Combining Microlensing with Made-to-measure Dynamical Models

Chris Wegg, Ortwin Gerhard & Matthieu Portail

Outline

Results in Measurement and Modelling of the Inner Galaxy:

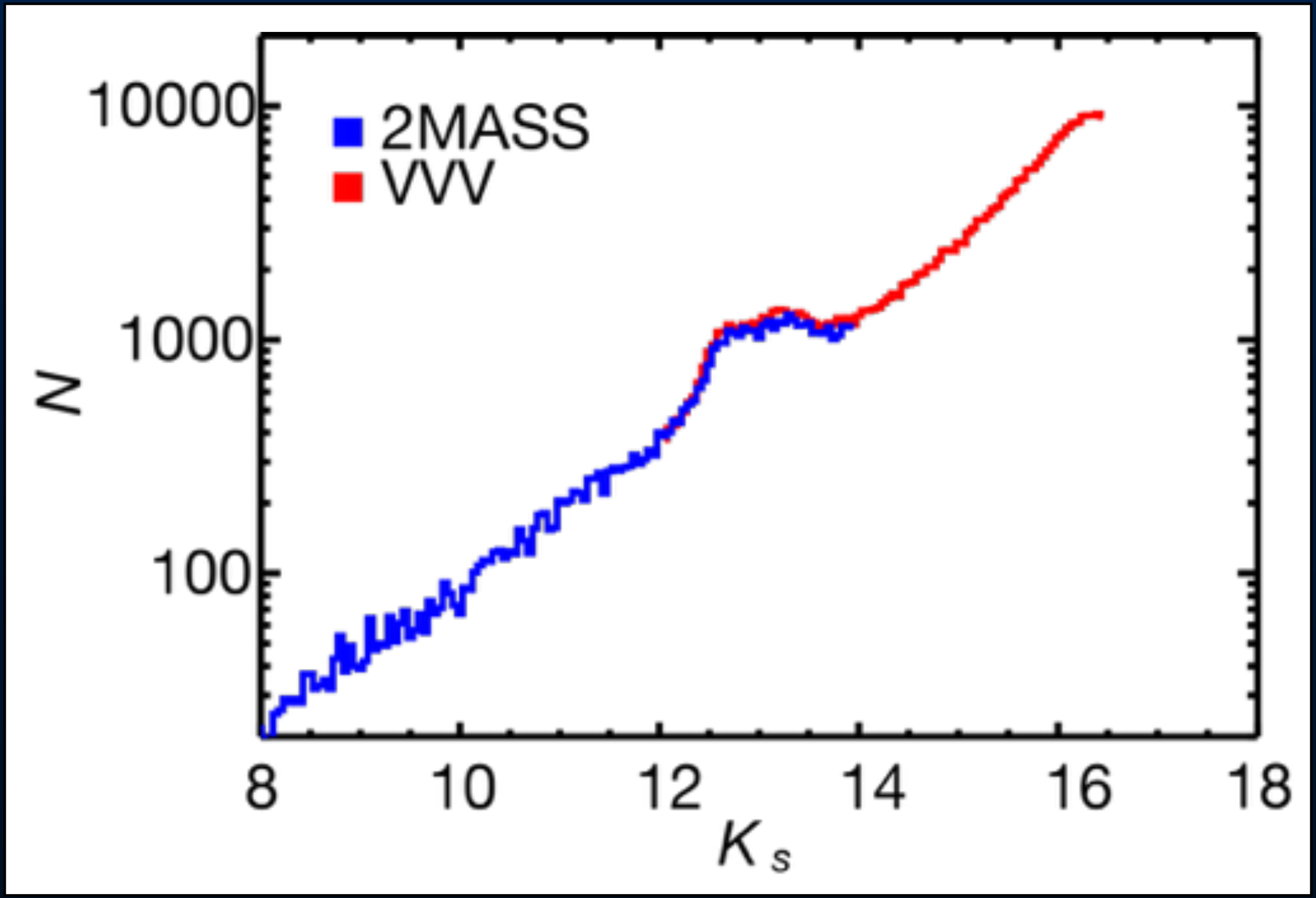
- The 3D shape of the bulge
- The Bar Outside the Bulge: The ‘Long Bar’
- Made-to-measure N-body models of the bulge

Application of Models to Microlensing:

- Optical depth: the DM fraction of the Inner Galaxy
- Timescale distribution: the IMF of the Inner Galaxy

Red Clump Giants

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

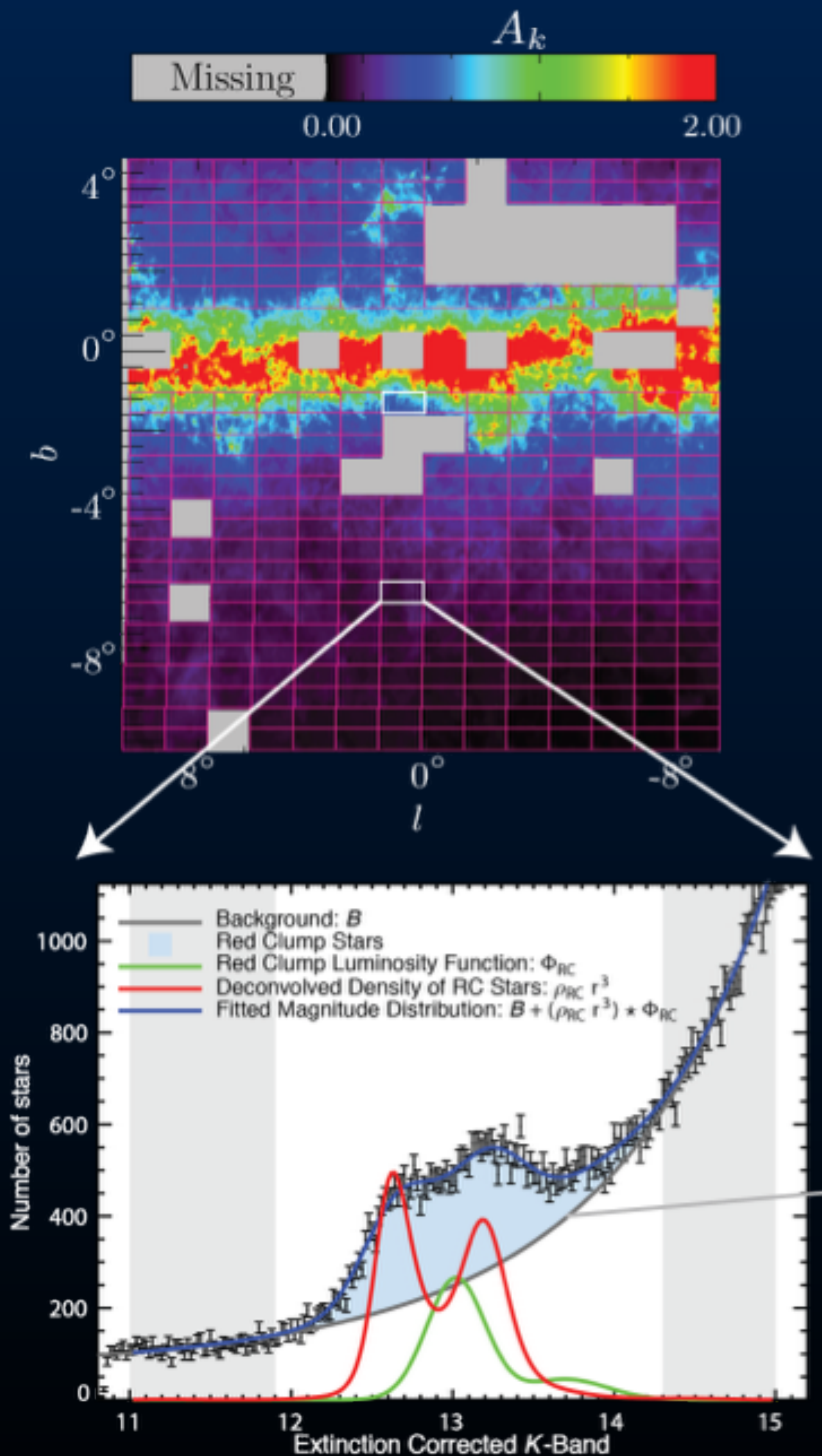


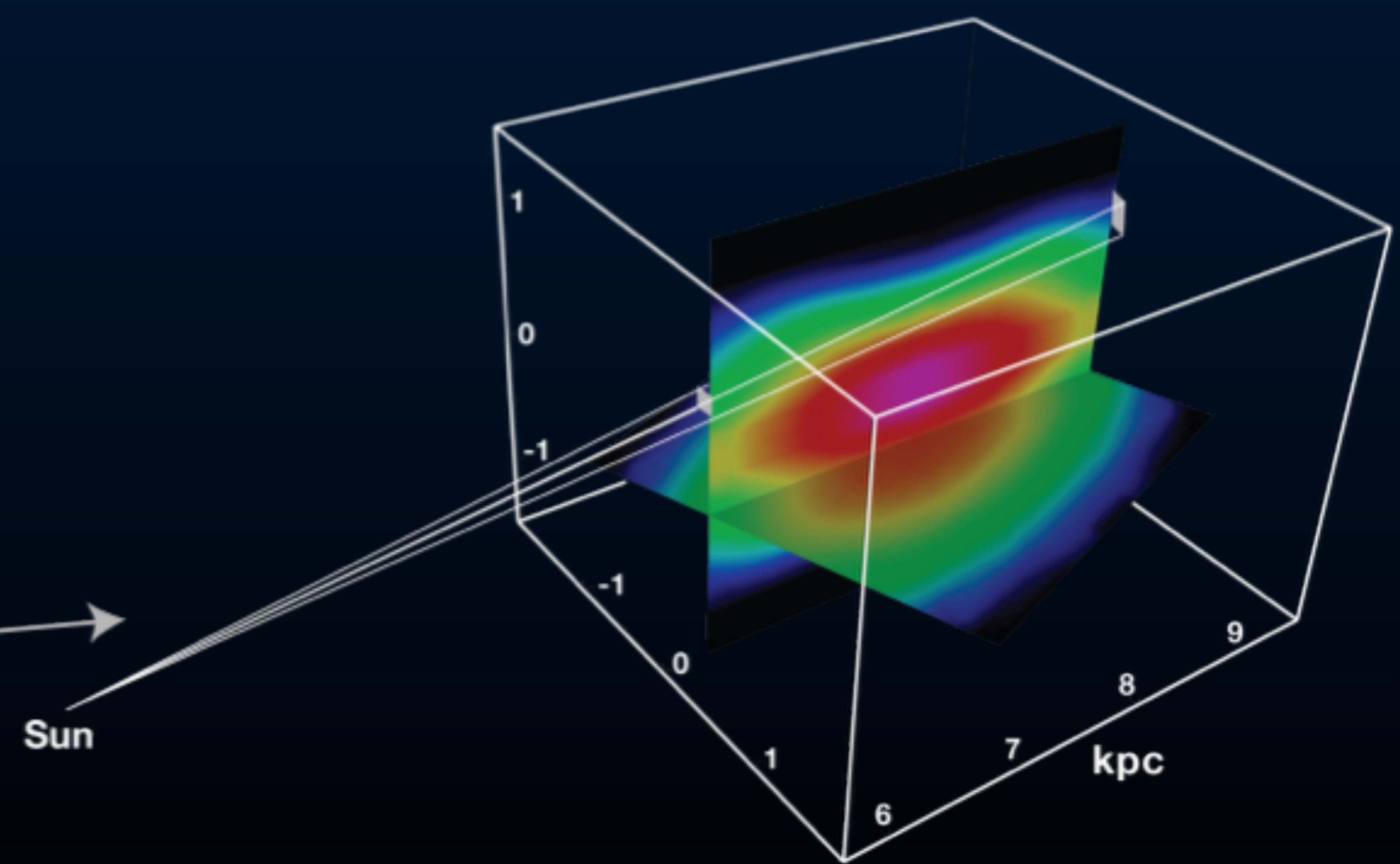
Nataf et al. 2010 and McWilliam and Zoccali (2010) found that the RC splits into two at high lattitude on the minor axis of the bulge (l~0)

Quickly realised that this was probably because the Milky Way has a Box/Peanut bulge.

Modelling the inner Galaxy: 3D Shape

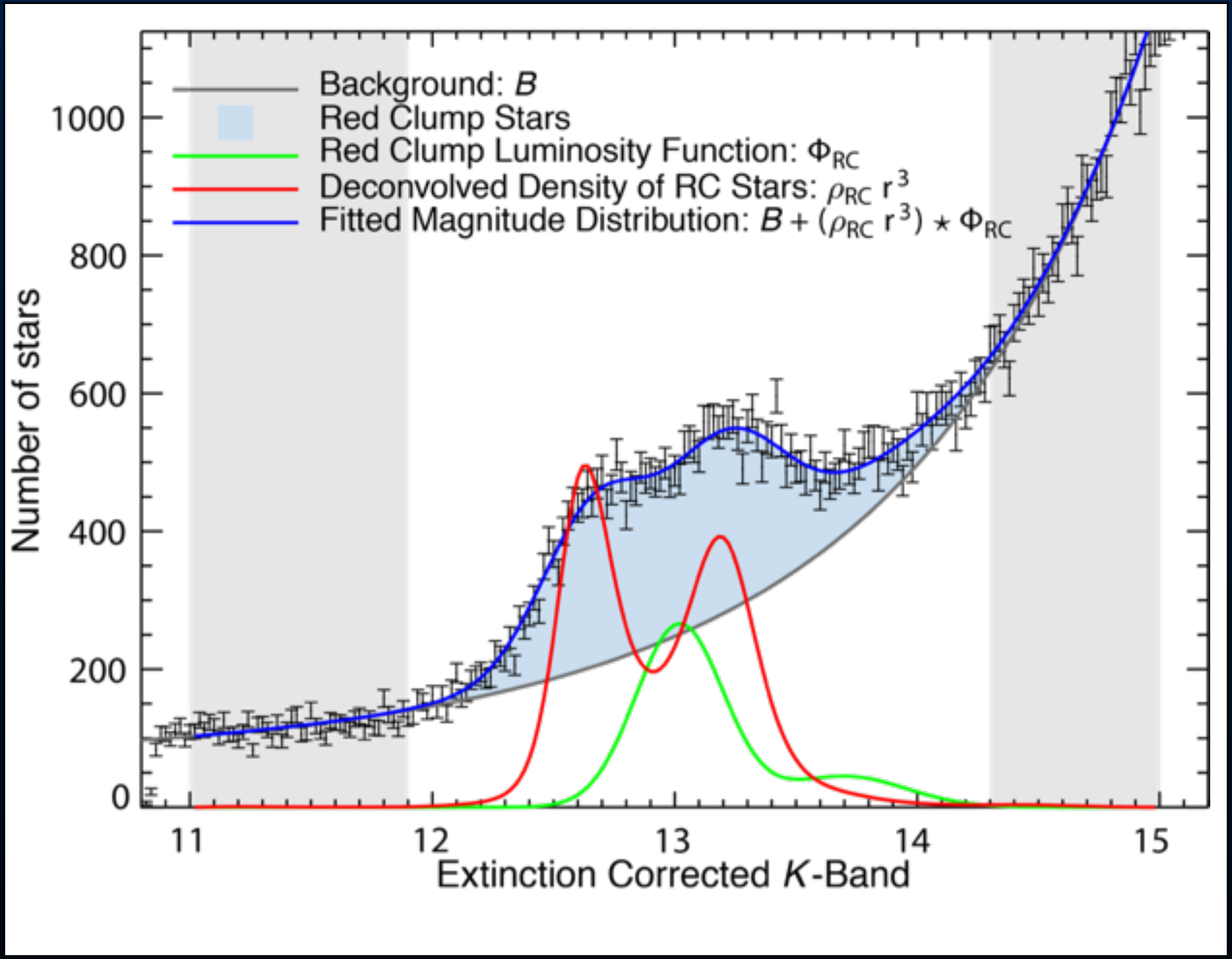
- Combine ~300 line-of-sight density estimates in 3D density
- 3D map non-parametric, assuming only 8-fold mirror symmetry, with small departures





Modelling the inner Galaxy: 3D Shape

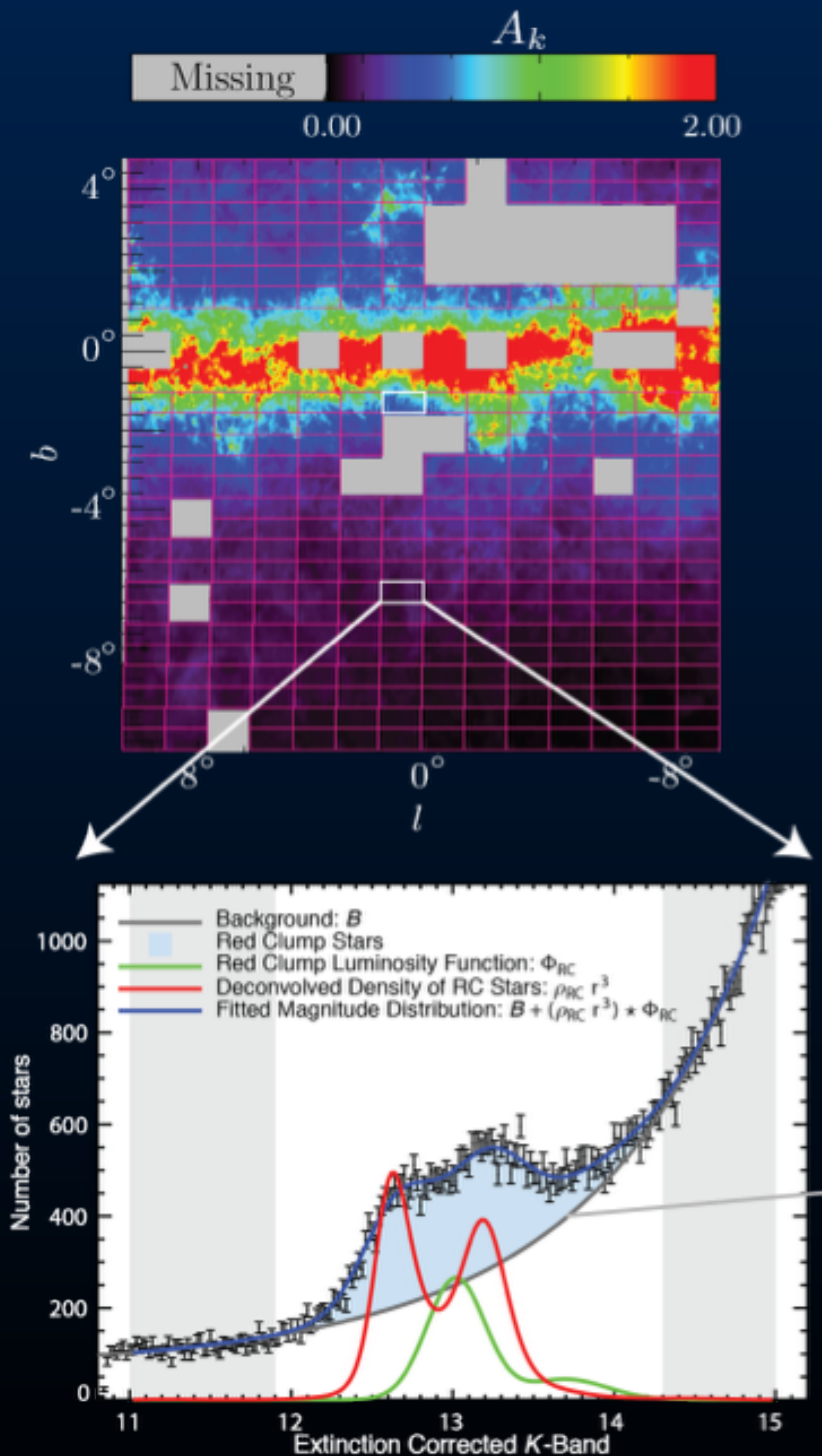
Line-of-sight density estimation

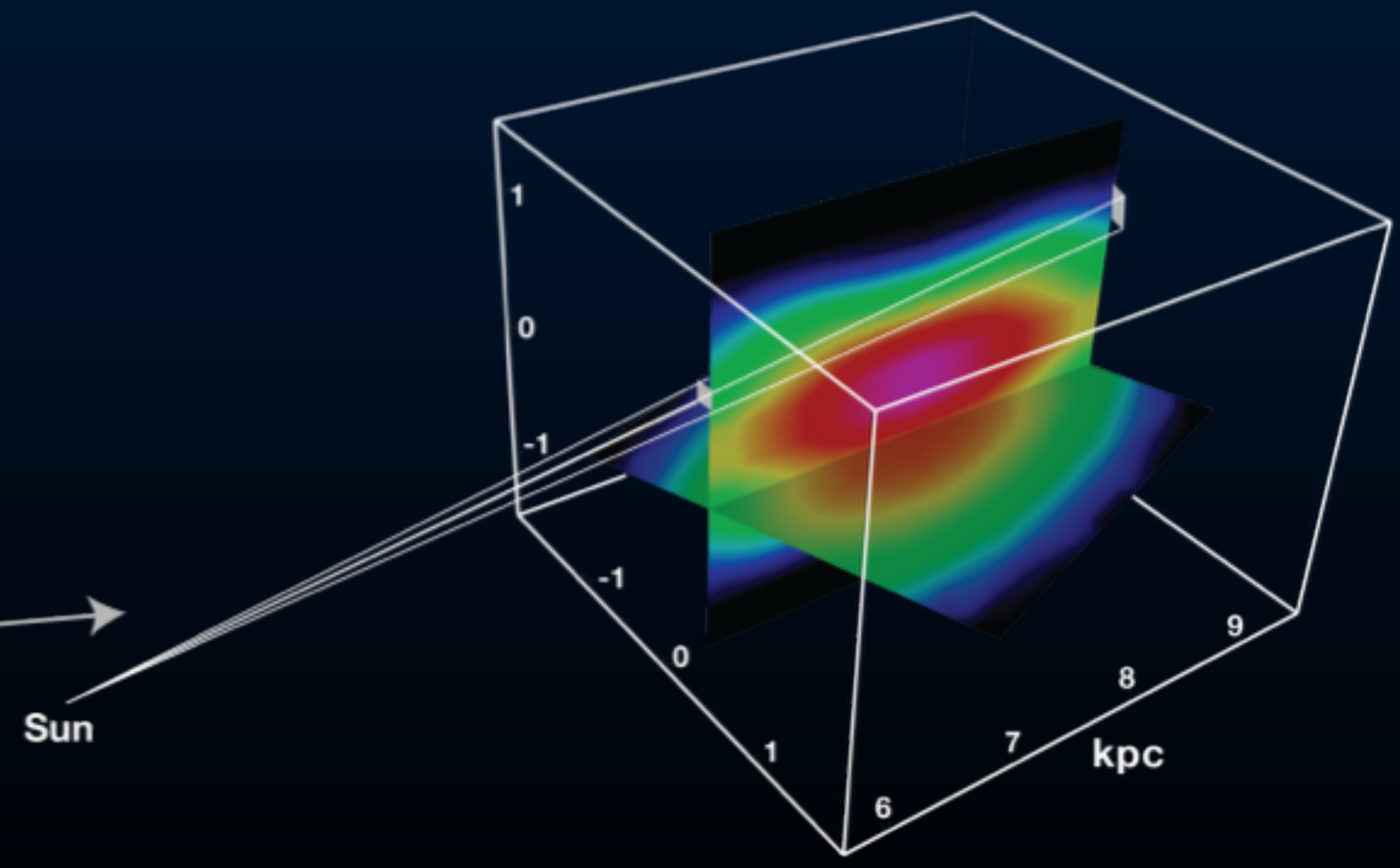


- Fit background to region outside Bulge's RC stars
- Statistically identified red clump stars are convolution of line-of-sight density with luminosity function.
- Deconvolve to estimate density using a slight variation on Lucy-Richardson algorithm

