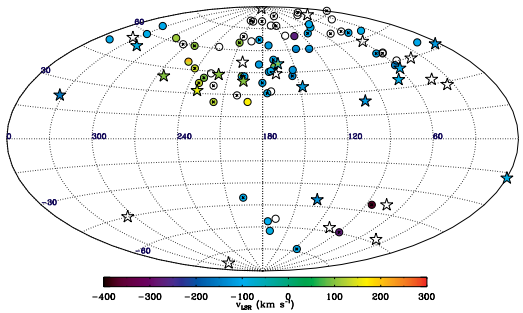
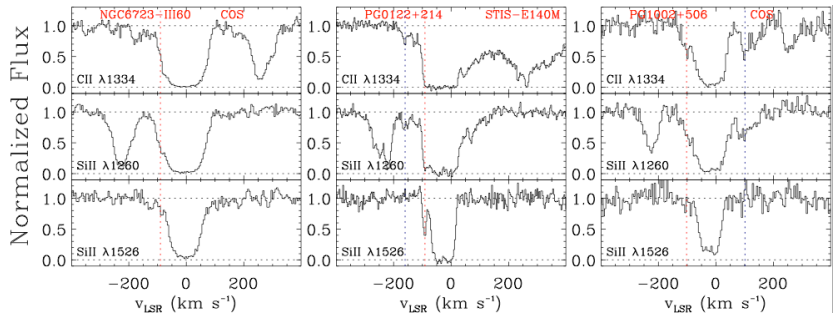




New Results from High Velocity Clouds

Nicolas Lehner

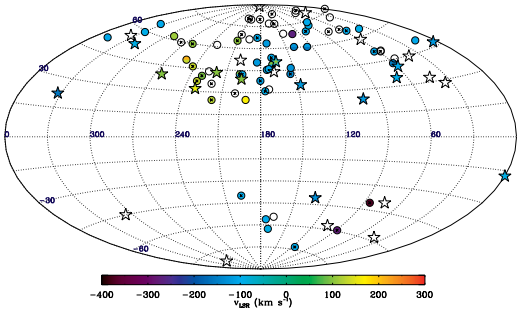
University of Notre Dame

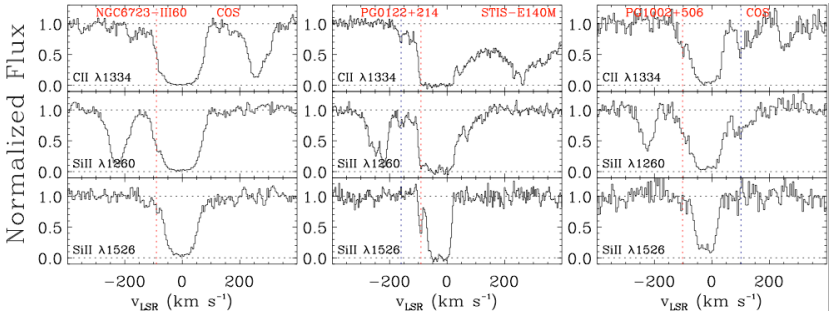
– In collaboration with: –

Chris Howk (ND)

&

Tripp (UMass), Tumlinson, Thom, Fox (STScI)

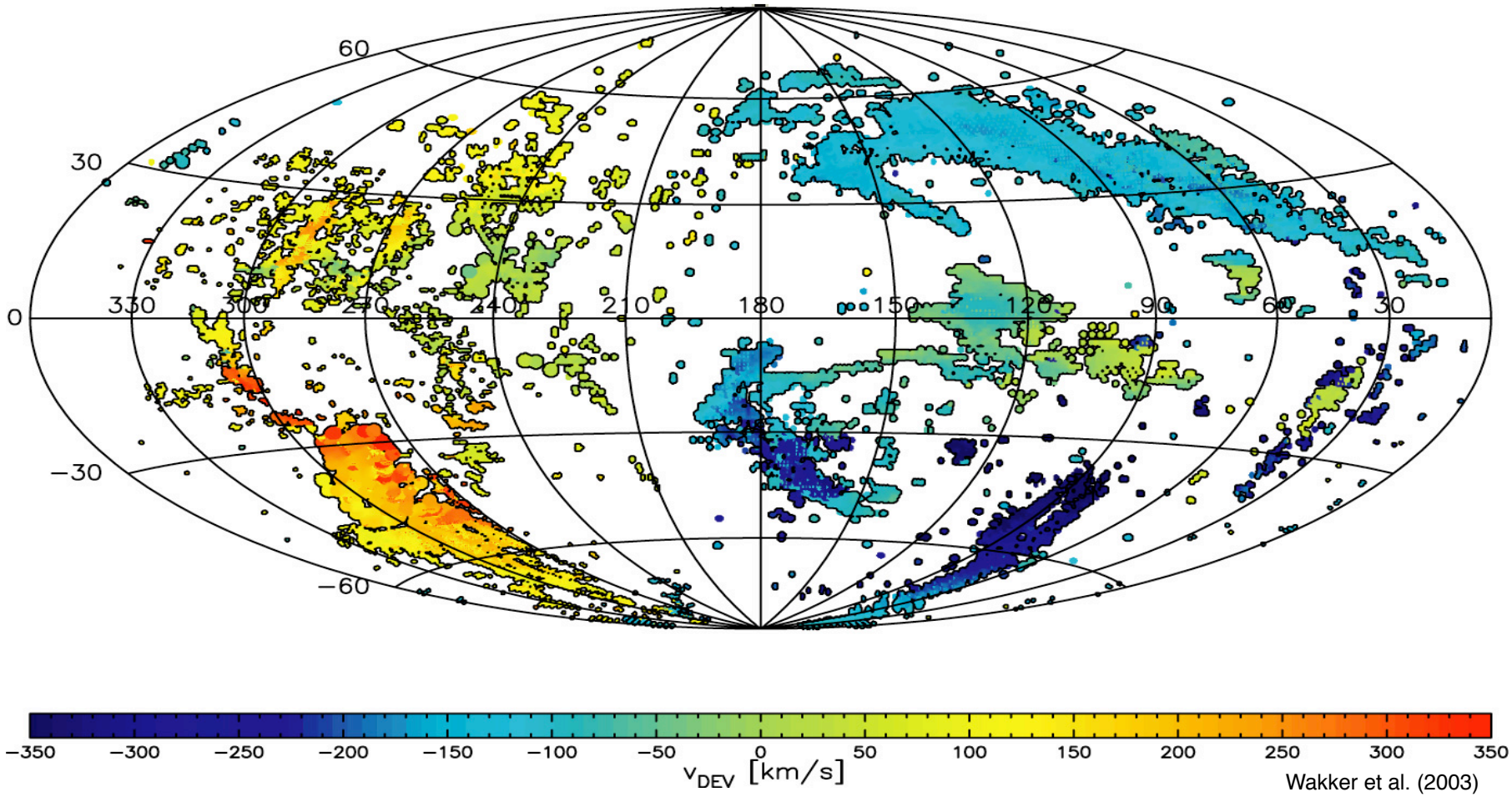




Outline

- What are high-velocity clouds (HVCs)?
- Why do we care?
- What are some of the key properties: distance, metallicity, velocity, mass
- New discoveries
- What are HVCs?
- Some new problems
- Future

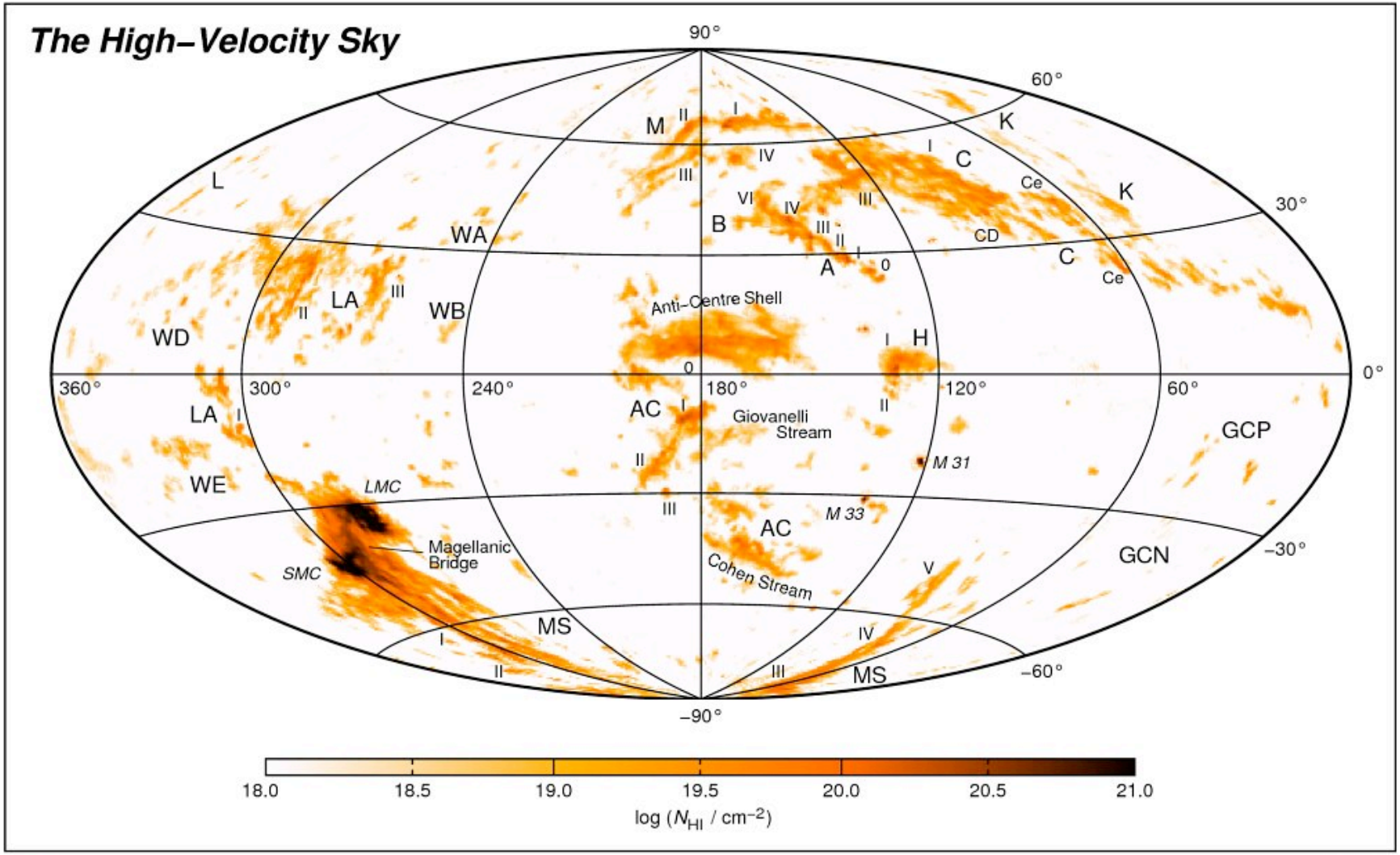
High-velocity clouds are clouds moving at fast speed



Wakker et al. (2003)

HVCs exhibit **H I 21cm emission** that covers ~18% HI covering factor at at $N_{HI} > 2 \times 10^{18}$ cm^{-2} (Wakker 1991).

High velocity clouds observed in HI 21 cm emission



Tobias Westmeier, CSIRO Australia Telescope National Facility

Based on the Leiden/Argentine/Bonn Survey (Kalberla et al. 2005, A&A 440, 775) and the Milky Way model of P. Kalberla (Kalberla et al. 2007, A&A, in press).

