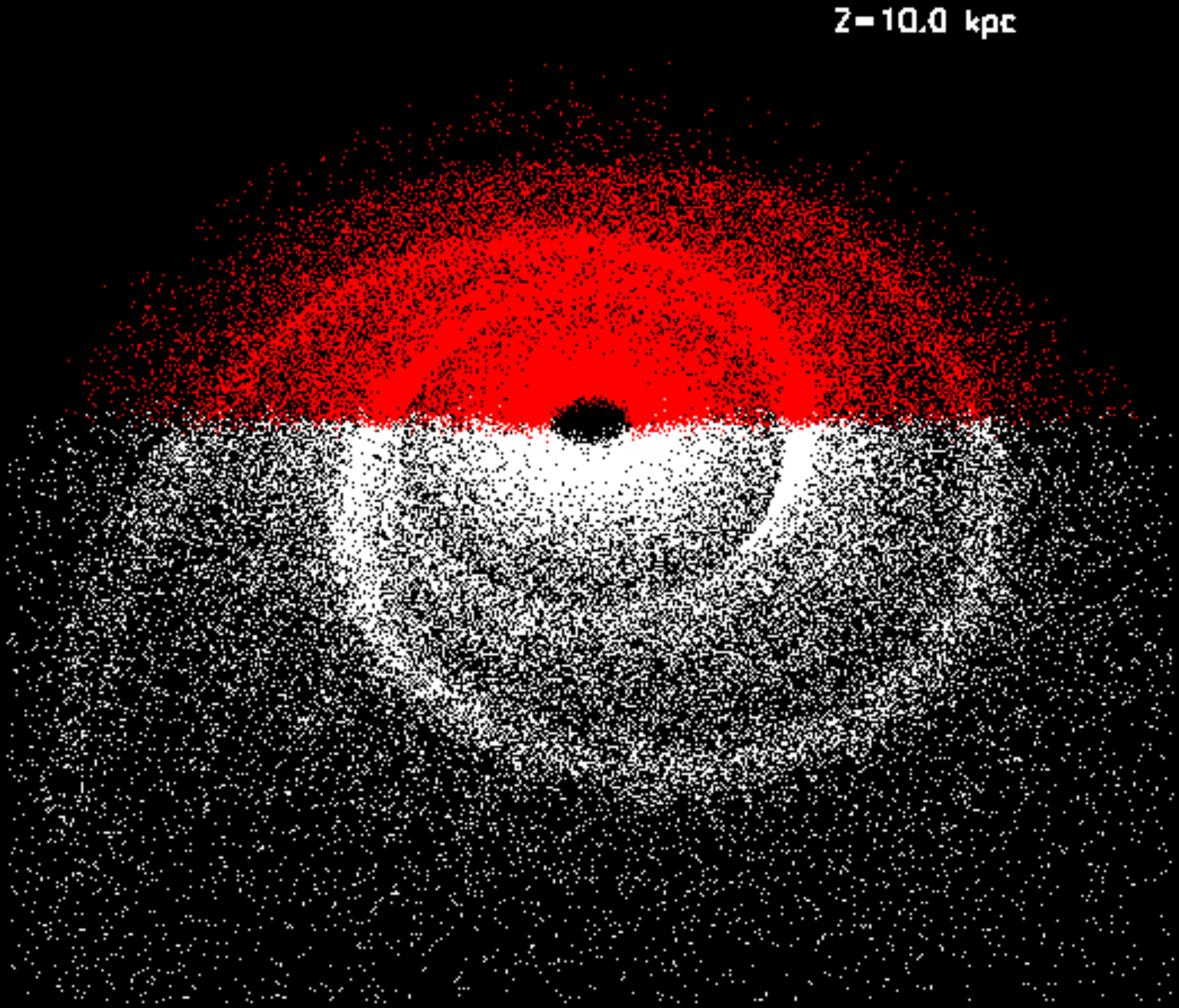
The Other Half of the Milky Way

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° (130°) 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
- 684 refereed publications (More than any other Spitzer Legacy Program!)
- 1,188 square degrees / 180 **days** of observing time
- 229,211,668 million sources

Isn’t Half the Milky Way Enough?



Isn't Half the Milky Way Enough?

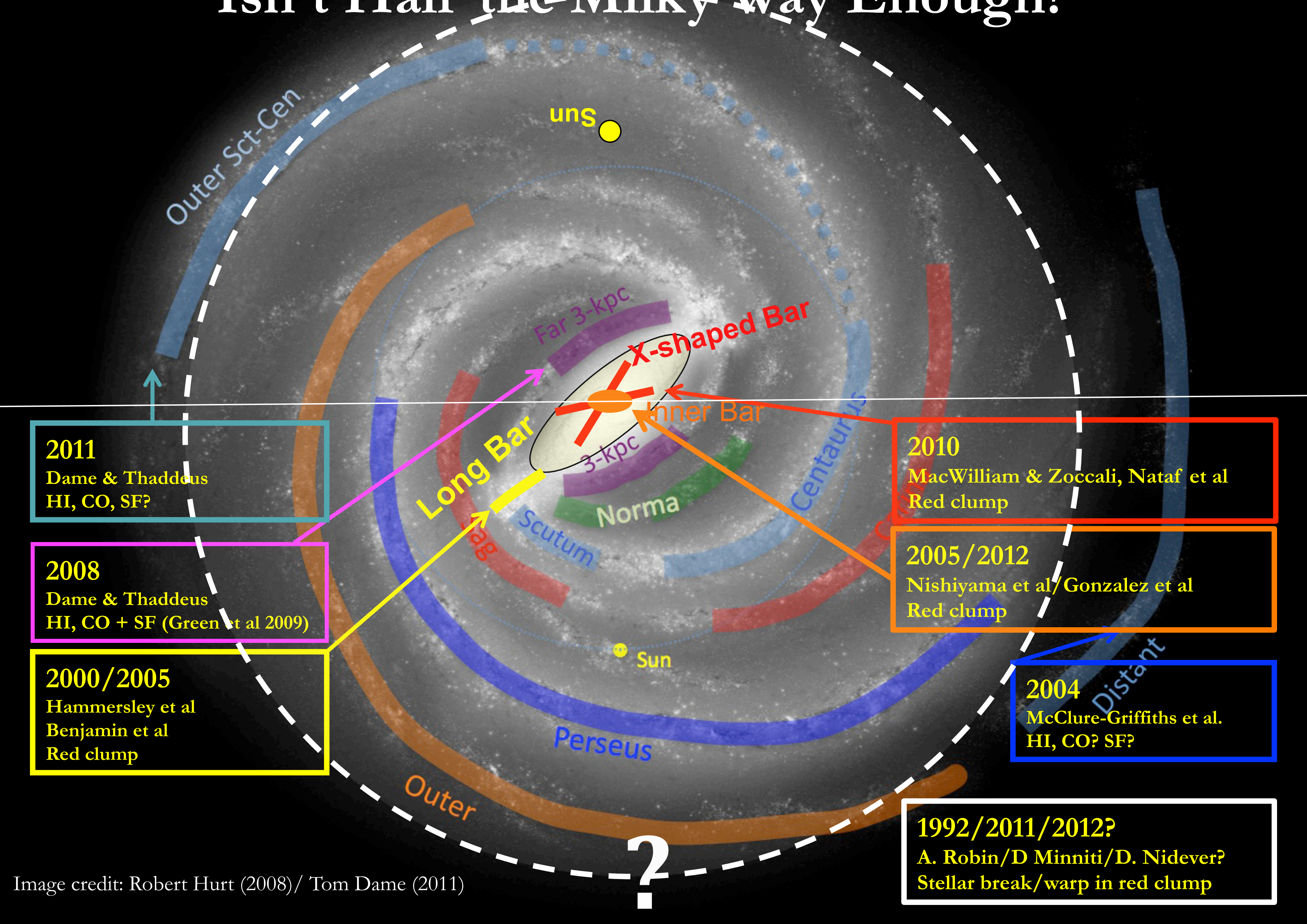


Image credit: Robert Hurt (2008)/ Tom Dame (2011)

Outline

1. Lessons from GLIMPSE

a. Infrared Galactic plane surveys always yield surprises
b. Well-designed (and supervised) Legacy programs work!
c. Think about the Future
d. Coverage vs. Depth vs. Epochs

2. What we don't know about the Milky Way (yet)

a. What is the exponential scale length? (Is there "a" scale-length?)
b. What happens beyond R_{gal}=13.5 kpc?
c. Is the Milky Way a ringed galaxy?

