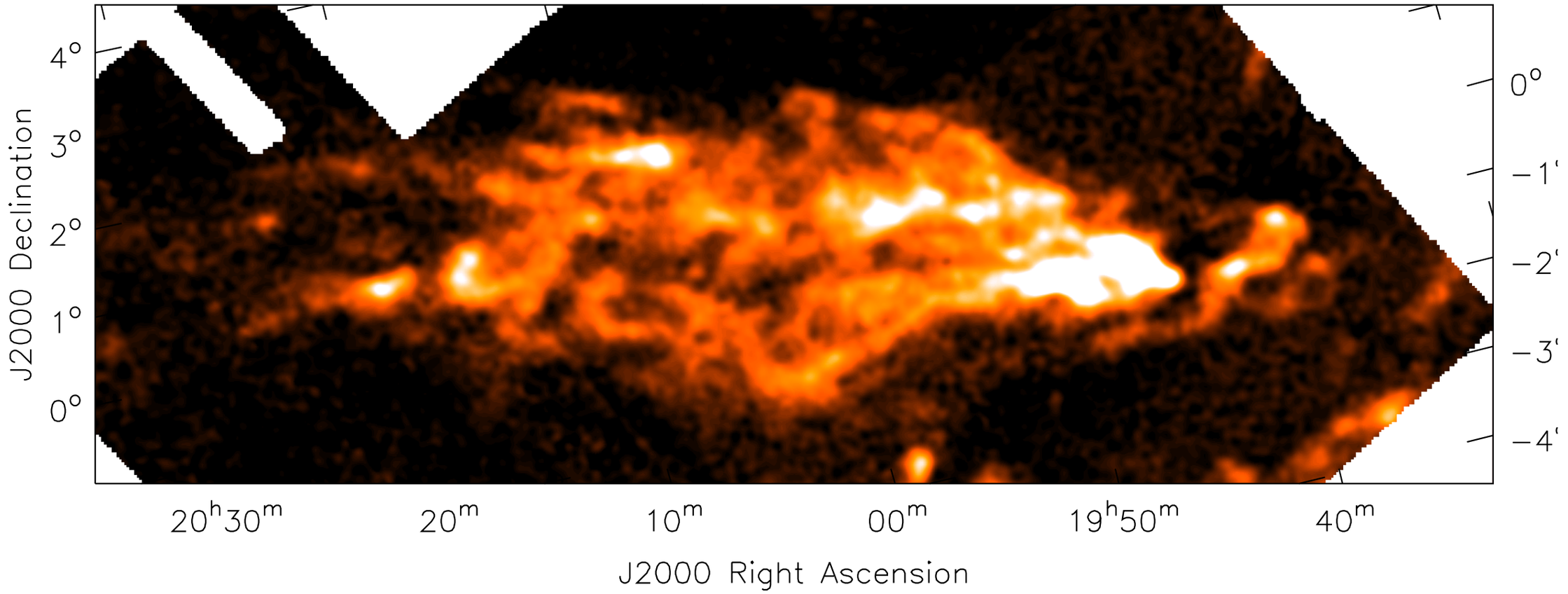
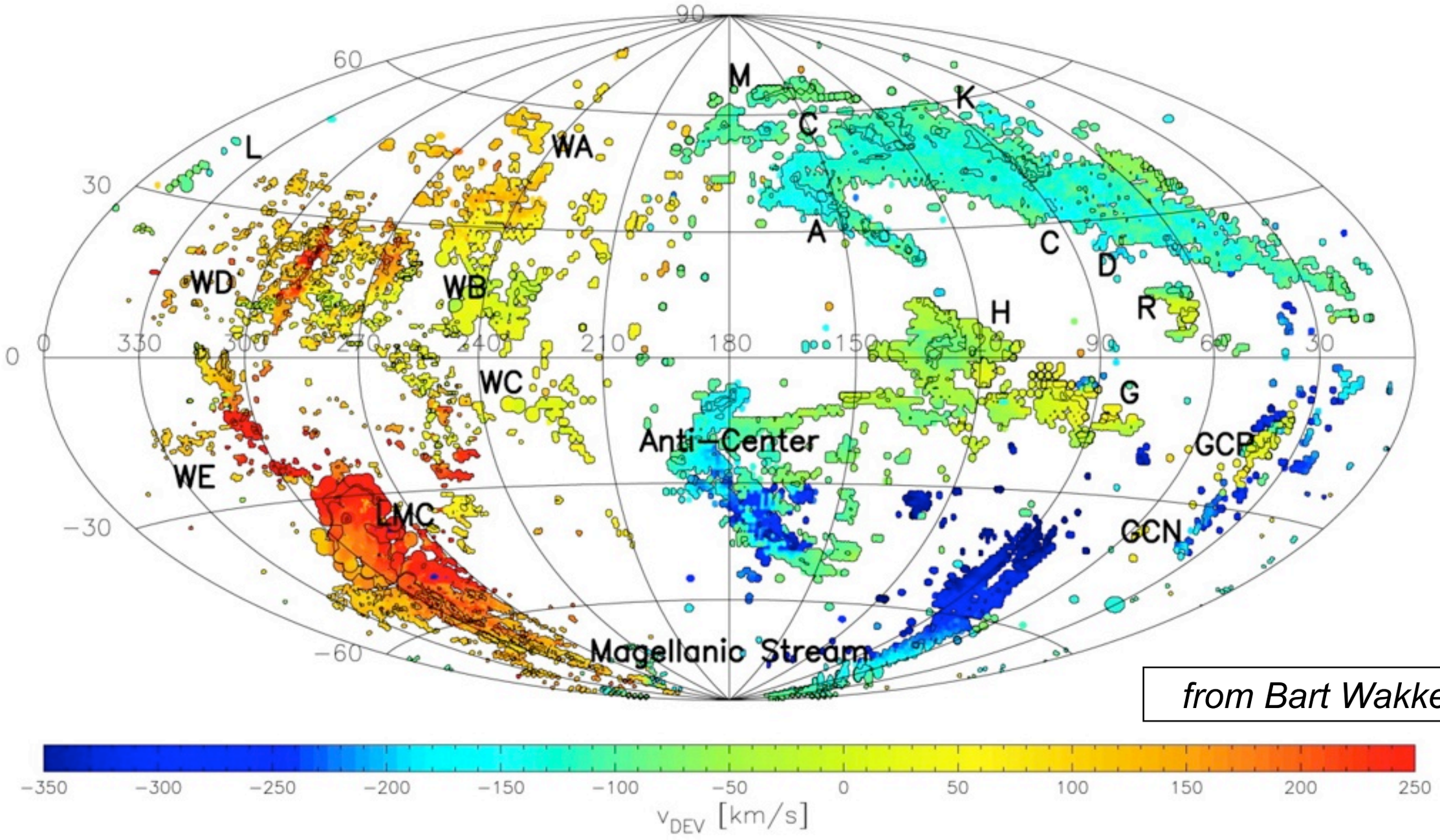
The Smith Cloud:
one very interesting high velocity cloud

Felix "Jay" Lockman
National Radio Astronomy Observatory
Green Bank, WV



High Velocity Clouds



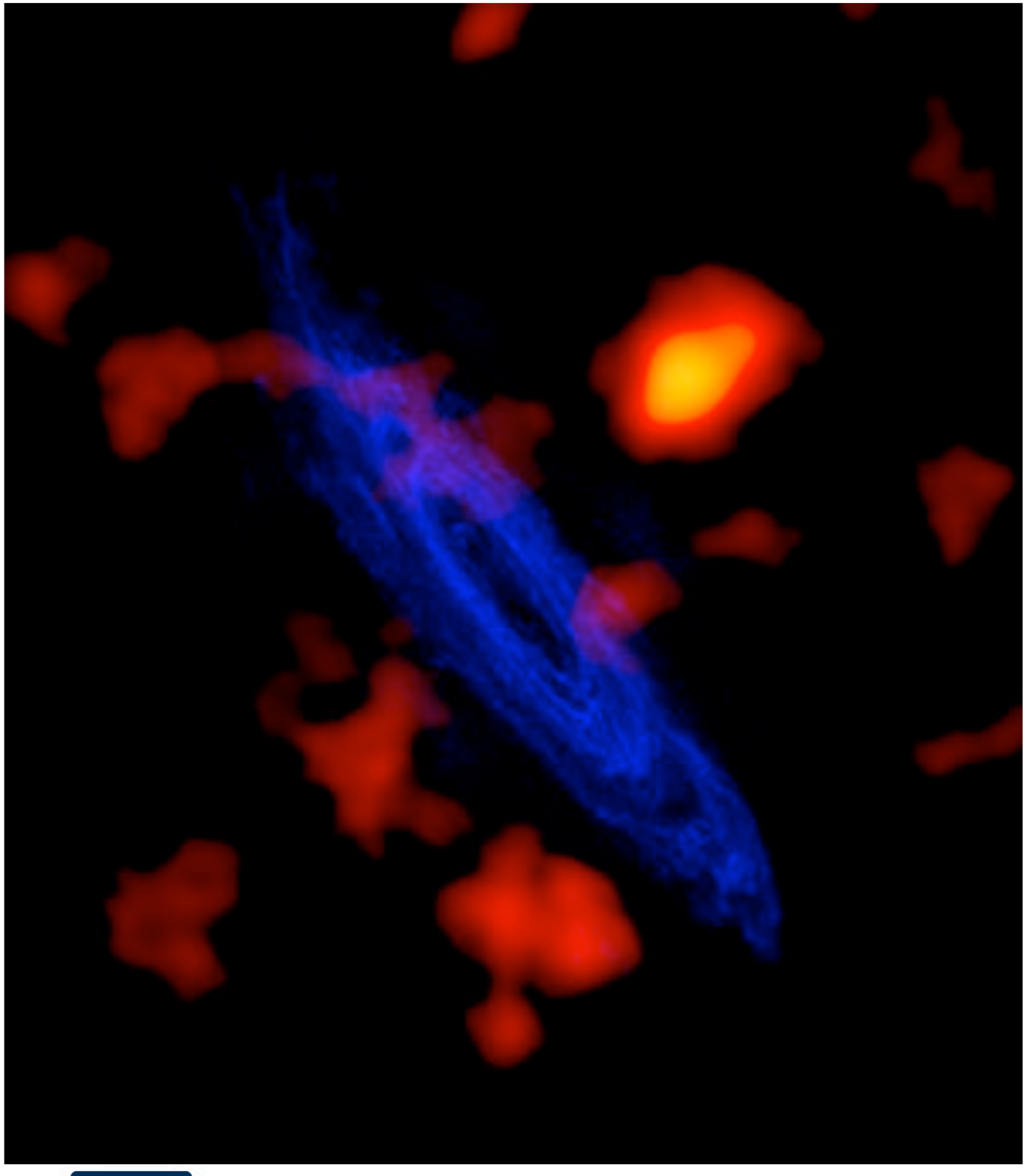
from Bart Wakker

Cover ~40% of the sky in HI (Murphy et al 1999; Lockman et al 2002)

>80% in H+ (Shull et al 2009)

No Galactic Plane, No Galactic Rotation

and yet... |Vmax|<300 km/s

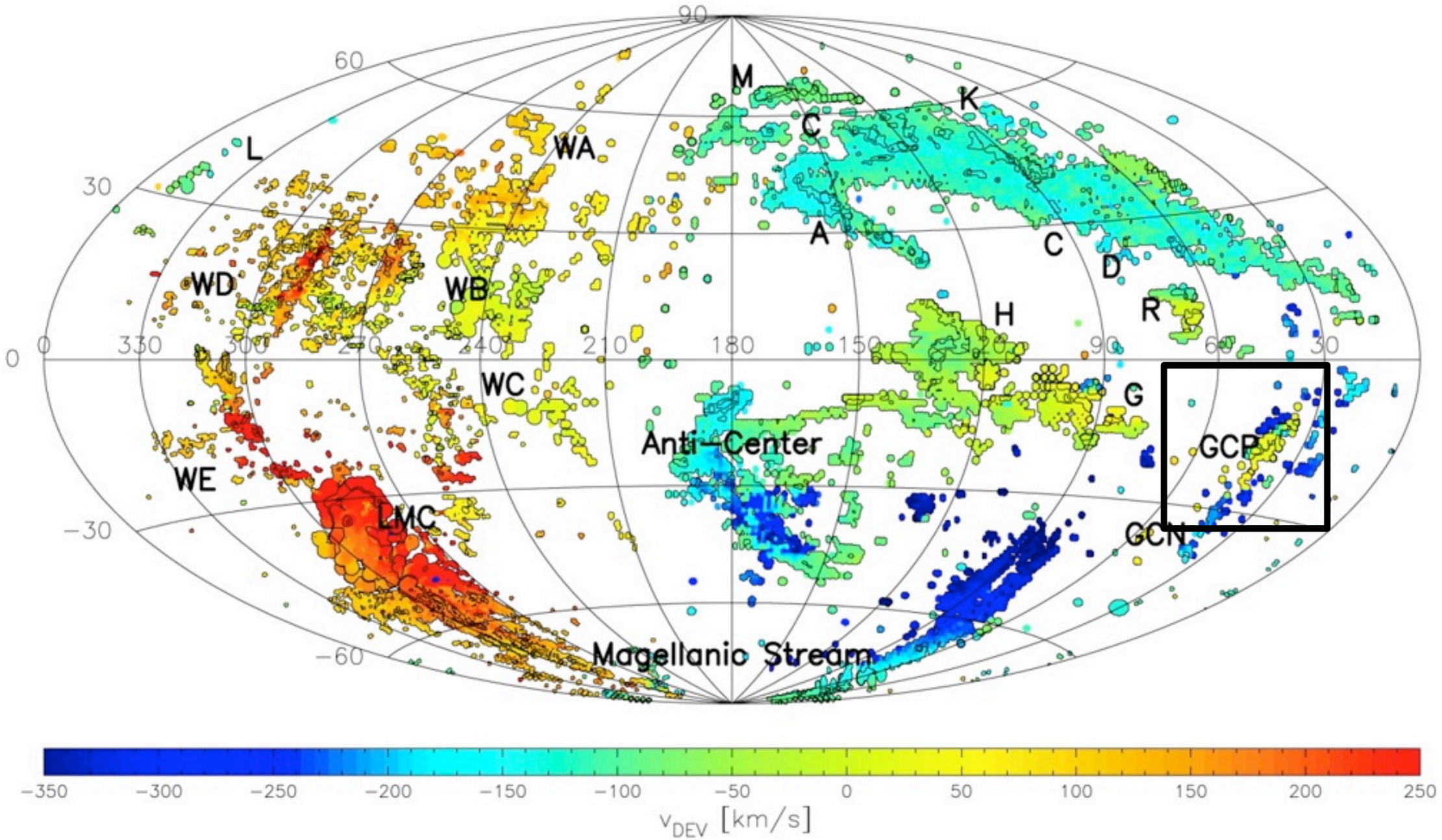


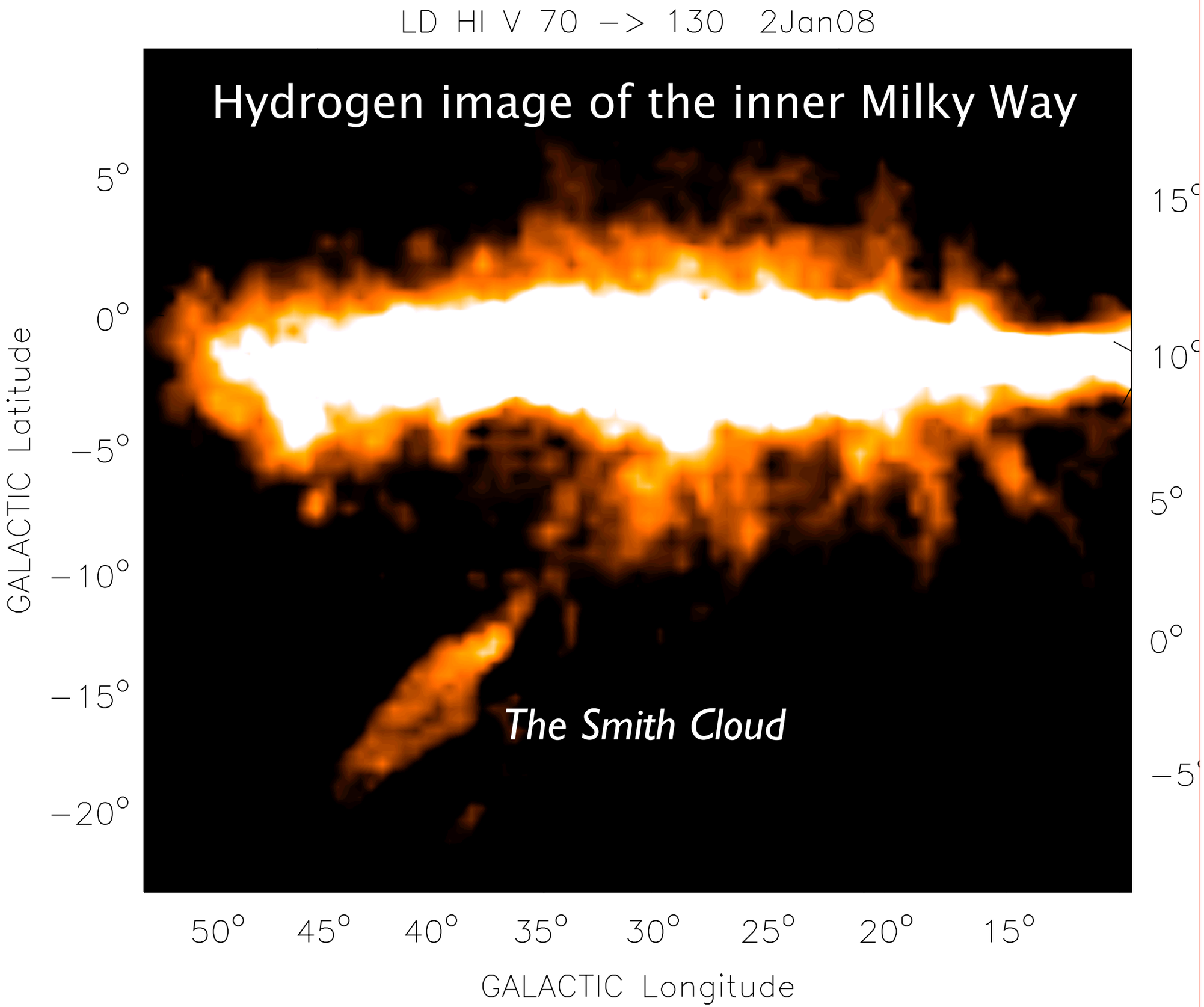
GBT Detection of Hydrogen Clouds Around Andromeda

(and distances to Milky Way HVCs)

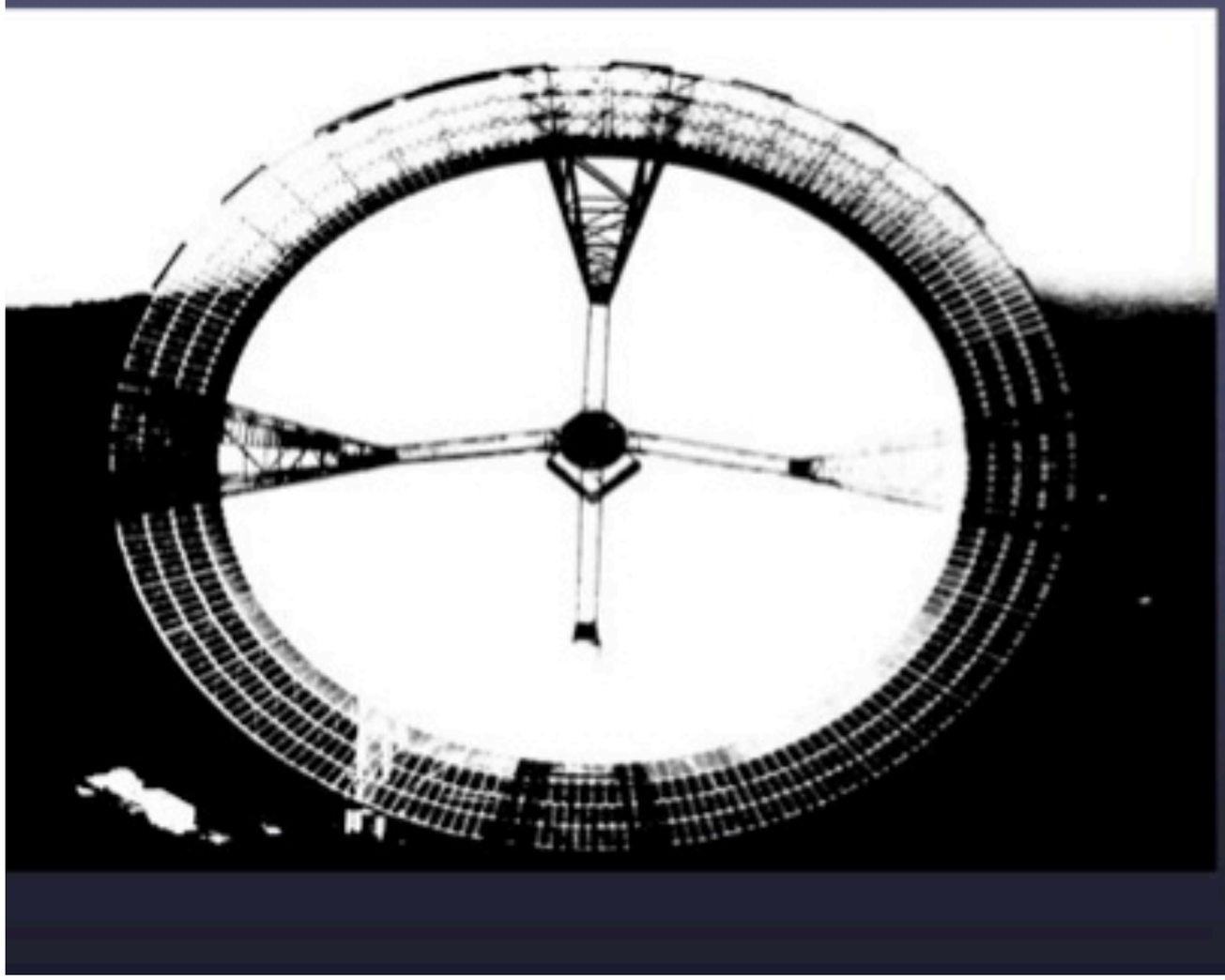
... suggests that most HVCs are
a galactic (d<50 kpc)
not an intergalactic (d~1 Mpc)
population

"On the continuing formation of the Andromeda Galaxy: Detection of HI Clouds in the M31 Halo"
Thilker et al 2004 ApJ

