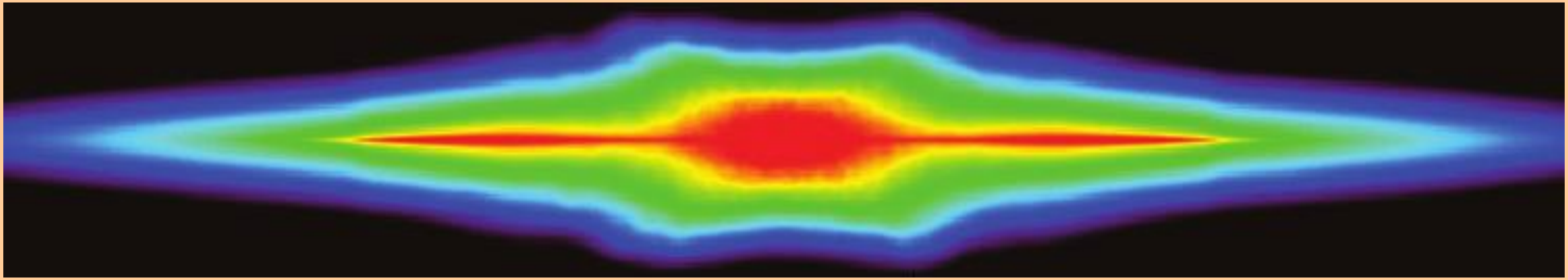
The Galactic Bar, the Kinematics of Nearby Stars in Gaia DR1, and Beyond

Ortwin Gerhard

Based on work with Matthieu Portail, Chris Wegg, Angeles Perez-Villegas (MPE), Melissa Ness (MPIA)

1. Overview: the barred Milky Way
2. Dynamical models for the Bulge-Bar: pattern speed, distribution of stellar and dark matter mass
3. Microlensing, IMF, Hercules
4. Chemo-Dynamics of different Bulge-Bar populations



The Milky Way Bar

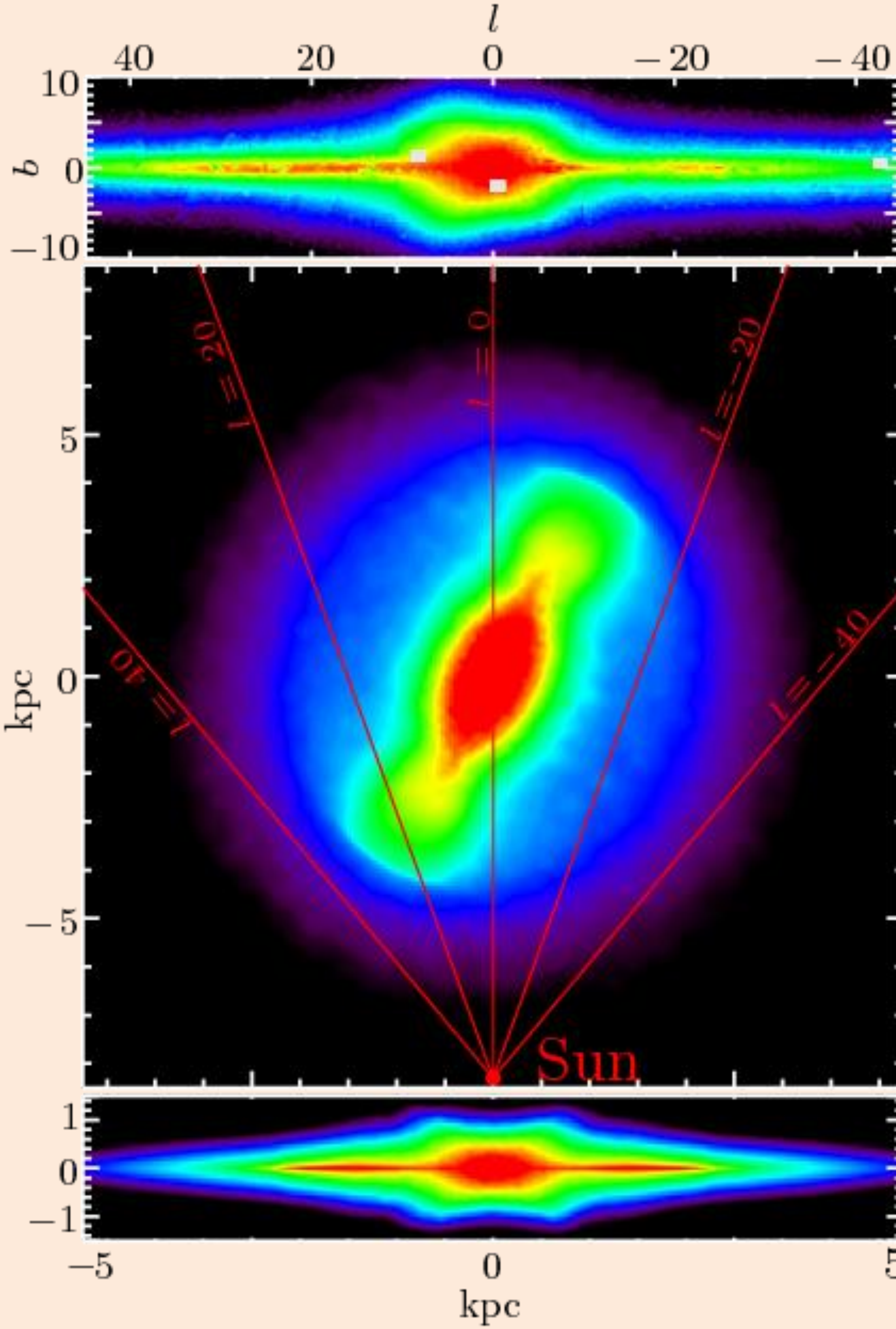
- Bulge looks like typical Box/Peanut bulge, as in external galaxies
- Shape naturally similar to N-body simulations where the central part buckles into a B/P bulge leaving a thinner long bar outside
- Based on RCG data from UKIDSS, VVV, 2MASS, with star-by-star extinction corrections

➢ B/P bulge and planar bar aligned, with bar angle 28-33 deg

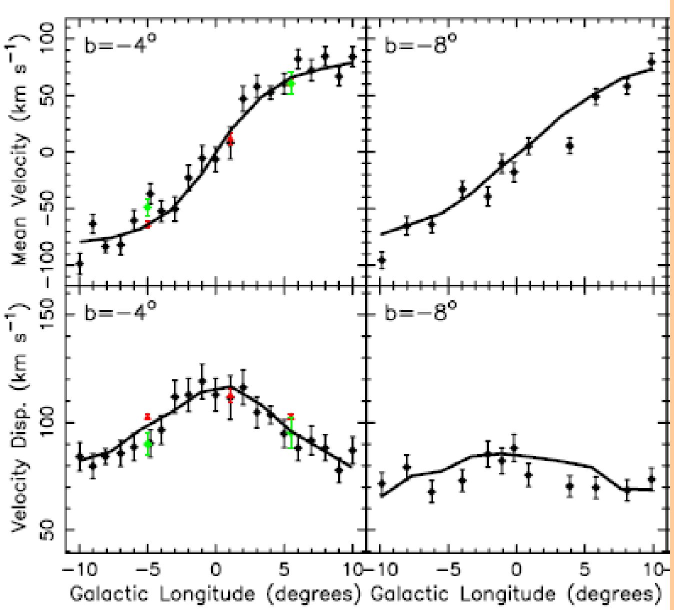
➢ Estimated bar length 5.0±0.2 kpc, then corotation radius ~ 6.0 kpc

