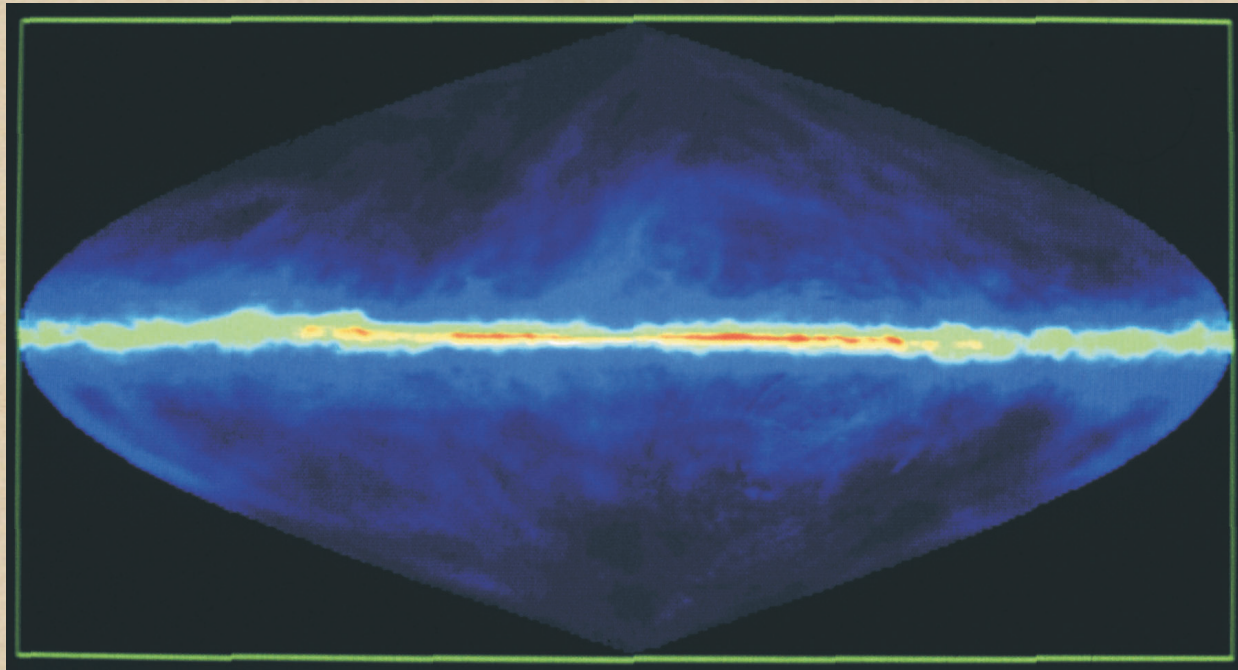


# Hydrogen Between the Disk and the Halo

Felix J. Lockman

NRAO

Green Bank, WV

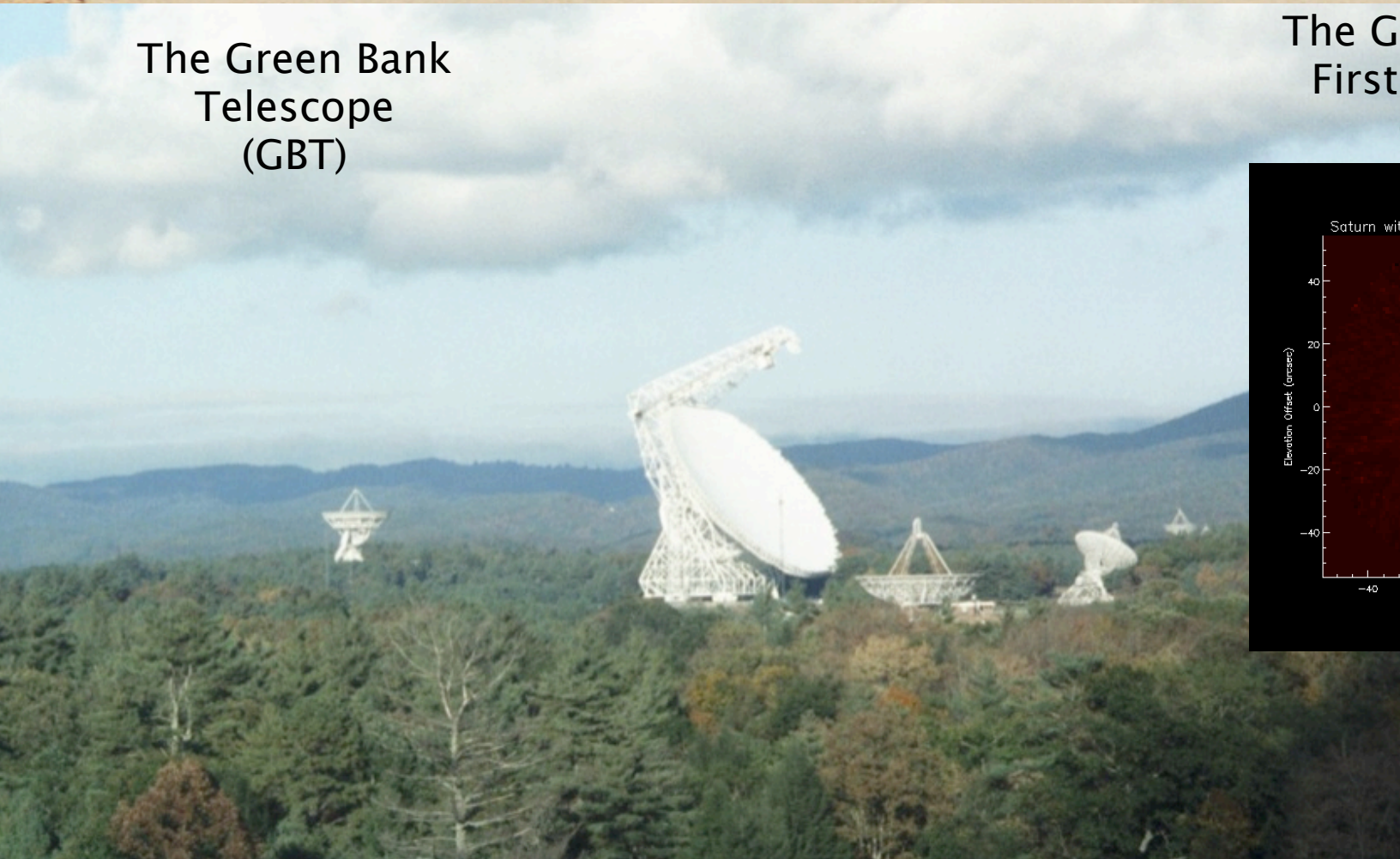


“Why should I feel lonely? Is not our planet in the Milky Way?  
--Henry David Thoreau

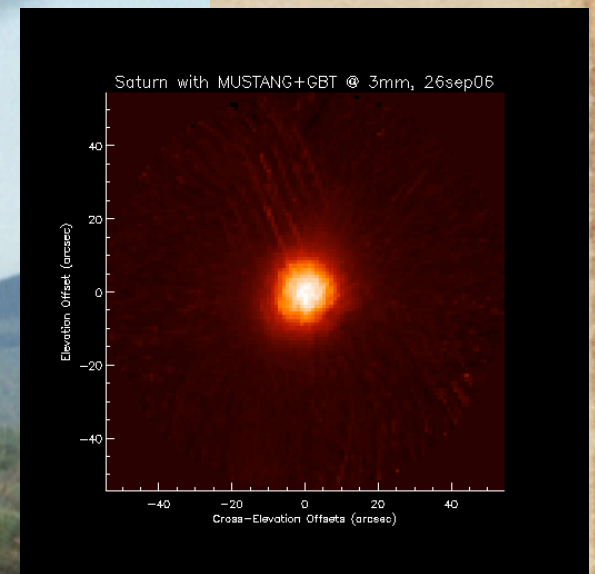


- 0. The Problem of the existence of HI far from the plane
  - I. HI Clouds in the lower halo
  - II. HI being lifted Upward
  - III. HI coming down

The Green Bank  
Telescope  
(GBT)



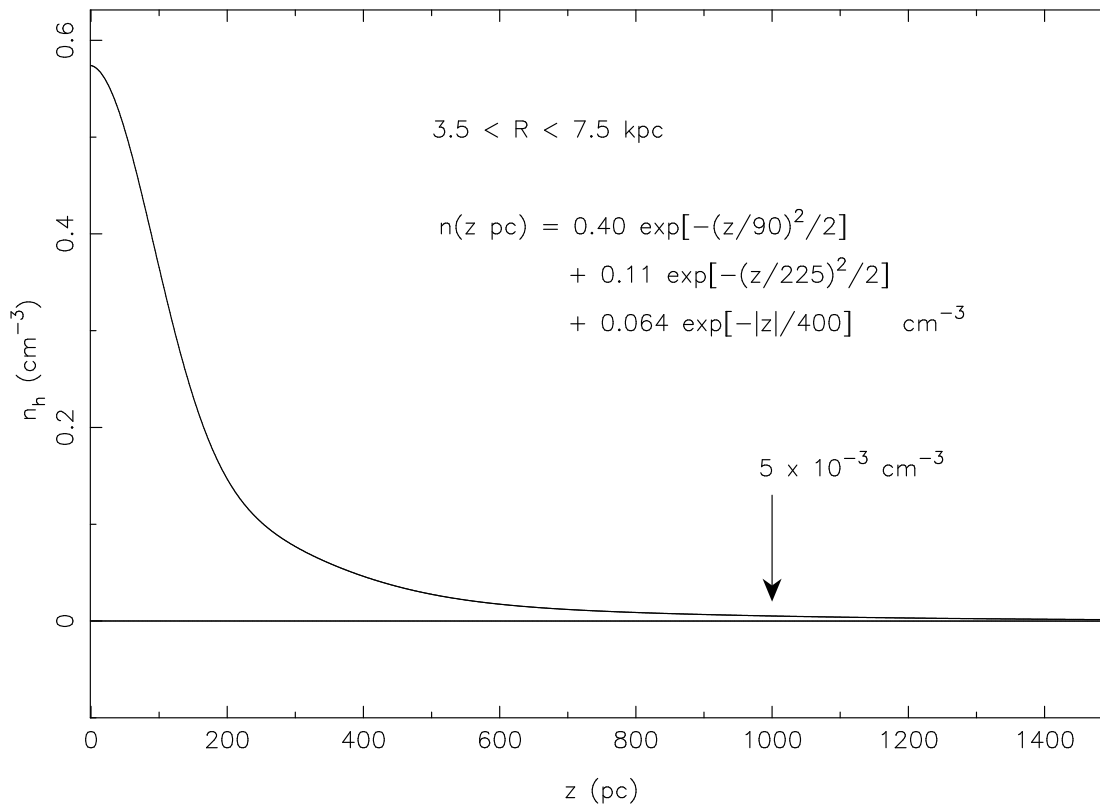
The GBT recently had  
First Light at 3mm  
(8" HPBW)



# 0. The Problem of the existence of HI far from the plane

Why is there neutral hydrogen more than 1 kpc from the Galactic Plane?

