The Galactic Bulge and Bar

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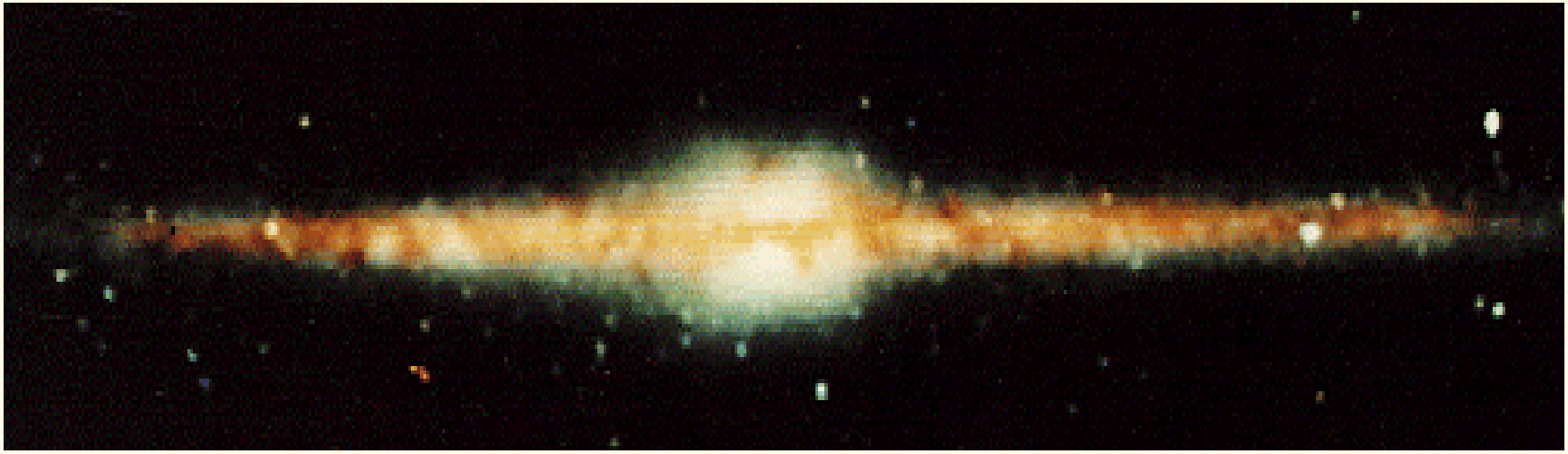
Outline:
1) Statistical parallax to GC
2) 3D bulge density
3) Dynamical models for X-shaped bulge
4) The bar outside the bulge

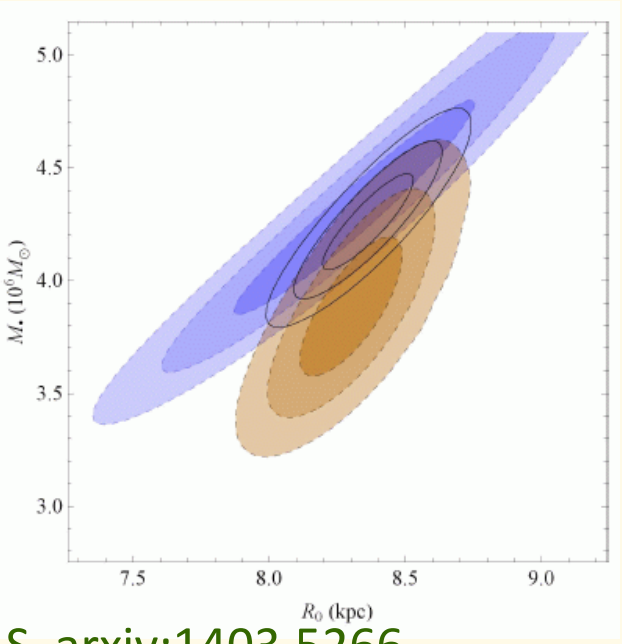


1. Distance to Galactic Center

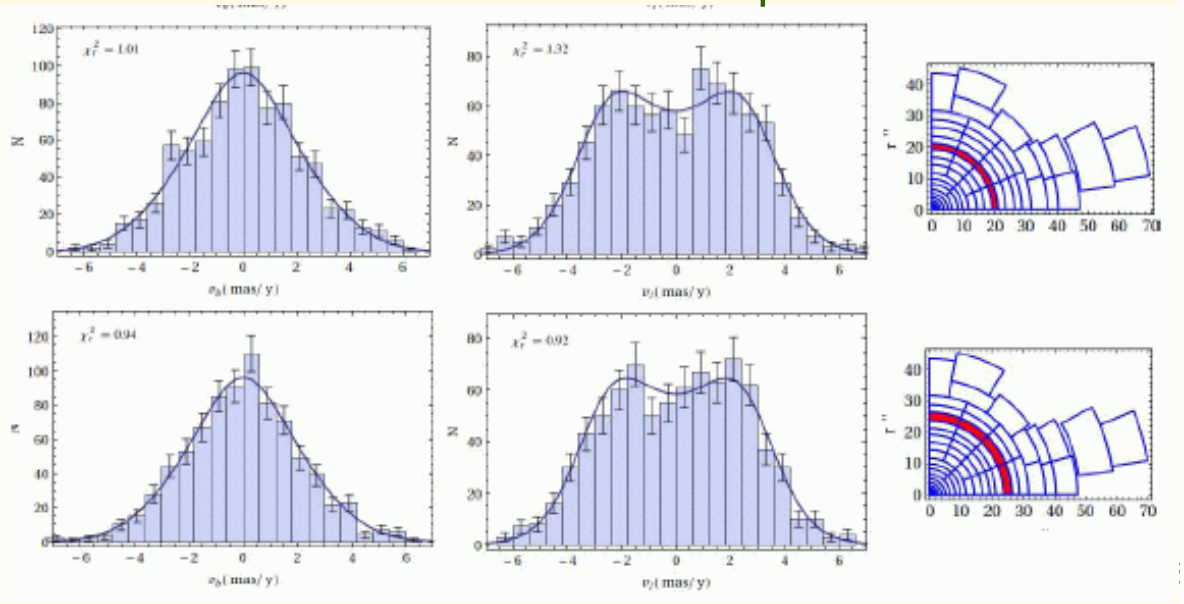
Statistical parallax of MW nuclear star cluster from 10'000 PMs and 3'000 vlos, linked together by dynamical model. F(E,Lz) fits PM and vlos histograms well (below). Combined analysis with stellar orbits around Sgr A* (Gillessen+09) gives

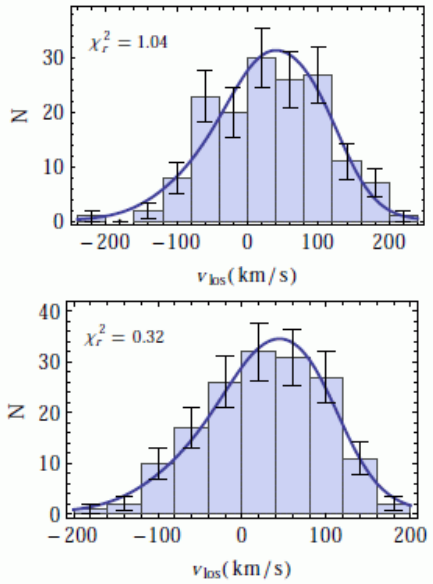
R_0 = 8.33±0.11 kpc (stat, syst ~±~0.1)