3. What WFIRST could do

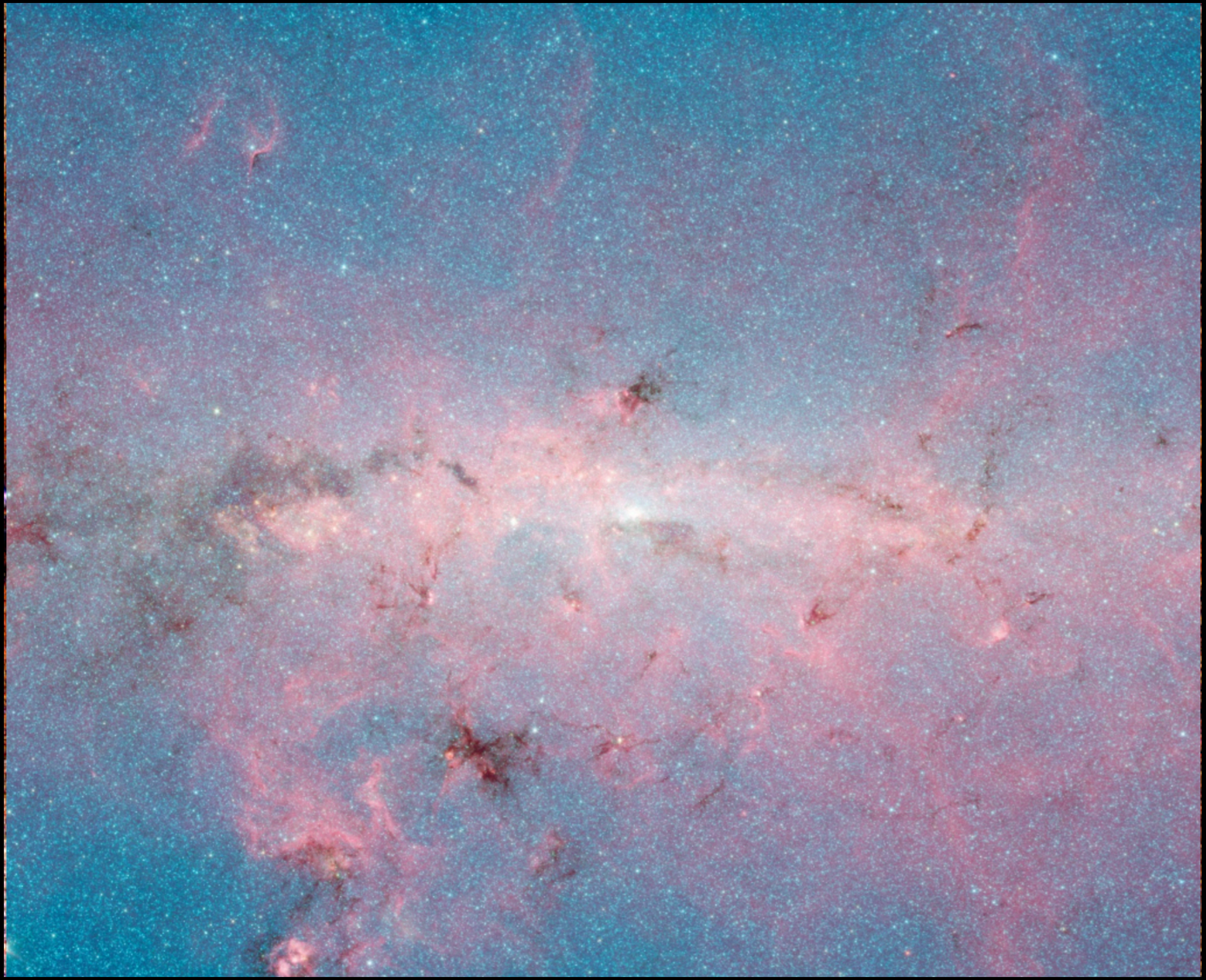
a. Break the angular resolution/extinction barrier in the inner Galaxy
b. Measure the streaming/rotational kinematics of stars <u>beyond</u> G.C.
c. Stellar clusters beyond Galactic center—testing symmetry of MW

4. Preparing for the future

a. The longer the λ, the better.
b. Figure out the data we've got: GLIMPSE, UKIDSS/VVV, APOGEE
c. Coordination in Galactic Research

1. Lessons from GLIMPSE

IR Galactic plane surveys always yield surprises



IRAS →

2MASS →

MSX →

Spitzer/
GLIMPSE →

Herschel/
HiGal →

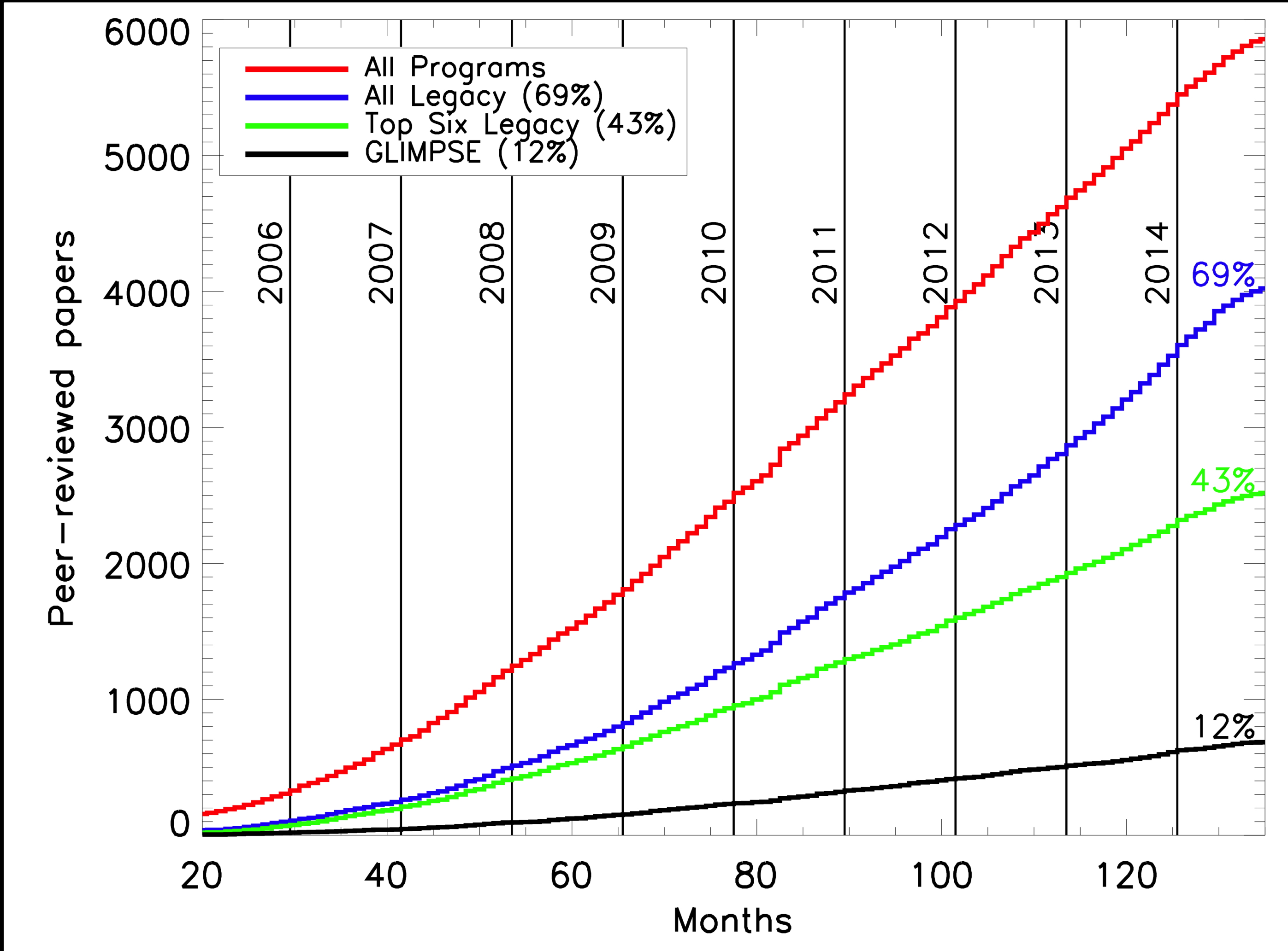
UKIDSS →

VVV →

WFIRST?

1. Lessons from GLIMPSE

Well-designed (and supervised) Legacy programs work!



Contribution of Legacy programs to Spitzer productivity

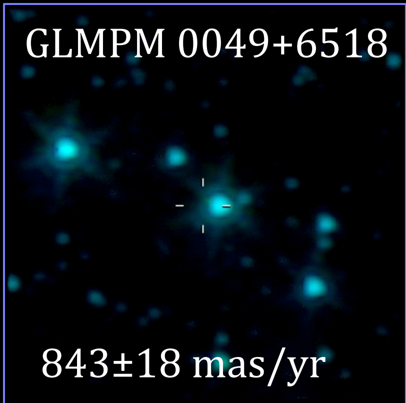
1. Encouraged us to form teams

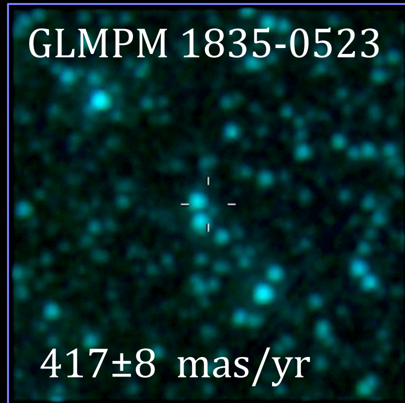
2. Made us think about "data products" and organizing ancillary data

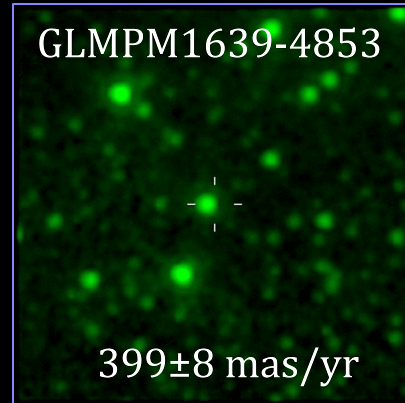
3. Provided a head start on crowded field photometry pipeline (also used in SAGE)

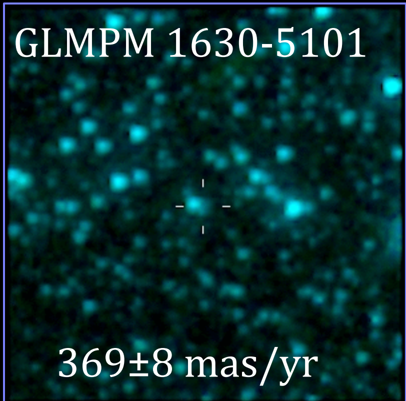
4. Close super-vision important!

1. Lessons from GLIMPSE
Plan for the Future









379+ new high (>100 mas/yr) proper motion stars from GLIMPSE (2004)/DeepGLIMPSE (2013):
l=255-355°, b~-1° to 0° l=25-65°, b~0° to +1°
The 150 square degree overlap was priority 3 time!

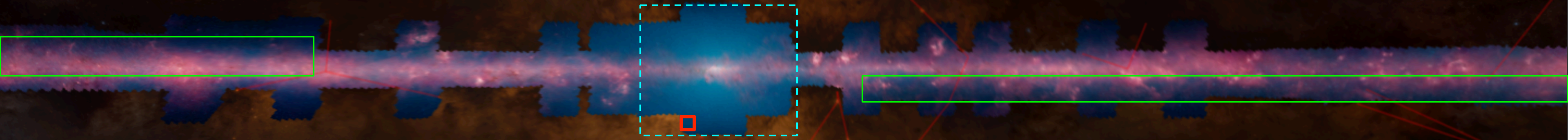
If we had known in 2004 that we would be observing in 2013, we might have thought about designing a better experiment to measure proper motions!

