Exploring the low frequency nature of nearby galaxies with observations and modelling

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LOFAR Magnetism Key Science Project

Interferometry Centre of Excellence

Outline

Nearby Galaxies at low frequencies

Observations of M51 with LOFAR HBA
(Mulcahy, Horneffer et al. 2014)

Modelling the cosmic ray propagation in M51
(Mulcahy, Fletcher et al. 2016)

Preliminary results on NGC891 with LOFAR
(Mulcahy, Horneffer et al. in prep)

Radio continuum tools to study Magnetic Field

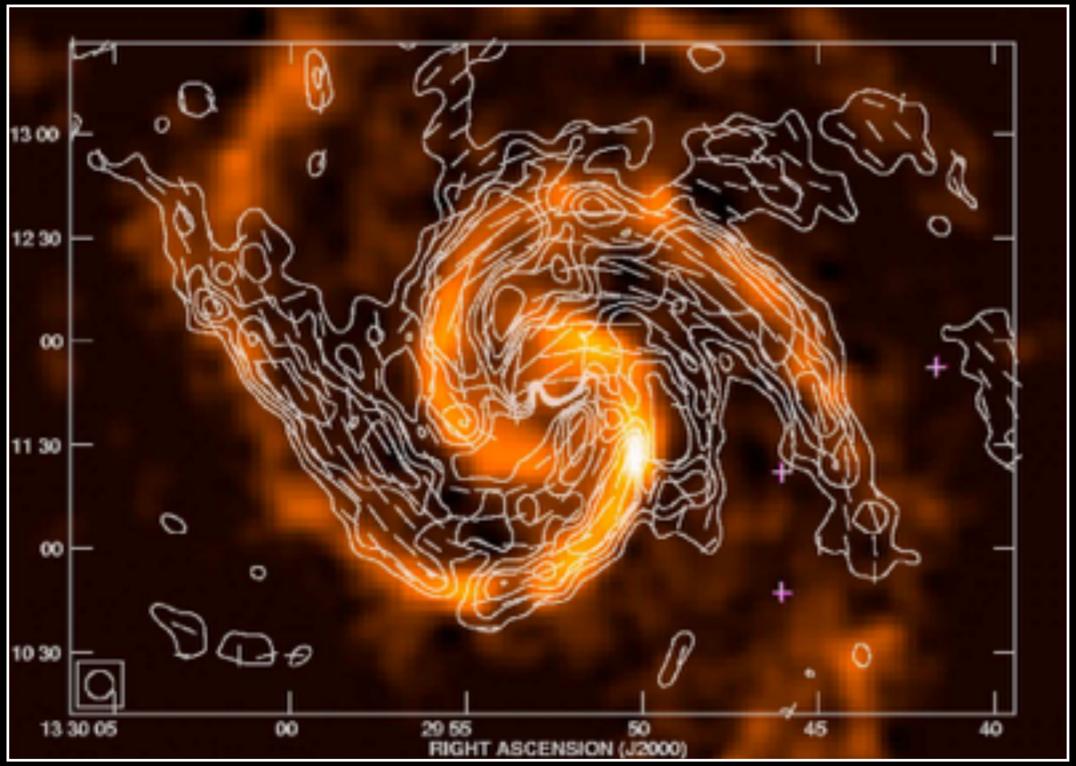
Several methods of observing magnetic fields most notably is synchrotron emission.

Total synchrotron intensity:
Strength of total $B_\perp$

Polarised synchrotron intensity:
Strength and structure of ordered $B_\perp$

Faraday rotation:
Strength and sign of ordered $B_{||}$

Faraday depolarisation (dispersion):
Strength and scale of turbulent fields



M51,polarised emission overlayed onto CO (Fletcher et al. 2011)

Radio continuum tools to study GeV Cosmic ray electrons (CRE)

Injected via Supernova
spectral index of -0.5

Synchrotron spectrum:
Energy density, energy spectrum, energy losses of CRE

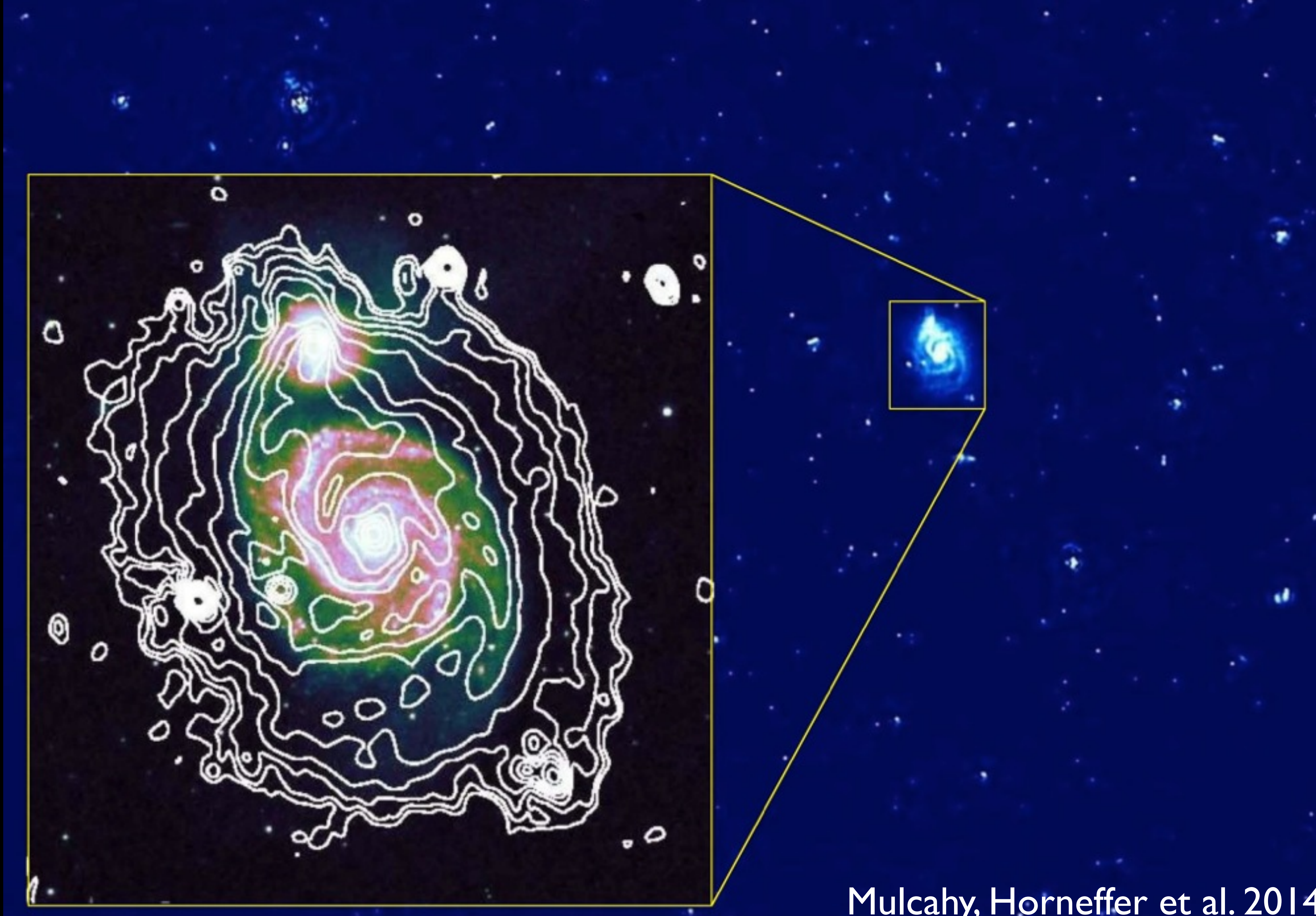
Distribution of synchrotron spectral index:
Propagation type and velocity of CRE

Scale height/length of galaxy disk and halos:
Bulk outflow velocity, diffusion coefficient

Cosmic ray propagation at low frequencies <300 MHz

- At low frequencies we are observing synchrotron emission originating from low energy cosmic ray electrons (CRE).
- In the Milky Way, propagation is mainly through diffusion-the result of scattering off turbulent magnetohydrodynamic waves and discontinuities of the interstellar plasma.
- Low energy CREs suffer less from synchrotron and inverse Compton losses.
- Cosmic ray lifetime is far longer at low frequencies and thus can travel further from their sites of origin.
- Can illuminate the magnetic field in the extended disk and halo.

