Perspectives on Galactic Structure

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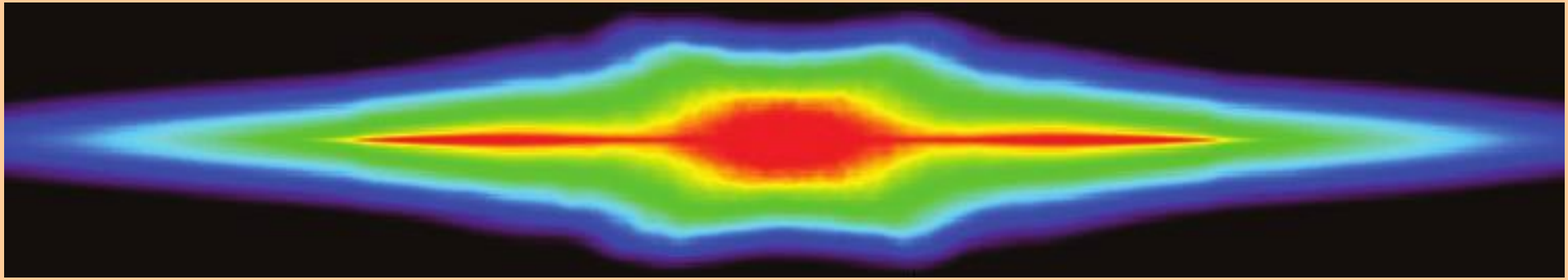
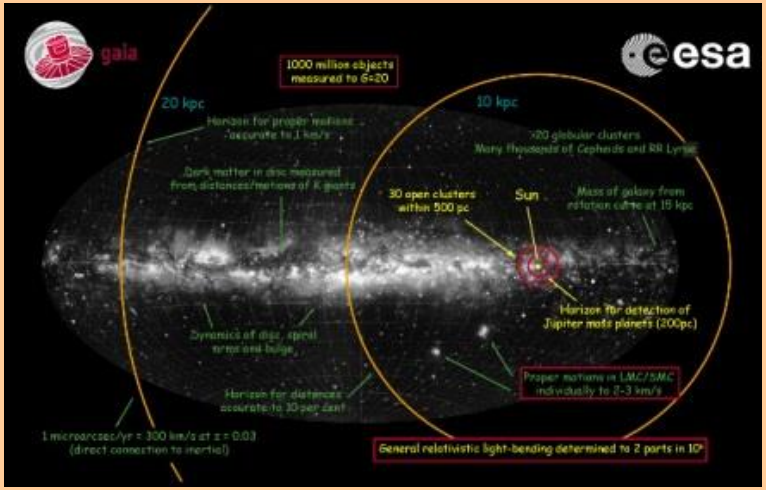
1. Milky Way surveys
2. The Bulge and Bar
3. The Disk
4. The Halo, stellar and dark



1. The Milky Way in the Age of Surveys

There is currently extraordinary interest and investment in **Milky Way studies:**

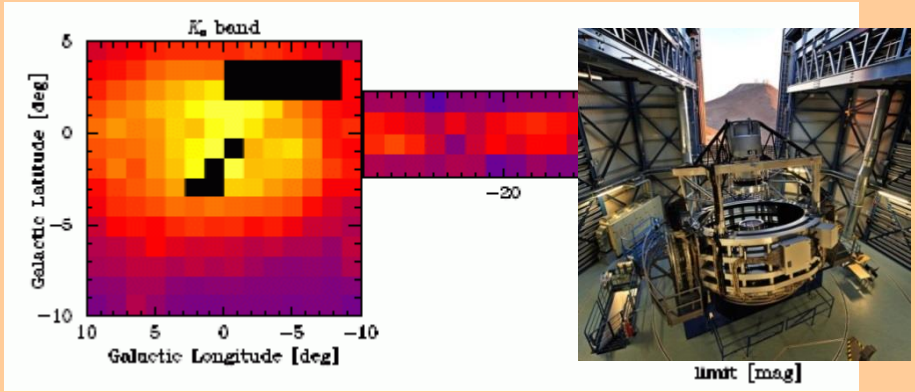


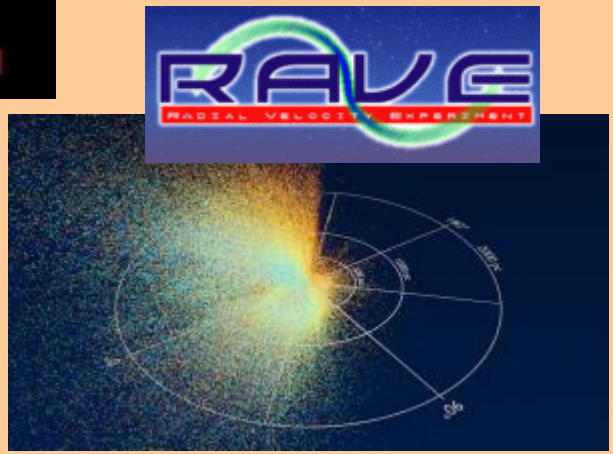




Segue, Segue-II, APOGEE

ESO-Vista
VVV





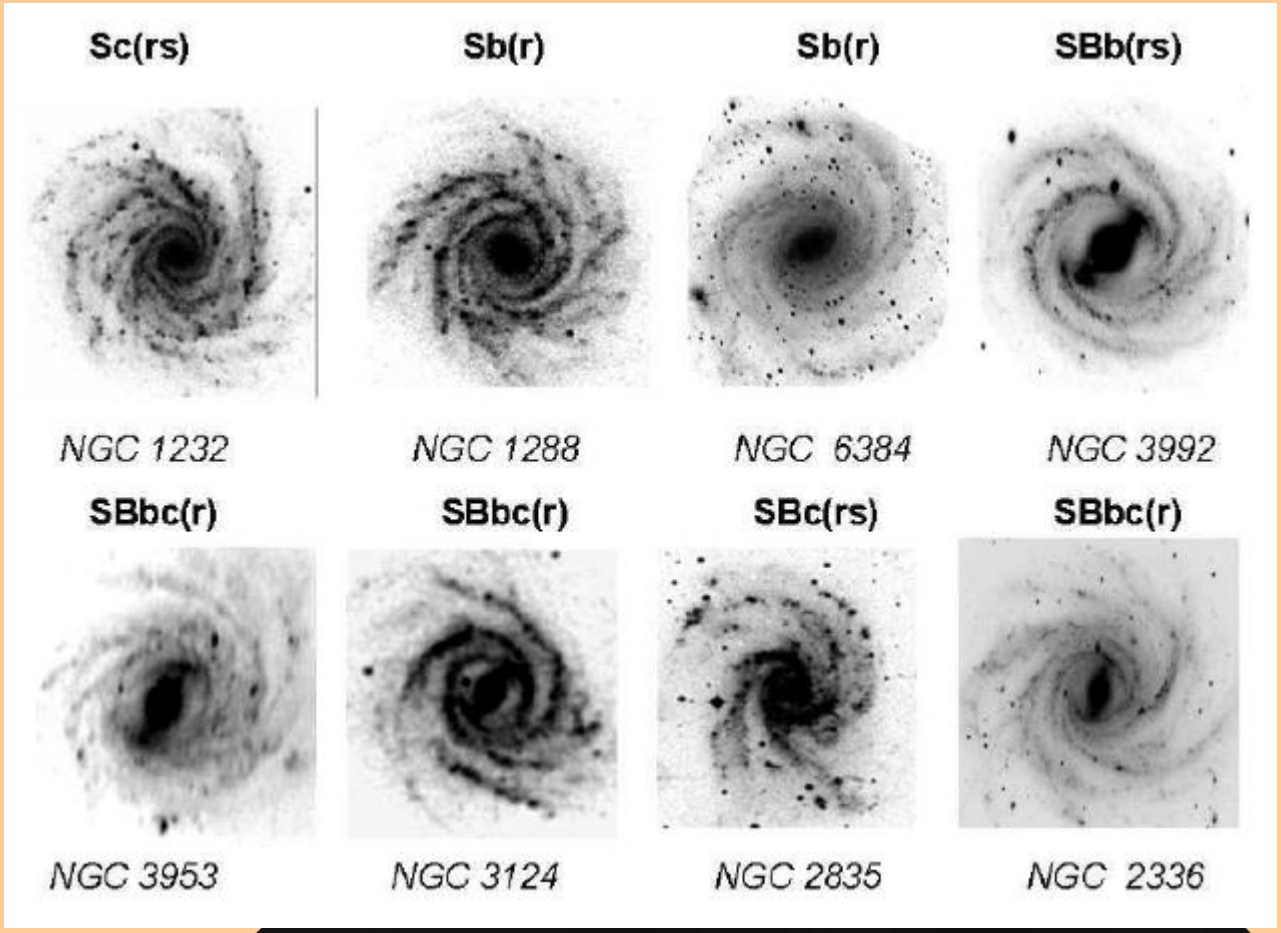
Many on-going and future surveys: DES, LSST, VVVX, WFIRST; APOGEE-2, GALAH, WEAVE, 4MOST, K2

The Milky Way is the only large galaxy whose formation history can be studied star by star. The oldest components provide us with unique insight into how galaxies evolve over billions of years.

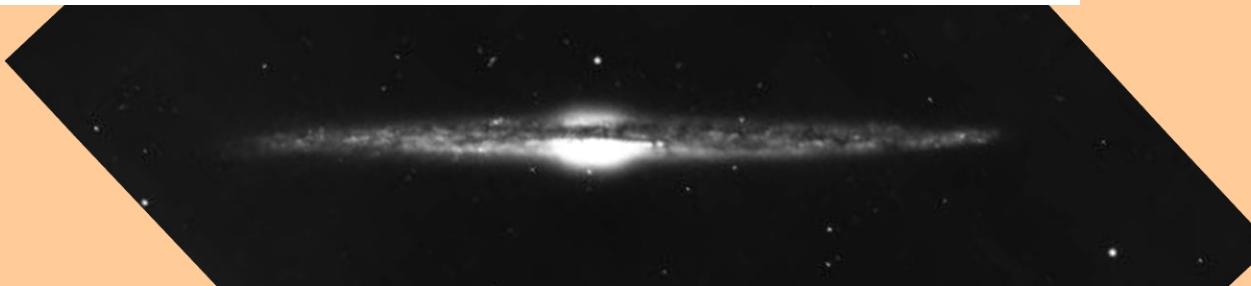
The Goals: Understanding Milky Way Structure: Understanding Disk Galaxy Formation

Milky Way Analogs

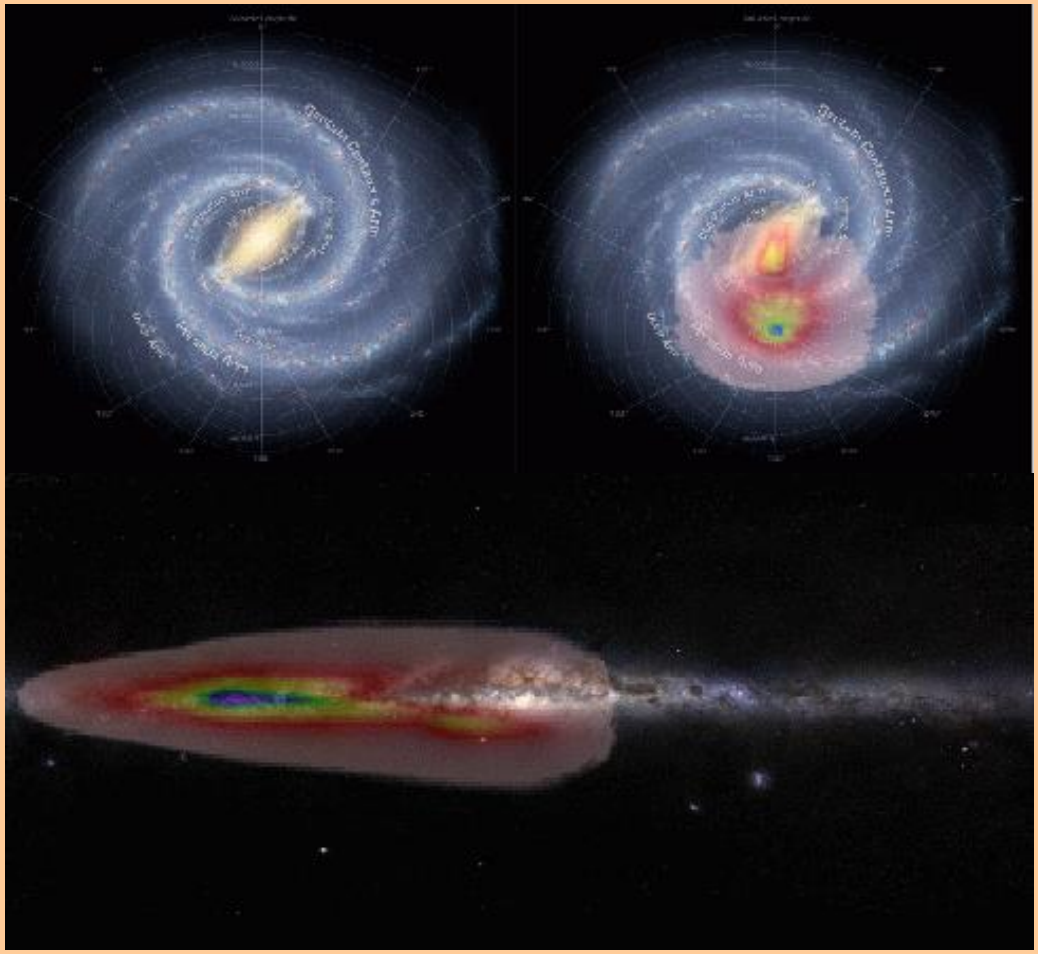
Efremov ’11



NGC 4565



The Gaia Satellite: Survey Volume



Figures from Xavier Luri, DPAC-CU2 and NASA/JPL-Caltech, R. Hurt
Constructed with Gaia Universe model, Robin+'13

Parallaxes and Proper Motions for ~10^9 stars

Magnitude limited, so
Best data < 3 kpc
Good PMs at 10 kpc
Brightest stars: LMC++

Main scientific goals re Galactic structure:

- Disk and nearby halo
- Gravitational potential and dark matter halo

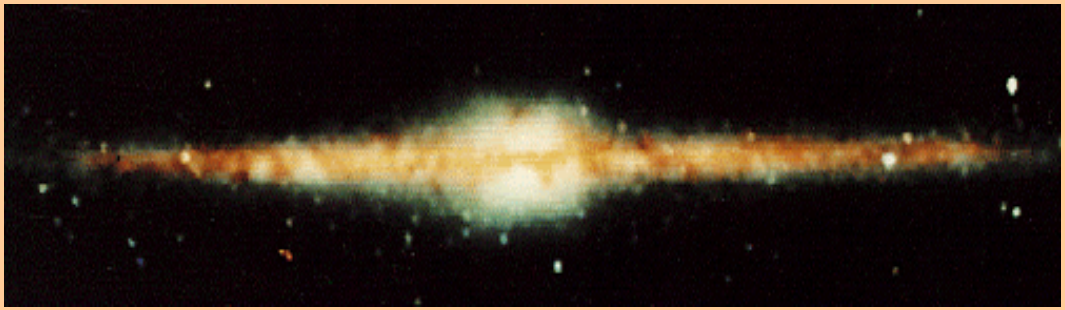
(and there will be much else)

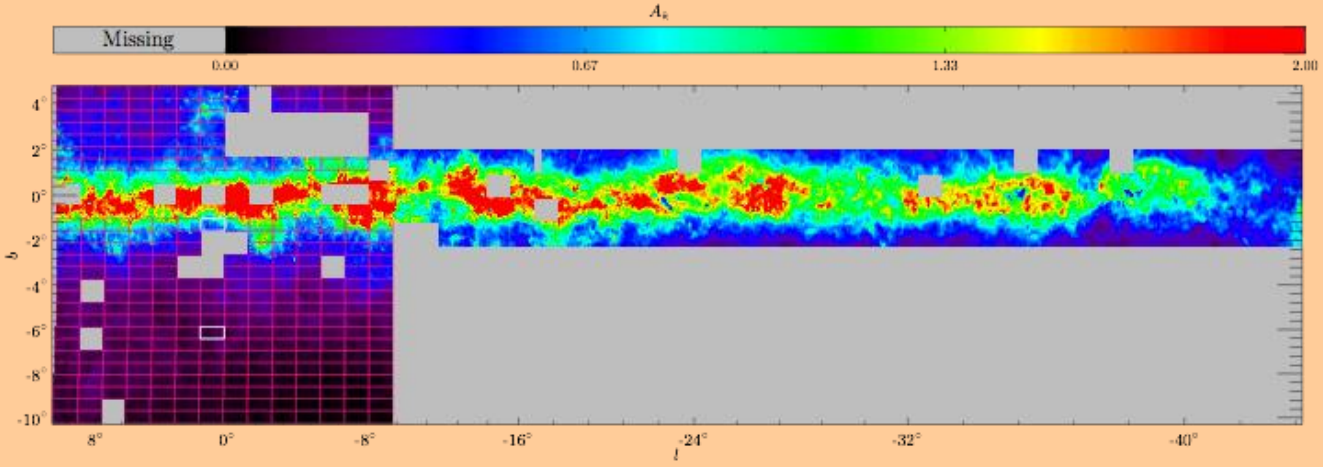
Talk by Mignard

Inner Galaxy Studies in Near-Infrared



Dust extinction: A_V = 1mag/kpc in local disk
Into Galactic Bulge and Center A_V = 2-40 mag
But "only" A_K = 0.2-3.. Crucial role of
NIR Surveys e.g. 2MASS, UKIDSS, VVV, APOGEE





