Diffuse HI and the Evolution of Galaxies: The New Frontier

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GBT Collaborations

- Caltech -- CCB
- Univ. Maryland -- Zspectrometer
- Univ. Penn, NIST -- MUSTANG
- UC Berkeley, WVU -- GUPPI
- UC Berkeley -- New Spectrometer
- BYU -- FLAG
- Nanograv
- Caltech, Stanford -- mm-cameras

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We’re faced with fundamental questions about the origin, growth and evolution of galaxies like the Milky Way.

MILKY WAY

History of star formation
Chemical Evolution
Structure and stability of the disk
The warp

Dynamics of the local group
History of the Magellanic clouds and effects on the Milky Way
Mass and energy flows between the disk, halo, group medium, IGM
Connections between dark and luminous matter
Fossil record of galaxy formation

All need sensitive HI observations

Hydrogen is abundant and observable

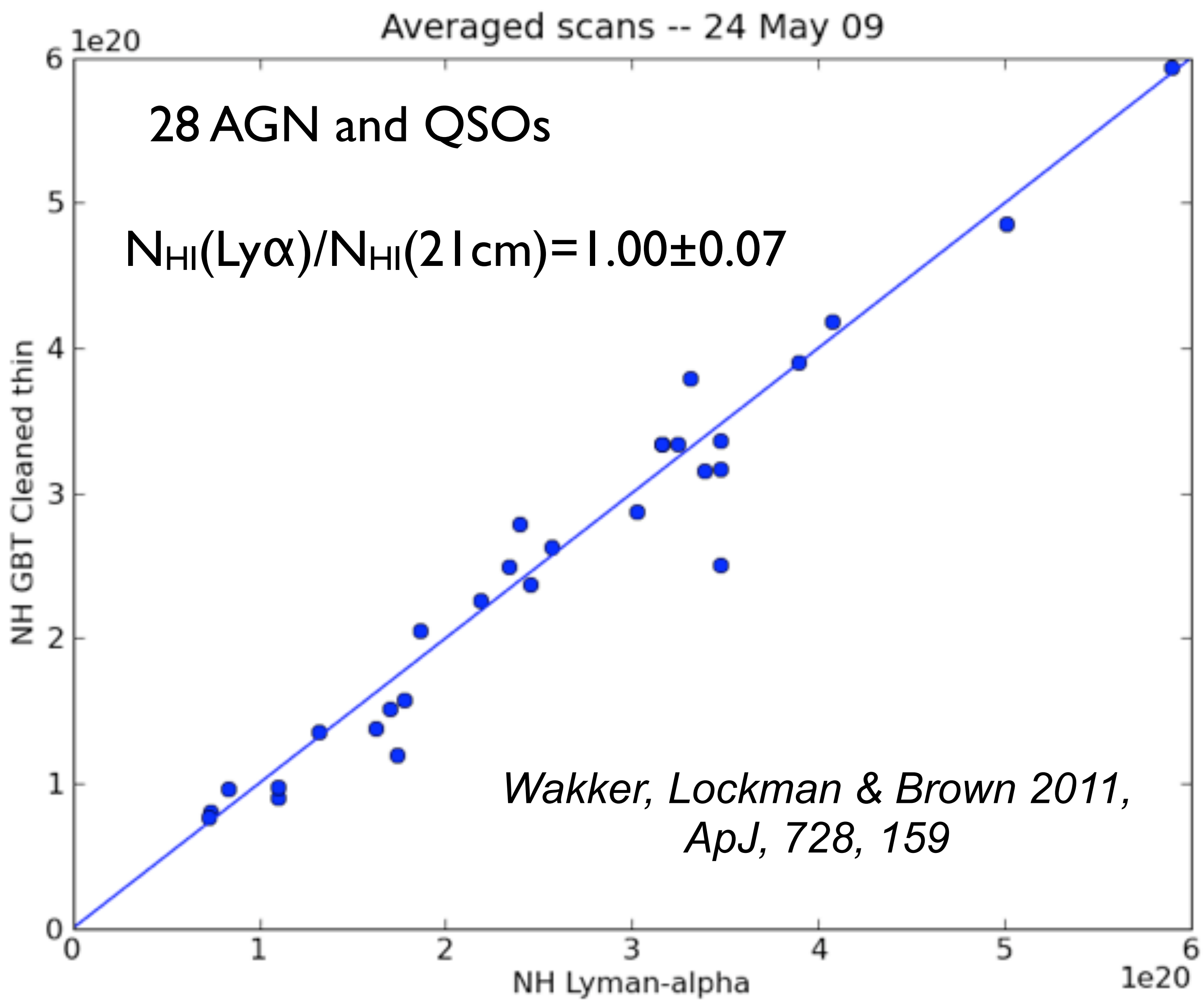
Key to understanding the growth
and evolution of galaxies

UV absorption lines
H+ emission lines
21cm in the radio

CONCLUSIONS

1) There is a lot to learn from the largely unexplored $N_{HI} << 10^{19}$ cm^{-2}
2) Current facilities can produce exciting results
3) Modest investments give significant improvements
4) The SKA promises even more, but...
5) No Bed of Procrustes for U.S. Astronomy

We know how to make accurate N_{HI} measurements



Agreement between GBT 21cm and HST Lyα values of N_{HI}

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Observing the 21cm line in emission

$$\sigma_T = \frac{20}{f\ (25000 \times 2 \times t_s)^{\frac{1}{2}}} \quad (\mathrm{K})$$

$$\sigma_T = 90\ f^{-1}\ t_s^{-\frac{1}{2}} \quad (\mathrm{mK})$$

$$T_b = 2.1\ \frac{\mathrm{N_{HI}}}{10^{20}}\ \Omega \quad \mathrm{K}$$

A 3σ detection takes

$$t = 1.6 \times 10^{-2}\ f^{-2}\ \Omega^{-2}\ \mathrm{N_{HI20}^{-2}} \quad (\mathrm{s})$$

τ<<1
5 km/s channel width
3σ detection
ΔV=25 km/s
no bandpass issues
f≤1 is surface brightness efficiency
Ω≤1 is beam dilution

Surface brightness efficiency factors

Instrument	f
GBT	~ 1
Arecibo	~ 1
EVLA-D	$\sim 10^{-2}$
EVLA-C	$\sim 10^{-3}$
EVLA-B	$\sim 10^{-4}$
ATA	$\sim 10^{-2}$
ASKAP	$\sim 10^{-3}$

Deep 21cm Surveys

from Popping (2010), PhD thesis, University of Groningen,

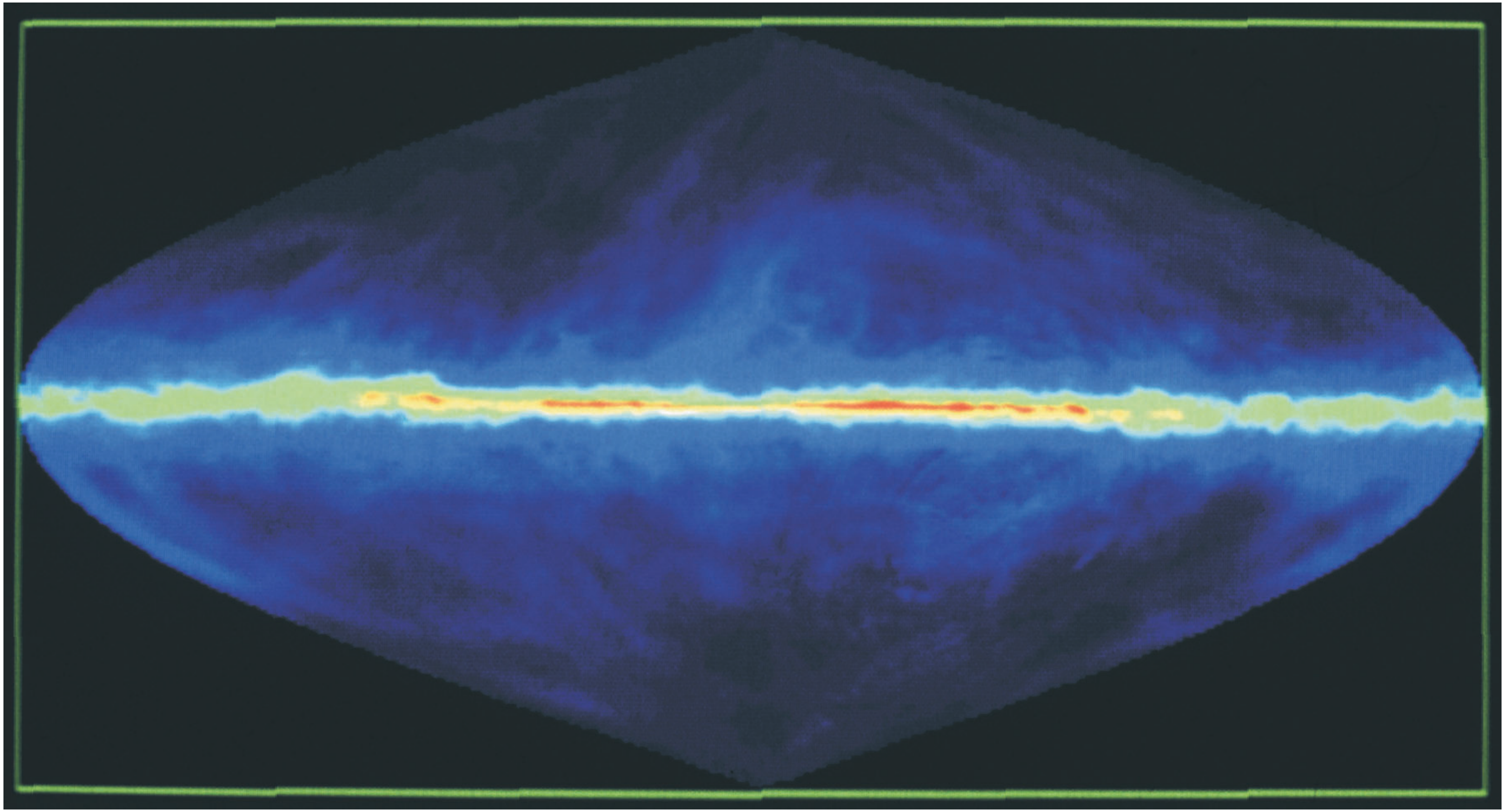
Survey	Beam [']	Area [deg^2]	δv [km s^{-1}]	rms(Flux)[a]	rms(N_{HI})[b]	Ref
AHISS	3.3	13	16	0.7	3.5e17	*c*
ADBS	3.3	430	34	3.3	1.7e18	*d*
WSRT WVF	49	1800	17	18	4.1e16	*e*
Nancay CVn	4 × 20	800	10	7.5	5.2e17	*f*
HIPASS	15.5	30000	18	13	3.0e17	*g*
HI-ZOA	15.5	1840	18	13	3.0e17	*h*
HIDEEP	15.5	32	18	3.2	7.4e16	*i*
HIJASS	12	1115	18	13	5.0e17	*j*
J-Virgo	12	32	18	4	1.5e17	*k*
AGES	3.5	200	11	0.7	3.2e17	*l*
ALFALFA	3.5	7074	11	1.7	7.7e17	*m*

$4\sigma < 10^{18}$

Table 1.1: Comparison of Blind H I Surveys: *(a)*: mJy beam^{-1} at 18 km s^{-1}, *(b)*: cm^{-2} over 18 km s^{-1}, *(c)*: Zwaan et al. (1997), *(d)*: Rosenberg & Schneider (2000), *(e)*: Braun et al. (2003), *(f)*: Kraan-Korteweg et al. (1999), *(g)*: Barnes et al. (2001), *(h)*: Henning et al. (2000), *(i)*: Minchin et al. (2003), *(j)*: Lang et al. (2003), *(k)*: Davies et al. (2004), *(l)*: Minchin et al. (2007), *(m)*: Giovanelli et al. (2007)

