
The Spitzer Space Telescope's New View of the Milky Way...
...And Its Neighbors
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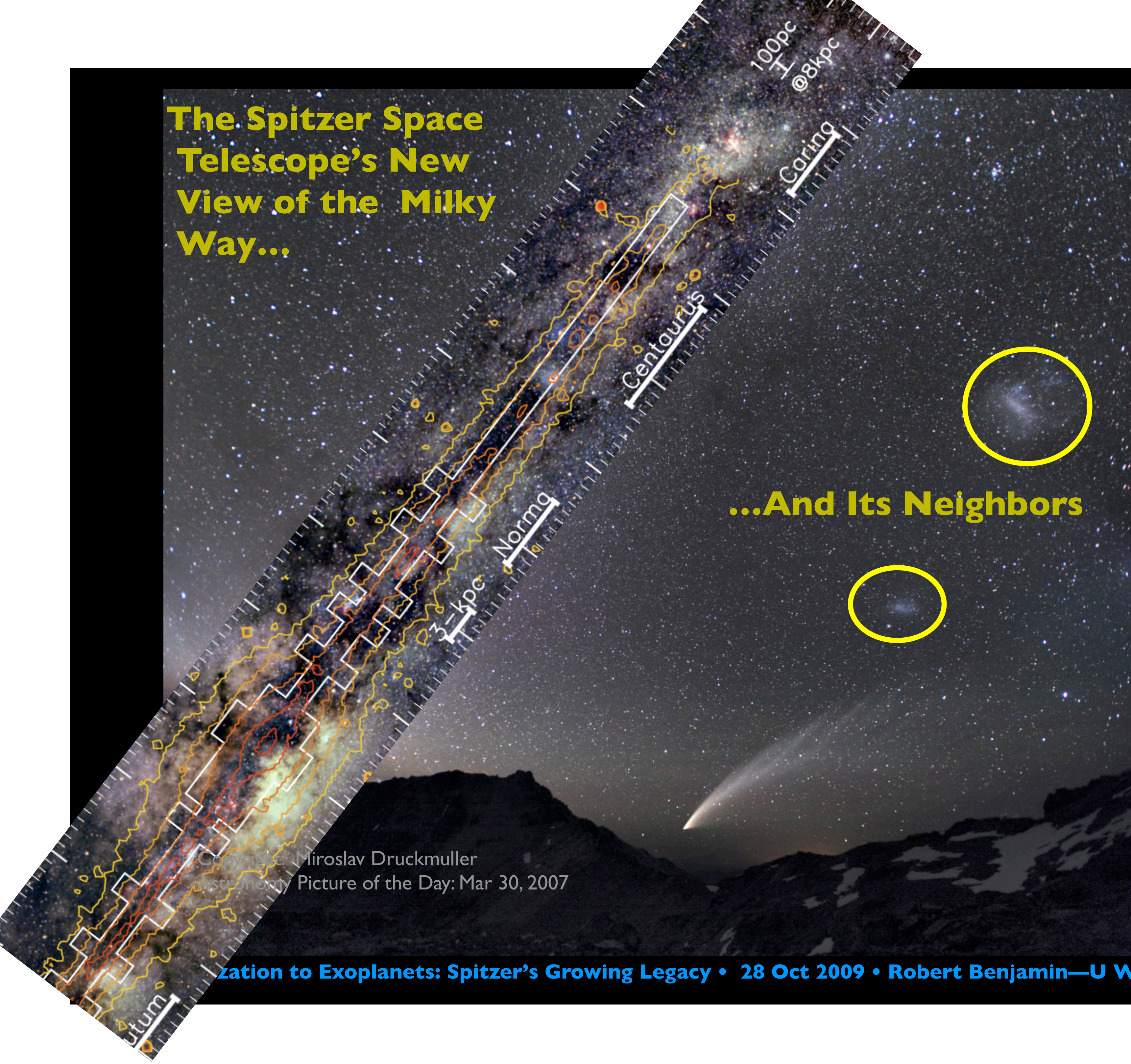
Astronomy Picture of the Day: Mar 30, 2007


The Spitzer Space Telescope's New View of the Milky Way...
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100pc
@8kpc
Carina
Centaurus
Norma
3-kpc
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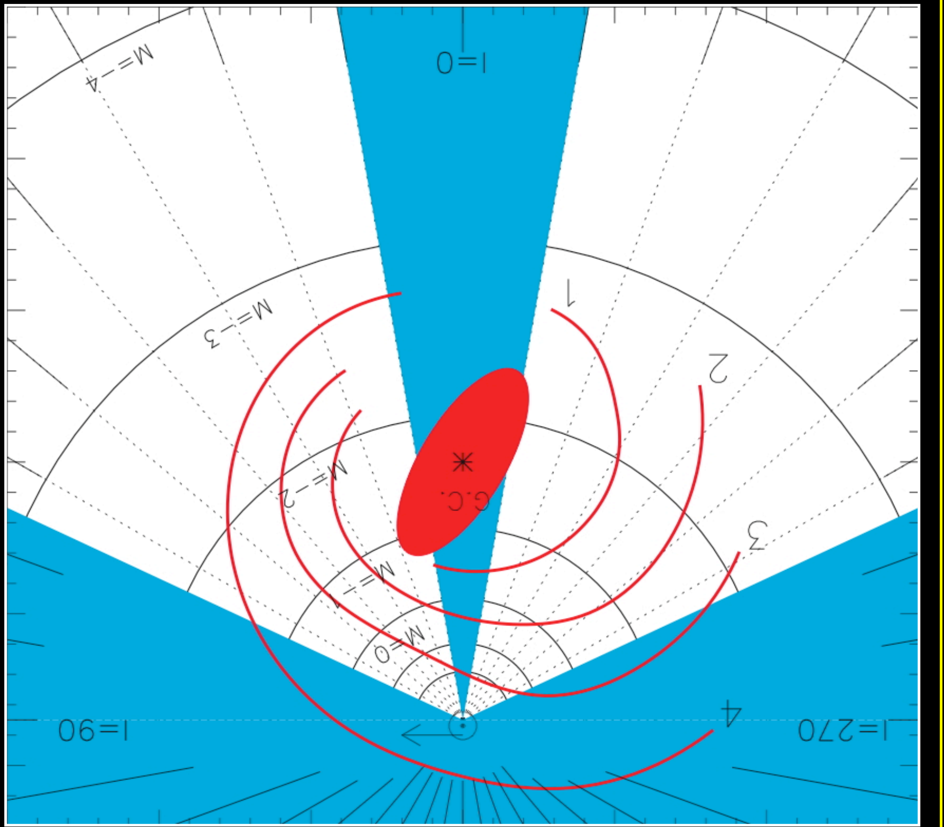
Overview of Talk

1. Advantages of Spitzer Space Telescope
2. SAGE-LMC highlights
3. Formation of Massive Stars in the Galaxy
4. Galactic Structure
5. A Galactic To-Do List

160 papers based on GLIMPSE data alone (51 team, 109 others)

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



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

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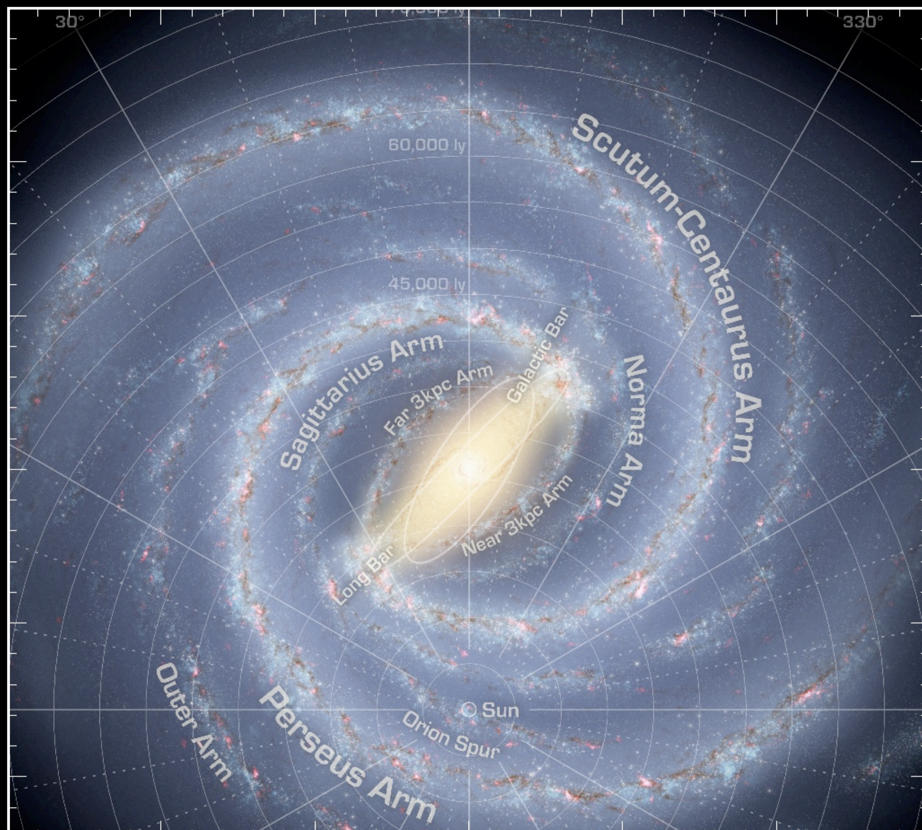


After:
Fig 15 (by R. Hurt)
Churchwell *et al* 2009, PASP, 121, 213

I. Spitzer ST Advantages

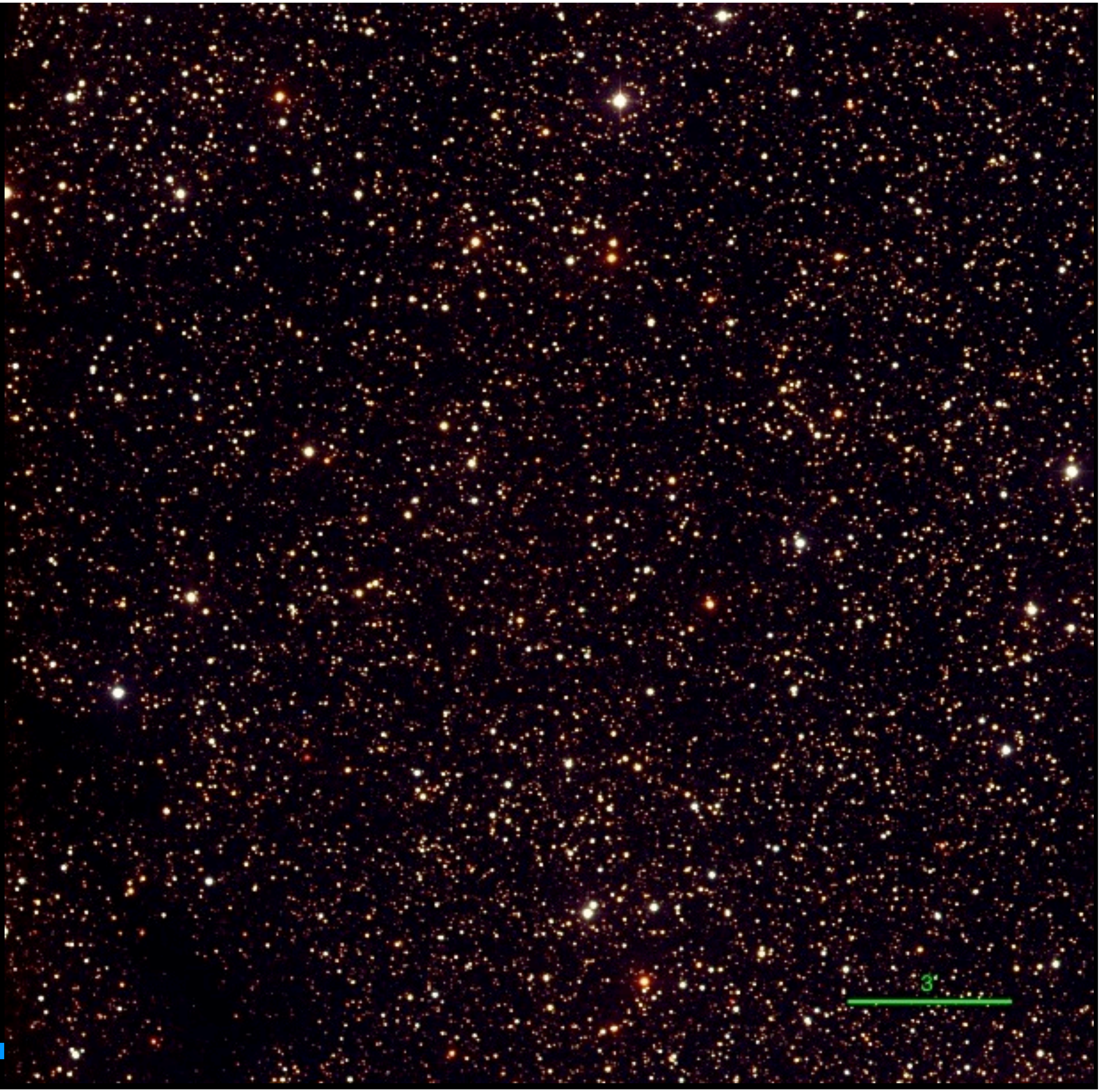
Great sensitivity
"2-sec" exposures
High ang. resolution
2" matches optical
Low extinction
$A_{[4.5]} \sim 0.04 A_V$

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



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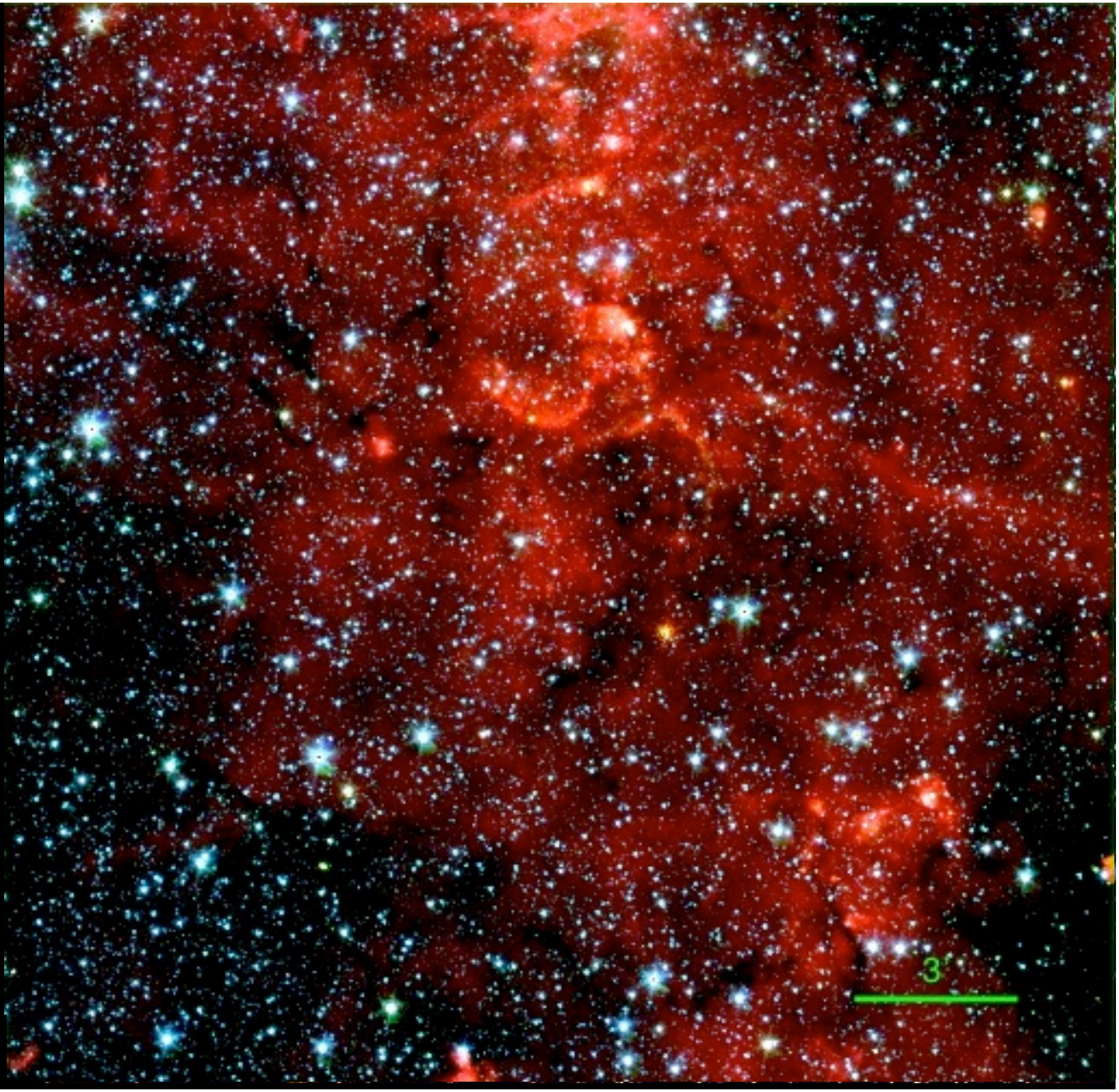

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Near IR
JHK (15 mag)
2MASS

Mid-IR
[3.6],[4.5],[8.0]
Spitzer/GLIMPSE

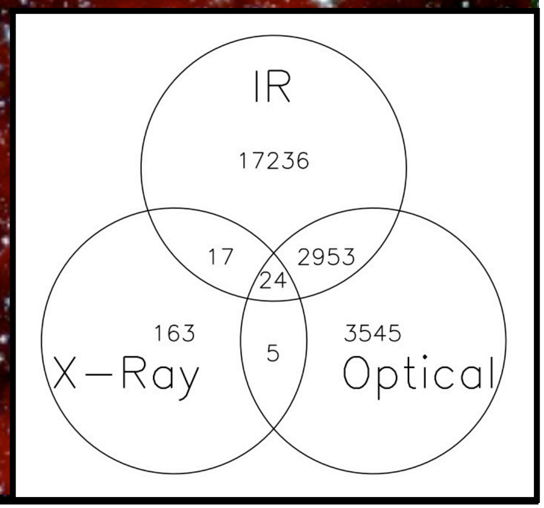
l=28.5
b=-0.5

The mid-infrared (3-5 μm) is the *ideal* wavelength window for star counts.

- Fluxes for giants, which dominate number counts for an extinction-free galaxy, peak in the near IR.
- Mid IR bands provide the best combination of low extinction and low diffuse emission.

One caveat: Mid IR colors of ordinary stars (dwarfs/giants) are all about zero, since mid IR is on the Rayleigh-Jeans tail.

Longer wavelength bands (8-24-70 μm) are optimum for detecting dust emission, and cold or dust-enshrouded objects, particular massive YSOs.



