

GAS AROUND GALAXIES - HVCs and the Ly α FOREST

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Supported by NASA/NSF

Collaborators

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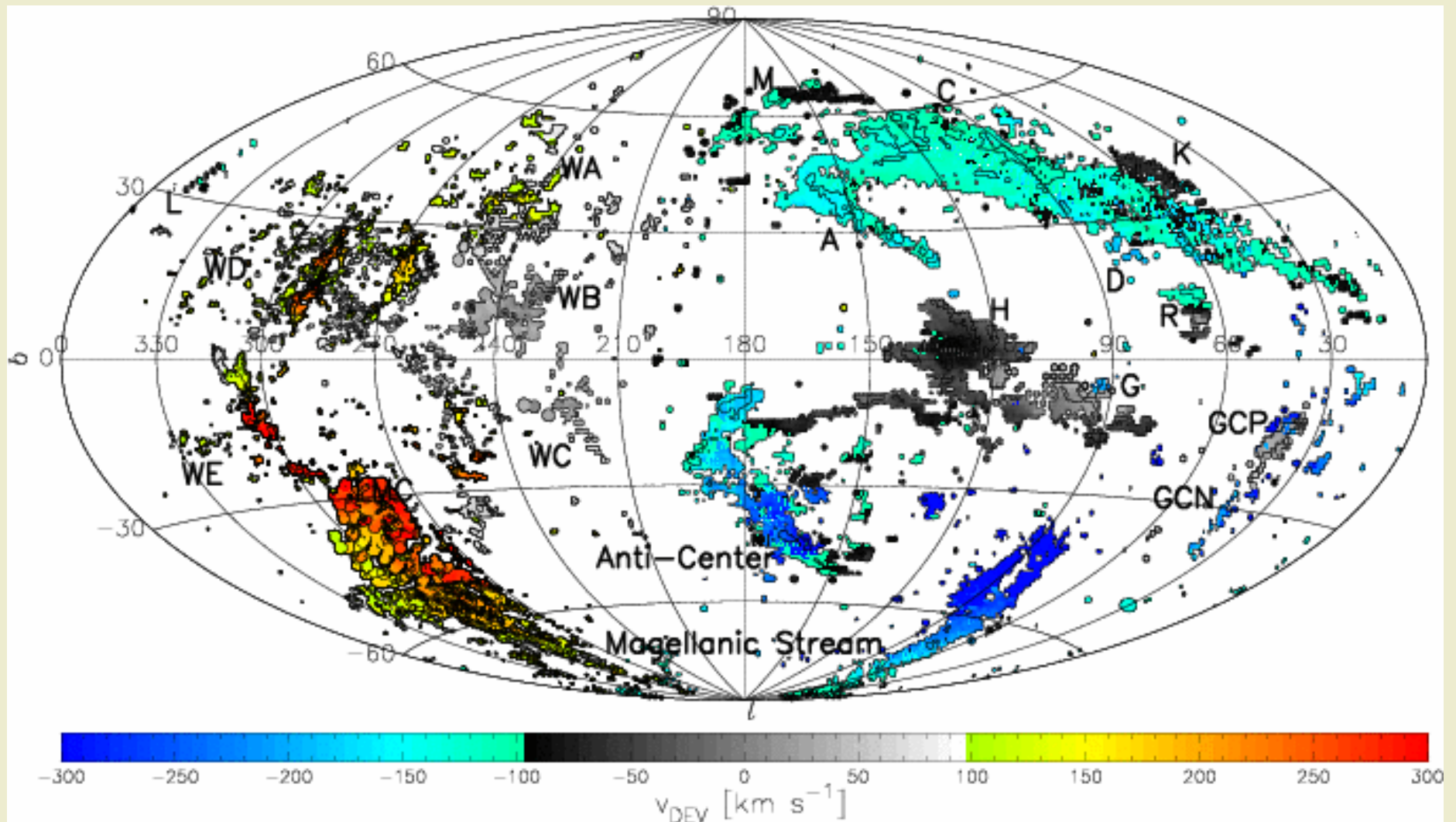
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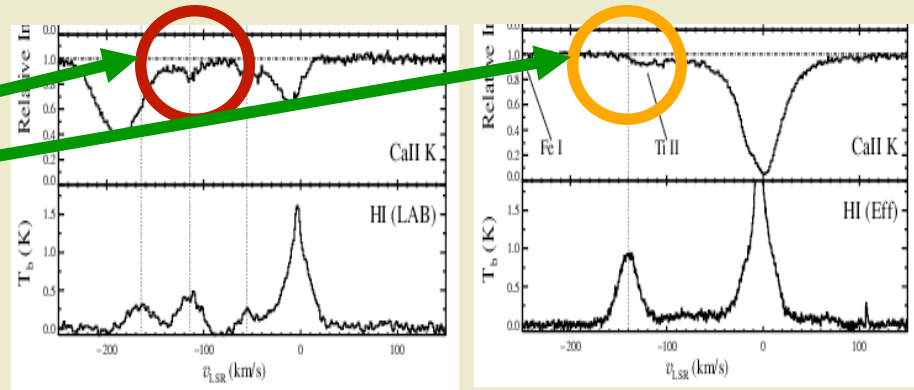
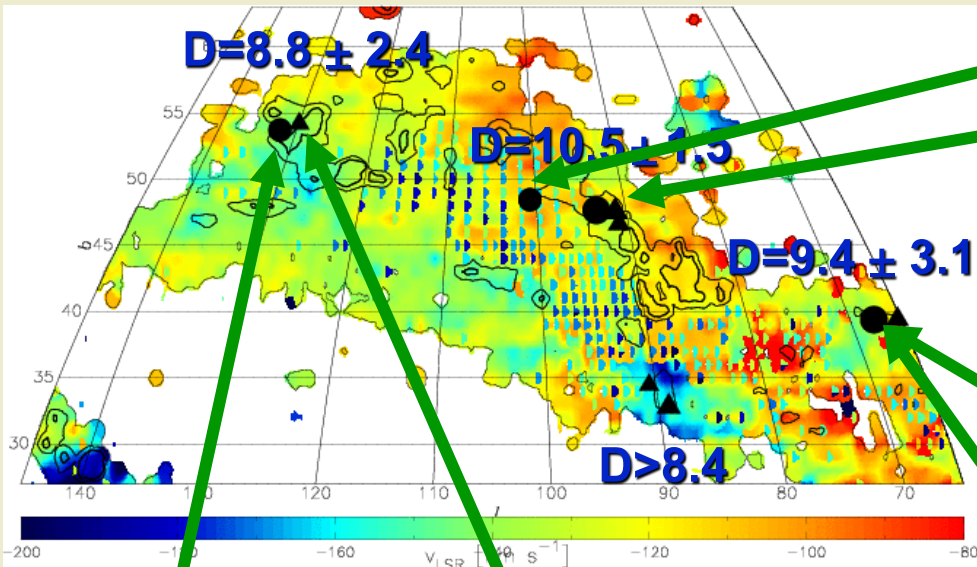
Andrew Fox - ESO, Cambridge

