# The Local ISM in Three Dimensions: Kinematics, Morphology and Physical Processes

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# Outline of this presentation

- We use radial velocities to identify comoving warm gas within 100 pc.
- Comoving warm gas has structures (clouds) first identified in two dimensions and then in 3D.
- Clouds have identifiable physical properties (temperature, turbulence, metal depletions).
- Are the warm gas clouds separated by Strömgren sphere ionized gas?
- Are the warm partially-ionized gas clouds Strömgren sphere shells?
- What happens when clouds interact?

# Objectives and Methodology of the LISM Program

- Develop a three-dimensional model for the warm gas clouds inside the Local Bubble (within log $N_{HI}$ = 19.2, about 100 pc). Relate to other phenomena in the Local Bubble.
- Warm gas clouds identified by kinematics (common velocity vectors) and common physical properties (T, ξ, D(Fe), and D(Mg)).
- Data consists of high-resolution UV spectra from HST/GHRS, HST/STIS, HST/COS, and ground-based Ca II.
- As a first approximation, we assume that "clouds" are rigid ($\Delta V<1.0$ km/s) homogeneous structures. Then will relax this assumption.
- We will compare with ionization models (e.g., Slavin & Frisch 2002).
- Redfield & Linsky (ApJ 673, 283 (2008)).
- Linsky, Rickett, & Redfield (ApJ 675, 413 (2008)).
- Malamut et al. (to be submitted).
- Redfield & Linsky (to be submitted).

# Two new papers in progress

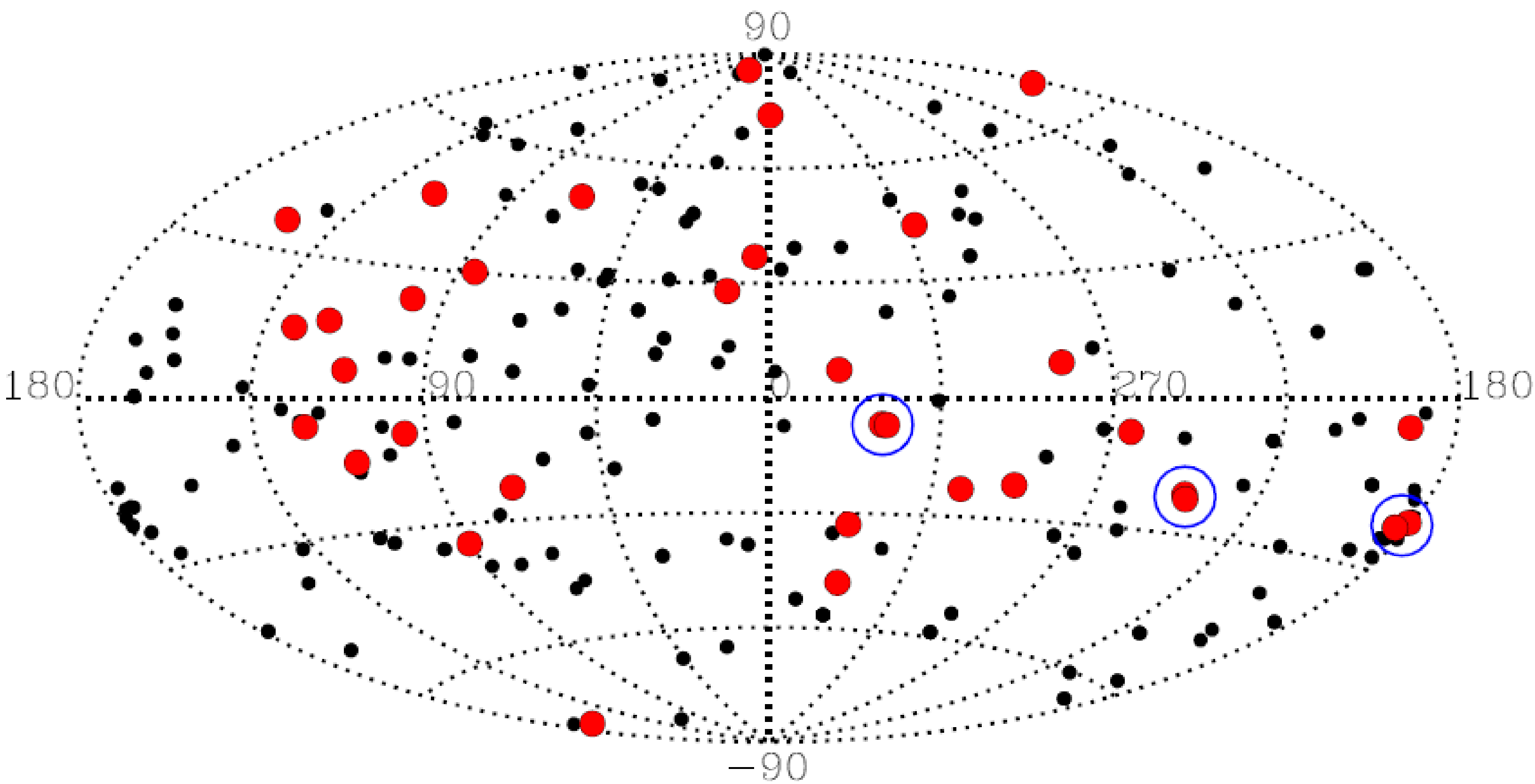
## Malamut et al.

- Based on HST/STIS SNAP survey of 34 stars.
- High-resolution E230H spectra of the Mg II and Fe II lines.
- 34 new sightlines to complement the existing H I and D I data.
- Velocity predictions based on cloud kinematics from Redfield & Linsky (2008) paper are all confirmed.

## Redfield & Linsky

- Analysis of all available data to produce a 3D model of the LISM.
- New 3D morphology model of the LIC based on 57 sightlines.
- Includes constraints of astrospheres and Strömgren sphere filler gas.
- Questions: rigid flows, new clouds, structure inside clouds, compare cores to edges, interactions, etc.

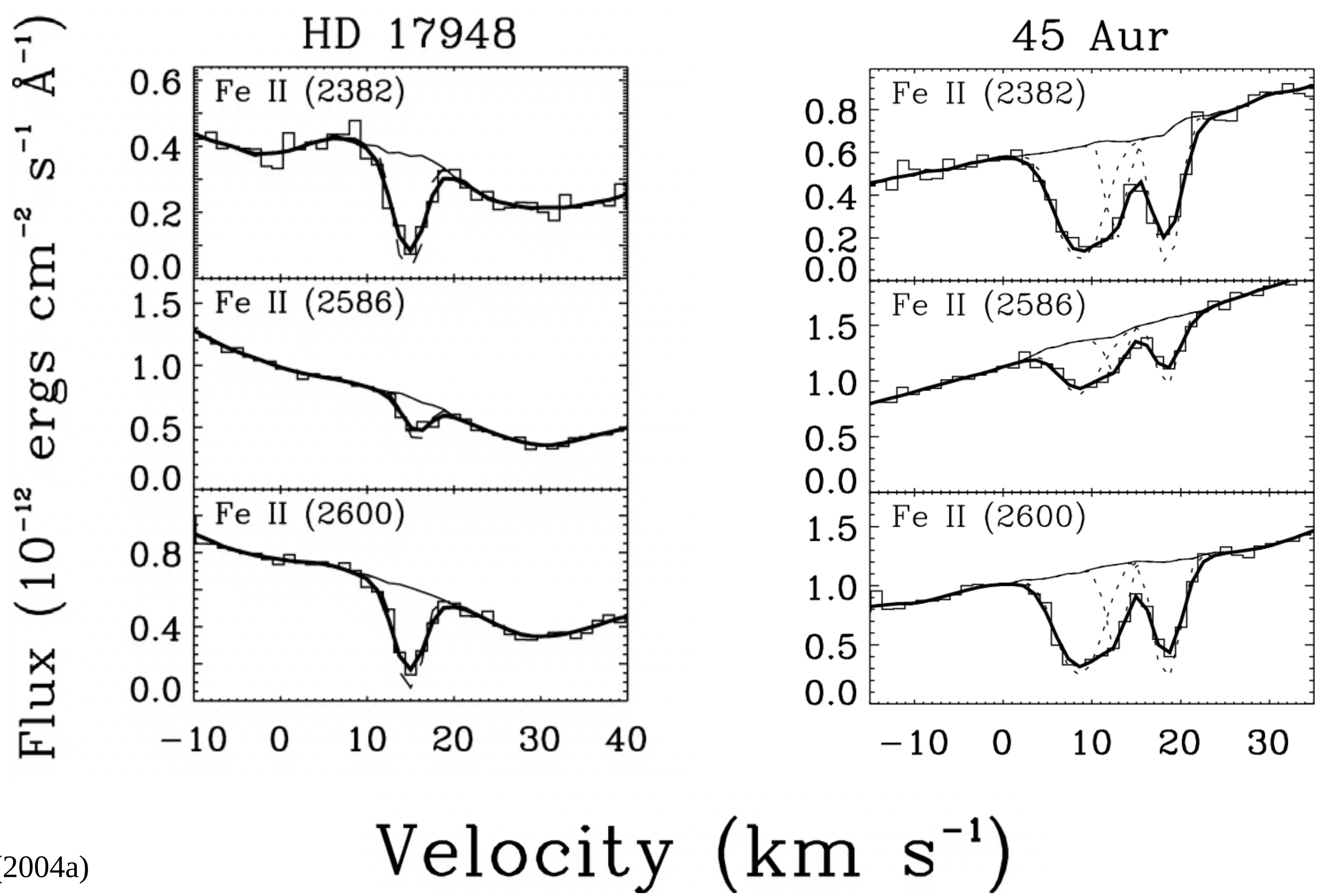
# LISM sample as of 10/2013. Red dots are lines of sight observed with the STIS SNAP program that already have FUV data.




Malamut, Redfield, Linsky, Wood, & Ayres, to be submitted.

# Observational Diagnostics

1 ion, 1 sightline → ***Velocity***, Column Density




Redfield & Linsky (2004a)

# Observational Diagnostics

1 ion, 1 sightline → ***Velocity***, Column Density

↓

multiple ions, 1 sightline → Temperature, Turbulence, Volume Density, Abundances, Depletion, Ionization Fraction

$$b^2 = \frac{2kT}{m} + \xi^2$$

$$D(X) = \log\left(\frac{X}{H}\right) - \log\left(\frac{X}{H}\right)_\odot$$

$$\frac{N_{\mathrm{CII}^*}}{N_{\mathrm{CII}}} = \frac{n_\mathrm{e} C_{12}(T)}{A_{21}}$$

# Observational Diagnostics

1 ion, 1 sightline → ***Velocity***, Column Density

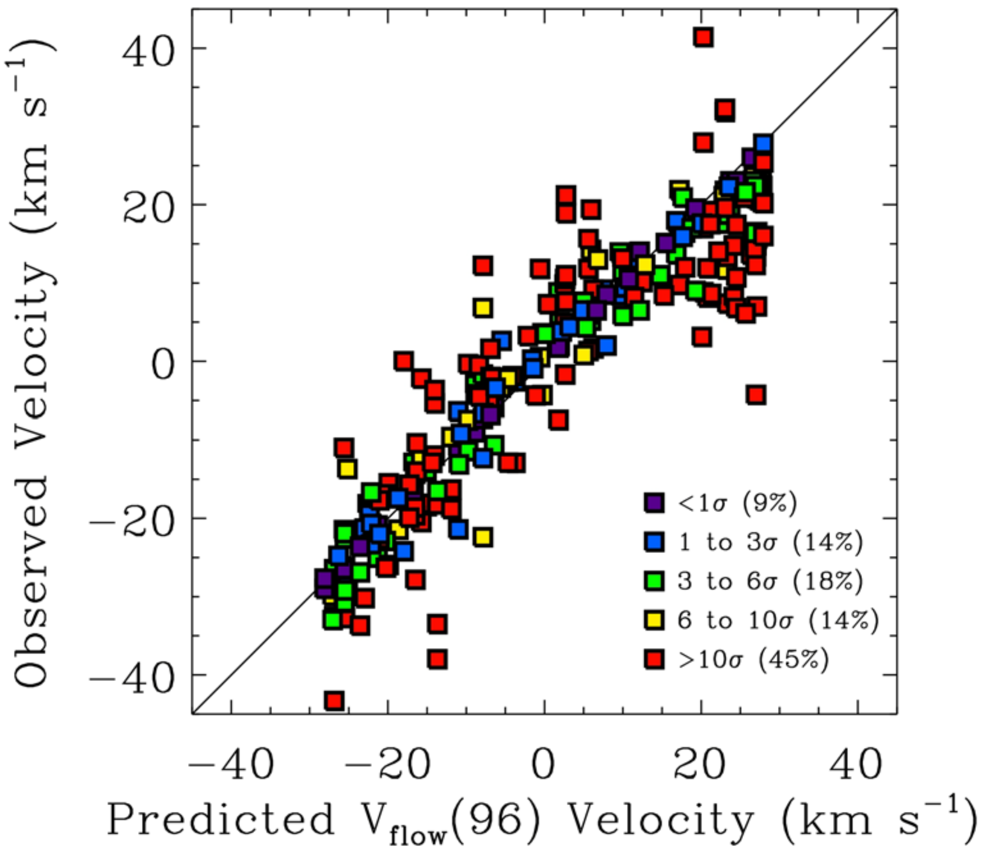
multiple ions, 1 sightline → Temperature, Turbulence, Volume Density, Abundances, Depletion, Ionization Fraction

multiple ions, multiple sightlines → Global Morphology, ***Global Kinematics***, Intercloud Variation

