Magnetic Fields in the Milky Way

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Why is the *Galactic* B-field of interest ?

- highest spatial resolution of B-fields
- clarify its role in spiral galaxies
- constraints on origin (primordial/dynamo)
- role in star formation
- pressure ($B^2/8\pi$) in the ISM
- cosmic-ray propagation
- foreground for extragalactic observations (CMB)

- *Galactic B-field knowledge is still incomplete*

The Galactic magnetic field

Observational methods for <u>local</u> B-fields

$B_{\perp}$ (*perpendicular field component)*

- Starlight polarization: extinction limited
- Polarized dust: star forming region
- Polarized spinning dust: ??
- SNRs: van der Laan-model

$B_{||}$ (*parallel field component)*

- Zeeman splitting: maser, clouds
- Faraday screens: HII regions, ‘bubbles’

The Galactic magnetic field

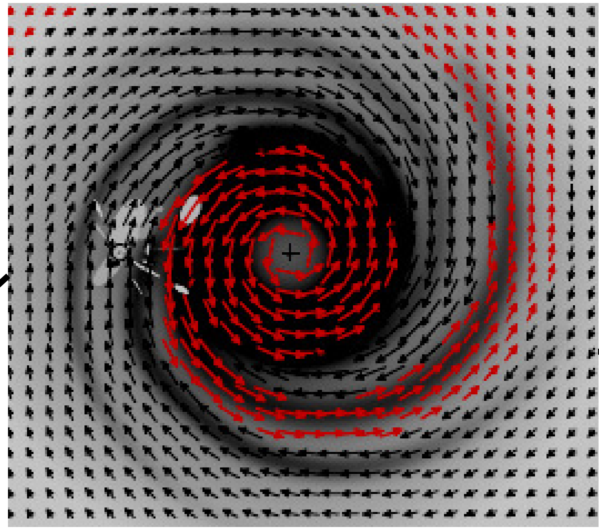
Observational methods (global results):

- Synchrotron emission I: perpendicular field
- Synchrotron emission PI: perpendicular / regular component
- Rotation measures (PSR, EGS): parallel field

- Needs: cosmic ray density/spectrum f(r,z) thermal electron density and filling factor f(r,z)

Galactic components

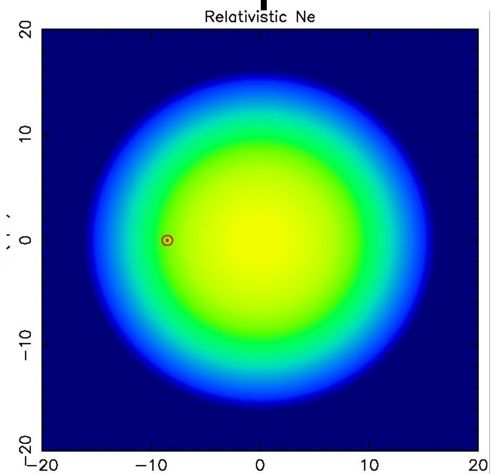
B-field



3D - model
➔ Xiaohui's talk

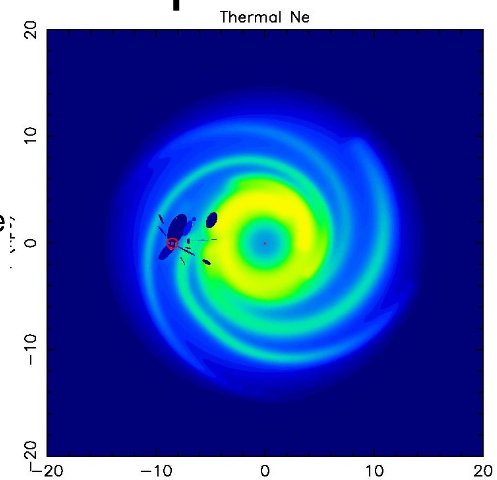
RM, $\varphi(\nu)$

Synchrotron Emission
I (ν) + PI (ν)



CR

thermal n_e



NE2001

Galactic magnetic field

- *Advantage*: highest spatial resolution
  ➔ turbulence spectrum, objects resolved

- *Disadvantage*: our position inside the Galaxy ➔ large scale magnetic field (+ other constituents) by 3D-modelling

The Galactic magnetic field

What we want to know :

- \- global field structure: disk + halo
- \- regular/random component f(r,z)
- \- field strength f(r,z)
- \- field reversals
- \- local peculiarities

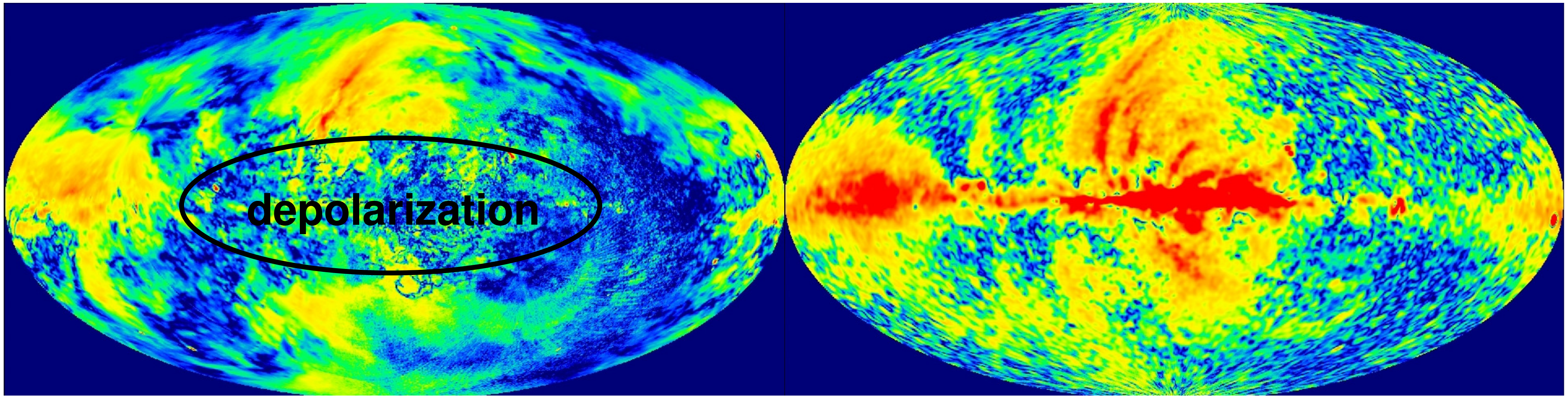
What we have to do:

- *- measurements (also Aris PSR talk)*
- *- large scale 3D-model (talk by Xiaohui)*

Polarized intensity all-sky surveys

1.4 GHz: DRAO (Wolleben et al., 2006) + Villa Elisa (Testori et al., 2008)

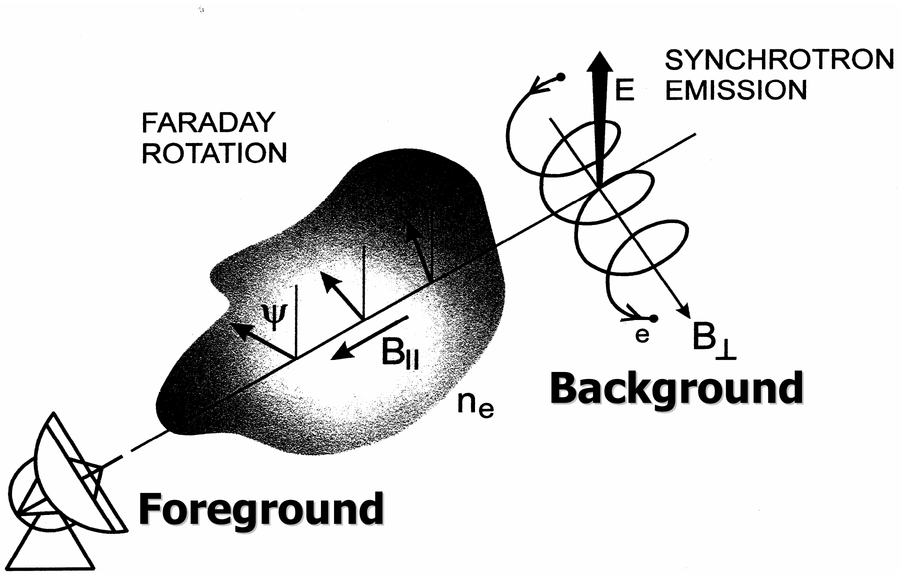
22.8 GHz WMAP (Page et al. 2007)



Low intrinsic percentage polarization outside of local features.

1.4 GHz polarization difficult to model ➔ coupling of B and n_e needed
➔ *topic for A1 (needs: high angular resolution, low frequencies)*

Faraday rotation ➔ ‚Faraday Screen' hosts B and n_e



Rotation Measure:

$$RM\ [rad/m^2] = 0.81\ n_e\ [cm^{-3}]\ B_{||}[\mu G]\ L[pc]$$

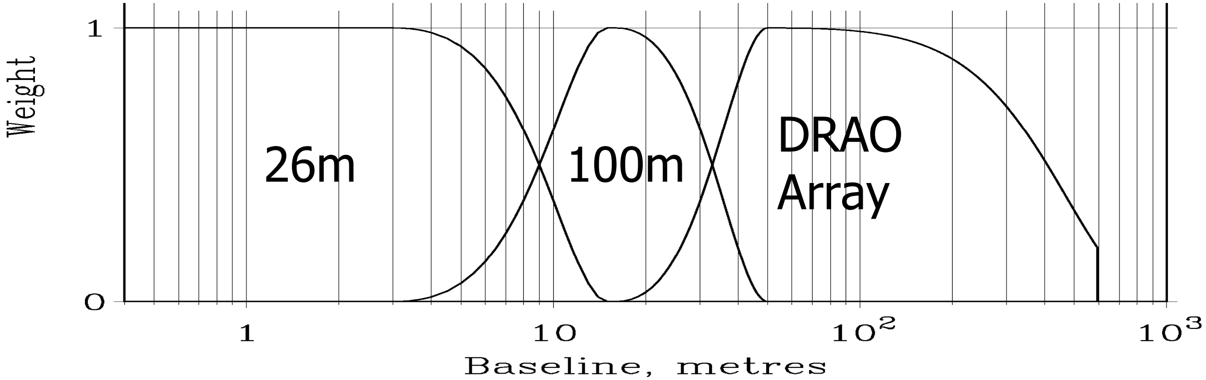
Polarization angle:

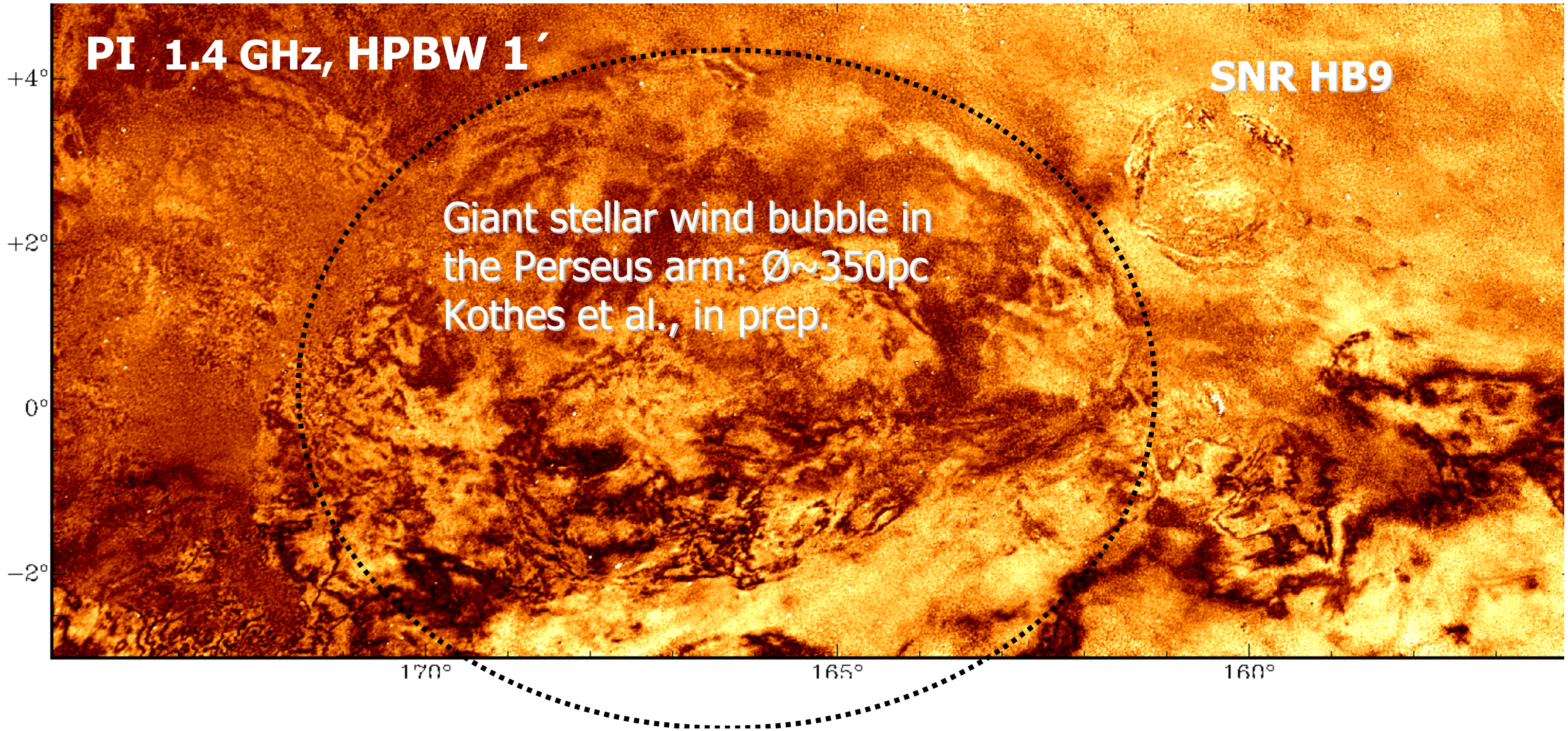
$$\varphi\ [rad] = \varphi_{int}\ [rad] + RM\ \lambda^2\ [m]$$

