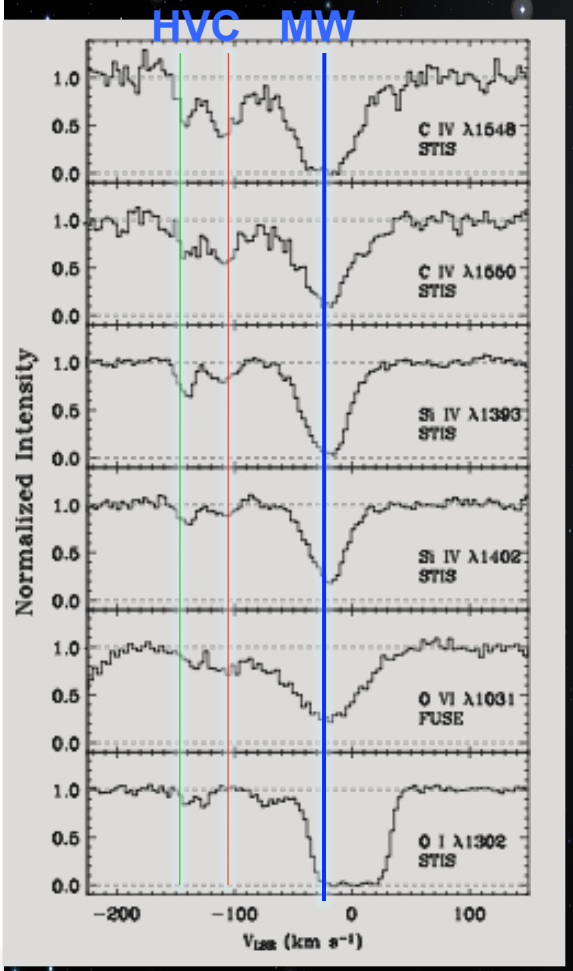
LOW HI COLUMN HIGH-VELOCITY CLOUDS (HVC): GALACTIC OR EXTRAGALACTIC?



