From Questions to Answers: The Milky Way bulge with MOONS

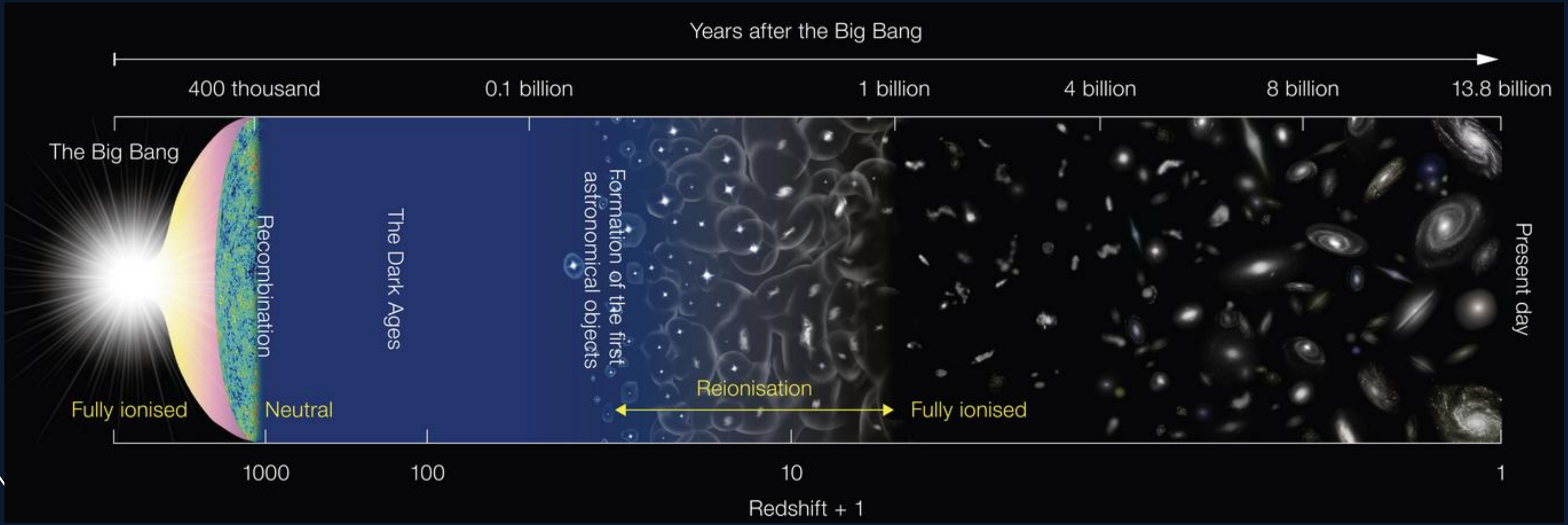
Elena Valenti
European Southern Observatory

Galaxy Formation & Evolution

Roughly 60%-70% of galaxies host bulges

Bulges formation remains a key open question in galaxy evolution, explored mainly through two complementary approaches:

- Observing high-z galaxies, where bulges are forming
- Studying local galaxies, where diverse bulge types are seen

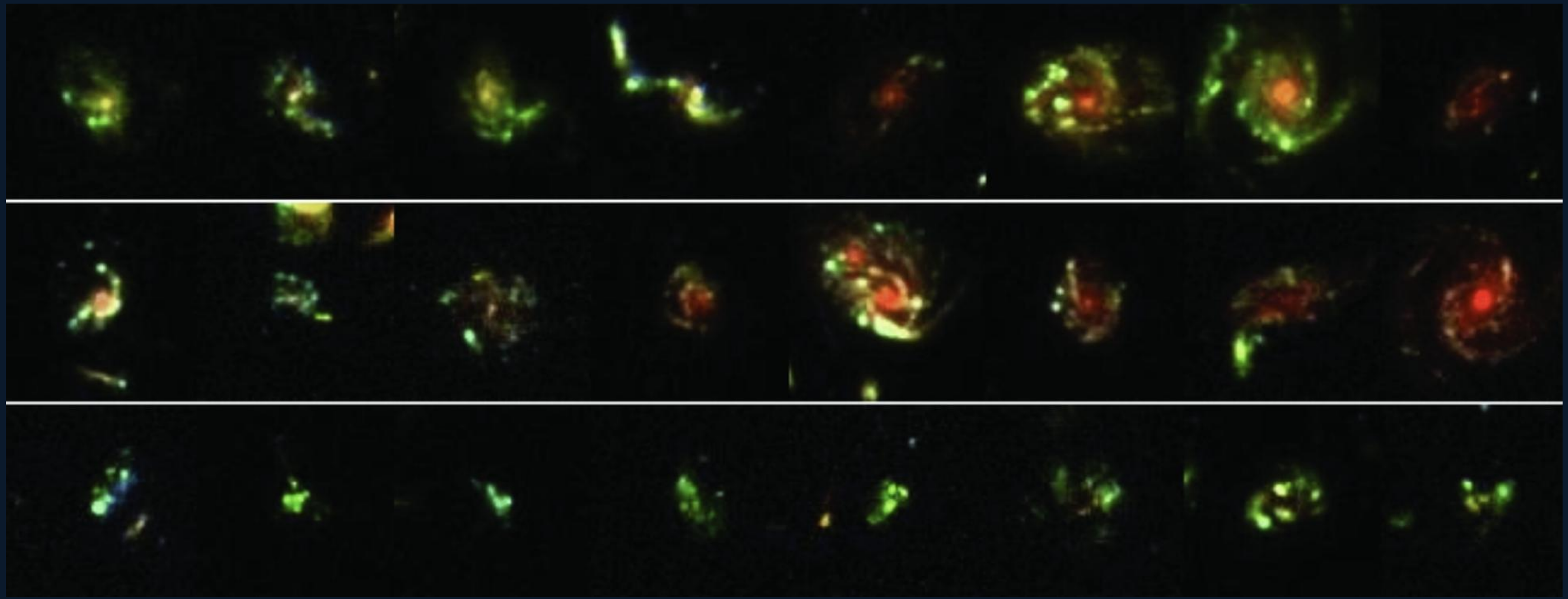


Bulges at High Redshift

High-z disks are gas-rich, turbulent, and highly star forming.

- giant clumps migrating and coalescing at the centre
- violent disk instabilities driving gas inward on short depletion timescales

→ Rapid formation from the disk within a dissipative gas-rich environment.



Immeli+2004;
Carollo+2007;
Elmegreen+2008;
Genzel+2008;
Bournaud+2009;
Dekel & Buret 2014;
Guo+ 2015;
Tacchella+2016

Bulges in the nearby Universe

Local bulges shows very different properties (Kormendy & Kennicutt 2004):

- *Classical bulges:* form through dissipationless mergers of stellar subunits
- *Psuedo bulges*: form via dynamical instability in gas-poor disk, where bars develop and subsequently buckle into thicker, boxy structures (B/P shape)

→ Unlike at high-z, stars form outside the bulge

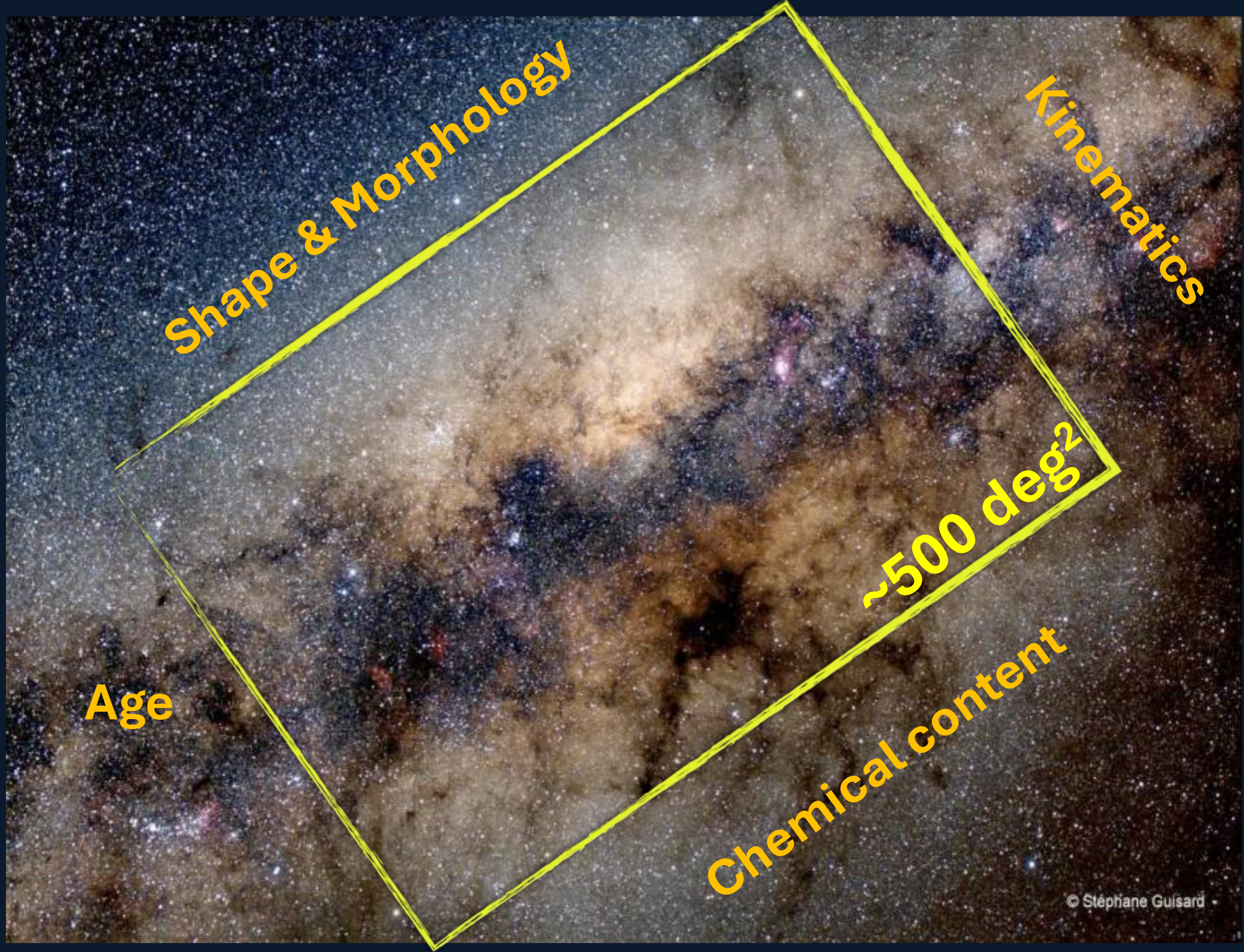



The Milky Way bulge

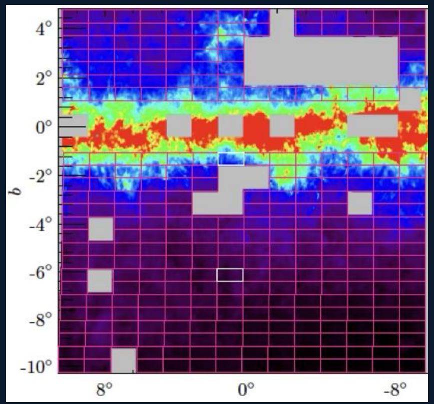
Bridging the high-z and local perspective!