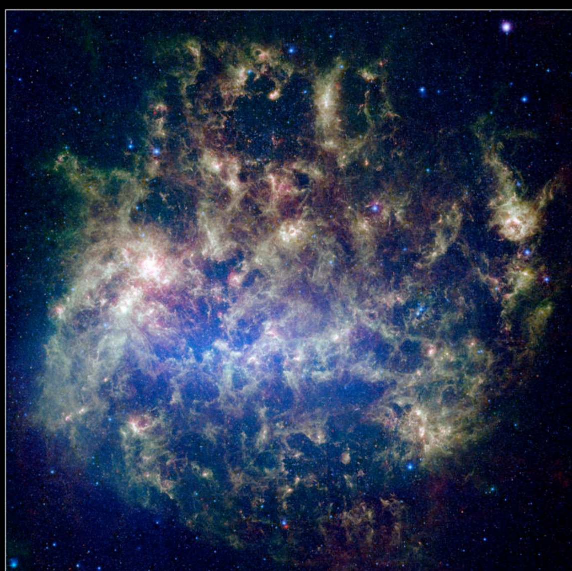
2. Surveying the Agents of Galaxy Evolution (SAGE)

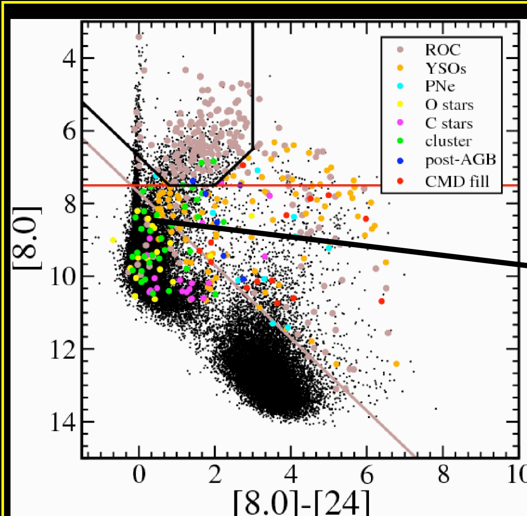
Tracing the lifecycle of baryonic matter via dust emission in the Magellanic Clouds (http://sage.stsci.edu/)

SAGE- Large Magellanic Cloud

SAGE-LMC

Meixner et al. 2006 AJ, 132, 2268

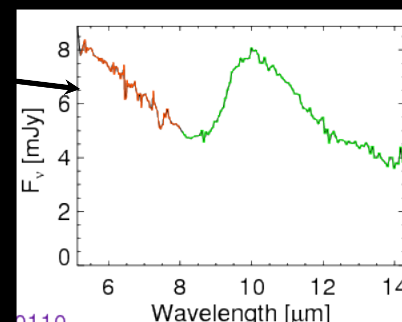


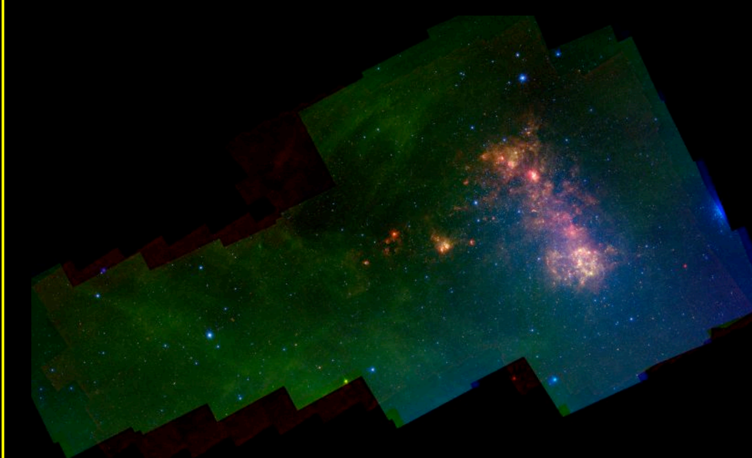


SAGE-Spectroscopy of LMC

SAGE-Spec

Kemper et al. submitted





SAGE - Small Magellanic Cloud

SAGE-SMC

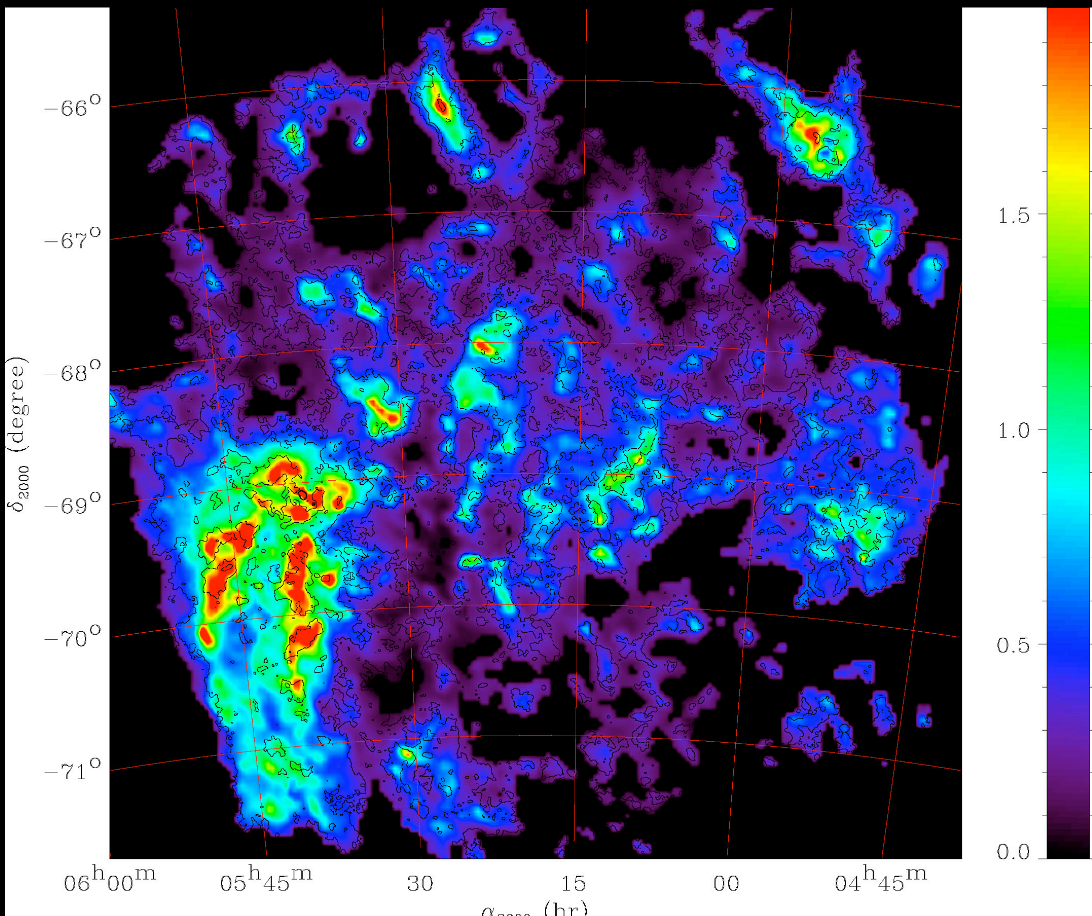
Gordon et al. in prep.

See poster!

Slide from M. Meixner

2. How much mass is currently in the ISM of LMC?

$\sim 10^9\ M_\odot$



Map based on MIPS 160 um & IRAS 100 um — *unbiased* tracer of ISM

Sees twice as much mass than seen in gas tracers alone (HI 21 cm + CO J=1-0)

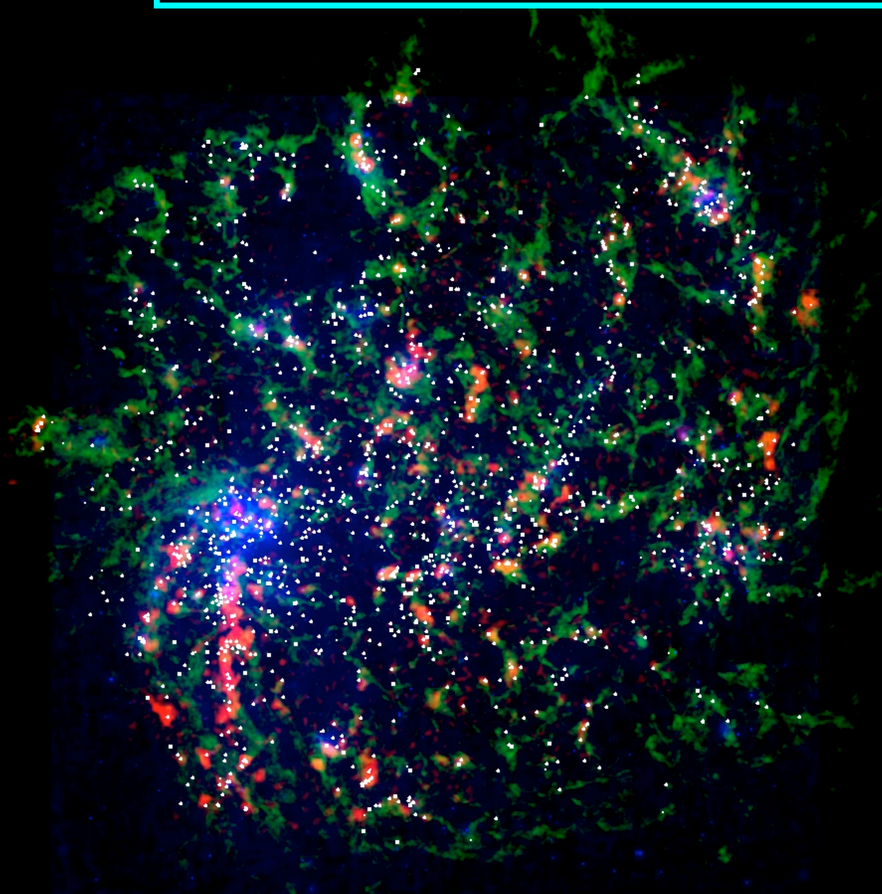
Bernard, Reach, Paradis et al. 2008, AJ, 136, 919

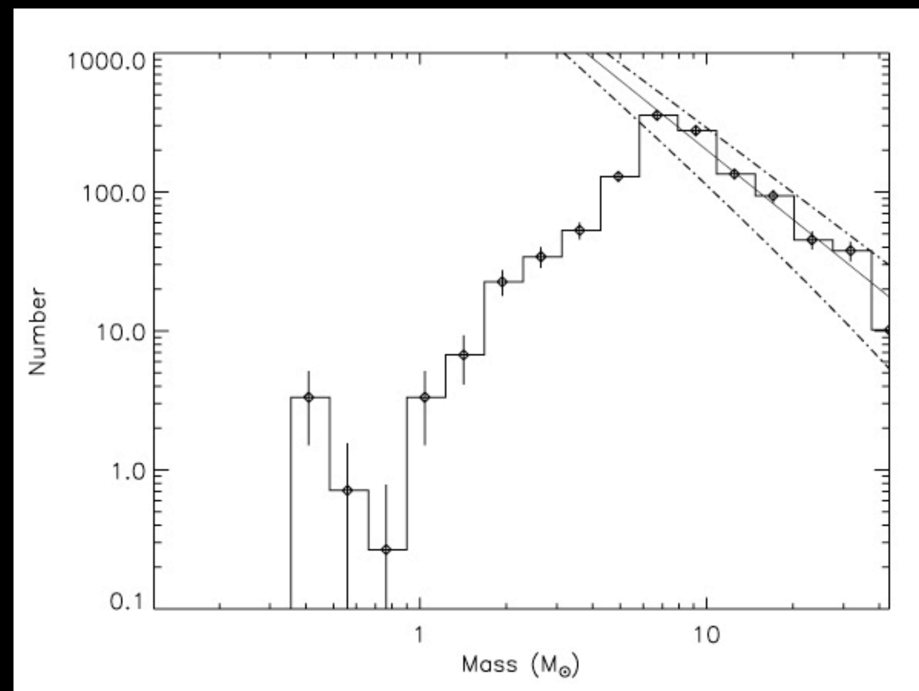
"Excess ISM" Color: N_H x 10^{22} H/cm^2 Contours: HI

Slide from M. Meixner

2. What is the galaxy-wide star formation rate of the LMC?

Bottom-up YSO count estimate >0.1 M_{sol} /yr





Whitney, Sewilo, Indebetouw, et al.
2008, AJ, 136, 18

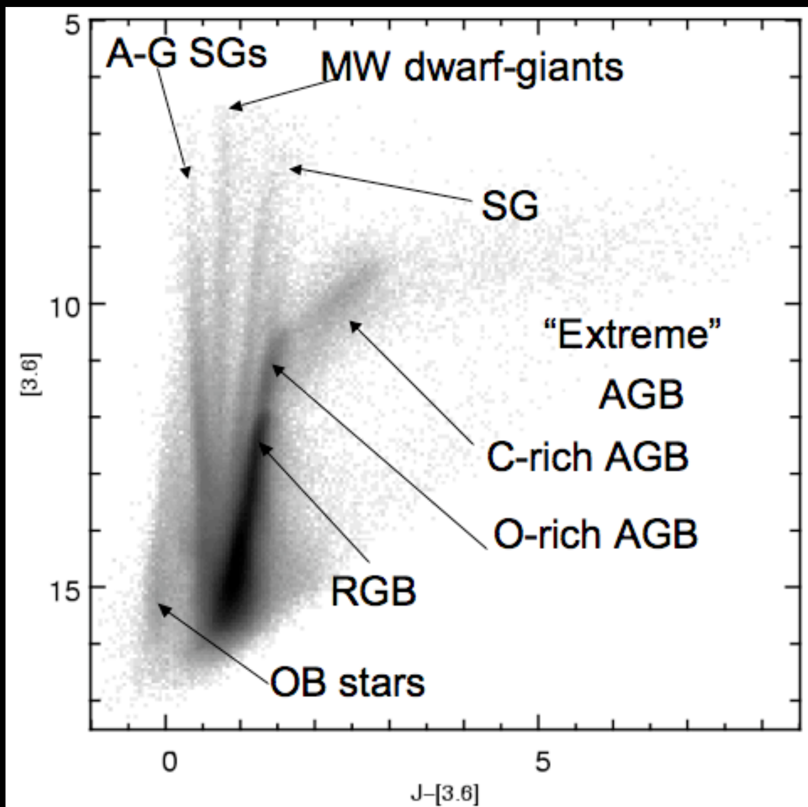
Slide from M. Meixner

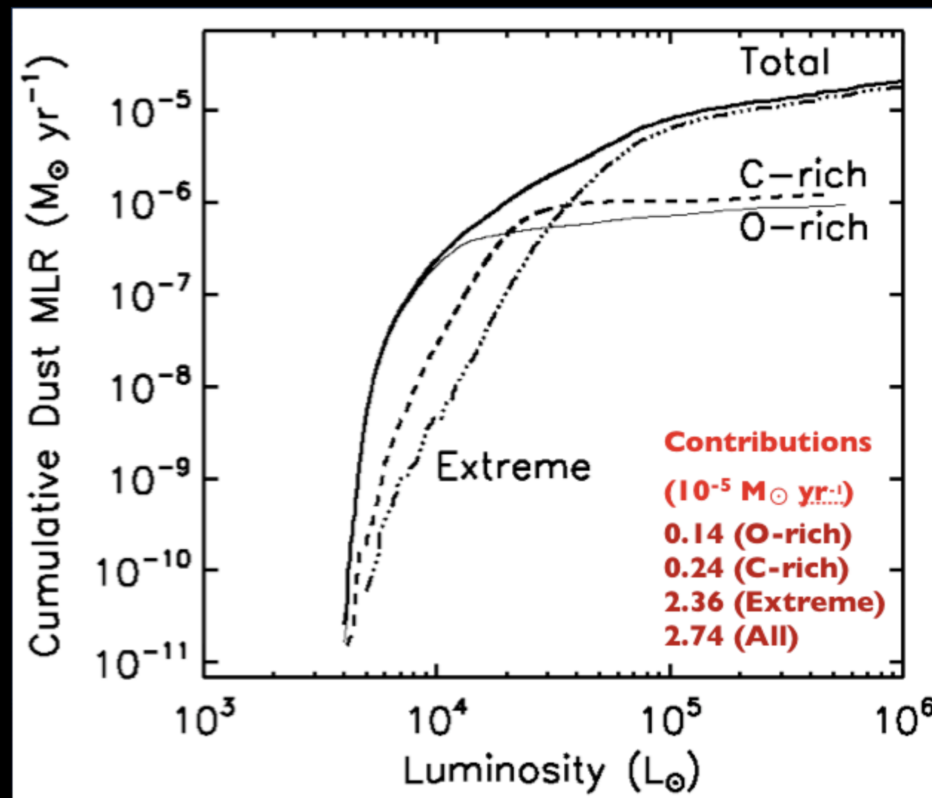
2. How much mass is injected by evolved stellar winds?

