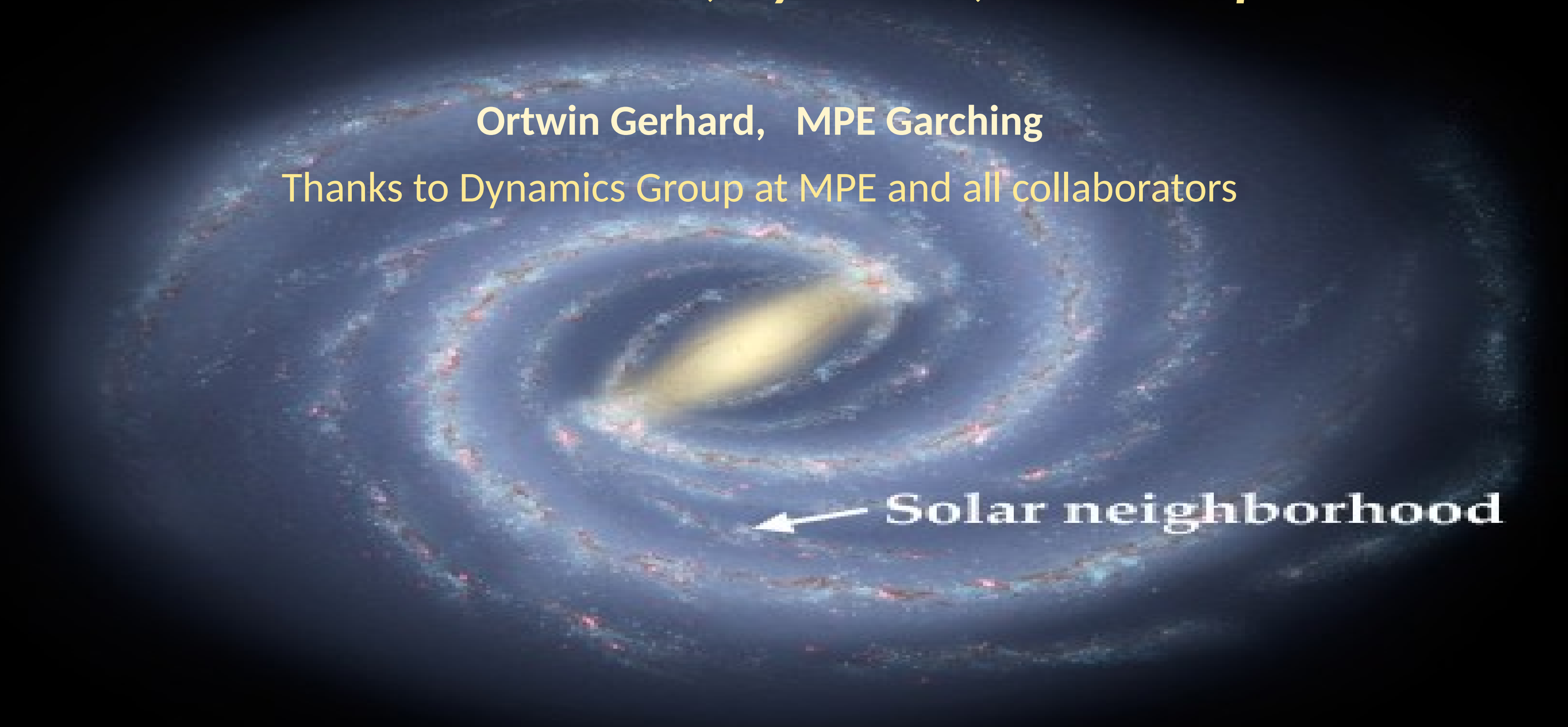
The Galactic Bar – Structure, Dynamics, Stellar Populations

Ortwin Gerhard, MPE Garching

Thanks to Dynamics Group at MPE and all collaborators

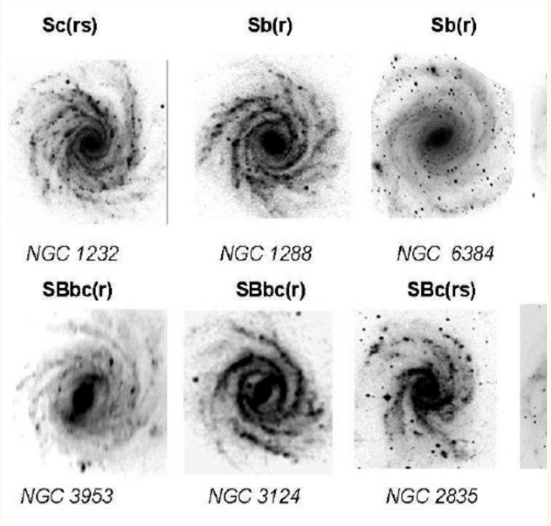


KCF@80

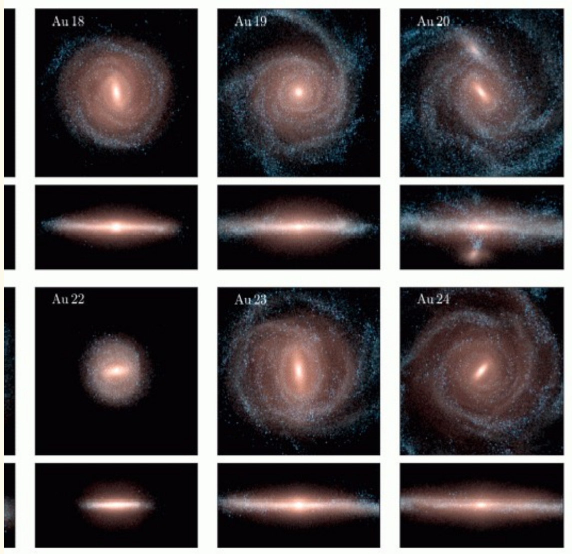
- First met Ken as a graduate student in Cambridge/UK. Discussed on analytic thesis work with Mike Fall to describe disk galaxy heating in clusters (later: ‘harassment’)
- Started to collaborate with Ken and Magda in 1990s on kinematics and dynamics in galaxy halos, planetary nebula surveys with the PN.S instrument, Virgo & Coma ICL, the PN.S disk mass project, M31, and the MW.
  As of now we are coauthors on 60 papers..
- Numerous mutual visits to Stromlo and MPE and quite a few conferences, always with inspiring discussions
- Attended 4 birthday parties – from Dunk Island 2001 to Perth 2022
- Seems Ken was behind Joss BH and me teaming up for our big MW review, and behind other good things..

- ***Happy Birthday Ken,***
- ***and many thanks for all the inspiration and friendship!!***

The Goals: Understanding Disk Galaxy Evolution



Milky Way Analogs, Efremov '11



Auriga cosmological simulations of realistic bulge-bar-disk galaxies Grand+'17ab

Role of Milky Way studies:

- can learn about formation history from the first stars to now, the large to the small, and in 3D, dissecting the stellar populations of different ages, [X/H], and kinematics
- may inform general galaxy evolution studies and simulations on small scale physics

The Galactic Bar – A Short History

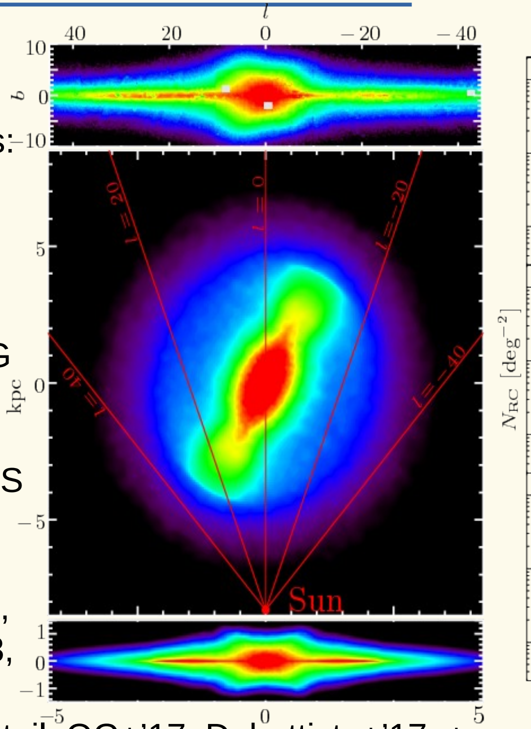
Argued by de Vaucouleurs 1964 from morphology
Early gas models by Peters 1972

Accepted by community in 1990s
- COBE/DIRBE image: Weiland+94 ff Blitz & Spergel’91
- as cause of non-circular motions: Binney, OG, Stark+91
- asymmetric RC starcounts: Stanek, Paczynski+94

Followed by numerous papers to understand structure of barred COBE bulge, gas motions in inner Galaxy, microlensing optical depth

IAP NIR starcounts – the long bar: Hammersley+00 ++
Bulge shape from 2MASS starcounts: Lopez-Corredoira, Cabrera-Lavers,OG’05, Skrutskie+’06

X-shaped bulge OGLE/2MASS:
Nataf’10, McWilliam & Zoccali ‘10
3D b/p bulge map from VVV RC stars:
Wegg & OG ‘13



First 3D bar densisty map including aligned long bar from VVV, UKIDDS, 2MASS, star-by-star extinctions & RCG distances: Wegg, OG, Portail’15

Radial velocity surveys BRAVA, ARGOS

Metal-rich, thick disk-like, metal-poor subpopulations: ARGOS, GES, GIBS, APOGEE surveys: Ness, Freeman+’13, Rojas-Arriagada+17,20
M2M, N-body, evolvg bar models: Portail, OG+’17, Debattista+’17, +
VIRAC/Gaia NIR PM maps: Sanders+19, Clarke+19
APOGEE kinematic [Fe/H], [Mg/H], age maps Bovy+19, Wylie+21
Orbit maps for APOGEE stars with Gaia PMs: Queiroz+21, Wylie+22
Starhorse bar/disk star count map: Anders+22
Gaia DR3 3D velocity maps: Drimmel+22
++ numerous other studies ++

