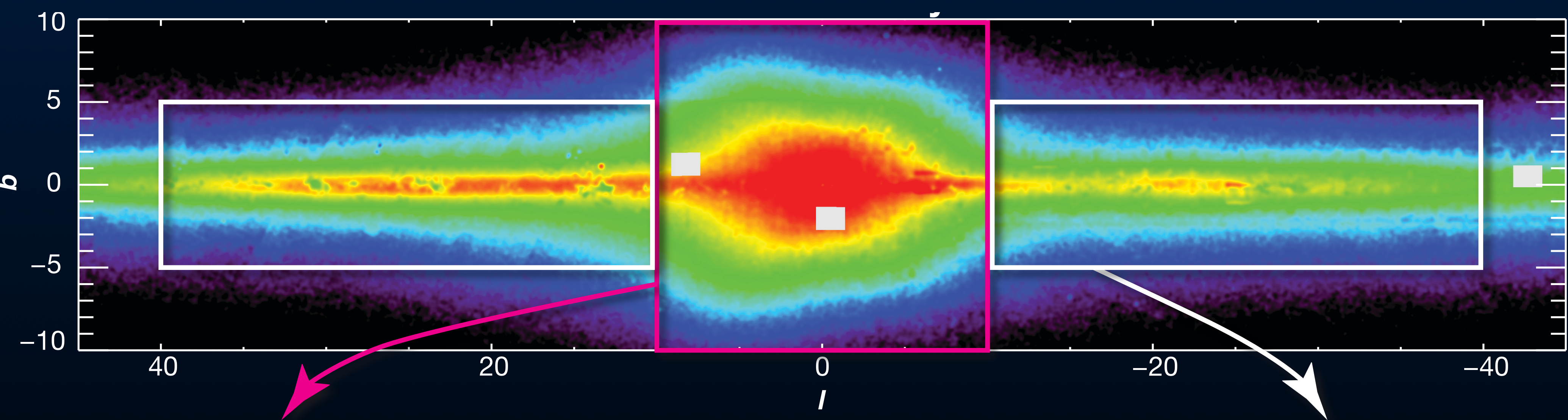
The structure of the Milky Way bar and bulge from photometric surveys

Chris Wegg, Matthieu Portail & Ortwin Gerhard



3D Structure of the Milky Way at $|l| < 10°$

Wegg & Gerhard

MNRAS, 435, 1874 (2013)

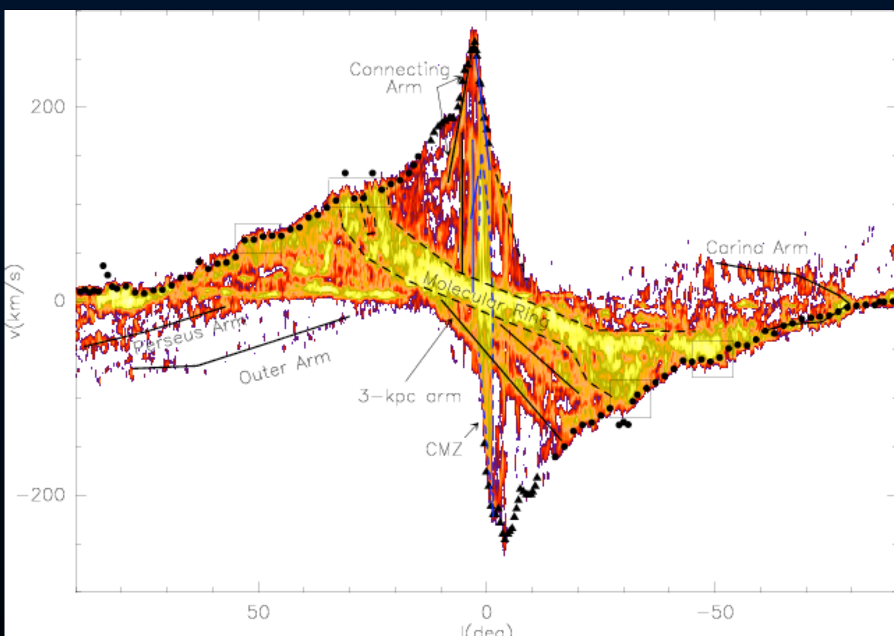
Structure of the Galactic Bar at $|l| > 10°$

Wegg, Gerhard & Portail

MNRAS, 450, 4050 (2015)

The Milky Way's Bulge

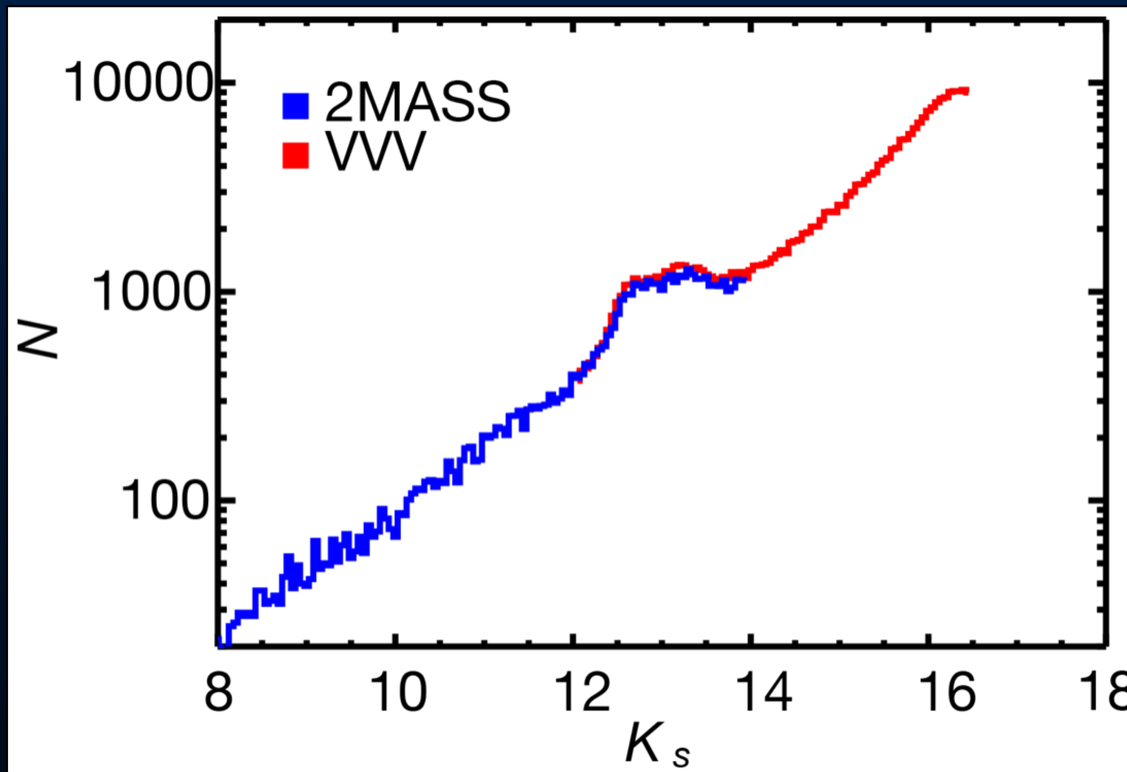
- We have known since 1990s that the Bulge is barred.
- Evidence coming from NIR photometry (Weiland *et al.* 1994), and gas kinematics (Binney *et al.* 1991).