A analogon of a Faraday Screen (Tom Landecker)

DRAO 26m + Effelsberg 100m + CGPS

Landecker, Reich et al., 2010, AA, in press

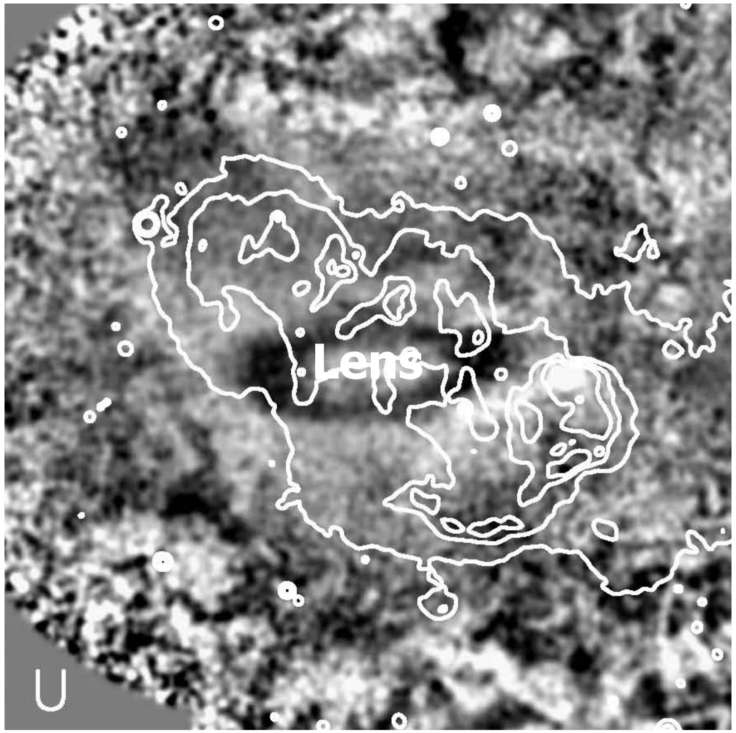




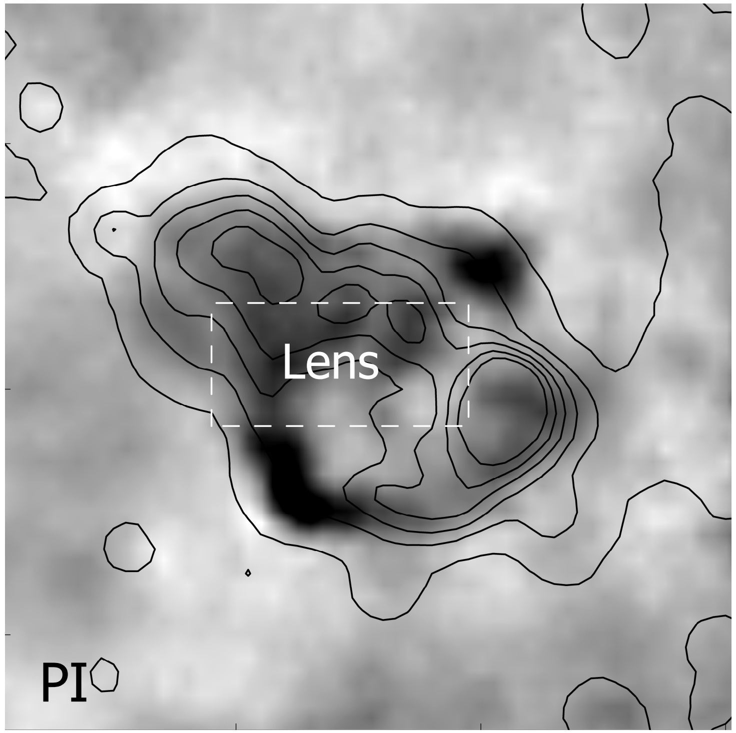
The *'lens'* Faraday screen in front of W5

Gray et al., 1999, Nature : RM ~ 110 rad m^{-2} *relative* zero-level

RM ~ 10 rad m^{-2} *absolute* zero-level ➔ invisible at 4.8 GHz



CGPS 1.4 GHz

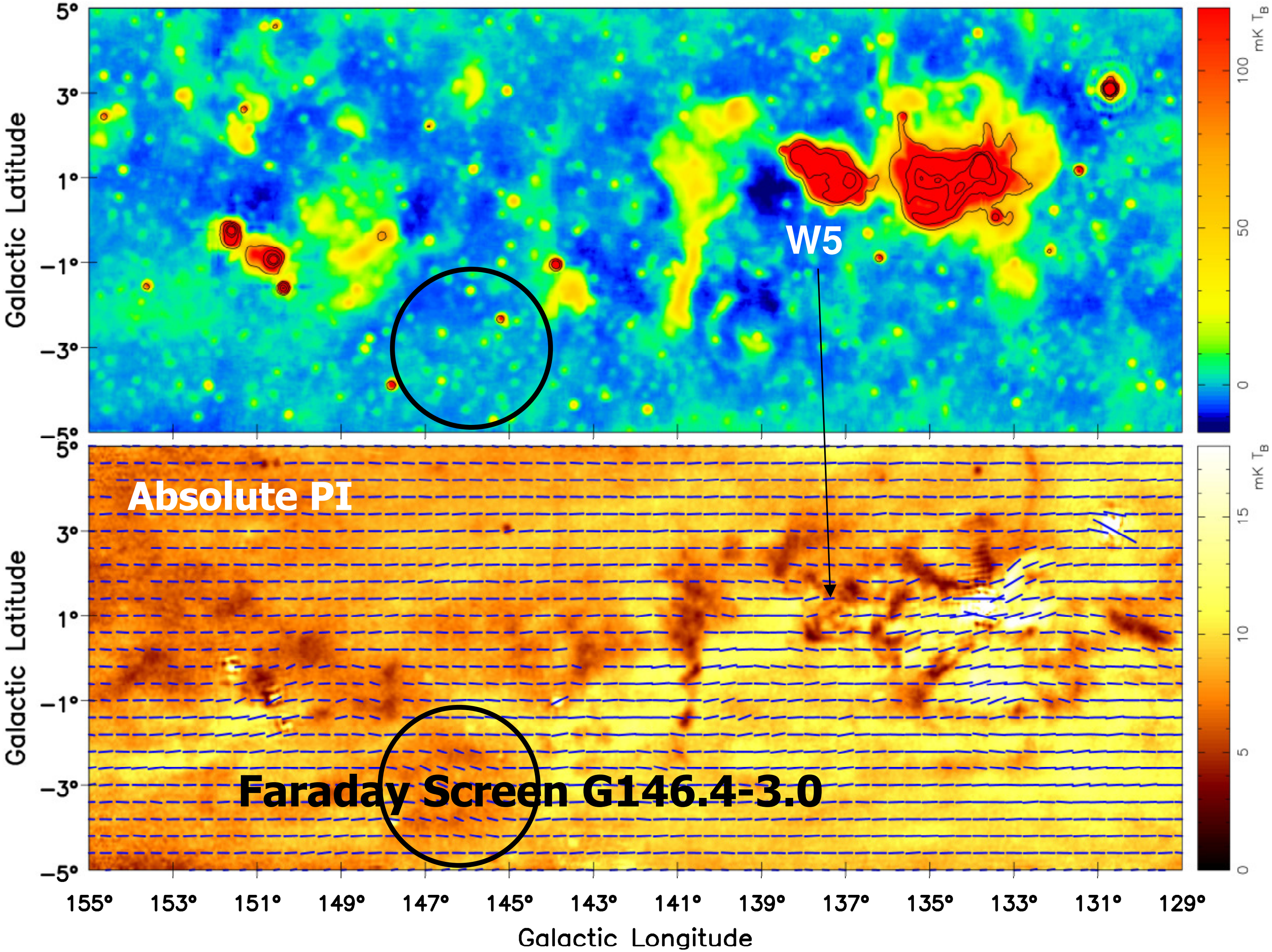


Urumqi 4.8 GHz

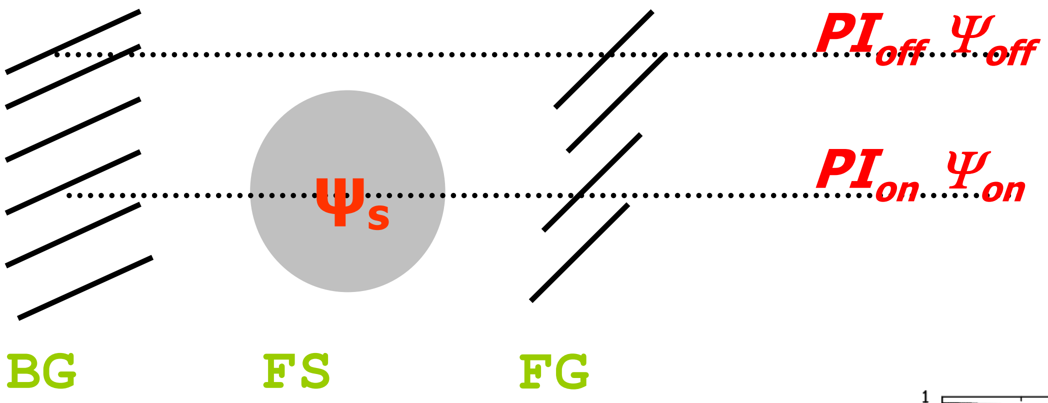
Shown again: absolute calibration is essential !

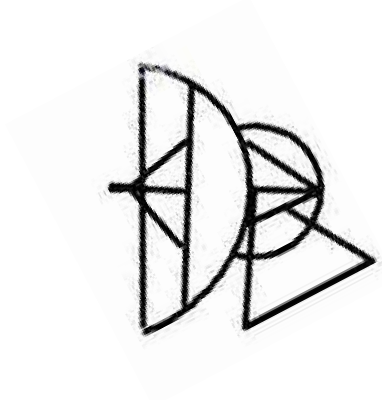
Sino-German 4.8 GHz polarization survey

Urumqi 25-m, HPBW 9.5´, Gao, et al., 2010, AA, 515, 64



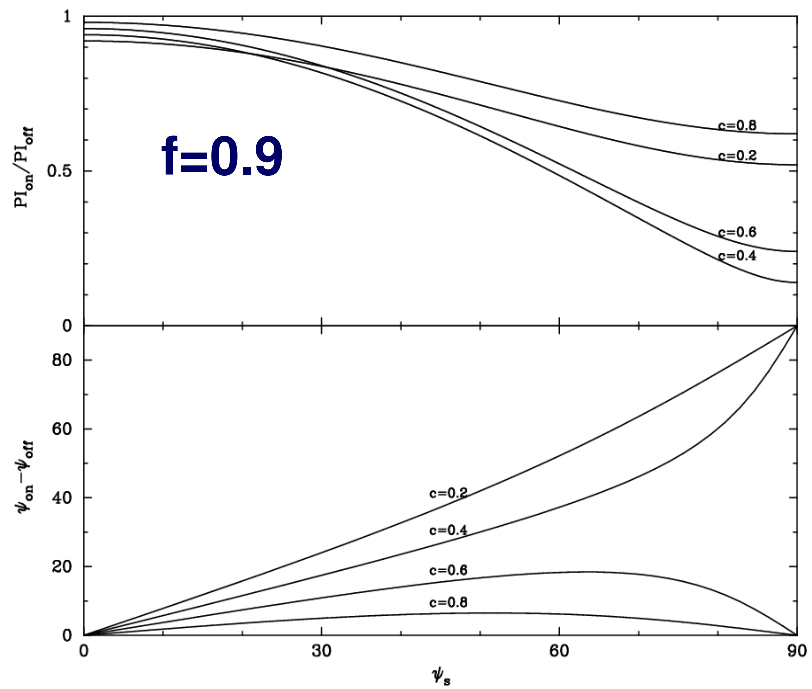
Faraday Screen model: ‚ON' versus ‚OFF'
Sun et al., 2007, AA, 469, 1003





$$\frac{PI_{\rm on}}{PI_{\rm off}} = \sqrt{f^2(1-c)^2 + c^2 + 2fc(1-c)\cos 2\psi_{\rm s}}$$

$$\psi_{\rm on} - \psi_{\rm off} = \frac{1}{2}\tan^{-1}\frac{f(1-c)\sin 2\psi_{\rm s}}{c + f(1-c)\cos 2\psi_{\rm s}}$$