Unique opportunity to study a bulge where individual stars can be resolved:

- Age, chemical composition & kinematics: *The three dominant parameters in the population concept* (cfr., Sandage)
- Global properties (e.g., age, kinematics and chemistry) inferred directly from details of its stellar content

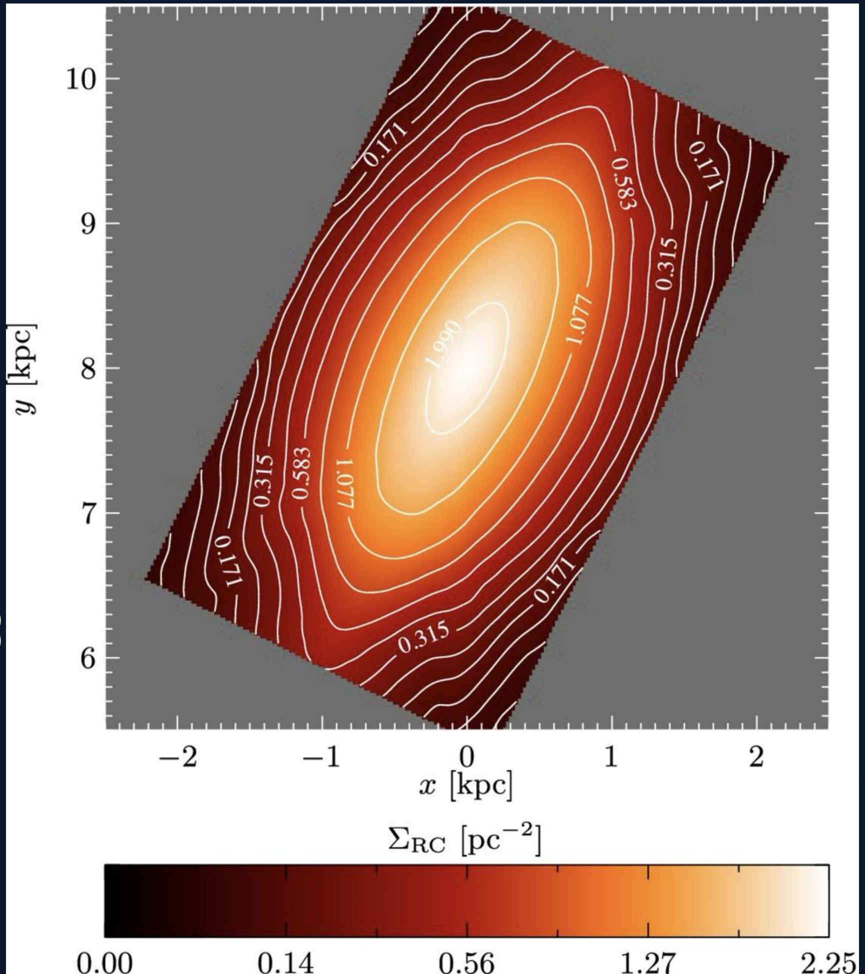


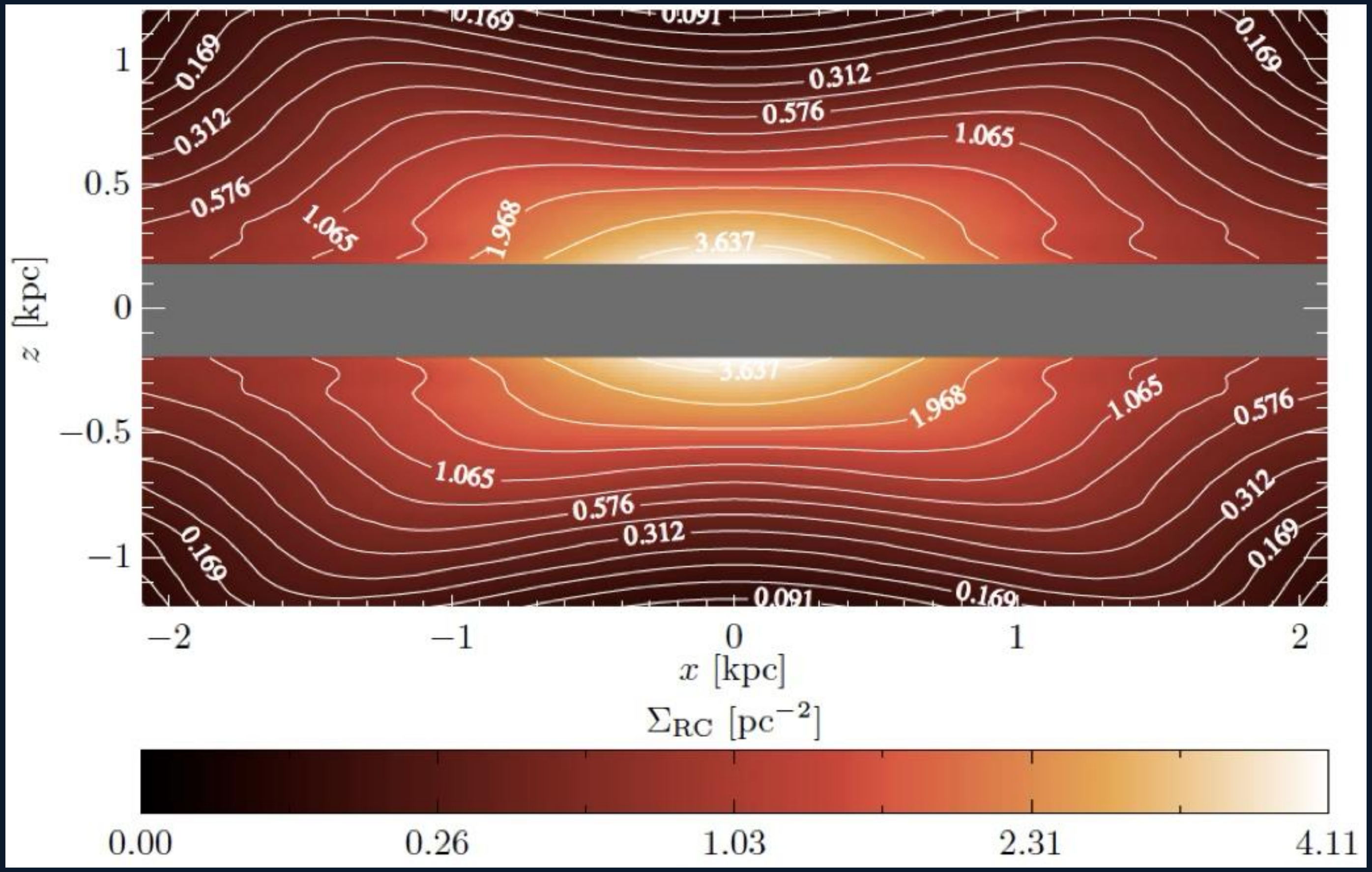
3D view of the bulge



triaxial bar density model based on VVV DR1:
(x0:y0:z0)=(0.7:0.44:0.18) kpc - Axis ratio: (10:6.3:2.6) kpc - pivot angle θ: 27º

Wegg & Gerhard 2013

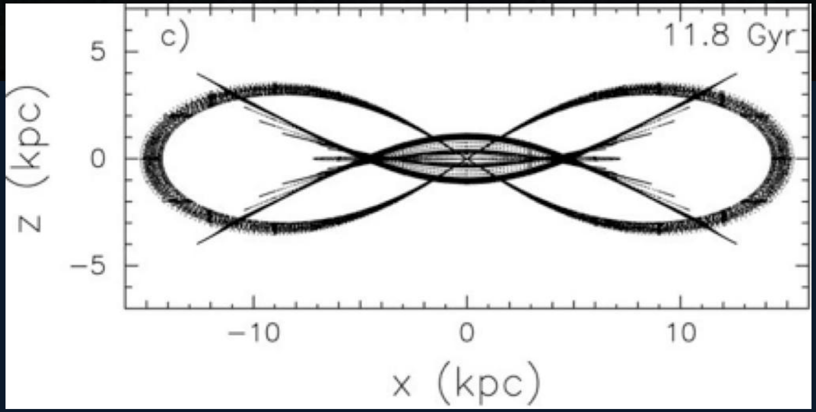




B/P & X-shape structures in galaxies

The boxy morphology is characteristic of all barred galaxies when seen edge-on (Laurikainen+2014)

The peanut shape (X-shape) is also a product of bar evolution, dynamical instabilities produce bending and buckling of the elongated stellar orbits within the bar resulting in the shape of peanut, or an X-shape when it is more pronounced, when seen edge-on (Patsis et al. 2002, Athanassoula 2005)

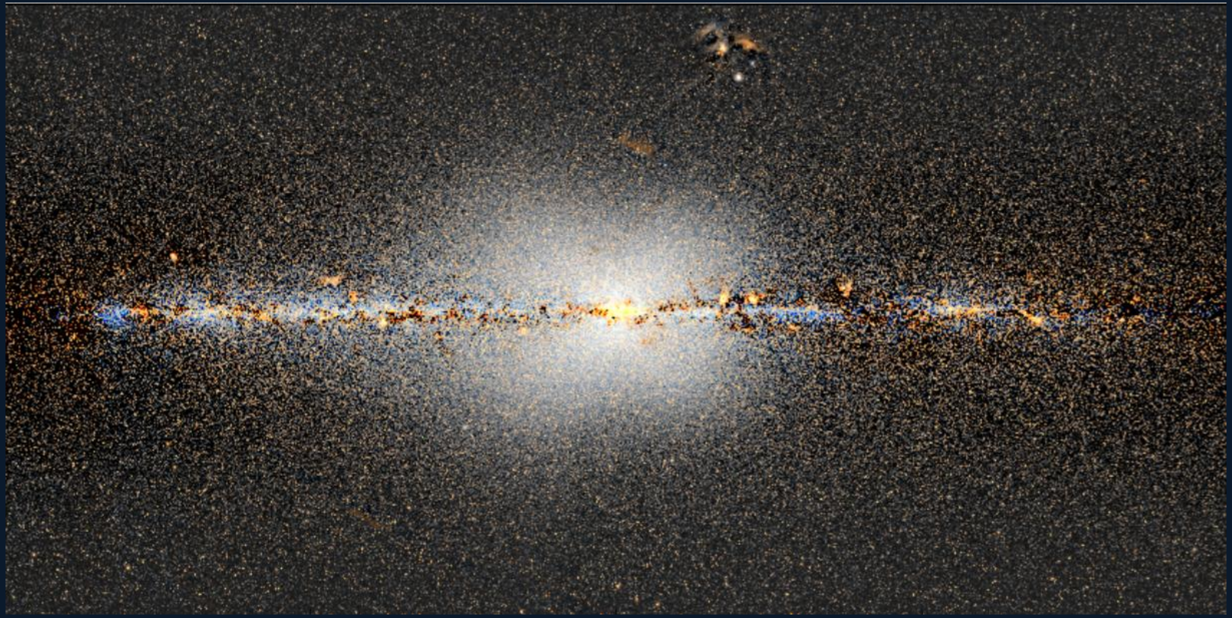


McWilliam& Zoccali 2010)
Nataf et al. 2010
Saito et al. 2010
Wegg & Gerhard 2013
Gonzalez et al. 2015
Ness & Lang 2016