- Can be studied in a detailed star-by-star basis.
- 6D phase space (x,v) and detailed chemical information of individual stars possible.
- Can be broken up into components including sub-dominant populations.
- Ultimate goal to construct a detailed evolutionary picture

Red clump stars

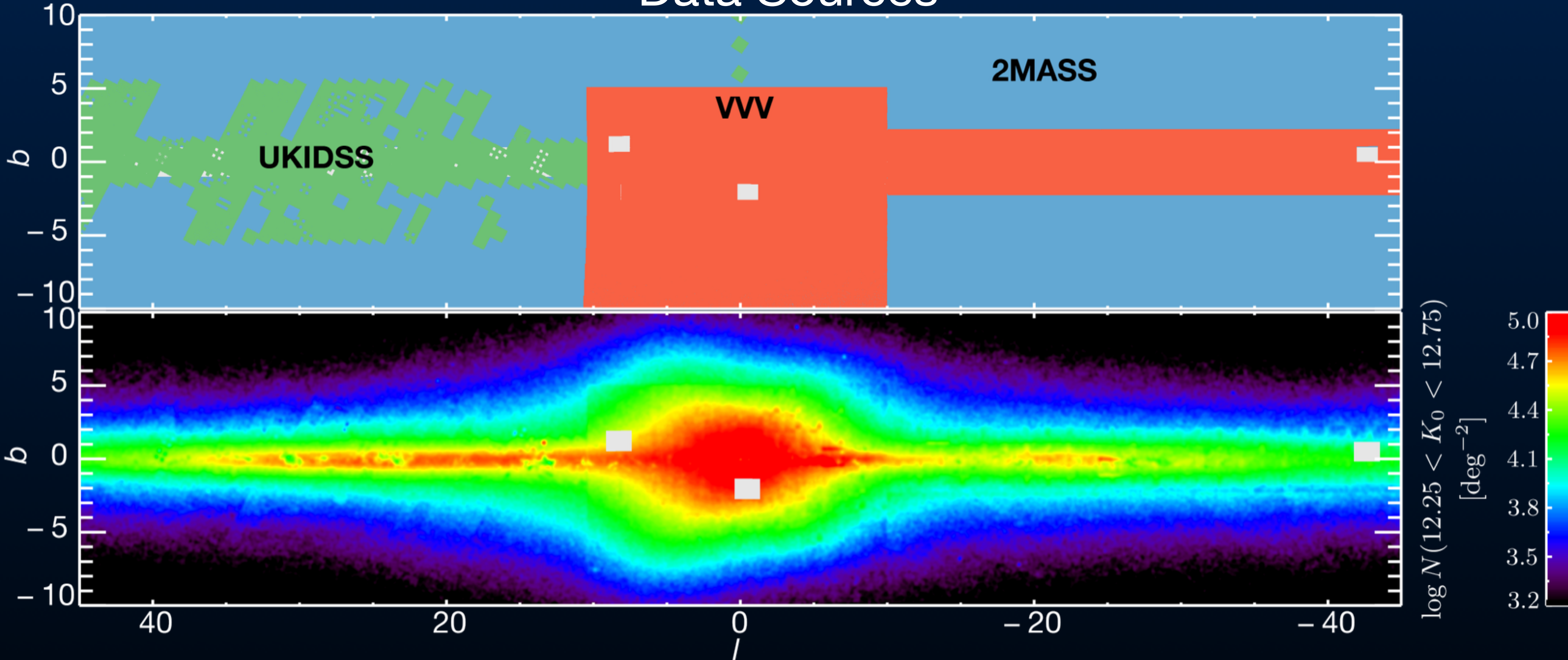
- Helium Core Burning Stars
- Standard Candle with: $\sigma(K_s) \sim 0.17$



- Used by Stanek ('94 & '97) to show bulge hosts triaxial bar-like structure
- X-shape by McWilliam & Zoccali (2010), Nataf *et al.* (2010), Saito *et al.* (2011), Ness *et al.* (2012)

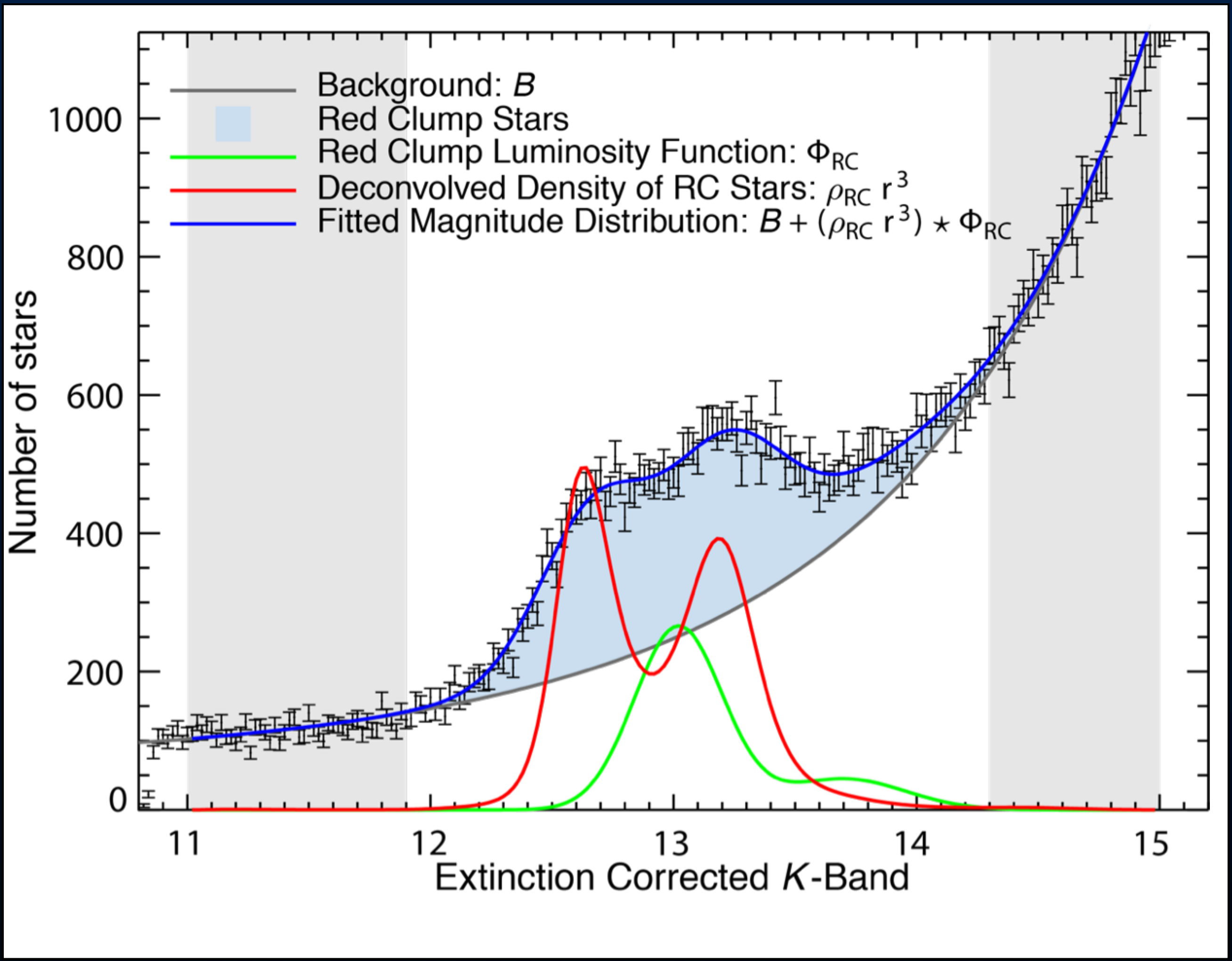
3D Structure of the Milky Way at $|l| < 10°$