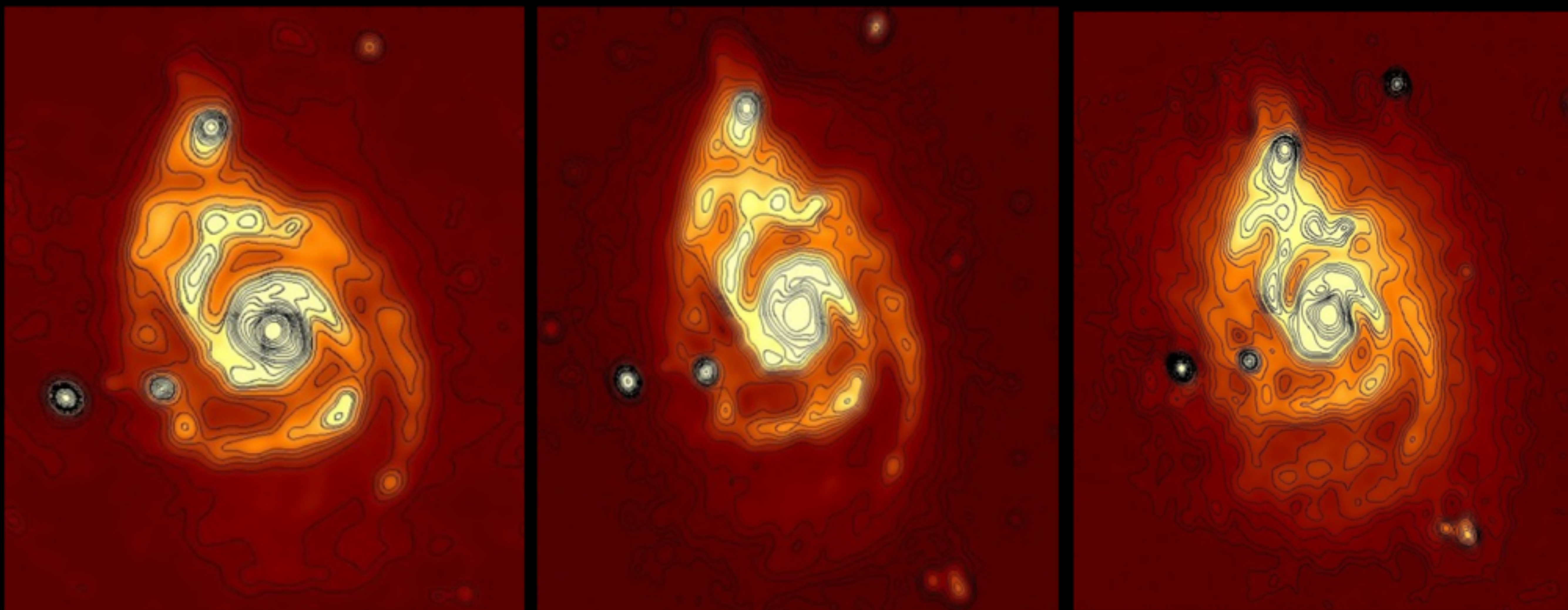
M51 observed with LOFAR at 150 MHz



Mulcahy, Horneffer et al. 2014

Comparison with Higher Frequencies

4.86 GHz | 1.4 GHz | 151 MHz



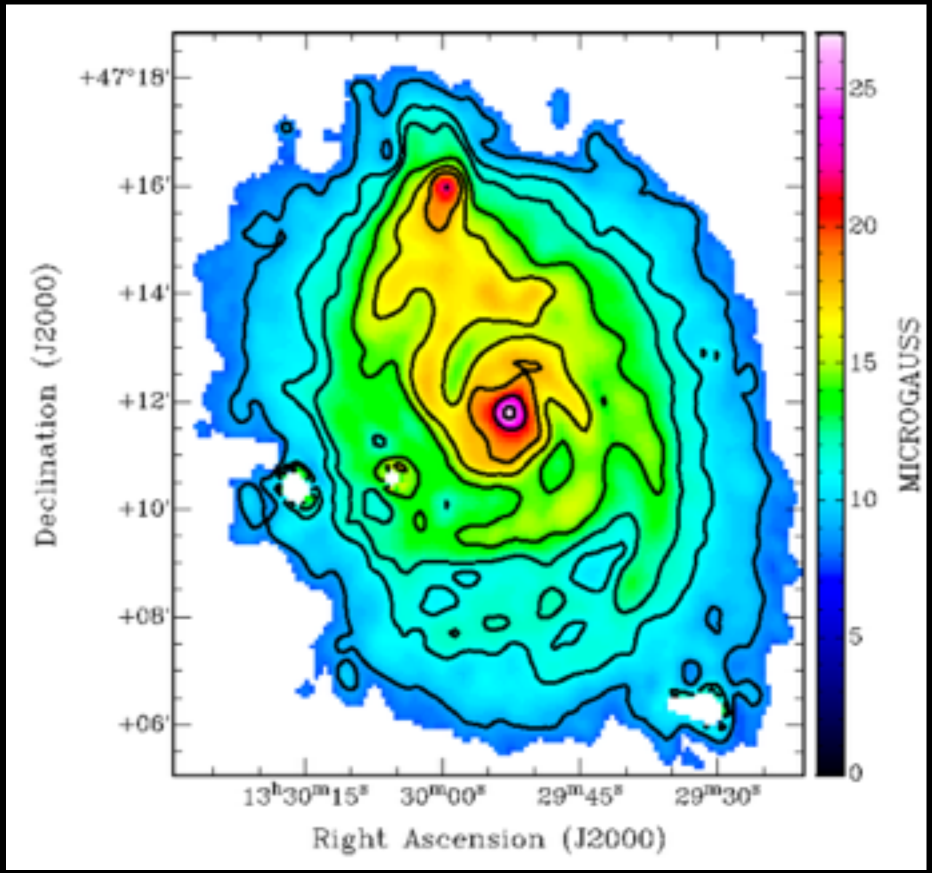
Fletcher et al. 2011

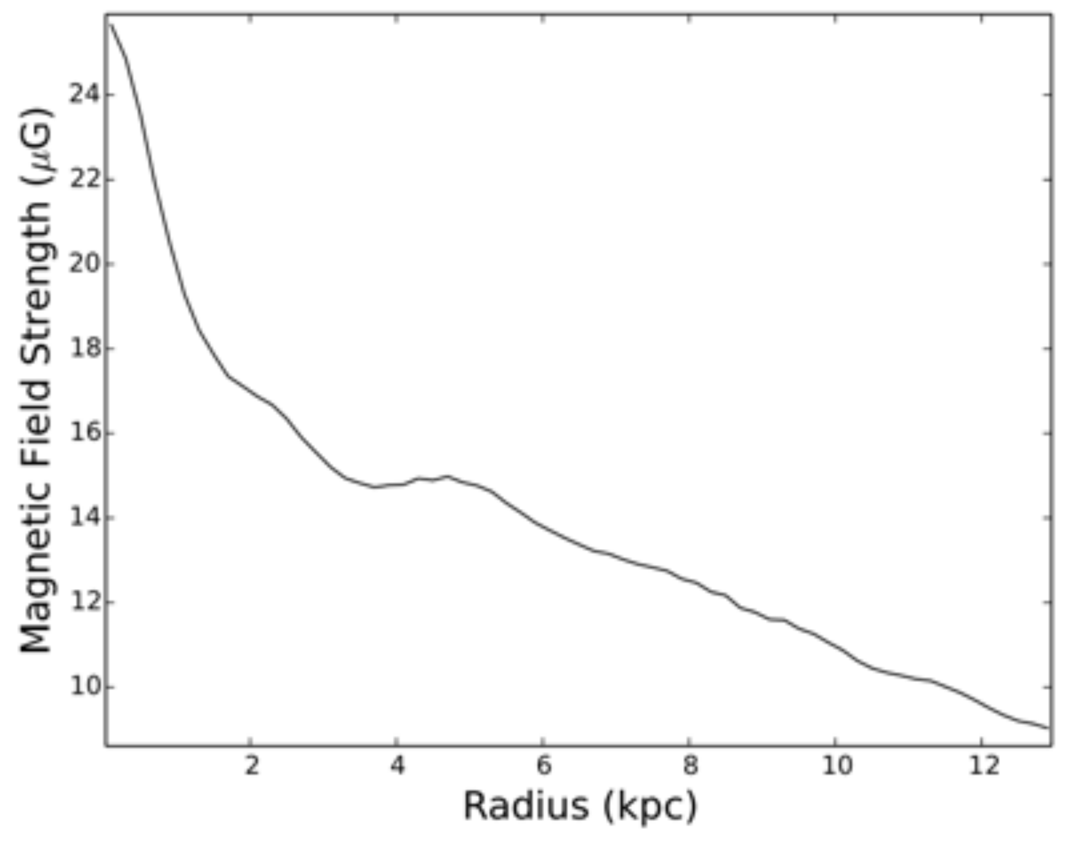
Magnetic field strength observed in the extended disk

Total Magnetic Field Strength is found assuming equipartition between the energy densities of the magnetic field and cosmic rays (Beck & Krause 2005)

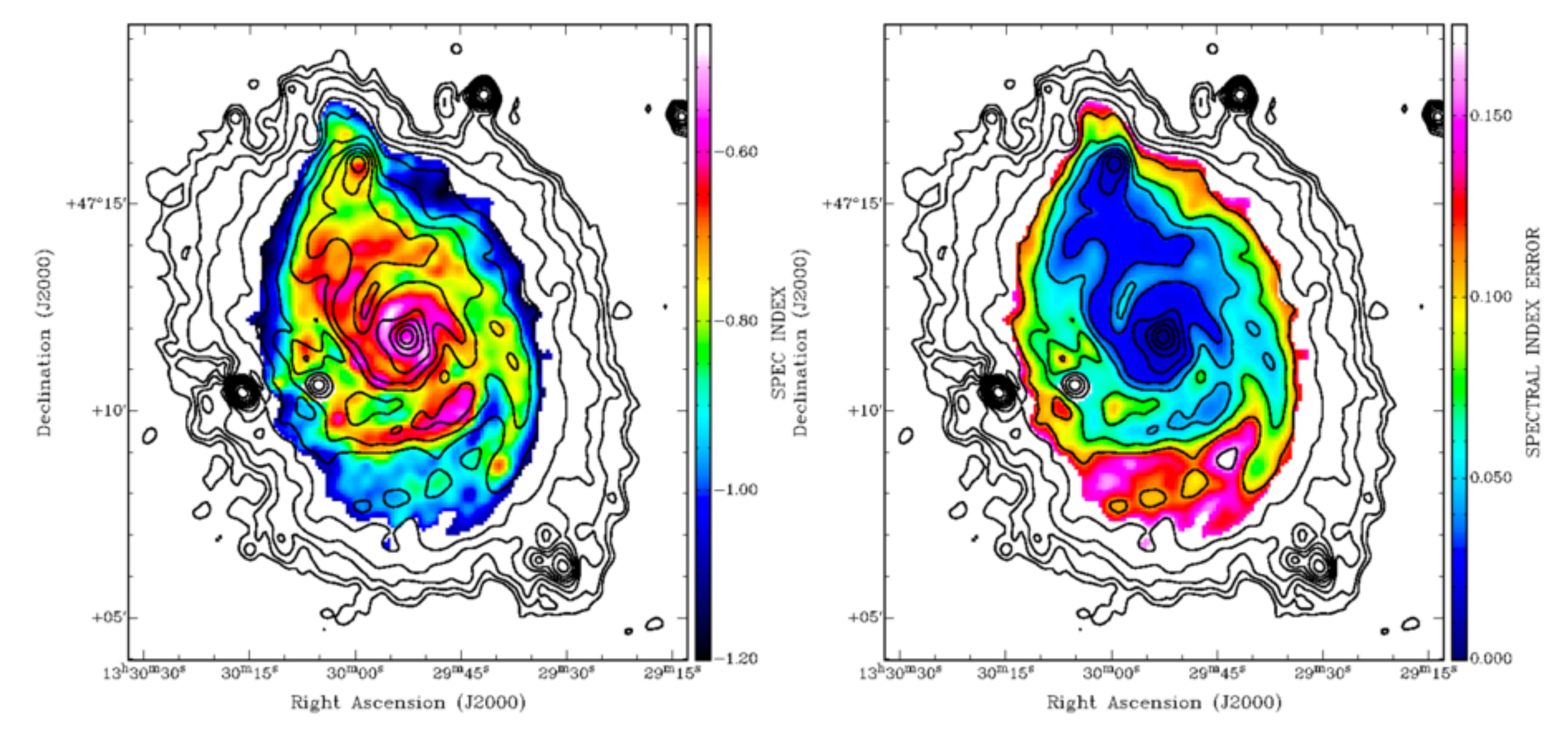
Assuming a ratio K between the numbers of cosmic-ray protons and electrons (usually K ≃ 100)

First time gives us estimates for the magnetic field strength in the extended disk for M51 (up to 15 kpc from centre)





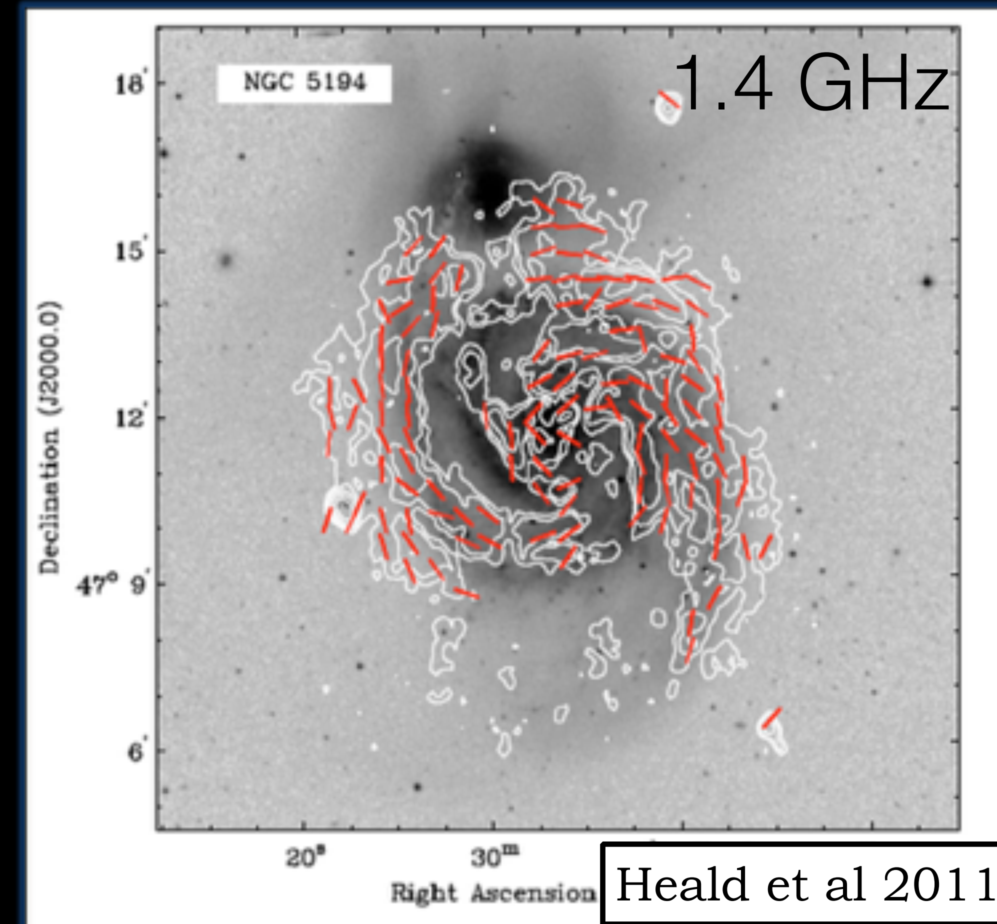
Spectral index map of M51 between 1.4 GHz and 151 MHz

