The Low-frequency Radio Window on Star Forming Galaxies

Gabriela Calistro Rivera

W. Williams, H. Röttgering

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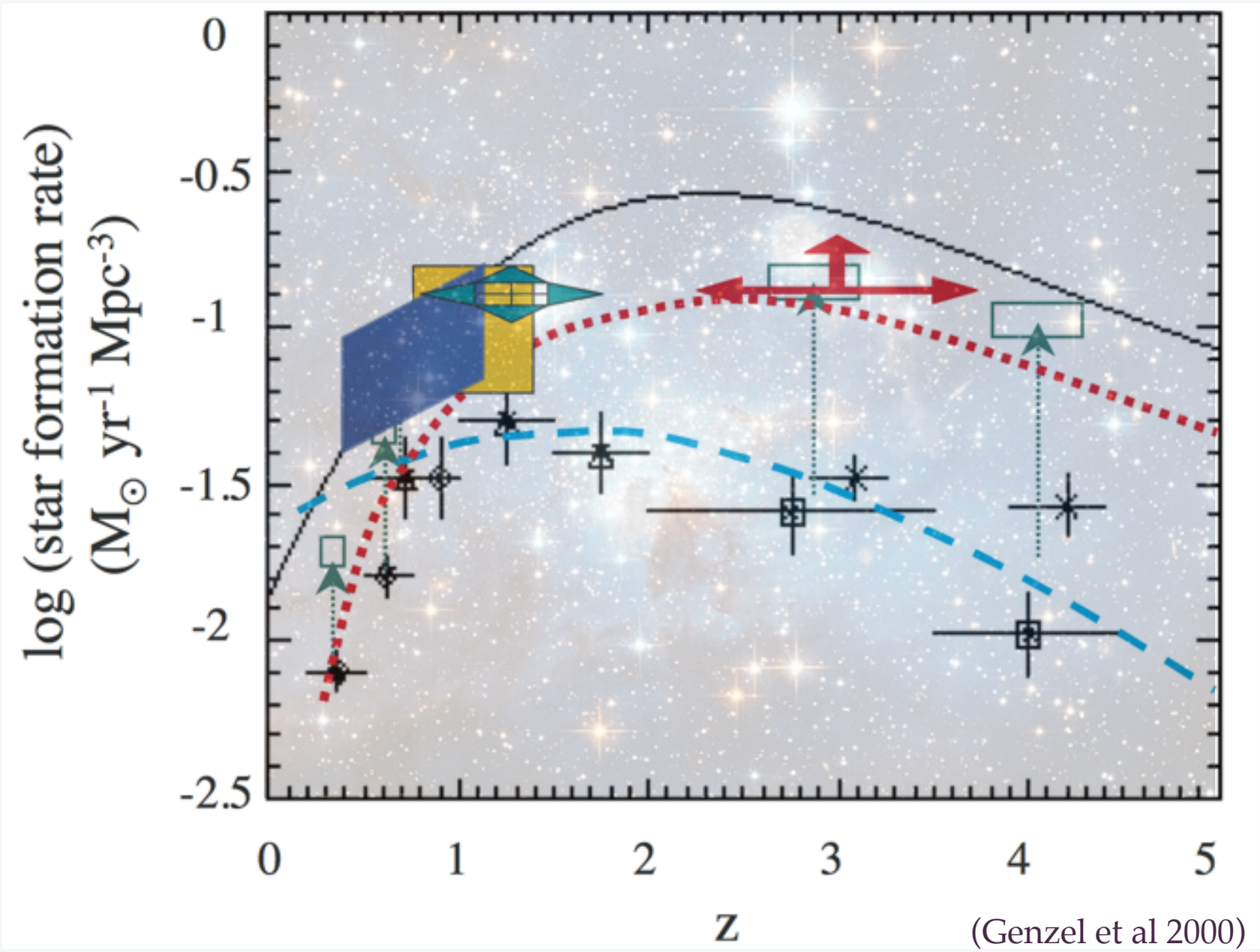
OUTLINE

1. **Low-Frequency Radio Spectra of galaxies**
2. **Böotes Field observed by LOFAR**
3. **Preliminary Analysis of radio spectra**
4. **Next steps**

Low frequency radio spectra of star forming galaxies

Low-freq radio spectra of galaxies

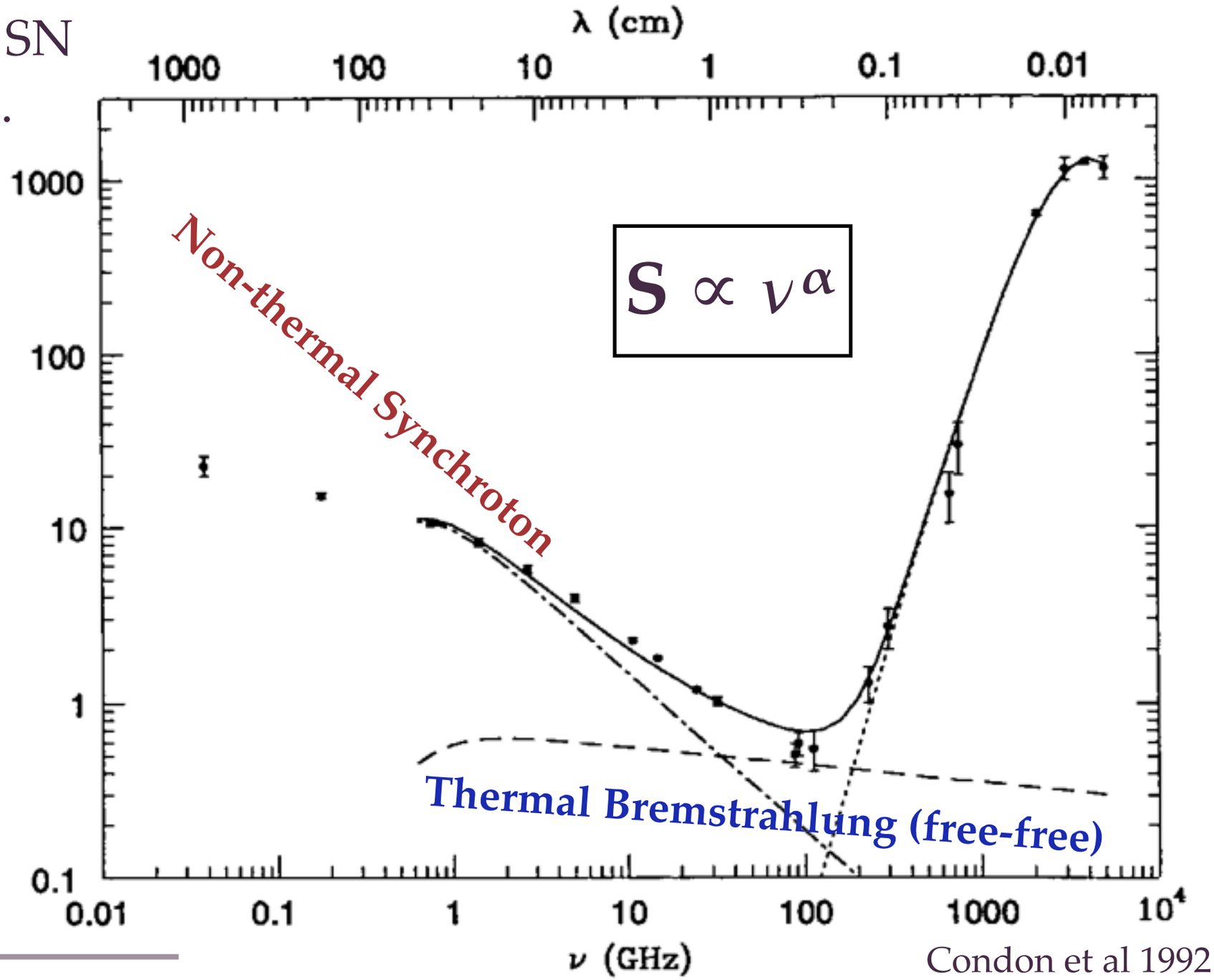


(Genzel et al 2000)

Low-freq radio spectra of galaxies

- Synchroton: Cosmic rays SN in diffuse magnetic fields.

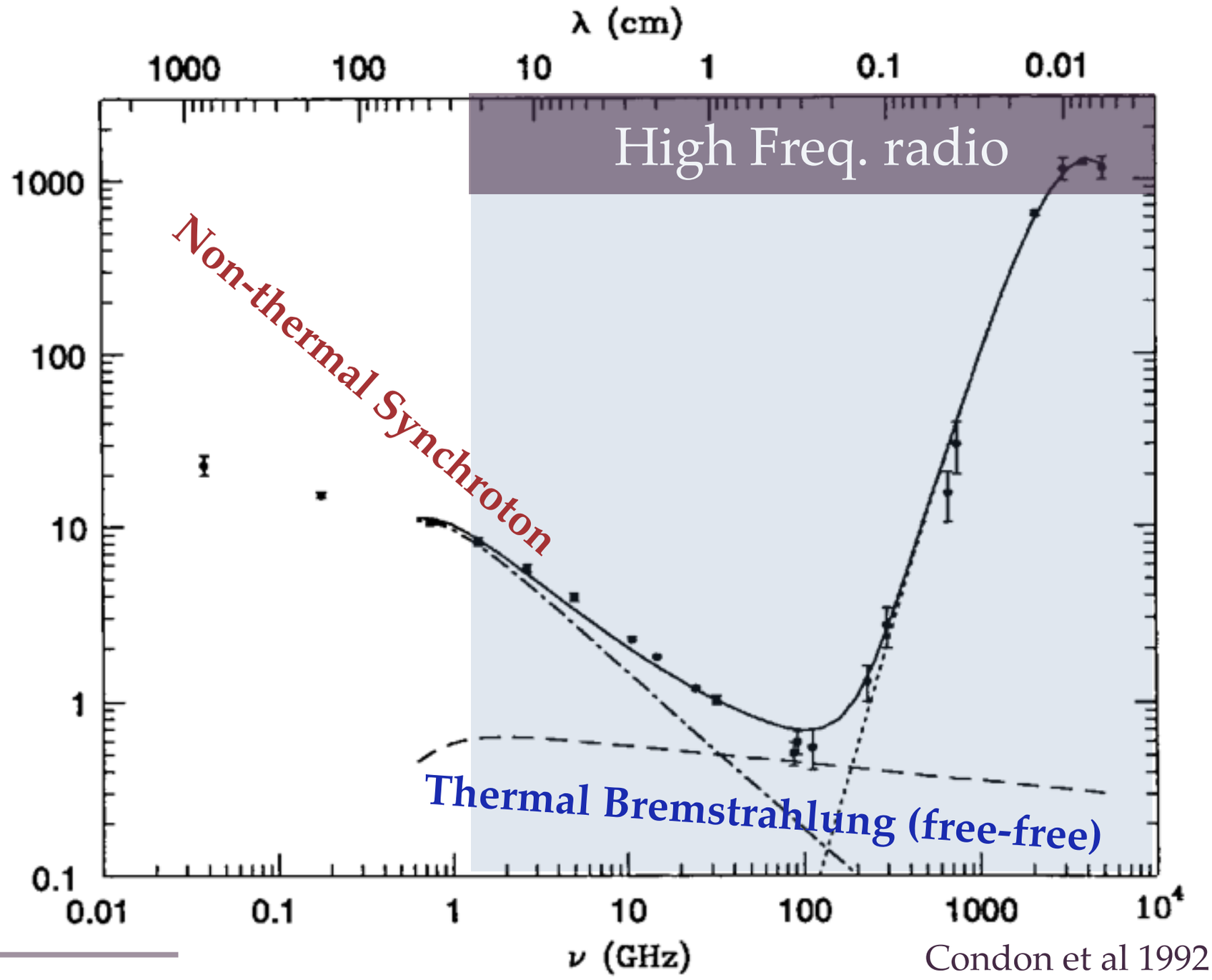
- Bremstrahlung emission:
  - HII regions



Condon et al 1992

Low-freq radio spectra of galaxies

- Radio($\nu \geq 1.4$ GHz) ↔ SFR ✔
  - e.g. Carilli and Yun (1999)

