interesting objects start to appear

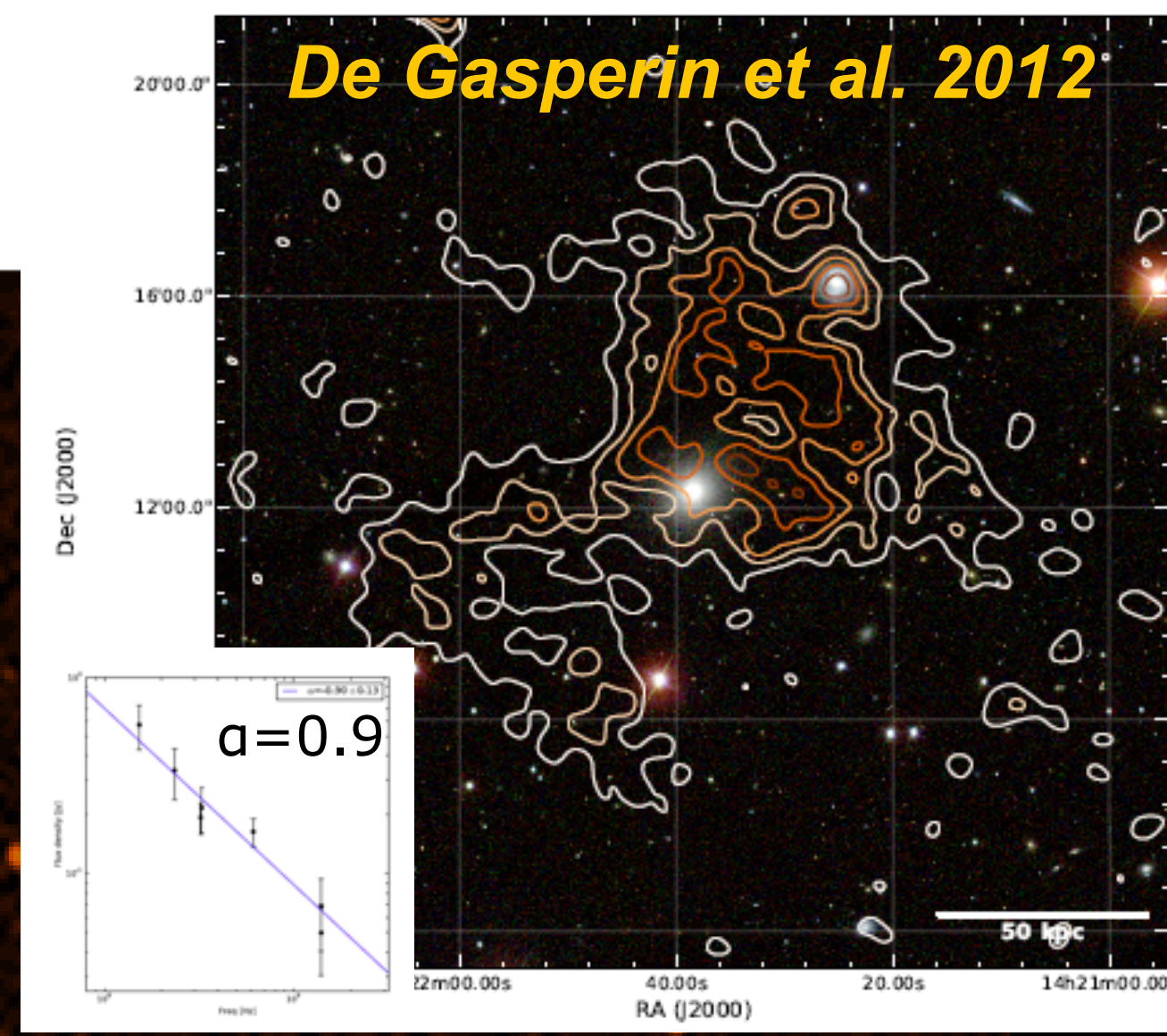
“Blob1”, Brienza et al.
Serendipitous, field 3C380



Candidate remnant around
B2 0258+35 - Brienza et al.

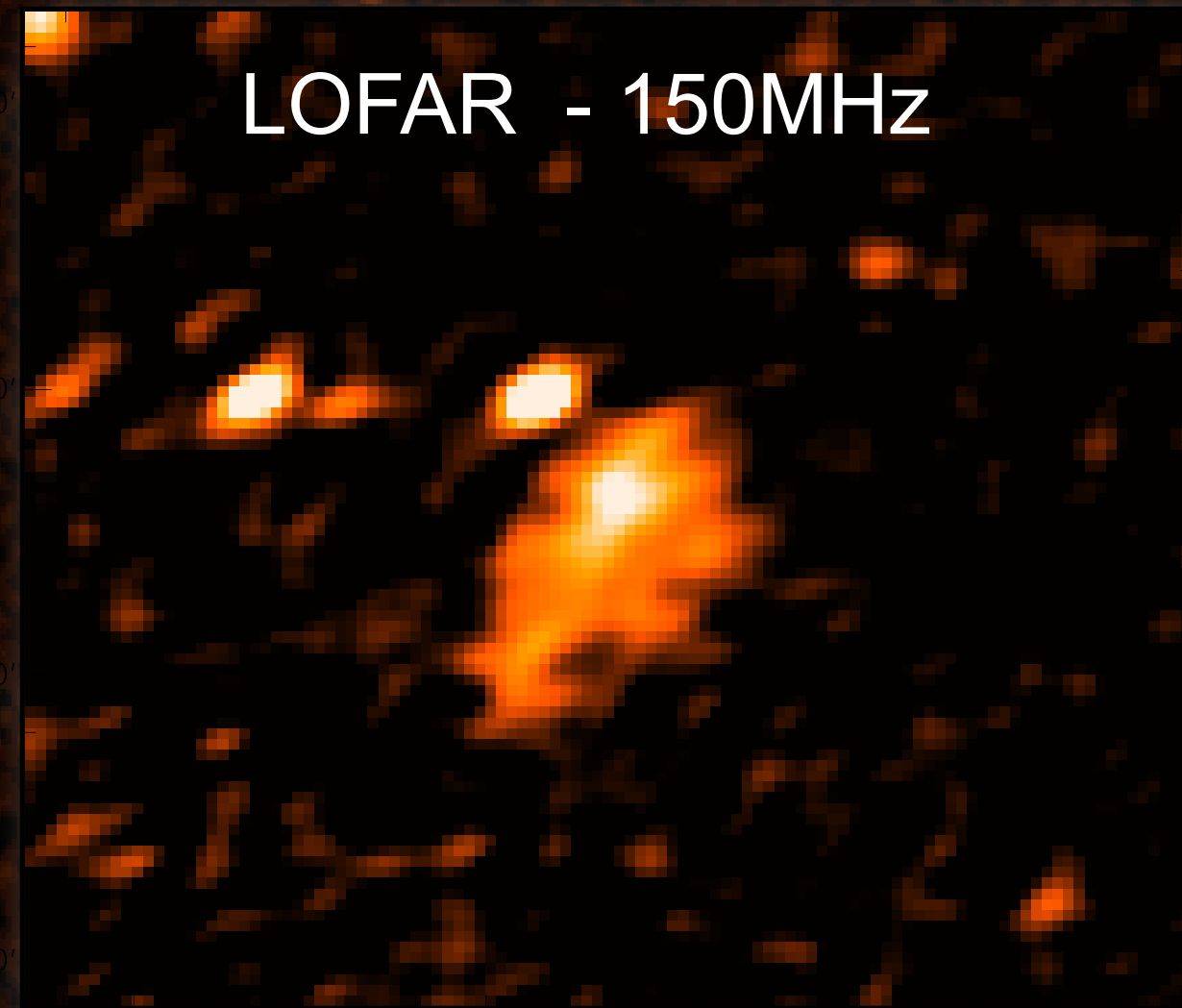


Serendipitous candidate remnant
(field J1431+14), Shulevski et al.



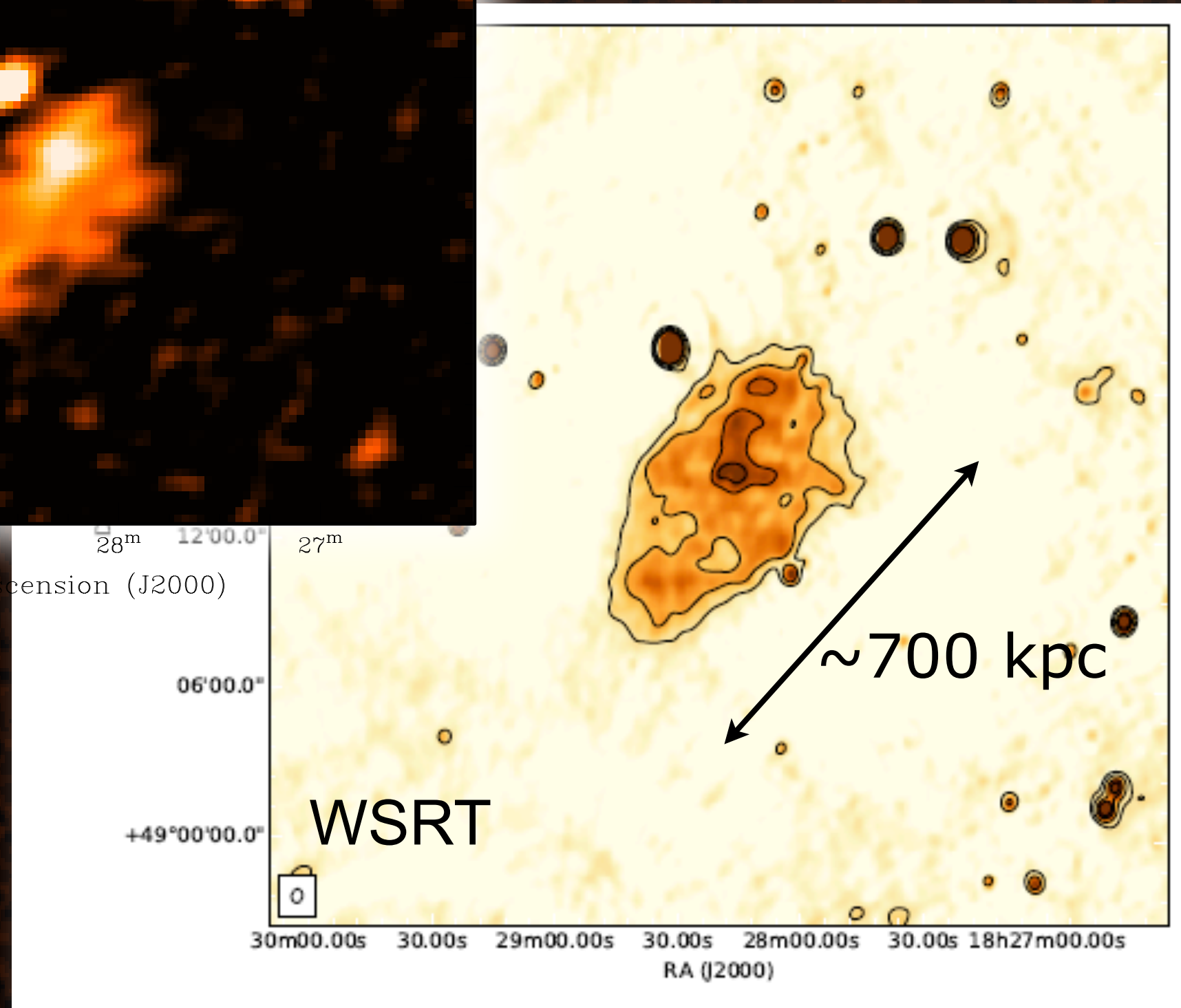
Candidate remnant, Bootes field
van Weeren et al. 2014

