Dynamics and Mass of the Galactic Bulge, Bar and Inner Disk

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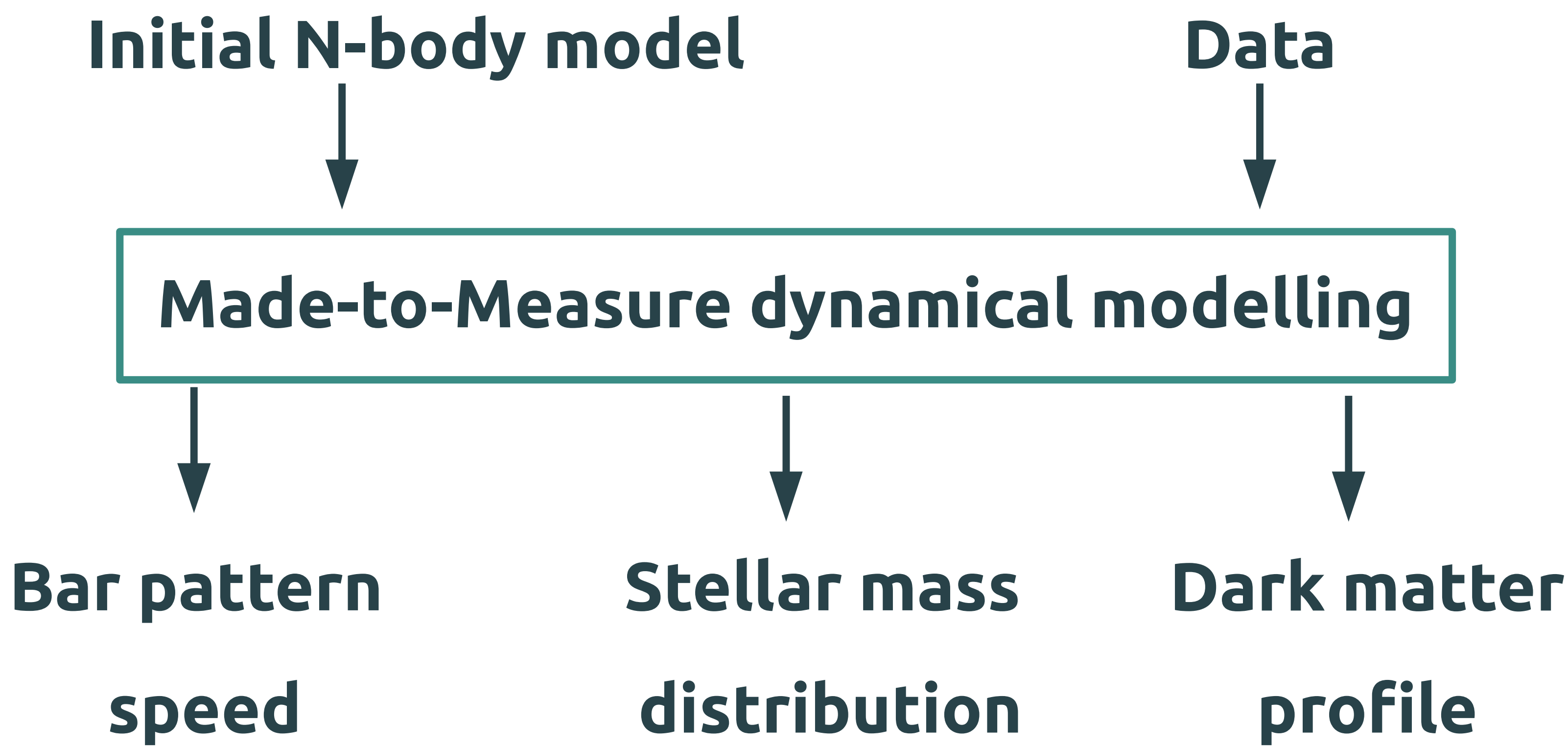
The Milky Way and its environment, IAP, Tuesday, September 20th