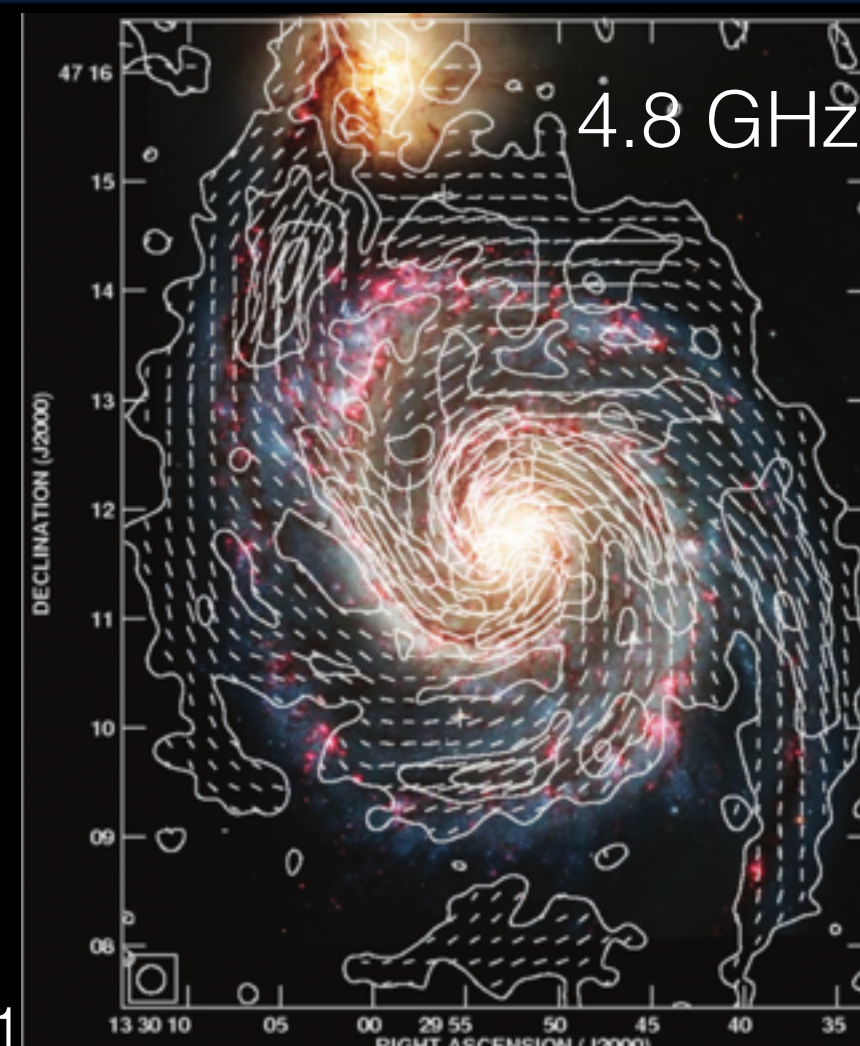


Spectral Index Map Spectral Index Error Map

Depolarisation of M51

- M51' s inner disk becomes depolarised at 1.4 GHz
- But significant polarisation can be seen in the outer disk of M51.
- Can see weak magnetic fields in the outer disk with LOFAR?
- M51 was not detected in polarisation, upper limit found to be 0.5mJy/beam—> polarisation degree of 0.006%.

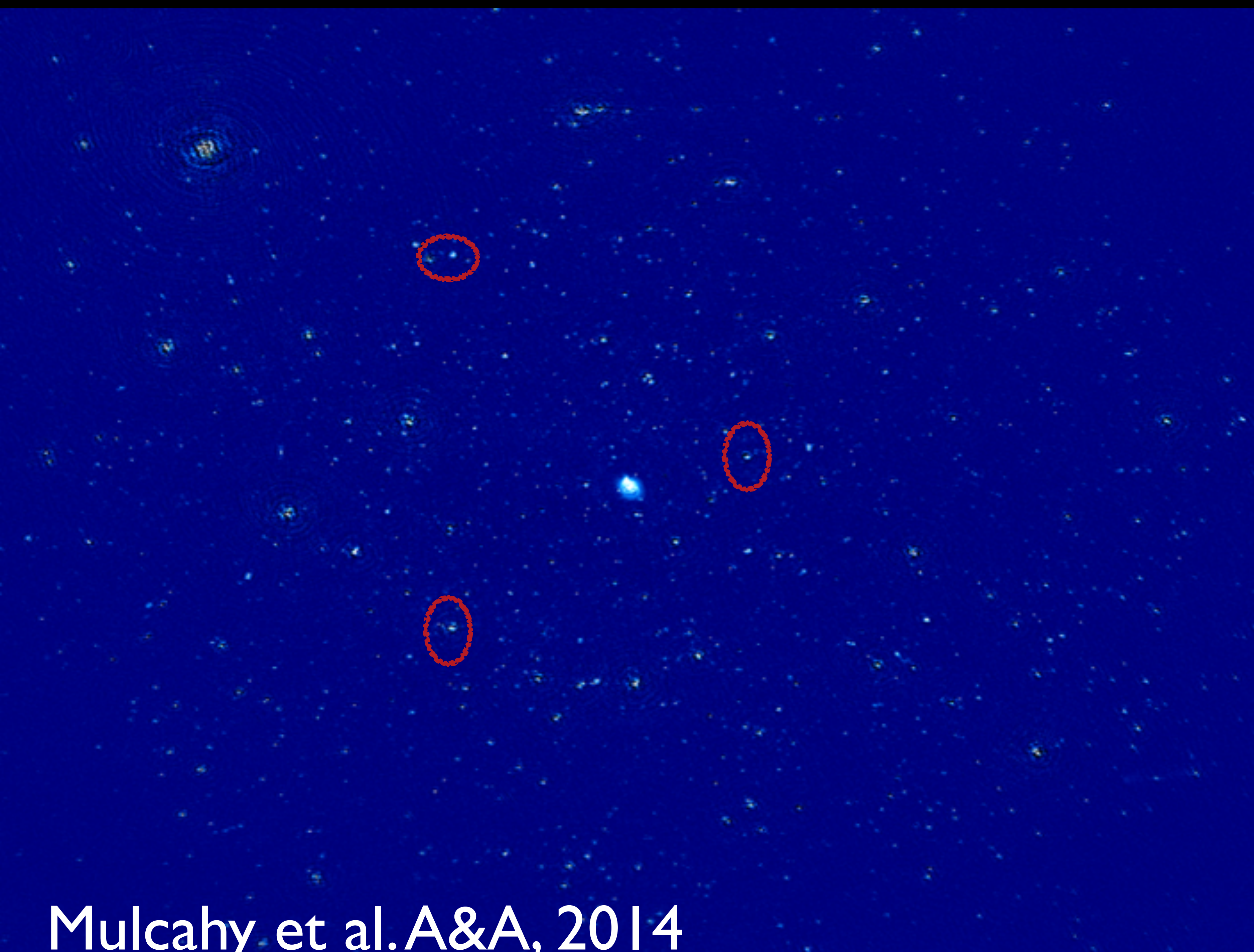


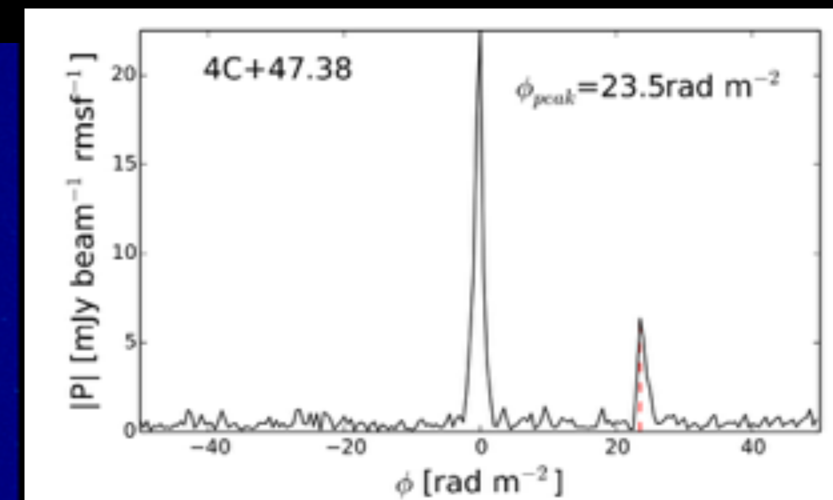


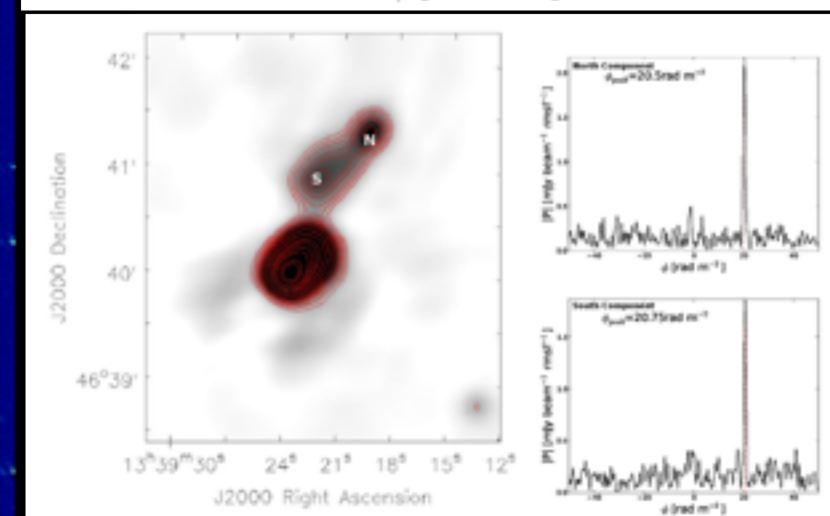
Fletcher et al. 2011

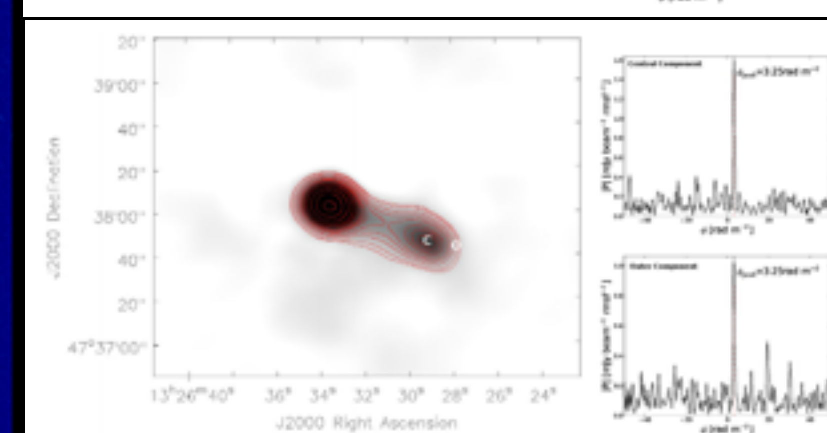
Extra galactic polarised sources with LOFAR

6 polarised sources observed in M51 field (approx 3X3 degrees)
1 polarised source per 1.7 square degrees









Mulcahy et al. A&A, 2014

Determining what CRe process is dominant in M51

Between 1.4 GHz and 151 MHz —>frequency ratio of 9.27

Diffusion

expect a ratio of propagation lengths to be 1/1.74

$$l_{diff} \propto B_{tot}^{-3/4} \nu^{-1/4}$$

Cosmic Ray Streaming

expect to see a ratio of propagation lengths to be 1/3.04

$$l_{stream} = v_A \tau_{CRE} \propto B_{tot}^{-1/2} \nu^{-1/2}$$

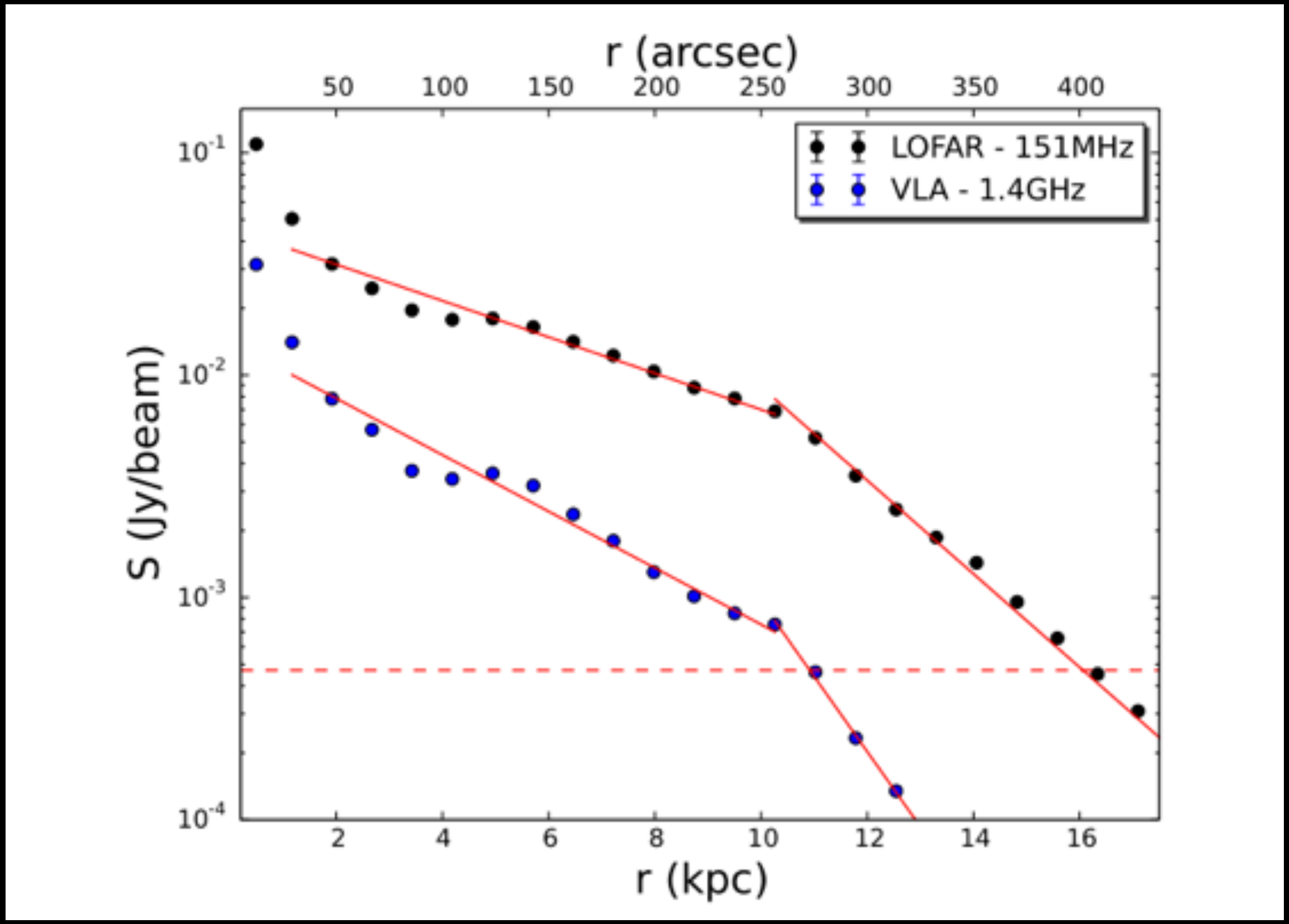
Propagation of Cosmic Ray Electrons

- Observe break in radio continuum profile

- Expect to see a ratio of scale lengths between 151 MHz and 1.4 GHz for diffusion to be 1/1.74.