Data Sources



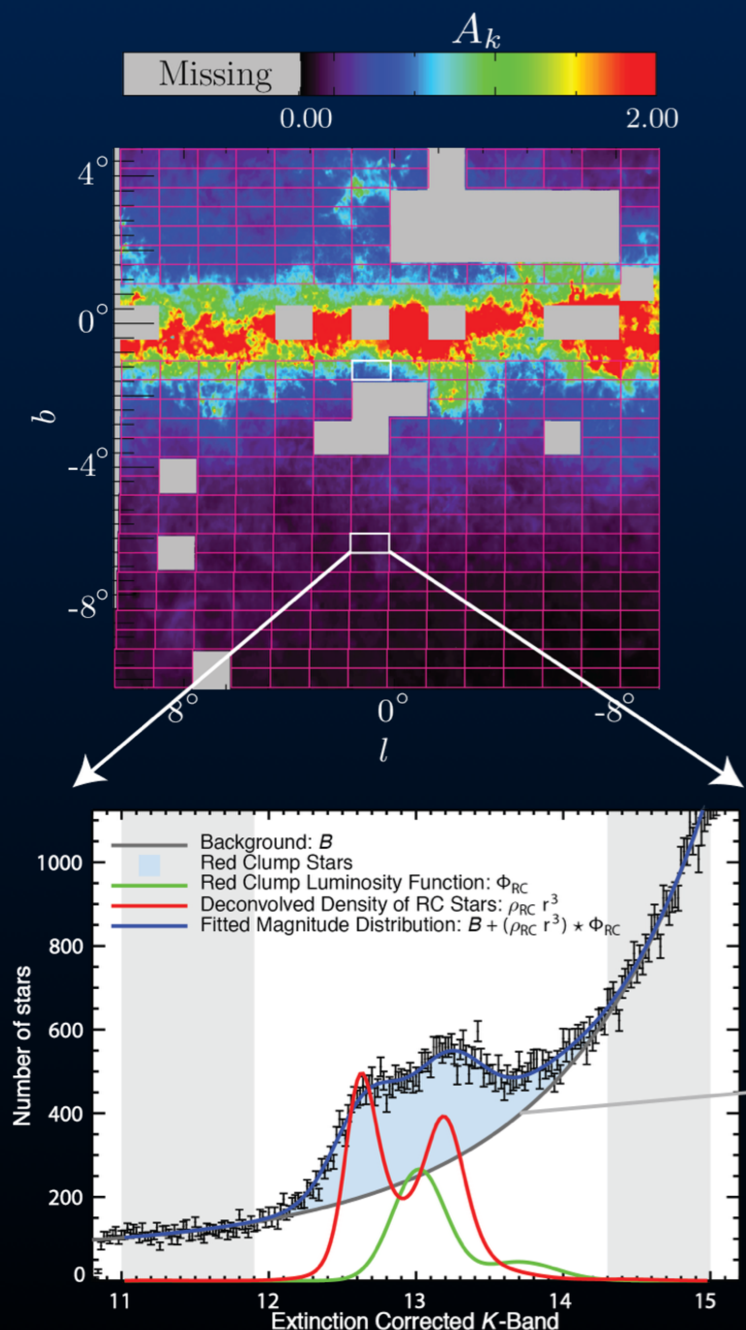
3D Structure of the Milky Way at $|l| < 10°$

Line-of-sight density estimation

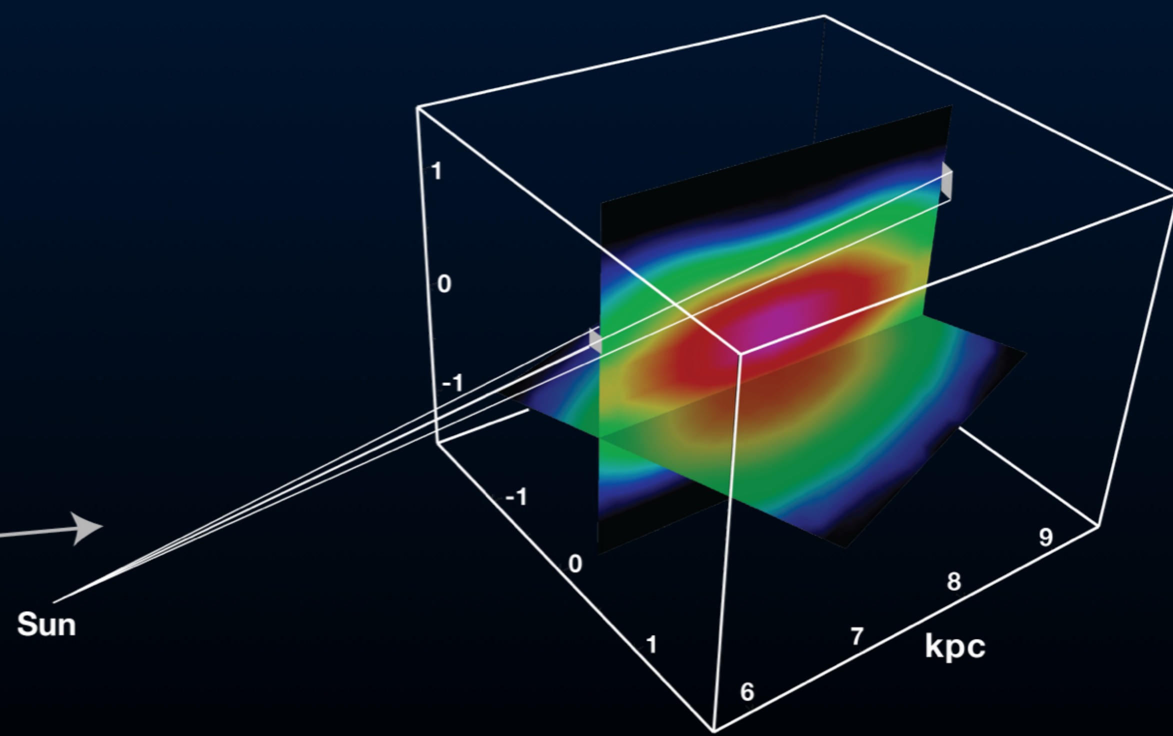


- Fit background to region outside Bulge's RC stars
- Statistically identified red clump stars are convolution of line-of-sight density with luminosity function.
- Deconvolve to estimate density using a slight variation on Lucy-Richardson algorithm

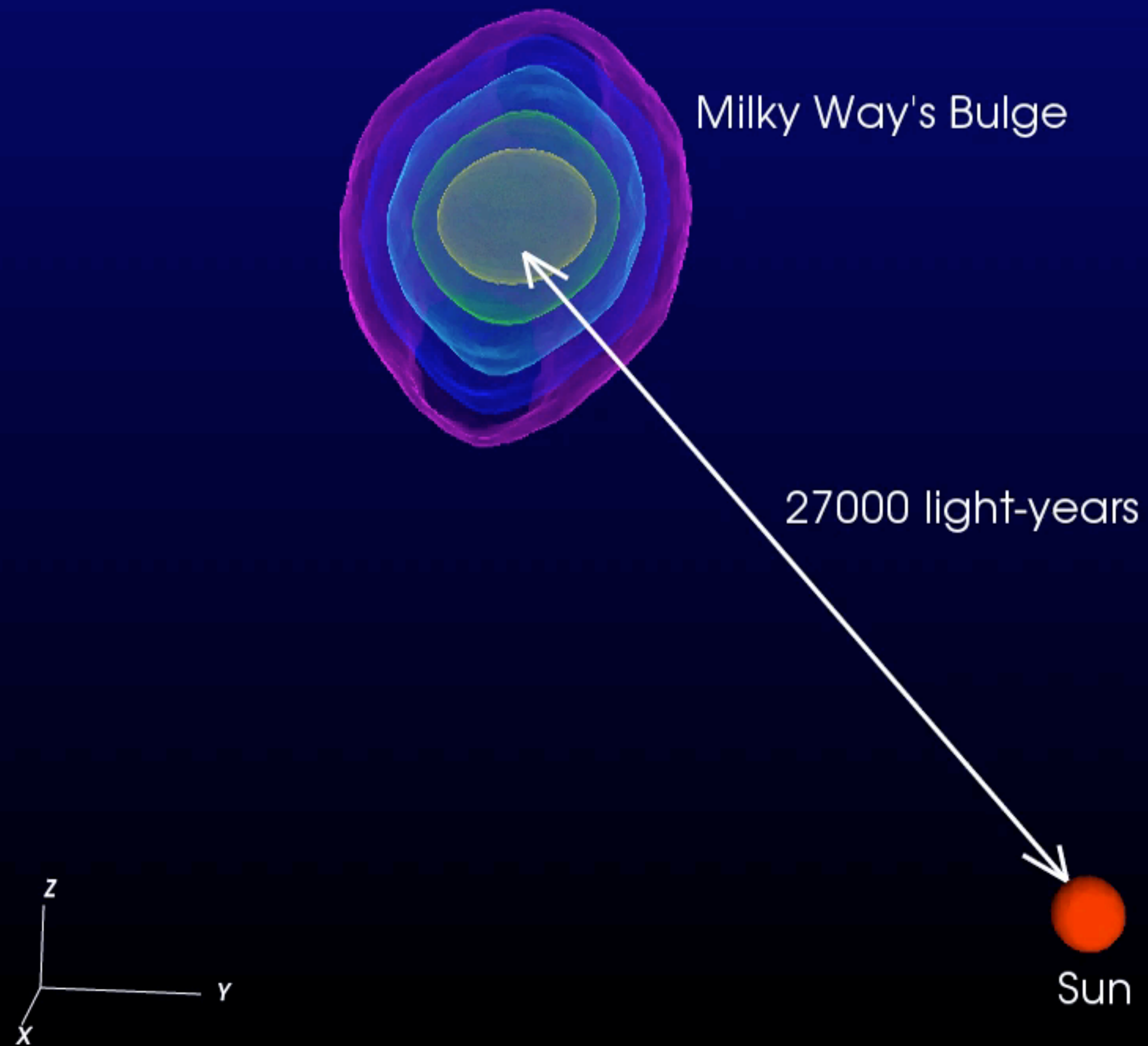
3D Structure of the Milky Way at $|l| < 10°$