Some surprises: spectral analysis of "Blob1"

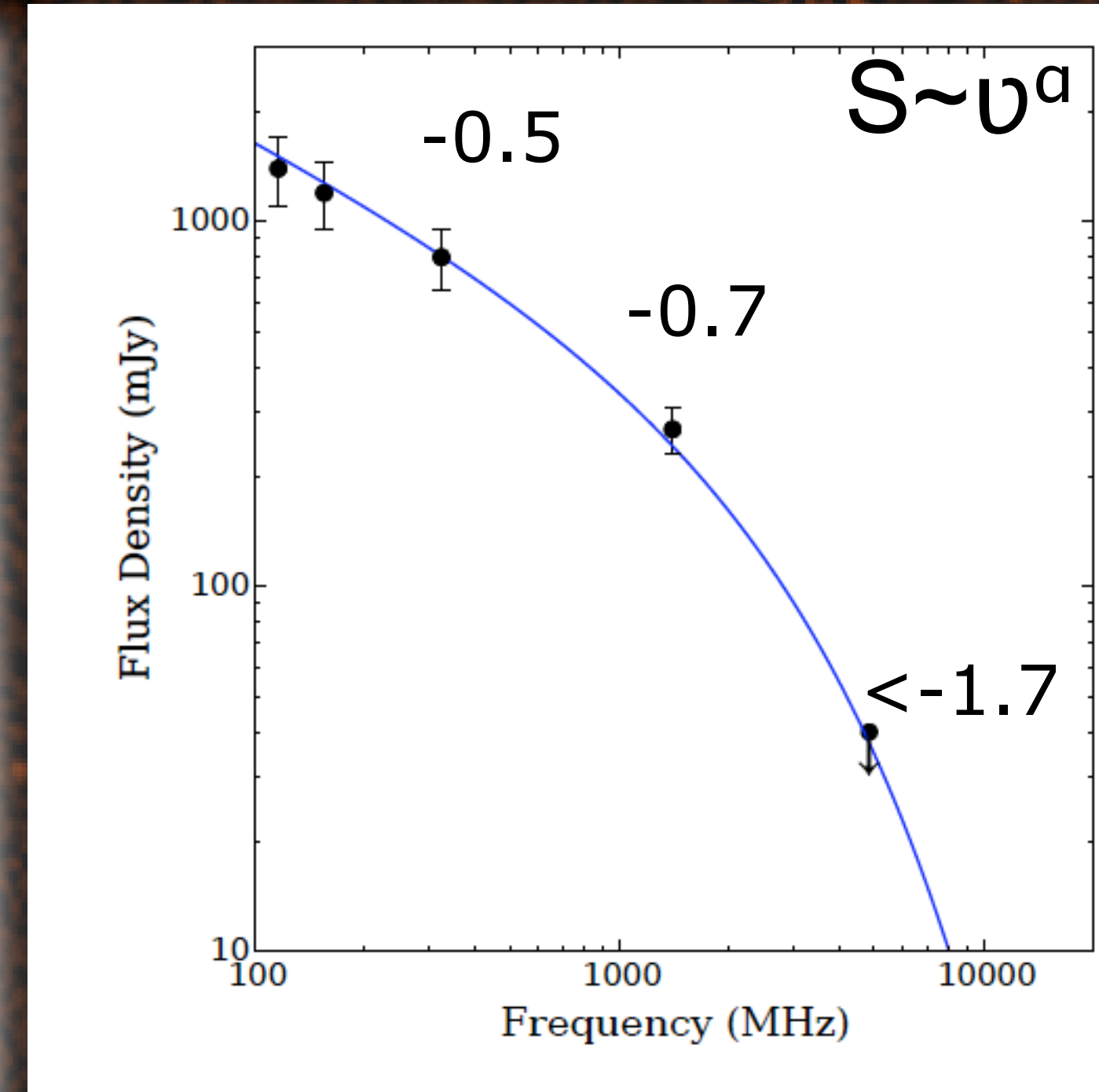


LOFAR - 150MHz

on phase shorter than off phase



~ 700 kpc



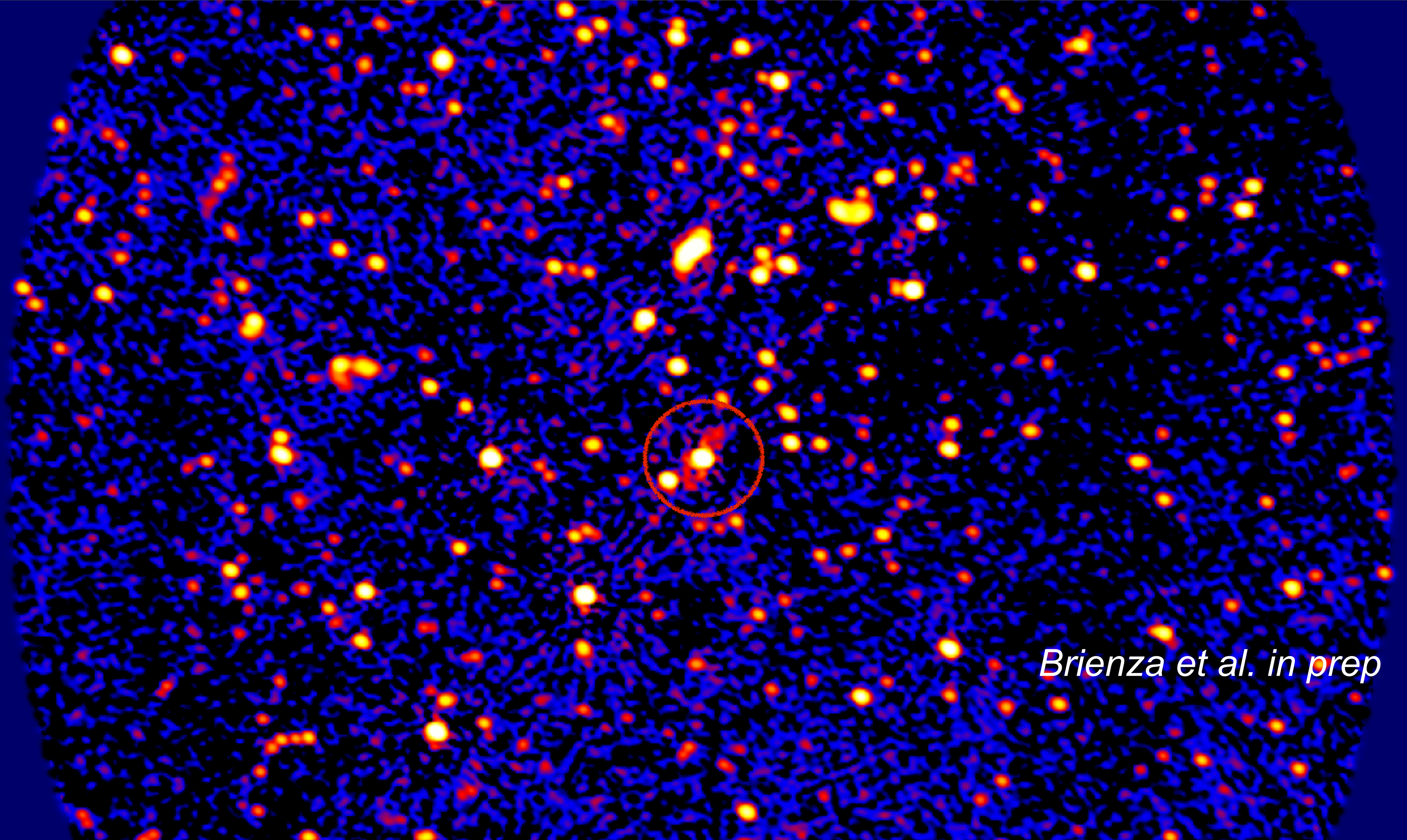
not detected by NVSS - deeper 1.4GHz (WSRT) image was needed

steep spectrum not enough as criteria → biasing against slow duty cycle? (active phase much shorter than remnant...)

Details in Marisa's talk....

Brienza et al. 2015 (about to be submitted)

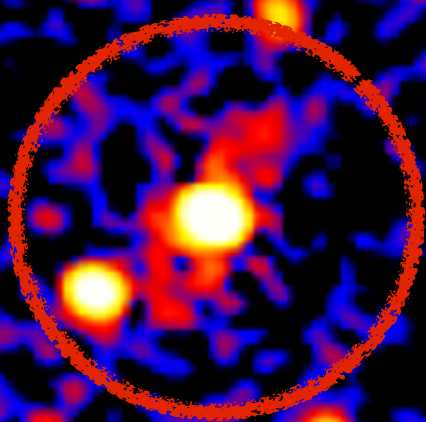
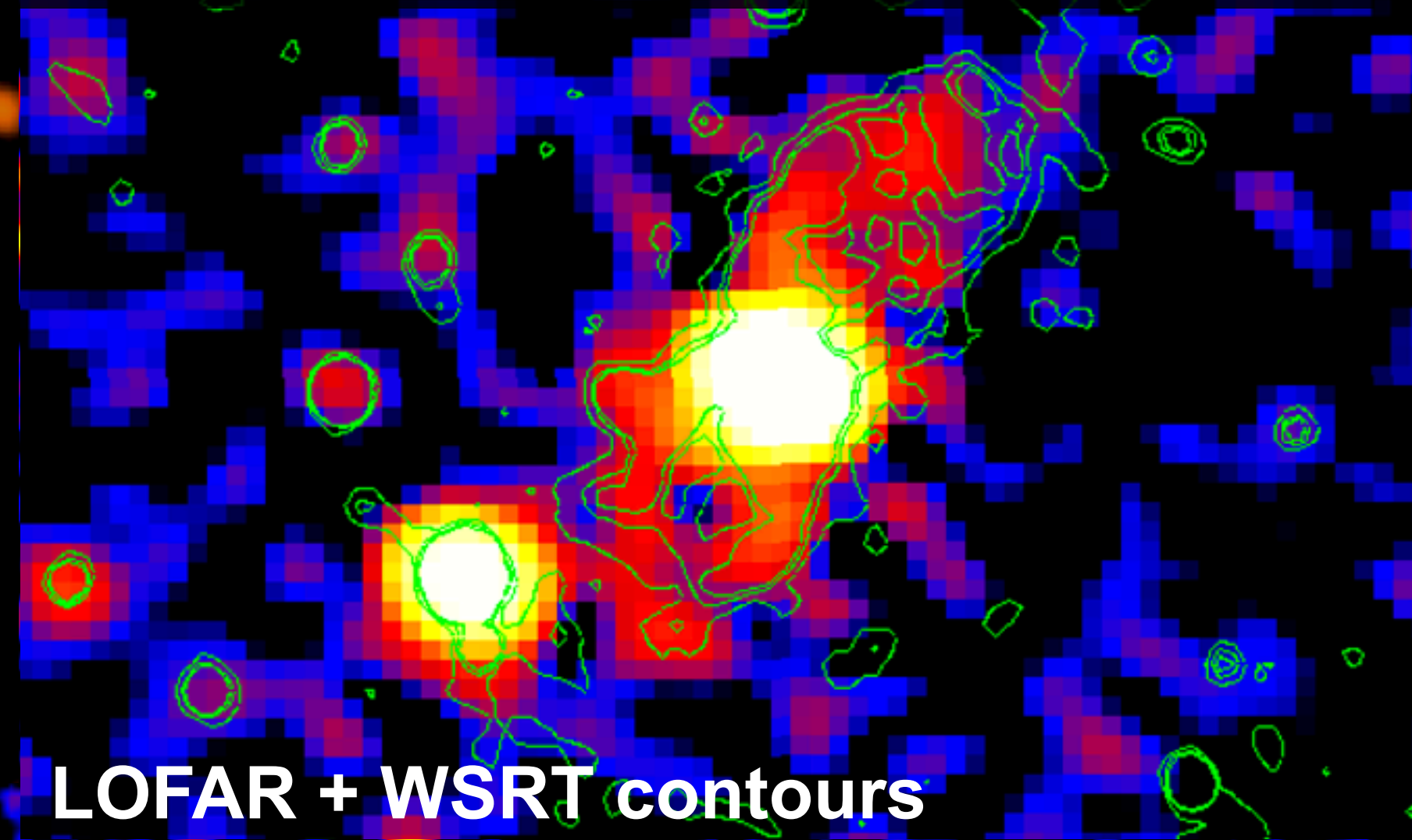
HBA field @ 1.5arcmin res., 2 mJy/b noise