LMC Asymptotic Giant Branch (AGB) stars

dust $2.74\times10^{-5}\ M_\odot\ yr^{-1}$

gas $6\text{-}13\times10^{-3}\ M_\odot\ yr^{-1}$



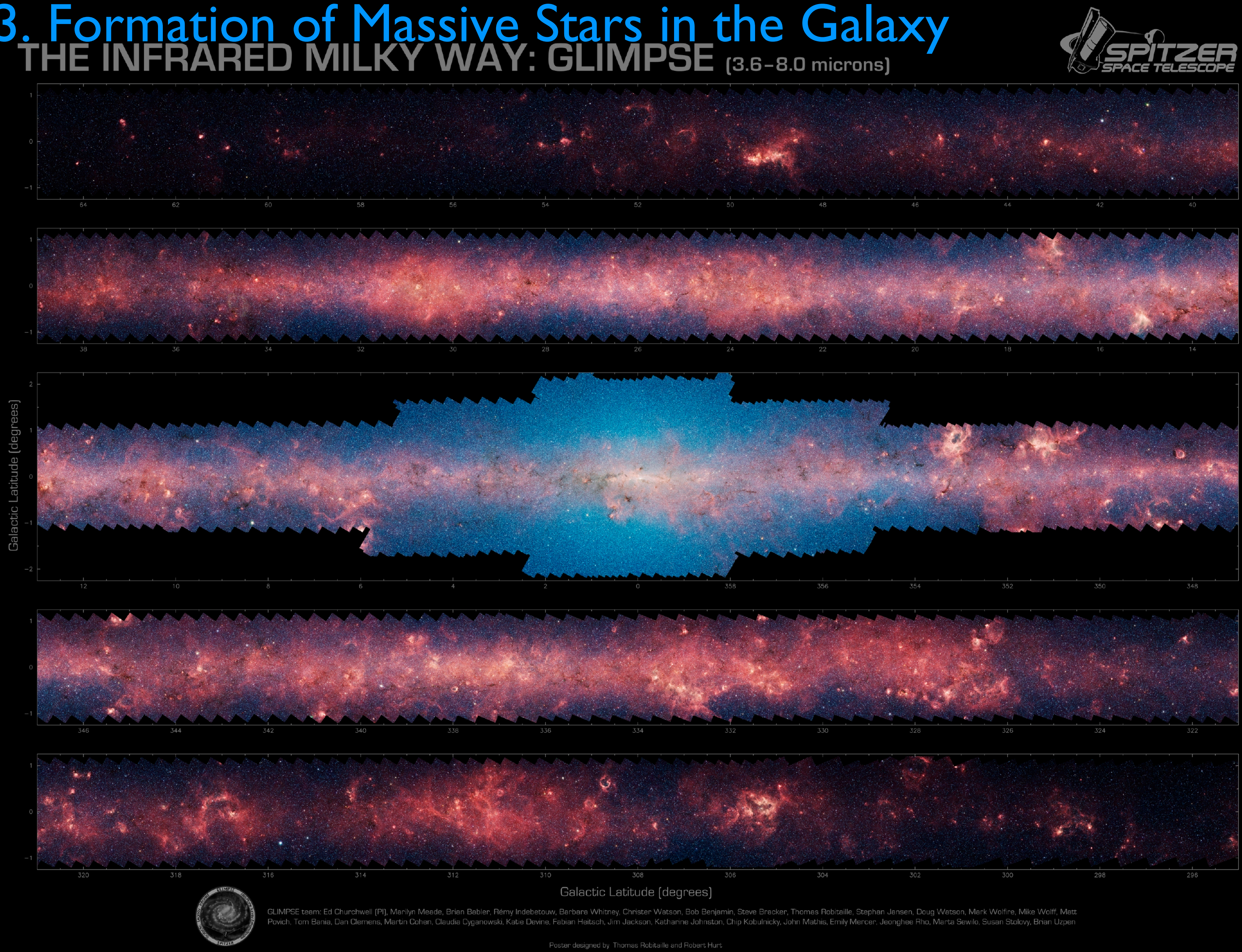


Blum, Mould, Olsen et al. 2006
AJ, 132, 2034

Srinivasan, Meixner, Leitherer et al. 2009
AJ, 137, 4810

Slide from M. Meixner

3. Formation of Massive Stars in the Galaxy



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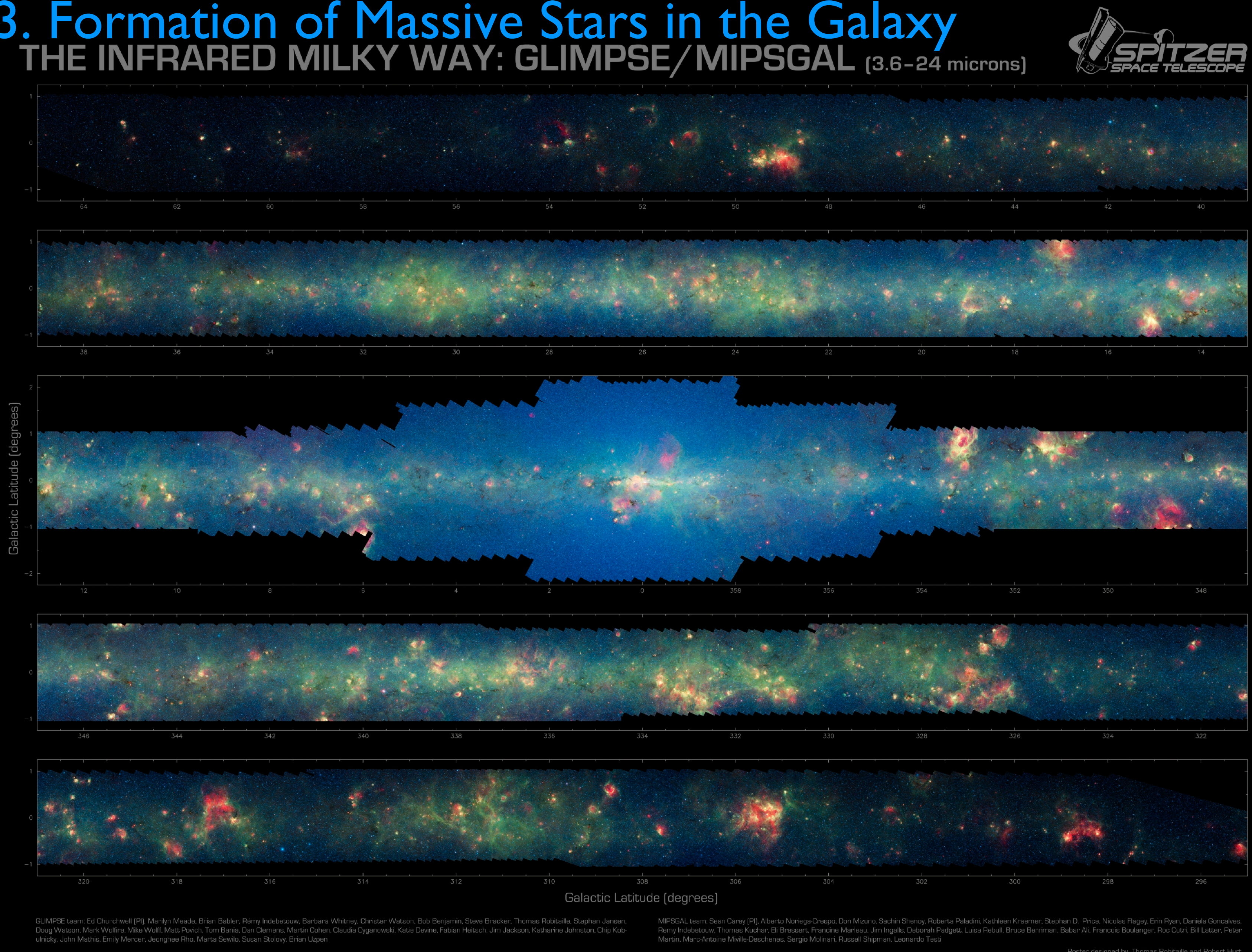
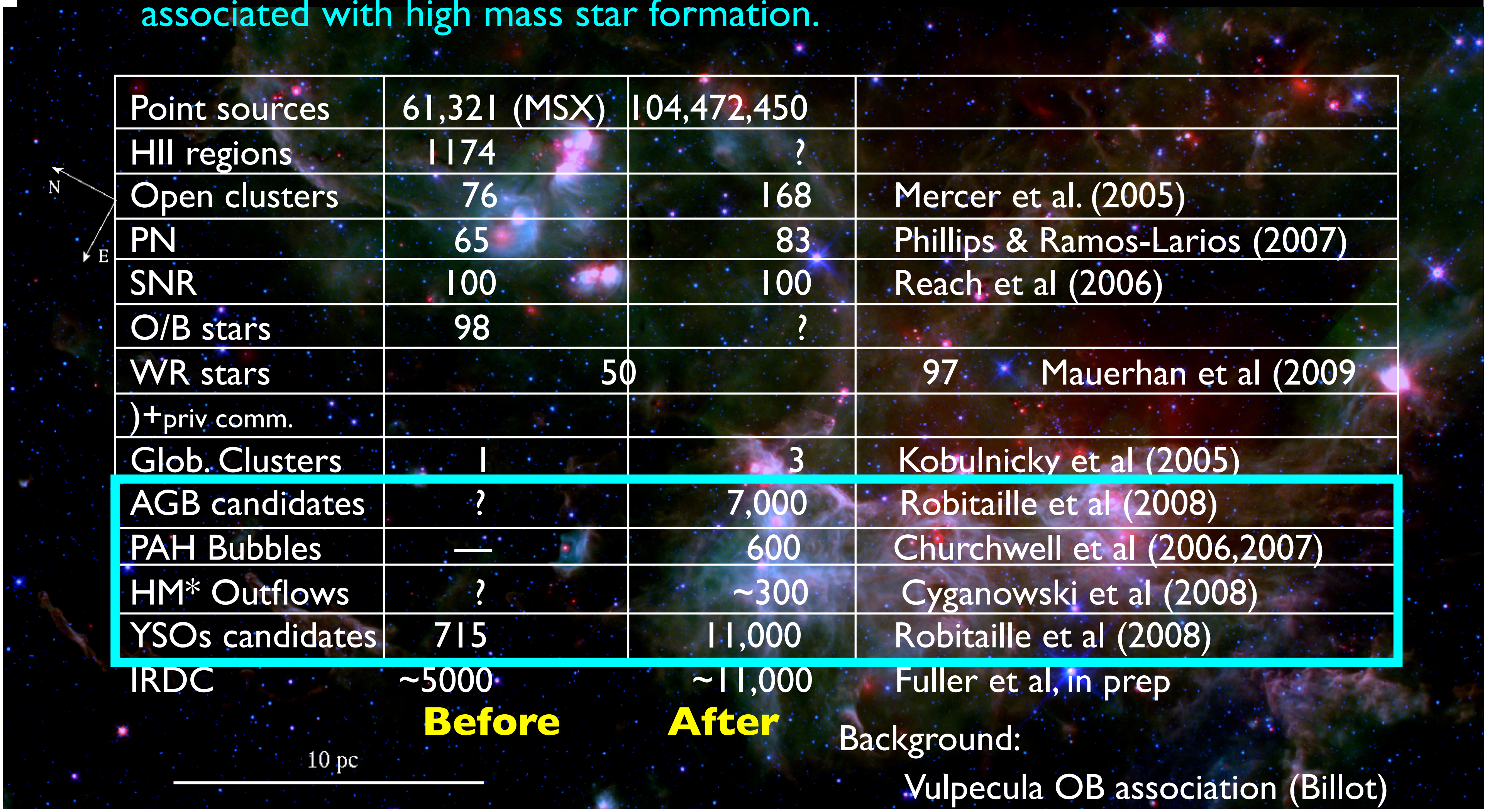


3. Formation of Massive Stars in the Galaxy

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.



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
	Before	**After**	

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!

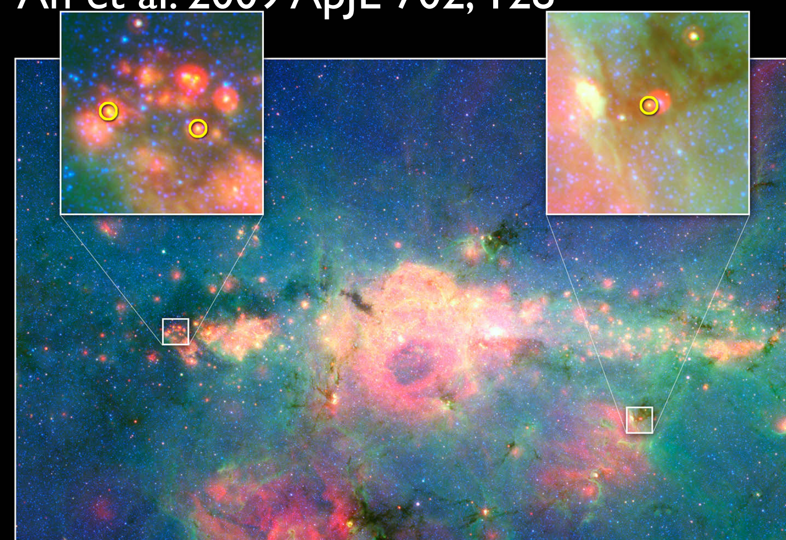
Catalog: Robitaille et al 2008 AJ 136, 2413

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. Ramirez (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):

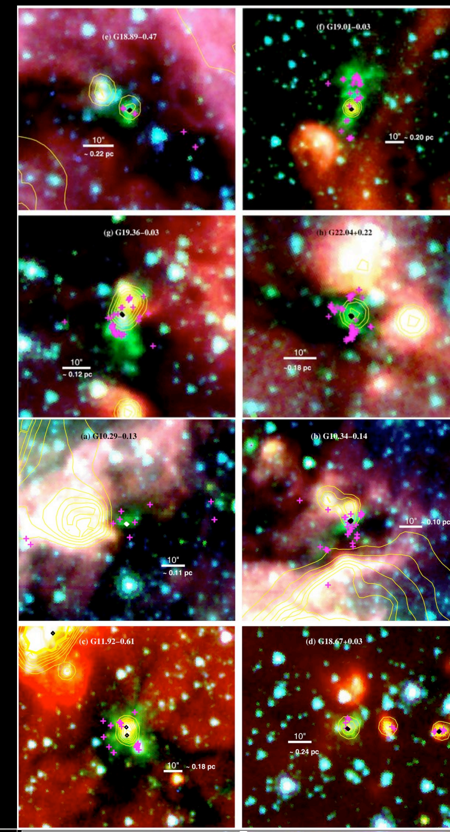
Extended objects bright in [4.5] band

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?

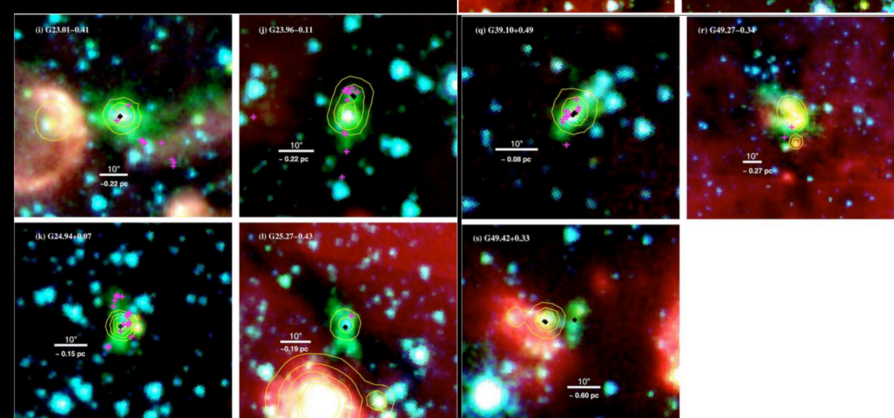


300 examples (not a complete catalog)

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:

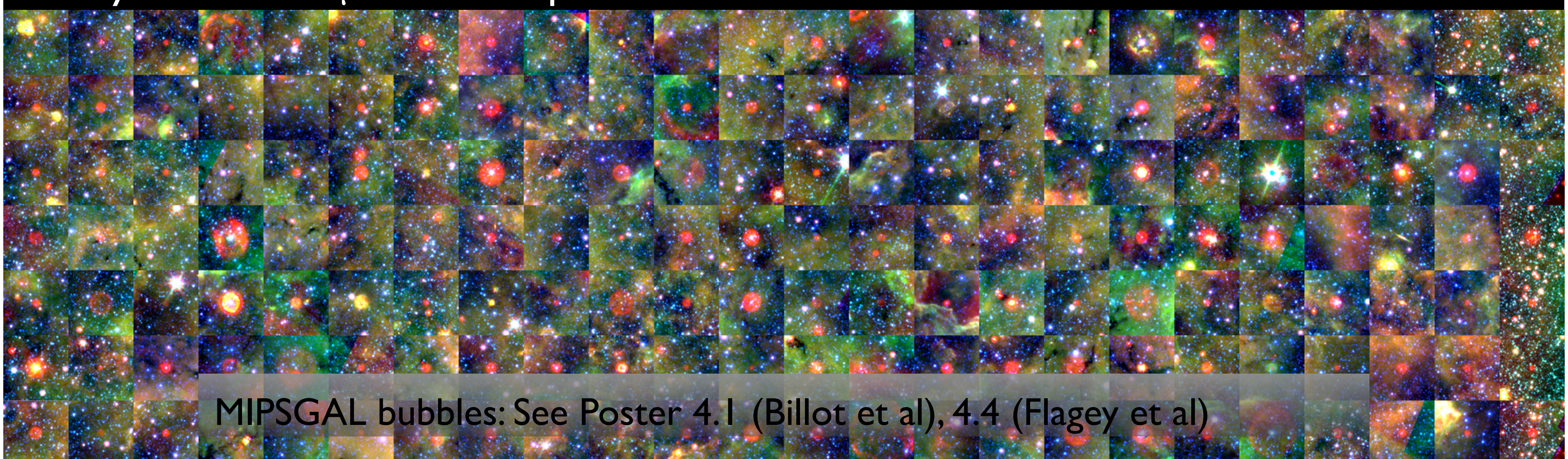
Watson et al 2008 ApJ, 681, 1341

Watson et al 2009 ApJ, 694, 546

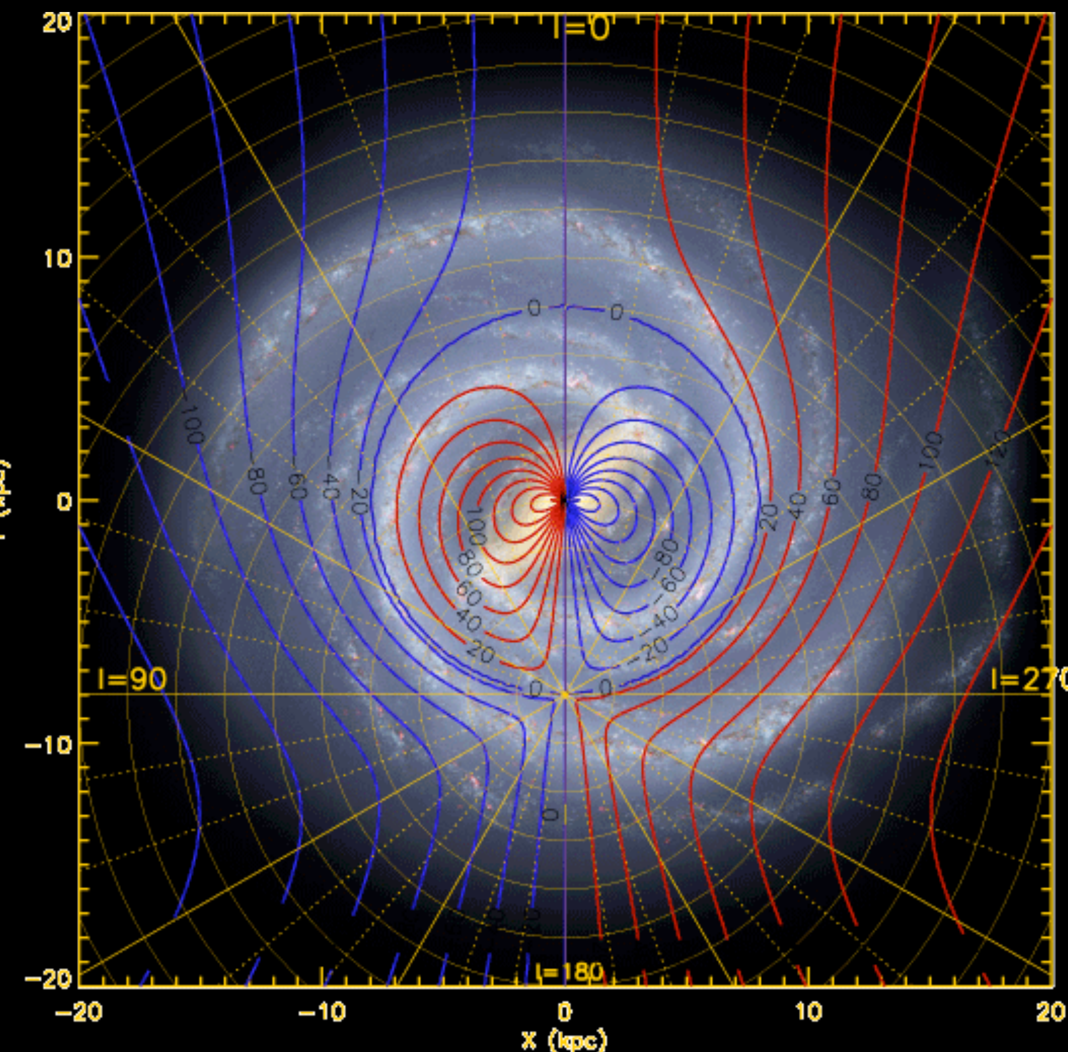
Everett et al 2009, in prep

24 μm Bubble Catalog (400):

Carey et al 2009, in prep



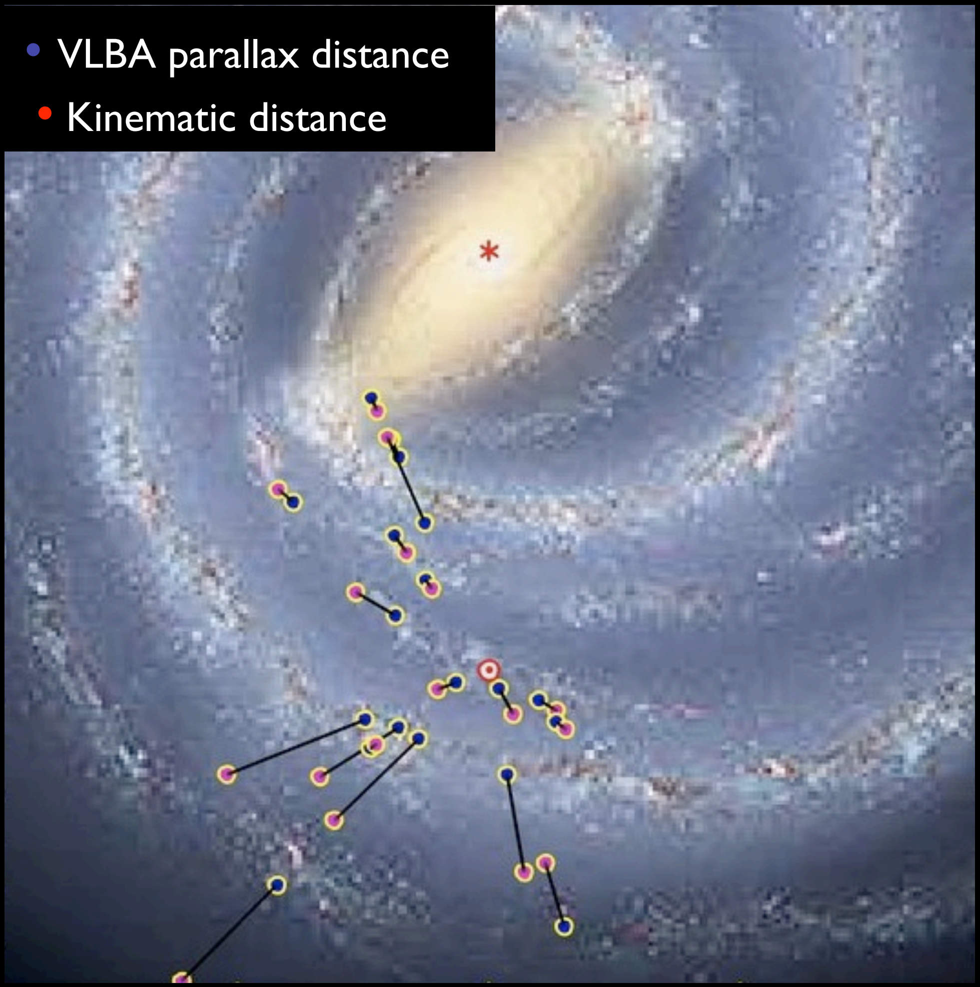
4. Galactic Structure: Turning a Poster into a Map



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.

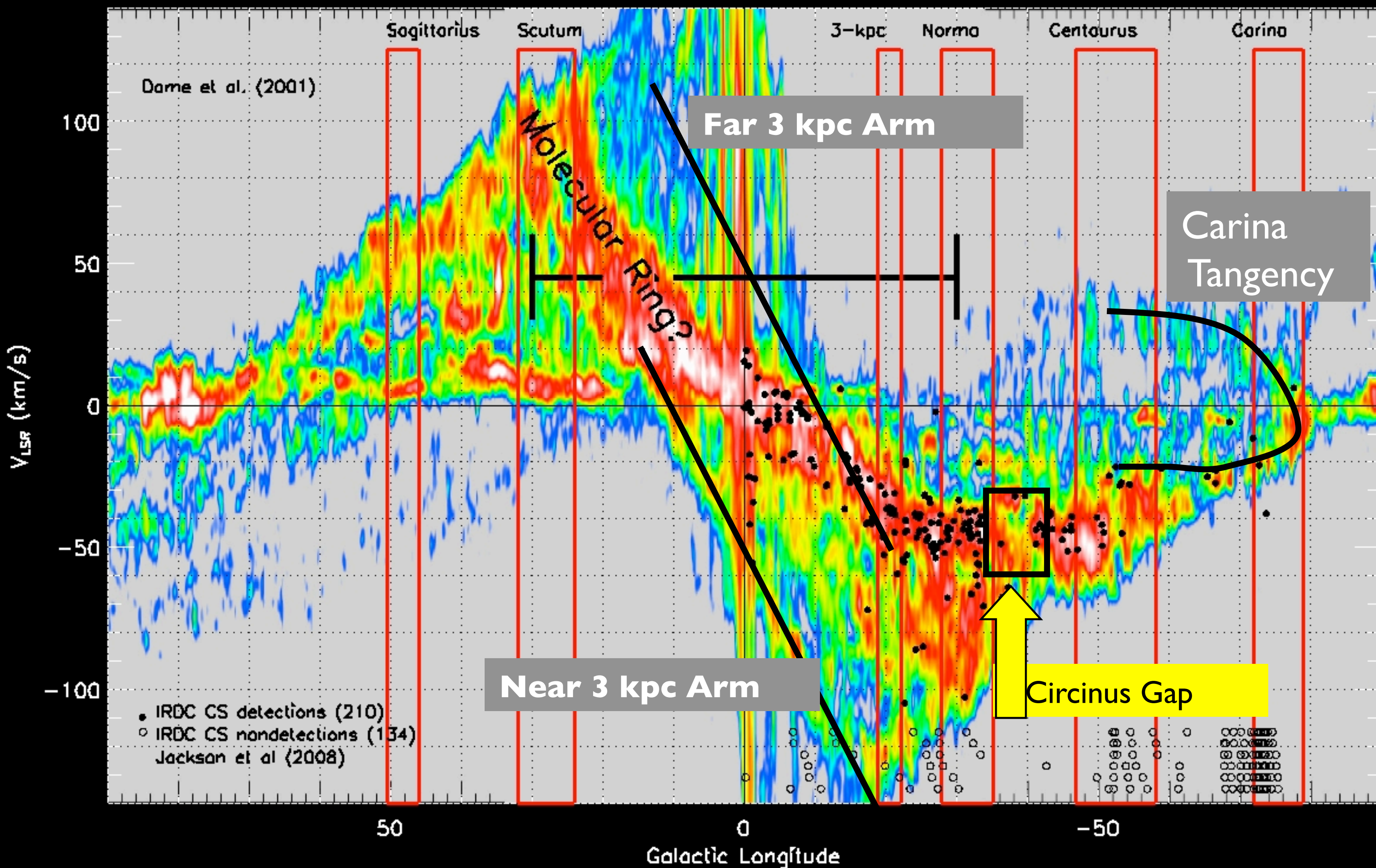
4. Galactic Structure



Problems with Kinematic Distances

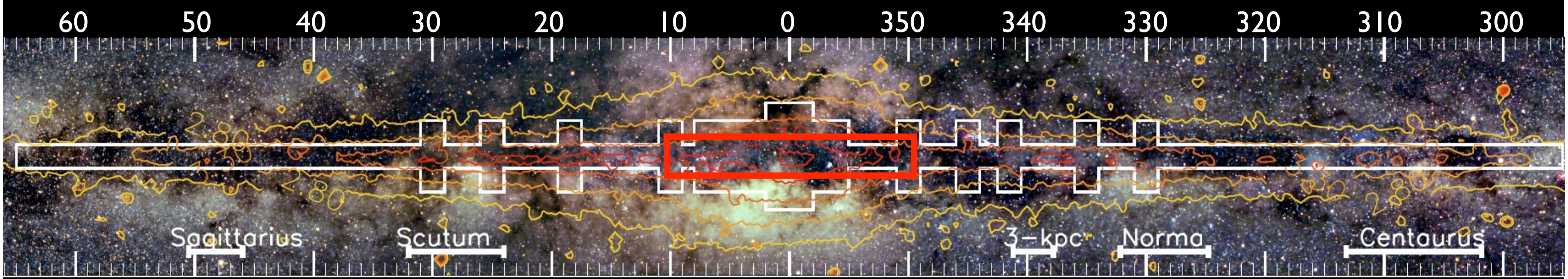
- Many objects smaller than resolution of available CO-HI-RRL surveys. Needs dedicated follow-up.
- Kinematic distances are double valued in inner galaxy.
- Random velocity and uncertainties in rotation curves fits produce longitude-dependence spread in distances.
- Deviation from circular flows due 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)