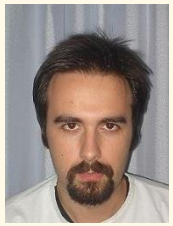
$M_\bullet$ = (4.23±0.14)×10^6 Msun



Chatzopoulos+15 Jan MNRAS, arxiv:1403.5266



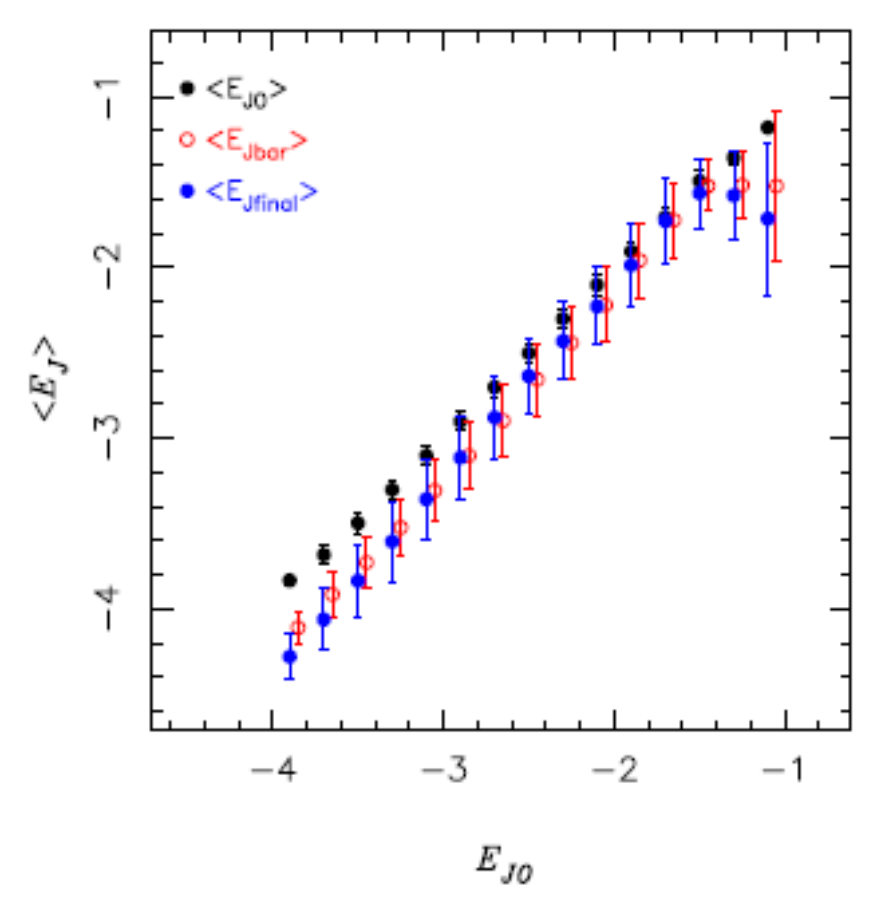




Metallicity Gradients Through Disk Instability

(Jacobi) binding energies scattered by << initial range. Hence stars have memory of formation site

Stellar populations with different initial distributions would end up having different kinematics and spatial distributions in the bulge

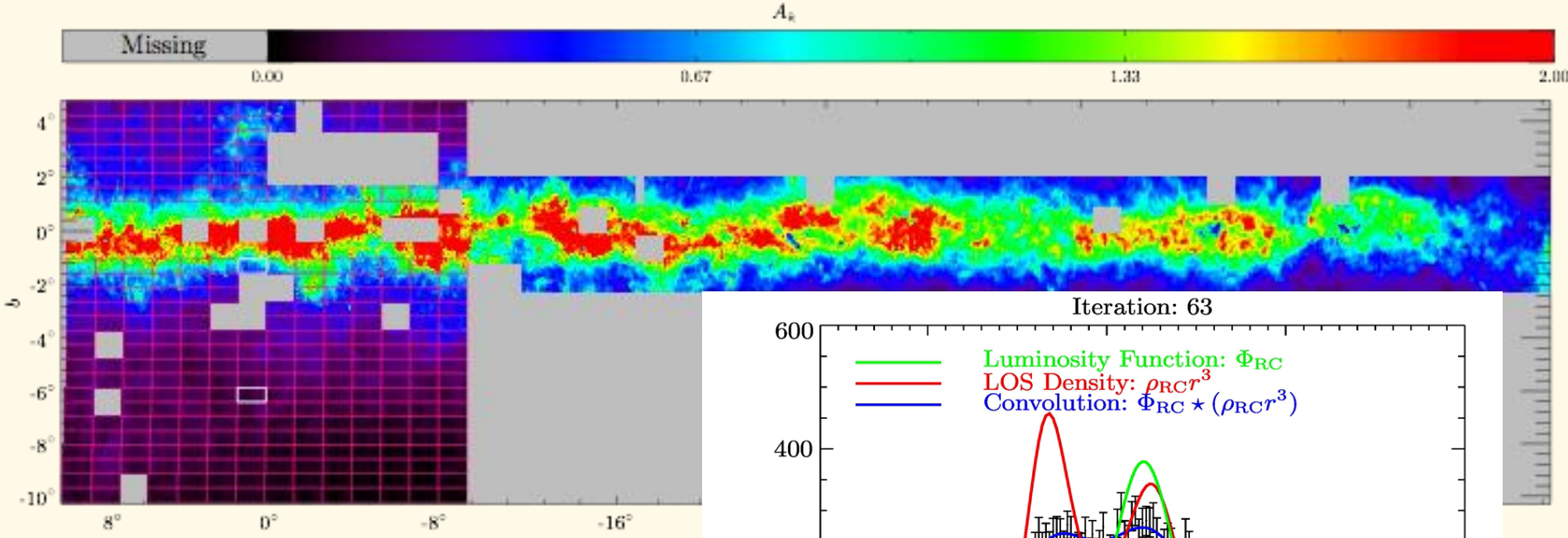


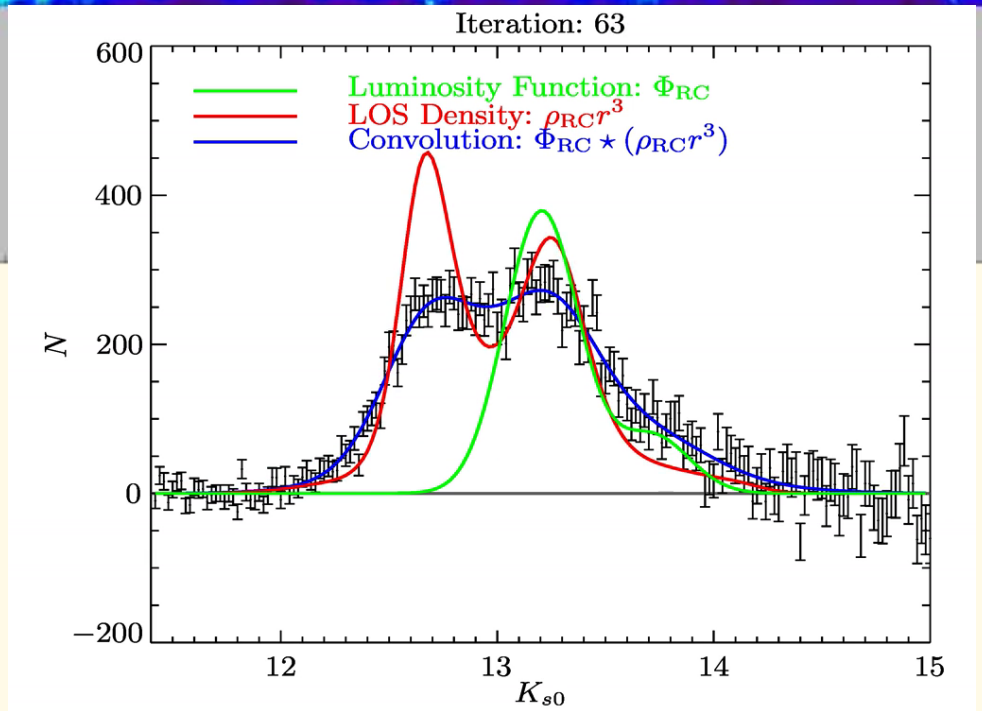
Martinez-Valpuesta+OG'13

2. Bulge 3D-Density *from VVV RCG Star Counts*

Extinction map calculated using same method as Gonzalez+(2011):

$$\text{Change in } J-K_s \text{ of red clump } \rightarrow E(J-K_s) \xrightarrow{\text{Extinction Law}} A_{K_s}$$





Pink: Sight lines considered

Completeness correction

Density deconvolution with LF

Wegg & OG '13 MNRAS

Correction for Extinction and Completeness

Example field at (l,b)=(-6,1)