High velocity clouds as evidence for a Galactic corona

ON A POSSIBLE INTERSTELLAR GALACTIC CORONA*

LYMAN SPITZER, JR.
Princeton University Observatory
Received March 24, 1956

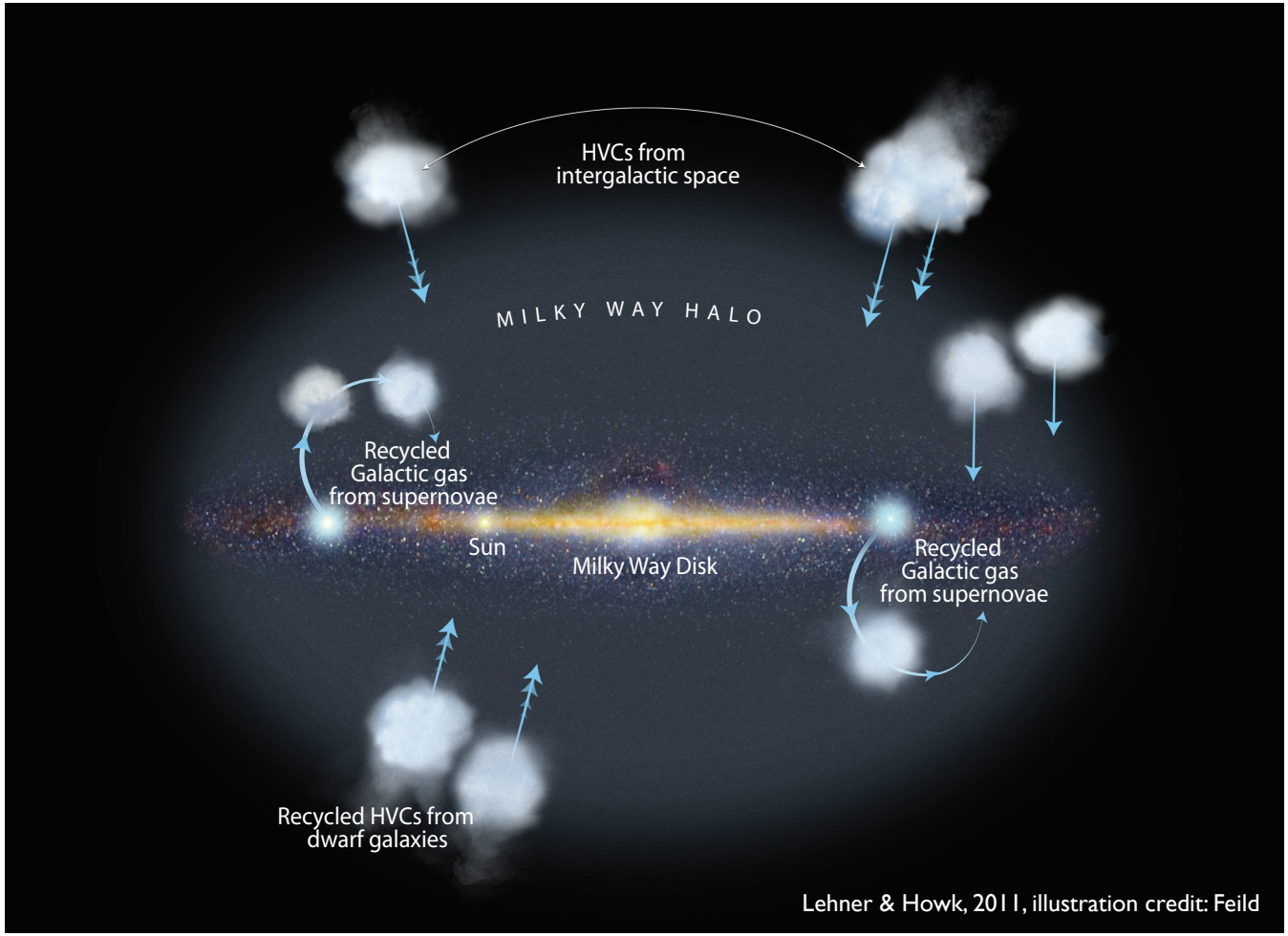
ABSTRACT

The physical conditions in a possible interstellar galactic corona are analyzed Pressure equilibrium between such a rarefied, high-temperature gas and normal interstellar clouds would account for the existence of such clouds far from the galactic plane and would facilitate the equilibrium of spiral arms in the presence of strong magnetic fields. Observations of radio noise also suggest such a corona.

At a temperature of 10^6 degrees K, the electron density in the corona would be $5 \times 10^{-4}/\text{cm}^3$; the extension perpendicular to the galactic plane, 8000 pc; the total number of electrons in a column perpendicular to the galactic plane, about $2 \times 10^{19}/\text{cm}^2$; the total mass, about $10^8 M_\odot$. The mean free path would be 4 pc, but the radius of gyration even in a field of 10^{-15} gauss would be a small fraction of this. Such a corona is apparently not observable optically except by absorption measures shortward of 2000 A.

Radiative cooling at 10^6 degrees would dissipate the assumed thermal energy in about 10^9 years. Cooling by conduction can apparently be ignored, especially since a chaotic magnetic field of only 10^{-15} gauss will sharply reduce the thermal conductivity At 3×10^6 degrees, near the maximum value consistent with confinement by the Galaxy's gravitational field, radiative cooling is unimportant, and a corona at this temperature might be primeval. The energy source needed at the lower temperatures may be provided by material ejected at high speed from stars or possibly by compressional waves produced by the observed moving clouds Condensation of cool matter from the corona may perhaps account for the formation of new spiral arms as the old ones dissipate.

What are high velocity clouds?



Evidence for gas flows in Galactic halo or intergalactic clouds

Key Parameter: Distances of HVCs

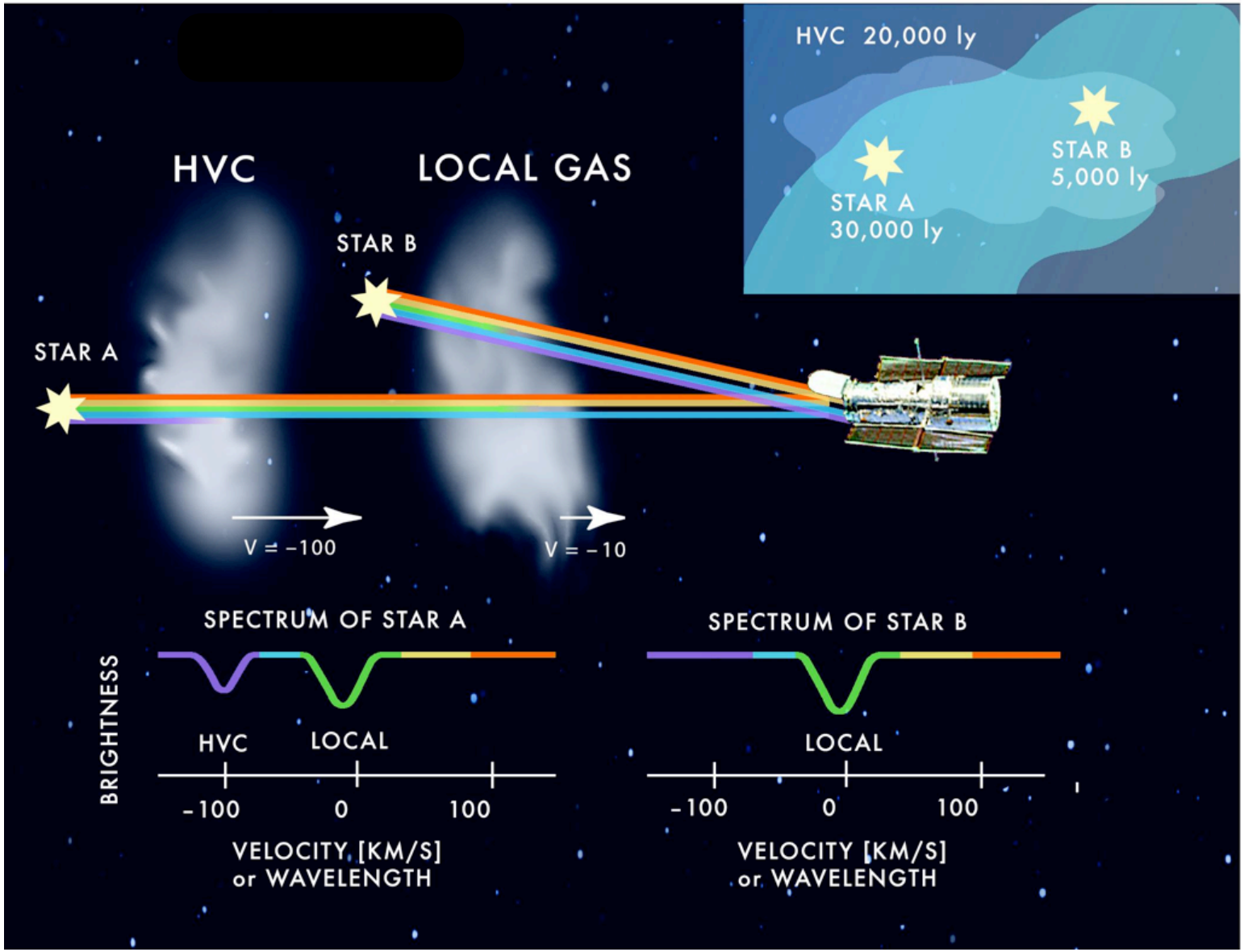
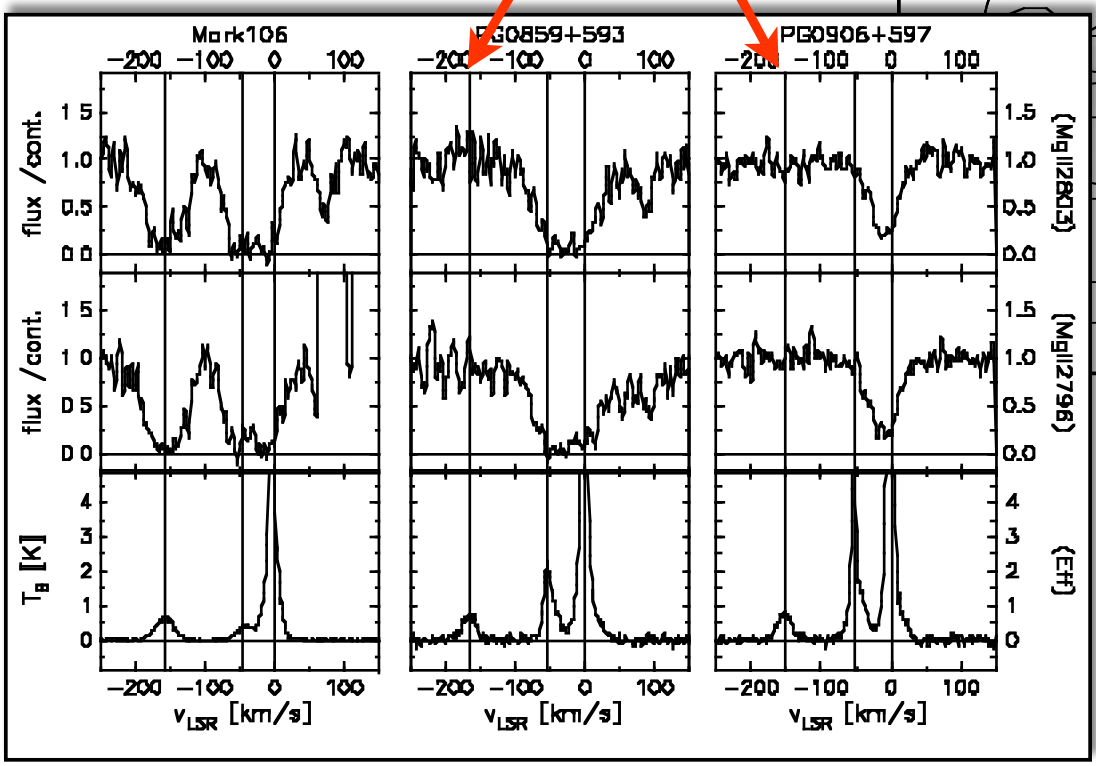
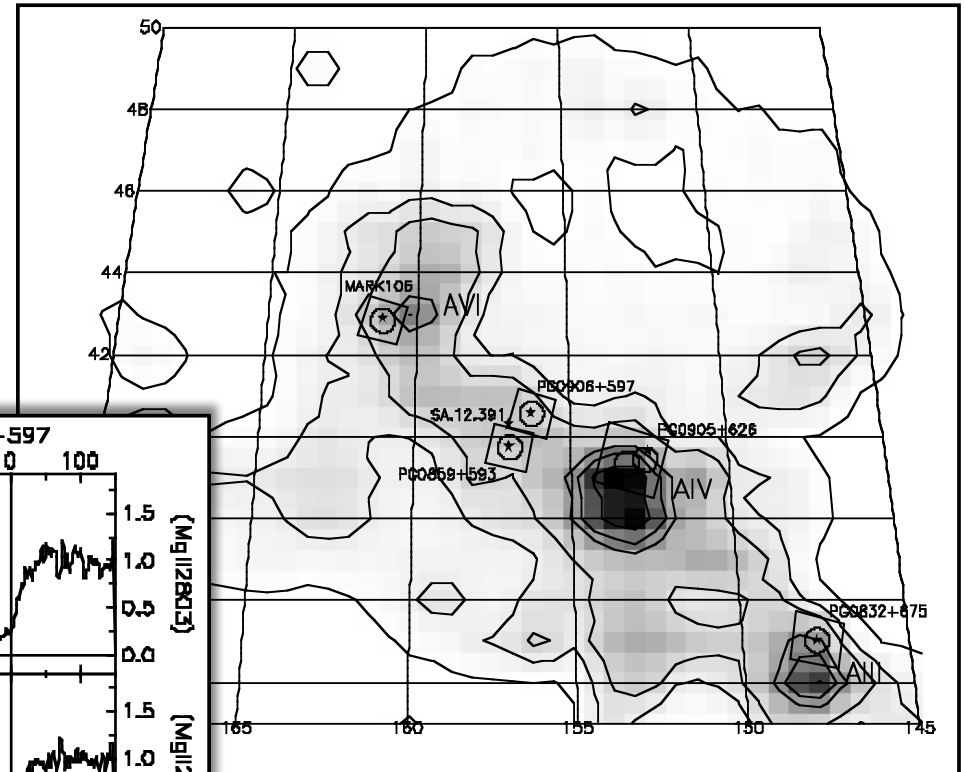


Illustration source: Wakker & Richter,SciAM, 2004

High velocity clouds located in the Milky Way's halo

Complex A not seen toward stars at -160 km/s, placing it beyond 4 kpc (z ~ 3 kpc).





