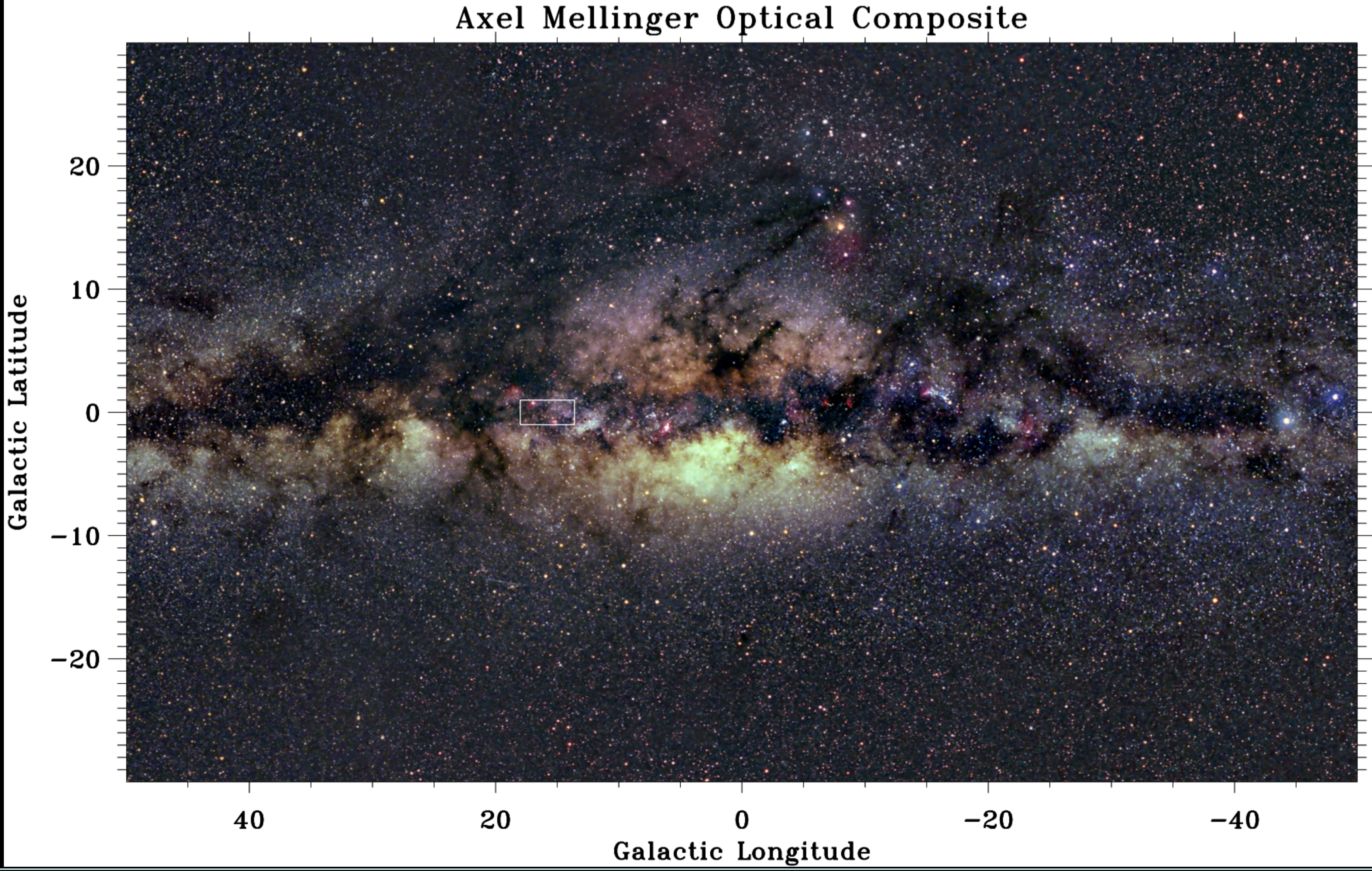
WFIRST: Opening New Frontiers in Our Understanding of the Milky Way



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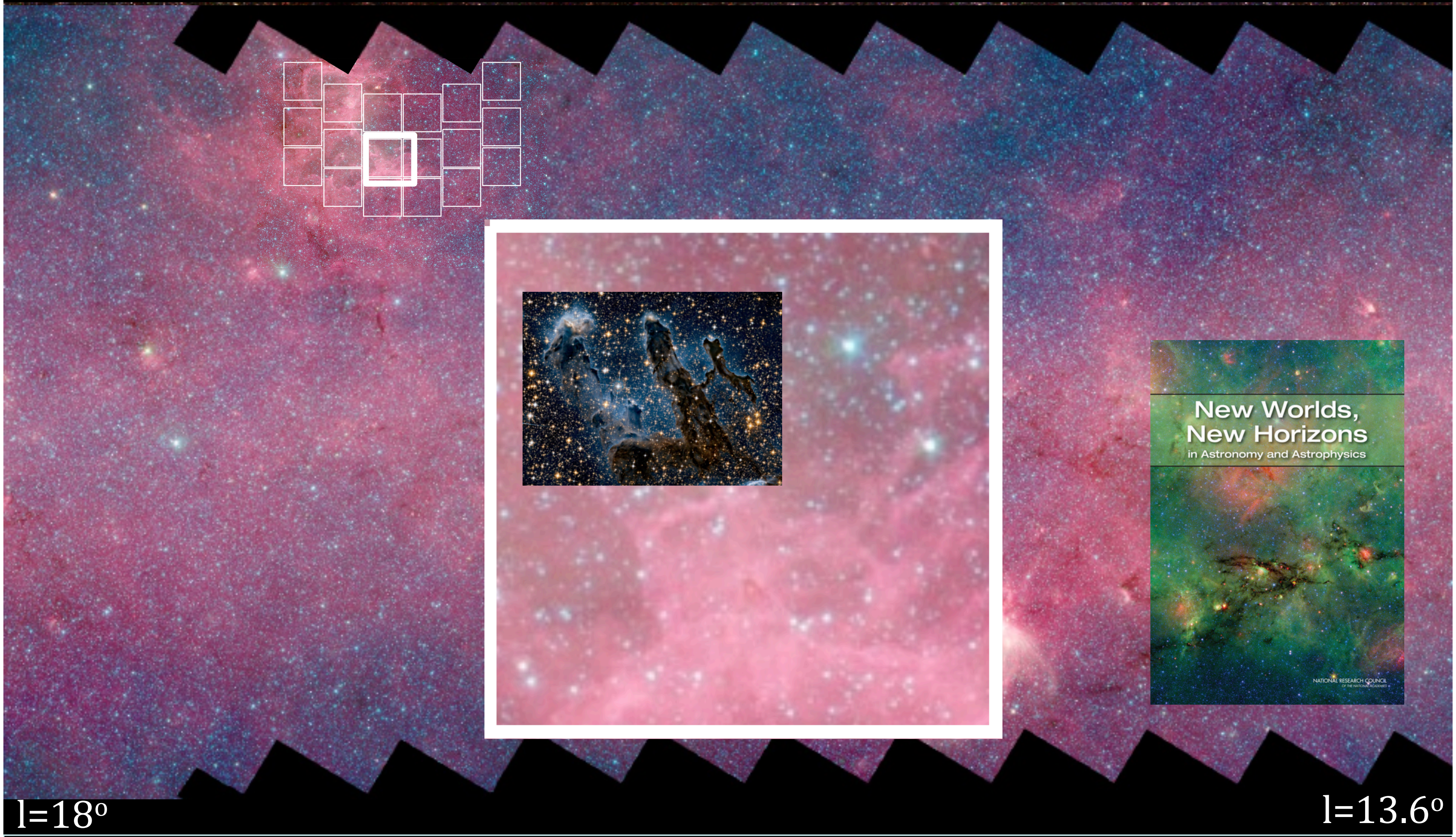
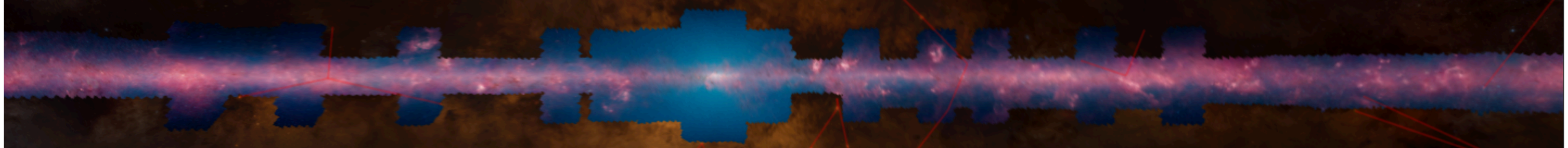


A GLIMPSE-o-mercial (Slide 1 of 2)

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



GLIMPSE (Galactic Legacy Infrared Midplane Survey Extraordinaire)

Benjamin et al (2003) / Churchwell et al (2009)

GLIMPSE core team: Ed Churchwell, Barb Whitney, RAB, Marilyn Meade, Brian Babler

PhDs: Tom Robitaille, Matt Povich, Claudia Cyganowski, Christer Watson, Katie Devine

- 3.6, 4.5 (2003-13) 5.8, 8.0 micron (2003-06) coverage of 360^{o} (130^{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
- 808 refereed publications (11.8% of all publications using Spitzer Data)
- 1,188 square degrees / 180 **days** of observing time (3.7% of cyro/6.1% of warm)
- 229,211,668 million sources + catalogs of several new classes of objects

A GLIMPSE-o-mercial (Slide 2 of 2)

New Classes of Objects related to SF

1. Near/mid-infrared extinction curve (Indebetouw et al 2005)
   452 citations
2. Infrared dark cloud catalog (Peretto & Fuller 2009)
   11303 clouds **145 citations**
3. YSO modelling—and catalogs (Robitaille et al 2008, 2006)
   11,000 high mass YSOs **513 citations/107 citations**
4. Extended green objects (Cyganowski et al 2008)
   300+(many more) EGOs **238 citations**
5. Yellow balls =Ultra compact HII regions (Kerton et al 2015)
   900 **No citations yet!**
6. PAH bubbles (Churchwell et al 2006→Beaumont et al 2016)
   322→~5000 **237 citations**
7. HII regions (WISE+GLIMPSE+MIPSGAL) (Anderson et al 2014)
   8398+ **26 citations**

Citizen Science Discovery

WFIRST could probe the stellar content, IMF, and rare sources in <u>all</u> of these regions in different Galactic environments (bar, arms, Galactic center, far side of the disk, etc.)

Outline

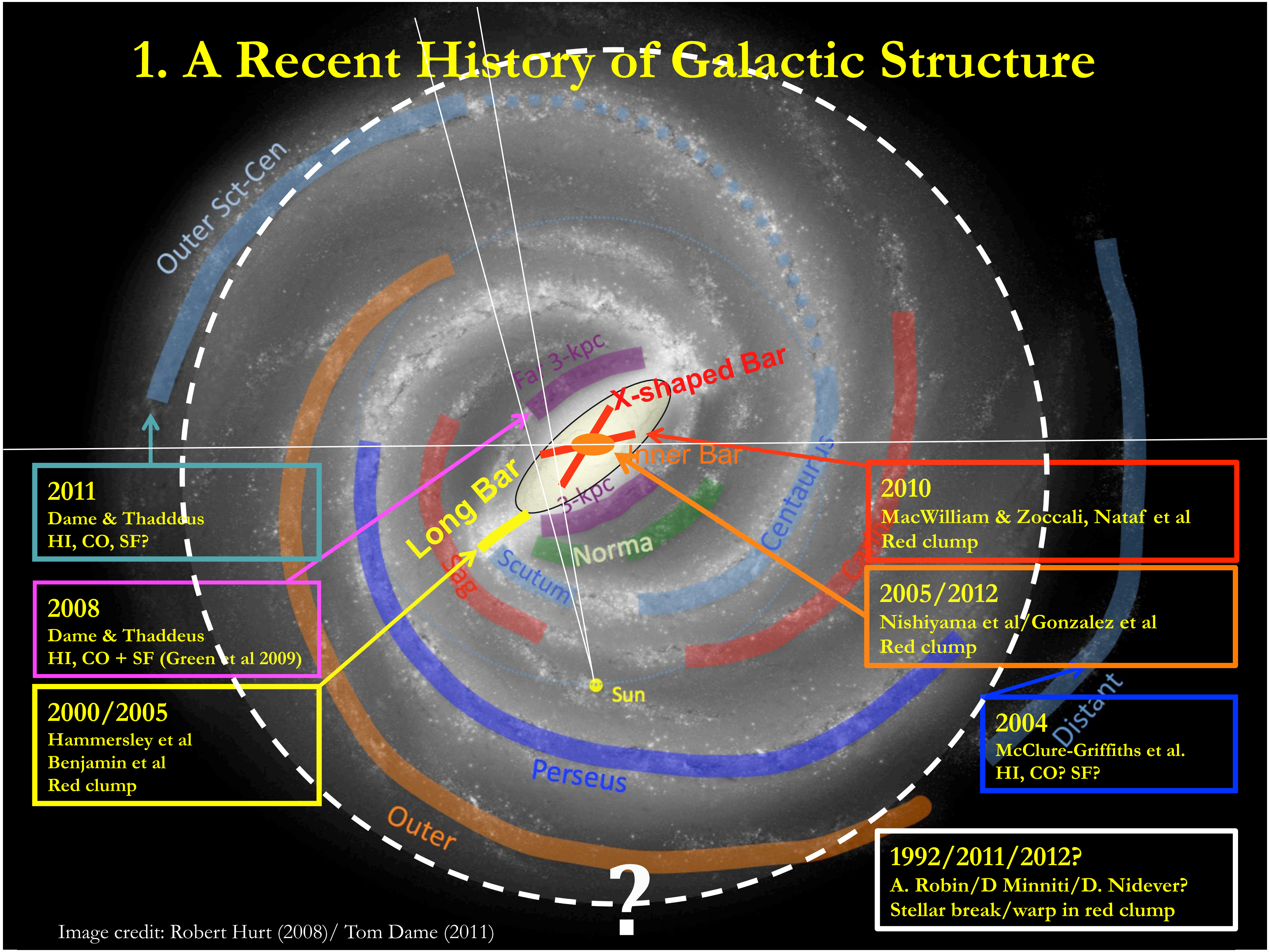
1. **Unsolved mysteries of Galactic structure**
   a. The History of Galactic Structure
   b. The Bulge/Bar(s)
   c. The Disk

