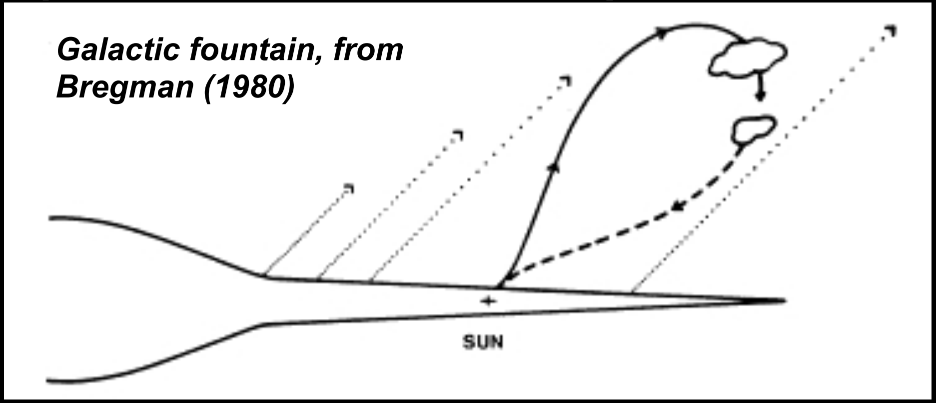
Kinematic Models of the Disk-Halo Interface: A Galactic Perspective

What does a Galactic fountain predict for the velocity field?



Galactic fountain, from Bregman (1980)

model. For model E1 with cooling, the rotational velocity decreases upward at the rate 13.5 km s^{-1} kpc^{-1} at $\tilde{\omega}$ = 15 kpc, 10.4 km s^{-1} kpc^{-1} at $\tilde{\omega}$ = 12.4 kpc, and ~8 km s^{-1} kpc^{-1} at $\tilde{\omega} \leq 9$ kpc. In the frame rotating with an element of coronal gas, the radial differential velocity gradient ($\partial u_\theta / \partial \tilde{\omega}$) is 15–40 km s^{-1} kpc^{-1}, where higher values occur at low elevation and

Outline of Talk

I. Kinematics of Disk-halo models: an overview

II. Another Galactic Wind? (Not the nuclear wind)

III. The Kinematics of the Warm Ionized Medium
(Some results edited out until all-sky WHAM release)

IV. Some Comments on Galactic Infall

Thanks to John Everett (Winds) and Matt Haffner (WHAM), Bart Wakker and Audra Hernandez (HVCs) and my summer students Andrew Eagon, Alexandre Fernandes, and Peter Doze.

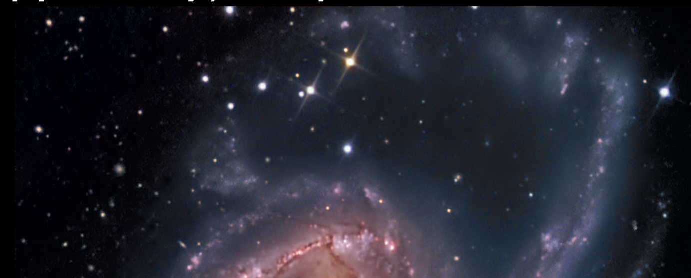
Models of Disk-Halo Gas

Modeling velocity fields

Types of motions in the ISM

Velocity dispersion	7-20 km/s
Streaming motions	10-30 km/s
Shells and bubbles	10-150 km/s
Vertical circulation	10-150(?) km/s
Rotation	220 km/s
Extragalactic Infall	10-400 km/s
Winds	100-1000(?) km/s

Galaxies are complicated systems, but there's one thing about them that is (apparently) simple…



FLAT ROTATION CURVES

NGC 1365
SSRO-South (R.Gilbert, D.Goldman, J.Harvey, D.Verschatse) - PROMPT (D.Reichart)

Velocities are something that we can measure. If you care about finding out whether or not your model works, **predict velocities**!

Classification of models

B1. Ballistic outflow
–Appropriate for neutral clouds formed in R-T instabilities for superbubbles?

B2a. Ballistic inflow (fountain)
–Appropriate for neutral clouds formed in a rotating gaseous halo?

B2b. Ballistic inflow (accretion)
–Depends on the angular momentum and column density distribution of intergalactic environment

MHD-1 Hydrostatic disks
– Is there an equilibrium figure of rotation (that is not unstable)?

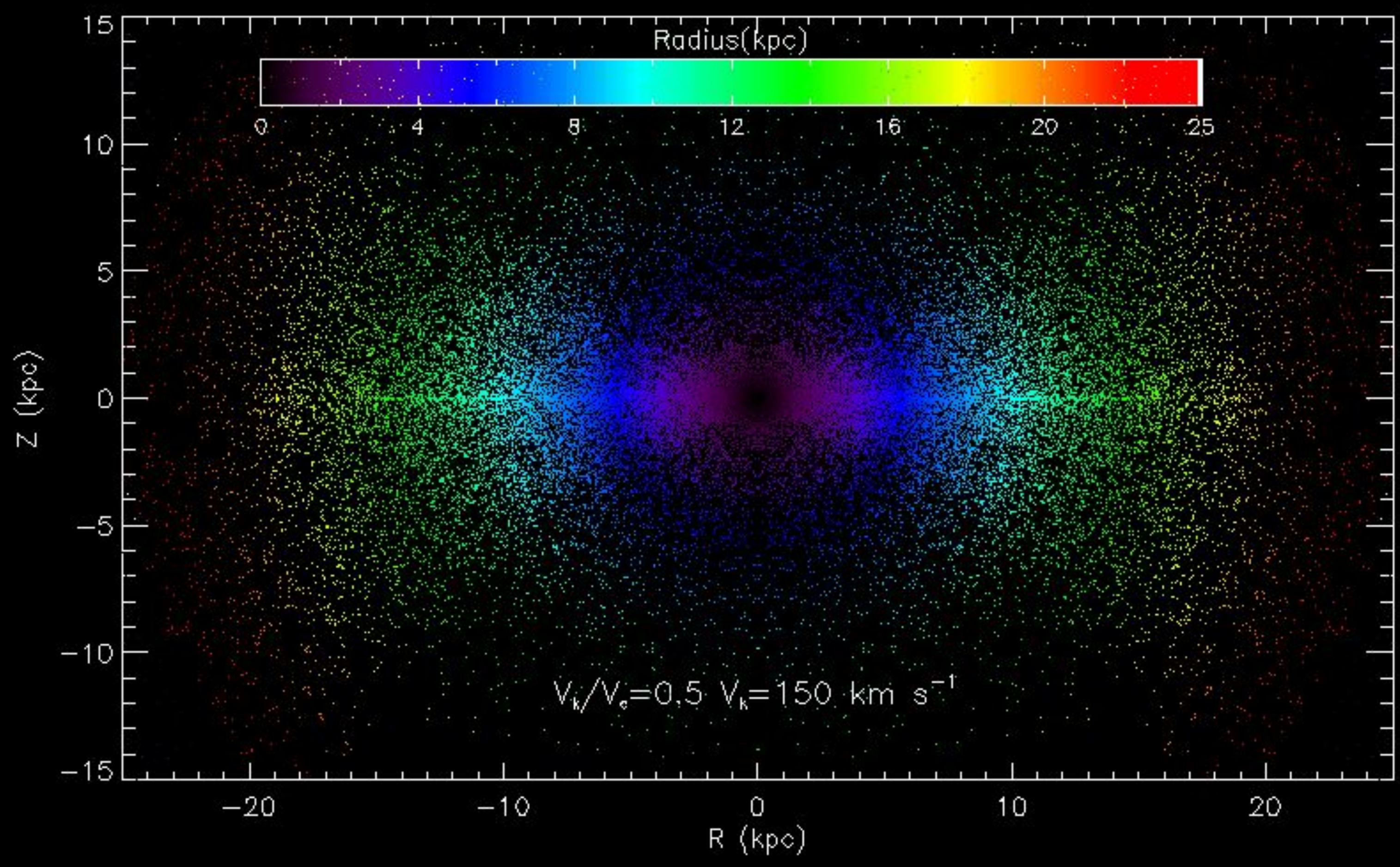
MHD-2 "Viscous" thick disk
– What is the likelihood of momentum transfer by "turbulent viscosity" or magnetic stresses?

MHD-3 Rotating winds
–What is the velocity structure of winds/ fountains in a rotating outflow?

MHD-4 "Dynamic equilibrium" disk
– What is the distribution of energy input? Does spiral structure matter?

Note: The question of the physics governing rotation vs. height and merdional circulation remains unresolved in many physical systems: solar interior, solar chromosphere/corona, accretion disks, etc.

Ballistic models outflow: Collins, Benjamin & Rand (2002)*



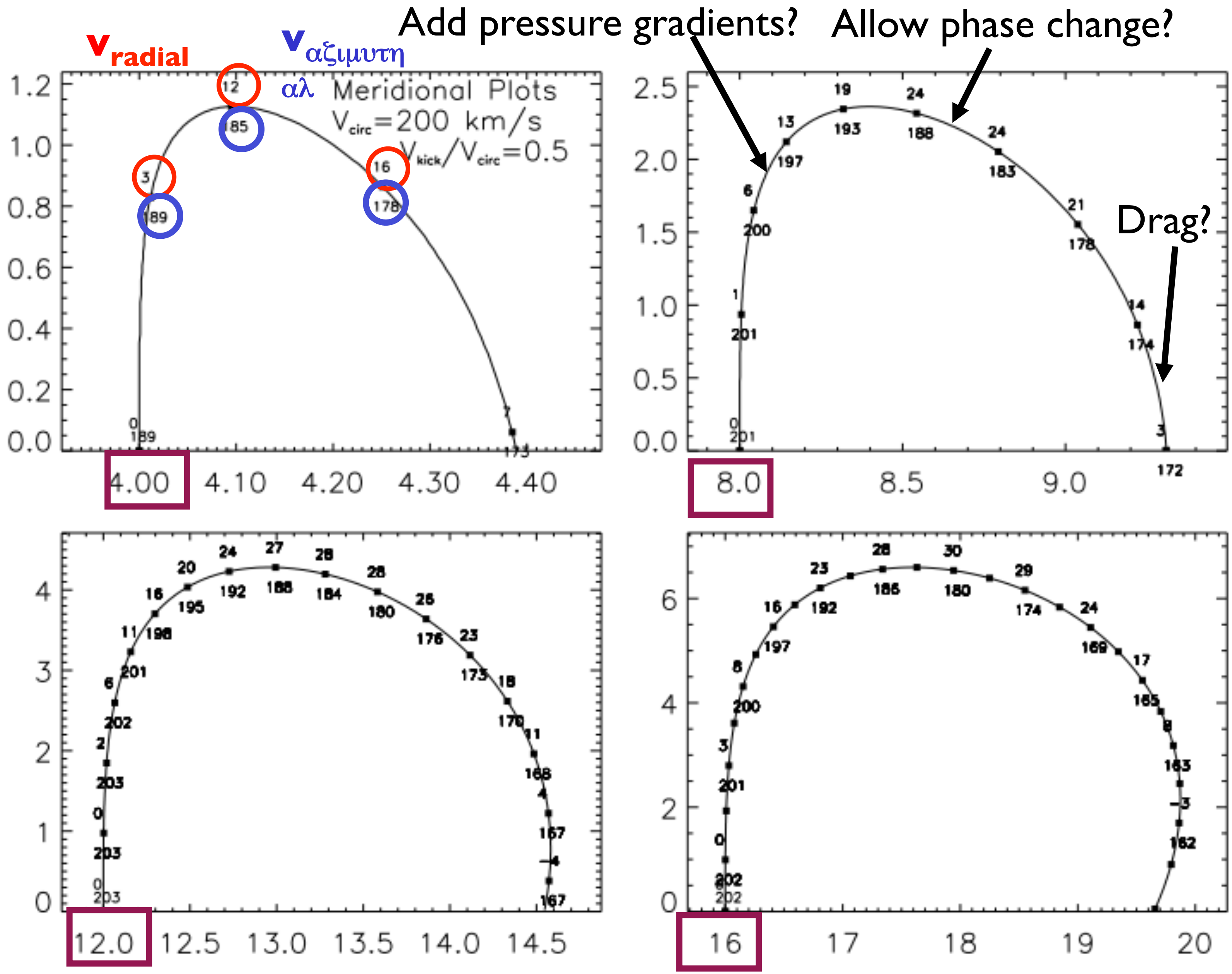
Specify:

- Potential
- Initial set of positions for clouds
- Initial set of velocities for clouds.

