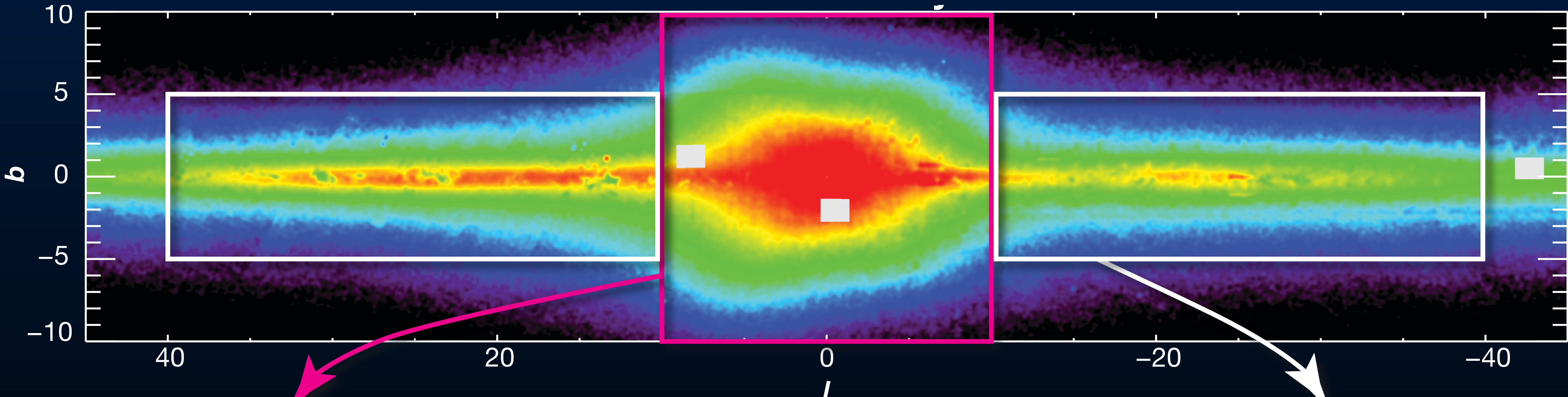
The Structure of the Bar, Bulge and Inner Disk of the Milky Way

Chris Wegg, Ortwin Gerhard & Matthieu Portail



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

CW & Gerhard
MNRAS, 435, 1874 (2013)

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

CW, Gerhard & Portail
MNRAS, 450, 4050 (2015)

MOA-II Galactic Microlensing Constraints: The Inner Milky Way has a Low Dark Matter Fraction and a Maximum Disk

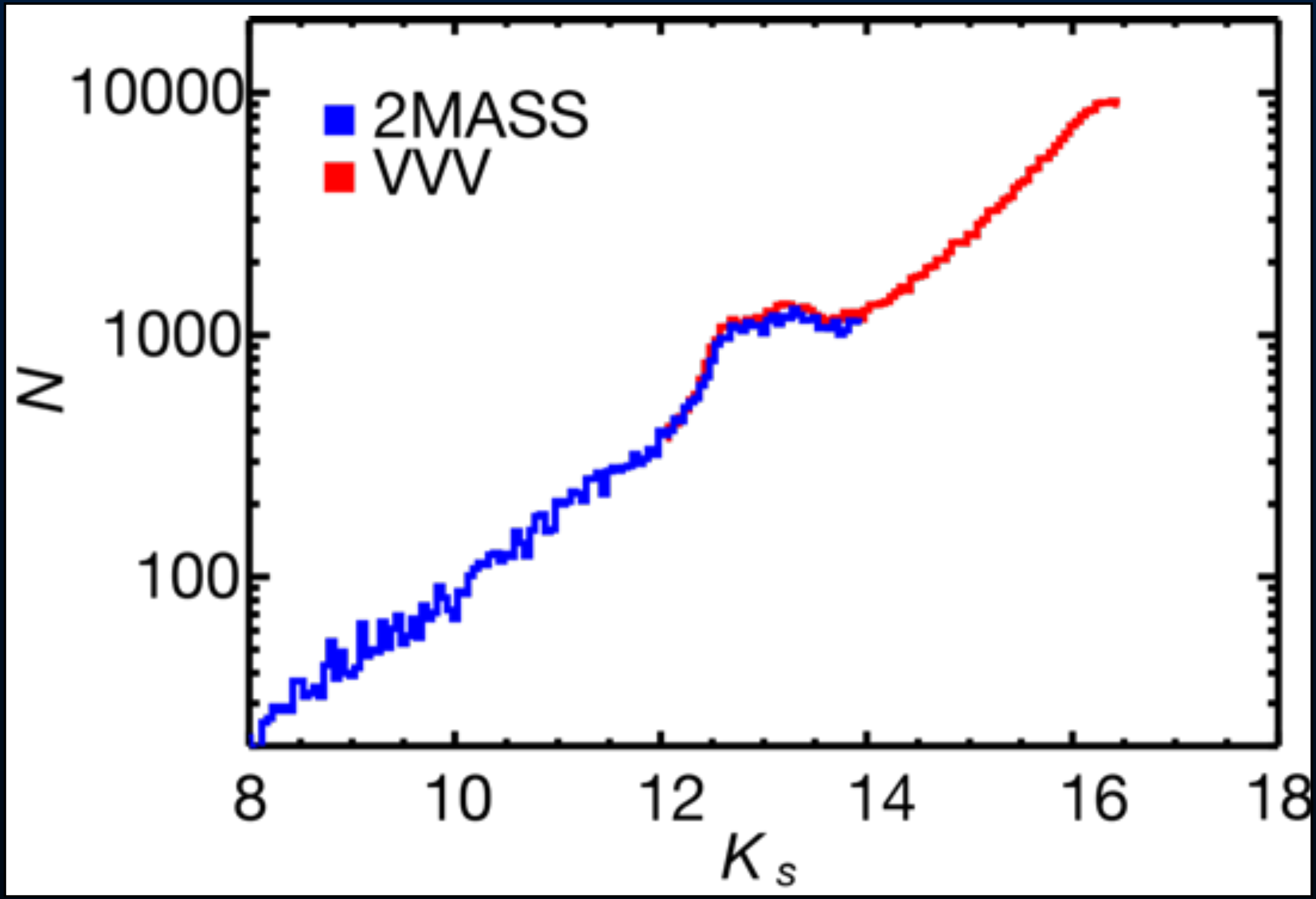
CW, Gerhard & Portail

Outline

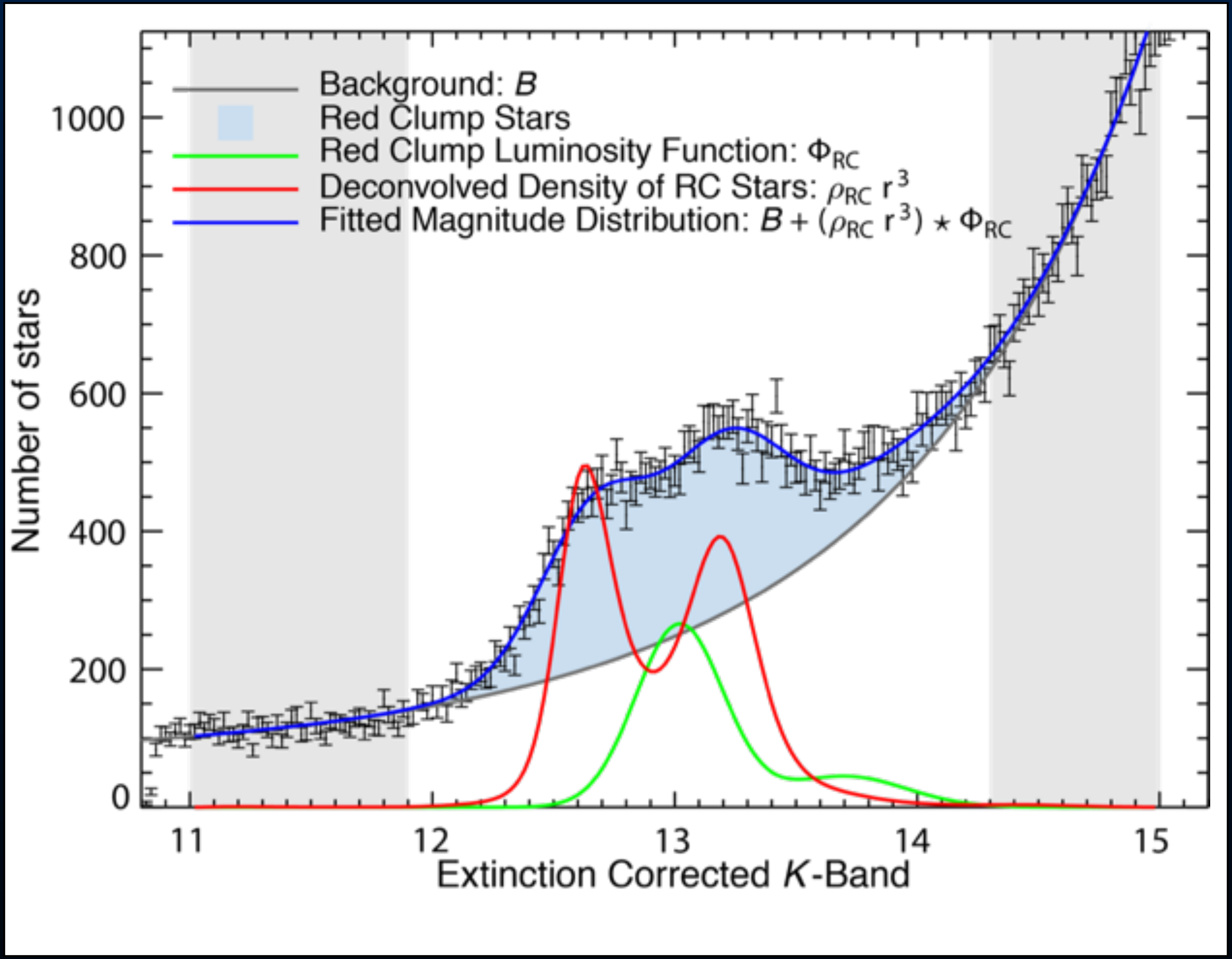
1. Measuring the 3D shape of the bulge (5 min)
2. The Bar Outside the Bulge: The 'Long Bar' (10 min)
3. Made-to-measure N-body models of the bulge (5 min)
4. Galactic Microlensing (10 min)

