# The nature of the low frequency emission in M51

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# The nature of the low frequency emission of M51

## First observations of a nearby galaxy with LOFAR

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**ABSTRACT**

*Context.* Low-frequency radio continuum observations (< 300 MHz) can provide valuable information on the propagation of low-energy cosmic ray electrons. Nearby spiral galaxies have hardly been studied in this frequency range due to the technical challenges of low frequency radio interferometry. This is now changing with the start of operations of LOFAR.
*Aims.* We aim to study the propagation of low energy cosmic ray electrons in the interarm regions and the extended disk of the face-on spiral galaxy Messier 51. We also search for polarization in M51 and other extragalactic objects.
*Methods.* The grand-design spiral galaxy M51 was observed with the LOFAR High Frequency Antennas (HBA) and imaged in total intensity and polarization. This observation covered the bandwidth between 115 MHz and 175 MHz with 244 subbands and 8 channels each, resulting in 1952 channels. This allowed us to use RM Synthesis to search for polarization.
*Results.* We produced a map of total emission of M51 at the mean frequency of 151 MHz with 20″ resolution and 0.2 mJy rms noise, which is the most sensitive map of a galaxy at frequencies below 300 MHz so far. The spectrum of total radio emission is straight, while flat spectral indices in the central region indicates thermal absorption. We observe the disk to extend out to 16 kpc and a break in the radial profile near the edge of the optical disk. The radial scale lengths in the inner and outer disks are larger at 151 MHz, and the break is smoother at 151 MHz than that observed at 1.4 GHz. The arm–interarm contrast is smaller at 151 MHz than at 1400 MHz, indicating propagation of cosmic ray electrons (CRE) from spiral arms into interarm regions. The correlations between the maps of radio emission at 151 MHz and 1400 MHz and the far-infrared emission at 70 $\mu$m reveal breaks at scales of 1.4 and 0.7 kpc, respectively, consistent with CRE diffusion. The total (equipartition) magnetic field strength decreases from about 30 $\mu$G in the central region to about 5 $\mu$G at 10 kpc radius. – No significant polarization was detected for M51, due to severe Faraday depolarization. Six extragalactic sources are detected in polarization in the M51 field of $4.1° \times 4.1°$ size. Two sources show a multiple structure.
*Conclusions.* Our main results, the scale lengths of the inner and outer disks at 151 MHz and 1.4 GHz, arm – interarm contrast and the break scales of the radio –far-infrared correlations, can consistently be explained by CRE diffusion, leading to a longer propagation length of CRE with lower energy. The distribution of CRE sources steepens at about 10 kpc radius, where the star formation rate also decreases sharply. We find evidence that thermal absorption is primarily caused by HII regions. The non-detection of polarization from M51 at 151 MHz is consistent with the estimates of Faraday depolarization. Future search for polarized emission in this frequency range should concentrate on regions with small density of thermal electrons and weak magnetic fields.

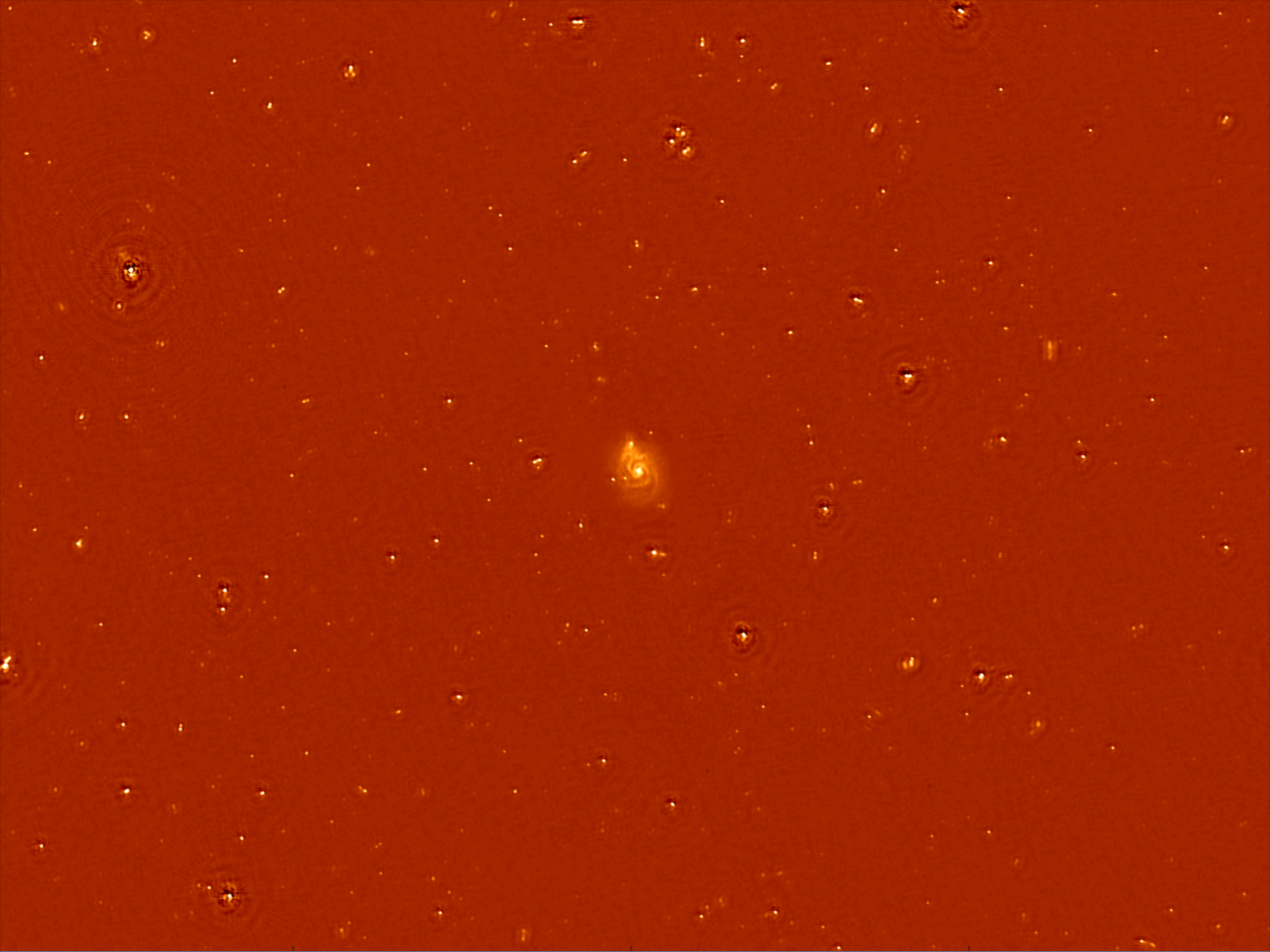
**Key words.** Polarization – ISM: cosmic rays – galaxies: individual: M51 – galaxies: ISM – galaxies: magnetic fields – radio continuum: galaxies

# Overview

- Observations and data reduction
- Presenting M51 at 151 MHz
- CRE propagation in M51
- Thermal absorption
- Polarization in the M51 field

