FARADAY ROTATION, MAGNETIC FIELDS,

and the

FIFTH PHASE OF THE INTERSTELLAR MEDIUM

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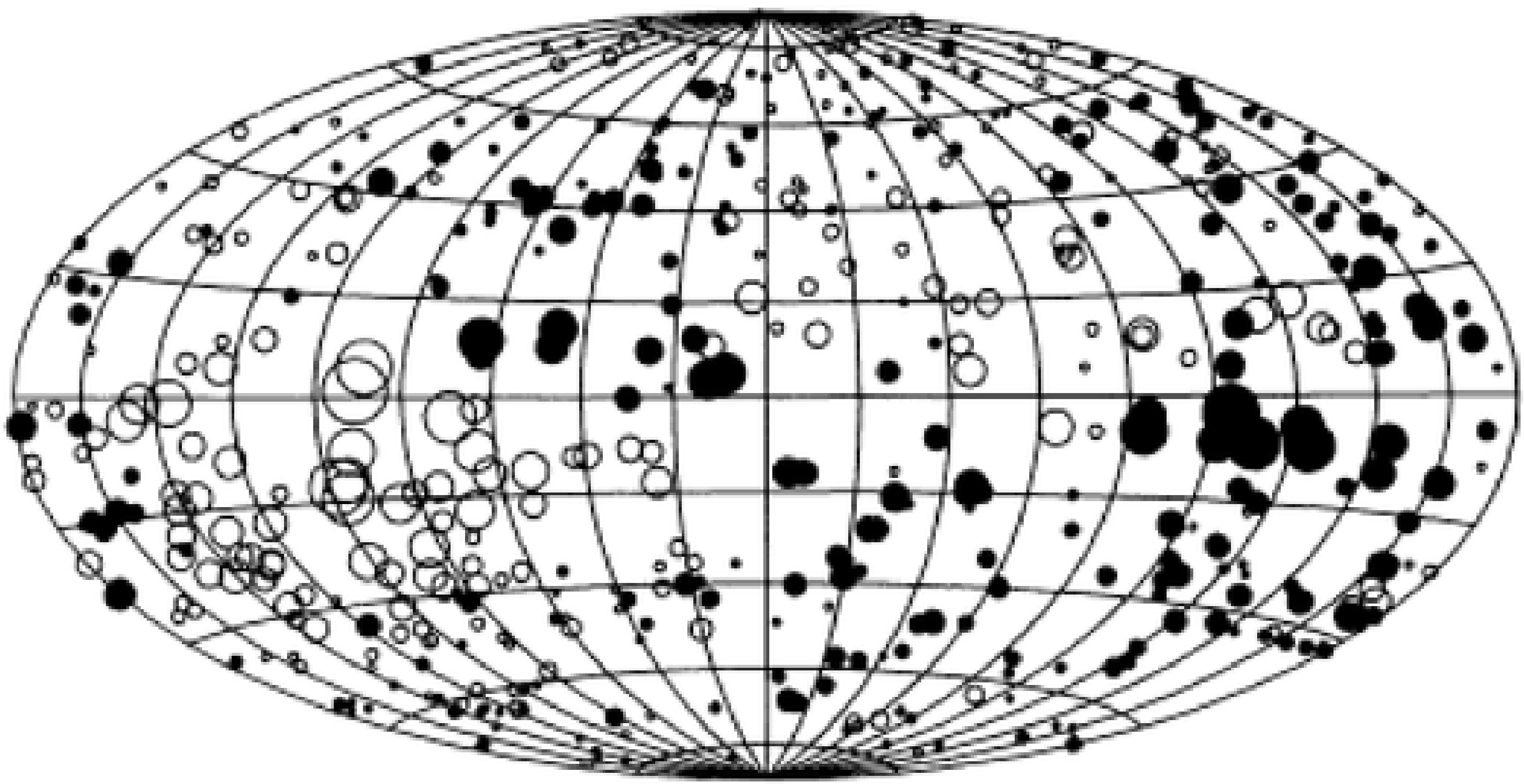
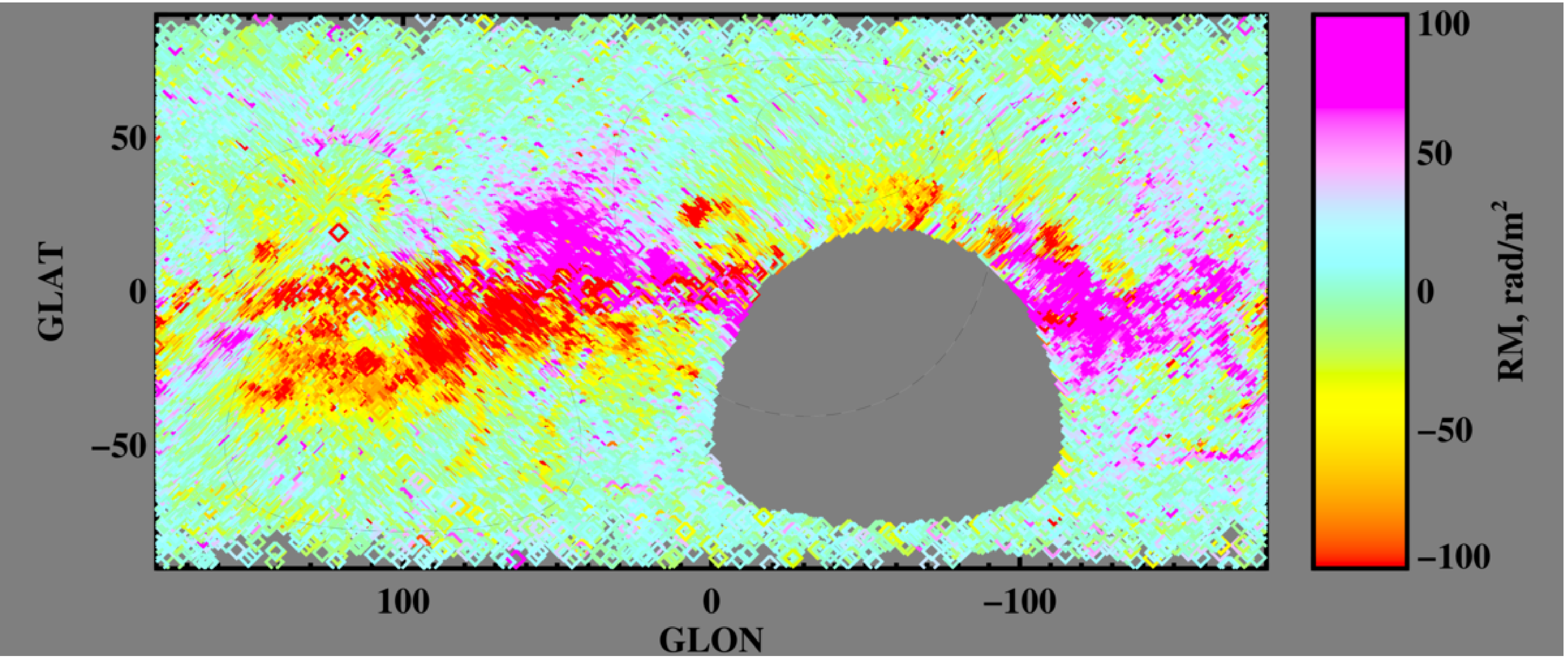
Taylor, Stil, Sumsrum (2009) derived 'best guess' RMs for all 37,543 NVSS sources. Most of these RMs are correct. They allow a detailed mapping of RM on the sky. This is a MAJOR ADVANCE. To understand this, we first look at the RM distribution given by Oren & Wolfe (1995)—for 499 sources…

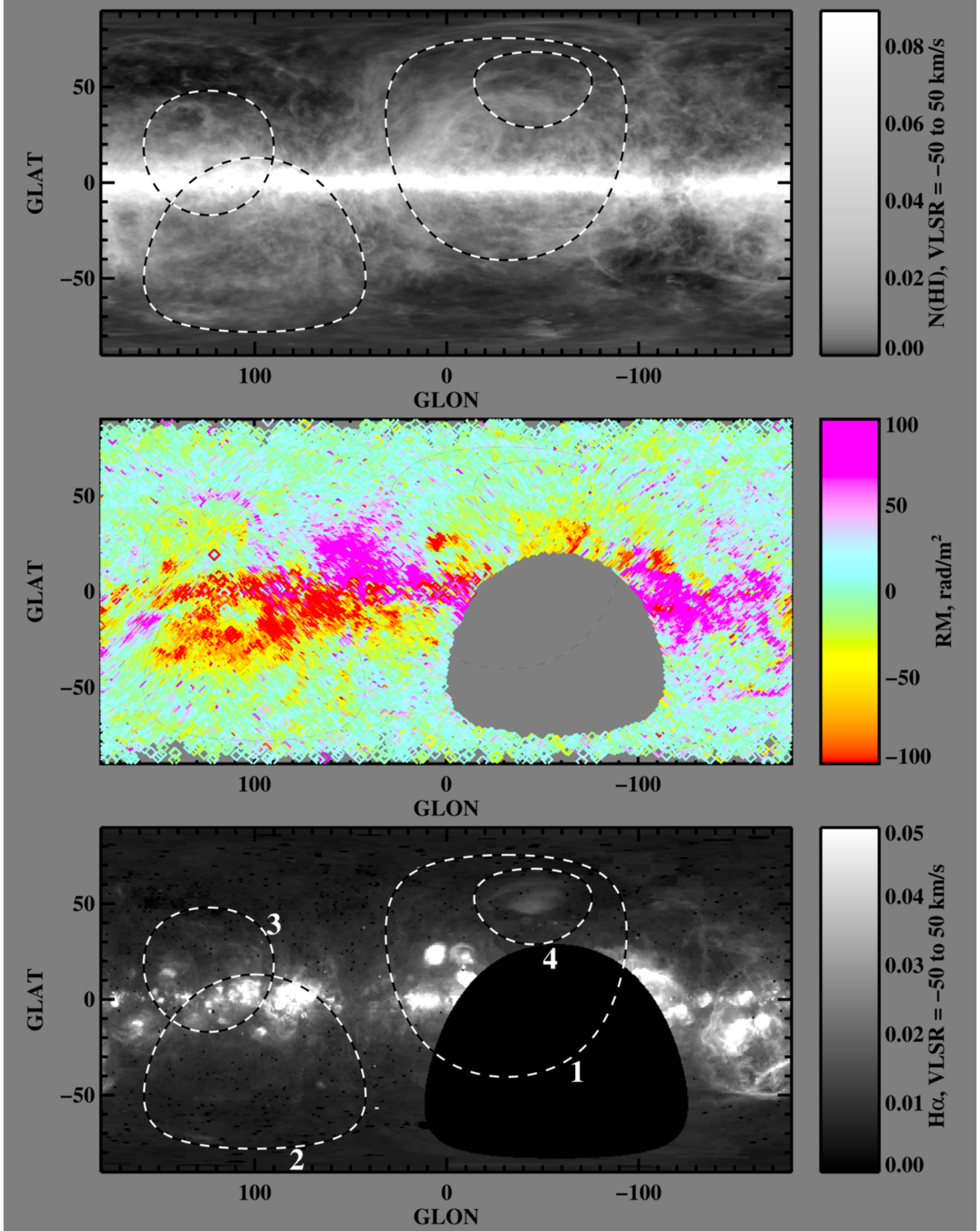


37,543 NVSS sources—that's more than one per square degree! The angular resolution is comparable to the WHAM (Hα) and LAB 21-cm line HI) surveys!

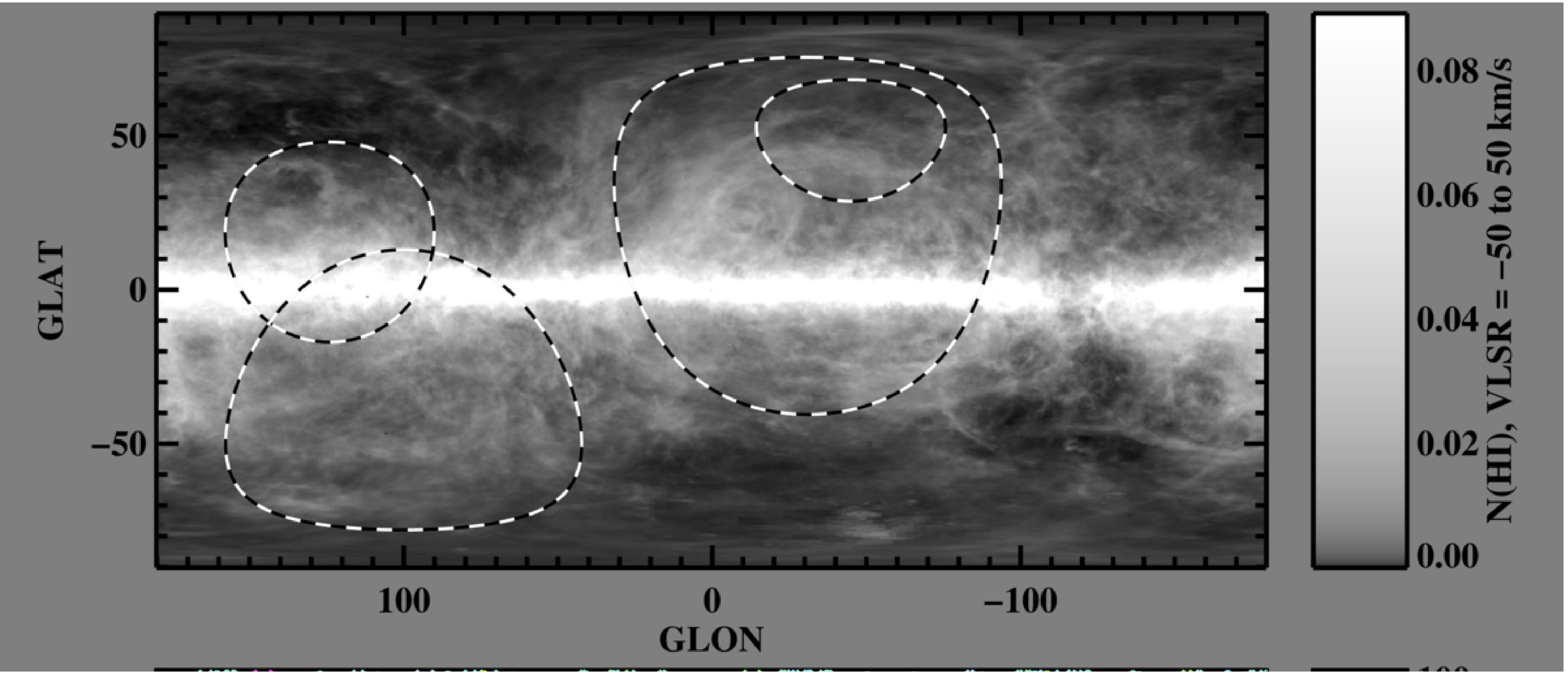


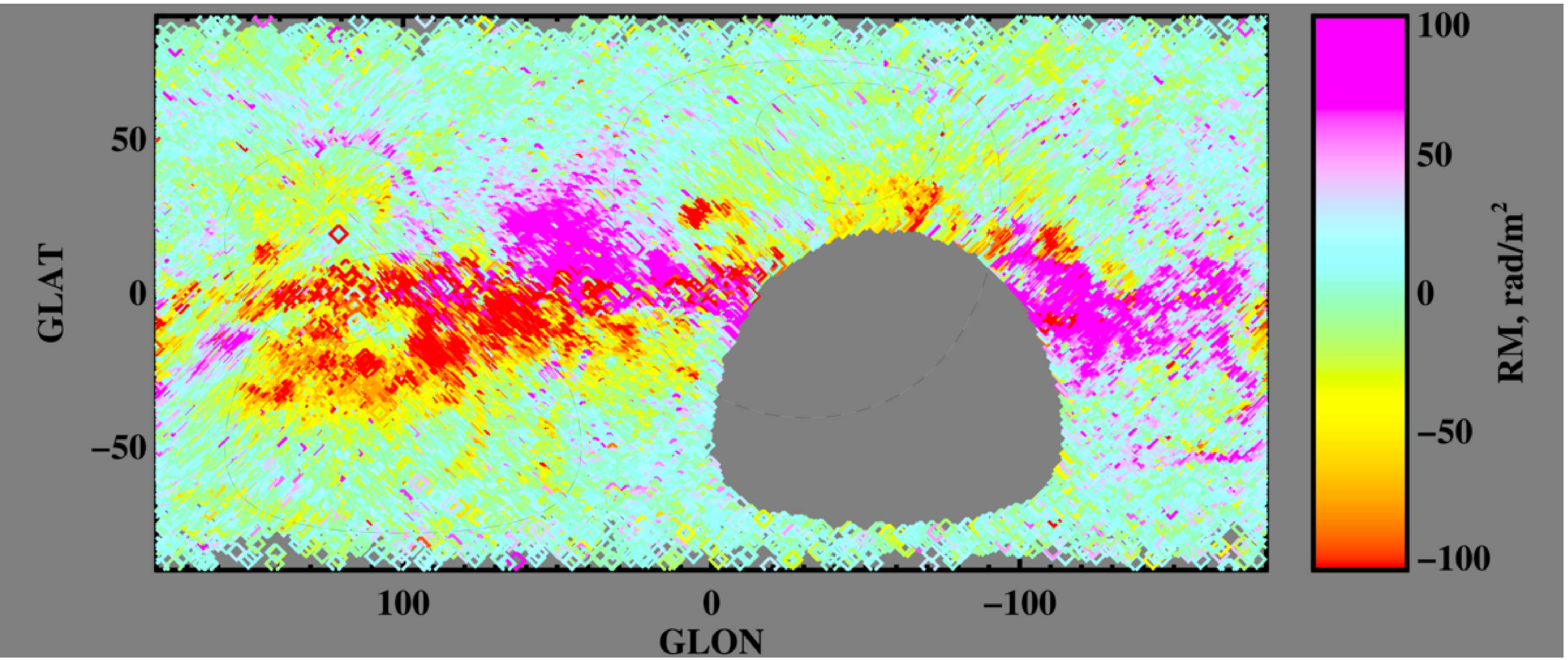
We'll compare the RM, HI, and Hα maps. We'll look at different velocity ranges so that we can isolate individual structures along the line of sight. We'll do detailed comparisons by 'flashing'.