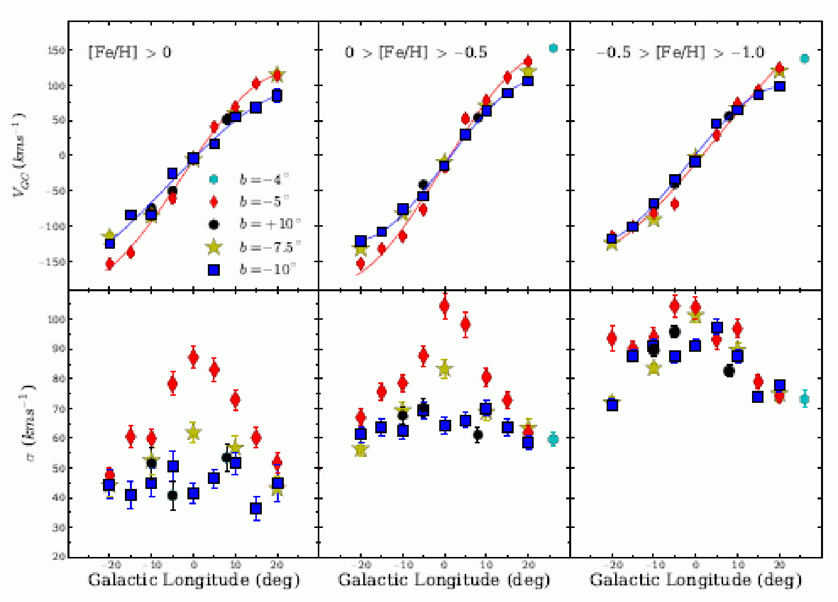
Shape of the bulge: Wegg & OG '13

Shape of long bar: Wegg, OG, Portail '15



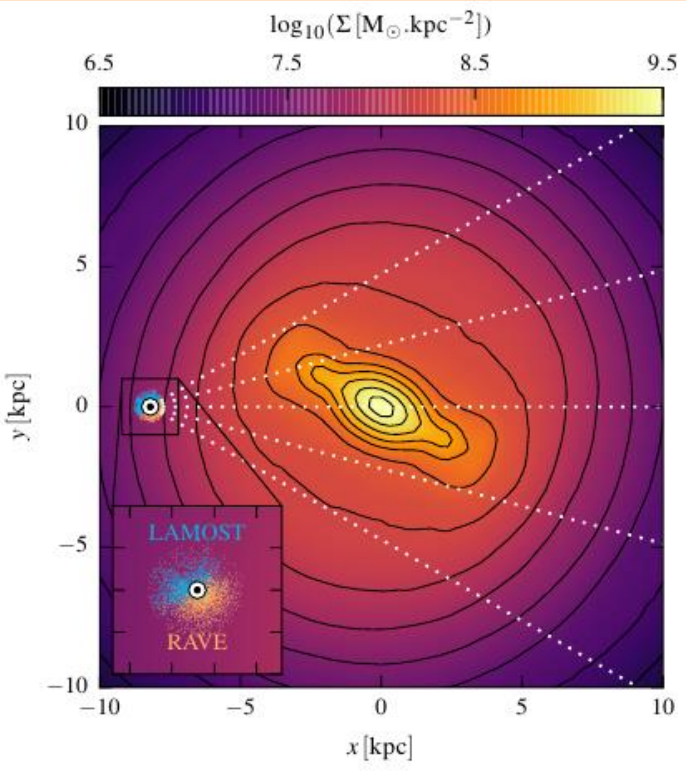
Bulge Kinematics & Metallicity





- The BRAVA data for M-giant stars (L: Howard+’08, Kunder+’12) show nearly cylindrical rotation.
- The cylindrical rotation is well fit by a boxy bulge formed from the disk. Simulations including a preexisting bulge of 8% (~25%) of the *disk* (bulge) mass give sign. worse fit – most of the bulge made from the disk!? (L: Shen+’10)
- The near-cylindrical rotation is seen for all metallicities up to [Fe/H]~-1 in the ARGOS survey (R: Ness+’13). More metal-poor stars have higher dispersions. (also Babusiaux+’10, GIBS & GES surveys (Zoccali+’17, Rojas-Arriagada+’17).

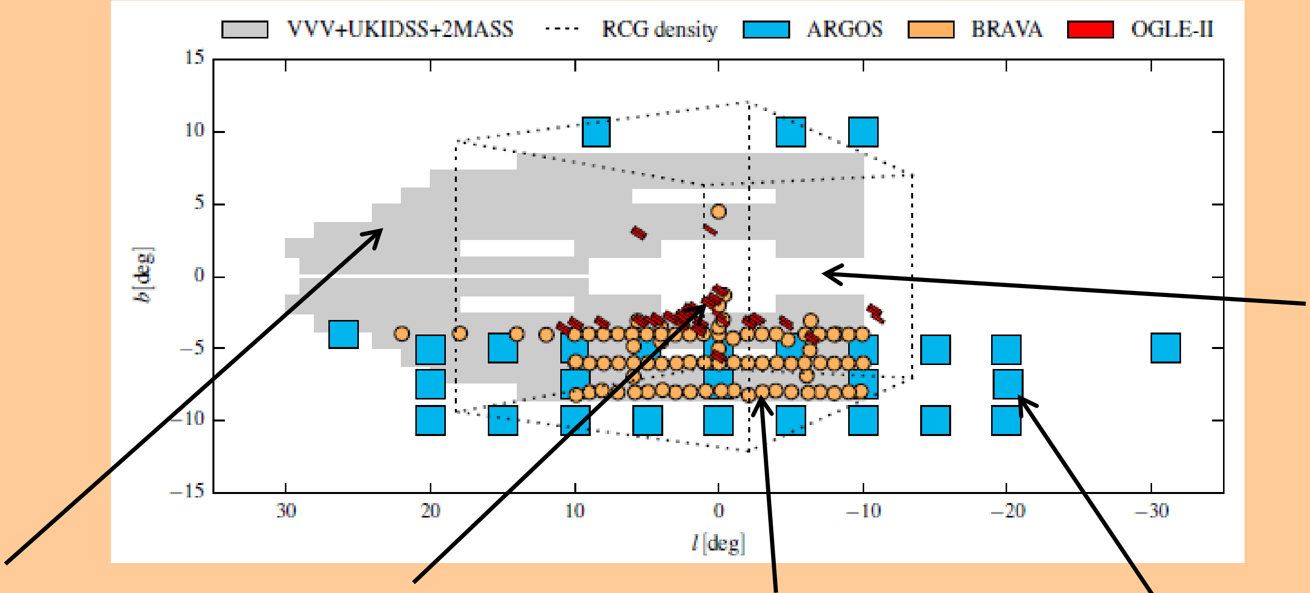
Overview: The Barred Milky Way



Sun's Distance to Gal. Centre:	R0 = 8.2 kpc (±0.1)
Circular velocity @ Sun	V0 = 238 km/s (+5,-15)
Solar motion wrt LSR	(11.1, 12.4, 7.2) km/s
	Schoenrich+2010
Exponential disk scale-length inwards from the Sun	Rd = 2.4 kpc (±0.5)
Length of bar	Rb = 5.0 kpc (± 0.2)
	Wegg, OG, Portail 2015
Corotation radius	Rc = 6.1 kpc (±0.5)
Photom. bulge+bar	$M_{bb} = 1.9 \times 10^{10}$ Msun (± 0.1)
Inner disk (<5.3 kpc)	$M_{id} = 1.3 \times 10^{10}$ Msun (± 0.1)
	Portail, OG, Wegg, Ness 2017a
Inner B+B+ID stellar mass fraction	~65%
Bulge stellar mass fraction	~30%

More discussion on structural parameters: Bland-Hawthorn+OG 2016 ARAA

Data Constraints for Bulge/Bar Dynamics



+ rotation
Curve

3D density
of RCGs

Magnitude
Distributions

Proper motion
dispersion

Mean radial
velocities and
dispersion

Mean radial velocities
and dispersions as a
function of distance

These are (only) the data included by Portail, OG, Wegg, Ness 2017a

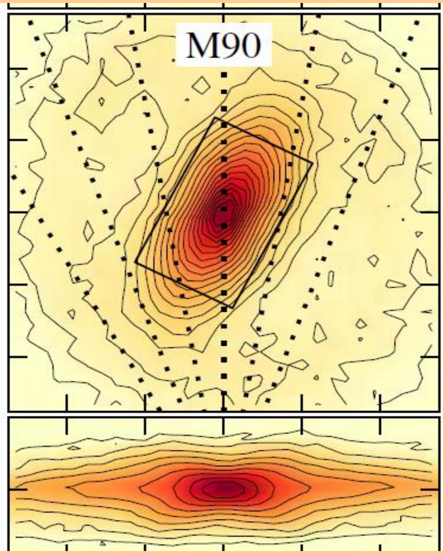
- Star counts can be described by a density model. But stars move along their orbits. Therefore we need to combine with velocities.
- Star counts and velocity data need to be described by a dynamical model.
- Even though not strictly true, need to start with equilibrium dynamical model.
- NB: importance of accurate data (e.g., density). As for DF|M ⇔ x,v, or ρ, σ, β

Made-to-Measure Particle Method

Need to fit many 1000s of observables (photometric, kinematics, population) in a rapidly rotating, complicated triaxial potential.

