HOT AND COLD GAS AROUND THE MILKY WAY AND NEARBY GALAXIES

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HOT AND COLD GAS AROUND THE MILKY WAY AND NEARBY GALAXIES

CONTENTS

- **Galactic HI High-Velocity Clouds (HVCs)**
- **Transition temp. gas (few 10^5 K) in HVCs**
- **HVC kinematics**
- **HI/OVI associated with nearby galaxies**

HIGH-VELOCITY CLOUDS

Gas with velocities incompatible with a simple model of differential galactic rotation.
In practice: $|v_{LSR}|$ or $|v_{DEV}| > 90$ km s^{-1} [50 km s^{-1} for IVCs]

ORIGINS

- **Galactic Fountain**
- **Tidal Streams**
- **Accreting material**
- **Remnants of Milky Way (Local Group?) formation**

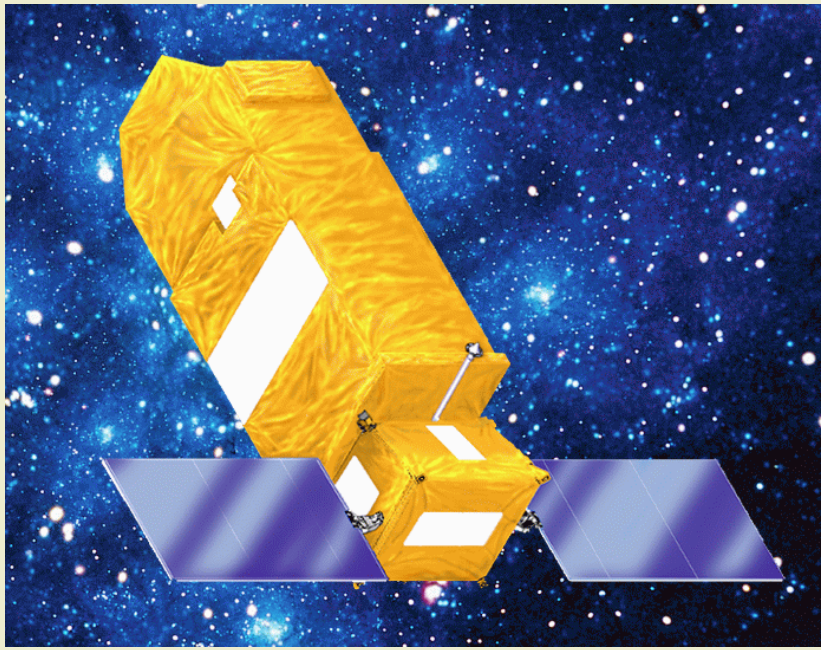
KEY MEASUREMENTS

- Metallicities
- Distances
- Ionization conditions

HI HIGH-VELOCITY CLOUDS

MEASURING HVC METALLICITIES

Absorption from dominant ionization stage of undepleted elements
=> UV spectra of OI, SII absorption



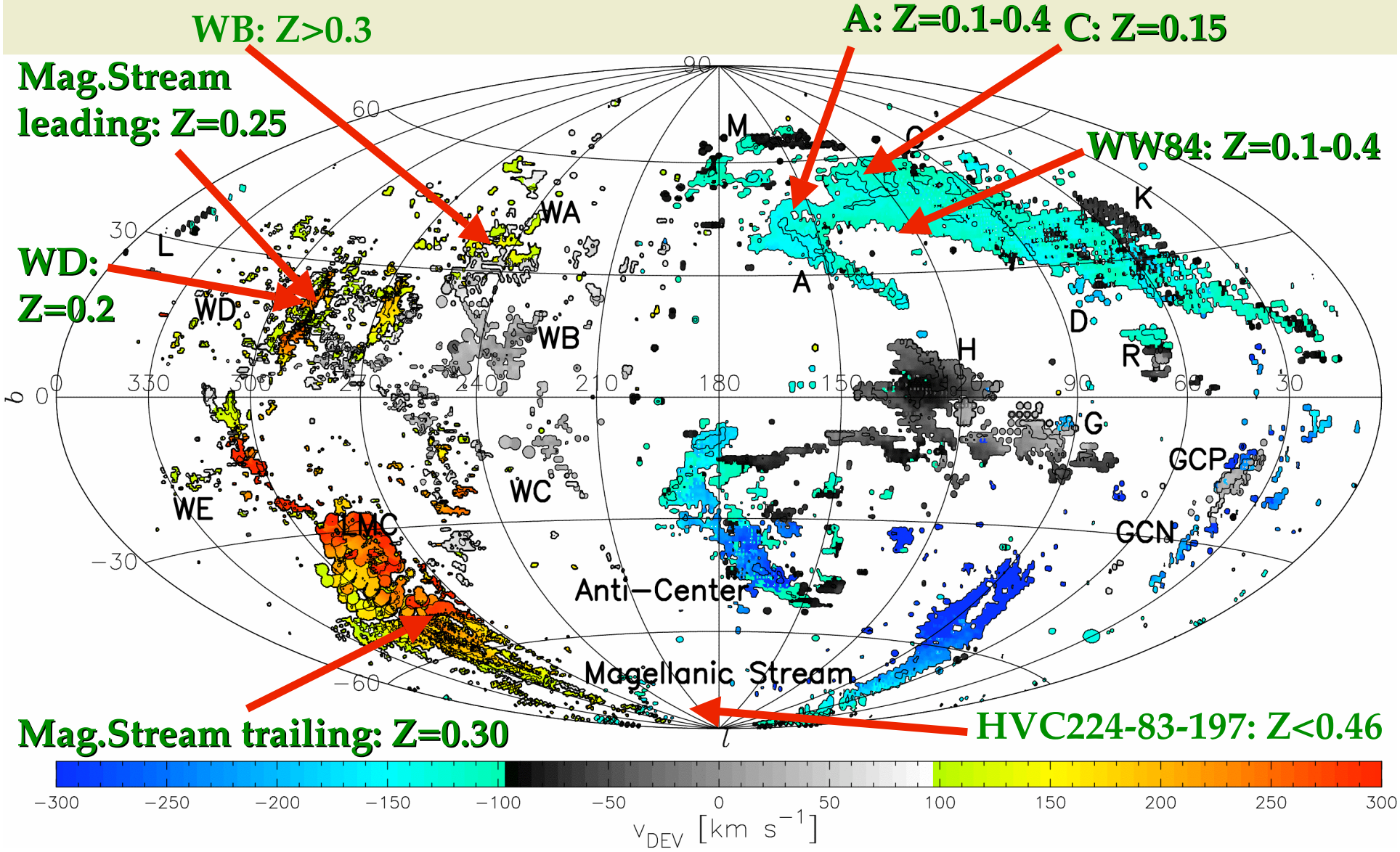
(FUSE)

- **Data from FUSE and HST:**

- **3 IVCs: 1+ stars => about solar metallicity**
- **7 HVCs: 1 AGN**
- **Complex C: 5 AGNs**

HI HIGH-VELOCITY CLOUDS

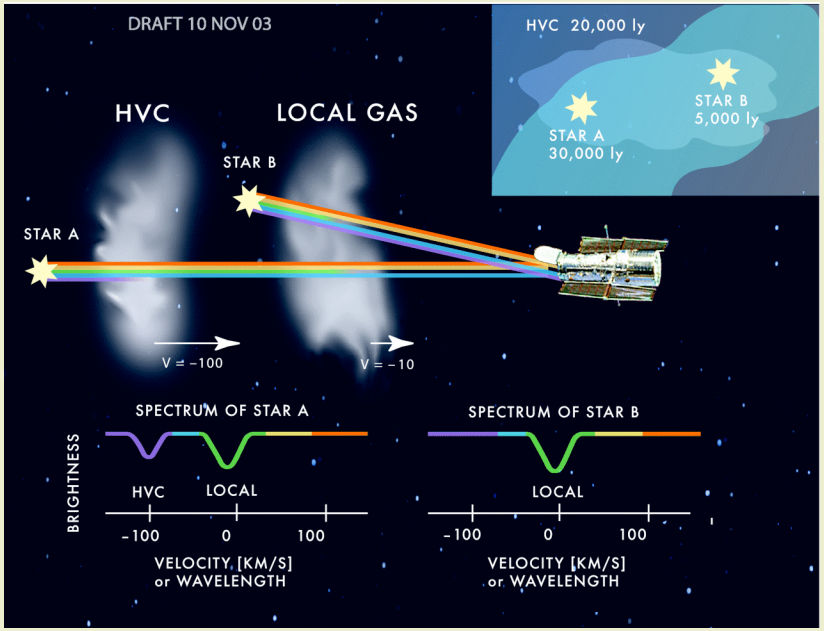
Six clouds with measured metallicity (Z); 2 with limits



HI HIGH-VELOCITY CLOUDS

MEASURING HVC DISTANCES

Look for absorption in stars behind HVC
and significant non-detection in stars in front of HVC
[usually using CaII K/H]



- SDSS+2MASS+Other: **30000 BHB/RR candidates**
- 60 HVC/IVC fields: **~10 stars per 3 kpc interval (3000 total)**
- SDSS/SEGUE/APO: **classification spectroscopy+photometry (500 stars and growing)**
- VLT/Keck: **30 stars, and growing**

HI HIGH-VELOCITY CLOUDS

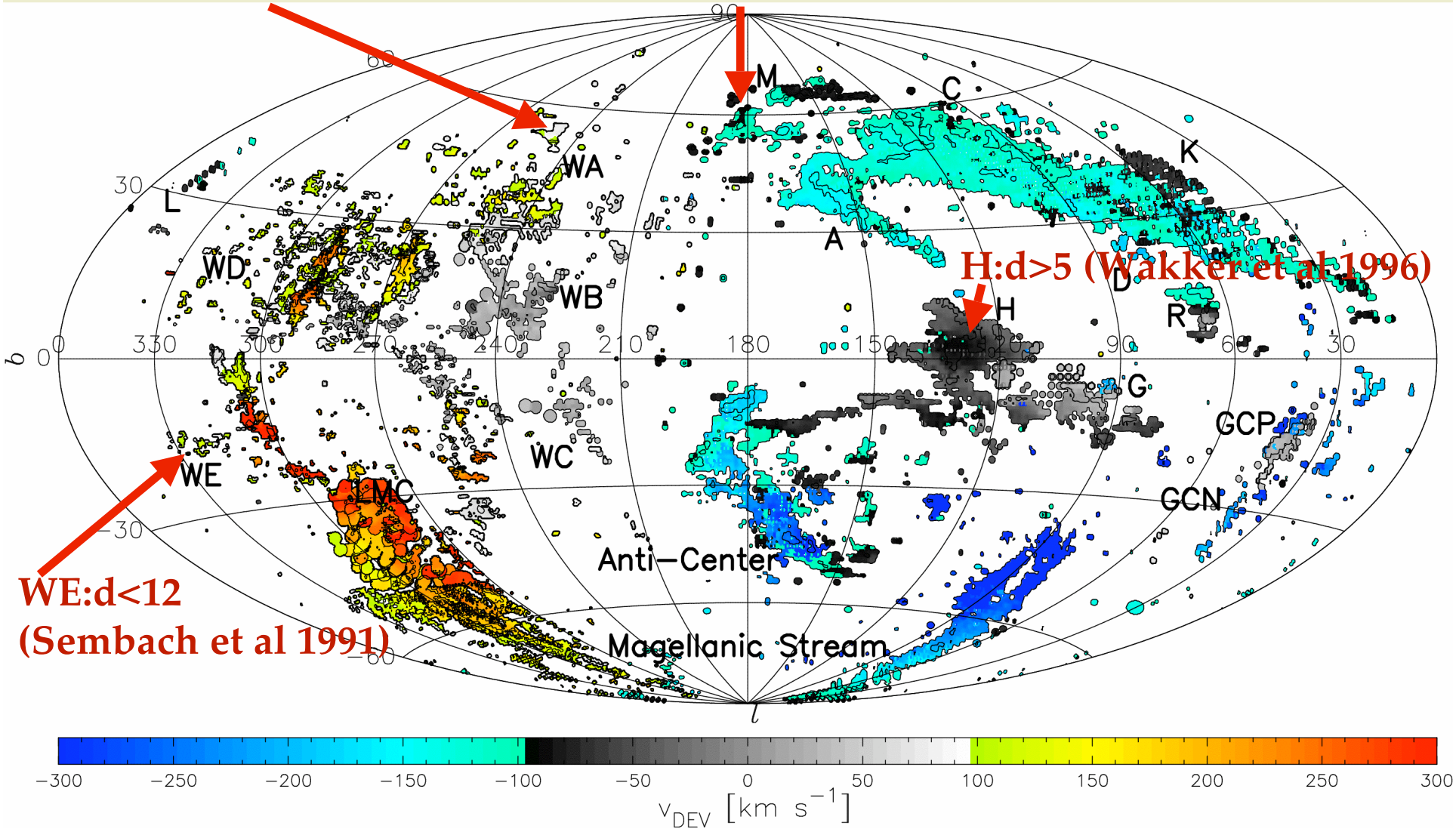
Four distance limits (3 upper; 1 lower)

WW35:d<8.8 (Thom et al 2006)

MII: d<4 (Danly et al 1993)

H:d>5 (Wakker et al 1996)

