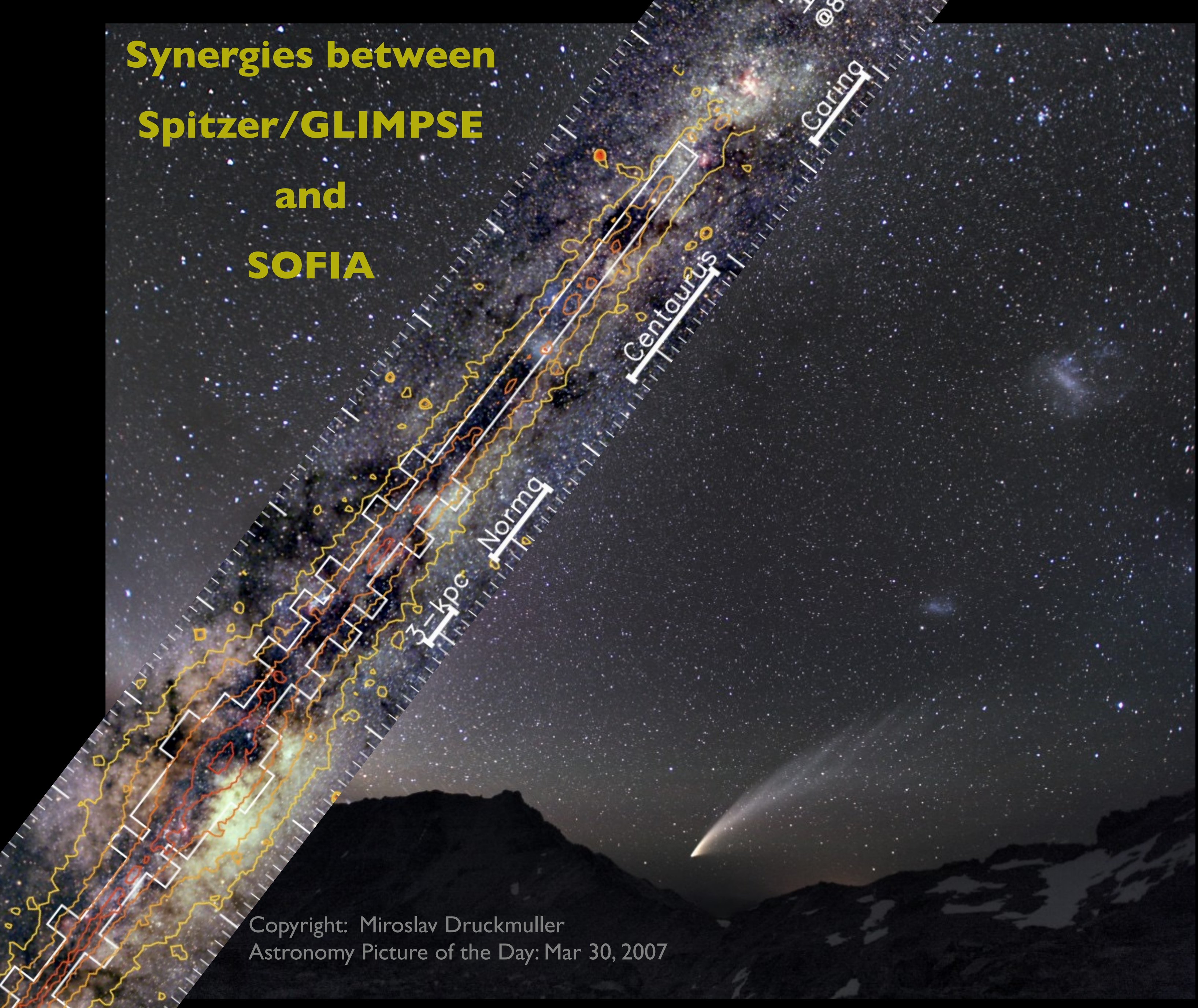
Synergies between Spitzer/GLIMPSE and SOFIA



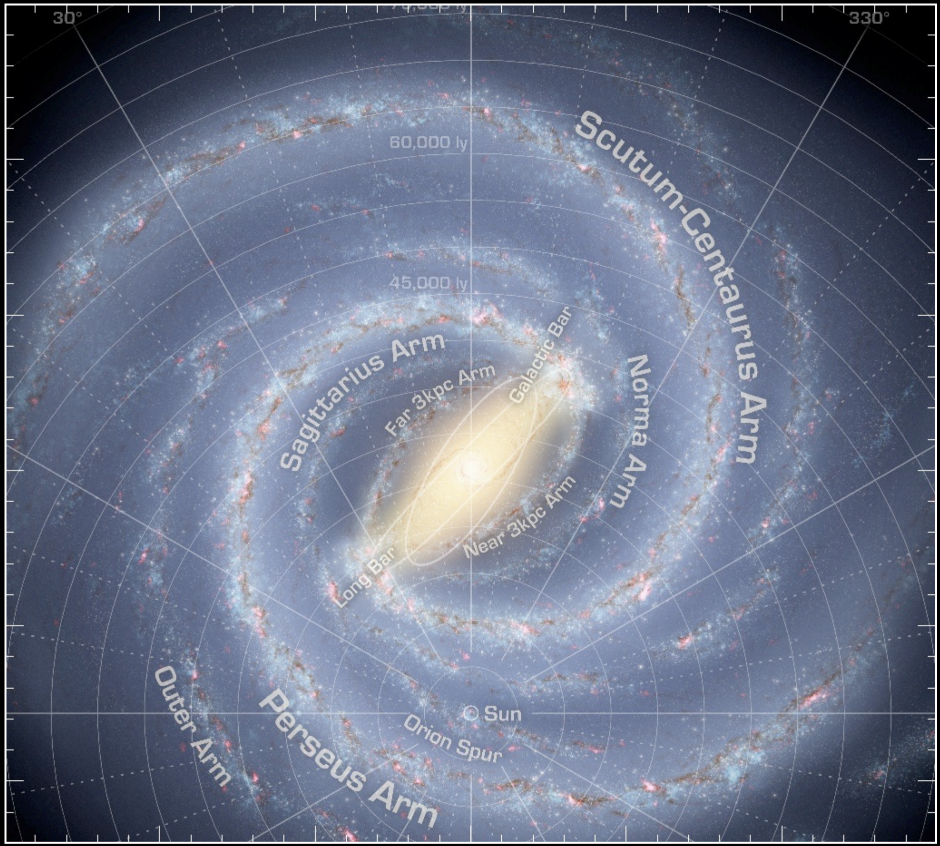
Overview of Talk

1. Advantages of the mid-infrared
2. Spitzer/GLIMPSE Legacy
3. Formation of Massive Stars in the Galaxy
4. Galactic Structure
5. A Galactic To-Do List

198 papers based on GLIMPSE data alone (57 team, 141 others)

Milky Way	
IRAC campaigns	
GLIMPSE	400 h
GLIMPSE II	144 h
GLIMPSE 3D	255 h
GALCEN	15 h
VelaCarina	119 h
Subtotal	933 h
MIPS campaigns	
MIPSGAL	417 h
MIPSGAL II	22 h
MIPSGALCEN	18 h
SMOG	149 h
Subtotal	606 h
SAGE-LMC	511 h
SAGE-SMC	285 h
SAGE-SPEC	225 h
TOTAL	2560 h
+GLIMPSE360	*1980 h*

Before:
Fig 1
Benjamin *et al* 2003, PASP, 115, 93



After:
Fig 15 (by R. Hurt)
Churchwell *et al* 2009, PASP, 121, 213

1. Mid-IR Advantages

Great sensitivity

"2-sec" exposures

High ang. resolution

2" matches optical

Low extinction

$A_{[4.5]} \sim 0.04 A_V$

Optical

BVR

WIYN 0.9m

Near IR

JHK (15 mag)