Image credit: ESO

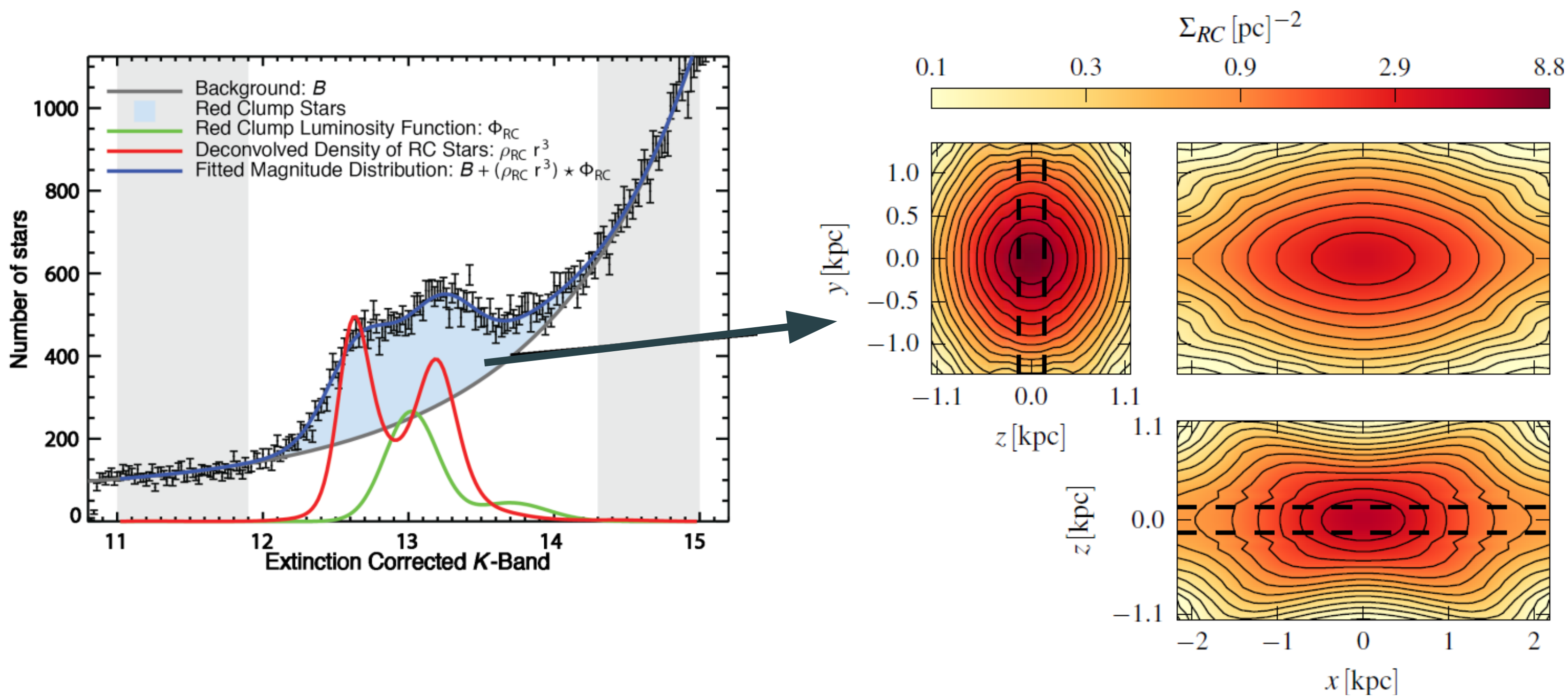
Outline

Introduction



The Galactic bulge

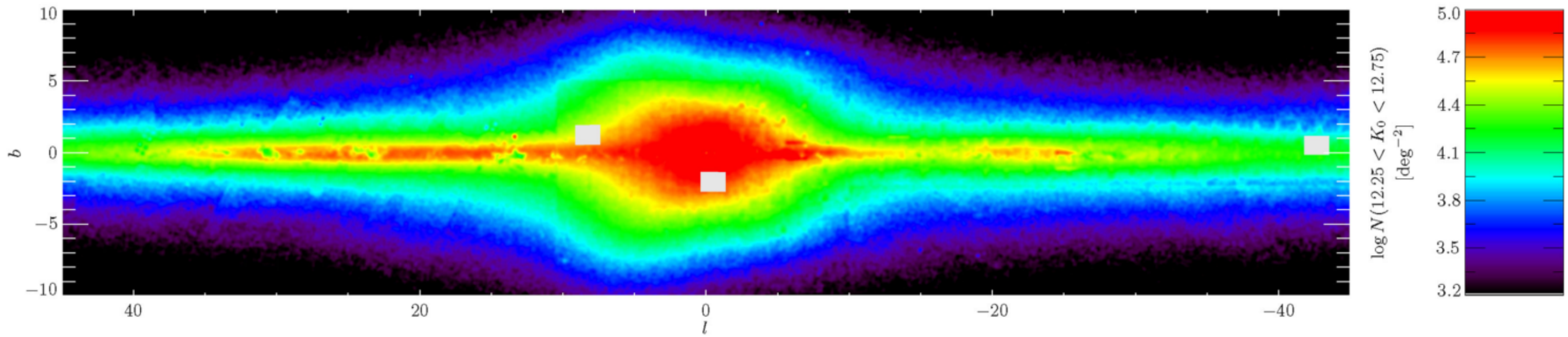
- The Galactic bulge has **a Boxy/Peanut shape**, mapped in 3D by direct deconvolution of 8 million Red Clump Giants (RCGs) identified from VVV data



Wegg C., Gerhard O., 2013, MNRAS, 435, 1874

The Galactic bar

- The Galactic bulge smoothly transition into the long bar, both appearing at a consistent angle of ~28°. **Long bar and bulge** are parts of the **same structure.**



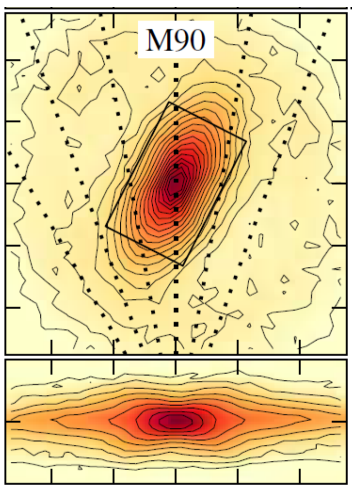
Wegg C., Gerhard O., Portail M., 2015, MNRAS, 450, 4050

- The bar extends to 5kpc from the center and has an extra **superthin component** (h_z = 45 pc !), predominantly near the end.