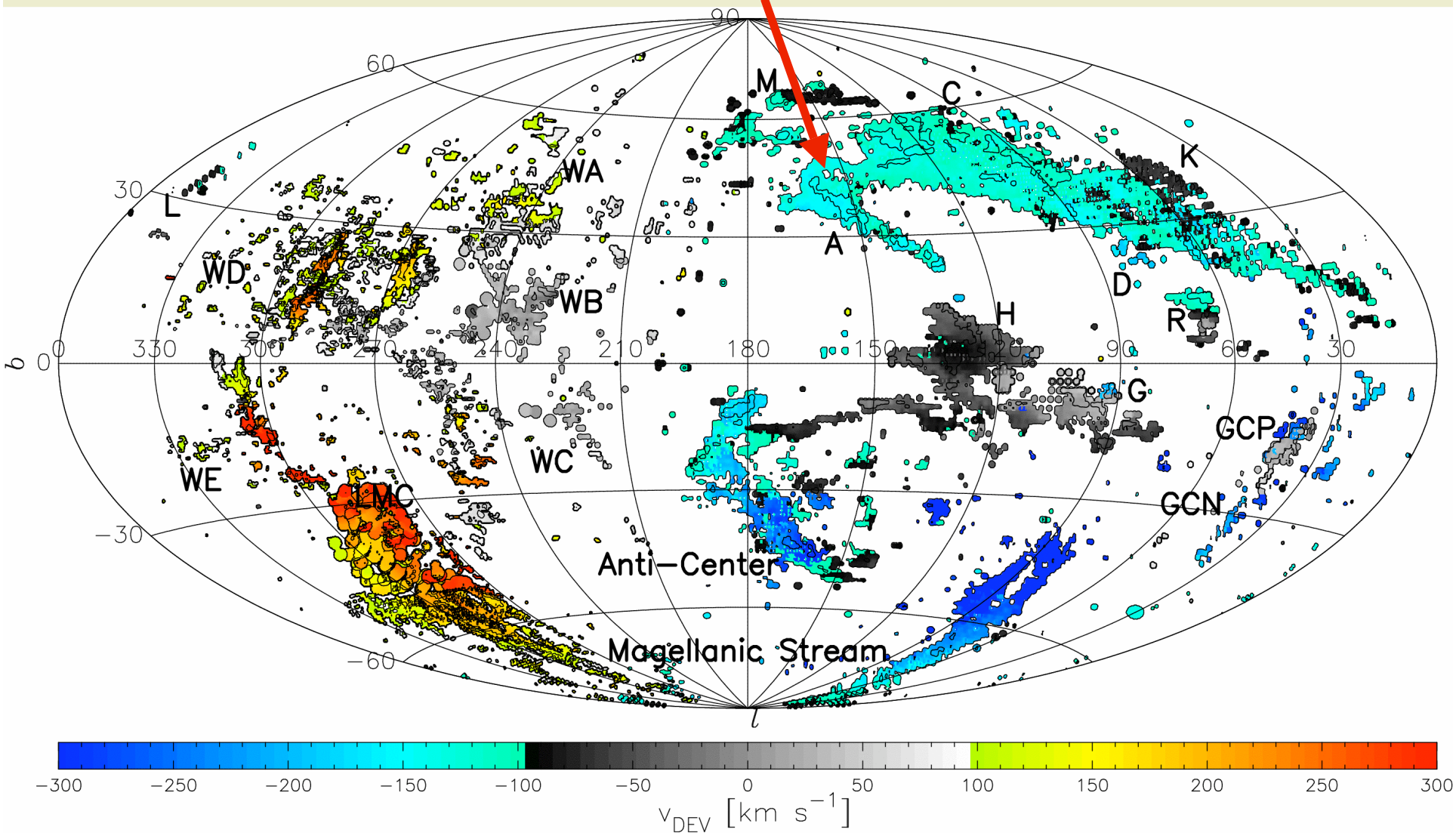
WE:d<12
(Sembach et al 1991)



HI HIGH-VELOCITY CLOUDS

Four distance brackets - complex A: 8-10 kpc

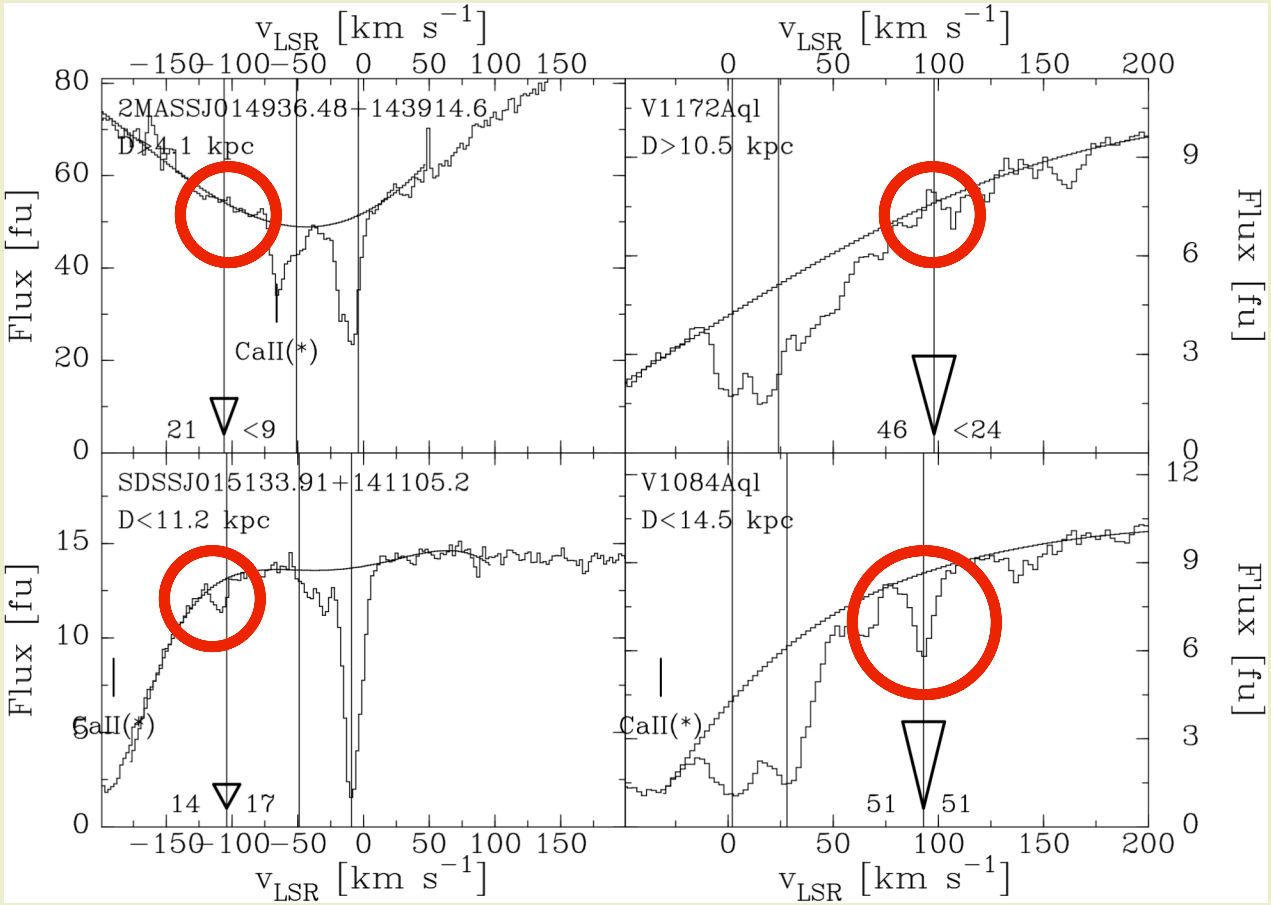
(van Woerden et al 1999)



HI HIGH-VELOCITY CLOUDS

VLT UVES data (2006) BHB/RR Lyrae stars (1-3 hours/star)

2MASS J014936 (4.1 kpc)



V1172Aql (10.5 kpc)

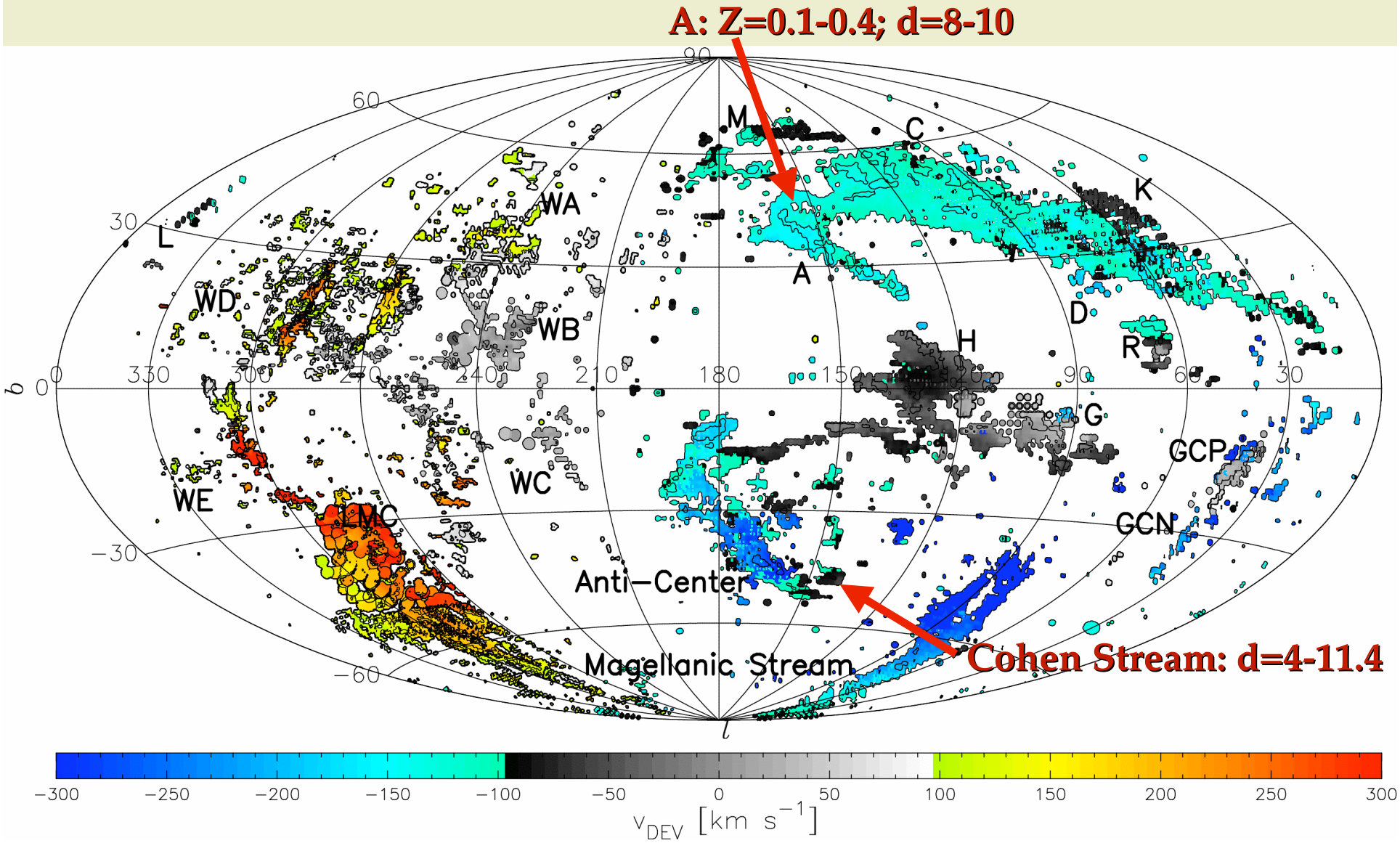
SDSS J015133 (11.2 kpc)

V1084Aql (14.5 kpc)