# Observational Diagnostics

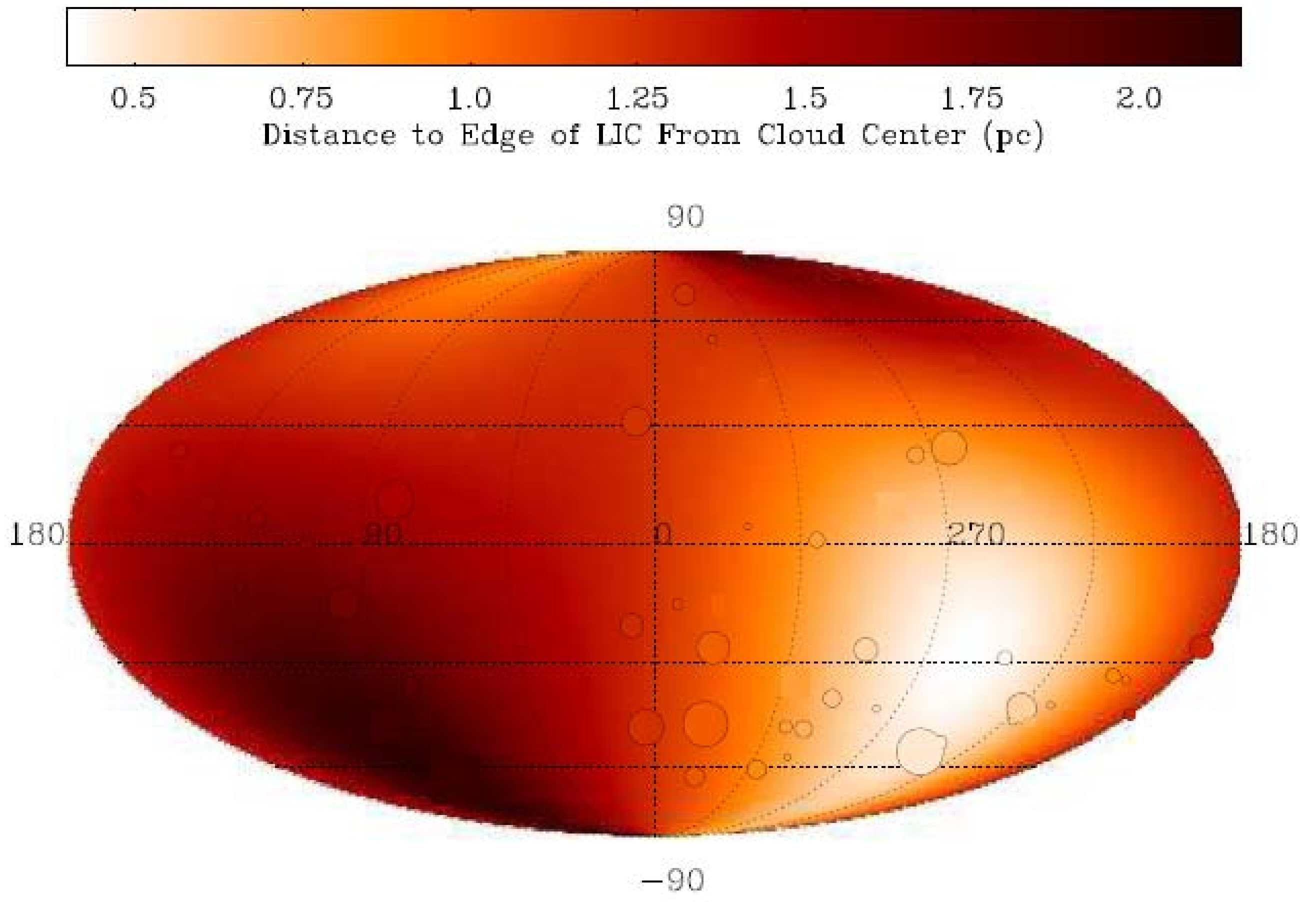
| | |
|---|---|
| 1 ion, 1 sightline → | ***Velocity***, Column Density |
| multiple ions, 1 sightline → | Temperature, Turbulence, Volume Density, Abundances, Depletion, Ionization Fraction |
| multiple ions, multiple sightlines → | Global Morphology, ***Global Kinematics***, Intercloud Variation |
| | Origin and Evolution, Interaction of LISM Phases |

# LISM Sample



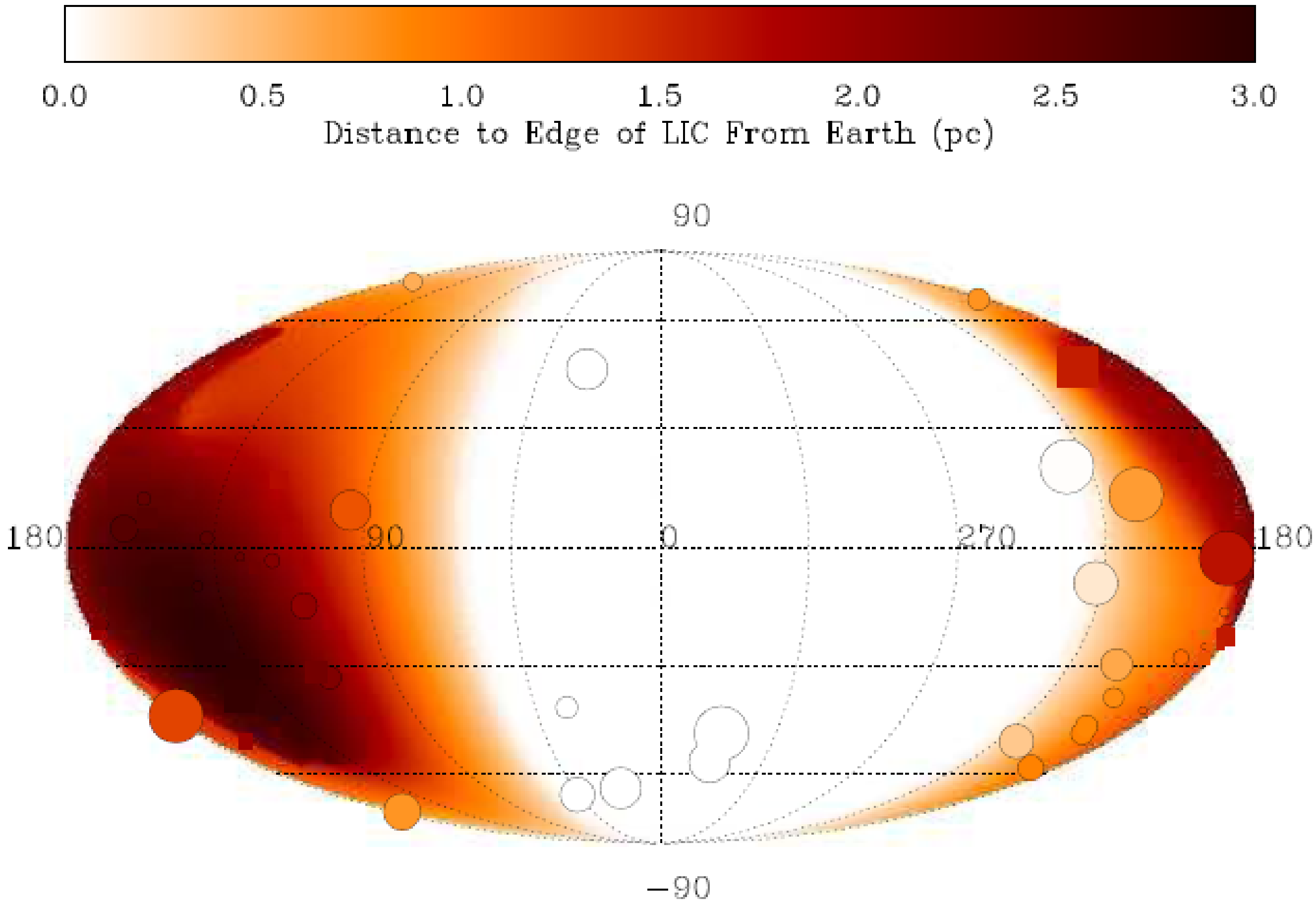
40
20
0
−20
−40
Observed Velocity (km s$^{-1}$)
−40
−20
0
20
40
Predicted $V_{flow}$(96) Velocity (km s$^{-1}$)
<1σ (9%)
1 to 3σ (14%)
3 to 6σ (18%)
6 to 10σ (14%)
>10σ (45%)

# Morphology of the Local Interstellar Cloud (LIC) as seen from cloud center



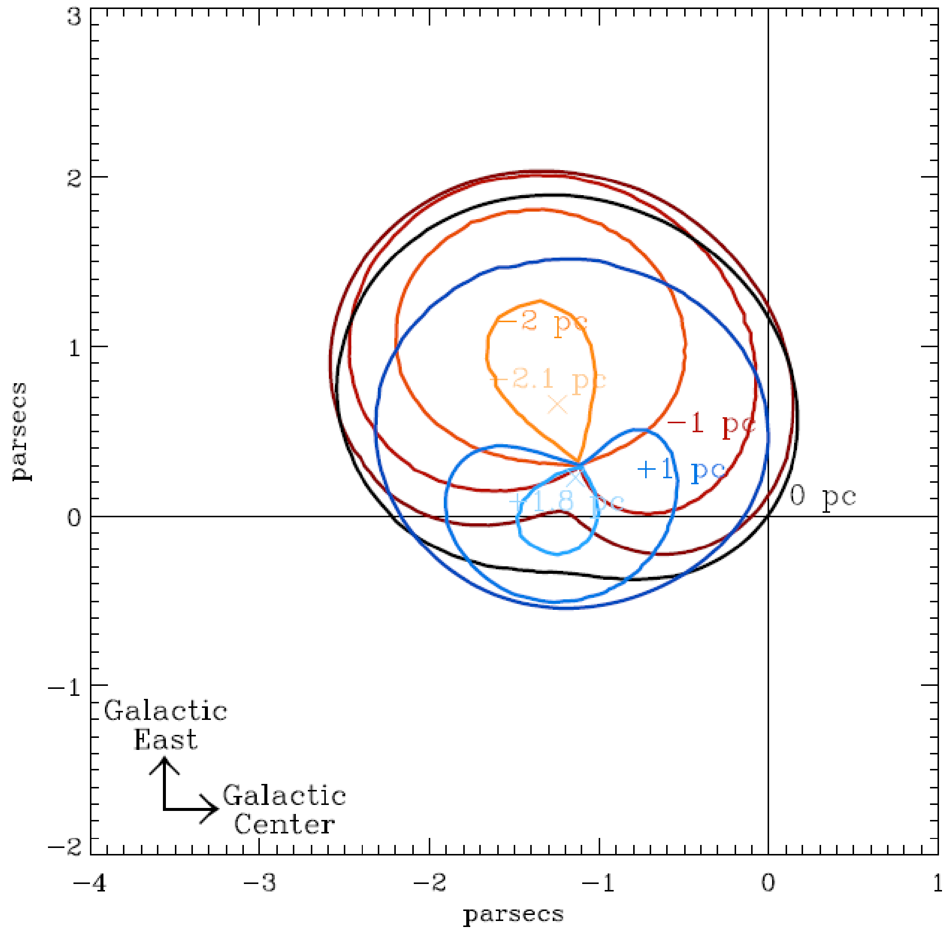

Large circles indicate nearby stars. Smallest circles indicate distant stars up to 100 pc. Distance scale assumes n(HI)=0.2 $cm^{-3}$.

# Morphology of the LIC as seen from Earth



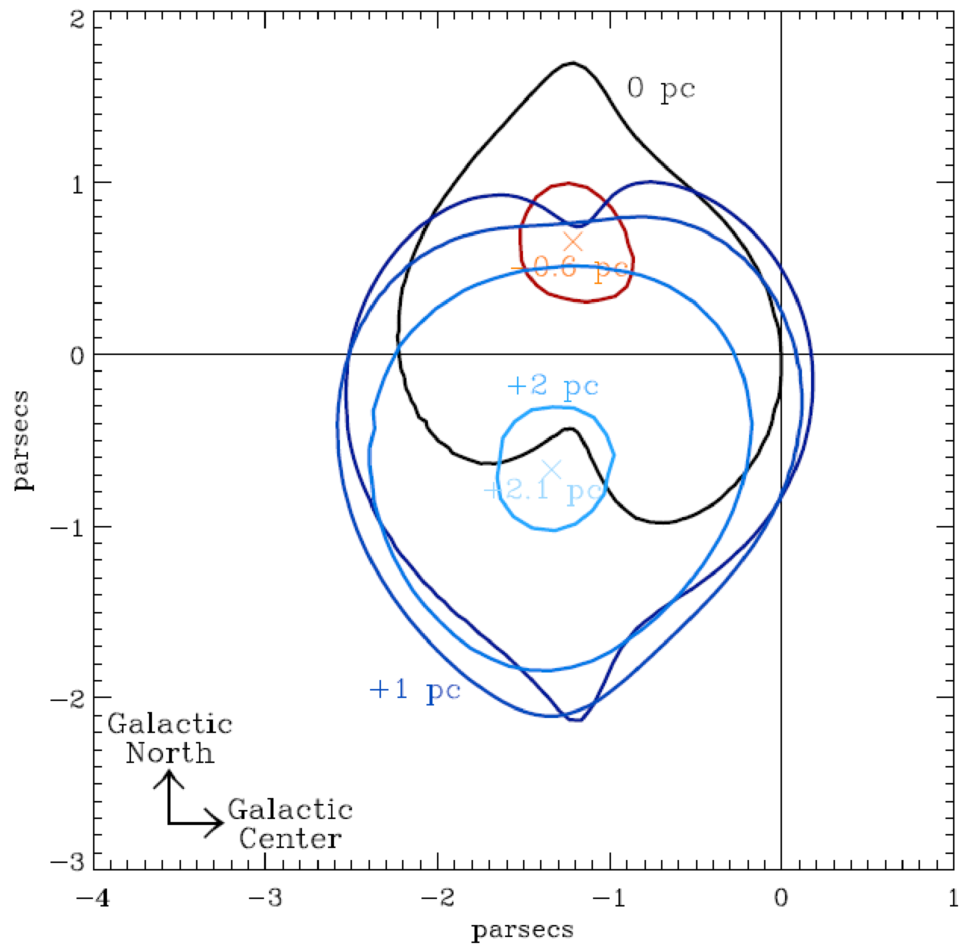

Question: Is the Sun inside or outside of the LIC?