The Plane of a Spiral Galaxy

$N_{HI} \geq 10^{22}$
$T_b = 200$ K
$t \approx 10^{-6} f^{-2}$ s

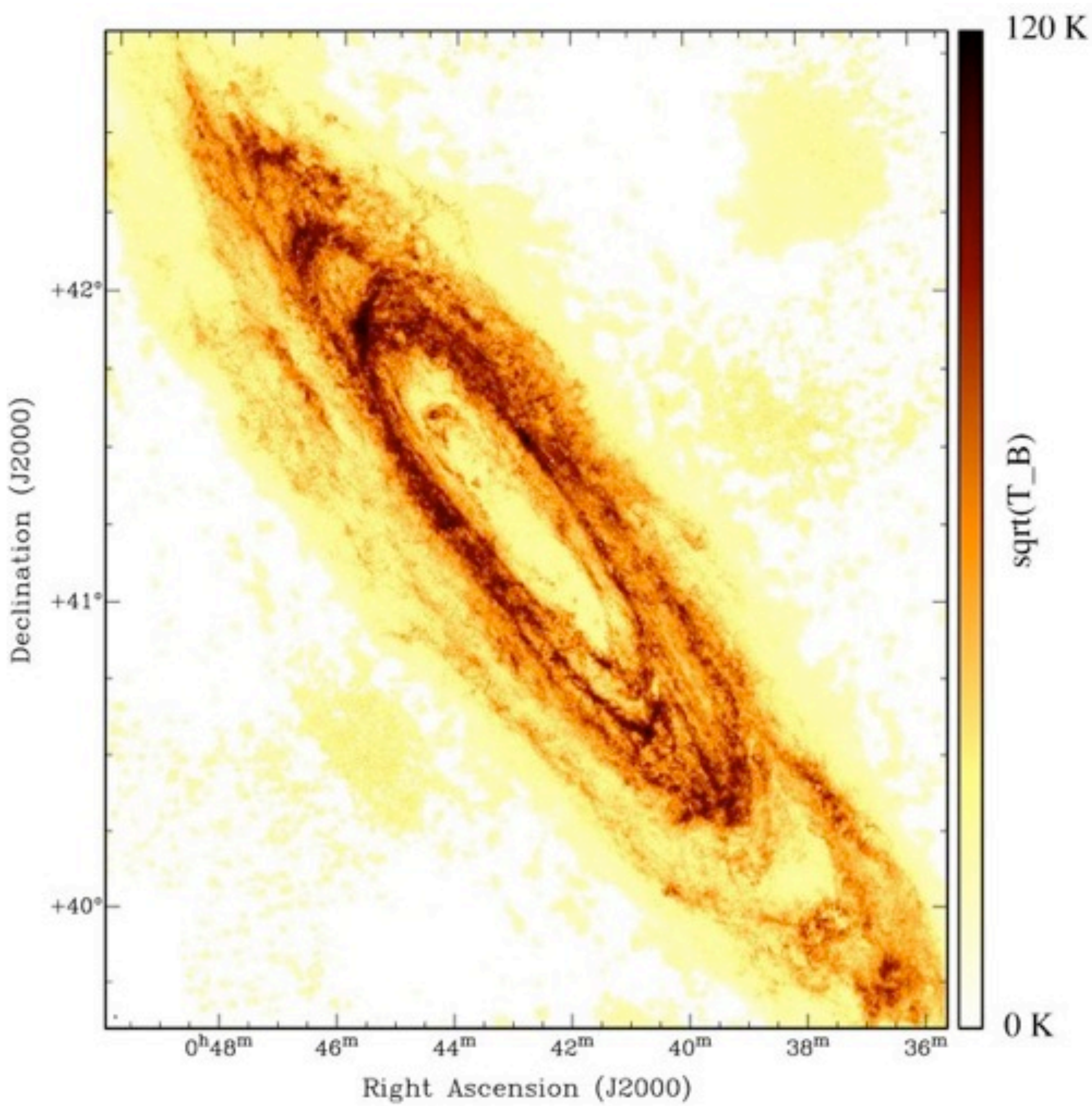


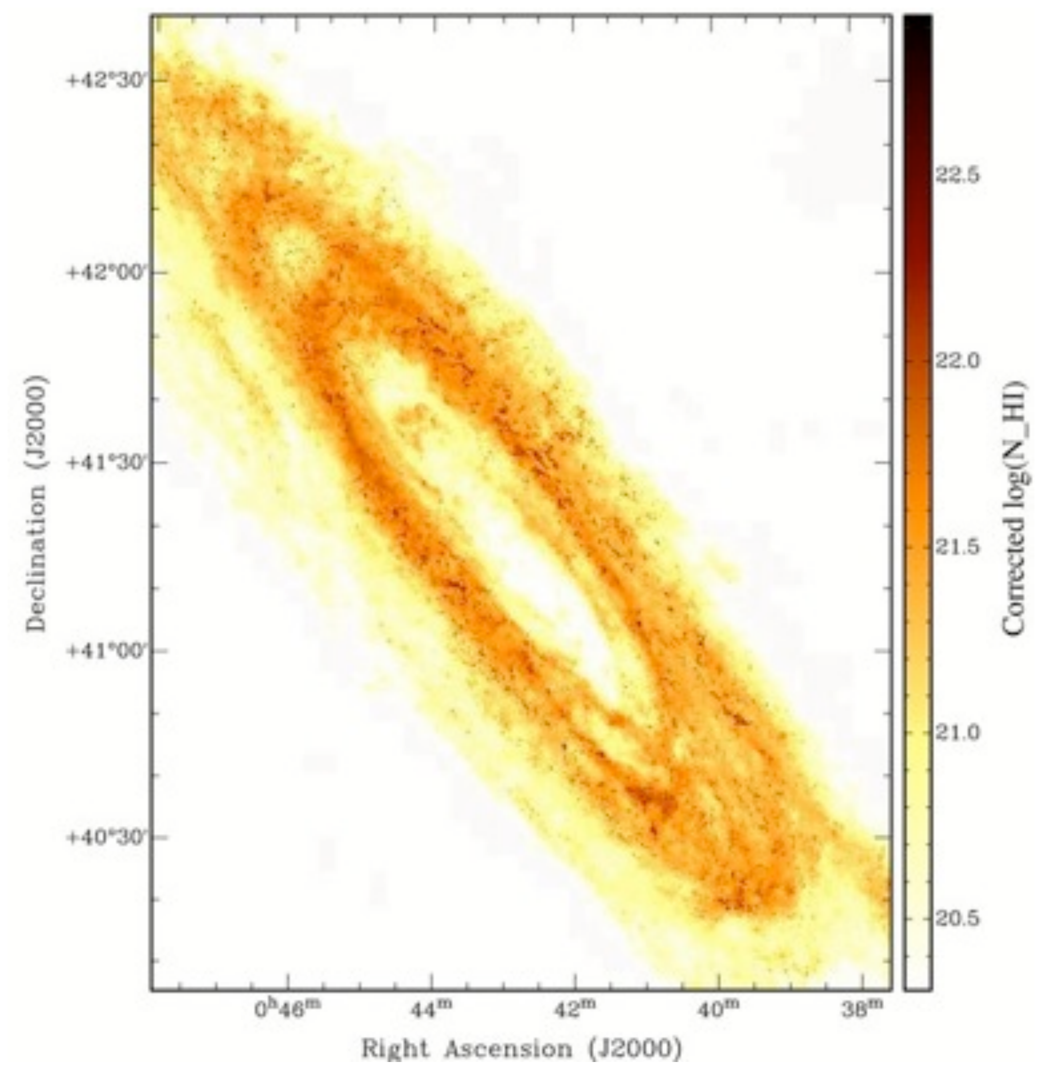
Dickey & Lockman 1990, ARAA, 28, 215

Through the spiral arms of galaxies

$N_{HI} = 10^{21.5}$
$T_b = 65$ K
$t \approx 2\times10^{-5} f^{-2}$ s

M31 WSRT + GBT

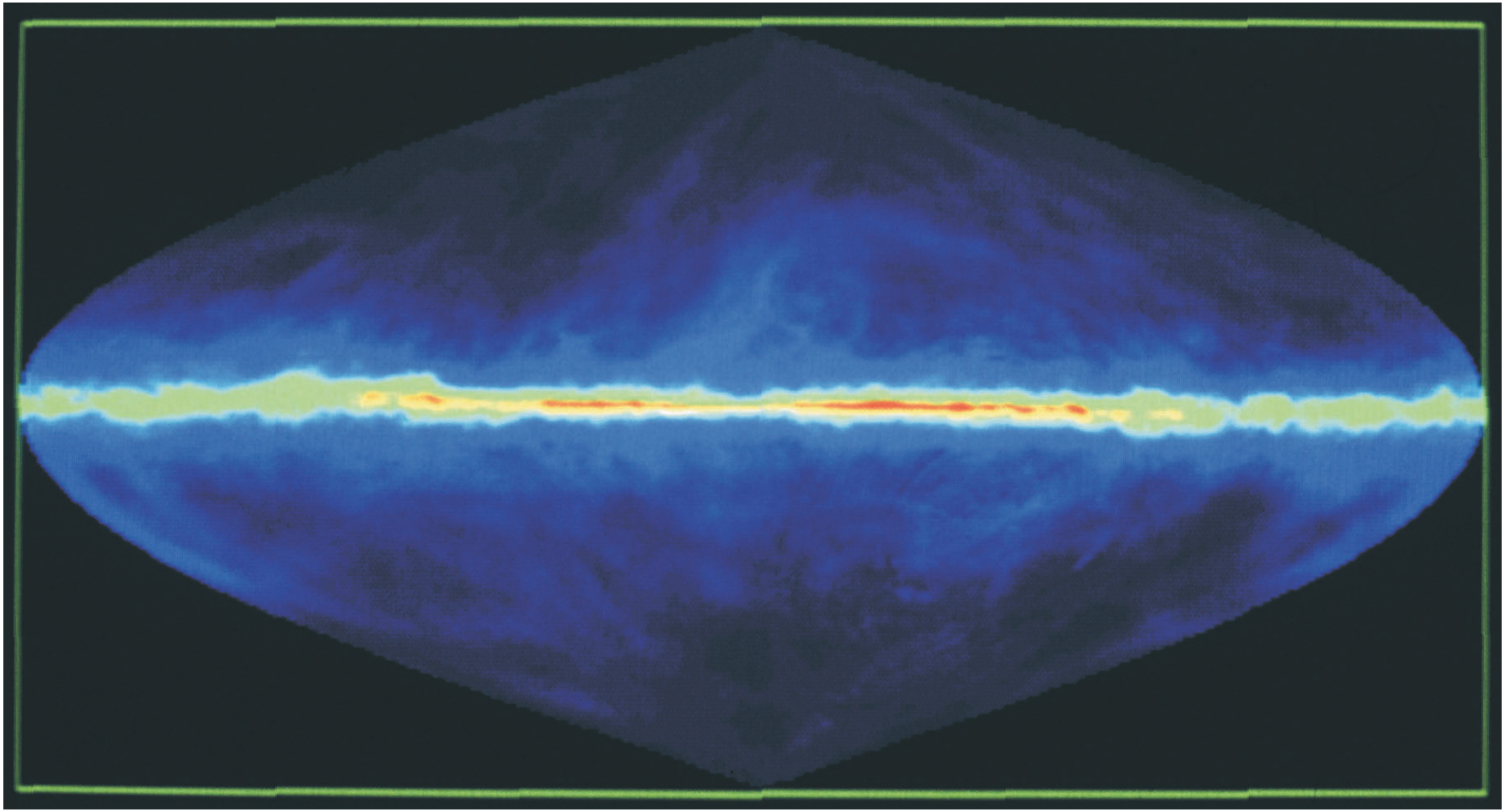




Braun et al. 2009, ApJ, 695, 937

Vertically through the disk at R_0

$N_{HI} = 10^{20.5}$
$T_b = 6.5$ K
$t \approx 2 \times 10^{-3} f^{-2}$ s

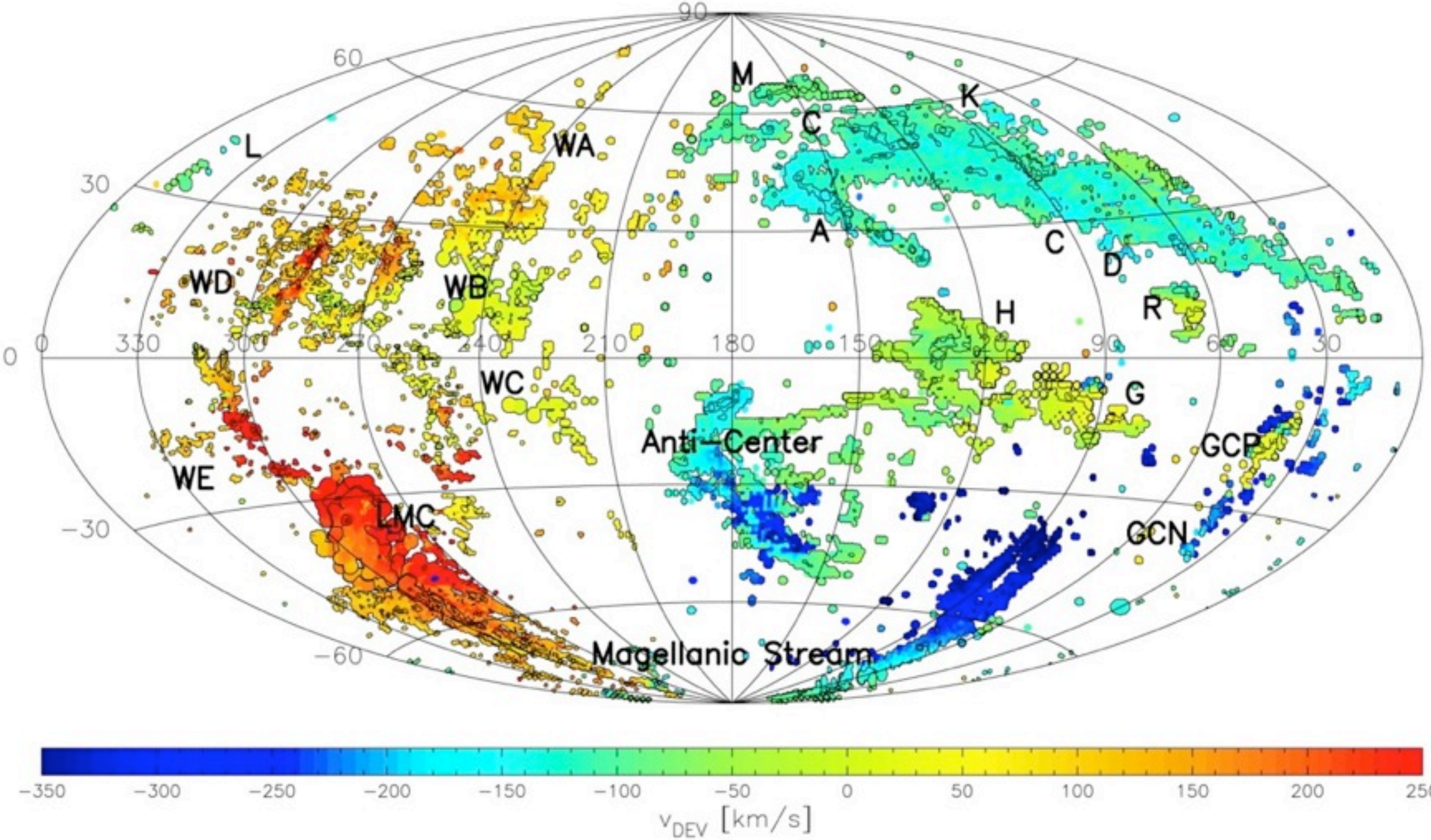


Dickey & Lockman 1990, ARAA, 28, 215

Brighter parts of high-velocity clouds

$N_{HI} = 10^{20}$
$T_b = 2$ K