HIGH-VELOCITY CLOUDS

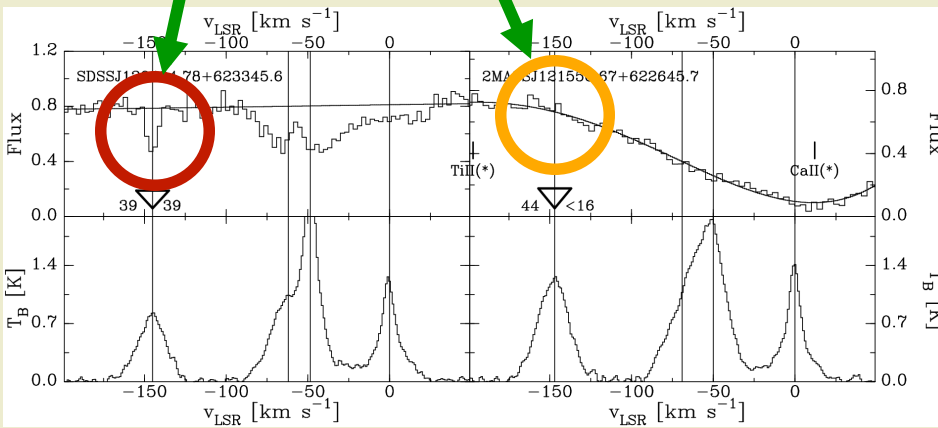


Hulsbosch & Wakker (1988, A&A, 75, 119); Morras et al. 2000, A&AS, 142, 25
Colors: deviation velocity $>100 \text{ km s}^{-1}$; grey: $v_{dev} < 100 \text{ km s}^{-1}$

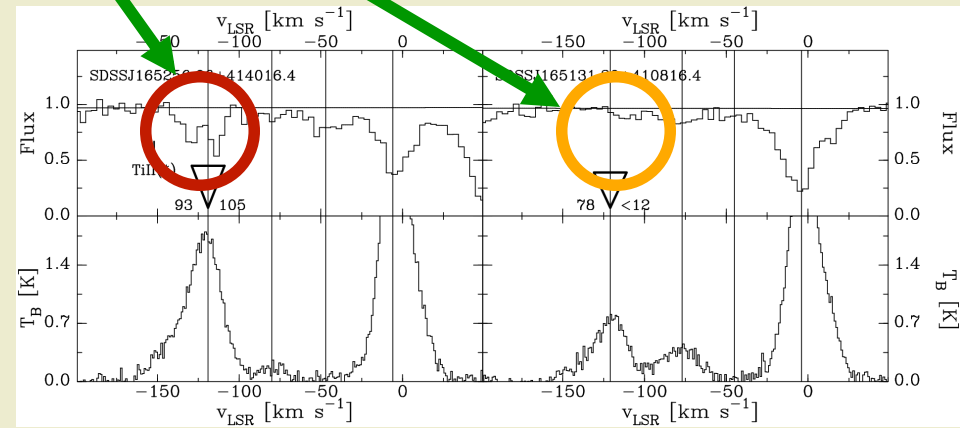
HVC DISTANCES - COMPLEX C



SDSSJ153915.24+575731.8 12 kpc upper limit
 SDSSJ150335.53+623513.6 9.0 kpc lower limit
 Thom et al 2008, astro-ph 0712-0612



SDSSJ120404.+623345.6 11.2 kpc upper limit
 2MASSJ121556.67+622645.7 6.4 kpc lower limit

