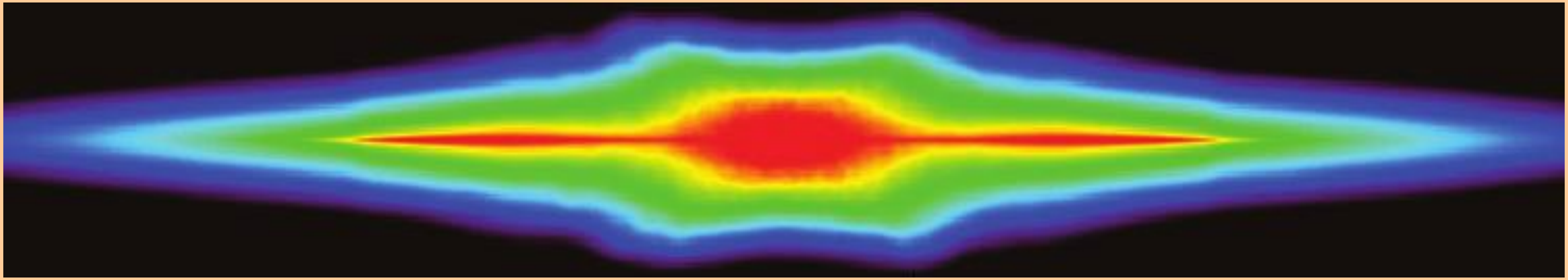
Dynamics of the MW bulge. A new 3D view from VIRAC and Gaia proper motions

Ortwin Gerhard

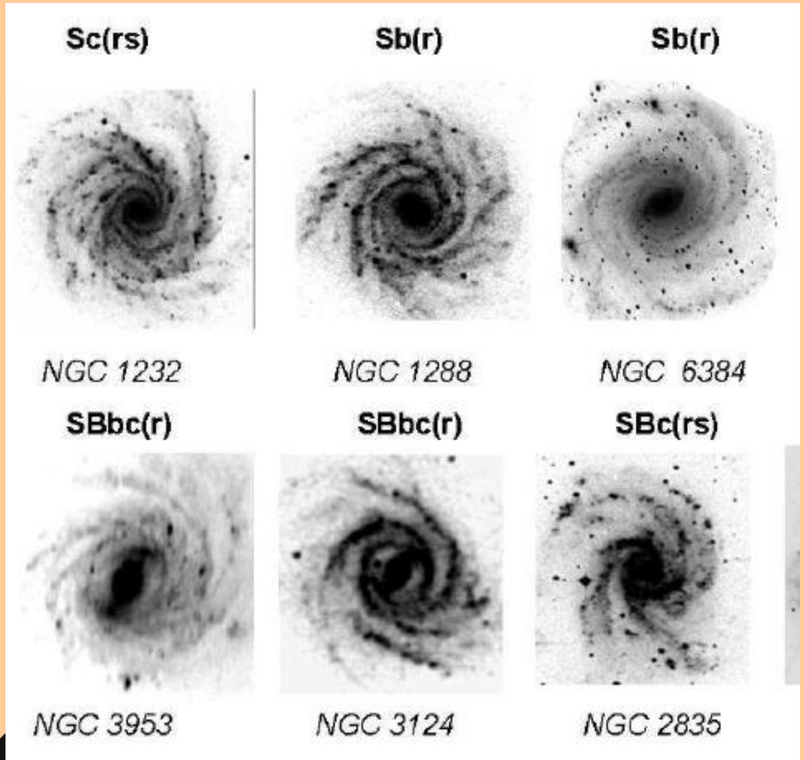
Max-Planck Institute for Extraterrestrial Physics, Garching

With J.Clarke, M.Portail, L.Smith, C.Wegg

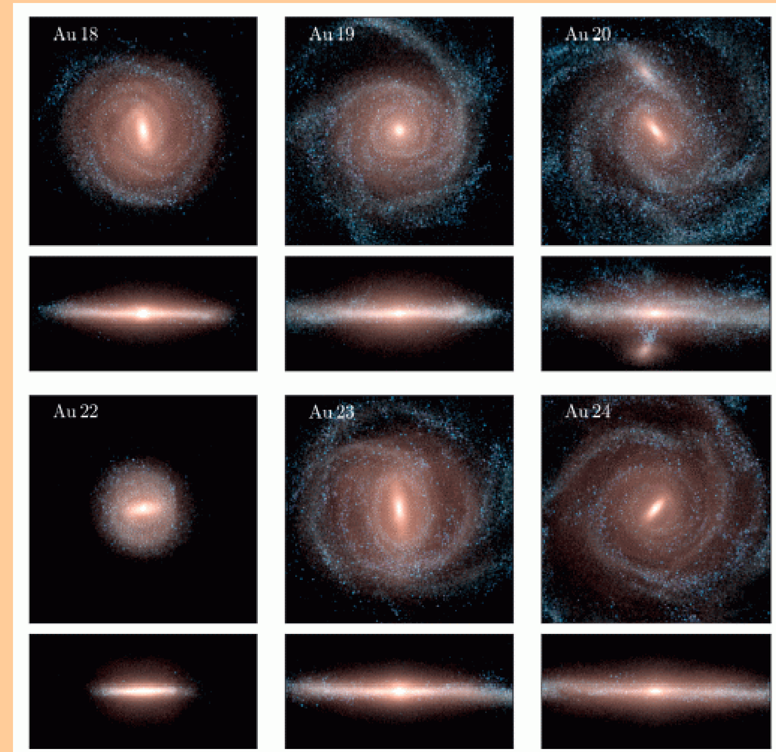
1. The goals
2. Bulge and bar structure from RCG star count tomography
3. Dynamical models from star counts and radial velocities
   - Cyl. Rotation; dynamical & stellar mass, dark matter, pattern speed
4. New 3D view from VIRAC/Gaia proper motions
   - Integr. PM maps, bulge rotation, split red clump kins., bar corotation
5. Conclusions and outlook



The Goals: Understanding Milky Way Structure: Understanding Disk Galaxy Evolution



Milky Way Analogs, Efremov '11



Auriga Project: Grand+'17ab:

Recent cosmological simulations of realistic bulge-bar-disk galaxies

Gas dynamics , star formation, stellar physics, energy return to the ISM, collisionless dynamics of stars and DM

What About the Milky Way Bulge?

MW bulge = mostly a bar (inner 3D parts of the MW bar). Therefore makes sense to discuss the bulge and bar together.

They are important to understand because the bulge/bar region contains ~2/3 of the stellar mass and because the bar interacts with the disk.

- What is its dynamical structure and mass of the bulge/bar?
- Is there a (small) classical bulge, a halo-bulge?
- Dark matter in the bulge?
- What are the pattern speed, and corotation radius of the bar?

- How does the bulge/bar interact with the disk and how does it influence the disk dynamics?

- How and when did the bulge/bar form?
- When did the bulge stars form?
- What is the chemo-dynamical structure of the bulge and bar?

2. Bulge/Bar Structure From RCG Star Count Tomography

- 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 star data from UKIDSS, VVV, 2MASS, with star-by-star extinction corrections

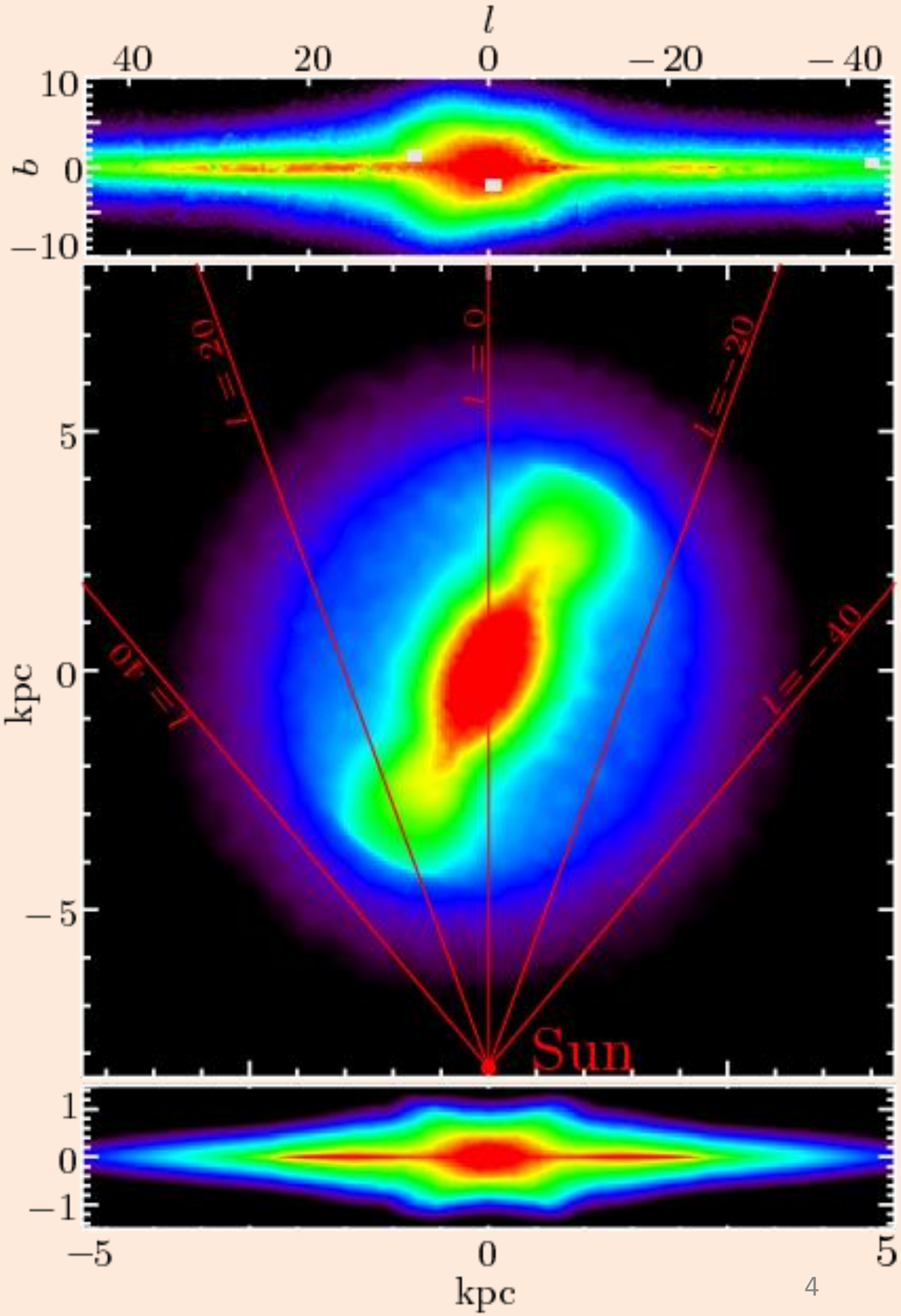
➢ B/P bulge and planar bar aligned, with bar angle 28-33 deg

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

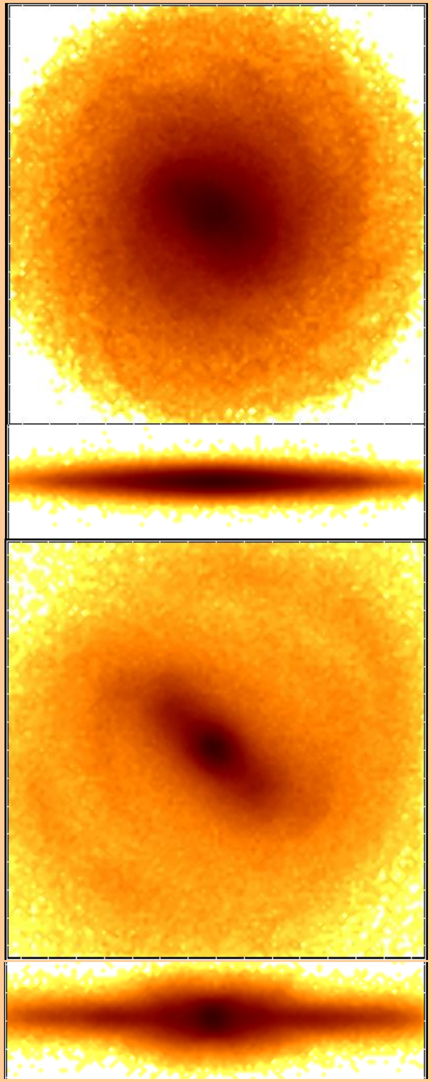
Shape of the bulge: Wegg & OG '13

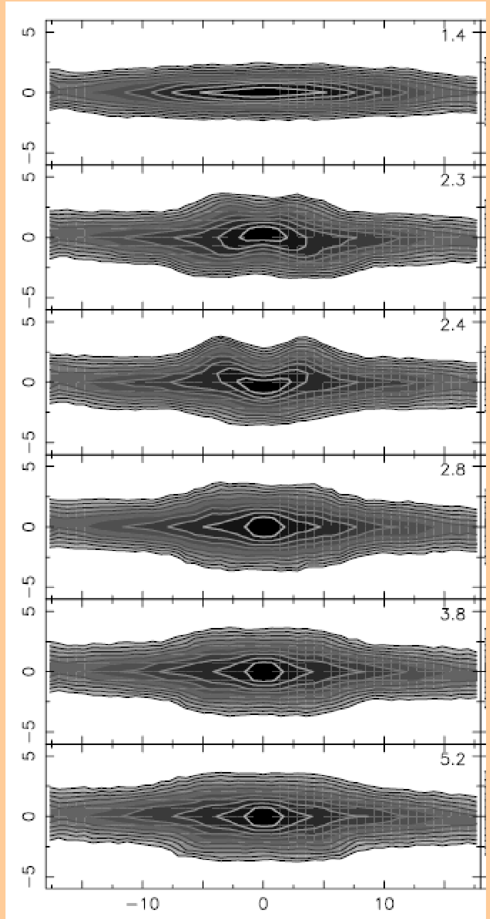
Shape of long bar: Wegg, OG, Portail '15