$t \approx 2 \times 10^{-2} f^{-2}$ s

Accretion of satellites, fountain, or cold flow?



From Bart Wakker

Brighter parts of high-velocity clouds

$N_{HI} = 10^{20}$
$T_b = 2$ K
$t \approx 2\times10^{-2} f^{-2}$ s

dist = 12.4 ± 1.3 kpc
R = 7.6 ± 1.0 kpc
z = -2.2 kpc
$M_{HI} > 10^6 M_\odot$
$M_{H+} \approx 3\times10^6 M_\odot$
size ≈ 3 x 1 kpc
[N\H] = 0.14 - 0.44

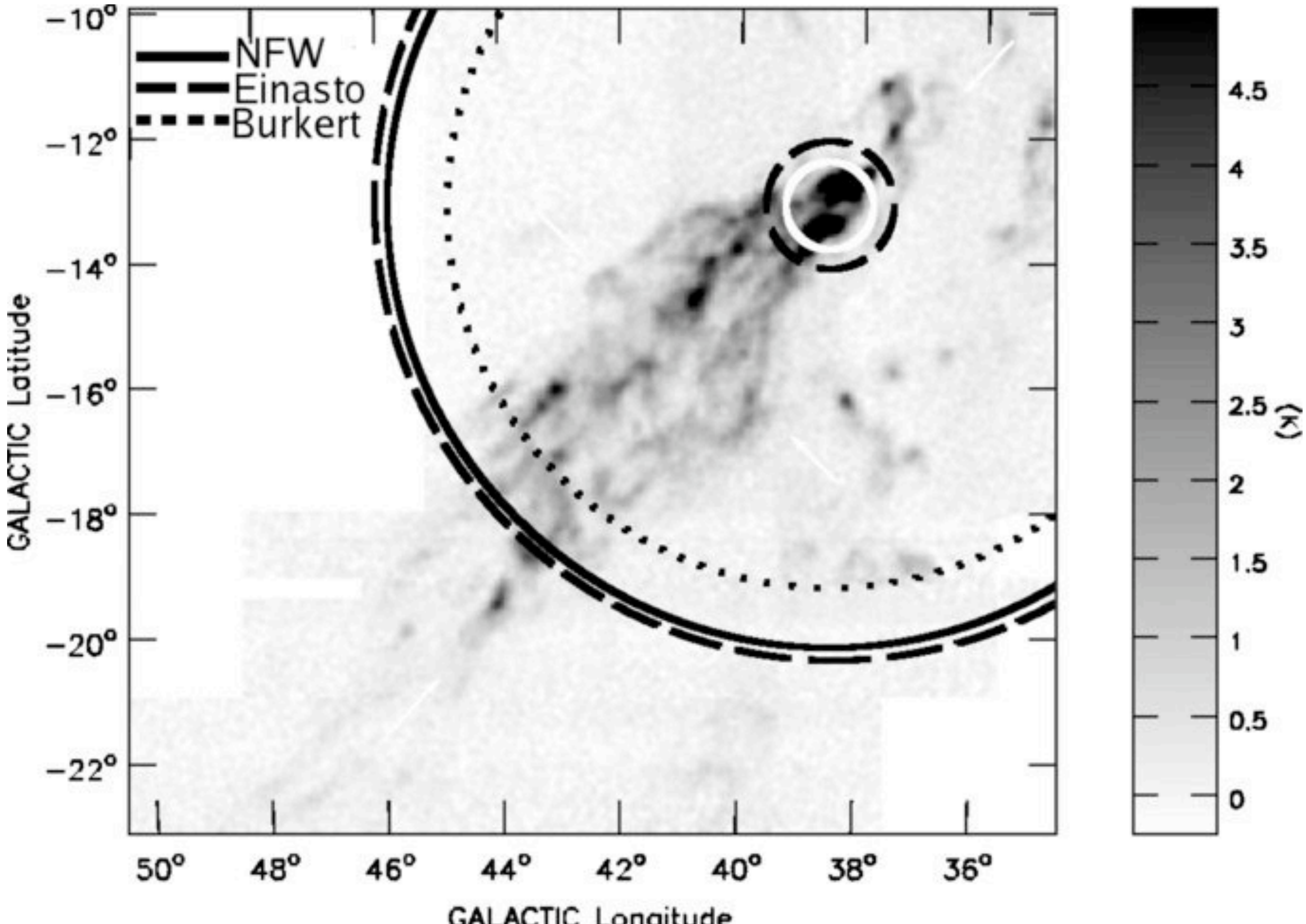
$V_{tot} \approx 300$ km/s
Will impact the disk
in 30 Myr

Lockman et al. 2008, ApJ, 679, L21
Hill, Haffner & Reynolds 2009, ApJ, 703, 1832

The Smith Cloud: Dark Matter Confinement?

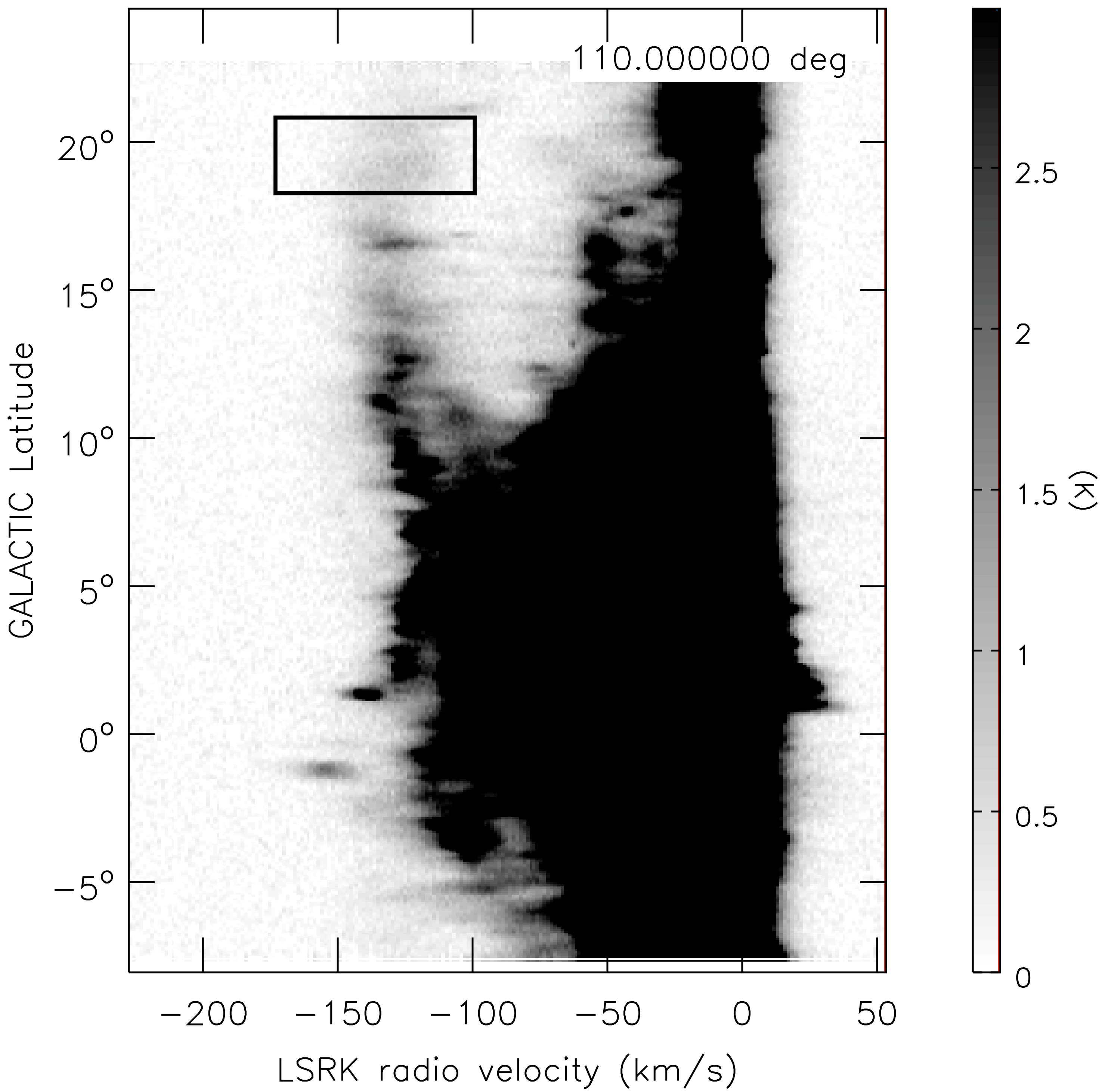
Nichols & Bland-Hawthorn 2009, ApJ, 707, 1642