First measurement of proper motion based velocity dispersion in the “bulge” was towards Baade’s window, using Baade’s 1950 plates :
σ_μ~3 mas/yr

1. Lessons from GLIMPSE

Coverage vs. Depth vs. Epochs

The Galaxy will surprise you! Don't assume anything!
X-shaped bar, Long Bar, non-axisymmetric disk, warped stellar break…



Once you know what you're seeing (or not seeing), go deep!
Initially, we could only detect red clump giants to d~9 kpc.

Make sure you get epochs when you need them! It's only late in the game that we are realising the value of mid-IR proper motions. This provides constraints on stellar kinematics for stars that are not easily detected in any other wavebands.

2. What we don't know about the Milky Way (yet)

What is the exponential scalelength? Is there a 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

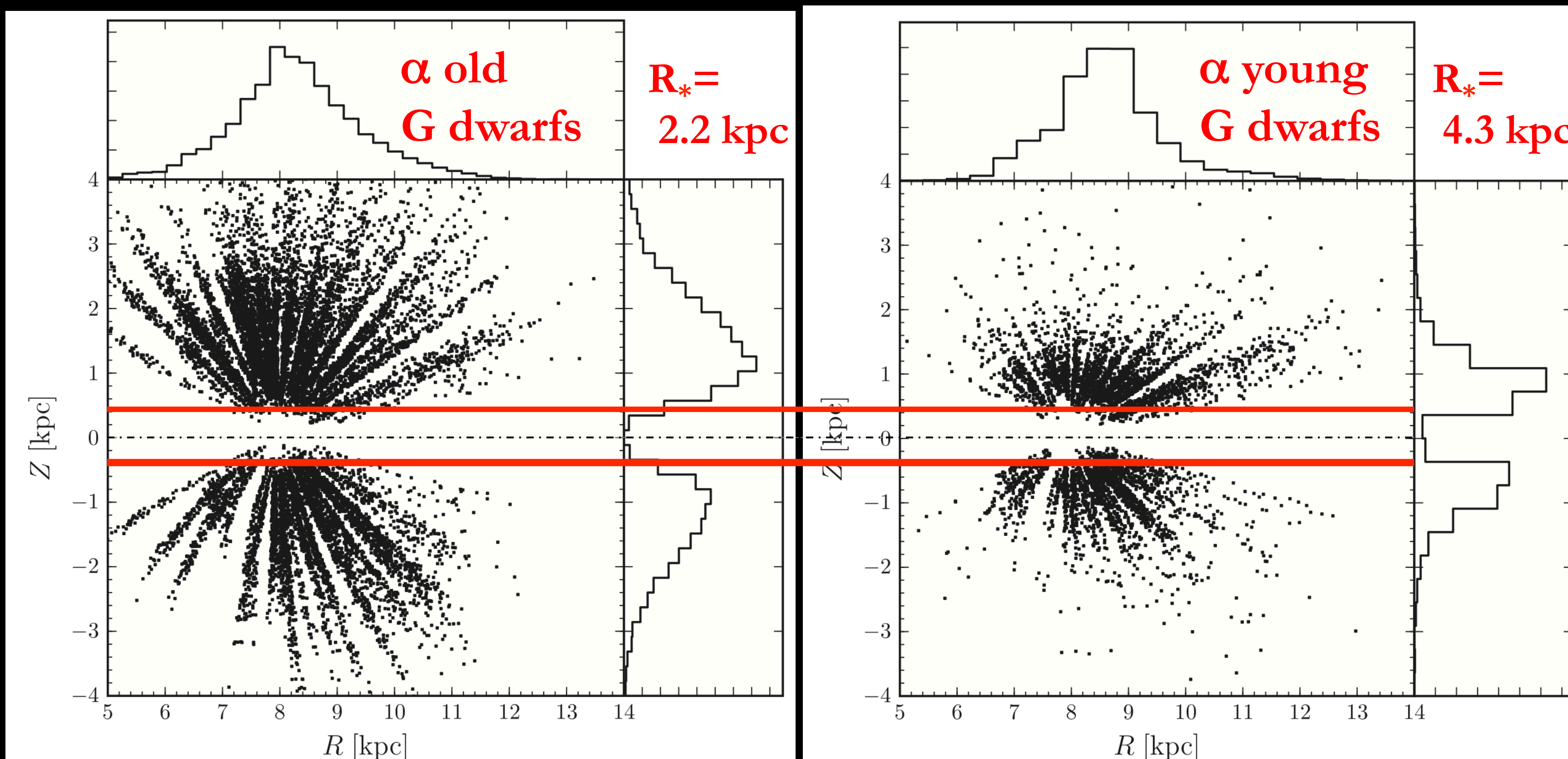
Infrared data:

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°, 239°
2.0 kpc	Reylé et al 2009	2MASS, l=90-270°
2.0 kpc	Lopez-Corredoira 2002	2MASS, l=45-315°, starcount,RG
2.4 kpc	"	Scalength of surface density
3.9 kpc*	Benjamin et al 2005	GLIMPSE, |l|=30-60°

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

2. What we don't know about the Milky Way (yet)

What is the exponential scalelength? Is there a scalelength?



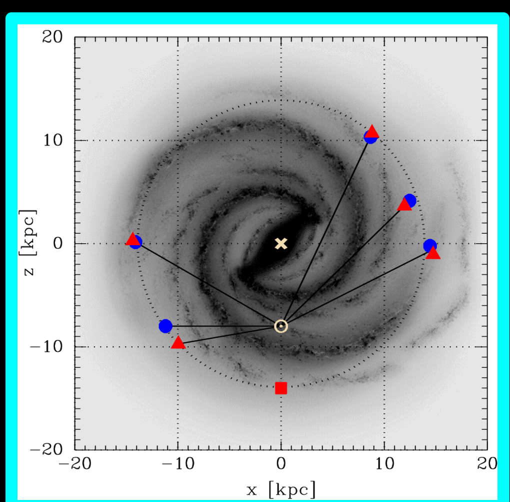
Bovy et al (2012) uses SDSS/SEGUE and finds radial scale-length varies with population. But optical data is limited to sources outside the disk and only in the solar environs.

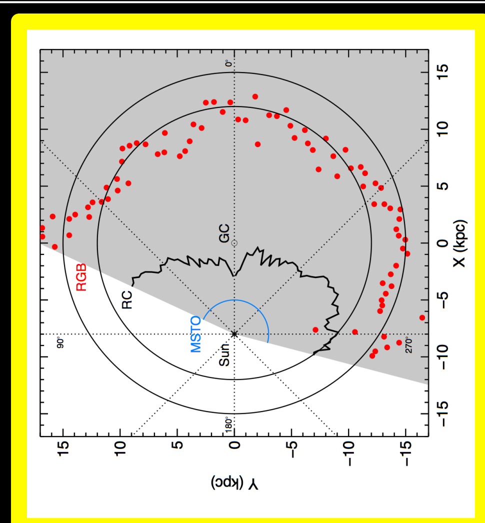
How does this mesh with red clump-based efforts in the disk?

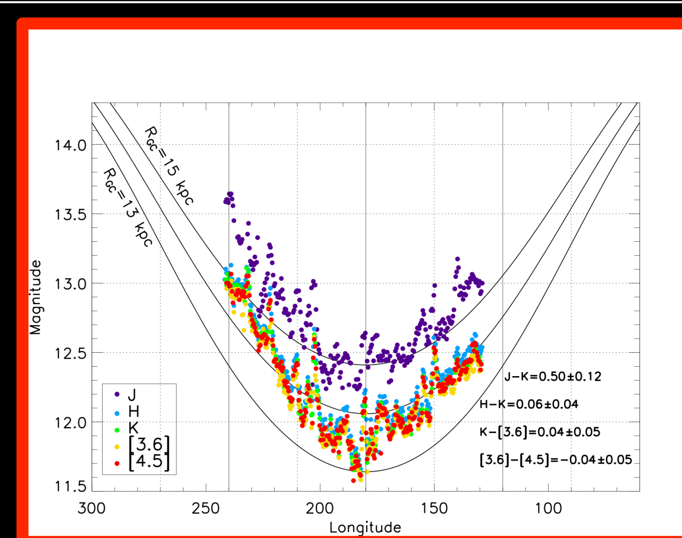
2. What we don't know about the Milky Way (yet)
What happens beyond R_{gal}=13.5 kpc?

Other spiral galaxies have "breaks" in stellar surface density. Does ours?