- Combine ~300 line-of-sight density estimates in 3D density
- 3D map non-parametric, assuming only 8-fold mirror symmetry, with small departures



3D Structure of the Milky Way at $|l| < 10°$

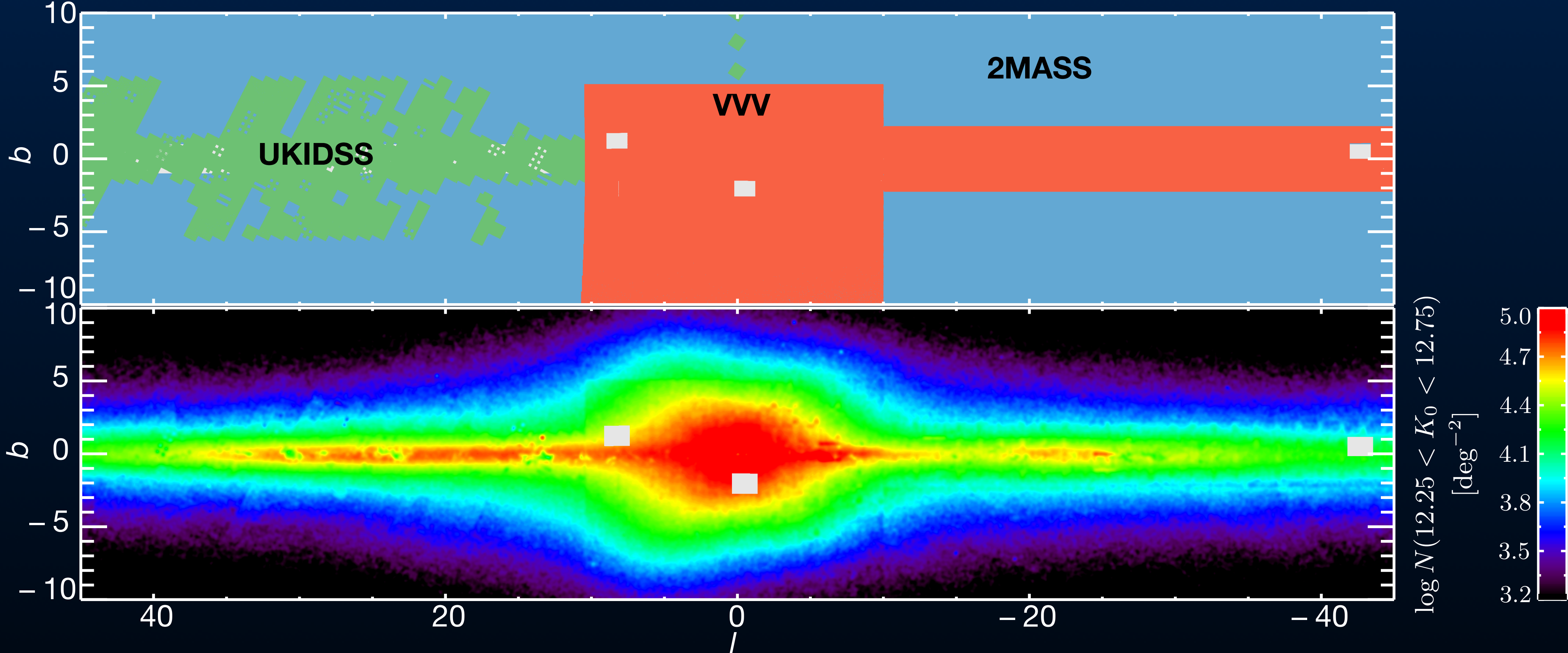


Wegg & Gerhard, MNRAS, 435, 1874 (2013)

3D Structure of the Milky Way at $|l| < 10^\circ$

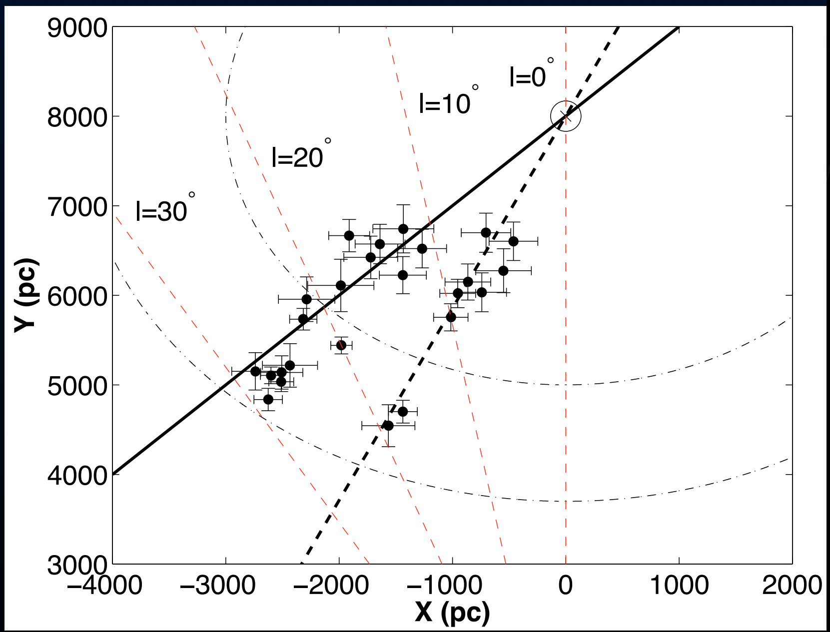
- We have used VVV data to make a 10% accurate 3D non-parametric measurement of the stellar density of the bulge.
- Applications include *e.g.* Gas Dynamics in the resultant potential & Matthieu Portail's talk on constructing N-body dynamical models of the bulge.
- Overall bulge has Box/Peanut shape. Similar to other external B/P bulges, and N-body bar simulations of the central parts of buckled bars.

