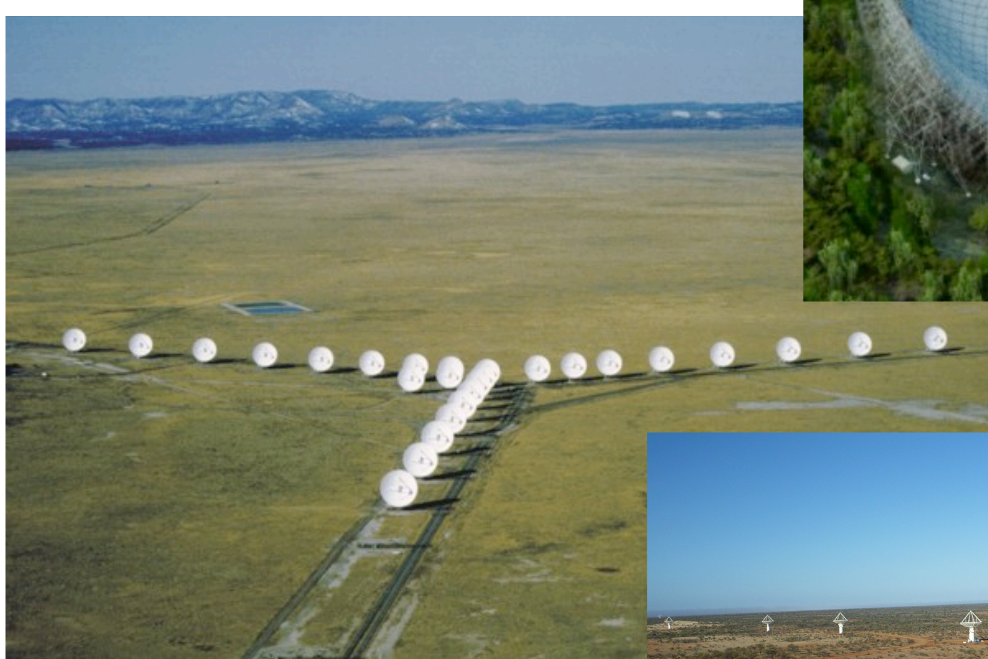
The Next Decade of 21cm HI Observations of the Local Universe

Felix J. "Jay" Lockman
NRAO, Green Bank



A digression on the sensitivity of a radio telescope

- for an unresolved (point) source, signal strength is proportional to collecting area

- for a resolved source it depends on the configuration of the collecting area

- time to detect goes as signal^{-2}

point source

resolved source

$$t \propto f^2 \propto \frac{Diam^4}{A_e^2}$$

A digression on the sensitivity of a radio telescope

- for an unresolved (point) source, signal strength is proportional to collecting area

- for a resolved source it depends on the configuration of the collecting area

- time to detect goes as signal^{-2}

point source

$$t \propto \frac{1}{A_e^2}$$

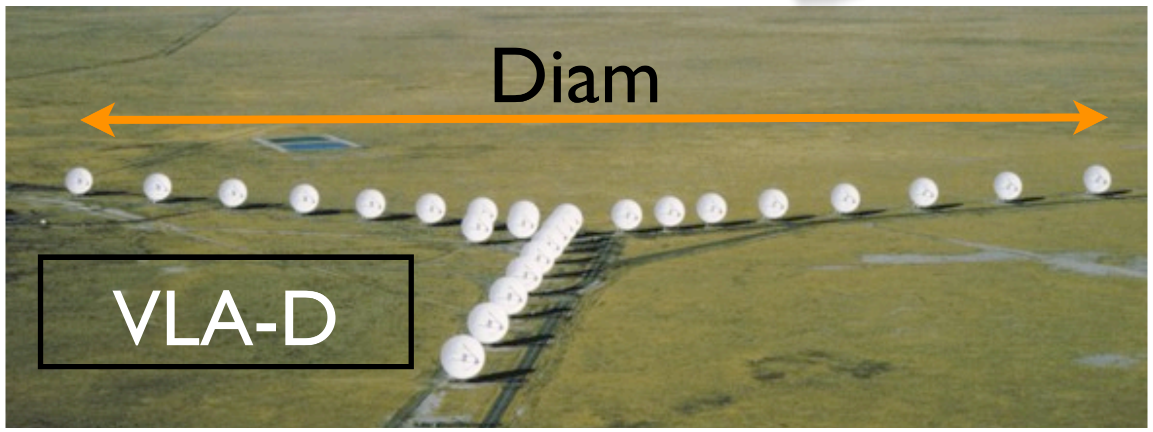
resolved source

$$t \propto f^2 \propto \frac{Diam^4}{A_e^2}$$

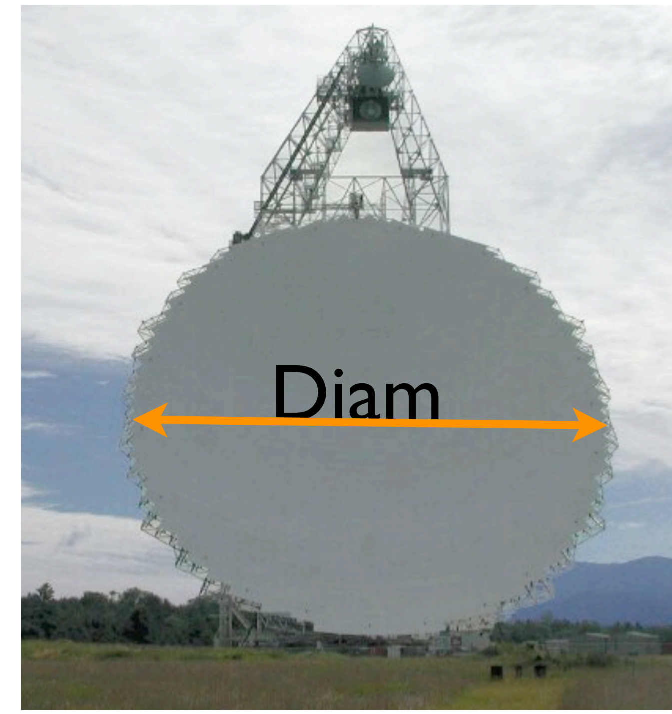
A digression on sensitivity

$$f \equiv \frac{Diam^2}{4r_a^2\ N_a}$$

Surface brightness efficiency



GBT



Instrument	f	21cm HPBW
GBT	1	9.1'
Arecibo	1	3.2'
VLA-D	~10^2	46''
VLA-C	~10^3	14''
VLA-B	~10^4	4.3''
ASKAP	~10^3	

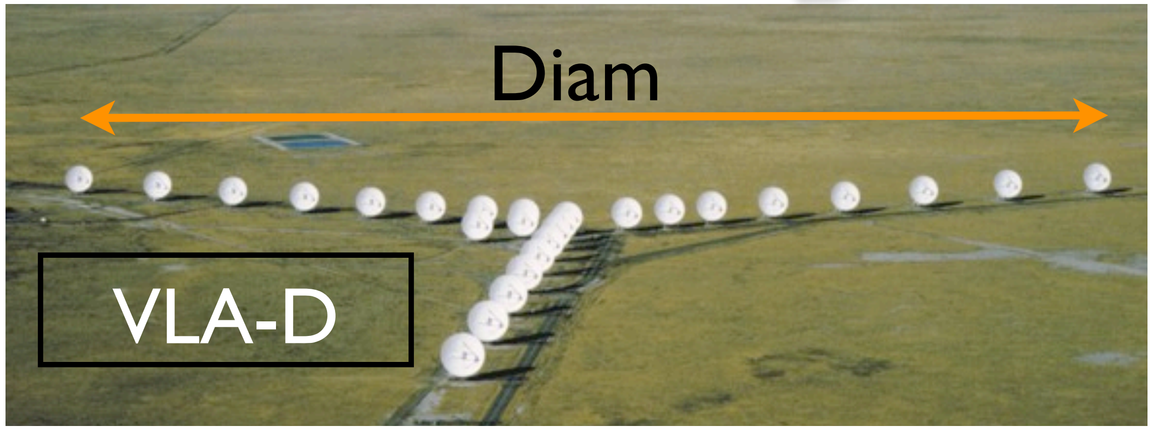
$$t \propto f^2 \propto \frac{Diam^4}{A_e^2}$$

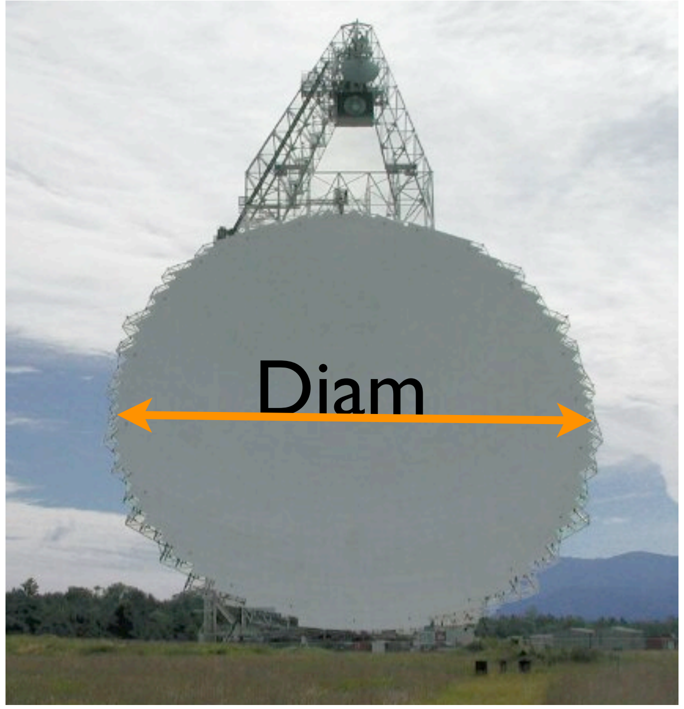
A digression on sensitivity

$$f \equiv \frac{Diam^2}{4r_a^2 \ N_a}$$

Surface brightness efficiency

GBT





Instrument	f	21cm HPBW
GBT	1	9.1'
Arecibo	1	3.2'
VLA-D	$\sim 10^2$	46''

$$t \propto f^2 \propto \frac{Diam^4}{A_e^2}$$

For a given collecting area, the brightness sensitivity is always greatest for a filled aperture

Aperture Synthesis:

* High angular resolution on bright emission
* High dynamic range
* Low confusion
* ...

Filled Aperture

* Extended source “short spacing” data
* Highest-performance receiving systems
* Low surface brightness phenomena
* ...

End of digression...

Aperture Synthesis:

* High angular resolution on bright emission
* High dynamic range
* Low confusion
* ...

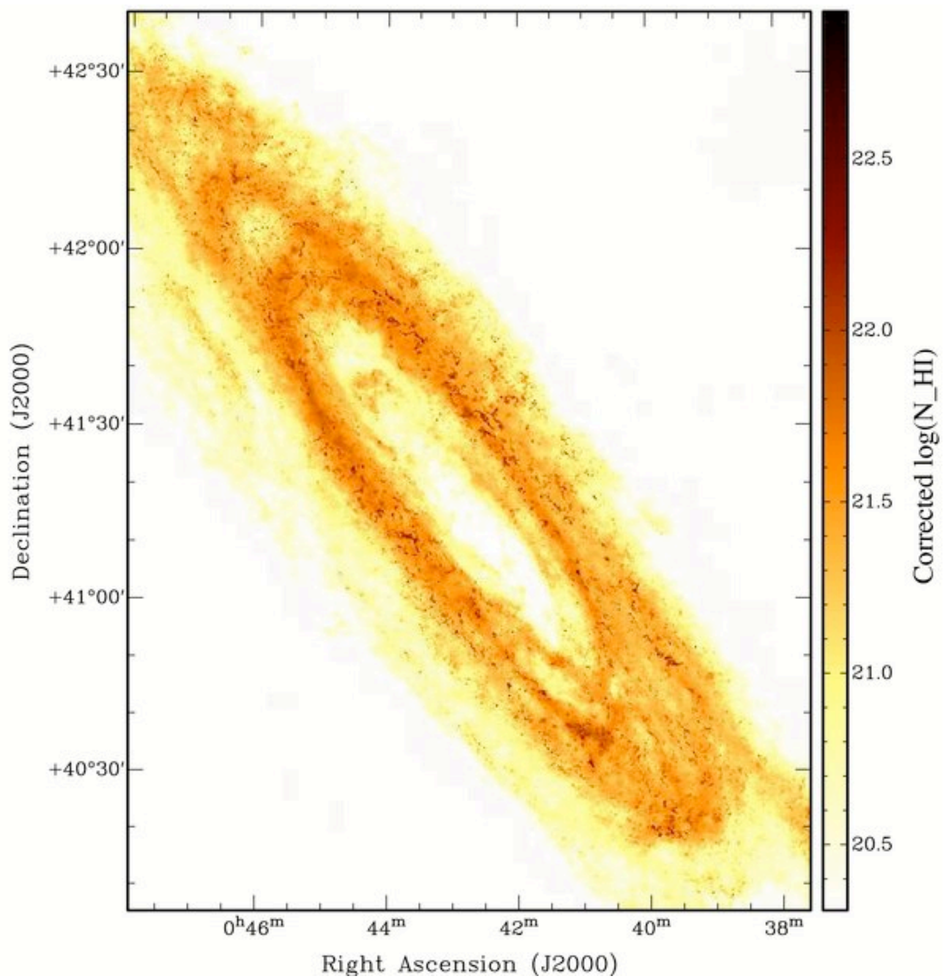
Filled Aperture

* Extended source "short spacing" data
* Highest-performance receiving systems
* Low surface brightness phenomena ←
* ...

End of digression...

Neutral Hydrogen (HI) in galaxies

t ≡3σ detection time for 21cm line



HI disks of galaxies

$N_{HI} = 10^{21.5}$ cm^{-2}

$T_b = 65$ K

$t \approx 2x10^{-5} f^2$ sec

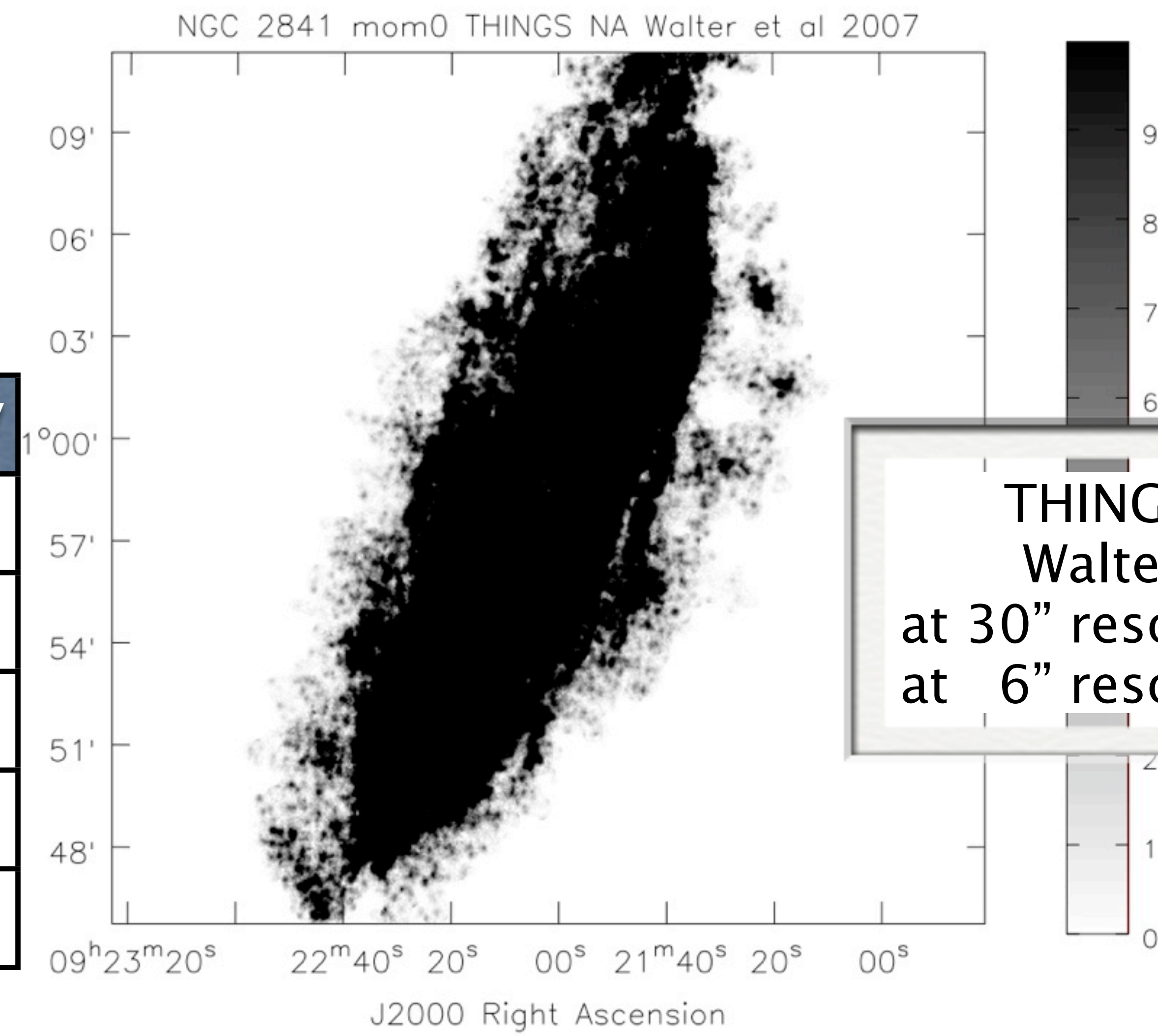
HI edges of galaxies

$N_{HI} = 10^{19.5}$

$T_b = 0.6$ K

$t \approx 0.2 f^2$ sec

Instrument	f^2	21 cm HPBW
GBT	1	9.1’
Arecibo	1	3.2’
VLA-D	~10^4	46”
VLA-C	~10^6	14”
VLA-B	~10^8	4.3”



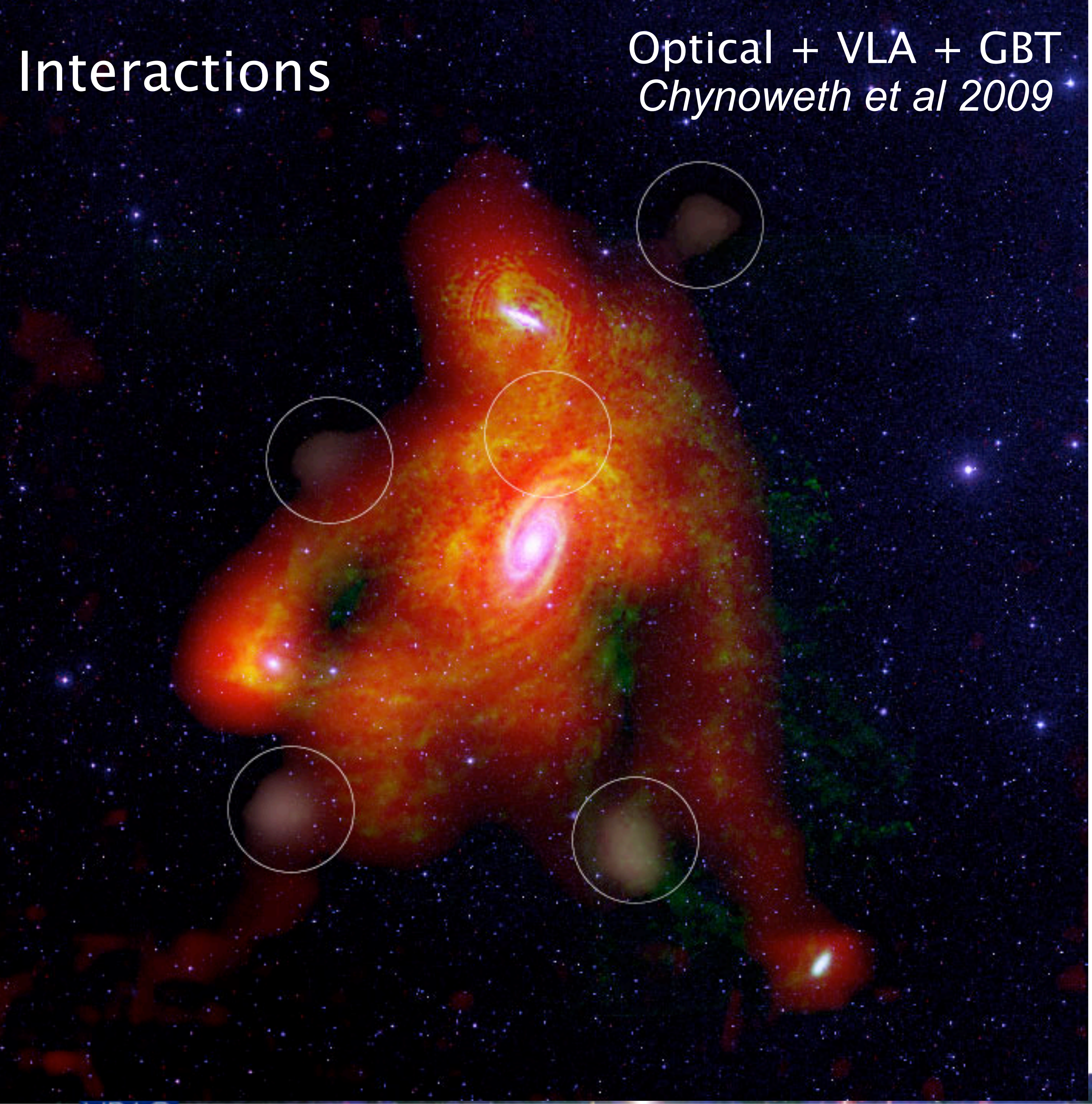
THINGS VLA Survey
Walter et al. 2008
at 30” resolution $3\sigma=10^{19.5}$
at 6” resolution $3\sigma=10^{20.5}$

What drives galaxy growth and evolution?