Only currently practical way is with **Made-to-Measure Particle (M2M) Models**

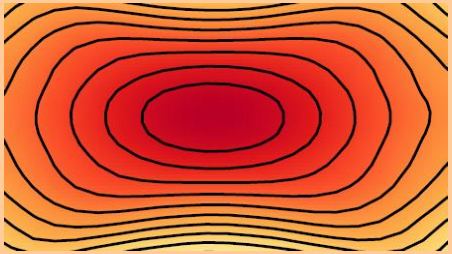
N-body model



"Observe"

Model observable

Real data



Compare

& quantify

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

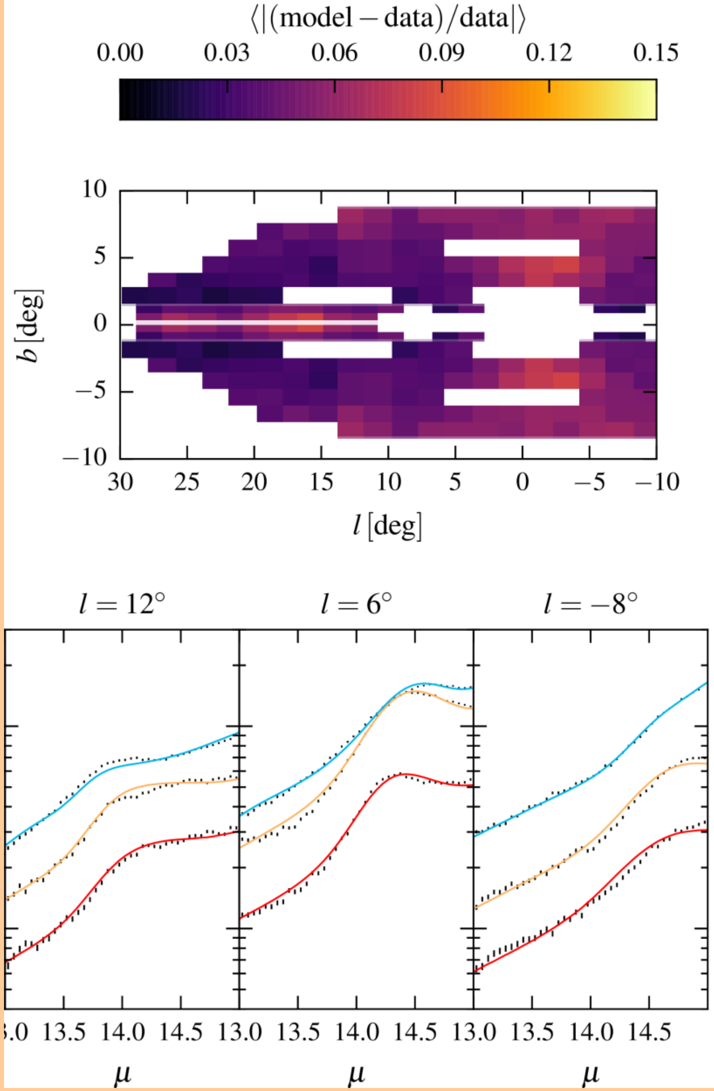
Profit function

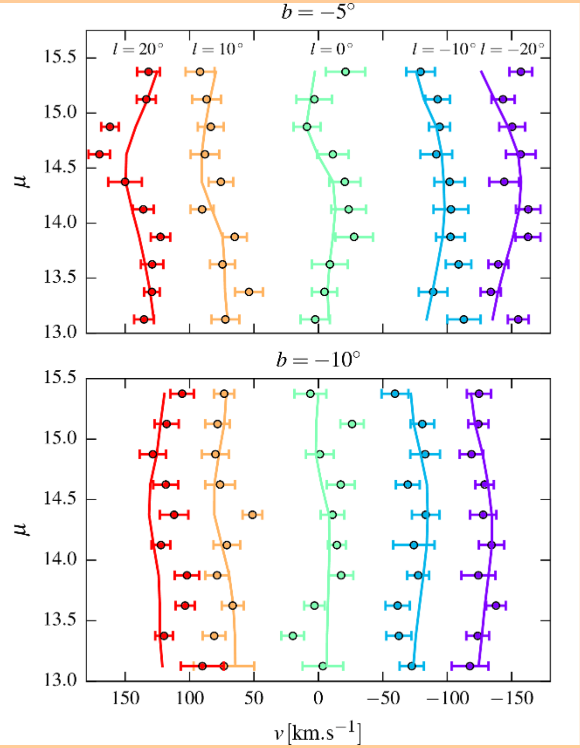
Change the particle weights

Evolve N-body model forward for dt

Syer & Tremaine (1996), De Lorenzi+(2007), Dehnen (2009), Portail+(2017a)

Some of the Data Fitted

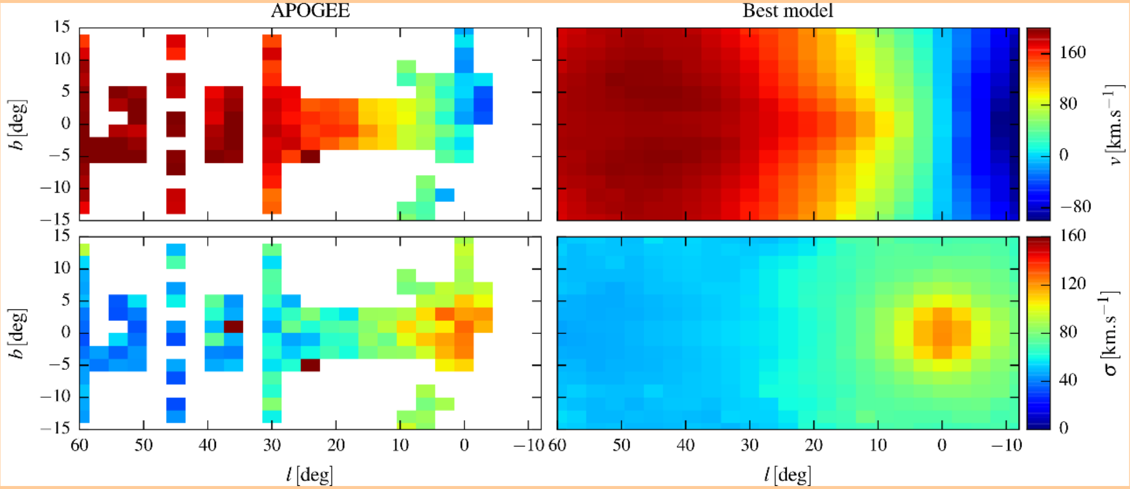




ARGOS: Observational selection criteria (Ness+’13) & mapping stars into distance bins using isochrones