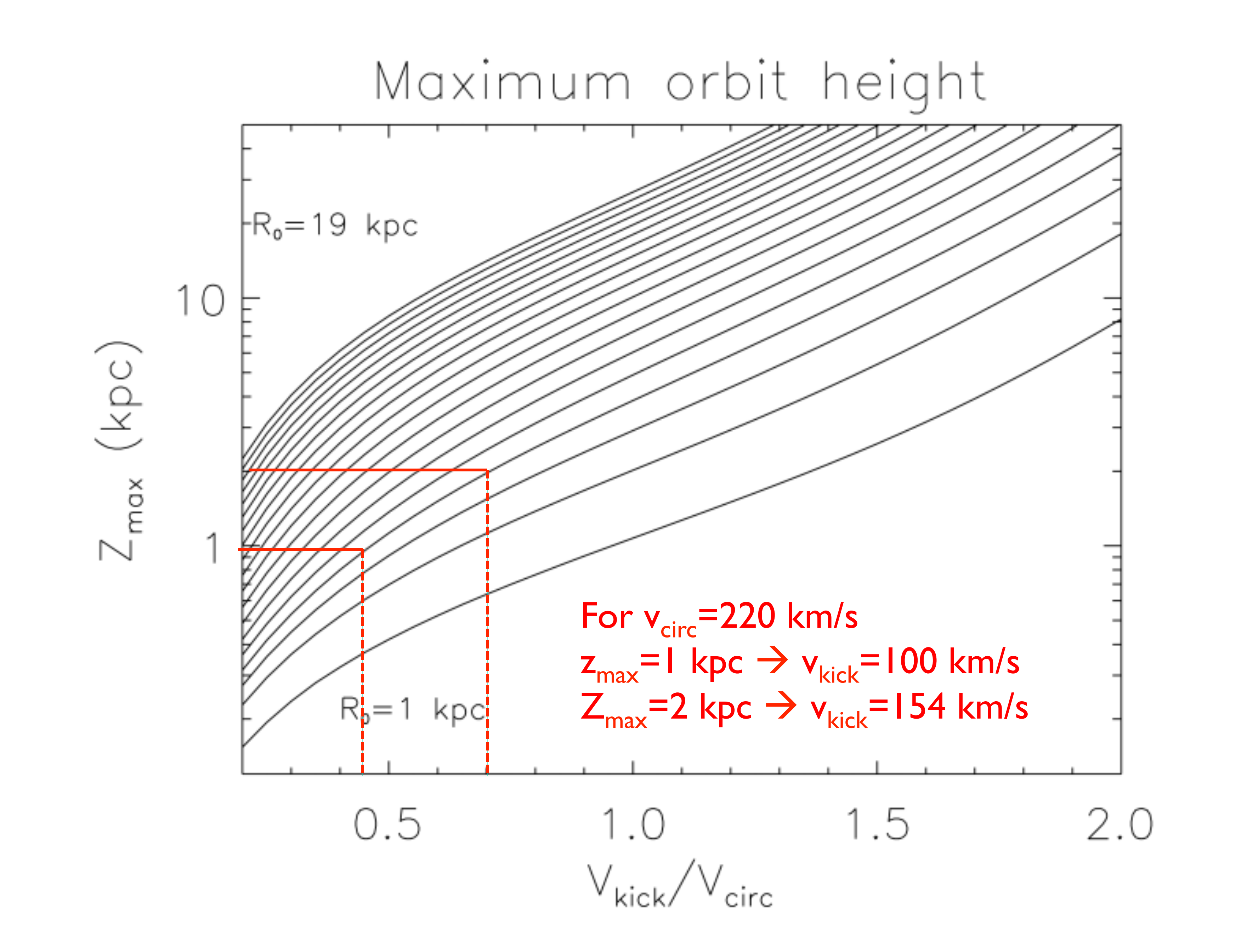
Observed scale height sets velocities.

$$\frac{d\mathbf{V}}{dt} = \mathbf{g} \quad \Rightarrow \quad \frac{d\mathbf{V}}{dt} = V_c^2\, \tilde{\mathbf{g}}(R,z) \quad \Rightarrow \quad \frac{d(\mathbf{V}/V_c)}{d(V_c t)} = \tilde{\mathbf{g}}(R,z)$$

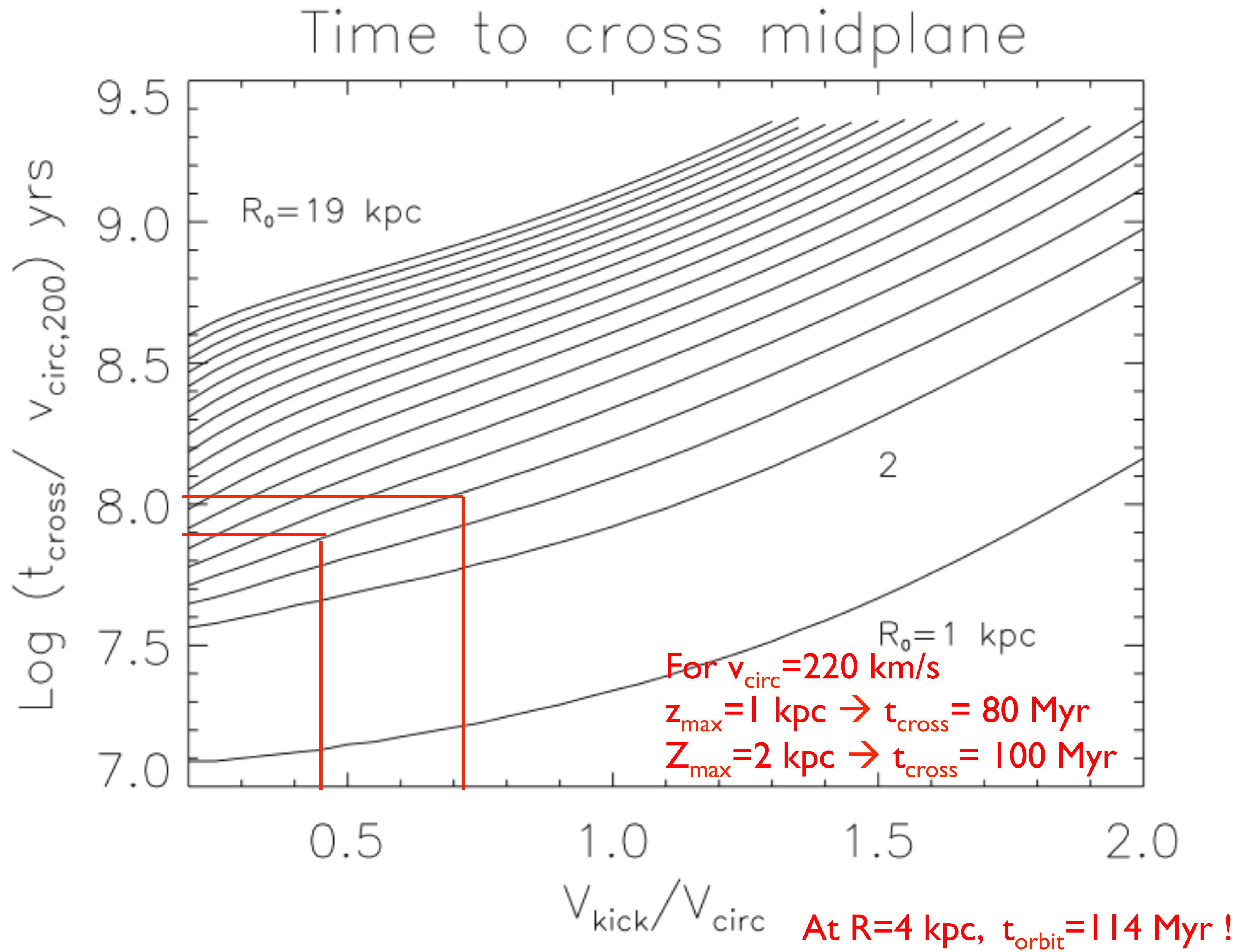
*See also, Charlton & Salpeter (1989), Wakker (1990)



Add pressure gradients?
Allow phase change?
Drag?
v radial
v αζιμυτηαλ
Meridional Plots
V circ=200 km/s
V kick/V circ=0.5



Maximum orbit height
R_0=19 kpc
R_0=1 kpc
10
1
Z_{max} (kpc)
0.5
1.0
1.5
2.0
V_{kick}/V_{circ}
For v_{circ}=220 km/s
z_{max}=1 kpc → v_{kick}=100 km/s
Z_{max}=2 kpc → v_{kick}=154 km/s


Time to cross midplane
Log (t_{cross}/ $v_{circ,200}$) yrs
V_{kick}/V_{circ}
R_0=19 kpc
2
R_0=1 kpc
For v_{circ}=220 km/s
z_{max}=1 kpc → t_{cross}= 80 Myr
Z_{max}=2 kpc → t_{cross}= 100 Myr
At R=4 kpc, t_{orbit}=114 Myr !

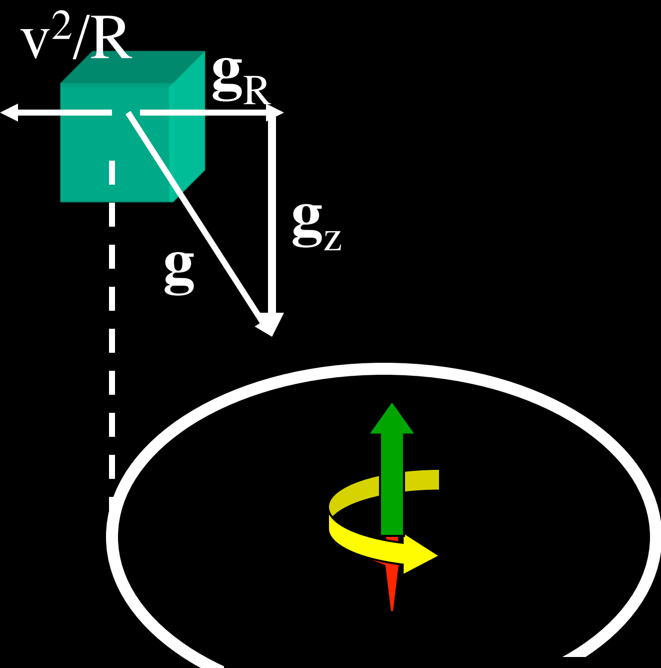
Common to all models: $g_R(R,z)$

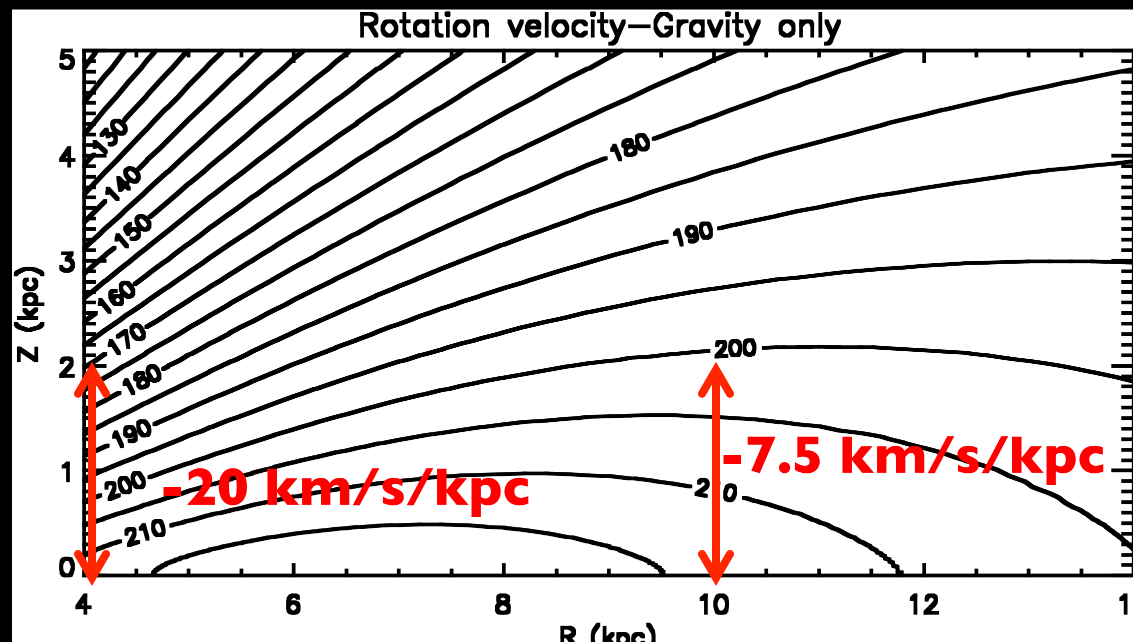
Ballistic implication: $g_R = v_{rot}^2 / R$ and $\ell = vR$: $g_R = \ell^2/R^3$

As g_R decreases, R increases (radial outflow).

As R increases, v decreases (rotational lag).

Hydrostatic implication: If rotation balances g_R, then the rate at which it drops with vertical height should be larger near the center of the galaxy and smaller at large radius; any mismatch could be attributed to other forces.





Calculated from Dehnen & Binney (1998)

Key point: $g_R(R,z)$ drops faster with height at small R than large R.

$V_{rot}(z, R)$: Galaxy rotation curves aren't flat above the midplane!

The Astrophysical Journal, 808:153 (14pp), 2015 August 1 doi:10.1088/0004-637X/808/2/153

THE H I KINEMATICS OF NGC 4013: A STEEP AND RADIALLY SHALLOWING EXTRA-PLANAR ROTATIONAL LAG

Laura K. Zschaechner[1,2] and Richard J. Rand[2]
[1] Max Planck Institute für Astronomie—Königstuhl 17, D-69117 Heidelberg, Germany; zschaechner@mpia.de
[2] Department of Physics and Astronomy, University of New Mexico, 1919 Lomas Blvd. NE, Albuquerque, NM 87131, USA; rjr@phys.unm.edu
Received 2015 March 27; accepted 2015 June 16; published 2015 July 29

ABSTRACT

NGC 4013 is a distinctly warped galaxy with evidence of disk–halo activity. Through deep H I observations and modeling we confirm that the H I disk is thin (central exponential scale height with an upper limit of 4″ or 280 pc), but flaring. We detect a vertical gradient in rotation velocity (lag), which shallows radially from a value of -35^{+7}_{-28} km s^{-1} kpc^{-1} at 1′.4 (5.8 kpc), to a value of zero near R_{25} (11.2 kpc). Over much of this radial range, the lag is relatively steep. Both the steepness and the radial shallowing are consistent with recent determinations for a number of edge-ons, which have been difficult to explain. We briefly consider the lag measured in NGC 4013 in the context of this larger sample and theoretical models, further illuminating disk–halo flows.