Data Sources

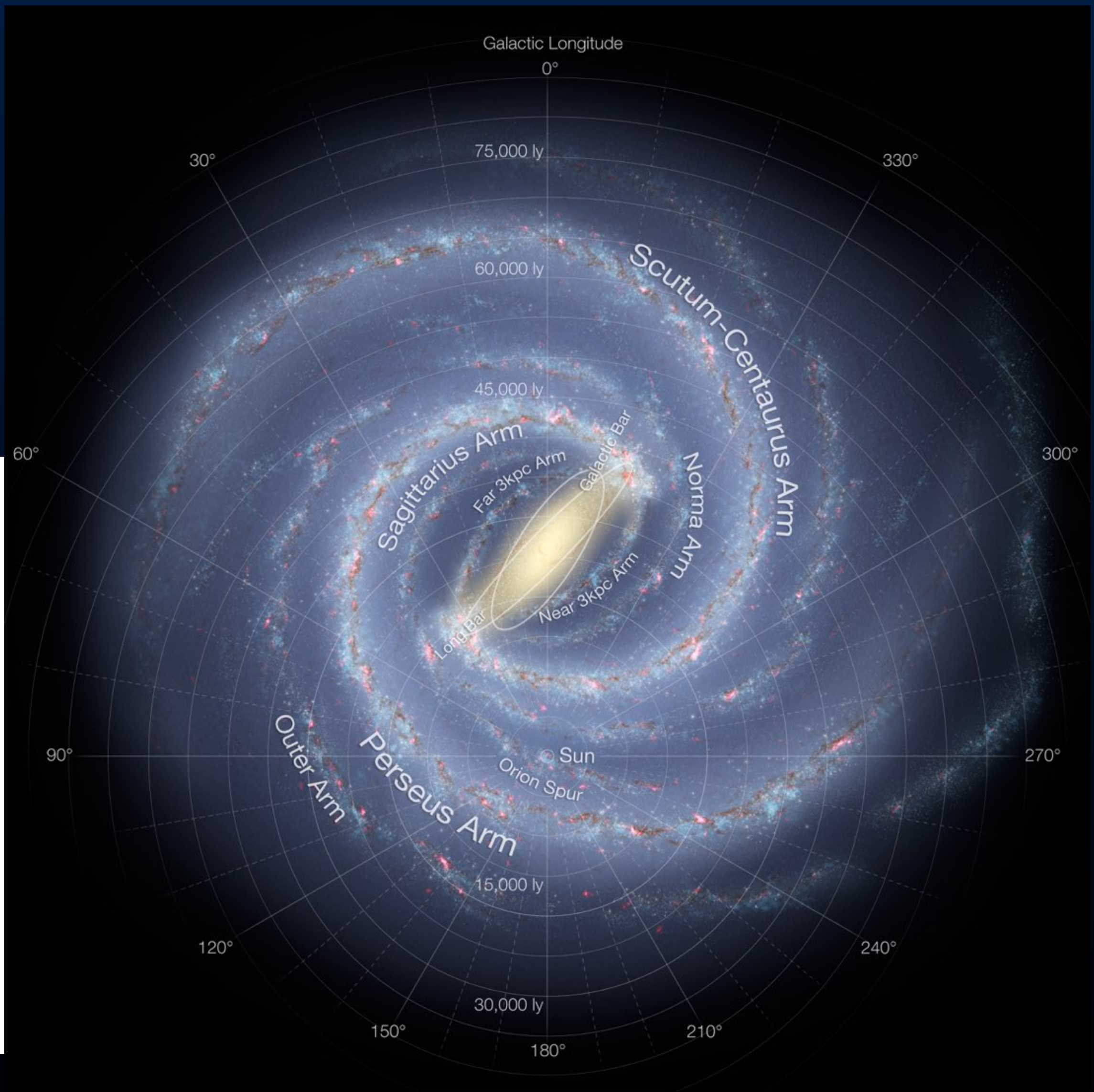


The Long Bar of the Milky Way

- The bar outside the bulge called the ***long bar*** was suggested by Hammersley et al. (1994).
- But we still have very few details or understanding
- Best investigation below. Long bar seems misaligned to bulge. Do we have two bars in the Milky Way?



Cabrera-Lavers *et al.* (2008)



Differences to the Bulge

- Extinction is more challenging. Can't make an extinction map, instead correct on a star-by-star basis.

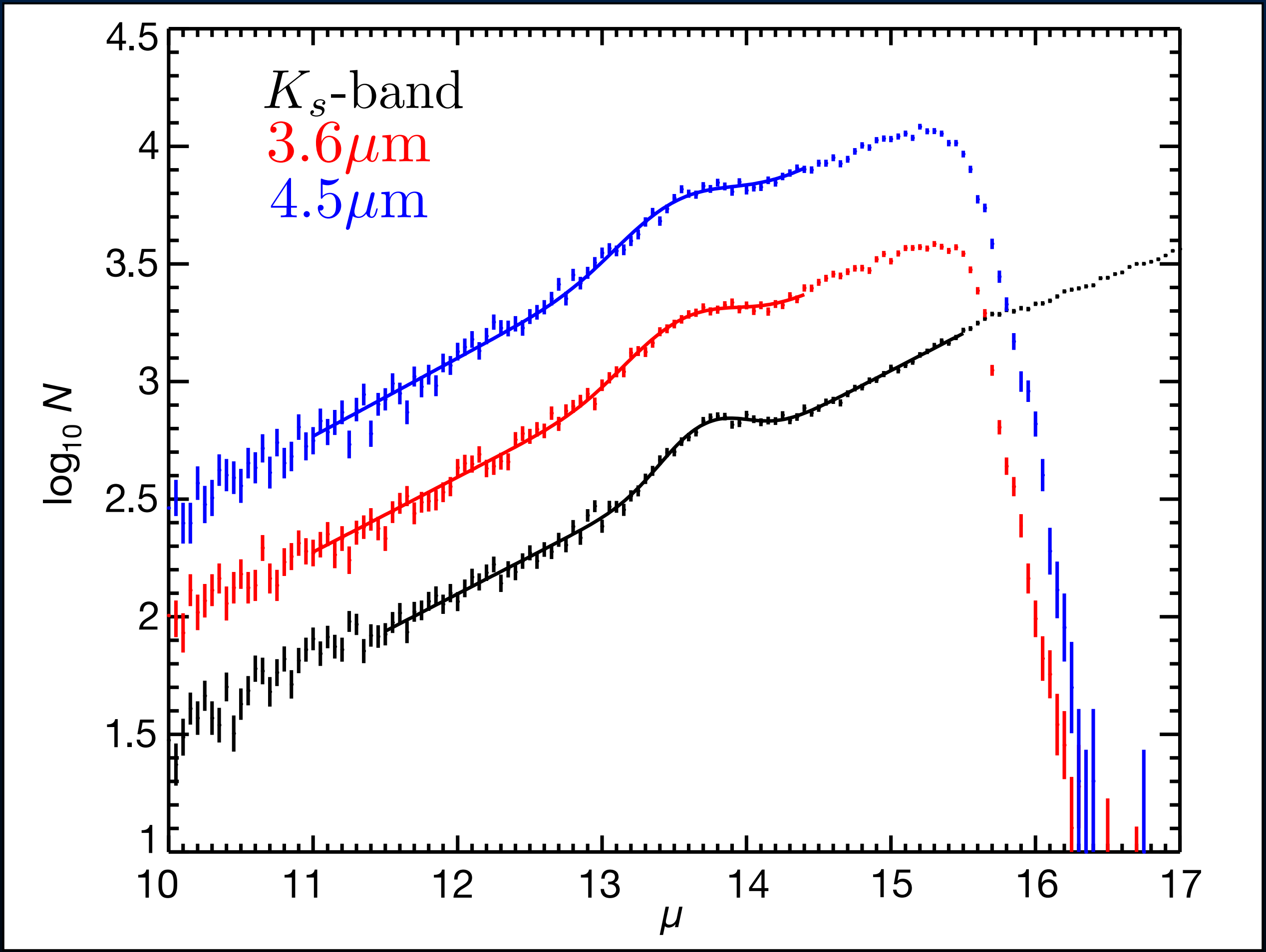
- Signal-to-noise of RCGs is smaller *i.e.* background of foreground disk stars is higher, number of RCGs lower.

  Can't field-by-field non-parametrically estimate density. Two approaches:

  1. Fit to clump in each field: gives a view as close to data as possible.
  2. Fit parametric models. Improves signal-to-noise by connecting fields and fitting for only parameters.