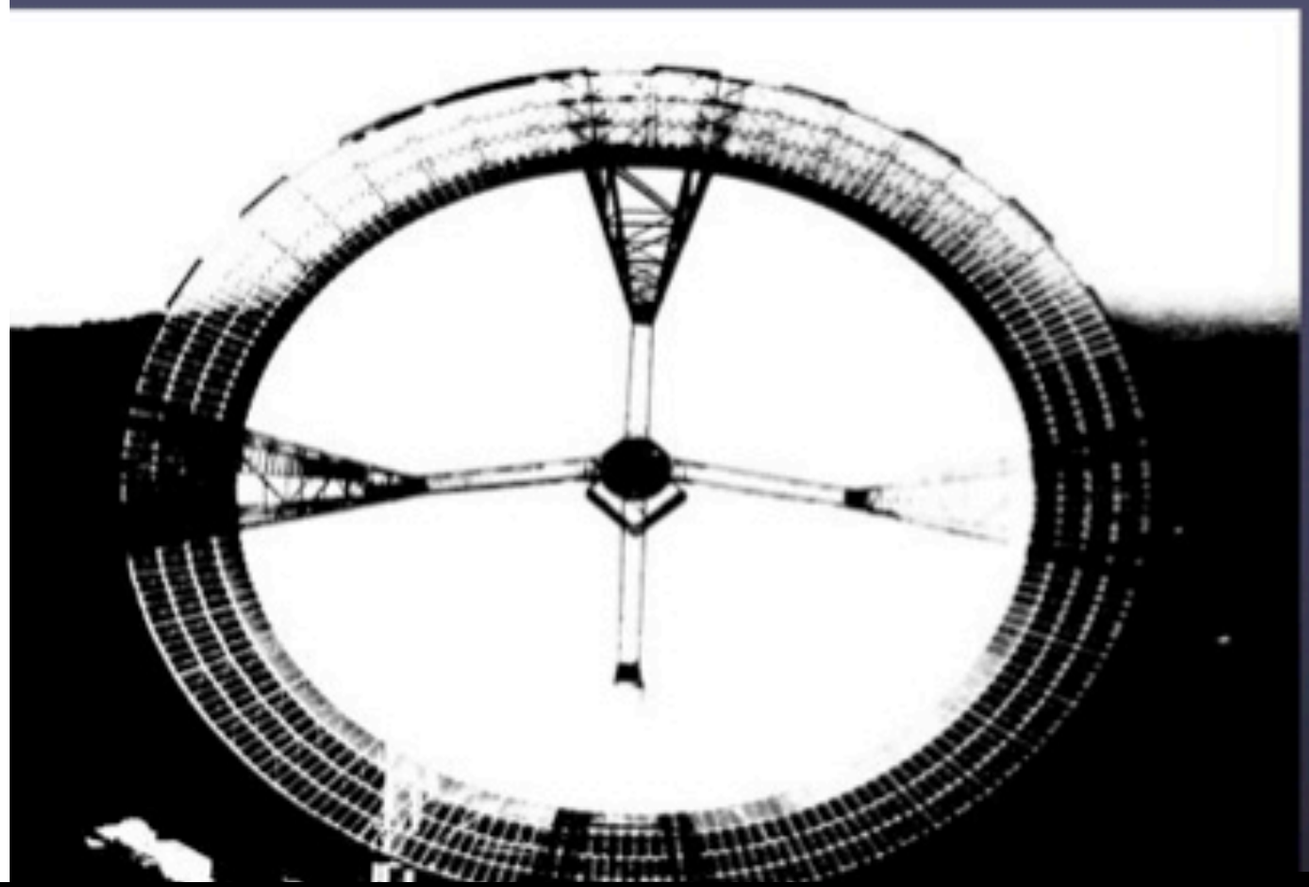

90
60
30
0
−30
−60
0
330
300
270
240
210
180
150
120
90
60
30
M
K
C
L
WA
A
C
D
R
H
WD
WB
WC
G
Anti−Center
GCP
GCN
WE
LMC
Magellanic Stream
−350
−300
−250
−200
−150
−100
−50
0
50
100
150
200
250
v_{DEV} [km/s]

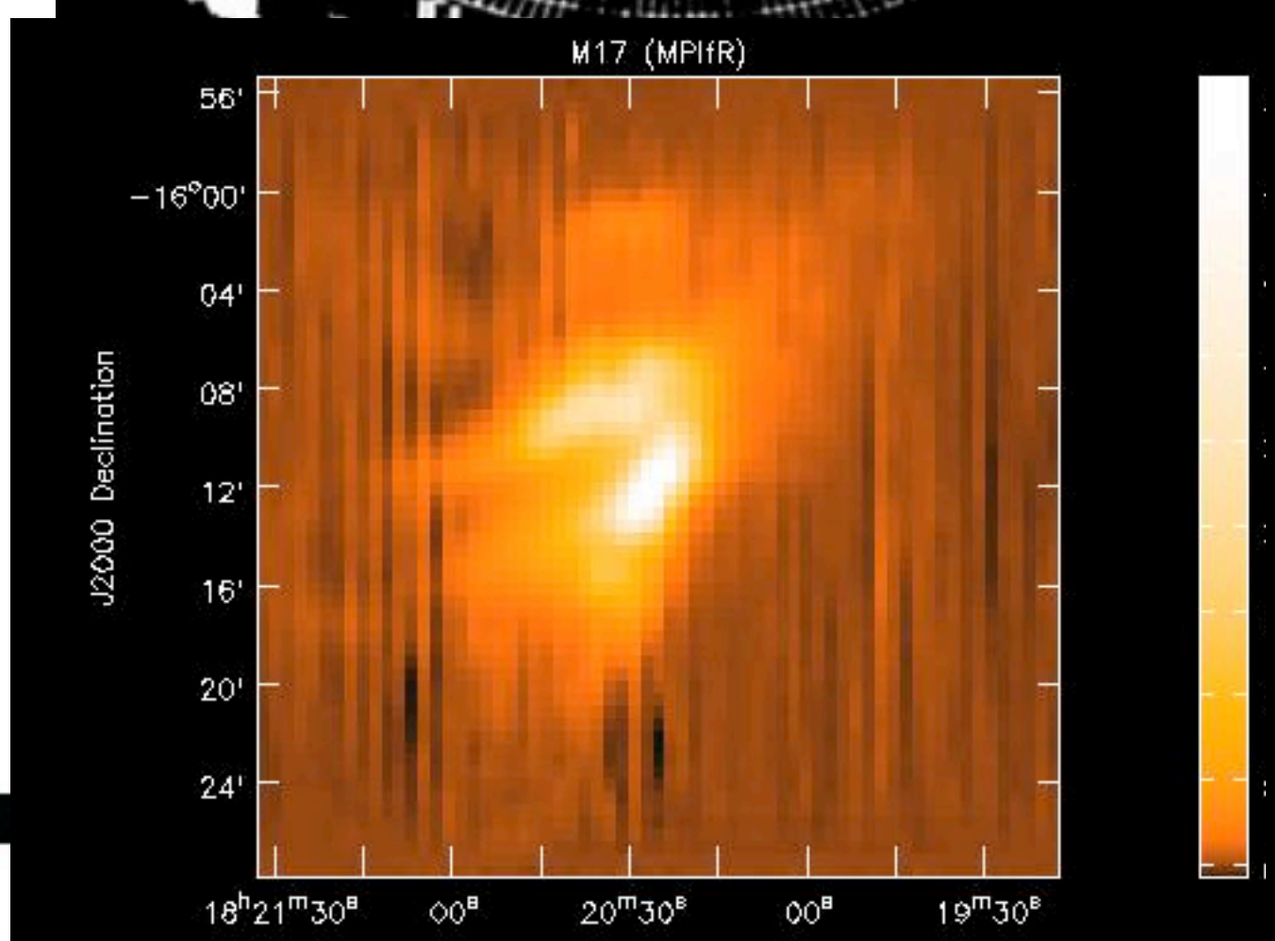

LD HI V 70 -> 130 2Jan08
Hydrogen image of the inner Milky Way
The Smith Cloud
5°
0°
−5°
−10°
−15°
−20°
GALACTIC Latitude
15°
10°
5°
0°
−5°
50°
45°
40°
35°
30°
25°
20°
15°
GALACTIC Longitude