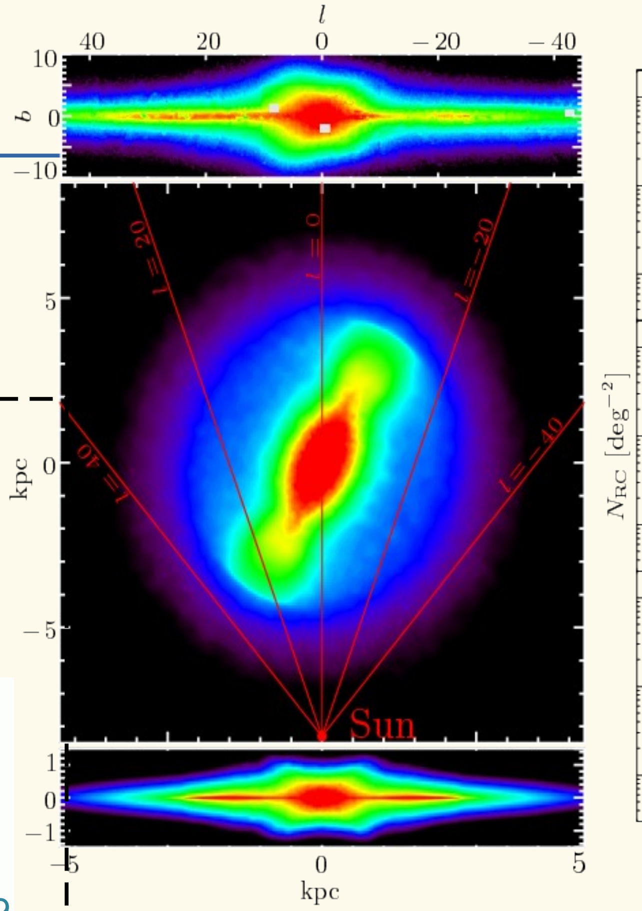
The Milky Way's Boxy/Peanut Bulge and Bar From Star Counts

- Based on NIR surveys: 2MASS, VVV (3-4mag deeper in the bulge), UKIDDS (near-side bar), GLIMPSE (star-by-star extinction)
- Red Clump star (sometimes incl. Red Giant) luminosity function deconvolved to get distance distribution (RC: ~10%)
- Resulting shape is B/P bulge embedded in aligned, longer, near-planar bar, 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
- Face-on slices show X-shape widening with height
- Few % oldest metal-poor stars no X-shape, less triaxial

➢ B/P bulge, planar bar aligned; for bar angle 28-33 dg
Bulge angle depends slightly on width of RC LF

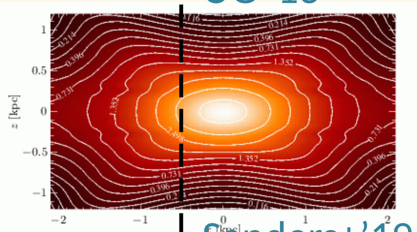
➢ Estimated bar length 5.0±0.2 kpc, then corotation radius expected ~6.0 kpc

Also Nataf +'10, McWilliam+Zoccali+'10, Saito+'11, Simion+'17 (B/P), Sanders+'19; Hammersley+'00, Cabrera-Lavers+07 ('long bar'); Gran+'16, Pietrukowicz+'15, Du+'20 (RR Lyr)

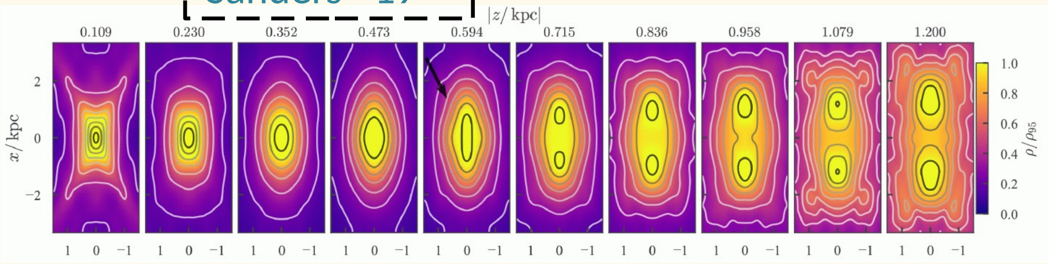


Wegg, OG, Portail '15

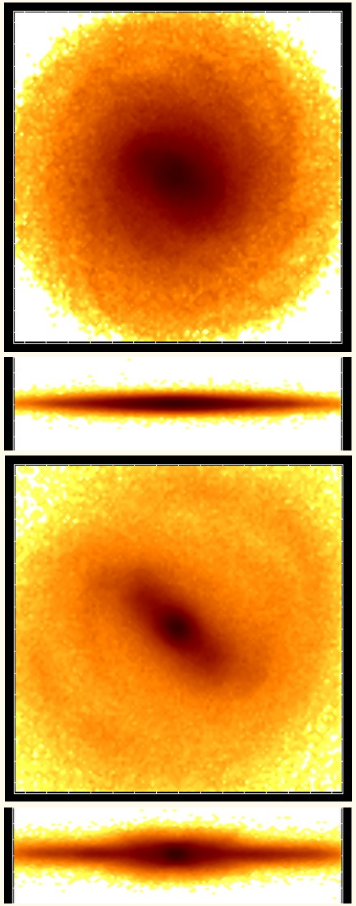
Wegg & OG '13

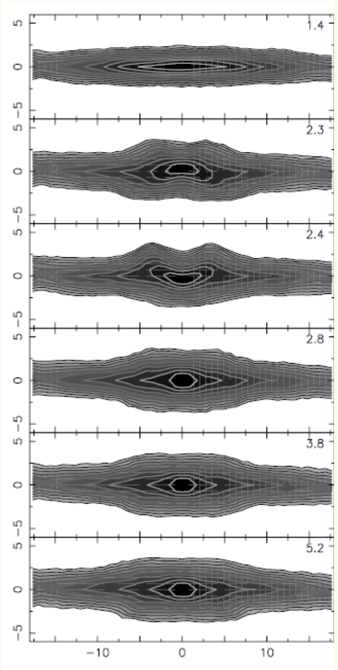


Sanders+'19

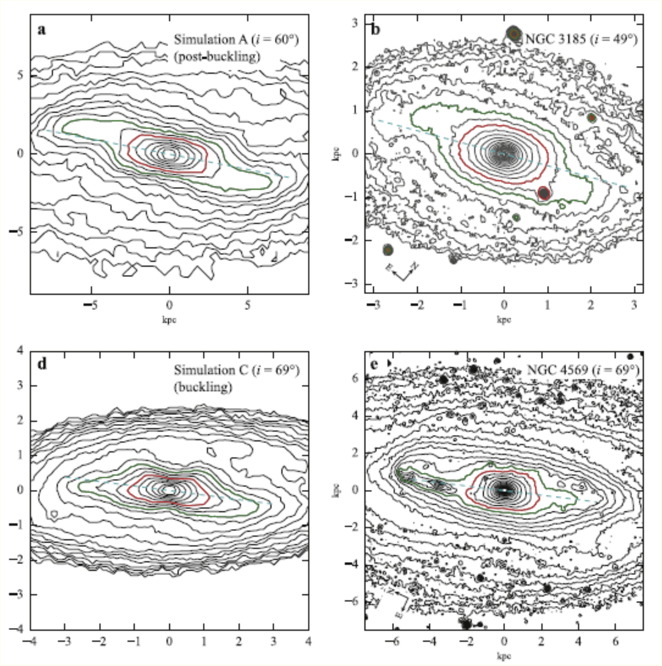


Buckling Instability and Box/Peanut Bulges





Martinez-Valpuesta+'06



Erwin+Debattista'16

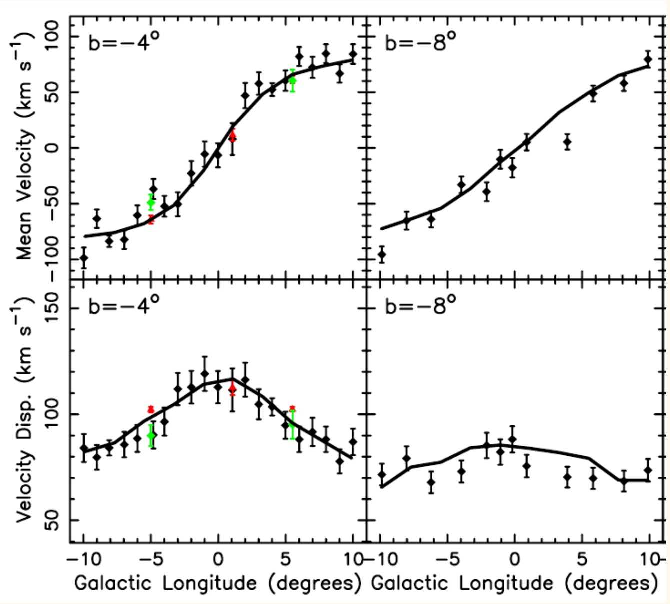
L: Bar-unstable N-body disk galaxy evolves through buckling instability

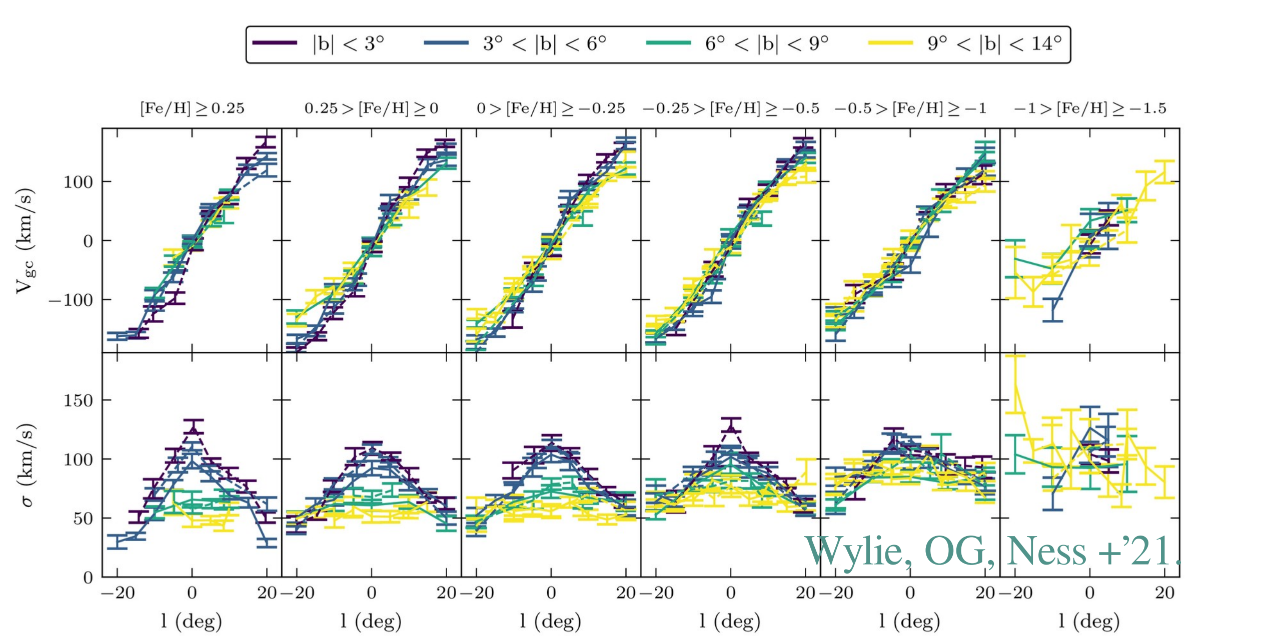
R: galaxy with trapezoidal isophotes in short-lived buckling stage