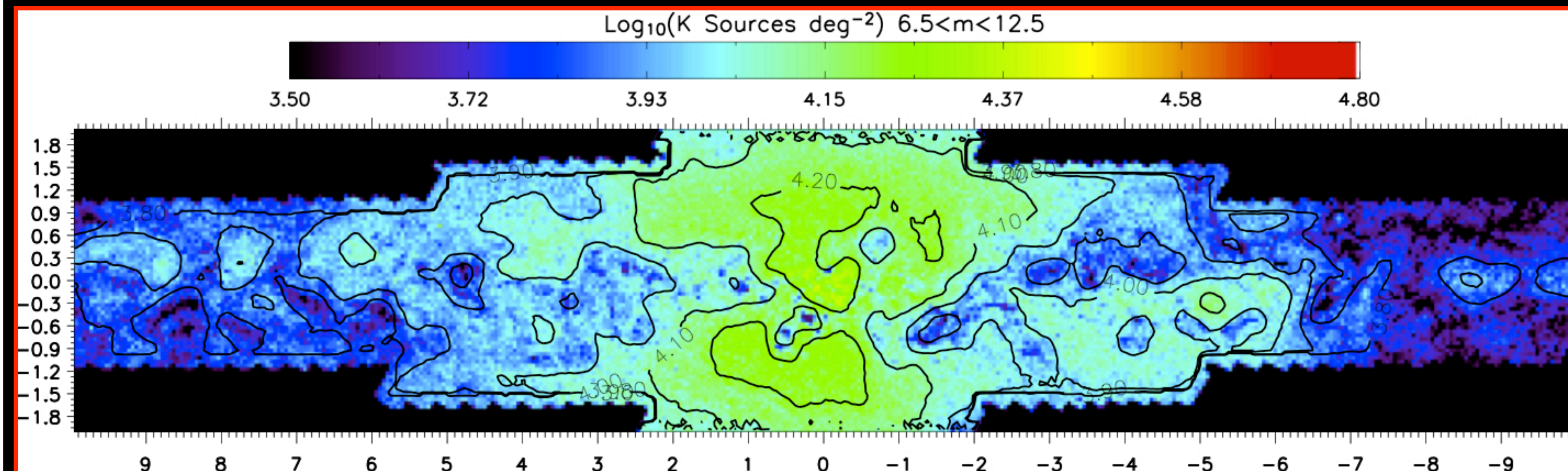


Doubts about the Molecular "Ring": Dame (1993), Englmaier & Gerhard (1997), Binney & Merrifield (1998), Ferriére (2001) , Stark & Lee (2006) , Jackson et al. (2008) , Rodriguez-Fernandez & Combes (2008)

4. Galactic Structure: GLIMPSE star count maps



Optical panorama courtesy of Axel Mellinger
"Historical" directions for spiral arm tangencies (Englmaier & Gerhard 1999) shown.



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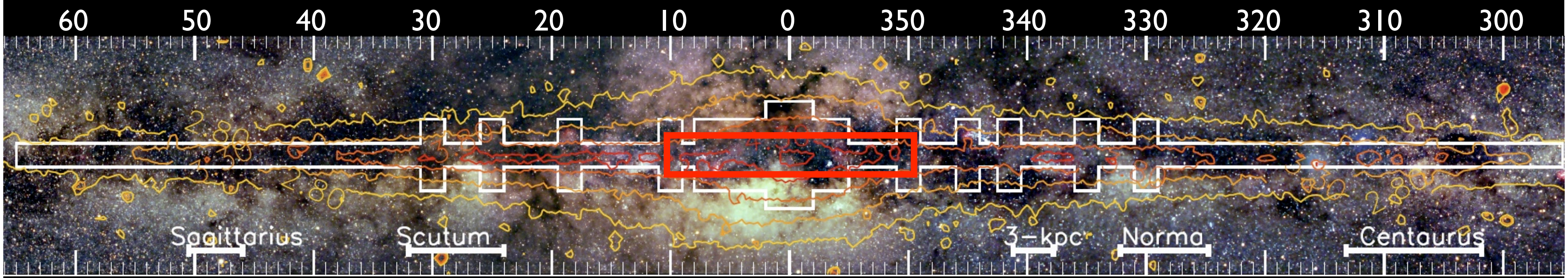

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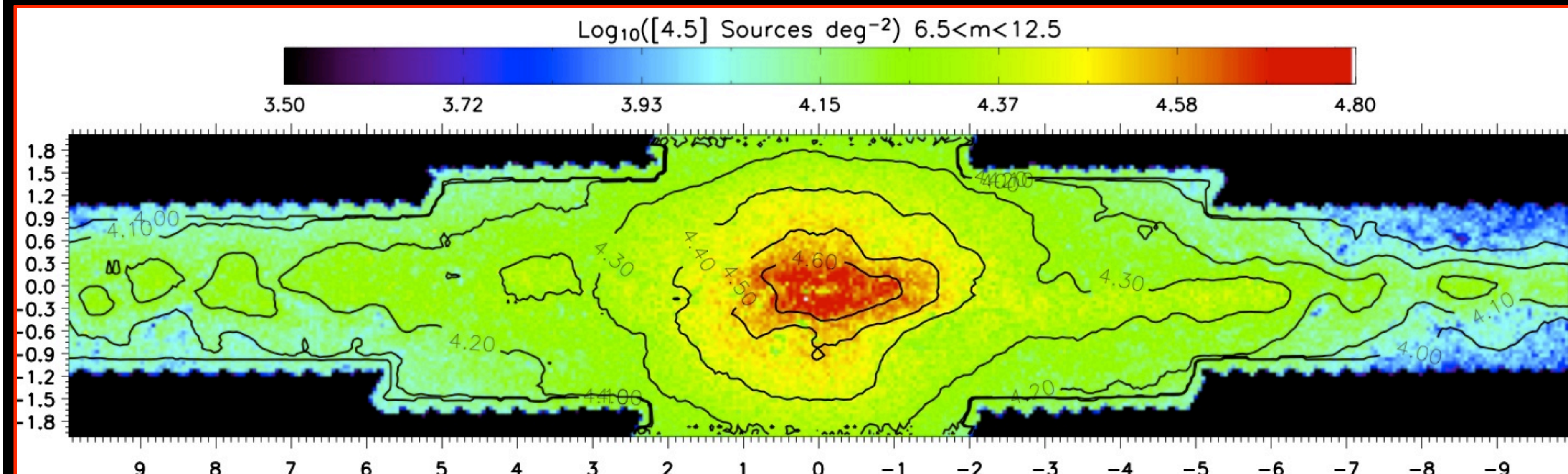
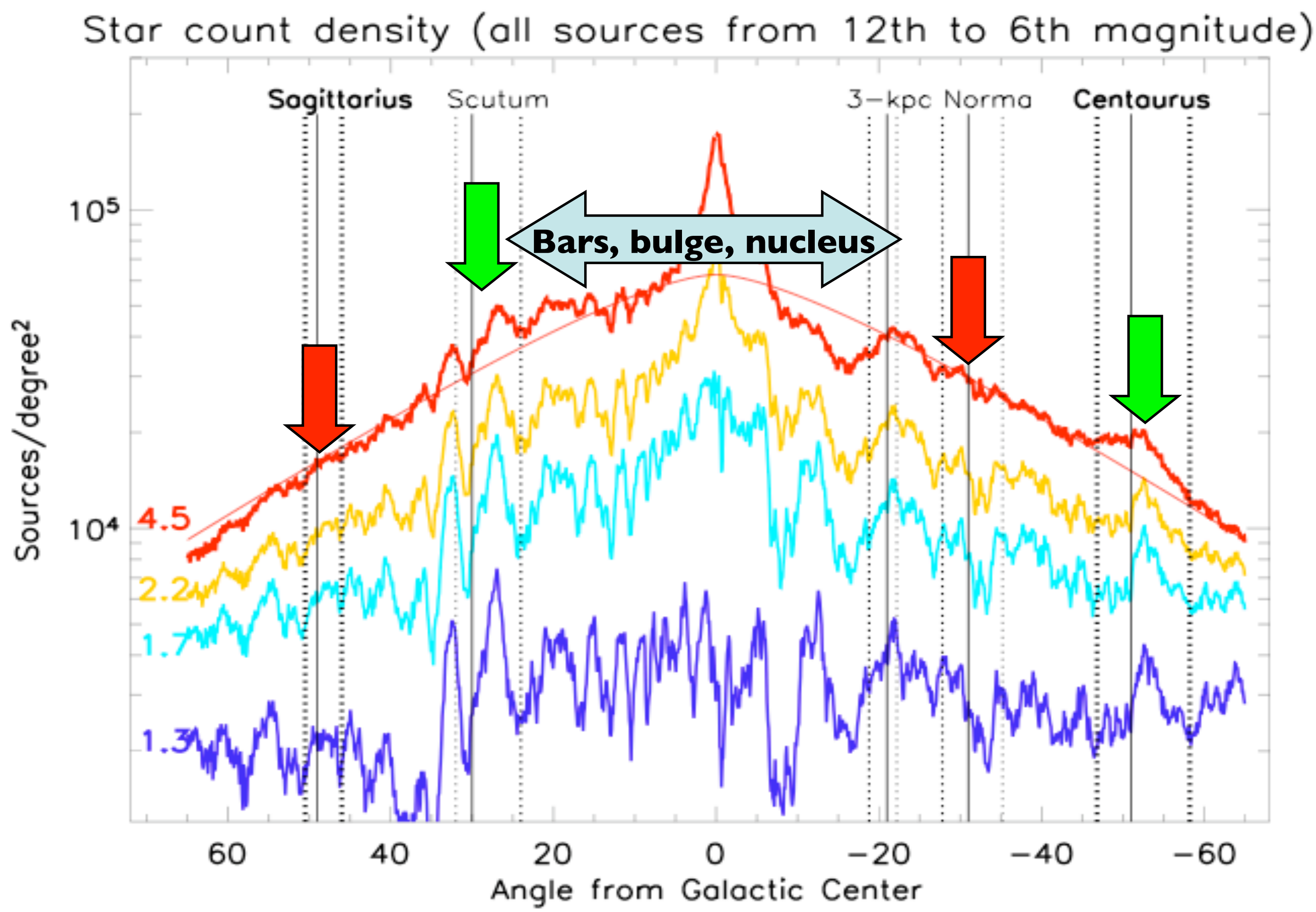
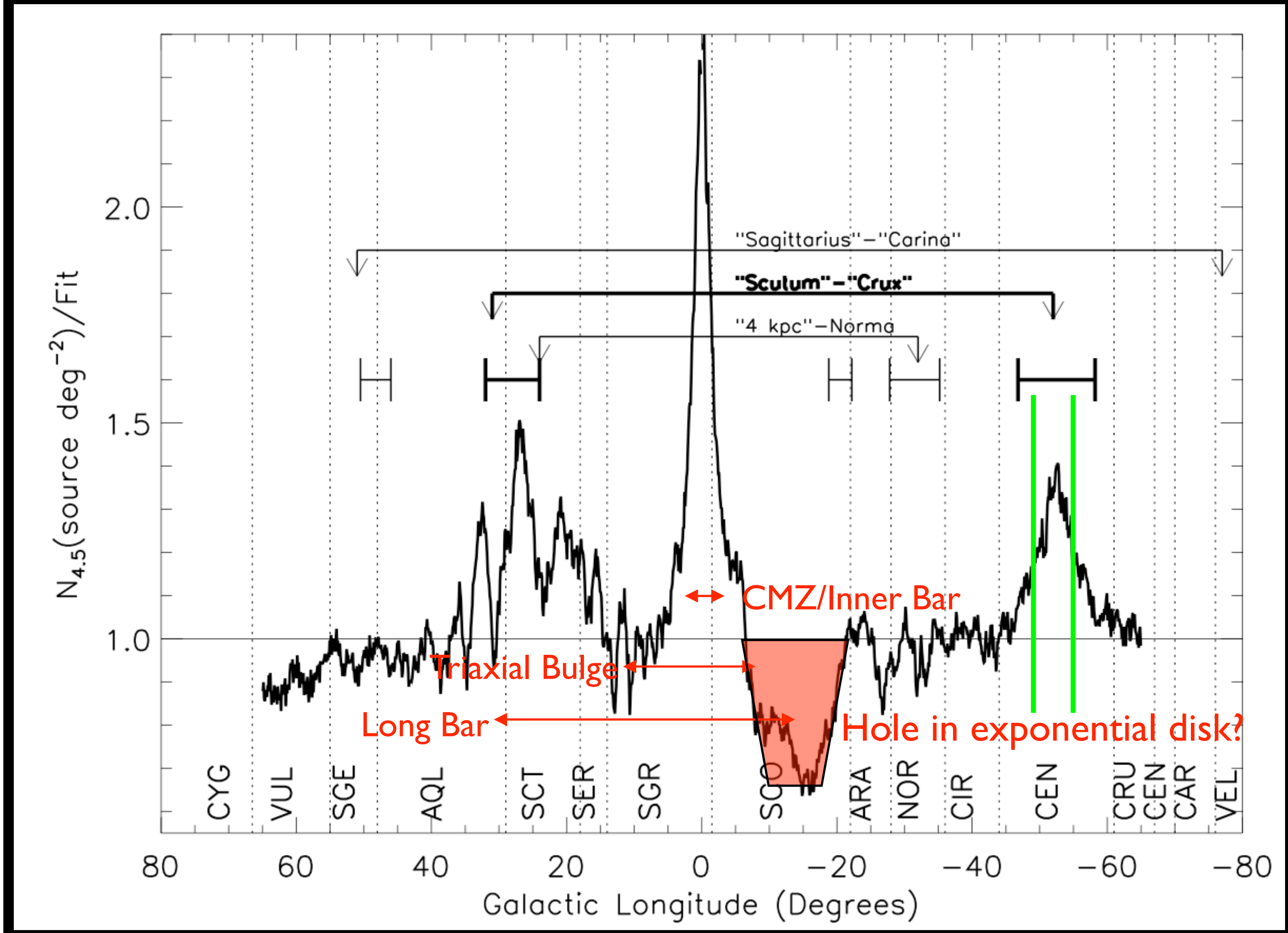




model R_{disk}=3.9 ±0.6 kpc (Benjamin et al 2005)

4. Galactic Structure: Dividing out the disk



Centaurus tangency in stellar disk

30% excess at maximum

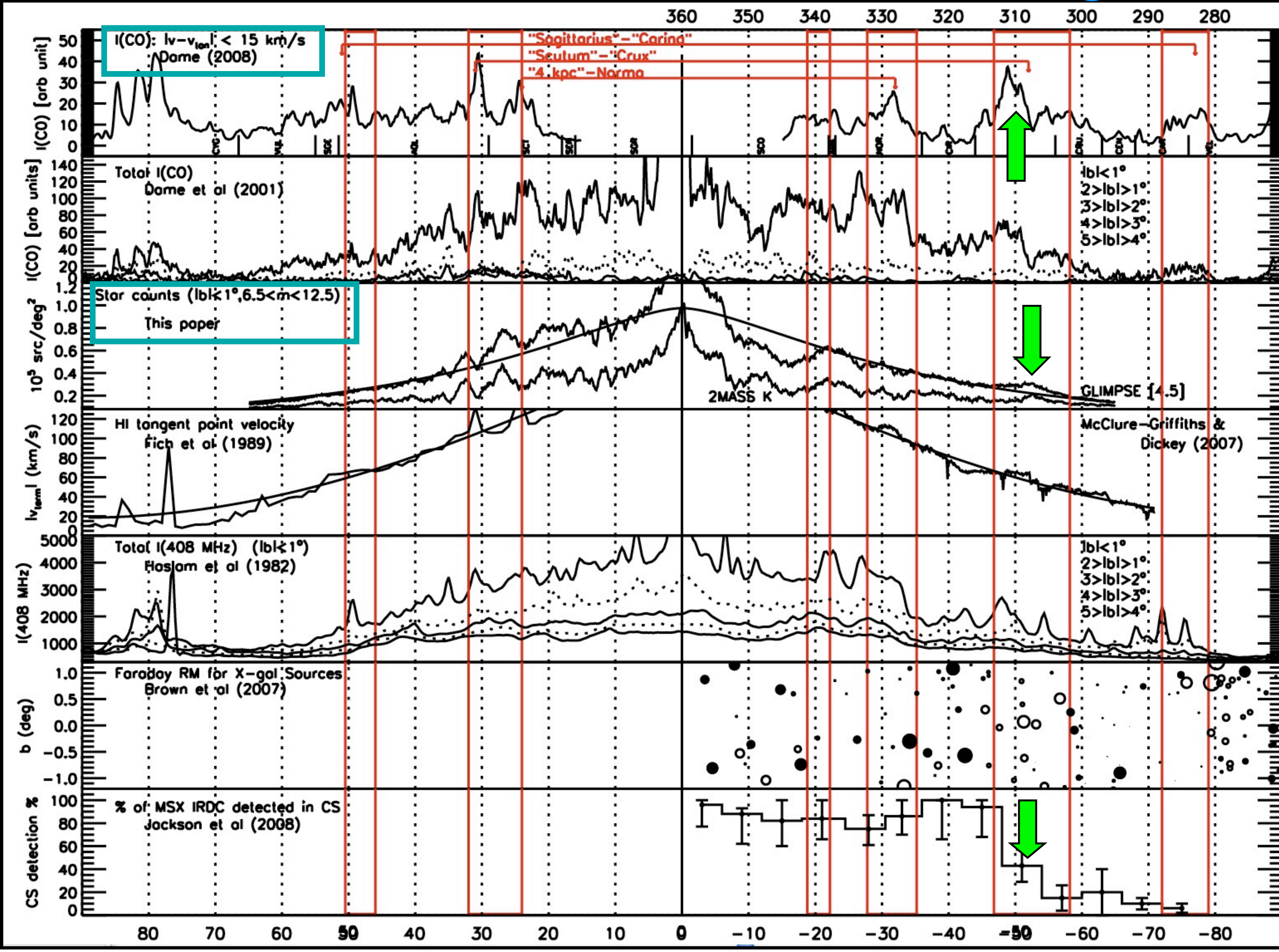
Center at l=307.4°

FWHM=4.4°

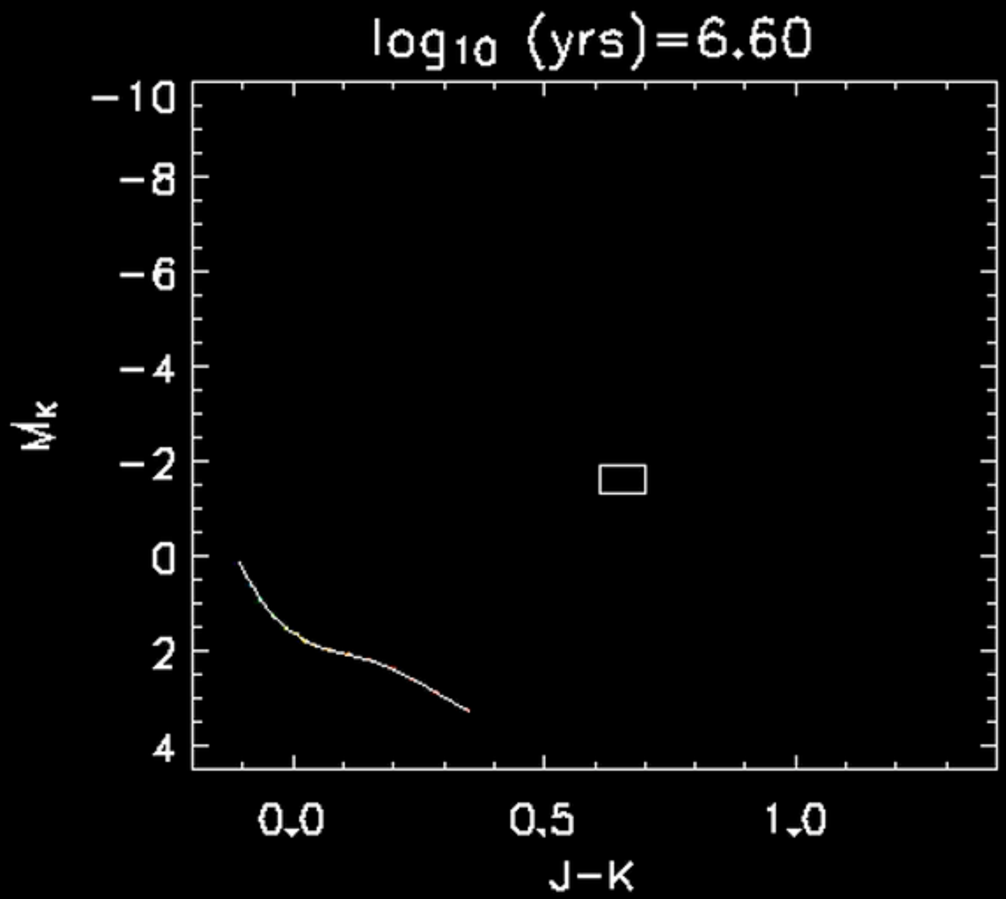
FWHM=460 pc @ 6 kpc

Benjamin (2009)