## The Vertical Profile of Galactic HI.

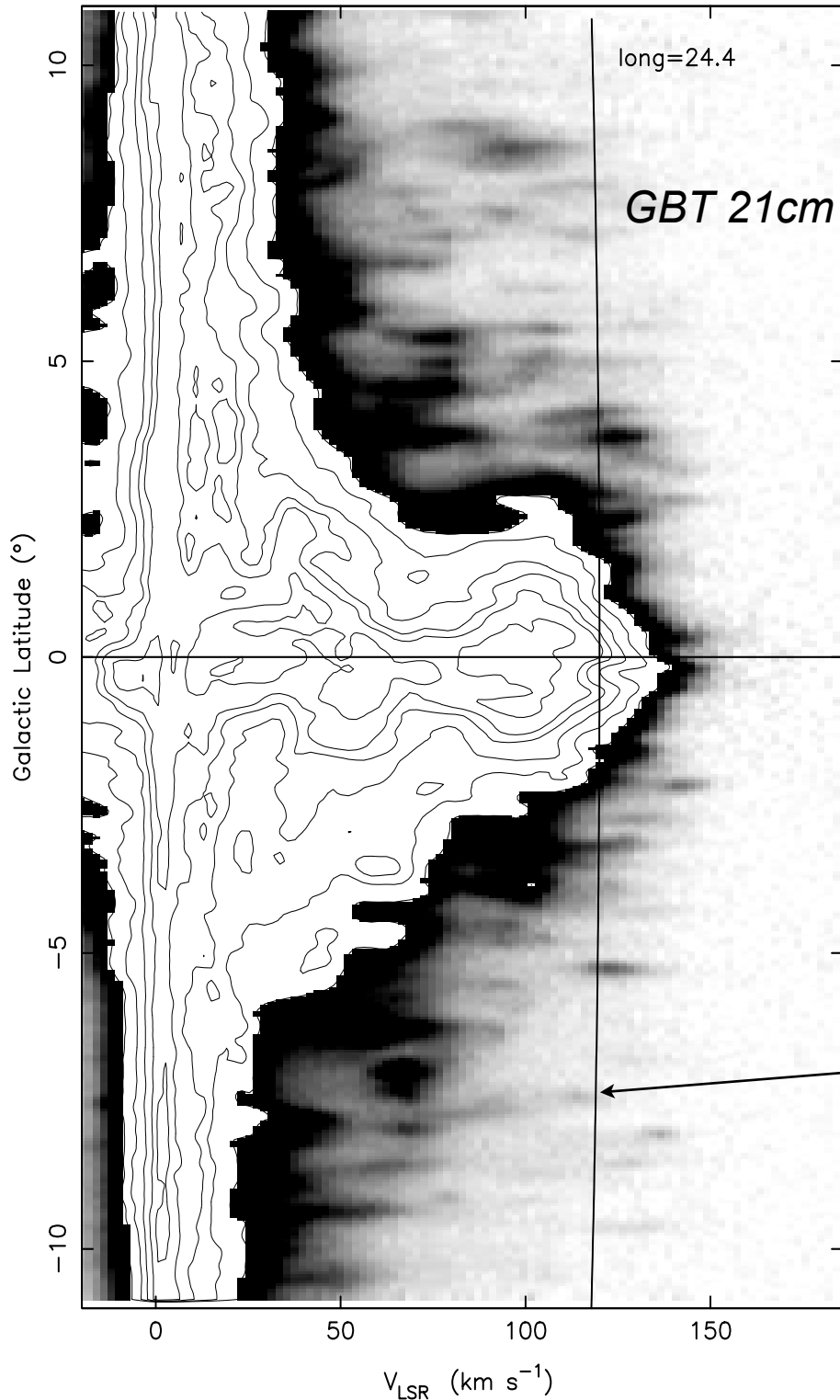


*Lockman 1984; Dickey & Lockman 1990 (DL)*

What supports the HI to  $z \gtrsim 1$  kpc?

- ~~Temperature~~
- CR & Magnetic fields?
- Turbulence?
- Galactic Fountain?
- Temporary Structures?

# 1. HI Clouds in the lower halo



With the angular resolution of the Green Bank Telescope [much of? all of ?] the HI layer above the plane in the inner Galaxy breaks up into “clouds”

In the Inner Galaxy kinematics  $\rightarrow$  distance

Velocity of the tangent point



# HI Clouds in/near the Milky Way

<u>Name</u>	<u>Galactic Plane?</u>	<u>Disk Rotation?</u>	<u>Abundances</u>	<u>FIR?</u>
High Velocity clouds	No	No	~0.1 Solar	weak
Disk-Halo Clouds	Yes	Yes	?	(yes)

The HI clouds seen above the disk in the inner Galaxy are not related to the “classic” high-velocity HI clouds!

# HI Clouds in the Inner Galaxy

Clouds at all distances from plane  
( $1^\circ$  in latitude at  $l=24^\circ \Rightarrow 135$  pc at tan pt.)

They follow normal Galactic rotation  
but with  $\sigma_{c-c} \gtrsim 20$  km/s

Narrow Lines  $\Rightarrow$  cool HI

Linear size 10 pc to few hundred pc

HI mass 10 to  $10^3 M_\odot$

Interesting internal composition

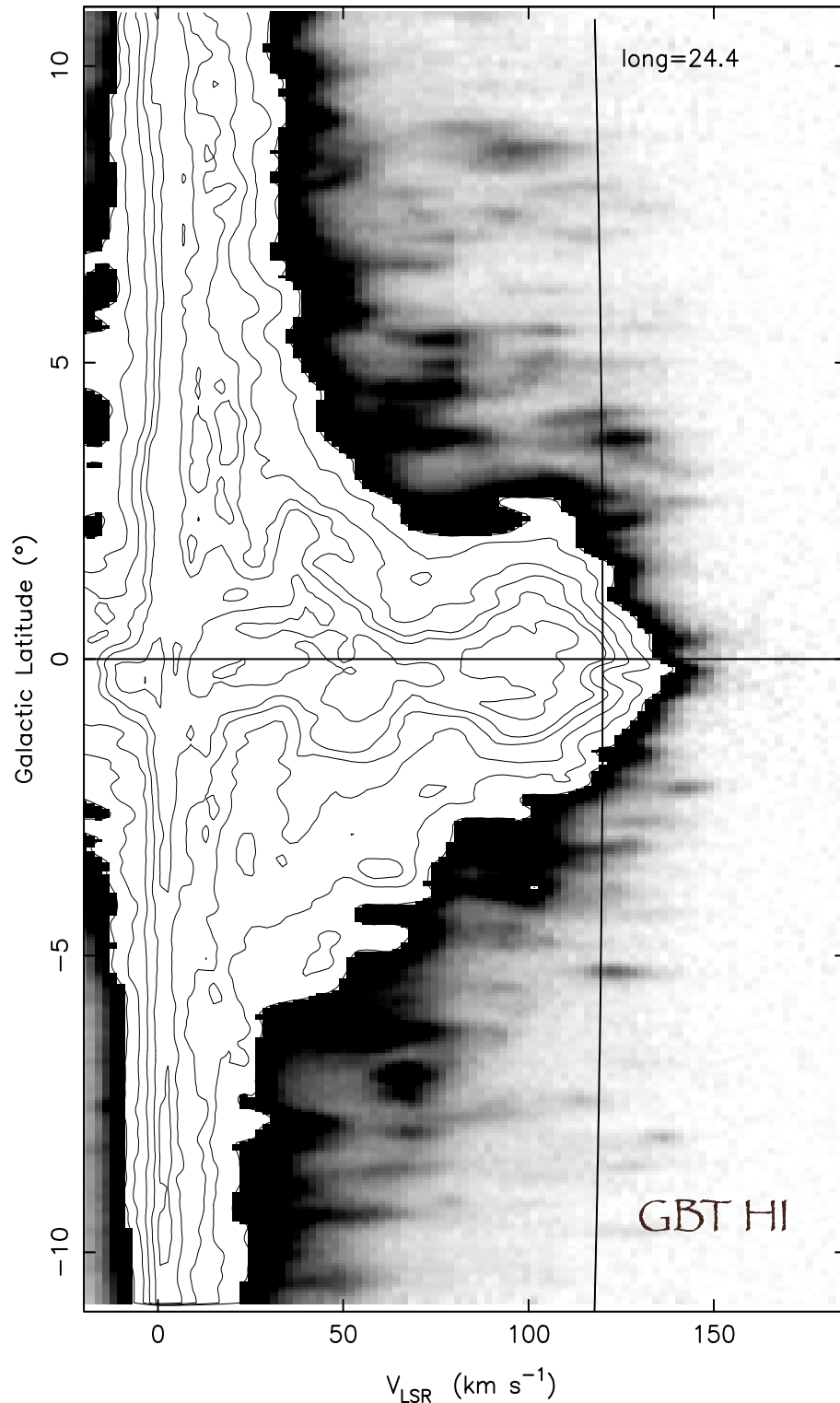
Often isolated, but sometimes in larger structures