Theory:
Interactions, Fountains and winds, Inflow

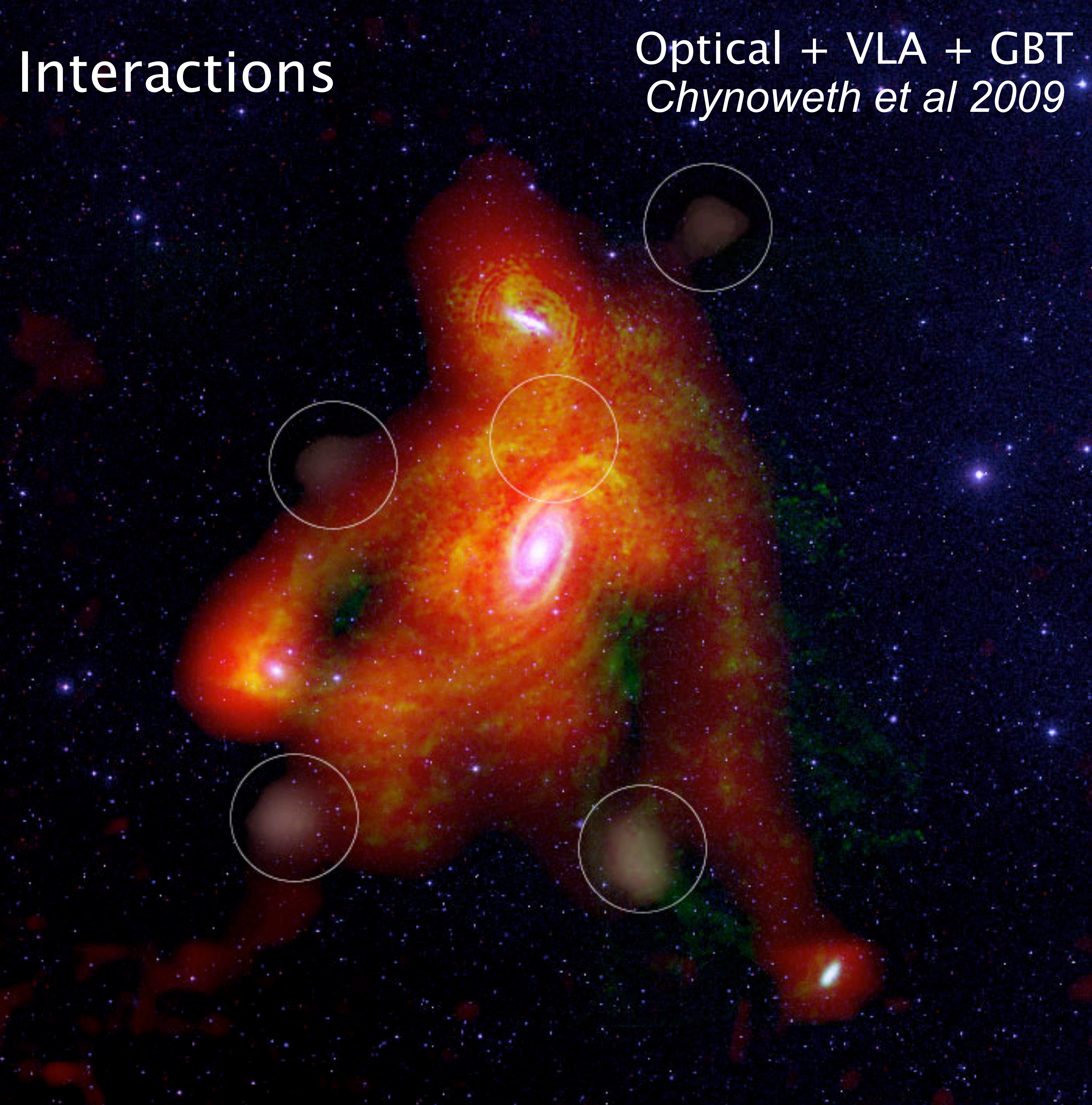
Measurement:
Interaction, Fountains & winds, Inflow?