Weiland+'94, Stanek+'94, Binney+'97, Hammersley +'00, Cabrera-Lavers+07, Rattenbury+'07, Nataf +'10, McWilliam+Zoccali+'10, Saito+'11, Nataf+'15

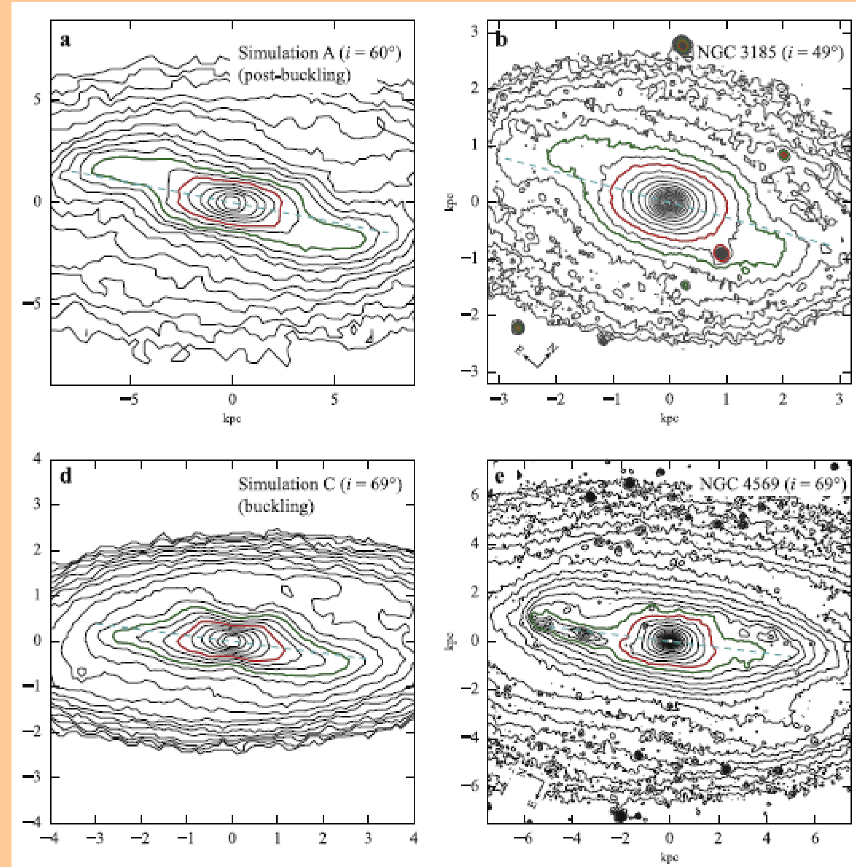


Buckling instability and box/peanut bulges





Martinez-Valpuesta+'06



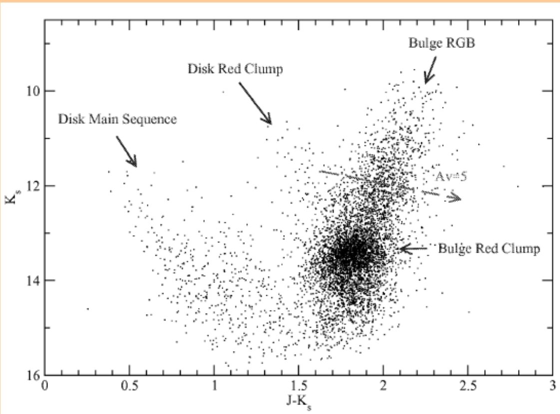
Erwin+Debattista'16

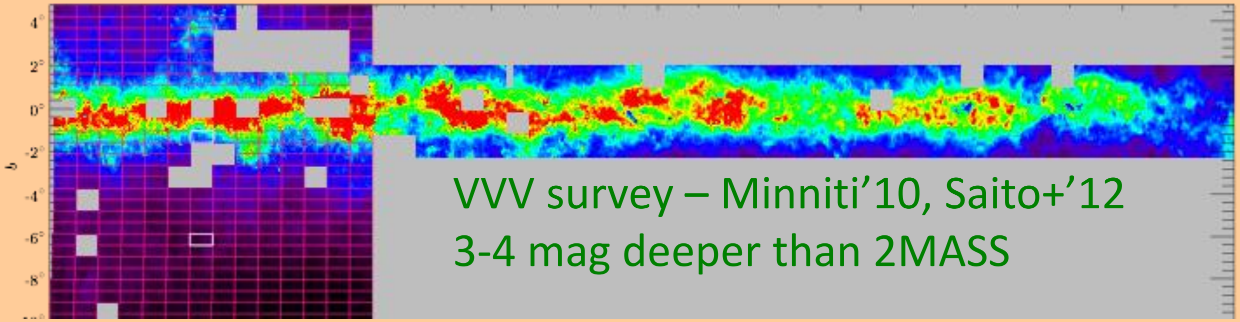
L: N-body model for bar-unstable disk galaxy evolves through buckling instability.

R: galaxy with trapezoidal isophotes found in the short-lived buckling stage

Hohl 1971, Sellwood '85, '89, Combes+'90, Raha+91, Debattista+'00,'06, Athanassoula+'02,'03

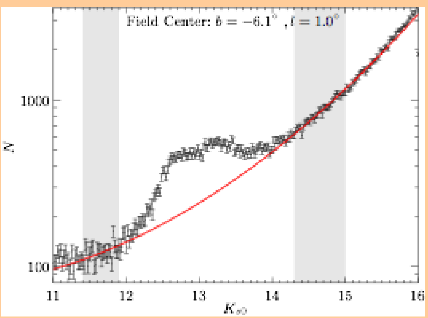
Red Clump Giant Distances & Bulge 3D Density

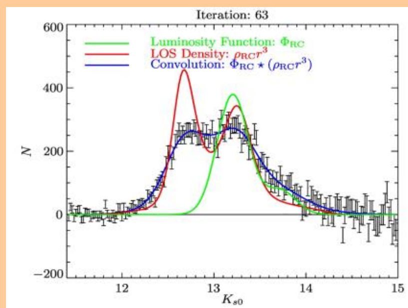


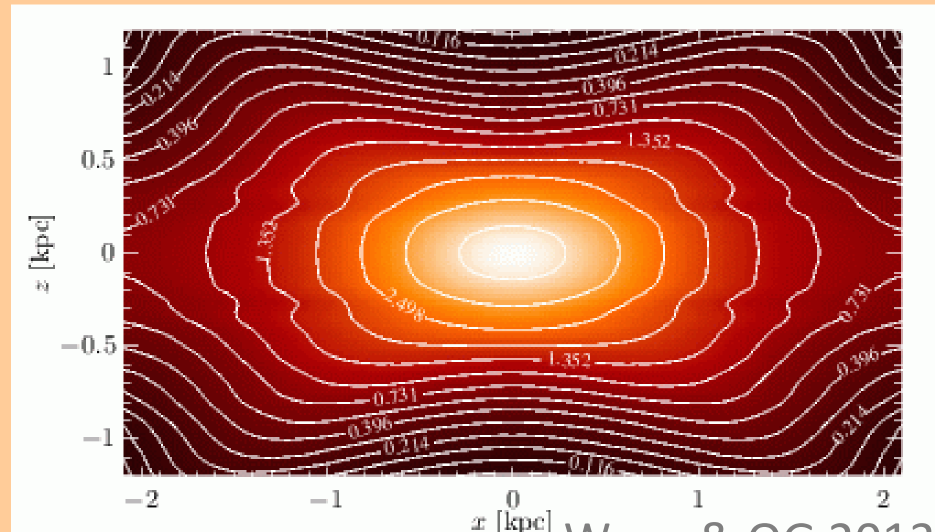


VVV survey – Minniti’10, Saito+’12
3-4 mag deeper than 2MASS

RCG as tracers since Stanek+’94







Wegg & OG 2013

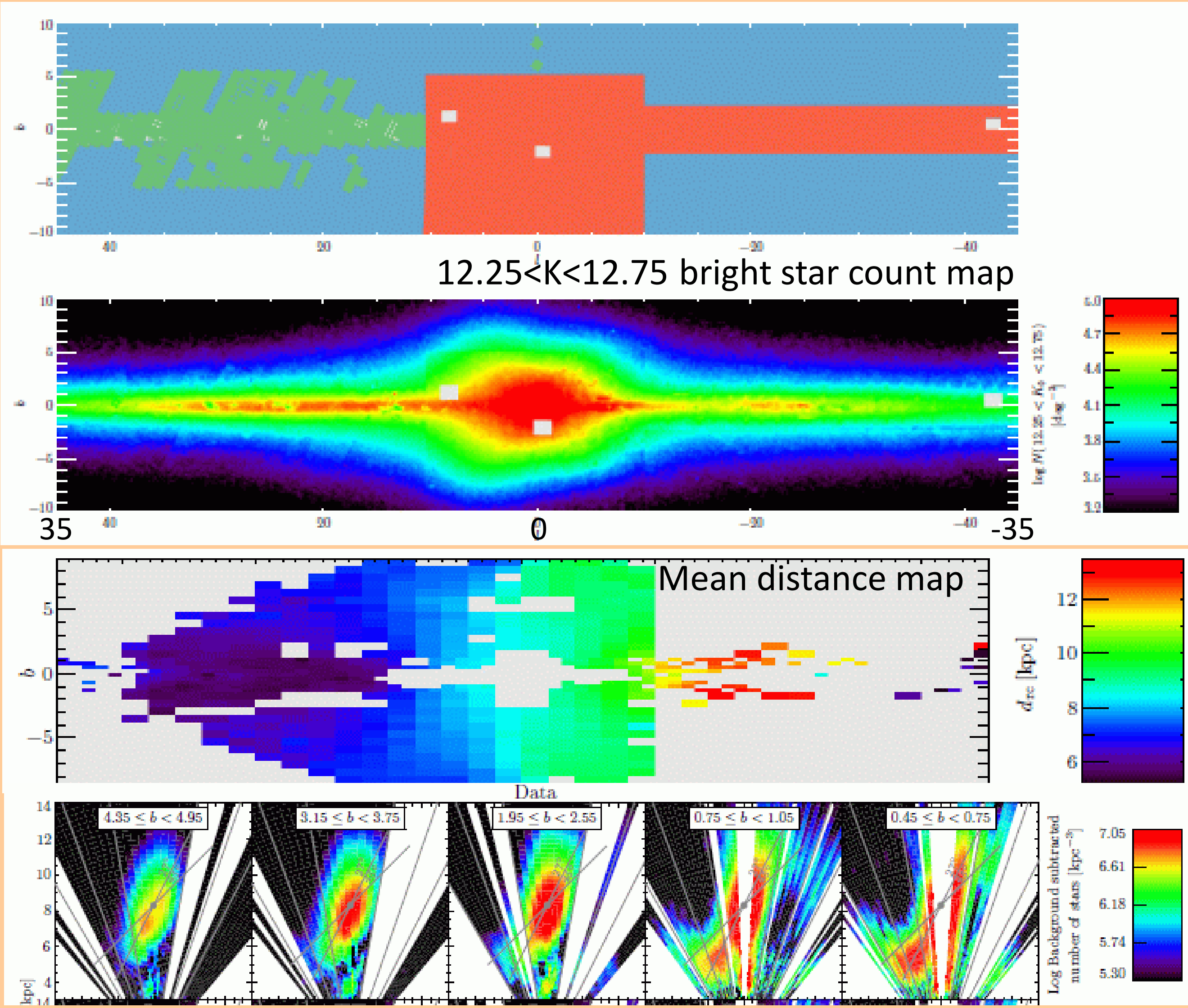
Split red clump: at b>5dg, two density maxima along the los (McWilliam+Zoccali’10, Nataf+’10, Saito+’11)

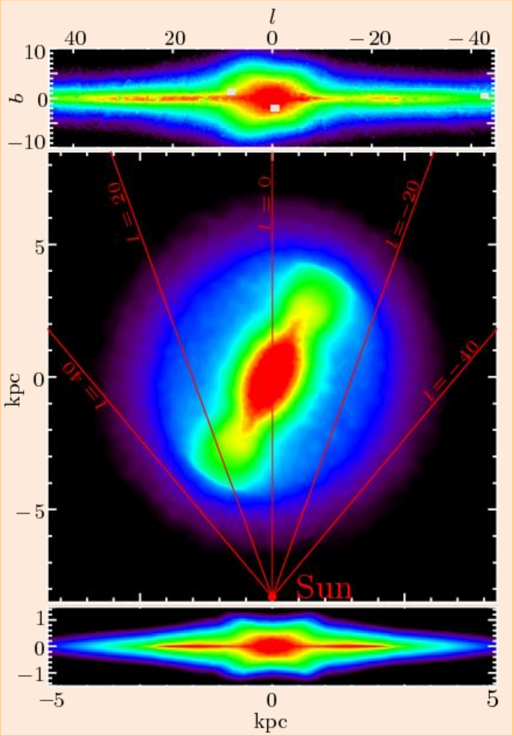
RCG: $\sigma(K_s)$~0.17, $\sigma(J-K_s)$~0.05, small spread because of age & metallicity (Salaris + Girardi ’02), tracer for [0.02,1.5] $Z_\odot$, ~90% of ARGOS sample (Ness+’13)