-50 to +50 km/s



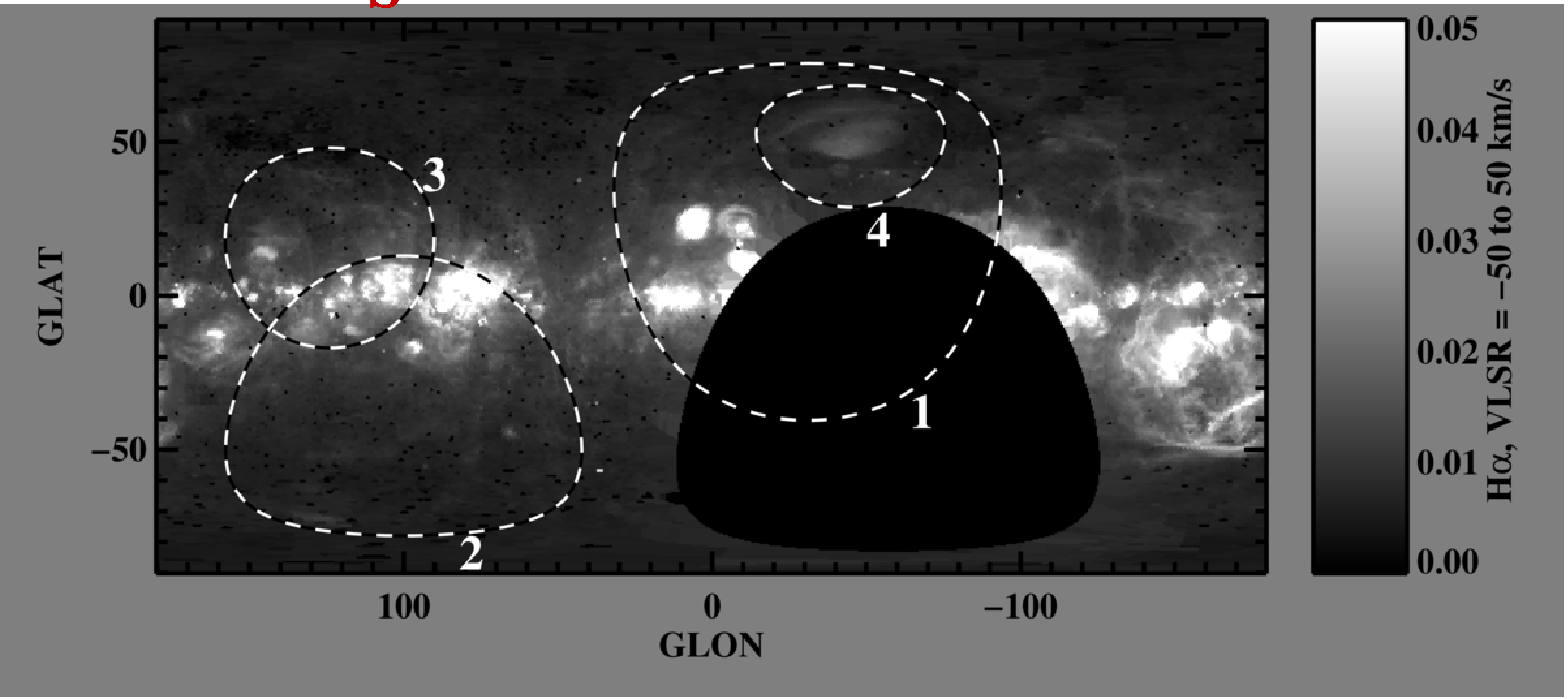
HI: -50 to +50 km/s



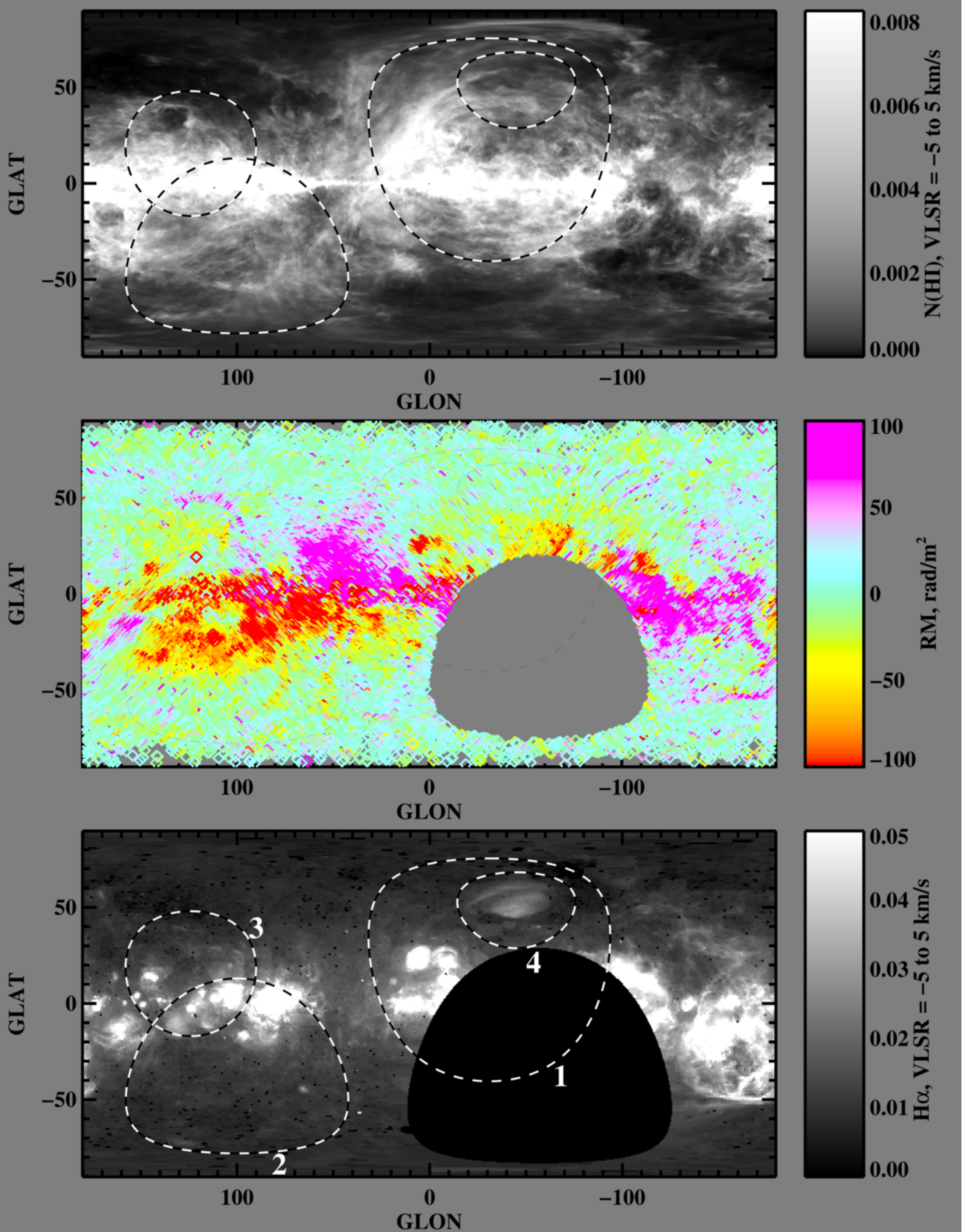


100
50
0
−50
−100
RM, rad/m²
50
0
−50
GLAT
100
0
−100
GLON

Hα: -50 to +50 km/s

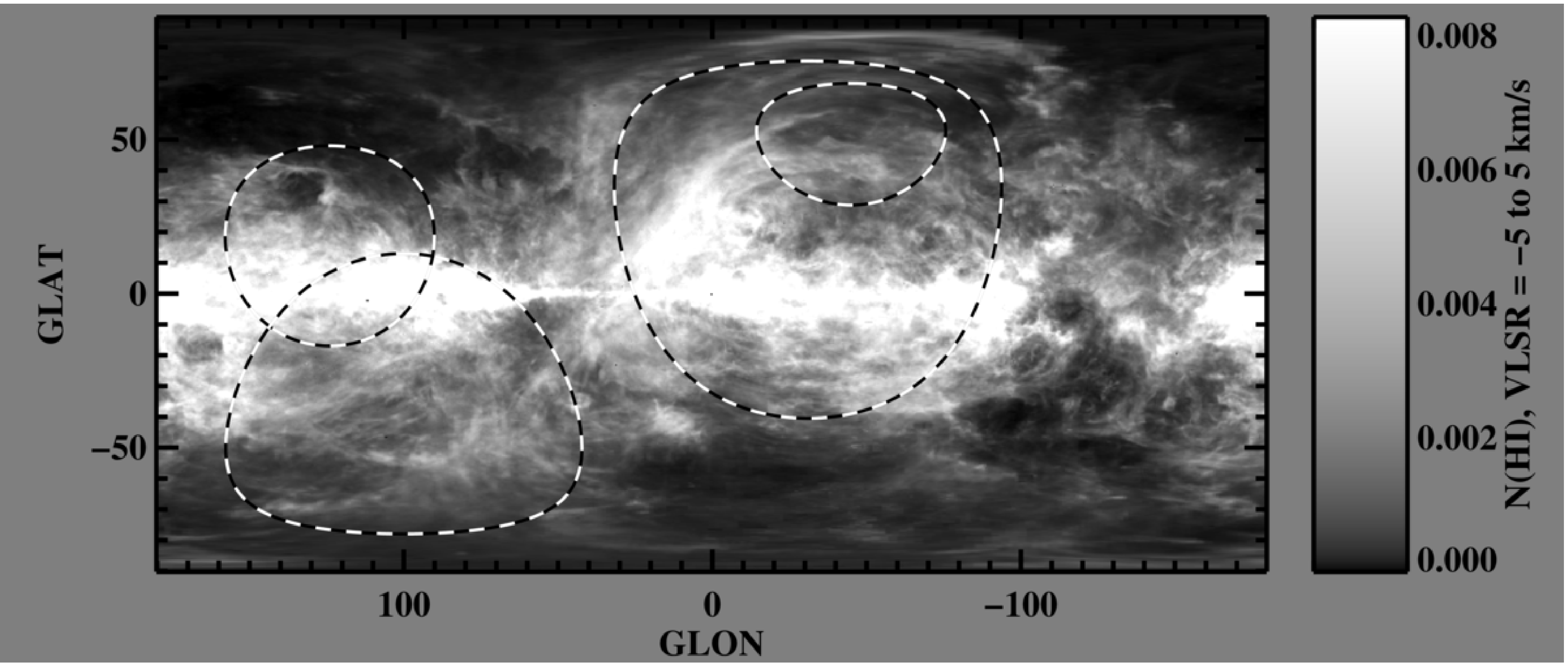


-5 to +5 km/s

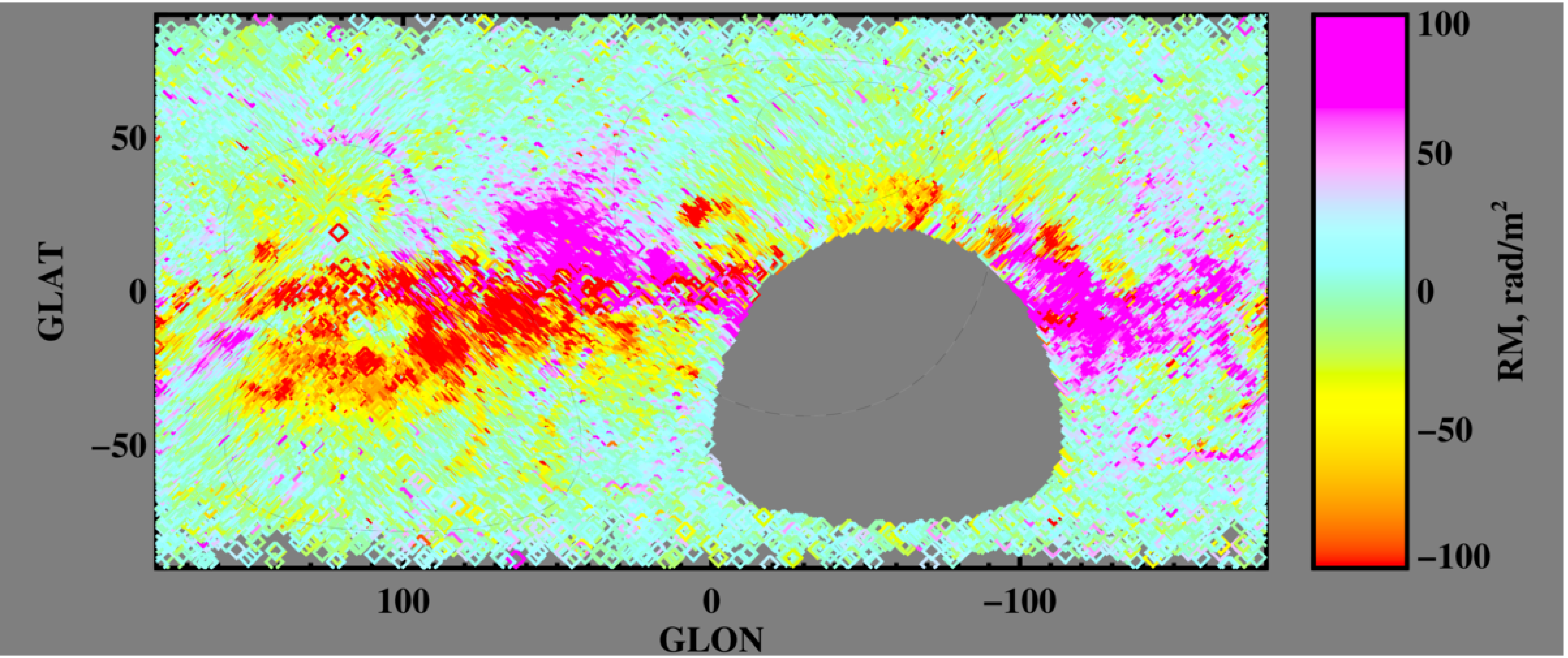


GLAT
GLON
50
0
−50
100
0
−100
0.008
0.006
0.004
0.002
0.000
N(HI), VLSR = −5 to 5 km/s
100
50
0
−50
−100
RM, rad/m^2
0.05
0.04
0.03
0.02
0.01
0.00
Hα, VLSR = −5 to 5 km/s
1
2
3
4

HI: -5 to +5 km/s

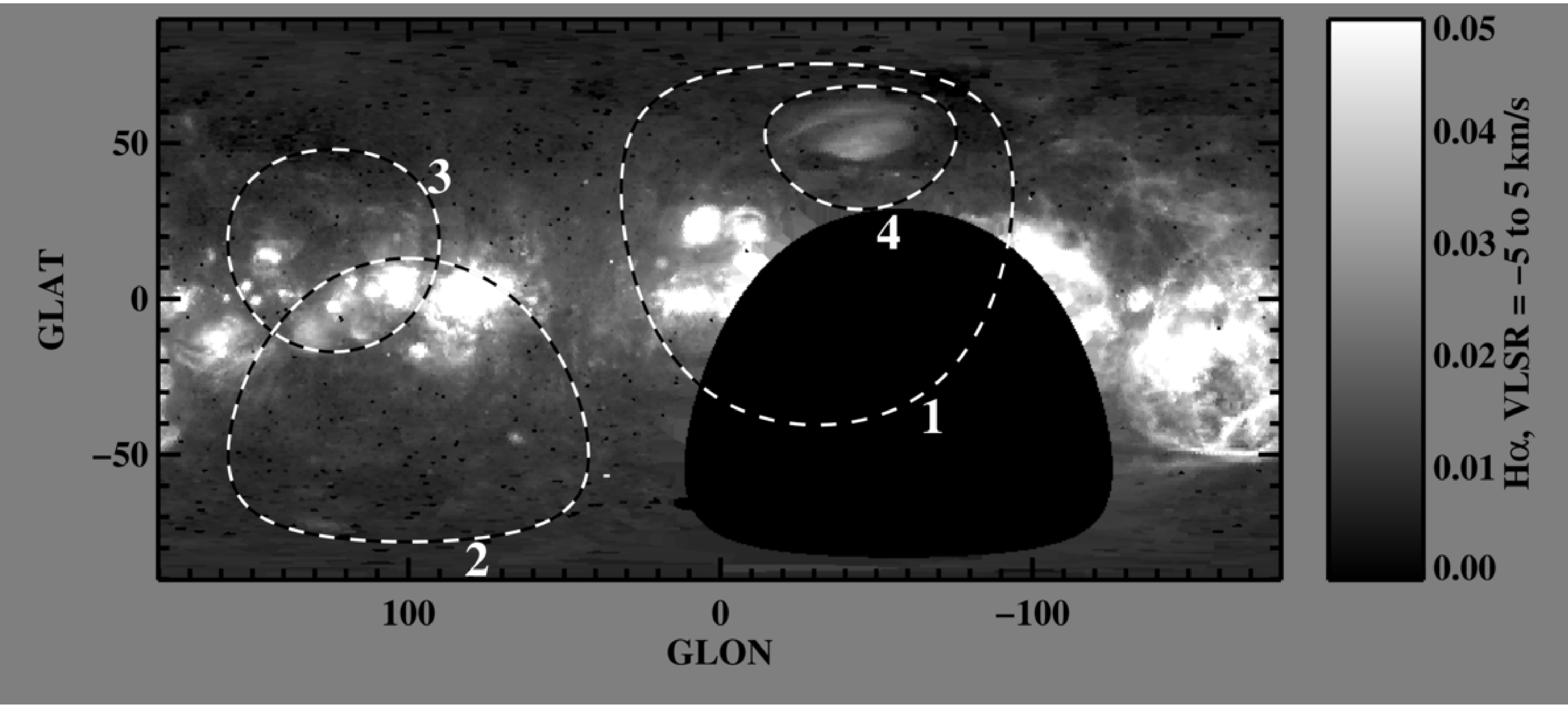


50
0
−50
GLAT
100
0
−100
GLON
0.008
0.006
0.004
0.002
0.000
N(HI), VLSR = −5 to 5 km/s