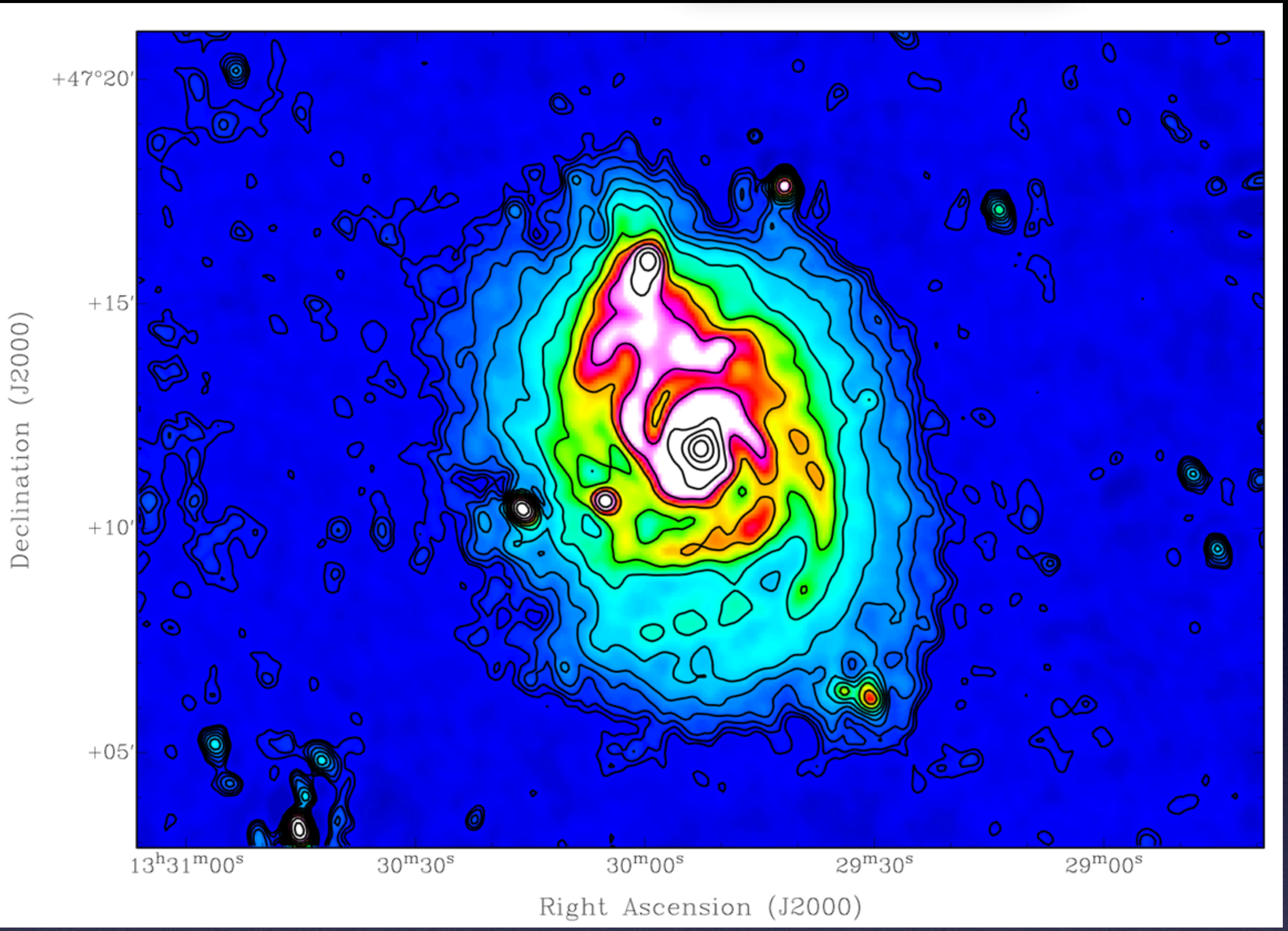
# Observations and Data Reduction

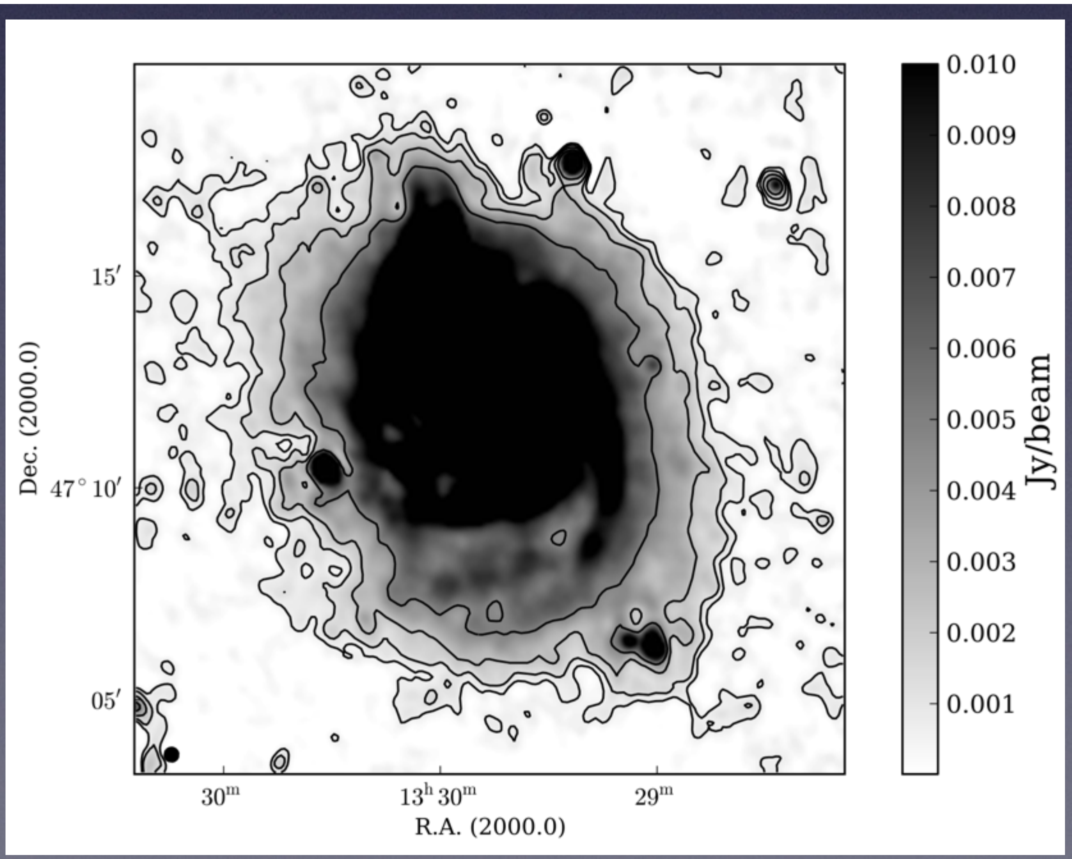
- Dual beam 8 hour observation of M51 and 3C295 took place in cycle 0.
- Transfer of gain amplitudes found from 3C295 to M51 performed. No interpolation done.
- Target subbands were grouped into blocks of 30 subands and then phased calibrated.
- Self cal was then performed.



# M51 at 151 MHz

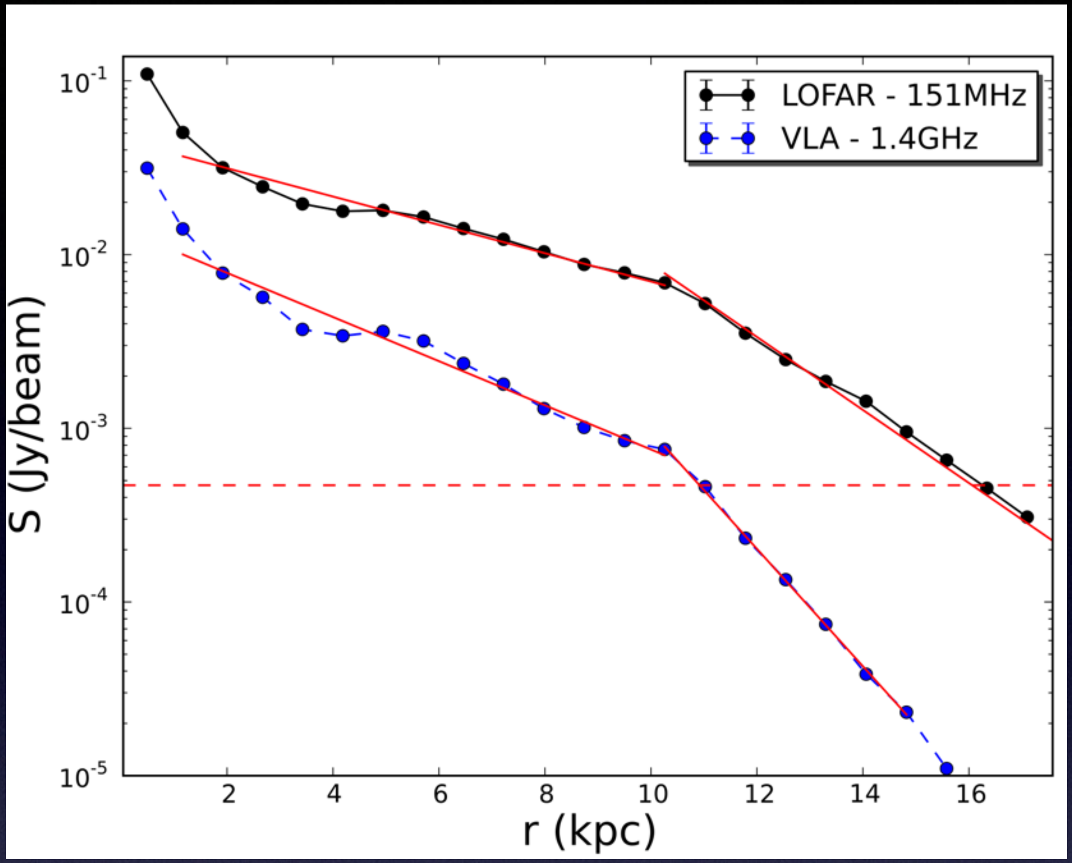
- Noise is found to be 300-400 microJy/beam near galaxy.
- Deepest image so far of any galaxy in low frequency regime.
- Able to detect the disk out to 16 kpc.
- Largest extent of M51 detected in radio continuum.