Raw CMD: red

Extinction corrected: blue

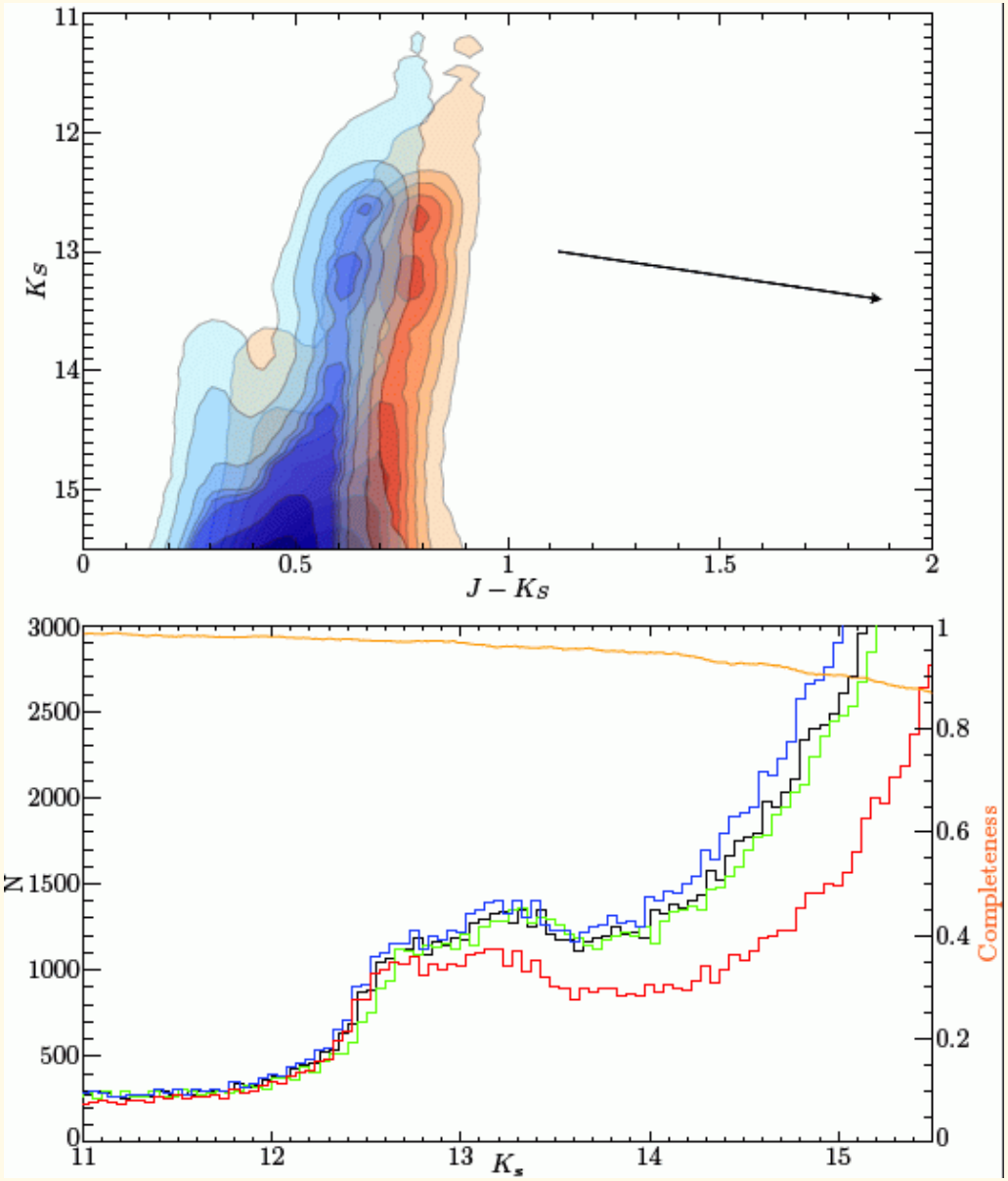
In low-extinction regions, estimate
σ(K)≈0.18mag σ(J-K)≈0.05mag