2. **WFIRST and Photometric Surveys of the Galaxy**
   a. Breaking the angular resolution/extinction barrier in the Inner Galaxy
   b. The Hubble Galactic Plane Survey
   c. The Galactic Importance of Long Wavelengths
   d. Key Science: Non-axisymmetric 3D stellar density, dust, clusters, IMF
   e. The Time Domain

3. **WFIRST and Proper Motion Surveys of the Galaxy**
   a. Why not GAIA?
   b. Proper Motion Surveys in the Galactic Plane
   c. Using PM to map stellar kinematics in the Galaxy!

4. **Lessons from GLIMPSE**
   a. Plan for the Future (Allow for multi-cycle proposals)
   b. Trade-offs (Go wide? Go deep? Go long?)
   c. Special modes and requirements for Galactic science

1. A Recent History of Galactic Structure



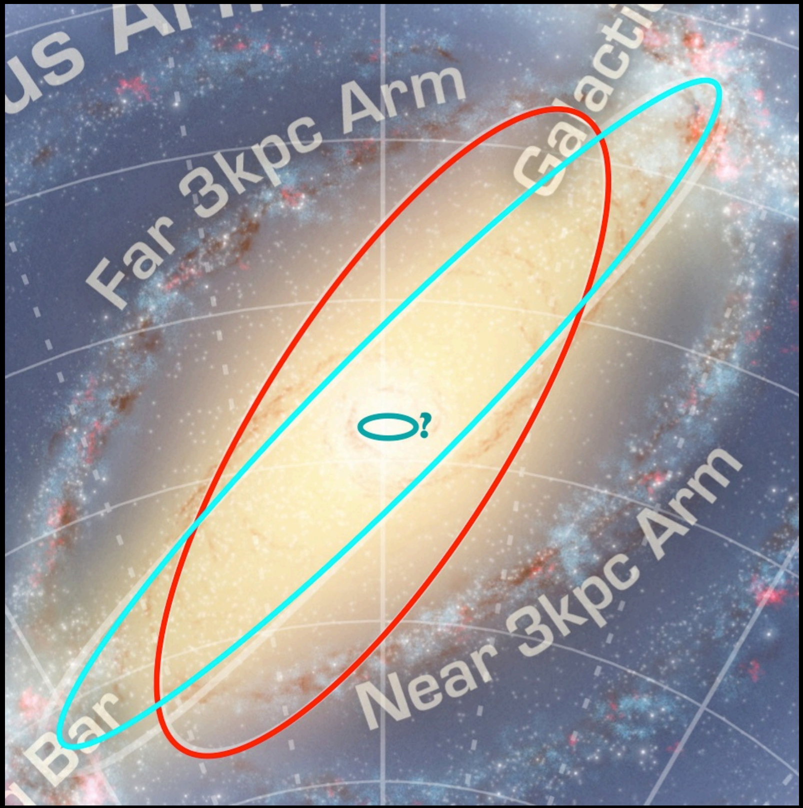
1. The Bulge/Bar(s)

The "Long Bar": A vertically thin, in-plane extension that extends to l=30^{o} on the near side [Hammersley et al 2000; Benjamin et al 2005]

The "X-shaped Bar": Sight-lines above/below the plane encounter two density maxima, whose distance separation increases with latitude. [McWilliam & Zoccali 2010; Nataf et al 2010; Saito et al 2011]

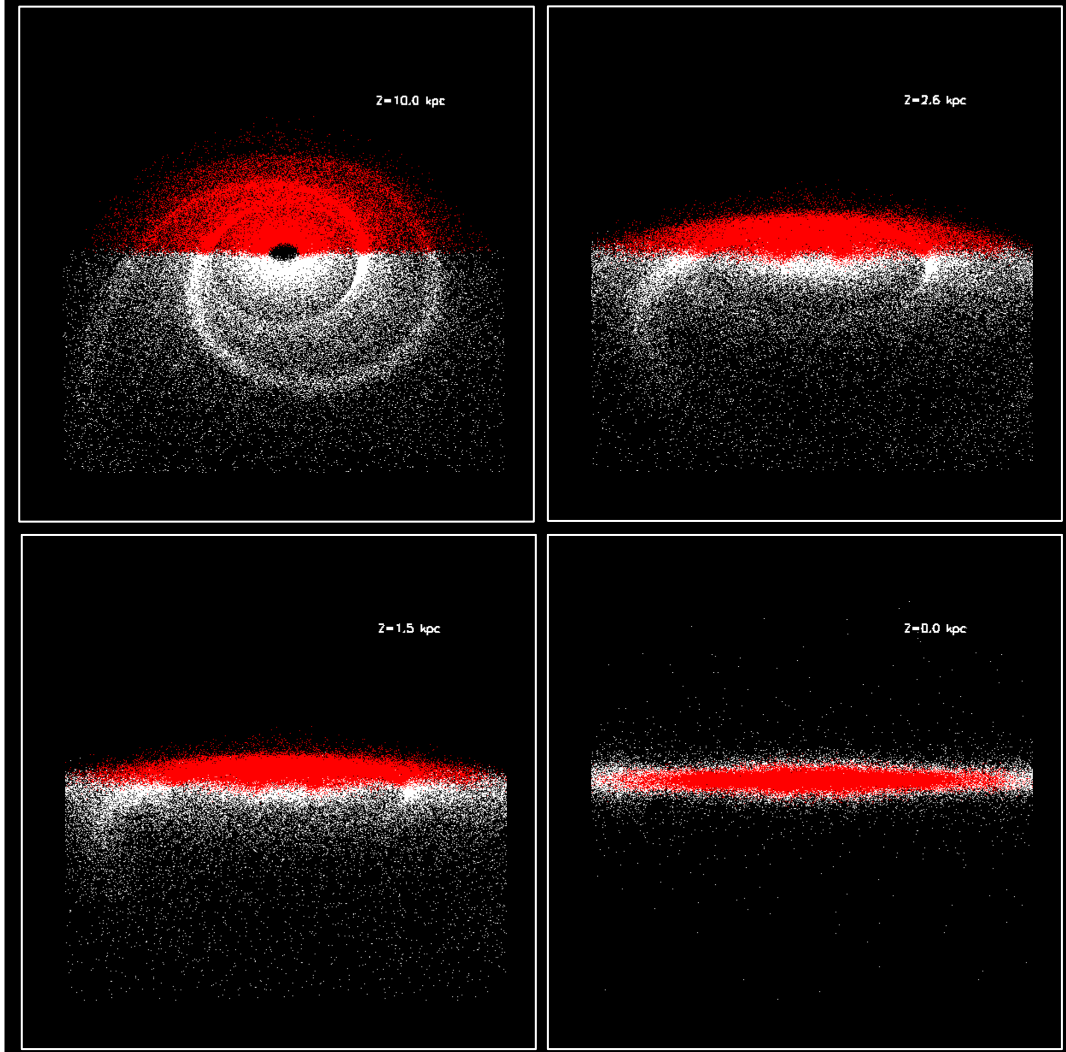
The "Inner Bar": Angle of density maximum twists for inner 10 degrees [Nishiyama et al 2005; Gonzalez et al 2011]

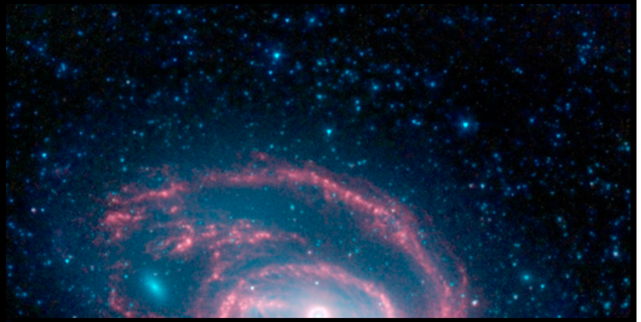
The "Nuclear Bar": Enhanced star counts, gas flows [Alard 2001; Rodriguez-Fernandez & Combes 2008]



How do we fit all of this together?
Required reading: Bland-Hawthorn & Gerhard (2016)
cf., Sec 4.2.3 Does the Milky Way have a Classical Bulge?