4. Galactic Structure: Multi-λ Tracers of Tangencies



4. Galactic Structure: Mapping with Red Clump Giants



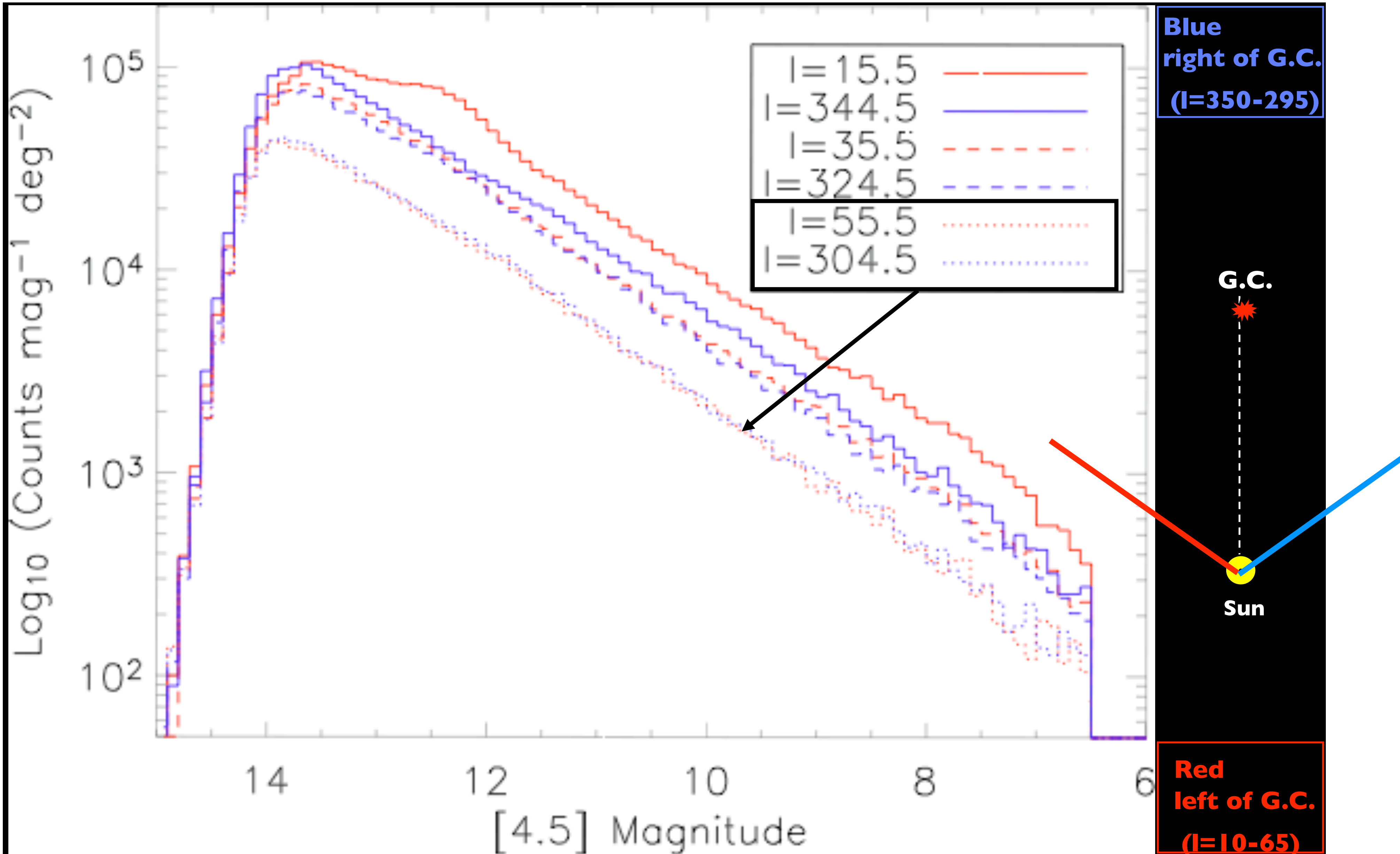
Isochrones of 1-5 M_o solar metallicity stars.
Note the red clump box starts to fill up at ~ 1 Gyr.

- Common 0.5 - 2.0 M_o 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.

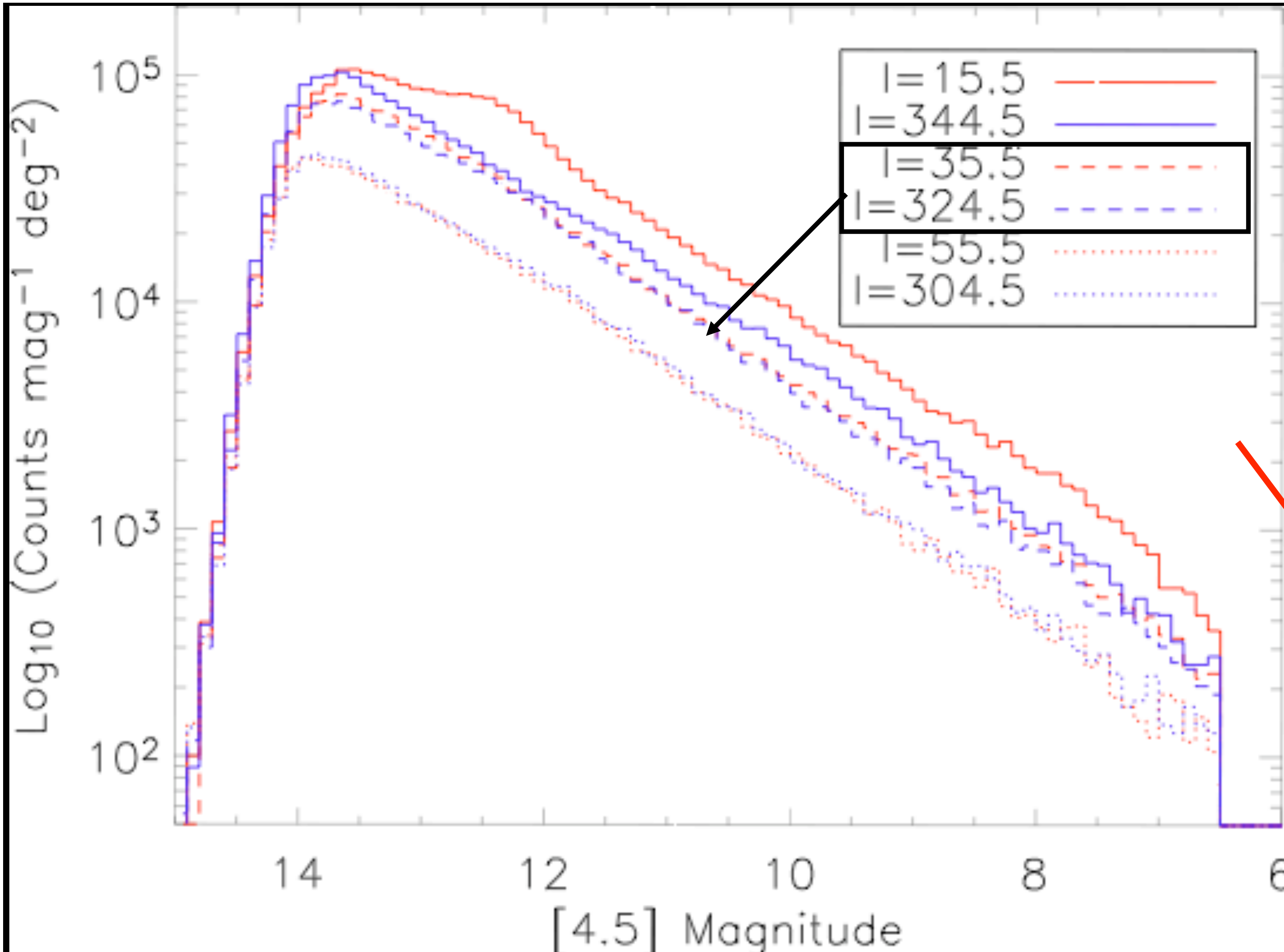
- Some concerns over age and metallicity effects (up to 0.3 mag), but these affect <u>absolute</u> calibration, not <u>relative</u> calibration.

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

Δm_{stat}=0.03 ⟶ **Δd/d=1.3%**



l=15.5
l=344.5
l=35.5
l=324.5
l=55.5
l=304.5
Log10 (Counts mag^-1 deg^-2)
[4.5] Magnitude
Blue
right of G.C.
(l=350-295)
G.C.
Sun
Red
left of G.C.
(l=10-65)



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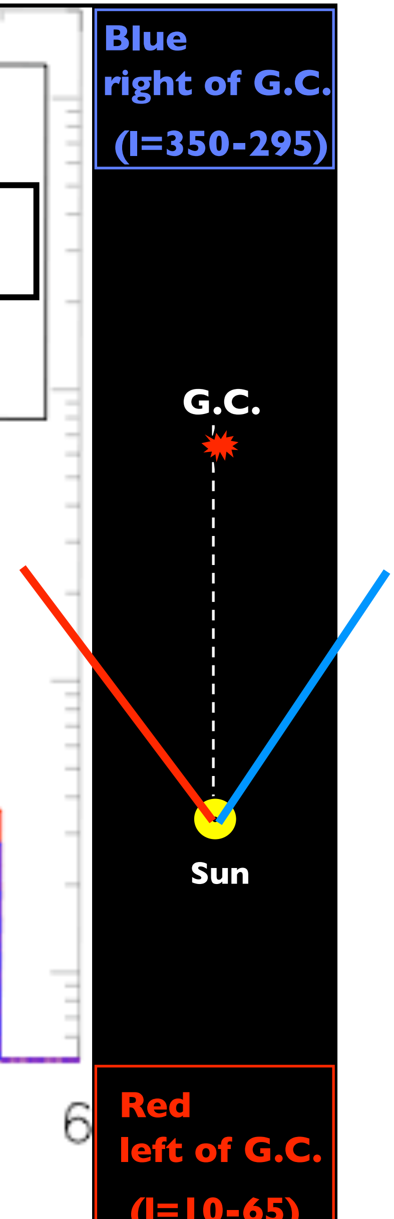

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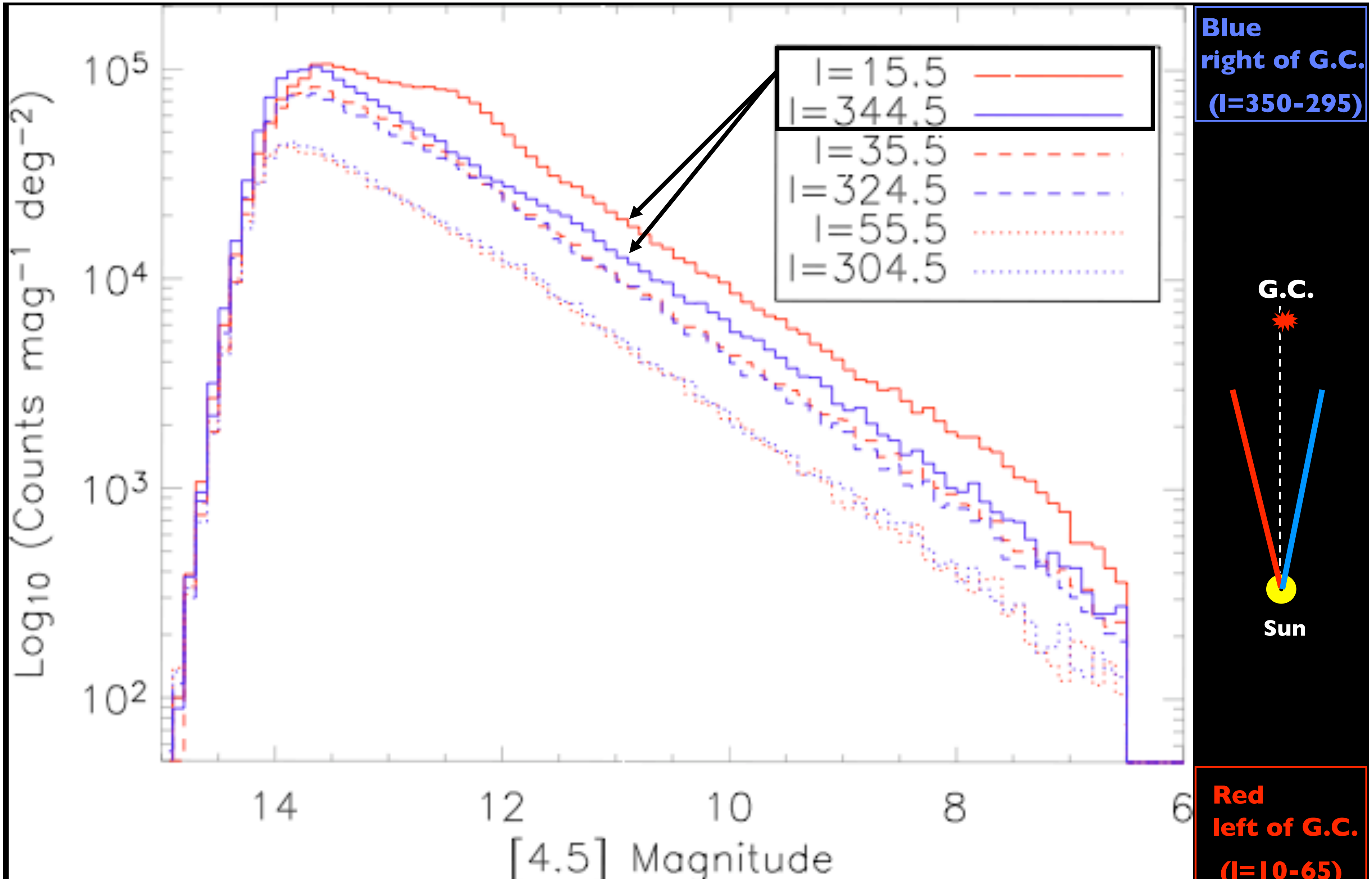

l=15.5
l=344.5
l=35.5
l=324.5
l=55.5
l=304.5
Log_{10} (Counts mag^{-1} deg^{-2})
10^5
10^4
10^3
10^2
14
12
10
8
6
[4.5] Magnitude
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right of G.C.
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G.C.
Sun
Red
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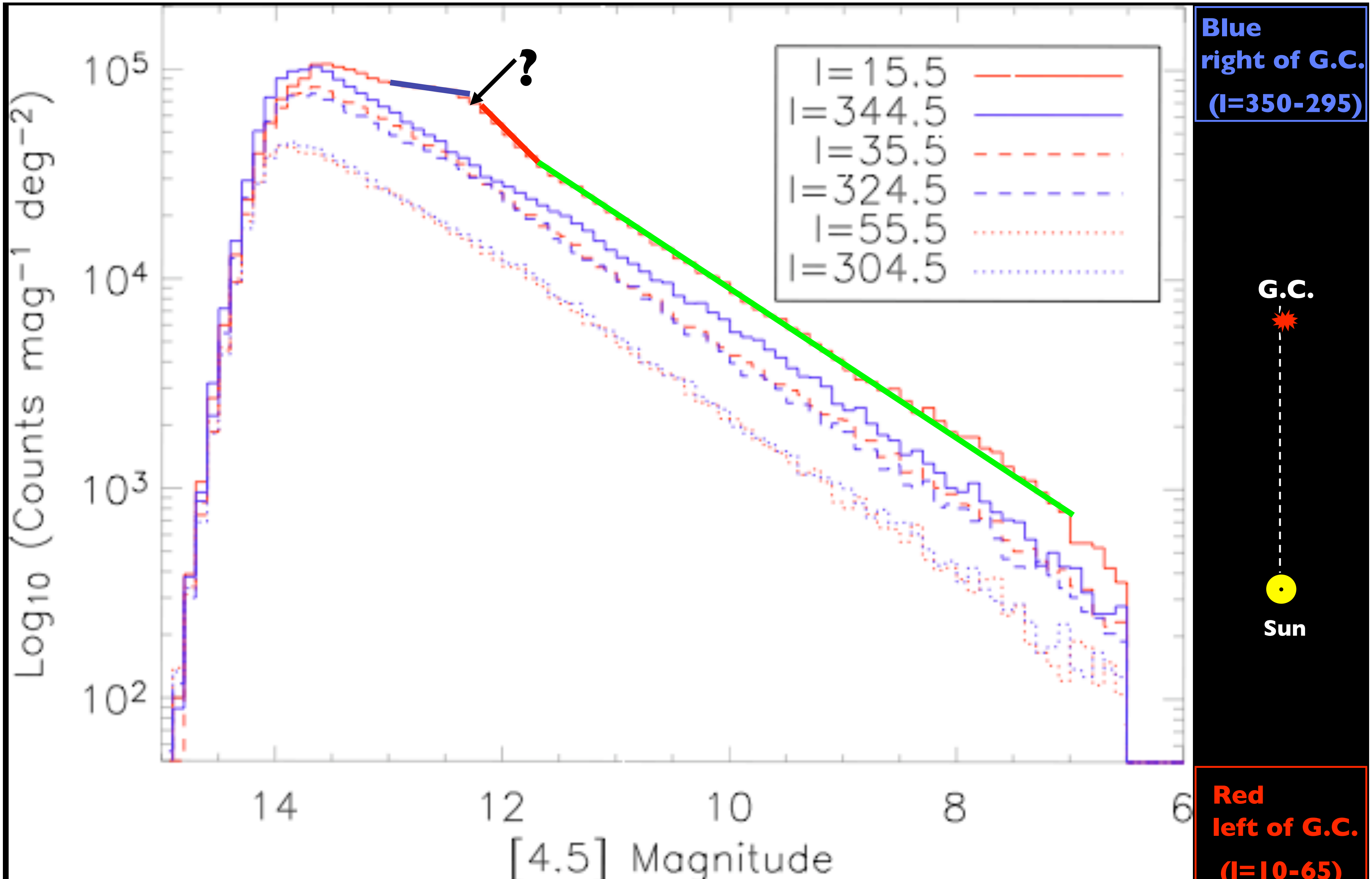
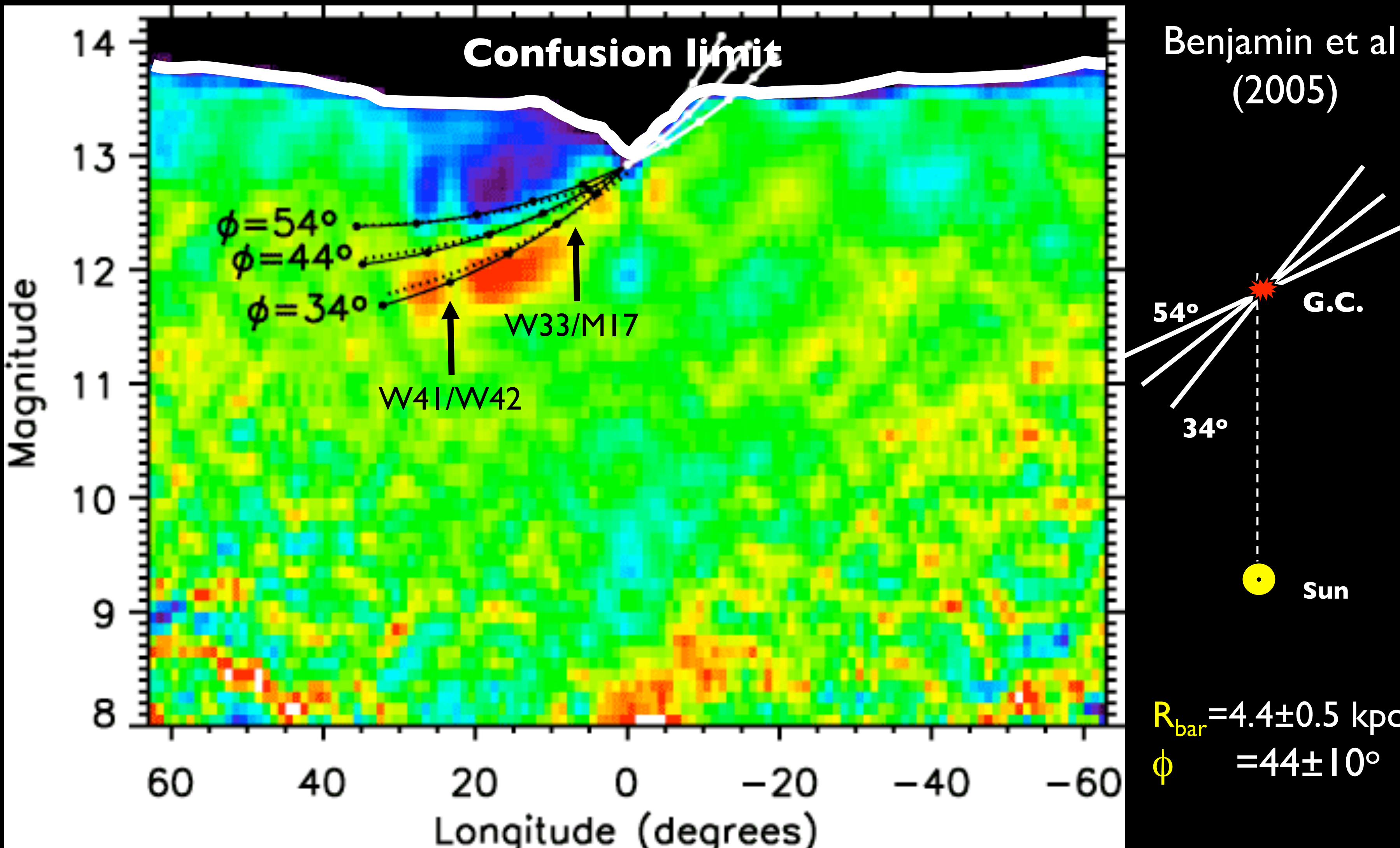
(l=10-65)