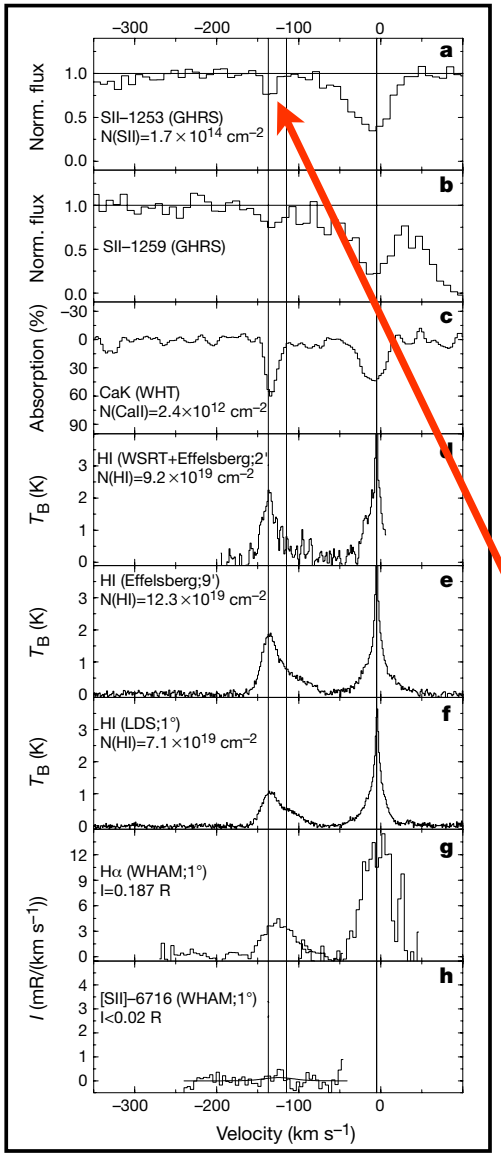
Wakker+ (1996)

d = ∞ d = 4 kpc d = 0.7 kpc

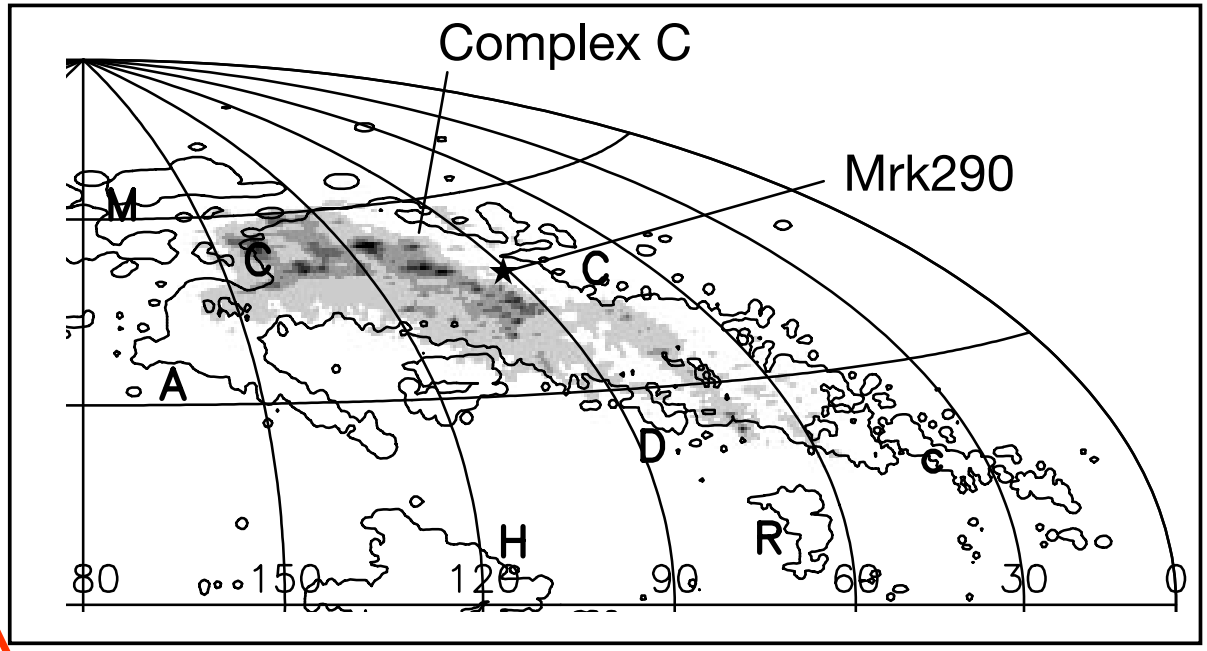
More recent work with Keck/VLT:
Thom+ (2008), Wakker+ (2008), Wakker+ (2007)

H I HVCs within ~5–15 kpc.

Key Parameter: Metallicity of HVCs



Wakker+ (1999)



Complex C absorption in S II → $(S/H)_{\text{complex C}} \sim 0.09 \times (S/H)_{\odot}$

Subsequent observations and analyses give values

$$(S/H)_{\text{complex C}} \sim [0.15 \text{ to } 0.33] \times (S/H)_{\odot}$$

(Gibson+ 2001; Tripp+ 2003; Collins+ 2007; Shull+ 2011)

Milky Way HVCs: recycled fountain matter

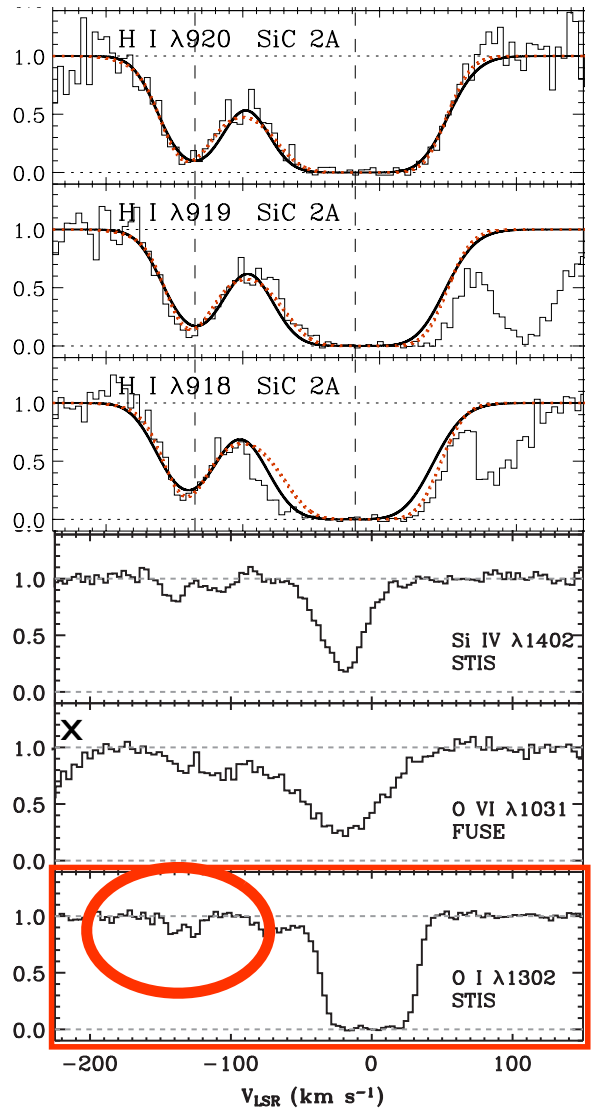
Not all the gas is coming in...and not all of it has low metallicities.

Zech+ (2008) identified an HVC along a sight line toward the inner Galaxy globular cluster Messier 5 with super-solar metallicity:

[O/H] = +0.22 ± 0.10

log N(H I) = 16.50±0.06

Messier 5: (l,b)=(3˚, 48˚); *d*~7.5 kpc, *z*~5.3 kpc

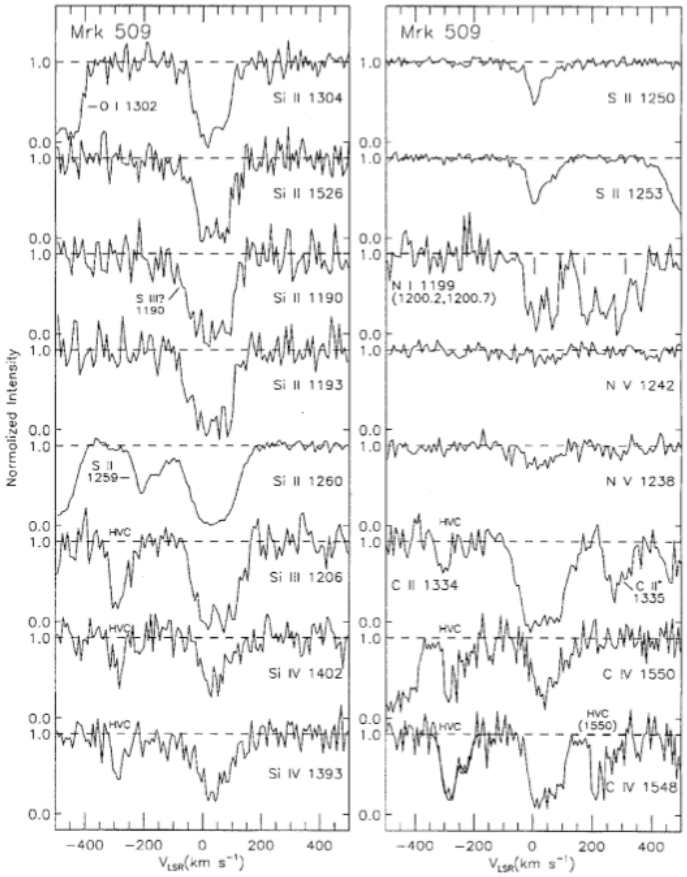


Zech+ (2008)

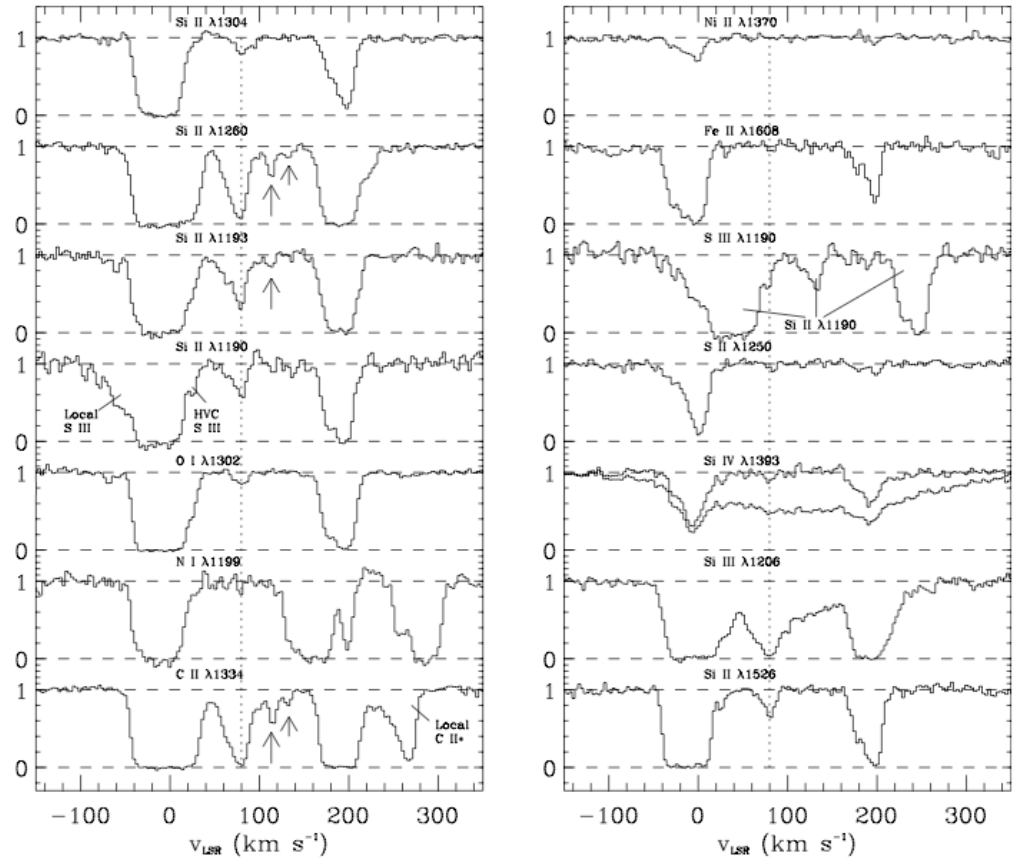
See Keeney+ (2006) for HVCs near Galactic bulge...

