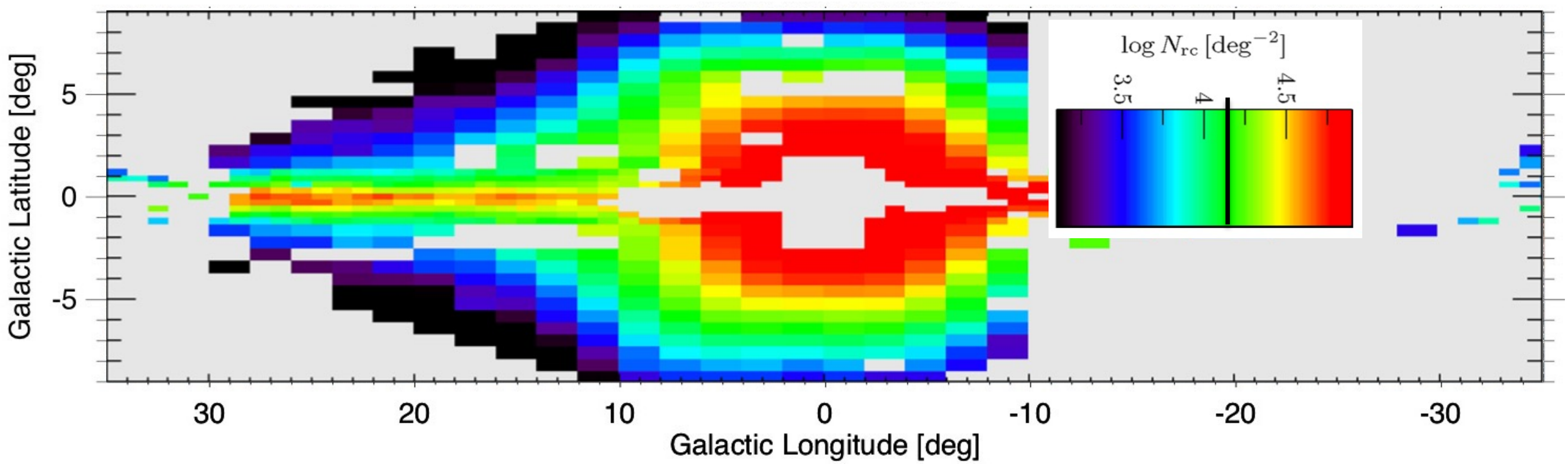
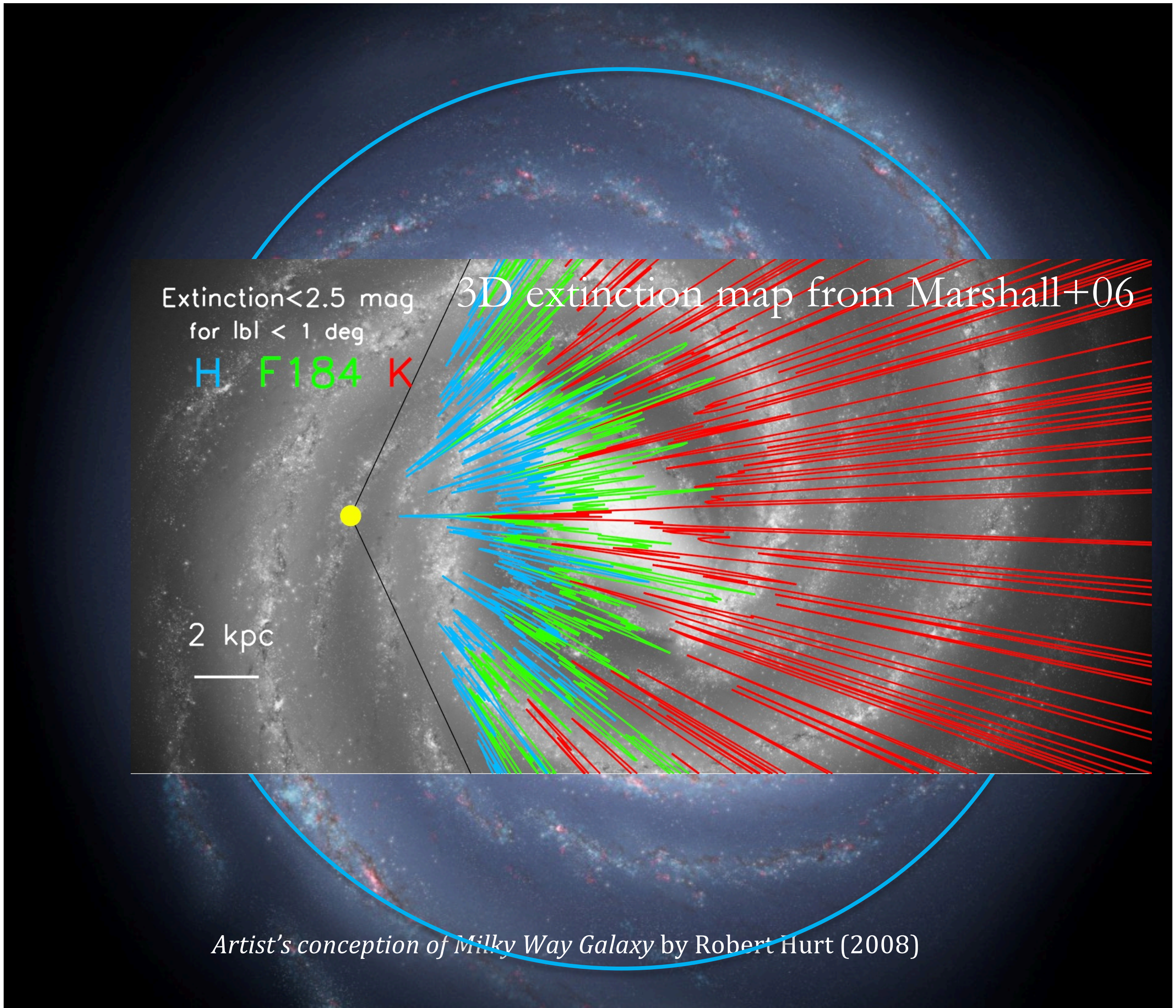
Dissecting the Inner Galaxy: The Role of Space Based Infrared Spectroscopy

Sky density of red clump giants towards Galactic bar (Wegg, Gerhard, & Portail 2015)



One ATLAS probe pointing : 6000 sources/0.4 deg^2 = $10^{4.18}$ source/deg^2

Mapping rate (10 min/pointing): 2.4 deg^2/hour =36,300 sources/hour



The Five Zones of the Milky Way

$R_G < 0.3$ kpc
Nuclear Stellar Disk+ Central Molecular Zone

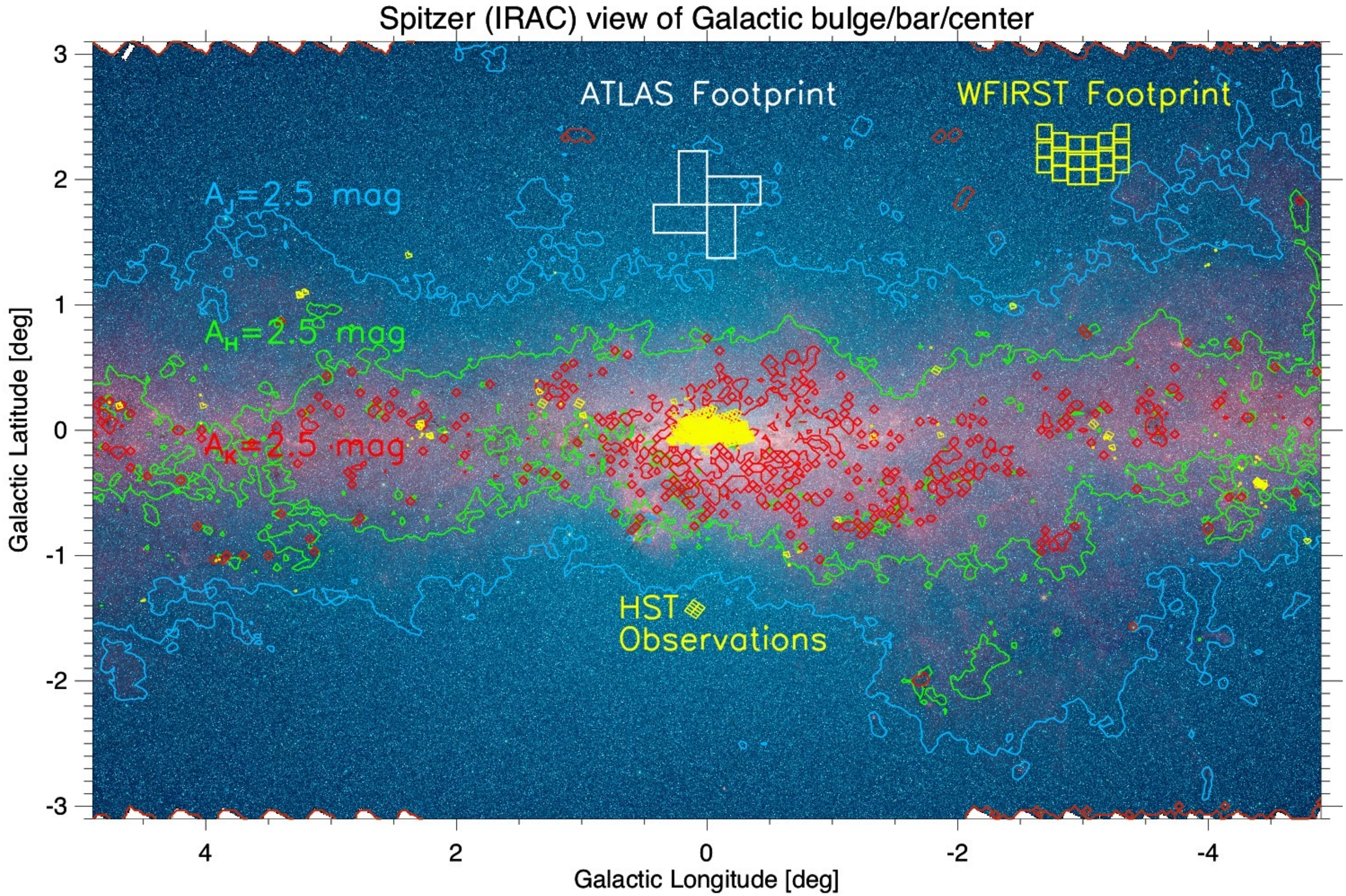
0.3 kpc $< R_G <$ 3.0 kpc
Boxy Peanut Bulge+Bar Dust Lanes

