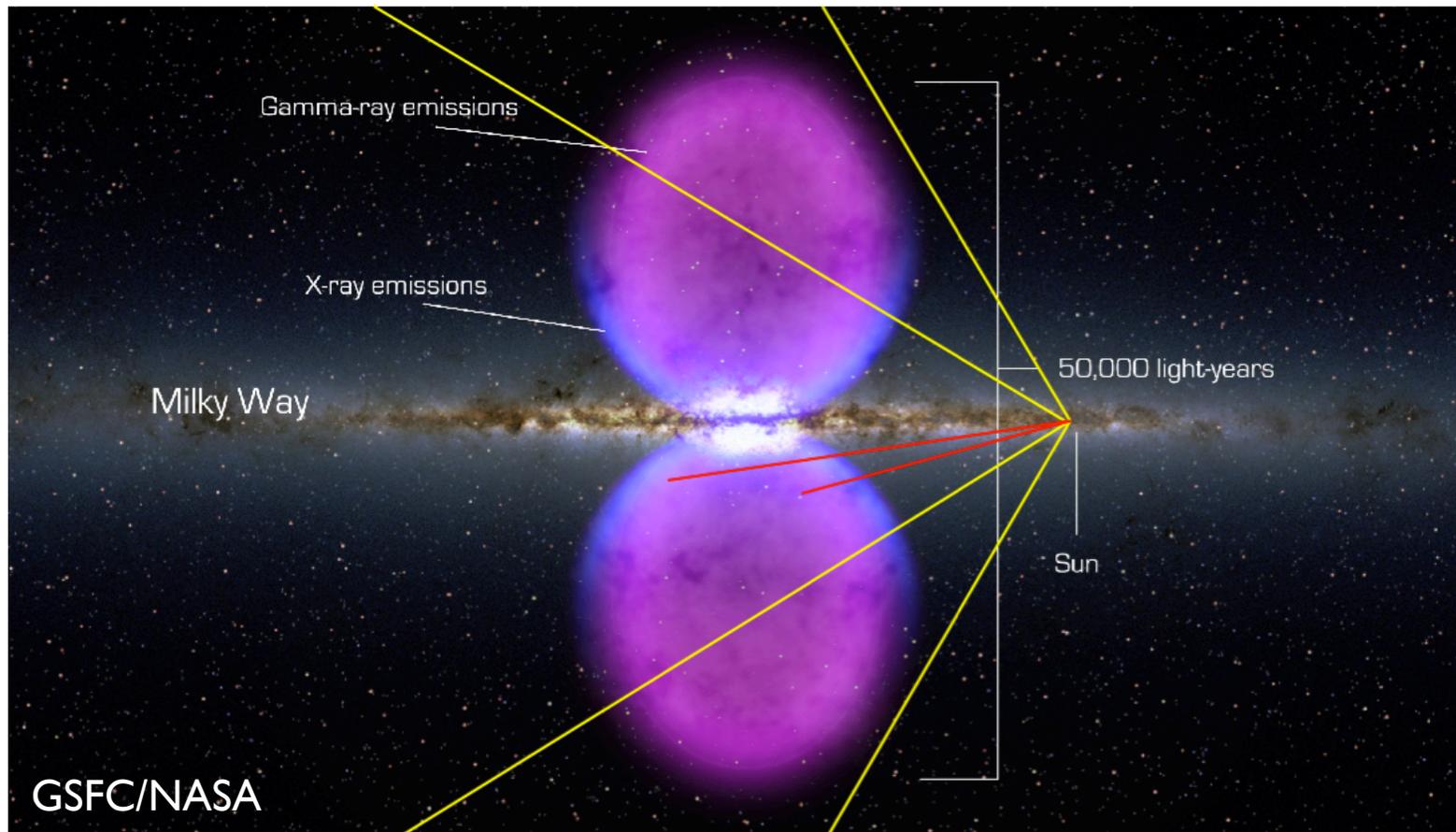


Insights on the Galactic Center Outflow from UV Absorption Lines



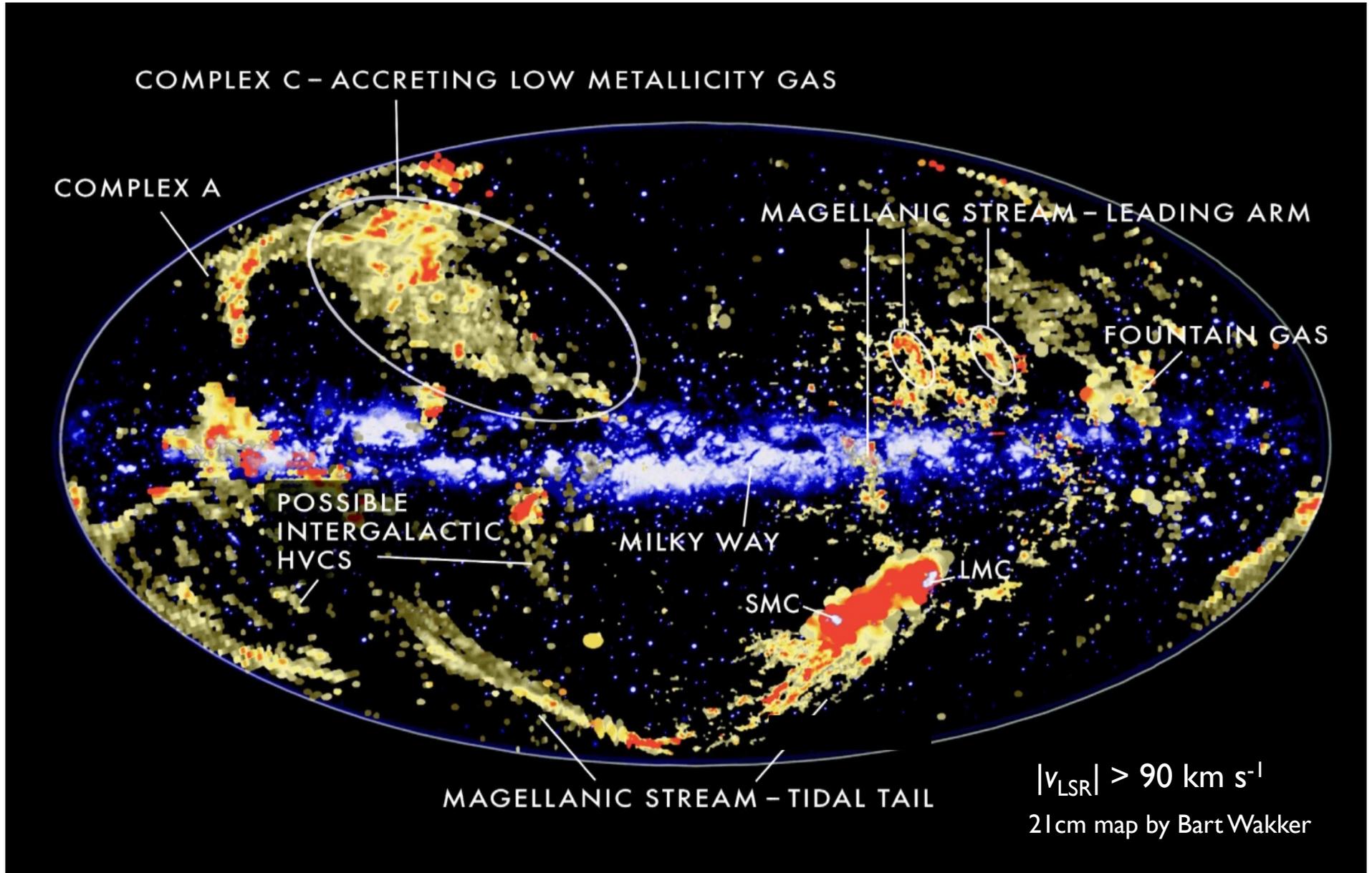
Andrew Fox (STScI)

The Fermi Bubbles: Theory and Observations

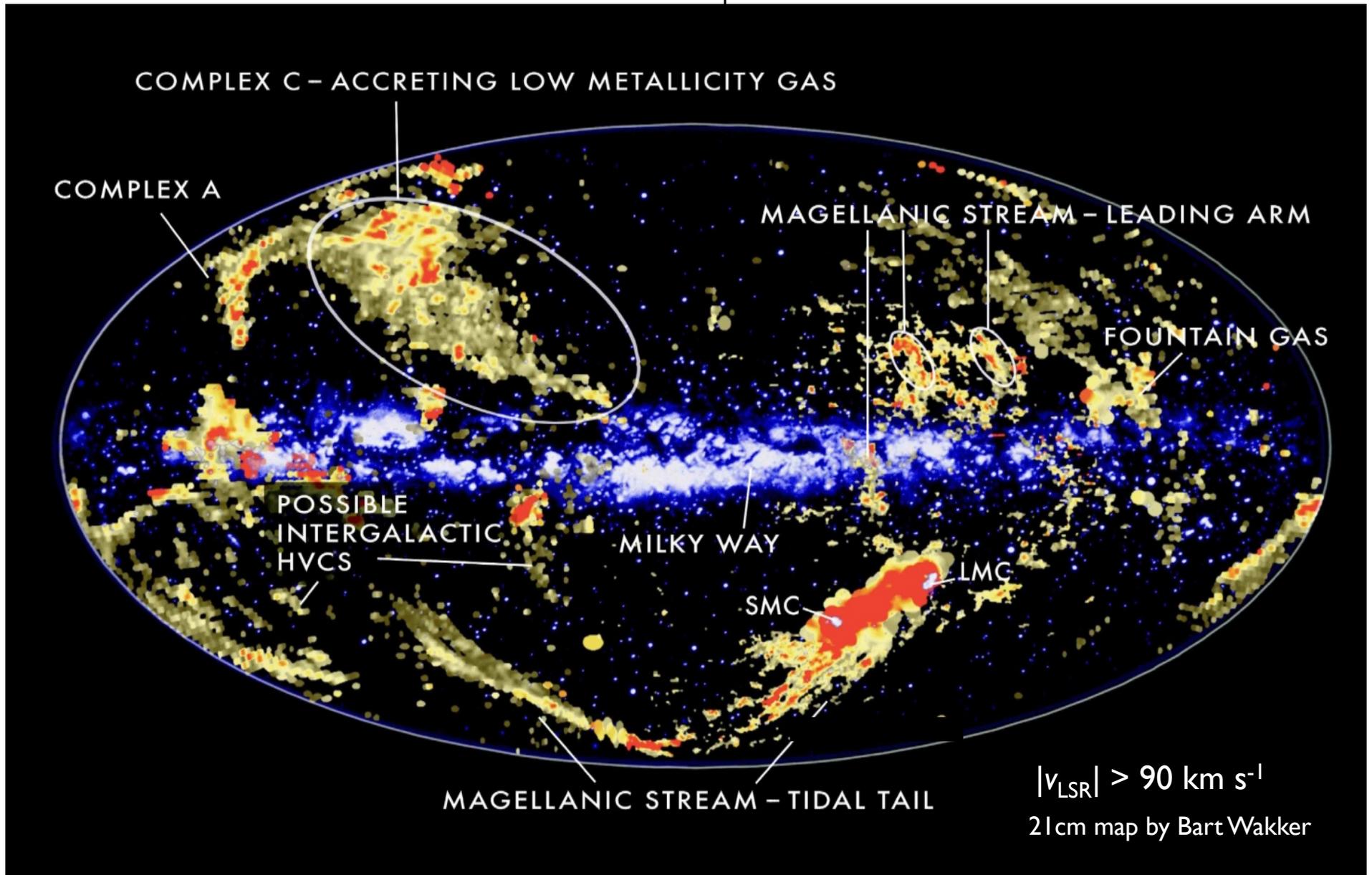
OUTLINE

- Introduction to UV studies of Galactic halo gas using high-velocity clouds (HVCs)
- Existing studies of HVC absorption in GC sightlines ($|| < 30^\circ$)
- Future studies of HVC absorption in GC sightlines