## References

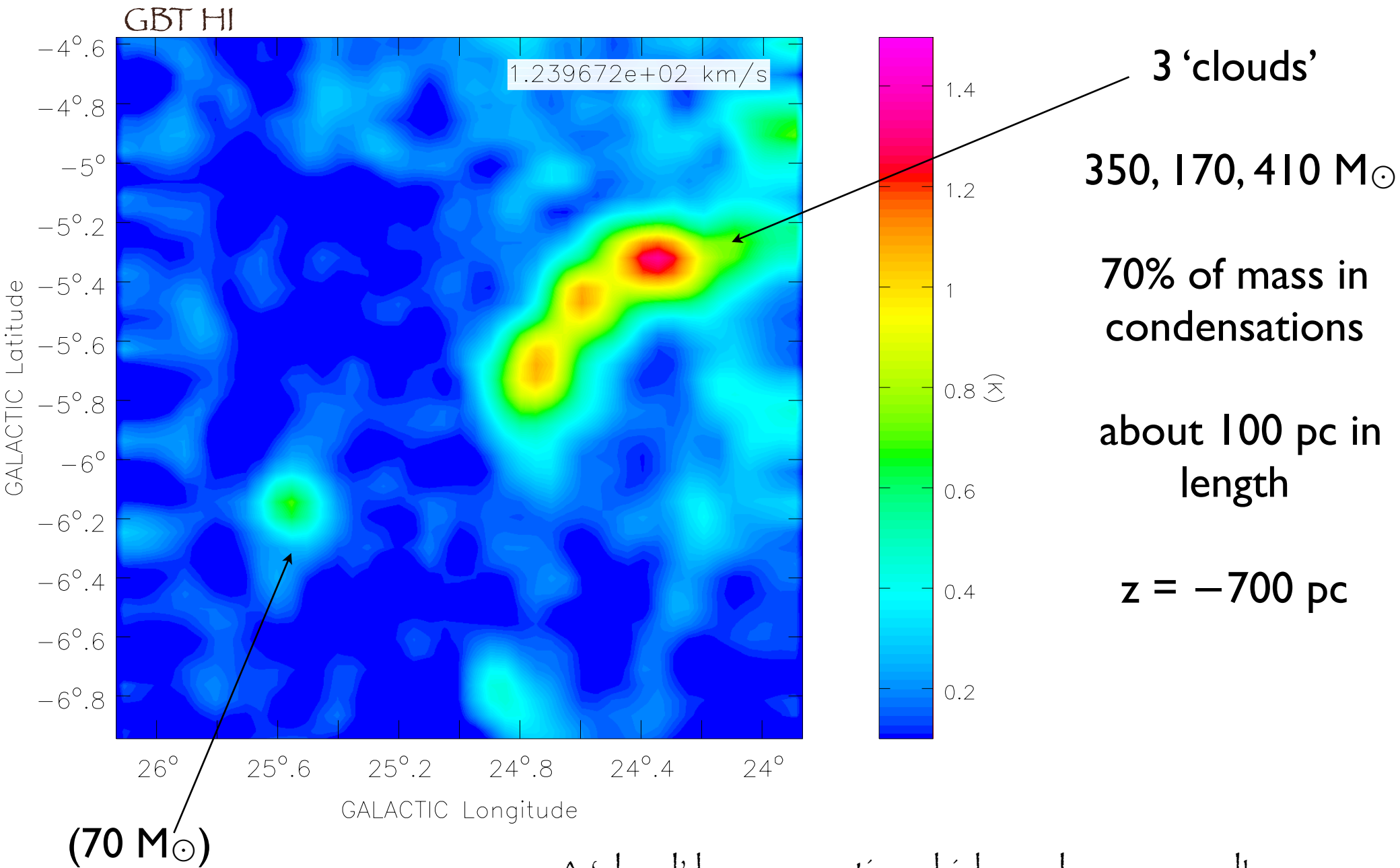
Lockman 2002, ApJ, 580, L47

Lockman 2004 in 'How the Milky Way Works', ASP 315, 17

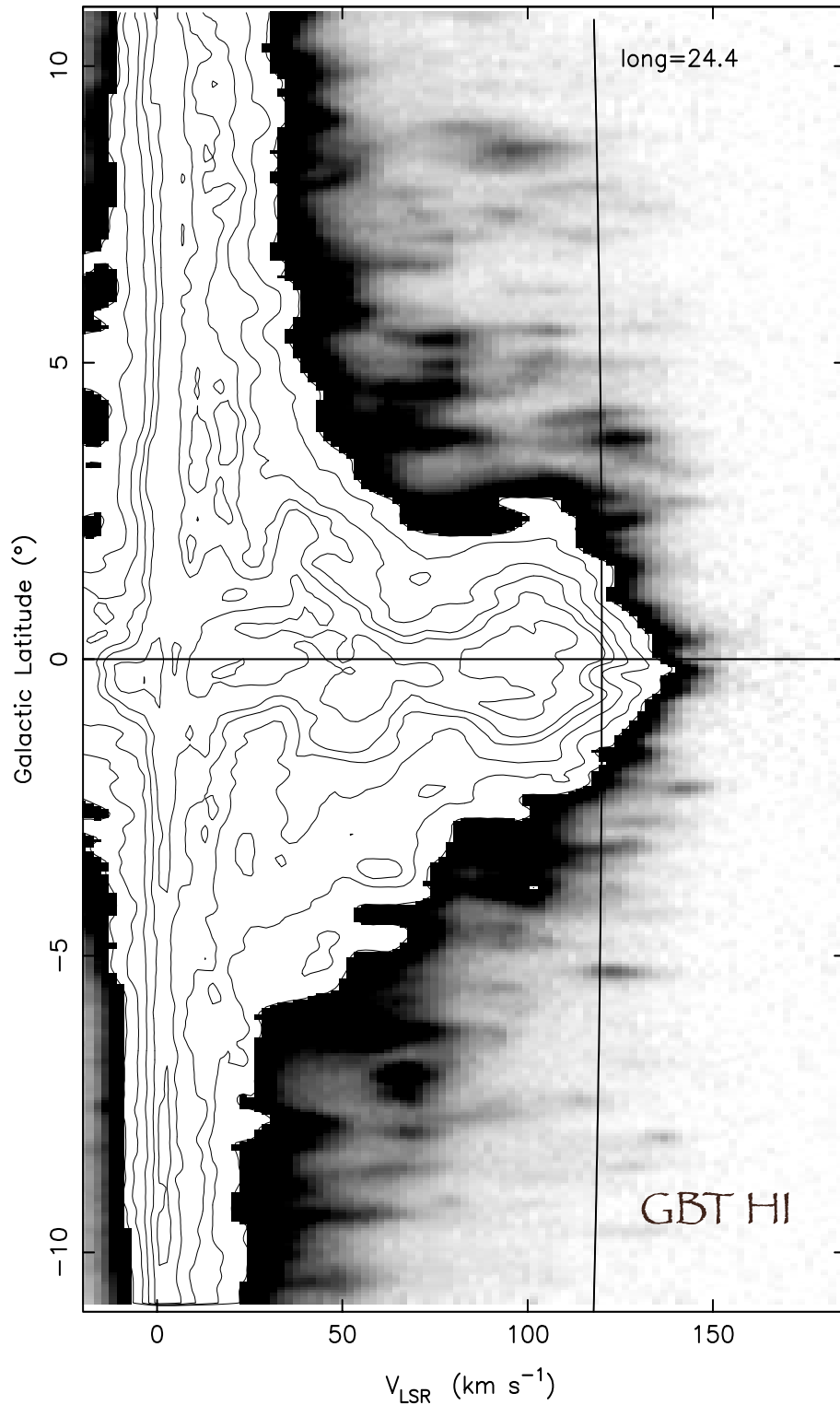
Lockman & Pidopryhora 2005, in 'Extraplanar Gas', ASP Conf. Ser. 331, 59.







A 'cloud' has properties which can be measured!  
 A cloud can be used as a probe of local conditions



## Features of 'halo' clouds

$$\langle n \rangle \sim 1 \text{ cm}^{-3}$$

$$\langle \text{size} \rangle \sim 25 \text{ pc}$$

$$T \geq 150 \text{ K}$$

⇒ Not self-gravitating

## Time Scales

$$t_{\text{eq}} < 10^4 \text{ yr}$$

$$t_{\text{dy}} \approx \text{size} / \Delta V \approx 10^6 \text{ yr}$$

$$t_{\text{ff}} > 10^7 \text{ yr}$$

⇒ Must be in 'local' equilibrium

Core Size  $< 2 \text{ pc}$

Core Density  $> 30 \text{ cm}^{-3}$

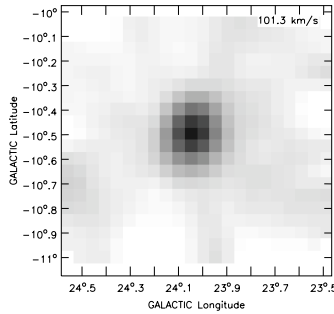
Central  $\text{NH} > 4 \times 10^{20}$

⇒ Molecules?

at  $z \approx 1 \text{ kpc}$  filling factor  $< 1\%$



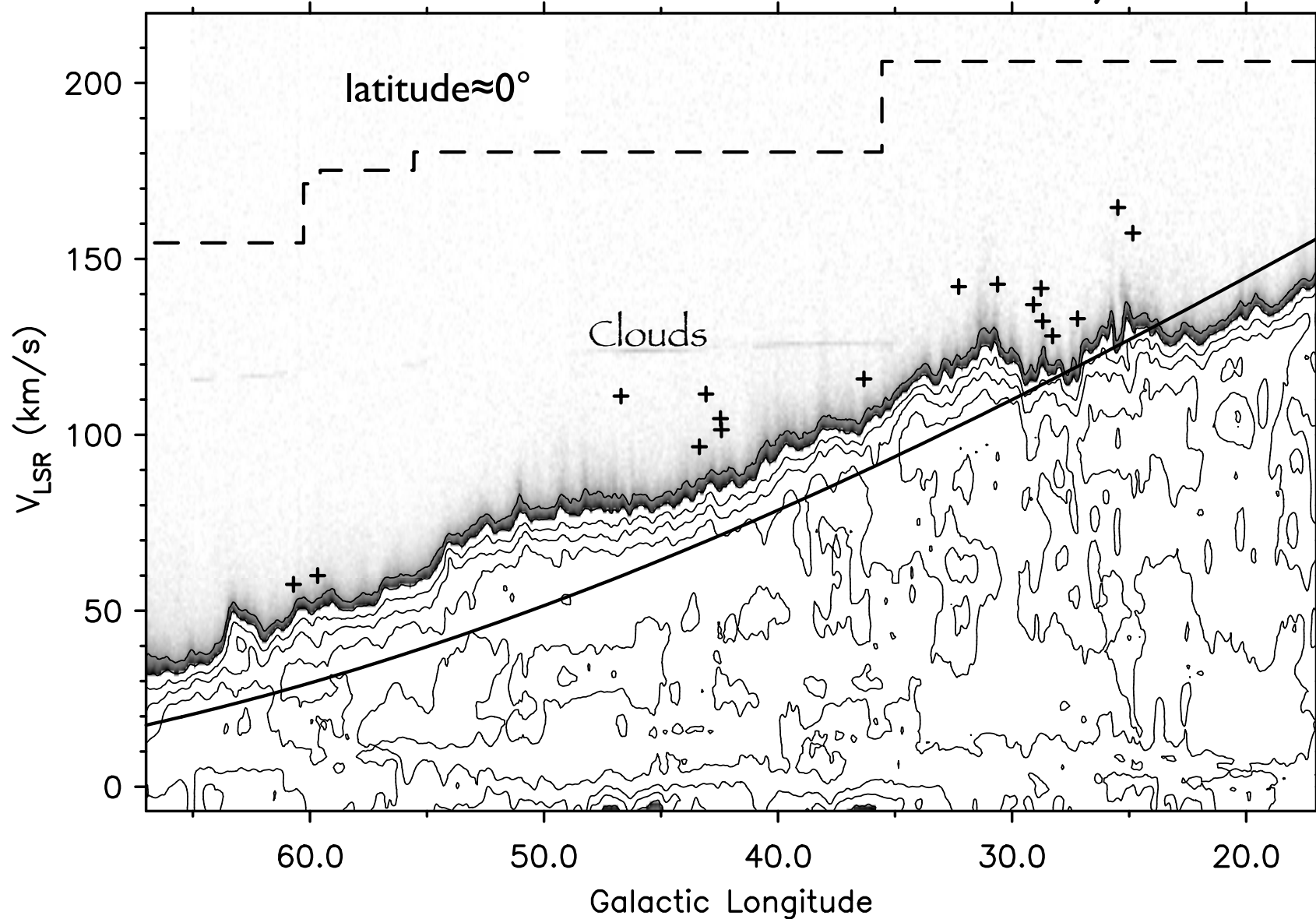
Table 1. GBT and VLA Observations of G24.0–10.5