3.0 kpc $< R_G <$ 4.5 kpc
Long/Thin Bar+Inner Spiral Arms

4.5 kpc $< R_G <$ 13.5 kpc
The Disk + Spiral (?) Structure

$R_G >$ 13-14 kpc
Extreme Outer Galaxy (beyond the "break")

The Importance of Longer Wavelengths



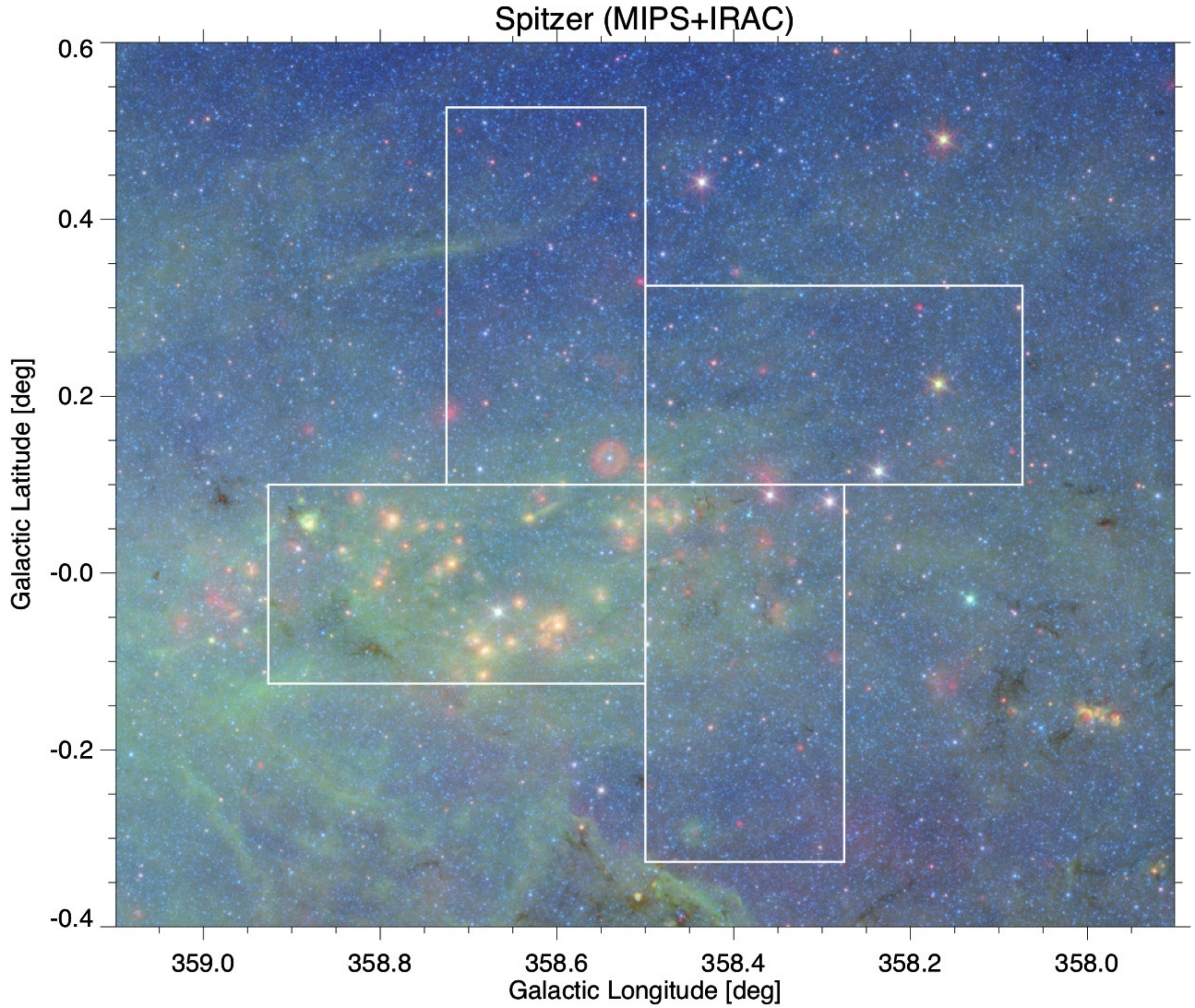
MW inner galaxy ISM fly-by
Sormani et al 2019, MNRAS, 488, 4663

http://www.ita.uni-heidelberg.de/~mattia/videos/EVF/flyby.mp4

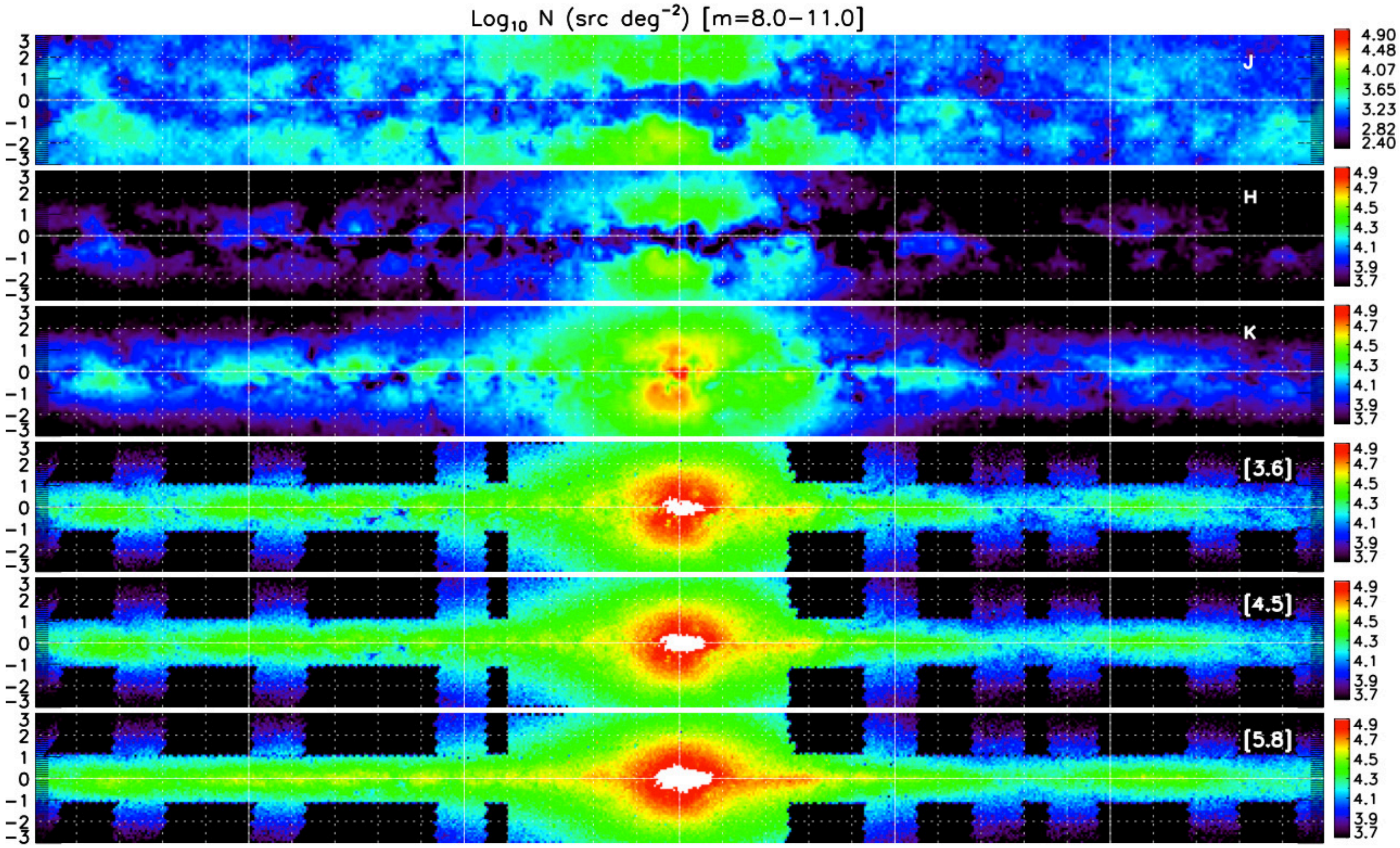
MW inner galaxy time evolution
Sormani et al 2019, MNRAS, 488, 4663
[http://www.ita.uni-heidelberg.de/~mattia/videos/EVF/lv12.mp4

What is the physical state (density, temperature, ionization, etc) of this gas? And how does it relate to the lack of star formation in the inner galaxy?