2MASS

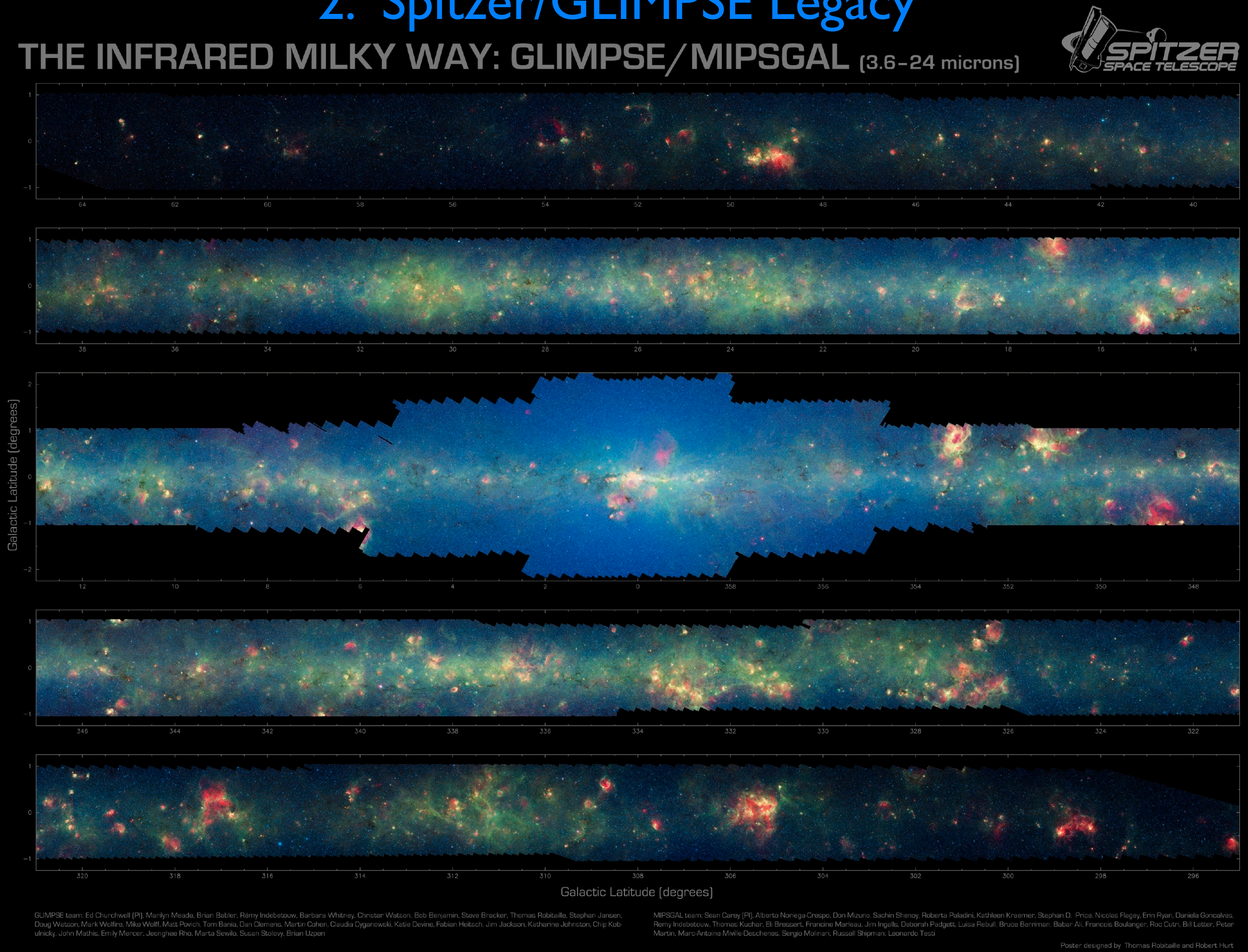
Mid-IR

[3.6],[4.5],[8.0]

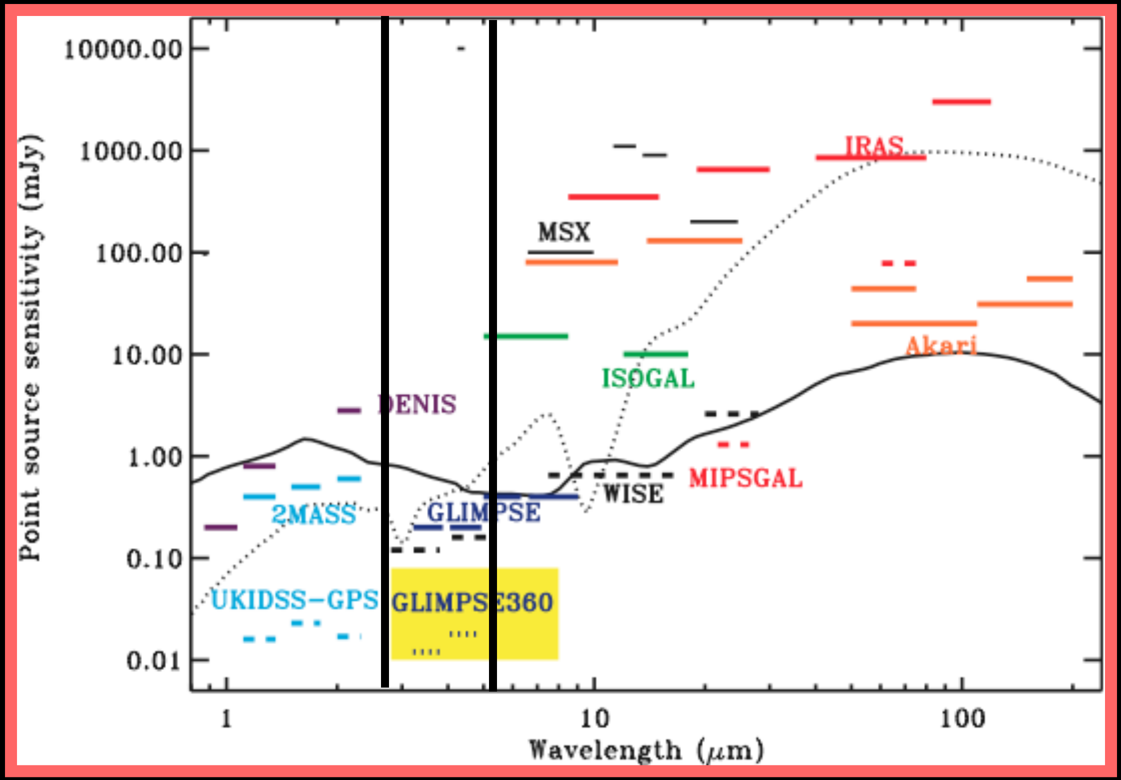
Spitzer/GLIMPSE

l=28.5
b=-0.5

2. Spitzer/GLIMPSE Legacy



Galactic Plane Surveys: A Comparison



- The 3.6-4.5 μm region is on the Rayleigh-Jeans tail for stellar blackbody curve.
- It is also the wavelength regime which minimizes the <u>combination</u> of dust extinction and diffuse dust/PAH emission.

- Warm Spitzer mission will allow for a significant fraction of the Galactic plane to be mapped down to 18.4/17.5 magnitude in [3.6]/[4.5] bands.

  This is well matched to the new generation near IR surveys: UKIDSS, Subaru, IAC…

- WISE has sensitivity close to GLIMPSE, but a 6” FWHM PSF at 3.3μm and 4.7μm.

  This give Spitzer a substantial advantage in source confused regions.

2. Spitzer/GLIMPSE Legacy

Data Products: www.astro.wisc.edu/glimpse/glimpsedata.html

Point Source Catalog: 99.5% reliable, $m_{[3.6],[4.5]}$=6.5-14, $m_{[5.8],[8.0]}$=4-10.5

Point Source Archive: Basically down to 5 σ in each band.

Mosaicked Images: ~1°x1°, pixel size=0.”6, 4 bands in MJy/sr
~2.5°x2.5° , pixel size=1.”2

“Missing” data products:

Extended source catalog, dark cloud catalog, point-source subtracted (residual) images.

Publications: www.astro.wisc.edu/glimpse/glimpsepubs.html

198 papers, as of Jan 13, 2010

Google-map style access to images (with coords):
www.alienearths.org/glimpse

3. Formation of Massive Stars in the Galaxy

GLIMPSE/MIPSGAL have greatly increased the number of rare objects, like distant open clusters and Wolf-Rayet stars.

However, their biggest impact has been in creating new classes of sources associated with high mass star formation.

	Before	After	
Point sources	61,321 (MSX)	104,472,450	
HII regions	1174	?	
Open clusters	76	168	Mercer et al. (2005)
PN	65	83	Phillips & Ramos-Larios (2007)
SNR	100	100	Reach et al (2006)
O/B stars	98	?	
WR stars	50	97	Mauerhan et al (2009)+priv comm.
Glob. Clusters	1	3	Kobulnicky et al (2005)
AGB candidates	?	7,000	Robitaille et al (2008)
PAH Bubbles	—	600	Churchwell et al (2006,2007)
HM* Outflows	?	~300	Cyganowski et al (2008)
YSOs candidates	715	11,000	Robitaille et al (2008)
IRDC	~5000	~11,000	Fuller et al, in prep

Background:
Vulpecula OB association (Billot)

3. Massive Star Formation: IRDCs

- Seen in silhouette against diffuse 8 μm background. None found at far kinematic distance.
- Very filamentary > 10:1
- Dense (> 10^5 cm^{-3}) and cold (< 20 K)
- Highest deuteration in the ISM NH_2D/NH_3 =0.1-0.7 (Pillai et al 2007)
- Embedded star formation found along clouds.
- Upcoming catalog/website doubles the number of clouds in GLIMPSE area, but has different selection criterion.
- Characterization still in progress.