Red clump stars

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

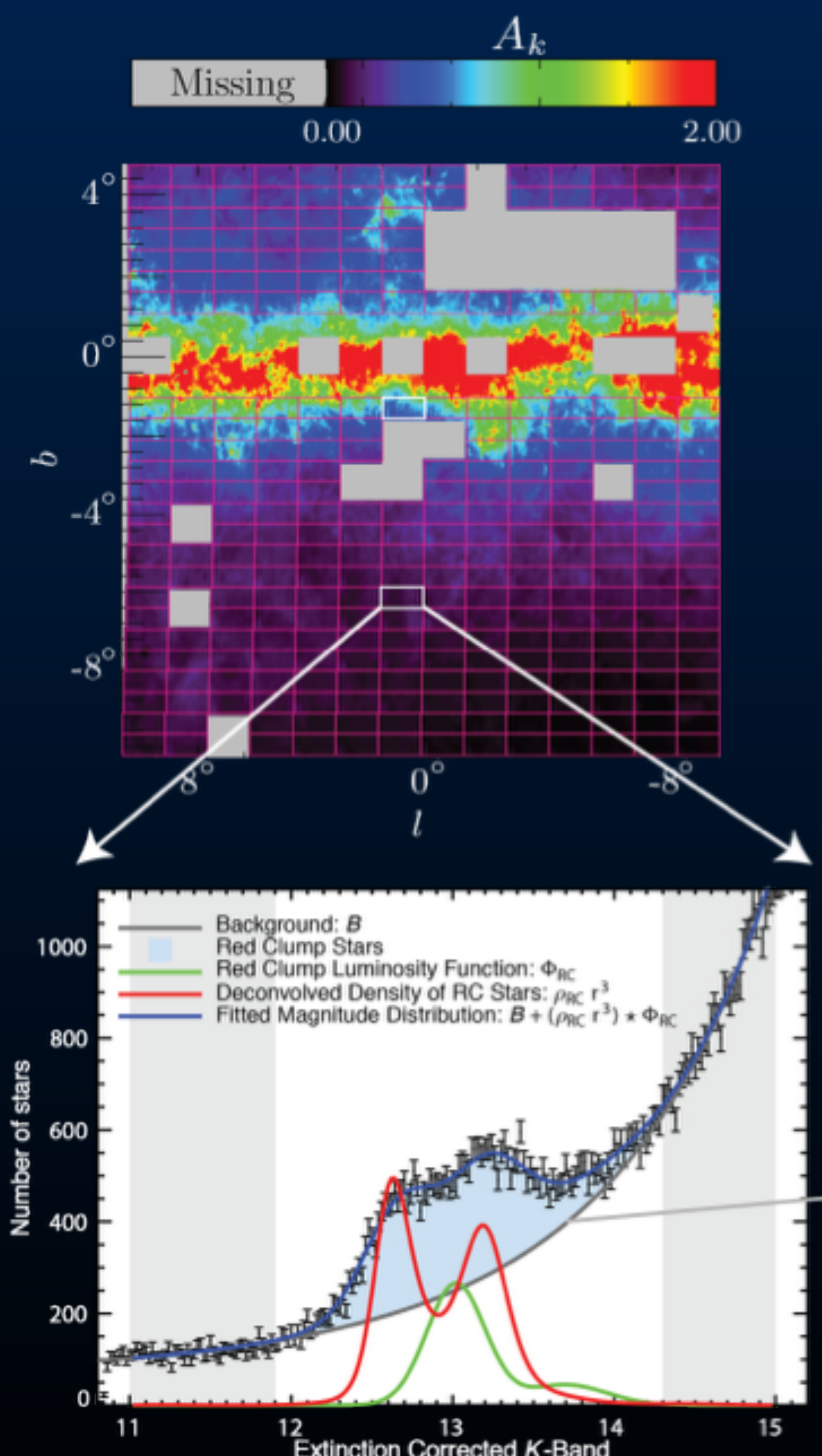


Line-of-sight density estimation

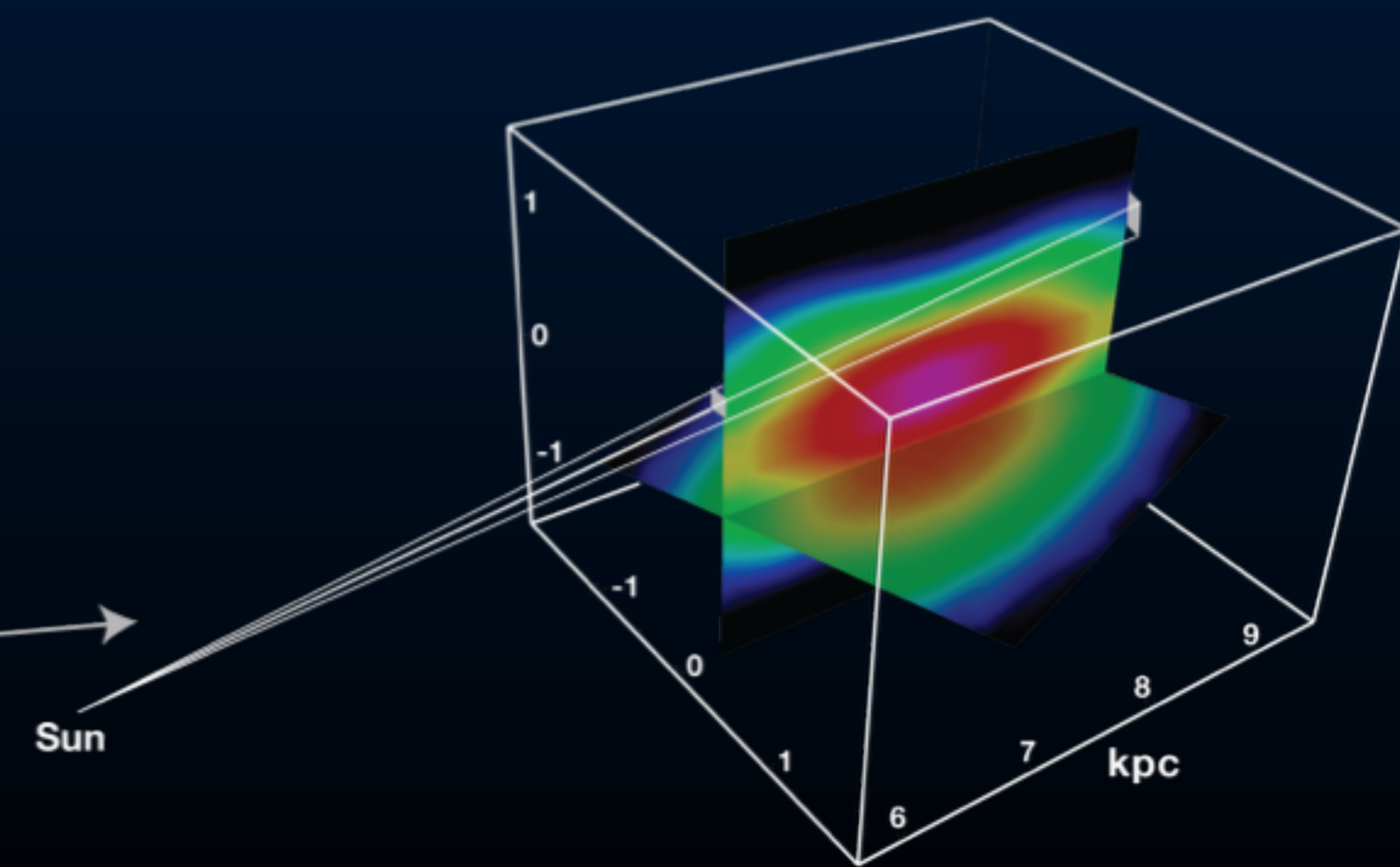


- Fit background to region outside Bulge's RC stars
- Statistically identified red clump stars are convolution of line-of-sight density with luminosity function.
- Deconvolve to estimate density using a slight variation on Lucy-Richardson algorithm

1.Measuring the 3D Shape of the Bulge



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



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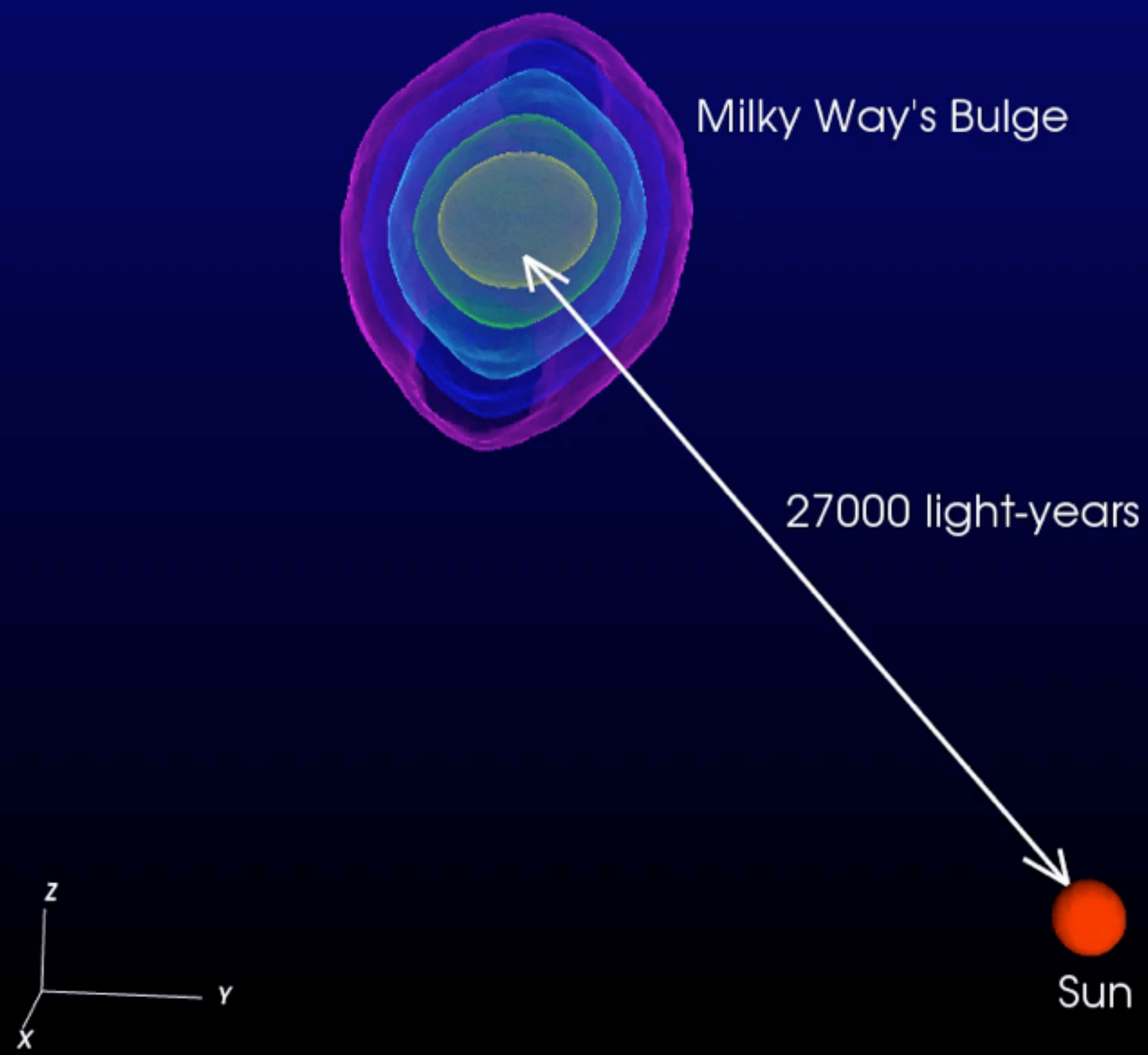
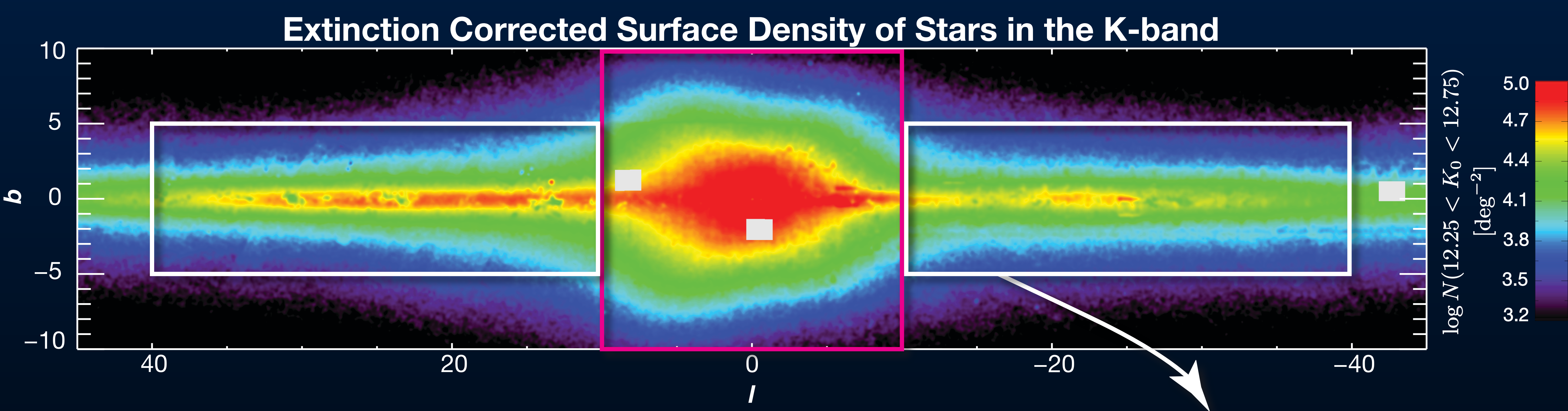


Wegg & Gerhard, MNRAS, 435, 1874 (2013)

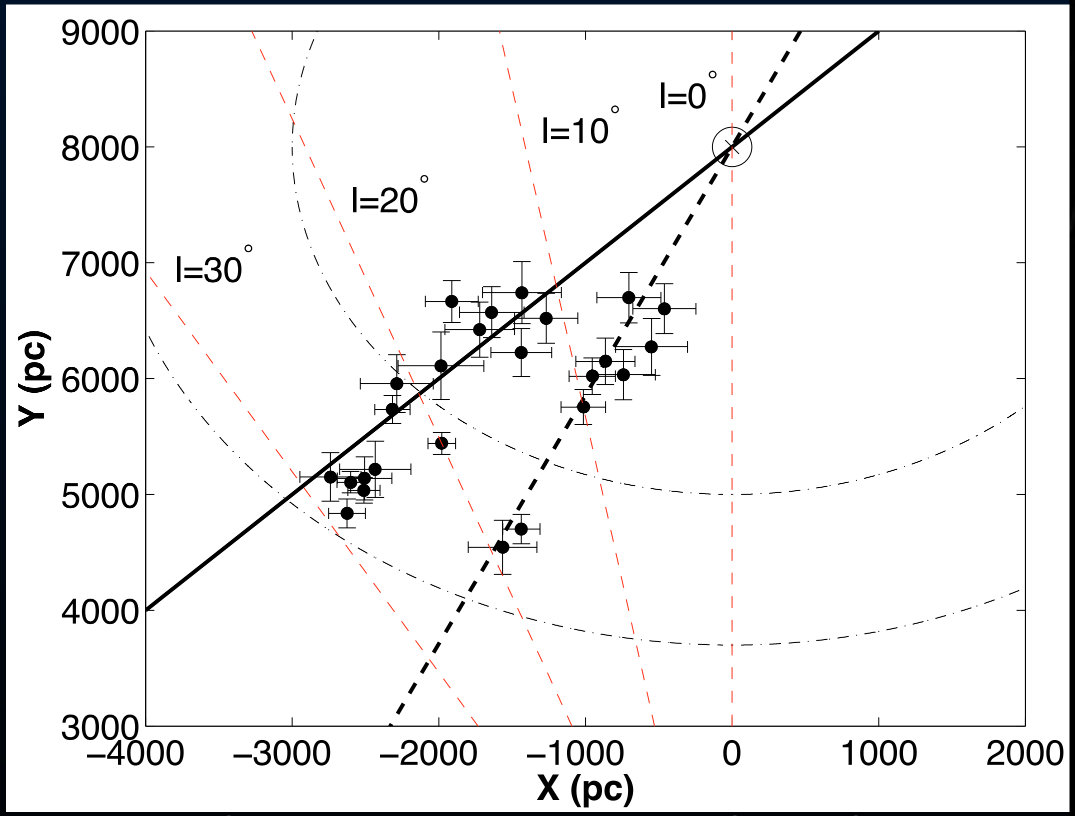


Structure of the Galactic Bar at $|l| > 10°$

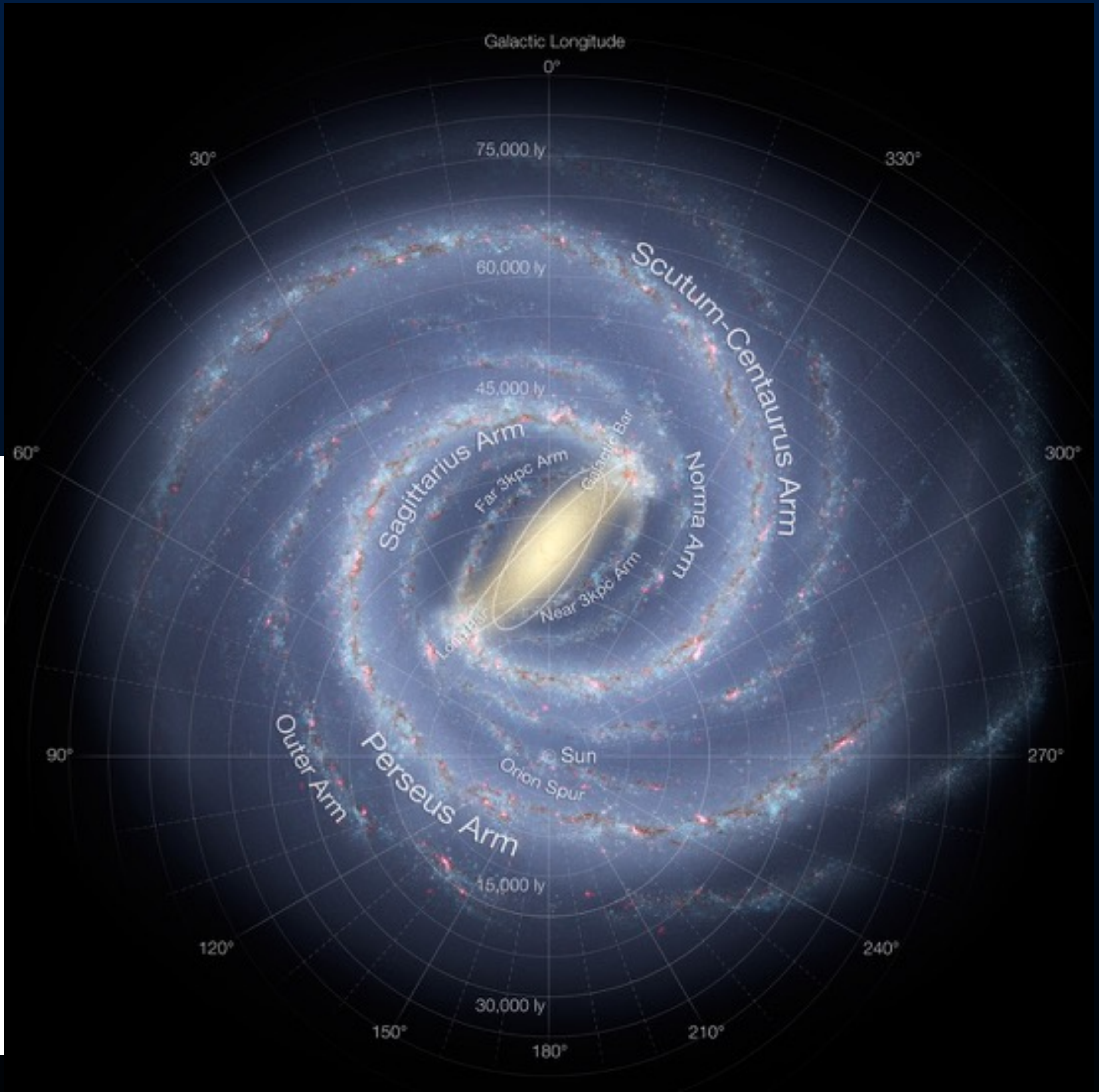
CW, Gerhard & Portail
MNRAS, 450, 4050 (2015)