Zoom in to Sagittarius E



Longer Wavelengths Are Better



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

Overview

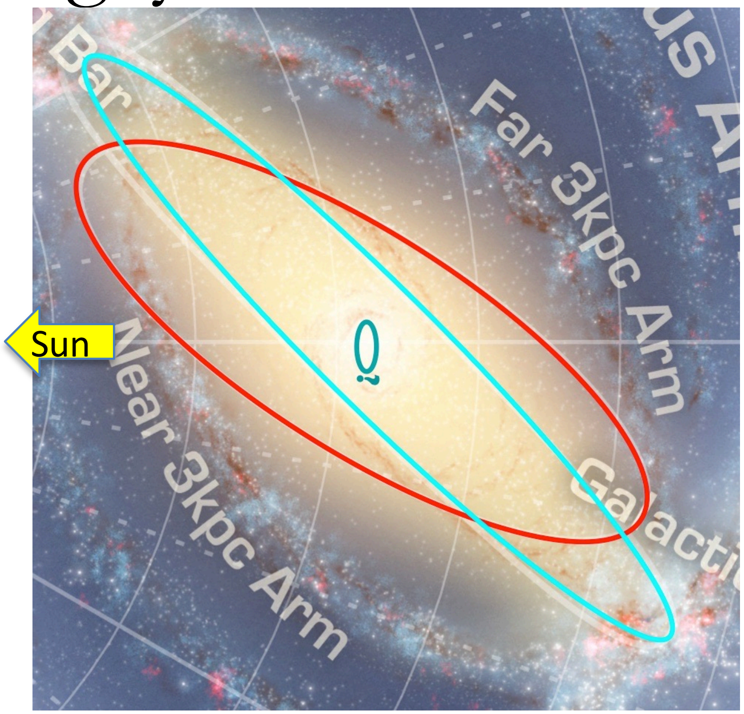
1. An Introduction to the Inner Milky Way
Key Questions and ATLAS advantages

***2. Photometric Surveys*:**
2MASS, *Spitzer*/GLIMPSE*, UKIDSS-GPS, VVVx,
HST Galactic Center, GALACTICNUCLEUS,
Roman Galactic Plane Survey(?)

3. Astrometric and Variability Surveys
Gaia and VVVx/VIRAC
+ Roman Galactic Plane Survey II (?)

4. *Two possible Spectroscopy Targets for ATLAS*
Red Clump Giants and OB stars

The Complexity of the Bulgey/Peanut Bar



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 "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 "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?

Recent APOGEE DR16 Results

Author/Year	Title	# of sources	Principal Results
Rojas-Arriagada+20	How many components? Quantifying complexity of the metallicty distribution in MW Bulge with APOGEE	~13,000 stars $\|l\|<11^o$, $\|b\|<13^o$	Three overlapping components at [Fe/H]=0.32, -0.17, and -0.66. Metal rich component associated with boxy/peanut.
Hasselquist+20	Exploring the stellar age distribution of the MW bulge using APOGEE	~6000 stars log g<2, [Fe/H]>-0.5	Age from *The Canon*. Metal rich bulge is mostly old (>8 Myr) stars.
Quieroz+20	The MW's bar and bulge as revealed by APOGEE DR16 and Gaia DR2	~7000 stars |X|<5 kpc |Y|<3 kpc	Chemical discontinuity suggesting star formation gap between high a and low a populations . Chemistry correlates with kinematics
Lian+21	The chemical properties of the Milky Way's on-bar and off-bar regions: evidence for inhomogeneous star formation history in the bulge	356+283 stars R<3 kpc 2538+3178 stars R=3-5 kpc	On-bar and off-bar stars have similar metallicity distributions. In bulge, more metal rich stars but fewer solar metallicity stars.
Griffiths+21	The similarity of abundance ratio trends and nucleosynthetic patterns in the Milky Way disk and bulge	~11,000 stars (R<3 kpc)	Divide sample into low-Ia (high [Mg/Fe] and high Ia (low [Mf/Fe]). Similar processes enriched stars in disk and bulge.

The Atlas Advantages

Spectroscopic Survey Facilities by 2020–2025								
Survey (facility)	N_{target}	$R_{spectra}$	N_{multi}	$\lambda\,[\mu m]$	Ω_{sky}	N_{epoch}	Timeframe	$m_{primary}$
SDSS-V	7×10^6	**22,000** **2,000**	**500**	**1.51–1.7** **0.37–1.0**	4π	**1–174**	**2020–2024**	$m_H \lesssim 13.4$ $m_i \lesssim 20$
Gaia (RVS)	8×10^6	11,000	—	0.85–0.87	4π	$\sim$60	2013–2020	$m_G \lesssim 12$
Gaia-ESO	0.1×10^6	17,000	140	0.55 & 0.85	0.02π	$\sim$1	2013–2018	$m_G \lesssim 17$
GALAH	0.8×10^6	28,000	400	0.40–0.85	π, $\lvert b \rvert \geq 10$	$\sim$1	2015–2020	$m_G \lesssim 13$
WEAVE	0.8×10^6	5,000 20,000	1000	0.37–0.9	$\sim\pi$	$\sim$1–2	2018–2023	$m_G \lesssim 19$
DESI	4×10^7	3,000	5000	0.36–0.98	1.35π, $\lvert b \rvert \geq 25°$	1–4	2019–2024	$m_r \lesssim 23$
LAMOST	8×10^6	1,800	4000	0.4–0.9	0.5π	$\sim$1	2010–2020	$m_G \lesssim 16$
4MOST	10×10^6	5,000 20,000	1600 800	0.4–0.9	1.5π	1–2	2023–2028	$m_r \lesssim 22$ $m_V \lesssim 16$
APOGEE-1& 2	5×10^5	22,000	300	1.51–1.7	0.5π	$\sim$1–30	2011–2019	$m_H \lesssim 12.2$
PFS	1×10^6	3,000	2400	0.4–1.6	0.05π	1	2018–2021	$m_i \lesssim 23$
MOONS	2×10^6	5,000 20,000	1000	0.6–1.8	0.05π	1	2020–2025	$m_g \lesssim 22$ $m_H \lesssim 17$

ATLAS goes further into the IR, greater depth, faster mapping, all sky.
7 x 10^6 sources: Sloan V in 4 years , ATLAS in 194 hours=8 days

Kollmeir et al 2017
arxiv.org/abs/1711.03234

2. Photometric Surveys as Fuel for ATLAS

Previous IR Photometric 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.

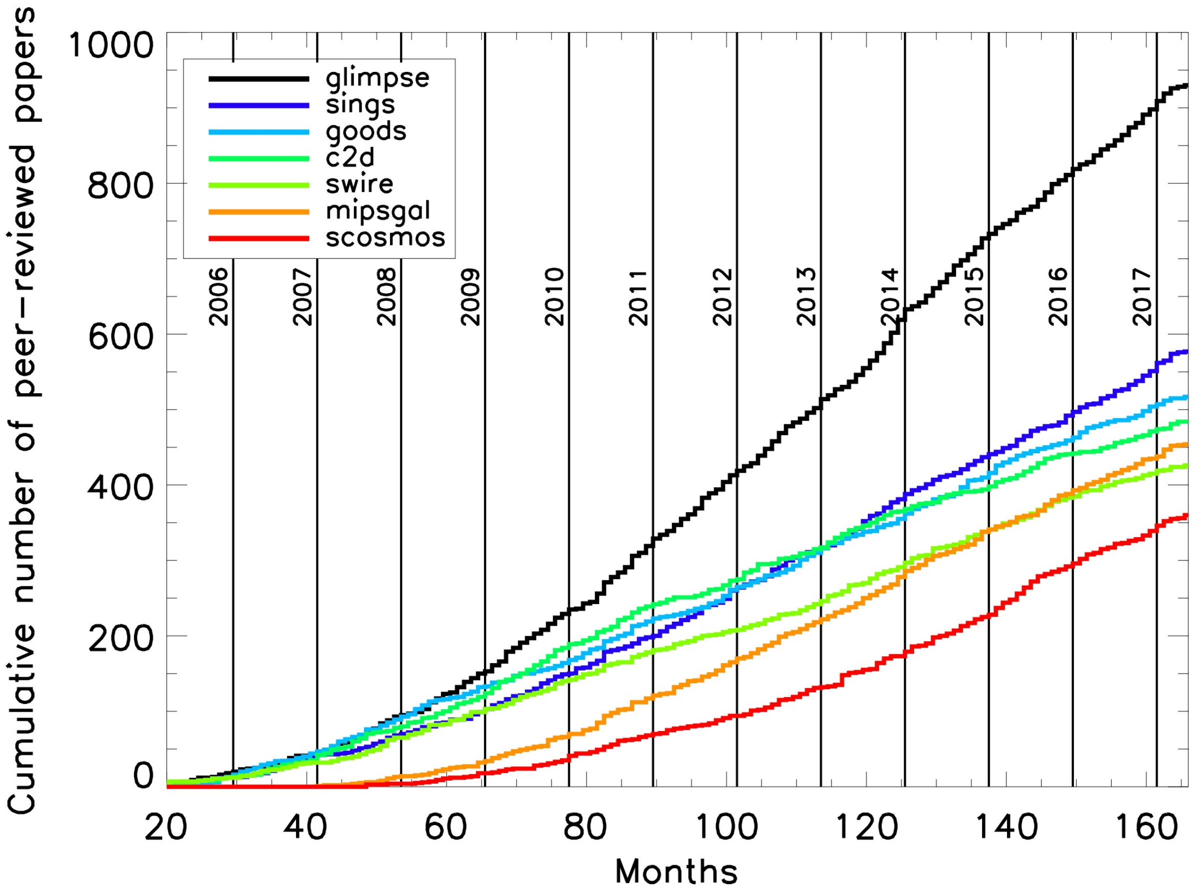
[d]GLIMPSE also has vertical extensions up to $|b| = 4°.5$ for selected longitudes. GLIMPSE style coverage was used for the *Spitzer* Vela-Carnina survey from $l = 295° - 255°$.

