LOFAR Imaging of a Nearby “Wimpy” AGN

Kristina Nyland

ASTRON/NRAO

New Mexico Symposium

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Acknowledgements

Tim Shimwell
(Leiden)

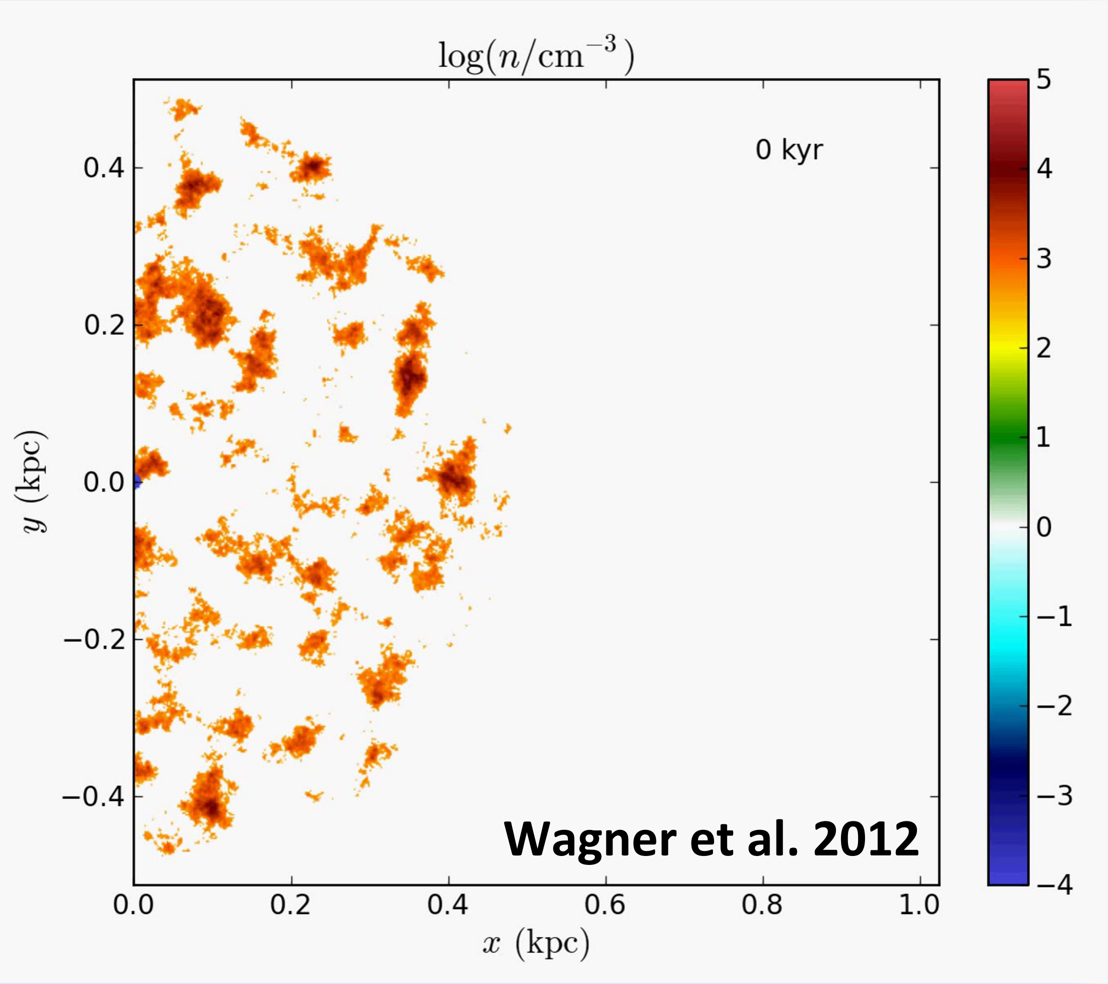
Raffaella Morganti
(ASTRON)

Brad Frank
(ASTRON)

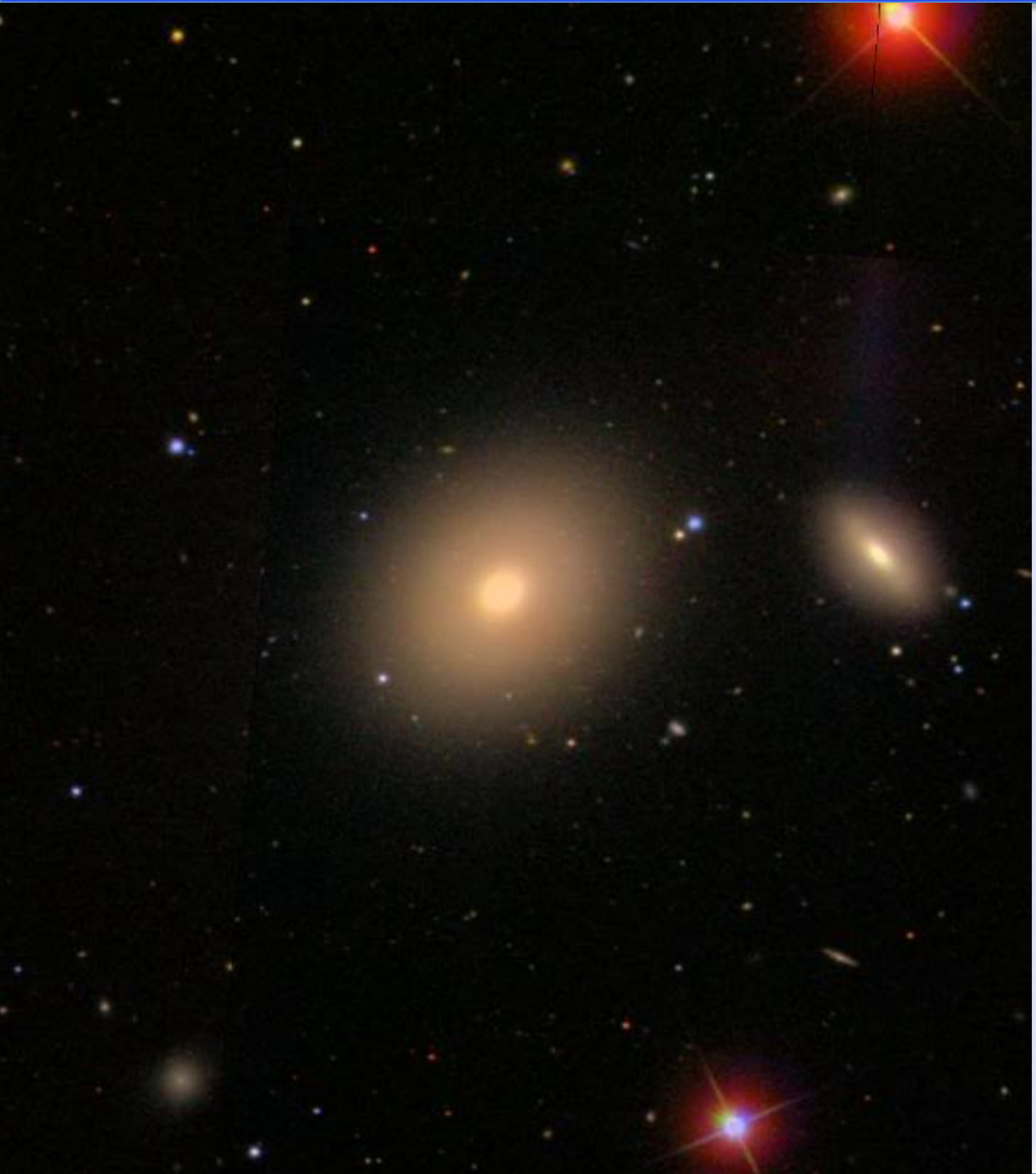
Radio-mode AGN Feedback

- Triggering/fueling?
- Duty cycle?
- Impact on galaxy evolution?
- Importance of feedback from low-power AGNs?

Radio jet interacting with a clumpy ISM

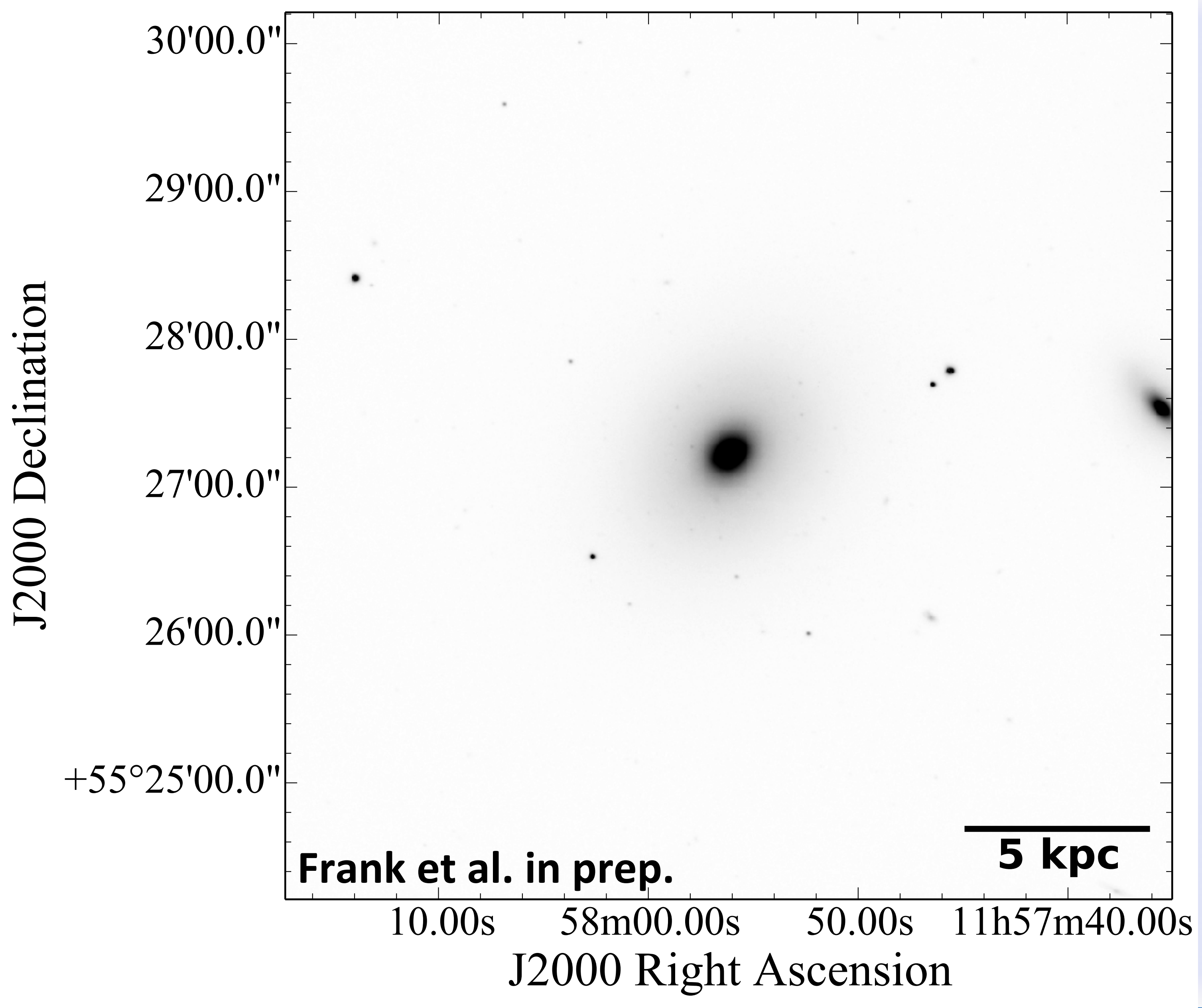


NGC3998: Overview

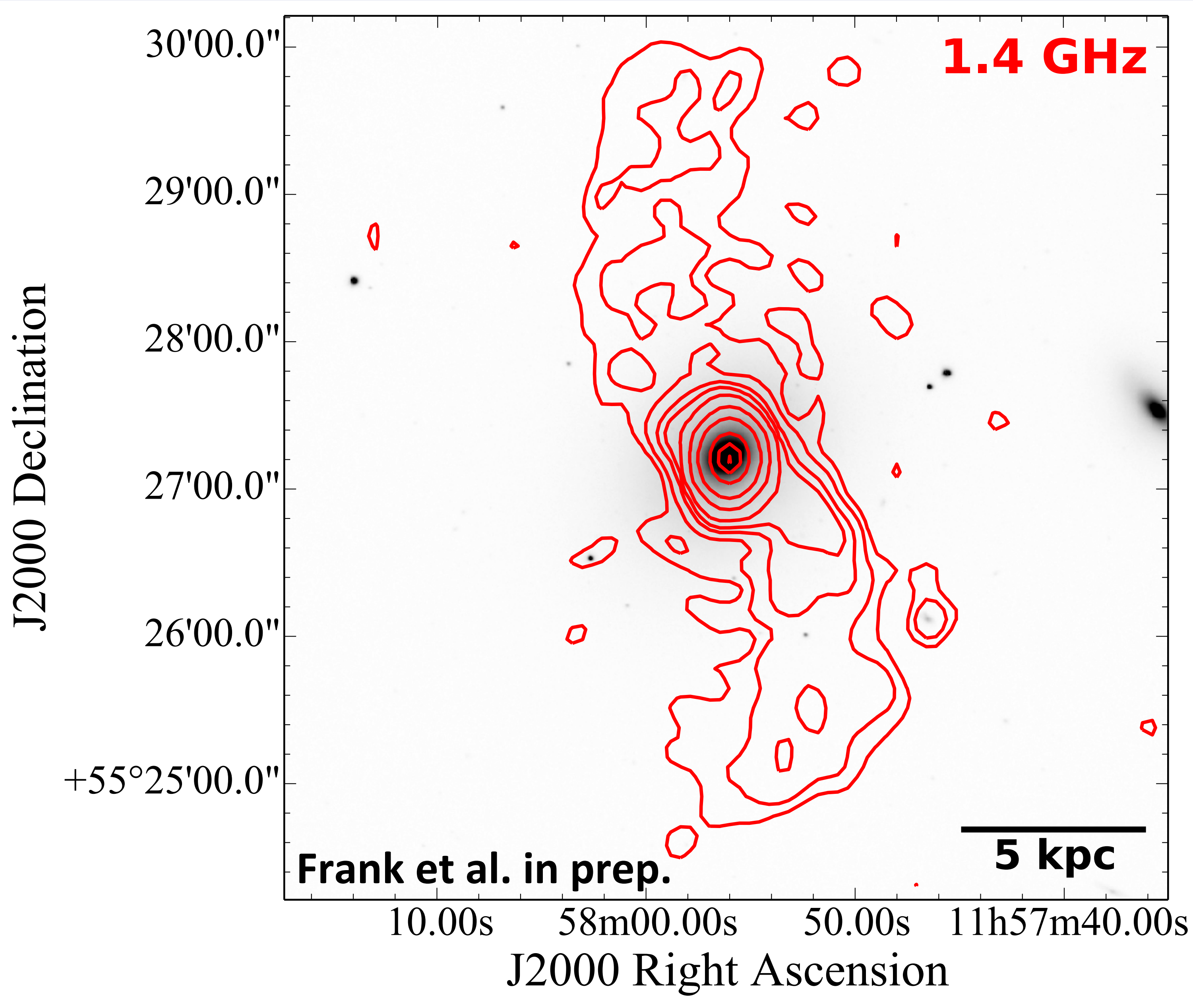


- D = 13.7 Mpc
- Morphology: S0
- Nuclear activity: LINER
- $M_{BH} \approx 8.93\ M_{\odot}$
- $M_{stellar} \approx 10.94\ M_{\odot}$

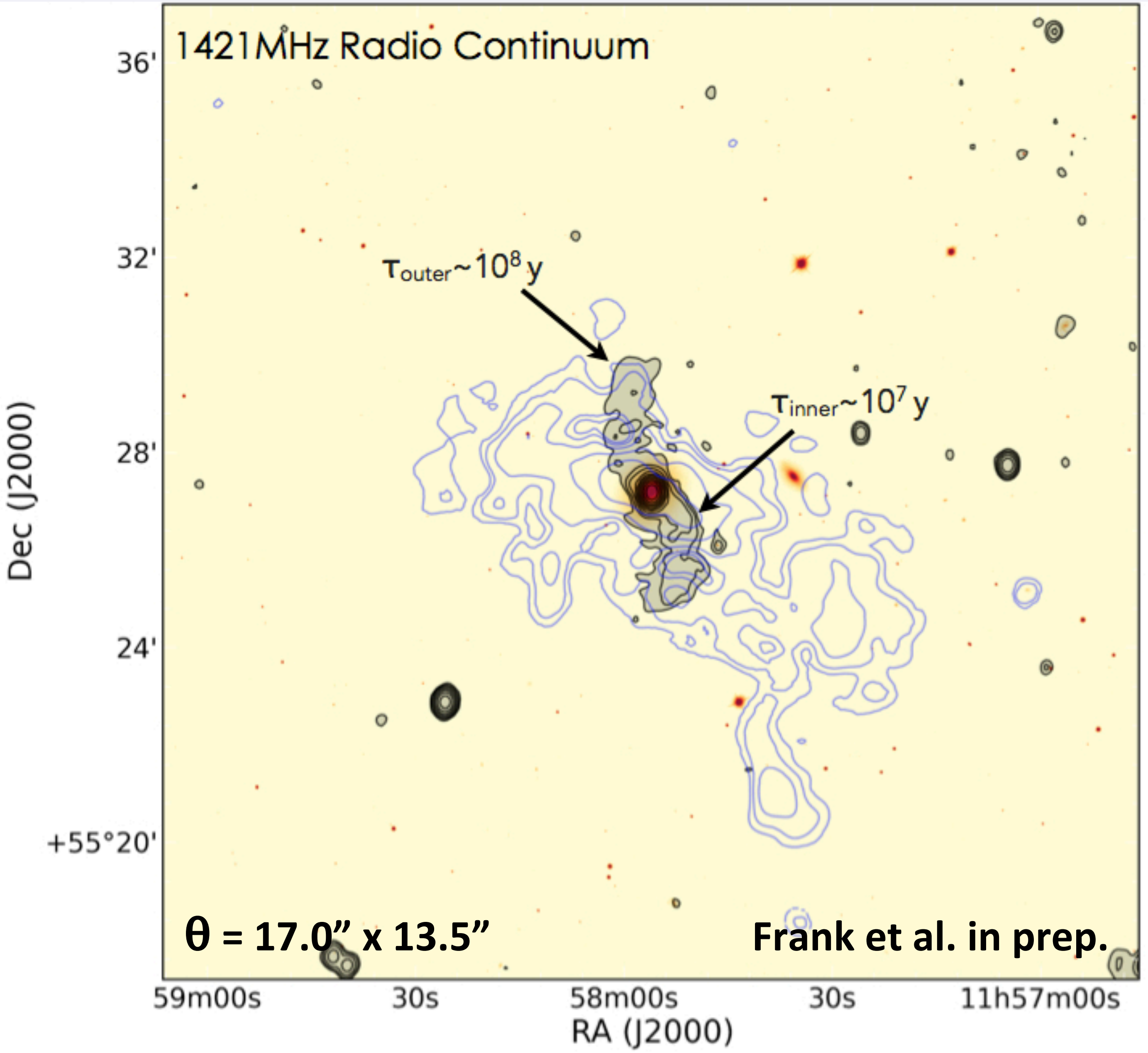
NGC 3998


30'00.0"
29'00.0"
28'00.0"
27'00.0"
26'00.0"
+55°25'00.0"
J2000 Declination
10.00s
58m00.00s
50.00s
11h57m40.00s
J2000 Right Ascension
5 kpc
Frank et al. in prep.