Infrared Dark Cloud Catalogs

MSX: Simon et al 2006, ApJ, 678, 1325

GLIMPSE: Fuller et al 2009, in prep

GLIMPSE/MIPSGAL image of IRDC G11.11-0.11

3. Massive Star Formation: YSOs

- 20,000 "red" sources
  [4.5]-[8.0] > 1
  found using GLIMPSE/MIPSGAL
- About 40% AGBs (uniformly distributed), 60% YSOs (clumped)
- Many YSOs lie outside the "traditional" cores of massive star formation regions.

See Poster 4.5 (Hora et al) for 14,000 YSOs candidates in Cyg X!

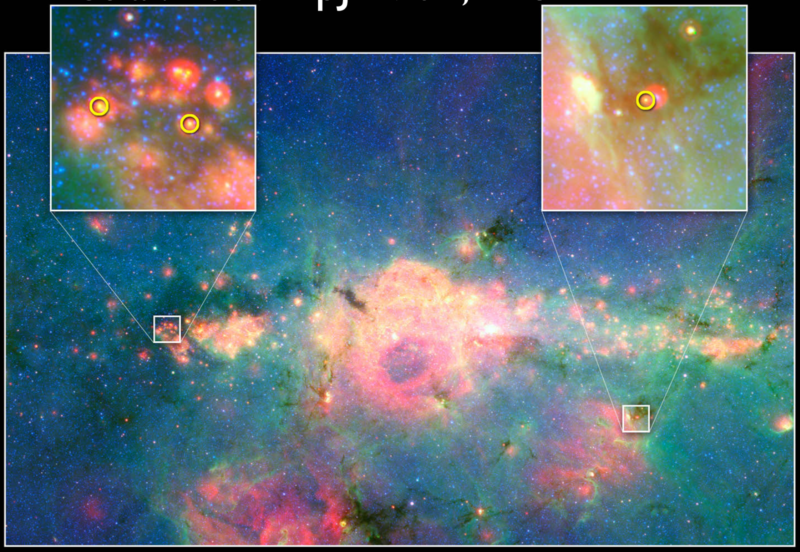
Catalog: Robitaille et al 2008 AJ 136, 2413

Models: Whitney et al 2003 ApJ 591, 1049
Whitney et al 2003 ApJ 598, 1079
Indebetouw et al 2006 ApJ 636, 3621

SED fitting: Robitaille et al 2006, ApJS 167, 256
Robtaille et al 2007, ApJ, 169, 328

www.astro.wisc.edu/protostars

YSOs near Galactic Center:
An et al. 2009 ApJL 702, 128



Young Stars Forming in the Galactic Center   Spitzer Space Telescope • IRAC • MIPS • IRS
NASA / JPL-Caltech / S. V. Ramírez (NExScI/Caltech)   ssc2009-13a

These surveys allows us to find all sources destined to become O and B stars and redetermine the global star formation rate. It has become easier to find embedded O stars than bare ones!

3. Massive Star Formation: EGOs

EGOs (Extended Green Objects):

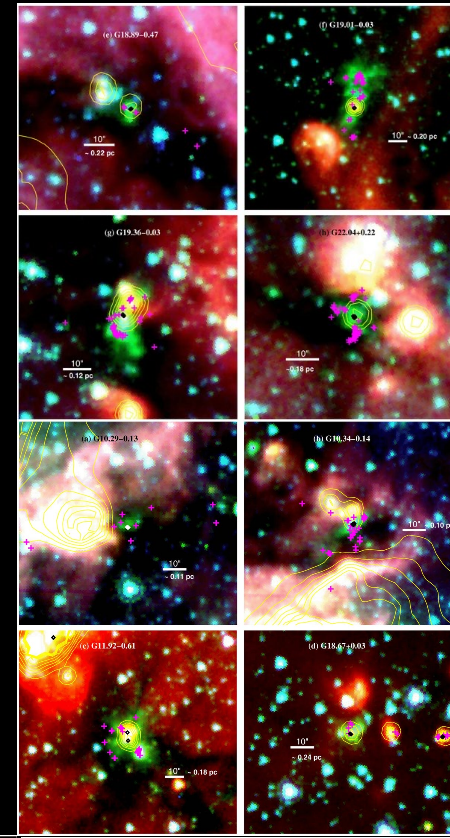
Extended objects bright in [4.5] band

Emission due to shocked H_2 (v=0 – 0) S(9,10,11) lines and/or CO(v=1 –0) bandheads.

Presumably bipolar outflow from central massive protostar shocking into ISM.

Commonly found in infrared dark clouds.

Early stage of star formation where infalling envelope is too opaque or cool to excite PAH emission?

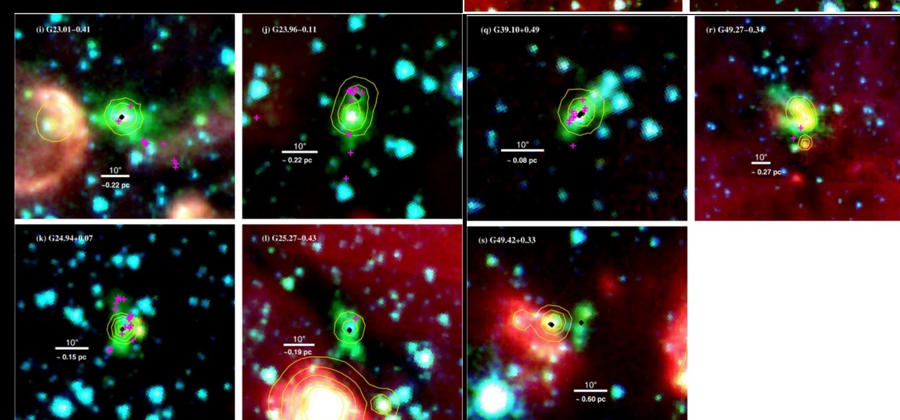


300 examples (not a complete catalog)

Cyganowski et al 2008, AJ 136, 2391

Methanol masers=EGOs?

Cyganowski et al 2009, ApJ in press



3. Massive Star Formation: Bubbles

8 μm Bubbles: Most luminous coincide with radio HII regions. Probably produced by O and B stars at ages of 1 Myr, but stellar content still being analyzed. 90% smaller than 4'. 38% have broken morphology. Eccentric with peak at e~0.65

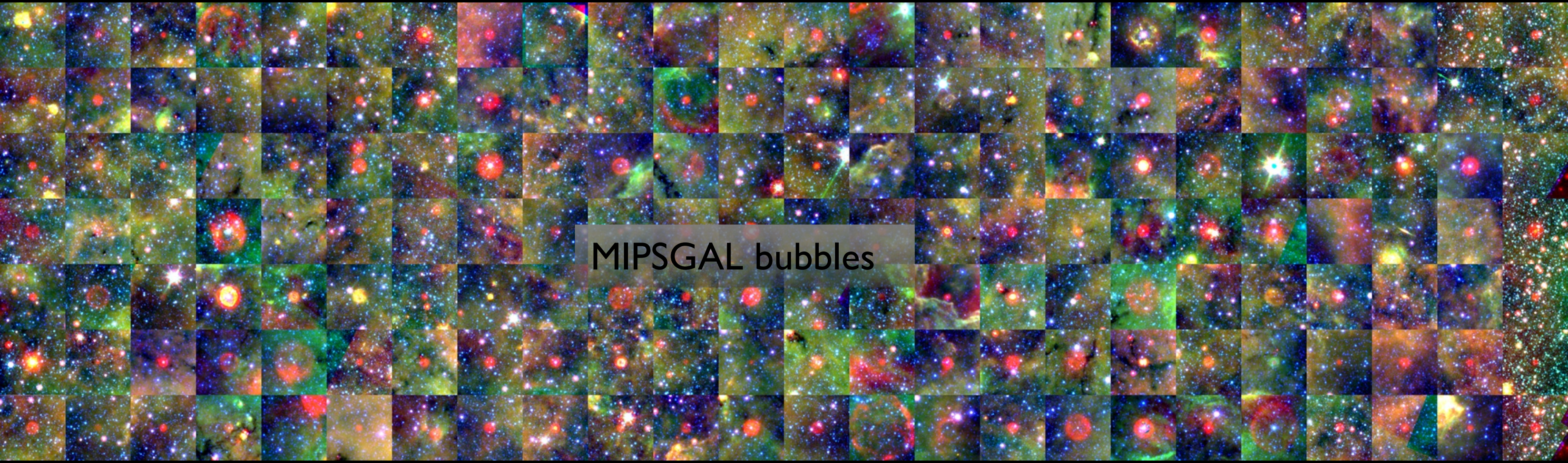
24 μm Bubbles: 226 disks, 112 rings, 54 with central 24 mm source, 24 two-lobed

Only 10% have 8μm counterpart!