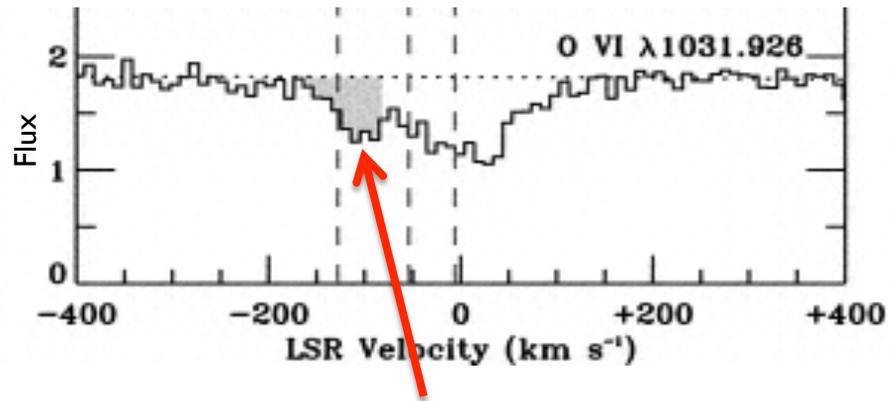
Gaseous Inflow and Outflow around Milky Way observed among the Galactic High-Velocity Clouds (HVCs) discovered in H I



- **Sky covering fraction** of HVC 21 cm emission $\sim 37\%$ (down to $N(\text{H I}) \sim 3 \times 10^{18} \text{ cm}^{-2}$; Murphy+ 1995)
- **HVC metallicities** ~ 0.1 - 1.0 solar; distances $< \sim 10$ kpc (Lehner & Howk 2011, except MS & compact HVCs)
- Trace variety of processes (infall, Galactic fountain, tidal stripping, gas condensation)

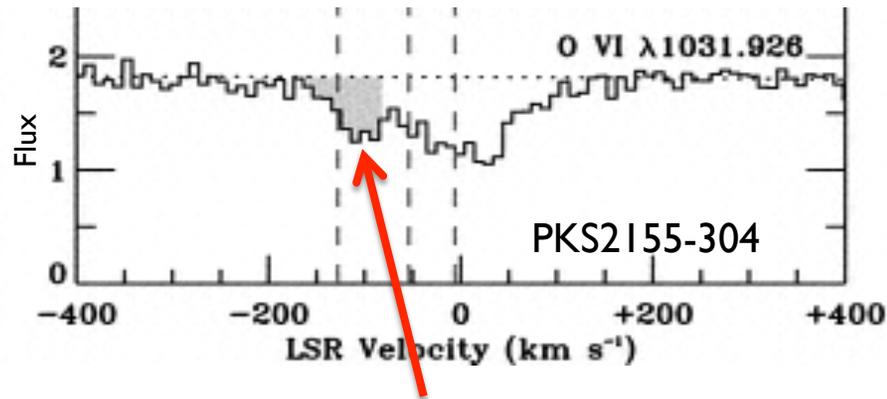


HVCs in O VI 1031 absorption (*FUSE*, Far Ultraviolet)



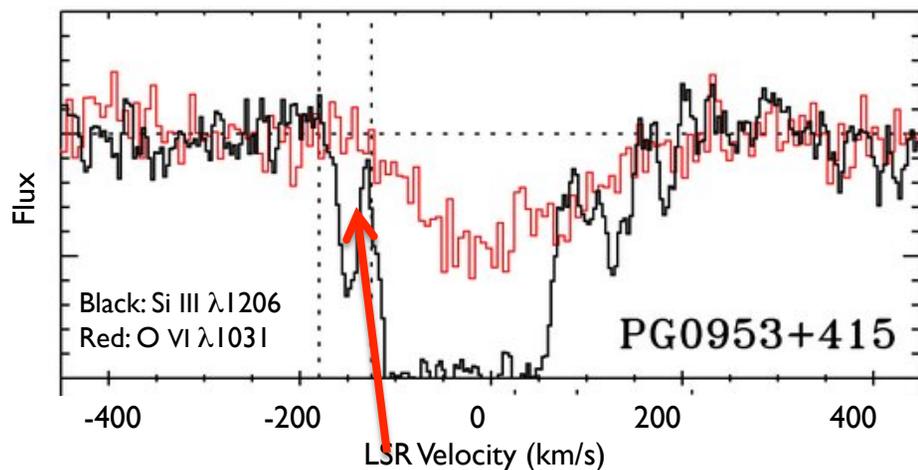
- ▶ HVC O VI: 60-85% sky coverage (Sembach+2003)
- ▶ Traces warm-hot plasma phase ($T \sim 300\,000$ K)

HVCs in O VI 1031 absorption (*FUSE*, Far Ultraviolet)



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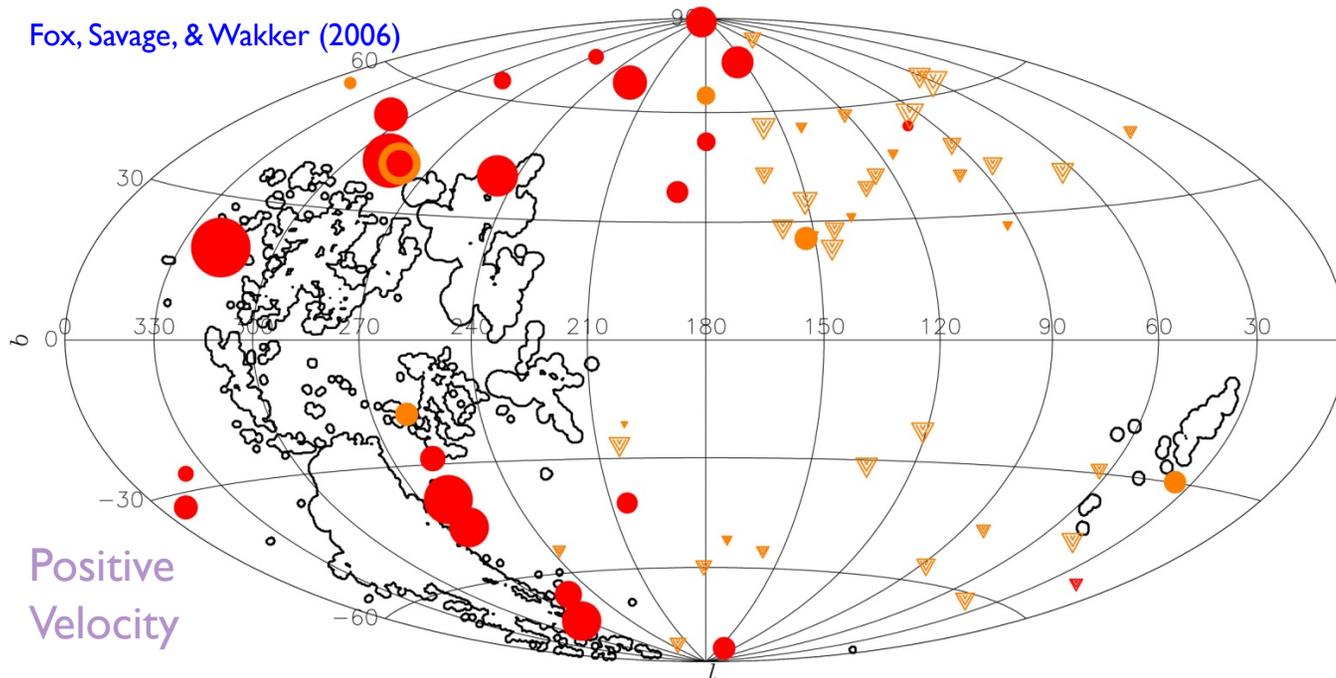
HVCs in Si III 1206 absorption (*HST*, Near Ultraviolet)



- ▶ HVC Si III : $91 \pm 4\%$ sky coverage (Shull+ 2009)
- ▶ Traces cooler, photoionized gas at $\sim 10^4$ K

Ionized gas ubiquitous in Galactic halo

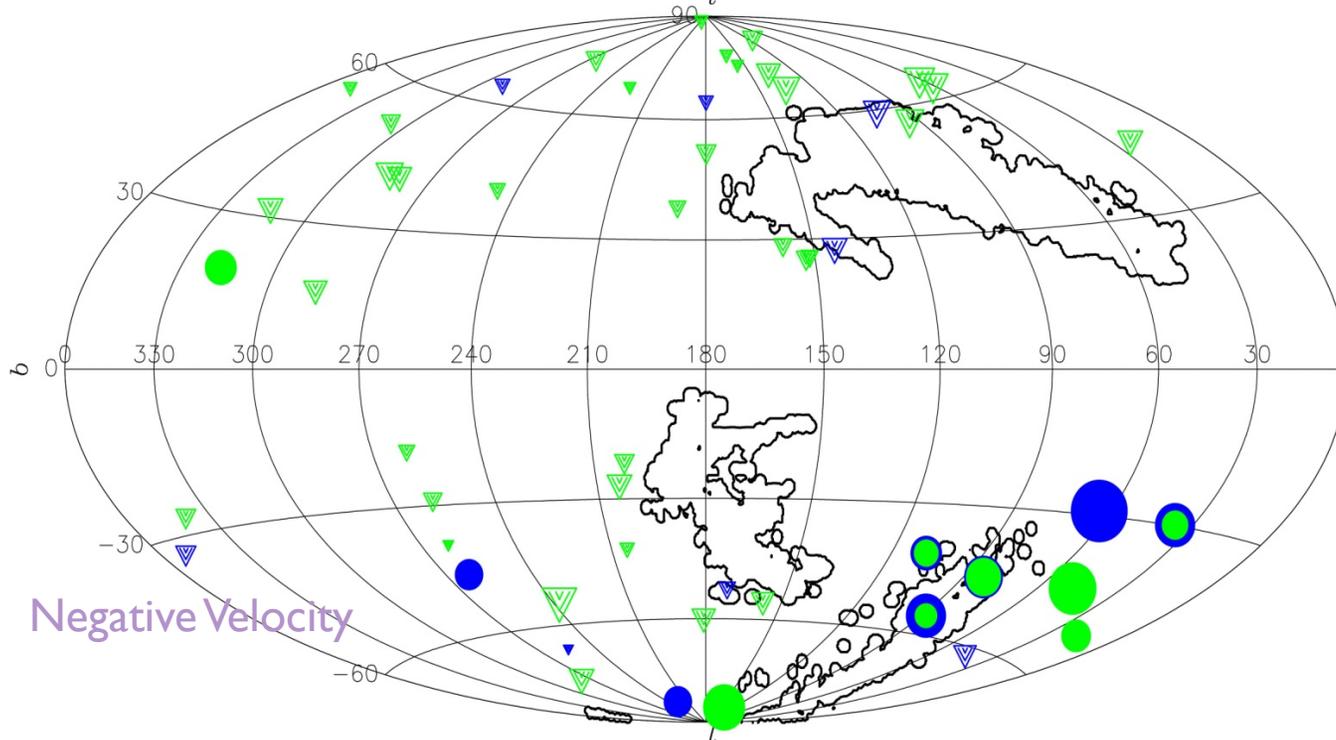
Fox, Savage, & Wakker (2006)