Wavy structure of v(μ) shows streaming velocity field within the bar

APOGEE predicted

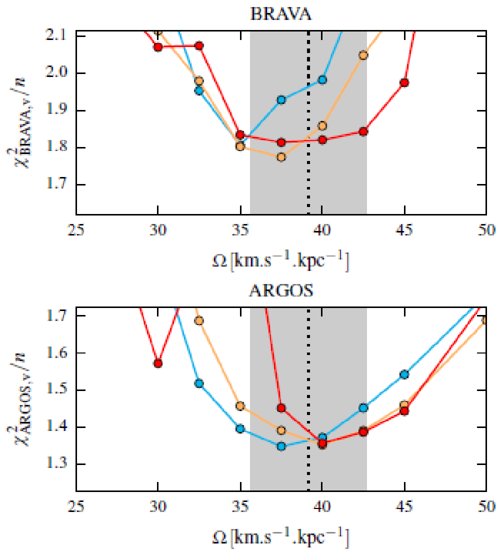


Portail, OG , Wegg, Ness 2017a

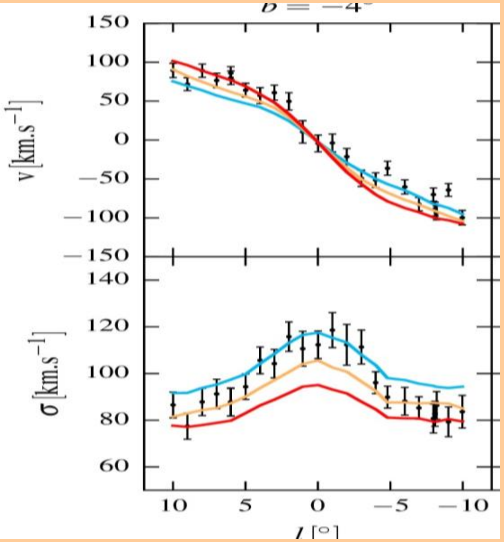
Bar Pattern Speed

Good fits to kinematic observables for 35-42.5 km/s/kpc, depending slightly on M/N_{RCG}. Joint $\chi 2$ for ARGOS & BRAVA & syst. error estimate gives best value of **pattern speed**

Ω_b =39±3.5 km/s/kpc



Ω_b influences bulge <v> and σ; whereas mass in bulge region influences only σ. Independent measurement from future long bar kinematics.

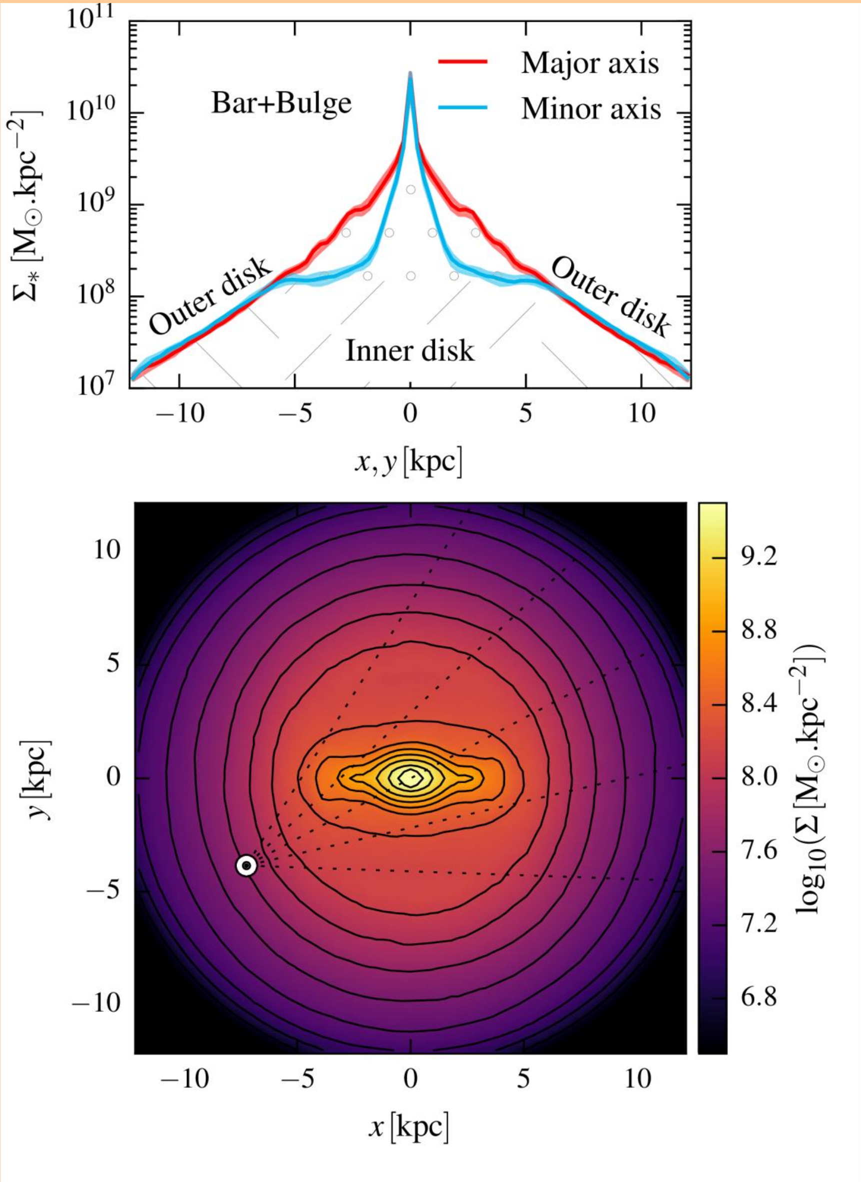


In good agreement with recent analysis of gas dynamics by Sormani+2015.

With **bar half-length** R_b=5.0±0.2 kpc find **corotation radius** R_{cr}=6.1±0.5 kpc, R=1.2±0.1

Portail, OG, Wegg, Ness, 2017a

Result from Model Fit: Stellar Mass Structure



Outer **disk surface density** meets bulge minor axis profile near end of bar; inner disk density nearly flat

The models measure **stellar masses** in the inner 5 kpc of

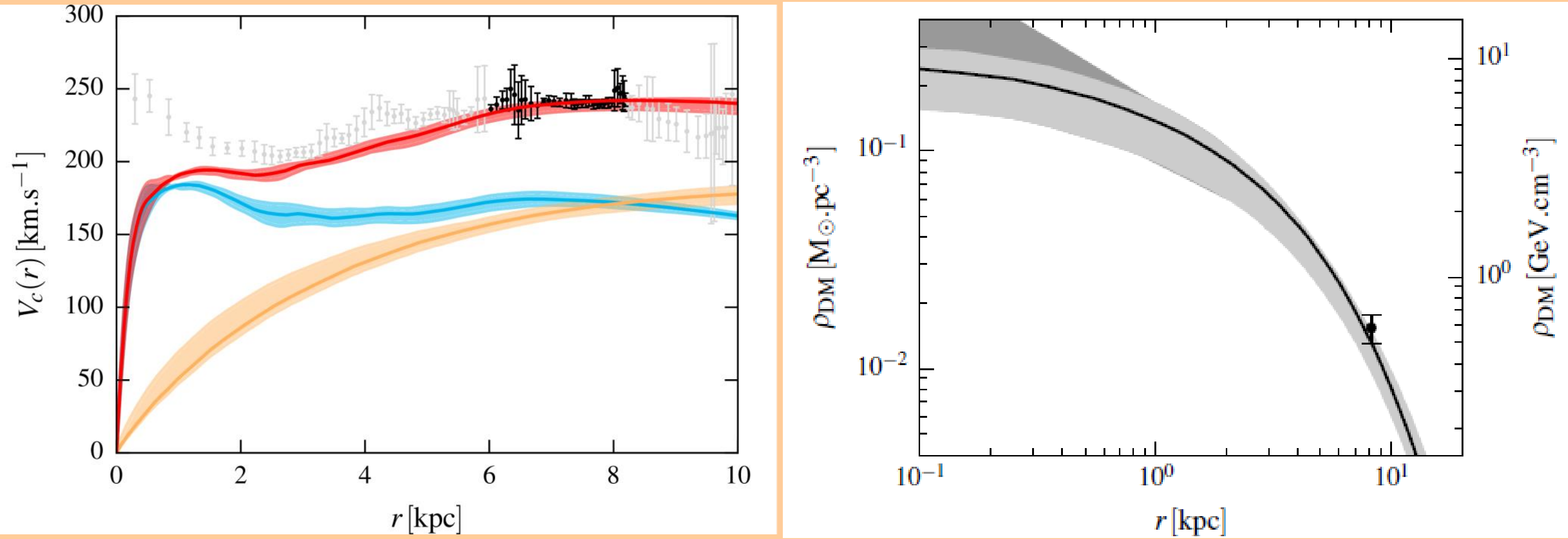
- **1.9×10^{10} $M_\odot$** in the **bulge and bar,**
- **1.3×10^{10} $M_\odot$** in the **inner disk,** with typical error **0.1×10^{10} $M_\odot$**
- **0.2×10^{10} $M_\odot$** in the **nuclear disk**