N_{HI} = 10^{20}
T_b=2 K
$t \approx 2x10^{-2} f^{-2}$ s



The ragged edges of HI disks

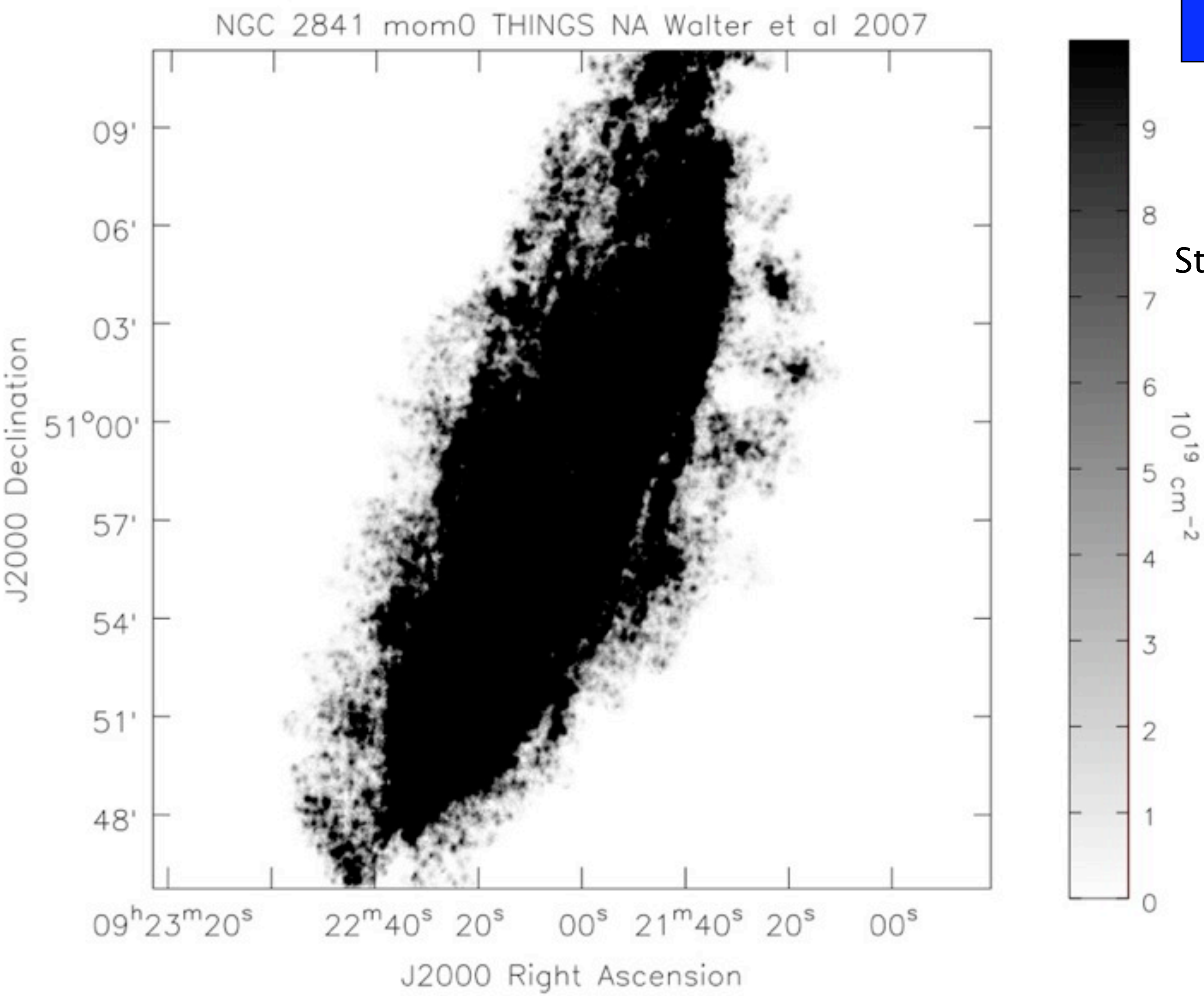
$N_{HI} = 10^{19.5}$
$T_b = 0.6$ K
$t \approx 0.2\ f^{-2}$ s



GBT observations of
The Milky Way Warp
$N_{HI} = 10^{19.5}$ at 20° latitude

The ragged edges of HI disks

$N_{HI} = 10^{19.5}$
$T_b = 0.6$ K
$t \approx 0.2 f^{-2}$ s



Structure, Accretion or outflow?

THINGS VLA Survey
Walter et al. 2008
at 30” resolution $3\sigma=10^{19.5}$
at 6” resolution $3\sigma=10^{20.5}$

The ragged edges of HI disks

HALOGAS WSRT Survey
Heald et al. 2011, in press
15” resolution to N_{HI} limit few 10^{19}
120 hours per galaxy

$N_{HI} = 10^{19}$
$T_b = 0.2$ K
$t \approx 2 f^{-2}$ s

G. Heald et al.: The WSRT HALOGAS survey. I.

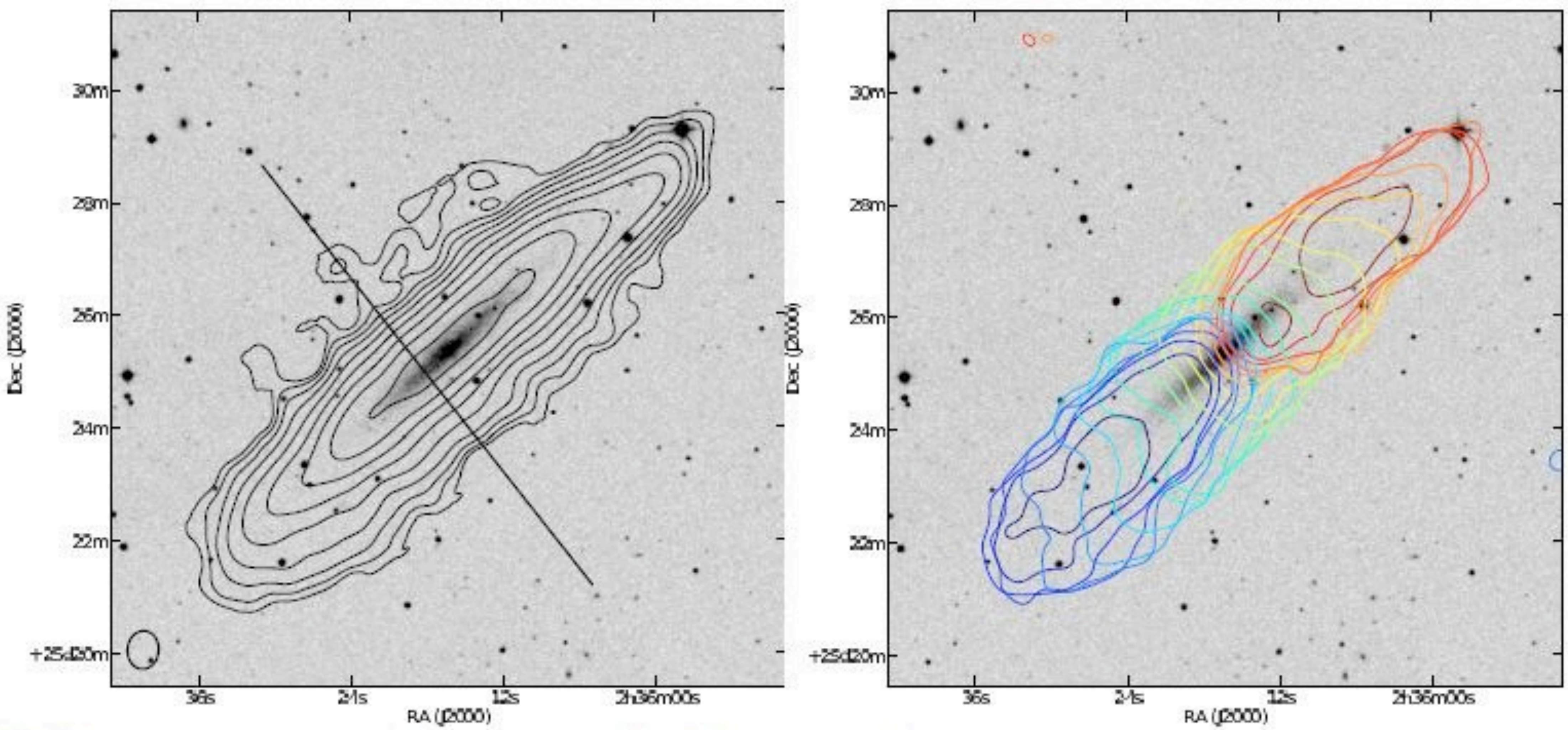
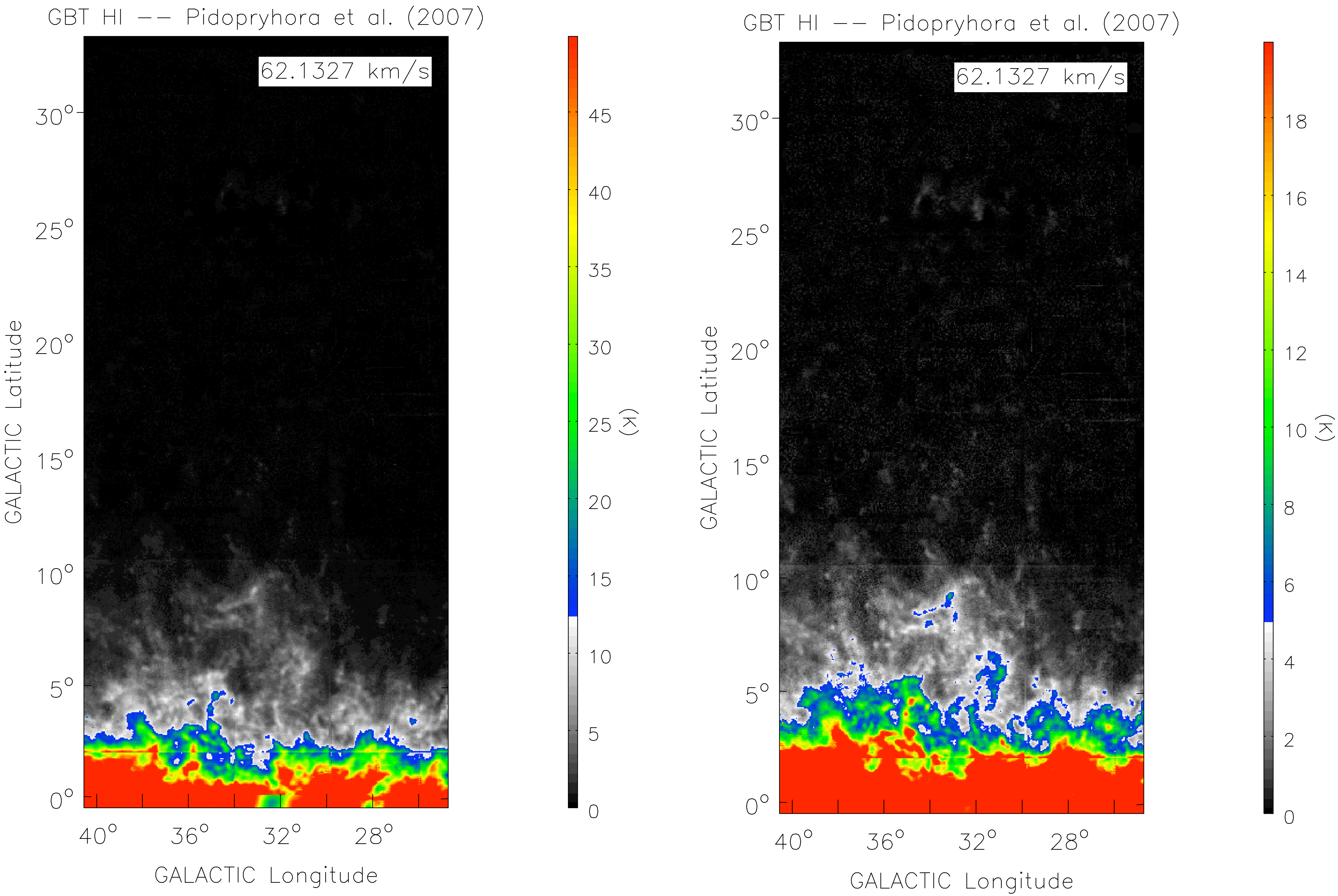


Fig. 1. Overview of the HALOGAS observations of UGC 2082. The *left panel* shows the H I total intensity overlaid on the DSS *R*-band image. The H I contours originate from the 30″-tapered image, begin at $N_{HI} = 1.0 \times 10^{19}$ cm^{-2} and increase by powers of two. The straight line shows the orientation of the PV slice shown in Fig. 2. The *right panel* shows an overlay of several channels in the lowest resolution data cube, all at a level of 0.9 mJy beam^{-1} ($\approx 3.75\sigma$). The contours are separated by 12.4 km s^{-1}, begin at 593 km s^{-1} (dark blue) and range upward to 815 km s^{-1} (dark red). *Both panels* show the same area of the sky. The beam size of the H I data is shown in the *lower left* corners of the *left panel*.