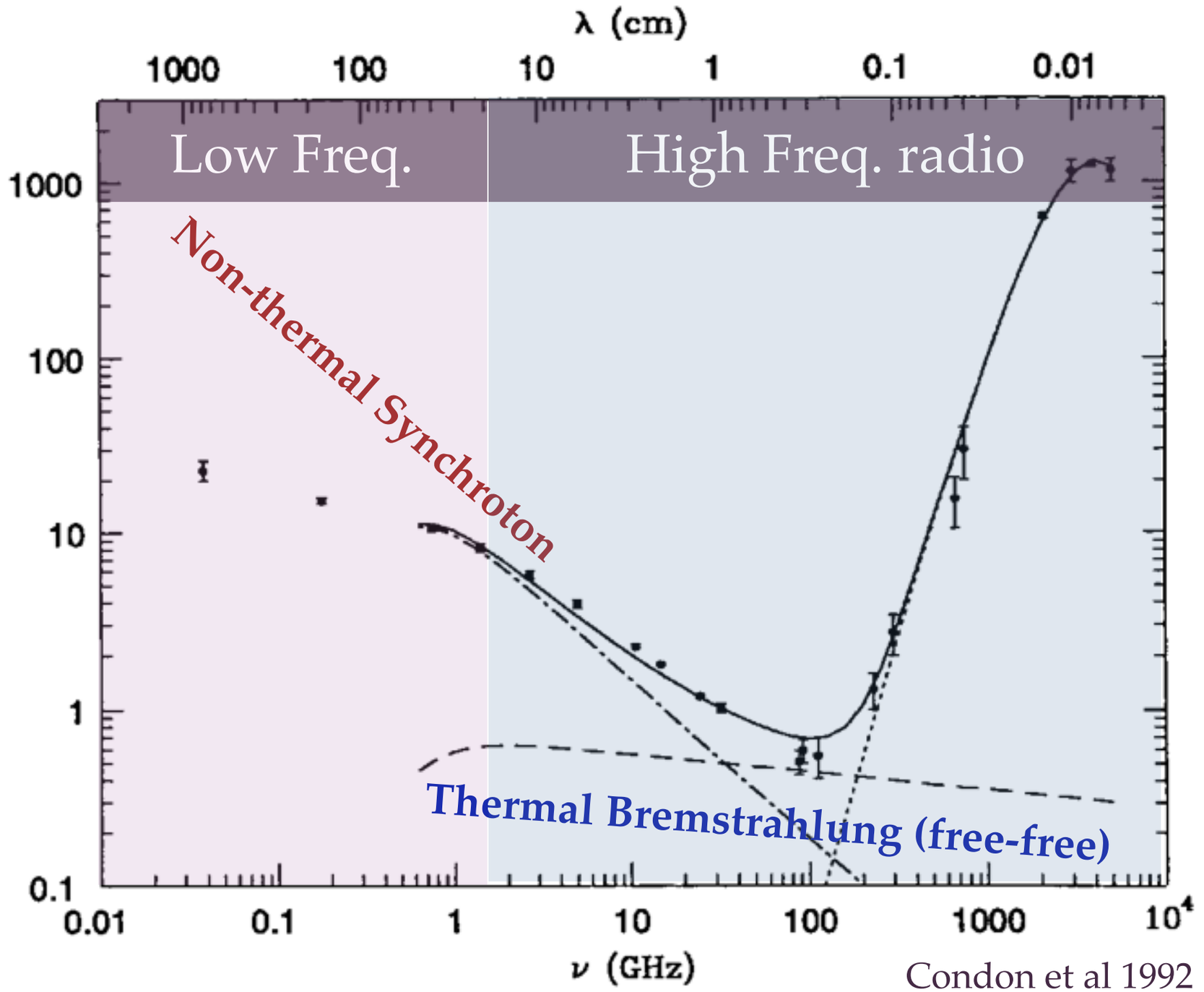


Condon et al 1992

Low-freq radio spectra of galaxies

- Radio($\nu \geq 1.4$ GHz) ↔ SFR ✔
  - e.g. Carilli and Yun (1999)

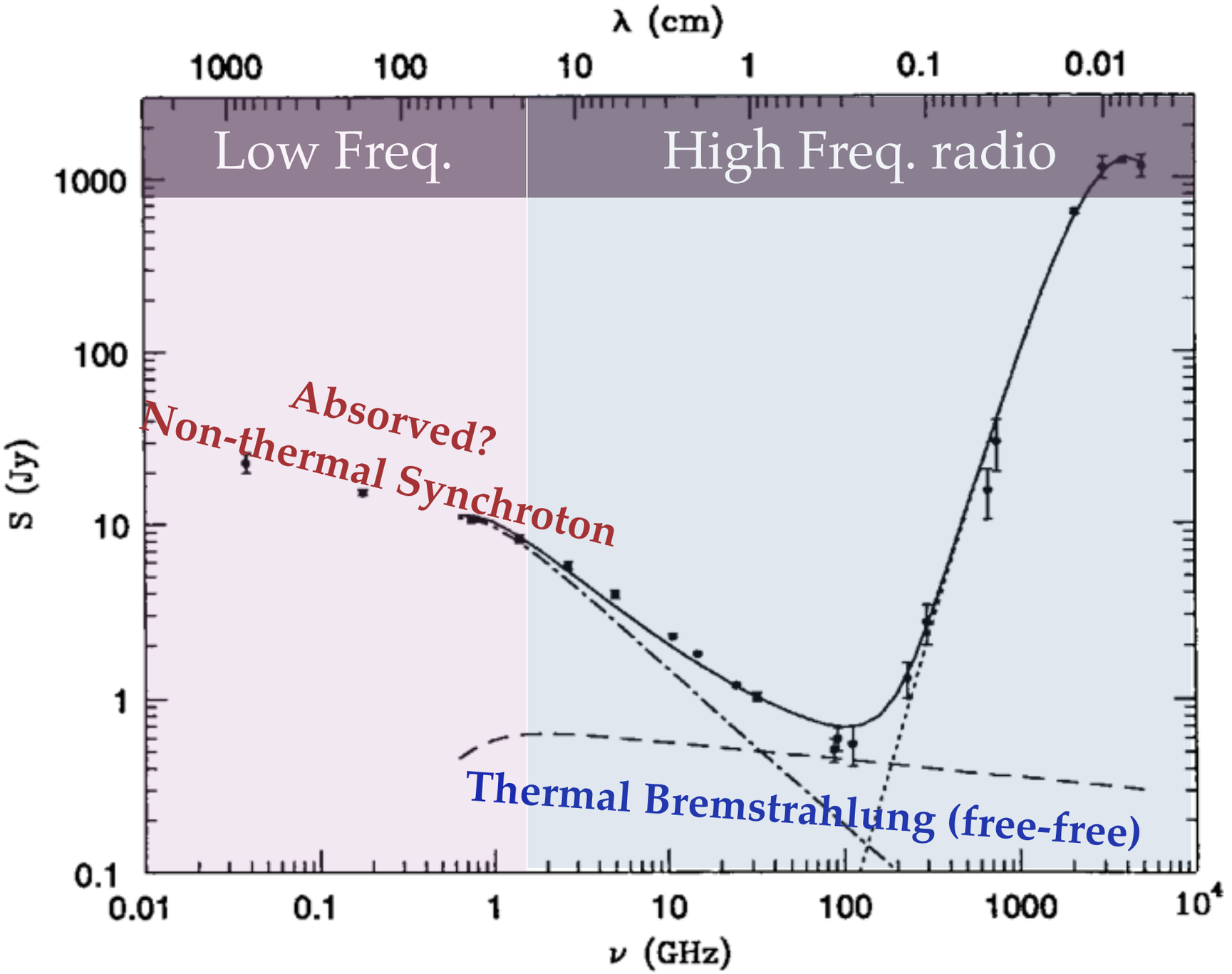
- Radio($\nu < 1$ GHz)
  - Marvil et al. (2014) (74 MHz and 5 GHz)
  - Clemens et al. (2010) (244 - 610 MHz)
  - Israel & Mahoney (1990)



Condon et al 1992

Low-freq radio spectra of galaxies

- Flattening?
- Absorption mechanisms:
  - Free-free absorption from HII regions.
- Ionisation losses



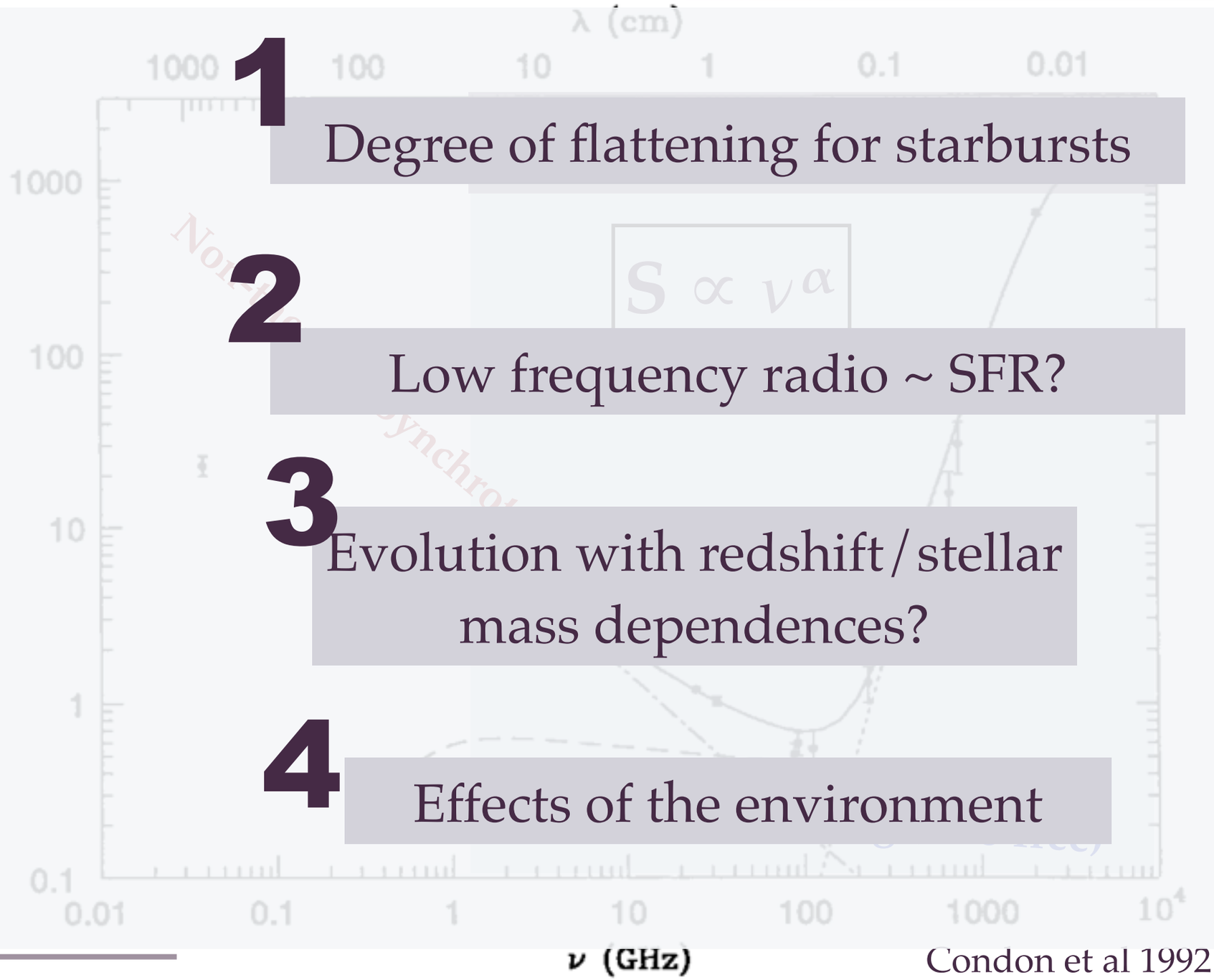
Low-freq radio spectra of galaxies

1 Degree of flattening for starbursts

2 Low frequency radio ~ SFR?

3 Evolution with redshift/stellar mass dependences?

4 Effects of the environment



Condon et al 1992

Low-freq radio spectra of galaxies

- Needed:
  - Large Coverage (statistics)
  - High Sensitivity
  - High Resolution
  - Multiwavelength follow-up

