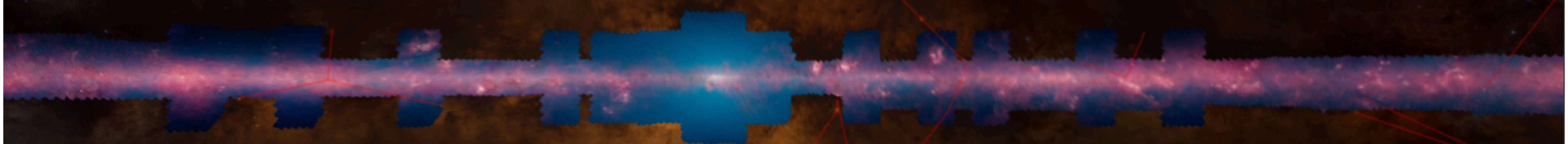
Three Dimensional Mapping of the Stellar and Star-Formation Break of the Milky Way Galaxy

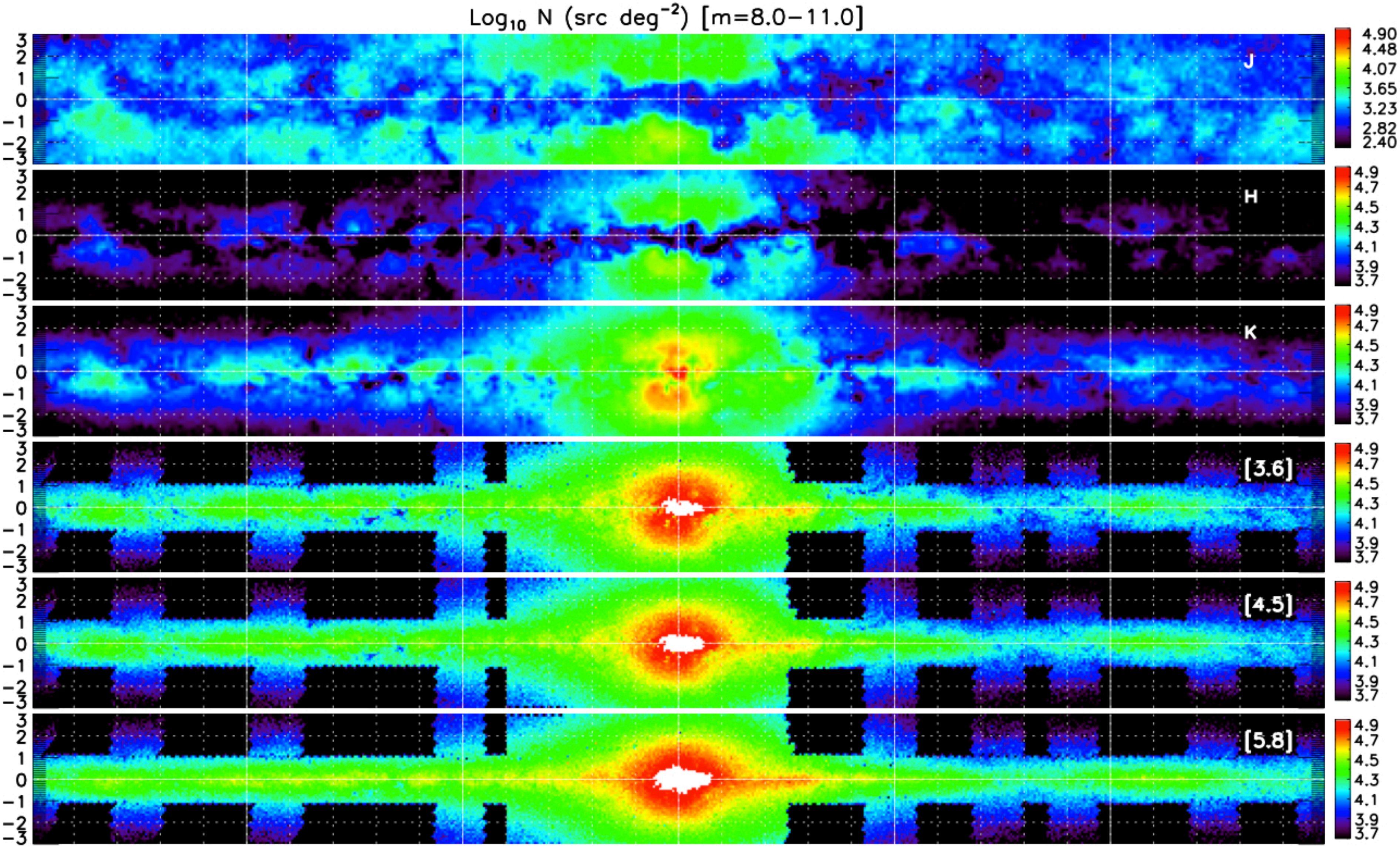


www.spitzer.caltech.edu/glimpse360
http://irsa.ipac.caltech.edu

GLIMPSE (Galactic Legacy Infrared Midplane Survey Extraordinaire)

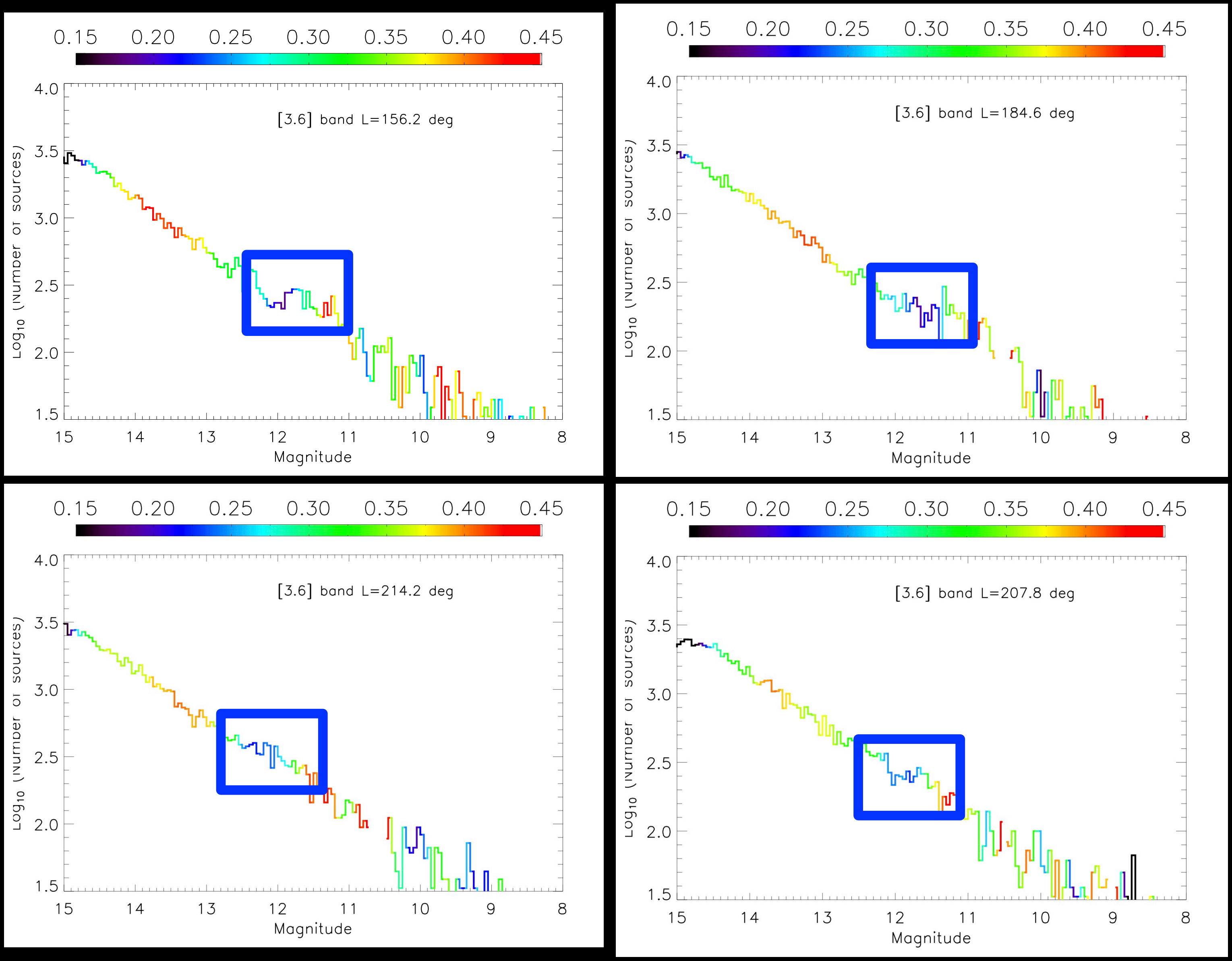
- 3.6, 4.5 (2003-13) 5.8, 8.0 μm (2003-06) coverage of 360^{o} of Galactic Plane
- 64% of all stars in the Galactic disk, bar, and bulge are in survey area
- 91% of all star formation in Galactic disk contained in survey area
- 677 refereed publications
  (More than any other Spitzer Legacy Program by 263.)
- 1,188 square degrees / 180 **days** of observing time
- 229,211,668 million sources