Cohen Stream **Complex GCP**

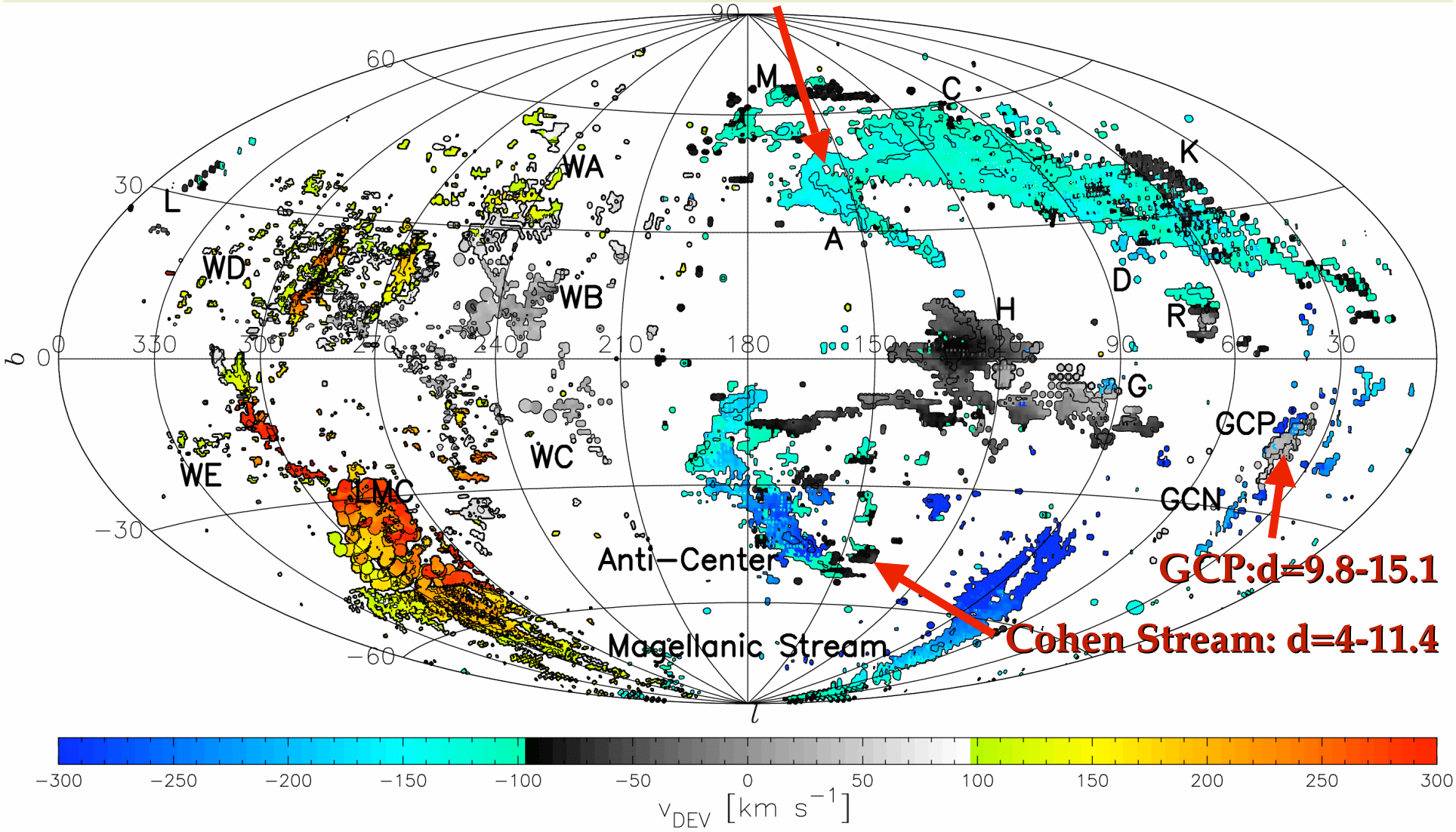
HI HIGH-VELOCITY CLOUDS

Four distance brackets - Cohen Stream: 4-11 kpc

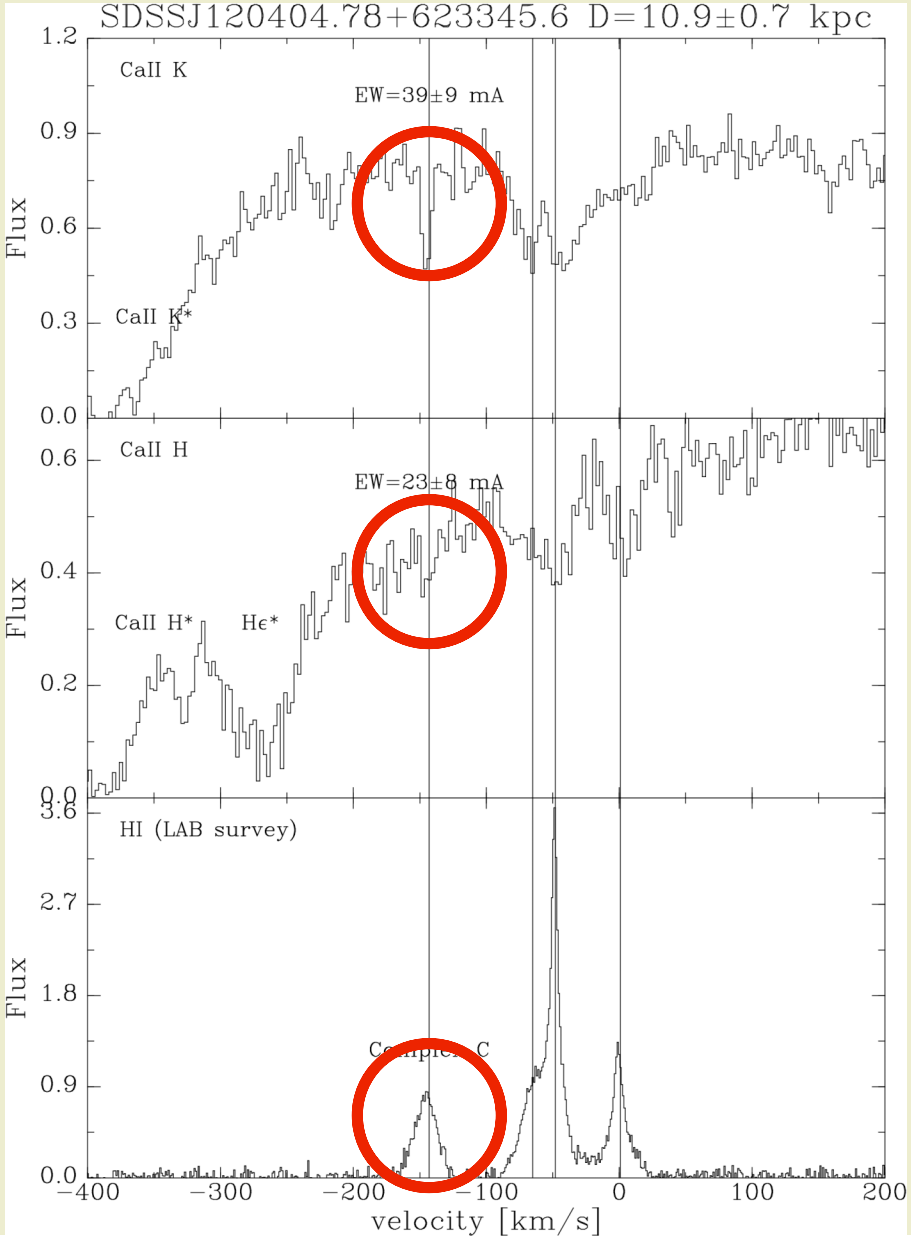


HI HIGH-VELOCITY CLOUDS

Four distance brackets - GCP/Smith Cloud/HVC40-15+100: 10-15



HI HIGH-VELOCITY CLOUDS



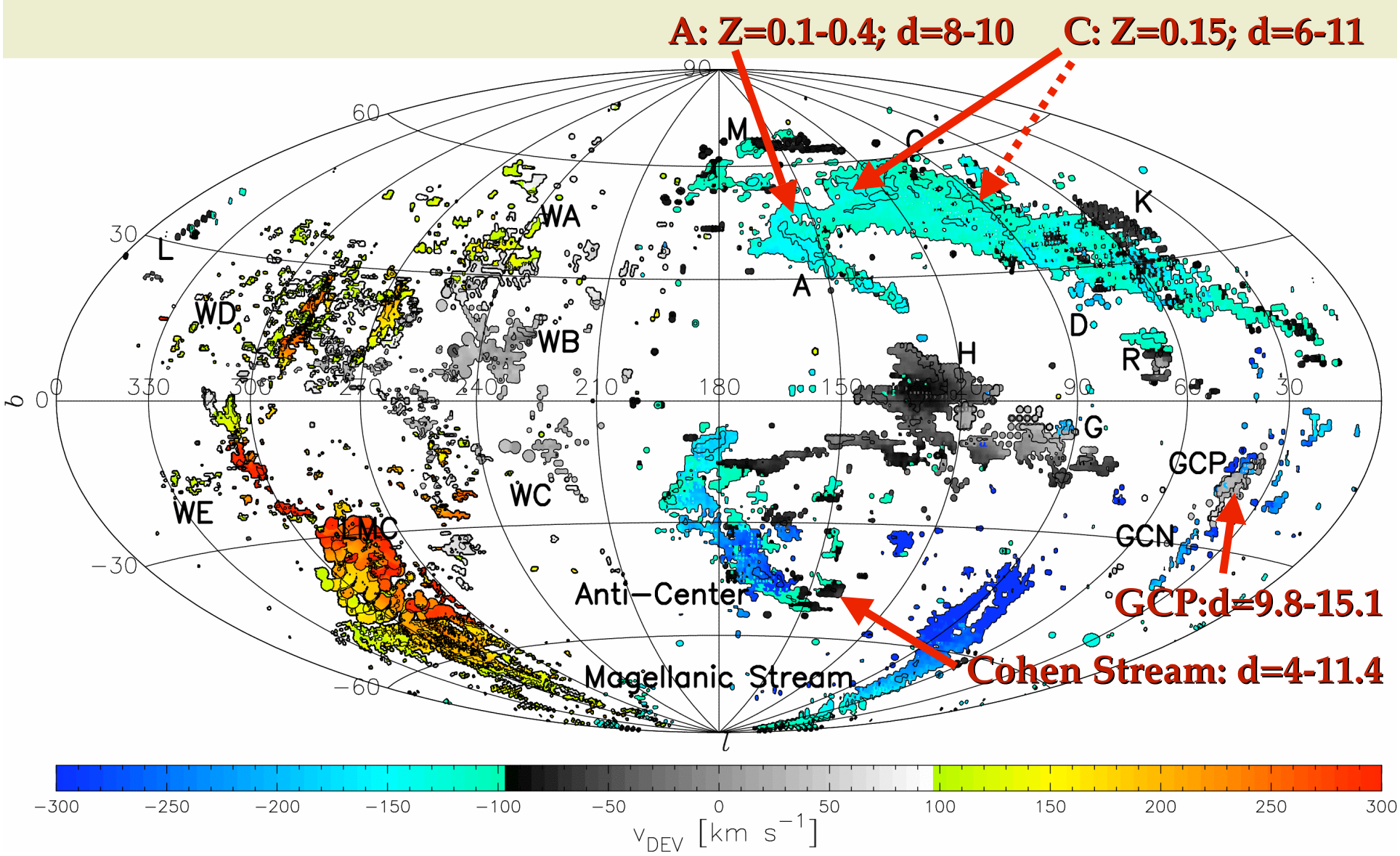
Keck data - April 24 2007
(preliminary reduction)

SDSSJ120404.78+623345.6
BHB star at 11 kpc

Apparent complex C
CaII K/H absorption

HI HIGH-VELOCITY CLOUDS

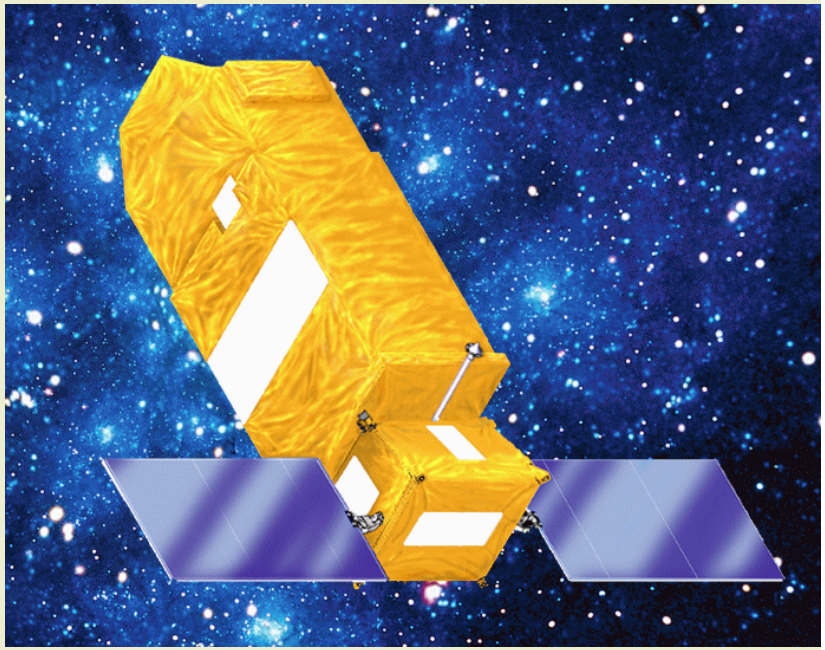
Four distance brackets - Complex C: 6-11 kpc