(~65% of total stellar mass)

The total **dynamical mass in the bulge** WG13 volume is **$1.85 \pm 0.05 \times 10^{10}$ $M_\odot$** (previously, 1.84±0.07, Portail+'15)

Portail, OG, Wegg, Ness 2017a, MNRAS

Dark Matter Density Profile



Portail, OG, Wegg, Ness, 2017a

- **First dynamical evidence that the dark matter profile of the MW must have a core or shallow cusp:** we know the total*, stellar, and hence the dark matter mass in the bulge, and that inside the radius of the Sun. The rotation curve wants it to be >~NFW just inside the Sun, but then it must turn over. *Mb=(1.85±0.05)×10^{10}M$_\odot$
- DM profile goes through local value from Piffl+'14 (not fitted), rises inwards, and flattens to a core or shallow cusp in the bulge region at ~2 kpc.
- Independently argued by Binney & Piffl '17, from halo model fitted to local data, extrapolated to center, and using constraints from microlensing τ.

IMF from Microlensing Time-Scales

- For individual lenses, ML time-scale is degenerate between lens mass, distance, transverse velocity.
- But we now have dynamical models providing the statistical distribution of distances and transverse velocities
- Also have ML time-scales of 3560 events from OGLE-III Wyrzykowski+’15

➢ Thus can adjust IMF, hence present-day stellar mass function, to match these time-scales using the model

- Assume a broken power-law IMF:

$$
\begin{aligned}
&dN \propto M^{-\alpha}\, dM \quad \text{where} \\
&\quad \alpha = \alpha_{\rm bd} \text{ for } 0.01 M_\odot \le M < 0.08 M_\odot \\
&\quad \alpha = \alpha_{\rm ms} \text{ for } 0.08 M_\odot \le M < 0.5 M_\odot \\
&\quad \alpha = 2.3 \text{ for } 0.5 M_\odot \le M < 100 M_\odot \ .
\end{aligned}
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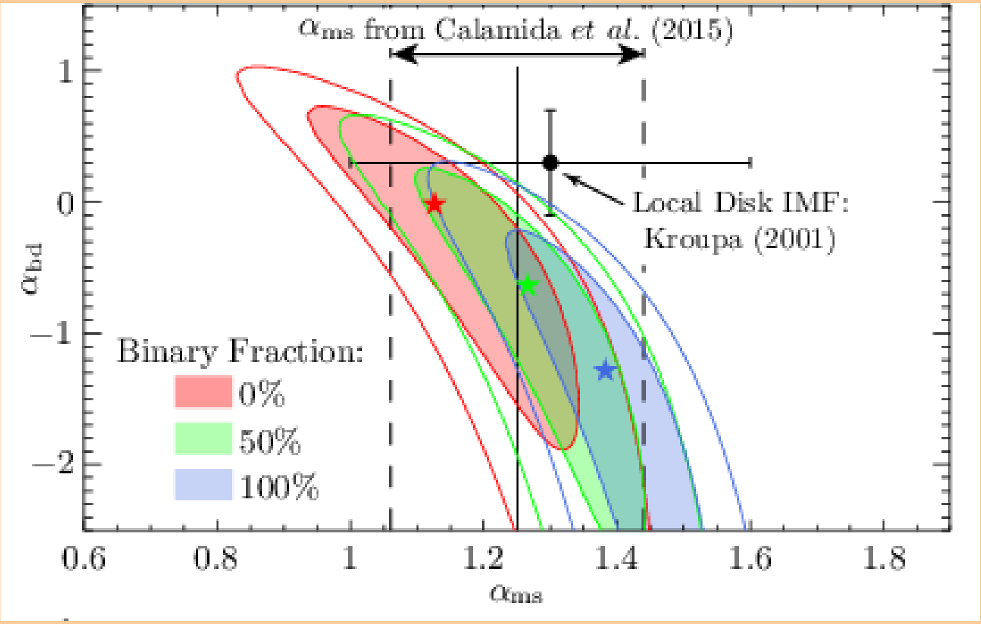

➢ Prefers near-Kroupa IMF very similar to local IMF, despite high-α, old, rapidly formed stars in the inner MW

➢ Also prefers a low brown dwarf fraction

Wegg et al. 2017 ApJL

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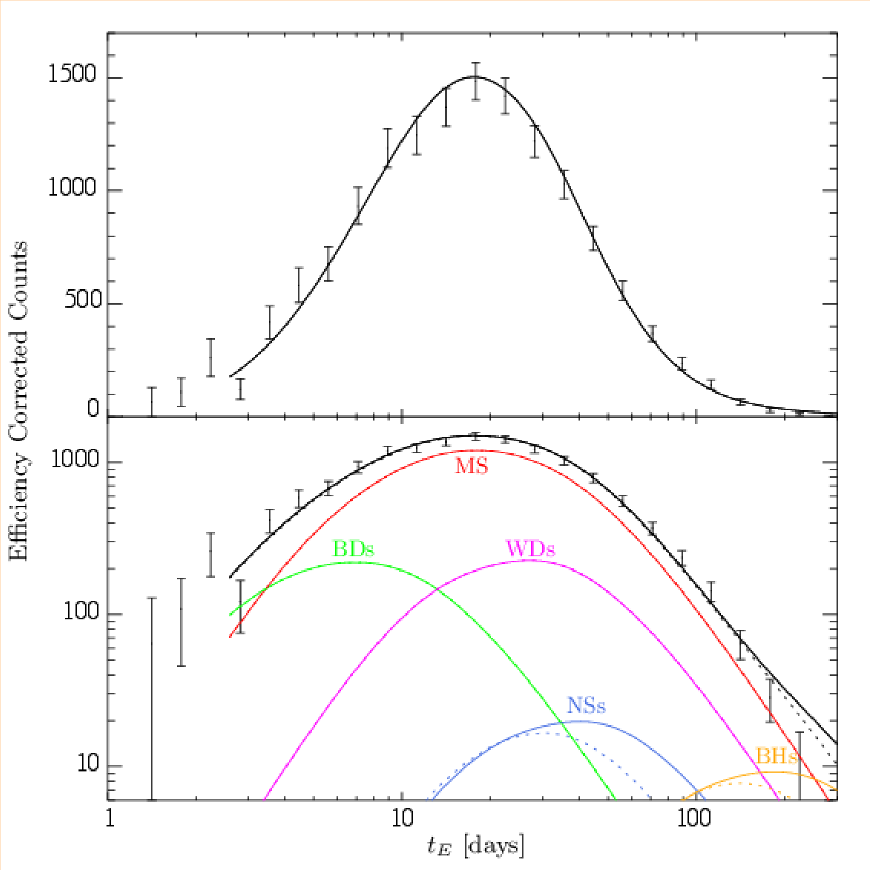