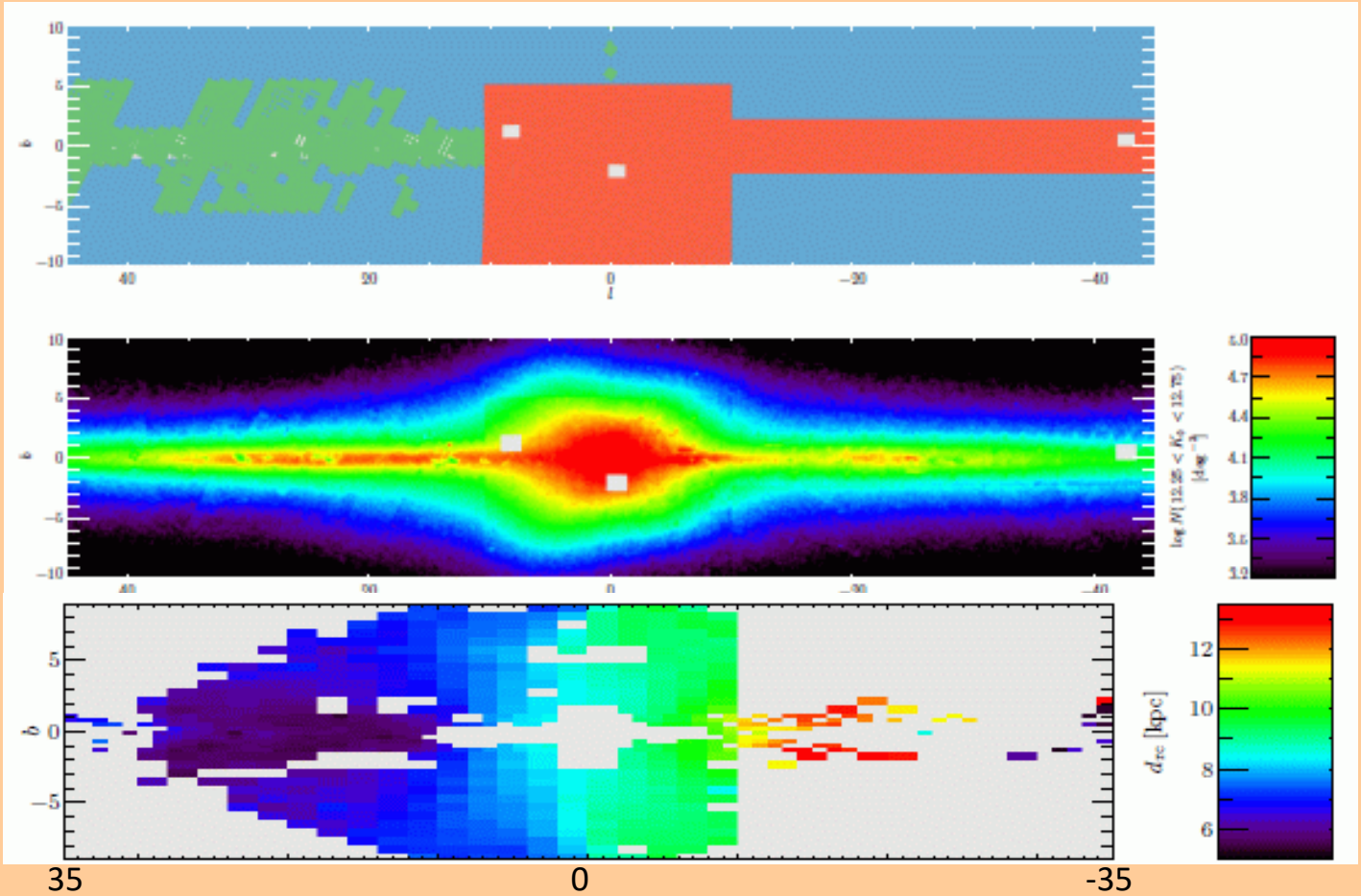
COBE NIR photometry (1990s)

VVV survey ~ 4 mag deeper than 2MASS
⇒ stellar distances
⇒ proper motions

NIR Surveys: Inner Galaxy in K-bd Star Counts

UKIDSS – VVV – 2MASS – GLIMPSE matched, extinction corrected, star-by-star, 12.25<K<12.75 bright star count map: Wegg, OG, Portail '15

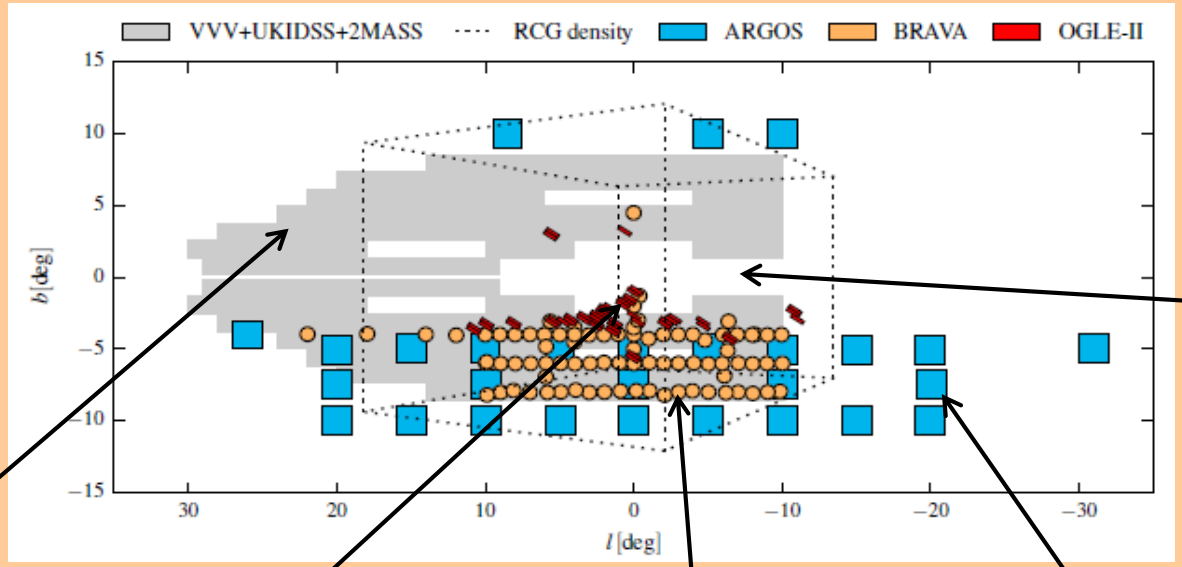




Mean distance map

In progress:
VVVX survey
(PI D. Minniti)
southern disk

Bulge Spectroscopic Surveys



+ rotation .
. Curve

3D density of RCGs

Magnitude Distributions

Proper motion dispersions

Mean radial velocities and dispersion

Mean radial velocities and dispersions as a function of distance

BRAVA, ARGOS, APOGEE, GIBS, GES surveys now provide ~2x10^4 radial (los) velocities and chemical abundances, ages in progress, now down to |b|=1.4 dg

Future: PM from VVV and Gaia, v_{rad} from APOGEE, WEAVE, 4MOST, MOONS (NIR)

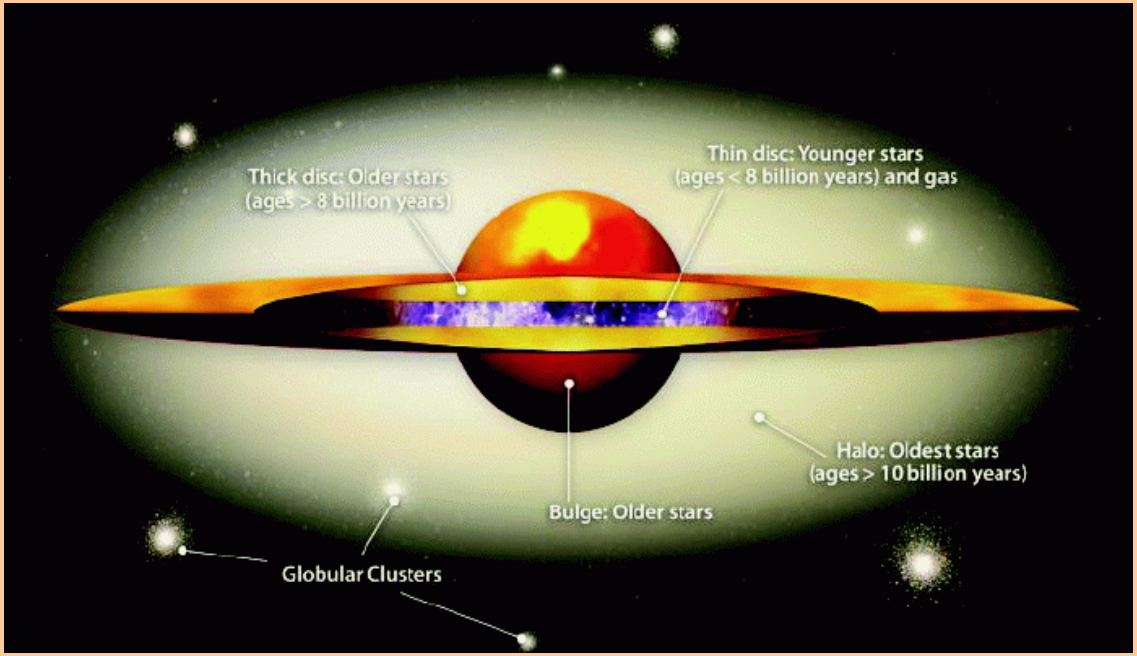
Milky Way Large Scale Structure

With large stellar surveys, we have been making tremendous progress in mapping out and understanding our "home galaxy"

The classical picture has changed:

- The Milky Way (MW) is a barred galaxy
- Most of the bulge formed from the disk
- The MW may or may not have a small, primordial bulge

Credit: IOA Cambridge



- The thick disk is a separate component in [α/Fe] which is prominent in the inner Galaxy and may be connected to the bulge
- Stars in the thin disk can move far from their birth places
- The stellar halo contains lots of substructure due to its accretion origin

J Bland-Hawthorn & OG 2016, ARAA

2. The Bulge & Bar

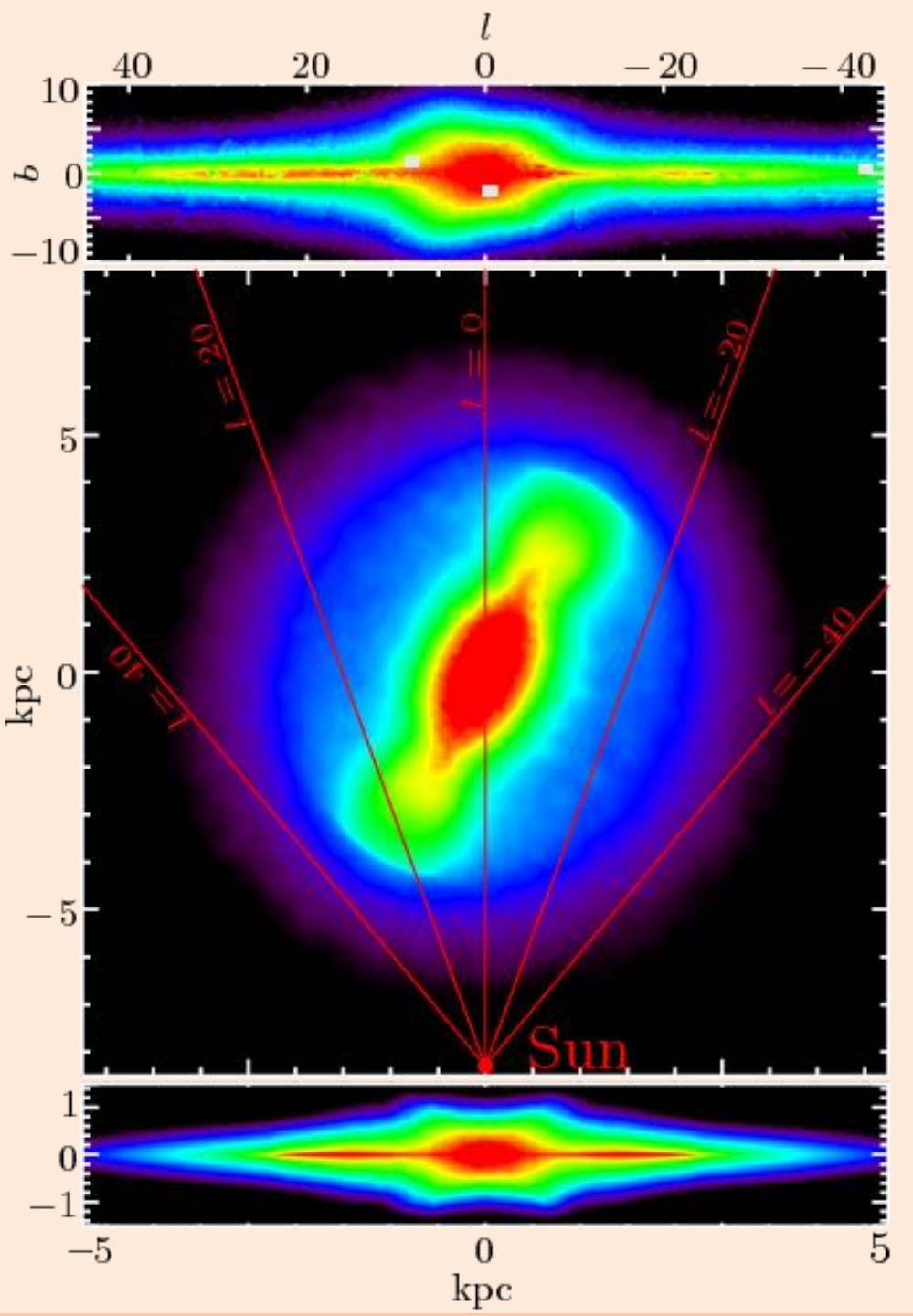
- Bulge looks like typical Box/Peanut bulge, as in external galaxies
- Shape naturally similar to N-body simulations where the central part buckles into a B/P bulge leaving a thinner long bar outside
- Based on RCG star data from UKIDSS VVV, 2MASS, with star-by-star extinction corrections

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

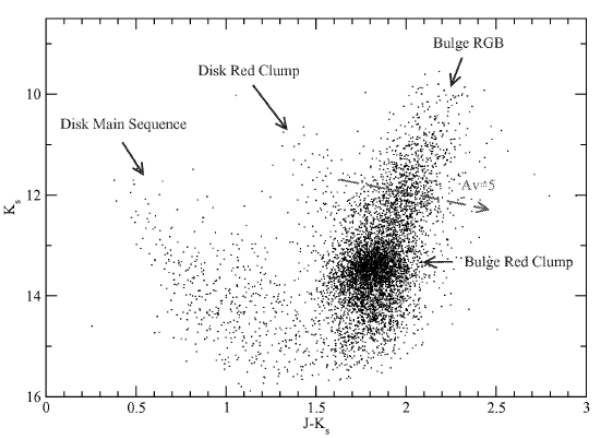
➢ Estimated bar length 5.0±0.2 kpc, then corotation radius ~ 6.0 kpc