**Also observed in C II, C IV, Si II, Si III, Fe II, Al II, S III*

HI emission observations: A bias view of the Galactic sky



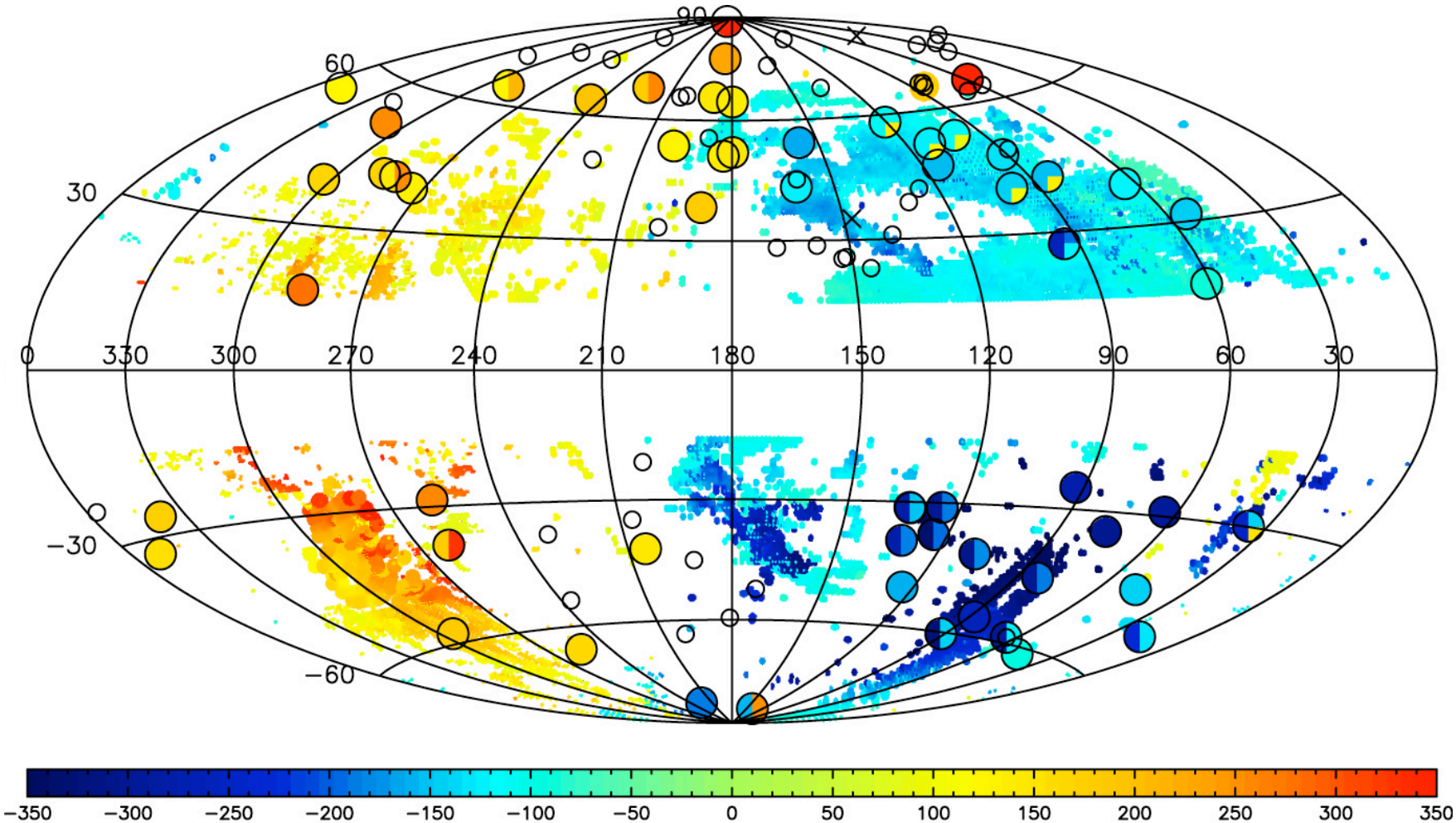
Sembach+95,99



Lehner+01

H I emission observations have a sensitivity cut-off determined by the depth of the observations and limitation of radio observations.

UV observations of the Galactic sky

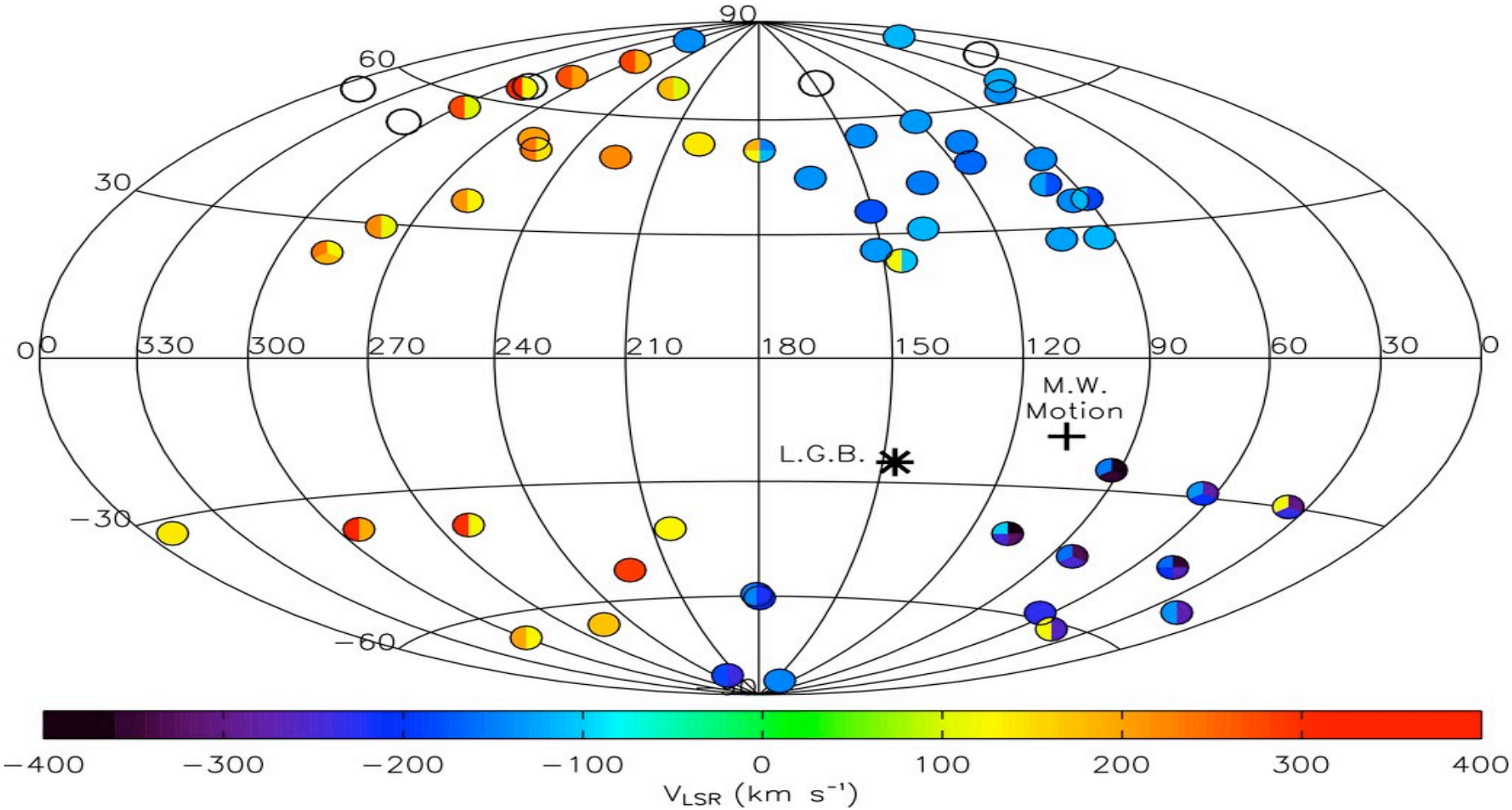


Sembach et al. 2003
Fox et al. 2006

H I 21cm Emission
FUSE O VI Absorption

<u>Covering fraction</u>: 60% – 85% of sky covered at $N(H^+) \geq 10^{18}$ cm^{-2} (for SMC metallicity)

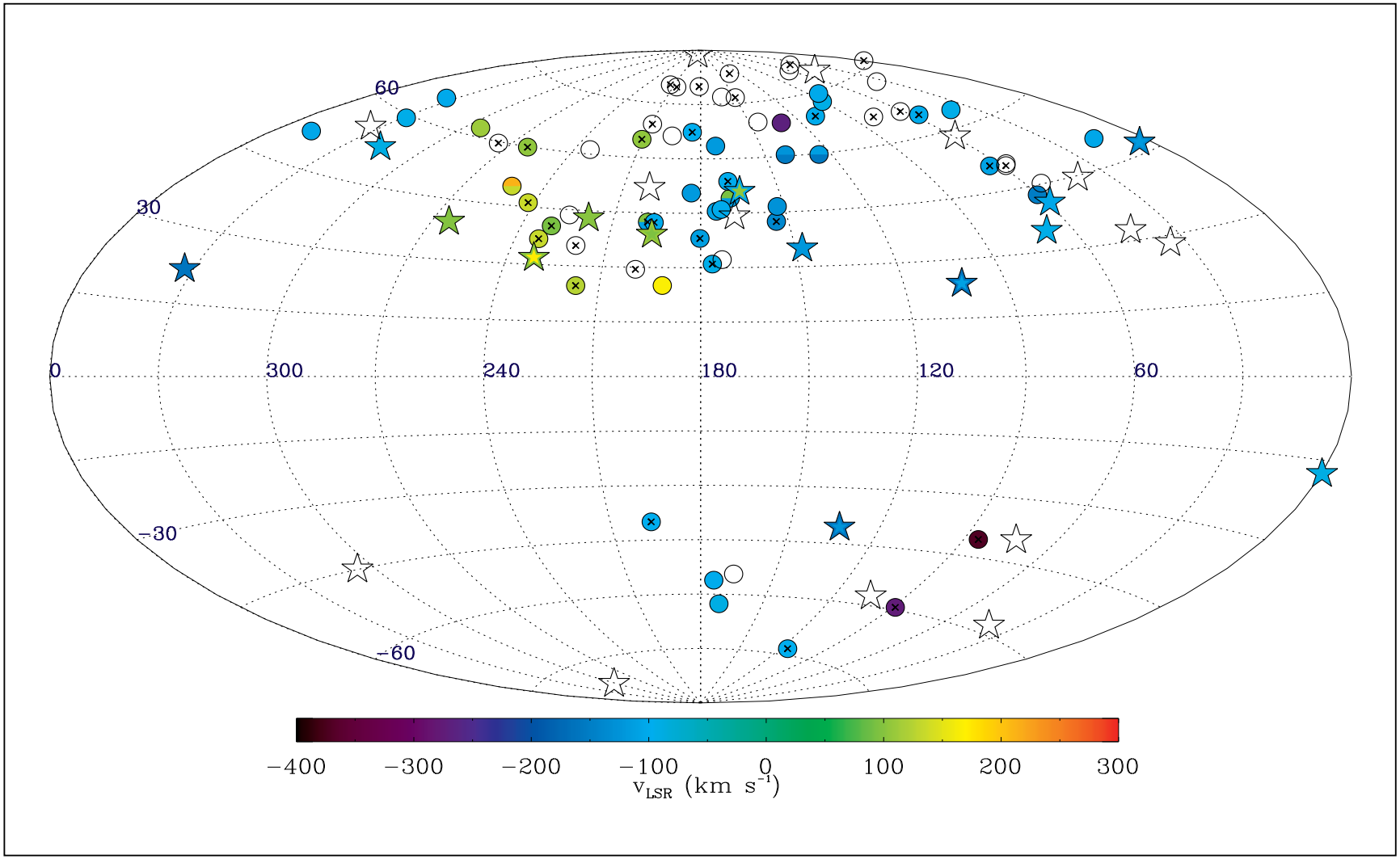
UV observations of the Galactic sky



Shull et al. 2009, Collins et al. 2009
(see also Richter et al. 2009 for CaII observations)