$f < 1$ depolarization

$c = PI_{FG}/(PI_{FG}+PI_{BG})$

ψ_s = FS rotation angle ➔ **RM**

Faraday Screen G146.4-3.0 Ø 3.3°

Gao et al., 2010, AA, 515, 64

FS model: RM -140+/- 20 rad m^{-2}

~3% depolarization, distance ~300 – 700 pc

➔ size ~17 – 40 pc

RM ~ n_e $B_{||}$ size

n_e: *no* Hα, upper limit from rms-TP

➔ n_e < 0.5 – 0.8 cm^{-3} ➔ $B_{||}$ > 8.6 - 13.5 μG

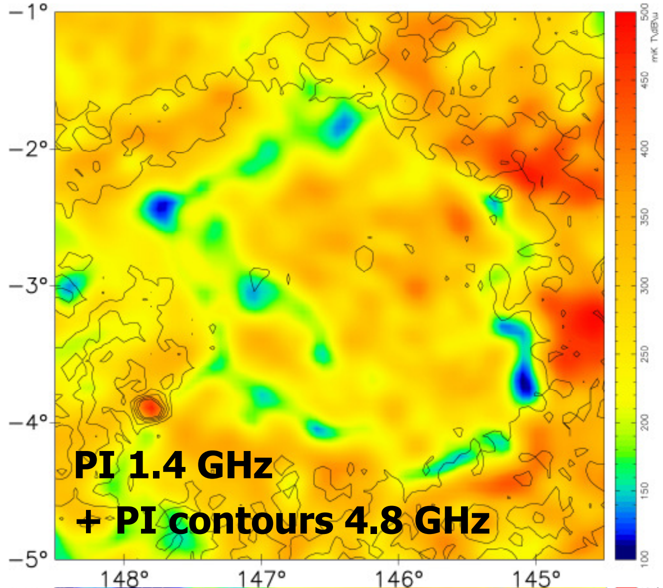
15 NVSS source RMs outside

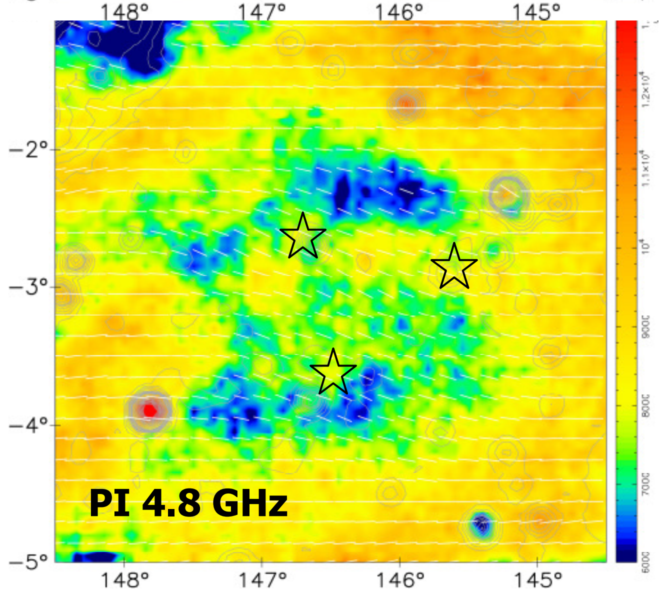
(Taylor et al., 2009): mean RM -76 rad m^{-2}

3 sources inside: -151, -222, -338 rad m^{-2}

➔ agrees with negative RM excess

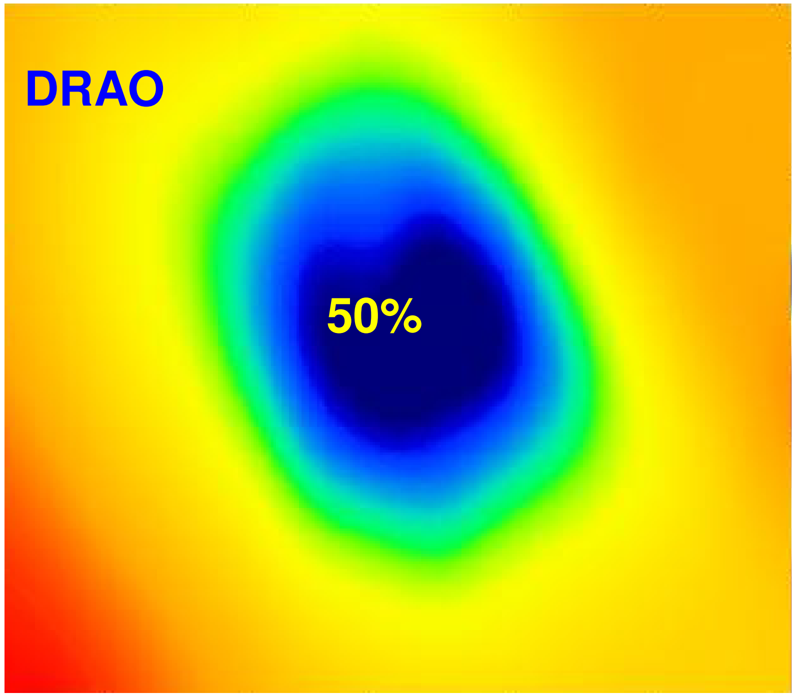
most high RM FS are invisible at low frequencies





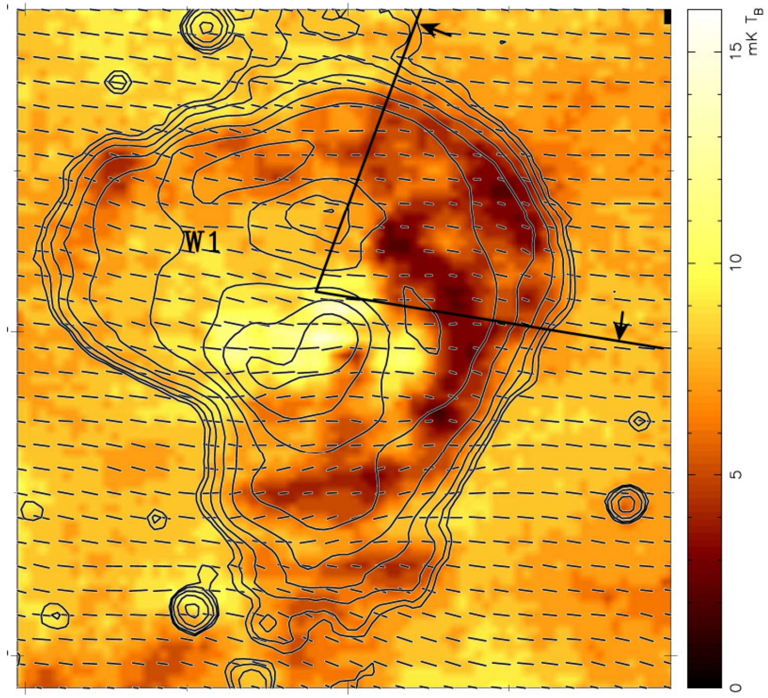
HII Region W1 at 850 pc distance

W1 in absorption at 22 MHz



➔ Synchrotron emissivity f(d)

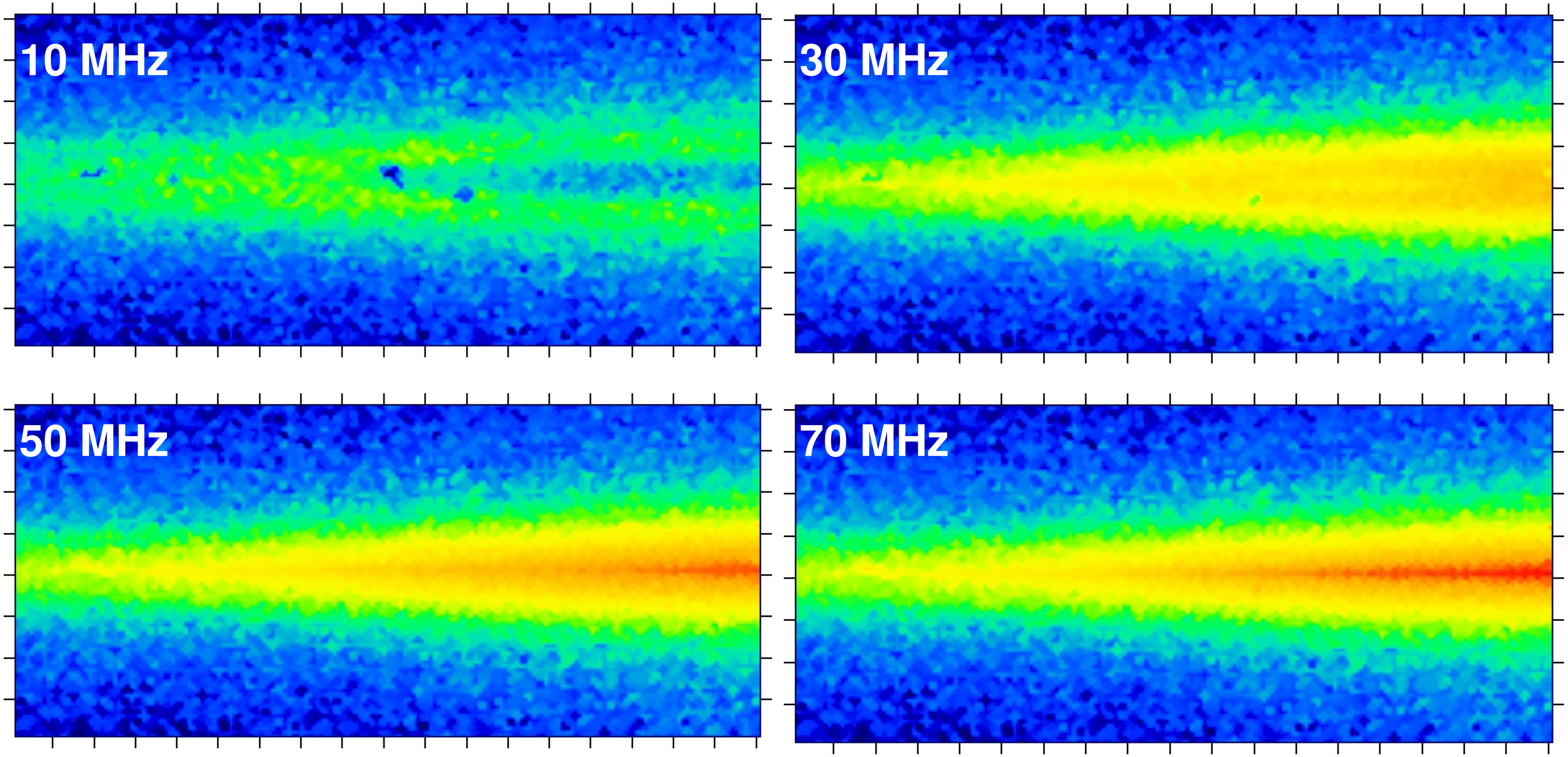
W1 at 4.8 GHz (Urumqi)



➔ B-field within HII-region, PI emissivity f(d)

All-sky simulations at 15‘ angular resolution: diffuse Galactic emission to be seen by LOFAR