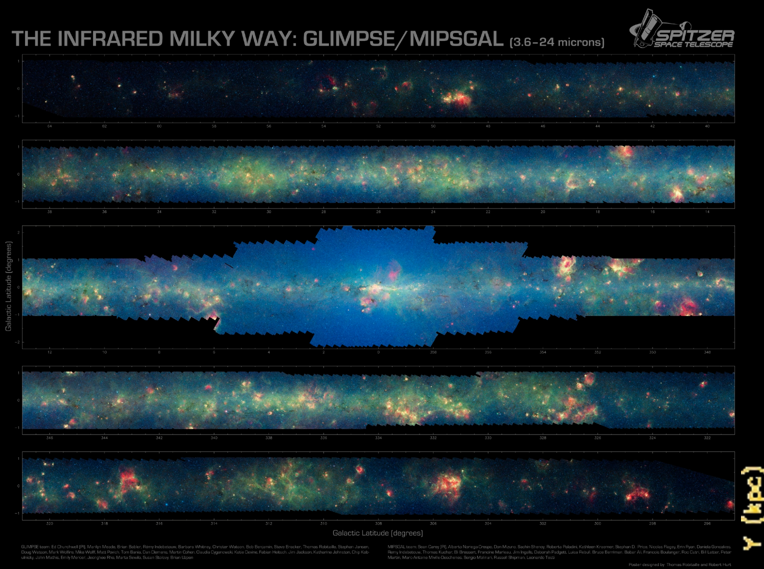
8 μm Bubble Catalog (600):
- Churchwell et al 2006 ApJ 649, 759
- Churchwell et al 2007 ApJ, 670, 428

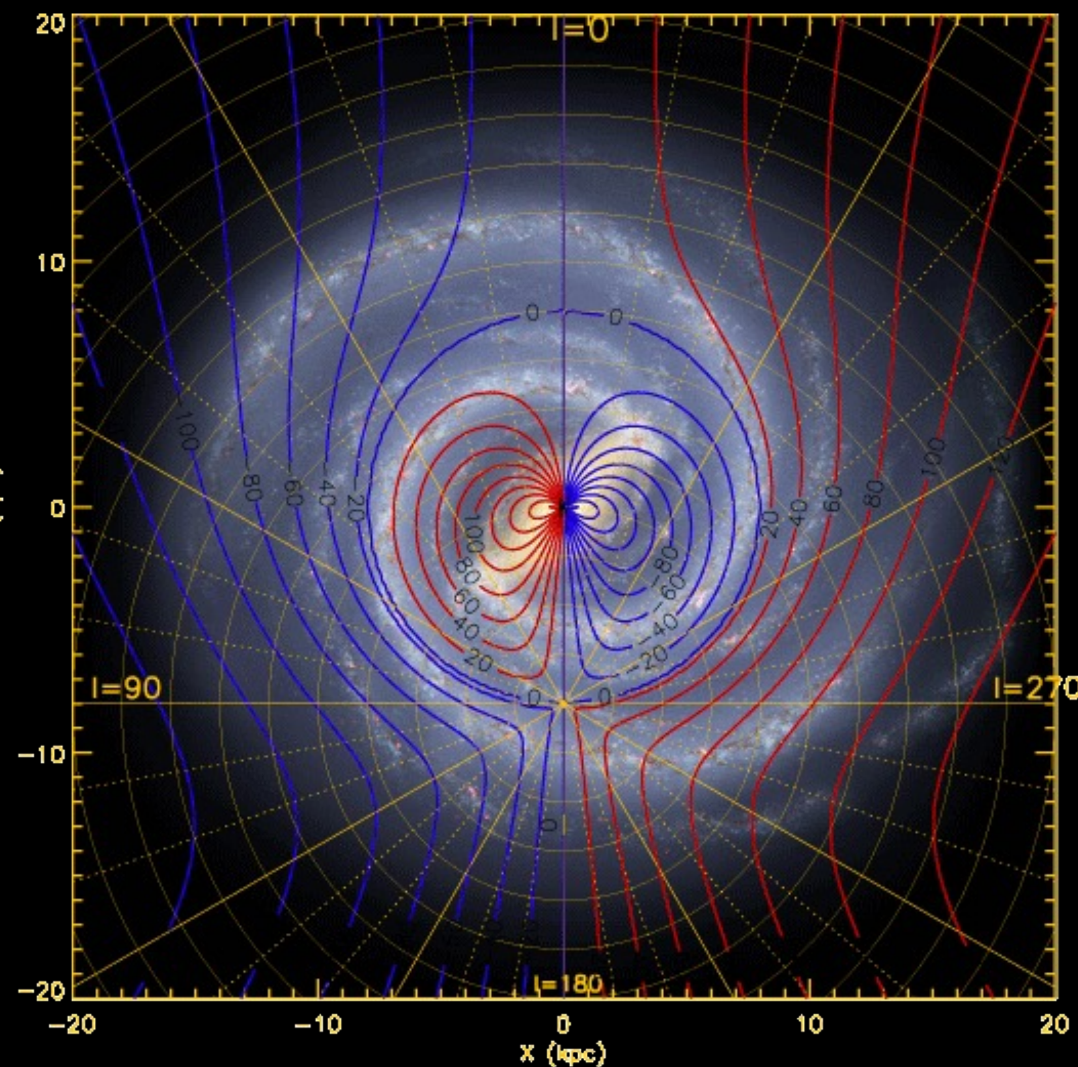
Bubble Follow-up/Models:
- Watson et al 2008 ApJ, 681, 1341
- Watson et al 2009 ApJ, 694, 546
- Everett et al 2009, in prep