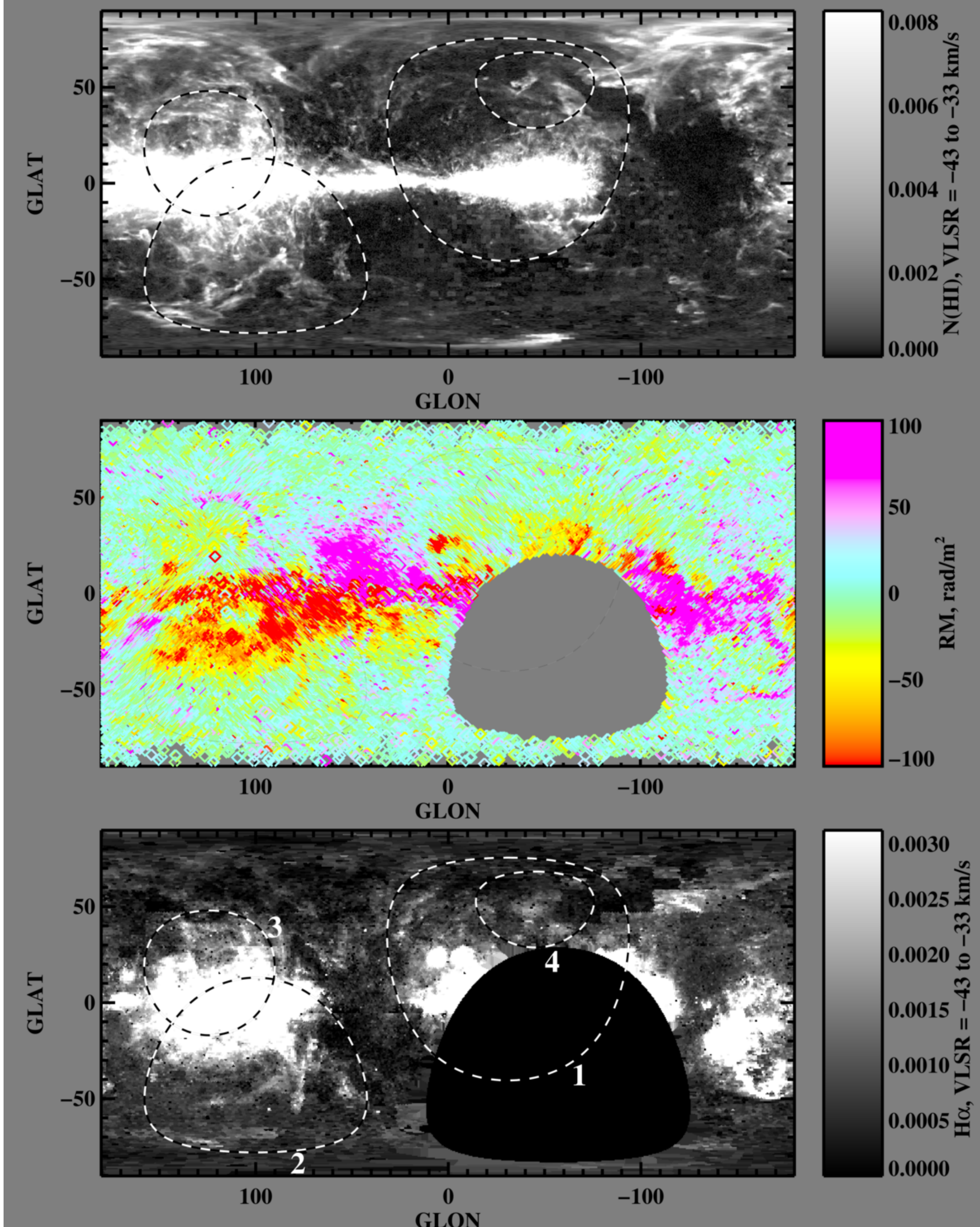
GLAT
GLON
RM, rad/m²
100
50
0
−50
−100

Hα: -5 to +5 km/s



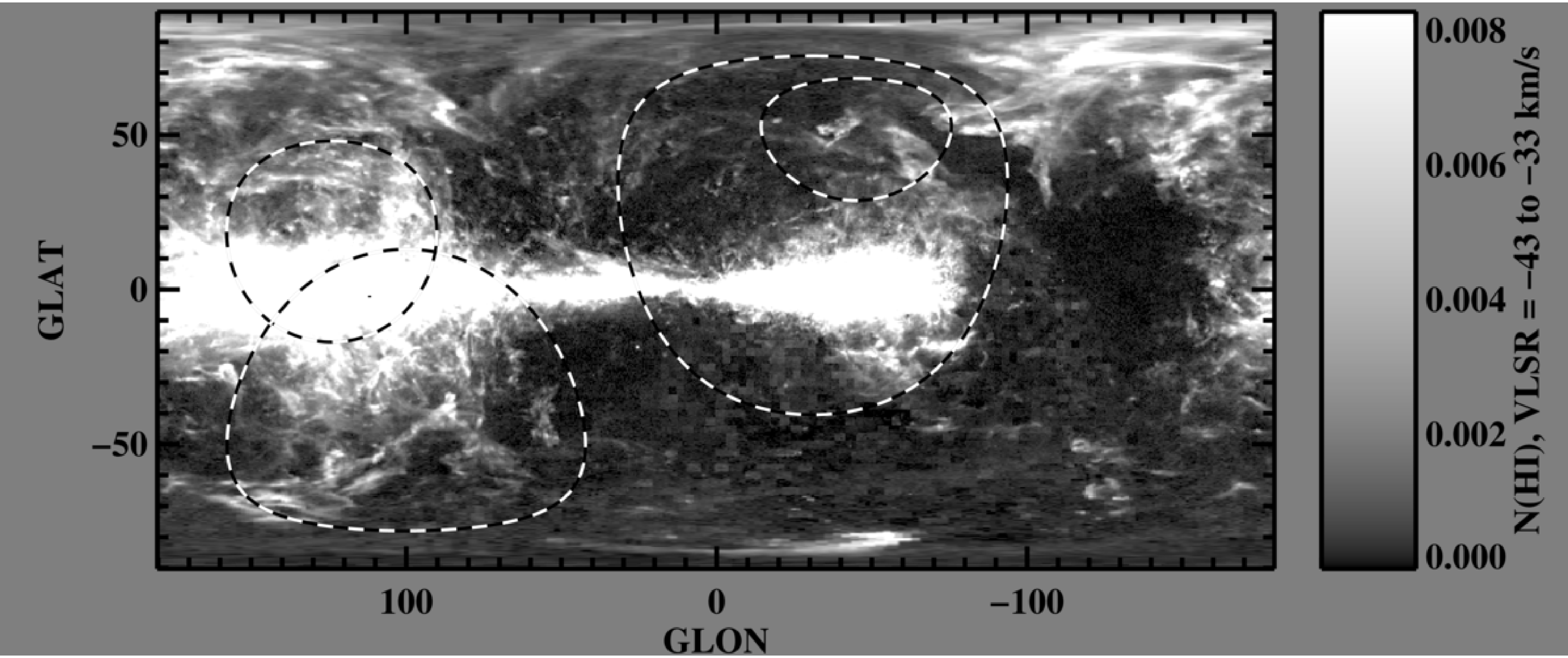
GLAT
50
0
−50
100
0
−100
GLON
1
2
3
4
0.05
0.04
0.03
0.02
0.01
0.00
Hα, VLSR = −5 to 5 km/s

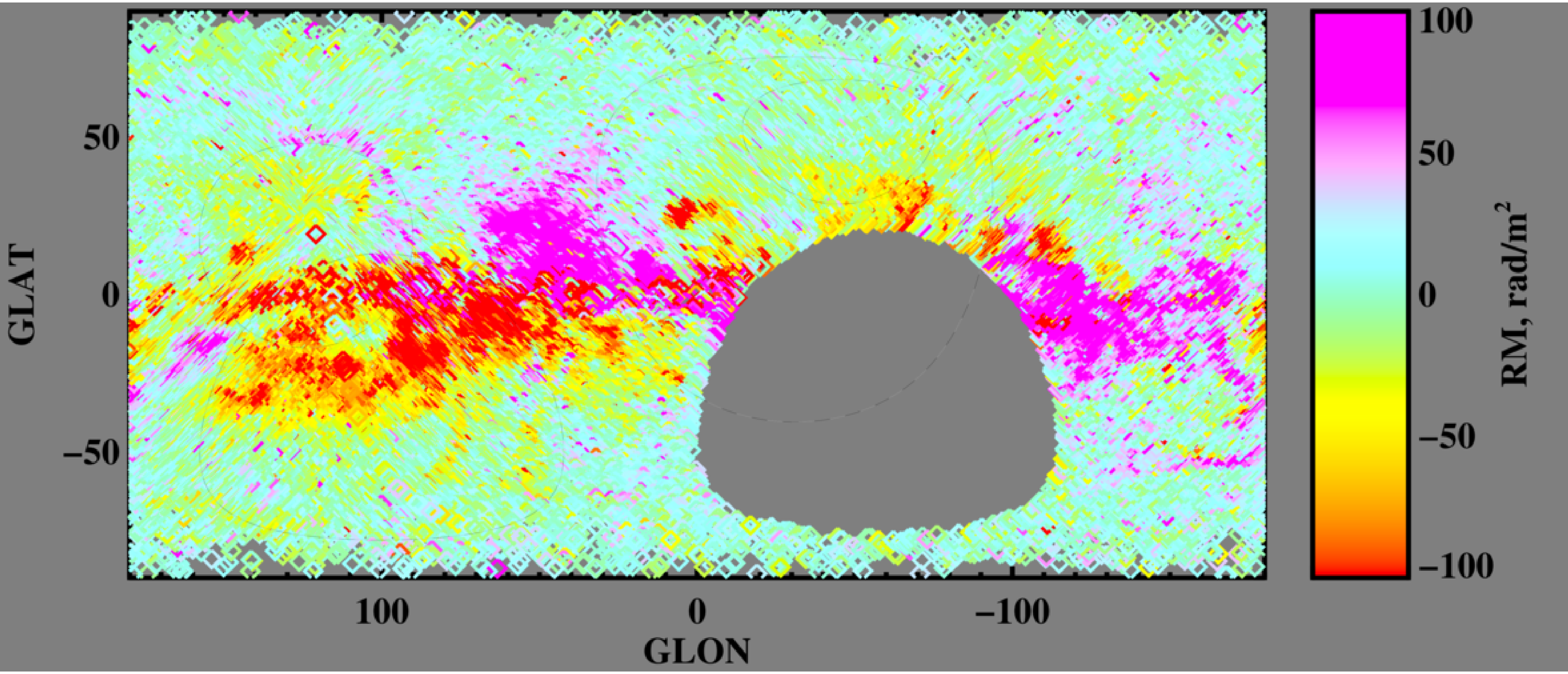
-43 to -33 km/s



GLAT
GLON
N(HI), VLSR = −43 to −33 km/s
RM, rad/m^2
Hα, VLSR = −43 to −33 km/s
1
2
3
4

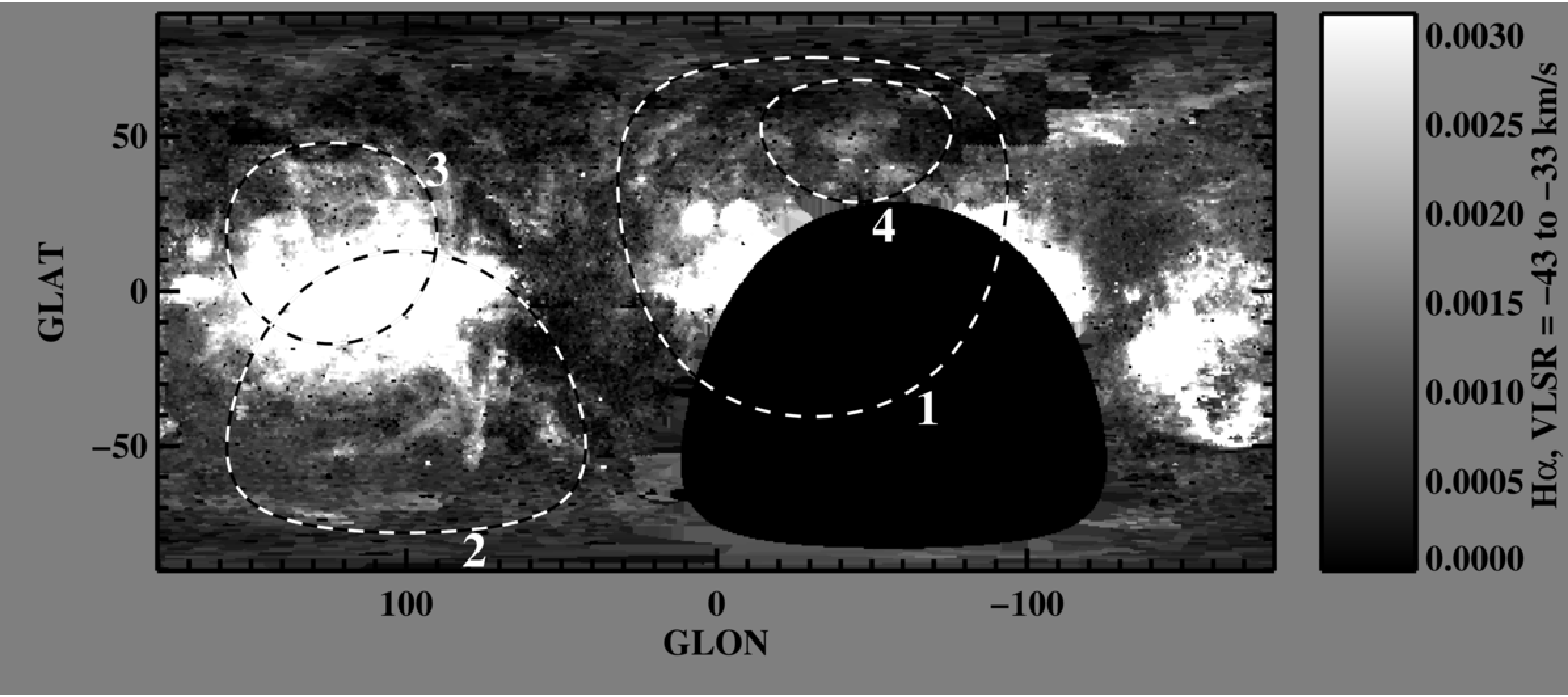
HI: -43 to -33 km/s



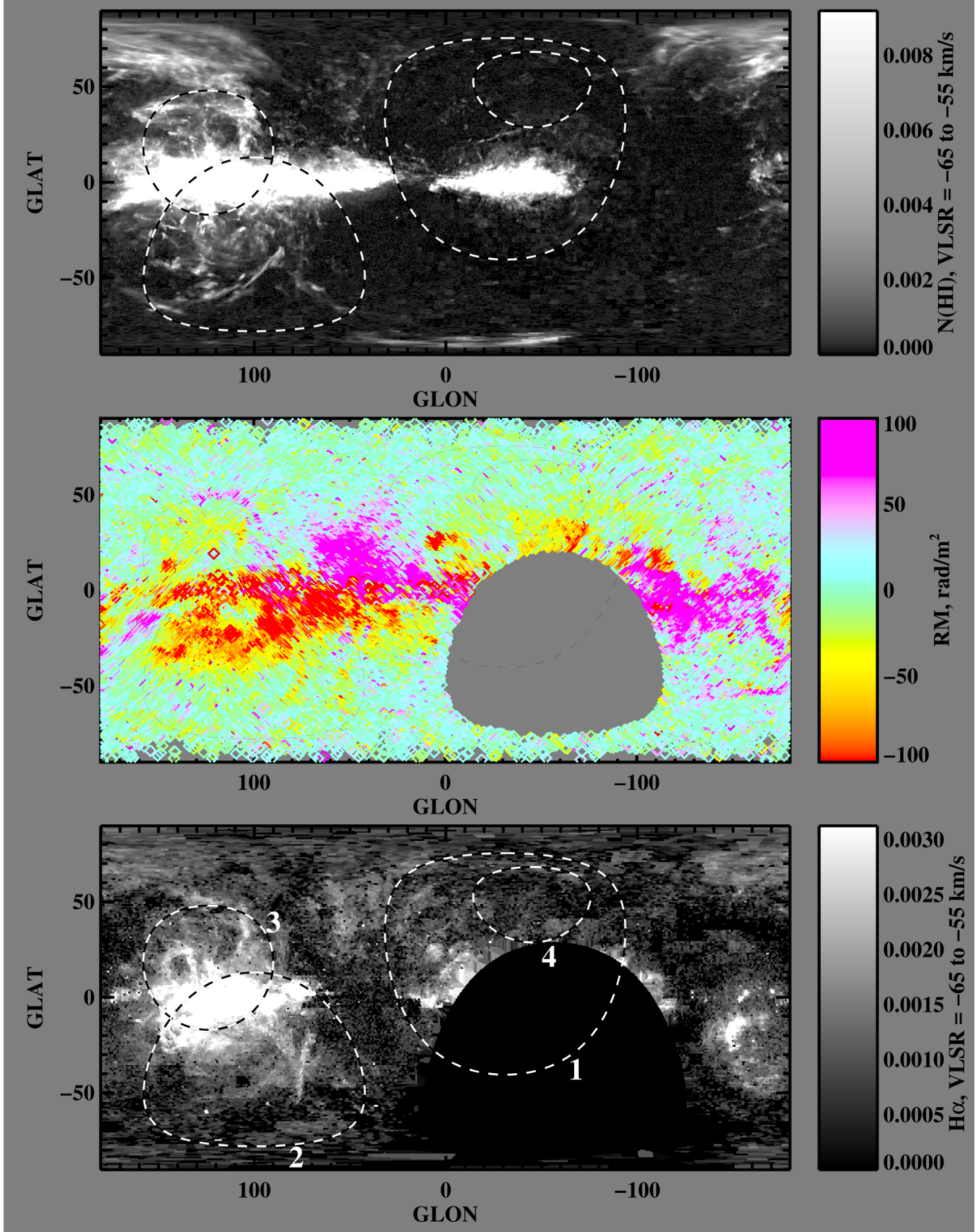


50
0
−50
GLAT
100
0
−100
GLON
100
50
0
−50
−100
RM, rad/m²

Hα: -43 to -33 km/s

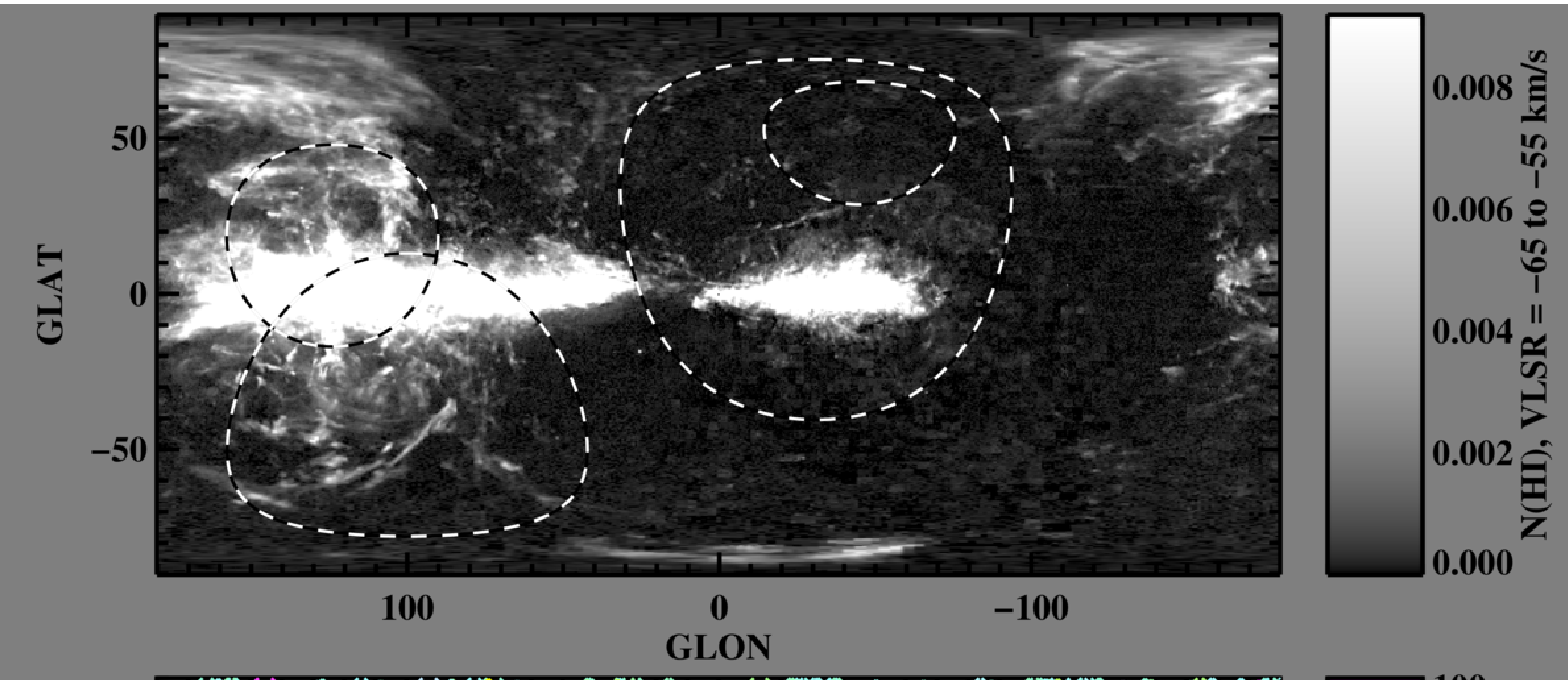


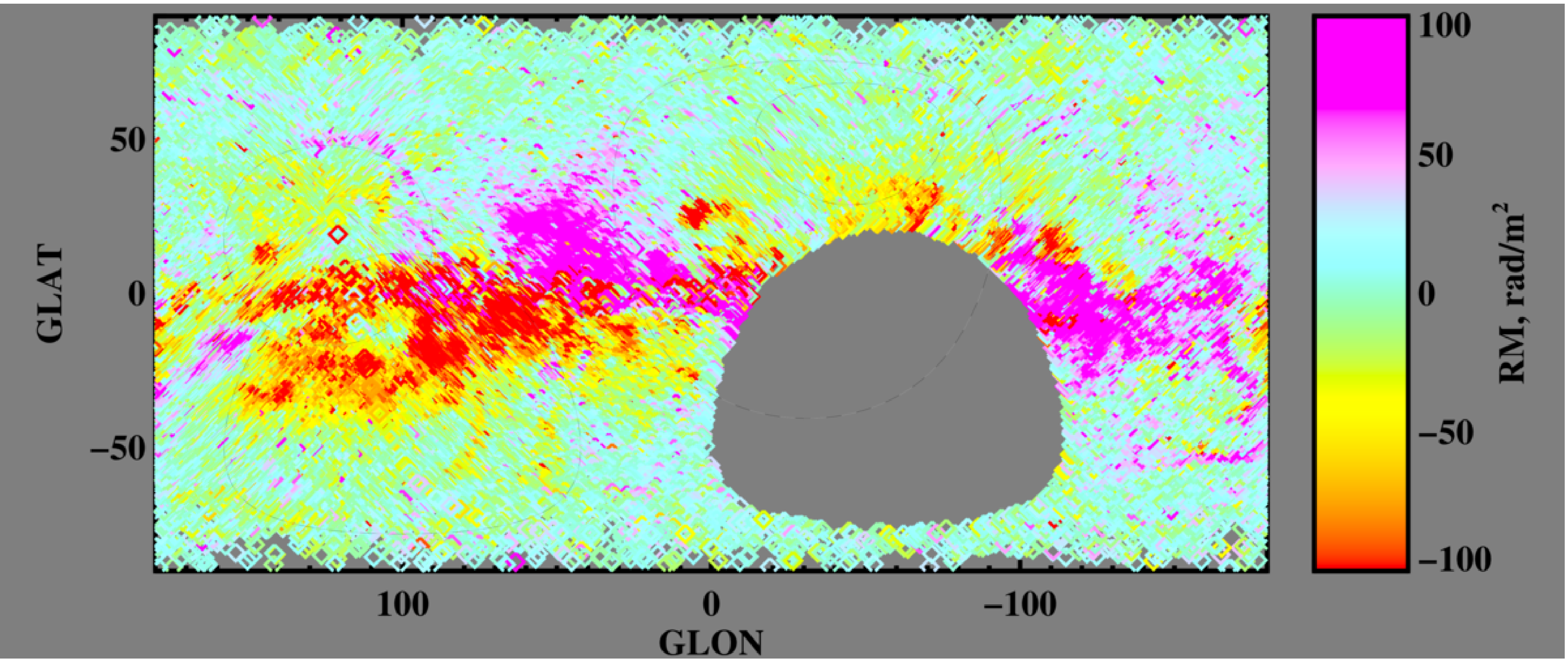
-65 to -55 km/s



GLAT
GLON
N(HI), VLSR = −65 to −55 km/s
RM, rad/m^2
Hα, VLSR = −65 to −55 km/s
50
0
−50
100
0
−100
0.008
0.006
0.004
0.002
0.000
100
50
0
−50
−100
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
1
2
3
4