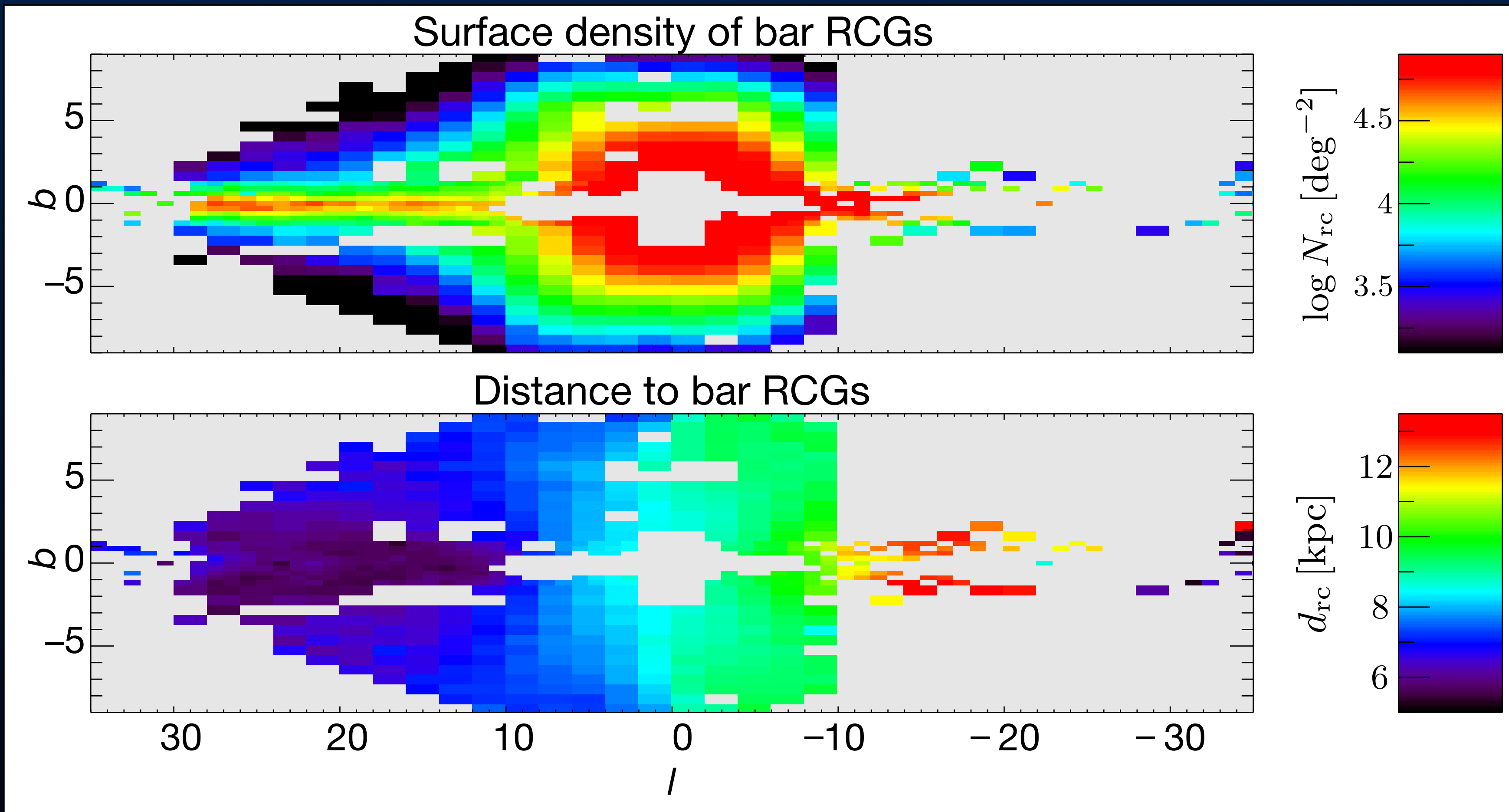
Typical Field

At l=18.5° b=0.9° with size Δl=1° Δb=0.3°



To each field fit Gaussian for RCGs + Exponential for background

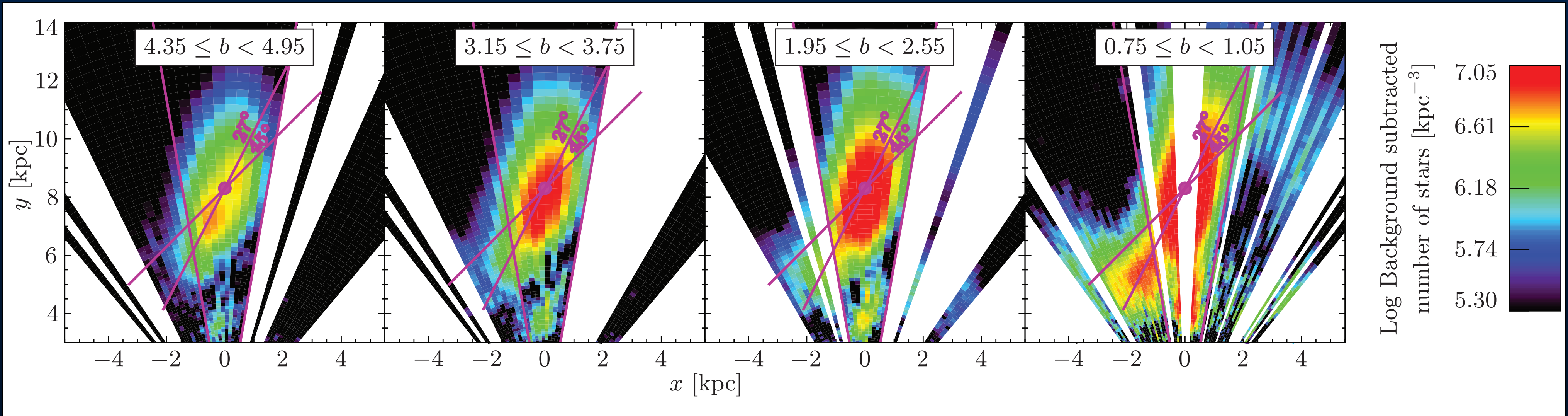
Results of fitting to the >1000 fields



- Only bar red clump giants shown
- No sharp transition from bulge to long bar
- Bar extends to all the way to |b|~5° at l~20°