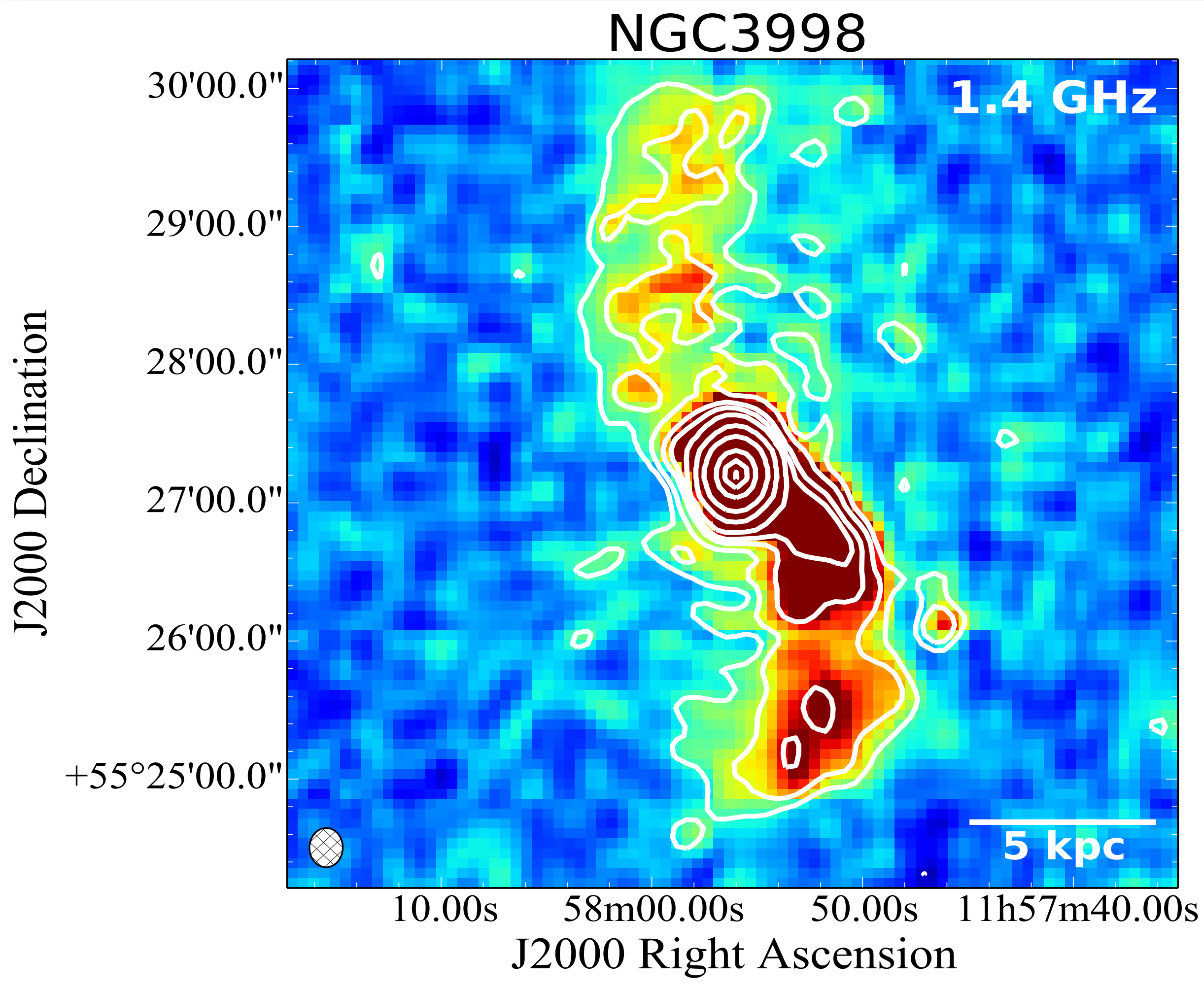
Large-Scale Radio Emission



Evolutionary Clues from HI



Radio Lobes: Key Questions

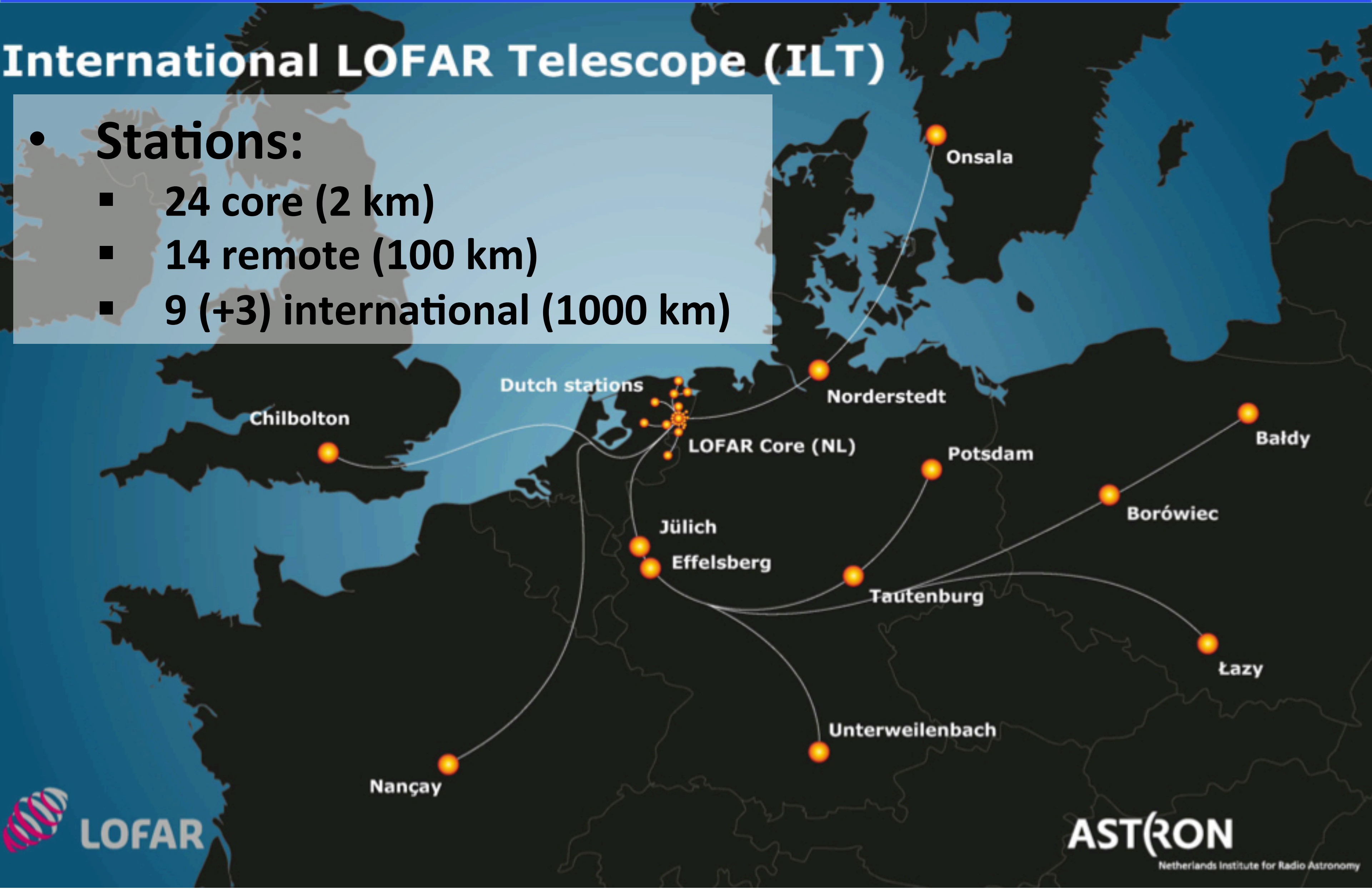


Frank et al., in prep.

- Low-frequency radio morphology?
- Evolutionary stage of the radio lobes?
- Connection between cold gas and radio activity?

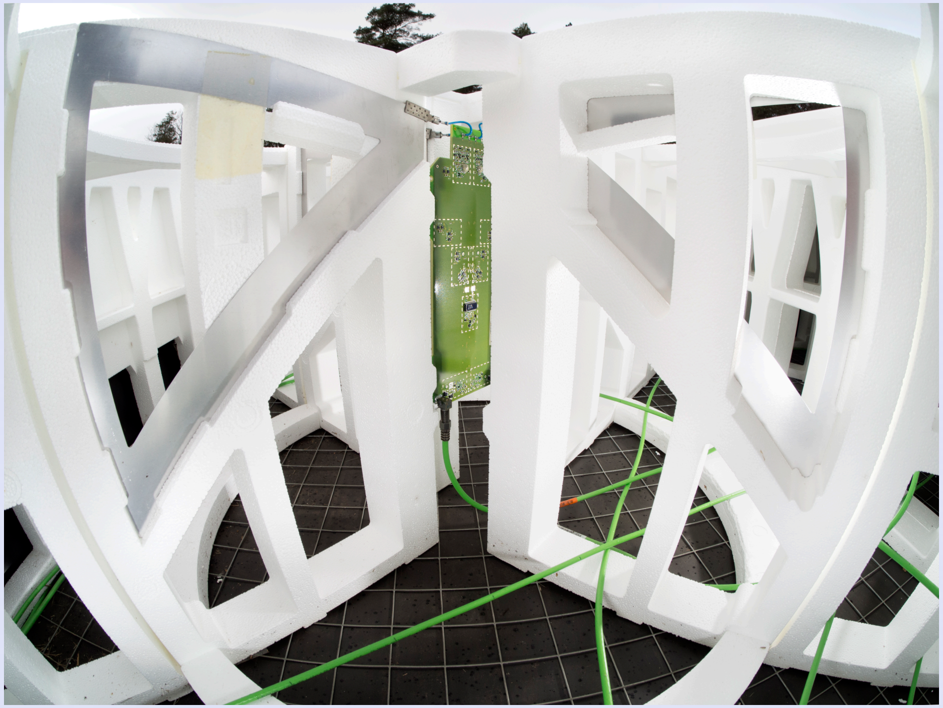
LOFAR: The Low-frequency Array

- **Stations:**
  - 24 core (2 km)
  - 14 remote (100 km)
  - 9 (+3) international (1000 km)

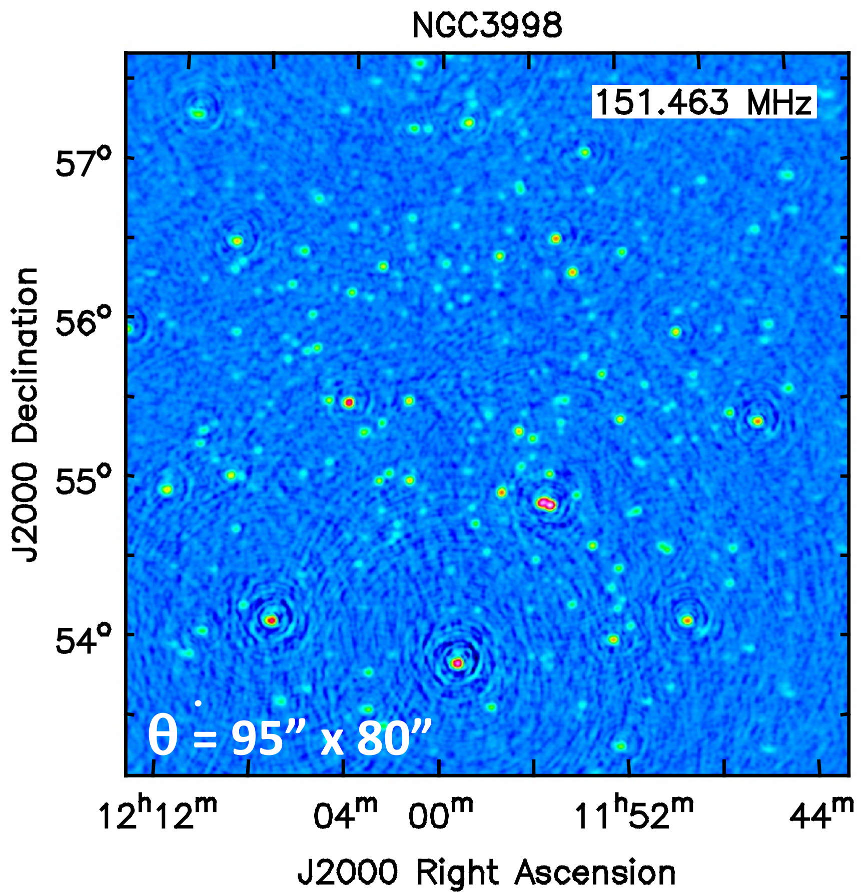


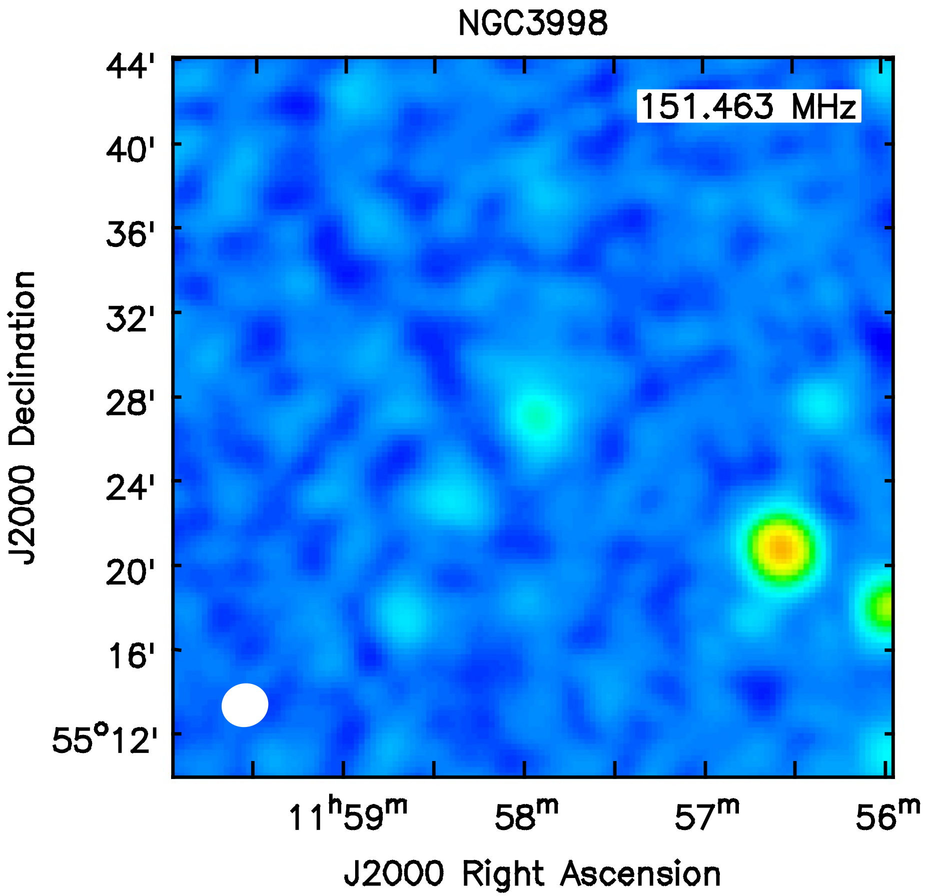
NGC3998: LOFAR Observations

- Cycle 3 (PI: Nyland)
- Bandwidth: 120-168 MHz
- Time: 8 hours (nighttime)
- Date: March 2015
- Pre-processing pipeline
- 38 stations



NGC3998: LOFAR Observations

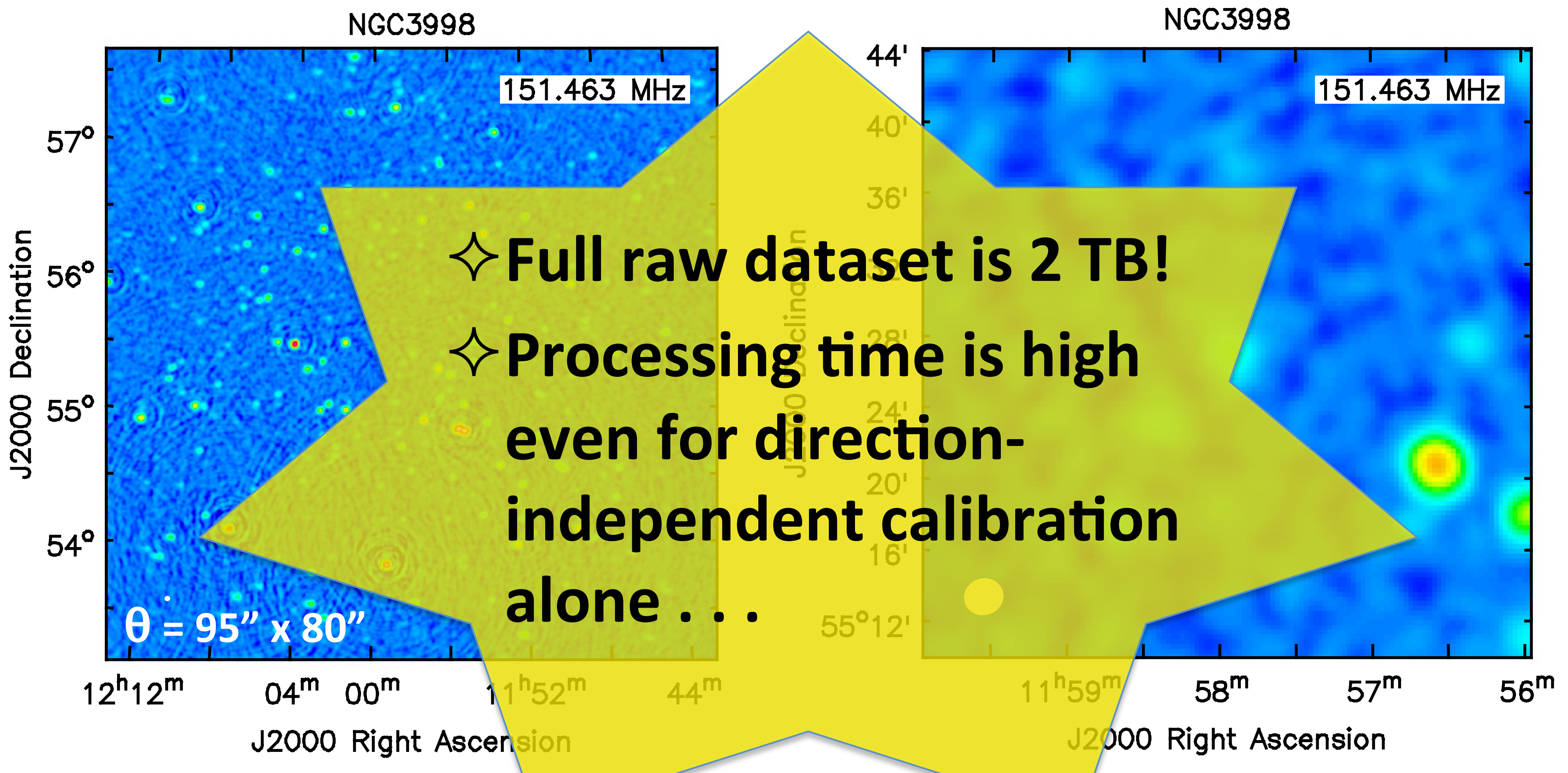




- **10 sub-bands (2 MHz)**
- **no self-calibration**
- **uv-range: 0-4 km**

- **rms ≈ 15 mJy/beam**
- F_{peak} **≈ 204 mJy/beam**
- **α ≈ -0.1**

NGC3998: LOFAR Observations



✧ **Full raw dataset is 2 TB!**

✧ **Processing time is high even for direction-independent calibration alone . . .**