Density map from ~8 Mio RCG in 300 VVV fields in the bulge, |b|>1°. ~10% density error in most of the bulge. Extrapolated into crowded Galactic plane by Portail+’15

NIR Surveys: Inner Galaxy in K Star Counts

UKIDSS – VVV – 2MASS – GLIMPSE matched, extinction corrected, star-by-star

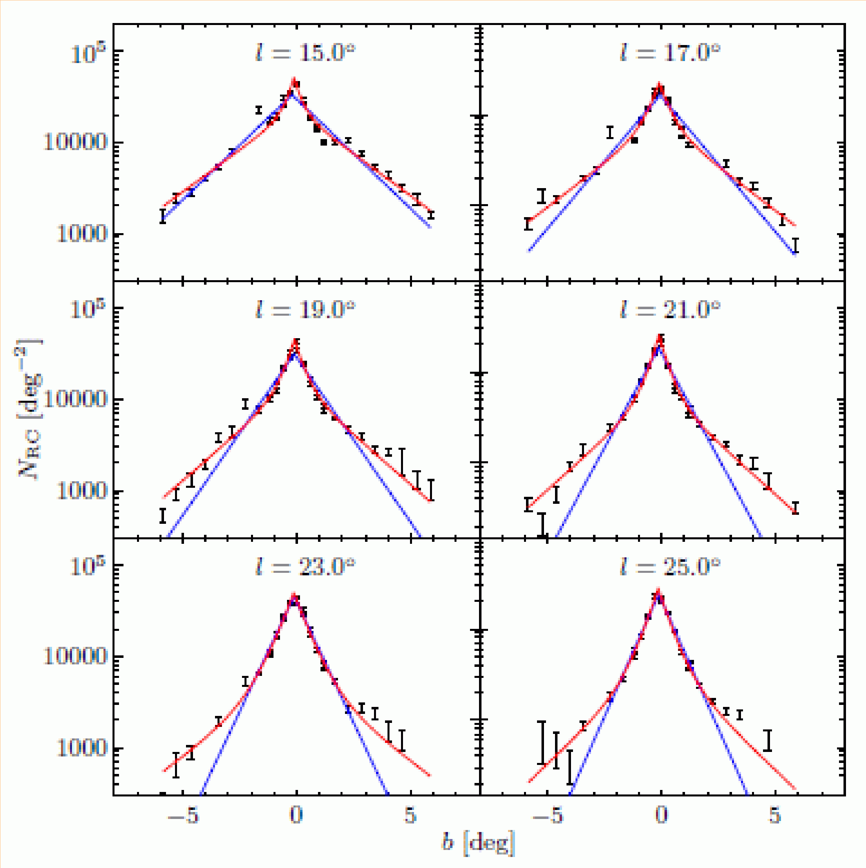


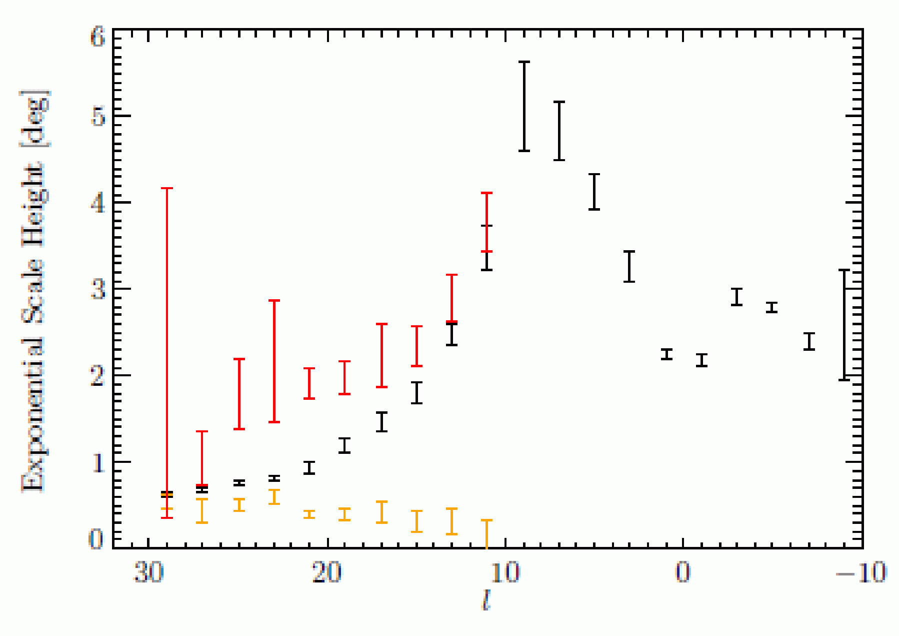


M2M + parametric long bar model matched to data in 4th panel

Wegg, OG, Portail '15

Vertical Exponential Scale-Heights for RCG

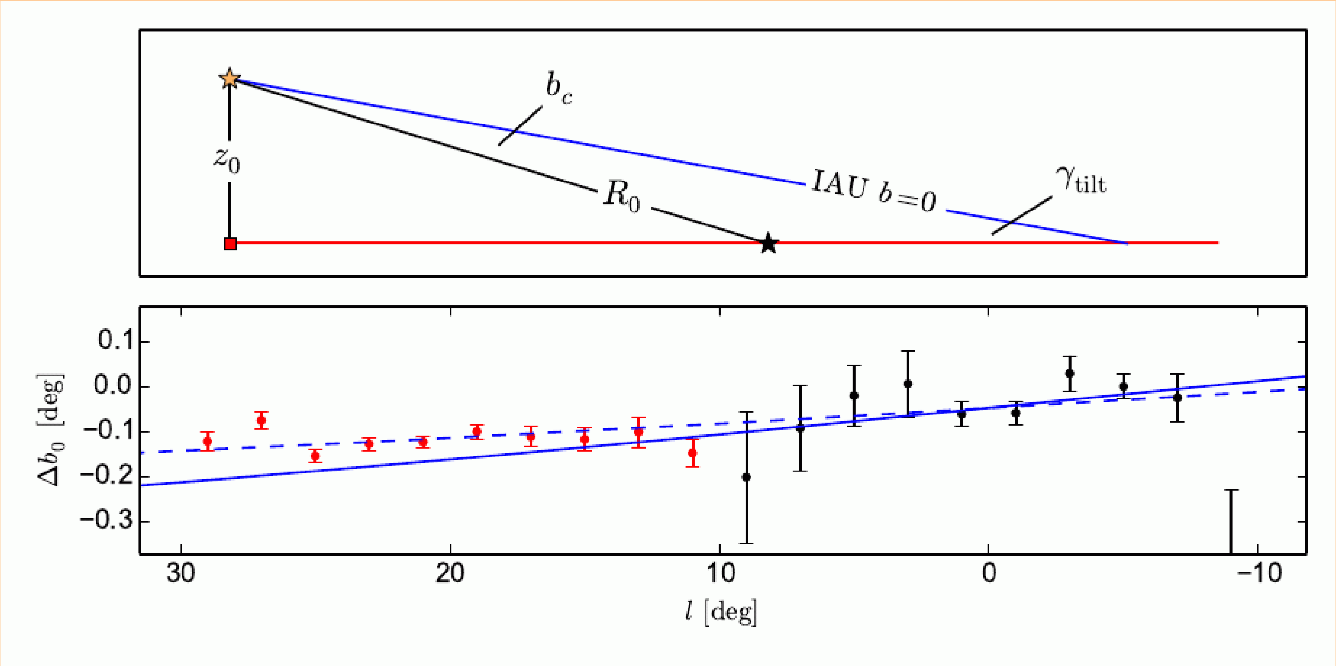




Wegg, OG, Portail '15

- Thin (hz=180pc) and super-thin bar components (hz=45pc)
- Two sides of the X-structure at l=10° and l=-5°
- Continuous variation to l=28° into the planar bar ⇒ one bar with inner 3D and outer 2D structure as simulations predict

The Bar in the Galactic Plane to 0.1%

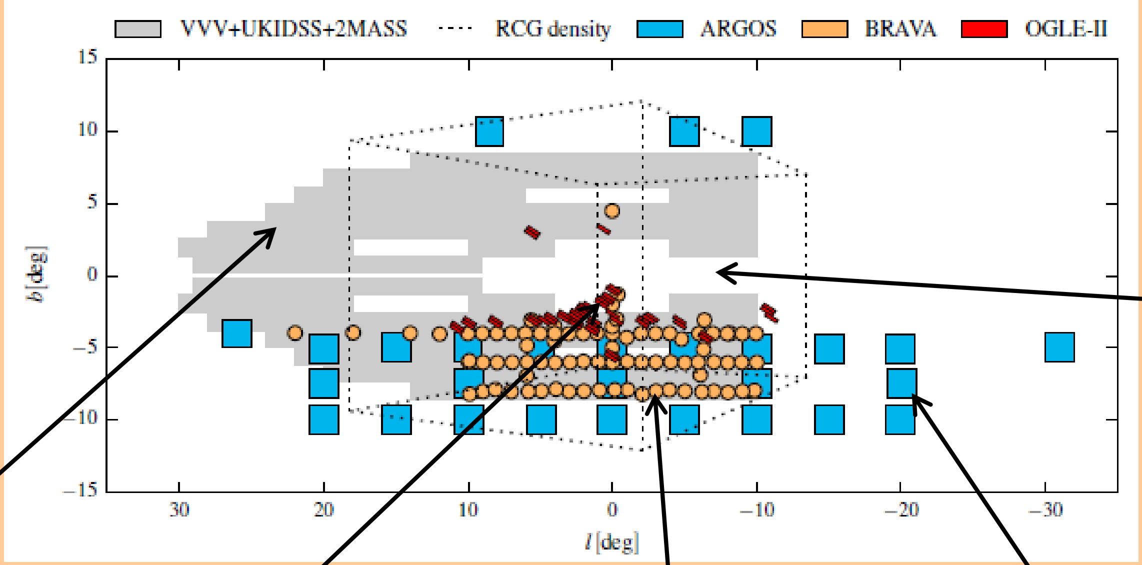


Measured latitude offsets – Wegg+15 Tilted Galactic Plane – Goodman+14
Figure from Bland-Hawthorn & OG '16

- Measured latitude offsets from vertical profile fits ~-0.1 dg
- Simplest model – linear bar in tilted Galactic plane through Sgr A* and LSR 25pc below Sun fits to within ~0.05 dg ~5pc
- With bar length of ~5 kpc, the bar is aligned with GP to 0.1%

3. Dynamical (and Chemo-Dynamical) Models

- Star counts described by a (static) density model. But stars move along orbits in potential **– to determine their orbit distribution needs** combining density and velocity data in **a dynamical model.**
- Even though not strictly true, need to start with **equilibrium dynamical model** which determines stellar DF(orbits) via **Jeans' theorem (∂DF/∂t=0 on orbits).** This automatically solves Jeans eqs. in 3D for ρ, σ, β.
- Based on data (D=1-3):



+ rotation . . Curve

3D density of RCGs

Magnitude Distributions

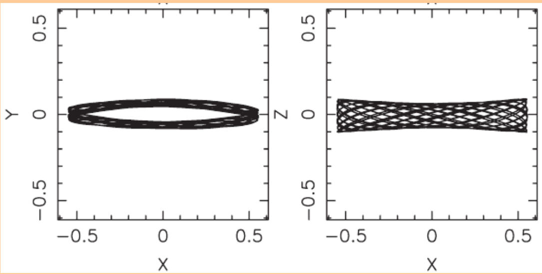
Proper motion dispersion

Mean radial velocities and dispersion

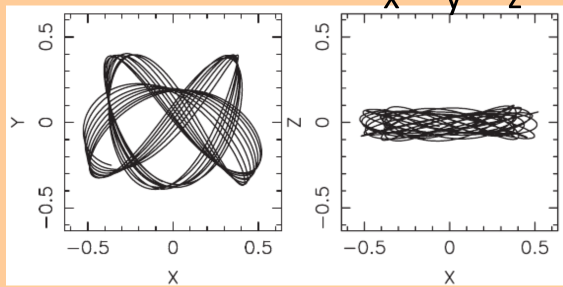
Mean radial velocities, dispersions, chemical abundances as function of distance

(Some) Orbits in (Rotating) B/P Bulges

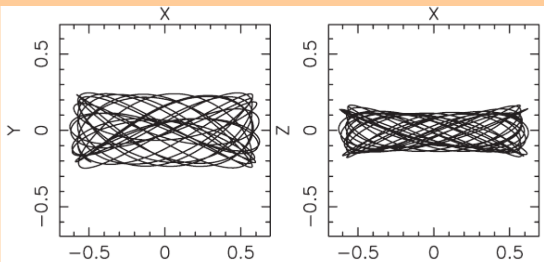
Resonant $\Omega_x{:}\Omega_y{:}\Omega_z$