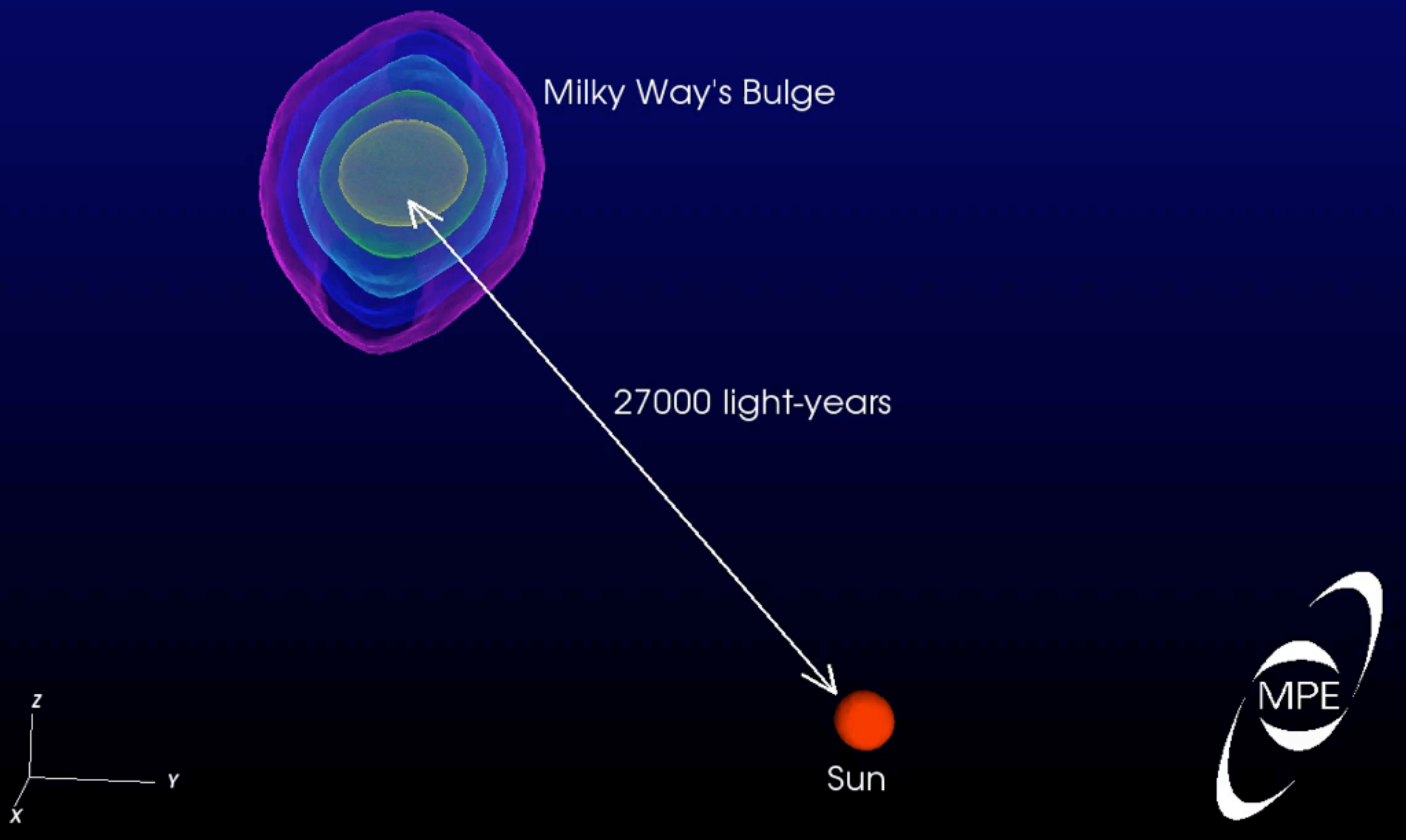
Modelling the inner Galaxy: 3D Shape

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



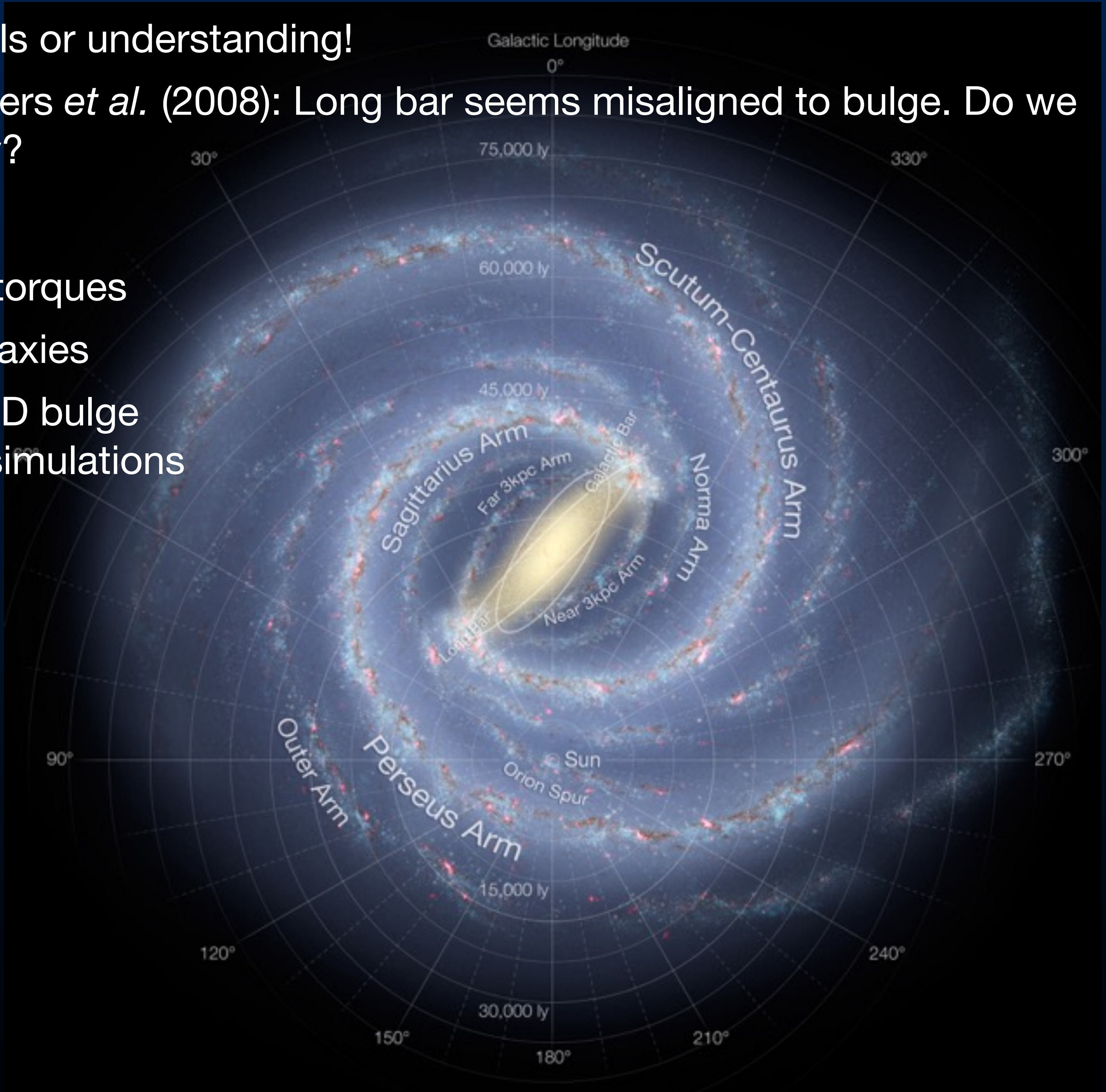


Modelling the inner Galaxy: 3D Shape

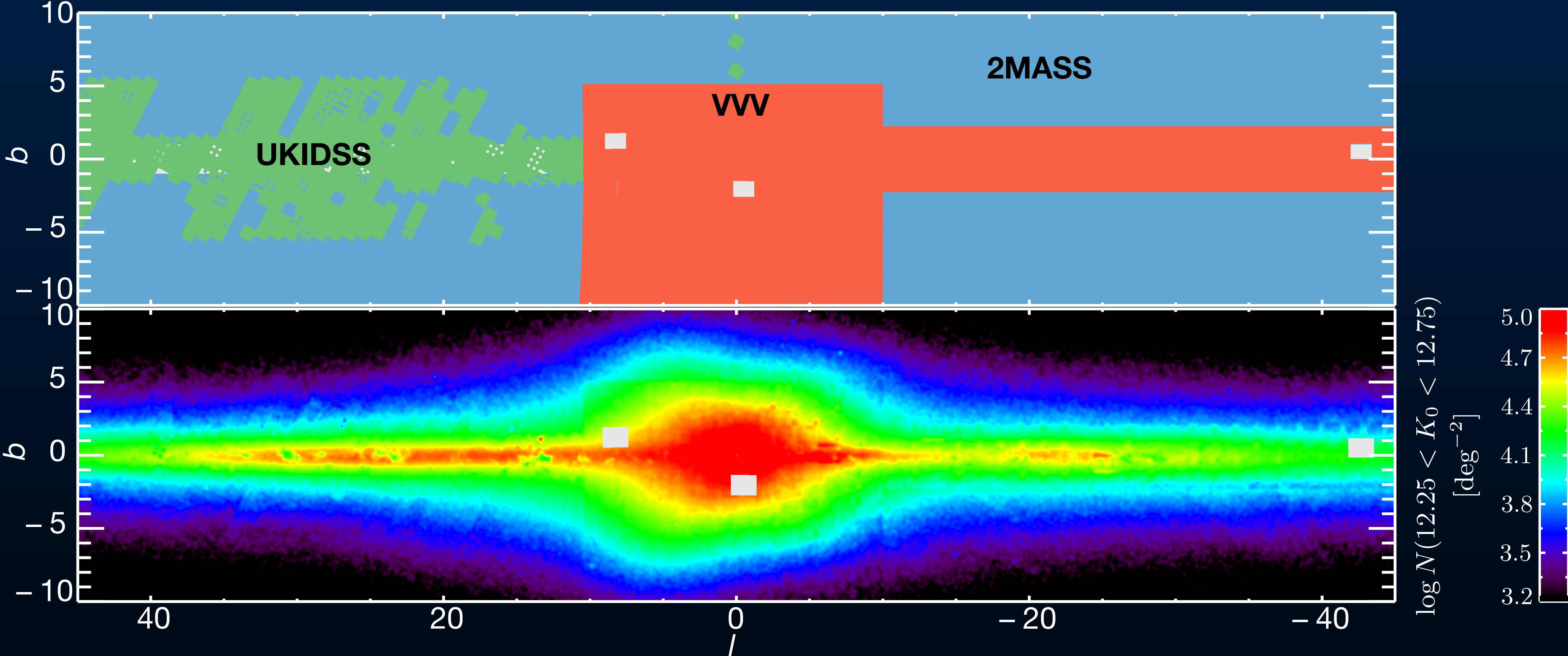


The Long Bar

- The bar outside the bulge called the ***long bar*** was found by Hammersley et al. (1994).
- But we still have very few details or understanding!
- Best investigation Cabrera-Lavers *et al.* (2008): Long bar seems misaligned to bulge. Do we have two bars in the Milky Way?
- Seems difficult:
  - Theoretically: Strong mutual torques
  - Observationally: External Galaxies
  - Philosophically: Connected 3D bulge +long bar arises naturally in simulations



Data Sources



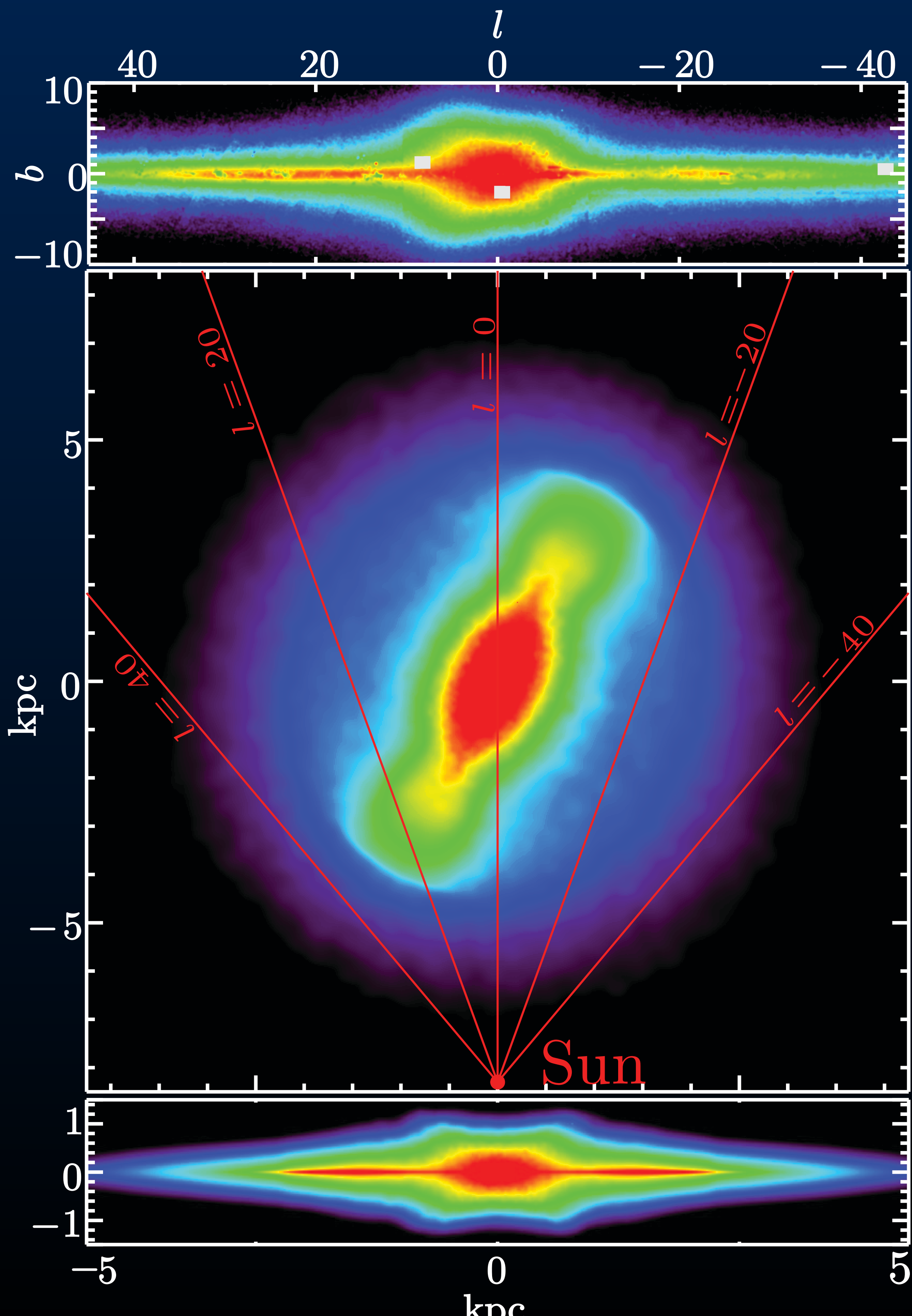
Differences to the Bulge

- 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. Fit parametric models. Improves signal-to-noise by connecting fields and fitting for only parameters.

Modelling the inner Galaxy: The Long Bar



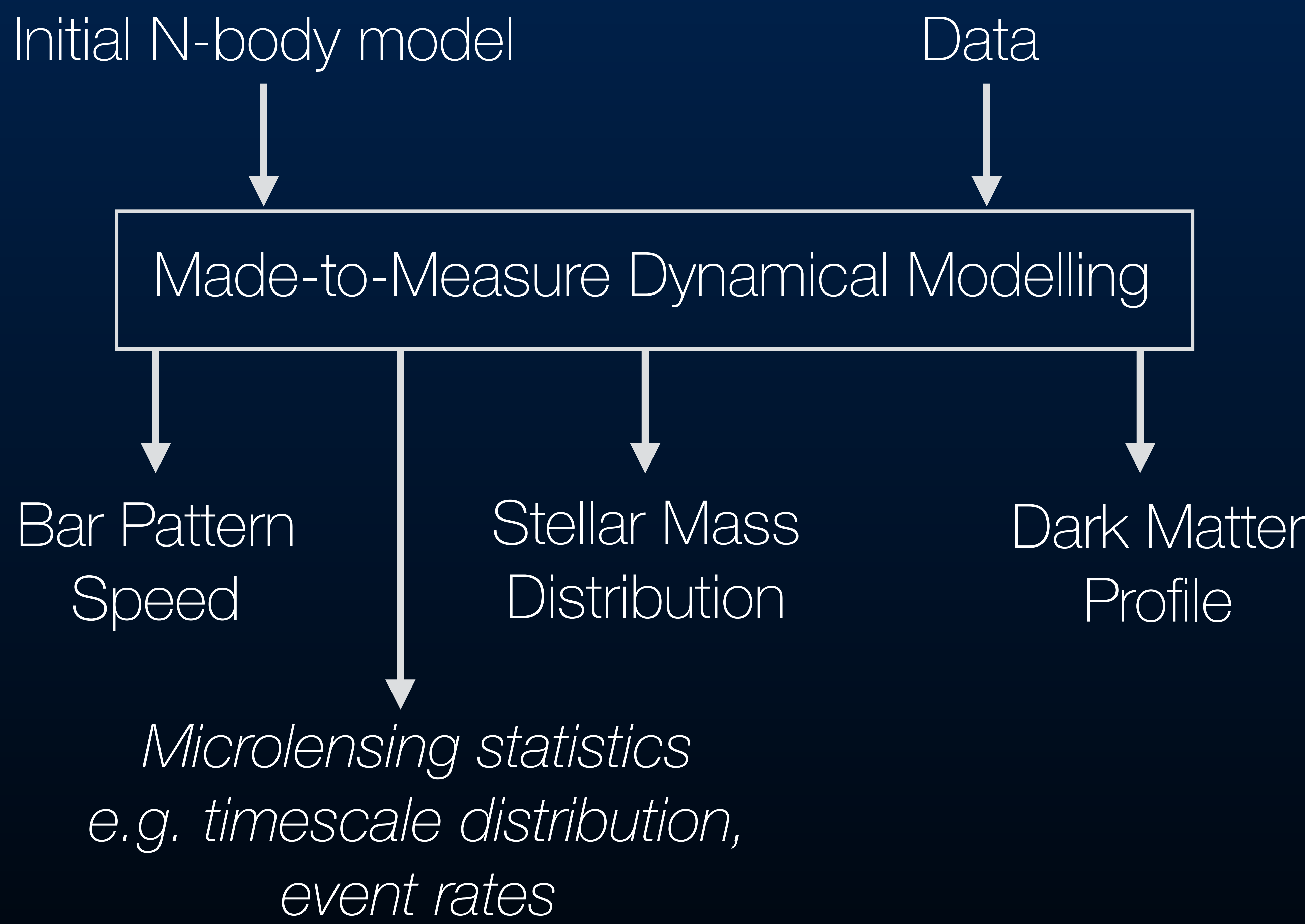
End result:

- Only one bar and is 5kpc long
- Bulge looks like a typical Box/ Peanut bulge.
- Looks just like other peanut bulges side-on e.g. NGC128.
- Shape naturally similar to N-body simulations of bars where the central part buckles into a B/P bulge leaving a thinner 'long bar' outside.