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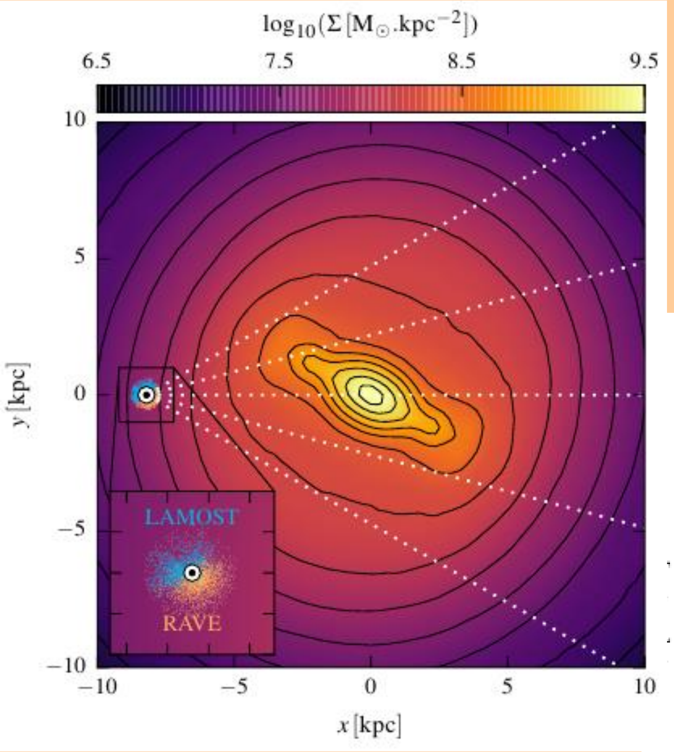
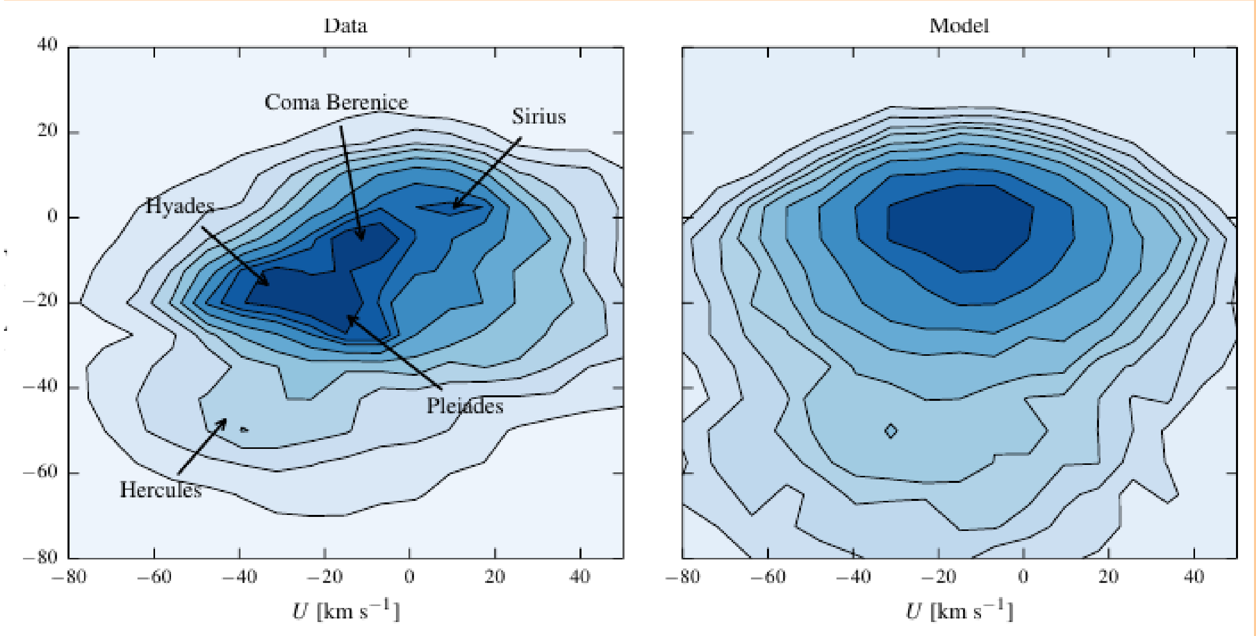
SNd: Revisiting the Hercules Stream

So far, the Hercules stream in the SNd was identified with OLR orbits near the Sun; this is incompatible with Ωb=40 km/s/kpc when the OLR is at 11.5 kpc (Dehnen'00, Antoja+'14,Monari+'16)

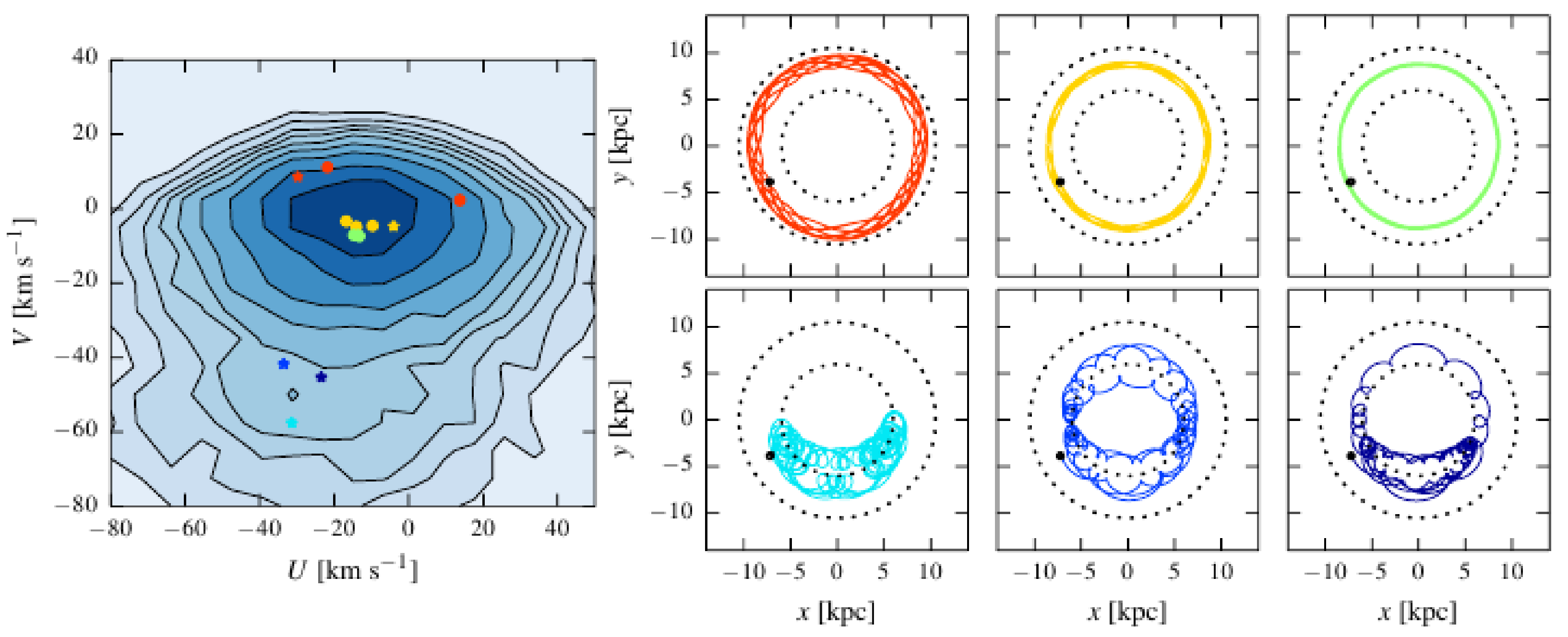
- Best model of P17a with increased resolution in the disk near Sun but no spiral arms
- Cross-matched with Gaia TGAS-RAVE-LAMOST
- Shows main bar-streaming component as well as low-V component consistent with (U,V) position of the Hercules stream