1 Degree of flattening for starbursts

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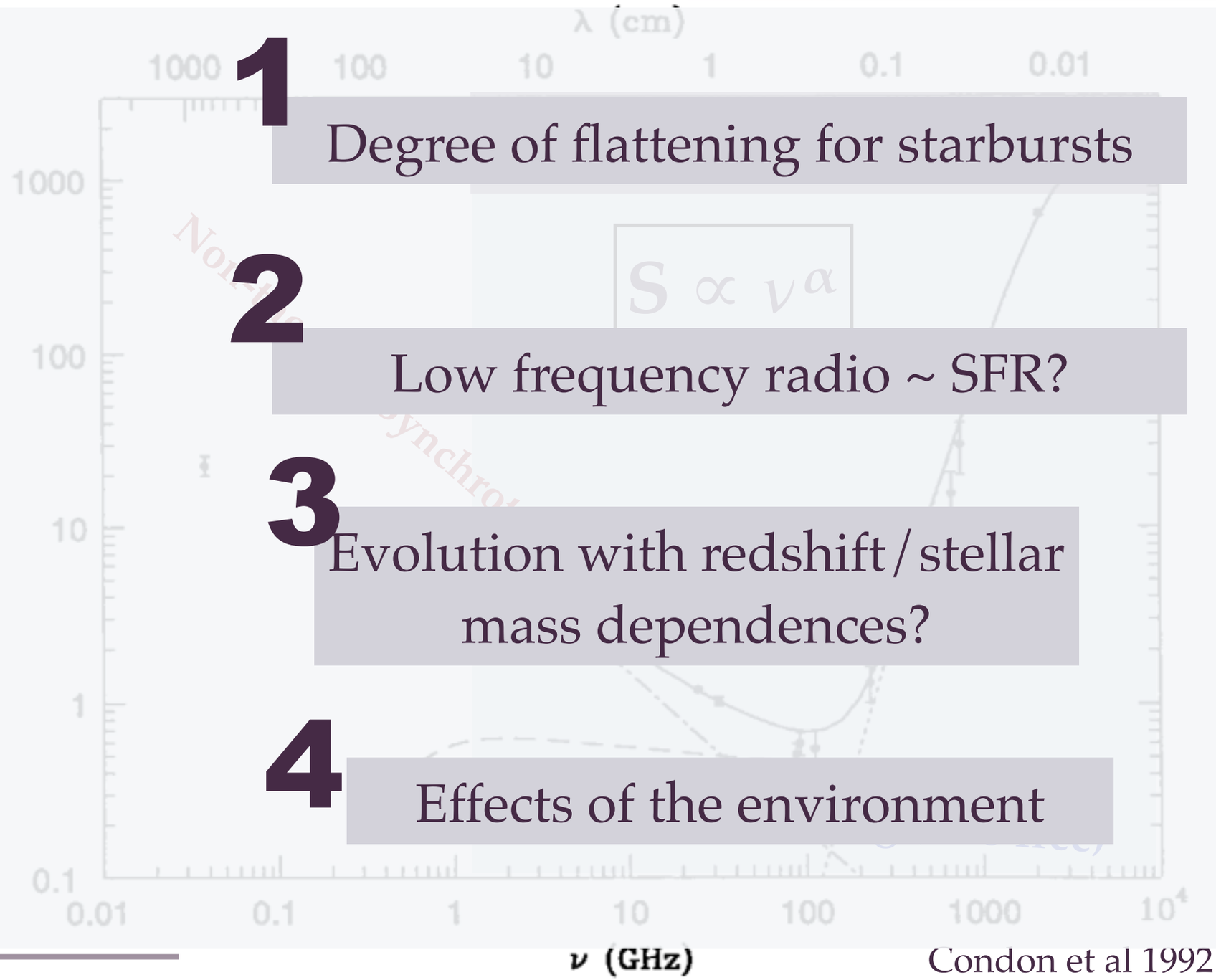

Condon et al 1992

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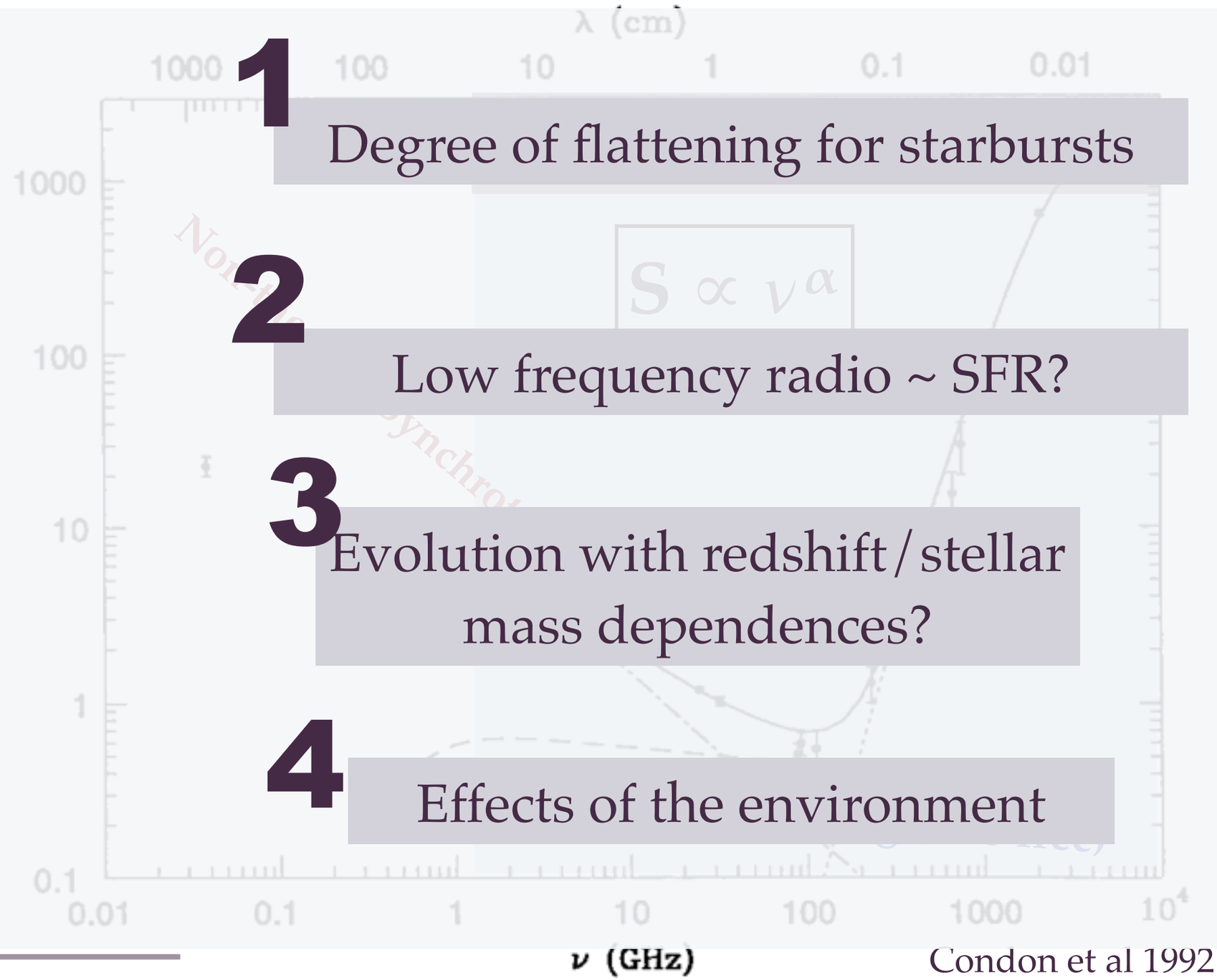