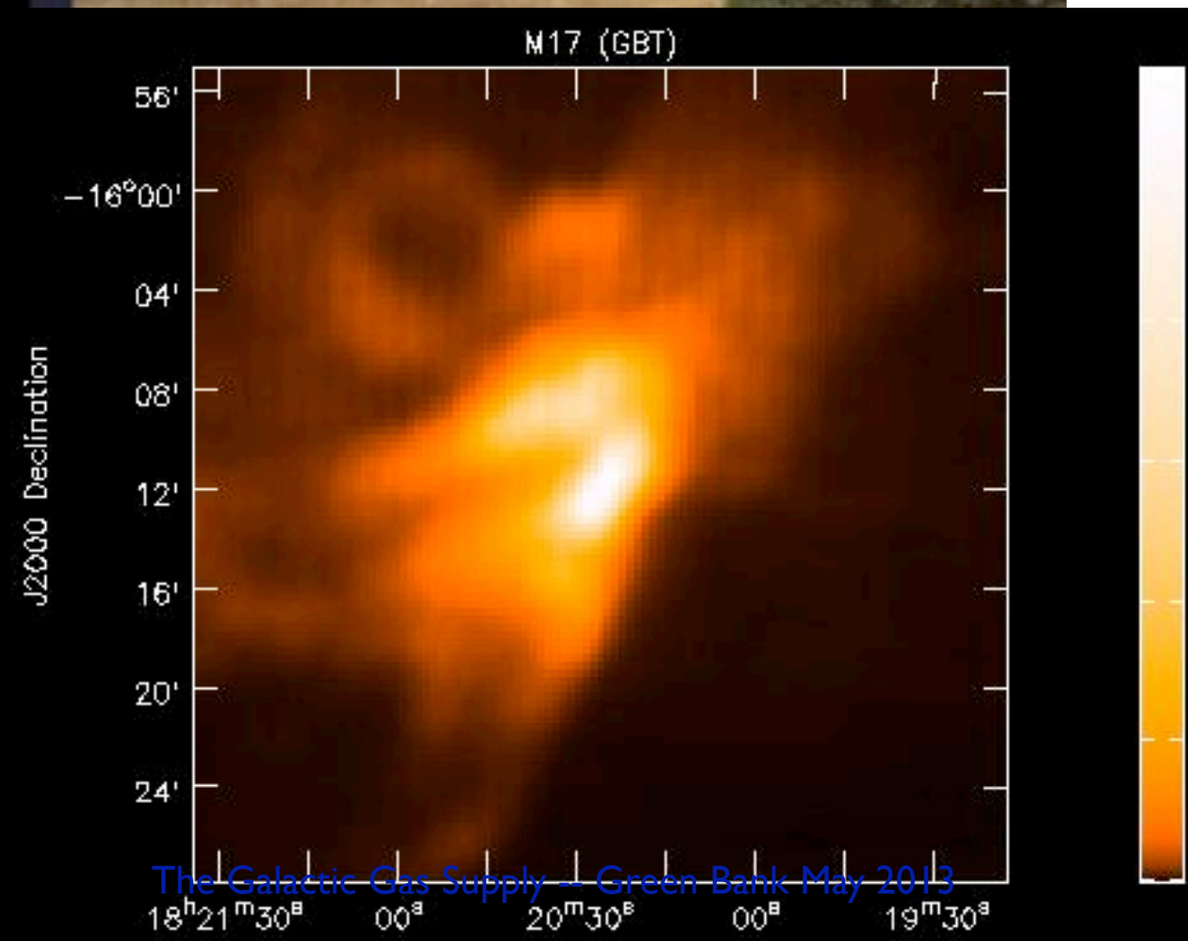
Unblocked Optics for High Dynamic Range



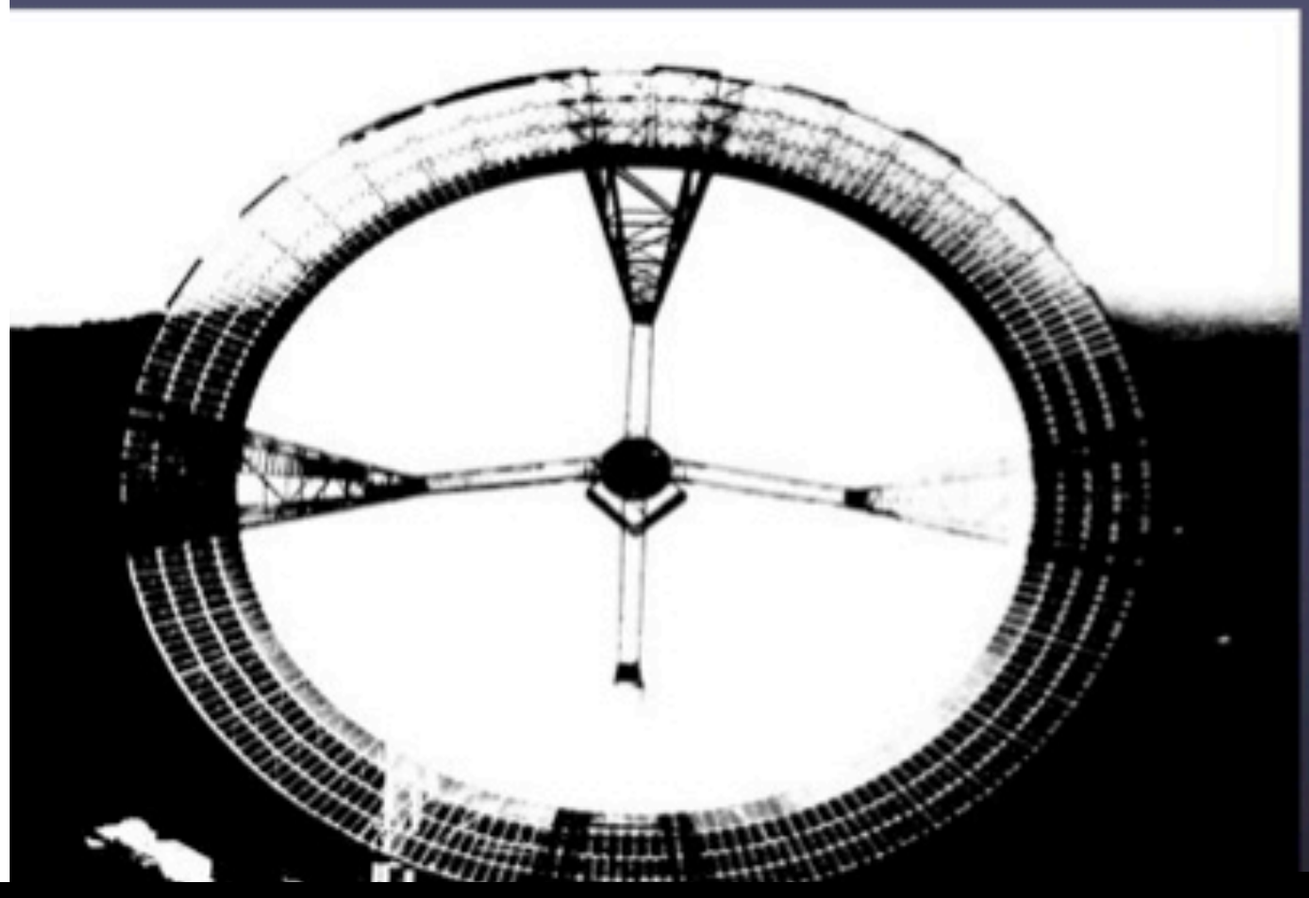
Unblocked Optics for High Dynamic Range

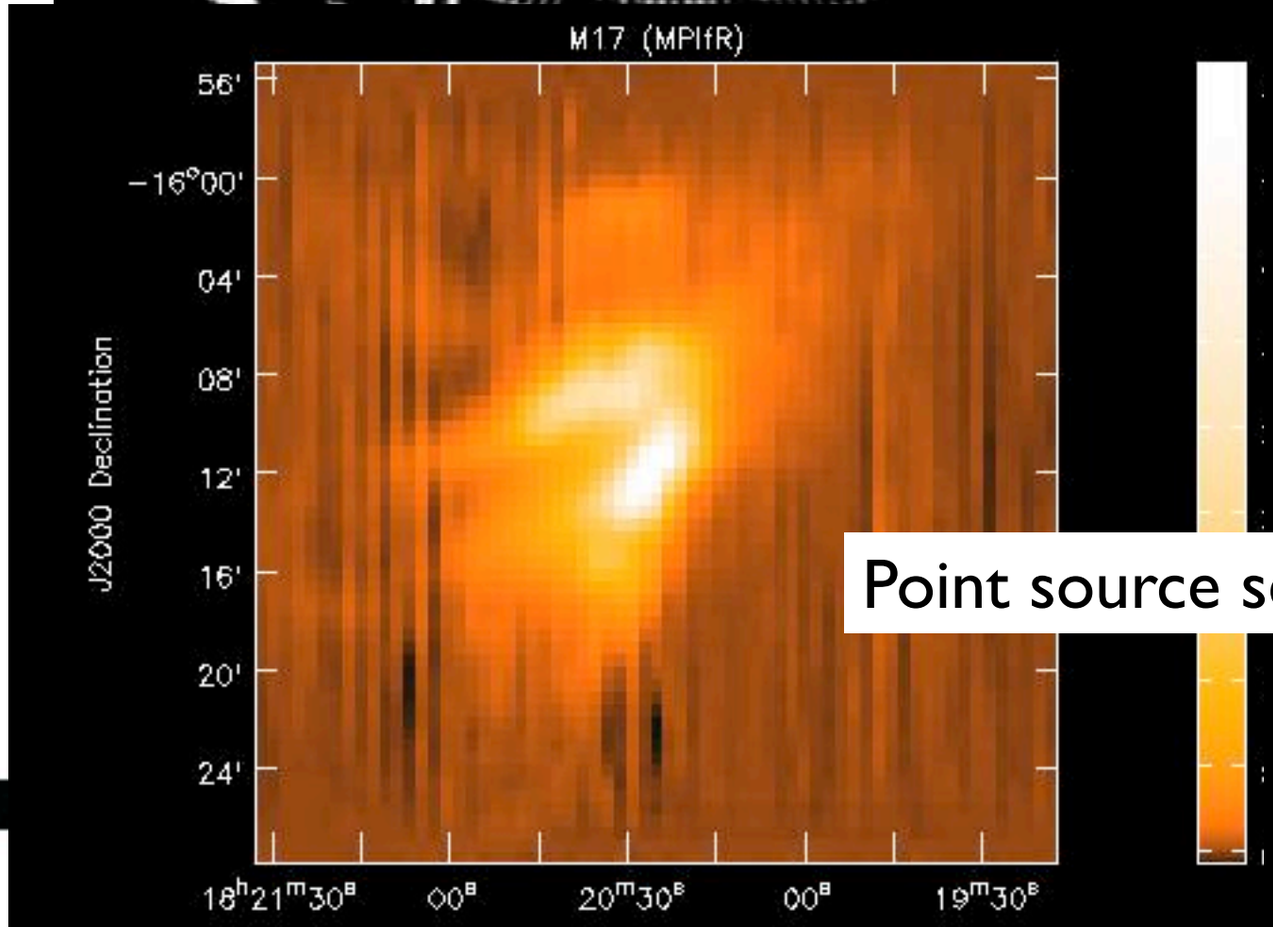


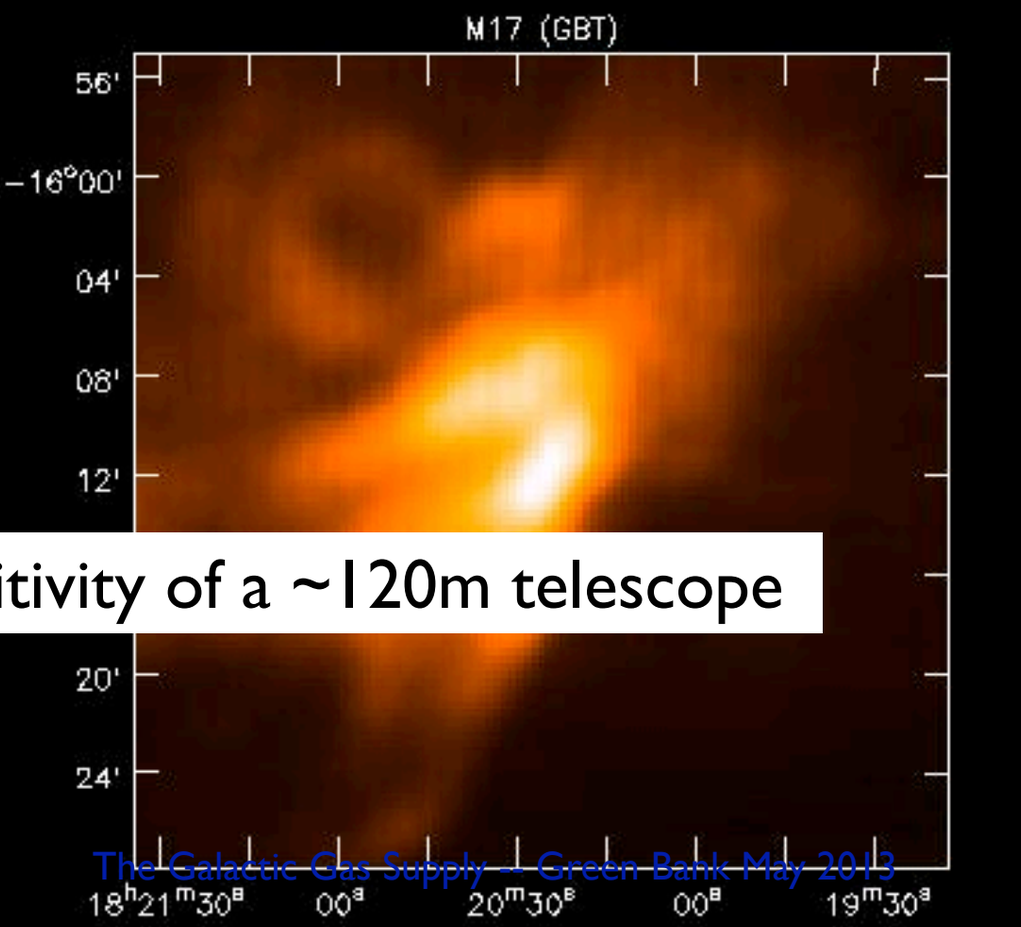




Unblocked Optics for High Dynamic Range





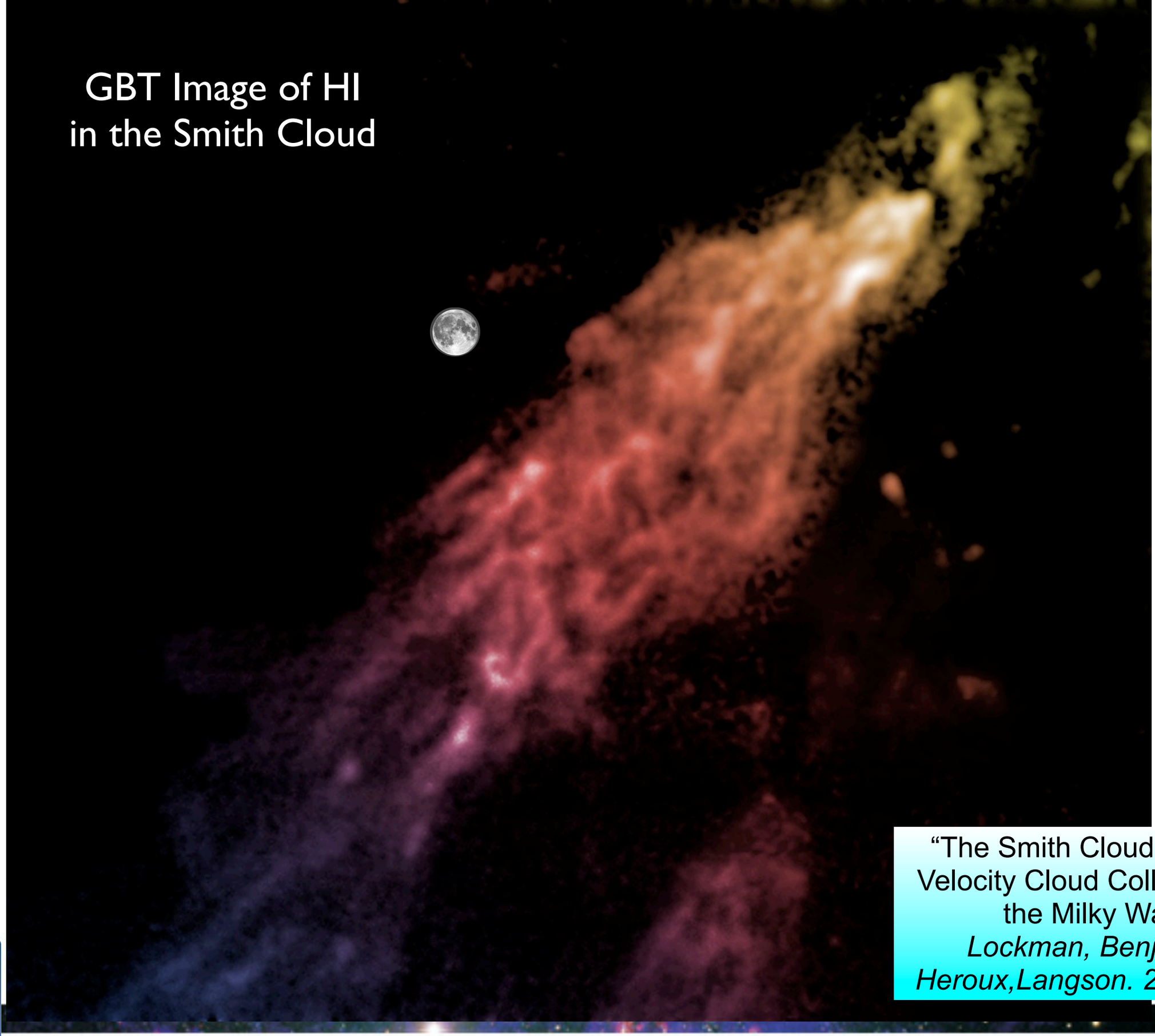


Point source sensitivity of a ~120m telescope

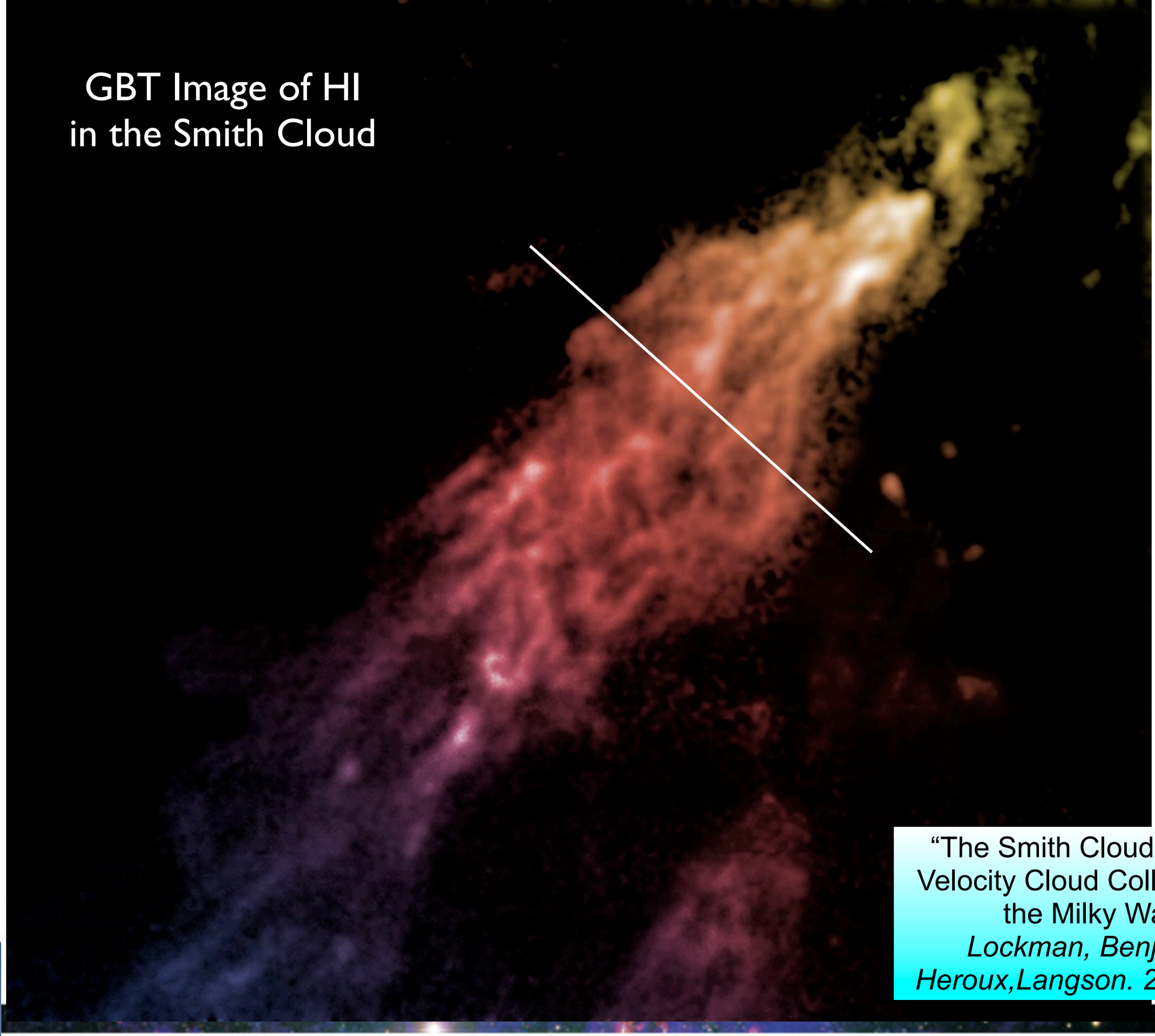
The Smith Cloud

GBT Image of HI
in the Smith Cloud

GBT Image of HI in the Smith Cloud



"The Smith Cloud: A High-Velocity Cloud Colliding with the Milky Way"
Lockman, Benjamin, Heroux,Langson. 2008 ApJL



"The Smith Cloud: A High-Velocity Cloud Colliding with the Milky Way"
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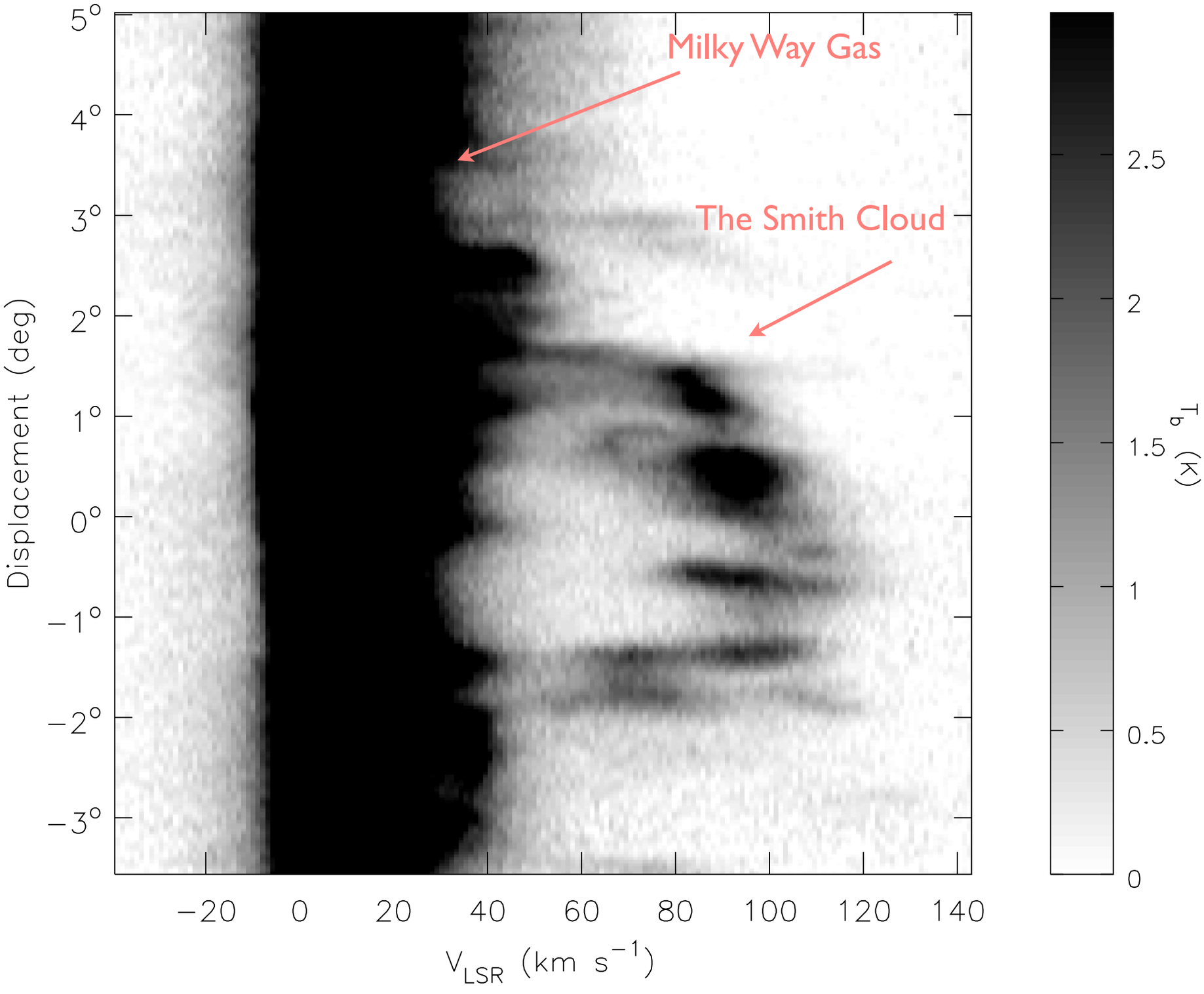
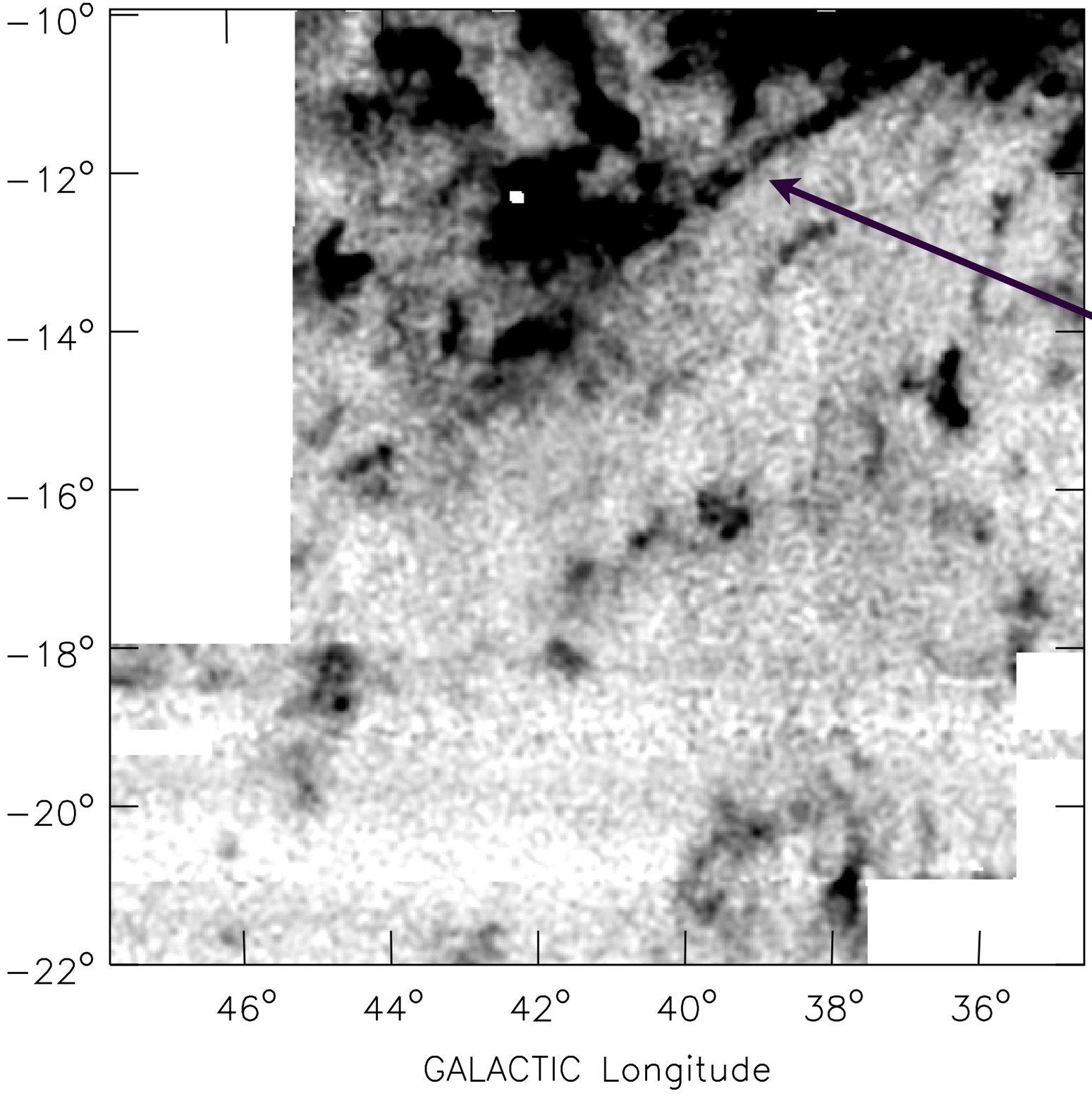
Interaction with the Milky Way