Zech et al. 2008

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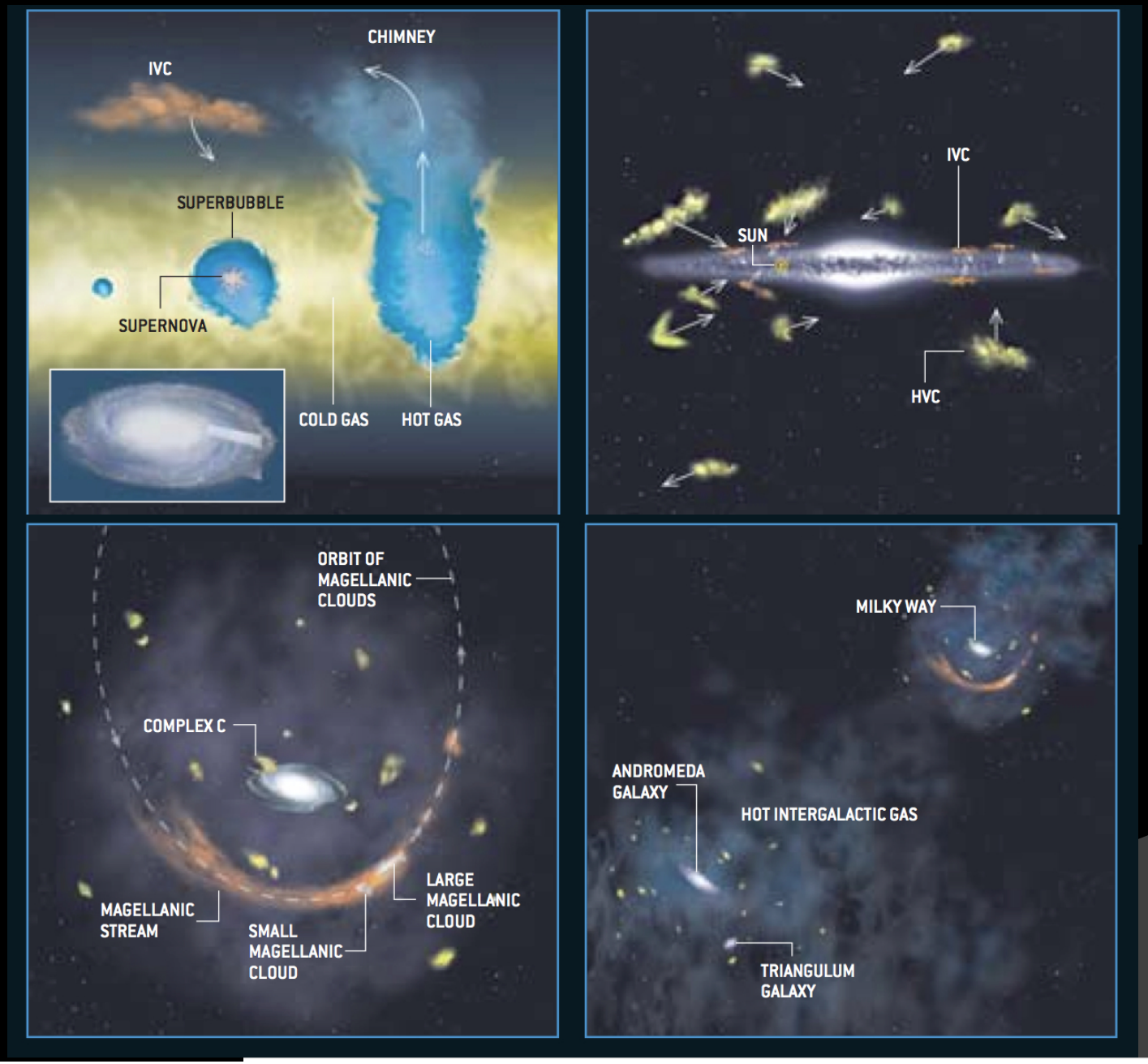
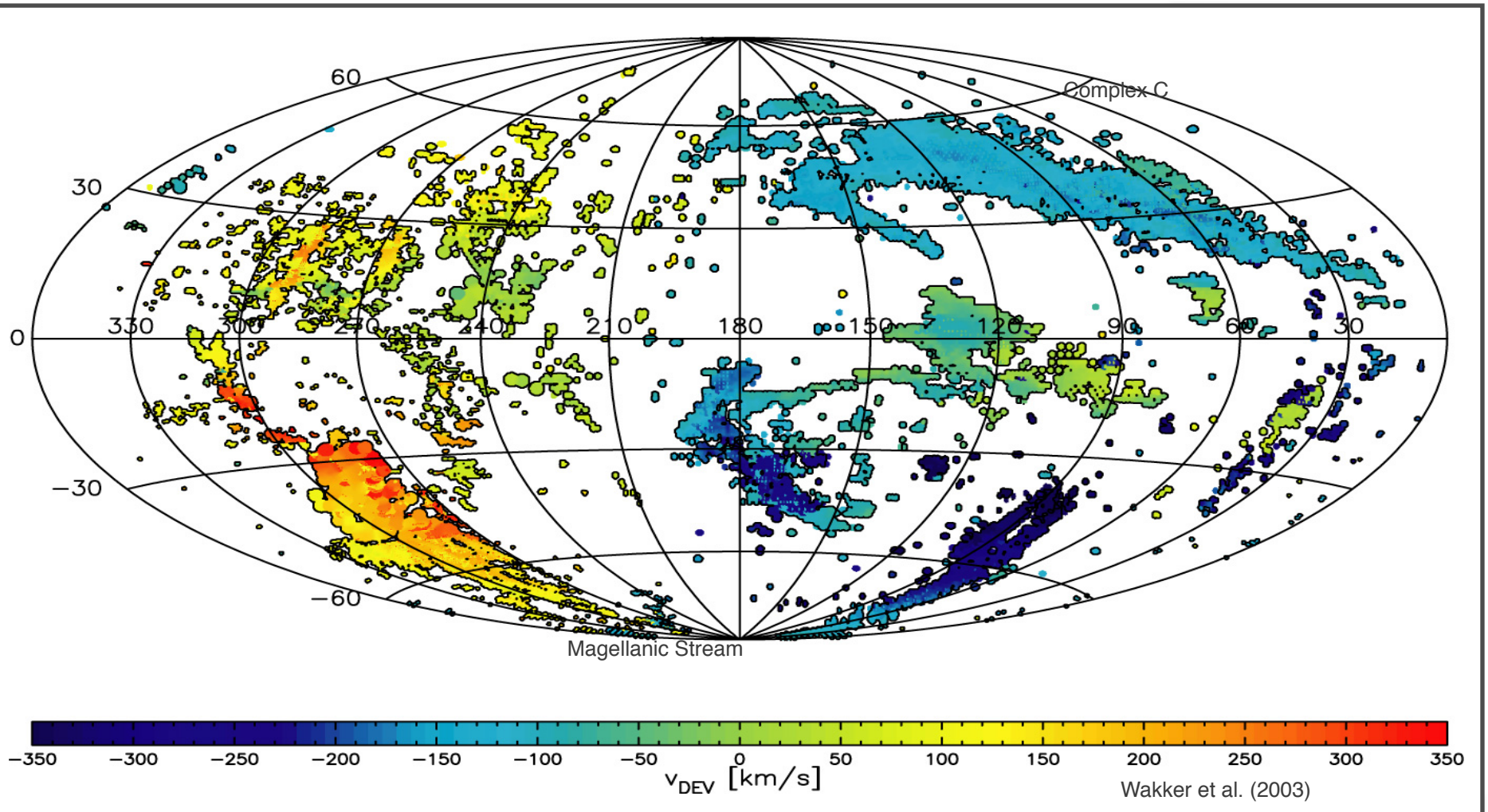
Main collaborator: Chris Howk

Image Credit: Wakker & Richter SciAm 2004

HVC Probes of Outflow/Inflow, IGM,…



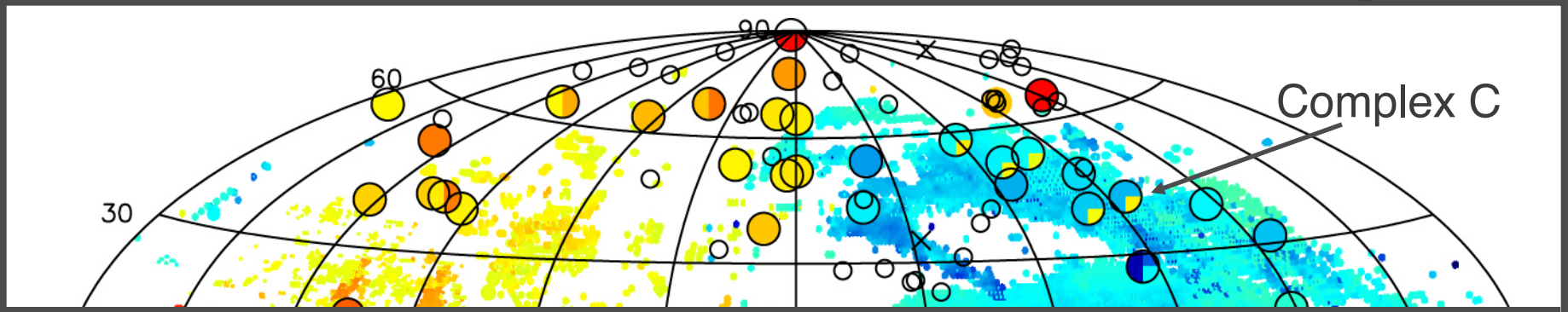
Images from Wakker & Richter,2004, SciAm
See also, e.g.,
Sembach et al. 2003,
Nicastro et al. 2003,
Blitz et al. 1999
Putman et al. 2003
Fox et al. 2006,
Collins et al. 2005
…