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 previous 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

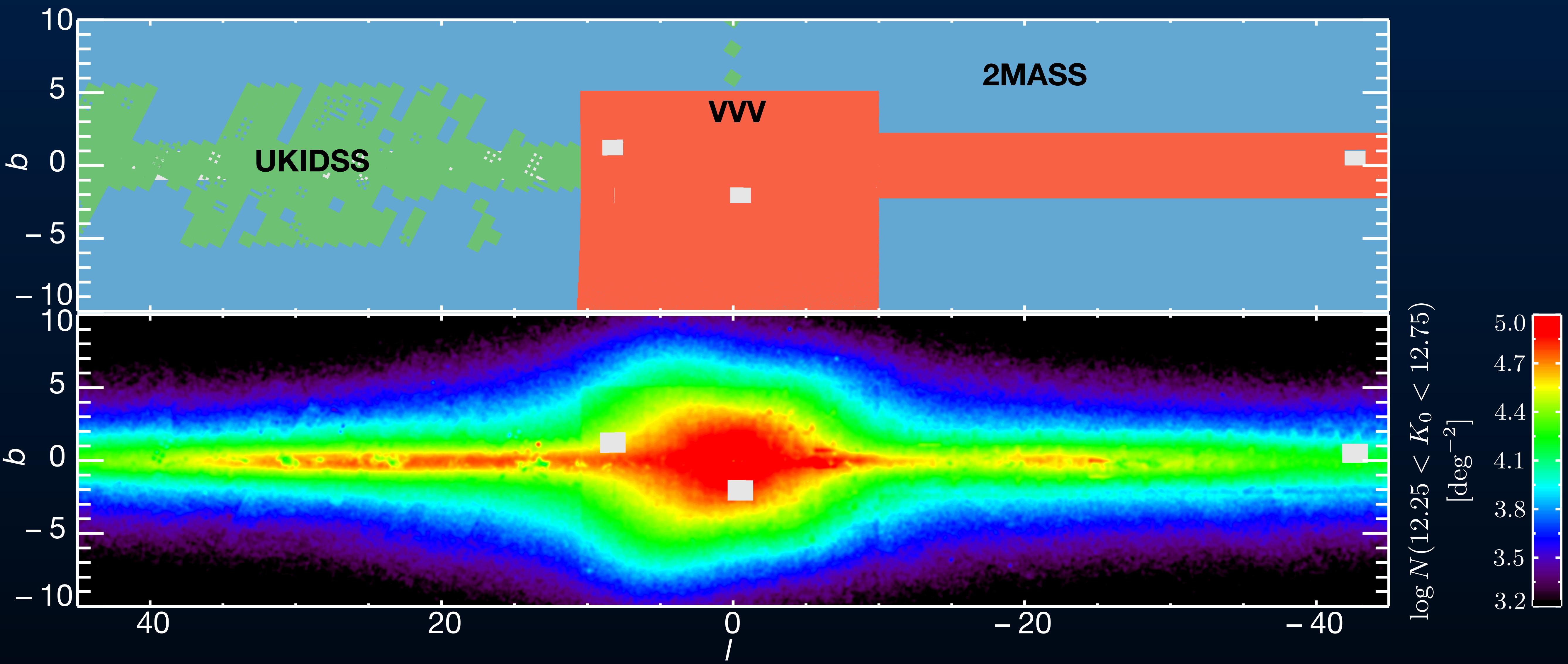
$$\mu_K = K_s - \overbrace{\frac{A_{K_s}}{E(H-K_s)} \underbrace{[(H-K_s)-(H-K_s)_{\mathrm{RC}}]}_{\text{Reddening}}}^{\text{Extinction Correction}} - M_{K_s,\mathrm{RC}}$$

- 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.

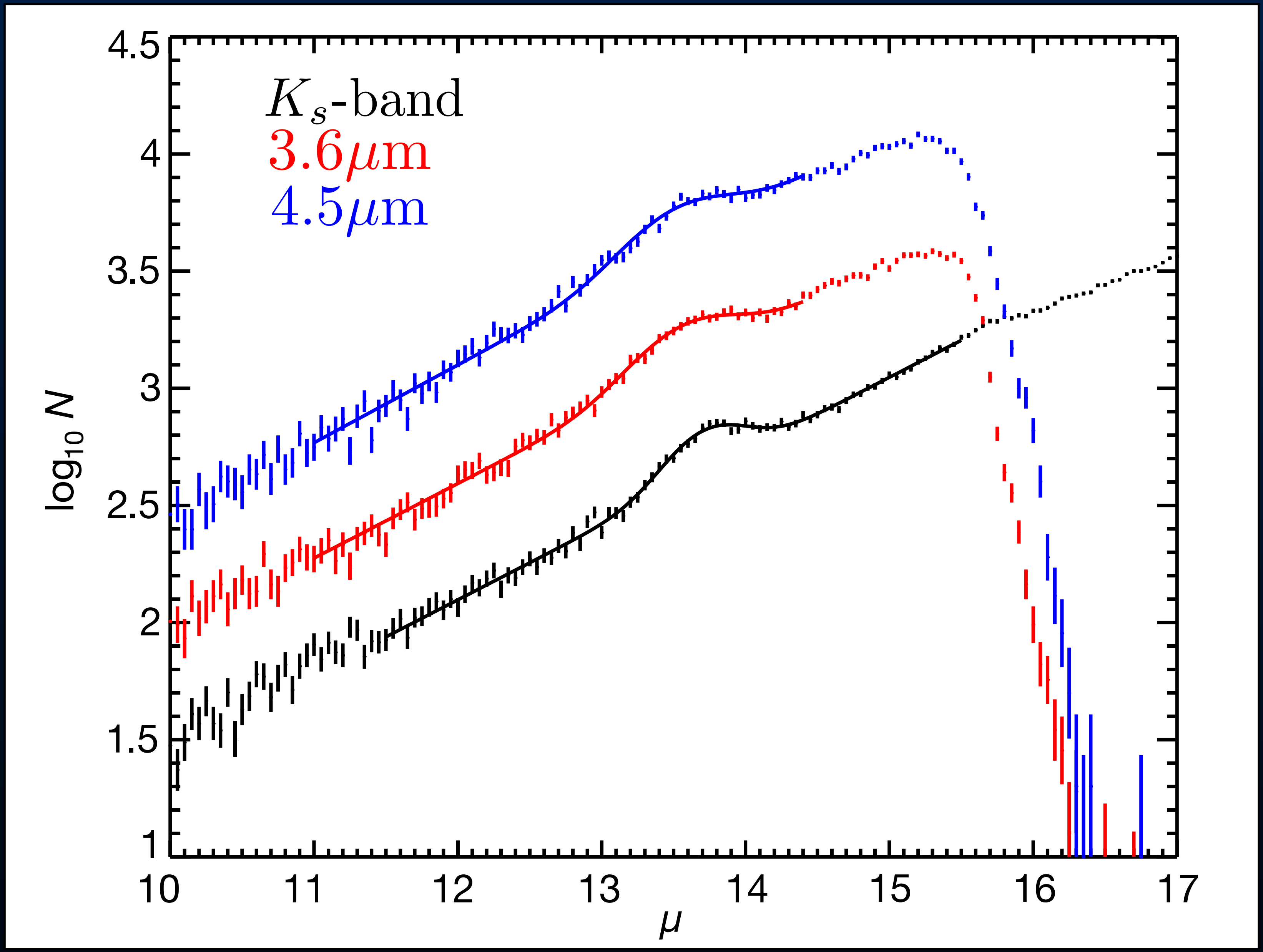
Data Sources



Chris Wegg

Typical Field

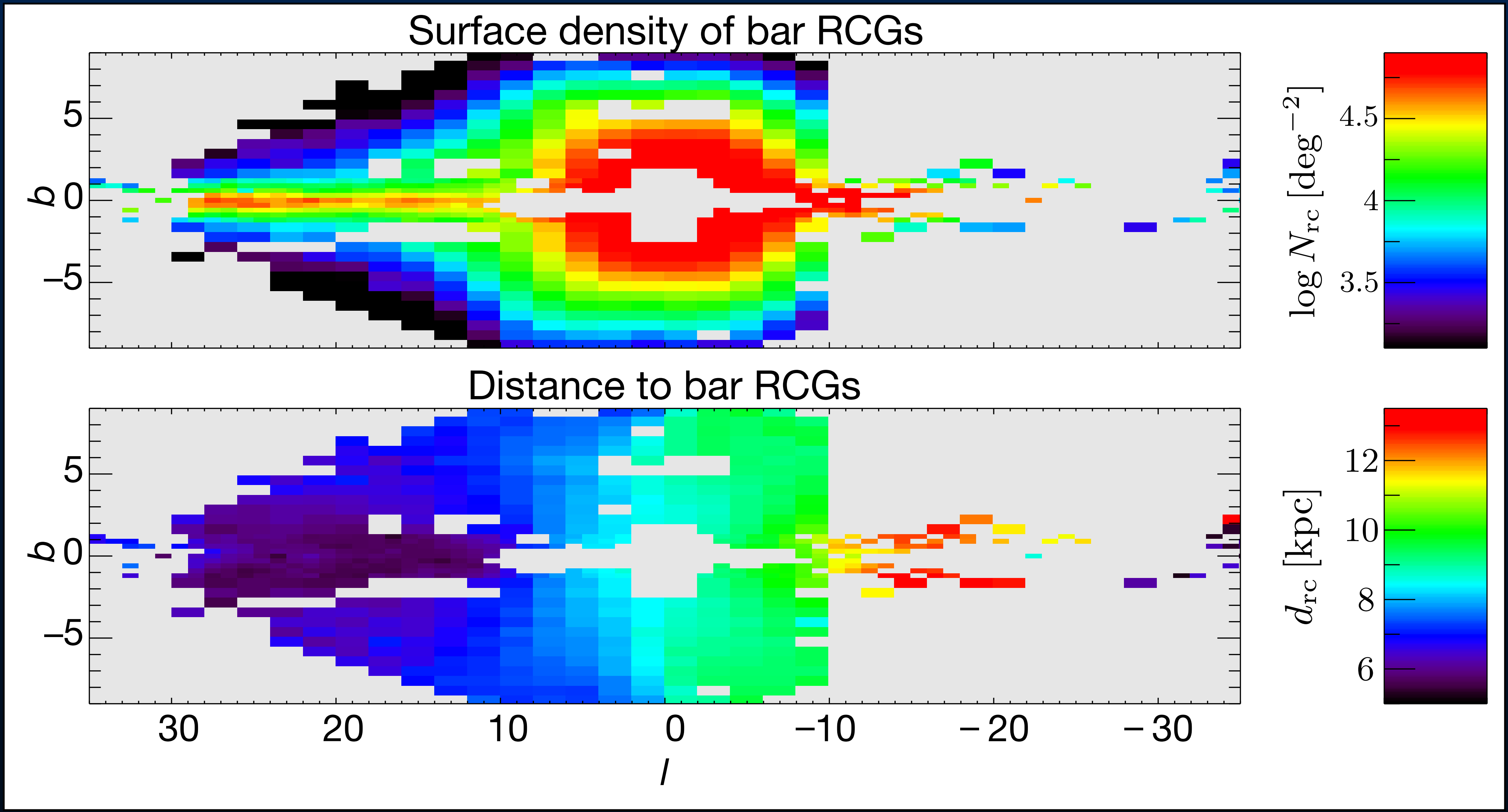
At l=18.5° b=0.9° with size Δl=1° Δb=0.3°



To each field fit Gaussian for RCGs + Exponential for background:

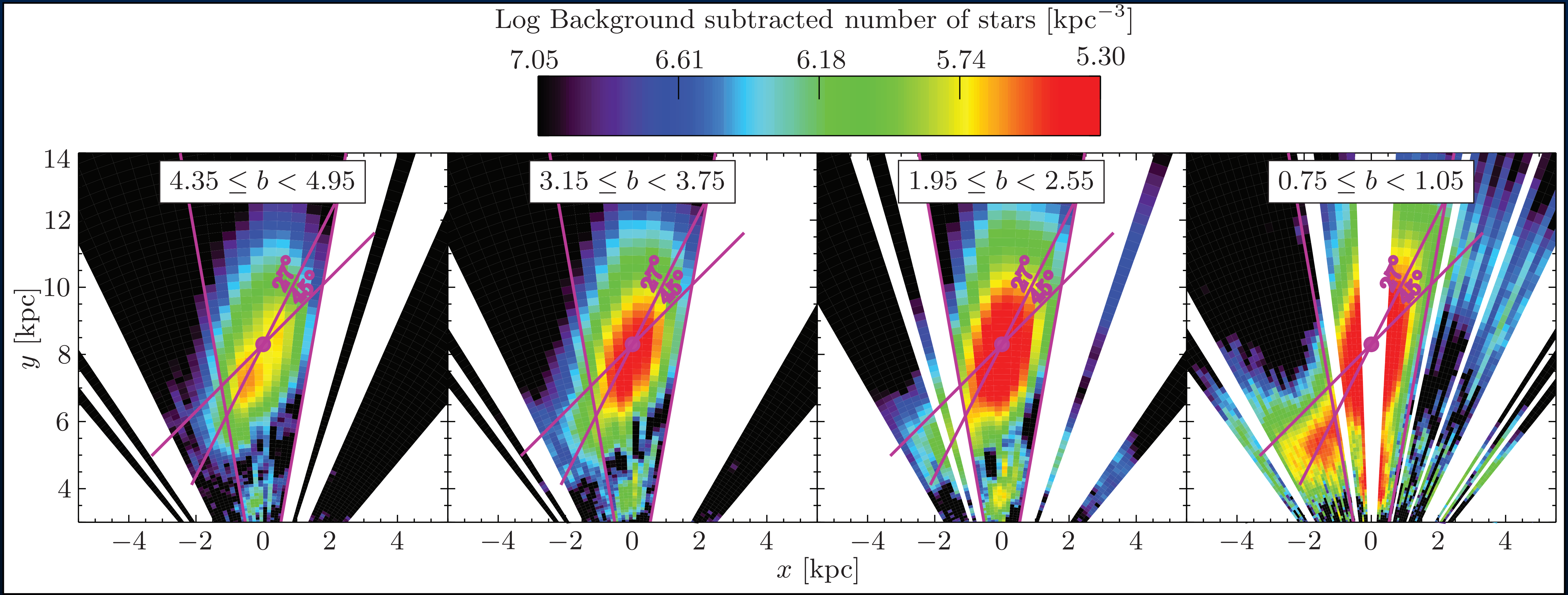
$$N(\mu) = \frac{N_{RC}}{\sigma_{RC}\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\mu-\mu_{RC}}{\sigma_{RC}}\right)^2\right] + A \exp B(\mu - \mu_{RC})$$