# Contour map of the LIC as seen from the North Galactic Pole

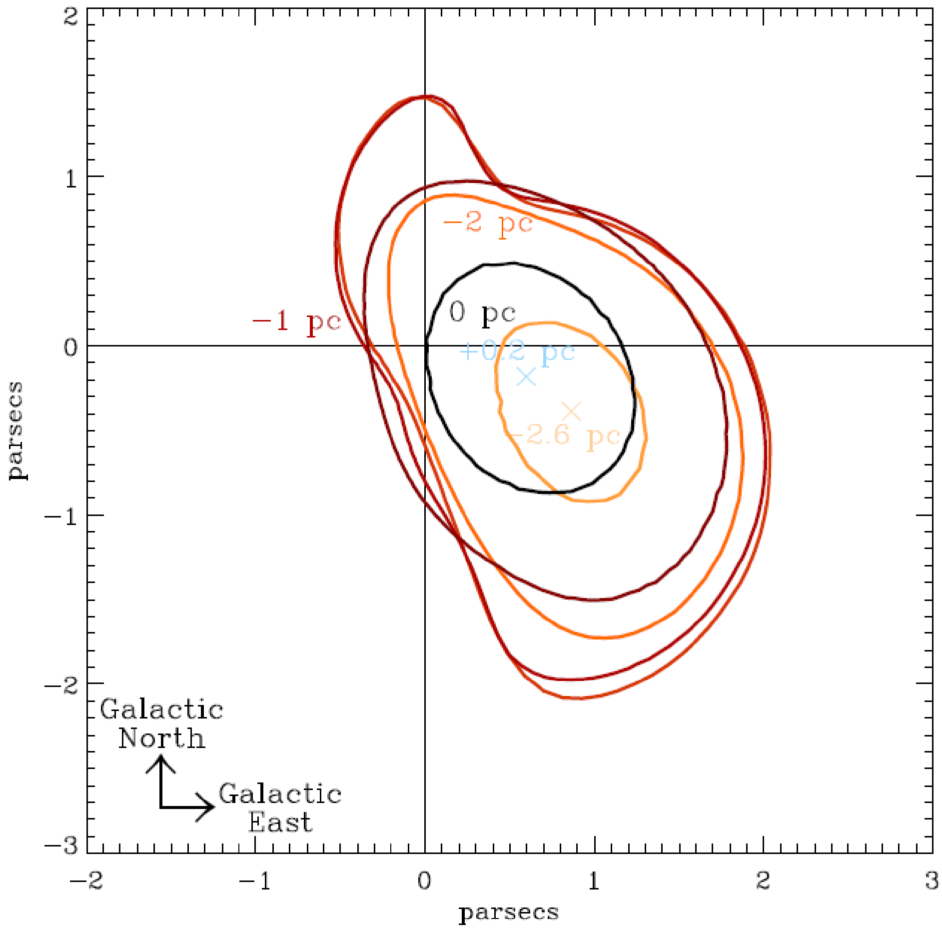



Assuming that n(HI)=0.2 $cm^{-3}$ when convert N(HI) to distance.
Based on 64 lines of sight through the LIC.

# Contour map of the LIC as seen from Galactic East

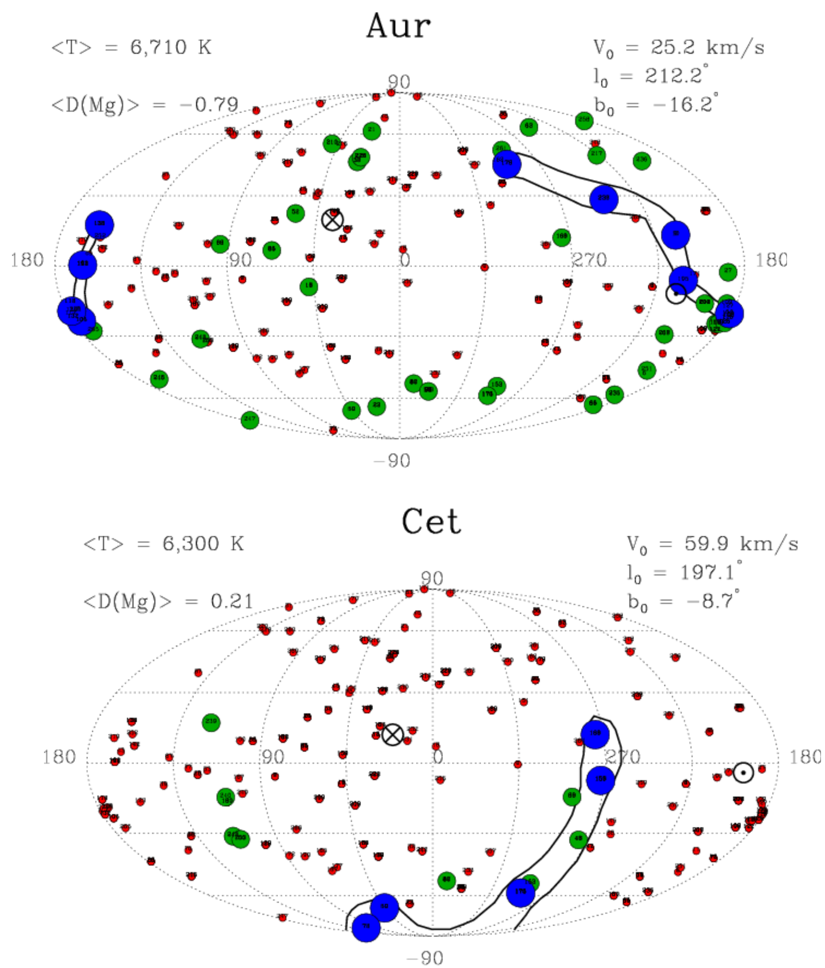


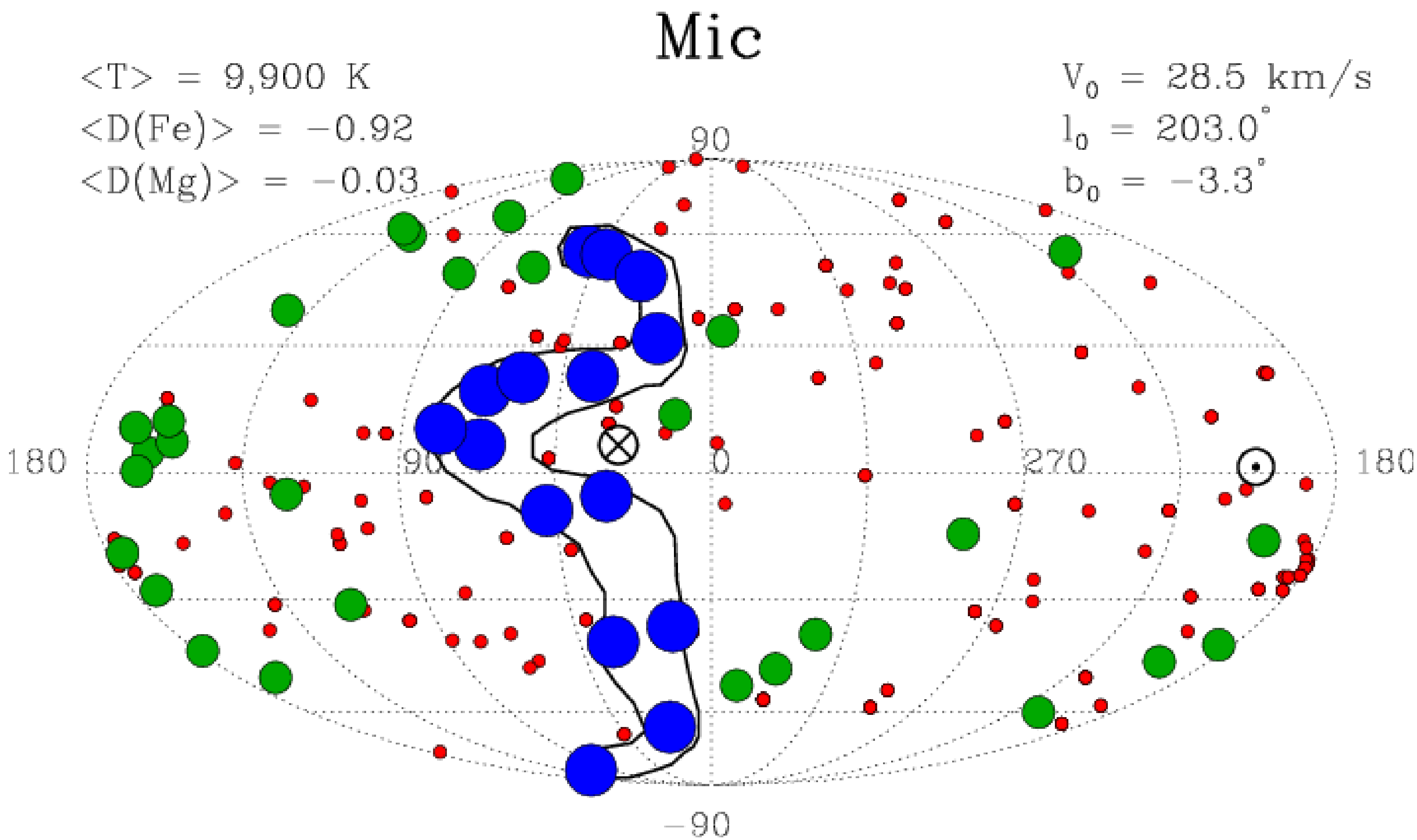
# Contour map of the LIC as seen from the Galactic Center



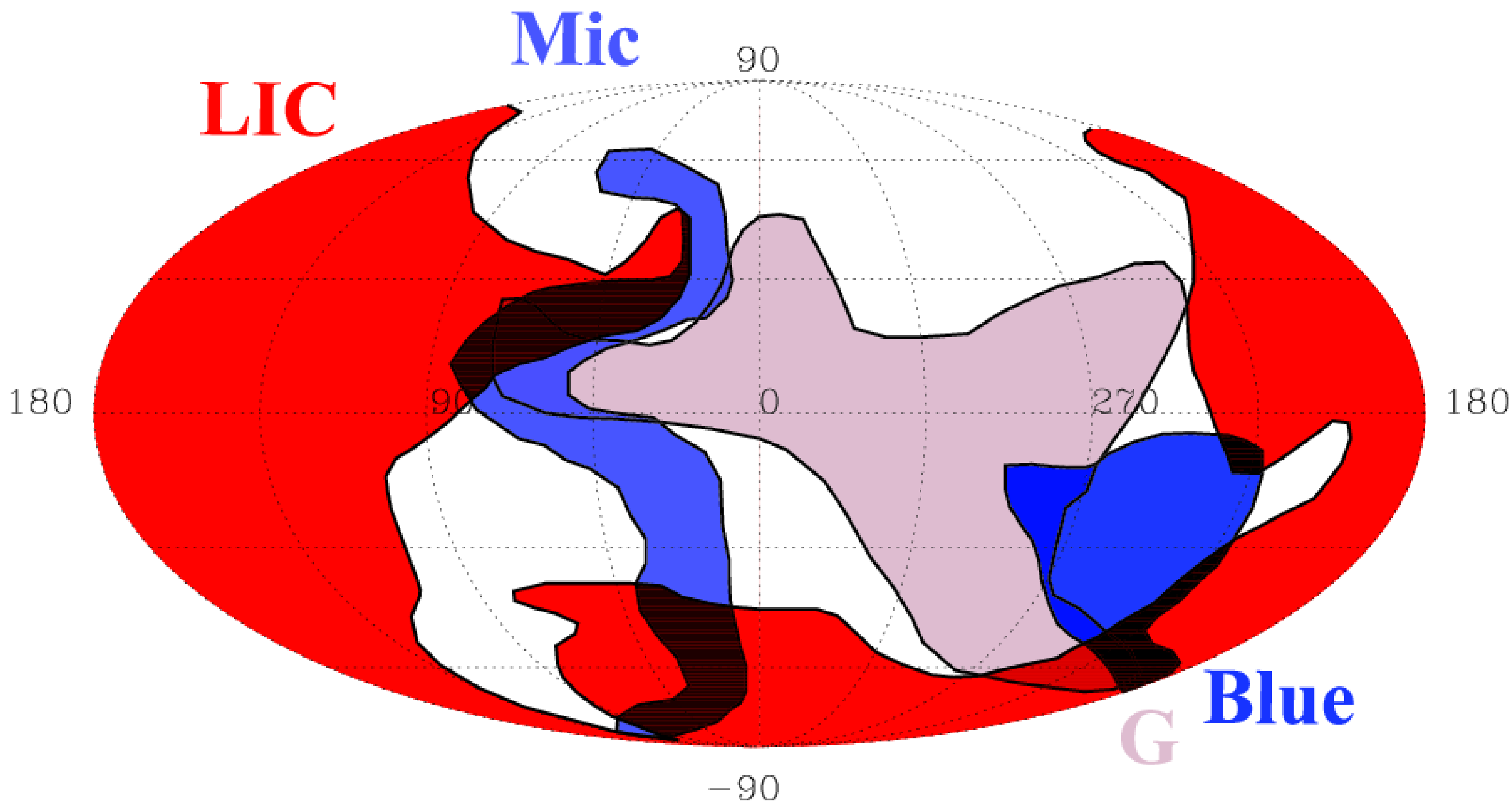
# What is the structure of warm gas clouds?