	Spitzer(1968)	cloud G24.0–10.5 (GBT)	core G24.03–10.46 (VLA)
$z$ (pc)		9'	1'
$M_{HI}$ ( $M_{\odot}$ )	400	250	2.5
$T_L$ (K)		2.5	8.2
$\Delta v$ ( $\text{km s}^{-1}$ )	5–11	29, 6	6
$T_k$ (K)			< 800
$N_{HI}$ ( $10^{20} \text{ cm}^{-2}$ )	4	0.4	0.9
Diameter (pc)	14	$35 \times 18$	$\leq 2.2$
$\langle n \rangle$ ( $\text{cm}^{-3}$ )	10	0.5	13

Lockman & Pidopryhora 2007 (in press)

# "Halo" Clouds also found in the Galactic Plane in The VLA-GBT Galactic Plane HI Survey



*Stil, Lockman, Taylor et al 2006, ApJ, 637, 366*



# Disk-Halo clouds?

A pervasive cloud population in the Inner Galaxy?

Most of the neutral halo in clouds?

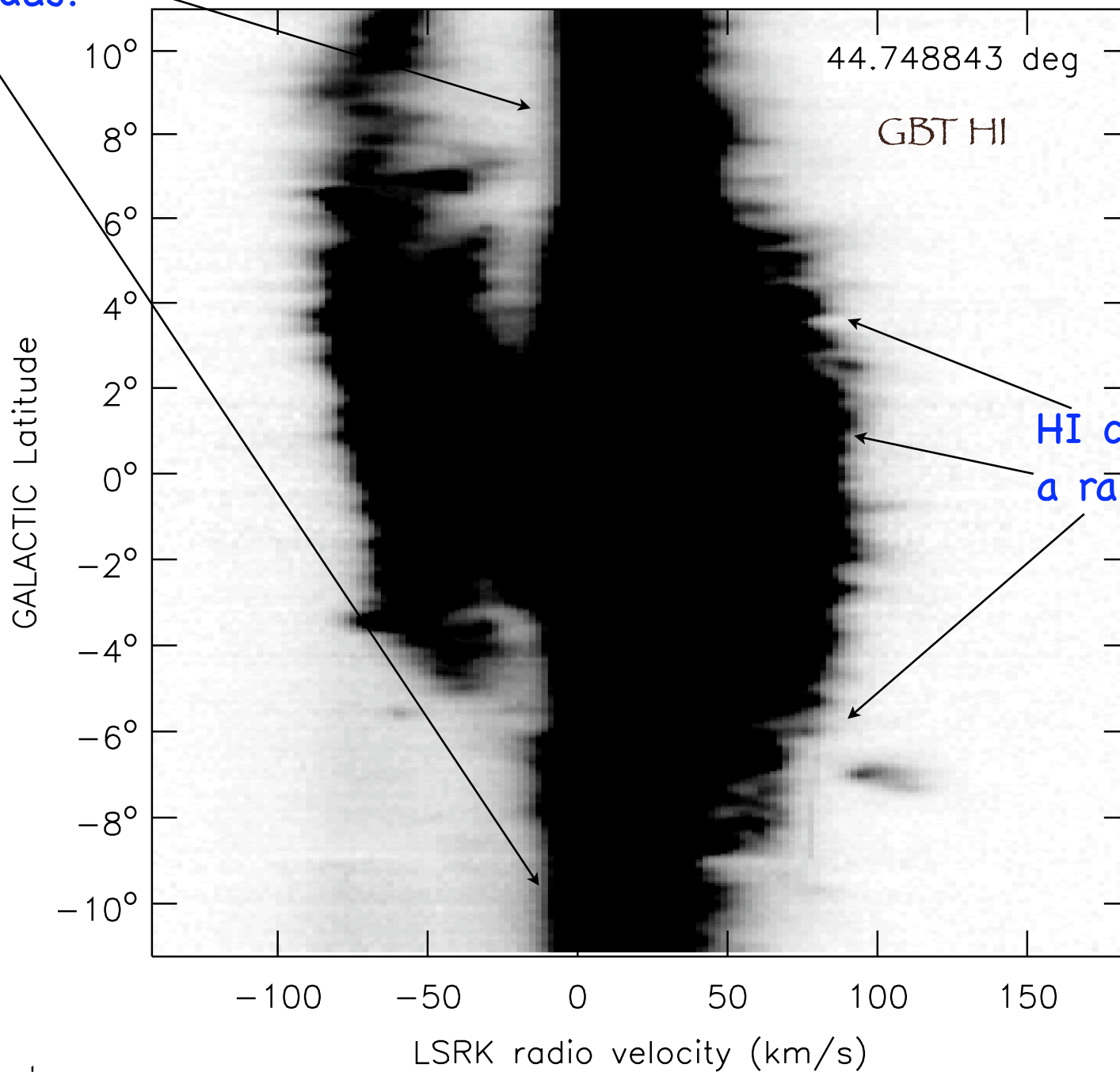
Turbulence?

→ Are there any near the Sun?

→ Do they have an ionized shell?

Where are the local clouds?

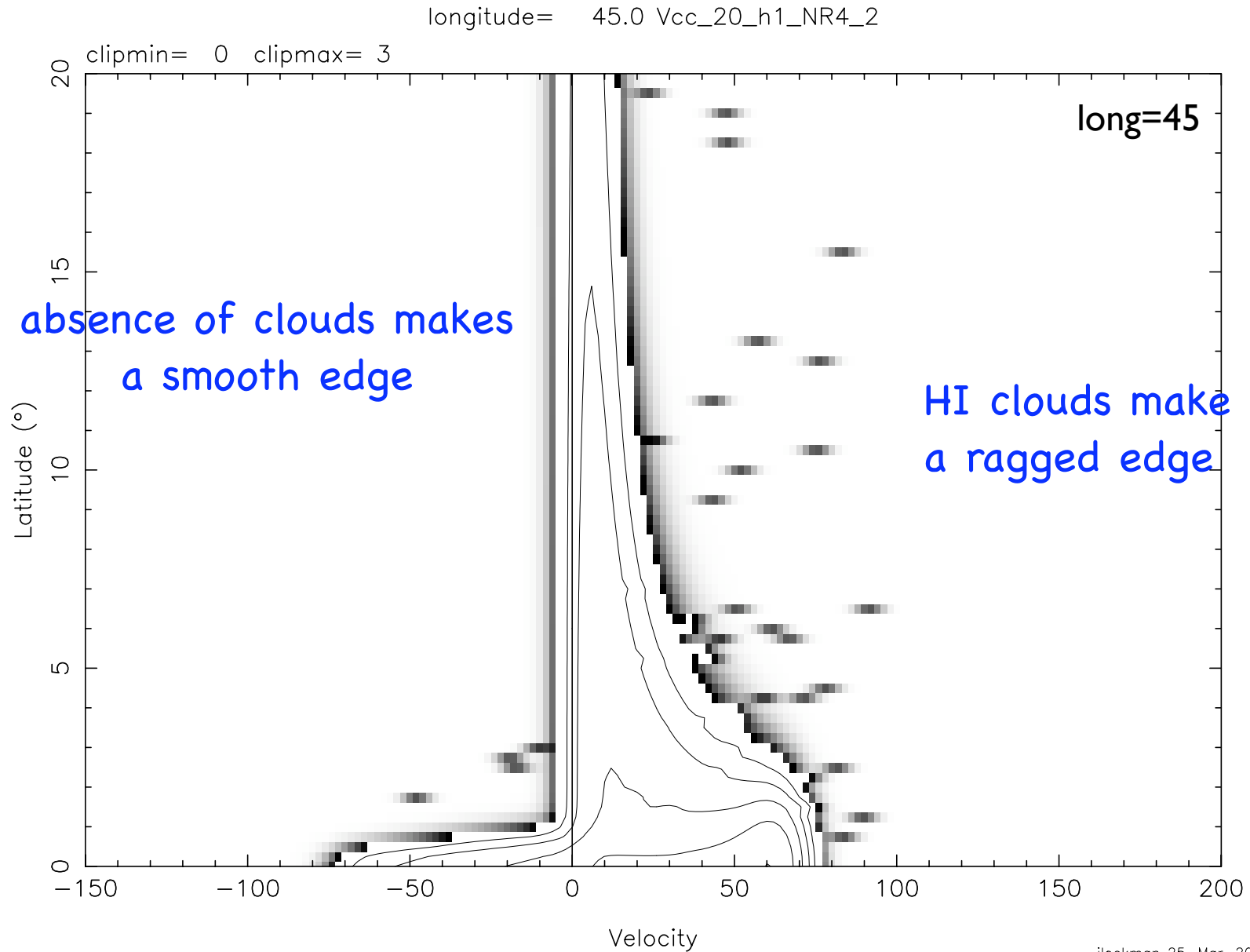
Are there few HI clouds at  $R \geq R_0$ ?



