A Kaleidoscopic Journey of the Radio Universe

Ger de Bruyn

Kapteyn Institute / ASTRON

The Radio Universe at ‘my’ wavelength ??

I have worked at lots of wavelengths !!
although, indeed, I am ‘ending’ at about 2 m

3.6 – 6 – 13 – 21cm

WSRT
VLA/GMRT
LOFAR

49cm - 92cm - 198 cm

= 151 MHz ‘protected’ band !

My family, in 1956, after the birth of #6 !

That's me at 7 years

Turning 90 today
Happy birthday, Mum !

My father and brothers grew tulips/chrysanthemums/azaleas.

Astronomy came in view at high school

1961 talk on
'Mariner flights to Venus'

Small 6 cm refractor at age 16

Starting out in Leiden:

1966-1972
study
masters

1972-1976
PhD

Contents of my talk

- Role of serendipity
- WSRT research: SN(R), (active) Galaxies, Seyferts → radio--optical
- High dynamic range imaging: 3C84, 3C147, CygA → AGN
- Radio Source Variability
- Interstellar Scintillation and the diffuse (very local) ISM
- The Galactic foreground and linear polarization (OH471,PSRJ0218)
- HI in the Universe (DLA's 3C196, 1830-21 inside TV-band !)

- Wide field imaging (3C196 view from 2007) , preparing for LOFAR

All this research prepared me for the LOFAR EoR project:

Technically challenging and scientifically exciting

- LOFAR and the EoR

From here to there and back: an exciting 40-year journey

EoR at z=10

Peter Shaver
Frank/Saleem/Leon
+ growing EoR team

Peter Katgert
Marijke/Dominic
Vibor

Very Local ISM /
diffuse polarization
(z=0.000000001)

HI in DLA
z = 3.4, z=0.8

Peter/Frank/Mark Wieringa
Nissim/Jayaram

Richard/Ignas
Jane/JP/Mark Walker
Leon + 'CLASS'

pulsars
recomb lines,
AGN / ISS
variability,
lensing

Arno/Huub/Harry

Harry/Tony
Andrew

Giant + DD Radio Galaxies
z = 0.5 - 1

Dolf/Michiel/Roberto

Synchrotron sources
R(SNe) / Galactic disks
Seyferts
↓

'70 – '80 ies

Clusters: Perseus/A2255
z = 0.02 – 0.08

Optical
Ernst/Colin/Giovanna/
Wal/Tony + 'LAG'

Serendipity and careers

Serendipity plays a big role in astronomy but especially in my astronomical career.

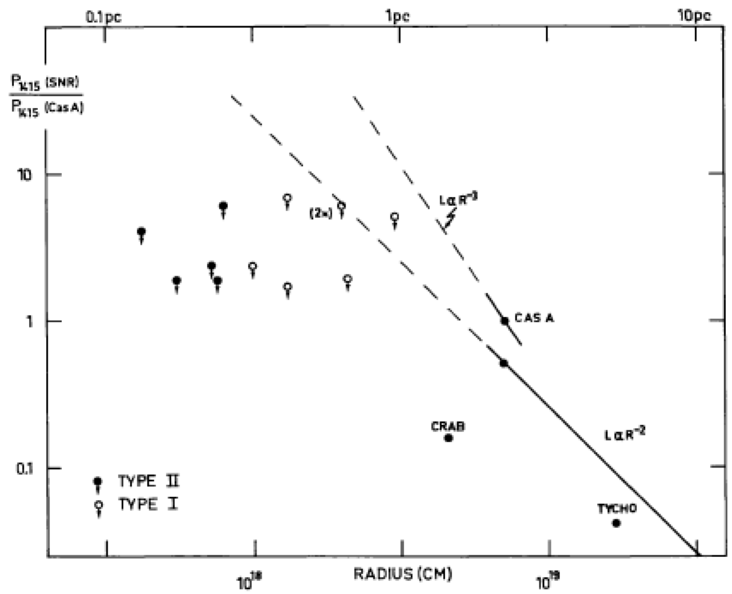
Some themes were chosen (like AGN), but the following were all in a significant way effected by serendipity

- Radio SNe
- Galactic foreground Polarization
- Double Double Radio Galaxies
- Scintillation in AGN

Radio SNe and SNR

Upper limits at the start of my career……… sigh !

Searching for radio emission of young (1-70 year old) RSNe and SNR in external galaxies using WSRT 1970-1972   (40x12h) !



Alas…..   only upper limits !

But they require you to think harder (remember Colin ?!)

This masters project taught me a lot about synchrotron theory, brightness temperatures, absorption (FFA and SSA),……. concepts and processes that I have used actively till today .

In hindsight, I am glad I had a chance to begin work on a totally different topic: AGN.   I have worked on this, on and off, for 40 years.

The many facets of AGN

The many faces of Active Galactic Nuclei

- Very broad-band phenomenon (m-mm, infrared, optical/UV, X-ray , γ-ray)
- Important role in feedback on Galaxy formation (especially in clusters)
- Relation between AGN and (nuclear) starburst galaxies
- NLR, BLR, accretion disk, reverberation mapping

What could radio studies tell us ?

- Fuelling, 'duty' cycle

- Lifetime, total energy → SMBH lower limit

- AGN as luminous ionizing probes in IGM and during EoR

- Ultra-compact source: energy release and jet launching

- LOFAR, (de-)polarization & tiny columns of magneto-ionic medium

- Using AGN as probe of (very) local ISM

From WENSS to MSSS

‘every astronomer should do at least one major survey’

(they broaden your horizon, and appreciate astronomy more)

But you should do only one !

Hence I am really glad George Heald so ably took over MSSS !

WENSS – WEsterbork Northern Sky Survey

When ? 1991-1995 (> 1 year telescope time)

How ? 70 mozaics, each 6x12h, 5500 pointings

(Robert Braun, Hans van Someren Greve,
Wim Brouw - NEWSTAR)

What ? 10,000 $\square^{o}$
Dec > +30^{o}
325 MHz B=5 MHz (7 channels)

Products: catalog ~ 250,000 sources
S > 18 mJy (5σ)
492 6^{o}x6^{o} frames (500 Mpixels)

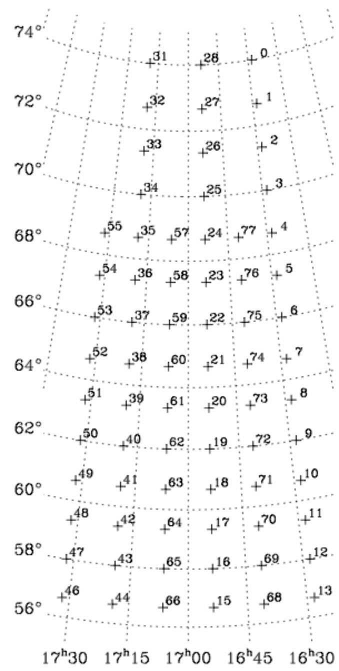


Fig. 3. The field pattern for the $\delta = 66°$ mosaics. In this case the pattern for mosaic WN66-255 is shown. The field are numbered according to the sequence of observation. Missing numbers refer to so-called "moving" pointings, inserted to bridge large field separations

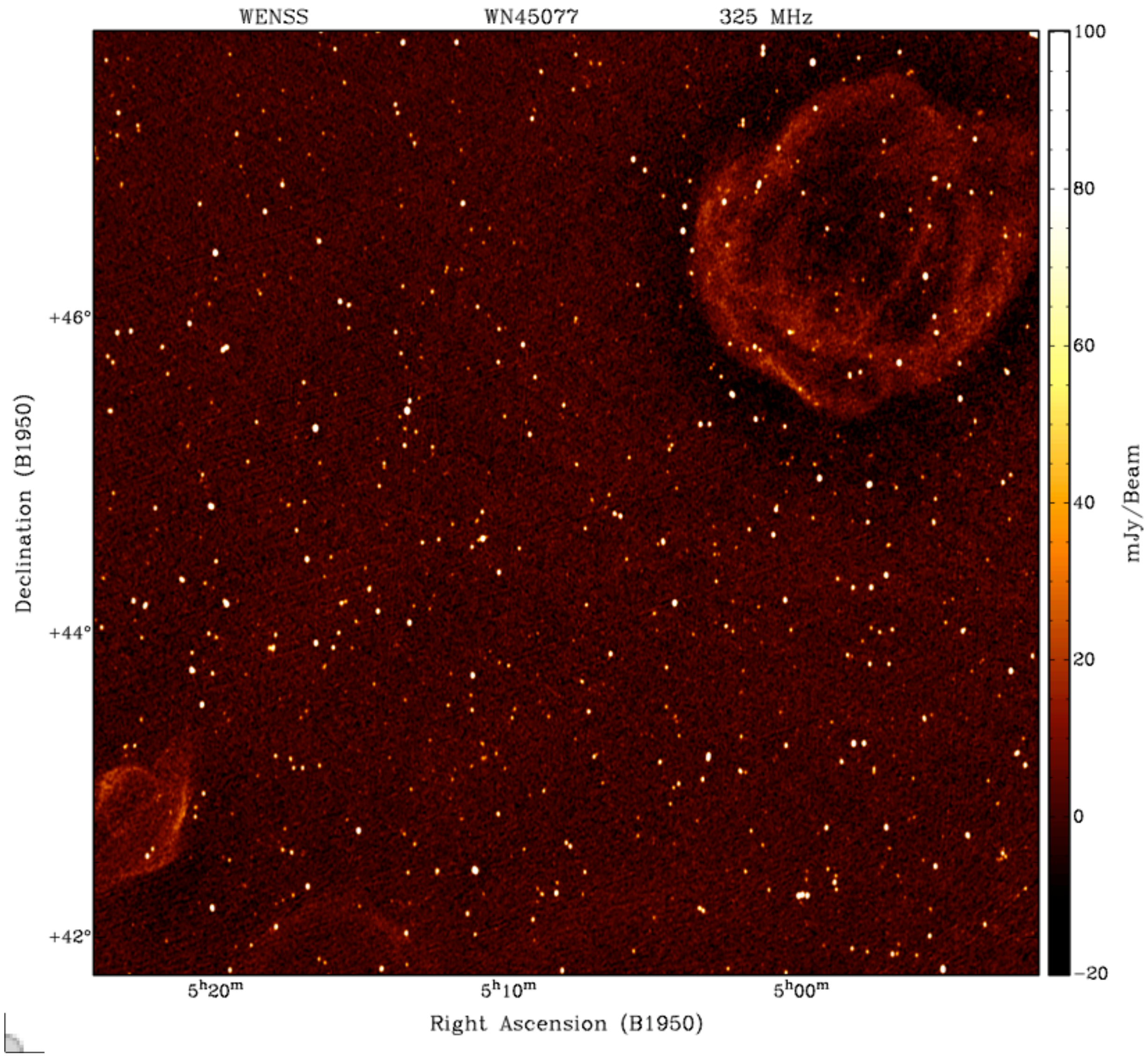
Who? ASTRON-Leiden project
(Ger de Bruyn, Yuan Tang, Wim Brouw, Ernst Raimond
George Miley, Roeland Rengelink, Martin Bremer, Malcolm Bremer,
Huub Rottgering, David Fullagar)

Refs? Rengelink et al, 1997 + ~5 - 10 theses (that used the data)
www.astron.nl/wow/ → images, catalogs and plots (B1950/J2000)

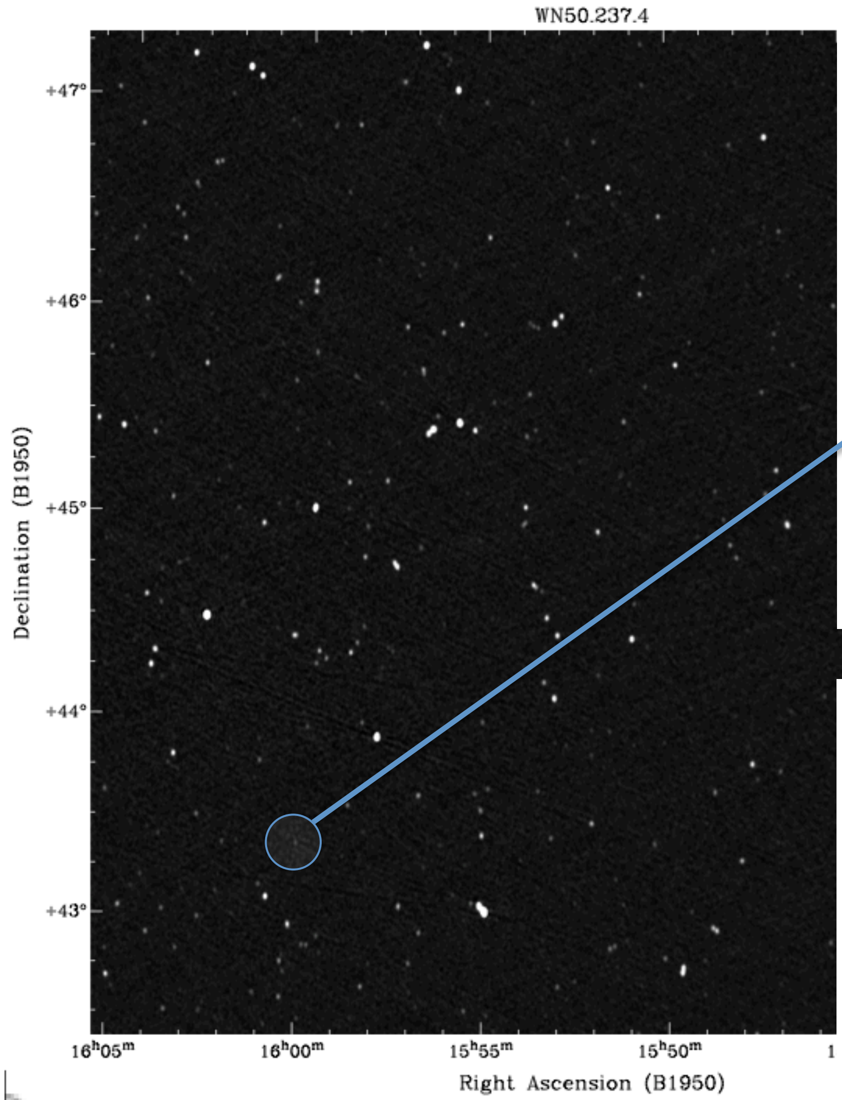
WENSS sample image

One of the 492 6 x 6° frames in the Galactic plane

Auriga A (~ 2°)



WENSS spinoff → CLASS lenses



Jackson et al, 1995

1600+434: a new gravitational lens system L27

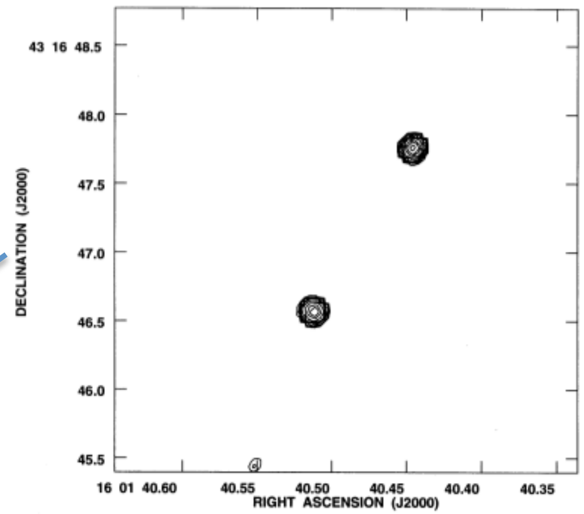


Figure 2. The radio map of 1600+434 at 8.4 GHz. Contours are given at 1 mJy beam^{-1} × [0.5, 0.8, 1.3, 2, 3, 5, 10, 20, 30, 50].

VLA-A
3.6cm

Koopmans, de Bruyn & Jackson, 2000

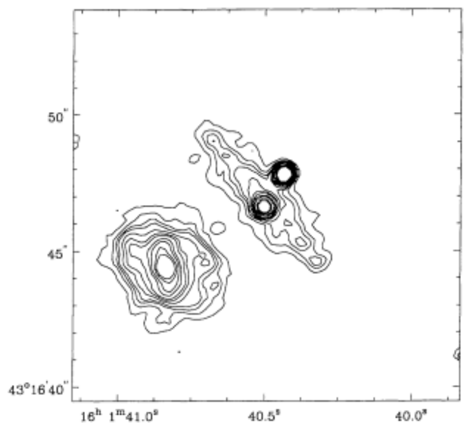
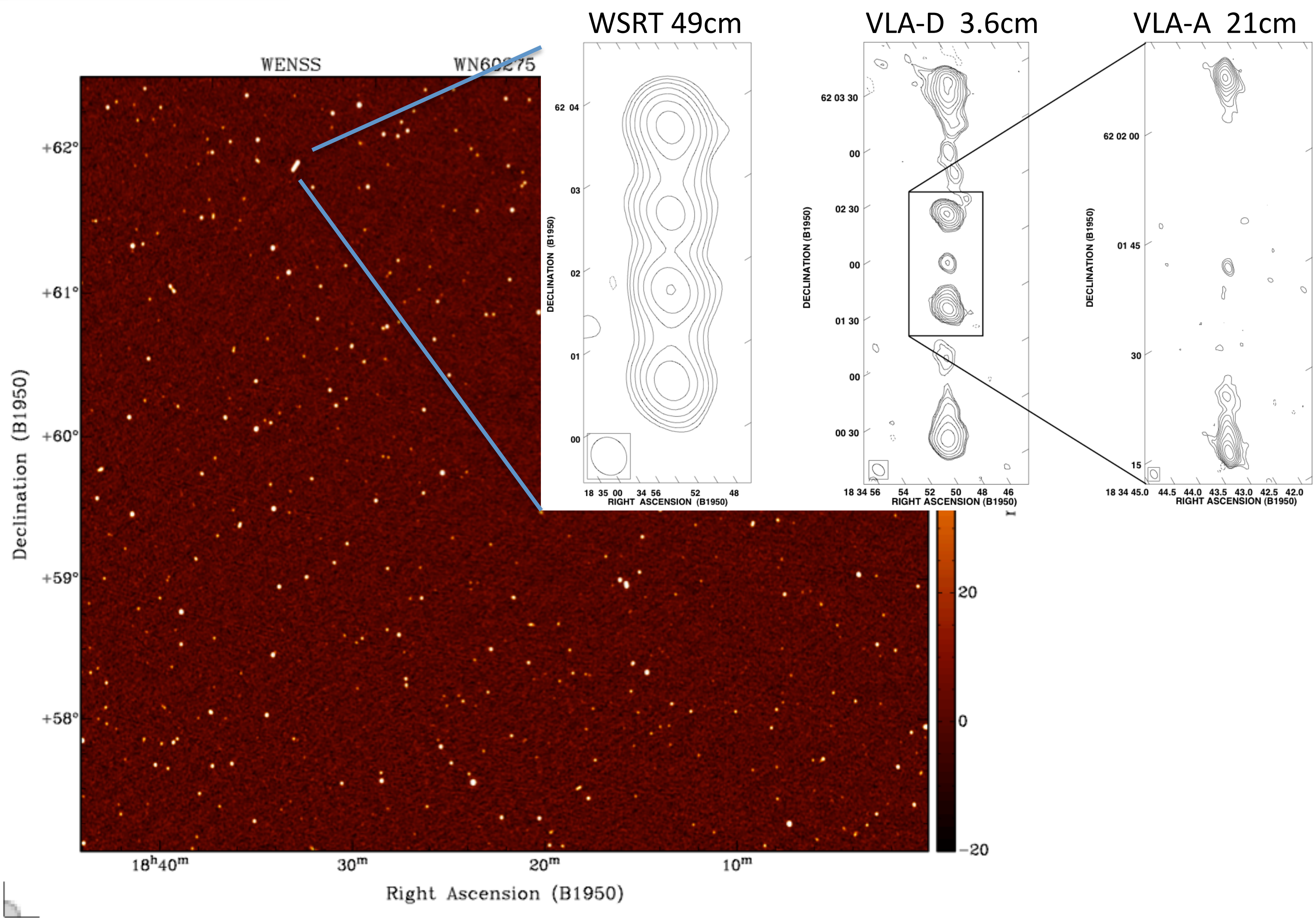


Figure 2. Upper left: Nordic Optical Telescope (NOT) *B*-band image, upper right: NOT *R*-band image, lower: deconvolved NOT *R*-band image. 1 arcsec corresponds to a physical size of 6.5 kpc at redshift $z_l = 0.415$ and $h_{50} = 1$.