Robin et al (1992)	Dwarf stars/star counts	R=14 kpc	Four fields
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**
Benjamin et al (2014)	**Red clumps**	**R=13.5-14.5**	**Midplane, l= 80-240 °**

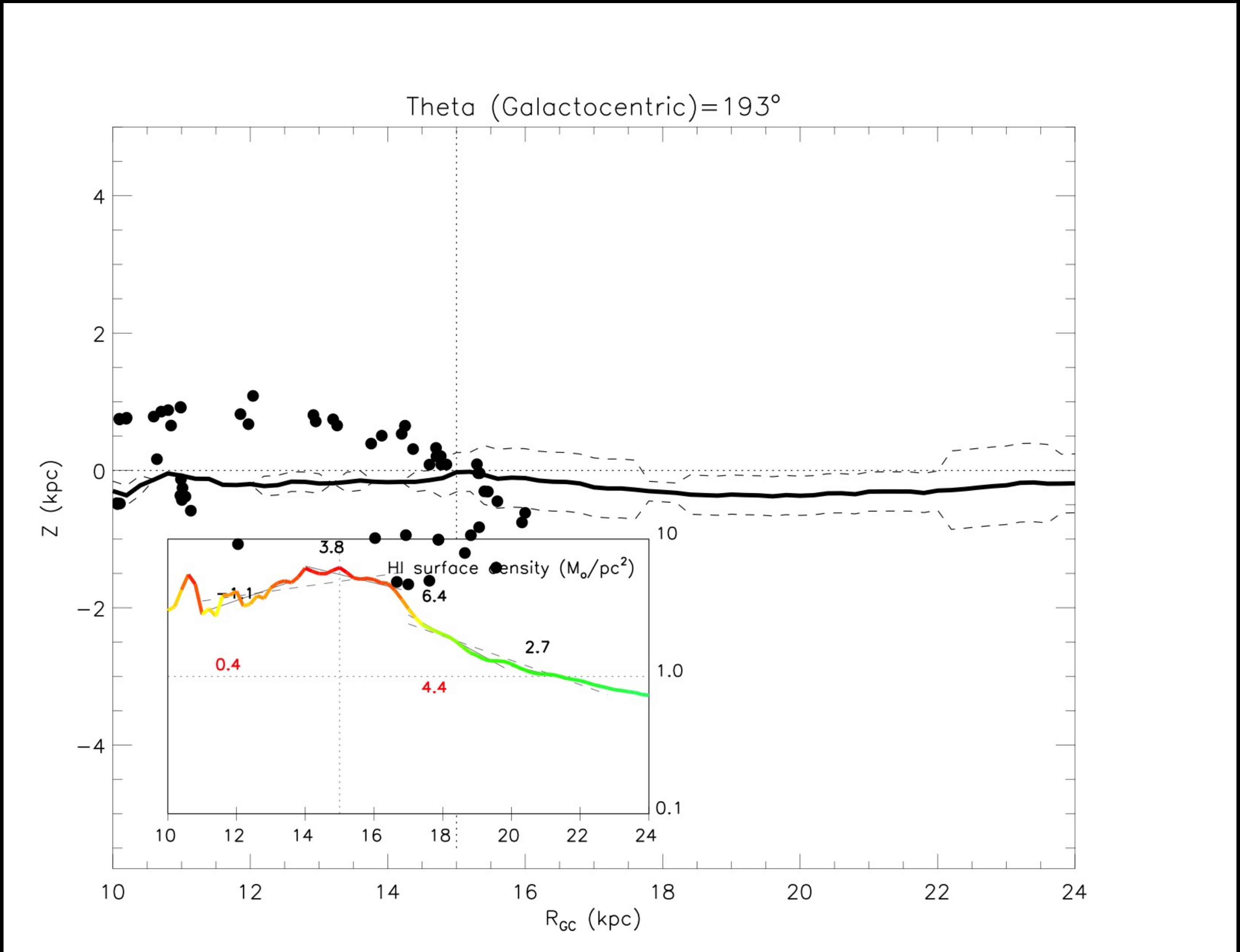






2. What we don't know about the Milky Way (yet)

What happens beyond R_{gal}=13.5 kpc?



Because the break can be seen in 2MASS K_s band histograms , it can be mapped in three dimensions!

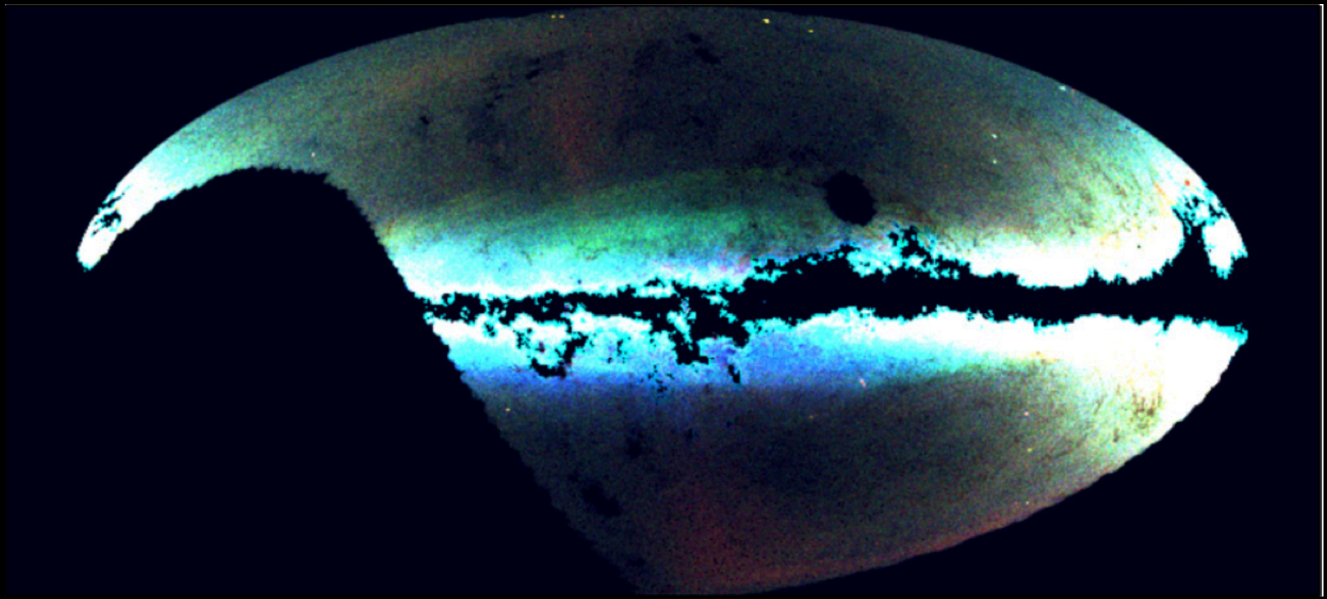
The warping of this surface qualitatively agrees with the HI warp. The HI surface density **also** breaks at R~14 kpc. (The HI "break" has been known for decades!)

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

2. What we don't know about the Milky Way (yet)

What happens beyond R_{gal}=13.5 kpc?

It remains to be seen whether observed "break" is a surface density break. Optical studies have characterized the flaring disk (Lopez-Corredoira & Molgo 2014) and/or satellites (Slater et al 2014), but can't do the midplane (where the stellar density is highest). **Right now, claims that the MW has or does not have a surface density stellar break are premature**. The HI surface density break at the same radius is certain.



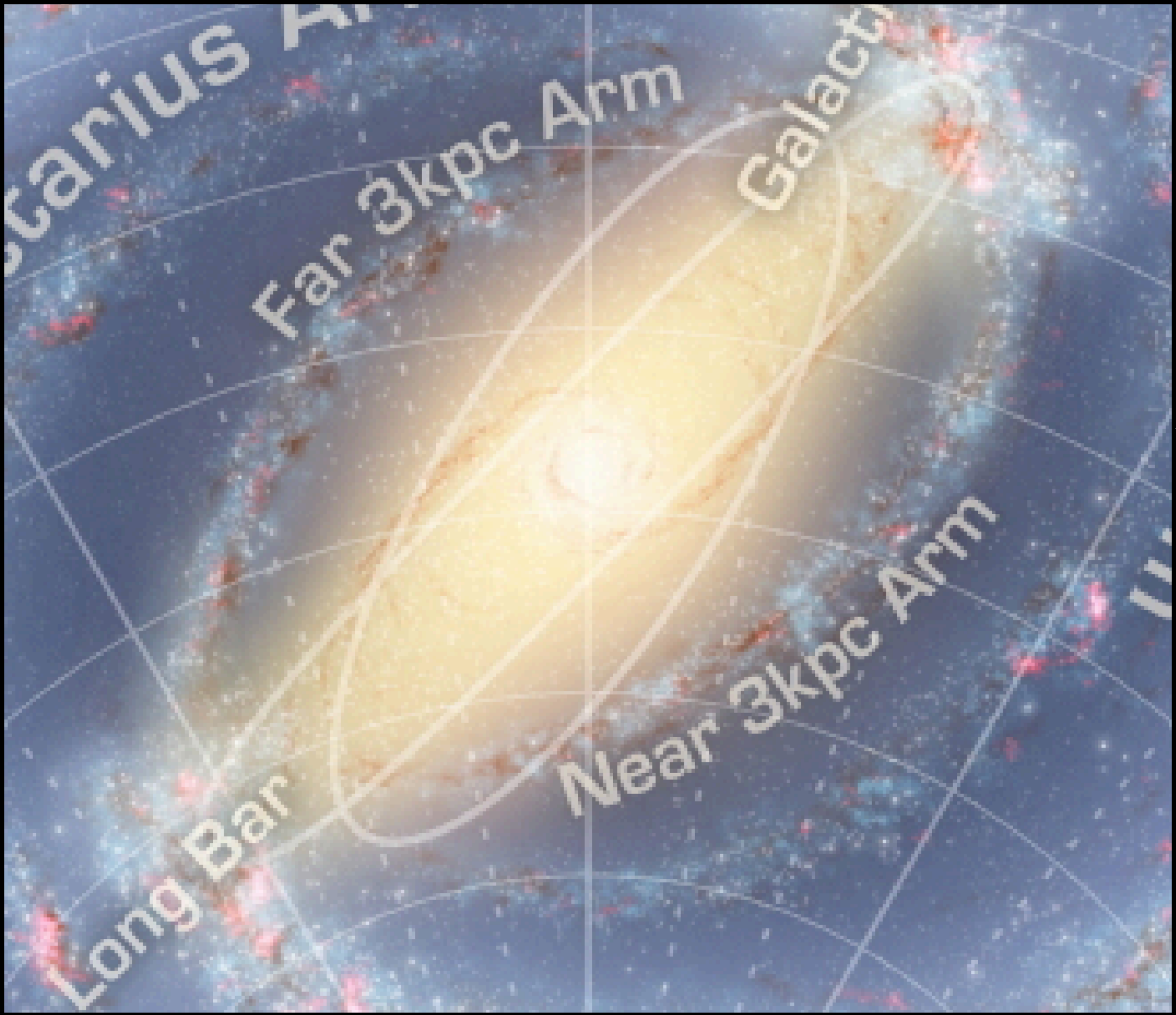
Optical SDSS/Pan-STARRS1 image of outer Galaxy (Slater et al 2014)

How does the stellar disk "end"?

What is the relationship between the disk break, flare, satellites and halo?

2. What we don't know about the Milky Way (yet)

Is the MW a ringed galaxy ?