Hohl 1971, Sellwood '85, '89, Combes+'81, Raha+'91, Debattista+'00,'06, Athanassoula+'02,'03

Alternative: resonant heating mechanism   Combes+'90, Pfenniger& Friedli '91, Quillen'+02,'14

Line-of-Sight Bulge Kinematics; with Metallicity

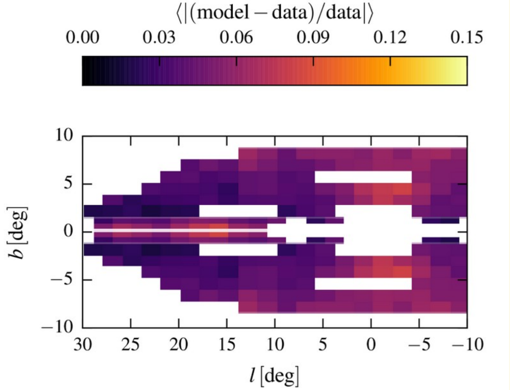




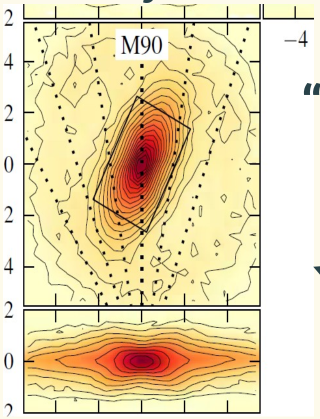
- Left: los <V> from BRAVA survey (Howard+’08, cylindrical rotation) compared to N-body bar model. Adding initial classical bulge of >10% of disk mass spoils the match (Shen+’10).
- Right: los <V> and σ from A2A and APOGEE (dashed) surveys. A2A is ARGOS converted to APOGEE label scale, using The Cannon. Incl 10’000 RC stars with good distances (Wylie, OG, Ness et al. ‘21)
- Cylindrical rotation up to at least [Fe/H]=-0.5 - see also BRAVA M-giants (Kunder+’12) and Argos K+M-giants (Ness+’13). More metal-poor stars have higher dispersions (Babusiaux+’10, GIBS: Zoccali+’17, GES: Rojas-Arriagada+’17). *Most of the bulge stars are in the b/p bulge.*

Dynamical Models for the Bulge/Bar

For a dynamical model, need to fit many 1000s of observables (photometric, kinematics, population) in a rapidly rotating, complicated triaxial potential. *Practical way* is with **Made-to-Measure Particle (M2M) Models.** Alternative: Schwarzschild orbit superposition (Hafner+'00)

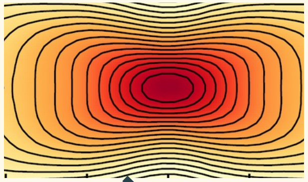


N-body model

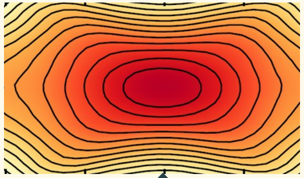


"Observe"

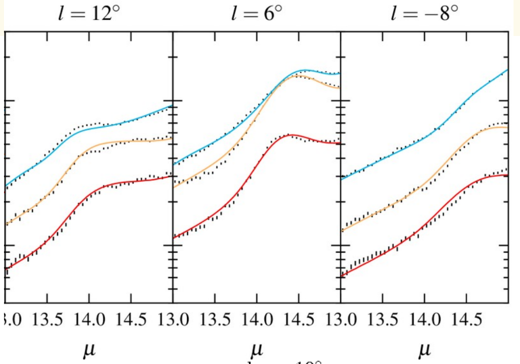
Model observable



Real data



star counts

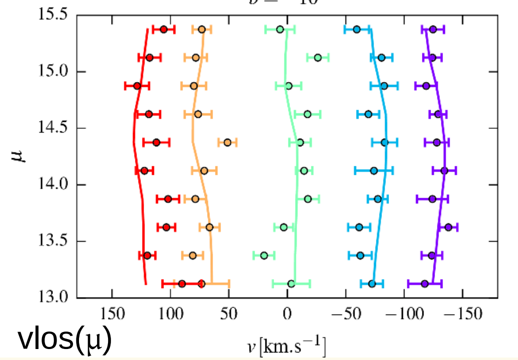


Compare & quantify
Change particle weights

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

Profit function F

Evolve N-body model forward for dt

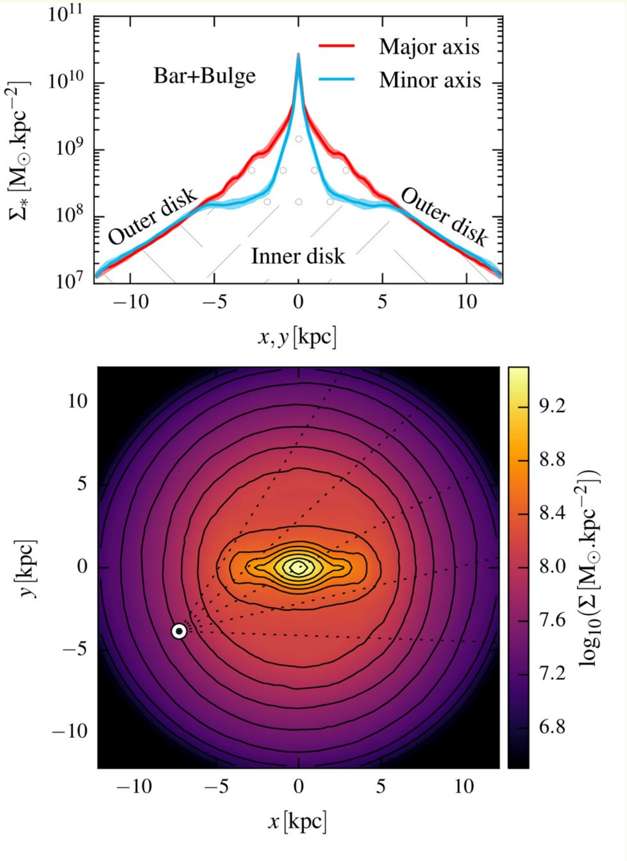


vlos(μ)

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

Portail, OG +2017

Dynamical Model Results: Stellar Masses



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

Made-to-measure dynamical model: Star counts and los v's
Length of thin/superthin bar (star counts) Rb = 4.5/5.0 kpc (± 0.2)

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

Sun's Distance to Gal. Centre:	R0 = 8.2 kpc (±0.1)
Gravity Collaboration '19:	8.18 ± 0.013 ± 0.022 kpc
Circular velocity @ Sun	V0 = 238 km/s (+5,-15)
Exponential disk scale-length <R0 (varied)	Rd = 2.4 kpc (±0.5)
Mass-to-RC ratio from HST/NIR & microlensing	1000±100 Msun/RC

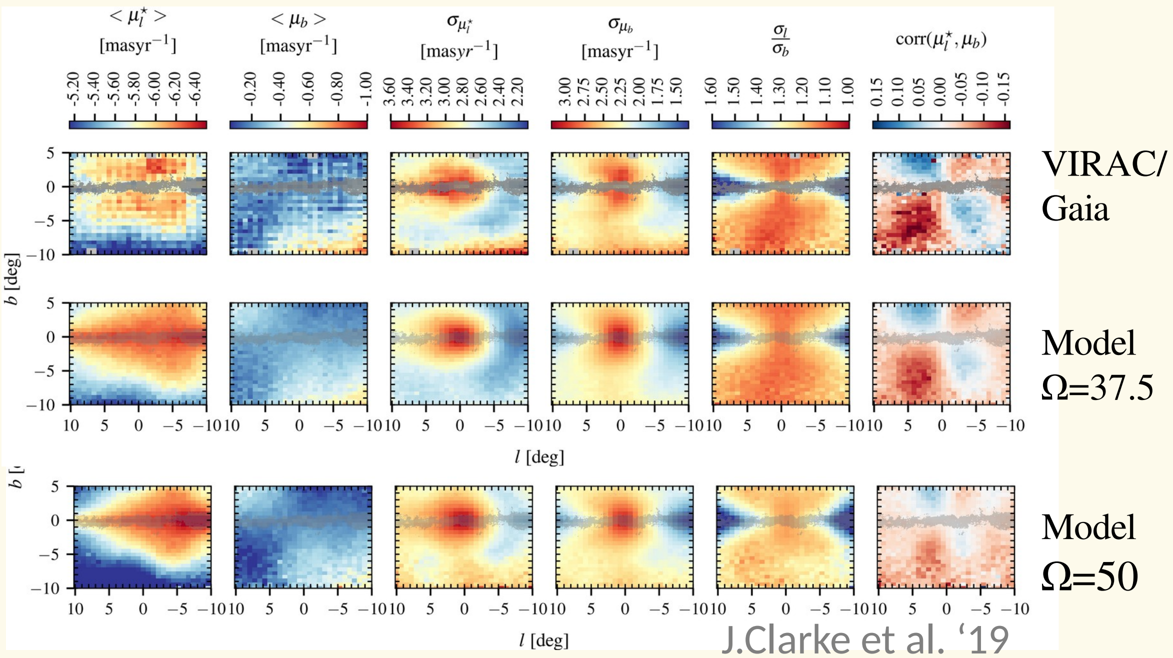
Results: B/P bulge/bar embedded in nearly flat inner disk density

Pattern speed	Ω_b =39 km/s/kpc (±3.5)
Corotation radius	Rc = 6.1 kpc (±0.5)

Mass/RCG star well-determined (star counts, microlensing)

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%

Dynamics From NIR Proper Motion Maps



VIRAC/Gaia PMs compared to 2 models from Portail+'17 fitted to star counts & RVs. Uses LF for Kroupa IMF, MDF from Zoccali+'08, parsec isochrones; VIRAC SSF. OGLE PM constraint for NSD.