Optical

Another WENSS spinoff →DD Radio Galaxies



Giant Radio Galaxies and DDRG's

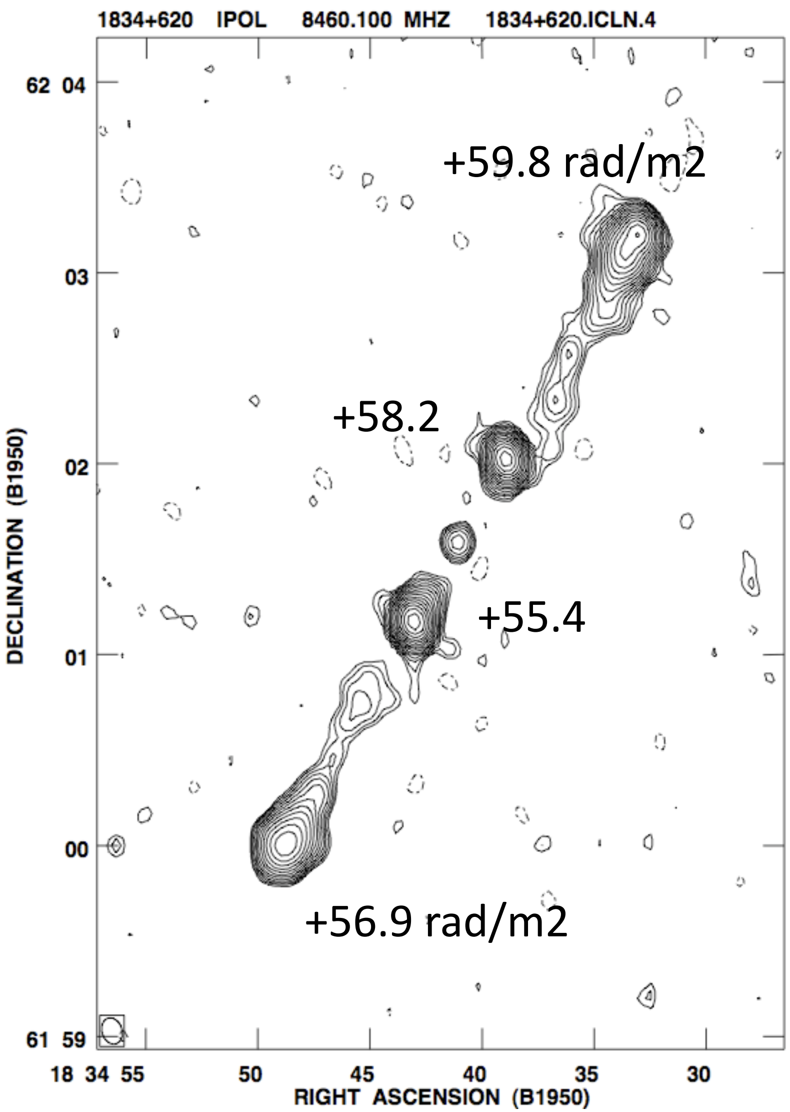
Why are giants and DDRG (mostly giants as well) interesting ?

(also discussed by Röttgering/Morganti/Shulevsky)

- AGN duty cycles
- AGN re-orientations after re-fuelling
- large lobes, tenuous medium → linear polarization (use as calibrators)
- probes of RM in the IGM

- Manu Orru talk on B1834+62, prototypical DDRG, was cancelled

The double-double radio galaxy B1834+62 (WSRT/VLA)



Schoenmakers et al (2000)

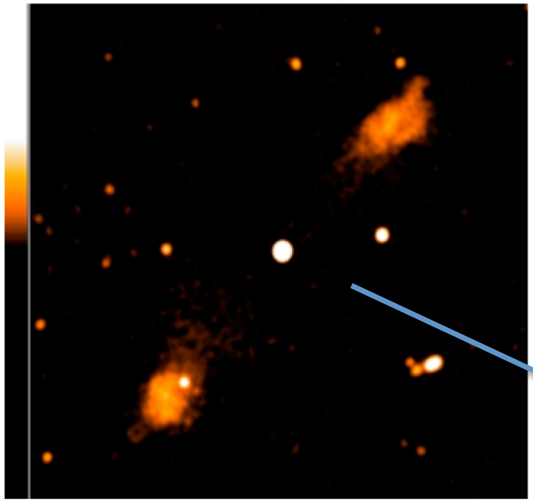
z = 0.54

1.2 Mpc size

Four highly polarized lobes at 92cm, possibly at 2 m as well.

Small RM difference ~ 3 rad/m^2

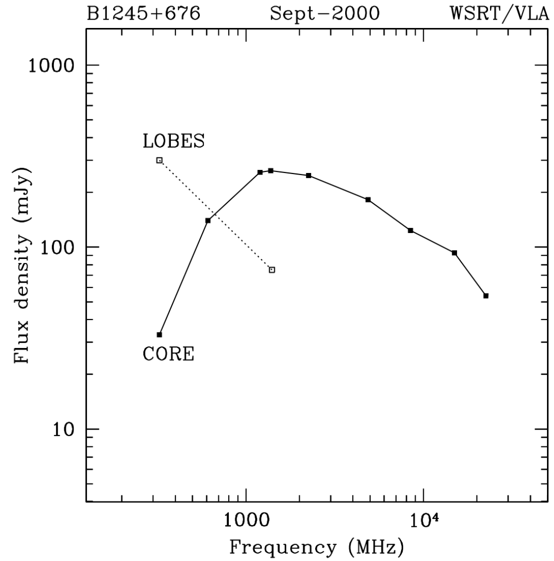
An extreme, misaligned, double-double: B1245+67


WSRT 21cm

10‘

de Bruyn, Wieringa 1991,2001 (unpublished)

Giant Radio Galaxy
z = 0.107, D = 1.4 Mpc
with a dominant core.



Lobe/core size ratio ~10^5:1

Core-components separate at
35 +- 2 µas/yr = 0.23c
→ kinematic age: 190 years

30^o misalignment core and lobes

VLBI: Marecki, Barthel et al, 2003

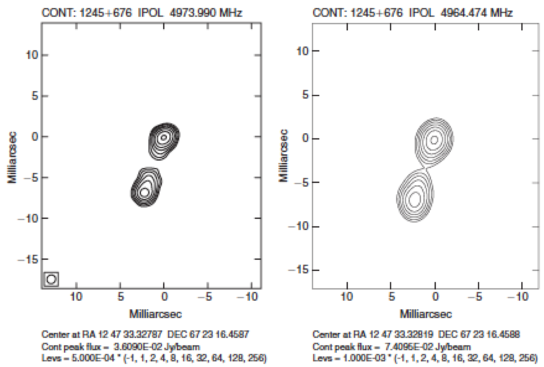
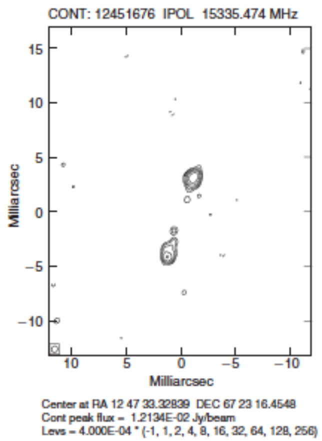


Figure 2 VLBI images of 1245+676 at 5 GHz for epochs 1991 and 1998.



A triple-double radio galaxy: B0925+420 *Brocksopp etal , 2007,2011*

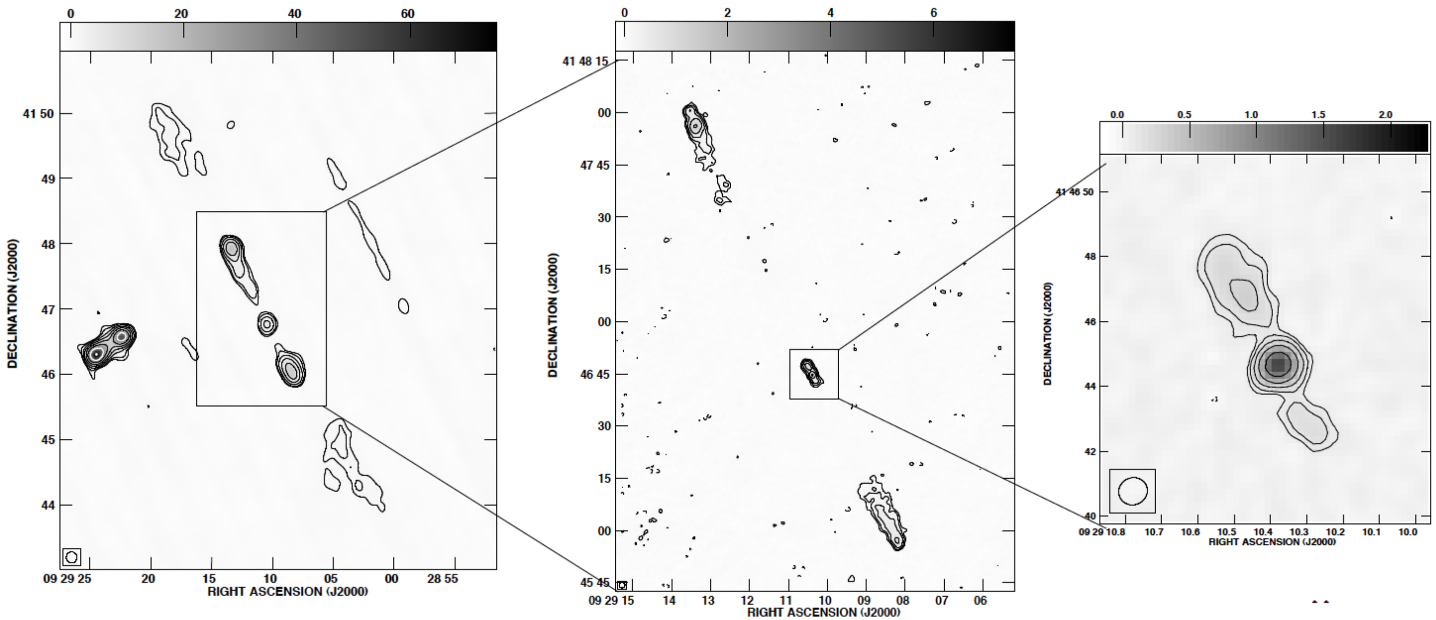


Figure 1. VLA images of B0925+420 showing the three pairs of lobes. All contours are at -3, 3, 6,

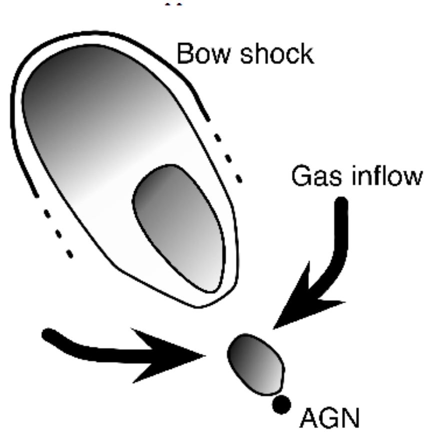
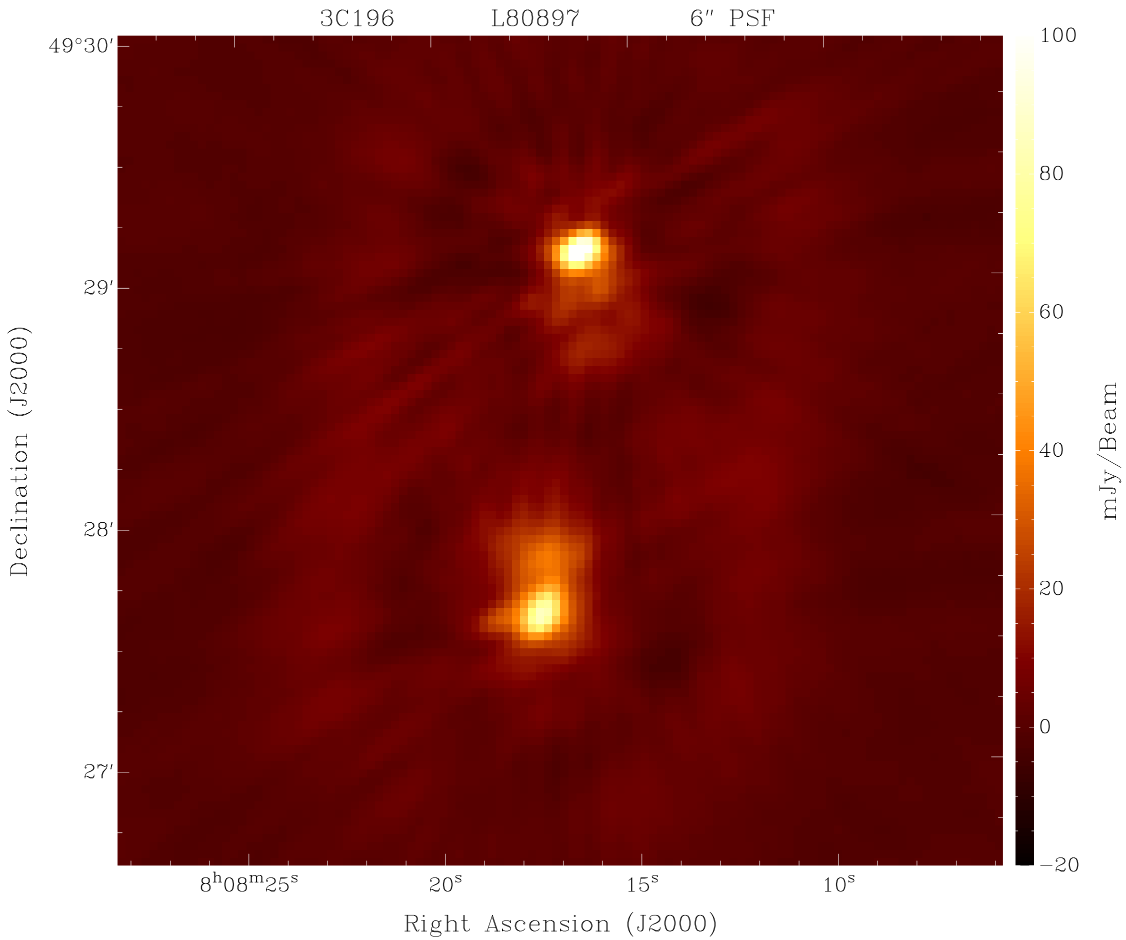


Figure 5. Schematic diagram illustrating the results of the modelling. The outer lobe, containing the middle lobe, has started to rise buoyantly and is being replaced with the heavier ambient medium. The darker shading represents the part of the lobe which may still be overpressured with respect to the surrounding medium and so may continue to drive a bow shock.

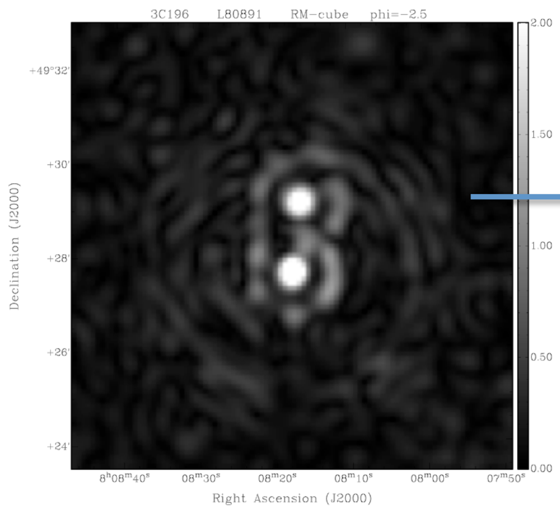
Note that the inner structures are true lobes, with hot spots, and not 'knots in a jet'

Polarized double radio galaxies in the 3C196 field

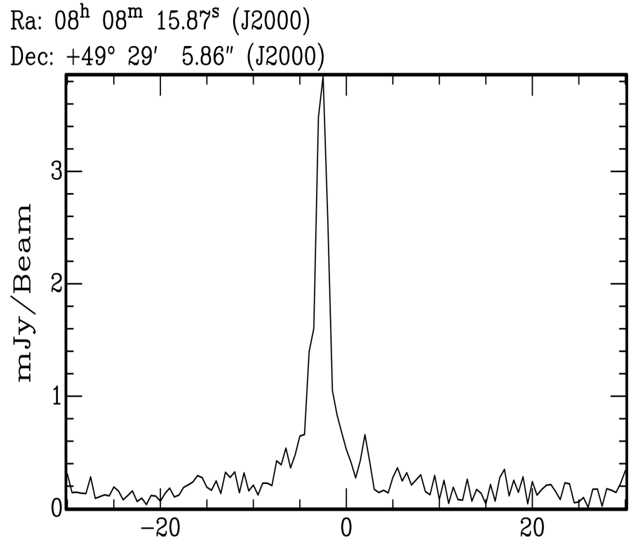


High resolution 6" PSF raw image

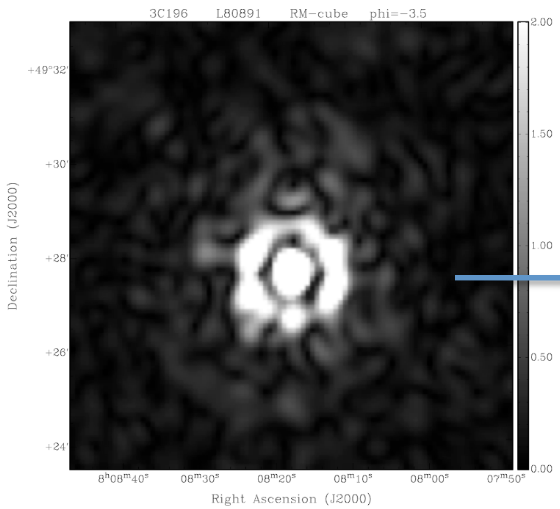
Frames and spectra at higher angular resolution (30”)



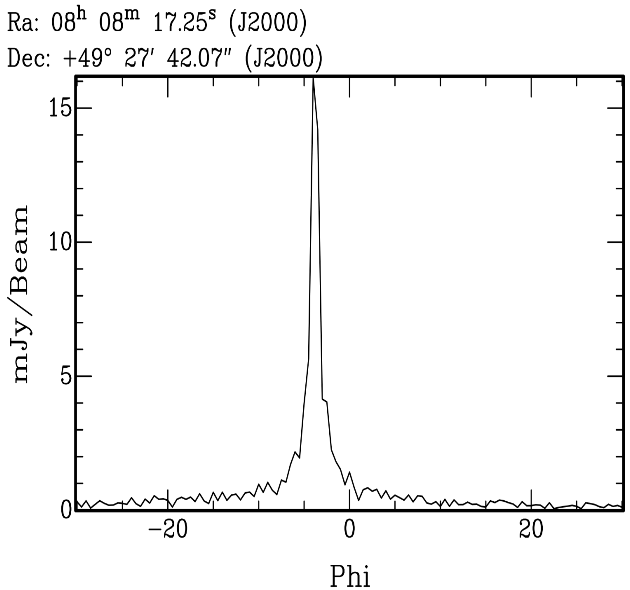
RM = -2.5 rad/m^2



9’x 9 ‘



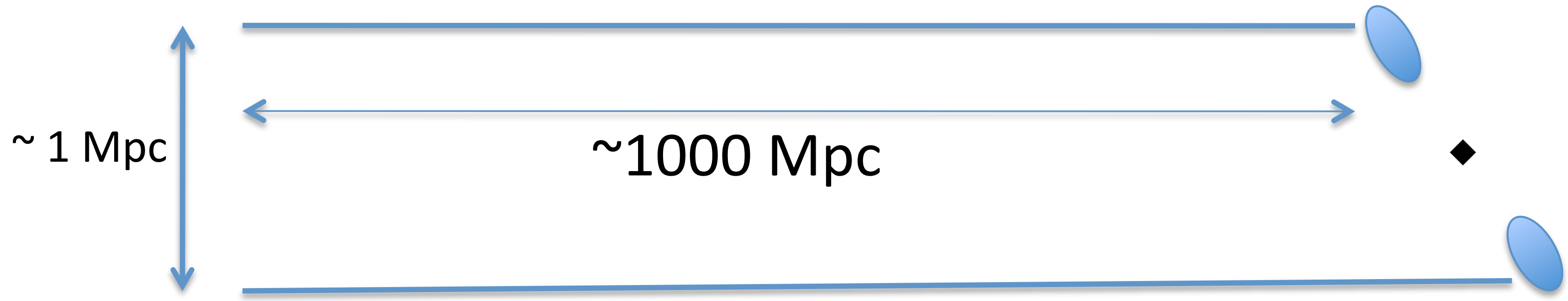
RM = - 3.5 rad/m^2



NB: halfwidth of RMSF = 1.0 rad/m^2 !!

Science at 1 rad/m^2:   physical implications

2 polarized lobes probe two very deep lines of sight in IGM



What does it take to build up a Faraday depth of 1 rad/m^2 ?