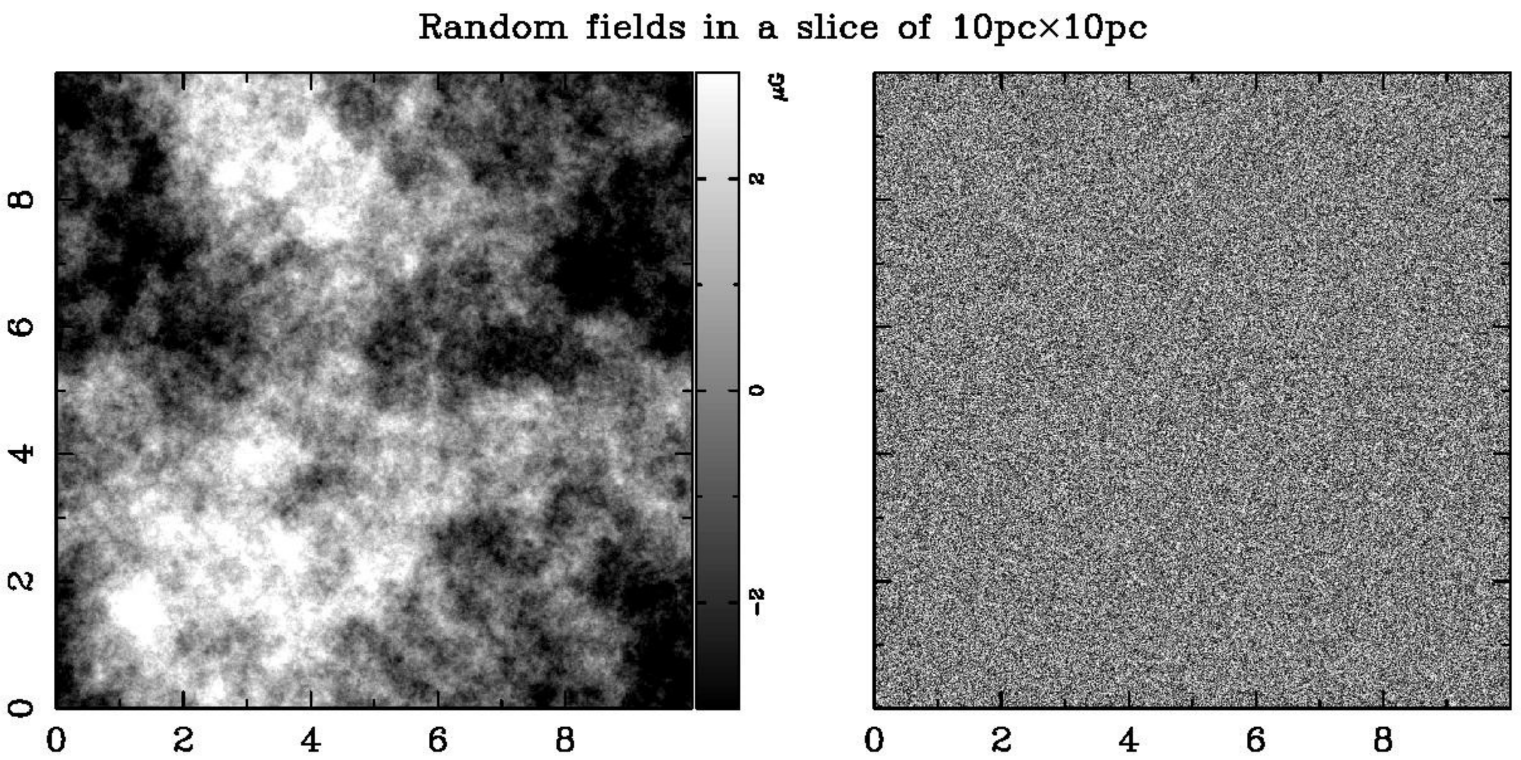
synchrotron spectral index β = 2.5



Galactic plane: 0° < L < 90°, -20° < B < 20°

Sun & Reich (2009), AA, 507, 1087:
arcsec (SKADS) simulations for patches

Kolmogorov-like turbulence spectrum for B-random

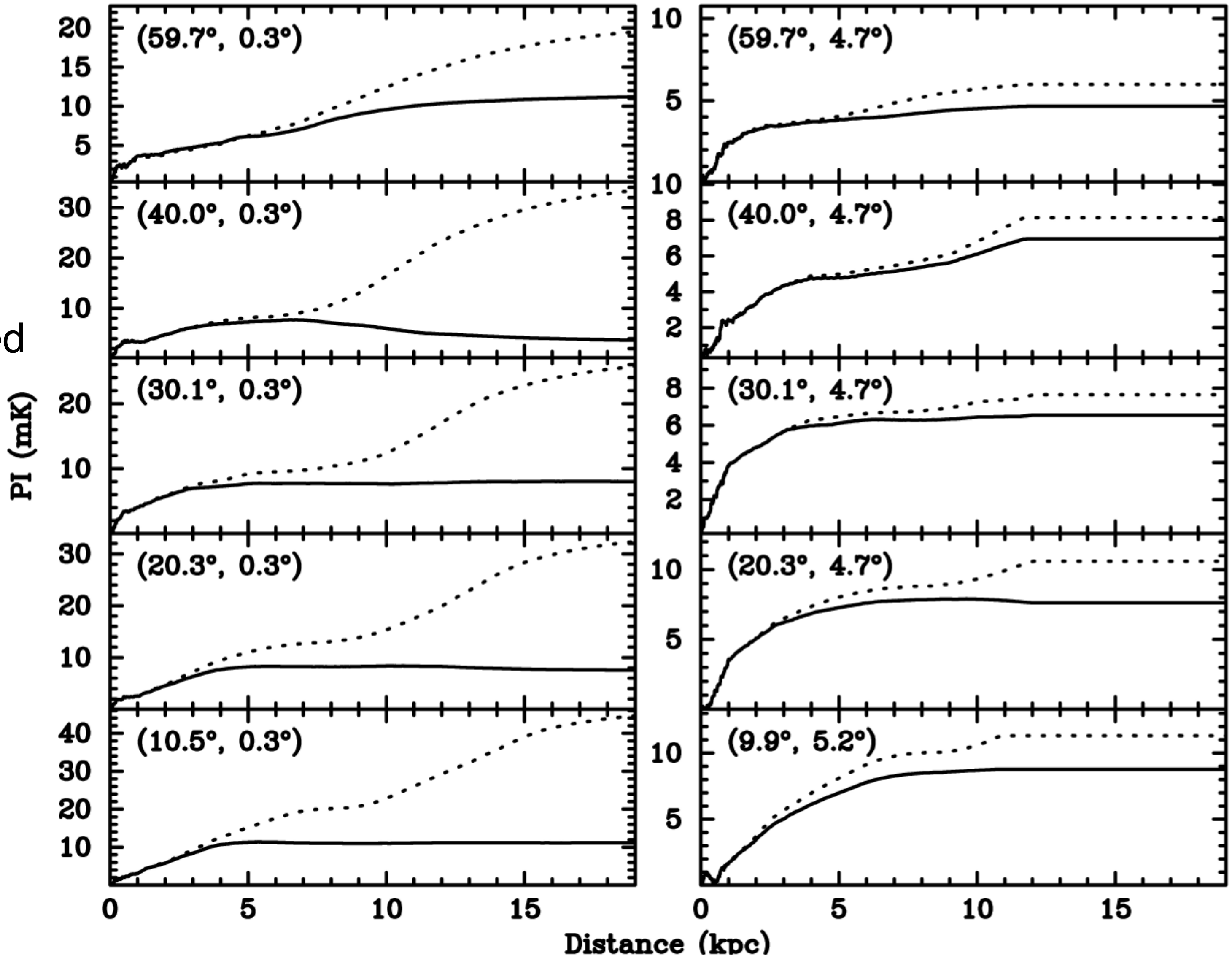


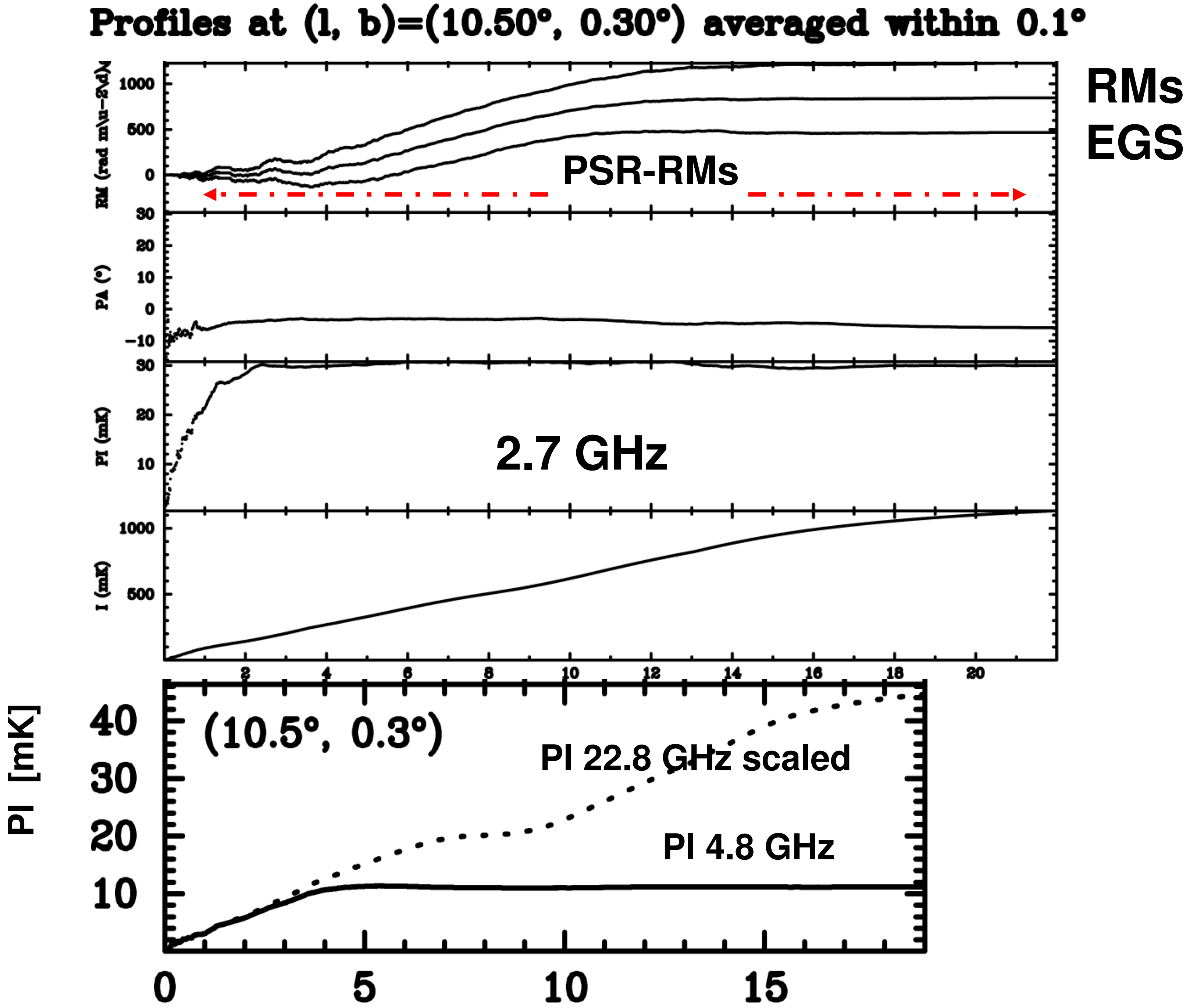
Gaussian random fields
for all-sky simulations

‚Polarization horizon‘ 4.8 GHz/22.8 GHz

Sun et al., 2010, AA, submitted

4.8 GHz PI +
22.8 GHz PI
scaled, dashed





Profiles at (l, b)=(10.50°, 0.30°) averaged within 0.1°
RMs
EGS
PSR-RMs
2.7 GHz
(10.5°, 0.3°)
PI 22.8 GHz scaled
PI 4.8 GHz
PI [mK]

Topics for A1

LOFAR related:

high angular resolution combined with
high RM sensitivity ➔ low frequencies

Galactic diffuse polarized emission:

Small scale turbulence of B (or RM, n_e)

Galactic foreground effect on EGS

RMs from ~1000 new LOFAR PSR

➔ Galactic B-field properties (Aris talk)

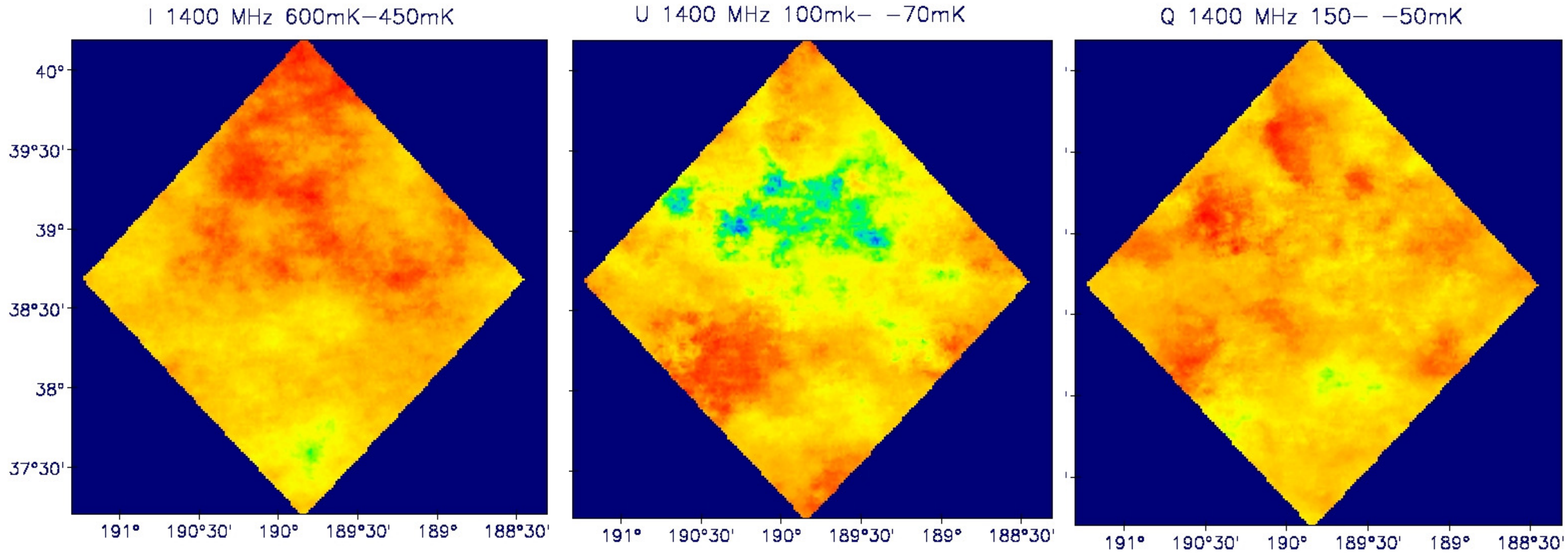
LOFAR MKSP Science Case

- claim: ΔRM ~ 0.1 rad/m^2 detection
- is this realistic ? – *likely not*
- LOFAR opens a ‚new sky' in polarization, multi-channels ➔ RM Synthesis needed