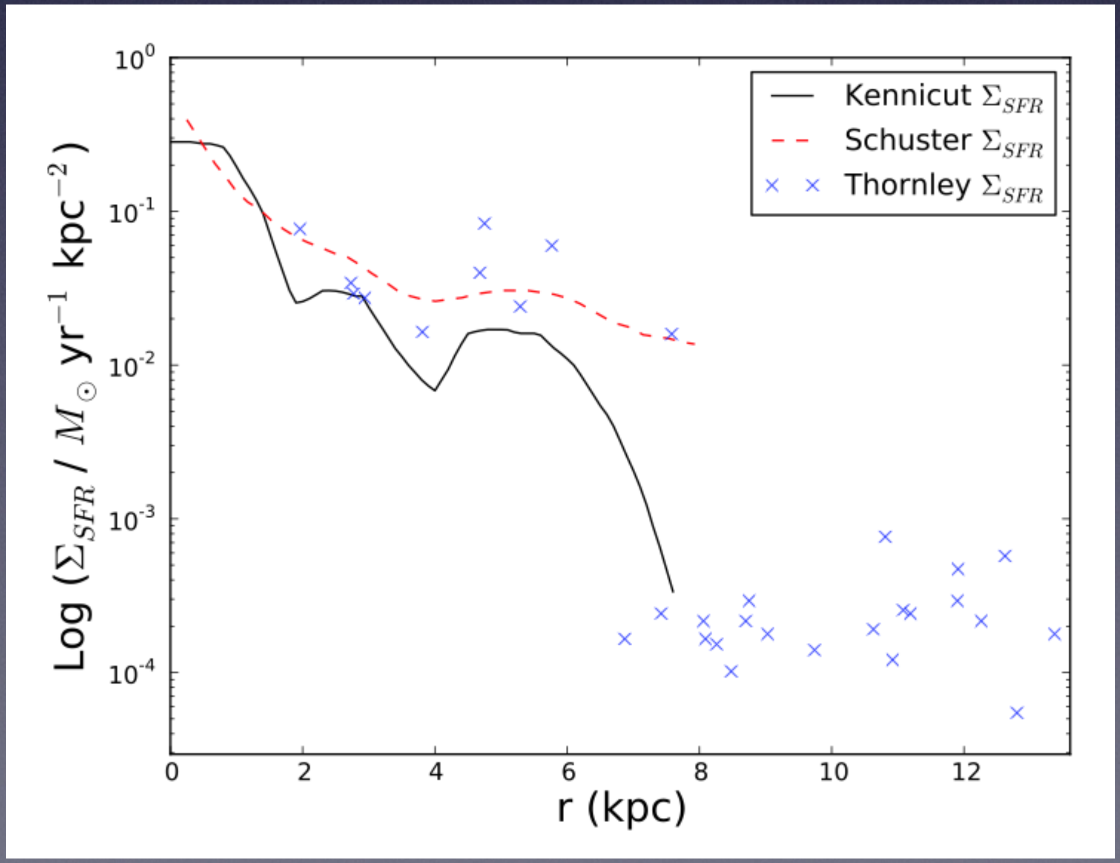



- In M51 we observe a break in the radial profile at approximately 10 kpc.
- The break becomes smoother with decreasing frequency.
- Therefore, detecting the extreme outer disk becomes more difficult than envisioned.

Radial profile of M51 at 1.4 GHz & 151 MHz




Radial profile of star formation rate



# Cosmic Ray Propagation in the star forming disk

Diffusion model

$$l_{\mathrm{dif}} \propto B_{\mathrm{tot}}^{-3/4}\, \nu^{-1/4}$$

Streaming instability model

$$l_{\mathrm{stream}} = v_{\mathrm{A}}\, t_{\mathrm{CRE}} \propto B_{\mathrm{tot}}^{-1/2}\, \nu^{-1/2}$$

- Diffusion model predicts a ratio of propagation length of 1/1.75 between 1.4 GHz and 151 MHz.
- Streaming model predicts a ratio of propagation length of 1/3.04

## Scale lengths used

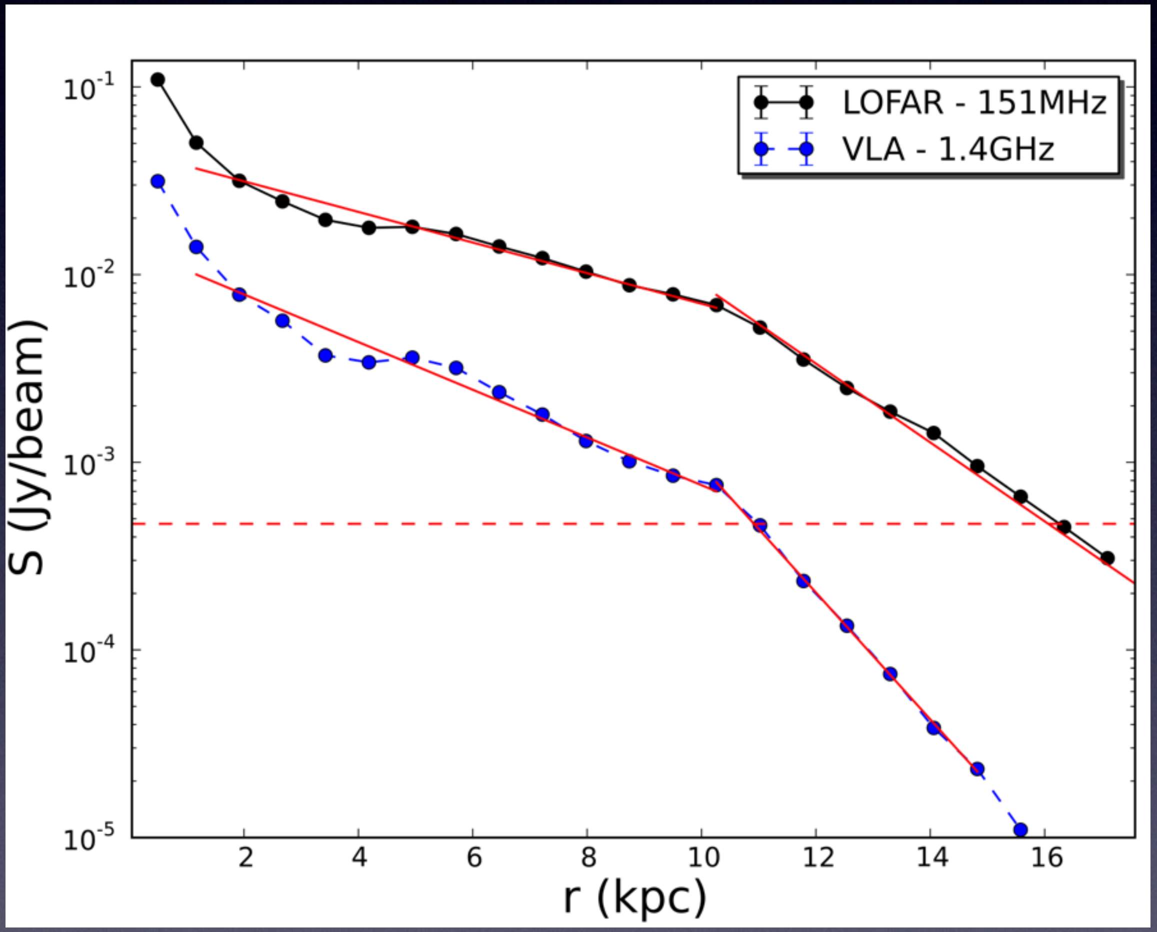
$$I(R) = \begin{cases} I_0\, exp(-r/l_{\rm inner}) & {\rm r} \le 10\,{\rm kpc} \\ I_{10}\, exp(-r/l_{\rm outer}) & {\rm r} \ge 10\,{\rm kpc}. \end{cases}$$