ISM:	0.1 cm^{-3}	x	10 pc	x	1 μGauss
IGM (z=1):	10^{-6} cm^{-3}	x	10 Mpc	x	100 nGauss or
			1000 Mpc	x	1 nGauss
RG cocoon	10^{-5} cm^{-3}	x	100 kpc	x	1 μGauss ?

but also:

ionosphere:	10^{6} cm^{-3}	x	100 km	x	0.3 Gauss

(differential ionospheric RM on 5’ scales <0.01 rad/m^2)

AGN and variability

Radio source variability

Recurrent theme in my research

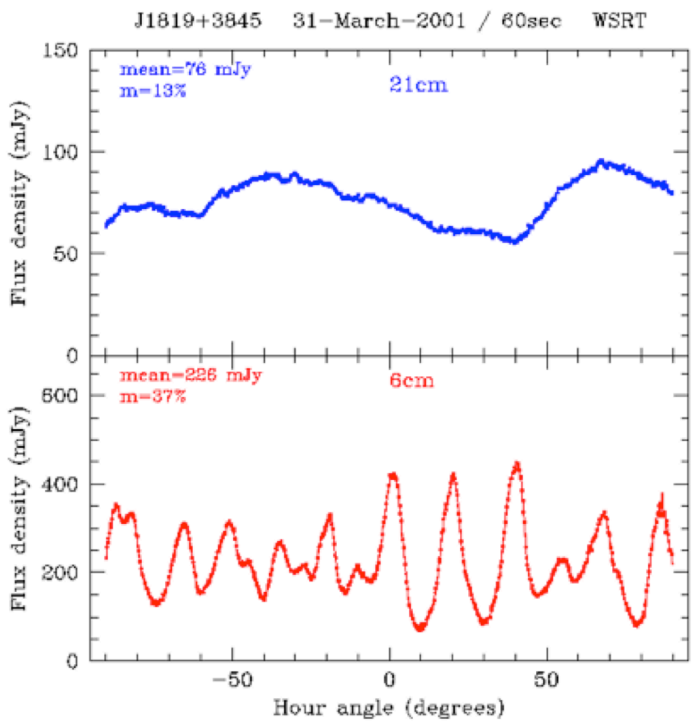
- Radio SNe
- Seyfert galaxies: radio/optical
- 3C84 majopr outburst starting in 1960
- OJ287 mispointed jets…
- GPS sources: e.g. OQ208

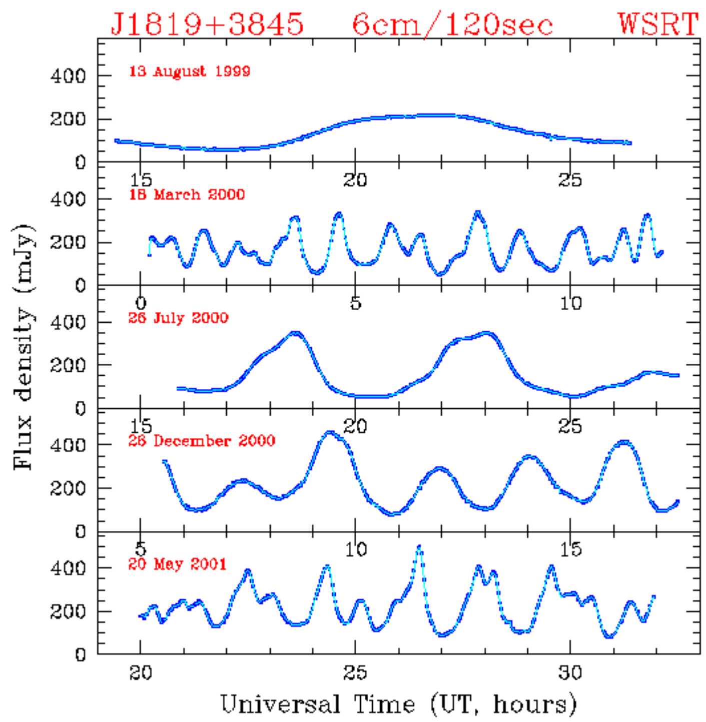
- All of this work did not quite prepare me for what was to come in Jan 1999:

With Jane Dennett-Thorpe: study of ultra-compact AGN

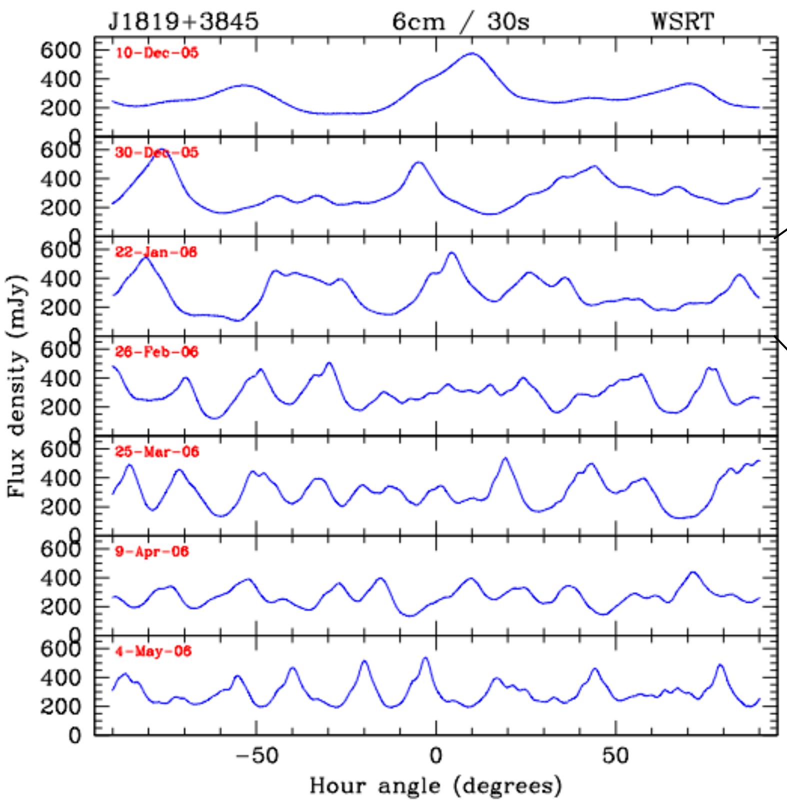
10,000 CLASS sources
100 inverted spectra sources (VLA, rising flux to 8 GHz)
10 follow up with WSRT
1 outstanding (+1 more ?) → J1819+3845

J1819+3845: early results

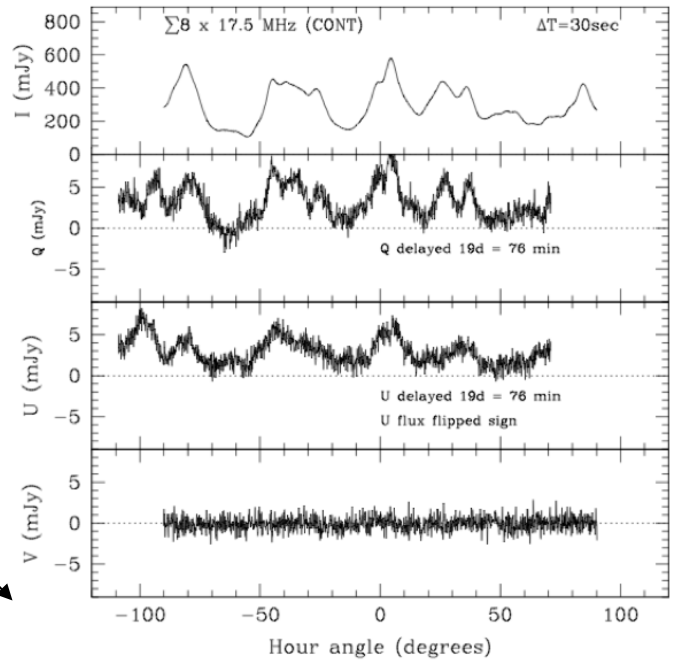


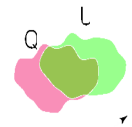


Stokes I,Q,U,V variations in Winter/Spring '05/'06

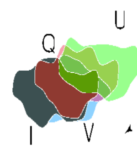


22 Jan 2006



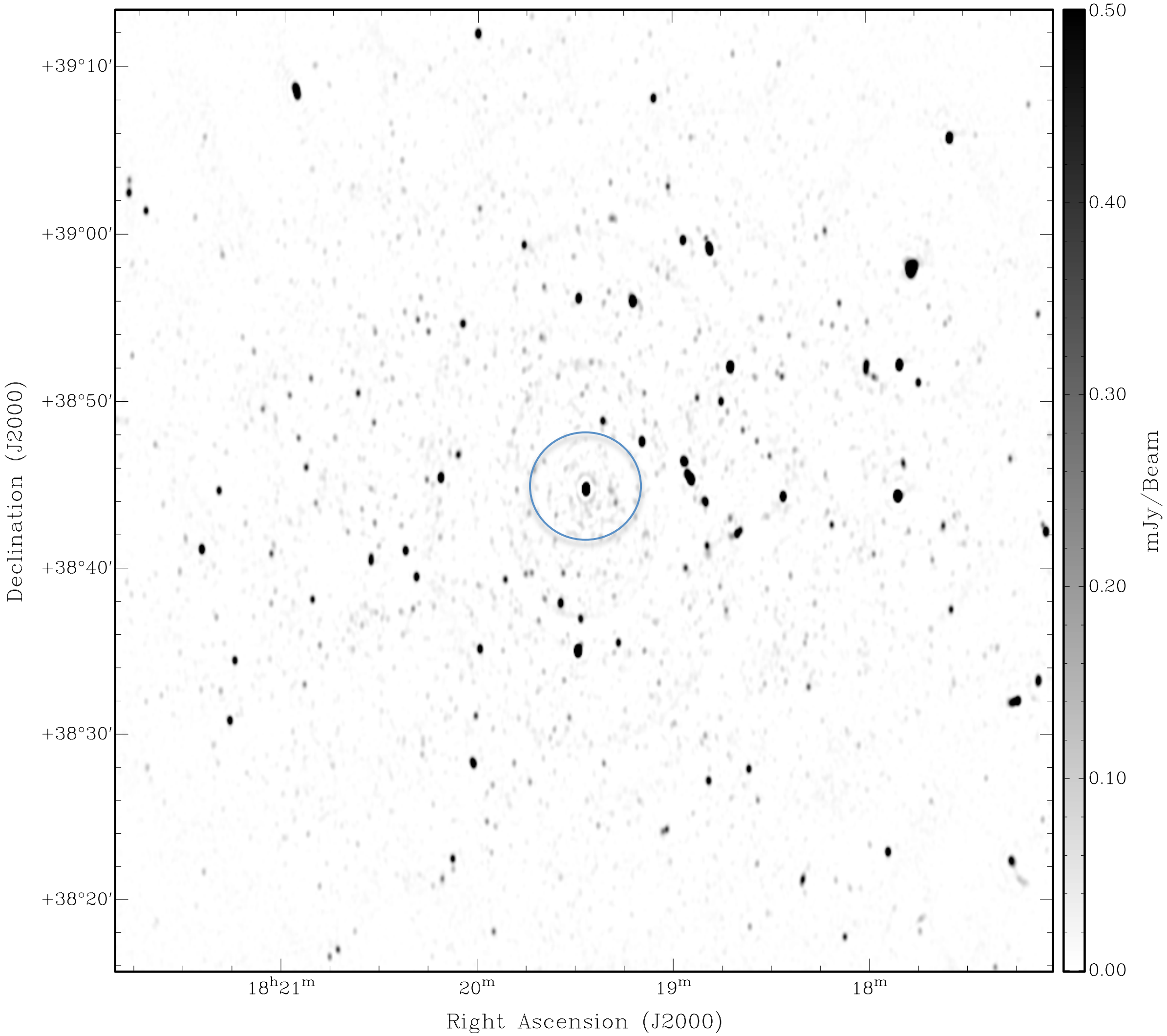


Time delay between I and Q/U varies smoothly
from > 4^h in Dec 2005   to 55^m in May 2006   →
small displacement between I in core and Q/U in jet



cartoon

J1819+3845 13x12h average 21cm



13x12h average of a variable ! source

Noise in the image corners ≈ 4 μJy

Elsewhere confusion limited.

High dynamic range imaging

WSRT observations aimed at high DR

Recent results: several successes but also problems:

- '21cm band' 1175 - 1460 MHz

  Perseus cluster 6x12h (1994 - 2003)
  3C147 3x12h (2003 - 2006)

- '1 meter band' 310 - 390 MHz

  Perseus cluster 6x12h (2002)
  J1819+3845 1x12h (2004)

- '2 meter band ' 115 - 175 MHz

  Cygnus A (2005 - 2006)

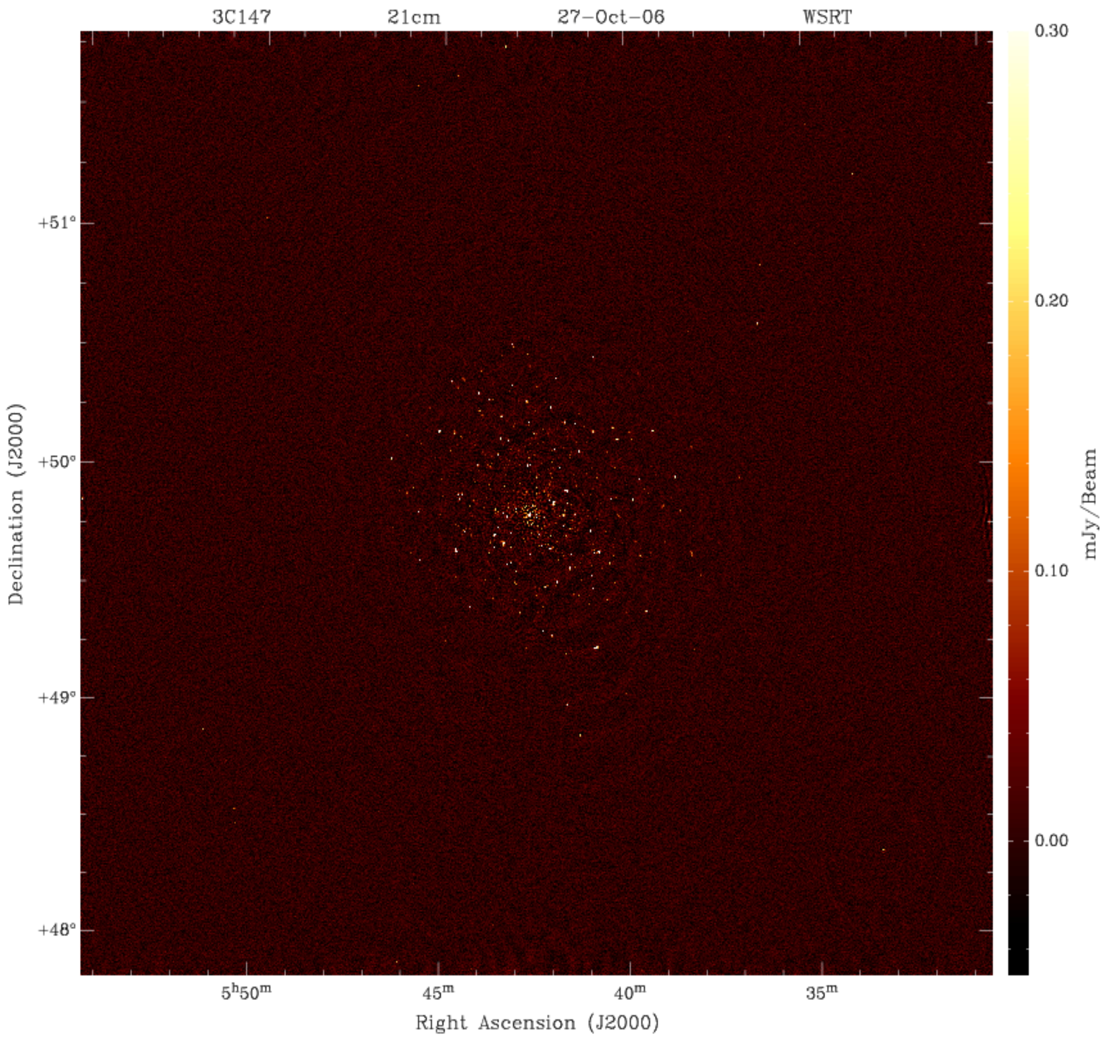
WSRT-backend:

8 x 20 MHz, each 64ch x 4pol

8 x 10 MHz, each 128ch x 4pol

8 x 2.5 MHz, each 512ch x 4pol
(70 Gbyte !)

WSRT 3C147 21cm with a very wide FOV



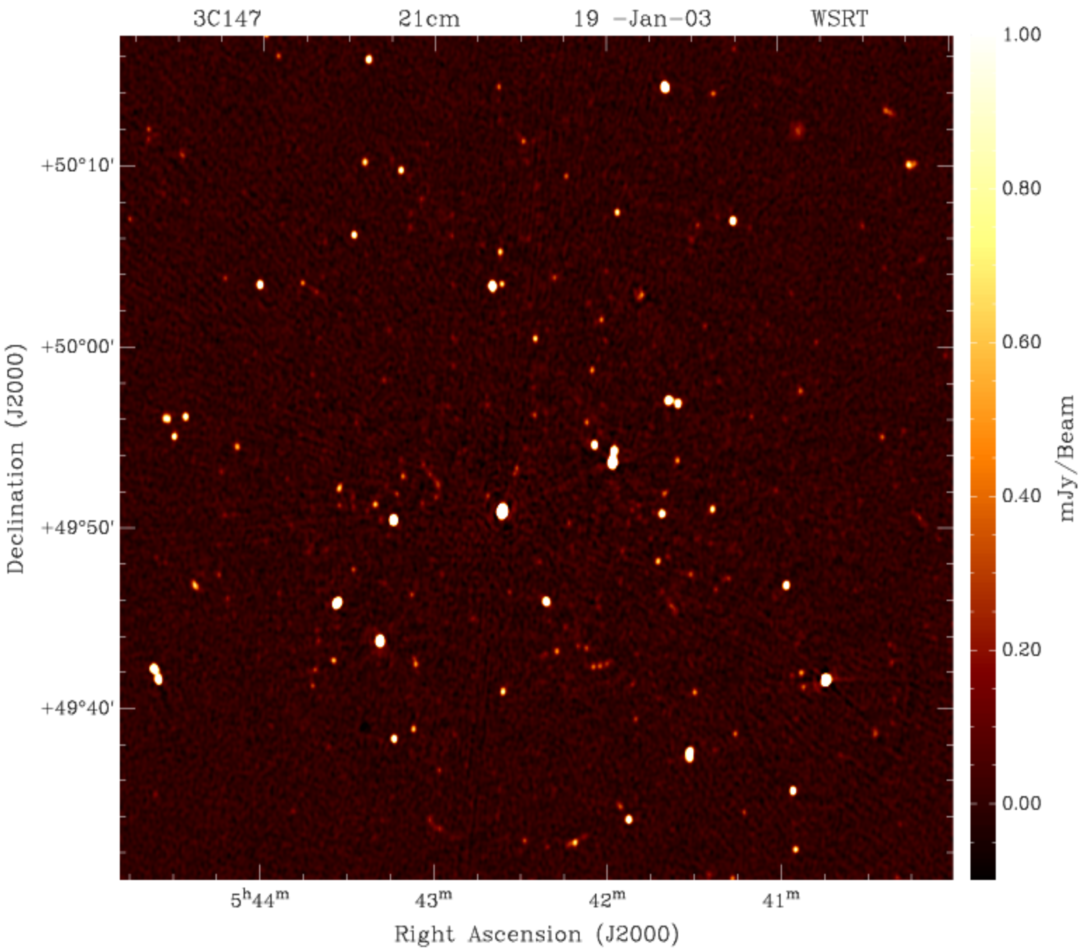
4° x 4° area

HPBW = 0.6°

Note that first sidelobe much lower than in Rick Perley's - VLA image

Perfect pointsources at 2° from phase-pointing centre

WSRT 3C147 21cm 0.75^o x 0.75^o



3C147 21cm 1x12h
B=160 MHz Jan 2003

22 Jy /13-17 μJy

1.5 million dynamic range

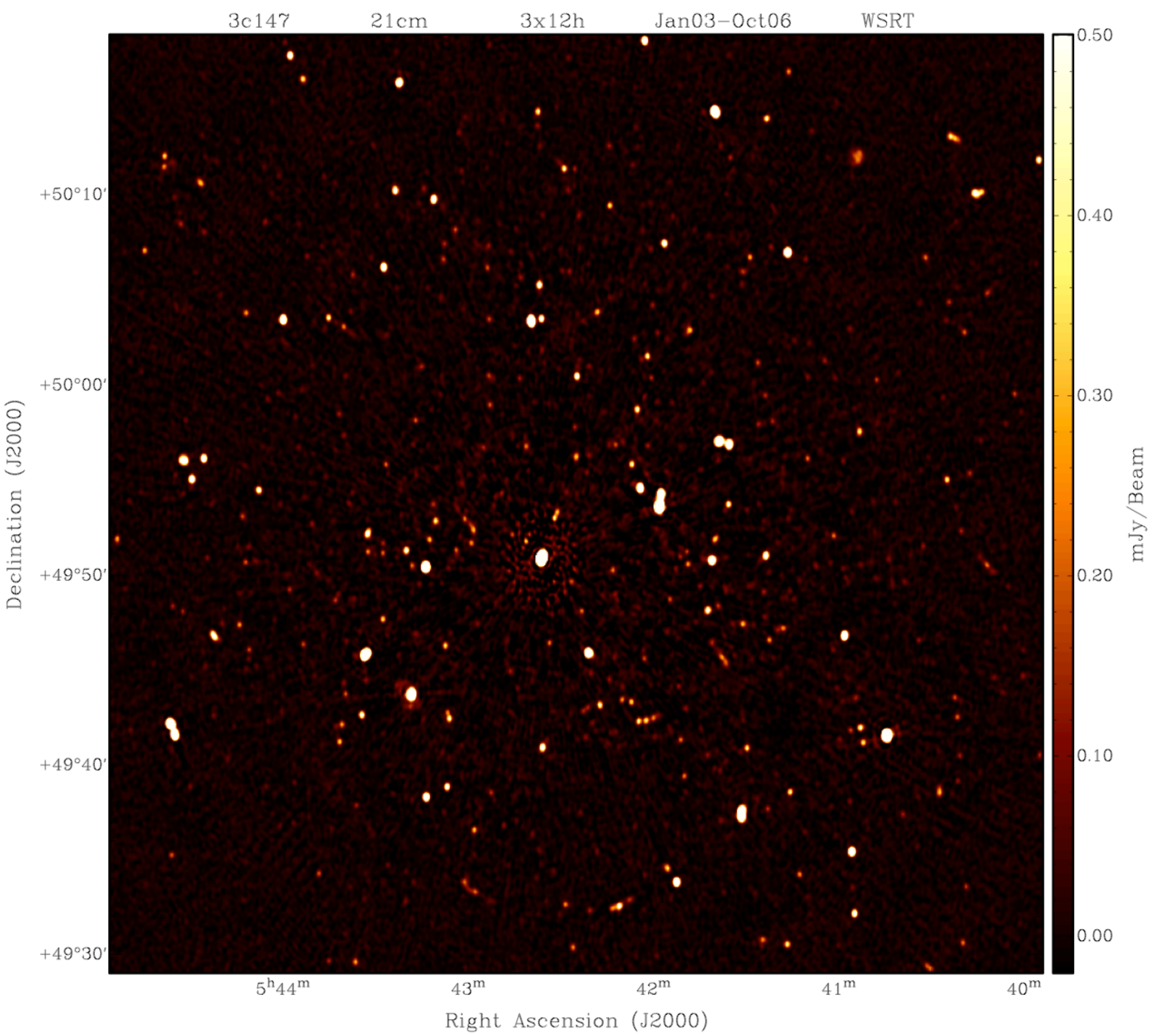
Still some problems:

- off-axis DR ~1000 (due to pointing?)