- **10 sub-bands (2 MHz)**
- **no self-calibration**
- **uv-range: 0-4 km**

- **rms ≈ 15 mJy/beam**
- **F_{peak} ≈ 204.0 mJy/beam**
- **α ≈ -0.1**

Tier 1 Survey "Sneak Preview"

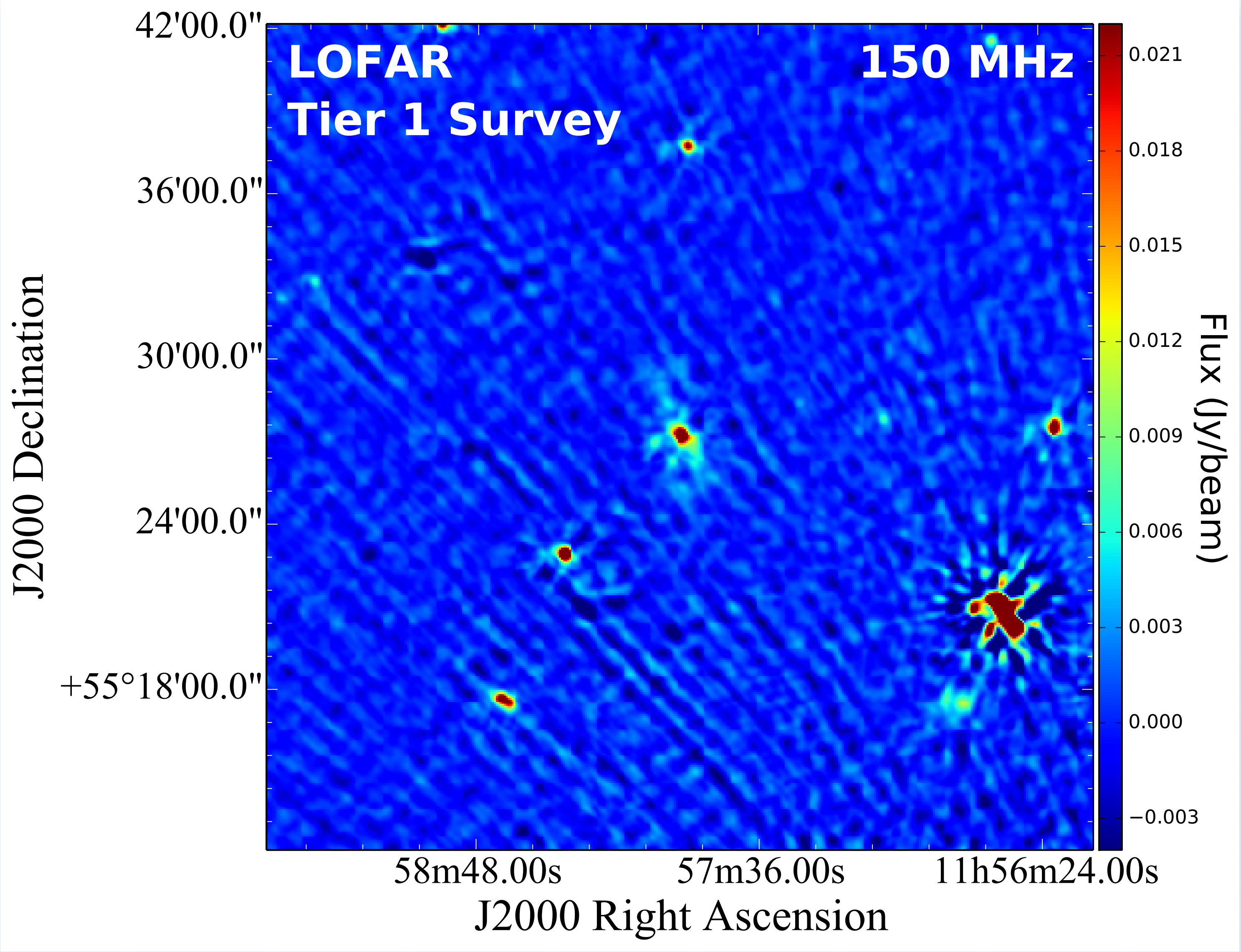
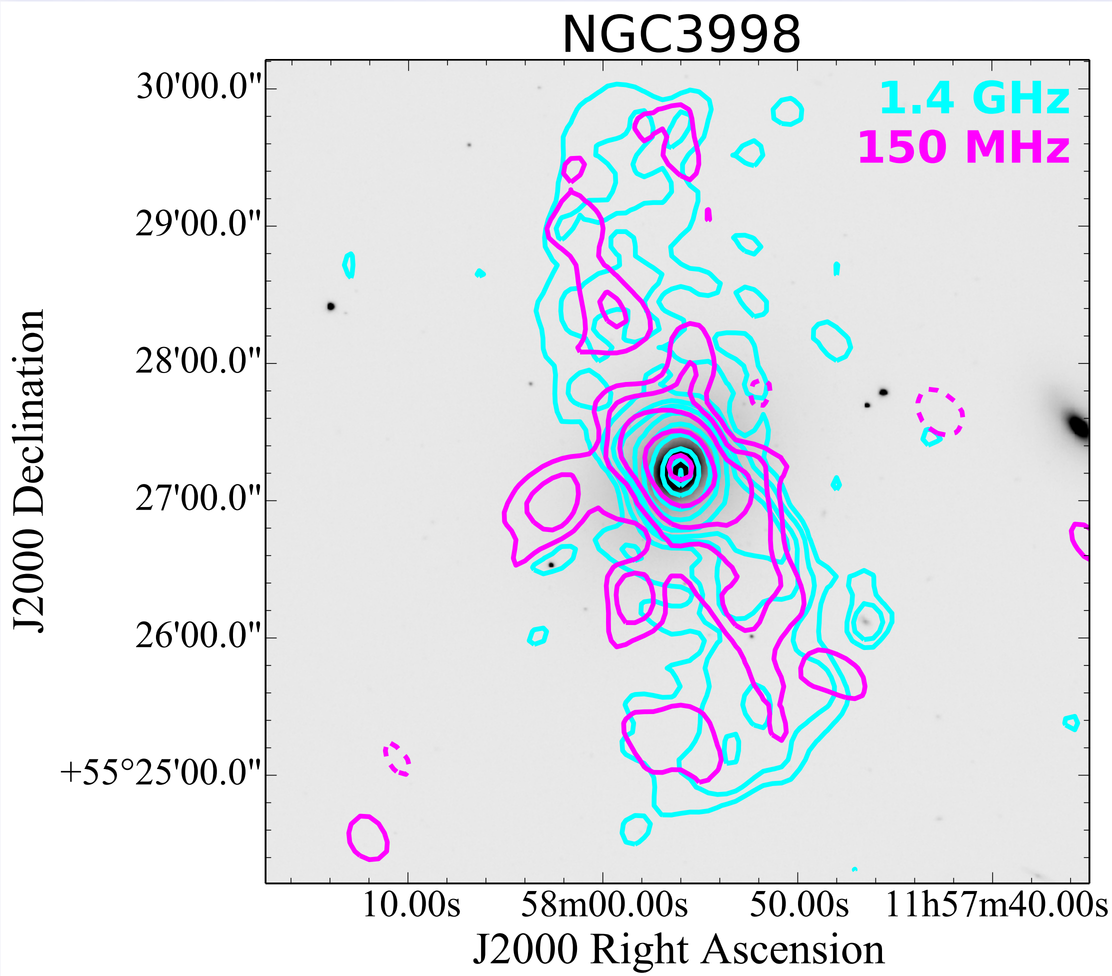


Image credit: Tim Shimwell

Tier 1 Survey “Sneak Preview”



- Distance from pointing center: 1º
- BW: 48 MHz
- Resolution: 20”
- Time: 8 hours
- RMS: 1 mJy/beam

Dir. dep. calibration needed for improved imaging . . . .

150 MHz: Tim Shimwell

1.4 GHz: Frank et al., in prep

Direction Dependent Calibration

http://www.astron.nl/citt/facet-doc/


Facet Calibration Pipeline 1.0 documentation »

Facet Calibration Software

This document describes the facet calibration software that im
(in prep.) and Williams et al. (in prep.).

- 1. Acknowledgements
- 2. Introduction
  - 2.1. The Factor Parset
  - 2.2. Running Factor
- 3. Pre-facet Calibration Pipeline
  - 3.1. timmap
  - 3.2. dppppprepcal
  - 3.3. calibcal
  - 3.4. ginst, gvdsfile, parmcoll and h5imp
  - 3.5. fitclock
  - 3.6. ampl
  - 3.7. plots
  - 3.8. concatmapcal and phase
  - 3.9. calib
  - 3.10. timtargetmap
  - 3.11. dppppreptar
  - 3.12. ateamtarget and ateamcliptar
  - 3.13. trans
  - 3.14. parmmap and calibtarget
  - 3.15. dpppaverage
  - 3.16. conatmaptar, createmap2 and dpppconcat
  - 3.17. flagrfi
  - 3.18. gsmcalibtarget
  - 3.19. pre-facet calibration alterations
- 4. Initial Subtract Operation

Next topic

1. Acknowledgements

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Enter search terms or a module, class or function name.

van weren et al. 2015, submitted

Facet Calibration (FACTOR)