Brienza et al. in prep

Spectral index diffuse emission $\sim -0.7...$

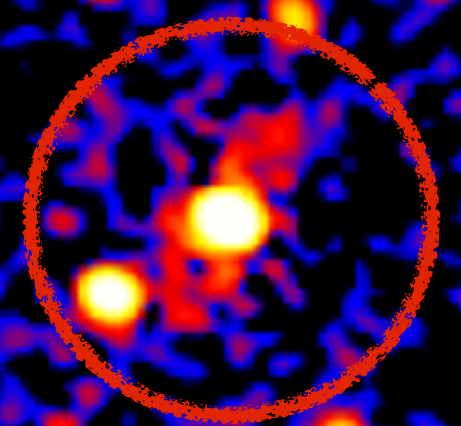
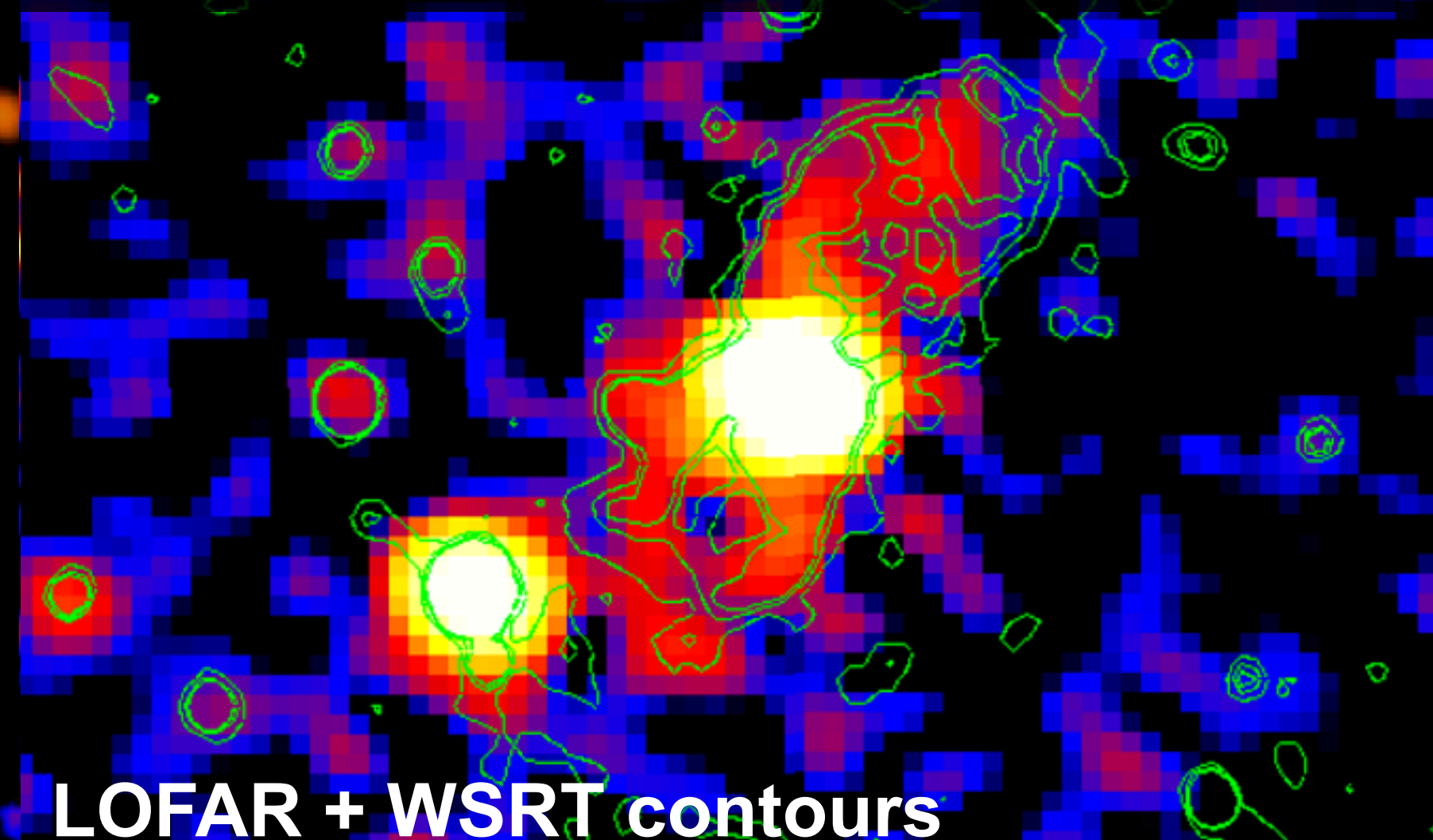
*Young radio galaxy
in the centre....*



Brienza et al. in prep

Spectral index diffuse emission $\sim -0.7...$

*Young radio galaxy
in the centre....*

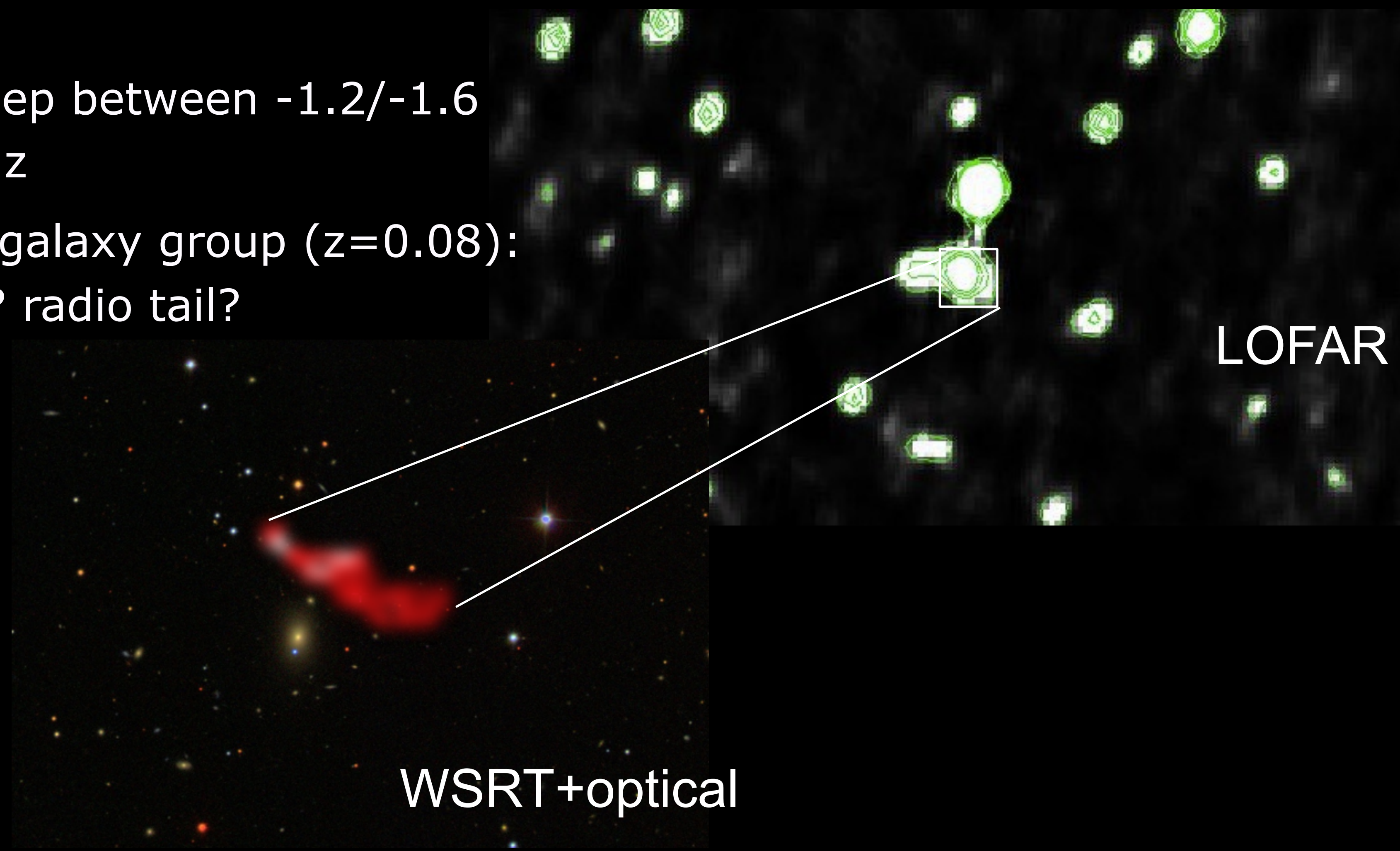


Brienza et al. in prep

Lesson learned: not every diffuse, low surface brightness emission has to be a remnant!
Some of these objects may be still fuel but at low rate and not by collimated jets ...
see cases of Cen A and M87

A. Shulevski

- ▶ Less clear what this is
- ▶ spectral index relatively steep between -1.2/-1.6 between 150MHz and 1.4GHz
- ▶ optical counterpart? small galaxy group ($z=0.08$): does it belong to this group? radio tail?