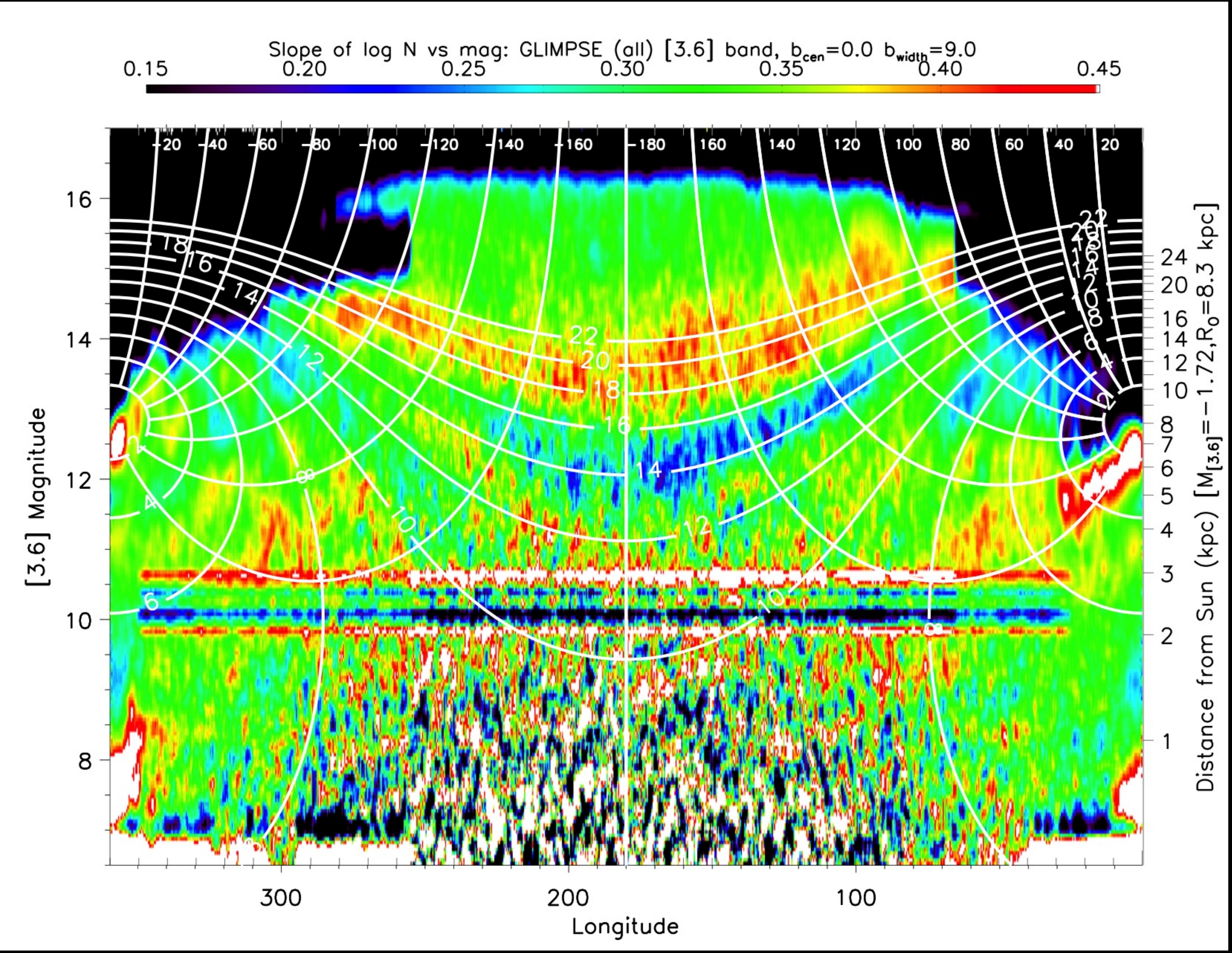


Near/Far 3 kpc arm were place in artist's conception using non-circular motion predicted due to barred potential (Fux 1999).

Positive longitude distances have been "checked" with parallaxes (Reid et al 2014), but ellipticity and velocity field needs to be tested! I think this picture may be wrong!

3. What WFIRST Could Do

Break the Angular Resolution/Extinction Barrier in Inner Galaxy.



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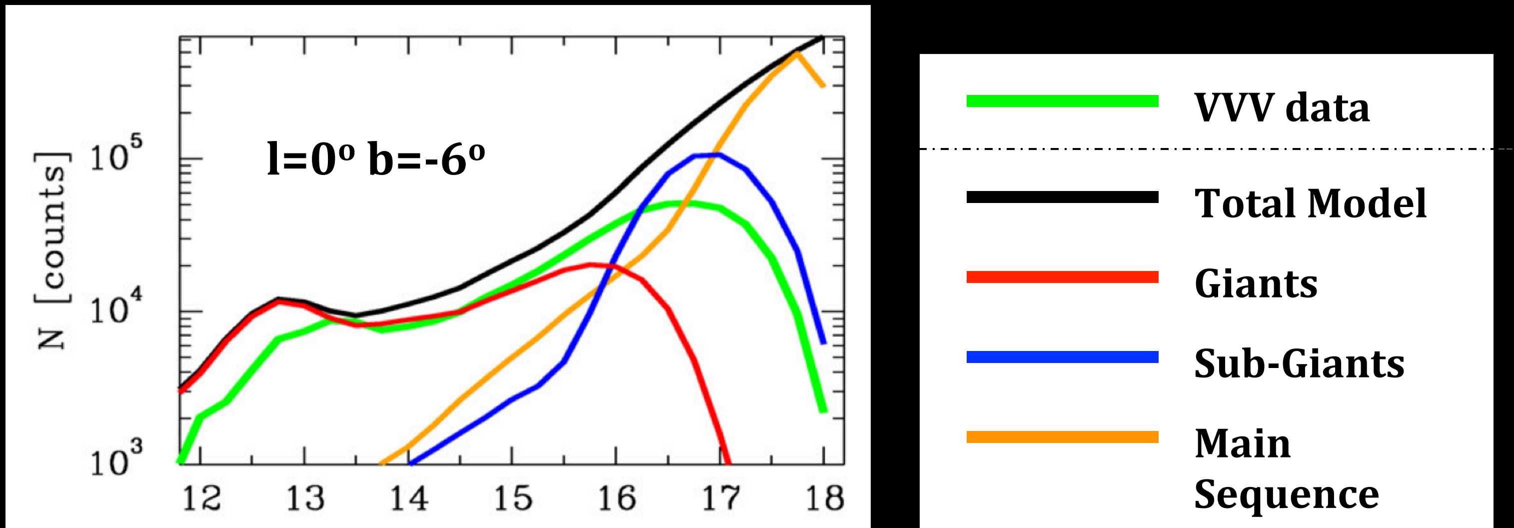
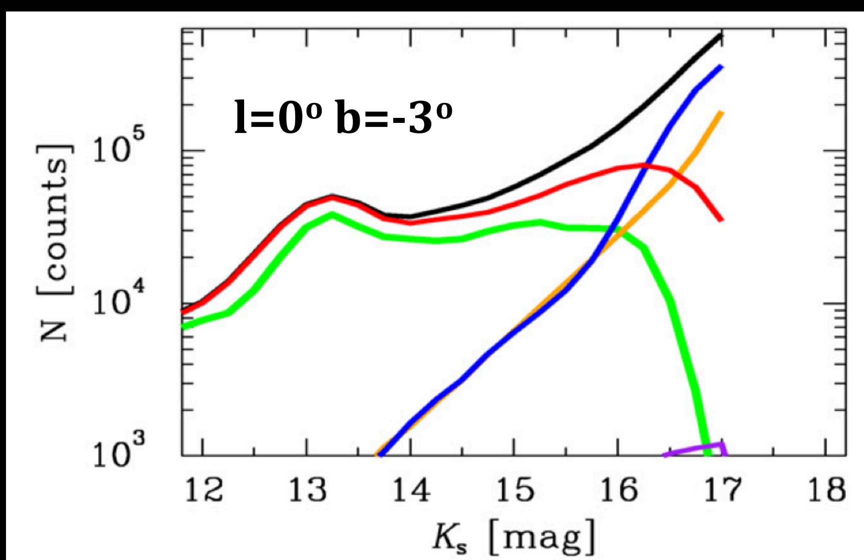