- Expect to see a ratio of scale lengths between 151 MHz and 1.4 GHz for streaming to be 1/3.04.

- Observe a of ratio 1/1.6, agrees with diffusion.



ν (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
H I*	5.5	2.1*

Motivation for modelling CR propagation

- From observations, one can estimate the diffusion coefficient. However, this estimate is only good for an order of magnitude.
- Modelling the CR propagation equation to obtain the theoretical non-thermal spectrum and compare to the observed spectrum would give a better estimation of the diffusion coefficient.
- Explore the nature of CRe injection and confinement.

Modelling the cosmic ray electron propagation in M51

We can model the spectral index by solving the CR propagation equation numerically

Has been modelled extensively in our own galaxy but lacking in other galaxies - only analytical models

$$\frac{\partial N}{\partial t} = \Theta \frac{1}{r'} \frac{\partial}{\partial r'}\left(r' \frac{\partial N}{\partial r'}\right) + \Phi \frac{\partial}{\partial E'}[E'^2 B'^2] + KQ(r')E'^{-p} - t_0 \frac{N(R,E)}{\tau_{esc}}$$

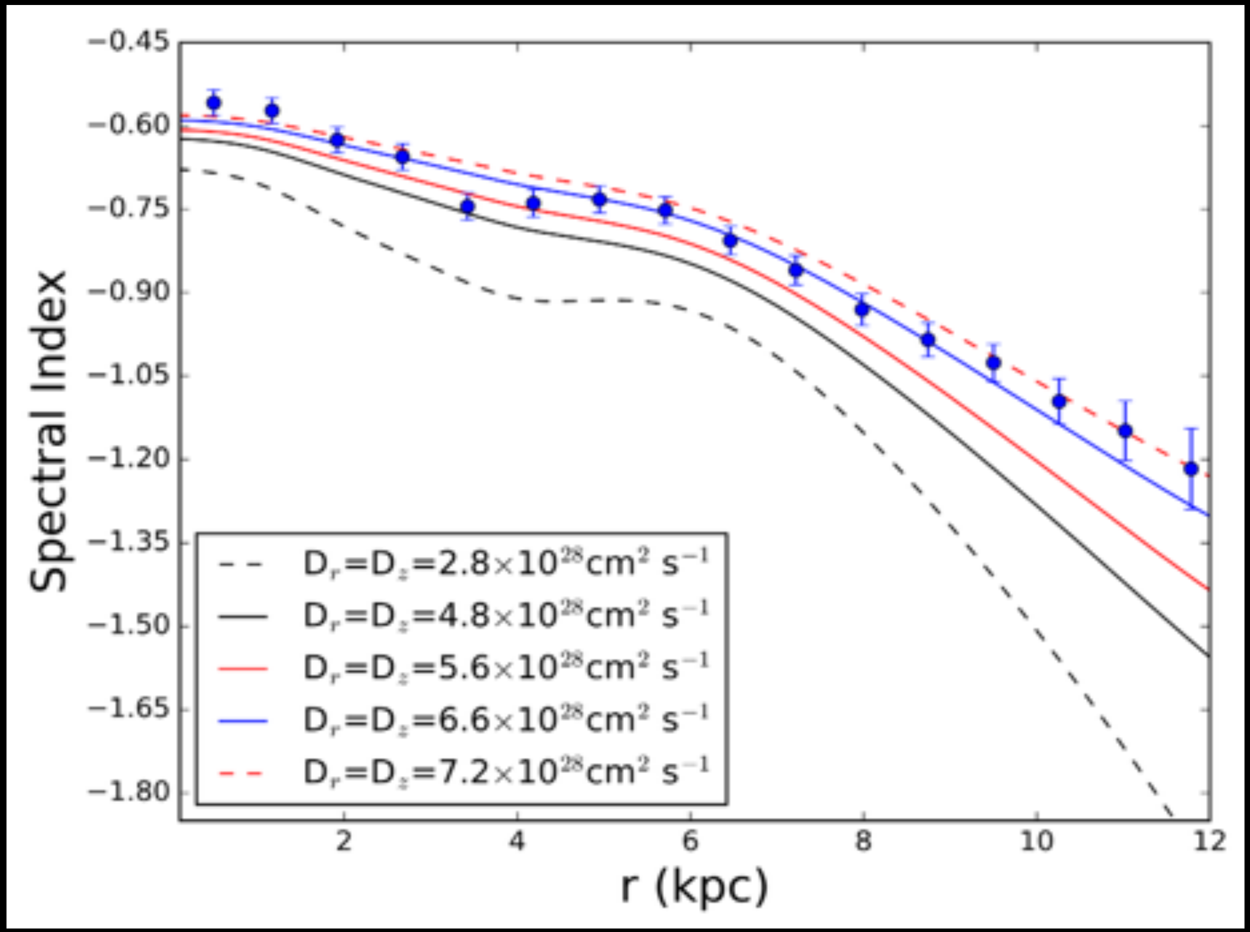
CRE Diffusion | Energy Losses | CRE Injection | Escape Term

Modelling the cosmic ray electron propagation in M51

$$\frac{\partial N}{\partial t} = \Theta \frac{1}{r'} \frac{\partial}{\partial r'}\left(r' \frac{\partial N}{\partial r'}\right) + \Phi \frac{\partial}{\partial E'}[E'^2 B'^2] + KQ(r')E'^{-p} - t_0 \frac{N(R,E)}{\tau_{esc}}$$

we find that a diffusion coefficient of
$D_r = D_z \simeq 6.6 \times 10^{28} \mathrm{cm}^2 \mathrm{s}^{-1}$
matches the observed spectrum very well.

The lifetime of CRE in M51 is about 11 Myr in the inner galaxy, increasing to over 88 Myr in the outer galaxy



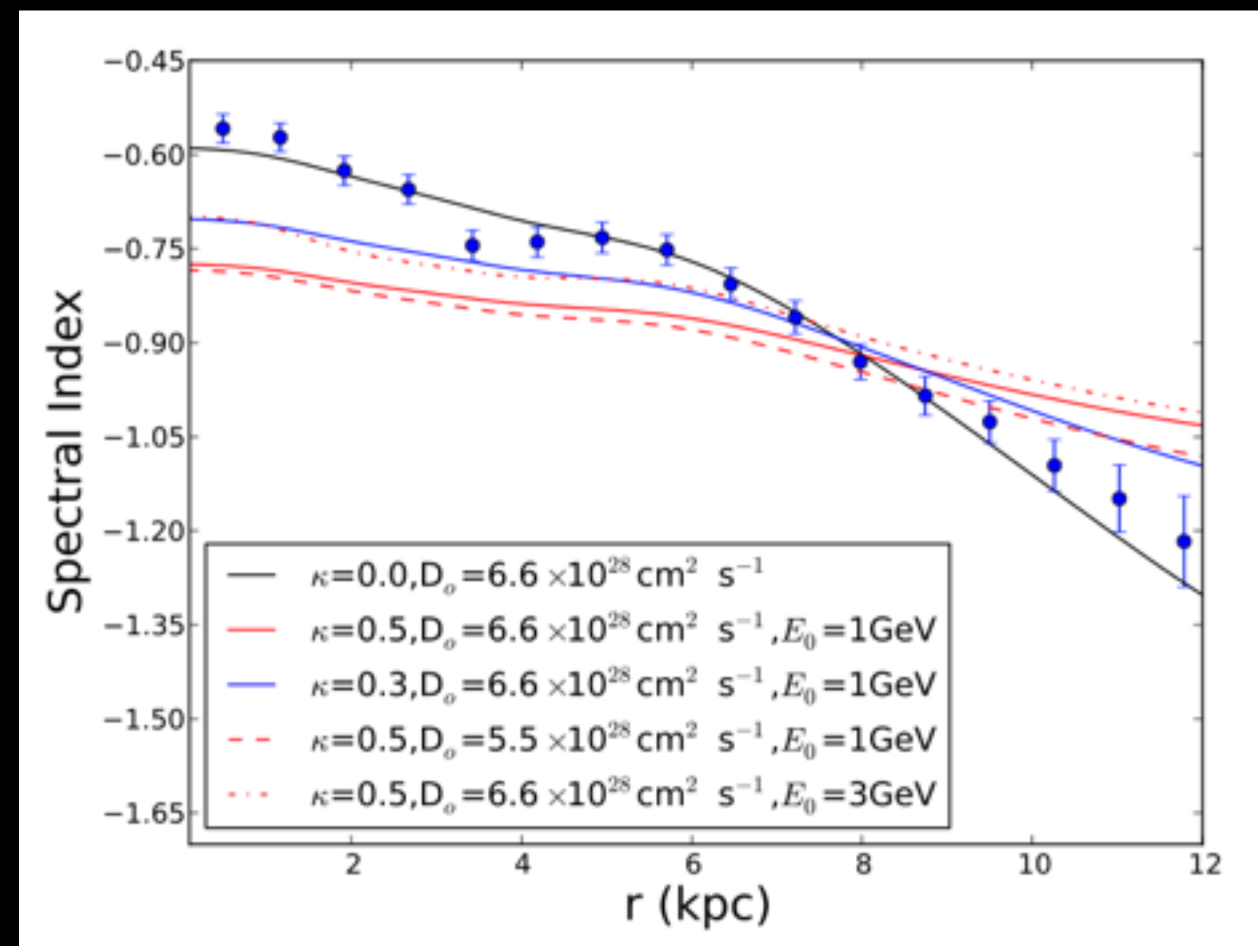
Mulcahy, Fletcher et al.2016

Testing the energy dependence of the diffusion coefficient

- There is debate about the relevance of the energy dependence of the diffusion coefficient at low energies, which correspond to low radio frequencies.