Shape of the bulge: CW & Gerhard (2013)

Shape of the bar outside the bulge: CW, Gerhard & Portail (2015)

Modelling the inner Galaxy: Made-to-measure N-body models



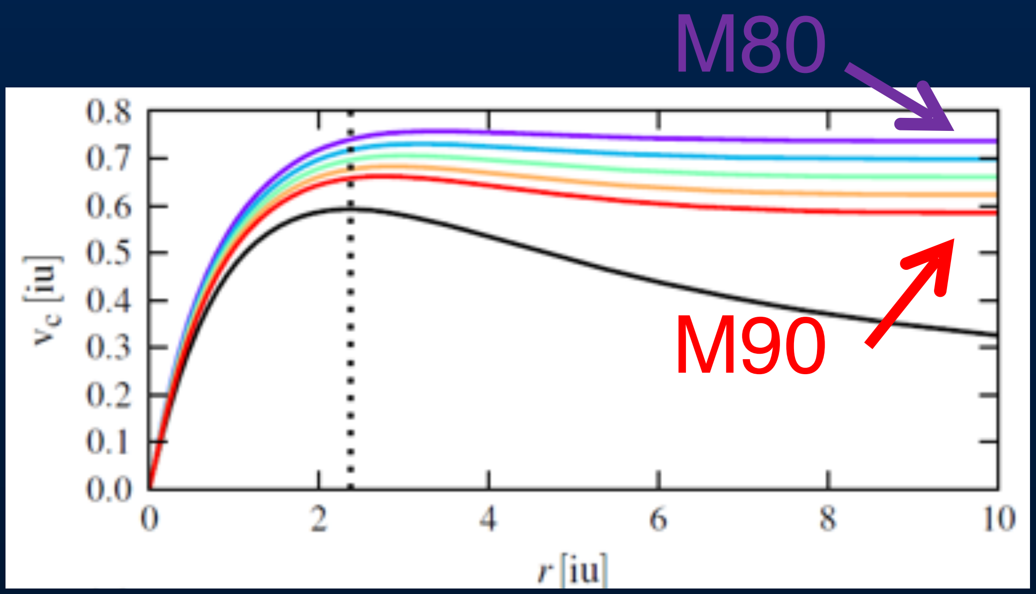
Application to Bulge: Portail, CW & Gerhard (2015)

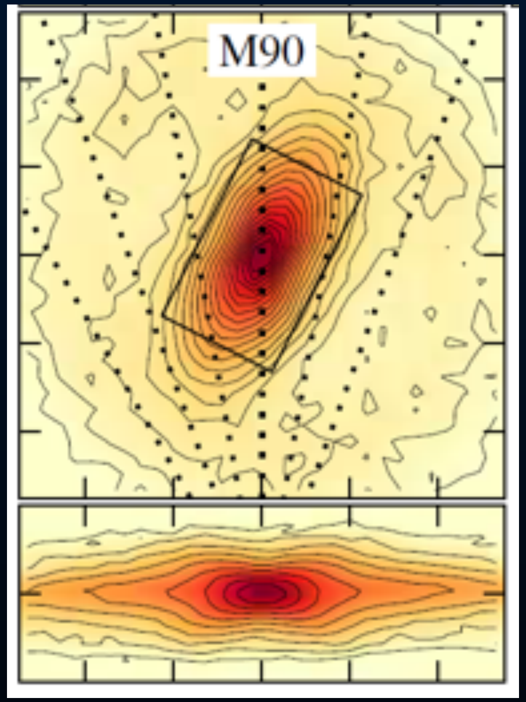
Application to Entire Inner Galaxy: Portail, Gehard, CW & Ness (2017)

Modelling the inner Galaxy: Made-to-measure N-body models

Matthieu Portail

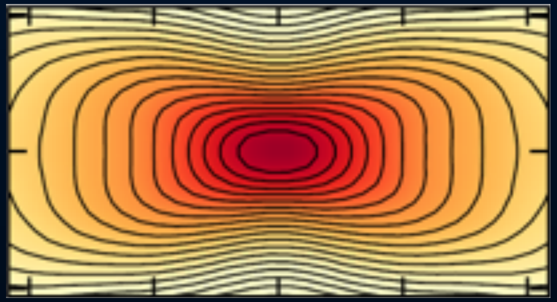
- We evolve a near-equilibrium stellar disk embedded in different dark matter haloes.



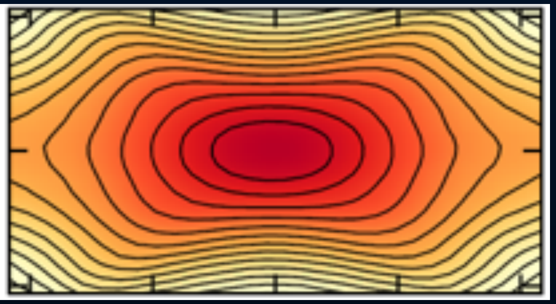


Self-graviting N-body model

Model observables



Real data with errors



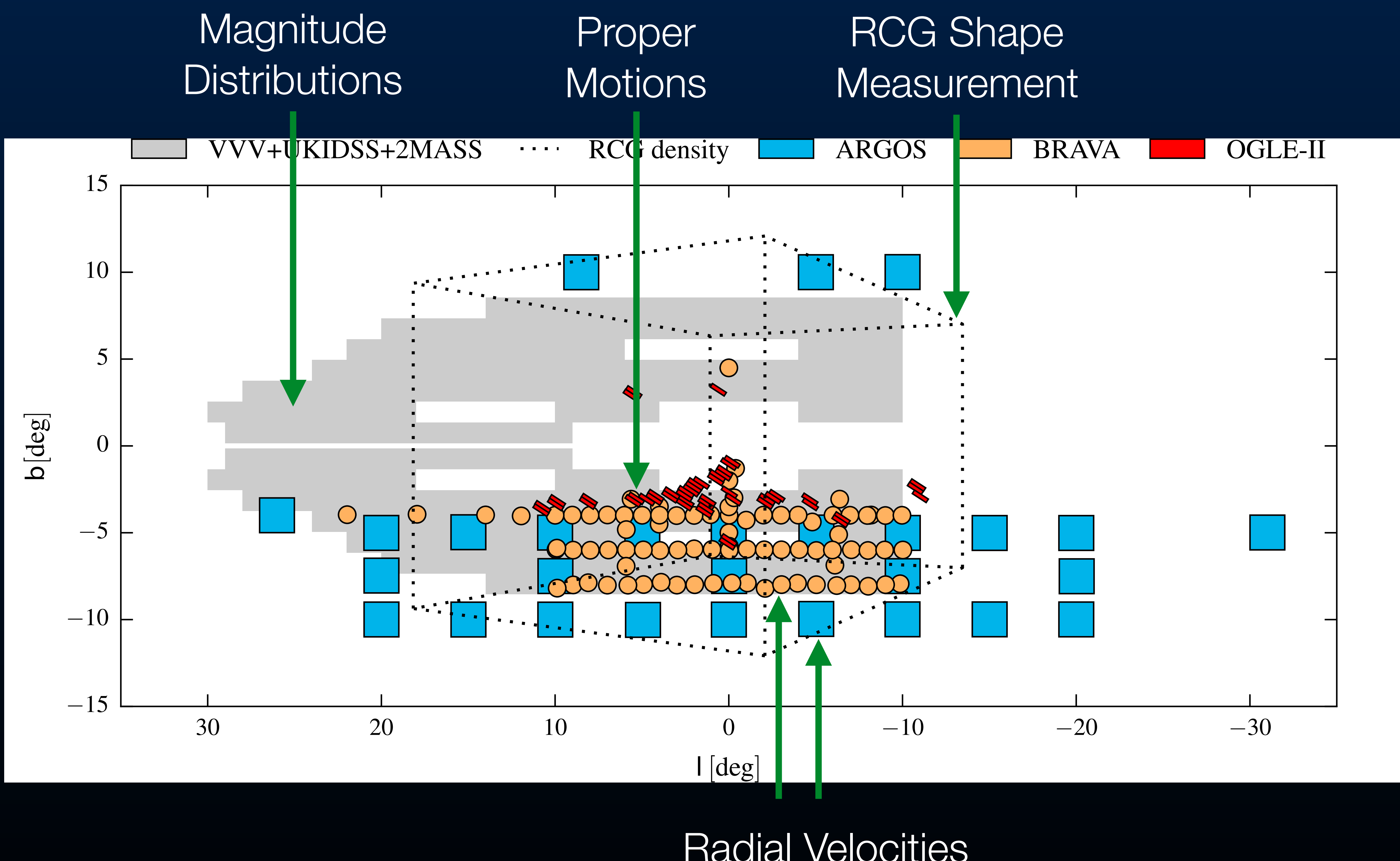
Compare

Update the particle masses

$$\frac{dw_i}{dt} = \epsilon w_i \frac{\partial F}{\partial w_i}$$

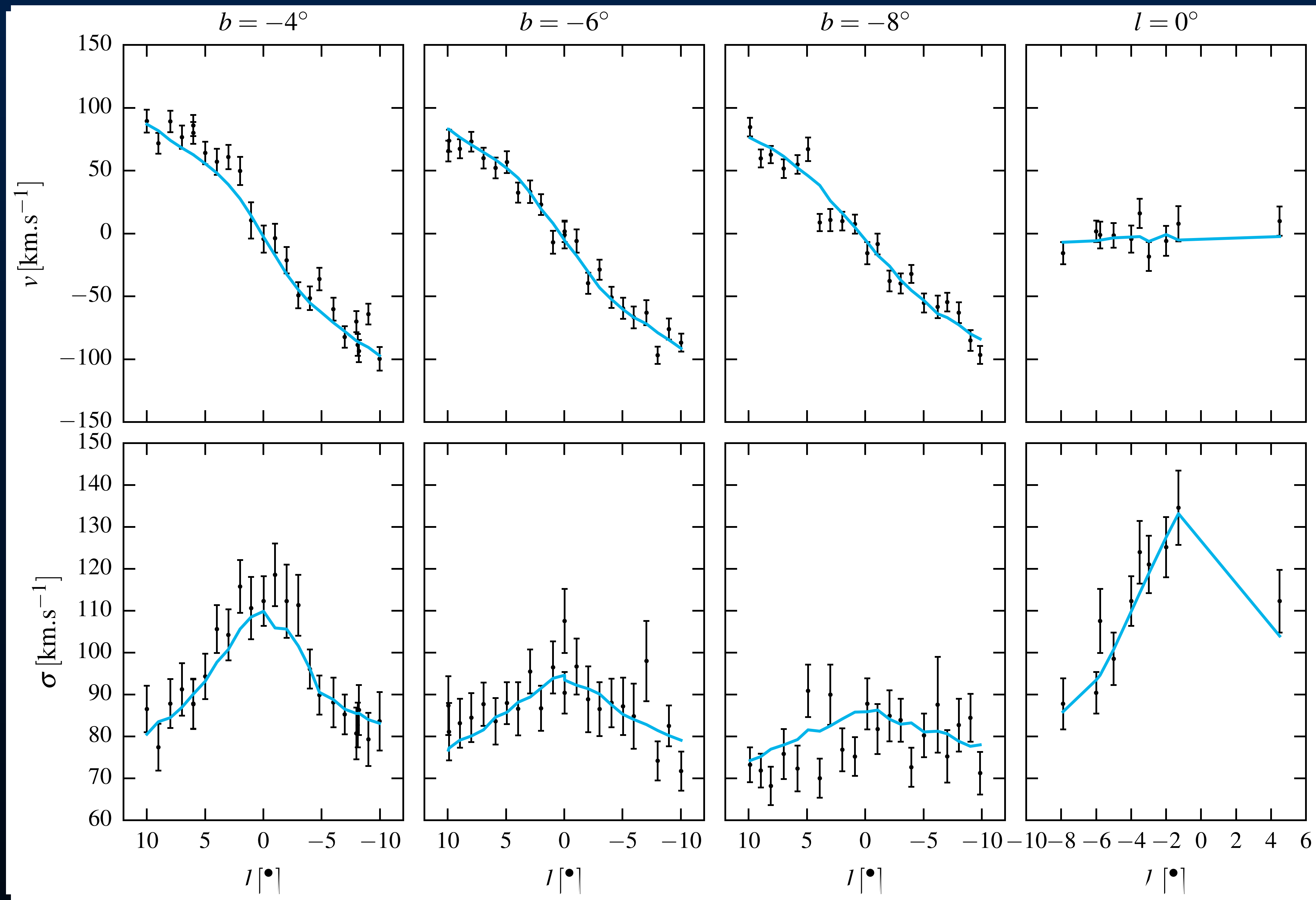
Syer & Tremaine (1996), De Lorenzi et al. (2007)

Fitted Data in Most Recent Models



Portail, Gehard, CW & Ness MNRAS (2017)

Fit to BRAVA radial velocities in the bulge



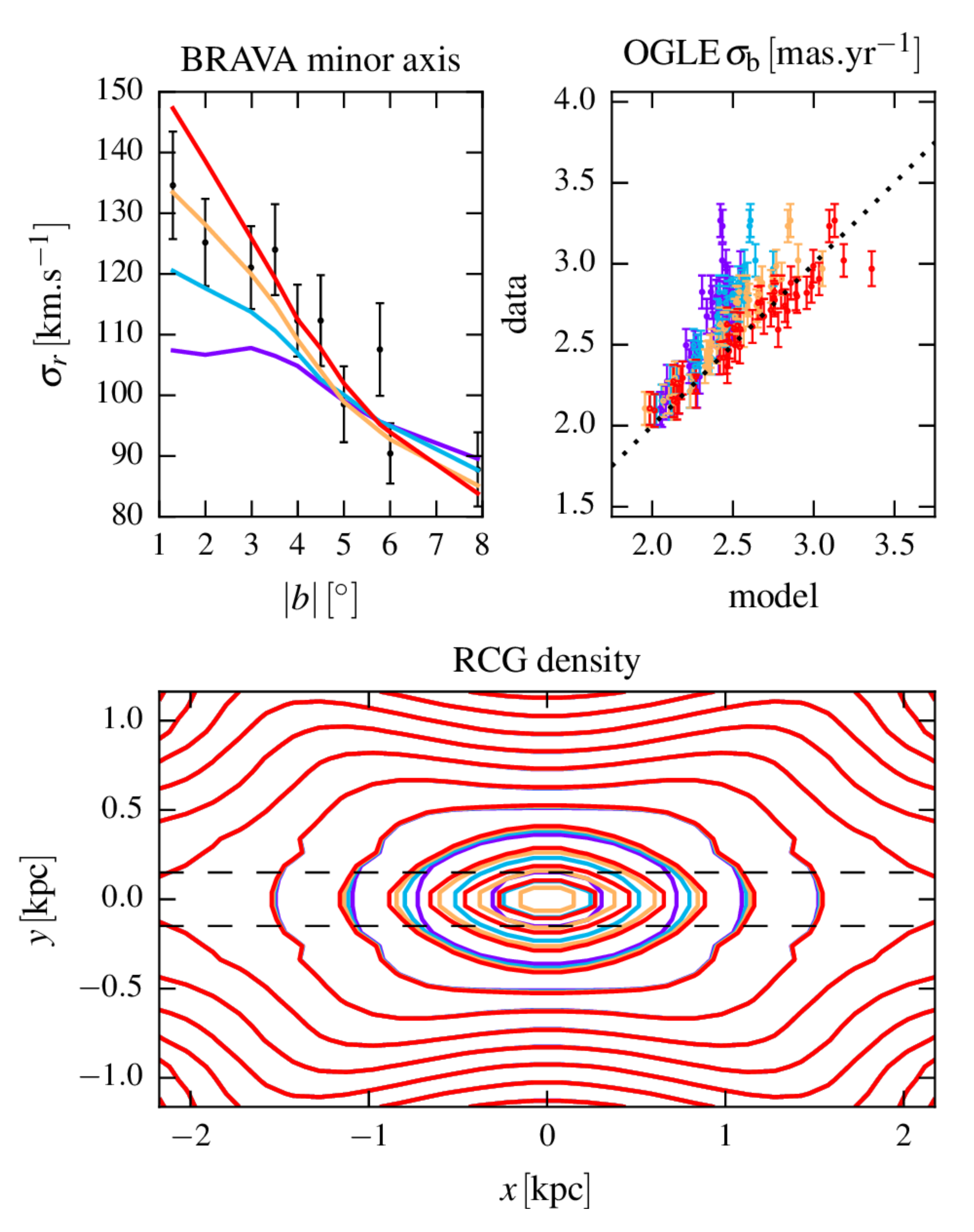
Reproduce quantitatively:

- The cylindrical rotation
- The dispersion profiles

Portail, Gehard, CW & Ness MNRAS (2017)

Central Mass Distribution

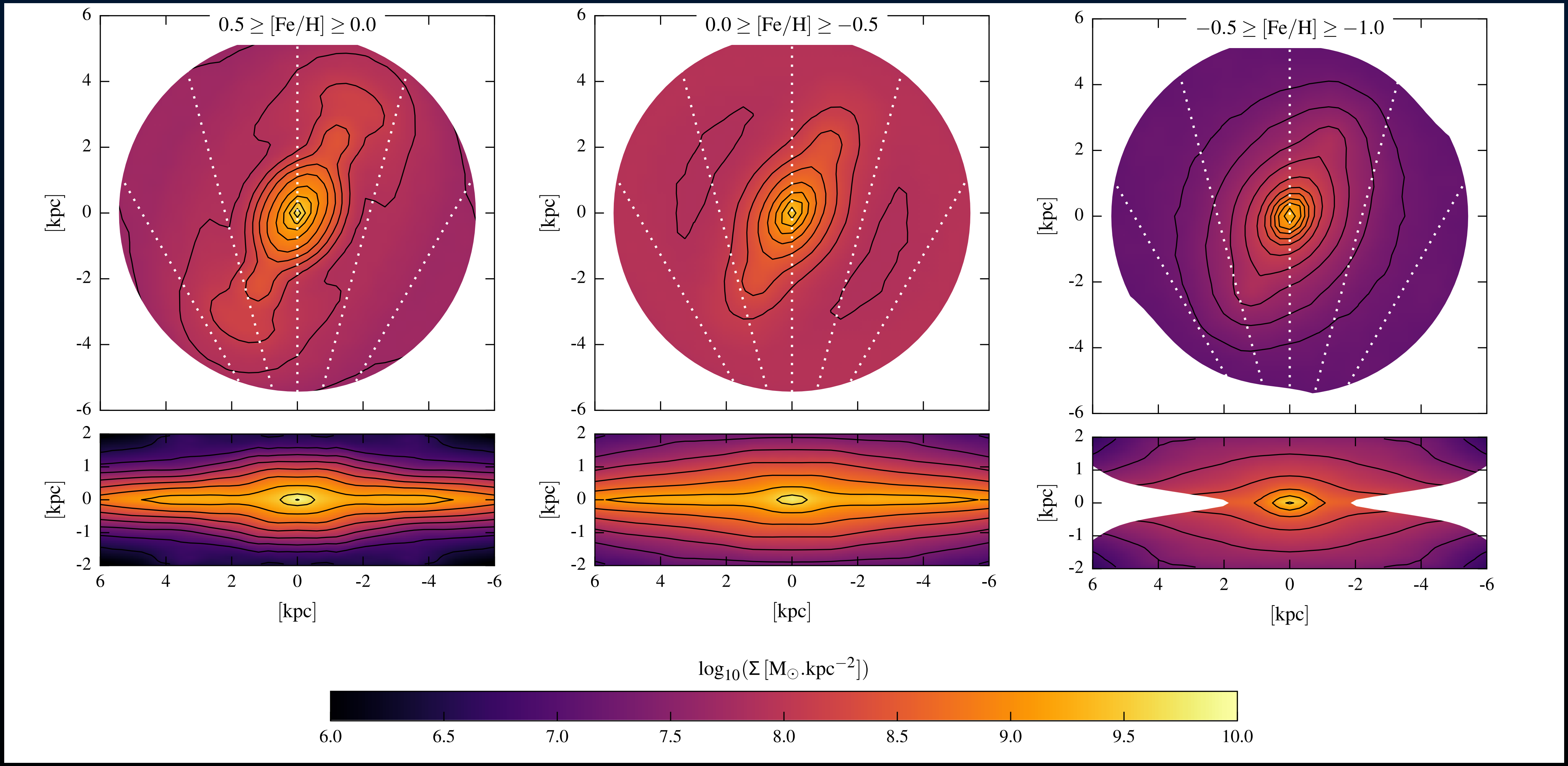
- We don't have information on the RCG shape inside |b|<1
- In order to fit the central proper motions and radial velocities need a central component of mass 2 10^9 $M_\odot$ inside the central 250pc
- This is probably the nuclear bulge e.g. Launhardt+2002 from COBE



Portail, Gehard, CW & Ness MNRAS (2017)

Chemodynamical models of the bulge

- Dynamical models only require velocities, but Spectroscopic surveys like APOGEE are giving abundances of 15-20 elements for 100,000s of stars
- We can use these as tags on the N-body particles, fitting them separately, all moving in a common potential
- Done for metallicity. Real promise is for e.g. [α/Fe] as 'chemical clocks' to do Galactic Archeology

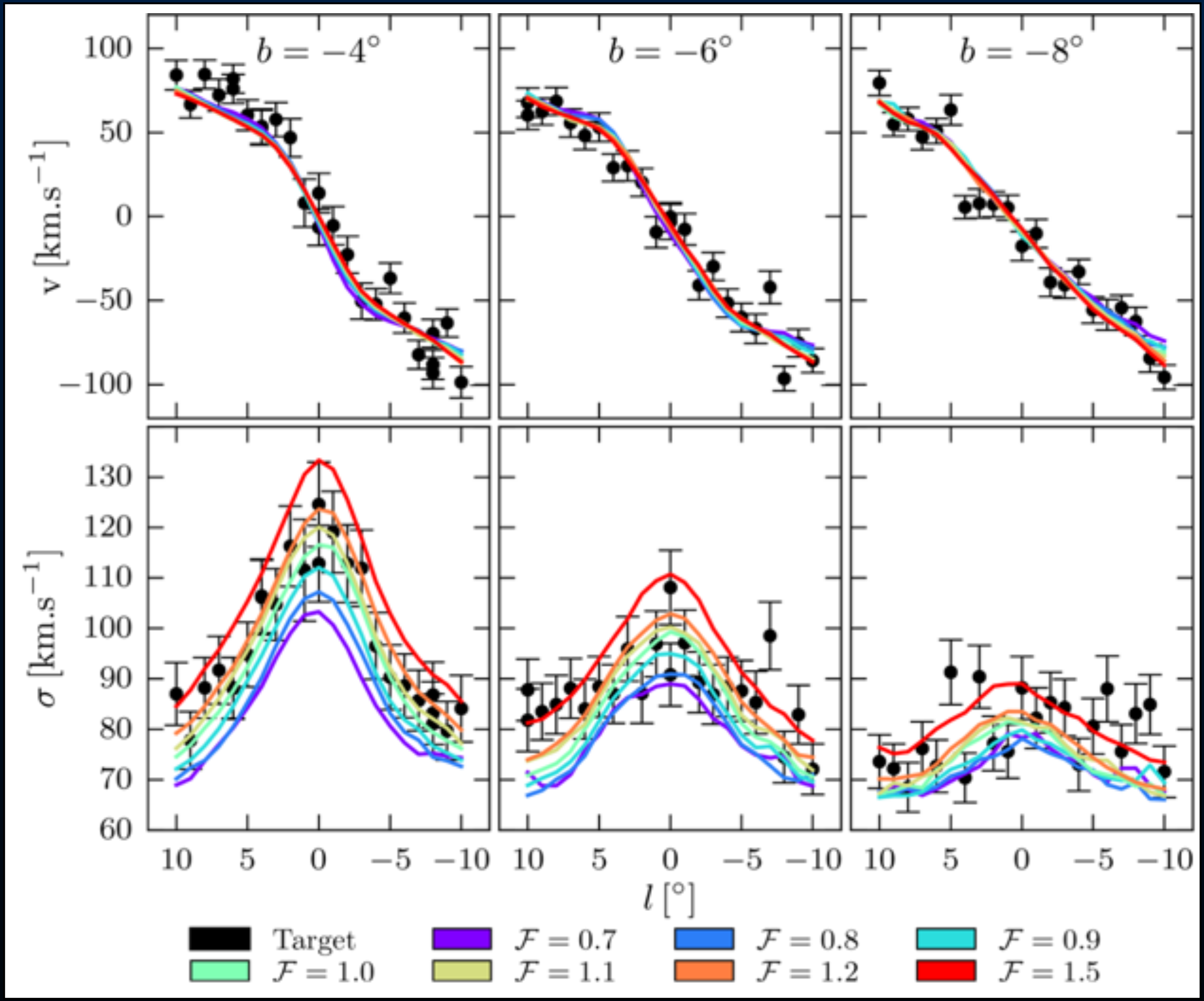


Portail, Gehard, CW & Ness (Submitted)