[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)

GLIMPSE overview



Spitzer/GLIMPSE (Dec '03-Jul '18)

- 1200 square degrees
- 195 days of observing
- 210M sources
- 1271 publications (13% of total)

But… not enough spectroscopic follow-up!

GLIMPSE catalogs for follow-up

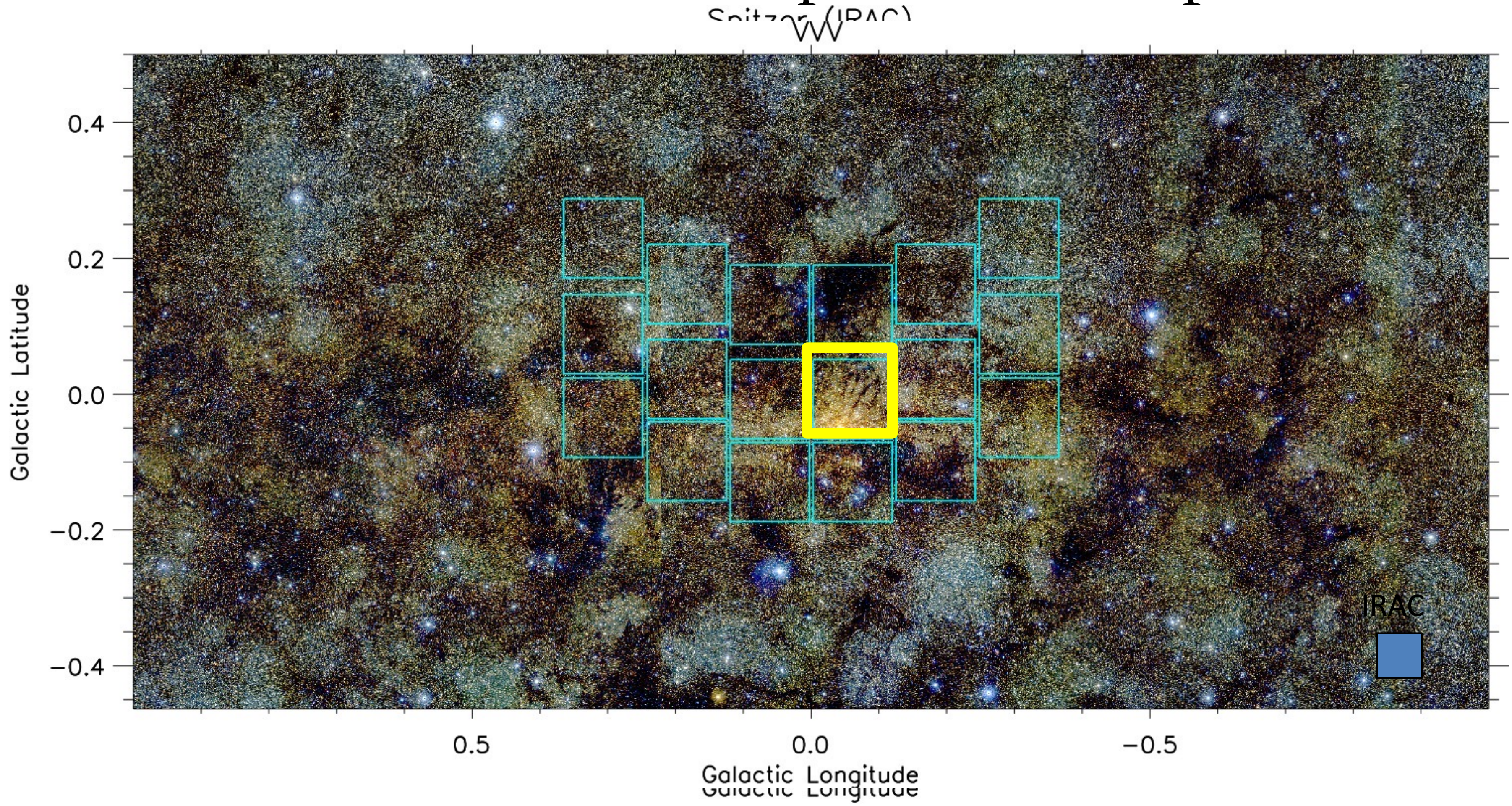
1. Near/mid-infrared extinction curve (Indebetouw et al 2005)
2. Infrared dark cloud catalog (Peretto & Fuller 2009) 11303 clouds
3. YSO modelling—and catalogs (Robitaille et al 2008, 2006) 11,000 high mass YSOs
4. Extended green objects (Cyganowski et al 2008) 300+(many more) EGOs
5. Yellow balls =Ultra compact HII regions (Kerton et al 2015) 900

   Citizen Science Discovery

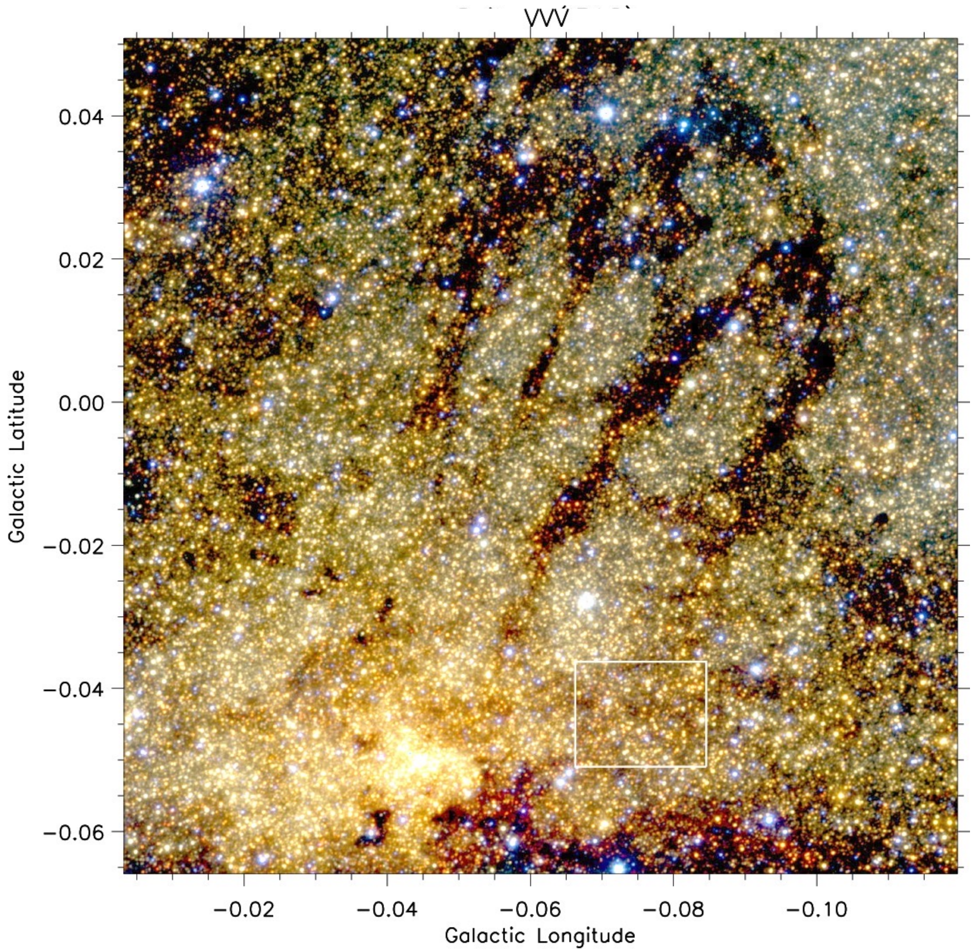
6. PAH bubbles (Churchwell et al 2006→Beaumont et al 2016) 322→~5000
7. HII regions (WISE+GLIMPSE+MIPSGAL) (Anderson et al 2014) 8398+

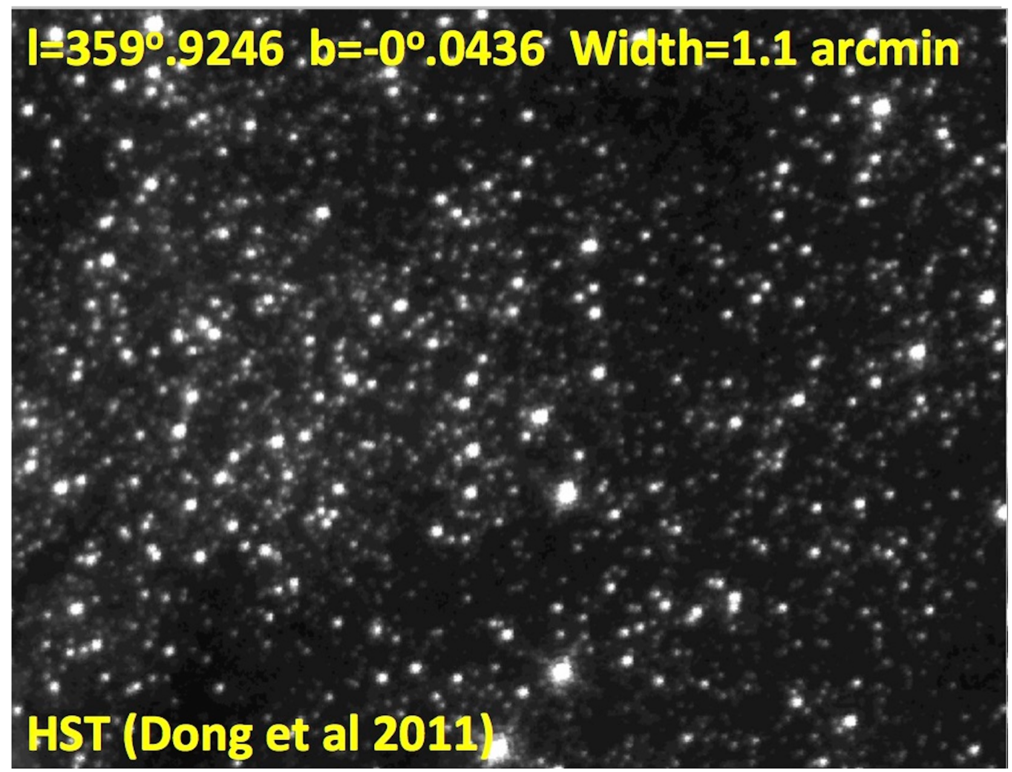
ATLAS can probe the physical properties of all of these samples in different Galactic environments (bar, arms, Galactic center, far side of the disk, etc.)