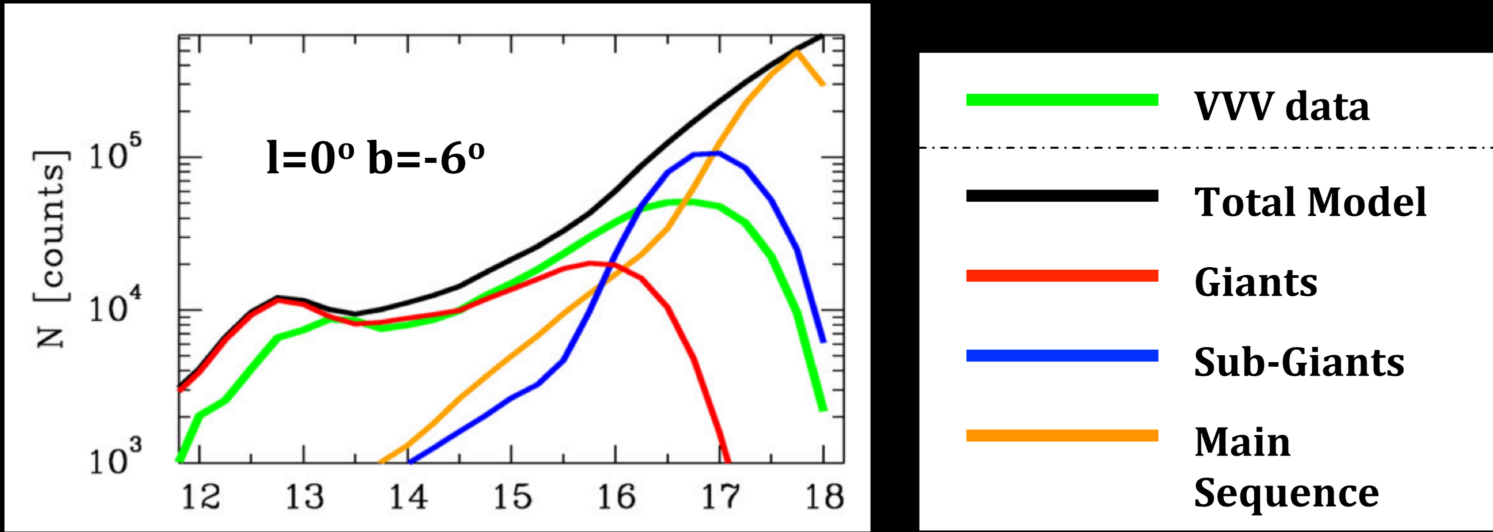
1. The Other Half of the Galactic Disk

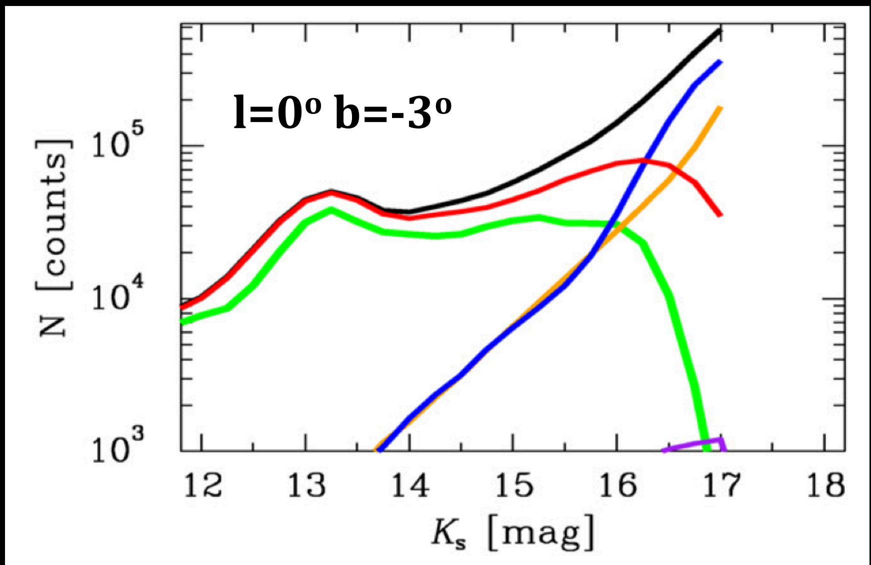




2. WFIRST And Photometric Surveys of the Galaxy

Break the Angular Resolution/Extinction Barrier in Inner Galaxy

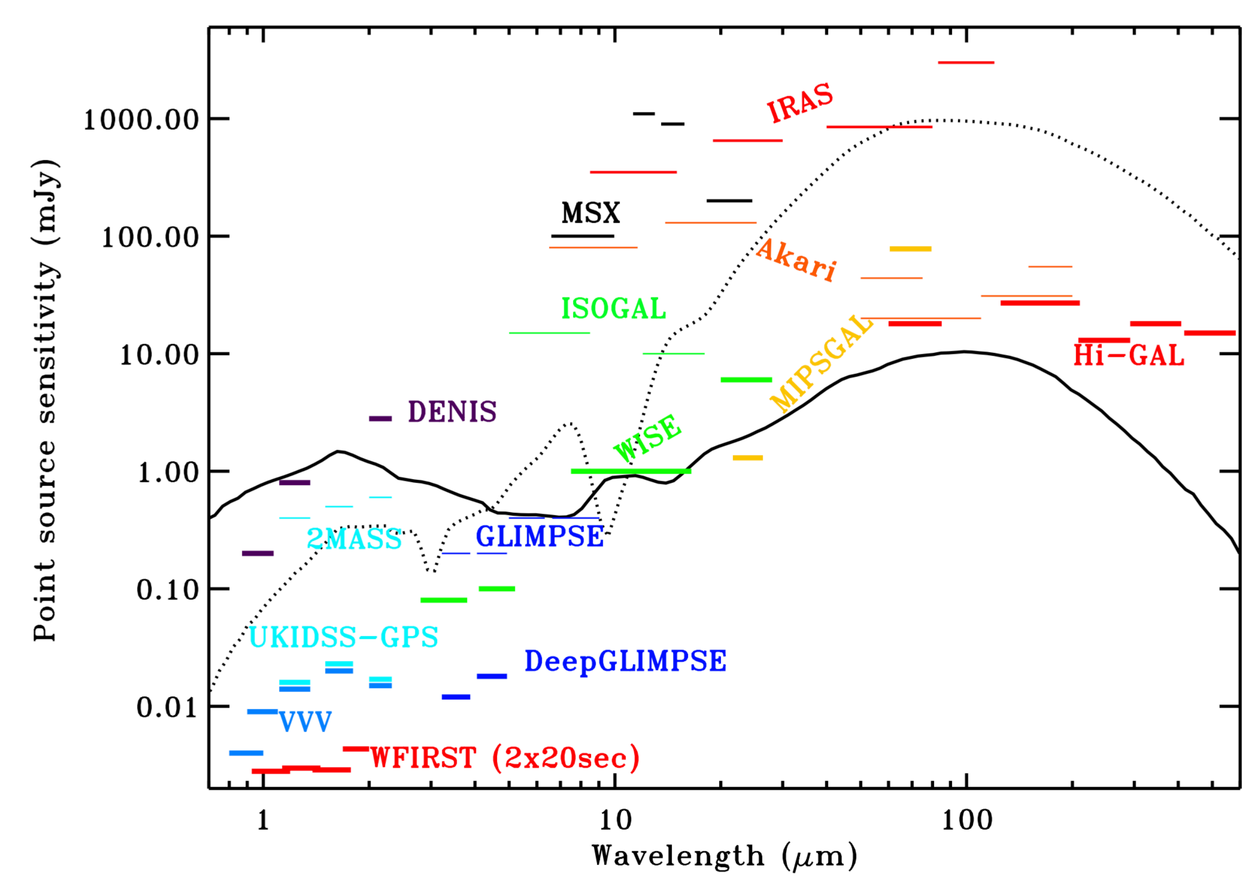




VVV source histograms
Minniti et al (2012)

KEY: A throrough analysis of the VVV and UKIDSS-GPS data should inform the design of any WFIRST Galactic plane survey.

2. A WFIRST Galactic Plane* Survey
Sensitivity and Coverage



Depth (2x20sec)

Band	m_{AB}	m_{Vega}
Y	22.6	22.0
J	22.7	21.8
H	22.7	21.4
F184	22.3	20.5

Coverage

with 40% overhead

$\|b\| < 1^o$	6.9 days
$\|b\| < 5^o$	34.6 days
$\|b\| < 10^o$	69.1 days
$\|b\| < 90^o$	398 days

Exposure times for 2 visits x 20 seconds calculated using
https://wfirst.ipac.caltech.edu/sims/tools/wfDepc/wfDepc.html
[Conversion from AB mag to Vega mags/flux units is approximate]

*** WFIRST low-latitude survey**

2. A WFIRST Galactic Plane Survey
Numbers from Previous Surveys

Table 1. Summary of Infrared Surveys[a]

Survey	Wavebands (μm)	Resolution ($''$)	Coverage	Sensitivity mJy	Website
DENIS	0.97,1.22,2.16	1-3	$\delta = +2$ to $-88°$	0.2,0.8,2.8	cdsweb.u-strasbg.fr/denis.html
2MASS	1.22,1.65,2.16	2	all-sky	0.4,0.5,0.6	www.ipac.caltech.edu/2mass
UKIDSS-GPS[b]	1.22, 1.65, 2.16	0.5	$l = -2$ to $107°$,142 to $230°$ [c]	0.016, 0.023,0.017	www.ukidss.org
GLIMPSE	3.6,4.5,5.8,8.0	≤ 2	$\|l\| \leq 65°, \|b\| \lesssim 1°$ [d]	0.2,0.2,0.4,0.4	www.astro.wisc.edu/glimpse
GLIMPSE360	3.6,4.5,5.8,8.0	≤ 2	$l = 65° - 255°, \|b\| \lesssim 2°$	0.012,0.018	www.astro.wisc.edu/glimpse
WISE	3.4, 4.6, 12, 22	6, 6, 6, 12	all-sky	0.08,0.1,1,6	wise.ssl.berkeley.edu
MSX	4.1,8.3,12,14,21	18.3	$l =$ 0-360°, $\|b\| \leq 5°$	10000,100,1100,900,200	www.ipac.caltech.edu/ipac/msx
MIPSGAL	24, 70	6, 18	$\|l\| =$ 0-65°, $\|b\| \lesssim 1°$	2, 75	mipsgal.ipac.caltech.edu
ISOGAL	7,15	6	$\|l\| \leq 60°, \|b\| \leq 1°$ [e]	15,10	www-isogal.iap.fr/
IRAS	12,24,60,100	25–100	all-sky	350,650,850,3000	irsa.ipac.caltech.edu/IRASdocs
Akari	8.5,20,62.5,80,155,175	5–44	all-sky	20-100	www.ir.isas.ac.jp
Hershel/Hi-GAL	70,170,250,350,500	5,13, 18, 25, 36	$\|l\| =$ 0-60°, $\|b\| \leq 1°$	18, 27, 13, 18, 15	hi-gal.ifsi-roma.inaf.it/higal
COBE/DIRBE[f]	1.25–240	0.7°	all-sky	0.01-1.0 MJy sr^{-1}	space.gsfc.nasa.gov/astro/cobe

[a] See text for appropriate references for these surveys.

[b] Much of the remainder of the Galactic Plane will be covered with similar depth and resolution in the five-band near infrared survey VVV Minniti et al. (2010)

[c] $l = -2$ to $15°$ has thickness $|b| < 2°$, otherwise the thickness is $|b| < 5°$. The longitude range $l = 142° - 230°$ is also covered.

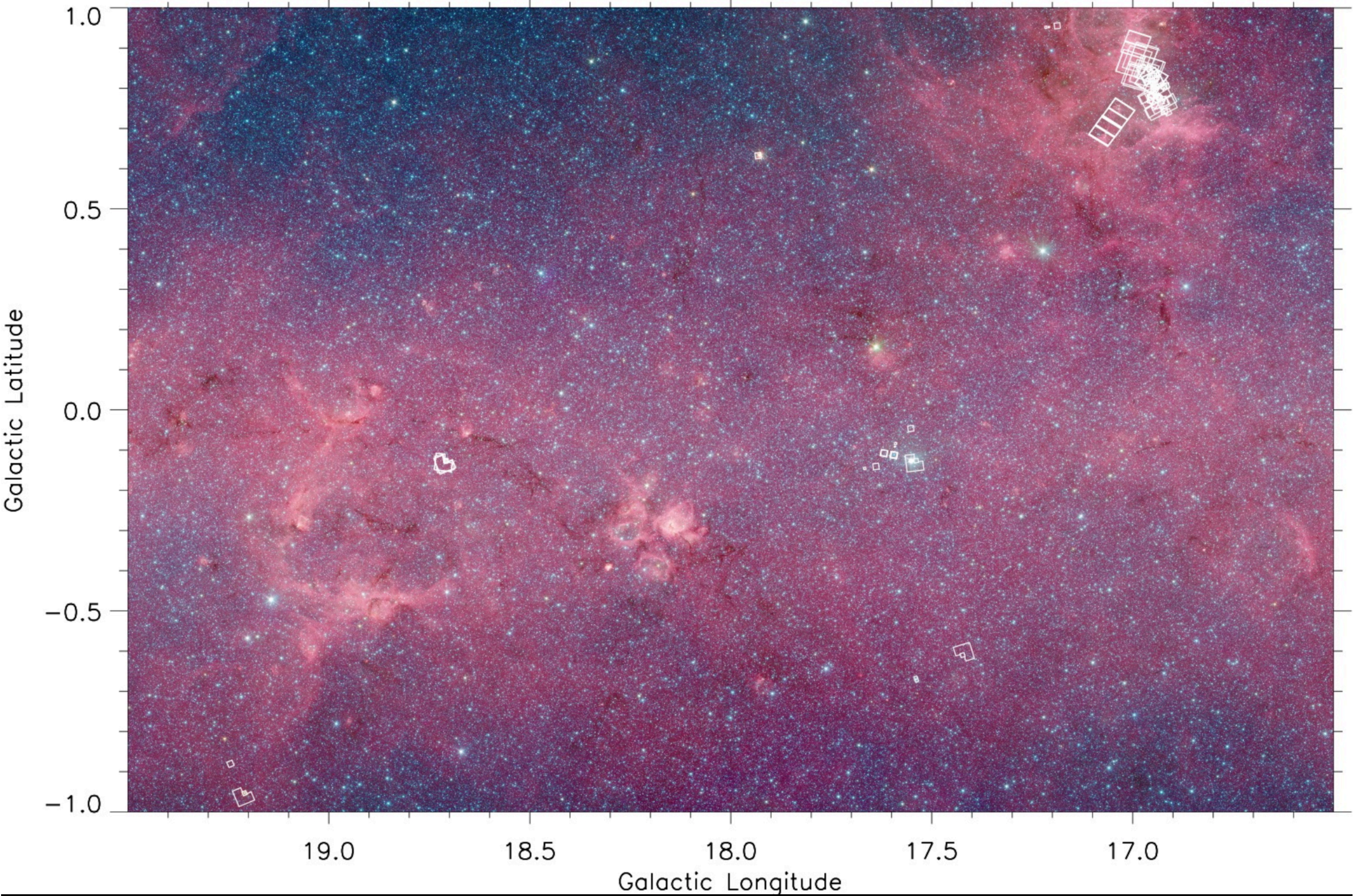
[d] GLIMPSE also has vertical extensions up to $|b| = 4°.5$ for selected longitudes. GLIMPSE style coverage was used for the *Spitzer* Vela-Carnina survey from $l = 295° - 255°$.

[e] Survey contained only selected fields in this region, totaling 16 square degrees.

[f] DIRBE photometric bands are 1.25, 2.2, 3.5, 4.9, 12, 25, 60, 100, 140, and 240 μm. We report the diffuse flux sensitivity rather than point source sensitivity due to the large beam size.