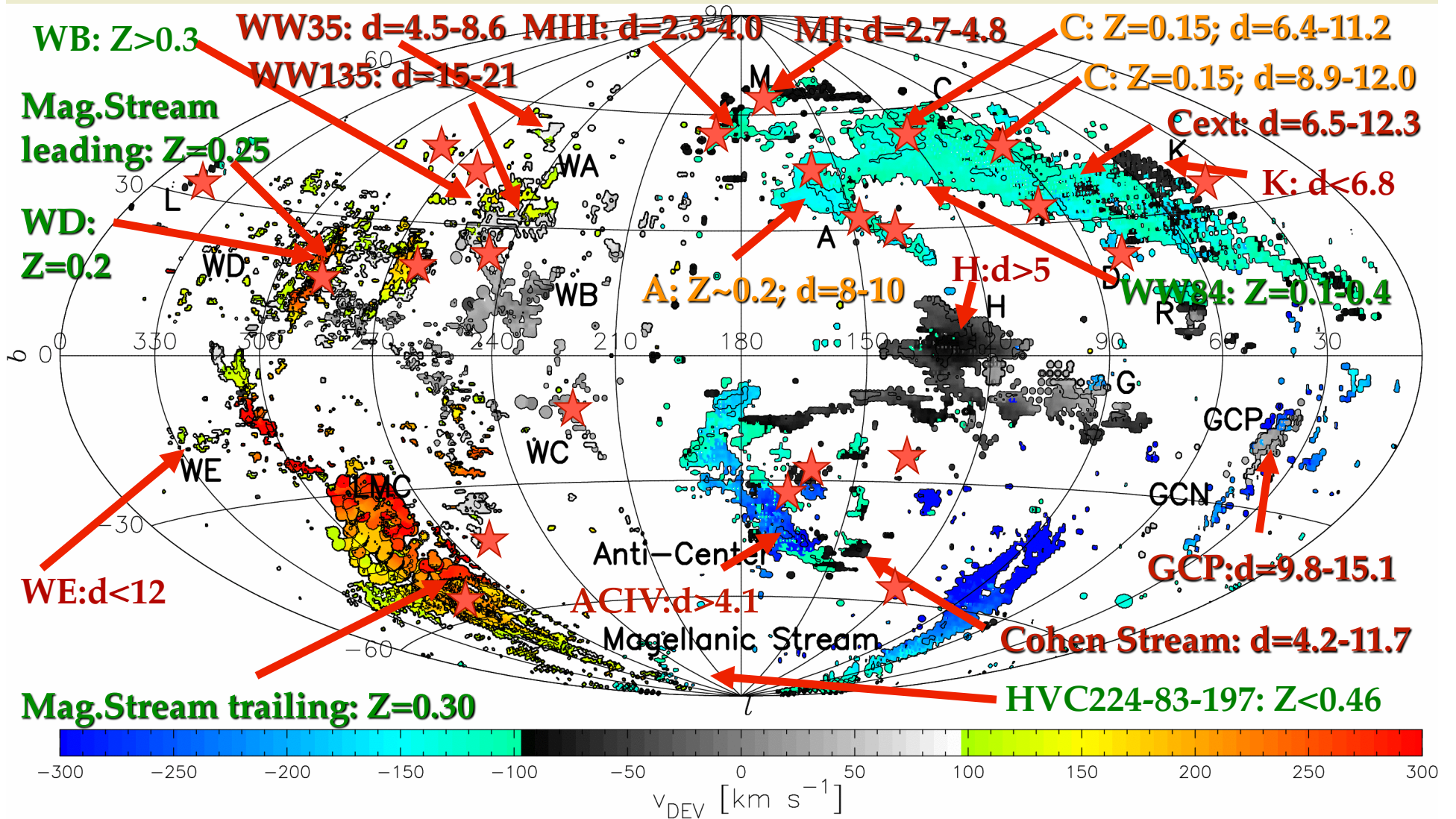


SDSSJ165256.96+415016.4 12.5 kpc upper limit
 SDSSJ165131.30+410816.4 6.3 kpc lower limit

$z=7.2, 7.8, 6.0$ kpc $M=4 \times 10^7 M_{\odot}$ $\dot{M}=0.15-0.25 M_{\odot}/\text{yr}$

HVC DISTANCES/METALLICITIES

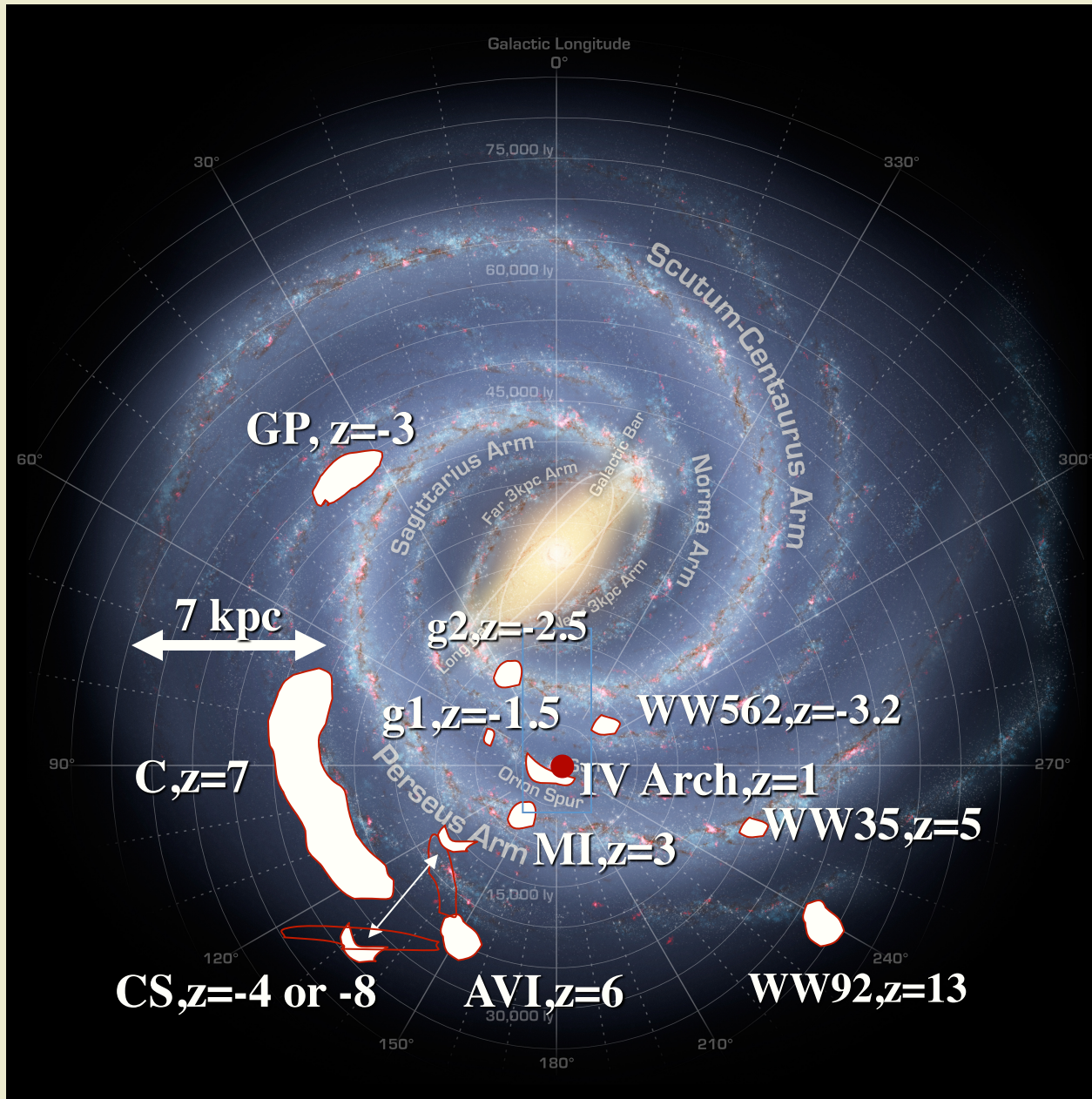
Distances ~ 1 -20 kpc, ~ 1 to 15 kpc above the plane; $Z=0.1, 0.25, 0.7$
 \Rightarrow Accreting material, tidal streams (+Galactic Fountain)



HVC COMPLEX C

- **7 kpc above Galactic plane**
- **Metallicity 0.15 solar: $[O/H]=-0.82$**
- **Underabundant in N: $(N/O)=0.3$ solar)**
- **$D/H=2.2 \times 10^{-5}$ (=cosmological value)**
- **No convincing evidence for dust**
- **Mass $\sim 2 \times 10^7 M_{\odot}$**
- **Size $\sim 10 \times 3$ kpc**
- **Looks tidally stretched**
- **Represents 0.2-0.3 M_{\odot}/yr of infall**