## Scale lengths found

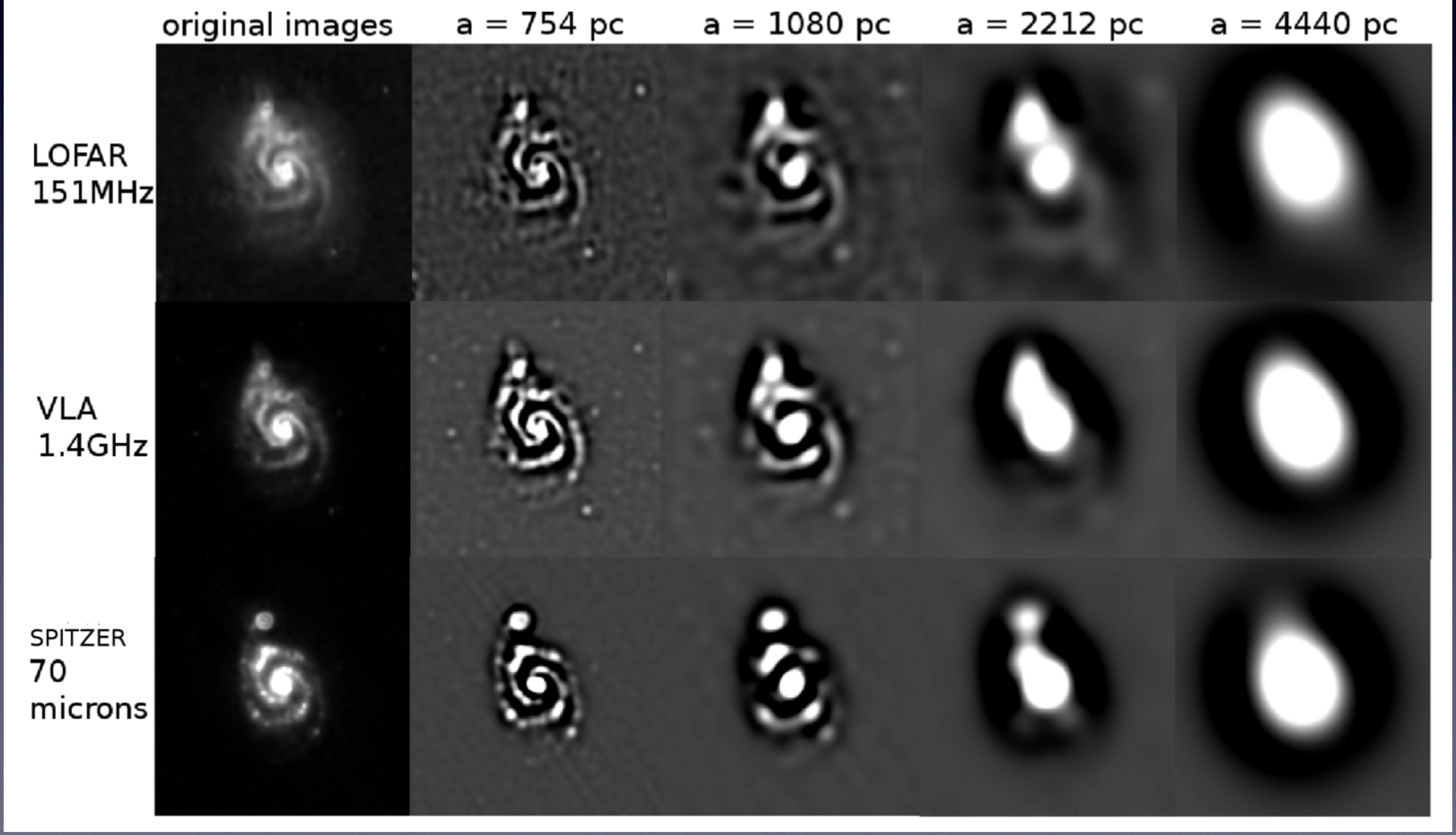
| $\nu$ (MHz) | $l_{inner}$ (kpc) | $l_{outer}$ (kpc) |
|---|---|---|
| 1400 | 3.4 ± 0.2 | 1.28 ± 0.02 |
| 151 | 5.32 ± 0.4 | 2.06 ± 0.06 |
| HI * | 5.5 | 2.1 |

* derived from Bigiel et al. (2010)

- Scale lengths in the inner and outer disks are larger at 151 MHz than at 1.4 GHz by a factor of 1.6+/- 0.1.
- Supports diffusion model.

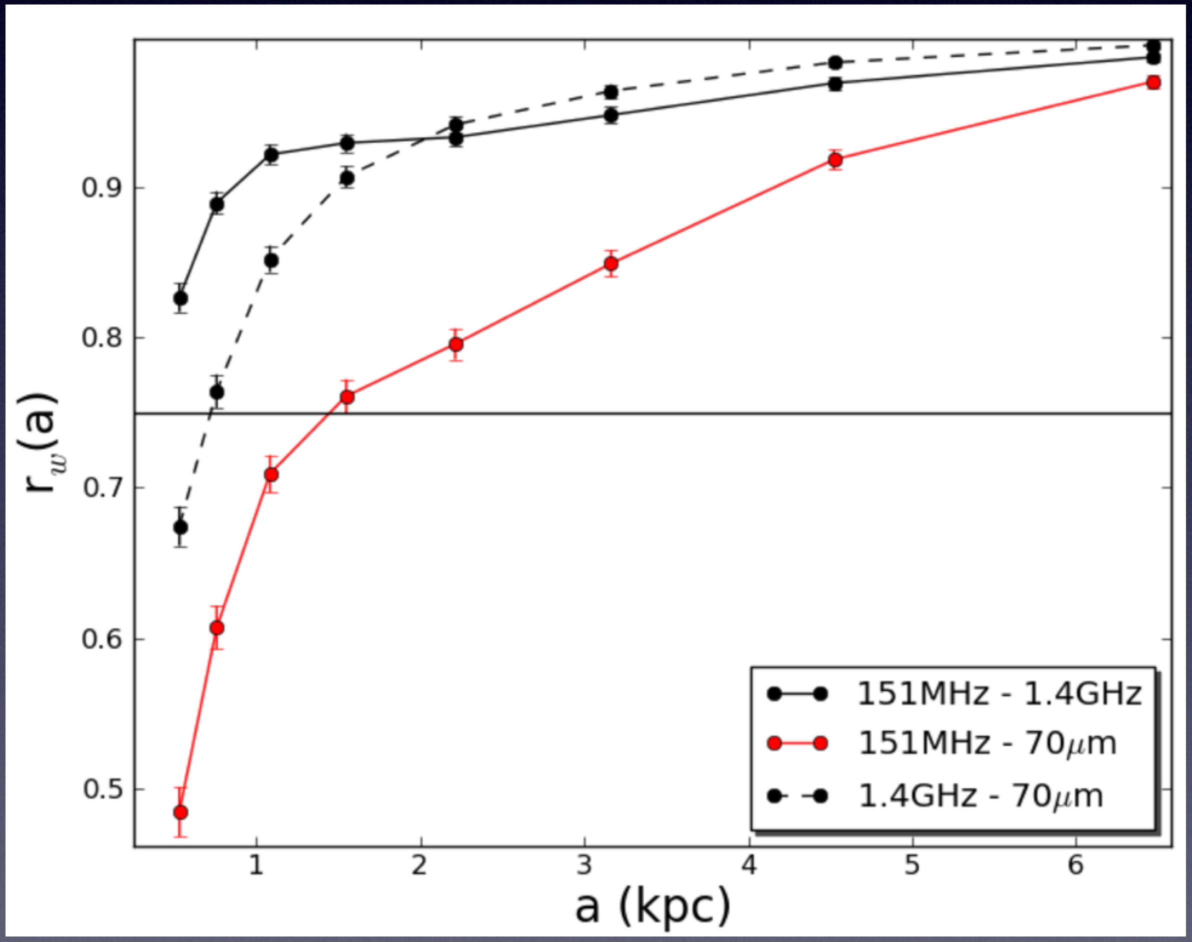


# Wavelet cross-correlation and CRE propagation length



# Wavelet cross-correlation and CRE propagation length

- Break scale of 0.75, is reached for a cross correlation spectrum between radio synchrotron and far-infrared emission is taken as a measure of the diffusion length ($l_{dif}$).
- $l_{dif}$ between Far-IR and 1.4 GHz is 720 pc.
- $l_{dif}$ between Far-IR and 151 MHz is 1.45 kpc.
- Again, ratio of propagation lengths of 2.0 is consistent with diffusive CRE propagation.