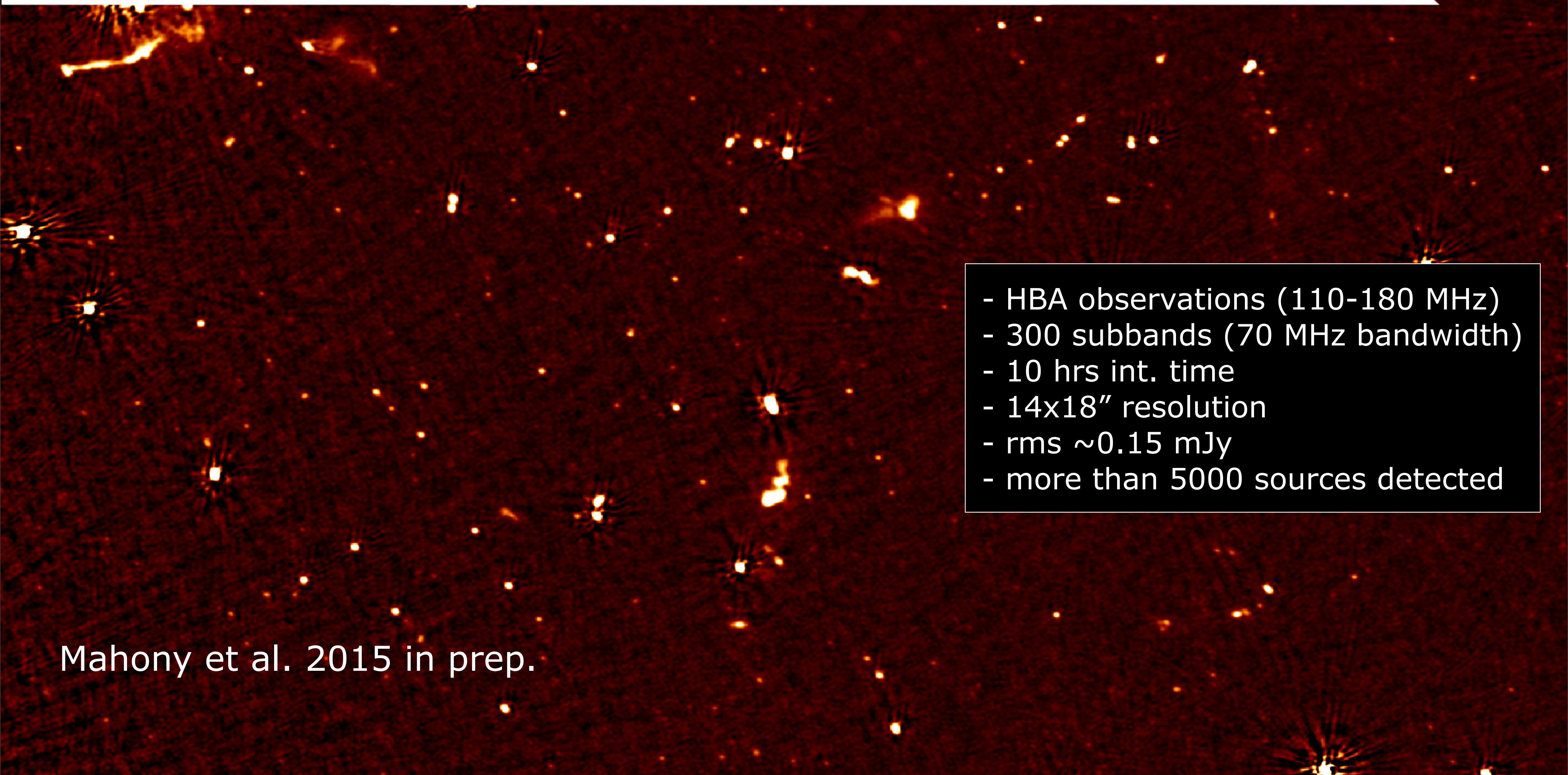


LOFAR

WSRT+optical

not detected by NVSS - deeper 1.4GHz (WSRT) image was needed

Selecting from spectral index

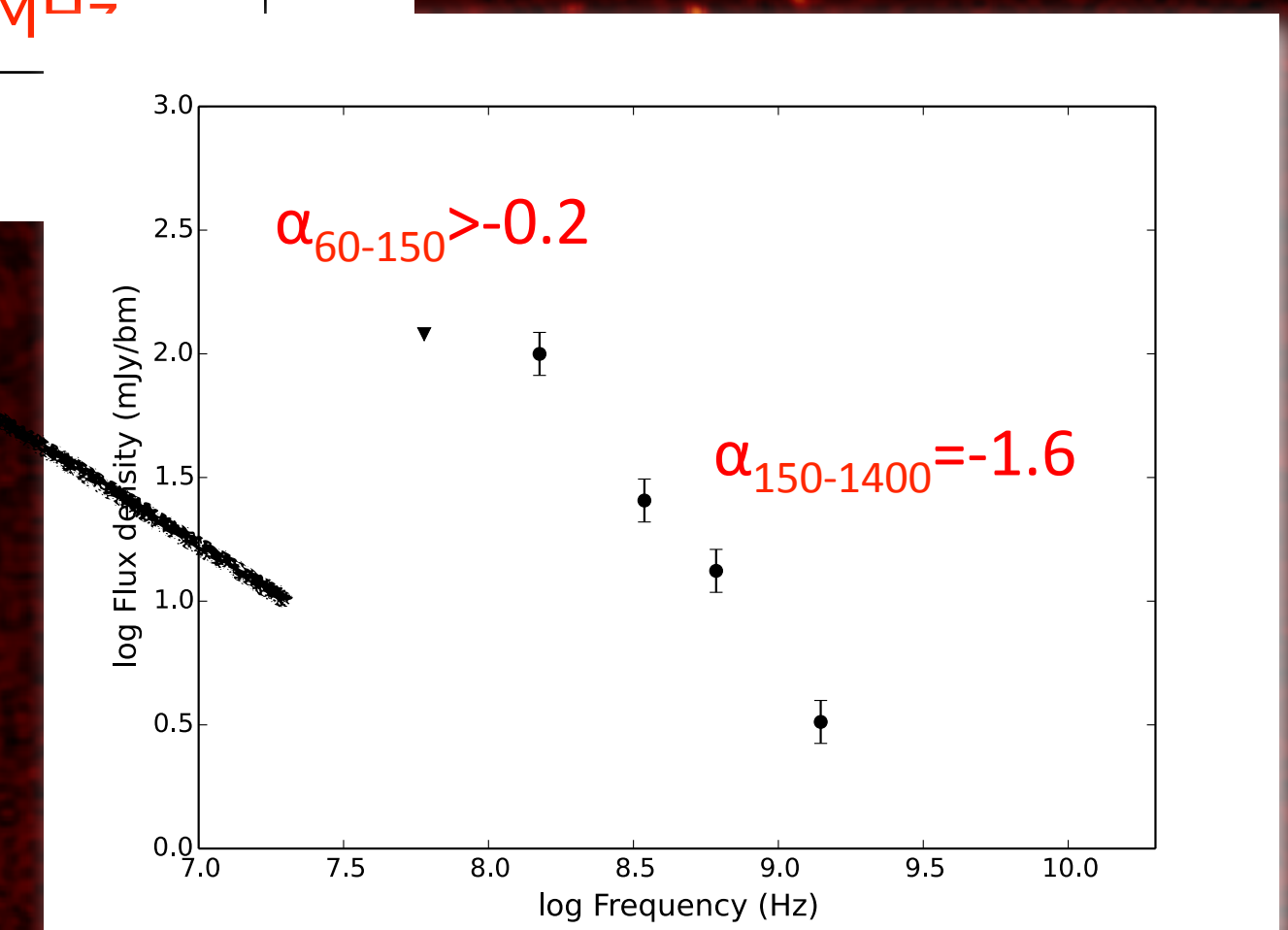
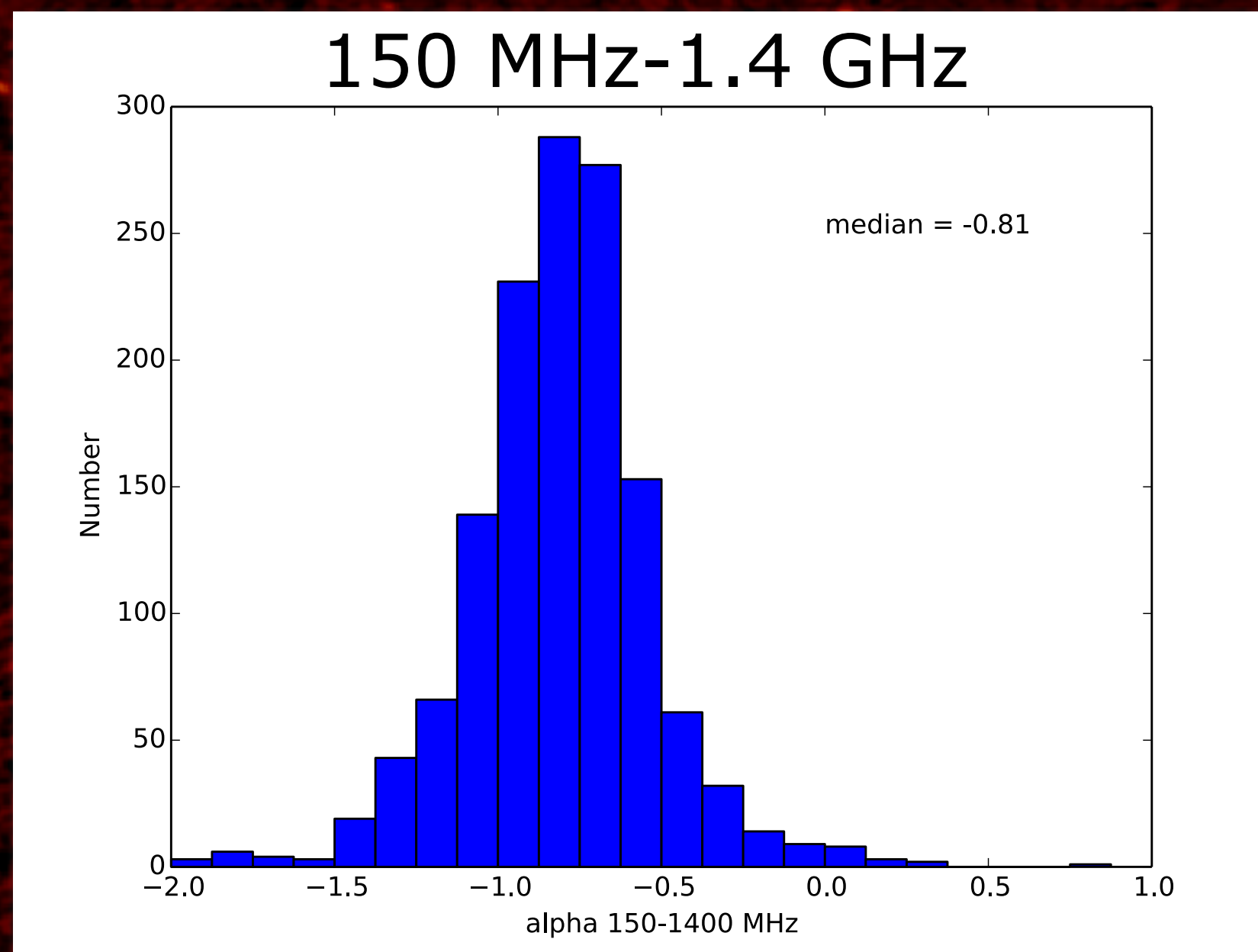
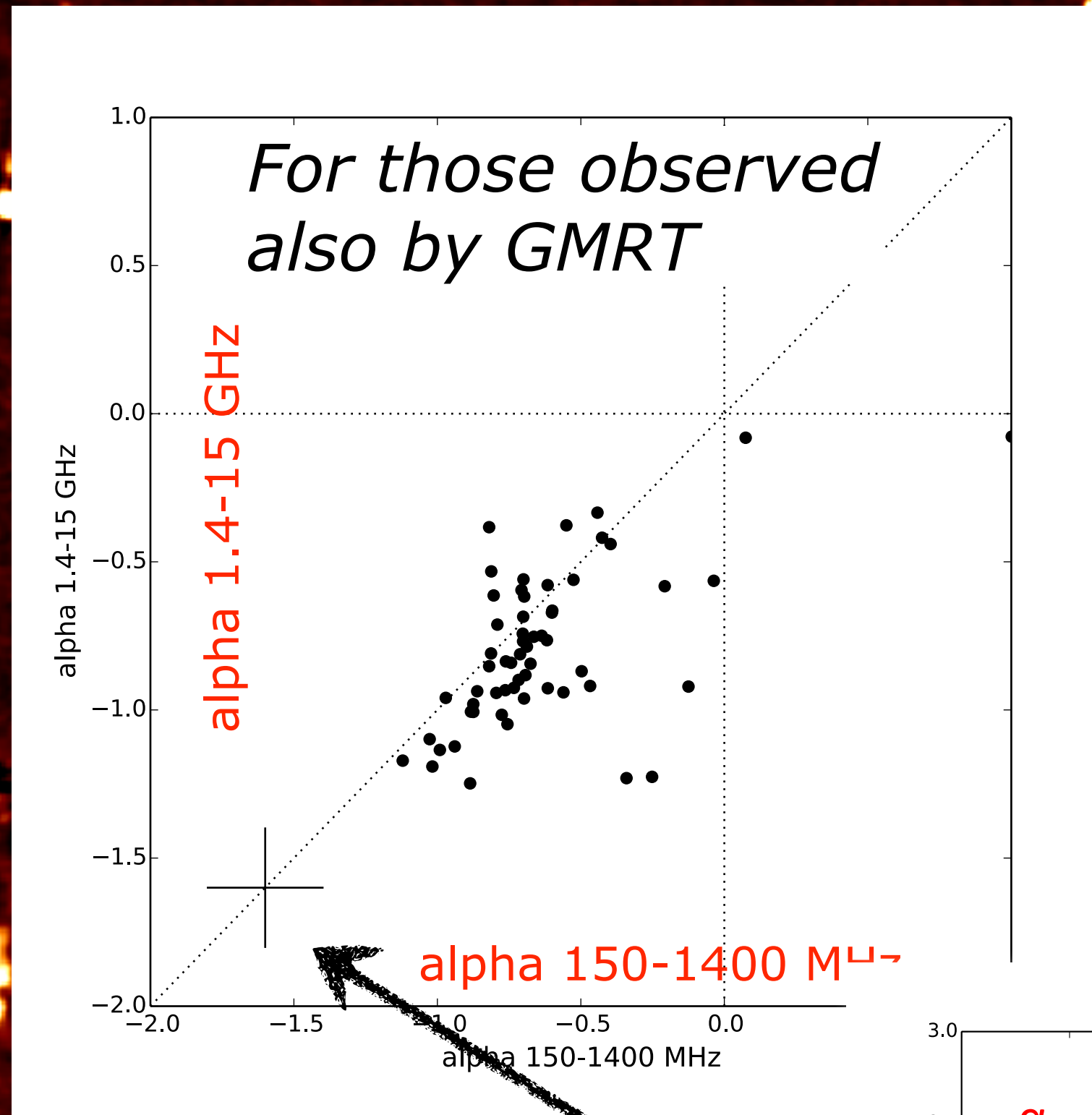