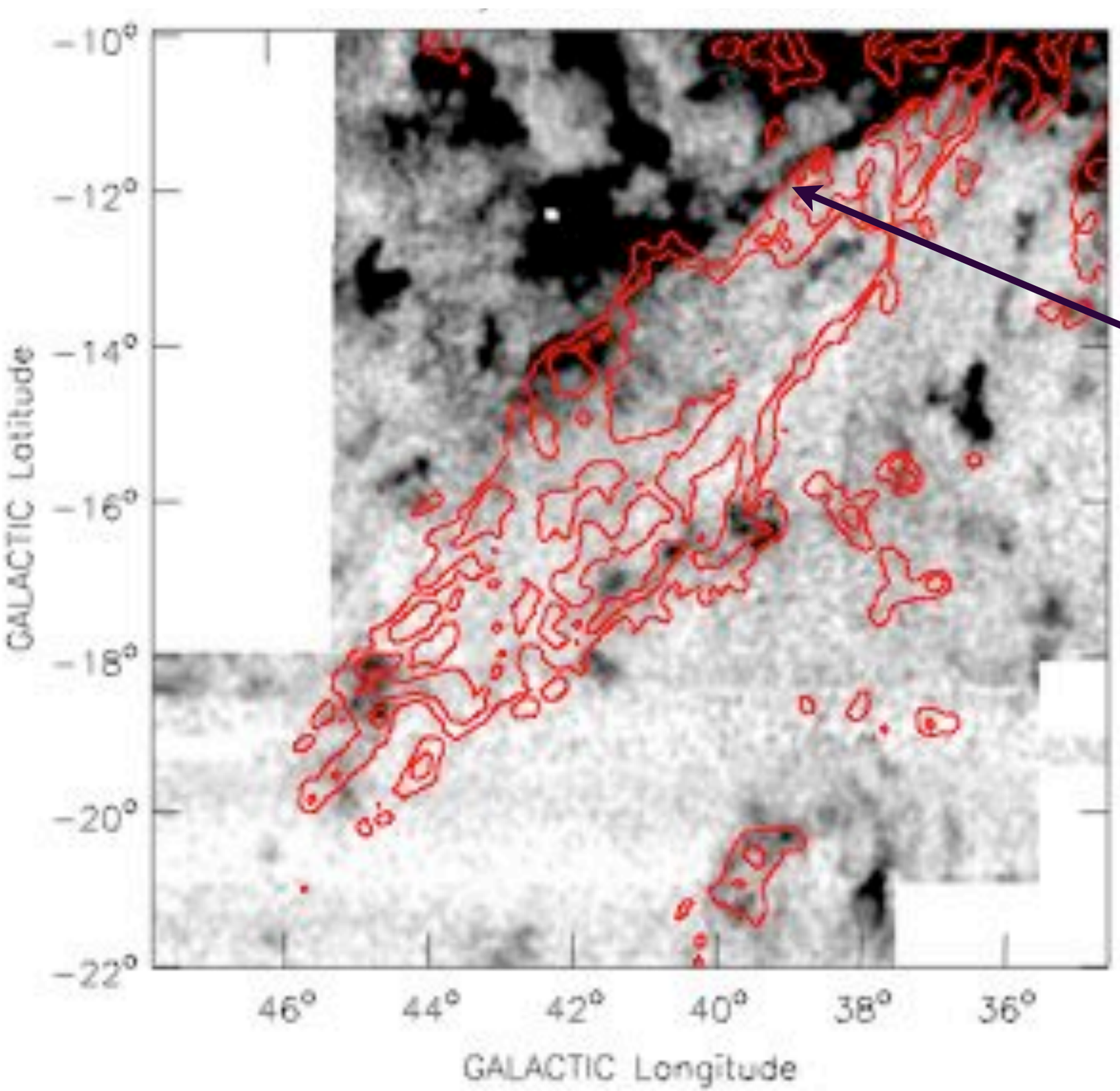


The Interaction of the Smith Cloud with the Galactic Halo

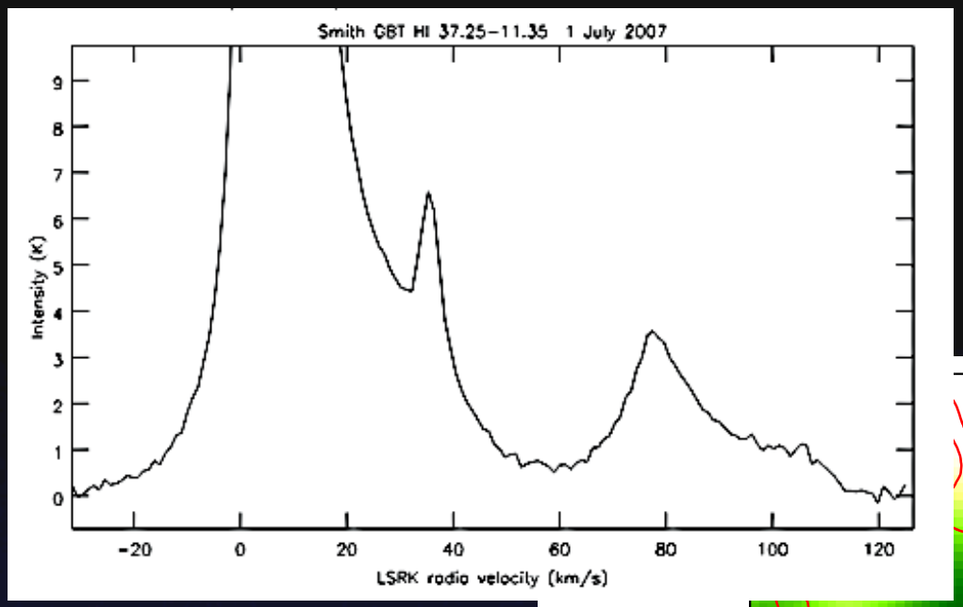


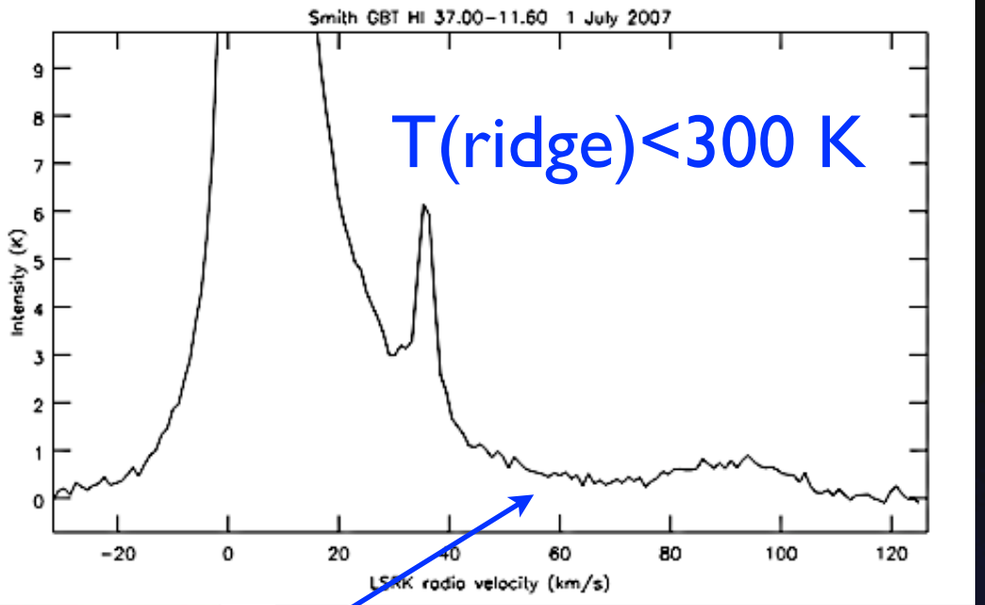
Low velocity ridge

The Interaction of the Smith Cloud with the Galactic Halo

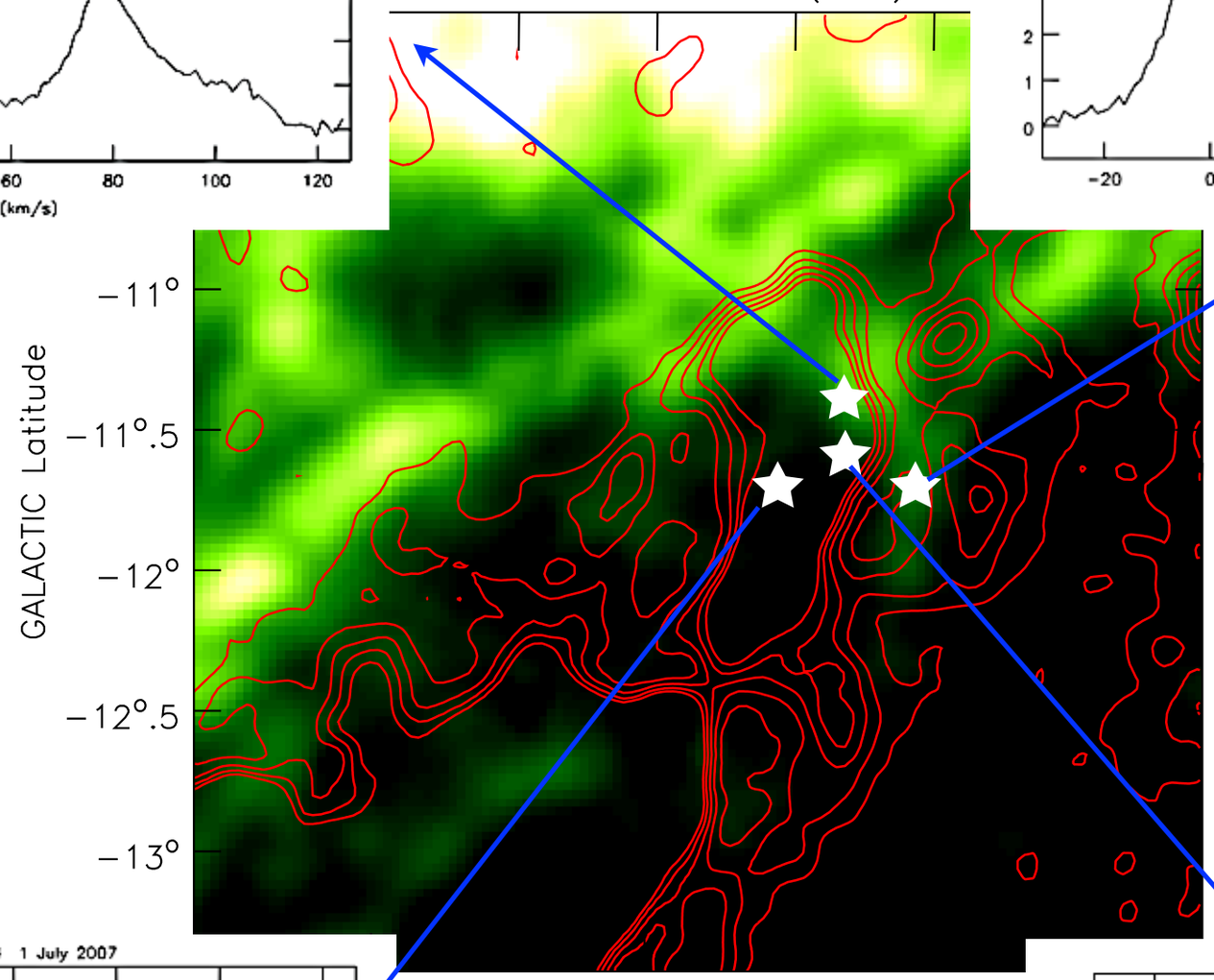


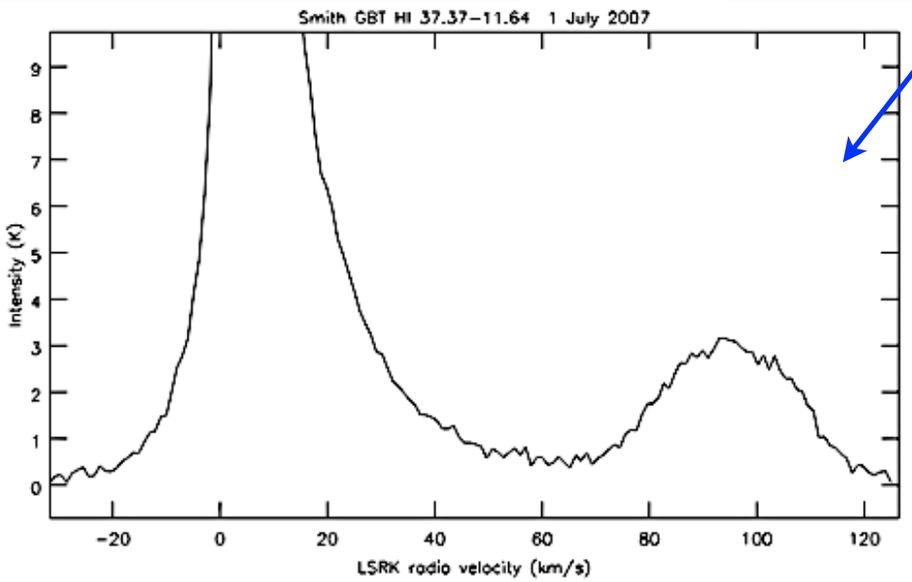
Low velocity ridge

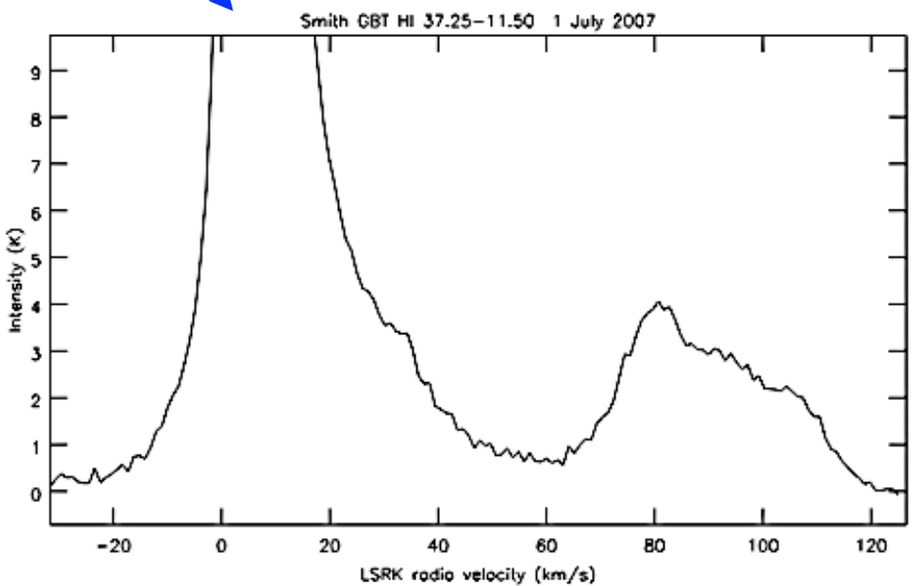

Smith GBT HI 37.25−11.35 1 July 2007
Intensity (K)
LSRK radio velocity (km/s)


Smith GBT HI 37.00−11.60 1 July 2007
Intensity (K)
LSRK radio velocity (km/s)

T(ridge)<300 K


−11°
−11°.5
−12°
−12°.5
−13°
GALACTIC Latitude
38°.5
38°
37°.5
37°
GALACTIC Longitude


Smith GBT HI 37.37−11.64 1 July 2007
Intensity (K)
LSRK radio velocity (km/s)


Smith GBT HI 37.25−11.50 1 July 2007
Intensity (K)
LSRK radio velocity (km/s)

The Distance to the Cloud

9.8 - 15.1 kpc -- Stellar Absorption Lines *Wakker et al 200*

11.1-13.7 kpc -- Kinematic distance to non-interacting HI
Lockman, Benjamin, et al. 2008

13.0 (or 1.2) kpc -- Hα flux and model for the Galaxy's UV
Bland-Hawthorn et al 1998;
Putman, Bland-Hawthorn et al 2003

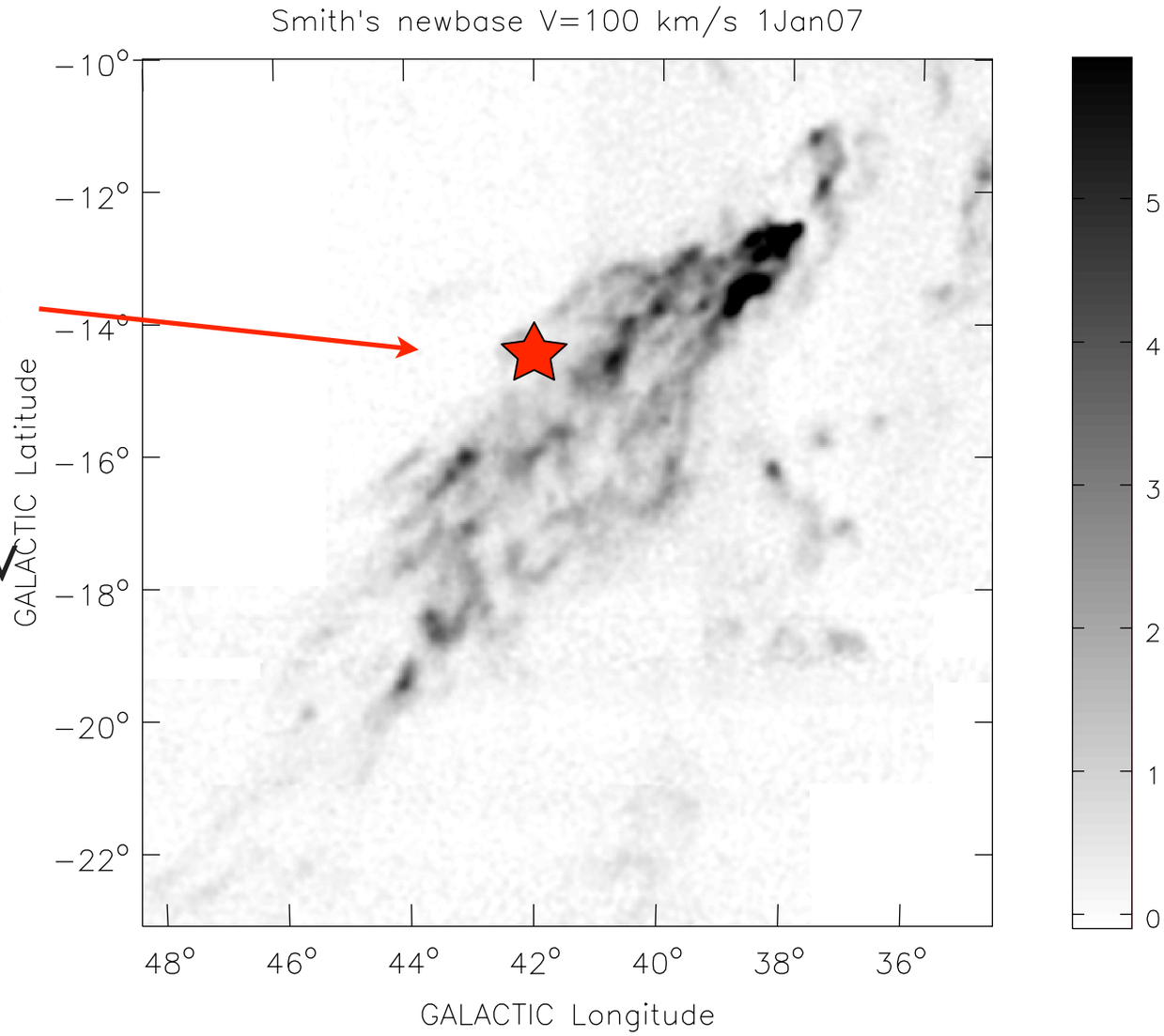
dist = 12.4 ± 1.3 kpc

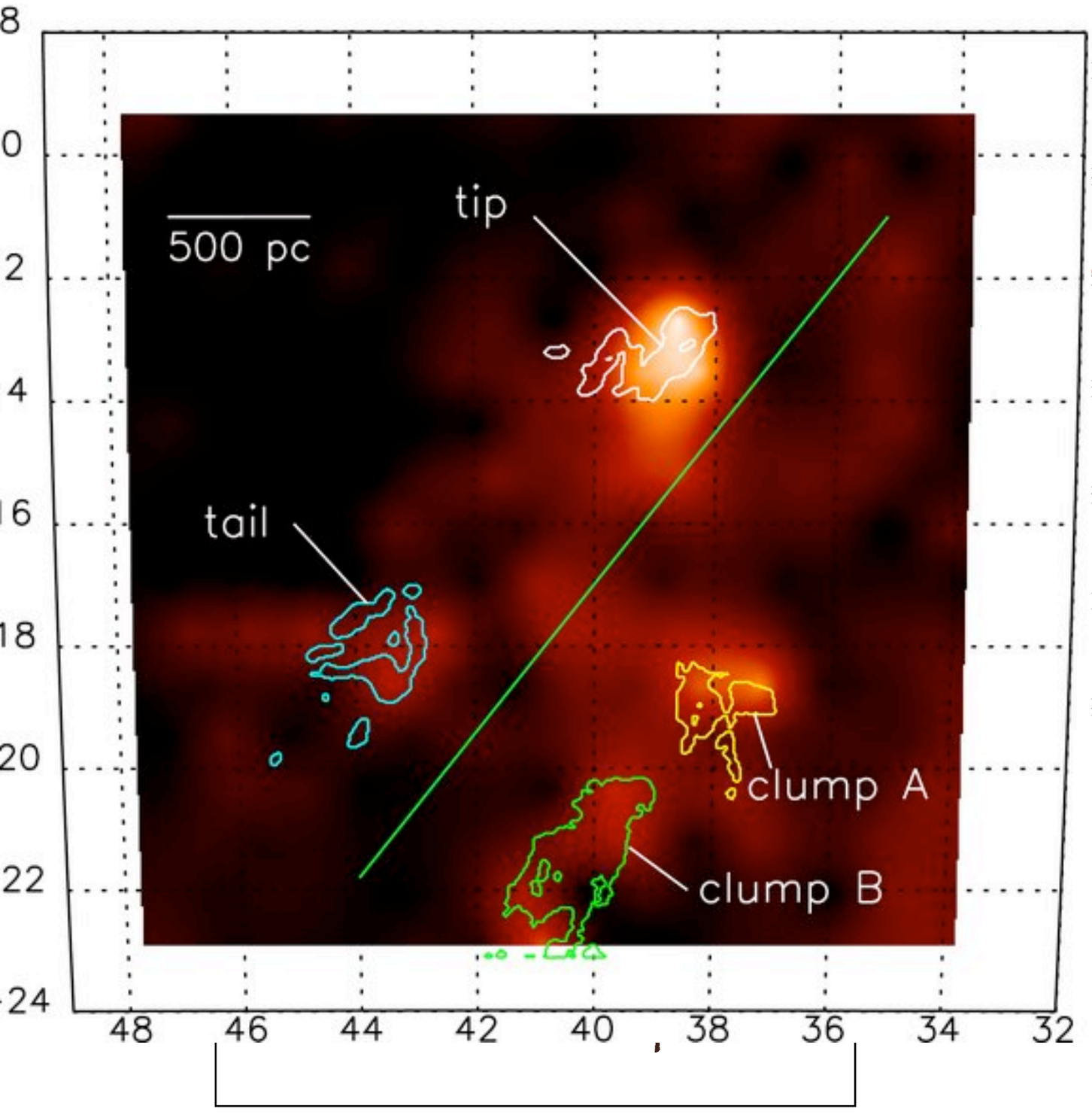
R_{gal} = 7.6 ± 1.0 kpc

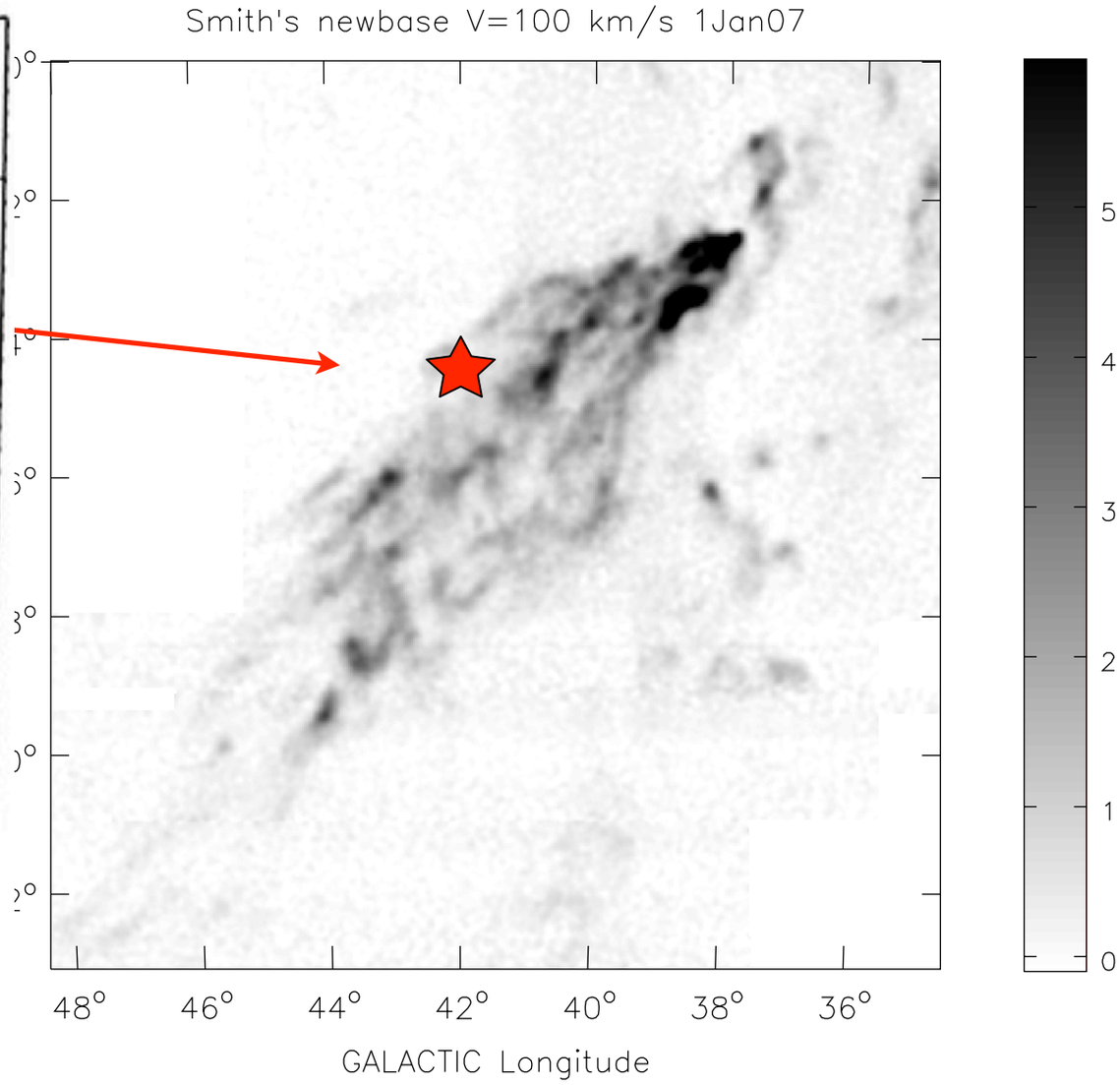
z = -2.2 kpc

$M_{HI} \geq 10^6 M_\odot$

size ≈ 3 x 1 kpc







Hill et al 2009 measured

Hα, [N II], [S II], [O III]

Hα ~ 0.4 R

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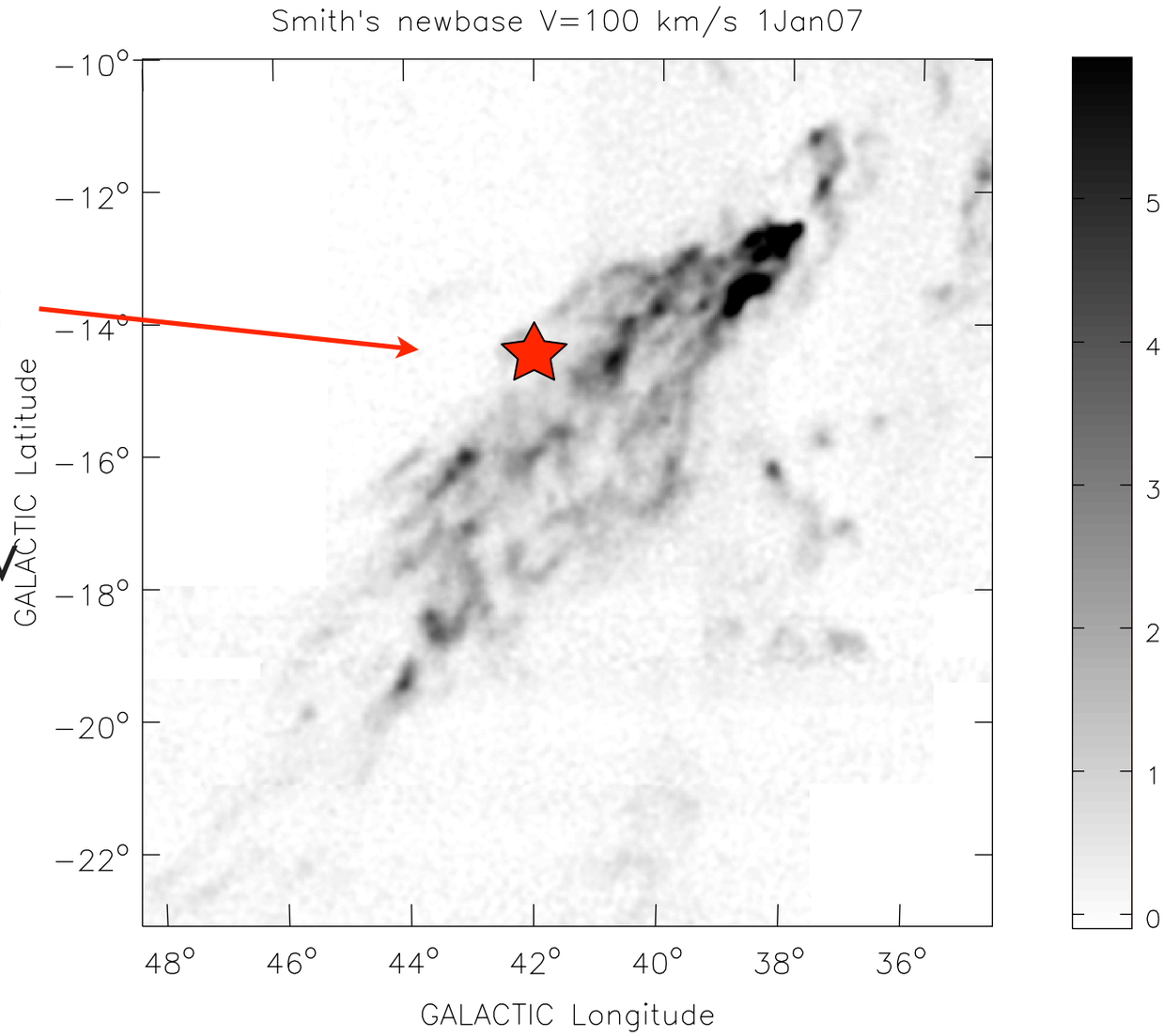


Hill et al 2009 measured
Hα, [N II], [S II], [O III]
Hα ~ 0.4 R

The Smith Cloud

dist = 12.4 ± 1.3 kpc

R = 7.6 ± 1.0 kpc

z = -2.2 kpc

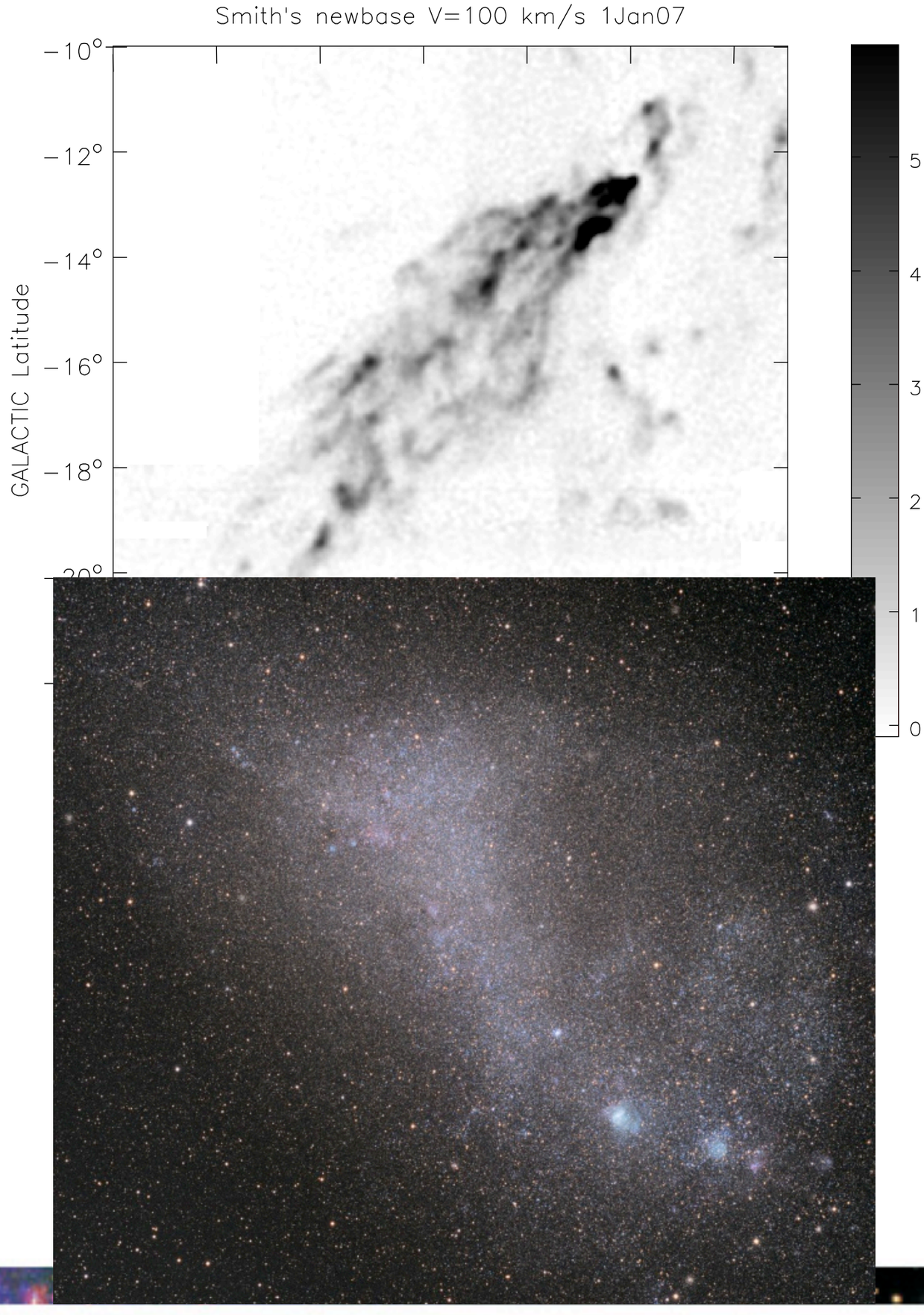
$M_{HI} \geq 10^6\ M_\odot$

$M_{H+} > 10^6\ M_\odot$

size ≈ 3 x 1 kpc

[N\H] = 0.14 - 0.44

Is the Smith Cloud a dwarf galaxy, like the SMC?