OVI HIGH-VELOCITY CLOUDS

MEASURING IONIZATION CONDITIONS

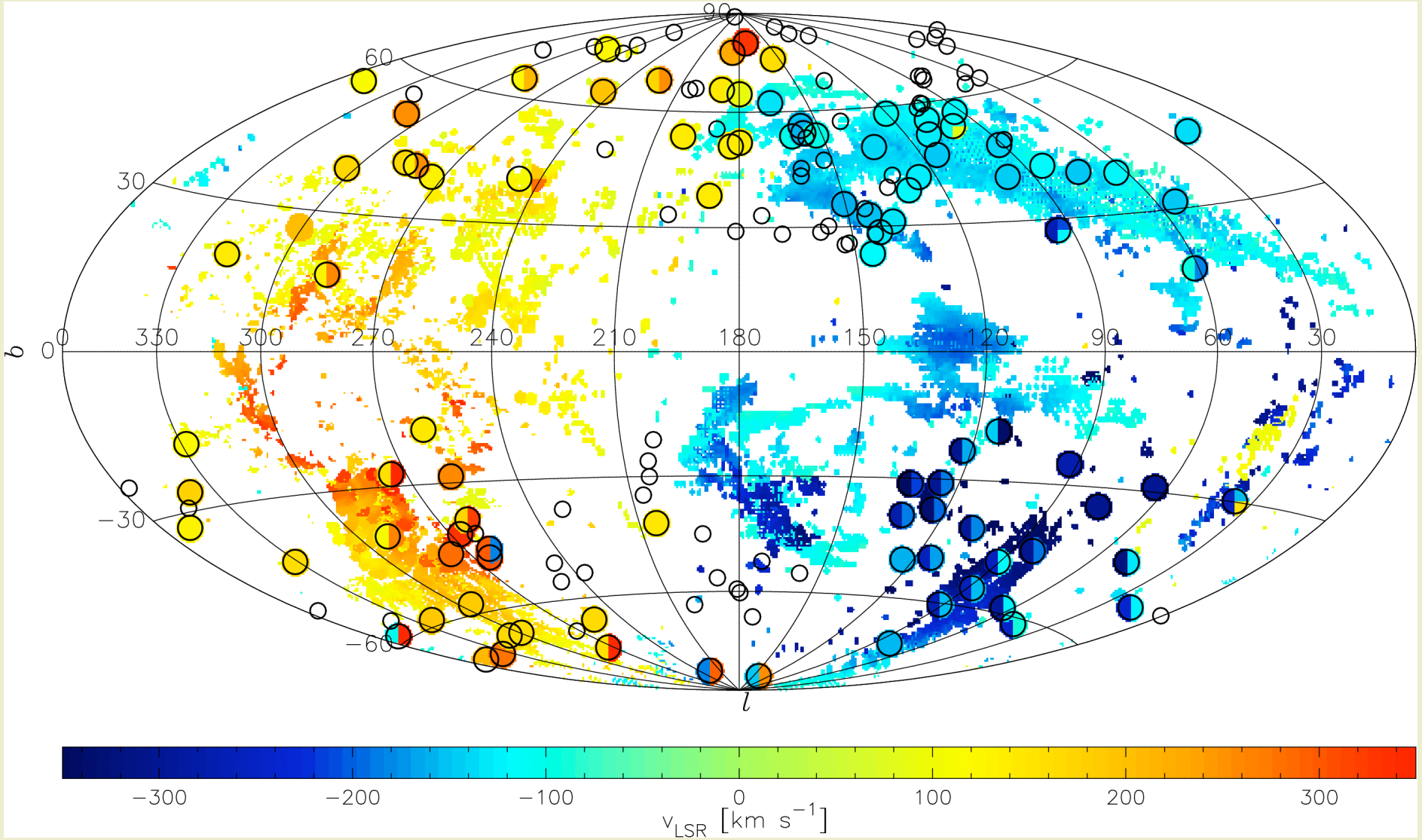
O abundance + ~20% O as OVI + linestrength + 113.9 eV I.P. =>



1031.93 Å line of OVI is good tracer of transition temperature (few 10^5 K) gas
[Gas that is cooling or heating]

- **FUSE**
  (Wakker/Savage/Sembach et al 2003)
- **176 lines of sight**
- **High-velocity OVI in 104 l.o.s. (60% of l.o.s.)**
- **85% (36 of 42) l.o.s. with 21-cm HVC have associated OVI**

OVI HIGH-VELOCITY CLOUDS



Continues colors: velocities of H I 21 cm emission ($|v_{LSR}| > 100$ km s^{-1})
Circles: velocities of OVI absorption

HVC KINEMATICS

Parametrize locations

- Number density = radial power law with some size scale
- distribute around MW or MW+M31 or MW+M31+LG

Parametrize velocity field

- Bulge+Disk+Halo potential => v(rot) => v(tangential)
- Add radial infall component (0 - 100 km/s)
- Add dispersions (~50 km/s)

=> Predictions for (l, b, v_{LSR})

Parametrize cloud parameters

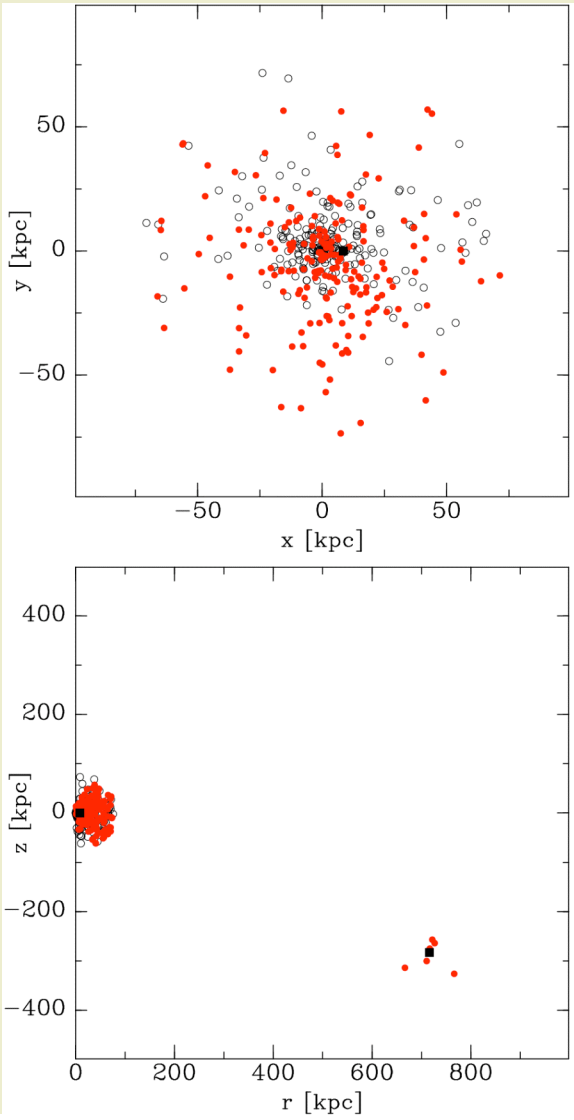
- Power law mass distribution, fixed density

=> Predictions for radius, area, flux, T_B(HI)

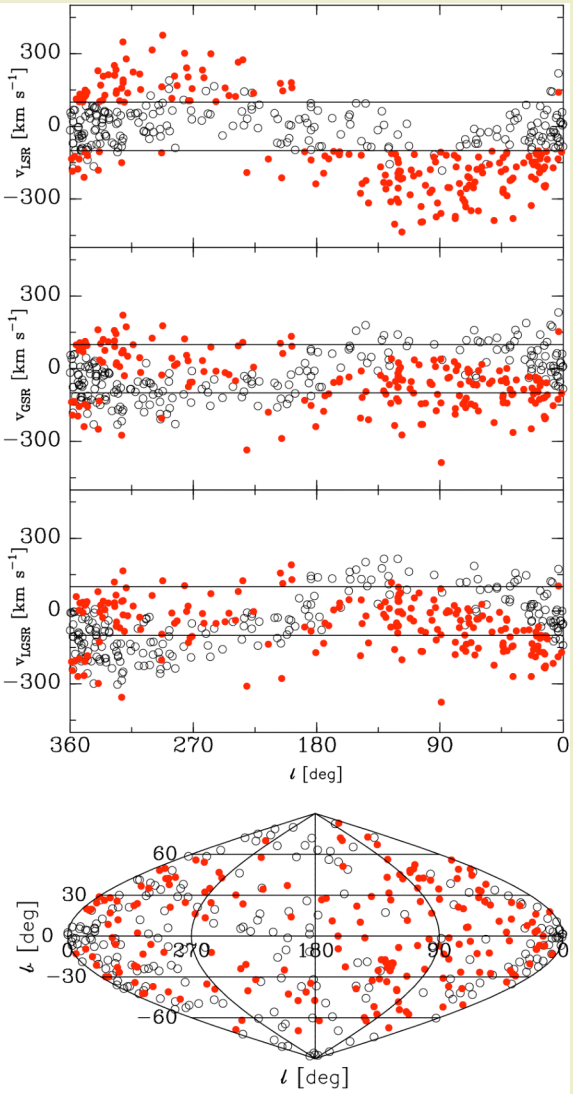
Apply observational selection criteria

HVC KINEMATICS

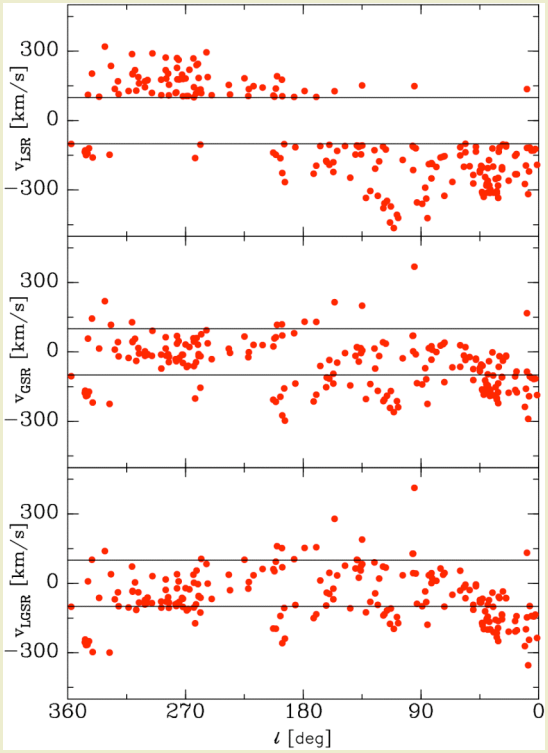
Model xy/rz view



$v_{LSR/GSR/LGSR}(l)$ (model)

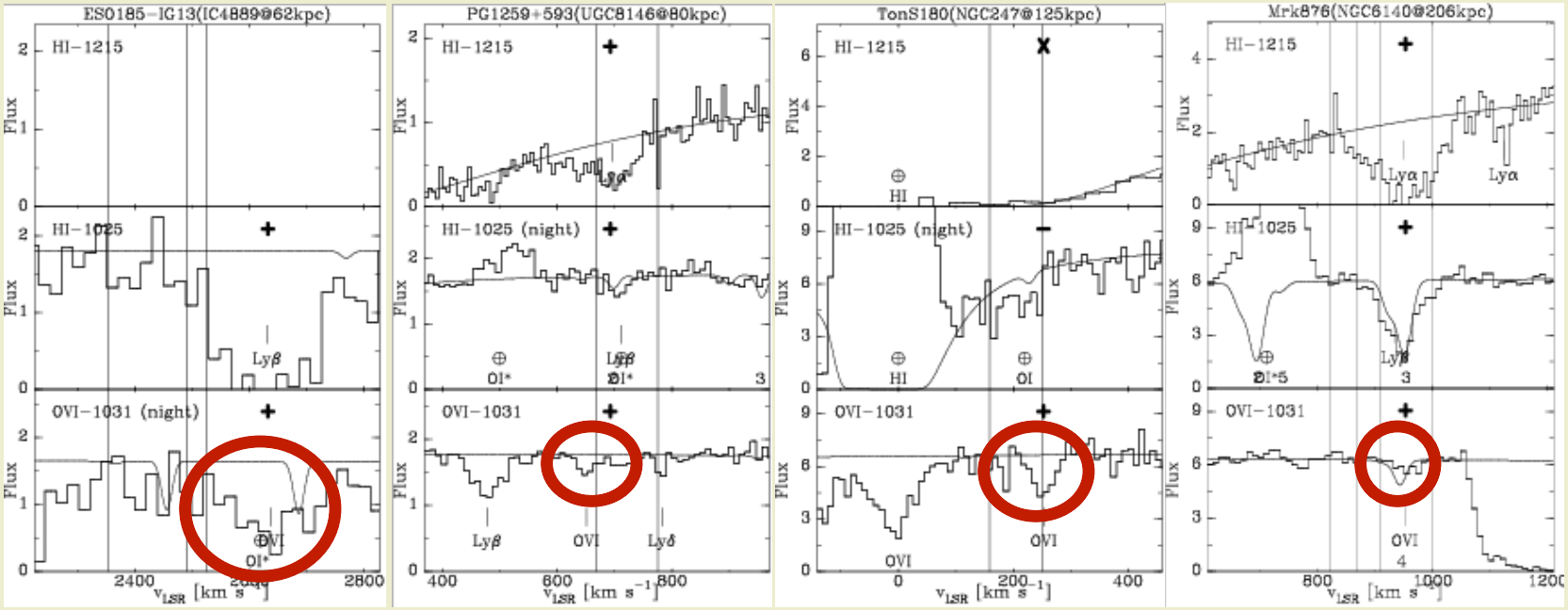


$v_{LSR/GSR/LGSR}(l)$ (data)