24 μm Bubble Catalog (400):
- Carey et al 2009, in prep



4. Galactic Structure: Turning a Poster into a Map

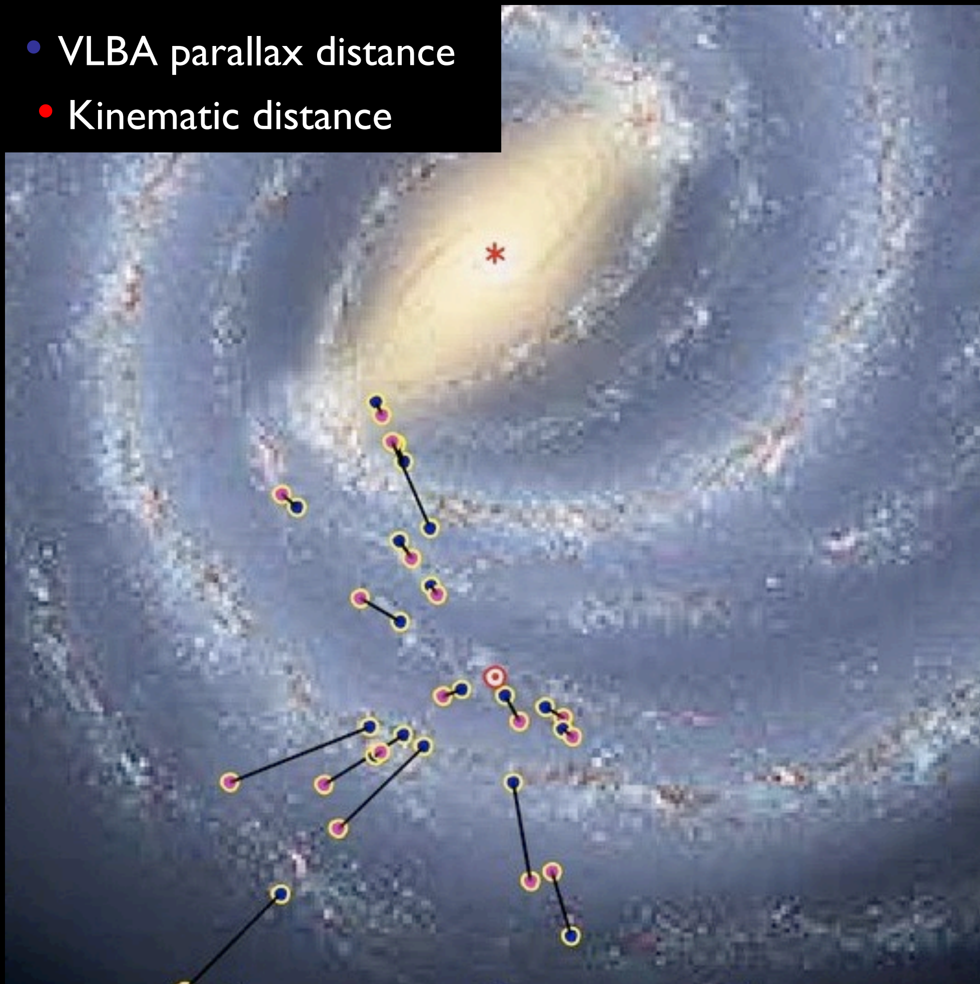




Luminosities, sizes, energetics, relation to Galactic structure of star formation regions all depend on **distance.**

We need to get radial velocities of all these objects and use kinematic distances.

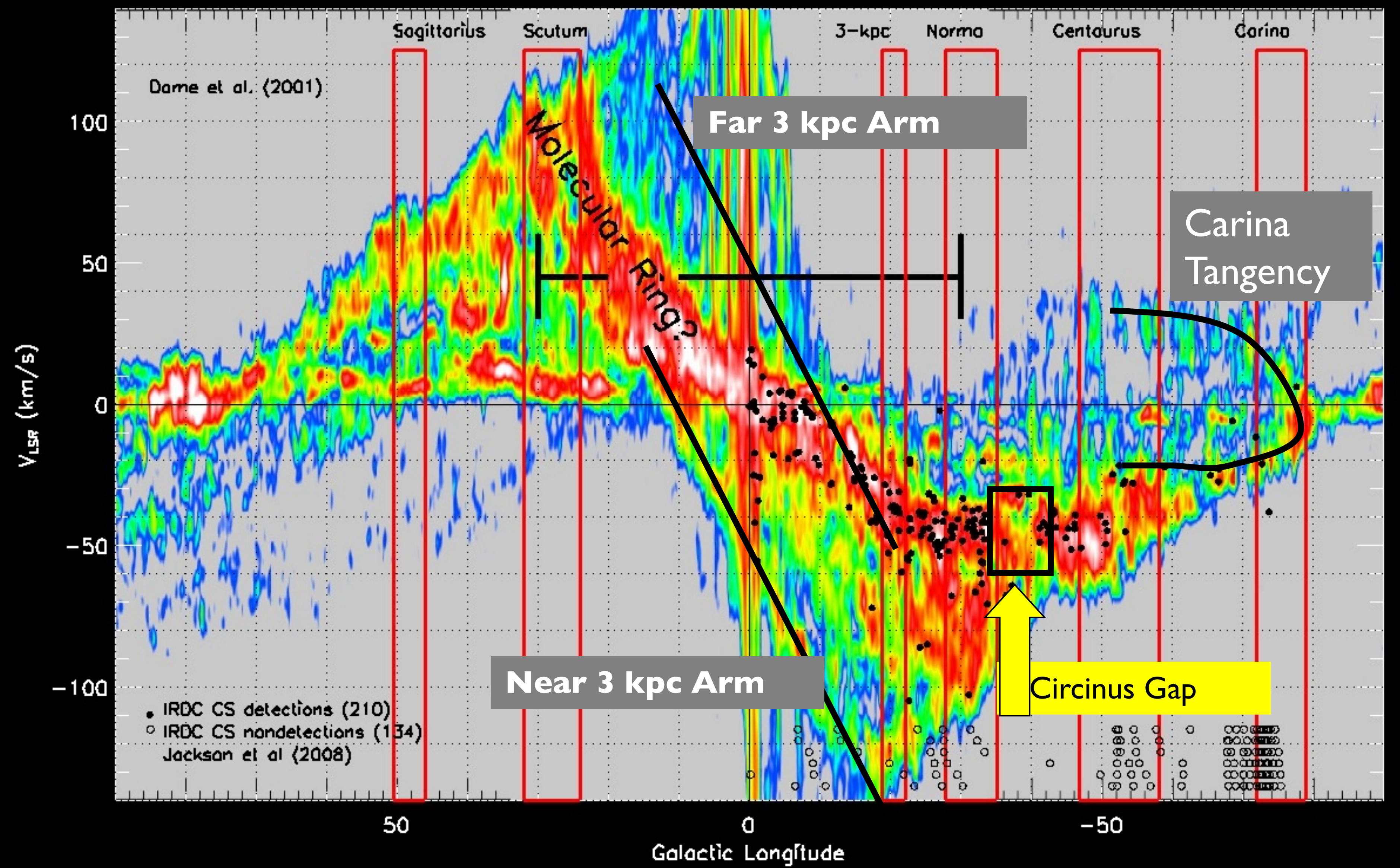
4. Galactic Structure



Problems with Kinematic Distances

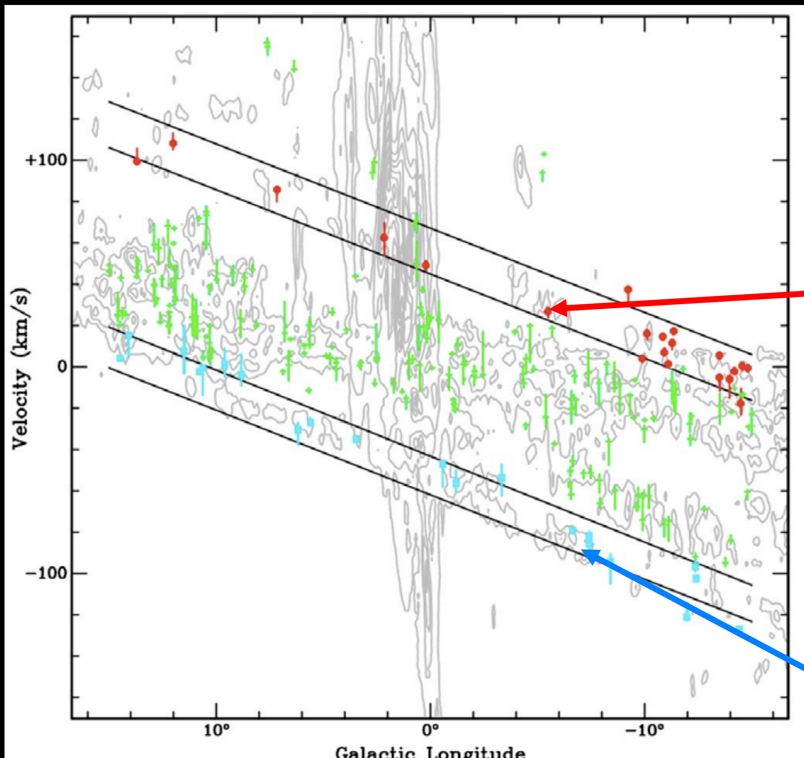
- Many objects smaller than resolution of available CO-HI-RRL surveys. Needs dedicated follow-up.
- Kinematic distances are double valued in inner galaxy.
- Random velocity and uncertainties in rotation curves fits produce longitude-dependence spread in distances.
- Deviation from circular flows due to bar/spiral arms, which are the very features you want to map!