- spikes due to non-linearity + 9.6^s radar --> 4^m beat

---> new observations requested

3C147 images at DR~ 2,500,000 : 1 (3x12h)

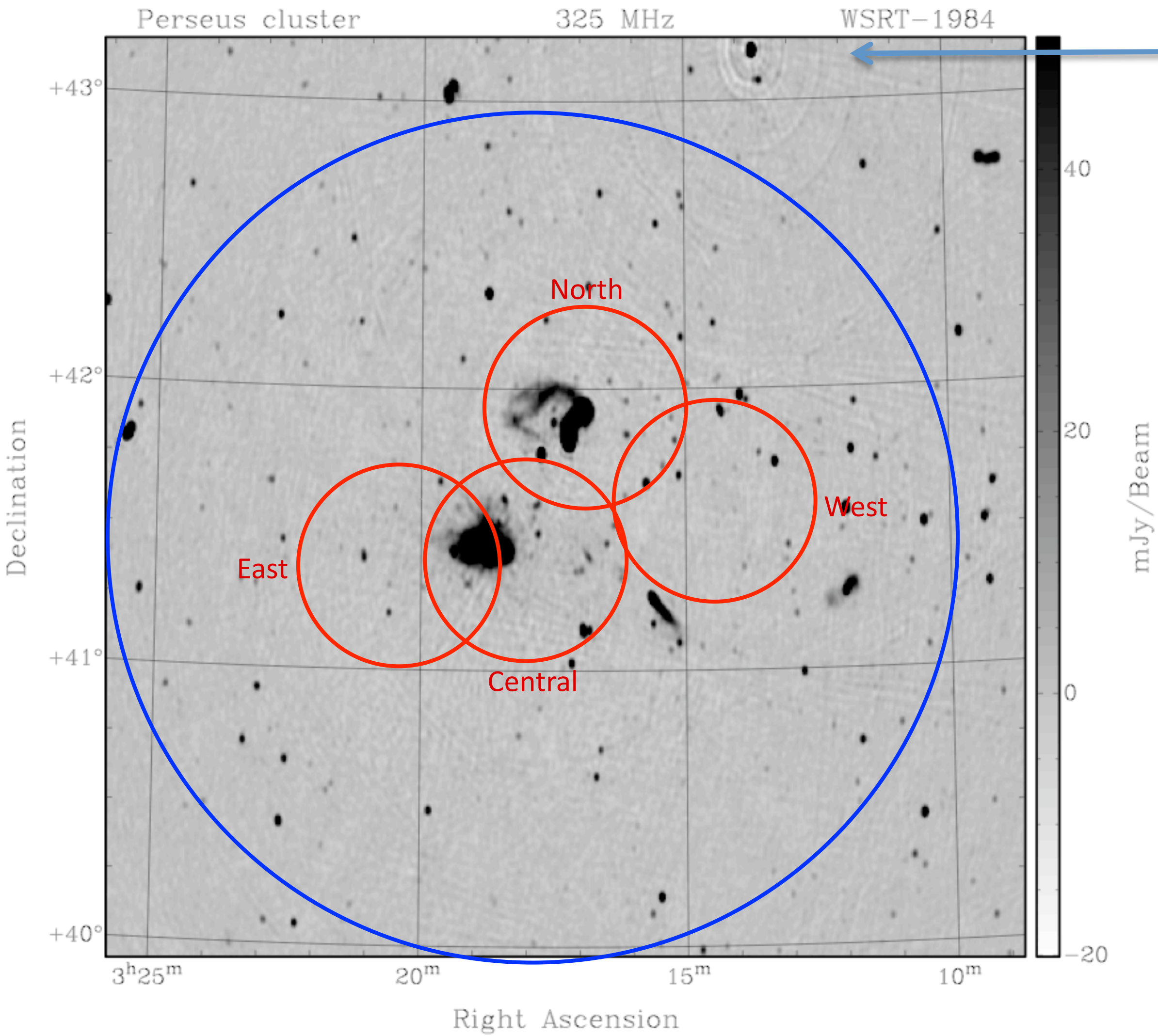


1° x 1°

22 Jy

8.5 μJy
noise far
from 3C147

WSRT 21cm pointings overlaid on 92cm image



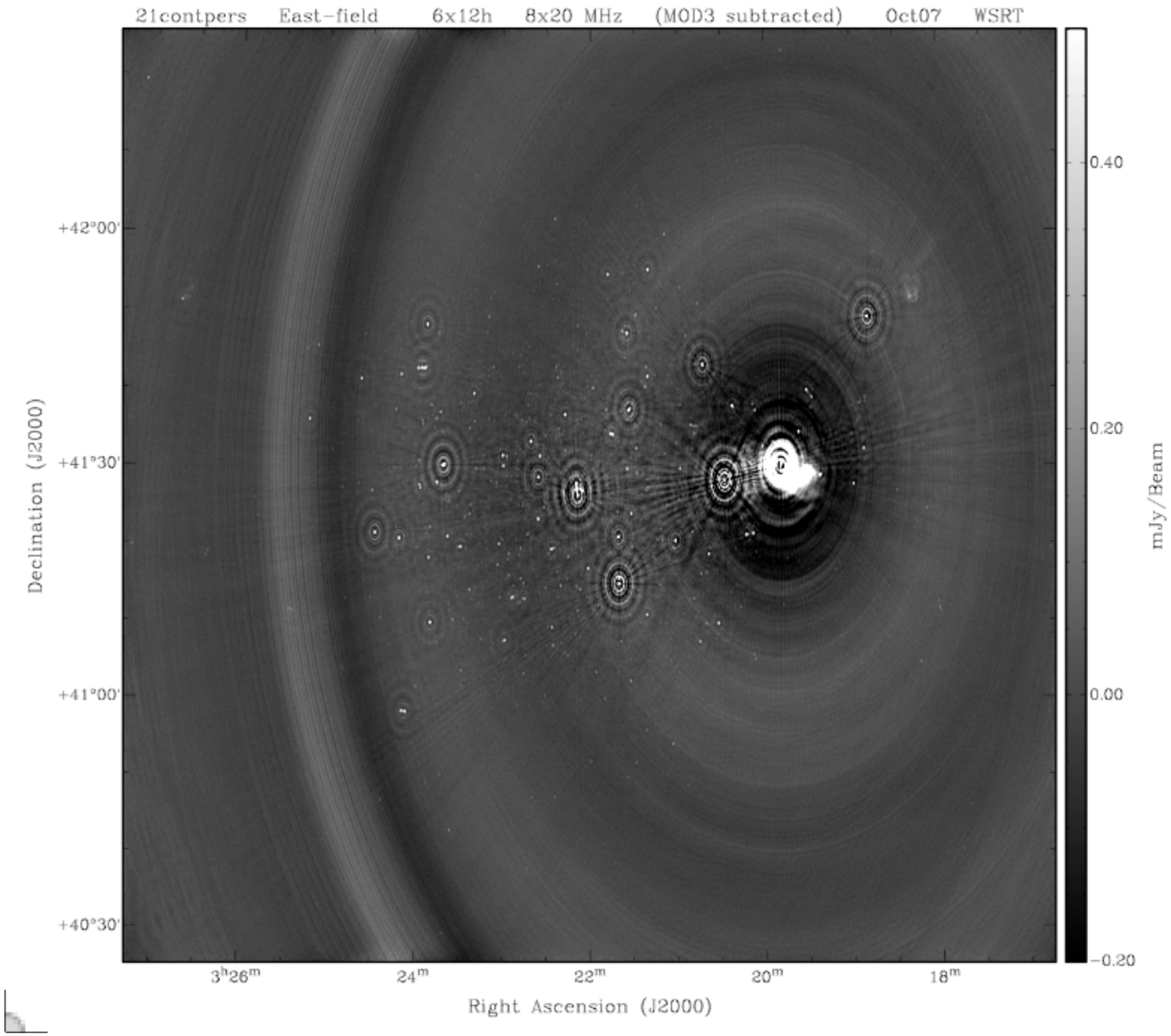
DD errors ... in 1984 !!

Perseus A

22 Jy peak brightness

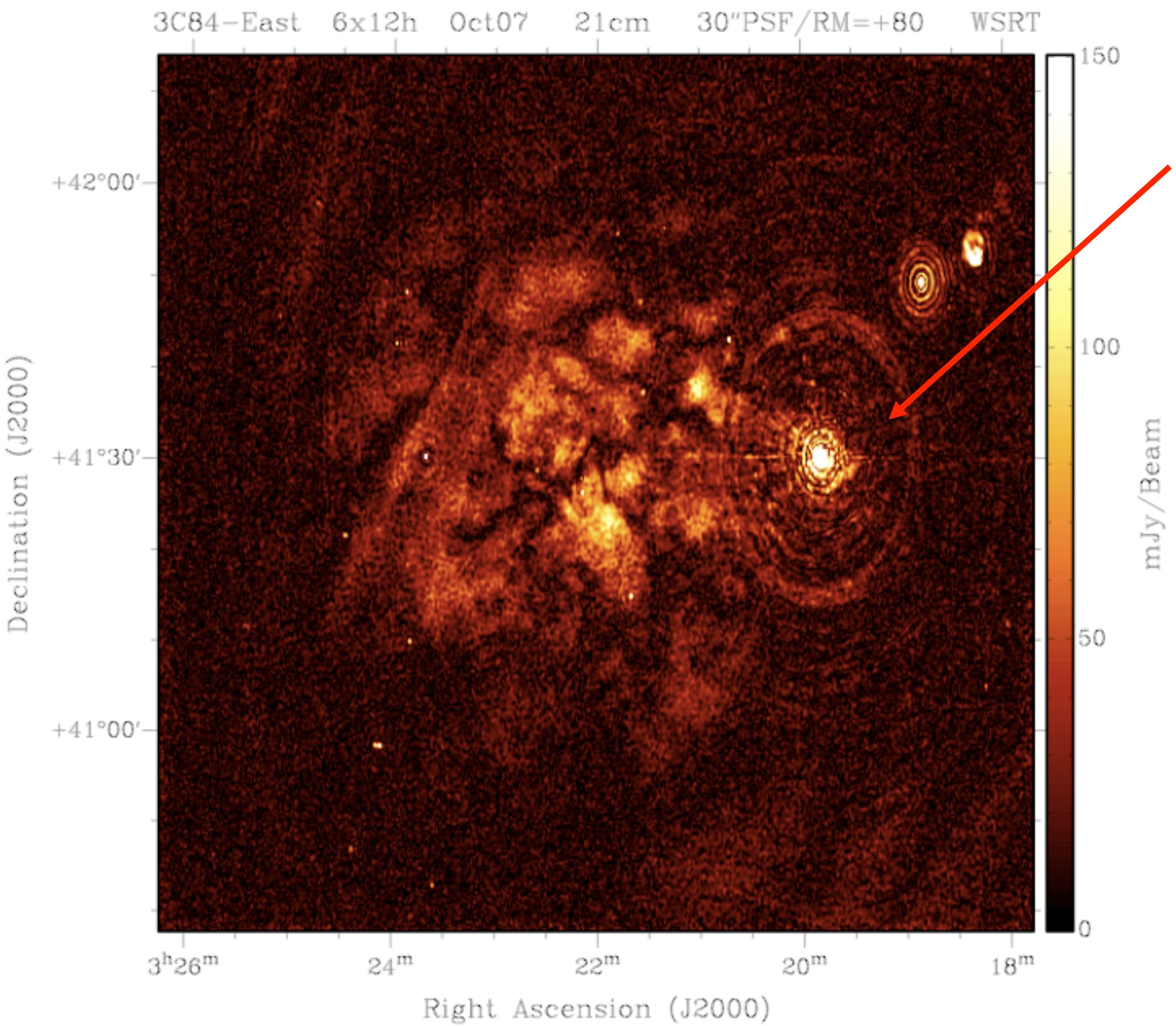
15 μJy noise in 12h
6 μJy noise in 72h

Perseus-EAST



Initial phase of cal/imaging

Perseus - EAST



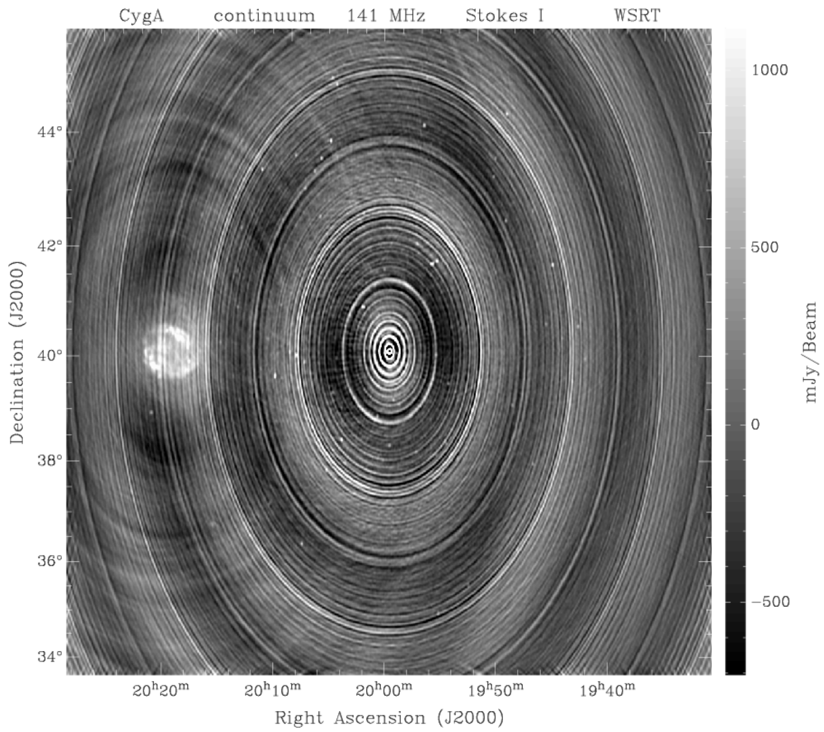
I-peak ≈ 5 Jy (3C84)

noise ≈ 5-7 μJy/PSF

⟹ DR ≈ 10^6

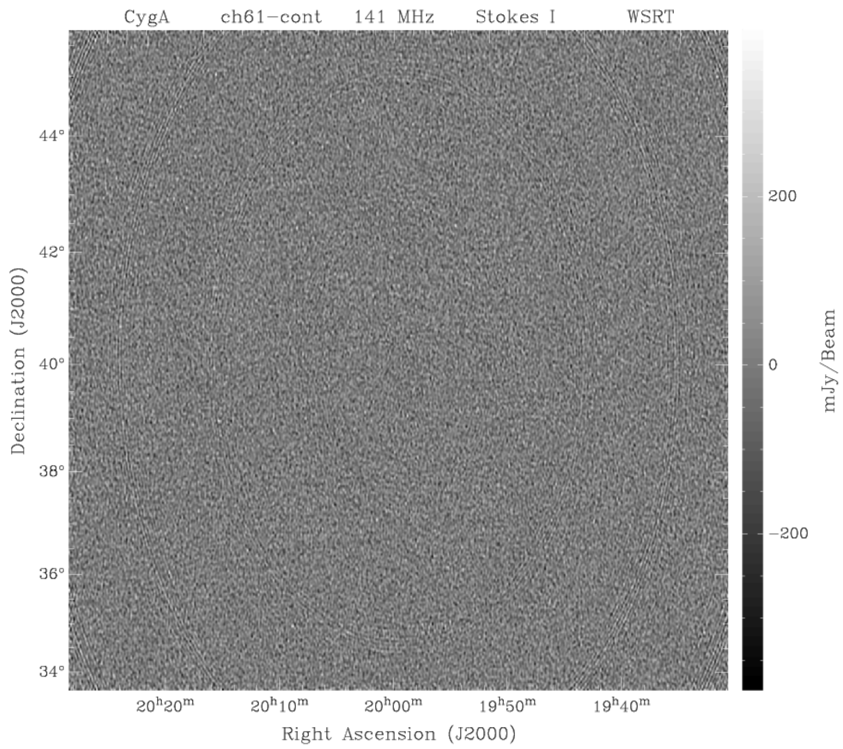
Deconvolution issues for barely resolved sources

141 MHz continuum



(Original) peak: 11000 Jy

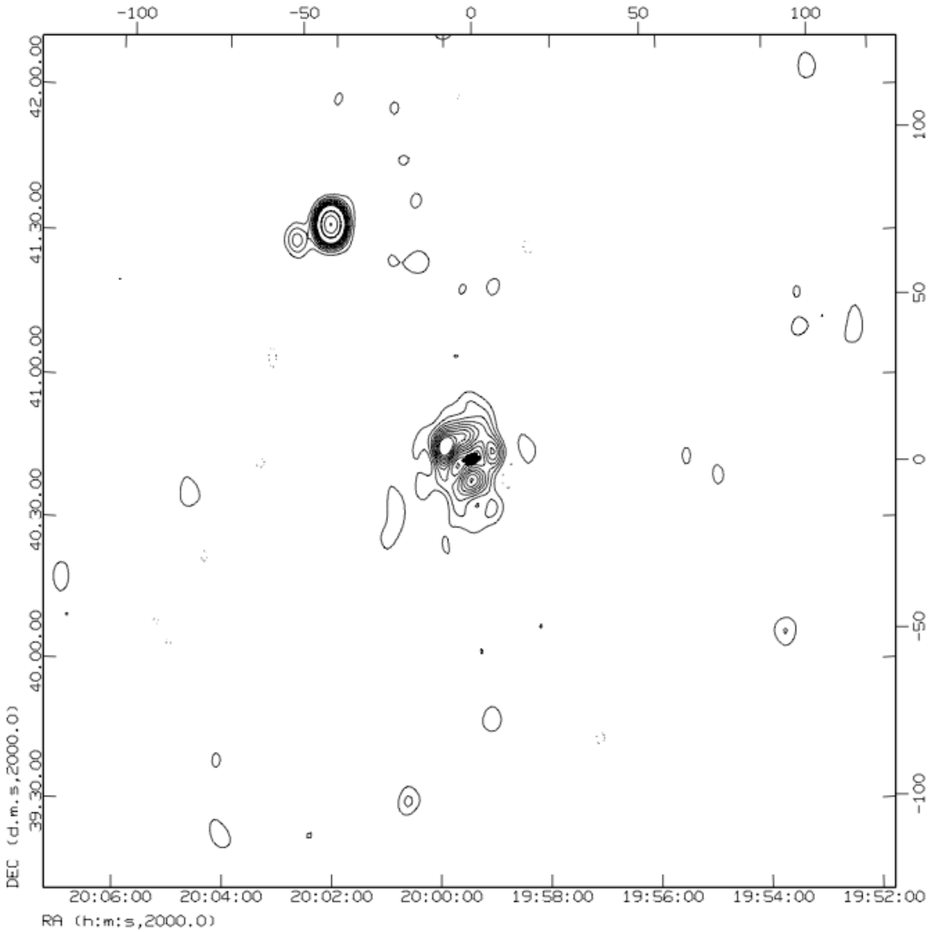
difference adjacent 10 kHz channels



noise 70 mJy

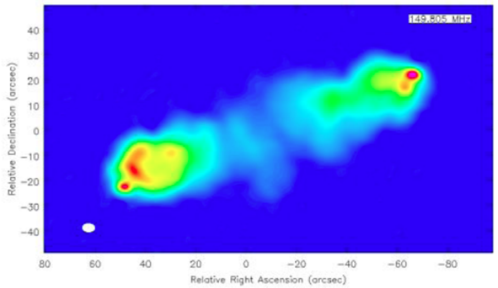
DR ≈ 150,000:1 !!