- HBA observations (110-180 MHz)
- 300 subbands (70 MHz bandwidth)
- 10 hrs int. time
- 14x18" resolution
- rms ~ 0.15 mJy
- more than 5000 sources detected

Mahony et al. 2015 in prep.

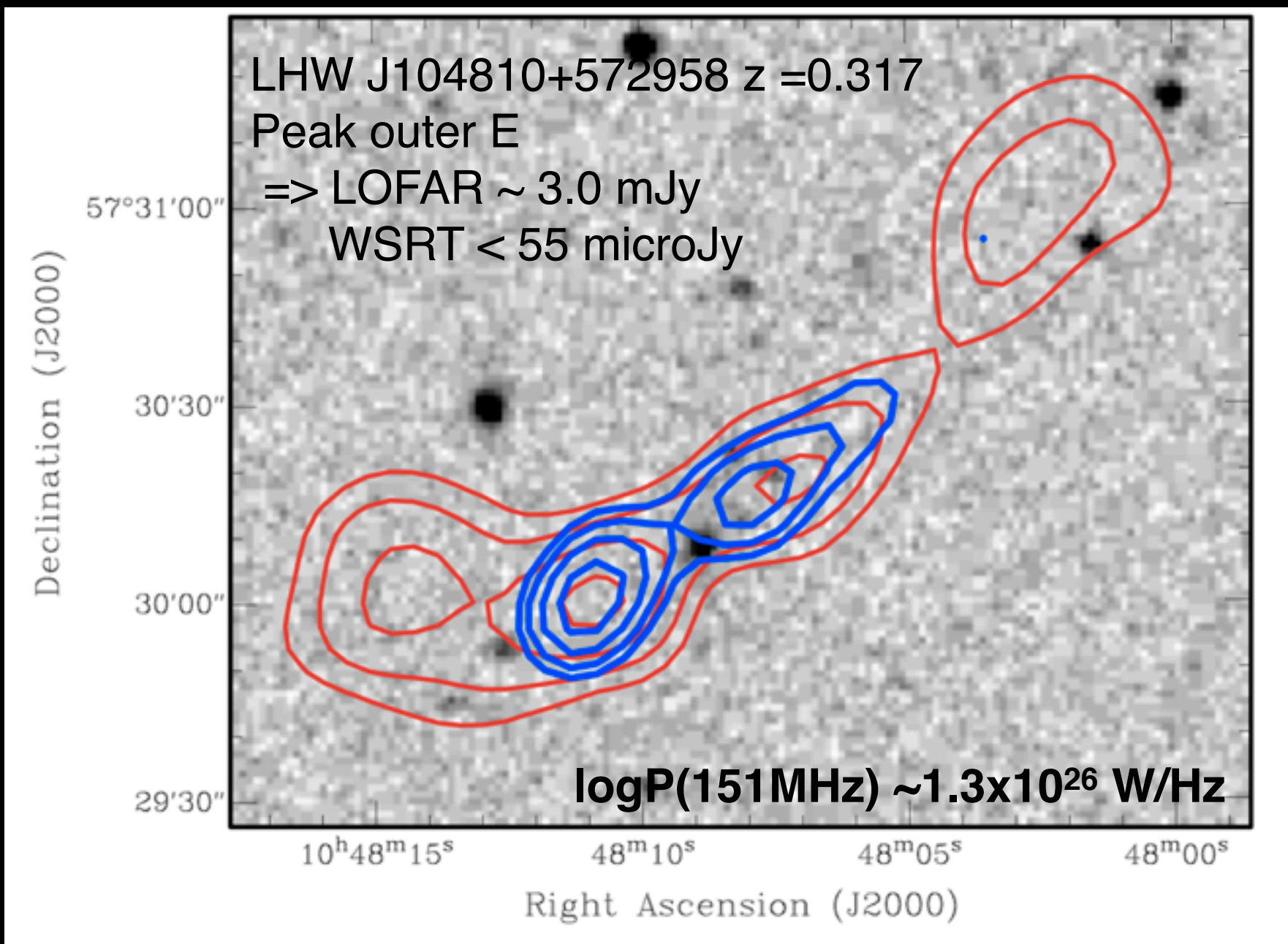
Selection based on (steep) spectral index: the Lockman Hole

- 6 sq deg overlap with a very deep WSRT mosaic (10 microJy rms): 1300 sources in common
- 28 sources ($\sim 2\%$) with $\alpha < -1.3$.