HVC DISTANCES



**Galaxy image from
Bob Benjamin**

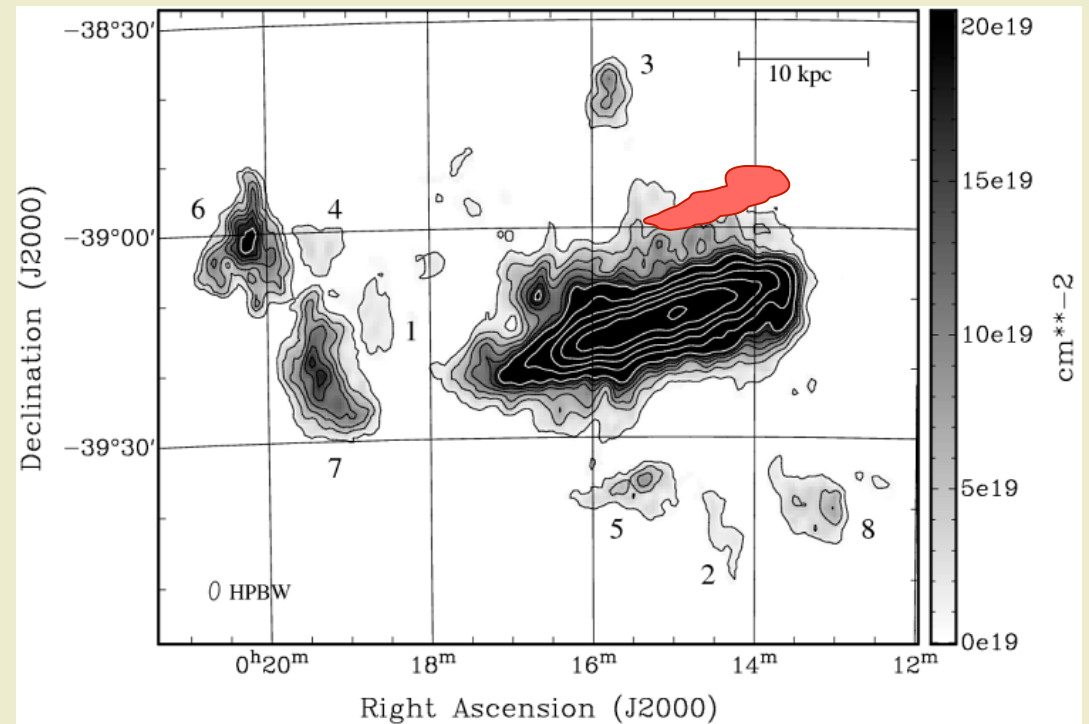
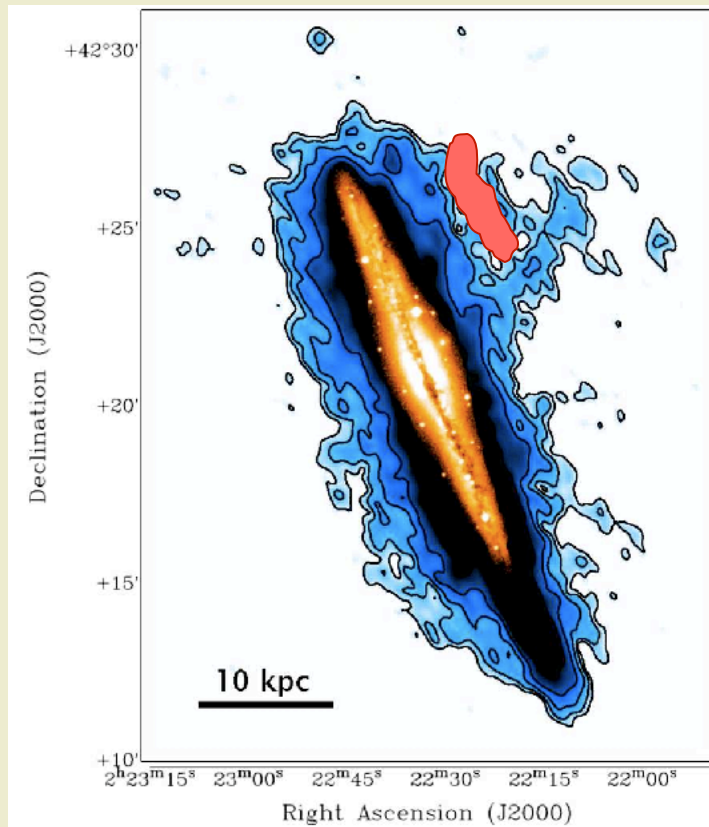
**HVCs with known
distance overlaid**

(van Woerden et al 1999,
Wakker et al 2007, 2008,
2012)

EXTRAGALACTIC HVCs

Mapping HVCs in nearby galaxies

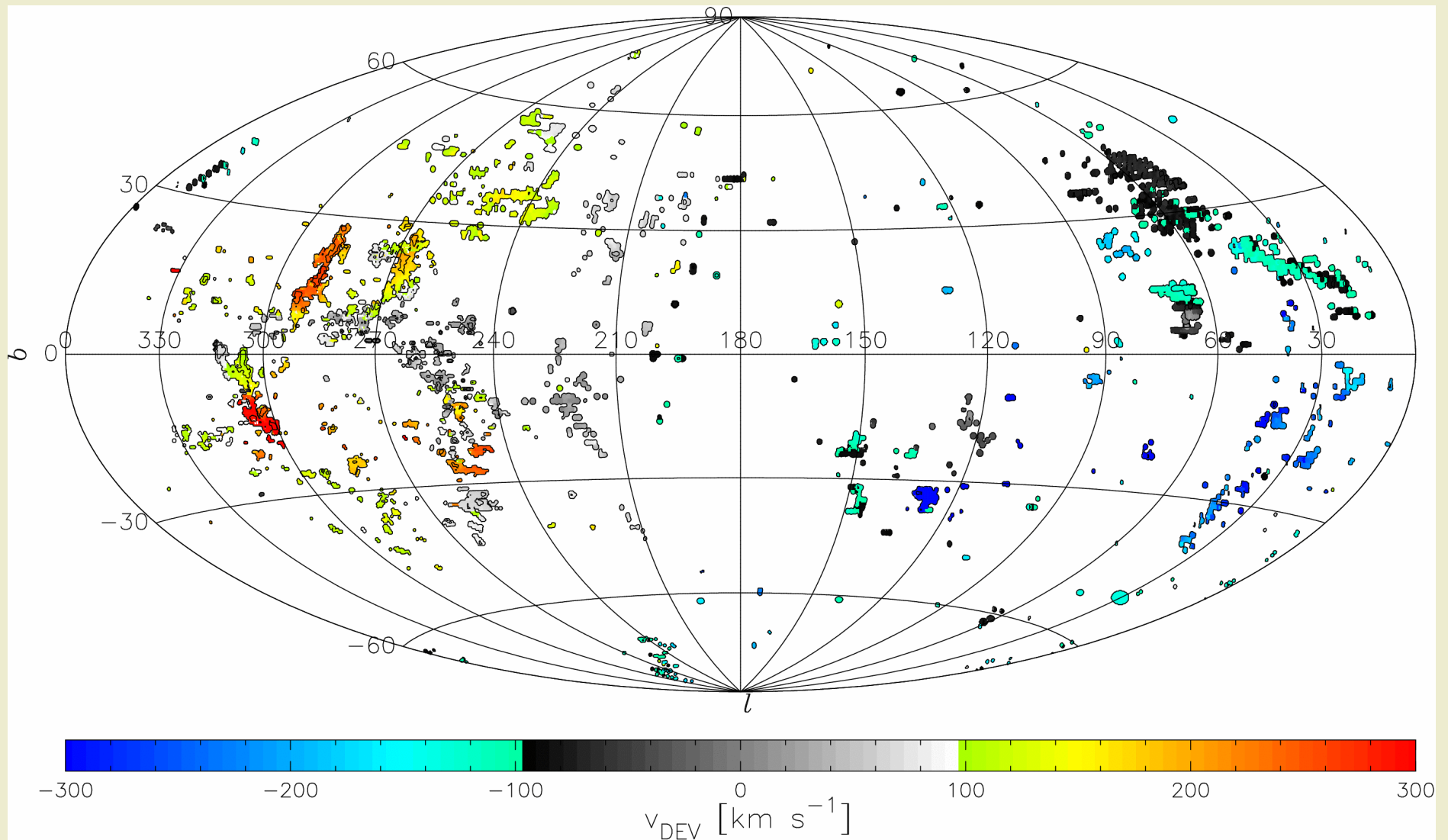
Complex C as it would look on NGC891 and NGC55