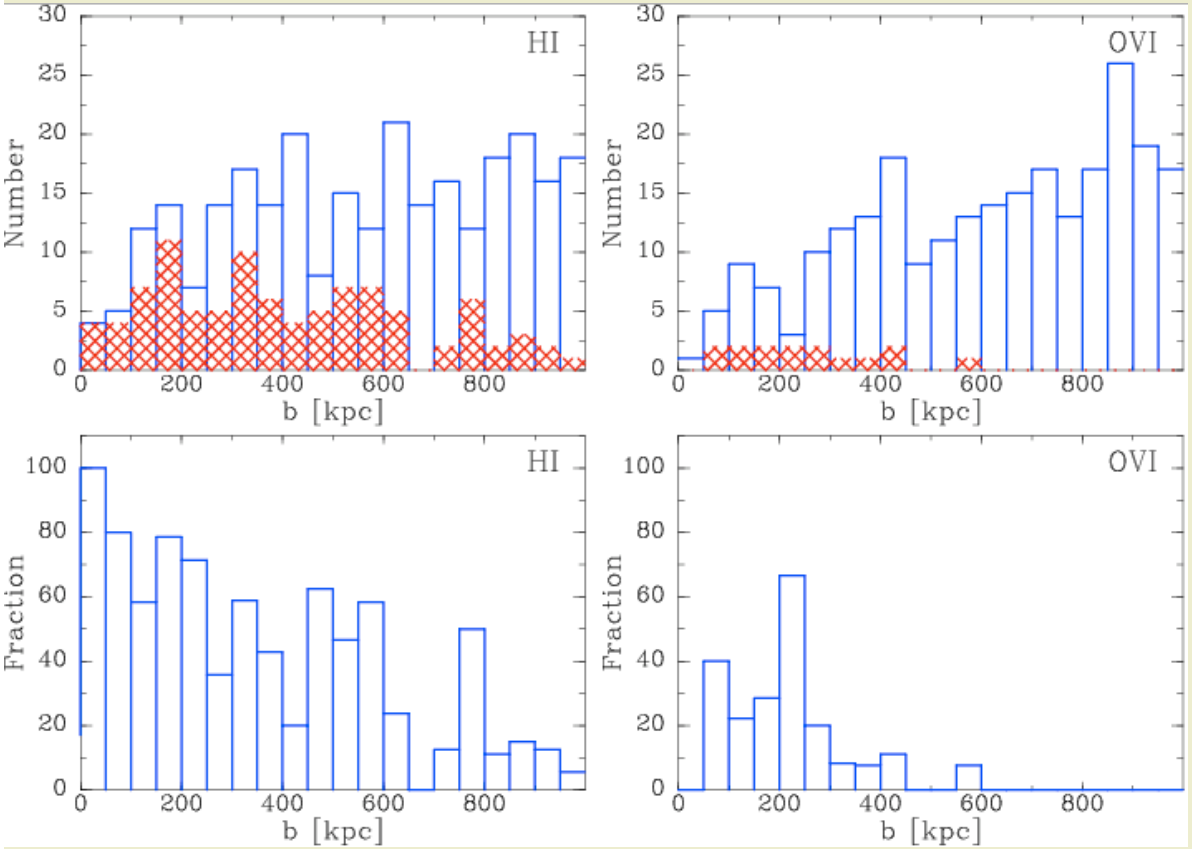
EXTRAGALACTIC OVI/HI SURVEY

- 73 AGN with v>7000 kms^{-1}
- Find galaxies with v<5000 kms^{-1} and b<1 Mpc
- Look for absorption at v~v(gal)



AGN	ESO185-IG13	PG1259+593	Ton S180	Mrk876
Galaxy	IC4889	UGC8146	NGC247	NGC6140
Imp.Par.	b=62 kpc	b=80 kpc	b=125 kpc	b=206 kpc

EXTRAGALACTIC OVI/HI SURVEY



b(kpc)

Top: number of sightlines/detections
Bottom: fraction of detections

OVI

b(kpc)	#det	#los	
560-1000	0	147	0%
300-560	5	68	7%
100-300	7	30	23%
<100	3	6	50%

HI

b(kpc)	#det	#los	
>1000	28		
560-1000	25	144	17%
300-560	35	79	44%
100-300	27	52	60%
<100	6	7	86%

EXTRAGALACTIC OVI/HI SURVEY

$N(H;OVI) = N(O\ VI) / f / A_O / Z$

$N(O\ VI) \sim 10^{13.2} - 10^{13.9}\ cm^{-2}$

f = fraction of O in OVI < 20%

A = oxygen abundance = $10^{-3.34}$

Z = metallicity, assume ~0.1 solar

$N(H;OVI) > 10^{18.2} - 10^{18.9}$ in interface containing OVI

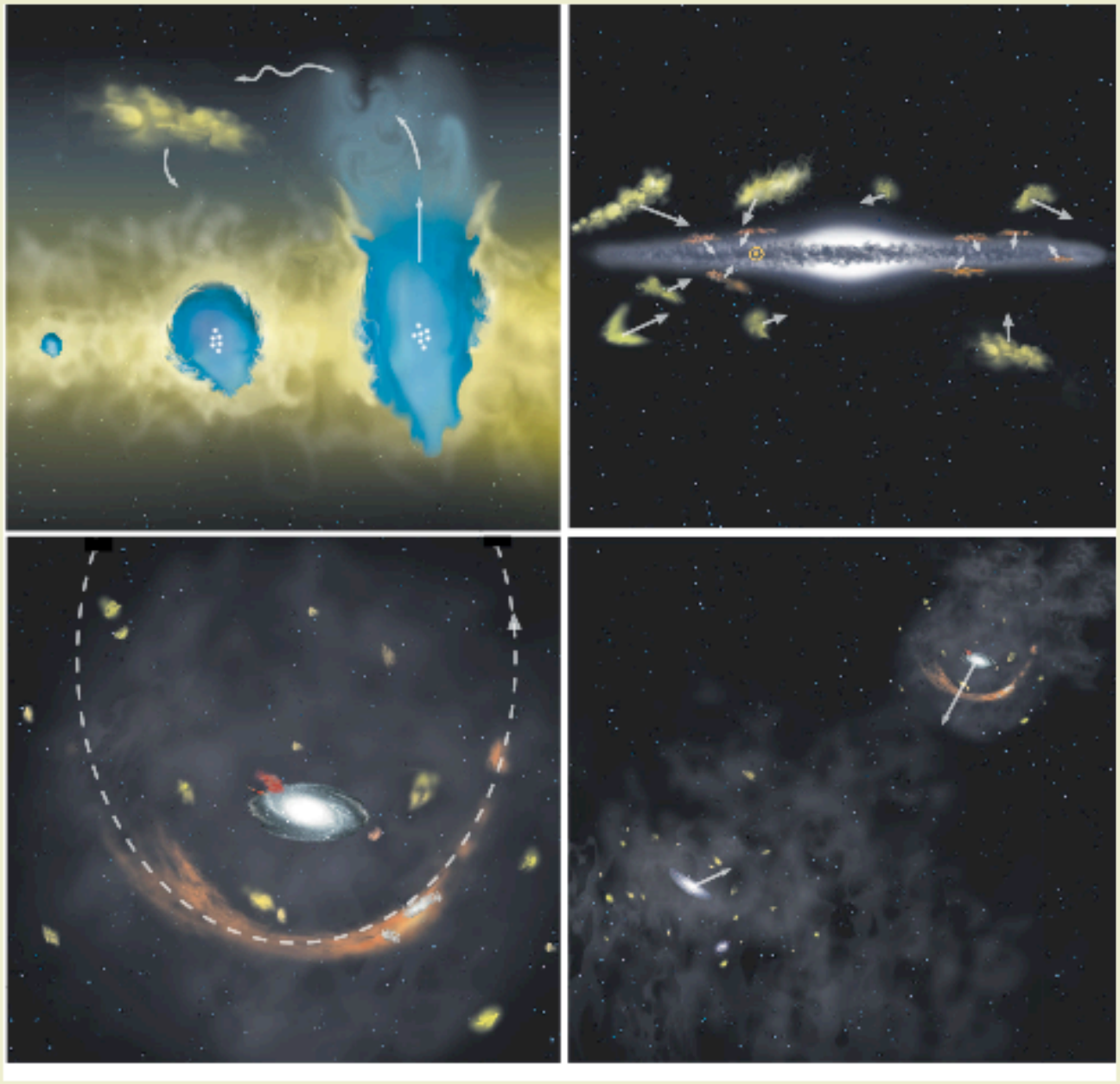
$M(H;OVI) = \Sigma\ A(R)\ N(H;OVI)\ c(OVI)$

A(R) = Area of 50 kpc ring

c(OVI) = detection fraction in ring

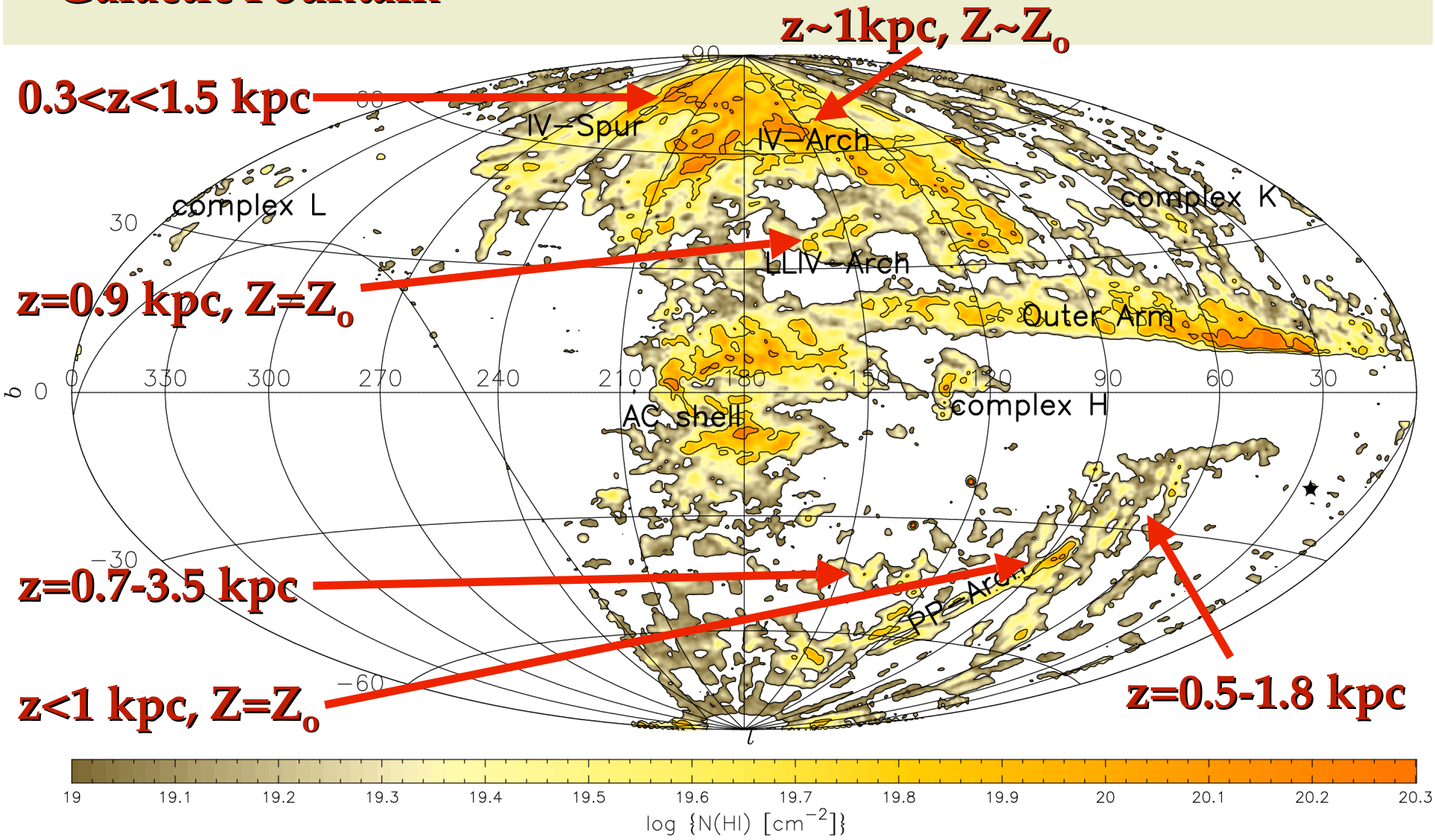
$M(H;OVI) \sim 10^{9.6}\ M_o$ of halo gas currently in interfaces