HVCs exhibit H I 21cm emission that covers ~37% of the sky at $N_{HI} > 7 \times 10^{17}$ cm^{-2} (Murphy et al. 1995). Observations motivated by the >50% Mg II detection rate from FOS Key project (Savage et al. 1993) compared to 18% HI covering factor at at $N_{HI} > 2 \times 10^{18}$ cm^{-2} (Wakker 1991).

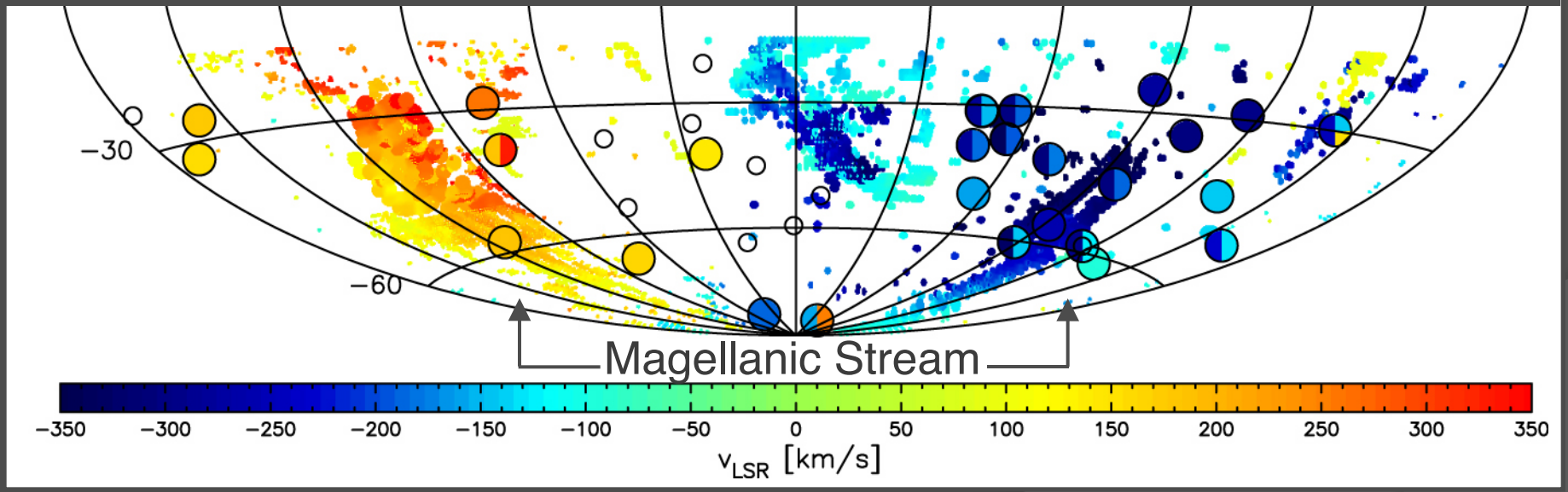
Knowledge on distances, ionization, metallicities have only started to be estimated in the last ~15 years thanks in part to HST, FUSE, and ground based observations.

H I + O VI HVC Galactic Sky



Covering fraction

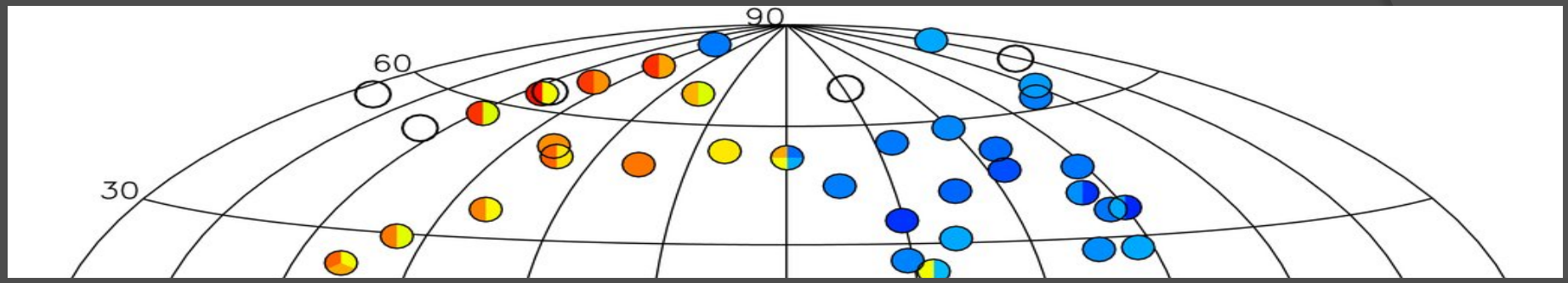
60% – 85% of sky covered at $N(H^+) \geq 10^{18}$ cm^{-2} (for SMC metallicity)



Sembach, Wakker, Savage, et al. 2003
See also Fox et al. 2006, Collins et al. 2007