Oosterloo et al 2007 AJ 134 1019

Westmeier et al. 2011

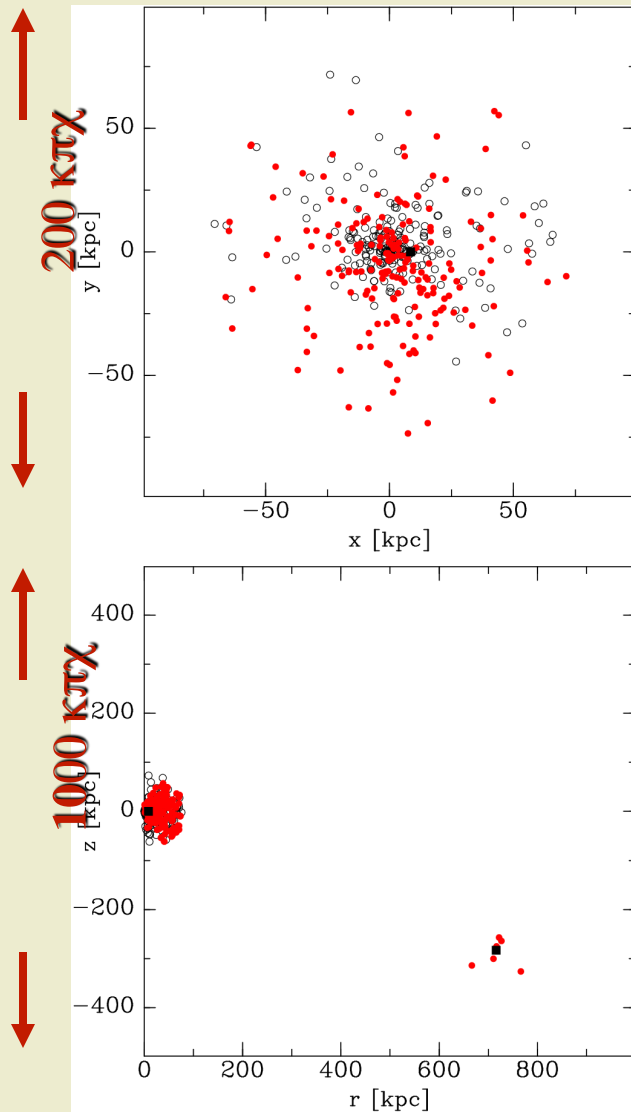
DISTANT HVCs



Hulsbosch & Wakker (1988, A&A, 75, 119); Morras et al. 2000, A&AS, 142, 25
Colors: deviation velocity $>100 \text{ km s}^{-1}$; grey: $v_{\text{dev}} < 100 \text{ km s}^{-1}$

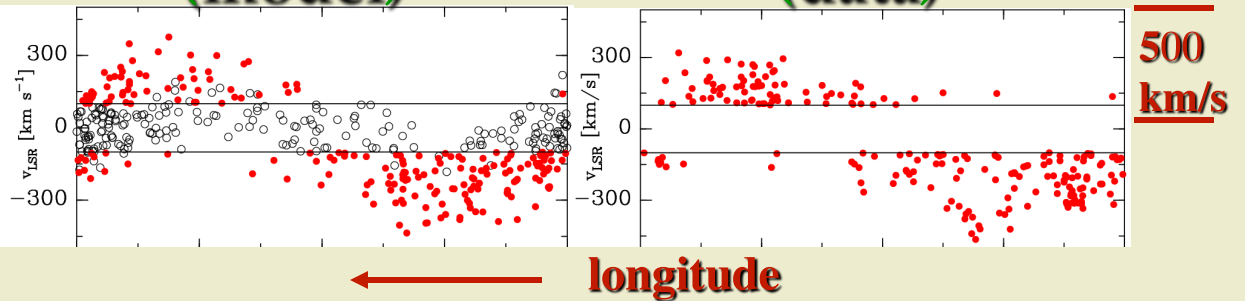
DISTANT HVCs

Model xy/rz view



$v_{\text{LSR}}(l)$
(model)

$v_{\text{LSR}}(l)$
(data)