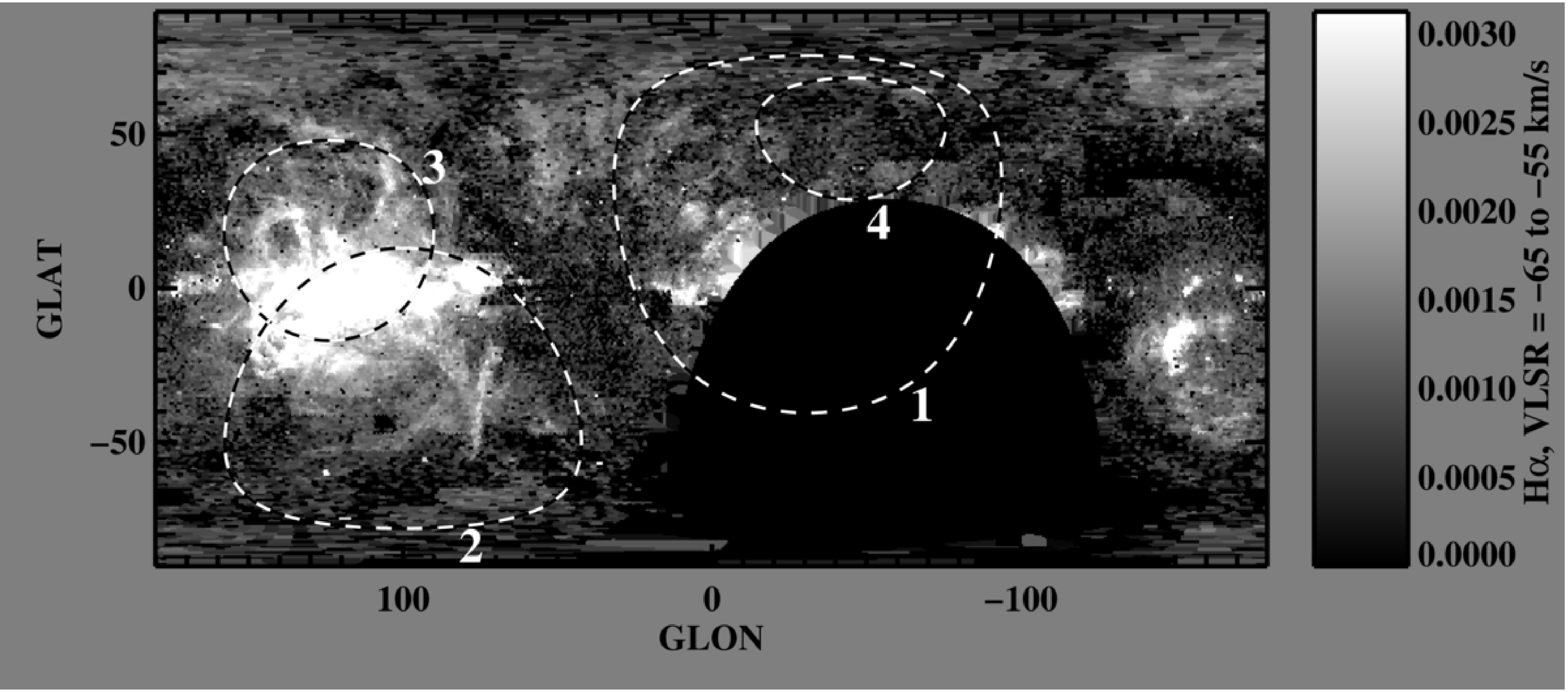
HI: -65 to -55 km/s





50
0
−50
GLAT
100
0
−100
GLON
100
50
0
−50
−100
RM, rad/m^2

Hα: -65 to -55 km/s



What we saw:

--RM structures lie near morphologically similar HI and Hα structures.

--HOWEVER, the RM structures seem OFFSET IN POSITION: they don't lie on top of either the HI or Hα.

--Many HI and Hα structures are morphologically similar, but are also OFFSET IN POSITION.

WHAT'S GOING ON?

The Fifth Phase of the Interstellar Medium

A SMALL CLOUD (M/O 1977)

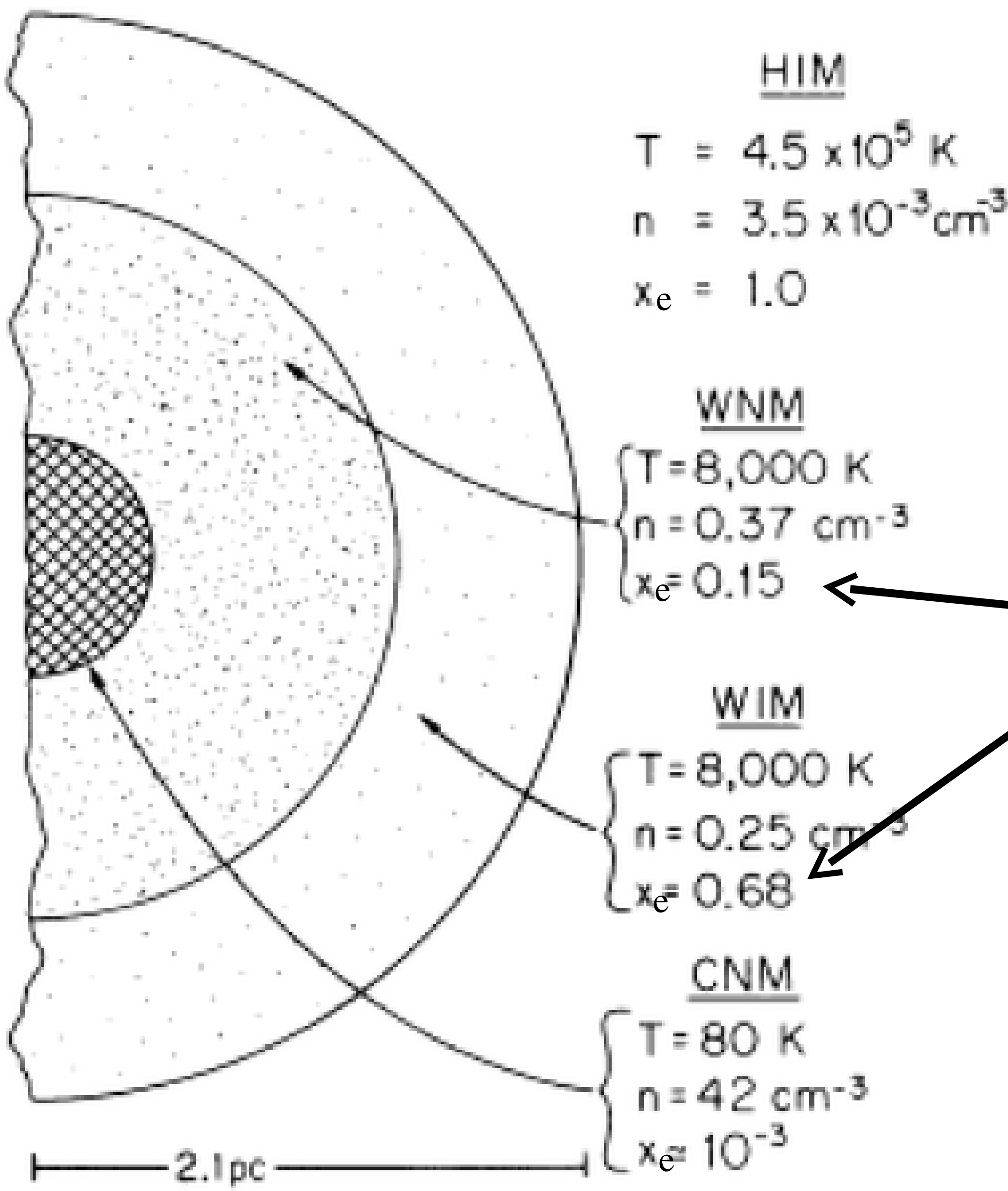


FIG. 1

IONIZATION AGENT:

Collisional

Cosmic Rays, Soft X-rays

PARTIALLY ionized!

Soft X-rays, Cosmic Rays

Cosmic Rays, C+

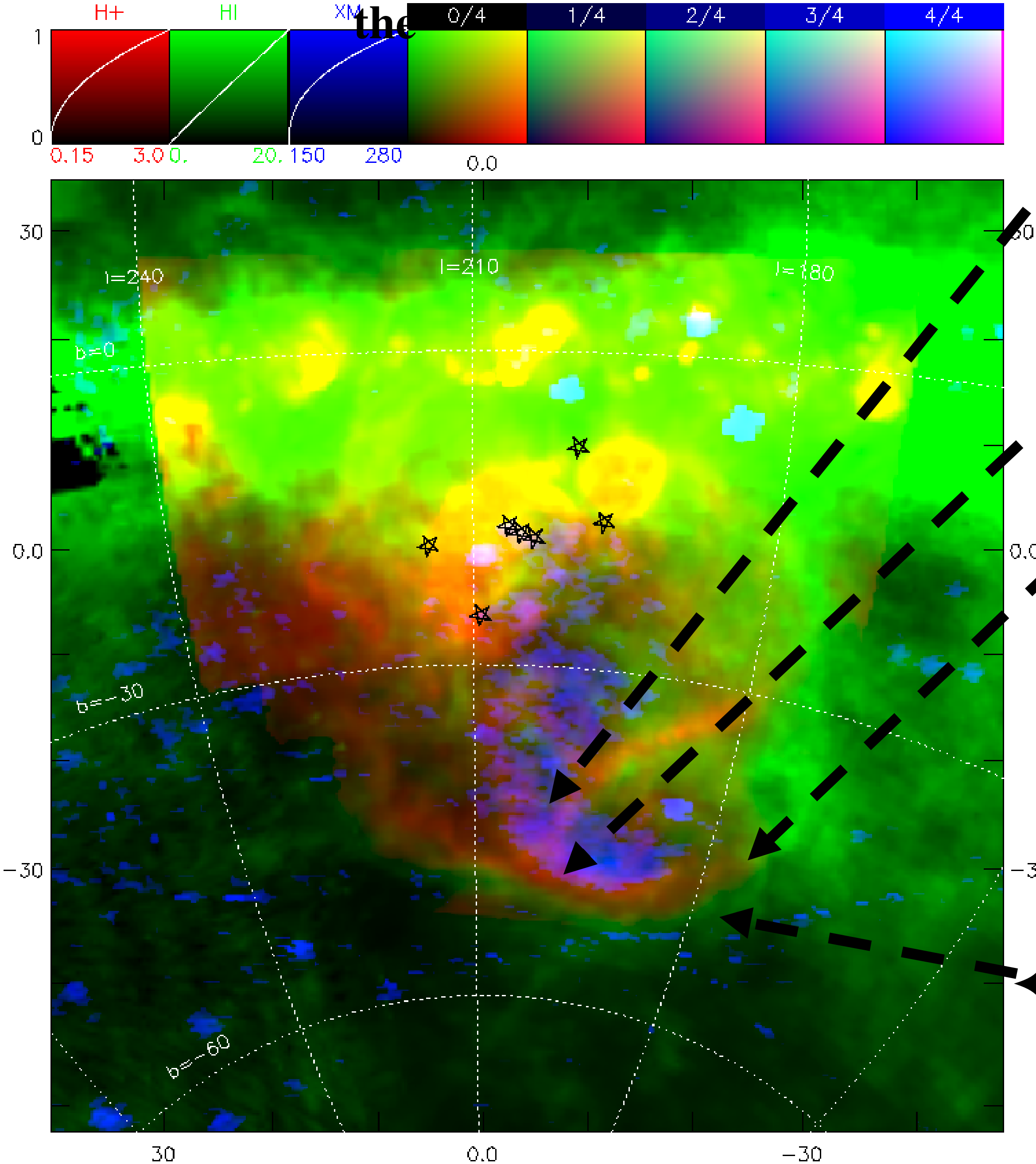
The original four phases, as defined by McKee & Ostriker, are not the four we think of today.

Today it's:

***The essentially <u>FULLY NEUTRAL</u> CNM and WNM**

***The essentially <u>FULLY IONIZED</u> WIM and HIM**

Current View: The Four Phases…and the *FIFTH*



HIM:
T ~ 2 x 10^6 K
x_e = 1; Collisional

WIM:
T ~ 0.8 x 10^4 K
x_e = 1; Stellar UV

WPIM:
T ~ 0.5 x 10^4 K
x_e ~ 0.1 – 0.9;
Soft XR (from HIM),
Stellar UV

WNM:
T ~ 0.5 x 10^4 K
x_e ~ 10^{-2}; Cosmic Rays

CNM:
T ~ 50 K
x_e ~ 10^{-4}; Carbon+

The WIM is starlight photoionized, x_e~1.0, like HII regions…

***``High'' emission measure [n_e N_e], hence high H-alpha (WHAM) visibility**

***Lowish N_e**

The *Fifth Phase* WPIM is probably XR photoionized, x_e~0.5 +/- 0.45…

***Lowish emission measure [n_e N_e]**

***Larger N_e**

***The ``Local Interstellar Clouds'' (LIC – Redfield & Linsky) are WPIM, with x_e~0.5.**

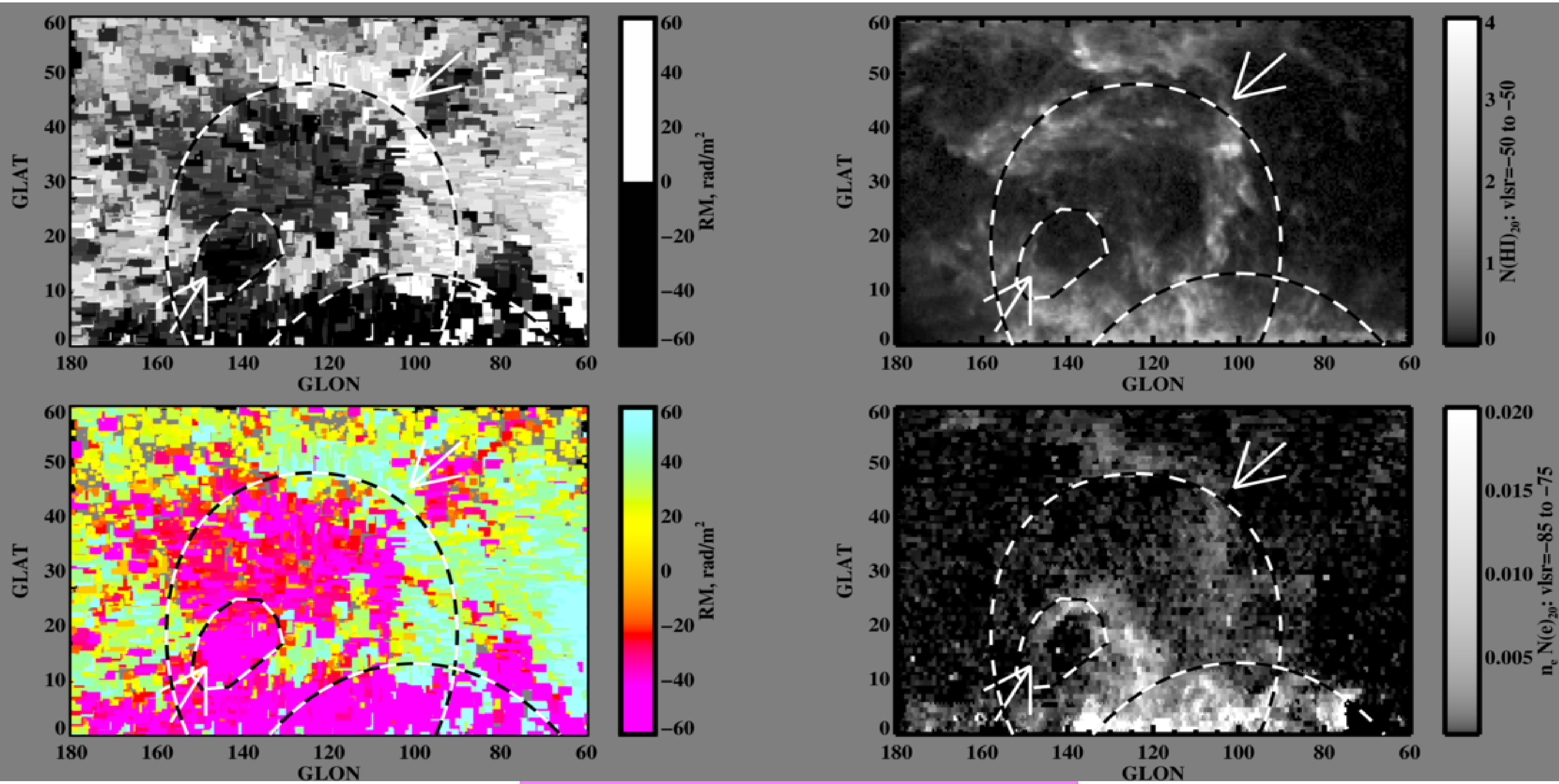
The Faraday Rotation Measure

$$RM \approx N_e \, B$$

We believe that its larger N_e, smaller n_e, and strong B are what make the *Fifth Phase* (WPIM) so visible in RM!