Key words: galaxies: halos – galaxies: individual (NGC 4013) – galaxies: kinematics and dynamics – galaxies: spiral – galaxies: structure

The Astrophysical Journal, 799:61 (21pp), 2015 January 20 doi:10.1088/0004-637X/799/1/61

INVESTIGATING DISK-HALO FLOWS AND ACCRETION: A KINEMATIC AND MORPHOLOGICAL ANALYSIS OF EXTRAPLANAR H I IN NGC 3044 AND NGC 4302

Laura K. Zschaechner[1,2], Richard J. Rand[2], and Rene Walterbos[3]
[1] Max Planck Institute for Astronomy, Königstuhl 17, D-69117 Heidelberg, Germany; zschaechner@mpia.de
[2] Department of Physics and Astronomy, University of New Mexico, 1919 Lomas Boulevard NE, Albuquerque, NM 87131, USA; rjr@phys.unm.edu
[3] Department of Astronomy, New Mexico State University, P.O. Box 30001, MSC 4500, Las Cruces, NM 88003, USA; rwalterb@nmsu.edu
Received 2014 September 24; accepted 2014 November 10; published 2015 January 15

ABSTRACT

To further understand the origins of and physical processes operating in extra-planar gas, we present observations and kinematic models of H I in the two nearby, edge-on spiral galaxies NGC 3044 and NGC 4302. We model NGC 3044 as a single, thick disk. Substantial amounts of extra-planar H I are also detected. We detect a decrease in rotation speed with height (a lag) that shallows radially, reaching zero at approximately R_{25}. The large-scale kinematic asymmetry of the approaching and receding halves suggests a recent disturbance. The kinematics and morphology of NGC 4302, a Virgo Cluster member, are greatly disturbed. We model NGC 4302 as a combination of a thin disk and a second, thicker disk, the latter having a hole near the center. We detect lagging extra-planar gas, with indications of shallowing in the receding half, although its characteristics are difficult to constrain. A bridge is detected between NGC 4302 and its companion, NGC 4298. We explore trends involving the extra-planar H I kinematics of these galaxies, as well as galaxies throughout the literature, as well as possible connections between lag properties with star formation and environment. Measured lags are found to be significantly steeper than those modeled by purely ballistic effects, indicating additional factors. Radial shallowing of extra-planar lags is typical and occurs between $0.5R_{25}$ and R_{25}, suggesting internal processes are important in dictating extra-planar kinematics.

Key words: galaxies: individual (NGC 3044, NGC 4302) – galaxies: halos – galaxies: kinematics and dynamics – galaxies: spiral – galaxies: structure

The Astrophysical Journal, 760:37 (17pp), 2012 November 20 doi:10.1088/0004-637X/760/1/37

HALOGAS: H I OBSERVATIONS AND MODELING OF THE NEARBY EDGE-ON SPIRAL GALAXY NGC 4565

Laura K. Zschaechner[1], Richard J. Rand[1], George H. Heald[2], Gianfranco Gentile[3,4], and Gyula Józsa[2]
[1] Department of Physics and Astronomy, University of New Mexico, 1919 Lomas Boulevard NE, Albuquerque, NM 87131-1156, USA; zschaech@unm.edu, rjr@phys.unm.edu
[2] Netherlands Institute for Radio Astronomy (ASTRON), Postbus 2, NL-7990 AA Dwingeloo, The Netherlands; heald@astron.nl, jozsa@astron.nl
[3] Sterrenkundig Observatorium, Ghent University, Krijgslaan 281 S9, B-9000 Ghent, Belgium; gianfranco.gentile@ugent.be
[4] Astrophysical Institute, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium
Received 2012 July 23; accepted 2012 October 1; published 2012 October 31

ABSTRACT

We present 21 cm observations and models of the neutral hydrogen in NGC 4565, a nearby, edge-on spiral galaxy, as part of the Westerbork Hydrogen Accretion in LOcal GAlaxieS survey. These models provide insight concerning both the morphology and kinematics of H I above, as well as within, the disk. NGC 4565 exhibits a distinctly warped and asymmetric disk with a flaring layer. Our modeling provides no evidence for a massive, extended H I halo. We see evidence for a bar and associated radial motions. Additionally, there are indications of radial motions within the disk, possibly associated with a ring of higher density. We see a substantial decrease in rotational velocity with height above the plane of the disk (a lag) of -40^{+5}_{-20} km s^{-1} kpc^{-1} and -30^{+5}_{-30} km s^{-1} kpc^{-1} in the approaching and receding halves, respectively. This lag is only seen within the inner ∼4′.75 (14.9 kpc) on the approaching half and ∼4′.25 (13.4 kpc) on the receding half, making this a radially shallowing lag, which is now seen in the H I layers of several galaxies. When comparing results for NGC 4565 and those for other galaxies, there are tentative indications of high star formation rate per unit area being associated with the presence of a halo. Finally, H I is found in two companion galaxies, one of which is clearly interacting with NGC 4565.

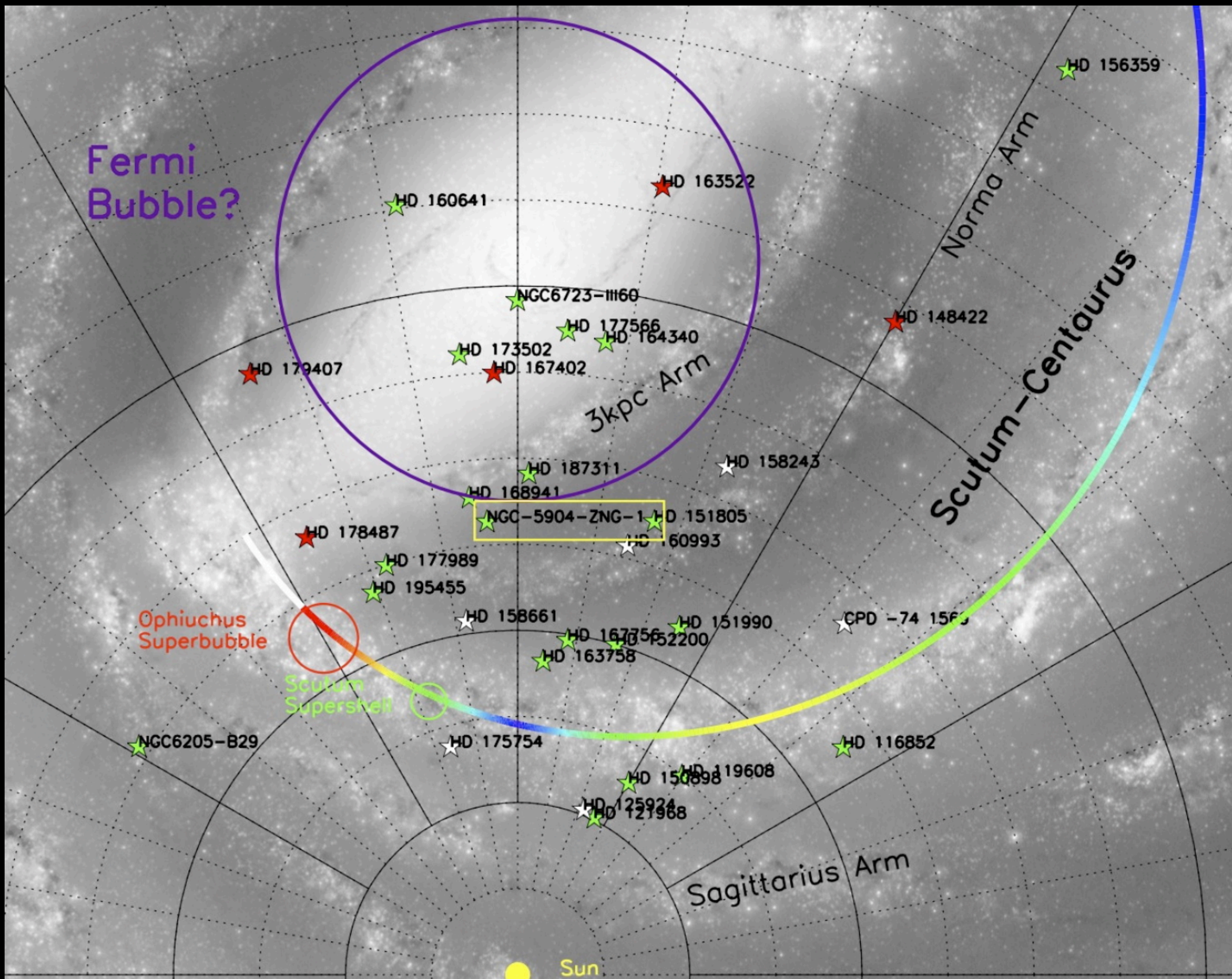
Key words: galaxies: halos – galaxies: individual (NGC 4565) – galaxies: kinematics and dynamics – galaxies: spiral – galaxies: structure

Zschaechner et al (2012, 2015ab)

A major result of HALOGAS in constraining the kinematics of extraplanar gas rotation. If only we knew which model to use!

Galactic Winds

Galactic Structure in One Slide
The Scutum Arm (Kwee et al 1954)



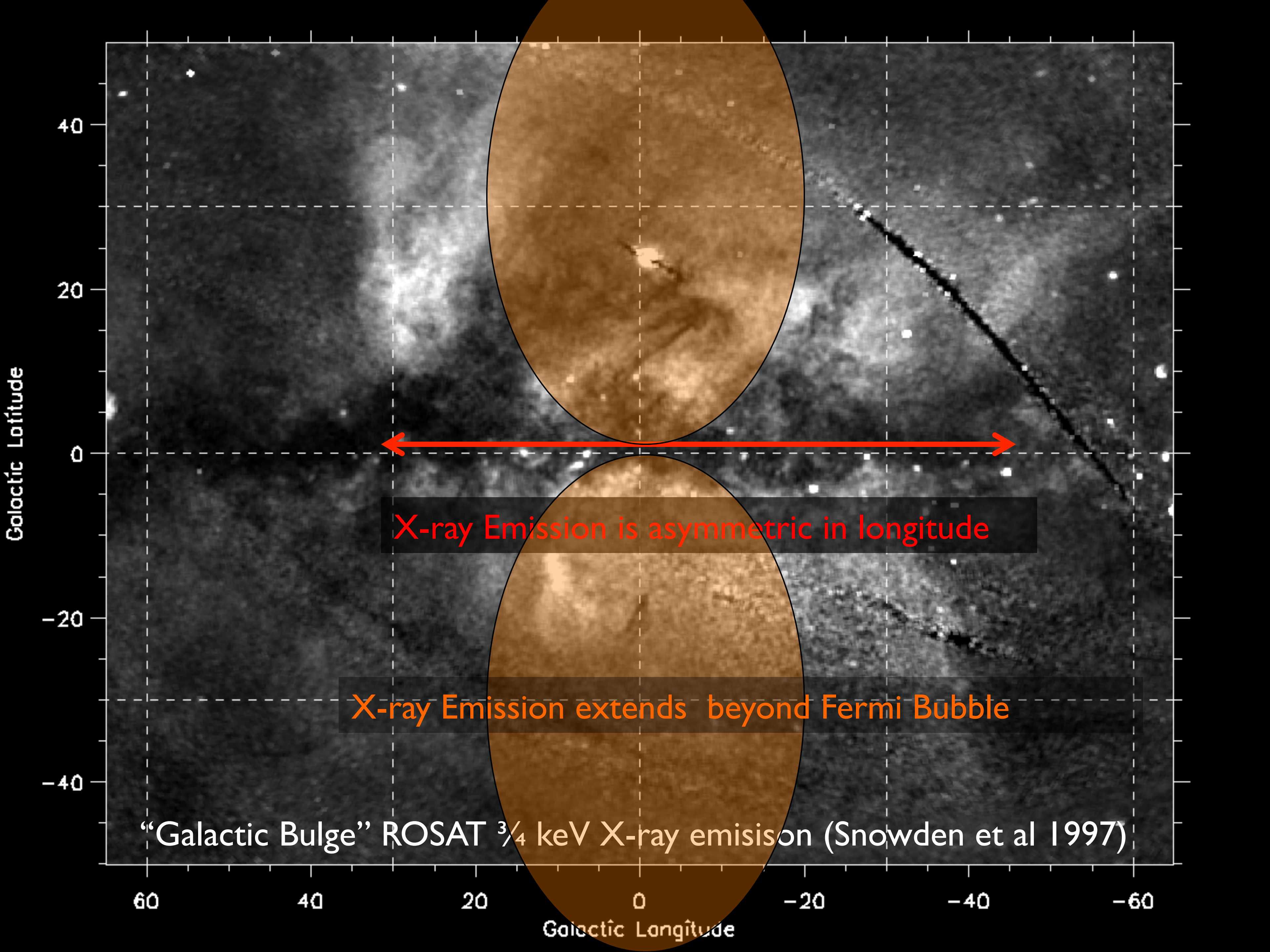
Reasons Sct-Cen is probably a "major" arm:

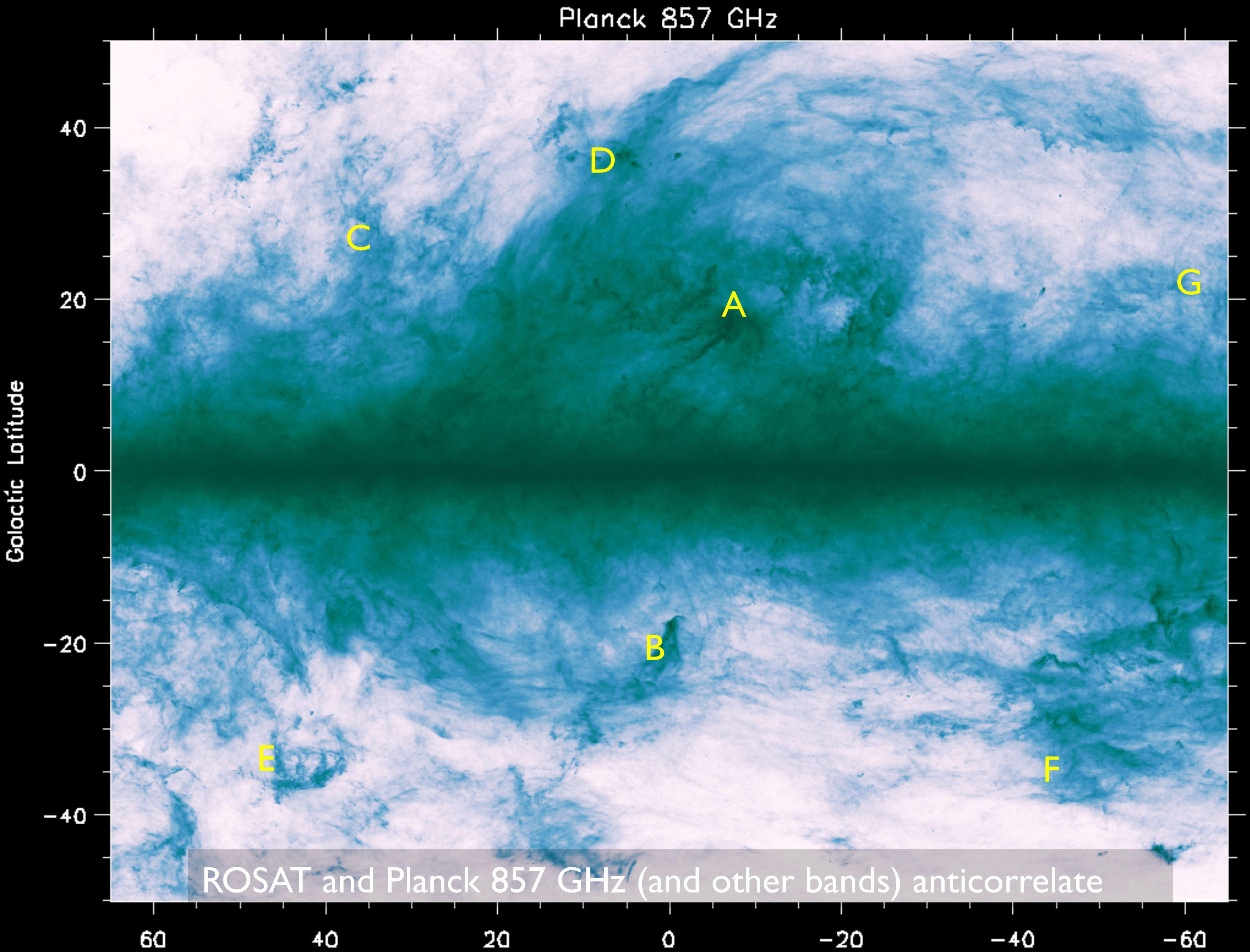
Only tangency in star counts (Drimmel 2000,Benjamin et al 2005,2008)

Also known as the "Molecular Ring" (Dobbs & Burkert 2012)

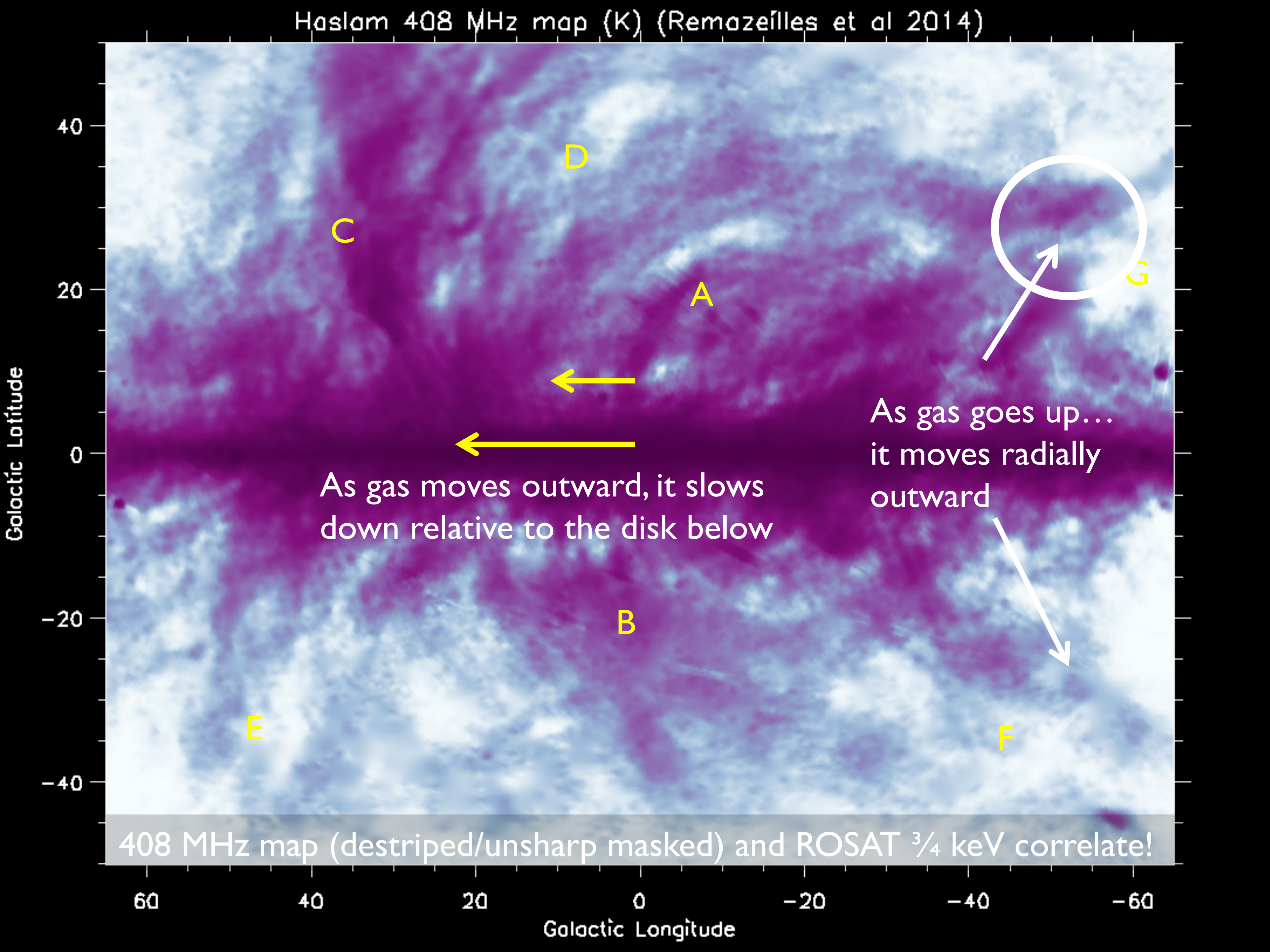
Extends to Outer Scutum-Centaurus Arm (Dame and Thaddeus 2011)

Very long dust lane parallel to the plane (Goodman et al 2014)


X-ray Emission is asymmetric in longitude
X-ray Emission extends beyond Fermi Bubble
"Galactic Bulge" ROSAT ¾ keV X-ray emisison (Snowden et al 1997)
Galactic Latitude
Galactic Longitude
40
20
0
−20
−40
60
40
20
0
−20
−40
−60

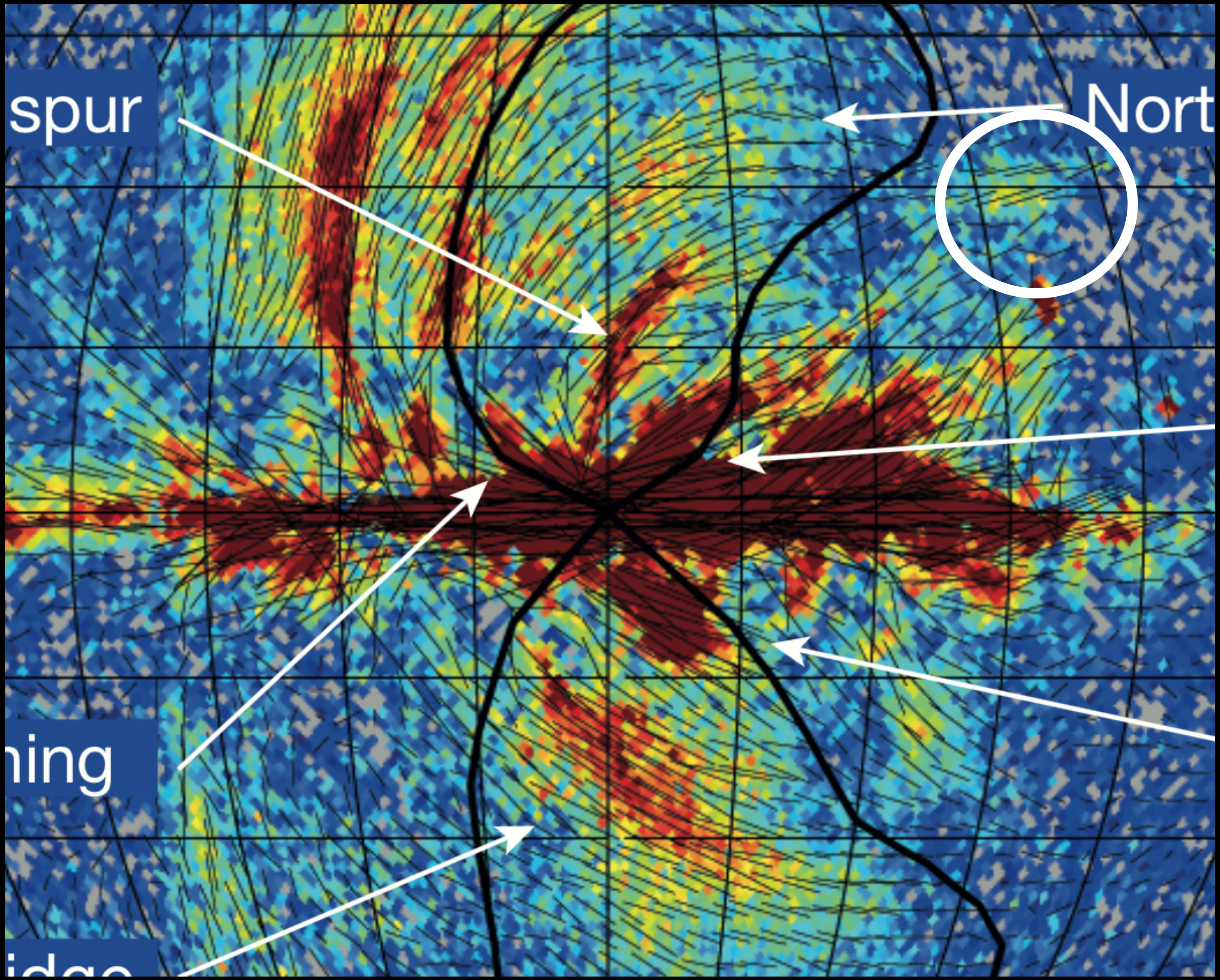


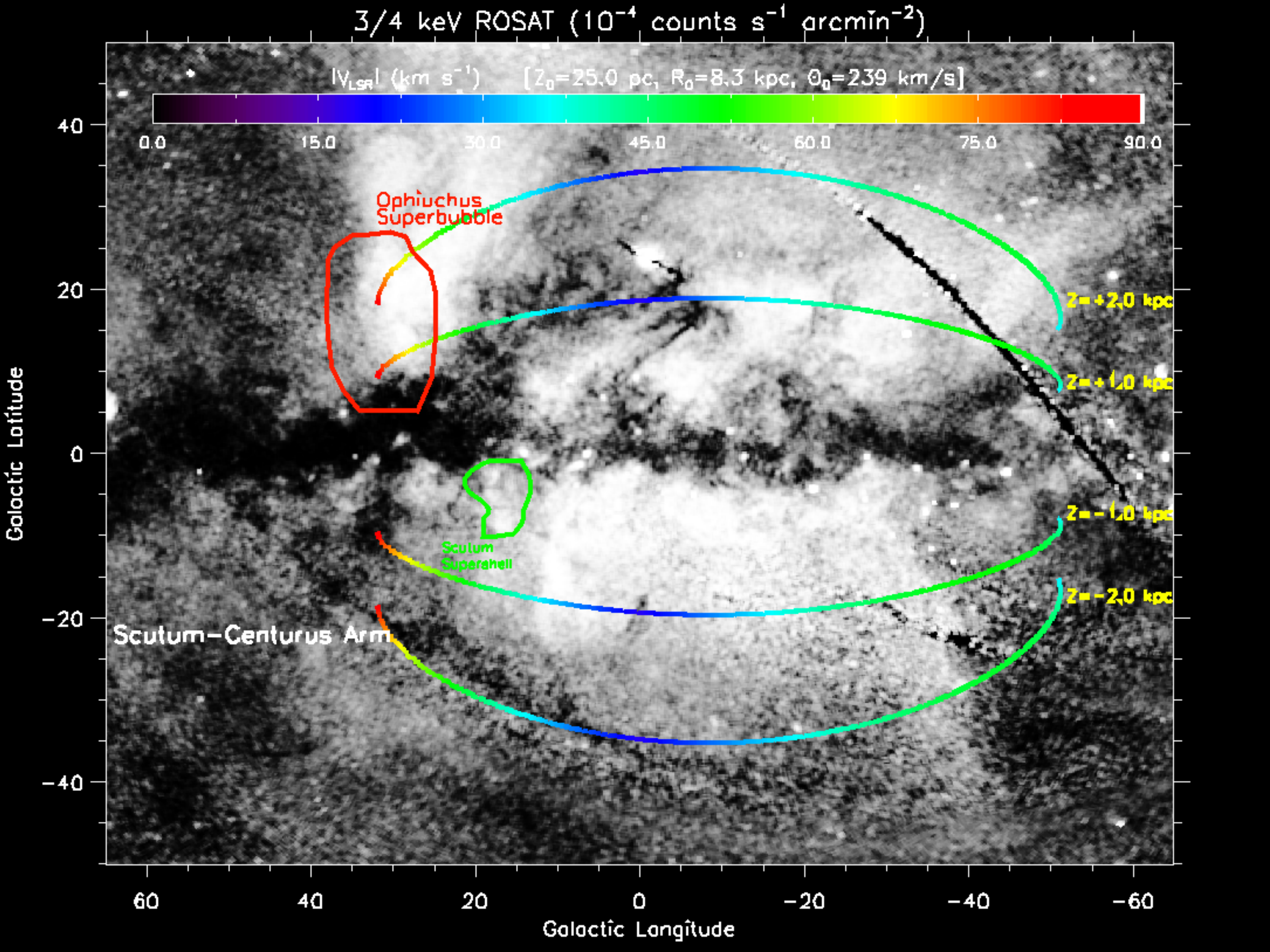
ROSAT and Planck 857 GHz (and other bands) anticorrelate


Haslam 408 MHz map (K) (Remazeilles et al 2014)
Galactic Latitude
Galactic Longitude
40
20
0
−20
−40
60
40
20
0
−20
−40
−60
A
B
C
D
E
F
G
As gas moves outward, it slows down relative to the disk below
As gas goes up… it moves radially outward
408 MHz map (destriped/unsharp masked) and ROSAT ¾ keV correlate!