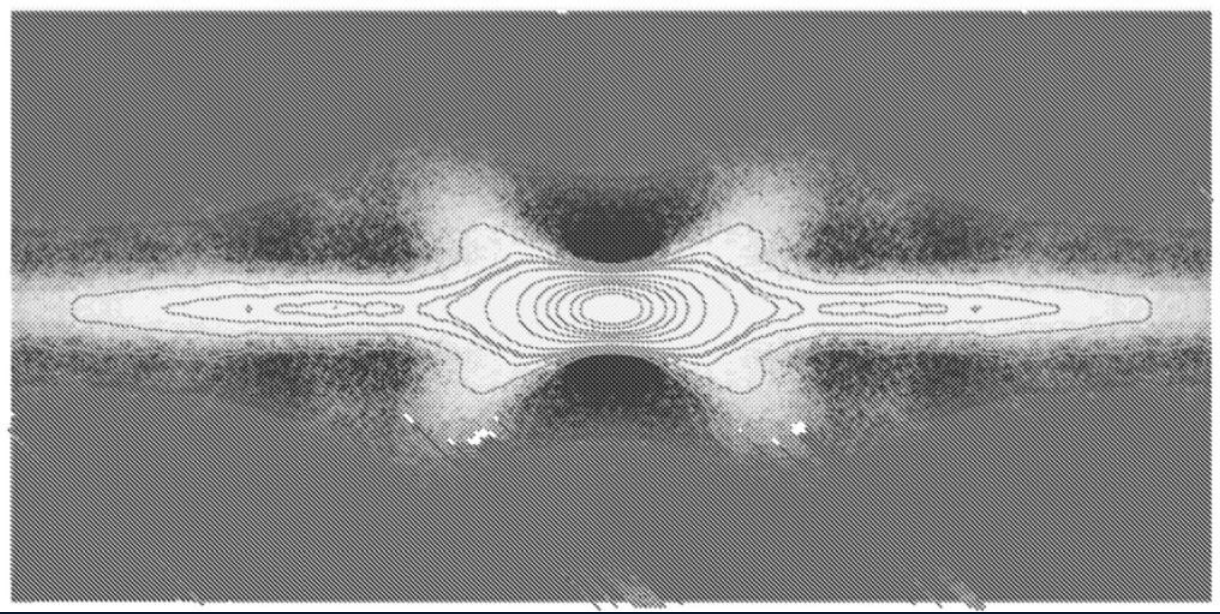
The MW bulge X-shape

The X-shape of the MW bar is a natural product of disk evolution

Ness & Land (2016) unWISE all sky map

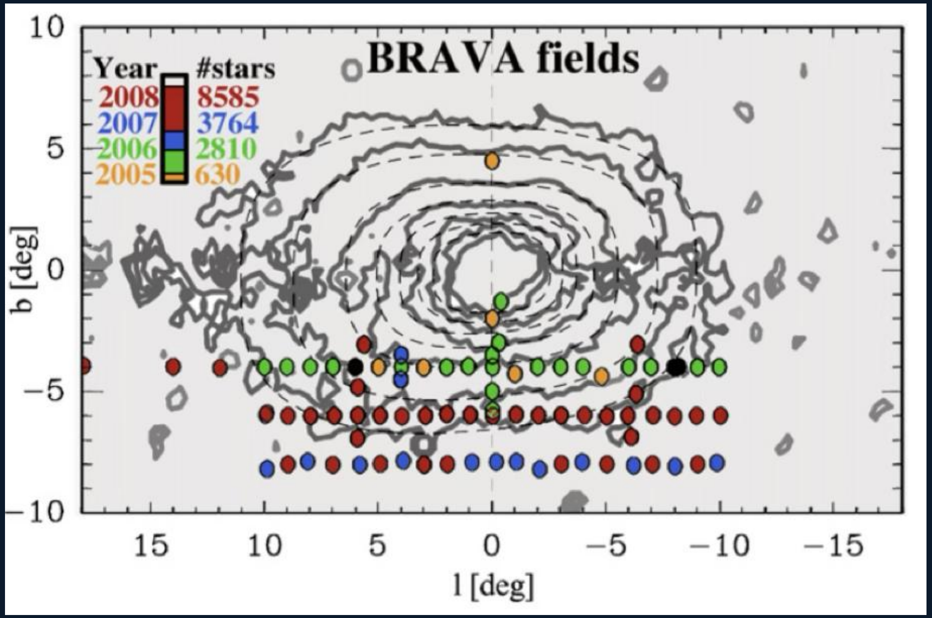


Simulations Athanassoula 2005



The Kinematics

BRAVA surveys

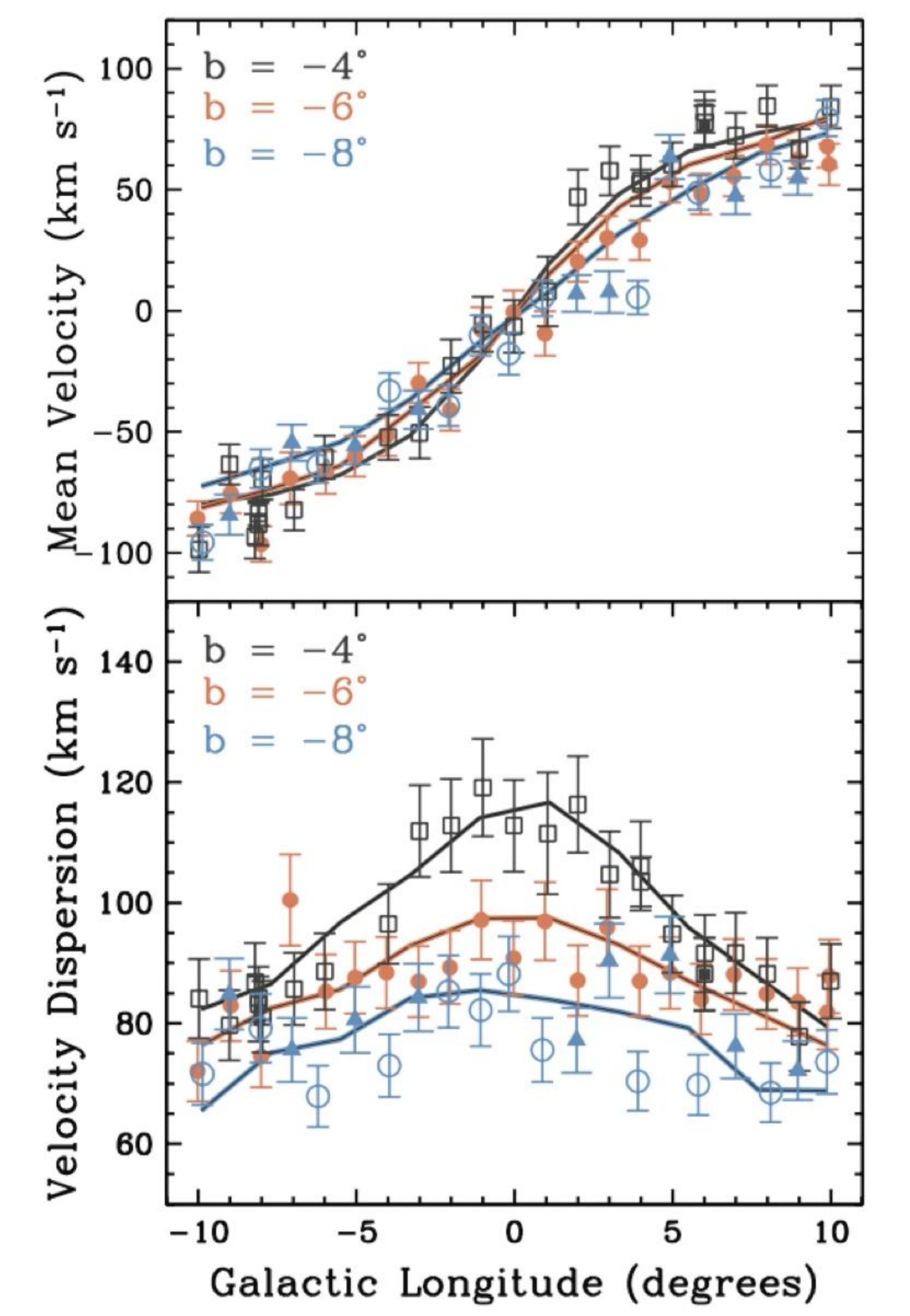


R~4200
~42 fields
> 6000 M-giants

Rich et al. 2007
Howard et al. 2008
Kunder et al. 2012

Cylindrical rotation

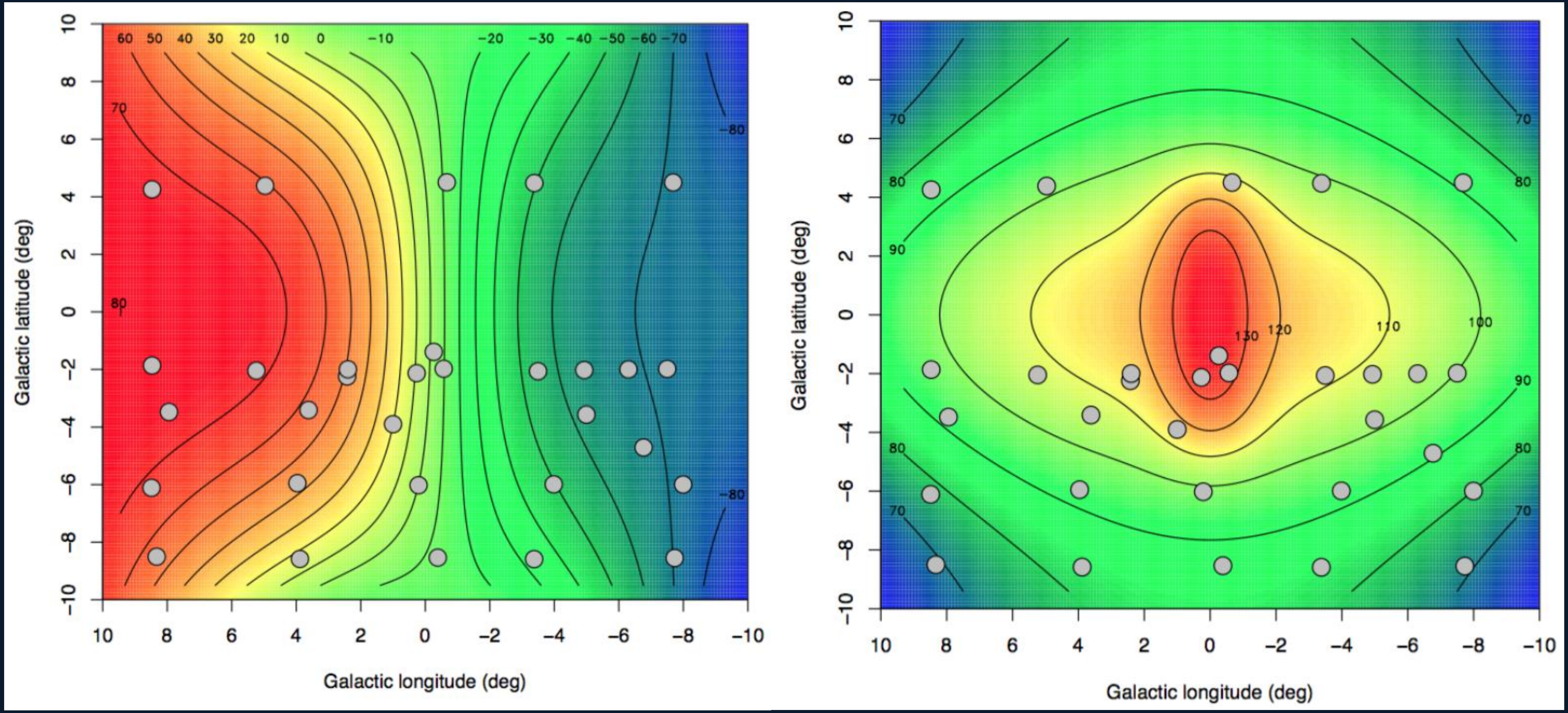
confirmed by other surveys (i.e., ARGOS, GIBS, APOGEE, GES)