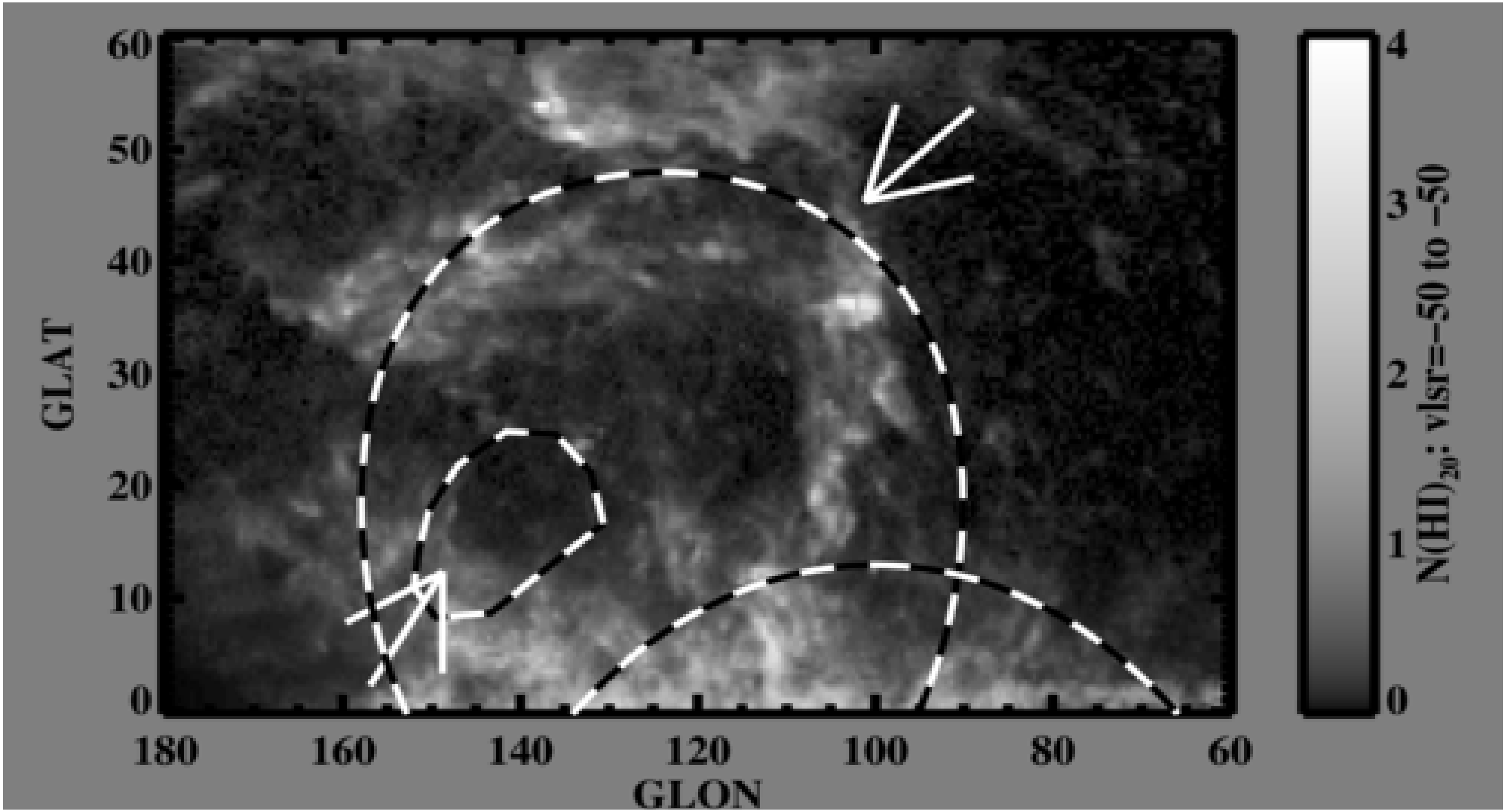
Let’s zoom in on the Radio Loop 3 vicinity…

RMs HI



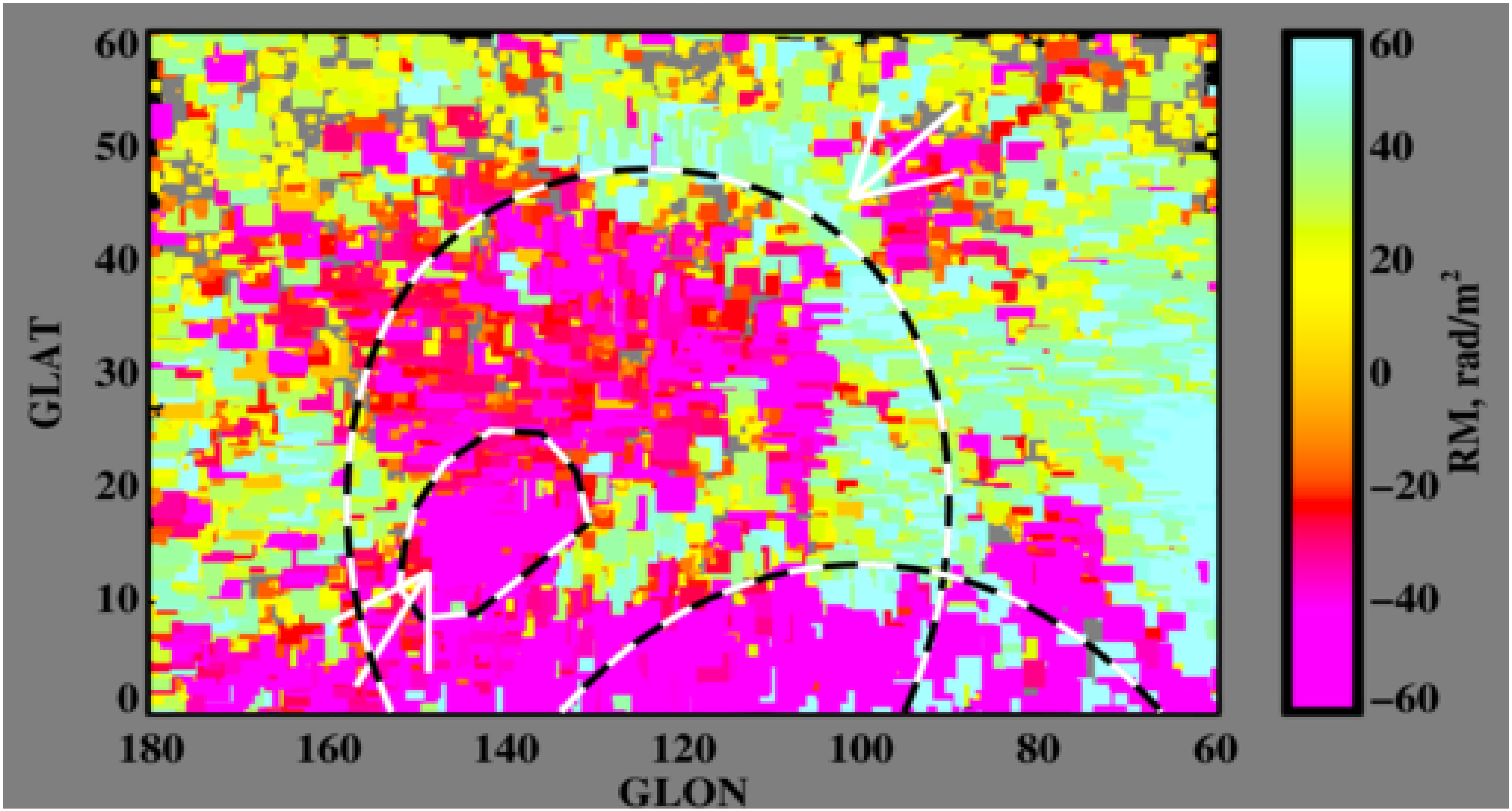
RMs H+

HI



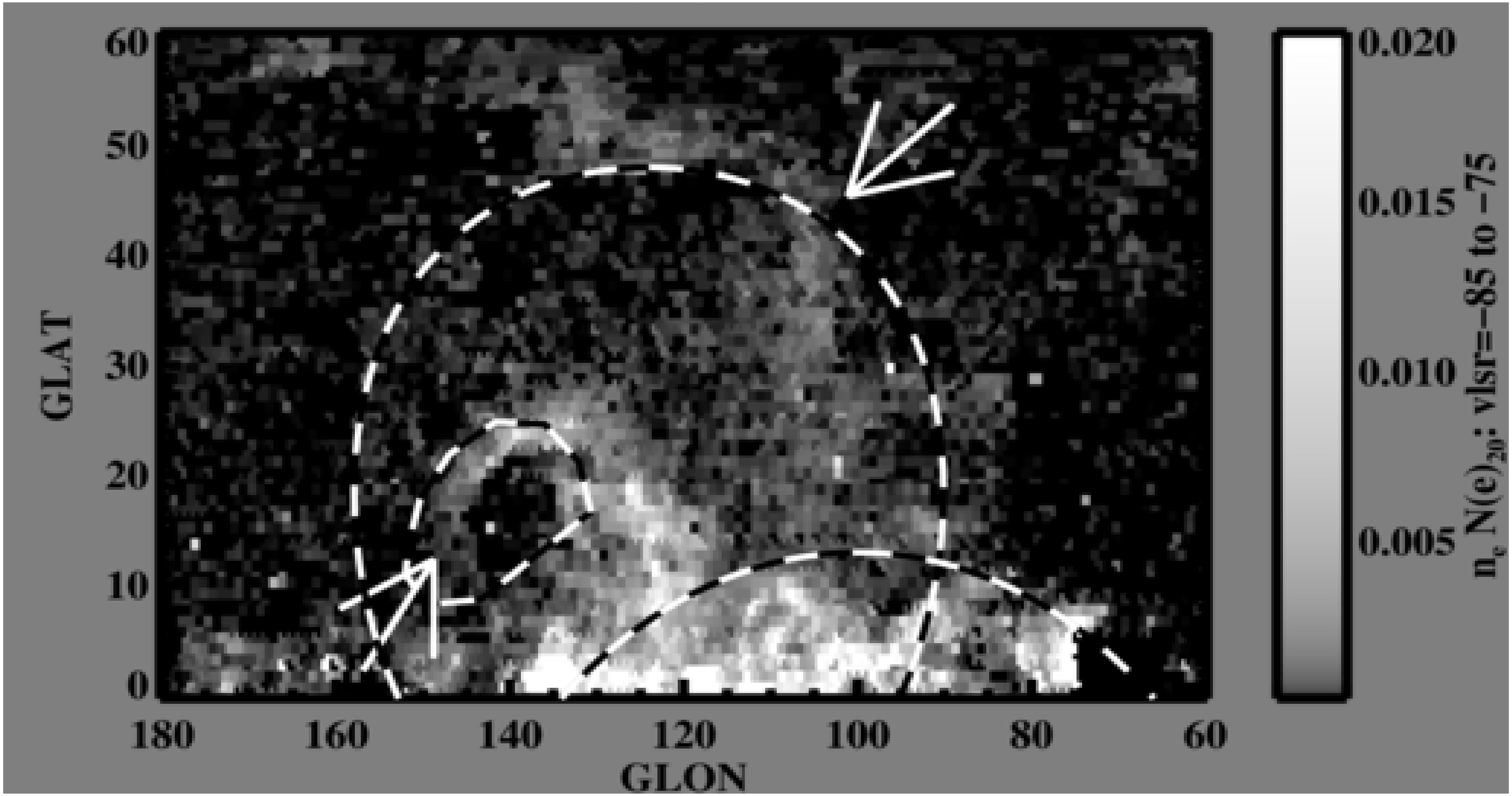
GLAT
60
50
40
30
20
10
0
180
160
140
120
100
80
60
GLON
4
3
2
1
0
N(HI)$_{20}$: vlsr=−50 to −50

HI



60
50
40
30
20
10
0
GLAT
180
160
140
120
100
80
60
GLON
60
40
20
0
−20
−40
−60
RM, rad/m^2

H+



60
50
40
30
20
10
0
GLAT
180
160
140
120
100
80
60
GLON
0.020
0.015
0.010
0.005
n_e $N(e)_{20}$; vlsr=−85 to −75

H+

Let's do some numbers…

$$RM = 0.81\, n_e B_{||} L \quad \mathrm{rad\ m^{-2}}$$

We see ΔRM ~ 100 rad m^{-2}

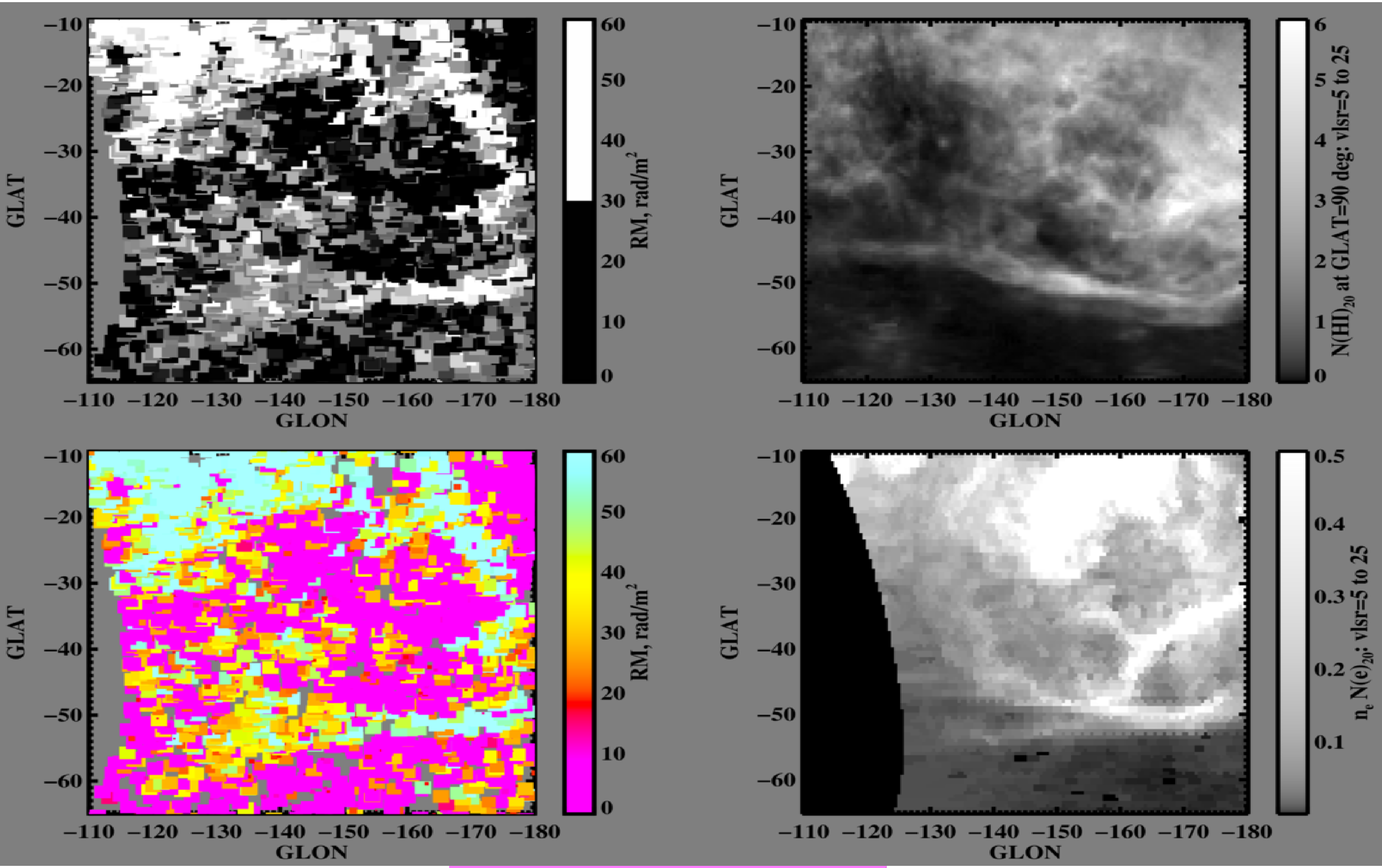
ΔEM ~ 2.0 cm^{-6} pc

If P_{WIM}~4000 cm^{-3} K, then n_e~0.25 cm^{-3} and $n_e L$~8 cm^{-3} pc, then

¡¡ B~15 μG; P_{mag}=50000 !!

Now let's zoom in on the Orion/Eridanus Superbubble…

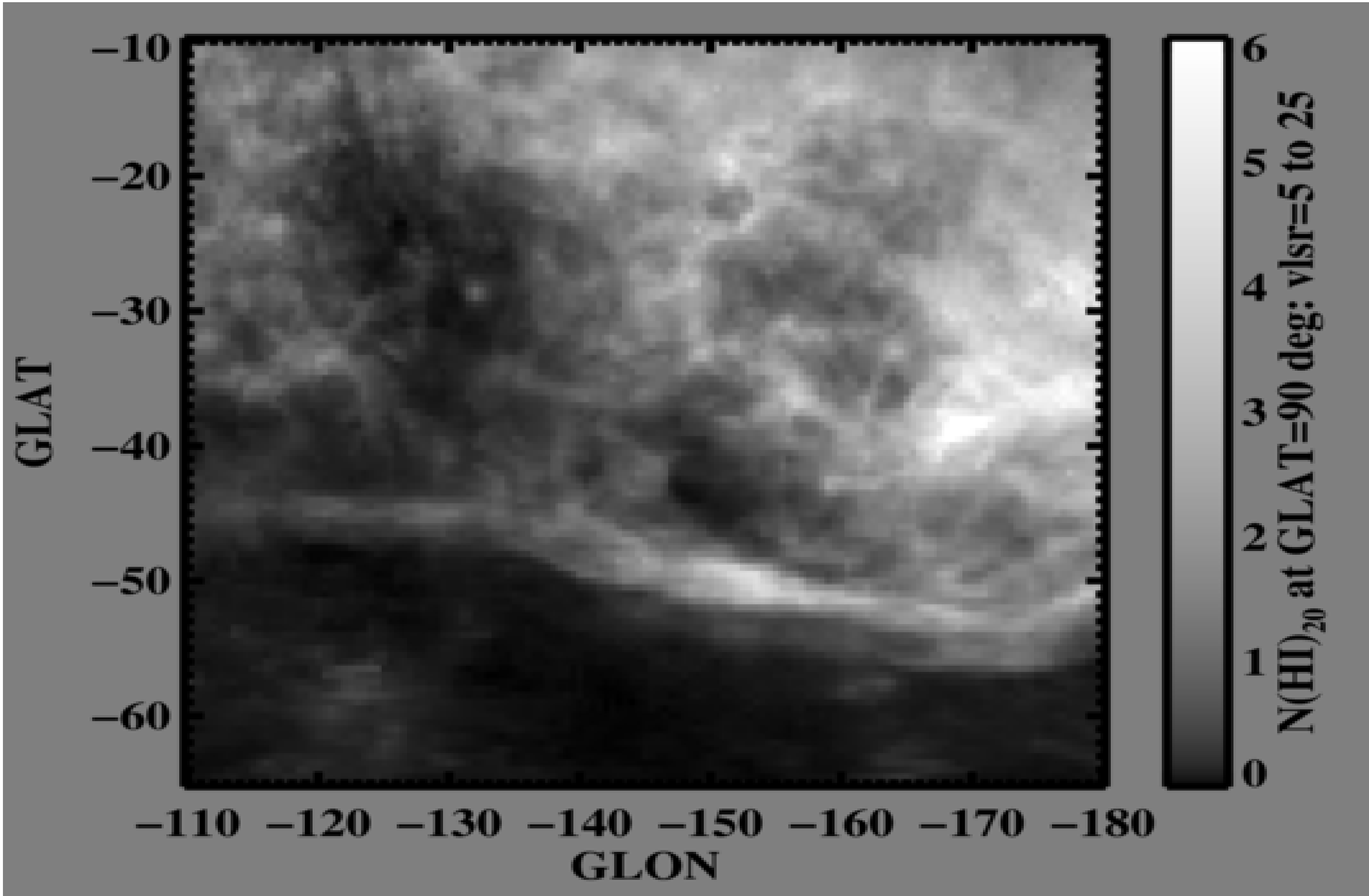
RMs HI



GLAT
GLON
-10 -20 -30 -40 -50 -60
-110 -120 -130 -140 -150 -160 -170 -180
RM, rad/m^2
0 10 20 30 40 50 60
N(HI)_20 at GLAT=90 deg: vlsr=5 to 25
0 1 2 3 4 5 6
n_e N(e)_20: vlsr=5 to 25
0.1 0.2 0.3 0.4 0.5