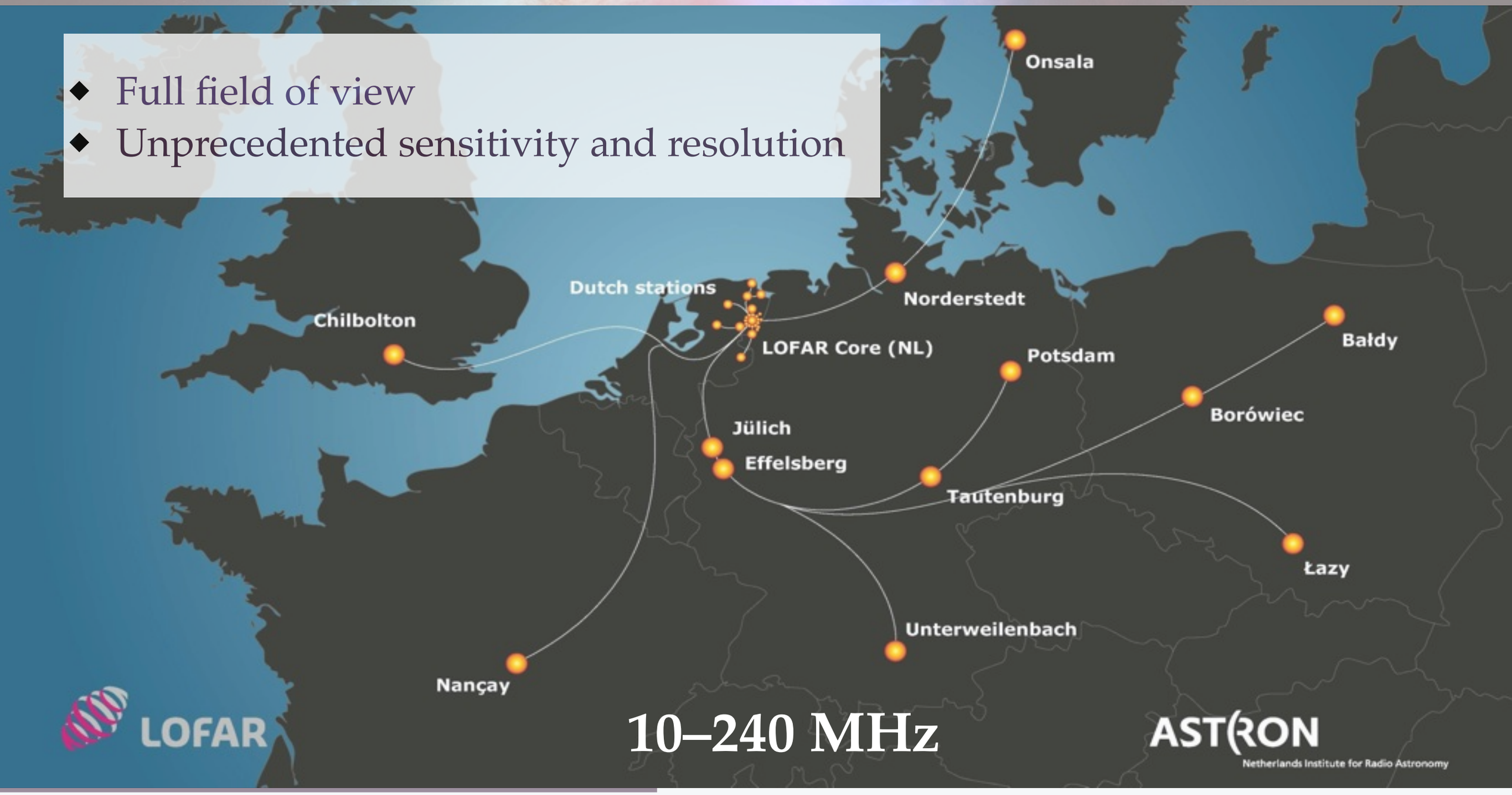
Condon et al 1992

LOFAR Böotes Field

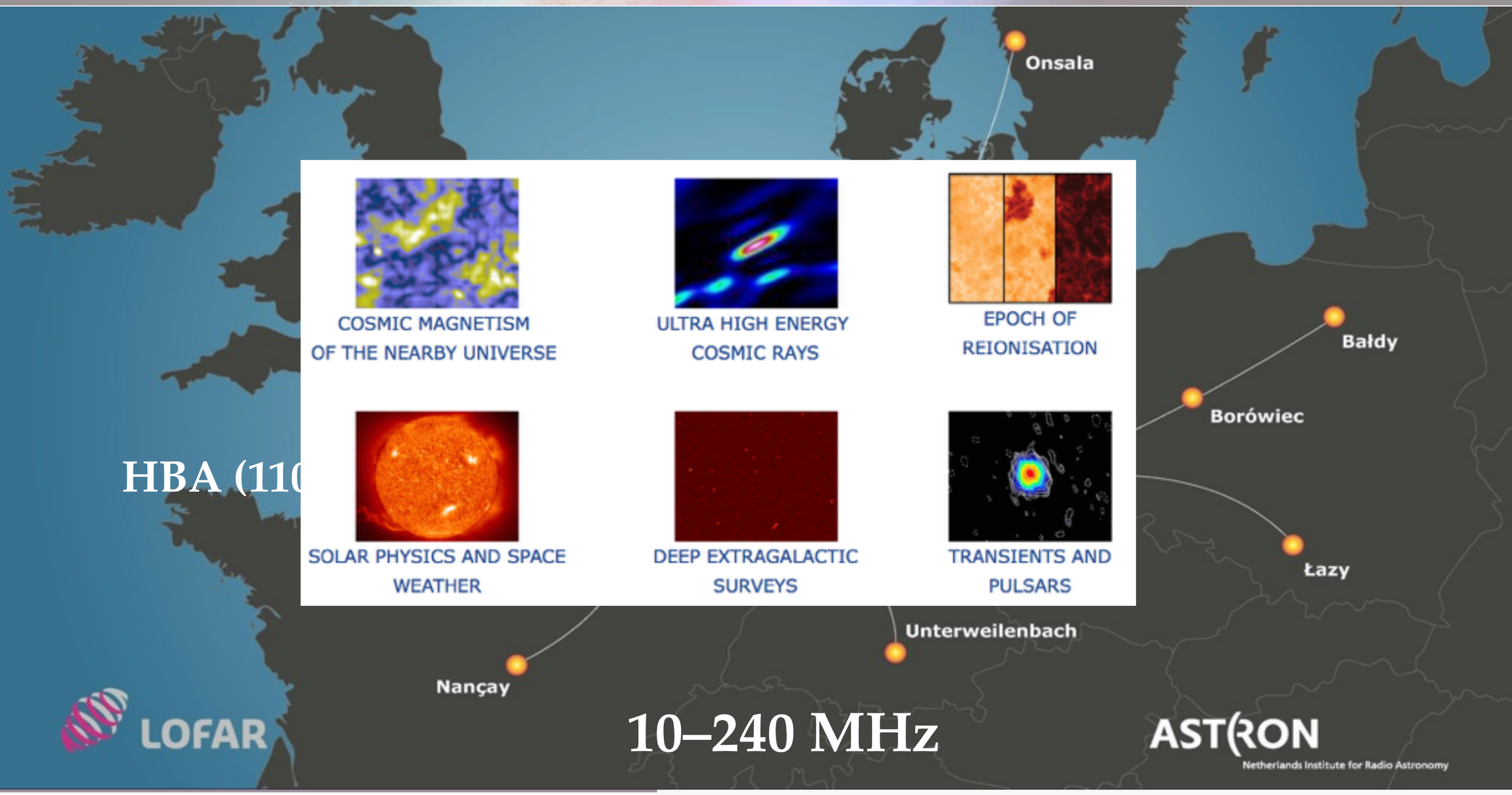
LOw Frequency ARray

LOFAR

- Full field of view
- Unprecedented sensitivity and resolution



Low Frequency Array
LOFAR



COSMIC MAGNETISM
OF THE NEARBY UNIVERSE

ULTRA HIGH ENERGY
COSMIC RAYS

EPOCH OF
REIONISATION

SOLAR PHYSICS AND SPACE
WEATHER

DEEP EXTRAGALACTIC
SURVEYS

TRANSIENTS AND
PULSARS

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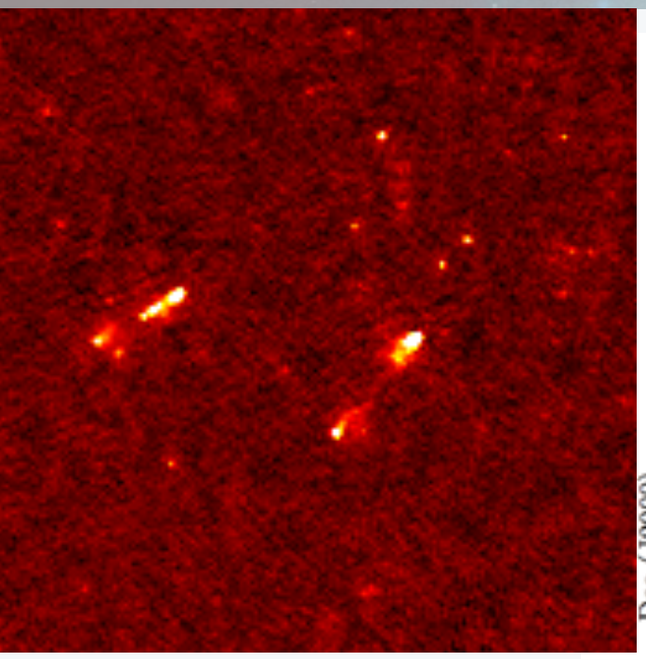
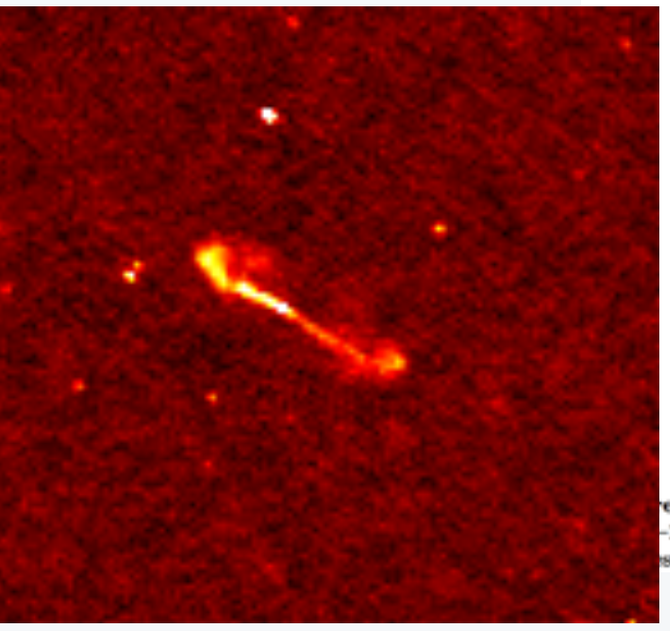
Böotes Field
Low Freq - LOFAR 150

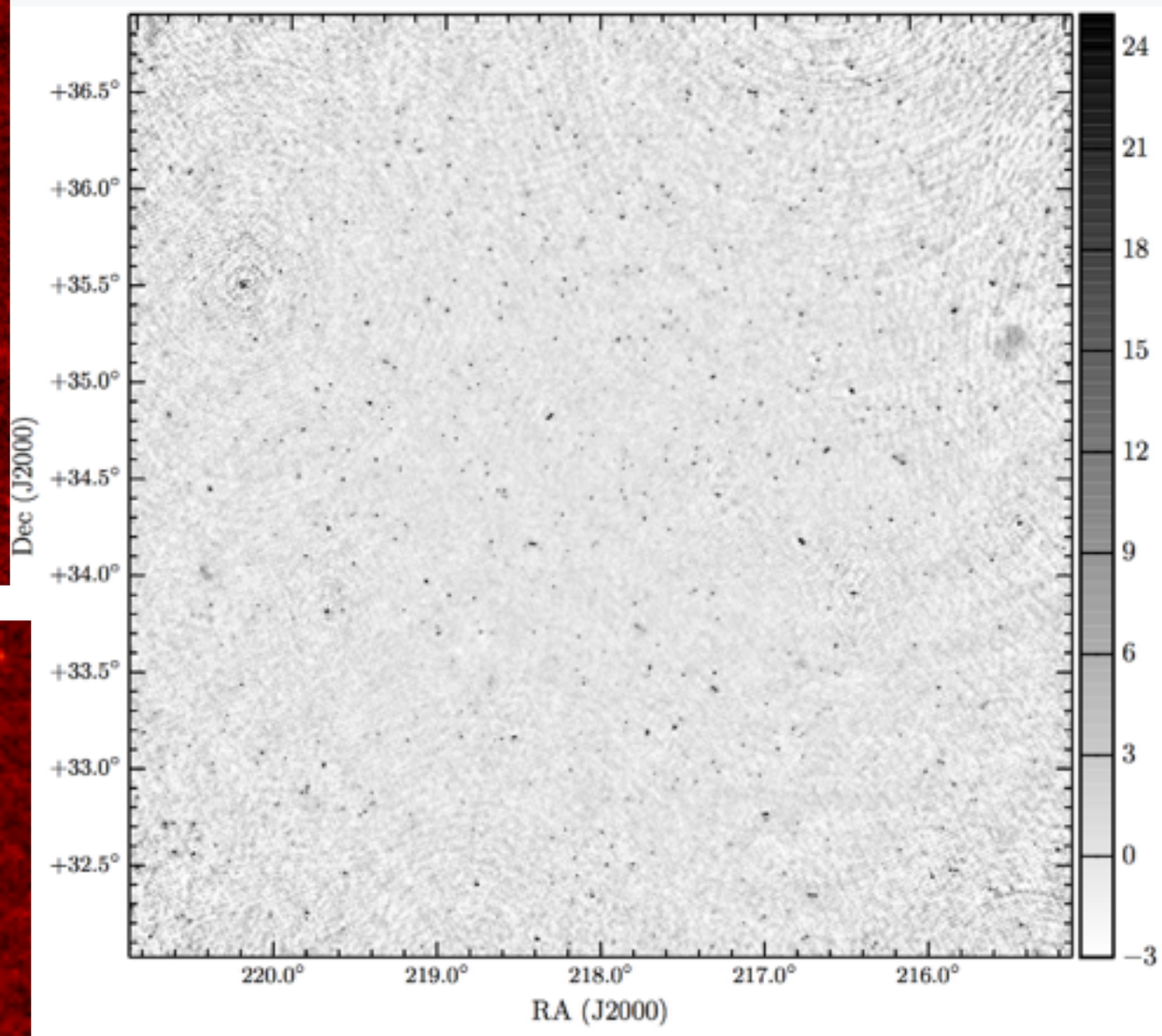
- Coverage: 9.3 deg^2
- **Multiwavelength data**
  - radio: LOFAR, VLAP, WSRT
  - Multiwavelength:
    ~ 10 bands IR, opt, UV
- **Redshifts** Δ (zphot-zspec) = 0.034
  - spec, AGES, EAZY
- **Environments studies**
  - Bootes clusters, protocluster candidates