What will Roman Space Telescope Do?



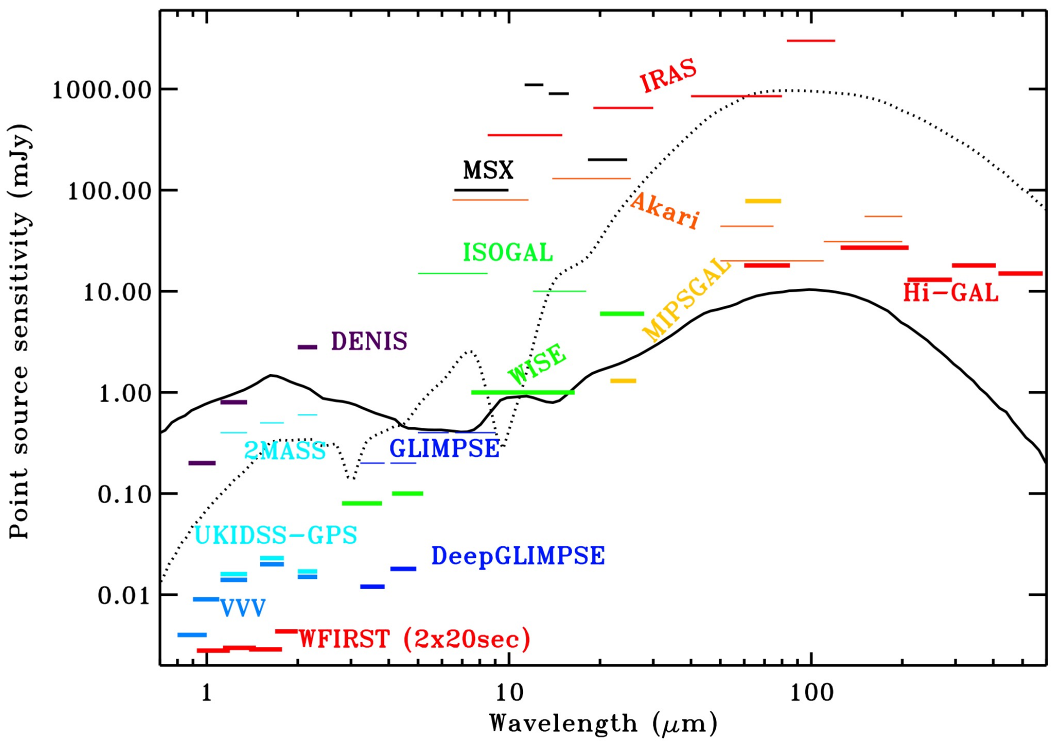
Galactic Center Zoom-In





F190 (1.9μm)

One (possible) Roman Galactic Plane Survey



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

Depth (2x20sec)

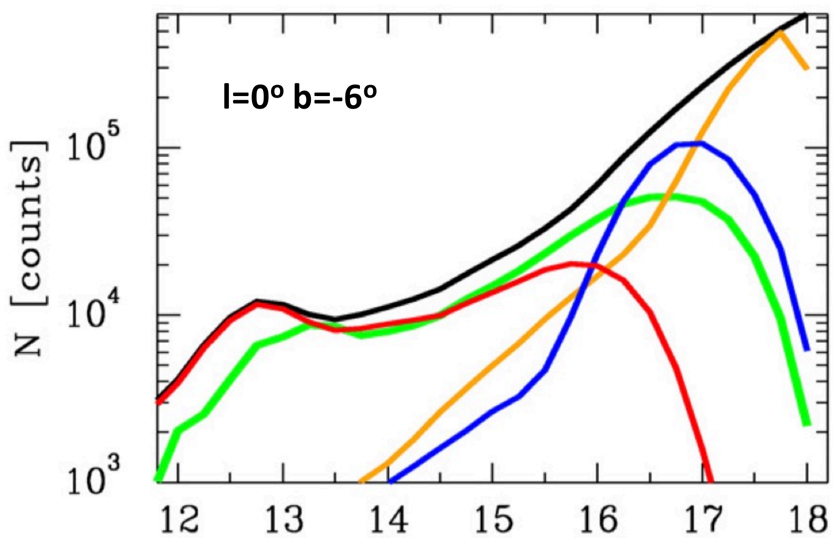
Band	m_{AB}	m_{Vega}
Y	22.6	22.0
J	22.7	21.8
H	22.7	21.4
F184	22.3	20.5

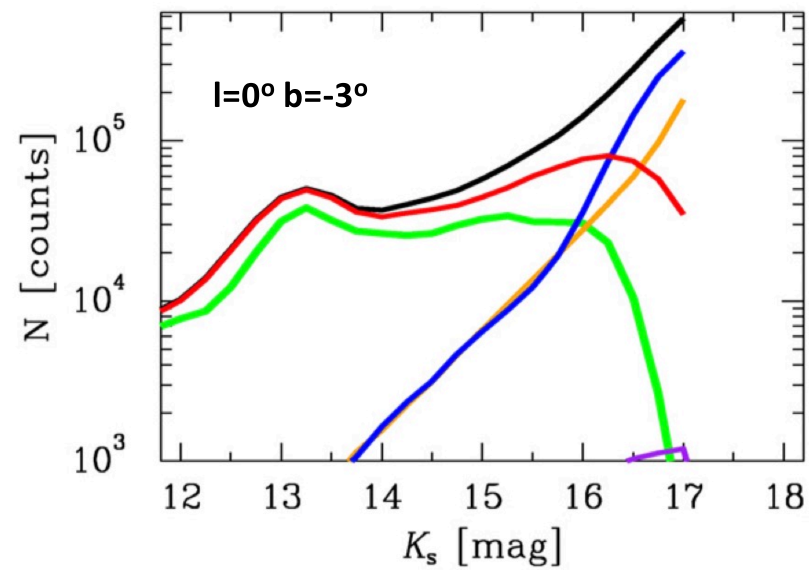
Coverage

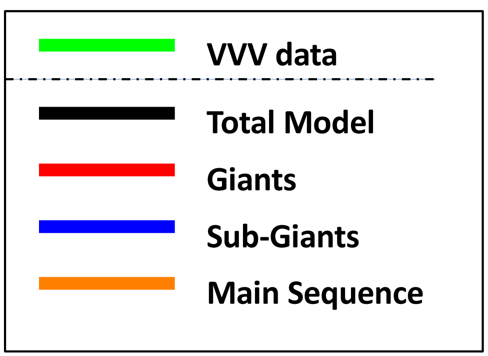
with 40% overhead

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

The Angular Resolution/Extinction Barrier in Inner Galaxy







VVV source histograms
Minniti et al (2012)

KEY: A thorough analysis of the VVV and UKIDSS-GPS data should inform the design of surveys by both ATLAS and Roman ST

ATLAS Possibilities for Galactic Bulge/Bar/Nucleus

Mapping stellar metallicity in different tracers: RR Lyrae, Red Clump Giants, RGB-bump stars, MSTO stars

JHKs GALACTIC NUCLEUS program (m<22 mag) VLT- HAWK-I (0.2" resolution) Nogueras-Lara , F. et al (2018ab,2019), Shahzamanian et al (2019), Schodel et al (2020)

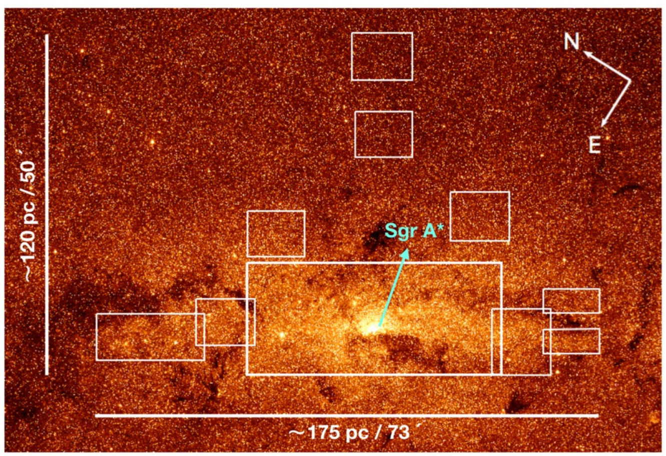
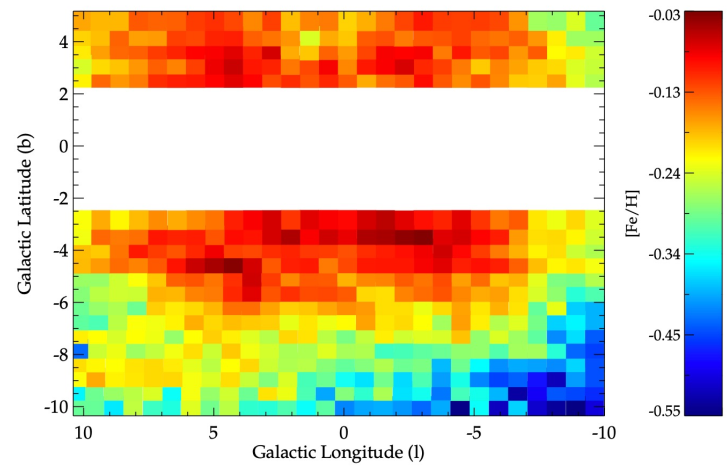


Fig. 1. Scheme of the target fields for the GALACTICNUCLEUS survey over-plotted on a *Spitzer*/IRAC image at 3.6 μm. The position of Sagittarius A* is highlighted in cyan.