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°

Background subtracted number of RCGS in different *b* slices



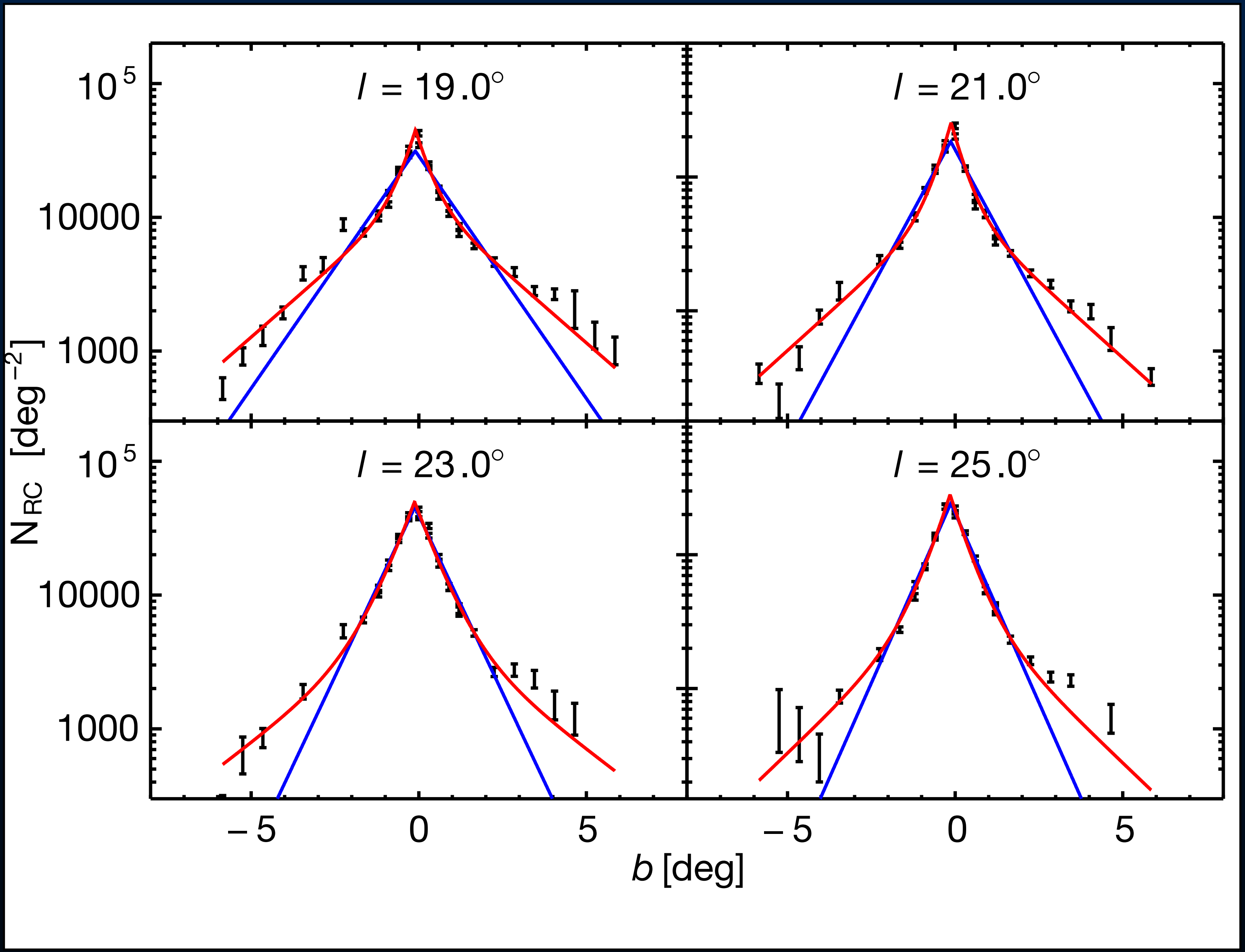
NOT deconvolved. Instead the density plotted if RCGs were perfect standard candles.

Still a useful way of visualising 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:

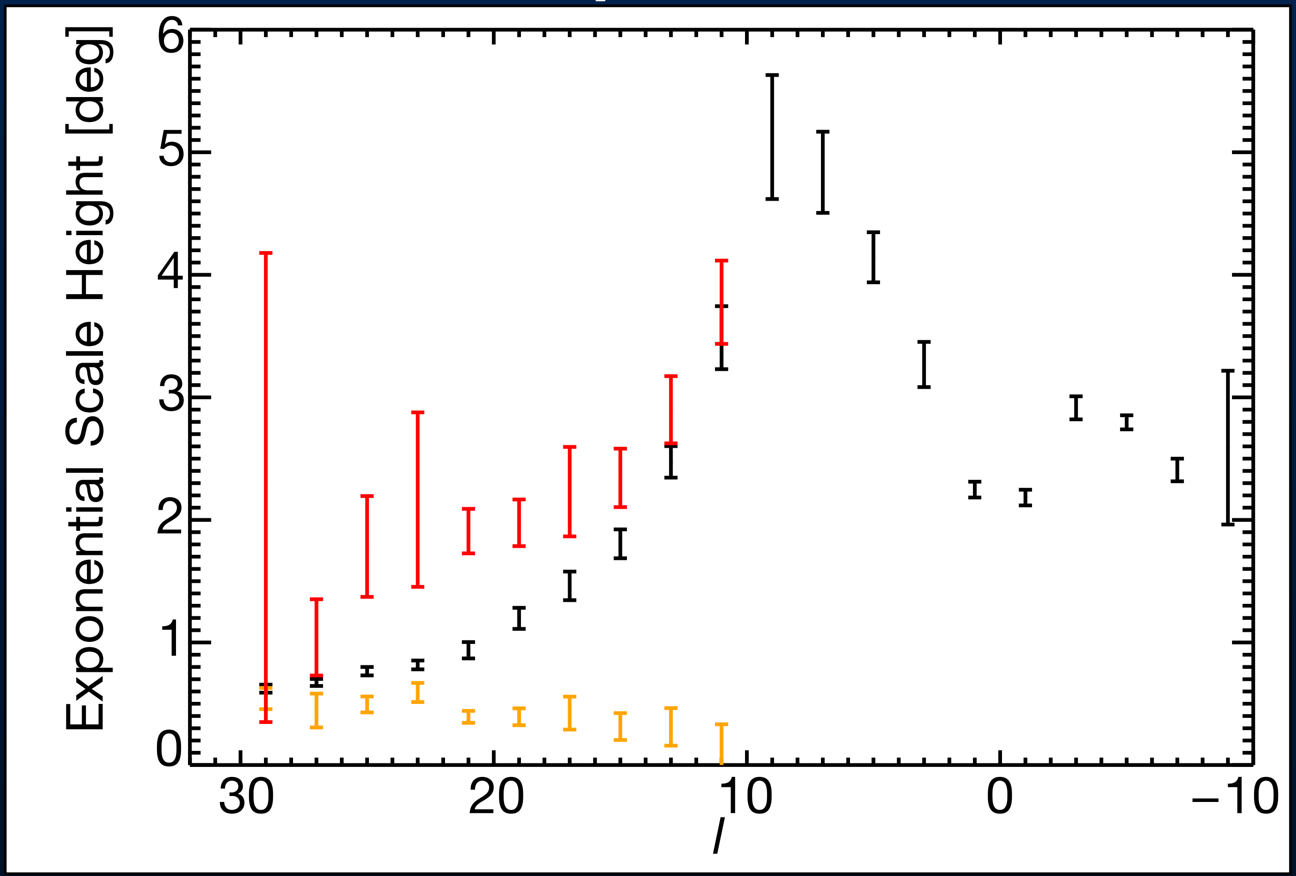
$$N_{RC}(b) = \frac{\Sigma_{RC,A}}{2b_{1,A}} \exp\left(-\frac{|b-b_0|}{b_{1,A}}\right)$$
$$\frac{\Sigma_{RC,B}}{2b_{1,B}} \exp\left(-\frac{|b-b_0|}{b_{1,B}}\right)$$

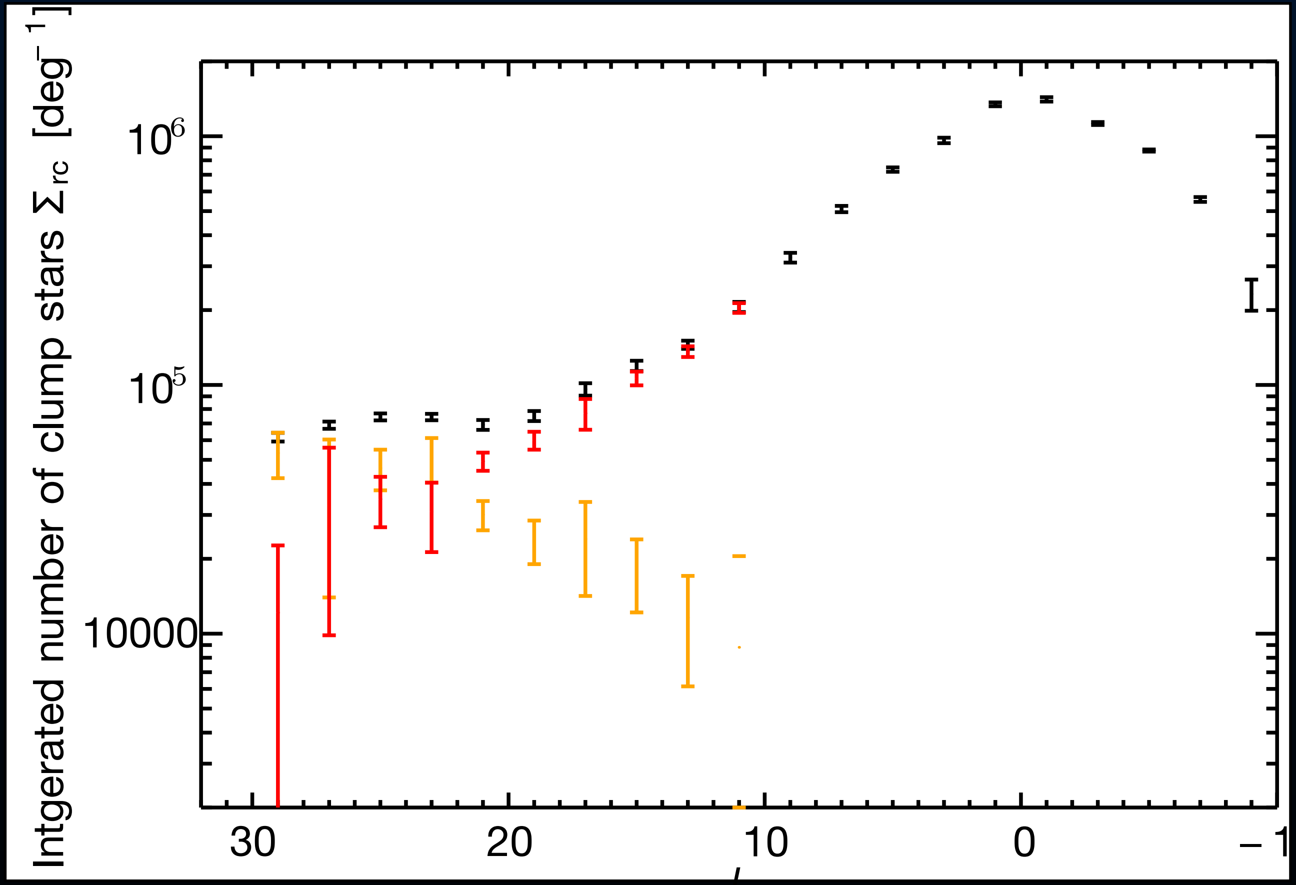


Vertical Structure: ‘Thin Bar’ and ‘Super-Thin Bar’

- 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?

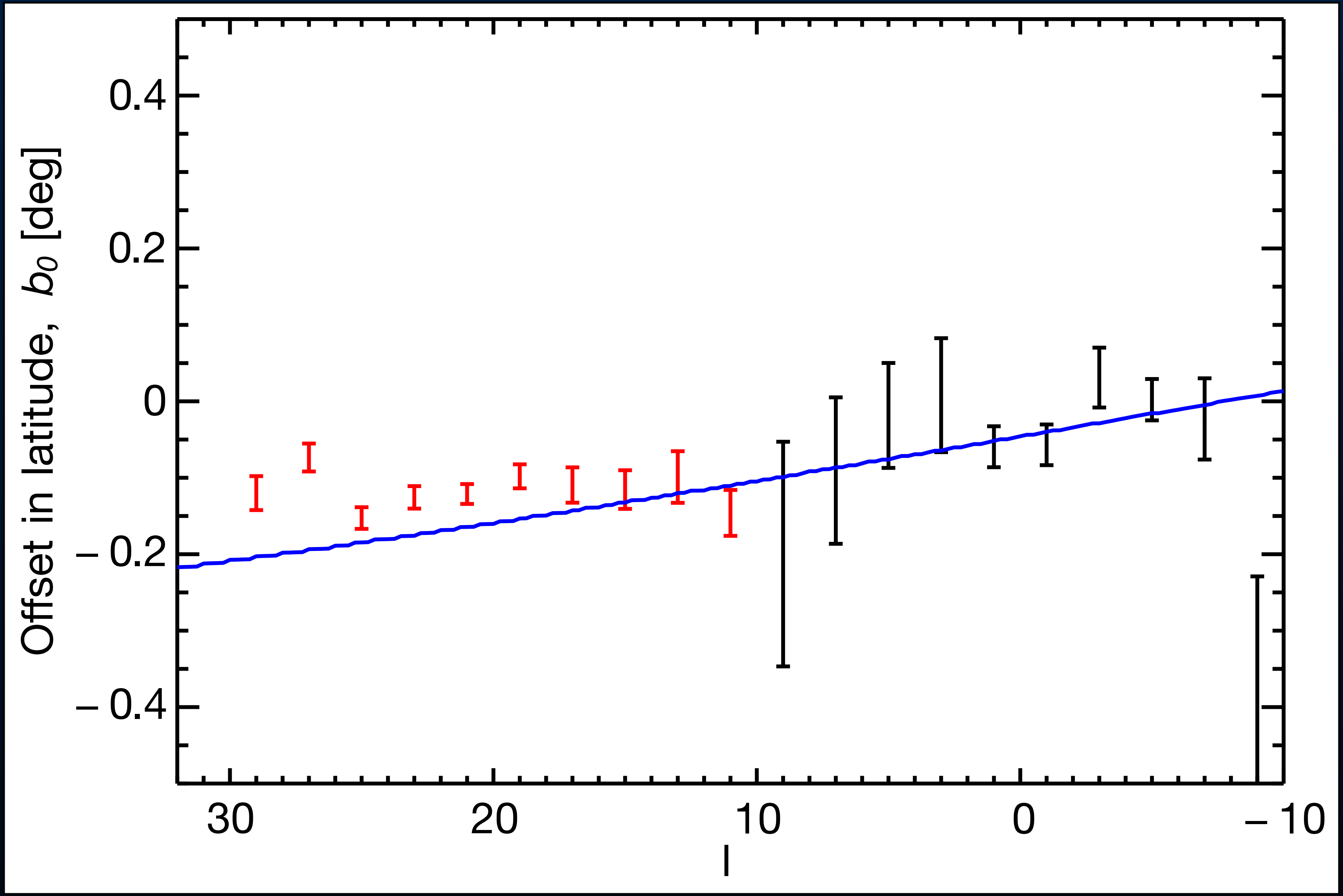




Vertical Structure: Alignment with Galactic Plane

- If we assume Sgr A* is in the physical Galactic mid-plane and sun is 25pc above the mid-plane we get the blue line.