Tim Shimwell,

David Raffertty,

Stephan Frolich,

Reinout van Weeren,

Wendy Williams,

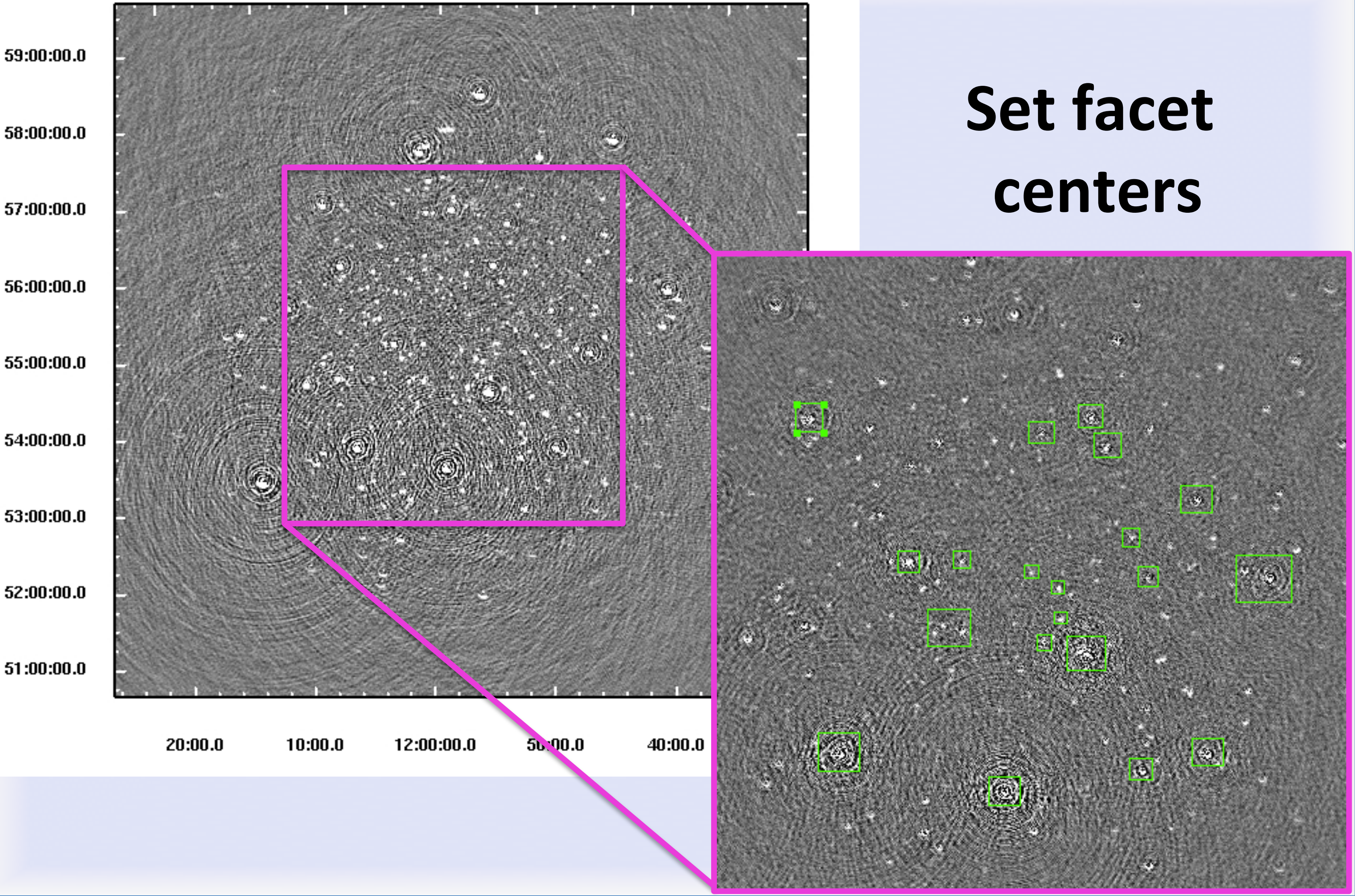
Martin Hardcastle,

Jose Sabater Montes,

Francesco de Gasperin,

and the Calibration and Imaging Tiger Team

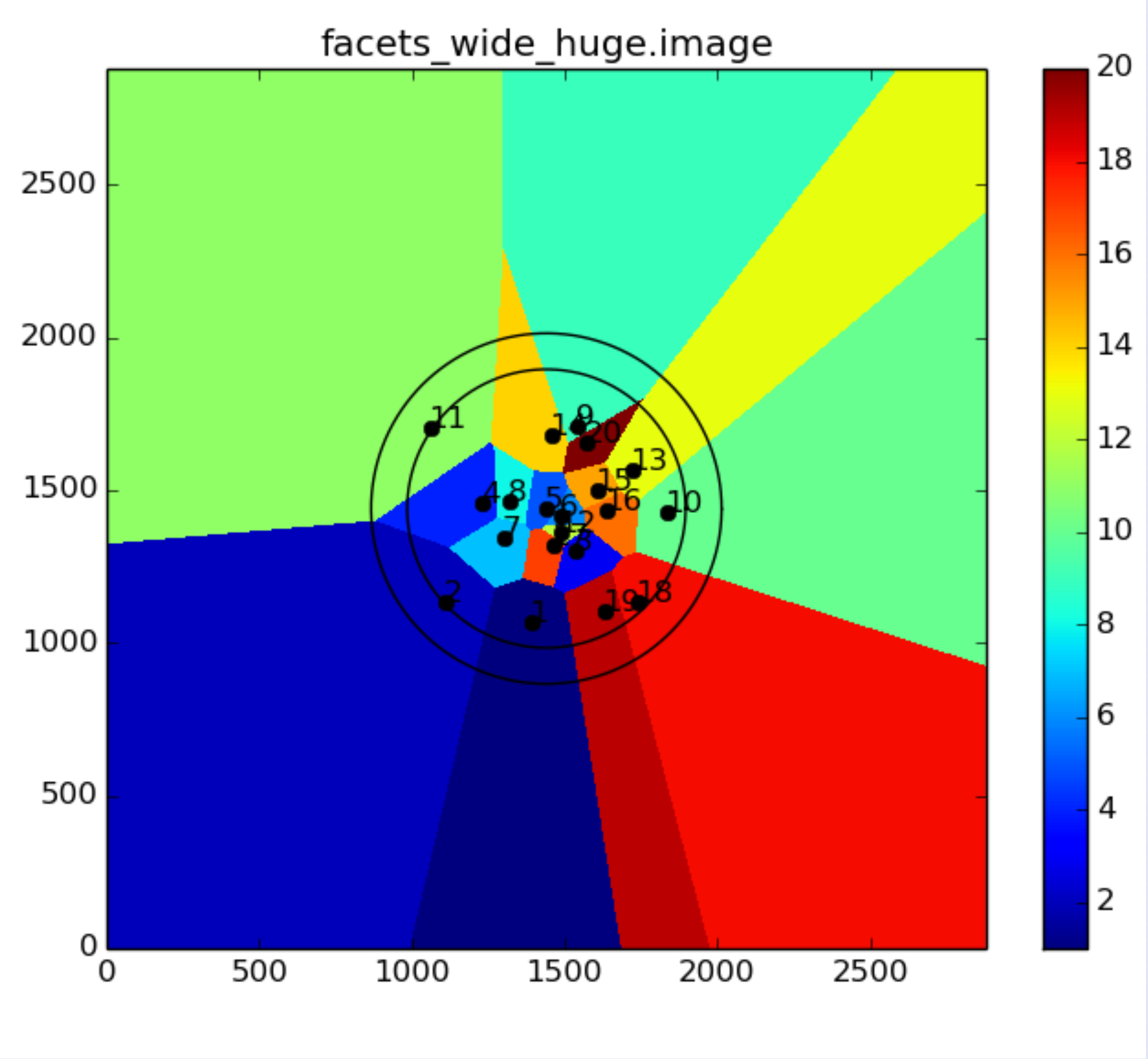
Facet Calibration



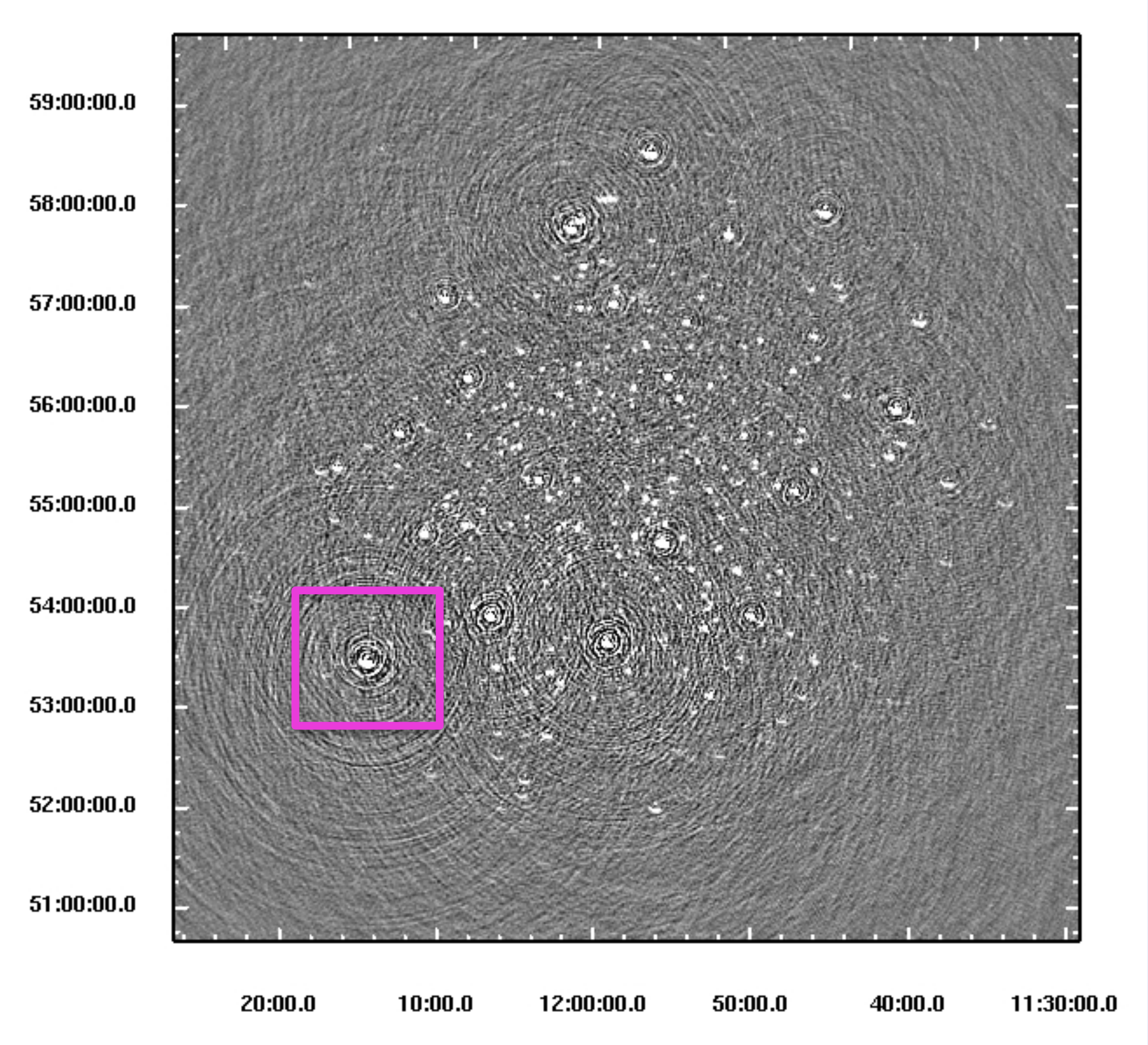
Set facet centers

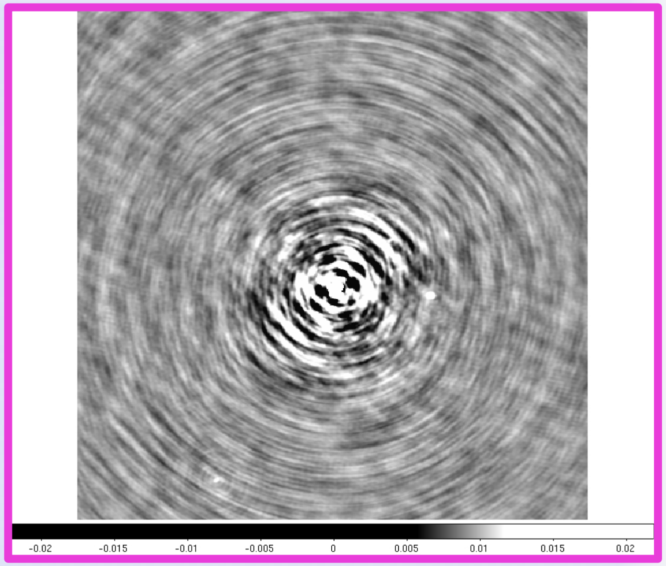
Facet Calibration

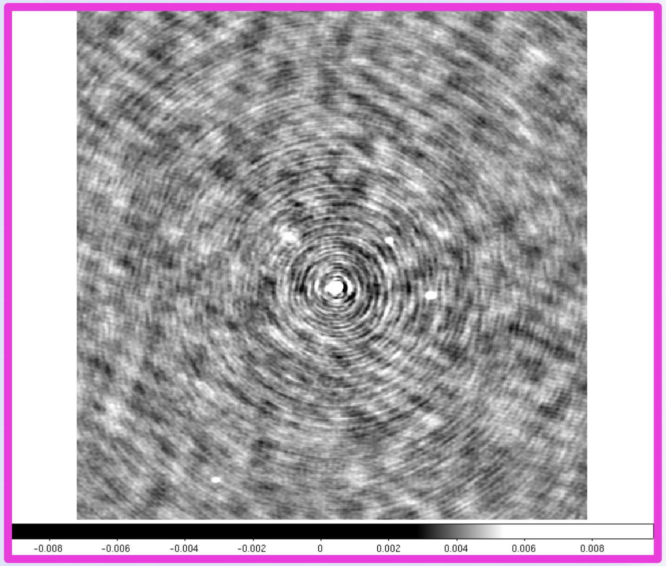
Voronoi Tesselation to form Facets



Facet Calibration

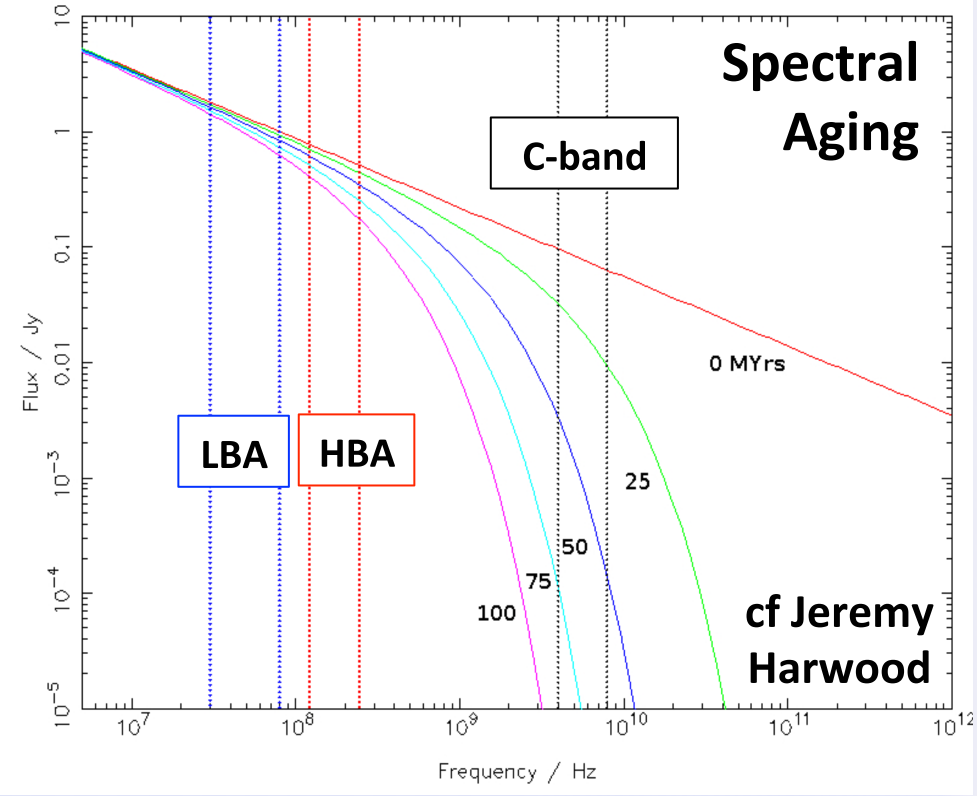






Future Work

- Complete facet calibration of LOFAR 150 MHz NGC 3998 data
- Perform radio spectral analysis
- Obtain higher-frequency VLA data to constrain radio spectral ages
- Study additional systems!

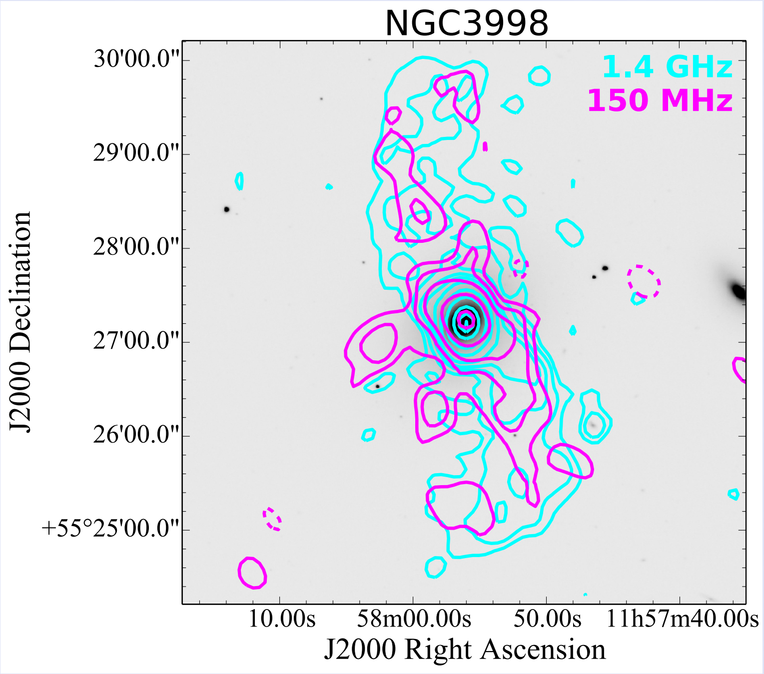


Summary

- LOFAR science not limited to "monsters" – low-luminosity radio source science is possible!

- Framework for *user-friendly*, dir.-dep. LOFAR calibration is publicly available (FACTOR)

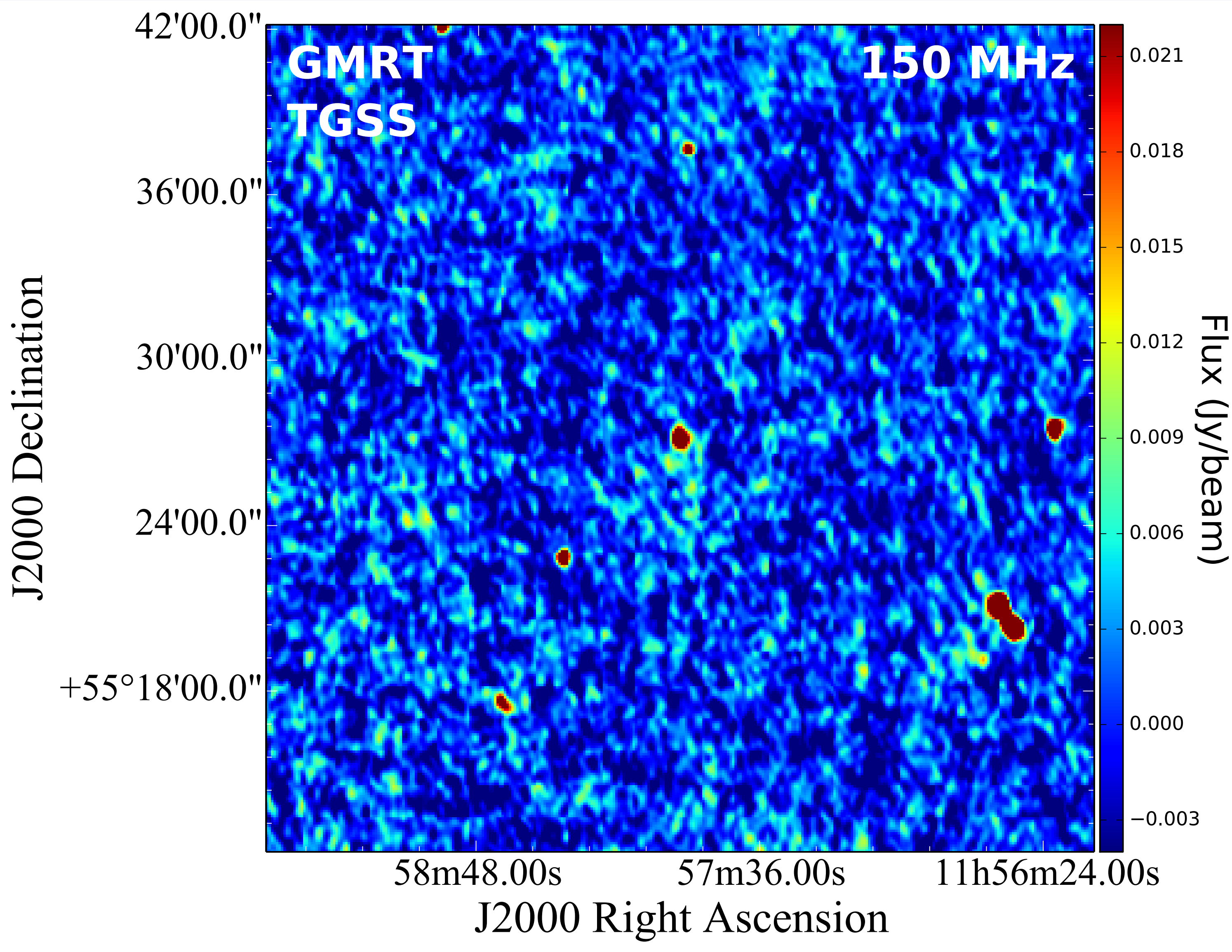
- Dir.-dep. calibration of the NGC 3998 LOFAR data will help provide constraints on the radio source age, evolutionary stage, and impact on the host galaxy



. . . . stay tuned for improved LOFAR 150 MHz imaging of NGC 3998!

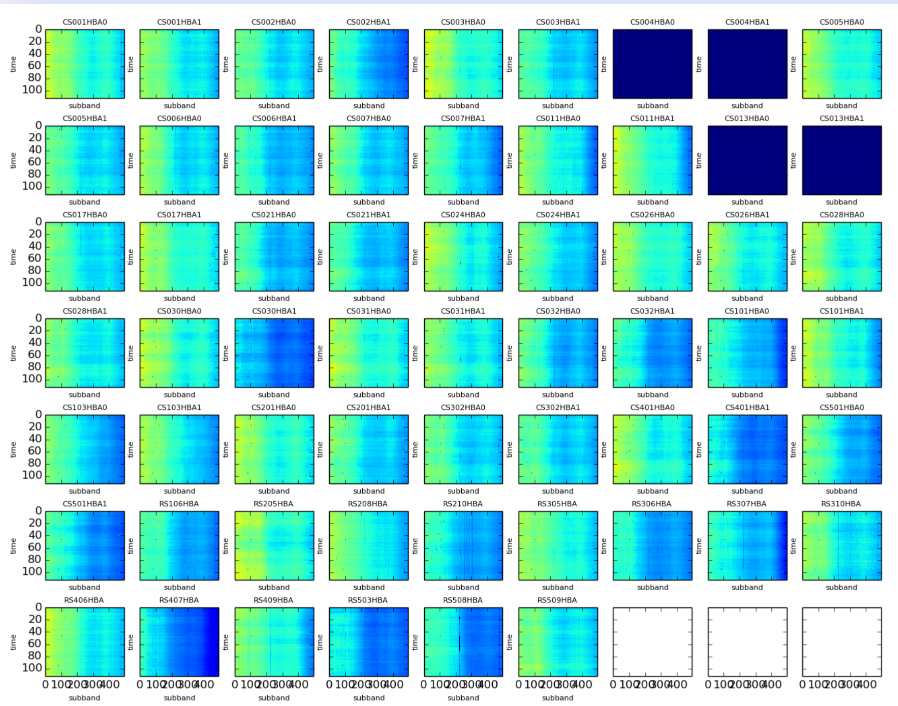
Additional Slides

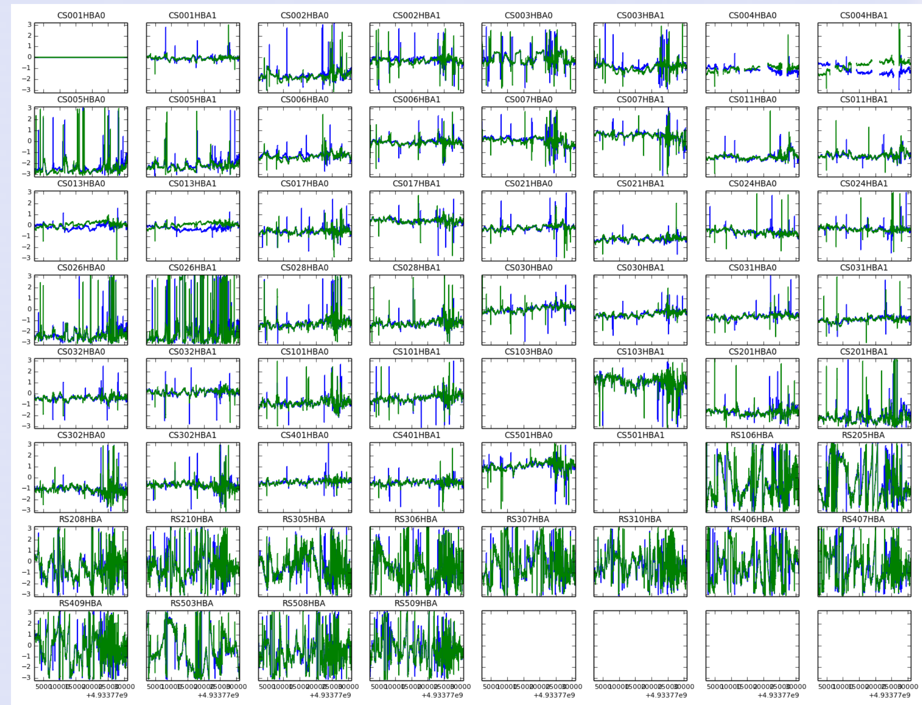
GMRT 150 MHz Observations



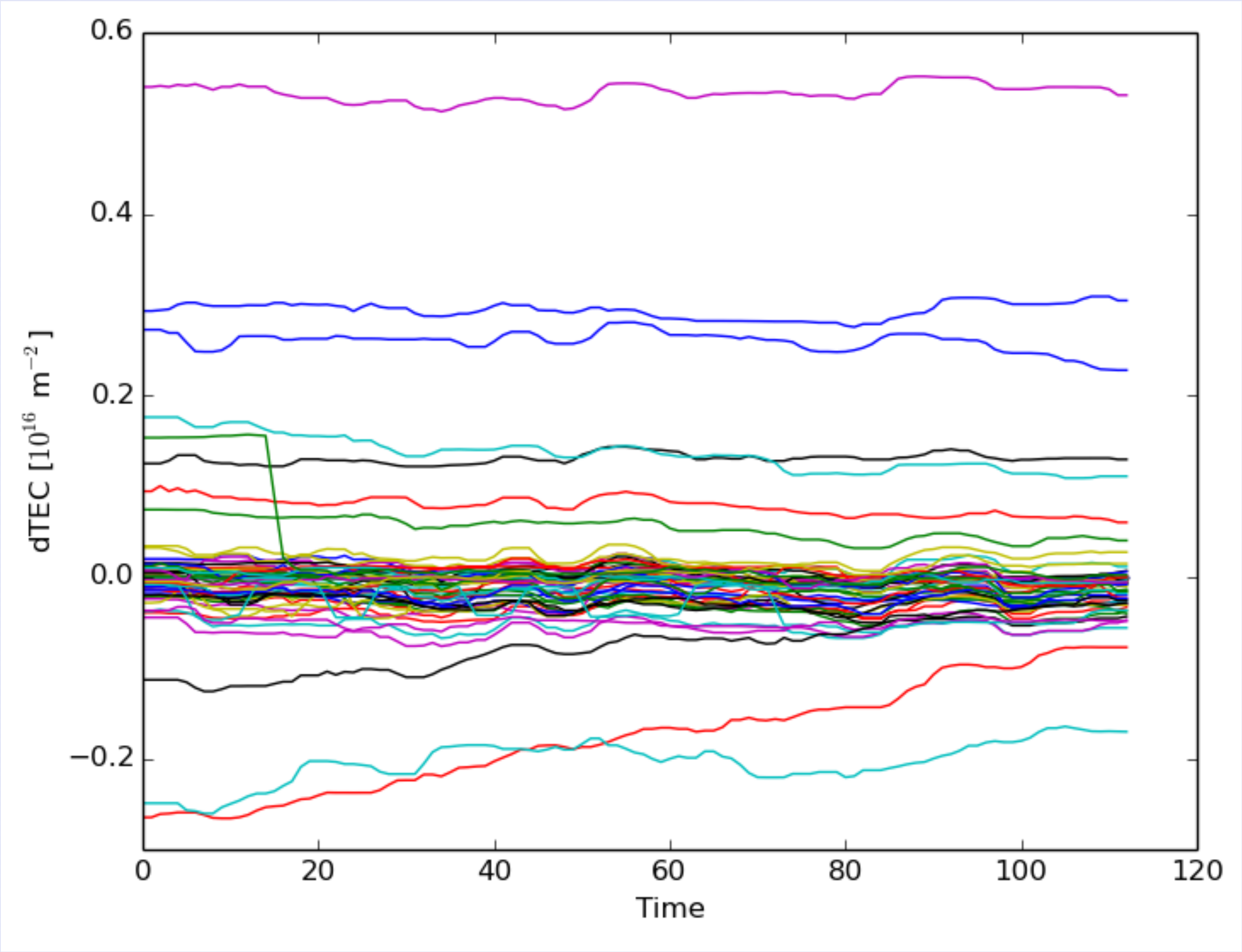
(Huib Intema)