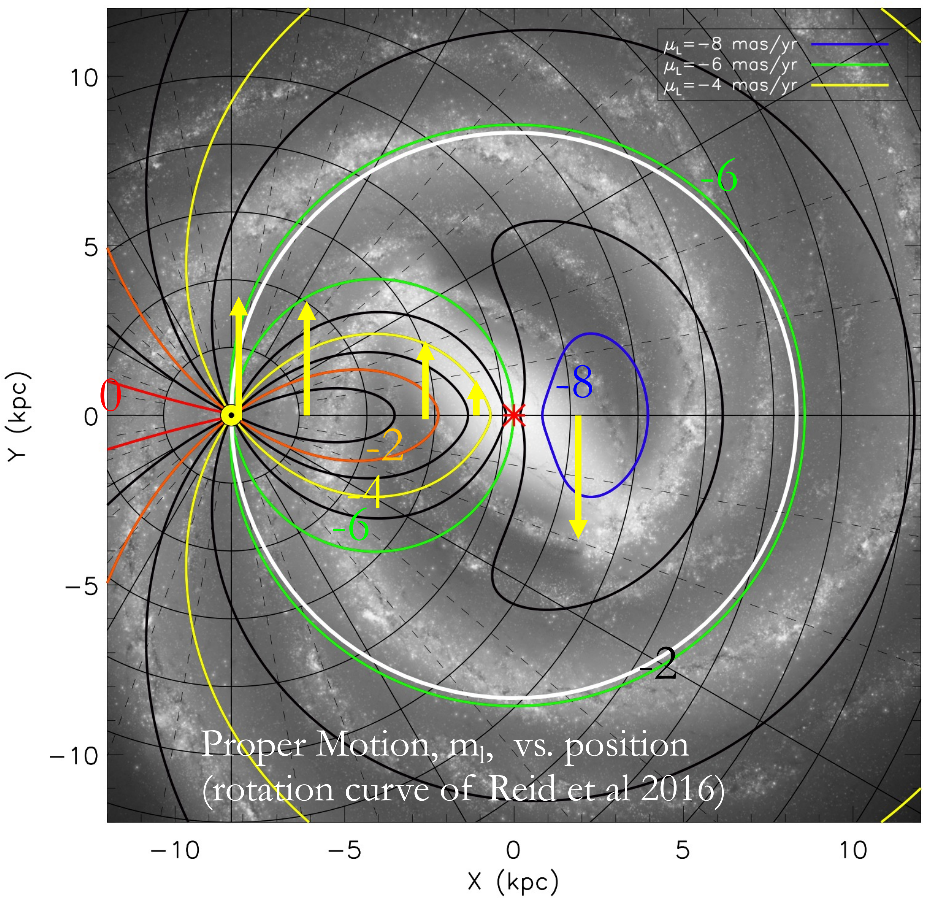
Nucleus is "old, metal rich and cuspy"

VVV Photometric metallicity maps of Bulge Gonzalez et al (2013)



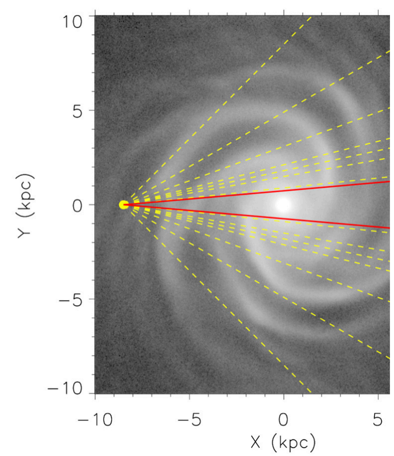
3. Astrometric Surveys Providing the Kinematic Context

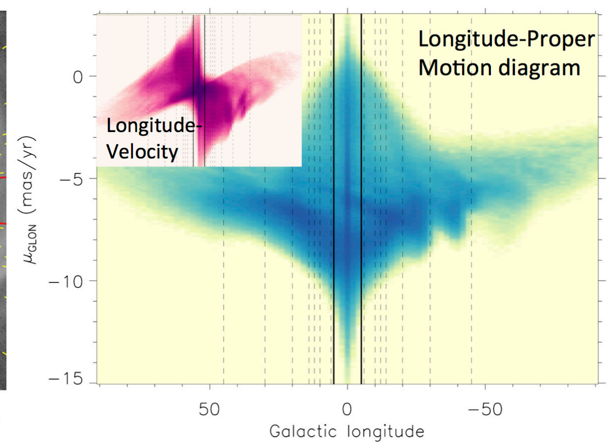
Getting Beyond the Galactic Bulge



Proper Motion, m_l, vs. position (rotation curve of Reid et al 2016)

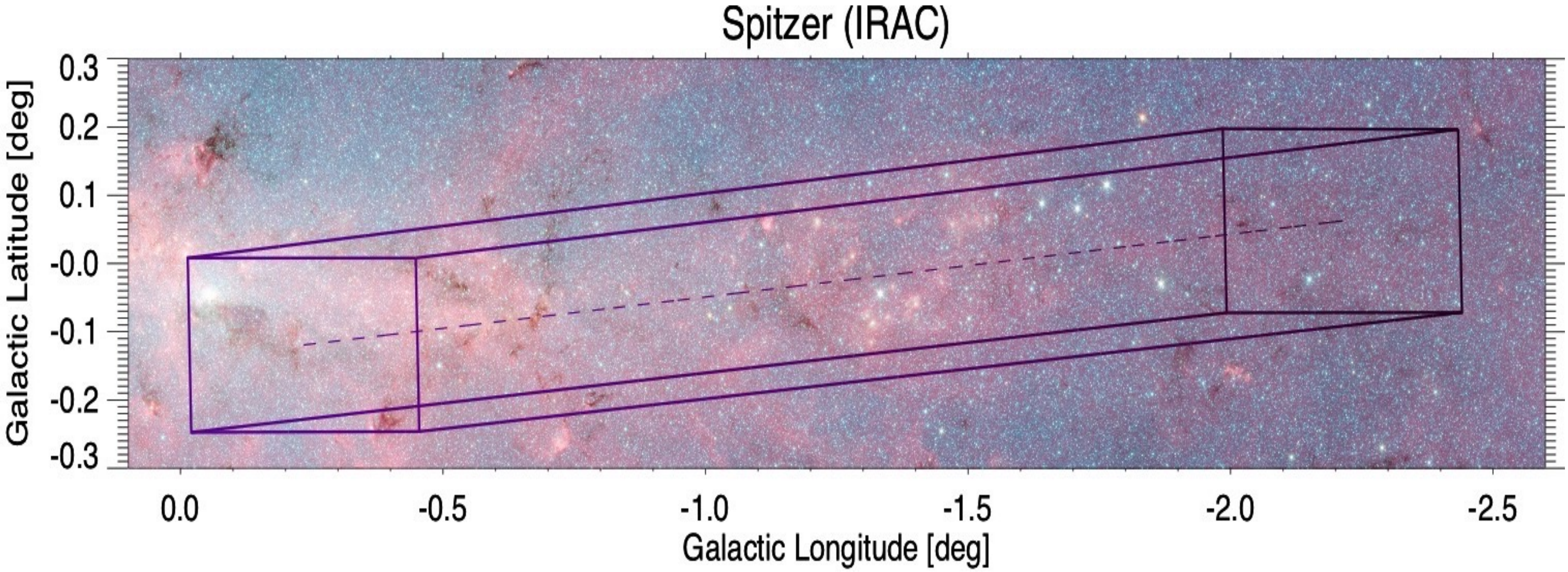
Proper Motions depend upon position in Galaxy. Maximum PM is just on other side of G.C. Sumi et al (2013), Poleski et al (2013) claim to see streaming on front/back of bar





Non-barred simulated galaxy (D'Onghia, priv comm.)