➔ *simulation of polarized Galactic emission*

(without noise, instrumental effects and constant resolution)

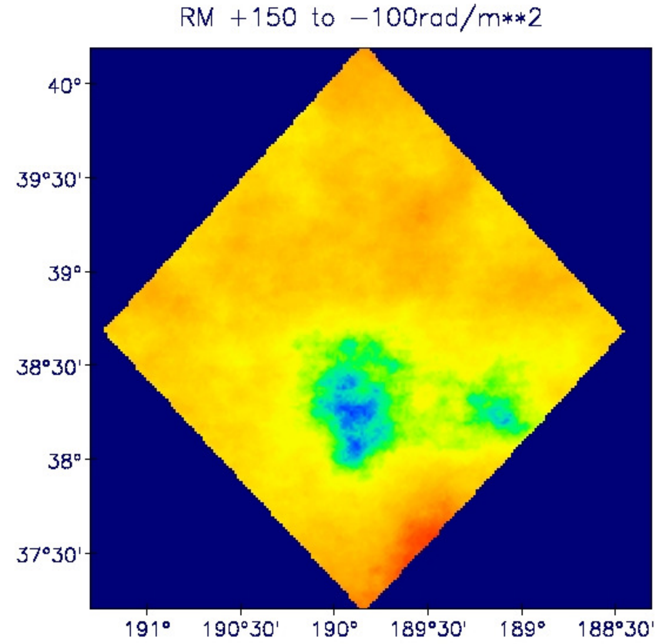
- (100 maps: 1.4-1.5 GHz, 1 MHz – *Test*)
- 800 maps: 135-175 MHz, 50 KHz, size 3°x3°, res. 51" – *compare RM Synthesis software*



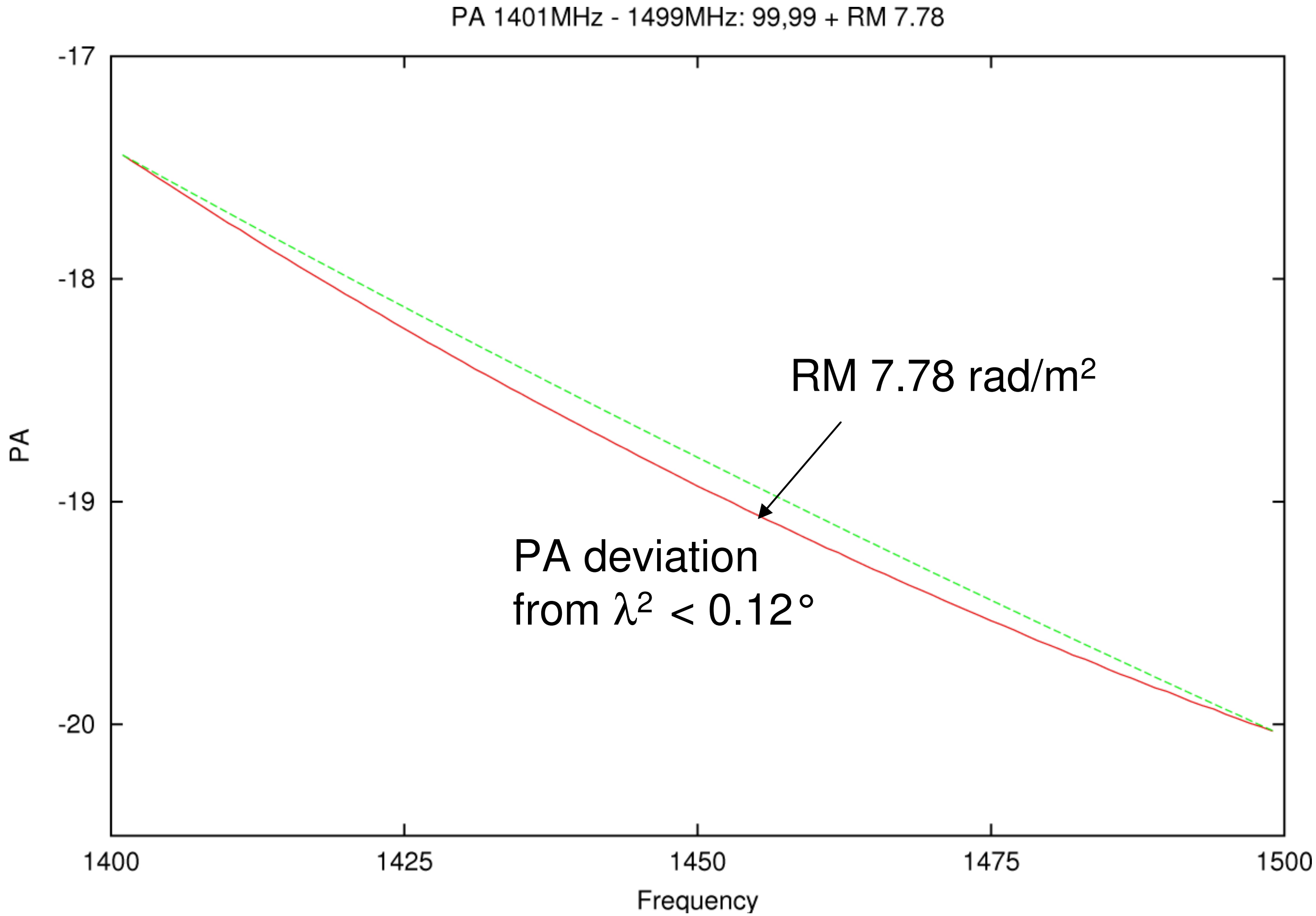
HAMMURABI code with HEALPIX projection
(Waelkens et al., 2009, AA, 495, 697)

Kolmogorov spectrum: Sun & Reich (2009)
51" resolution, 1.4-1.5 GHz (100 maps)

RM: mean/rms 4.9/31.2 rad/m^2
affects EGS observations

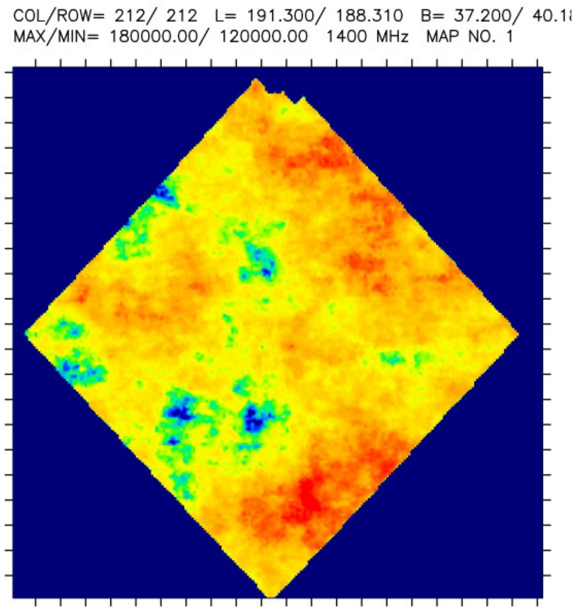


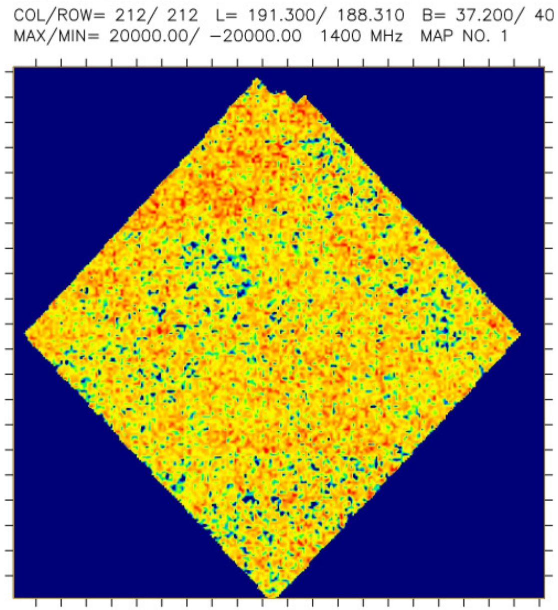
PA for pixel 99,99 (Δf = 1 MHz)

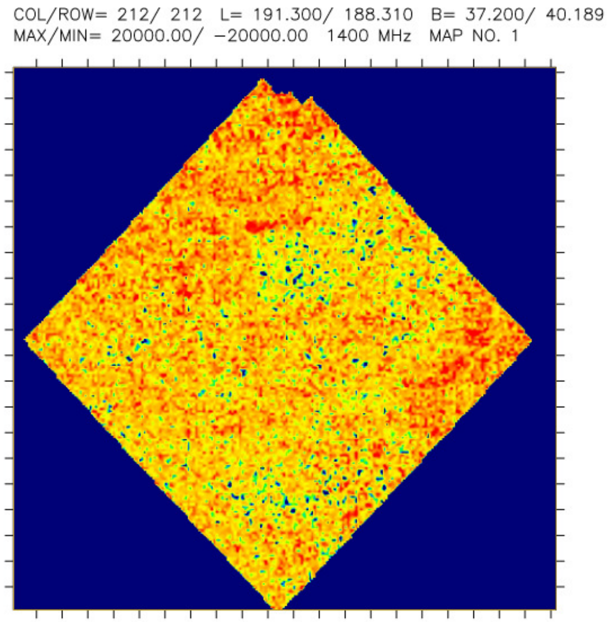


wide RM spread function ~ 590 rad/m^2 ➔ single component – almost no signature for turbulence

800x I, U, Q HBA-Maps : 135 MHz - 175 MHz



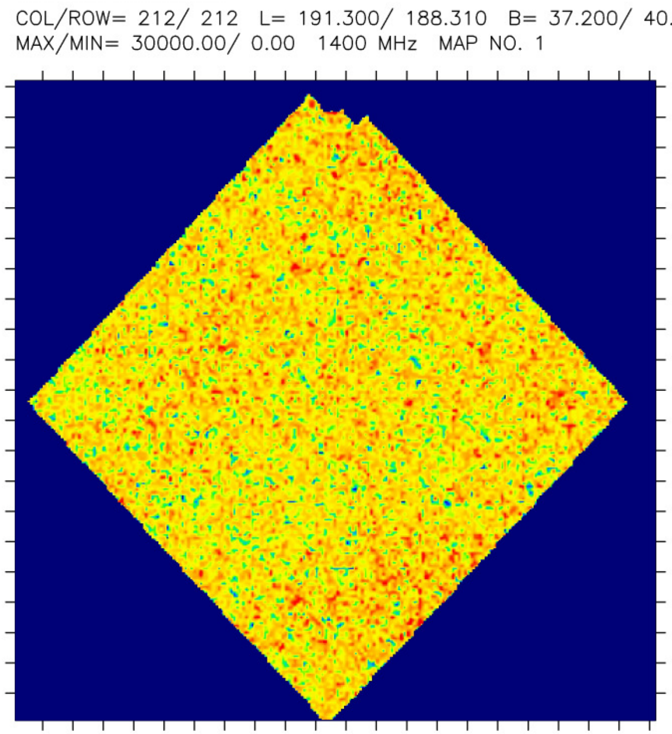


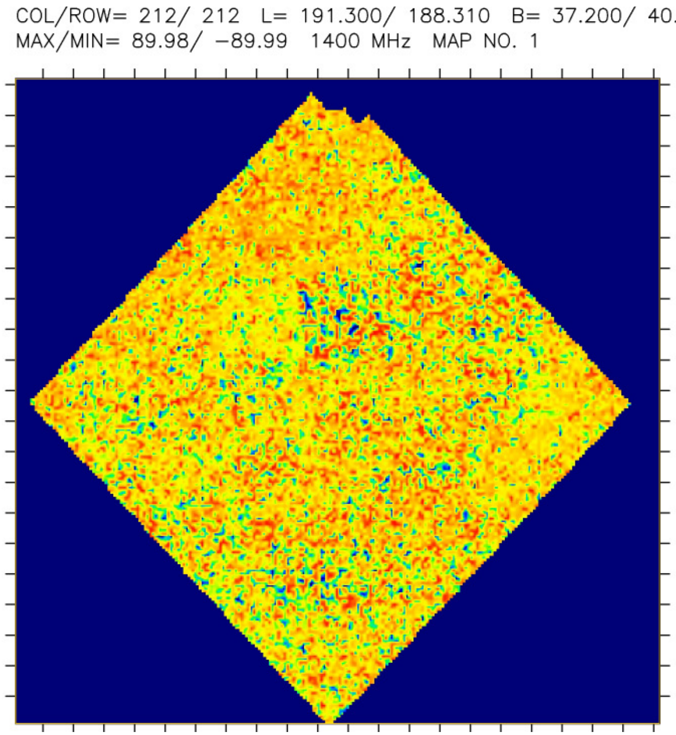


I at 174.95 MHz :
scales in frequency
with CR spectral index

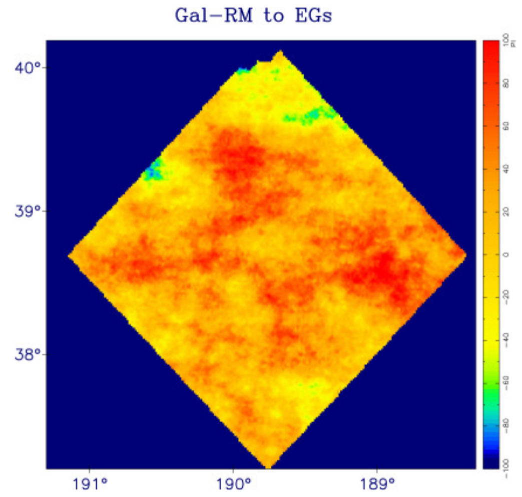
U, Q maps stuctures almost resolved,
highly variable with frequency