HI clouds make a ragged edge



# Simulation with a corotating cloud population confined to the inner Galaxy -- but at all z

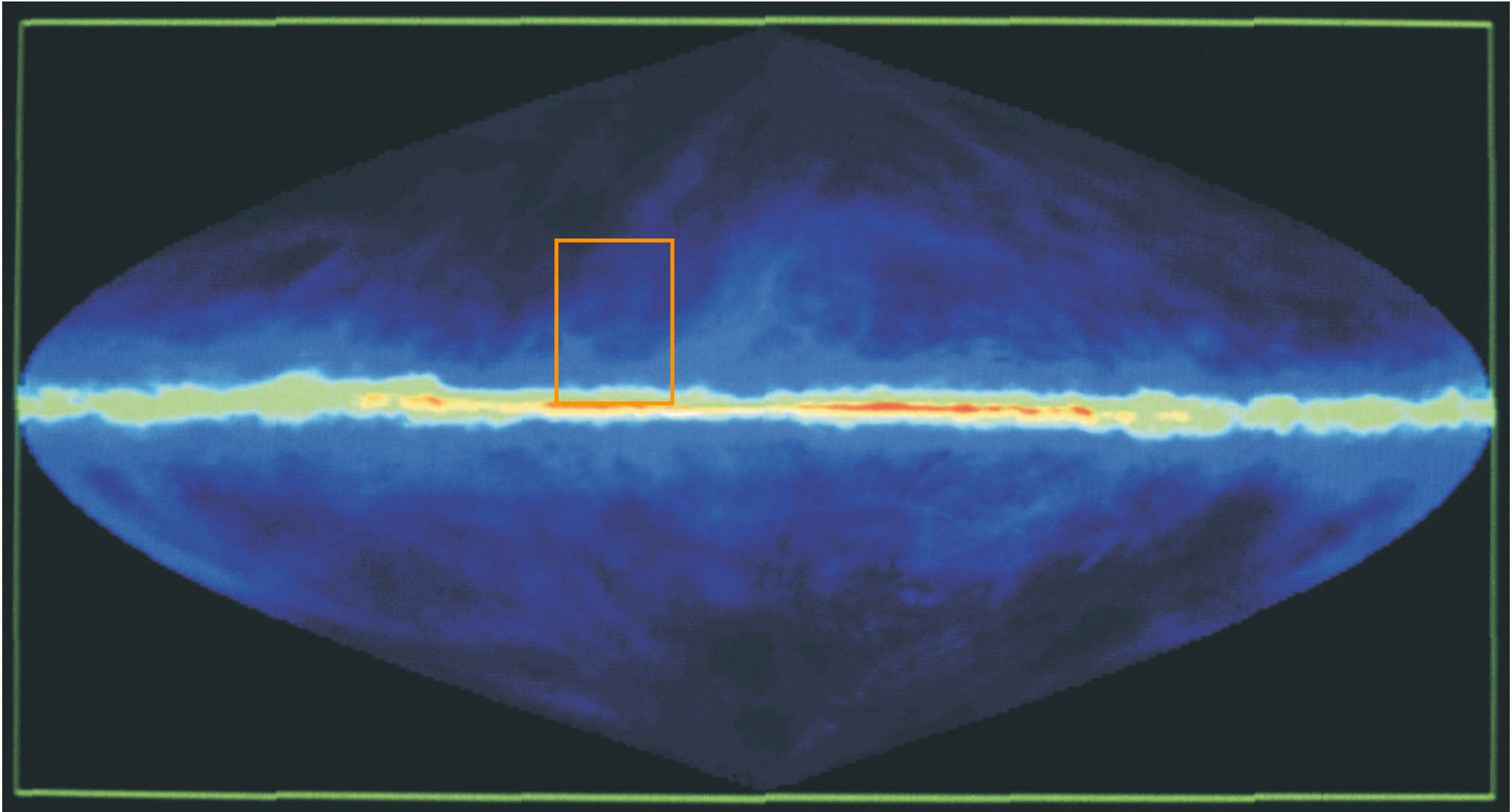


jlockman 25-Mar-2005 10:59

hz=1 kpc

$N(R)=\text{Gauss at } R=4, \sigma=2 \text{ kpc}$

## II. HI being lifted Upward

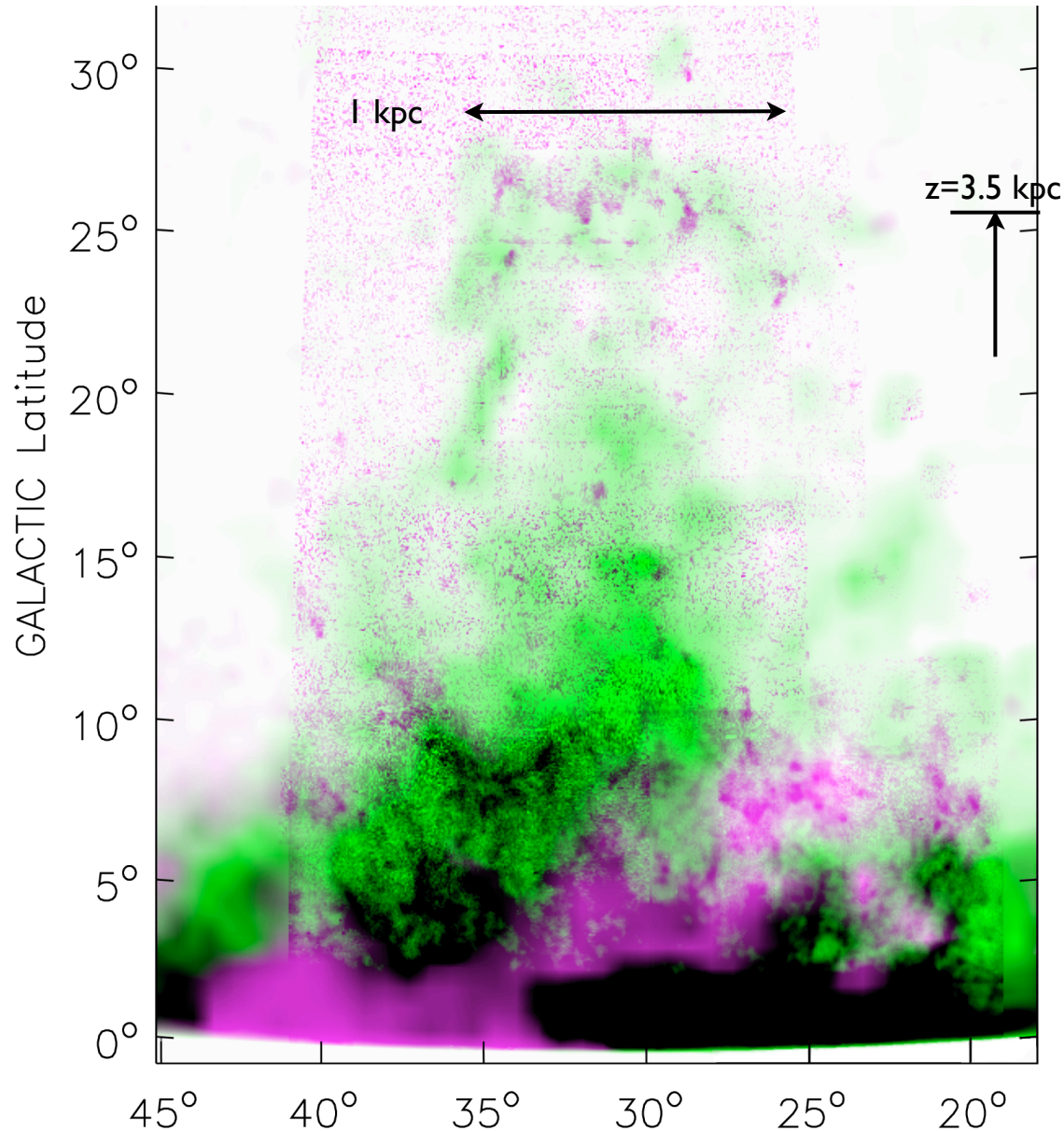


A GBT Survey of HI around longitude  $30^\circ$   
PhD Thesis of Yuriï Pidopryhora -- Ohio Univ., NRAO, JIVE  
(see poster this meeting)