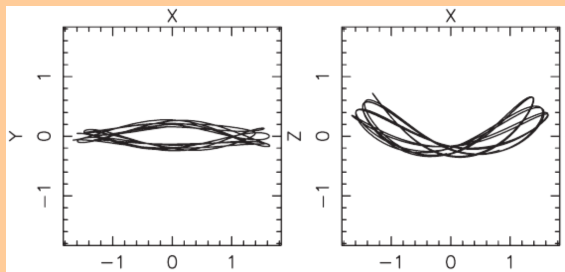
Thin x1



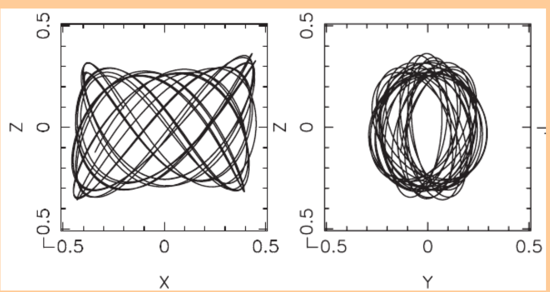
3:2:0 Pretzel



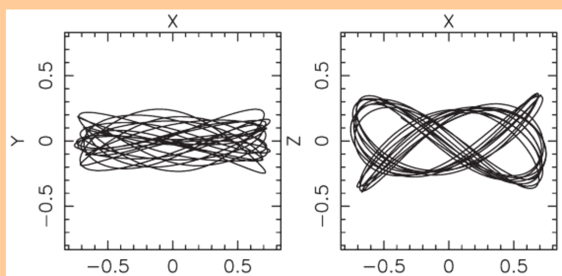
Thick x1/box



2:0:1 Banana

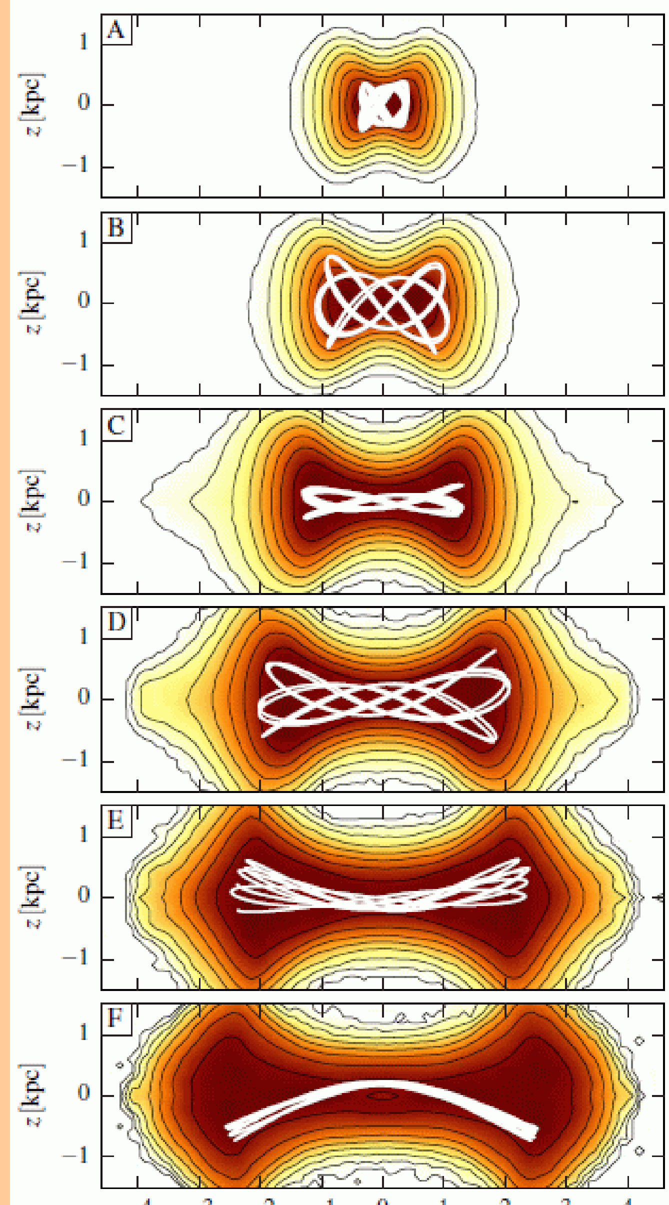


X-tube



3:0:5 Brezel

Valluri+'16



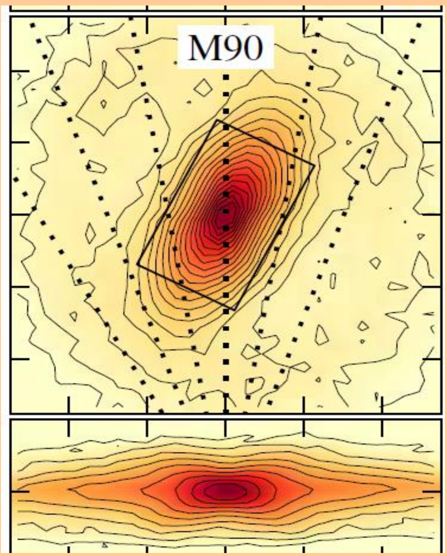
Portail+'15

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**

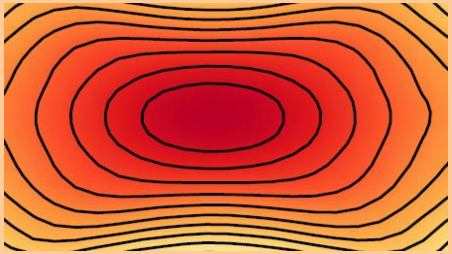
N-body model



"Observe" (SSF)

Model observable

Real data



Compare

& quantify

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

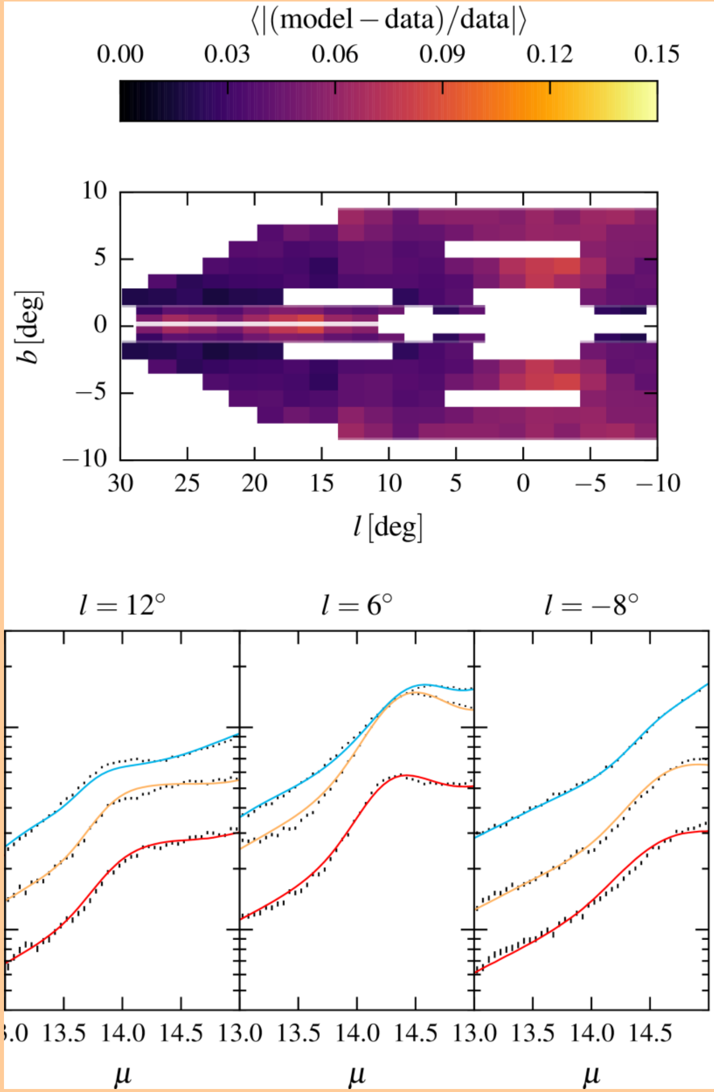
Profit function

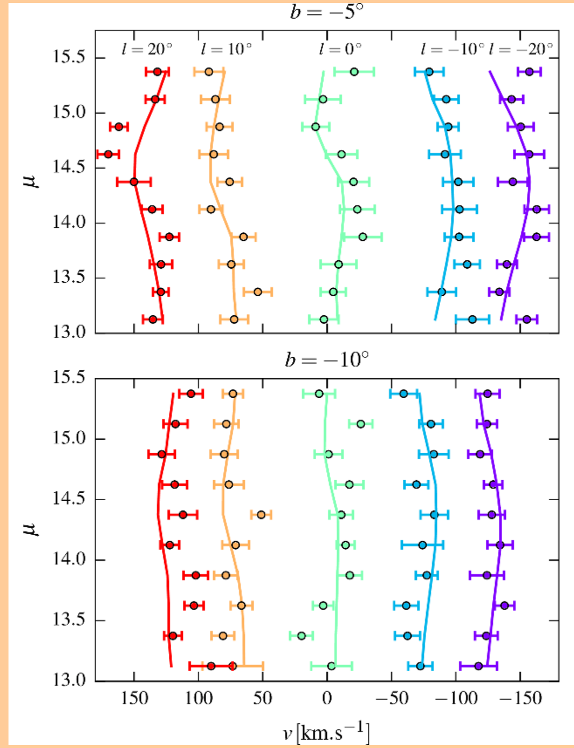
Change the particle weights

Evolve N-body model forward for dt

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

Some of the Data Fitted



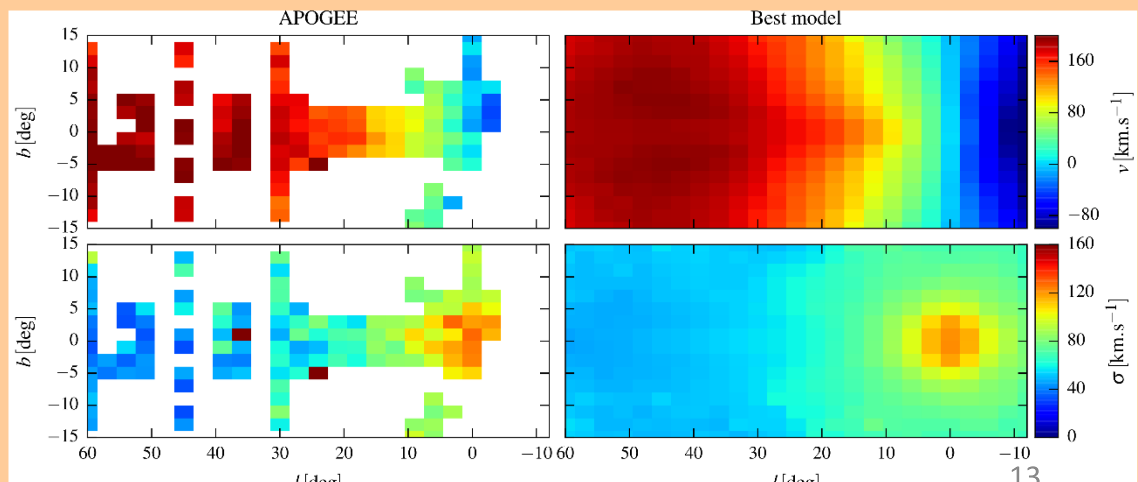


ARGOS: Observational selection criteria (Ness+’13) & mapping stars into distance bins using isochrones

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

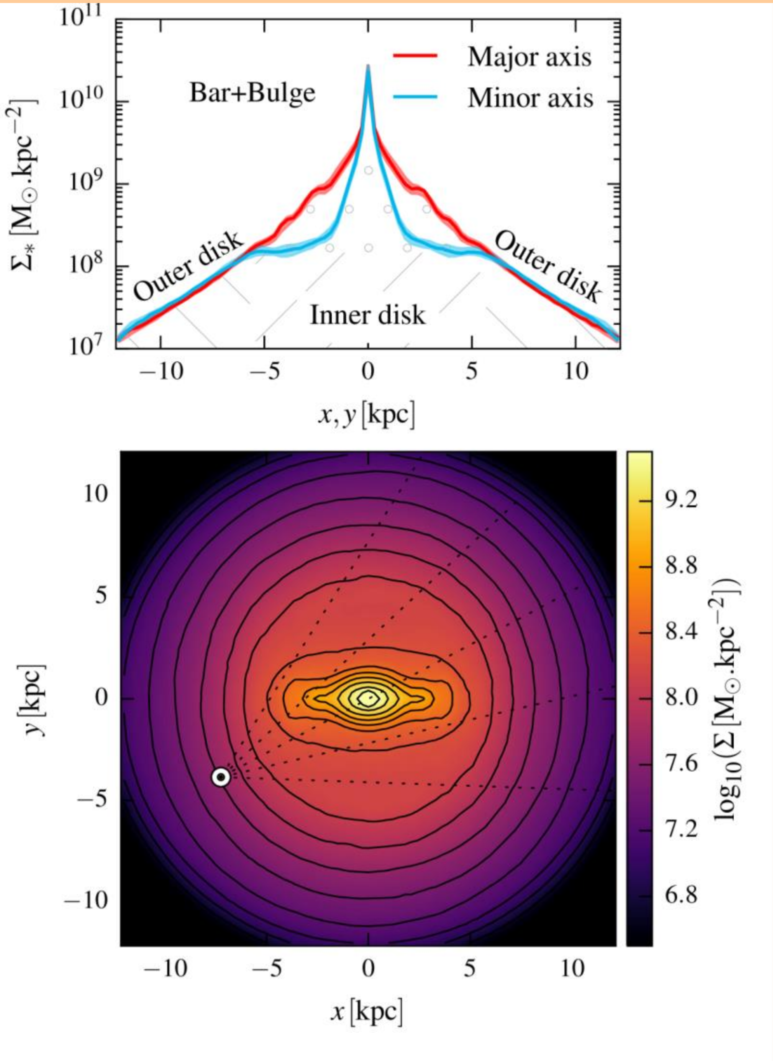
BRAVA

APOGEE predicted



Portail, OG , Wegg, Ness 2017a

Milky Way Model: Scales & Stellar Masses



Model surface density map obtained from fit to all data, Portail, OG et al '17a

Dynamical Model Results (Portail, OG et al '17a)