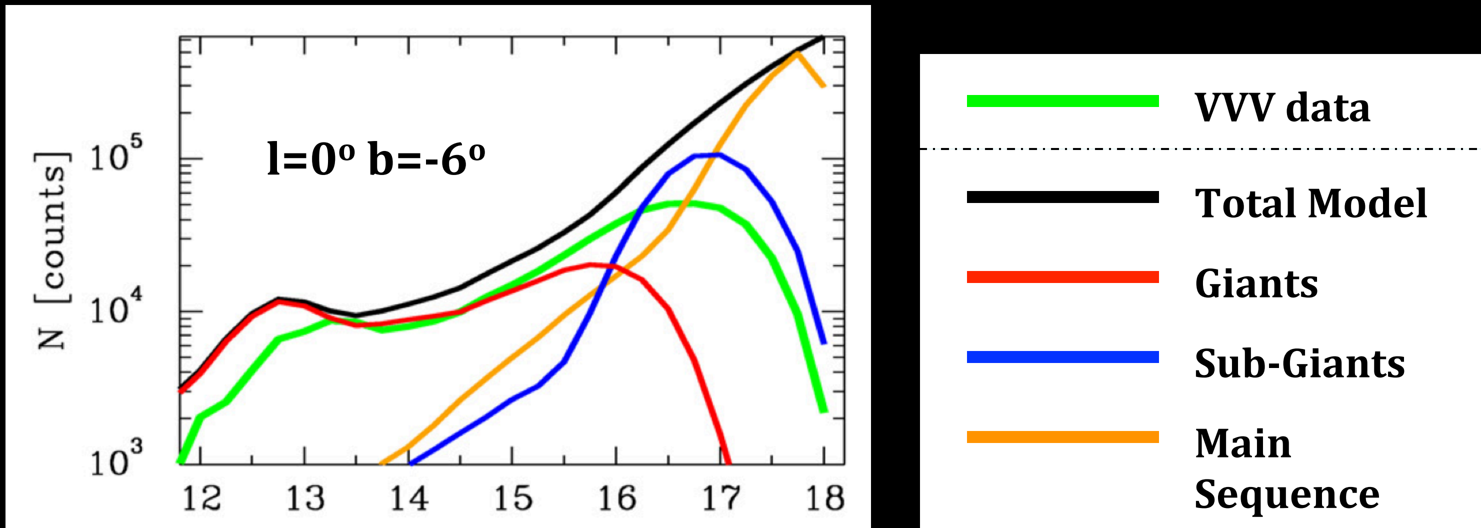


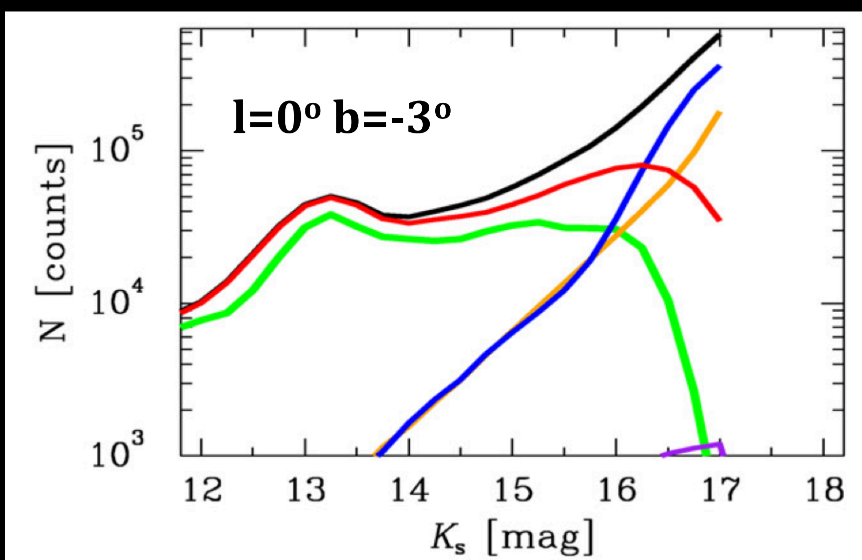
VVV source histograms
Minniti et al (2012)

For reference, without extinction, "unS" would have m_K=19.4 at the symmetric position on the other side of the Galaxy

3. What WFIRST Could Do

Break the Angular Resolution/Extinction Barrier in Inner Galaxy.





VVV source histograms
Minniti et al (2012)

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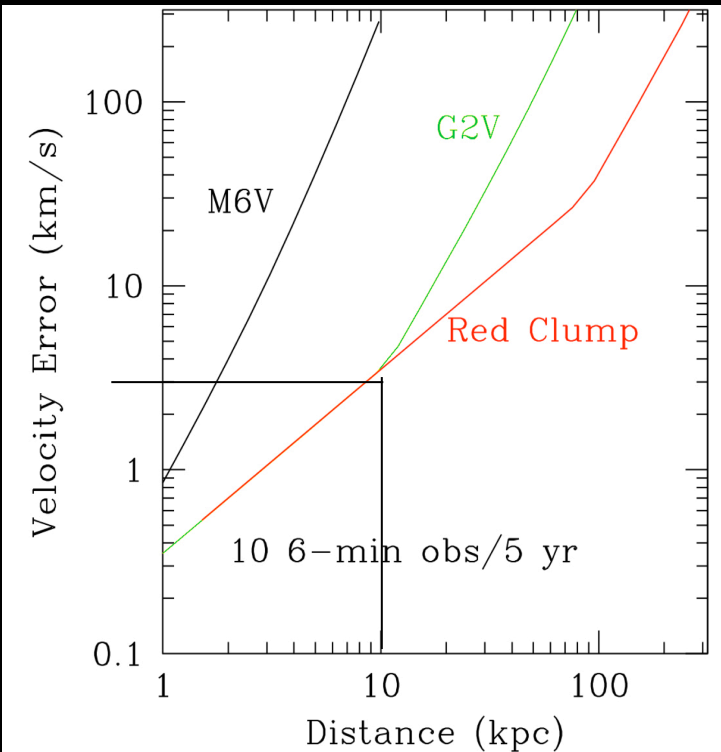
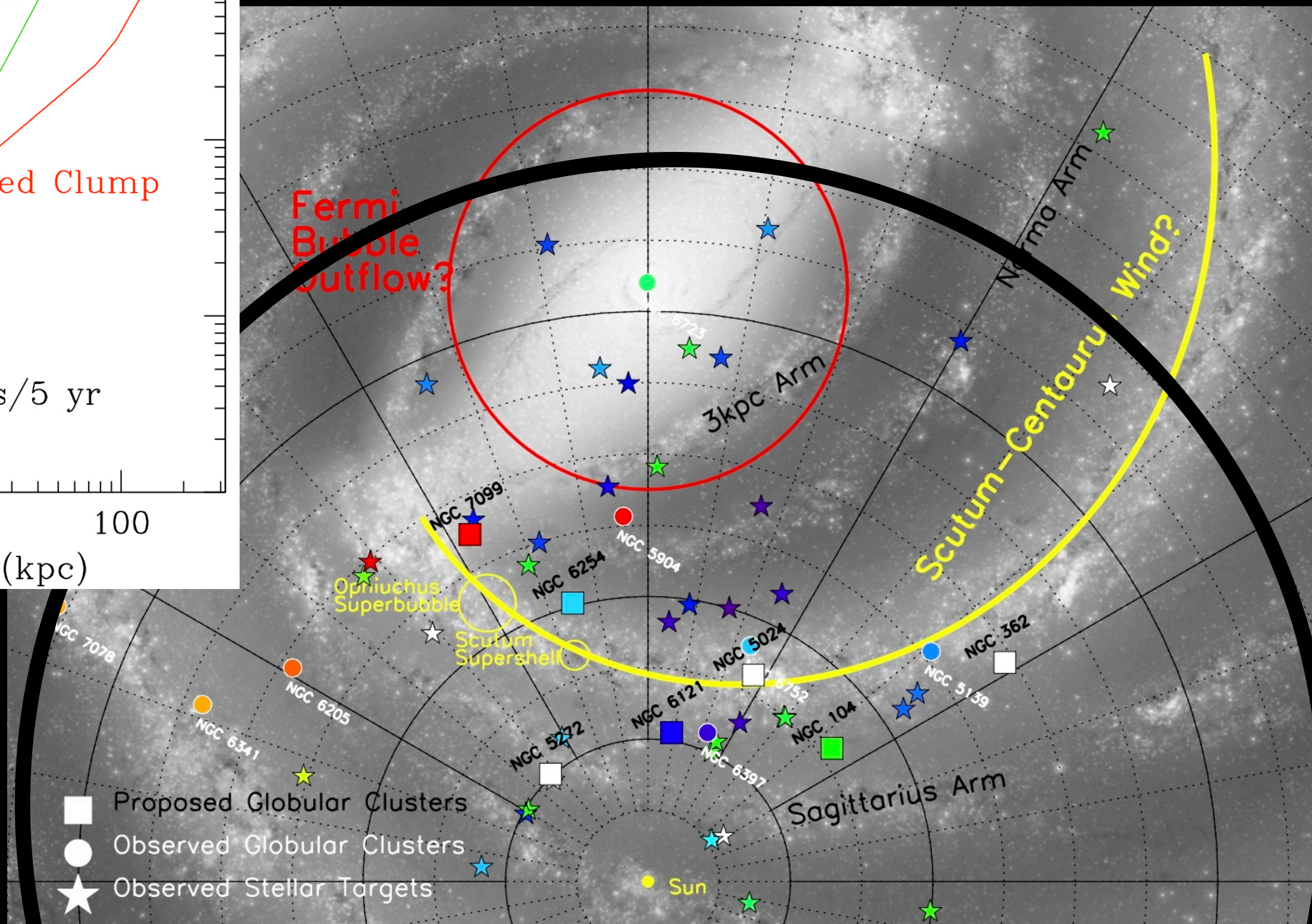
3. What WFIRST Could Do

Measure the streaming/rotational kinematics of stars beyond G.C.

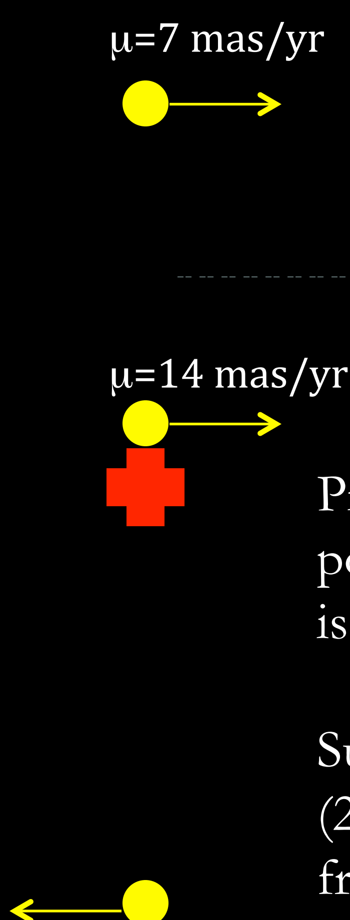


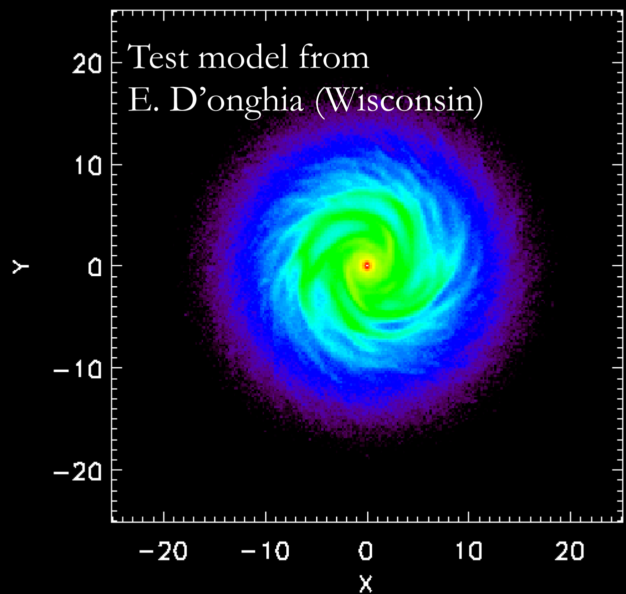
Look for systematic deviations from rotation near spiral arms, bar(s), ring?