Impressive match to PMs (not fitted!) for visually best Portail+'17 model with Ω=37.5 km/s/kpc. The power of dynamical modelling

Coming: M2M models using distance-resolved VIRAC PMs

Recent measurements of Ω:

From bulge stellar-dynamical models

Ω = 39.0 ± 3.5 **Portail+'17** density, RVs
Ω = (37.5; 40.) **Clarke+'19** intPMs + P17mod
Ω ~ 33 ±2 **Clarke, OG '22** **rsv**PMs + P17mod

From continuity eqn

Ω = 41 ± 3 global bulge **Sanders+'19**
Ω = 41 ± 3 local in long bar **Bovy+'19**

From gas-dynamical models for (l,v)-plot

Ω = (40, 42) (**Sormani+'15**)
Ω = (33, 37-40) (**Li+'16, 22**)

From SNd bar resonances

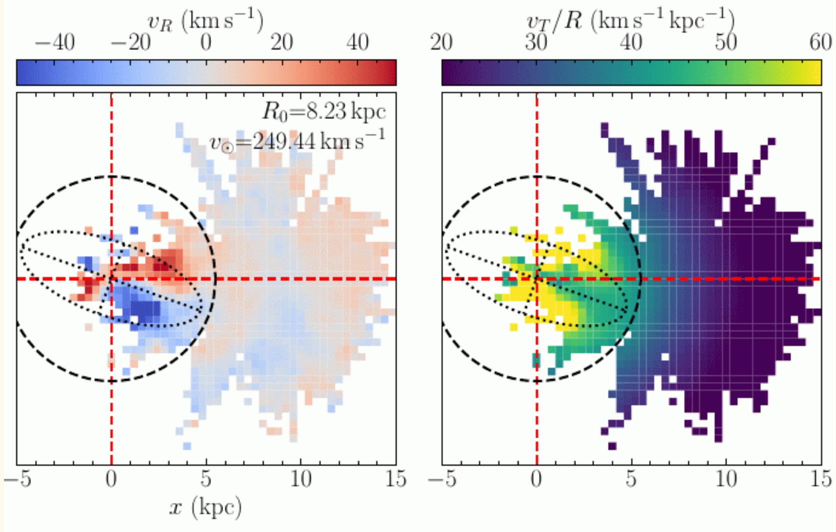
Ω = 39 (**Monari+'19**)
Ω = 36 (**Binney '20, Chiba+'21**)

Typical Ω = 40 km/s/kpc ⇒ corotation R_c~5.8 kpc and R = R_c/a_b = 5.8/5.0 = 1.16.

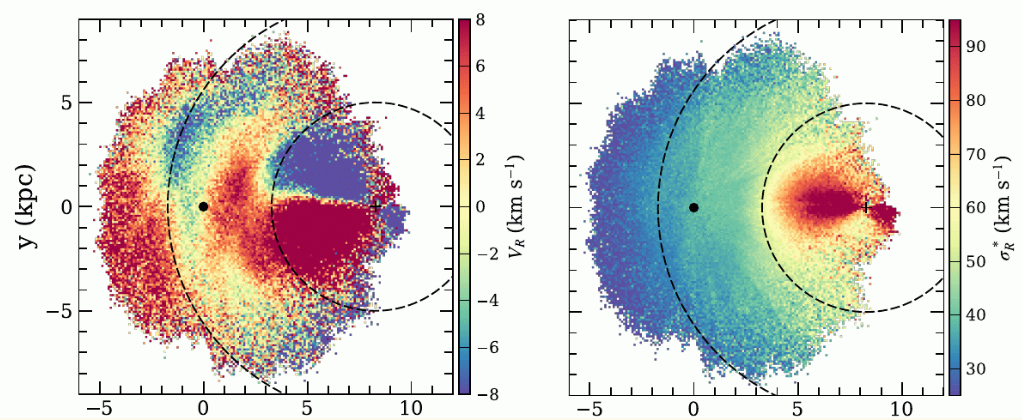
This is a dynamically fast, but large bar.

Recent Kinematic Maps of the Bar

Kinematic map from APOGEE-DR17 using AstroNN distances (Leung+2022), showing the quadrupole signature in v_R and dip on major axis in v_T/R.

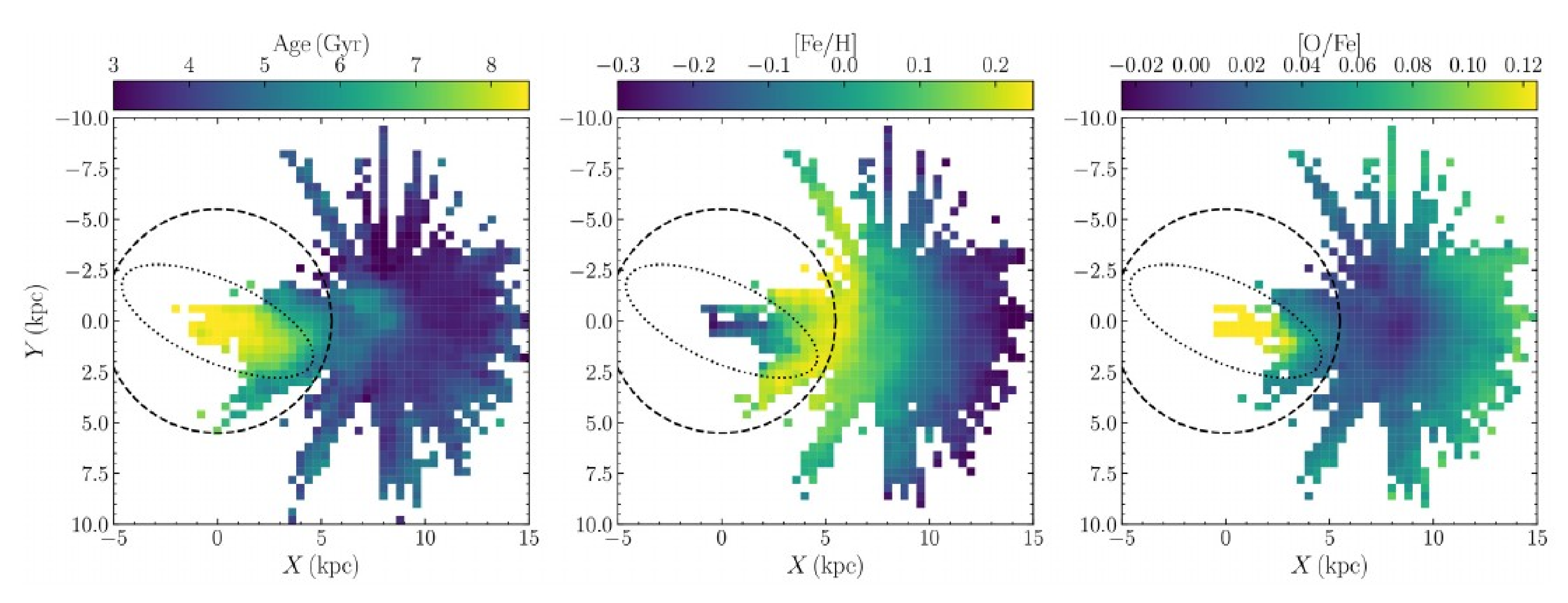


Kinematic maps for red giants from Gaia using “photo-geo”-distances from Bayler-Jones+2021, showing again quadrupole signature in V_R as well as some curvature in σ_R. (Drimmel+GaiaColln+2022).



Both studies estimate bar angle ~20dg and pattern speed ~40 km/s/kpc from these data.

APOGEE View of Bar Star Ages & Metallicities

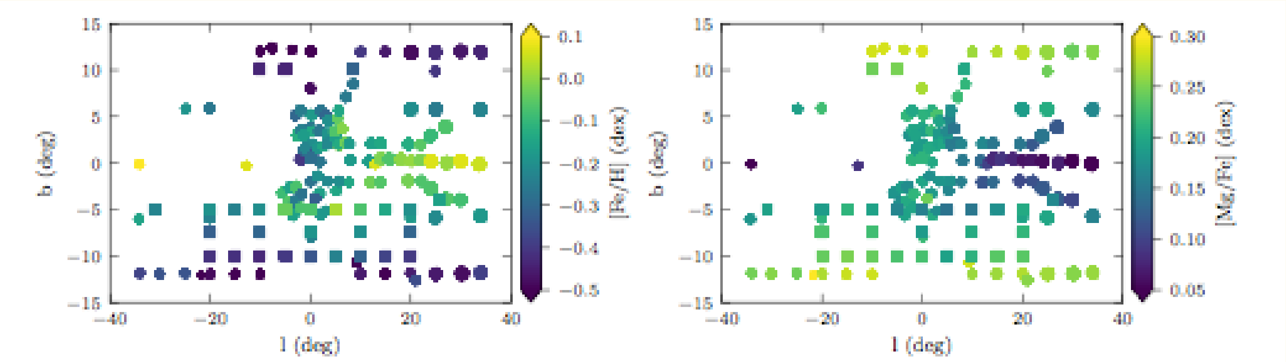


Stellar distances from astroNN neural network, typically ~20% precision.
Ages from overlap with APOKASC *disk* sample of stars with asteroseismology data, typical precision ~30%.
Typical inferred stellar age in (planar) bar ~8 Gyr, slightly older at higher b, but still systematic uncertainties. Metal-rich outer bar.