We can learn the most looking outside a galaxy's disk



Galaxies in groups interact

The M81 group

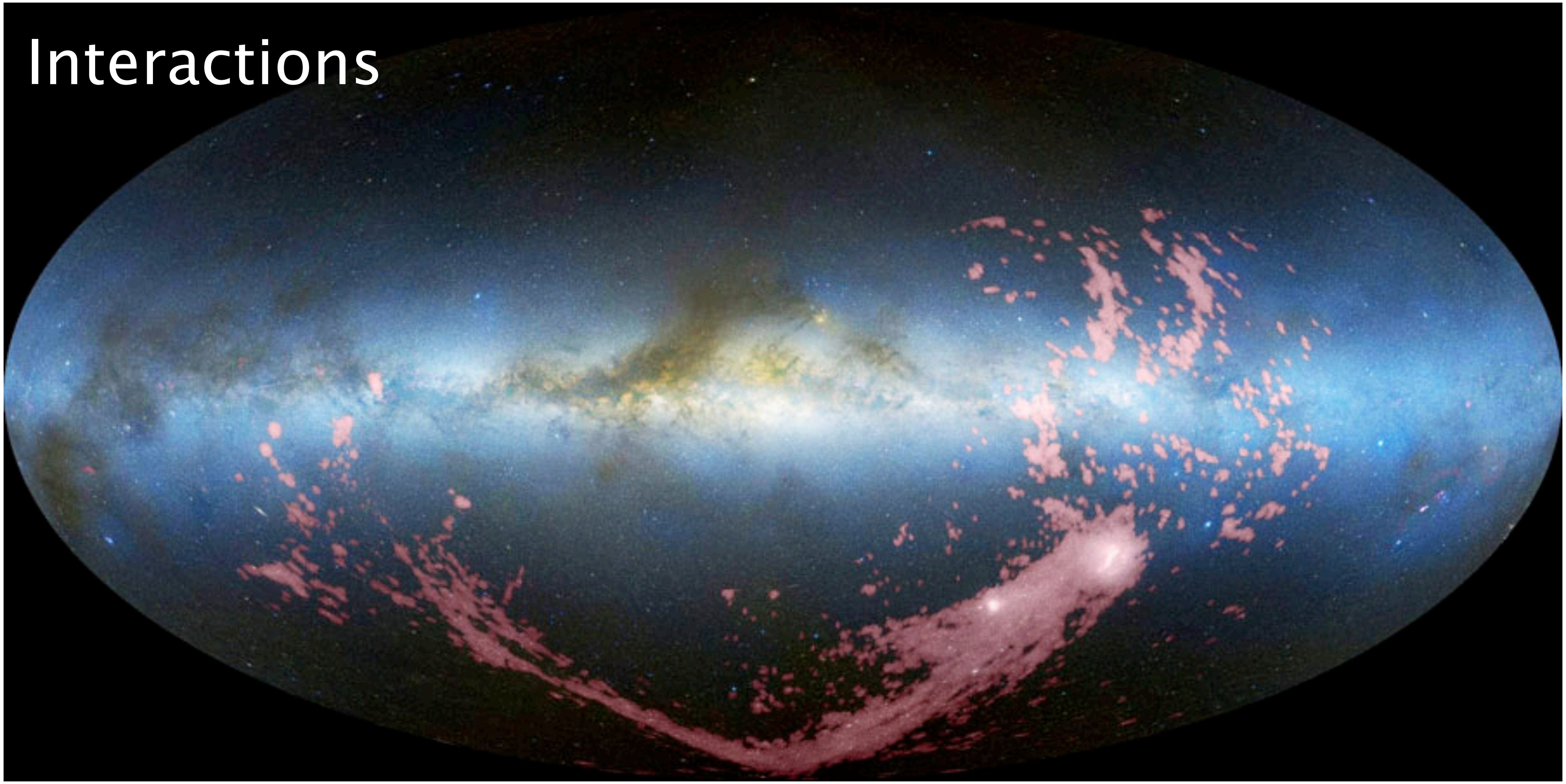


Galaxies in groups interact

Group HI
$N_{HI} = 10^{18.5}$
$T_b = 0.06$ K
$t \approx 20 f^2$ sec

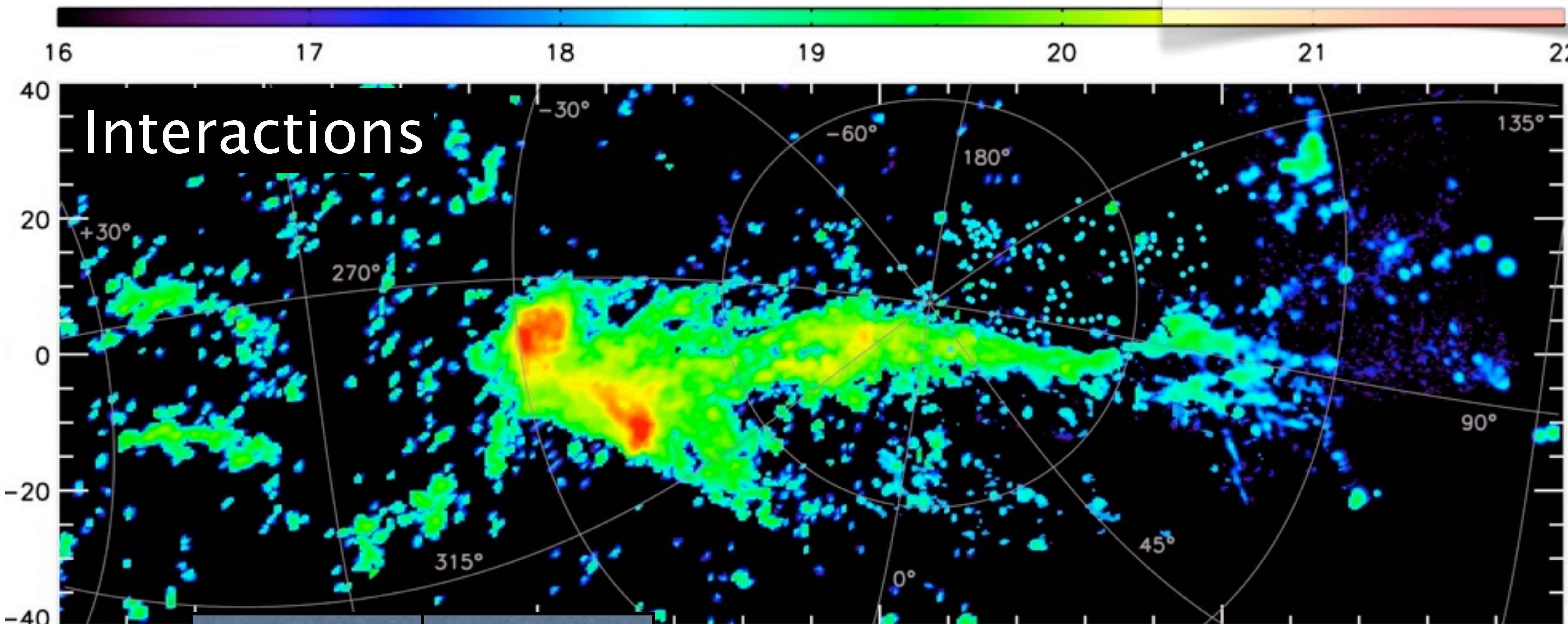
The M81 group

The Magellanic Stream



The tip of the Magellanic Stream

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

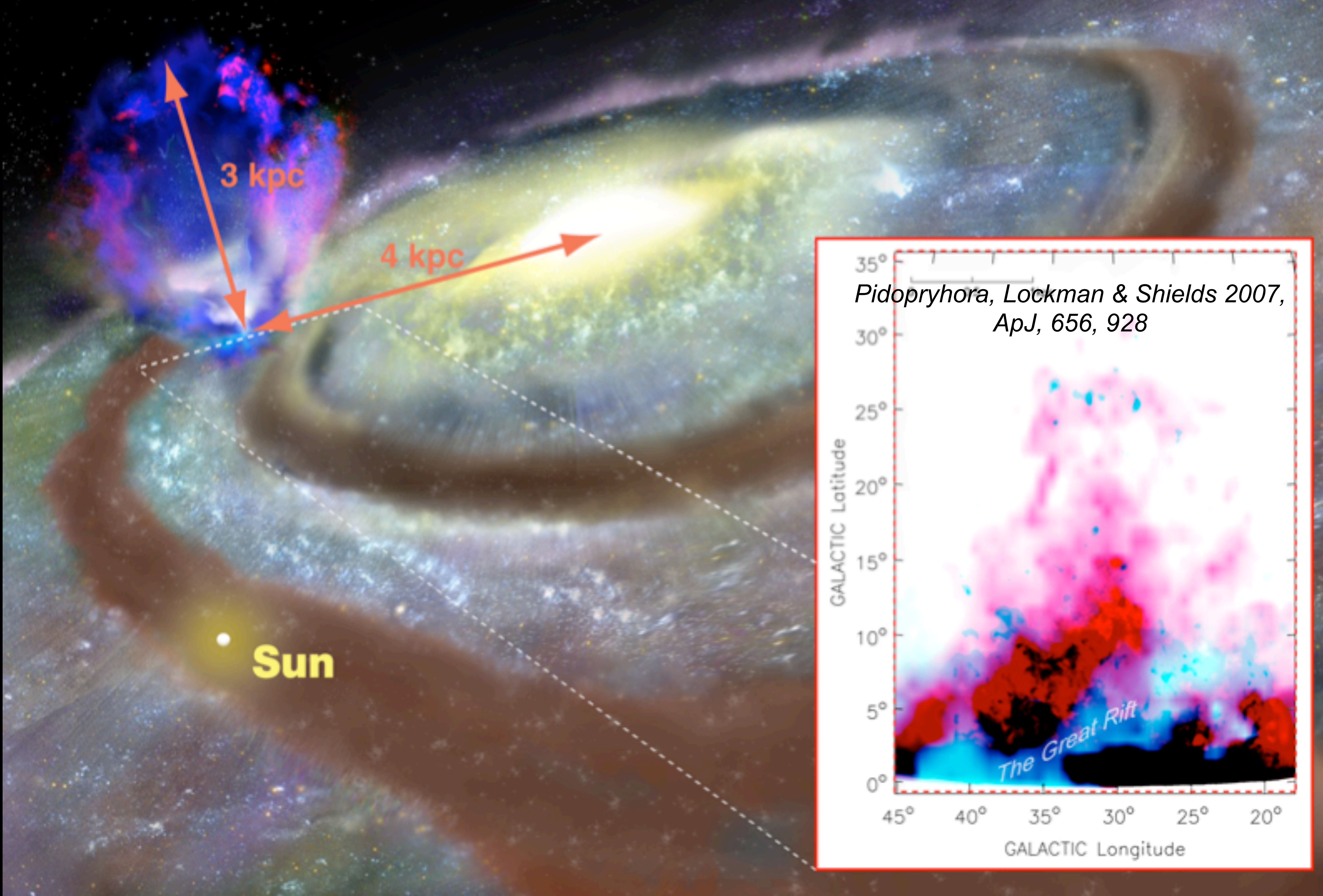


Instrument	f^2
GBT	~1
EVLA-D	$\sim 10^4$
EVLA-C	$\sim 10^6$
EVLA-B	$\sim 10^8$

Nidever et al 2010
Composite of Parkes, GBT, WSRT-SD

Superbubbles are one mechanism for putting HI into the halo

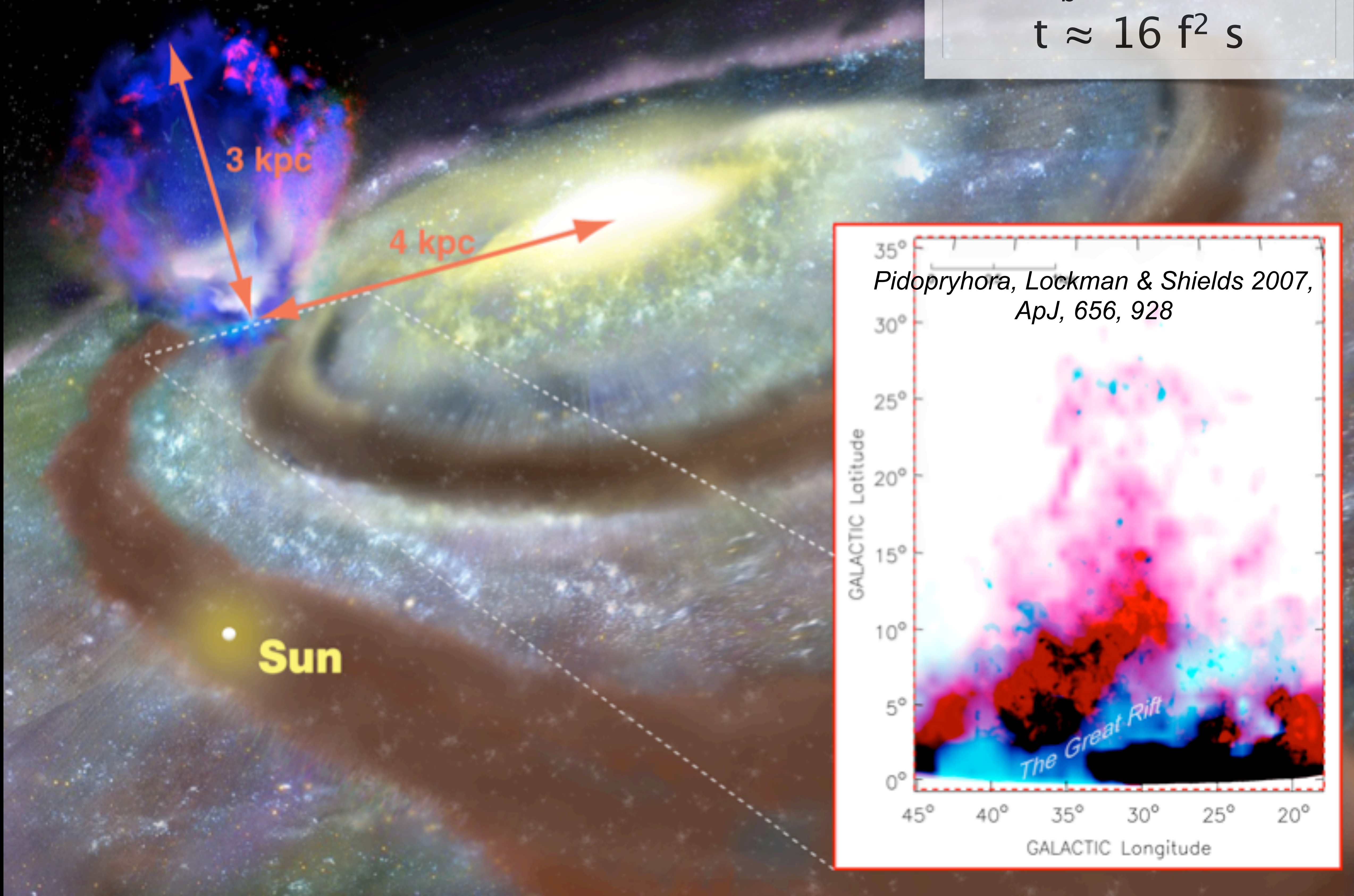
Fountains & winds

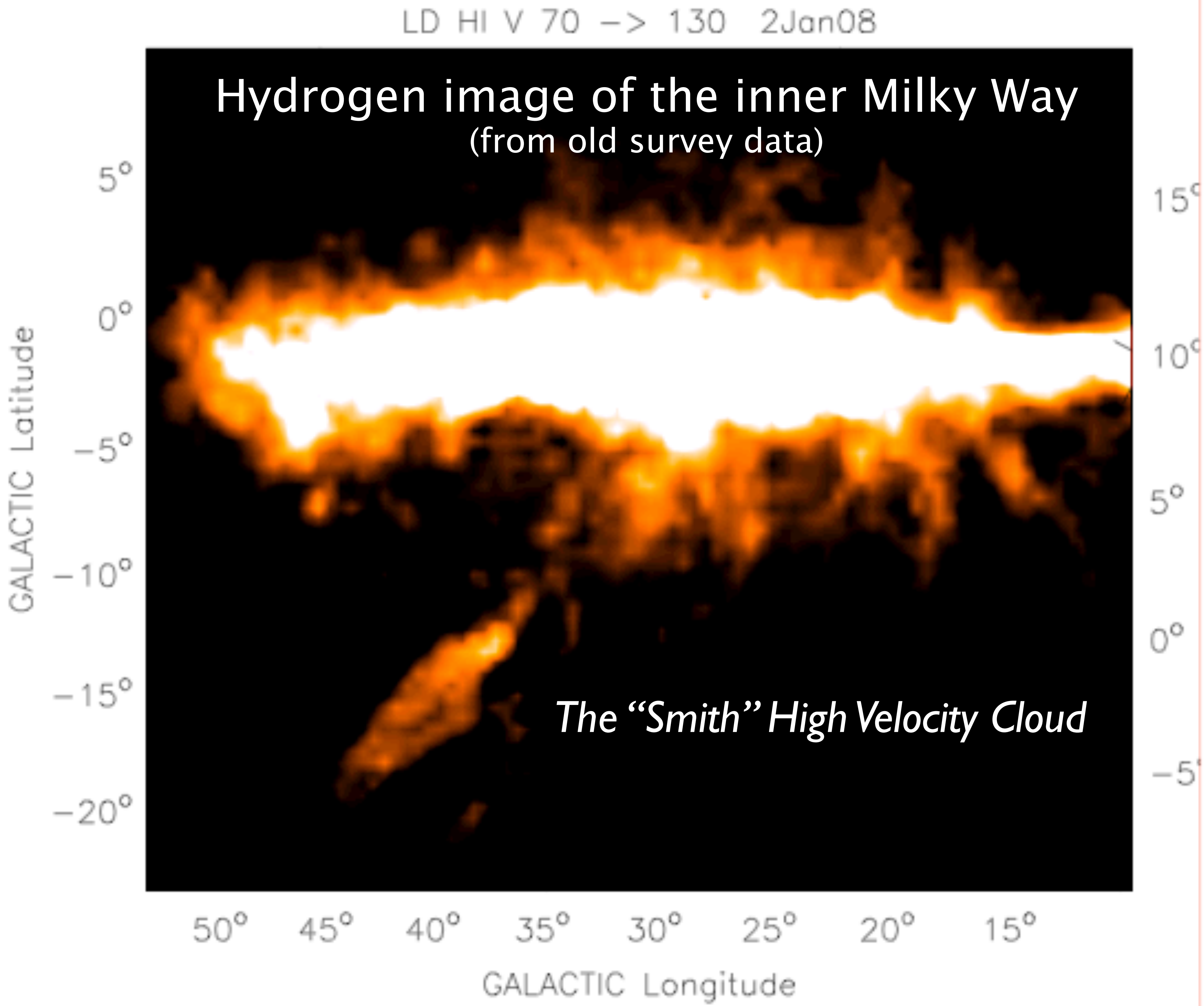


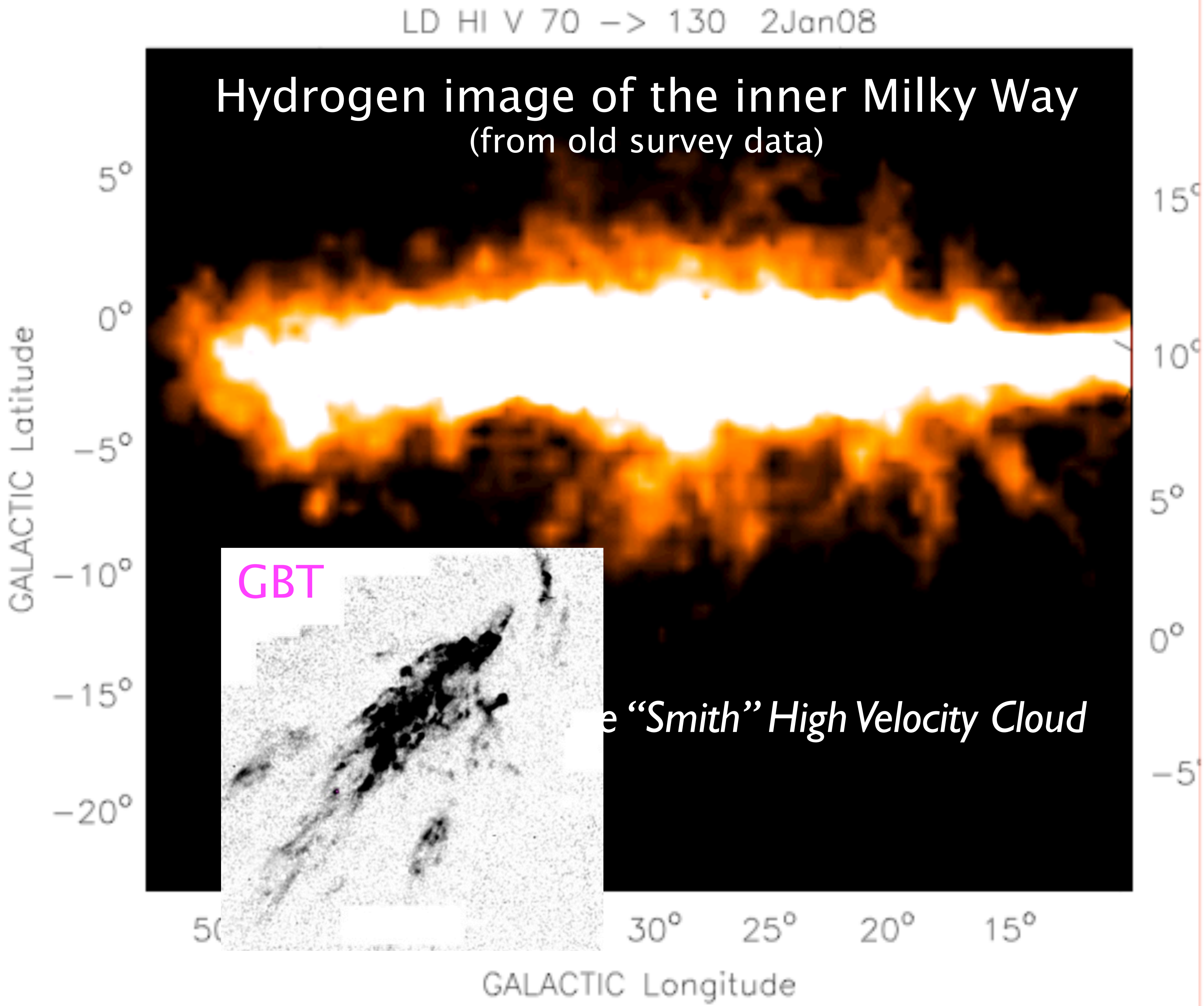
Superbubbles are one mechanism for putting HI into the halo

Fountains & winds

$N_{HI} = 10^{18.5}$
T_b=60 mK
$t \approx 16\ f^2$ s




LD HI V 70 -> 130 2Jan08
Hydrogen image of the inner Milky Way
(from old survey data)
5°
0°
−5°
−10°
−15°
−20°
GALACTIC Latitude
15°
10°
5°
0°
−5
The "Smith" High Velocity Cloud
50°
45°
40°
35°
30°
25°
20°
15°
GALACTIC Longitude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15°
GALACTIC Longitude
15°
10°
5°
0°

The Smith Cloud is bound to the Galaxy

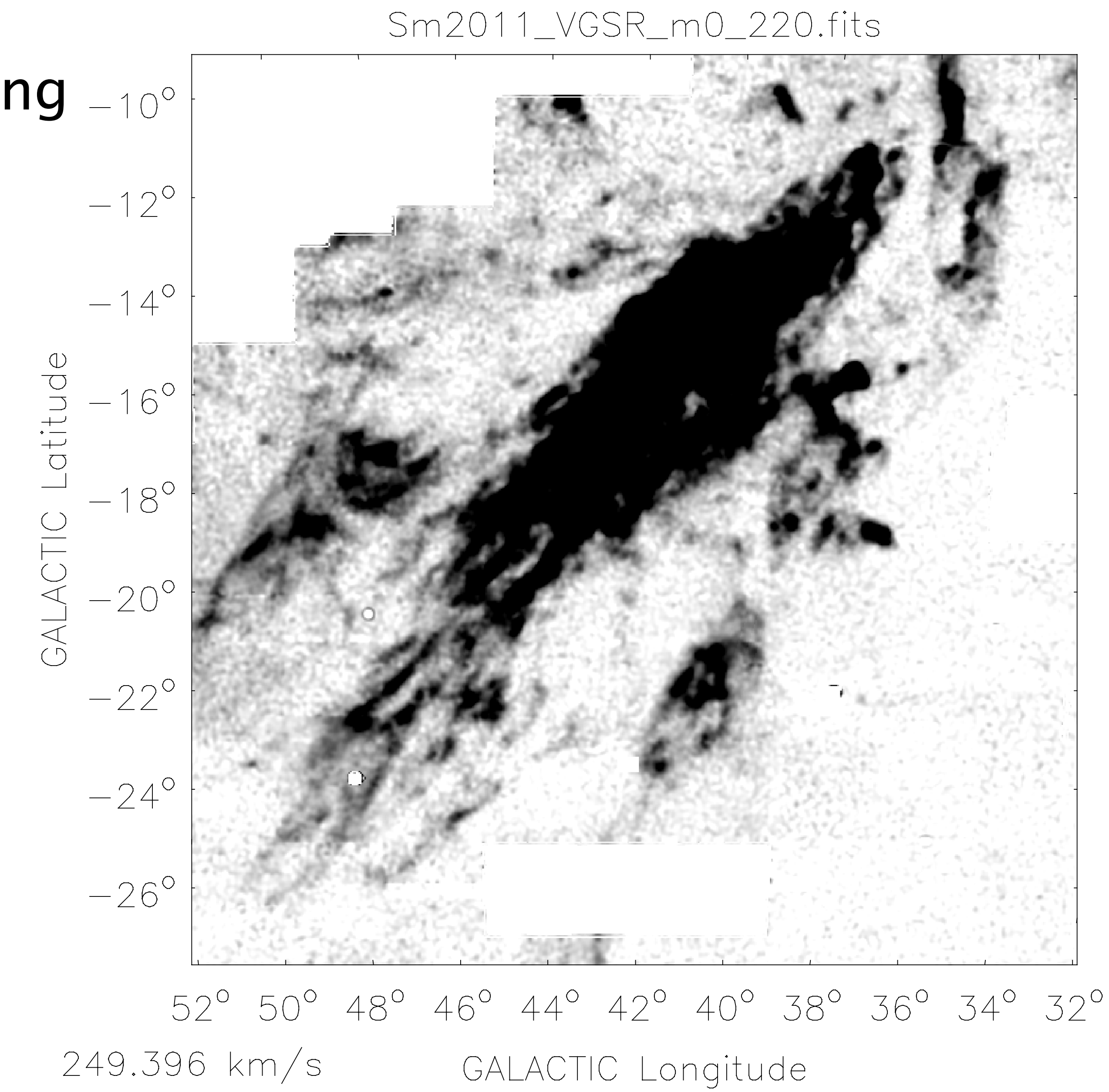
$$V_{LSR} = \left[R_0 sin(\ell)\{\frac{V_\theta}{R} - \frac{V_0}{R_0}\} - V_R \cos(\ell + \theta) \right] \cos(b) + V_z sin(b)$$

Infall?

... and will hit the Galactic plane adding angular momentum to the disk

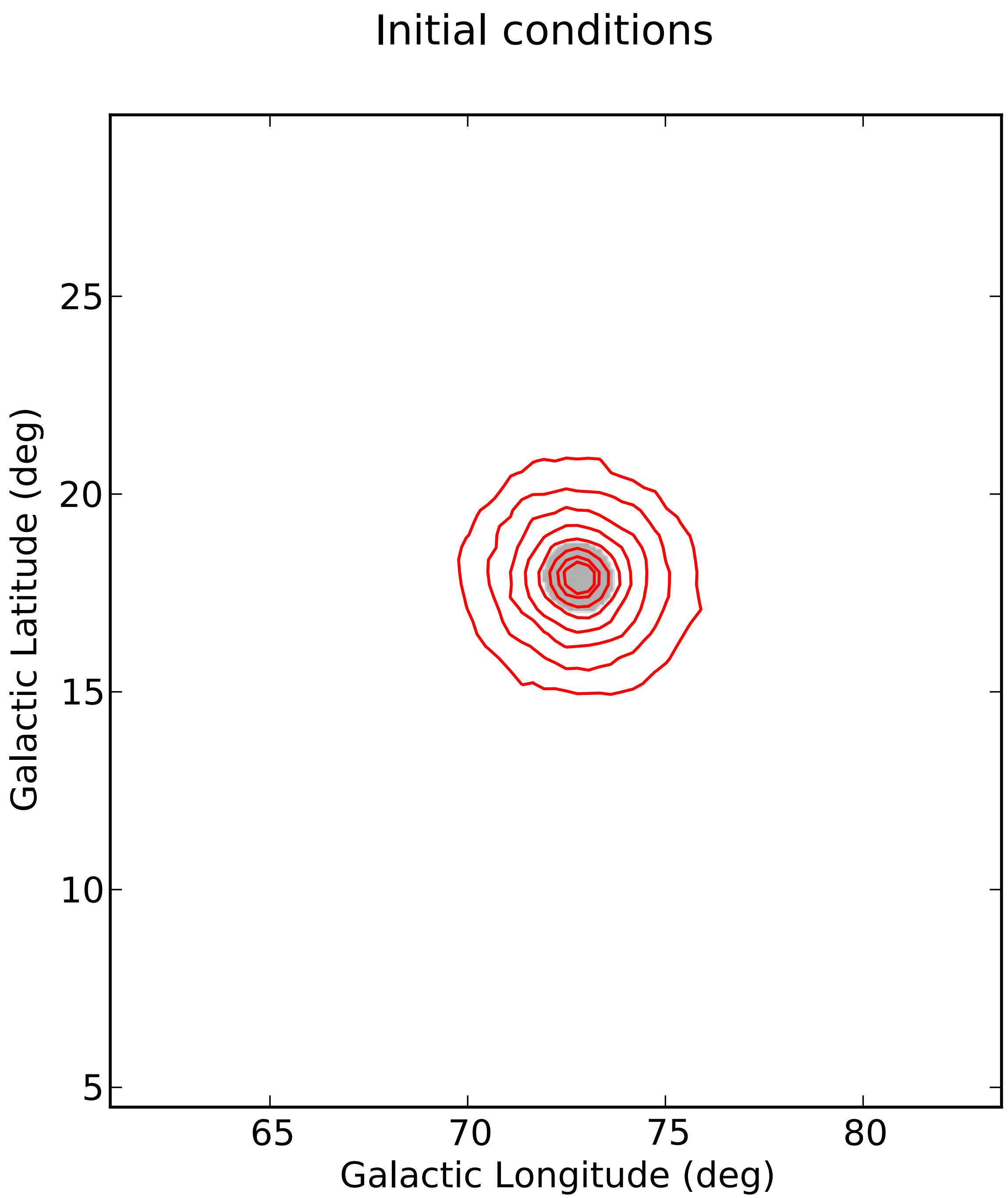
Milky Way	V_{esc} ~ 500 km/s
Smith	Vtot ≲ 300 km/s
Smith	$V_\theta \approx 260$ km/s

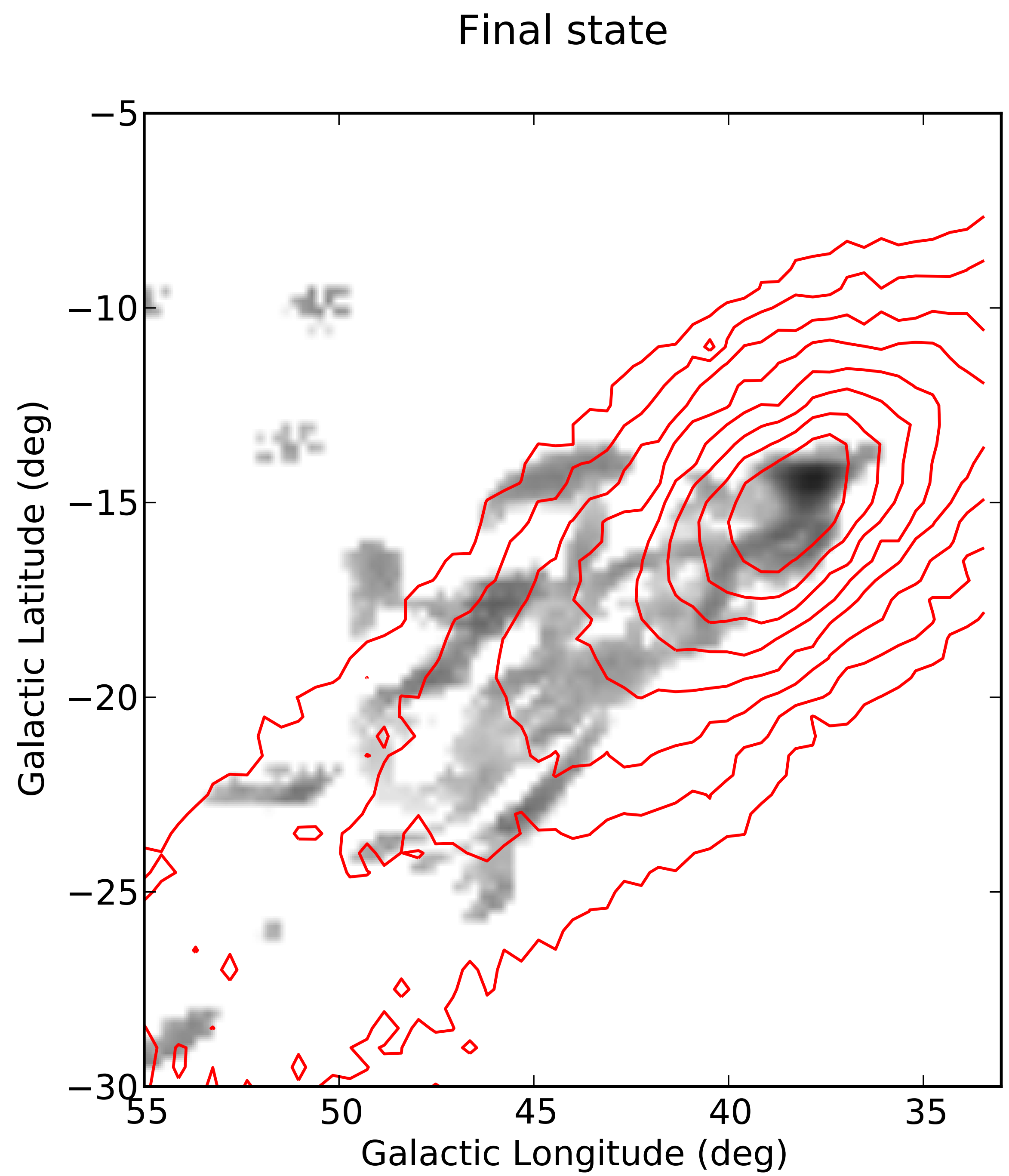
Lockman et al (2008, 2014)

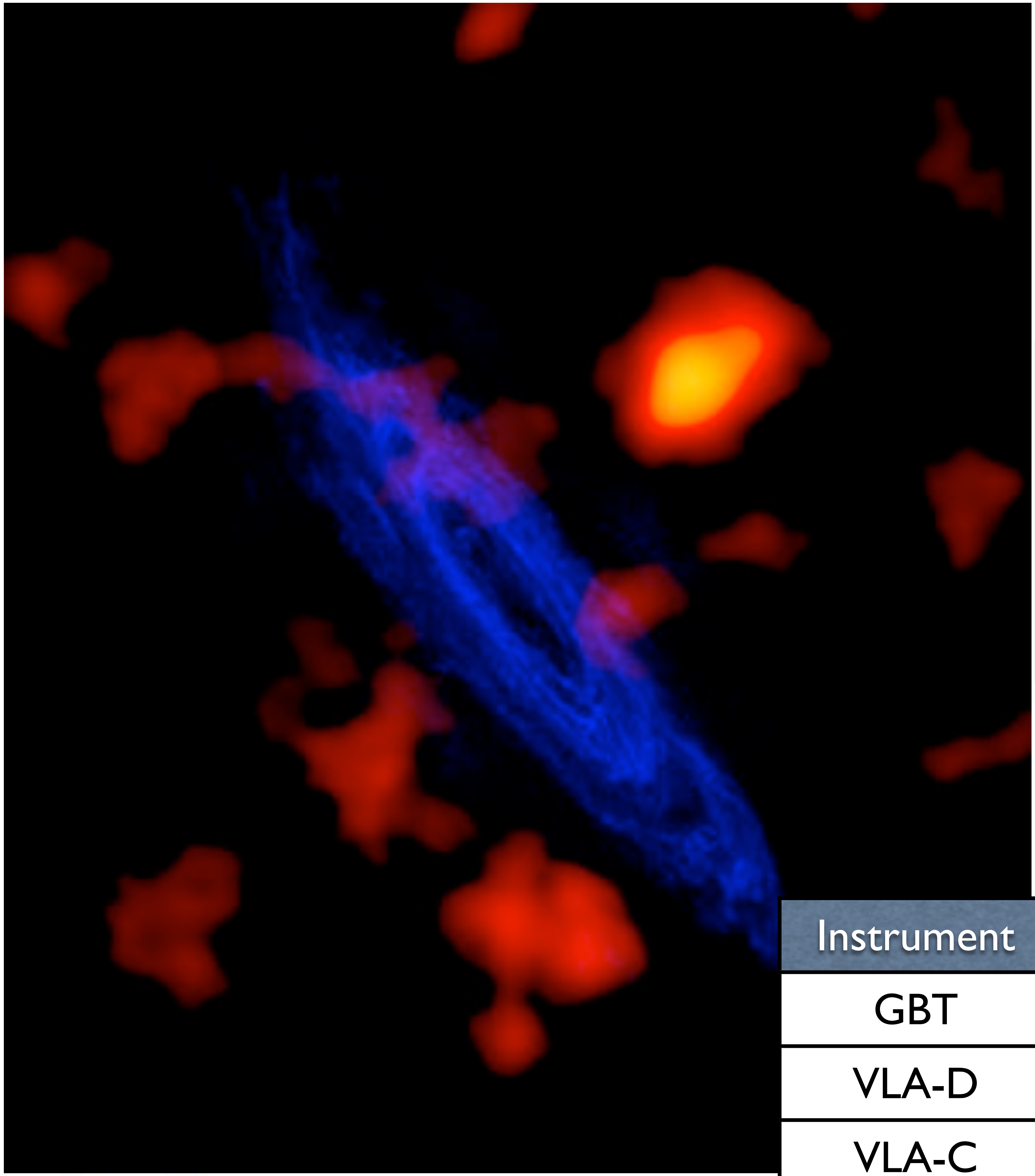


Does the Smith Cloud have dark matter?