The Milky Way disk-halo transition

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

$N_{HI} = 10^{19}$
$T_b = 0.2$ K
$t \approx 2 f^{-2}$ s



The Milky Way disk-halo transition

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$N_{HI} = 10^{19}$
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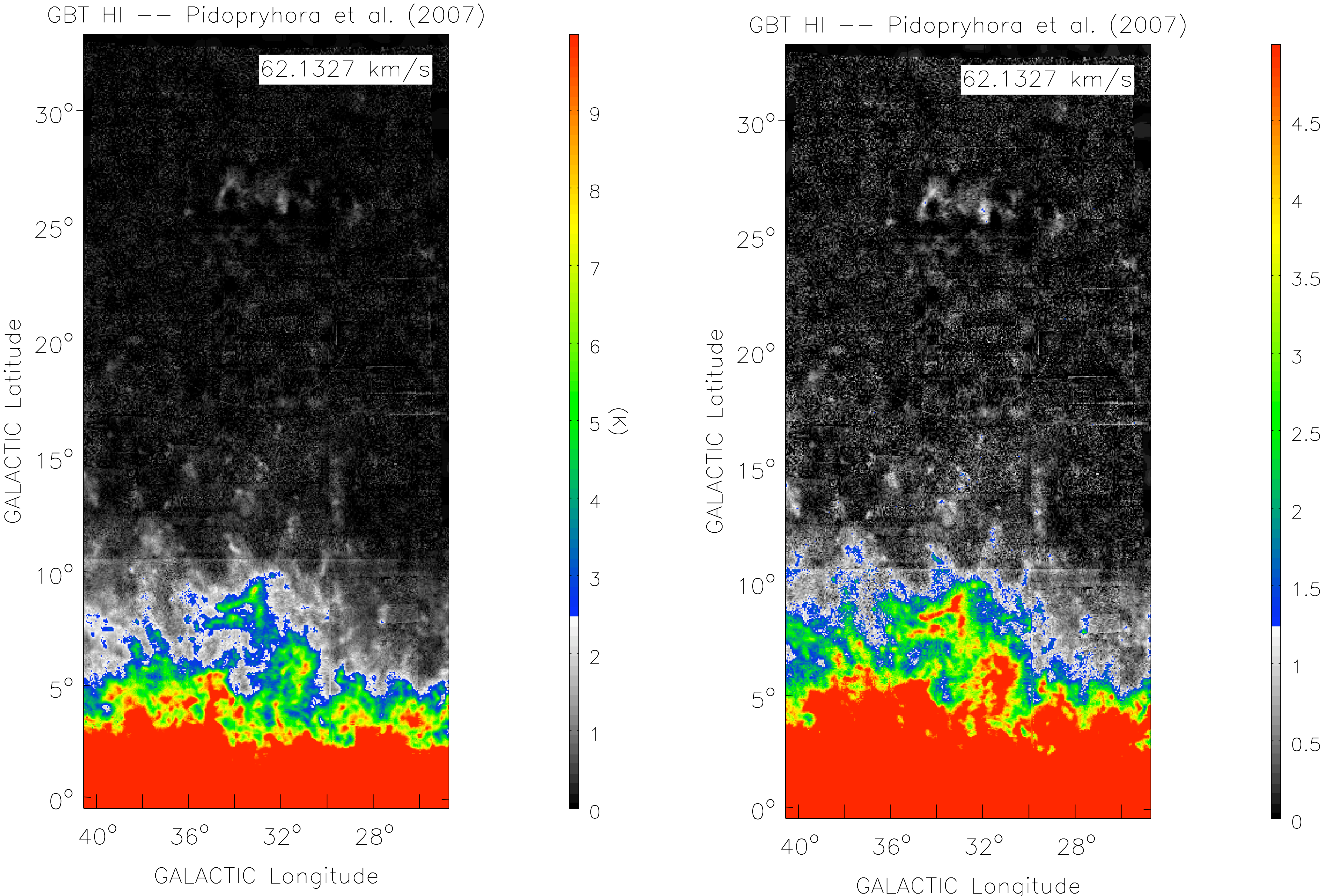
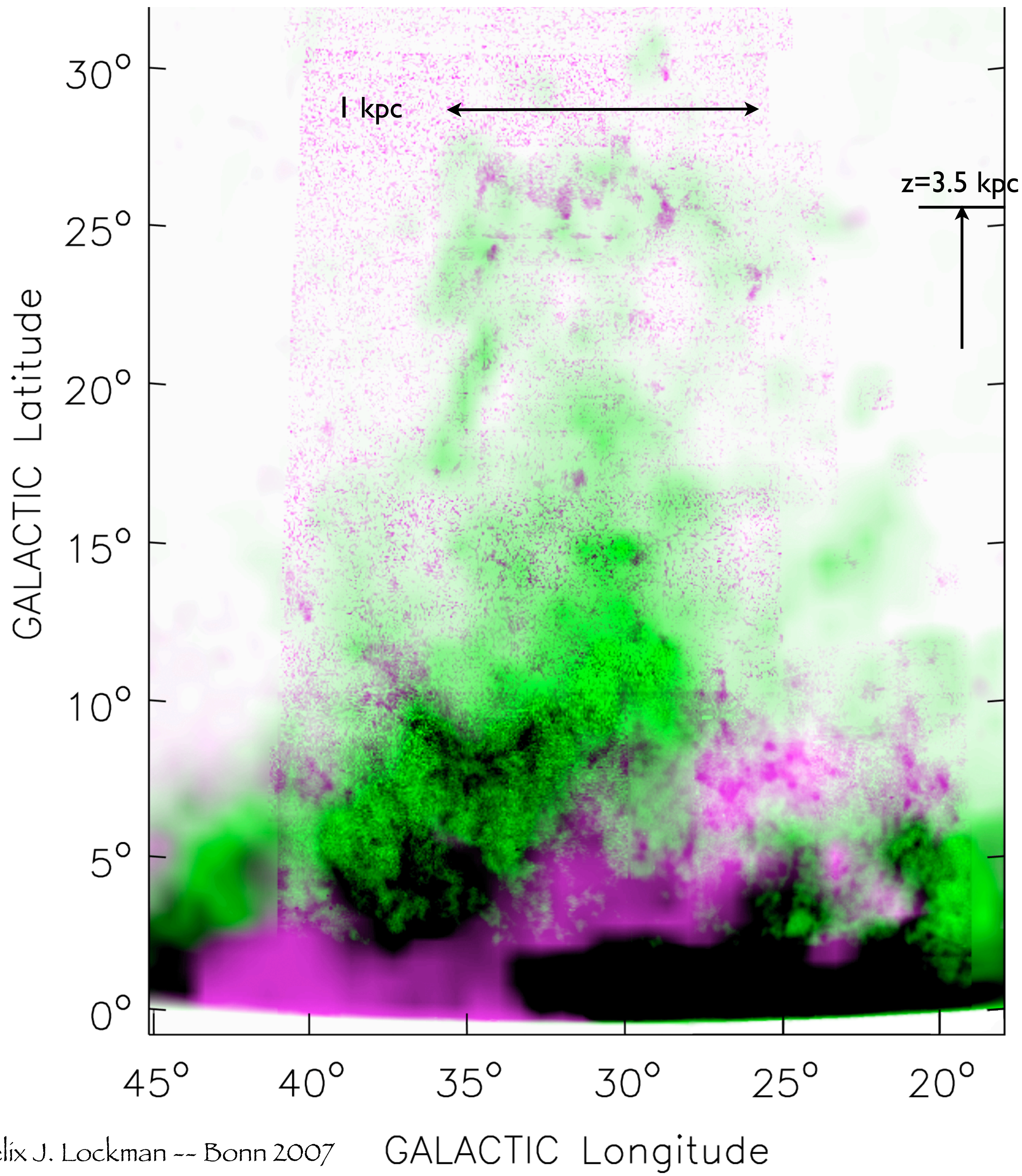


HI from GBT
Hα from WHAM

The Ophiucus superbubble: a starburst in the inner Galaxy?

$N_{HI} = 10^{19}$
$T_b = 0.2$ K
$t \approx 2 f^{-2}$ s



A coherent structure to more than 3 kpc above the disk.

HI mass 10^6 Mo

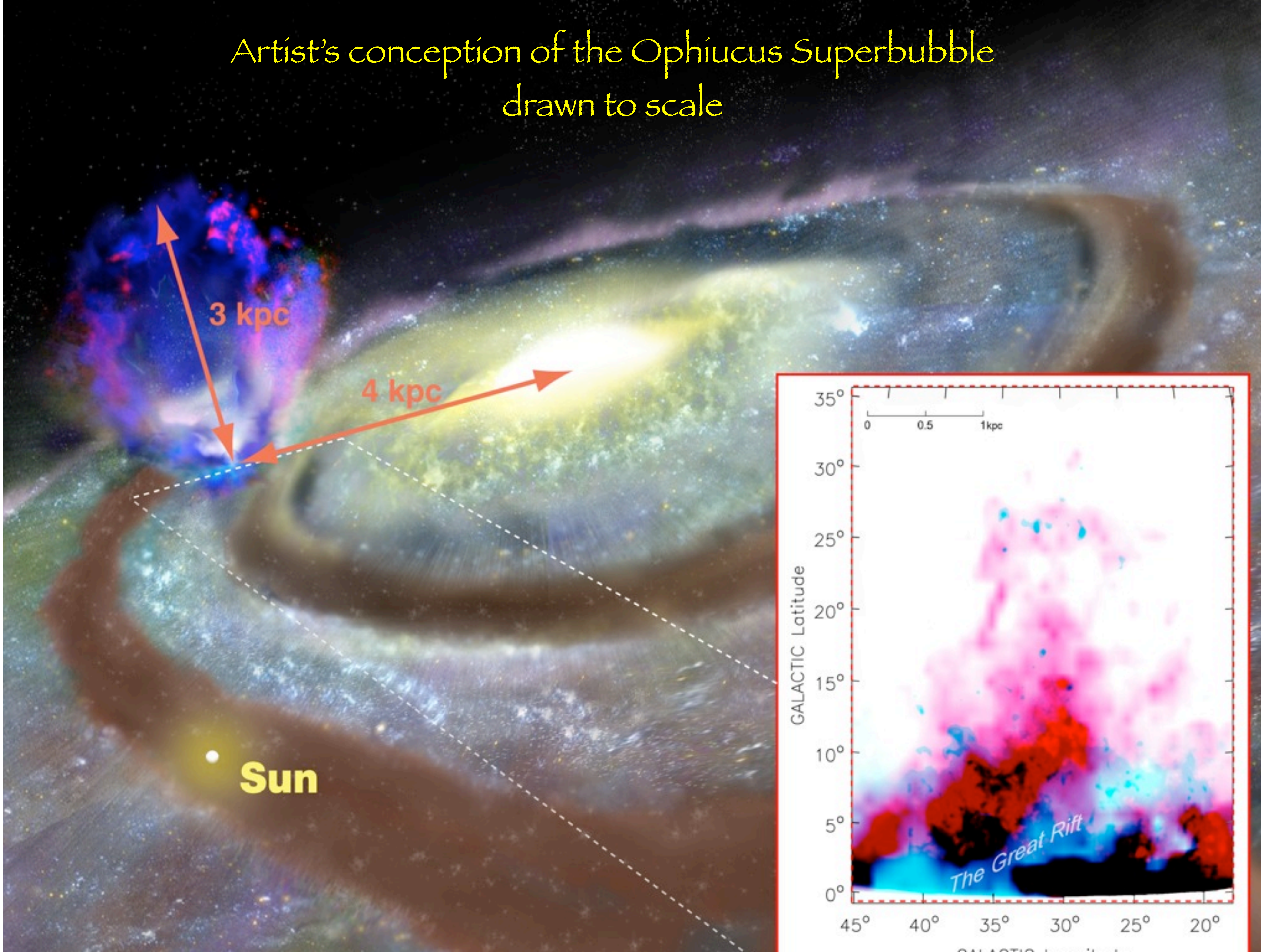
Equal amount in H+

Age 30 Myr

E ≈ 10^{53} ergs

Cap lags behind Galactic rotation

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


Artist's conception of the Ophiucus Superbubble
drawn to scale
3 kpc
4 kpc
Sun
35°
30°
25°
20°
15°
10°
5°
0°
GALACTIC Latitude
0
0.5
1kpc
The Great Rift
45°
40°
35°
30°
25°
20°