(Almost) extinction free view of the Disk: $A_{[4.5]} = 0.04\ A_V$

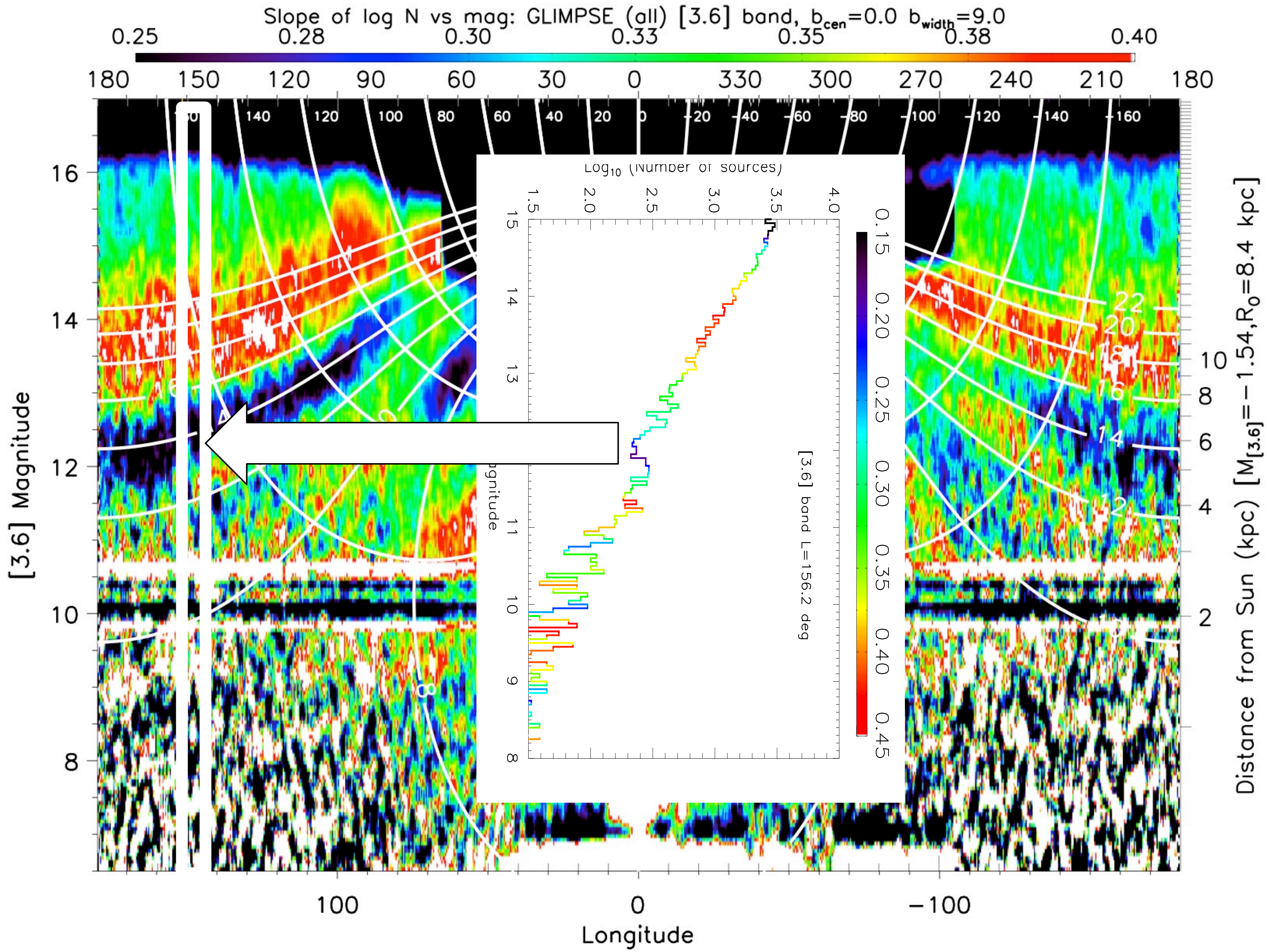


Infrared starcount map as a function of wavelength (2MASS + GLIMPSE)

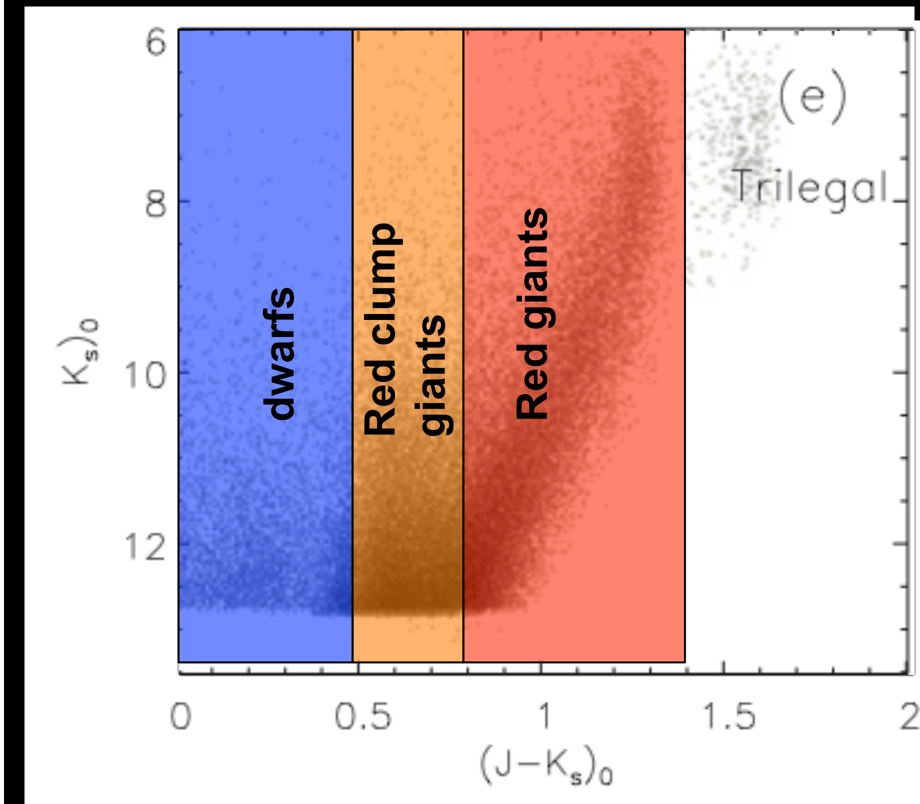
Four Outer Galaxy Source Histograms: l°=156-214