Positive
Velocity

Highly Ionized HVCs

HVCs seen in O VI/C IV
but not at 21 cm
(Sembach+1995, 1999
Collins+ 2004, 2005, 2006,
Fox+2005, 2006, Zech+2008)

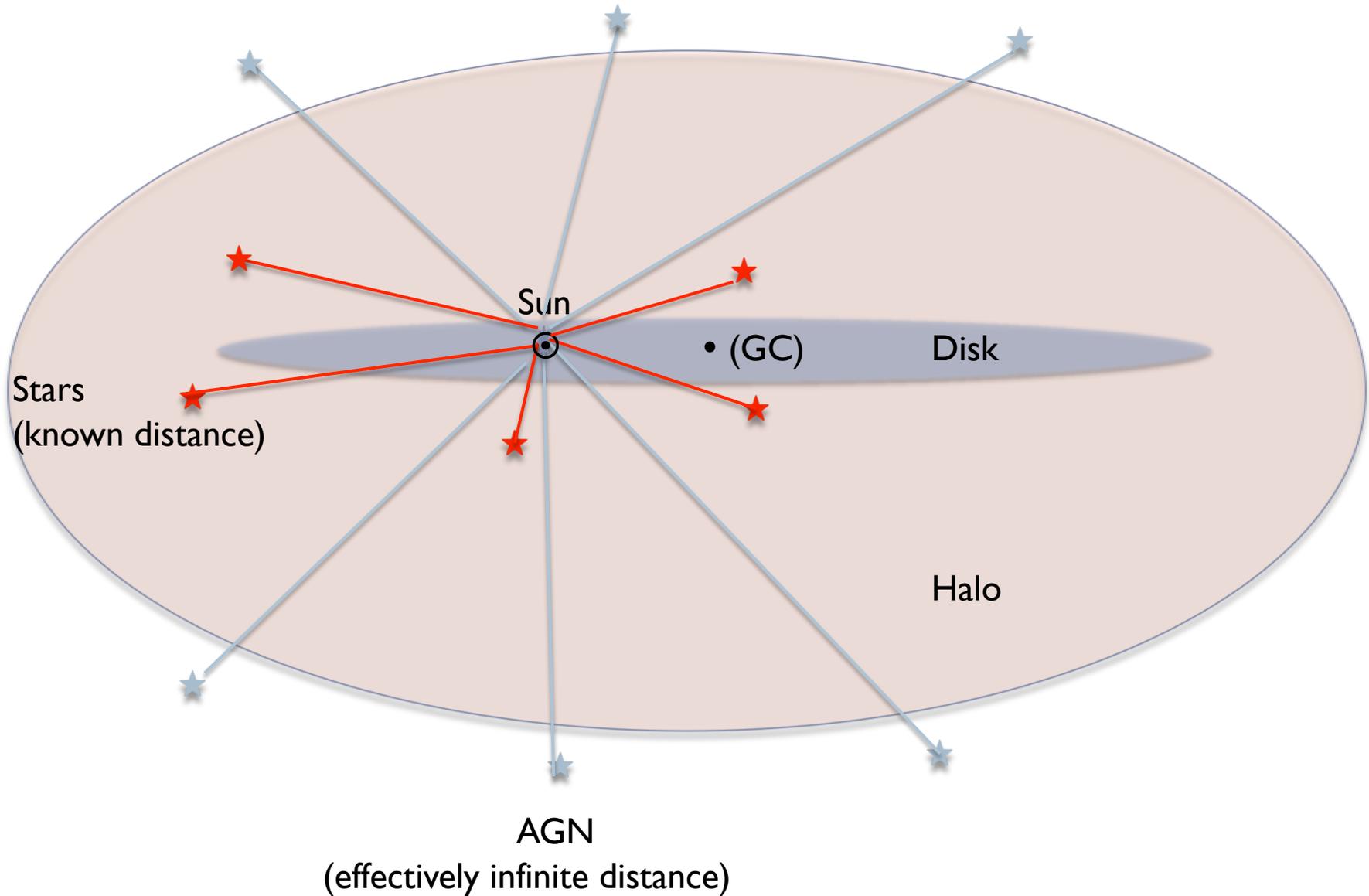


Negative
Velocity

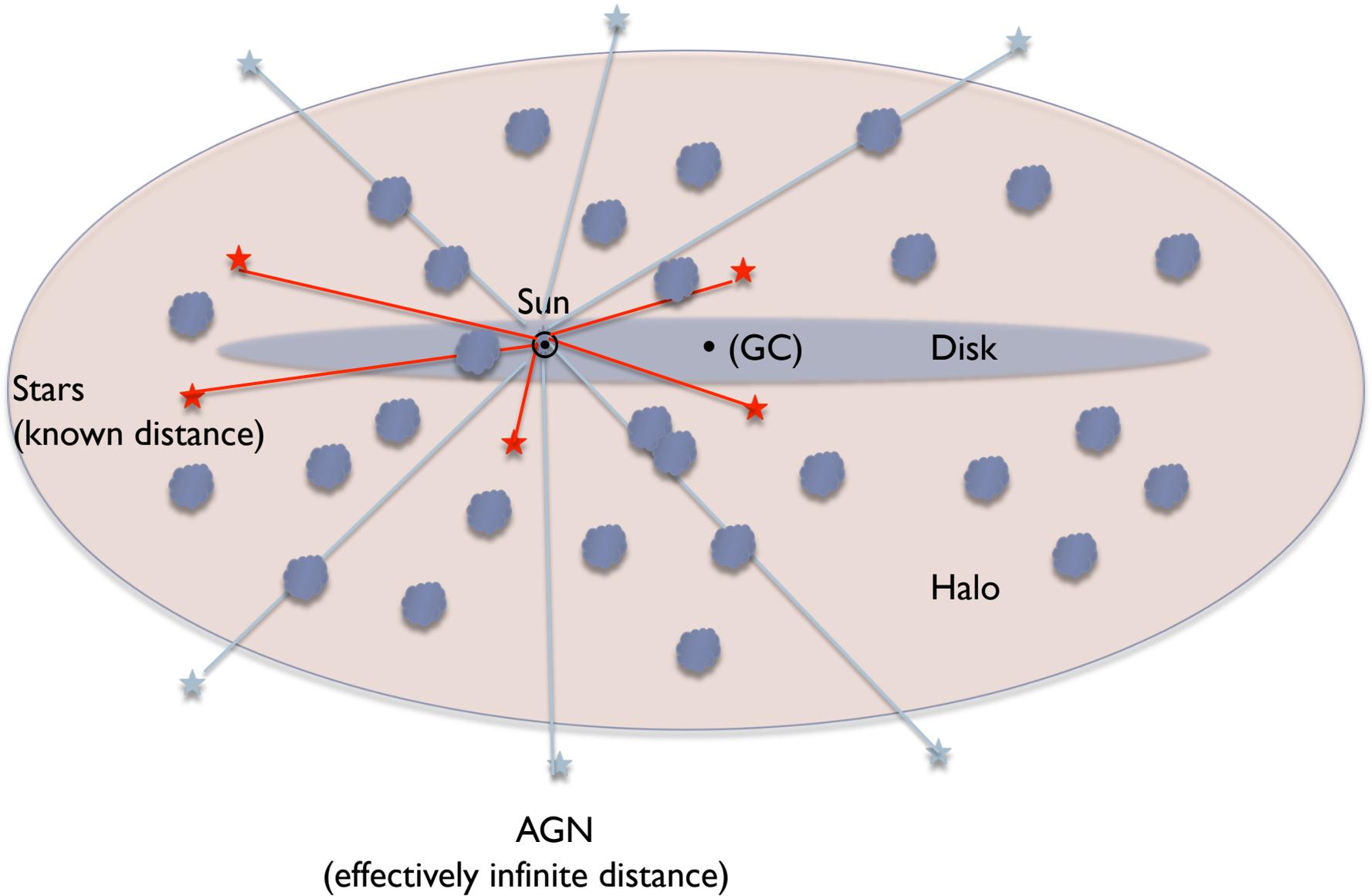
Red: 200 to 400 km s⁻¹
Orange: 100 to 200 km s⁻¹
Blue: -400 to -150 km s⁻¹
Green: -150 to -100 km s⁻¹

HVC Distances: new statistical method: Lehner & Howk 2011; Lehner+ 2012

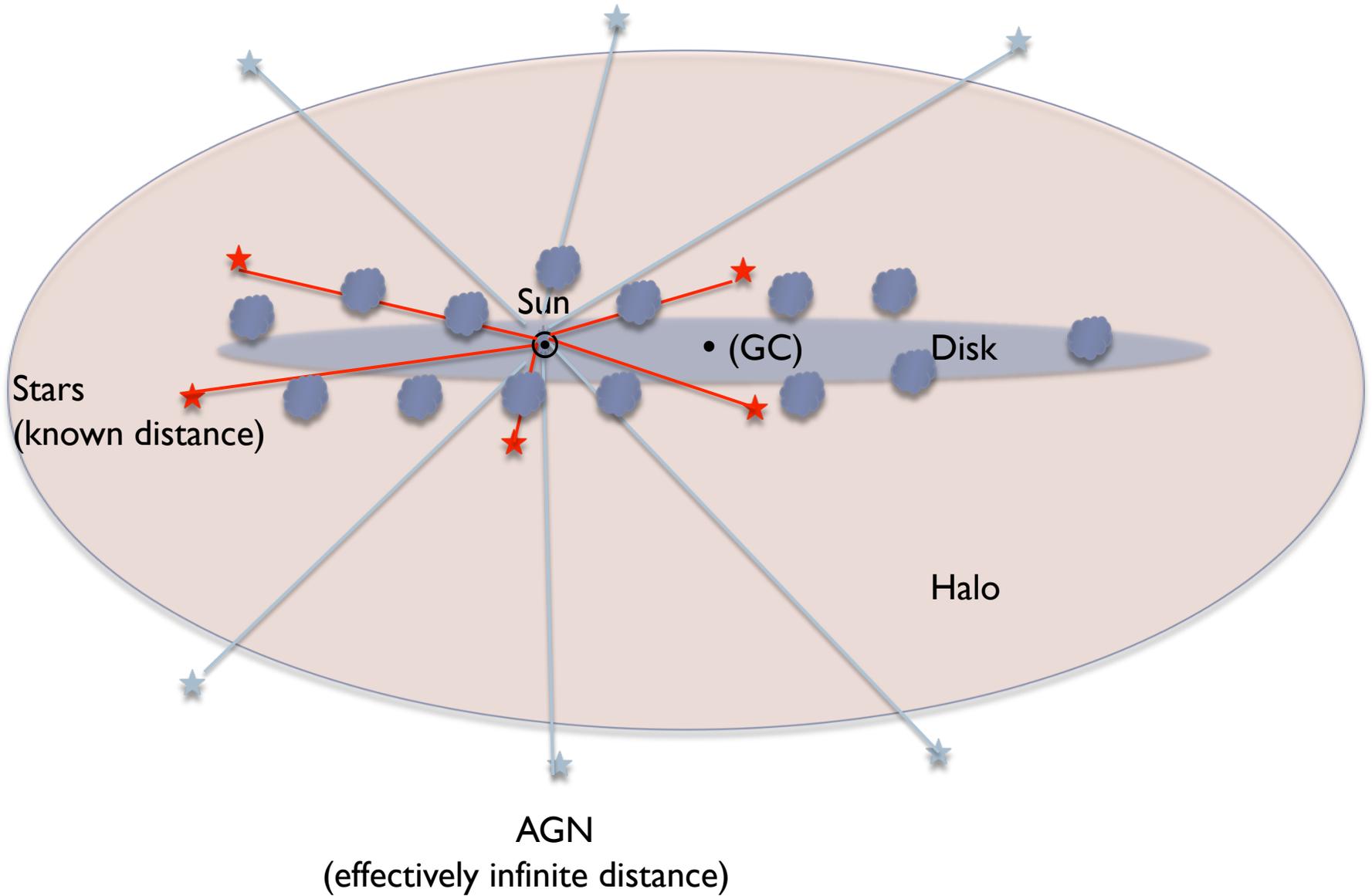
Basic idea: compare HVC covering fractions toward stars & AGN