WMAP 23 GHz

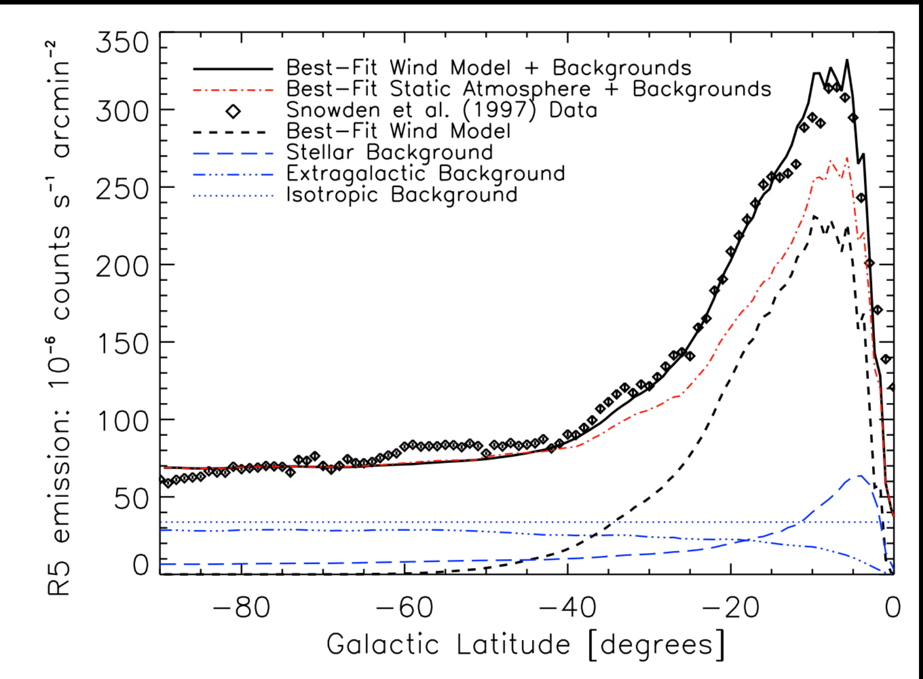
(Hinshaw et al 2009; Carretti et al 2013)



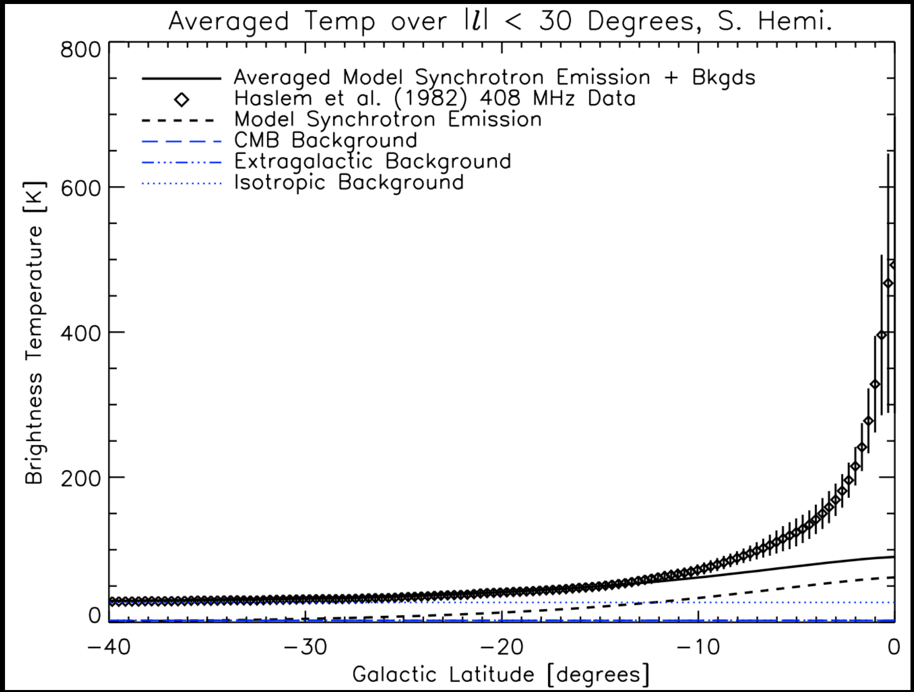


3/4 keV ROSAT (10^{-4} counts s^{-1} $arcmin^{-2}$)
$|V_{LSR}|$ (km s^{-1}) [Z_0=25.0 pc, R_0=8.3 kpc, Θ_0=239 km/s]
0.0
15.0
30.0
45.0
60.0
75.0
90.0
Ophiuchus Superbubble
Scutum Supershell
Scutum-Centurus Arm
Z=+2.0 kpc
Z=+1.0 kpc
Z=-1.0 kpc
Z=-2.0 kpc
Galactic Latitude
Galactic Longitude
40
20
0
−20
−40
60
40
20
0
−20
−40
−60

A Hybrid Cosmic-Ray/Thermal Pressure Wind



Everett, Zweibel, Benjamin, McCammon, Rocks, Gallagher (2008)

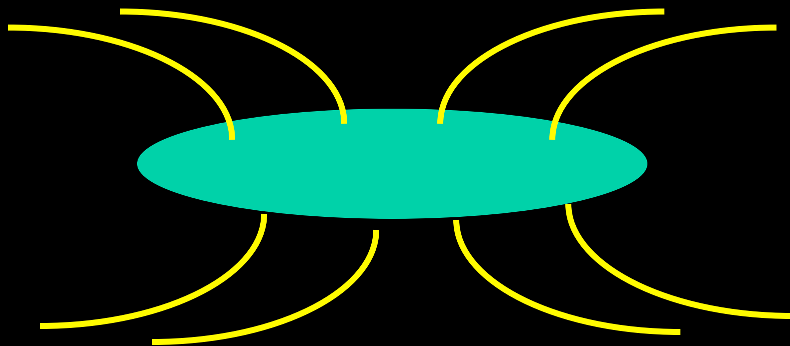


Everett, Schiller, Zweibel (2010)

1. Matches X-ray emission (left) and does not violate 408 MHz synchrotron constraints (right)
2. Thickness ~ 1 kpc, mass flux of 2.2 M_o/yr, initial density/temperature/pressures consistent with observations. Mechanical luminosity is high (twice supernova power) if you assume no radial/azimuthal drop off. (1 D model, 1D match).

Adding in Rotation (w. John Everett)

NUIT
Northwestern University Information Technology



We are currently redoing the winds but with rotation. Solution is affected dramatically, so we are still searching through parameter space for wind solutions that match X-ray, synchrotron, and now velocity field. Code has been tested against previous results and Zirakashvili et al (1996)

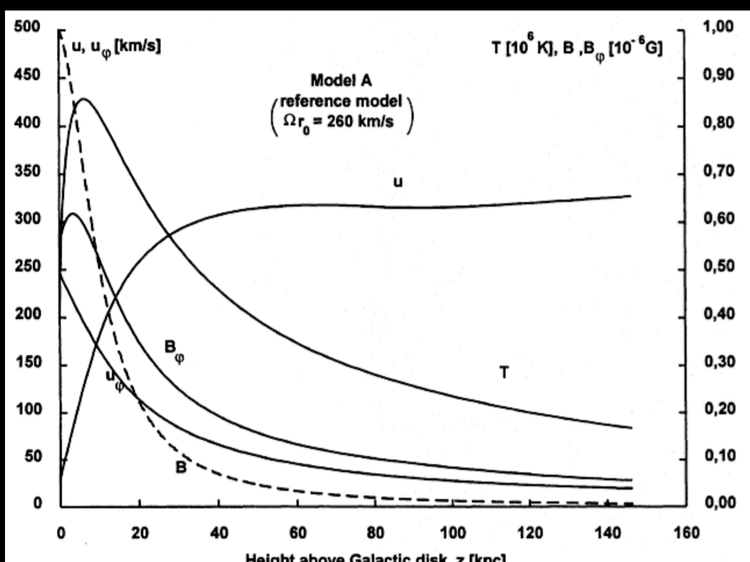
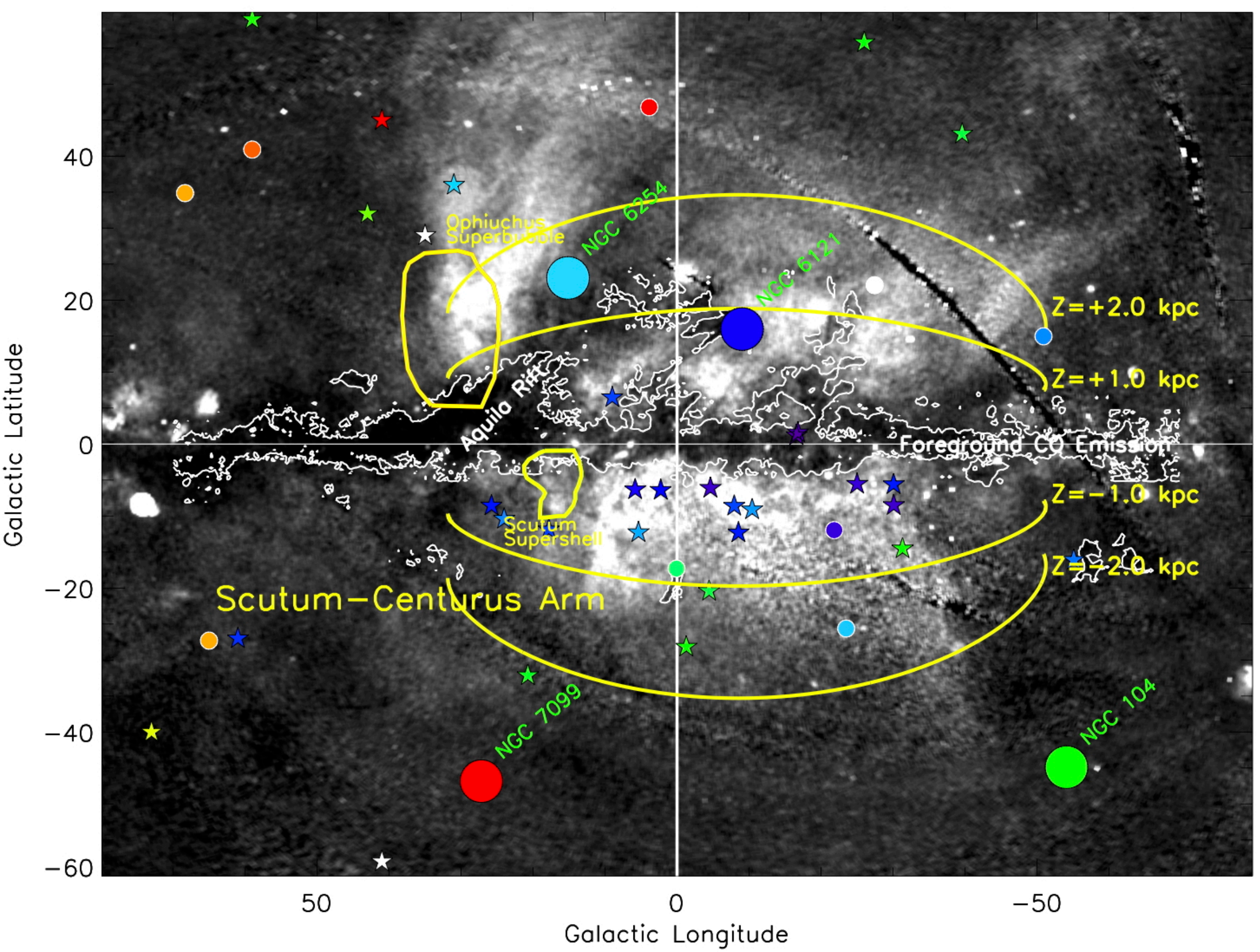