Modelling the inner Galaxy: Made-to-measure N-body models

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

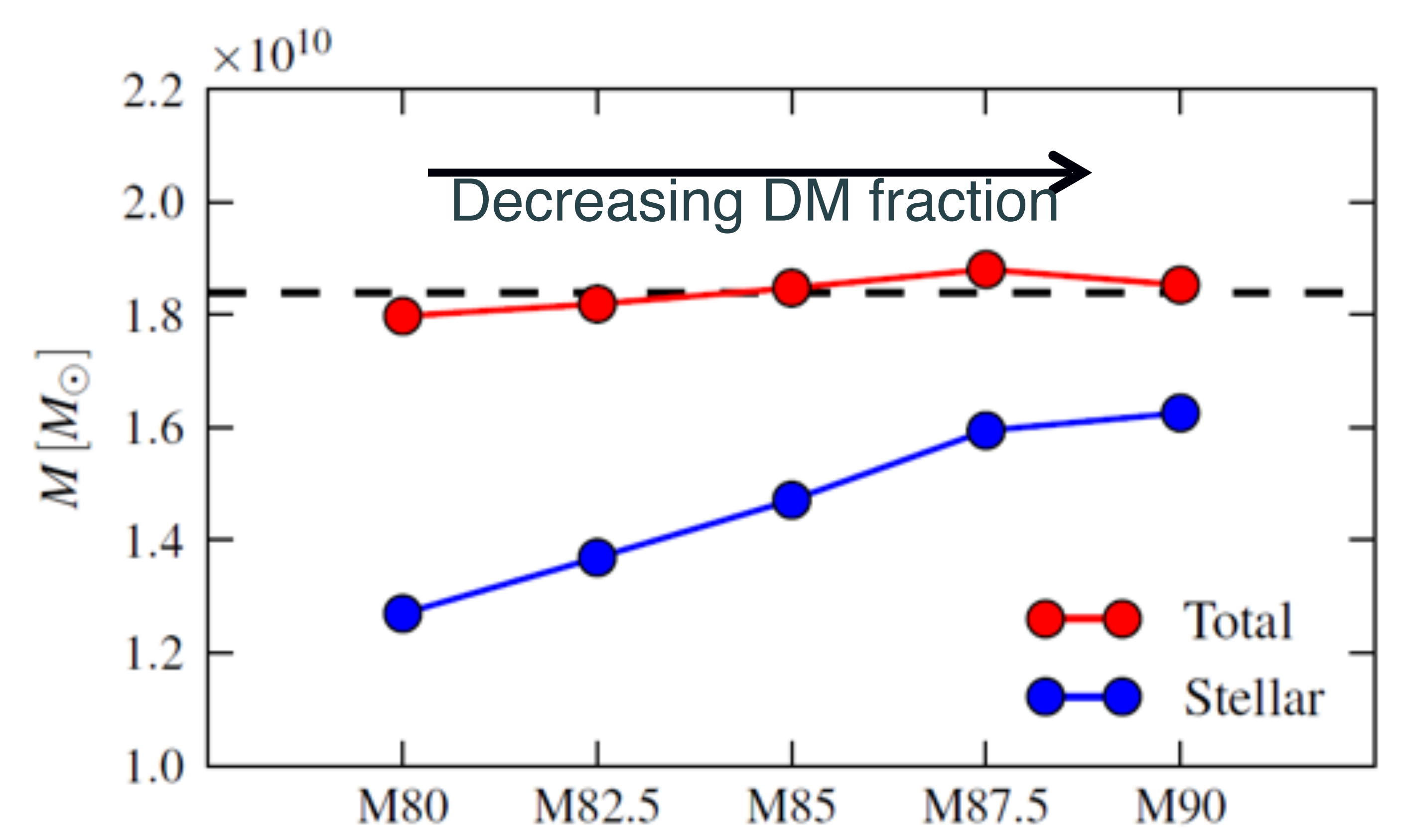
One model, different stellar masses



Portail, CW, Gerhard MNRAS (2015)

Modelling the inner Galaxy: Made-to-measure N-body models

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



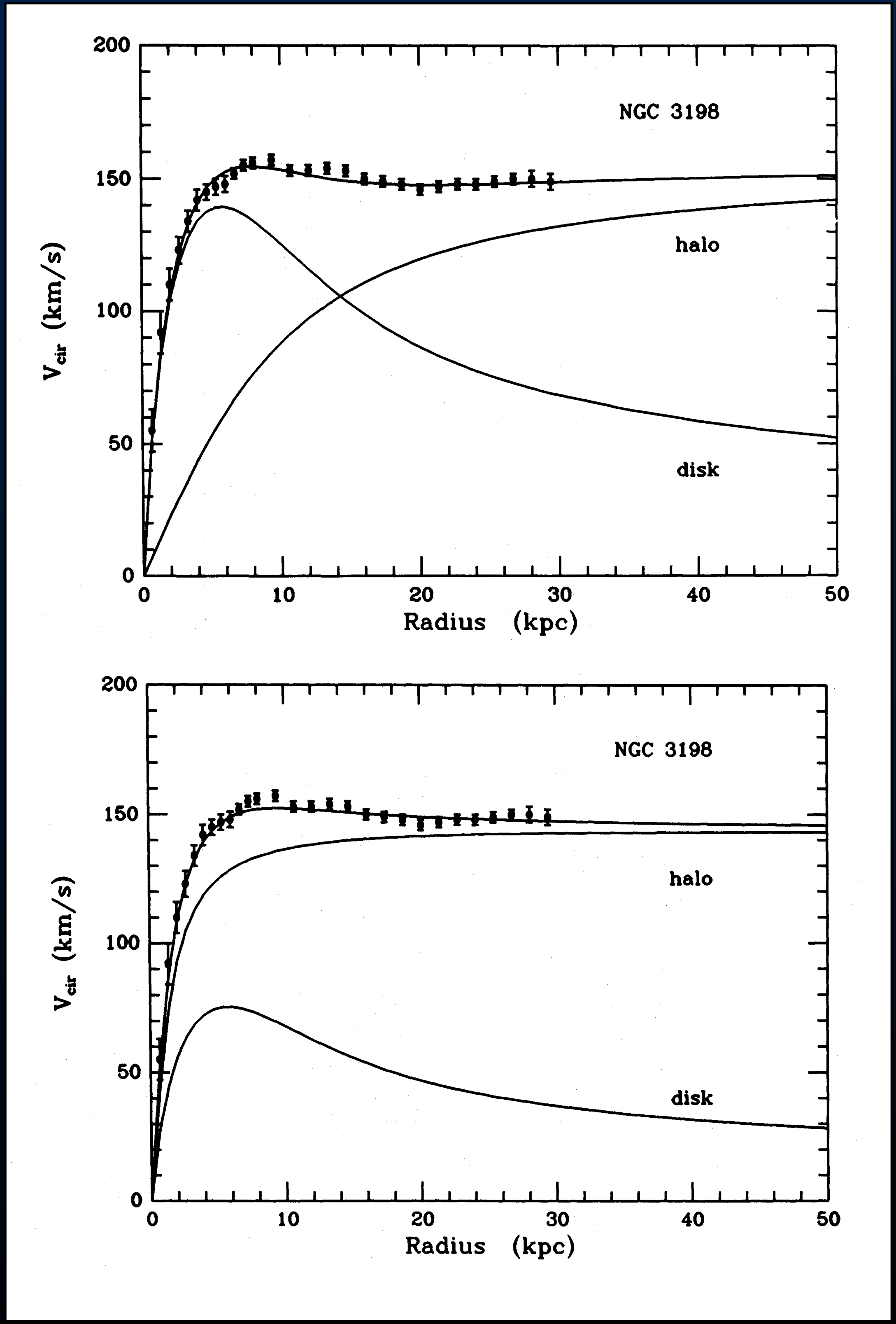
- We find a systematic error on the total mass of less than 5%

- We have equally good models of the bulge with different dark matter fraction.

Portail, CW, Gerhard MNRAS (2015)

Modelling the inner Galaxy: Made-to-measure N-body models

- In external galaxies we see exactly the same degeneracy: we know the shape of the stellar matter but not its mass.
- e.g. in disk galaxies rotation curve fits work equally well with very different stellar contributions



Three lines of evidence, ***two from microlensing***, that give a ***consistent picture***, pointing to a low DM fraction in the inner MW:

1. Microlensing Optical Depth
2. Present Day Mass Function (PDMF) from Microlensing Timescales
3. Dynamical modelling using mass-to-clump measured directly from HST counts

Application of Models to Microlensing: Optical Depth

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

$$\tau(D_s) = \frac{4\pi G}{c^2} \int_0^{D_S} \rho_l(D_l) \left(\frac{1}{D_l} - \frac{1}{D_s} \right) D_l \, dD_l$$

- Effectively the (weighted) surface density towards the Galactic bulge
- Theoretically very attractive: Depends only on the density of lenses. Not on mass and velocity distribution
- Long game of (not) matching optical depth towards bulge with models *e.g.* Bissantz+97, Binney+01

Two 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

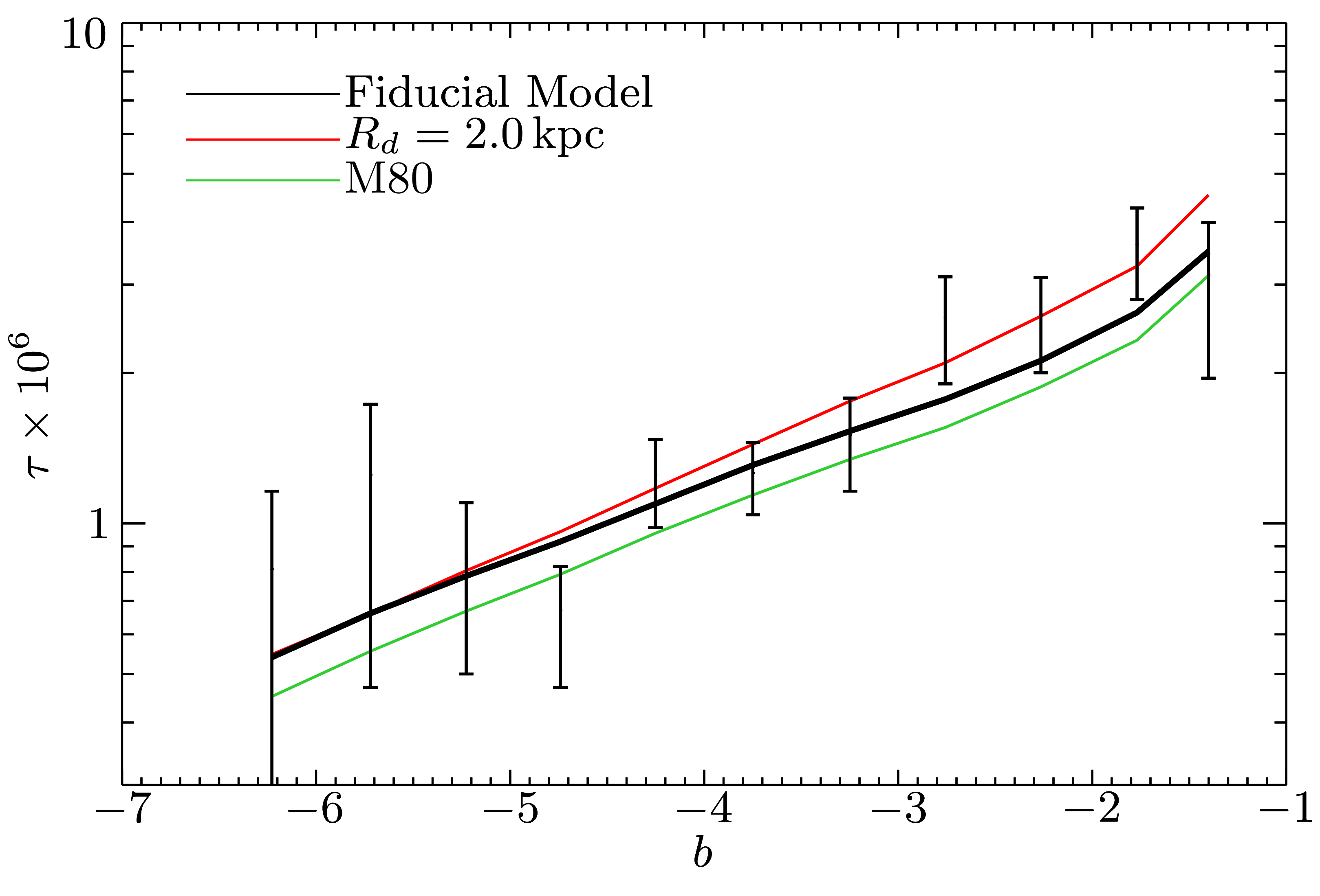
CW, Gerhard & Portail, 463, 557, MNRAS (2016)

Application of Models to Microlensing: Optical Depth

- Shorter disk scale lengths place more mass in front of bulge → increase optical depth

- Larger disk scale height places mass at higher attitude → increase optical depth away from Galactic plane

Sumi & Penny (2016) MOA-II data:



CW, Gerhard & Portail, 463, 557, MNRAS (2016)

Application of Models to Microlensing: Optical Depth

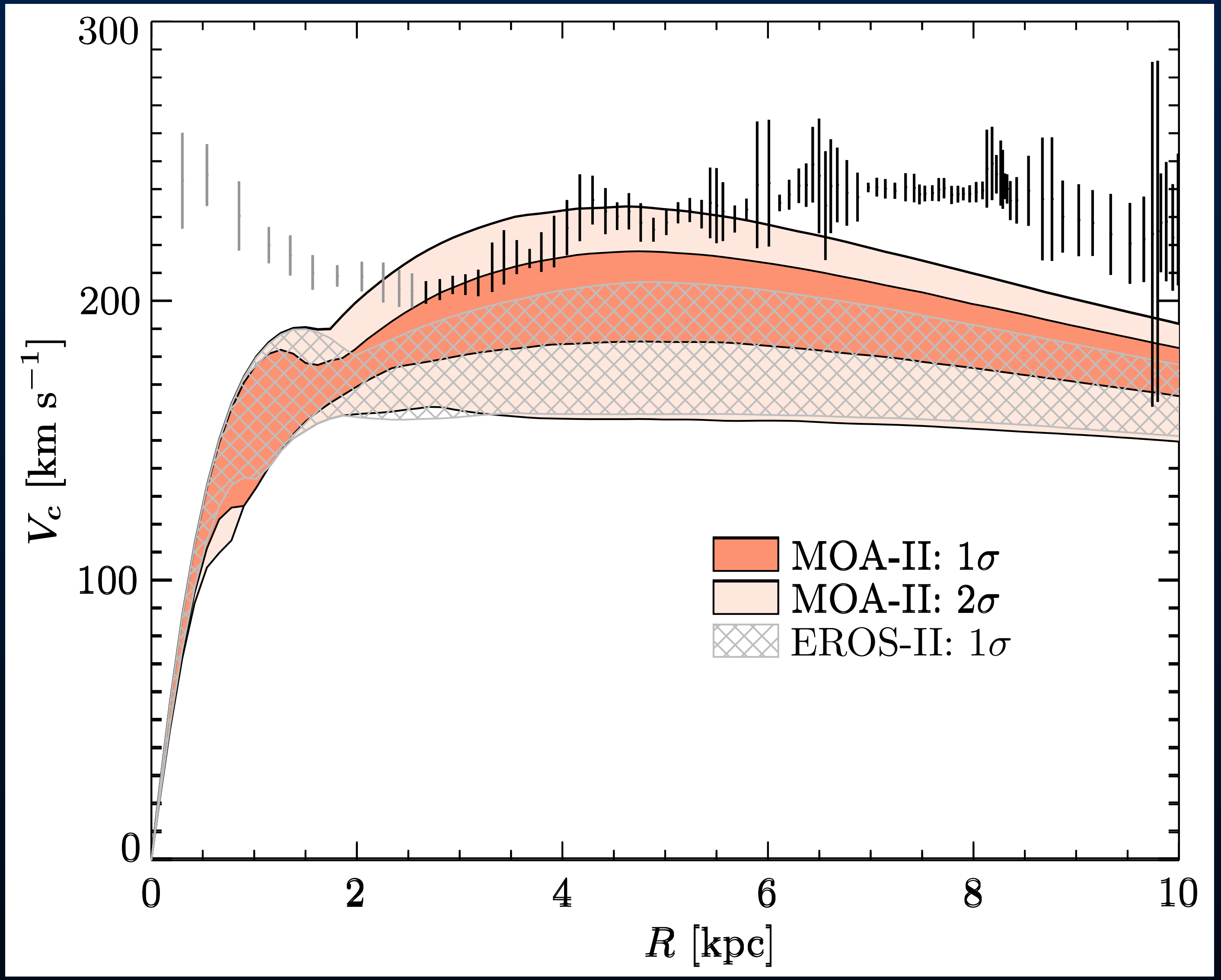
- Marginalising over bulge and disk models gives us a range of allowed rotation curves
- Resultant disks are maximal or near maximal.
- At the peak of the baryonic rotation curve the baryonic contribution f_v is

$$f_v = (0.88 \pm 0.07) \quad \text{at } 1\sigma$$

$$f_v > 0.75 \quad \text{at } 2\sigma$$

- Consistent with same analysis on EROS-II:

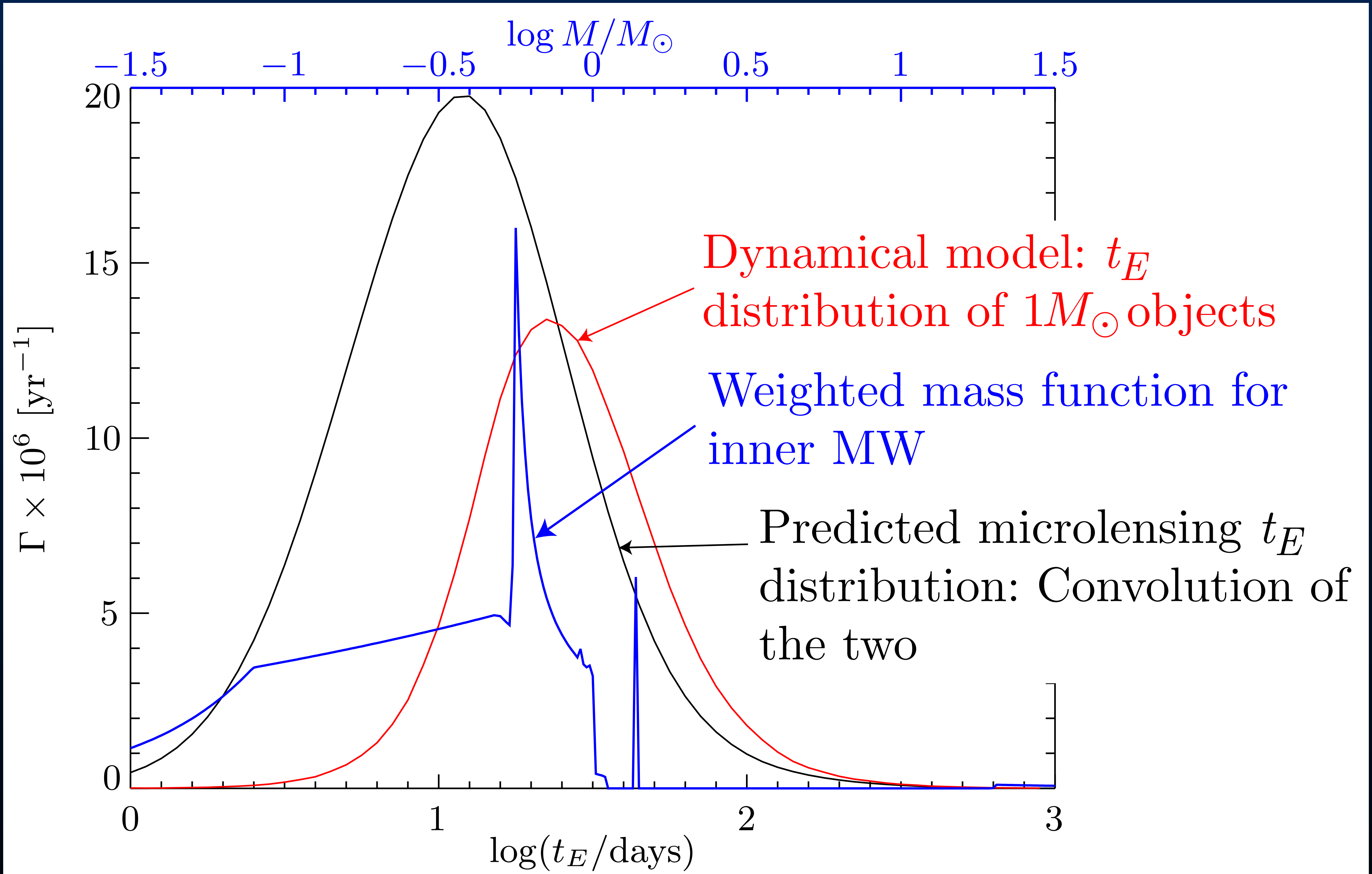
$$f_v = (0.9 \pm 0.1) \quad \text{at } 1\sigma$$