Bovy+19, Hasselquist+20, Grady+20

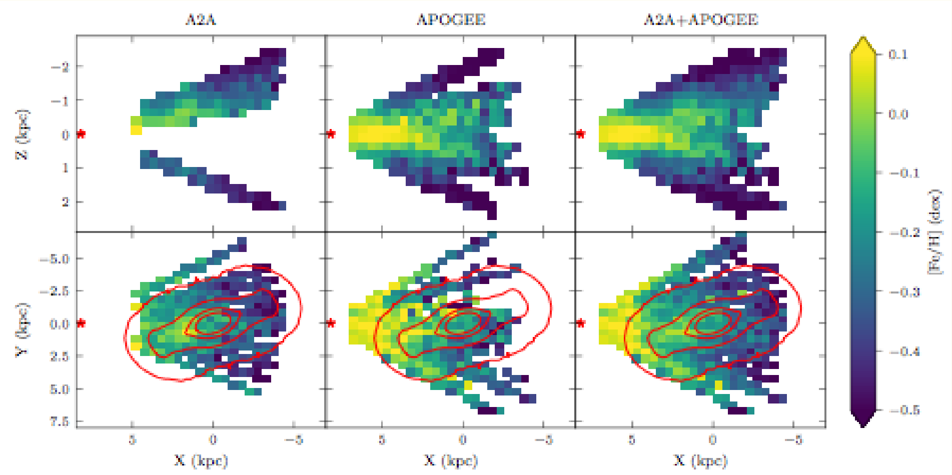
Bulge/Bar Abundance Distributions

Galactic longitude and latitude



(See also: Zoccali+2008, Rich+2012, Ness+2016, Fragkoudi+2017)

Galactic coordinates: X, Y, Z



- Clear longitudinal [Fe/H] and [Mg/Fe] gradients - especially strong in the plane
- Clear latitudinal gradients

<u>Distances:</u>

APOGEE: ASTRONN distances (Leung & Bovy 2019; Mackereth+2019)

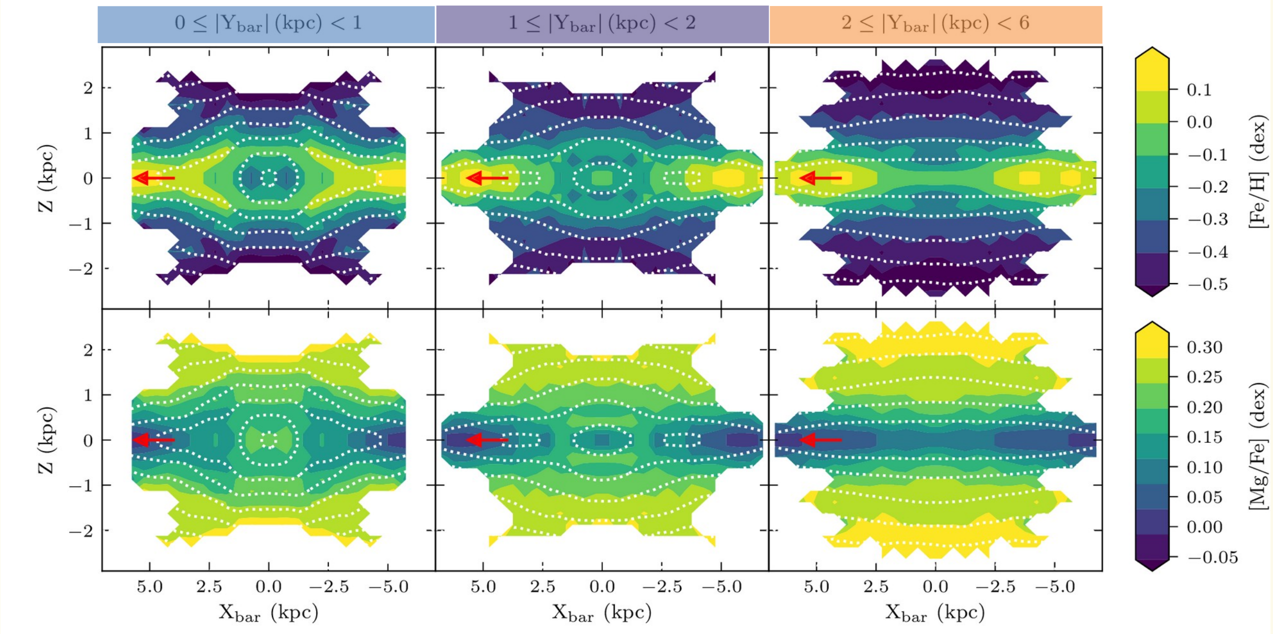
A2A: Red clump extraction

Bar density contours obtained from Portail+2017

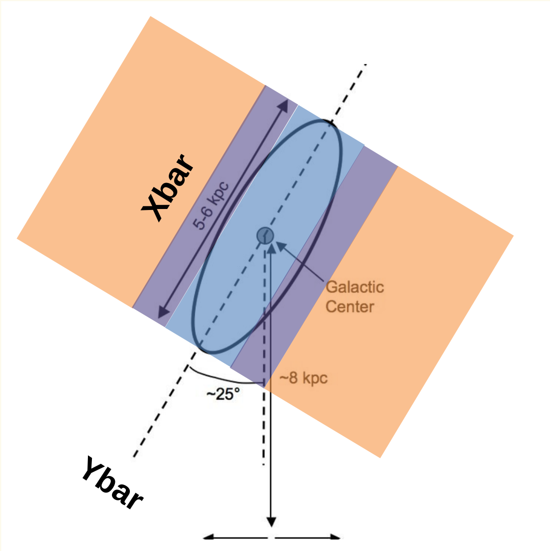
Wylie, OG, Ness et al. 2021

Symmetrised Bulge Abundance Distributions

Bar coordinates Xbar, Ybar, Z



Assuming that the bar is triaxially symmetric



Wylie, OG, Ness et al. 2021

- Clear radial and vertical gradients
- Peanut-shaped [Fe/H] and [Mg/Fe] contours in the bulge
- [Fe/H] and [Mg/Fe] distributions are more “pinched” than the density distribution
  disk origin for bulge

Mapping the Disk Populations into the Bulge through the bar/buckling instabilities

How is the population-structure of the disk before bar/buckling related to the final bulge chemo-kinematics?

- Stars from larger radii in the disk (Martinez-Valpuesta+OG'13) or with larger velocity dispersions at the same radius in the disk (di Matteo+'15, Debattista+'17) are mapped to larger heights in the bulge.

- Single disk models with metallicity gradients predict similar split RC for all metallicities at fixed b, and do not match the flat σ-profiles with longitude for the metal-poor bulge stars (di Matteo '16).

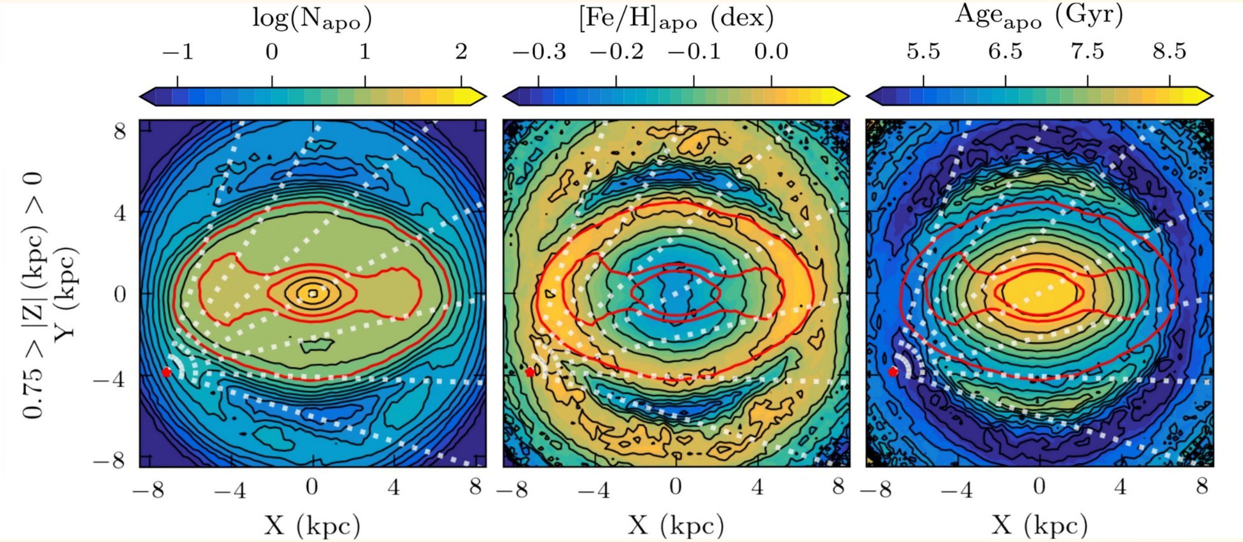
- Both models including thick disk(s) before the instability, and models with thin disks with age-[Fe/H]-σ relations (old-metal-poor-hot) reproduce many of the trends for densities, kinematics, metallicities in the MW bulge (Fragkoudi+'17, Debattista+17)

- The behaviour of the split RC with metallicity at given height favours the thick disk model (di Matteo+'19), i.e. that an

early thick disk component formed on α-element enhanced time-scale was already present when a somewhat later, cooler thinner disk triggered the bar formation & buckling

The Milky Way’s Middle-Aged Inner Ring

30000 inner MW APOGEE stars, SNR>60, abundances, AstronNN ages & distances (Leung+19), ⊗ Gaia DR2.
Orbits integrated in Portail+17 model (agrees well in heliocentric l-vμ spaces).



symmetric orbits
(non-Lagrange)

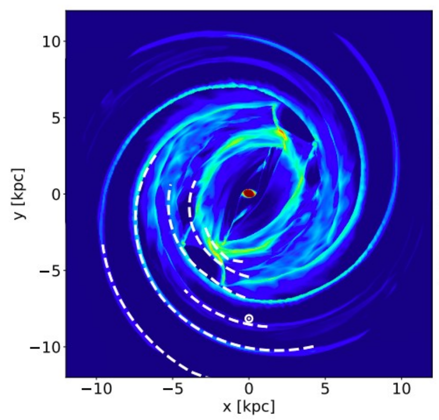
Wylie, Clarke, OG 2022, A&A

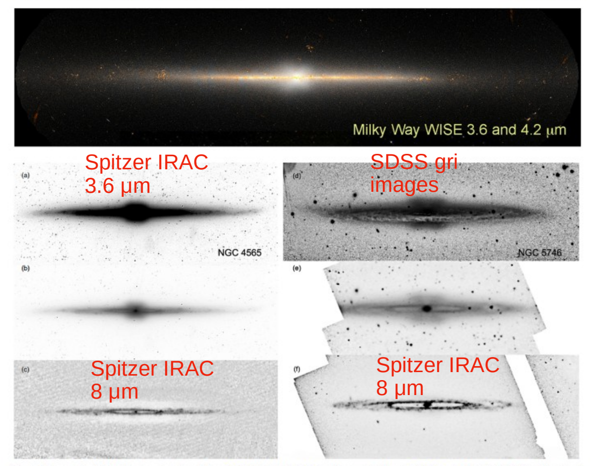
- Orbit-density map: bulge+flat bar (nb: SSF).
- Orbit-metallicity and orbit-age maps show ~2 kpc-thick elliptical ring inside corotation (CR); it is a time-averaged structure built from stars on (non-elliptical) resonant orbits. Variations with Ω small.
- Eccentric planar bar slightly older and less metal-rich; inner bulge old/metal-poor
- In two Auriga simulated MWA galaxies, main part of ring forms from gas driven into CR shortly after quenching of star formation in the bar (Fragkoudi+2020). ⇒ From AstroNN age distributions estimate bar formation in MW at > 7 Gyr ago.