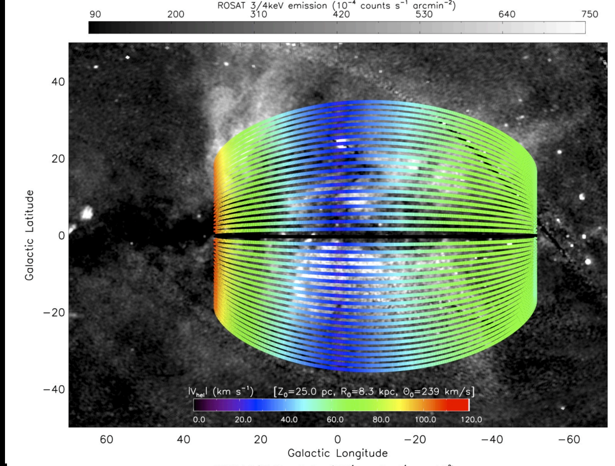
Fig. 5. Variation of the meridional and azimuthal velocities u and u_φ, azimuthal and meridional magnetic field strength B_φ and B, and gas temperature T, with distance from the disk for the reference model A. The resulting initial velocity is u_0 = 27.9 km/s, and the critical point positions are z_s = 5.1 kpc, z_a = 6.8 kpc, and z_f = 18.7 kpc. The terminal velocity is u_f = 476 km/s

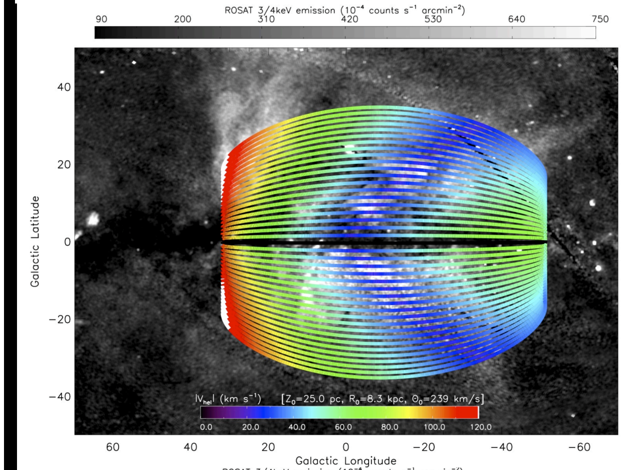
Gas is constrained to flow along a pre-specified magnetic field structure, accelerates through the various critical points. It is NOT conserving angular momentum due to stresses in the B field.

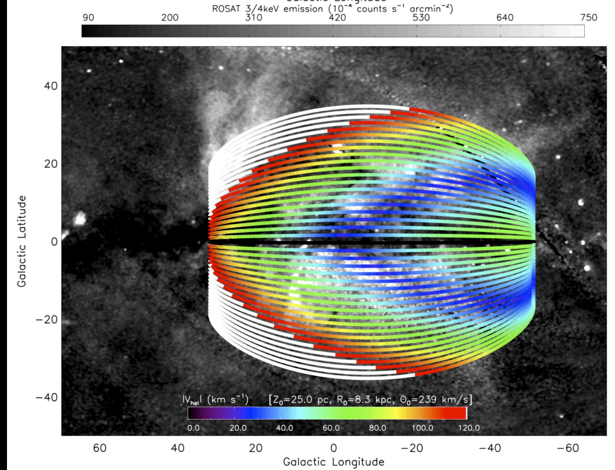
Major source of angular momentum loss for ISM!

Probing the velocity field with UV absn targets









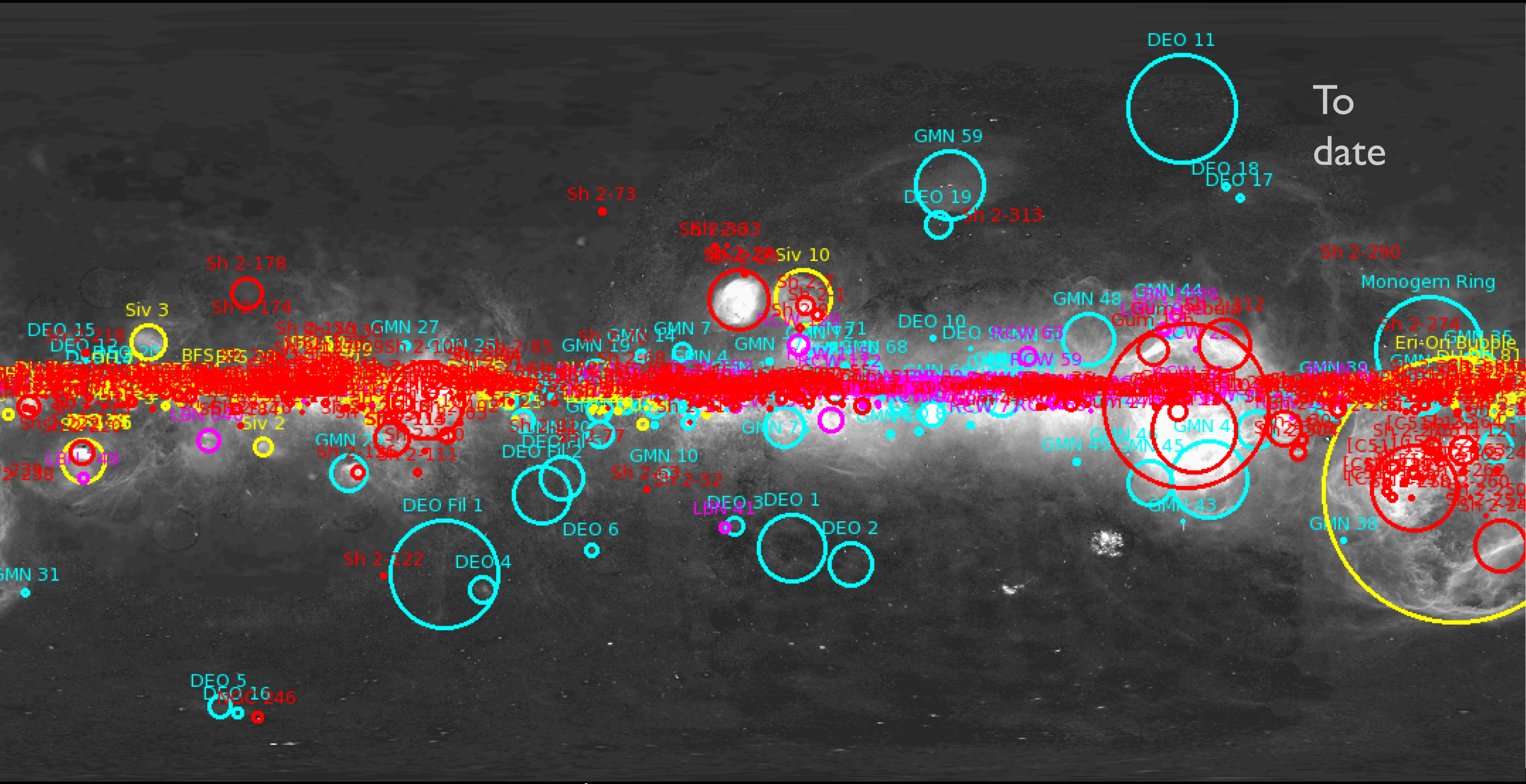
Kinematics of the Warm Ionized Medium

The Wisconsin H-alpha Mapper (WHAM)

- Wisconsin H-Alpha Mapper (WHAM) detects faint optical emission lines from the diffuse warm interstellar medium.
  - —One-degree beam
  - —Velocity baseline of ~200 km/s
  - —Velocity resolution of 12 km/s
- Much of the sky was observed from Kitt Peak (Haffner et al 2003); the southern sky is currently being observed from Cerro-Tololo observatory .

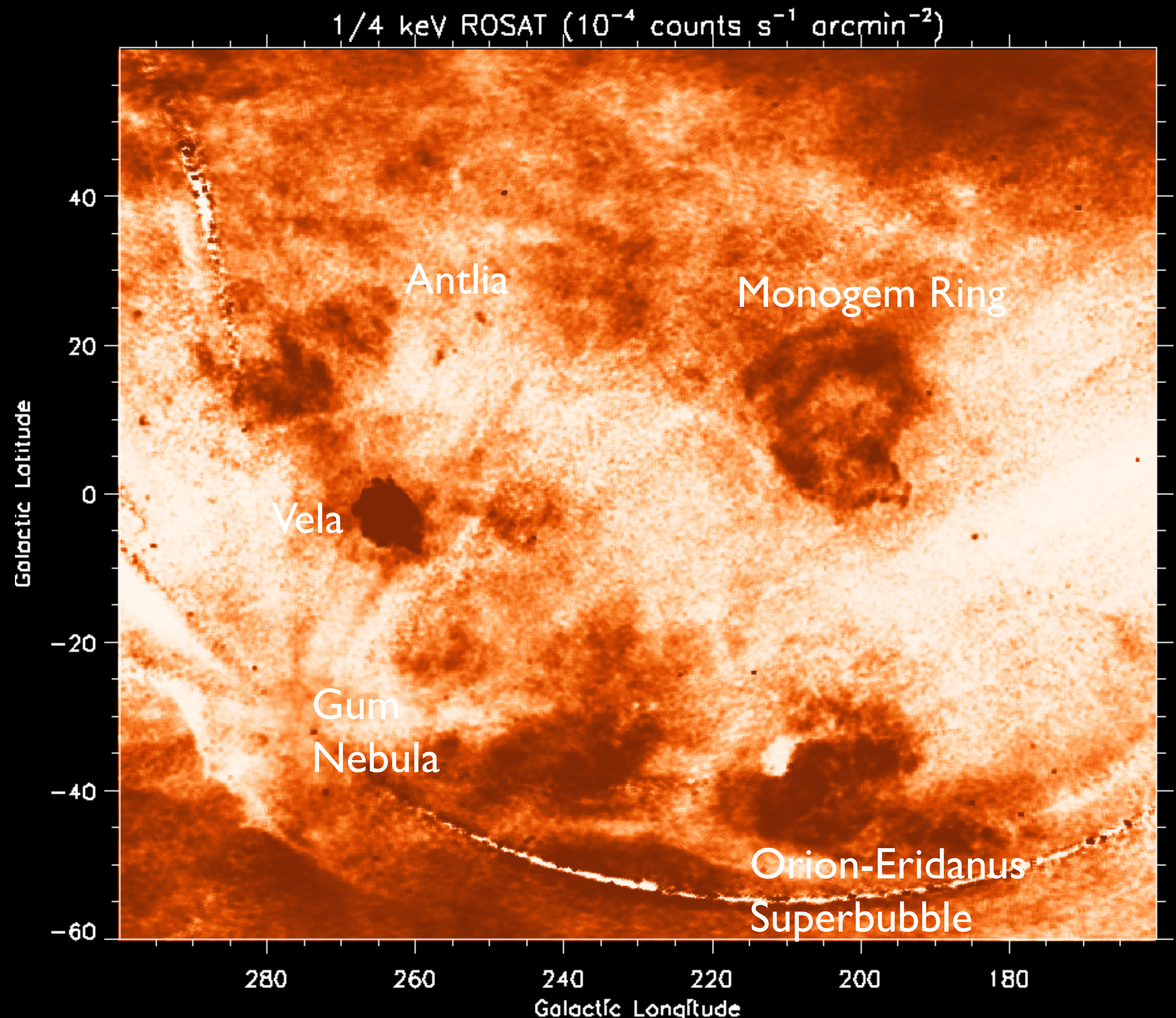
This is the FIRST velocity resolved all-sky survey of H-alpha emission. The major goal is to characterize the diffuse ionized gas. It’s sort of like the very first 21 cm survey of HI in the 1950s.

Ionized Nebulae in the "Warm Ionized Medium" (WIM)