SUMMARY

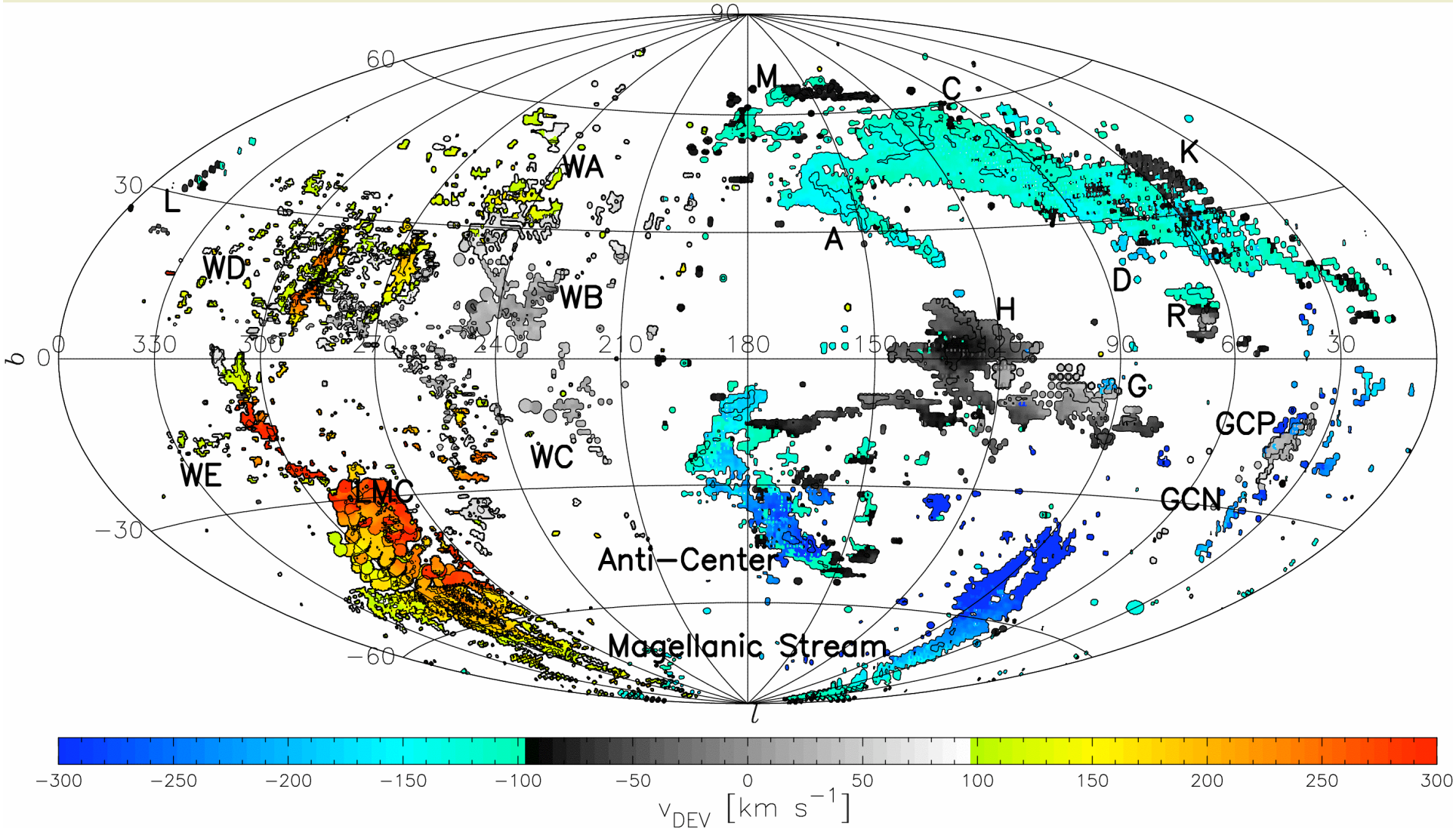


INTERMEDIATE-VELOCITY CLOUDS

About 1 kpc above Galactic plane, solar metallicity => Galactic Fountain

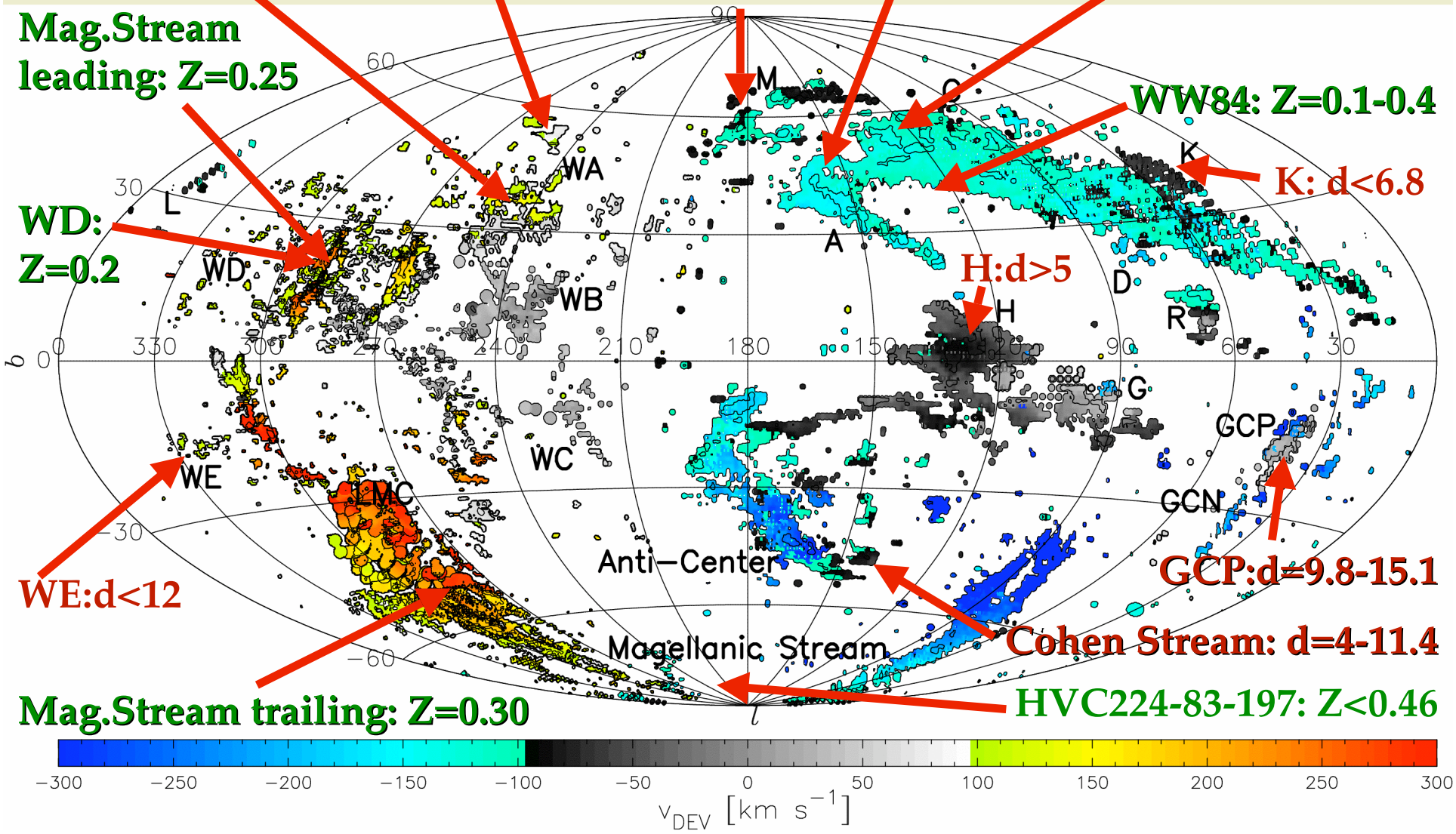


HI HIGH-VELOCITY CLOUDS



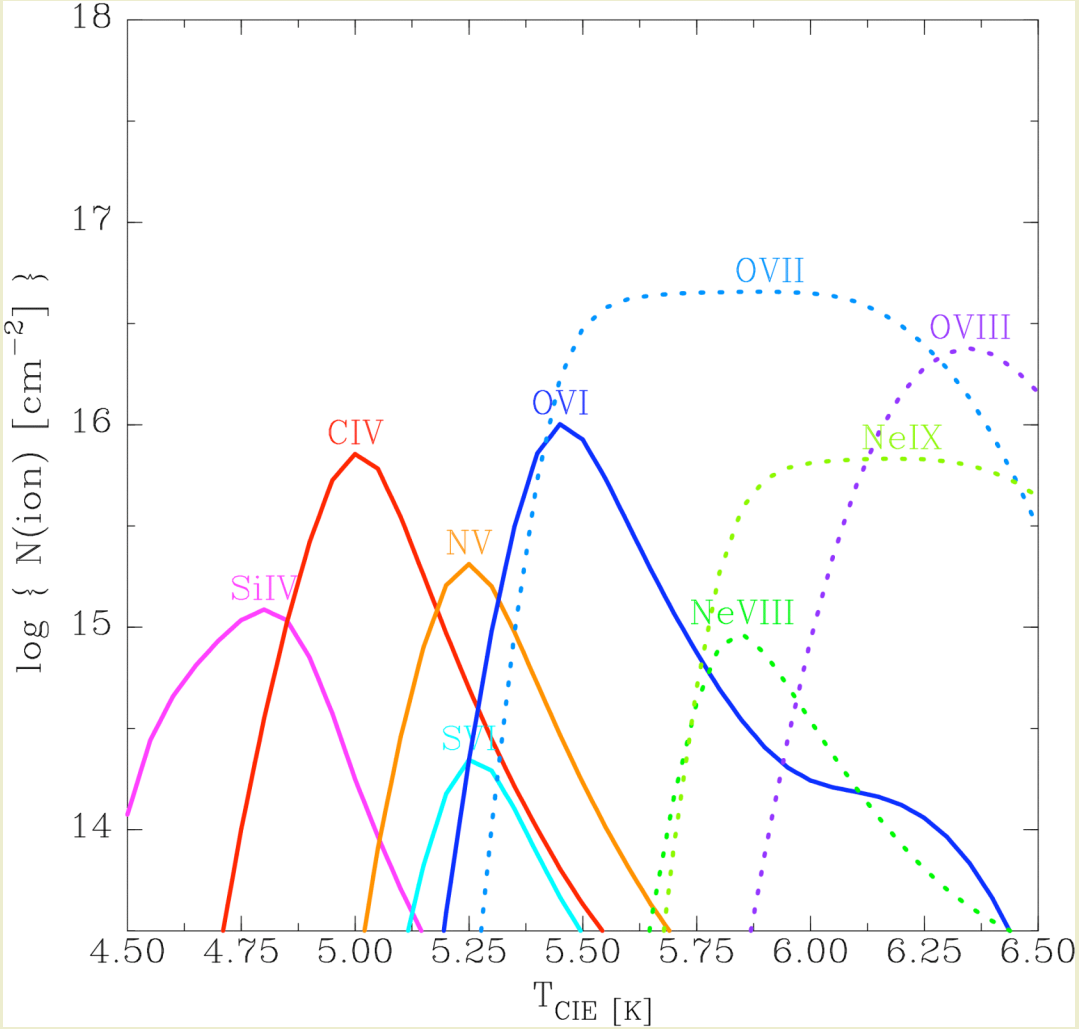
HI HIGH-VELOCITY CLOUDS

Metallicity (Z) measured



HIGH IONIZATION ISM/IGM SPECIES

N(ion) in CIE at N(H) = 10 ^{20} cm^{-2}



(Sutherland & Dopita 1991)

HST
C IV, N V, Si IV

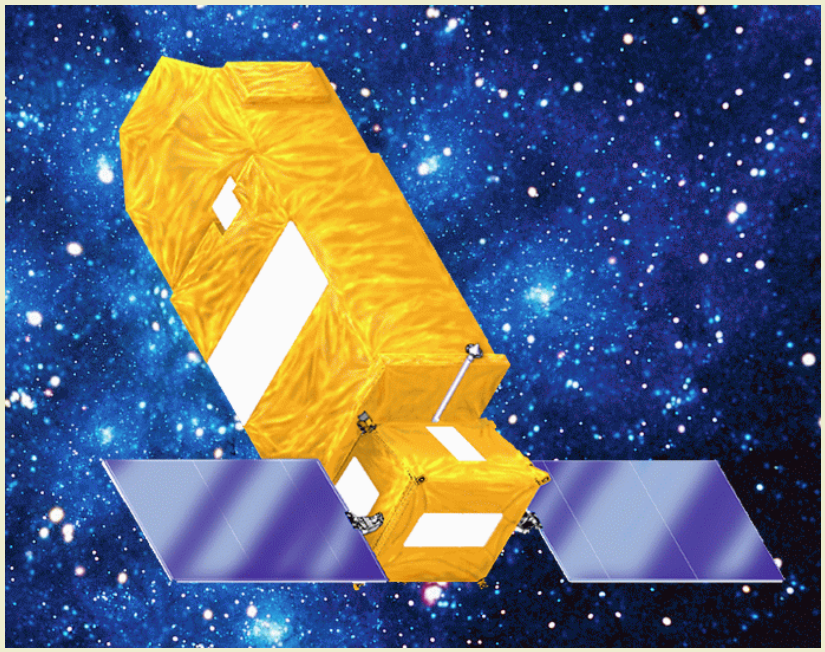
FUSE
O VI, S VI, (Ne VIII)