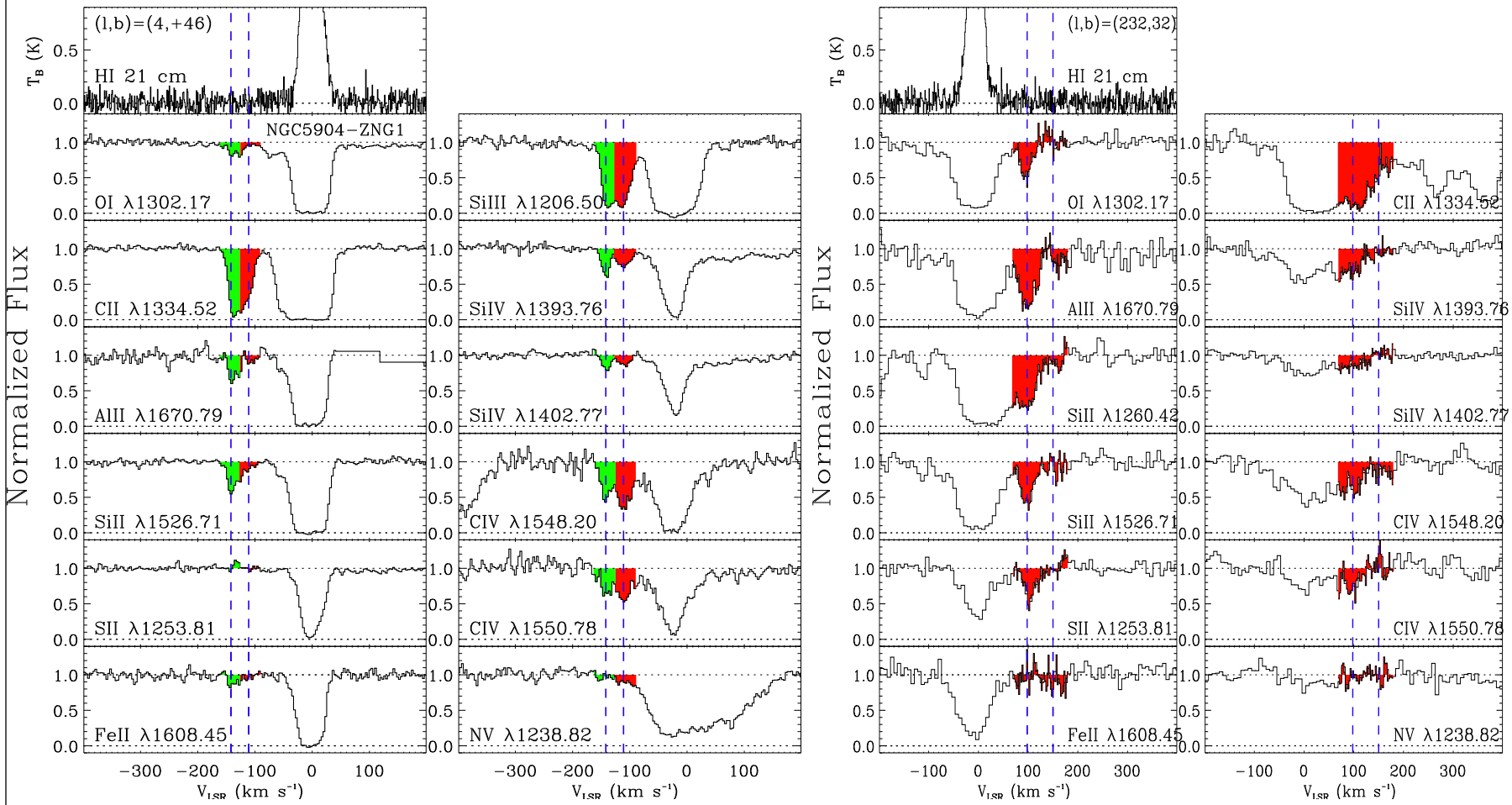
STIS Si III Absorption

High velocity clouds: New COS results



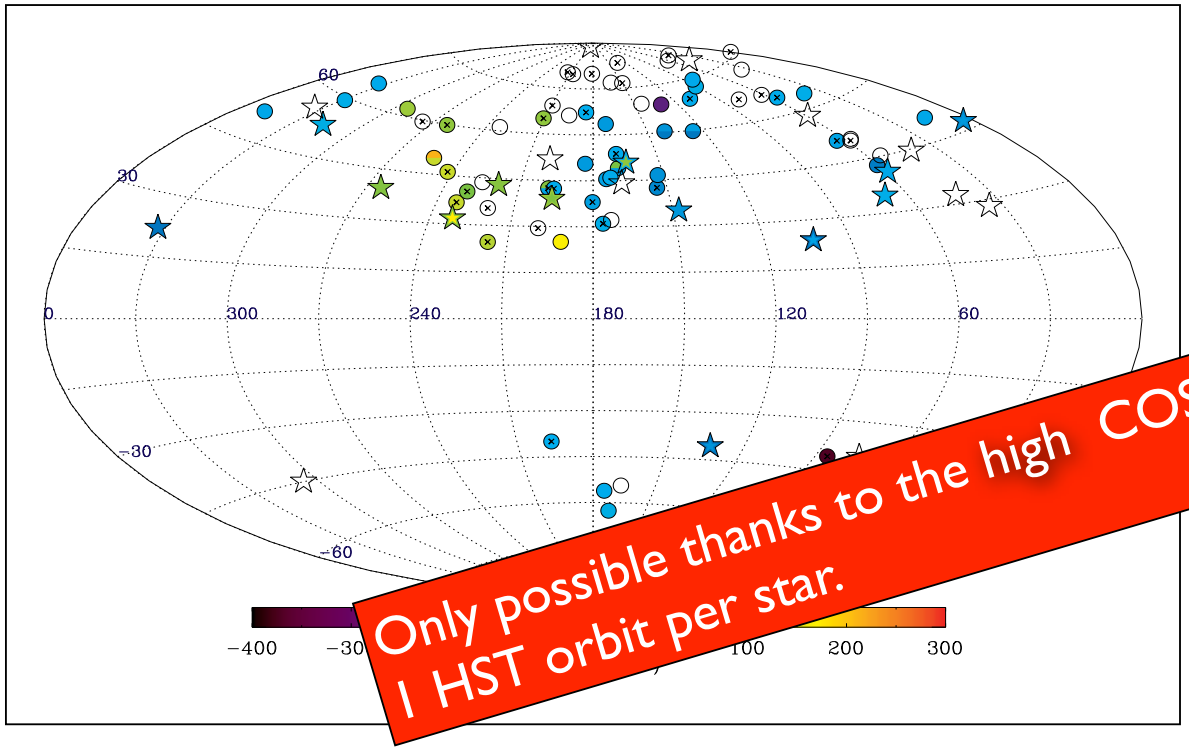
Lehner+ (2012), Lehner & Howk (2011)

Examples of HVC absorption in stellar spectra



Lehner & Howk 10,11 - Zech, Lehner, Howk+08

A statistical measure of HVC distances



Only possible thanks to the high COS sensitivity: 1 HST orbit per star.

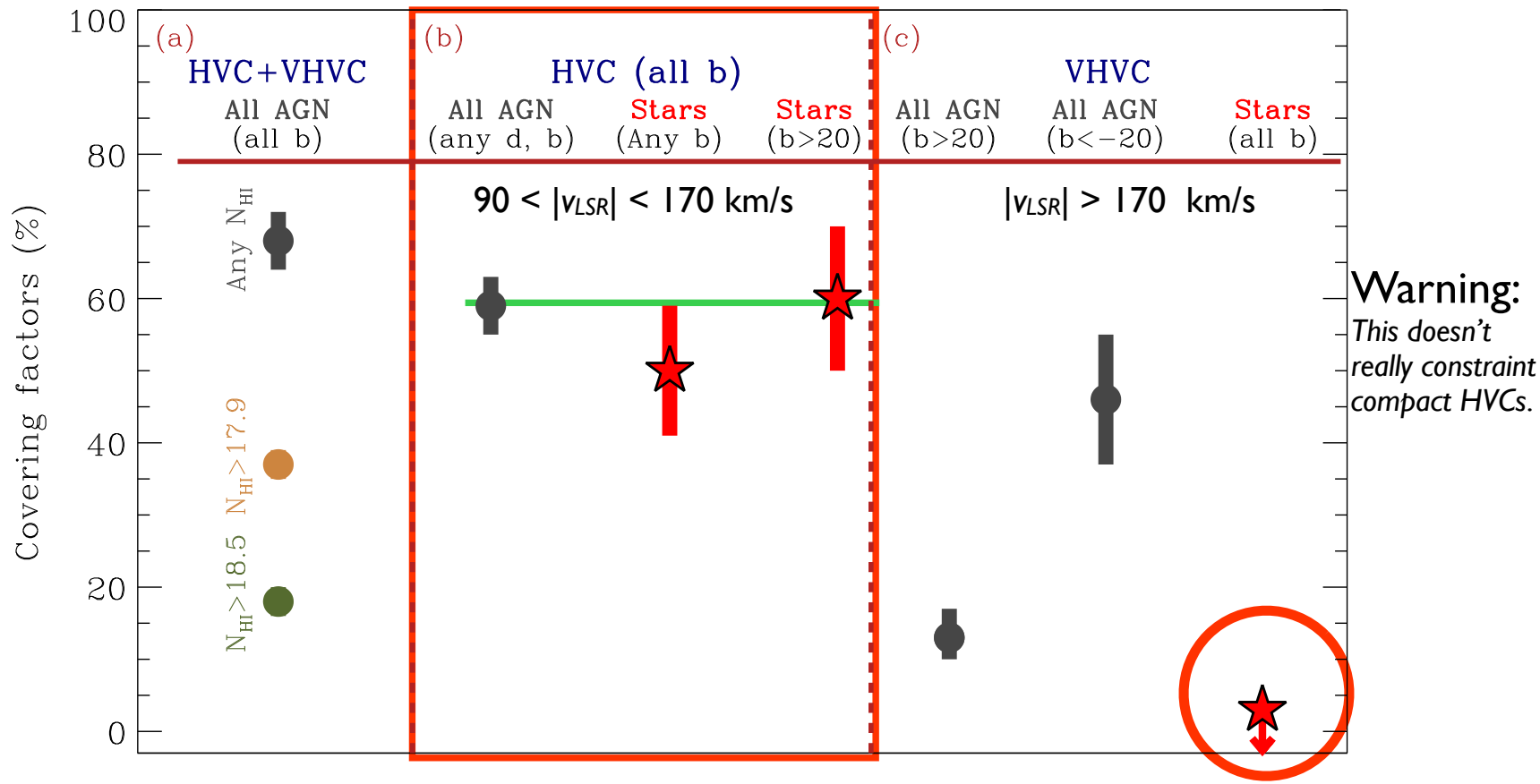
Lehner+ (2012), Lehner & Howk (2011)

About 70% of the high latitude sky is covered with high velocity metal ion absorption.

Because the covering factor is so high, any random sight line to [illegible] ore distant than [illegible] f the HVCs will [illegible] chance of showing [illegible] sorption.

Comparing the covering factor of AGN sight lines with that for stellar sight lines can show what fraction of the low H I column density HVCs are within ~5-15 kpc of the sun (z ~ 10 kpc).

A statistical measure of HVC distances



The detection rates toward AGNs (~infinite distance) and stars are indistinguishable. Thus, the absorbing HVCs are at d < 5–15 kpc and z < 6-10 kpc.

The mass of the population is M_{HVC} ~ (0.2 – 2.0)x10^8 $M_\odot$ giving an infall rate of ~ 0.4 – 1.0 $M_\odot$ yr^{-1}(see also Shull+ 2009).

Lehner+ (2012), Lehner & Howk (2011)