Measured rotation curve from compilation of gas kinematics by Sofue+09

CW, Gerhard & Portail, 463, 557, MNRAS (2016)

Application of Models to Microlensing: t_E distribution



Microlensing t_E distribution + dynamical model, can therefore be used to measure (initial) mass function in the inner Galaxy

Application of Models to Microlensing: t_E distribution

- Use broken power law IMF:

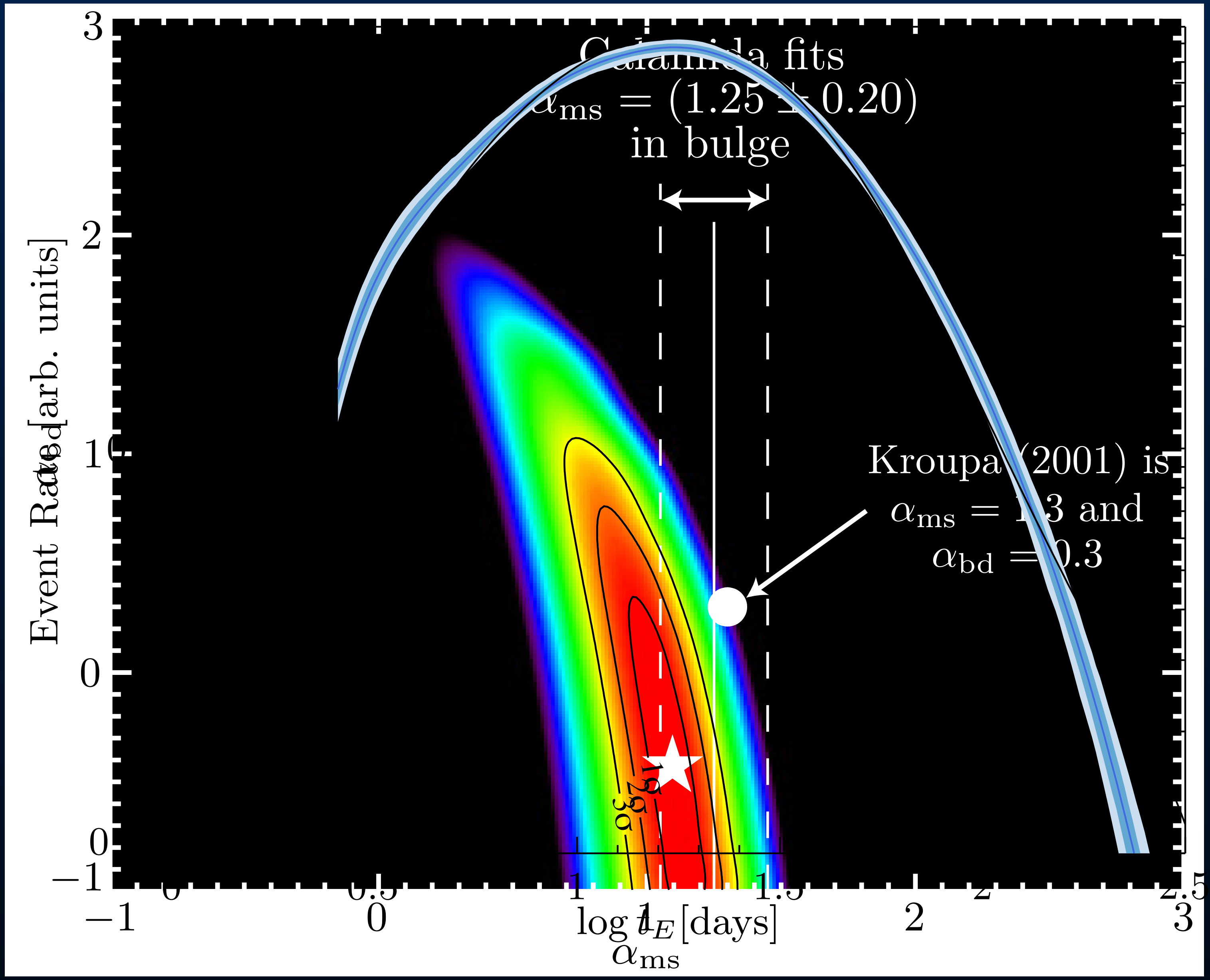
$dN \propto M^{-\alpha}\, dM$ where

$\alpha = \alpha_{\rm bd}$ for $0.01 M_\odot \le M < 0.08 M_\odot$

$\alpha = \alpha_{\rm ms}$ for $0.08 M_\odot \le M < 0.5 M_\odot$

$\alpha = 2.3$ for $0.5 M_\odot \le M < 100 M_\odot$

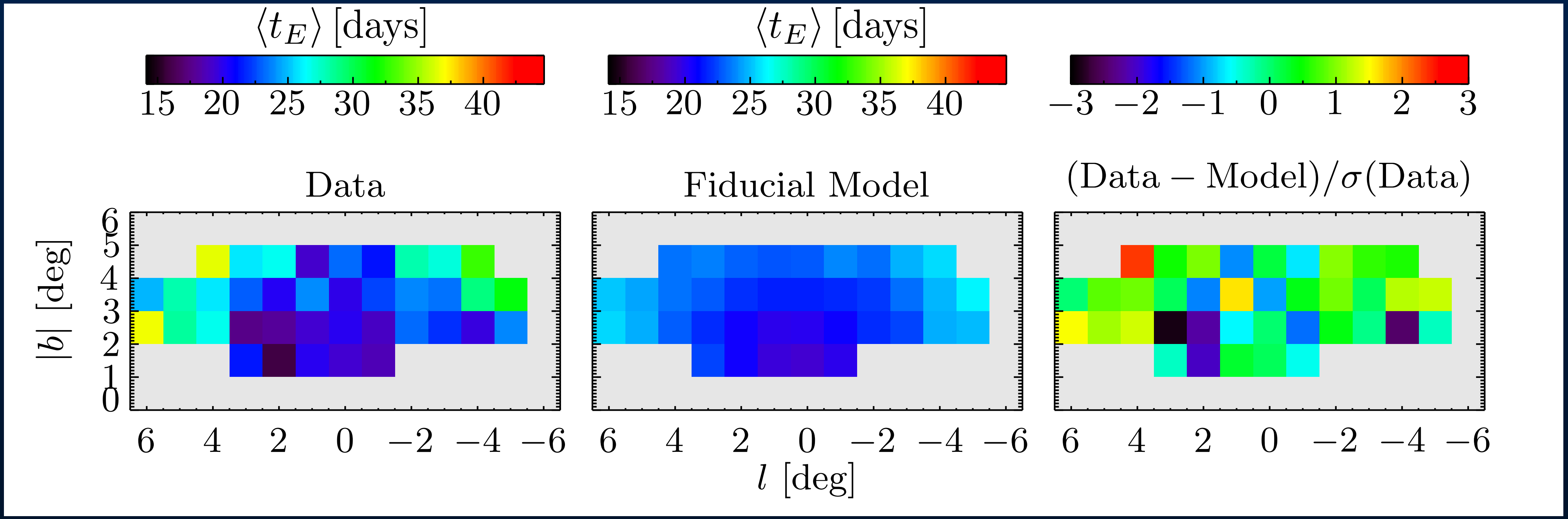
- Similar to Calchi Novati+08 but we now have more than an OOM more events, and new dynamical models



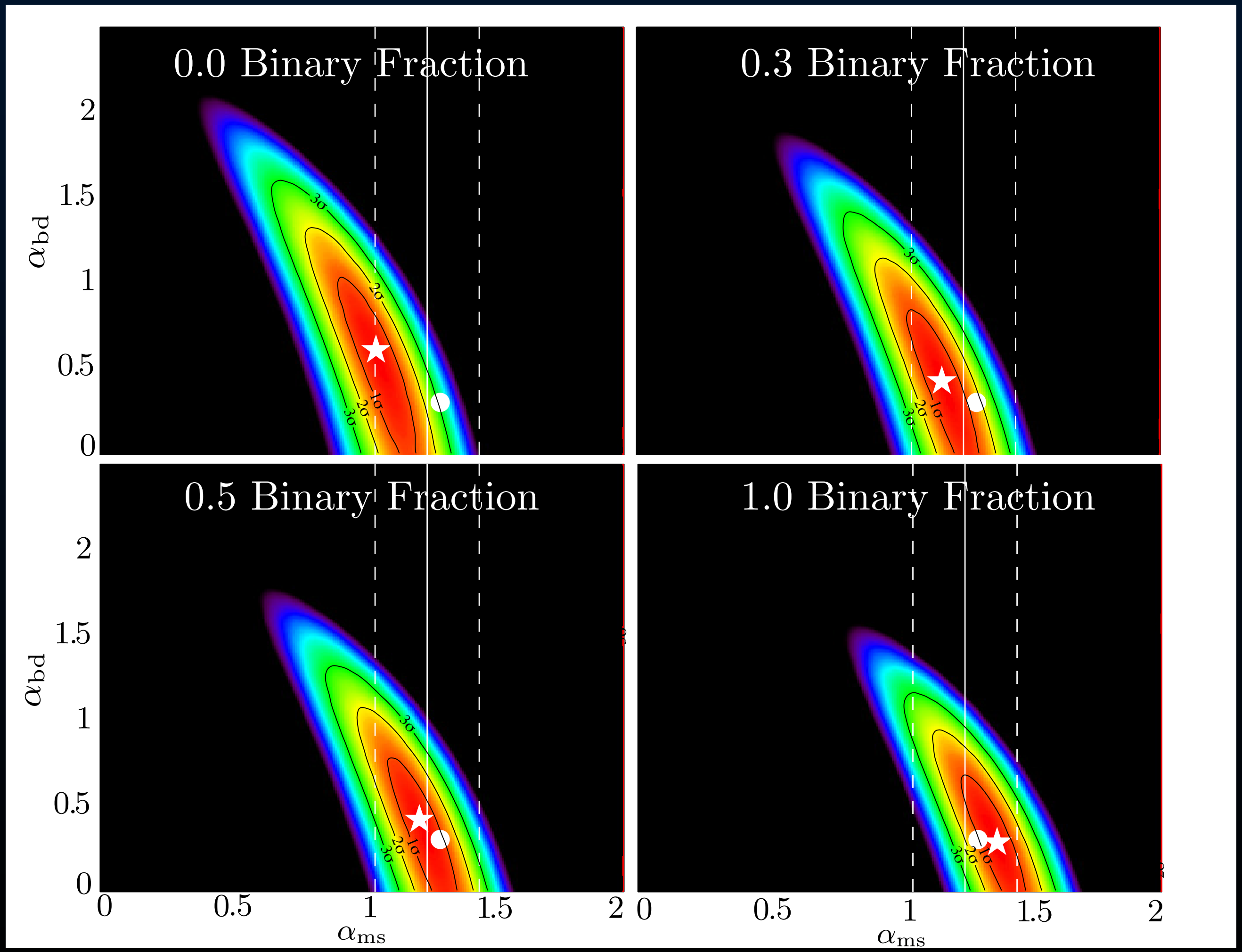
- Adjust IMF to fit timescales of 3560 OGLE-III events (Wyrzykowski+15)
- Overall very similar to local IMF, despite very different formation redshift and timescale

CW, Portail, Gerhard (In prep)

Application of Models to Microlensing: t_E distribution

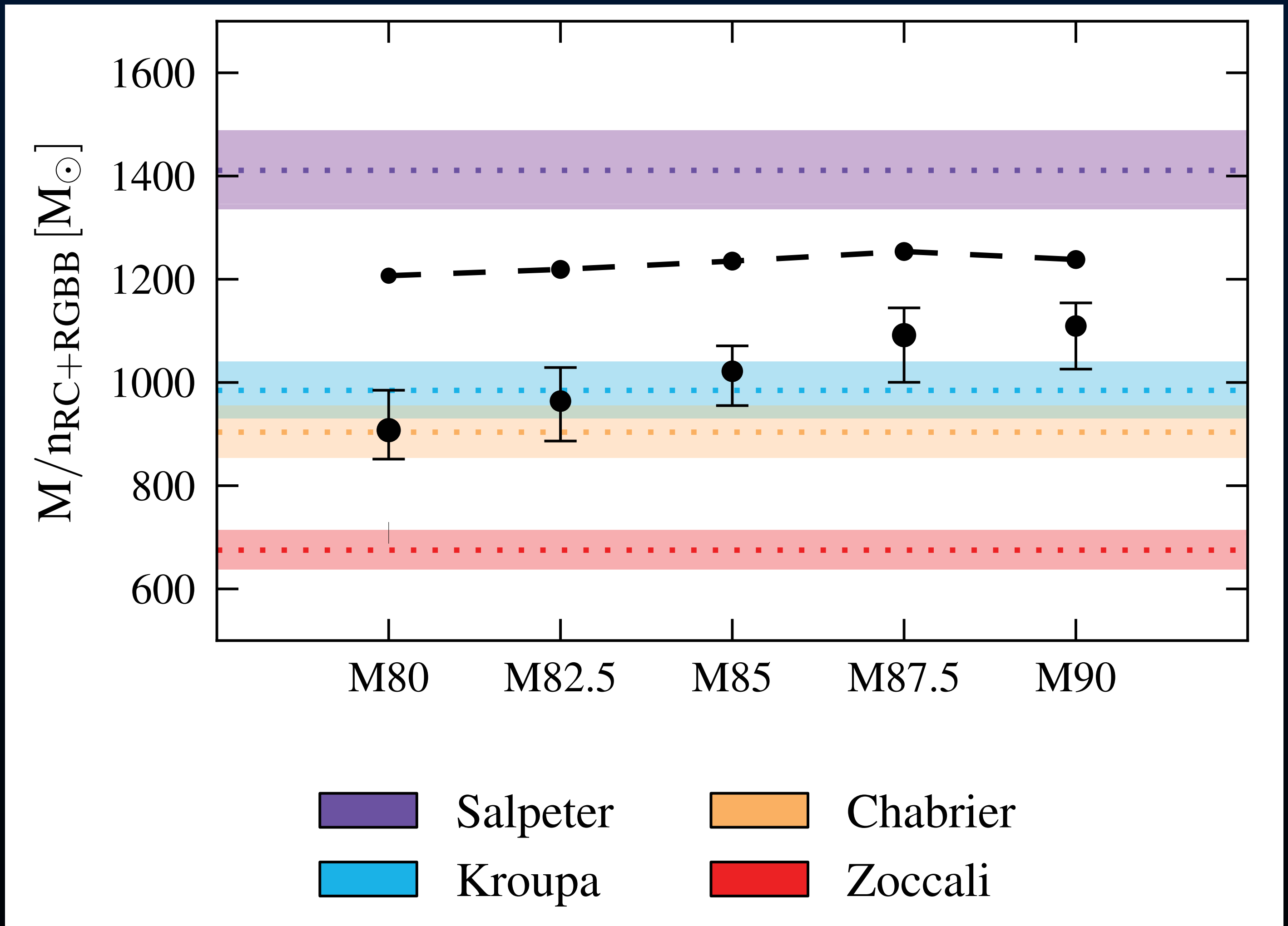


- Timescale changes with position seem to be reproduced reasonably. Test both of model and assumption of constant mass function in disk/bulge
- Binary fraction impact assessed with pop. synthesis. Separations <4au unresolved and seen as $M_l=M_1+M_2$



Application of Models to Microlensing: t_E distribution

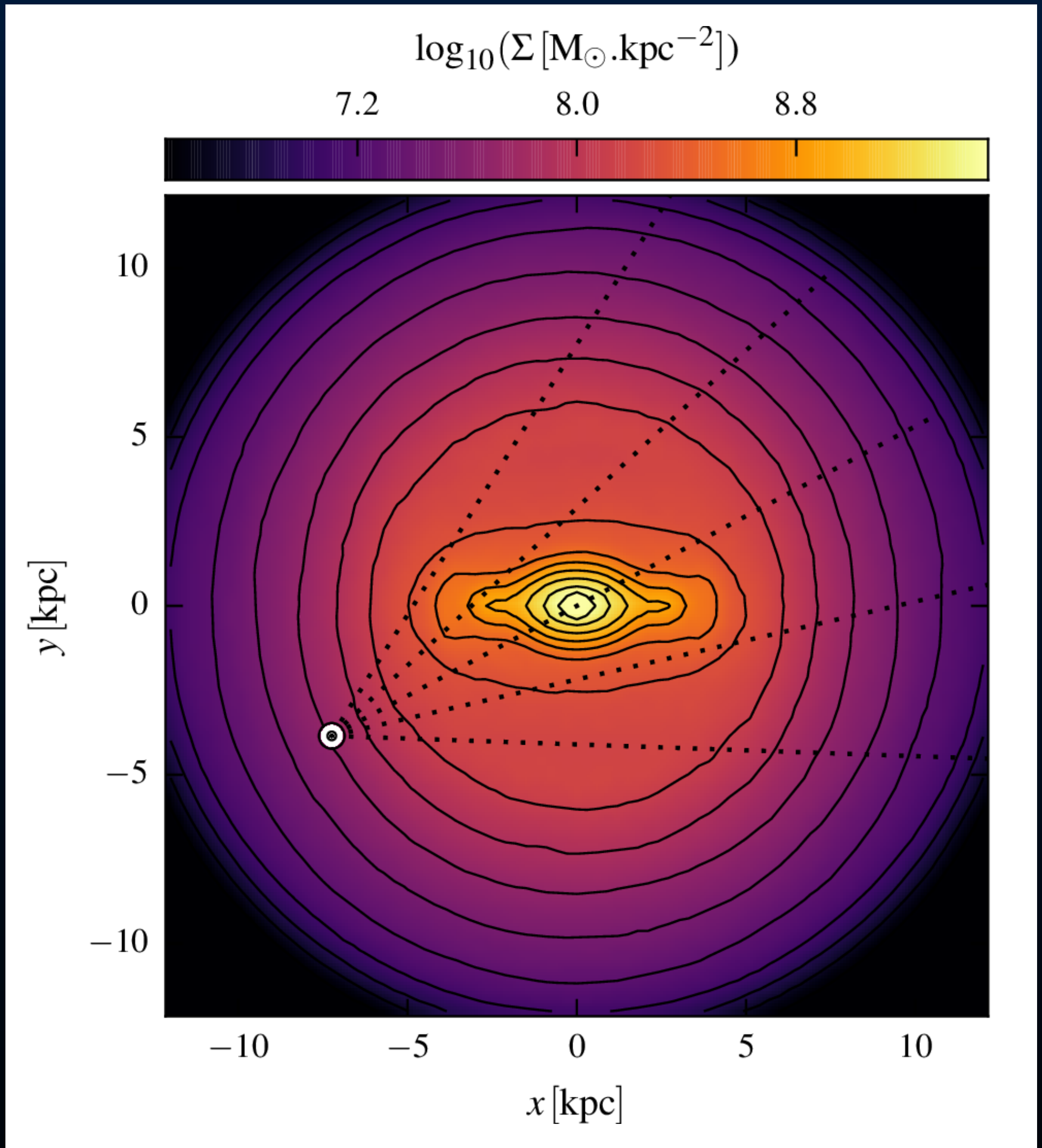
- A near Kroupa IMF also points to low DM fraction in the inner MW
- From star counting in the deep HST fields used to measure the IMF we measure 1000 $M_\odot$/RCG

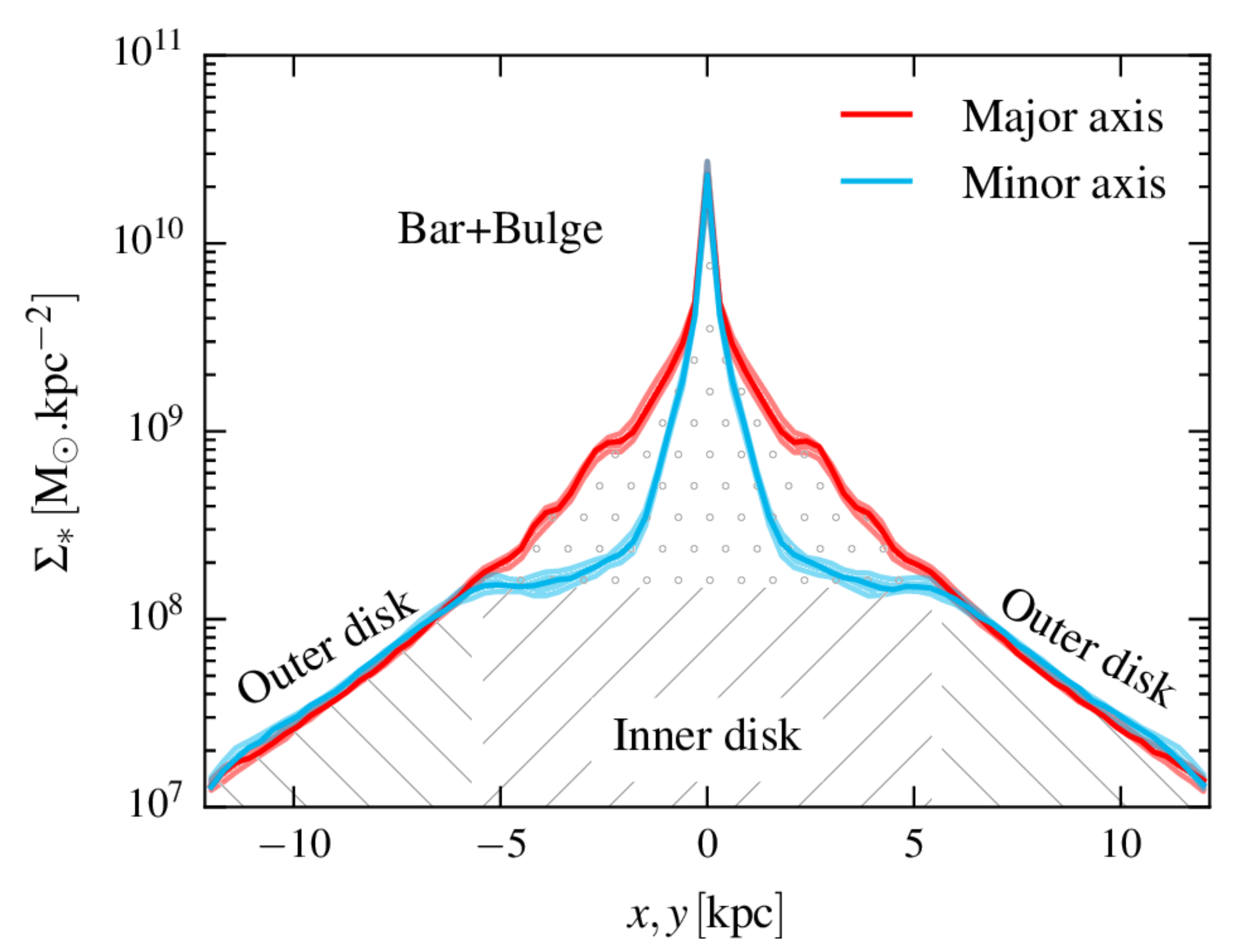


Stellar Mass Distribution

- In the inner 5kpc of the Galaxy, we measure
- 1.9 10^{10} $M_\odot$ of stars in the bulge and bar
- 1.3 10^{10} $M_\odot$ of stars in the inner disk