The Smith Cloud

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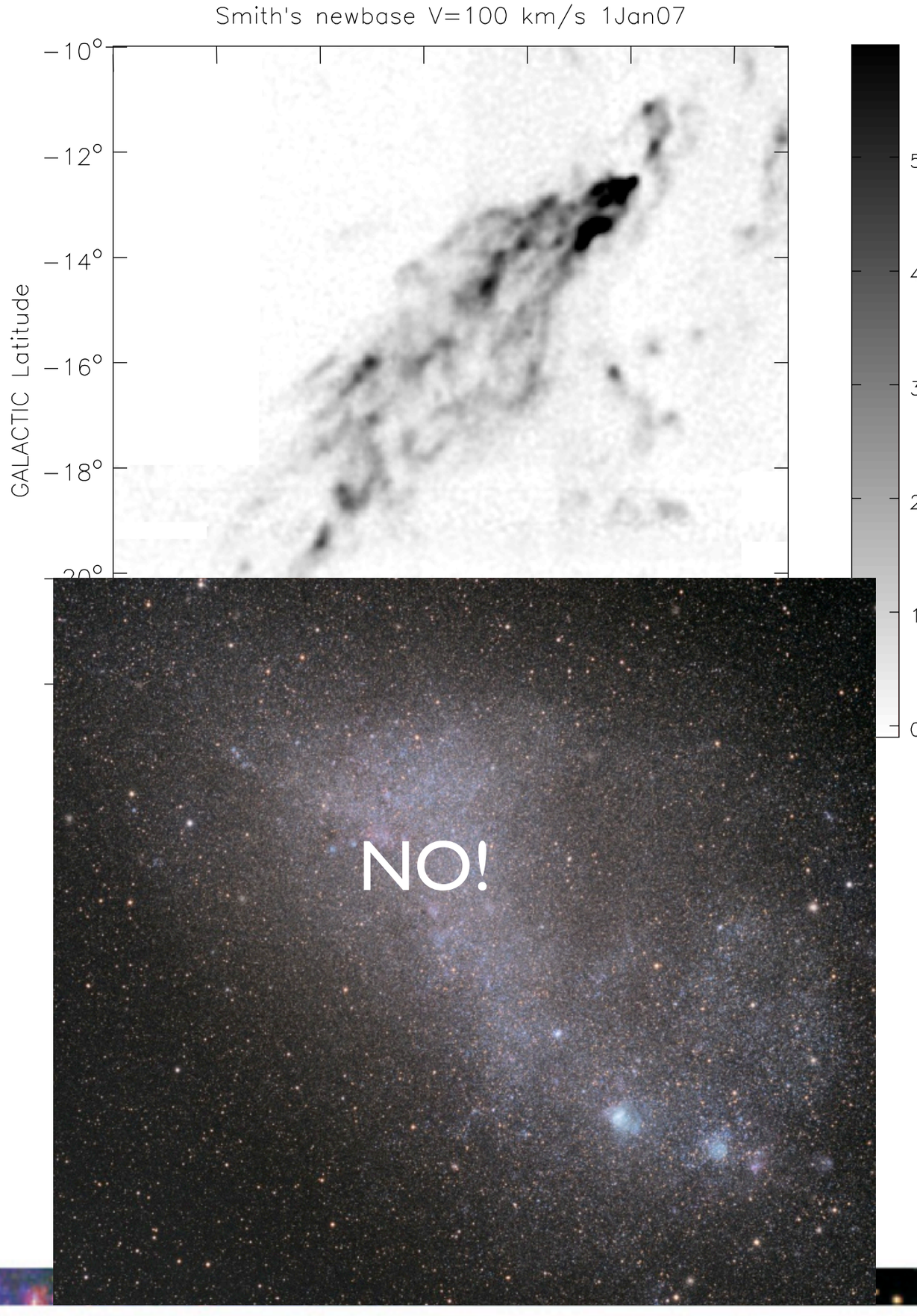
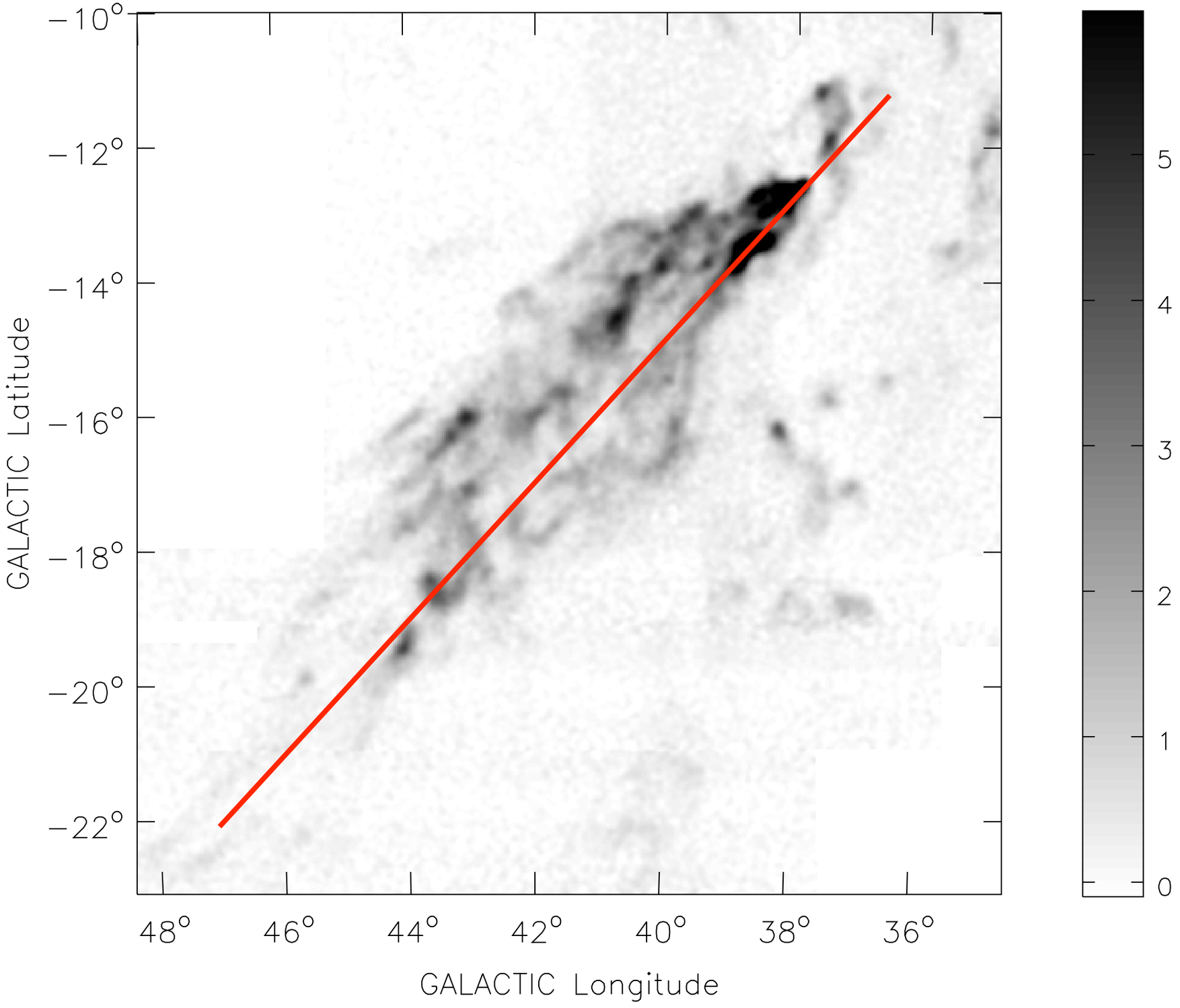
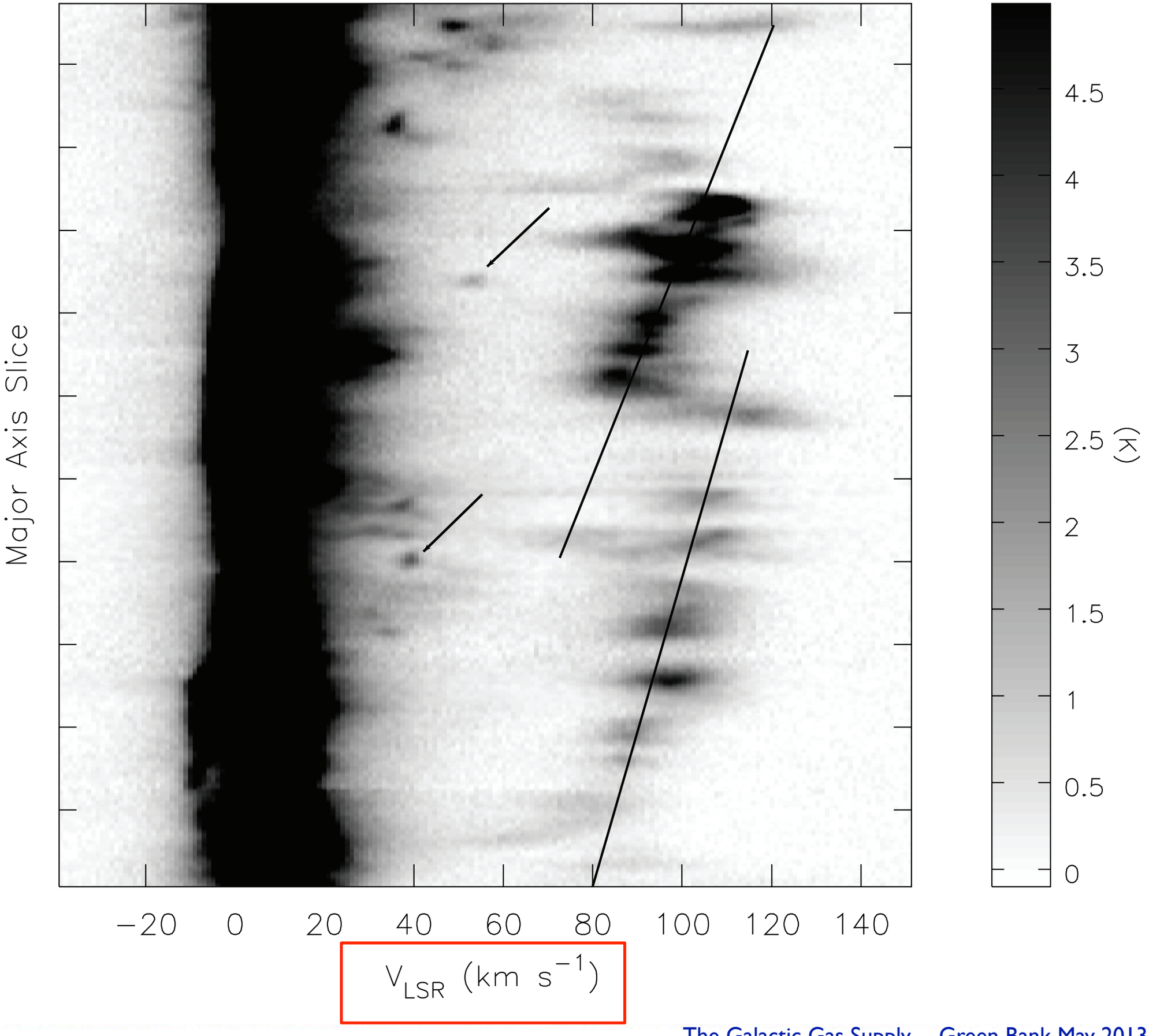



−10°
−12°
−14°
−16°
−18°
−20°
−22°
GALACTIC Latitude
48°
46°
44°
42°
40°
38°
36°
GALACTIC Longitude
5
4
3
2
1
0


Major Axis Slice
−20
0
20
40
60
80
100
120
140
V_{LSR} (km s^{-1})
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
(K)

$$V_{LSR} = \left[R_0 sin(\ell) \{ \frac{V_\theta}{R} - \frac{V_0}{R_0} \} - V_R \cos(\ell + \theta) \right] \cos(b) + V_z sin(b)$$

$$V_{LSR} = \left[R_0 sin(\ell) \{ \frac{V_\theta}{R} - \frac{V_0}{R_0} \} - V_R \cos(\ell + \theta) \right] \cos(b) + V_z sin(b)$$

for the Smith Cloud we know all distances and angles,

V_{LSR} (ℓ ,b)

direction of motion (45°±10°)

d(ℓ)/dt and d(b)/dt

If Smith's Cloud is a coherent object, its 3-d space motion can be determined with no ambiguity.

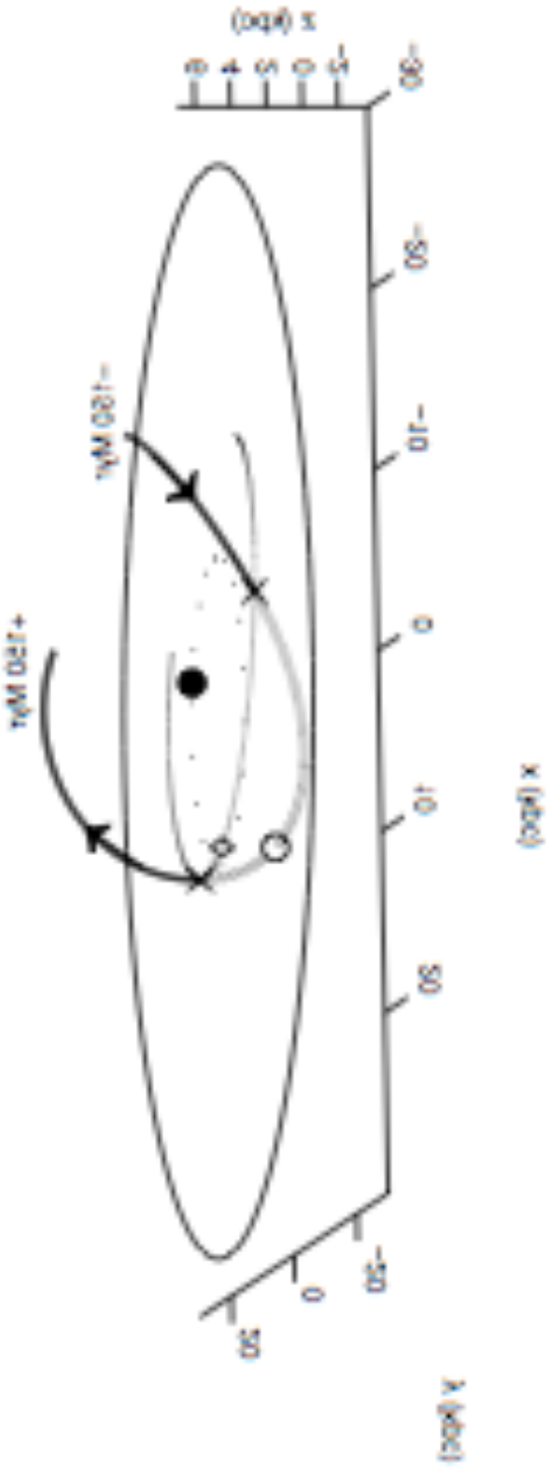
The picture in 2008

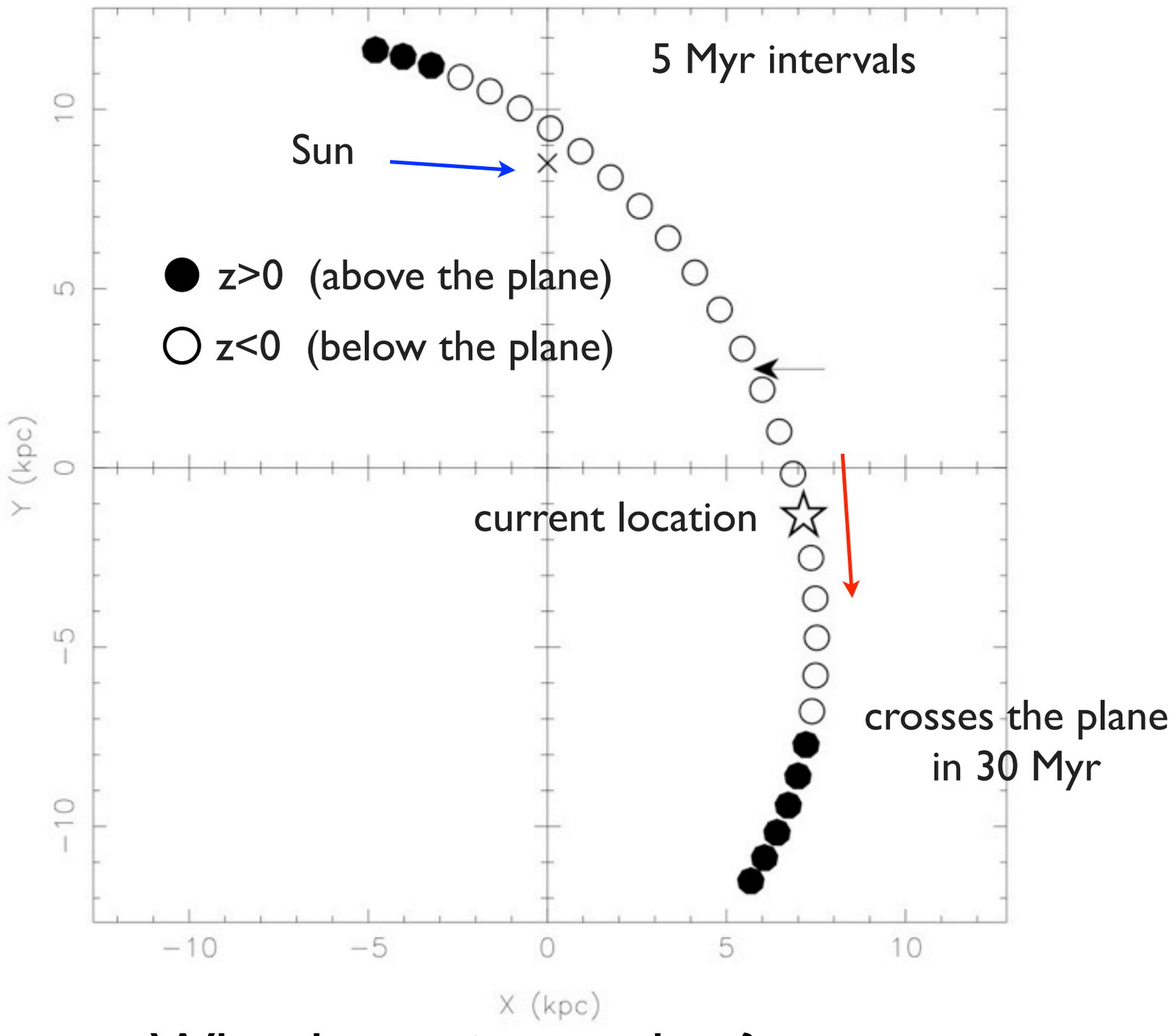
Table 2. Derived Kinematics of Smith's Cloud

Location	V_R	V_θ	V_z	V_{tot}	V_{ISM}
(1)	(2)	(3)	(4)	(5)	(6)
		V_0=220 km/s			
Tip	113 ± 21	264 ± 21	70 ± 25	296 ± 18	139 ± 10
Tail	129 ± 6	220 ± 11	8 ± 11	271 ± 6	130 ± 5
		$V_\theta \approx V_0$		Bound to the MW	

Note. — V_{ISM} is the total velocity of the cloud with respect to the corotating Galactic ISM at its location.

Smith Cloud Trajectory





What keeps it together?