VLBA/VERA parallax distances to masers in SFR could lead to models for kinematic distance "correction" (Reid et al 2008, ApJ 700, 137)



The plot for interpreting Galactic structure: Dame et al (2001)

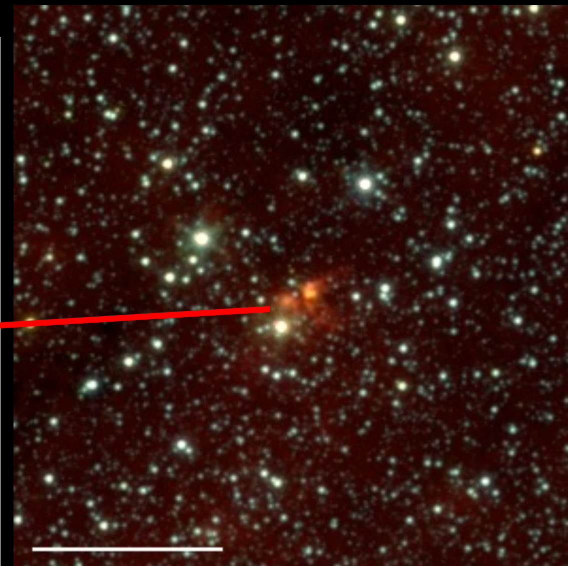
Star Formation: Near and Far 3 kpc "Arms"



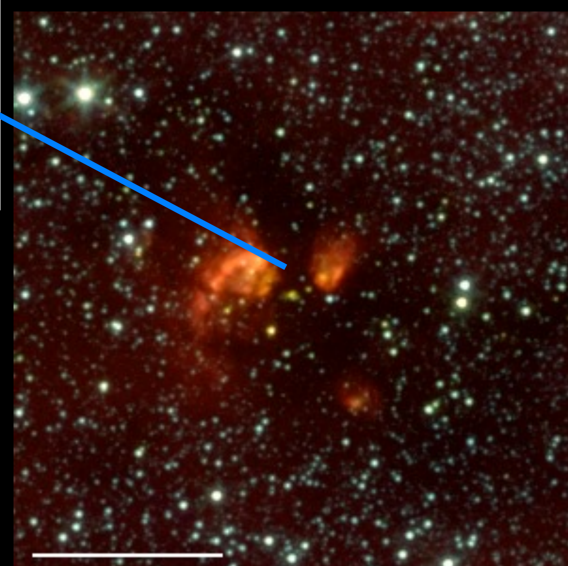
l-v diagram of masers in near 3 kpc arm (blue) and far 3 kpc arm (red)
Green et al (2009)

GLIMPSE images of Class II methanol masers

(6' x 6')



Far 3 kpc arm



Near 3 kpc arm

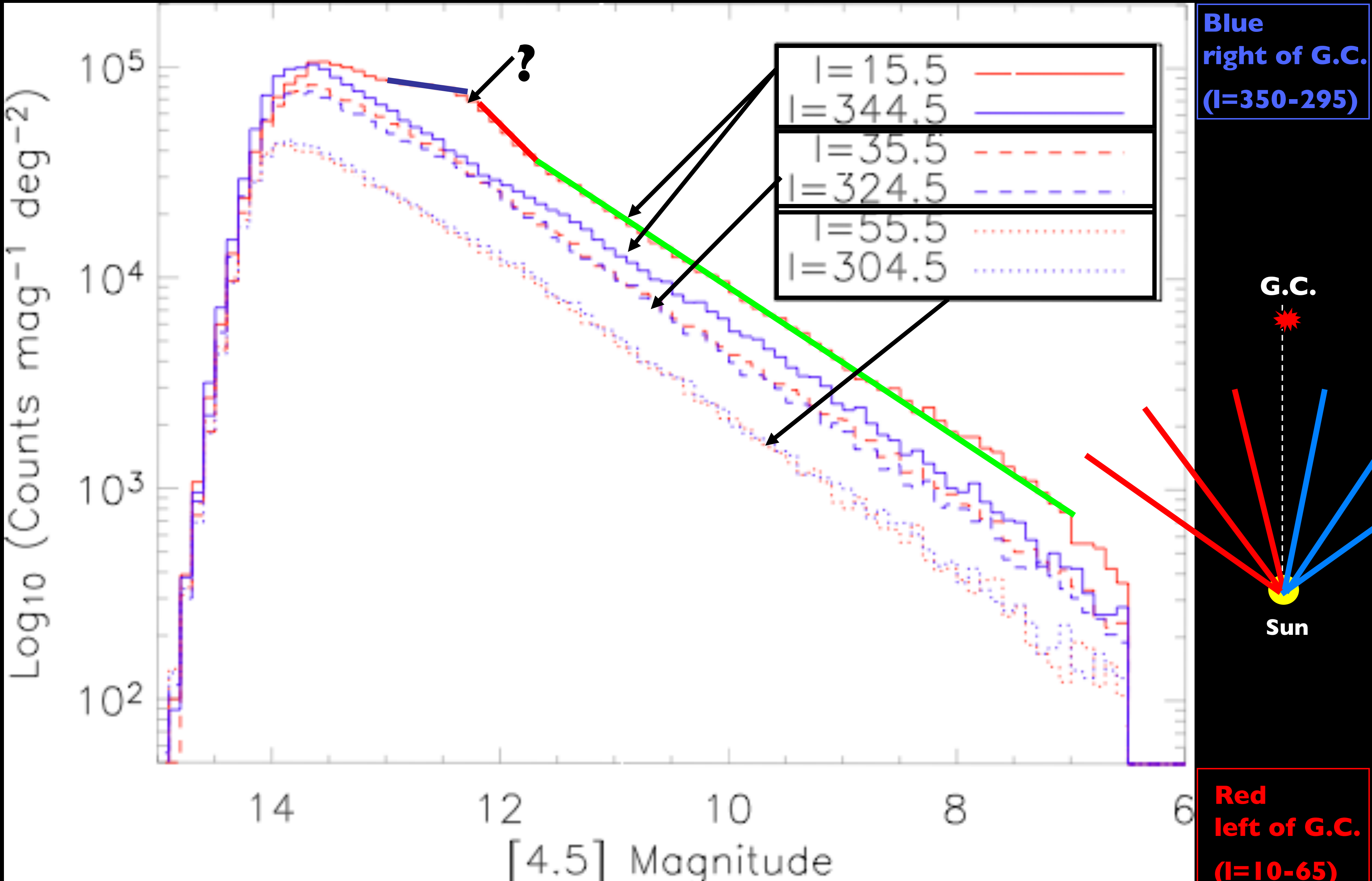
4. Galactic Structure: Mapping with Red Clump Giants

- Common 0.5 - 2.0 $M_{\odot}$ stars
- Long lived -10% of MS lifetime
- Tight luminosity function- L determined by He core mass at ignition
- Absolute calibration– A few dozen RC giants have Hipparcos parallaxes.

- Some concerns over age and metallicity effects (up to 0.3 mag), but these affect <u>absolute</u> calibration, not <u>relative</u> calibration.

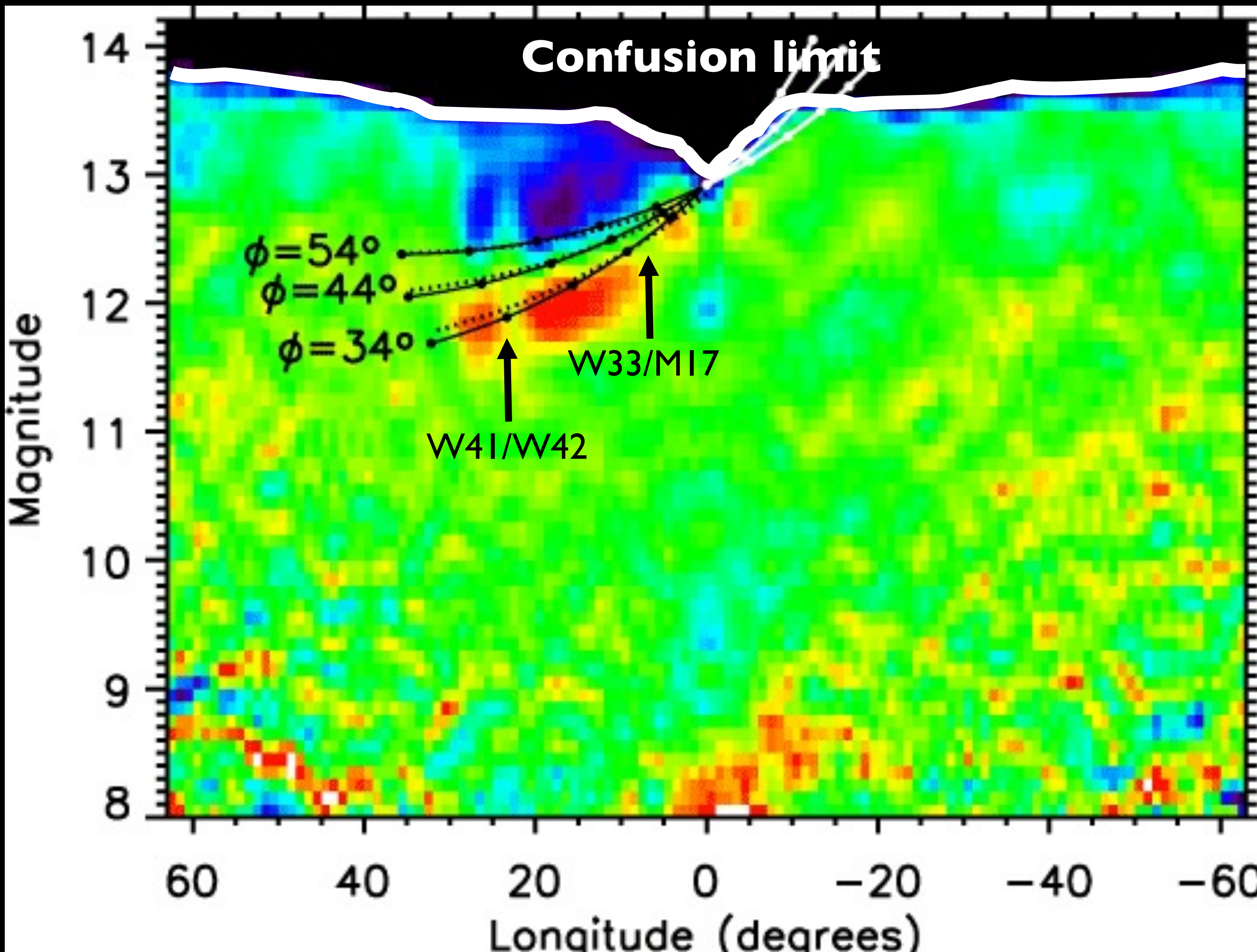
M_K=-1.62±0.03 mag
See Cabrera-Lavers (2007)