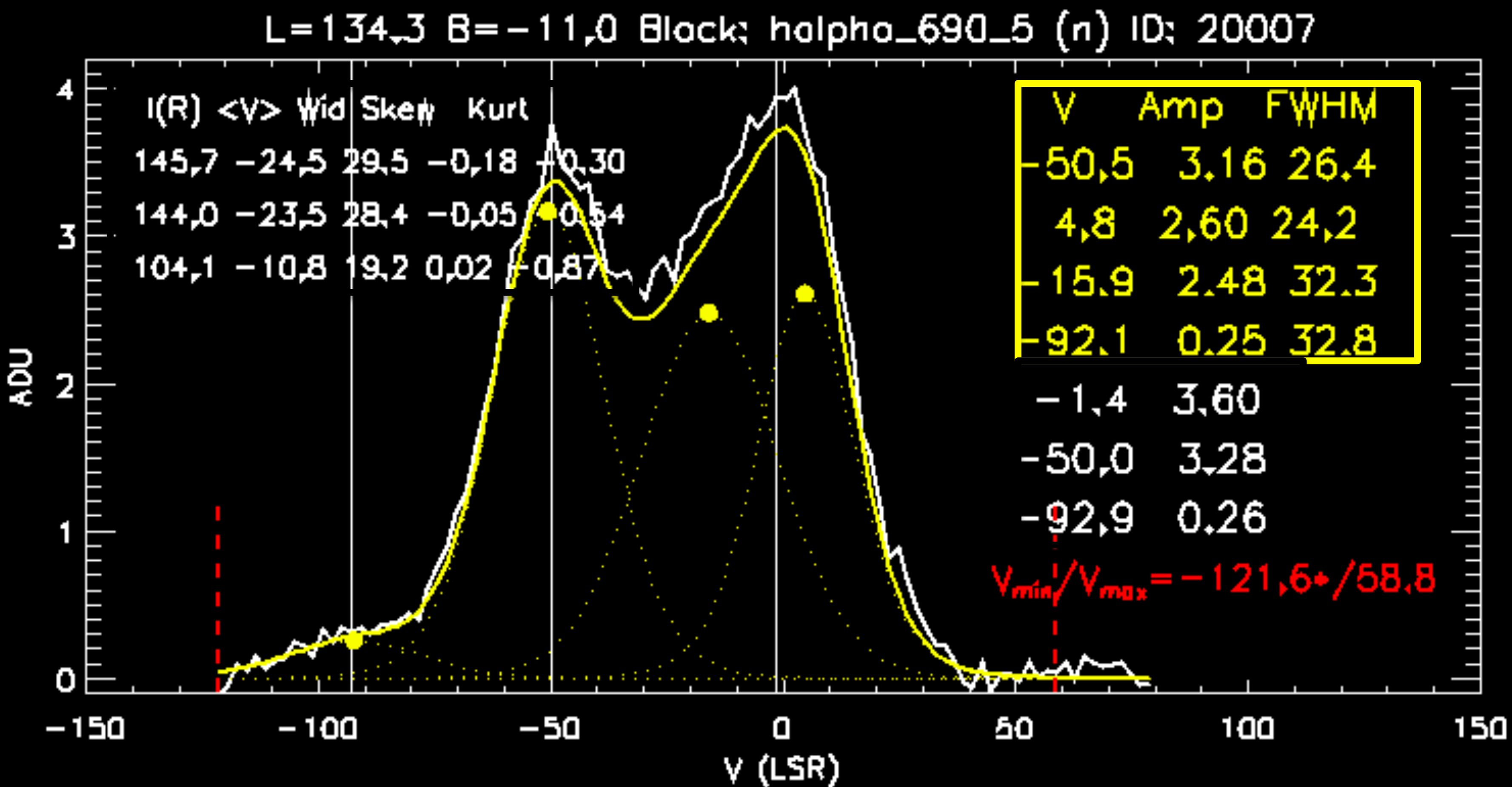


Started off by searching for bubbles/ionized regions in a combined H-alpha image from Finkbeiner (2003) using data from Southern H-alpha Sky Survey Atlas (SHASSA Gaustad et al 2001), Virginia Tech Spectral survey (VTSS, Dennison et al 1998) and WHAM. **We had 758 H-alpha nebulae total and 105 new (uncatalogued?) regions. Measured** kinematic distances, intensites, velocity moments and (when available) [S II]/H-alpha line ratios for 278 objects.

Many, many nearby supernovae!



Different statistics we can use

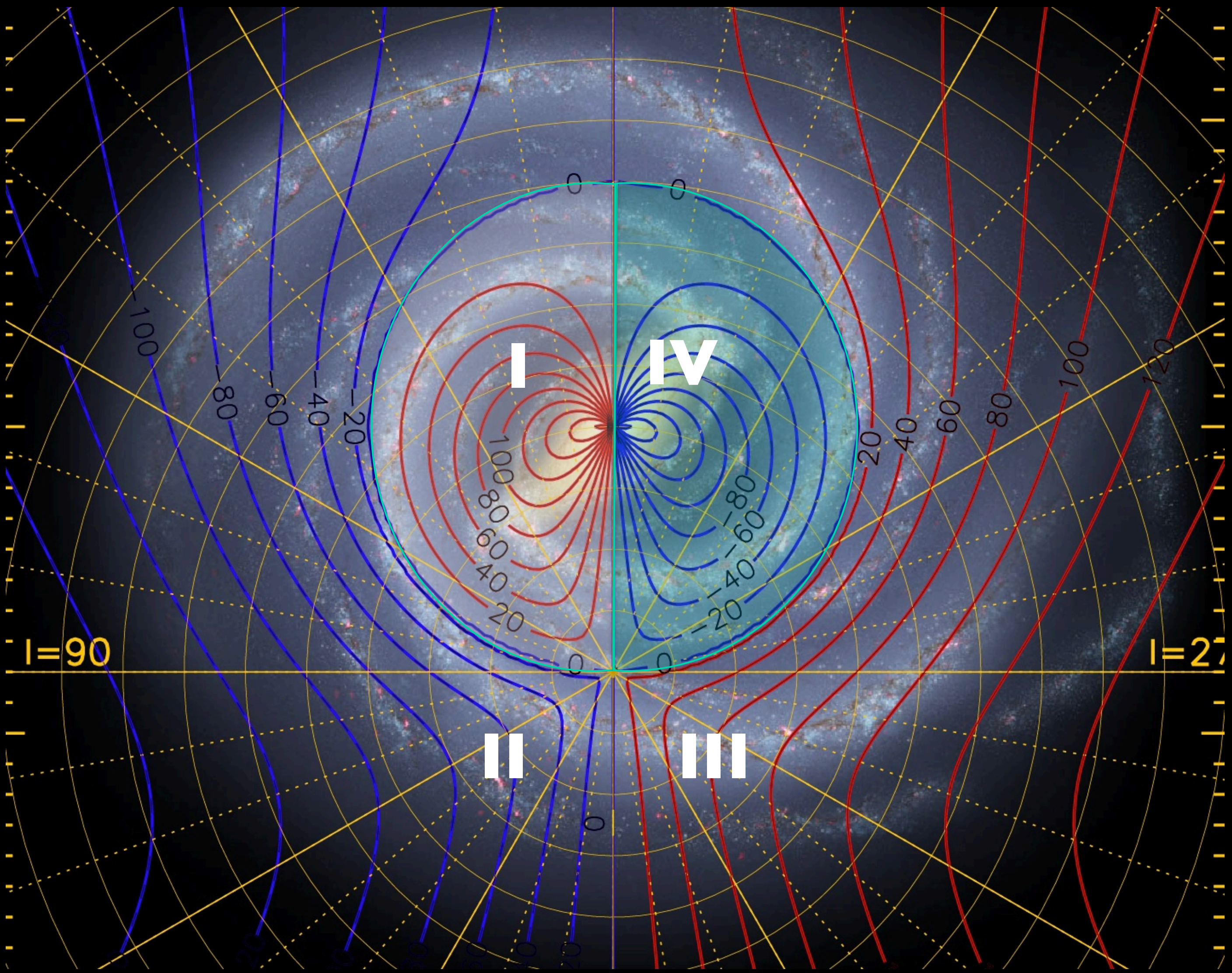


MOMENTS (calculated over three different velocity ranges)

GAUSSIAN DECOMPOSITION

LOCAL MAXIMA

WHAM measures n_e^2-weighted velocity along the line of sight



H-alpha: Upflow or Downflow (Haffner et al 2003)

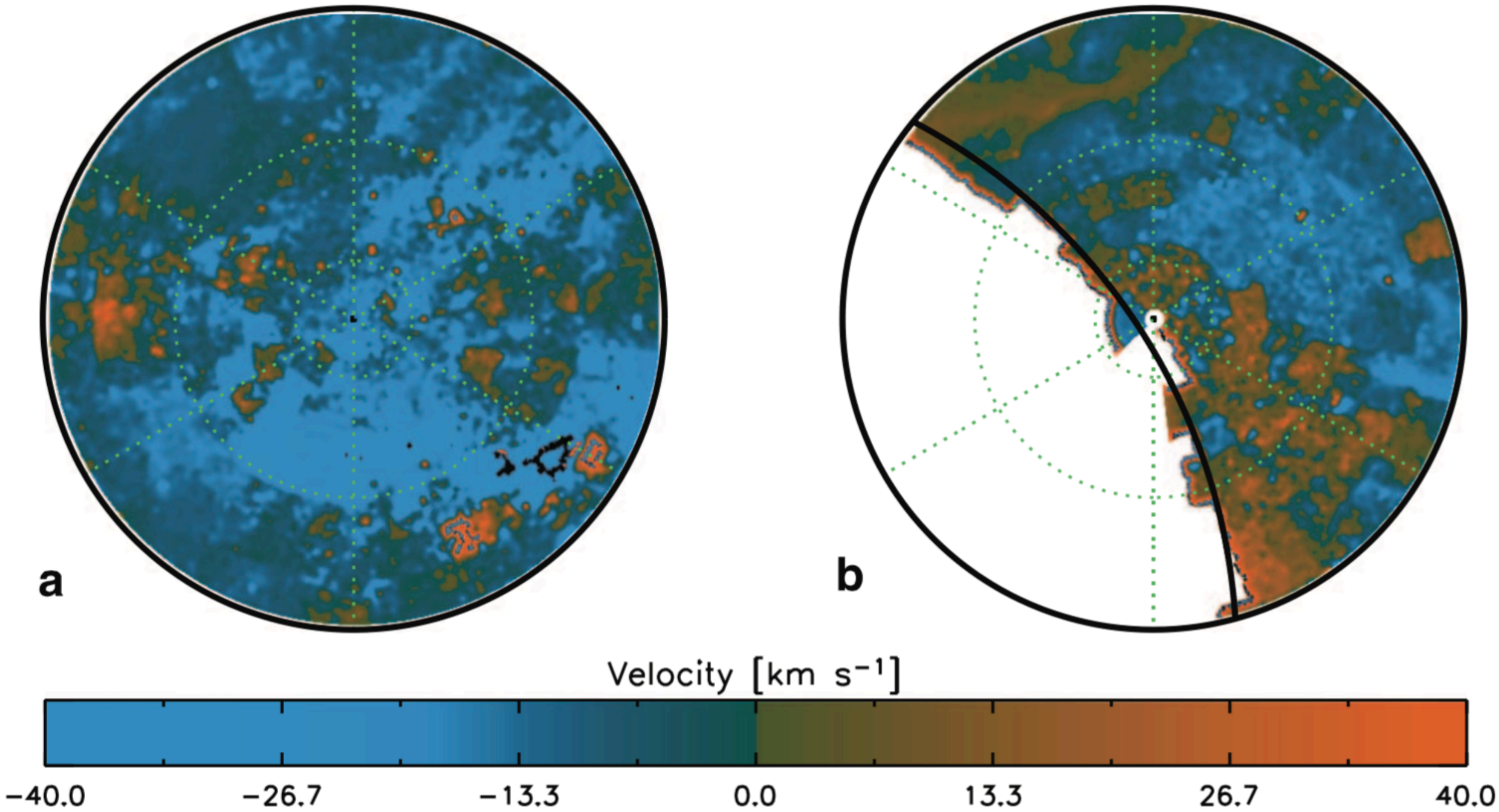
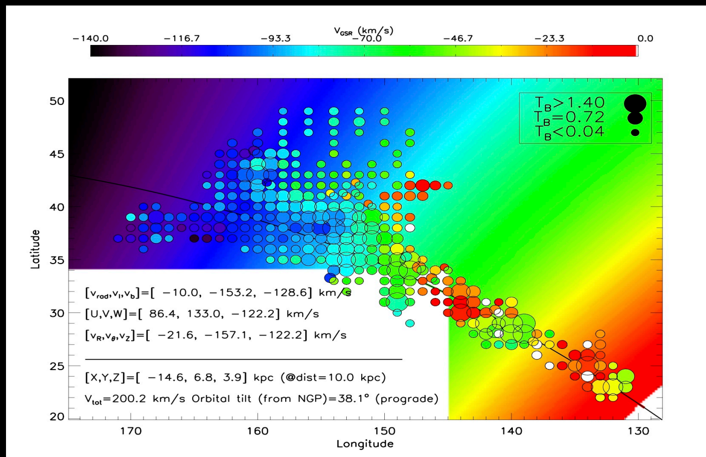


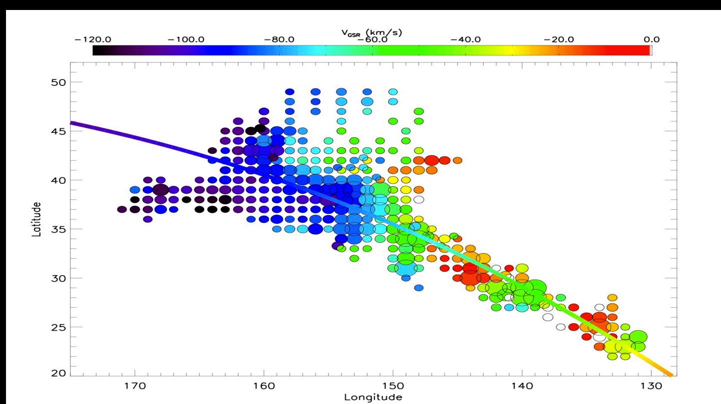
FIG. 14.—Velocities at high latitudes. These maps mirror the projection aspects of Fig. 7 but display intensity-weighted velocity averages (see § 5), which highlight a negative velocity preference for ionized emission toward both Galactic poles.