NEUTRAL AND IONIZED HVCs IN 3D SPACE

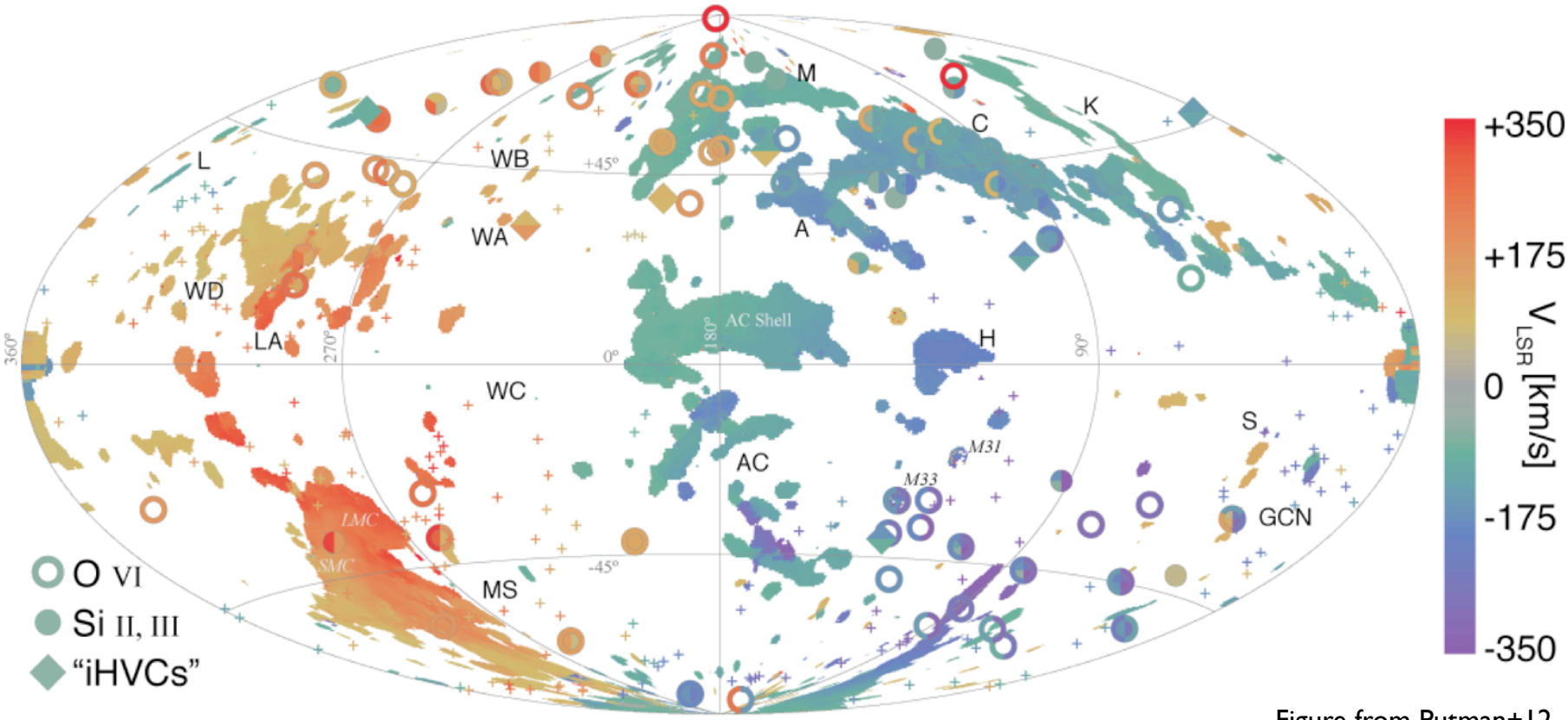
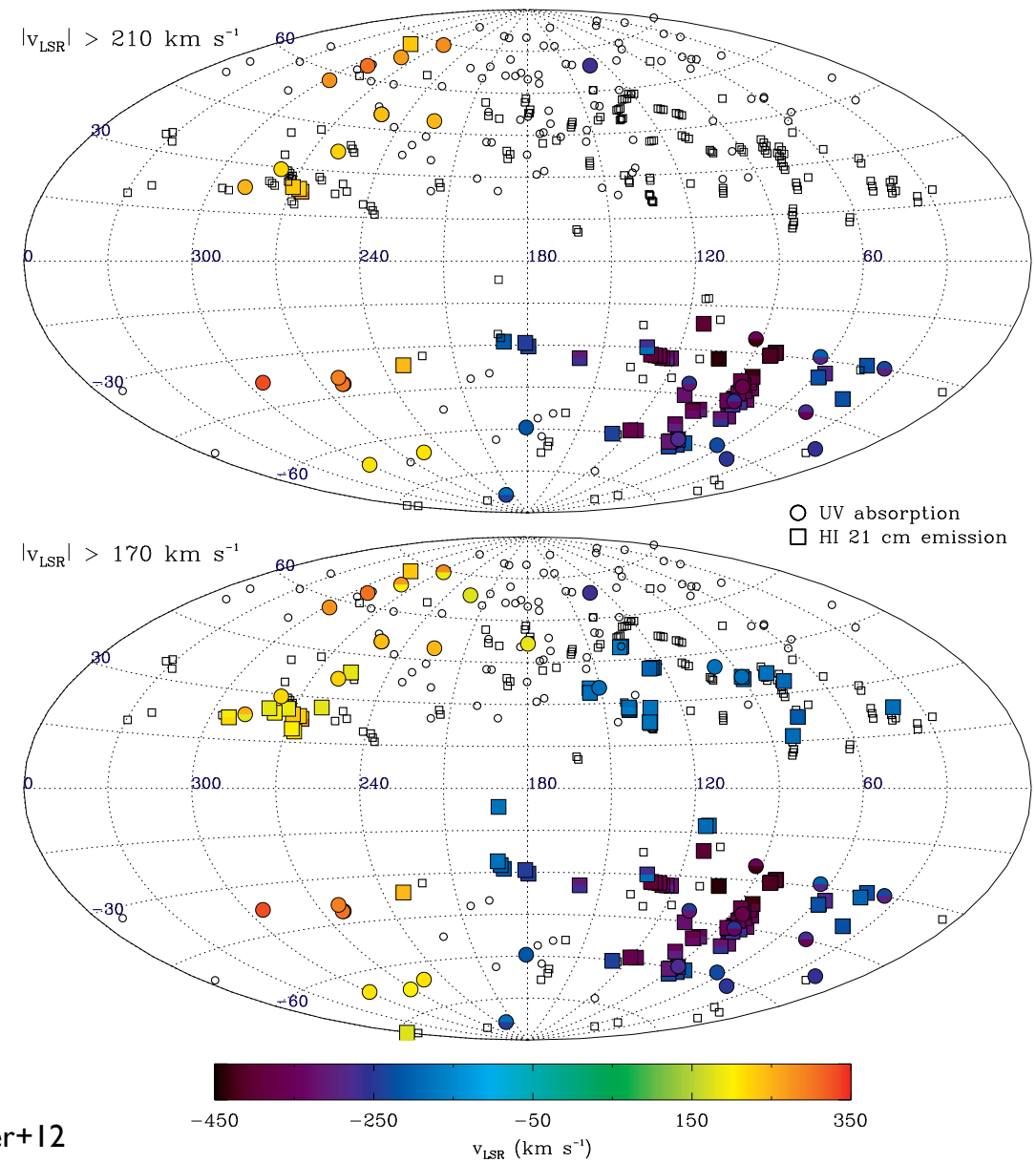


Figure from Putman+12

Several HVCs seen in UV absorption are the extended ionized halos of their neutral counterparts.

Very high-velocity Galactic sky

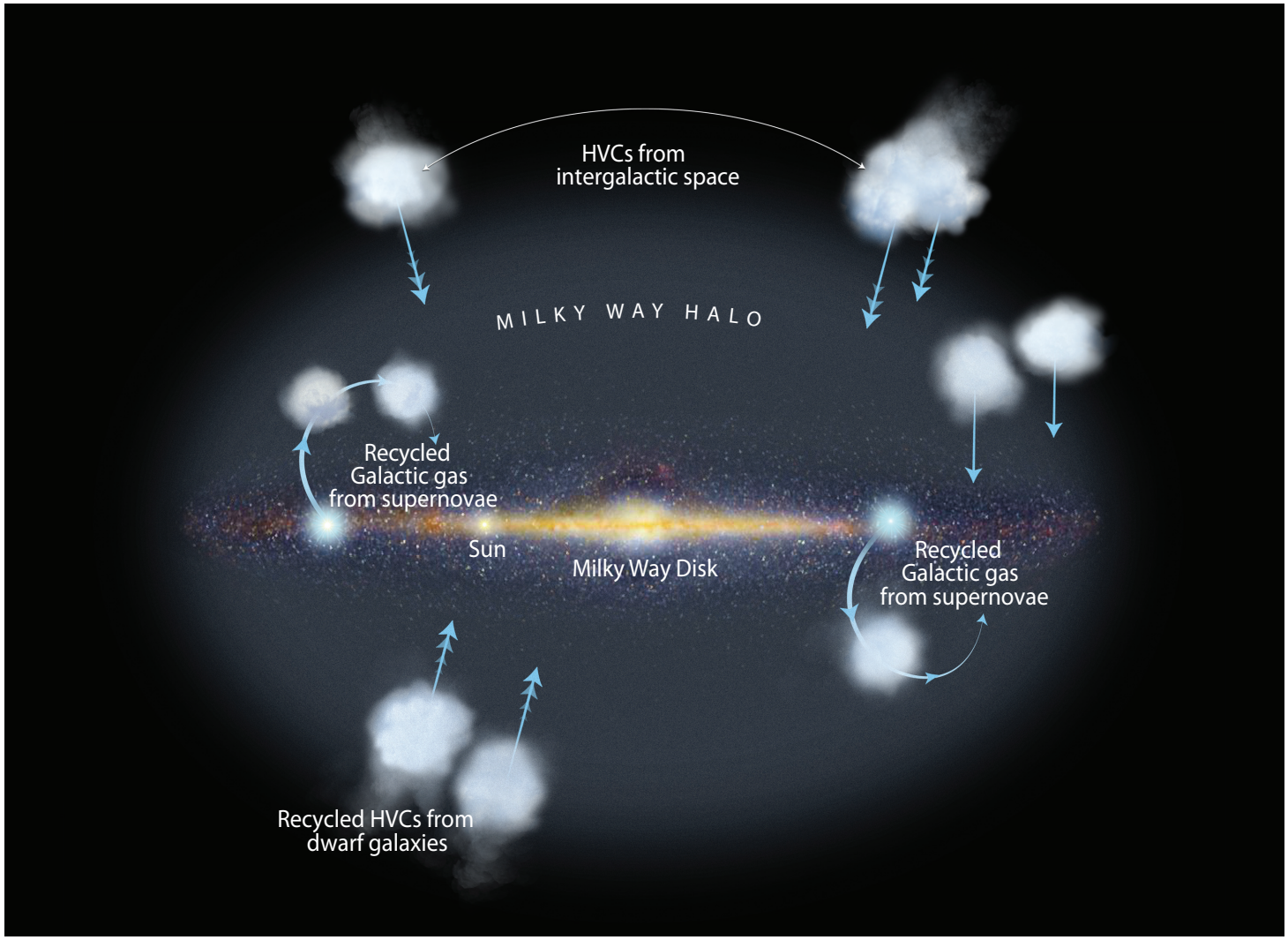


Lehner+12

The VHVCs are not randomly distributed on the Galactic sky and appear mostly to be associated to known large structures.

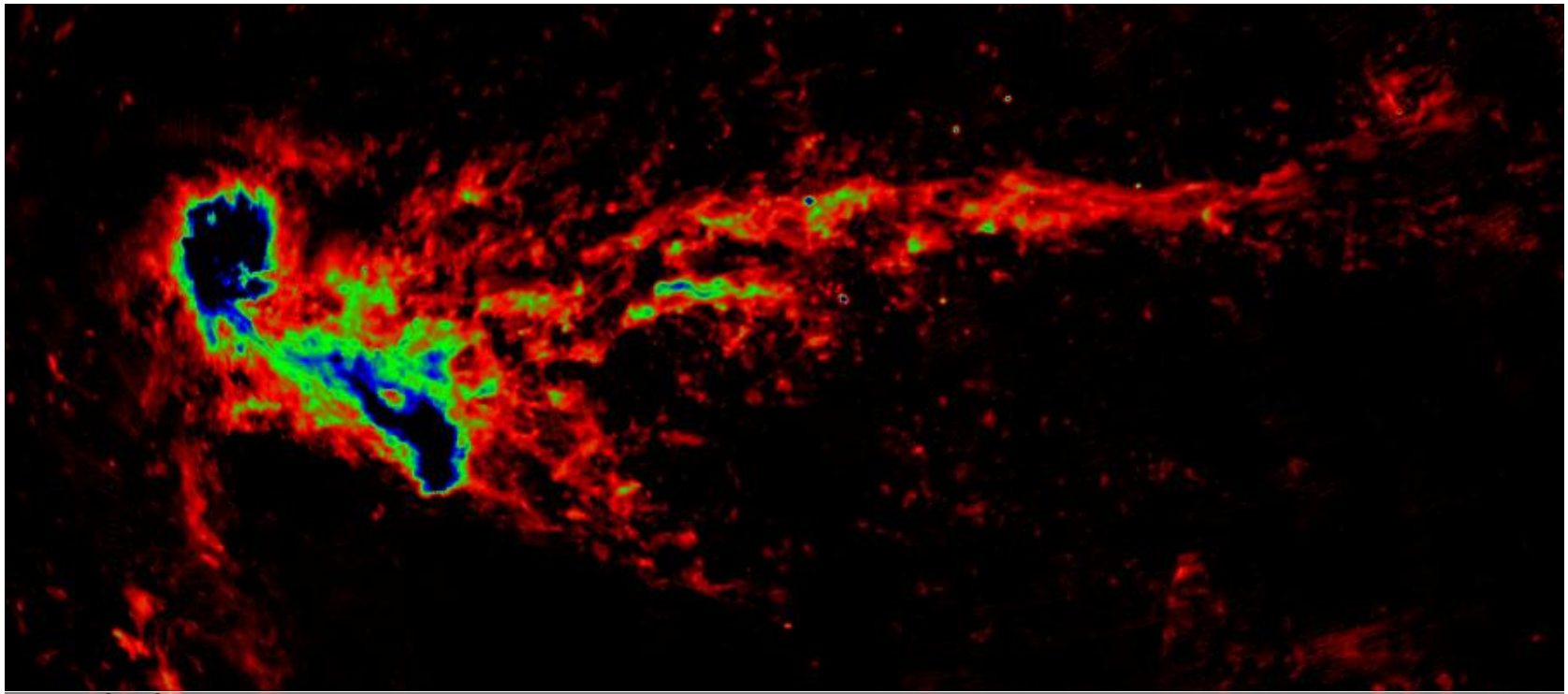
***We might miss a population of compact HVCs with very small angular scales at very large distances (or that they may be confused with the more nearby VHVCs).*

New problem: Extended hot Galactic halo?



Most HVCs are within 5-15 kpc, including the **OVI HVCs.**

New problem: Extended hot Galactic halo?