Iso-density contours containing
10%, 20%... of stars

Raw counts: green
Extinction corrected: black
Completeness corrected: blue

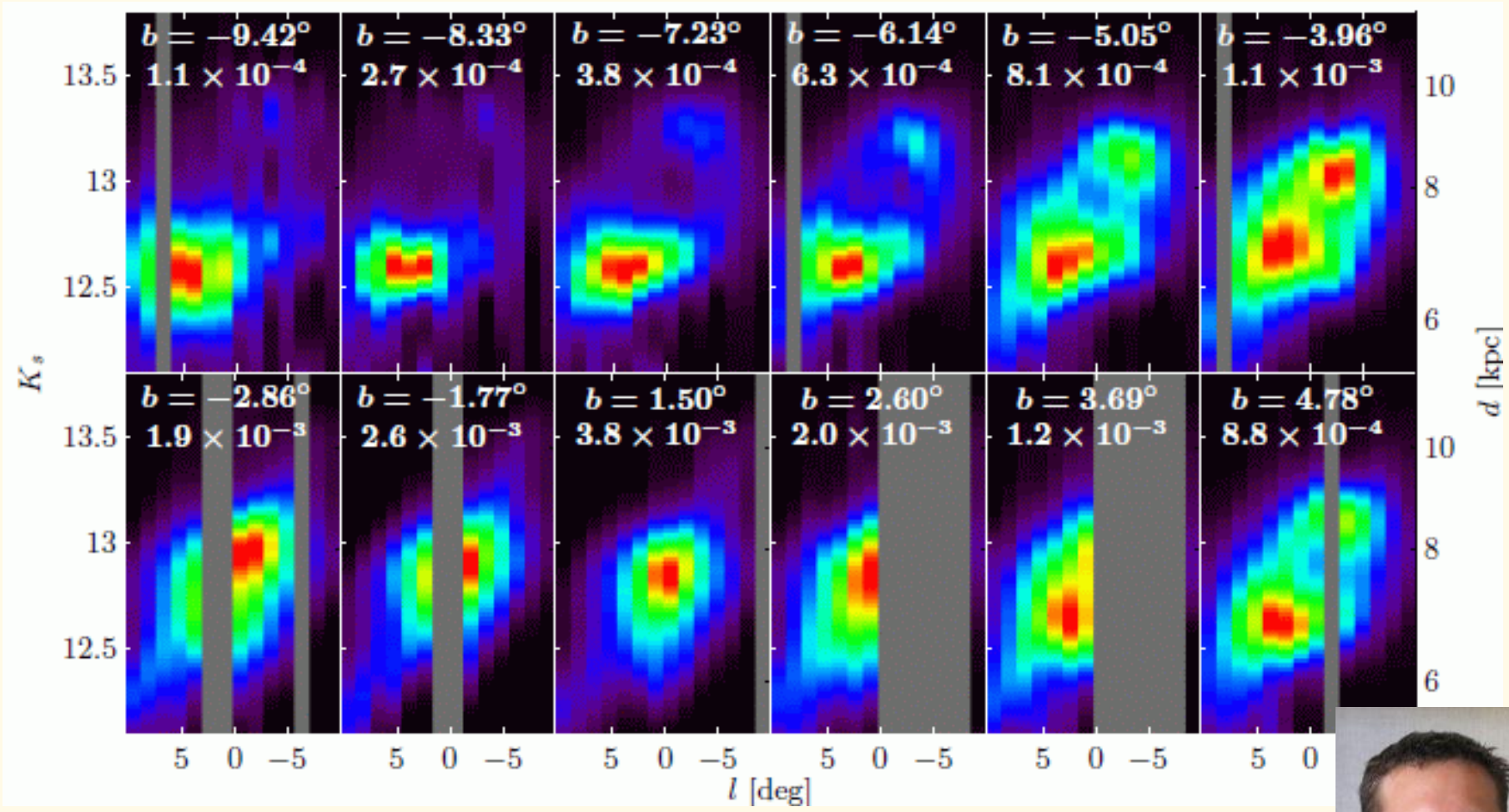
Orange: completeness

Red line with colour cuts

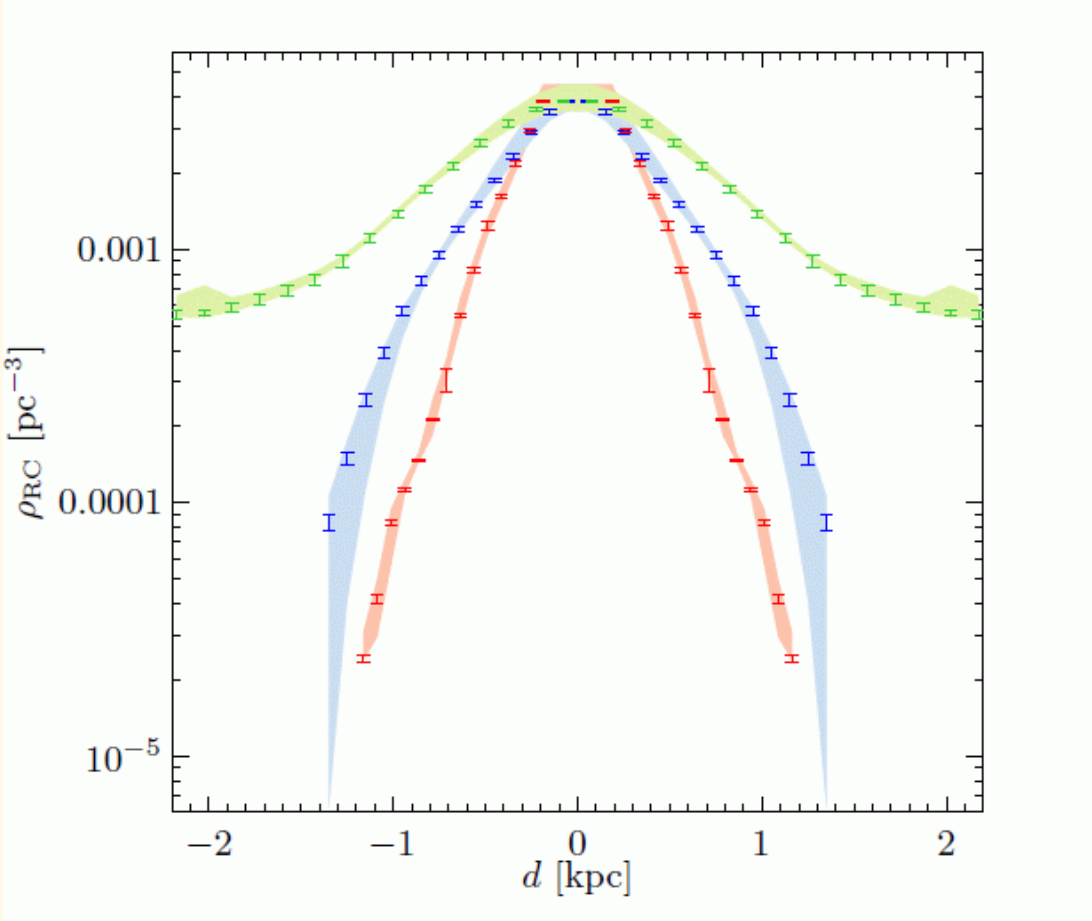


Gives an estimate of for each of 300 sight lines

$$\rho_{\rm RC}(l,b,r)$$



Axis Ratios



Major Axis

Intermediate Axis

Minor Axis

Error Bars: Internal Errors. From std. dev. of symmetrisation

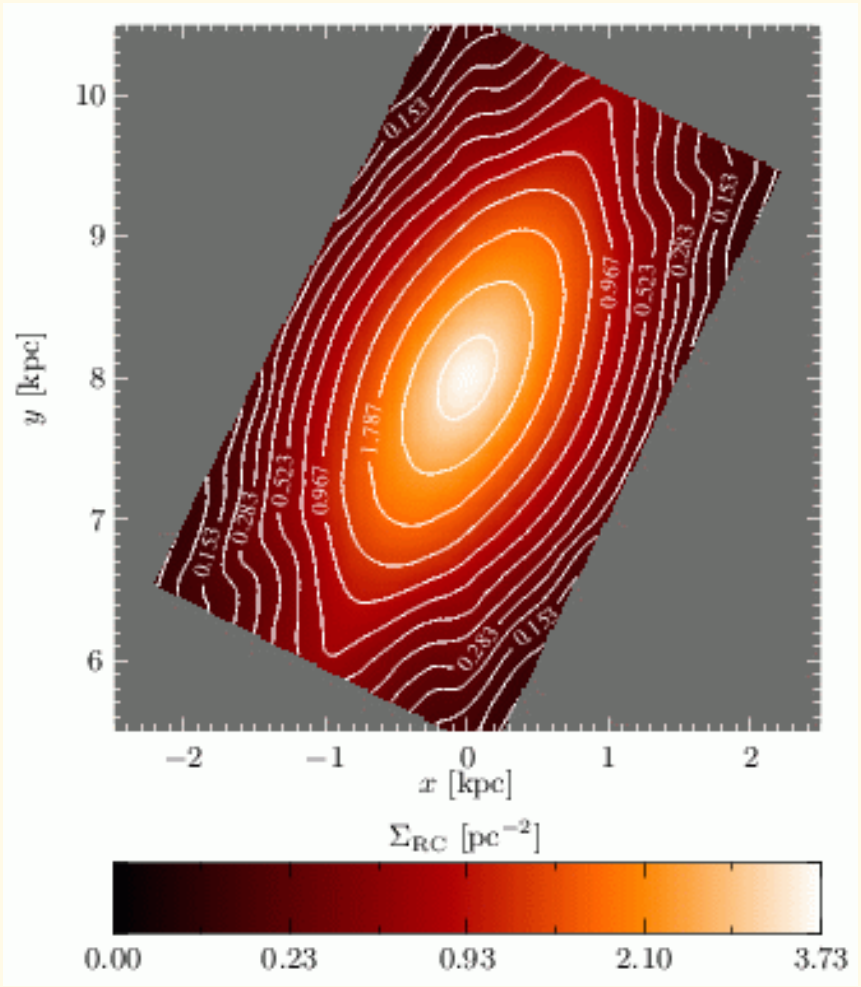
Shaded Region: Systematic Errors. From Changing LF, Background Fitting Function.

Central exponential scale-lengths: (0.70 : 0.44 : 0.18) kpc in (x : y: z)
Vertical scale-length at x=1.1-1.7 kpc: ~0.5 kpc (X-shape)

Galactic Bulge 3D Density from RCGs

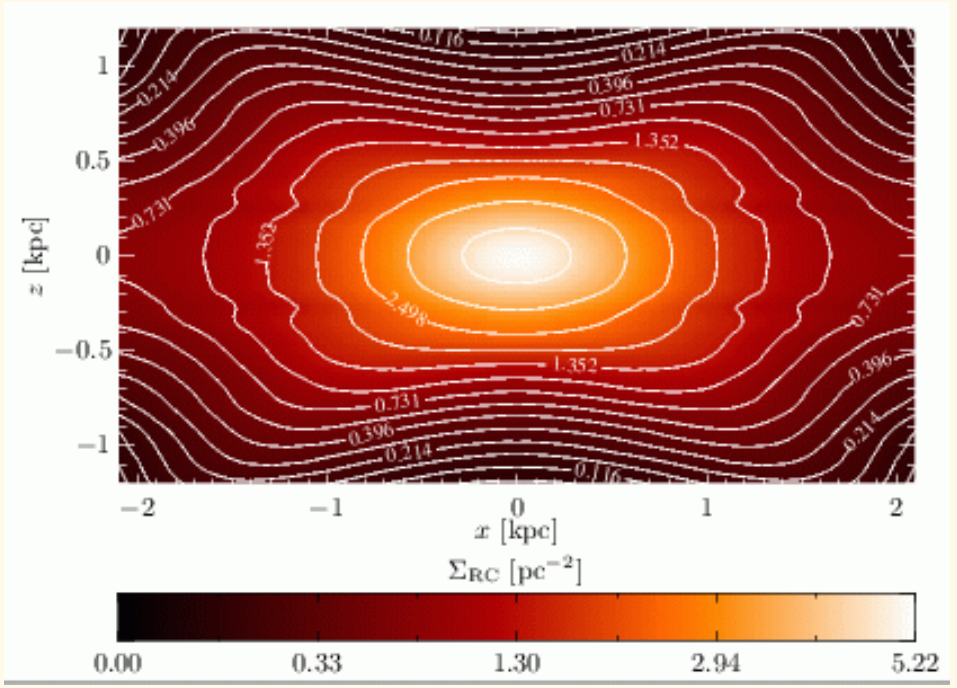
Projections

Above (from north Galactic pole):



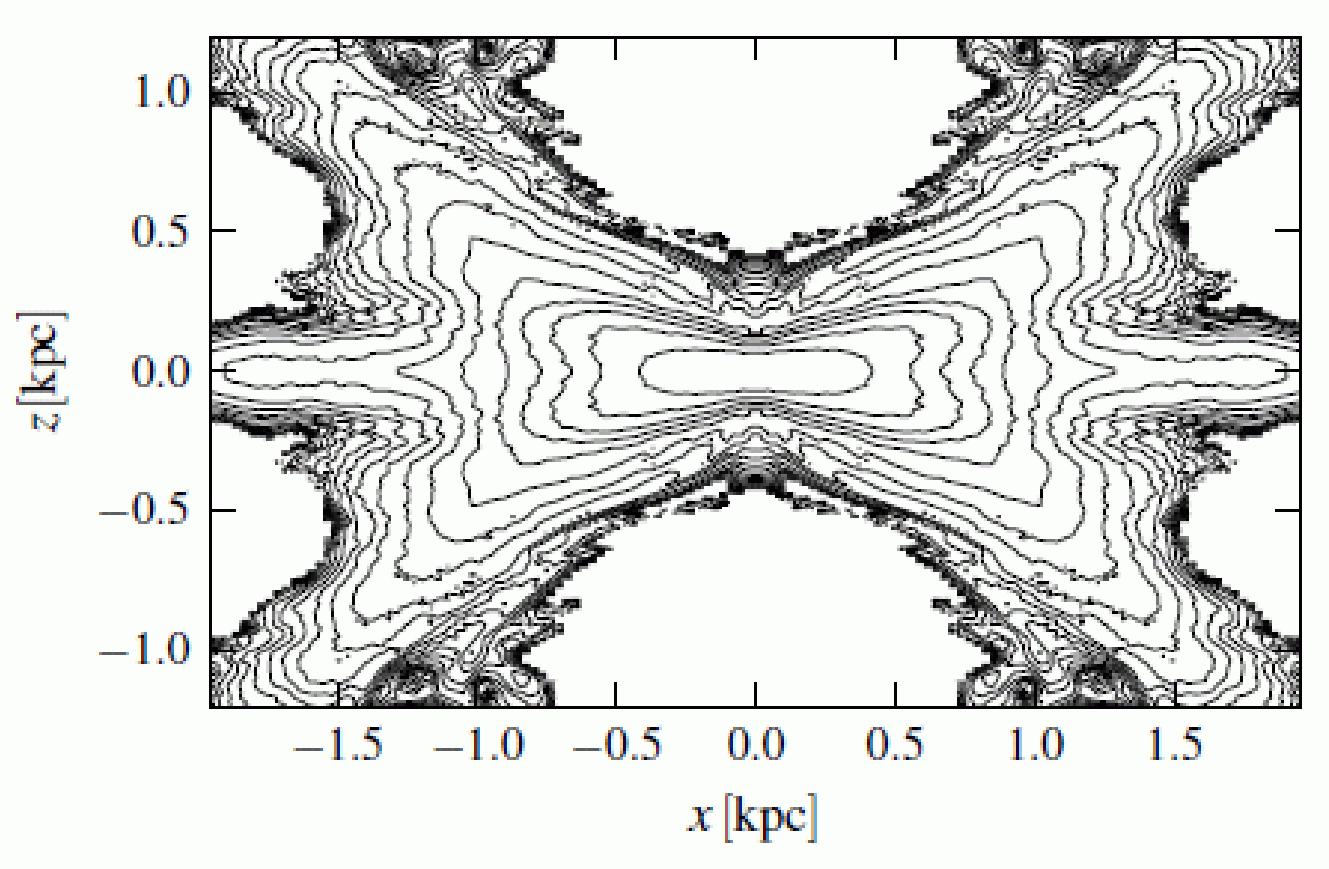
$\alpha=27°\pm2°$ (system.)