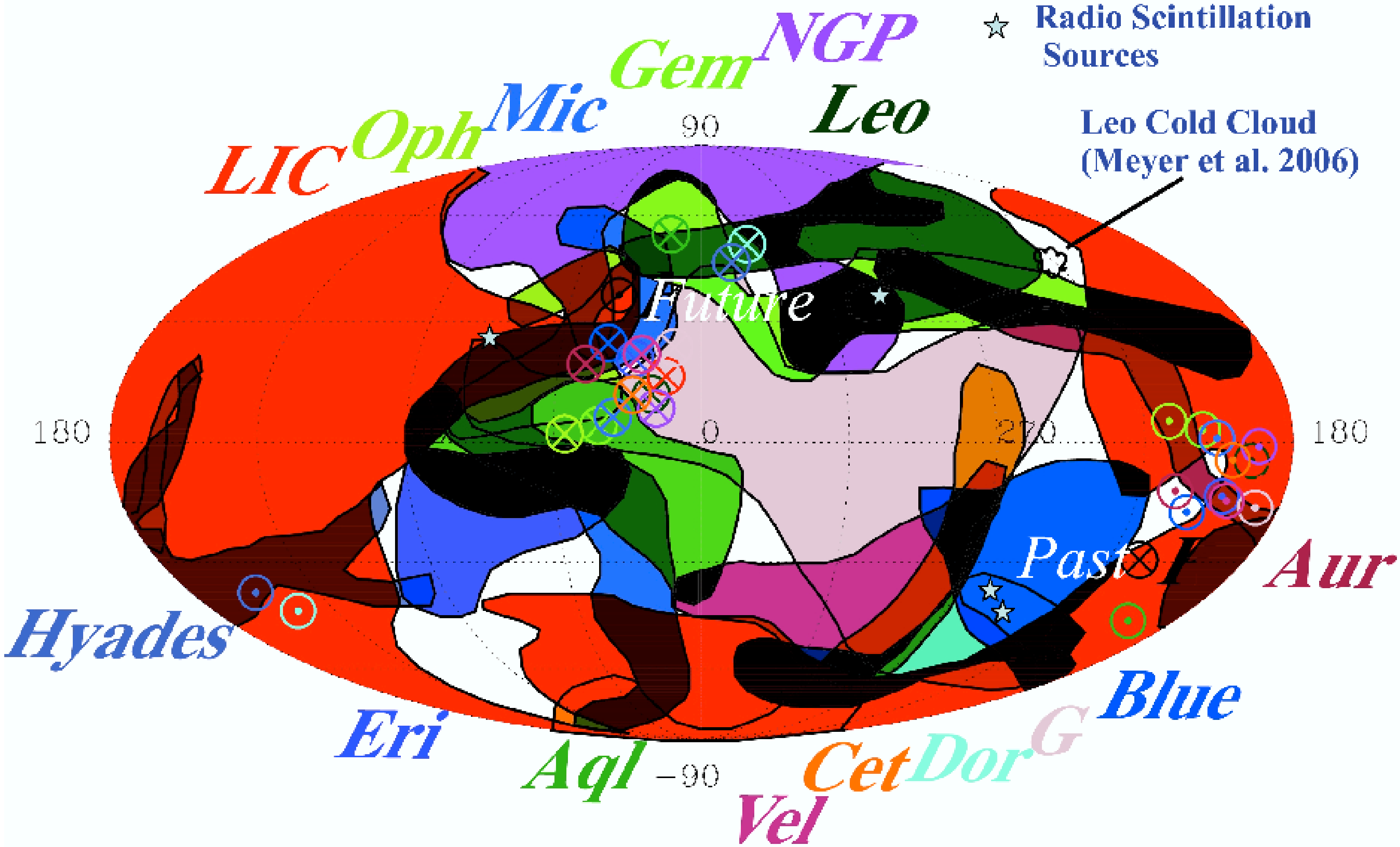
- Are thin filamentary structures typical for warm IS clouds?
- How realistic is the assumption that the clouds have rigid gas flows?
- Are clouds filled or “swiss cheese”?
- Are outer edges sharp or soft?
- What are the roles played by magnetic fields and cloud-cloud interactions?
- Figures from Redfield & Linsky (2008) ApJ 673, 283.




Mic
<T> = 9,900 K
<D(Fe)> = −0.92
<D(Mg)> = −0.03
V0 = 28.5 km/s
l0 = 203.0°
b0 = −3.3°
90
180
90
0
270
180
−90

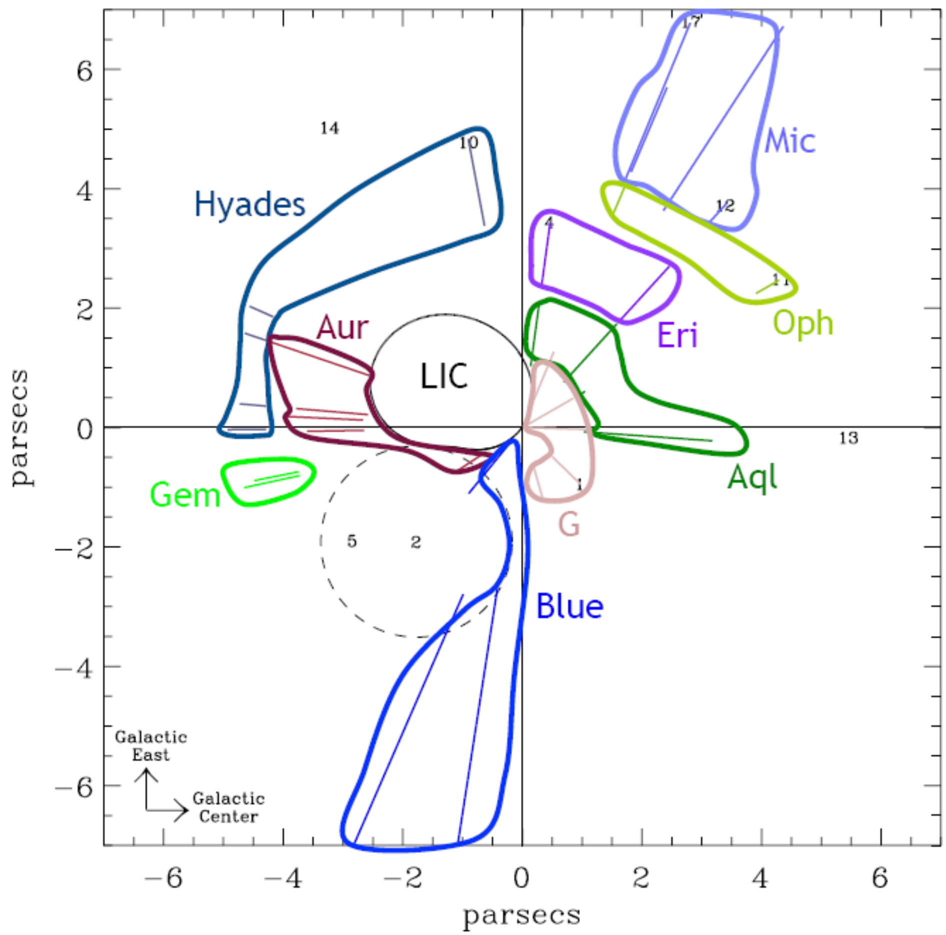
# View of 4 nearby warm clouds as seen from the Earth





Radio Scintillation Sources
Leo Cold Cloud (Meyer et al. 2006)
LIC
Oph
Mic
Gem
NGP
Leo
90
180
0
270
180
Future
Past
Aur
Hyades
Eri
Aql
-90
Vel
Cet
Dor
G
Blue

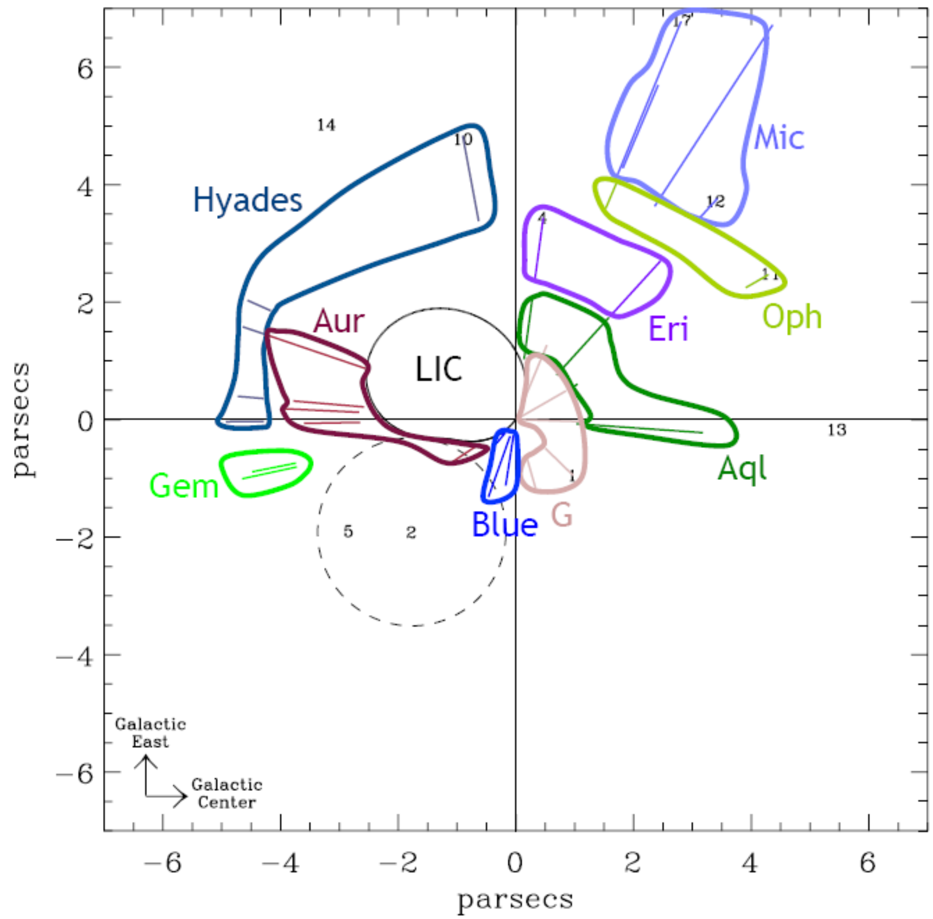
# Schematic morphological map of the LISM as viewed from the North Galactic Pole




Assuming that n(HI)=0.2 $cm^{-3}$ in all clouds.

1=α Cen; 2=Sirius B; 4=61 Cyg; 5=Procyon; 10=EV Lac; 11=70Oph; 12=α Aql; 13=36 Oph; 14=η Cas; 17=Vega. Dashed is the Strömgren sphere of Sirius B.

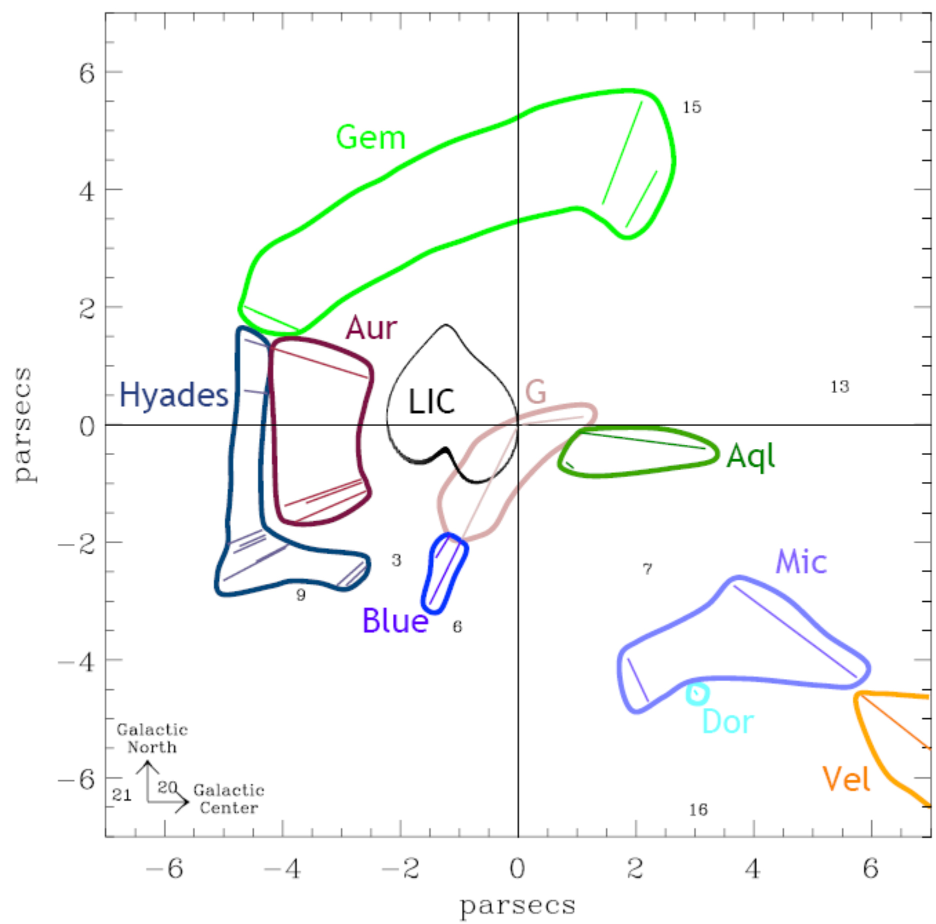
# Schematic morphological map of the LISM as viewed from the North Galactic Pole