- **XMM/Chandra**
  O VII, O VIII, Ne IX

O VI is always <20% of total O

λ 1031.926, 1037.617 A

FUSE: THE SATELLITE

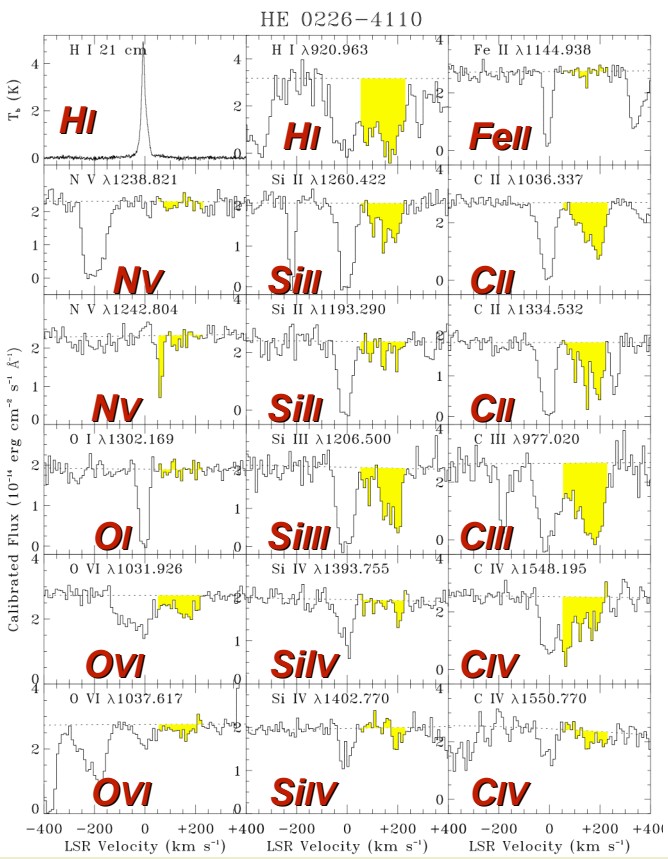


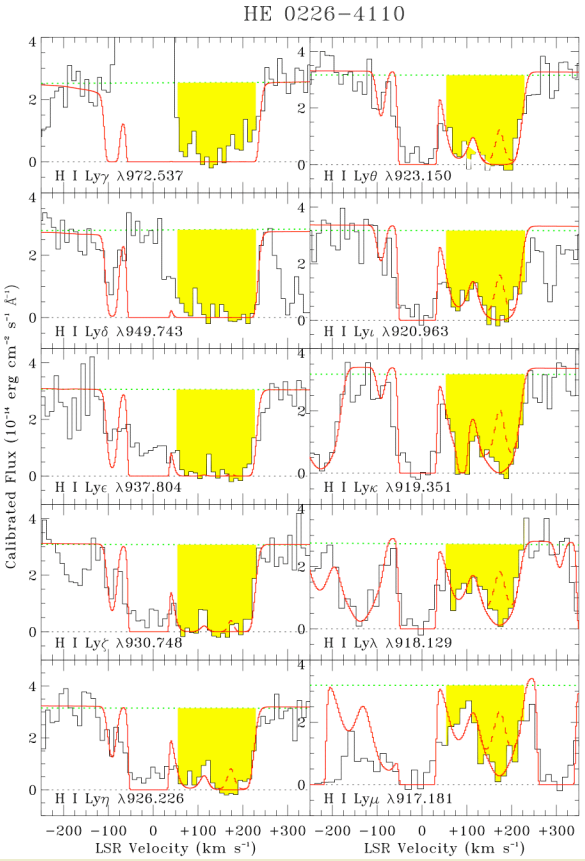
Launch: June 1999

Spectra from 912 to 1180 A
White dwarfs, CVs, OB stars, AGN

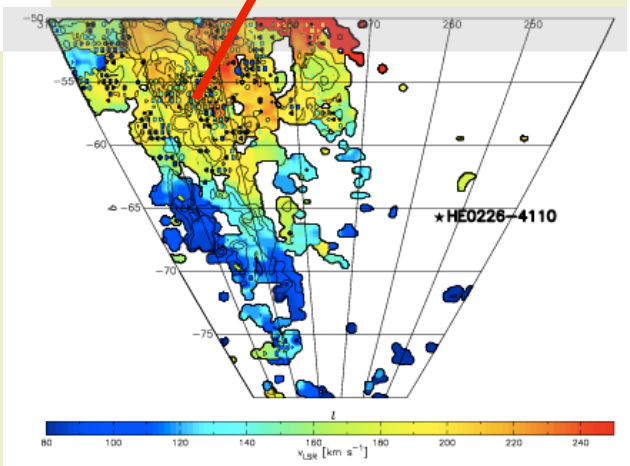
Lines of
Deuterium (DI)
Cold gas (H_2)
Cool gas (HI, CII, NI, OI, FI, SiII, PII, ArI, FeII)
Excited states (CII*)
Warm gas (CIII, NII, FeIII)
Hot gas (OVI, PIII, PV, SVI)

HIGH-VELOCITY OVI: ANALYSIS





Magellanic Stream

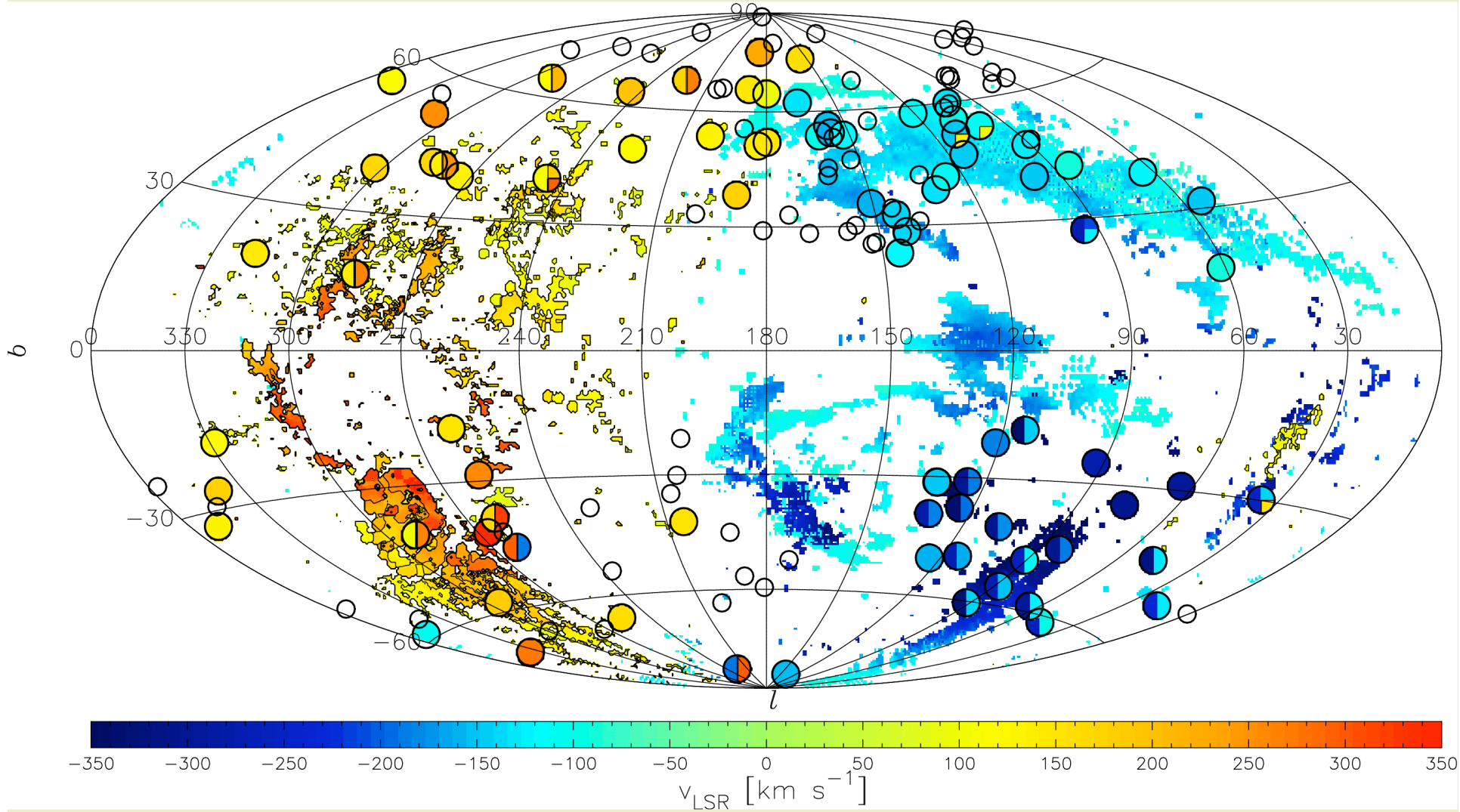


HE0226-4110, PG0953+414

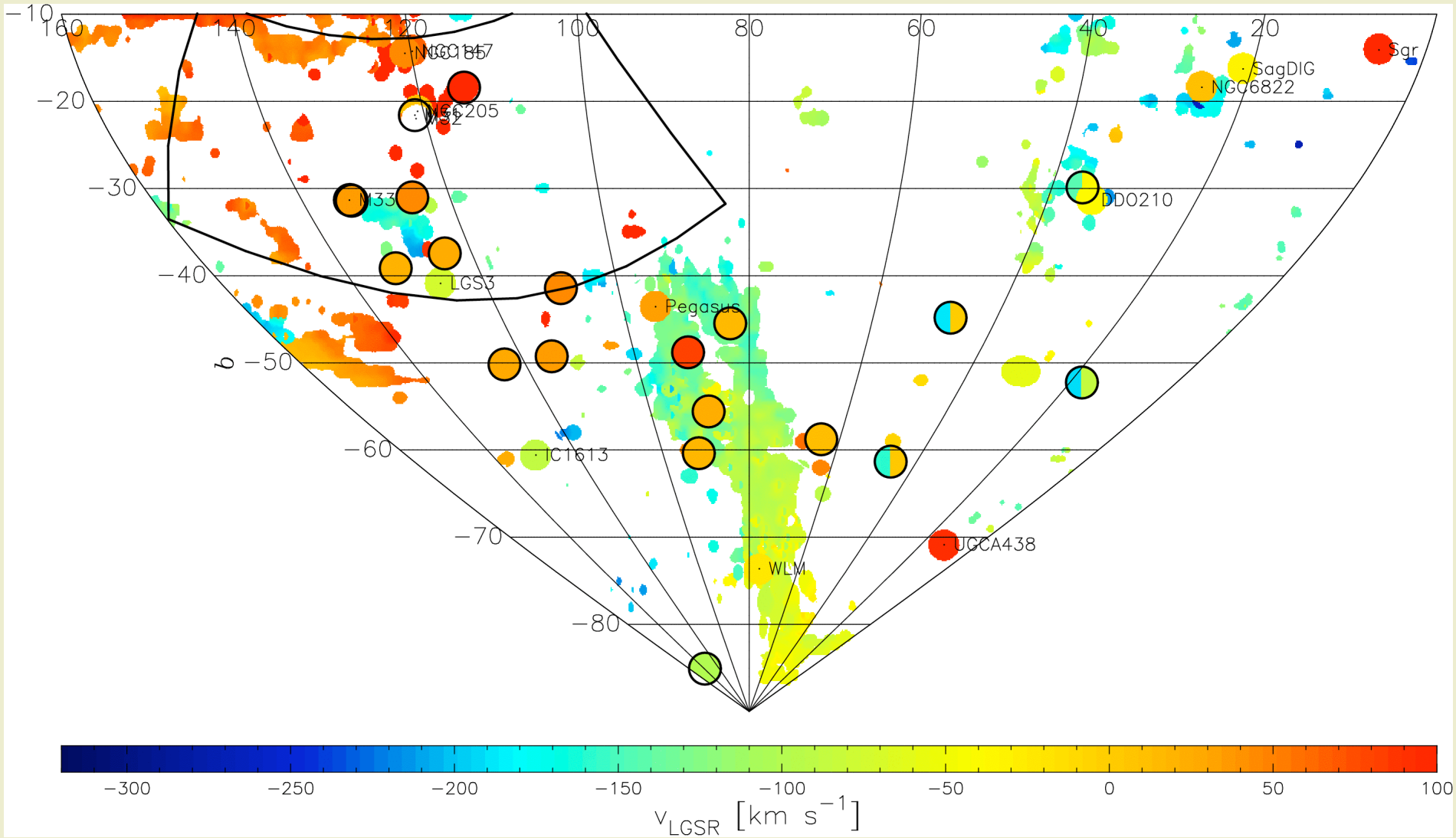
Measure: H I, O VI, N V, C II, C III, C IV, Si II, Si III, Si IV

(Fox et al. 2006, ApJ, 630, 332)

THE HIGH-VELOCITY SKY IN H I & O VI



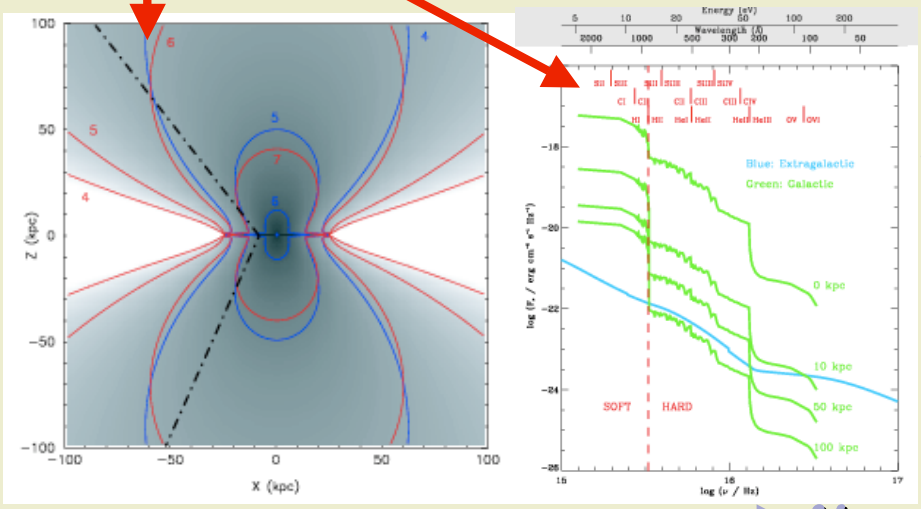
O VI vs H I (Local Group gas?)