WSRT image …. using 30km LOFAR cc-model of CygA



With the improved model we can also determine and remove closure errors (≤ 0.05%) (12h-average)

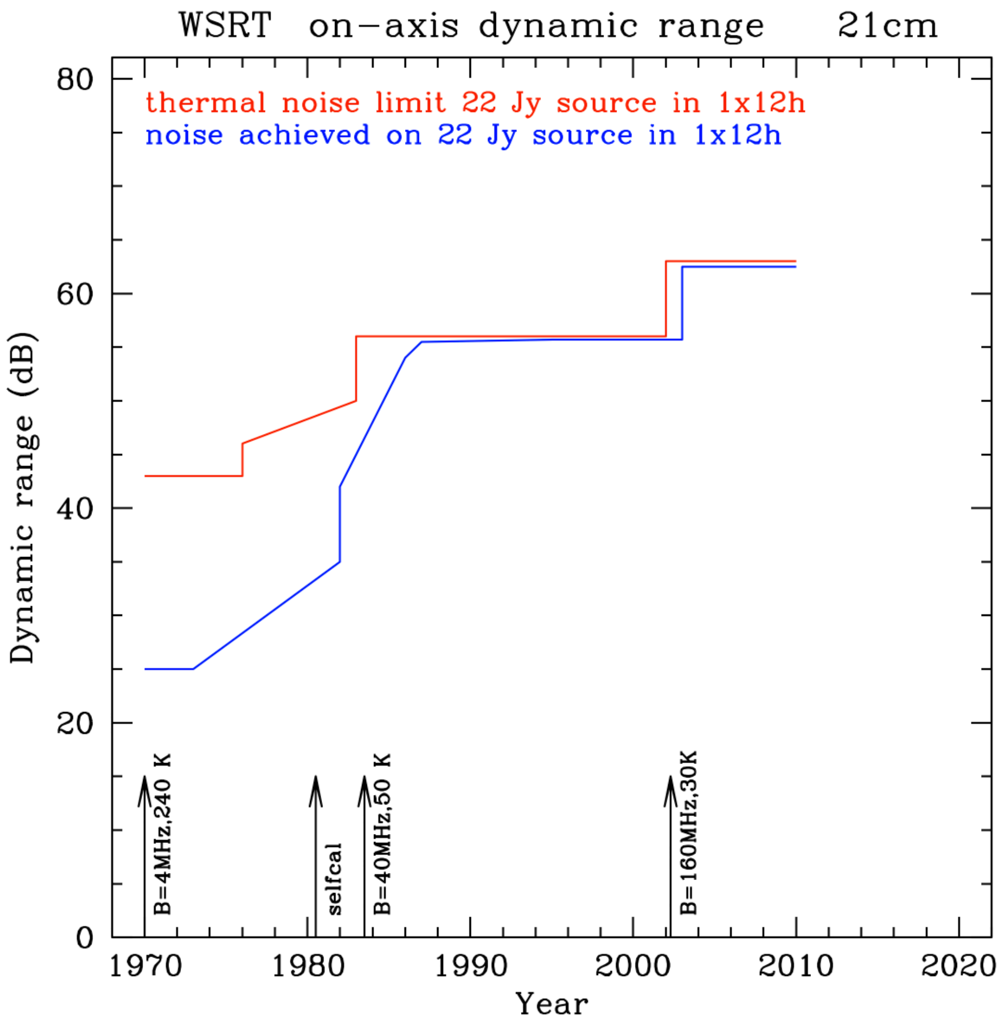
Only do that when model is very good !



McKean, Wise etal, 2013

CygA /cluster emission 15’ size !!!

WSRT 21cm dynamic range history over a 40 year period !



WSRT-40 meeting
22 Oct 2010

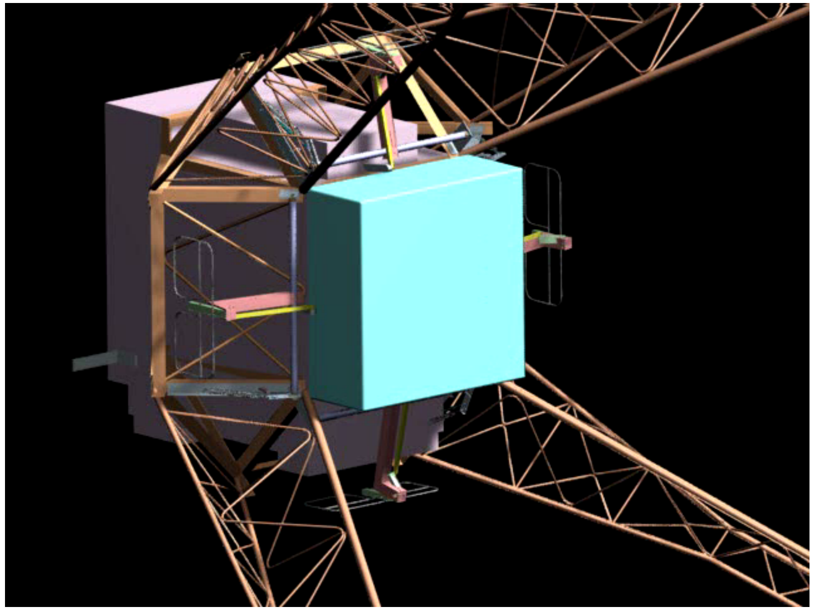
Noordam & de Bruyn, 1982
Sybring thesis, 1993
de Bruyn, 1996
de Bruyn et al, 2010

Very wide-field (→ all-sky) imaging

The WSRT Low Frequency Front Ends (LFFE)

Preparing for LOFAR

~400 kEuro for 14 WSRT frontends.
It took only 1 year from subsidy to fully commissioned instrument !

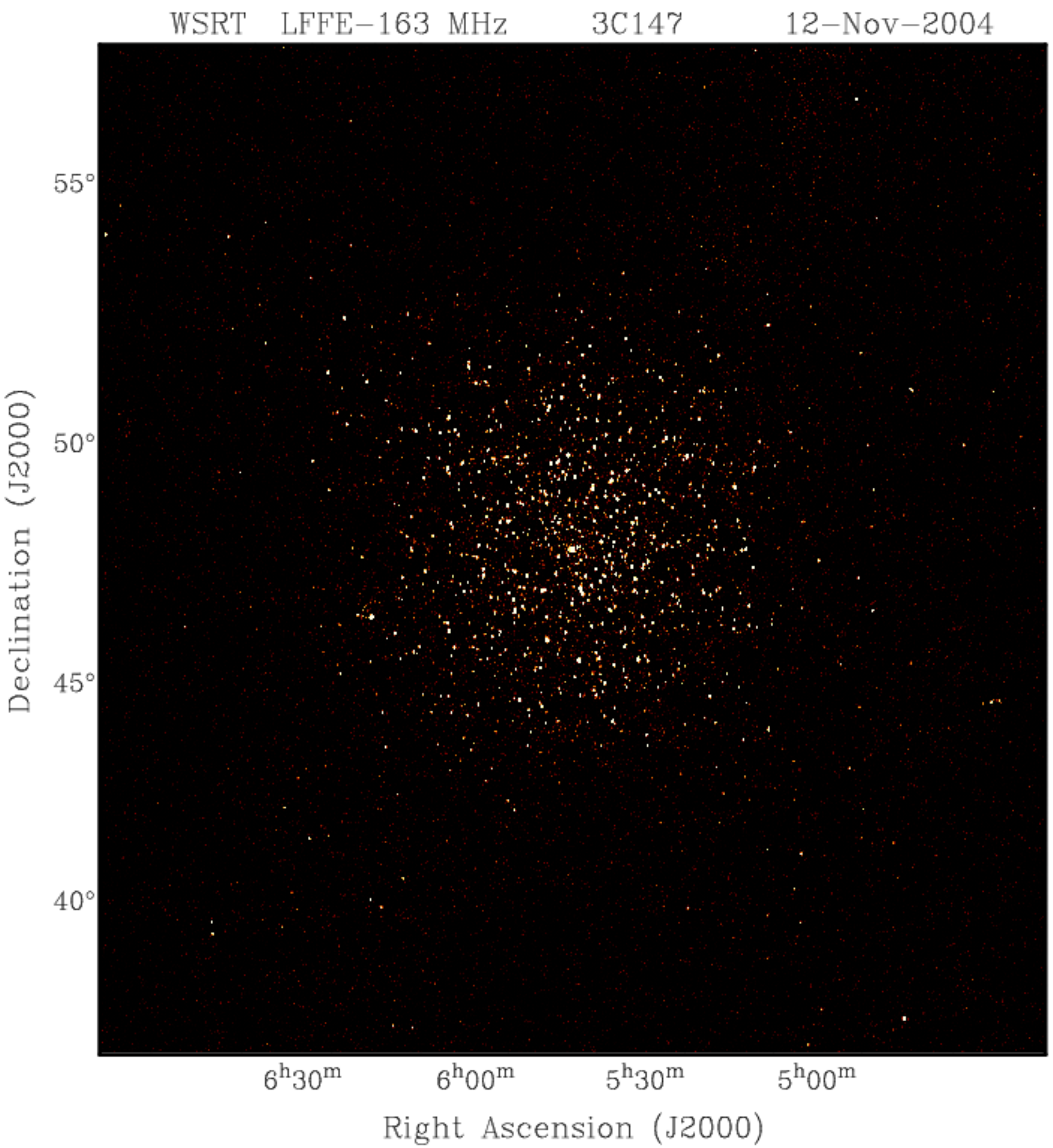


LFFE design animation

Bert Woestenburg - Project Manager
Ger de Bruyn - Project Scientist
Hans van der Marel
Paul Riemers

Early concept

The first LFFE image at 163 MHz (Nov 2004)



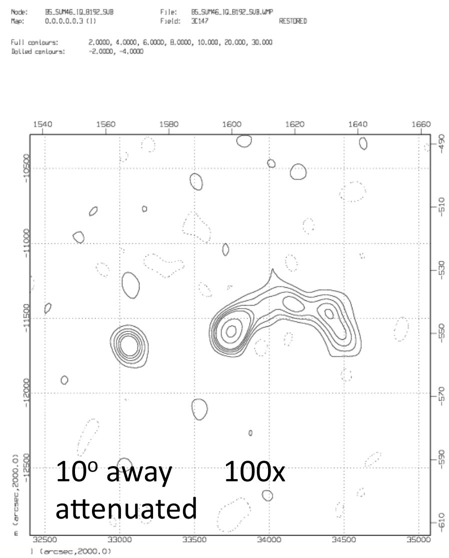
3C147 60 Jy pointsource

rms noise 3-4 mJy

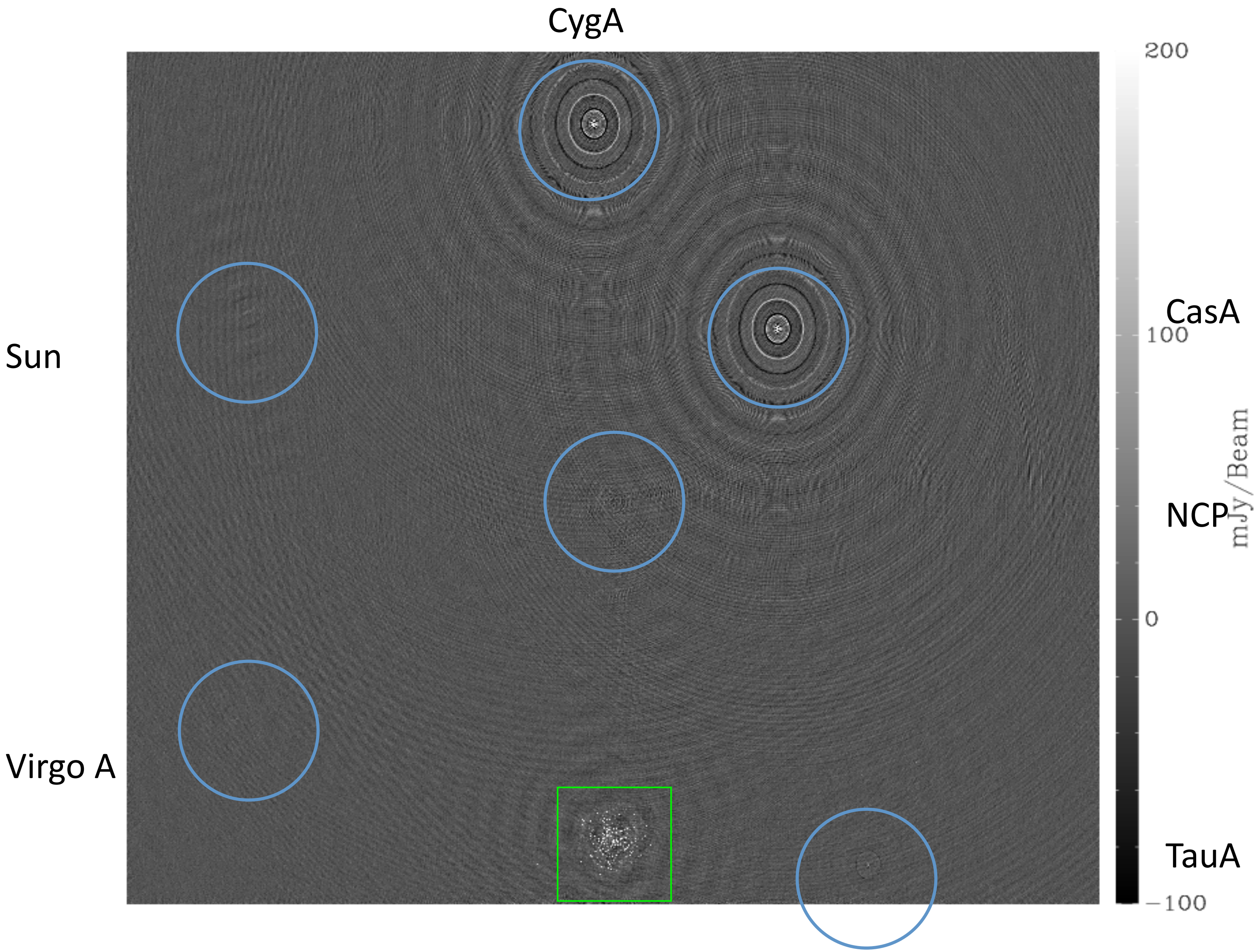
VERY quiet ionosphere

Isoplanatic scale > 20° !!

3C129/129.1

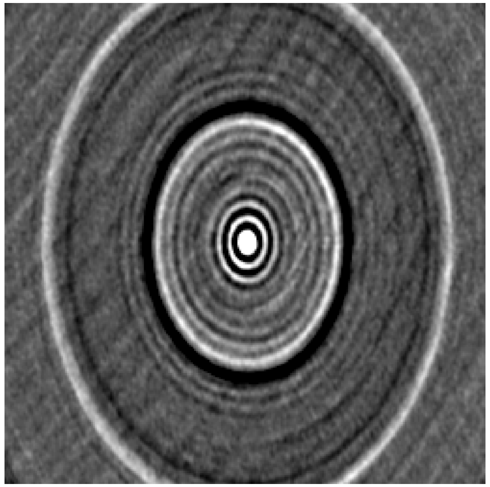


WSRT 'all-sky' image at 150 MHz, centered on 3C196



Images of the A-team within the 3C196 field

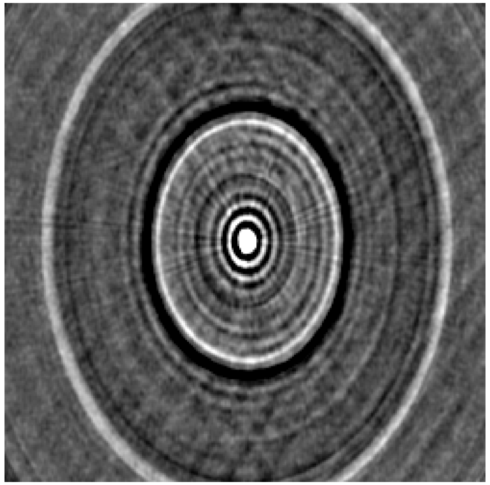
The A-team is about 30dB attenuated yet looks remarkably stable in both flux and position. This is great, but called for a detailed investigation….

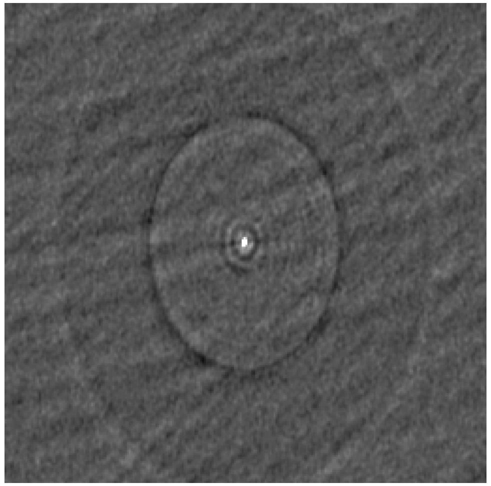


~5’ PSF

CasA CygA

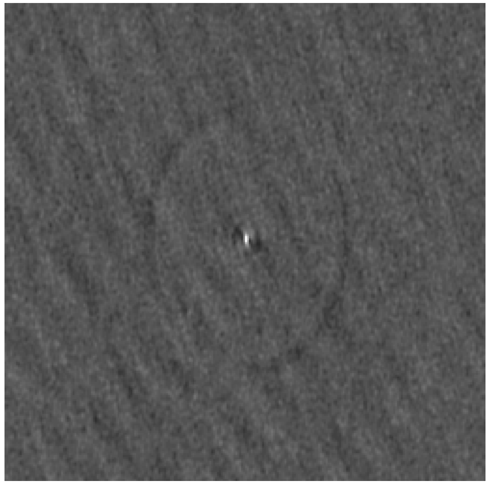
both ~ 10 Jy peak





- 0.1 to +0.2 Jy greyscale range

TauA VirA



Linear polarization of the diffuse Galactic fore/background

The very local ISM :

Confucius:

‘When a man points his finger at the Moon
only the fool will examine the finger’

Is this applicable in the LOFAR EoR project ? No !

What do we know about the magneto-ionic properties of the very local ISM ?

Towards J1819: a ‘screen at 1.5 pc !

Towards 3C196: where is all this polarized stuff ?