Density distribution of a B/P bulge and bar embedded in nearly flat inner disk density

(from modelling, little data sideways from bar)

Length of bar from star counts Rb = 5.0 kpc (± 0.2)

Pattern speed Ω_b =39 km/s/kpc (±3.5)

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)

Inner B+B+ID stellar mass fraction ~65%

Bulge stellar mass fraction ~30%

Structure param's (Bland-Hawthorn+OG '16 ARAA)

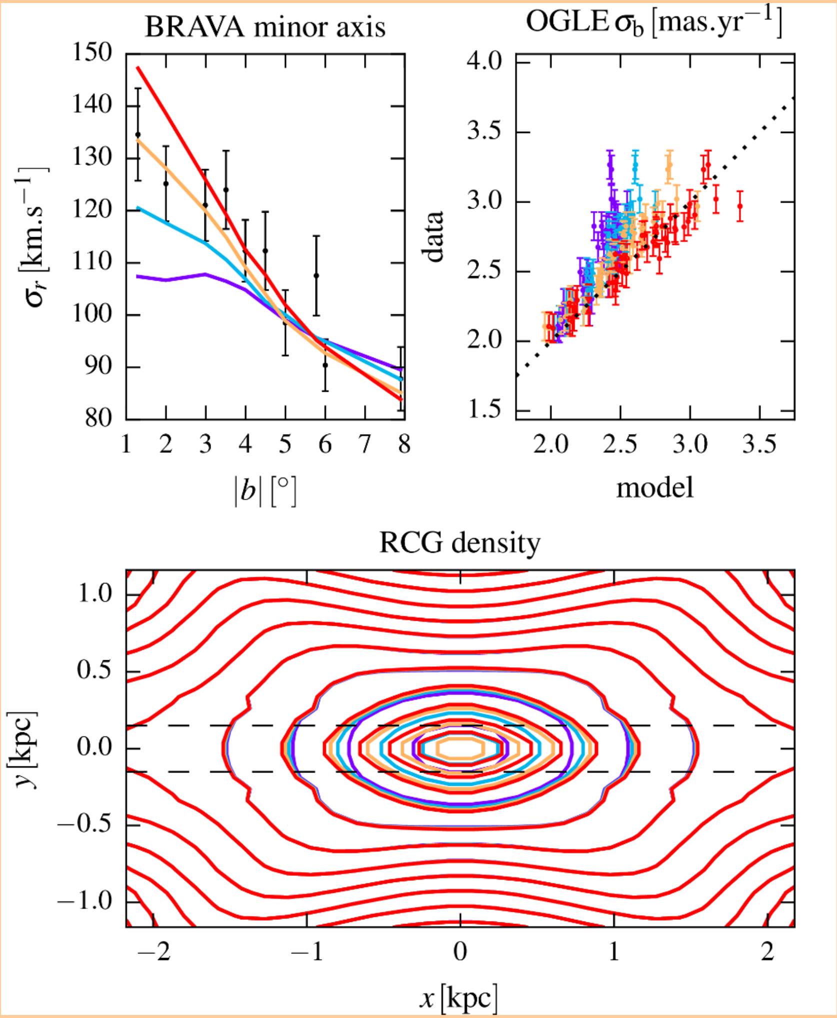
Sun's Distance to Gal. Centre: R0 = 8.2 kpc (±0.1)

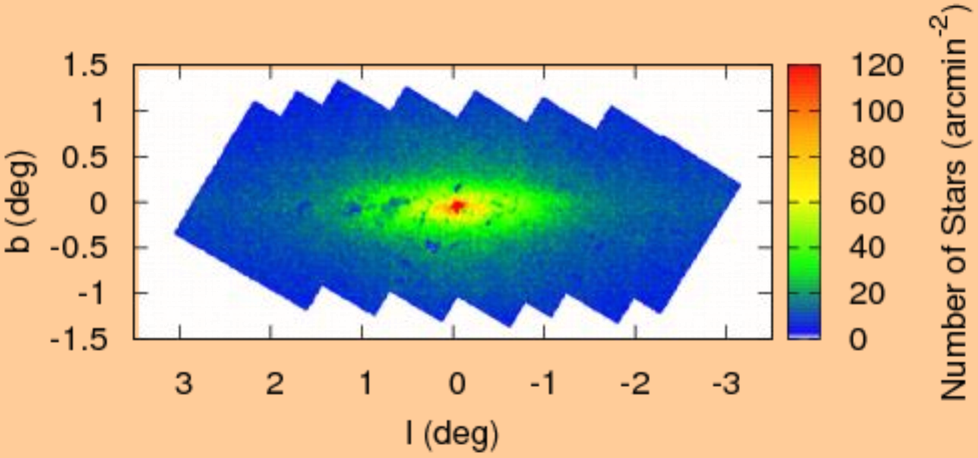
Circular velocity @ Sun V0 = 238 km/s (+5,-15)

Exponential disk scale-length Rd = 2.4 kpc (±0.5) inwards from the Sun (sign.uncert.)

The Milky Way's Massive Nuclear Disk

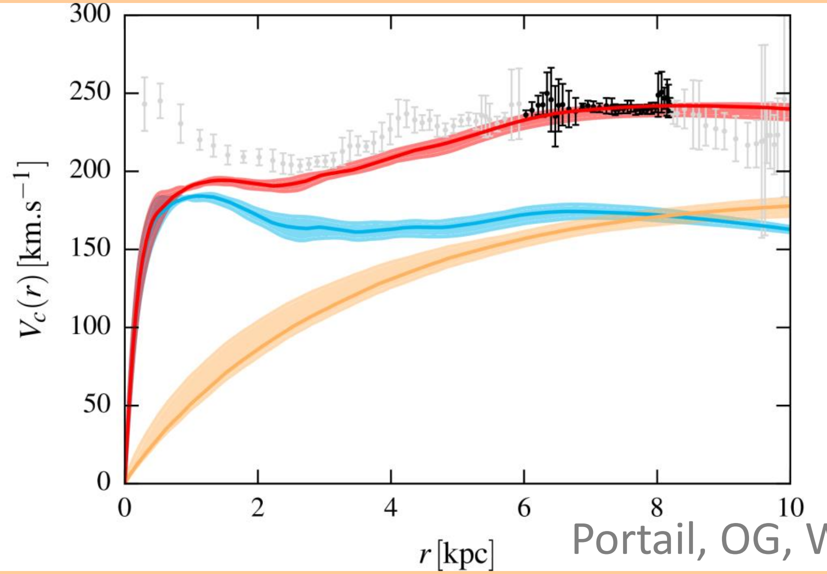
See Bland-Hawthorn+OG 2016 ARAA
Inferred from COBE Launhardt+'02
Starcount image from Nishiyama '13

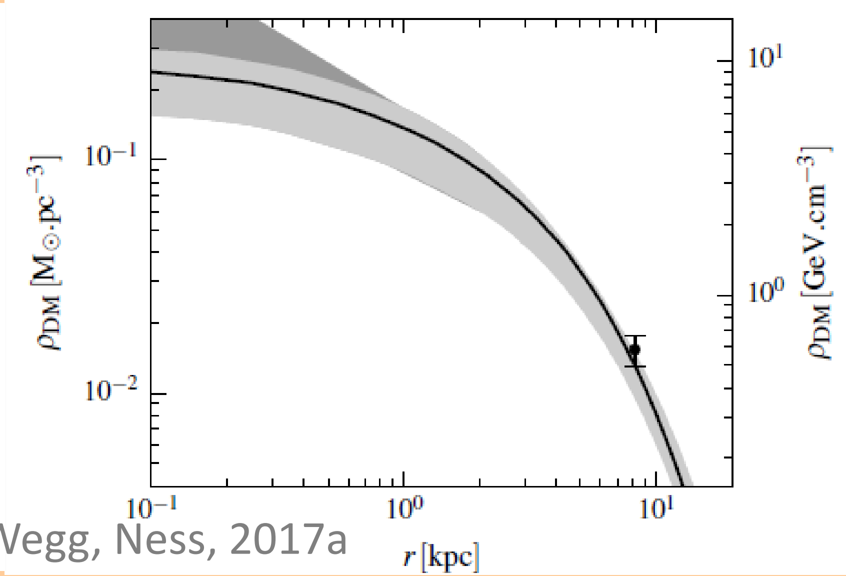




- Dynamically required by 2 kinematic data sets; need potential depth to explain high velocities
- Mass ~2×10^9 $M_\odot$ but best value varies between data sets
- Scale-length ~250 pc, highly flattened
- Needs further study, vs Launhardt's (2002) NSD, Kormendy's (2013) disky pseudobulges
- High mass suggests bar is old!?

The Dark Matter Density Profile



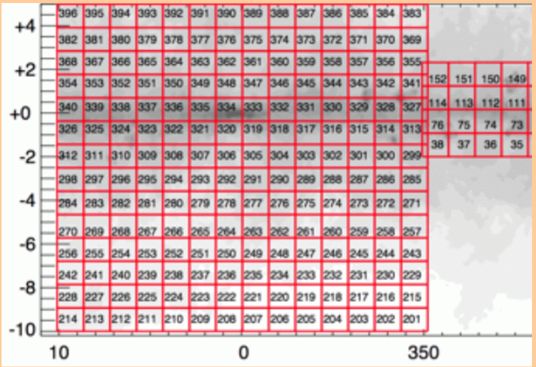


Portail, OG, Wegg, Ness, 2017a

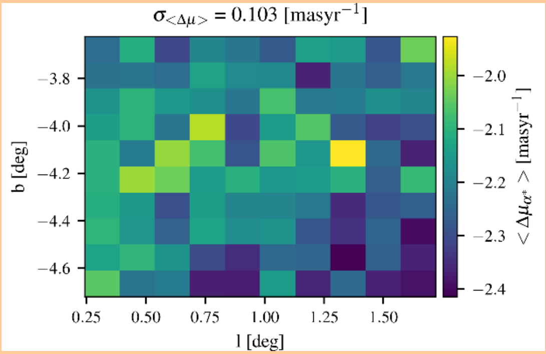
- We know the total **dynamical mass in the bulge** WG13 volume well, **1.85±0.05 × 10^{10} $M_\odot$** (previously, 1.84±0.07, Portail+'15). Also know stellar, and hence dark matter mass in the bulge, and mass & rotation curve inside the radius of the Sun.
- **⇒ Dynamical evidence that the dark matter profile of the MW must have a core or shallow cusp at ~2kpc:** The rotation curve wants it to be steep just inside the Sun, but then it must turn over to meet low DM mass in the bulge.
- DM profile goes through local value from Piffl+'14 (not fitted). Independently argued by Binney & Piffl '17, from halo model fitted to local data, and inward continuation constrained with microlensing τ.

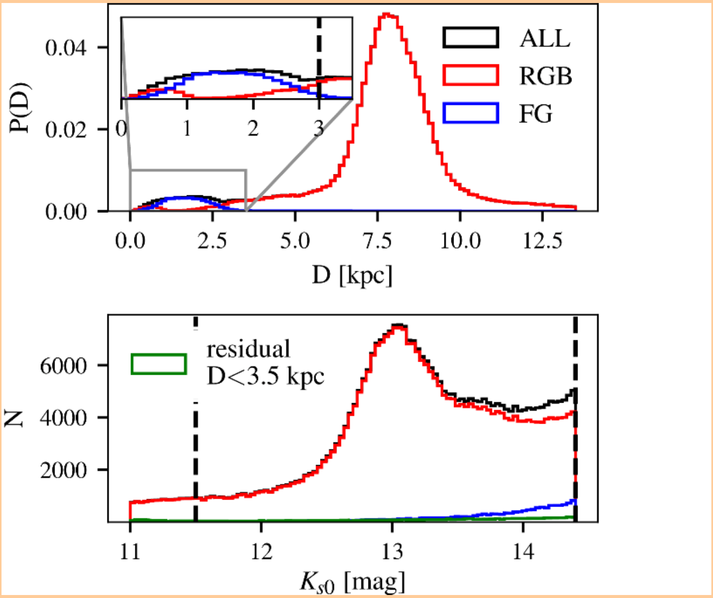
New 3D view from VIRAC/Gaia proper motions

Clarke+1903.02003;   see also Sanders+1903.02008



- VIRAC is a VVV-based deep NIR astrometric survey in the bulge and southern disk, providing ~313 Mio relative PMs accurate on scale of VVV tile (1.4dgx1.1dg). Median error ~0.67 mas/yr (Smith+18)
- Each VVV tile is cross-matched with Gaia-DR2 to obtain absolute PMs. Typical scatter on a sub-tile scale is 0.1 mas/yr.