Does the Milky Way host an "inner ring"?

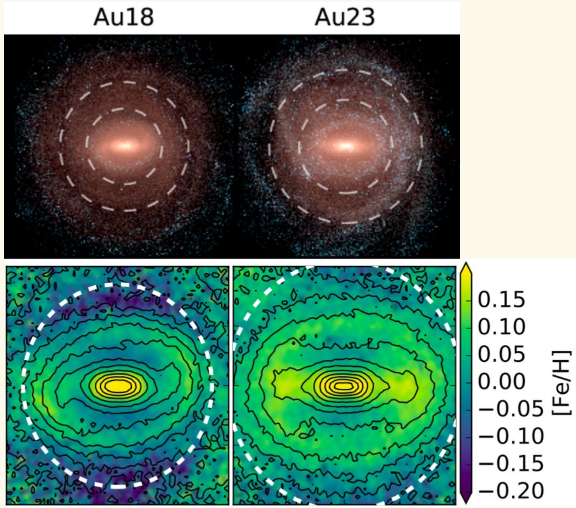
The radially thick stellar inner ring would have formed over time by the stars made from the gas, including from a gaseous inner ring at late times.

Recent MW gas model in P+17 bar Φ, Li et al. 2022





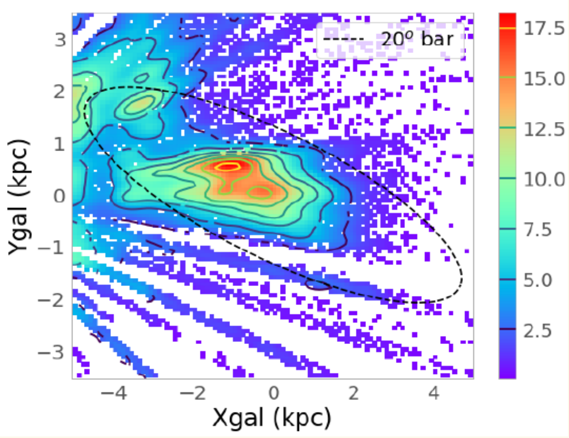
NGC 4565 and NGC 5746, two Milky Way analogs, were both found to host inner rings by Kormendy & Bender 2019.

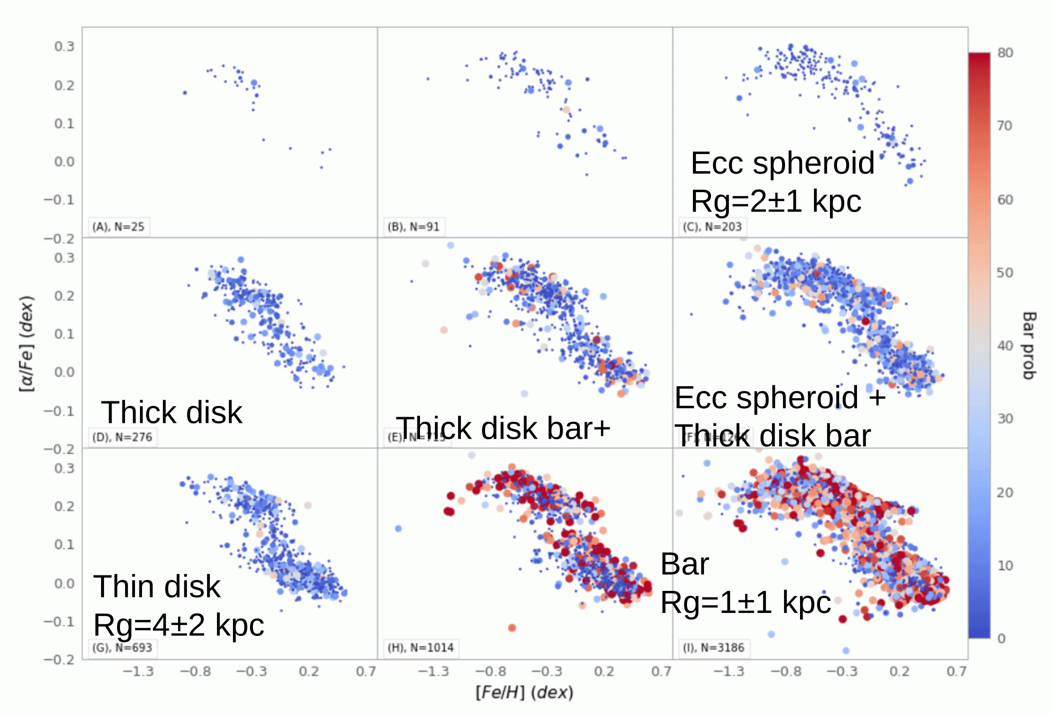


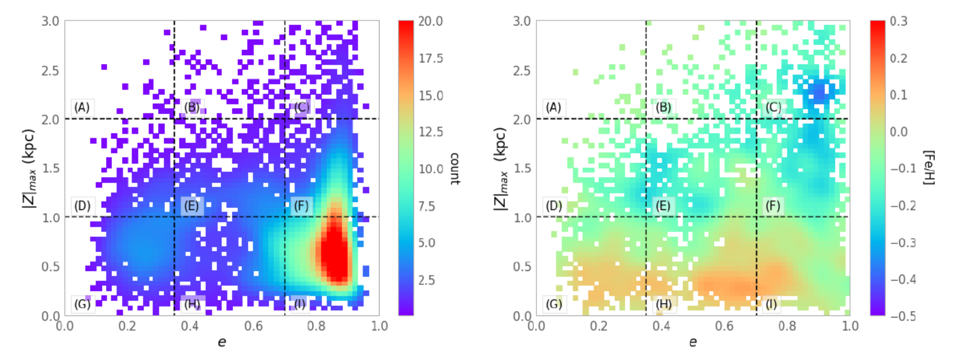
Two Milky Way-like barred galaxies from the Auriga cosmological simulations were found by Fragkoudi et al. 2020 to have metal-rich inner rings.

Bulge/Bar Dissection Using APOGEE and Gaia DR2

APOGEE stars with Starhorse spectroscopic distances







Combined with Gaia DR2 PMs - stellar orbits in approx. potential and classified acc. to eccentricity and Zmax

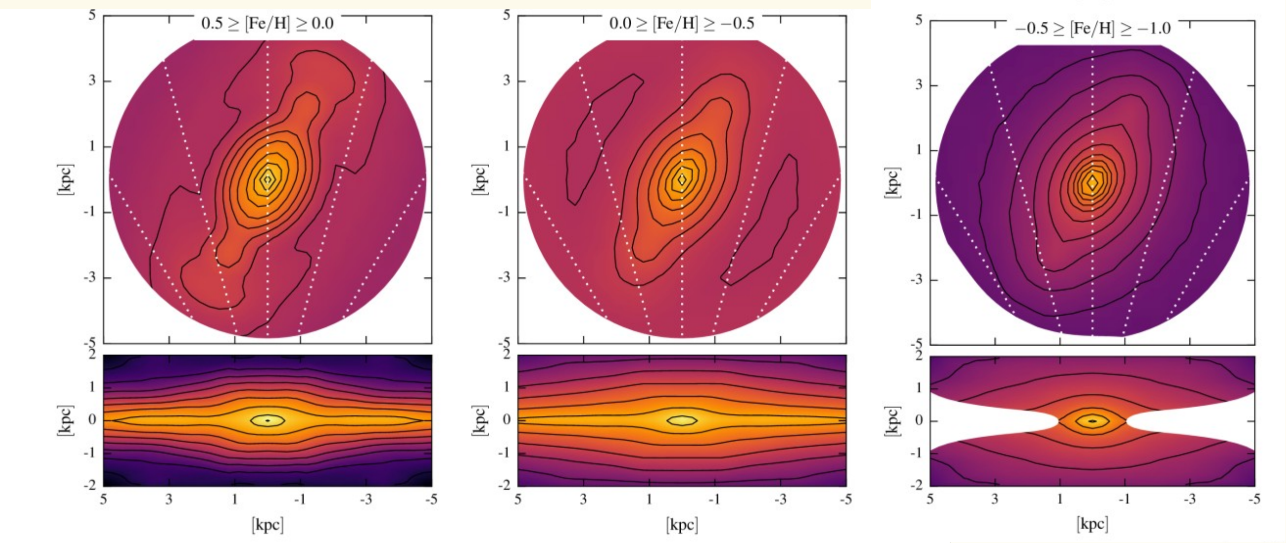
Bar-orbit probability for stars in different ecc-Zmax regions plotted over [α/Fe] vs [Fe/H]

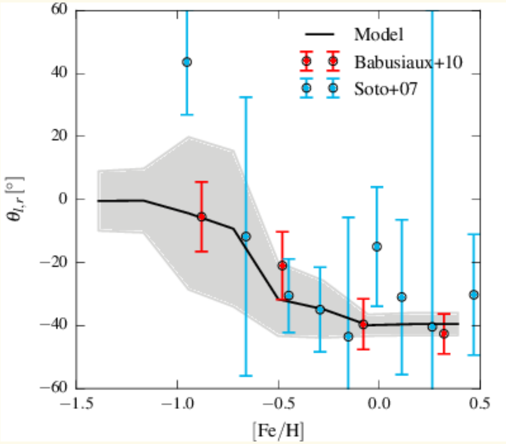
Queiroz et al. 2021

Approx designations, populations overlap – dynamical modelling !?