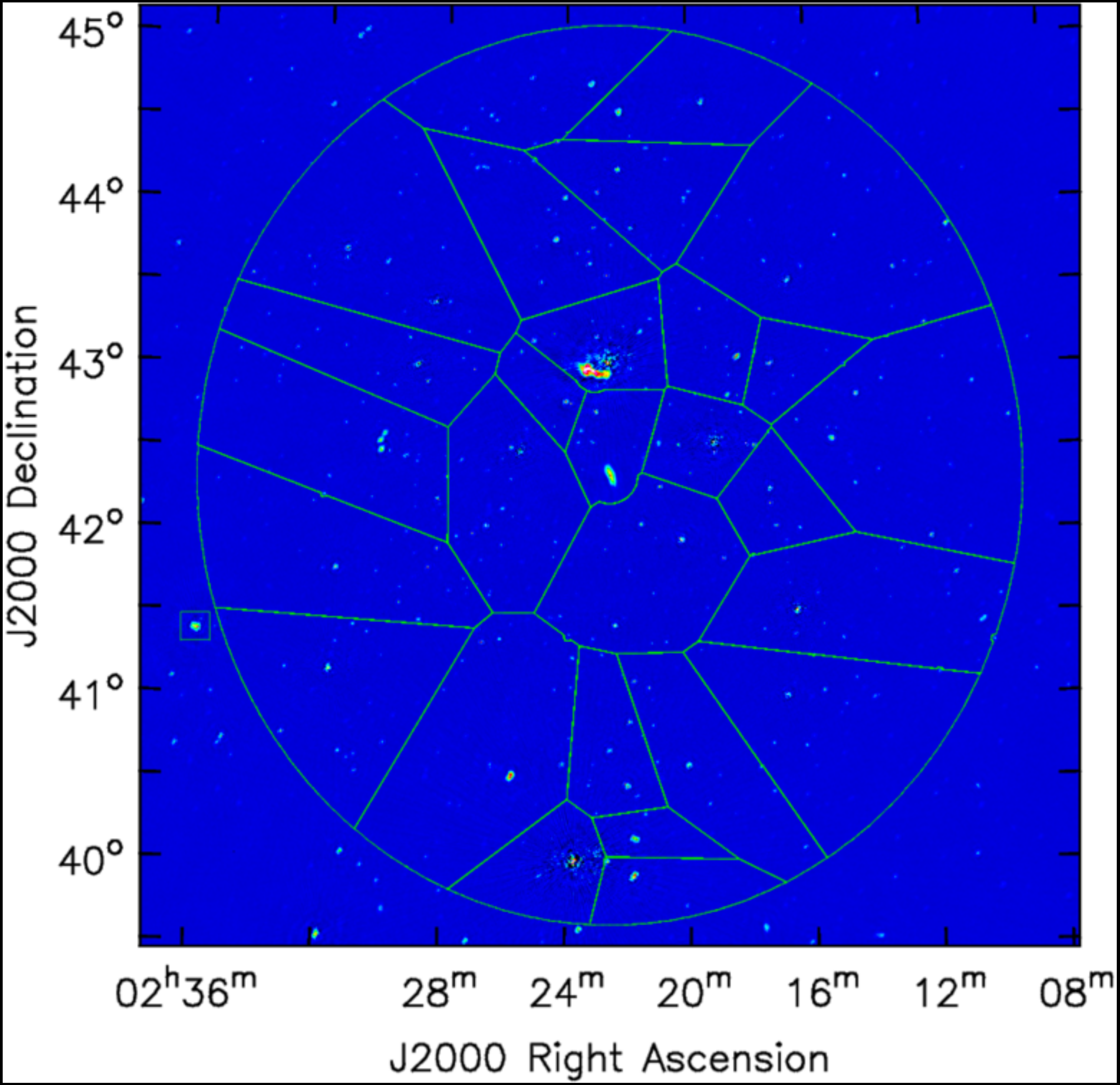
$$D(E) = \begin{cases} D_0 & \text{if} E \leq E_0 \\ D_0 E^{\kappa} & \text{if } E \geq E_0 \end{cases}$$

- Tested various energy dependence and starting energies.
- Energy dependence would not fit to observed values.

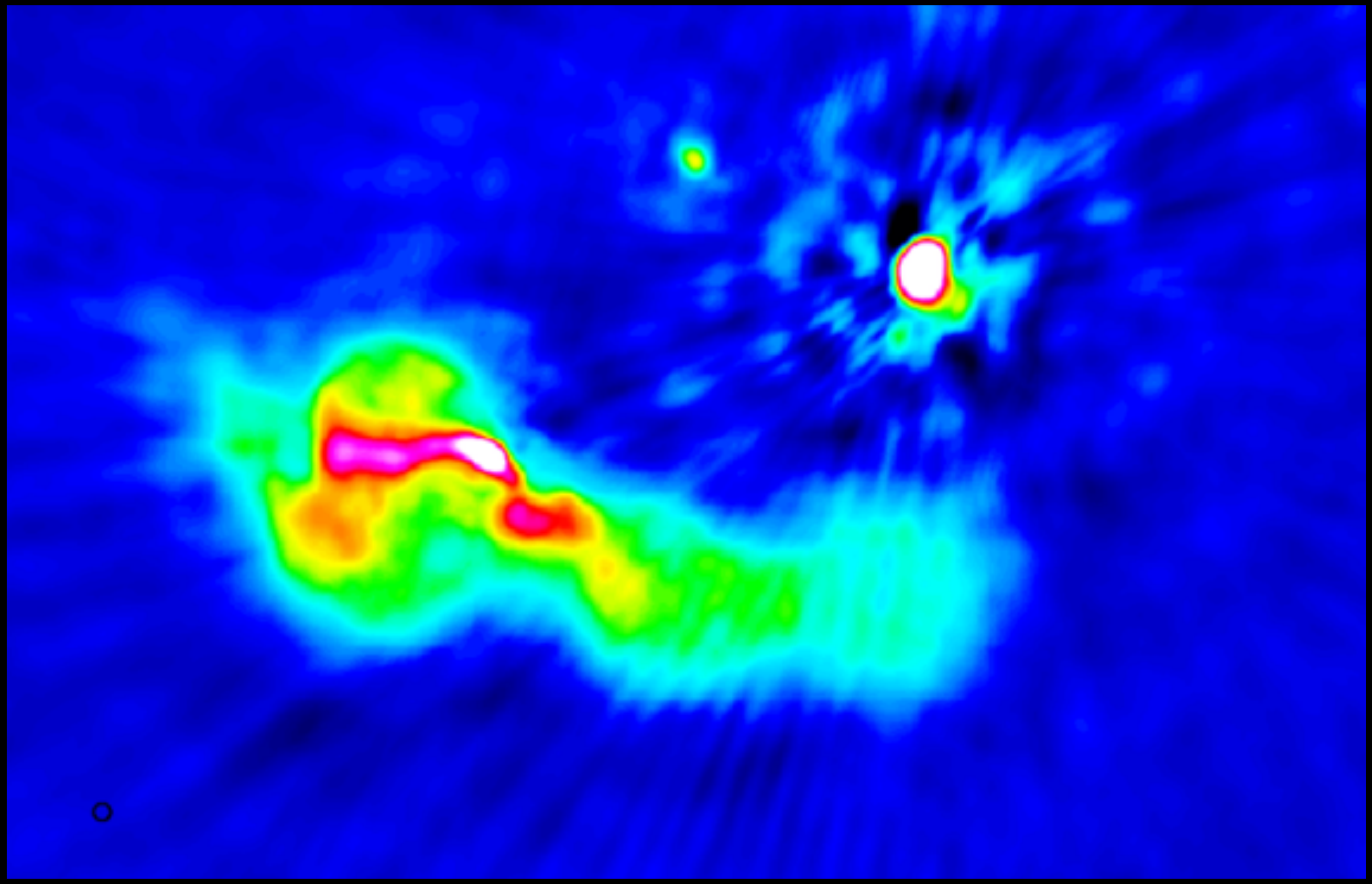


Mulcahy, Fletcher et al.2016

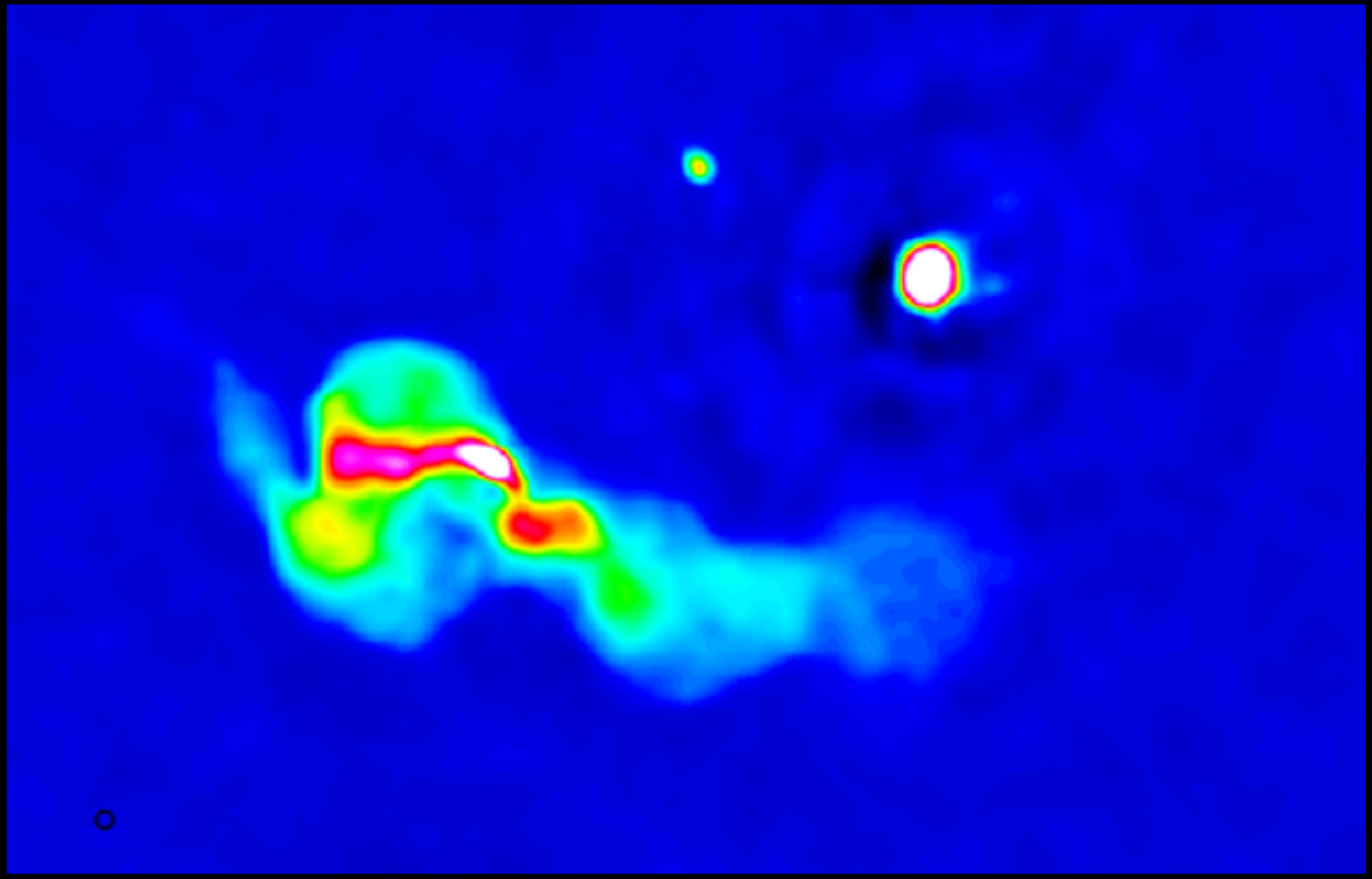
Observations of NGC891 with LOFAR



45°
44°
43°
42°
41°
40°
J2000 Declination
02h36m
28m
24m
20m
16m
12m
08m
J2000 Right Ascension