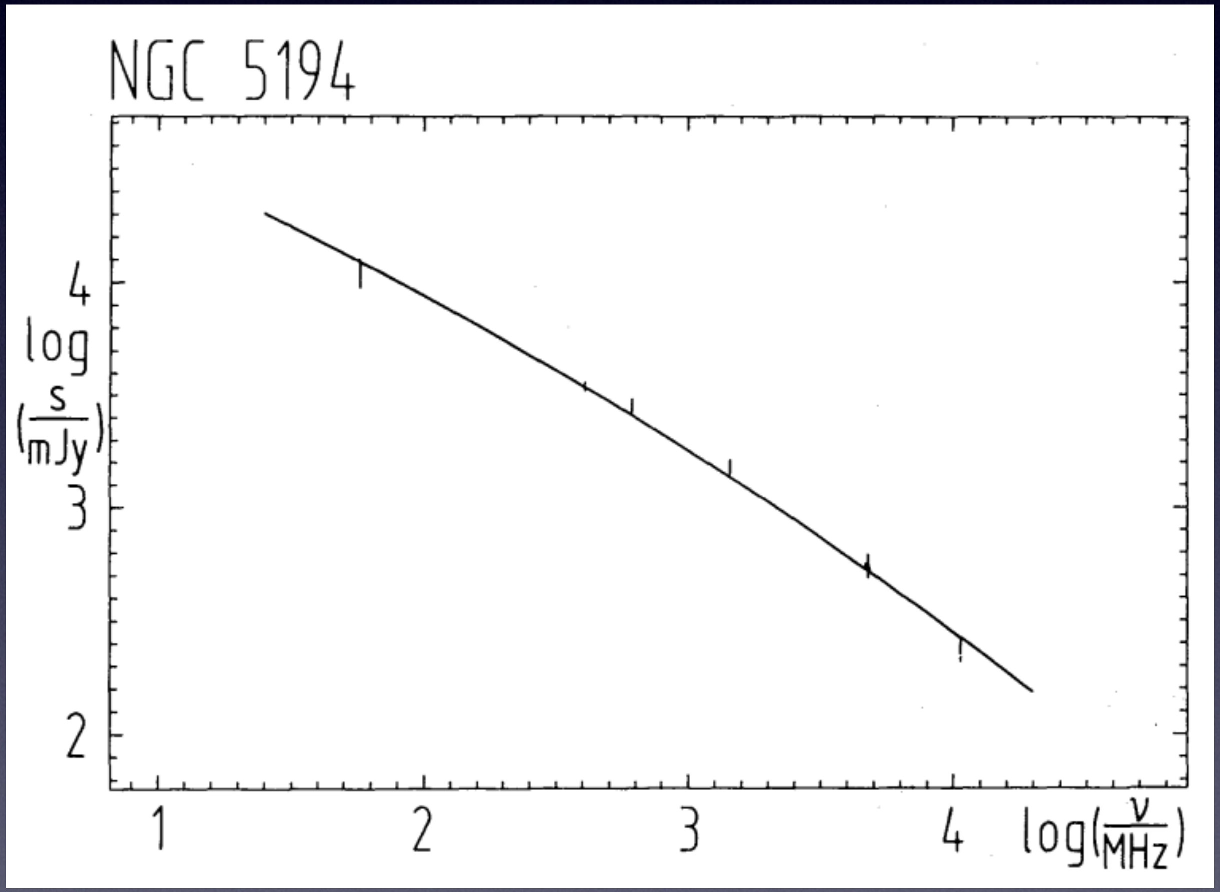
# Thermal absorption in M51

# Integrated Spectrum of Spiral Galaxies

- Israel & Mahoney (1990) observed nearby galaxies at 57.5 MHz and found a flattening of the integrated spectrum at low frequencies.
- Found flattening greatest with increasing inclination of galaxy.
- Interpreted as thermal absorption, by a clumpy medium of low electron temperature. No such medium has been observed in our own Galaxy.

# Another interpretation for the low frequency flattening

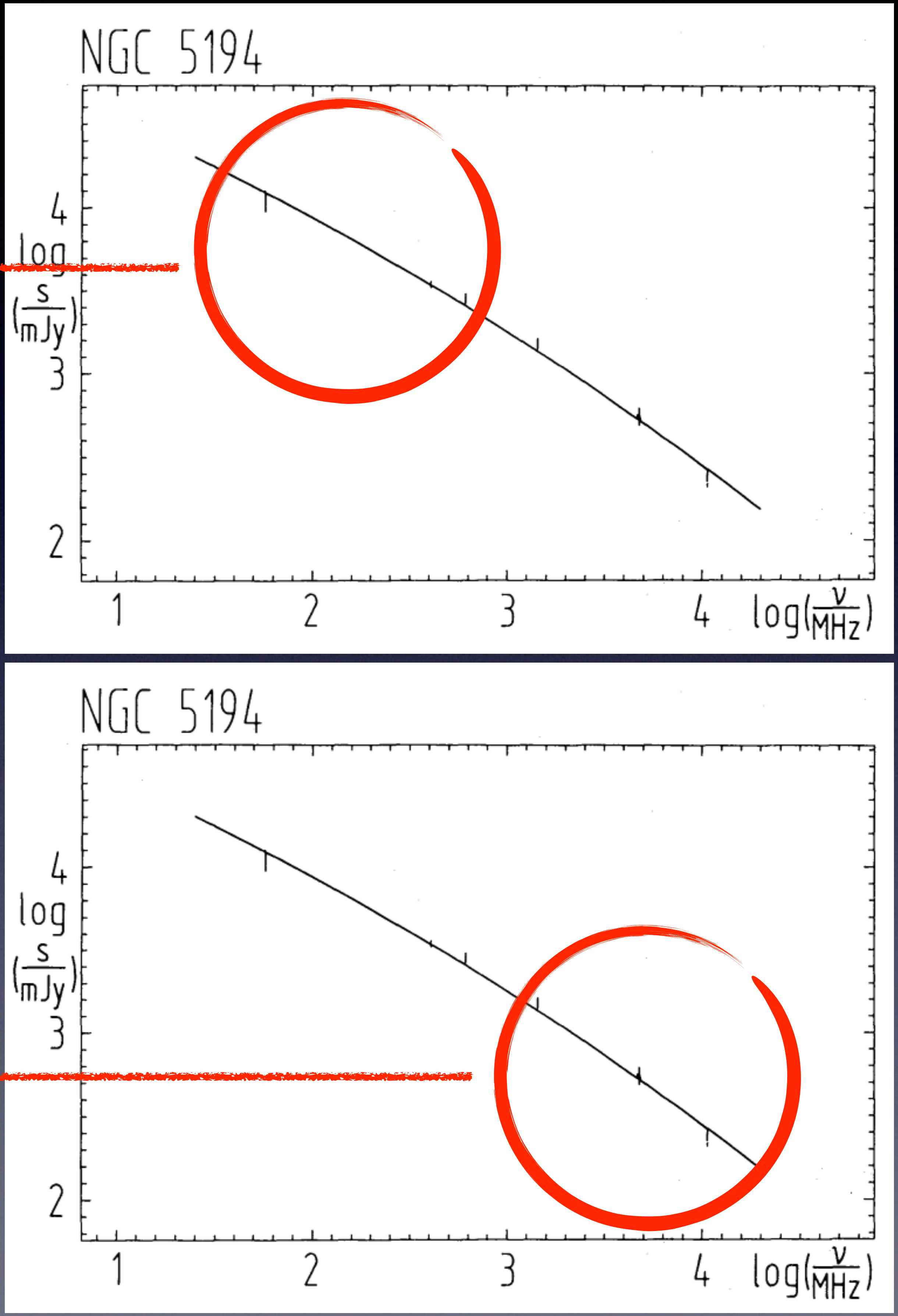
- A reanalysis of this data by Hummel (1991), found no dependence on inclination.
- Therefore, thermal absorption argument is weakened.
- Claims that energy losses at higher frequencies causes frequency change seen in I&M, i.e. dynamical Halo Model




Pohl et al. (1991)

Bremsstrahlung and
perhaps adiabatic losses
are more important
at low frequencies.

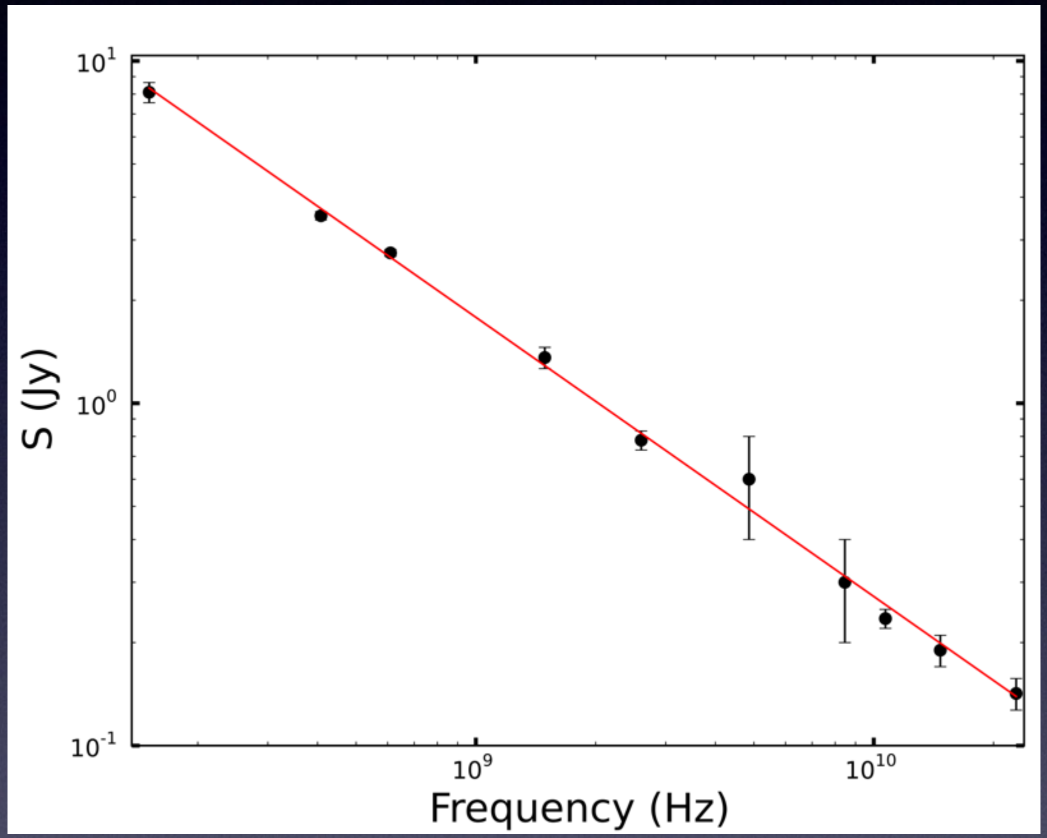
Synchrotron and
Inverse Compton losses
become important
at higher frequencies
and thus steepen spectrum