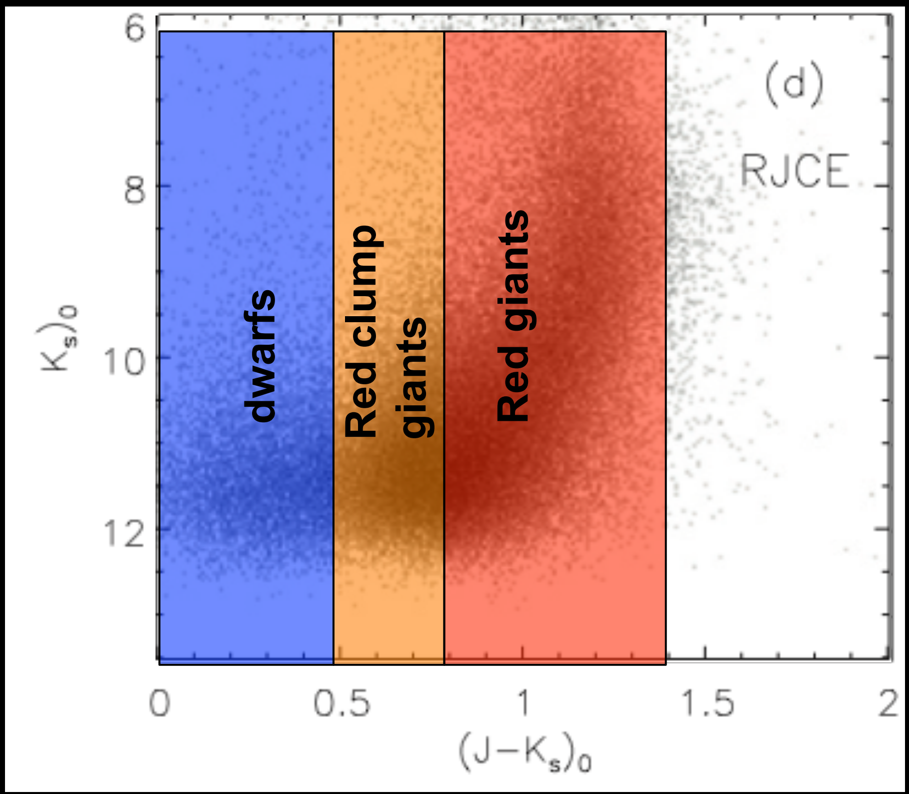


1800 GLIMPSE histograms in a single plot



Correcting for Extinction

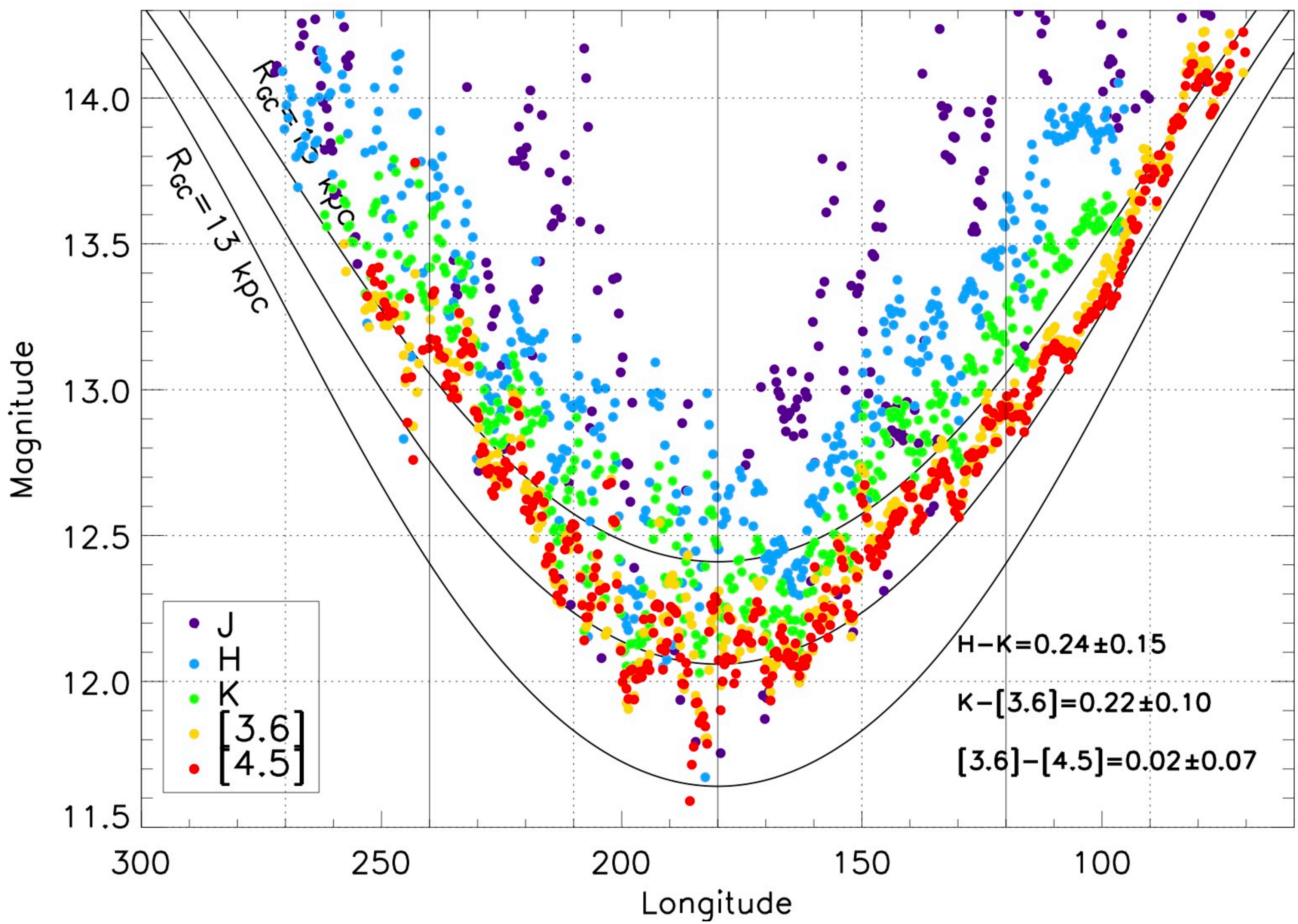




Near Infrared Color Excess (NICE): $(H\text{-}K)_0$=0.15 (Lada et al 1994).

NICE Revisited (NICER): Use J,H, and K color info (Lombardi & Alves 2001)

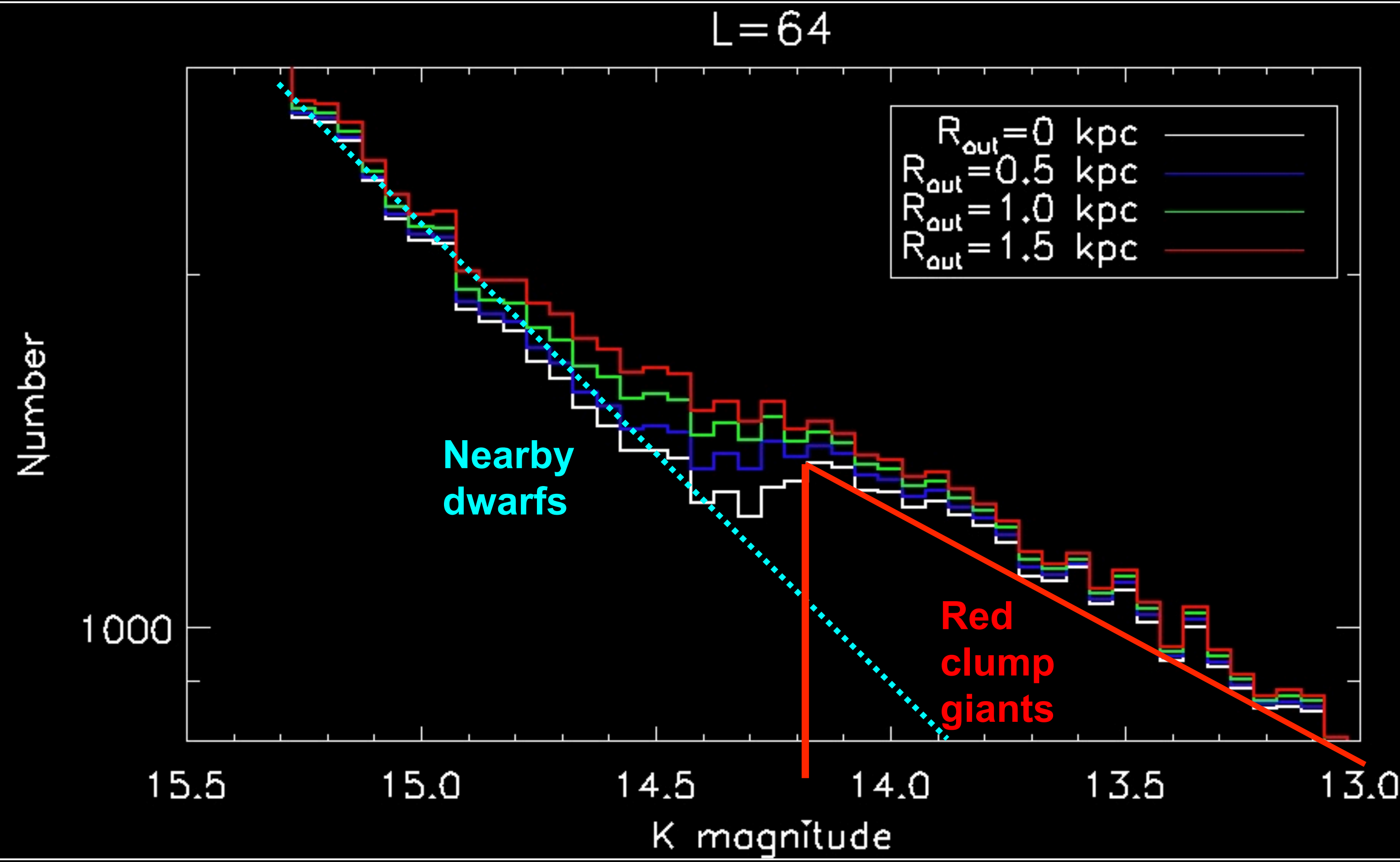
Rayleigh-Jeans Color Excess (RJCE): H-[4.5] (Majewski et al. 2011)