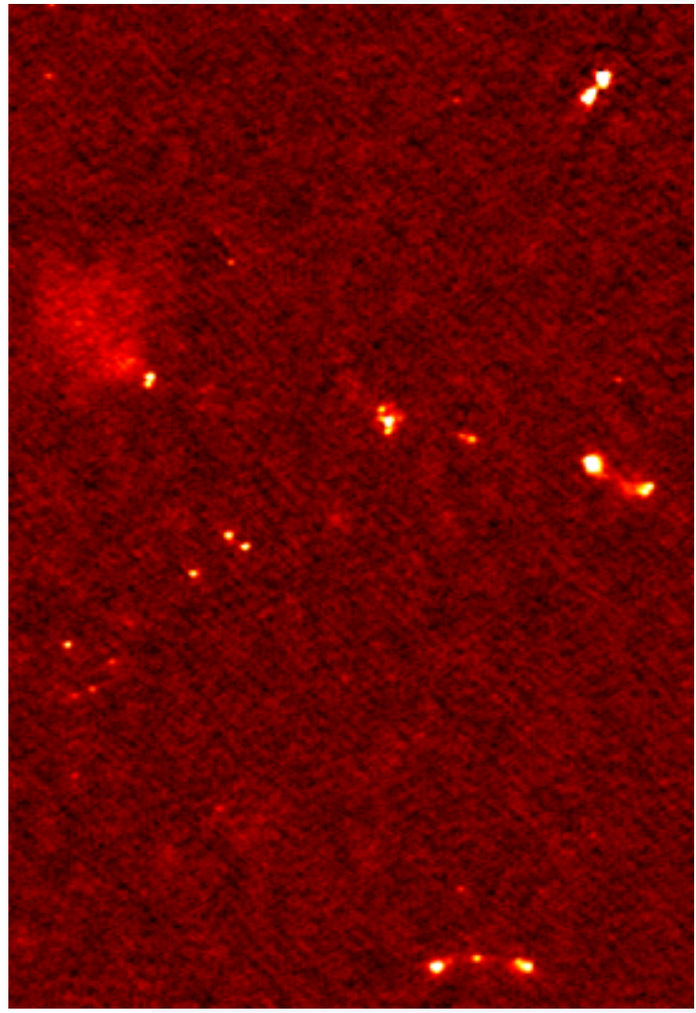
Böotes Field

Low Freq - LOFAR 150 MHz









e 3. Final self-calibrated image for the 10–SB block at *XX* MHz. The resolution is 23 × 20″. The greyscale shows the flux density
-3σ to 25σ where $\sigma = 1\,\mathrm{mJy\,beam^{-1}}$ is the rms noise in the image. Calibration artefacts are clearly visible around the brightest
s as only direction-independent self-calibration has been performed.

Williams et al (in prep)

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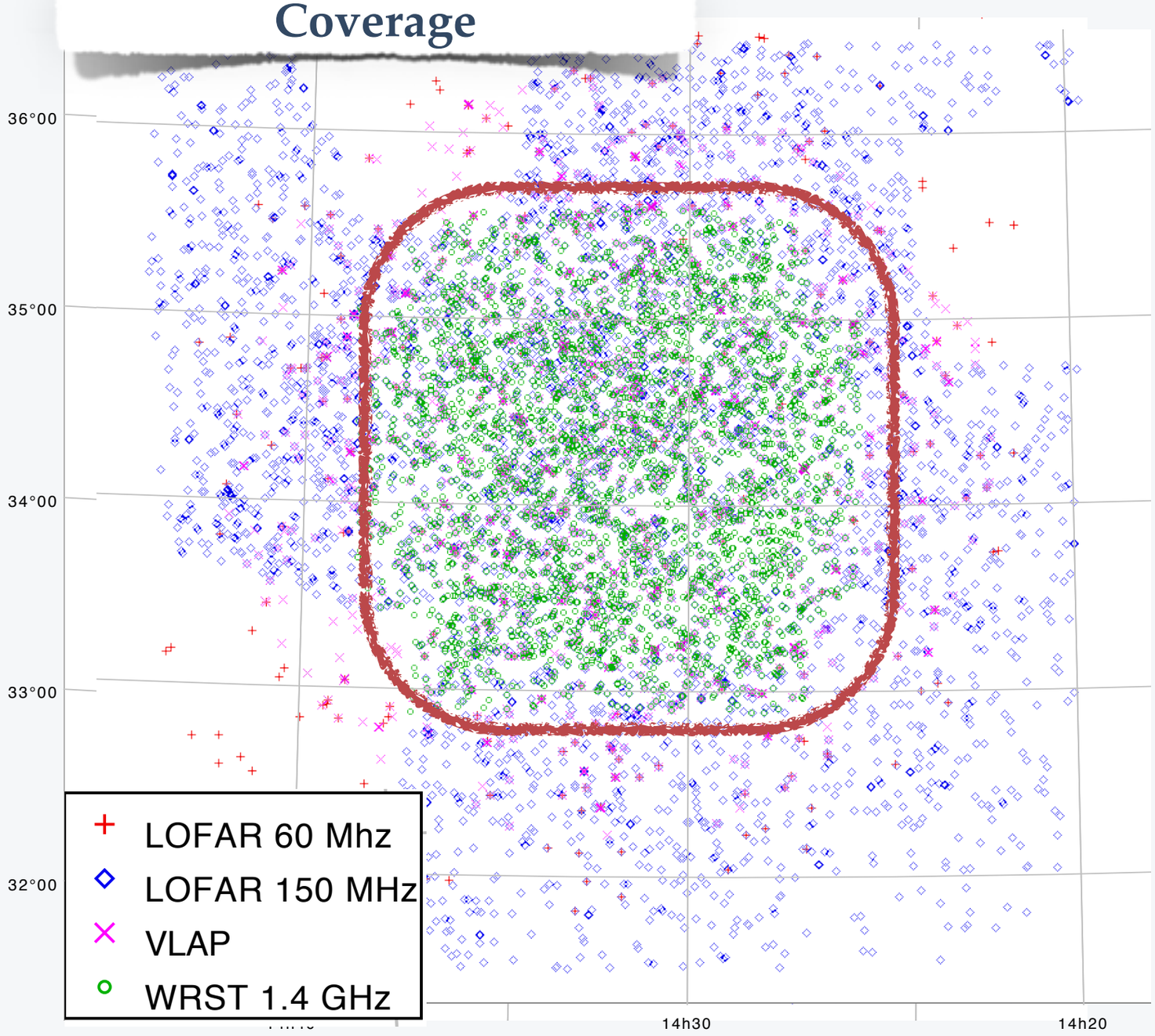
The DEEP Böotes Sample

Böotes Field
WRST - VLA

Coverage



Sensitivity

WSRT rms ~ 28 μJy
(De Vries 2002)
VLAP rms ~ 200 μJy
(Coppejans 2014)

LOFAR 150 rms ~ 135 μJy
(Williams in prep)
LOFAR 60 rms ~ 6 mJy
(Van Weeren 2014)

- 7 deg^2
- Completeness:
  - ~85% of WSRT/VLAP has a LOFAR counterpart
- **~ 464 sources**
- **0 ~ z ~ 2.5** (few above, z<4)

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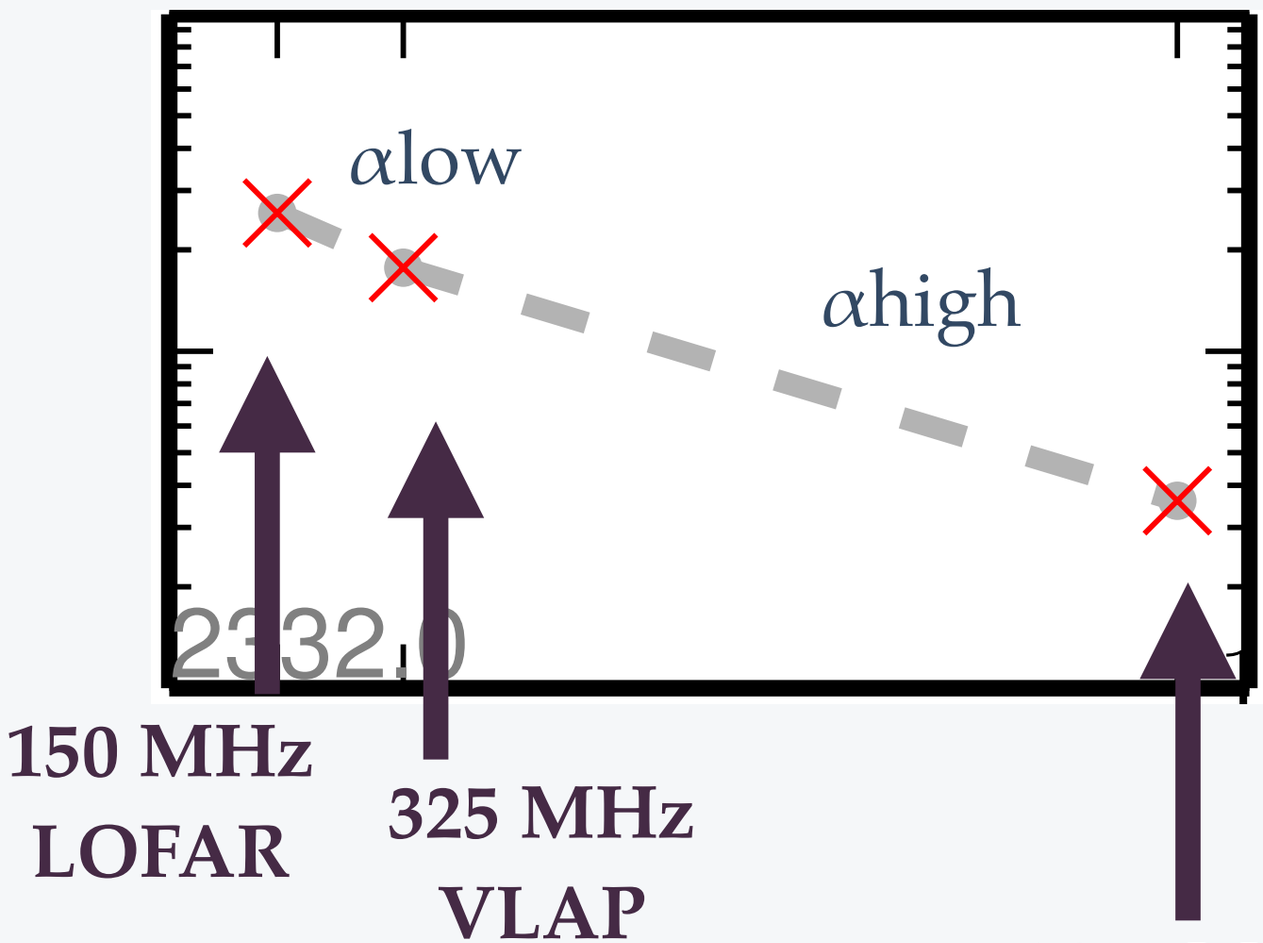
Böotes Field
WRST - VLA