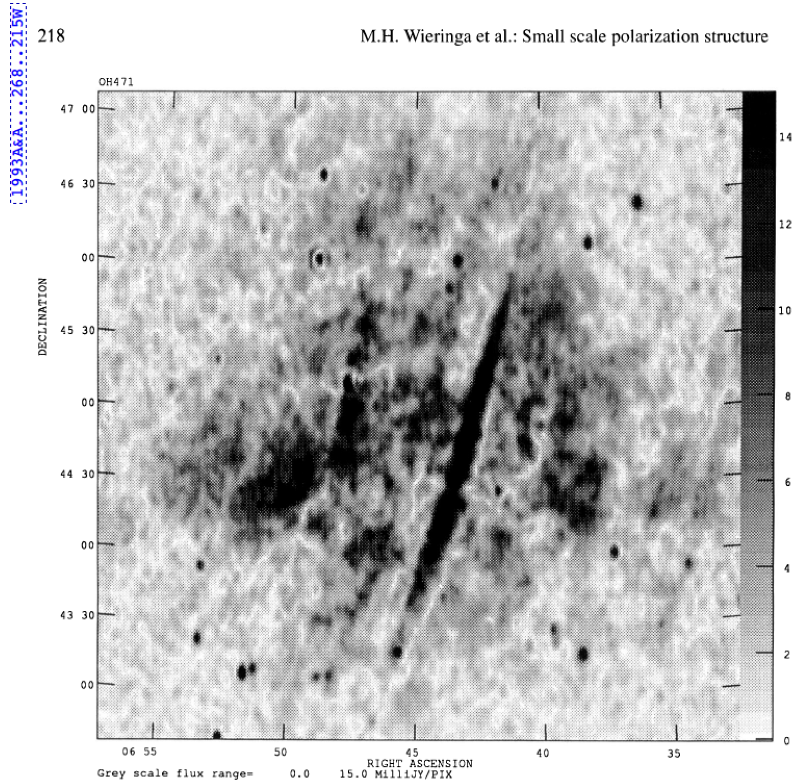
Galactic linear polarization filaments

WSRT 327 MHz :
probably most important discovery was detection of Galactic polarization

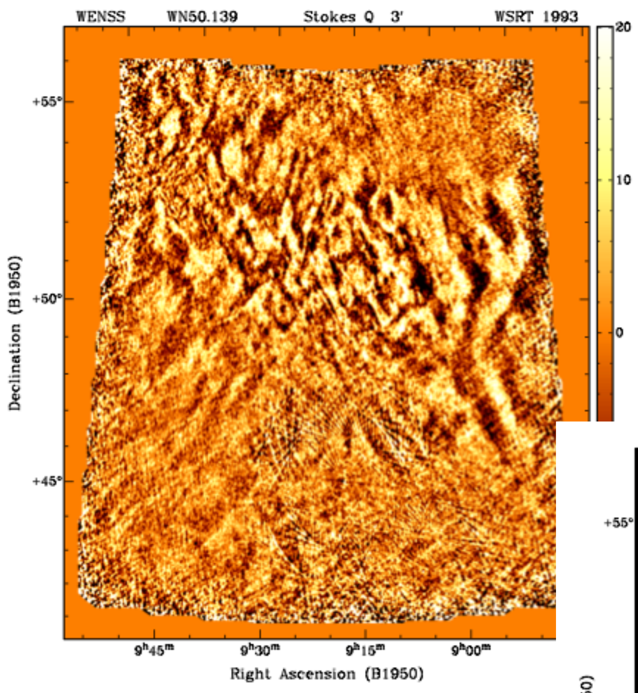
1987-1991 Mark Wieringa
Funding for continuation easy ?
…..
…..
1998-2002 Marijke Haverkorn
2003-2007 Dominic Schnitzeler

But persevere !   Peter Katgert !

Also advice from O.E. Wilson in “Letters to a young scientist”

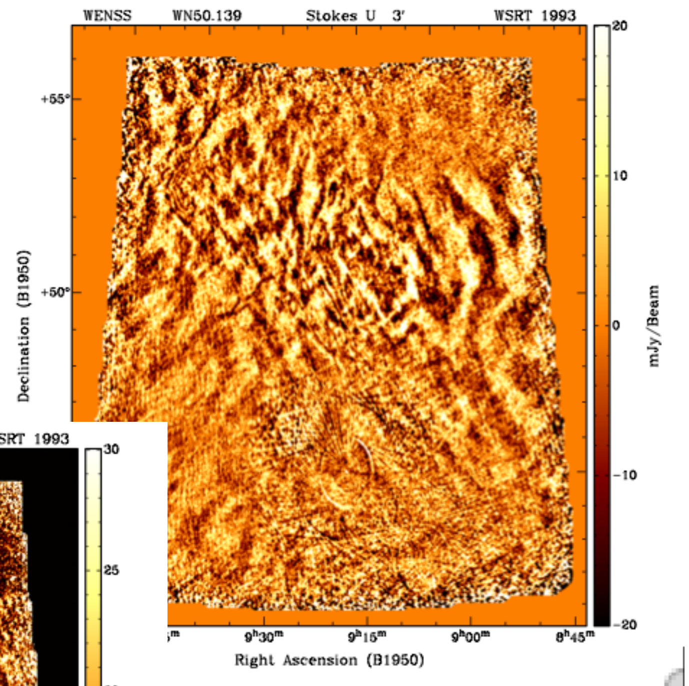


WENSS polarization data of the MAZE–region (325 MHz)

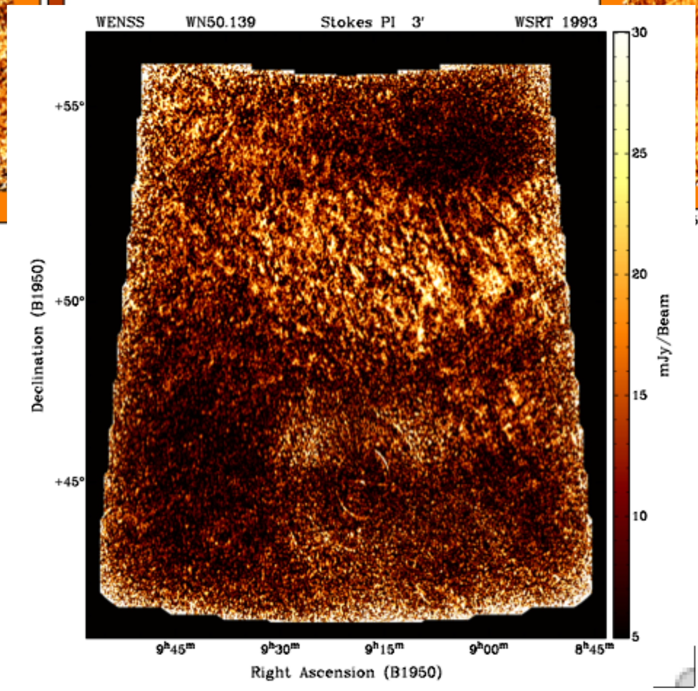


Q

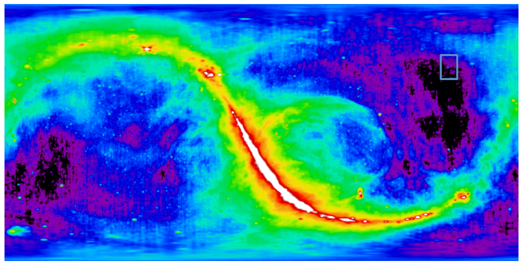
U



PI



Field is at high Galactic latitude (b ~ +40°)



Peak T_b of ~ 5-10 K At 325 MHz

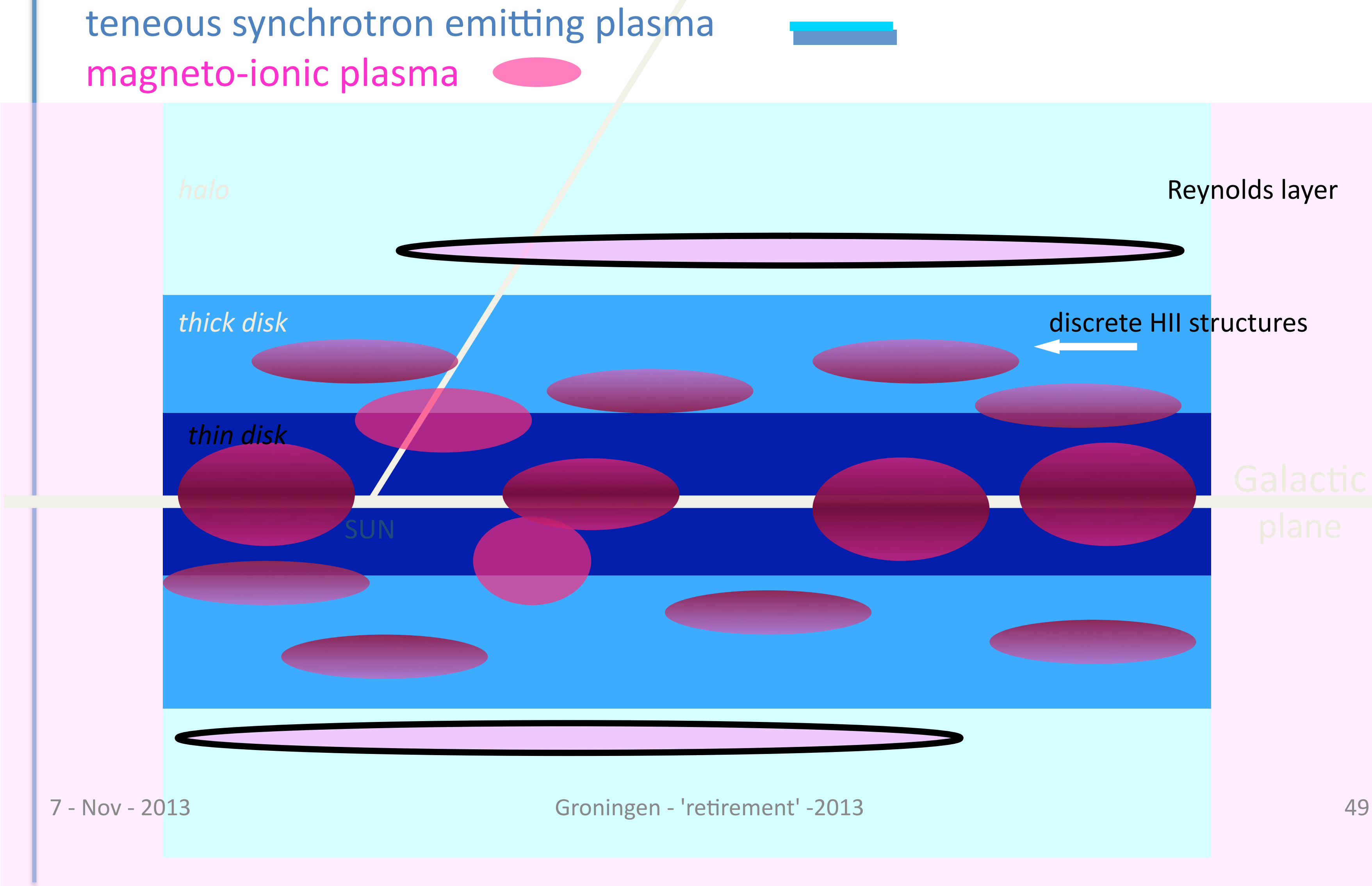
IF Faraday-thin → 50 K at 140 MHz !!

A cartoon of nonthermal and magneto-ionic components

A case of Faraday thin versus
Faraday thick plasma !

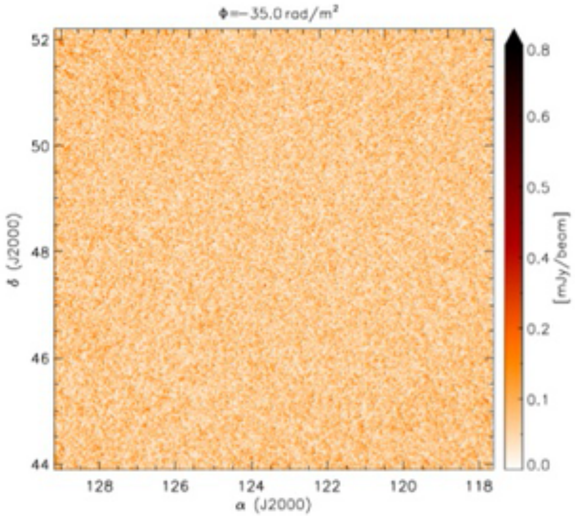
see e.g. Beuermann et al, 1985
Subrahmanyan and Cowsik, 2013

teneous synchrotron emitting plasma
magneto-ionic plasma

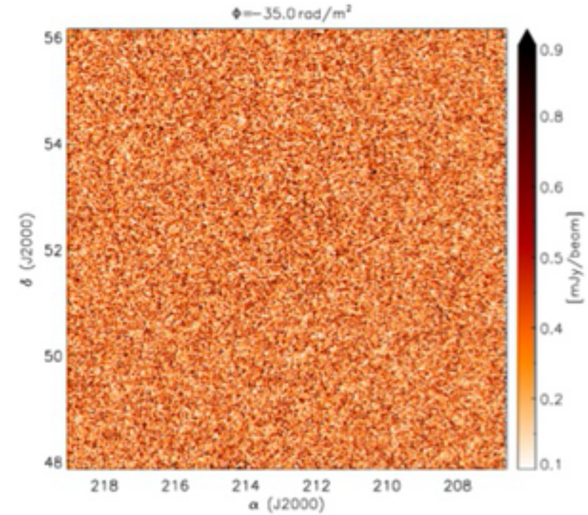


Polarized intensity: RM-cubes *Jelic*

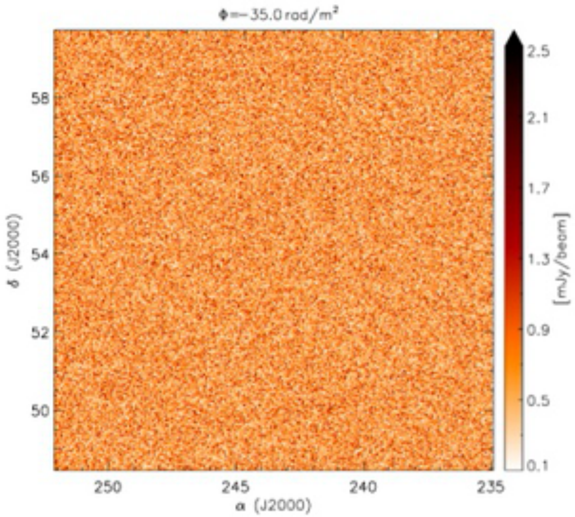
3C196



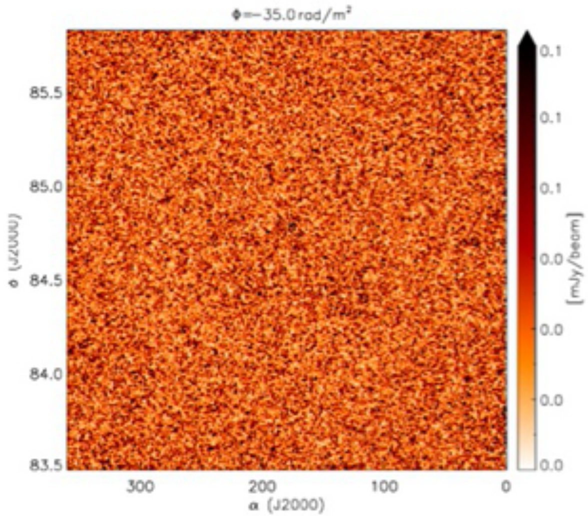
EliasN1



3C295



NCP



LOFAR 3C196 polarized emission

ϕ = +1.5 rad/m^2 +2.5 rad/m^2

Filled with Galactic diffuse emission , typical brightness 2-3 K !

screens ? edge-on sheets ? filaments ?

Applications using diffuse Galactic polarization

Very accurate determination of ionospheric Faraday rotation

Proper motion of magneto-ionic ‘screens’ (if very nearby, a la J1819+3845)

Probing coronal/IPM magnetic field after CME ejection !

HI in the Universe

3C196 keeps coming back

45 Jy very compact 3C source at 325 MHz +
straight spectrum down to 10 MHz ? (Laing & Peacock, 1980)

→ 3C196 Primary WSRT flux calibrator !

3C196 QSR at z=0.87 (DLA) HI absorption at
Briggs et al 2001 , HI absorption mapping
Chengalur (1995) WSRT CI

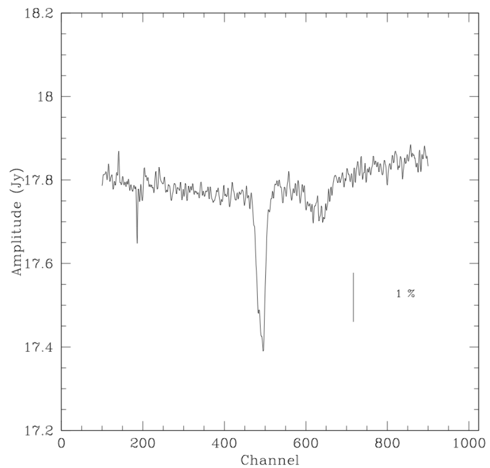


Fig. 1. Compound interferometer spectrum of 3C 196. The total spectral range displayed measures about 4 MHz or 1200 km s^{-1}. The velocity resolution is about 4.5 km s^{-1}.

3C196 as primary calibration test field for LOFAR

3C196 as primary EoR window: Dynamic Range not an issue

The LOFAR E-o-R Key Science Project

Some history on my early involvement with the EoR

1985-1991: search for 'pancakes' ($10^{14\text{-}15}$ M_{sun} of HI !!) Katgert, Wieringa

1991-2001: DLA studies: Briggs, Chengalur, Kanekar

Oct 1997: Mauritius 151 MHz opening Kassim → LOFAR

July 1998: phone call Peter Shaver …. → Shaver, Madau,Windhorst, de Bruyn (1999)

For me it was clear that a global signal was next to impossible to detect.
Why? Required SDR > 100,000:1 (200K : 2mK).
Problem is: Who calibrates the calibrator *
So I suggested we should do this with a Low Frequency Array or the Moon

Nov 2003: 53 MEuro !!
March 2004: arrival Saleem Zaroubi and Leon Koopmans at Kapteyn: project kickoff !

* Similar problems in international finance/banking:
---Who checks the accountants or checks the Authority that checks the accountants!)

Early ideas on the EoR and the foregrounds

Astron. Astrophys. 345, 380–390 (1999)

ASTRONOMY AND ASTROPHYSICS

Can the reionization epoch be detected as a global signature in the cosmic background?

P.A. Shaver[1], R.A. Windhorst[2], P. Madau[3], and A.G. de Bruyn[4,5]

$$\Delta T = (1+z)^{-1}(T_S - T_{\rm CMB})(1-e^{-\tau}) \approx (0.01\ {\rm K})h^{-1}\left(\frac{\Omega_b h^2}{0.02}\right)\left(\frac{1+z_{ion}}{9}\right)^{1/2}$$

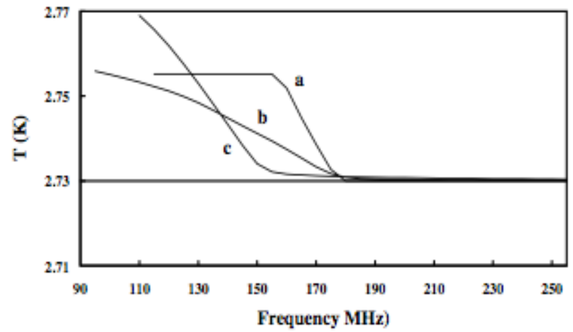


Fig. 1. Expected brightness temperature of the cosmic background in the vicinity of the H I reionization edge as a function of observing frequency. Three cases are shown for the H I step, (a): the case from Eq. (5) with $z_{ion} = 7$, $\Delta z = 1$ and $h = 0.7$, (b) and (c): revised results provided by N. Gnedin (private communication) from the simulations by Gnedin & Ostriker (1997) and Baltz et al. (1998) case A respectively, with $\Omega_M = 0.35$, $\Omega_\Lambda = 0.65$, and $h = 0.7$.

T_{halo} ~ 180 K at 150 MHz of which:

- 27 % Extragalactic sources
- 70 % Galactic nonthermal emission
- 1 % Galactic thermal emission

+ 2.73 K from the CMB

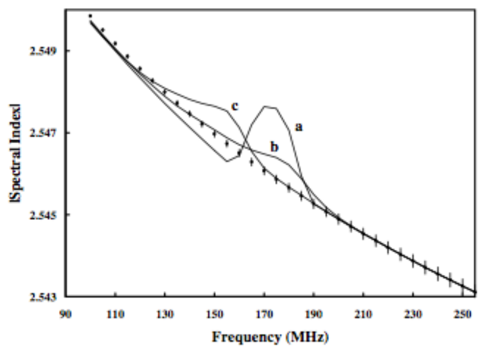


Fig. 2. Spectral index *vs.* observing frequency, as deduced over 10 MHz

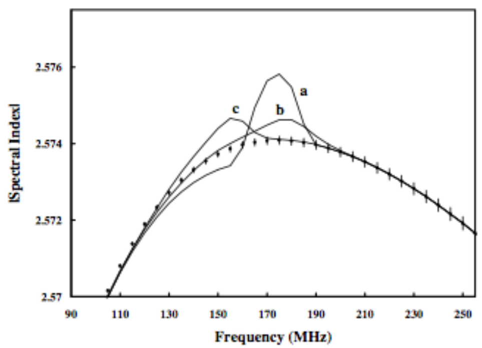


Fig. 3. Spectral index *vs.* observing frequency as in Fig. 2, except that

Spectrum without and with extragalactic sources

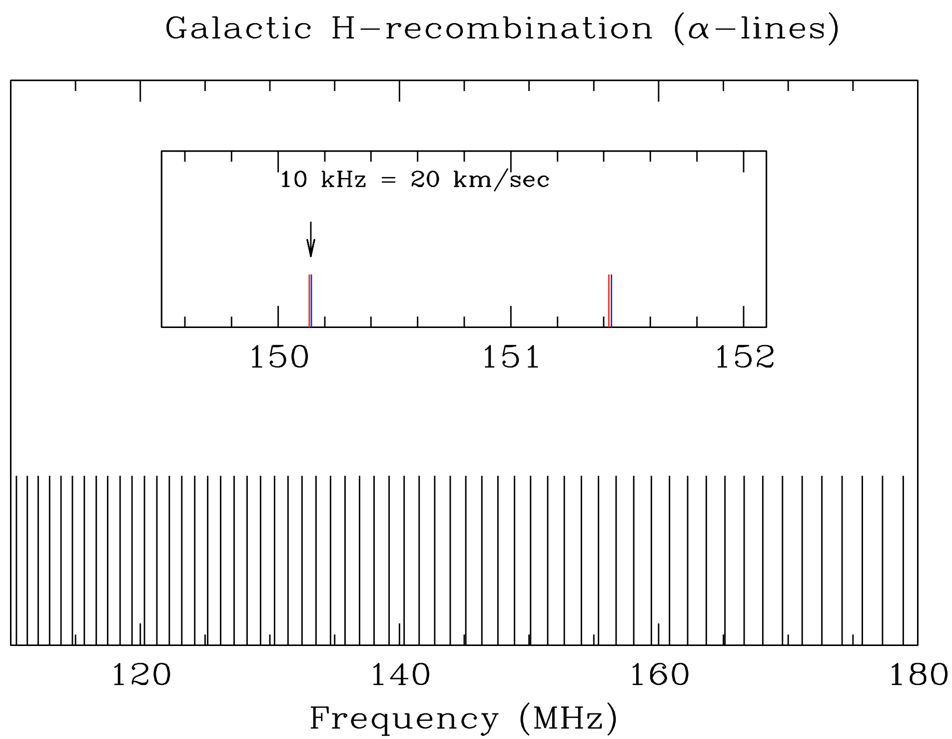
Galactic recombination lines: not an issue

In the Galactic Halo radio recombination lines (RRL) around 150 MHz are very weak (< ~ 0.01 K ?).