- Our goal is to make a dynamical model of the **entire Galactic bar region**

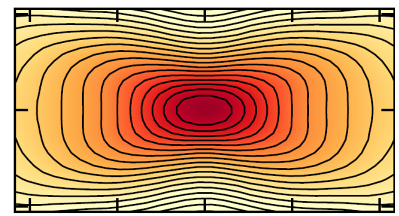
The Made-to-Measure method

N-body model

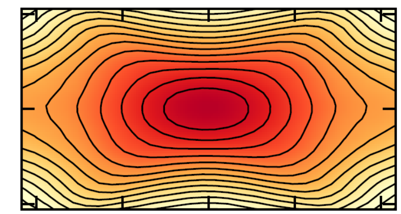


Observe

Model observable



Real data



Compare

Evolve N-body model

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

Profit function

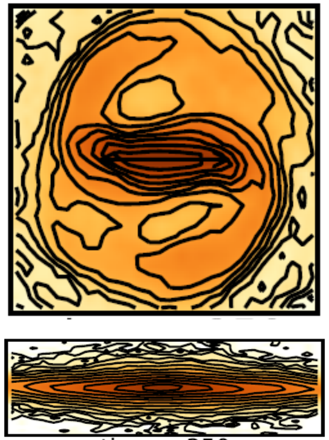
Change N-body weights

N-body weights are simultaneously:

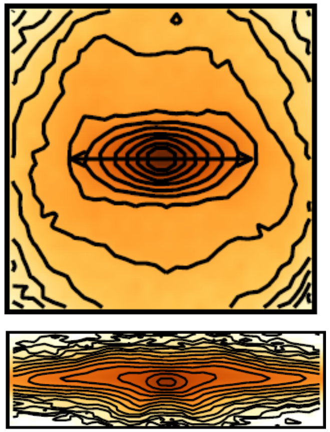
- Mass elements (N-body modelling)
- Orbital weights (Schwarzschild's method)

Initial N-body models

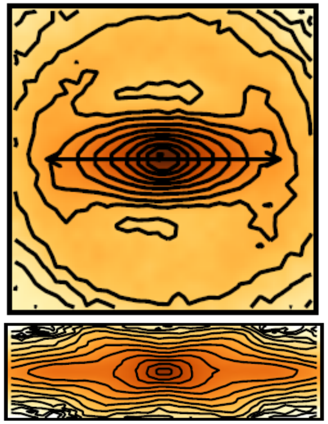
- N-body models of B/P bulges **naturally produced** by evolution of a stellar disk in a **live** dark matter halo



Bar forms



Bar buckles



Bulged bar

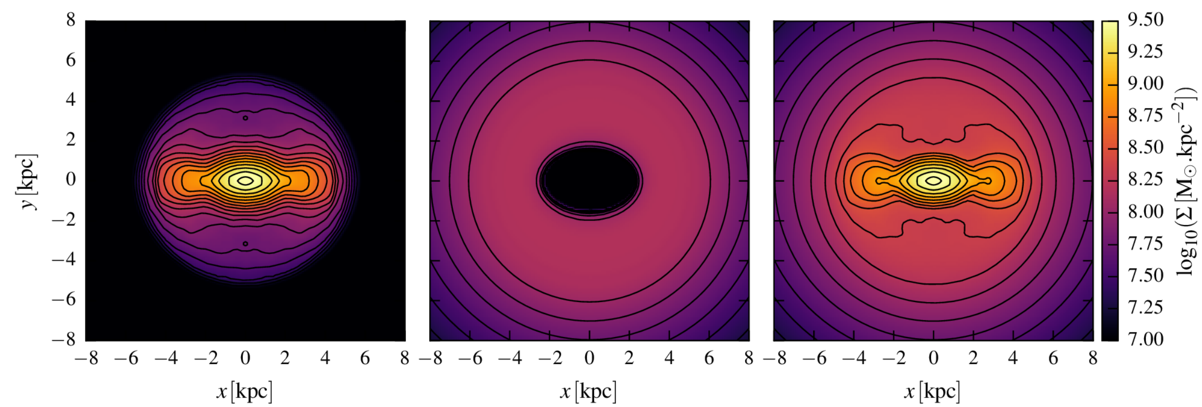
But ...

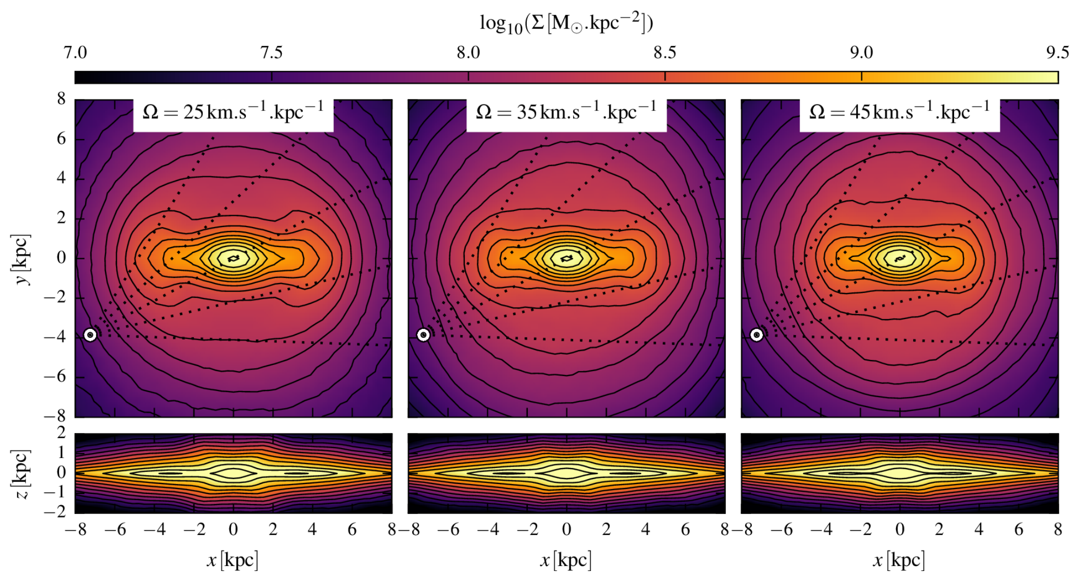
Such models have **issues**:

- Bars are generally **too long**
- **No control** on mass distribution and bar pattern speed
- Evolution is **very sensitive** to initial conditions, microstate matters

Initial N-body models

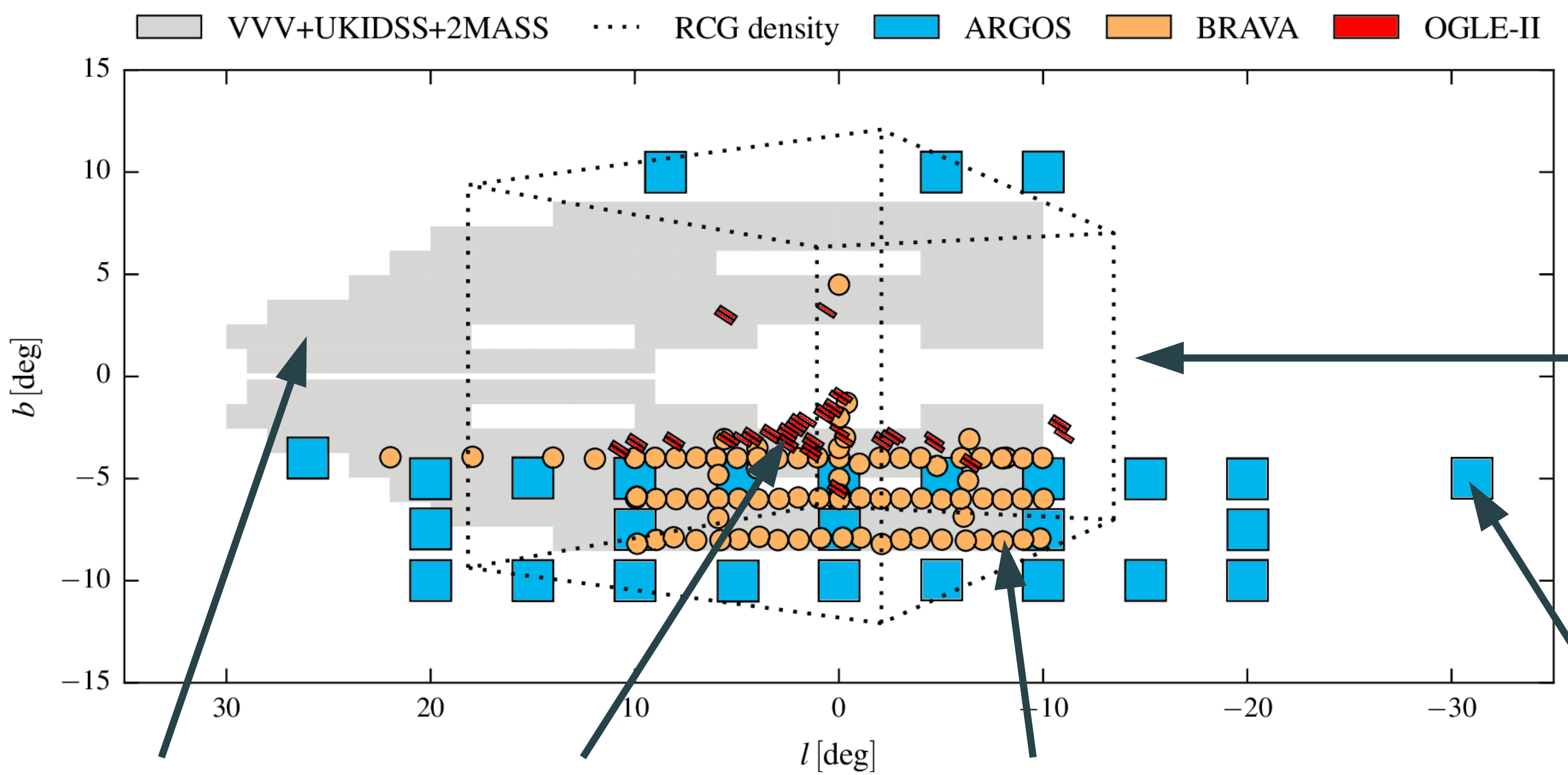
- What **would be** a reasonable initial N-body for modelling the inner Galaxy ?
- We add up bulge, bar and disk...





... and **adiabatically adapt** a N-body model to match our target Galactic **density** and change the **pattern speed.**