- Bar seems aligned to this at <0.05° =5 pc !



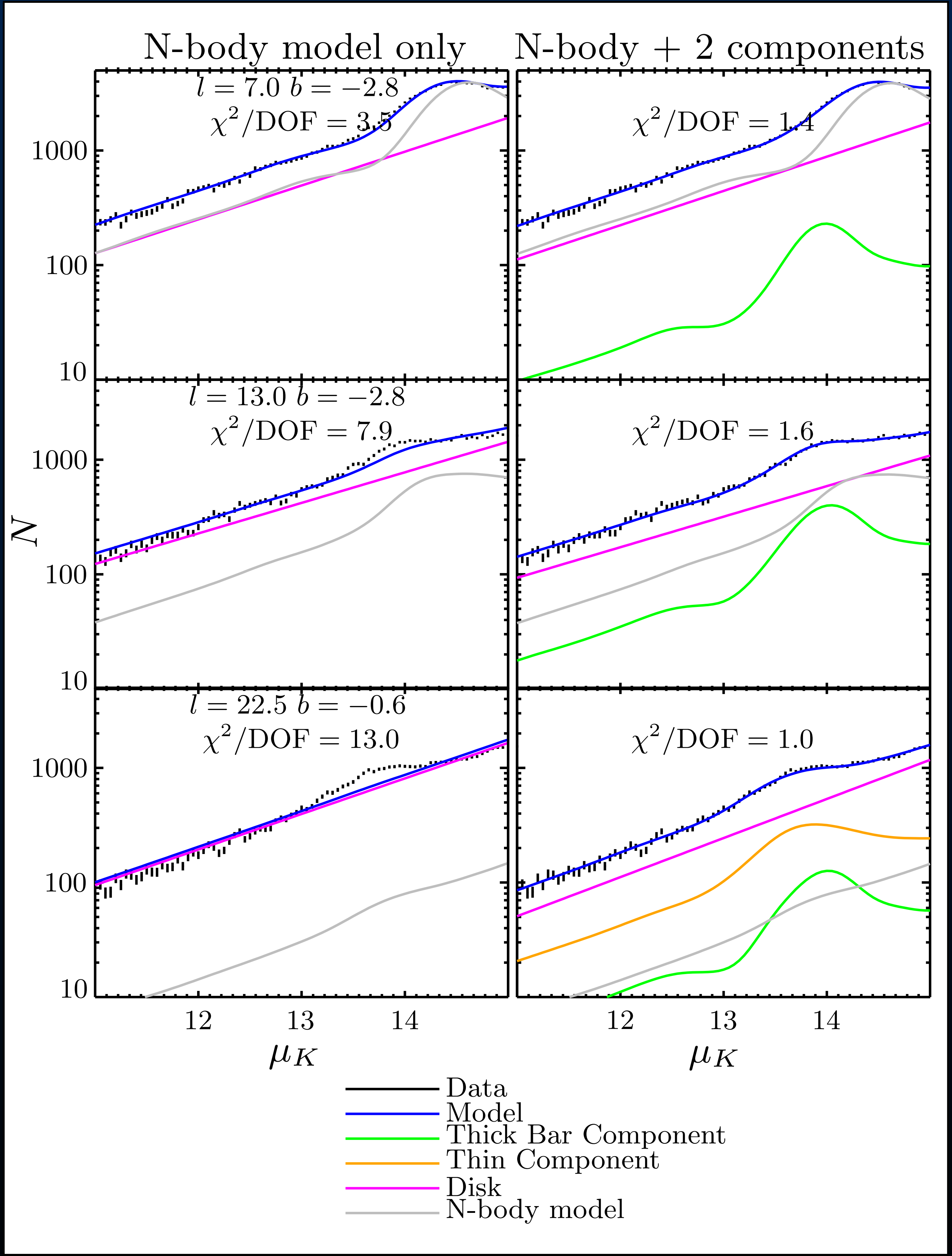
Modelling the Bar

Convolve density with a luminosity function constructed from isochrones to predict number counts in all fields

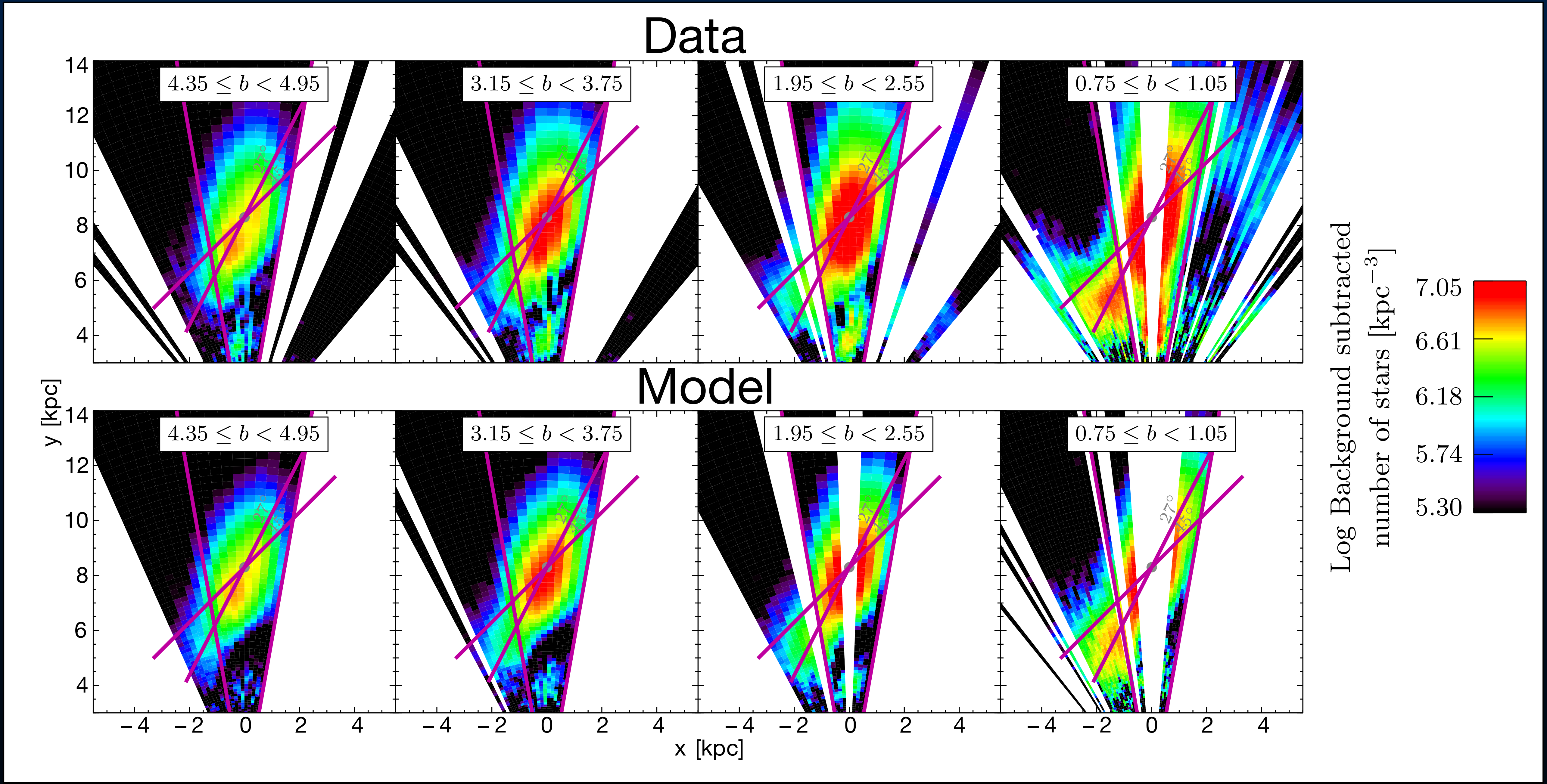
Adjust density until predicted number counts agree with observed

Density made up of:

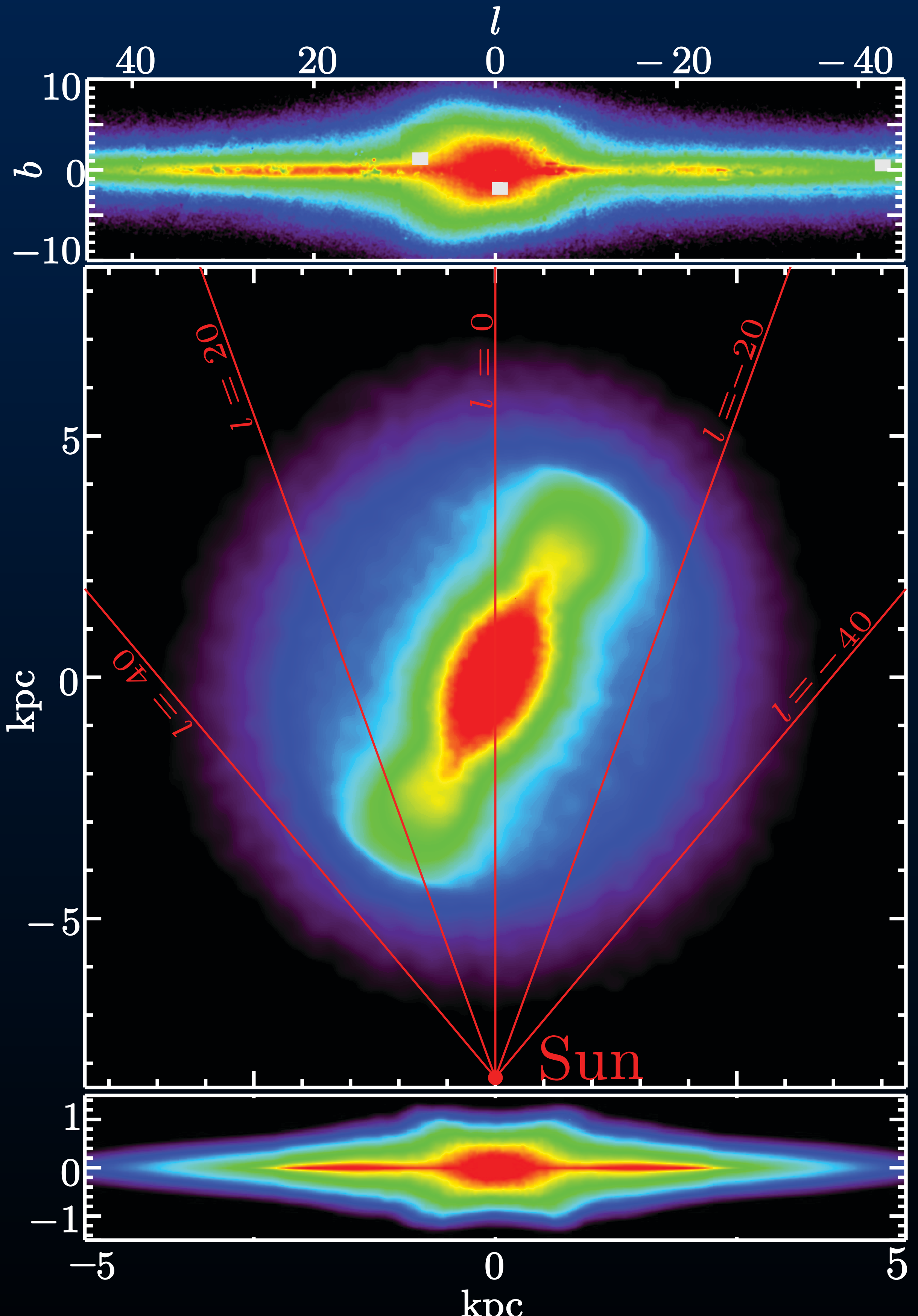
- N-body bar fitted to the bulge.
- Exponential in magnitude to represent inadequate background: N-body disk scale length too short.
- Parametric model for inadequate bar outside the bulge



Comparison of number count predictions of density model to data



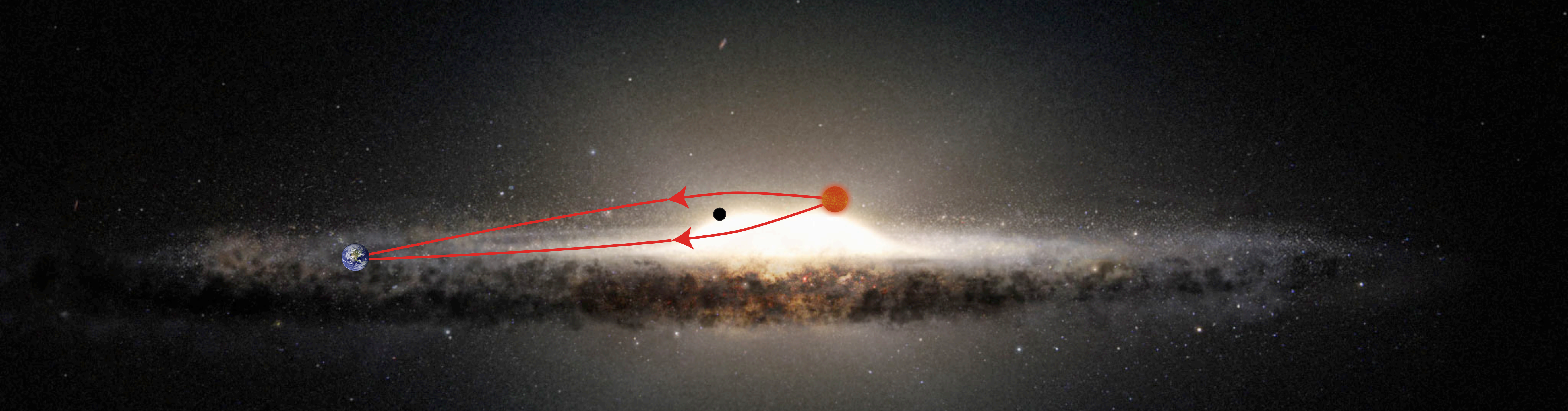
Structure of the Galactic Bar at $|l| > 10°$