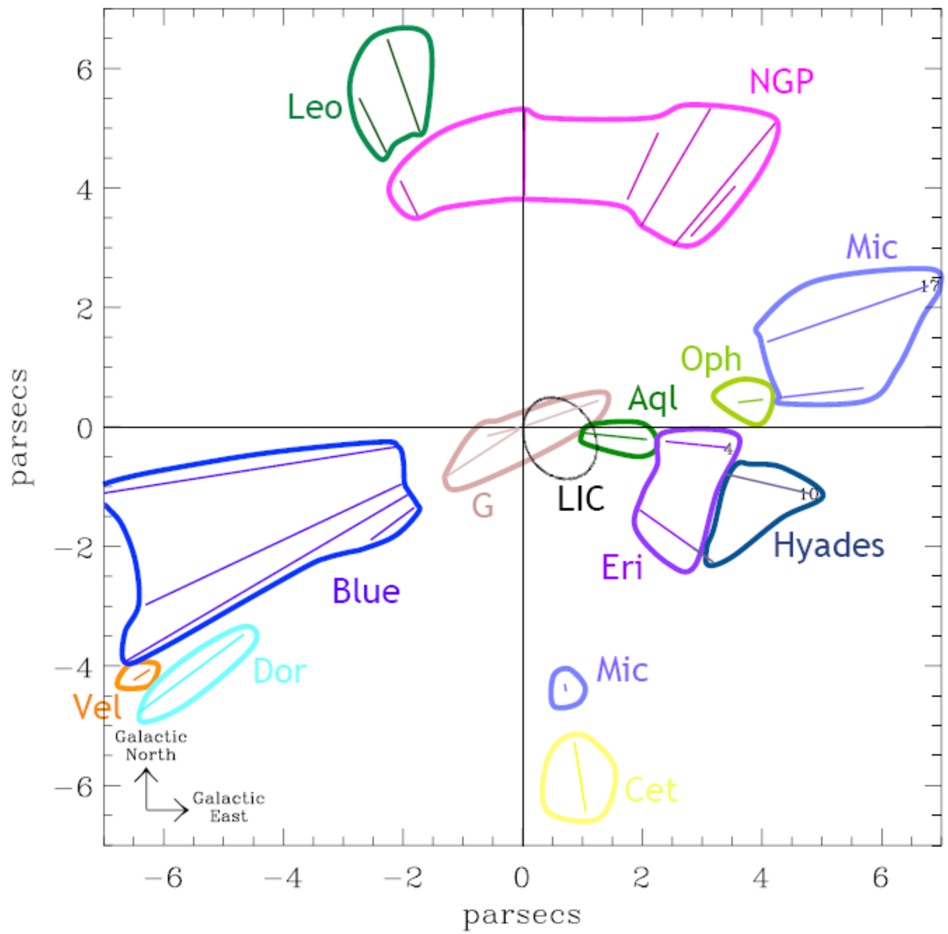

Assuming that n(HI)=1.0 $cm^{-3}$ in Blue cloud and 0.2 in other clouds.

1=α Cen; 2=Sirius B; 4=61 Cyg; 5=Procyon; 10=EV Lac; 11=70Oph; 12=α Aql; 13=36 Oph; 14=η Cas; 17=Vega. Dashed is the Strömgren sphere of Sirius B.

# Schematic morphological map of the LISM as viewed from Galactic East

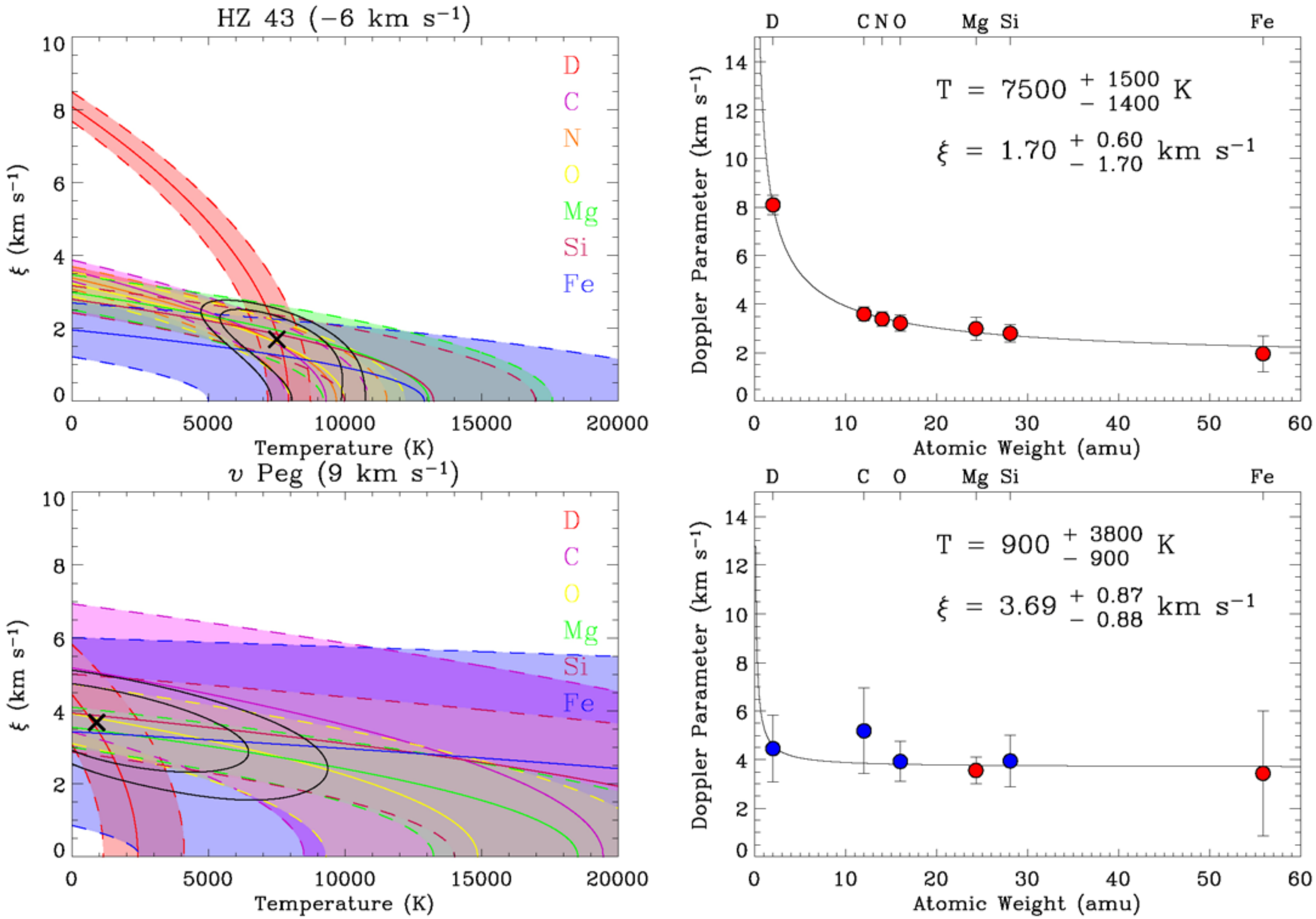


# Schematic morphological map of the LISM as viewed from the Galactic Center



# What are the Properties of the Local Interstellar Cloud (LIC)? Is this a Typical Warm Cloud?

- From Slavin & Frisch (A&A 491, 53 (2008)).
- $n(H^0)$=0.19-0.20 $cm^{-3}$
- n(e)=0.07  0.01 $cm^{-3}$ (Photoionization from ε CMa, other stars, and photoevaporation at warm cloud boundaries for harder photons)
- T≈6300  340 K (inflowing He I gas)
- Fractional H ionization ~0.2
- Heat sources: photoelectrons from ionization of H I and He I
- Cooling: [C II] 157.6μm, [S II] 6731Å, other lines
- $P_{th}/k$=2100 $cm^{-3}$K, $P_{th}=P_{mag}$ at B~2.7μG
- Inflow velocity 26.3 km/s from Sco-Cen Association
- LIC assumed to be in ionization, thermal, and dynamic equilibrium




$$b^2 = \frac{2kT}{m} + \xi^2$$

Redfield & Linsky (2004b)

# Distributions of temperatures and nonthermal broadening for warm clouds in the Local Bubble with HST spectra (Redfield and Linsky ApJ 613, 1004 (2004))

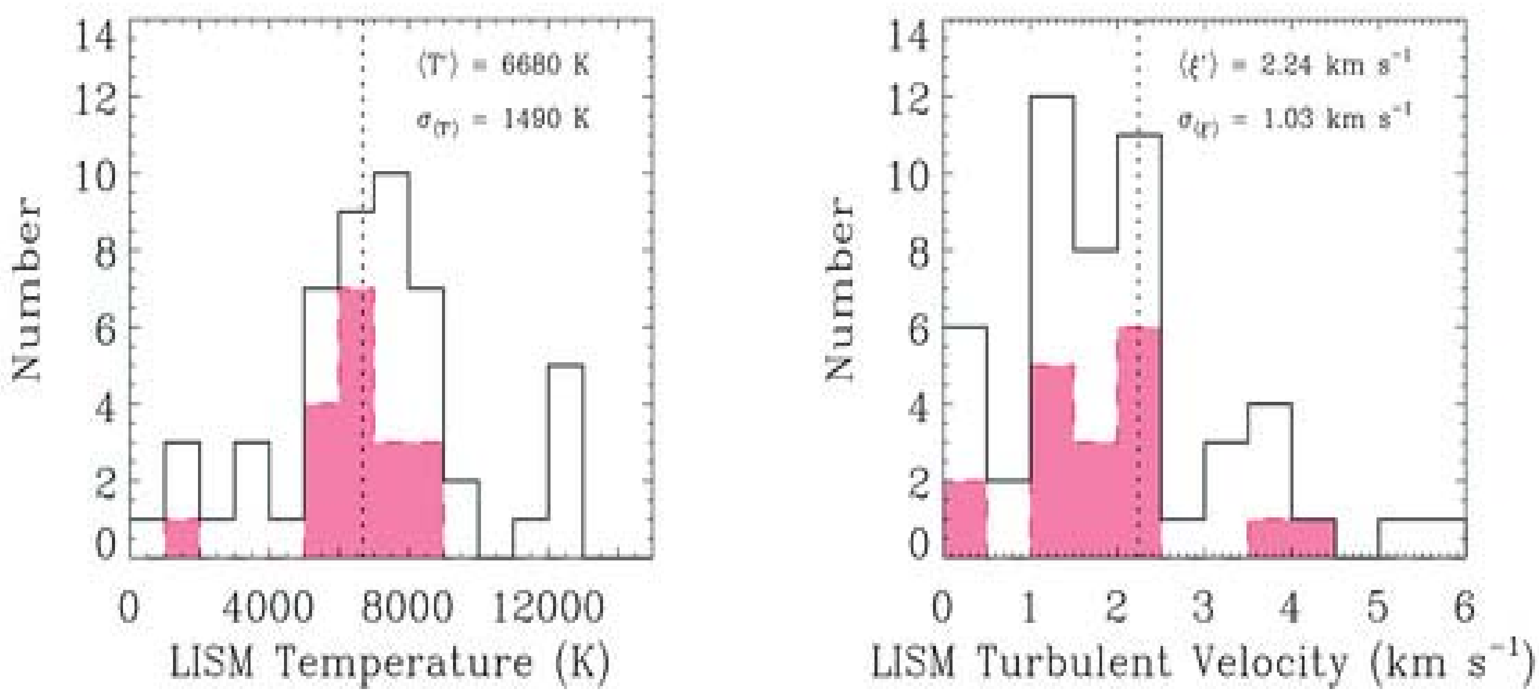


Table 1. Summary of Cloud Properties

| Cloud Name | Number of Stars | Central Coordinates $l(^\circ)$ | $b(^\circ)$ | Closest Star (pc) | $< T >$ (K) | $< D(Fe) >$ |
|---|---|---|---|---|---|---|
| G | 21 | 315 | +00 | 1.3 | 5500 | –0.54 |
| LIC | 78 | 170 | −10 | 2.6 | 7500 | –1.12 |
| Blue | 10 | 250 | −30 | 2.6 | 3900 | –0.84 |
| Eri | 8 | 70 | −20 | 3.5 | 5300 | –0.39 |
| Aql | 9 | 40 | −05 | 3.5 | 7000 | –0.96 |
| Aur | 9 | 210 | +10 | 3.5 | 6710 | |
| Hyades | 14 | 180 | −20 | 5.0 | 6200 | –0.32 |
| Mic | 15 | 40 | +15 | 5.1 | 9900 | –0.92 |
| Oph | 6 | 45 | +25 | 5.1 | 1700 | |
| Gem | 10 | 300 | +40 | 6.7 | 6000 | –1.29 |
| NGP | 15 | 5 | +75 | 8.5 | 8000 | –1.04 |
| Leo | 7 | 270 | +55 | 11.1 | | |
| Dor | 4 | 270 | −50 | 11.7 | 7000 | –0.80 |
| Vel | 6 | 300 | −45 | 14.9 | 10600 | |
| Cet | 5 | 290 | −40 | 15.5 | 6300 | |