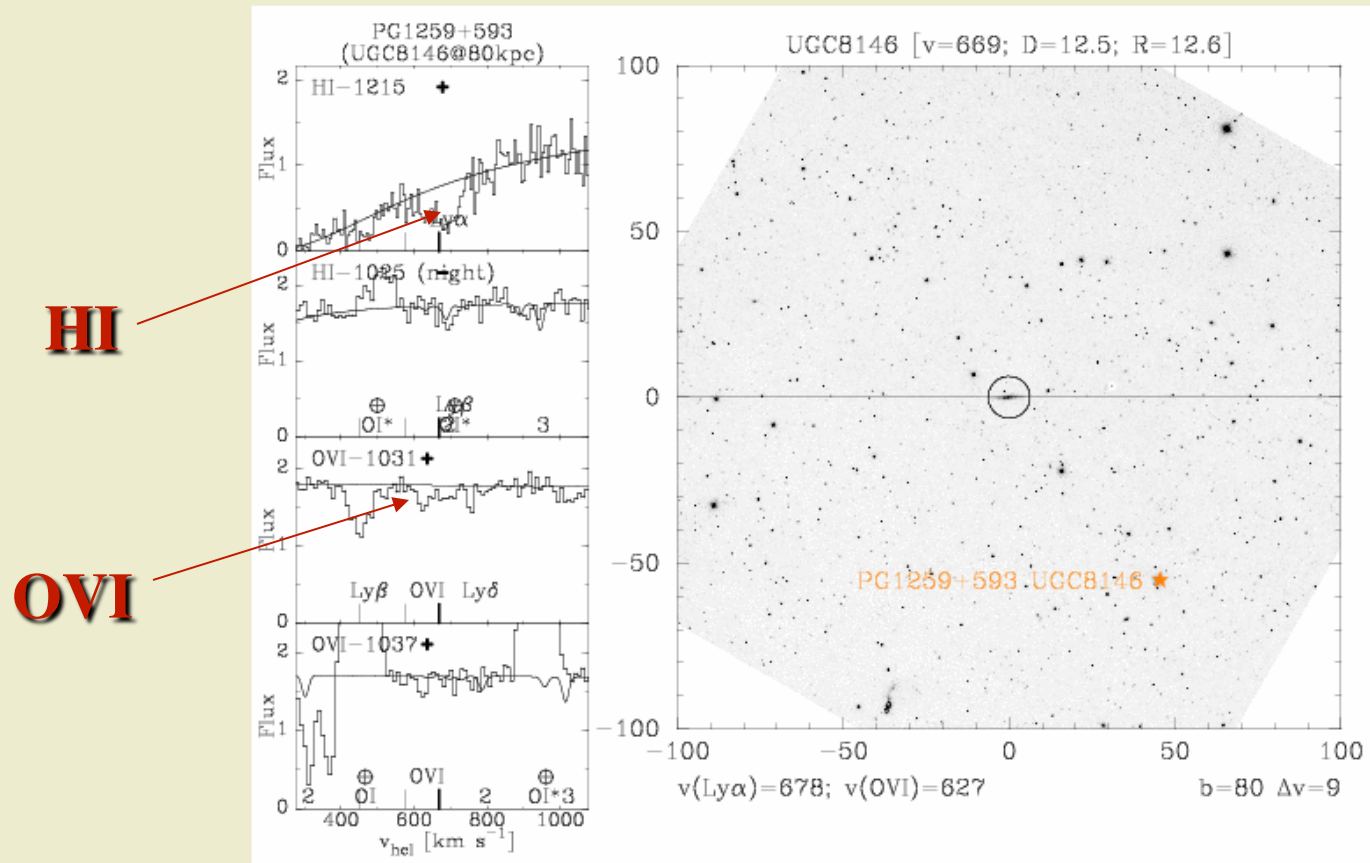


Red dots: clouds observable as HVCs
Black dots: clouds in the population that will be confused with low-velocity gas

Best fit:

- Population of few hundred clouds around MW and M31 with
- $R < 80$ kpc; $\rho(R) \propto R^{-2}$
- $v_{\text{tangential}}$ set by $F_{\text{grav}} = F_{\text{centrif}}$.
- Average infall velocity of 50 km s^{-1}
- $\sigma_{x,y,z} = 50 \text{ km s}^{-1}$

OVI/HI AT $z < 0.02$ vs GALAXIES

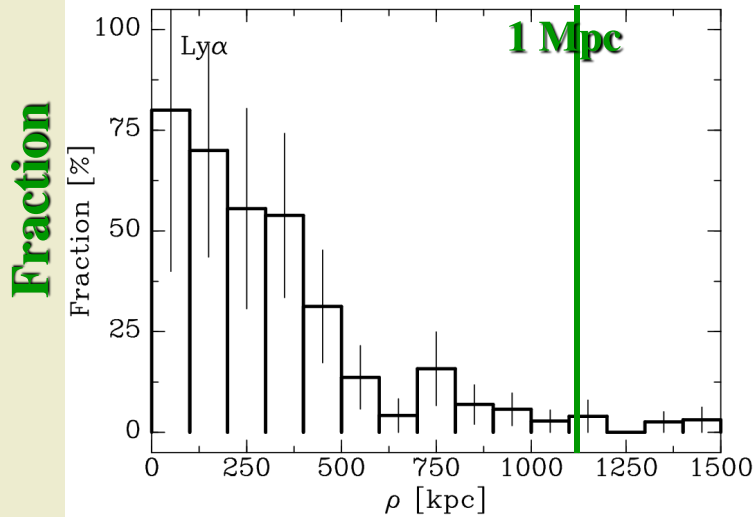
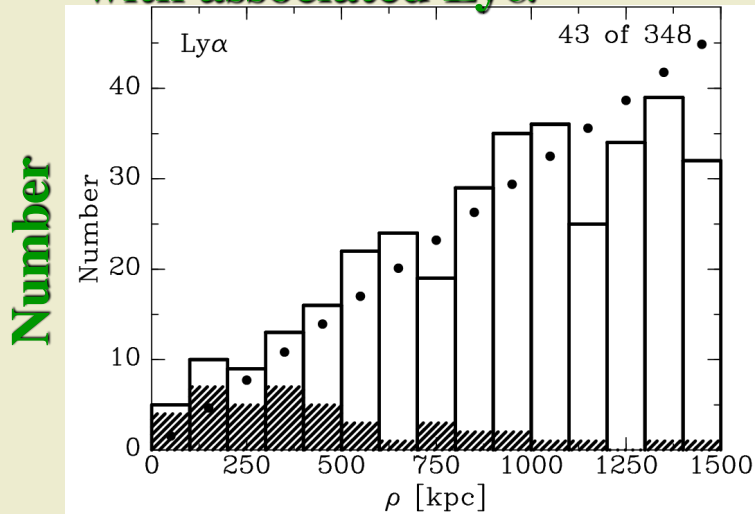


PG1259+593
80 kpc from
UGC8146

- **FUSE+HST archive:**
 - **76 AGNs with $v > 7000$ km s $^{-1}$ and $S/N > 8$**
 - **Find impact parameter to all ~ 6000 galaxies with $v < 5000$ km s $^{-1}$**
 - **115 Ly α , 40 Ly β , 14 OVI absorptions at $v \sim v(\text{gal})$**
- (Wakker & Savage 2009, ApJS, 182, 378)**

OVI/HI AT $z < 0.02$ vs GALAXIES

Number/fraction of galaxies
with associated Ly α



ρ [kpc] \rightarrow

How many galaxies have
associated gas as function of
impact parameter?