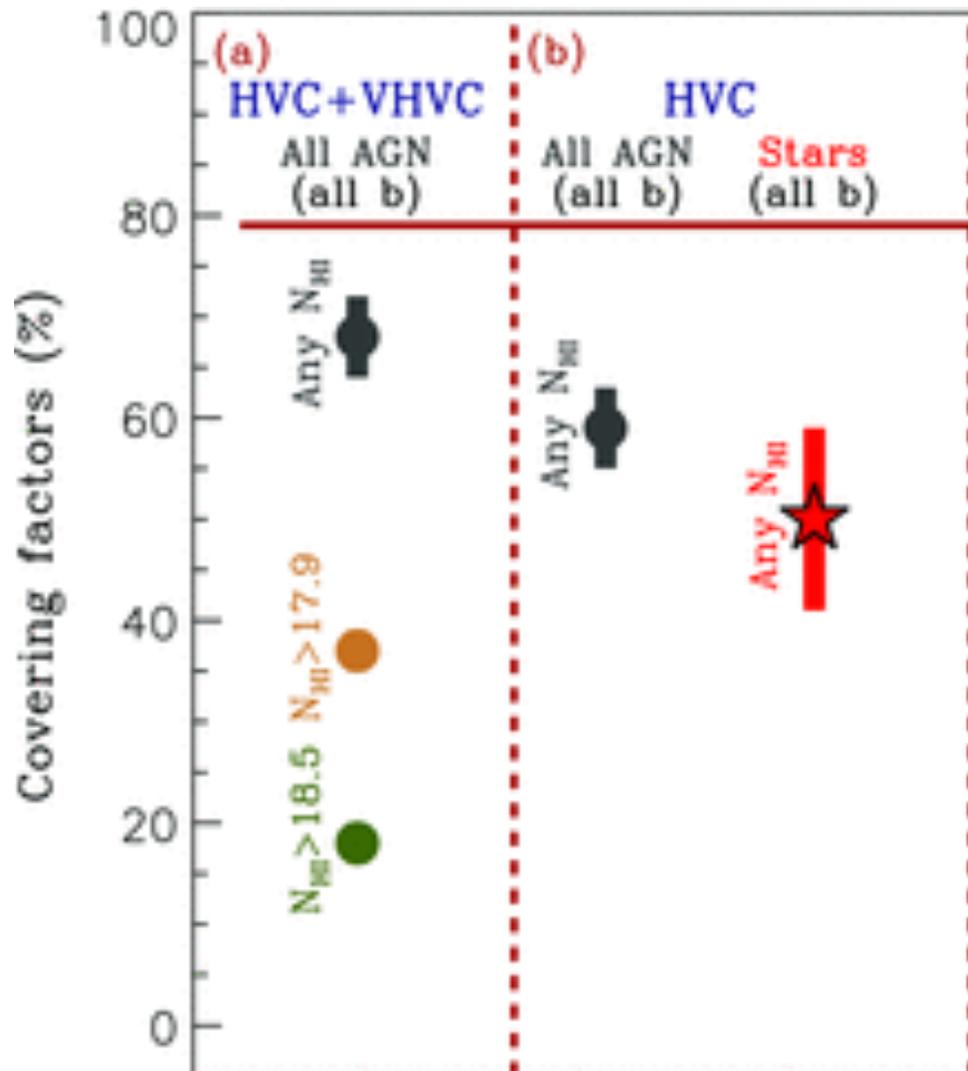
Scenario I: HVCs distributed out to large distances (tens of kpc or more)



Scenario 2: HVCs located close to Galactic disk (<10 kpc)



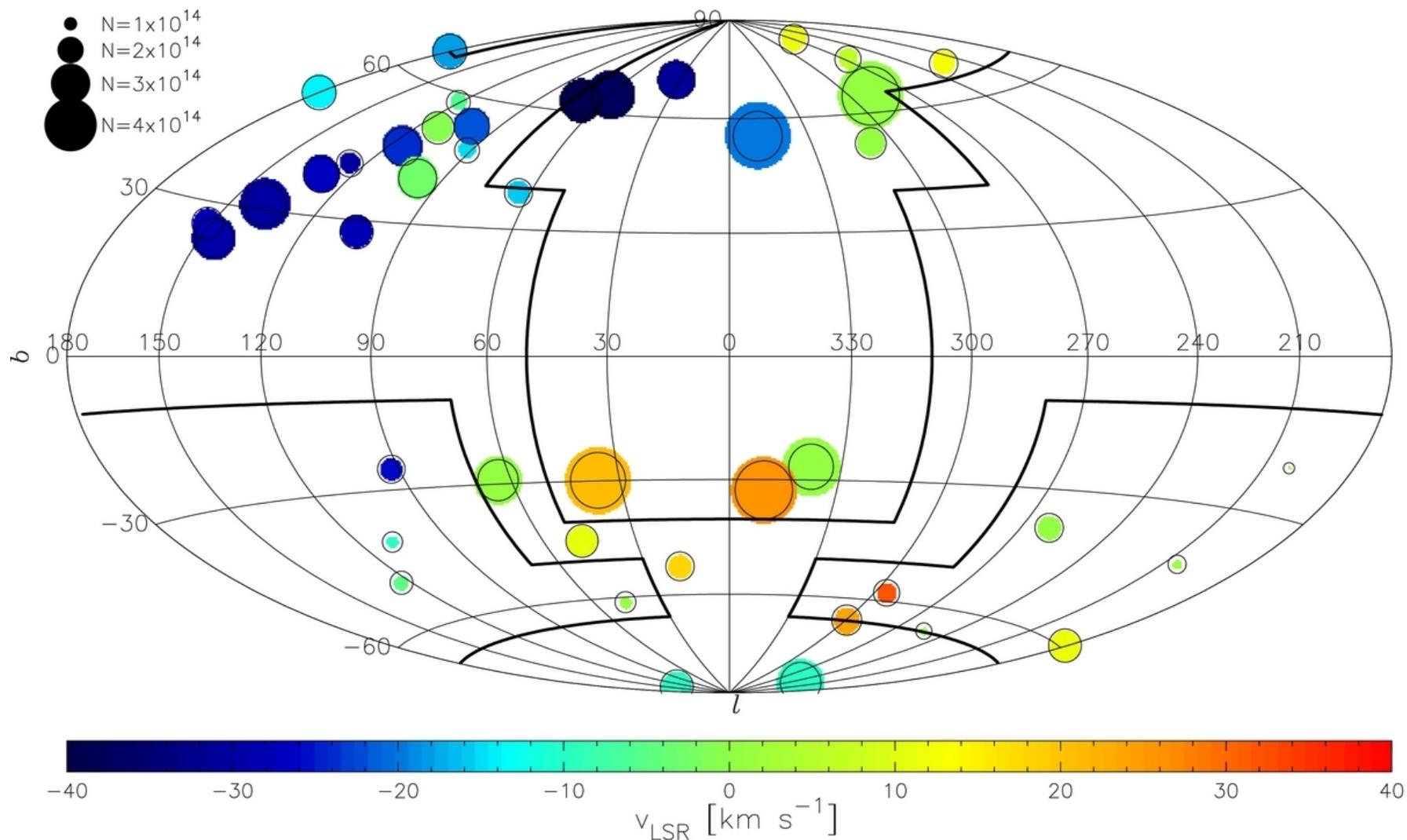
HVC Covering Fractions measured from UV absorption lines