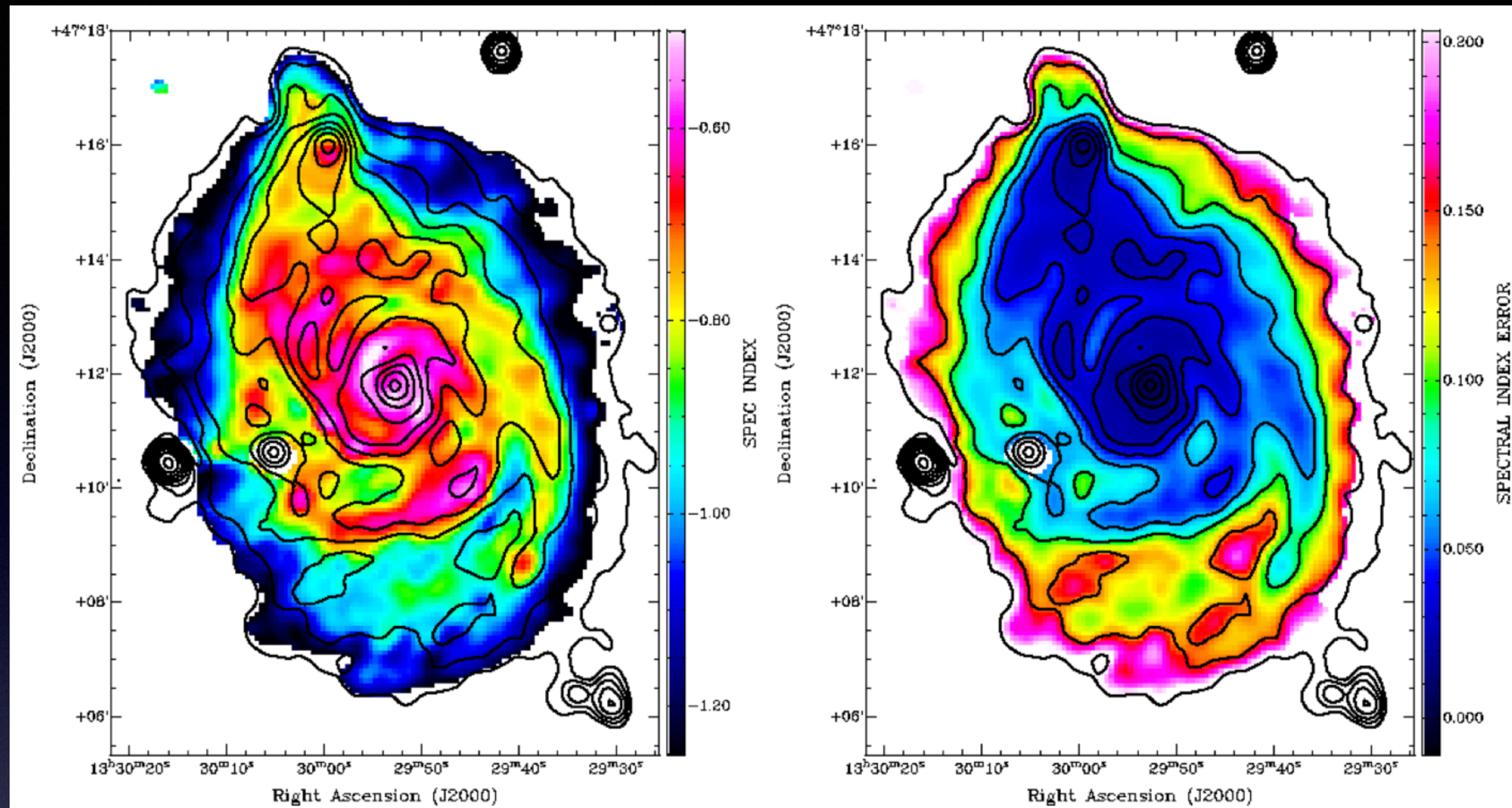



Pohl et al. (1991)

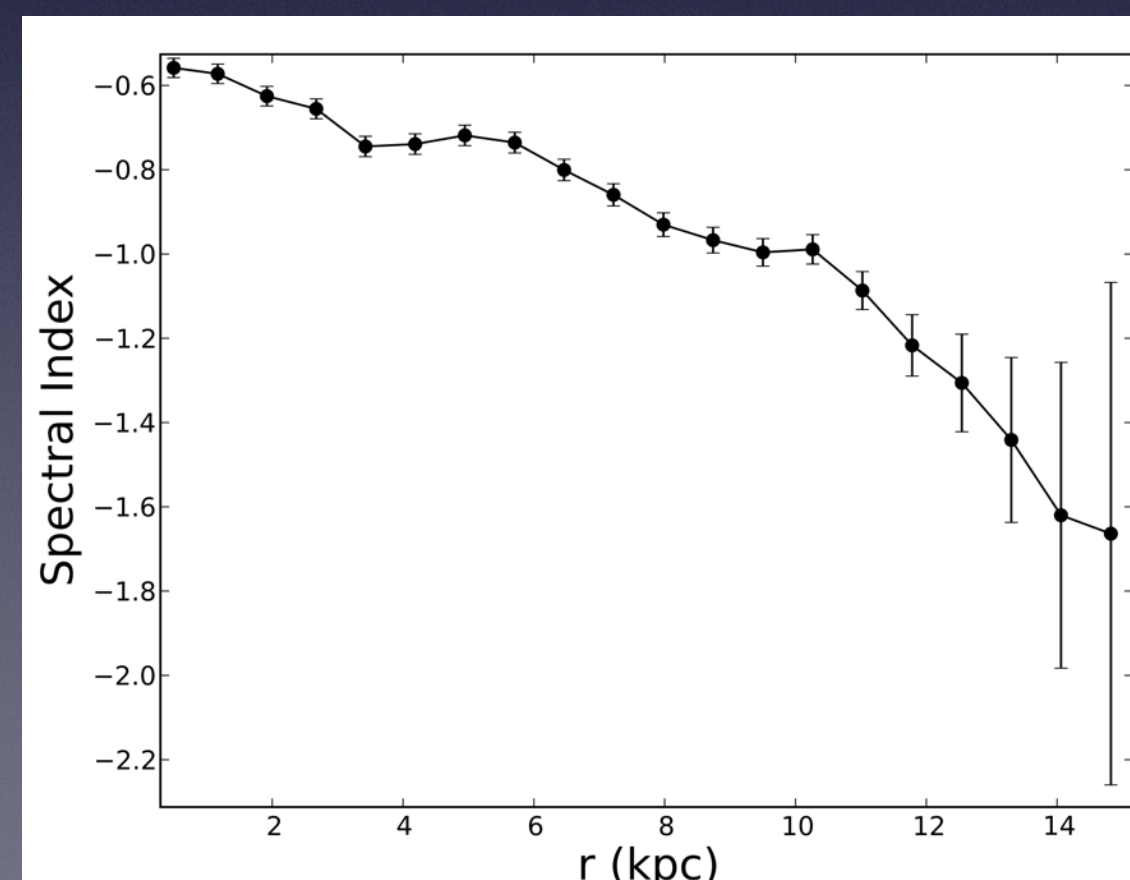
- Integrated spectral index is found to be -0.81+/-0.02.
- No sign of flattening down to 151 MHz.
- This disagrees with findings from Pohl et al (1991).