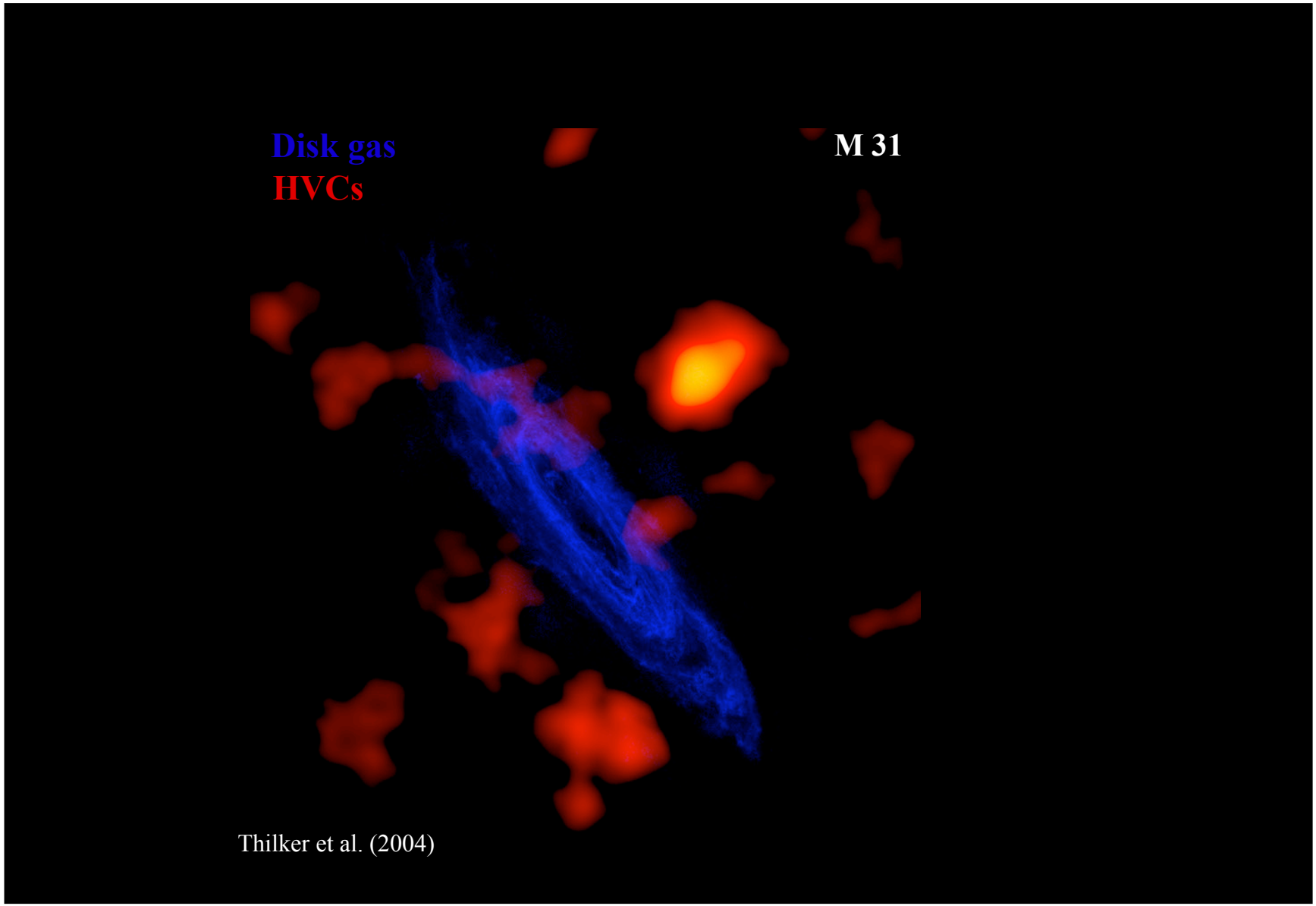


d ~ 50-70 kpc

Putman+ (2003)

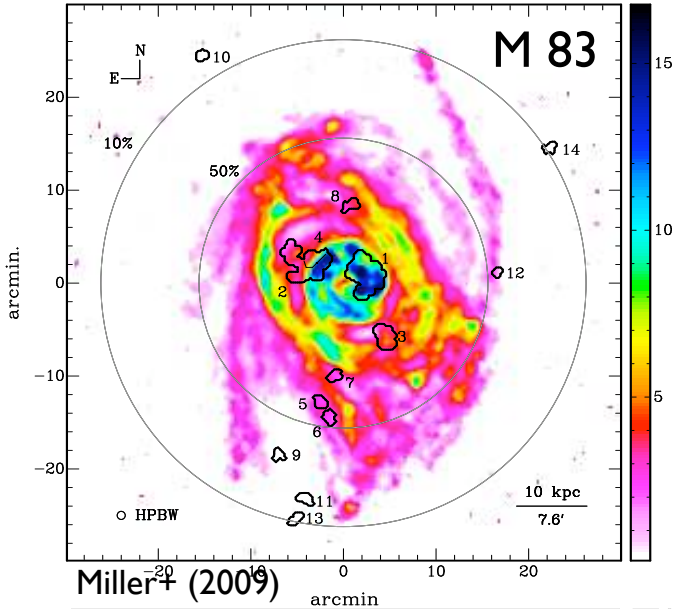
Magellanic stream is probably the best evidence for an extended hot Galaxy halo.

HVCs are found in other galaxies

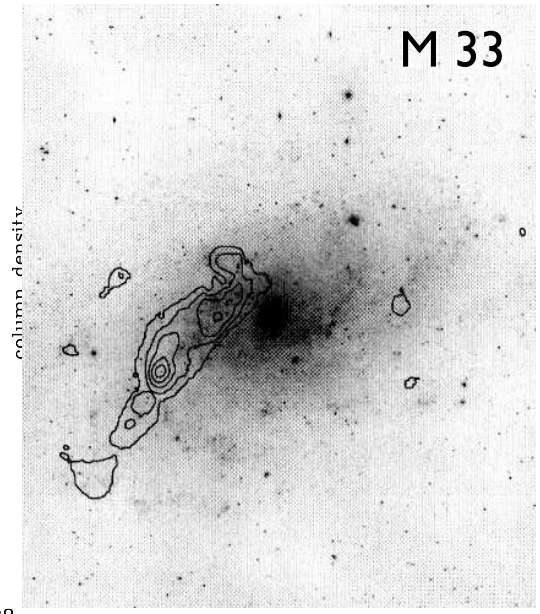


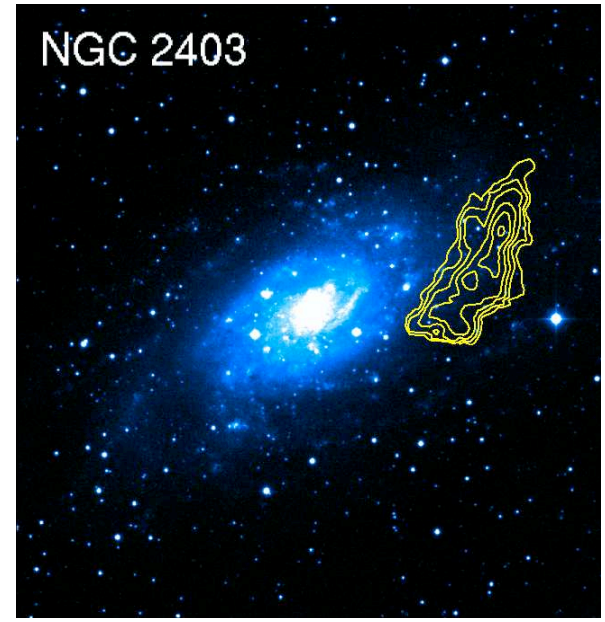
Thilker et al. (2004)

“Anomalous” velocity gas is common around other galaxies



Miller+ (2009)





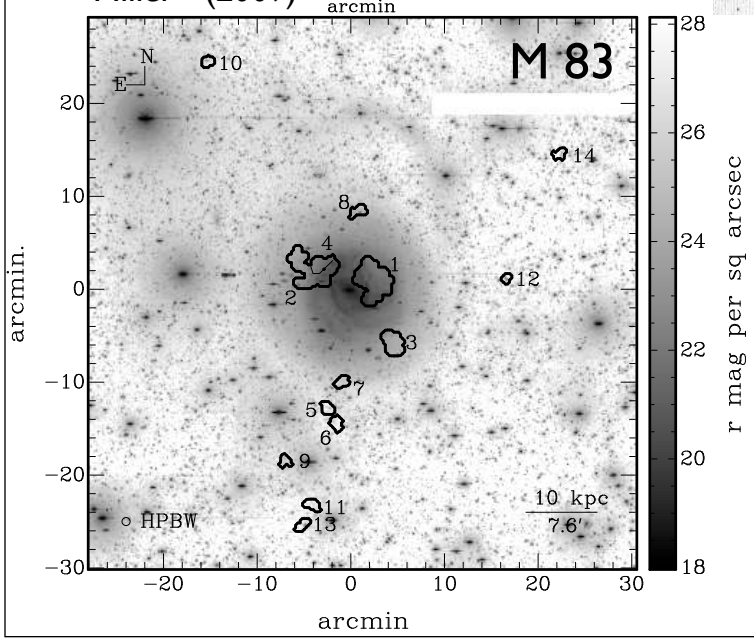


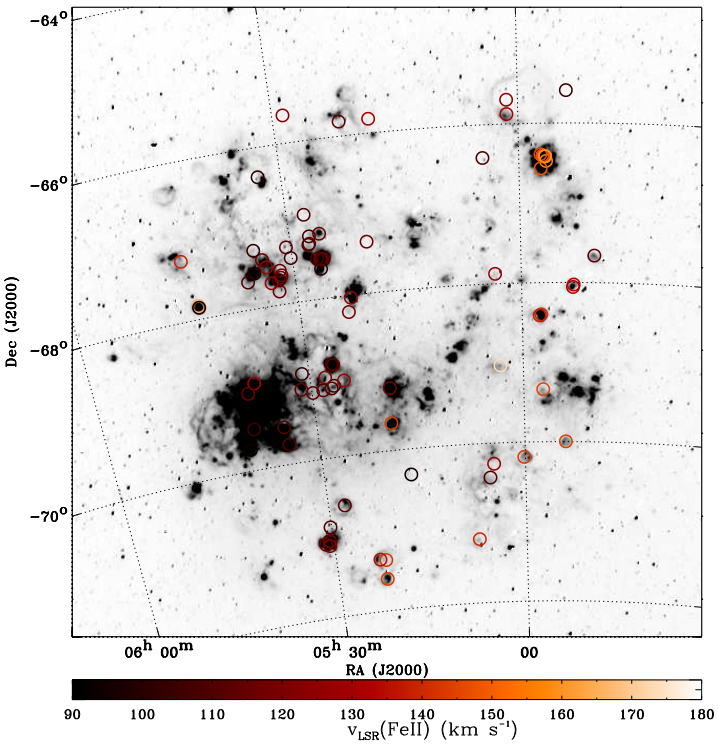
Table 2 Extra-planar gas in spiral galaxies

Galaxy	Type	incl (deg)	v_{flat} ($km\,s^{-1}$)	$M_{HI_{halo}}$ ($10^8\,M_\odot$)	$\frac{M_{HI_{halo}}}{M_{HI_{tot}}}$ (%)	Ref.
Milky Way	Sb	-	220	> 0.2	$> 1^a$	[141]
M 31	Sb	77	226	> 0.3	> 1	[127]
NGC 891	Sb	90	230	12	30	[85]
NGC 6946	Scd	38	175	>2.9	>4	[15]
NGC 4559	Scd	67	120	5.9	11	[4]
NGC 2403	Scd	63	130	3	10	[37]
UGC 7321	Sd	88	110	$\gtrsim 0.1$	$\gtrsim 1$	[77]
NGC 2613	Sb	$\sim$80	$\sim$300	4.4^b	5	[27]
NGC 253	Sc	$\sim$75	$\sim$185	0.8	3	[14]

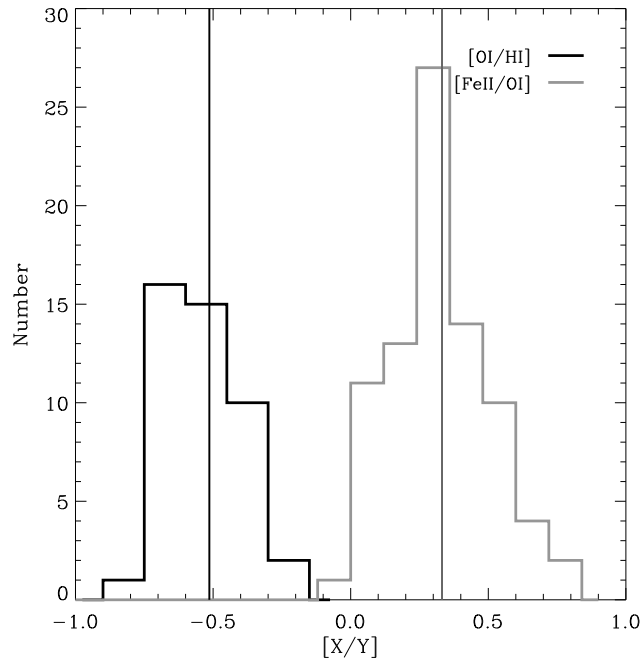
^{a} Only HVCs (IVCs not included); ^{b} from sum of the various extra-planar clouds.