Side (along intermediate axis):



|b|>1°: Wegg & OG '13
Extrapolating into Galactic plane:
Portail+'15 MNRAS in press

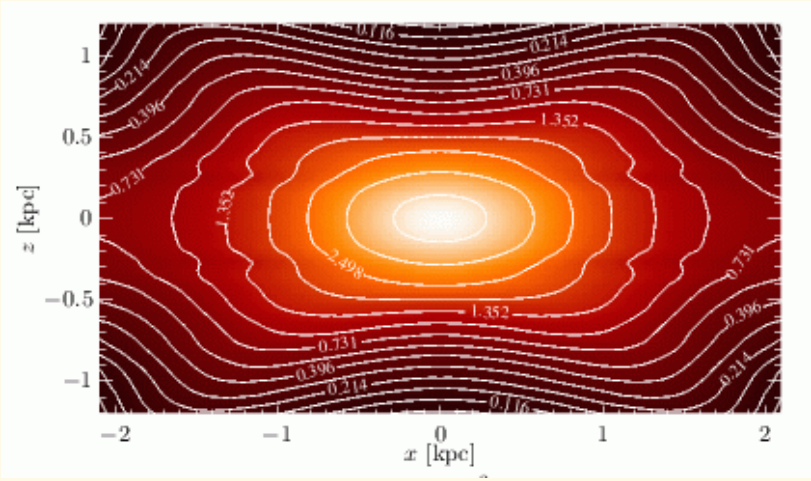
Unsharp-Masked X-Shape



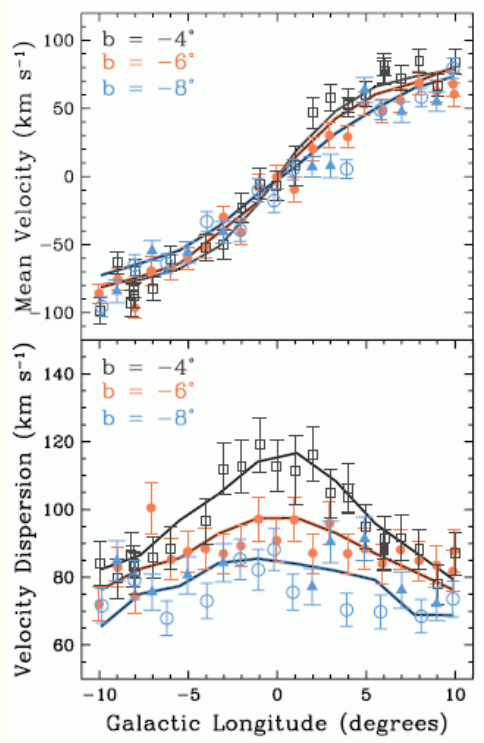
- Unsharp masking: removing median-filtered image from the original image. Reveals off-centered X-structure in the MW (after Bureau+'06)
- Mass in peanut shape = excess over ellipsoidal bulge shape
  > 20% of the bulge mass Portail+'15 MNRAS in press

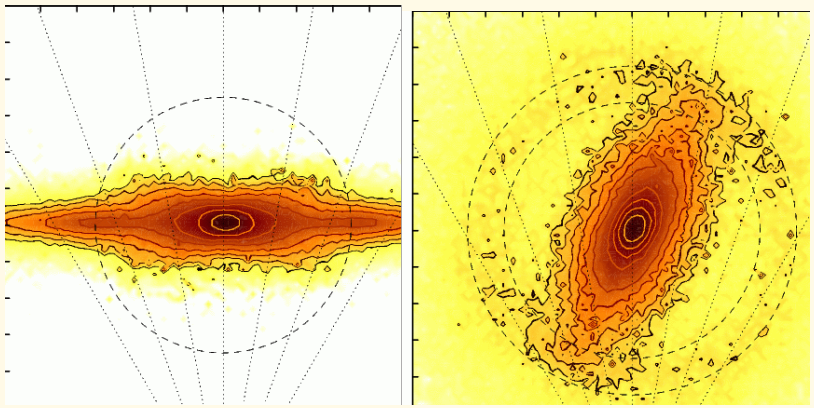
3. Dynamical Models for the MW B/P Bulge

Using NMAGIC Made-to-Measure method to fit N-body barred galaxy models to the 3D bulge RCG density and the BRAVA kinematics