Nichols, Mirabal, Agertz, Lockman, Bland-Hawthorn (2014)





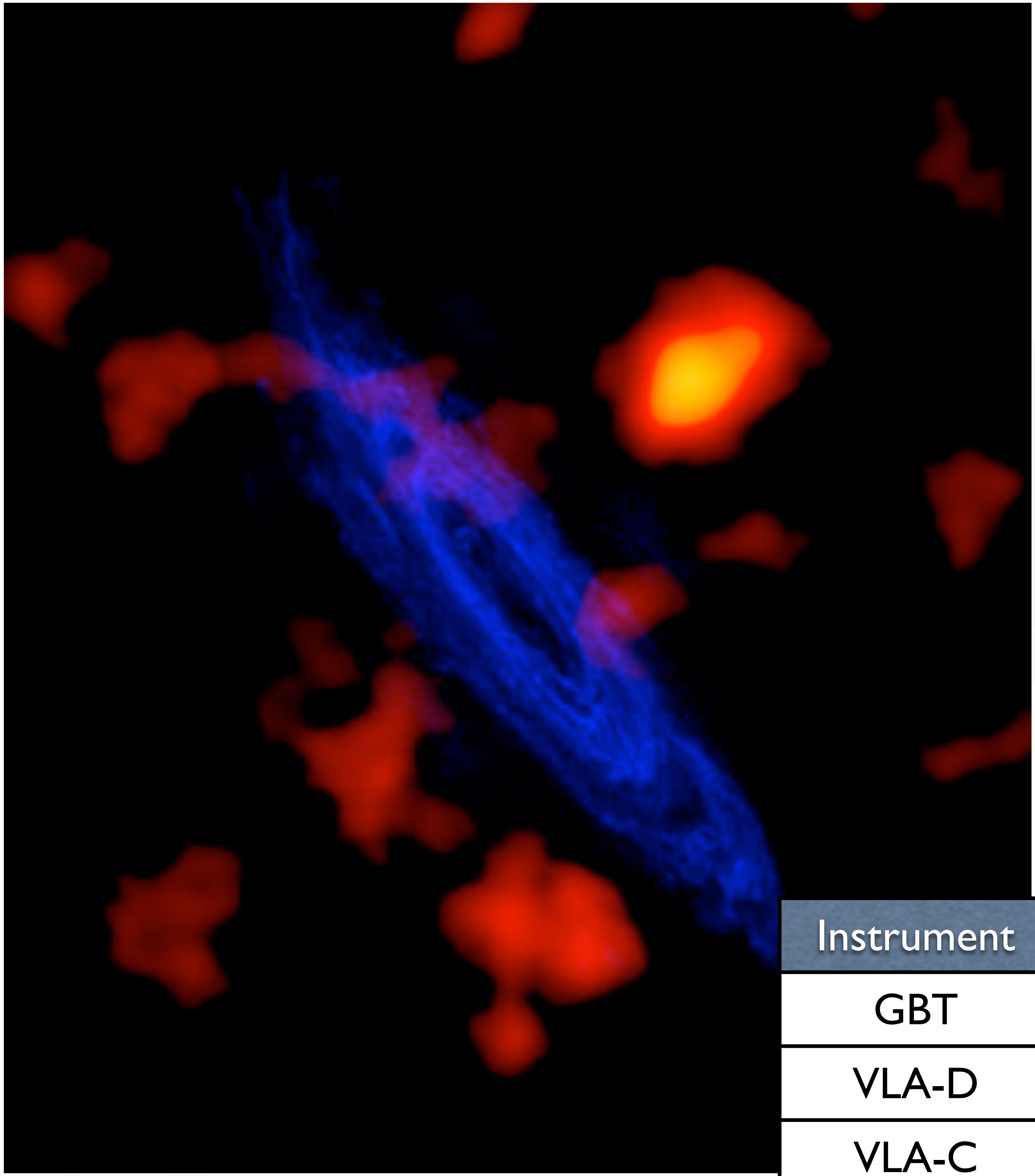


GBT Detection of High-velocity HI Clouds Around Andromeda 10^{6-7} M⊙

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

Instrument	f^2
GBT	1
VLA-D	~10^4
VLA-C	~10^6
VLA-B	~10^8

What is the origin of this gas?



Extraplanar HI

$N_{HI} = 10^{18.5}$

$T_b = 0.06$ K

$t \approx 20 f^2$ sec

GBT Detection of High-velocity HI Clouds Around Andromeda

10^{6-7} M⊙

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Instrument	f^2
GBT	1
VLA-D	$\sim 10^4$
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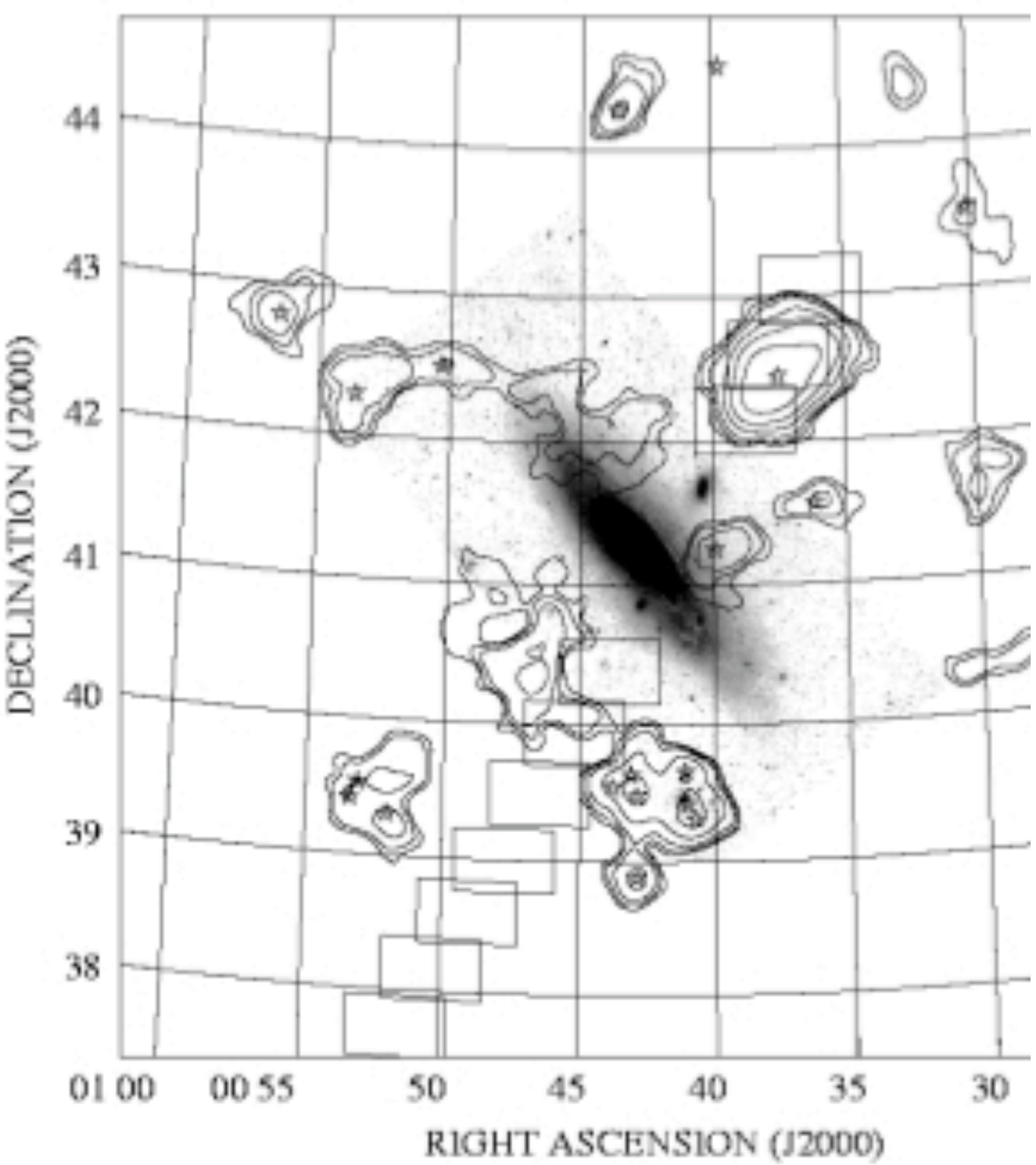
VLA-B	$\sim 10^8$

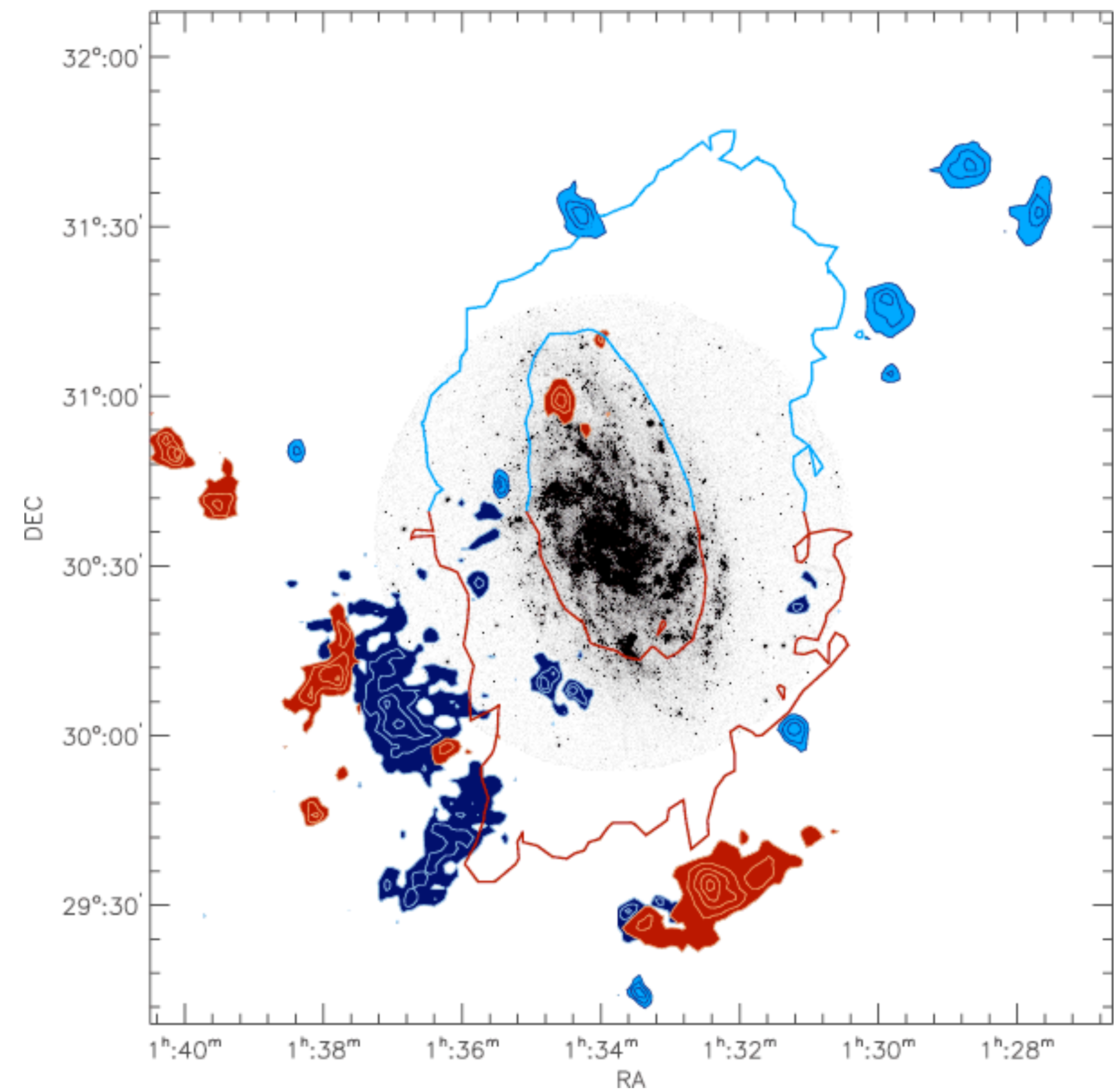
What is the origin of this gas?

High Velocity Clouds around galaxies

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}



The Milky Way has HVCs covering 40% – 80% of the sky

The distribution of gas in the Local Group from constrained cosmological simulations: the case for Andromeda and the Milky Way galaxies

Nuza et al. 2014 arXiv:1403.7528

Infall?

$N_{HI} = 10^{17}$

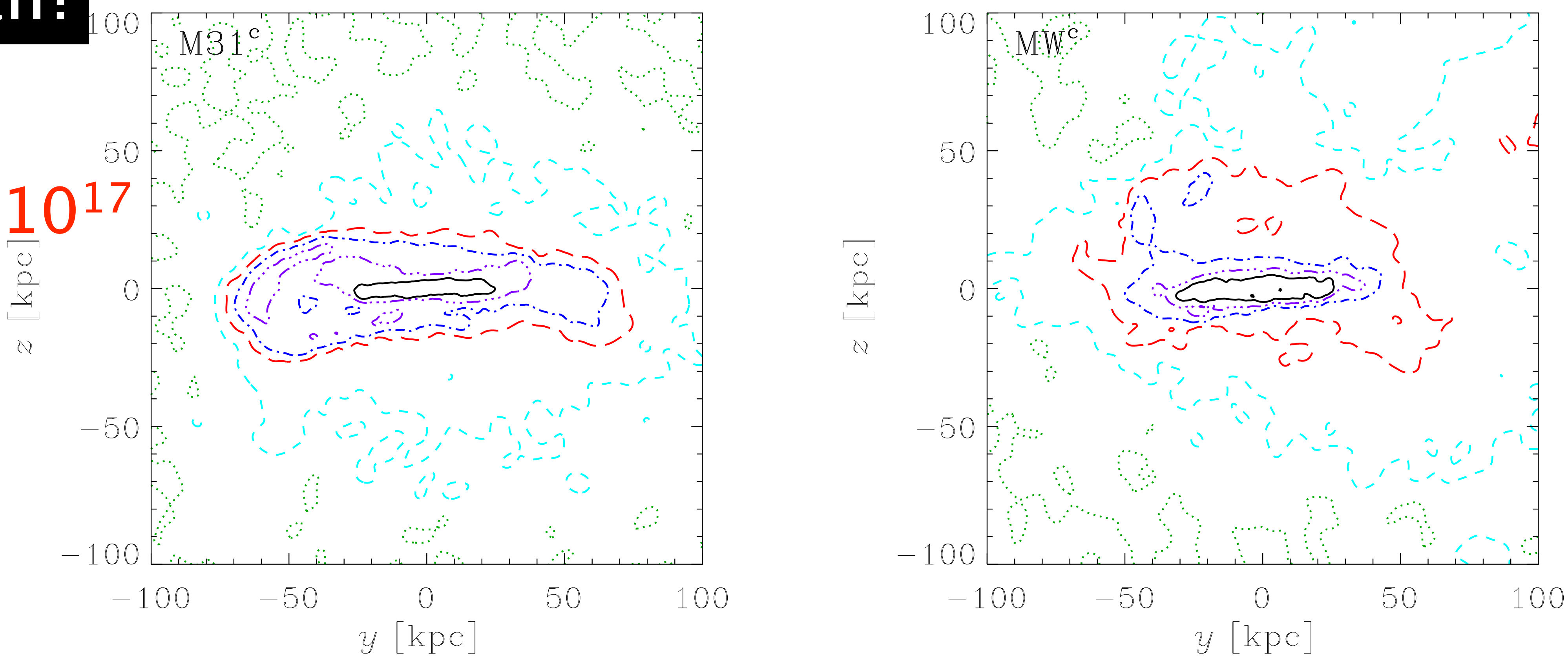


Figure 10. Contours of the H I gas distribution around the simulated M31^c (left-hand panel) and MW^c (right-hand panel) for two arbitrary edge-on views. The contours indicate column densities of $N_{HI} \geq 10^{15}\,cm^{-2}$ (dotted lines); $N_{HI} \geq 10^{16}\,cm^{-2}$ (short-dashed lines); $N_{HI} \geq 10^{17}\,cm^{-2}$ (long-dashed lines); $N_{HI} \geq 10^{18}\,cm^{-2}$ (dotted-dashed lines); $N_{HI} \geq 10^{19}\,cm^{-2}$ (three-dotted-dashed lines), and $N_{HI} \geq 10^{20}\,cm^{-2}$ (solid lines).

NRAO

The distribution of gas in the Local Group from constrained cosmological simulations: the case for Andromeda and the Milky Way galaxies

Nuza et al. 2014 arXiv:1403.7528

2

Infall?