Parametric model tells us:

- Long bar angle is (28-33)° - 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 $1.8 \times 10^{10}\ M_{\odot}$

MOA-II Galactic Microlensing Constraints: The Inner Milky Way has a Low Dark Matter Fraction and a Maximum Disk



Microlensing of Milky Way stars allows the stellar mass-to-light vs dark matter degeneracy to be uniquely broken

Microlensing event *not* to scale…

Chris Wegg, Ortwin Gerhard & Matthieu Portail

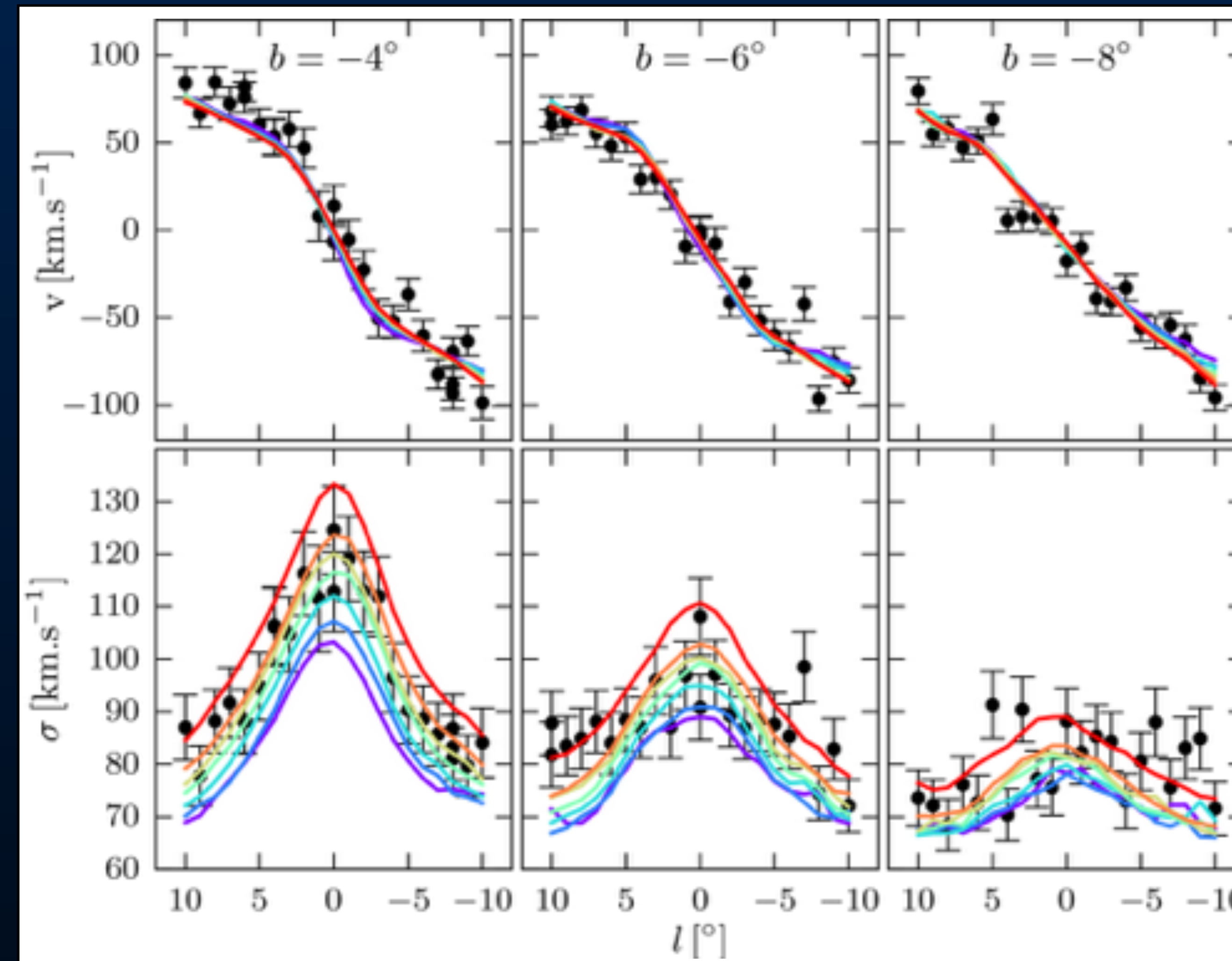
MPE

Made-to-measure N-body models of the bulge

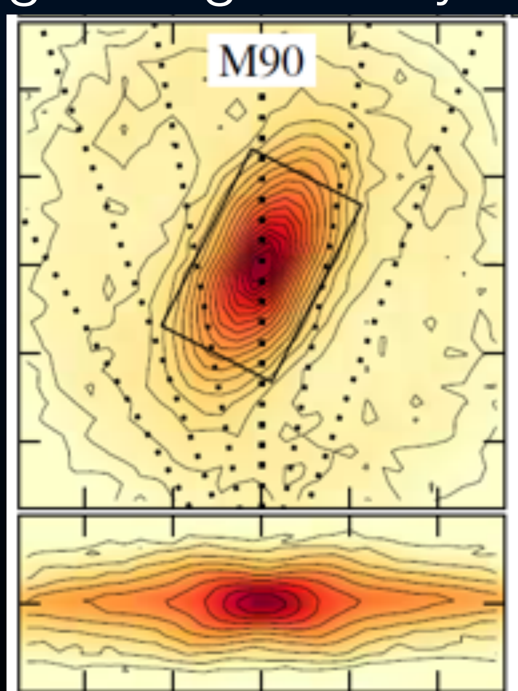
Portail, CW, OG+ MNRAS (2015)

Matthieu Portail

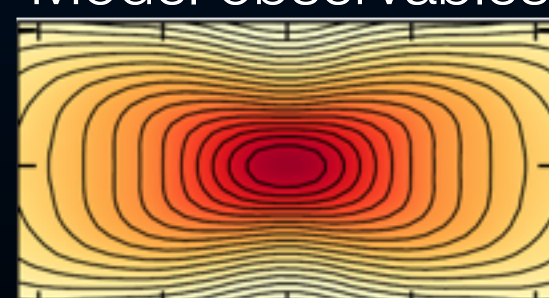
We can recover the stellar mass required by the model to match the BRAVA dispersion in its dark matter halo.



Self-graviting N-body model

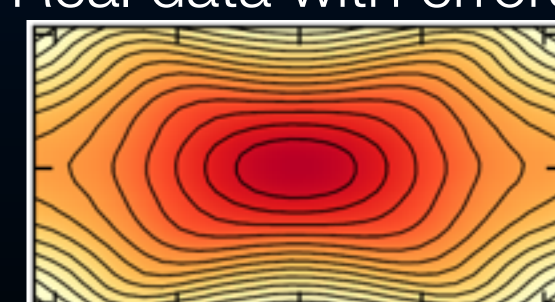


Model observables



Compare

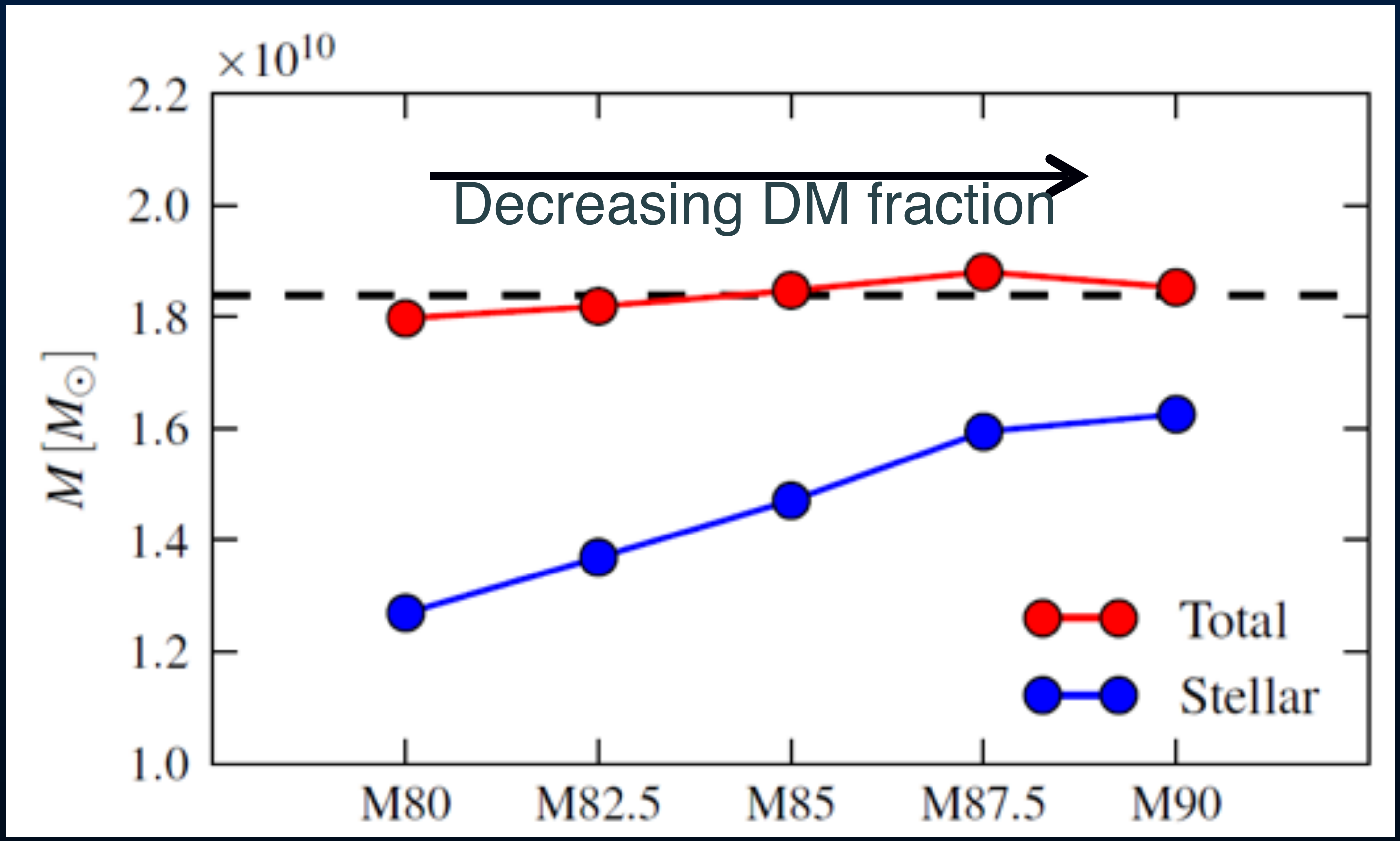
Real data with errors



Update the particle masses

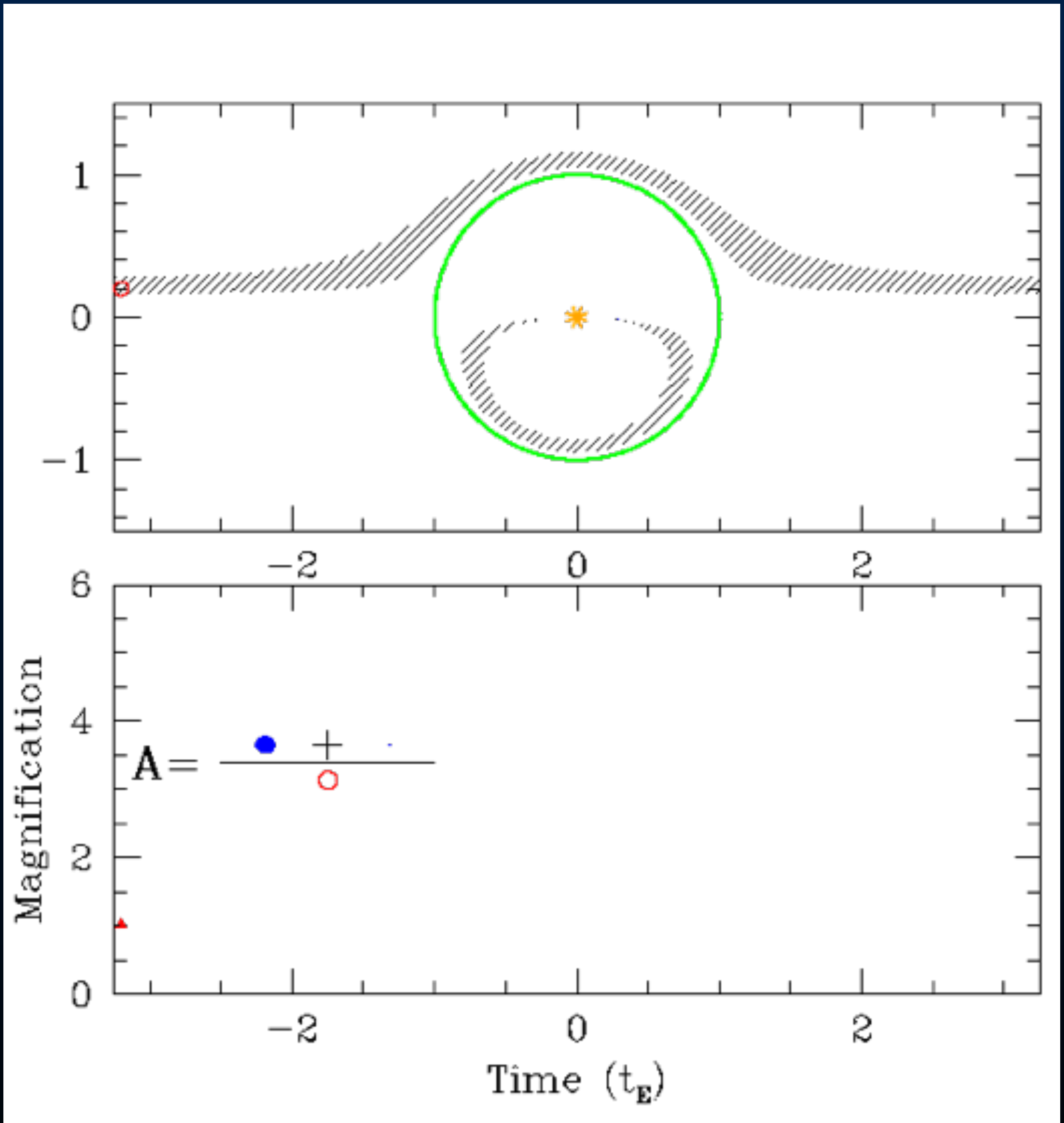
Made-to-measure N-body models of the bulge