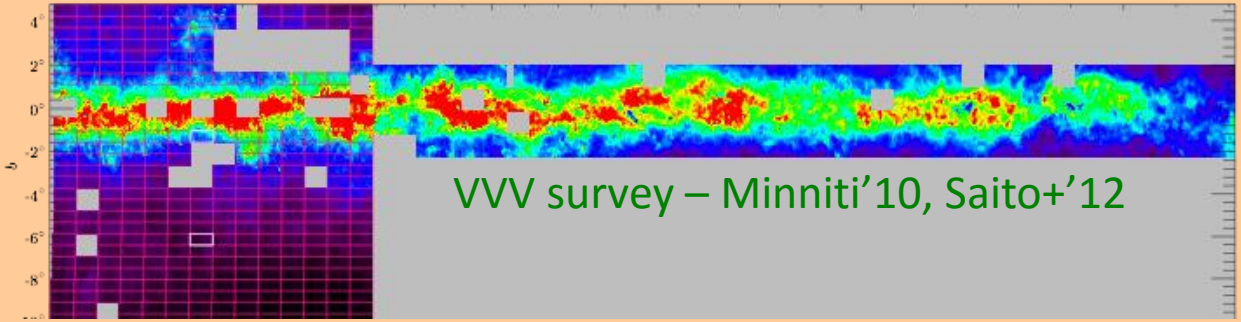
Shape of the bulge: Wegg & OG ‘13

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

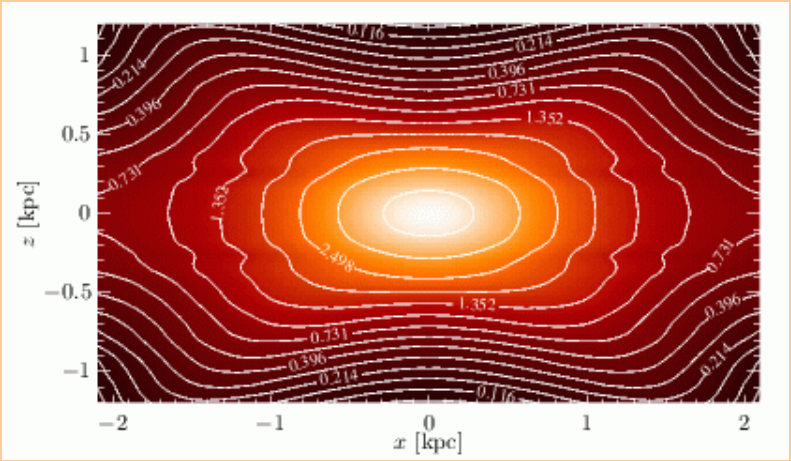


Red Clump Giant Distances & Bulge 3D Density

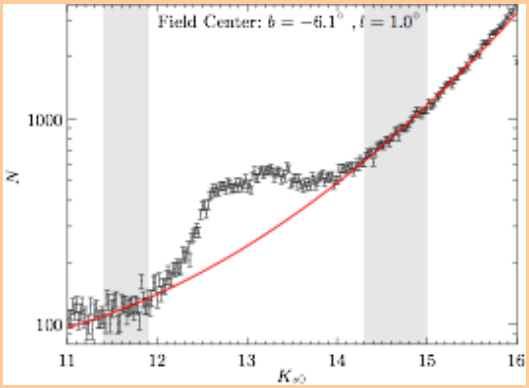


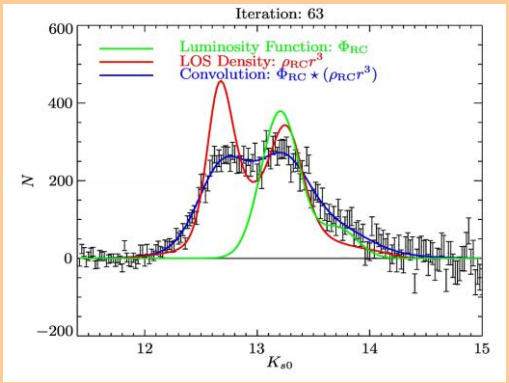


RCG as tracers since Stanek+'94



Wegg & OG 2013

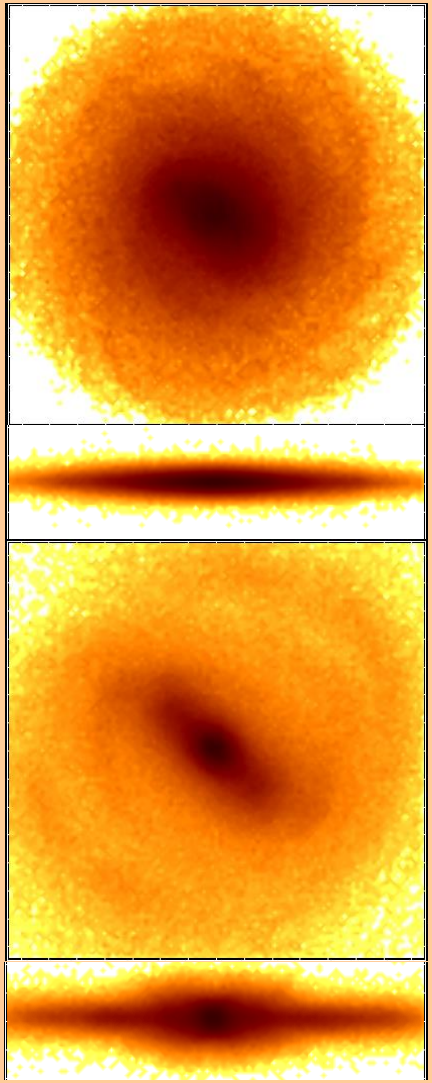


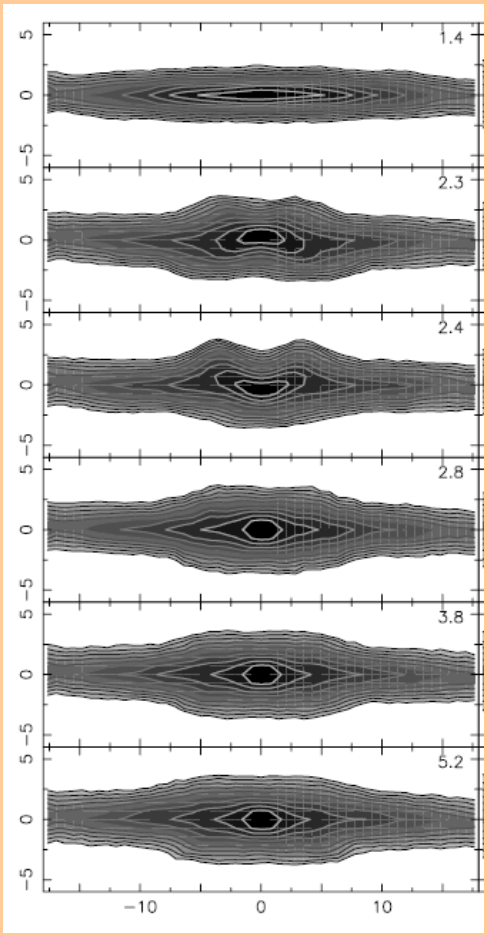


RCG: $\sigma(K_s)$~0.17, $\sigma(J-K_s)$~0.05, $\Delta N_{cl}/N$~10% in [0.02,1.5] $Z_\odot$, spread because of age (~0.03/Gyr at 10 Gyr), & metallicity (-0.275/dex, σ~0.11 for bulge FWHM) (Salaris + Girardi '02), prominent in 90% of ARGOS sample (Ness+'13)

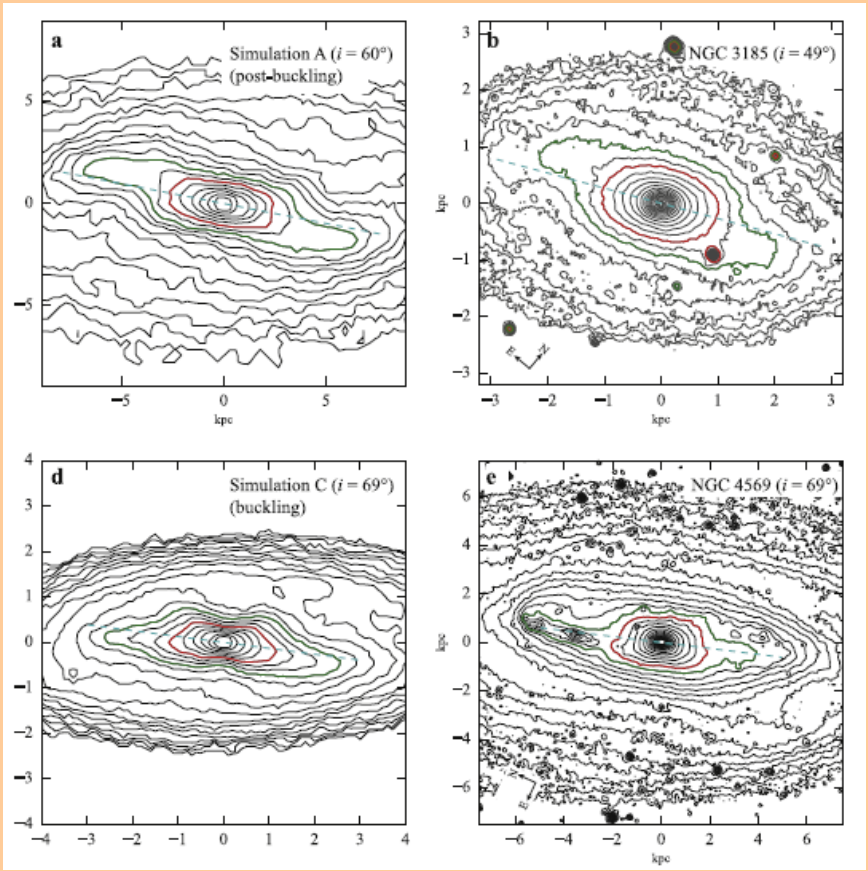
Density map from ~8 Mio RCG in 300 VVV fields in the bulge, |b|>1°. ~10% density error in most of the bulge. Extrapolated into crowded Galactic plane by Portail+'15

Buckling instability and box/peanut bulges





Martinez-Valpuesta+'06

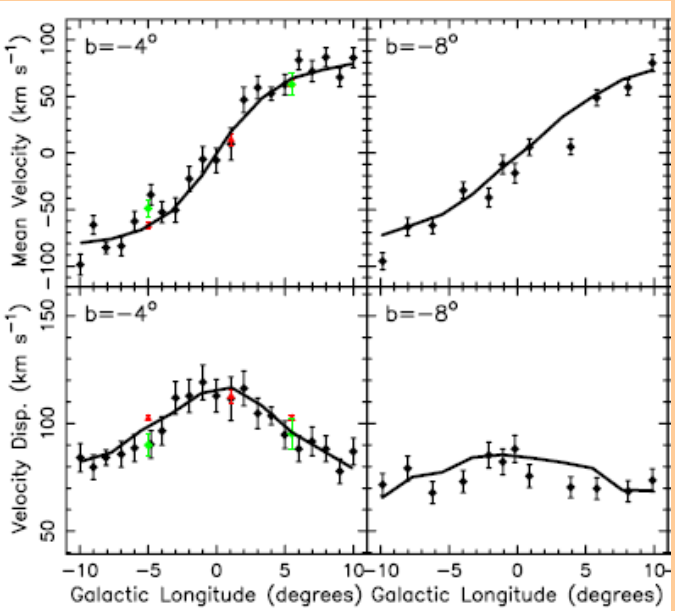


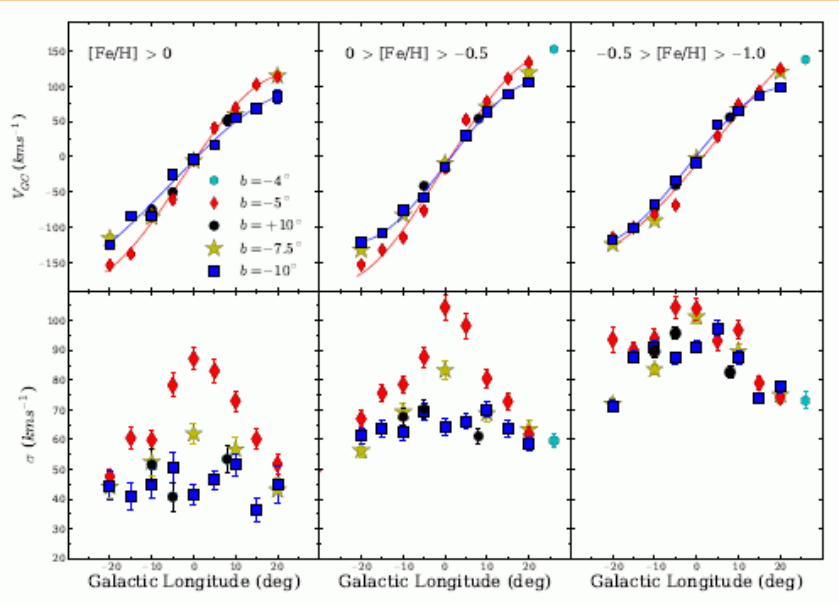
Erwin+Debattista'16

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

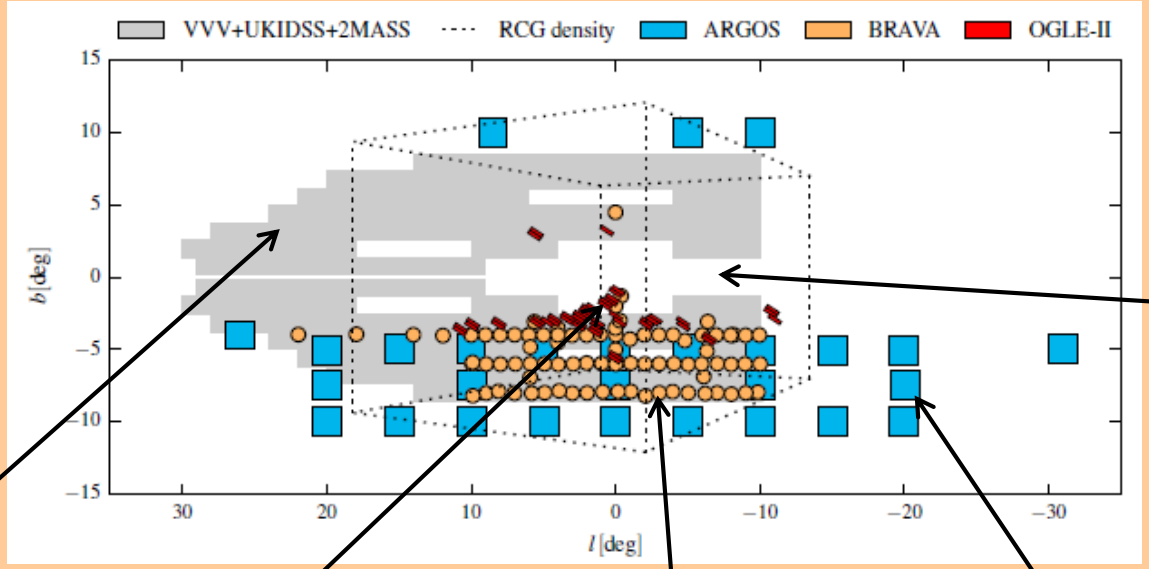
Bulge Kinematics & Metallicity





- 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).

Need for Dynamical Models - Bulge/Bar



+ 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

- Star counts can be described by a density model. But stars move along their orbits. Therefore we need to combine with velocities.

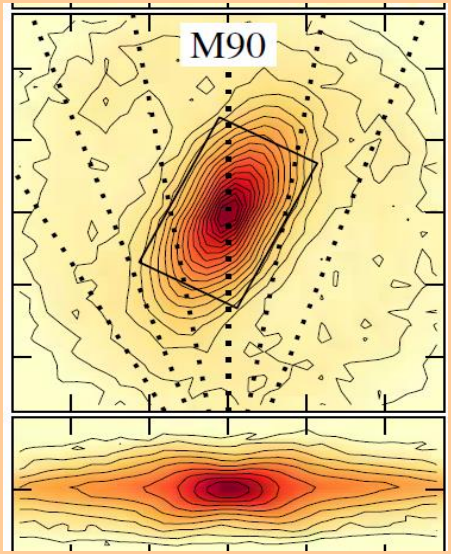
- Star counts and velocity data need to be described by a dynamical model.
- Even though not strictly true, need to start with equilibrium dynamical model.
- This determines stellar DF on orbits. For DF|M $\Leftrightarrow$ x,v, or ρ, σ, β but is 3D.