Data



+ rotation curve

3D density of RCGs

Magnitude distributions

Proper motion dispersions

Integrated mean radial velocities and dispersions

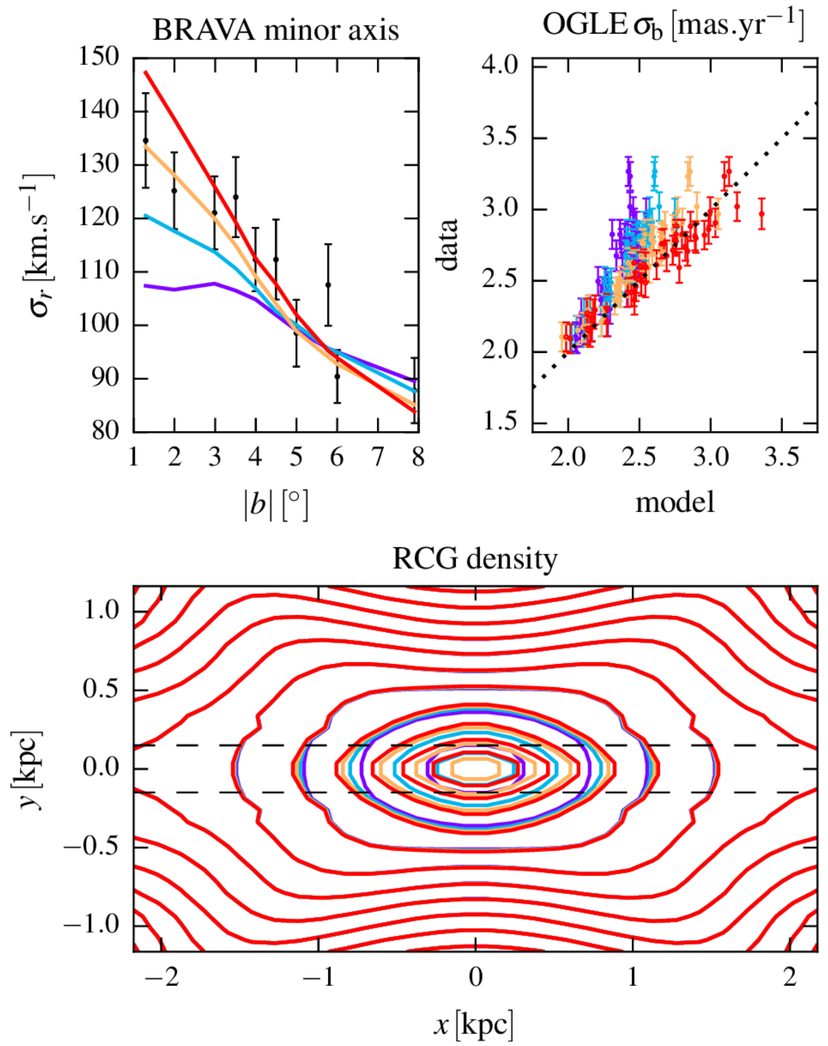
Mean radial velocities and dispersions as a function of distance

Dynamical modelling

Unknowns	Constraints
Bar pattern speed	From BRAVA and ARGOS
Dark Matter	Einasto profile, constrained • In the bulge from BRAVA dispersion • For R>6kpc from the rotation curve
Mass-to-clump ratio	Measured by deep HST data (Zoccali et al. 2000)

Central mass distribution

- This is not enough to get a good match **to all datasets**.
- We need an additional **central mass concentration of 2 x 10^9 $M_\odot$** inside the central 250 pc.
- This probably corresponds to the **Nuclear Bulge**.

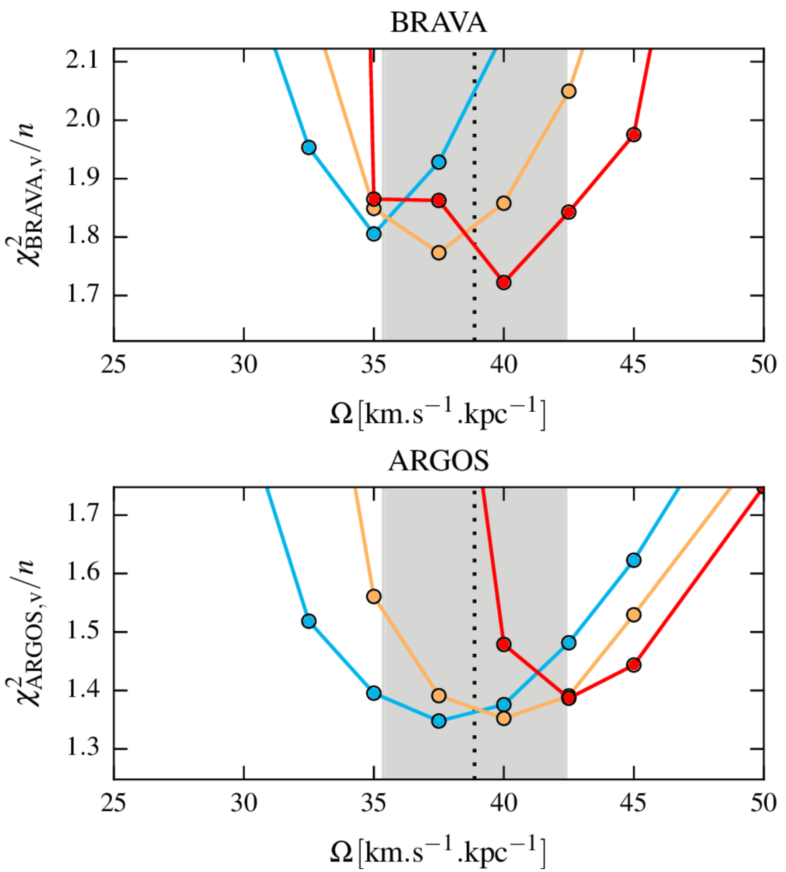


Pattern speed

- From stellar dynamics in the bulge (BRAVA) and bar region (ARGOS), we find a pattern speed of

$$\Omega = 39 \pm \sim 4\ \mathrm{km.s^{-1}.kpc^{-1}}$$

- Co-rotation is at 6.1 ± 0.5 kpc from the Galactic Center, making the Milky Way a typical fast rotator.