The Challenge of Mapping the Far Side

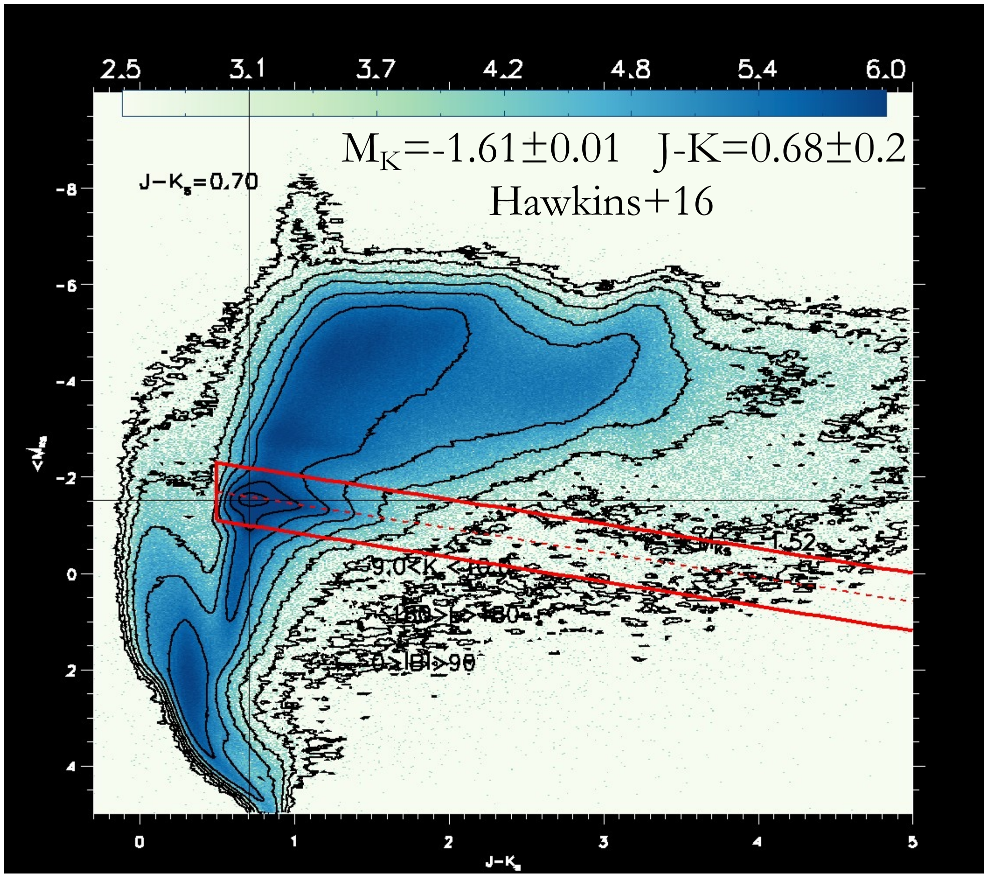


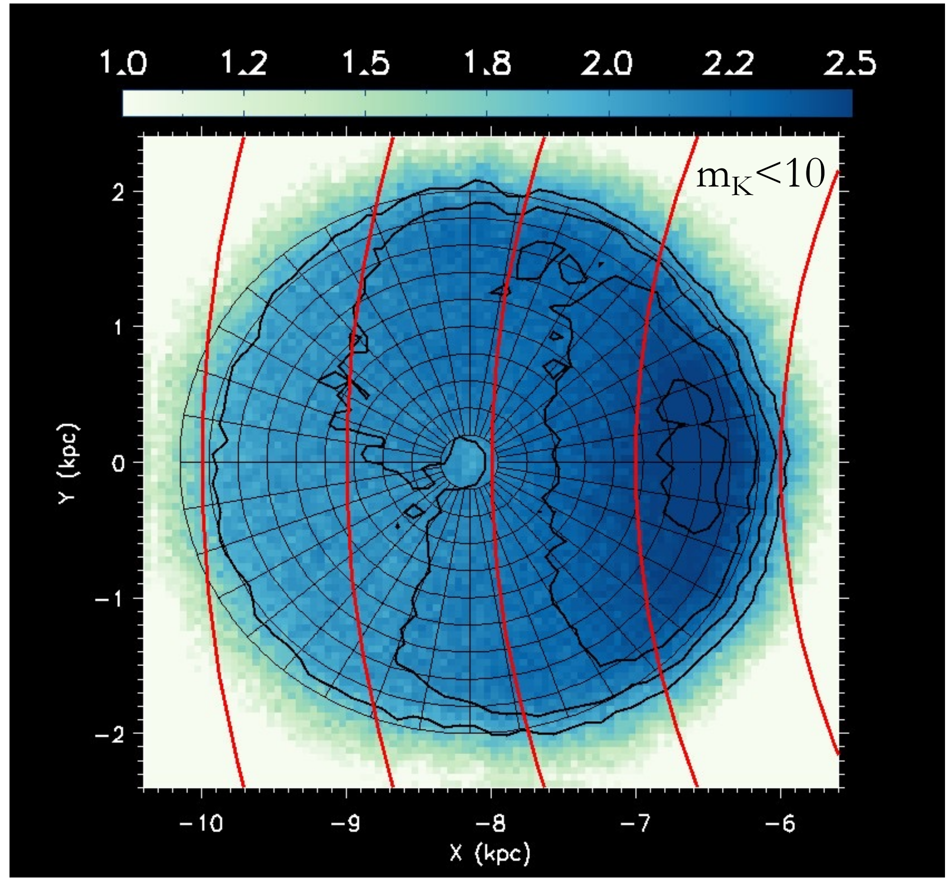
Three dimensional mapping of section of Sagittarius Arm (Kuhn+21)