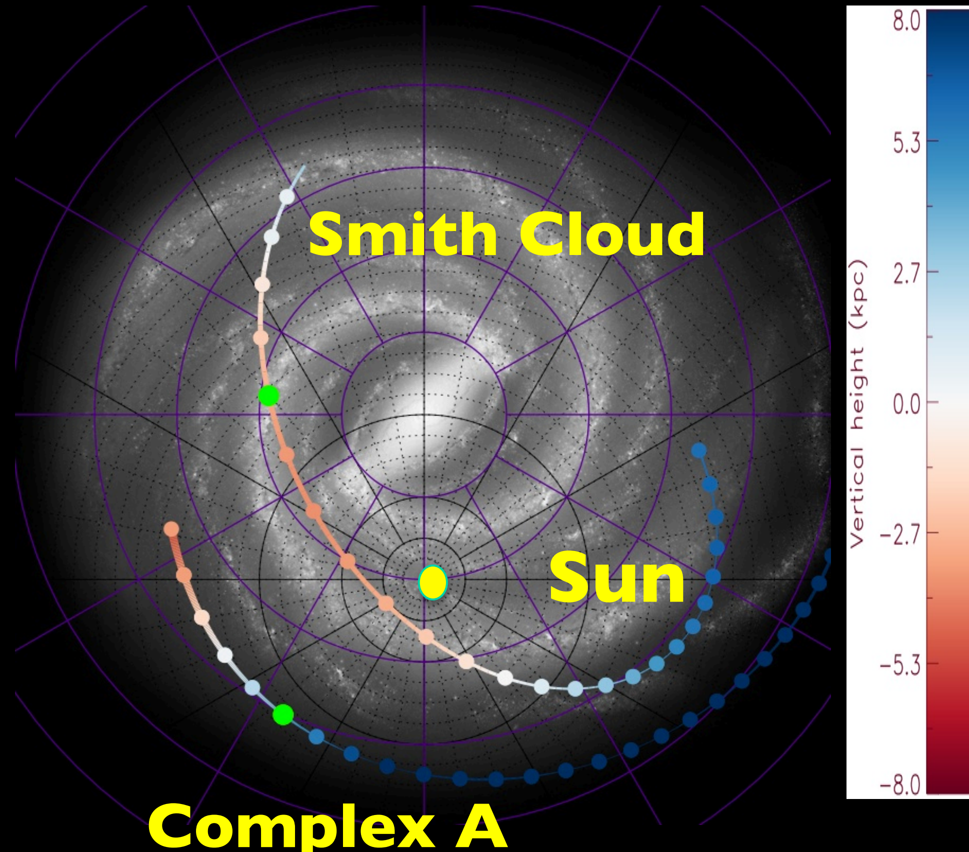
20° in latitude. In (*a*), $\ell = 0°$ is at the twelve o'clock position, and longitude increases clockwise. In (*b*), $\ell = 180°$ is at the six o'clock position, and longitude increases counter-clockwise. The solid line marking the border of data in the southern projection denotes $\delta = -30°$, the limit of the WHAM-NSS.

High Velocity Clouds (odds and ends)

An Orbit for Complex A (Alexandre Fernandes)

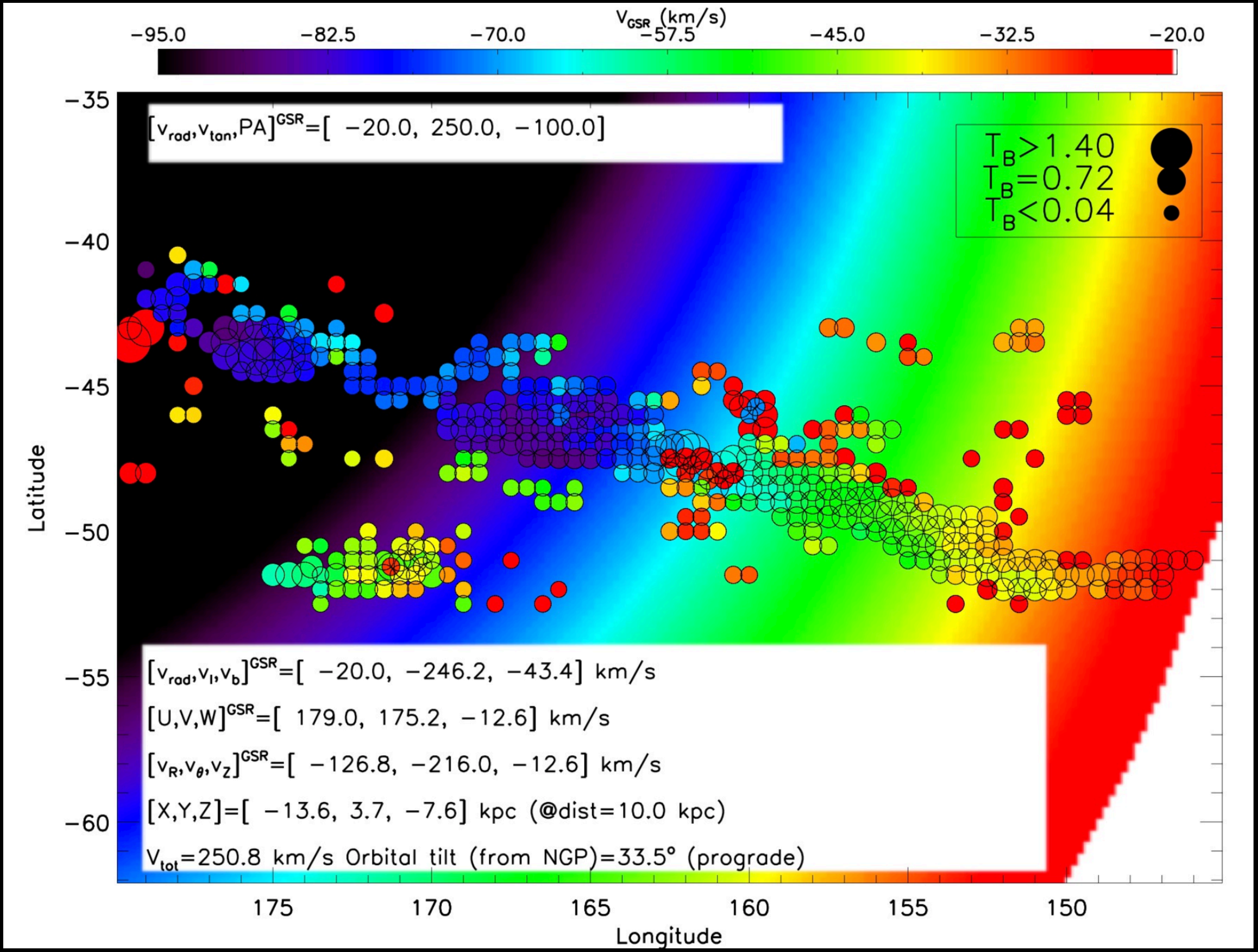




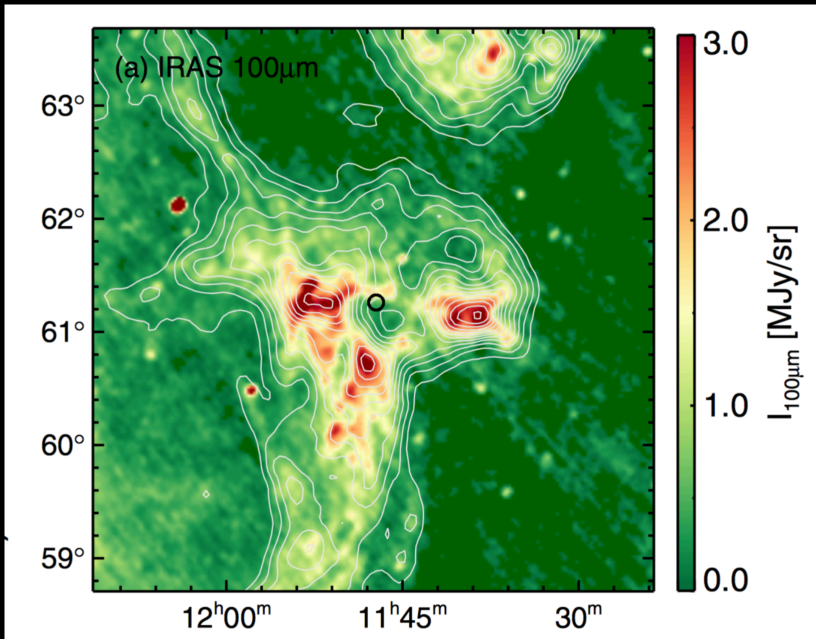


Conclusions: Analysis of HVC Complex A velocity field suggests a cloud with space velocity ~250-280 km/s in a prograde, but non-circular, orbit tipped by about 40° from Galactic plane. • Drag forces are shown to have very little effect on the orbit of Complex A for the past ~200 Myr. As the distance of modeled orbits increases, higher cloud velocities are required to match the data due to the curvature of the orbit.

Cohen Stream (similar deal)



A low metallicity log (Z/Zo)=-0.43±0.12 IVC (with dust)!



The Astrophysical Journal, 777:19 (14pp), 2013 November 1 doi:10.1088/0004-637X/777/1/19

A LOW-METALLICITY MOLECULAR CLOUD IN THE LOWER GALACTIC HALO*

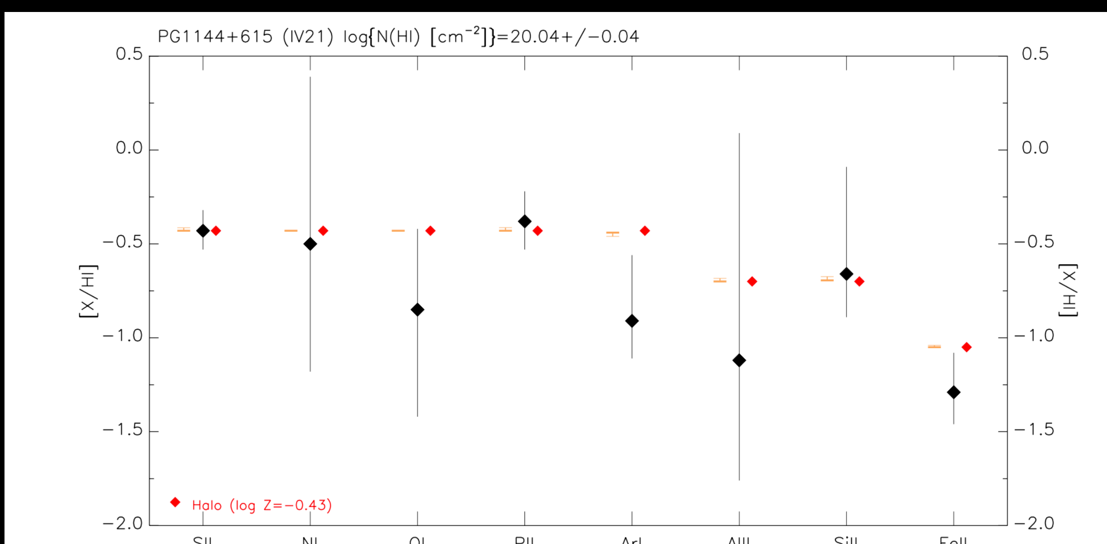
Audra K. Hernandez[1], Bart P. Wakker[1], Robert A. Benjamin[2], David French[1], Juergen Kerp[3], Felix J. Lockman[4], Simon O'Toole[5], and Benjamin Winkel[6]
[1] Department of Astronomy, University of Wisconsin, 475 North Charter Street, Madison, WI 53706, USA; hernande@astro.wisc.edu, wakker@astro.wisc.edu, frenchd@astro.wisc.edu
[2] Department of Physics, University of Wisconsin-Whitewater, Whitewater, WI 53190, USA; benjamin@astro.wisc.edu
[3] Argelander-Institut für Astronomie, Auf dem Hügel 71, D-53121 Bonn, Germany; jkerp@astro.uni-bonn.de
[4] National Radio Astronomy Observatory, Green Bank, WV 24944, USA; fjlockman@nrao.edu
[5] Australian Astronomical Observatory, P.O. Box 296, Epping 1710, Australia; otoole@aao.gov.au
[6] Max-Planck-Institut für Radioastronomie (MPIfR), Auf dem Hügel 69, D-53121 Bonn, Germany; bwinkel@mpifr.de
Received 2013 July 1; accepted 2013 August 26; published 2013 October 9

ABSTRACT

We find evidence for the impact of infalling, low-metallicity gas on the Galactic disk. This is based on FUV absorption line spectra, 21 cm emission line spectra, and far-infrared (FIR) mapping to estimate the abundance and physical properties of IV21 (IVC135+54-45), a galactic intermediate-velocity molecular cloud that lies ~300 pc above the disk. The metallicity of IV21 was estimated using observations toward the subdwarf B star PG1144+615, located at a projected distance of 16 pc from the cloud's densest core, by measuring ion and H I column densities for comparison with known solar abundances. Despite the cloud's bright FIR emission and large column densities of molecular gas as traced by CO, we find that it has a sub-solar metallicity of $\log(Z/Z_{\odot}) = -0.43 \pm 0.12$ dex. IV21 is thus the first known sub-solar metallicity cloud in the solar neighborhood. In contrast, most intermediate-velocity clouds (IVC) have near-solar metallicities and are believed to originate in the Galactic Fountain. The cloud's low metallicity is also atypical for Galactic molecular clouds, especially in light of the bright FIR emission which suggest a substantial dust content. The measured $I_{100\,\mu m}/N(\mathrm{H\,I})$ ratio is a factor of three below the average found in high latitude H I clouds within the solar neighborhood. We argue that IV21 represents the impact of an infalling, low-metallicity high-velocity cloud that is mixing with disk gas in the lower Galactic halo.

Key words: Galaxy: disk – Galaxy: halo – ISM: clouds – ISM: general – ultraviolet: ISM

Online-only material: color figures



Hernandez et al (2013)

Why study low metallicity molecule formation in other galaxies when we <u>may*</u> have an example ~300 pc away!

*Depends on swept-up column

Summary

Models: Gas that moves up, generically moves radially outward and slows down. The fact that halo lags have a radial dependence is an important constraint on all the classes of models.

Galactic Winds: The Milky Way might well have two winds (or outflow regions), the nuclear Fermi bubble, and the annular/spiral wind from Scutum-Centaurus. Models have already been developed to match ROSAT ¾ keV and 408 MHz synchrotron emission, and are being redeveloped to include rotation and test against kinematic data. This wind is an important foreground to consider when looking at halo kinematics.

WHAM: A lot of bubbles, many of them new 105 of them new. Completion of the all-sky survey will allow us characterize the global velocity field of the WIM.

HVCs: Several HVC streams have well-characterized v_{GSR} along their lengths, allowing one to estimate a velocity vector for the gas and experiment with different orbits. Strangely, Smith Cloud, Cohen Stream and Complex A have similarly tipped prograde orbits. In addition, we have identified a metal poor IVC (a former HVC?) which may be a mixture of pristine and swept-up gas.