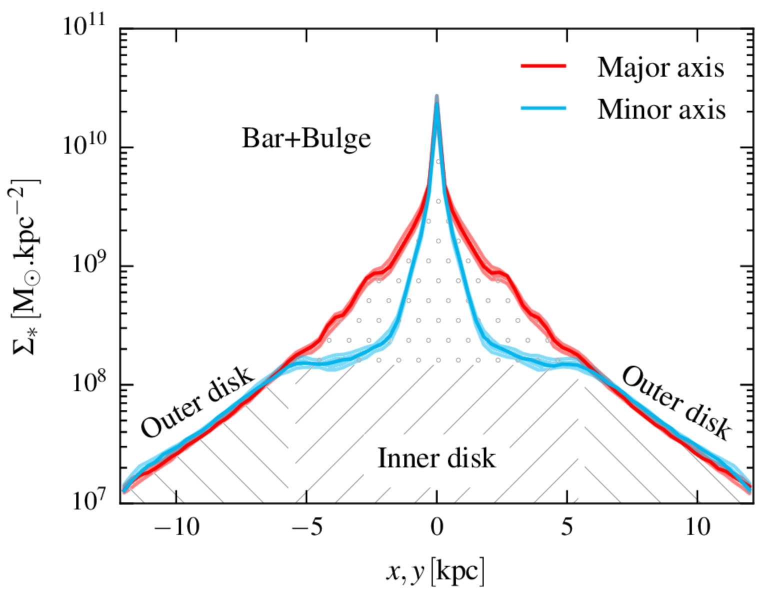


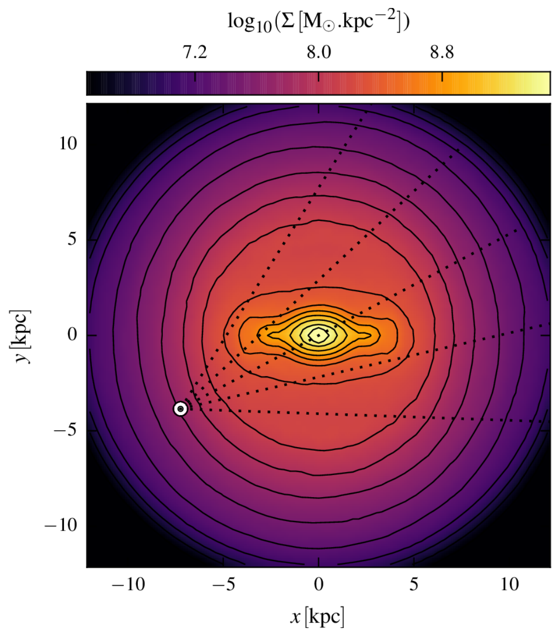
Stellar mass distribution

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

Typical error

~ 0.1 x 10^{10} $M_\odot$



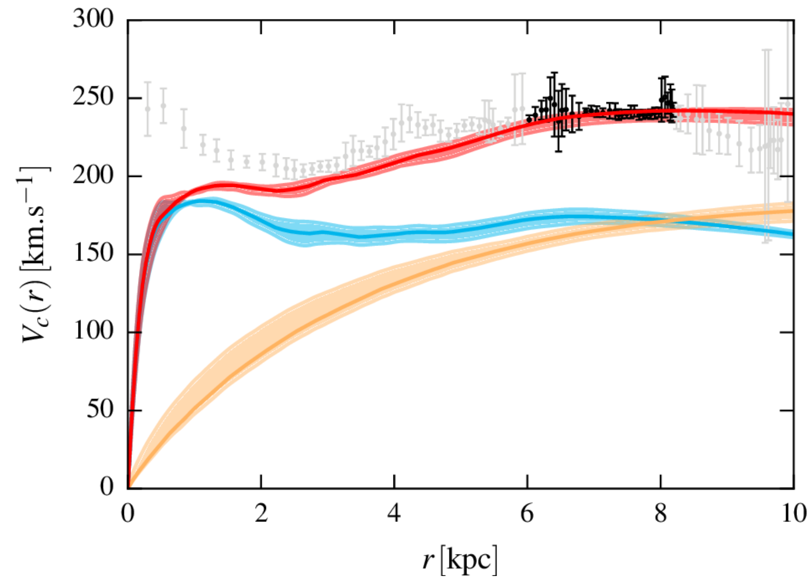


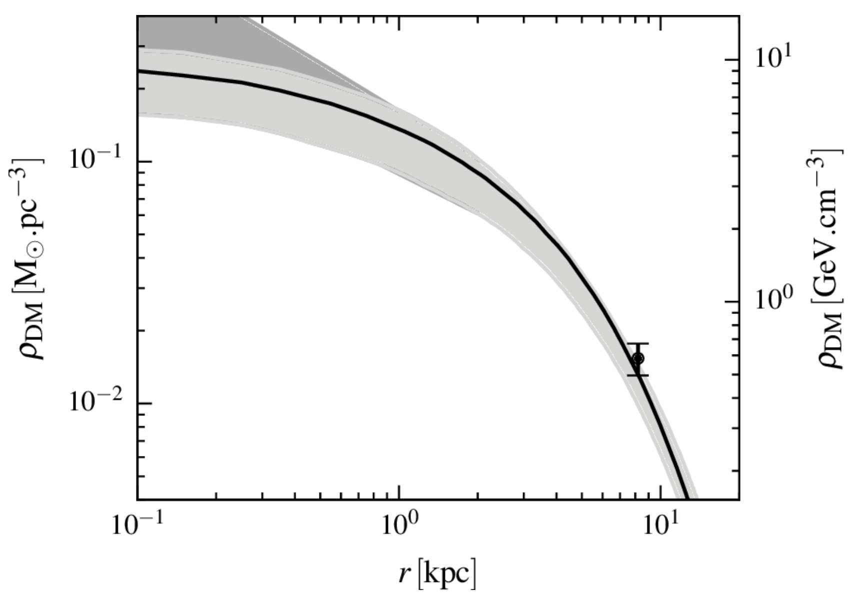
- In the bulge, we measure a total dynamical mass of **1.85 ± 0.05 x 10^{10} $M_\odot$**