Global Kinematics

GIBS surveys

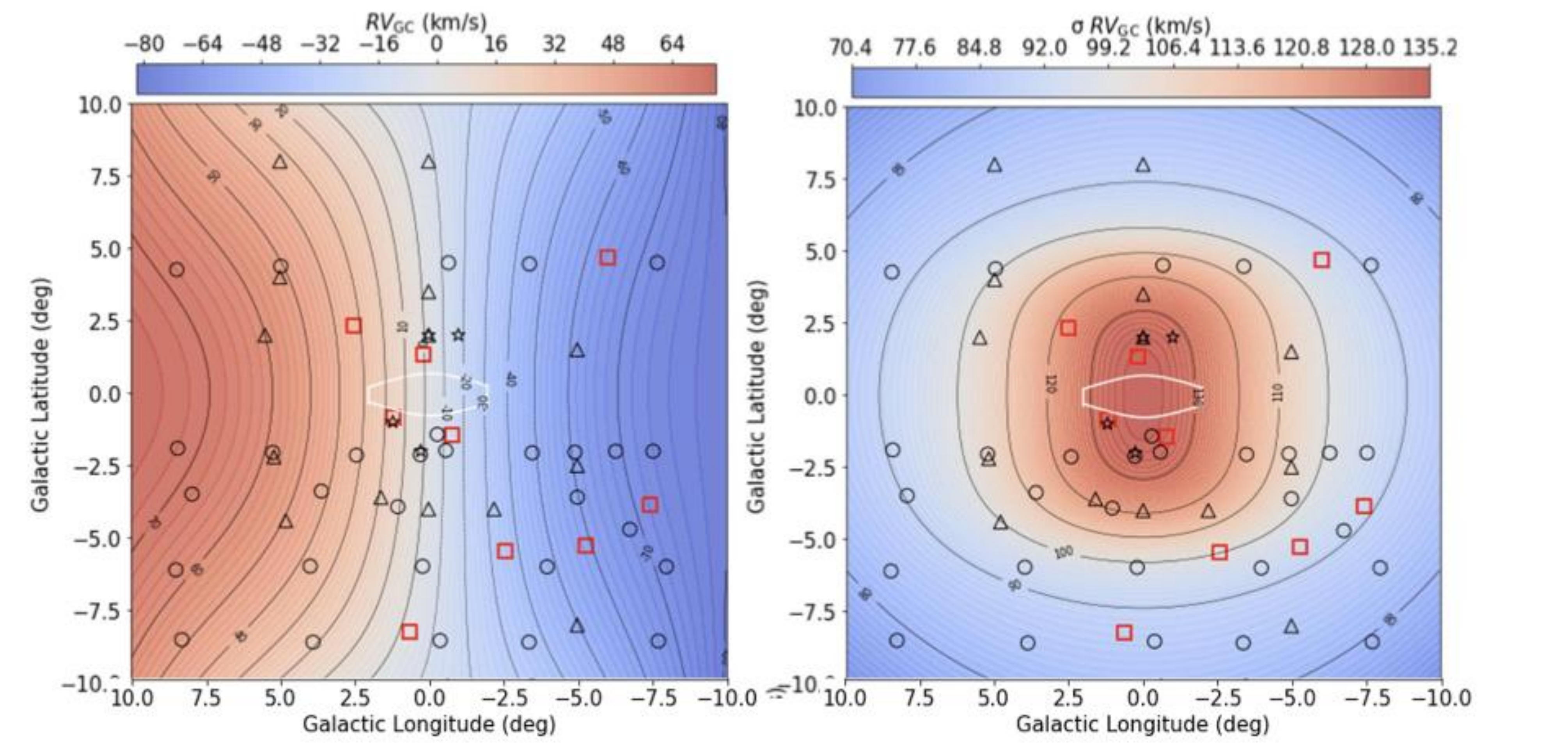
Zoccali et al. 2014



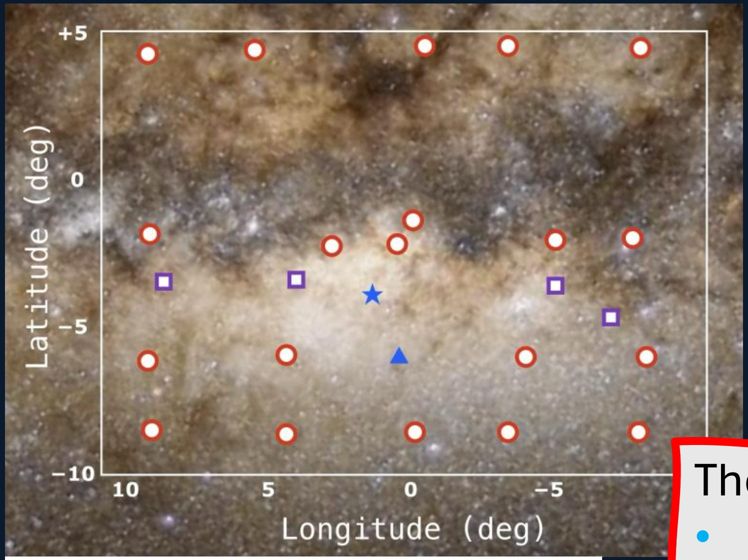
Global Kinematics

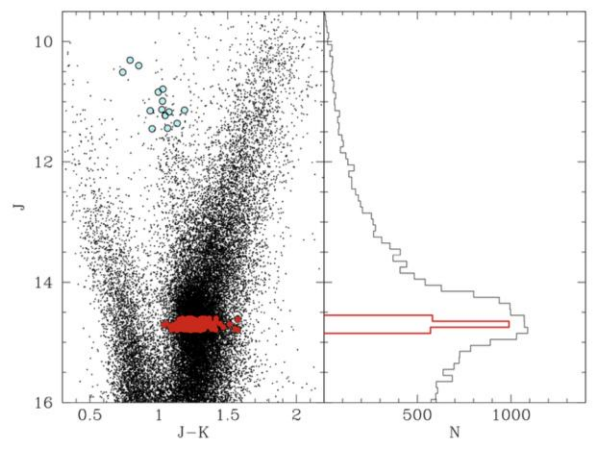
GIBS surveys + Apogee + MUSE

Quezada, Zoccali, Valenti et al. 2025



The MDF in the survey's era





GIBS survey:

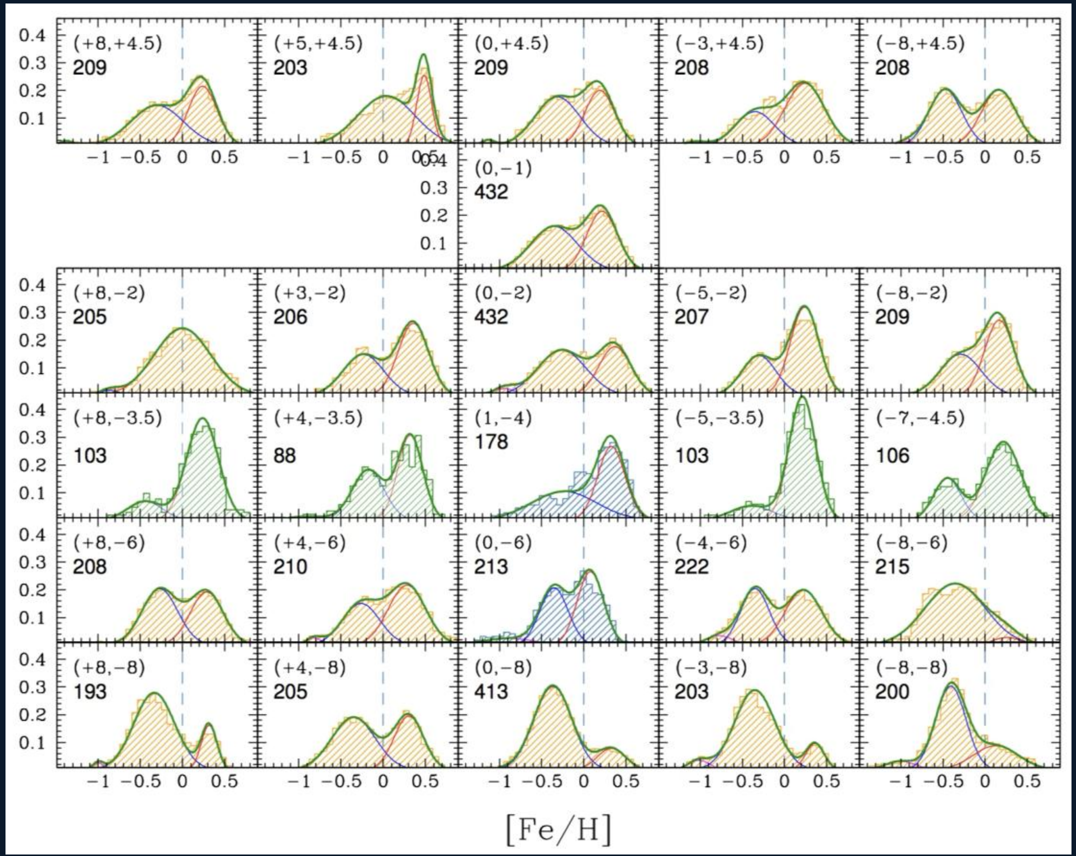
- 26 fields
- ~5000 K-giant, MR opt spectra
- ~600 K-giant, HR opt spectra

The MDF is clearly bimodal:

- m-poor SP (i.e., [Fe/H]>0]) dominates in the outer regions
- m-rich SP (i.e., [Fe/H]<0]) increases towards the center

➢ the previously observed global metallicity gradient is due to changes in the relative fraction m-poor/m-rich