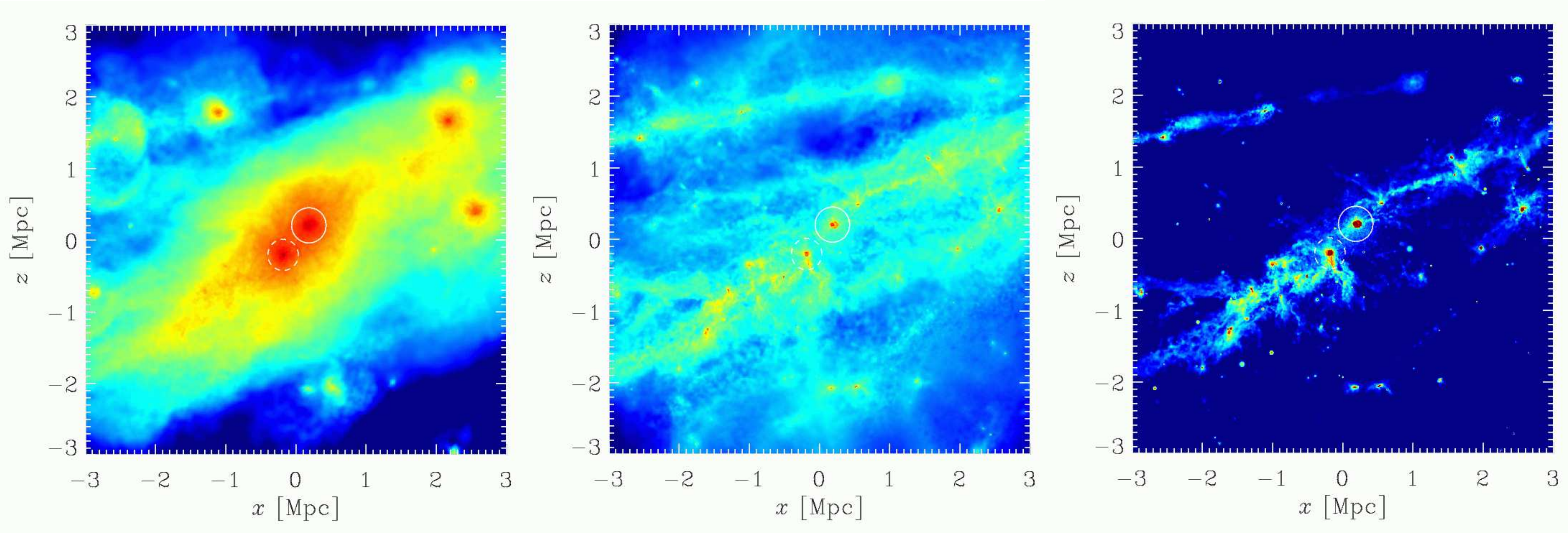
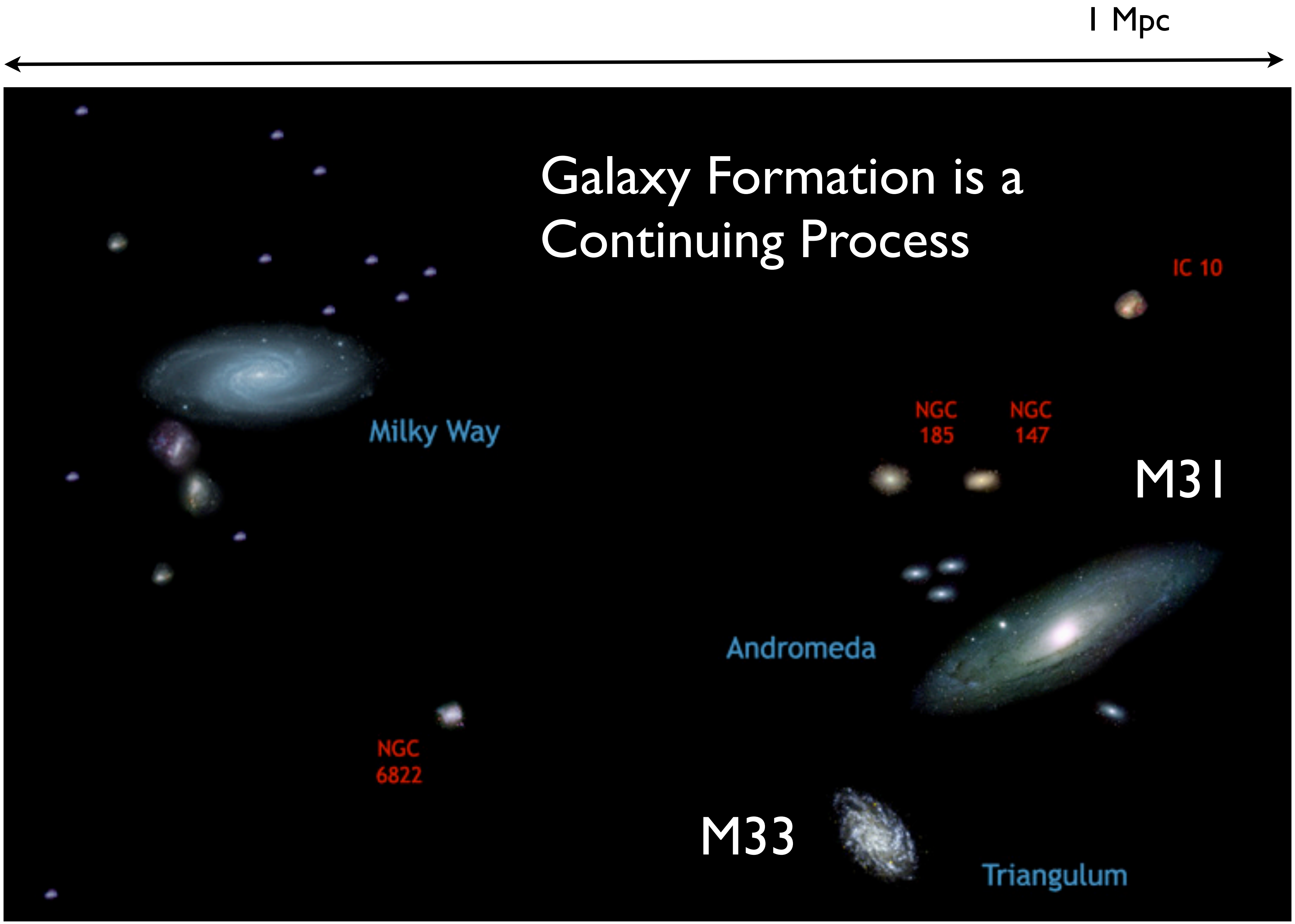
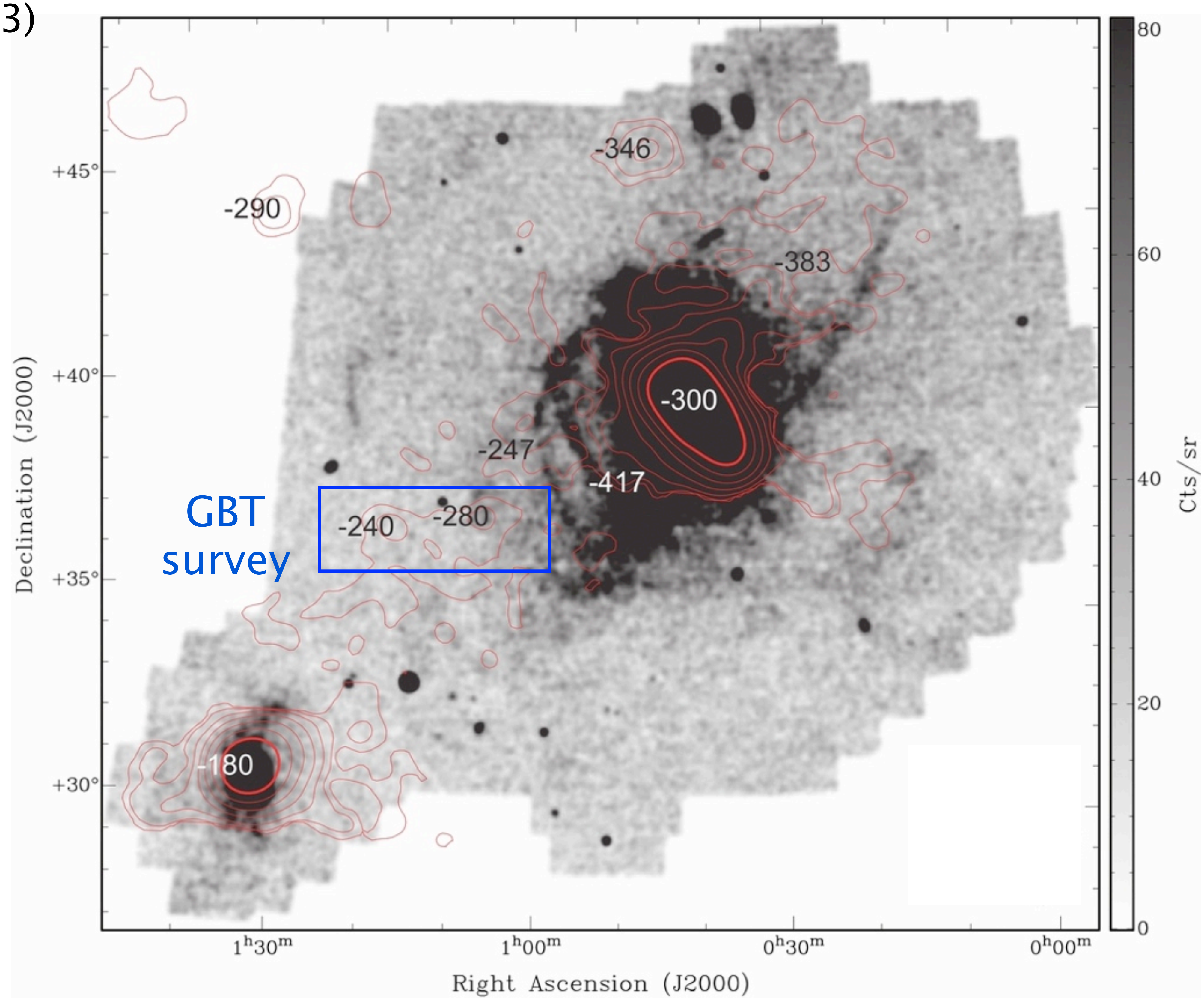


Figure 1. Gas density maps of the simulated LG at $z = 0$ for the hot ($T \geq 10^5$ K; left-hand panel), cold ($T < 10^5$ K; middle panel) and H I (right-hand panel) components. The plots are centred in the $MW^c/M31^c$ system. The virial radii of our Milky Way and Andromeda candidates are shown as dashed and solid lines respectively. In order to highlight the differences in the distribution of the hot, cold and neutral gas components, each plot shows the projected density in a color scale covering four orders of magnitude.

HI in the Local Group of Galaxies

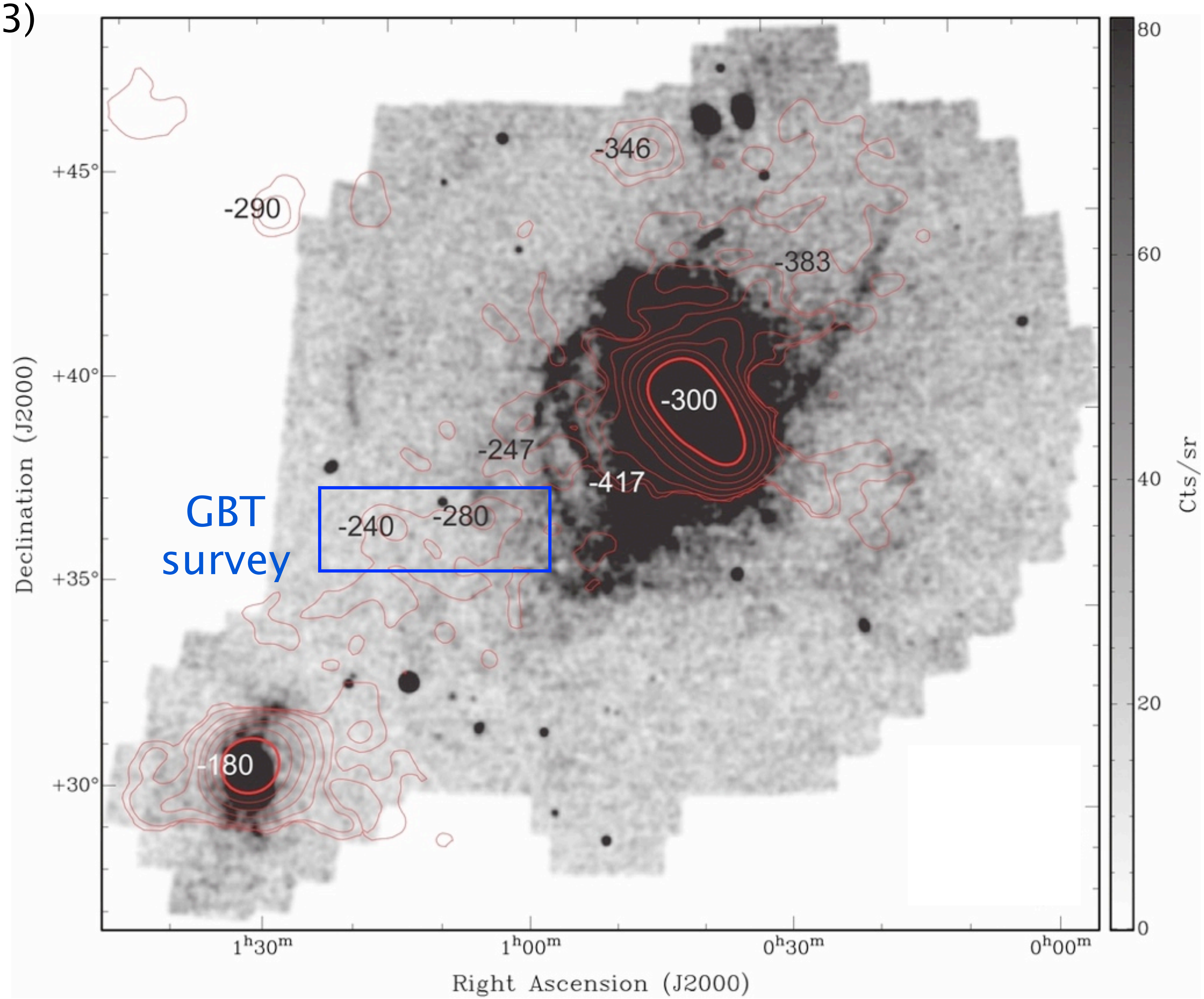


M31 Interactions
(Lewis et al 2013)

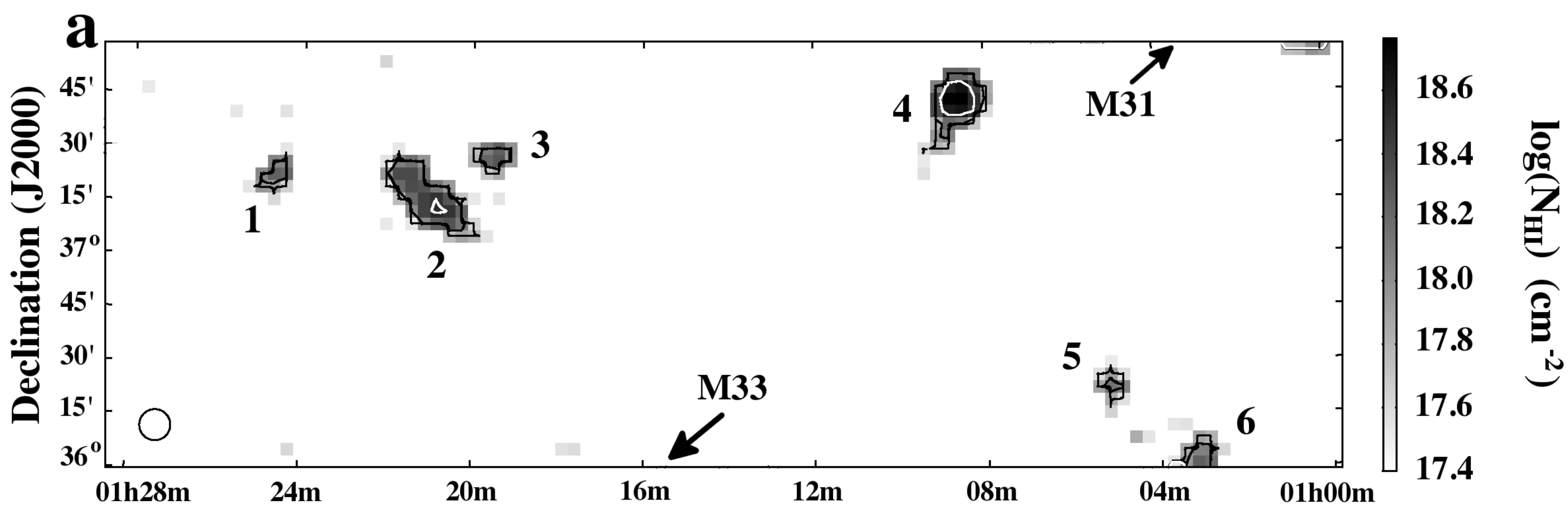


M31 Interactions
(Lewis et al 2013)

GBT 21cm HI
$N_{HI} = 10^{17.5}$
$T_b = 0.006$ K
$t \approx 2\,000\ f^2$ s



Discrete HI Clouds between M31 and M33



Wolfe et al. (2013)

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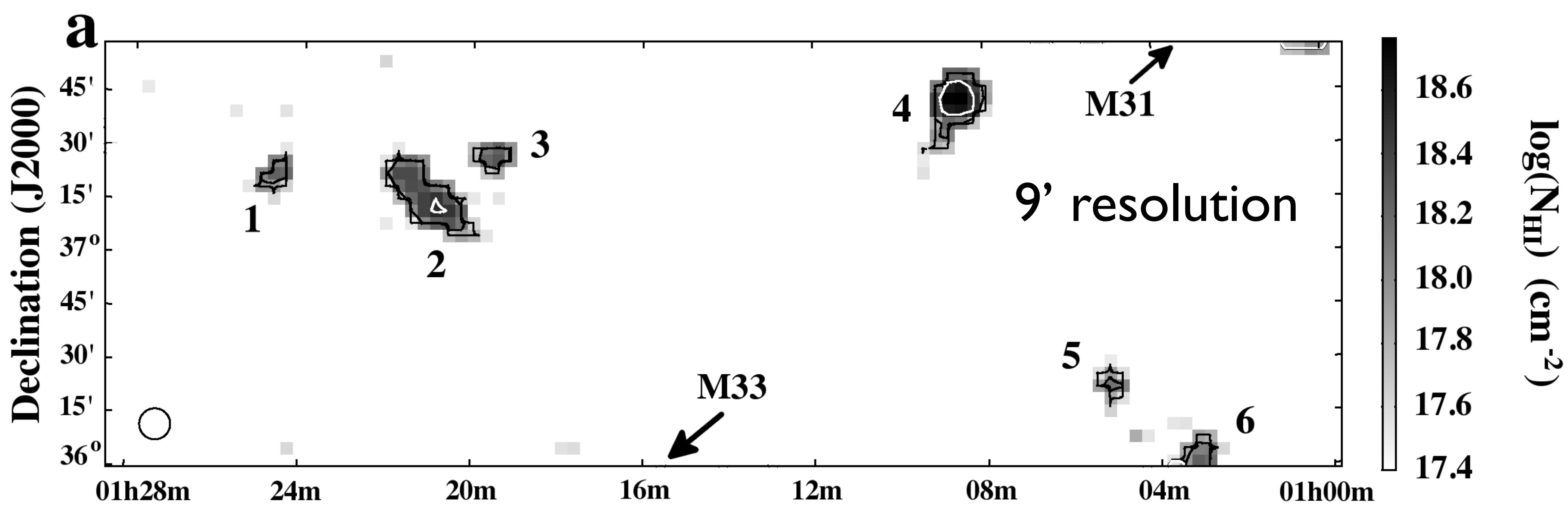

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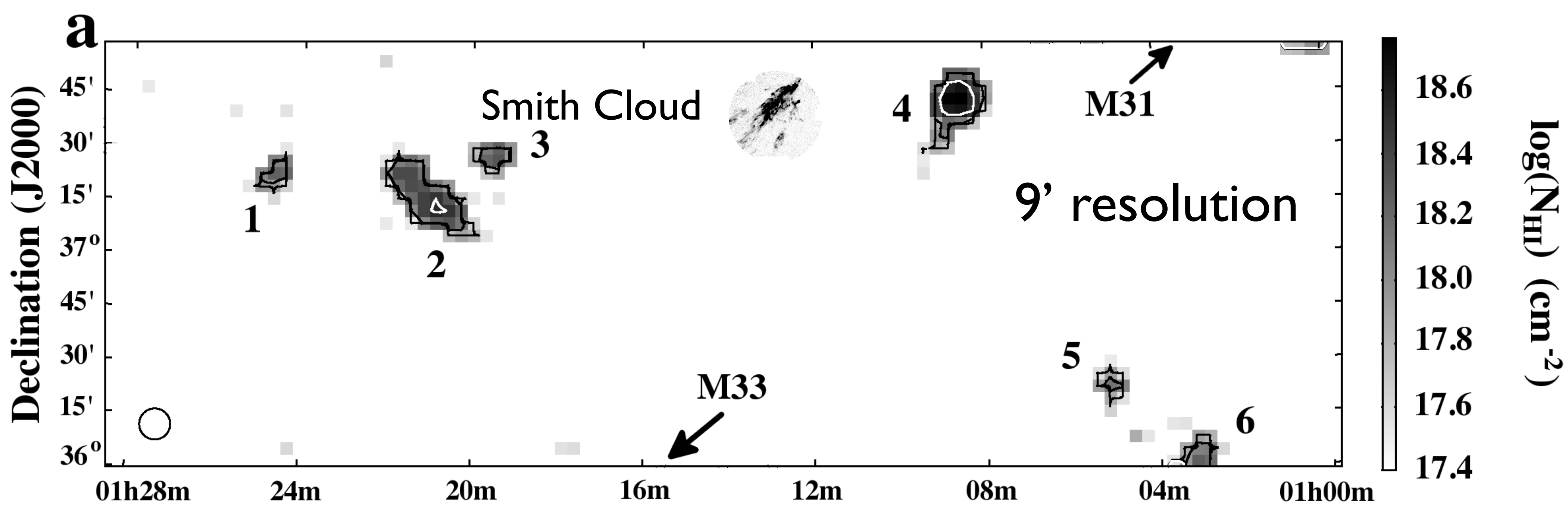


Wolfe et al. (2013)