# The Ophiucus superbubble: a starburst in the inner Galaxy?

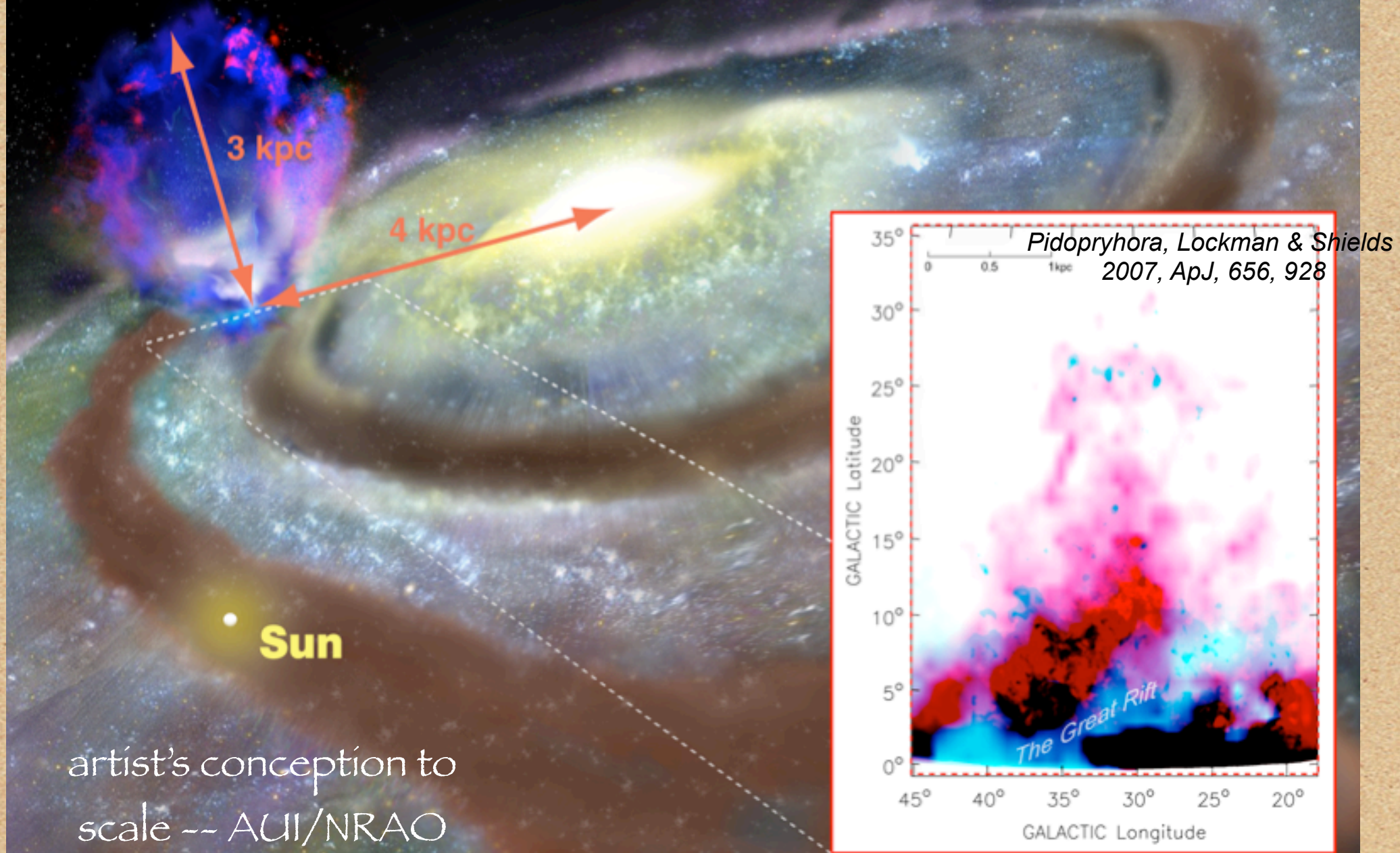
HI from GBT  
H $\alpha$  from WHAM



A coherent structure to  
more than 3 kpc above the disk.  
A cap 1 kpc across,  
HI mass  $10^6 M_{\odot}$   
Equal amount in H $^+$   
Age 30 Myr  
 $E = 10^{53}$  ergs  
Cap lags behind Galactic rotation

*Pidopryhora, Lockman & Shields 2007,  
ApJ, 656, 928*

# The Ophiucus superbubble: a starburst in the inner Galaxy?





### III. HI coming down

## High Velocity Clouds

Not subject to Galactic Rotation

Not Part of the Galactic Disk

but they are coming...

*“There are several indications that a considerable flux of gas is constantly flowing into the galactic system, and that intergalactic gas probably makes up a large fraction of the mass of the universe...”*

*J. Oort 1969, Science, 224, 1158*

Complex H  
Smith's Cloud





# HVC Complex H -- interacting with the disk

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

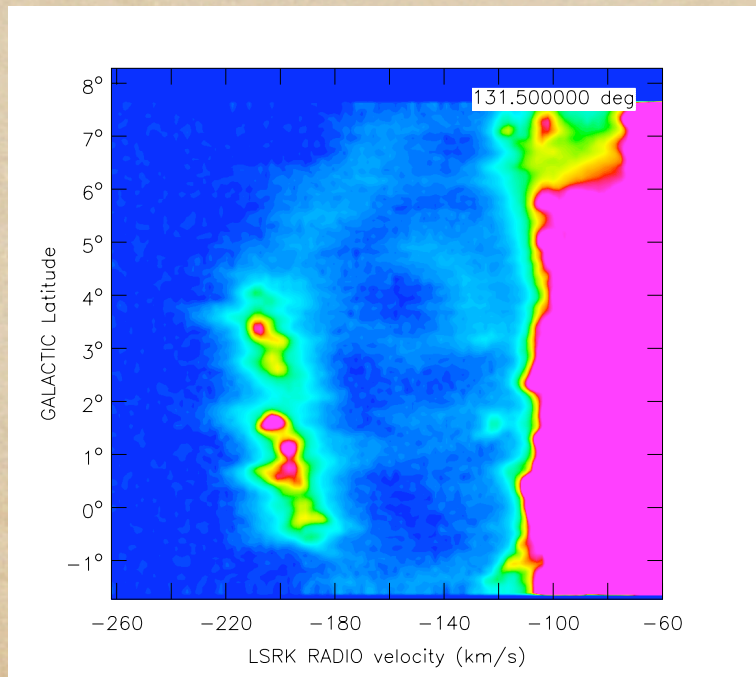
At  $b=0$

$$dV_{LSR}/db = V_z$$

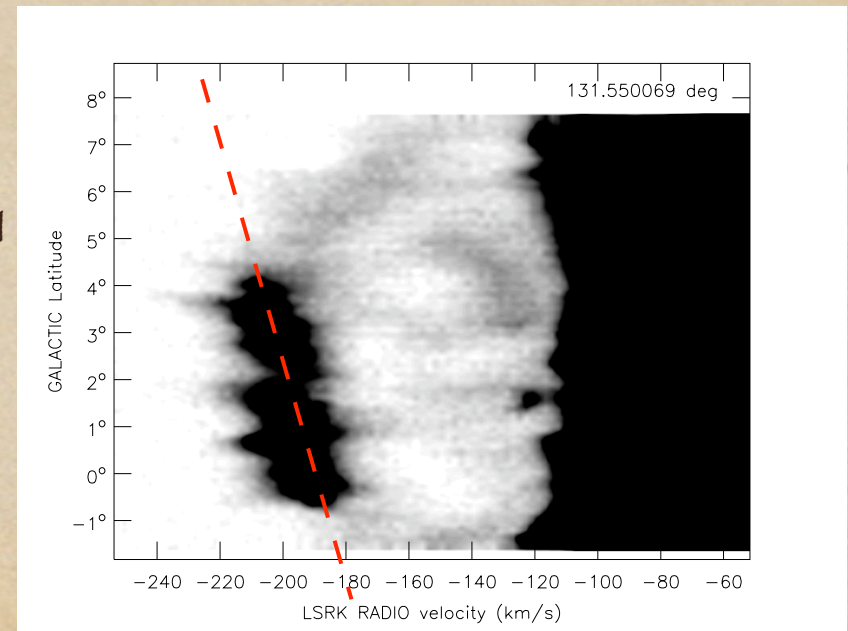
Lockman 2003, *ApJ*, 591, L33

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$$-3 \text{ km s}^{-1} \text{ deg}^{-1} \Rightarrow V_z = -170 \text{ km s}^{-1}$$