"The Smith Cloud: High-Velocity Accretion and Dark Matter Confinement"

M. Nichols & J. Bland-Hawthorn 2009, ApJ

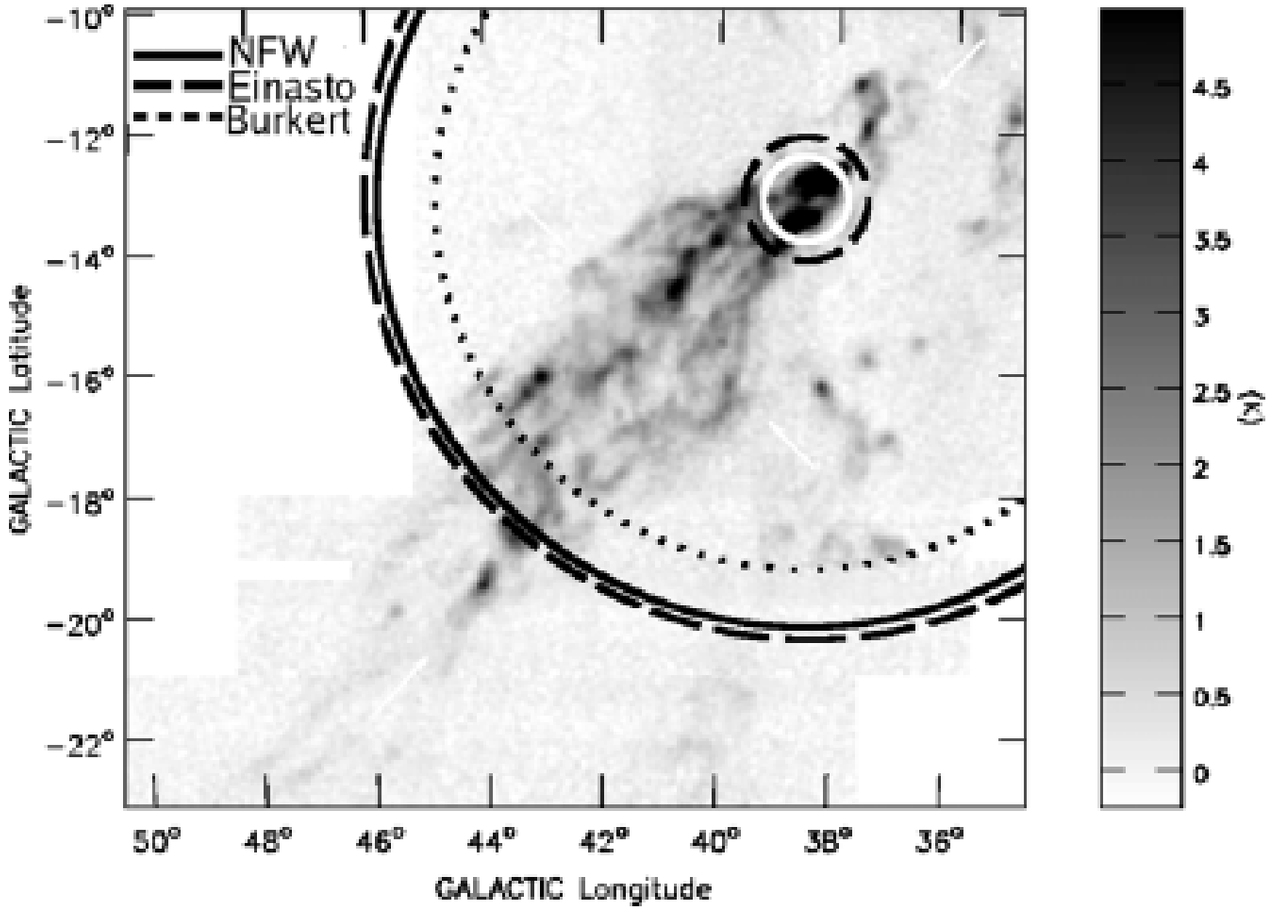
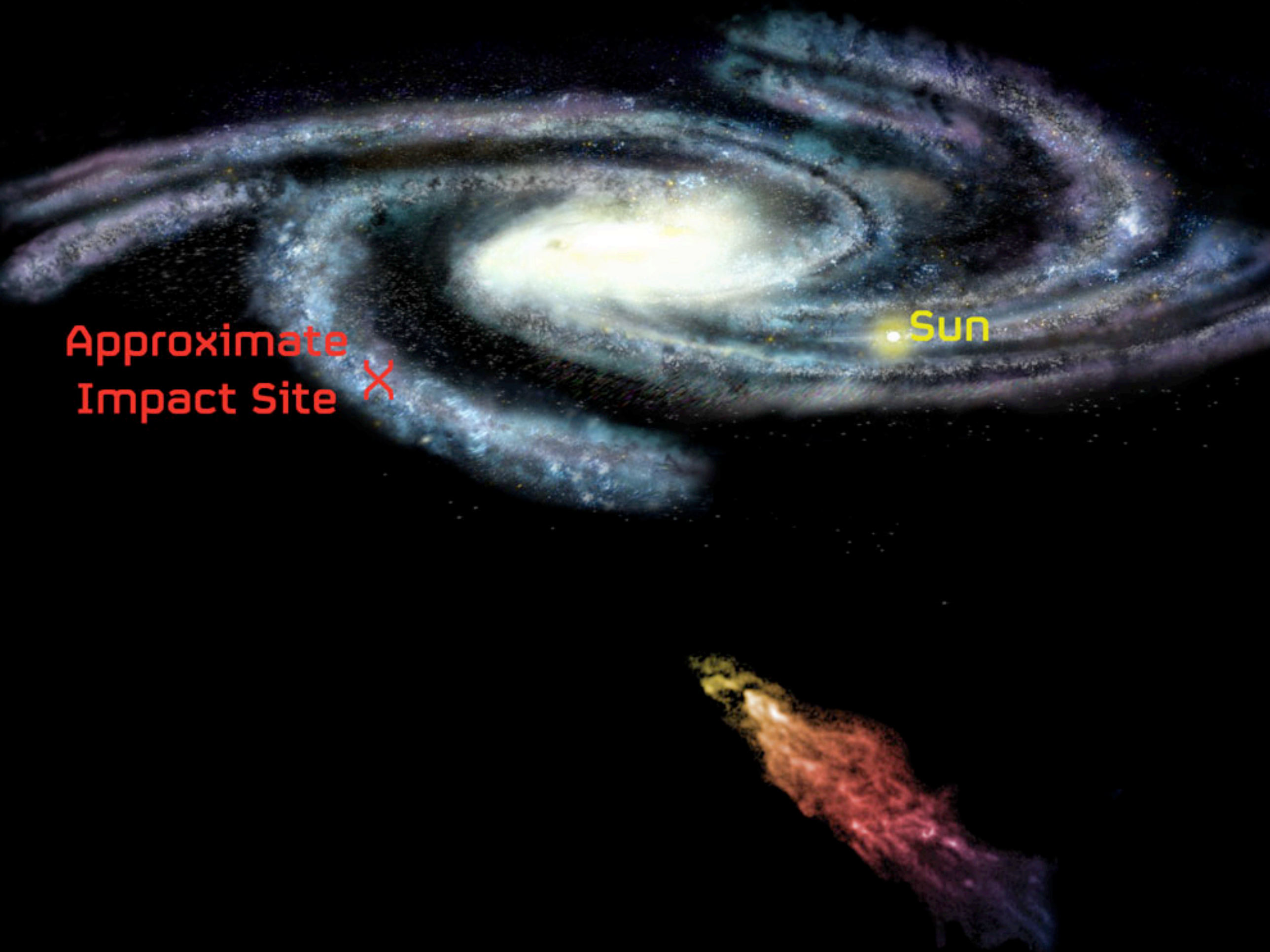
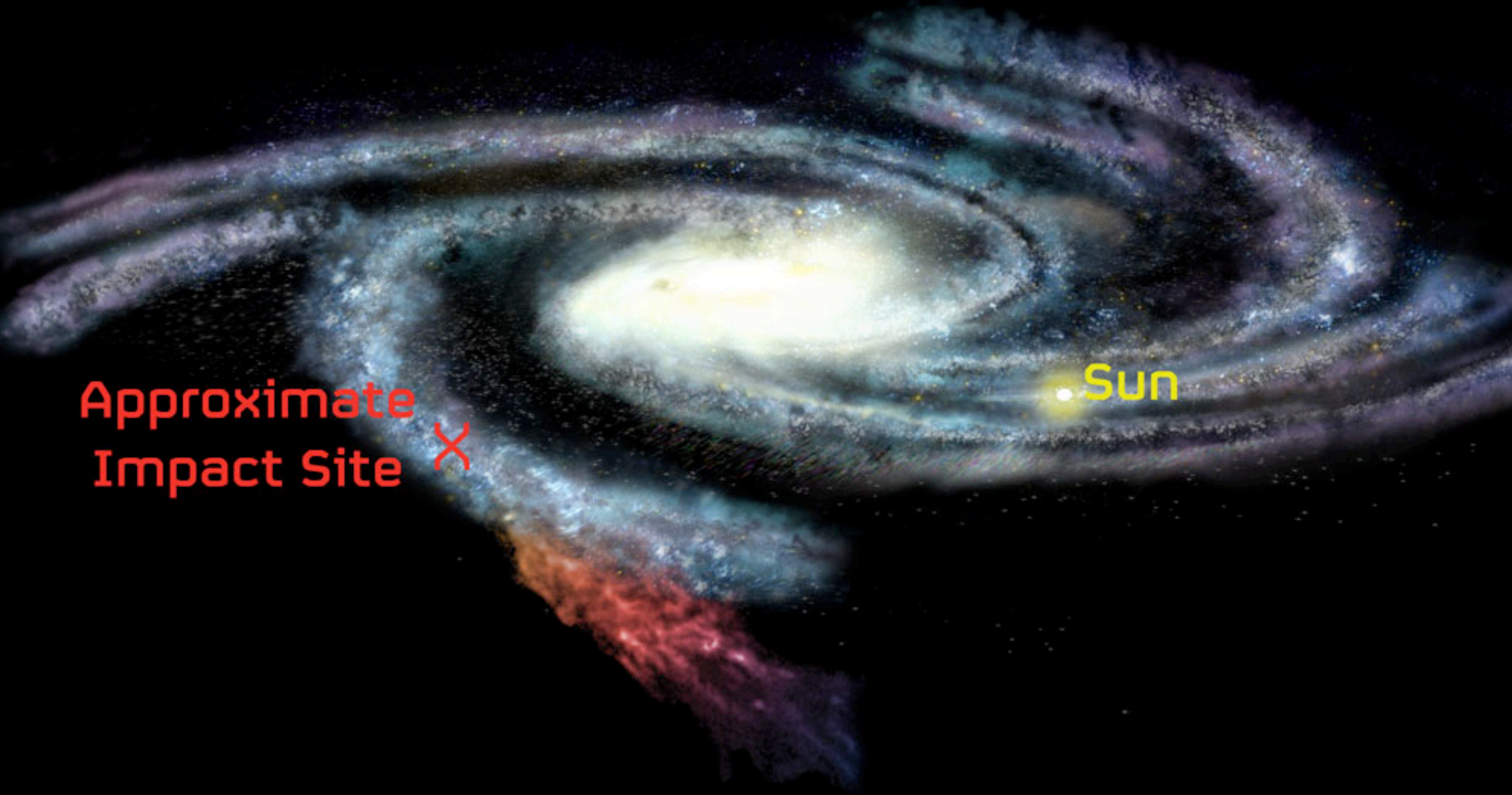


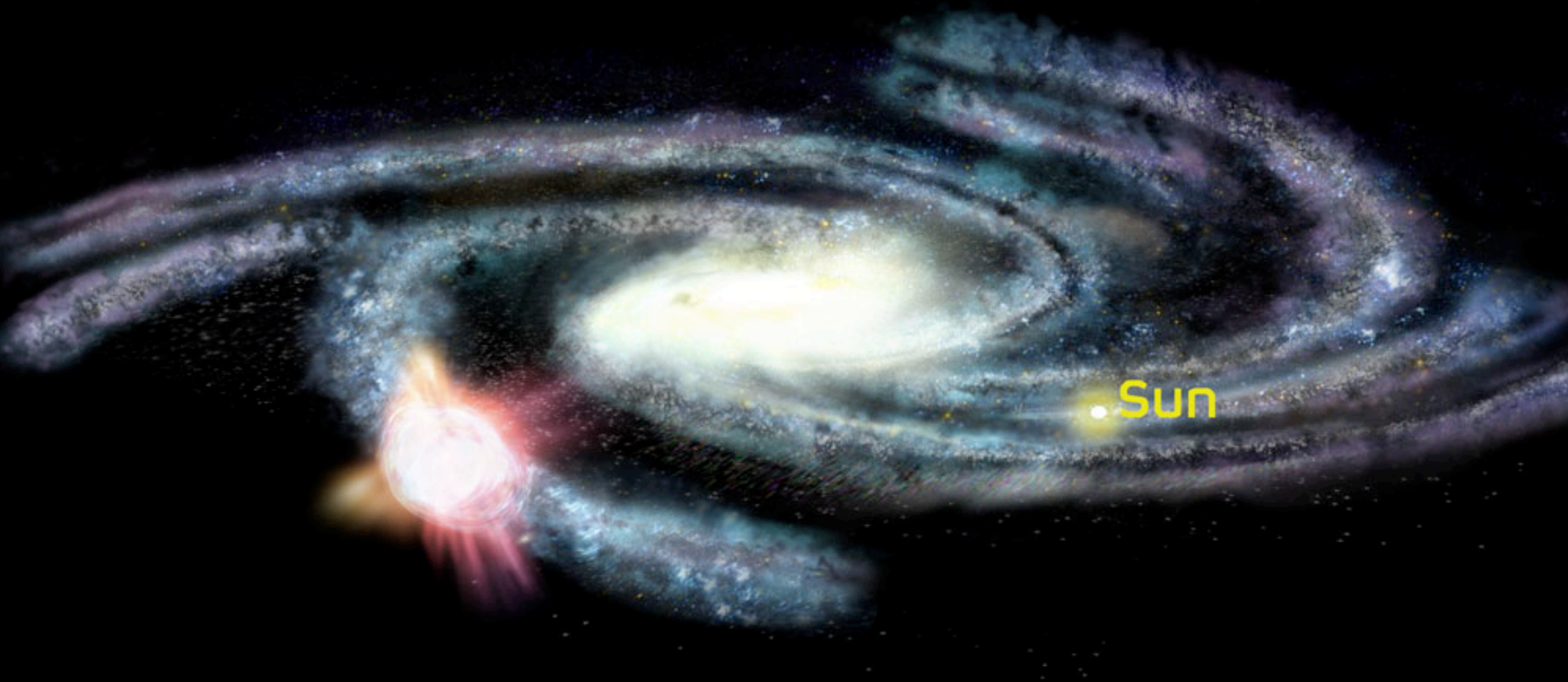
Figure 1. H I image of the Smith Cloud (Figure 1 in Lockman et al. 2008) with superimposed core and halo for three different dark matter models (NFW, Einasto, and Burkert) discussed further in Section 5. The tidally stripped mass today is (1–2) × 10^8 $M_\odot$ in dark matter. The core size assumes an initial gas mass at apogalacticon of 1.1 × 10^7 $M_\odot$, although most of this gas is distributed along the orbit of the Smith Cloud today. We note that the Burkert profile has no surviving core, and the NFW core is displayed in white for visibility.

The Nichols & Bland-Hawthorn Model

- A dark matter "subhalo"
- Initial dark matter ~3x10^8 M⊙
- Initial gas mass ~10^7 M⊙
- Current dark matter ~2x10^8 M⊙
- Current gas mass ~3x10^6 M⊙


Approximate
Impact Site
Sun


Approximate
Impact Site
Sun



30 Million Years from Now

New for 2013

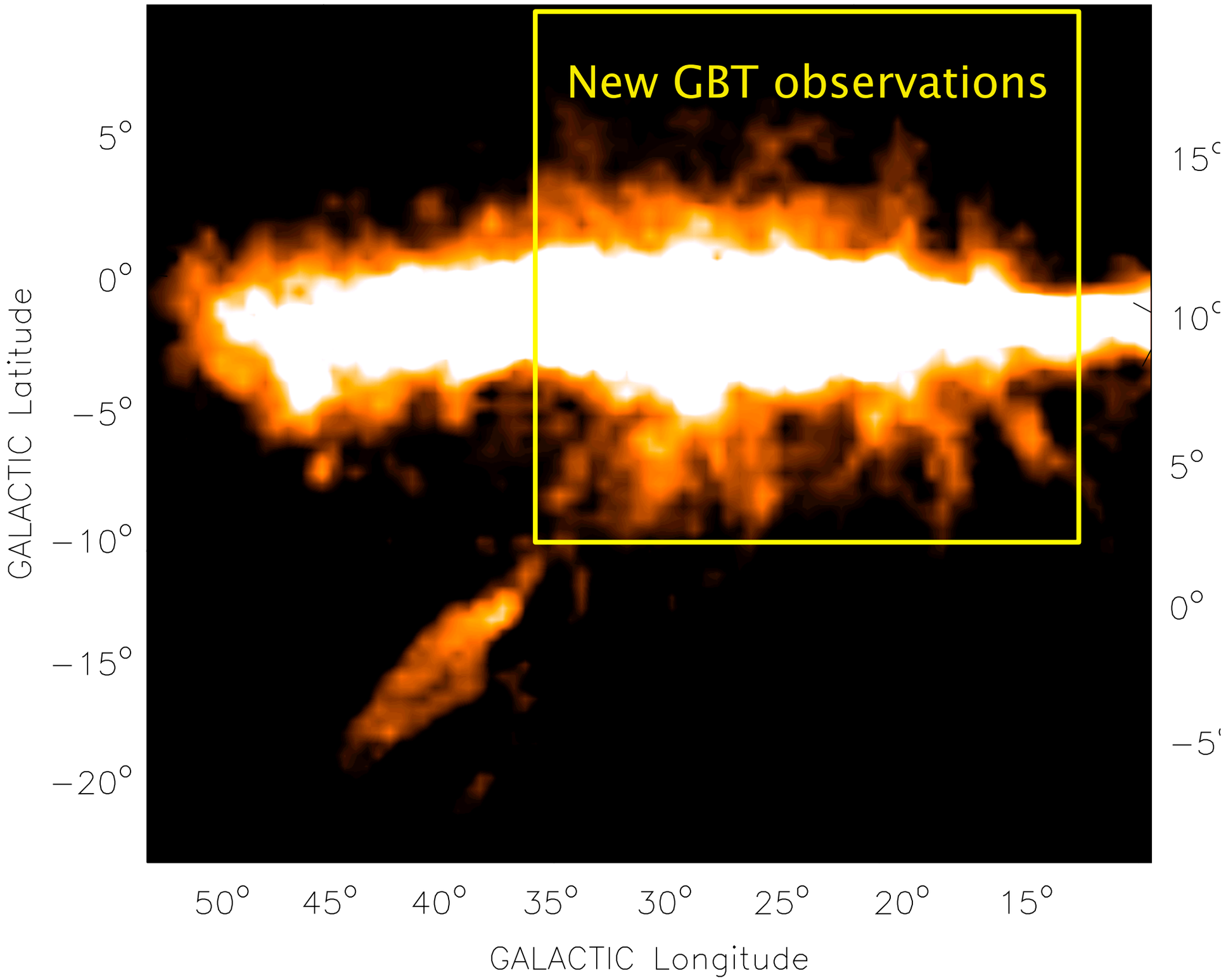
* GBT Observations of the HI 'ahead' of the Smith Cloud

* A New GBT map of the Cloud

* HST Observations?

* Faraday Rotation

Low Resolution HI -- Smith Cloud and Galactic Plane



GBT VLSR Cut 27Oct2010

102.932 km/s

10°
5°
0°
−5°
−10°

GALACTIC Latitude

40°
35°
30°
25°
20°
15°

GALACTIC Longitude

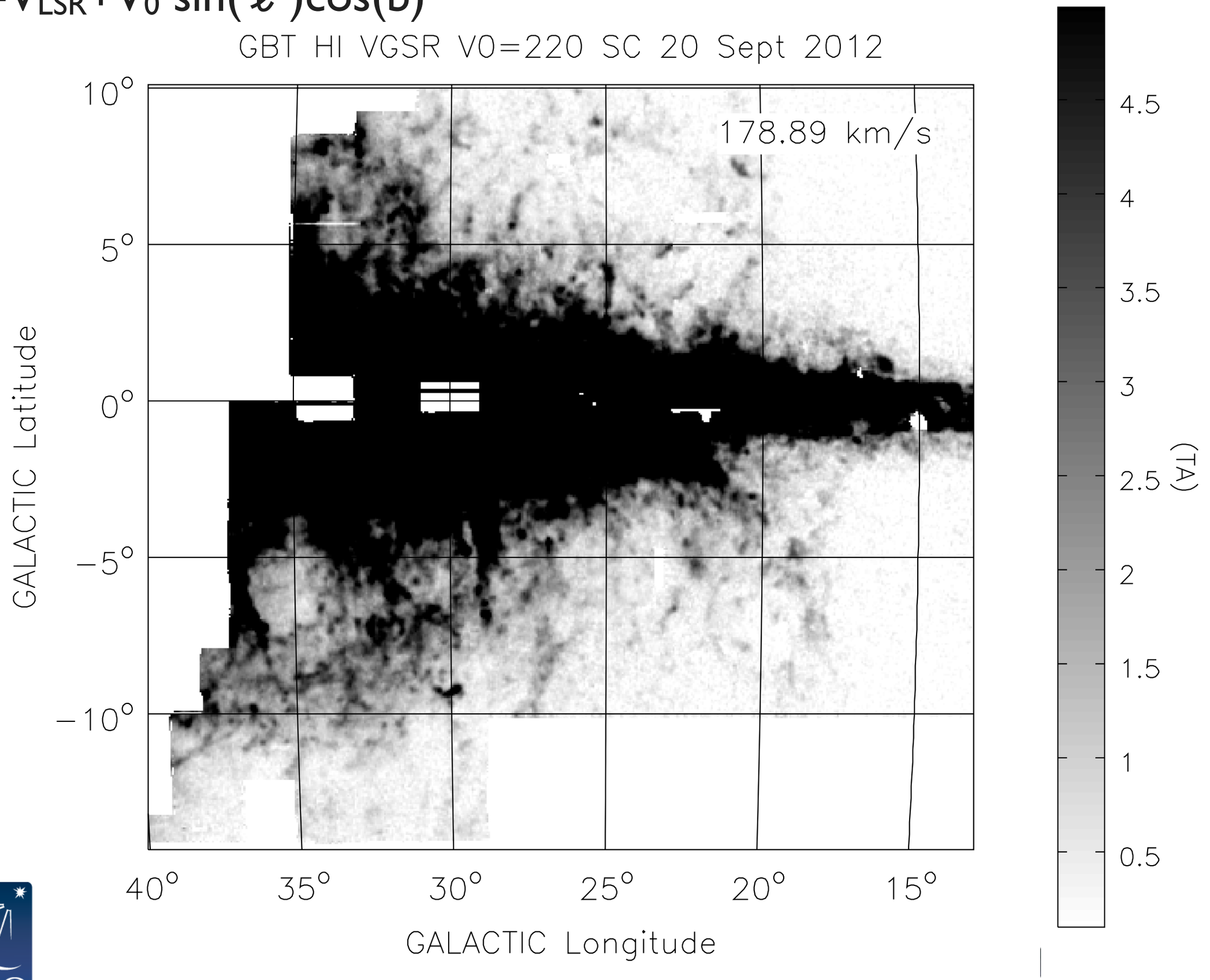
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0

(Ta)