Structure of the Galactic Bar at $|l| > 10^\circ$

Background subtracted number of RCGS in different *b* slices



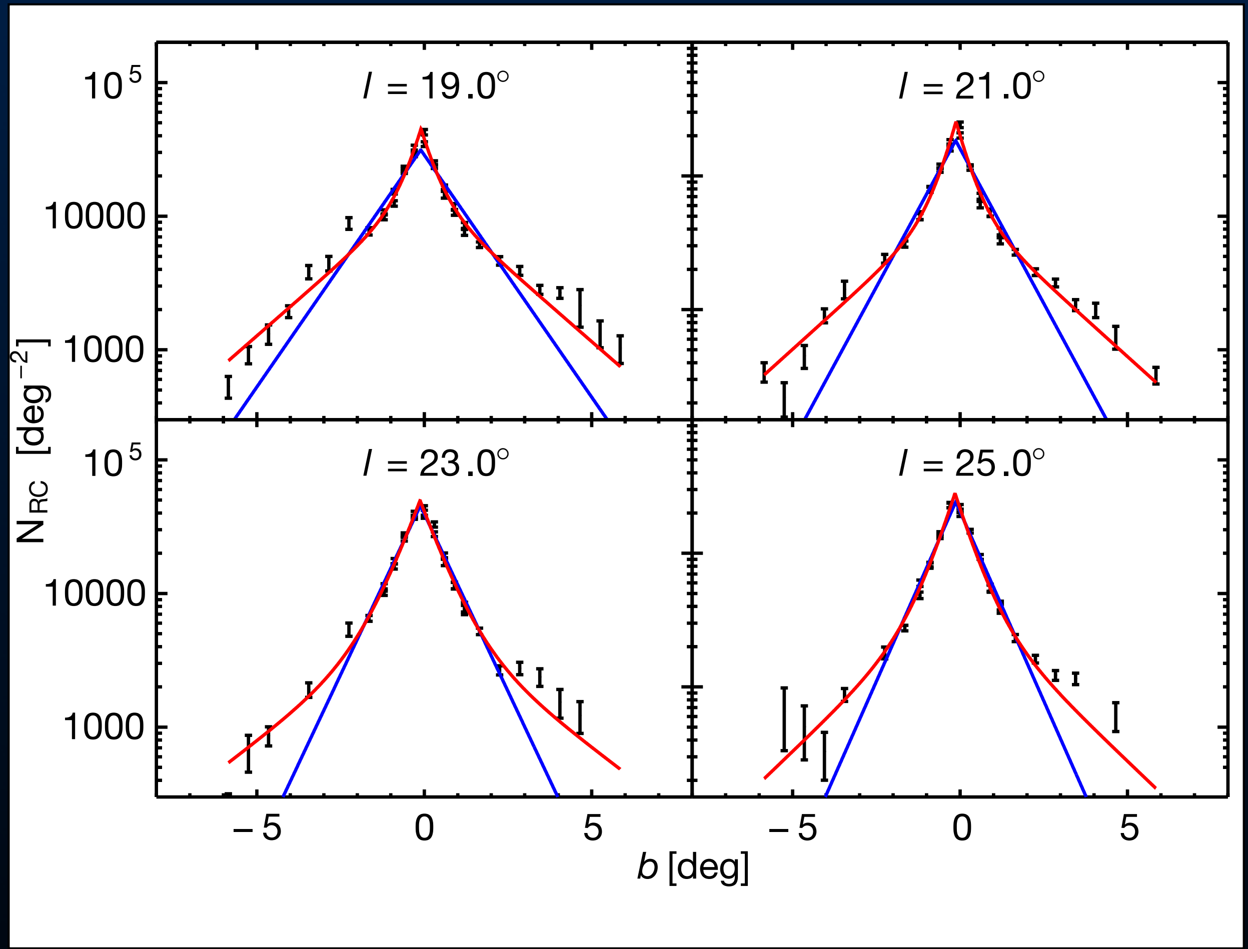
NOT deconvolved. Instead the density plotted if RCGs were perfect standard candles.

Still a useful way of visualizing the data: we can see the data is much closer to bar angle of 27° than the previous measurement of 45°

Vertical Structure

- Examine number of RCGs in the bar *vs. l* . Vertical structure better represented by two exponentials:

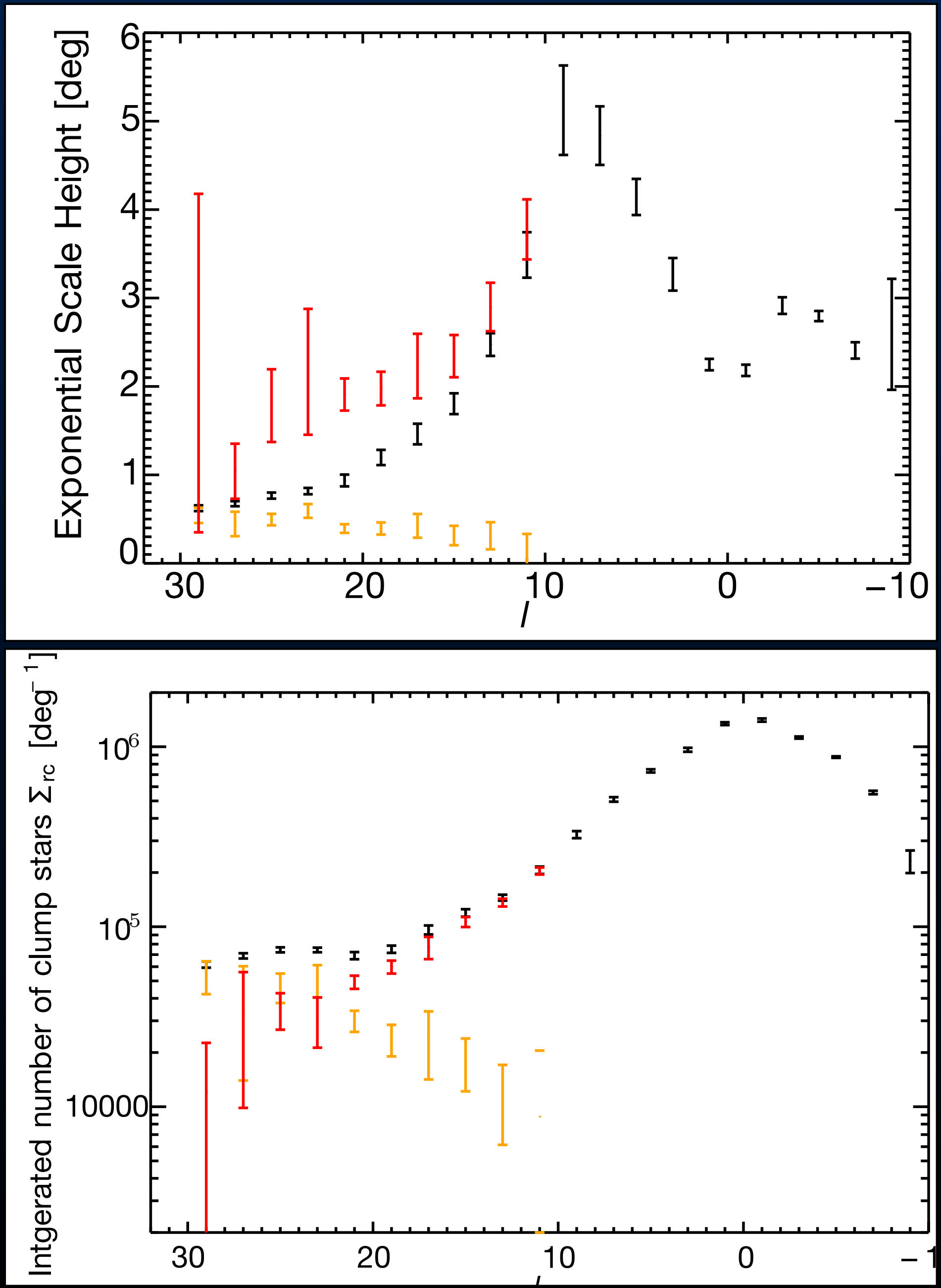
$$N_{RC}(b) = \frac{\Sigma_{RC,A}}{2b_{1,A}} \exp\left(-\frac{|b-b_0|}{b_{1,A}}\right)$$
$$\frac{\Sigma_{RC,B}}{2b_{1,B}} \exp\left(-\frac{|b-b_0|}{b_{1,B}}\right)$$



Vertical Structure: ‘Thin Bar’ and ‘Super-Thin Bar’