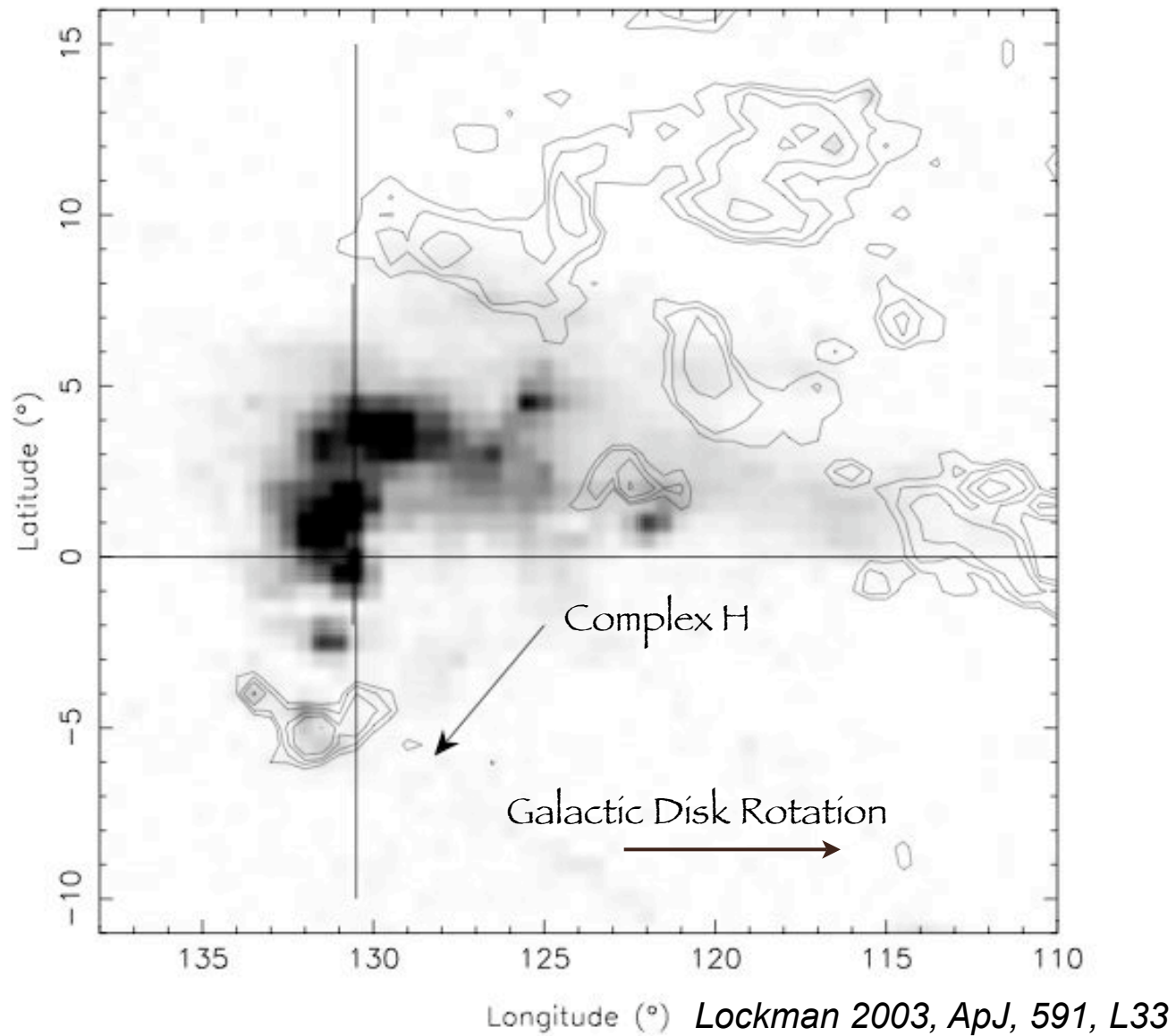


GBT HI





# Complex H: A Milky Way Satellite in a Retrograde Orbit

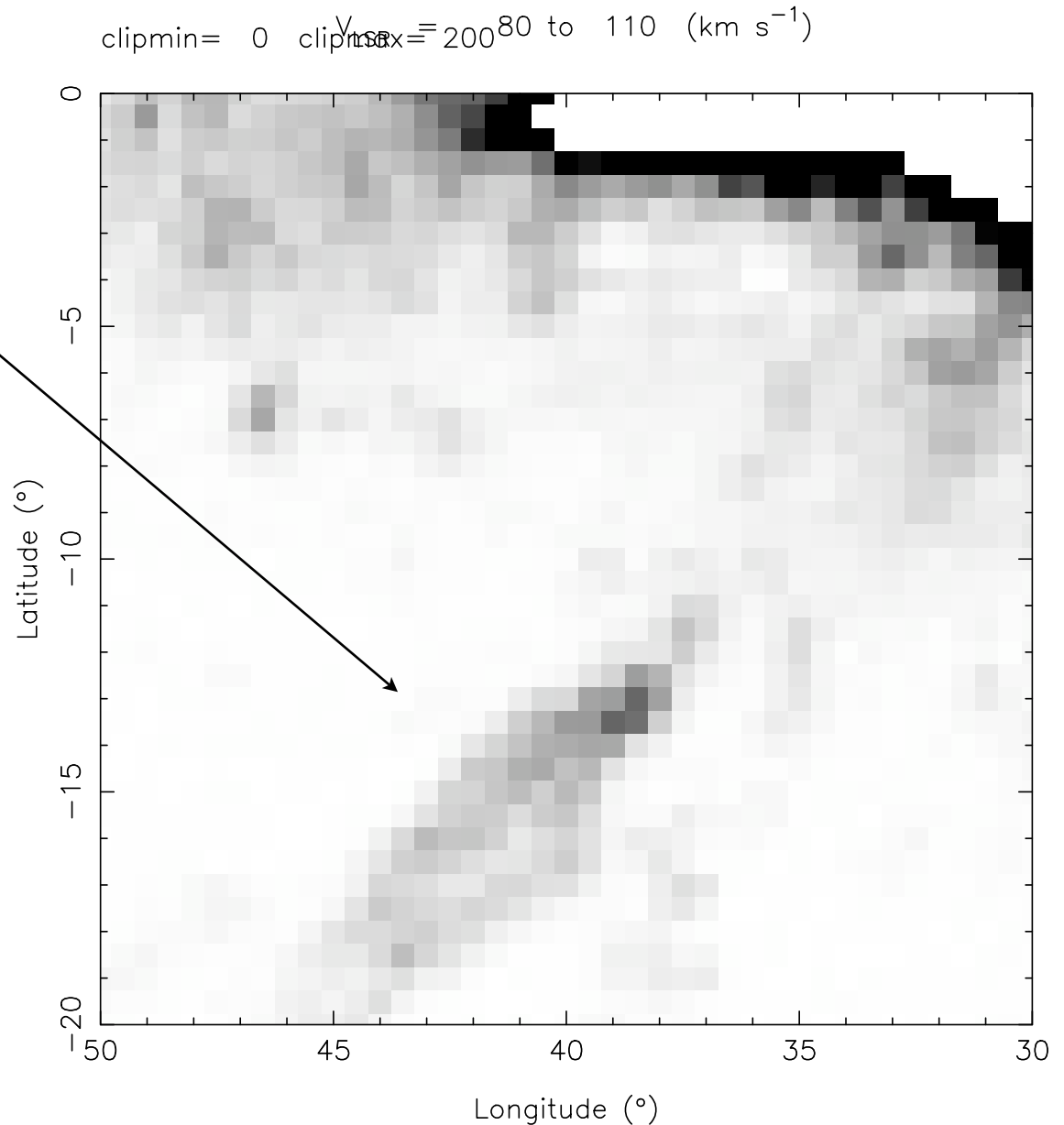




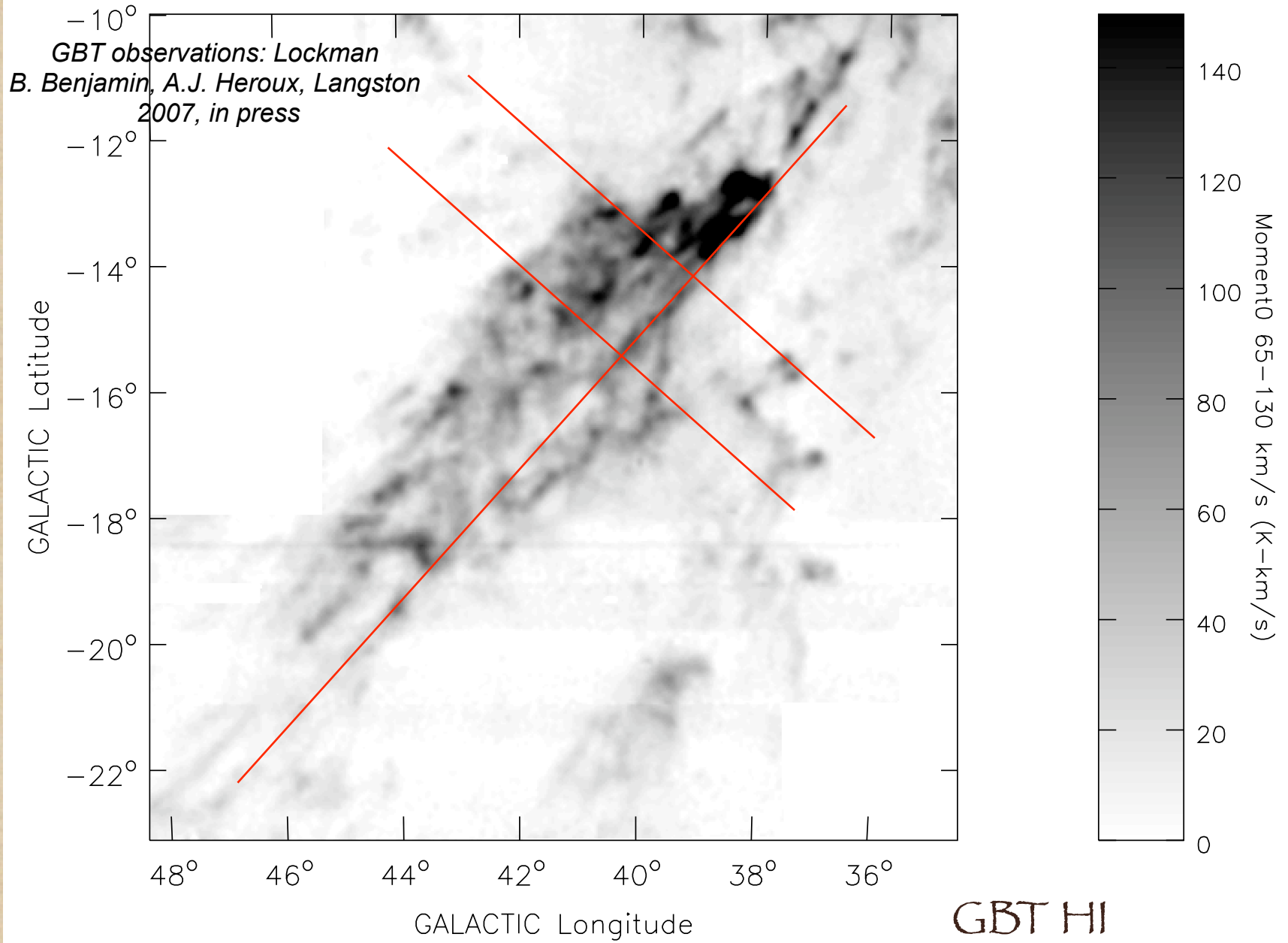
# Smith's Cloud: Another HVC interacting with the Milky Way Disk