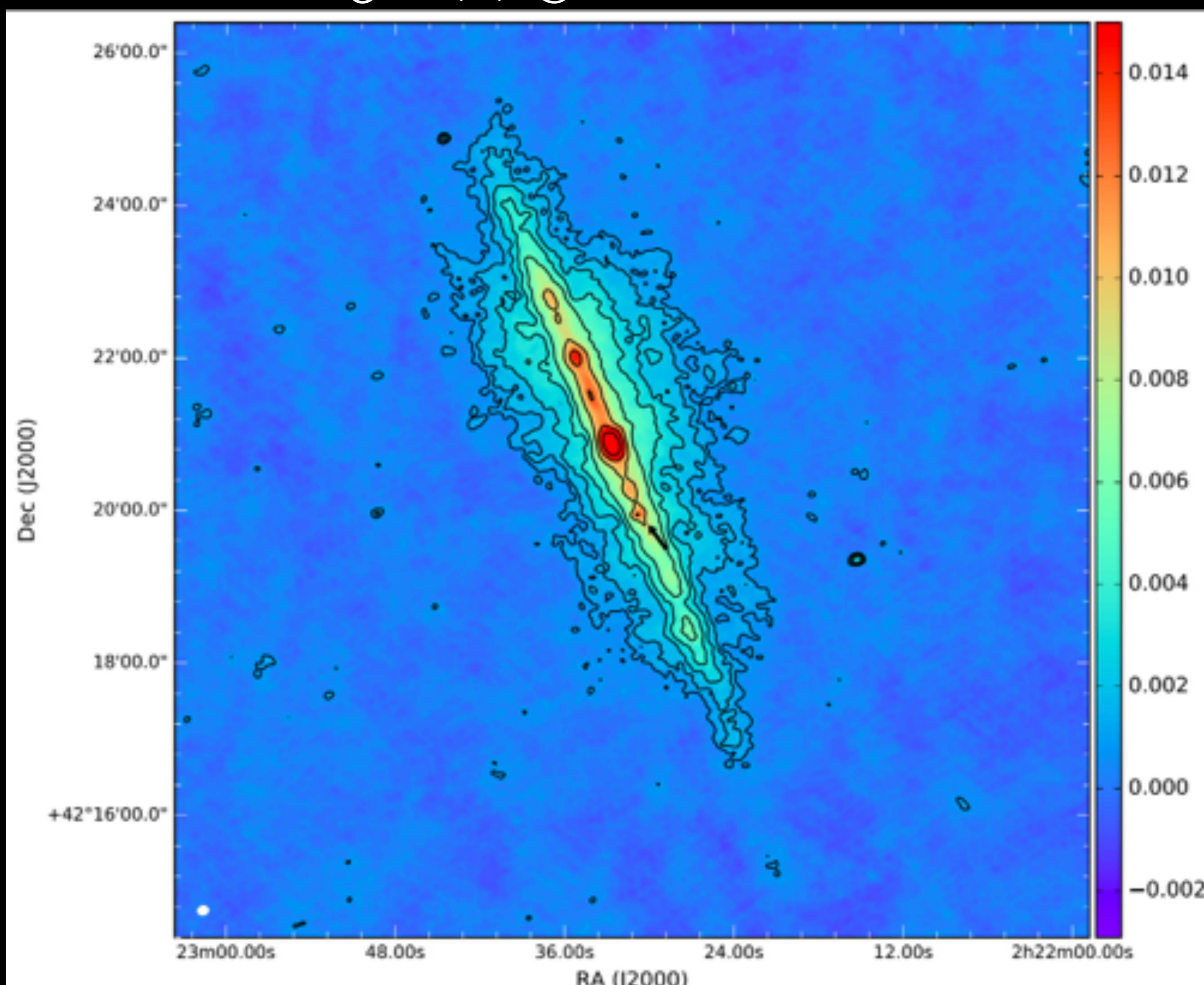
PreFactor



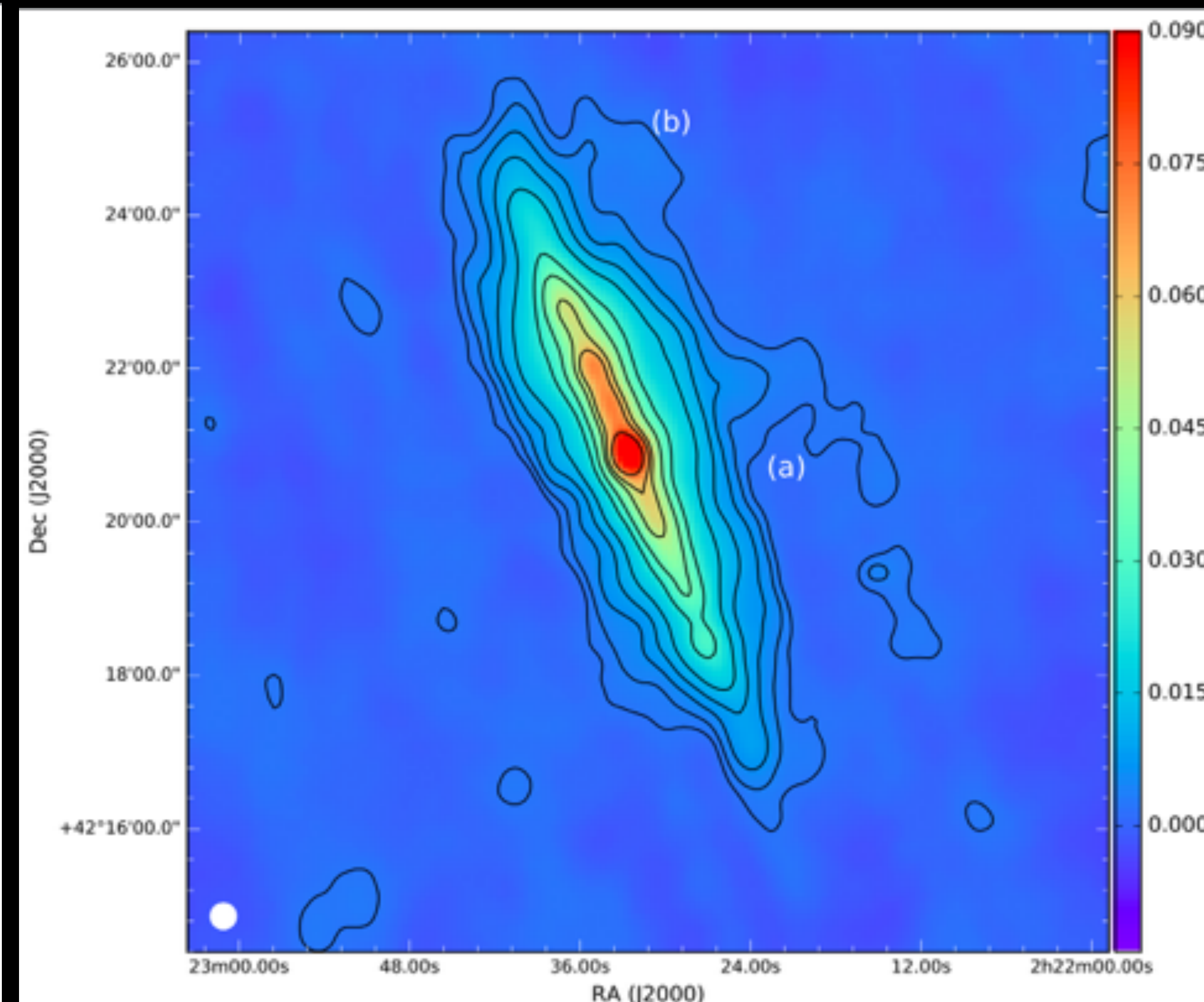
Factor

NGC891 at 146 MHz with LOFAR

$6'' \times 8''$ resolution



$20'' \times 20''$ resolution

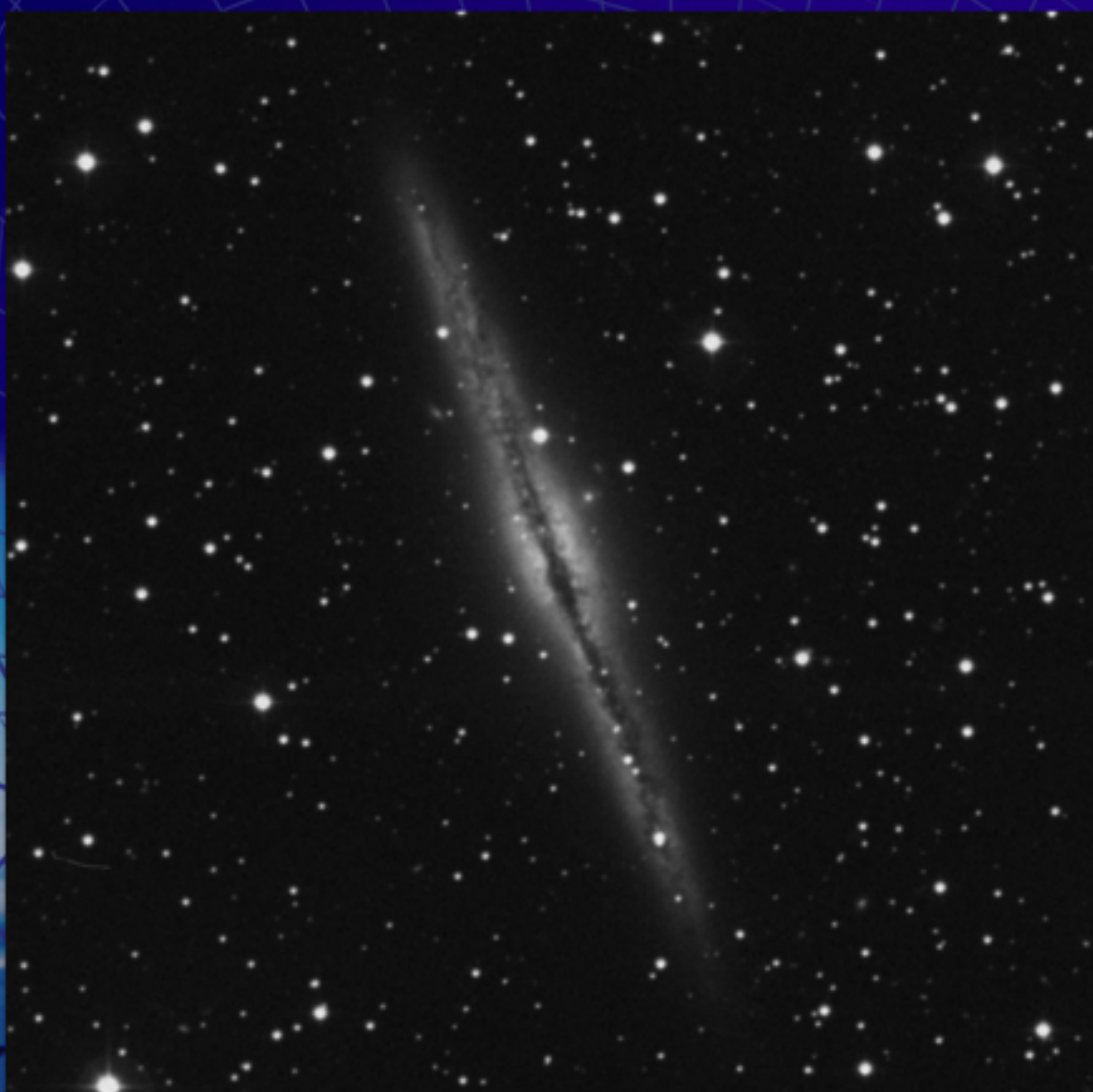


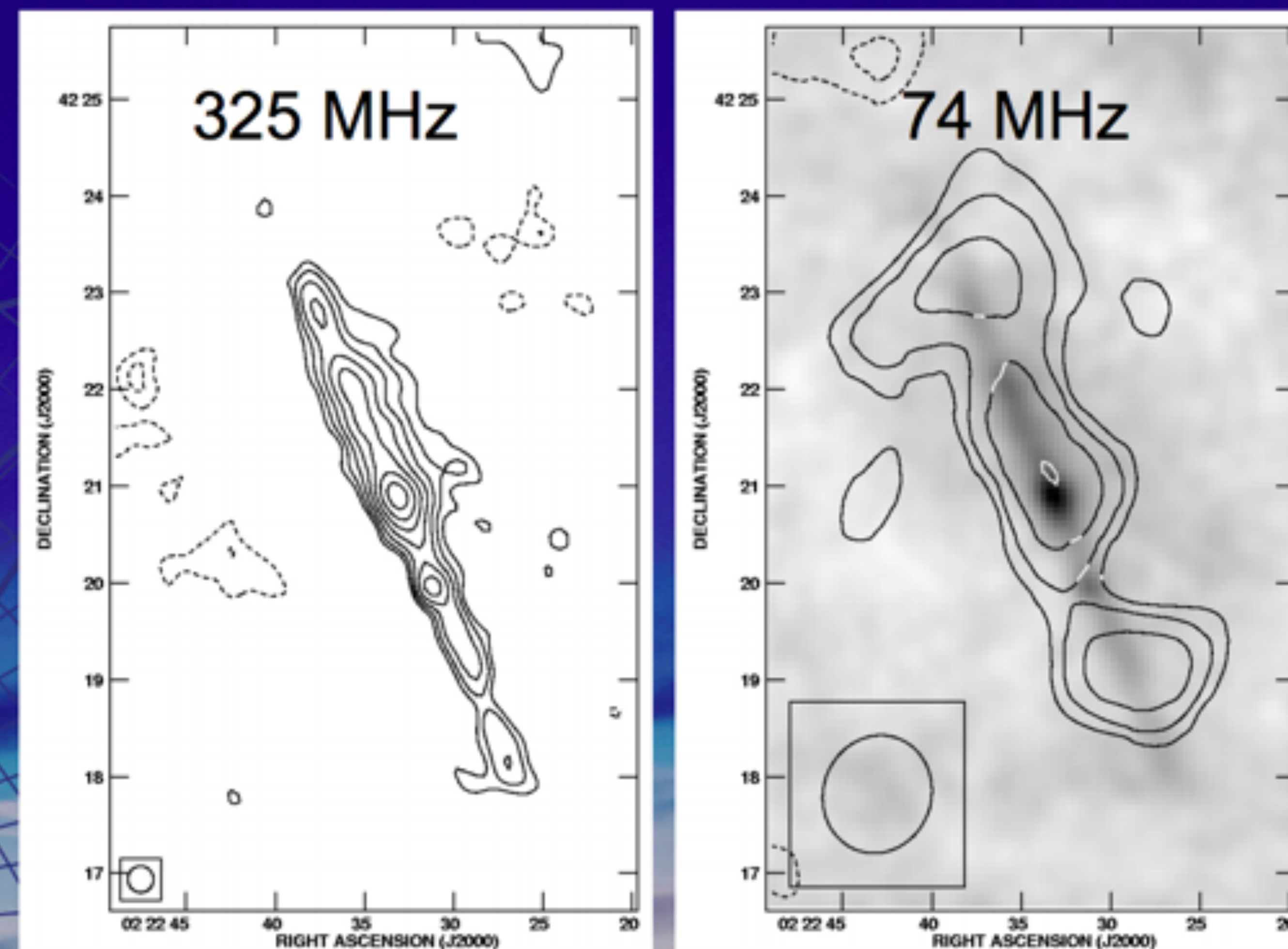
Mulcahy, Horneffer et al. in prep

Courtesy of Namir Kassim

Resolved extragalactic thermal absorption? It must be there, and LOFAR can find it!