Magnitude
Longitude
14.0
13.5
13.0
12.5
12.0
11.5
300
250
200
150
100
Rgc=15 kpc
Rgc=13 kpc
J
H
K
[3.6]
[4.5]
H−K=0.24±0.15
K−[3.6]=0.22±0.10
[3.6]−[4.5]=0.02±0.07

Origin of the Histogram Flattening

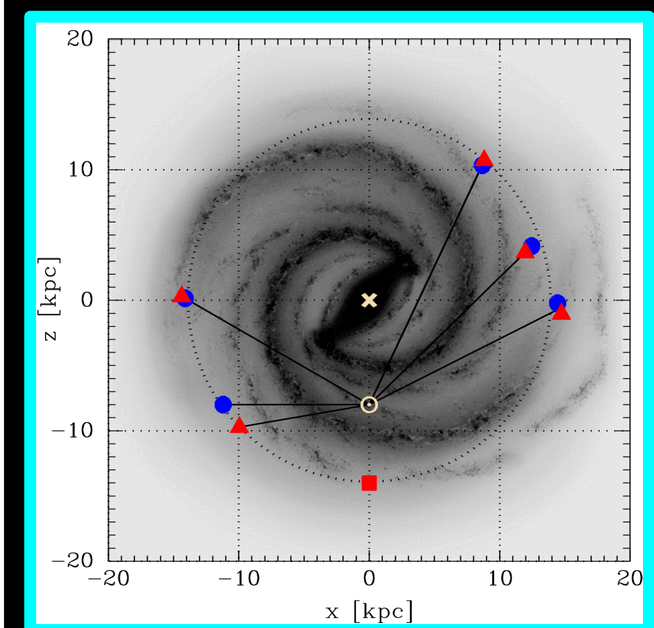
TRILEGAL simulation of a disk break, with transition to an outer scalelength.

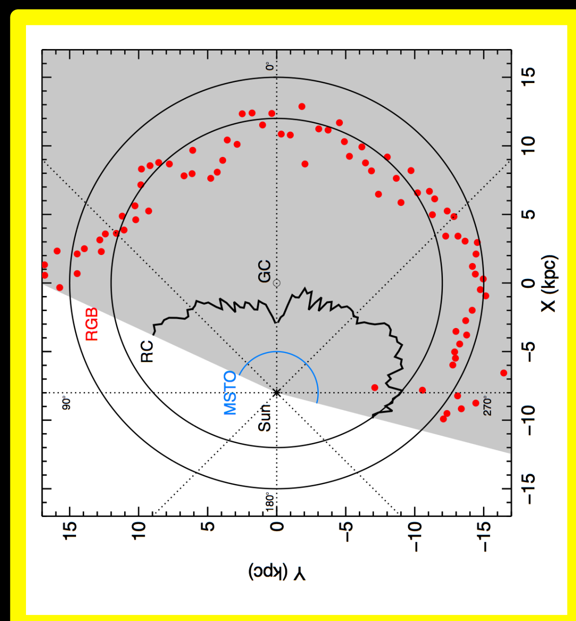


The flattening of the observed histograms is due to a transition to an outer (shorter) scalelength. This indicates a "break" in the stellar <u>volume</u> density continuously from l=70-250° along the Galactic plane that occurs at R(galactocentric)=13.5-14.5 kpc.

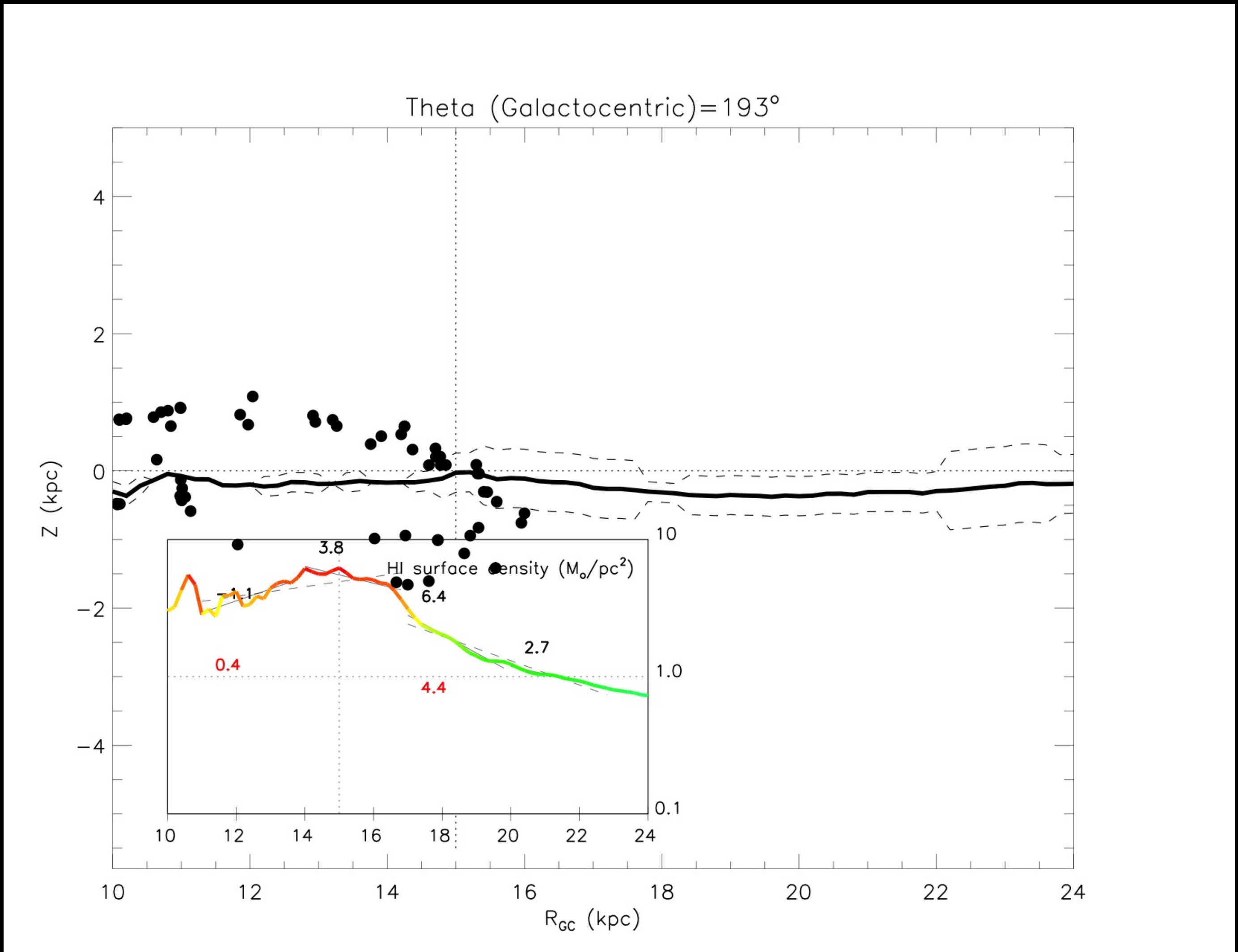
Previous measurements of R_{br}

Robin et al (1992)	Dwarf stars/star counts	R=14 kpc	Four field
Ruphy et al (1996)	Red giants/star counts	R=15 kpc	l=217°, 239°
Freudenreich(1998)	IR light/param. model	R=12 kpc	All sky
Reylé et al (2009)	2MASS star count model	R=14 kpc	All sky
Sale et al (2010)	A stars	R=13±0.5kpc	l=160-200°
Minniti et al (2010)	**Red clumps**	**R=13.9±0.5kpc**	**11 fields**
Nidever et al (2012)	**Red giant branch**	**R=12-15**	**Midplane**
This talk, so far	**Red clumps**	**R=13.5-14.5**	**Midplane, l= 80-240 °**





Three-Dimensional Structure of Break



Because the break can be seen in histograms of total star counts in 2MASS K band, it can be mapped above and below the midplane!

The warping of this surface qualitatively agrees with the HI warp.

There are some vexing complications that I am skipping for today.

Does the MW have a molecular break?