HVCs around other galaxies

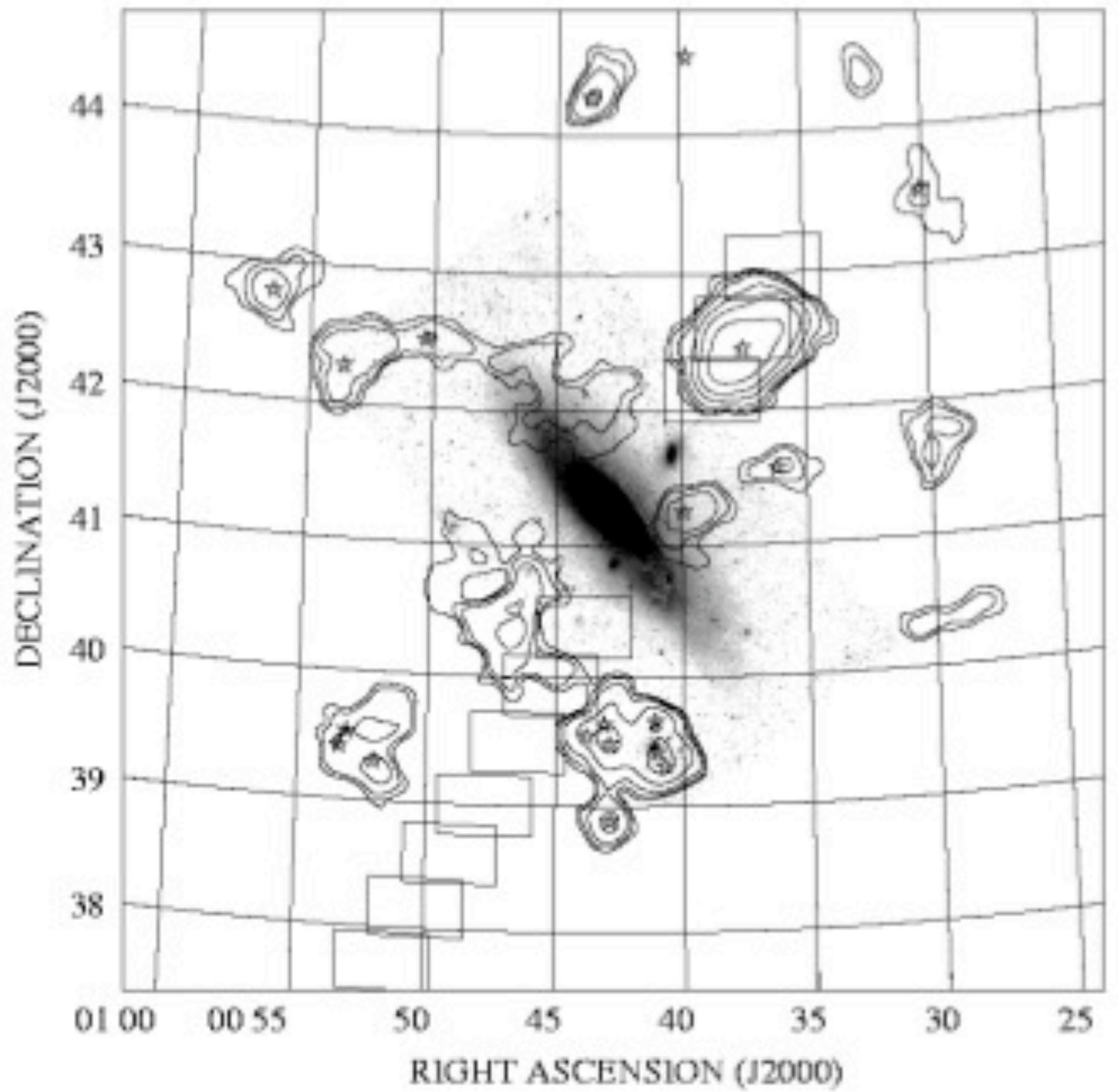
$N_{HI} = 10^{18.5}$
$T_b = 0.065$ K
$t \approx 16\ f^{-2}$ s

M31 -- GBT

Thilker et al. 2004, ApJ, 601, L39

contours at 0.5,1,2,10,20 x 10^{18}

HI Masses = 10^{6-7} M☉



M33 -- Arecibo

Grossi et al. 2008, A&A, 487, 161

lowest contour 2x10^{18}

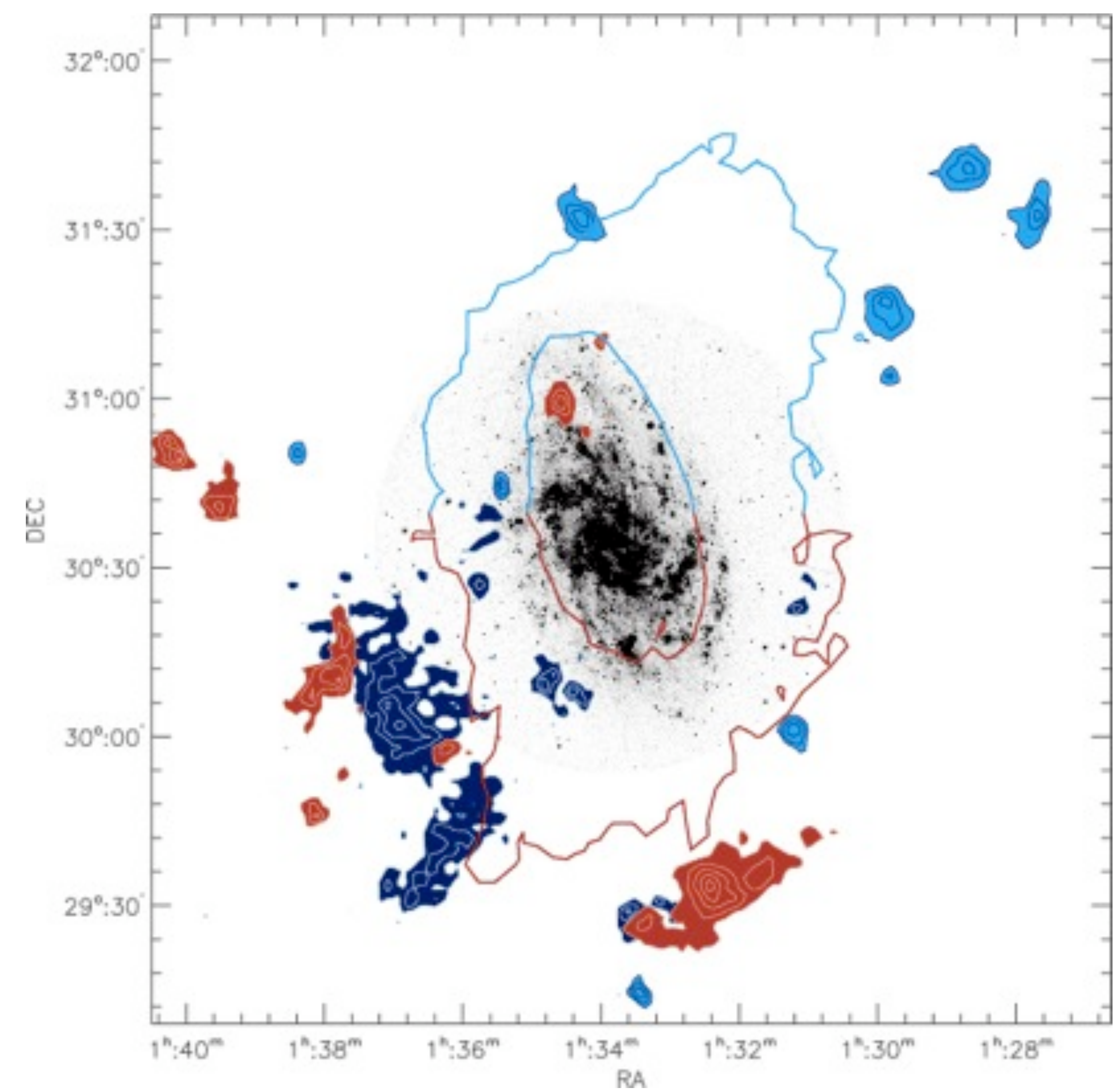


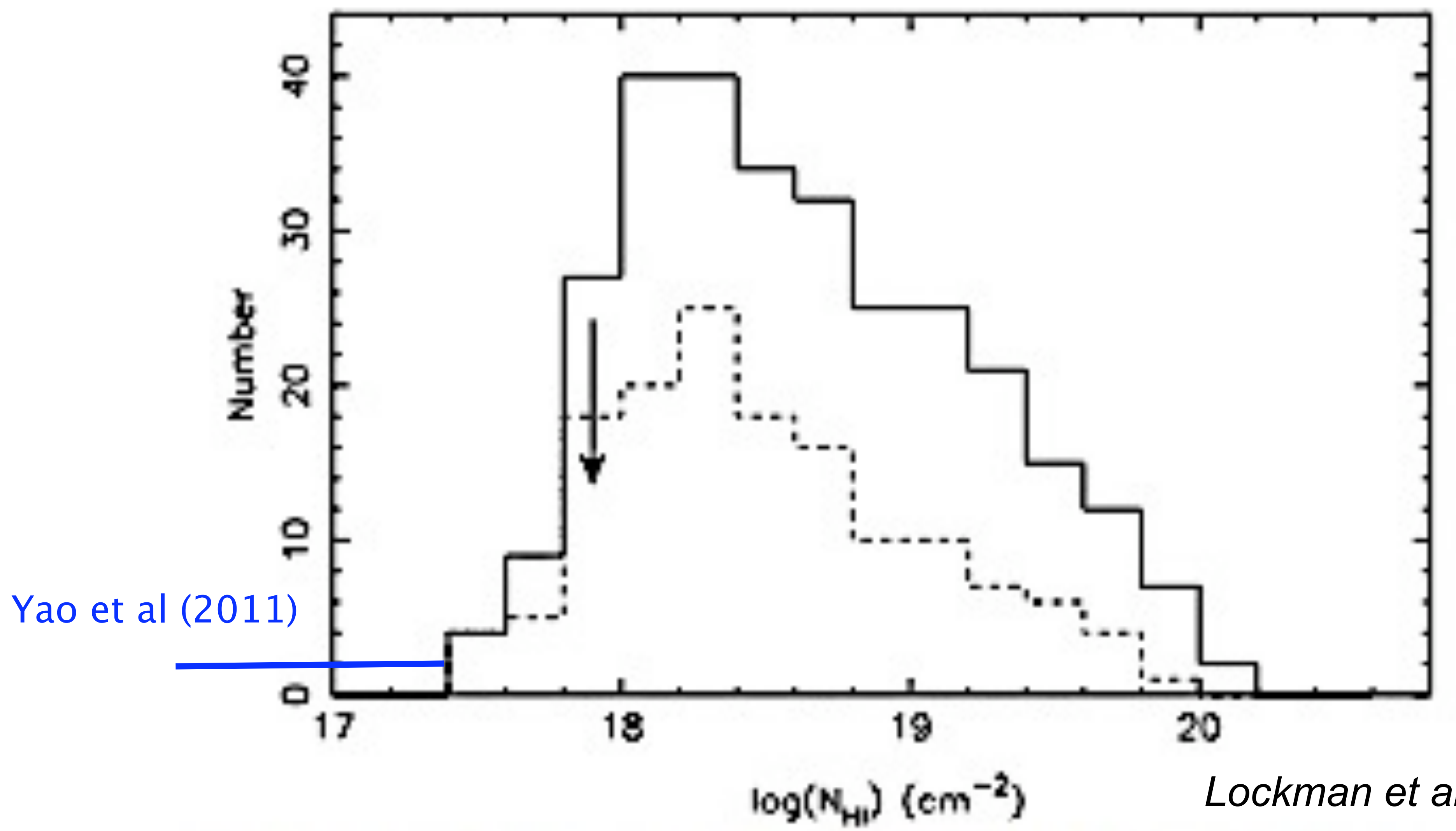
Fig. 2.— Total column density for discrete and diffuse high-velocity H I in the M31 GBT field, after masking emission from Andromeda's inclined, rotating disk. Contours were evaluated at (3 kpc, 72 km s^{-1}) resolution and rendered at 0.5, 1, 2, 10, and 20 × 10^{18} cm^{-2}, then overlaid