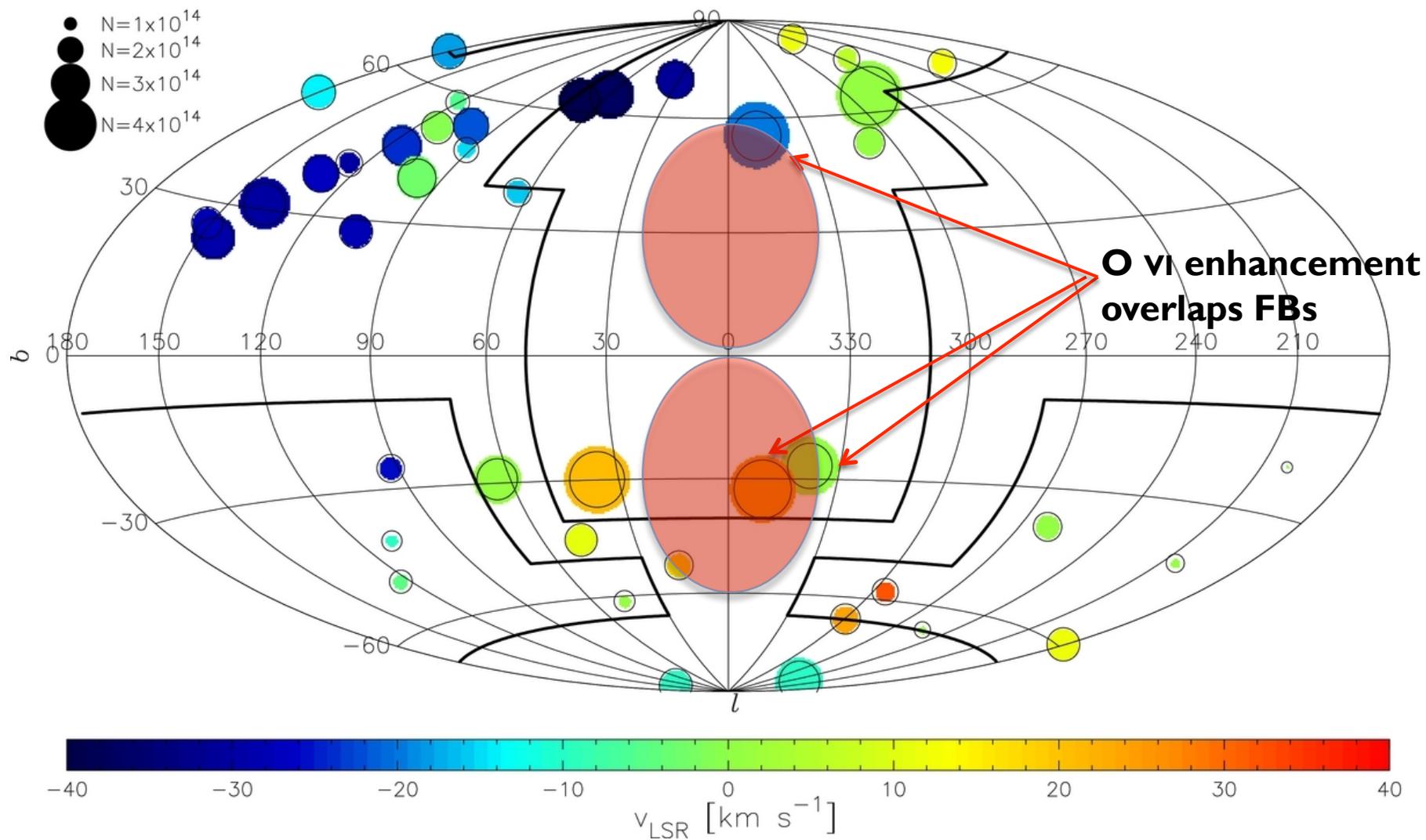
Lehner, Howk, Thom, Fox, et al 2012

- similar covering fraction toward stars (~50%) and AGN (~60%)
- measured from C II, Si II, Si III
- most HVCs lie in front of the halo stars, i.e. within ~10 kpc of the Sun
- based on 28 stars and 133 AGN

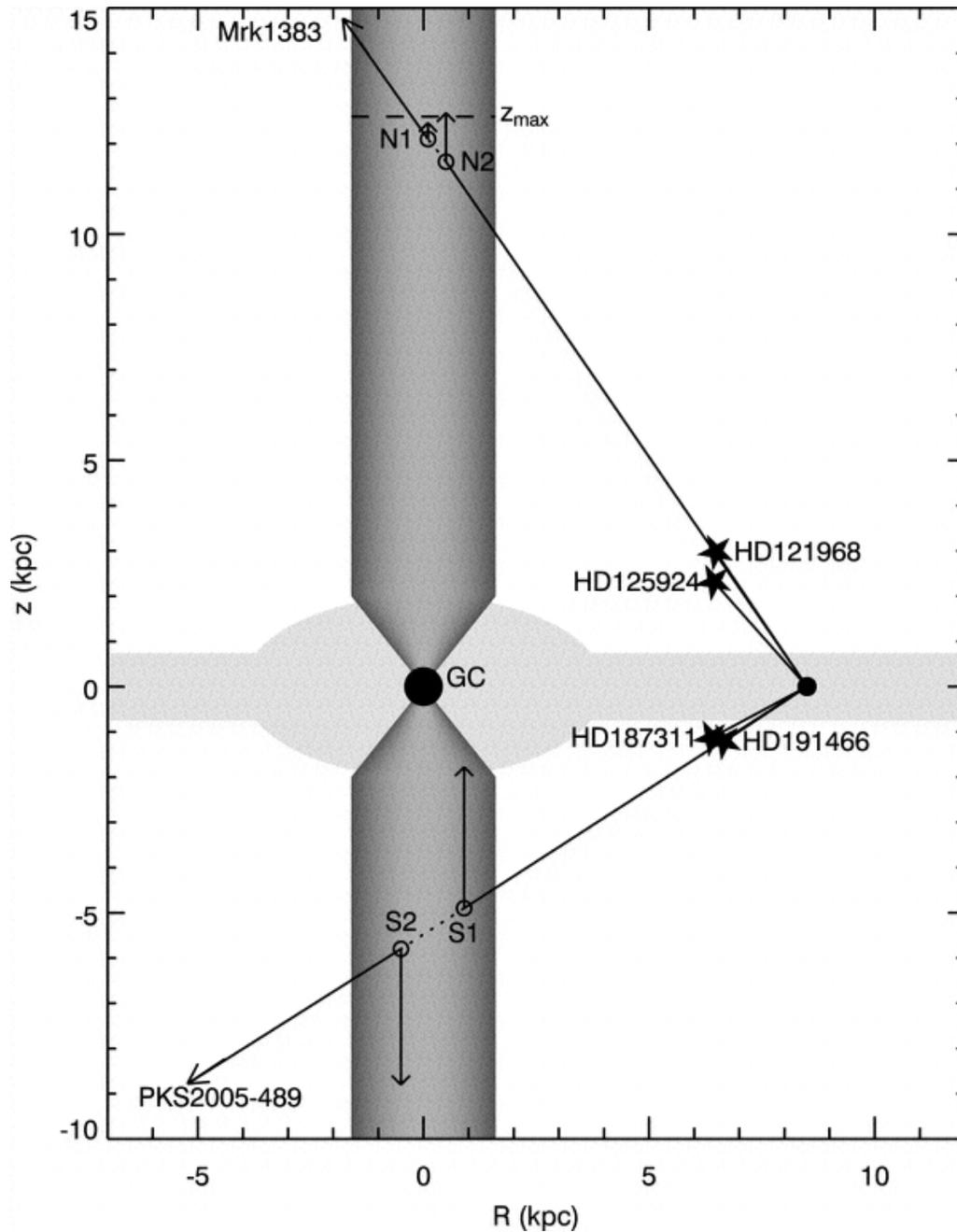
Part II: Existing UV absorption-line information on GC region



All-sky *FUSE* map of integrated O VI column toward extragalactic targets
Wakker, Savage, Fox, et al. 2012; GC-centered projection



All-sky *FUSE* map of integrated O VI column toward extragalactic targets
 Wakker, Savage, Fox, et al. 2012; GC-centered projection



Keeney et al. (2006)

Studied GC outflow with *HST*/STIS & *FUSE* spectra of 2 AGN and 4 foreground stars:

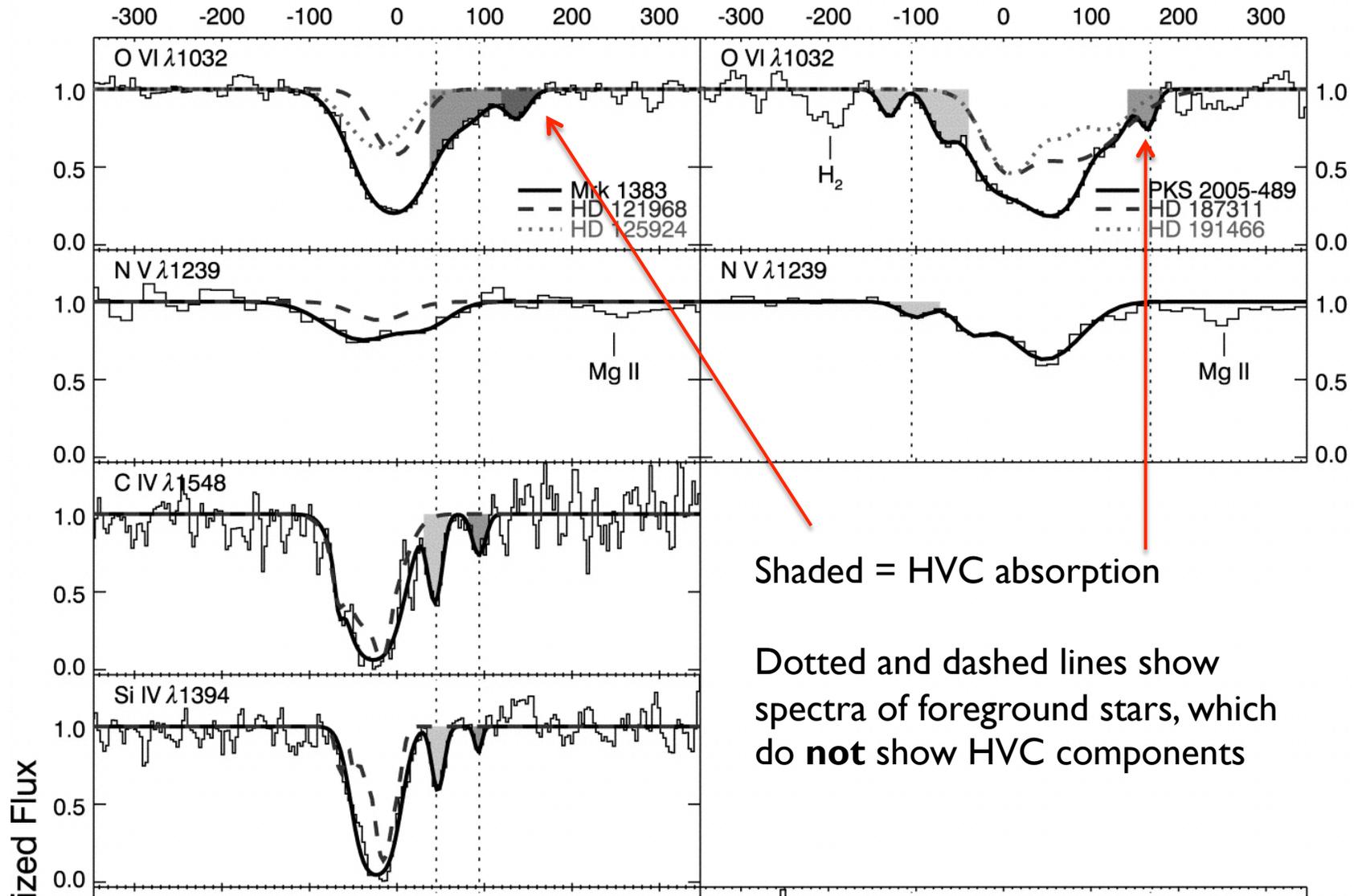
AGN sightlines probe full GC region

Halo-star sightlines probe foregrounds (disk absorption, spiral-arm outflows)

Outflow geometry of Bland-Hawthorn & Cohen (2003): central biconic outflow, cylindrical wind at large z-distances

Mrk 1383 ($b=55.1^\circ$)