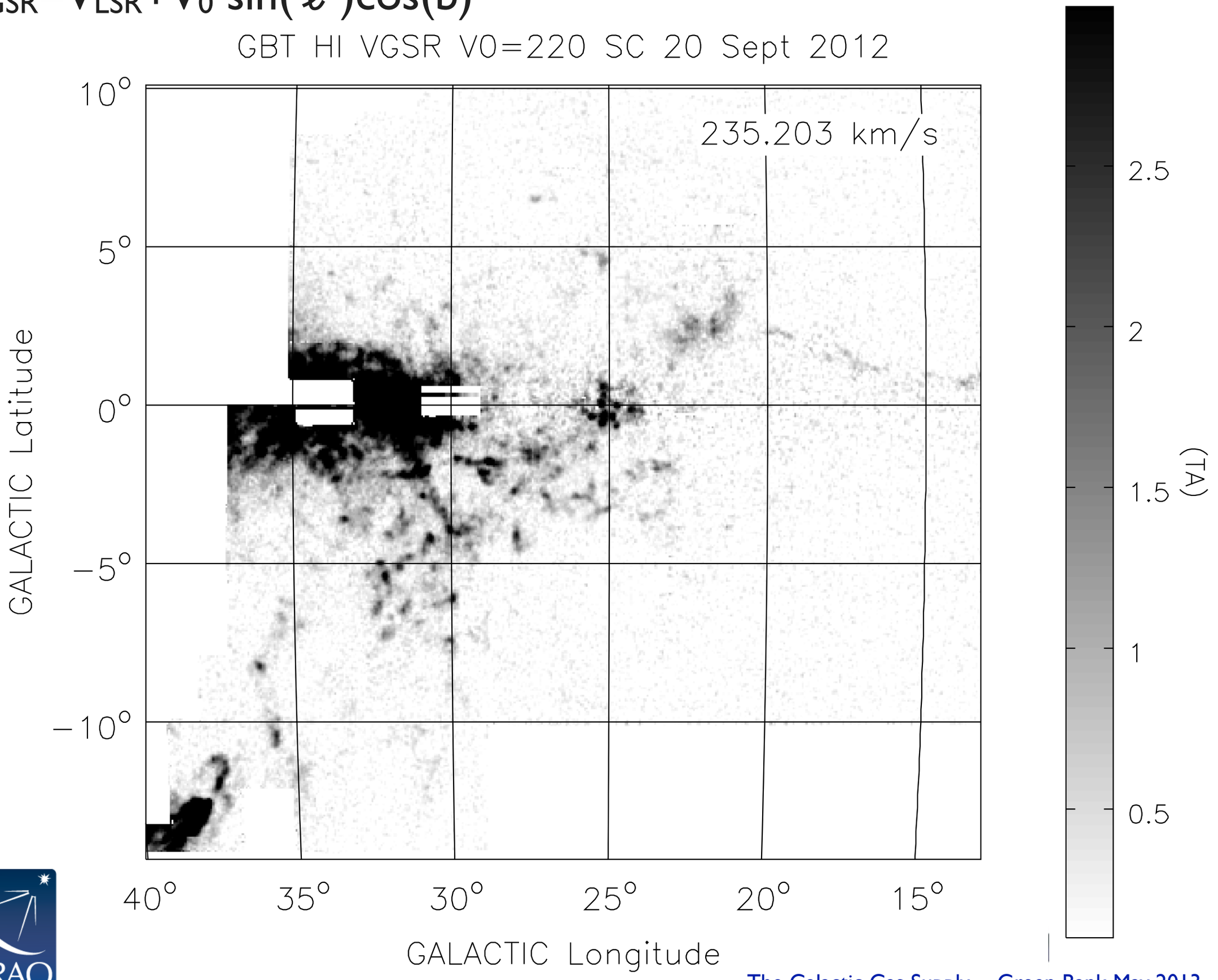
$$V_{LSR} = \left[R_0 sin(\ell) \{ \frac{V_\theta}{R} - \cancel{\frac{V_0}{R_0}} \} - V_R \cos(\ell + \theta) \right] \cos(b) + V_z sin(b)$$

$$V_{GSR} = V_{LSR} + V_0 \sin(\ell) \cos(b)$$

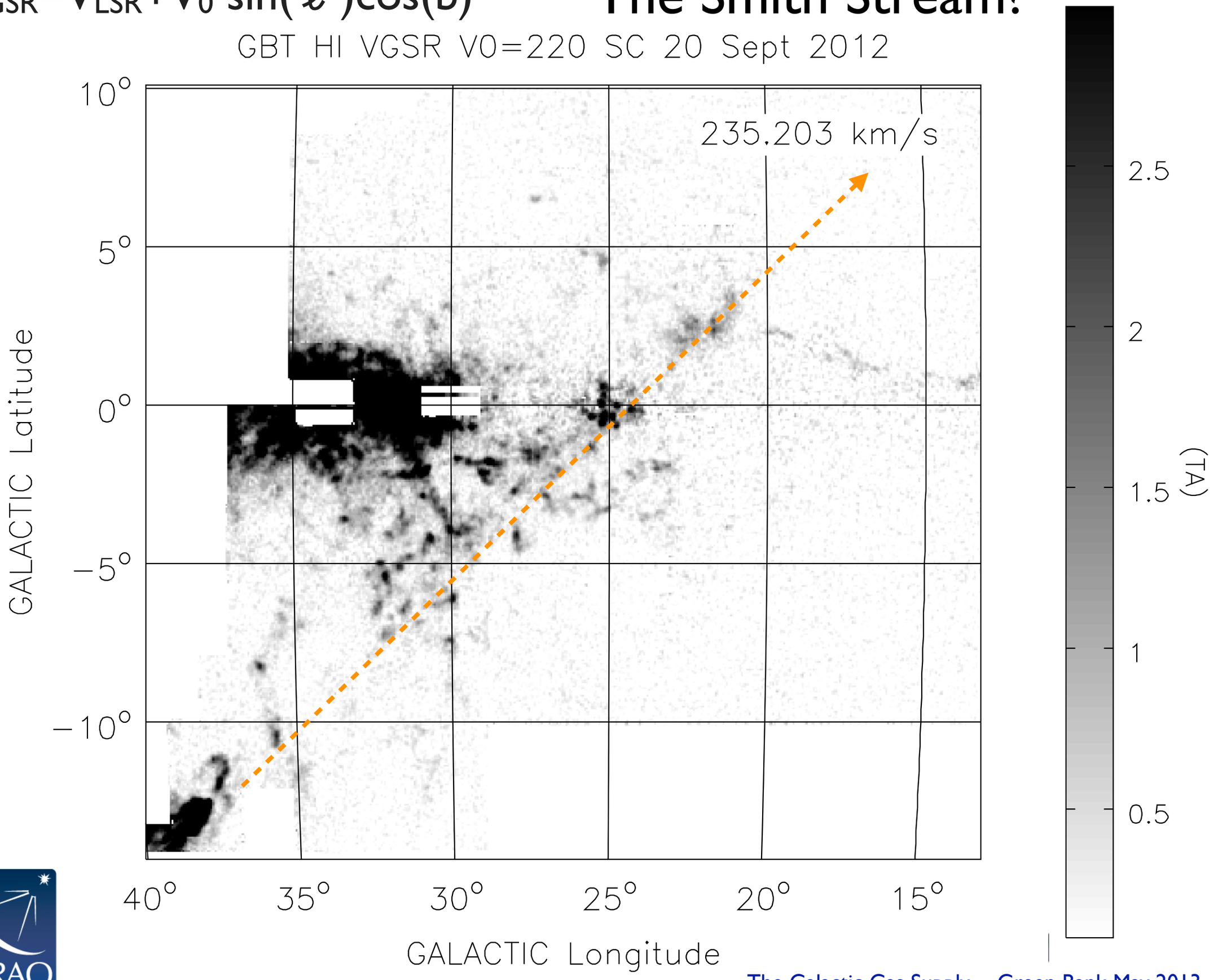
$V_{GSR}=V_{LSR}+V_0 \sin(\ell)\cos(b)$



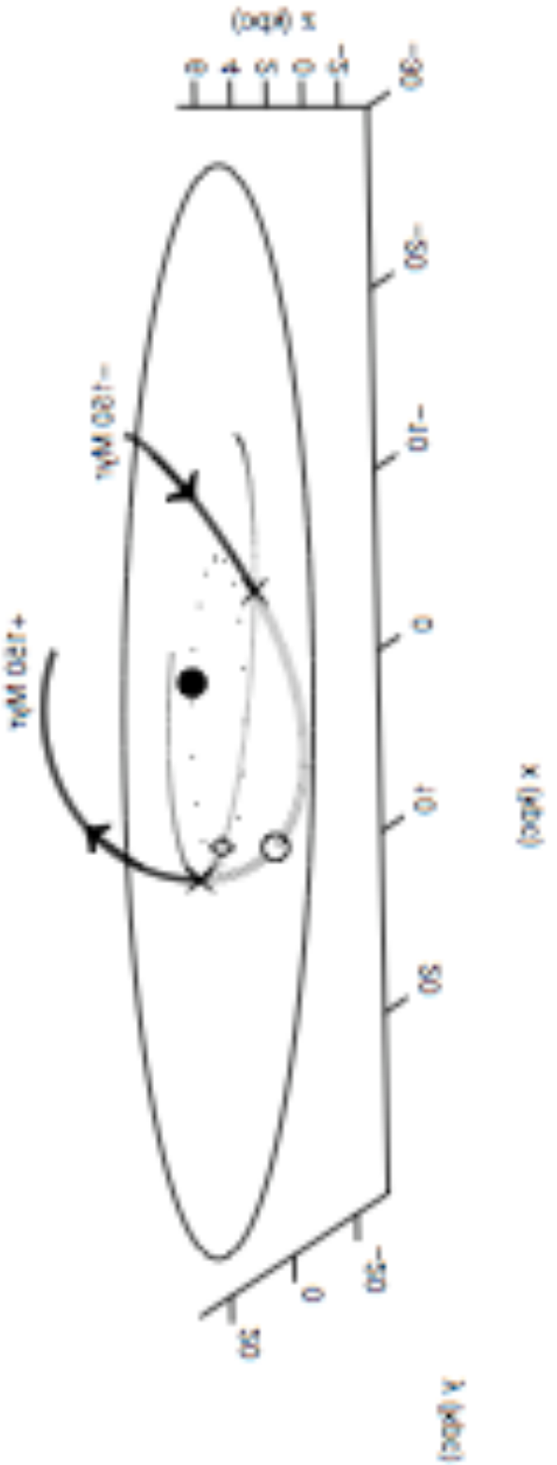
$V_{GSR}=V_{LSR}+V_0 \sin(\ell)\cos(b)$

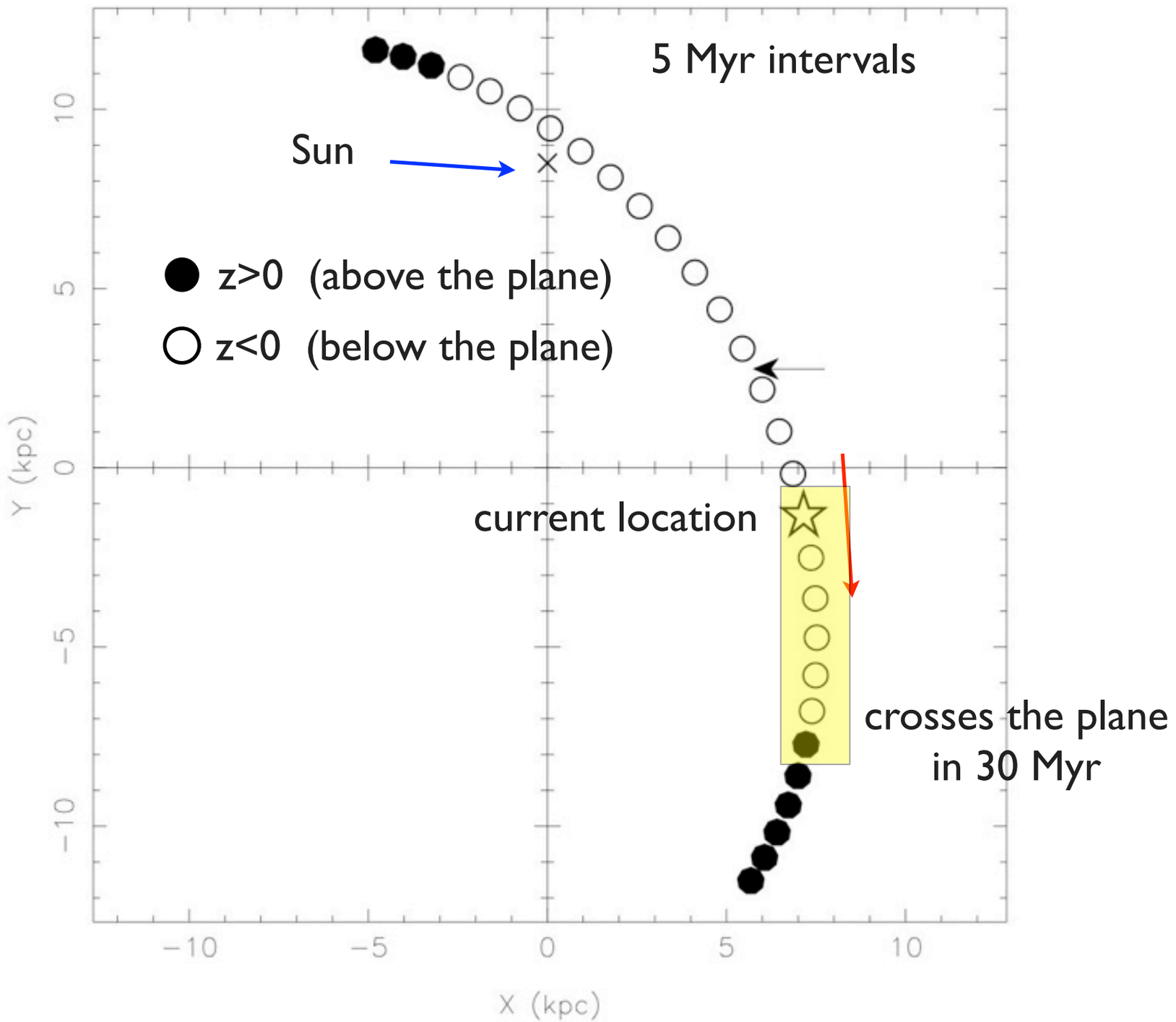


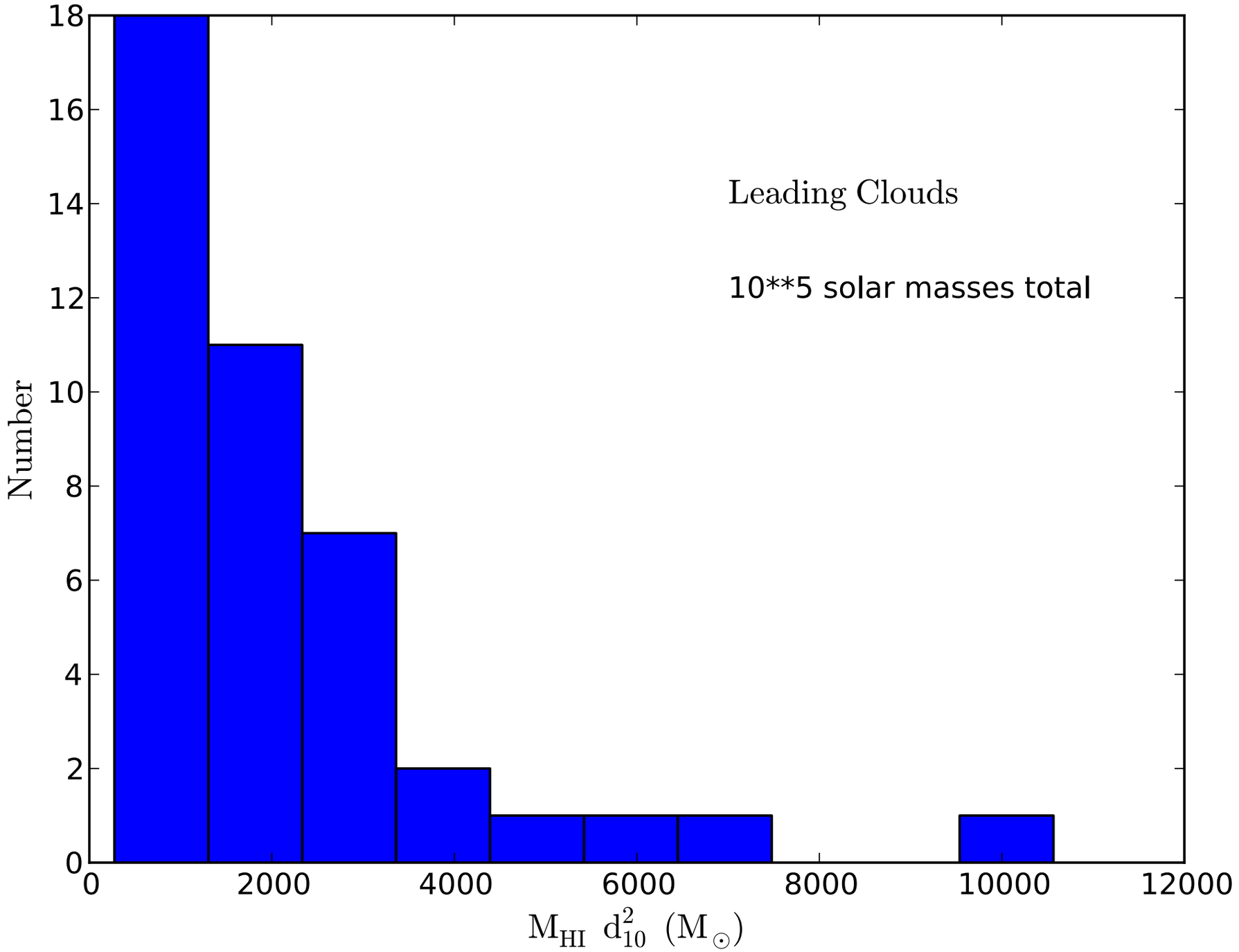
$V_{GSR}=V_{LSR}+V_0 \sin(\ell)\cos(b)$ The Smith Stream?



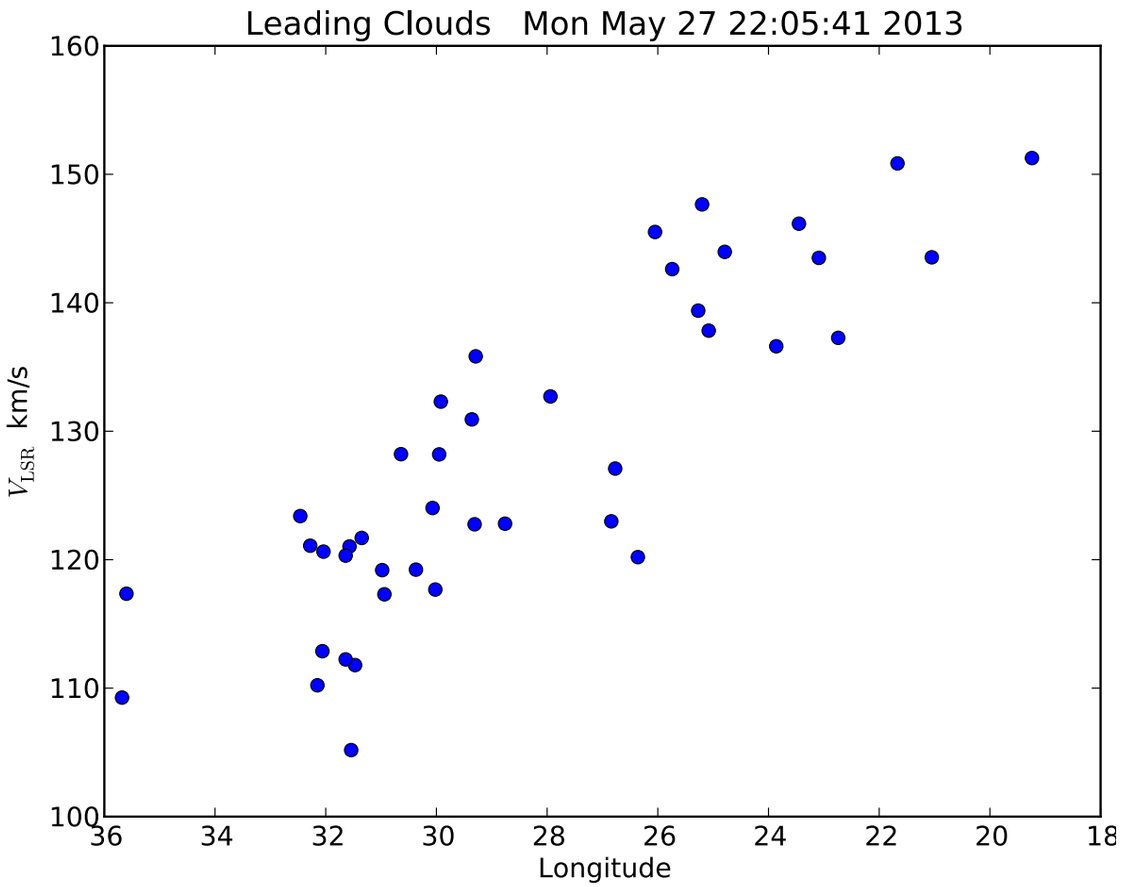
The Smith Stream??

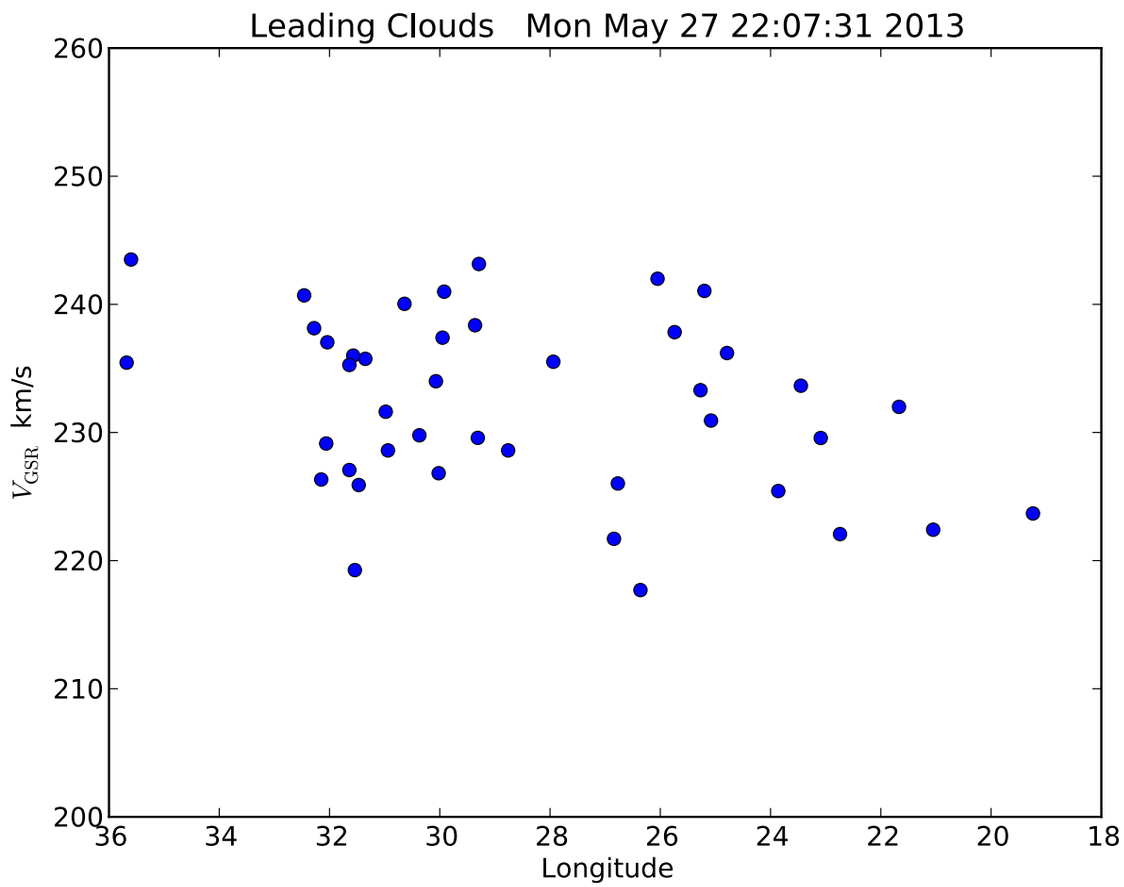




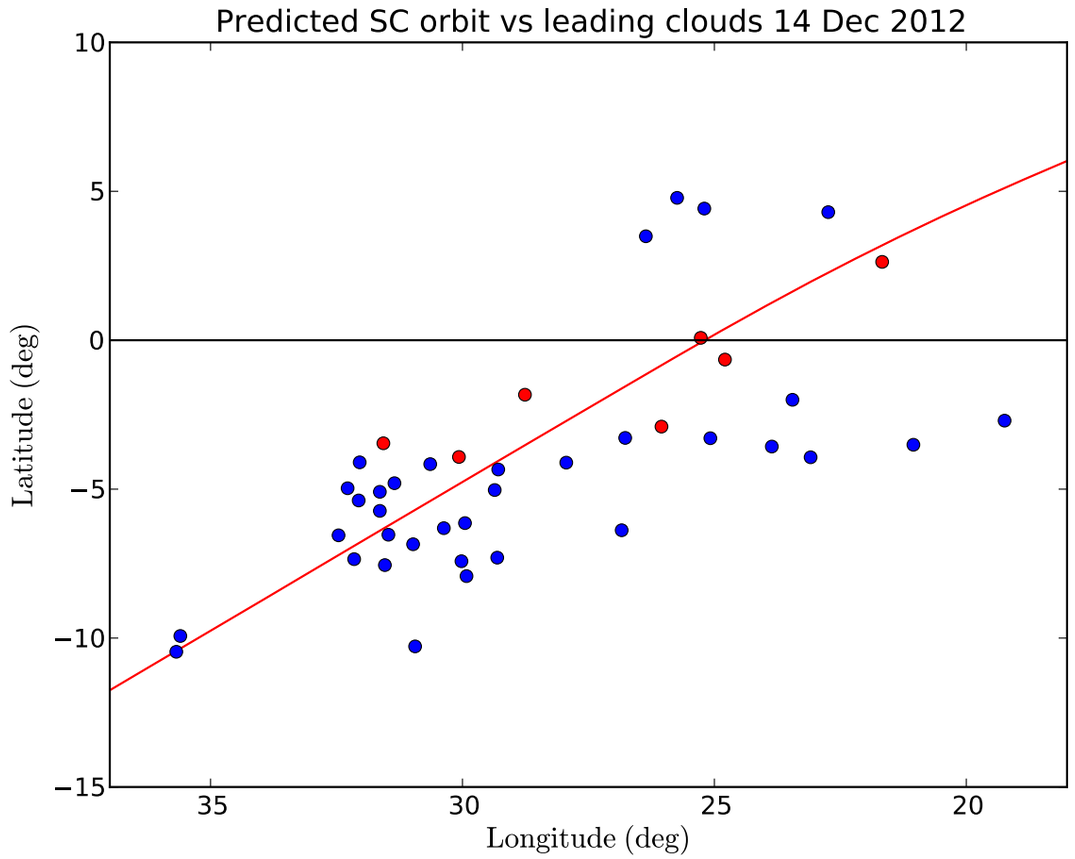

Leading Clouds
10**5 solar masses total
Number
0
2
4
6
8
10
12
14
16
18
0
2000
4000
6000
8000
10000
12000
$M_{HI}\ d_{10}^2\ (M_\odot)$

The Smith Stream??