Perez-Villegas et al 2017

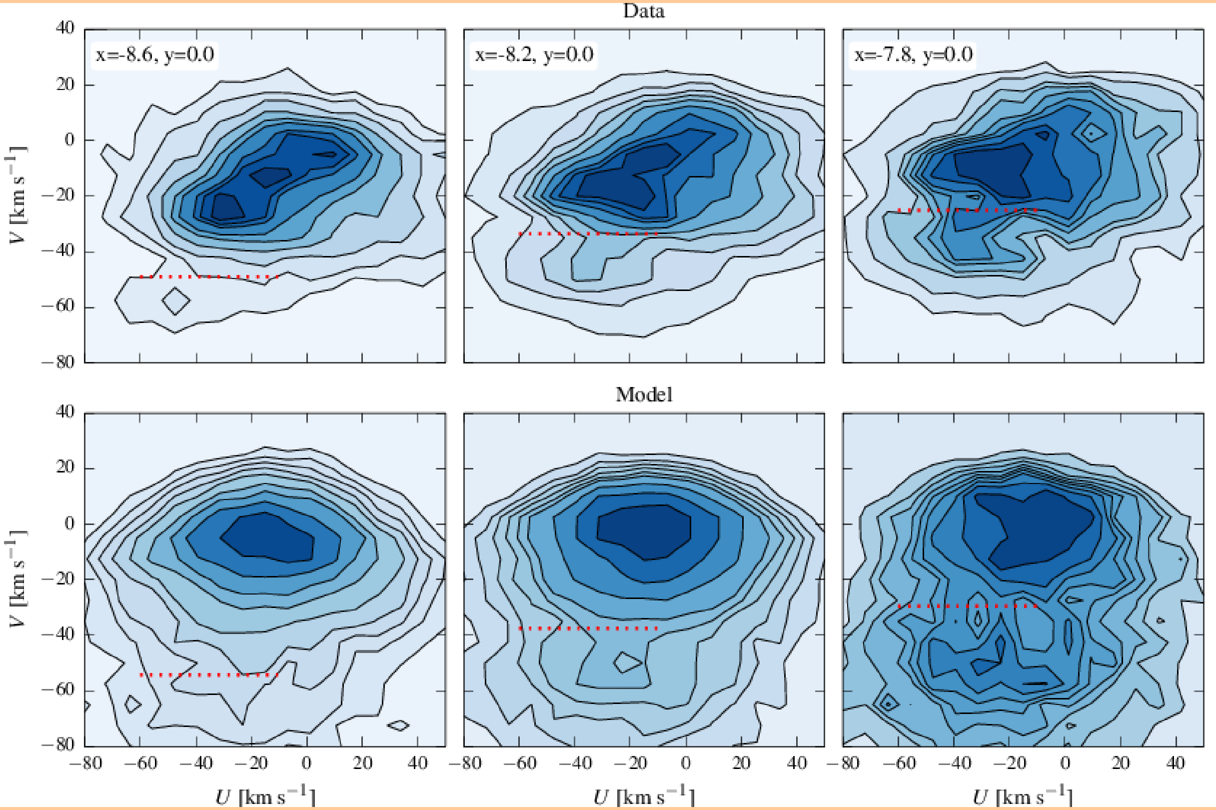
What Orbits Make Hercules in a Slow Bar

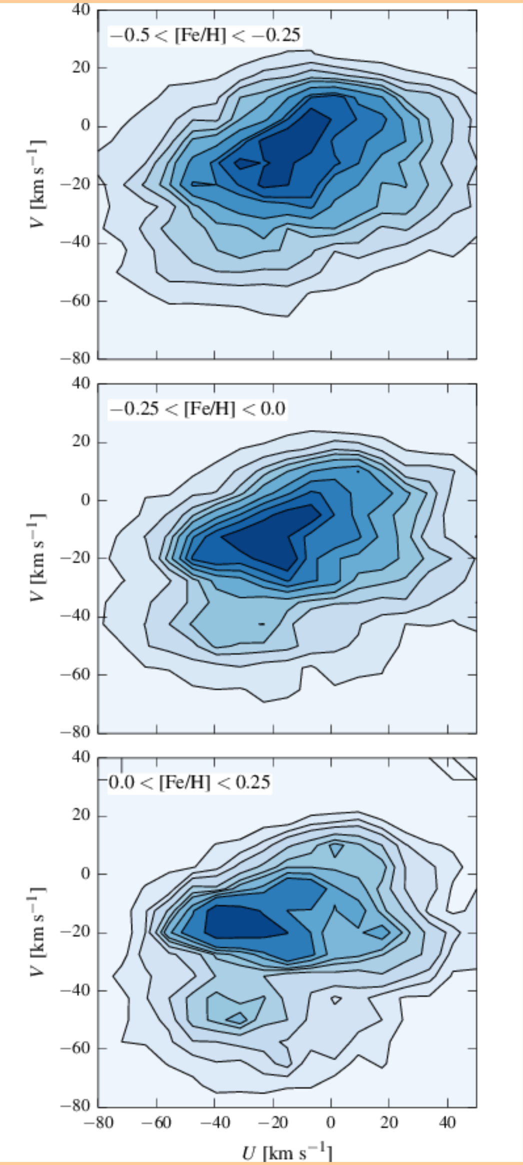


- These are orbits circulating the L4 and L5 Lagrange points. Good fraction go to both L4 and L5 i.e. are stochastic.
- They have long orbital periods in the rotating frame

“Hercules goes to see the Galactic bar”

Perez-Villegas et al 2017





This model predicts that

(i) Hercules stream fades outwards of the Sun

(ii) Could be more prominent in the metal-rich stars

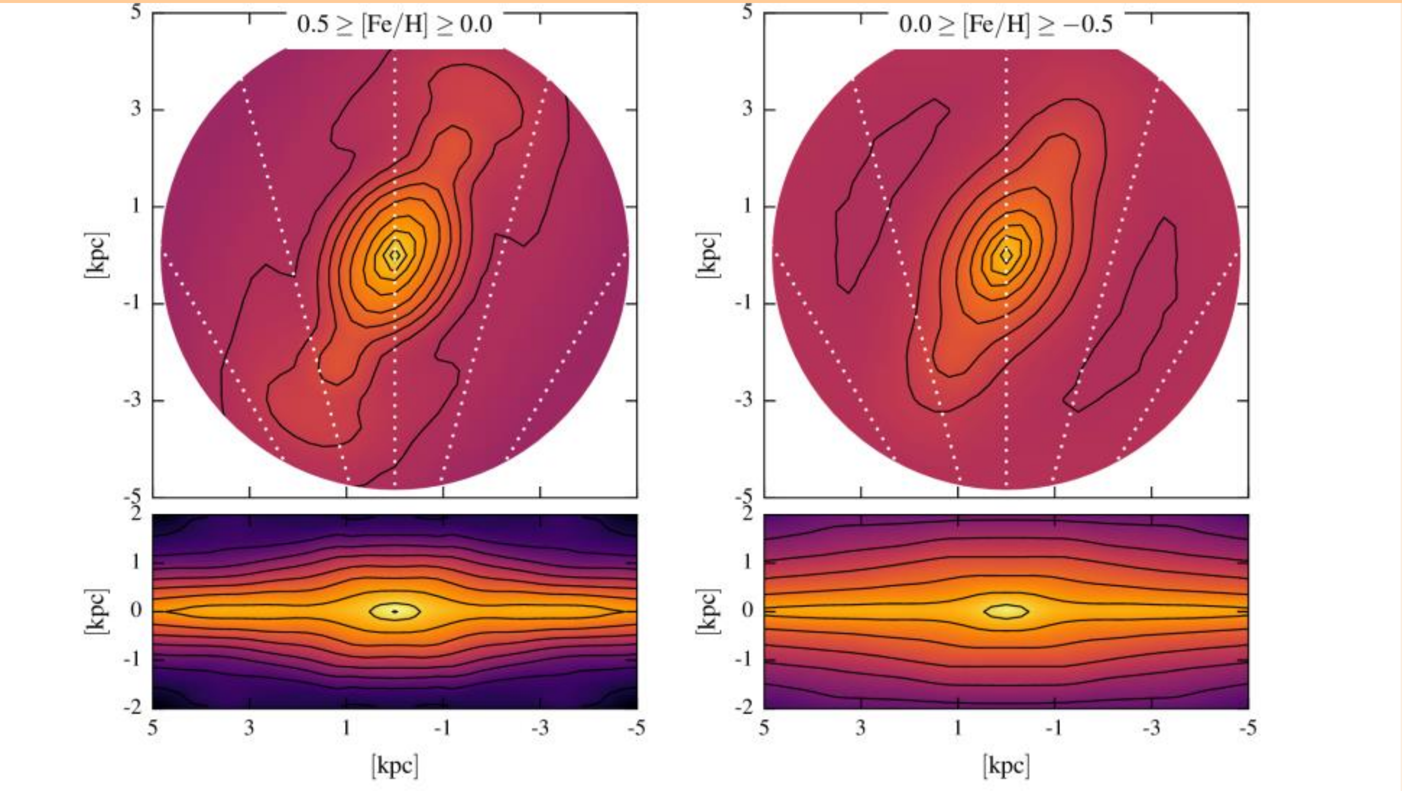
(iii) Even the structure of the 'gap' with radius is not bad (NB: neither potential nor DF were made to match the disk though)