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

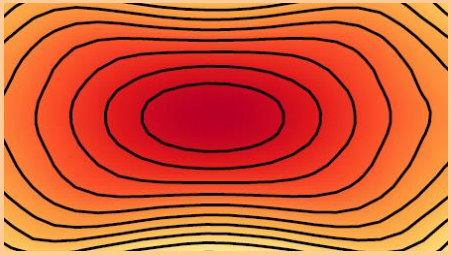


"Observe"

Model observable



Real data



Compare & quantify

Evolve N-body model forward for dt

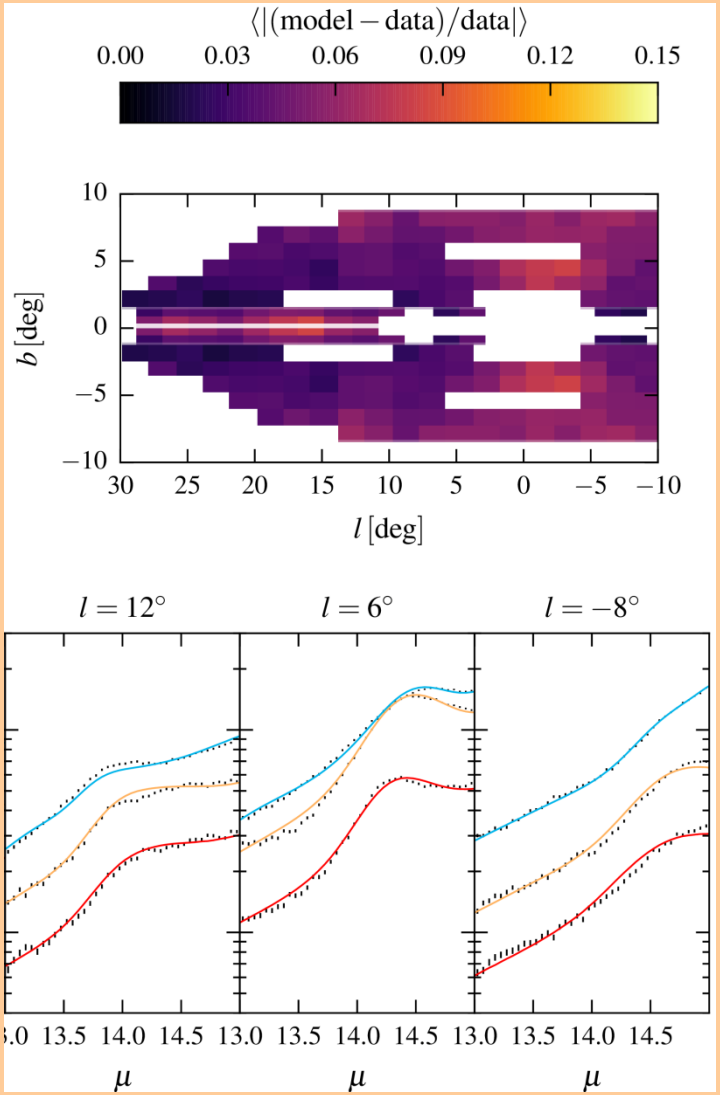
$$\frac{dw_i}{dt} = \varepsilon w_i \frac{\partial F}{\partial w_i}$$

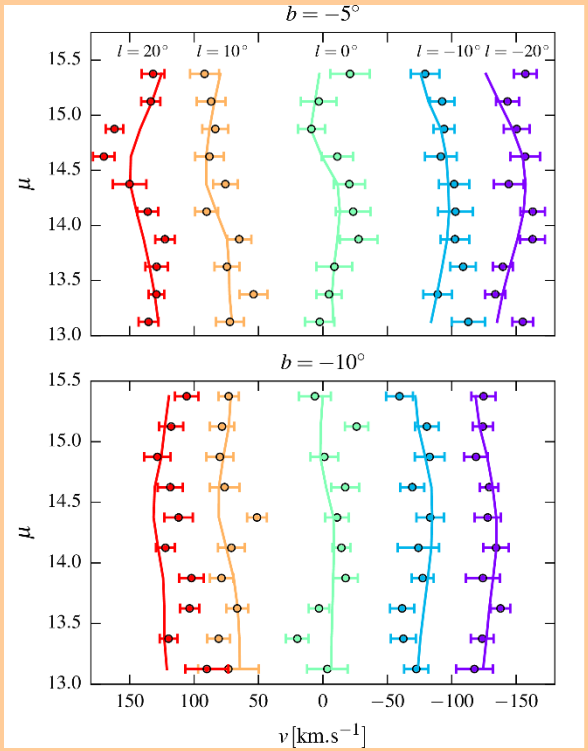
Profit function

Change the particle weights

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

Some of the Data Fitted

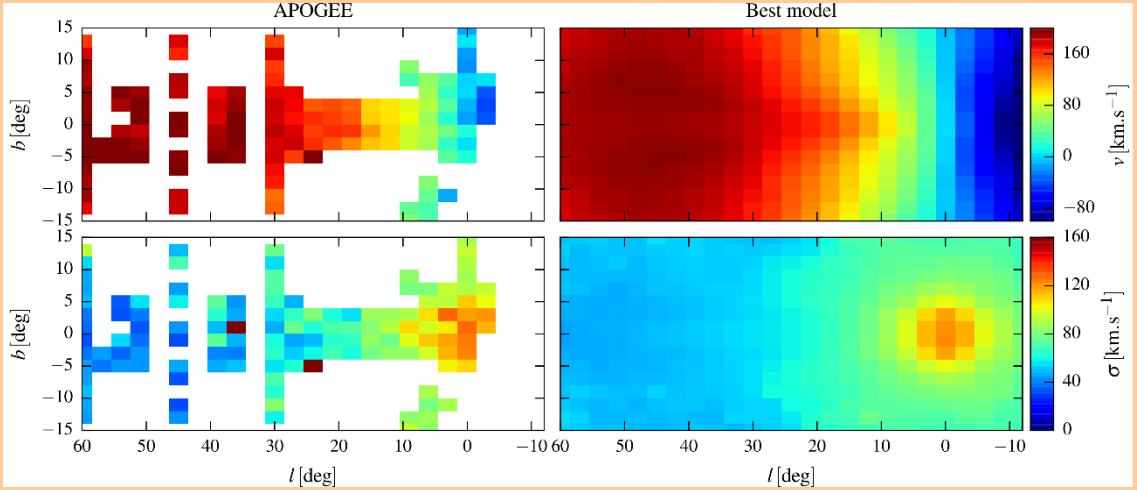




ARGOS: Observational selection criteria (Ness+'13) & mapping stars into distance bins using isochrones

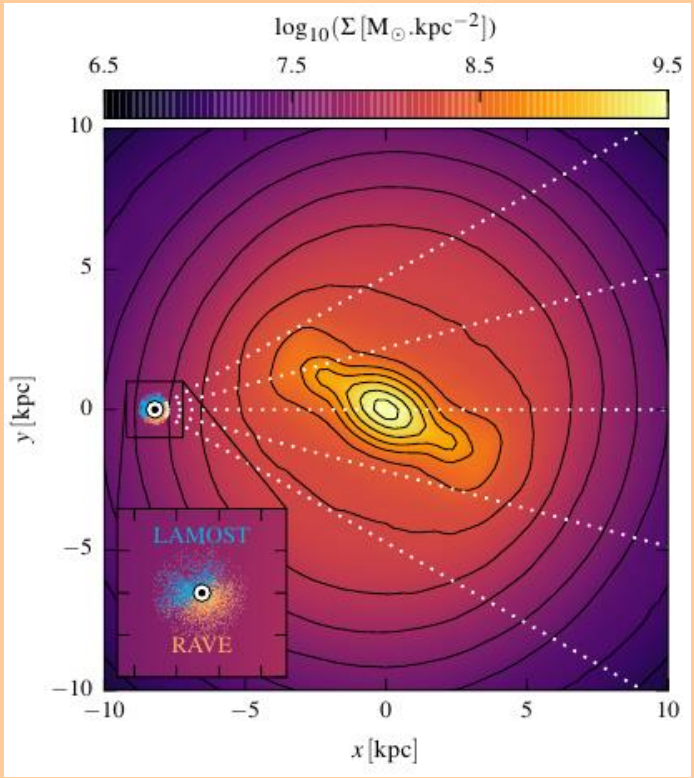
Wavy structure of v(μ) shows streaming velocity field within the bar

APOGEE predicted



Portail, OG , Wegg, Ness 2017a

The Barred Milky Way



Portail, OG et al 2017a

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

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

Length of bar Rb = 5.0 kpc (± 0.2)

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

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)

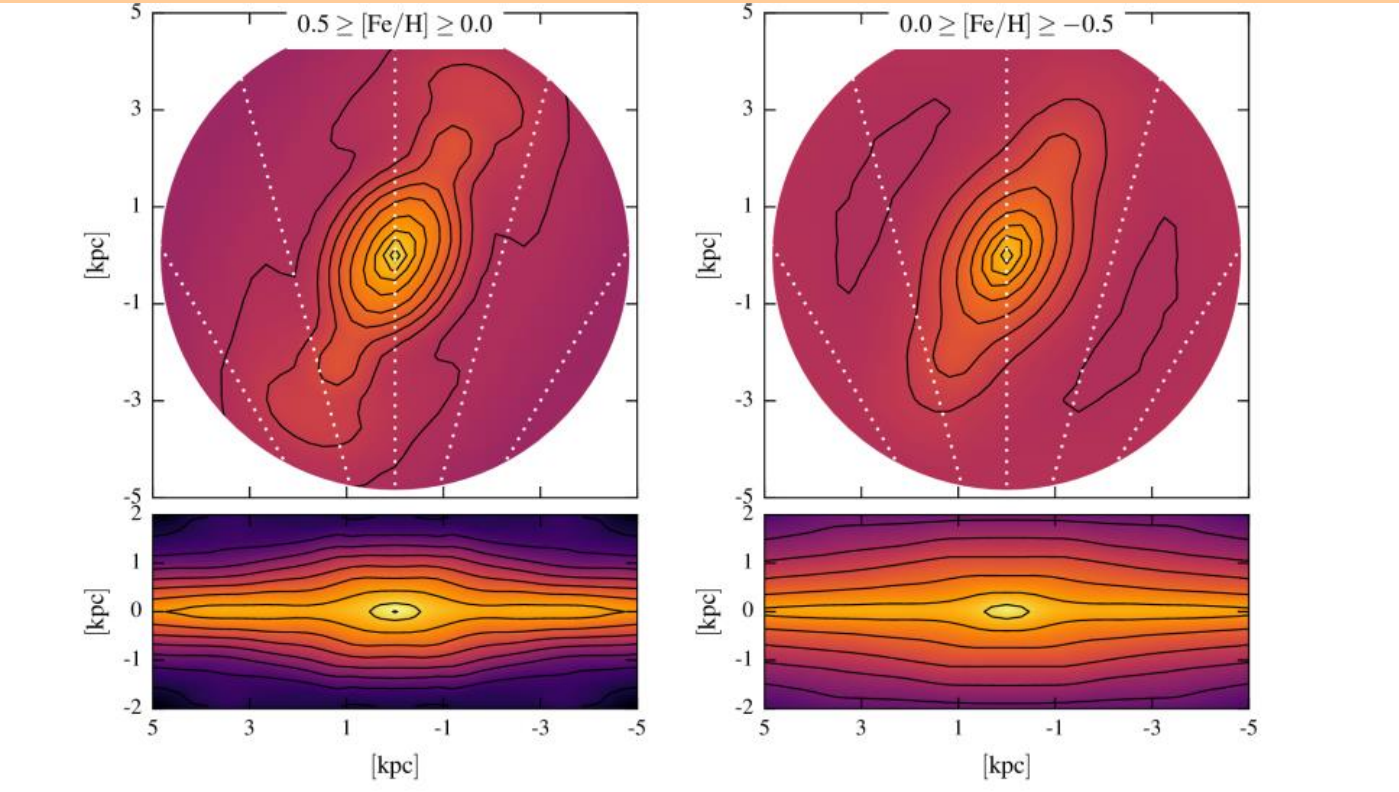
Inner disk (<5.3 kpc) $M_{id} = 1.3 \times 10^{10}$ Msun (± 0.1)

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

Bulge stellar mass fraction ~30%

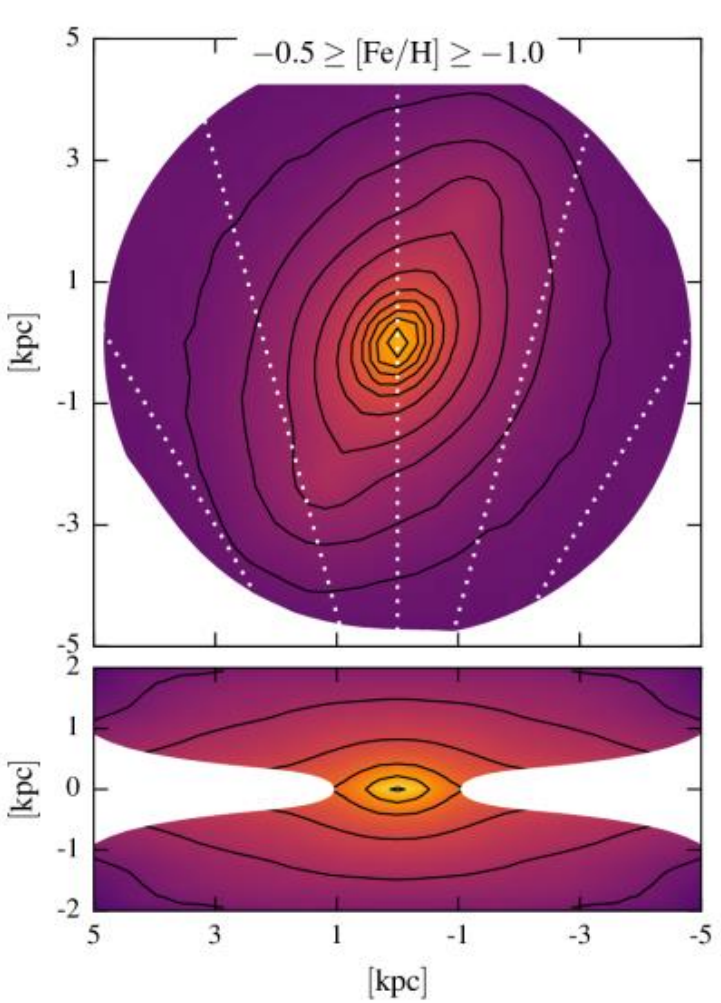
Chemo-Dynamical Bulge Models

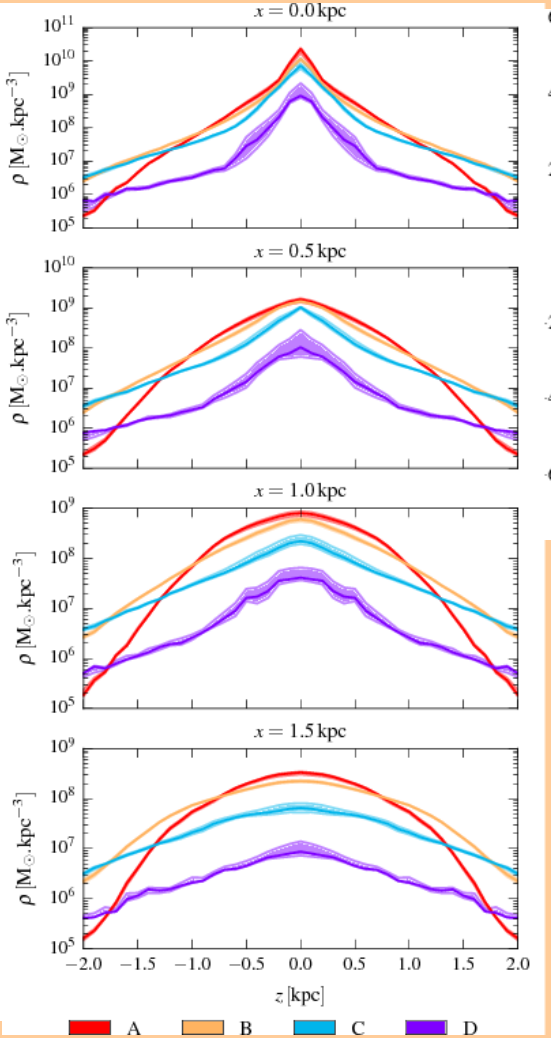
- M2M particles carry [**x, v,** f(M)] Portail et al 2017b
- MDF f(M) parameterized as MGE with indiv. Gaussians adjusted to ARGOS components
- Particles projected into obsv space using isochrones and M-dependent selection fn
- Particle metallicity weights w_c adjusted by comparing with similar data in distance bins

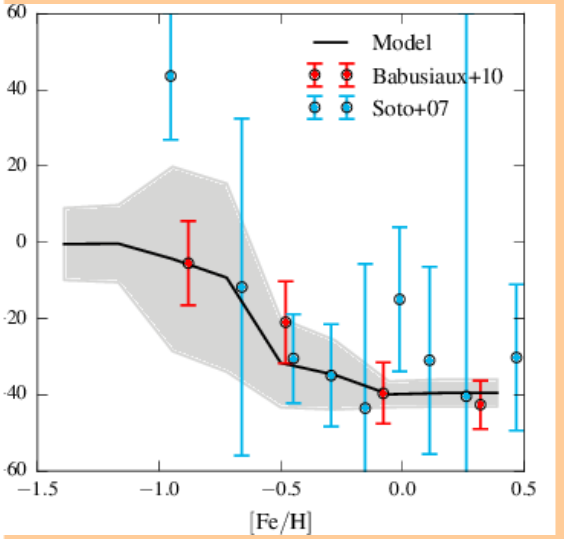


- The supersolar A bin has very pronounced bar ends. Contains younger stars?
- B + A contribute roughly equal number of bar-supporting orbits. Stars in B have higher v,σ and could come from further out in the initial unstable disk Ness+'13, di Matteo+'14

The Intermediate-Metal-Poor Bin C



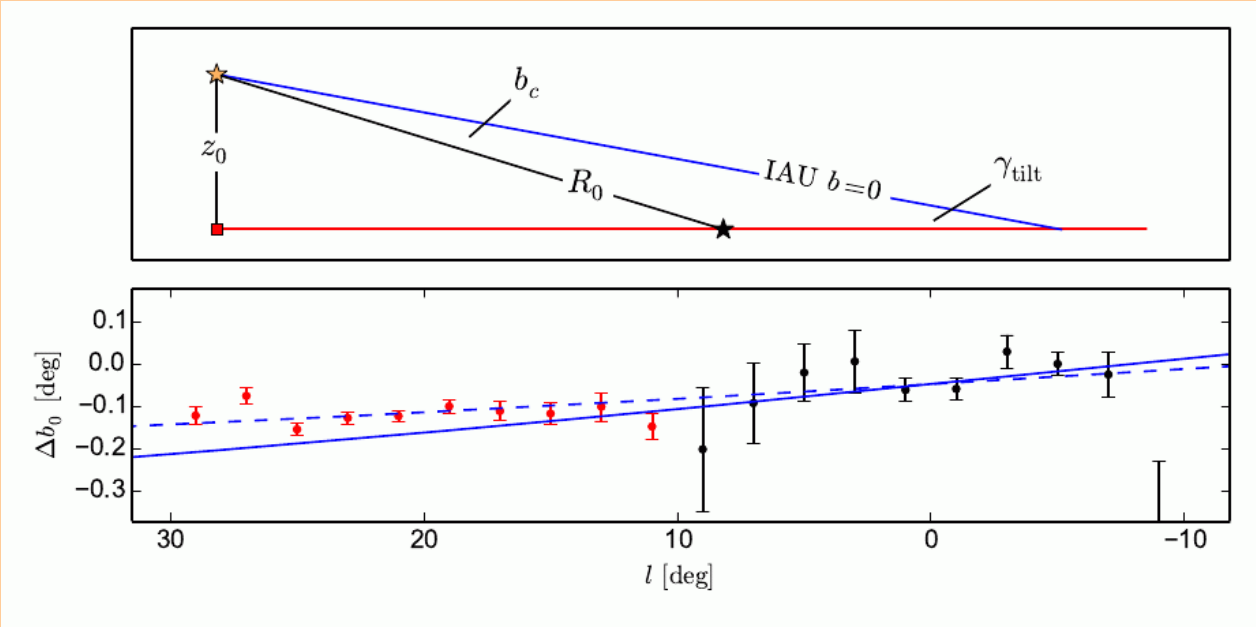




Portail et al 2017b

- 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.