Typical error
~0.1 10^{10} $M_\odot$



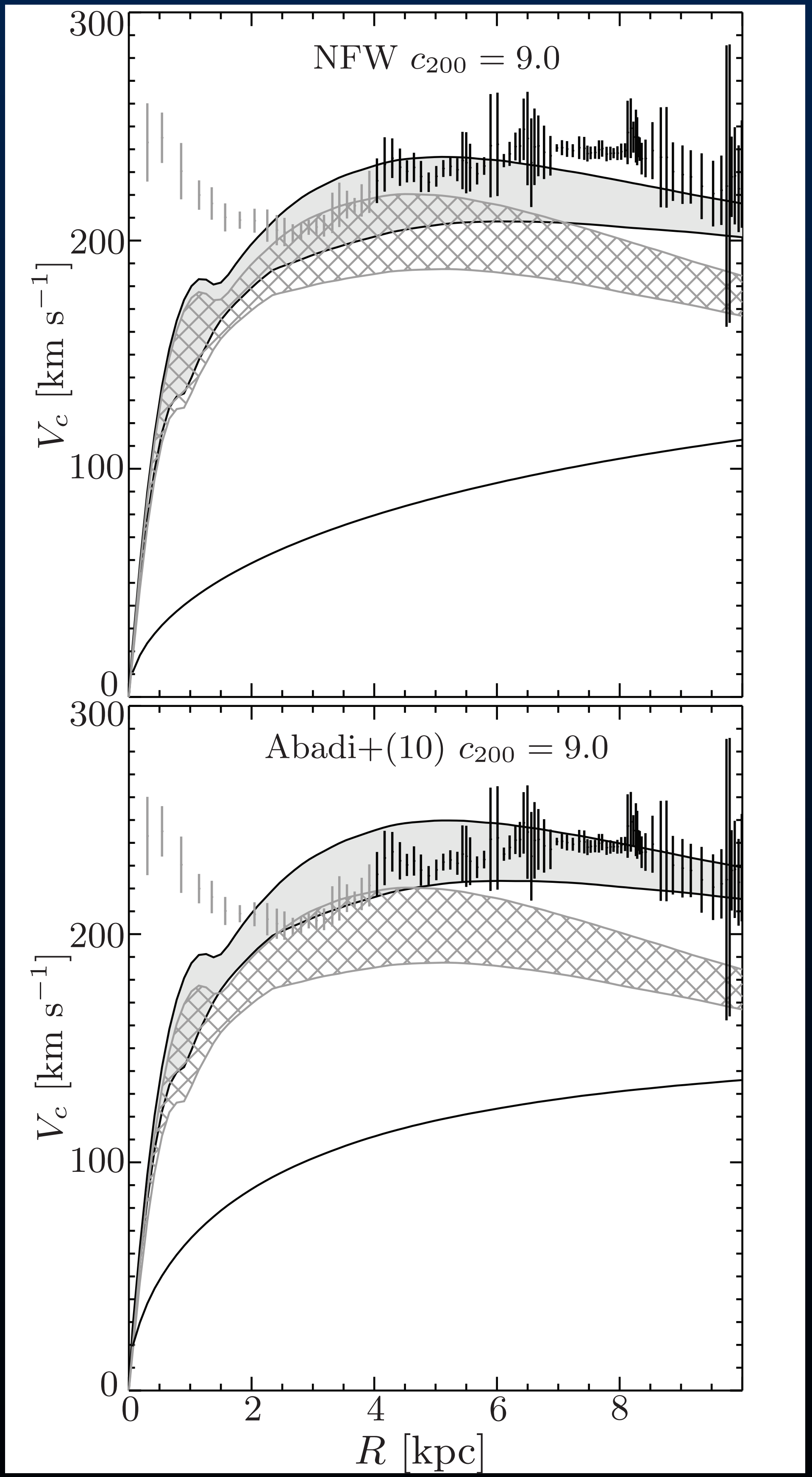


- In the bulge we measure a total dynamical mass of 1.85±0.05 10^{10} $M_\odot$

Portail, Gehard, CW & Ness MNRAS (2017)

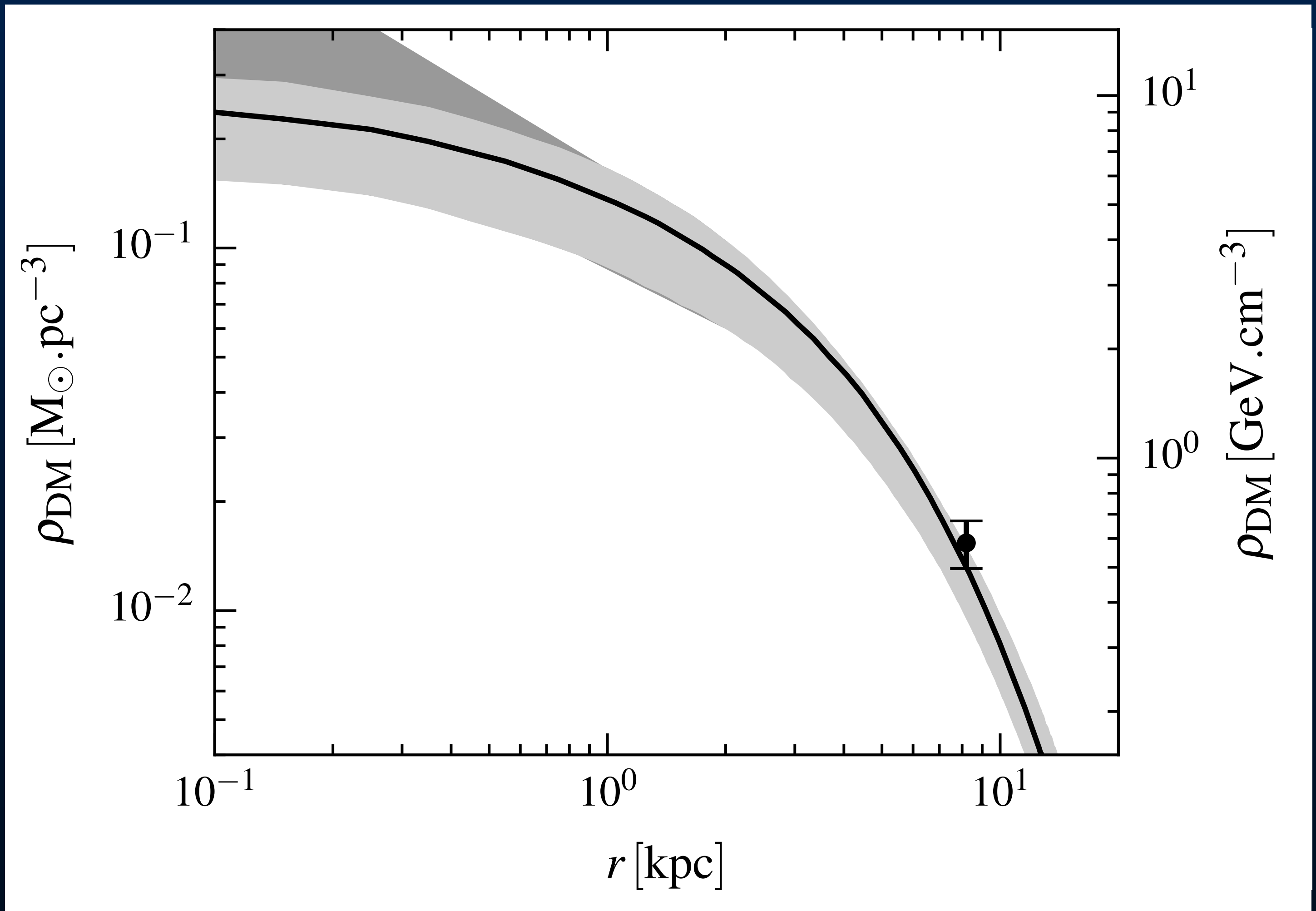
A low DM fraction in the inner MW: Implications

- Dissipationless cosmological simulations predict NFW profile with concentration of ~7-11. Our central DM fractions are consistent with these.
- In reality there is interplay between baryonic and dark matter. Our constraints are still consistent if contraction is mild.
- But there is some tension between these profiles and recent higher local dark matter densities $0.014\,M_\odot\,\mathrm{pc}^{-3}$ (Piffl+2014)



DM is cored?

- In Portail+16 models we also fitted the rotation curve near the sun (Vc~238km/s, ~flat)
- The models naturally give the Piffl +2014 local DM density of $0.014\, M_\odot\, \mathrm{pc}^{-3}$
- To be consistent with the low central DM fractions and that ~half radial force at the sun is in DM needs a kpc size core (or shallow cusp) in DM profile
- Surprising! Its simulations it is very hard to make cores this size in MW sized haloes. Telling us something about the nature of DM?
- See also Cole & Binney (2017)



Conclusions

- We have a ***measurement*** of the shape of the bulge using RCGs as tracers. 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).
- **Dynamical models are generally available on request.**
- Three independent lines of evidence point to a low DM fraction in the inner MW

1. Microlensing optical depth requires a disk maximality:

MOA-II: $f_v = (0.88 \pm 0.07) \quad (\text{at } 1\sigma, \ f_v > 0.75 \ at \ 2\sigma)$

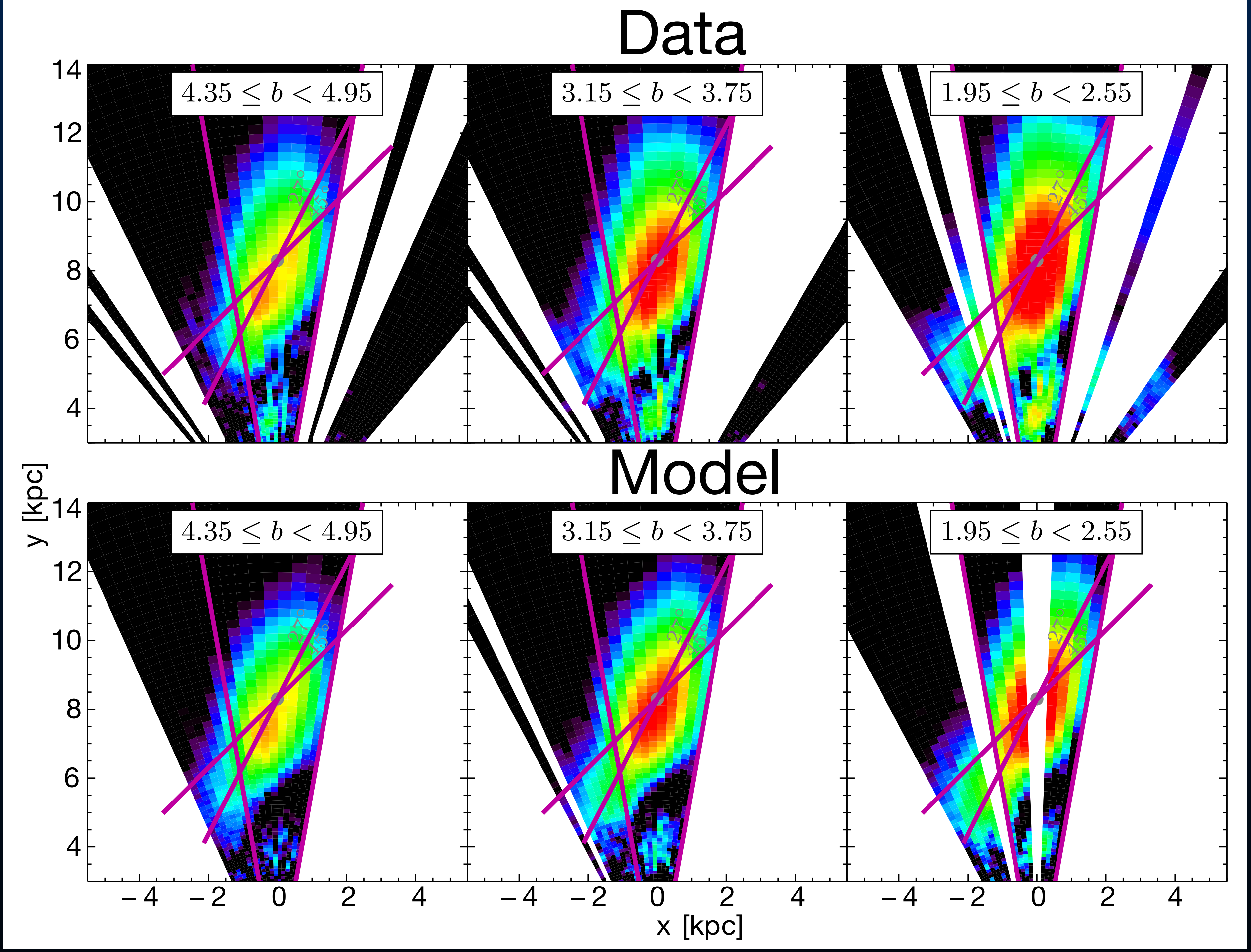
EROS-II: $f_v = (0.9 \pm 0.1) \quad \text{at } 1\sigma$

2. Microlensing timescale distribution shows that the IMF in the inner galaxy is close to Kroupa (2001). This points to high mass-to-clump and therefore low DM fraction.
3. Empirical measurement of the mass-to-clump agrees with this. The resultant dynamical models require a ***core in the DM*** to match local constraints.

- IMF in the inner galaxy is close to Kroupa (2001). Very similar to local disk despite different time/timescale of formation.

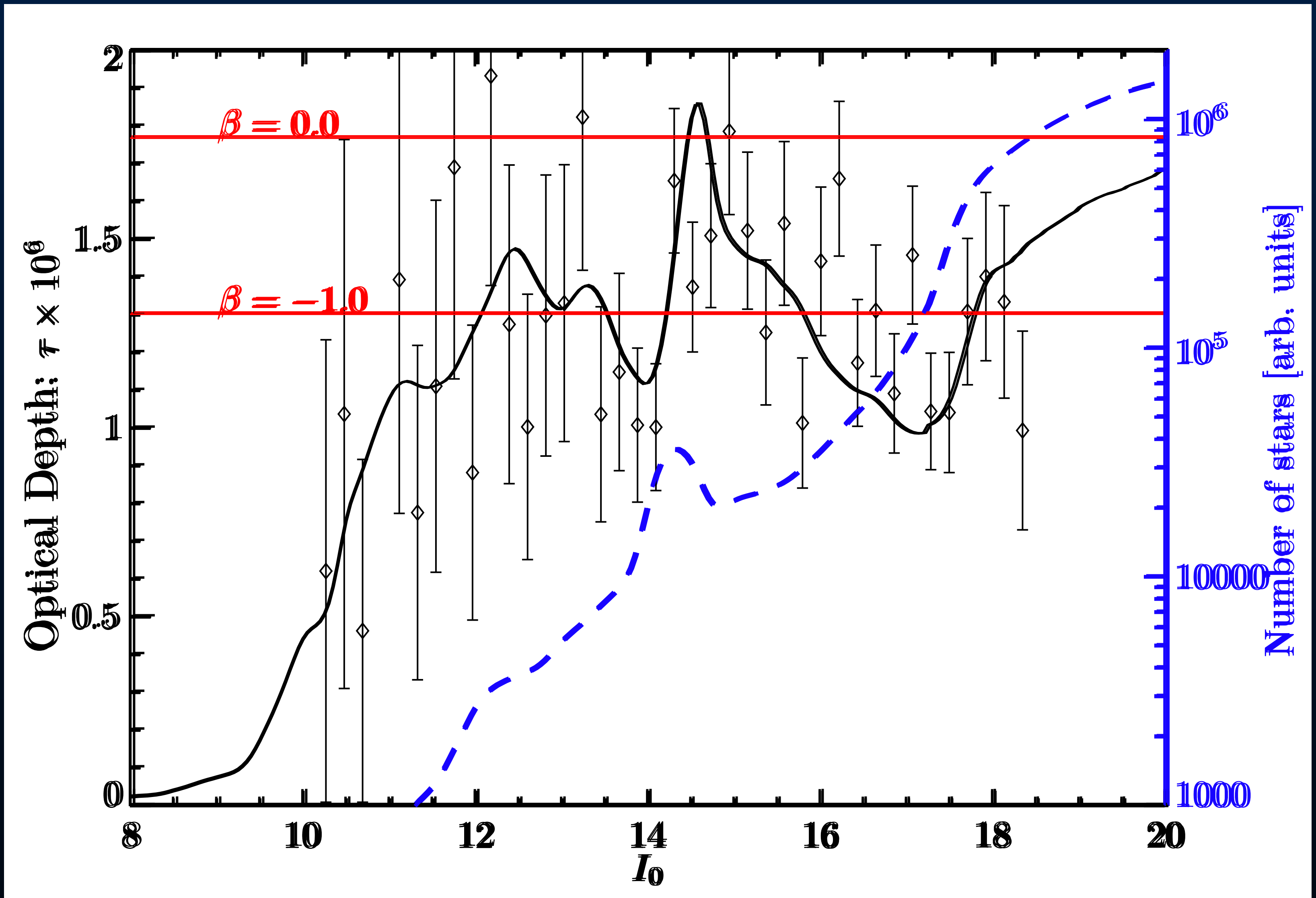
Modelling the inner Galaxy: The Long Bar

- Slices through the magnitude distributions
- Statistically identified RCGs plotted as if they were perfect standard candles



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)



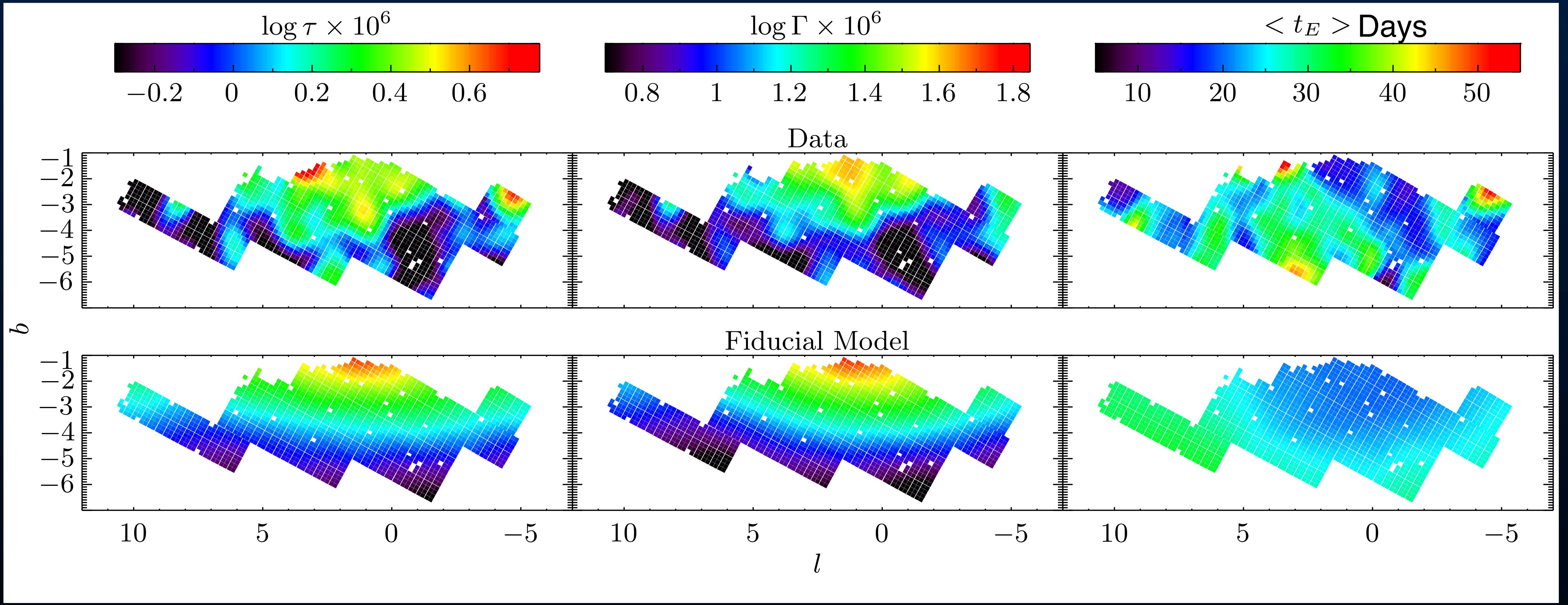
Accurate comparison requires modelling of magnitude distribution and source selection

Application of Models to Microlensing: Optical Depth

Microlensing Properties of Fiducial Model

- Fiducial model: M90 & R_d = 2.6 kpc & $H_{4.5}$ = 0.18 kpc

Comparison to maps from MOA-II (Sumi & Penny 2016):