There are many lines with a width of 20 km/s ~ 10 kHz.

The lines are typically ~ 1.25 MHz apart hence occupy only ~ 1% of the spectrum, and at known frequencies.

The lines are very narrow and, if detectable, could even be used as calibrators.



Our LOFAR EoR (core + associates) team + some guests

Ger
Saleem
Leon
Michiel

Sarod
Pandey
Vibor
Oscar
Bene
Joop
Ilian
Abhik
Soobash
Stefan
Sanaz, Harish, Ajinkya, Hannes
Khan, Sander, Alexandros, Elizabeth
(Kohei, Keri, Suman?)

Not in the picture
Garrelt, Filipe, Emma
Rajat,Gianni

Going back to July 2003, before the 'divorce' Sydney1

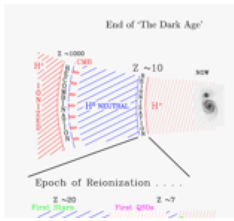
IAU216, Sydney, 14-17 July 2003

LOFAR, the E-o-R and the Galactic foreground

A.G. de Bruyn (ASTRON & Groningen), F.H. Briggs (ANU/ATNF), M.P. van Haarlem (ASTRON)

One of the most exciting astronomical drivers of LOFAR, a new radio observatory designed to operate in the frequency range from 10-220 MHz, is the study of the 21cm line emission of neutral hydrogen during the Epoch of Reionization (E-o-R). This era, at the end of the Dark Ages (figure right), is subject of extensive modeling and speculation It is likely that the E-o-R phase has been both long and complex and observational clues on the most important processes and sources that played a role will be required to constrain theories about what happened. The LOw Frequency ARray could play a key role in this endeavour.

Among the most important problems that LOFAR will be able to address are the following:
-- What is the redshift range during which the bulk of the HI disappeared ?
-- What are the spatial and spectral characteristics of the HI (and HII) distributions?
-- What were the sources of re-ionization?
-- How did the baryonic structures and ionizing sources evolve during the relevant redshift range?



LOFAR Low Frequency Array

The LOFAR consortium consists of ASTRON, MIT-Haystack and NRL (see www.lofar.org).

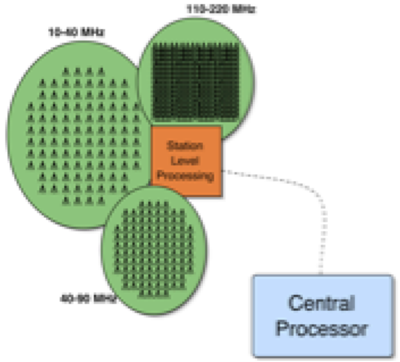
LOFAR is an aperture synthesis array composed of phased array stations that perform the same function as individual dishes in conventional synthesis radio telescopes (e.g. the Westerbork array or the VLA). It uses a large number of low-cost antennas and relies on broad-band data links and advanced digital signal processing to implement the majority of its functionality in (embedded) software.

In 2003 many things happened:

- Decision to go for High-Band tiles of 4x4 dipoles
- Allocation of 53 MEuro by Dutch Government in Nov 2003: LOFAR → Netherlands
- NRL, MIT-Haystack and ASTRON decide to go on independently
- Leon Koopmans and Saleem Zaroubi appointed to Kapteyn Institute (arrive Feb 2004

→ Start of formation of EoR Key Science Project team

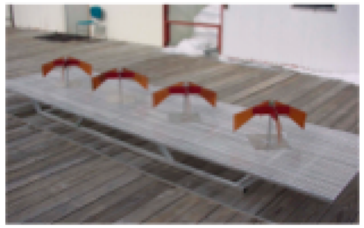
The array layout in 2003



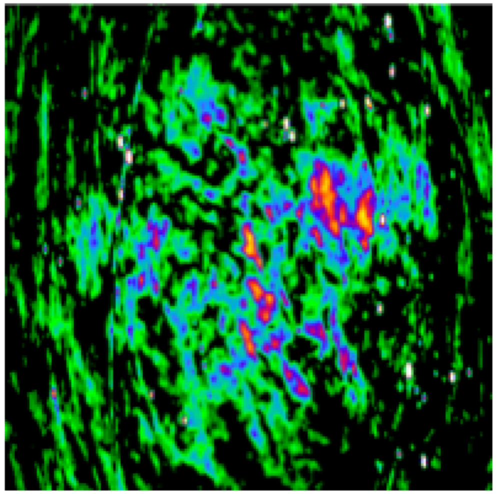
Schematic lay-out of a LOFAR station. Three types of antenna's are located at each of the stations. Depending on the operating mode and observing frequency, one (or more) of the antenna types is chosen

The figure above gives an artist's impression of one of approximately 100 LOFAR stations. The antennas in the station form a phased array, producing one or many station beams on the sky. Multi-beaming is a major advantage of the phased array concept. It is not only used to increase observational efficiency by allowing the telescope to point to different regions of sky at the same time, but may also be vital for calibration purposes. Effectively each station beam is a collection of many monochromatic beams centred at the same position on the sky.

LOFAR Compact Core – Parameters relevant to EoR Detection	
Number of HF Dipoles	53460 (3340 x 16)
Baseline range	20 m – 2 km
Frequency Range	110-220 MHz
Antenna field of View (HPBW)	~25 degrees
Angular resolution	2-4 arcmin

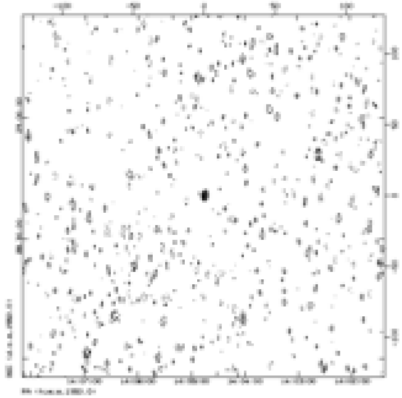


Prototype of the High Frequency Antenna (developed at Haystack Observatory) which will operate between 110 and 220 MHz. The final design will probably consist of a 4x4 array of these kind of antenna's together with an RF beamformer.



The power of self-calibrated differential imaging !

The contoured image on the right shows the difference between the skies at 325 and 341 MHz. Apart from the central source with a highly inverted spectrum (OQ208) and several very steep spectrum sources, the field shows only noise. The field shown measures 1.5 ° x 1.5 °, with contours at 1 mJy /beam



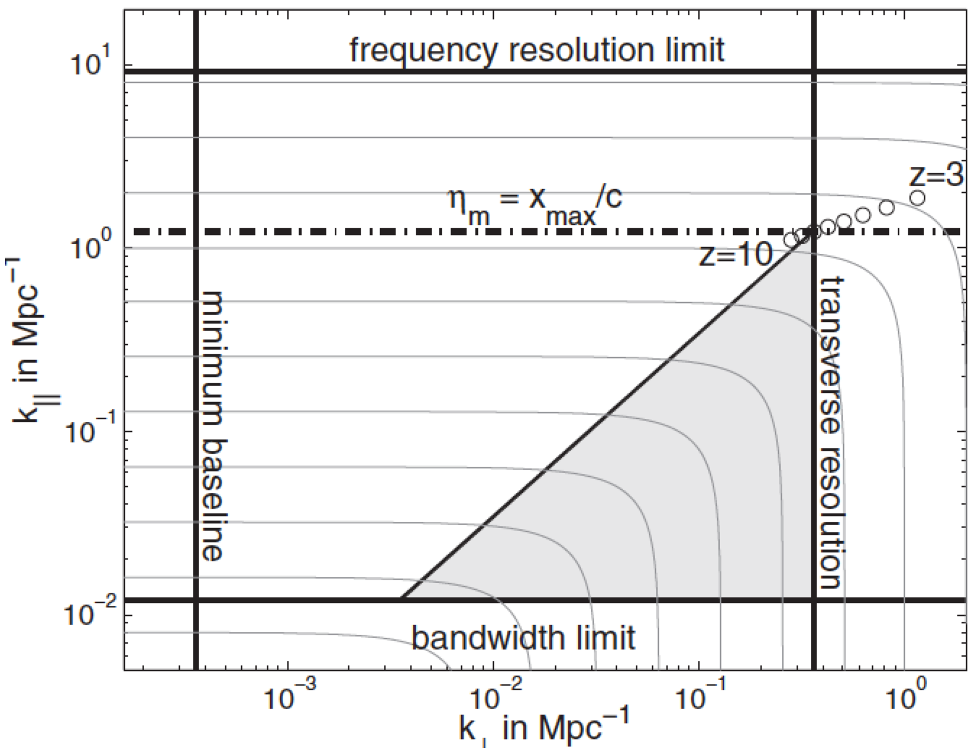
Some of the concerns and challenges for LOFAR

The extremely long integrations required to reach the tens of mJy noise levels per compact core beamarea can only be achieved after calibration of the time-variable and direction-dependent ionospheric phase distortions. This is one of the major (software) challenges and concerns for LOFAR. However, the fact that E-o-R signals are at relatively 'high' frequencies and at short baselines and the signal analysis is done in the spectral domain make us relatively insensitive to phase-calibration errors. On the other hand, the image and spectral dynamic range requirements for a succesful experiment surpass current WSRT achievements by an order of magnitude. Still, we are confident that we can meet these challenges.

Preparing for E-o-R observations with the WSRT

We have started a program on the WSRT to explore parts of the northern Galactic hemisphere to characterize the properties of the Galactic synchrotron foreground. The 'P-band' receivers on the WSRT, in combination with the new backend (80 MHz in 512 full polarization channels), recently allowed us to reach ~ 50 mJy noise in a 72^h integration (note that the WSRT has an effective collecting area of 'only' about 4000 m^2, more than one order of magnitude less than the LOFAR compact core). New receivers designed to operate from 120 - 180 MHz should be operational on the WSRT in the fall of 2004. They will allow us to start observing within the E-o-R band. One of the areas where we need to get quantitative data and experience, is that of very low frequency instrumental and celestial polarization. Linearly polarized emission, which we expect to be present at significant intensities in the Galactic halo at frequencies around 150 MHz will, if not properly calibrated, leak into the Stokes I signal and introduce via frequency-dependent Faraday rotation undesired spectral signals.

Observing in $k_{//}$ and/or k_{perp} space



From Vedantham etal, 2012

Boundaries refer to:
Upper-lower: 40 kHz -30 MHz
Left-right: m and m

$10' \approx 28$ cMpc ≈ 1.6 MHz

assuming $H_o = 70$, $z = 9.5$

Working at 10' scales is optimum (see also plot on next slide.

The LOFAR array: tailored to the EoR ?

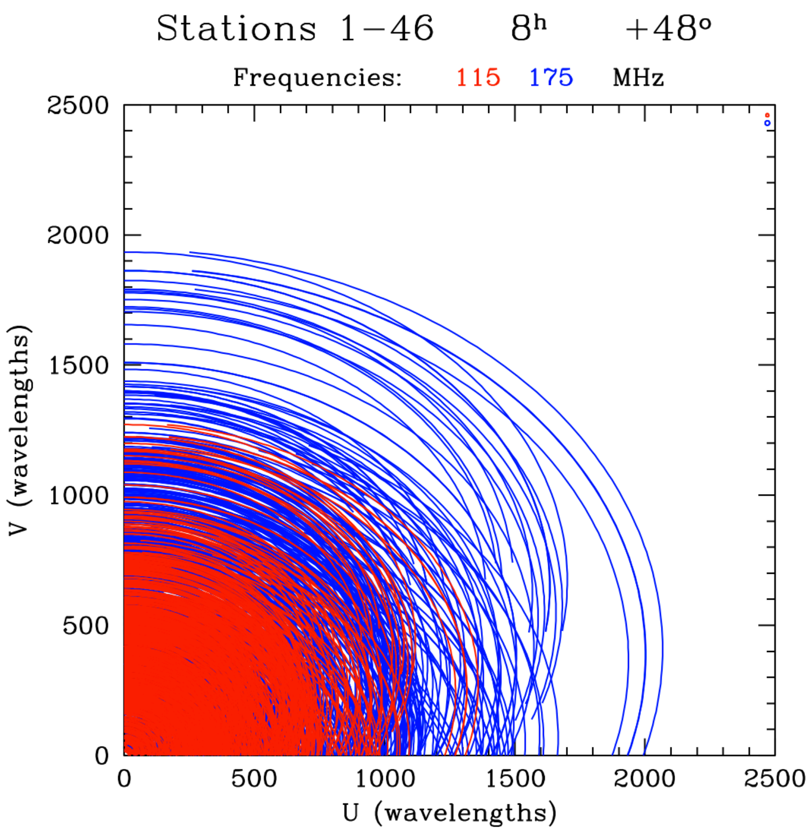
Which scales best to detect the EoR?
Some boundary conditions
Imperfect (=realistic) arrays

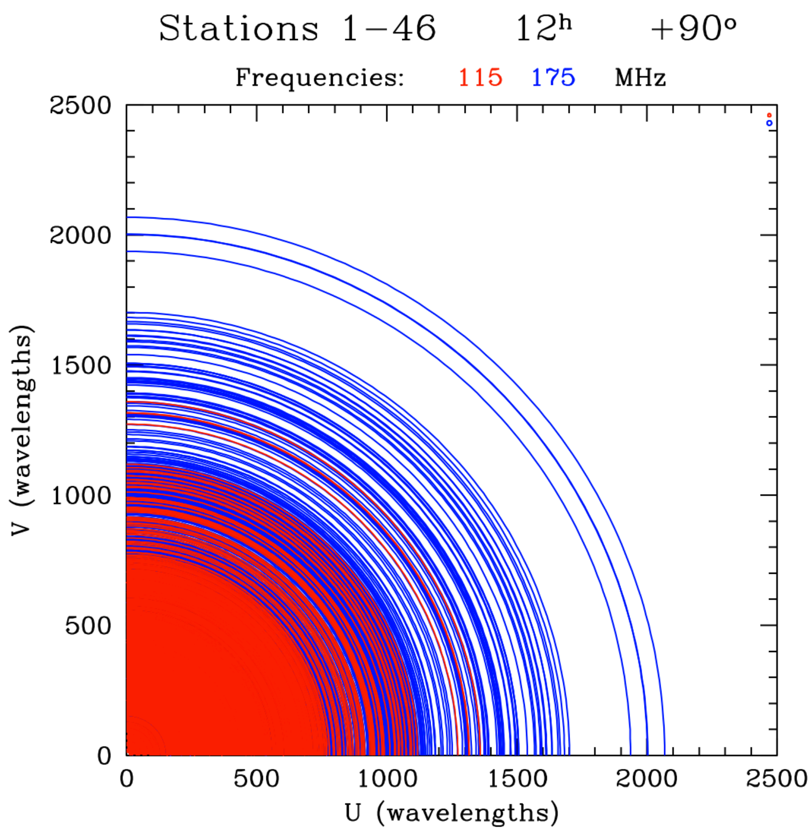
A short list of technical issues that occupied us

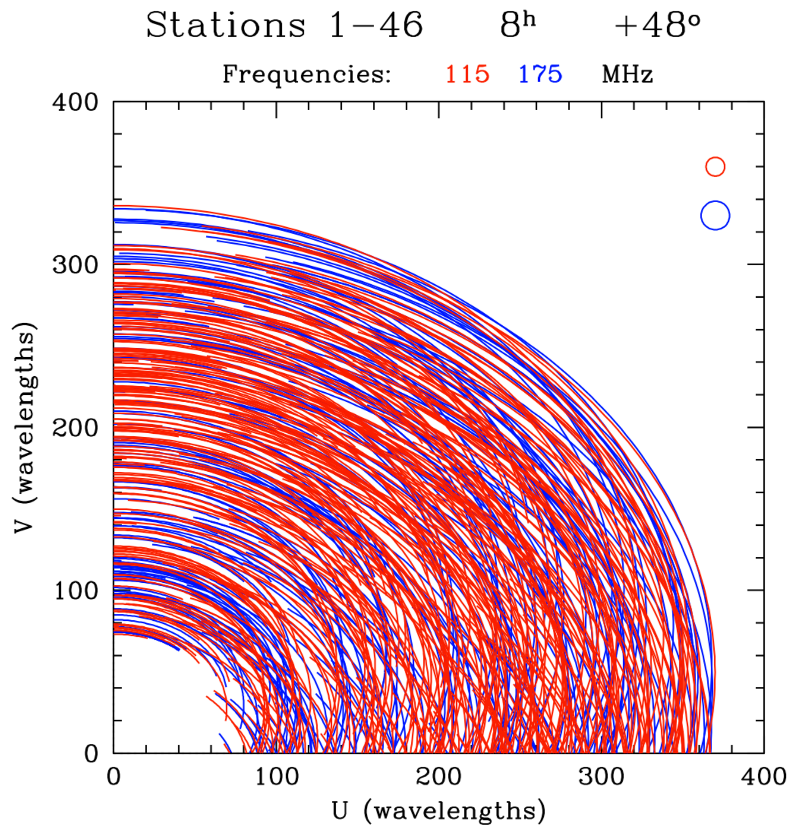
1) RFI in the Netherlands . Not a serious issues above 110 MHz ? Some worries about DAB bands, though
2) The LOFAR array configuration: balance short and long baselines ! (LOFAR serves a large and scientifically very broad community)
3) Polarized emission a show-stopper ?
4) Dealing with variable beam shapes
6) Worries about chromatic sidelobe confusion (3C-sources, A-team, Galactic plane)
7) Storage/computing requirements

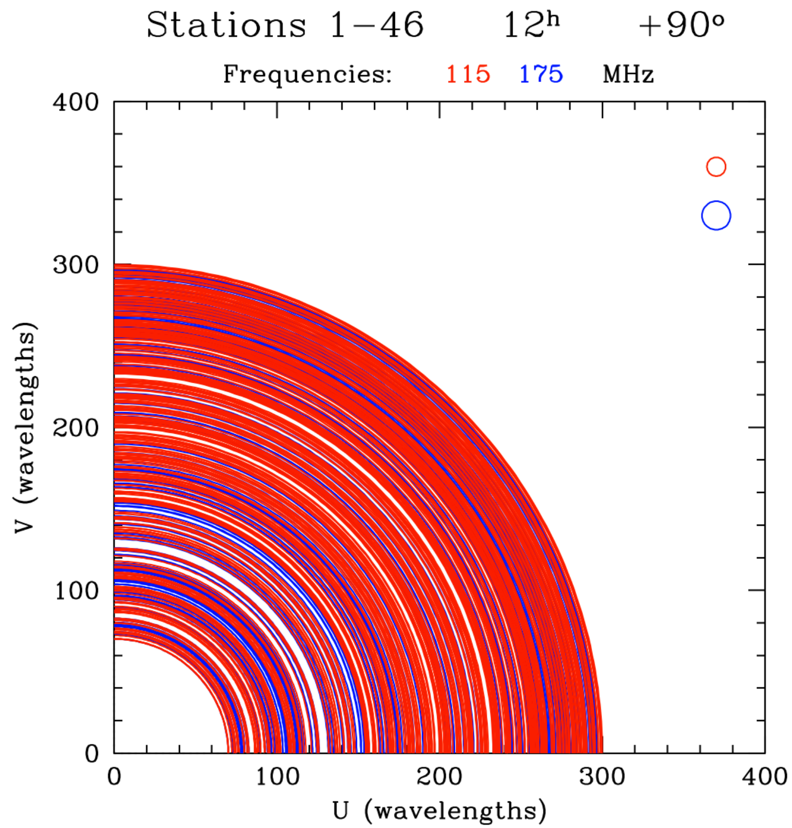
LOFAR uv-coverages for the two primary EoR windows