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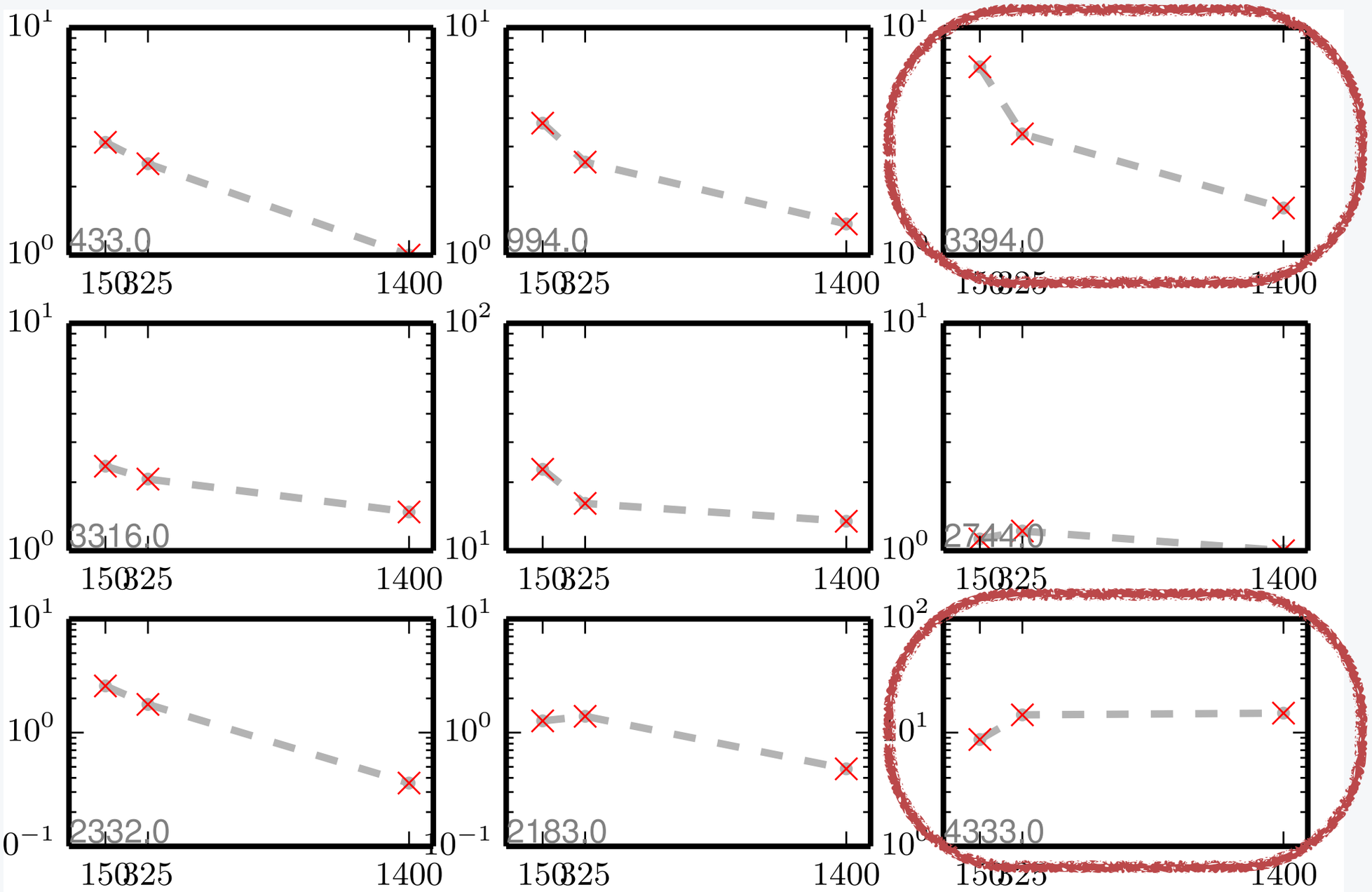
Böotes Field
Radio SEDS

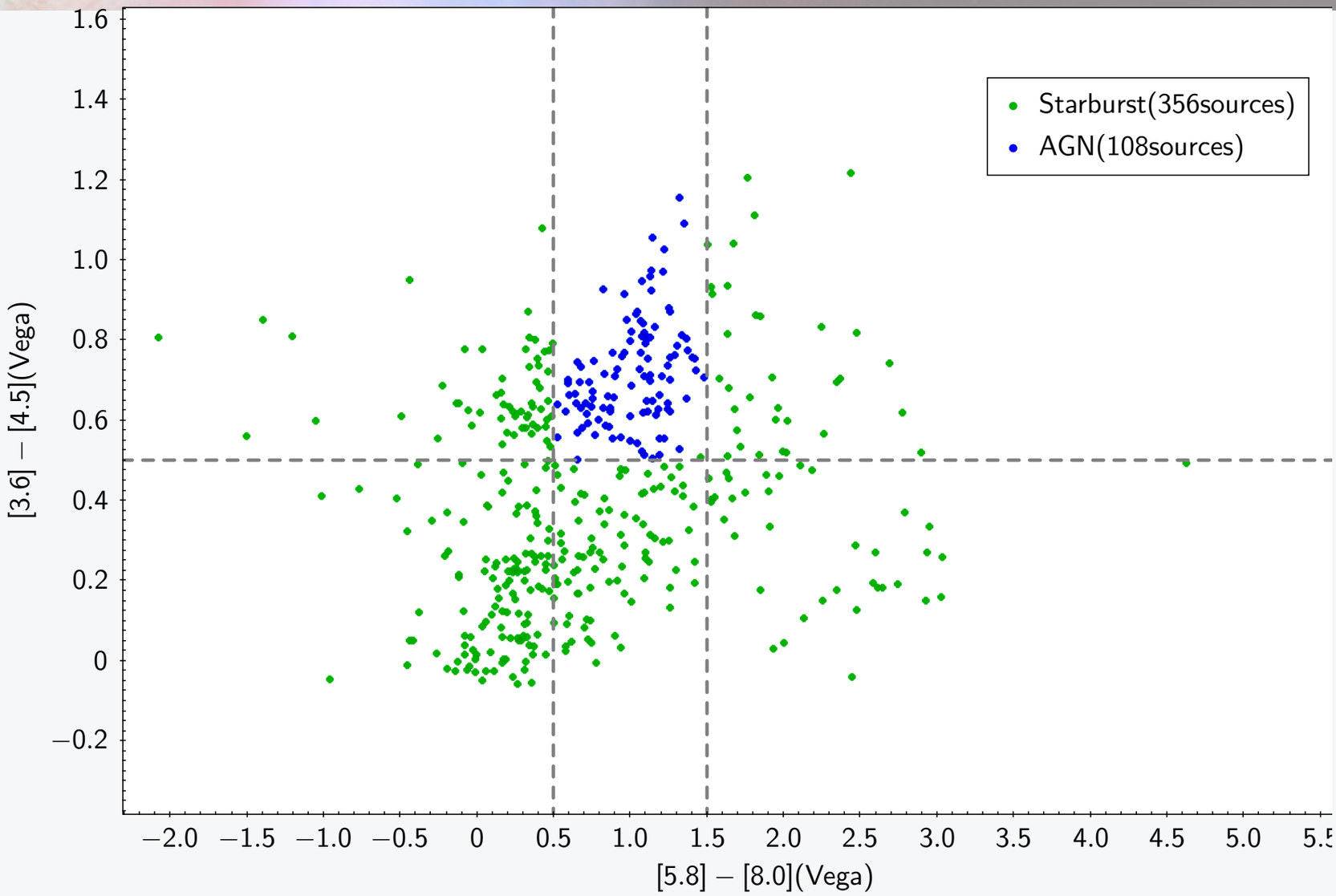


Böotes Field
Starburst Selection

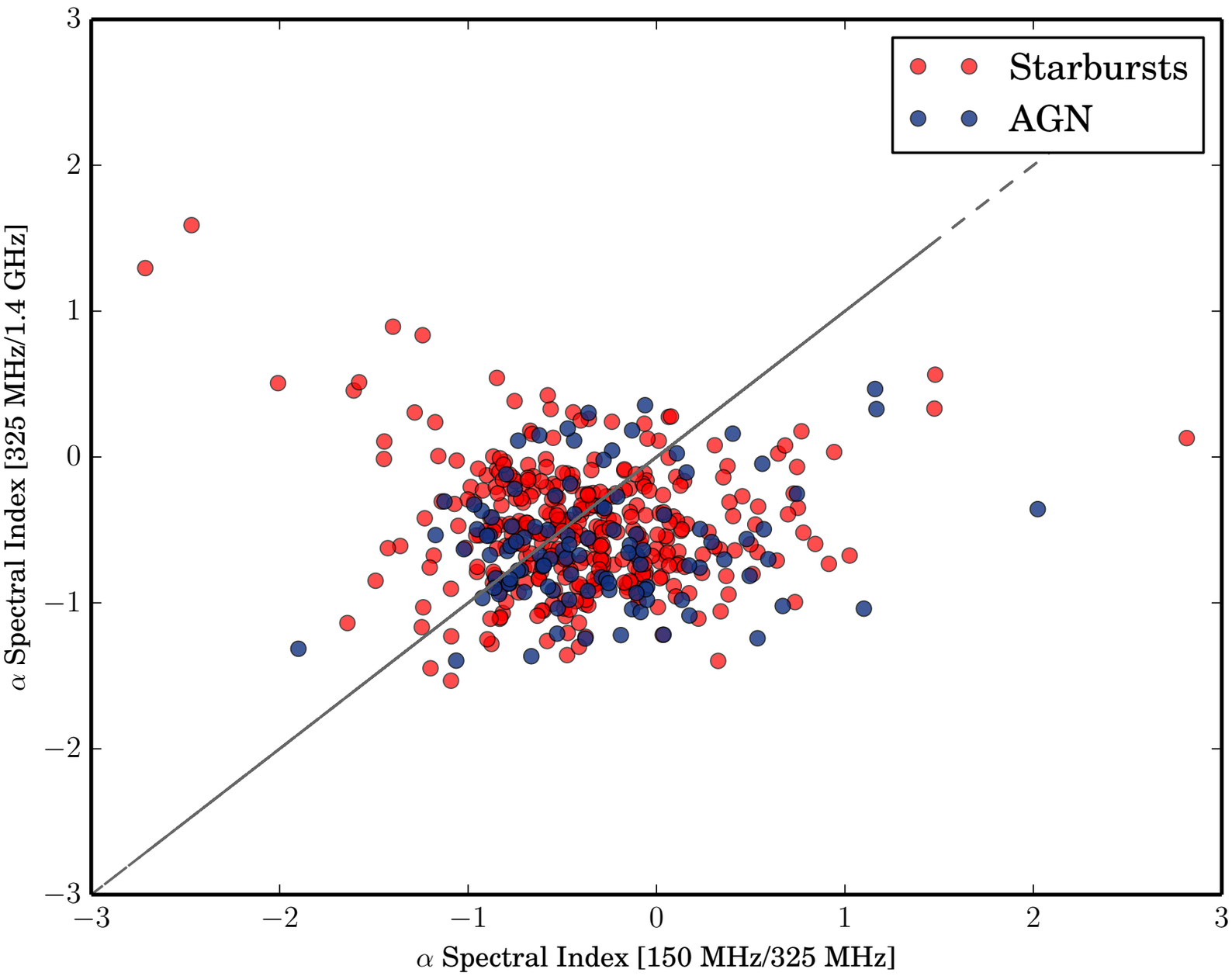
- **MIR selected** starburst.
  Based on IRAC color cuts
  (Stern 2008, Donley 2013)

- Contamination of AGN possible.