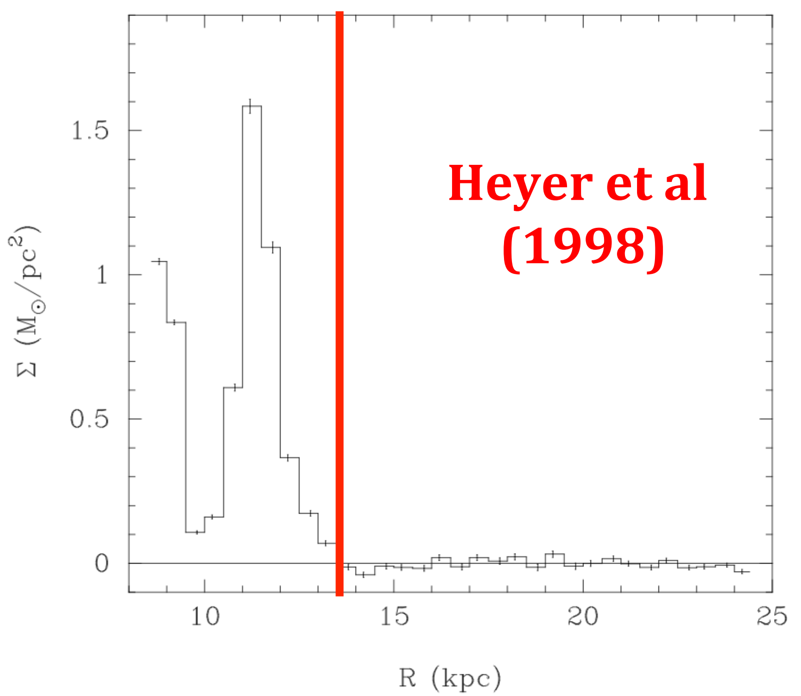
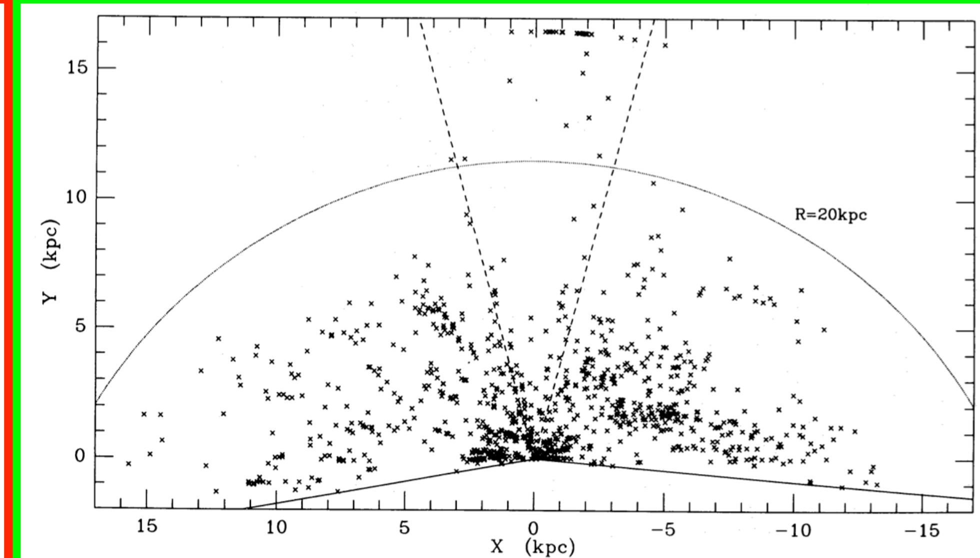


FIG. 13.—Mass surface density as a function of galactocentric radius for the outer Galaxy.



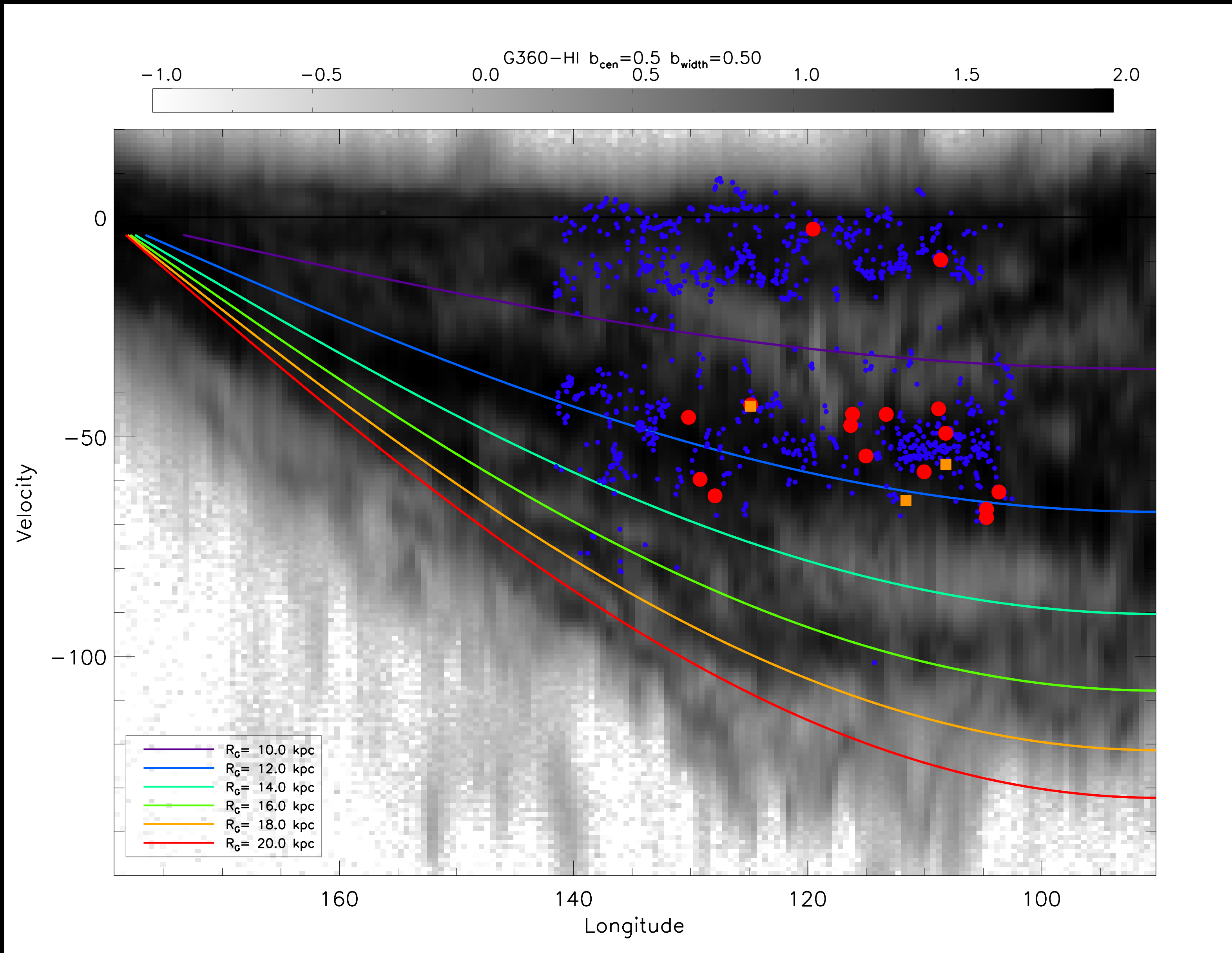
scale height. While a small number of emission features are located in the far outer Galaxy, the molecular disk is effectively truncated at $R = 13.5$ kpc.

The FCRAO CO Survey of the Outer Galaxy is enabled by the instrumentation development within the FCRAO labs and the dedicated Observatory staff. This work is supported by NSF grant AST 94-20159 to the Five College Radio Astronomy Observatory.