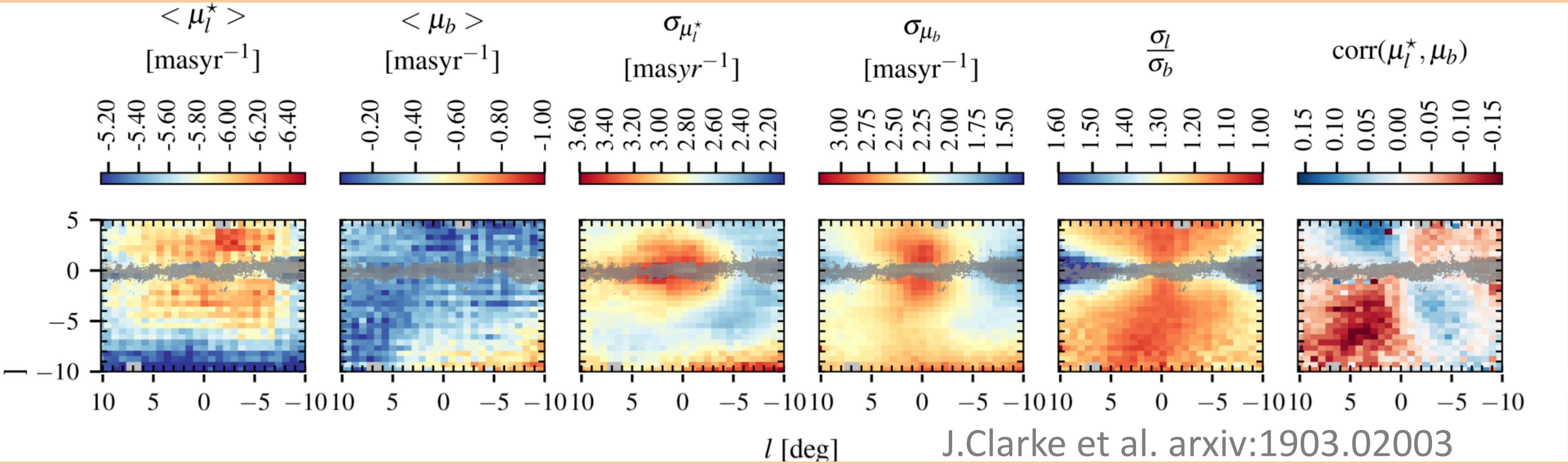




- Foreground disk stars are separated from stars in the bulge/bar with a colour-colour selection tested on Galaxia mock models, leaving <1% fg disk stars with D<3.5 kpc in the sample.
- Dust extinction is assumed from a foreground sheet and removed as in Gonzalez+'12. Regions with Ak>1.0mag are masked.

Final sample: ~40 Mio bulge giant PMs

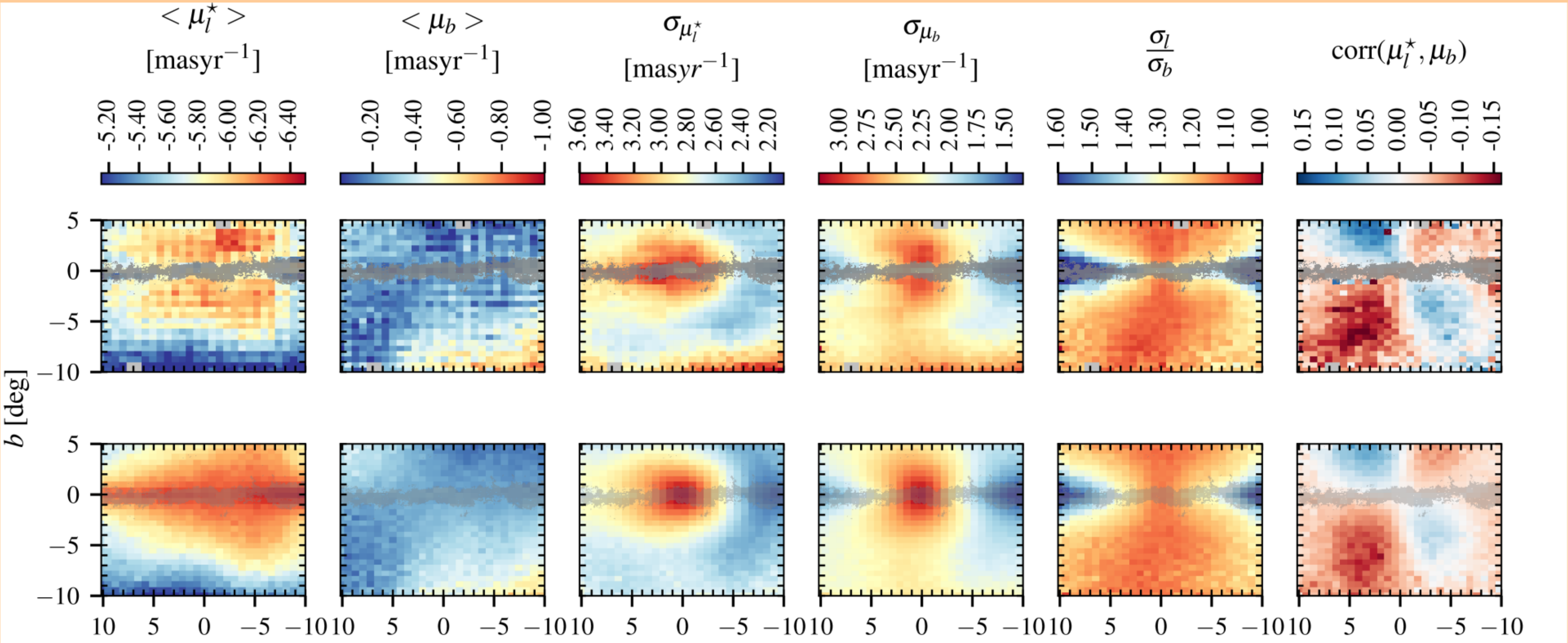
Line-of-sight Integrated Maps



Integrated kinematic maps in $11.8<K_{s0}<13.6$ mag (~±3 kpc around R_0)

- Clear evidence for bar rotation and internal streaming in <μ> maps; cf. quadrupole in $<\mu_b>$ shifted by solar reflex motion
- High central dispersions in both (l,b) due to deep central potential
- Dispersion ratio σ_l/σ_b shows X-structure with min/max on minor axis / disk
- Correlation stronger at $l > 0^o$ and quadrupole consistent with boxy orbits

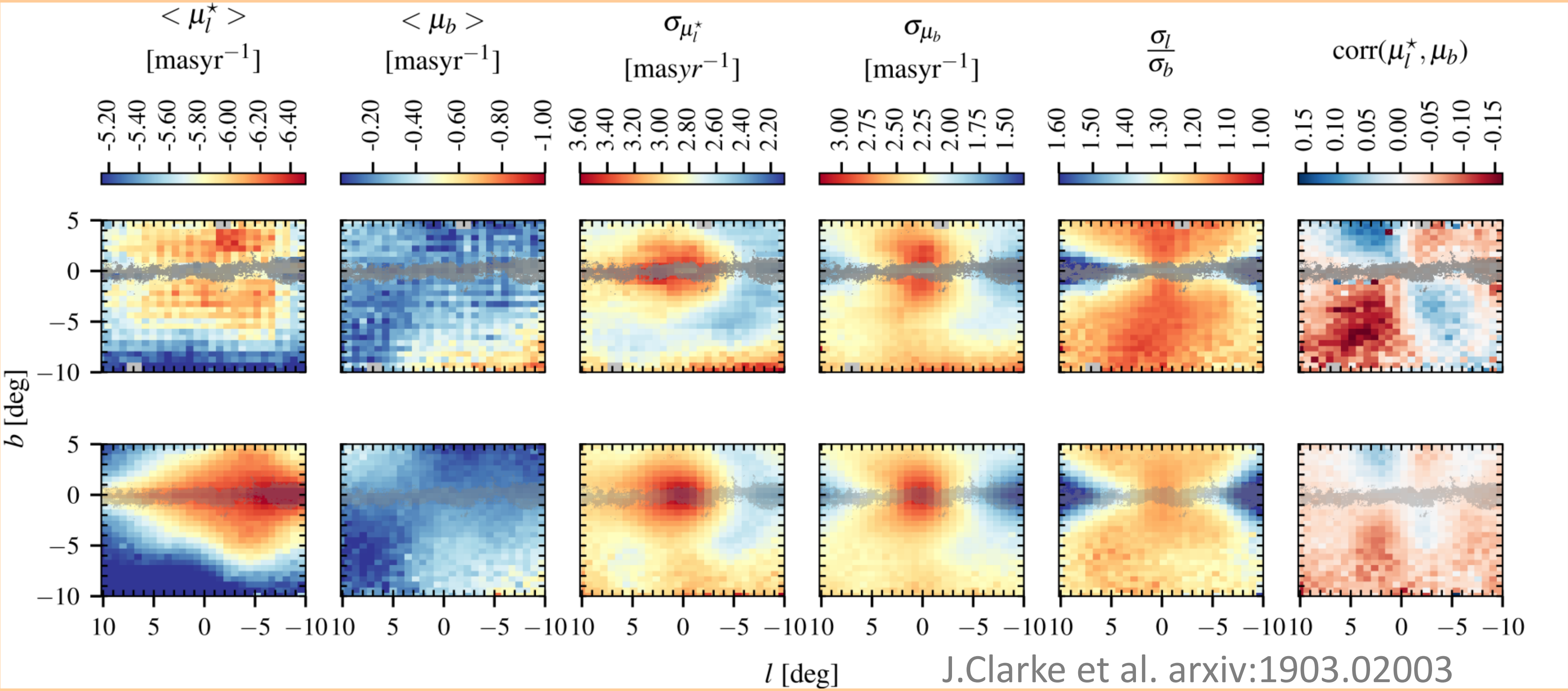
Line-of-sight Integrated Maps vs Model



J.Clarke et al. arxiv:1903.02003

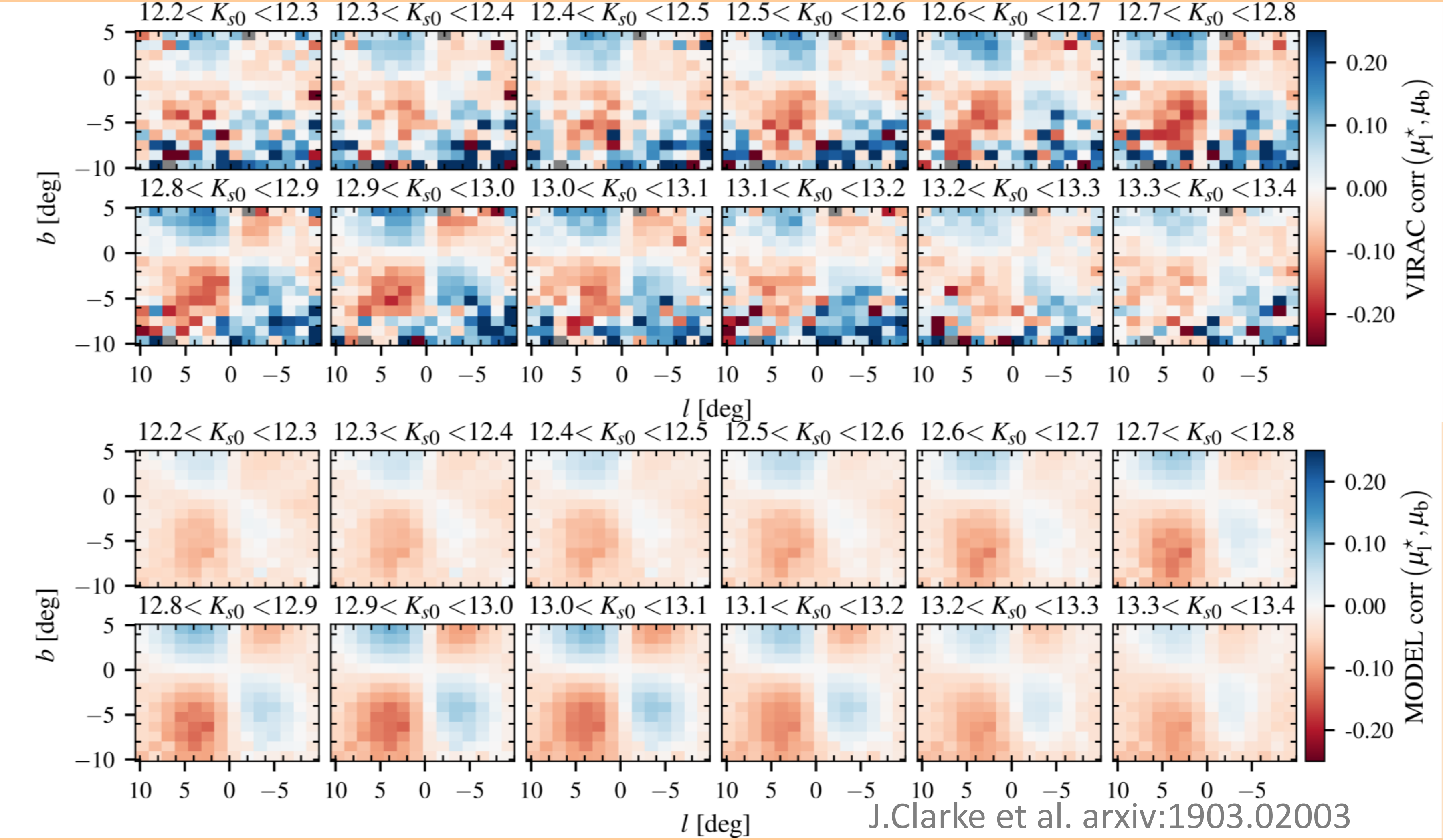
- Used models from Portail, OG+17 fitted to star counts & radial velocities, and using OGLE PM constraint for NSD. Reconstructed LF using Kroupa ’01 IMF, MDF from Zoccali+’08 , parsec isochrones Bressan+’12, and VIRAC select.fn.
- Impressive match for visually best Portail+’17 model with Ω=37.5 km/s/kpc
- “Hell of an advertisement” for dynamical modelling!