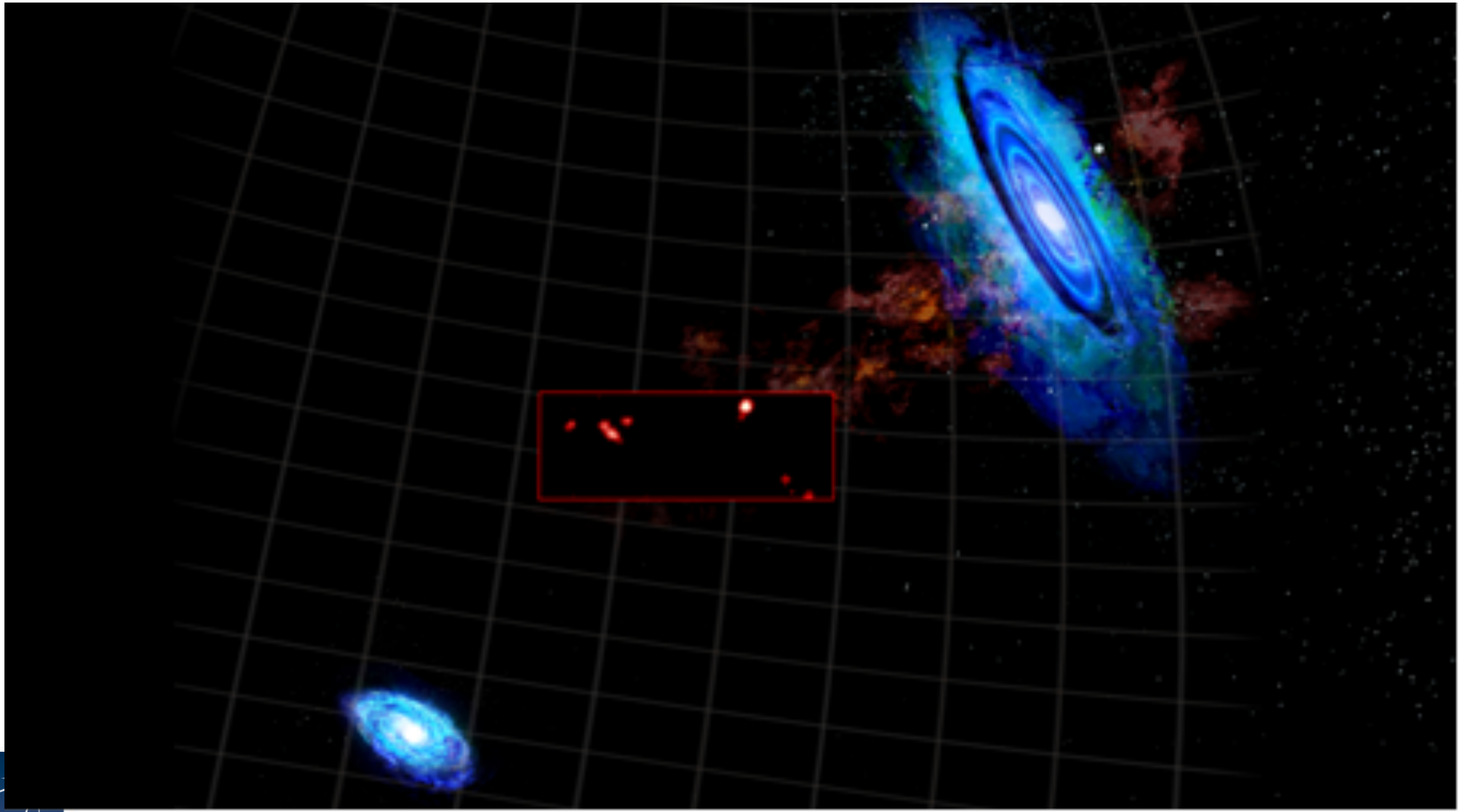
LETTER

NATURE May 9, 2013

doi:10.1038/nature12082

Discrete clouds of neutral gas between galaxies M31 and M33

Spencer A. Wolfe[1], D. J. Pisano[1], Felix J. Lockman[2], Stacy S. McGaugh[3] & Edward J. Shaya[4]



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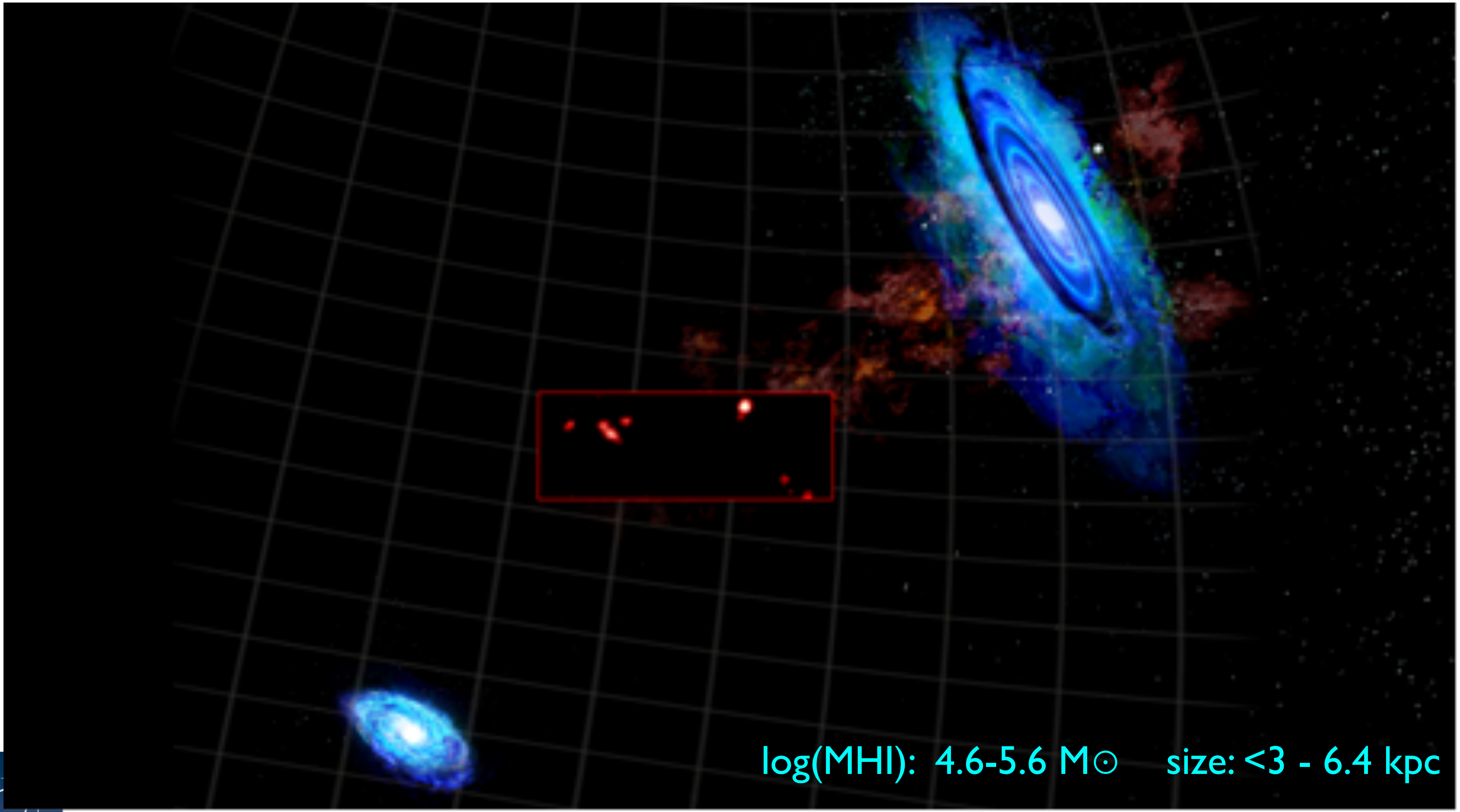

The Next Decade of 21cm HI Observations of the Local Universe

Theory:

Interactions, Fountains and winds, Inflow

Measurement:

* Diffuse gas in the Local Group
* Diffuse HI around other spirals
* Studies of HVCs in the MW and other galaxies
* The wind from the Galactic Center

Measurements at $N_{HI} = 10^{17}$ cm^{-2} will be key

A Wind from the Center of the Milky Way

A wind in the Galaxy -- Bregman, 1980
The HI Halo in the Inner Galaxy -- Lockman 1984
The Large-Scale Bipolar Wind in the Galactic Center -- Bland-Hawthorn & Cohen 2003
Does the Milky Way Produce a Nuclear Galactic Wind? -- Keeney et al 2006
Giant Gamma-ray Bubbles from Fermi-LAT: Active Galactic Nucleus Activity or Bipolar Galactic Wind? -- Su et al 2010
Non-thermal insights on mass and energy flows through the Galactic Centre and into the Fermi bubbles -- Crocker 2012
Giant magnetized outflows from the centre of the Milky Way -- Carretti et al. 2013
The Fermi bubbles as starburst wind termination shocks -- Lacki, 2013
The Fermi Bubbles: Possible Nearby Laboratory for AGN Jet Activity -- Yang et al. 2013

Atomic Hydrogen in a Galactic Center Outflow -- McClure-Griffiths et al 2013

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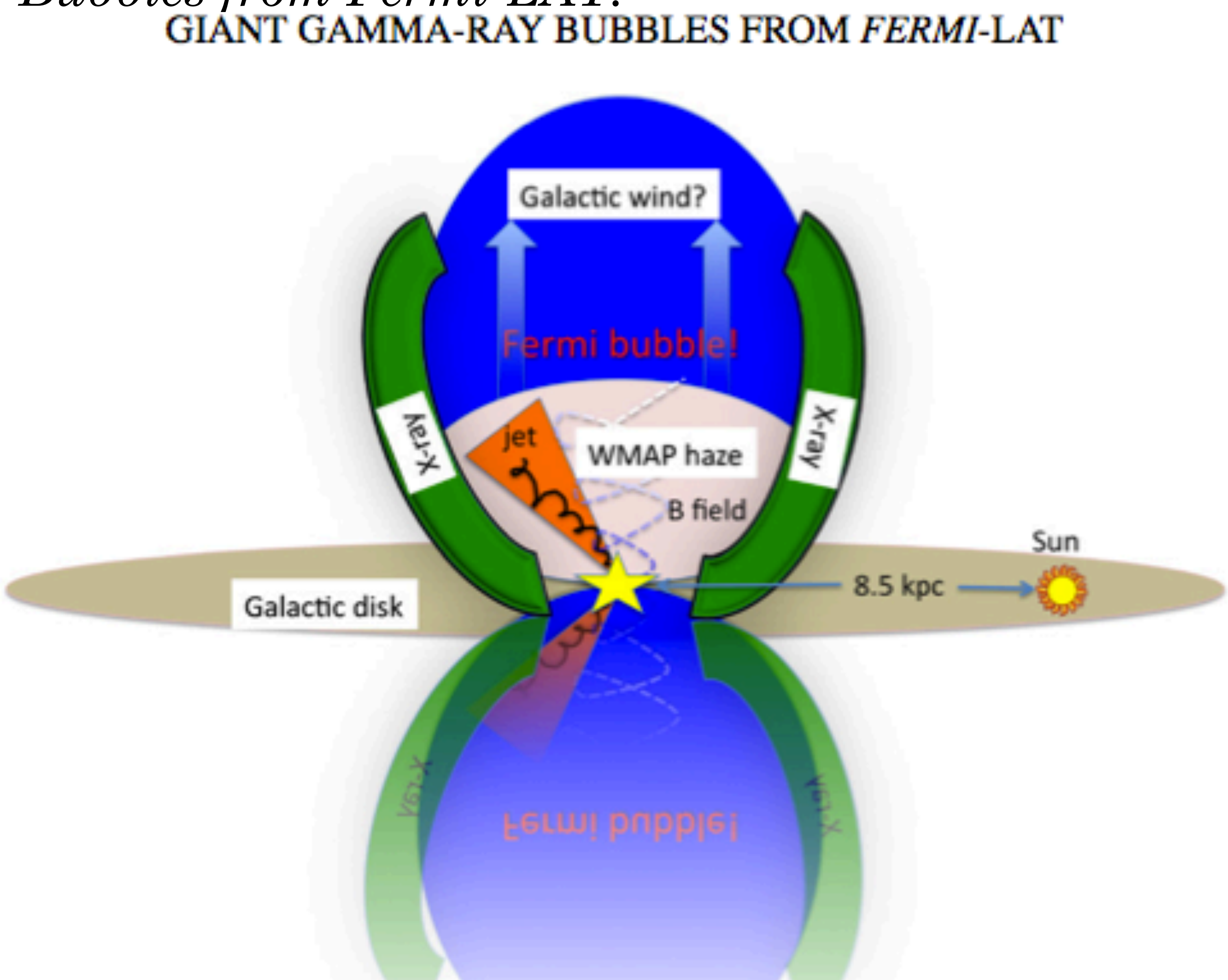
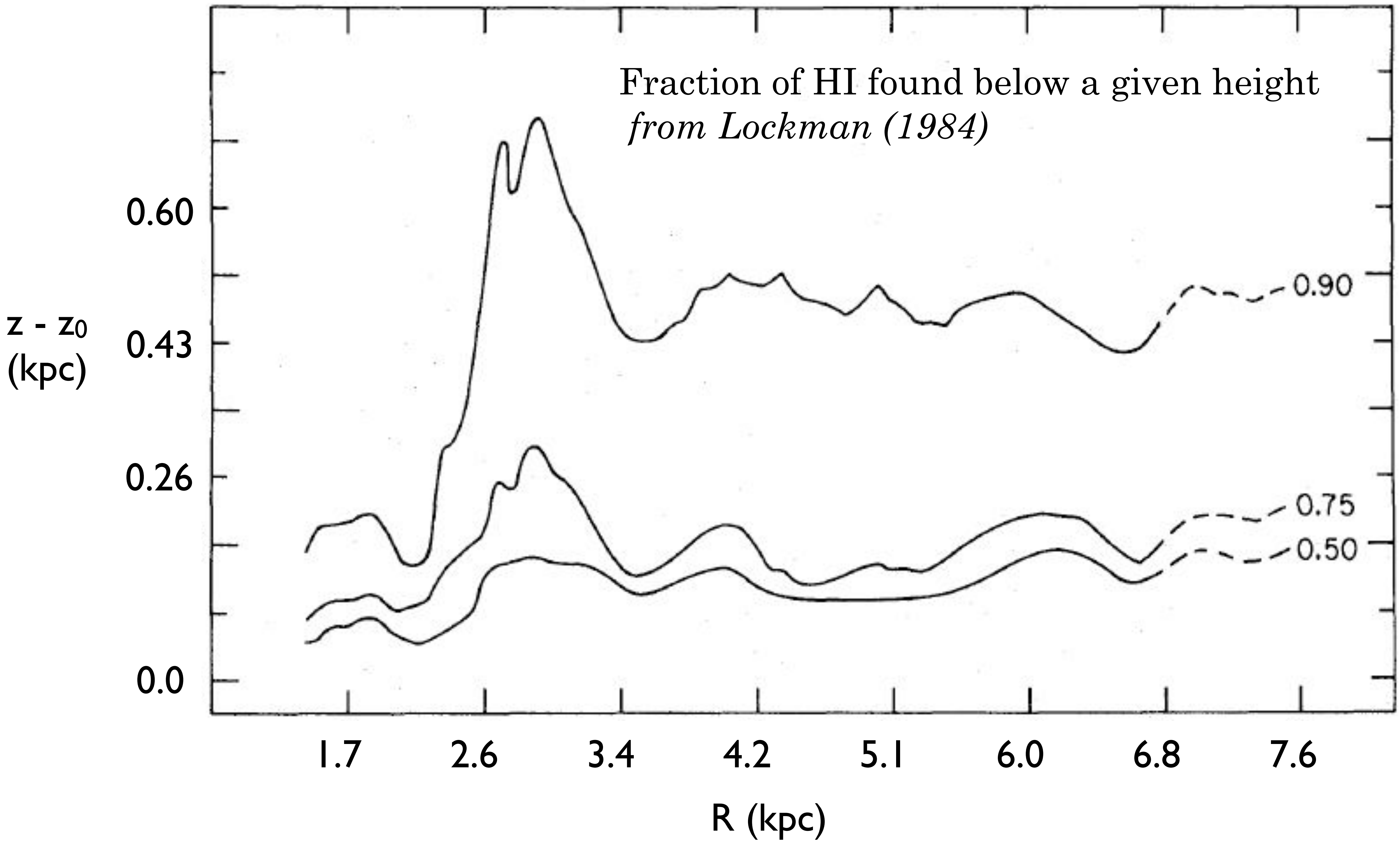
The Fermi bub
The Fermi Bul ng et al. 2013

Atomic Hydrog)13

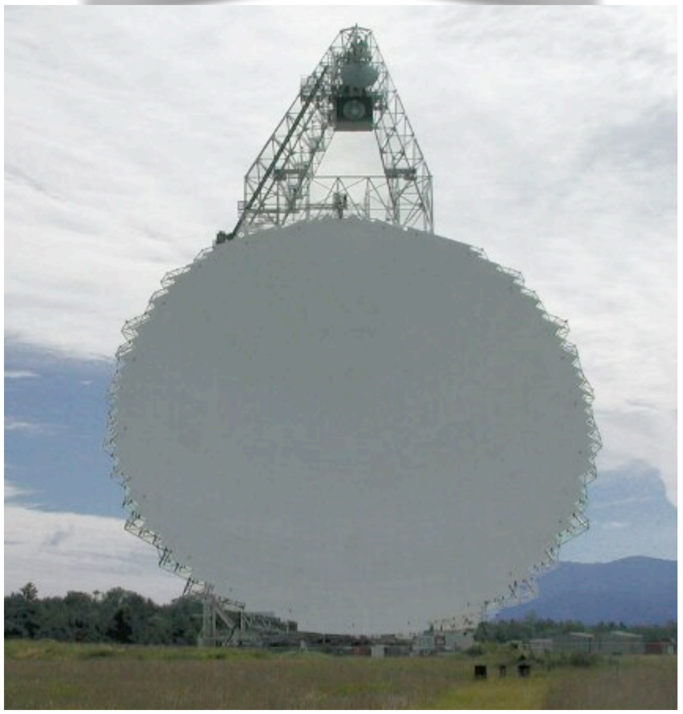


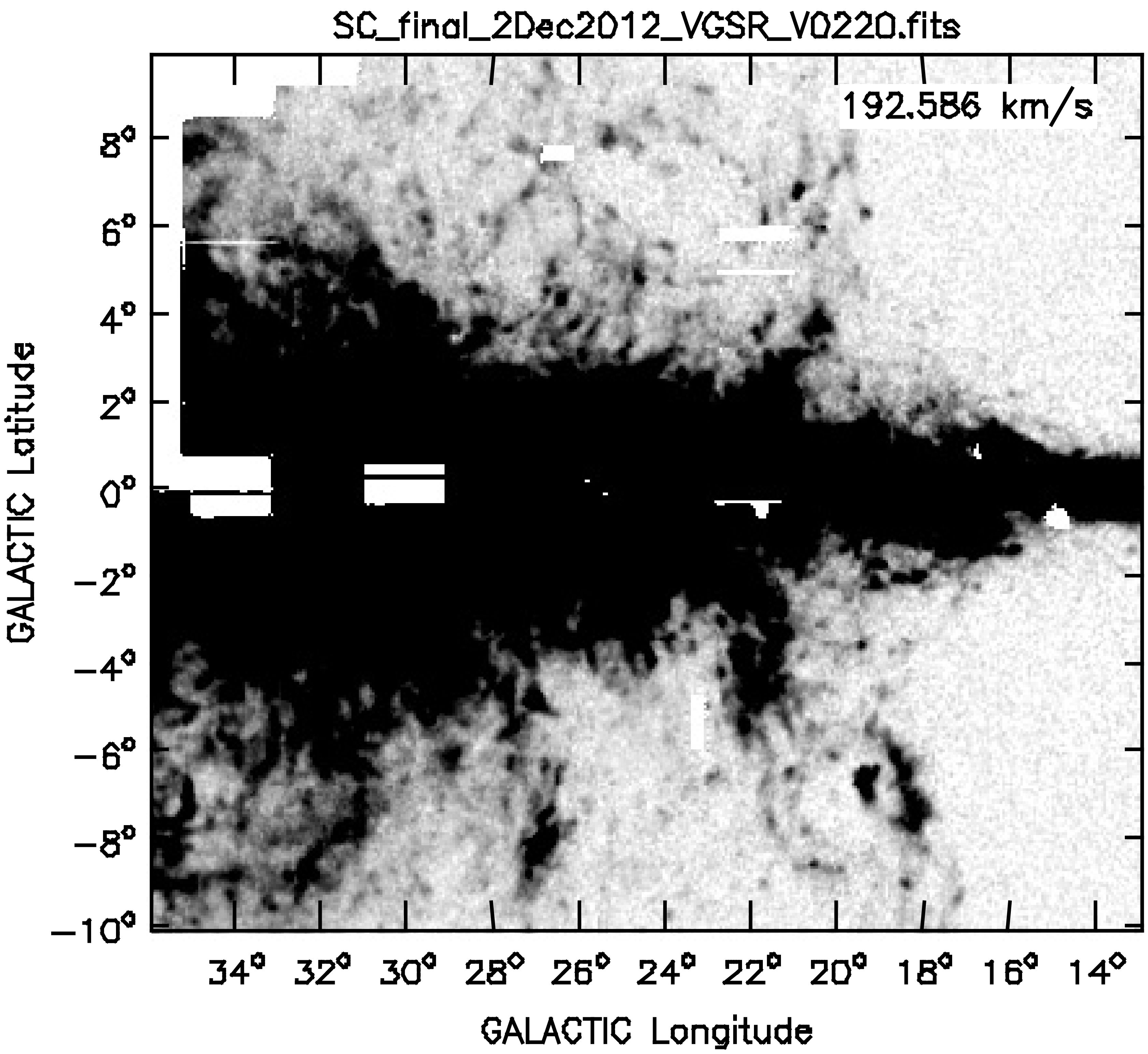
Why is there no extended HI halo in the inner Milky Way?