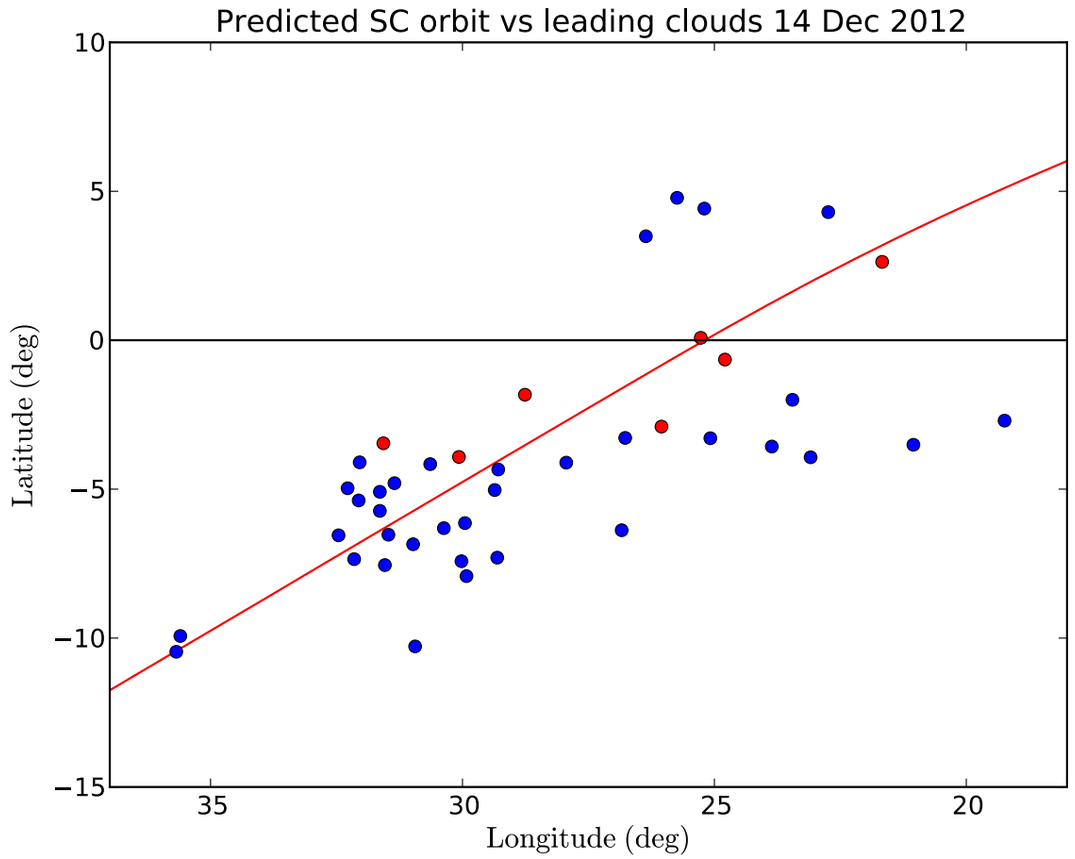


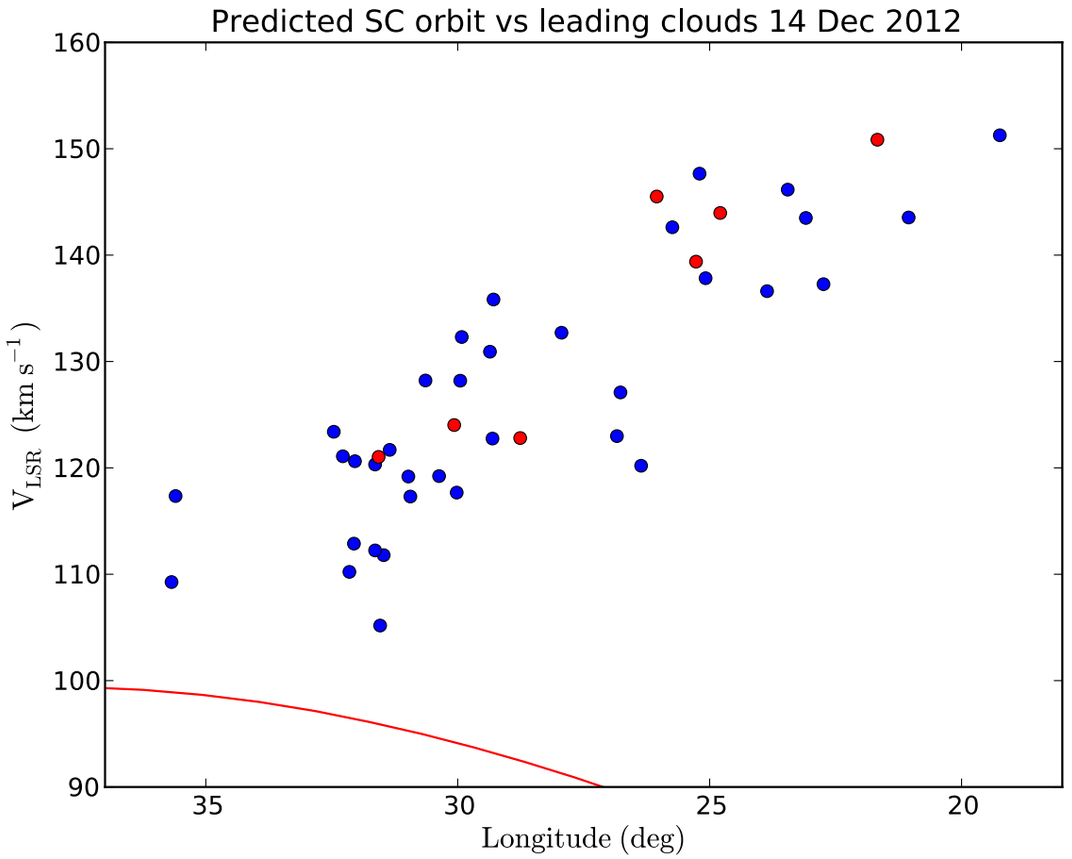


The Smith Stream??



The Smith Stream??

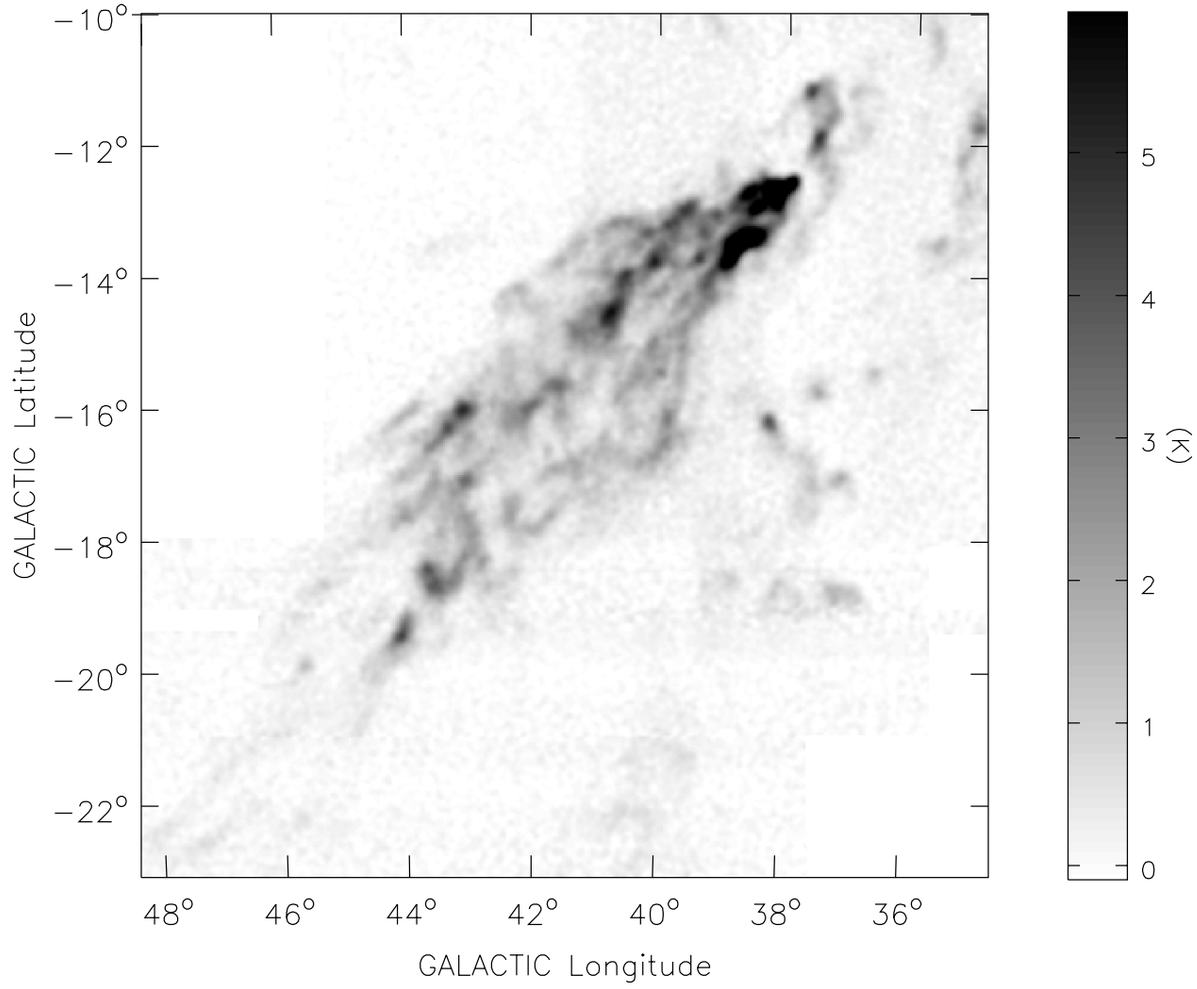




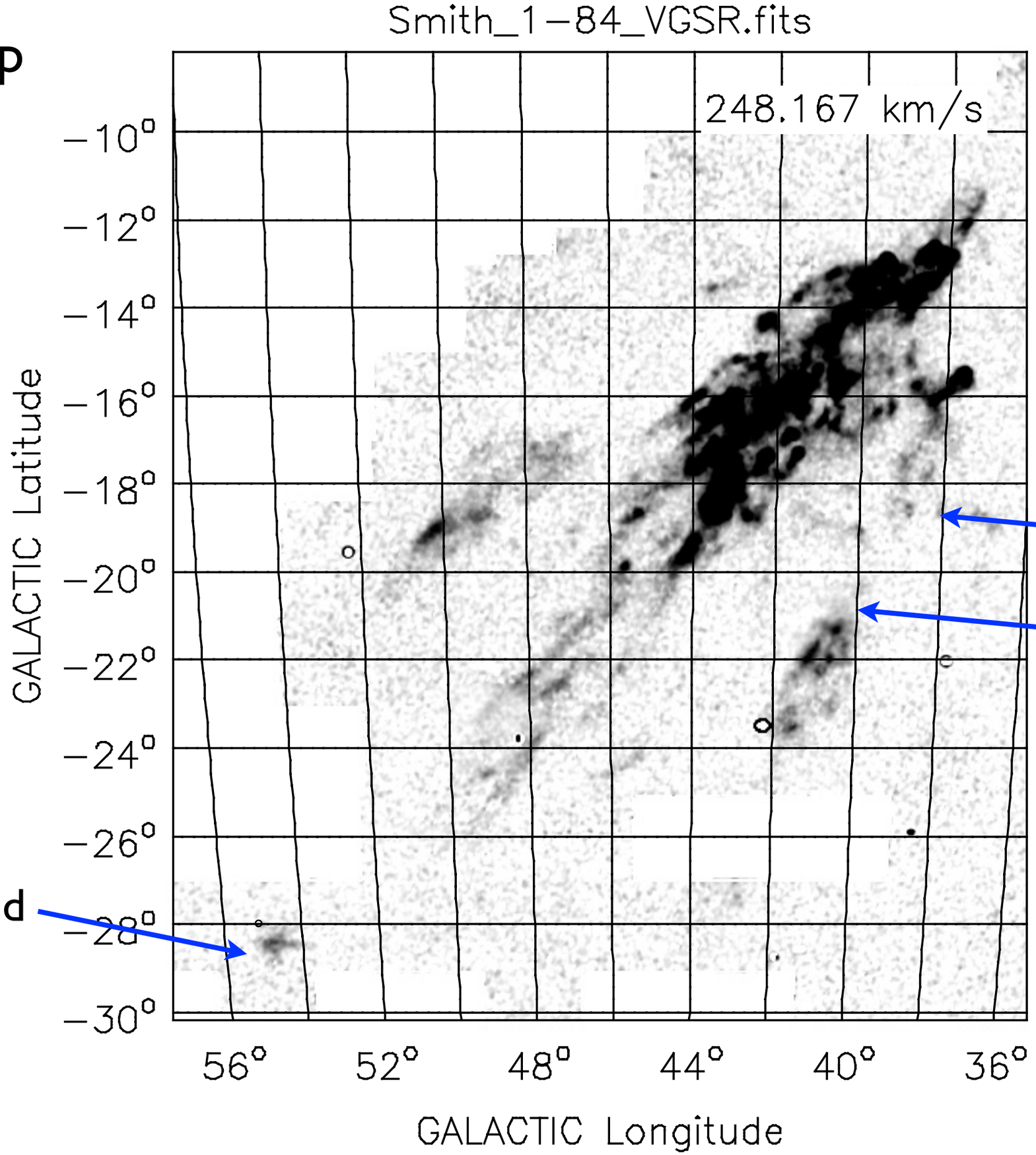
Oops! Predicted position is good. Predicted velocity is not.

A new GBT map of HI in the Cloud

old map



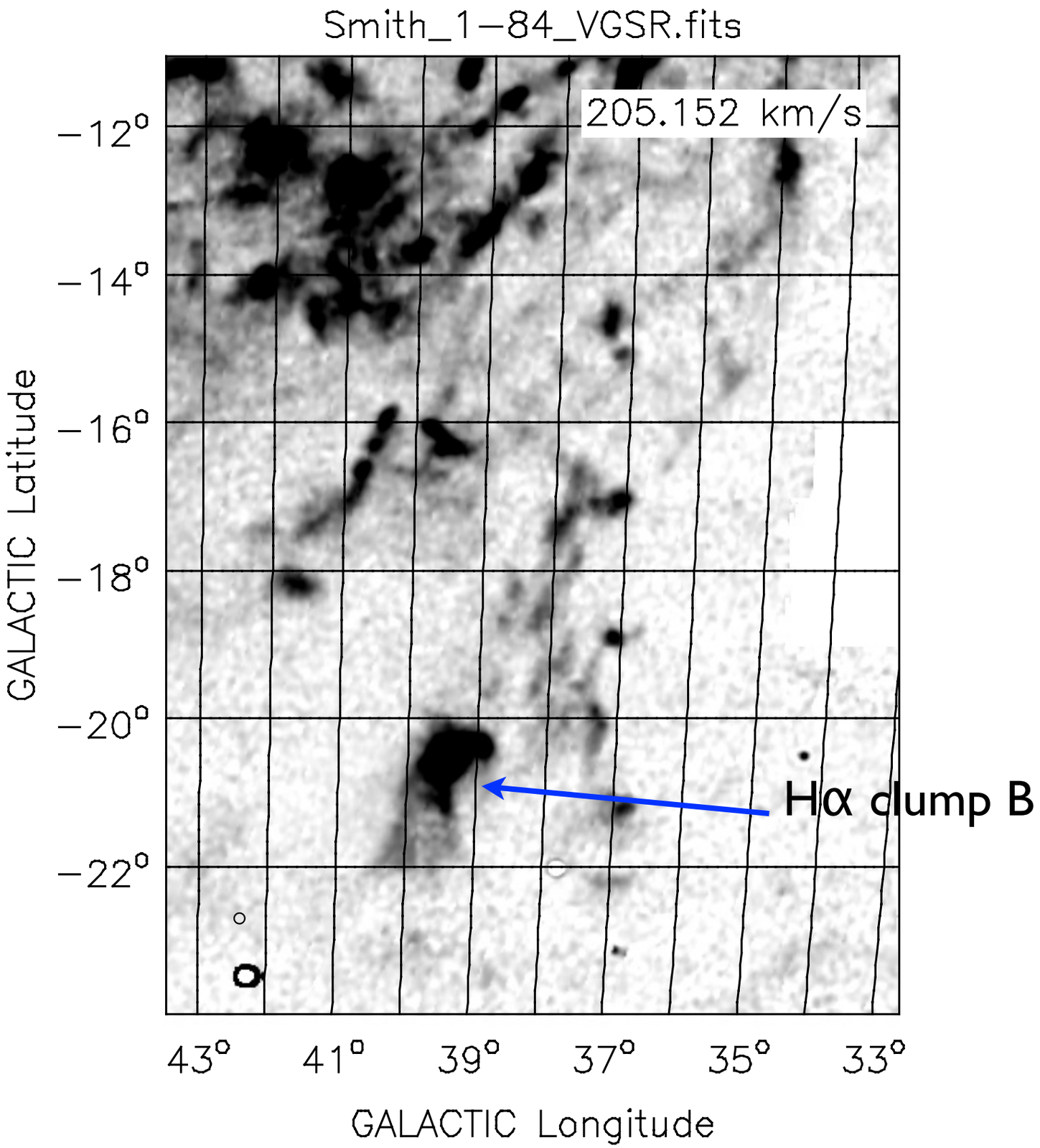
New map



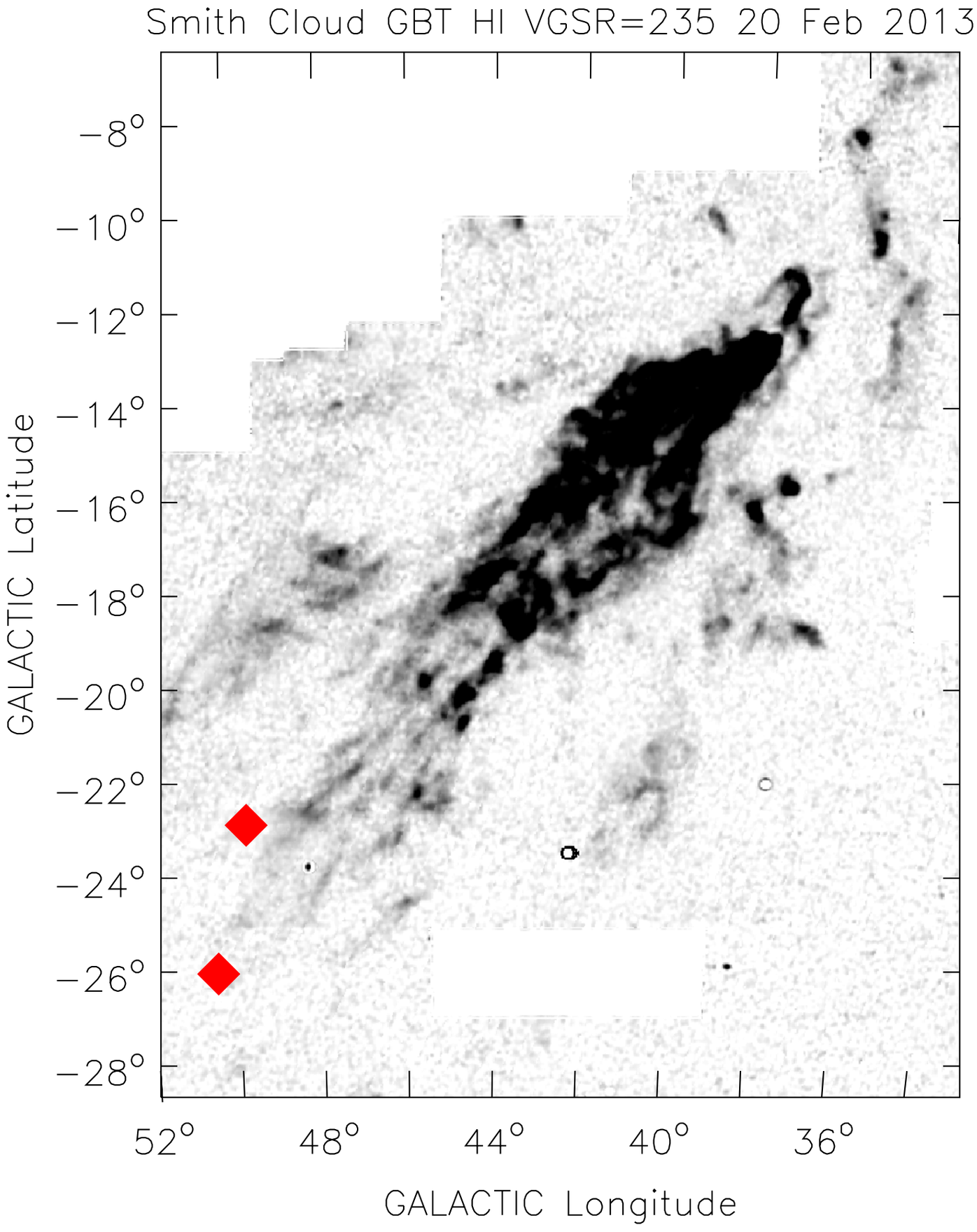
Hα clump A

Hα clump B

part of the cloud


Smith_1−84_VGSR.fits
205.152 km/s
−12°
−14°
−16°
−18°
−20°
−22°
GALACTIC Latitude
43°
41°
39°
37°
35°
33°
GALACTIC Longitude
Hα clump B

HST data?


Smith Cloud GBT HI VGSR=235 20 Feb 2013
−8°
−10°
−12°
−14°
−16°
−18°
−20°
−22°
−24°
−26°
−28°
GALACTIC Latitude
52°
48°
44°
40°
36°
GALACTIC Longitude

I would like

* A better map of H+ over the Cloud

* A rigorous estimate of the stellar content

* A self-consistent model for the Cloud's location

* UV data on metal lines

* Faraday Rotation

Final Comments

- Gas is being added to the Milky Way from High Velocity Clouds at $R<R_0$, more than 0.1 $M_\odot$ y^{-1} from the Smith Cloud alone. We've got a lot to learn from this object.

- The Smith Cloud is the brightest (central?) part of a larger stream, without a counterpart in stars. However while its trajectory is consistent with our understanding, its kinematics is not.

- The true extent of the Cloud has yet to be determined

- What is its origin?