Perez-Villegas et al 2017

Chemo-Dynamical Bulge Models

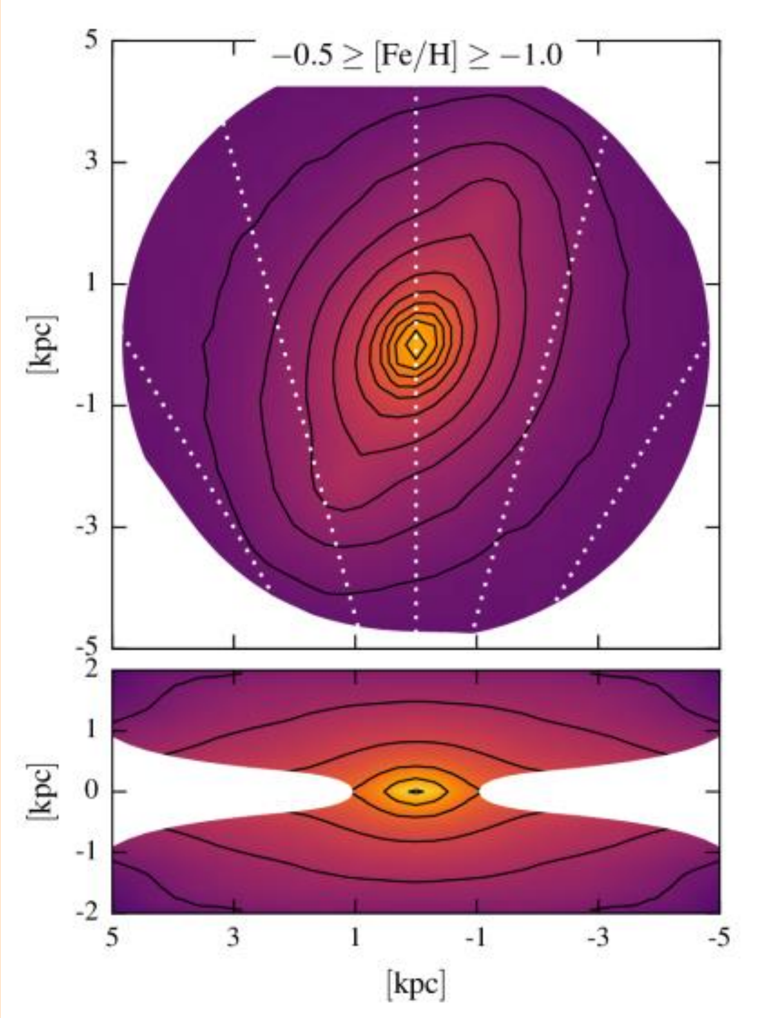
Portail et al 2017b

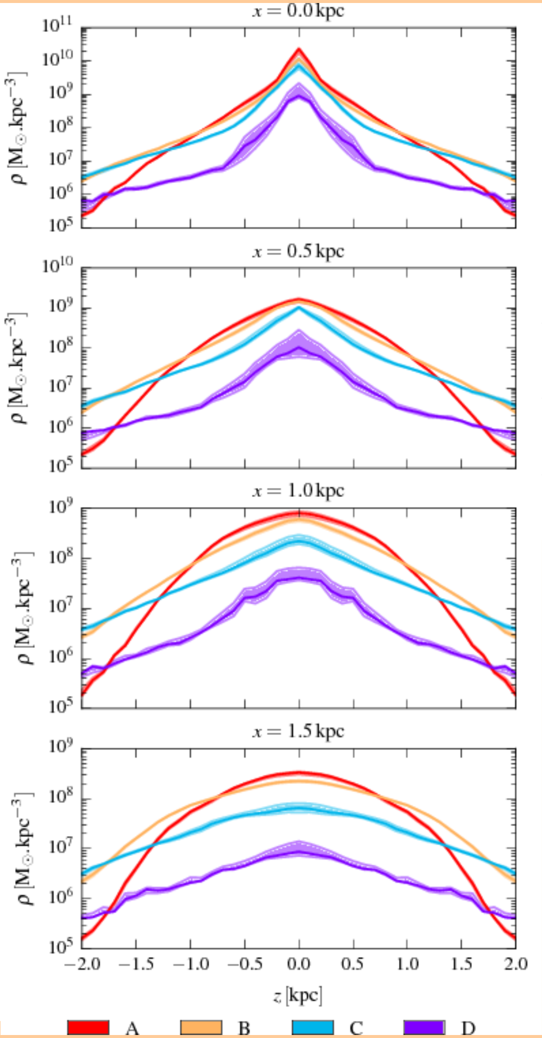
- M2M particles carry [**x, v,** f(M)]
- MDF f(M) parameterized as MGE with indiv. Gaussians adjusted to ARGOS components
- Particles projected into obsv space using isochrones and M-dependent selection fn
- Particle metallicity weights w_c adjusted by comparing with similar data in distance bins

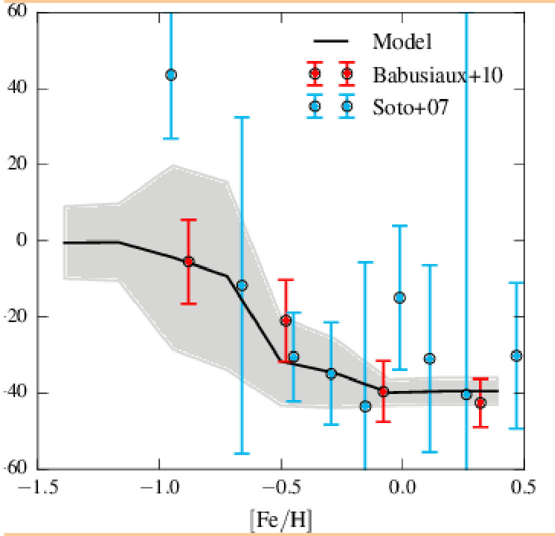


- The supersolar A bin has very pronounced bar ends. Contains younger stars?
- B + A contribute roughly equal number of bar-supporting orbits. Stars in B have higher v,σ and could come from further out in the initial unstable disk Ness+’13, di Matteo+’14

The Intermediate-Metal-Poor Bin C







Portail et al 2017b

- For x>1 kpc, bin-C stars are a thick disk bar with hz=500pc. For x<1 kpc, addl dense compt also seen in even more metal-poor stars. Could be bar-intrinsic, due to deep potential, or due to small classical bulge, or stellar halo.
- Together with A,B it reproduces the vertex deviations in the bulge.

Conclusions

- We live in a barred galaxy with a predominant B/P bulge. The bar region contains 2/3 of the MW's stellar mass.
- Nearby rotation curve and low DM fraction in the bulge imply that the MW's DM halo has a ~2 kpc core
- The pattern speed from bulge/bar data (Ω_b =39±3.5 km/s/kpc) puts the OLR at ~11 kpc. In this framework, the Hercules stream is from stars orbiting the bar's Lagrange points
- The bulge/inner disk IMF statistically inferred from microlensing time-scales is near-Kroupa, indistinguishable from the local disk IMF, despite the bulge formed on α-enhanced timescales
- The bulge/bar stellar populations broken up in metallicity bins have different orbit distributions. Find a strong metal-rich bar, a thick disk bar, and a dense central component in metal-poor stars with unclear origin