Why is there no extended HI halo in the inner Milky Way?

Data from a new GBT survey (in prep)

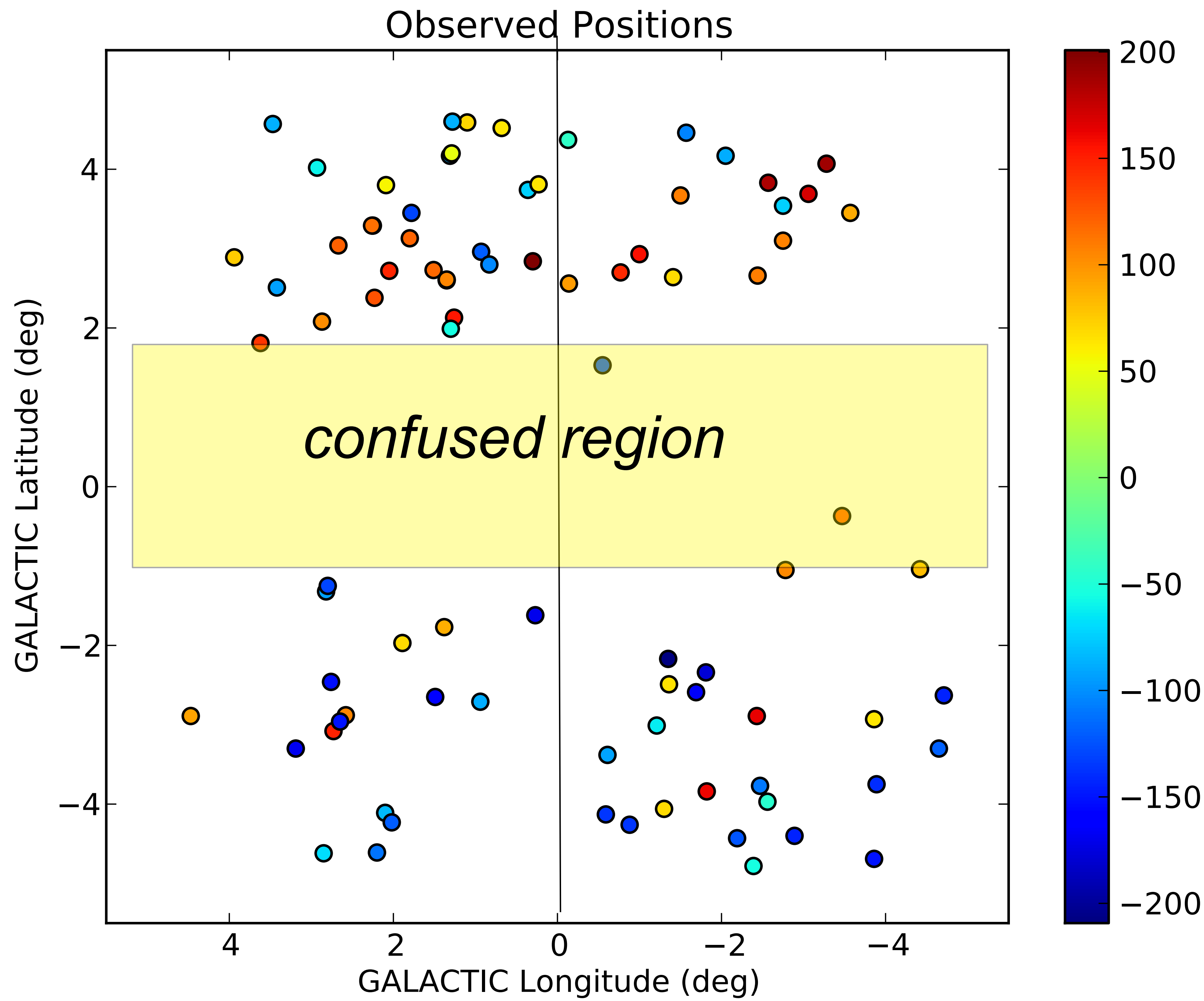


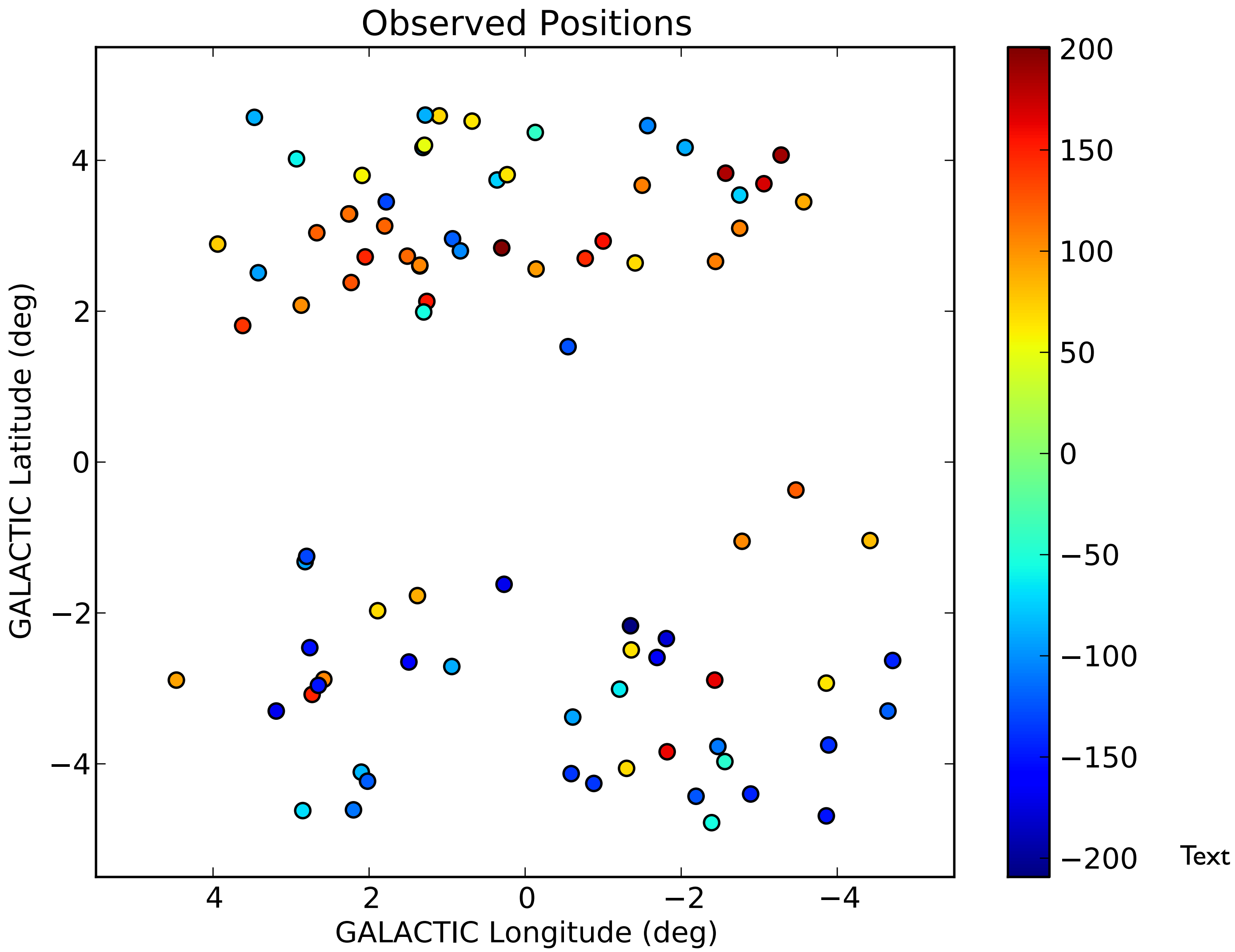


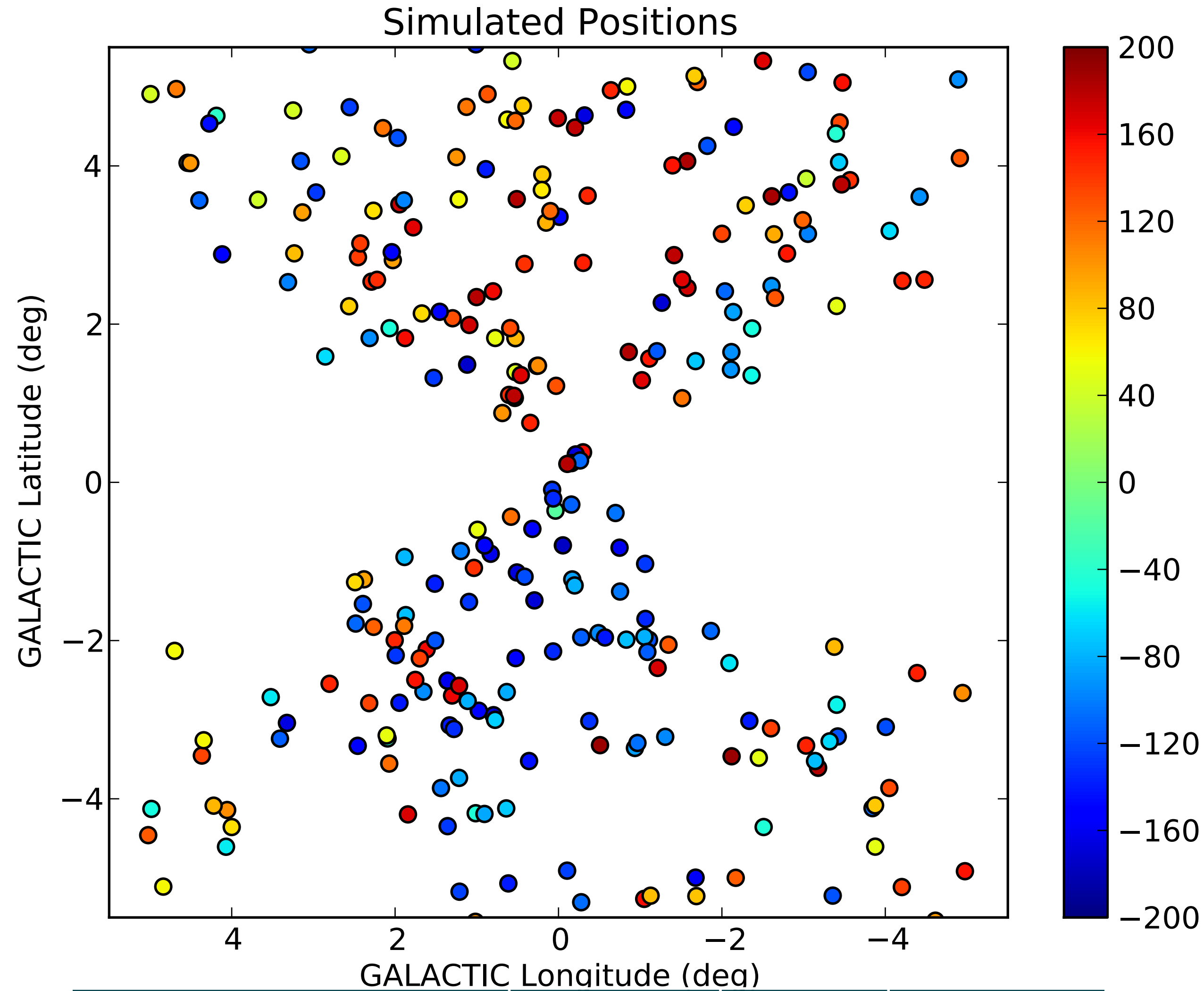
Atomic Hydrogen in a Galactic Center Outflow

McClure-Griffiths, Green, Hill, Lockman, Dickey, Gaensler & Green, 2013 ApJ 770, L4

A population of small HI clouds toward the Galactic Center







Cloud radial velocity ~200 km/s
opening angle ~135°
cloud lifetime ≳3 Myr

Property	Med	Min	Max
r (pc)	15.0	3.5	32.9
M_c (M_{sun})	270	5	2100
Δv (km s^{-1})	13.6	3.0	30.9
T_k (K)	4000	200	105
N_H (10^{19} cm^{-2})	9.9	1.0	35
Total HI Mass	$4x10^4$		
HI E_k (ergs)	$2x10^{52}$		

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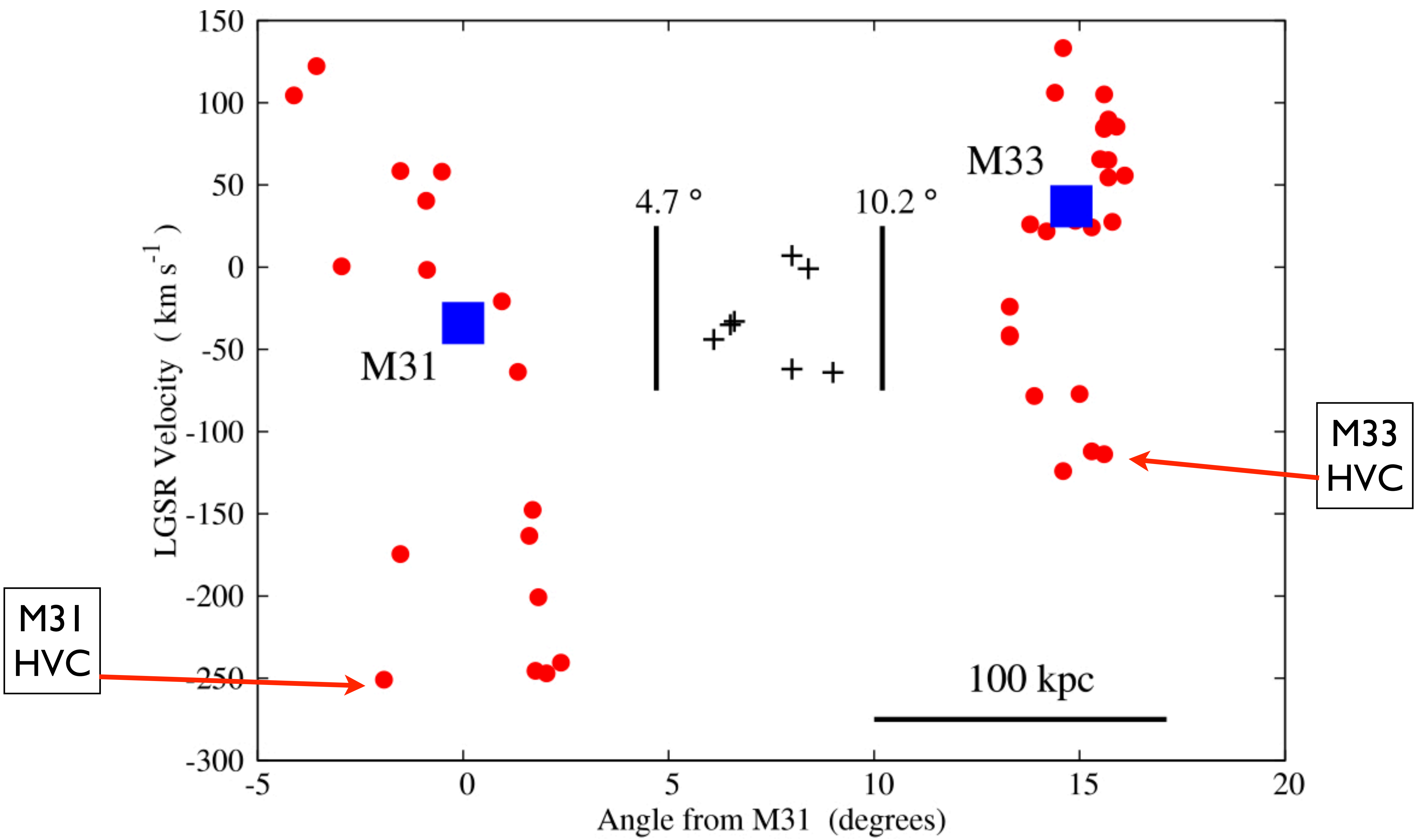
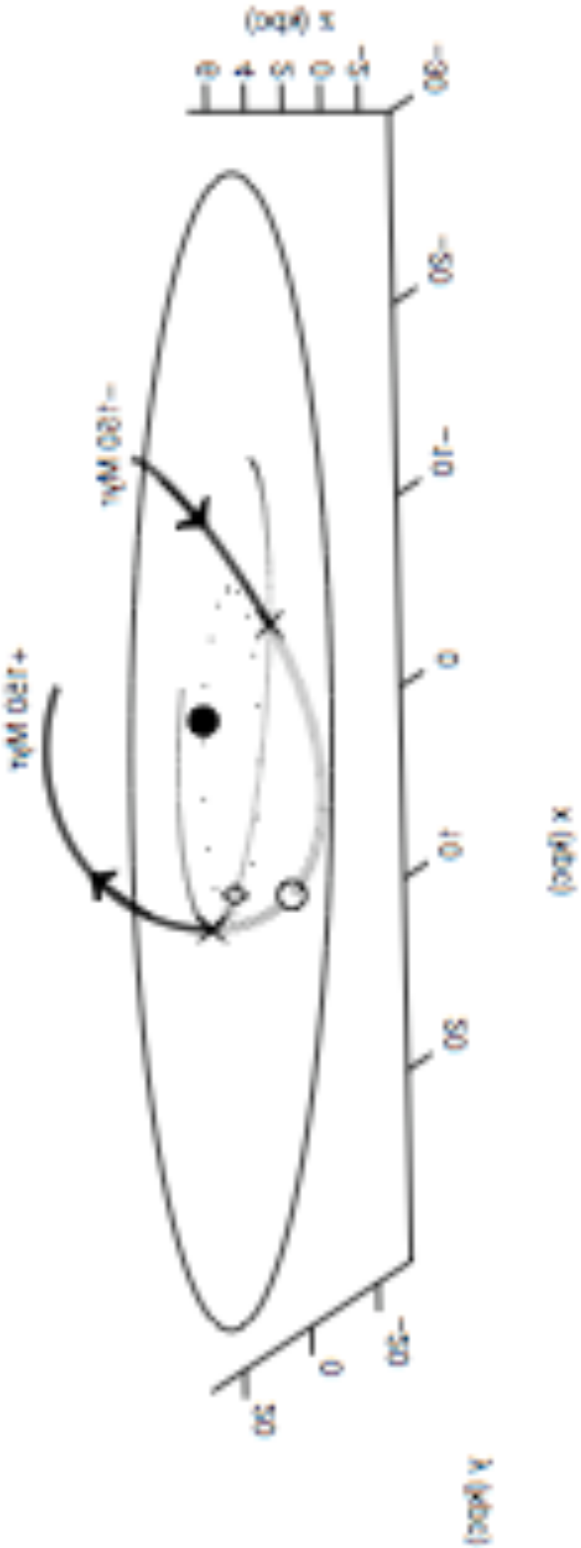
The M31-M33 HI clouds are not part of the high velocity cloud systems of M31 or M33