- AGN/SB?
  - High resolution morphology study needed



Böotes Field
Spectral Indexes



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Böotes Field
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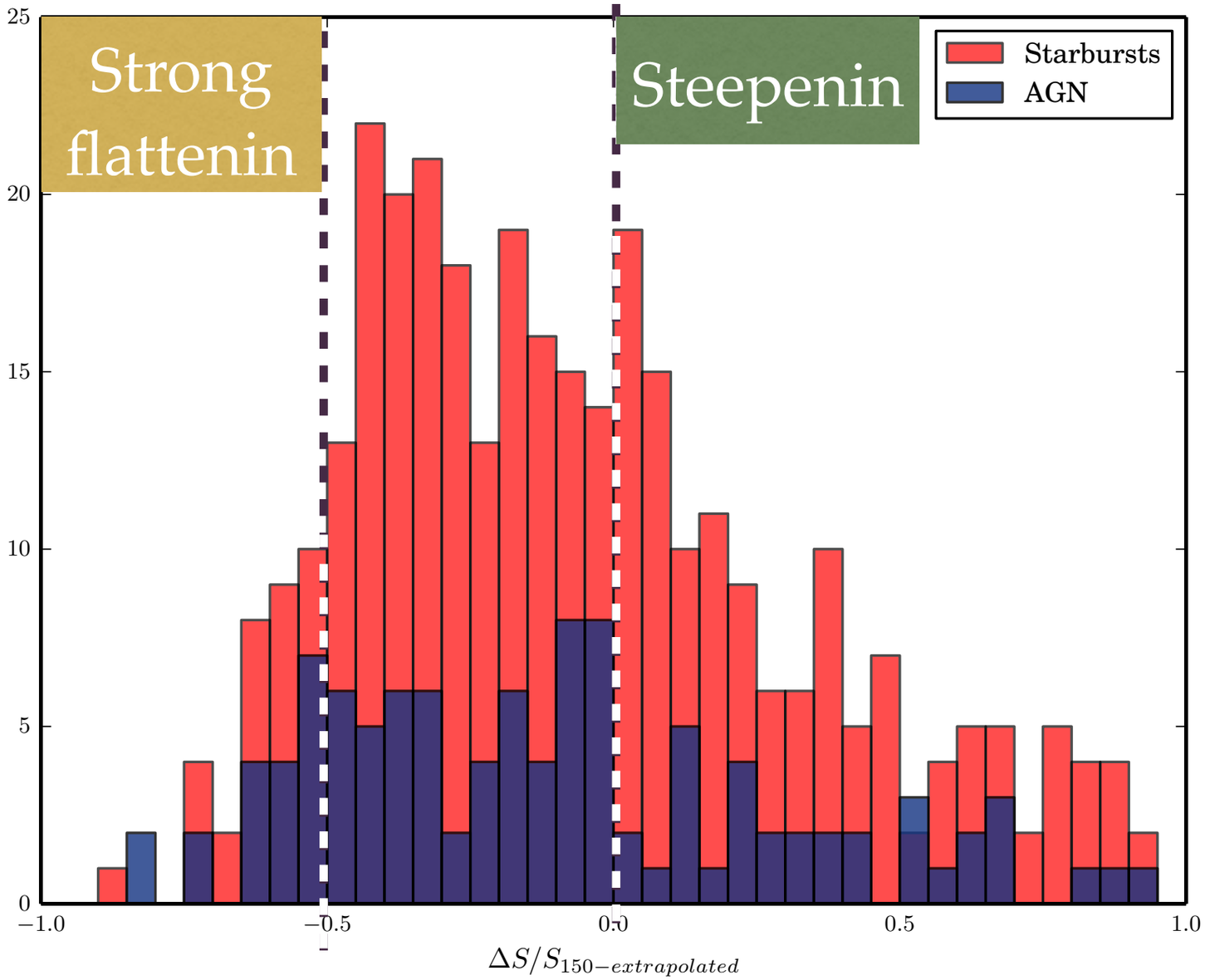
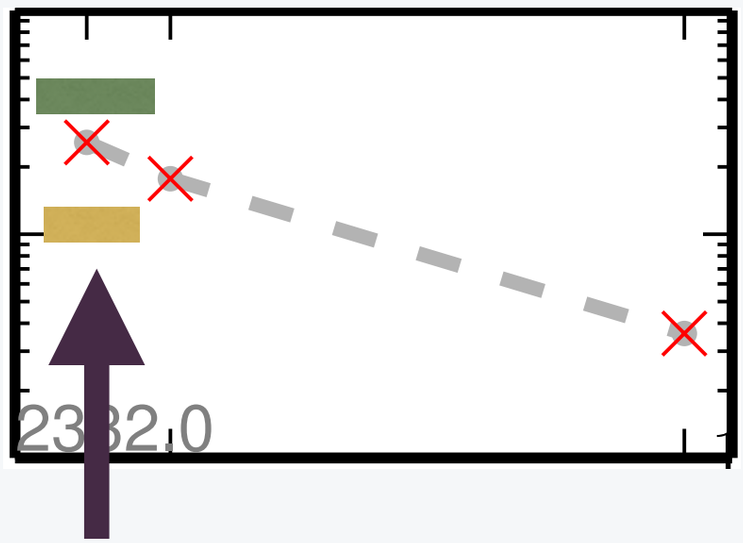


$$\Delta S/S^{extra} \propto \frac{(S^{obs} - S^{extrap})}{S^{extrap}}$$



150 MHz LOFAR

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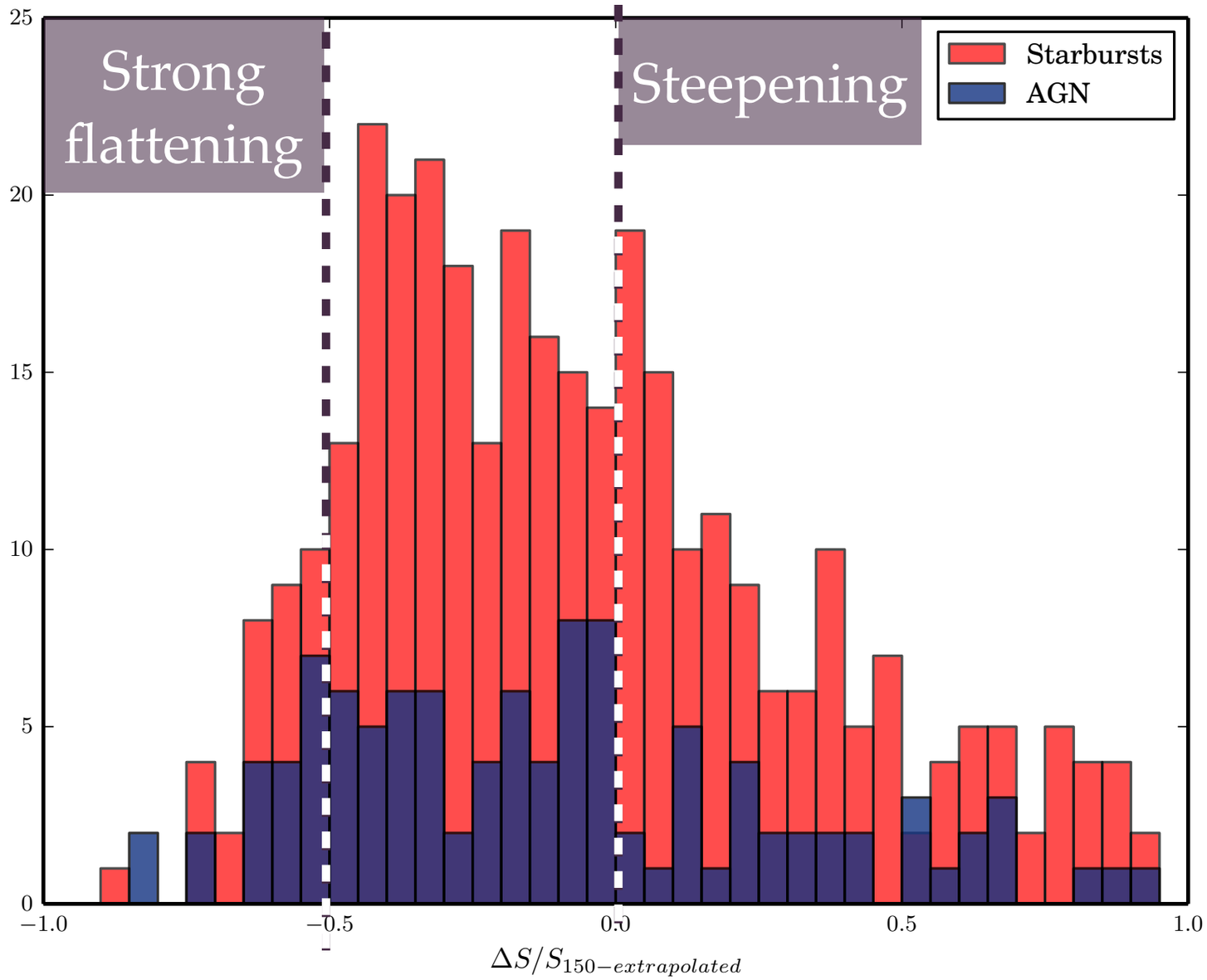
Böotes Field
Spectral Indexes



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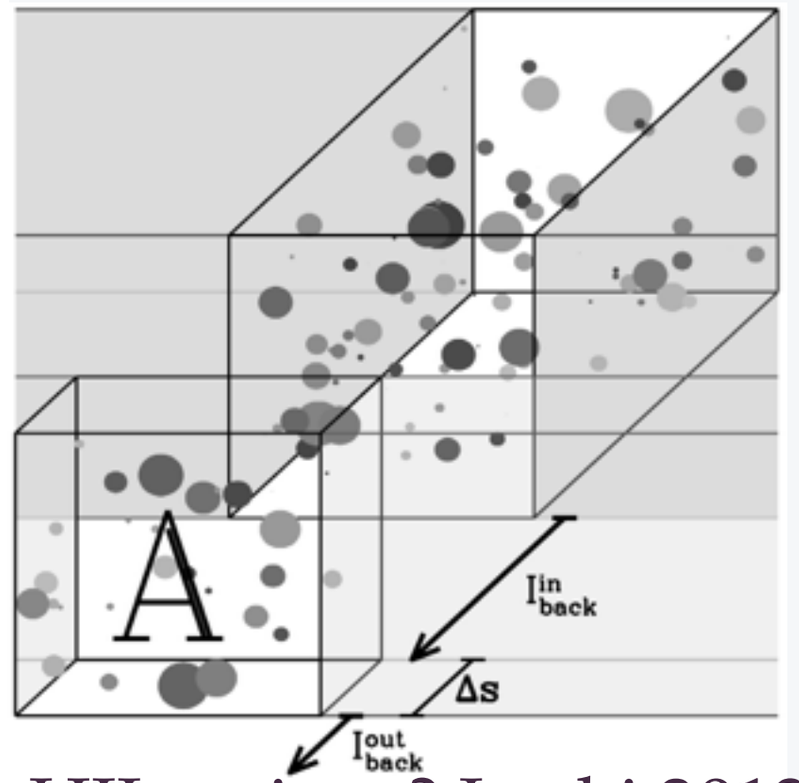

Clumpy HII regions? Lacki 2013

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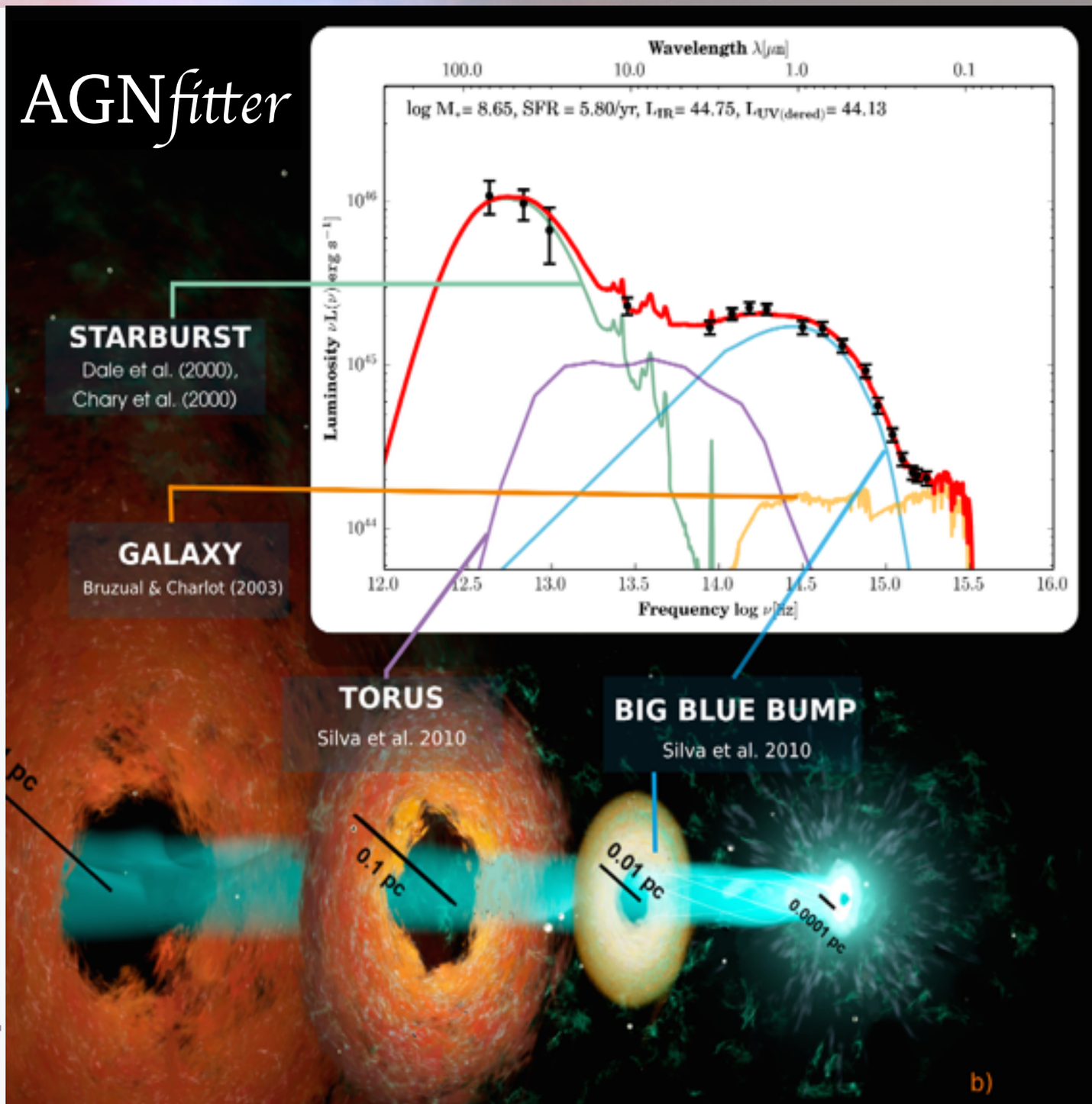
Böotes Field
What is next?