Smith's Cloud  
Leiden-Dwingeloo Survey  
36' resolution

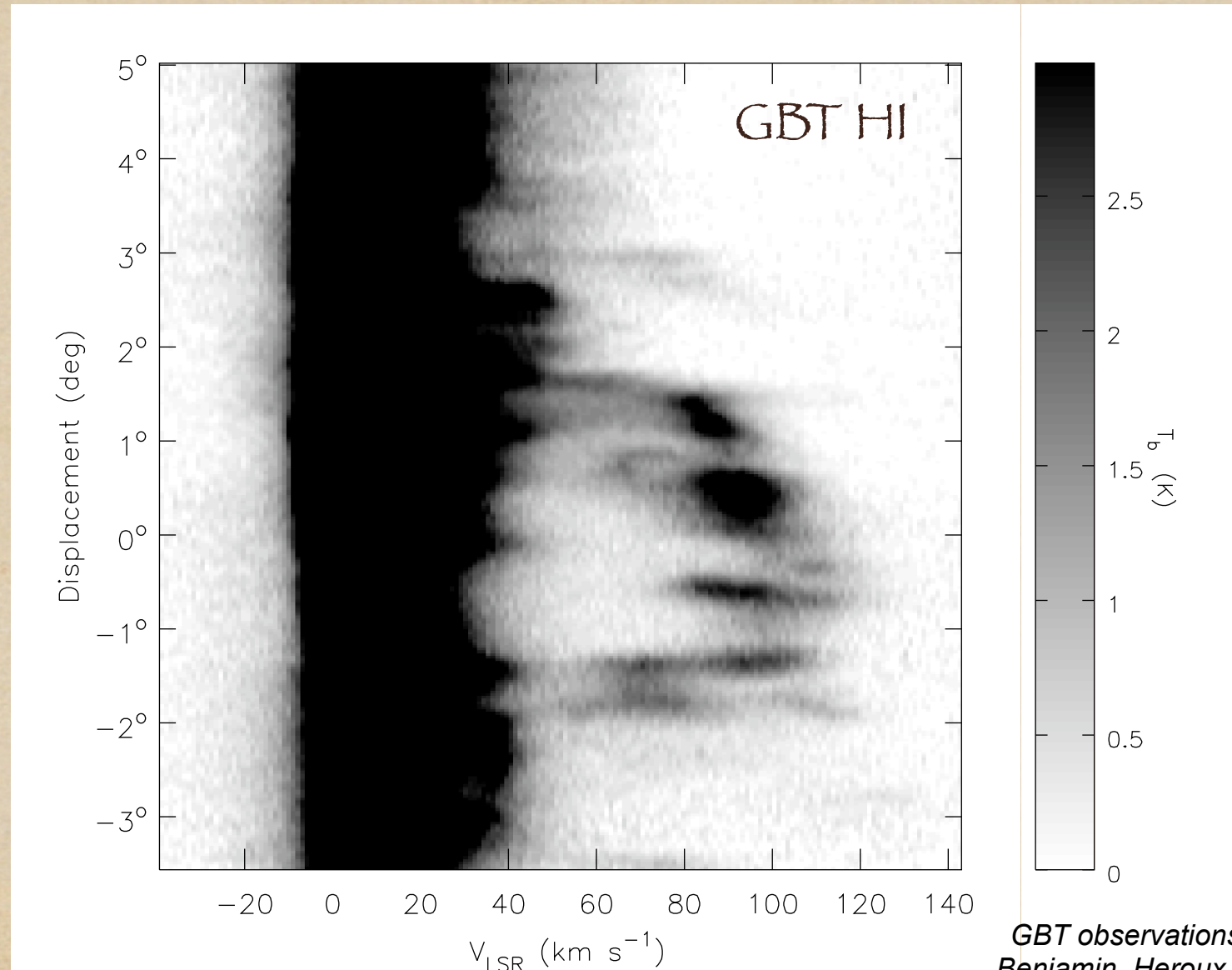
*Smith, G. 1963 BAN, 17, 203*



Smith's Cloud newbase Moment0 1Jan07



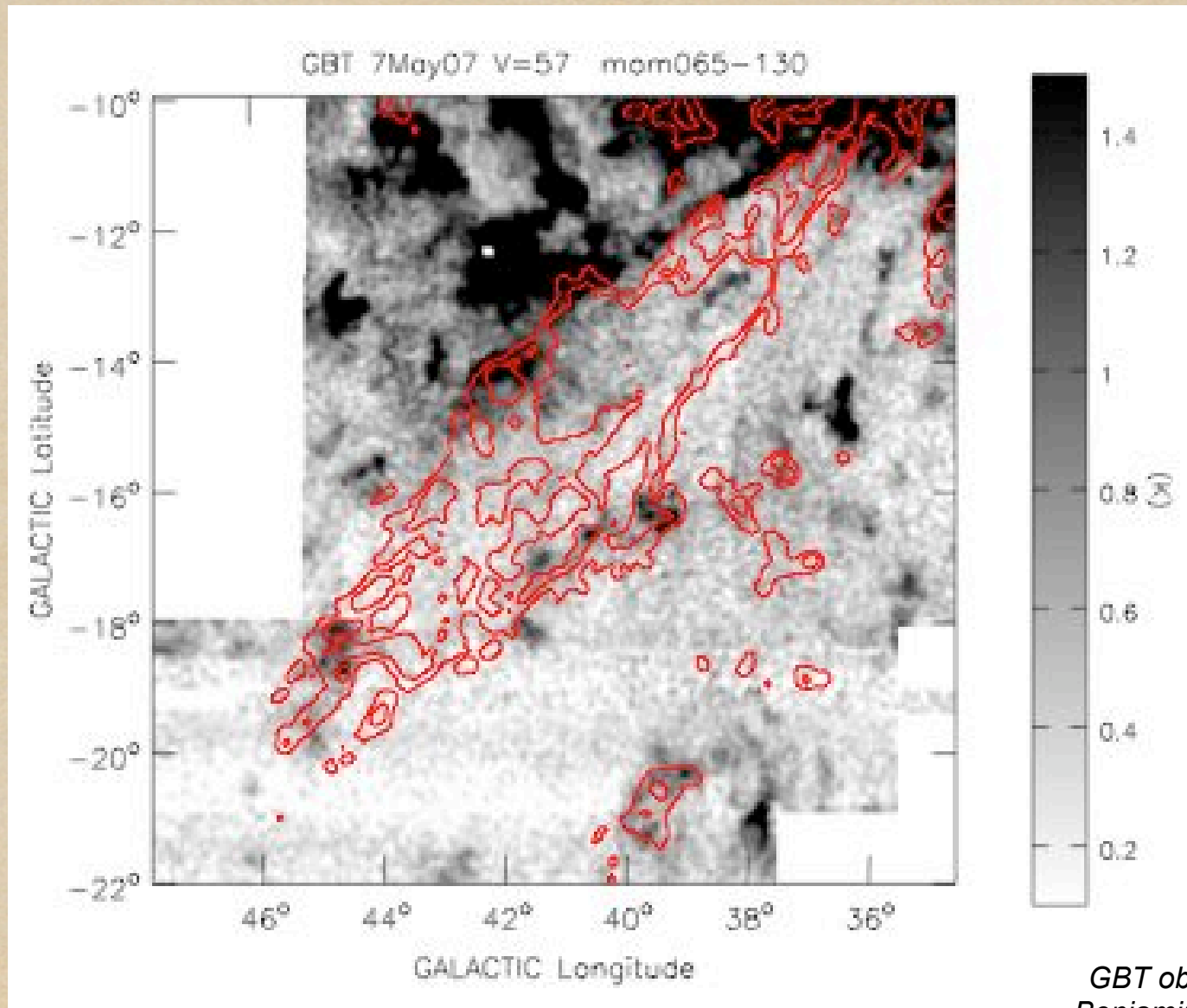
# The Edges of Smiths Cloud are being decelerated by its interaction with the Milky Way Disk



GBT observations: Lockman  
Benjamin, Heroux, & Langston  
2007, in press

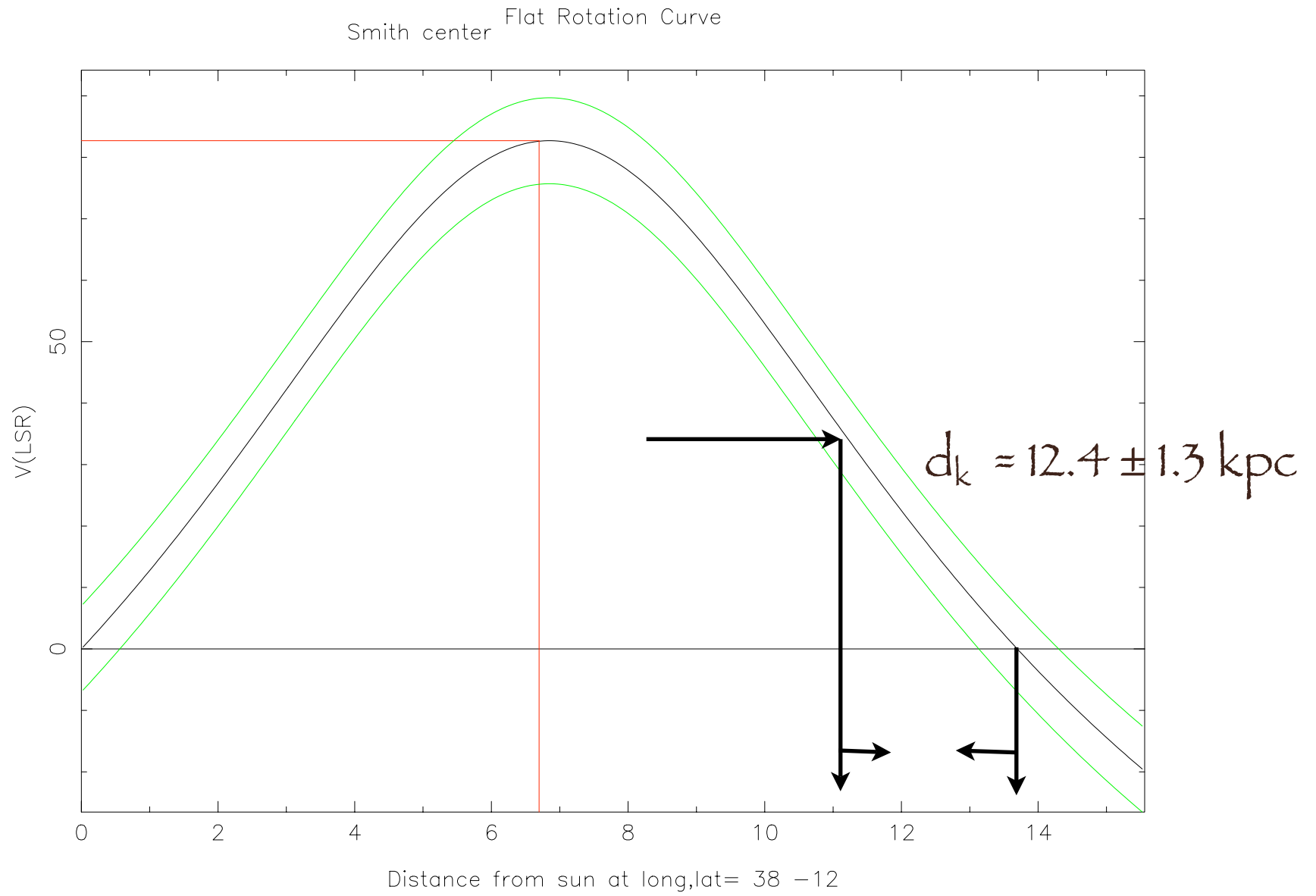


# Smith's Cloud: Interacting with disk gas



GBT observations: Lockman  
Benjamin, Heroux, & Langston  
2007, in press

# Velocity of disk gas towards Smith's Cloud limits its distance





Properties of two accreting HVCs  
(careful -- very preliminary numbers)

	Complex H*	Smith's Cloud**
Distance (kpc)	$27 \pm 9$	11-14
$R_{gal}$ (kpc)	$33 \pm 9$	$7 \pm 1?$
HI Mass ( $M_{\odot}$ )	$> 6 \times 10^6$	$> 10^6$
Total Extent (kpc)	$10 \times 5$	$3 \times 1$
$z$ (peak NH)	0	-2.5 kpc
"orbit"	inclined, retrograde	???

\* from Lockman, 2003 ApJ 591, L33

see also Simon, Blitz, Cole, Weinberg & Cohen 2006, ApJ, 640, 270

\*\* from Lockman, Benjamin, Heroux & Langston 2007 (in press)



It would be interesting to know ...

The physical state of halo clouds

The past location of HVCs

Vertical motions of halo clouds

An accurate census

Why don't halo clouds and HVCs disperse?



Prospects for progress are excellent,  
however...

“The future is an abstract dog who comes when you whistle. That is, if you are a candidate for office, high or low. For the rest of us, the future is a real dog, that bites you when you least expect it.”

--Andre Codrescu (1994) in Zombification