Integrated spectrum of M51





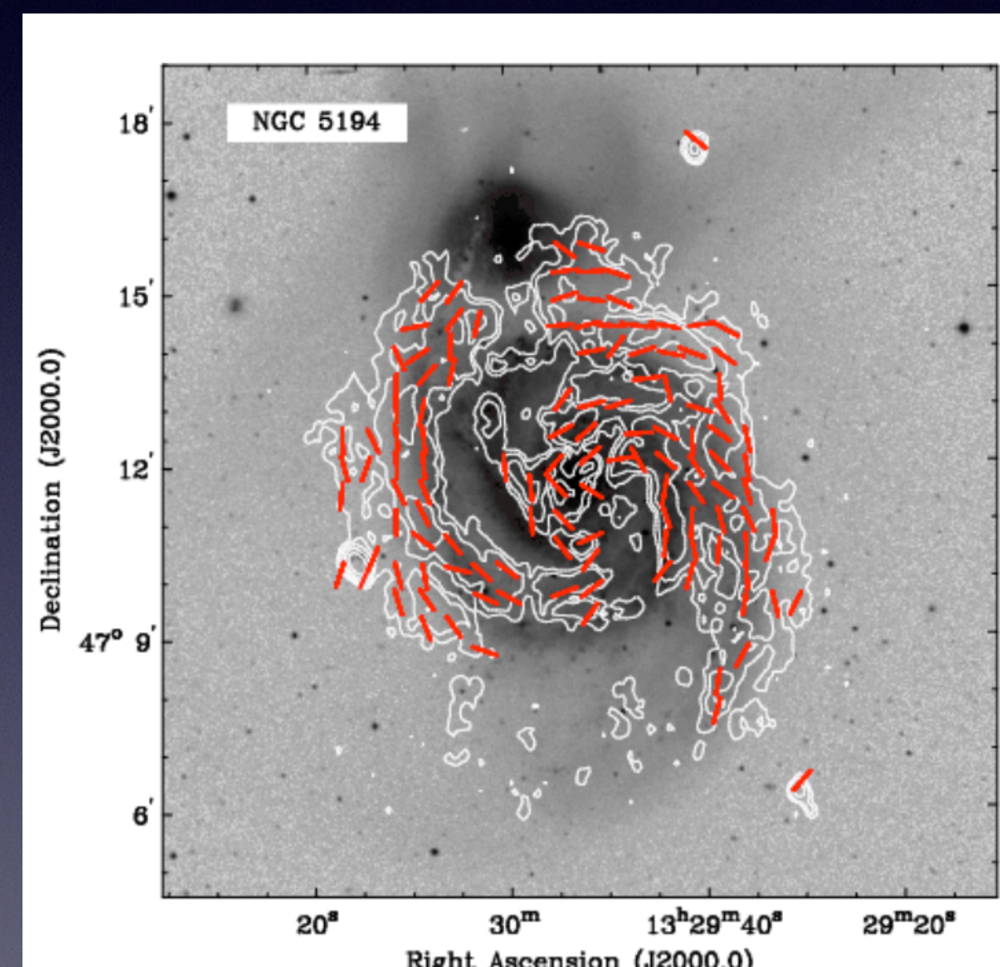

- HII regions in center seen to have spectral index less than -0.5.
- Thermal absorption seen at HII regions.
- Indicates thermal absorption but disagrees with findings with Israel & Mahoney (1991).



# Extragalactic polarized detections in M51 field

# Non detection of diffuse polarization emission in M51

- Diffuse polarization was not detected in M51 with HBA.
- Detection of diffuse polarisation in star forming regions at such frequencies is unrealistic.
- Targets with significant magnetic fields but little star formation may offer better choices to detect polarisation.



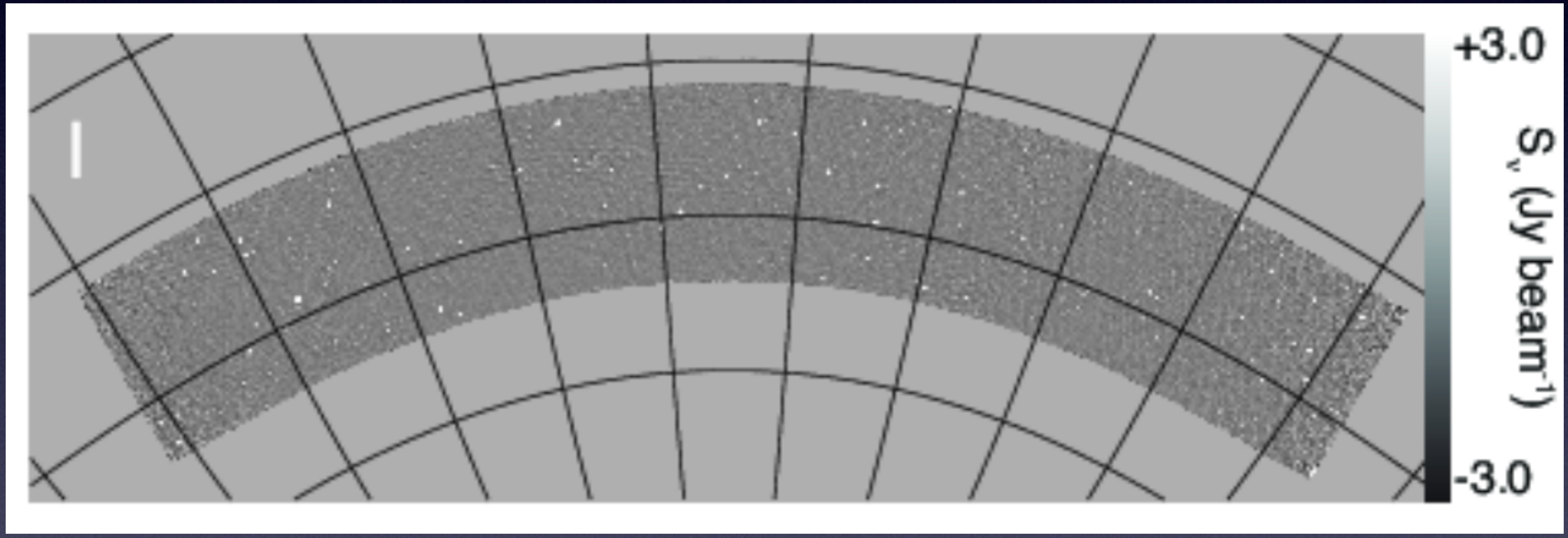

Braun et al. (2010)

# Previous polarization surveys with MWA

## MWA survey of 2400 square degree by Bernardi et al (2013)

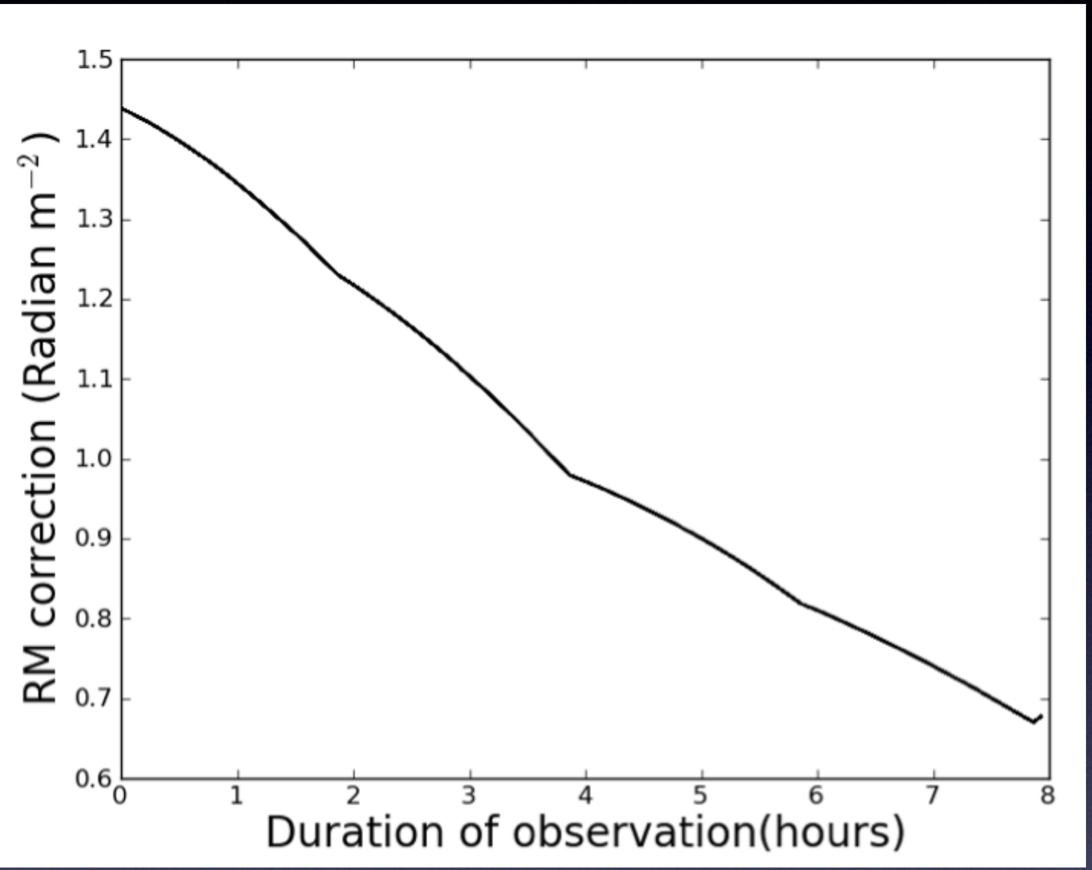
In this survey, only one polarized source was detected.

Both beam depolarization and internal Faraday dispersion could reduce polarized emission. Therefore, higher resolution is needed.