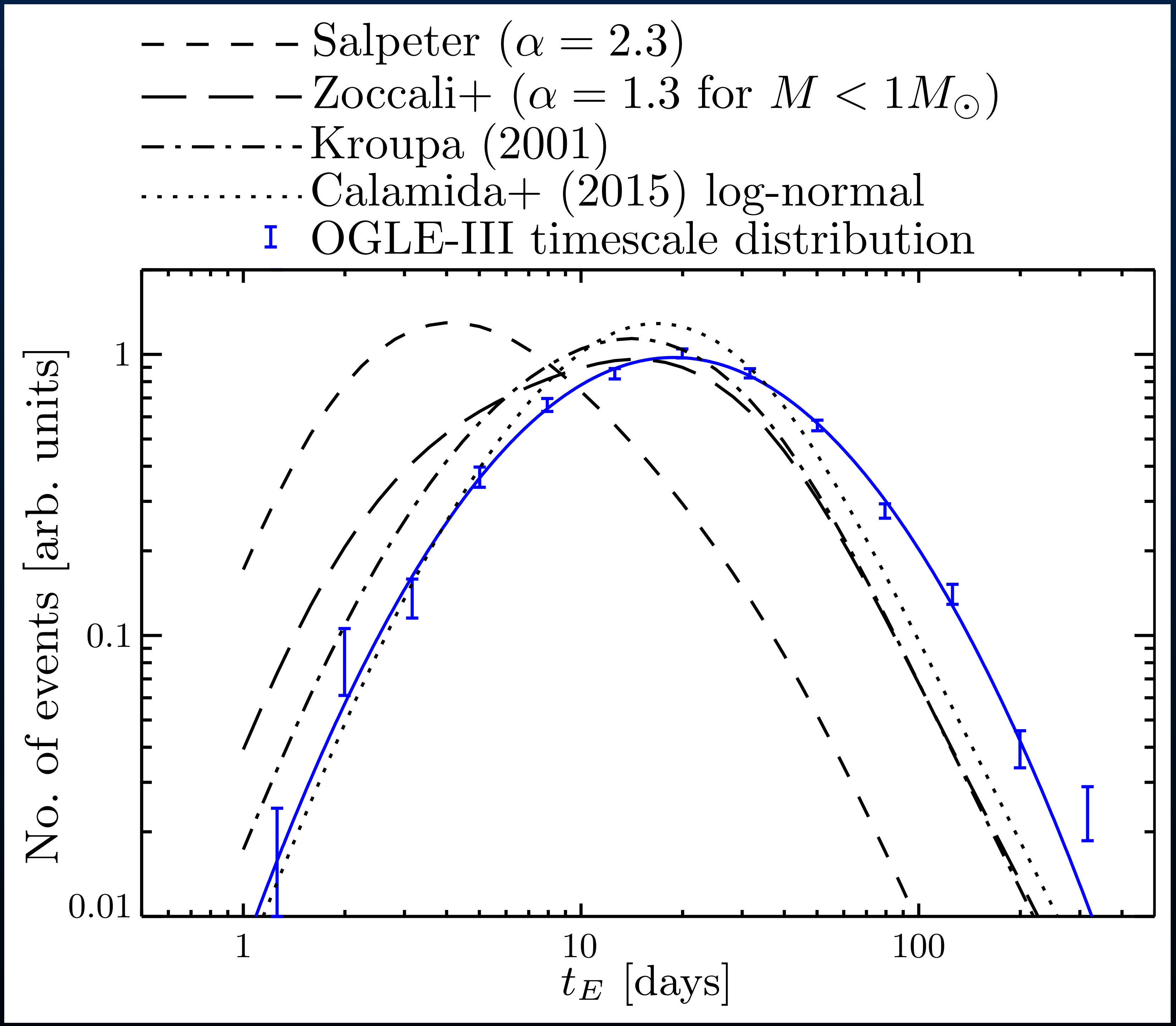


Agreement seems qualitatively good

CW, Gerhard & Portail, 463, 557, MNRAS (2016)

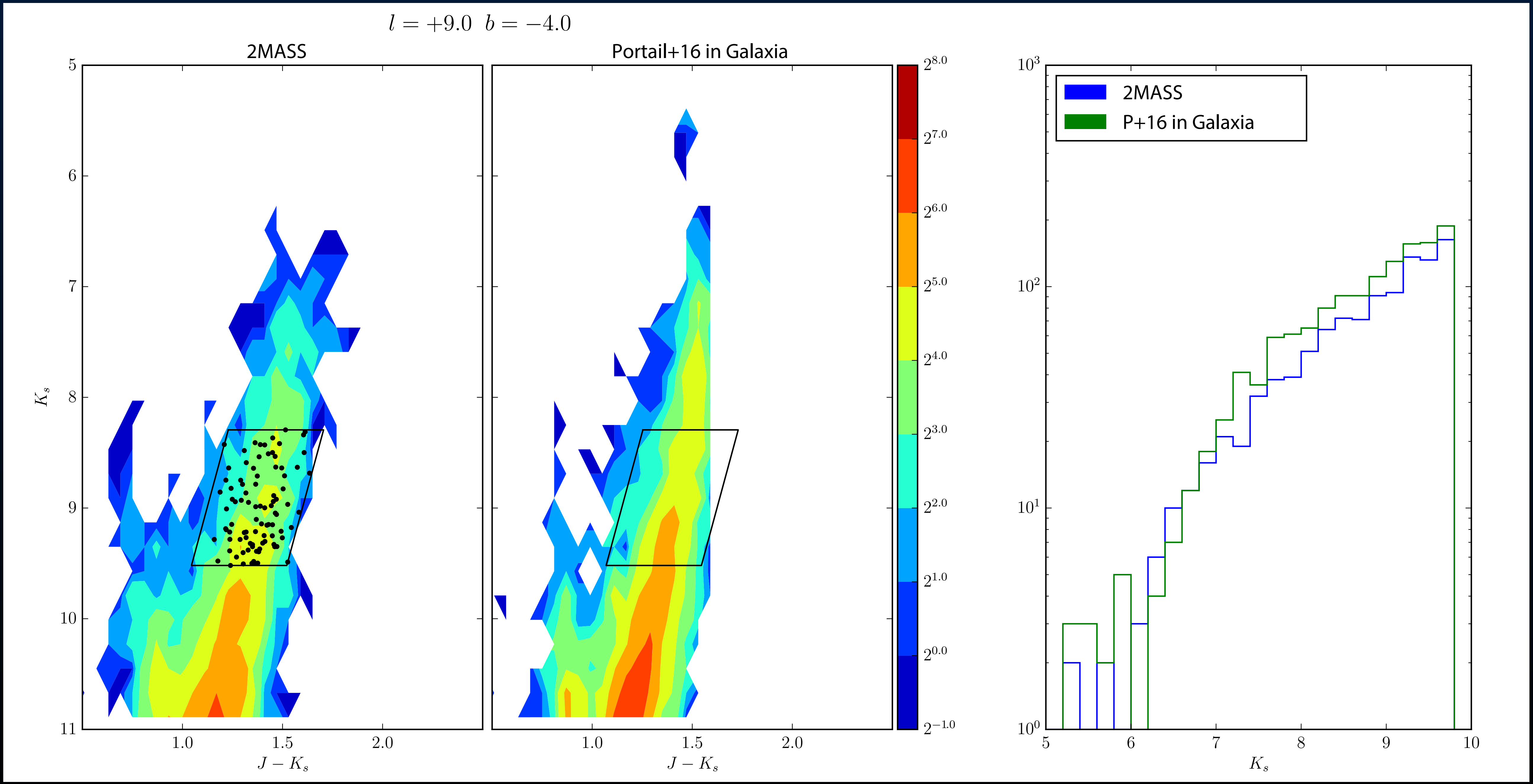
Application of Models to Microlensing: t_E distribution

- Fiducial dynamical model with different IMFs
- Model matches very well with Kroupa or especially Calamida log-normal IMF
- Low number of brown dwarfs required (similar to but less than Awiphan +15 with Besancon + MOA-II)

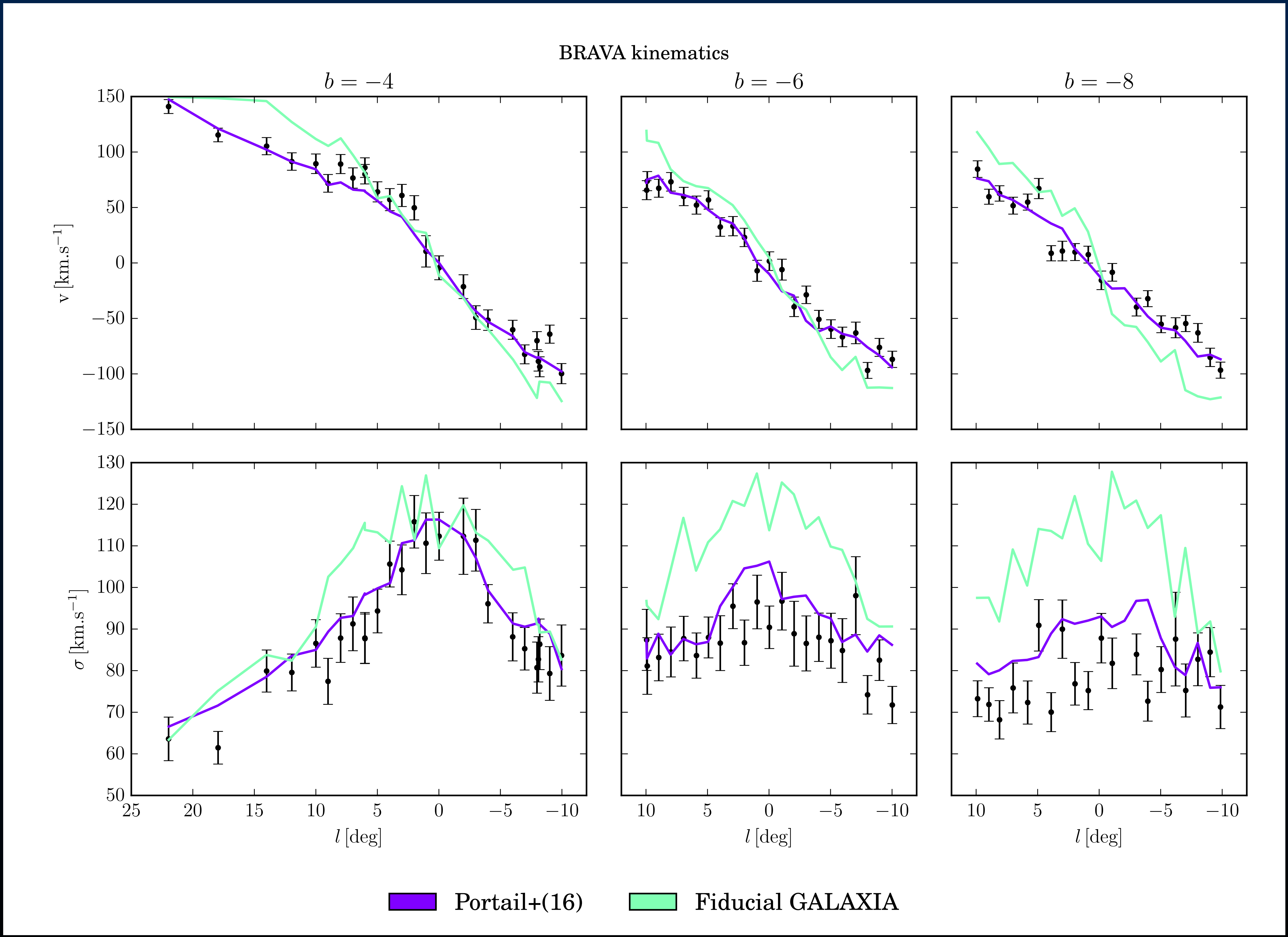


Improved Galaxia Bulge Models

- Would like to release the made-to-measure models of the bulge
- To maximize ease of use release through Galaxia
- Users can easily produce mock catalogues with magnitudes, colours, radial velocities, proper motions…

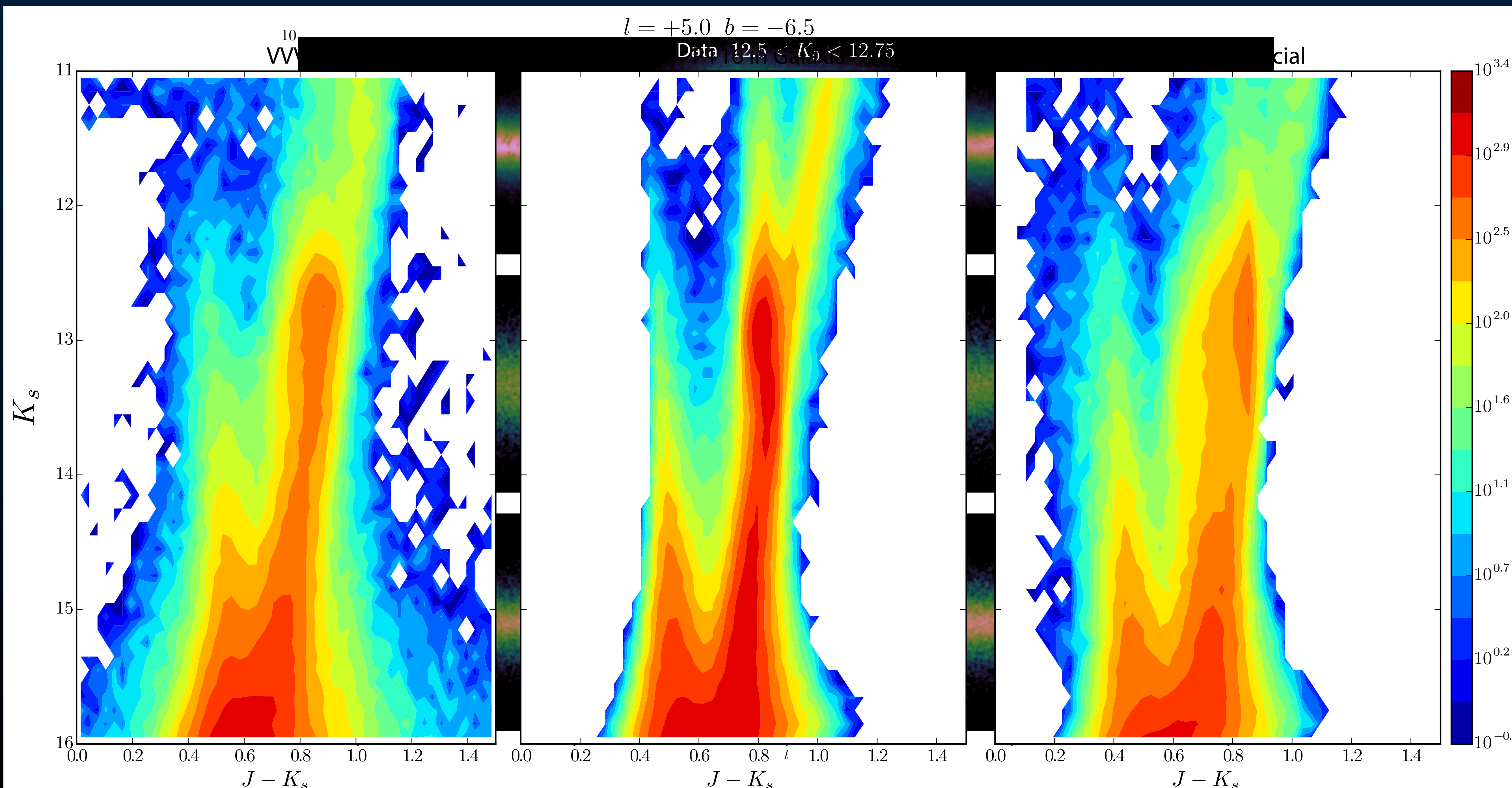


Improved Galaxia Bulge Models



Issues

- Made-to-measure particles don't have age or chemistry attached.
- Current disk not realistic e.g. no age-dispersion relation giving thin young disk
- No stellar halo or local thick disk



Issues

- Made-to-measure particles don't have age or chemistry attached.
- Current disk not realistic e.g. no age-dispersion relation giving thin young disk
- No stellar halo or local thick disk

Solution

- Take made-to-measure bulge models in inner MW assigning age (mostly old), chemisty (alpha-enhanced, bulge MDF)
- Add current Besancon-like disk outside
- Lose dynamical self-consistency, but still more self-consistent than Besancon

Microlensing Optical Depth

- Fraction of observed stars that are strongly lensed
- Effectively the (weighted) surface density towards the Galactic bulge
- 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

Microlensing Model

- To N-body bulge models add a double exponential disk
- Local disk properties:

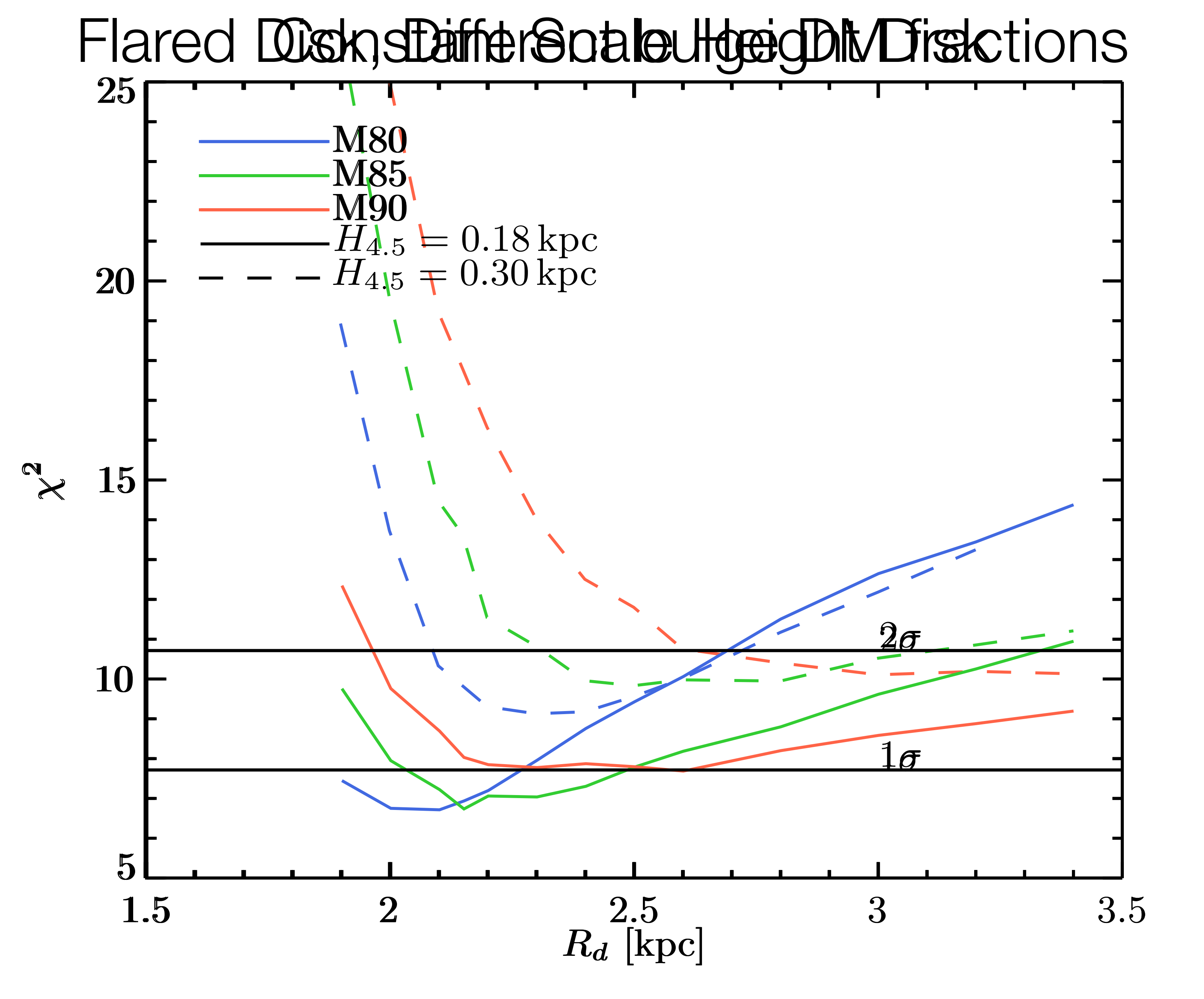
$$H_\odot = 0.3\,\mathrm{kpc}\,,\;\; \Sigma_\odot = 38\,M_\odot\;\mathrm{pc}^{-2}$$

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 disk scale length and scale height: R_d & $H_{4.5}$