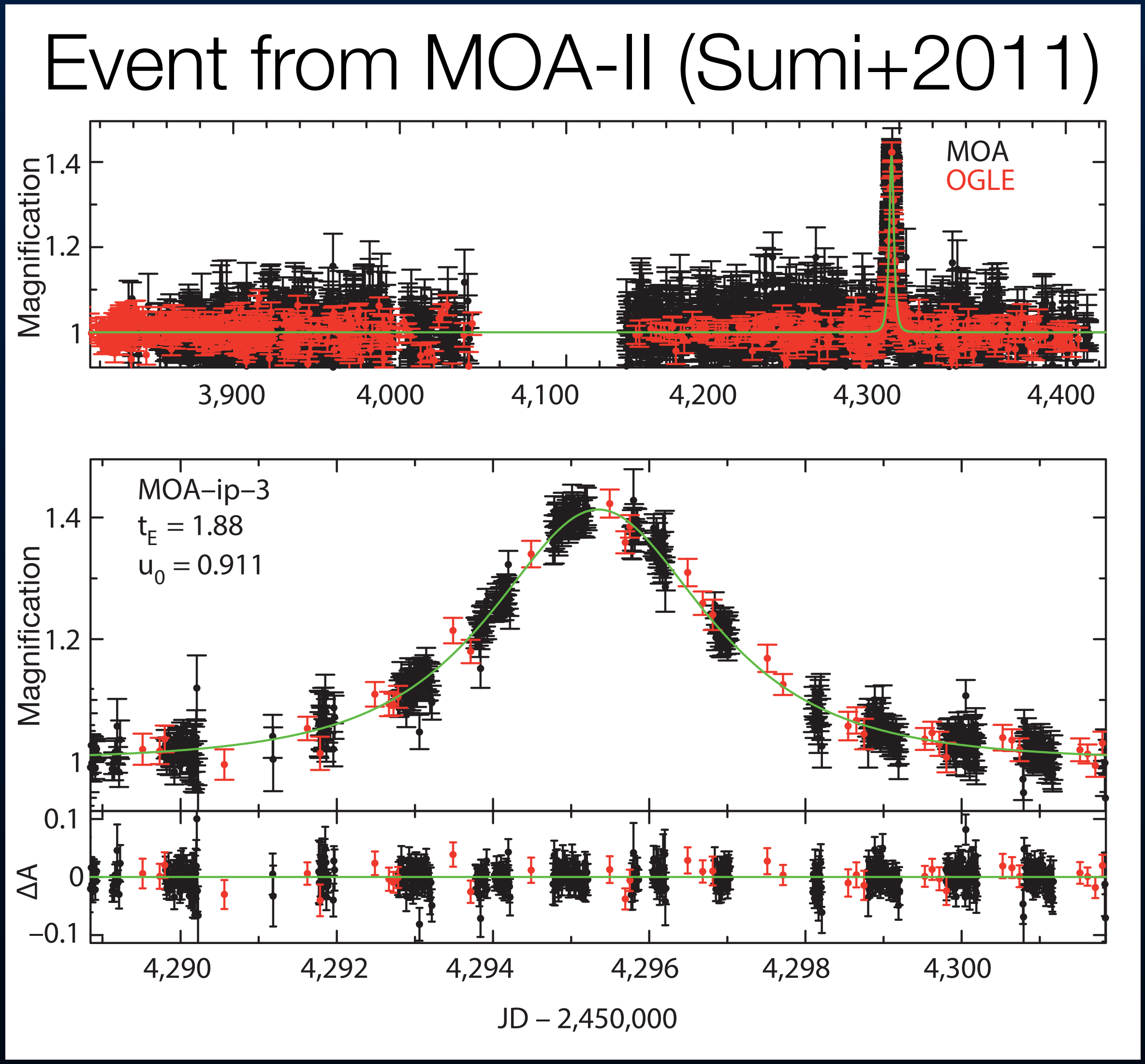
- We measure the ***total mass*** in the bulge ± (2.2 x 1.4 x 1.2kpc) to be 1.84 10^{10} $M_{\odot}$



- We find a systematic error on the total mass of less than 5%
- We have equally good models of the bulge with different dark matter fraction.

Microlensing of Milky Way stars allows us to break the mass-to-light vs dark matter degeneracy





Microlensing Optical Depth

- Fraction of observed stars that are strongly lensed
- For a star at a distance D_s given by:

$$\tau(D_s) = \frac{4\pi G}{c^2} \int \rho_l(D_l) \left(\frac{1}{D_l} - \frac{1}{D_s} \right) D_l \, dD_l$$

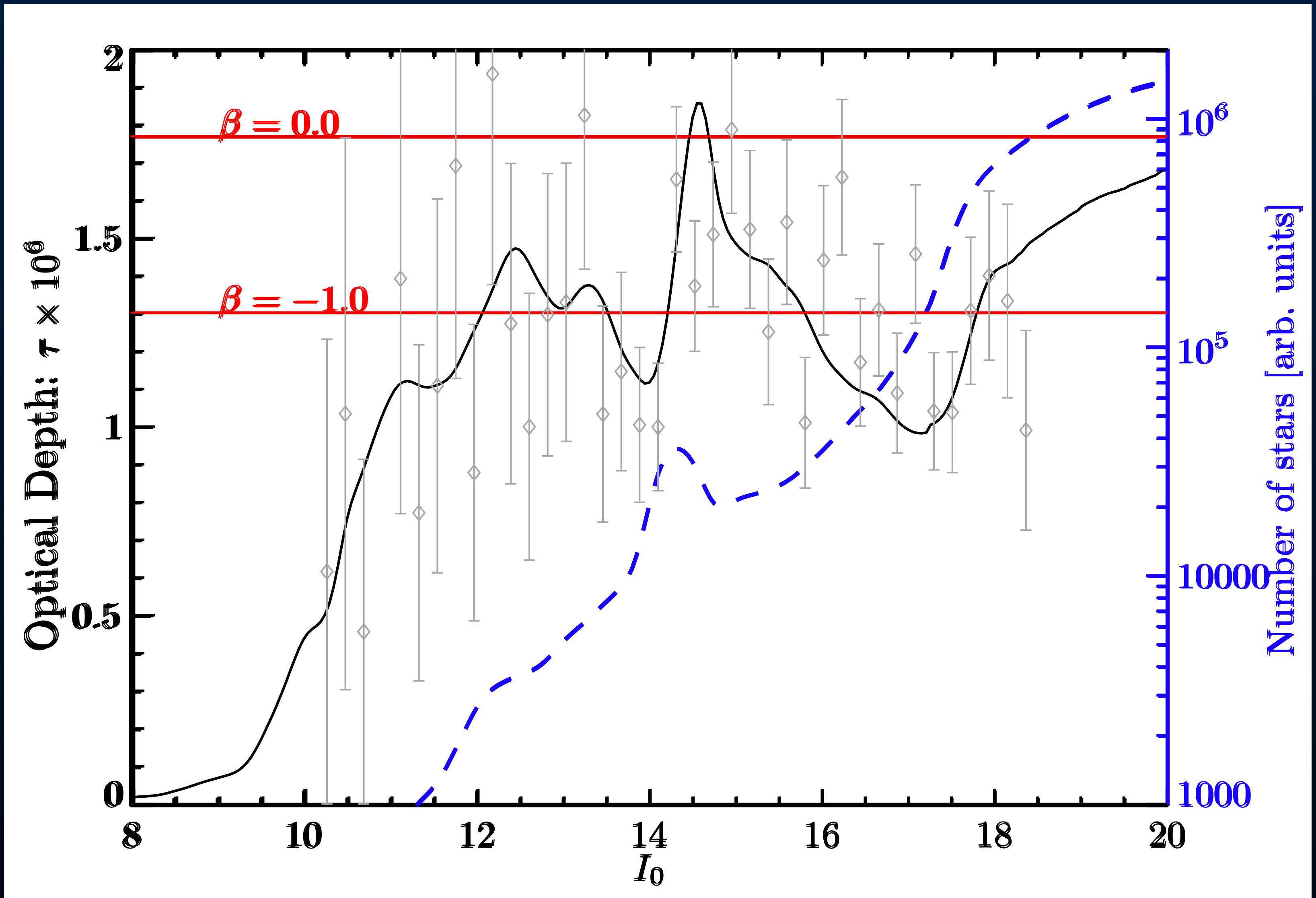
- Theoretically very attractive: Depends only on the density of lenses. Not on mass and velocity distribution

Two Major Issues:

1. Finite length of observations limits range of event timescales. A dynamical model and mass distribution is needed to correct for this
2. What is observed is an average over observable stars i.e. brighter than magnitude cut

2. *What is observed is an average over observable stars i.e. brighter than magnitude cut*

- Usually a power-law β-parameterisation for luminosity function assumed (red lines)
- Using models + isochrones things are more complex (black line)
- Variation in OGLE-III data seen (grey points)



Accurate comparison requires modelling of magnitude distribution and source selection

Microlensing Model

- To N-body bulge models add a double exponential disk

$$\rho = \frac{\Sigma_\odot}{2H_\odot} \exp\left(\frac{R_0 - R}{R_d}\right) \exp\left(\frac{z_0 - z}{H(z)}\right)$$

- Local disk properties:

$$H_\odot = 0.3\,\mathrm{kpc}\,,\ \ \Sigma_\odot = 38\,M_\odot\ \mathrm{pc}^{-2}$$

Inner disk is highly uncertain

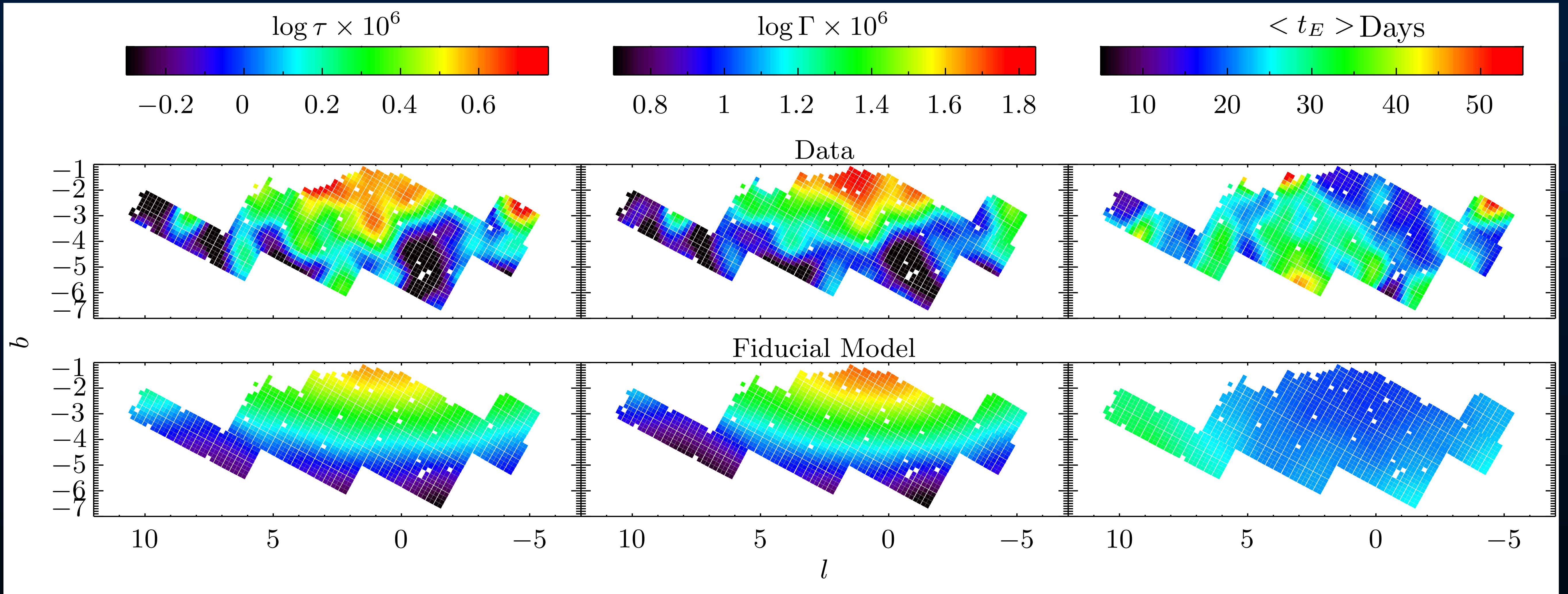
- Allow the disk to be flared *i.e.* scale height decrease inwards. We found the long bar had a scale height of $\boldsymbol{H}_{4.5}$=0.18 kpc.