# Is the Sun located inside the LIC or the G Cloud? (Redfield & Linsky ApJ 673, 283 (2008))

| Parameter | Interstellar He atoms inside the heliosphere | LIC R+L(2008) | G Cloud R+L(2008) |
|---|---|---|---|
| V (km/s) (upwind) | 26.24  0.45 (Möbius et al. 2004) | 23.84  0.90 (79 LOS) | 29.6  1.1 (21 LOS) |
| T (K) | 6300  390 (Möbius et al. 2004) | 7500  1300 (19 LOS) | 5500  400 (5 LOS) |

Is the Sun located inside the LIC or the G Cloud?
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| Parameter | Interstellar He atoms inside the heliosphere | LIC R+L(2008) | G Cloud R+L(2008) |
|---|---|---|---|
| V (km/s) (upwind) | $23.5^{+3.0}_{-2.0}$ (Möbius et al. 2012) | 23.84  0.90 (79 LOS) | 29.6  1.1 (21 LOS) |
| T (K) | 5000-8200 (Möbius et al. 2012) | 7500  1300 (19 LOS) | 5500  400 (5 LOS) |

# Is the Sun located inside the LIC or the G Cloud? (Redfield & Linsky ApJ 673, 283 (2008))

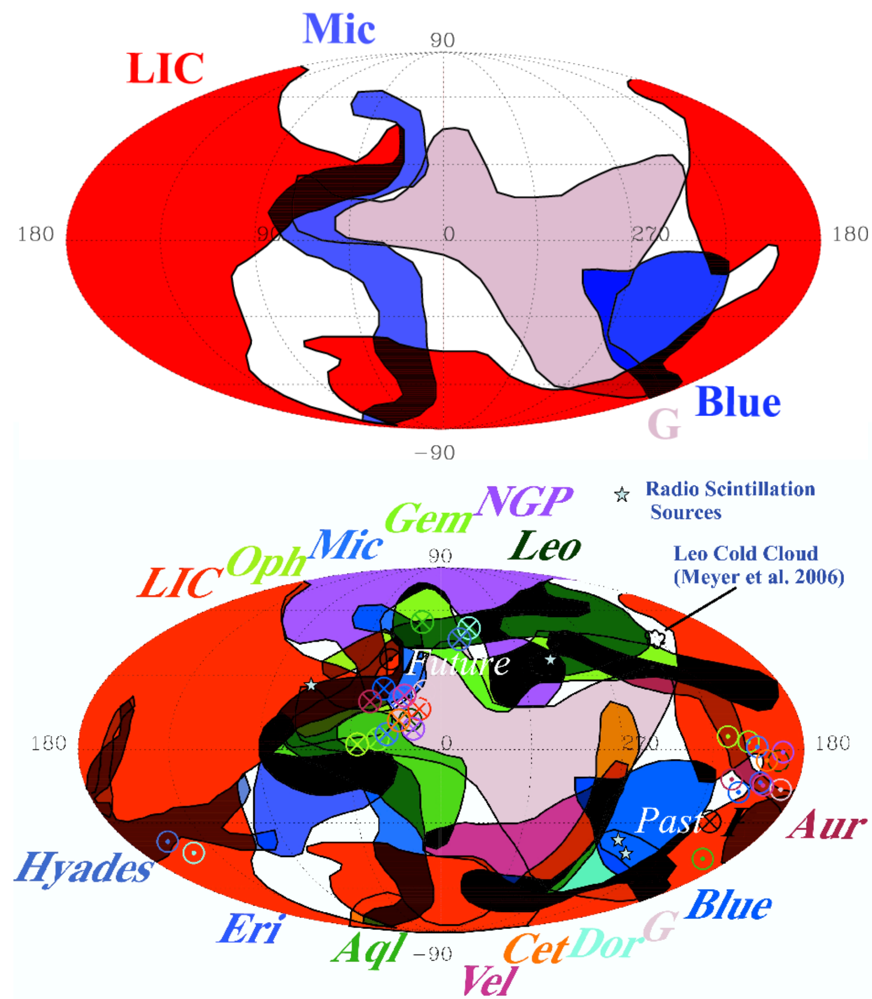
| Parameter | Interstellar He atoms inside the heliosphere | LIC R+L(2008) | G Cloud R+L(2008) |
|---|---|---|---|
| V (km/s) (upwind) | 23.2  0.3 (McComas et al. 2012) | 23.84  0.90 (79 LOS) | 29.6  1.1 (21 LOS) |
| T (K) | 6300  390 (McComas et al. 2012) | 7500  1300 (19 LOS) | 5500  400 (5 LOS) |

If the values reported here settle around their current center value, after reducing the error bars, we may find ourselves still fully in the LIC. However, such a conclusion should await further refinement of the analysis.

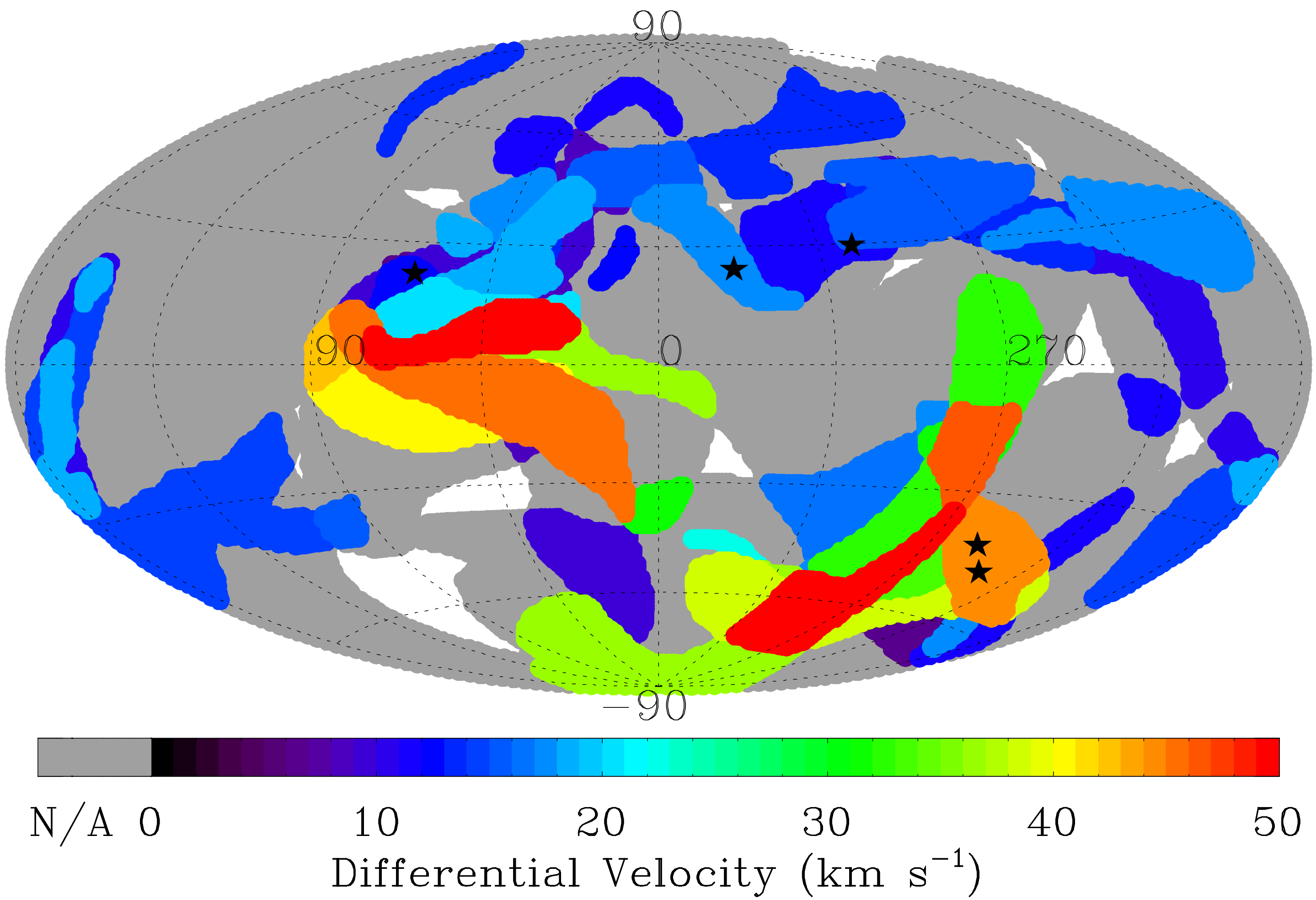
Möbius et al. (ApJS 198, 11 (2012))

# What happens when interstellar clouds interact?

- 15 warm clouds within 15 pc of Sun. Shapes determined by kinematics (velocity vectors) from high-resolution STIS and GHRS data (Redfield & Linsky 2008).
- Mic and Blue clouds may be due to compression.
- Radio scintillation screens where clouds interact (Linsky et al. ApJ 675, 413).
- Leo cold cloud probably surrounded by warm gas.
- Relative cloud motions often supersonic (>8 km/s).
- More sightlines and T measurements from UV absorption line widths in progress.



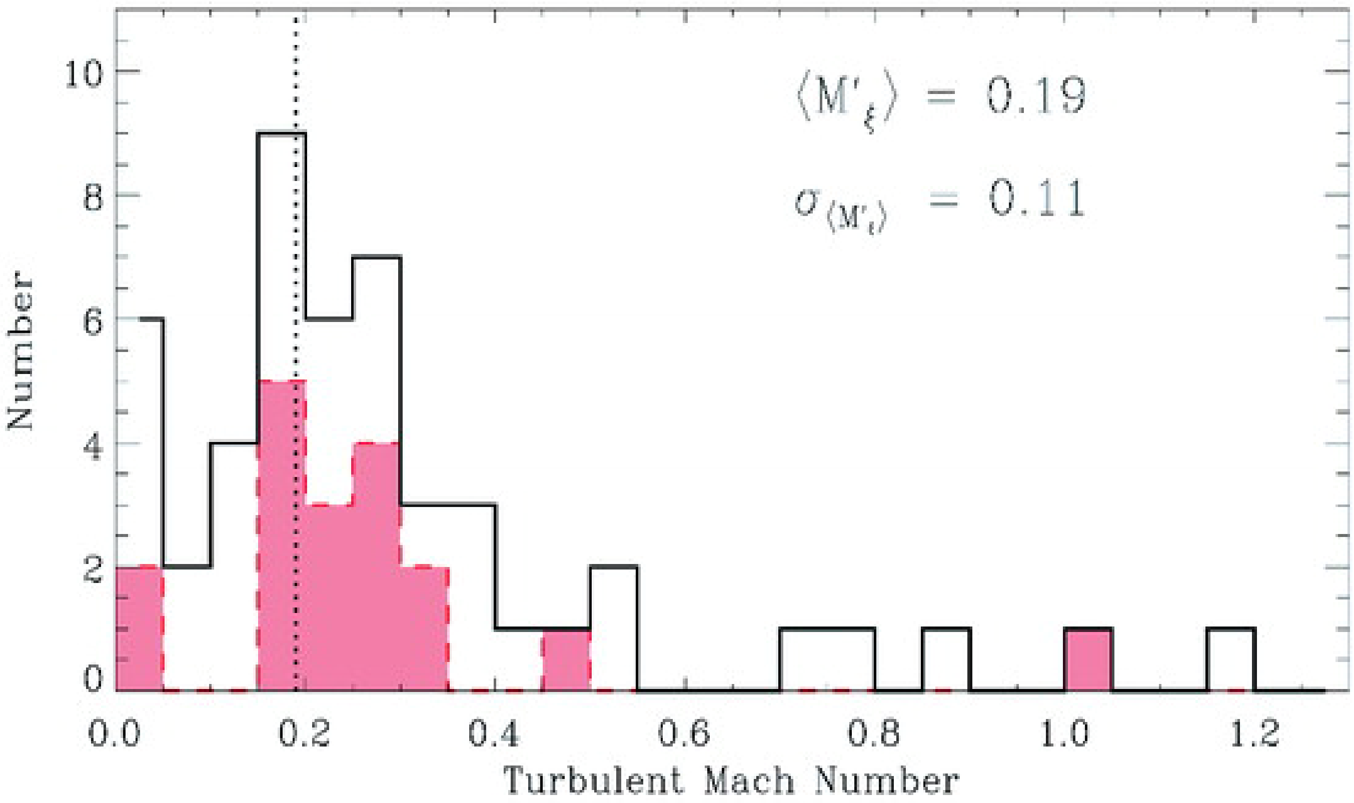
# Differential velocity between LISM clouds along same line of sight. Large amplitude scintillating quasars are indicated



# Could the Mic cloud be a shock front or a compressed cloud?

- Shape similar to the LIC-G interface.
- Velocity difference between the LIC and G clouds is 9.2 km/s (similar to the shock speed).
- Temperature of the Mic cloud is the largest of the 15 local clouds (9900  2000 K).
- Turbulence of the Mic cloud is the largest of the 15 local clouds (3.1  1.0 km/s).
- Depletion of metals is smallest of the 15 local clouds.

# Warm cloud turbulence is very subsonic



# What fills the space between the warm partially-ionized gas clouds?

- Most/all of the diffuse soft X-ray emission is produced by charge-exchange between solar wind ions and interstellar H (Snowden, Koutroumpa). No evidence for hot gas nearby.
- Filler gas could be ionized and warm (T~20,000 K) (Welsh+Shelton 2009).
- Filler gas could be Strömgren sphere gas (T~10,000 K) ionized by hot stars and WDs (Tat&Terzian 1999).
- Warm partially ionized cloud gas could be Strömgren sphere shells (recombining gas). Thickness ≈ 0.2 [0.2/n(HI)] pc.