Churchwell & Benjamin (2013)

2. The "Hubble Galactic Plane Survey" (l=+20^o to –3^o only)



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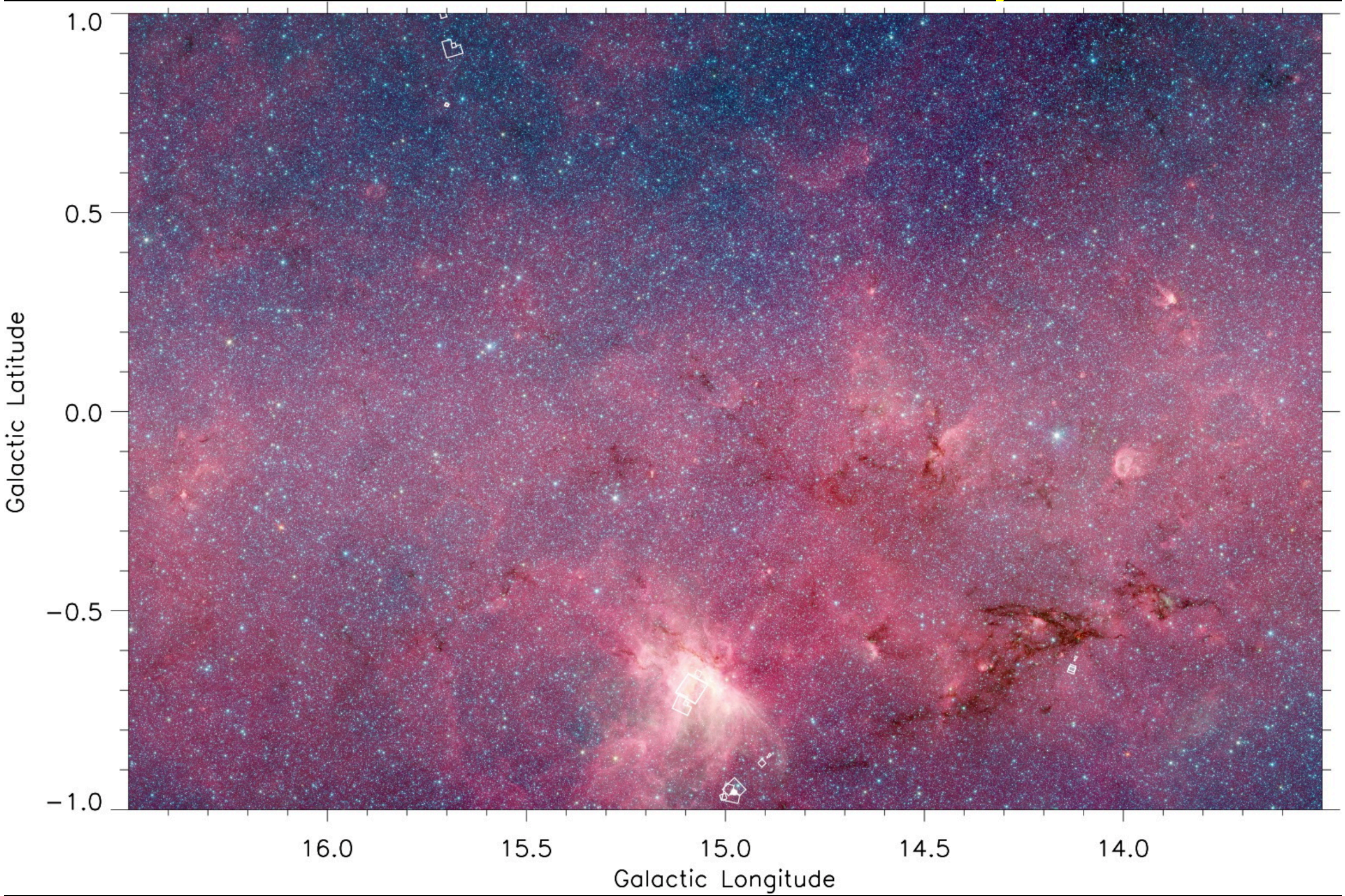
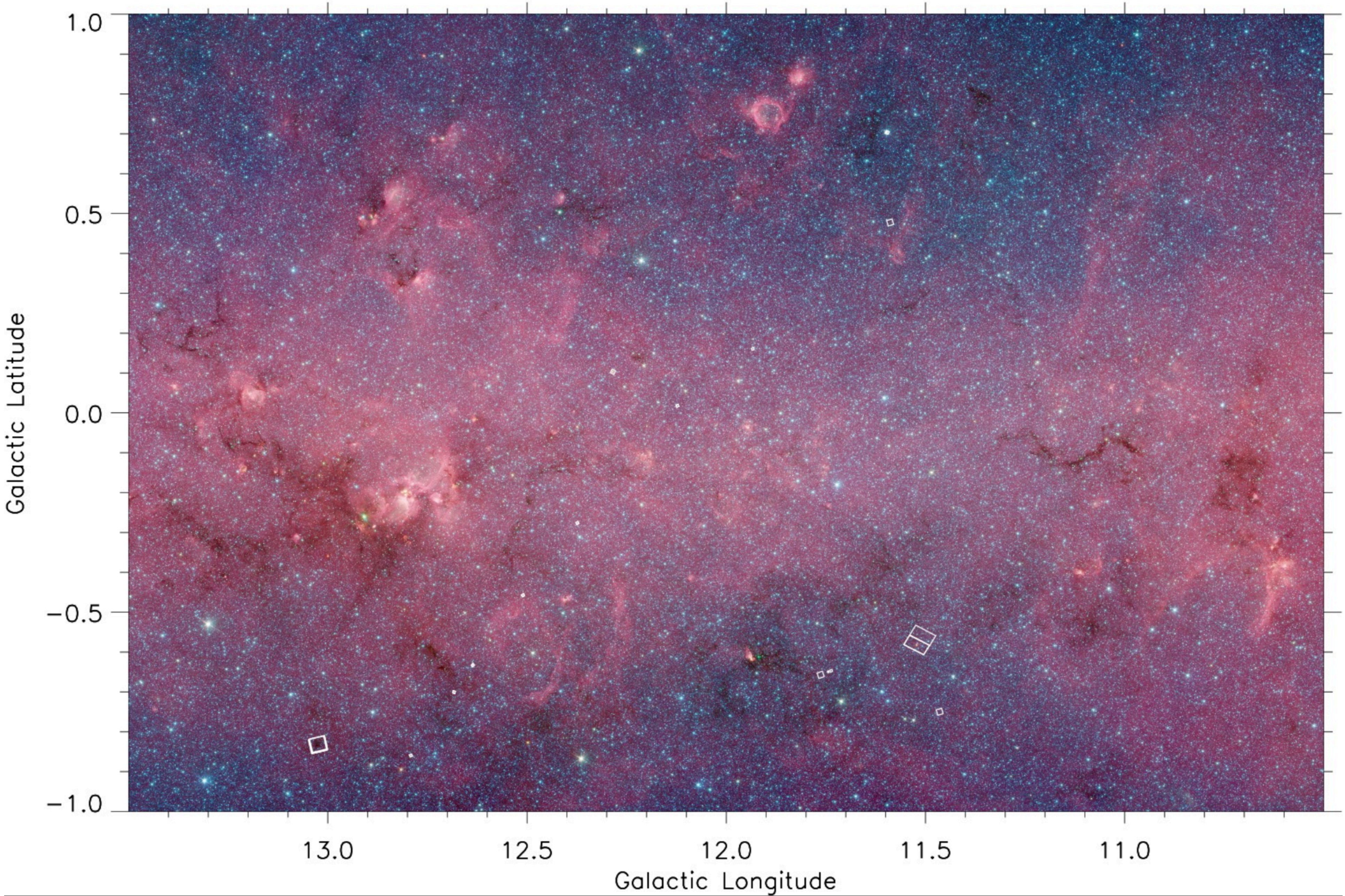


2. The "Hubble Galactic Plane Survey"



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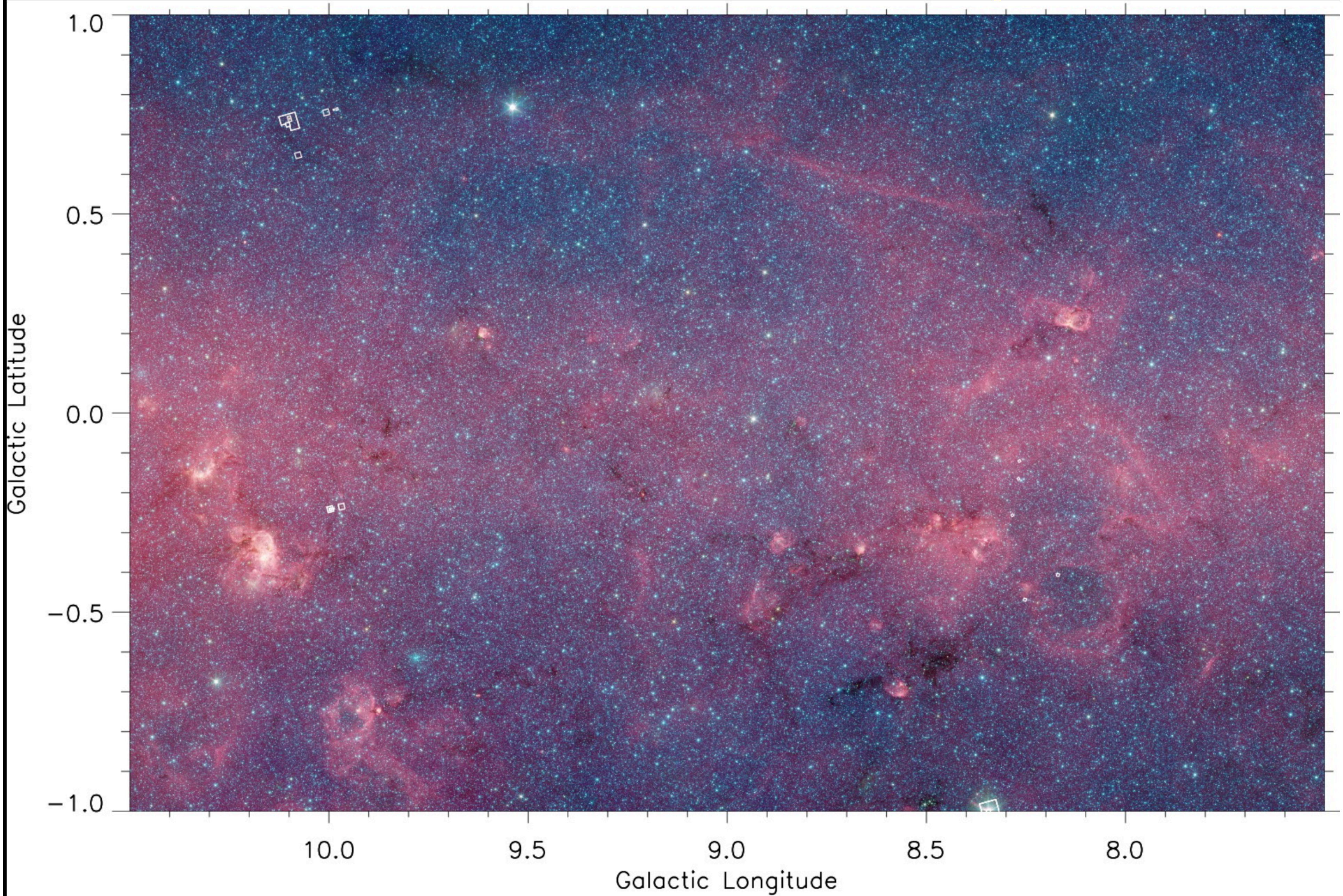

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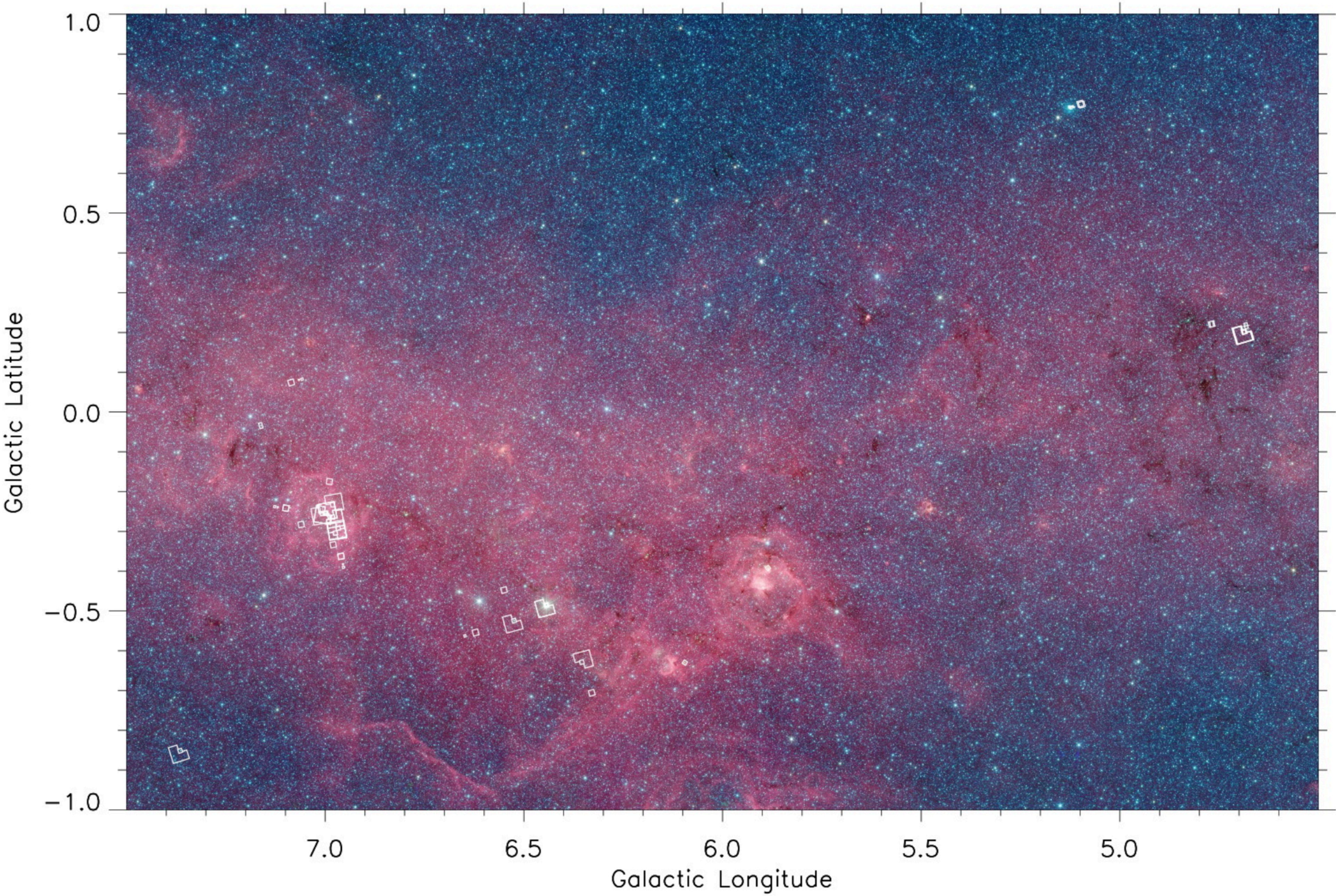