- Uncertainty on the disk of the inner Milky Way parameterised by 2 quantities: R_d & $H_{4.5}$

Microlensing Properties of Fiducial Model

- Fiducial model: M90 & R_d = 2.15 kpc & $H_{4.5}$ = 0.18 kpc

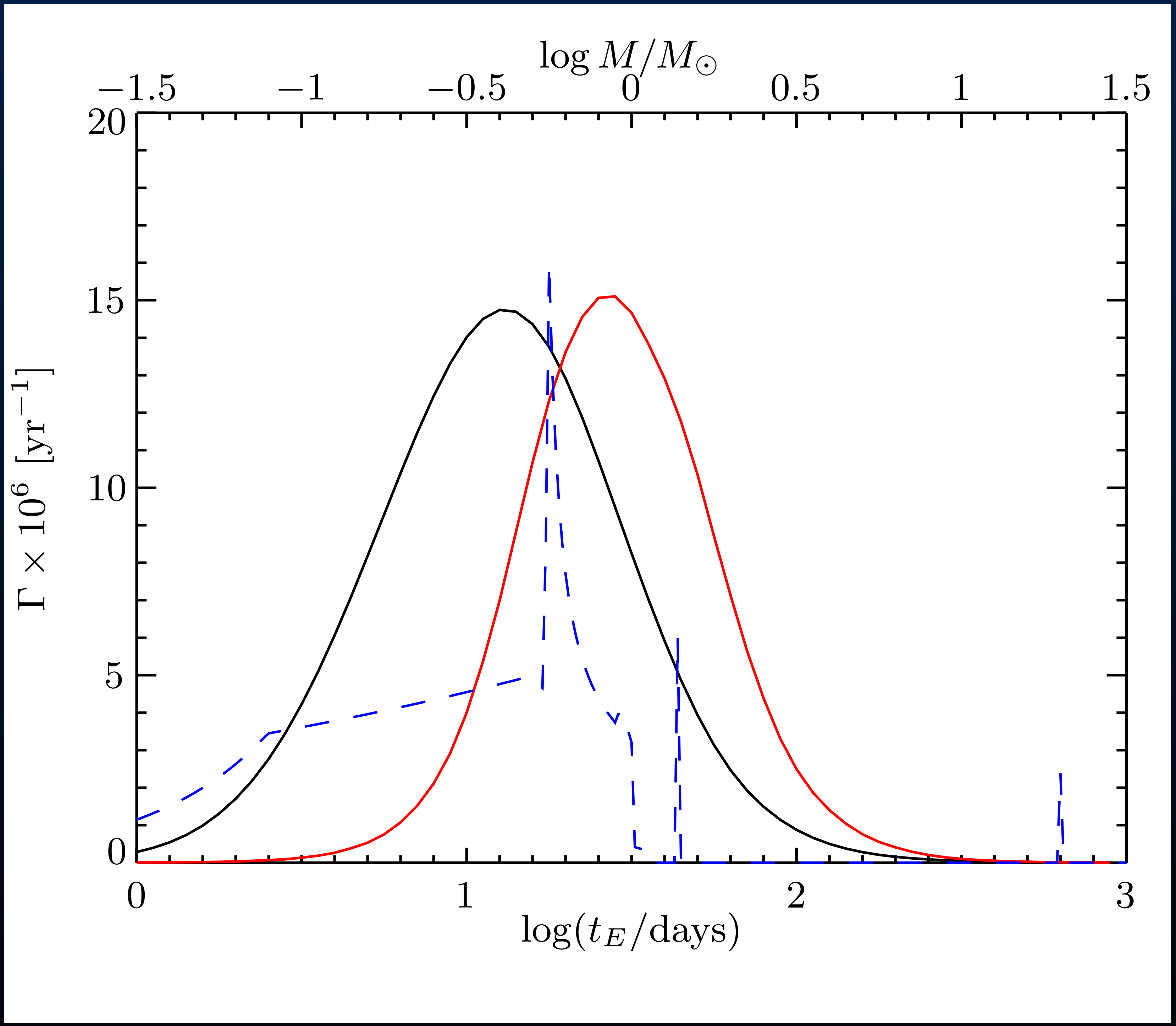
Comparison to maps from MOA-II (Sumi+2013):



Agreement seems qualitatively good

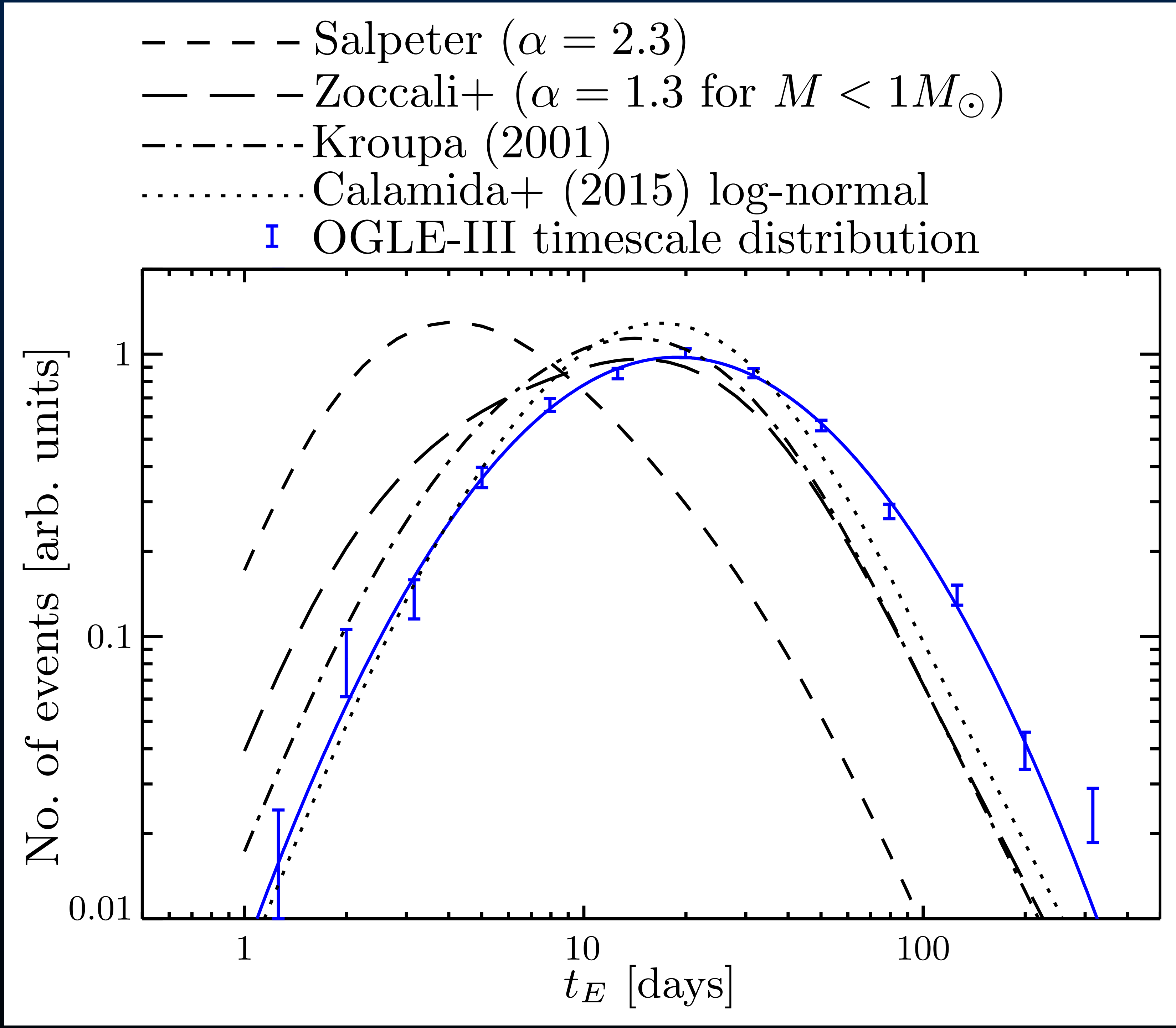
Timescale Distribution

- Timescale distribution is the timescale distribution for $1M_\odot$ convolved with the scaled mass distribution.
- Can therefore be used to place constraints on the mass function and IMF



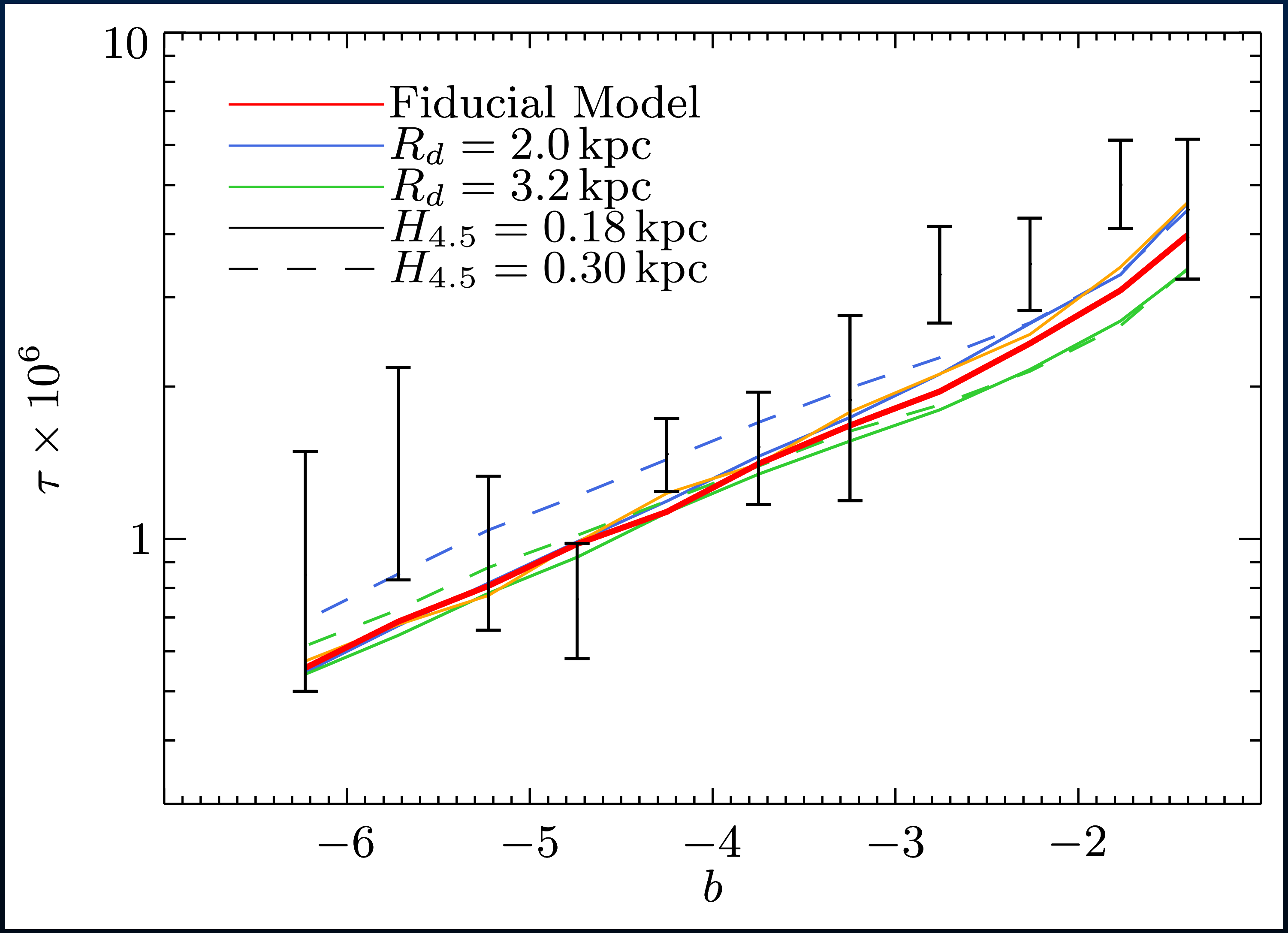
Timescale Distribution

- Fiducial dynamical model with different IMFs
- Model matches very well with Kroupa or especially Calamida log-normal IMF: $<\log t_E>= 1.21$ vs $<\log t_E>= (1.275 \pm 0.008)$ in OGLE-III
- Low number of brown dwarfs required (similar to but less than Awiphan +15 with Besancon + MOA-II)



Optical Depth Comparison

- Shorter disk scale lengths place more mass in front of bulge→ increase optical depth
- For this bulge model short disk scale lengths required
- Driven by data at |b|<3°. Even shortest disk scale lengths undershoot 3 of 4 points here.



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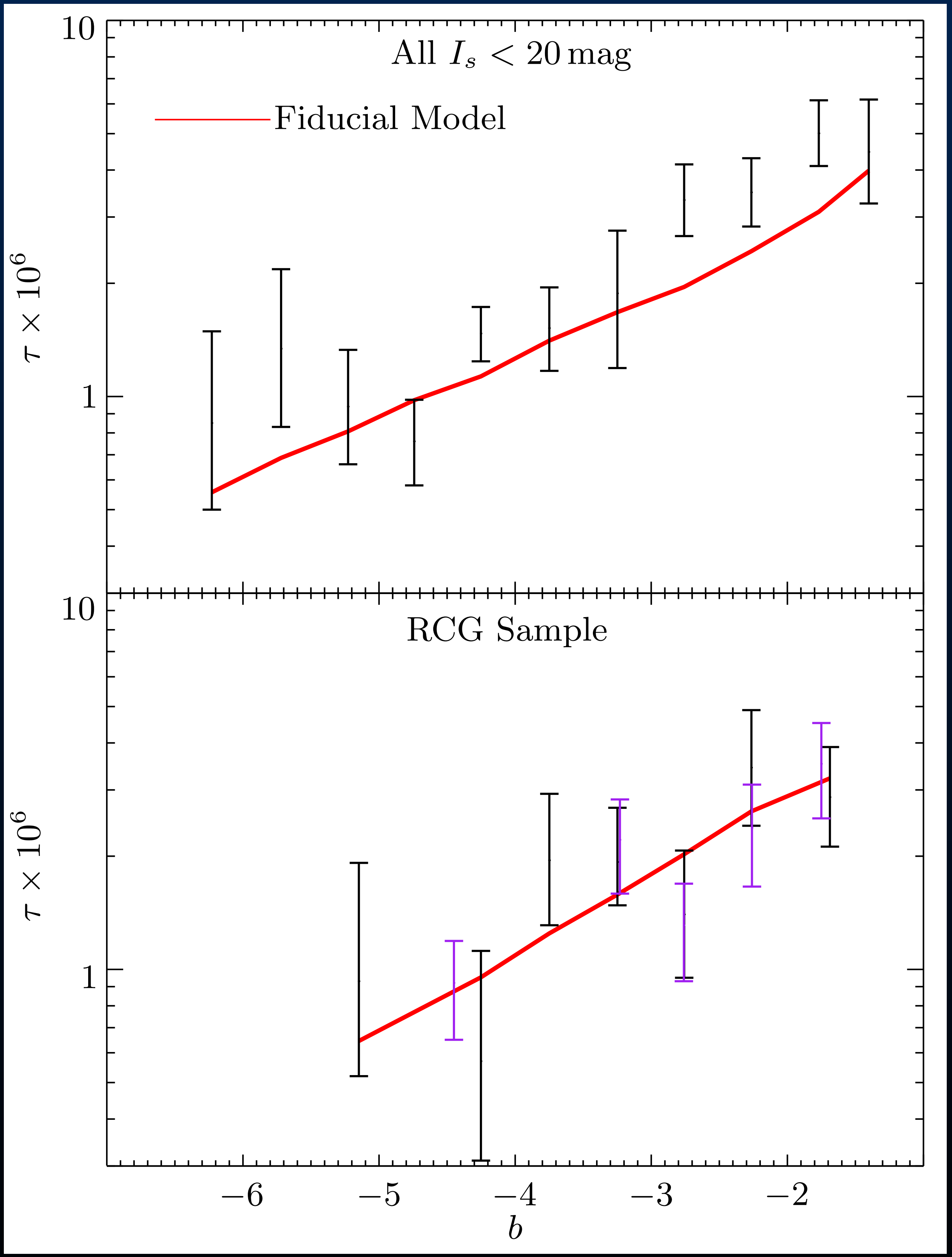

Conclusions

- We have a ***measurement*** of the 3D shape of the bulge using RCGs as tracers.
- Bar outside the bulge has length 5.0±0.2 kpc, angle (28-33)$^{\circ}$. Appears naturally innately connected to barred bulge.
- Two components in bar. 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?
- Constructing made-to-measure N-body models we find the total mass of the bulge to be 1.84 10^{10} $M_{\odot}$ with an accuracy <5% (systematics). This mass is degenerate between dark and stellar matter.