Evidence for CO "break" at R=13.5 kpc needs modern confirmation

Scoville/Sanders (1987)
Wouterloot et al (1990)
Heyer et al (1998)
Snell et al (2002)

Spiral structure complicates local measurement of R_{br}(CO)

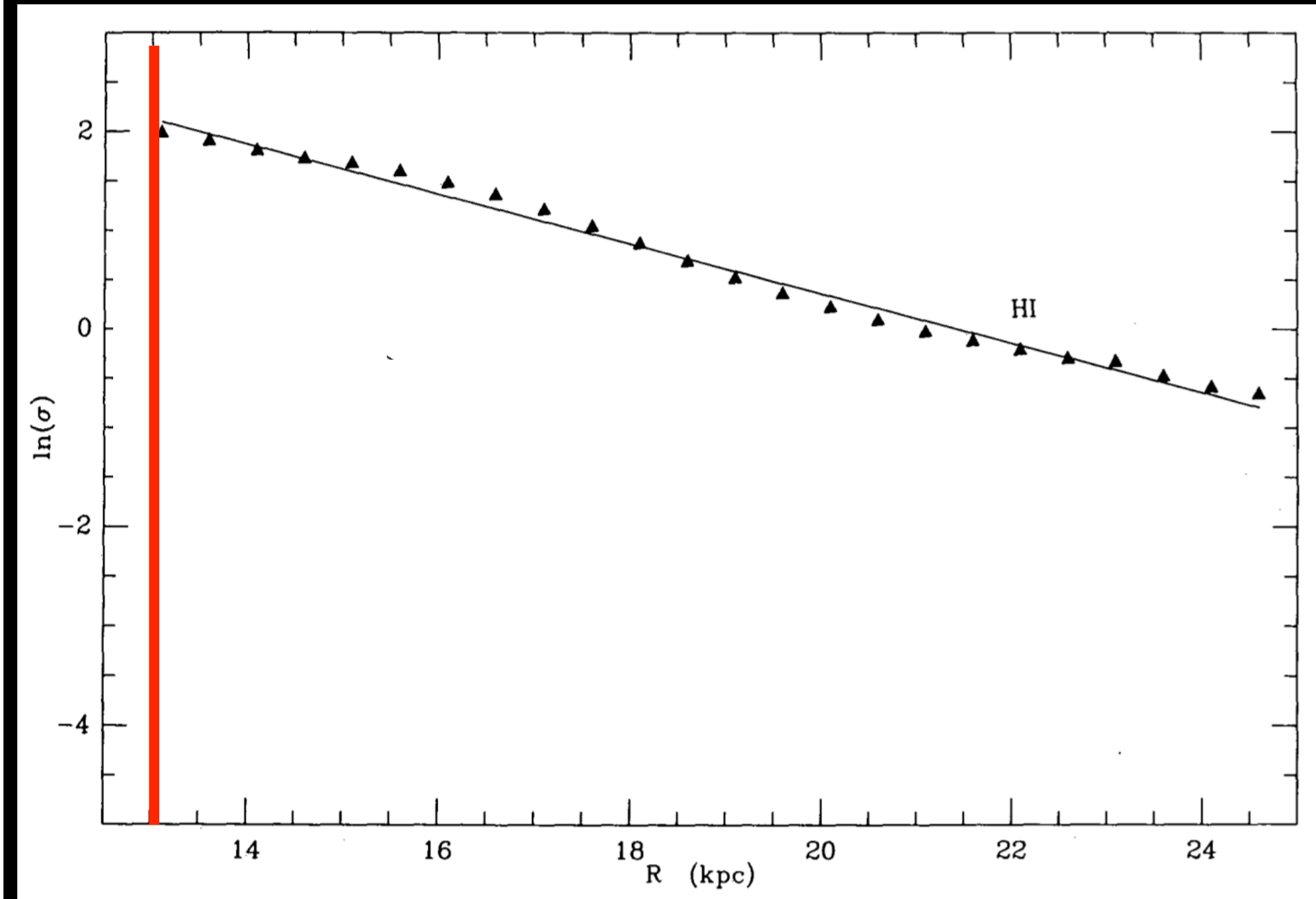


Blue points = Molecular clouds

Heyer et al 1998

Greyscale is LAB HI data

The MW has an HI break. Guess where it is?!



Kalberla & Kerp (2009)

Kalberla & Dedes (2008)

Levine et al (2006)

Diplas & Savage 1991 (with Henderson et al 1982)

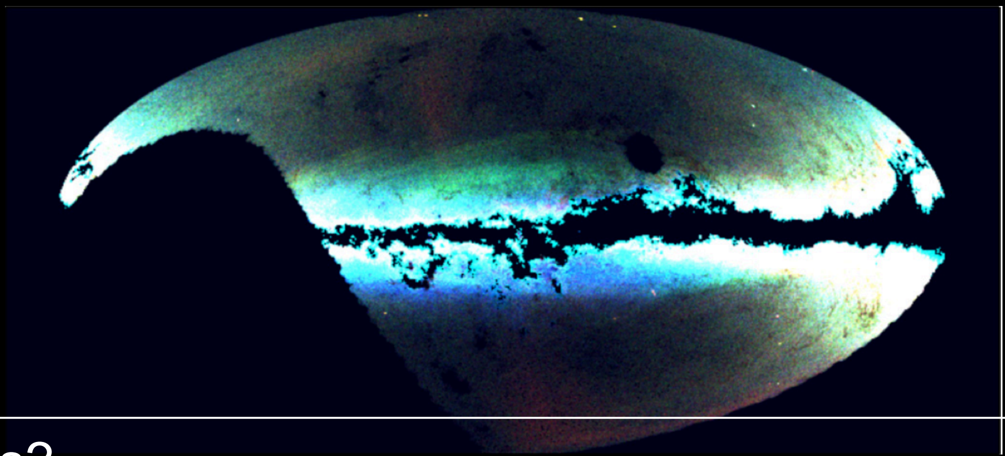
Wouterloot et al 1990 (with Burton 1985)

An Interlude

It remains to be seen whether observed "break" is a surface density break. I demonstrate a volume density break at low latitudes, but haven't done high latitudes or characterized an outer scale length (yet).

Optical studies, e.g. have characterized the flaring disk, cf. Lopez-Corredoira & Molgo (2014) and/or satellites, cf. Slater et al (2014), but can't do the midplane (where the stellar density is highest). **Right now any claims that the MW has or does not have a surface density break are premature**.

But the HI break is **known** to be a break in surface density. The coincidence in radius with the stellar volume break raises questions:



1. Is this seen in other galaxies?
2. Do the models that generate exponential stellar disks (and breaks) create gas breaks in the same place?
3. What regulates the inner/outer scale-lengths for both components?

Star Formation Breaks

Many, many models for regulation, but my favorite is "hydrostatic pressure" (Elmegreen & Parravano 1994) which seems to work pretty well in an extragalactic context (Wong & Blitz 2002, Blitz & Roslowsky 2006, Leroy et al 2008).

$$\text{Midplane weight(R)} = \int_0^\infty \rho(R,z) K_z(R,z) dz$$

My version

$$[p/k](R) = (67 \text{ cm}^{-3}\text{ K}) \left[\frac{c}{c+1} \left(\frac{\Sigma_g(R)}{M_\odot\ pc^{-2}} \right) \left(\frac{\Sigma_*(R)}{M_\odot\ pc^{-2}} \right) + \frac{1}{2} \left(\frac{\Sigma_g(R)}{M_\odot\ pc^{-2}} \right)^2 \right]$$

$$c(R) = \frac{z_g(R)}{z_*(R)}$$

This formula neglects (1) the contribution of the thick warm ionized medium (c/c+1)=0.75 which provides more weight than you would guess from its surface density and (2) the contribution to K_z from dark matter. These and the (c/c+1) factor are constrained better in the MW than any other galaxy.

Example: Solar neighborhood
Σ_{HI}=10 M_o/pc^{-2} Σ_*=40 M_o/pc^{-2}
c=130 pc/300 pc → (c/c+1)=0.30

p/k= 67 (0.30 * 400 + 0.5 * 100) cm^{-3} K
= 67 (120 + 50) cm^{-3} K
= 11,000 cm^{-3} K [total, not thermal]

Compare to Cox (2005) ARAA, 43, 337

Star Formation Breaks: A Prediction

If you assume an exponential disk in gas (R_g) and in stars (R_*):

$$\mathrm{SFR}(R) \propto \left[\frac{c(R)}{c(R)+1} \Sigma_{g,\odot}\Sigma_{*,\odot}\, e^{-(R-R_\odot)/\bar{R}} + \frac{1}{2}\Sigma^2_{g,\odot}\, e^{-(R-R_\odot)/(R_g/2)} \right]$$

$$\frac{1}{\bar{R}} = \frac{1}{R_g} + \frac{1}{R_*} \qquad \frac{1}{(R_g/2)} = \frac{1}{R_g} + \frac{1}{R_g}$$