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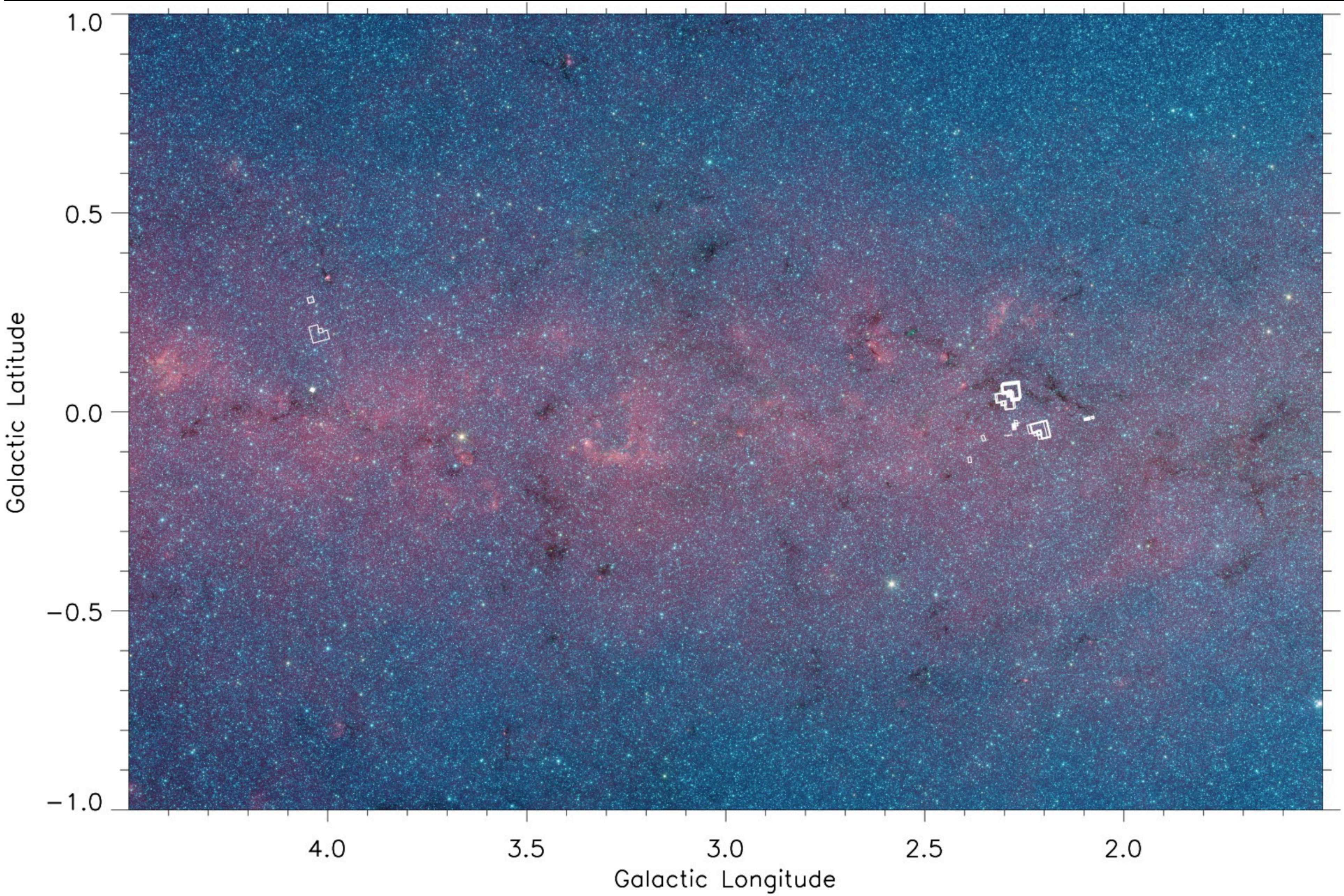

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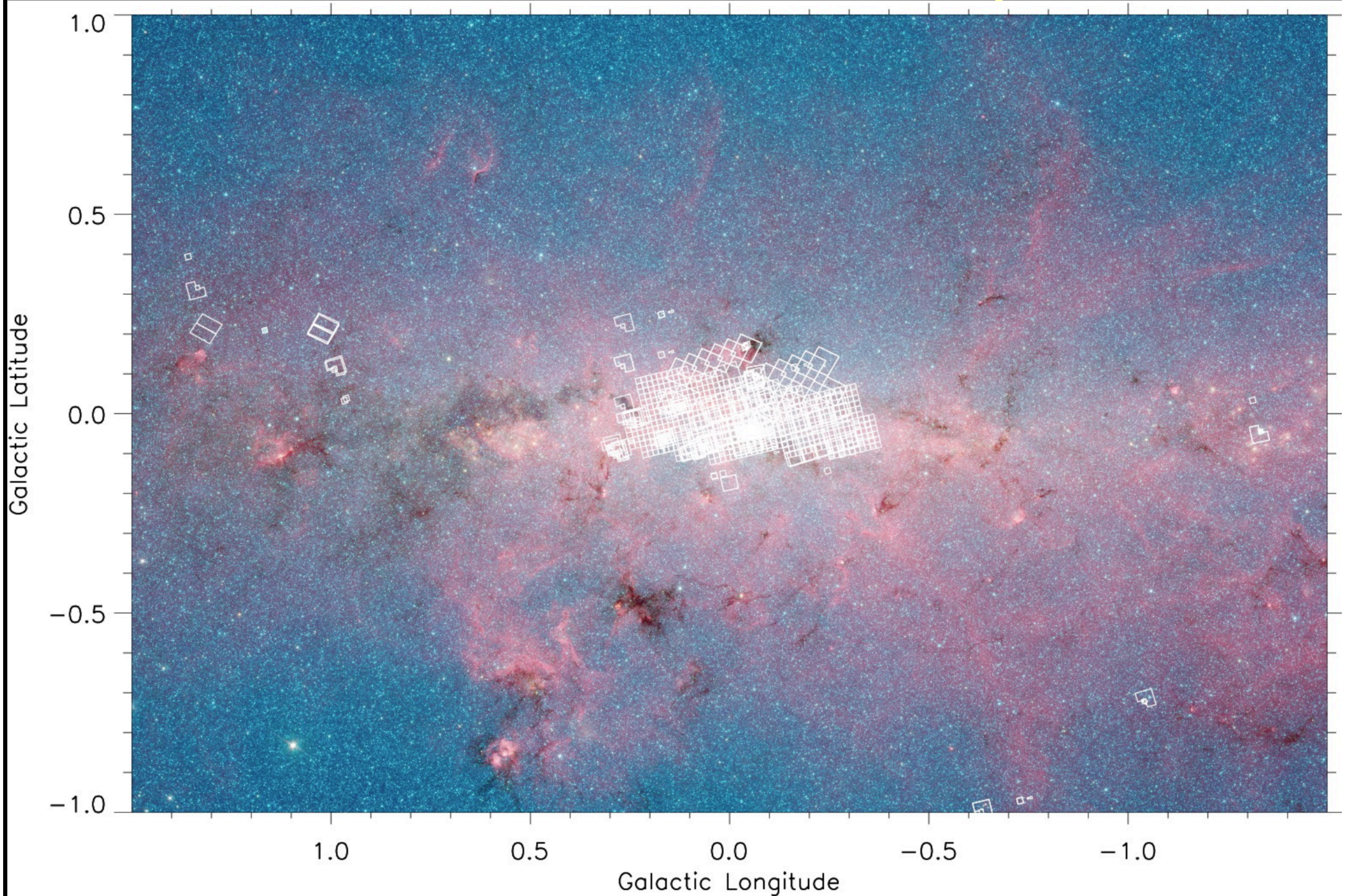

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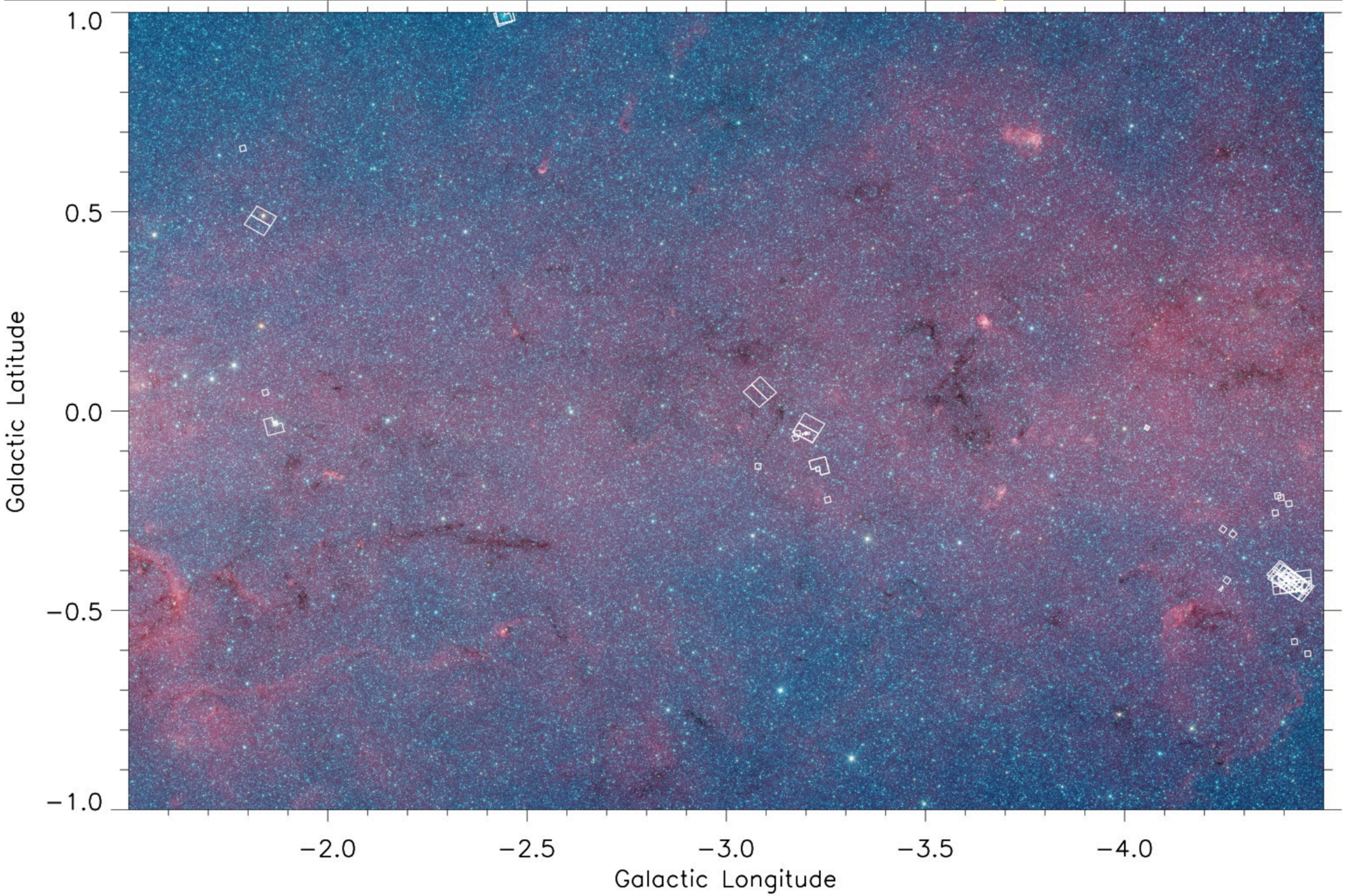