RMs ? H+

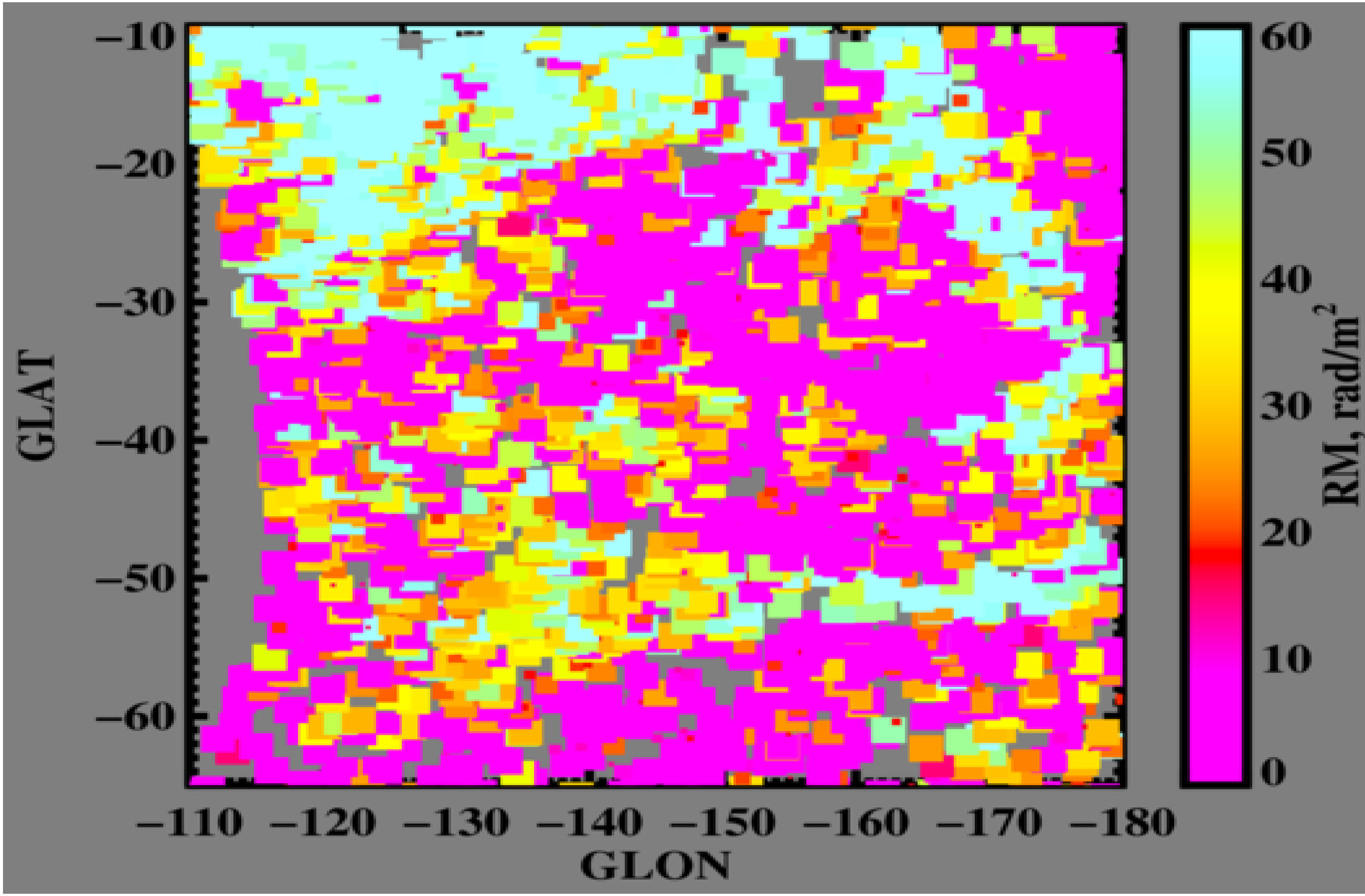
HI



GLAT
GLON
−10
−20
−30
−40
−50
−60
−110
−120
−130
−140
−150
−160
−170
−180
N(HI)20 at GLAT=90 deg: vlsr=5 to 25
0
1
2
3
4
5
6

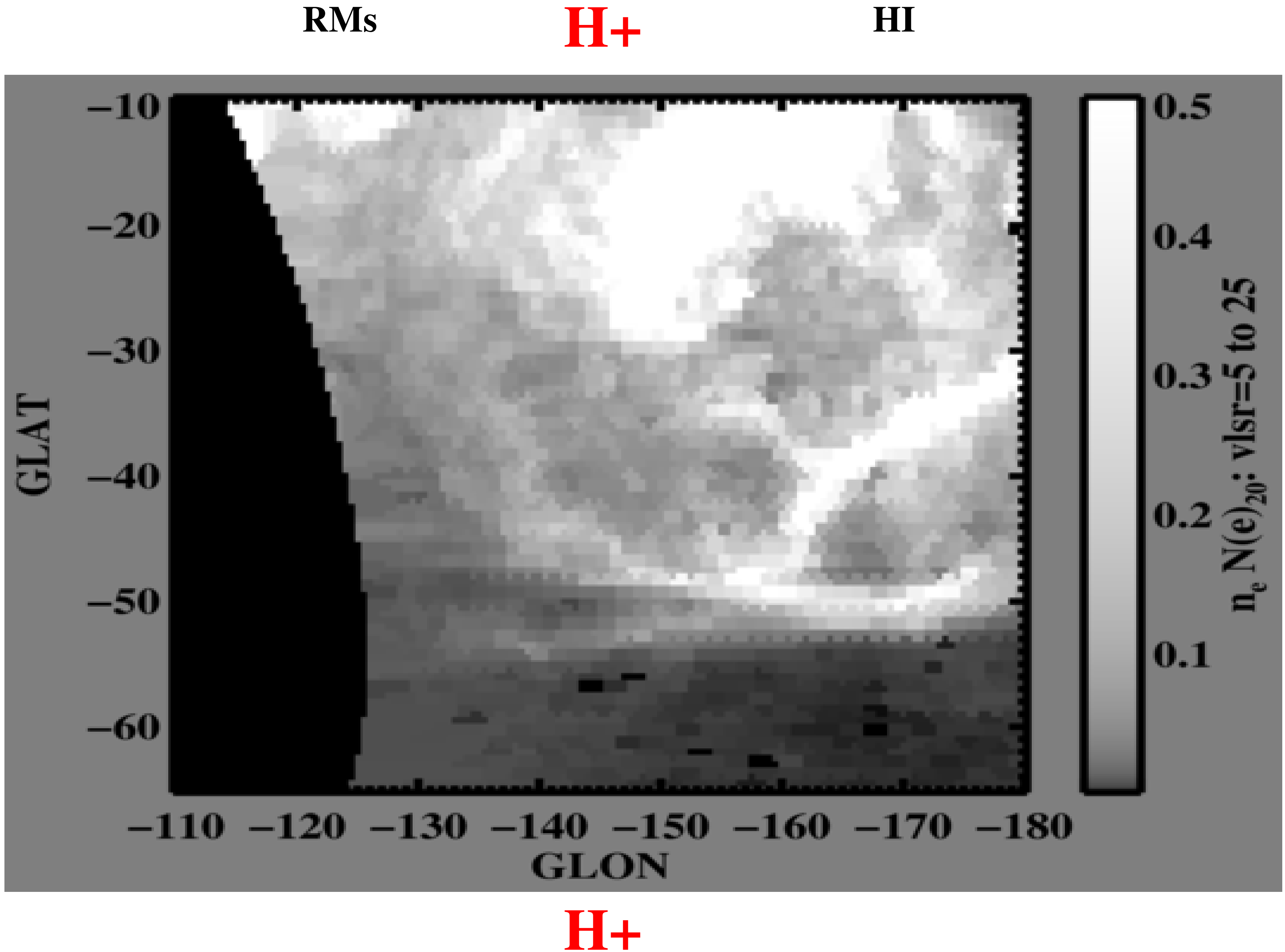
HI

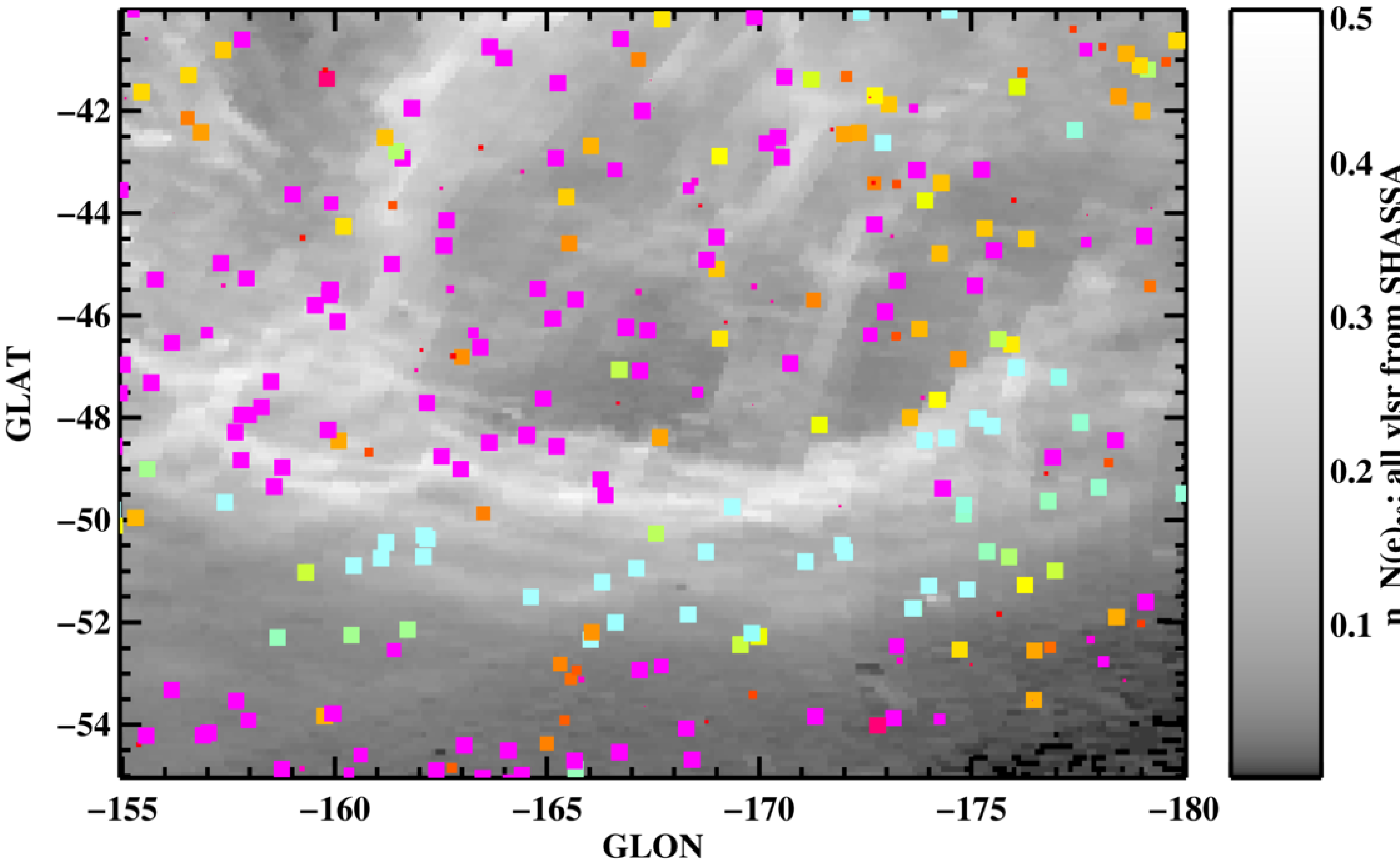
RM



−10
−20
−30
−40
−50
−60
GLAT
−110
−120
−130
−140
−150
−160
−170
−180
GLON
60
50
40
30
20
10
0
RM, rad/m^2

RM


RMs
H+
HI
GLAT
GLON
−10
−20
−30
−40
−50
−60
−110
−120
−130
−140
−150
−160
−170
−180
0.5
0.4
0.3
0.2
0.1
n_e $N(e)_{20}$; vlsr=5 to 25
H+



Higher angular resolution of H-alpha.

RMs are not well correlated with H-alpha line---i.e., the standard WIM.

Sensible conclusion: RMs are associated with large electron column, small emission measure—the WPIM.

<u>THIS IS THE FIFTH PHASE!</u>

best revealed by

<u>FARADAY ROTATION!</u>

Many of the RM morphological structures are loop features that are associated with supershells. Some of these supershells are old.

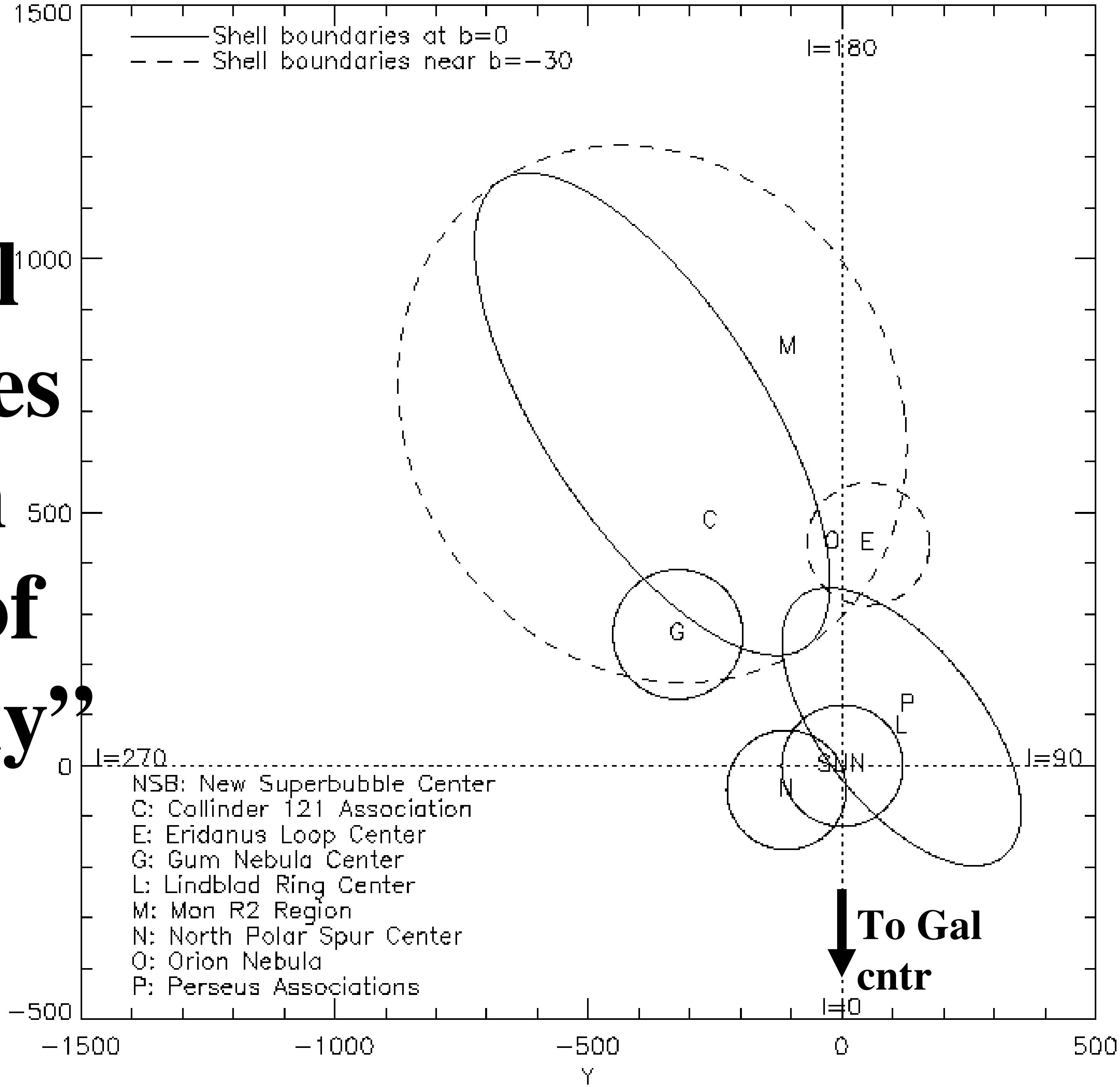
The nearby ISM is DOMINATED BY SUPERSHELLS...

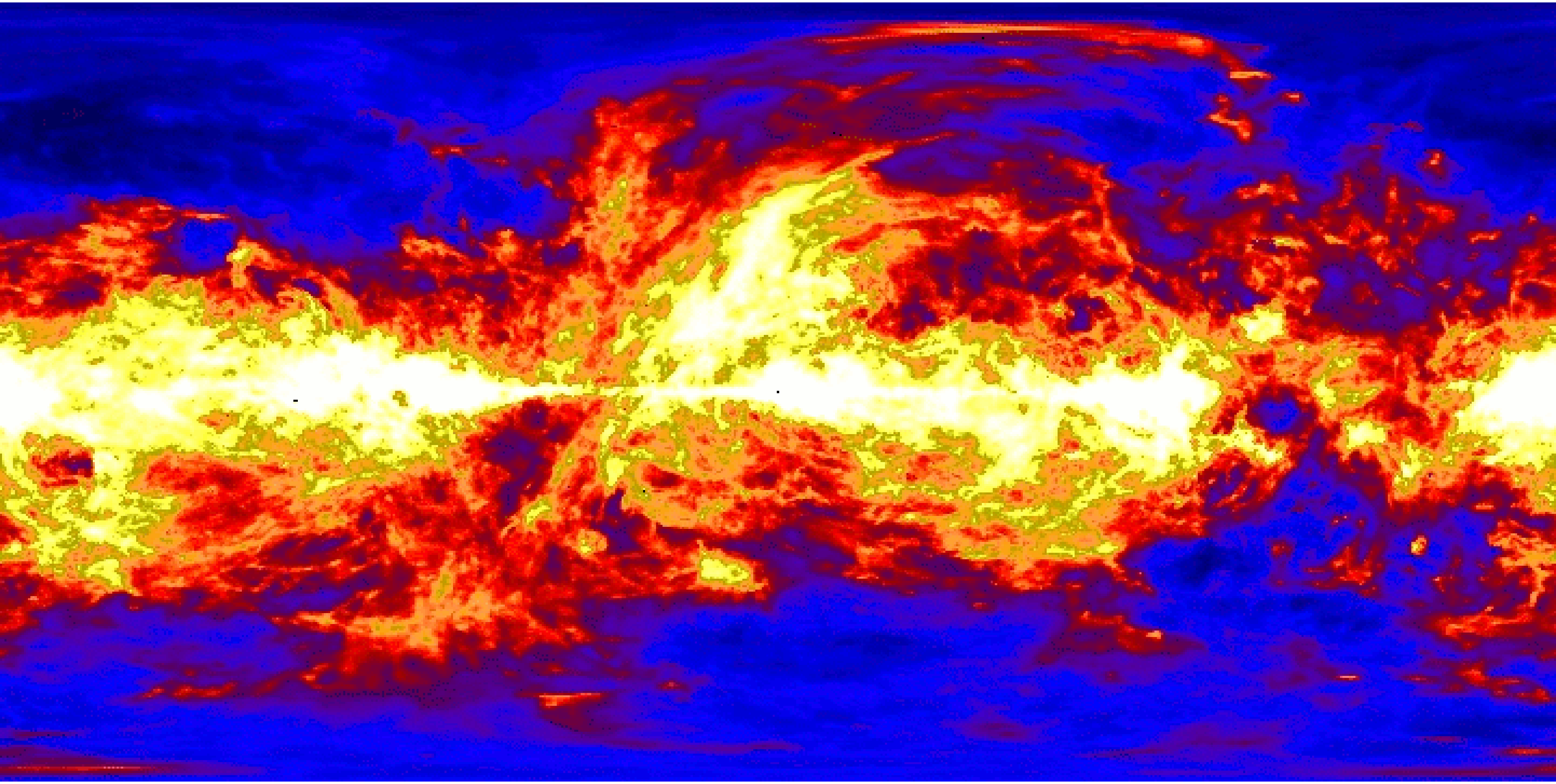
The Local Supershell Environment includes:

- **-the Orion/Eridanus Superbubble**
- **-the North Polar Spur**
- **-GSR 238+00+09**
- **-Lindblad's Ring**
- **-the Local Bubble**

Their observed properties differ enormously. Let's look at them!