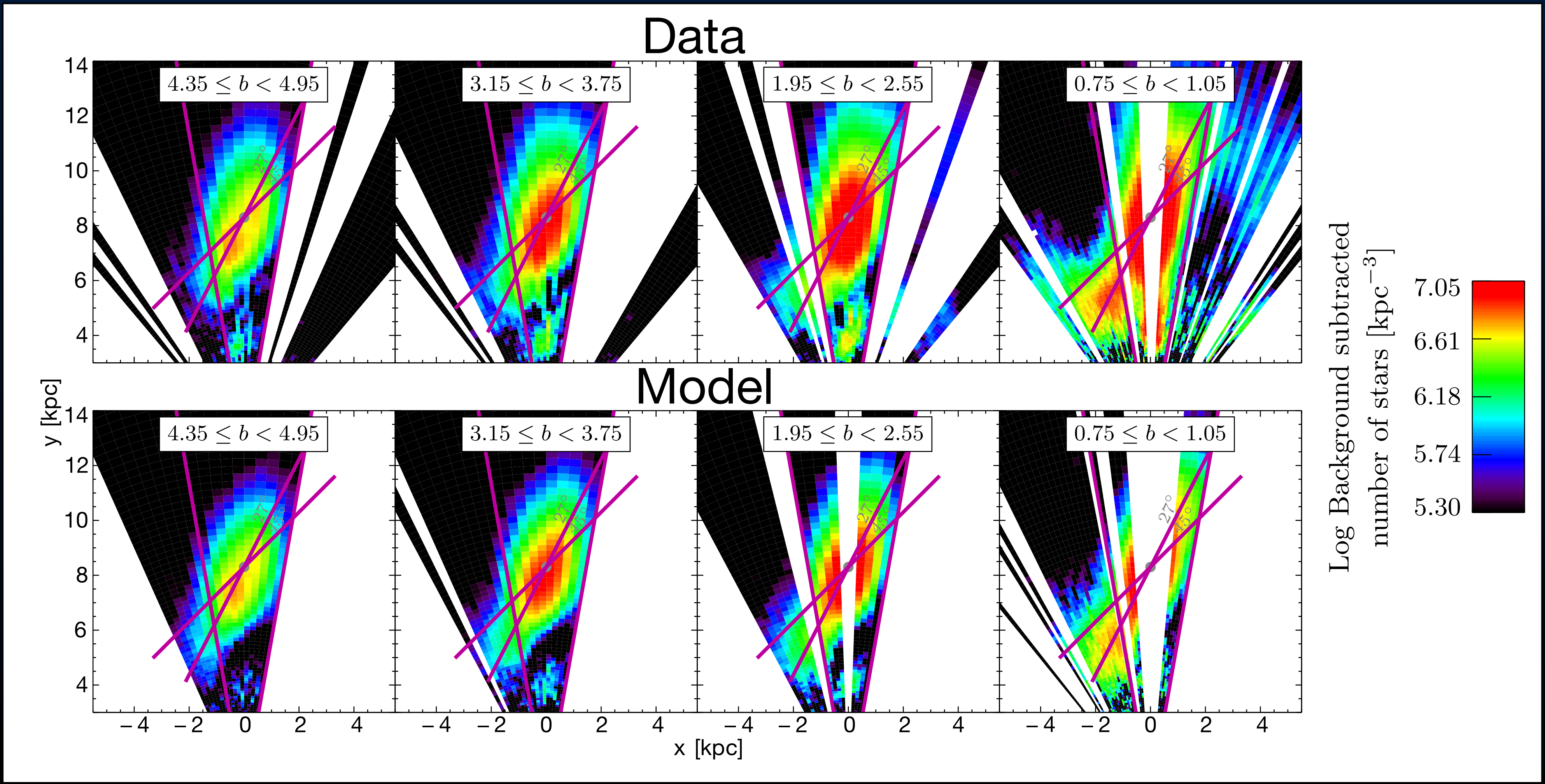
- Thicker component has scale height 2° = 180pc. Similar to thickness of thin disk in solar neighborhood - we call it the ***thin bar*** by analogy.

- Thinner component has scale height 0.5° = 45pc. Exists mostly near bar end. We call it the ***super-thin bar*** by analogy to some external galaxies (Schechtman-Rook+2013).
- Related to recent (~1Gyr) star formation? Stars captured by bar?

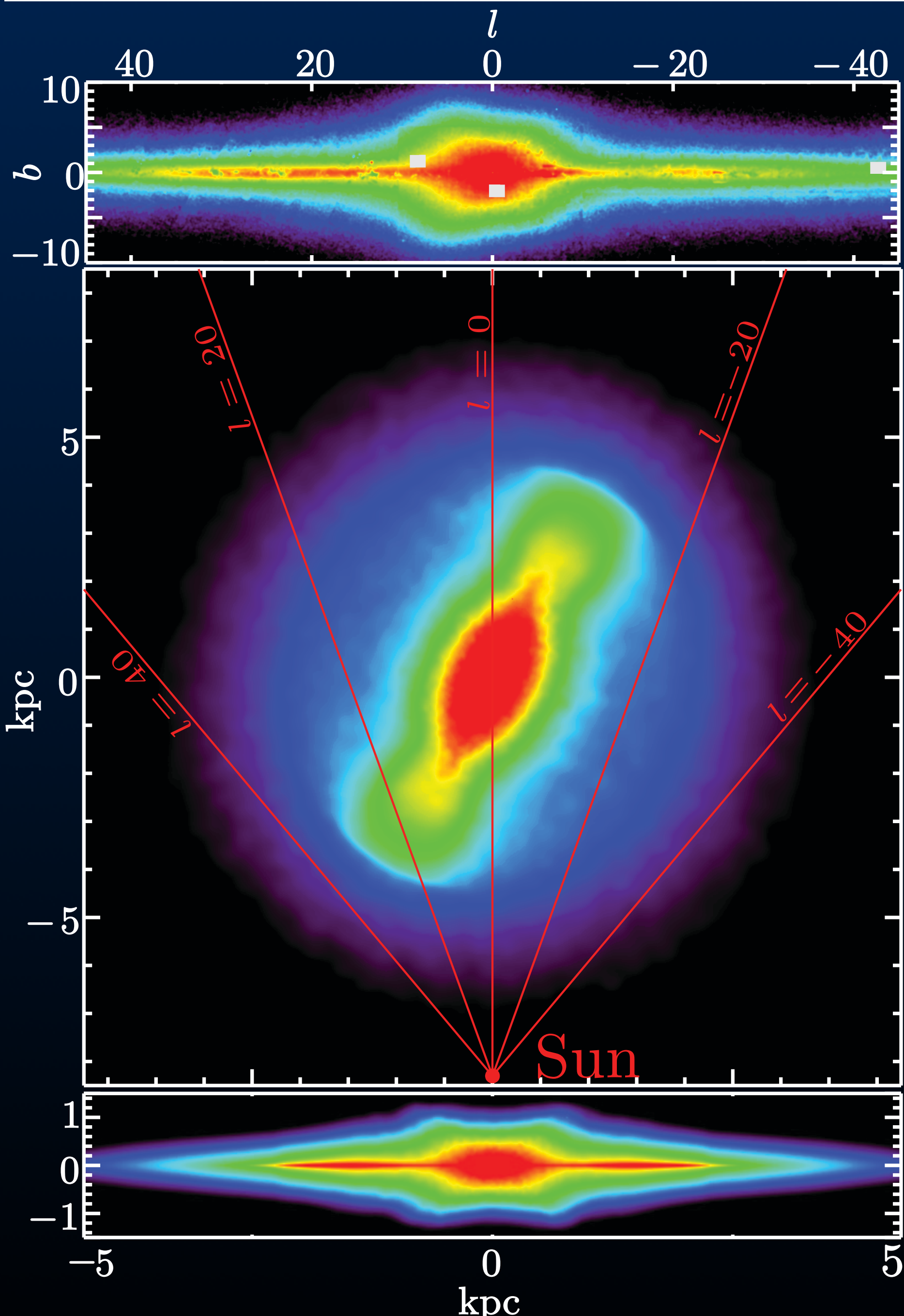


Parametric Modeling

- Convolve 3 component density with a luminosity function constructed from isochrones to predict number counts in all fields
- Adjust density until predicted number counts agree with observed



Structure of the Galactic Bar at $|l| > 10^\circ$



Parametric model tells us:

- Long bar angle is $(28\text{-}33)^\circ$ - Aligned with the bulge!
- Bar half length is 5.0±0.2 kpc.
- Surprisingly long, therefore likely to have a greater influence on disk in solar neighbourhood, and on the gas.
- Bar mass is $1.8\text{x}10^{10}\ M_\odot$

Conclusions

- We have a 10% accurate 3D non-parametric measurement of the stellar density of the bulge. Applications include *e.g.* Gas Dynamics in the resultant potential & Matthieu Portail's talk on constructing N-body dynamical models of the bulge.
- Long bar: Bar has length 5.0±0.2 kpc, angle $(28\text{-}33)^{\circ}$, mass $1.8 \times 10^{10}\,M_{\odot}$
- The bar outside the bulge is aligned to the barred bulge. The scale height smoothy transitions from bulge to long bar.
- The bar outside the bulge (long bar) naturally innately connected to barred bulge.
- There is evidence for two components. A 180pc scale height ***thin bar***, analogous to the solar neighbourhood thin disk. A 45pc scale height ***super-thin bar***, mostly towards bar end. Related to more recent, 1Gyr ago, star formation?