- Multiwavelength study with **AGN***fitter* (SED-fitting tool with MCMC)
  - Stellar Masses calculation
- High resolution morphology study
- Environment studies



CONCLUSIONS

- LOFAR opens the low-frequency window on starburst with unprecedented sensitivity and resolution.

- Böotes field a rich laboratory for variate studies of radio-SFR connection.

- No strong flattening has been observed below ~ 60 MHz.

- Very preliminary -
  stay tuned and suggestions are more than welcome! :)

Thank you for your attention

Böotes Field
Compared to others

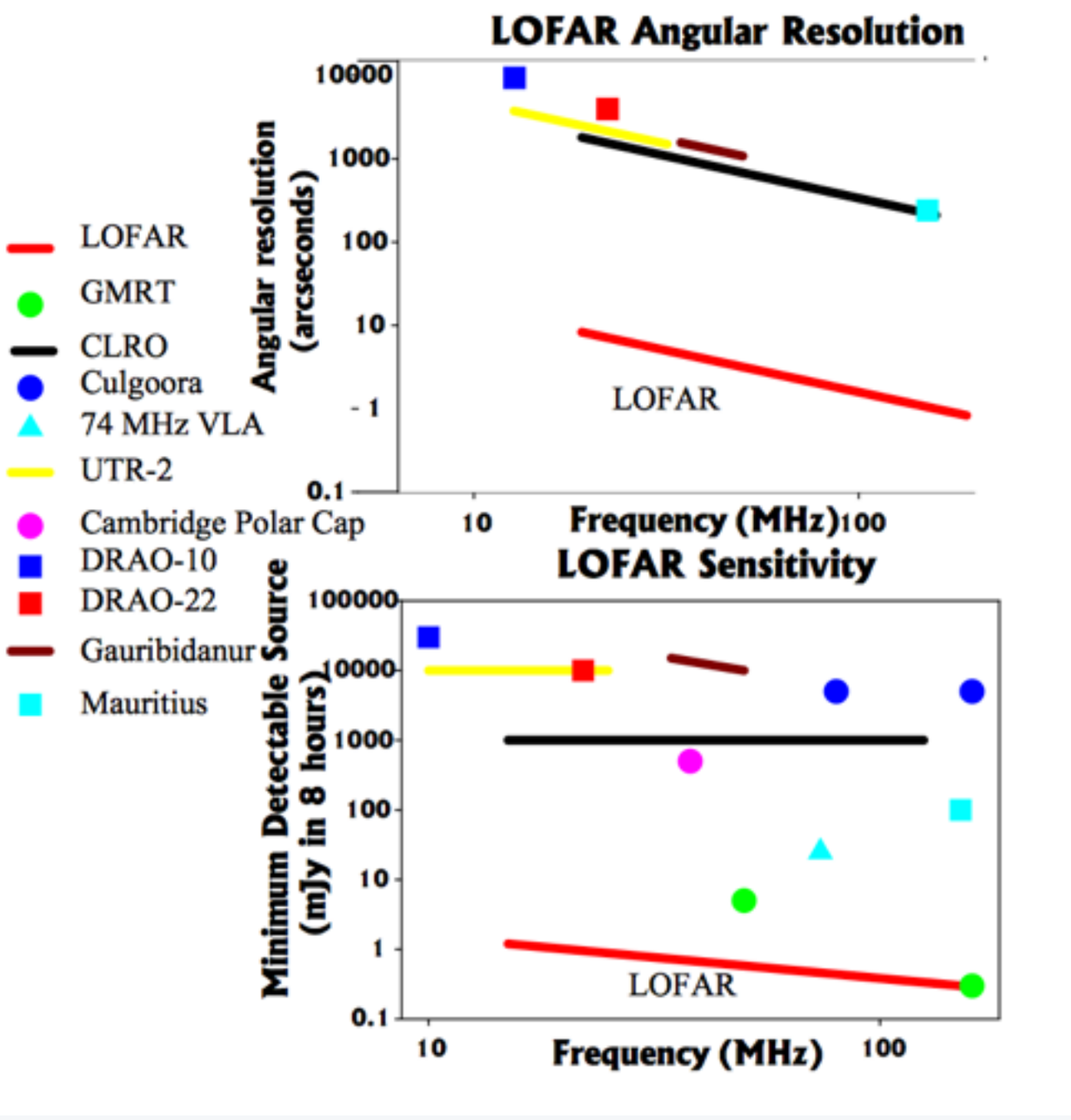


FIG. 6.— Angular Resolution and Sensitivity of LOFAR as compared to other past, present, and proposed imaging instruments in the 10–200 MHz range. The LOFAR sensitivity calculation is based on a λ^2-dependent collecting area assumed to be 10^6 m^2 at 15 MHz. A bandwidth of 3 MHz and integration time of 8 hours have also been assumed. In both panels, in addition to LOFAR, the angular resolution and point-source sensitivity of the CLRO, Culgoora, 74 MHz VLA, UTR2, Cambridge Polar cap survey, DRAO-10 and DRAO-22, Gauribidanur, Mauritius, and GMRT are shown.

Böotes Field

RMS

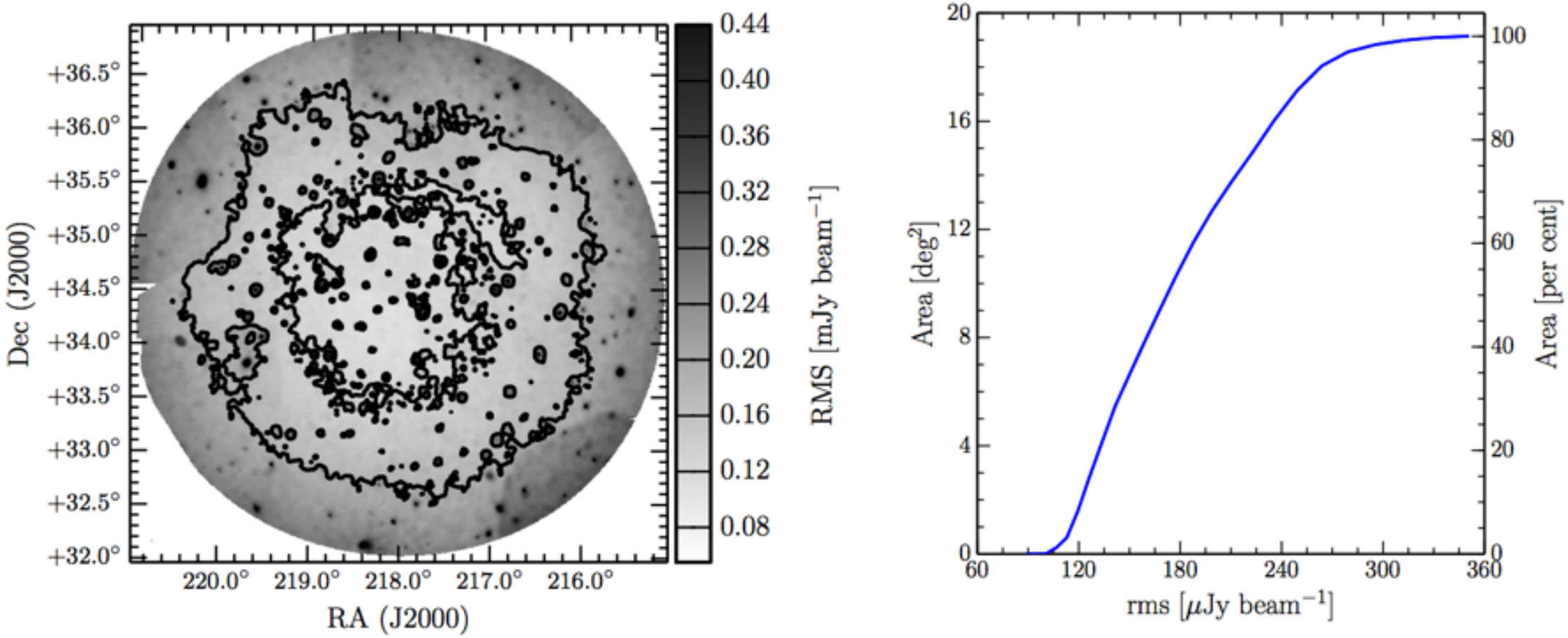


Figure 11. Left: Greyscale map showing the local ***rms*** noise measured in the mosaic image. The greyscale shows the ***rms*** noise from $0.5\sigma_{cen}$ to $4\sigma_{cen}$, where $\sigma_{cen} = 110\,\mu$Jy beam^{-1} is the approximate ***rms*** in the mosaic centre. The contours are plotted at 125μJy beam^{-1} and 175μJy beam^{-1}. Peaks in the local noise coincide with the locations of bright sources. Right: Cumulative area of the map with a measured ***rms*** noise level below the given value.

Böotes Field
Sensitivity

Freq. (MHz)	λ (m)	Sensitivity			
		Superterp (mJy)	NL Core (mJy)	Full NL (mJy)	Full EU (mJy)
15	20.0	...	...	...	...
30	10.0	36	9.0	5.7	3.8
45	6.67	29	7.4	4.7	3.1
60	5.00	25	6.2	3.9	2.6
75	4.00	44	10.8	6.8	4.5
120	2.50	1.5	0.38	0.30	0.20
150	2.00	1.3	0.31	0.24	0.16
180	1.67	1.5	0.38	0.30	0.20
200	1.50	(2.5)	(0.62)	(0.48)	(0.32)
210	1.43	(2.5)	(0.62)	(0.48)	(0.32)
240	1.25	(5.6)	(1.4)	(1.1)	(0.73)

Table 4: *LOFAR sensitivities. The different columns refer to the case of a 6-station Superterp, a 24-station core array, a 40-station Dutch array, and a 48-station full array.*

The values quoted for the HBA in Table 4 agree with empirical values derived from recent observations on 3C196 and the North Celestial Pole (NCP) where all NL remote stations were tapered to match 24-tile core stations. With improved station calibration, these estimates can likely be improved in the future by a factor of about 1.2. For the more compact LOFAR configurations, confusion noise will exceed the quoted values. The quoted sensitivities for the lower LBA frequencies have not yet been achieved in practice

Böotes Field
Resolution

Note: The numbers on the table below are indicative. For example in the NL the maximum baseline of ~82 km is only at a North-South direction. At the east-west direction the resolution is significantly lower; currently the maximum east-west baseline is ~21 km.

		Resolution			
Freq.	λ	$L = 320$ m	$L = 2$ km	$L = 100$ km	$L = 1000$ km
(MHz)	(m)	(arcsec)	(arcsec)	(arcsec)	(arcsec)
15	20.0	10310.00	1650.00	33.00	3.30
30	10.0	5157.00	825.00	16.50	1.65
45	6.67	3438.00	550.00	11.00	1.10
60	5.00	2578.00	412.50	8.25	0.83
75	4.00	2063.00	330.00	6.60	0.66
120	2.50	1289.00	206.30	4.13	0.41
150	2.00	1031.00	165.00	3.30	0.33
180	1.67	859.40	137.50	2.75	0.28
200	1.50	773.50	123.80	2.48	0.25
210	1.43	736.70	117.90	2.36	0.24
240	1.25	644.60	103.10	2.06	0.21

Table 2. *Indicative resolution of the LOFAR array with frequency (see text for details).*