CS013 excluded





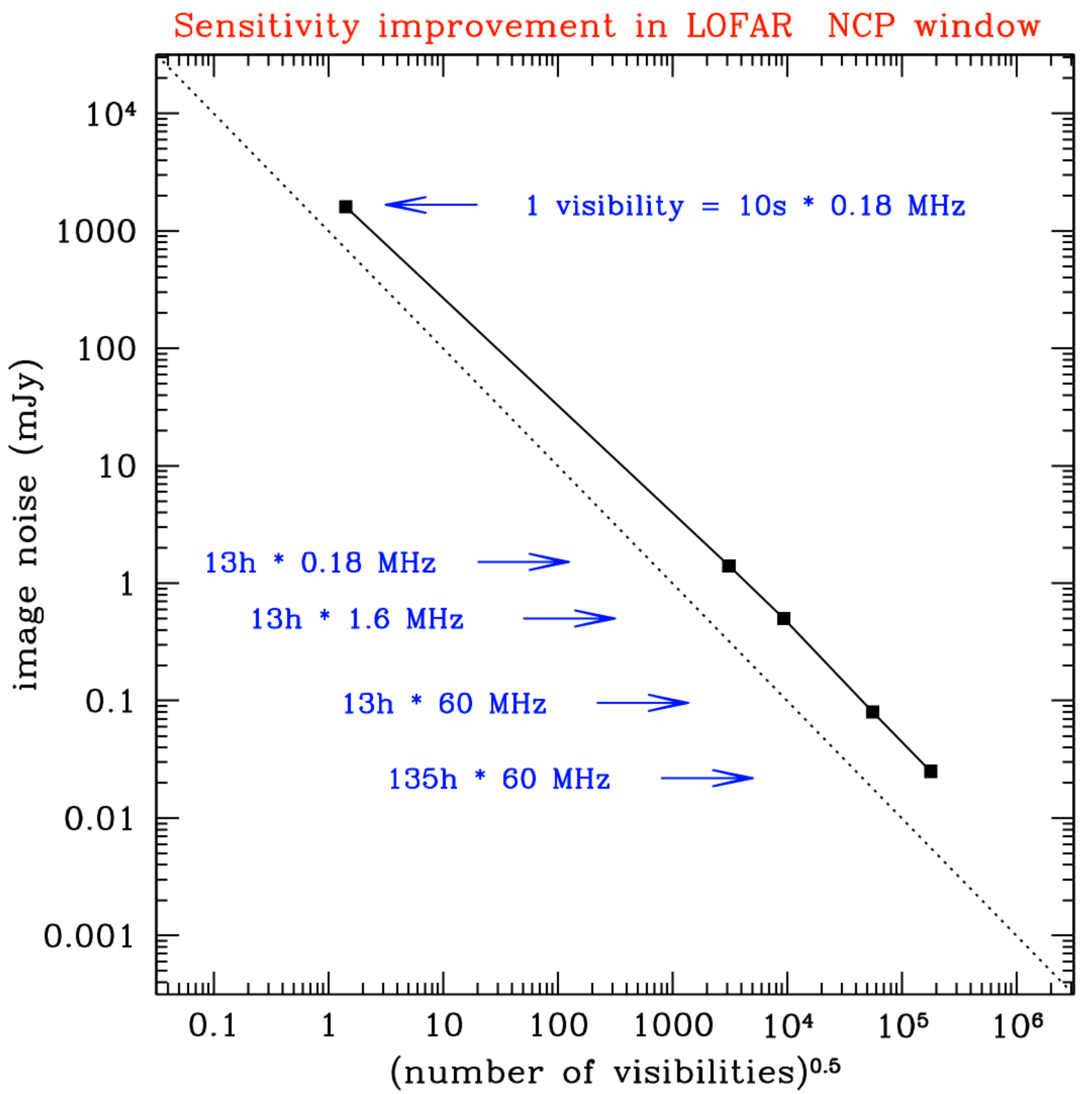

Stations 1–46 8h +48°
Frequencies: 115 175 MHz
V (wavelengths)
U (wavelengths)
0
100
200
300
400

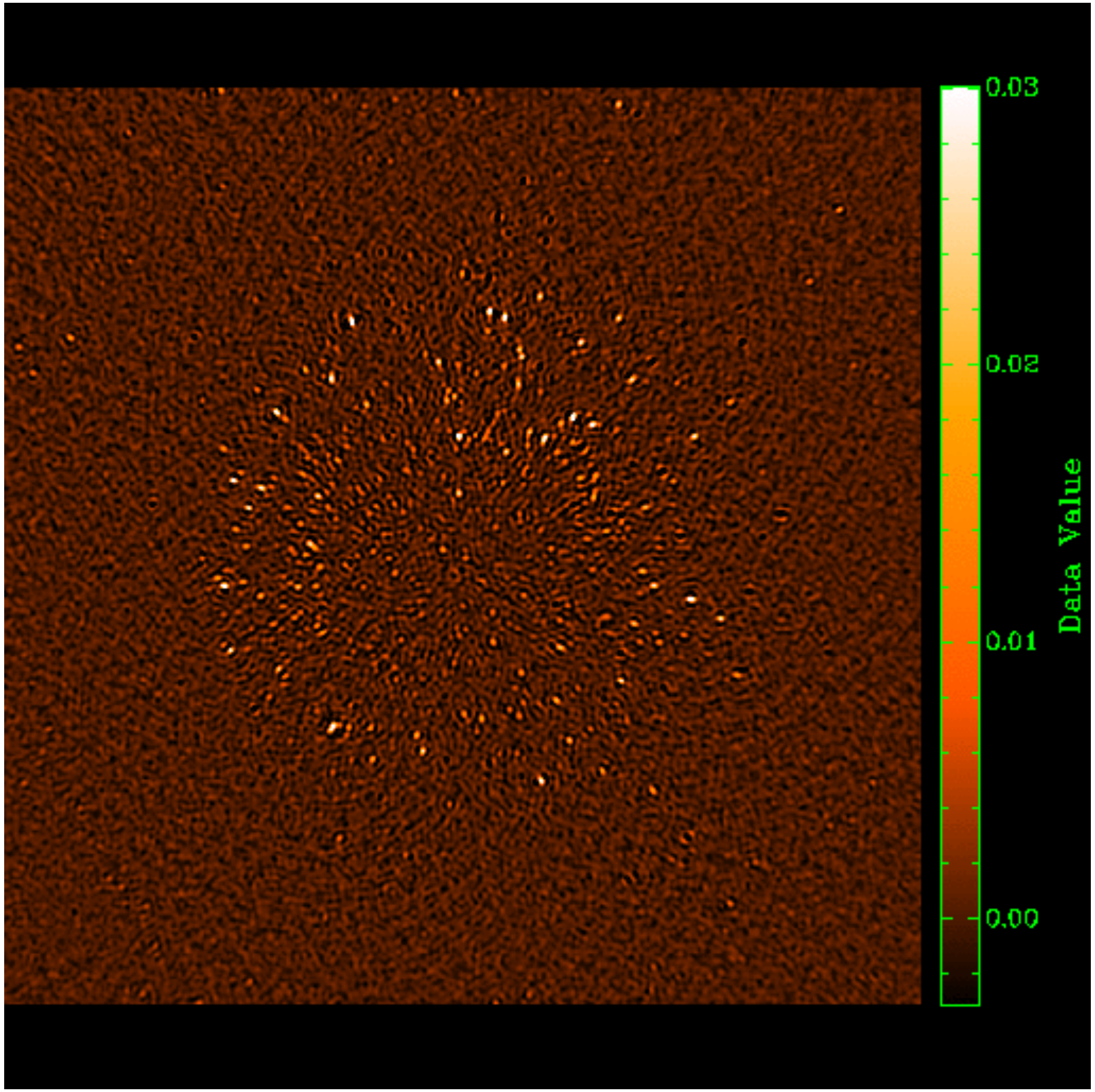

Stations 1–46 12h +90°
Frequencies: 115 175 MHz
V (wavelengths)
U (wavelengths)
0
100
200
300
400

Beating down the noise

Noise from images with uv-range

70-150λ
70-300λ
70-600λ
70-1200λ
70-2400λ




0.03
0.02
0.01
0.00
Data Value

3C196 4 nights integration *Pandey*

10 x 10 degrees

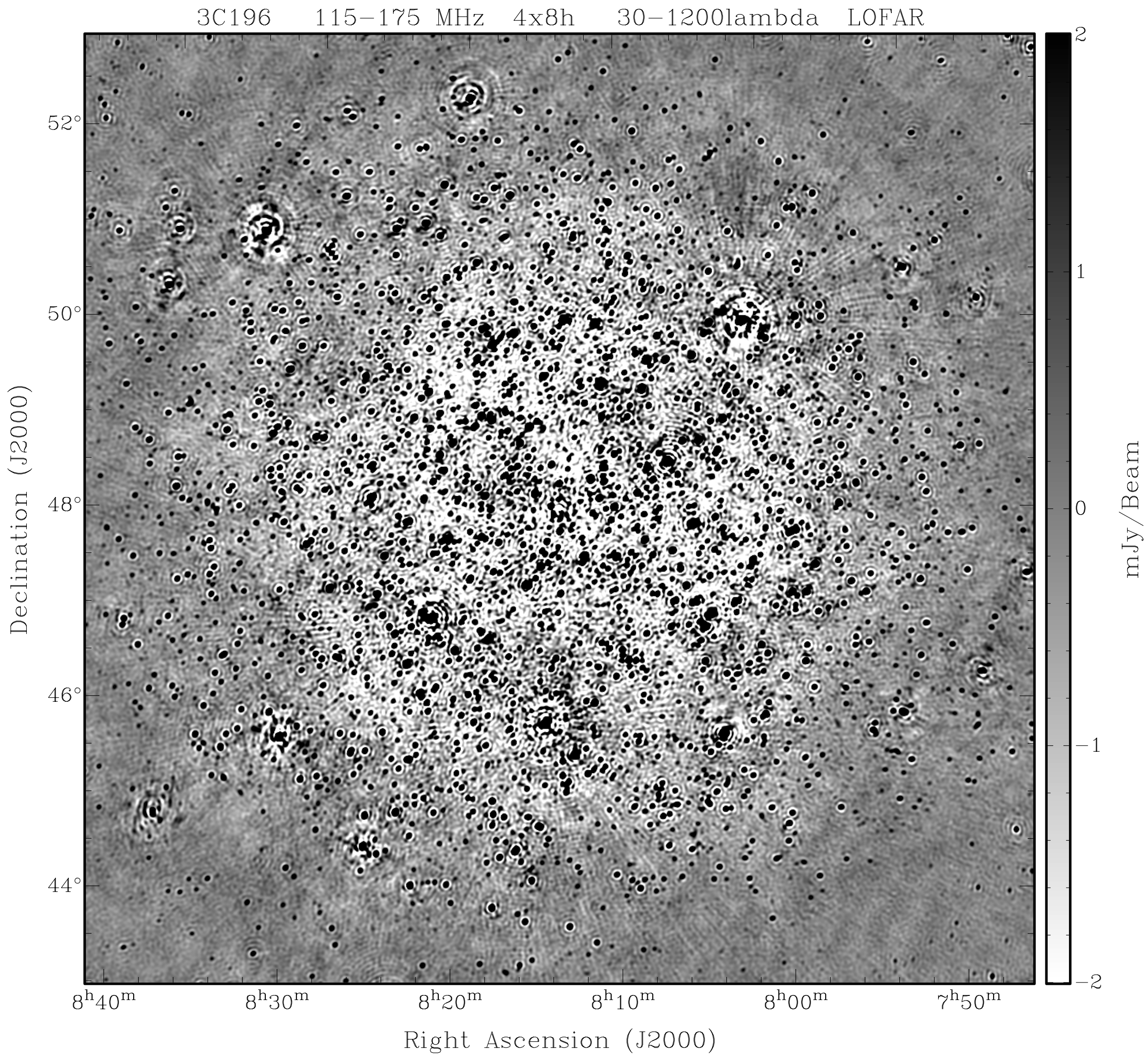
+- 2 mJy range

800 sources subtracted

Sidelobe issues

Ionospheric issues

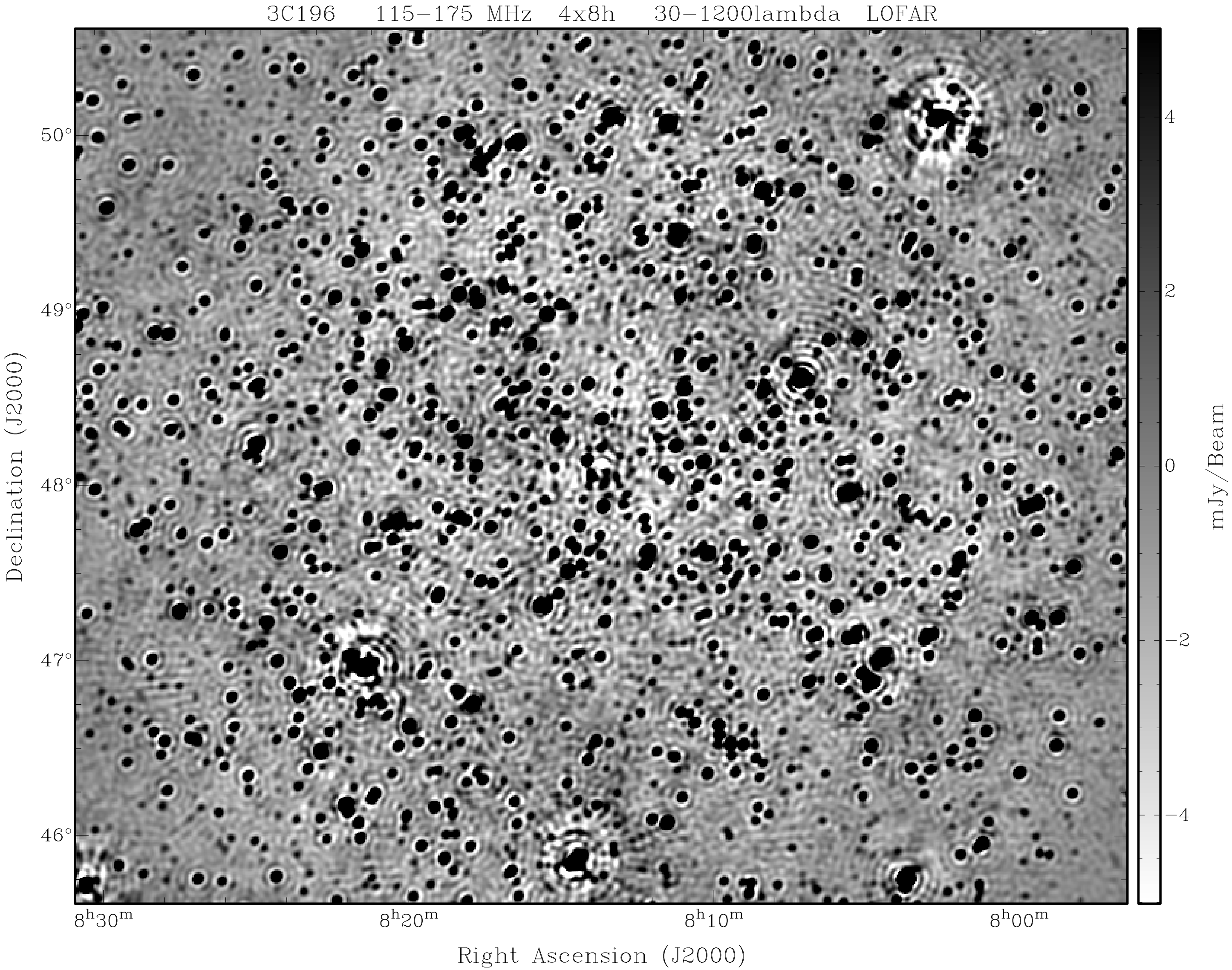
Distorted off-axis sources → SAGECal



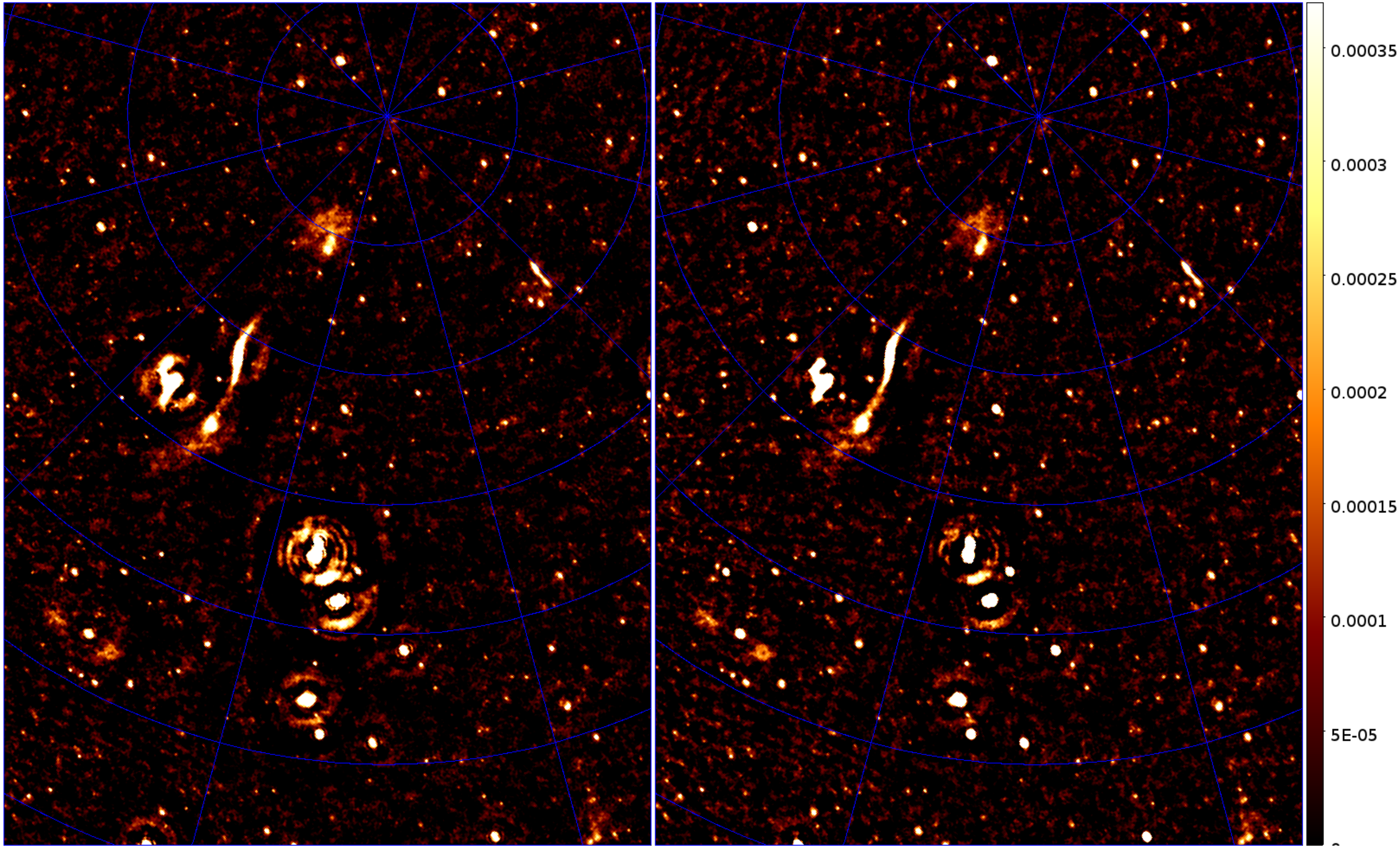
3C196   inner area

4 x 4 degree

+- 5 mJy



NCP 114 h Sarod Yatawatta



LOFAR EoR Project status

Cycle 0   (ending 15 nov 2013)

~ 300h NCP   150h ‘processed’
~ 200h 3C196   32h ‘processed’
~ 100h Elais-N1
~ 50h 3C295

Busy with analysis and planning writing up results:

Cycle1   (15-Nov-2013 → 15-May-2014)

+ 300h NCP
+ 200h 3C196

What is in store after my ‘retirement’ ?

Many more years of EoR related work including ancillary science

- Understanding foregrounds (the local ISM in 3-D !)
- Study polarized giants and DDRGs → IGM at z=0-4
- 21cm forest at z=5→ 8 ?

As the ’Eagles’ sang in ‘Hotel California’

‘You can check out any time you want, but you can never leave’

A big thanks you to all.   It has been a wonderful week !

Recorded by Robert Noordam, Feb 2012