Local supershell boundaries seen from the "top of the Galaxy"





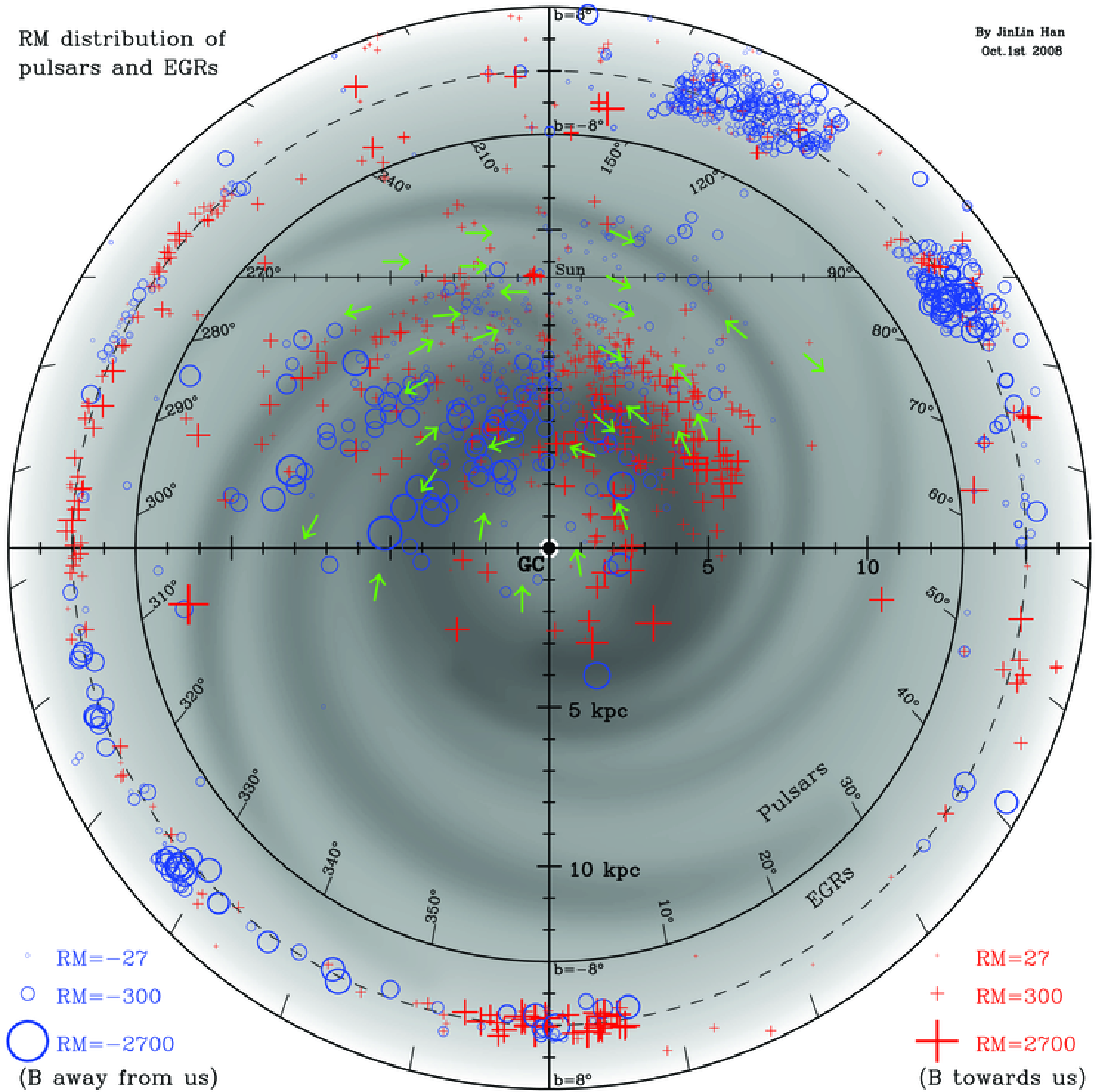
B follows HI morphology! So pay attention to these supershells!

People fit RMs to Galactic global field models. In the Galactic plane:

Han et al., van Eps et al., Haverkorn et al. find that field lines follow spiral arms with pitch angle decreasing with Galactocentric radius, with reversals. Details differ.

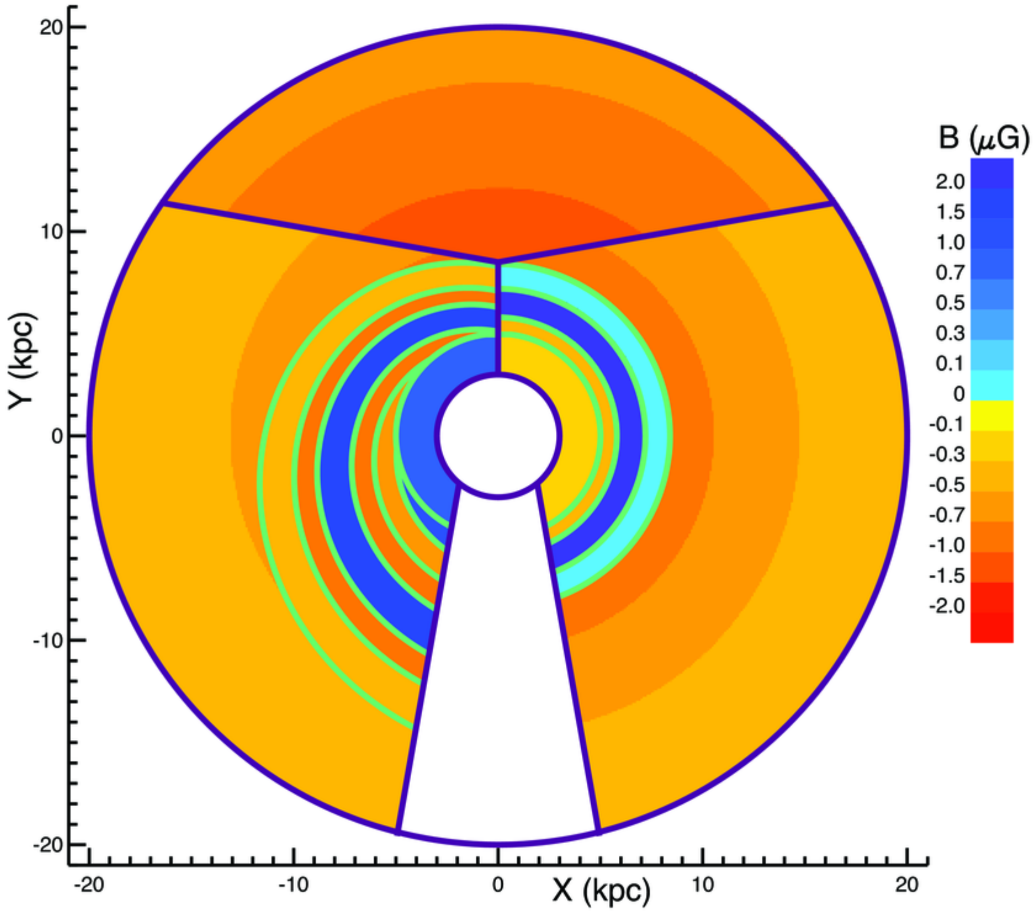
Some pictures:

The Galaxy according to Han (2009). Arm/interarm reversals of field lines that follow spiral arms.

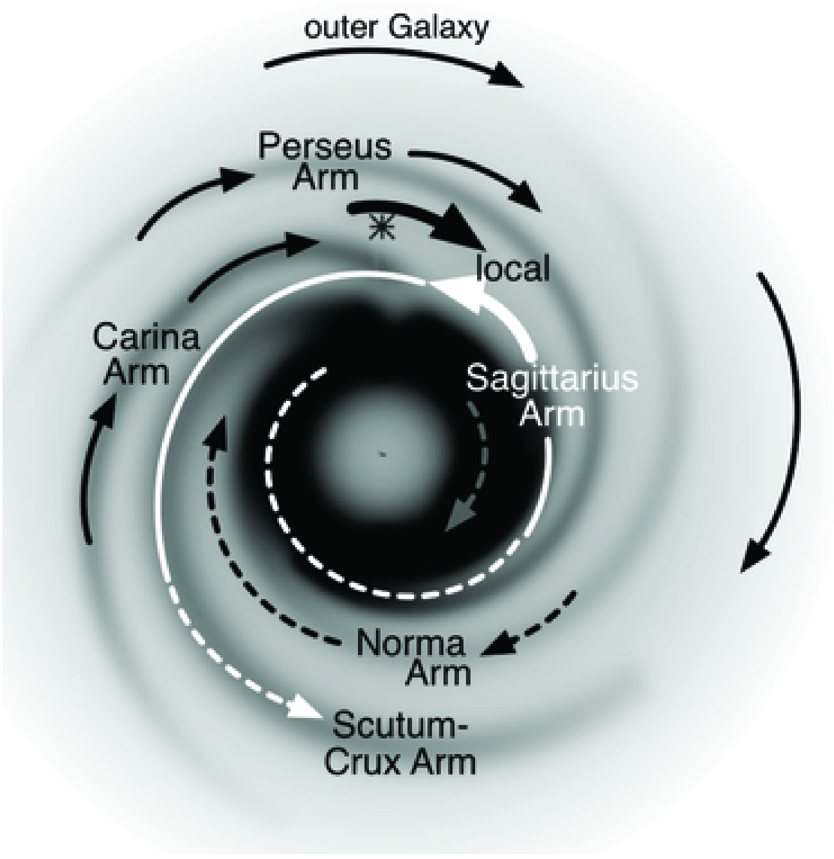


The Galaxy according to Van Eck et al. (2011): One spiral-shaped reversal, only inside the Solar circle.

Field Strength



Field Morphology



The in-plane models are getting really good at matching the RM data! The data sample large swaths of the Galactic plane. Even though current studies differ on the details, I believe that IN PRINCIPLE the approach is valid and, with lots more data, will reveal the truth.

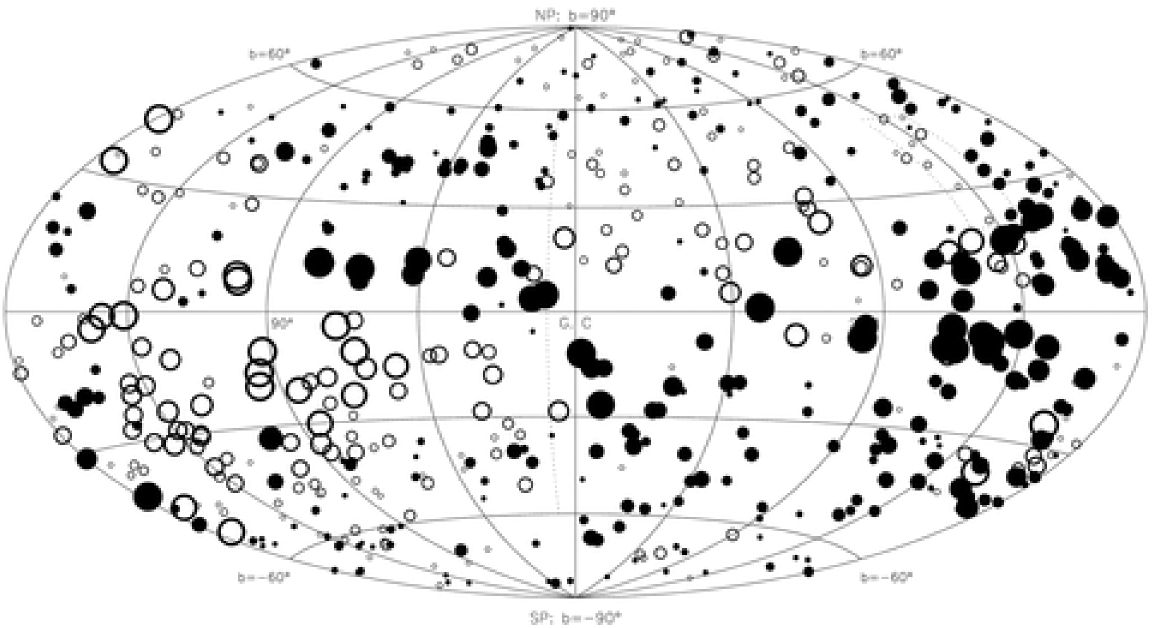
People fit off-plane RMs to derive the global magnetic field configuration in the 'Galactic Halo':

--Vertical 'Halo' field near Sun: Taylor et al. and Mao et al. agree for SGP (RM= [-6.7 +/- 0.5] rad/m^2), disagree for NGP ([3.1 +/- 0.5] vs [0.0 +/- 0.5] rad/m^2).

--Horizontal 'Halo' field near Sun: Taylor et al. find -0.4 μG at b= +45, +0.8 μG at b= -45, towards l~280. NOTE: they find a REVERSAL above/below b=0!

This reversal agrees with Han et al. A picture:

The Galactic Halo according to Han (2009). Antisymmetric RMs: the signs reverse across the b=0 line and across the l=0 line. This leads to the global field configuration on the right hand side, which is consistent with an A0 dynamo.



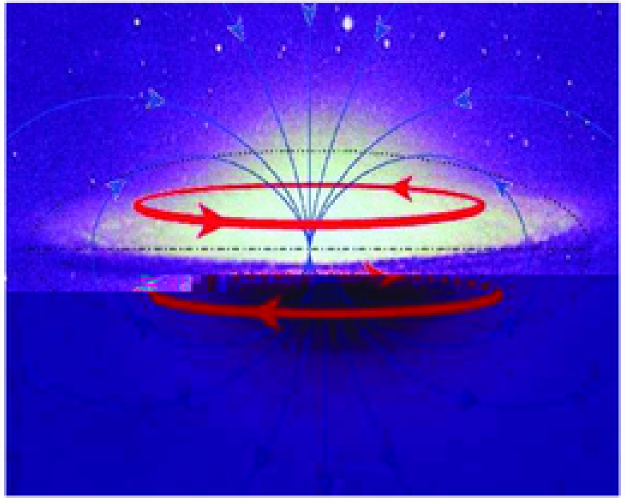


Figure 5. The antisymmetric rotation measure sky, derived from RMs of extragalactic radio sources after filtering out the outliers with anomalous RM values. The distribution corresponds to magnetic structure in the Galactic halo as illustrated on the right. See Han et al. (1997, 1999).

These 'halo field models' use high-latitude RMs, so they rely on the field within ~1 kpc reliably tracing the Galactic-wide halo field. The preponderance of supershells and the nearby large-scale in-plane field reversal produce `cosmic variance' and I suspect this is serious.

For these halo models, the RM data sample about 1/64 of the Galactic plane's area and extrapolate to the whole Galaxy.

What would we measure if we moved 1 kpc away from our present position?

Fin

MODELING THE MAGNETIC FIELD IN THE GALACTIC DISK USING NEW ROTATION MEASURE OBSERVATIONS FROM THE VERY LARGE ARRAY

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Accepted for publication in ApJ; December 13, 2010

ABSTRACT

We have determined 194 Faraday rotation measures (RMs) of polarized extragalactic radio sources using new, multi-channel polarization observations at frequencies around 1.4 GHz from the Very Large Array (VLA) in the Galactic plane at $17° \leq l \leq 63°$ and $205° \leq l \leq 253°$. This catalog fills in gaps in the RM coverage of the Galactic plane between the Canadian Galactic Plane Survey and Southern Galactic Plane Survey. Using this catalog we have tested the validity of recently-proposed axisymmetric and bisymmetric models of the large-scale (or regular) Galactic magnetic field, and found that of the existing models we tested, an axisymmetric spiral model with reversals occurring in rings (as opposed to along spiral arms) best matched our observations. Building on this, we have performed our own modeling, using RMs from both extragalactic sources and pulsars. By developing independent models for the magnetic field in the outer and inner Galaxy, we conclude that in the inner Galaxy, the magnetic field closely follows the spiral arms, while in the outer Galaxy, the field is consistent with being purely azimuthal. Furthermore, the models contain no reversals in the outer Galaxy, and together seem to suggest the existence of a single reversed region that spirals out from the Galactic center.

Subject headings: Galaxy: structure — ISM: magnetic fields — polarization

We (or at least I; how about you?) believe that high-latitude RMs are dominated by INDIVIDUAL STRUCTURES— contrary to conventional viewpoint that they trace the GLOBAL GALACTIC FIELD.

A ROTATION MEASURE IMAGE OF THE SKY

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Received 2009 March 28; accepted 2009 July 20; published 2009 August 19

ABSTRACT

We have re-analyzed the NRAO VLA Sky Survey (NVSS) data to derive rotation measures (RMs) toward 37,543 polarized radio sources. The resulting catalog of RM values covers the sky area north of declination -40° with an average density of more than one RM per square degree. We present an image of the median RM over 82% of the sky with a resolution of 8° and a typical error of ±1–2 rad m^{-2}. The image shows large-scale structures in RM that extend to very high Galactic latitudes. A simple analysis of the RM structure at high Galactic latitudes is used to derive properties of the Galactic halo magnetic field in the solar neighborhood. We find the component of the local field perpendicular to the plane (the z-component) equal to $+0.30\ \mu$G for $z < 0$ and $-0.14\ \mu$G for $z > 0$. The reversal of sign across the Galactic plane is consistent with a quadrupole field geometry for the poloidal component of the halo field. The halo magnetic field component parallel to the disk is also found to be antisymmetric and generally consistent with a toroidal field, with strength $+0.83\ \mu$G for $z < 0$ and $-0.39\ \mu$G for $z > 0$. We have identified five regions of the sky where the foreground median RM is consistently less than 1 rad m^{-2} over several degrees. These holes in the foreground RM will be useful for future studies of possible small-scale fluctuations in cosmic magnetic field structures. In addition to allowing measurement of RMs toward polarized sources, the new analysis of the NVSS data removes the effects of bandwidth depolarization for $|\mathrm{RM}| \gtrsim 100$ rad m^{-2} inherent in the original NVSS source catalog. This new catalog of RMs and polarized flux densities is available online, and will be a valuable resource for further studies of the Galactic magnetic field and magnetoionic medium, and extragalactic magnetic fields.

You probably missed that important highlight---print too small! The essence:

*** The Inner-Galaxy field has one reversal and the field follows the spiral arms**

*** The Outer-Galaxy field has no reversals and follows circles**

My own perspective:

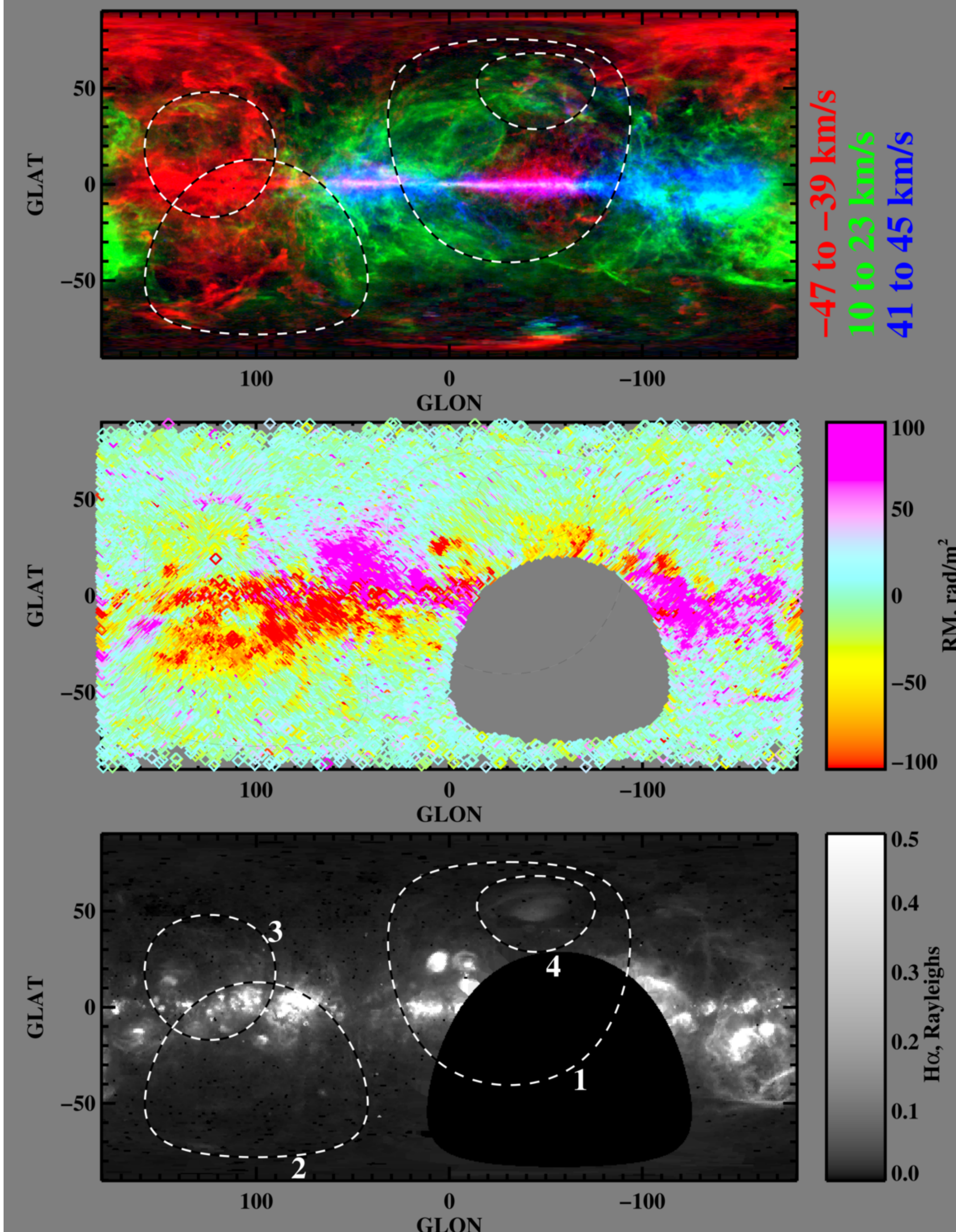
--The preponderance of supershells and the nearby large-scale in-plane reversal produce `cosmic variance' and I suspect this is serious.