HVCs around the Milky Way

$N_{HI} = 10^{18}$
$T_b = 20$ mK
$t \approx 160 f^{-2}$ s

37% of sky covered with HVC HI to this level

Shull et al. (2009) find 81% coverage from UV lines of ionized gas



Lockman et al. 2002, ApJS, 140, 331

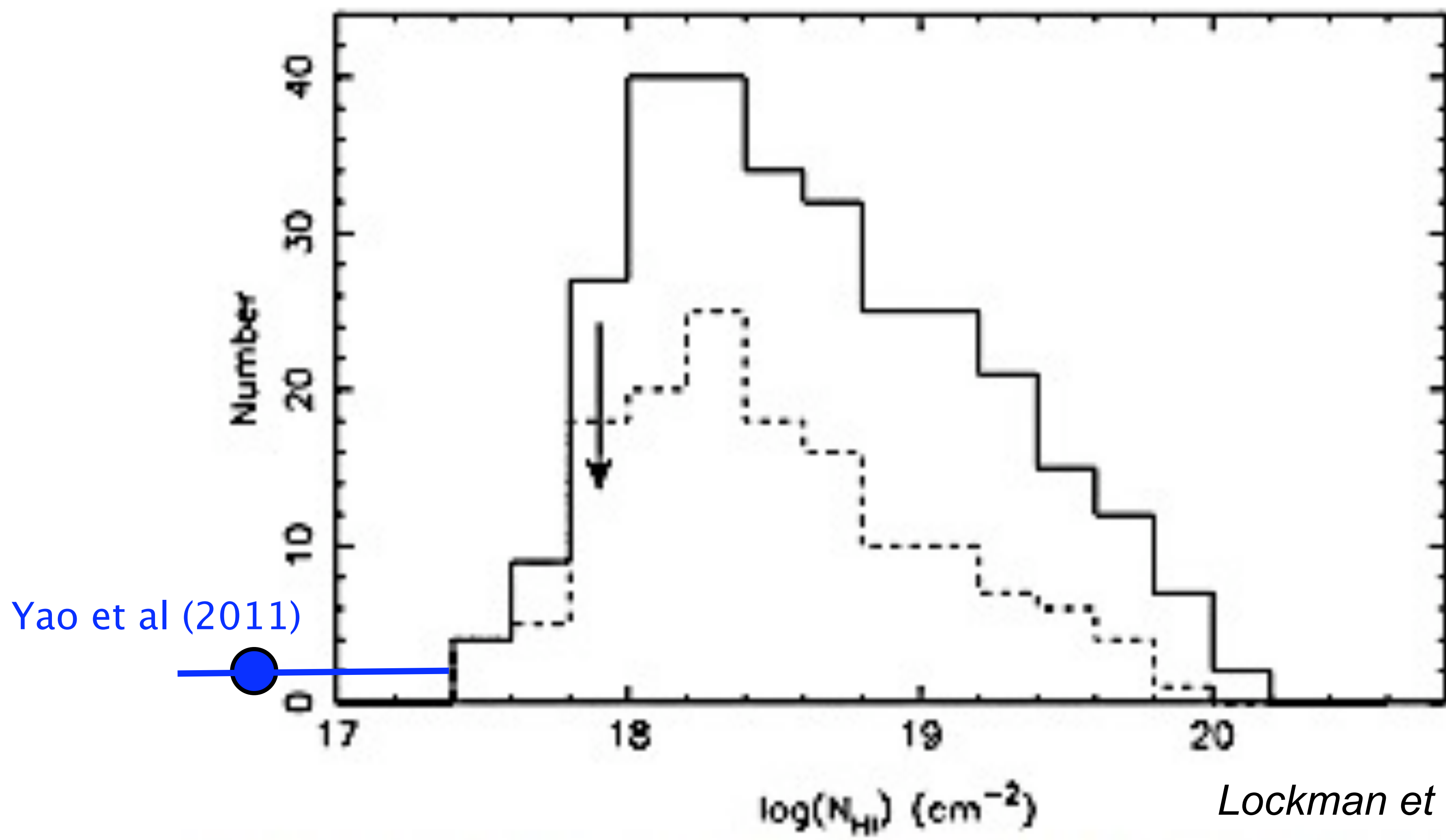
FIG. 12.—Number of Gaussian high-velocity H I lines detected in the survey as a function of their log (N_{HI}). The solid curve is for all lines with $|V_{pk}| \geq 100$ km s^{-1}, and the dashed curve is for the higher velocity lines with $|V_{pk}| \geq 150$ km s^{-1} only. The arrow shows the completeness level of the survey.

HVCs around the Milky Way

$N_{HI} = 10^{18}$
$T_b = 20$ mK
$t \approx 160 f^{-2}$ s

37% of sky covered with HVC HI to this level

Shull et al. (2009) find 81% coverage from UV lines of ionized gas



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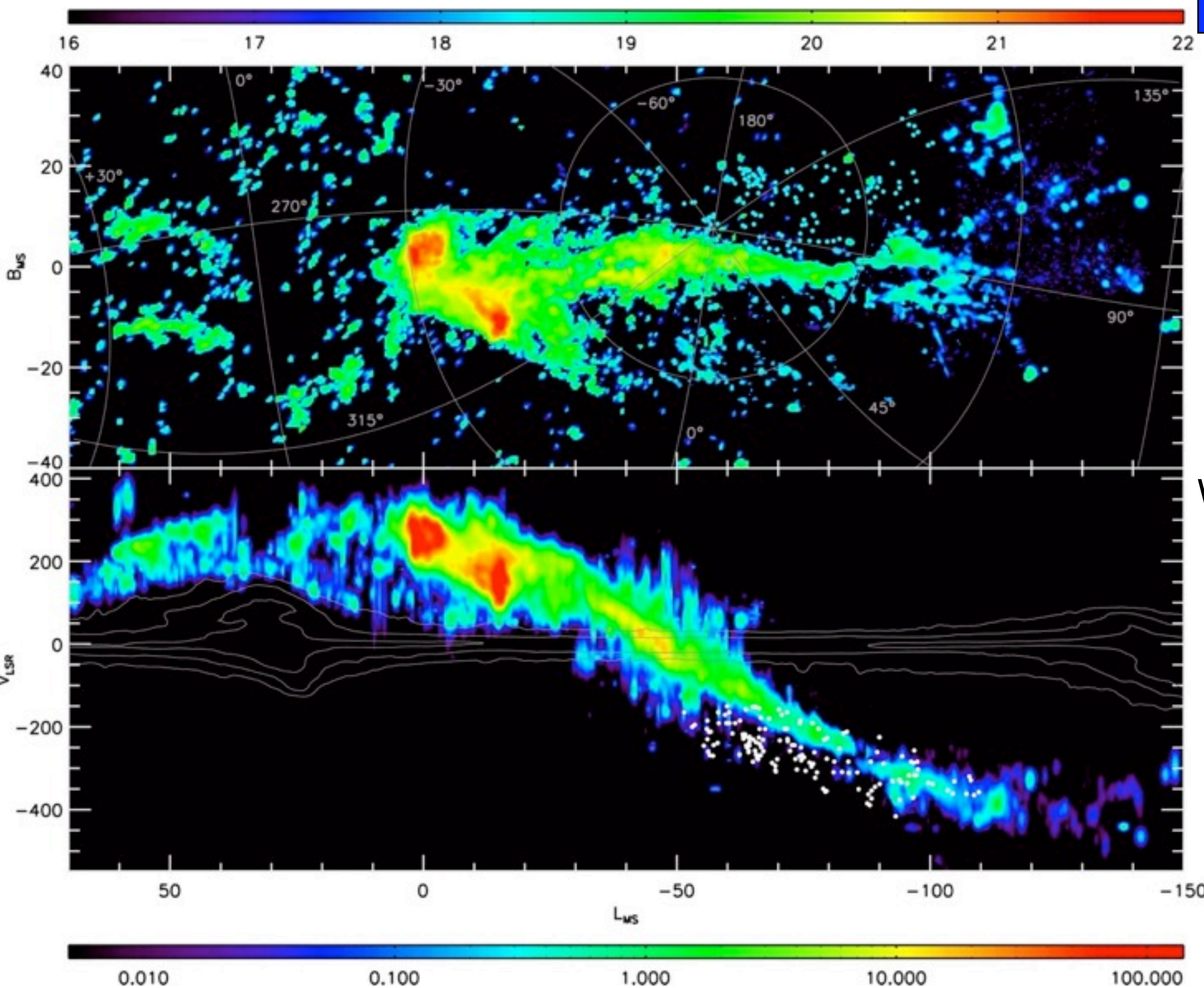
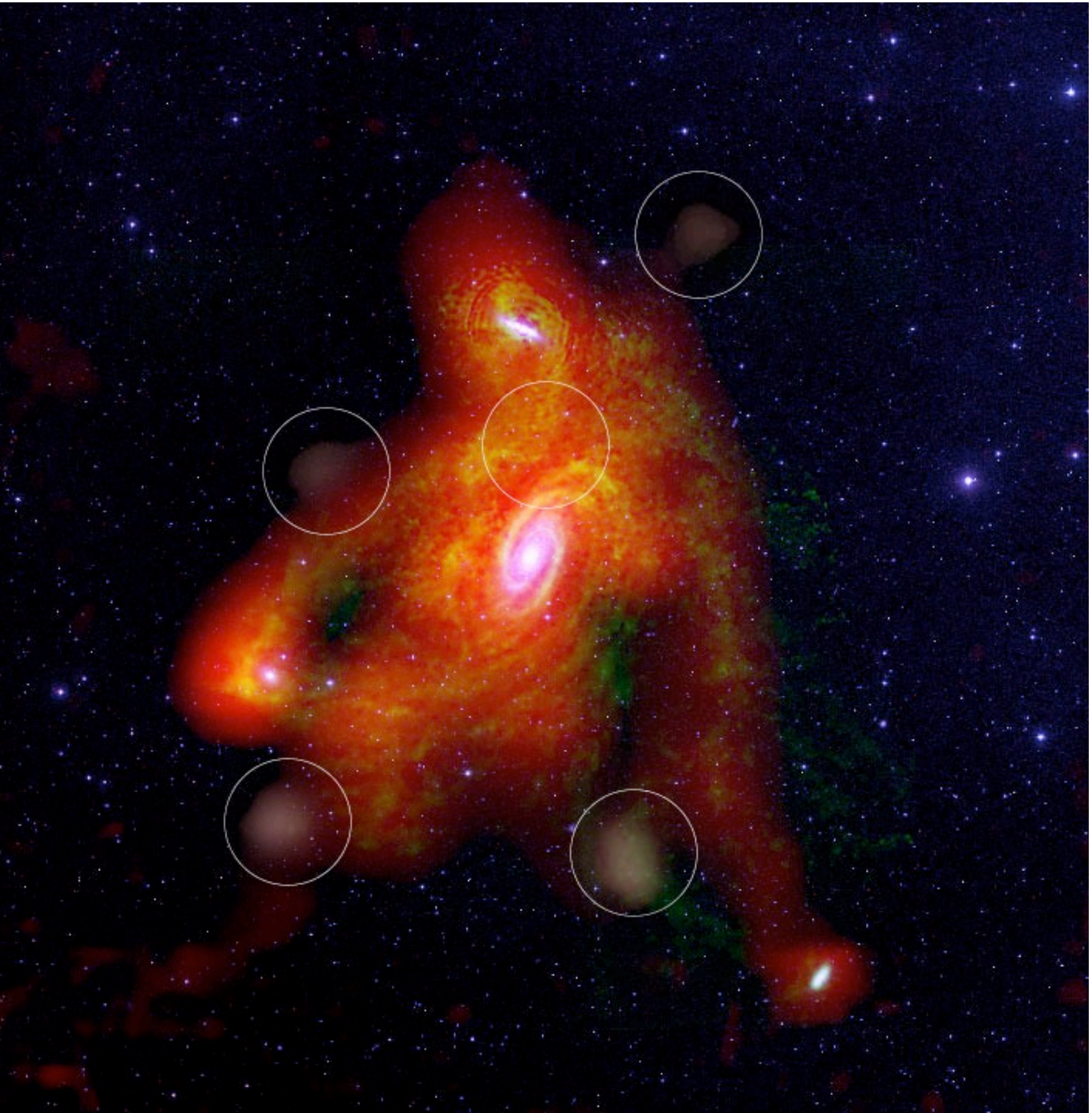
The tip of the Magellanic Stream