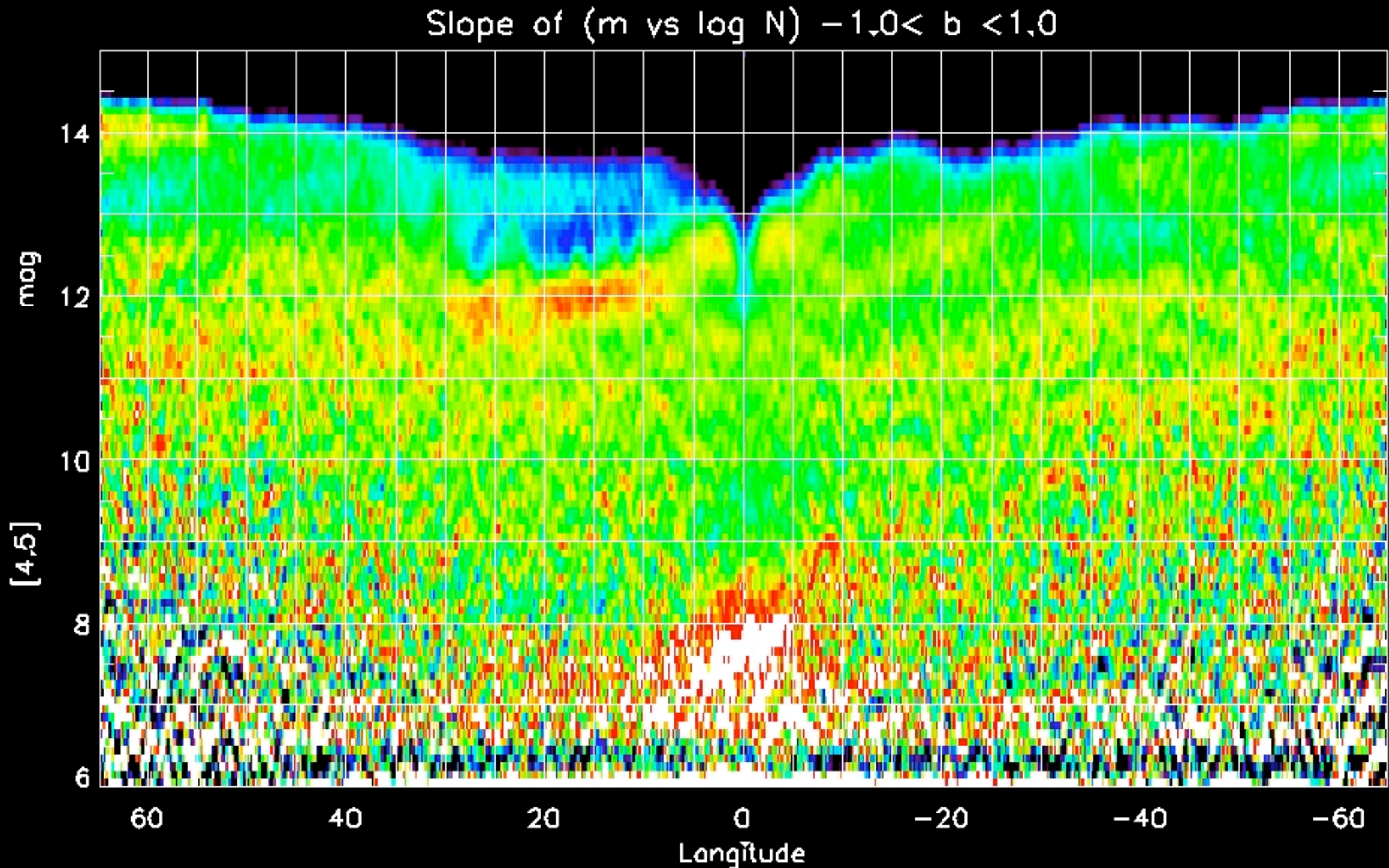
Fits of data to $n=n_o(S/S_o)^{-\alpha}$ yield α_{avg}=1.83-1.95

4. Galactic Structure: Red Clump Mapping of Long Bar

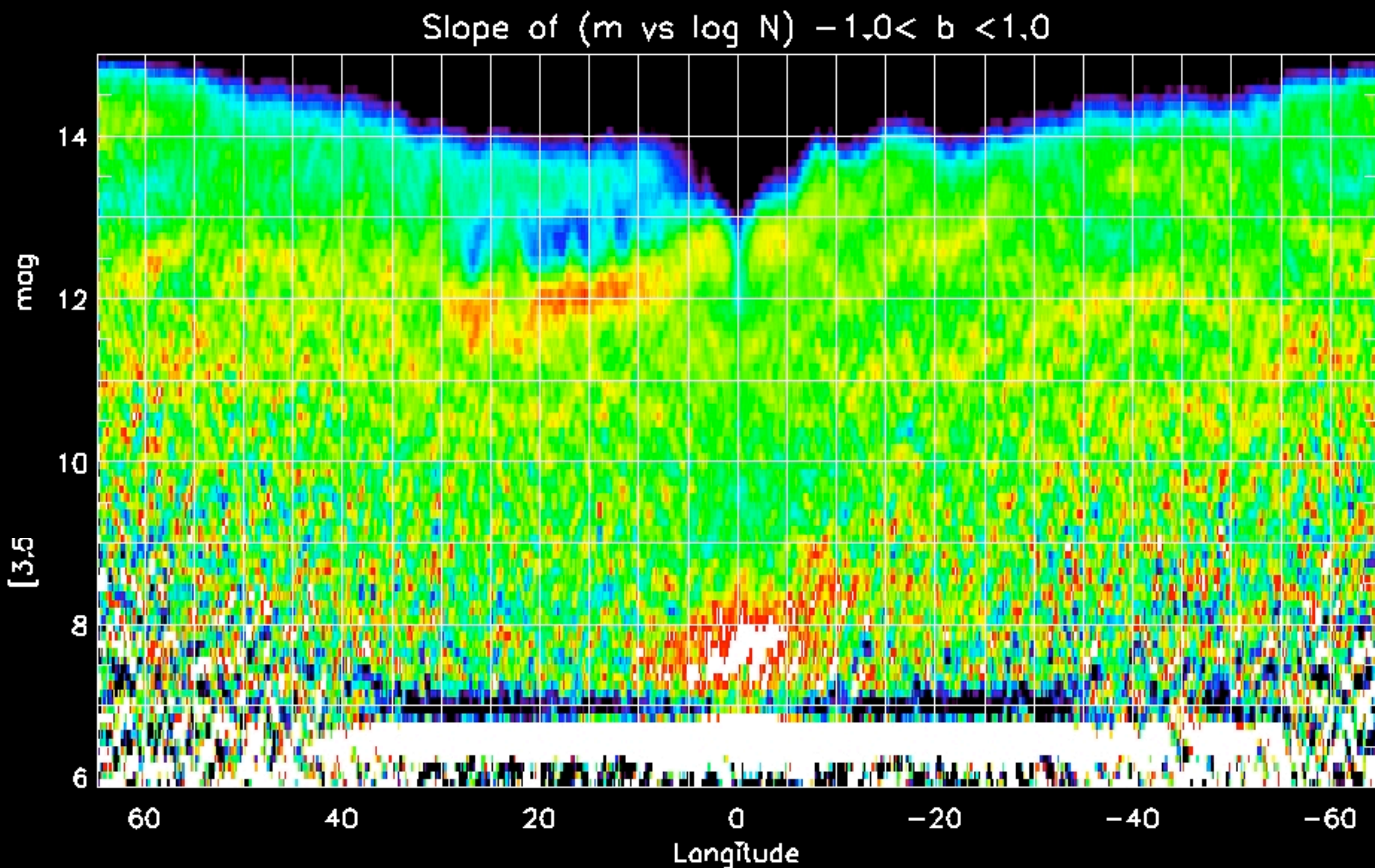


R_{bar}=4.4±0.5 kpc
ϕ =44±10°

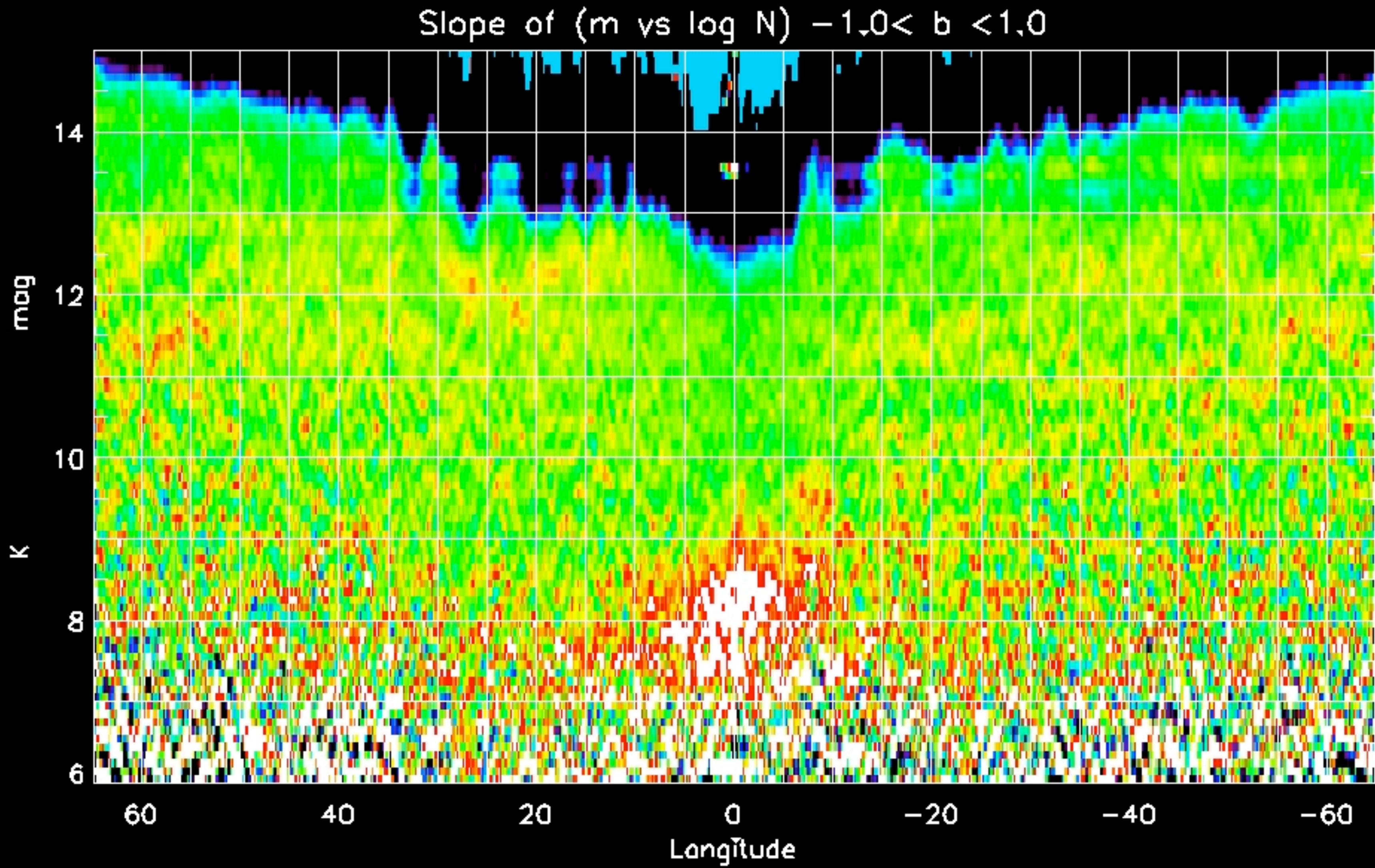
4. Galactic Structure: Red Clump Mapping (λ Dependence)



4. Galactic Structure: Red Clump Mapping (λ Dependence)

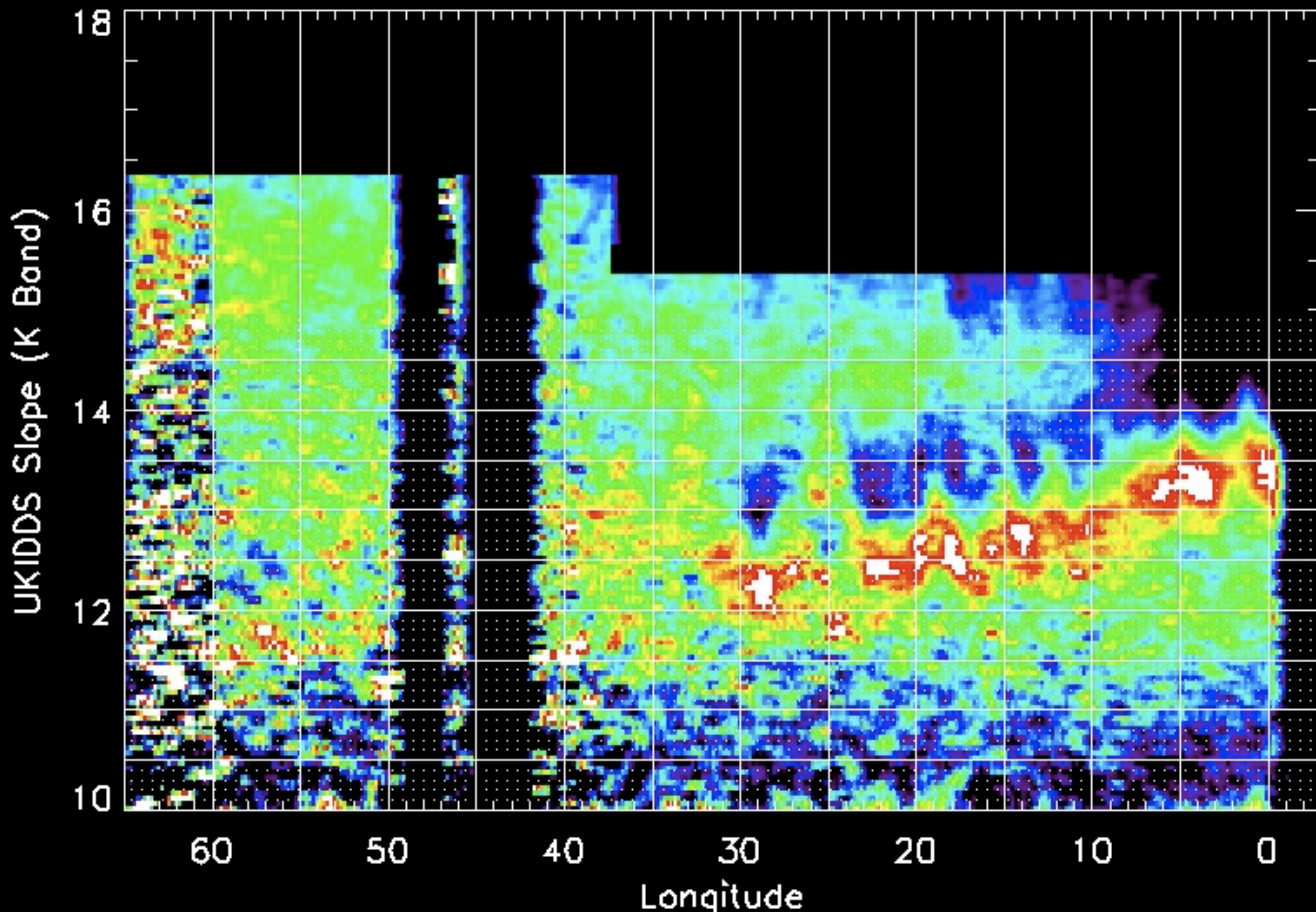


4. Galactic Structure: Red Clump Mapping (λ Dependence)



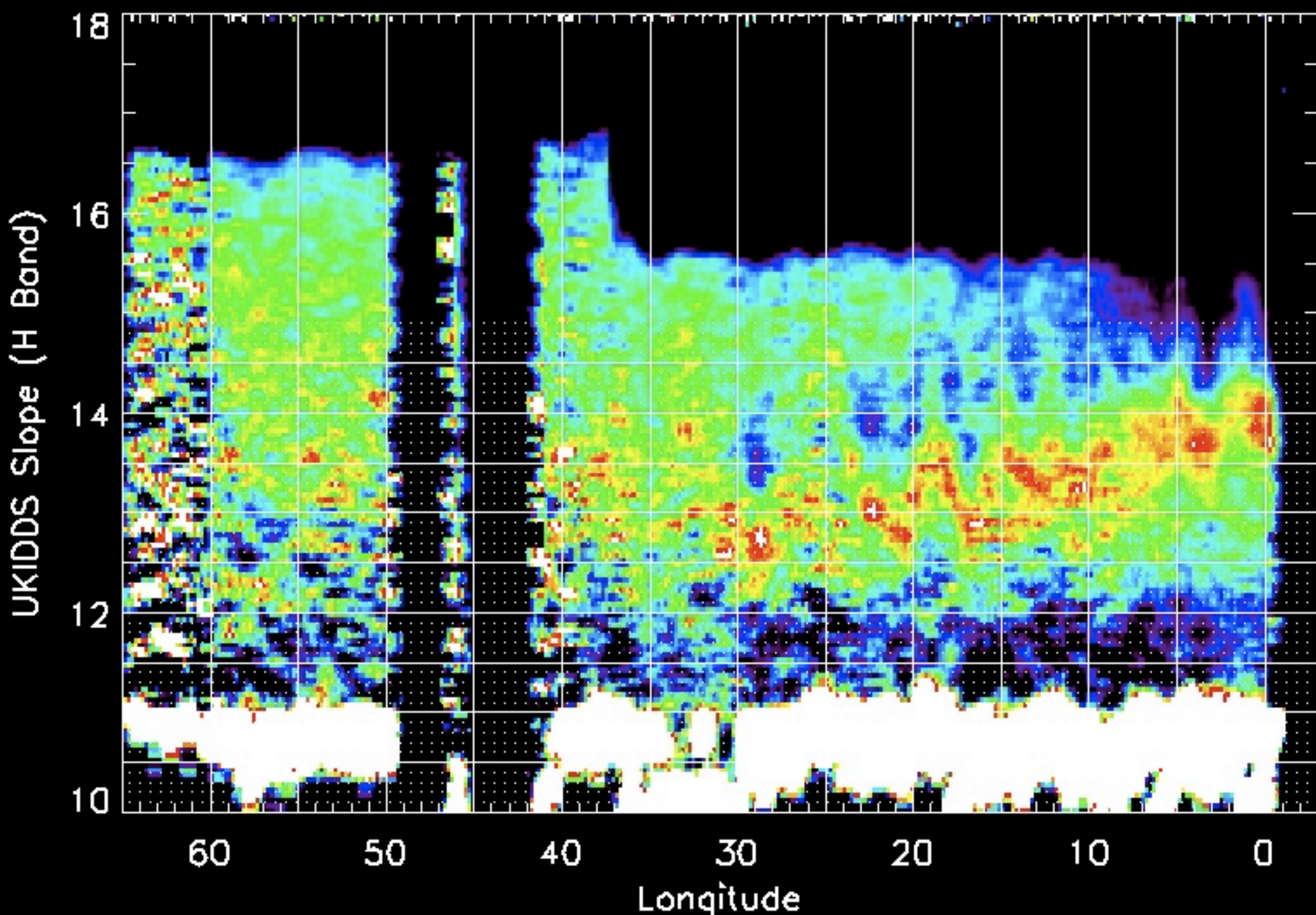
4. Galactic Structure: Red Clump Mapping