Dark matter profile

- We find a rather **low dark matter** fraction is the bulge of **17 %**

  - For fitting the rotation curve between 6kpc and the Sun, the dark matter density needs to flatten to a **shallow cusp or core.**



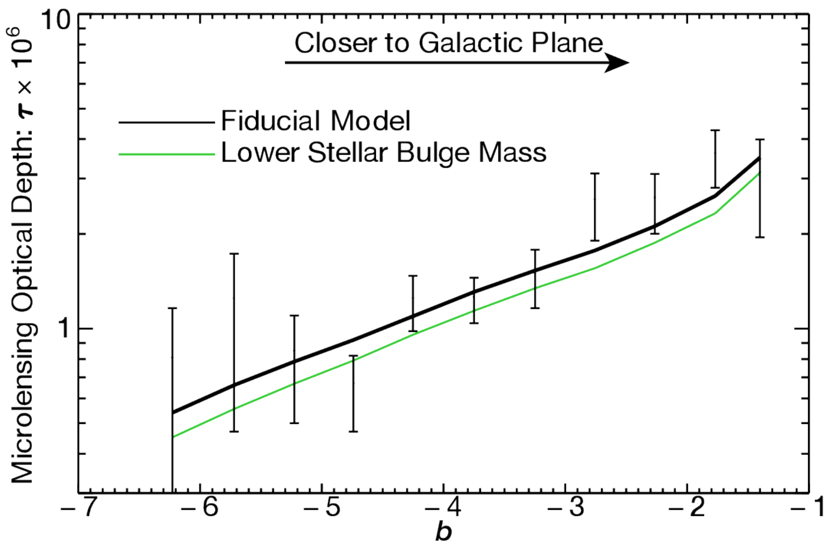


- Our model agrees well with the **local dark matter density** measured by Piffl+2014 from the RAVE kinematics

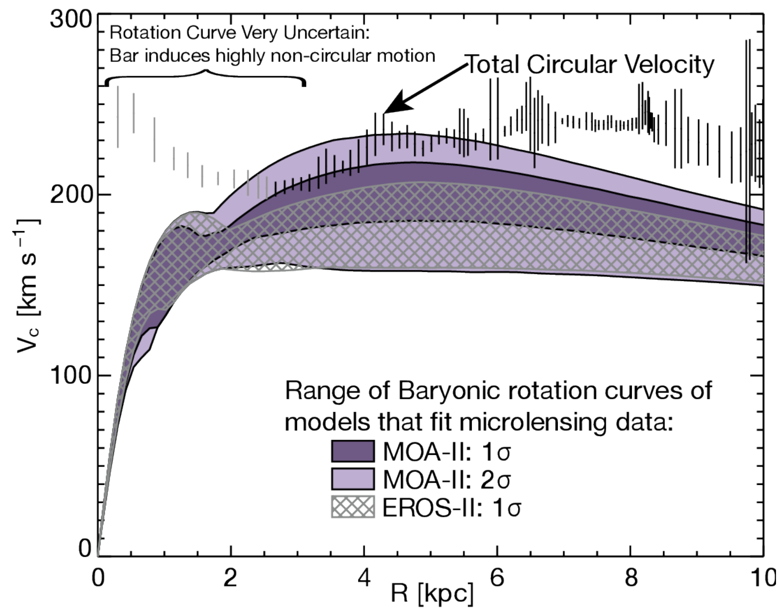
A Low Dark Matter Fraction and a Maximum Disk in the Inner Milky Way: Constraints from MOA-II Microlensing

Poster

We model the revised MOA-II + EROS-II microlensing data



The bulge optical depth indicates a **low dark matter fraction**

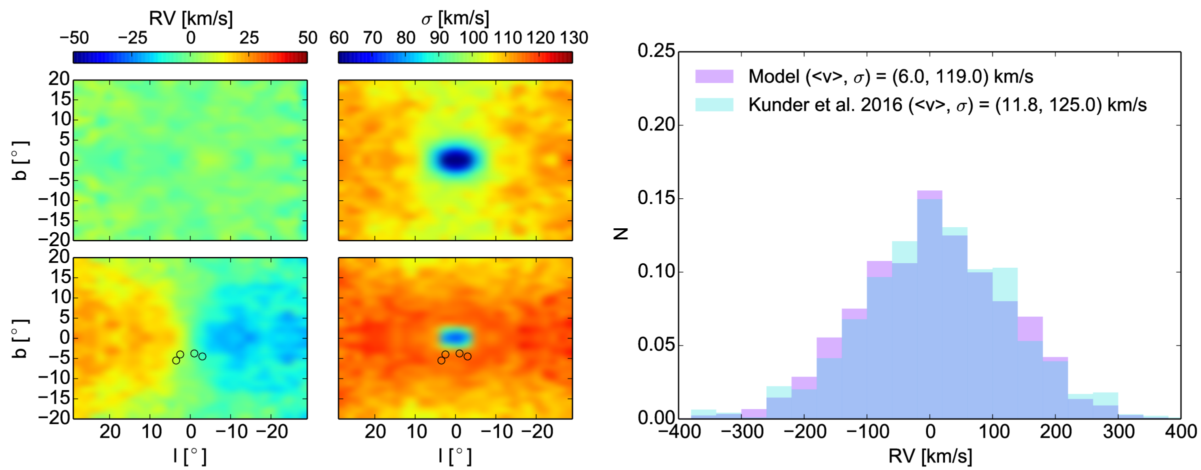


Consistency with the **rotation curve** shows a **maximum disk with maximality = 88% ± 7%**