Generic Pipeline Diagnostics

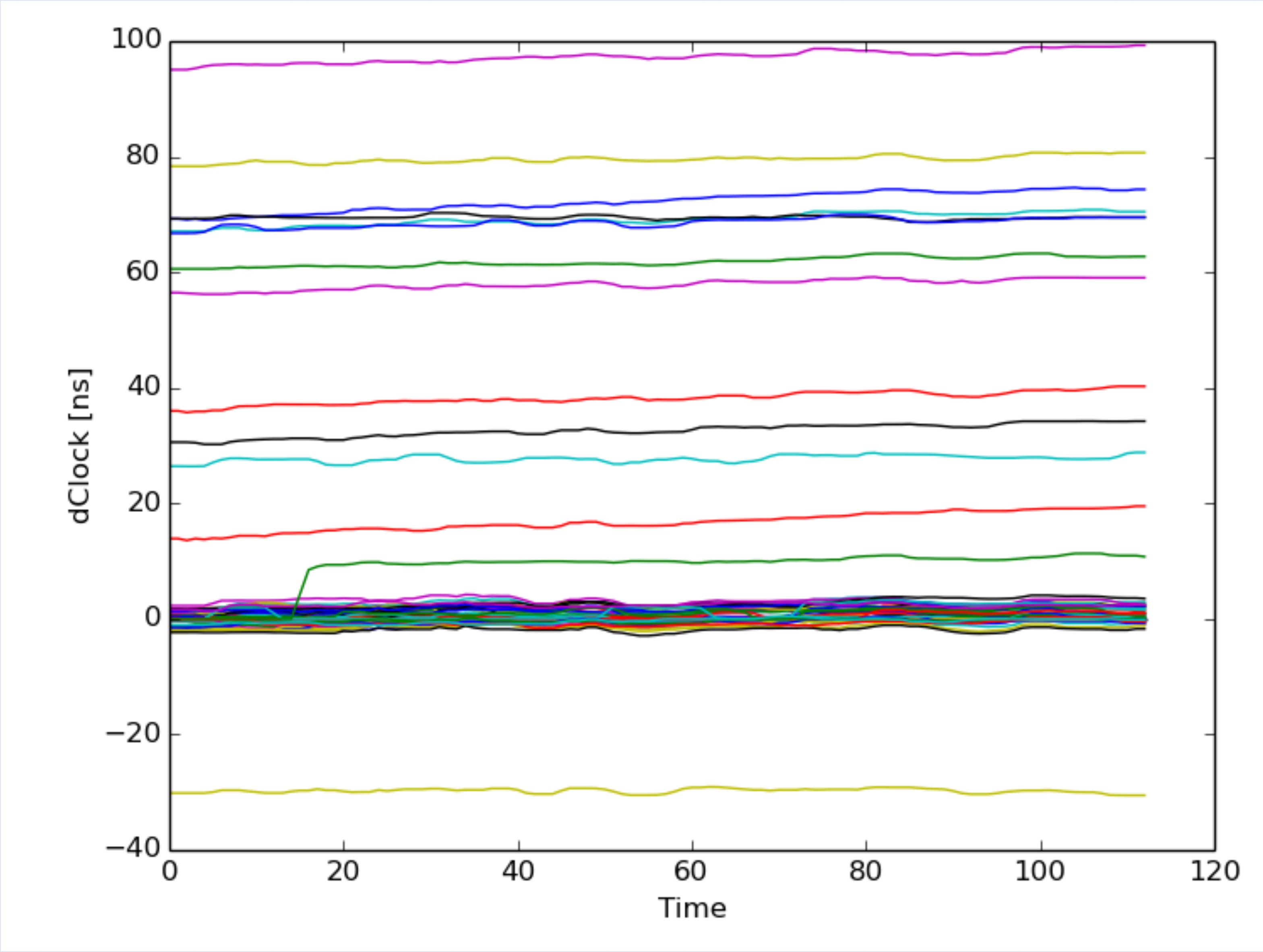




Generic Pipeline Diagnostics

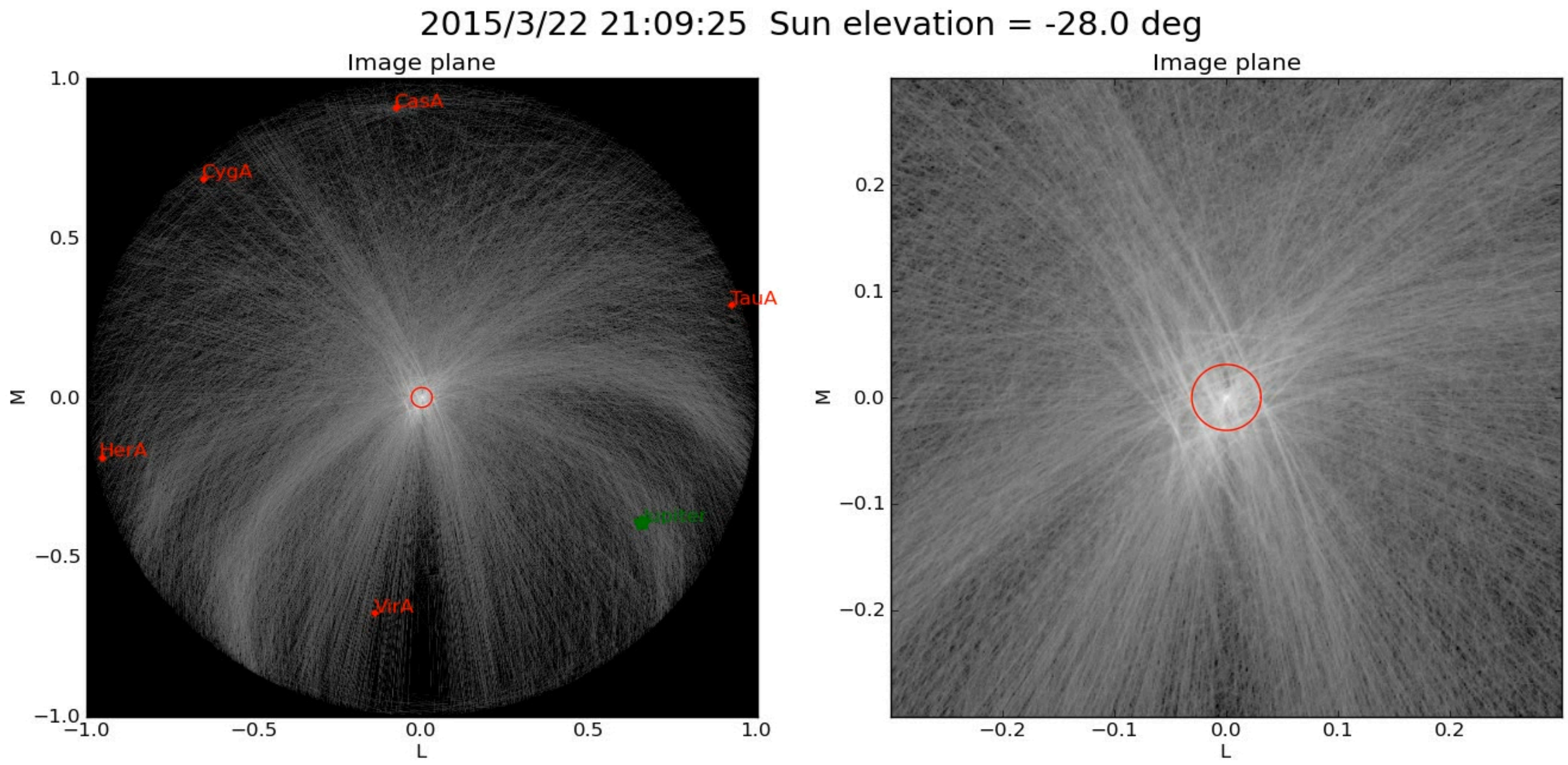


Generic Pipeline Diagnostics



NGC3998 LOFAR Observations

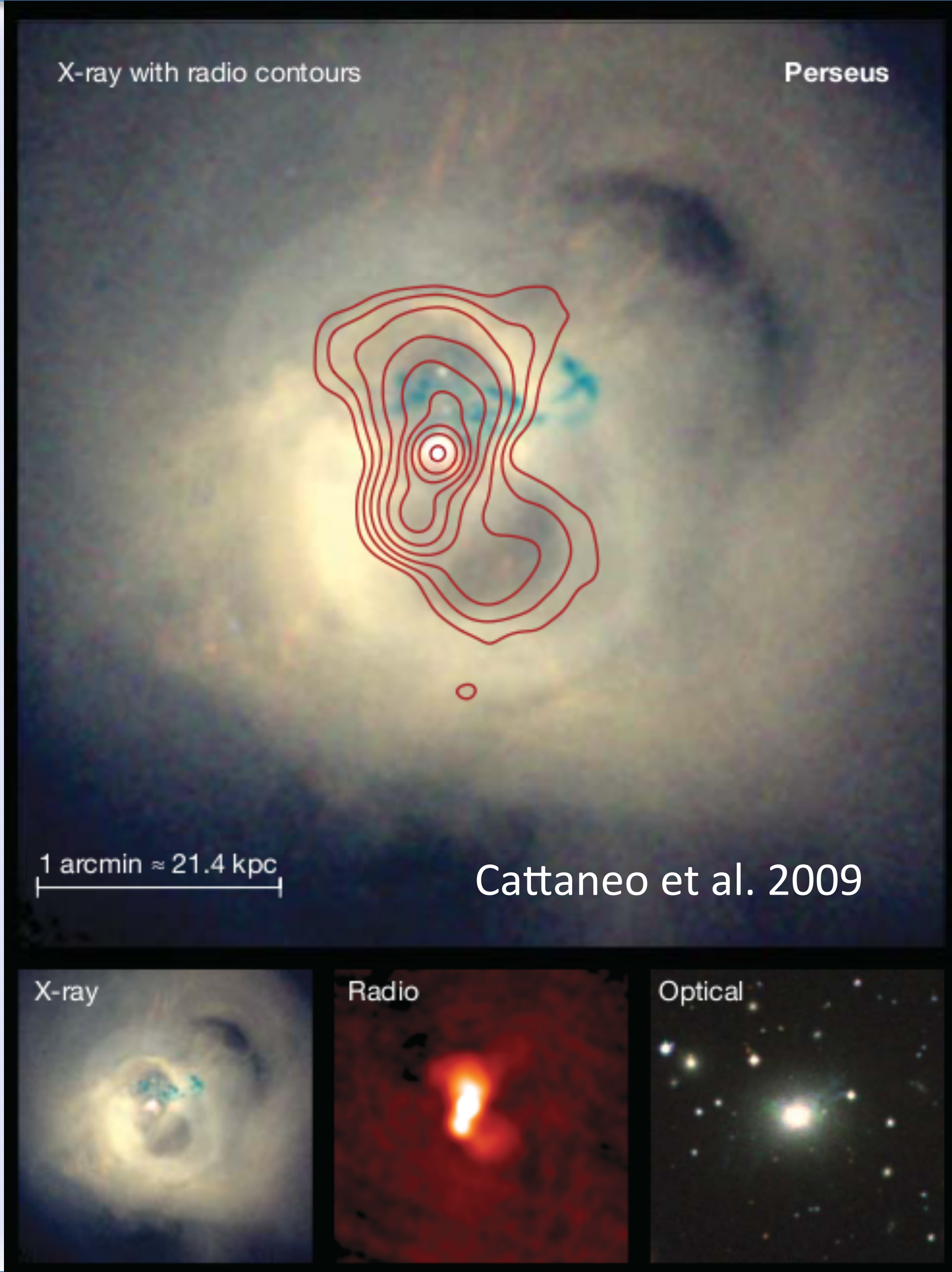
Fringe Rate Spectra



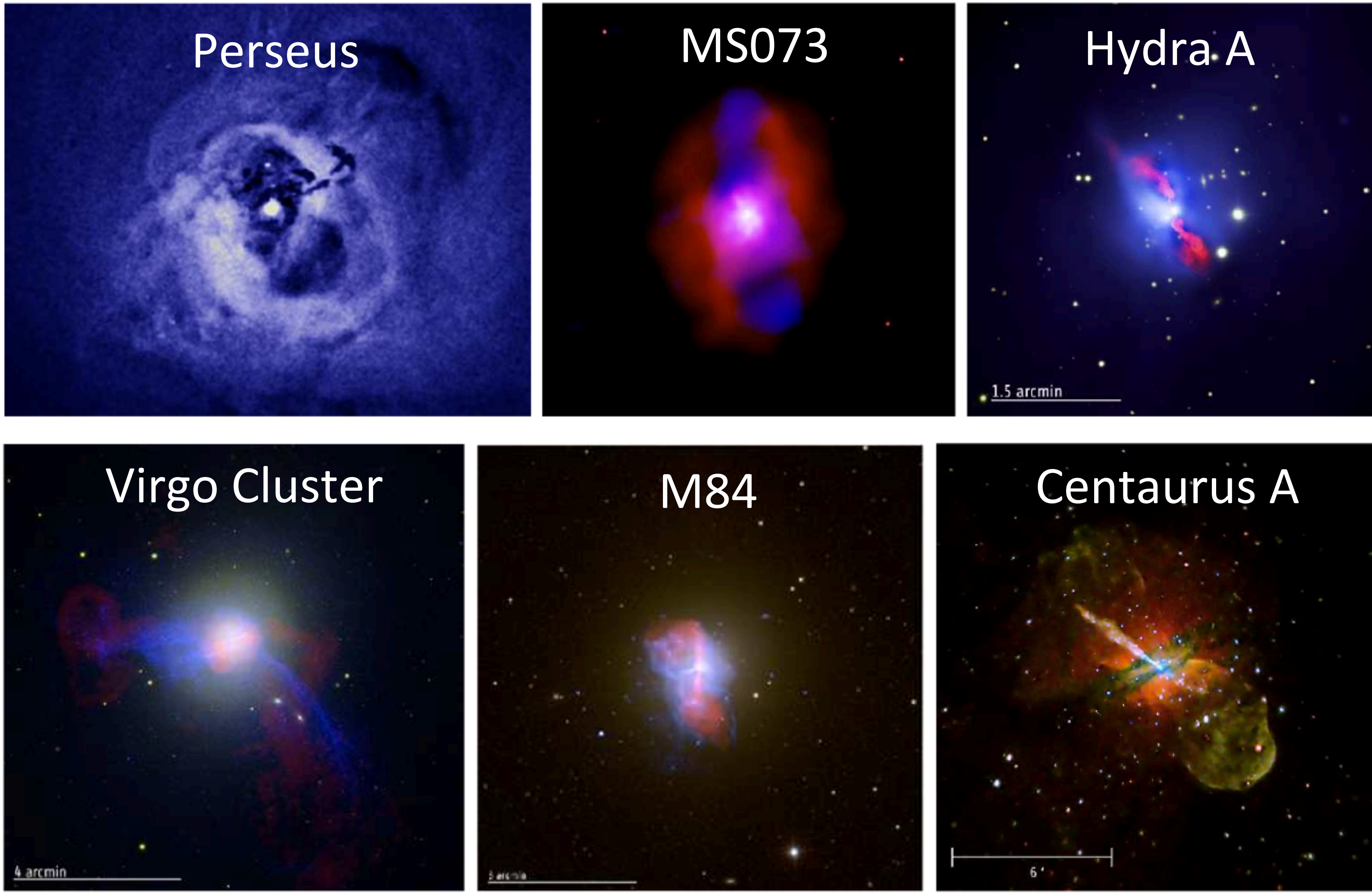
How does AGN Feedback "Work"?