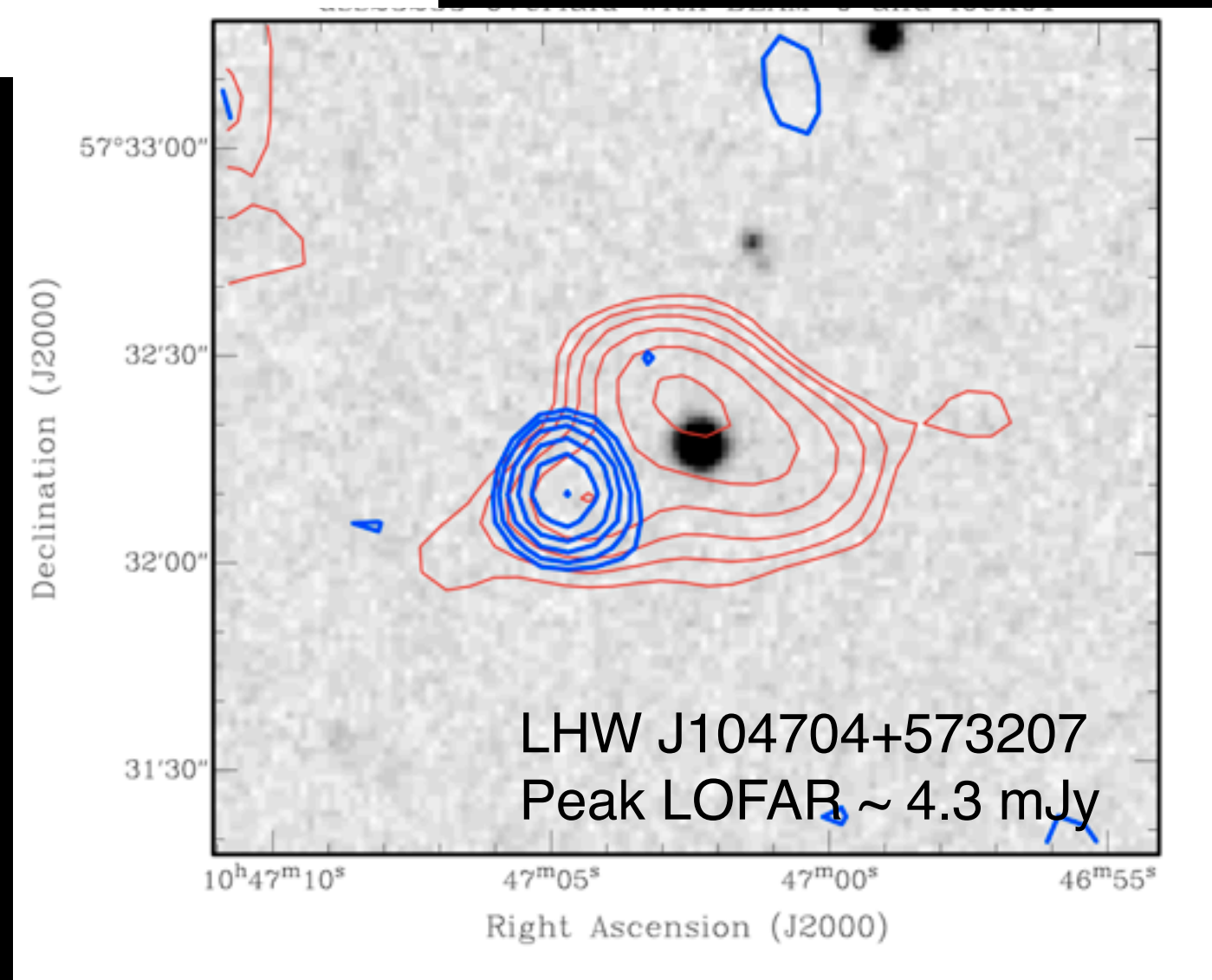
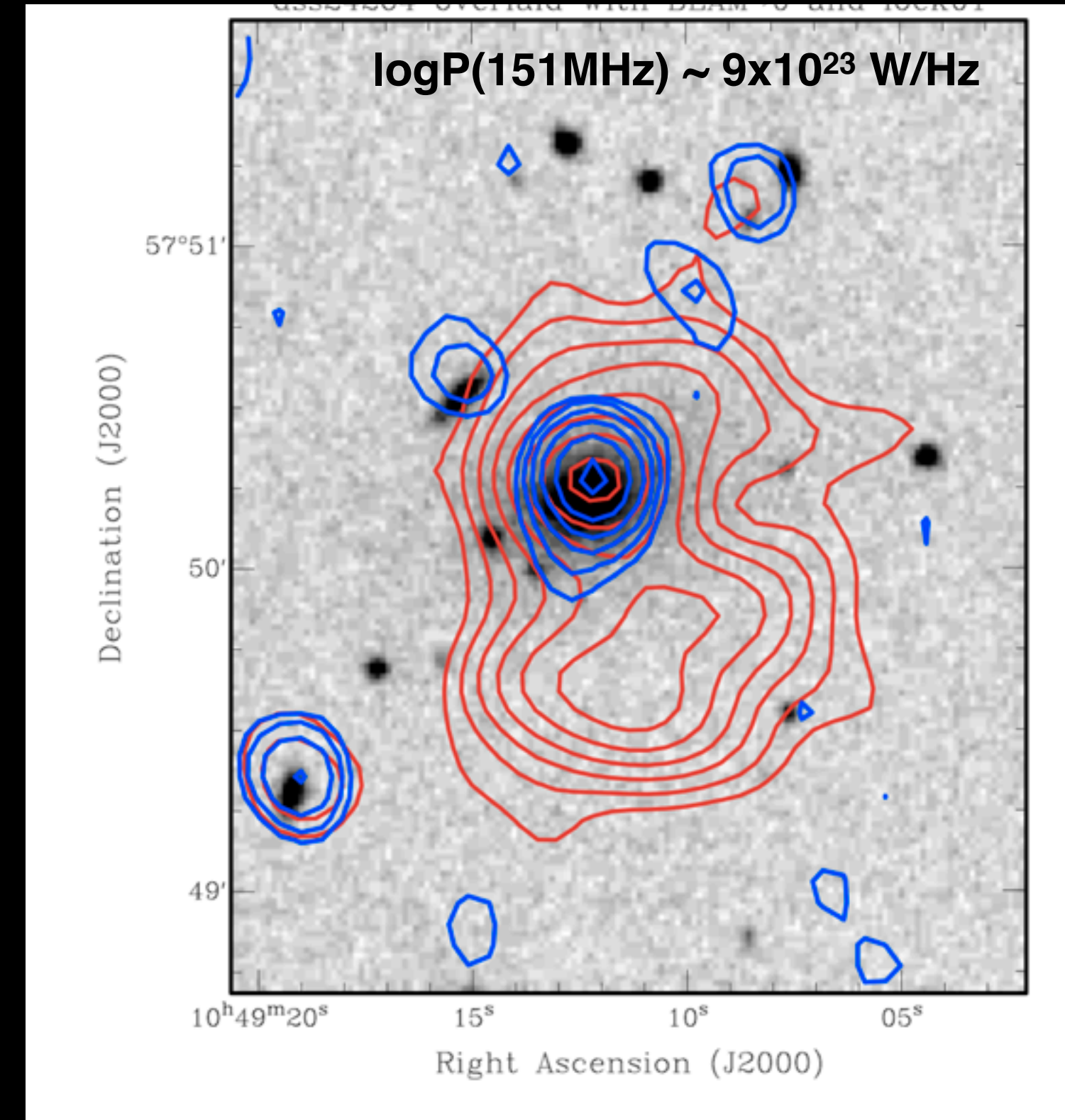


Mahony et al. 2015 in prep.

Combining morphology and spectrum



Part of the extension
ONLY seen in LOFAR:
 regions with steep
 spectrum (< -1.5)
 emission



Red = LOFAR
Blue = WSRT
Grey = DSS2 (red)

LHW J104912+575014
 MCG +10-16-011
 $z = 0.073$ (1.398 kpc")
 Peak South
 \Rightarrow LOFAR 8.1 mJy, WSRT
 extension ~ 40 kpc

Mahony et al. 2015 in prep.

Interesting and intriguing results, already some new objects:
now using the different diagnostics provided by LOFAR **AND** ancillary data to understand their nature

- ▶ not all AGN remnants have steep spectrum at low frequencies
=> cases with e.g. active phase much shorter than remnant
- ▶ not all diffuse, low surface brightness emission is signature of AGN remnants
=> cases of low level activity, uncollimated jets etc.
- ▶ mixed morphology (restarted?) can complicate the selection based on spectral index

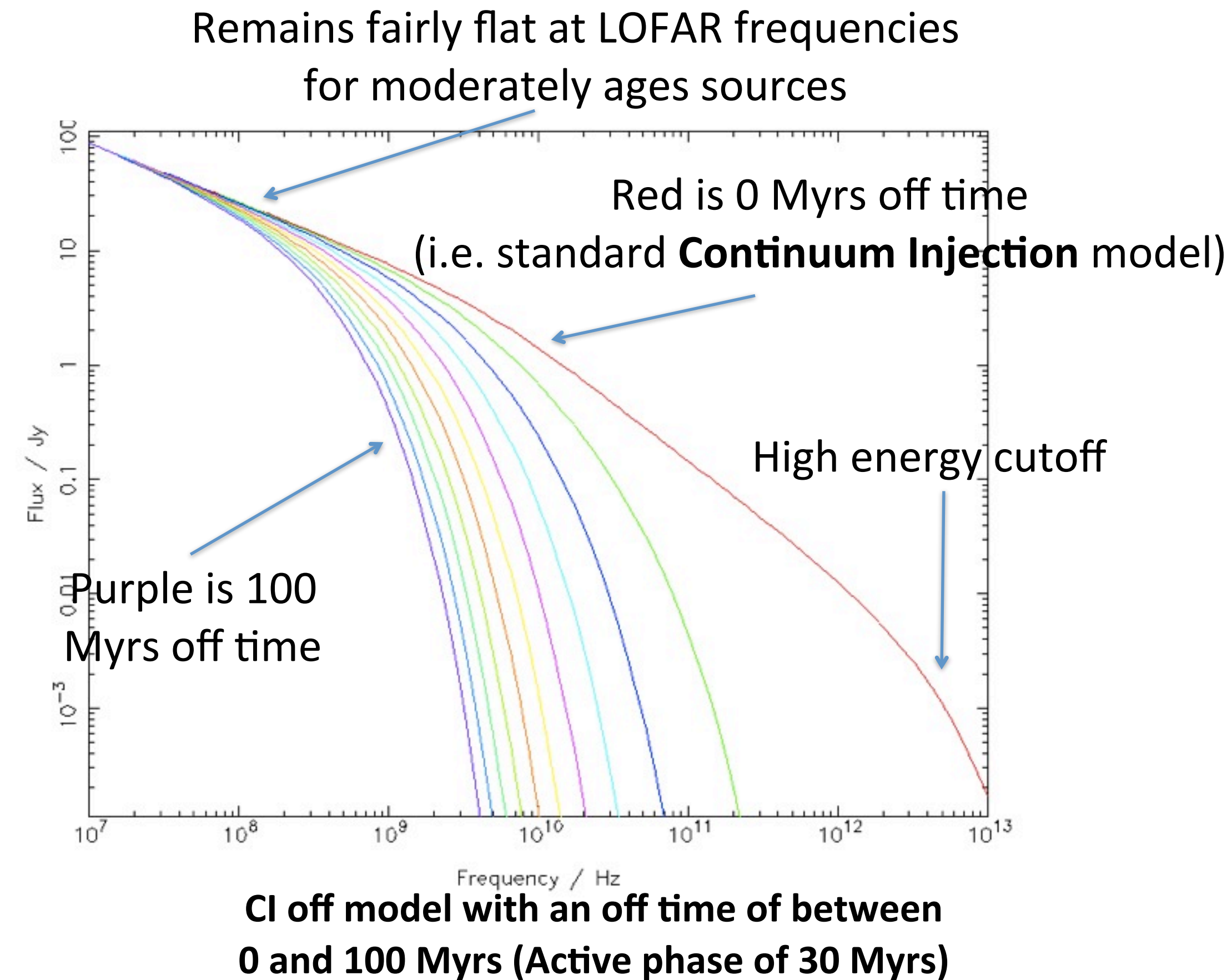
What we are developing to expand this:

- Radio spectrum: selection and deriving parameters...
- A framework for interpretation

The radio spectrum: selection and interpretation...