H I 21cm Emission
FUSE O VI Absorption

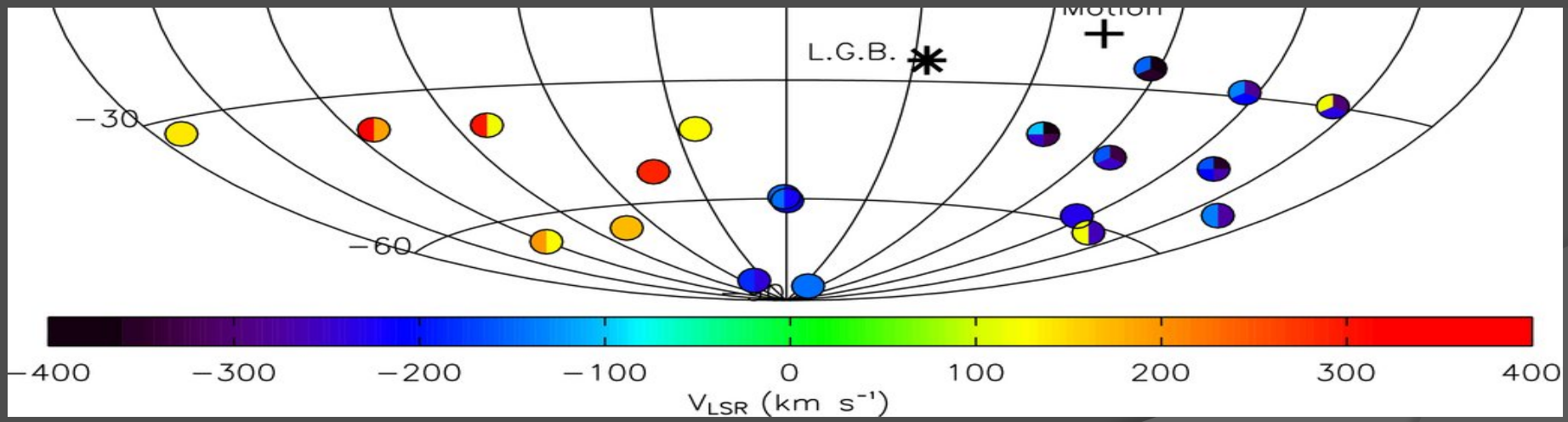
Si III HVC Galactic Sky



Si III HVC coverage about 80-90%.

$N_{HII} \approx (6 \times 10^{18}\ cm^{-2})(Z_{Si}/0.2Z_{sun})^{-1}$;typical neutral fractions $N_{H\,I}/N_{H} \approx 0.01$

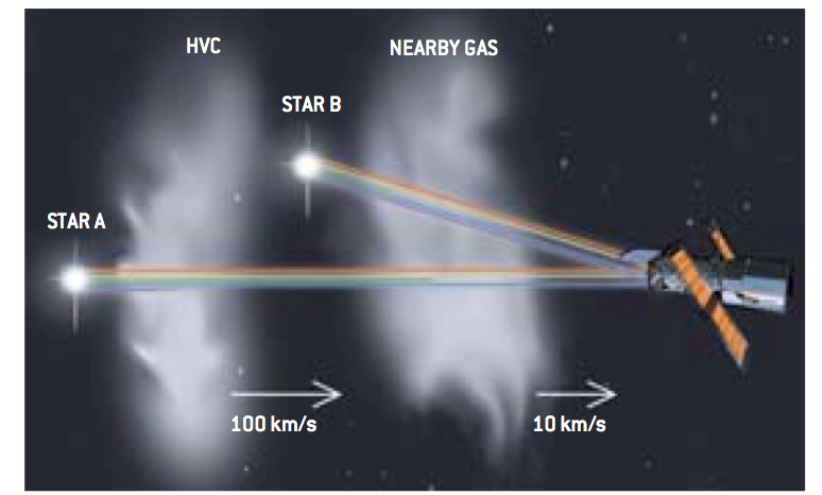
$M_{HVC} \sim 10^{7}\ M_{sun}\ (d_{HVC}/10\ kpc)^{2}\ (Z_{HVC}/0.2Z_{sun})^{-1}$ -> <0.1 to 1 solar mass per year



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

STIS Si III Absorption

COS Program: Targeting Distant High-Latitude Stars



HVCs with N(HI)>10^{19} cm^{-2} are found toward distant and high z-height stars:
Complex C at 10 kpc
Complex M at <4 kpc
Complex A at 4-10 kpc

(e.g., Wakker 2001, Wakker et al. 2007, Thom et al. 2008).