Fast Ω=50 km/s/kpc doesn't work



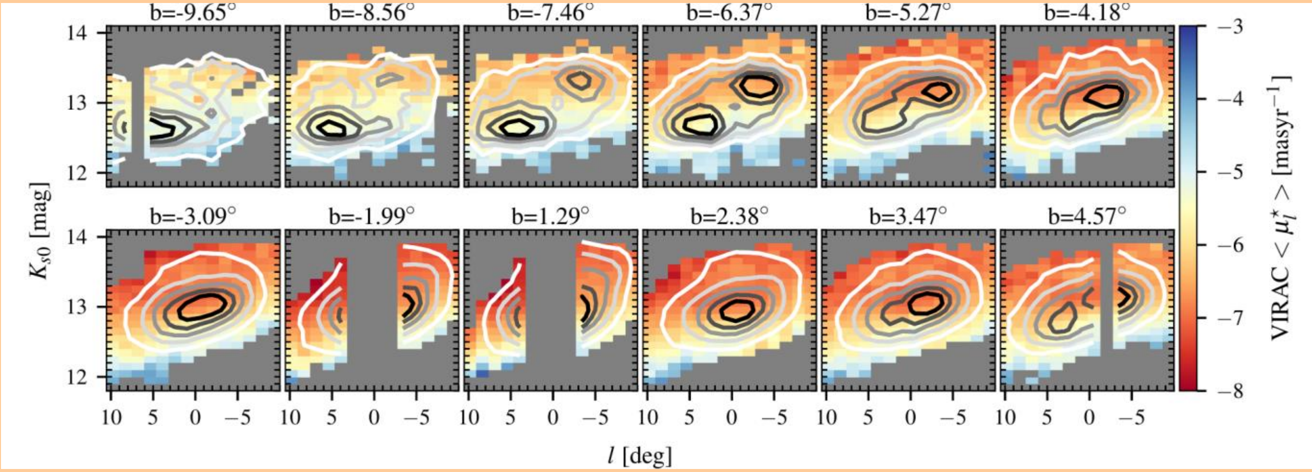
..because the bar is too distant and too small

σ_{lb} correlation with mag: the barred inner bulge



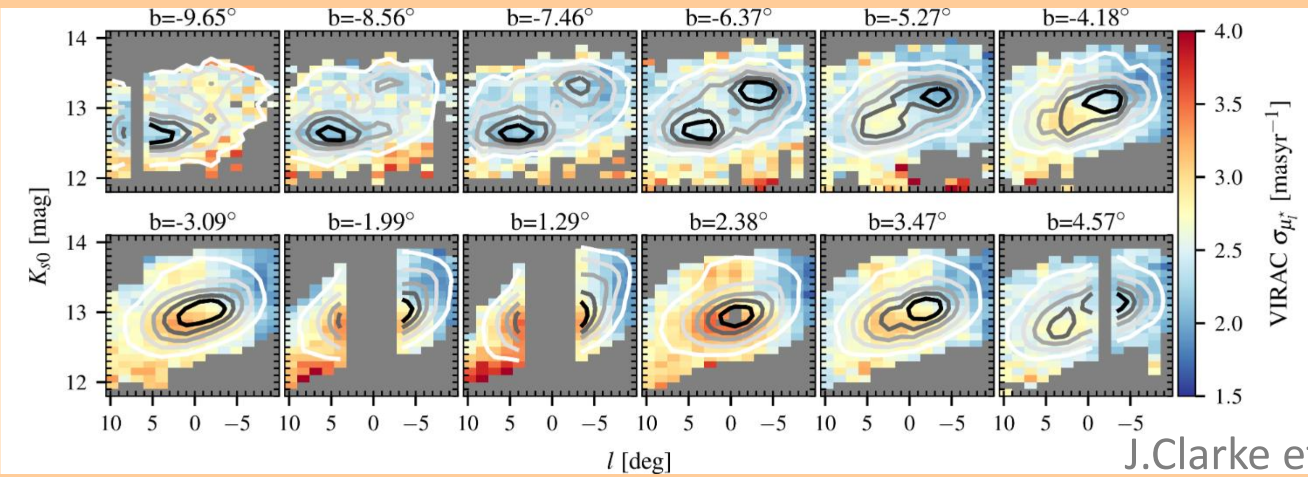
- Bulge has correlated PMs at all magnitudes
- No evidence for a further axisymmetric component at the center

Mag-resolved RCG maps: distinct split RC kinematics



- $<\mu_l^*>$ gradient from bright to faint, ~1.5mas/yr
- $<\mu_l^*>$ isocontours tilted due to bar inclination, curved due to streaming motions

Constructed by statistically subtracting exponential RGBC



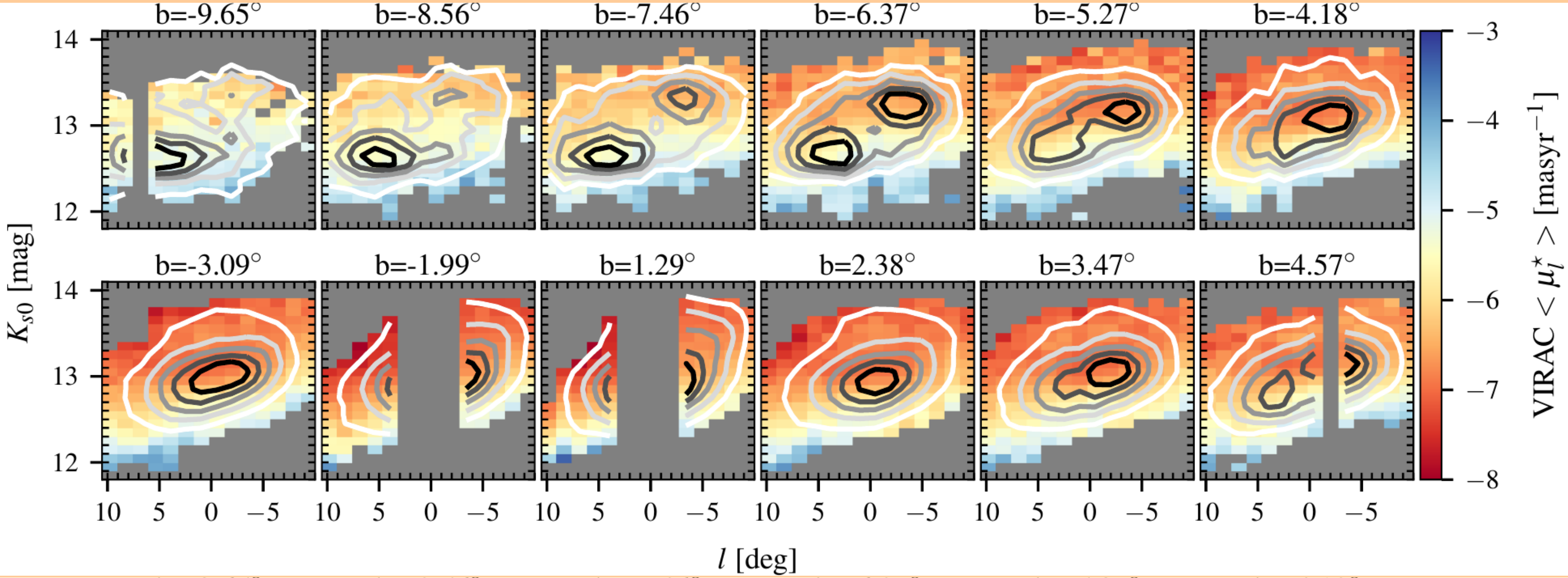
- Strong peak in σ_l dispersion at Gal. ctr
- Higher dispersion at bright mags due to disk-like motions

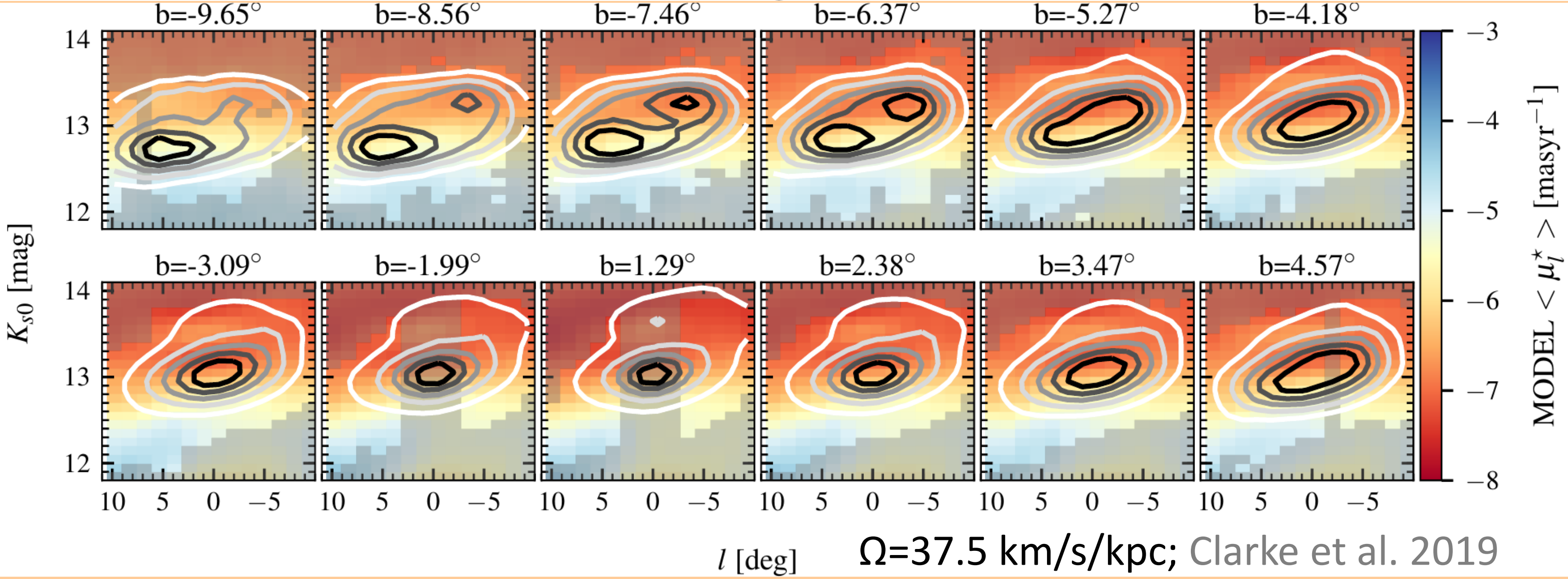
J.Clarke et al. arxiv:1903.02003

Constructed by statistically subtracting the exponential RGBC

Kinematic separation of the two branches of the split red clump in both $<\mu_l^*>$ and σ_l

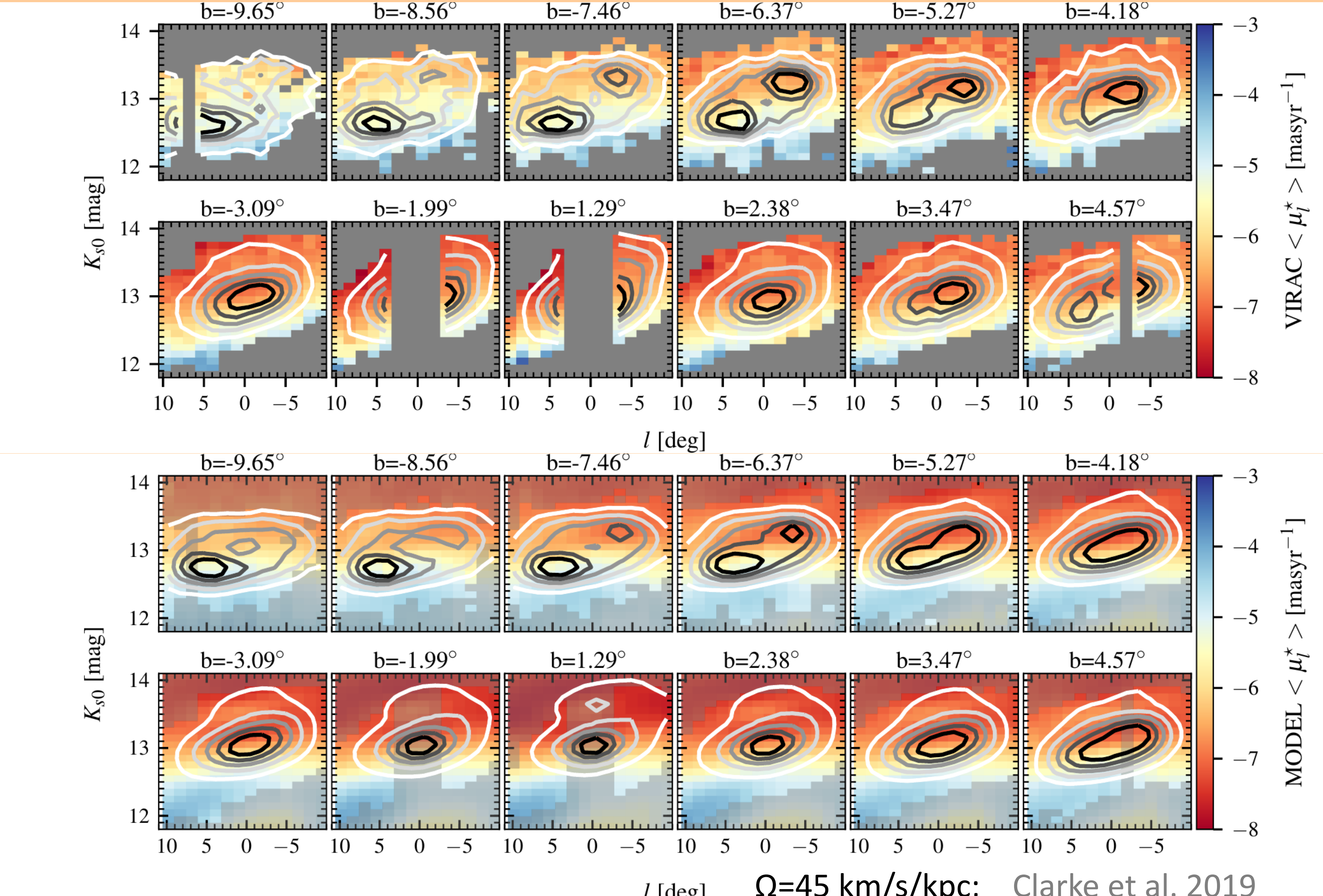
Mag-resolved RCG maps: <μ_l> model comparison*