Jeremy Harwood et al. in preparation

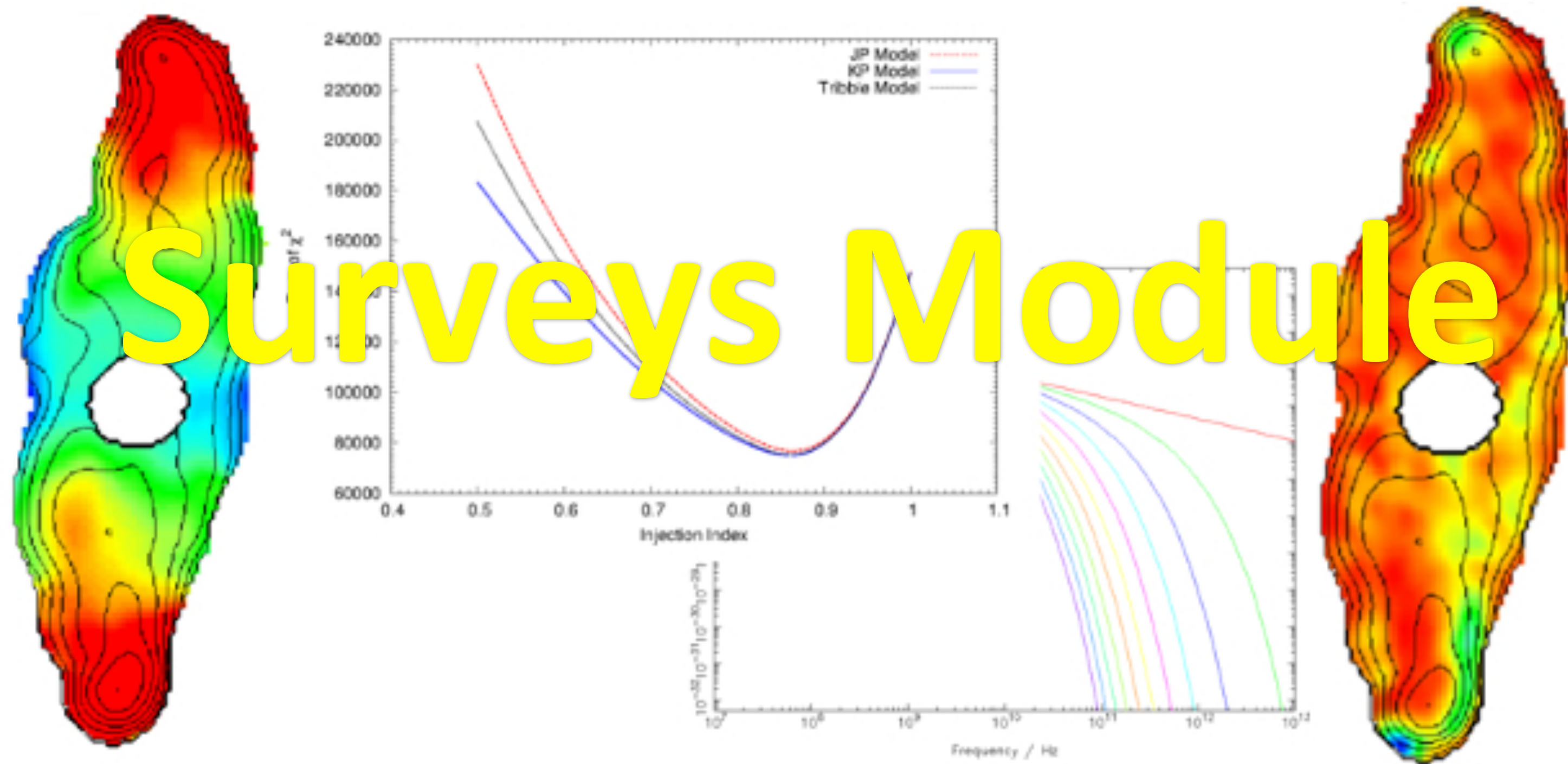
Searching for relic sources



- The continuum injection search function provides a way to systematically look for relic sources
- Provides information on whether a source is likely to be active or not, along with characteristic ages
- (Reasonable) upper limits are not a problem
- Multiple modes designed to search for 'interesting' sources and populations, not just relics
- Based on an established, user friendly code
- Fitting of CI models to individual sources is ready (available in the next BRATS release)
- Full survey module is under development. If you would like to use it on your LOFAR field prior to public release (i.e. the non-user friendly version) speak to Jeremy

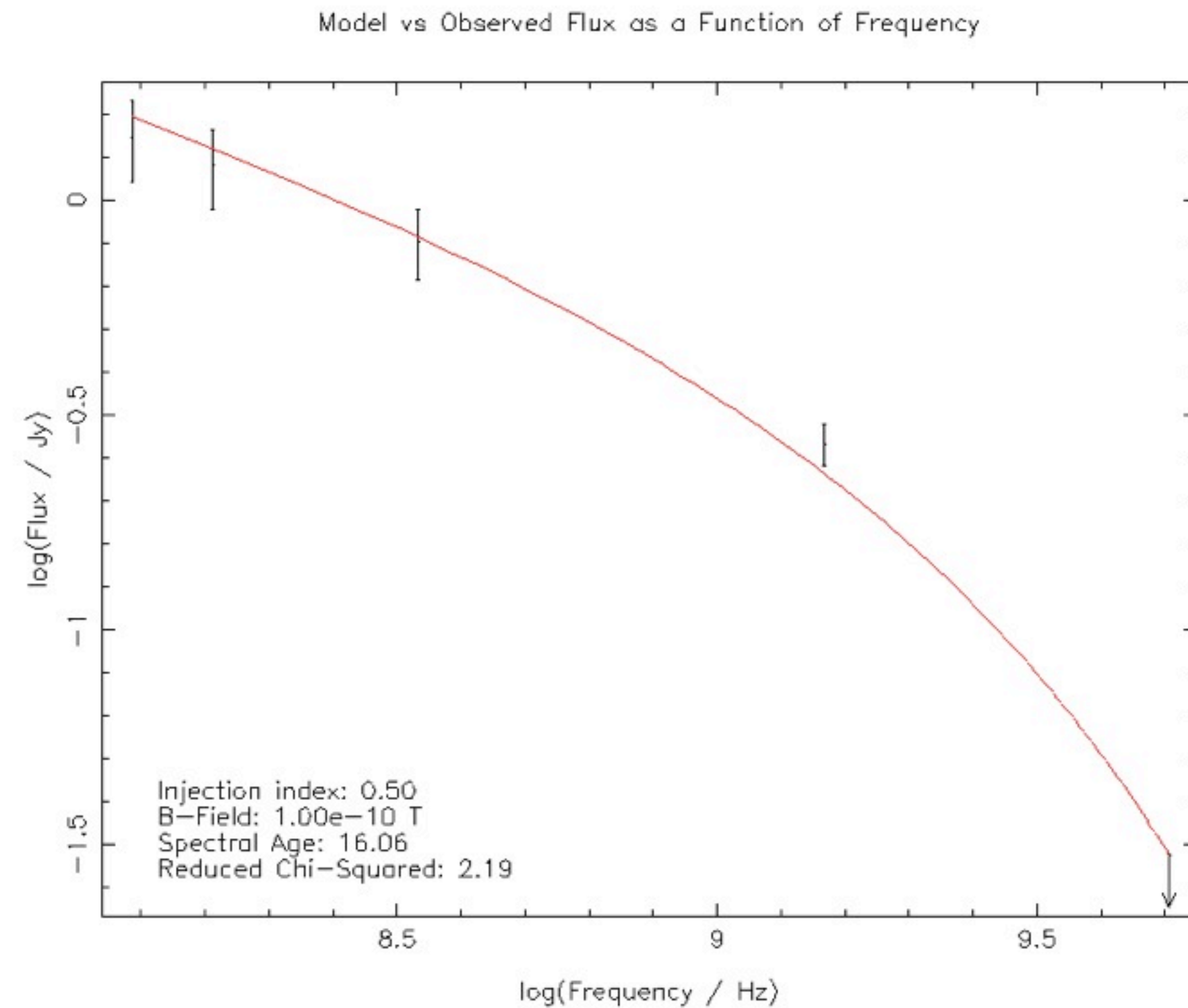
BRATS: Broadband Radio Astronomy Tools

Spectral analysis software for the new generation of broadband of radio telescope



<http://www.askanastronomer.co.uk/brats>

Example of spectral fit from BRATS surveys module



CI off model fitting of BLOB1

Best fitting age is 16 Myrs (on) 60 Myrs (off)

- The continuum injection search function provides a way to systematically look for relic sources
- Provides information on whether a source is likely to be active or not, along with characteristic ages
- (Reasonable) upper limits are not a problem
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A framework for planning and interpretation

Leith Godfrey et al. in preparation

Modelling the active and remnant radio galaxy populations

There is a broad expectation that deep low frequency radio surveys will reveal an abundance of steep spectrum remnant radio galaxies

Is this expectation well founded?

No predictions available: our initial results seem to be different!

Evolutionary history \Leftrightarrow Spectral shape

Approach:

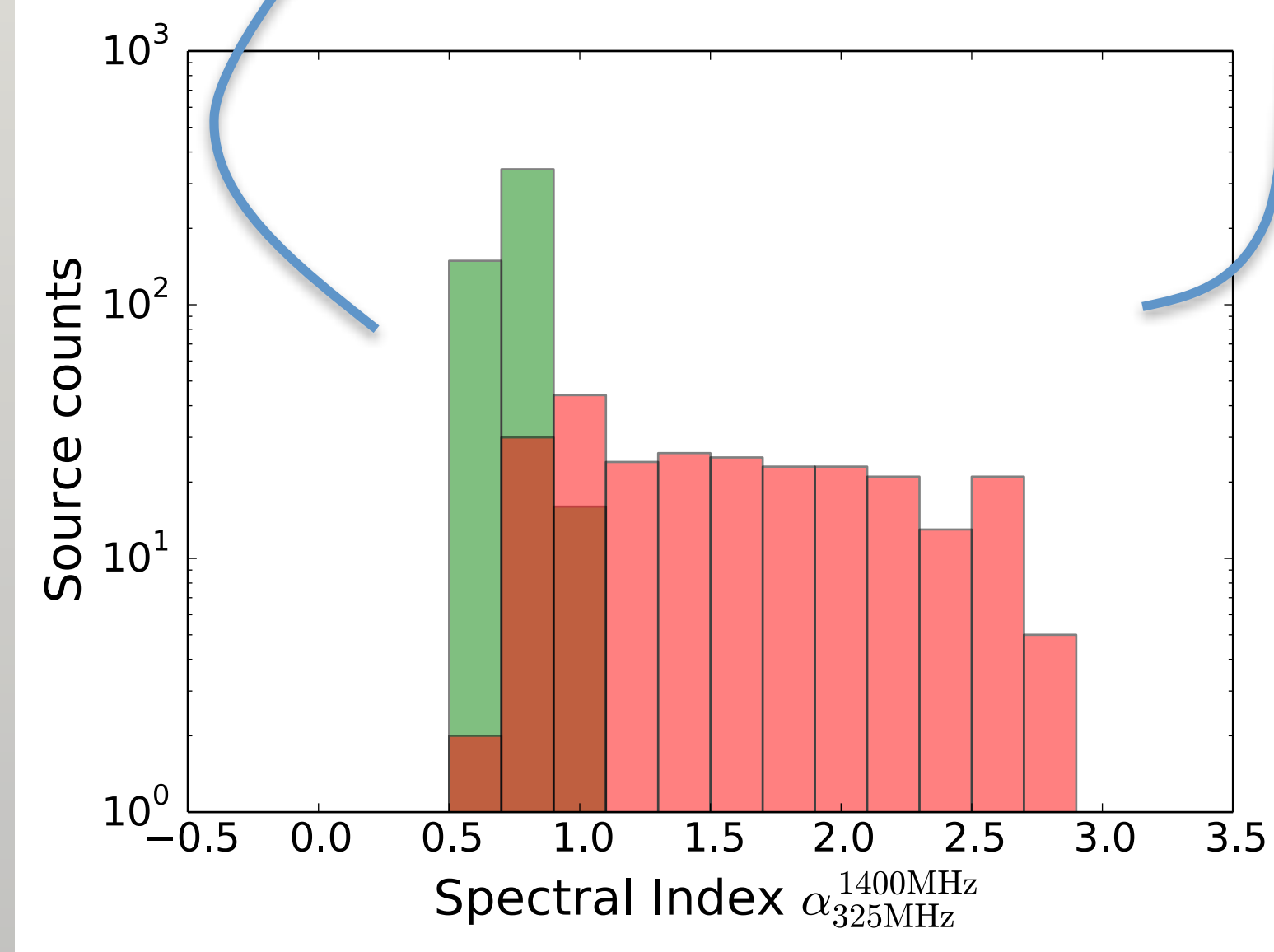
Extend the standard continuous injection models (*Kaiser and Alexander 1997, Kaiser & Cotter 2002*) to incorporate adiabatic as well as synchrotron + inverse Compton losses in both the active and remnant phases.

- ▶ **Create mock catalogues** from the above model along with a set of assumptions about the population of radio galaxies and their environments.
- ▶ **Guide the planning, and interpretation of LOFAR survey data** pertaining to the remnant radio galaxy population.