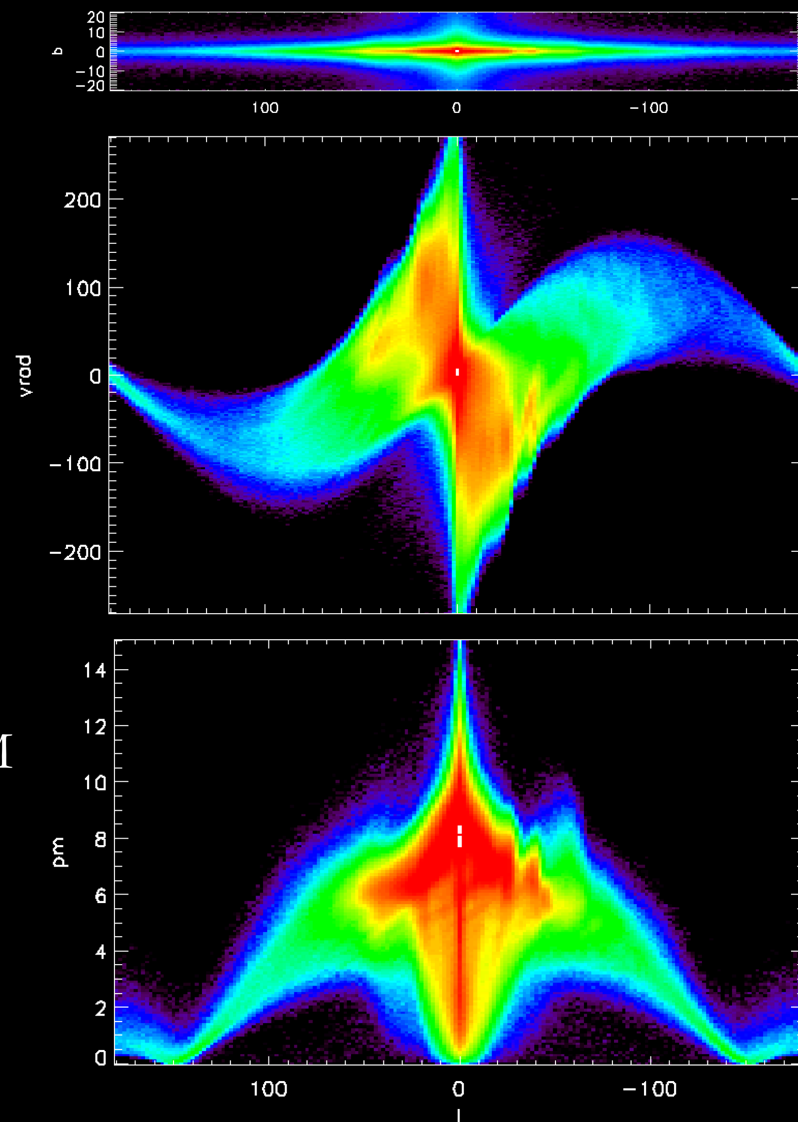


3. What WFIRST Could Do

Measure the streaming/rotational kinematics of stars <u>beyond</u> G.C.







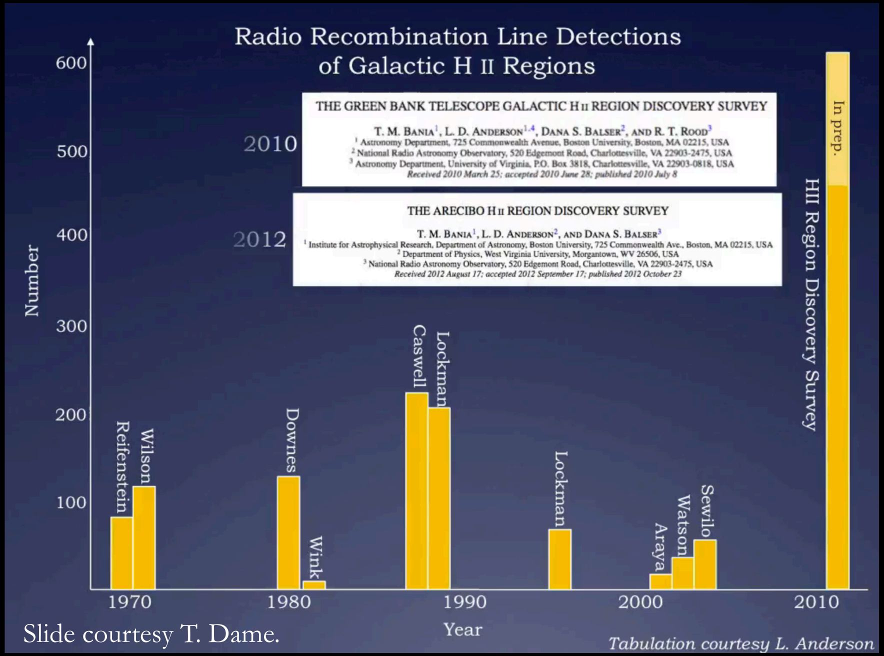
Proper Motions depend upon position in Galaxy! Maximum PM is just on other side of G.C.

Sumi et al (2013), Poleski et al (2013) claim to see streaming on front/back of bar

3. What WFIRST Could Do

Stellar clusters beyond Galactic center—testing symmetry of MW

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



GLIMPSE C01
Kobulnicky et al (2005)
d~5 kpc, M>8 x10^4 M_o, age=400-800 Myr,
(Davies et al 2011)

Thanks to mid-IR surveys, we now know where (nearly) all of the star formation in the Milky Way is. But we can't resolve the stellar content of many of the most massive and interesting systems, like GLIMPSE C01.

3. What WFIRST Could Do

Stellar clusters beyond Galactic center—testing symmetry of MW

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

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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

WISE HII region catalog: 8398 objects

Milky Way Project: 5106 objects

Red MSX Survey: 4651 objects

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

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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.

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

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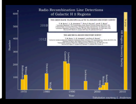
ABSTRACT

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.

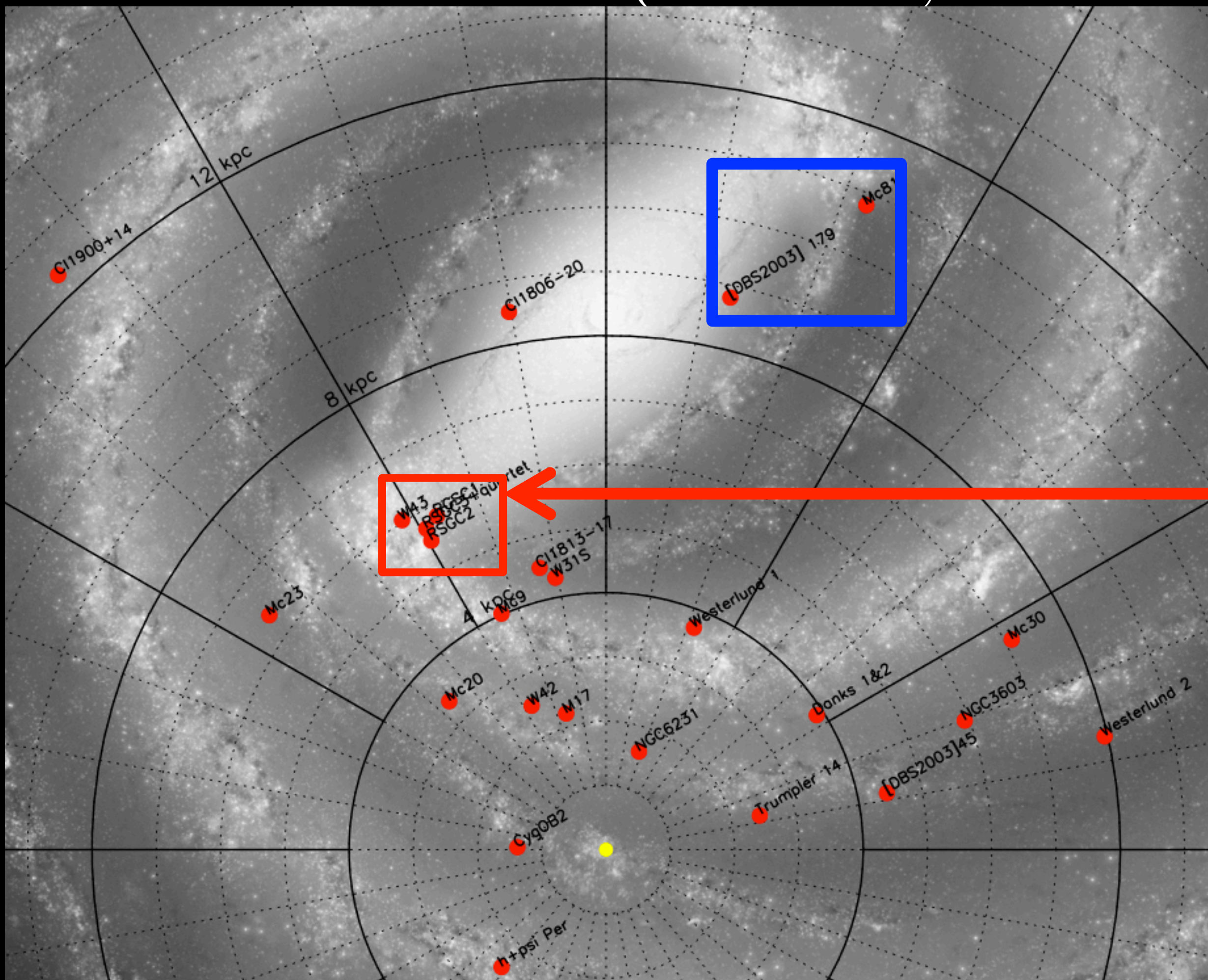
Key words: Galaxy: stellar content – infrared: stars – stars: formation – stars: late-type – stars: pre-main sequence – surveys
Online-only material: color figures, machine-readable table