Radio Mode

- Mechanical energy from jets can drive gas out and carve "bubbles" in the ISM/IGM
- Duty cycle is much longer than for the quasar mode
- Generally more important at lower redshifts
- "Maintenance-mode" feedback

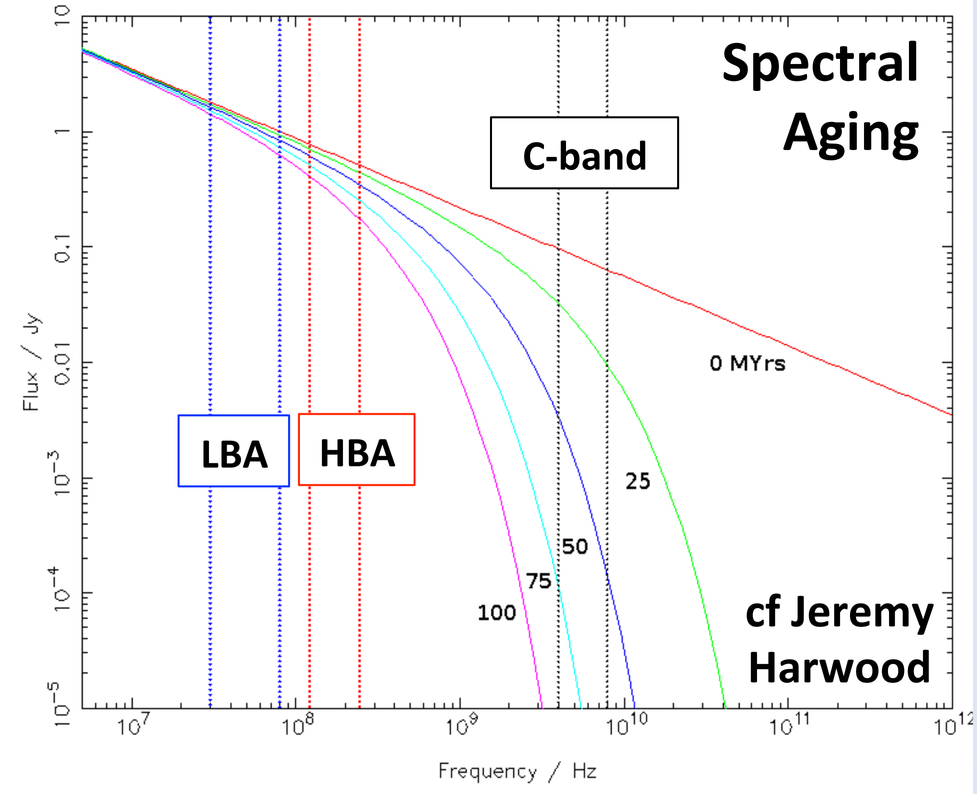


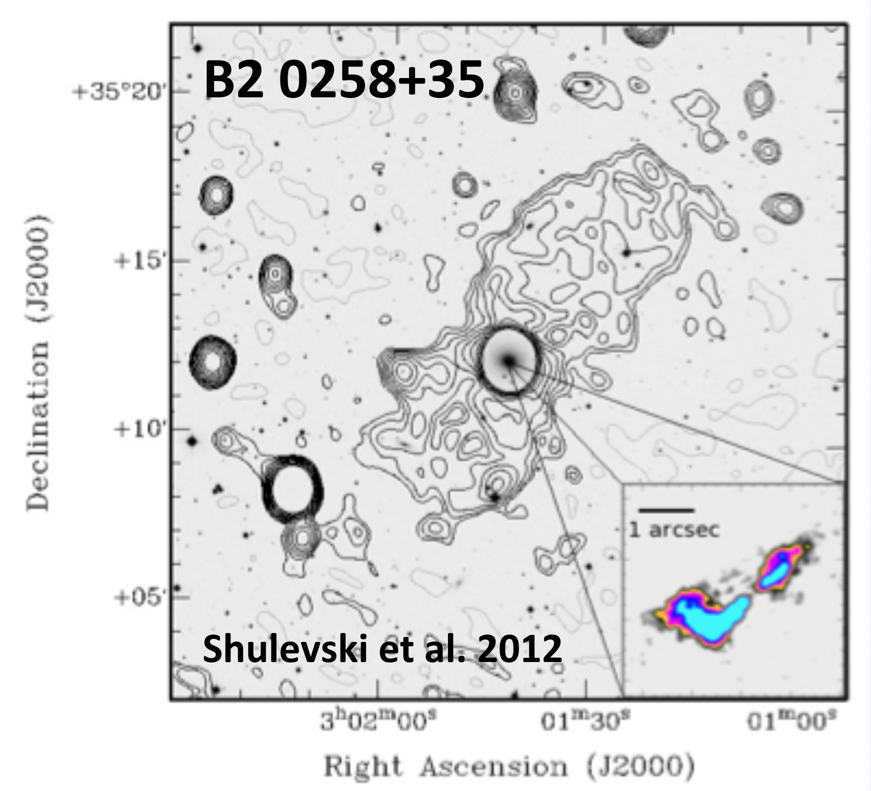
Radio Mode Feedback in Action

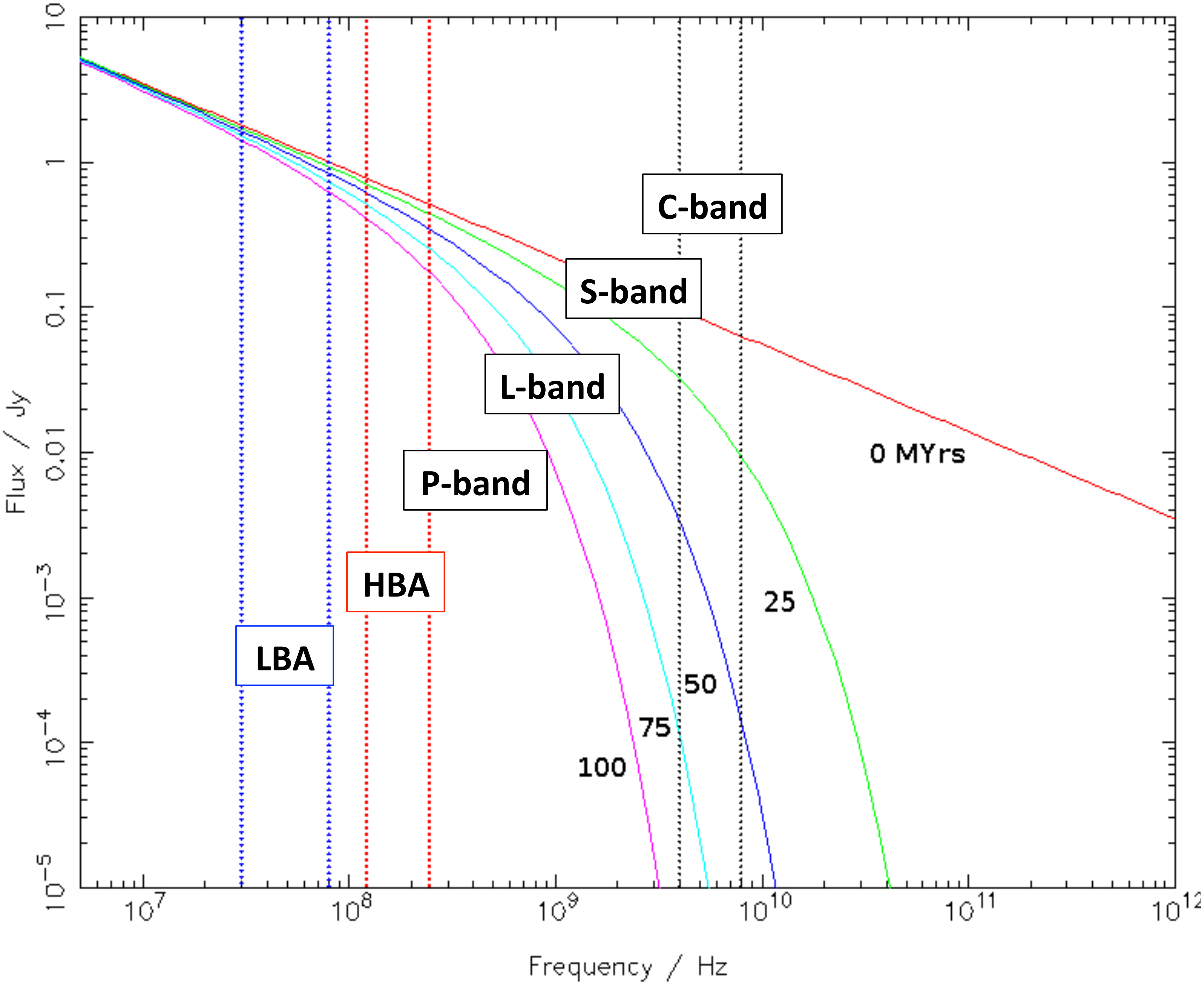


AGNs at Low Radio Frequencies: Why?

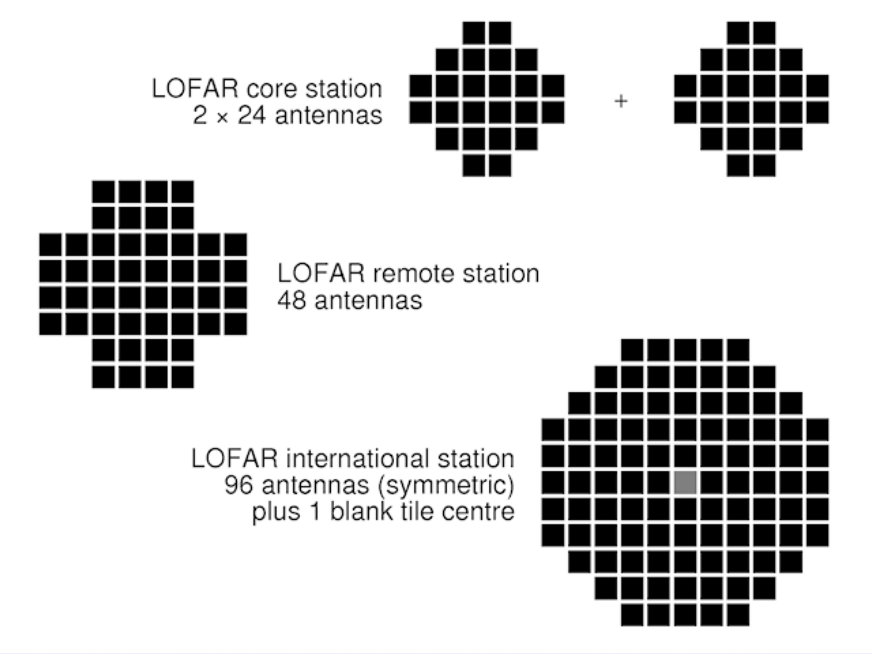
- "Fossil" record of source evolution
- Information on the "life cycle" of a radio source
- Radio source age/duty cycle estimates
- Constraints on cosmic ray acceleration/loss mechanisms

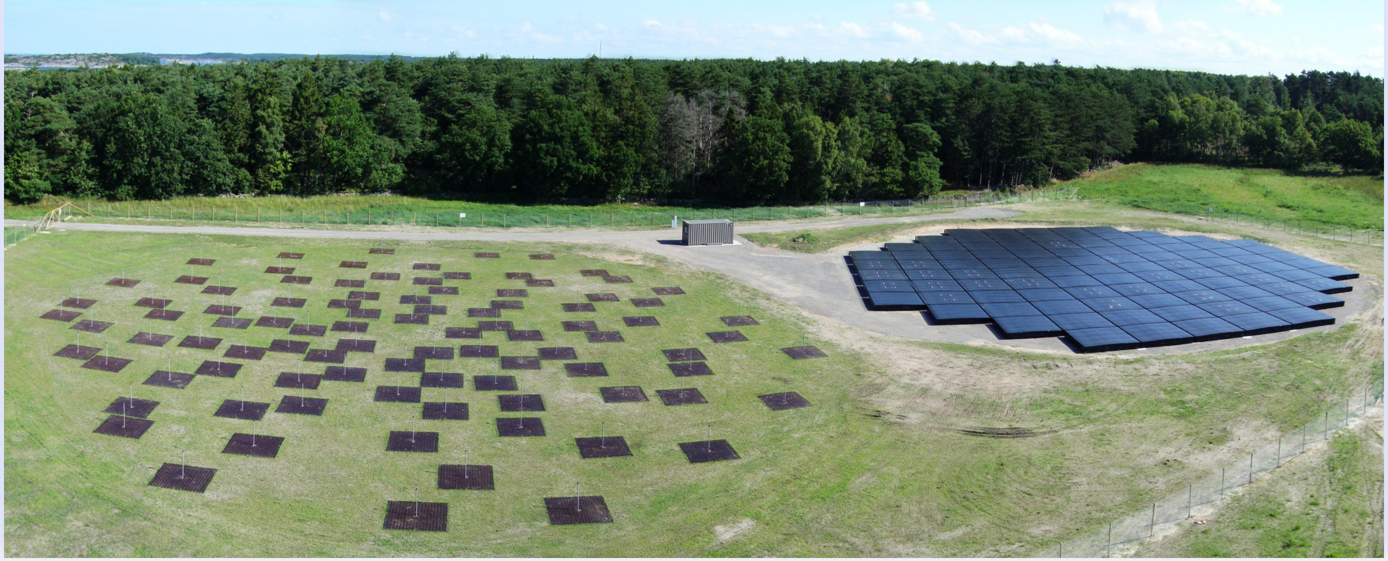





C-band
S-band
L-band
P-band
HBA
LBA
0 MYrs
25
50
75
100
Flux / Jy
Frequency / Hz

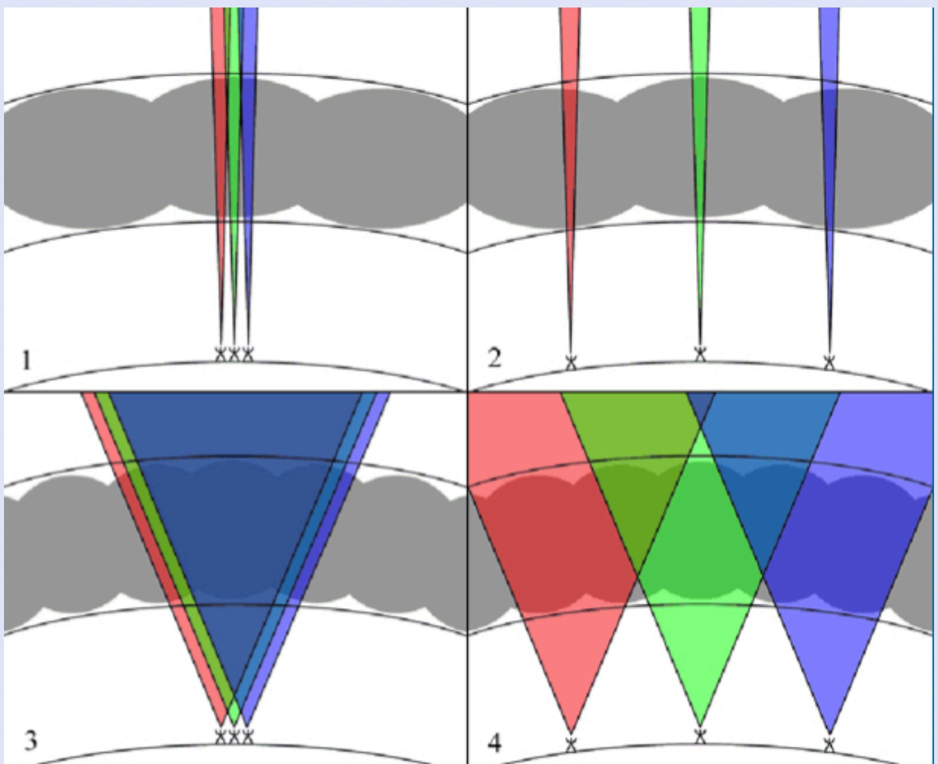
LOFAR Stations





LOFAR: Challenges

- **Direction dependent effects:**
  - Each antenna looks through a different patch of ionosphere
  - Need to calibrate each direction separately
  - Various techniques currently under development
  - Most methods are extremely computationally expensive

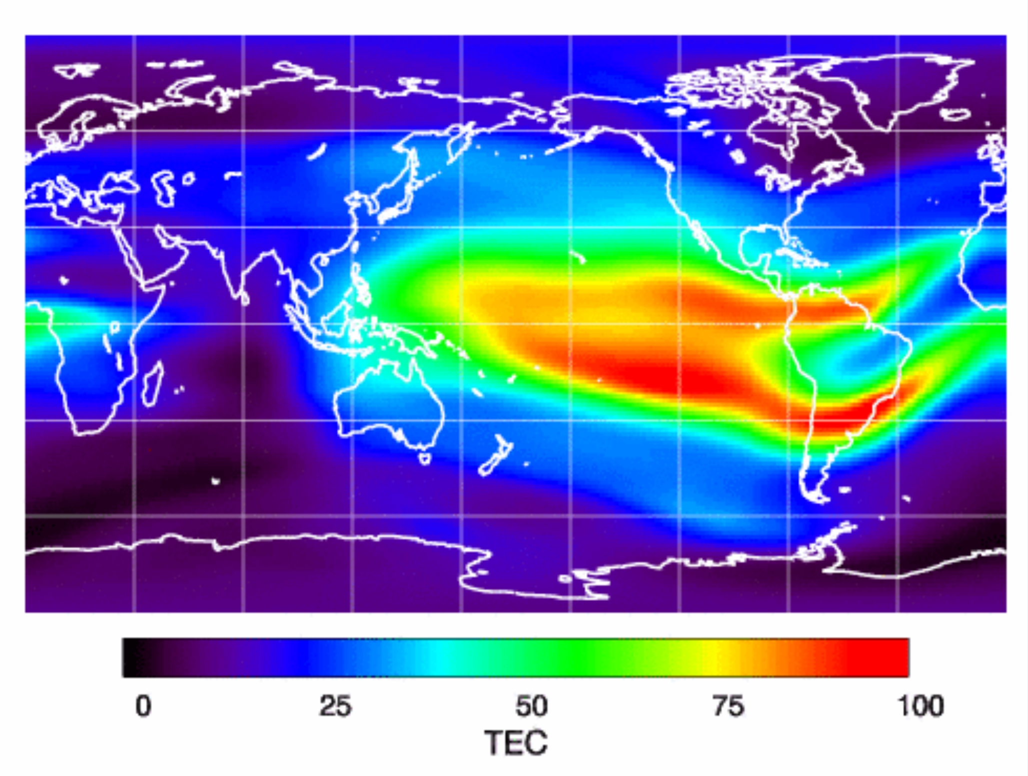


Intema et al. 2009

Need direction-dependent calibration!