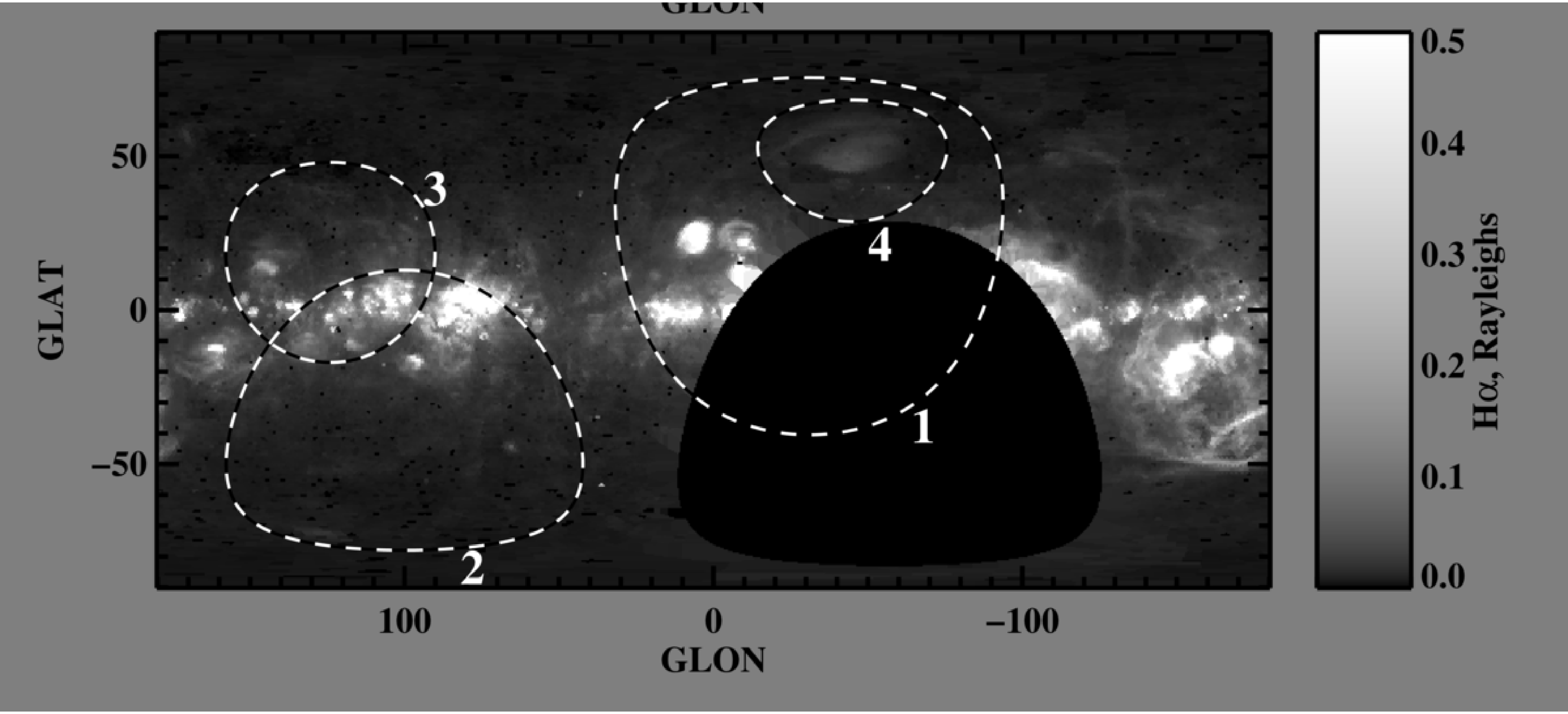
--What would we measure if we moved 1 kpc away from our present position?

HI: 21-cm line (LAB)

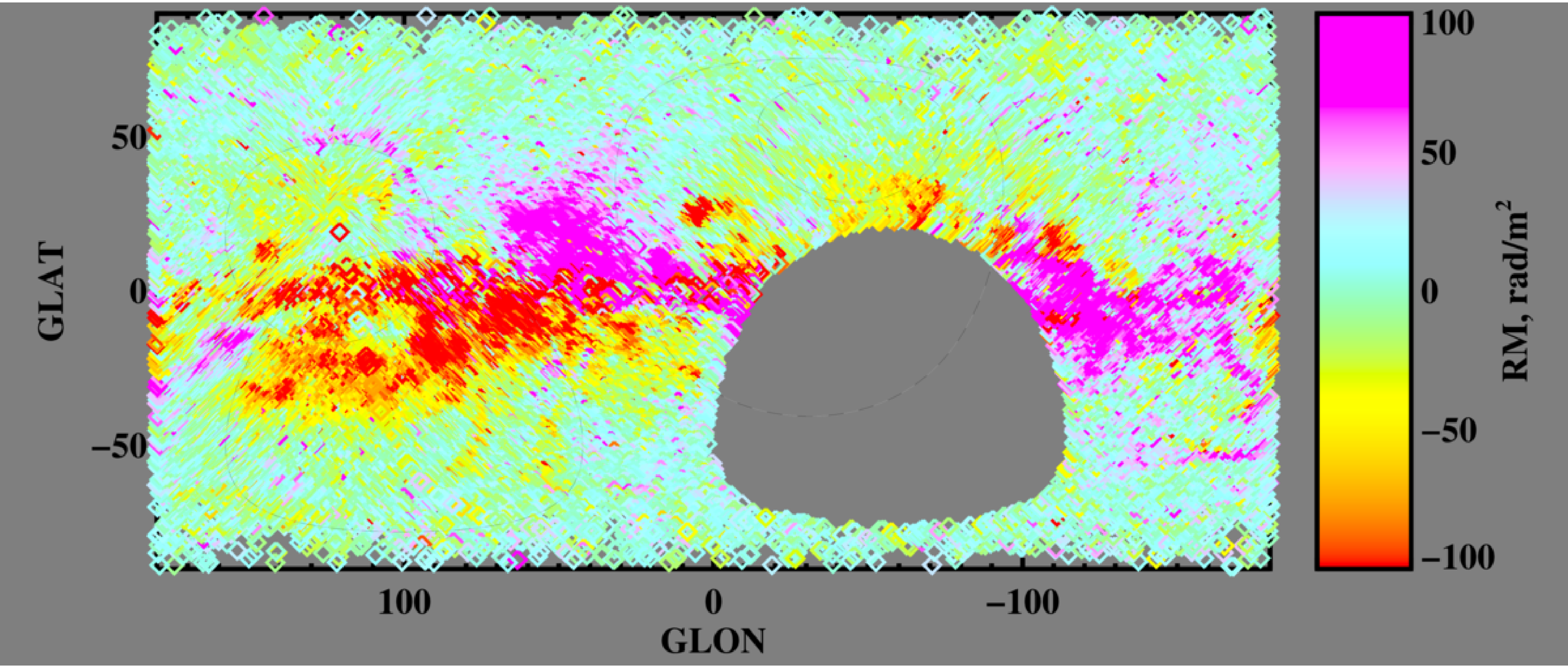
Faraday RMs (Taylor, Stil, Sumsrum 2009)

H+: H-alpha line (WHAM)

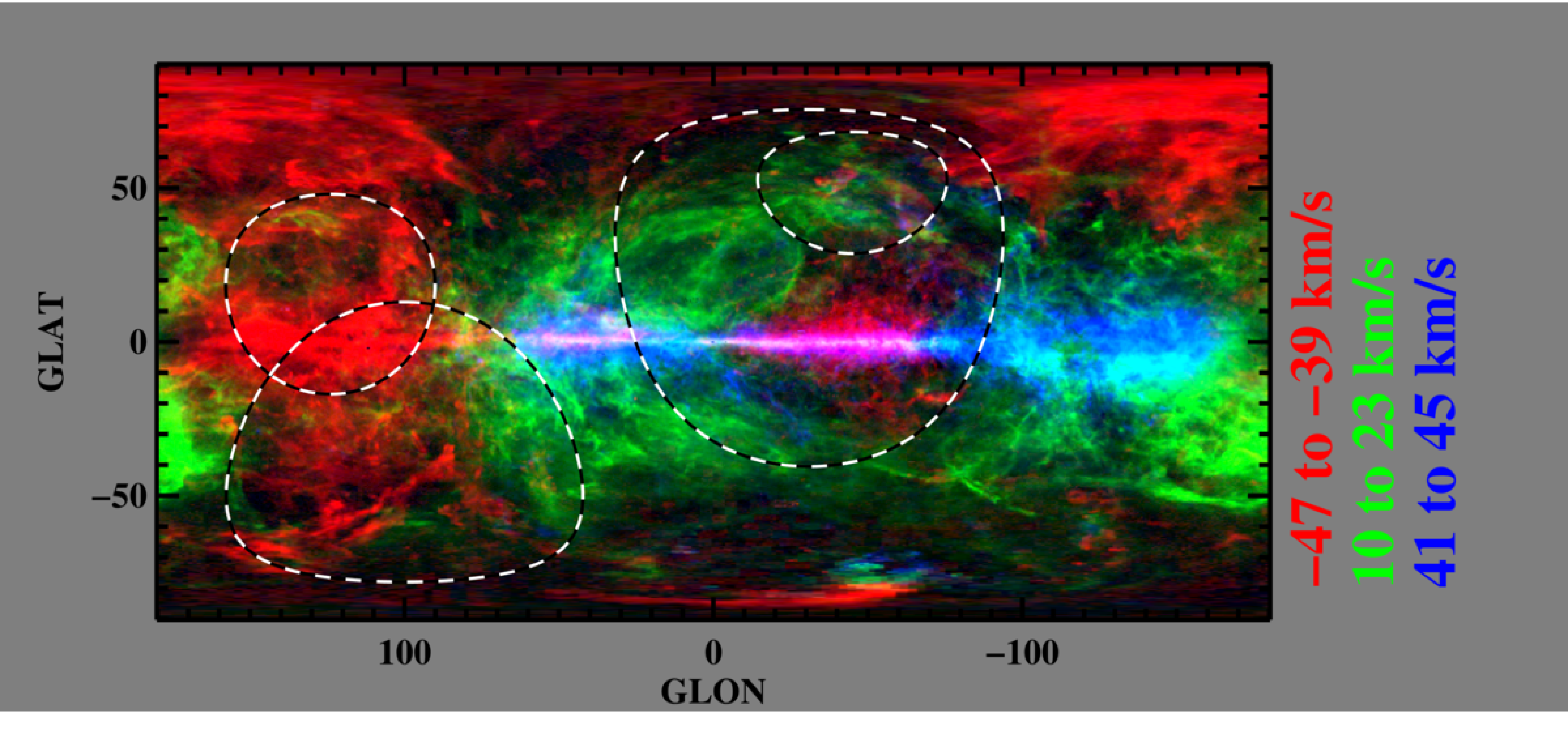




GLON
GLAT
GLON
50
0
−50
100
0
−100
1
2
3
4
0.5
0.4
0.3
0.2
0.1
0.0
Hα, Rayleighs



50
0
−50
GLAT
100
0
−100
GLON
100
50
0
−50
−100
RM, rad/m^2



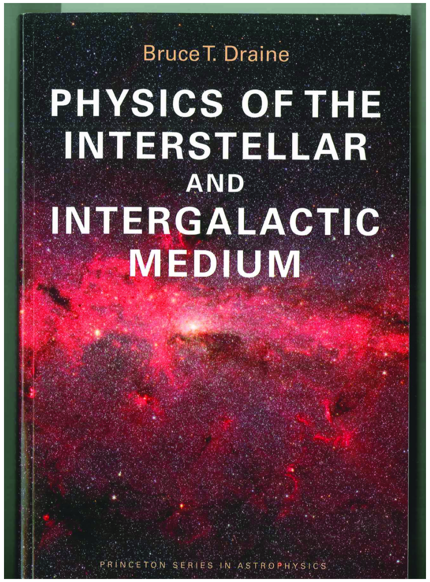
GLAT
50
0
−50
100
0
−100
GLON
−47 to −39 km/s
10 to 23 km/s
41 to 45 km/s

The original four phases, as defined by McKee & Ostriker, are not the four we think of today.

Today it's:

***The essentially FULLY NEUTRAL CNM and WNM**

***The essentially FULLY IONIZED WIM and HIM**



(Brand-new 2011 textbook)

Table 1.3 Phases of Interstellar Gas

Phase	T(K)	n_H(cm^{-3})	Comments
Coronal gas (HIM) $f_V \approx 0.5?$ $\langle n_H \rangle f_V \approx 0.002\,\mathrm{cm}^{-3}$ ($f_V \equiv$ volume filling factor)	$\gtrsim 10^{5.5}$	~ 0.004	Shock-heated Collisionally ionized Either expanding or in pressure equilibrium Cooling by: ◇ Adiabatic expansion ◇ X ray emission Observed by: • UV and x ray emission • Radio synchrotron emission
H II gas $f_V \approx 0.1$ $\langle n_H \rangle f_V \approx 0.02\,\mathrm{cm}^{-3}$	10^4	$0.3 - 10^4$	Heating by photoelectrons from H, He Photoionized Either expanding or in pressure equilibrium Cooling by: ◇ Optical line emission ◇ Free–free emission ◇ Fine-structure line emission Observed by: • Optical line emission • Thermal radio continuum
Warm H I (WNM) $f_V \approx 0.4$ $n_H f_V \approx 0.2\,\mathrm{cm}^{-3}$	~ 5000	0.6	Heating by photoelectrons from dust Ionization by starlight, cosmic rays Pressure equilibrium Cooling by: ◇ Optical line emission ◇ Fine structure line emission Observed by: • H I 21 cm emission, absorption • Optical, UV absorption lines
Cool H I (CNM) $f_V \approx 0.01$ $n_H f_V \approx 0.3\,\mathrm{cm}^{-3}$	~ 100	30	Heating by photoelectrons from dust Ionization by starlight, cosmic rays Cooling by: ◇ Fine structure line emission Observed by: • H I 21-cm emission, absorption • Optical, UV absorption lines
Diffuse H_2 $f_V \approx 0.001$	~ 50 K	~ 100	Heating by photoelectrons from dust

1.3. The Five Phases

We summarize these five phases' physical properties in Table 1, which is an update and expansion of Table 1 of Heiles (2001). The table includes column densities for a typical individual cloud (N_{typ}) and through the Galaxy for a vertical ($b = 90°$) sightline extending to infinity ($N_{\perp}$) .

Table 1: Properties of phases

Property	CNM	WNM	WIM	WPIM[(1)]	HIM Erid[(2)]
P_{th}/k (cm^{-3} - K)	4000	4000	4000	2000	50000
T (K)	50	6000	8000	7000	1.5×10^6
n_{Hn} (cm^{-3})	80	0.7	0.25	0.2	0.015
x_e	2×10^{-4}	$\lesssim 1 \times 10^{-2}$	1	0.5 ± 0.49	1
$N_{typ,Hn,20}$	0.5	1	0.08	0.06	0.06
$\boldsymbol{N_{typ,e,20}}$	1×10^{-4}	$\lesssim 1 \times 10^{-2}$	0.08	0.03	0.06
$N_{\perp,Hn,20}$	1.5	1.5	1.0	?	—
$\boldsymbol{N_{\perp,e,20}}$	3×10^{-4}	$\lesssim 1.5 \times 10^{-2}$	1.0	?	—

The subscript Hn means N-nuclei (i.e., both neutral and ionized H).
The subscript $\perp$ means line-of-sight at Galactic latitude 90°.
The subscript typ means a typical individual structure.
(1) From Redfield & Linsky (2004, 2008).
(2) For the Orion/Eridanus superbubble (Guo et al. 1995).

Let's start with the CNM and WNM.

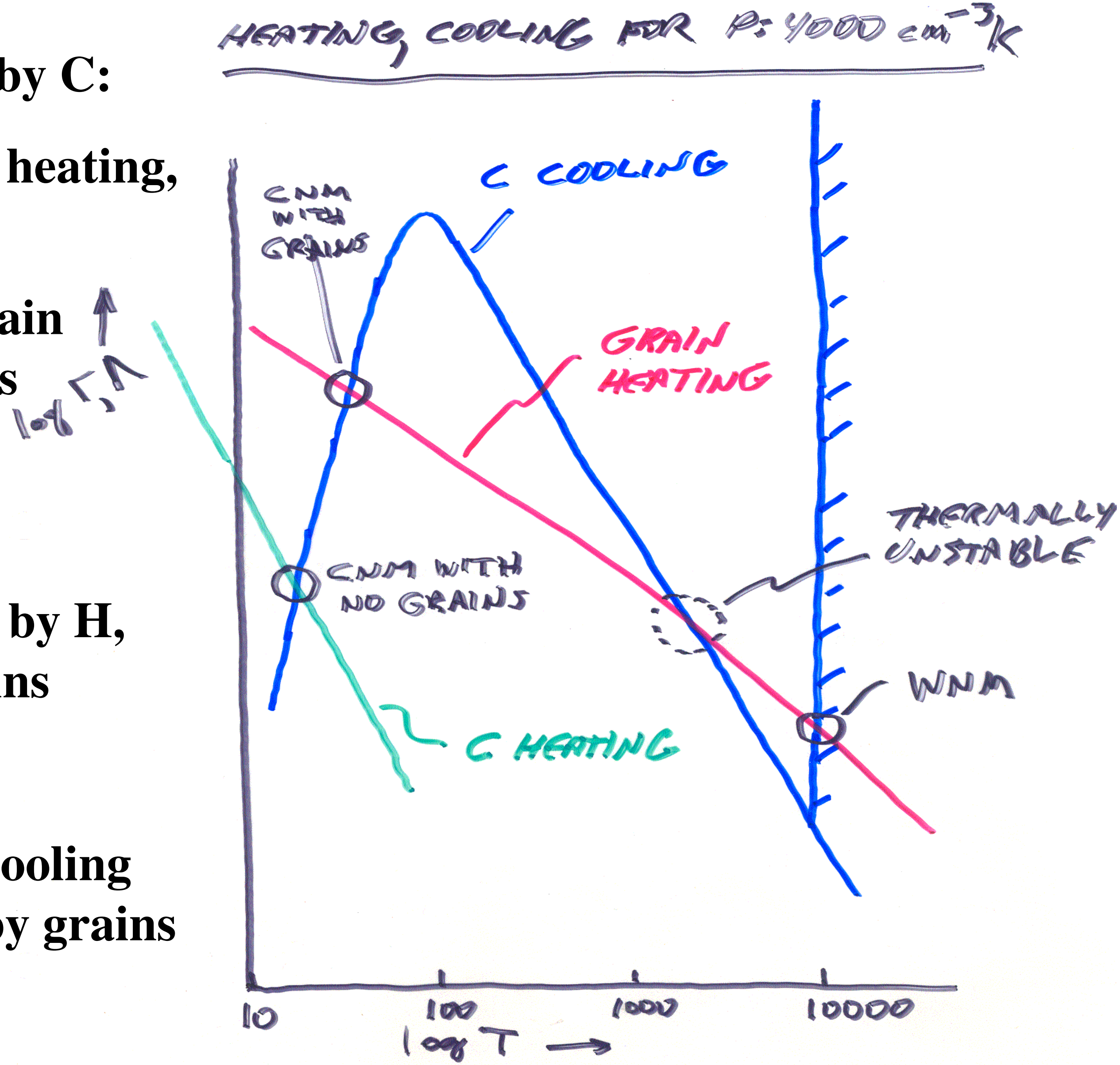
CNM: cooling by C:

With ONLY C heating, temp is 16 K.

With ALSO grain heating, temp is ~50 K

WNM: cooling by H, heating by grains

UNSTABLE: cooling by C, heating by grains



Now let's consider the WIM and HIM.