$\Delta m_{stat}=0.03 \rightarrow$ **Δd/d=1.3%**

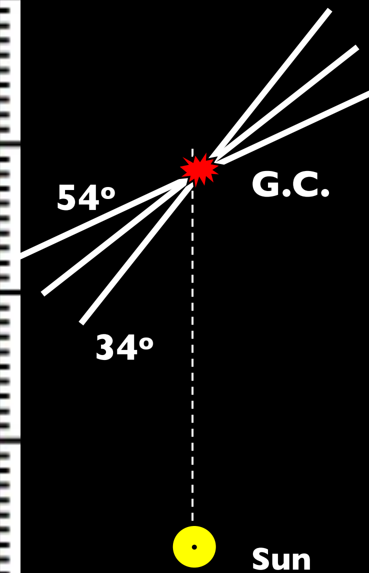


Fits of data to $n=n_o(S/S_o)^{-\alpha}$ yield **α_{avg}=1.83-1.95**

4. Galactic Structure: Red Clump Mapping of Long Bar

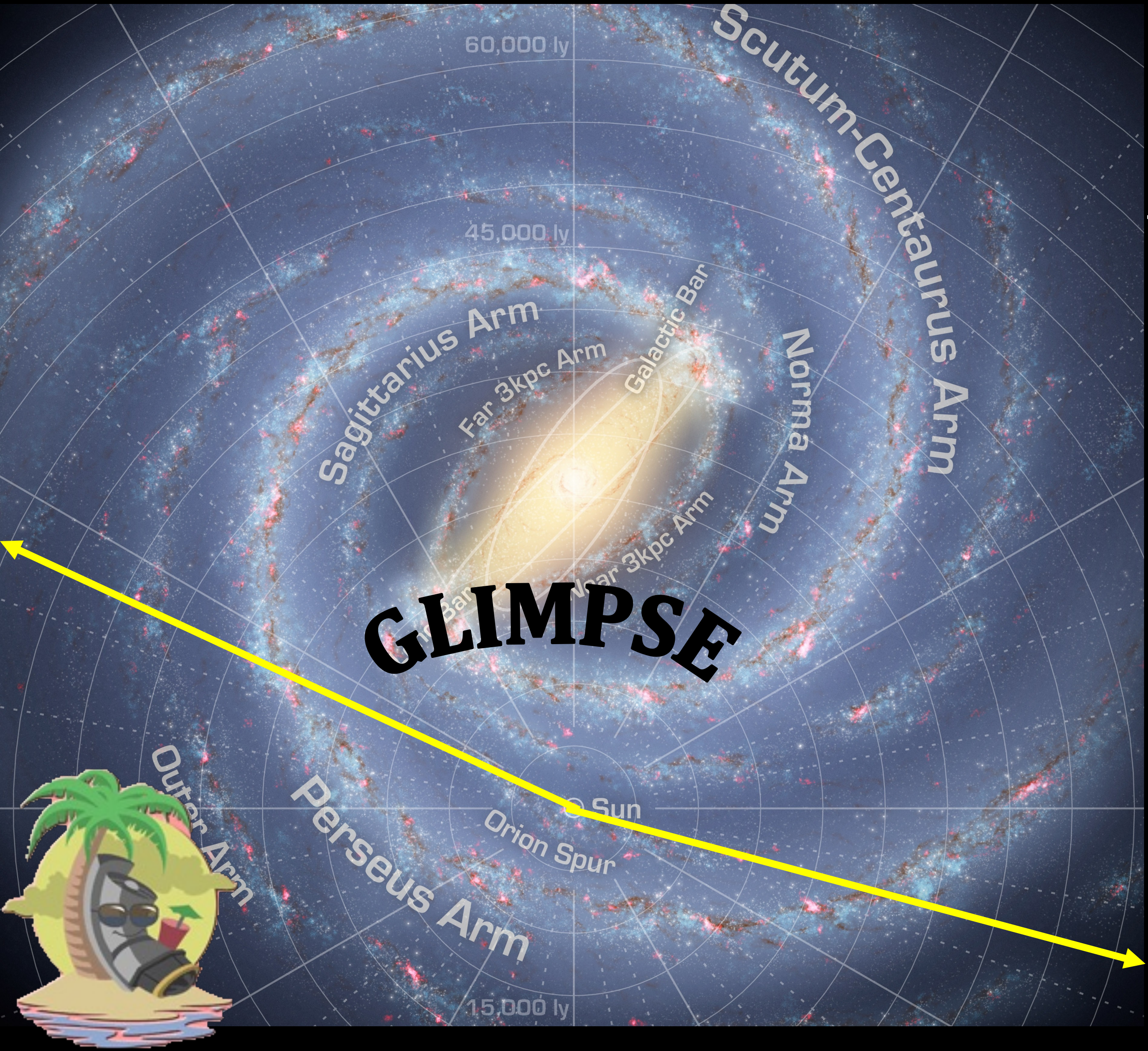


Benjamin et al (2005)



R_{bar}=4.4±0.5 kpc
ϕ =44±10°

5. A Galactic To-Do List: Warm Spitzer Mission



GLIMPSE 360
PI: Barb Whitney

Mapping the stellar and star formation content of the outer galaxy

Deeper than GLIMPSE (~ 18 vs. 13.5 mag)

GOALS:

Warp
Flare
Perseus Arm
  (red clump mapping?)
Outer/Distant Arm
Disk truncation?
Change in disk scalelength?