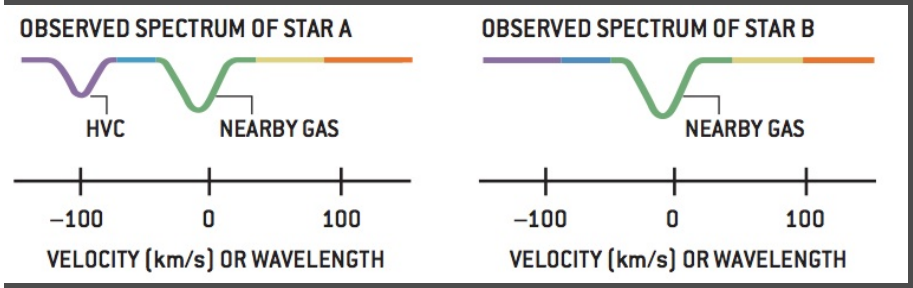
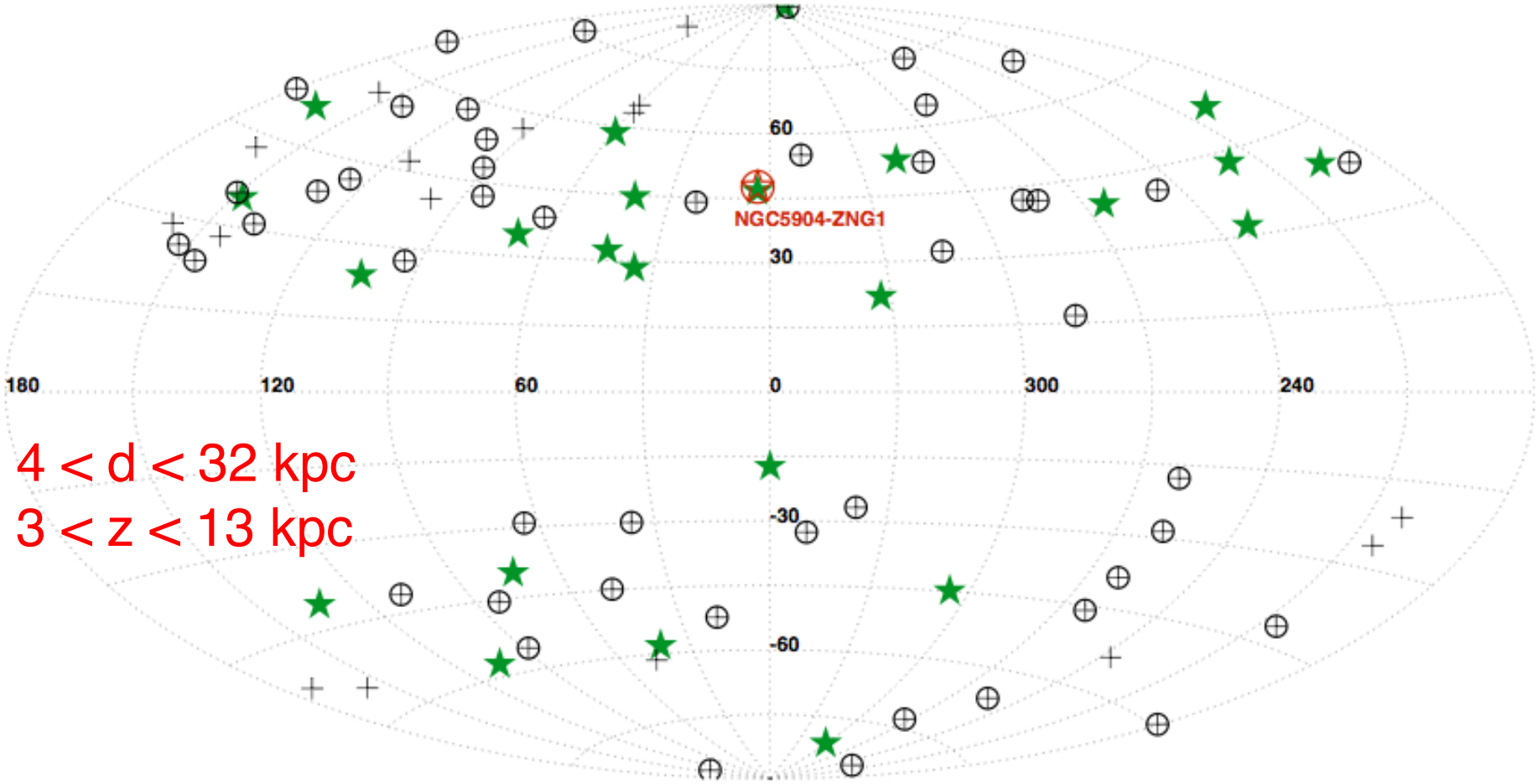


Illustration source: Wakker & Richter,SciAM, 2004

Cycle 17 Program:

24 stars at 3<d<32 kpc and 3<z<13 kpc
Blind survey
COS G130M & G160M and STIS E140M
24 orbits