OVI HIGH-VELOCITY CLOUDS

MW+EGB ionizing radiation
spatial + spectral distribution

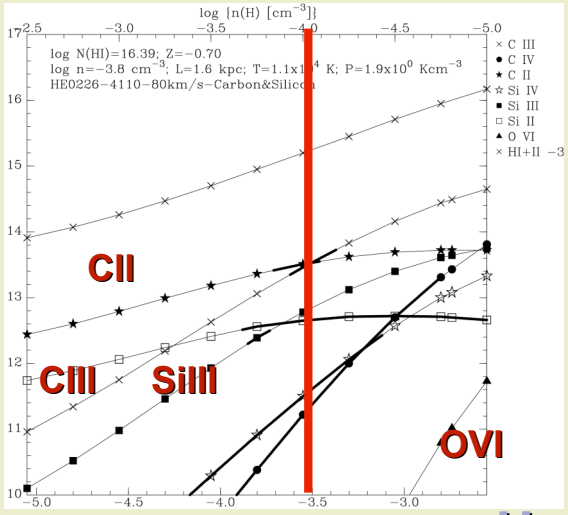
Modeling of conductive interfaces, turbulent mixing, shock ionization, adiative cooling, CIE



F_ν

ν

N



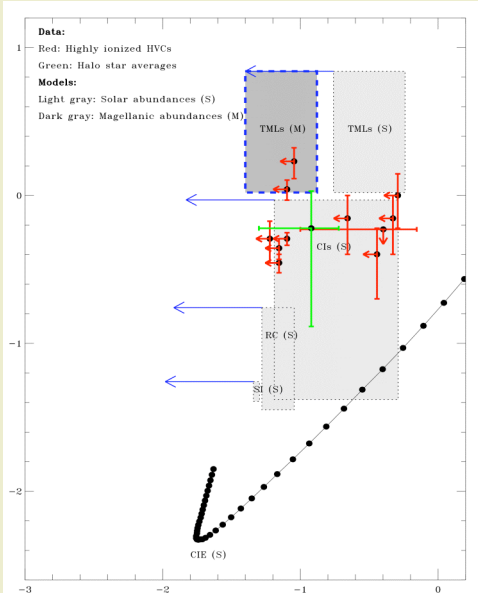
n ⟵ ⟶ U

=>
Photoionized gas at T~10^4 K explains H I, C II, CIII, Si II, Si III, Si IV

=>
Conductive interfaces at T = 10^5 K explains O VI, C IV

NV/OVI

CIV/OVI

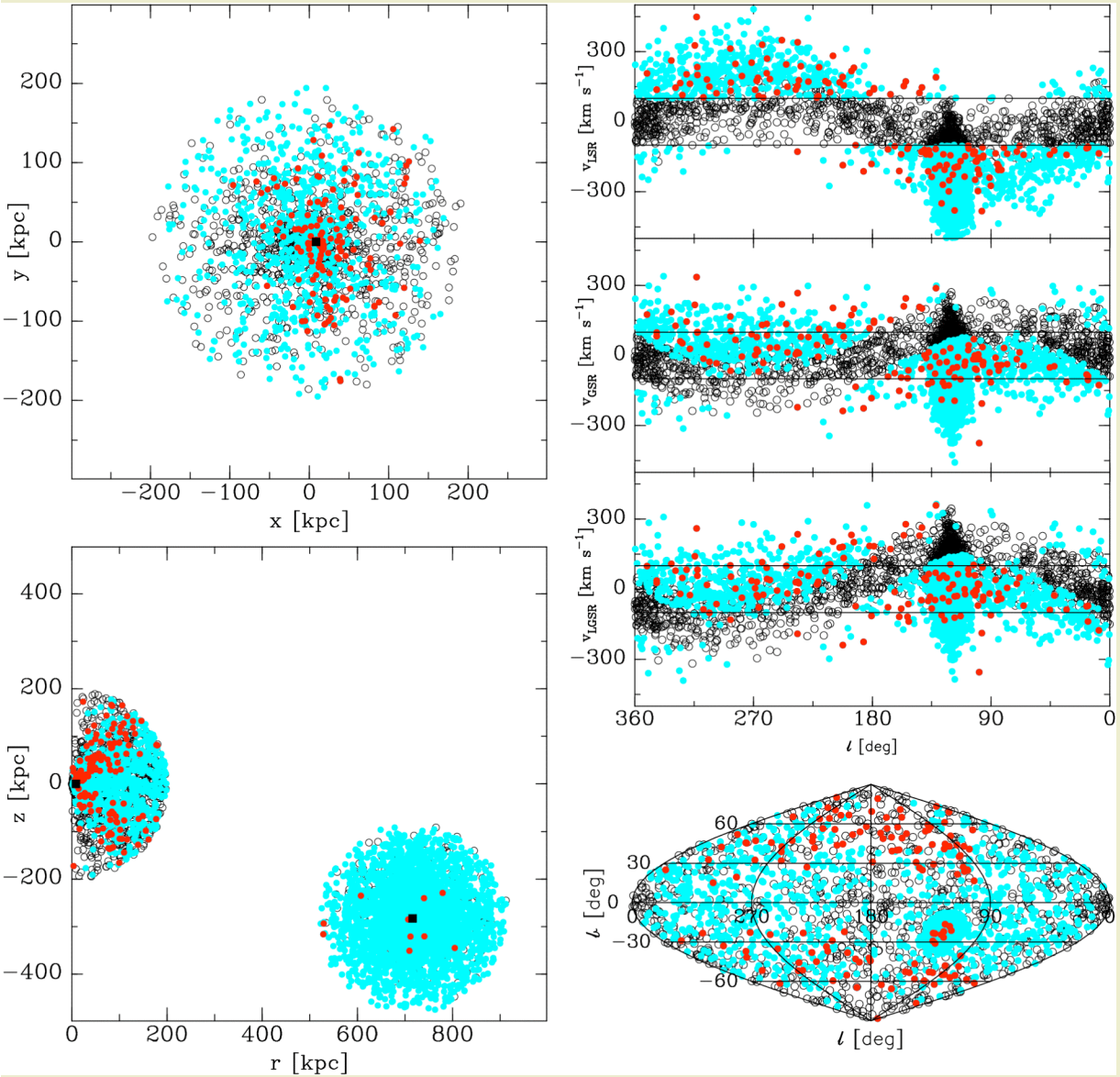


HVC KINEMATICS

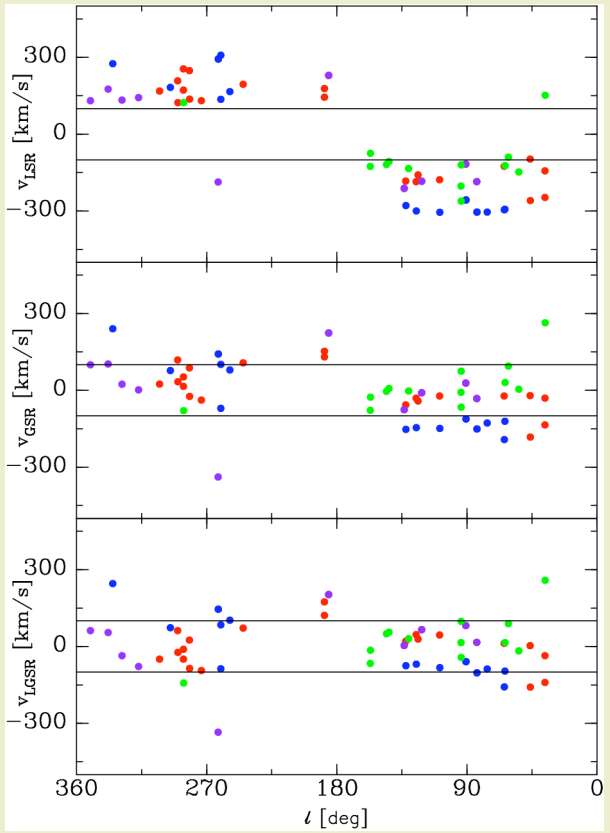
Parametrize locations	**Number density = radial power law**
	around MW, MW+M31, MW+M31+LG
Parametrize velocity field	**Bulge+Disk+Halo potential => v(rot)**
	Radial infall; Add dispersions
Simulate observations	**Power-law mass distribution**
	Fix density (0.005 cm^{-3}) => radius, area, flux, T_B(HI)
	OR
	145 sightlines distributed like OVI sample
=> Predictions	**Longitude, latitude, LSR/GSR/LGSR velocities**
Compare to actual data	**Globular Clusters**
	Local Group samples
	H I HVC samples
	O VI HVC samples

HIGH-VELOCITY OVI: PREDICTION

Modeled



Observed

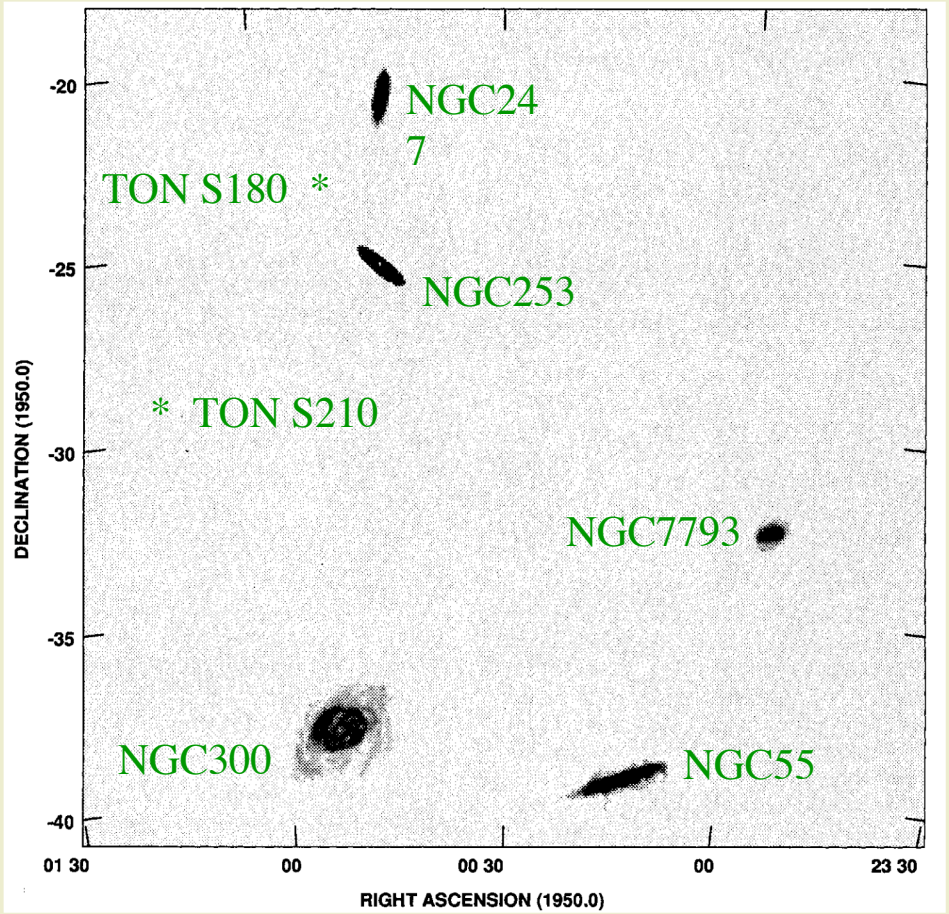


v

l

⇒OVI originates in corona with R~200 kpc

EXTRAGALACTIC OVI: TON S180



OVI absorpion toward Ton S180 at v=+250 km s-1

V(HI rotation curve NGC247) at Ton S180 = +250 km s^{-1}

V(HI rotation curve NGC253) at Ton S180 = +60 km s^{-1}

HI map: Puche & Carignan (1991, ApJ 378, 487)

(GALAXIES ENLARGED 4 TIMES)

SUMMARY

- HVC metallicities vary: 0.1 to 1 solar
- Distances of large clouds are ~ 10 kpc
  (Complex A/C: distance~10 kpc; metallicity ~0.15 solar)
- Smaller clouds: population with D_{max}~200 kpc
- OVI HVCs present in ~60% of the sky
- HVCs are embedded in hotter gas
- OVI is seen around nearby galaxies out to few 100 kpc
- HI (Lyα) around nearby galaxies out to 1 Mpc

High-velocity clouds suggest the presence of a reservoir of hot gas with radius ~200 kpc out of which cool clouds condense and accrete

EXTRAGALACTIC OVI/HI SURVEY

$N(H;OVI) = N(O\ VI) / f / A_O / Z$

$N(O\ VI) \sim 10^{13.2} - 10^{13.9}\ cm^{-2}$

f = fraction of O in OVI < 20%

A = oxygen abundance = $10^{-3.34}$

Z = metallicity, assume ~0.1 solar

$N(H;OVI) > 10^{18.2} - 10^{18.9}$ in interface containing OVI

$M(H;OVI) = \Sigma\ A(R)\ N(H;OVI)\ c(OVI)$

A(R) = Area of 50 kpc ring

c(OVI) = detection fraction in ring

$M(H;OVI) \sim 10^{9.6}\ M_o$ of halo gas currently in interfaces

$\dot{M}(H;OVI) = M / t = M\ D / v$

D = typical distance ~ 200 kpc

v = typical infall velocity ~ 50 km/s

$\dot{M}(H;OVI) \sim 10^{9.6}\ M_o$ in 2 Gyr or 1 M_o/yr of gas cooling