UKIDSS-Galactic Plane Survey Lucas et al (2008)



4. Galactic Structure: Red Clump Mapping

UKIDSS-Galactic Plane Survey Lucas et al (2008)



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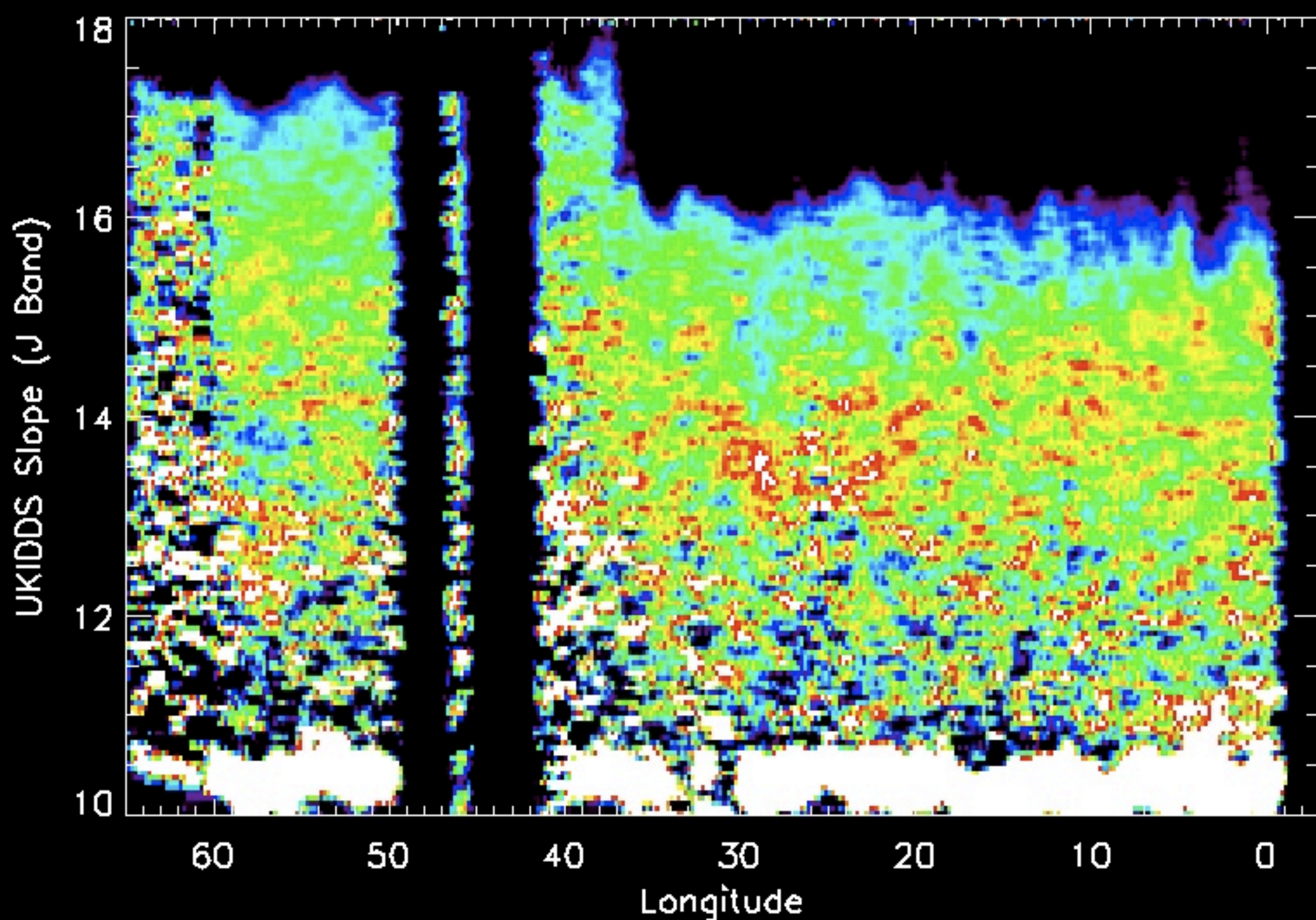
UKIDSS-Galactic Plane Survey Lucas et al (2008)



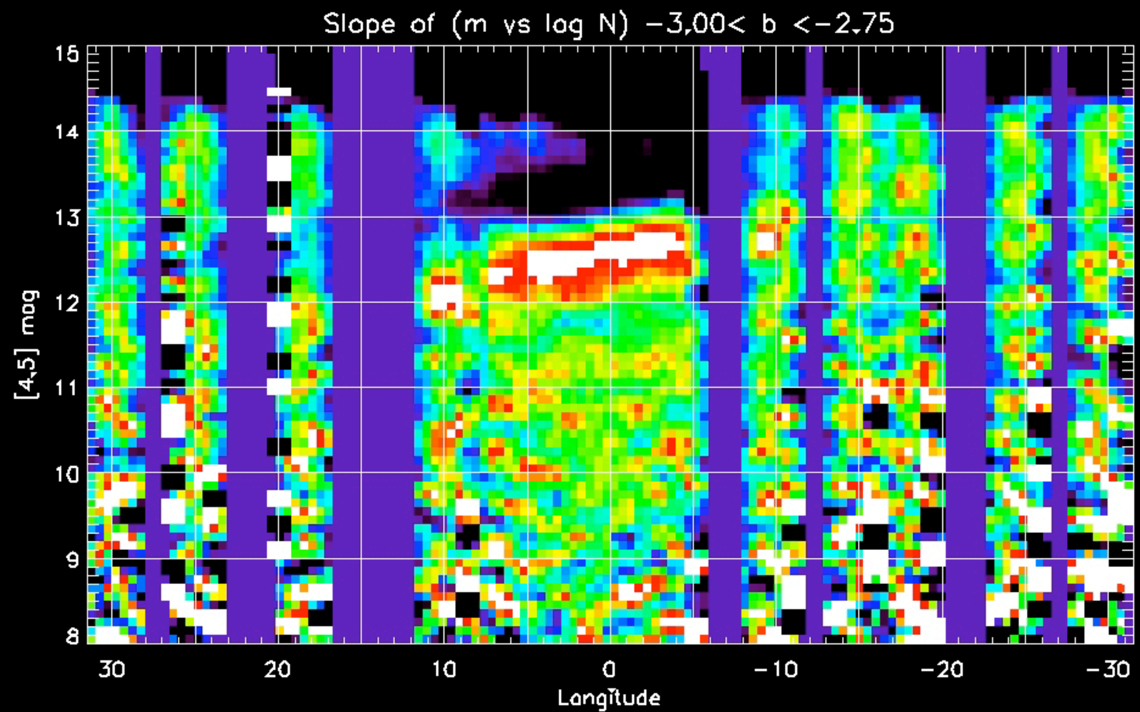
4. Galactic Structure: Comparison with Other Results

The GLIMPSE results were a confirmation of several previous group who detected the same structure in the midplane using near IR color-selected red clump giants (Hammersley et al 2000…. see López-Corredoira et al 2007).

Two recent claims:

Cabrera-Lavers et al (2008) use UKIDDS selected red clump stars to show that at b=0, l<10°, the red clump stars indicate an angle of ϕ=24°, not ϕ=44°.

Nishiyama et al (2005) use ISRF/SIRIUS selected red clump stars for b=+1, l =+10° to -10° to show a flattening at l=+5° to -5°.



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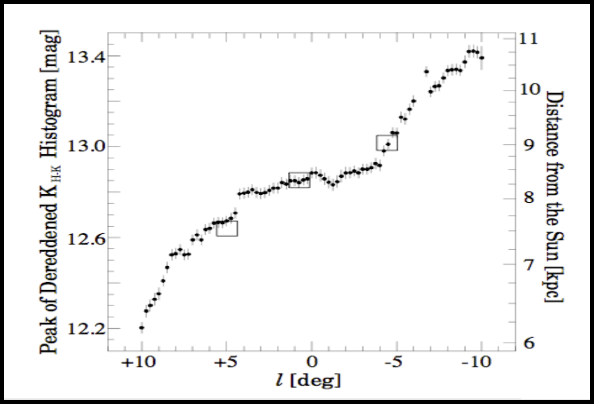
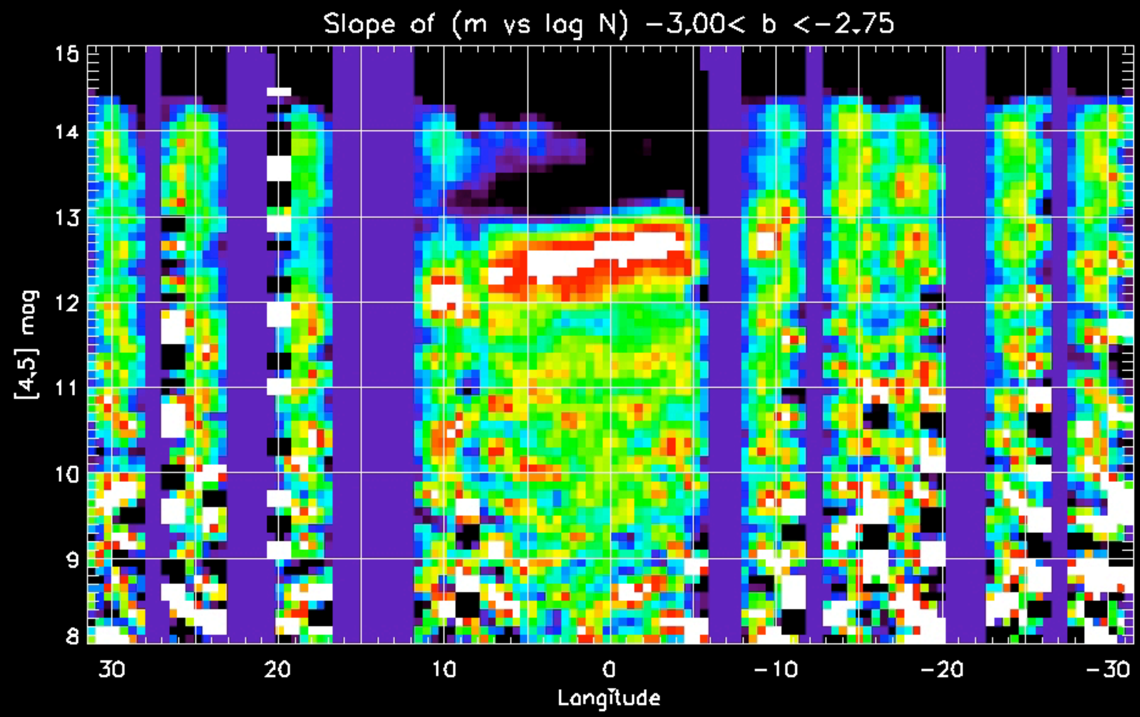


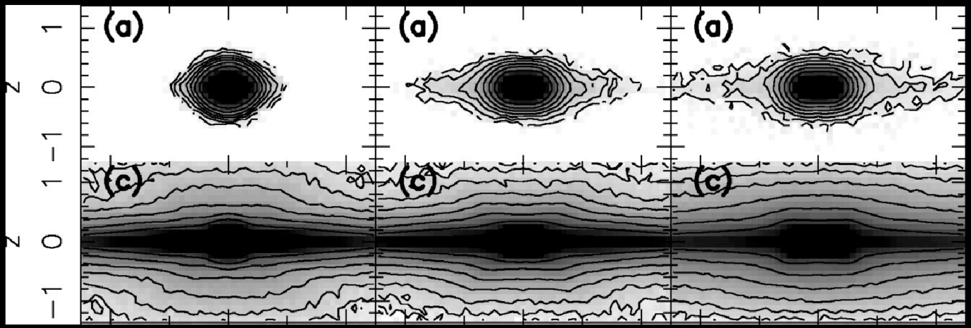


4. Galactic Structure: Questions about the Long Bar

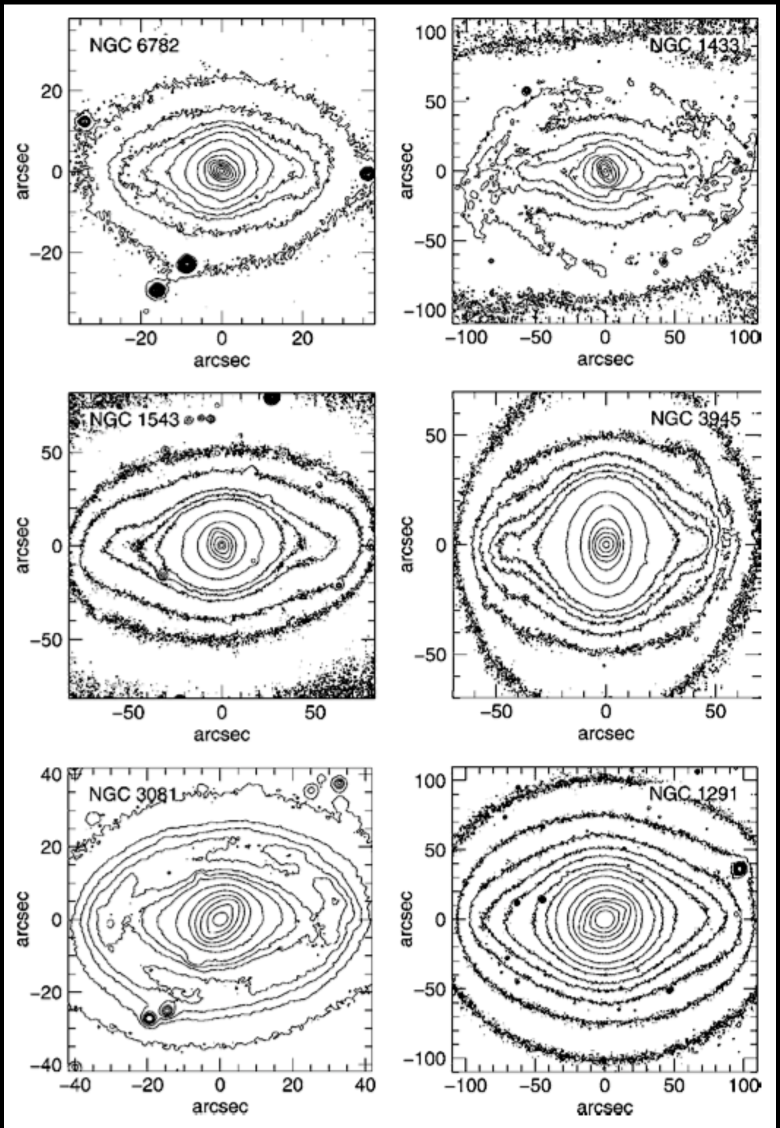
Discrepant angles for Galactic Bar (ϕ_B=24°), Long Bar(ϕ_{LB}=42°)?

1. Could a 20° "twist" in similar length bars (3.5 vs. 4.5 kpc) be observed in other galaxies?
   (Not claimed, but not searched for.)

2. Can the same models that explain how the central parts of thin bars thicken over time explain the observed twisting?



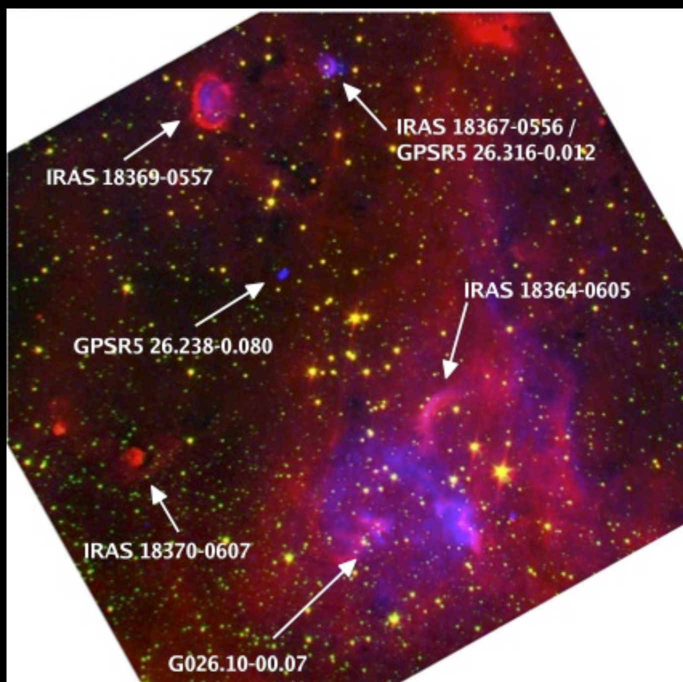
Debattista et al (2005)
See also *Athanassoula (2005,2007)*

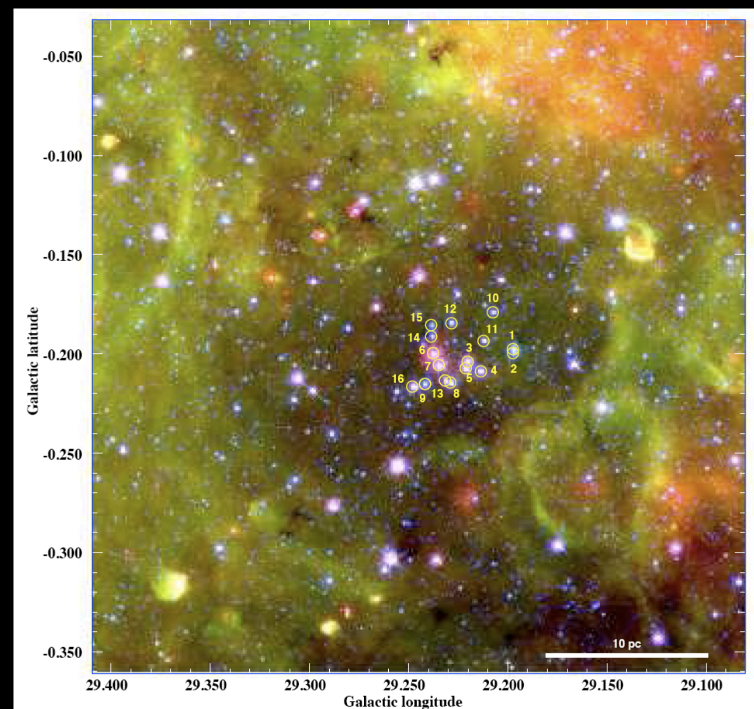


Kormendy & Kennicutt (2004) Fig 14

4. Galactic Structure: Star Formation and the Long Bar

• Vigorous star formation appears to occur at the end of the Long Bar at l~28.5-31.5°. This also appears to be the among the densest concentration of infrared dark clouds (Jackson et al 2008).