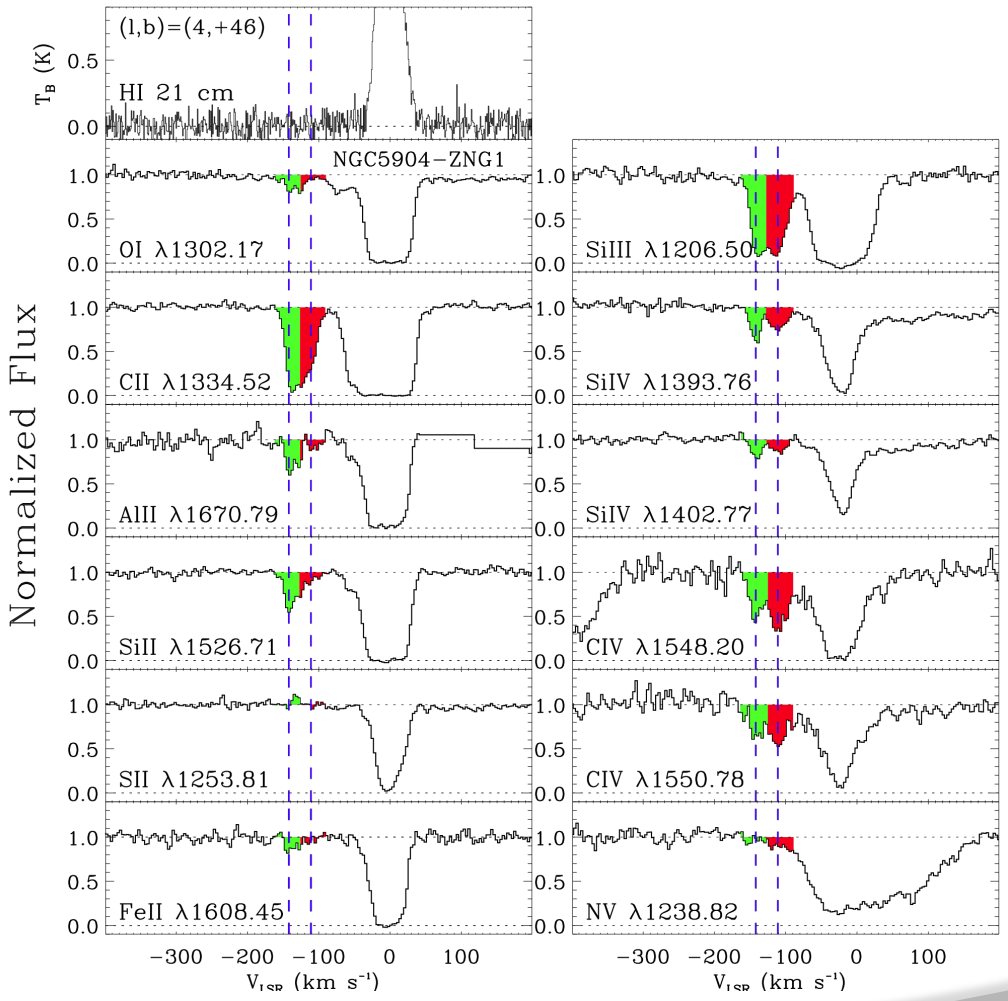
The Cycle 17 HST COS/STIS Program



4 < d < 32 kpc

3 < z < 13 kpc

First Example of Low HI Column HVCs Toward a Star



Zech et al. 2008

Two negative HVCs toward the center of the Galaxy at 7.5 kpc and z=+5.3 kpc

-OVI and HI absorption lines are also detected thanks to FUSE observations.

-Relative abundances:

[Fe/Si] = -0.3, [Al/Si] = -0.3

⇒ Evidence of dust

⇒ Likely a Galactic Origin

⇒ Galactic outflow, fountain

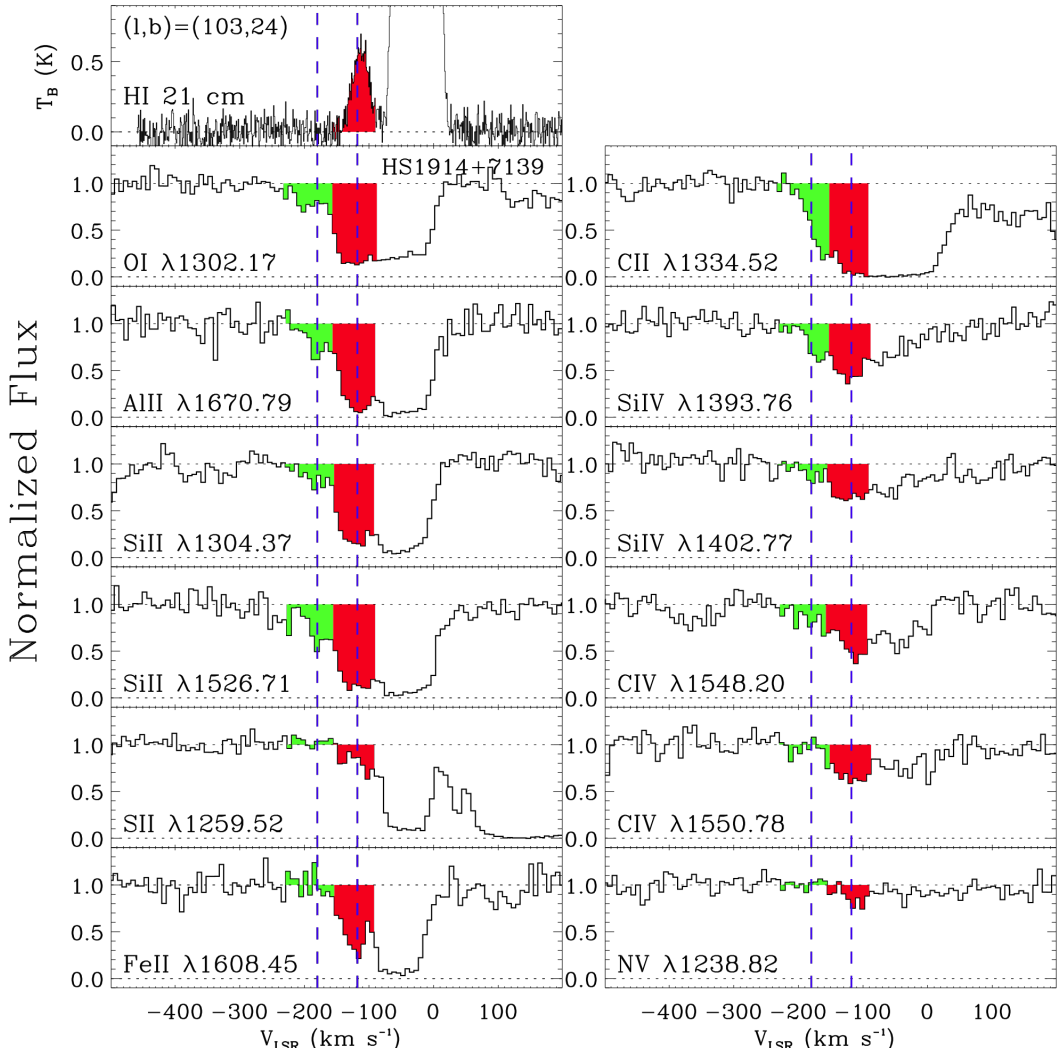
-With OI and HI, we can directly deduce that: [O/H]=+0.2, supersolar abundance

⇒ Galactic Origin!