$N_{HI} = 10^{17.5}$
T_b=6 mK
$t \approx 1600\ f^{-2}$ s



Composite of data from Parkes, the GBT, and WSRT (used as single dishes

Nidever et al. 2010, ApJ, 732, 1618



The M81 group the classic example of interactions

Optical + VLA HI + GBT HI
Chynoweth et al. 2008, AJ, 135, 1983

The M31–M33 stream

$N_{HI} = 10^{17}$
$T_b = 2$ mK
$t \approx 16\,000\, f^{-2}$ s

Braun & Thilker 2006, A&A, 417, 421
WSRT as single dishes
49' Resolution

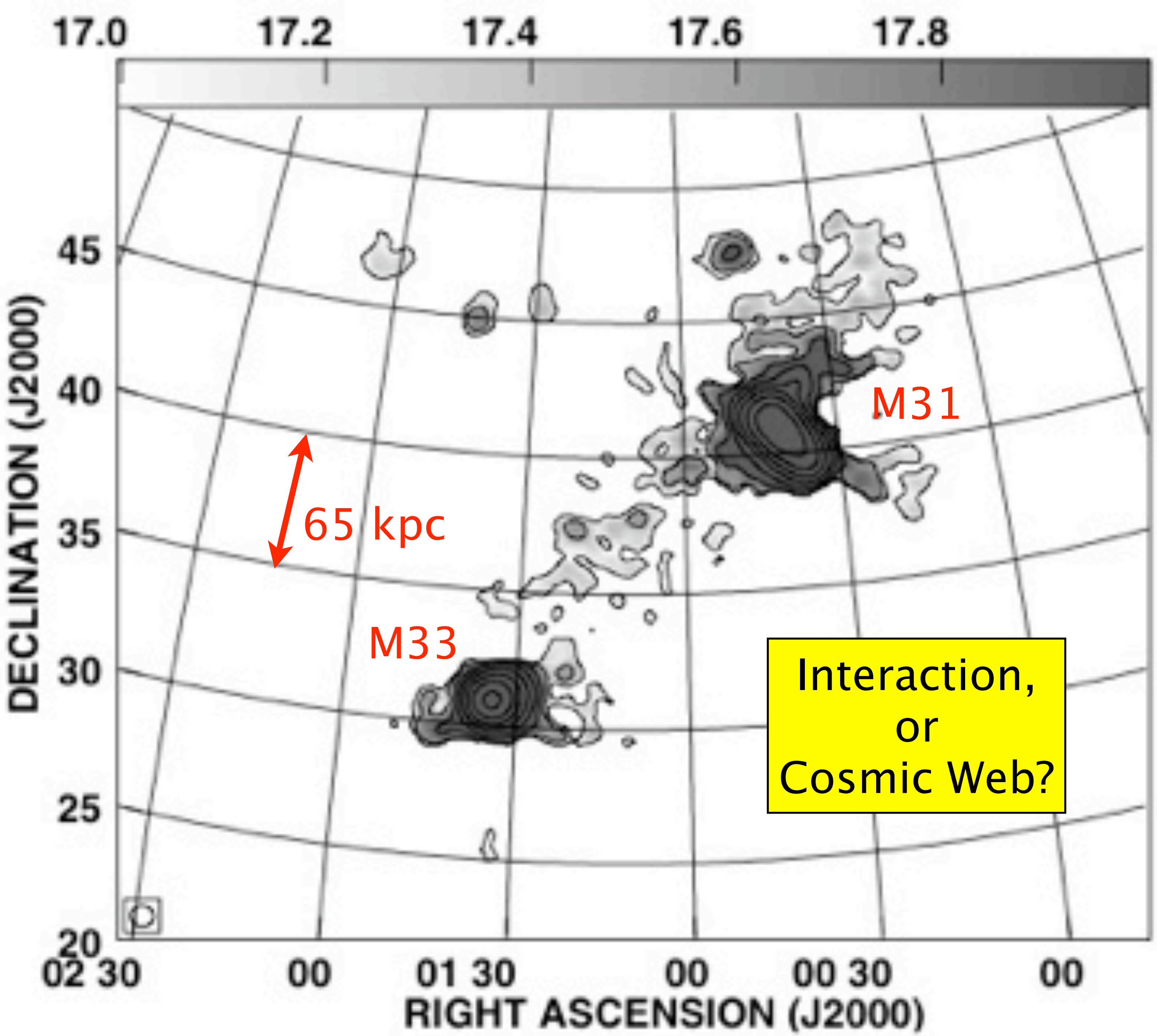


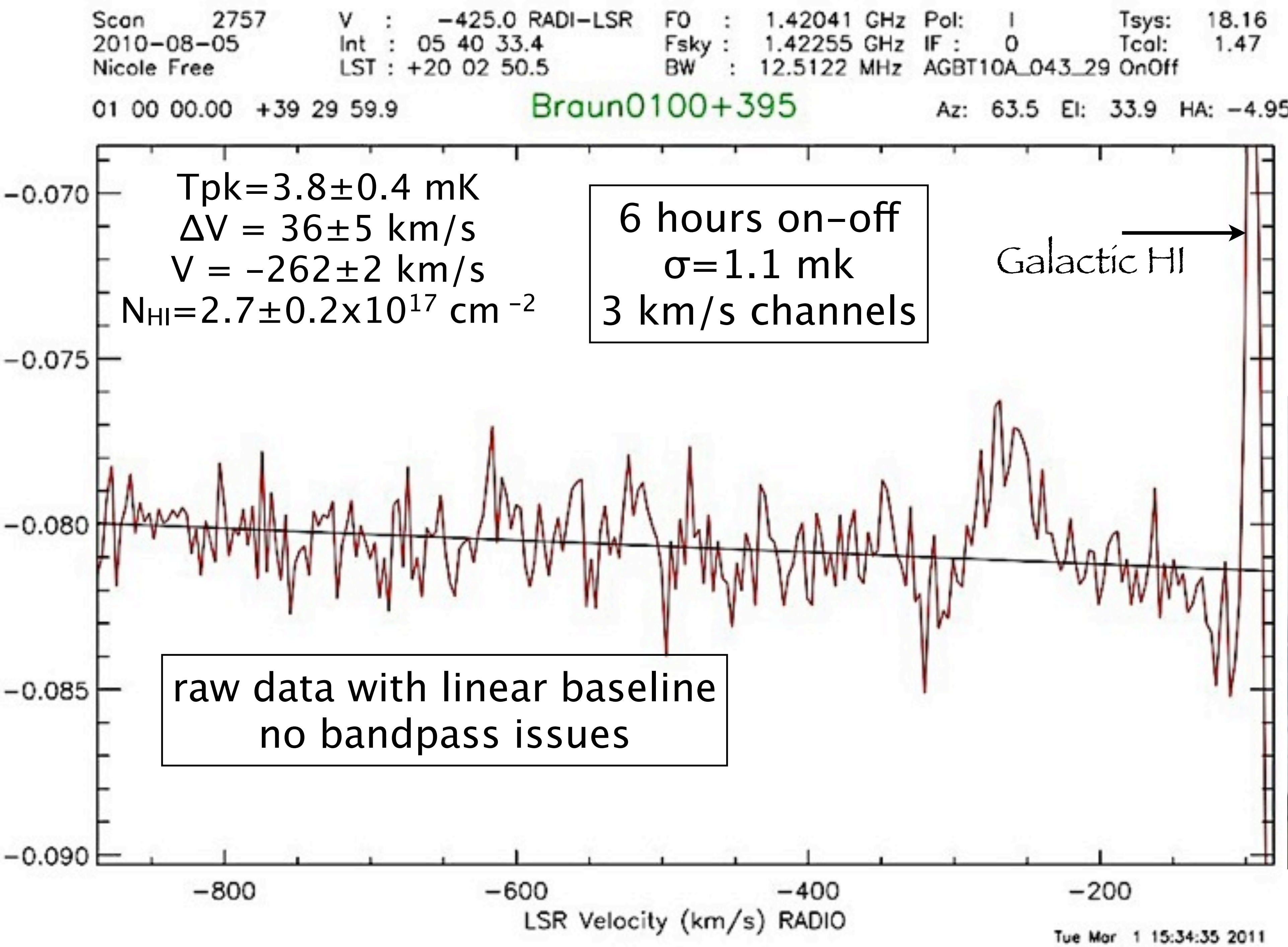
Fig. 9. Integrated H I emission from the subset of detected features apparently associated with M 31 and M 33. The grey-scale varies between $\log(N_{HI}) = 17-18$, for N_{HI} in units of cm^{-2}. Contours are drawn at $\log(N_{HI}) = 17, 17.5, 18, \ldots 20.5$.

Putman et al.
(2009, ApJ, 703, 1486)
say it's not real!

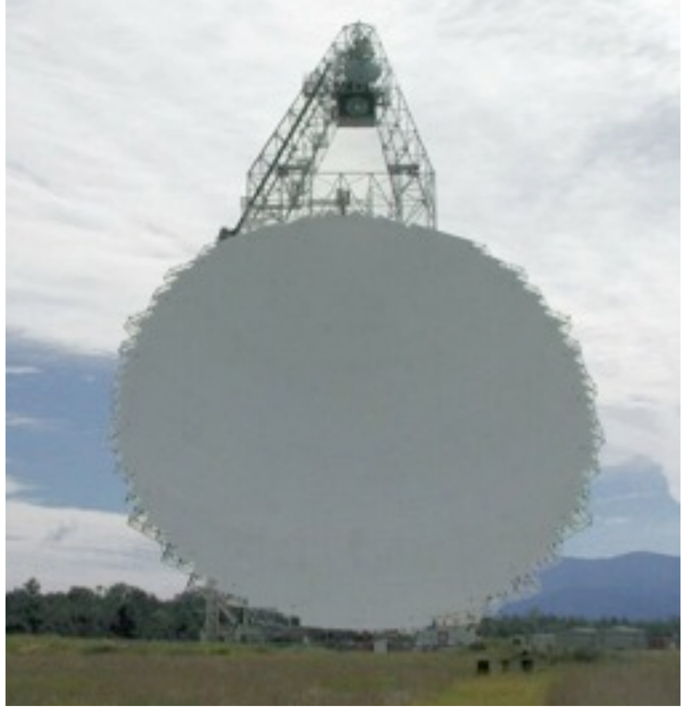
GBT spectrum of the M31-M33 stream

Free, Lockman & Shields (2011, in prep)

N_{HI} = 10^{17}
T_b=2 mK
t ≈16 000 f^{-2} s



This is the frontier



Hydrogen is abundant and observable

- The potential of HI studies at 10^{17}
  - Flow of gas into and out of the Milky Way and other galaxies
  - Tracing past interactions
  - The cosmic web?
- The challenge of studies at 10^{17}
  - Signals are very weak, and yet likely extended
  - Possible with current instruments, it just takes time
- Near term
  - Better receivers -- Tsys=10 K?
  - Phased array feed receivers -- still not competitive, but...
  - EVLA-E -- f≈0.25
- Long term
  - SKA -- HPBW=2.5' reaches 1.6 mK over 25 km/s in 1 hour
  - (but GBT at 9' now reaches 0.7 mK over 25 km/s in 1 hr)

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HI brightness and integration times

Δv=25 km/s

New HI Surveys cover the brighter emission

GASS δ≲0° 14'
McClure-Griffiths et al. (2009)

Bonn survey 0°≲δ 10'
Kerp et al. (2011)

Arecibo Surveys
0°≲δ≲40°
GALFA
ALFALFA

log N_{HI} (cm^{-2})	T_b (τ<<1) (K)	3σ t / f^2 (sec)
22	200	$2x10^{-6}$
21.5	65	$2x10^{-5}$
21	21	$2x10^{-4}$
20.5	6.5	$2x10^{-3}$
20	2.1	$2x10^{-2}$
19.5	0.65	0.2
19	0.2	2
18.5	0.065	16
18	0.02	160
17.5	0.0065	1600
17	0.002	16 000

⋮

FLAG -- Focal Plane L-Band Array for the GBT

B. Jeff, K. Warnick et al (BYU)
J.R. Fisher, R. Norrod, A. Roshi (NRAO)

The future?

- 19 dual polarized elements. Cryogenic PAF system
- Tsys $\sim$ 20 K; Aperture efficiency $\sim$ 75 to 80 %
- 7 beams; spacing 0.5 FWHM to 1 FWHM
- Frequency coverage – 1300 to 1800 MHz; Backend for processing signals

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