NGC 891: POSS II image

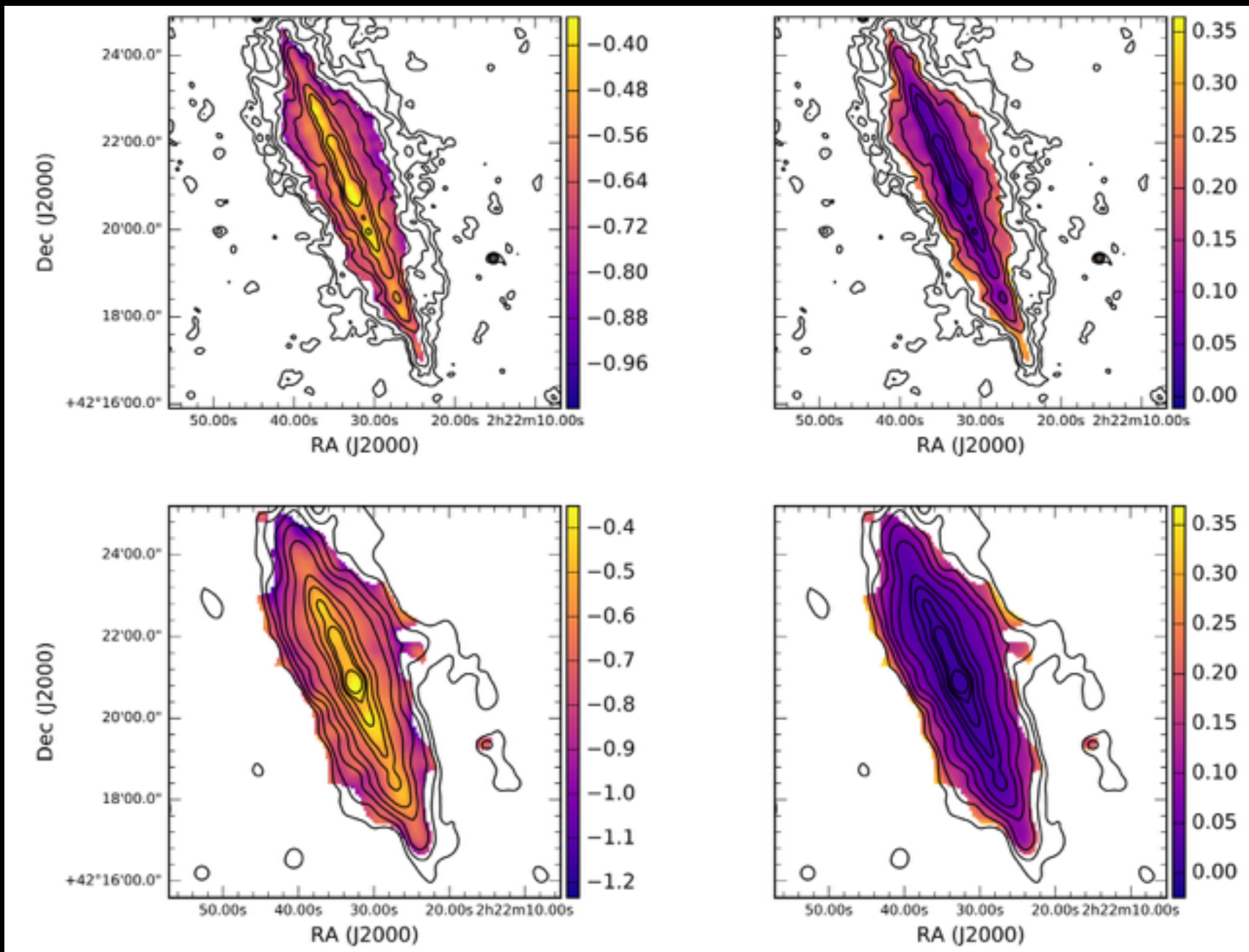




- Cohen, Israel & Kassim, 2004

- Hint of resolved spectral turnover in NGC 891 – spectrum flatter in disk – we need LOFAR to confirm!
  - EG thermal absorption has been predicted by Ger & others & seen at higher freq. (e.g. MERLIN @408 MHz) from higher density HII gas.

Spectral Index of NGC891 146 MHz ->1.5 GHz



Very flat spectral indices observed in the disk

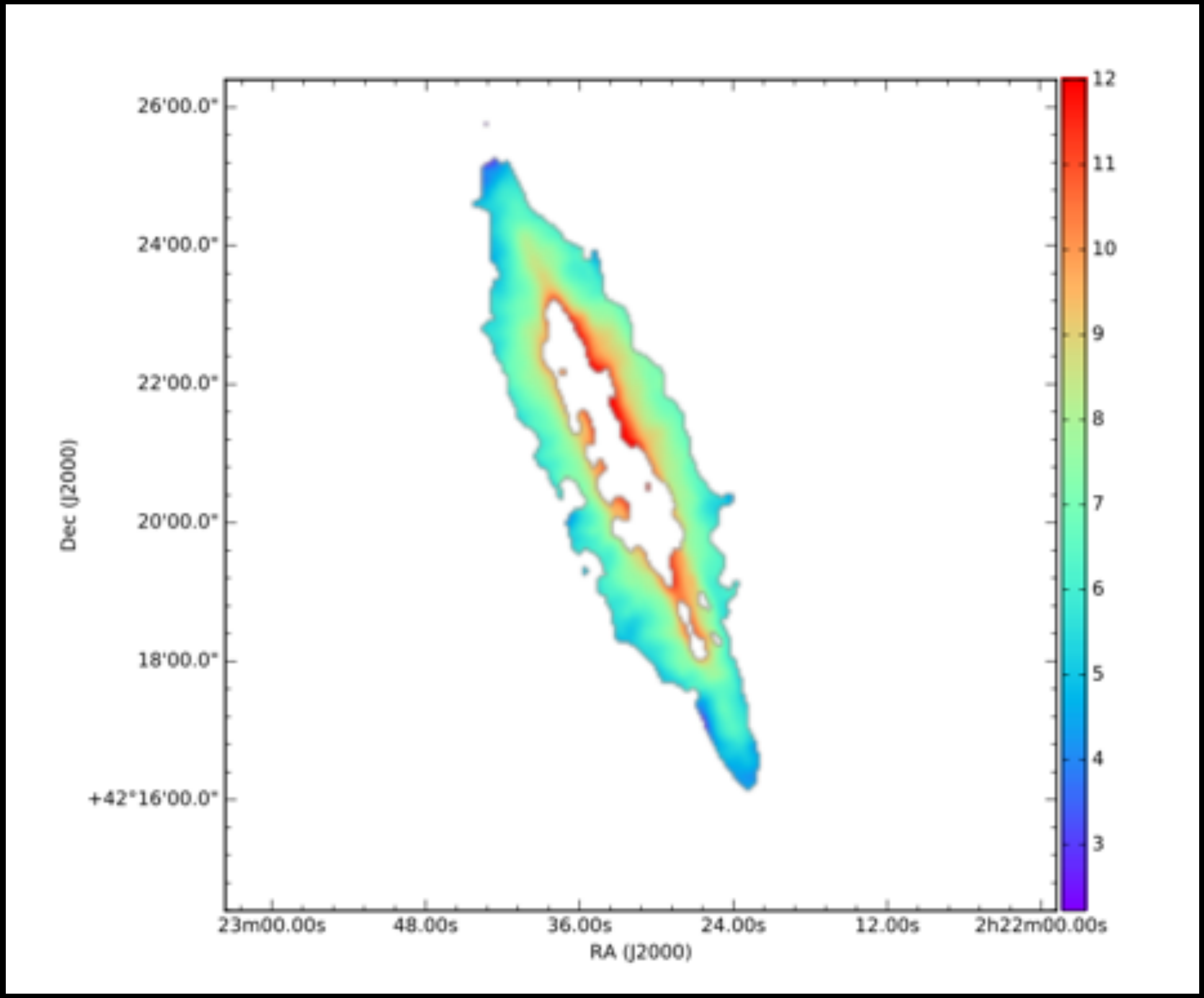
$$\alpha \approx -0.3 \rightarrow -0.6$$

$$\alpha < \alpha_{inj}$$

Significant absorption taking place!