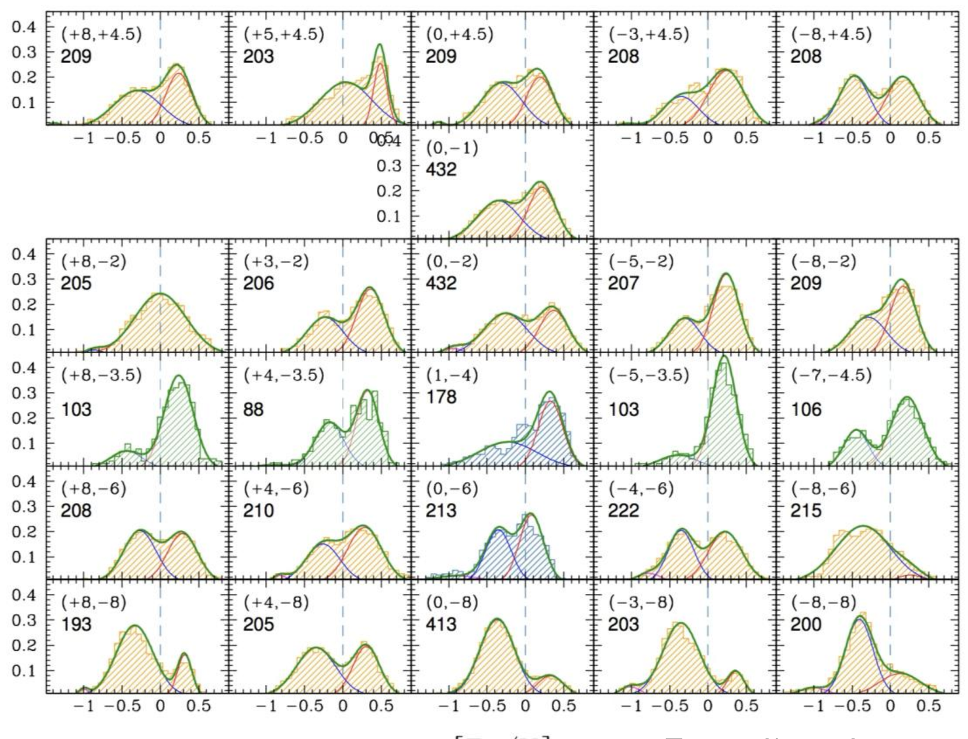
Zoccali et al. 2017



CONFIRMED by other surveys, see also: **GaiaESO** (Rojas-Arriagada et al. 2014, 2017), **ARGOS**: (Ness et al. 2013)