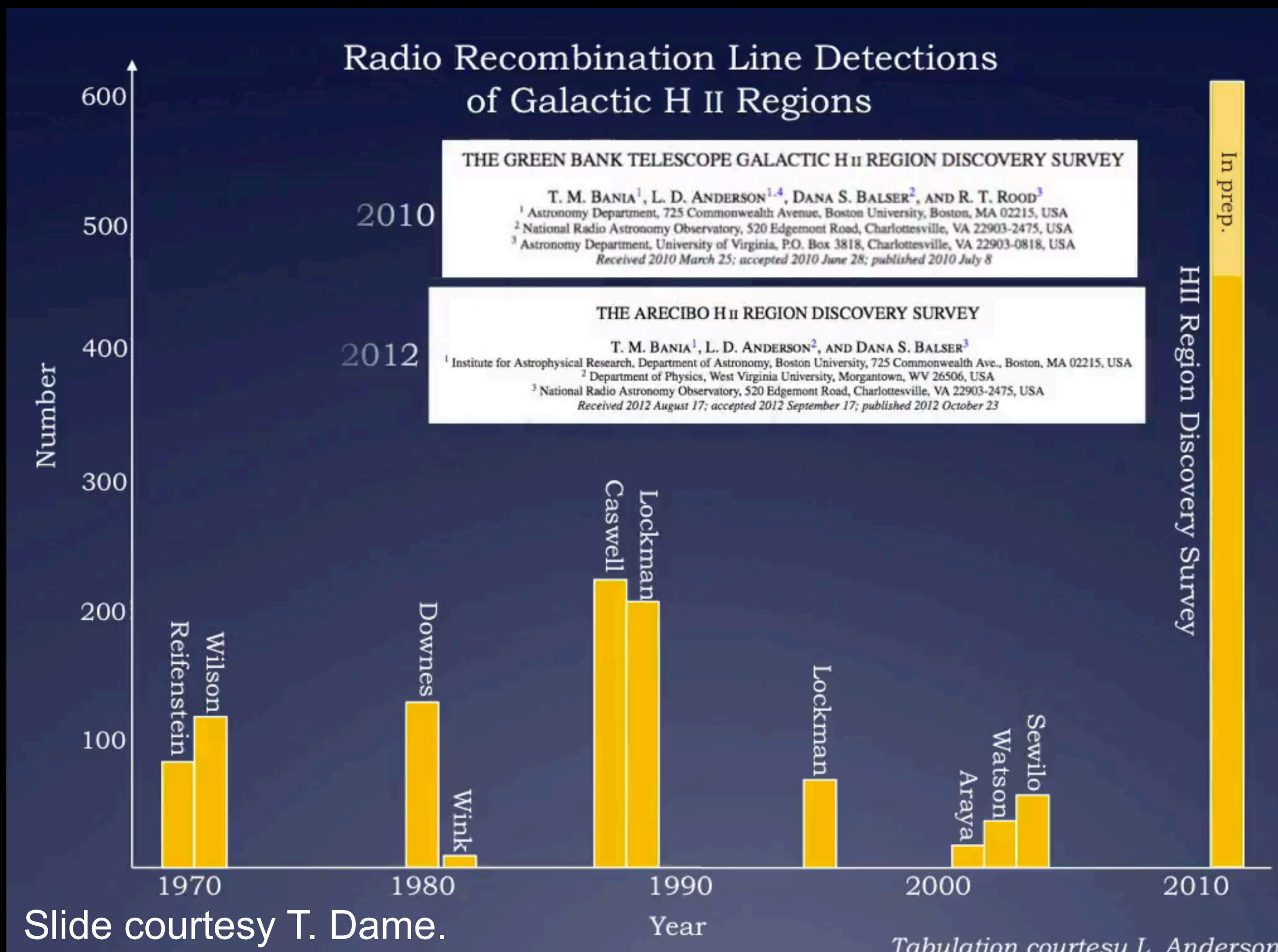
Prediction: The scale-length of star formation should either go as $\bar{R}$ ("reduced scalelength") or (R_g/2) depending upon the surface densities of gas, stars, and their respective scaleheights. (I may revise this prediction based on testing against the MW data.) *Has this been suggested before?*

In the MW

- Interior to the break, the first term dominates and $R_g \sim \infty$, so $R_{SFR} = R_*$
- At the break, it's a close call which of the two terms dominates.
- But there is no shortage of data on HI, stars, molecular clouds, etc!
- What's not nailed down yet: R_* (inside/outside break), R_{CO} (outside break)
- One curiosity: No break in CNM / WNM out to R~20 kpc (Dickey et al 2009)

SFR in the MW: A Rapidly Moving Target

Radial characterization of SFR of the MW has been done for decades, but not with current debates in mind and without many new known sources.



Slide courtesy T. Dame.

WISE HII region catalog: 8398 objects

The Astrophysical Journal Supplement Series, 212:1 (18pp), 2014 May doi:10.1088/0067-0049/212/1/1

THE *WISE* CATALOG OF GALACTIC H II REGIONS

L. D. Anderson[1,5], T. M. Bania[2], Dana S. Balser[3], V. Cunningham[1], T. V. Wenger[3,4],
B. M. Johnstone[1], and W. P. Armentrout[1]
[1] Department of Physics and Astronomy, West Virginia University, Morgantown, WV 26506, USA
[2] Institute for Astrophysical Research, Department of Astronomy, Boston University, 725 Commonwealth Avenue, Boston, MA 02215, USA
[3] National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903, USA
[4] Department of Astronomy, University of Virginia, P.O. Box 3813, Charlottesville, VA 22904, USA
Received 2013 November 8; accepted 2013 December 20; published 2014 April 10

ABSTRACT

Using data from the all-sky *Wide-Field Infrared Survey Explorer* (*WISE*) satellite, we made a catalog of over 8000 Galactic H II regions and H II region candidates by searching for their characteristic mid-infrared (MIR) morphology. *WISE* has sufficient sensitivity to detect the MIR emission from H II regions located anywhere in the Galactic disk. We believe this is the most complete catalog yet of regions forming massive stars in the Milky Way. Of the ~8000 cataloged sources, ~1500 have measured radio recombination line (RRL) or Hα emission, and are thus known to be H II regions. This sample improves on previous efforts by resolving H II region complexes into multiple sources and by removing duplicate entries. There are ~2500 candidate H II regions in the catalog that are spatially coincident with radio continuum emission. Our group's previous RRL studies show that ~95% of such targets are H II regions. We find that ~500 of these candidates are also positionally associated with known H II region complexes, so the probability of their being bona fide H II regions is even higher. At the sensitivity limits of existing surveys, ~4000 catalog sources show no radio continuum emission. Using data from the literature, we find distances for ~1500 catalog sources, and molecular velocities for ~1500 H II region candidates.

Key words: Galaxy: structure – H II regions – infrared: ISM – ISM: bubbles – stars: formation

Online-only material: color figures, machine-readable tables

Milky Way Project

5106 objects

The Milky Way Project First Data Release: a bubblier Galactic disc

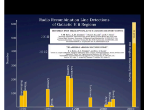
R. J. Simpson,[1★] M. S. Povich,[2†] S. Kendrew,[3] C. J. Lintott,[1,4] E. Bressert,[5,6,7] K. Arvidsson,[4] C. Cyganowski,[7†] S. Maddison,[8] K. Schawinski,[9,10‡] R. Sherman,[11] A. M. Smith[1,4] and G. Wolf-Chase[4,11]
[1] *Oxford Astrophysics, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH*
[2] *Department of Astronomy and Astrophysics, The Pennsylvania State University, 525 Davey Laboratory, University Park, PA 16802, USA*
[3] *Max Planck Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany*
[4] *Astronomy Department, Adler Planetarium, 1300 S. Lake Shore Drive, Chicago, IL 60605, USA*
[5] *ESO, Karl-Schwarzschild-Strasse 2, D87548, Garching, Germany*
[6] *School of Physics, University of Exeter, Stocker Road, Exeter EX4 4QL*
[7] *Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA*
[8] *Centre for Astrophysics & Supercomputing, Swinburne University, H39, PO Box 218, Hawthorn, VIC 3122, Australia*
[9] *Department of Physics, Yale University, PO Box 208121, New Haven, CT 06520, USA*
[10] *Yale Center for Astronomy and Astrophysics, Yale University, PO Box 208121, New Haven, CT 06520, USA*
[11] *Department of Astronomy & Astrophysics, University of Chicago, 5640 S. Ellis Ave., Chicago, IL 60637, USA*

Accepted 2012 February 19. Received 2012 February 13; in original form 2011 December 7

ABSTRACT
We present a new catalogue of 5106 infrared bubbles created through visual classification via the online citizen science website 'The Milky Way Project'. Bubbles in the new catalogue have been independently measured by at least five individuals, producing consensus parameters for their position, radius, thickness, eccentricity and position angle. Citizen scientists – volunteers recruited online and taking part in this research – have independently rediscovered the locations of at least 86 per cent of three widely used catalogues of bubbles and H II regions whilst finding an order of magnitude more objects. 29 per cent of the Milky Way Project catalogue bubbles lie on the rim of a larger bubble, or have smaller bubbles located within them, opening up the possibility of better statistical studies of triggered star formation. Also outlined is the creation of a 'heat map' of star formation activity in the Galactic plane. This online resource provides a crowd-sourced map of bubbles and arcs in the Milky Way, and will enable better statistical analysis of Galactic star formation sites.