Chris Wegg et al. (2016, MNRAS, 463, 557)

Are the metal-poor stars in the Galactic bulge part of the inner stellar halo?

We model the **stellar halo** and study its shape and kinematics after **bar formation**



Poster

The halo becomes slightly barred and acquires a slow rotation, in good agreement with recent measurements of RRLyrae in the bulge

→ Bulge RRLyrae could simply be the inner part of the stellar halo

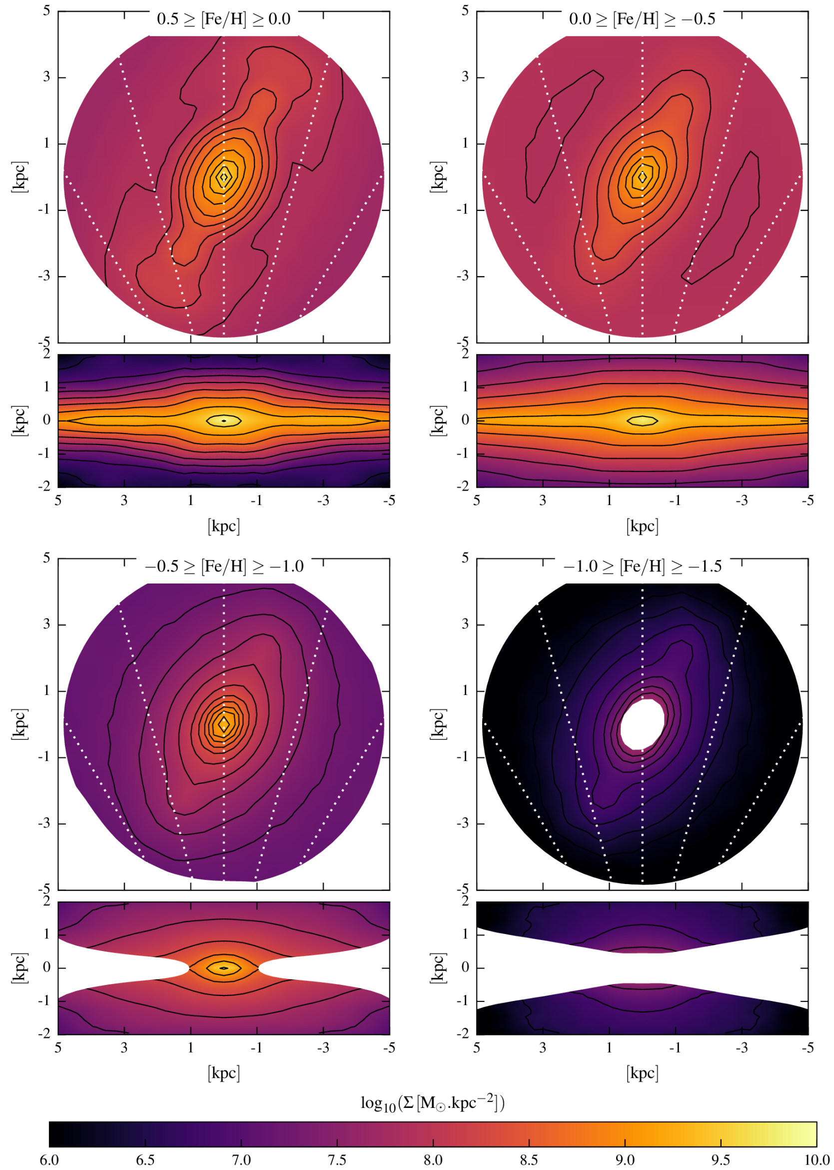
Angeles Pérez-Villegas et al. (accepted for publication in MNRASL)

Conclusion

- We made a large number of dynamical models of the Galaxy, fitting the RCGs density from **VVV, UKIDSS** and **2MASS** surveys and stellar kinematics from the **BRAVA**, **ARGOS** and **OGLE-II** surveys.

- We find:
  - An **intermediate bar pattern speed** of **39 ± ~4 $km.s^{-1}.kpc^{-1}$**
  - Kinematic evidence for a **nuclear bulge component** of about **2** x **10^9 $M_\odot$**
  - A bulge and bar mass of **1.9 ± ~0.1** x **10^{10} $M_\odot$**
  - An inner disk mass of **1.3 ± ~0.1** x **10^{10} $M_\odot$**
  - An indication that the **dark matter** halo density **flattens** in the central 2kpc to a **shallow cusp** or **core**.

What's next ?



M2M chemodynamical models !

- We extended the M2M method to an augmented phase-space including the metallicity of stars.
- We fit the dynamical model of the bar to the fractional density and stellar kinematics of the different metallicity components observed in ARGOS and APOGEE.

Preliminary