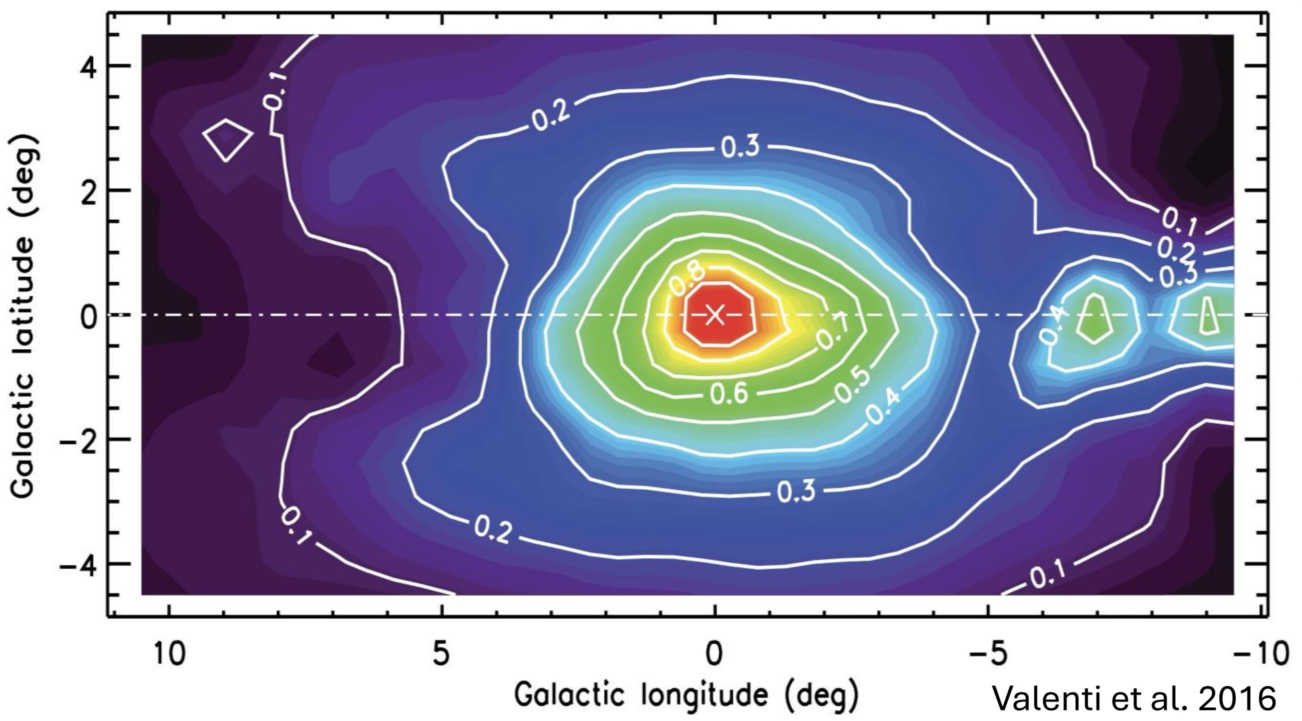
Two Bulge metallicity components

Combining the Metallicity Distribution with Stellar Density map



Zoccali et al. 2017

X

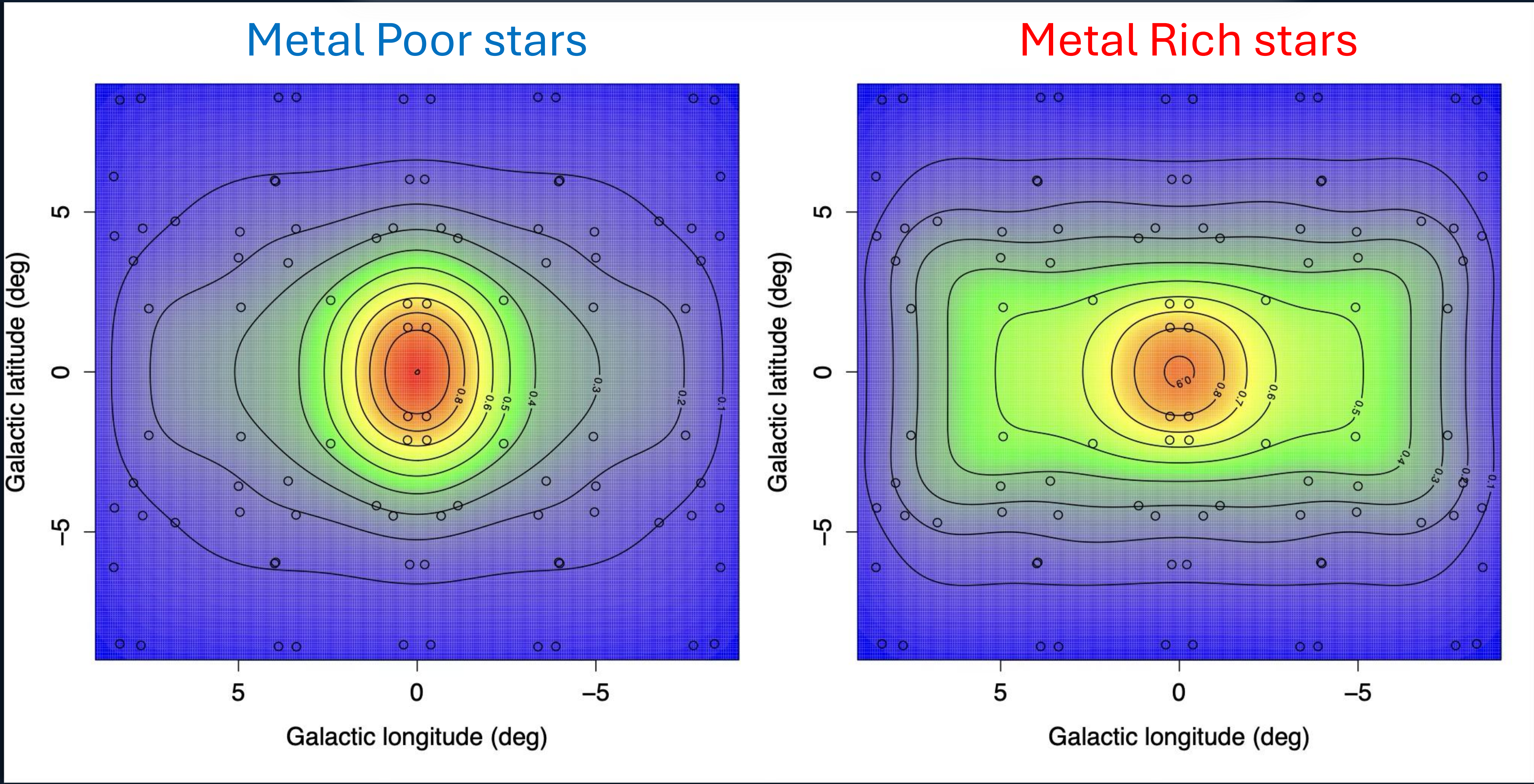


Valenti et al. 2016

Zoccali et al. 2017

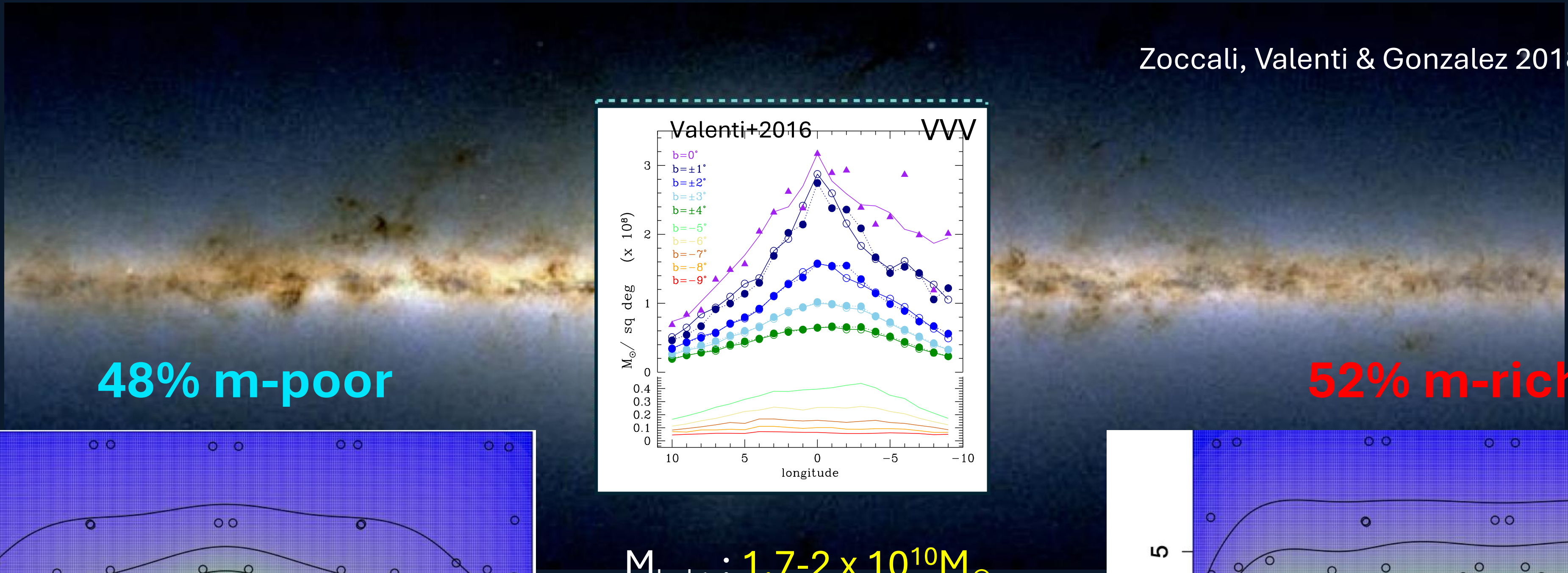
Two Stellar Density Maps

m-poor component is spherically concentrated
m-rich component traces the bar



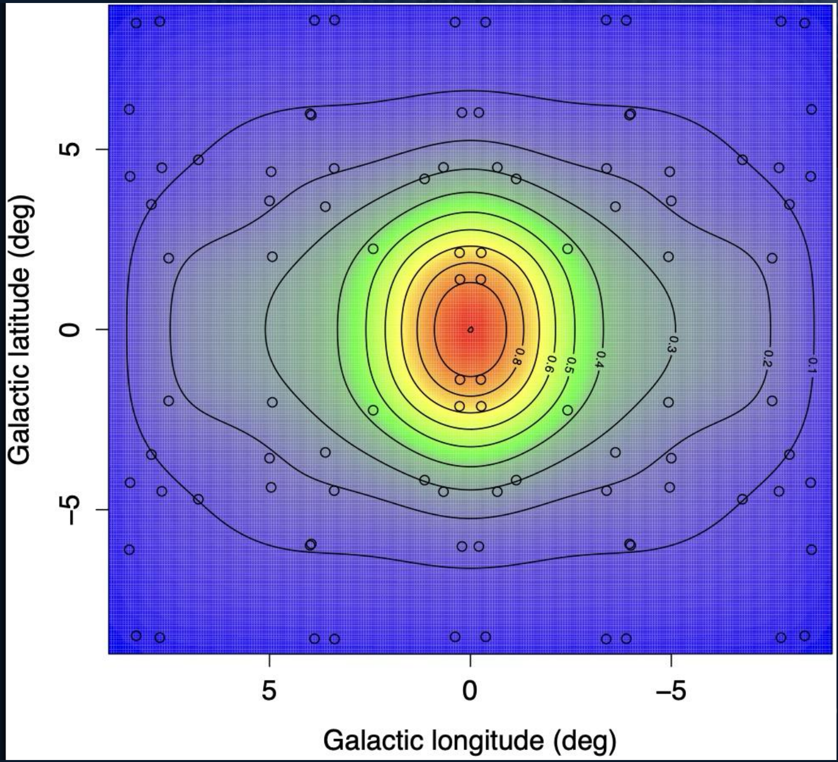
The Stellar Mass of the Bulge

Zoccali, Valenti & Gonzalez 2018

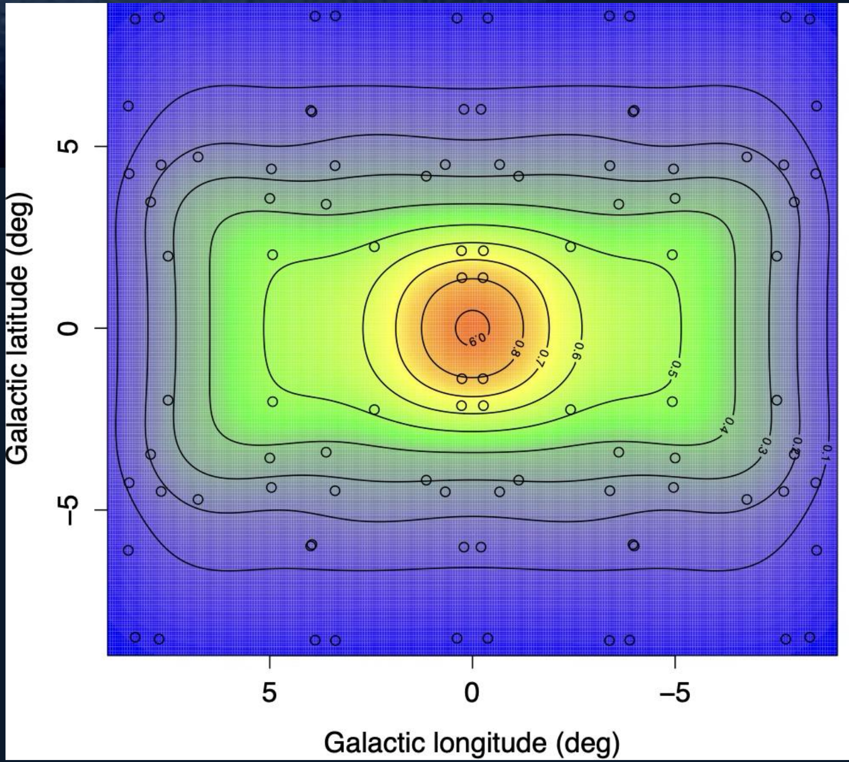


M_{bulge}: 1.7-2 x $10^{10} M_{\odot}$

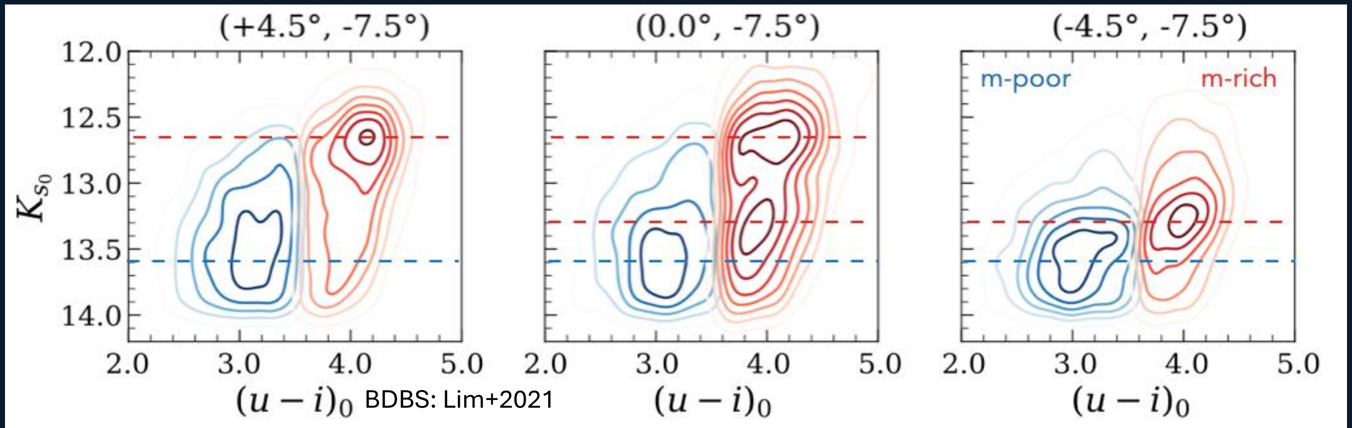
48% m-poor

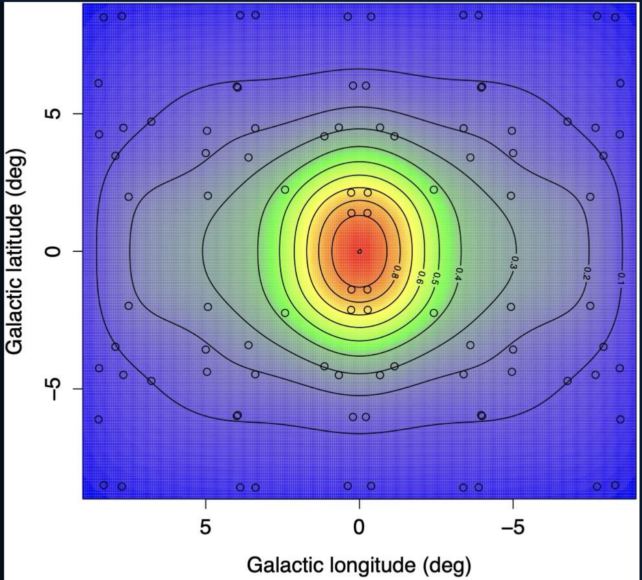


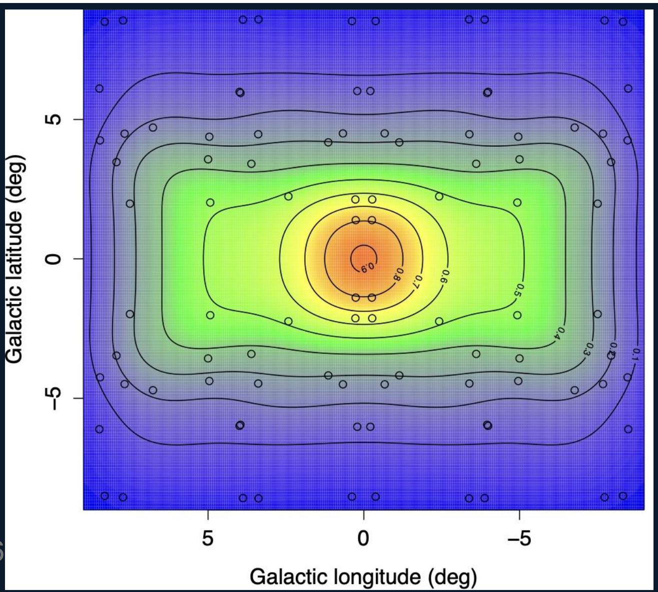
52% m-rich

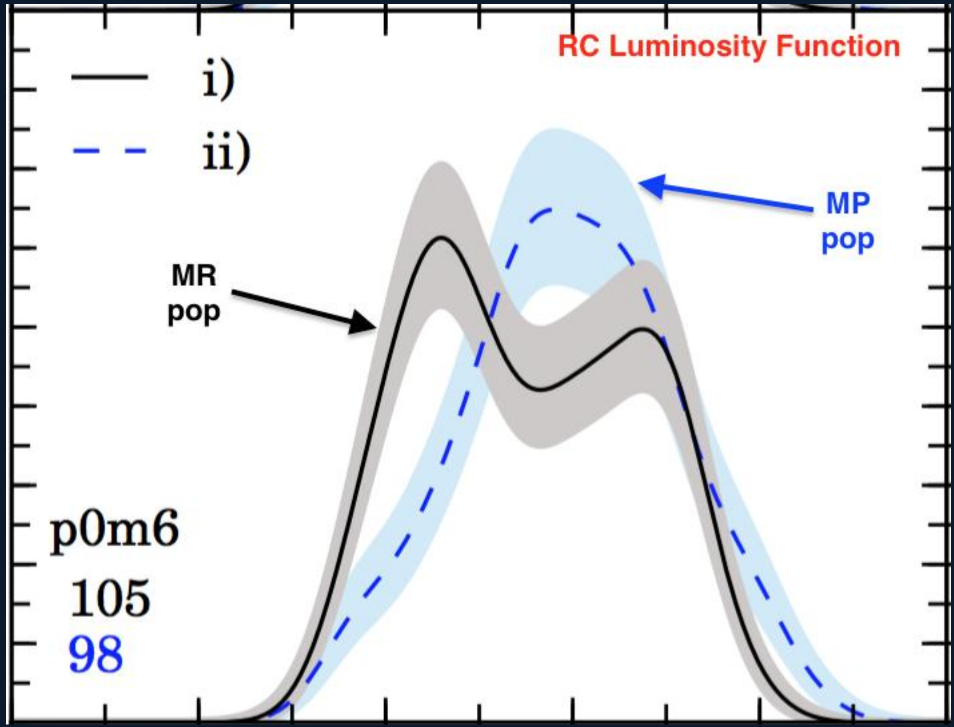