Table 8. Hot White Dwarfs and their Strömgren Sphere Radii

| WD | $l$ | $b$ | $d$(pc) | R(7,500K) | R(10,000K) | R(15,000K) | R(20,000K) | R($n_e = 0.03$) |
|---|---|---|---|---|---|---|---|---|
| Sirius B | 227.2 | –9.9 | 2.64 | 1.29 | 1.56 | 2.04 | 2.48 | 4.12 |
| Sirius A+B | 227.2 | –9.9 | 2.64 | 1.59 | 1.93 | 2.51 | 3.05 | 5.08 |
| 40 Eri B | 200.8 | –38.0 | 5.04 | 0.37 | 0.44 | 0.58 | 0.70 | 1.17 |
| GJ3753 | 123.3 | +62.0 | 14.1 | 0.75 | 0.91 | 1.18 | 1.44 | 2.39 |
| GJ433.1 | 284.9 | +27.7 | 14.8 | 0.72 | 0.88 | 1.14 | 1.39 | 2.31 |
| UZ Sex | 245.3 | +46.3 | 18.2 | 0.52 | 0.63 | 0.82 | 0.99 | 1.65 |
| GD 50 | 188.9 | –40.1 | 29. | 1.55 | 1.88 | 2.47 | 2.99 | 4.11[a] |
| G191-B2B | 155.9 | +7.1 | 59. | 6.75 | 8.18 | 10.72 | 12.98 | 17.86[a] |
| HZ 43 | 54.1 | +84.2 | 68. | 3.88 | 4.70 | 6.16 | 7.47 | 10.27[a] |
| Feige 24 | 166.0 | –50.3 | 74. | 7.88 | 9.55 | 12.51 | 15.16 | 20.85[a] |
| $\epsilon$ CMa | 239.8 | –11.3 | 124. | 26.2 | 31.7 | 41.5 | 50.3 | 69.2[a] |
| $\beta$ CMa | 226.1 | –14.3 | 151. | 10.4 | 12.6 | 16.5 | 20.0 | 27.5[a] |
| $n_e$ | | | | 0.172 | 0.129 | 0.0860 | 0.0645 | 0.03 |
| $(n_e/0.03)^{-2/3}$ | | | | 0.313 | 0.379 | 0.495 | 0.601 | 1.00 |
| $(n_e/0.04)^{-2/3}$ | | | | 0.378 | 0.458 | 0.600 | 0.727 | 1.00 |

[a] R($n_e = 0.04$).

Strömgren sphere radius: $R^3=(3/4\pi n_i n_e \alpha)dN_i/dt$

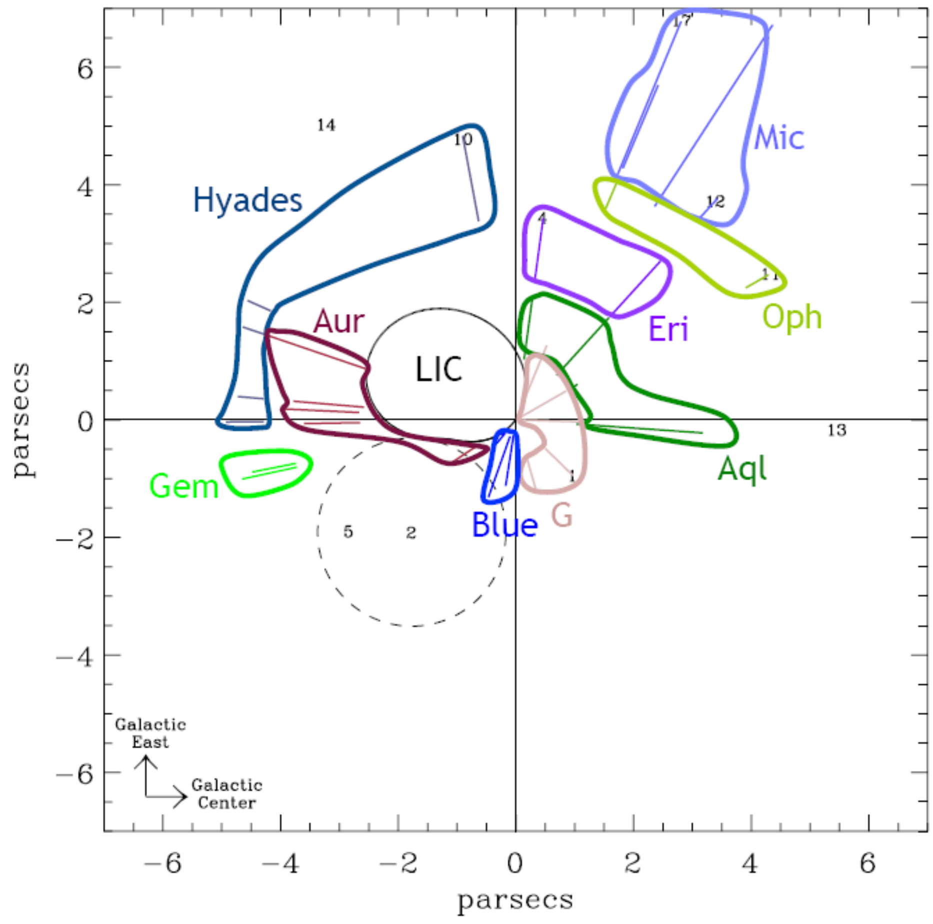
Table 7. Composition of Gas Along Selected Lines of Sight

| Star | $l$ | $b$ | $d$(pc) | Cloud | log[N(HI)] | $\Delta d$(neutral) | $\Delta d$(ionized) |
|---|---|---|---|---|---|---|---|
| $\alpha$ Cen[a] | 315.7 | –0.9 | 1.32 | G | 17.6 | 0.70 | 0.62 |
| Sirius A | 227.2 | –8.9 | 2.64 | LIC | 17.4 | 0.44 | |
| | | | | Blue | 17.2 | 0.28 | |
| | | | | Sum | | 0.72 | 1.92 |
| $\epsilon$ Eri[a] | 5.8 | –48.1 | 3.22 | LIC | 17.8 | 1.10 | 2.12 |
| 61 Cyg[a] | 82.3 | –5.8 | 3.49 | Aql | 17.8 | 1.10 | |
| | | | | Eri | 17.8 | 1.10 | |
| | | | | Sum | | 2.20 | 1.29 |
| Procyon | 213.7 | +13.0 | 3.51 | LIC | 17.9 | 1.56 | |
| | | | | Aur | 17.6 | 0.70 | |
| | | | | Sum | | 2.26 | 1.25 |
| $\epsilon$ Ind[a] | 336.2 | –48.0 | 3.63 | LIC | 16.6 | 0.14 | 3.49 |
| 61 Vir[a] | 311.9 | +44.1 | 8.53 | NGP | (18.0) | (1.7) | (6.8) |
| $\beta$ Com | 43.5 | +85.4 | 9.15 | NGP | (18.0) | (1.7) | (7.4) |
| $\pi^1$ UMa | 150.6 | +35.7 | 14.6 | LIC | 17.85 | 2.30 | 12.3 |
| $\tau$ Boo | 358.9 | +73.9 | 15,6 | NGP | (18.0) | (1.7) | 13.9 |
| 51 Peg | 90.1 | –34.7 | 15.6 | Eri | (17.9) | (1.6) | |
| | | | | Hya | (17.4) | (0.4) | |
| | | | | Sum | | (2.0) | (13.6) |
| $\chi$ Her[b] | 67.7 | +50.3 | 15.9 | NGP | (18.0) | (1.7) | 14.2 |

[a]Astrosphere detected by Wood et al. (2005) indicates that a cloud with neutral hydrogen must surround the star.

[b]No astrosphere detected by Wood et al. (2005).

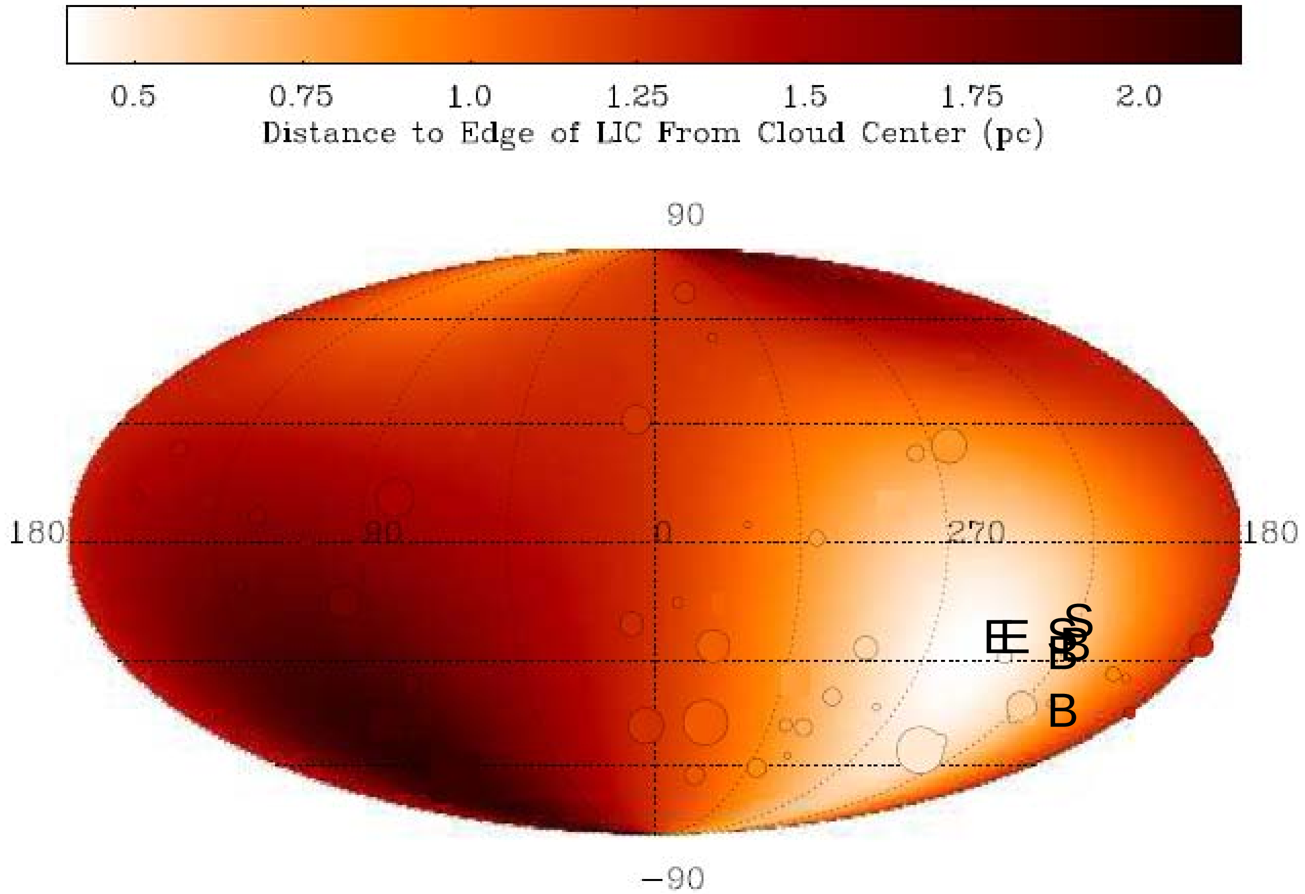
# Schematic morphological map of the LISM as viewed from the North Galactic Pole




Assuming that n(HI)=1.0 $cm^{-3}$ in Blue cloud and 0.2 in other clouds.

1=α Cen; 2=Sirius B; 4=61 Cyg; 5=Procyon; 10=EV Lac; 11=70Oph; 12=α Aql; 13=36 Oph; 14=η Cas; 17=Vega. Dashed is the Strömgren sphere of Sirius B.

# Morphology of the Local Interstellar Cloud (LIC) as seen from cloud center




S=Sirius B

E=ε CMa

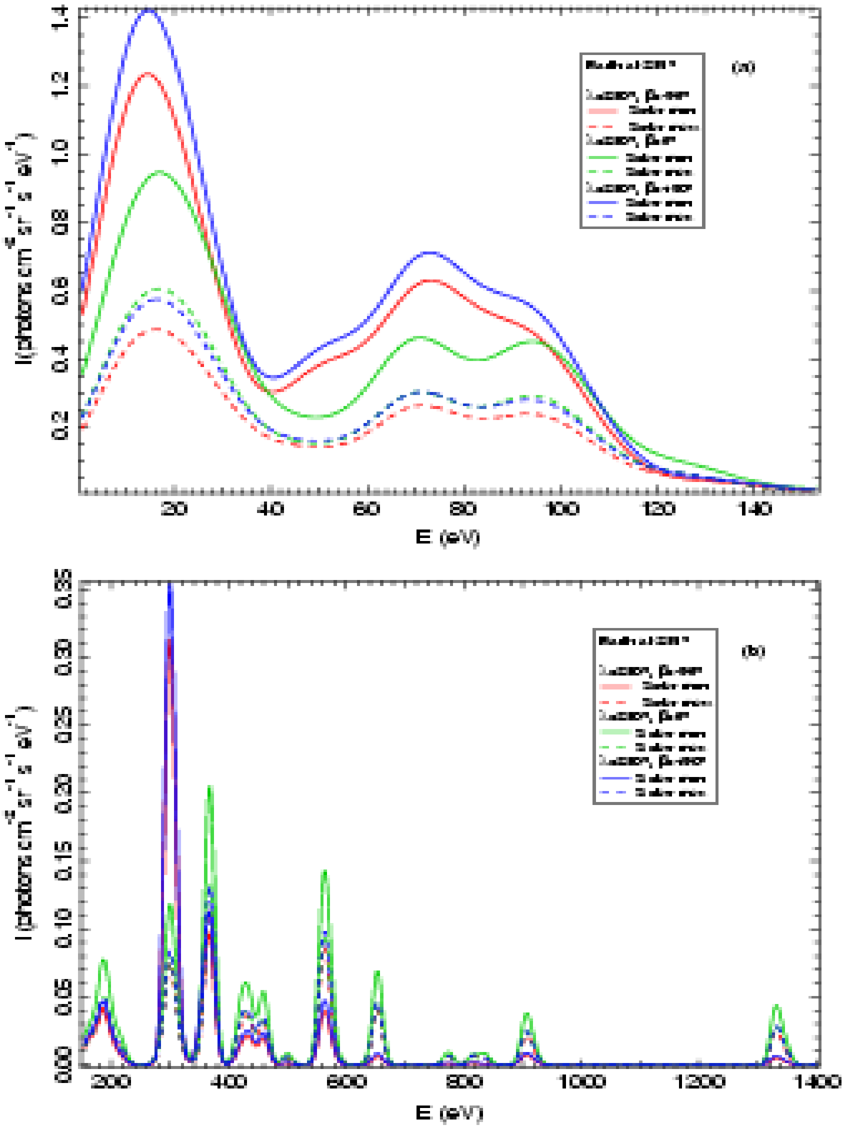
B=β CMa

Epsilon CMa (B2 Iab, d=124 pc) is the brightest EUV source observed by EUVE (Vallerga & Welsh ApJ 444, 702 (1995)).