⇒ Galactic fountain

Very ionized, HII/H=0.97, HII/HI>>1 (N(HI)=$10^{16.7}$ cm^{-2})

Example of Negative-Velocity HVCs Toward a Star



Two negative HVCs at d<15 kpc and z<6 kpc

-At -118 km/s: Galactic Outer arm, first direct distance estimate of this Galactic arm (d≤15 kpc, Galactocentric radius 17.7 kpc).

-At -180 km/s:

-[Fe/Si]<+0.2, [Al/Si]~+0.1, [C/Si]~0

⇒ No evidence of dust

⇒ Likely an Extragalactic Origin

⇒ Accretion

[O I/Si II]~ -0.5, [O I/C II]~ -0.5

-> Very ionized, HII/HI>>1

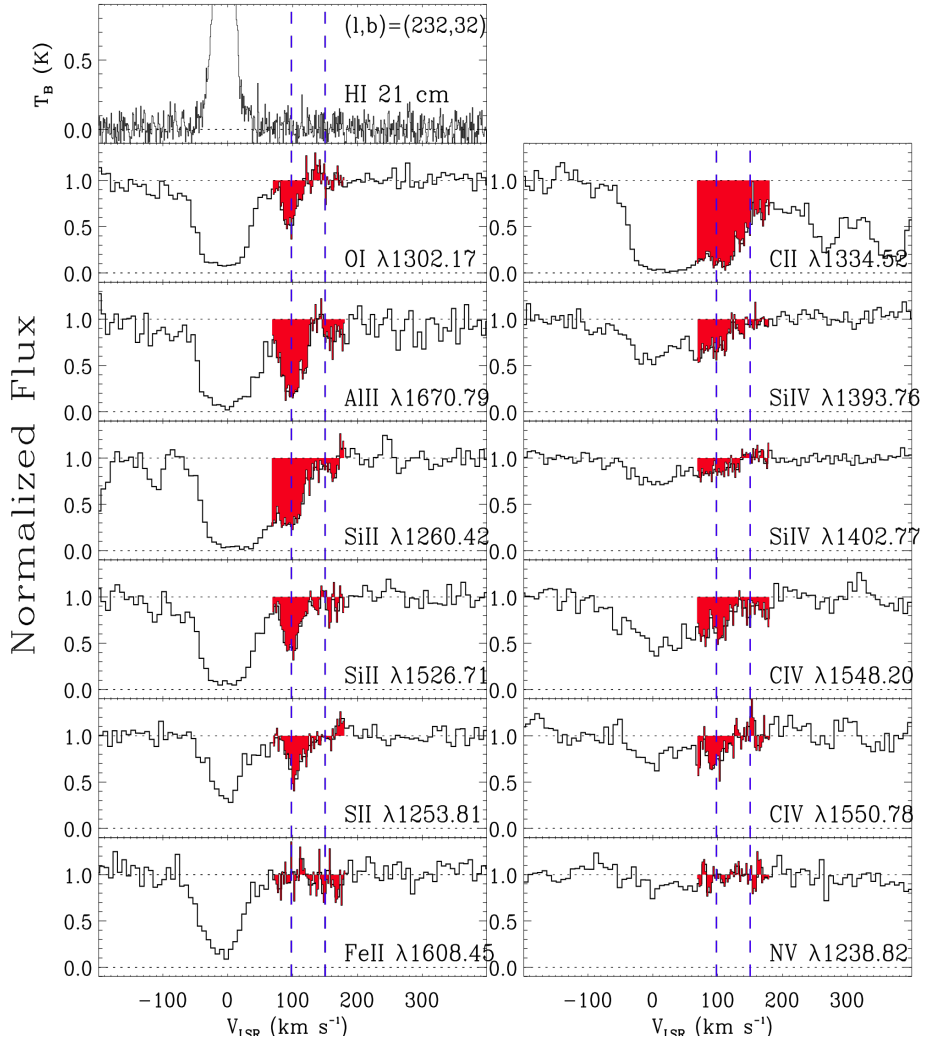
If 0.3 solar abundance,

N(H II) ≥ $10^{18.2}$ cm^{-2}

N(H I) ~ $10^{17.7}$ cm^{-2}

Lehner & Howk 2010, ApJL, 709, L138, Lehner & Howk 2011

Example of a Positive-Velocity HVC Toward a Star



HVC at d<16 kpc and z<+8.4 kpc

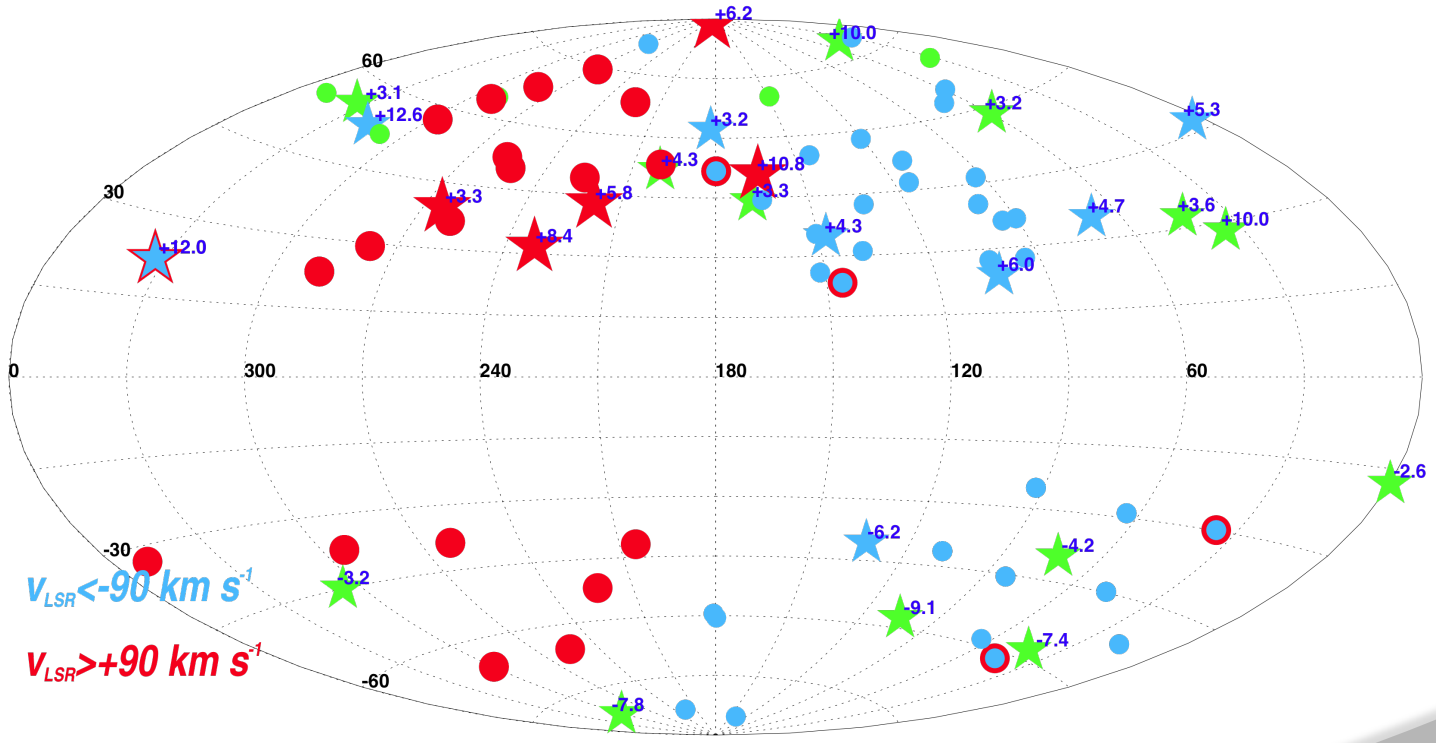
[Fe/S] < -1.5, [Al/S] > -1.0
[Si/S] ~ -1.2, [Fe/Si]< -0.3
⇒ Evidence of dust
⇒ Likely a Galactic Origin
⇒ Galactic outflow, fountain

[O I/Si II]~ -0.7, [O I/S II]~ -2.1
-> Very ionized, HII/HI>>1

If solar abundance,
N(H II) ≥ $10^{19.5}$ cm^{-2}
N(H I) ~ $10^{17.3}$ cm^{-2}

Lehner & Howk 2011

HVCs toward Galactic stars (star symbols) with z-heights (kpc) and QSOs (circles, SiII)



Lehner & Howk 2011 (star symbols); Collins et al. 2010 (circles)

Detection Rate Comparison between Galactic and Extragalactic Samples

Sample	HVC Detection Rate (%)
QSO sightlines – Si III (a)	80-90
QSO sightlines – O VI (b)	60-90
H I emission (>7x10^{17} cm^{-2}) (c)	37
Stellar sample (all)	50
Stellar sample (|z|>4 kpc and b>20^{o})	77

(a) Collins et al. 2009, Shull et al. 2009; (b) Sembach et al. 2003, Fox et al. 2006; (c) Murphy et al. 1995; stellar sample: Lehner & Howk (2011)

Comparison of Properties between Galactic and Extragalactic Samples

Extragalactic Sample	Stellar Sample