The Peaceful Inner Galaxy !?

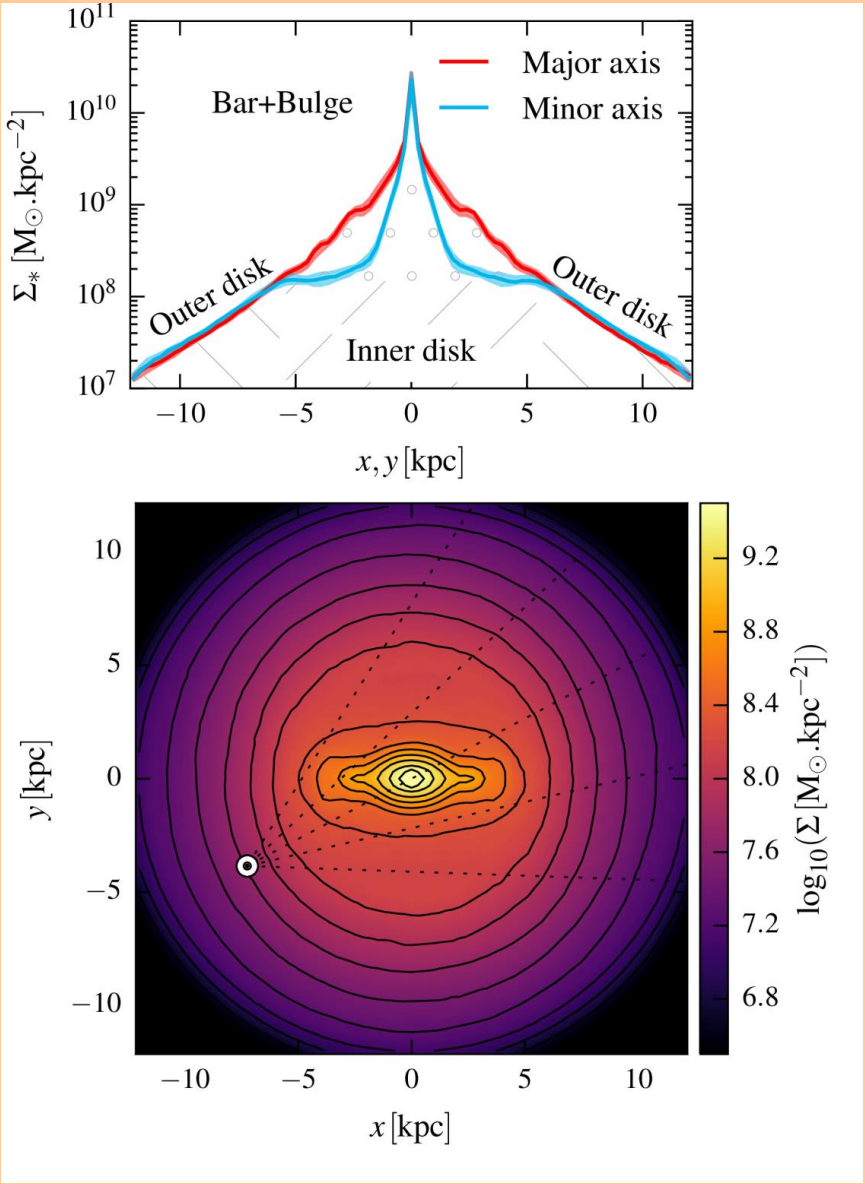


Measured latitude offsets – Wegg+15 Tilted Galactic Plane – Goodman+14

- 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 length of ~5 kpc, the bar seems aligned with Galactic plane to 0.1%

Versus coherent motions, bending & breathing in the disk near Sun – William+13, Widrow+'17 Gaia will clarify ref frame and how this fits together

3. The Disk
Inner Stellar Mass Profile from Model



Outer **disk surface density** meets bulge minor axis profile near end of bar; inner disk density nearly flat. Therefore low **stellar mass:** in the inner 5 kpc

- **1.3×10^{10} $M_\odot$** in the **inner disk,**
- **0.2×10^{10} $M_\odot$** in the **nuclear disk**

with typical error **0.1×10^{10} $M_\odot$**

However, comes from modelling all the data; there is not much data that specifically constrains the disk on the side of the bar

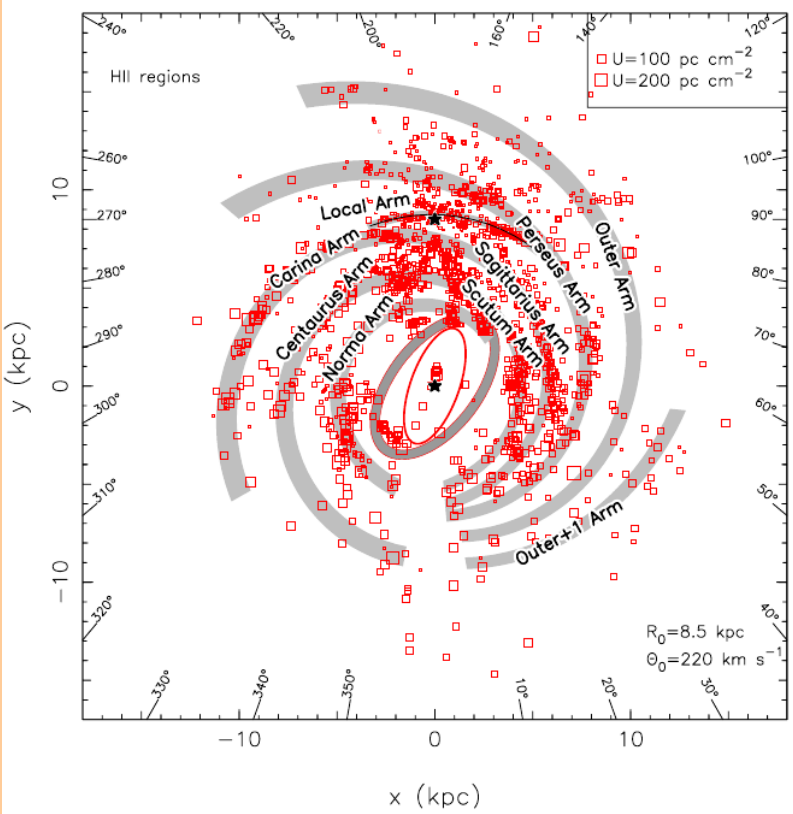
Tracing Spiral Arms with HII Regions & Masers

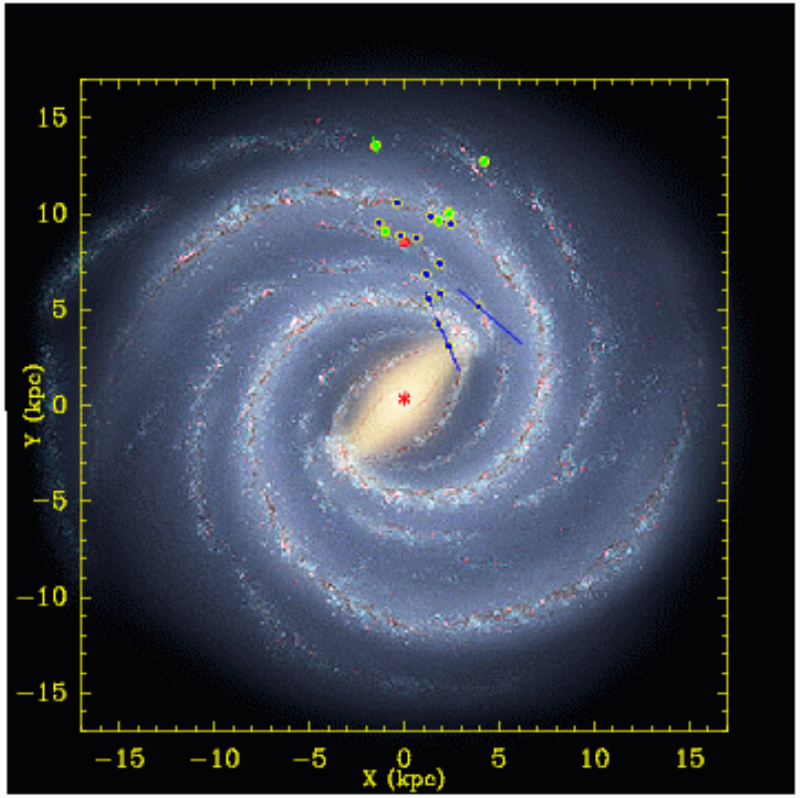
NB: little information on spiral arms in stellar mass (as for density wave)

- Left: pattern deduced from HII regions with approx. distances (e.g., Georgelin & Georgelin 1976, Taylor & Cordes 1993, Hou & Han 2014):

  Perseus, [Sagittarius/Carina], Scutum/Centaurus, [Norma/Outer]

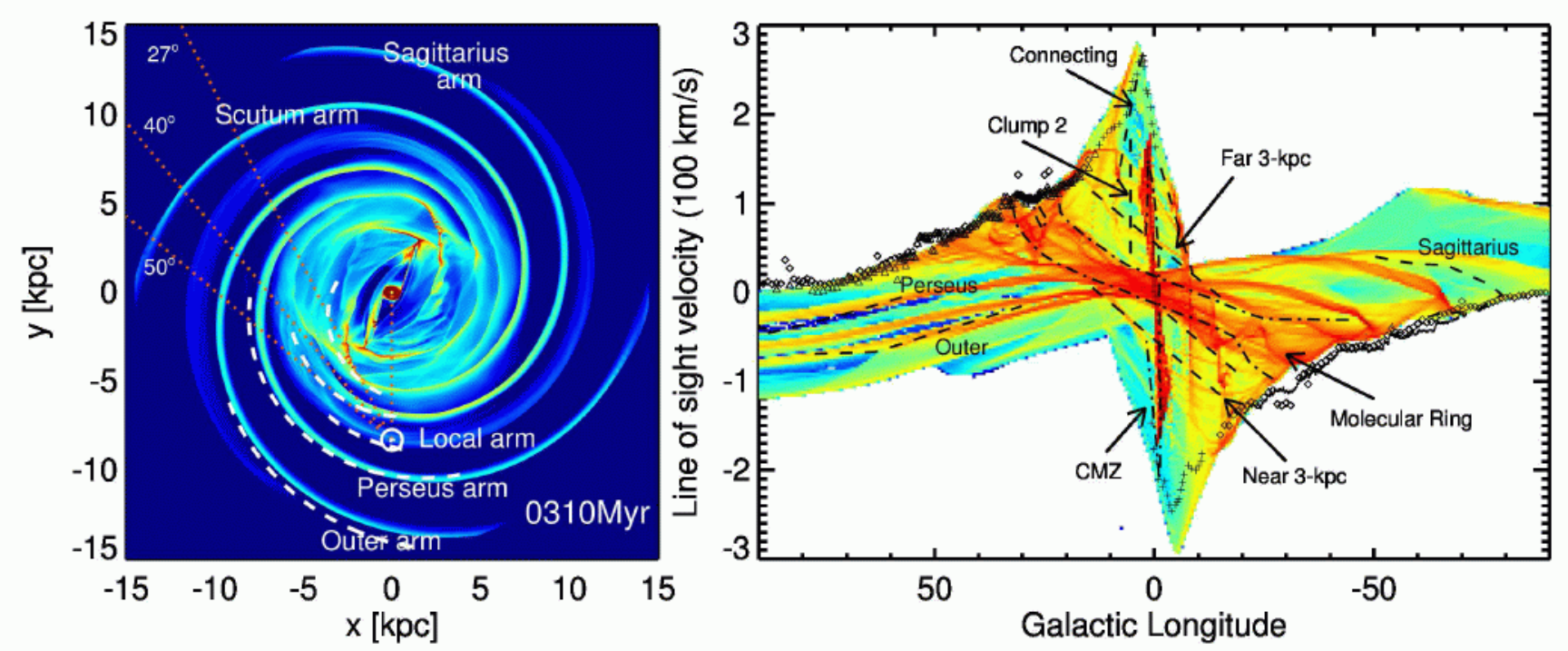
- Right: Artist picture (R.Hunt) and superposed SF regions with accurate parallaxes (Reid et al 2009)





Gas Dynamical Models – Potential and Ω_p

- Gas-Flow Model in potential of b/p bulge, nuclear cusp, approx long bar, spiral arms, for low Ω_p , $R_{cr} \approx 6.5$ kpc
- Reproduces many features in (l,v)-plot

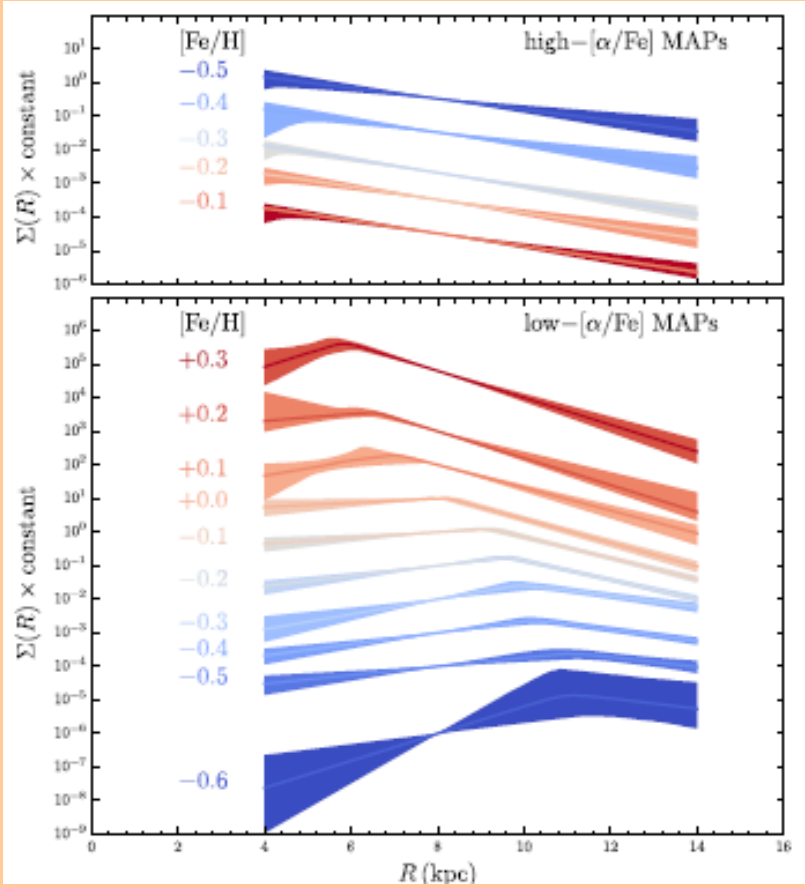


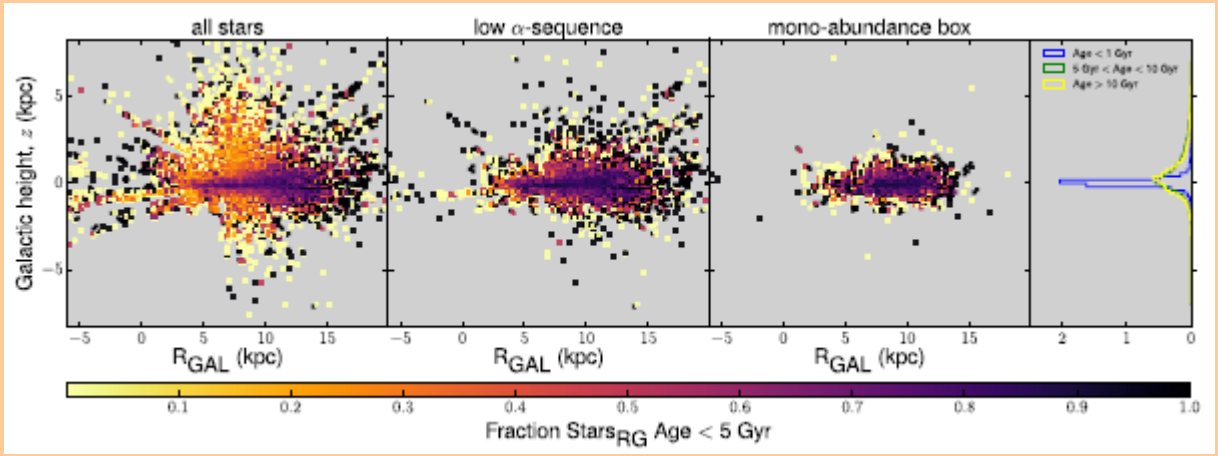
Li, OG, Shen +2016 ApJ, also Sormani, Binney +2015 and many previous