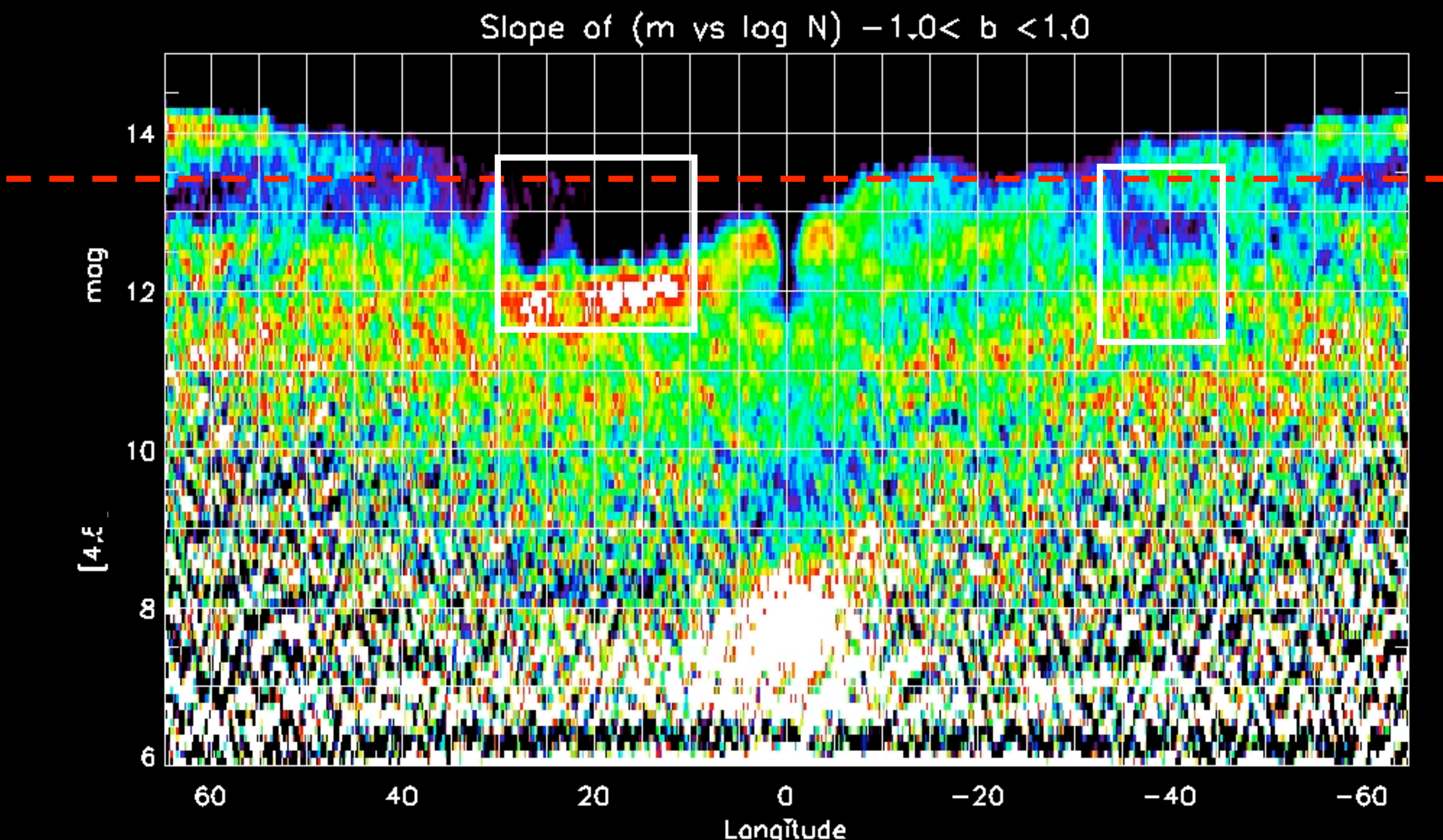




Davies et al (2007)
26 RSGs!
d=5.83(+1.9/-0.8)

Alexander et al 2009/Clark et al 2009
M_{cl}=20,000 M_o!
d=6±1 kpc

4. Galactic Structure: Mapping Scutum-Centaurus Spiral Arm



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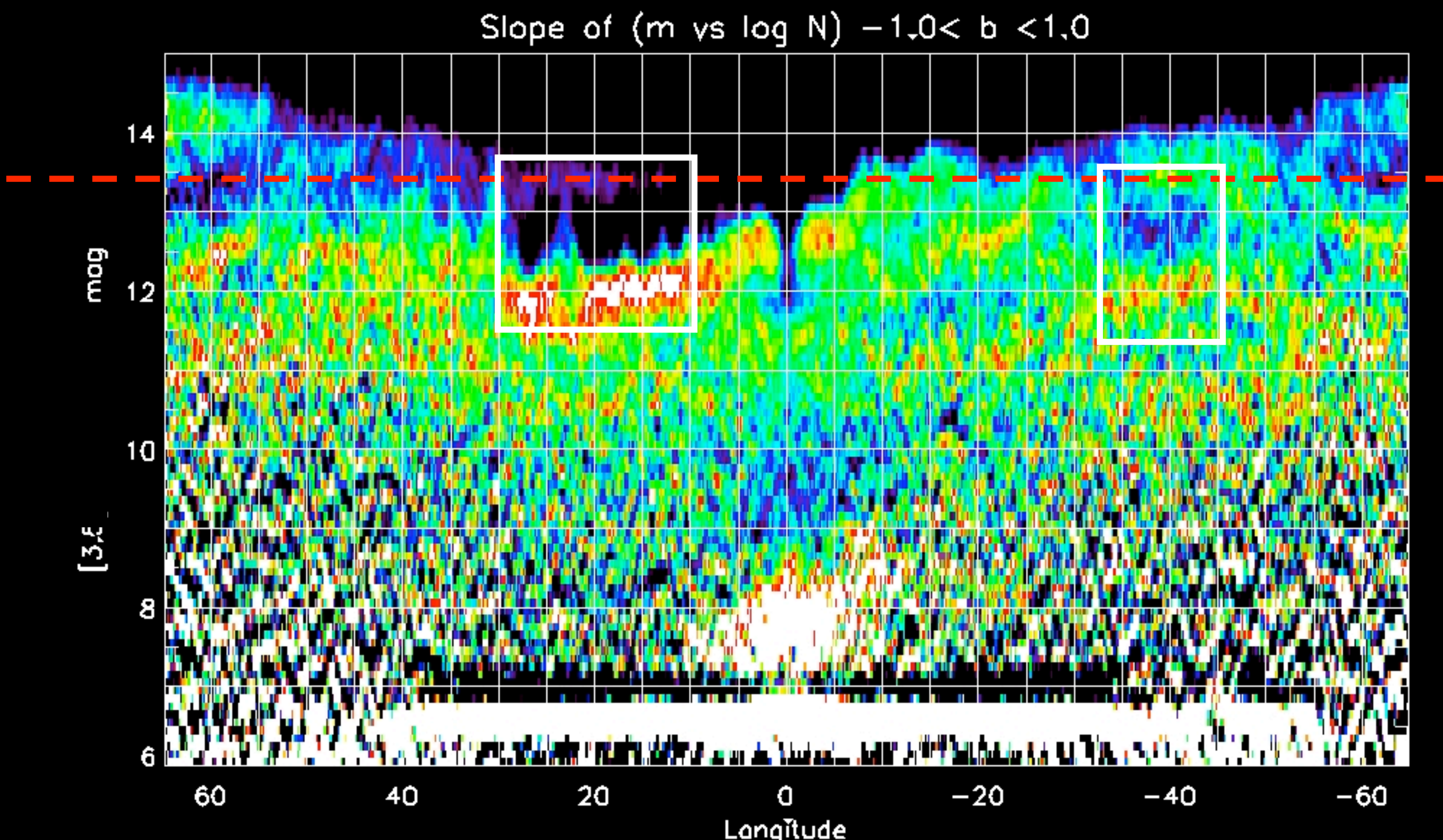

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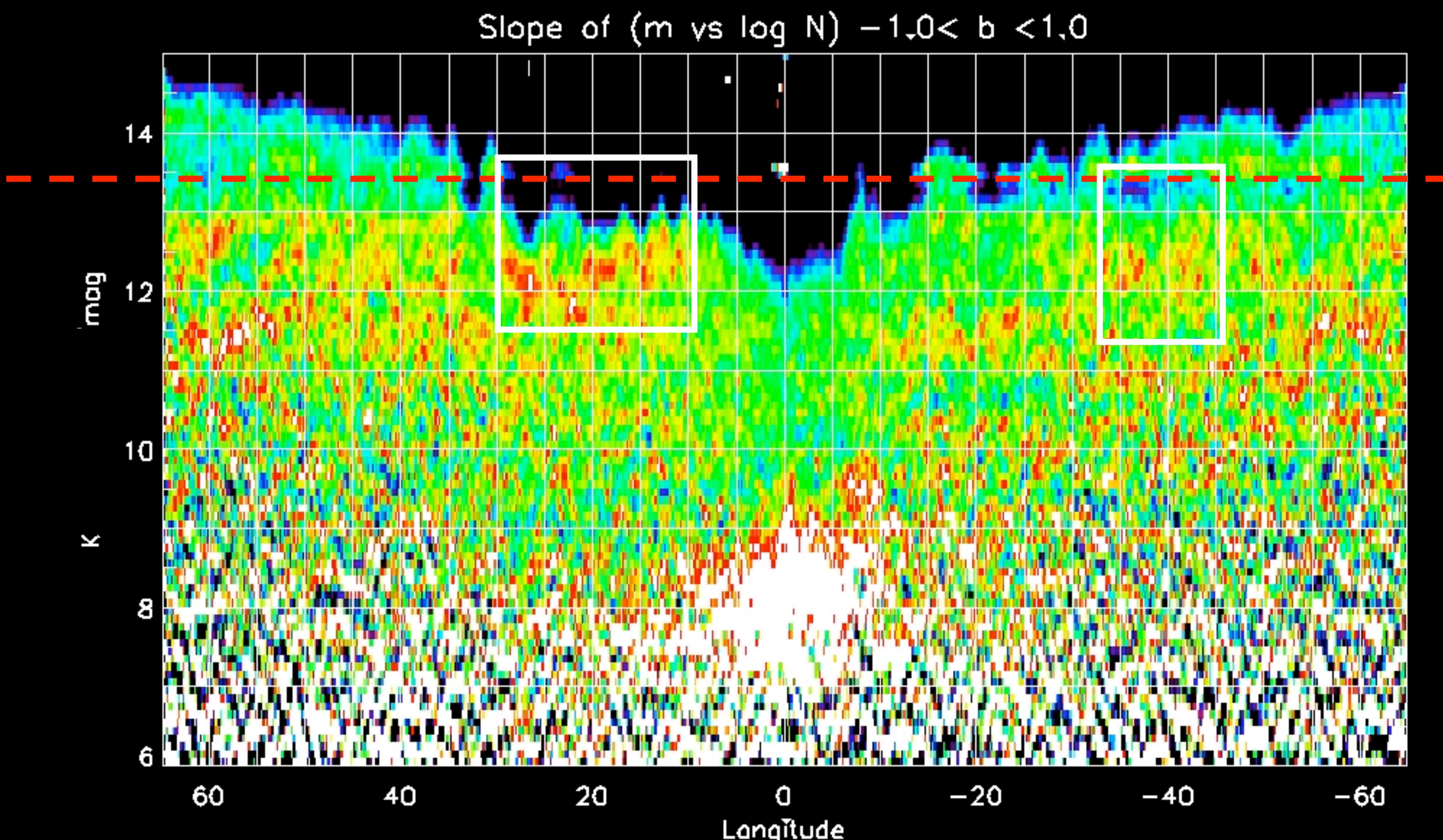

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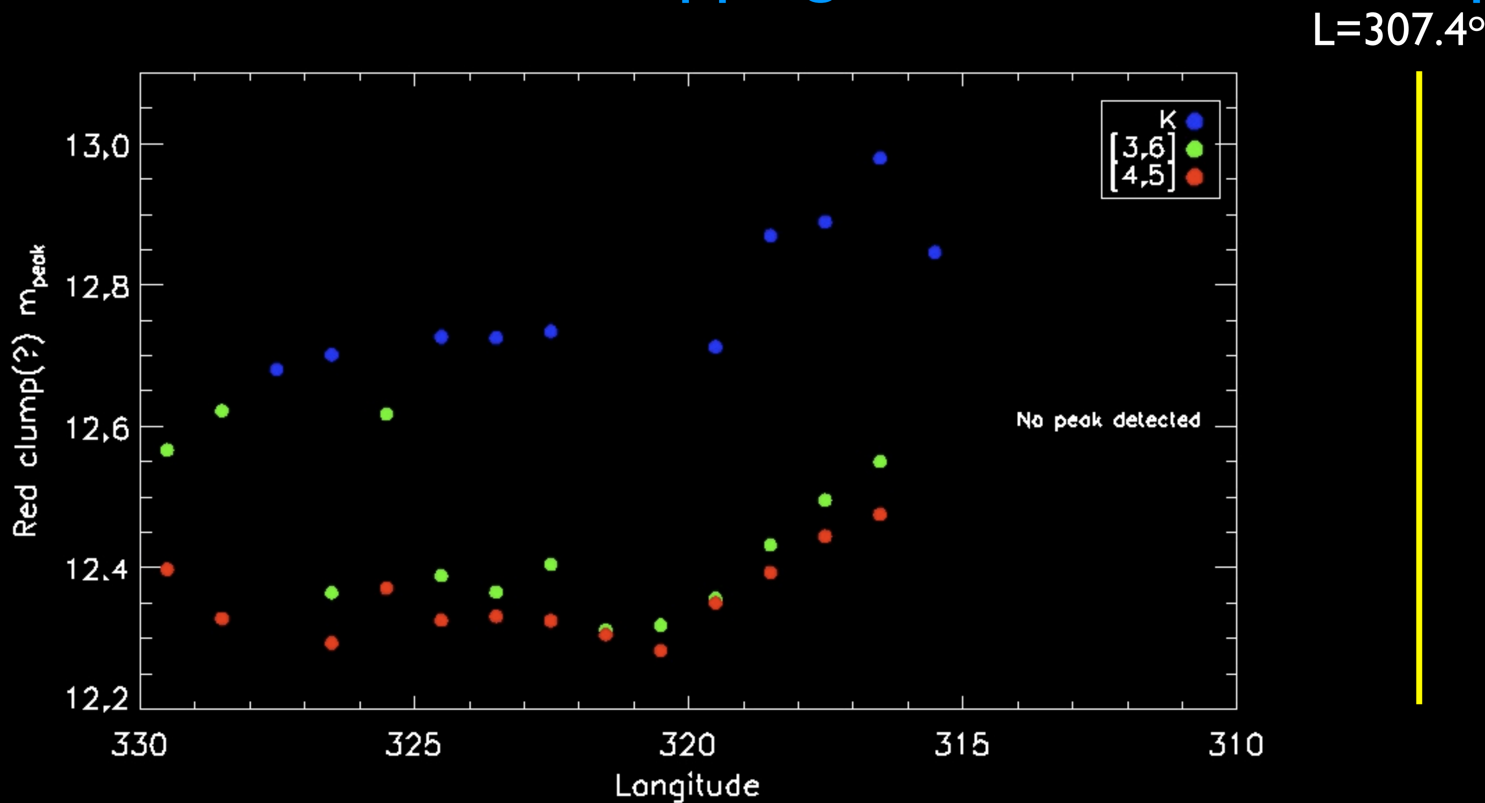
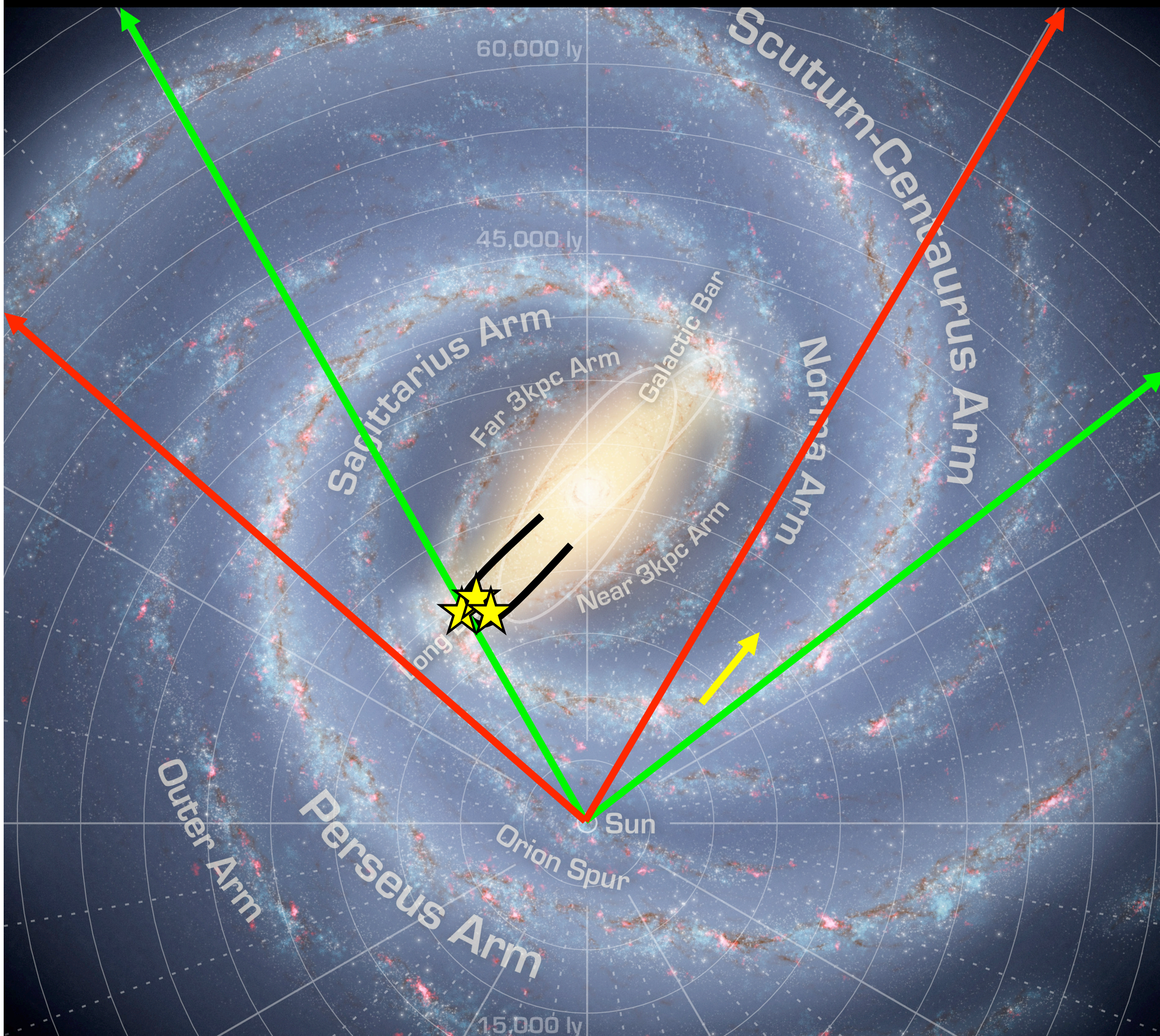


The 4th quadrant feature is consistent with an excess of red clump stars 2 kpc beyond the kinematic distance of the Scutum-Centaurus Arm. Uncertainties in position of peak ranges from 0.03 to 0.07 mag.

We probably only see it from l=316° to 324° because of a gap in the CO distribution (the Circinus Gap). We probably don't see it in the tangency direction because the spread of clump giants in distance smears out the feature. (Benjamin, 2009, in prep)

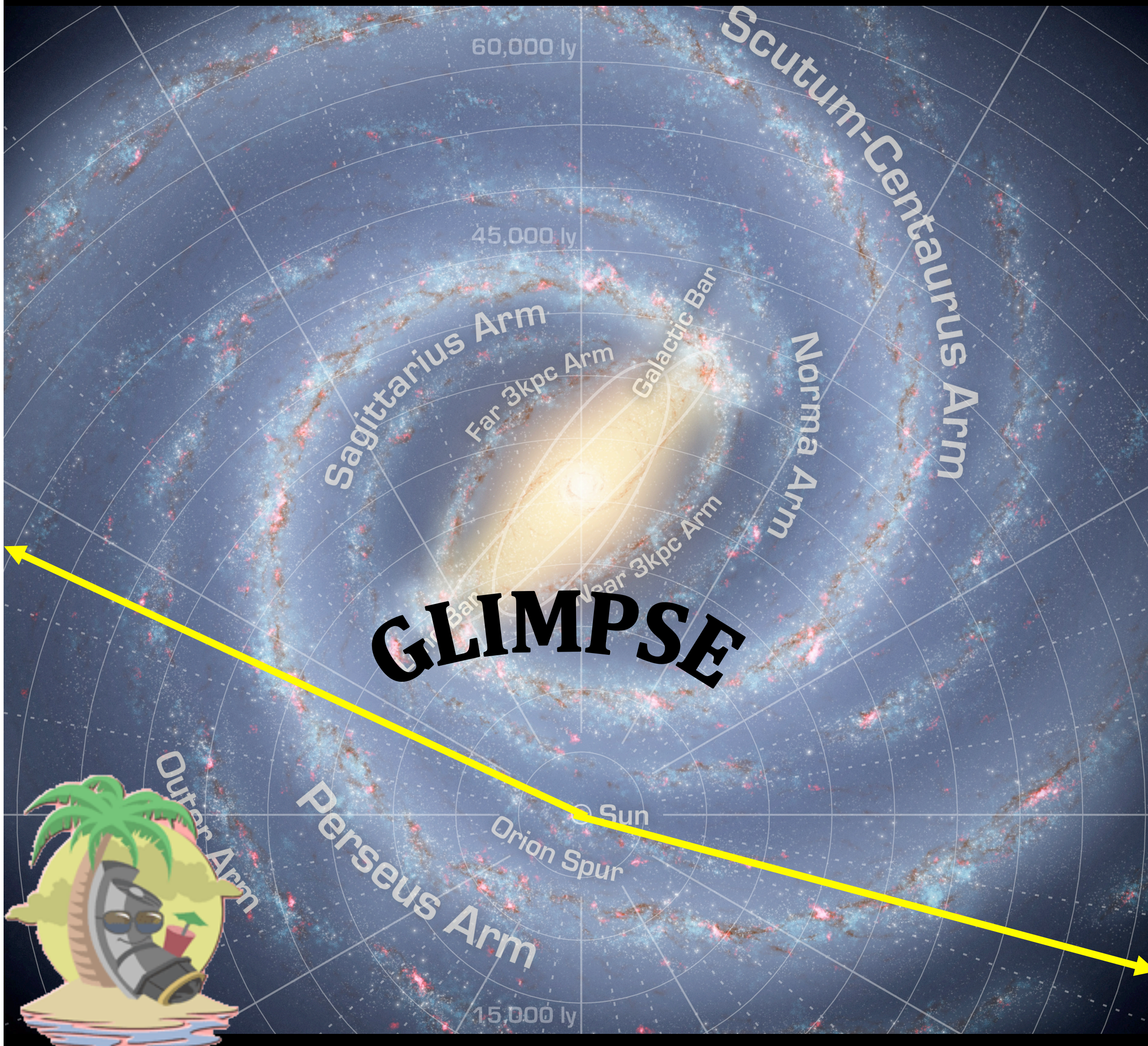
4. Galactic Structure: Summary



Artist's conception by Robert Hurt (SSC/IPAC/JPL)

1. Long Bar confirmed and (partially) mapped.
2. Tangencies confirm Drimmel (2000) and Drimmel & Spergel (2001) based on K band light from COBE, but provide more precise information.
3. Lack of stellar tangencies for other arms indicates qualitative difference between spiral arms.
4. Vigorours star formation detected at near end of Long Bar.
5. Part of Scutum Centaurus arm mapped!

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: Warm Spitzer Mission

But will there be pretty pictures?

l= 24°.470
b=-0°.203

12` x 12`

[3.6], [4.5], [8.0]

K, [3.6], [4.5]

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?

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 <u>ringed</u>, barred spiral?

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