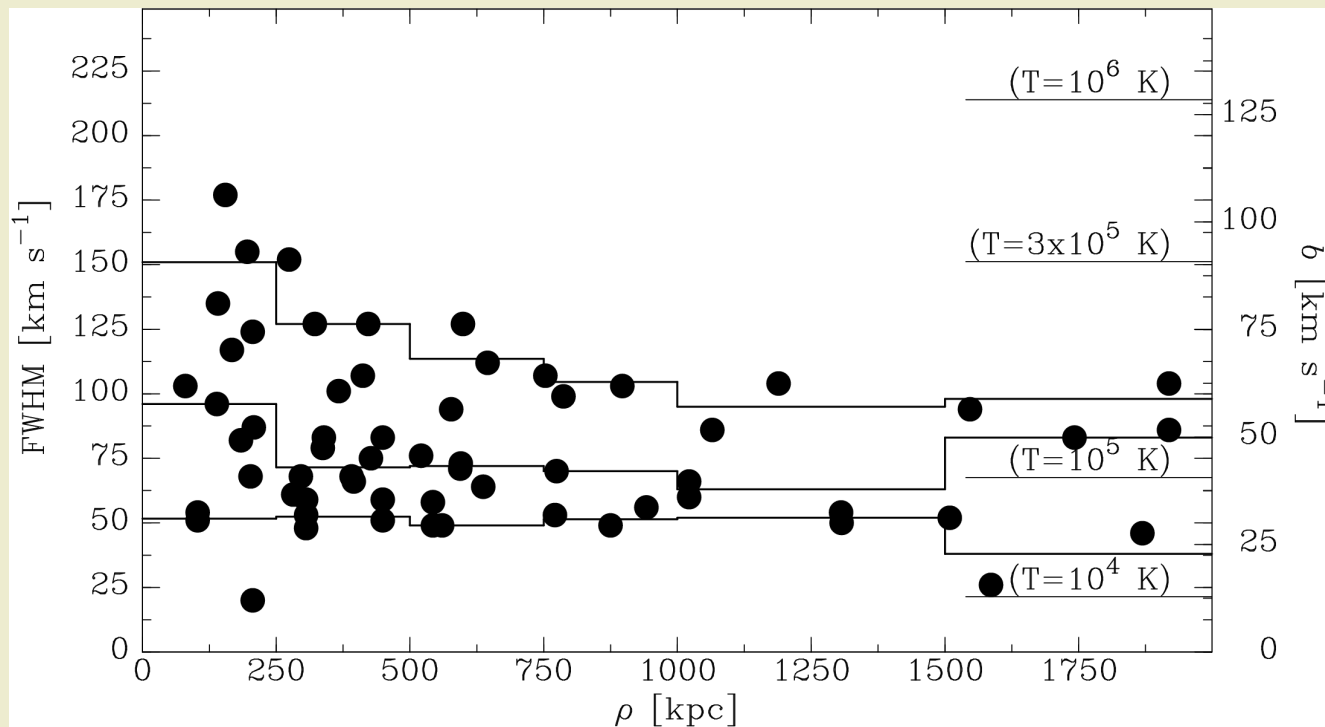
luminous galaxies ($L > 0.1 L_*$),
low impact parameter ($\rho < 350$ kpc),
low velocity difference ($\Delta v < 400$ kms $^{-1}$)

\Rightarrow

Field gals: Ly α : 100%, OVI: 70%
Group gals: Ly α : 65%, OVI: 10%

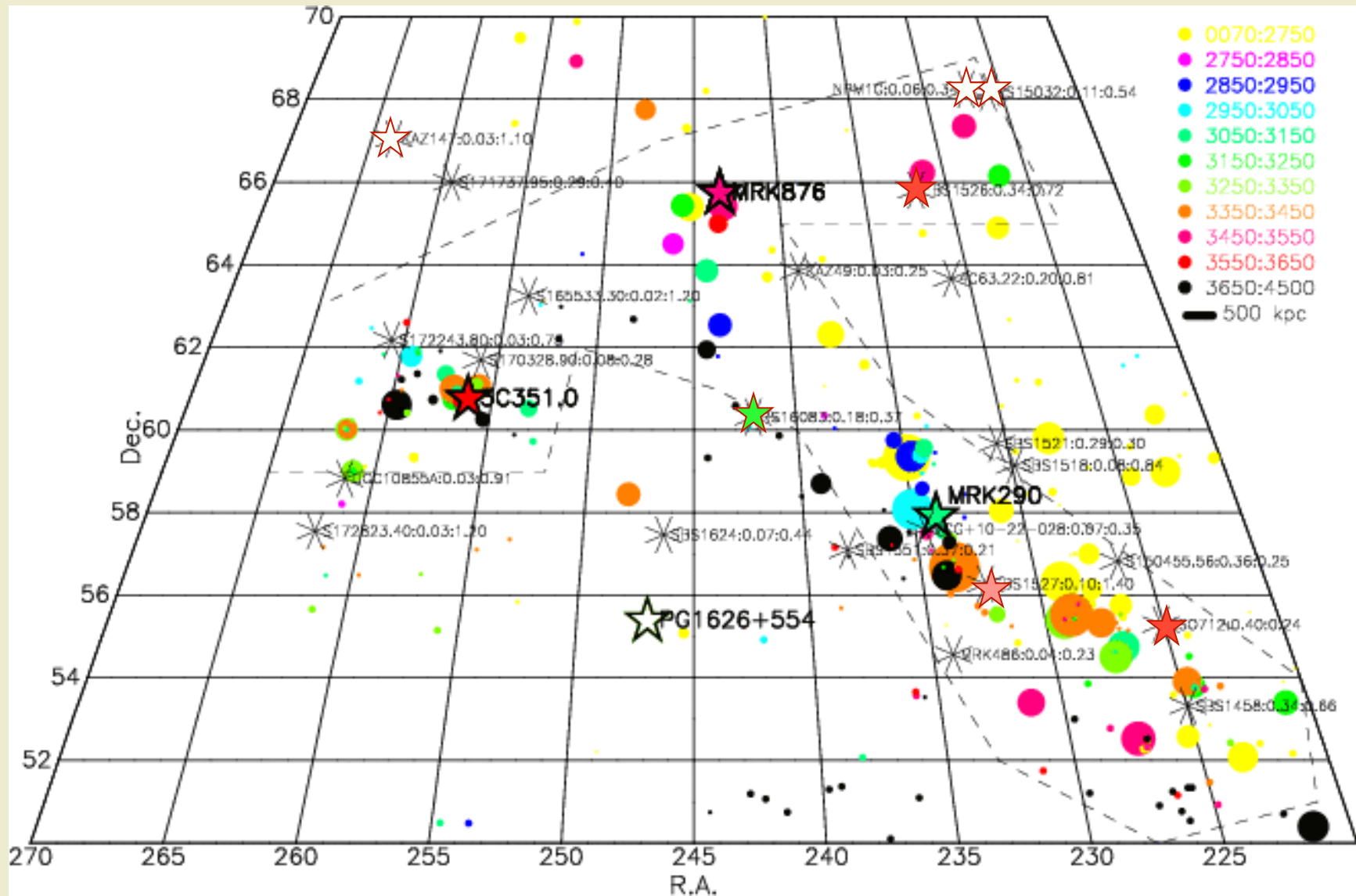
OVI/HI AT $z < 0.02$ vs GALAXIES

FWHM as function of impact parameter



- **Large spread in linewidths at all impact parameters**
- **Widest lines only close to galaxies**