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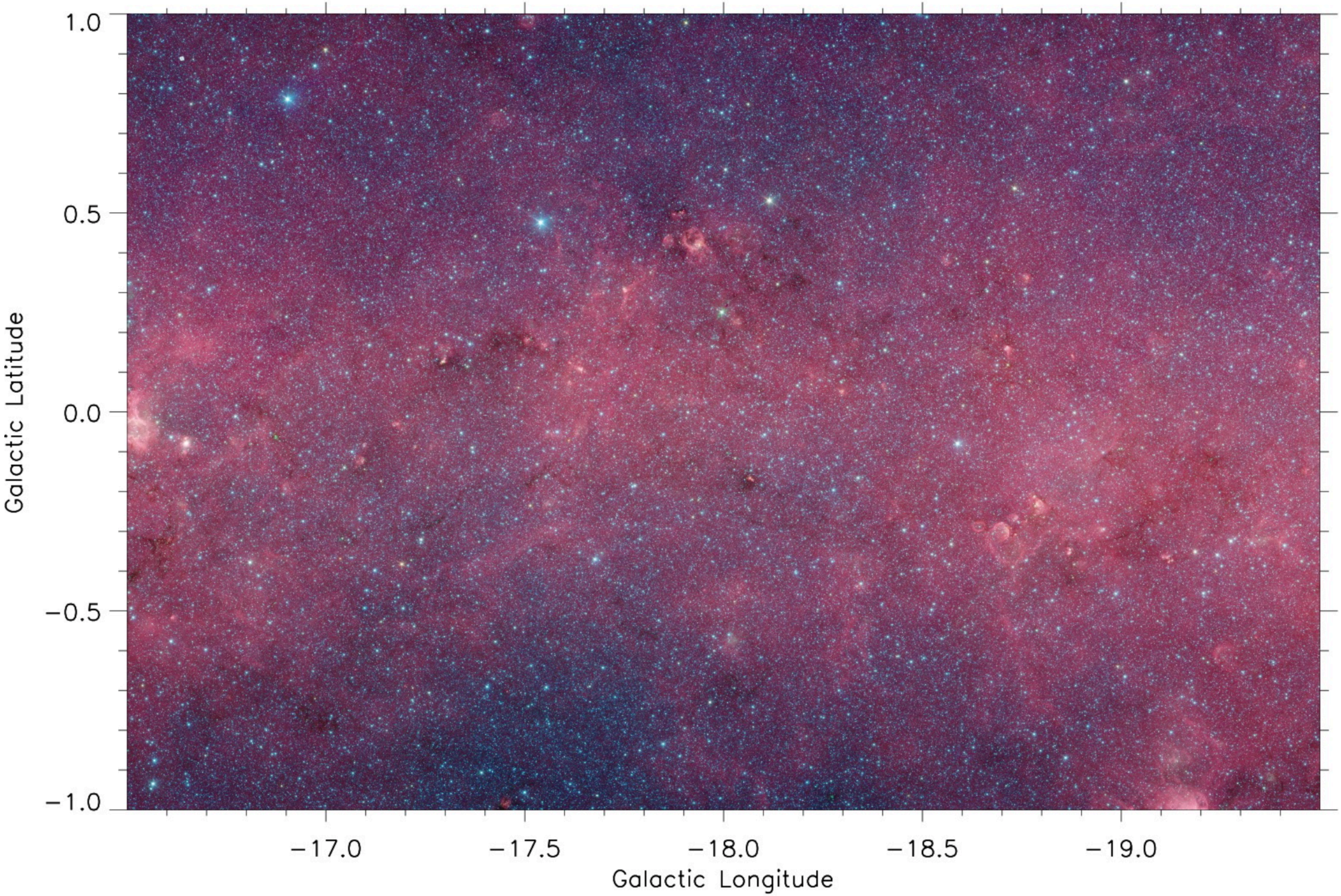
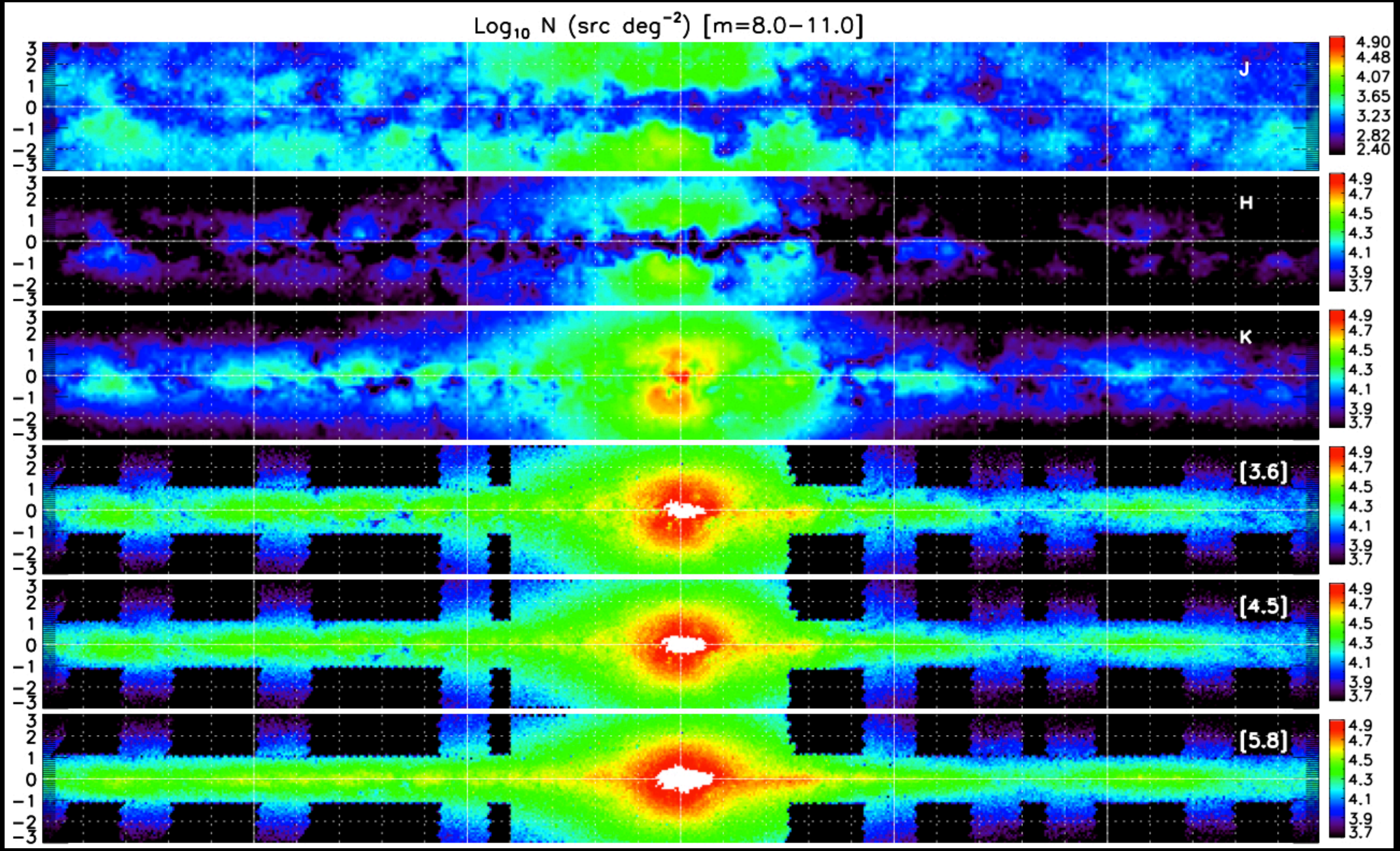


2. The Galactic Importance of Long Wavelengths



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

The percentage of the Galaxy that will be inaccessible can be estimated using the 3D (infrared based) maps of Marshall et al (2006) and Nidever et al (2012).

2. Key Photometric Science Goals

1. Non-axisymmetric stellar (mass) density models using (1) RGB , (2) red clump giants, and (3) MS turnoff stars.

- 3D maps of stellar "truncation" (volume density break)
- 3D maps of non-axisymmetric density in disk, e.g. spiral arms
- 3D maps of bar(s) and "hole" inside R=4.X kpc.

2. Non-axisymmetric dust density models, cf. Marshall et al (2006), Schlafly et al (2014a,b).

3. Identification of stellar content of massive star forming regions, clusters across the Galaxy, cf. Davies et al (2012).

4. IMF to much lower mass for thousands of star forming regions.

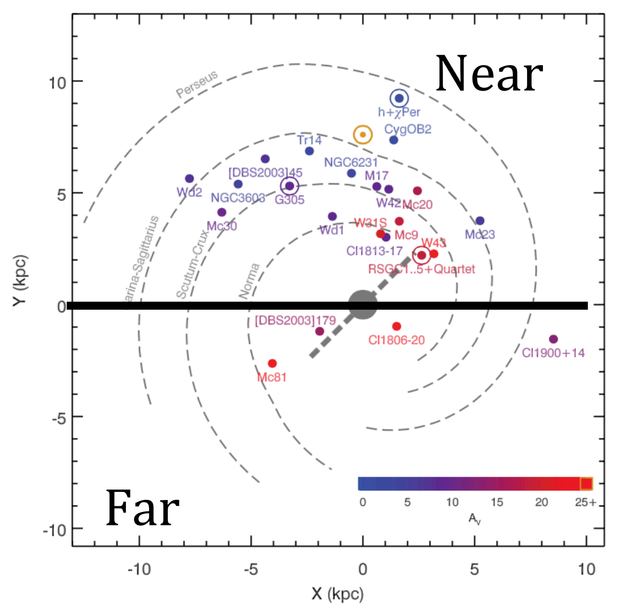


Figure 9. Top down view of the Galaxy, showing the locations of young star clusters. The colour of the plotting symbols indicate the extinction of each cluster, derived from their NIR colours and assuming an extinction law slope of −2.0. The spiral arms are those defined by Cordes & Lazio (2002). Sites of multiple star clusters are indicated by a filled circle surrounded by an open circle.

From Davies et al (2012)

All of these tracers can be calibrated using the local sample in the disk observed by Gaia!

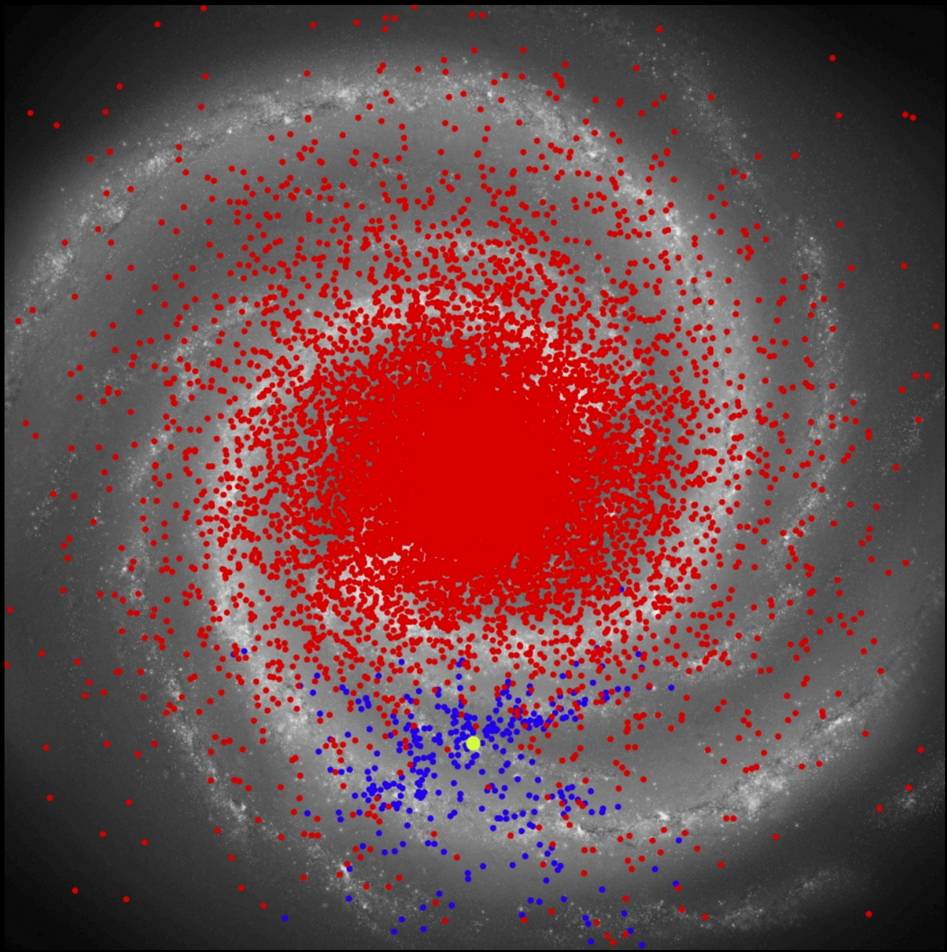
2. Adding the Time Domain

If one can do a ±1 degree strip of the Galactic plane in 6.9 hours, *why not observe it with a cadence to identify all of the variable stars in the galactic disk and bulge/ bar(s)?*

Targets: RR Lyrae, Cepheids, accreting and eclipsing YSOs, etc.