Apply the "Tom Dame MW Symmetry" Test

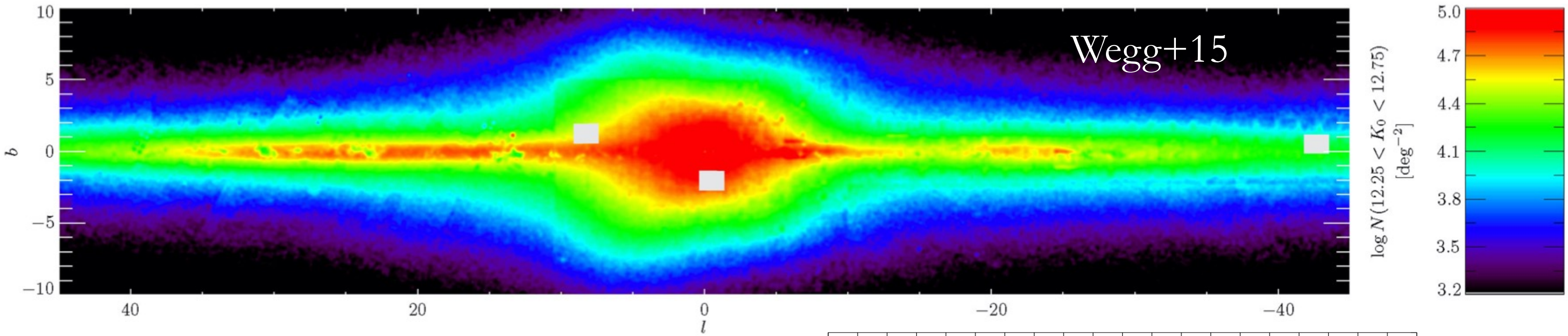
4. Spectroscopic Targets

One useful probe: Red Clump Giants



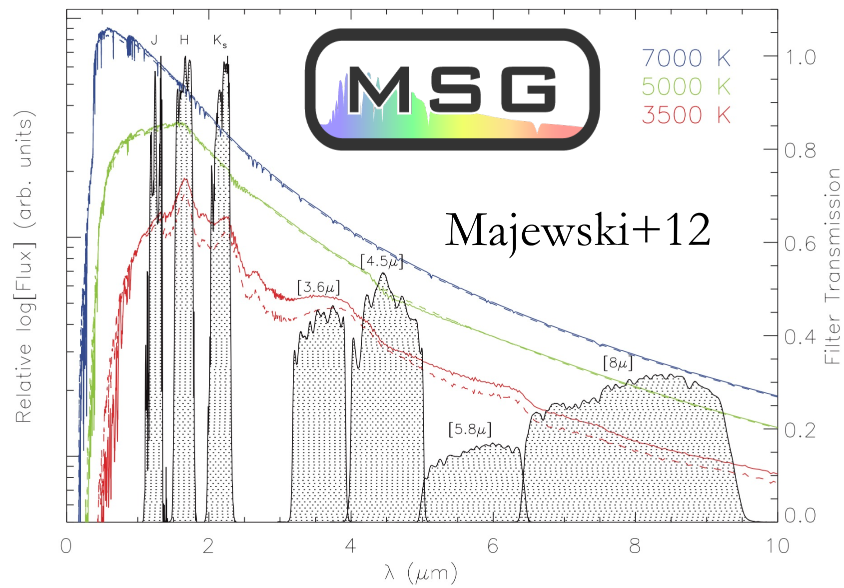


One useful probe: Red Clump Giants

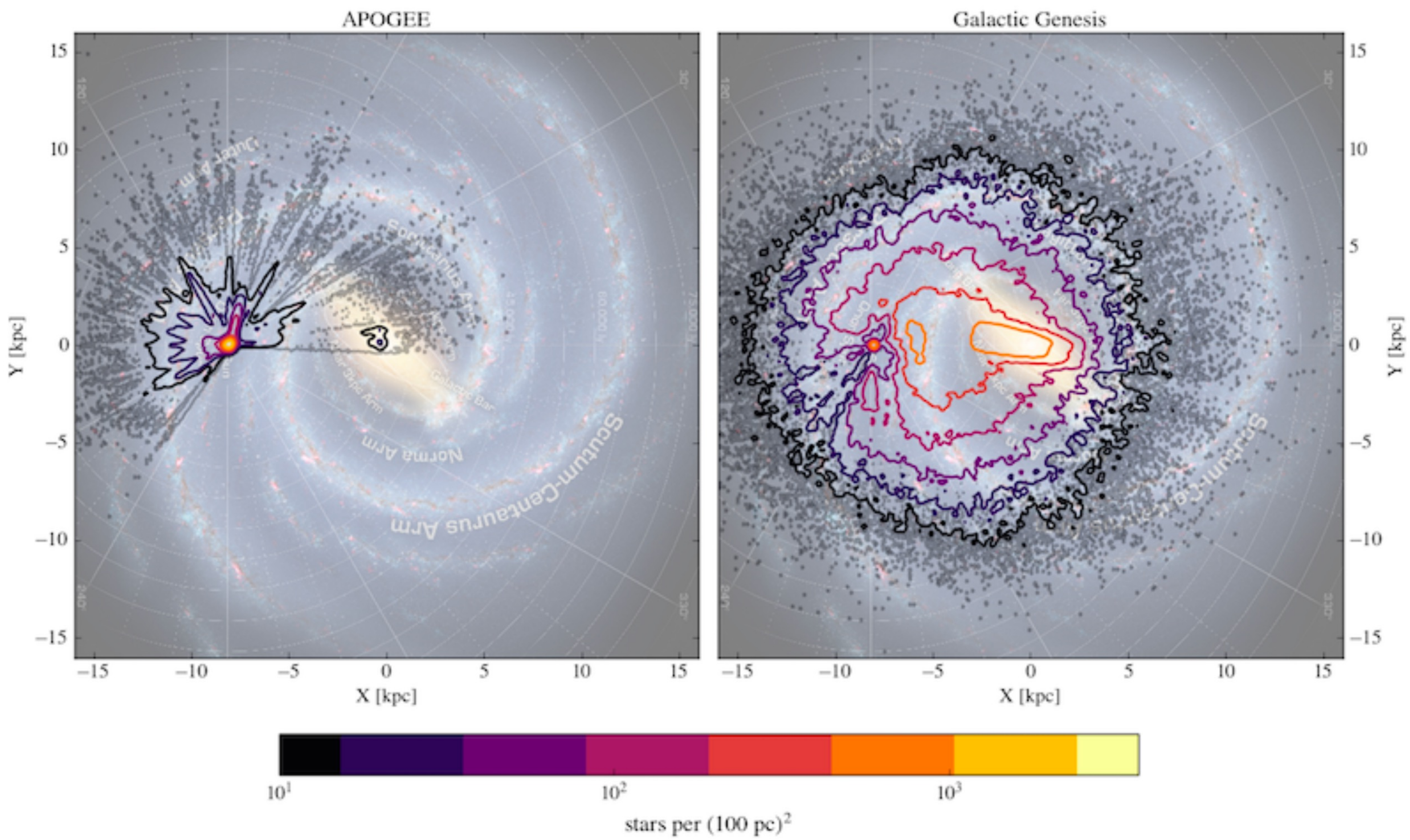


At the distance of Galactic Center
(R_G=8.3 kpc, distance modulus=14.6)
m_K(RC)=12.9 (M_K=-1.61)

As was the case for the APOGEE **local** sample of Red Clump Giants, ATLAS can do spectroscopic follow-up of all (uncrowded) red clump giant in the Galactic Bulge.



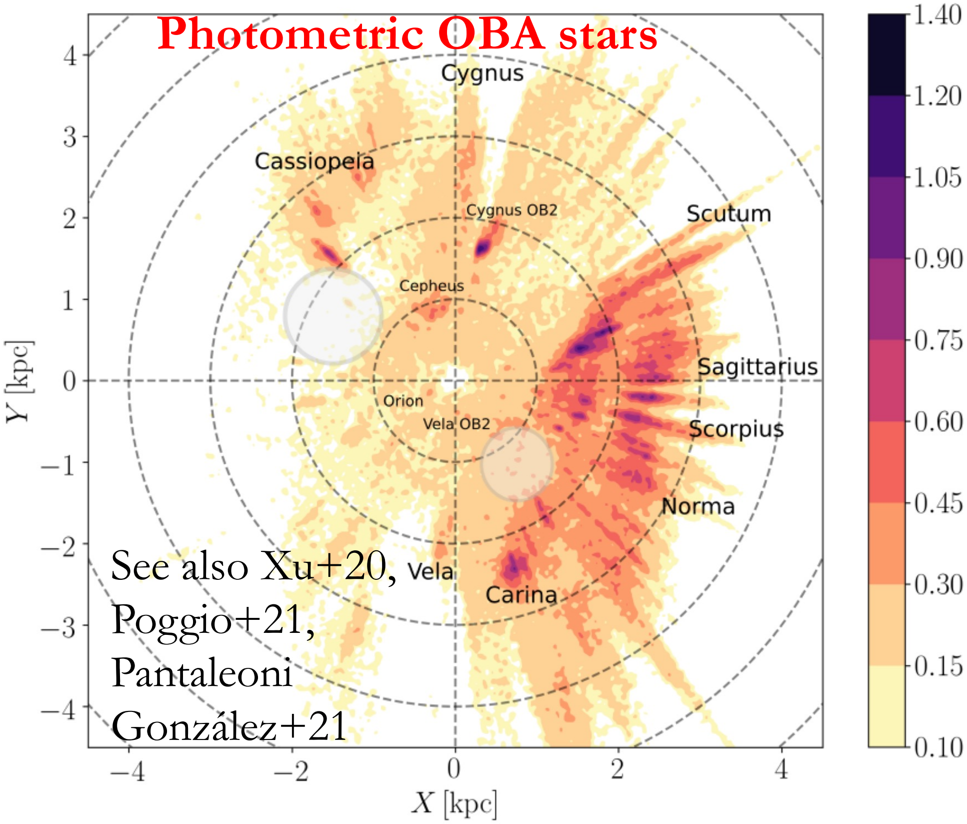
Sloan V: Milky Way Mapper Galactic Genesis Survey



This will complement the sample of bulge red giants from Sloan V.

The Search for OB stars

Eleanora Zari+21



See also Xu+20, Poggio+21, Pantaleoni González+21

Roman-Lopes +18,+19,+20

APOGEE can identify OB stars!
But the K-band is probably the most useful.

Hanson, Conti, & Rieke (1996)

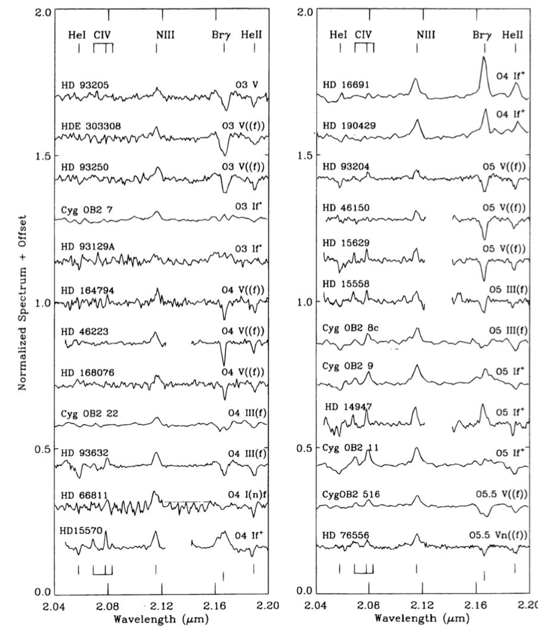
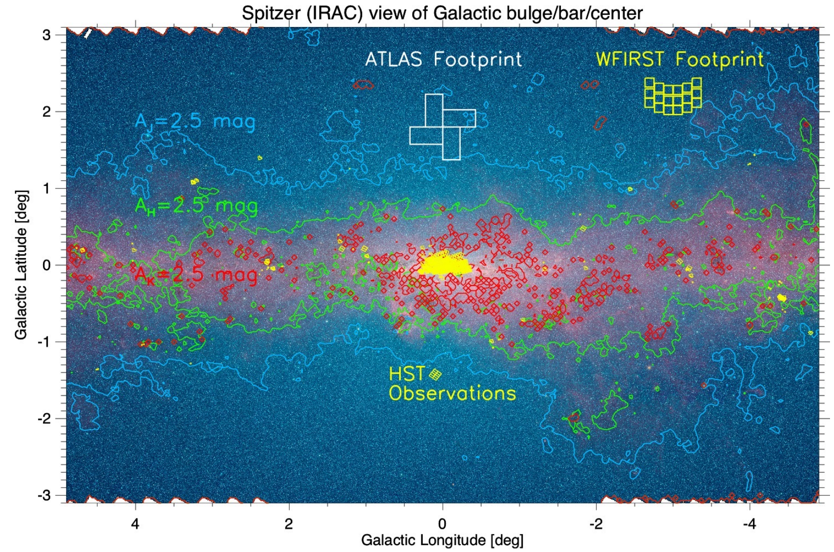


FIG. 1.—(*left*) Spectral atlas: O3 and O4 stars
FIG. 2.—(*right*) Spectral atlas: O4 and O5.5 stars

Conclusions and Questions



• Photometric surveys (past, present, and future) have provided an abundance of targets for near- and mid-IR spectroscopy. Many of these sources are bright and can be rapidly mapped.

• Roman ST and Vera Rubin Observatory will provide even more fuel. Proper motion constraints of IR sources could be paired with radial velocities from ATLAS

• Near- and mid-infrared spectra should be modelled for both stellar targets (RC and OB stars) targets and star formation targets to characterize science return (metallicity and radial velocity) vs. resolution. This is necessary for SPHEREx anyway, and will also benefit ATLAS.

• The bulge is bright(!) and lumpy. This may be a challenging environment for ATLAS to work (diffraction,scattering, and saturation) and should be explored. But high angular resolution images are already available for simulations.