m-poor vs m-rich spatial distribution



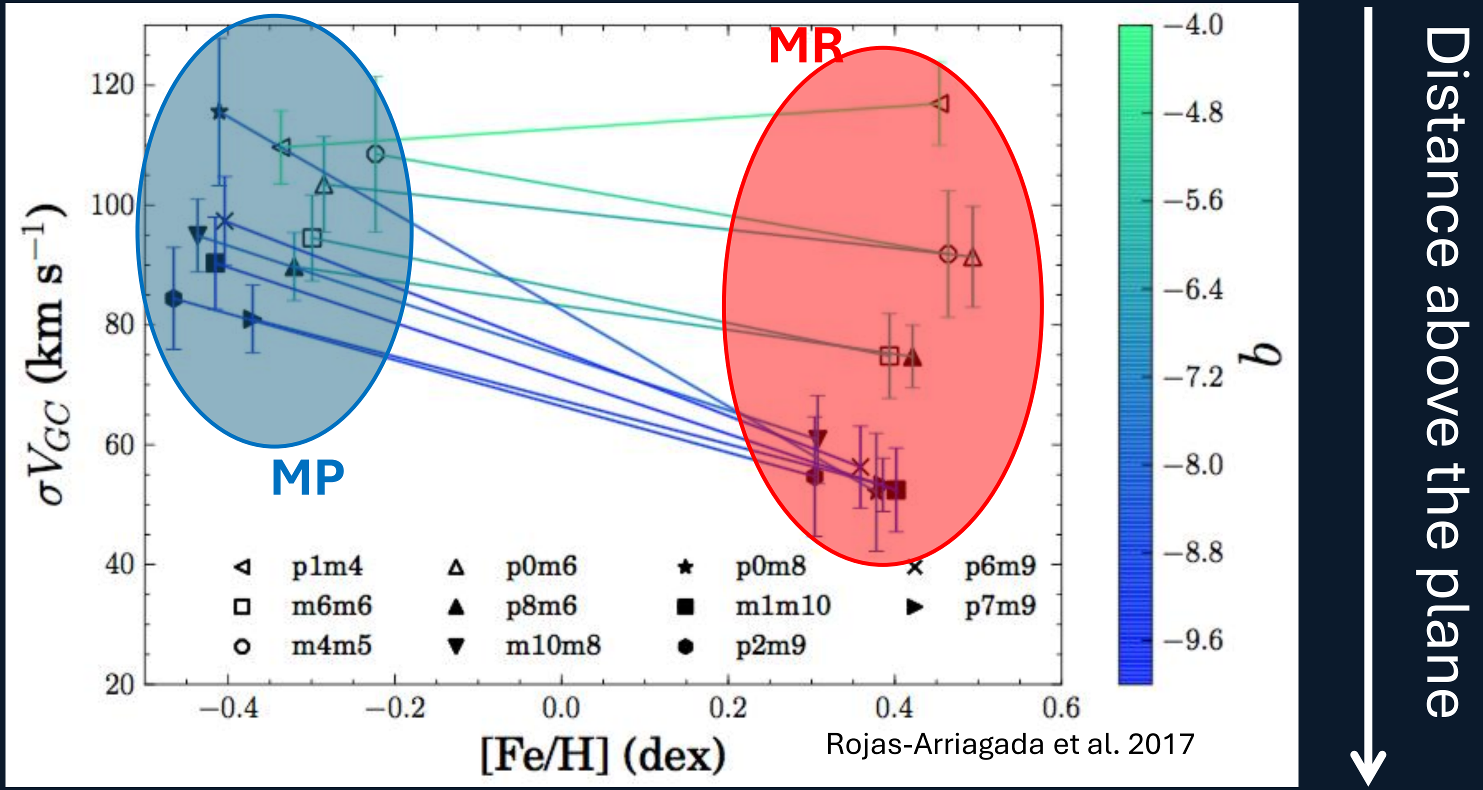






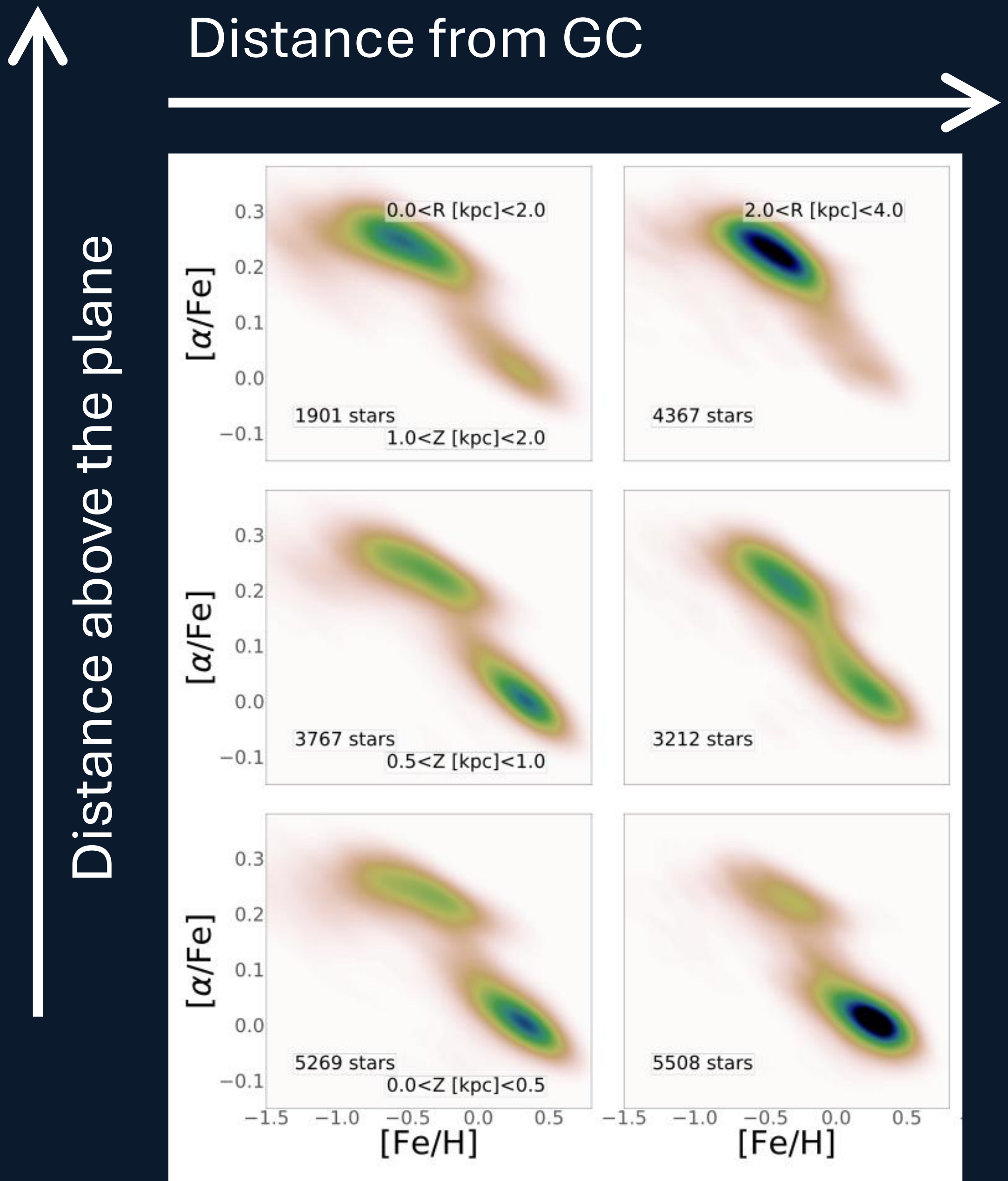
Coupling metallicity & kinematics

The velocity dispersion of m-rich stars show a steeper gradient (50-120 km/s) than m-poor stars, which rotate slower (i.e., m-poor kin hotter than m-rich)



Rojas-Arriagada et al. 2017

Queiroz et al. 2021



APOGEE DR16 + StarHorse + Gaia DR2

- m-poor stars are α-rich
- m-rich are α-poor

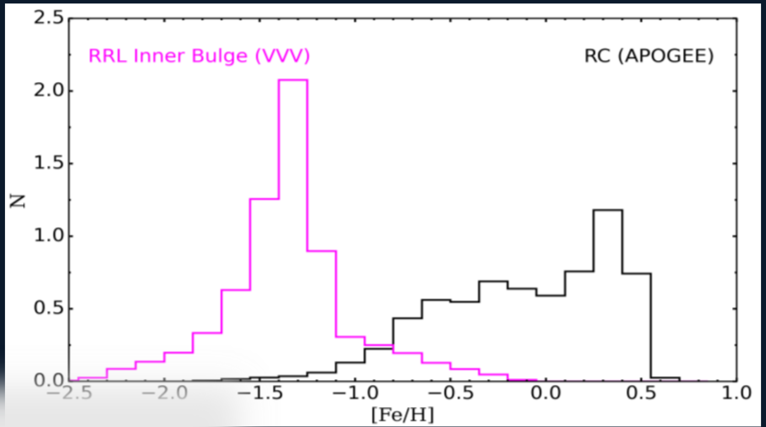
→ **True chemical discontinuity suggesting different formation scenarios**

Debattista et al. 2023: stars originally formed within one of the disk clumps are α-rich, while those formed outside the clumps, in the disk field where star formation proceeded at a slower rate, are α-poor.