[Athena MHD code, 14.6pc resolution, 30kpc×30kpc box, zero gradient except for P bdy condition, 2d isothermal c=10km/s, non-selfgrav., unmagnetized gas]

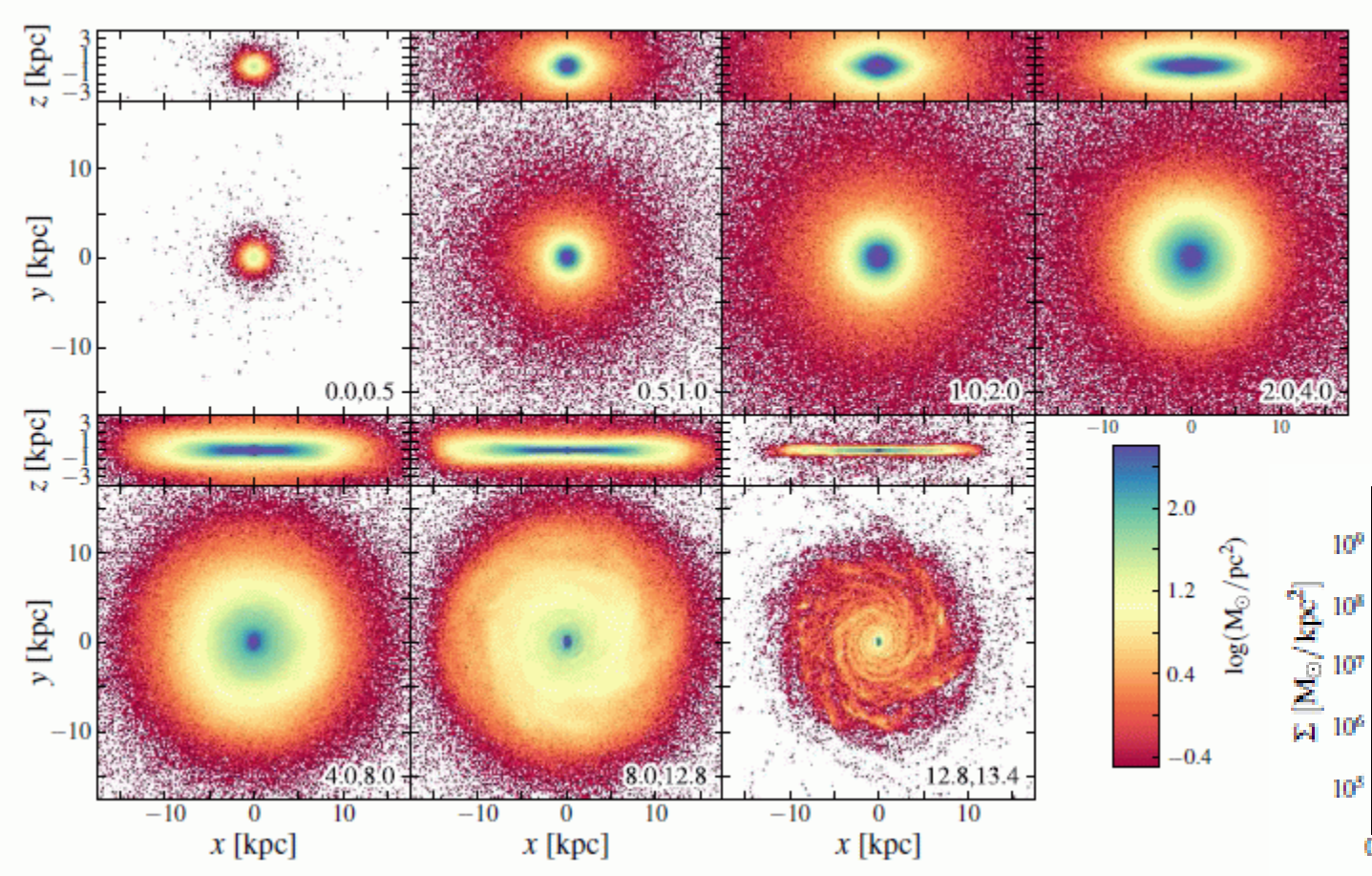
Chemical and Age Structure from APOGEE

- Right: Surface density profiles for high-α and low-α disk components Bovy+'16
- Below: fraction of your/intermd age stars with Gal. radius Ness+'16

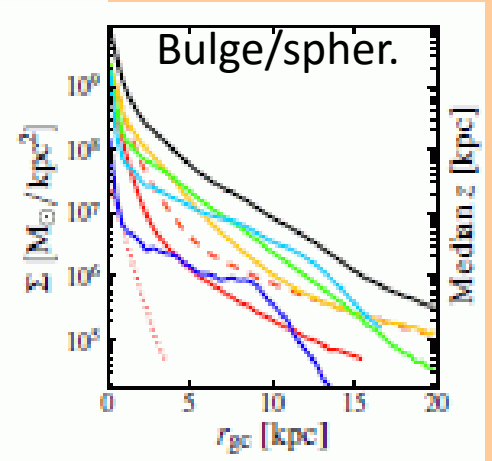




Predicted Distribution of Stars selected by Age



Bird+'13
Simulation as in Guedes+'11 but with 0.5× SF efficiency

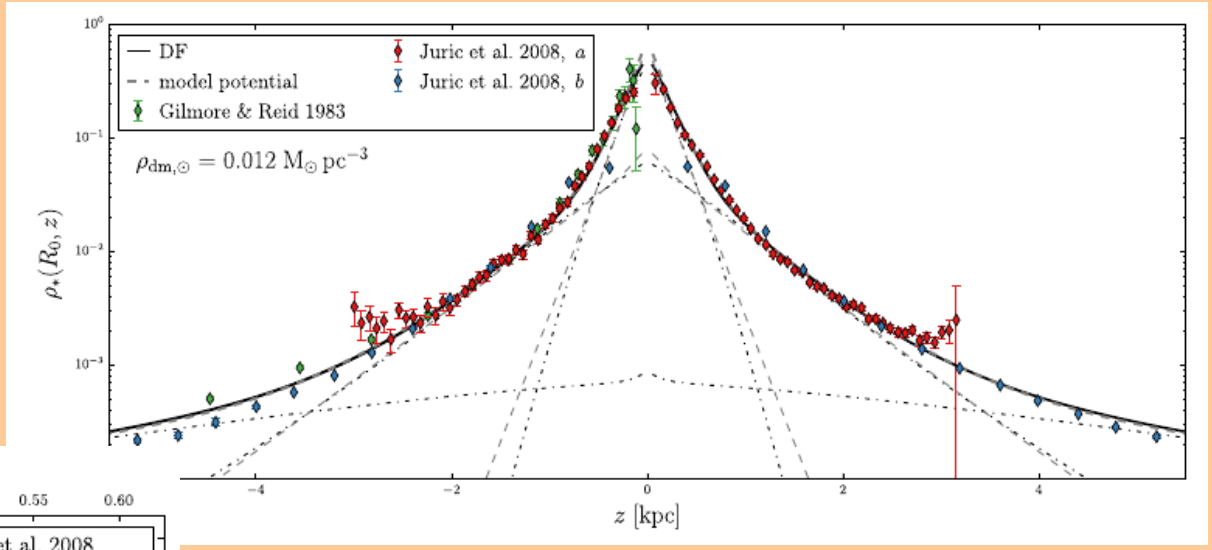


- Successive generations of stars from from inside out and from upside down.
- Essentially unbarred galaxy showing the old bulge/spheroid

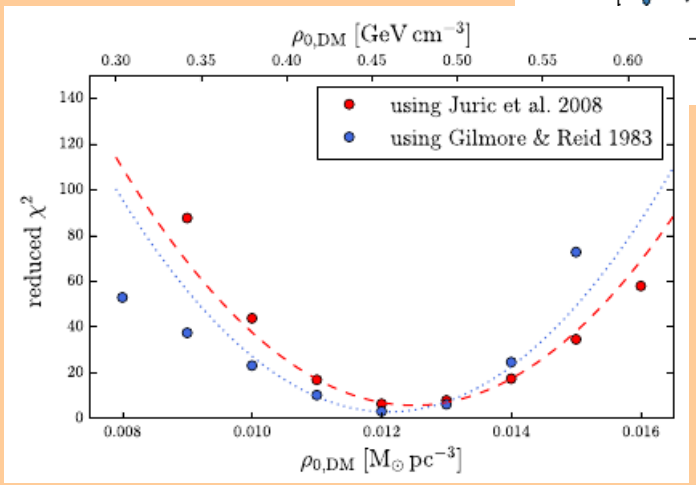
Local Disk Dynamics in SNd

Large body of modelling work by Binney's group in Oxford understanding

- Thin/thick disk kinematics from GCS, RAVE
- metallicity-dep. APOGEE data with extended DFs
- stellar and DM mass density



Piffl, Binney et al '14



Further issues

- disk wobbling – local streaming v's
- local velocity distribution
- Influence of spiral arms

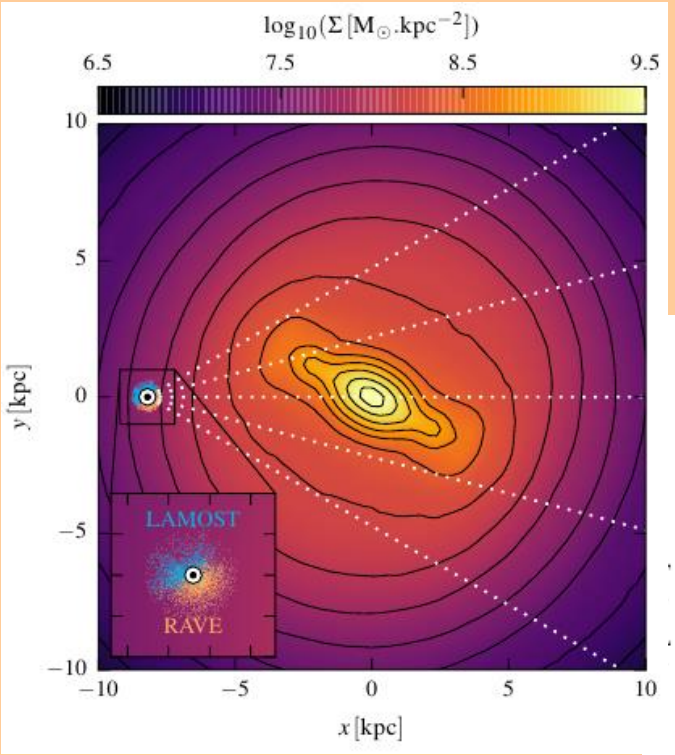
Much progress expected from Gaia DR2

SNd: The Hercules Stream

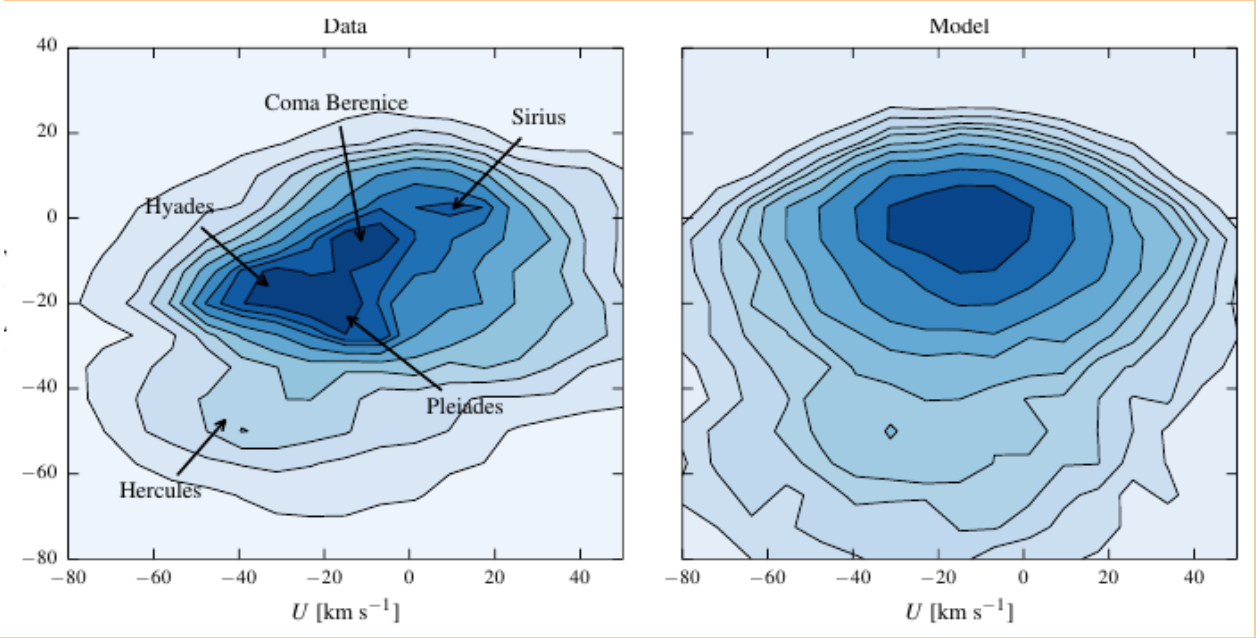
So far, the Hercules stream in the SNd was identified with OLR orbits near the Sun; this is incompatible with Ωb=40 km/s/kpc when the OLR is at 10.5 kpc (Dehnen'00, Antoja+'14,Monari+'16)

Could it be due to the Galactic bar? w or w/o spiral arms?

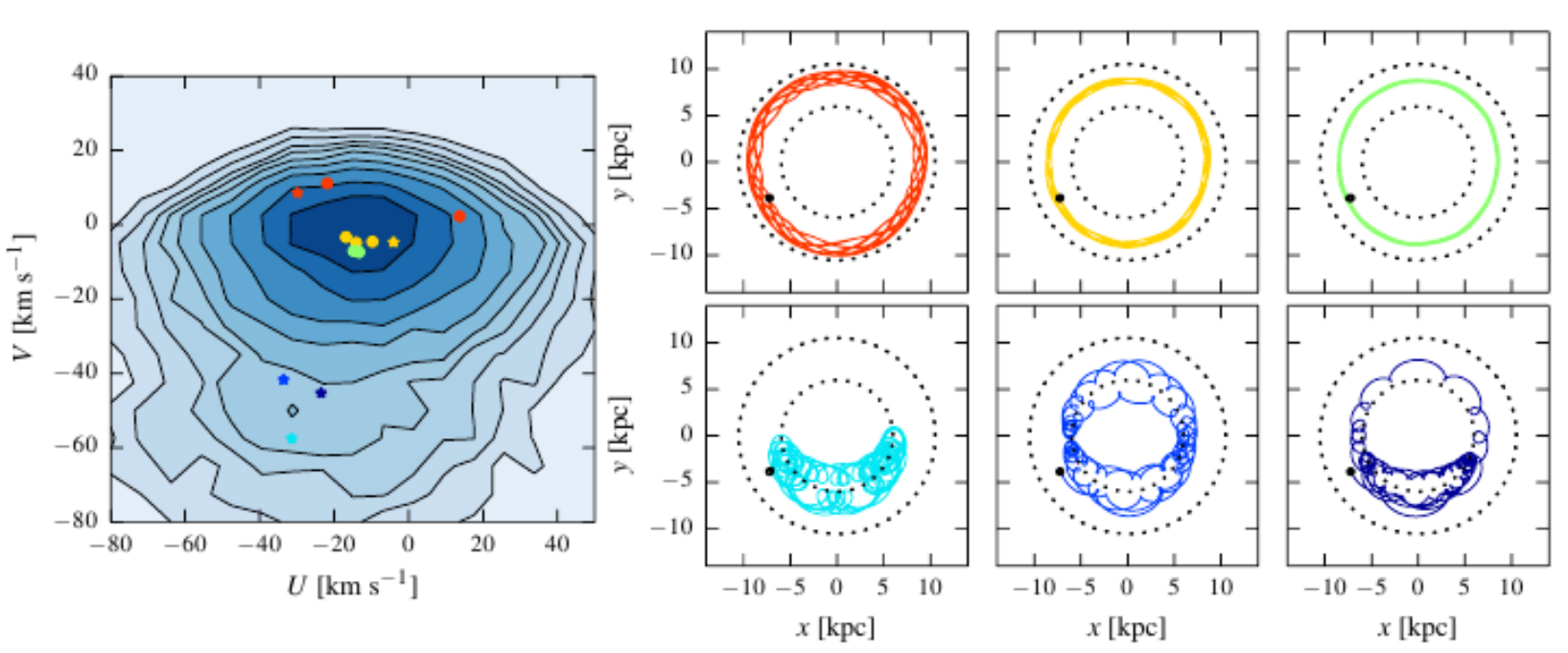
- Cross-matched with Gaia TGAS-RAVE-LAMOST
- Shows main bar-streaming component as well as low-V component consistent with (U,V) position of the Hercules stream