Sancisi+ (2008)

HVCs toward LMC: Evidence for outflow in a dwarf galaxy



Lehner & Howk 2007, Lehner+09

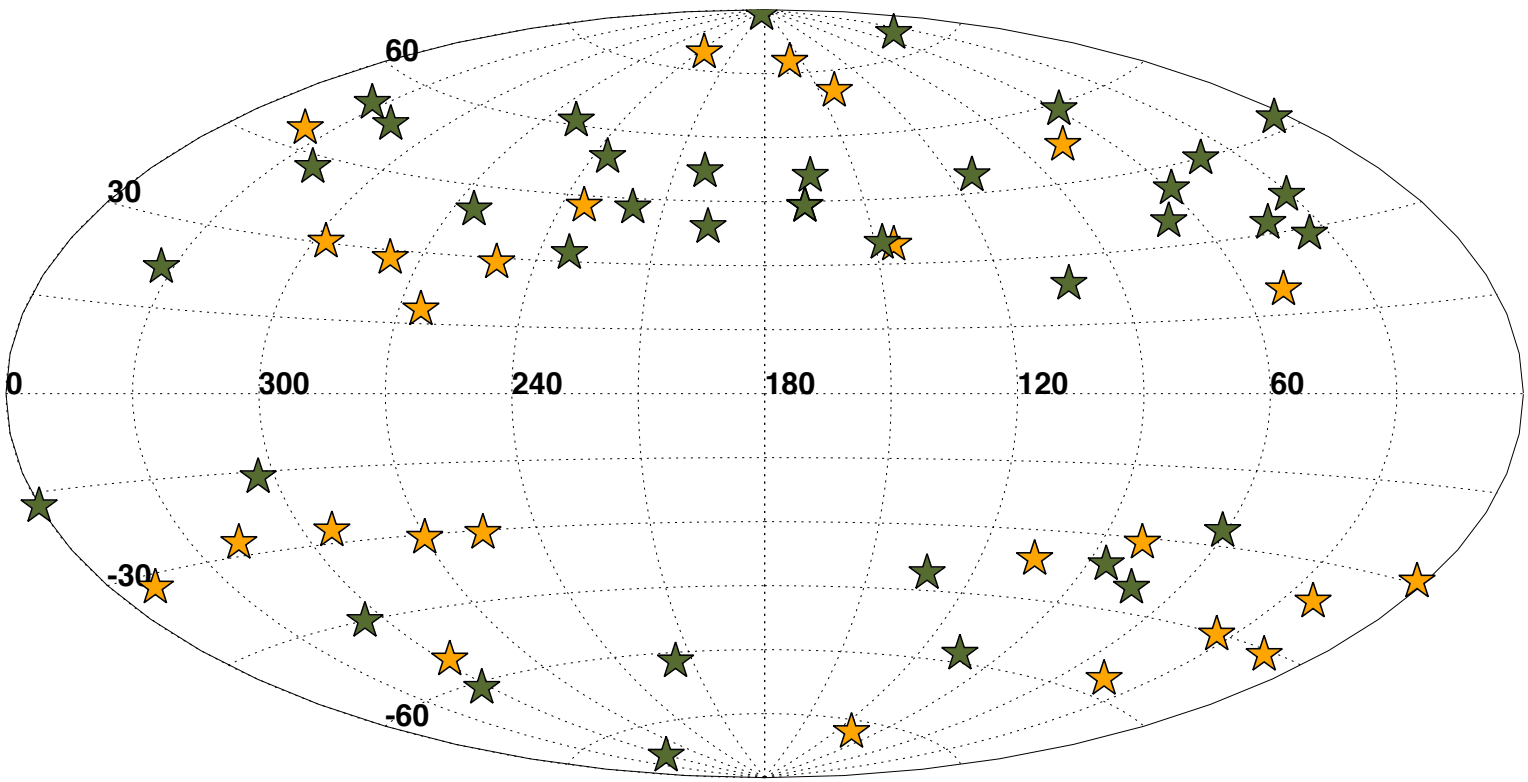


Large (> 10^6 M⊙) HVC complex that is linked to stellar feedback occurring in a dwarf spiral galaxy.

But all the HVCs in the Local group are within about 15-50 kpc (except possibly the Magellanic Stream, but that could a pretty unique feature, see Putman+12).

What are the higher redshift analogs?

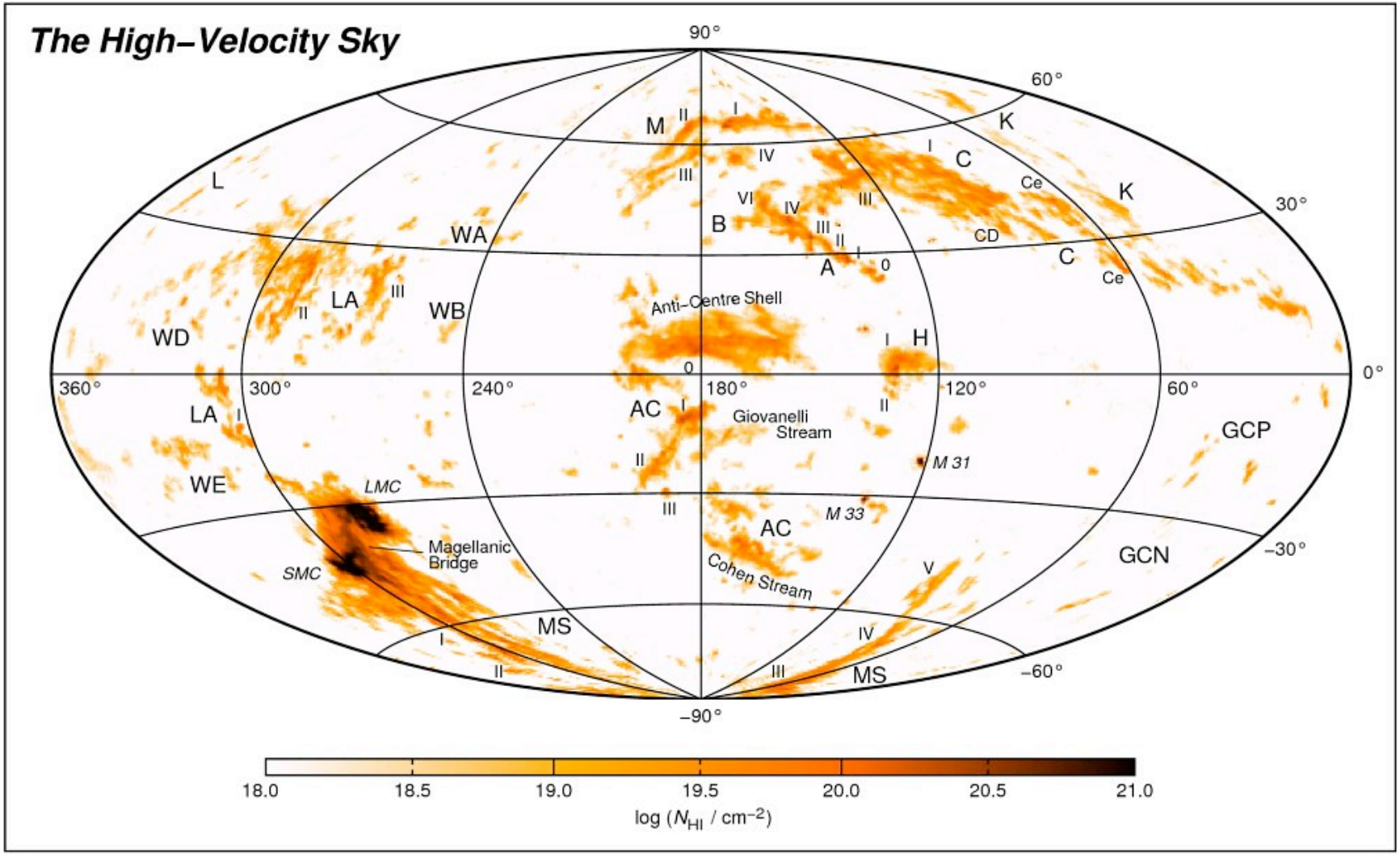
Near future: Studying the fall of HVCs onto the Galactic disk



Approved Cycle 20 program: COS/STIS observations of lower z-height stars.

Are the Milky Way's High Velocity Clouds Fuel for Star Formation or for the Galactic Corona?

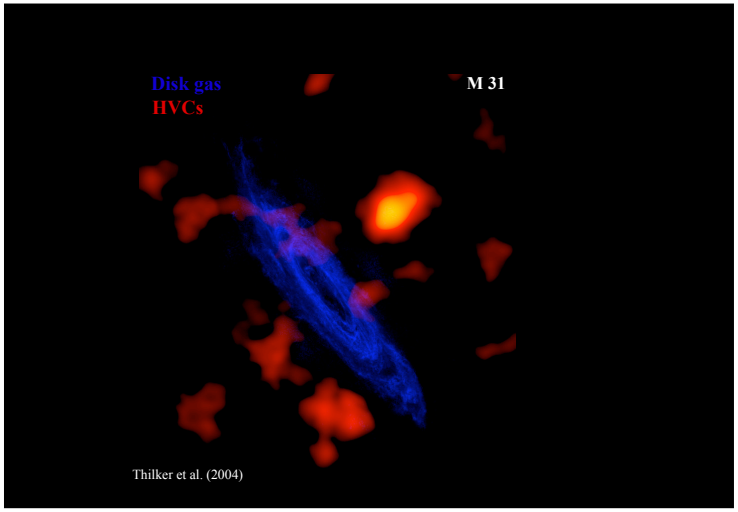
Near future: Metallicity "map" of the HI HVCs



Tobias Westmeier, CSIRO Australia Telescope National Facility

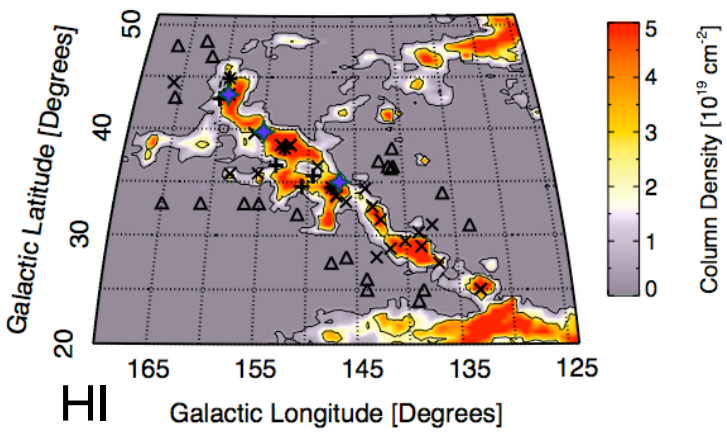
Based on the Leiden/Argentine/Bonn Survey (Kalberla et al. 2005, A&A 440, 775) and the Milky Way model of P. Kalberla (Kalberla et al. 2007, A&A, in press).

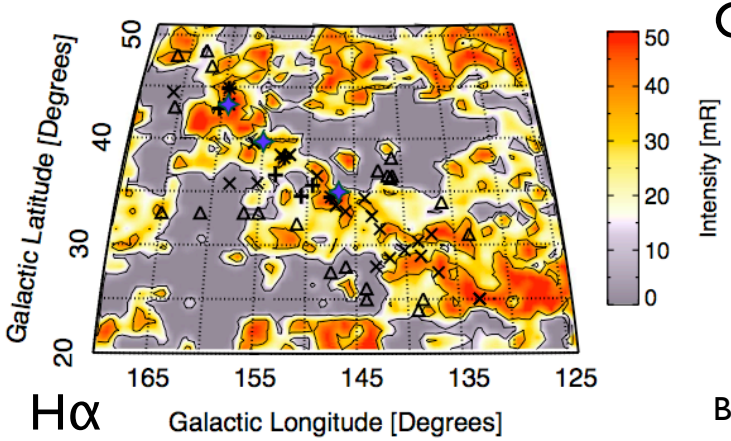
Future beyond HST (?)



Transforming mission/instrument: **FUSE** and **COS**
- hundreds of background targets, wavelength, resolution, S/N

Important instruments: **STIS** (GHRS) (metallicity, ionization structure).





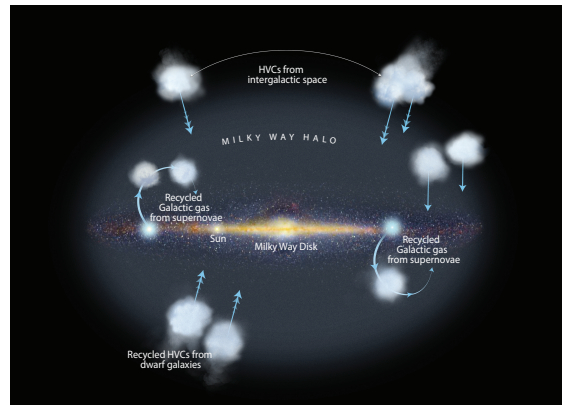
Complex A

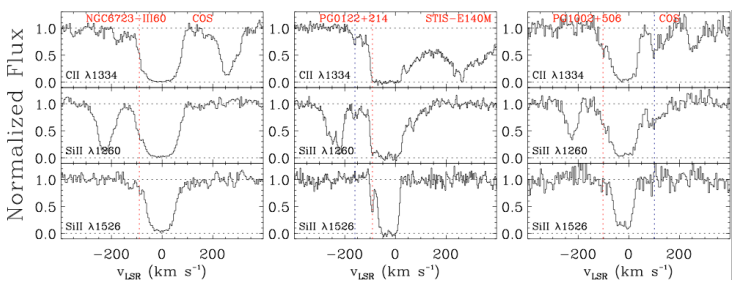
Bagger+12

HVC absorption study in other galaxies beyond the Milky Way and LMC/SMC
Need even more sensitive UV spectrograph
Tomography in the UV of the HVCs (CII, CIV, OI, OVI), their metallicity.

Summary

- UV spectroscopy has transformed our understanding of the large-scale flows through the Galaxy halo.





- In the near future, we should have a better idea of the metallicity distribution and if/how HVCs can reach the galactic disk.

- In the future, we should aim to study the HVCs (gas flows) in the local group of galaxies of different masses or stellar activities.