Population-resolved dynamical models: How the GalacticBar depends on Metallicity

- Chemodynamical M2M method: particles carry [**x, v,** f(M)]; MDF f(M) parameterized metallicity weights w_c for MGE expansion adjusted to metallicity bins.
- Particles projected into obsv space and weights w_c adjusted by comparing with data in distance bins





Portail et al 2017b

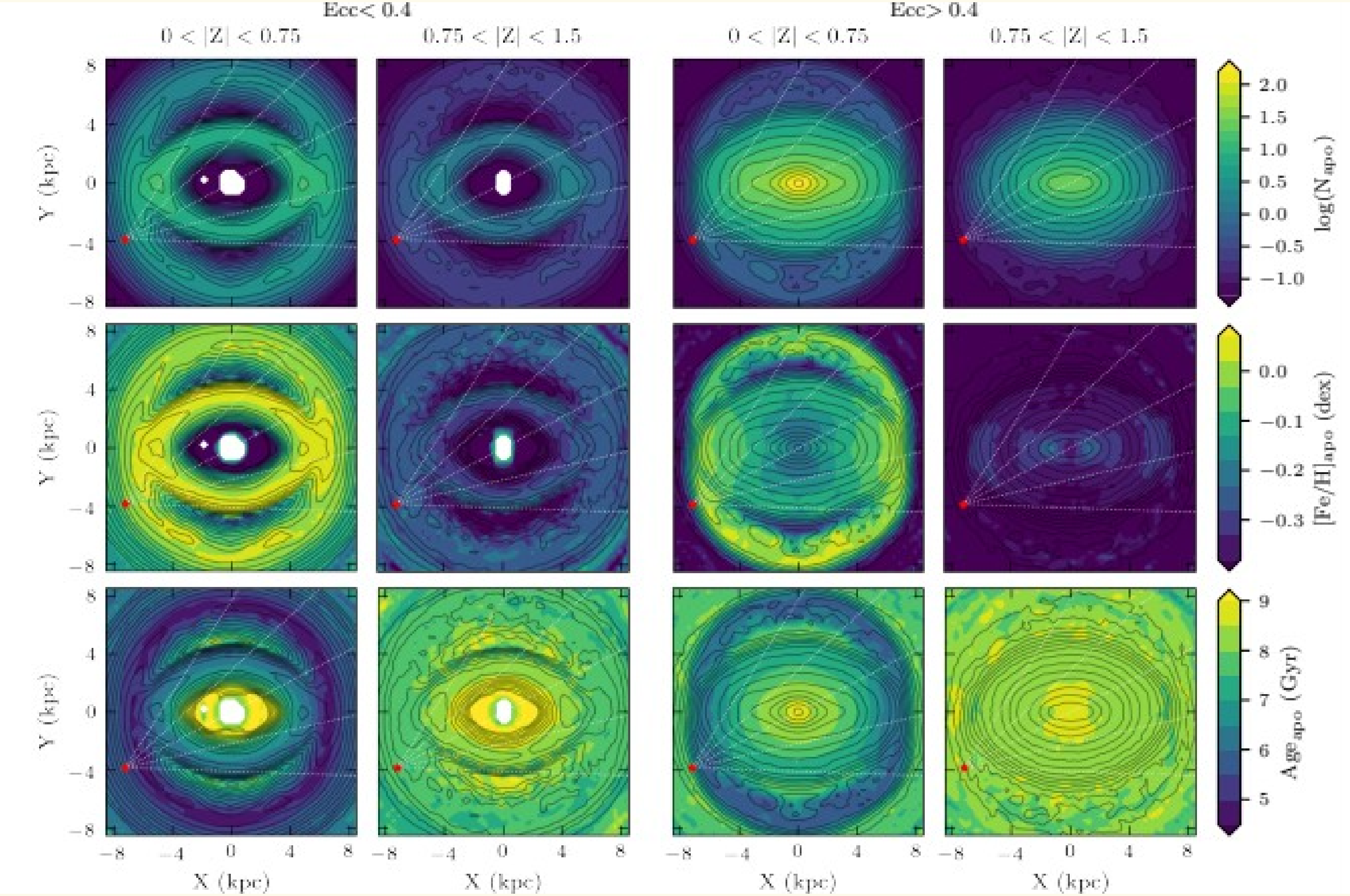
- Previous results for ARGOS and APOGEE DR12 find that supersolar stars show pronounced bar ends and more metal-poor stars show weaker bar structure (Portail et al 2017b). Together reproduce bulge vertex deviation.

  - *New models based on A2A and APOGEE DR17 in progress*

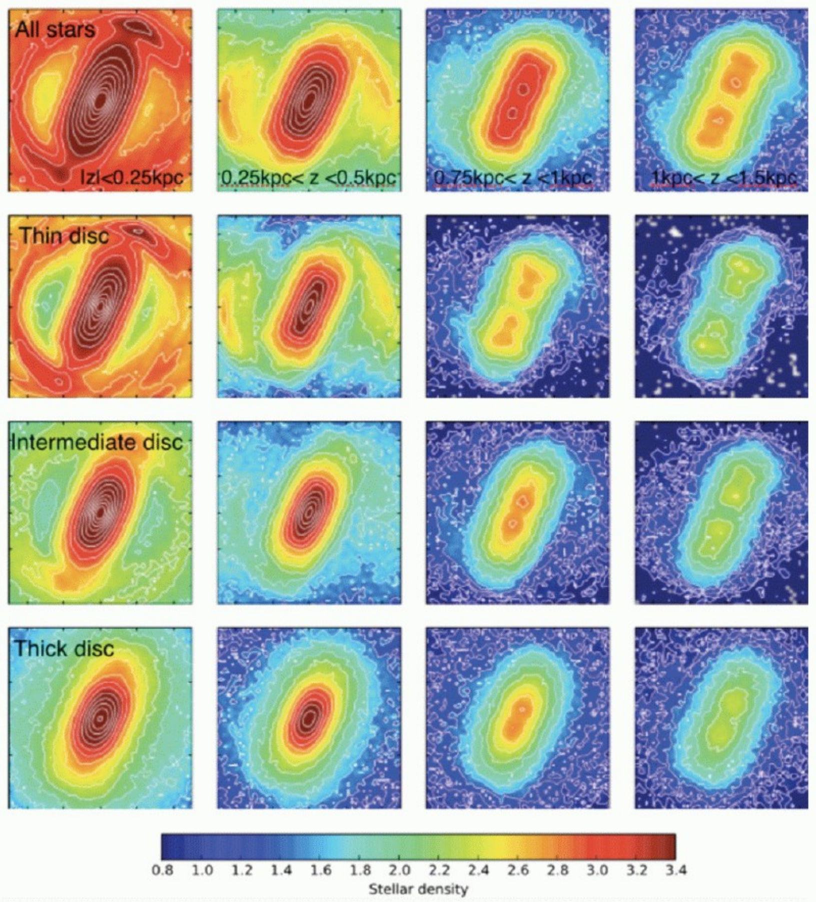
Conclusions

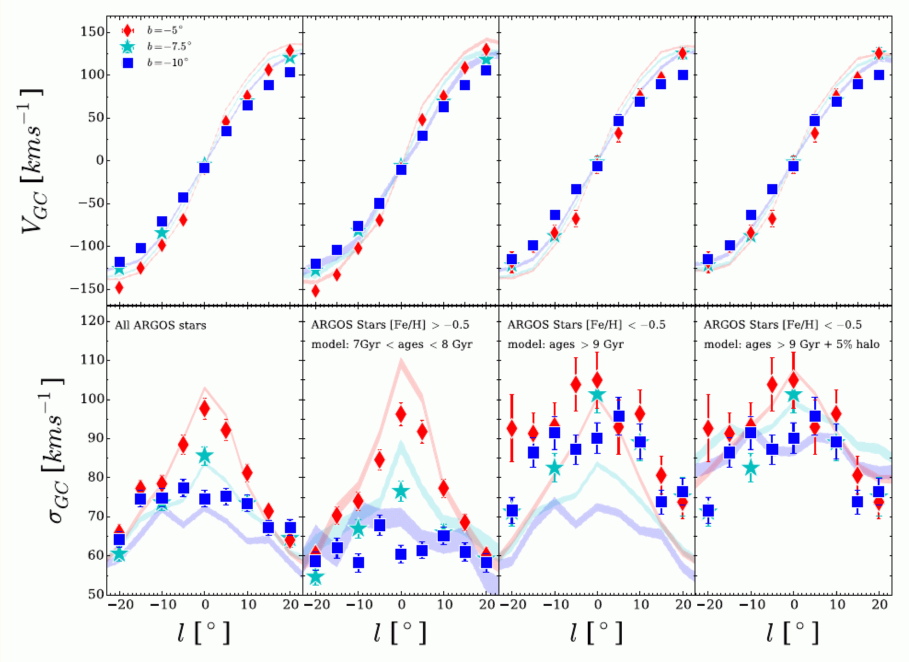
- The inner Milky Way is dominated by a large bar (from star counts) and a central b/p bulge, with double peaked density-X-shape and cylindrical rotation.
- Dynamical models based on kinematic surveys give precise dynamical mass in bulge region; stellar masses of bulge, long bar, inner disk of 30%, 10%, 20% of total ~5E10 Msun; and low pattern speed ($\lesssim$40km/s/kpc, CR~6kpc).
- The b/p bulge contains stellar populations with difft kinematics and abundances (thin bar, thick disk bar, low-metallicity spheroid). Main structure well-explained by models mapping unstable thin+thick disk into the bulge/bar. Typical AstroNN ages for bar stars ~8 Gyr, higher at large b.
- Metal-rich stars seen by APOGEE in the outer bar region are on resonant orbits and form a radially thick, metal-rich inner ring of peak age ~7 Gyr. Based on similar barred galaxies in Auriga simulations gives estimate of bar age $\gtrsim 7$ Gyr.

The Milky Way’s Inner Ring for $\Omega = 40$



Mapping the Disk into the Bulge II



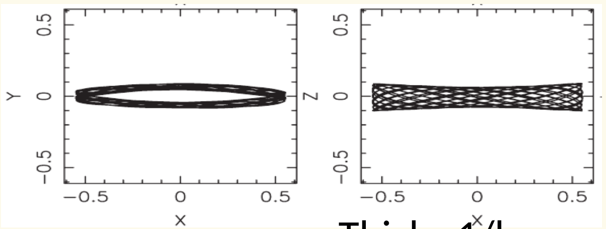


Left: Split red clump at various heights for model with thin/intermed/thick disks (di Matteo '16)

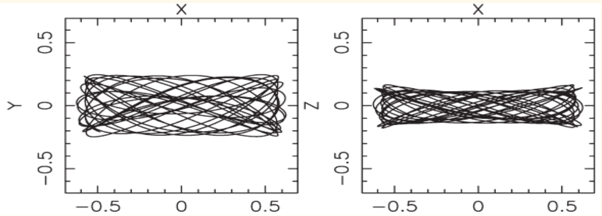
Right: Cyl.rotation and dispersion profile as f(age) in star-forming simulation (Debattista+'17)