Perez-Villegas et al 2017



What Orbits Make Hercules in a Slow Bar

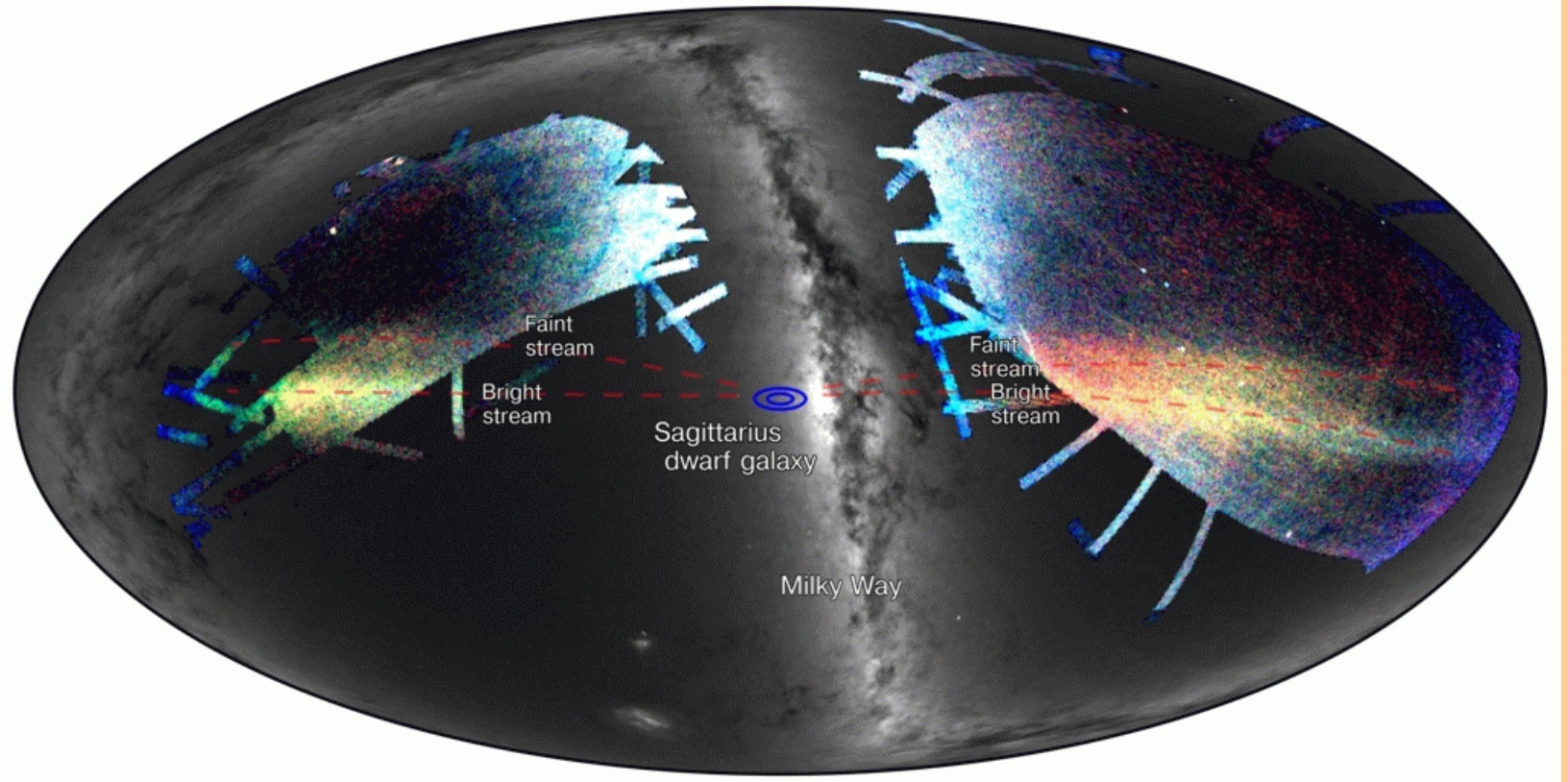


Perez-Villegas et al 2017

- 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

Need to test by looking at larger portions of the local disk – this will be solved by Gaia DR2

4. The Stellar Halo



A complex structure with many components and substructures, unrelaxed and of variable shape, composed of different stellar populations, still accreting matter

Map of MS/MSTO stars from SDSS-DR8 with colour roughly showing distance in 10-50 kpc (blue-green-red with incr D). Sagittarius streams, Koposov et al. 2012

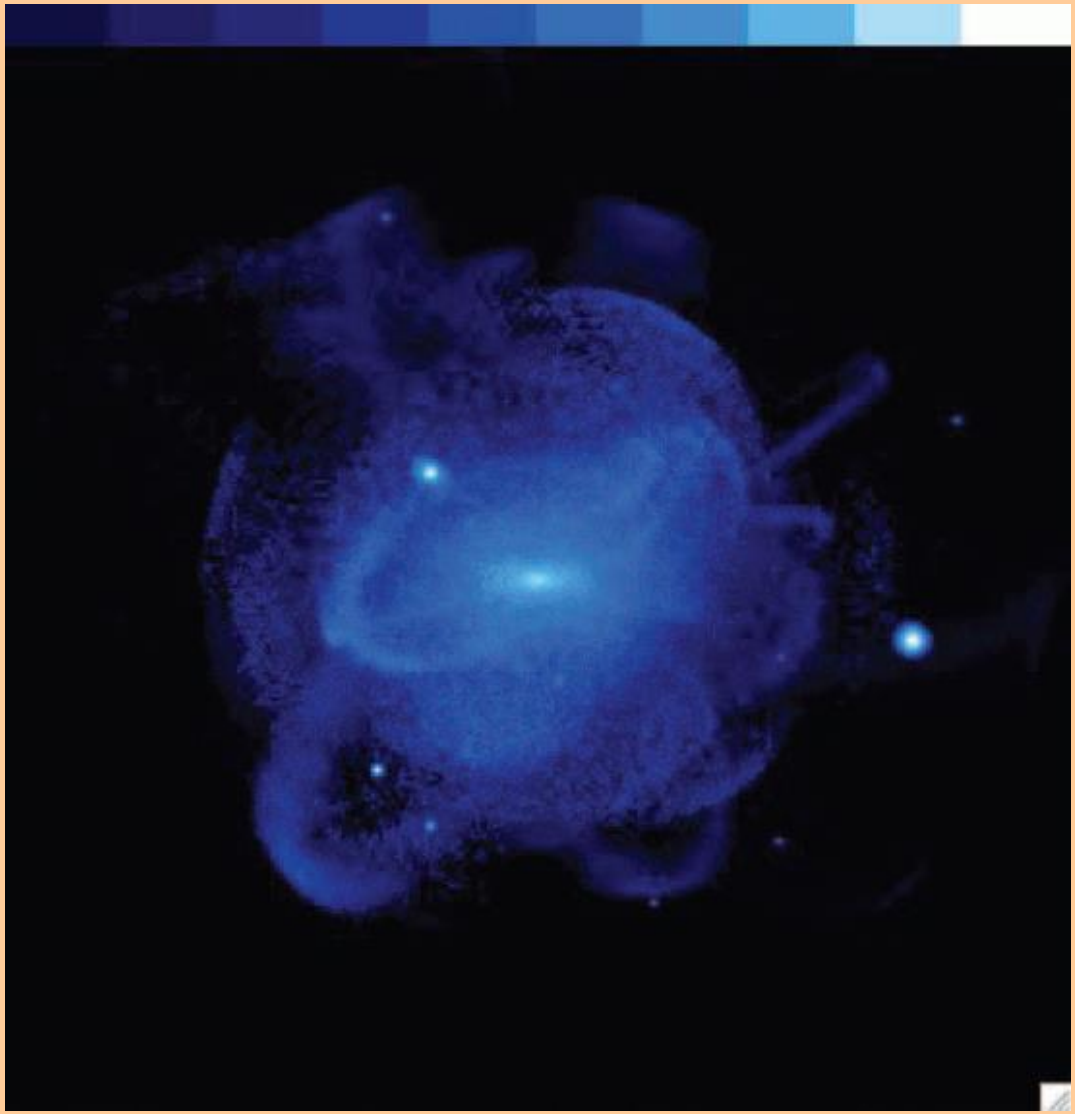
Predictions from Hierarchical Cosmological Model

In the hierarchical model, MW should have accreted ~100-200 satellite galaxies which would mostly have been disrupted by the tidal field

⇒ Accreted stellar halo

One of the halos based on the modelling of Bullock+Johnston 05 (using simplification of idealized bulge+ disk+halo potential, but confirmed by self-consistent models, e.g. Cooper+10)

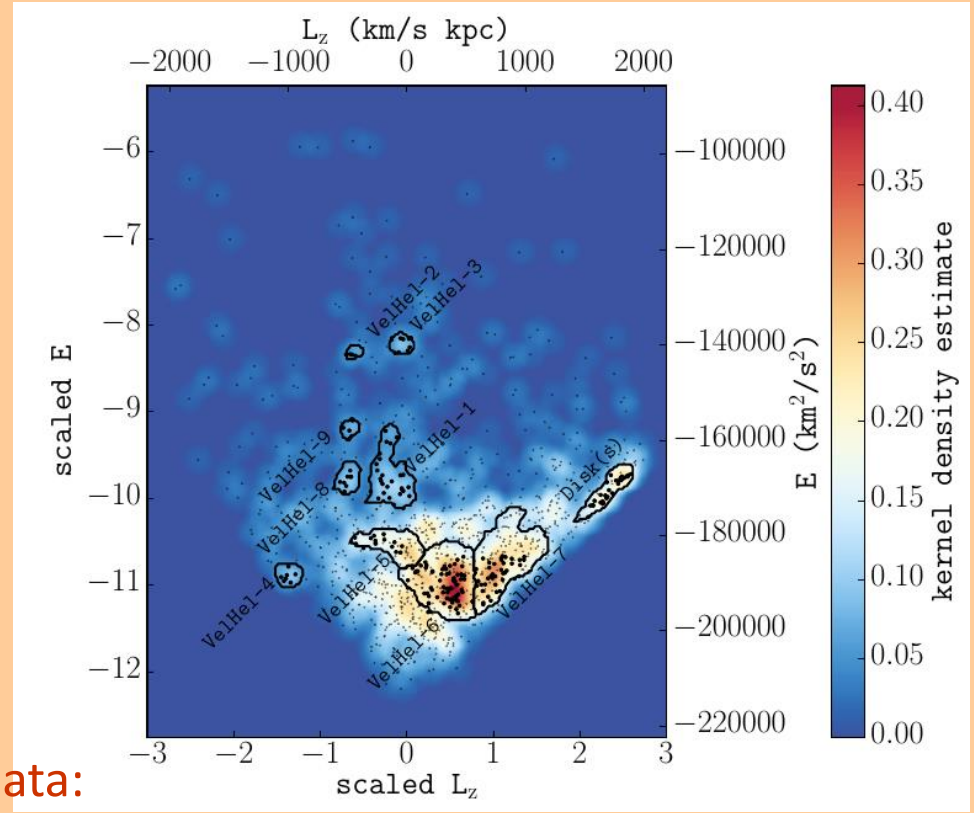
⇒ Irregular structure due to shells and tidal streams



Learning the Halo Accretion History

The stellar halo contains only 1% of the MW's stellar mass, but contains important clues to the MW's accretion history

SDSS data: most of the halo stars in substructures Bell+'08; 4 big ones +?



Goals with 6D phase-space Gaia DR2 data:

- Identify many more substructures, streams, tails, etc
- Maybe best in integral (E,Lz) or action space Helmi+de Zeeuw '02, first identification with DR1 in figure from Helmi+'17
- Characterize these streams in dynamics, mass, metallicity, [α/Fe], ..
- Thereby learn about halo accretion history – what accreted when

The MW Potential and Dark Matter Halo

Outer halo

- from kinematics / orbits of best halo streams (e.g., Bovy+'16)
- from minimizing spread in actions for other streams (e.g. Sanderson+'17)
- from modelling the kinematics/orbits of halo stars (e.g., Xue+'08, Deason+'12) – needs large samples of stars to large distances – probably best to combine known distances for RR Lyrae or BHB stars with Gaia PMs

Inner halo

- from rotation curve and modelling bulge / halo star kinematics (e.g., P17a)
- determining baryonic mass from star counts and PSMF (Wegg+'17)

Microlensing Optical Depth for B+D

Microlensing optical depth

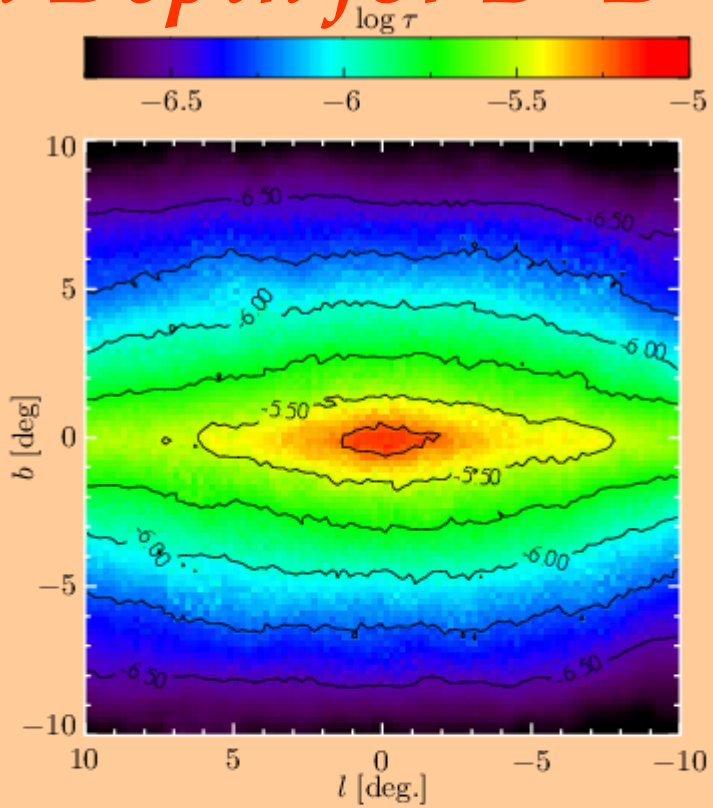
- is probability for microlensing to occur
- Is measure of weighted stellar surface density towards the bulge

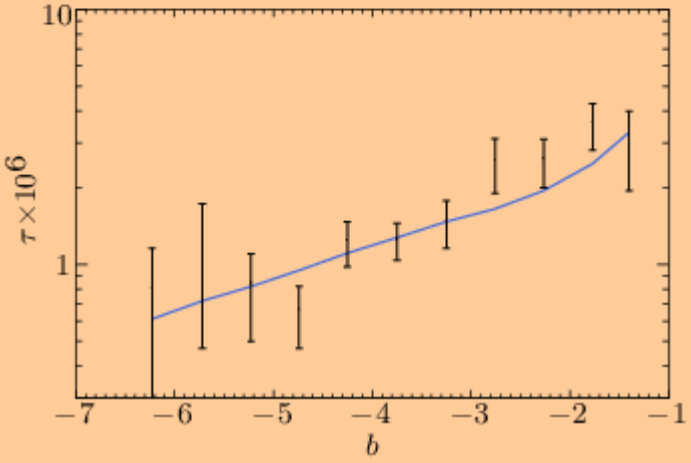
Current best dataset is revised MOA-II (Sumi & Penny '16); OGLE-III pending

Bulge-Bar-inner Disk dynamical model from Portail+17a has not been fitted to these data but has reduced $\chi 2=0.9$

➢ Reliable stellar mass distribution

Wegg, OG, Portail 2017





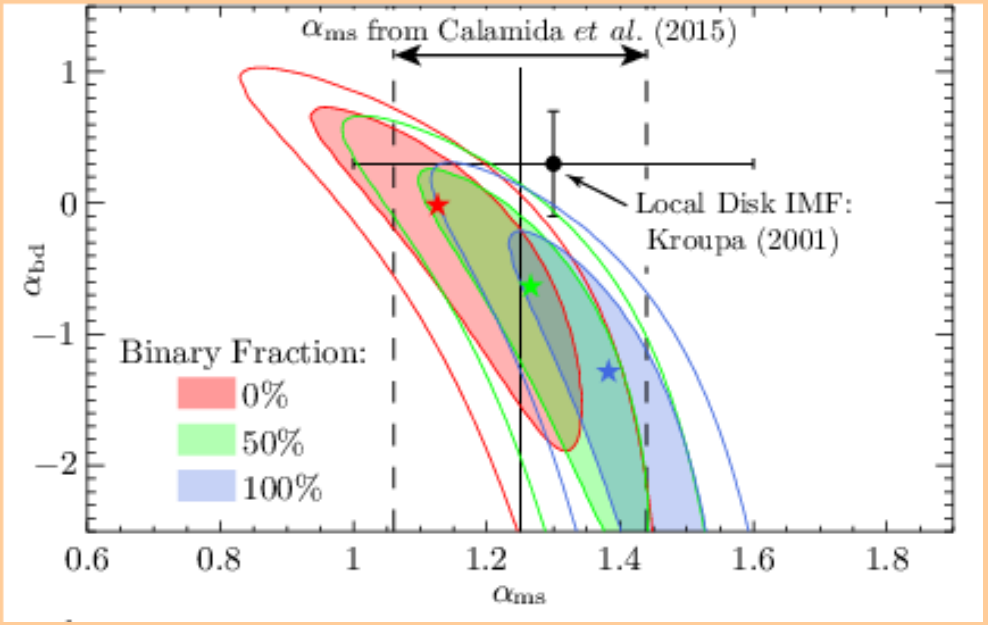
IMF from Microlensing Time-Scales

- 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:

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



➢ 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

➢ Implies M/Ncl = 960 ± 100 Msun/Ncl

Wegg et al. 2017 ApJL

IMF from Microlensing Time-Scales

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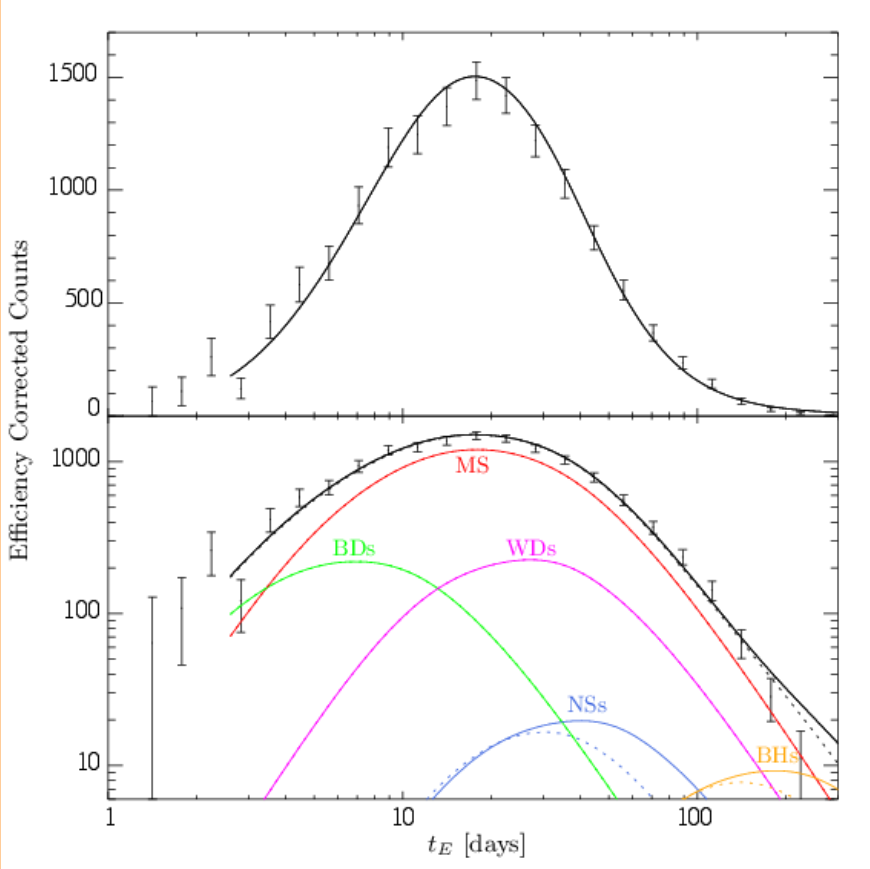

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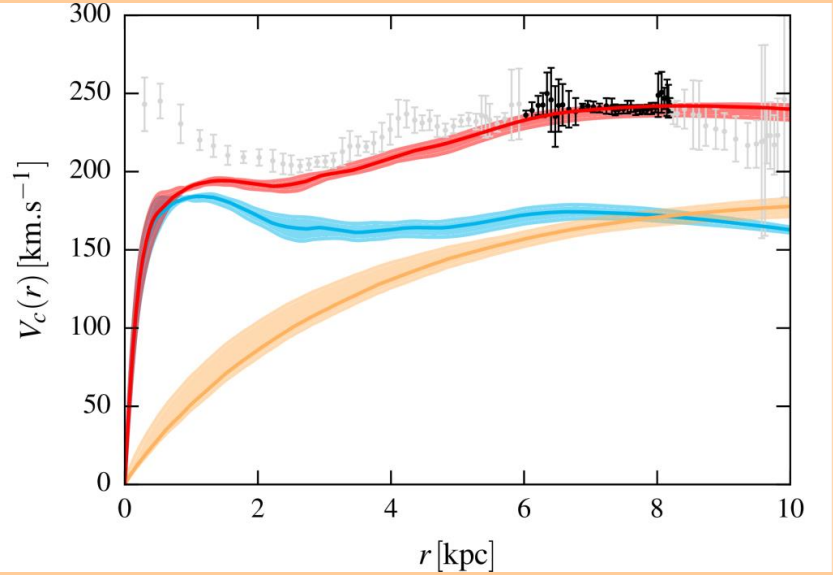
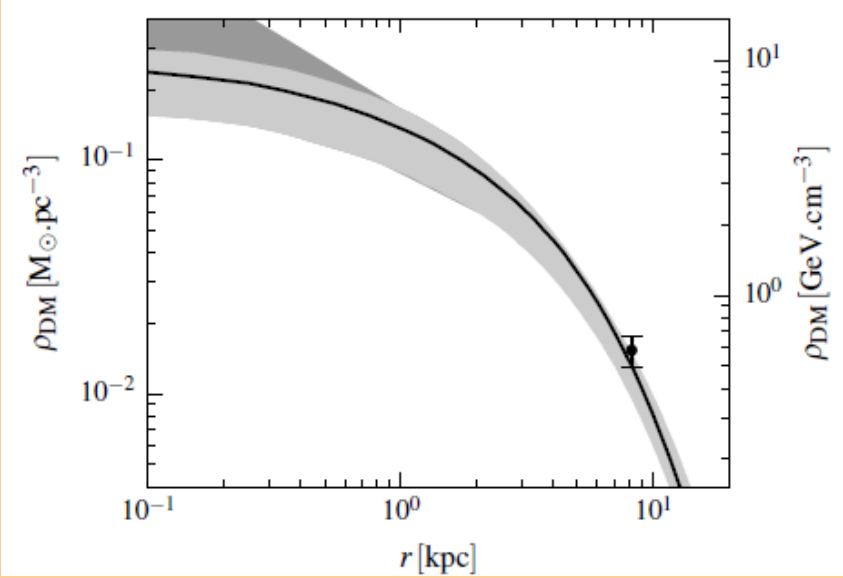
Wegg et al. 2017 ApJL

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, and inward continuation constrained with microlensing τ.

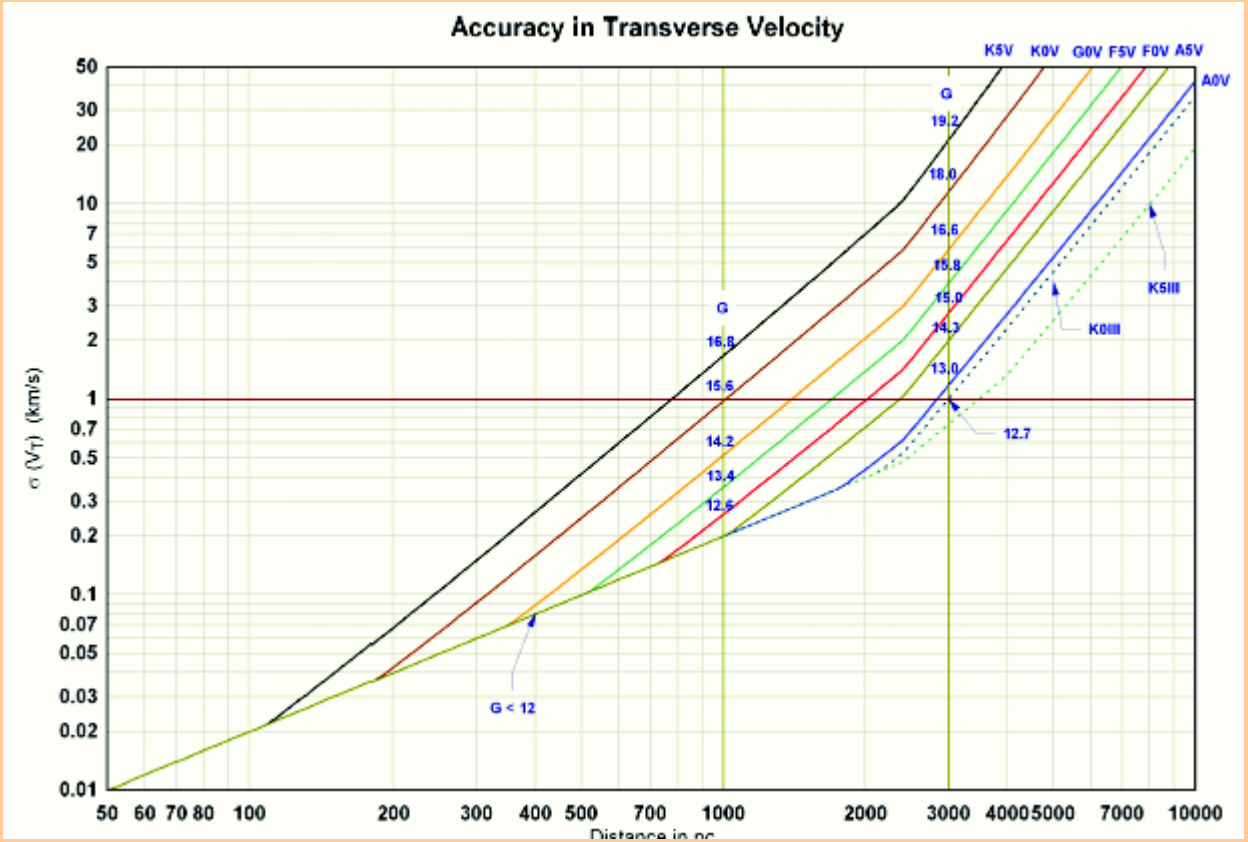
Prospects: proper motions

Summary

- Many new possibilities from combining NIR photometric surveys, spectroscropic surveys, and Gaia DR2 (4/18)
- We live in a barred galaxy with a predominant B/P bulge. The bar region contains 2/3 of the MW's stellar mass.
- The bulge/bar stellar populations broken up by metallicity have different orbit distributions: strong metal-rich bar, a thick disk bar, and a dense central component in metal-poor stars with unclear origin
- Thin disk likewise structured: old, metal-rich, inner parts $\Rightarrow$ younger, more metal-poor, outer parts. α-rich thick disk sequence
- Nearby disk equilibrium stellar dynamics modelled, disk wobbling & influence of bar and spiral arms to be clarified
- Much of stellar halo in accreted substructures – work on their detailed nature & accretion history coming
- Gravitational potential of the MW one of the big Gaia projects. Recent modelling requires core in the inner DM halo
- Maser distances and PMs will continue to be very valuable in regions of high extinction especially in inner Galaxy and distant spiral arms

Gaia Transverse Velocity Accuracy

Gaia will reach ~10 km/s accuracy in the transverse velocities for typical stars within D=3-10 kpc and further for the brightest stars.

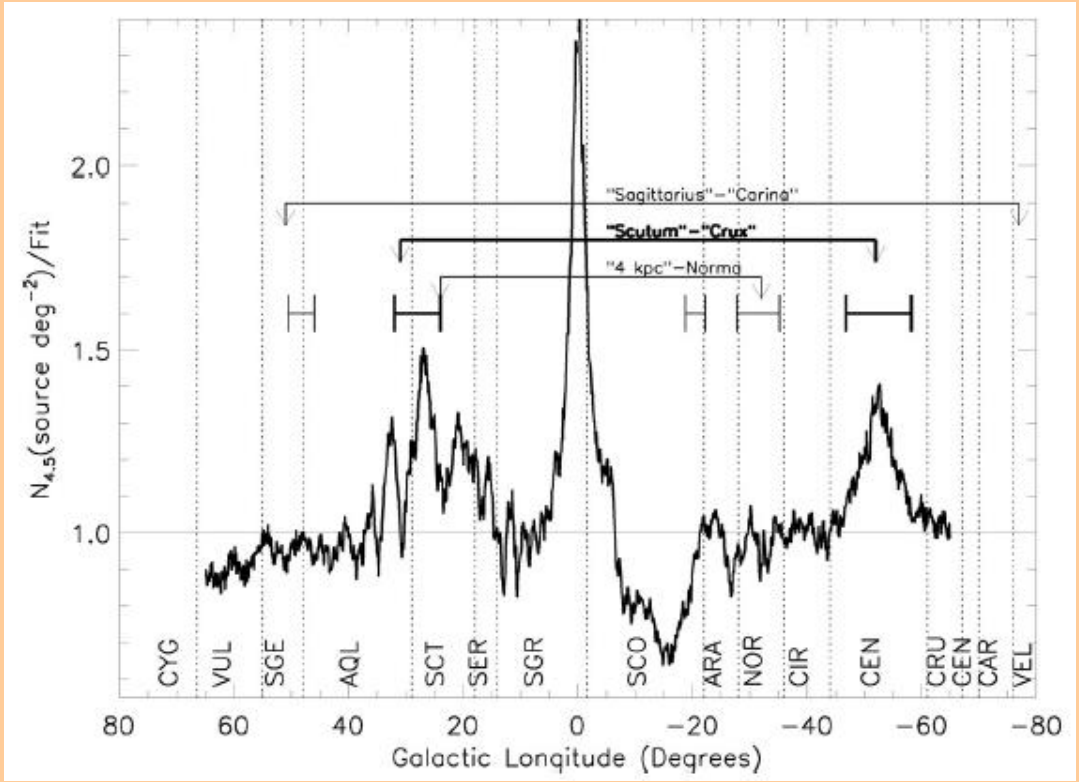


Credit: Francois Mignard

How Many Gaseous and Stellar Arms in the MW?

- Frustratingly hard to see tangent point overdensities of old stars in the NIR light or star counts (Drimmel 2000, Drimmel & Spergel 2001, 2MASS, Lopez-C. etal)
- Mid-IR star counts show overdensities at Scutum and Crux tangent points but not at Sagittarius tangent (Benjamin et al 2005, Churchwell et al 2009).

  Suggests the MW may only have two stellar spiral arms outside bar corotation.



Virial Mass of MW Dark Halo

Table 8 Total mass estimates for the Galaxy

Reference	Method	M_{200}	M_{100}	$M^r_{\rm kpc}$	R_{200}	R_{100}	r
Wilkinson & Evans (1999)	Distribution function based	1.67	2.39	0.54	243.9	346.0	50
Sakamoto et al. (2003)	Mixed halo object kinematics	1.67	2.39	0.54	243.9	346.0	50
Dehnen et al. (2006)	Halo star kinematics	1.75	1.96	1.05	247.7	324.3	120
Smith et al. (2007)	Escape velocity	1.03	1.43	0.39	207.7	291.7	50
Xue et al. (2008)	Halo star kinematics	0.87	0.91	0.40	196.1	267.0	60
Gnedin et al. (2010)	Hypervelocity star kinematics	1.33	1.74	0.69	226.4	311.3	80
Watkins et al. (2010)	Satellite galaxy kinematics	2.62	3.05	2.70	283.4	375.4	300
McMillan (2011)	Modeling local observables	1.26	1.76	0.84	222.0	312.7	100
Kafle et al. (2012)	Halo star kinematics	1.21	1.99	0.21	219.1	325.5	25
Deason et al. (2012)	Halo star kinematics	0.87	1.03	0.75	196.0	261.9	150
Gonzalez et al. (2013)	Satellite galaxy kinematics	1.15	1.39	–	215.3	289.0	–
Kafle et al. (2014)	Halo star kinematics	0.72	0.80	–	184.2	239.1	–
Piffl et al. (2014b)	Escape velocity	1.60	1.90	–	235.0	322.0	–
Gibbons et al. (2014)	Stream modeling	0.55	0.68	0.41	168.7	227.3	100

Note: M_Δ is the mass within the radius defined with respect to the overdensity Δ; the radius computed by the authors is indicated by R_Δ. $M^r_{\rm kpc}$ is the mass within radius r in kiloparsecs as indicated. All masses are in units of $10^{12}\,M_\odot$; all radii are in units of kiloparsecs. Dashes, –, indicate no data.

Using variety of kinematic tracers. All estimates in units of $10^{12}\ M_\odot$

Bland-Hawthorn & Gerhard 2016 ARAA 54, 529

- Estimated 1.3 $10^{12}\ M_\odot$ from (largest) halo kinematics samples
- Timing mass of MW + M31 $M_{vir,t}$=3.2±0.6 $10^{12}\ M_\odot$, $M_{vir,MW} < 1.6\ 10^{12}\ M_\odot$ (van der Marel et al. 2012)
- Implied virial radius rvir=280 ± 30 kpc

$$r_{\rm vir} = 258 \left(\frac{\Delta_{\rm vir}\Omega_{\rm M}}{102}\right)^{-1/3} \left(\frac{M_{\rm vir}}{10^{12}\,{\rm M}_\odot}\right)^{1/3} \ {\rm kpc}.$$

- Halo shape nearly spherical on 10-20 kpc scales from analysis of Pal 5 and GD 1 tidal streams (Bovy et al 2016)