Scaling the luminosity and # of Cepheids from the LMC suggests that there should be >10,000 Cepheids in the MW.

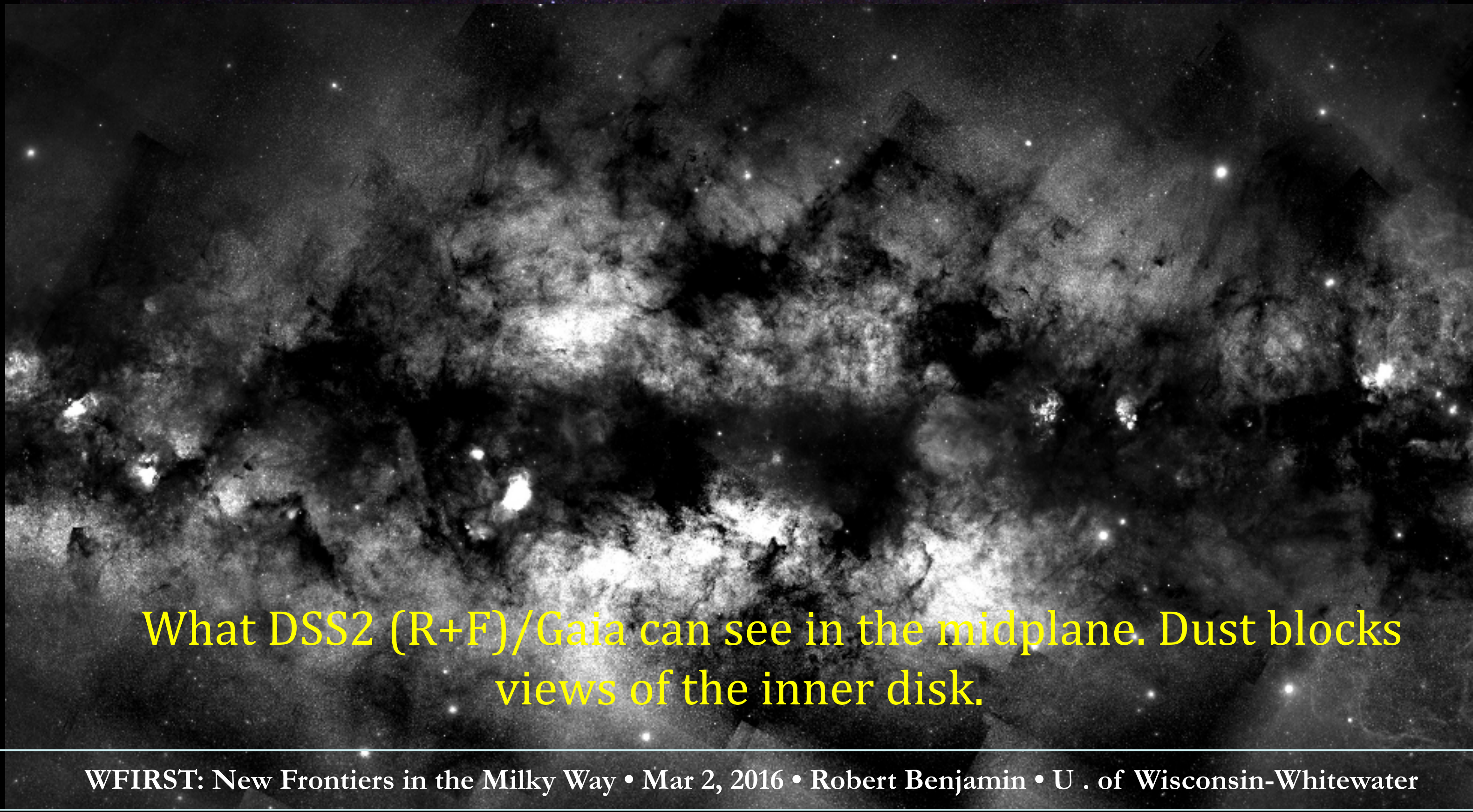
Less than 1000 are known; most will be behind a lot of dust!



Known / Modelled

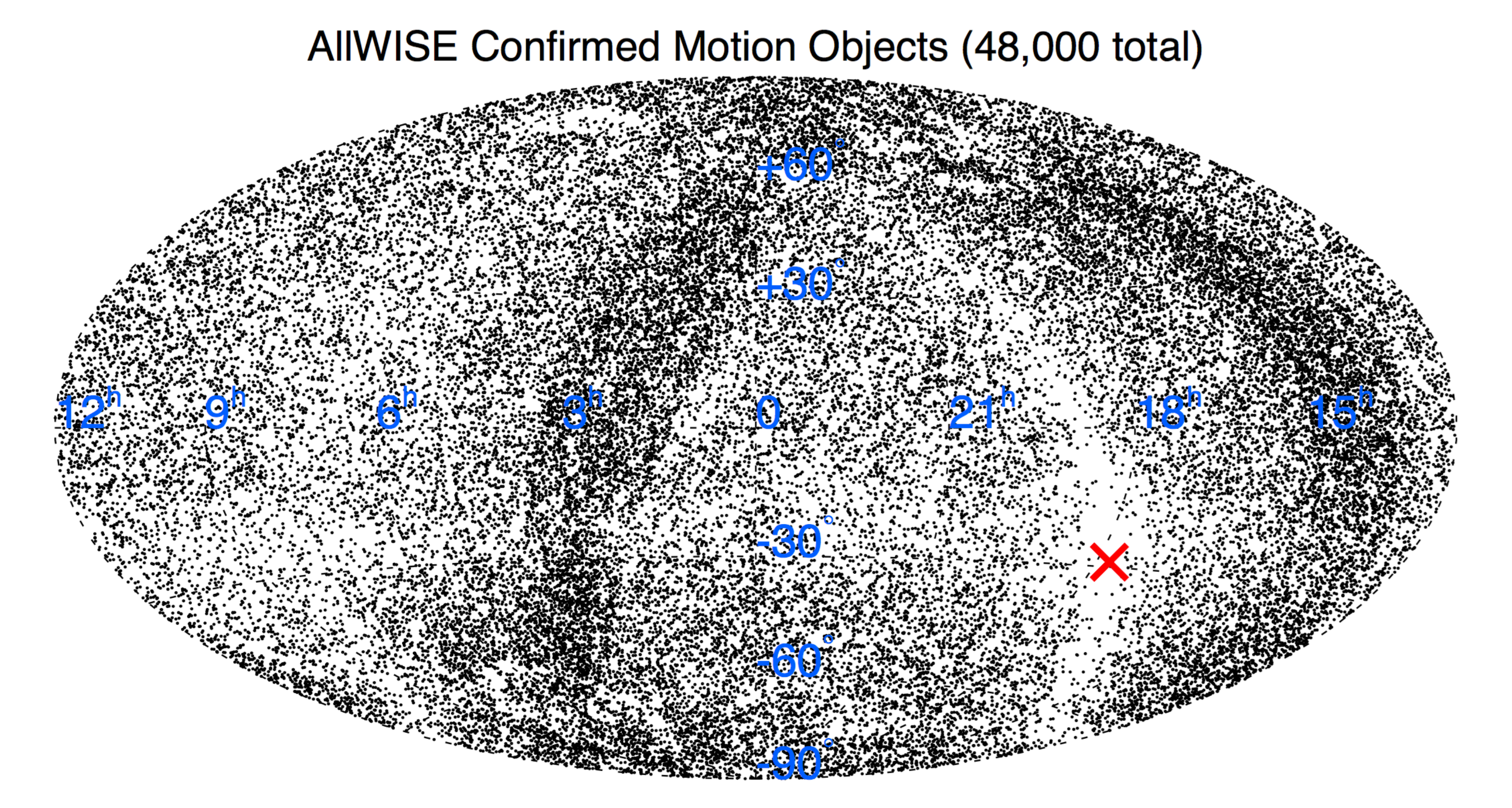
3. Proper Motions in the Disk: Why Not Gaia?

What 2MASS/WFIRST can see in the midplane



What DSS2 (R+F)/Gaia can see in the midplane. Dust blocks views of the inner disk.

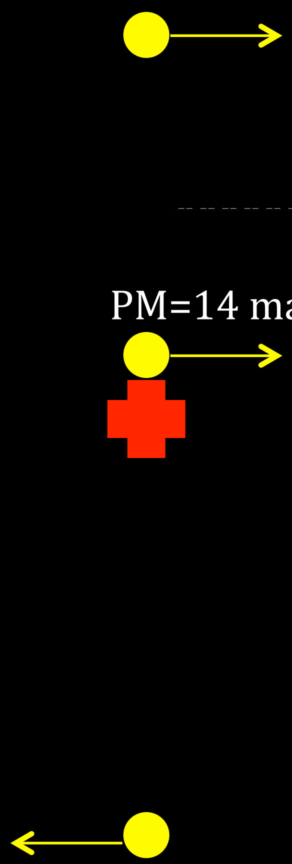
3. Proper Motions Surveys in the Inner Galaxy



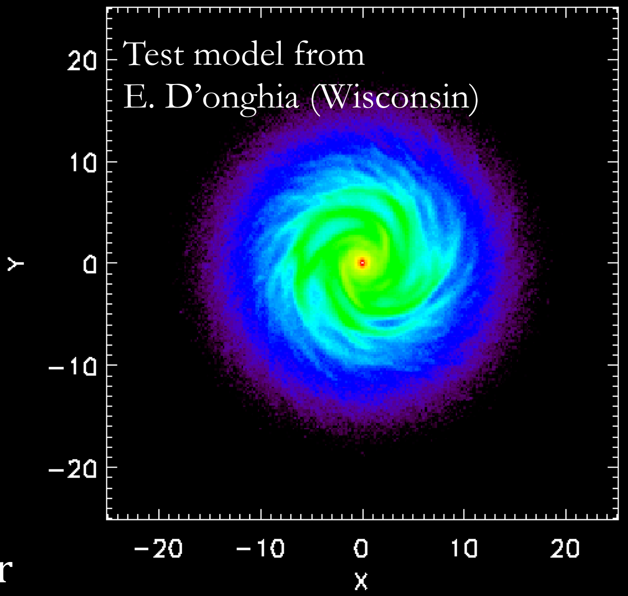
Search for high proper motion sources suffer from "Zone of Avoidance" effect (e.g. AllWISE study, Kirkpatrick et al 2014,2016). WFIRST could yield truly complete distribution of these sources.

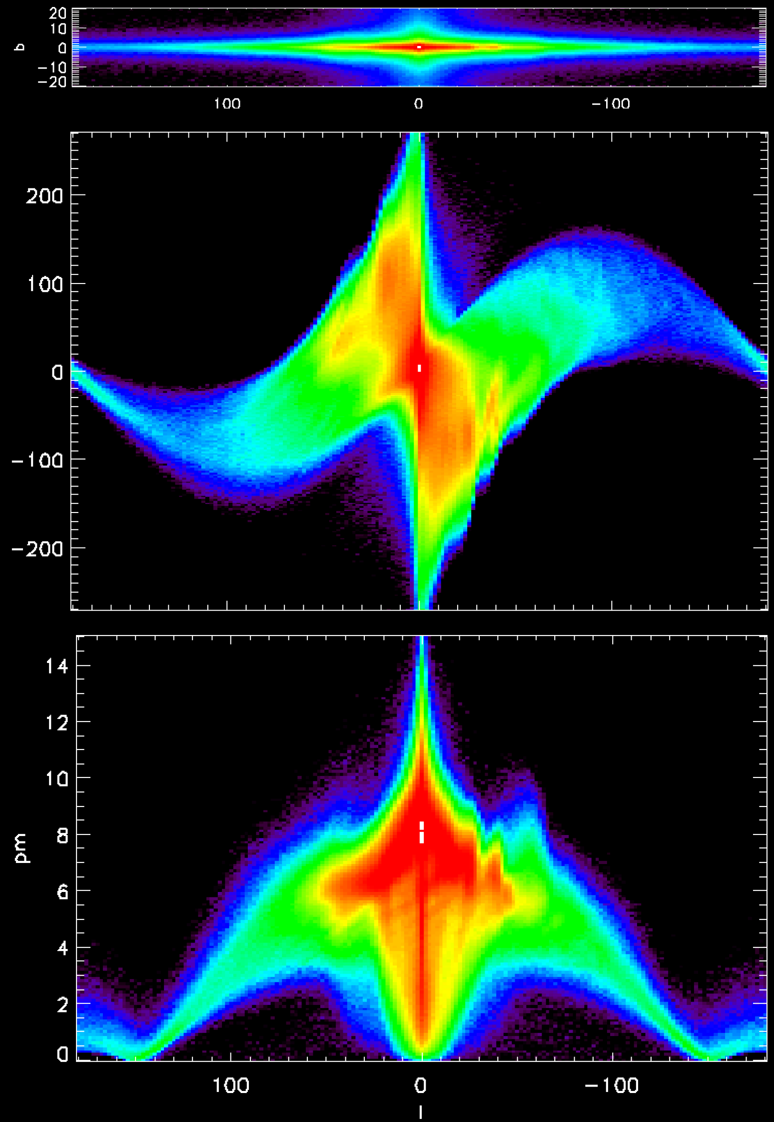
3. Measure the streaming/rotational kinematics of stars beyond G.C.