HI, OVI, CIV, SiIV, SiIII, CII, SiII, OI…	HI, OVI, CIV, SiIV, SiIII, CII, SiII, OI…
H II/H I >> 1	H II/H I >> 1
[Z/H] ≤ 0 (3 HVCs with OI and HI)	[Z/H] = +0.2 for 1 HVC
100 < $\|v_{LSR}\|$ < 400 km/s ~100% of HVCs 100 < $\|v_{LSR}\|$ < 200 km/s ~25% of HVCs 200 < $\|v_{LSR}\|$ < 400 km/s	100 < $\|v_{LSR}\|$ < 200 km/s
distance? Associated with Complex C ~ 10 kpc, Magellanic Stream ~ 50-100 kpc	3<d< 30 kpc 3<|z|<13 kpc
Origin(s)? Accretion, galactic interaction, outflow,WHIM(?)…	Origins: Galactic fountain/outflow Accretion (Galactic inflow)

Other (low) N(HI) HVCs Near Galaxies

✓ HVCs between LMC and Milky Way (~50 kpc), probing the outflows from the LMC (Lehner et al. 2009, Staveley-Smith et al. 2003, Lehner & Howk 2007).

✓ HVCs detected toward other galaxies (M31, M33, e.g., Thilker et al. 2004, Westmeier et al. 2005, Putman et al. 2009).

✓ Lyman limit systems (HI 10^{16}-10^{19} cm^{-2}), likely higher redshift analogs of HVCs are found within <100 kpc from a galaxy (Stocke et al. 2010, Richter al. 2009, 2010, Lehner et al. 2009).

HVC: probes of galactic phenomena (accretion, outflow, galactic Interaction)

Summary

- Low HI column HVCs are unlikely to trace the warm-hot ionized medium.
- Instead many are located at 3<|z|<13 kpc from the Milky Way plane, and probably within <50-100 kpc for most of them.
- They are therefore a key source of gas for future star formation and ingredient for studying the recycling of matter in the Universe.
- Our new understanding of the HVCs would not have been possible without HST and FUSE and the rich archive at MAST!
- Next few years look bright: COS observations of many QSOs will lead to better statistics/understanding of the covering factor, ionization, and metallicities.

Grazie mille - Thank you