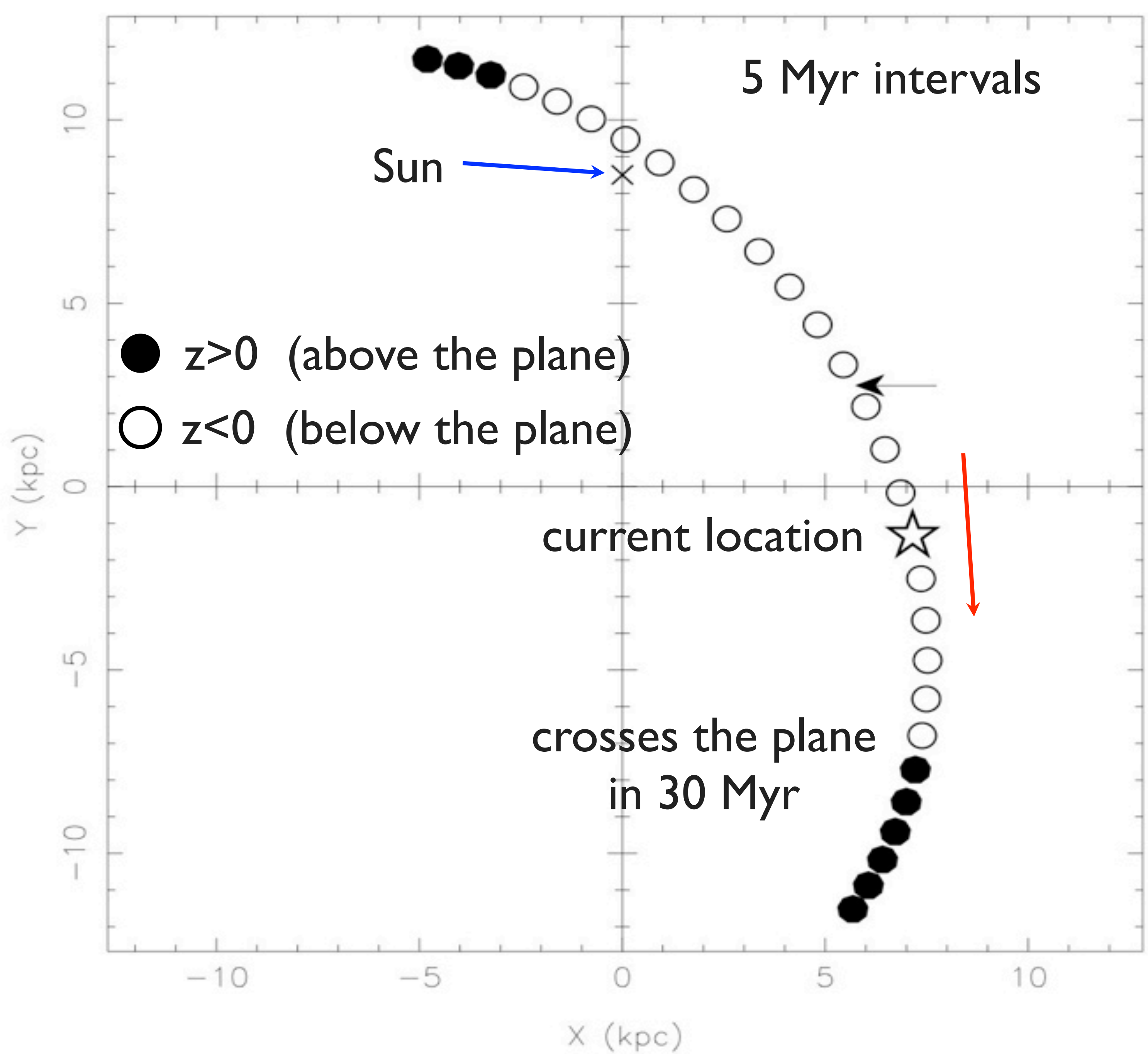


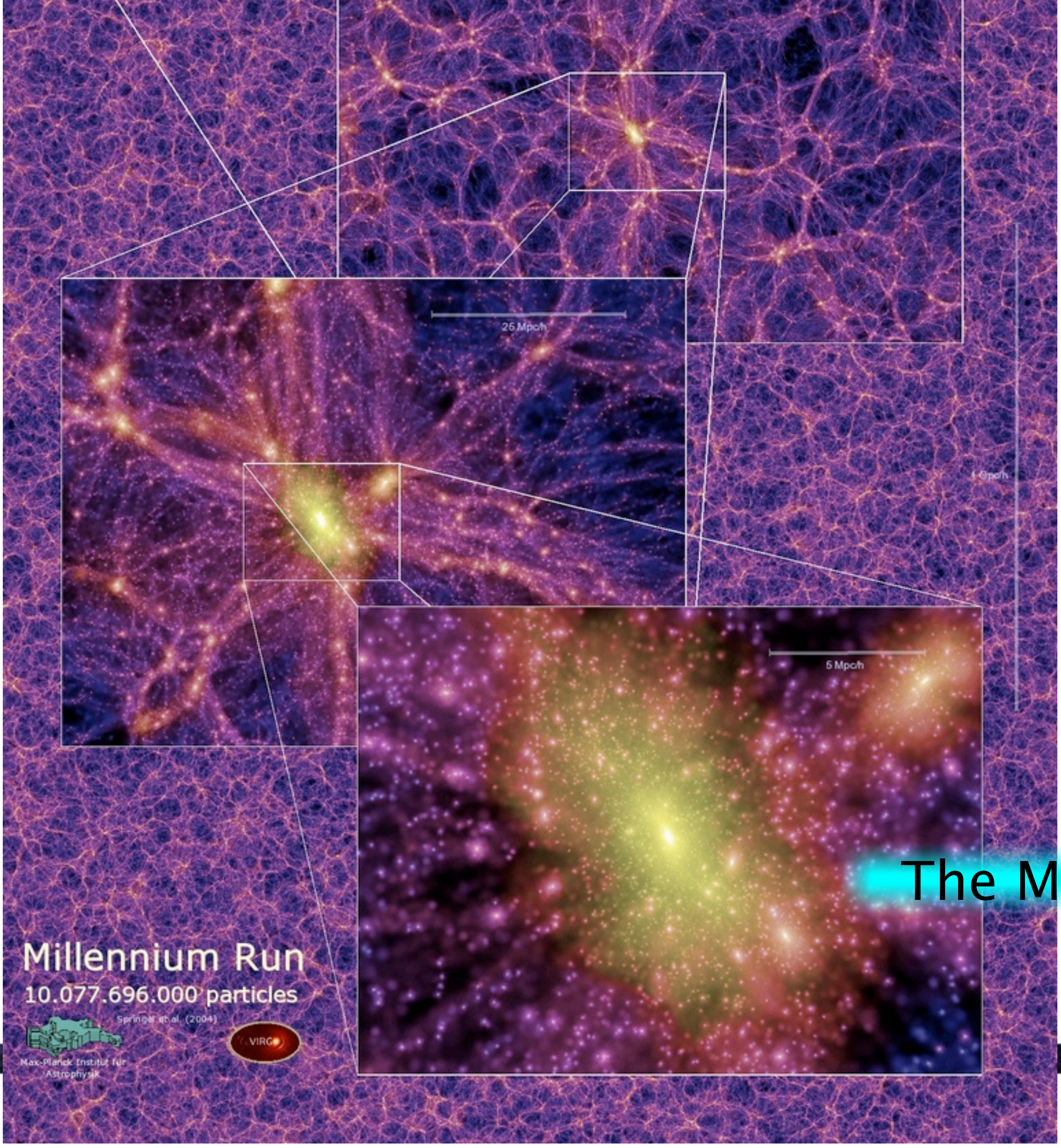
Wolfe et al. (2013)

The Smith Cloud Trajectory??

Where did the Cloud arise?







The Milky Way?

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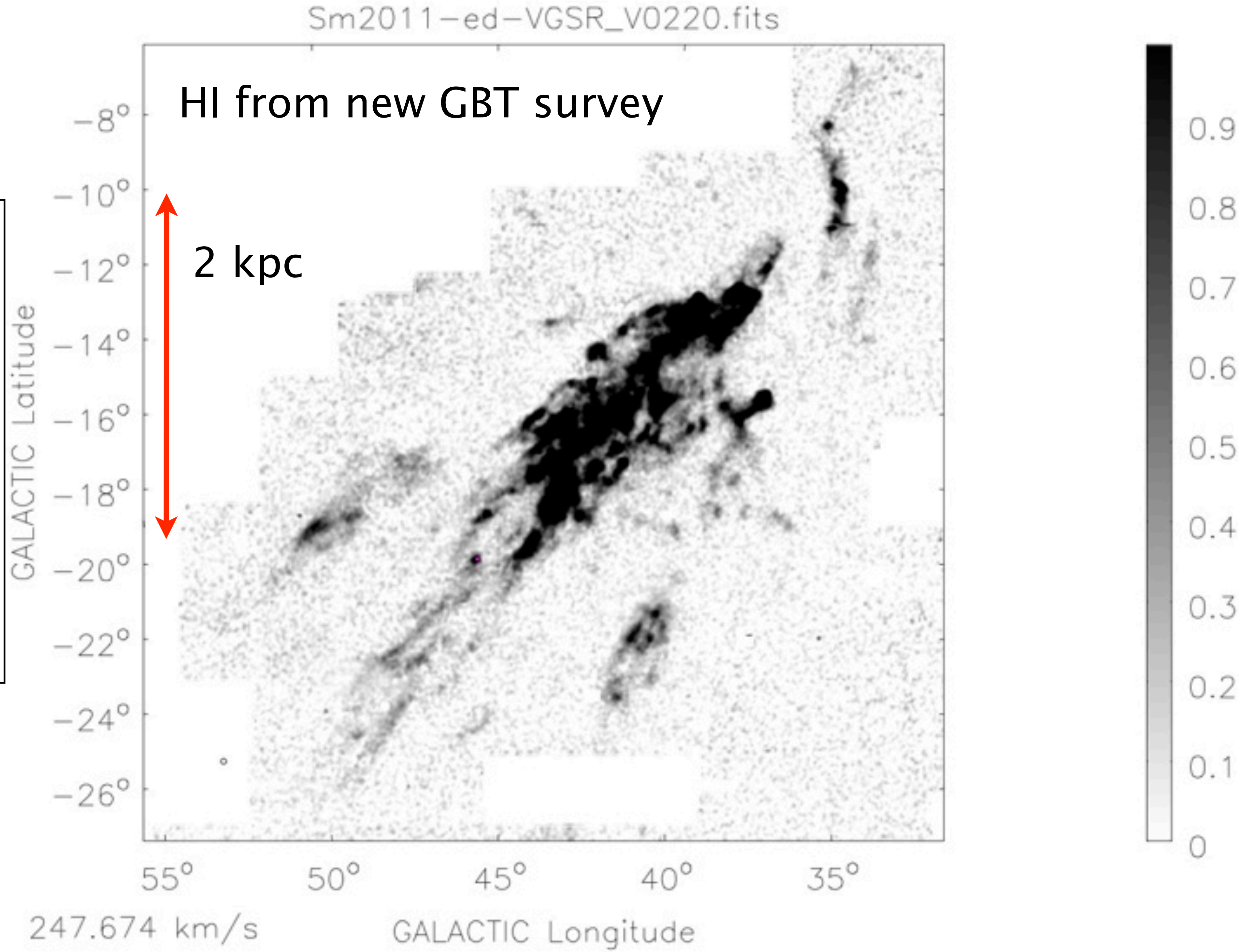
The “Smith” Milky Way High Velocity Cloud

Infall?

dist = 12.4 ± 1.3 kpc
R = 7.6 ± 1.0 kpc
z = -2.2 kpc
$M_{HI} > 2 \times 10^6\ M_\odot$
size ≈ 3 x 1 kpc
No Stars!

Wakker et al (2008)
Lockman et al (2008, 2014)



Discrete HI Clouds between M31 and M33

Cloud ...	R.A. H:M:S	DEC D:M:S	LSR Velocity $km\ s^{-1}$	FWHM $km\ s^{-1}$	$T_{B,Peak}$ mK	$\log(N_{HI})_{Peak}$ cm^{-2}	M_{HI} $(\pm 3 \times 10^3)$ $M_\odot$	Diameter (± 1) kpc
1	01:24:42	+37:23:02	-297 ± 1	23 ± 3	47 ± 4	17.6 ± 0.04	1.2×10^5	≤ 2.8
2	01:20:52	+37:16:58	-236 ± 1	28 ± 2	69 ± 4	17.8 ± 0.03	3.5×10^5	6.4
3	01:19:25	+37:31:12	-226 ± 2	28 ± 4	41 ± 4	17.6 ± 0.04	1.1×10^5	≤ 2.4
4	01:08:30	+37:44:51	-277 ± 1	34 ± 3	91 ± 4	17.9 ± 0.02	4.0×10^5	4.8
5	01:05:09	+36:23:28	-209 ± 4	26 ± 3	34 ± 4	17.5 ± 0.05	4.2×10^4	≤ 2.4
6	01:03:10	+36:01:46	-282 ± 4	29 ± 3	39 ± 4	17.6 ± 0.05	1.4×10^5	≤ 3.2
7	01:17:02	+36:49:34	-309 ± 2	24 ± 4	10 ± 2	17.0 ± 0.1	4.0×10^4	≤ 3.4

Table 1: A listing of the HI cloud properties. R.A. and DEC are the right-ascension

Smith: $M_{HI} > 10^6\ M_\odot$ Diameter 1x3 kpc

No stars in any of these!
Not self-gravitating

Wolfe et al. (2013, Nature)

The Smith Cloud has ionized gas

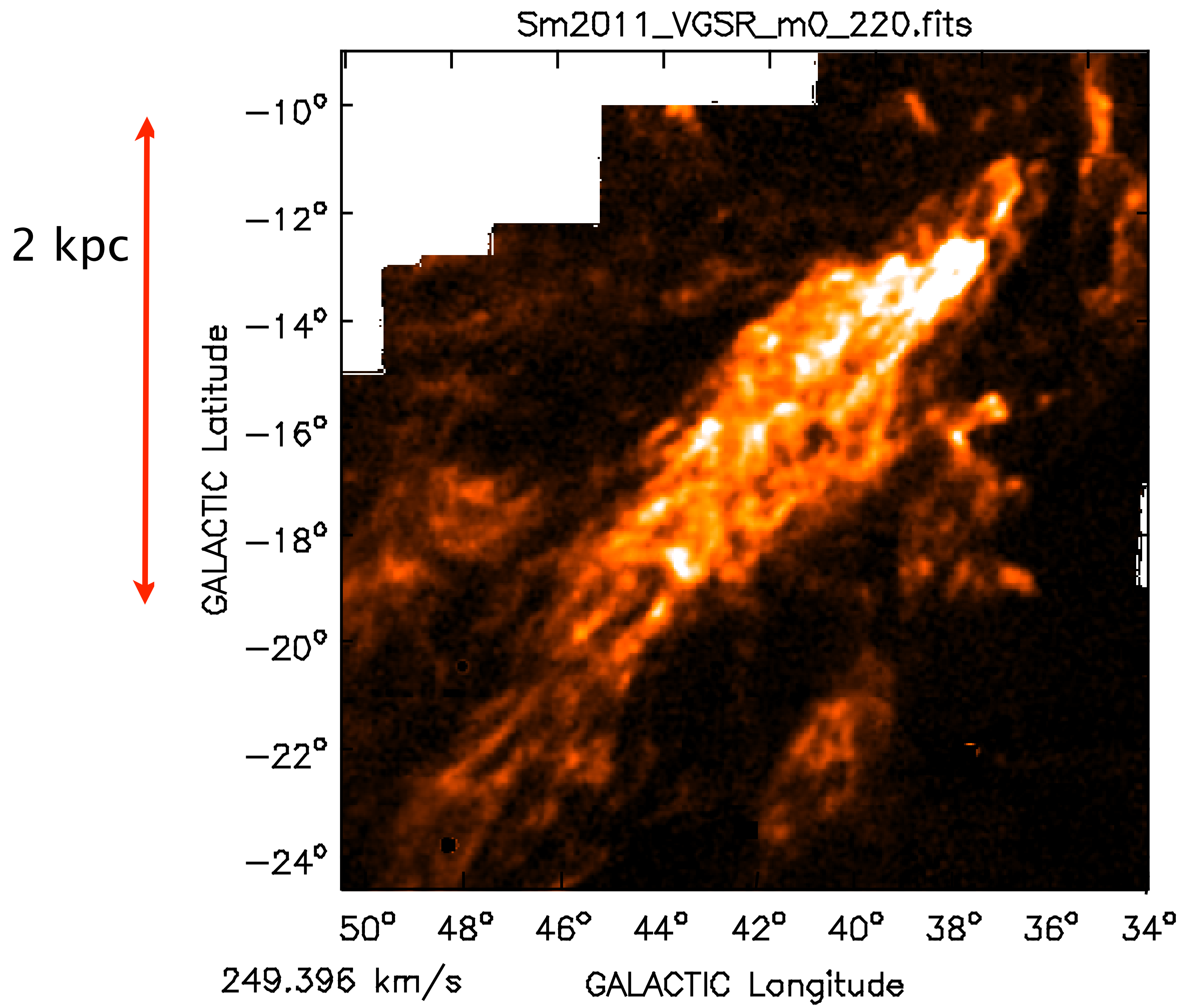
Infall?

dist = 12.4 ± 1.3 kpc
R = 7.6 ± 1.0 kpc
z = -2.2 kpc
$M_{HI} > 2 \times 10^6 M_\odot$
size ≈ 3 x 1 kpc
No Stars!

H+ data from WHAM
(Wisconsin H-alpha mapper)
$M_{H+} > 10^6 M_\odot$
[N\H] = 0.14 - 0.44

Lockman et al (2008, 2014)
Hill et al (2009)

At M31 <Tb>≈0.084 K



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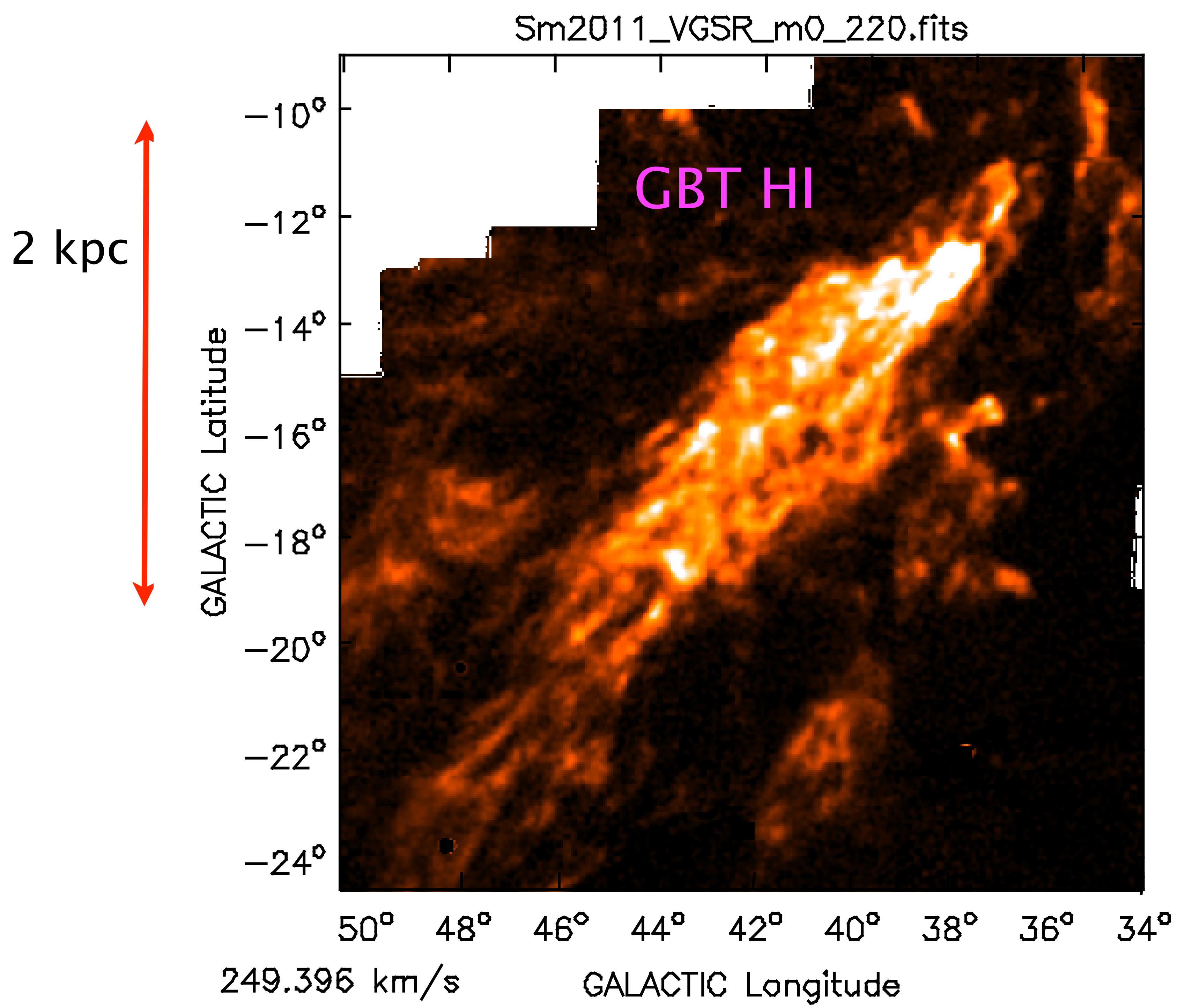

This is why the VLBA can't detect anything below ~10^5 K