LOFAR: Challenges

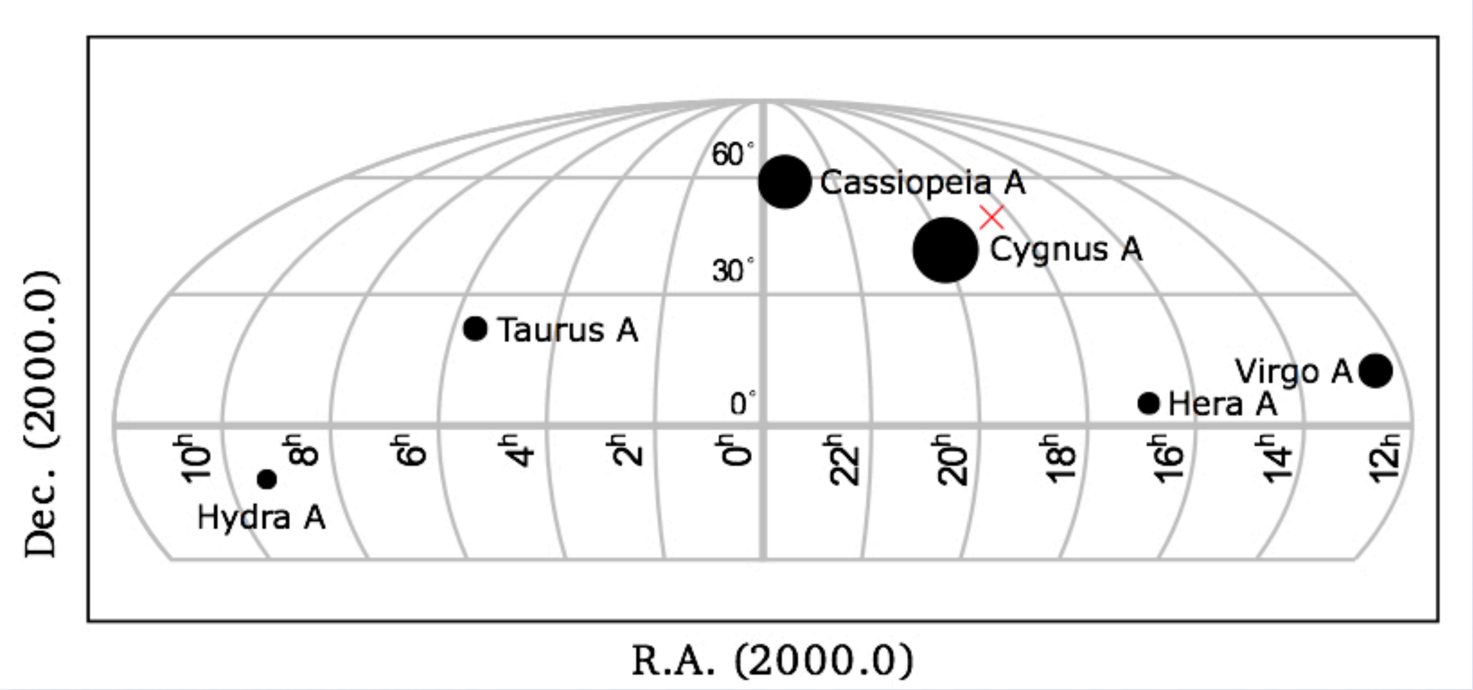
- **Ionosphere:**
  - Partially ionized gas layer
  - Electron density variable in space/time
  - Units: Total Electron Content Unit (TECU)
  - 1 TECU = 10^{16} m^{-2}

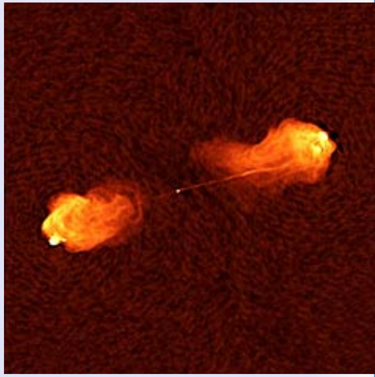


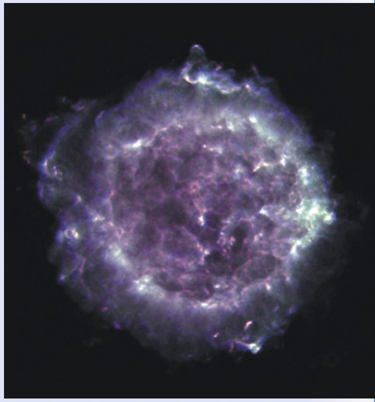
- **Effect on images:**
  - Phase errors
  - Positional shifts
  - Source distortions

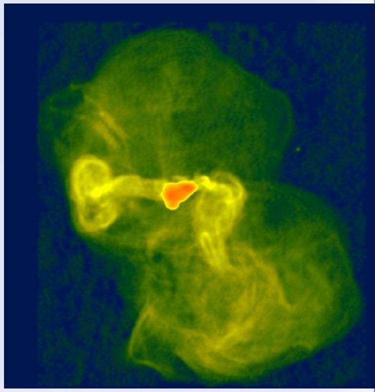
LOFAR: Challenges

- **The A-team:** CygA, CasA, VirA, TauA, HerA, HydA





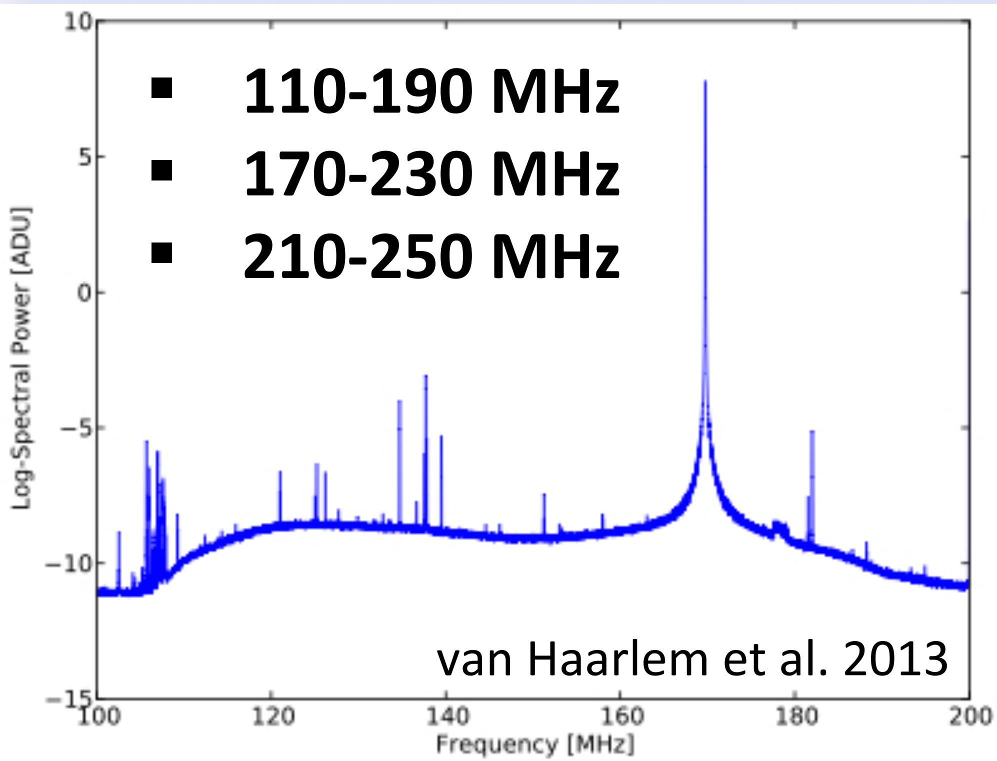




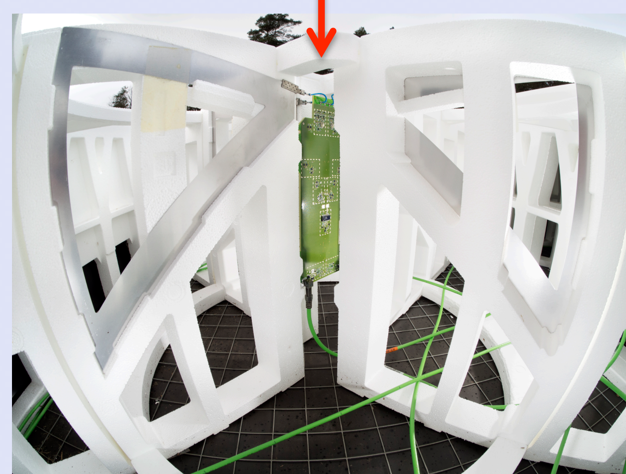
- **Demixing:** Subtraction of A-team signal from the raw visibilities required for all LBA and some HBA datasets

LOFAR: High Band Antenna (HBA)

- **Frequency range: 110-250 MHz**
  - **110-190 MHz**
  - **170-230 MHz**
  - **210-250 MHz**

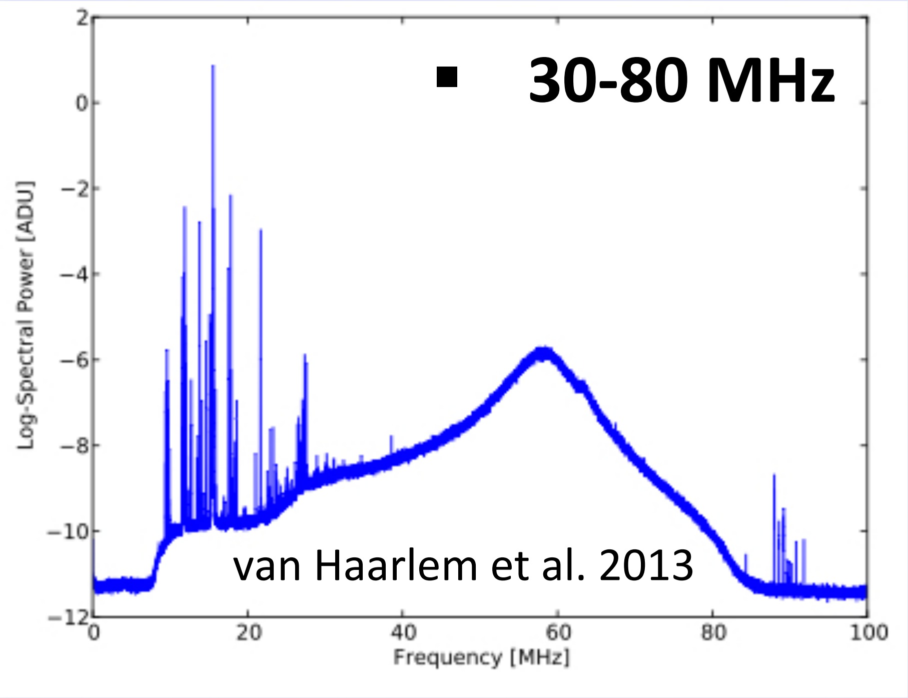


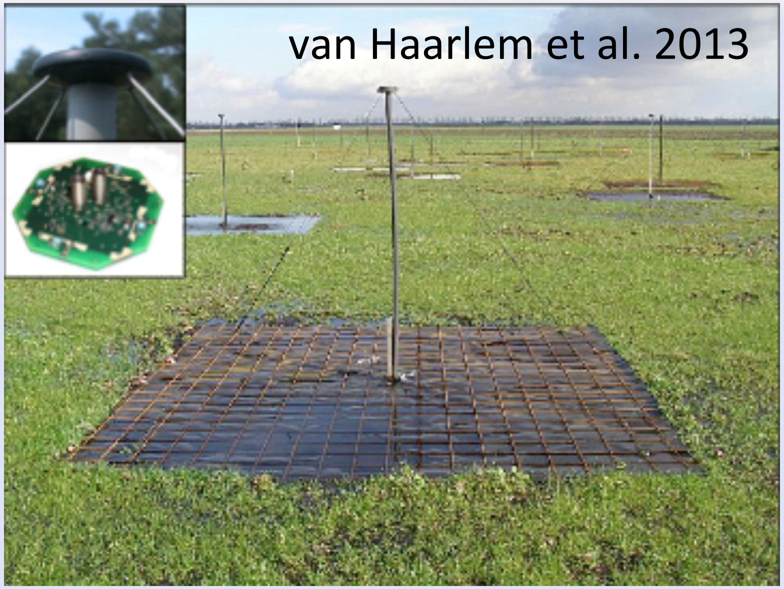
- **F.O.V. = 1-4° (FWHM)**



LOFAR: Low Band Antenna (LBA)

- **Frequency range: 10-90 MHz**



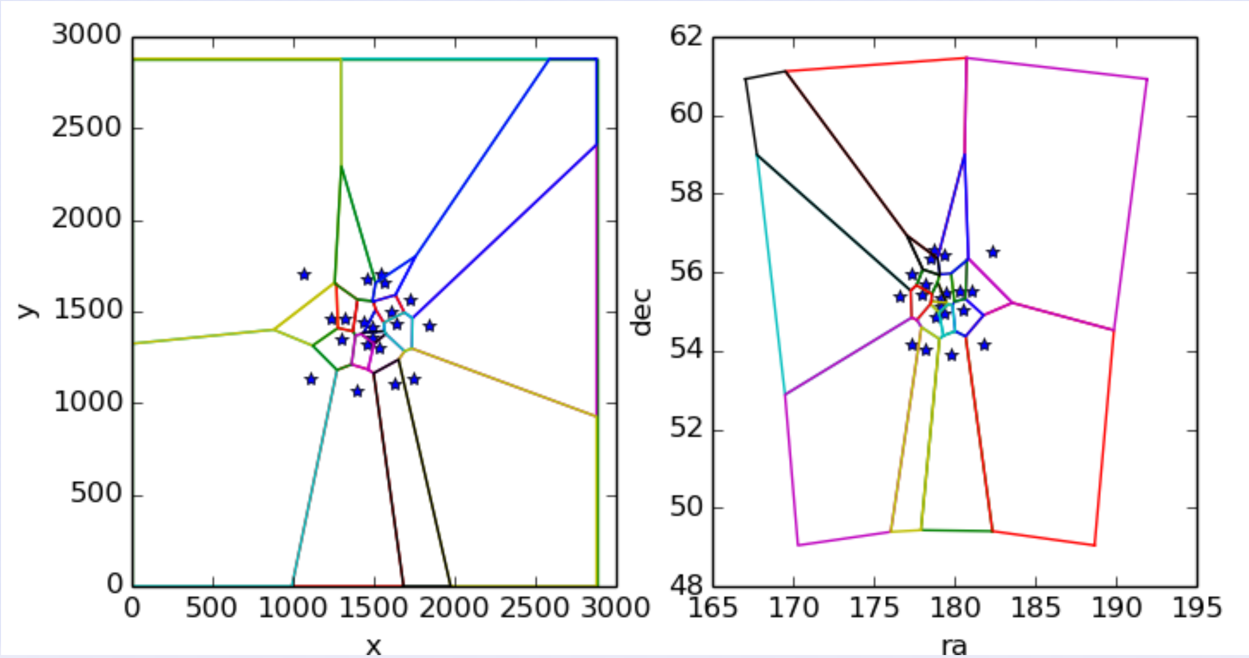


- **F.O.V. = 3-40^o (FWHM)**

Facet Calibration

Assumptions:

- Station beam varies slowly in time and frequency
- Phase α frequency^{-1} (clock offsets corrected)
- No other frequency-dependent phase errors
- Ionosphere and beam errors vary slowly across FOV
- Differential Faraday Rotation can be neglected



The ATLAS^{3D} Survey

William Herschel Telescope

260

WSRT

170

IRAM 30m

260

- ★ 260 ETGs
- ★ D < 42 Mpc
- ★ M_K < -21.5 mag

Canada France Hawaii Telescope

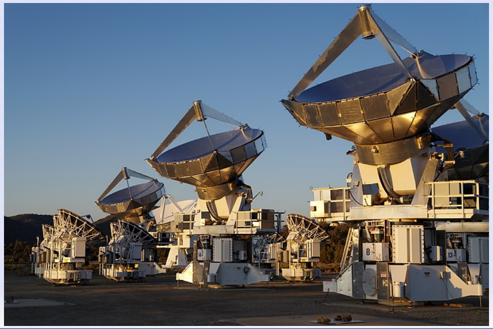
92

SDSS

260

Isaac Newton Telescope

CARMA



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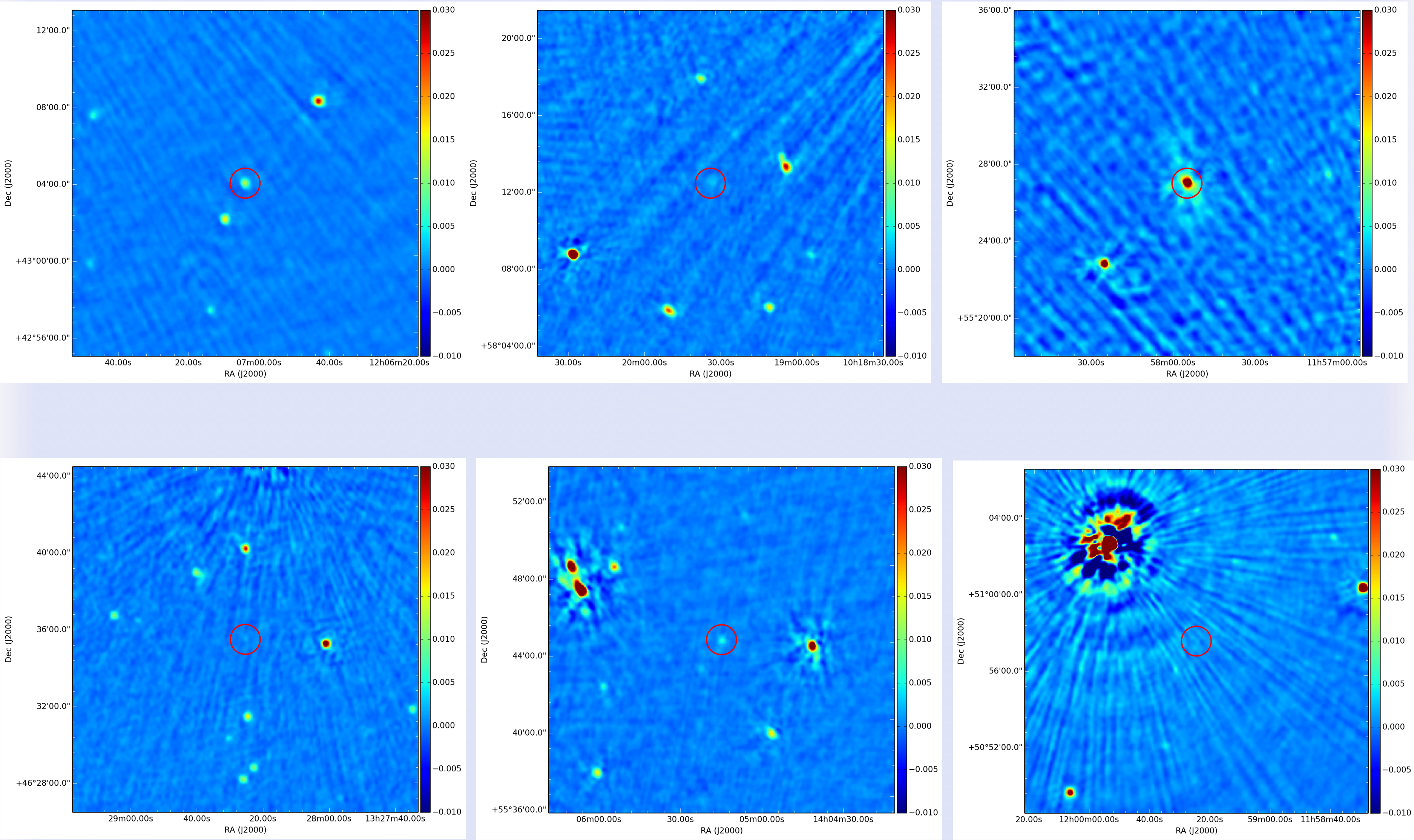
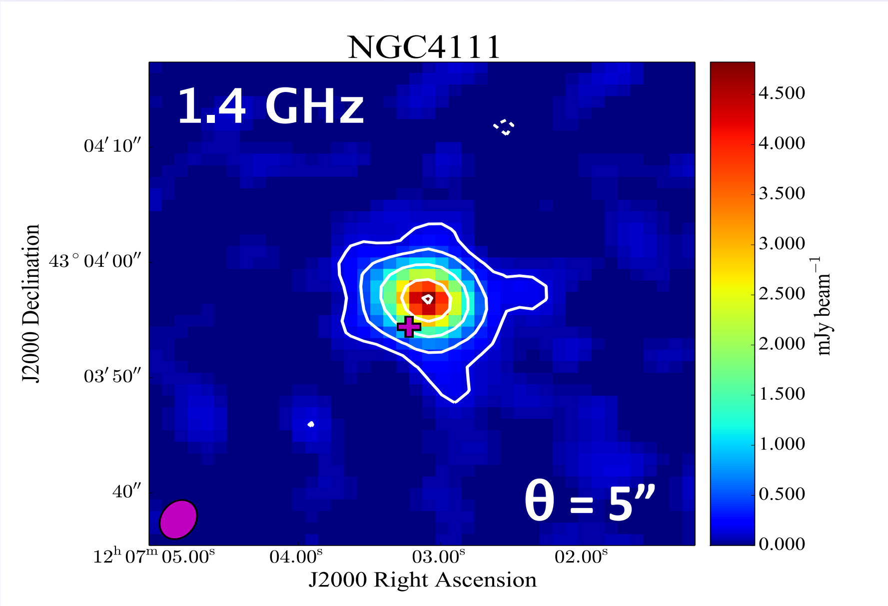
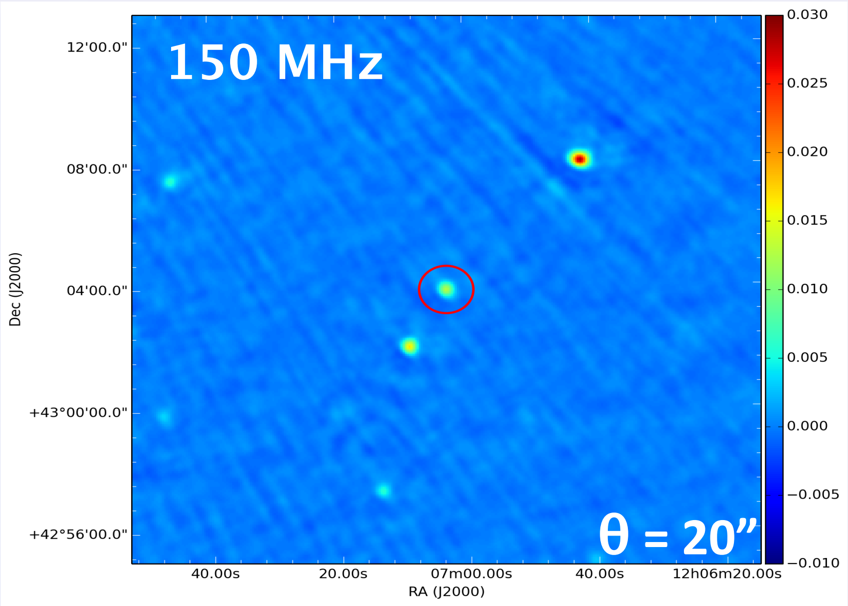
ATLAS^{3D} in the Tier 1 Survey