Sample of Orbits in Rotating B/P Bulges

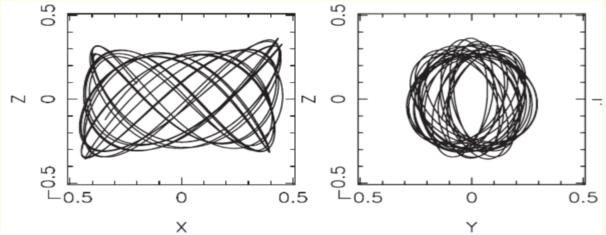
Thin x1



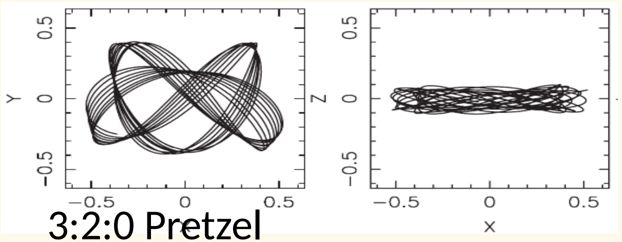
Thick x1/box



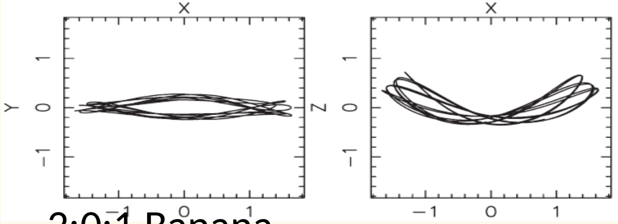
X-tube



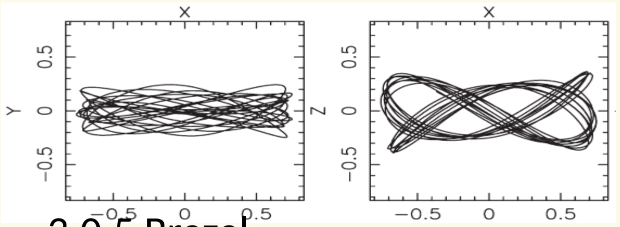
Resonant $\Omega_x:\Omega_y:\Omega_z$



3:2:0 Pretzel

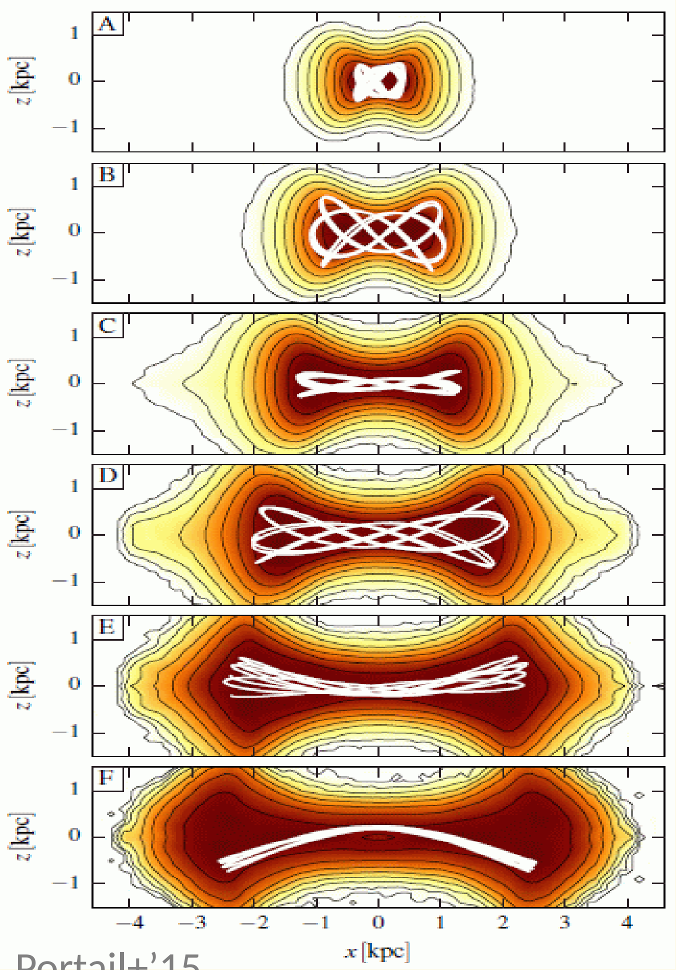


2:0:1 Banana



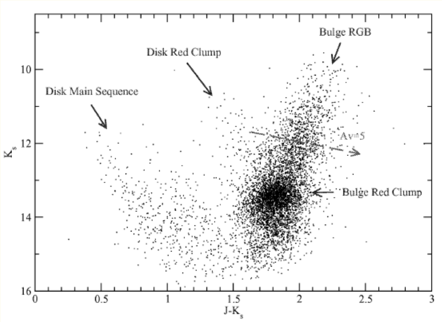
3:0:5 Brezel

Valluri+’16

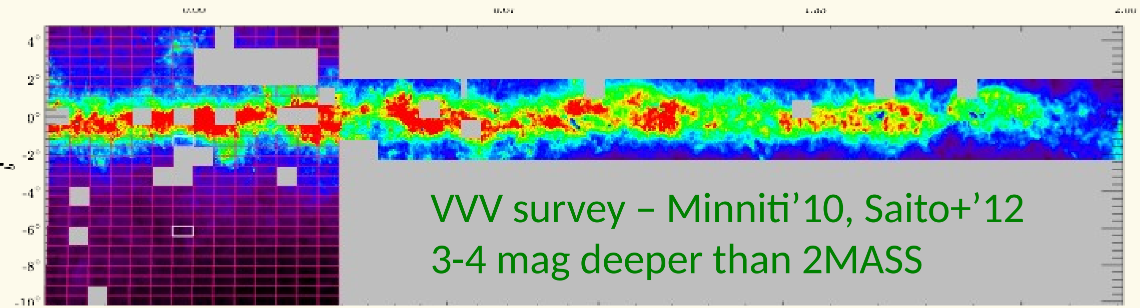


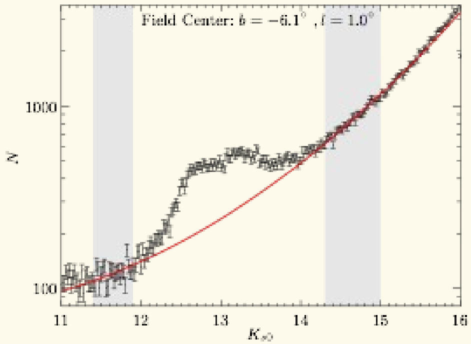
Portail+’15

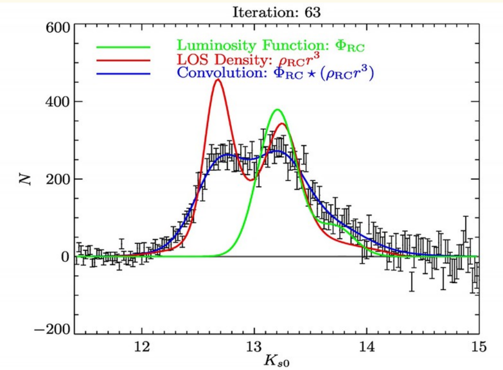
Red Clump Giant Distances & Bulge 3D Density

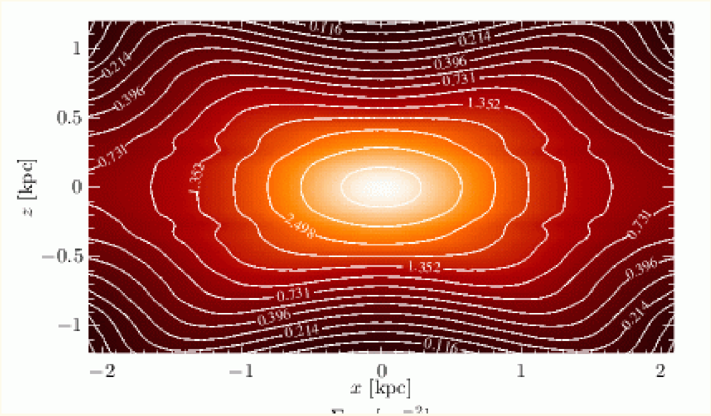


RCG as tracers since Stanek+'94









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

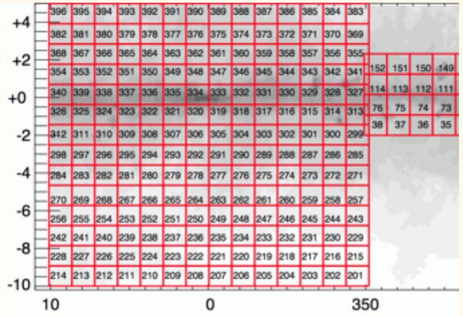
RCG: ~(K_s)~0.17, σ(J-K_s)~0.05, small spread because of age & metallicity (Salaris + Girardi '02), tracer for old [0.02,1.5] $Z_\odot$ populations, ~90% of ARGOS sample (Ness+'13)

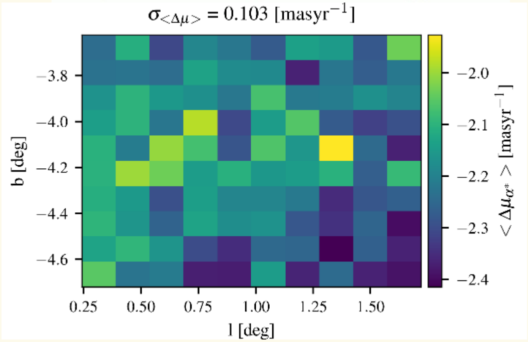
Density map from ⟷8 Mio RCG in 300 VVV fields in the bulge, |b|>1 dg Wegg & OG 2013
~10% density error in most of the bulge. Extra-polated into crowded Galactic plane by Portail+'15

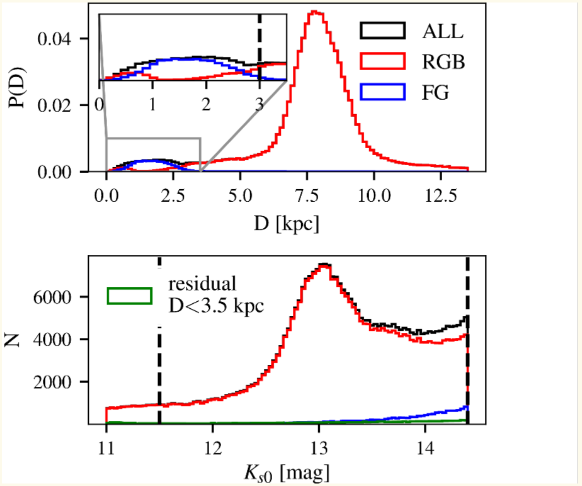
New 3D view from VIRAC/Gaia proper motions

Clarke+'19 also Sanders+'19

- 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.







Final sample: ~40 Mio bulge giant PMs

- 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.