Thank you

# Could the soft X-ray background be foreground? (Koutroumpa et al. A+A 460, 289 (2006))

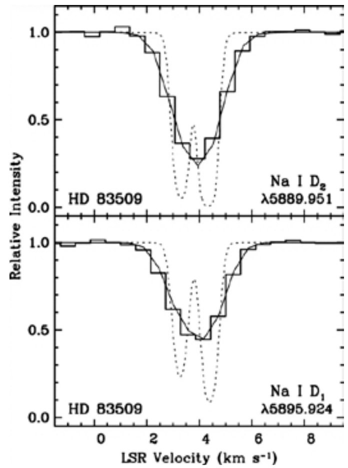
- Calculation of EUV/soft X-ray emission from charge transfer between solar wind heavy ions and interstellar neutral atoms.
- Solid lines are: N ecliptic pole, South ecliptic pole, equitorial antisolar. Solid: solar min. Dashed: solar max.
- Important emission ions: C VI, O VII, O VIII, Ne IX, and Mg XI.
- A large fraction of the EUV and soft X-ray background is heliospheric foreground.
- Earlier studies by Cravens and Lallement with similar conclusion.
- Welsh & Shelton (2009) argue that most of the LB is filled with highly-ionized warm gas.

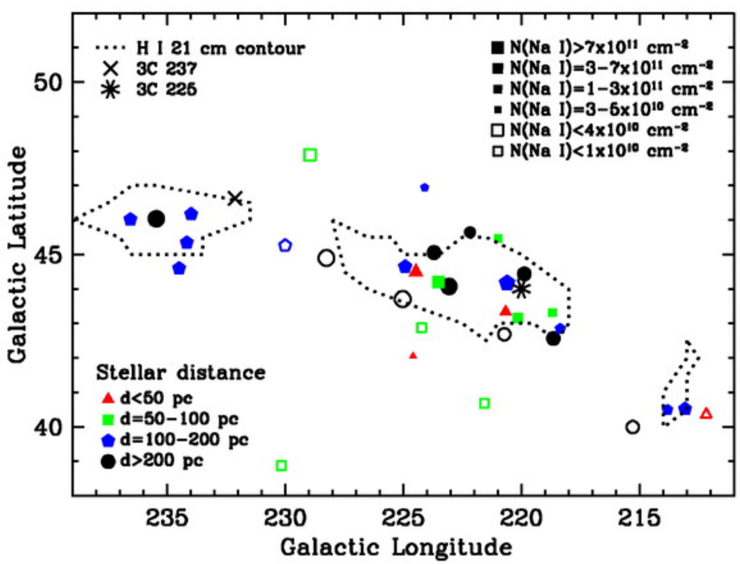


# Possible hot gas models

- If $n_e$ = 0.1 $cm^{-3}$ like in warm clouds, then $EM_{LB}$= 1 $cm^{-6}$pc (>1000 times too large).
- If gas pressure equilibrium P/k=2280 $Kcm^{-3}$, and log T=6.0, then $EM_{LB}$=0.001 (5 times too small).
- If gas pressure equilibrium and logT as low as 5.6, then $EM_{LB}$=0.001 (but does not account for significant foreground emission).
- Some semi-hot gas could fill most of volume of the Local Bubble (but not seen in O VI).
- But, there are other pressure terms and the LB could be far from any equilibrium.

# How do cold gas clouds survive in an unfriendly environment?

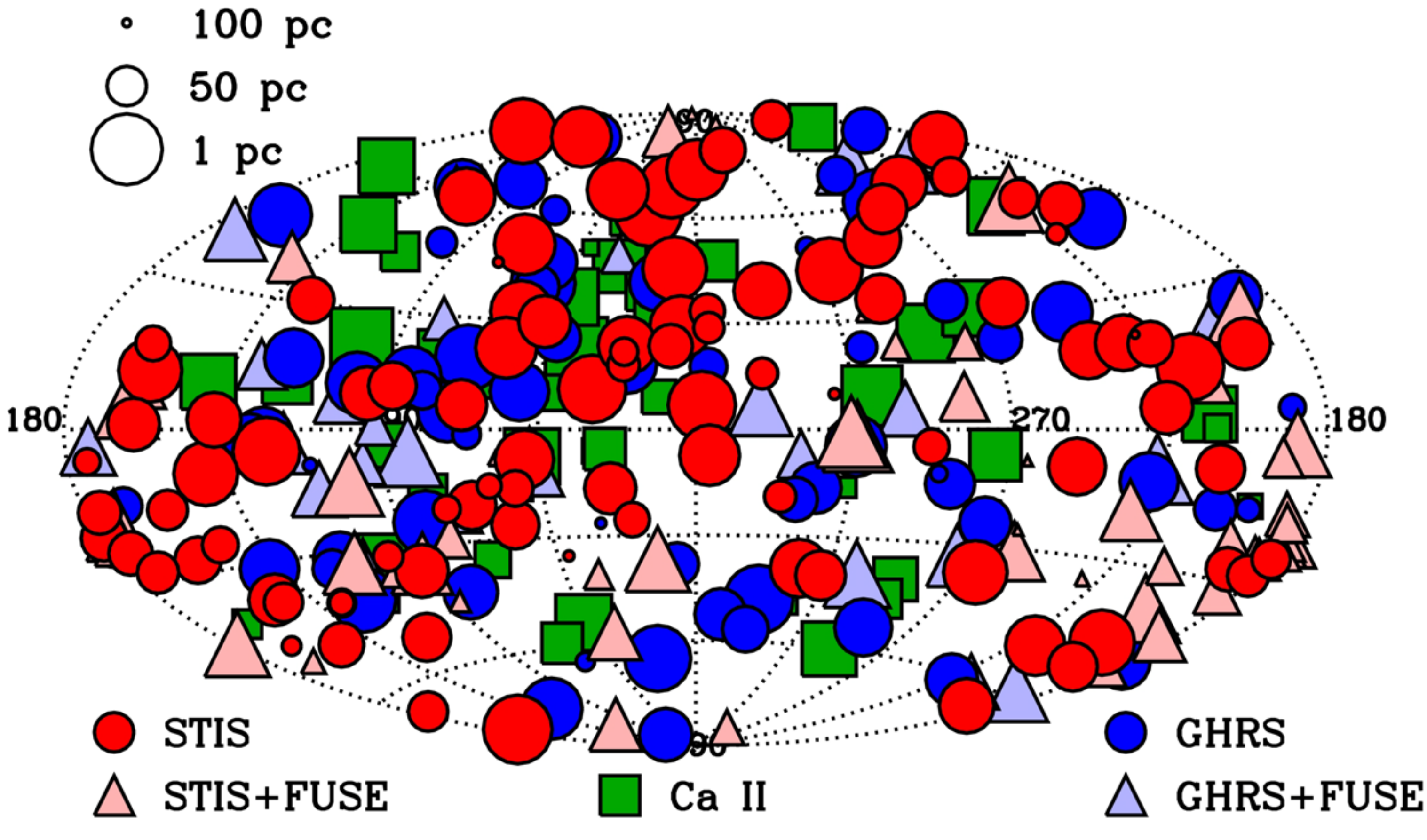


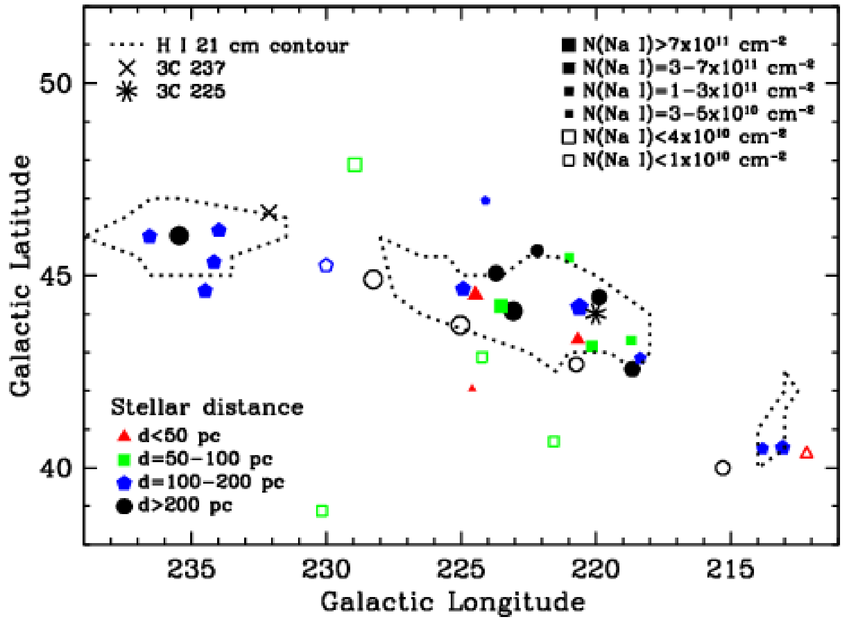

- Leo cold cloud (T~20 K) inside the Local Bubble (11pc<d<24 pc).
- Cold cloud must be shielded from external UV by neutral H (probably in warm clouds).
- Need to identify the warm surrounding gas and whether compression is present.
- Figures from Meyer et al. (2006) and Heiles and Troland (2003).

# LISM Sample

160 targets within 100 pc observed at high and moderate resolution that contain 270 LISM absorption components (~60% of UV observations taken for other purposes).



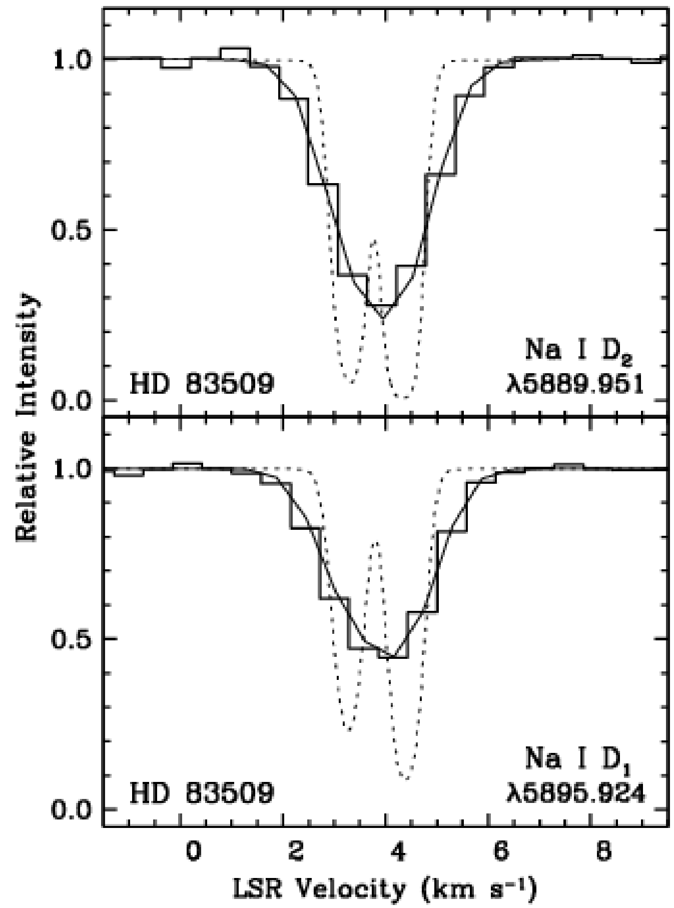
# Is there cold gas inside the Local Bubble?




- Contours of HI 21 cm absorption from Heiles & Troland (ApJ 586, 1067 (2003)) survey.
- Triad Region CNM cloud: $T_{spin}$~25 K. $V_{LSR}$=4 km/s. logN(HI)~19.5. [log N(H2)~20.6 for globulettes in Rosetta Nebula].
- Extends over 20 degrees but length/thickness ratio about 280 (clumpy sheet model).
- Superimposed are Na I targets through the cold cloud.

# Where is the Triad Region CNM cloud? (Meyer et al. ApJ 650, L67 (2006))

- Na I absorption measurements toward stars behind the cloud.
- Very narrow hyperfine split lines.
- Cloud T=20  7 K.
- d<45 pc (distance to closest star showing absorption). Inside LB.
- $V_{LSR}$=4 km/s (like HI).
- Near edges of LIC, G, Leo, Gem, Aur warm clouds.



Views of the Local Bubble from the North Galactic Pole (left) and the Galactic plane (right). Dark is NaI absorption

(Welsh SSR 143, 241 (2009))