Key words: stars: formation – dust, extinction – H II regions – infrared: ISM.

Red MSX Survey: 4651 objects



The Astrophysical Journal Supplement Series, 208:11 (17pp), 2013 September doi:10.1088/0067-0049/208/1/11

THE RED MSX SOURCE SURVEY: THE MASSIVE YOUNG STELLAR POPULATION OF OUR GALAXY

S. L. Lumsden[1], M. G. Hoare[1], J. S. Urquhart[2], R. D. Oudmaijer[1], B. Davies[3], J. C. Mottram[4],
H. D. B. Cooper[1], and T. J. T. Moore[3]
[1] School of Physics and Astronomy, University of Leeds, Leeds LS2 9JT, UK
[2] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, Bonn, Germany
[3] Astrophysics Research Institute, Liverpool John Moores University, Liverpool L3 5RF, UK
[4] Leiden Observatory, Leiden University, P.O. Box 9513, 2300 RA Leiden, The Netherlands
Received 2013 May 1; accepted 2013 July 27; published 2013 September 4

ABSTRACT

We present the Red MSX Source survey, the largest statistically selected catalog of young massive protostars and H II regions to date. We outline the construction of the catalog using mid- and near-infrared color selection. We also discuss the detailed follow up work at other wavelengths, including higher spatial resolution data in the infrared. We show that within the adopted selection bounds we are more than 90% complete for the massive protostellar population, with a positional accuracy of the exciting source of better than 2 arcsec. We briefly summarize some of the results that can be obtained from studying the properties of the objects in the catalog as a whole; we find evidence that the most massive stars form: (1) preferentially nearer the Galactic center than the anti-center; (2) in the most heavily reddened environments, suggestive of high accretion rates; and (3) from the most massive cloud cores.

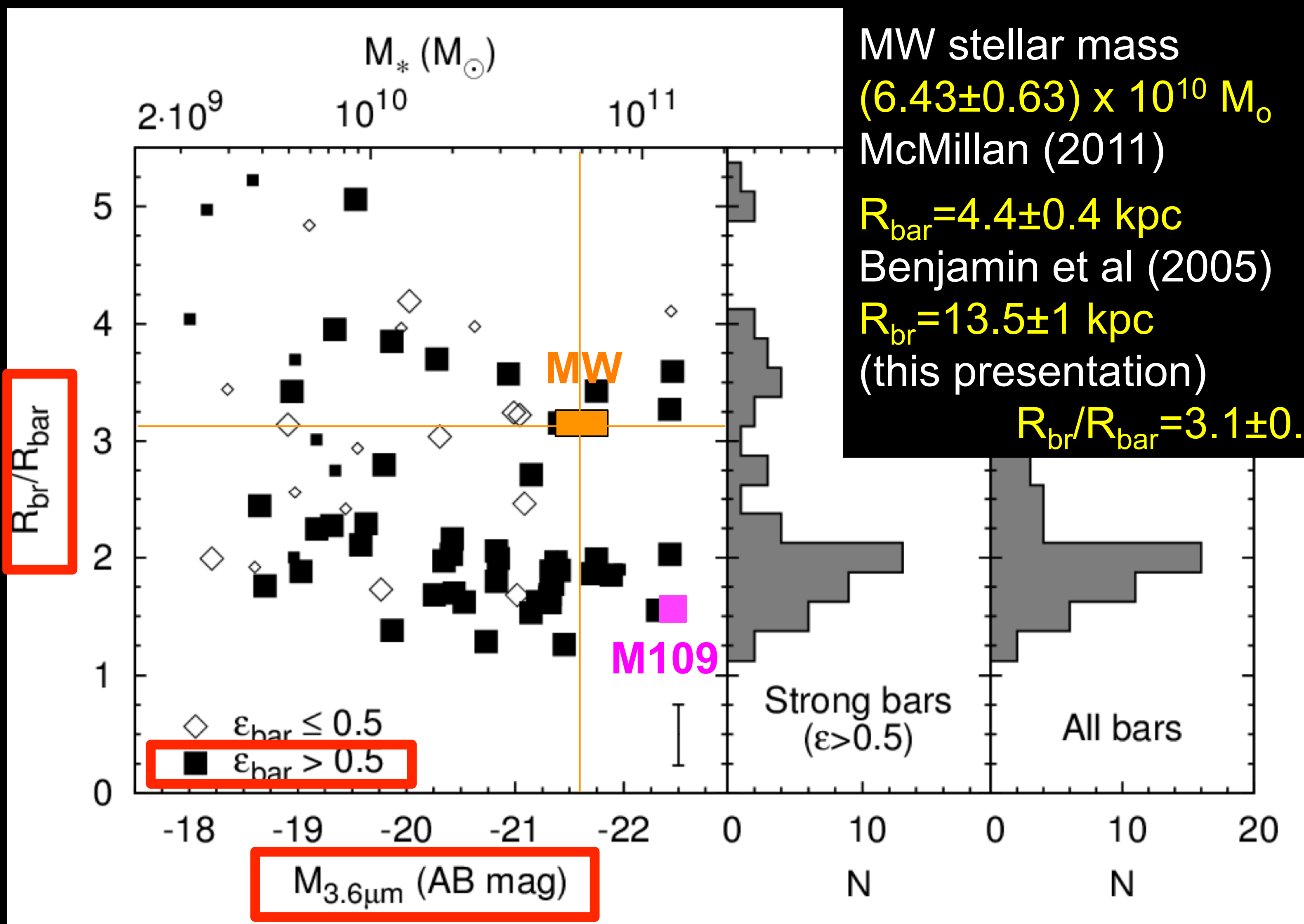
Key words: Galaxy: stellar content – infrared: stars – stars: formation – stars: late-type – stars: pre-main sequence – surveys

Online-only material: color figures, machine-readable table

Using the break to select a new MW Analog

Munoz-Mateos et al (2013)

Munoz-Mateos (priv comm)
Erwin (priv comm)



MW stellar mass
$(6.43 \pm 0.63) \times 10^{10}\ M_o$
McMillan (2011)

$R_{bar}=4.4 \pm 0.4$ kpc
Benjamin et al (2005)
$R_{br}=13.5 \pm 1$ kpc
(this presentation)
$R_{br}/R_{bar}=3.1 \pm 0.2$

The Winner?

NGC 3953

Summary

GLIMPSE confirms that the Galaxy has a **stellar volume density break**, at the distance previously claimed. **R_{br}=13.5-14.5 kpc**, but now one can map this break in 3D! The stellar break is coincident with the HI in the Galaxy, discovered independently. *A stars* also show a break with inner/outer scalelength of 3.0/1.2 kpc (Sale et al 2010). **What is the outer scale length for the molecular gas/SFR and red giants? What do we learn about breaks in general?**

I predict that depending on the relative surface densities of gas and stars at the break point, that the surface density of SFR tracers should go as either the reduced radius $R = R_g R_* /(R_g + R_*)$ or $R_g/2$. I'm testing this in the MW, where we can study all the microphysics and non-axisymmetries.

We use R_{br}/R_{bar} and M[3.6] to propose a new MW analog: NGC 3953. If the MW truly resembles this galaxy, it would explain a lot about the history of spiral structure and raises the question: Is the MW ringed?

The Mystery of the Galactic Stellar Scalelength

Reviews by Robin (1992): R_d=3.5-4.5 kpc /Sackett (1997): R_d=2.5-3.0 kpc

Optical data (solar nbhd):

2.5 kpc	Robin et al 1996	Besancon
3.2 kpc	Larsen 1996	APS-POSS
4.0 kpc	Buser et al. 1999	Basel Halo program
2.7 kpc	Zheng et al 2001	HST obs of M dwarfs
2.3 kpc	Siegel et al 2002	Kapteyn Selected Area stars
2.6 kpc	Juric et al 2008	SDSS

Infrared data:

2.5 kpc	Freudenreich 1998	COBE/DIRBE
2.3 kpc	Drimmel & Spergel 2001	COBE/DIRBE
2.3 kpc	Ruphy et al 1996	DENIS, l=217^o, 239^o
2.0 kpc	Reylé et al 2009	2MASS, l=90-270^o
2.0 kpc	Lopez-Corredoira 2002	2MASS, l=45-315^o, starcount,RG
2.4 kpc	“	Scalength of surface density
3.9 kpc	Benjamin et al 2005	GLIMPSE, |l|=30-60^o

Complications of vertical structure, stellar breaks and outer disks, thin/thick disk, and wavelength dependence for populations/extinction.