Absorption can cause problems

Magnetic Field strength in NGC891

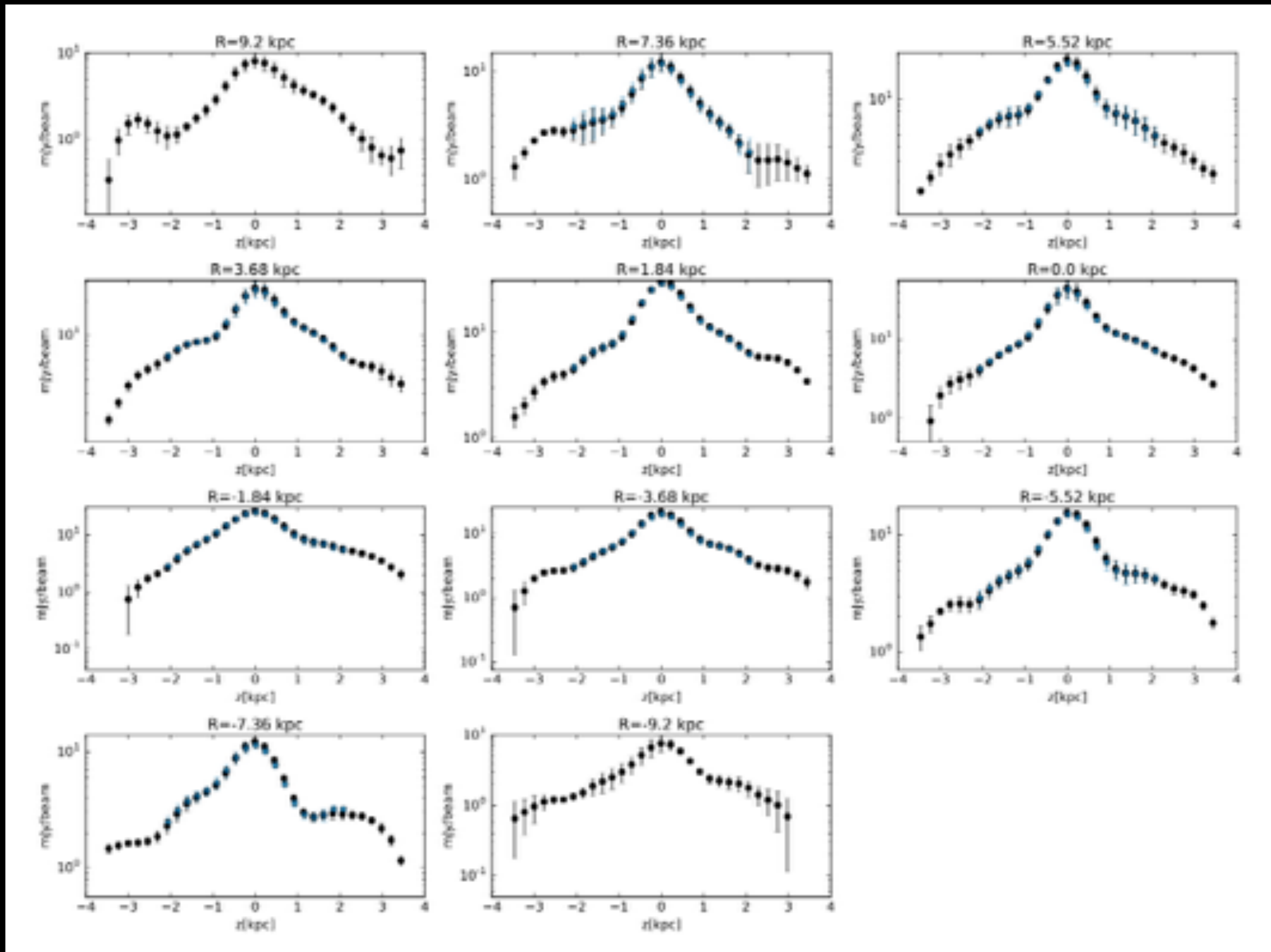


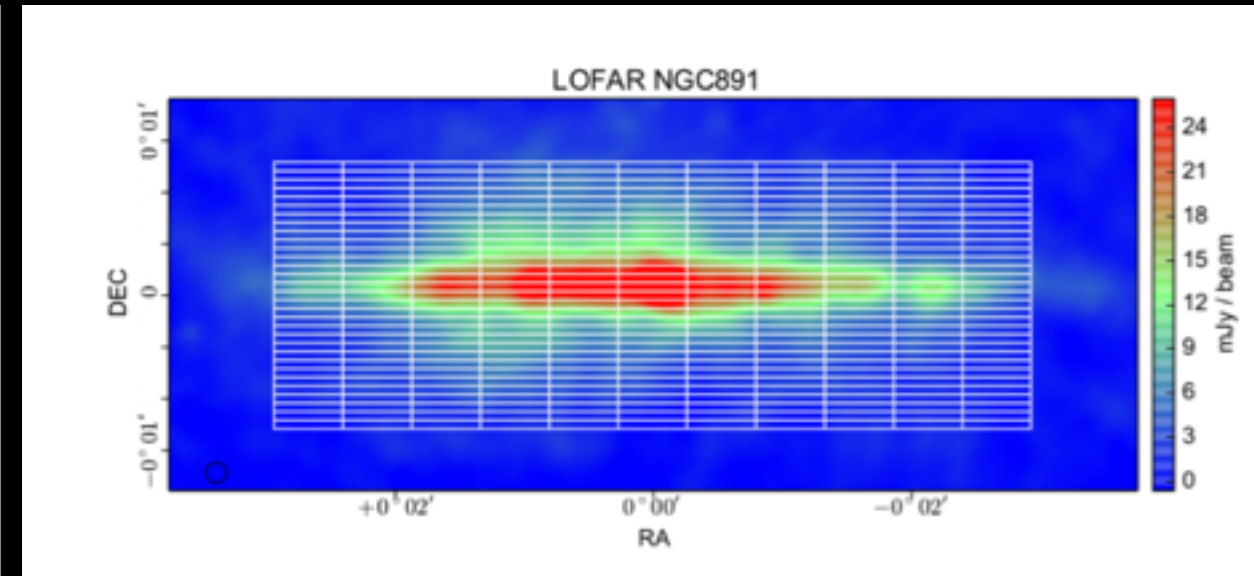
Estimation of magnetic field strength in the disk is impossible with LOFAR due to absorption —> underestimating the magnetic field strength.

Thermal fraction in the disk is also overestimated.

High resolution together with excellent frequency coverage is needed for separation.

Obtaining scale heights





Scale heights at low frequency are consistently larger than higher frequencies.

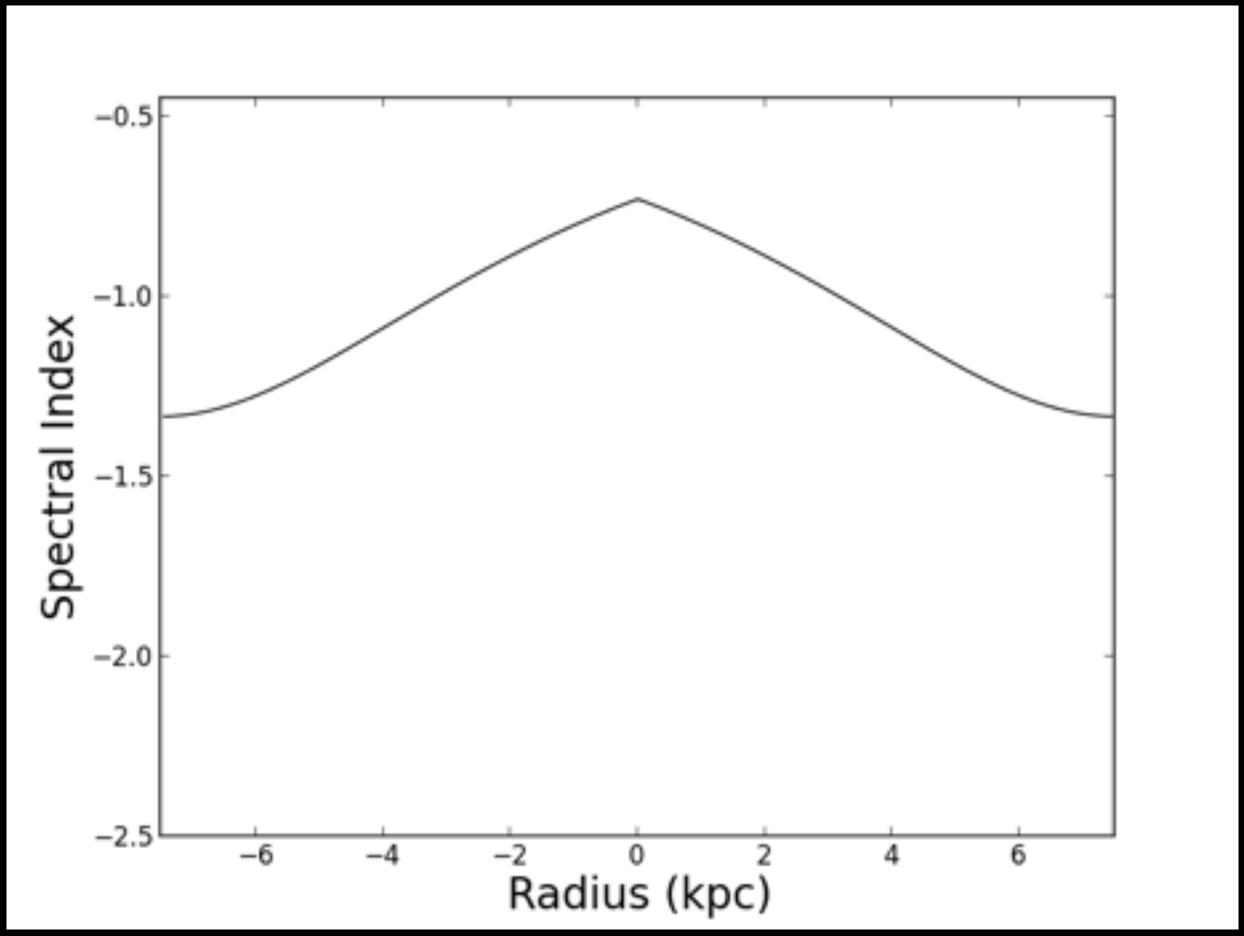
r (kpc)	h_{disk} (kpc) 146 MHz	h_{halo} (kpc) 146 MHz	χ^2_{red}	h_{disk} (kpc) 1.5 GHz	h_{halo} (kpc) 1.5 GHz	χ^2_{red}	$ratio_{disk}$	$ratio_{halo}$
+9.2	0.77 ± 0.22	-	1.9	0.23±0.08	1.51±0.21	2.5	3.34±	-
+7.36	0.4 ± 0.1	3.2 ± 1.3	2.3	0.20±0.014	1.61±0.06	0.27	2.00±	1.98±
+5.52	0.22±0.04	2.03 ± 0.14	1.7	0.13±0.008	1.38±0.03	0.4	1.69±	1.47±
+3.68	0.232±0.066	2.00±0.17	3.8	0.13±0.02	1.35±0.06	5.5	1.78±	1.48±
+1.84	0.357±0.088	2.2±0.5	5.9	0.24±0.04	1.42±0.17	16.5	1.48±	1.55±
0.0	0.24±0.06	1.65±0.29	9.6	0.12±0.02	1.1±0.09	32.2	2.0±	1.5±
-1.84	0.4±0.2	1.6±0.75	7.4	0.18±0.04	1.06±0.078	7.4	2.22±	1.5±
-3.68	0.3±0.06	1.7±0.2	3.2	0.18±0.03	1.14±0.08	5.85	1.6±	1.49±
-5.52	0.31±0.06	2.68±0.43	1.1	0.2±0.02	1.44±0.06	1.46	1.55±	1.86±
-7.36	0.38±0.08	3.21±1.08	4.3	0.17±0.012	1.47±0.05	0.27	2.2±	2.1±
-9.2	0.35±0.06	2.06±0.3	0.2	0.24±0.04	1.36±0.13	0.52	1.45±	1.5±

Further work (modelling)

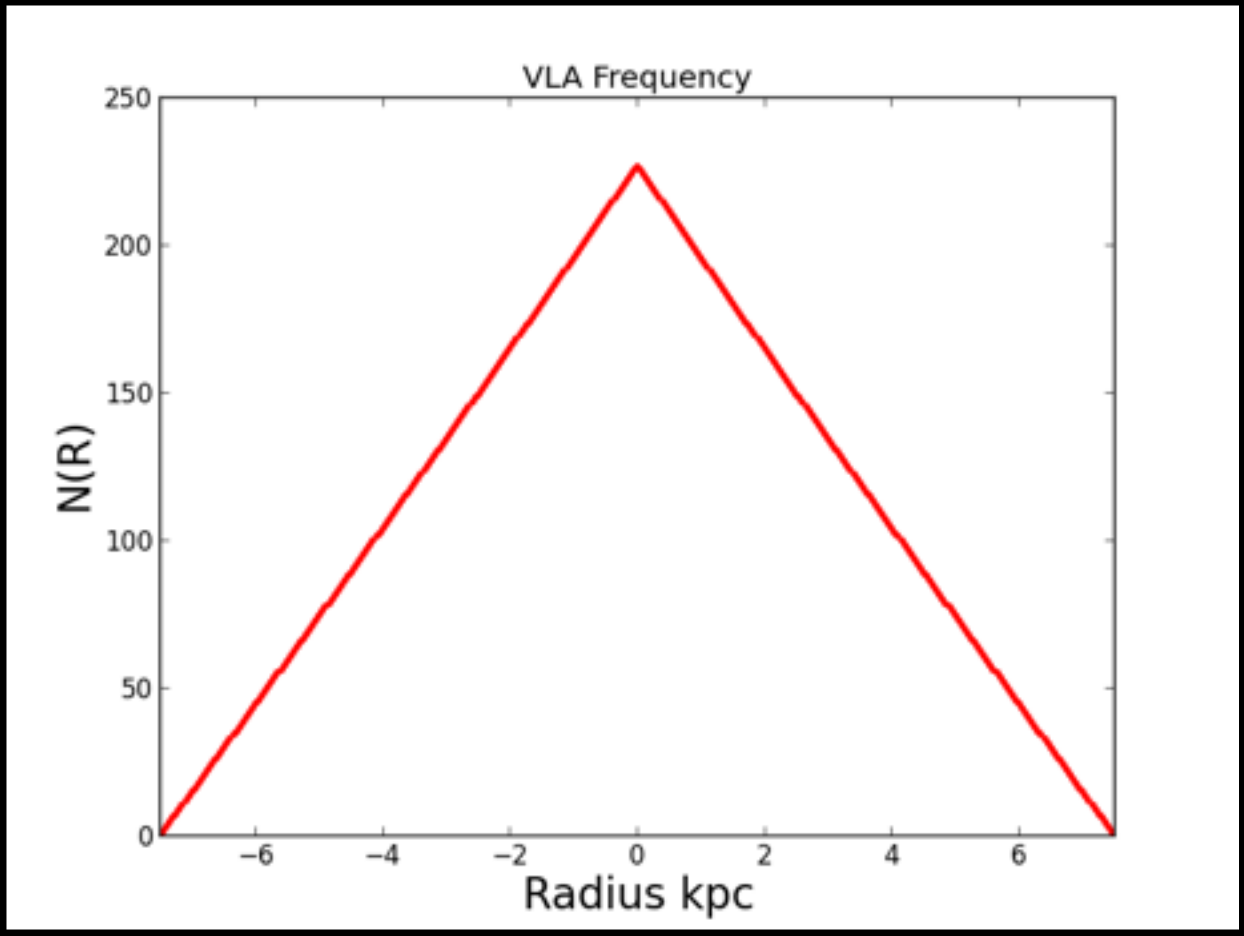
Modelling the CRE propagation in edge-on galaxies

Adapted model for edge-on galaxies.
Need to look into adding convection
and compare to data.

Spectral Index



CRE distribution



Conclusions

- A new generation of radio telescopes are now opening up a new parameter space in the study of nearby galaxies.

- LOFAR is now delivering high res, low noise images of nearby galaxies and we are now able for the first time to resolve different regions of galaxies.

- Able to detect the extended disk in M51 and measure the magnetic field strength

- Found that diffusion is the main mode of propagation of CREs in M51. The combination of observations and numerical modelling enable us to determine the diffusion coefficient and CRE escape time.

- Observations of the edge on galaxy NGC891 show significant absorption in the disk posing problems in the estimation of magnetic field strength and thermal fraction.

Any Questions?

http://lofar-mksp.com

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