BRAVA data (Kunder+'12) ~ cylindridal rotation



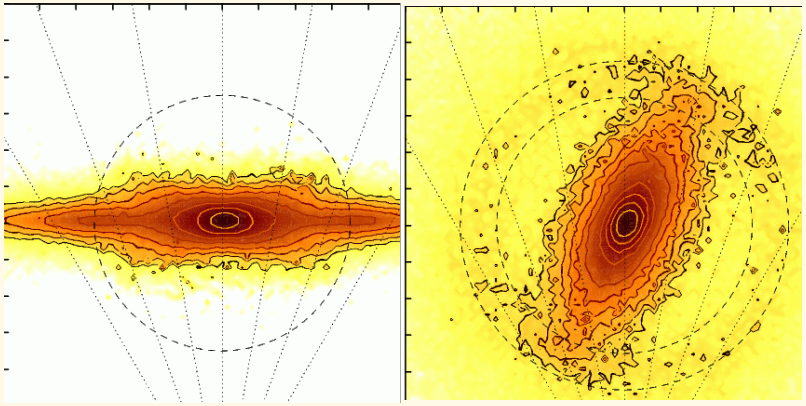


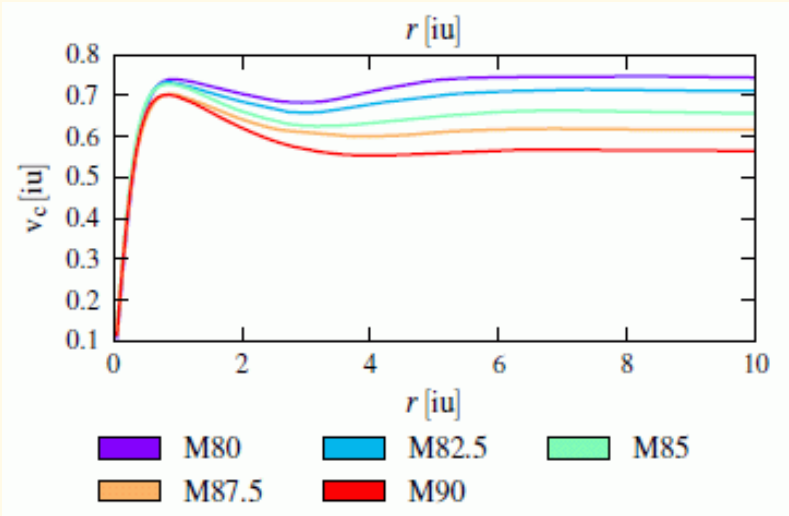
Initial N-body model

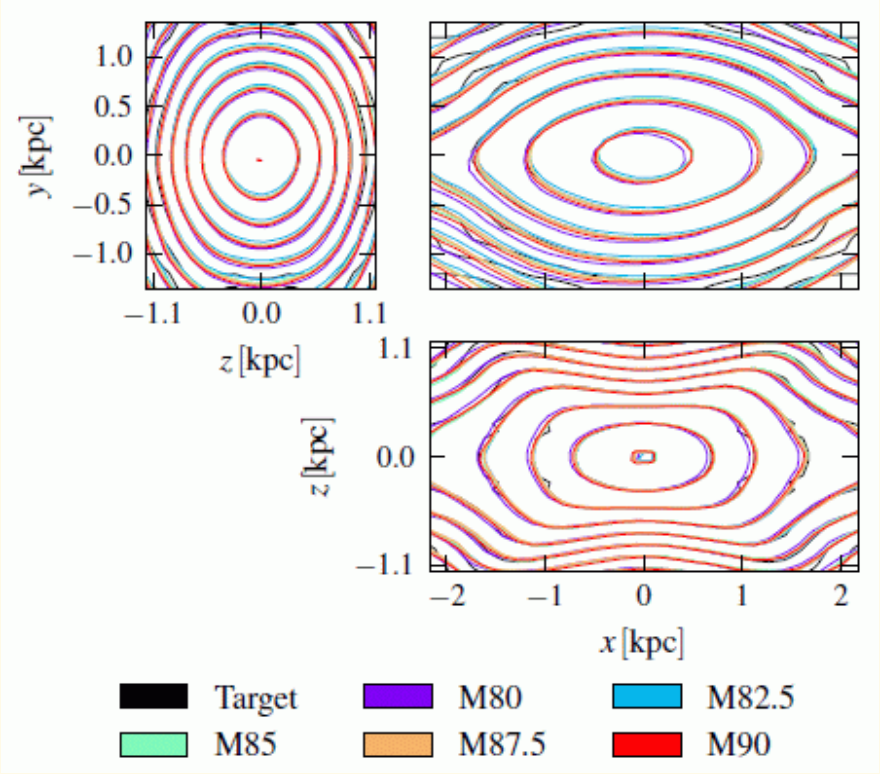
Portail+'15 MNRAS in press

Bar Models With Different Dark Matter Density

Generate bars with different pattern speed and DM halos. All fitted to the 3D bulge density and BRAVA RCG kinematics using NMAGIC M2M method

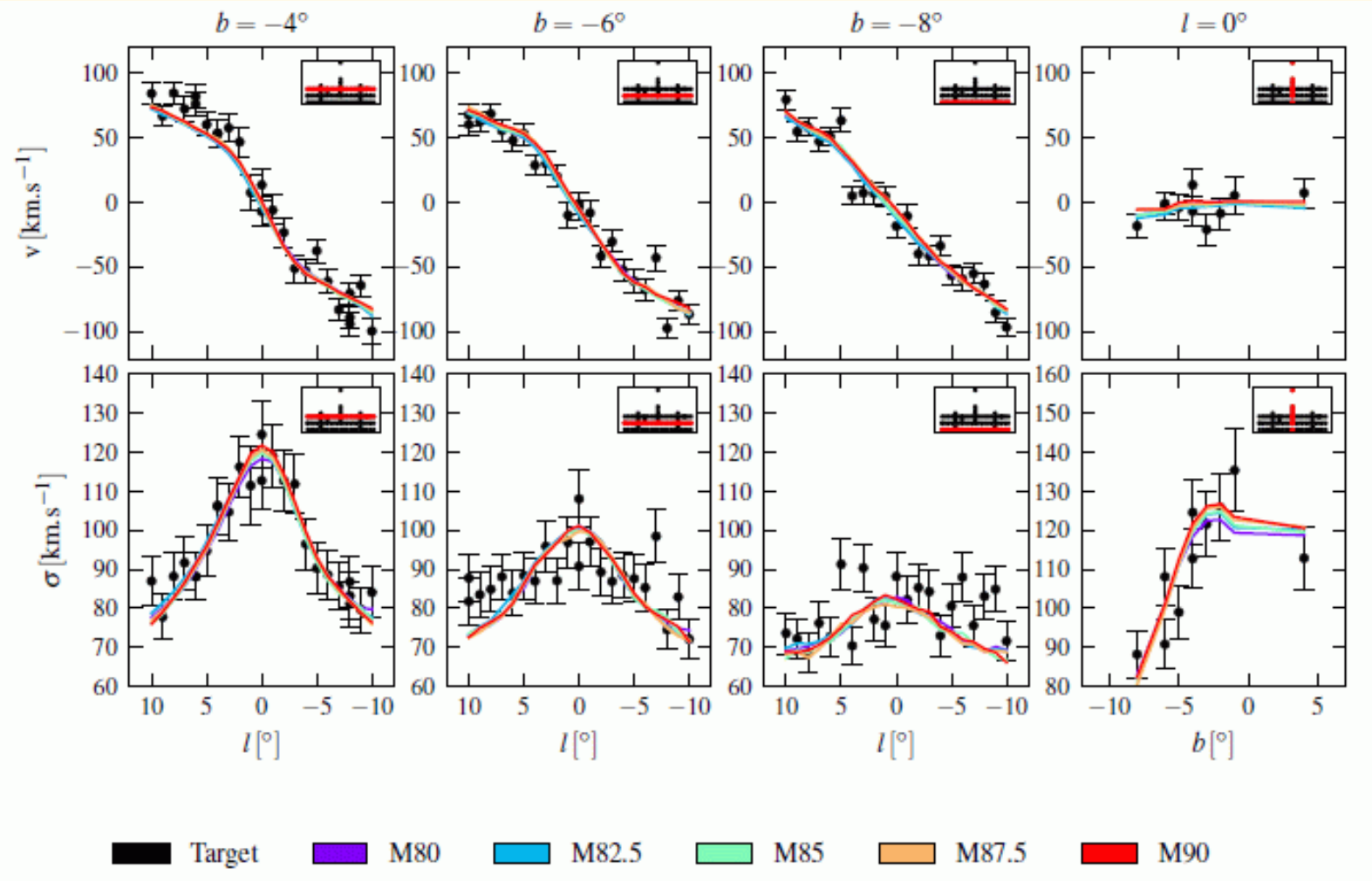






Portail+'15 in press

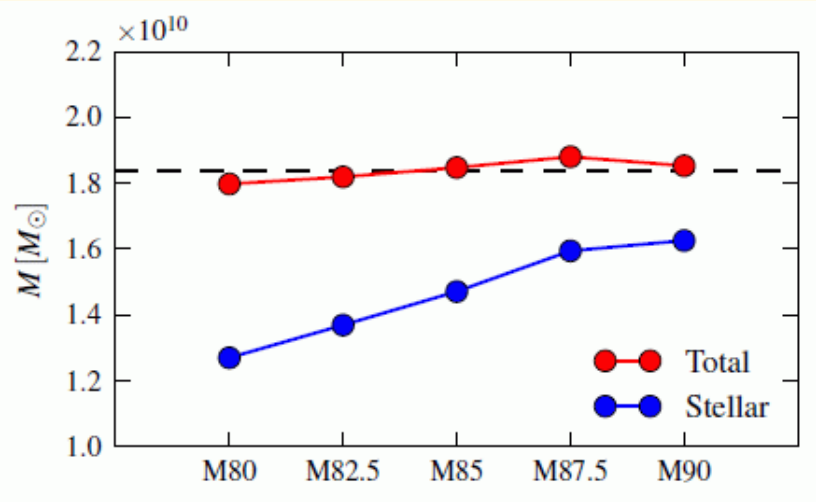
M2M Model Kinematics for RCG Bulge Density



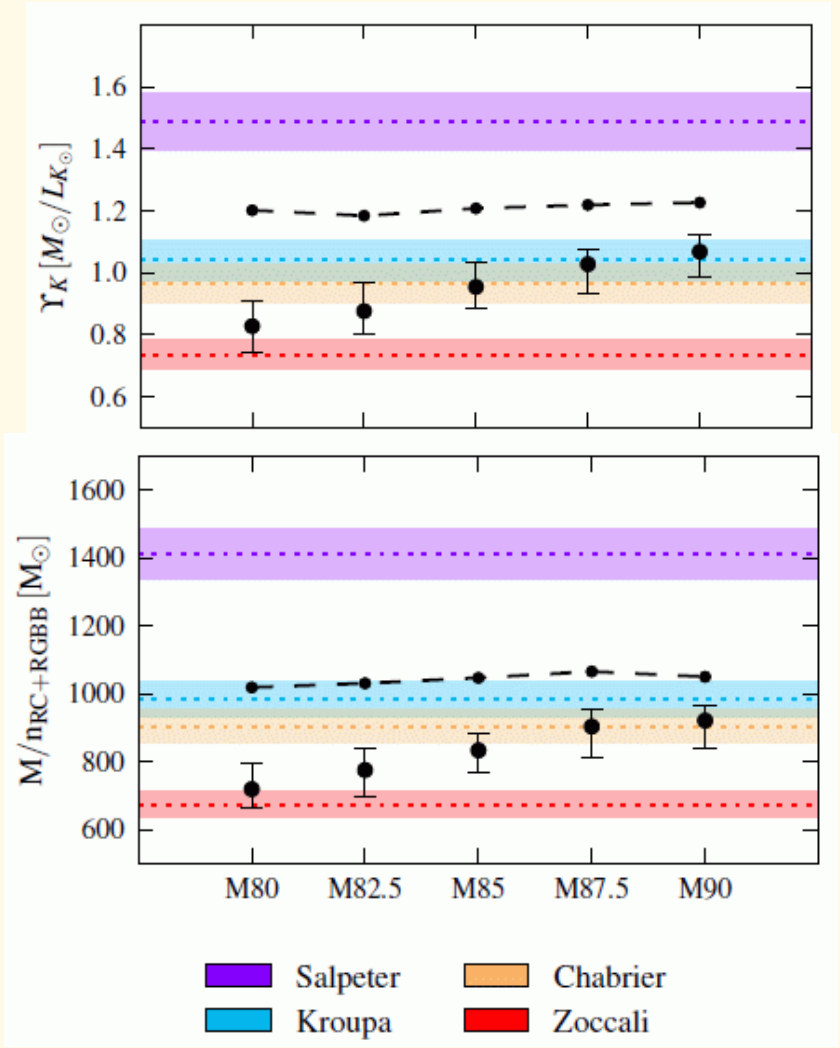
Dynamical mass of bulge inside 3D bulge region (4.5×2.8×2.4 kpc^3 box) is 1.84 ± 0.07 ×10^{10}M$_\odot$