Bernardi et al (2013)

# Calibration and performing RM Synthesis

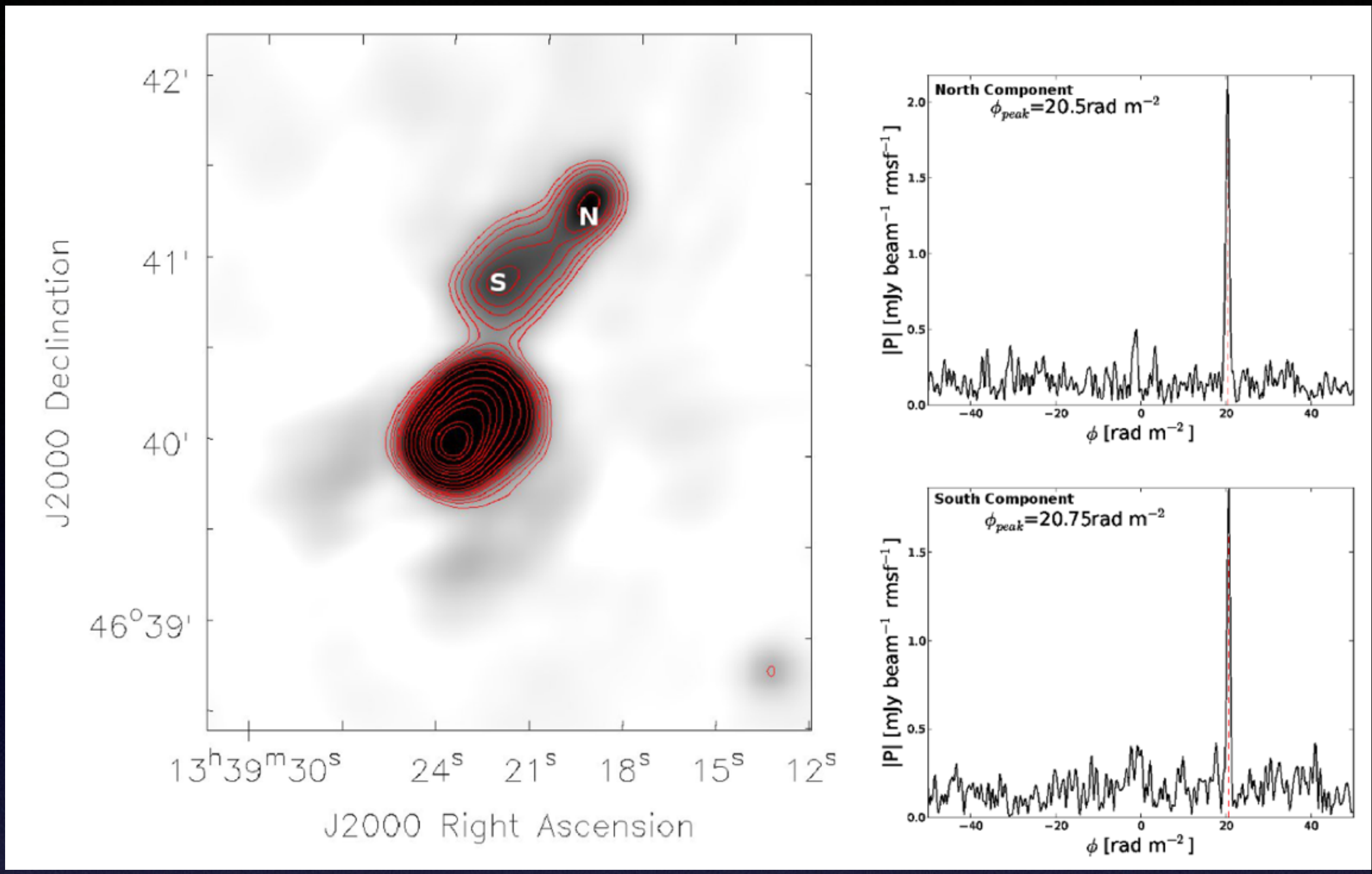


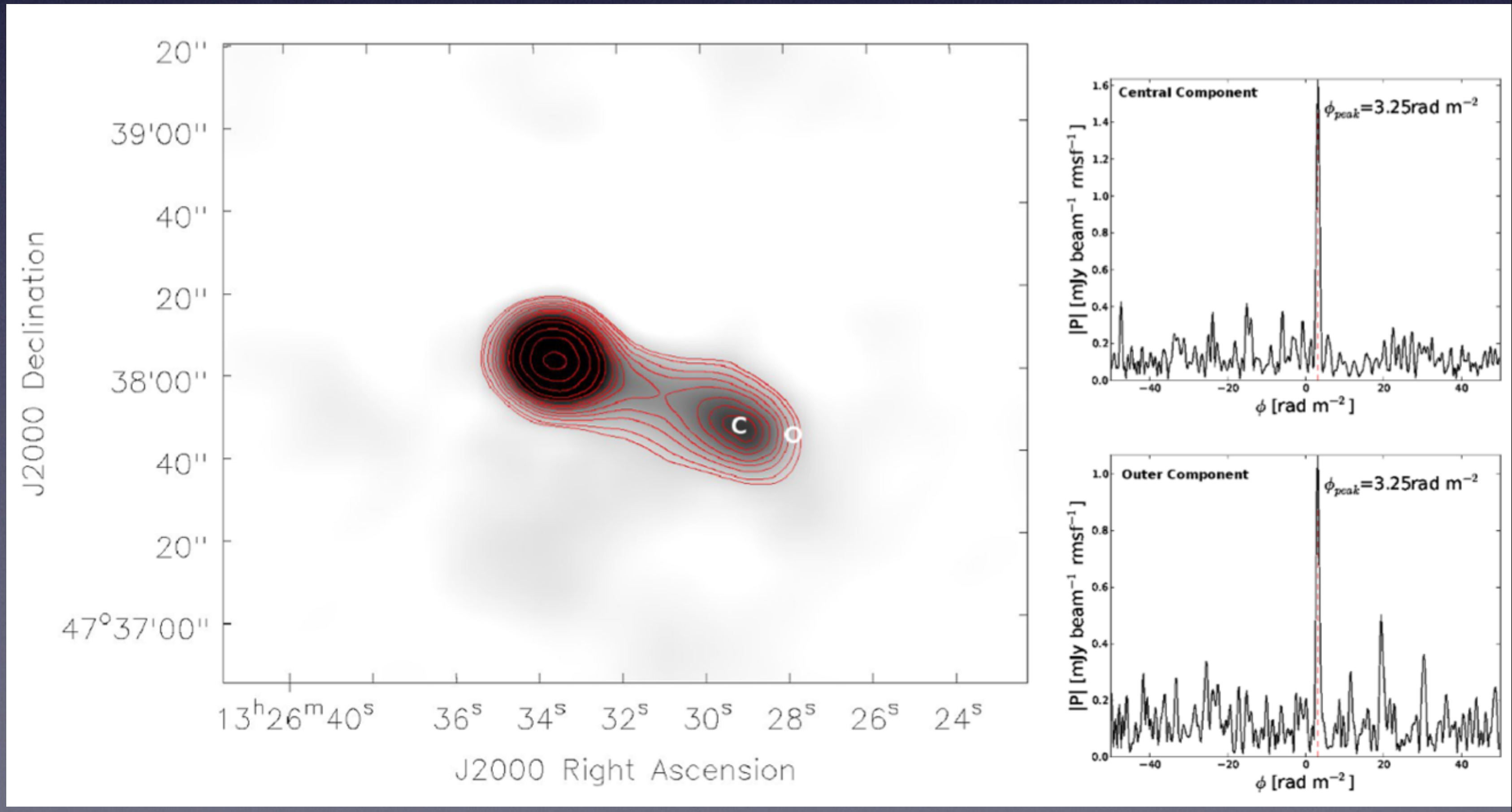

- Faraday rotation caused by the ionosphere was corrected for using CODE TEC data and the RM writer code by M.Mevius.

- Performed RM Synthesis on all sources in field over 5 sigma in intensity.

- rms=79microJy/beam

- M51 was not detected in polarisation due to strong polarisation.
- We detected six extra galactic sources in a field of approximately 4.9 * 4.9 degrees.
- Number density is one polarized source per 2.9 square degrees.



# Conclusions

- Diffusion is found to be the most dominant process of CRE propagation in the star forming disk of M51.
- Thermal absorption is seen in M51 and is greatest in HII regions.
- Non detection of diffuse polarized emission from M51.
- RM grids of nearby galaxies will be extremely difficult at these low frequencies due to the sparsity of polarized sources.

# Future Work

- LBA observations are being proposed for cycle 2 to further constrain the parameters of thermal absorption and CRE diffusion.
- More galaxies at a range of inclinations and SFR rates are being observed,reduced and analysed by the MKSP, such as NGC891 (paper is being prepared)
- Theoretical modelling of the diffusion loss equation are being performed and compared to observations.
- Preliminary results from this future work will shown at the LOFAR meeting in Amsterdam