GAS IN A GALAXY FILAMENT



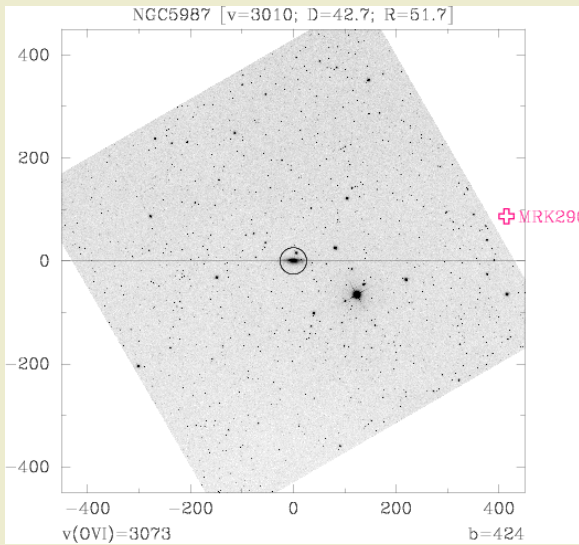
OVI/HI AT $z < 0.02$ vs GALAXIES

- **Ly α around field galaxies brighter than $0.1 L_*$:**
100% covering factor out to 350 kpc (for $N(\text{HI}) > \text{few } 10^{13} \text{ cm}^{-2}$)
- **Ly α around group galaxies brighter than $0.1 L_*$:**
65% covering factor out to 350 kpc

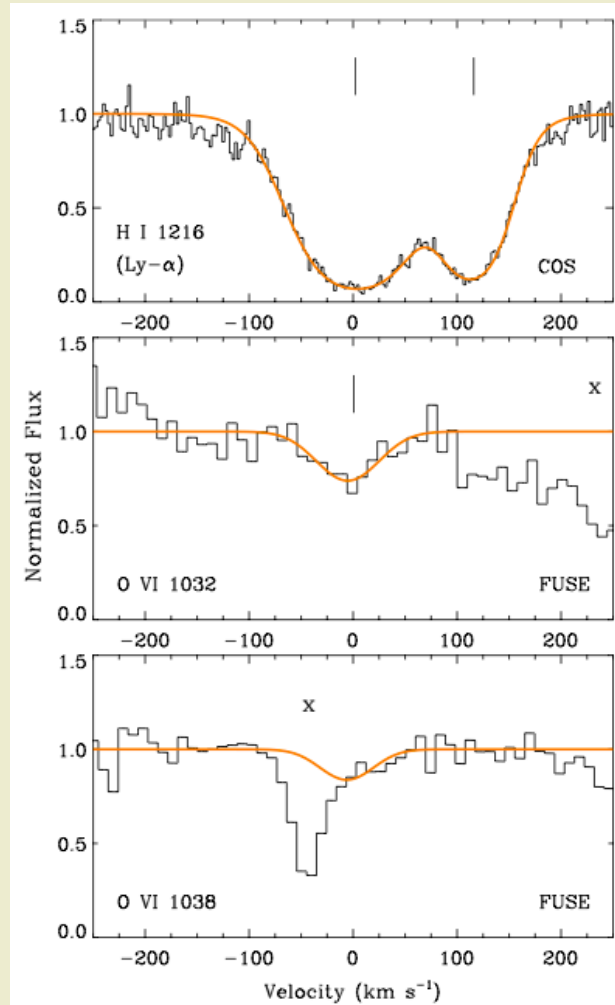
- **OVI around field galaxies brighter than $0.1 L_*$:**
70% covering factor out to 300 kpc (for $N(\text{OVI}) > 5 \times 10^{13} \text{ cm}^{-2}$)
- **OVI around group galaxies brighter than $0.1 L_*$:**
10% covering factor out to 300 kpc

- **10-30% of the baryons are in the Ly α forest (6% inside galaxies)**
- **50% of Ly α lines occur within 400 kpc of galaxy with $L > 0.1 L_*$**
 \Rightarrow 2.5 times as many baryons in Ly α forest near galaxies as in galaxies (and ~ 5 times more in the 10^5 - 10^7 K WHIM)

GAS IN A GALAXY FILAMENT



NGC5987
($D_{25}=50$ kpc)



BLA: $b=55$ km/s
OVI: $b=29$ km/s

**Hybrid collisional
plus photoionization
model =>**

$T = 1.4 \times 10^5$ K

$N(\text{H}) = 4 \times 10^{19} \text{ cm}^{-2}$

Narayanan et al., 2010, ApJ, 721, 960)

HVCs AND GALAXY FORMATION

**Condensations in hot halo at $R=20-500$ kpc form proto-HVCs
would be seen as broad $\text{Ly}\alpha$ plus broad OVI (10^5 K gas)**

Maller & Bullock (2004) - 10^4 10^6 M_\odot clouds to 150 kpc

Sommer-Larsen (2006) - 500 $10^{5.5}$ M_\odot clouds to 50 kpc

Kaufman et al. (2007) - 200 10^5 M_\odot clouds to 20 kpc

**Clouds cool further, creating distant, fairly neutral HVCs
would be seen as CHVC in 21cm; as OVI HVC in absorption
[photoionized clump (\Rightarrow HI, low ions) with interface (\Rightarrow OVI)]**

Clouds evaporate, shear, fragment, remix

Murali 2000 - cloud with $v=220$ moving through $n(\text{hot})=10^{-4.5}$ evaporates in 10^8 yr

Heitsch & Putman 2009: clouds fragment in $<10^8$ yr, traveling <10 kpc

**Condensations forming at $z<15$ kpc
would be seen as large 21-cm HVC complexes**