Portail+'15 in press

Total Mass, M/L_K, and IMF in 3D Bulge



Portail+'14 submitted

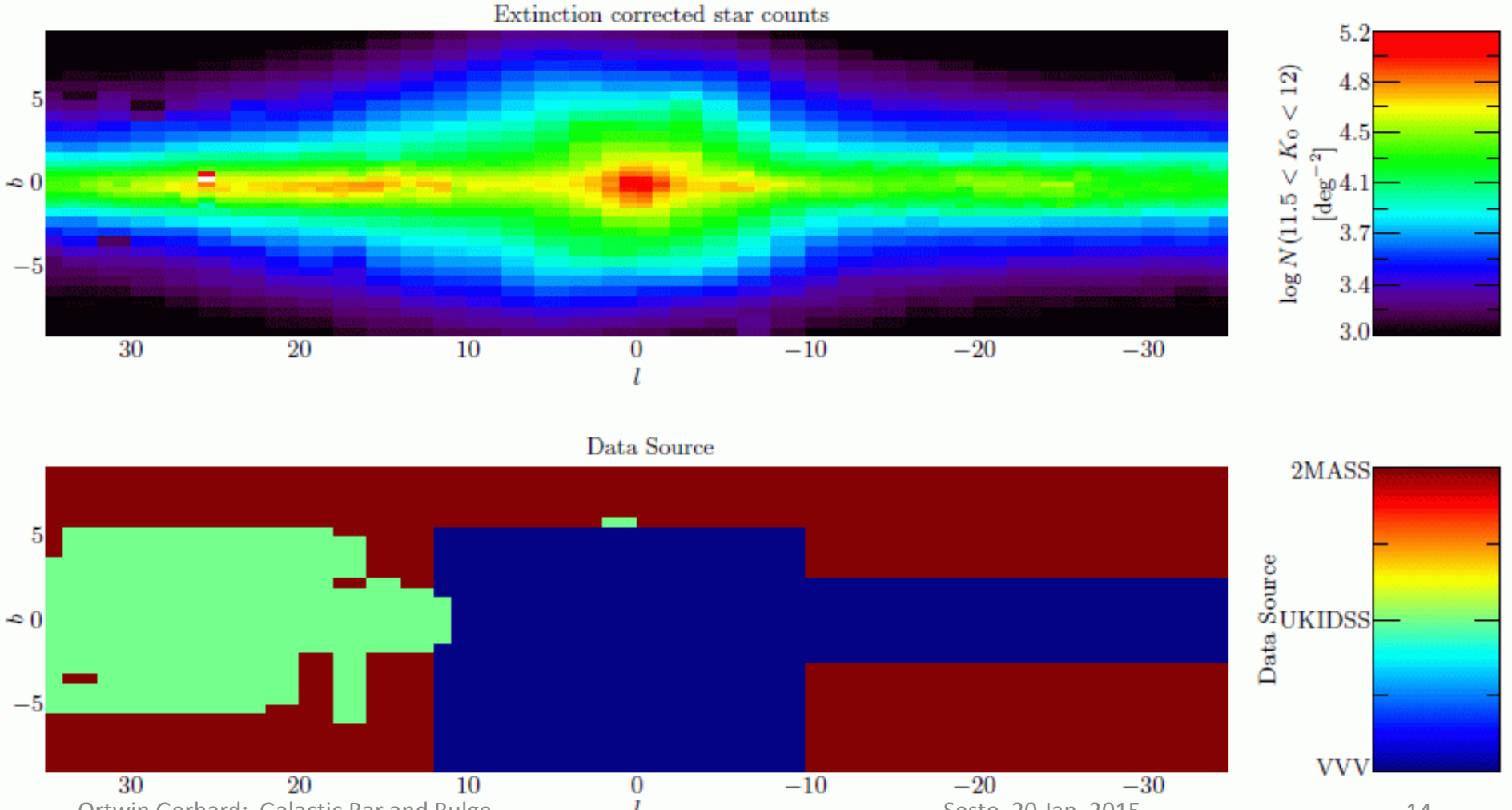


- Total mass in 3D bulge well-determined, is 1.84 ± 0.07 $\times 10^{10} M_{\odot}$ including variations of model assumptions. Stellar mass depends on model.
- K-band M/L_K and M/N_{RC} rule out Salpeter IMF. Zoccali and Chabrier/Kroupa IMF require 40% and 20% dark matter in the 3D bulge region

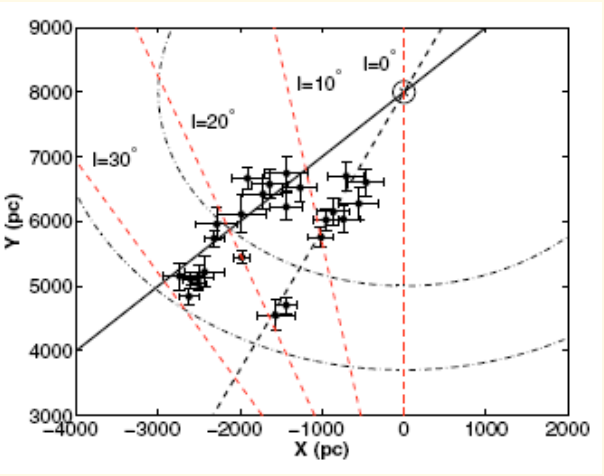
4. Bar and Bulge in K-band Star Counts

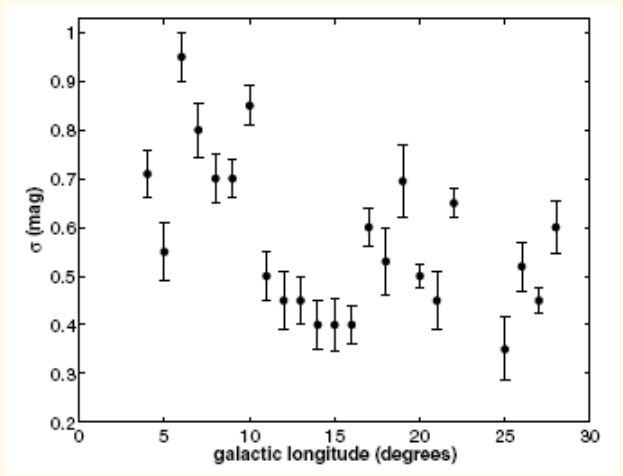
UKIDSS – VVV – 2MASS – GLIMPSE matched, extinction corrected, star-by-star, 11.5<K<12

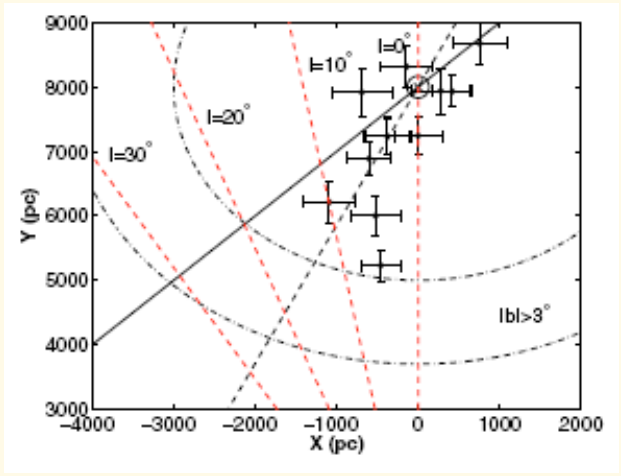
Wegg, OG, et al. to be submitted



The "Long Bar" – Previous Results from RCG Method







UKIDDS data at b=0º Cabrera-Lavers et al. 2007, 2008 TCS-Cain data at b=3º

Two structures with different PA in Galactic plane: ~25º (bulge, corrected for l.o.s. broadening: ~15º), in-plane "long bar": ~45º. Also Benjamin+'05 Spitzer-Glimpse