800x I, U, Q HBA-Maps :   135 MHz - 175 MHz

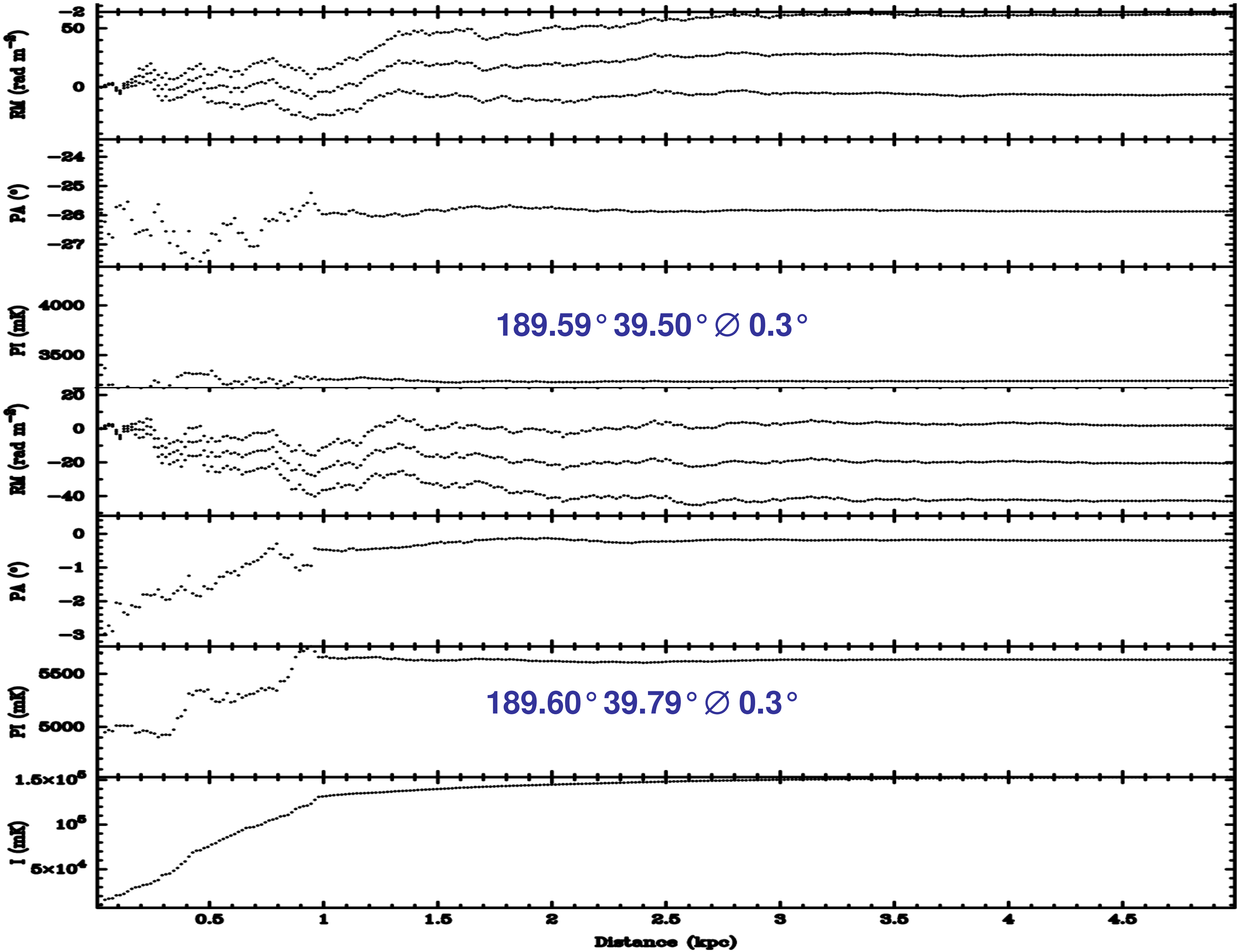




PI and PA map at 174.95 MHz

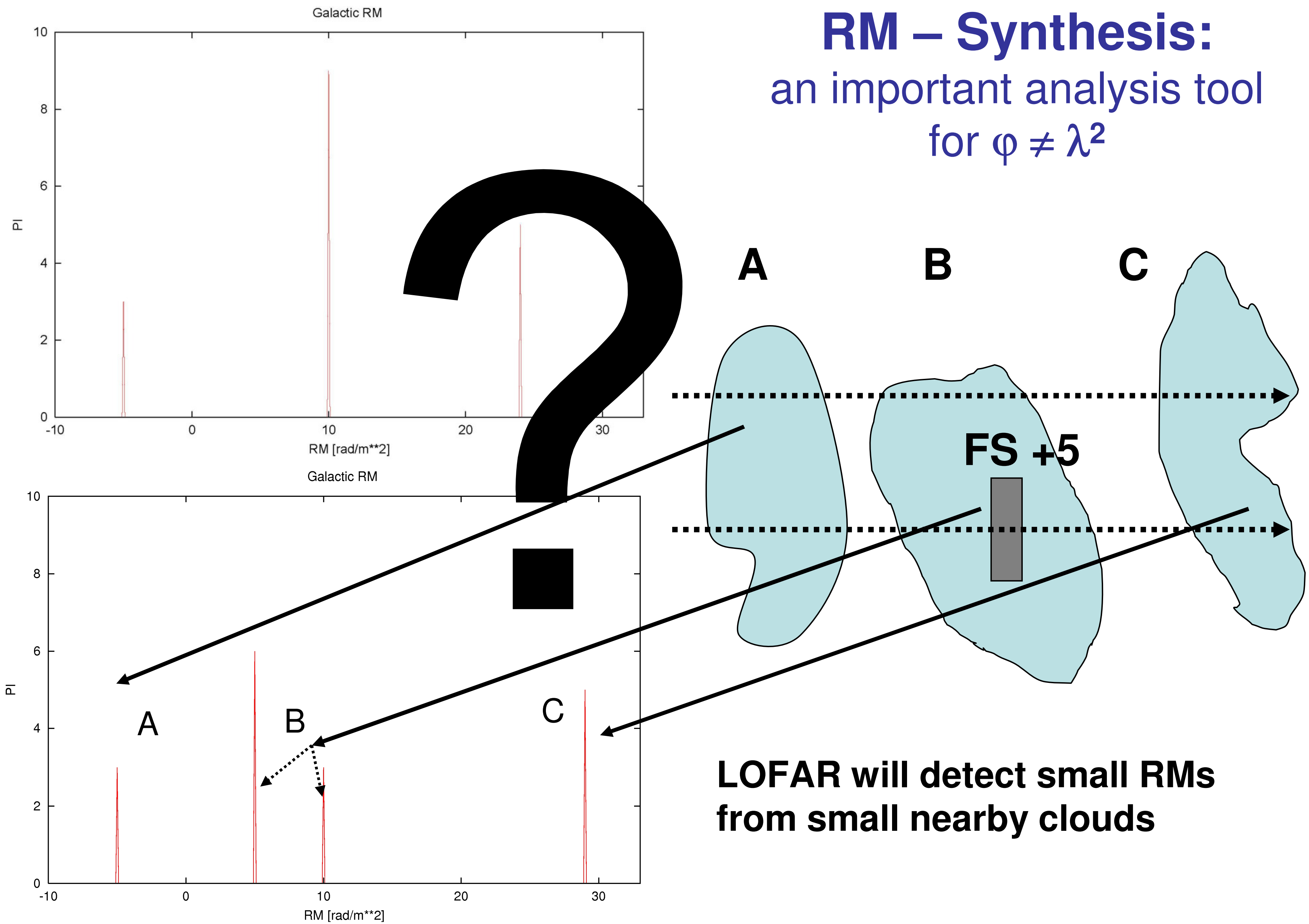


RM foreground map

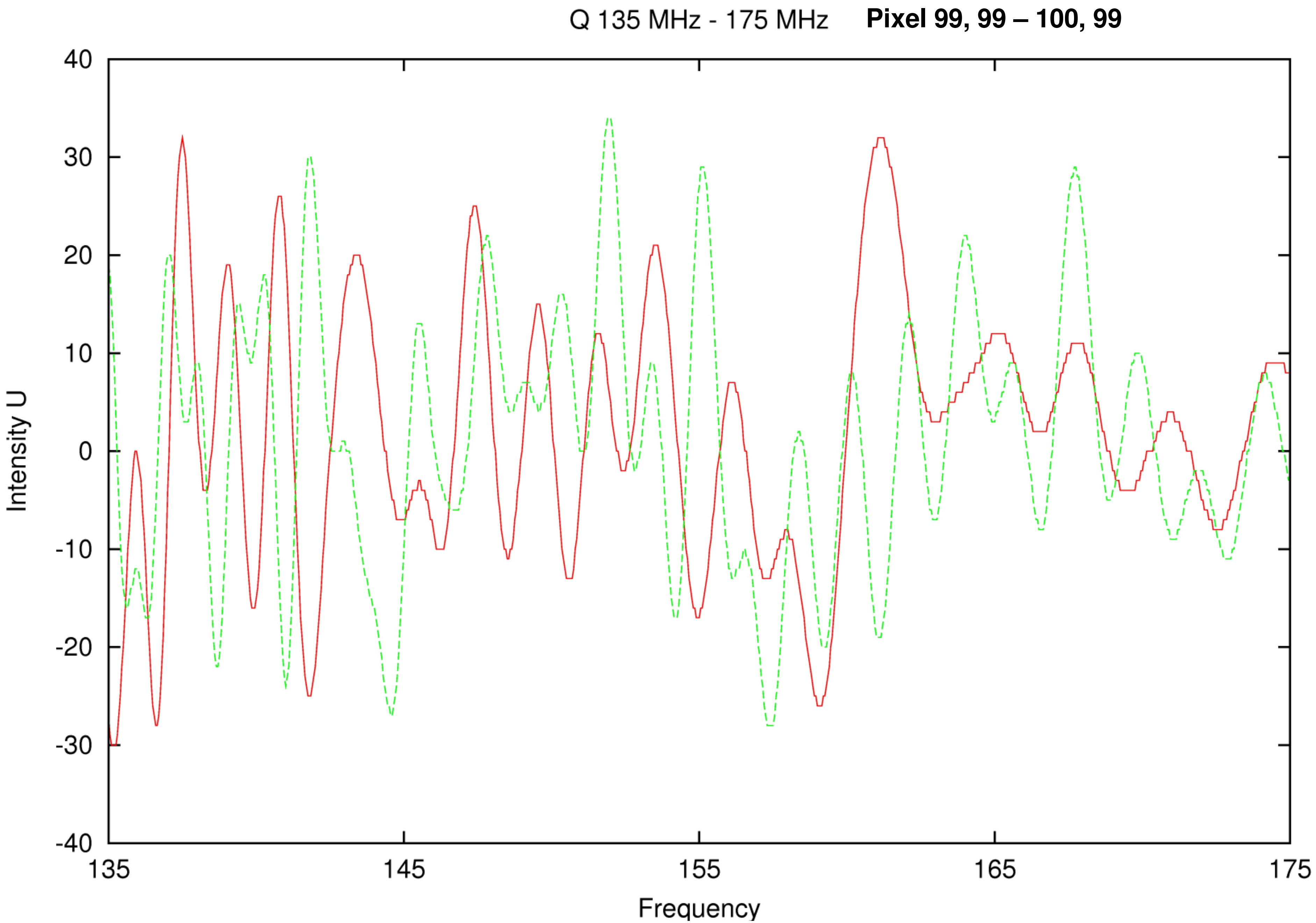

RM (rad m^-2)
PA (°)
PI (mK)
I (mK)
189.59° 39.50° ∅ 0.3°
189.60° 39.79° ∅ 0.3°
Distance (kpc)
0.5
1
1.5
2
2.5
3
3.5
4
4.5

RM – Synthesis:

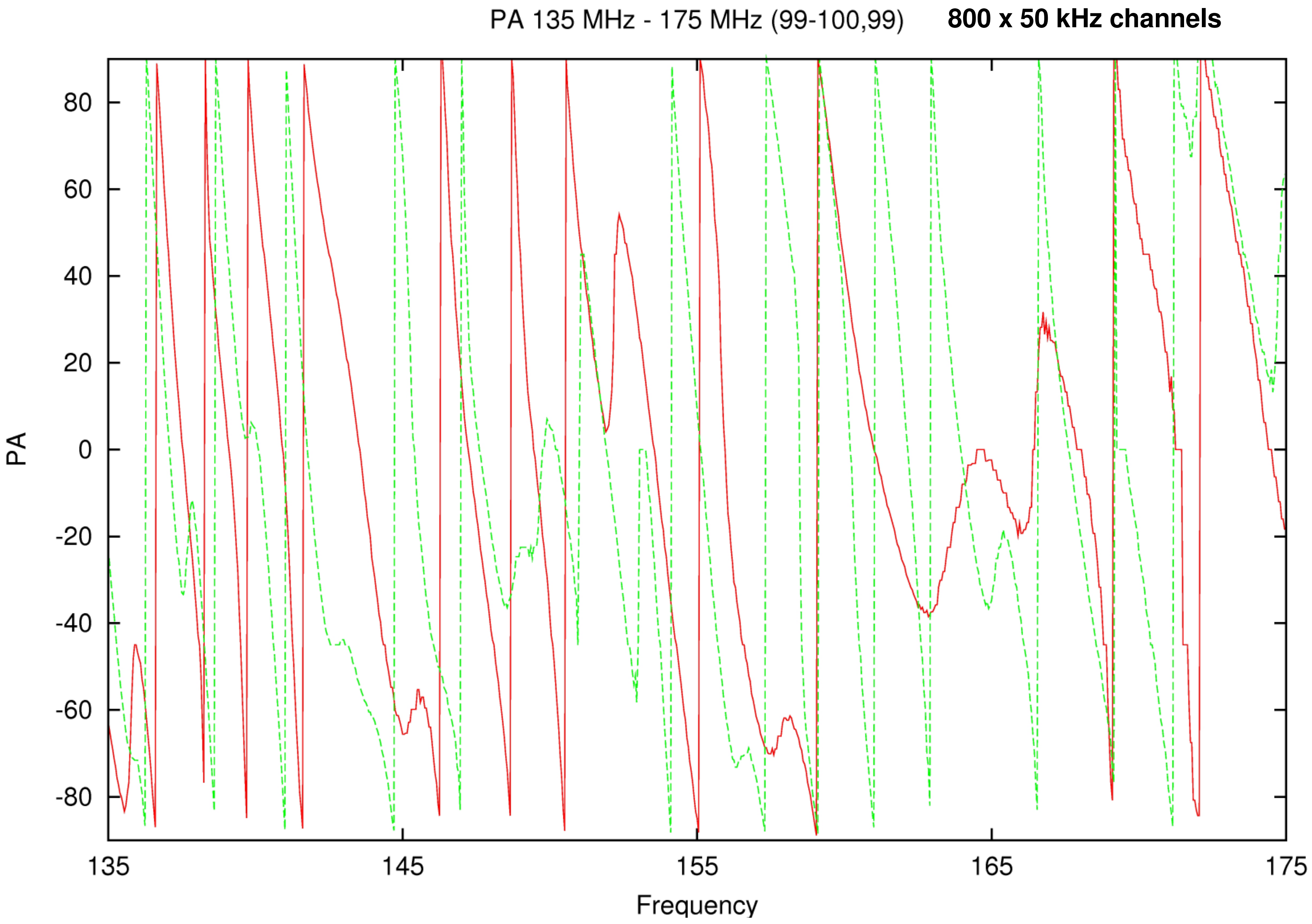
an important analysis tool
for $\varphi \neq \lambda^2$



LOFAR will detect small RMs from small nearby clouds



Q 135 MHz - 175 MHz
Pixel 99, 99 – 100, 99
Intensity U
Frequency
40
30
20
10
0
-10
-20
-30
-40
135
145
155
165
175

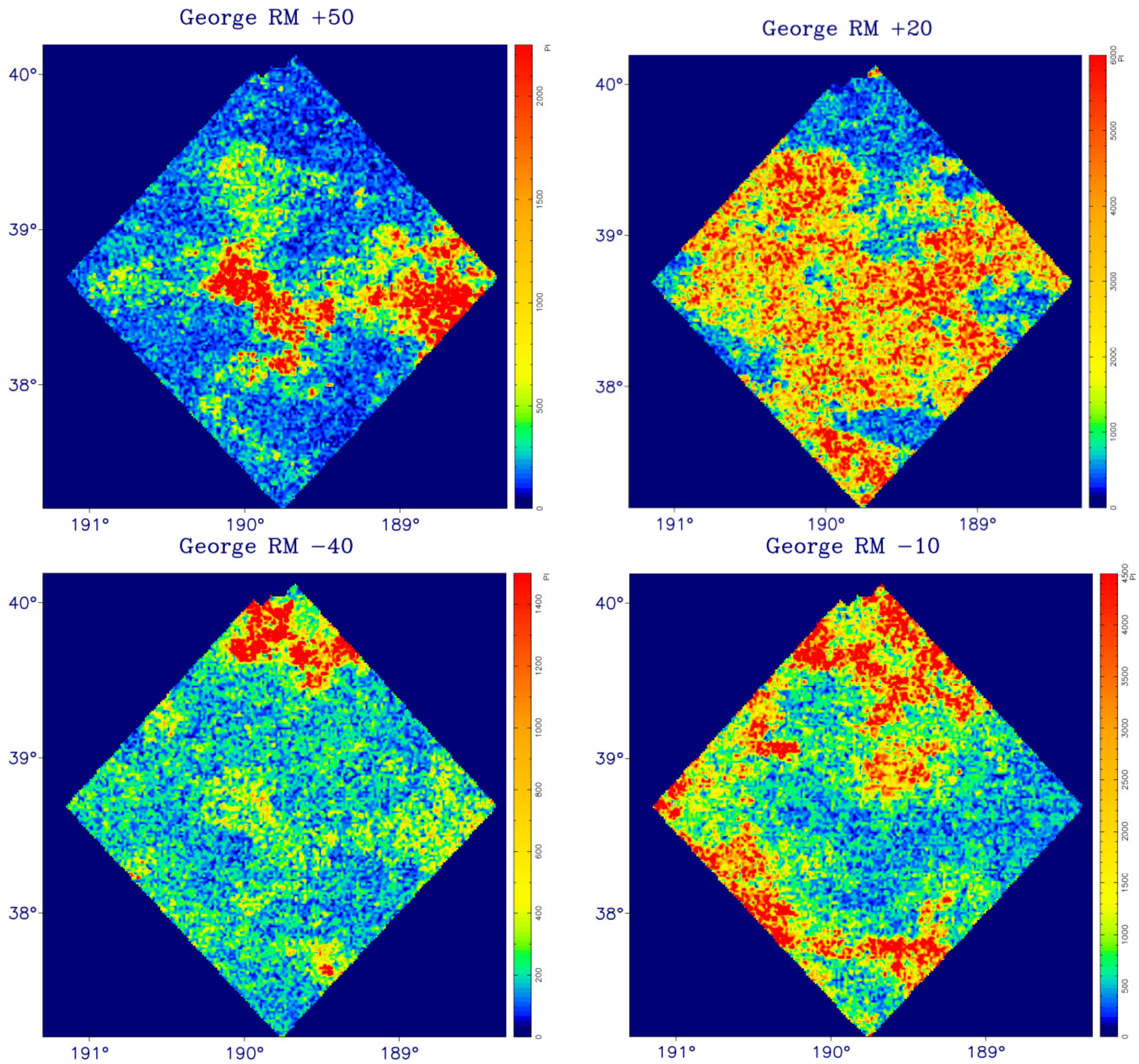

PA 135 MHz - 175 MHz (99-100,99)
800 x 50 kHz channels
PA
80
60
40
20
0
-20
-40
-60
-80
135
145
155
165
175
Frequency

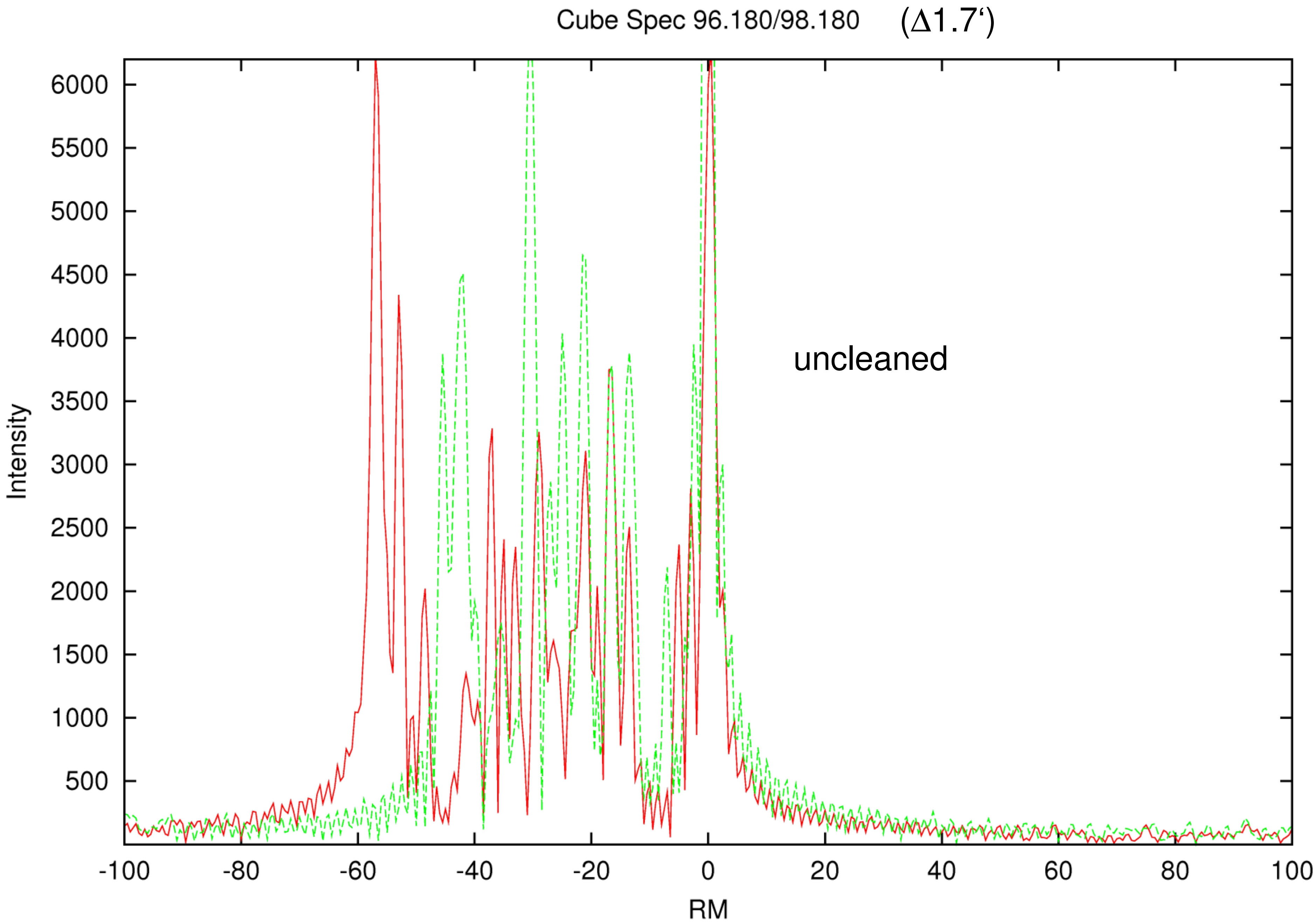
Selected RM-channel maps: 401 x 0.5 rad/m^2

RMSF ~ 2 rad/m^2

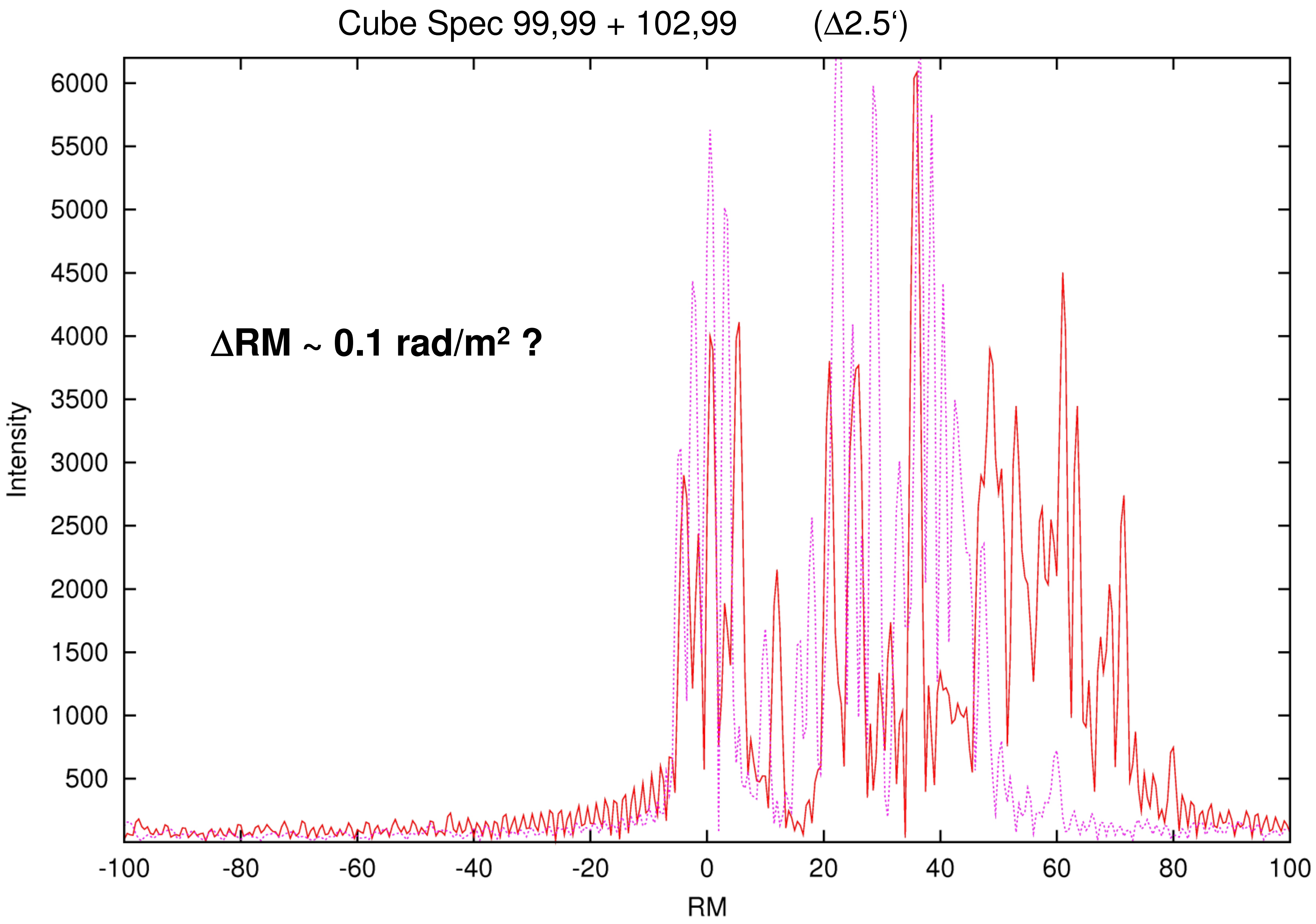
sidelobes:

1. ~ 20%
2. ~ 12%



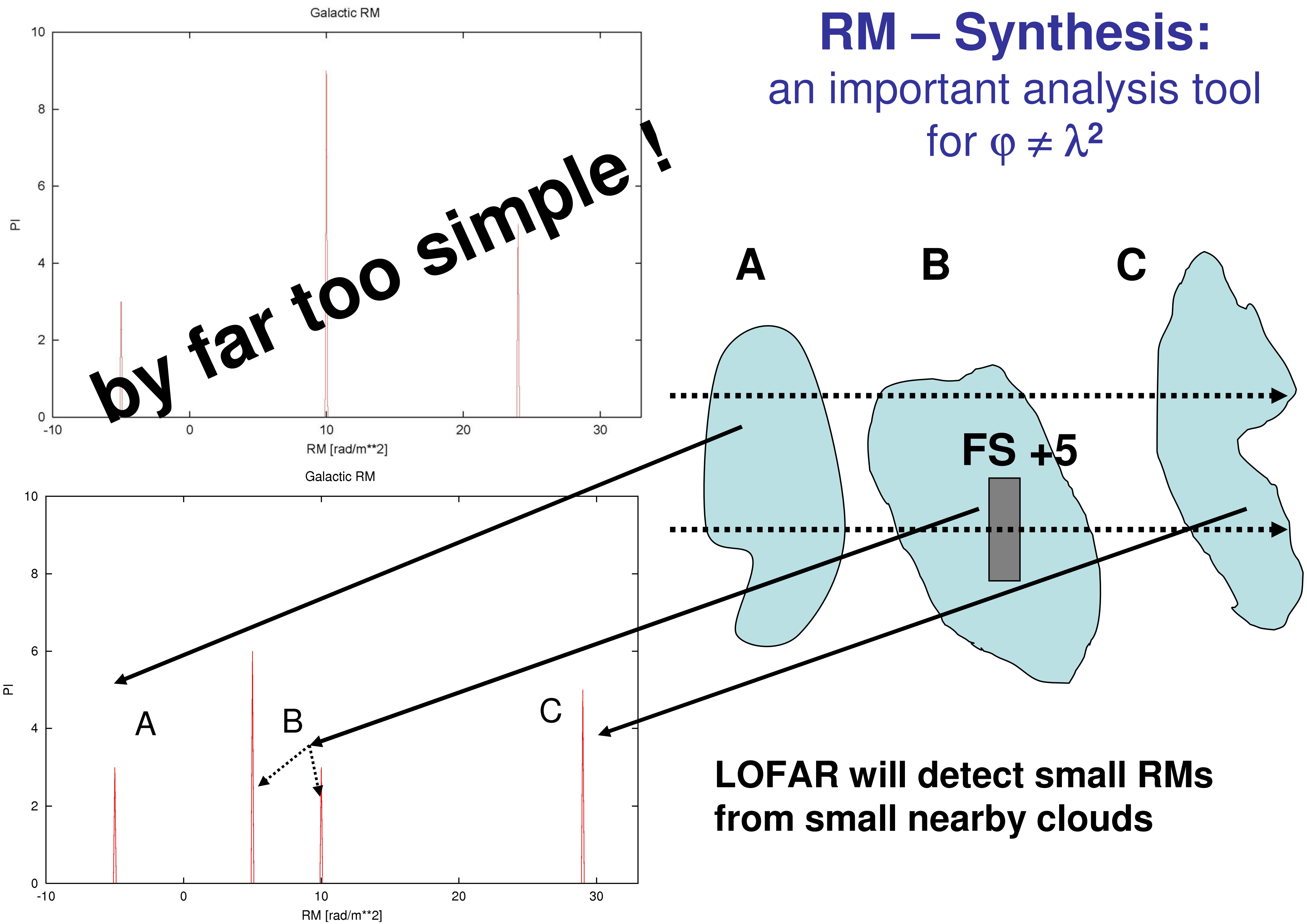


Cube Spec 96.180/98.180 (Δ1.7‘)
uncleaned
Intensity
RM
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
-100
-80
-60
-40
-20
0
20
40
60
80
100


Cube Spec 99,99 + 102,99 (Δ2.5‘)
ΔRM ~ 0.1 rad/m² ?
Intensity
RM
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
-100
-80
-60
-40
-20
0
20
40
60
80
100

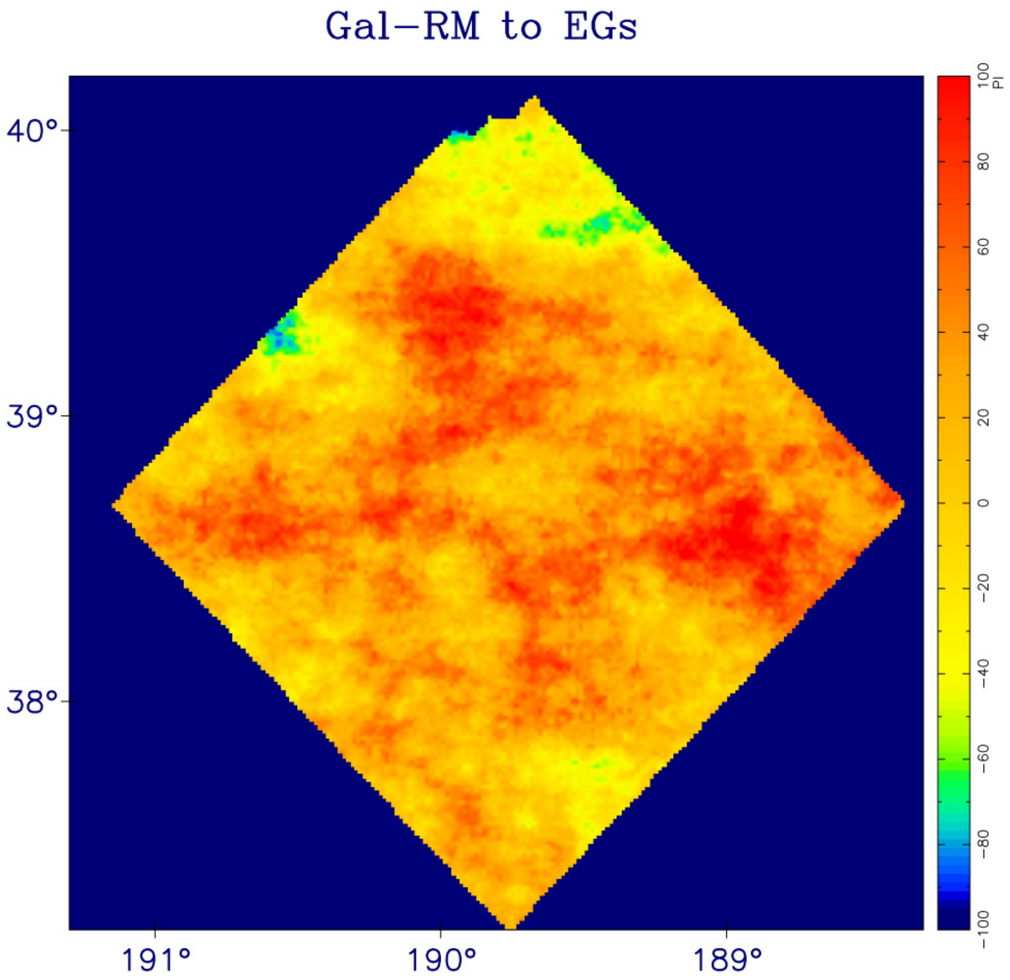
RM – Synthesis:

an important analysis tool for $\varphi \neq \lambda^2$



LOFAR will detect small RMs from small nearby clouds

How much affects the Galactic foreground RM studies of EGs at LOFAR frequencies ?

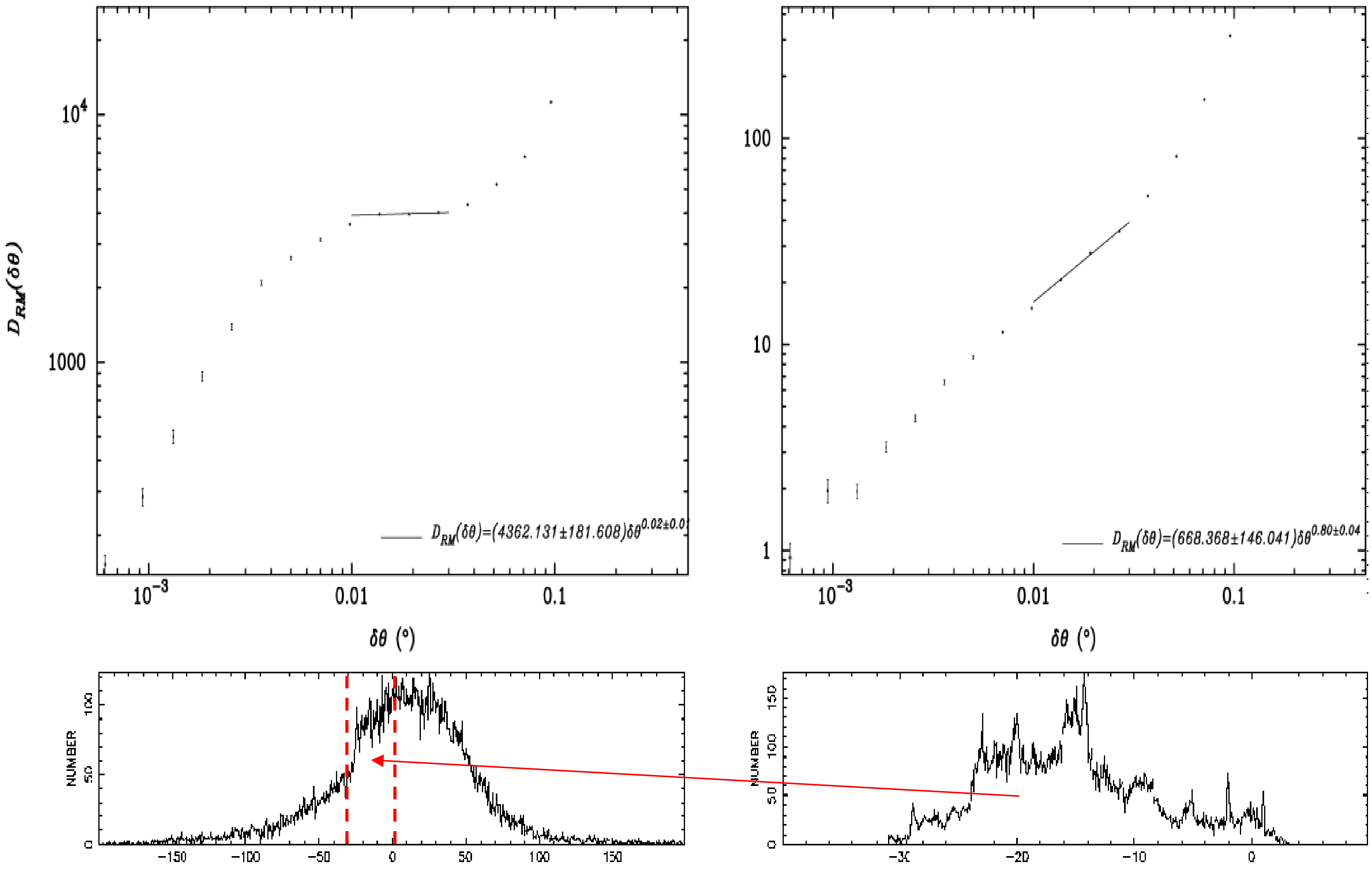


RM Synthesis Testfield

Mean RM: 23.4 rad/m²
rms 31.8 rad/m²

Resolution 51“

M51 (Fletcher et al. 2010) – Galactic foreground



M51 RMs from 3cm + 6cm
observations at 15" resolution

noise-free simulation

Galaxy halos with low RM at LOFAR frequencies