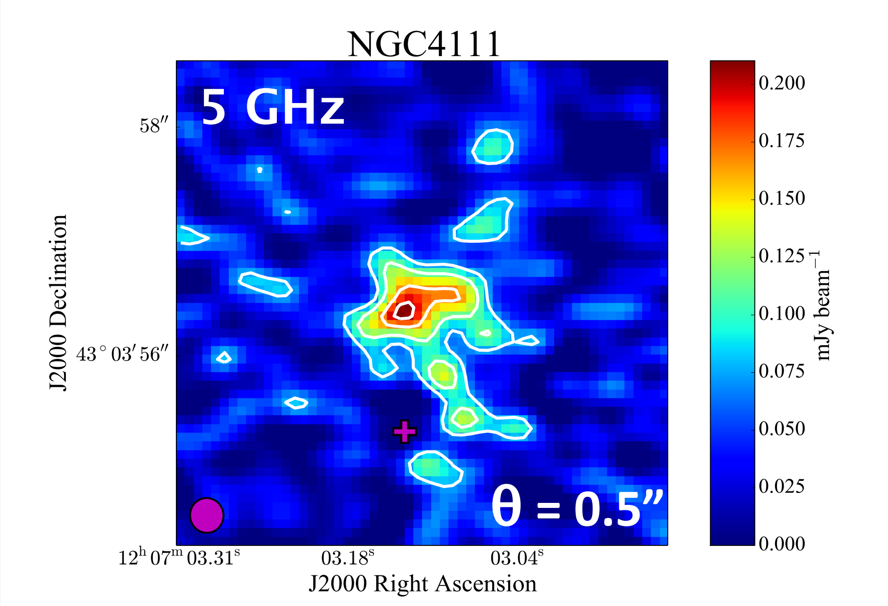
NGC 4111



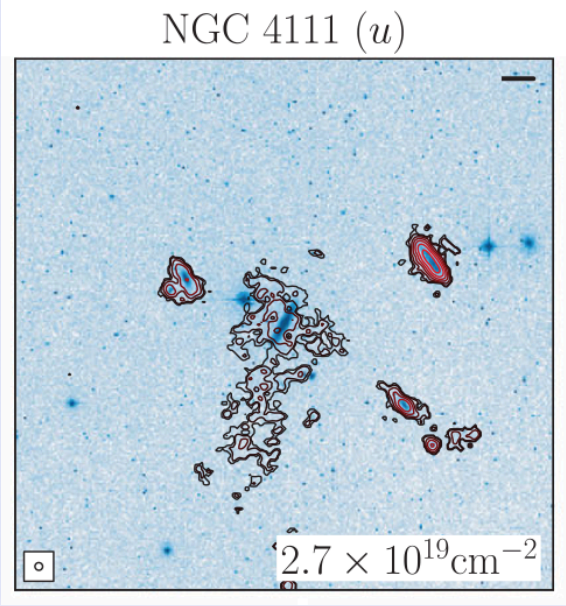
NGC4111
1.4 GHz
θ = 5”
J2000 Declination
J2000 Right Ascension
mJy beam^{-1}



150 MHz
θ = 20”
Dec (J2000)
RA (J2000)

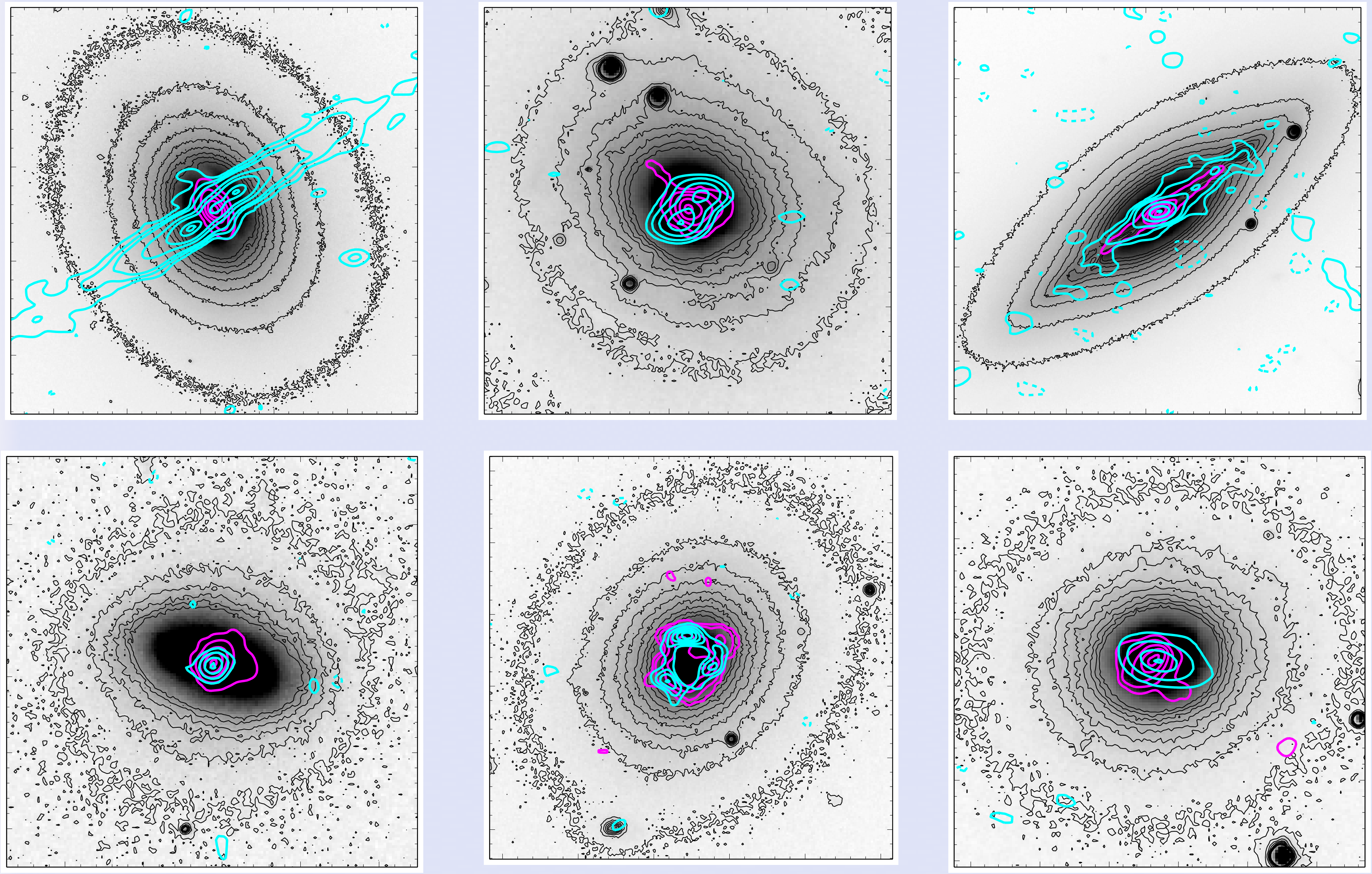


NGC4111
5 GHz
θ = 0.5”
J2000 Declination
J2000 Right Ascension
mJy beam^{-1}

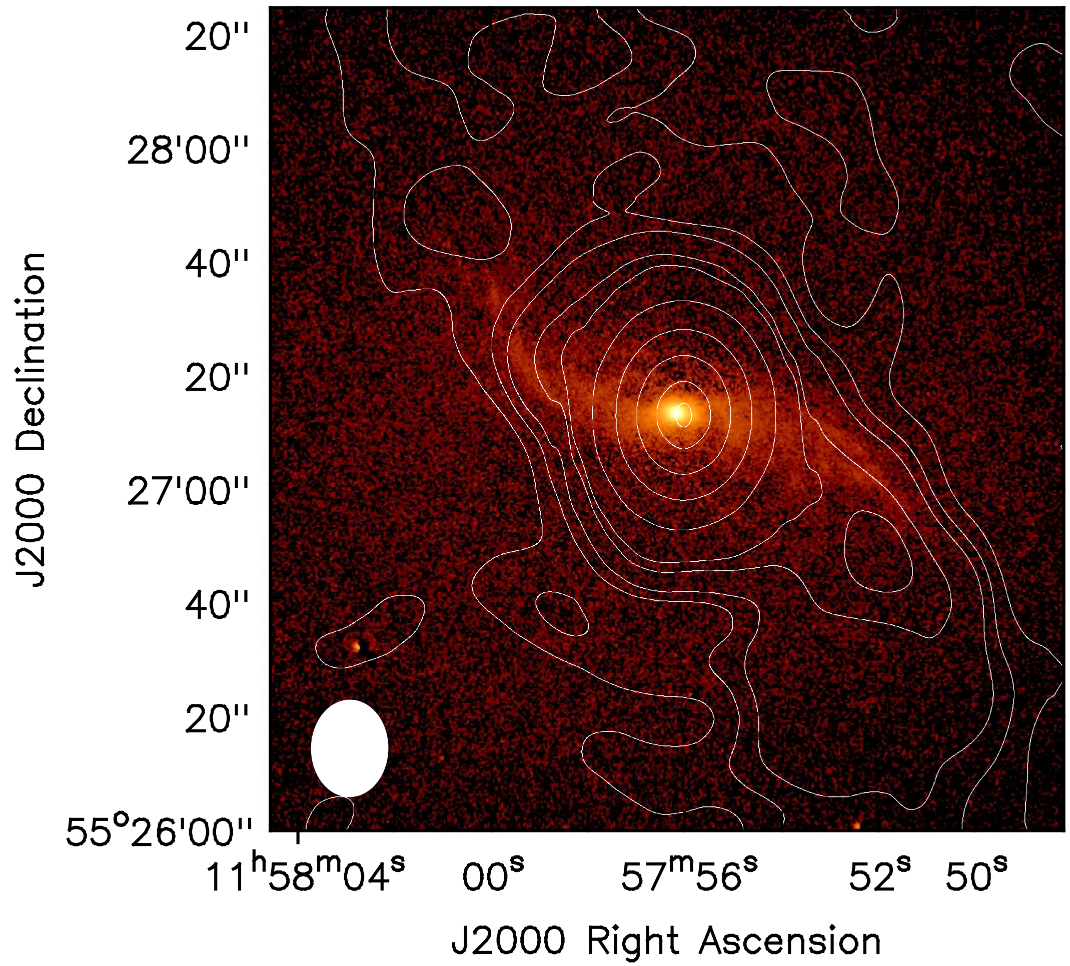


NGC 4111 (u)
$2.7 \times 10^{19}\mathrm{cm}^{-2}$

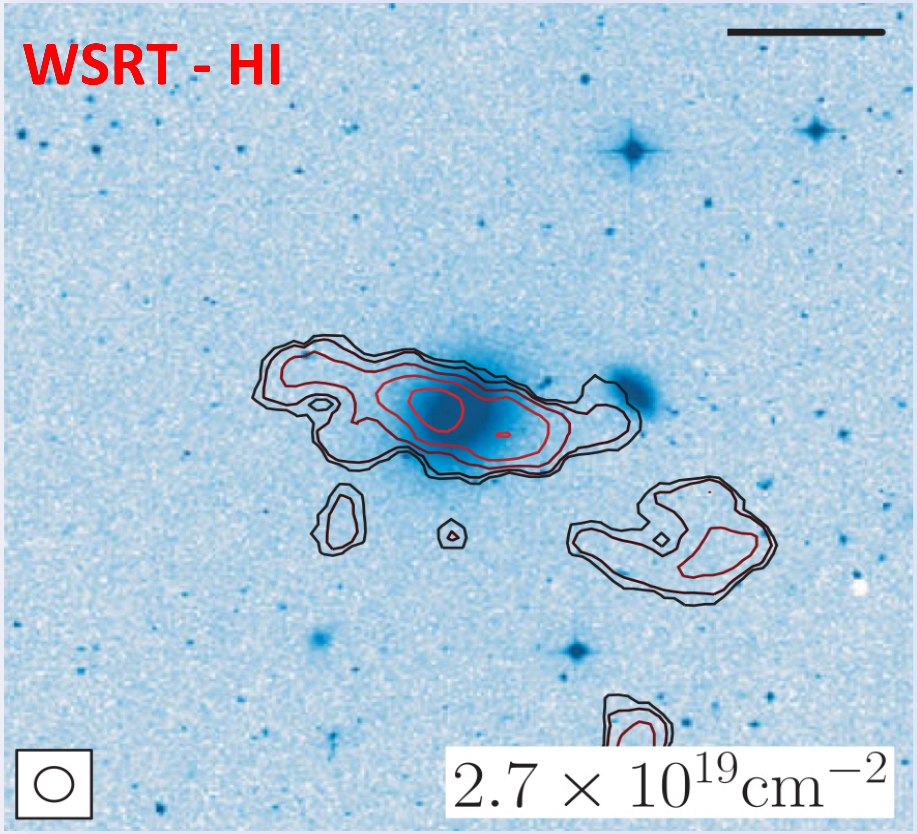
Other ATLAS^{3D} Galaxies . . .



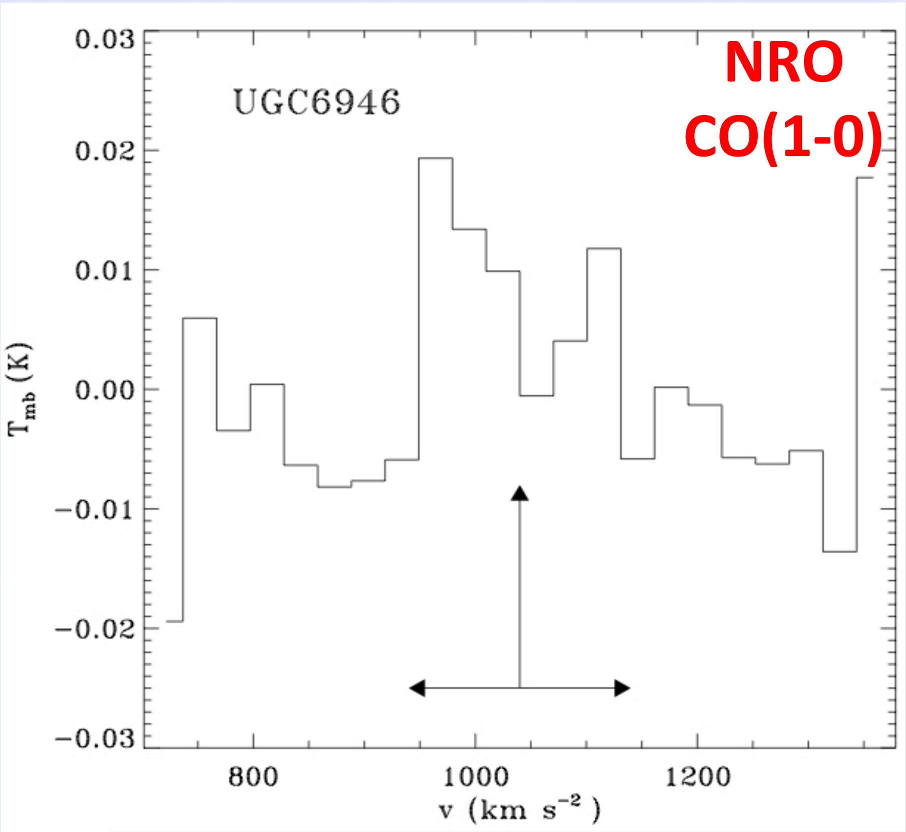
NGC3998: Hα


20''
28'00''
40''
20''
27'00''
40''
20''
55°26'00''
J2000 Declination
11h58m04s
00s
57m56s
52s
50s
J2000 Right Ascension

A Gas-rich, Massive Lenticular Galaxy



Serra et al. 2013



Baldi et al. 2015

$M_{HI} = 2.8 \times 10^8 M_\odot$ $M_{H2} = 1.7 \times 10^7 M_\odot$


Superterp (320 m)
Low Band Antenna (LBA)
High Band Antenna (HBA)