Ω=37.5 km/s/kpc; Clarke et al. 2019

Mag-resolved RCG maps: near-far gradient measures Ω



Ω=45 km/s/kpc; Clarke et al. 2019

Summary Bar Pattern Speed

Recent measurements of Ω appear to be converging so systematics may be in reasonable control:

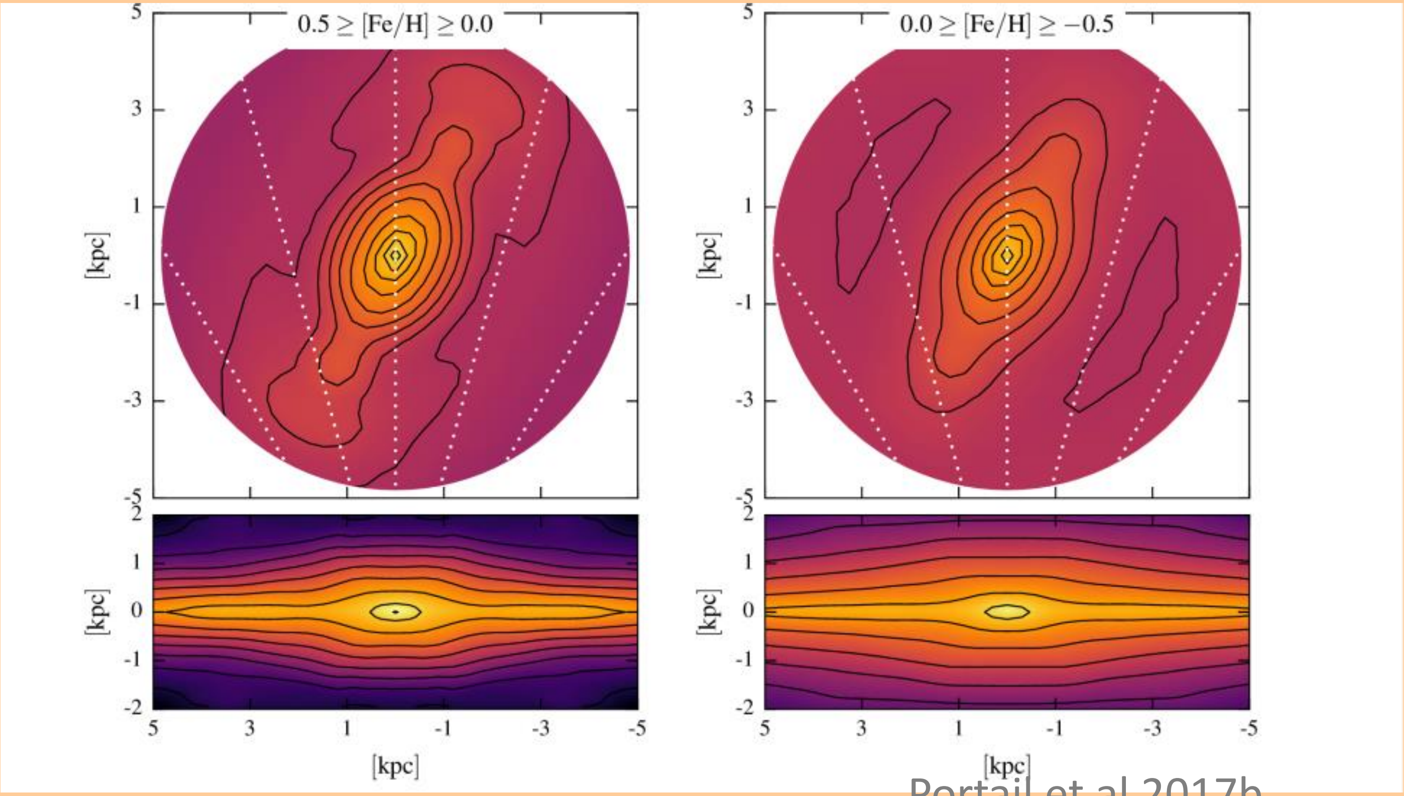
- From bulge stellar-dynamical models
  - Ω = 39.0 ± 3.5 Portail+'17 density, RVs & OGLE NSD constraint
  - Ω = ~37.5 ± few Clarke+'19 VIRAC PMs + P17 models for size/gradient
- From continuity eqn
  - Ω = 41 ± 3 Sanders+'1903.02009
- From gas-dynamical models for (l,v)-plot (more dicy)
  - Ω = 40 Sormani+'15
  - Ω = 33 Li+'16

Typical Ω = 40 km/s/kpc corresponds to corotation radius ~5.8 kpc and R = R_c/a_b = 5.8/5.0 = 1.16. This is a dynamically fast, large bar.

Then what causes the Hercules stream?

Outlook: How the Galactic Bar depends on Metallicity *(Chemo-dynamical Models)*

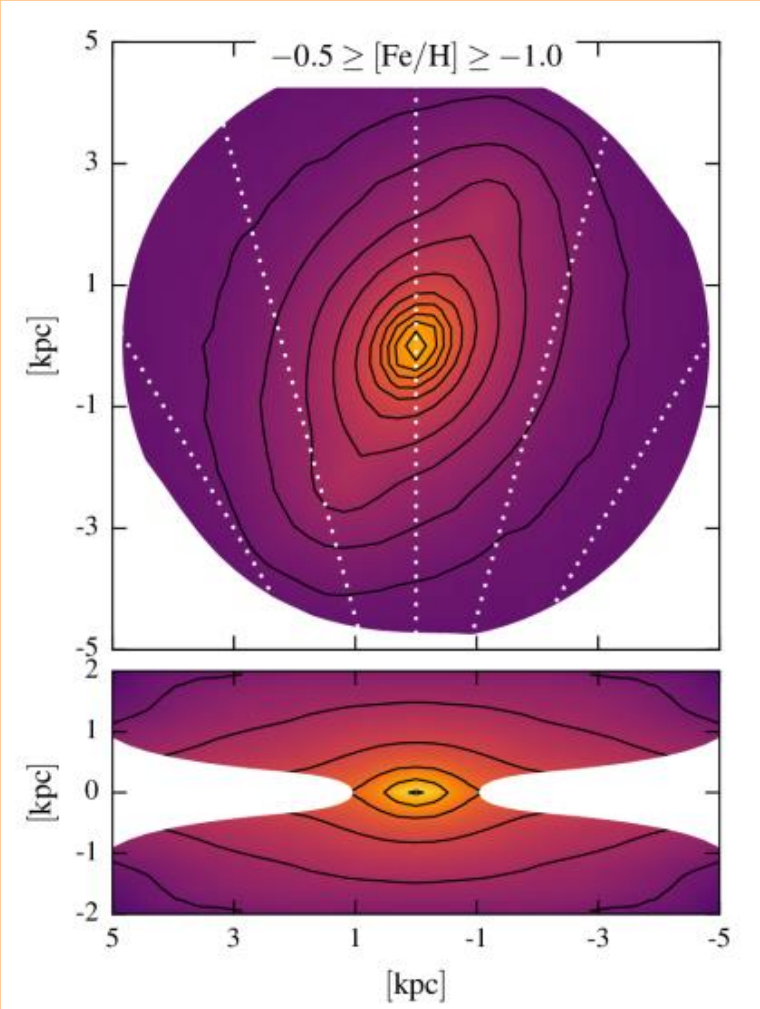
- M2M particles carry [**x, v,** f(M)]; MDF f(M) parameterized as MGE adjusted to ARGOS bins
- Particles projected into obsv space using isochrones and M-dependent selection fn
- Particle metallicity weights w_c adjusted by comparing with similar data in distance bins

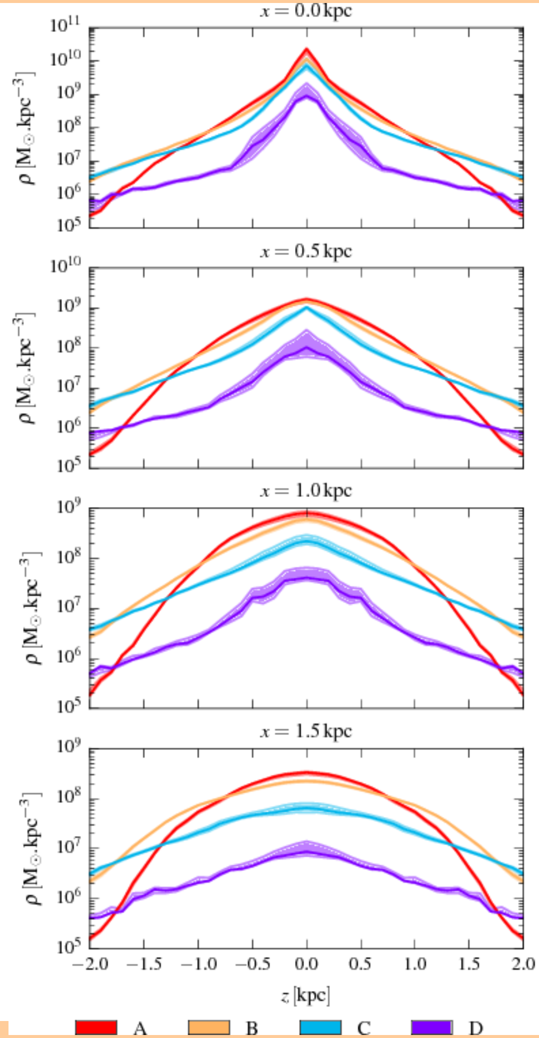


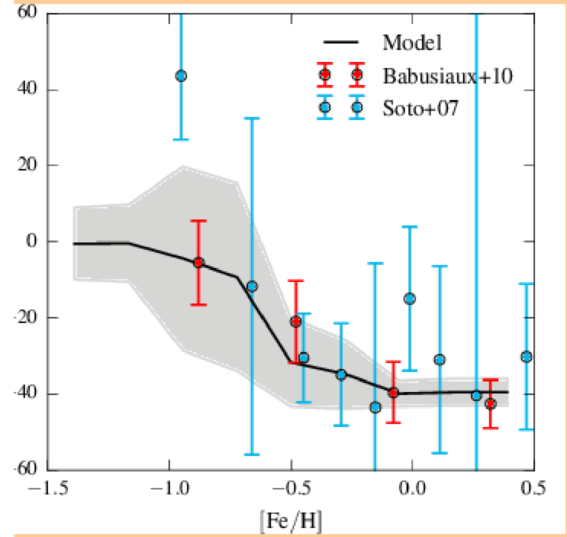
Portail et al 2017b

- 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 Metal-Poor Thick Disk-like Stars







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 - *Outlook for the Future*

- We live in a strongly barred MW galaxy with a predominant BP bulge made from the disk. If a primordial bulge exists, it must be of low mass.
- The combined VIRAC + Gaia PM data give us a new 3D view of the bulge kinematics. They essentially confirm previous dynamical models based on RC star counts and RVs.
- The pattern speed can be 'seen' as a near-far gradient in the PMs and through the size and amplitude of the bar signatures in integrated maps. Quantitatively, $\Omega \sim 41 \pm 3$ km/s/kpc from continuity eq (Sanders et al.) and similar, perhaps a few km/s/kpc lower from the dynamical models. This corr. to a corotation radius ~ 5.5-6 kpc and a dynamically fast, large bar.
- From the dyn. models, the bar region contains 2/3 of the MW's stellar mass. The models also predict that the MW's DM halo has a ~2 kpc core, and ~20% of the mass in the bulge region.
- Different stellar populations in the bulge have clearly different orbit distributions, which must be exemplary for all other bulge-like stellar systems.

Further new data from Gaia and ground-based surveys and further modelling is likely to lead to improved dynamical constraints and new understanding of the stellar populations in the bulge.