PM=7 mas/yr



PM=14 mas/yr



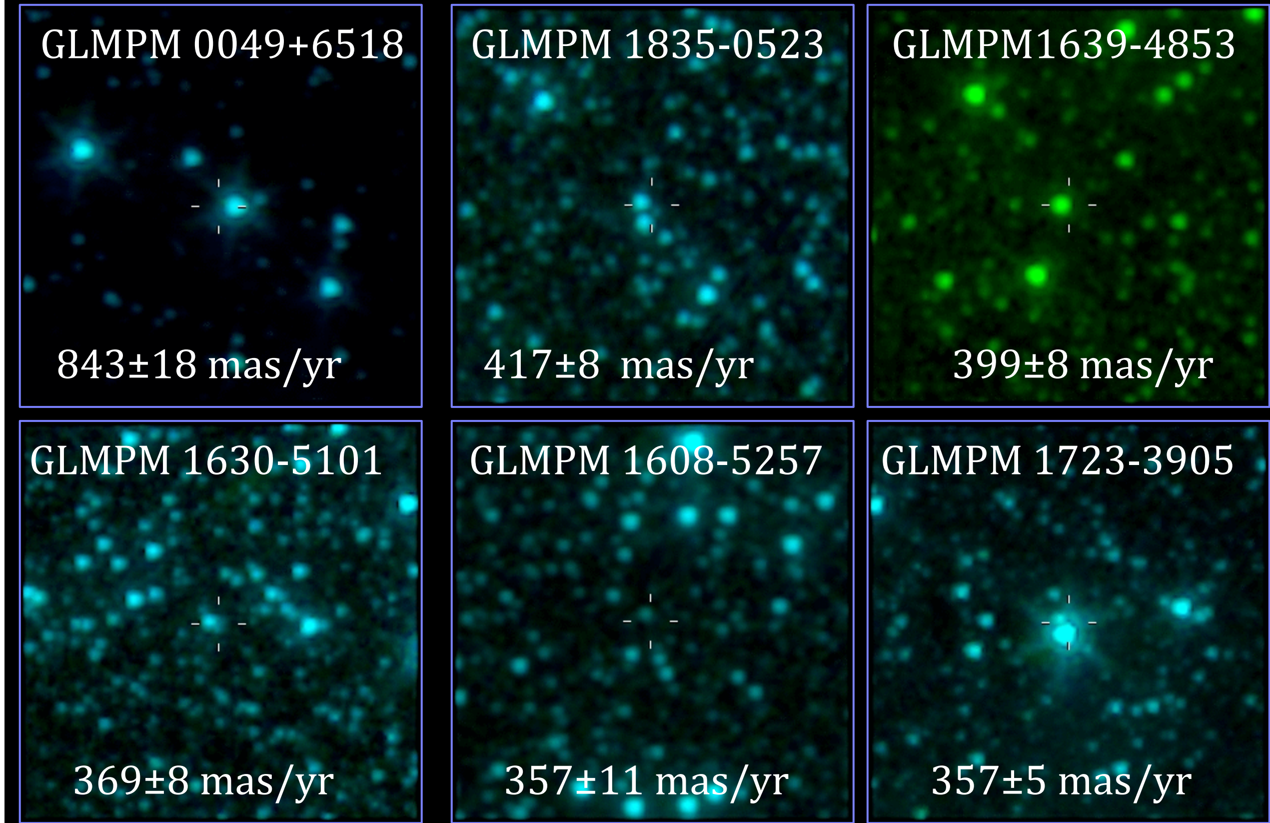


Proper Motions depend upon position in Galaxy! Maximum PM is just on other side of G.C.

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

4. 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!

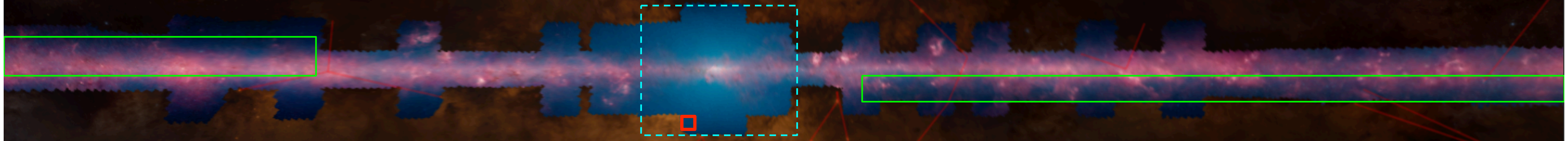
If we had known in 2004 that we would be observing in 2013, we might have thought about designing a better experiment to measure proper motions!

First measurement of proper motion based velocity dispersion in the "bulge" was towards Baade's window, using Baade's 1950 plates :
sigma~3 mas/yr

4. 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 realizing the value of mid-IR proper motions. This provides constraints on stellar kinematics for stars that are not easily detected in any other wavebands.

4. Special Modes and Issues for Galactic Science

1. Saturation With a WFIRST, saturation will be a VERY serious issue; high extinction in the inner Galaxy may be a blessing in disguise! (*Spitzer* gave GLIMPSE a special integration mode!)

—Red clump giants (M=-1.6) at Galactic center = 13 mag

—O stars (M=-4.35) at distance of 20 kpc = 12.15 mag

2. Crowded field photometry Most pipelines degrade or break in the mid-plane! 2MASS didn't extract many sources; SDSS avoided the plane. GLIMPSE became the crowded field photometry division of Spitzer and processed data for the MW, LMC, and SMC. (We were also the Christmas card division.)

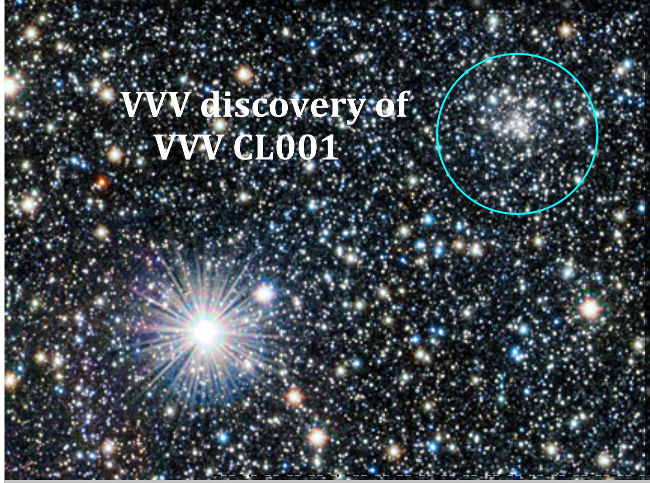
3. Overhead Most Galactic surveys will benefit from fast mapping. Very important to minimize the overhead.

4. Filters A redder filter will allow WFIRST to probe further through the Galaxy; a bluer filter could improve color selection. How do these trade off?

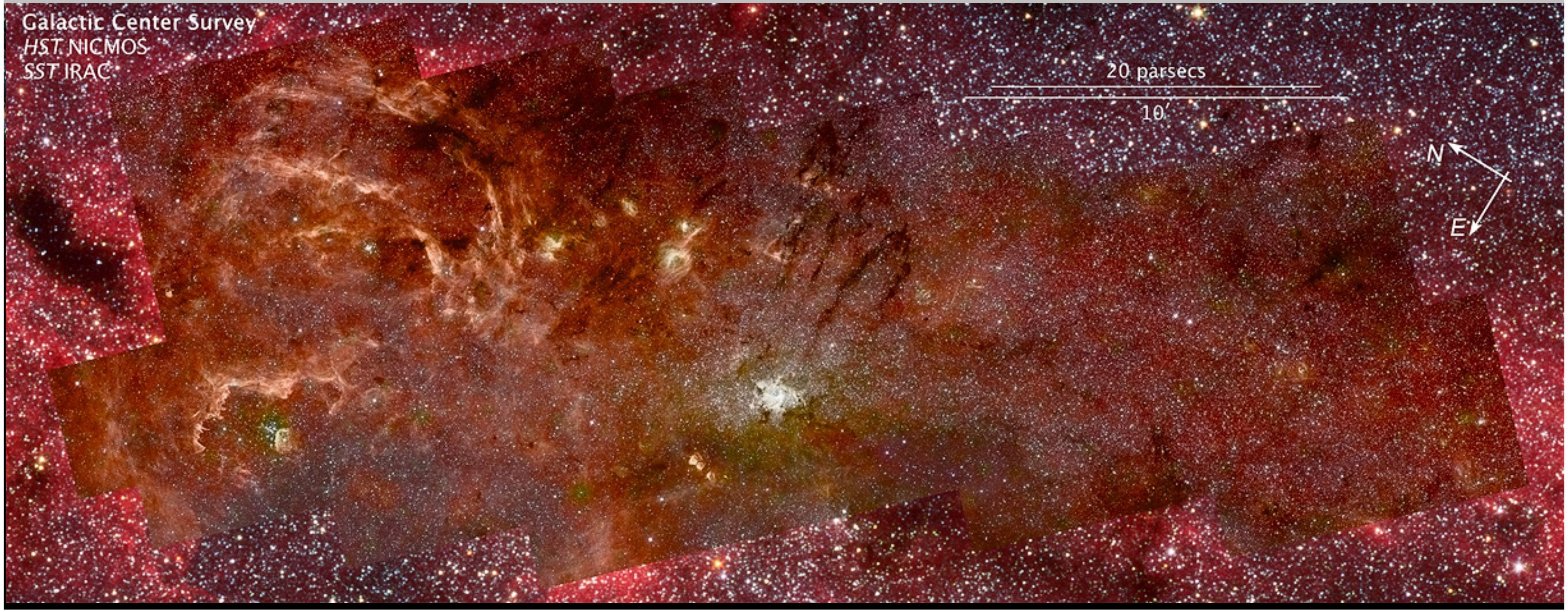
5. Huge (underexploited) heritage from previous Galactic surveys, particularly VVV and UKIDSS-Galactic plane surveys. Use these to define the goals of WFIRST survey.

4. Lessons from GLIMPSE

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).

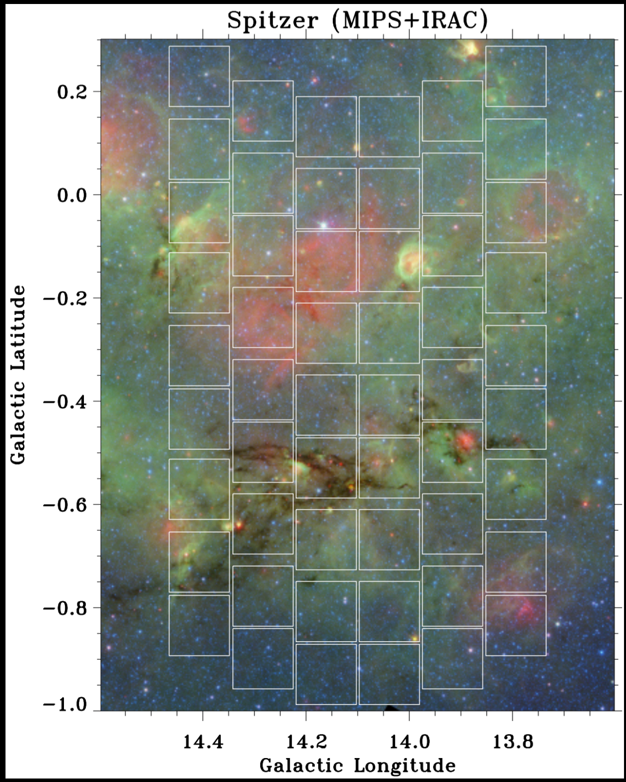


Conclusions

A WFIRST Galactic plane (Low Latitude) survey would allow us to measure the stellar content and properties of thousands of star formation regions across the Milky Way.

It would allow for 3D mapping of the stellar and dust content of the Milky Way, particularly the far half of the Galaxy where very little is known.

It would allow for the measurement of circular and non-circular motion via proper motion measurements, referenced to the GAIA astrometry and external galaxies seen through the disk in the IR.



Recommended reading:

- Churchwell, E. & Benjamin, R. 2013 *The Infrared Galaxy* in Planets, Stars, and Stellar Systems (Galactic Structure, Vol 5), p. 447-497.
- Bland-Hawthorn, J. & Gerhard, O. 2016, *The Galaxy in Context: Structural, Kinematic & Integrated Properties*, ARA&A, 54, 1-69.