3. What WFIRST Could Do

Stellar clusters beyond Galactic center—testing symmetry of MW

"A newly-discovered young massive star cluster at the far end of the Galactic Bar" (Davies et al 2012)



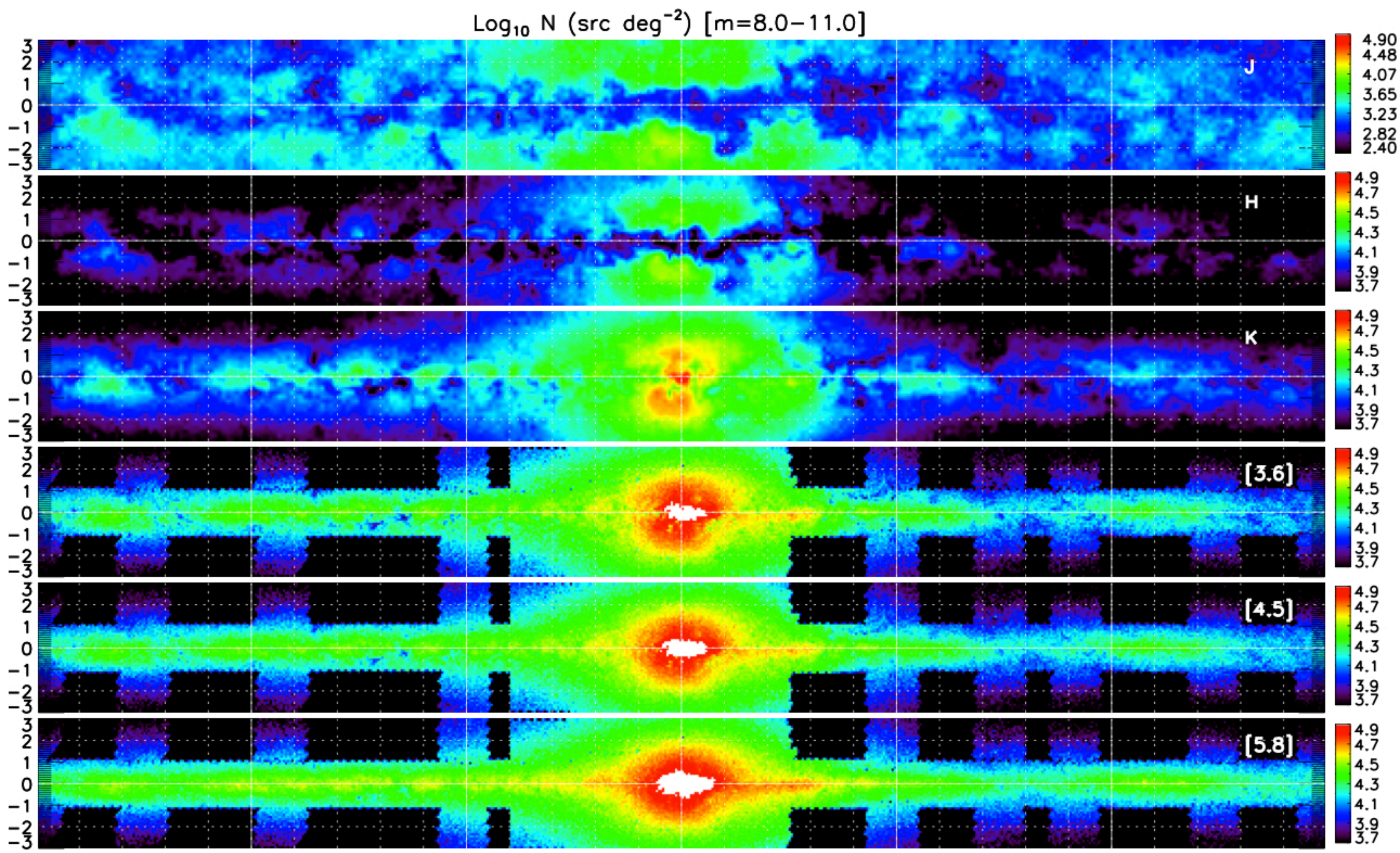
Young Galactic star clusters
Davies et al 2012, and refs therein)

Analogous situation at far end of bar?

- Five clusters of red supergiants+W43
  Davies et al 2012
- Three HI super-shells 2-4 kpc high
  Ford et al 2010
- Multiple velocity components for HII recom line observations
  Anderson et al 2011

4. Preparing for the Future

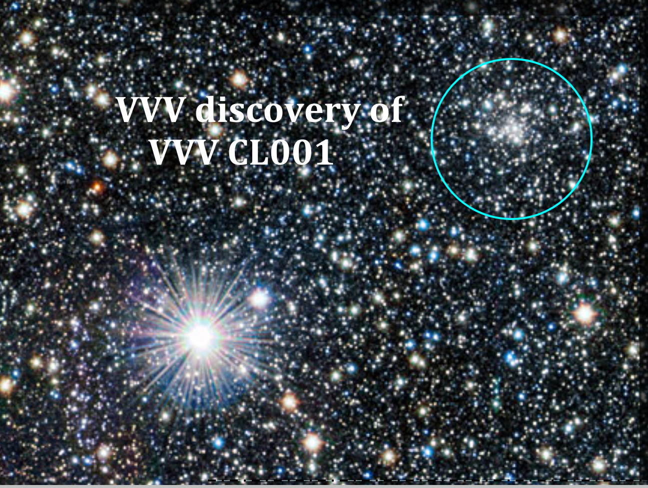
The longer the wavelength, the better.



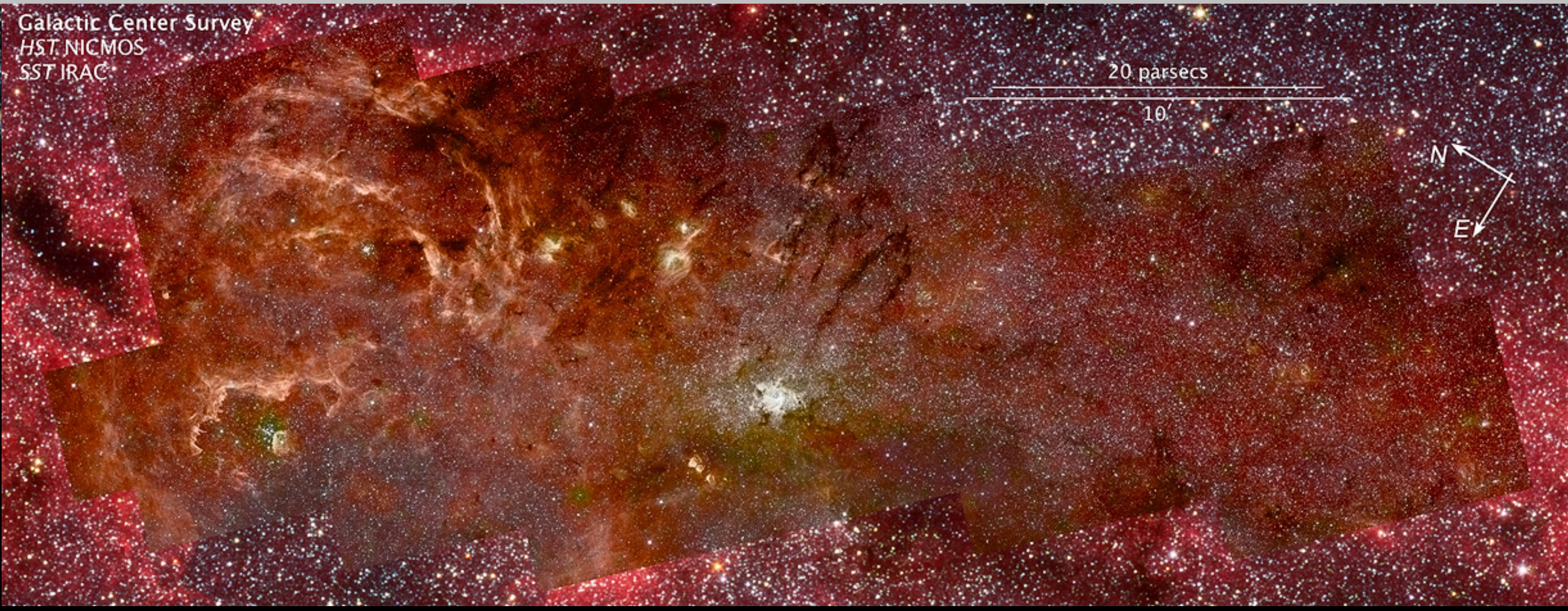
Infrared star-count map as a function of wavelength (2MASS + GLIMPSE)

4. Preparing for the Future

Work with the data we've got (GLIMPSE, VVV/UKIDSS, HST fields)



To make the best use of WFIRST, we really should have a major effort to merge/explore/model/systematize all of the existing IR data on the Galactic disk (including HST).



4. Preparing for the Future

Conference on Coordination in Galactic Research

IAU Symposium No 1. (1953, Groningen) From left to right: Guillermo Haro, Bertil Lindblad, W. Becker, R.H. Stoy, Walter Baade, Otto Heckmann, Viktor Kourganoff, Jöran Ramberg, Jan Hendrik Oort, L. Plaut, C. Schalen, Adriaan Blaauw, W.W. Morgan, H. Spencer-Jones, Mrs. Nassau, P. Th. Oosterhoff, J.J. Nassau, P. Bok, P.J. van Rhijn, P.G. Kulikovski, B.V. Kukarkin, V.A. Ambartsumanian, P.P. Parenago and O.A. Melnikov. This image shows 24 of the 27 participants. Credit: ESO

Conclusions

The Galaxy is still a mysterious place with much yet to discover. Much of it lies in a narrow band of the sky where confusion and extinction obscure our view.

WFIRST will allow us to better resolve the stellar content of the Galactic disk, to measure the stellar kinematics, and to measure the nonaxisymmetric mass distribution of the Milky Way and its underlying symmetries.