Godfrey et al. in preparation

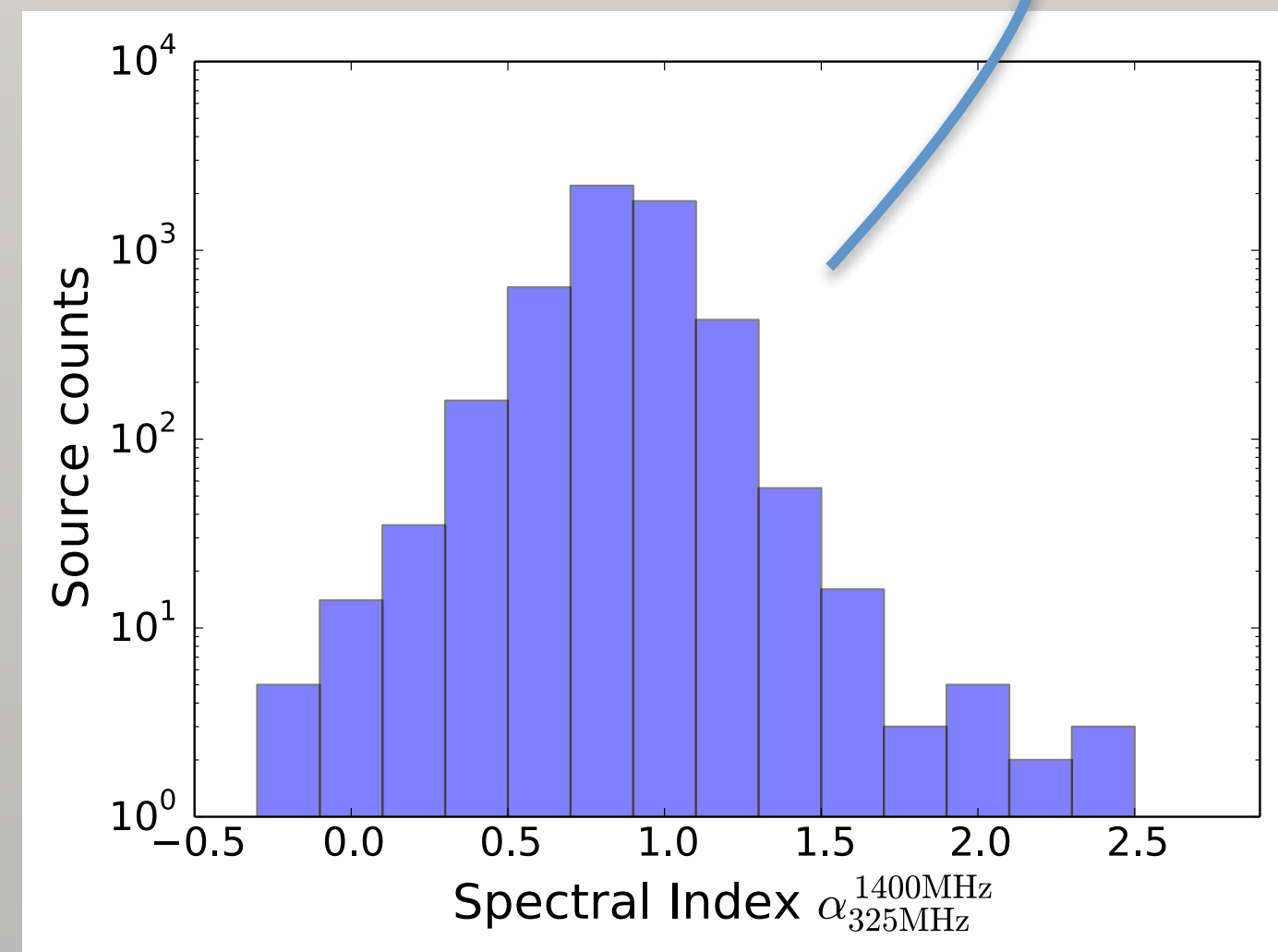
Modelling the active and remnant radio galaxy populations

Create mock catalogue using our generalised continuous injection model, including remnant radio galaxies (coloured red).



Compare mock distributions of luminosity, spectral index and spectral curvature with real catalogues from low frequency surveys.

Mock catalogues enable correct treatment of selection effects, and optimisation of selection criteria for remnant radio galaxies.

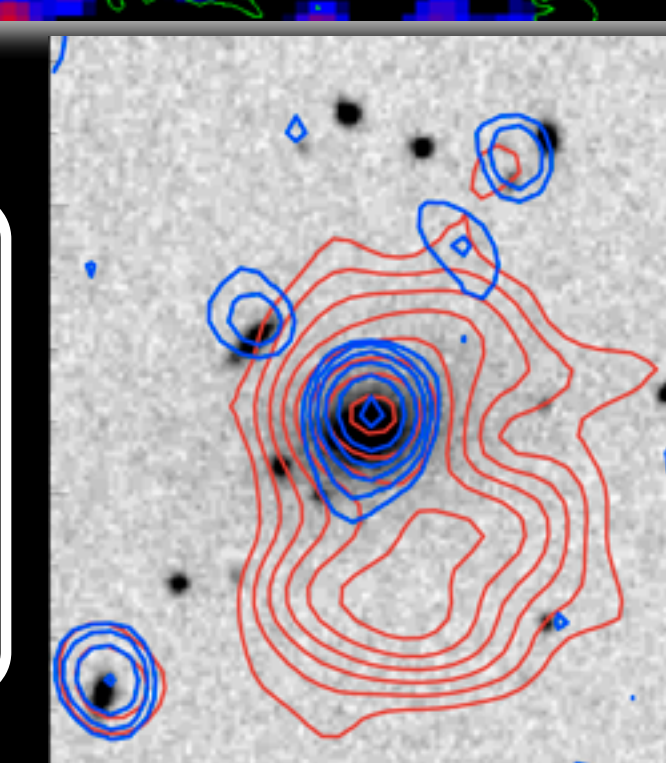
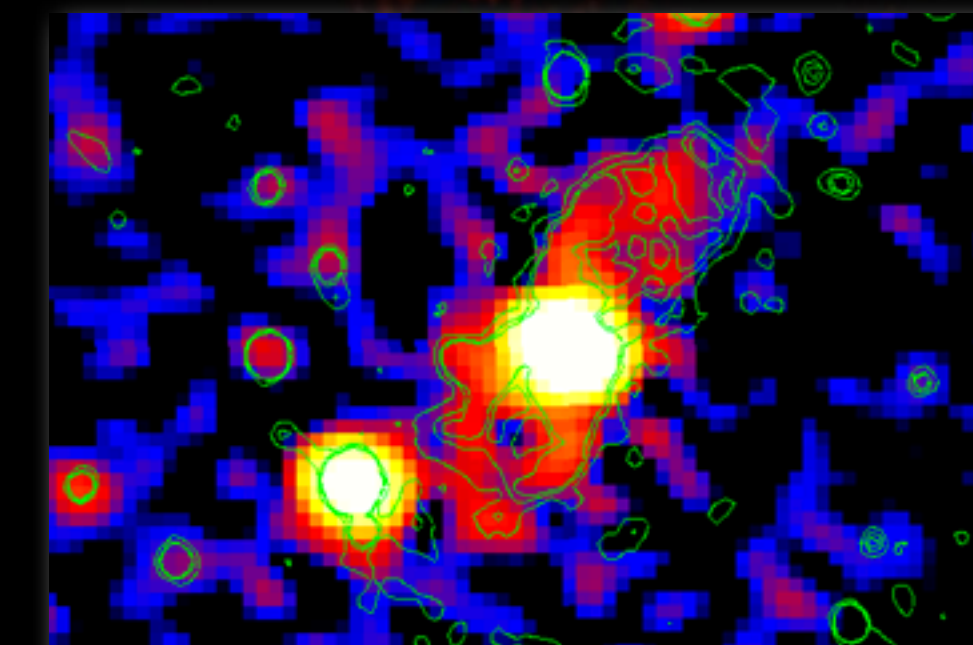
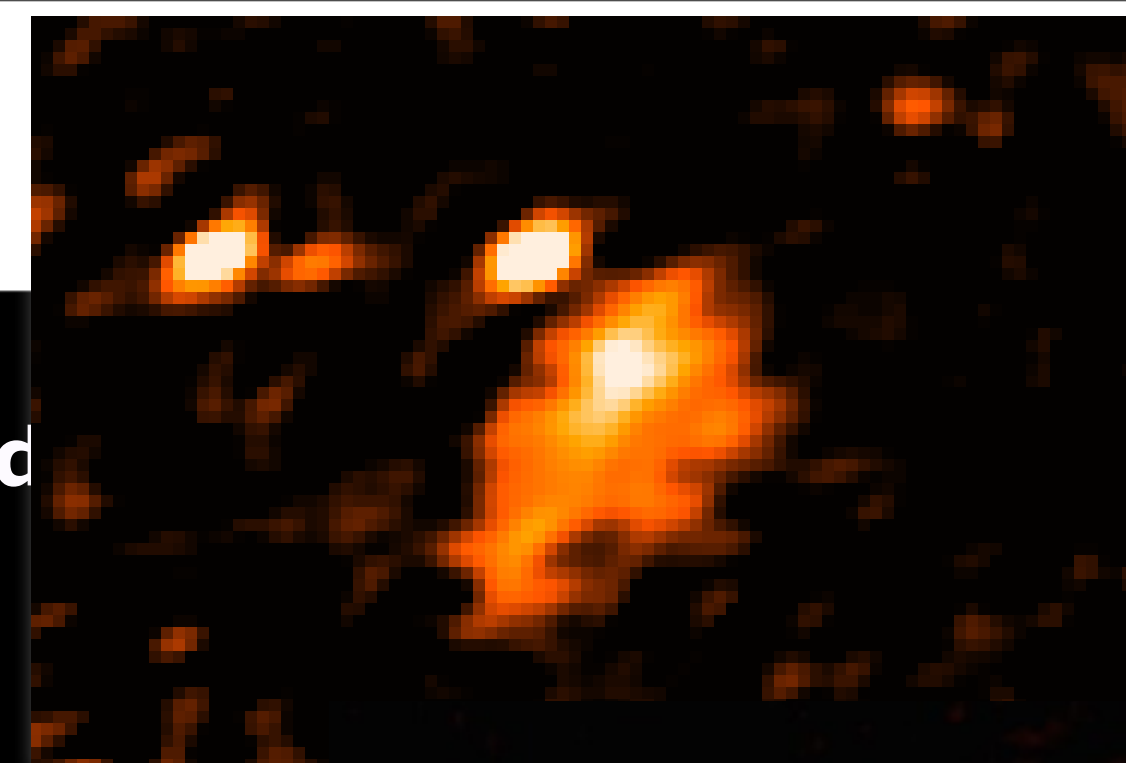


Godfrey et al. in prep.

Summary and what next...

We are using LOFAR images to find and characterise **remnants of radio AGN and restarted radio sources**

- ✦ Using all the possibilities offered by LOFAR in order to expand the search: HBA and LBA, morphology, low and high spatial resolution, spectral index, spectral curvature
- ✦ **A number of interesting objects already found in the few fields searched.** Very promising for future searches in the LOFAR surveys: already showing the complexity and variety of evolution
- ✦ **Prepare for the spectral index analysis:** first using the integrated spectra and then resolved spectral analysis → derive parameters (e.g. injection index, ages etc.) and energetics (*Jeremy Harwood*)
- ✦ **Prepare for more sophisticated treatment of the dying phase,** incorporating e.g. expansion losses → refined search techniques for the LOFAR survey fields (*Leith Godfrey*)



- ✦ **Need for deep high frequency (e.g. 1.4GHz) images → synergy with Apertif surveys**
- ✦ **STILL MISSING: in-band reliable spectral information, more/good/deep LBA images**