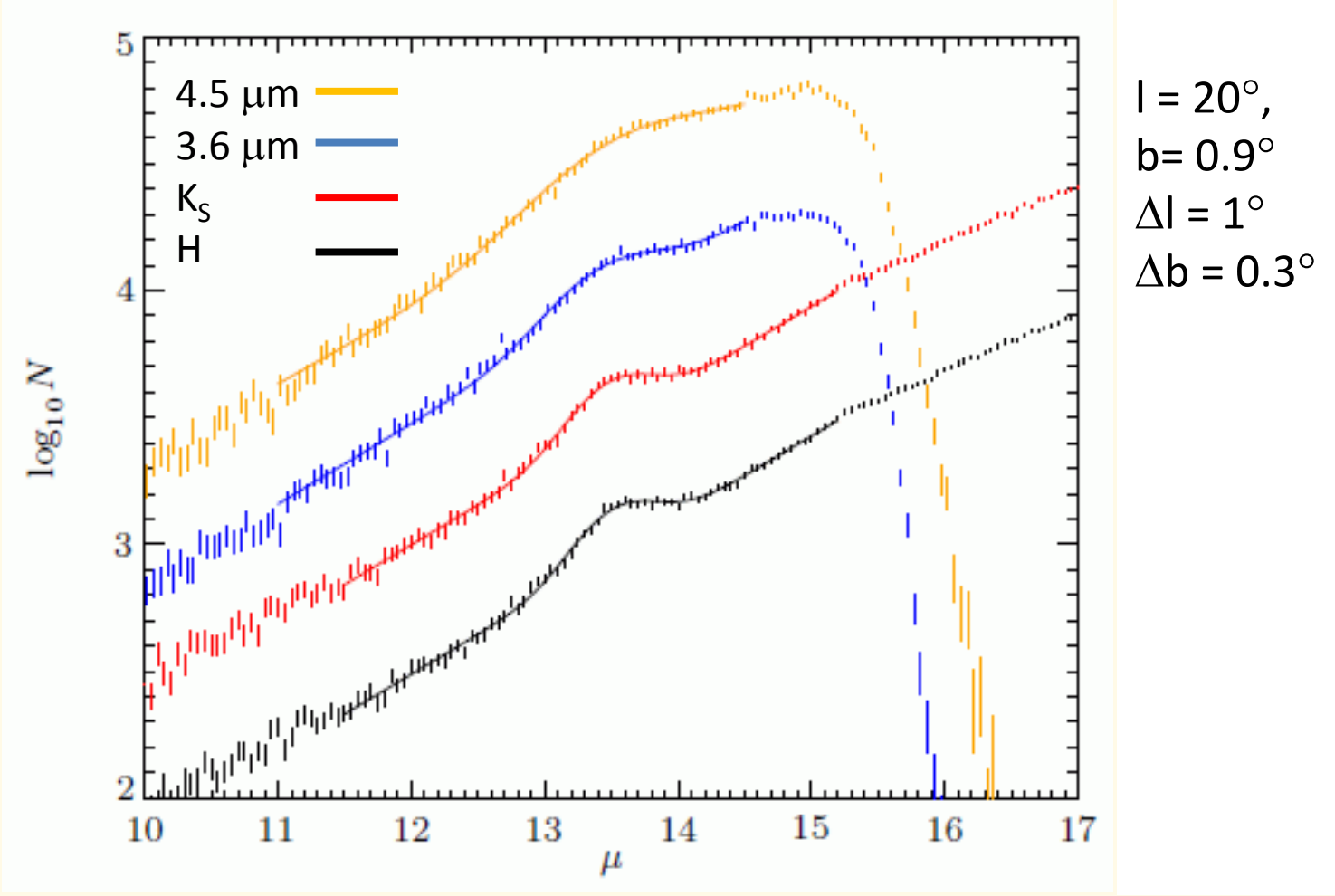
Good

- At b=3º, only bulge
- Bulge scale-height ~300 pc
- "Long bar" scale-height ~100 pc

Question marks

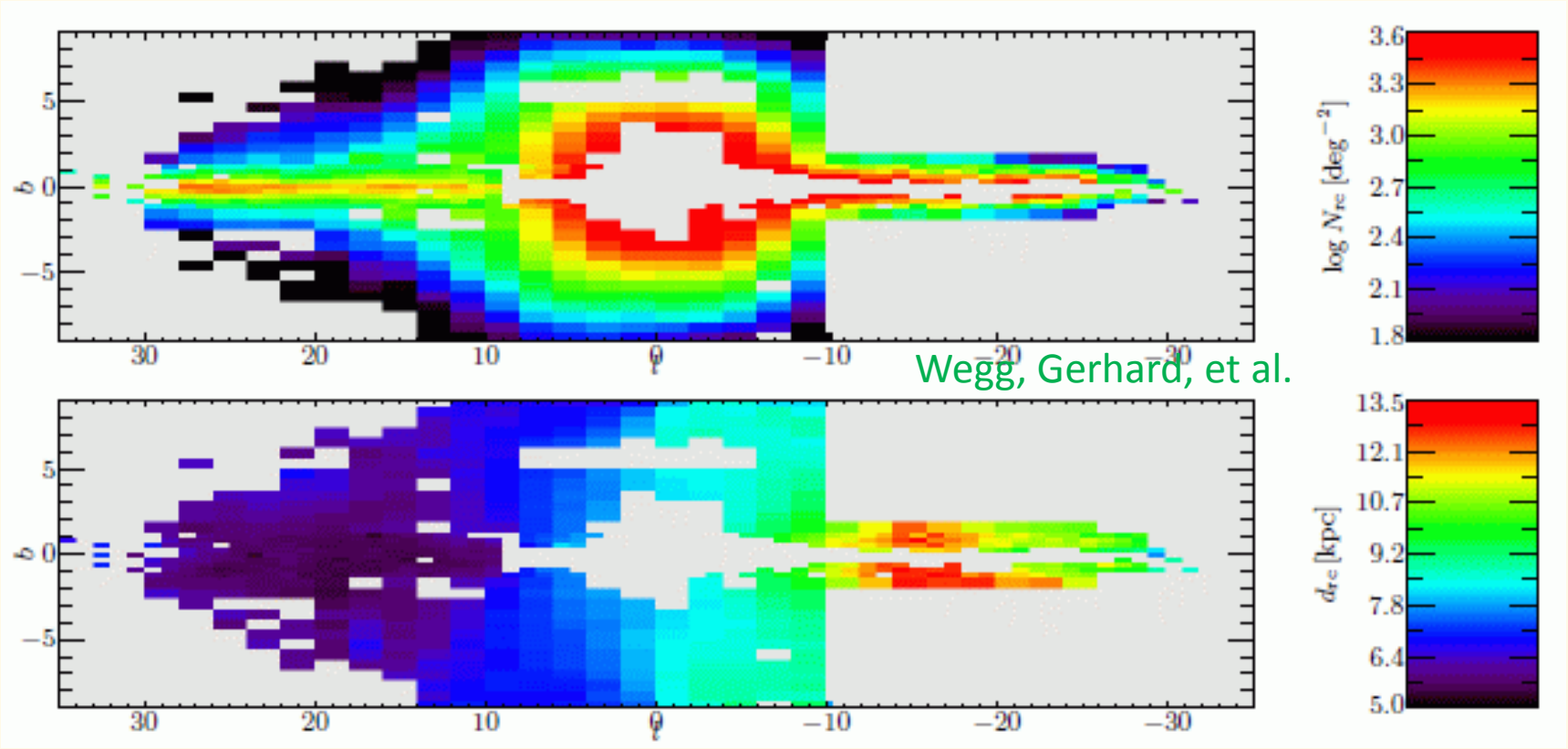
- Sudden jumps near l=10º, l=20º
- Distance dispersion scatters
- Very little data for l<0 (survey limit)

Red Clump in NIR and MIR



- Distance modulus assuming RCG mag M_K=-1.72 etc.
- Galactic Centre is put at μ=14.6 (8.3 kpc) see Chatzopoulos+'15

Inner Milky Way in Red Clump Stars



Wegg, Gerhard, et al.

- N, D from Gaussian fits to background-subtracted histograms
- RC peak visible (3σ) visible to $|l| \approx 30^\circ$ - this is the long bar

Summary

- The Milky Way has a strongly peanut-shaped b/p bulge. This is the 3D part of the Galactic bar, is ~ 2 kpc long, and is bounded by a strongly X-shaped structure.
- It transits continuously into a planar bar of approximately similar orientation whose transition into the surrounding disk is not yet understood. This is as predicted by simulations and seen in external b/p galaxies.
- The inner in-plane star distribution may be rounder than the main bar and has a very short vertical scale-height, ~ 180 pc.
- Dynamical models of the b/p bulge with the density from RCG have been constructed giving mass of the bulge. Based on LF data, they require 20-40% dark matter in the bulge region.
- Current main uncertainties: bar-disk transition in density and stellar population; implications of slow bar pattern speed.