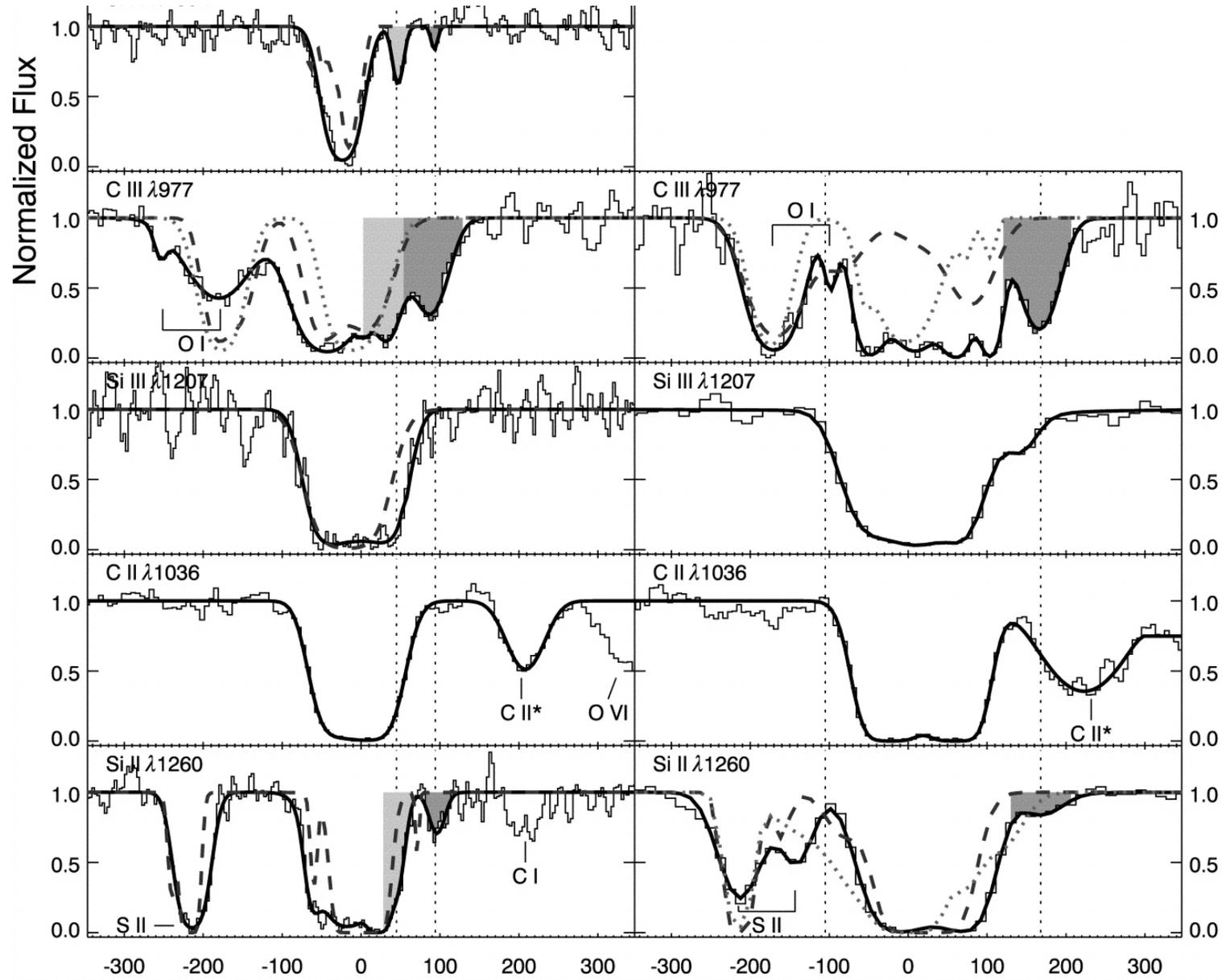
PKS 2005-489 ($b=-32.6^\circ$)