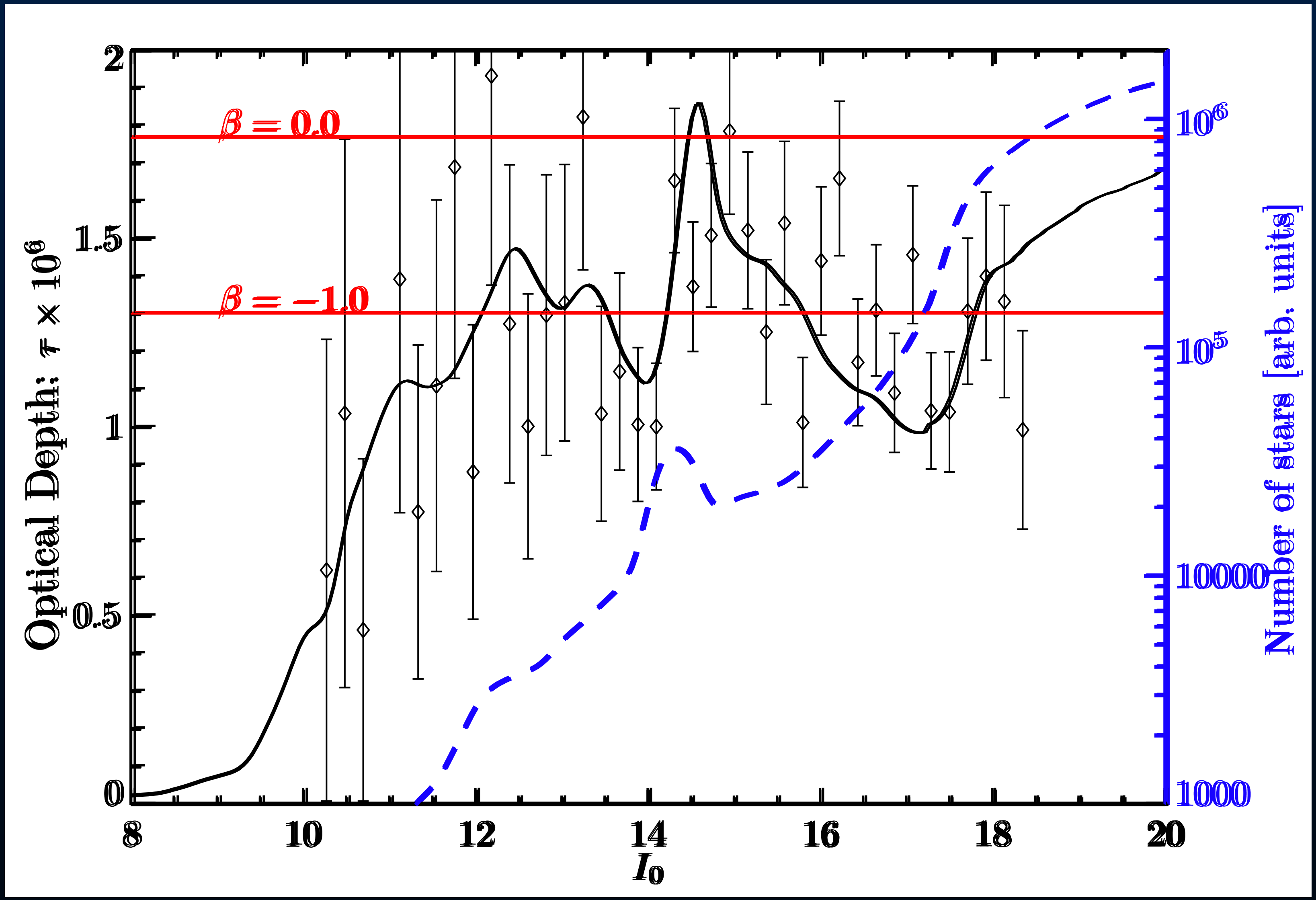
Marginalising over bulge models

- Degeneracy between stellar matter in bulge and disk
- Models with more mass in the bulge *i.e.* M90, M100 require less mass in front → longer disk scale length required
- M80 has less stellar matter in bulge → short disk scale length required



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)



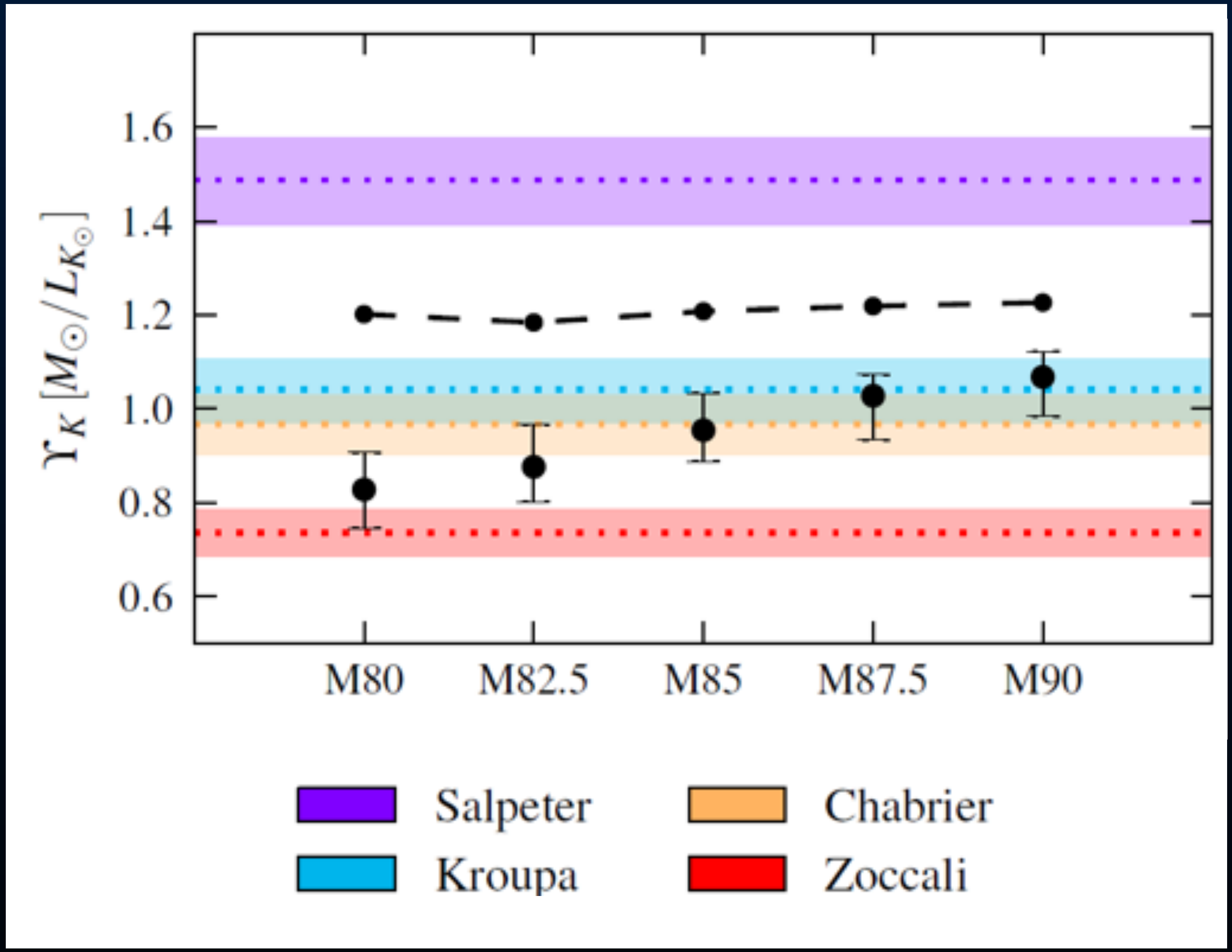
Accurate comparison requires modelling of magnitude distribution and source selection

1.Motivation: Made-to-measure N-body models of the bulge

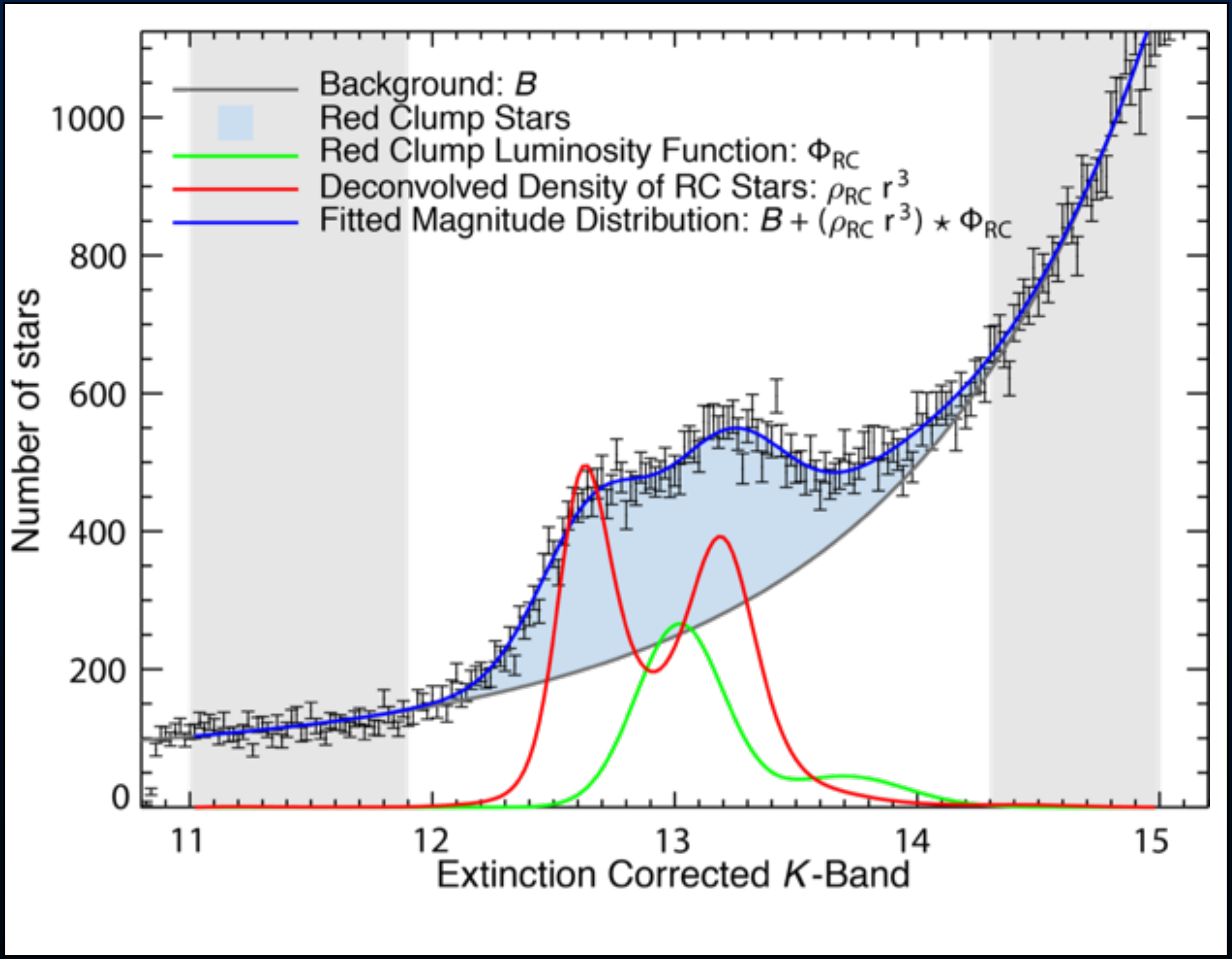
- We use the COBE/DIRBE K-band measurements, and correct for extinction using the extinction map from Wegg & Gerhard (2013)

- The Salpeter IMF can be ruled out, predicting a too large mass-to-light ratio

- Zoccali IMF imply about 40% dark matter in the bulge while the Kroupa IMF imply only about 12%.

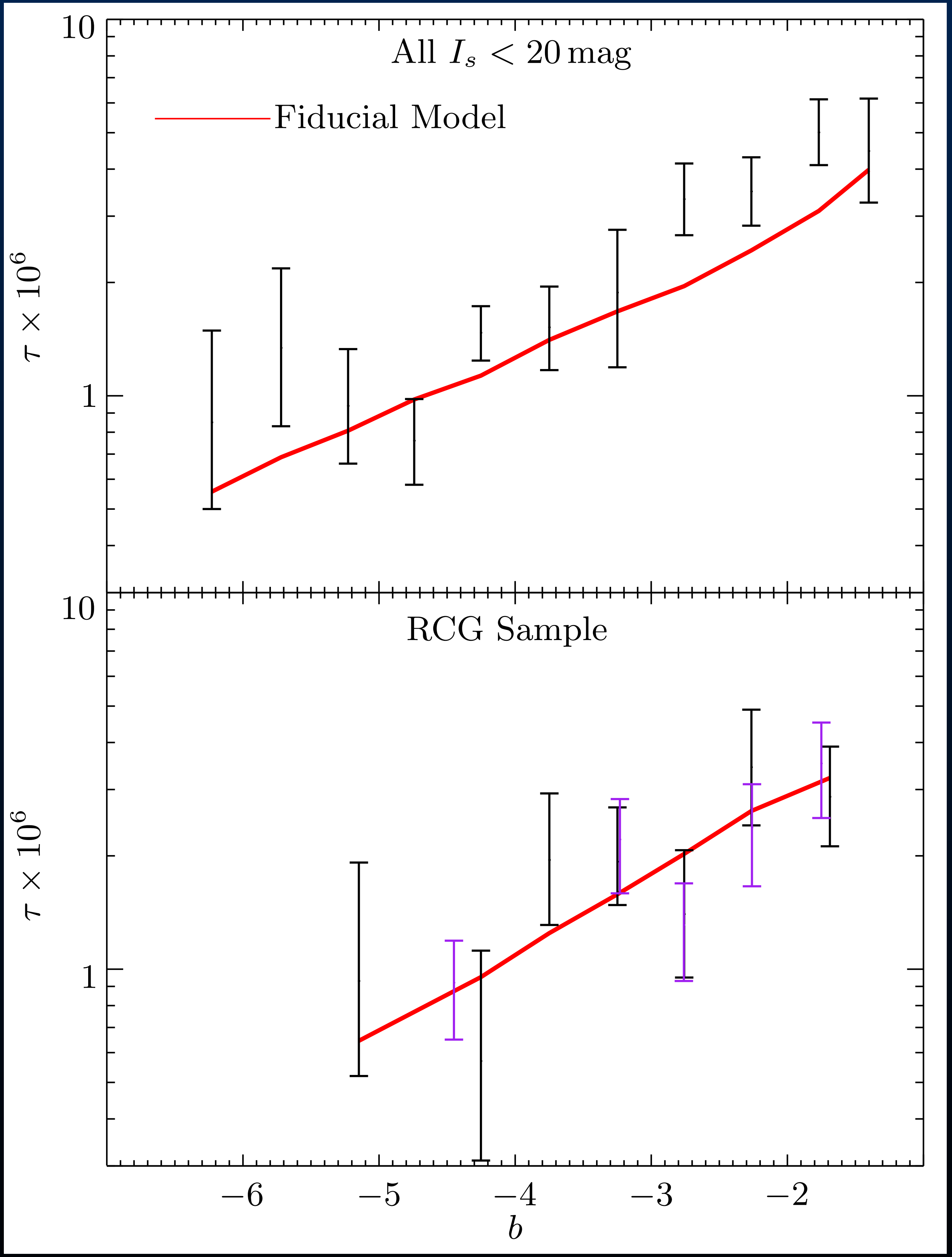


Line-of-sight density estimation



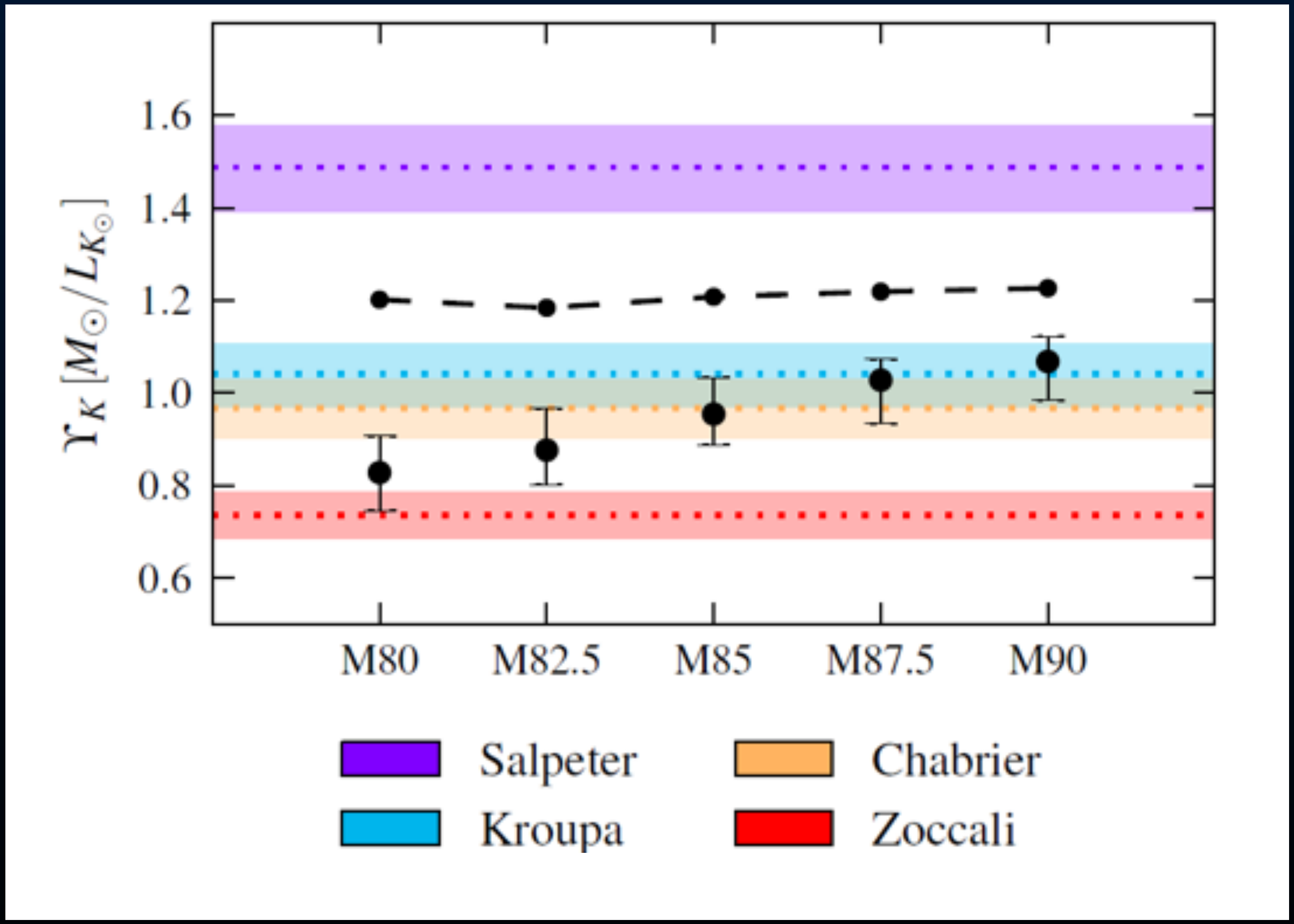
- Fit background to region outside Bulge's RC stars
- Statistically identified red clump stars are convolution of line-of-sight density with luminosity function.
- Deconvolve to estimate density using a slight variation on Lucy-Richardson algorithm

- 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.



Prospects

- Much larger and better sample of microlensing events already exists: OGLE-III. >2000 events at |b|<3. ***But we need efficiencies.***
- Matthieu is working on Milky Way dynamical models utilising more data and other constrains unique to the galaxy to break degeneracy

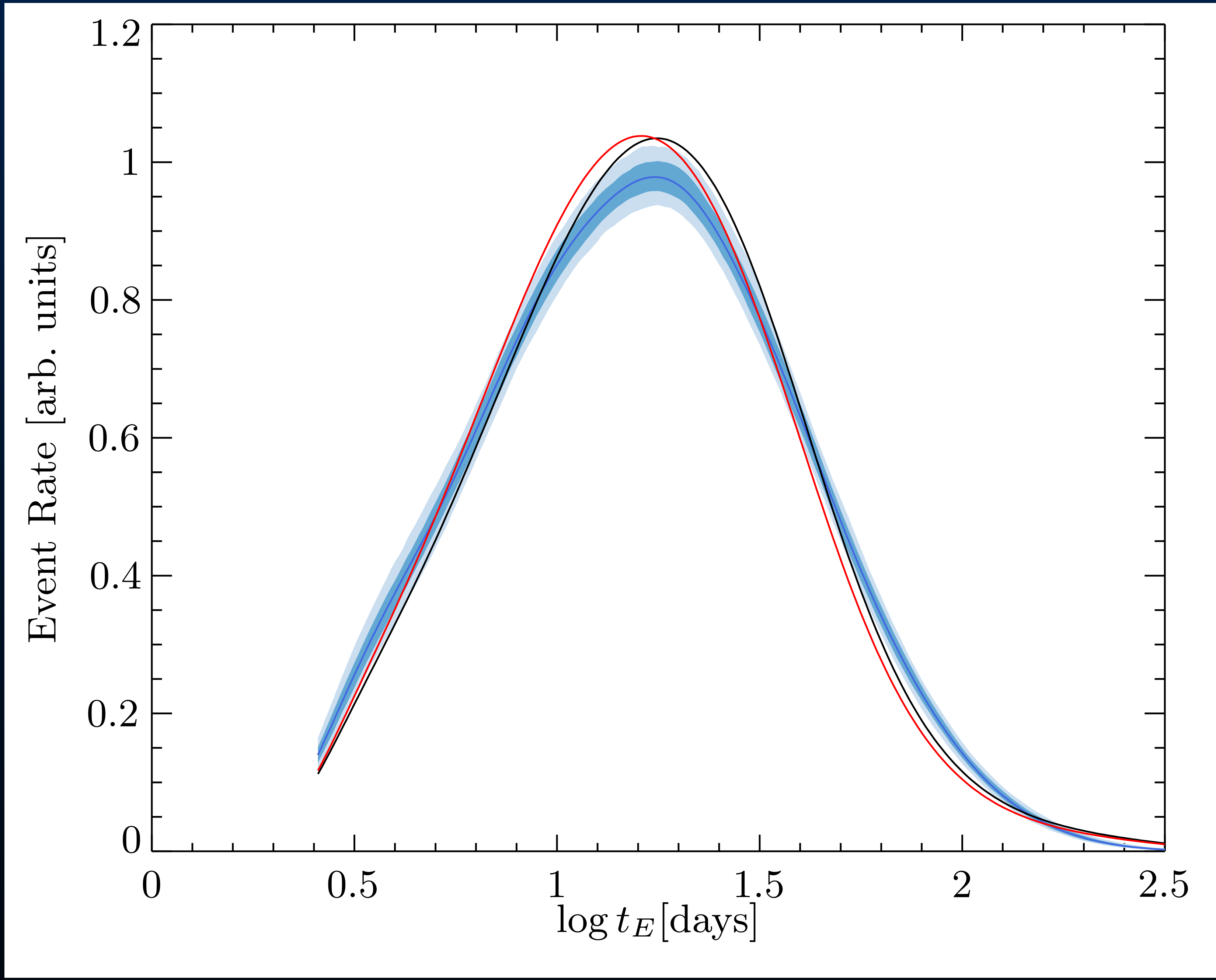


Outline

1. Motivation: Breaking dark-matter vs stellar degeneracy (5 min)
   - -Shape of the inner MW
   - -Made to measure MW bulge models
2. Galactic Microlensing (7 min)

2. Mass Function from Microlensing Timescales

- We now have dynamical models fitting data across entire inner MW <5kpc
- Can use these to fit IMF



- Low number of brown dwarfs required (similar to but less than Awiphan +15 with Besancon + MOA-II)