5. A Galactic To-Do List: Things Not Yet Done

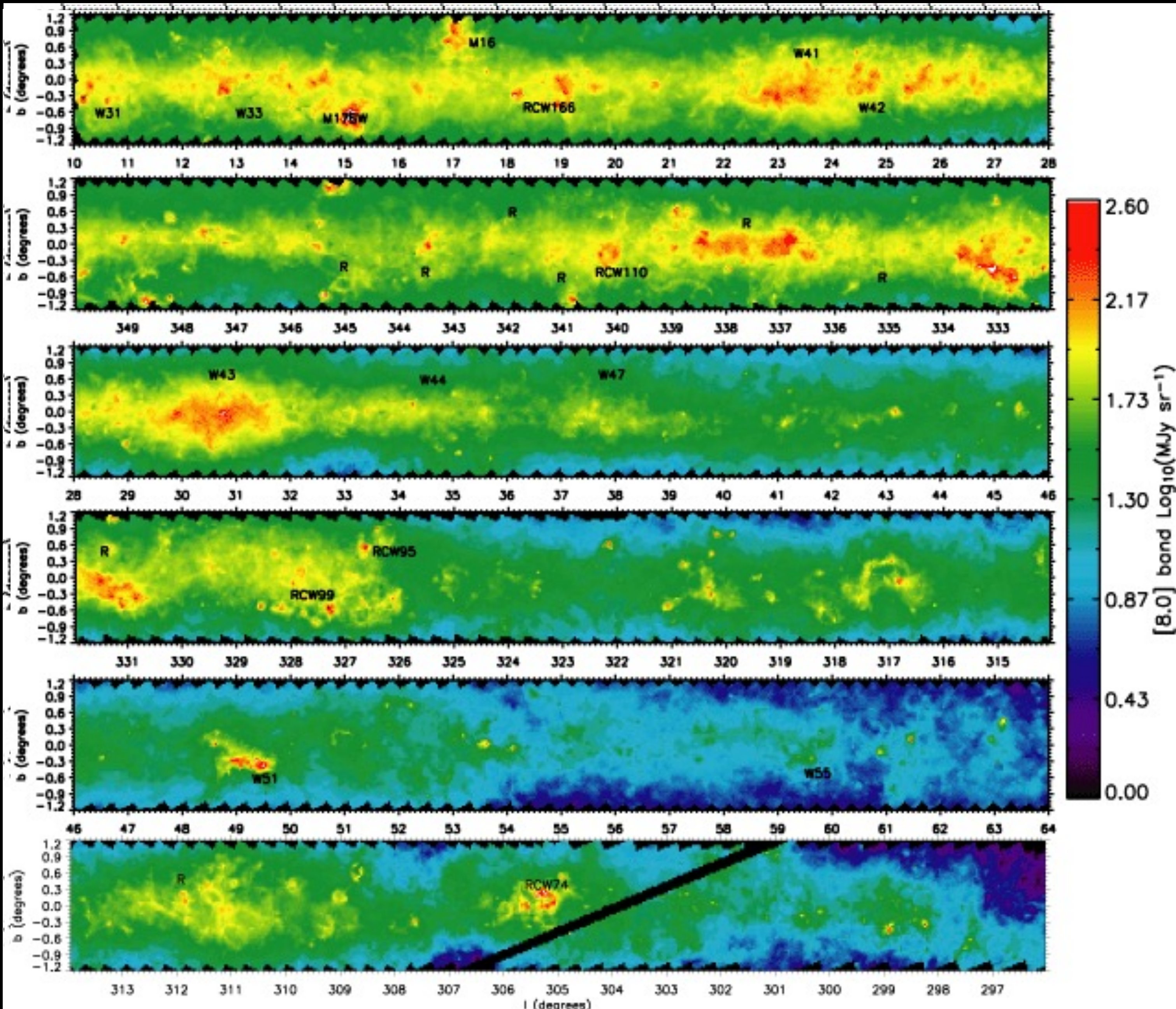
A GLIMPSE HII region Catalog— Many of the smaller (more distant?) star formation regions remain to be cataloged (and lack velocities).

Systematic search for O stars—Every O star that I've noticed is associated with a bubble or smudge of diffuse 24 μm emission and sometimes bowshocks (see poster 4.7, Iping et al) Interstellar emission is needed to find O stars, since mid IR colors of the O stars are indistinguishable from other stars.

Galactic Variation of Diffuse PAH emission—How does the PAH emission ratios vary with longitude and environment? GLIMPSE residual images can help. Also, see AKARI posters 4.3 (Doi et al) and 4.9 (Sakon et al)

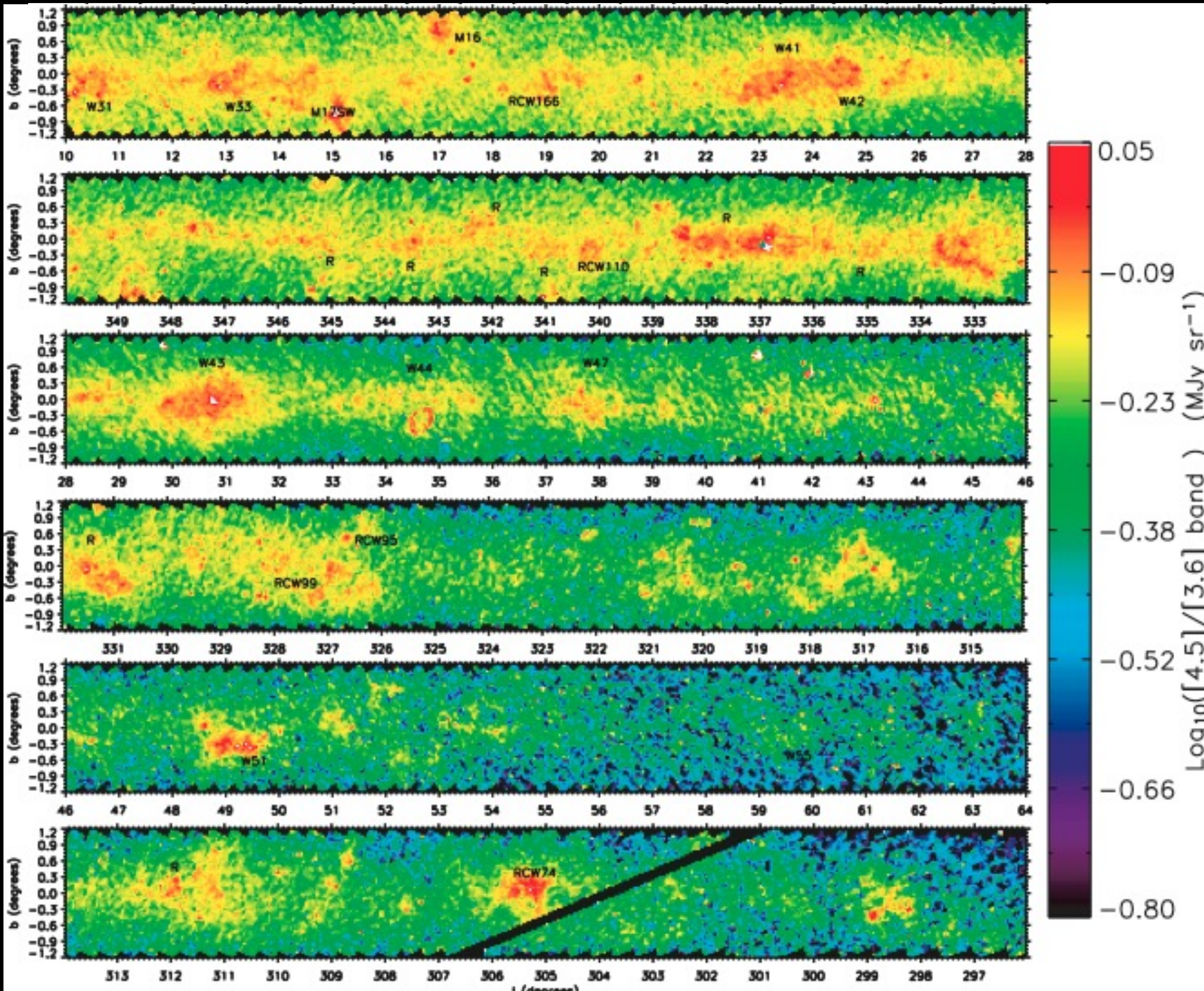
Star Formation in Different Spiral Arms—Do bubbles, clusters, triggered star formation, etc. change from arm to arm? Despite the fact that the (Near) Three Kiloparsec arm was discovered in 1957, we didn't even know it **had** star formation until *this year* (Dame & Thaddeus 2008; Green et al 2009).

Testing MW bi-symmetry— Star formation at the far end of the Long Bar? Finding the start of the Perseus arm? Comparison of Near/Far 3 kpc arm?



Diffuse emission maps

Prelim.



Diffuse emission ratio maps

Prelim.

Summary

• The combination of transparency, sensitivity, and resolution have made *Spitzer* a vital tool in laying bare the structure and workings of the Milky Way, LMC and SMC. One hundred and sixty papers have been published so far using GLIMPSE data alone. Hopefully, GLIMPSE 360 will have yet more surprises!

Star formation: "Buried" high mass star formation is now detected throughout the Galaxy. Hundreds to thousands of new examples of different evolutionary stages are being cataloged, including infrared dark clouds (IRDCs), young stellar objects (YSOs), massive star outflow sources (EGOs), and stellar wind formed PAH bubbles. Dozens of examples of apparent triggered star formation can be found.

Galactic structure: The MW is looking more and more like a typical barred spiral galaxy. It has a Long Bar that appears misaligned with the triaxial bulge by about 20°. Inner Galaxy spiral arms seem to come in matched pairs (Near/Far 3kpc, Scutum-Centaurus/Perseus, Norma/Sagittarius). Gas flows in the inner Galaxy and the Central Molecular Zone (not discussed here) are also typical of barred spirals. *One unresolved question*: Is it a ringed, barred spiral?

For fun public access to GLIMPSE images—http://www.alienearths.org/glimpse