Keeney et al. 2006

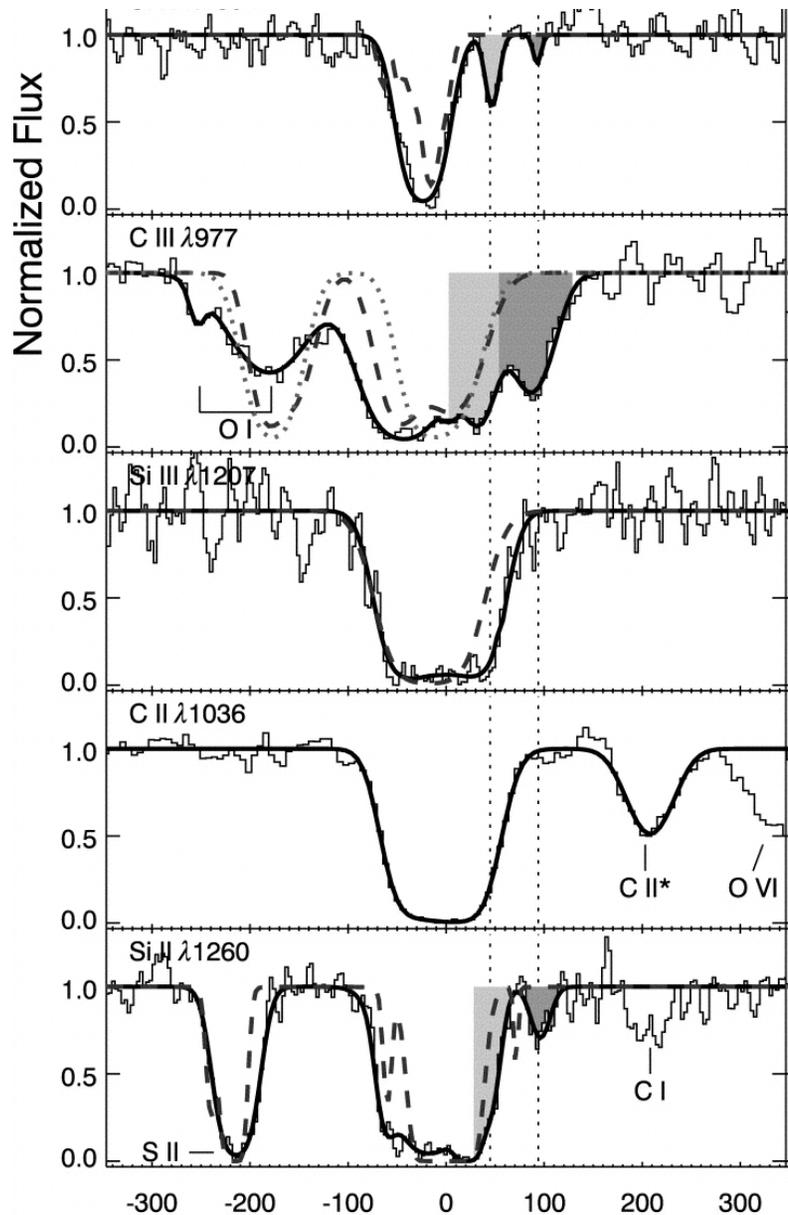
Mrk 1383

PKS 2005-489



Keeney et al. 2006

Mrk 1383



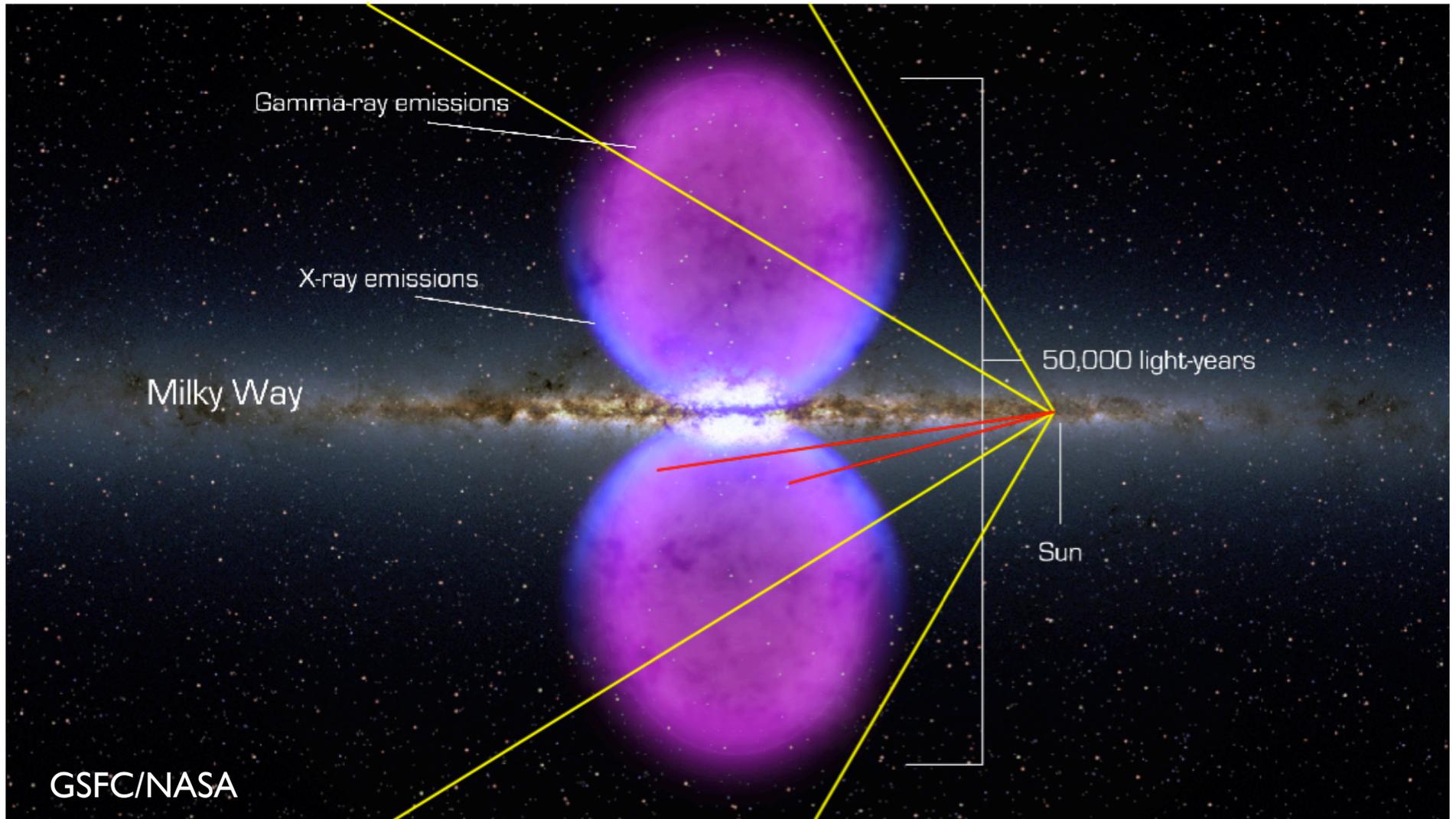
Keeney et al. 2006

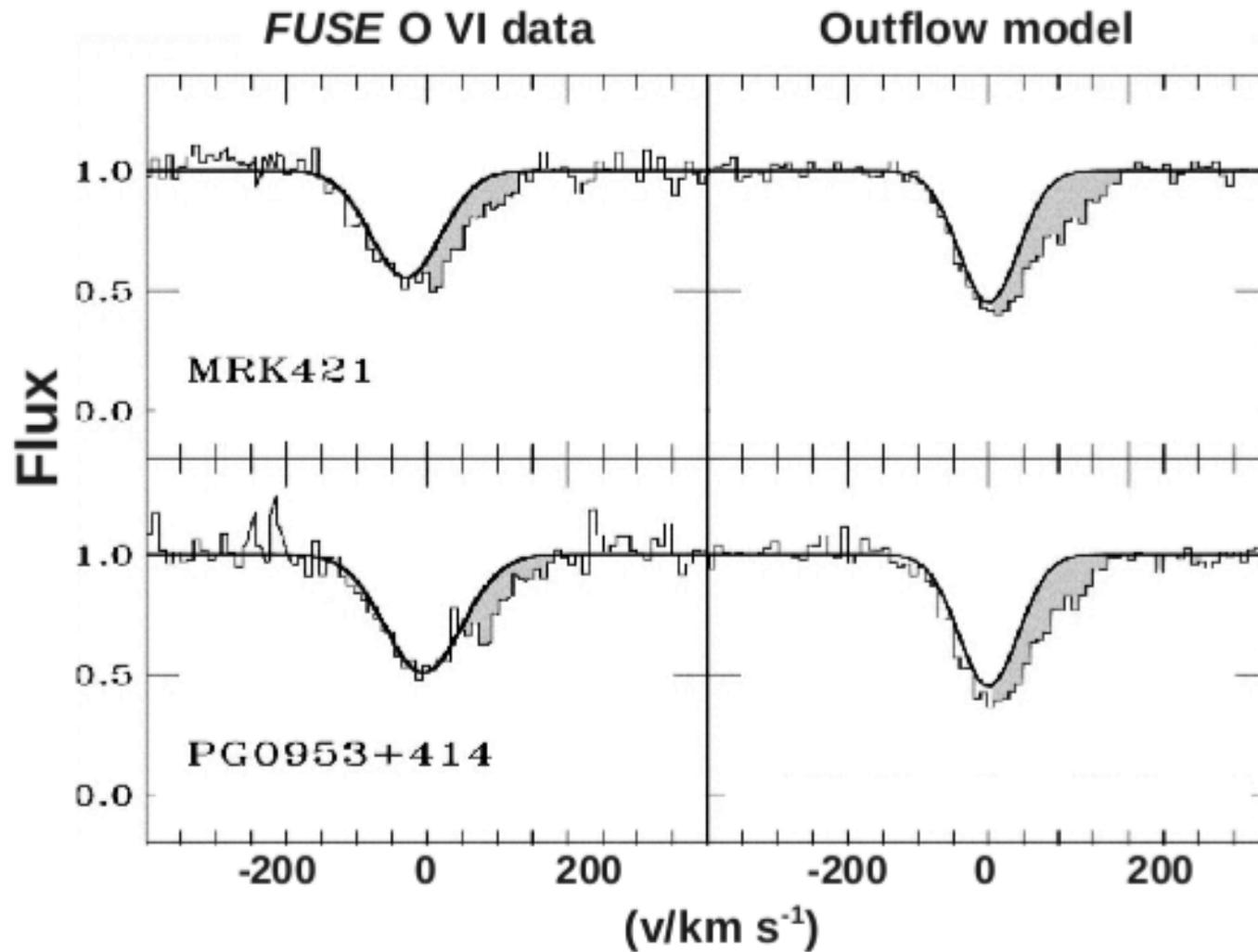
Keeney et al. (2006) results

- detected 4 high-velocity ($|v_{\text{LSR}}| > 100 \text{ km s}^{-1}$) components tracing the GC wind
- maximum $v_{\text{wind}} = 250 \pm 20 \text{ km s}^{-1} \ll$ calculated MW escape velocity ($\sim 550 \text{ km s}^{-1}$)
- *bound* outflow reaching maximum z-height $12 \pm 1 \text{ kpc}$ (if motion is ballistic)
- launched $\sim 50 \text{ Myr}$ ago from GC region
- metallicity $\sim 0.1\text{-}0.2$ solar, surprisingly low for nuclear outflow (though depends on ionization corrections and values of H I column)
- HVCs appear similar to those observed in other (non-GC) directions
- No tracer of truly hot ($T > 10^6 \text{ K}$) plasma present in UV (need X-ray)

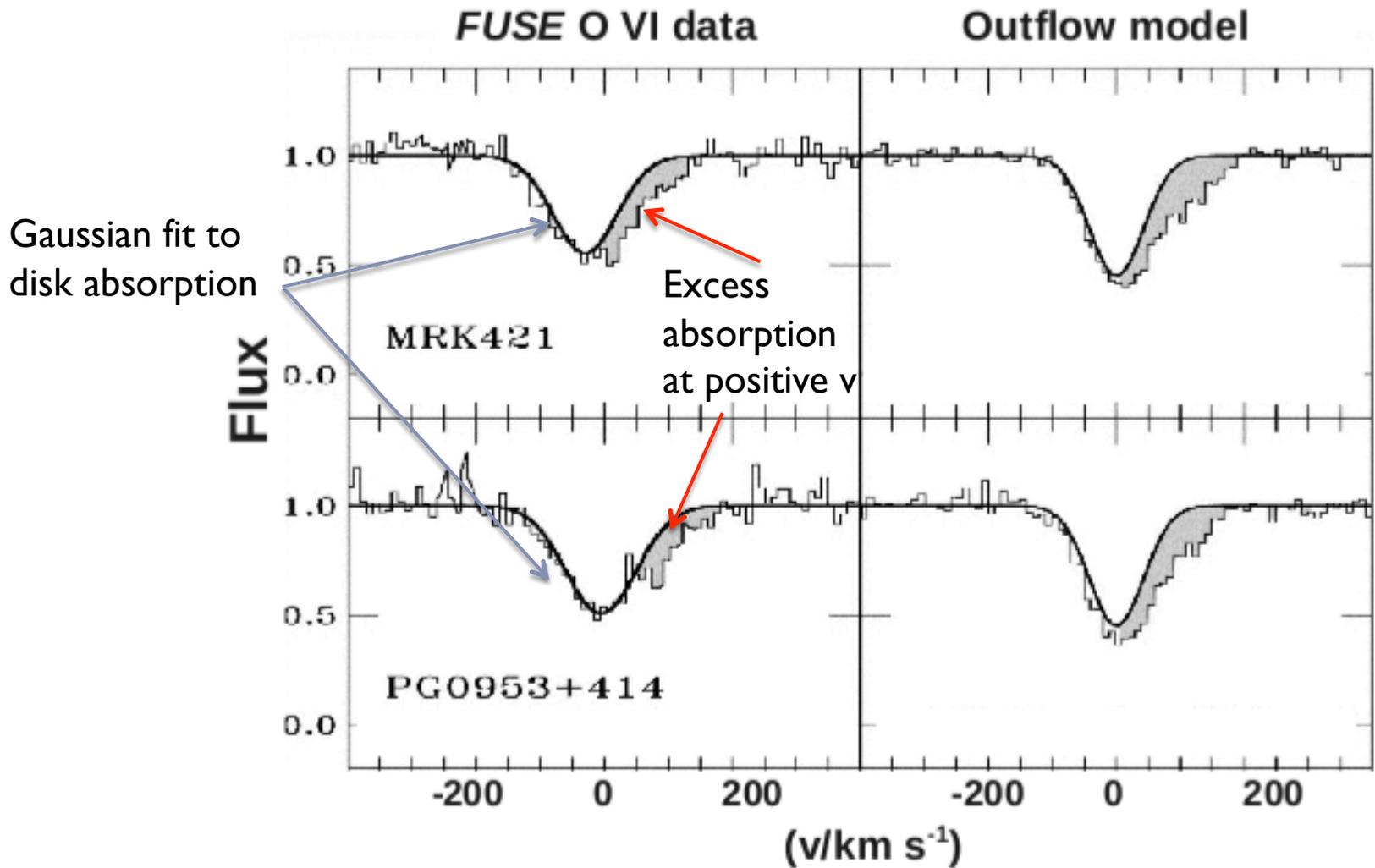
Part III: What could be done with more UV observations

To test the vertical extent of the UV outflow, need targets at a range of latitudes



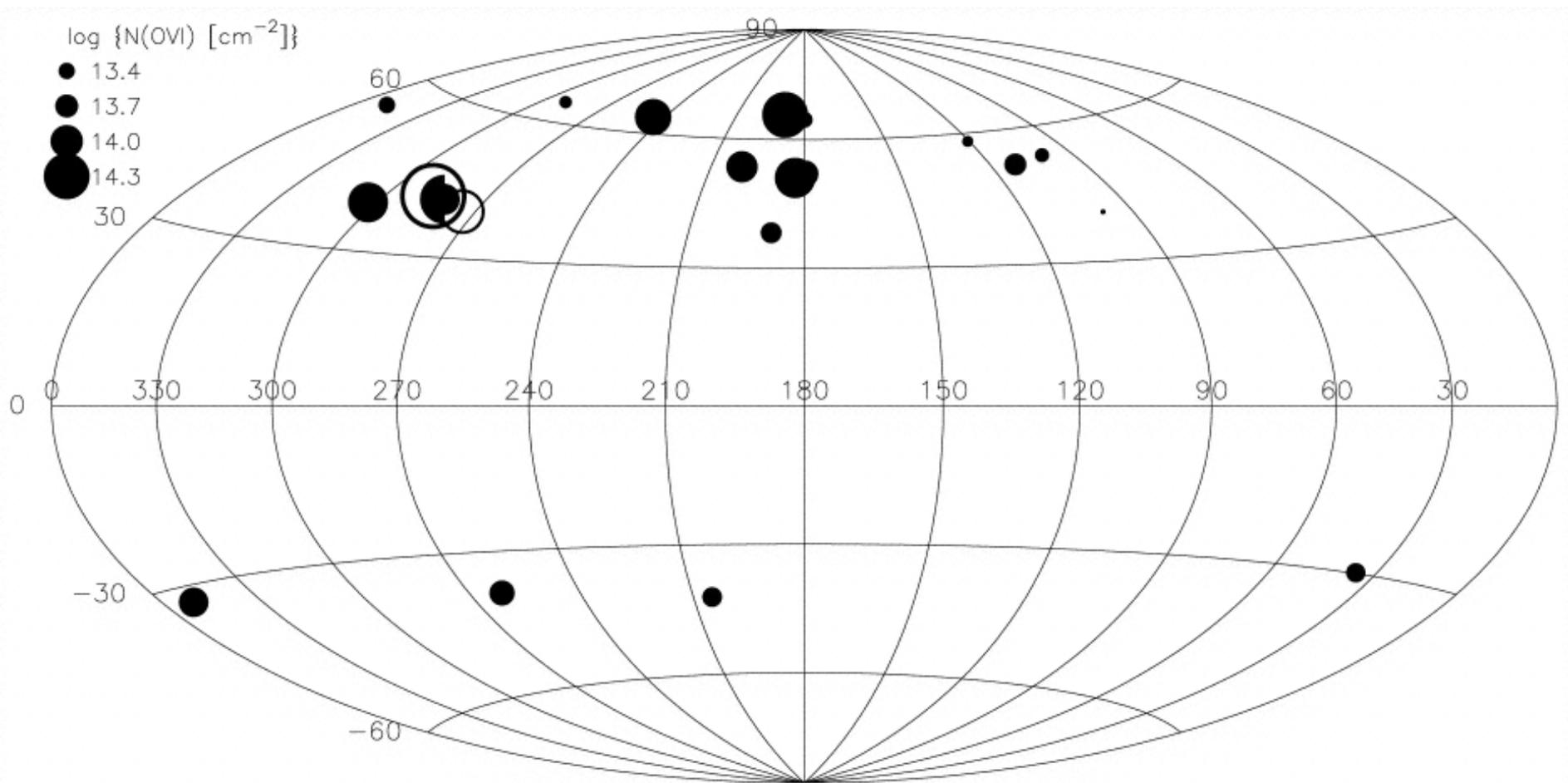


Outflow signature: **positive-velocity wings** on the *FUSE* O VI absorption profiles in two anti-center directions (Fox+ 2006). The wings (excess absorption) reach $v_{\text{LSR}} = +200 \text{ km s}^{-1}$

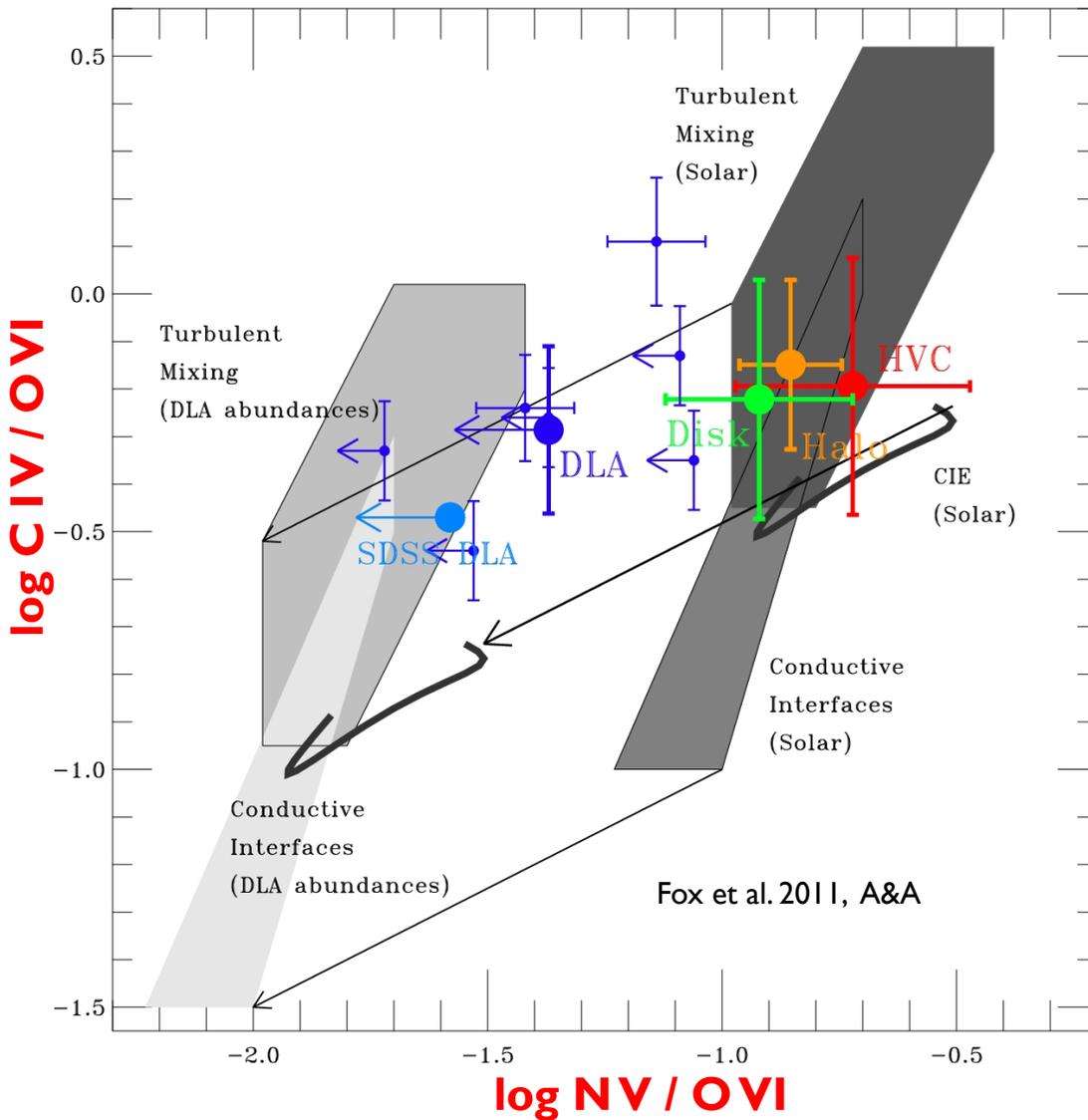


Outflow signature: **positive-velocity wings** on the *FUSE* O VI absorption profiles in two anti-center directions (Fox+ 2006). The wings (excess absorption) reach $v_{\text{LSR}} = +200 \text{ km s}^{-1}$

Need new data to search for wings in GC directions and constrain mass flow rate



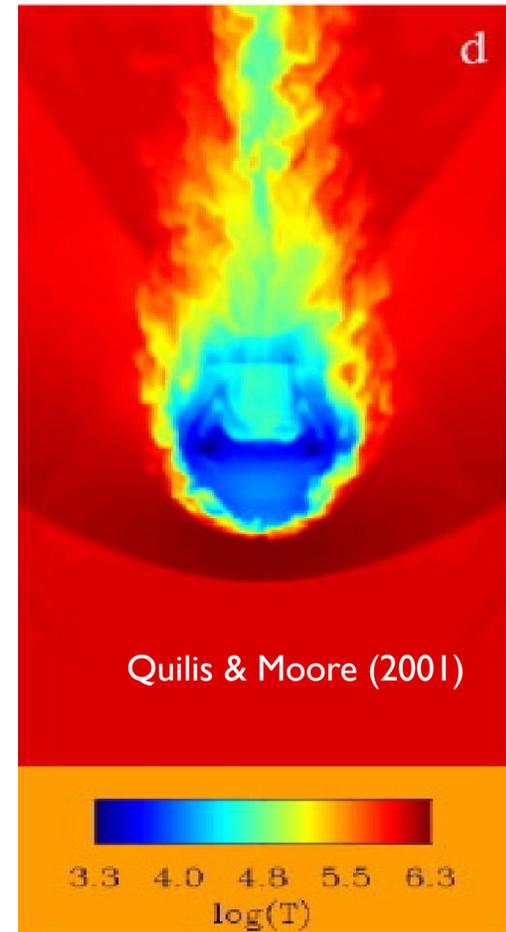
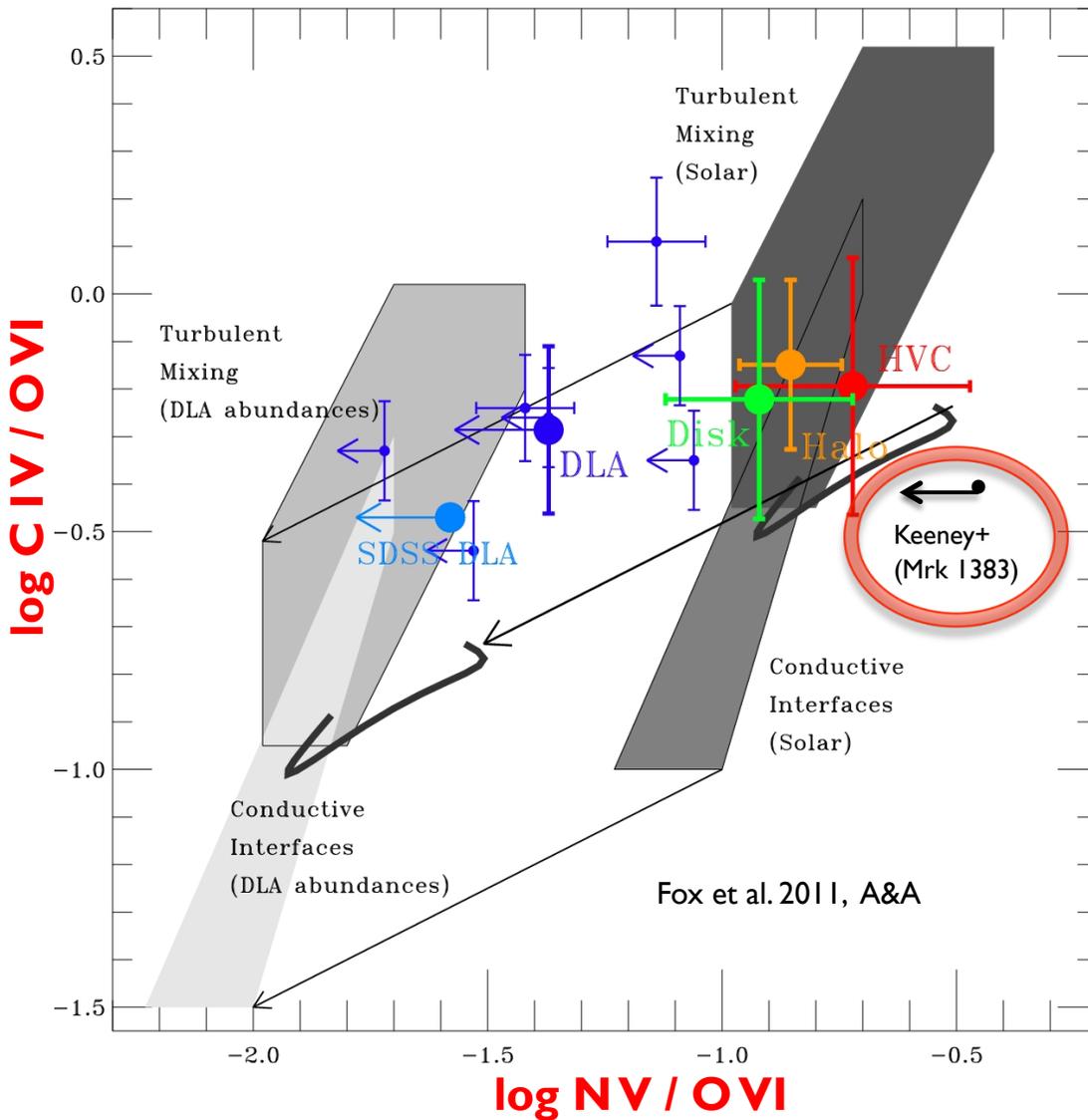
Distribution of O VI positive velocity wings, Sembach+ 2003



Still to be done in HVCs in GC directions:

Constrain ionization mechanism using high-ion column density ratios

Average values known in Galactic disk (green), halo (orange), and HVCs (red)



Constrain ionization mechanism using high-ion column density ratios
 Average values known in Galactic disk (green), halo (orange), and HVCs (red)
 Enhanced C IV/OVI ratios would indicate turbulence in the wind

Summary

HVCs probe inflow/outflow/circulation around the MW.

Clear enhancement in O VI in Fermi Bubble region $||l| < 30^\circ$ (*FUSE*)

Multiple HVCs detected in 2 GC sightlines (IN+IS; Keeney+ 2006), interpreted as bound outflow reaching $z=12\pm 1$ kpc (\sim size of FBs) launched ~ 50 Myr ago

More *HST* data needed to constrain

- empirically how far UV outflow extends
- whether UV outflow is accelerating or decelerating
- whether absorption wings (outflow signatures) are seen in GC directions
- whether ionization mechanism shows trend with z-distance