Queiroz et al. 2022: m-poor stars trace pressure supported spheroid, while m-rich stars the bar (i.e., disk evolution)

The RRL variables

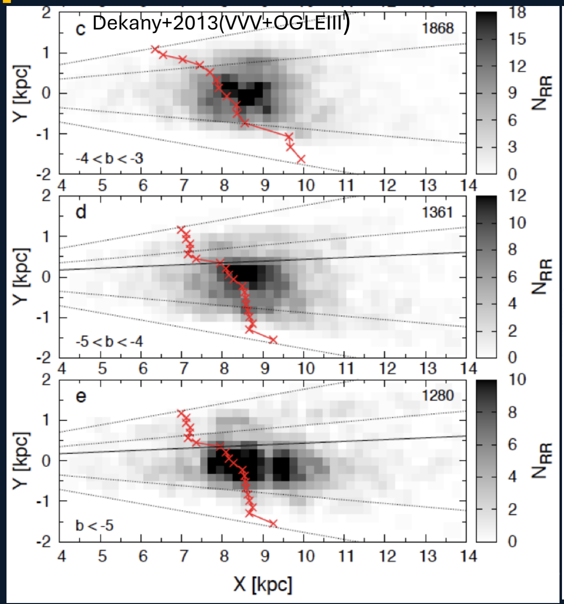
- RRL are possibly the cleanest tracers to infer 3D structure
  - Old (i.e., >10 Gyr)
  - Metal-poor
  - Accu

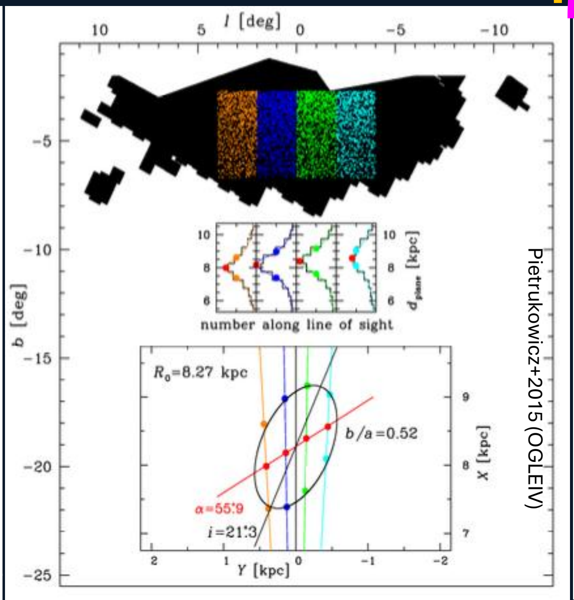


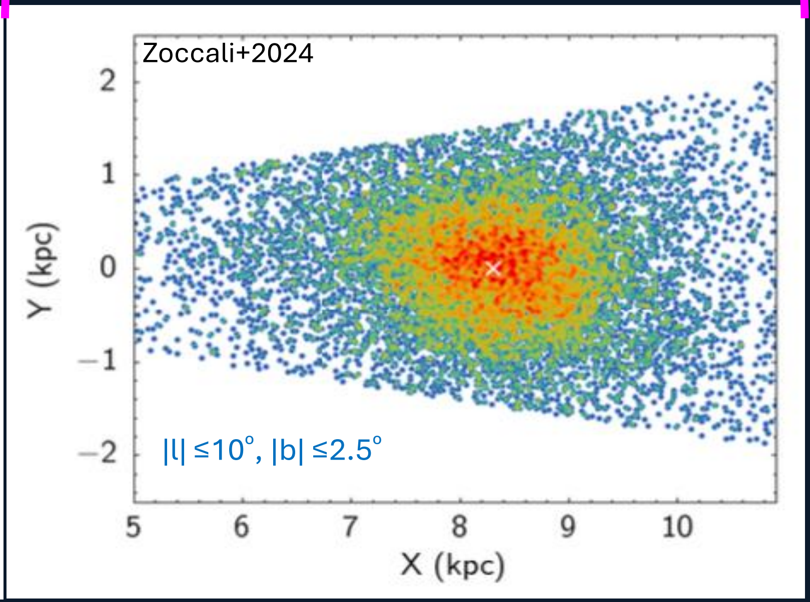
RRL spatial distribution is more spherical

Outer Bulge RRL

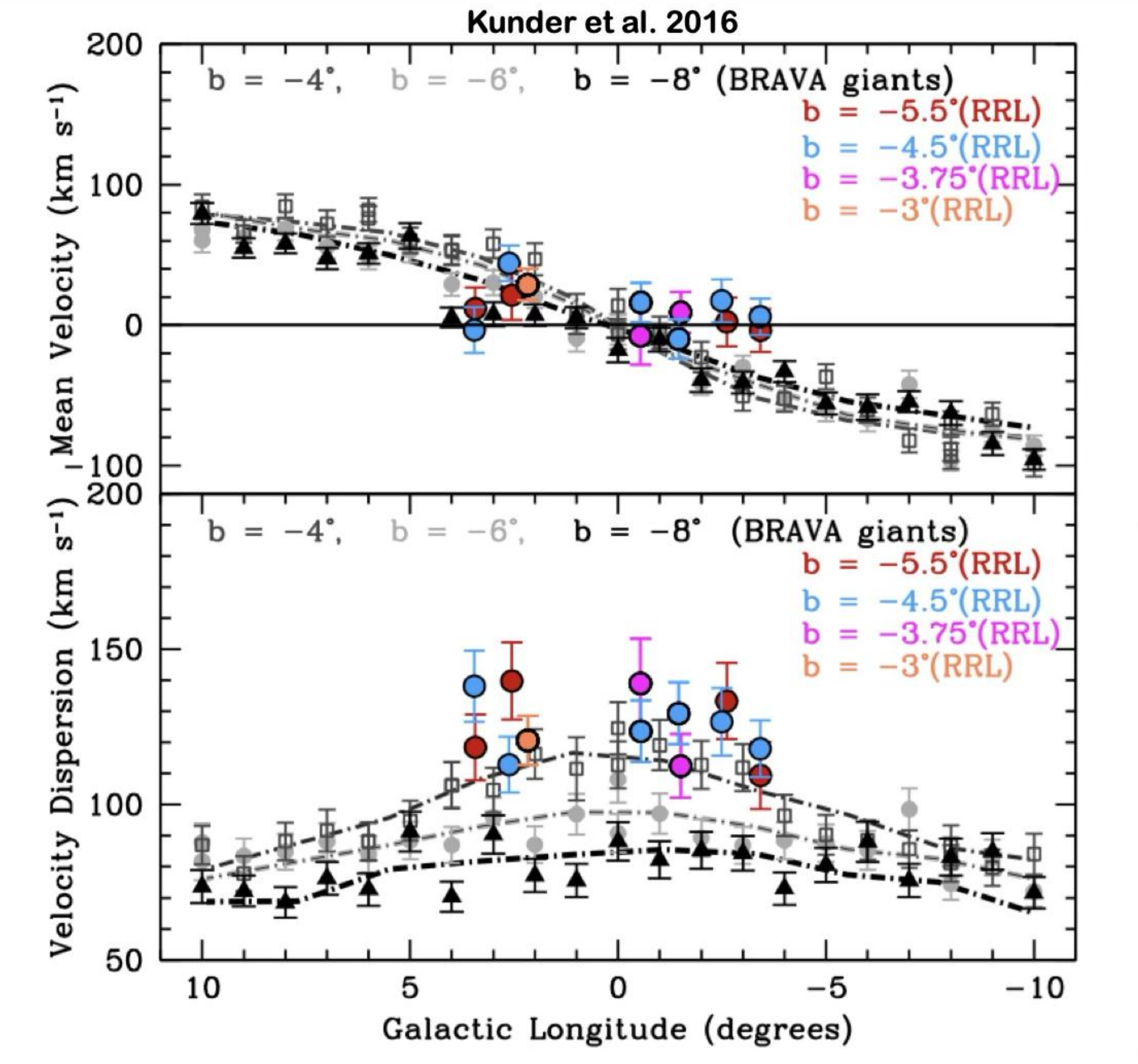
Inner Bulge RRL

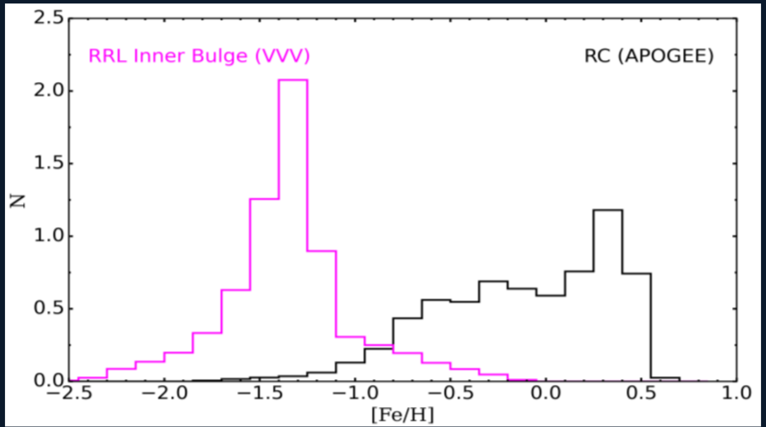






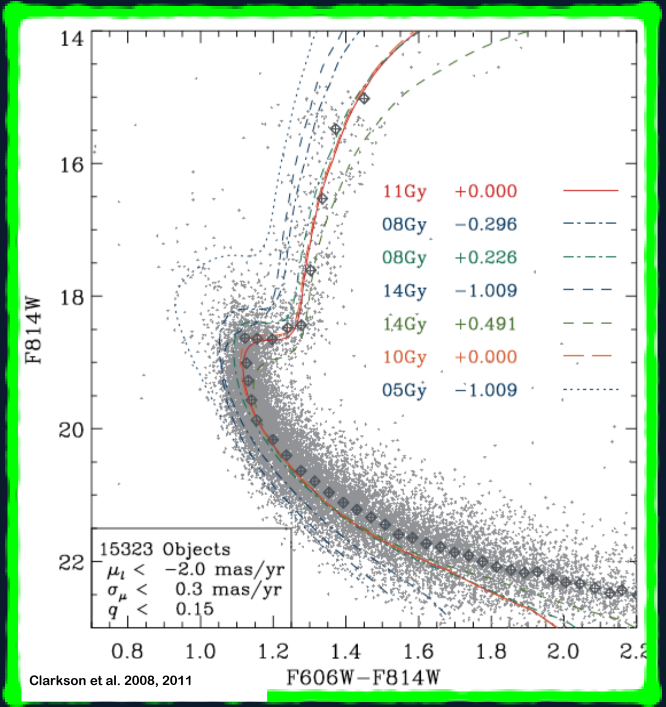
The RRL variables





RRLs rotate slower than K and M giants → hot kinematics with negligible rotation

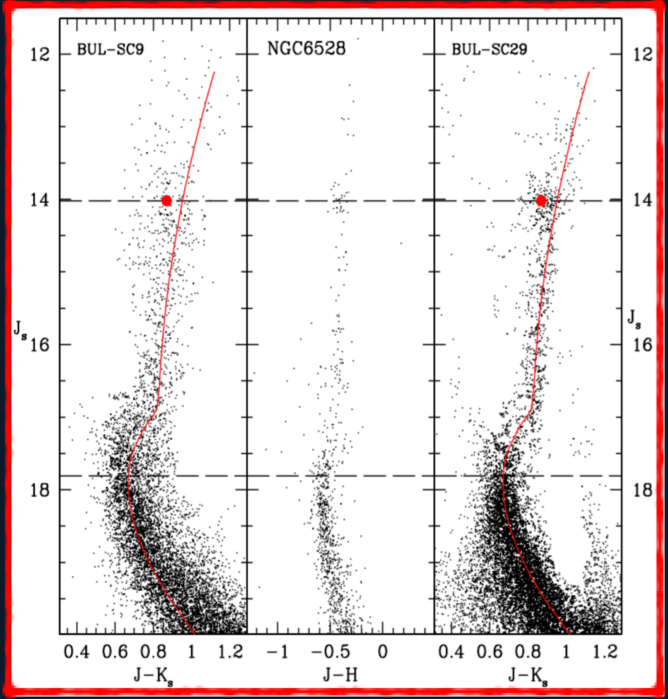
Photometric determinations of the AGE of SP in the several bulge fields suggest that the bulk of the Bulge is uniformly OLD (i.e., >10Gyr)



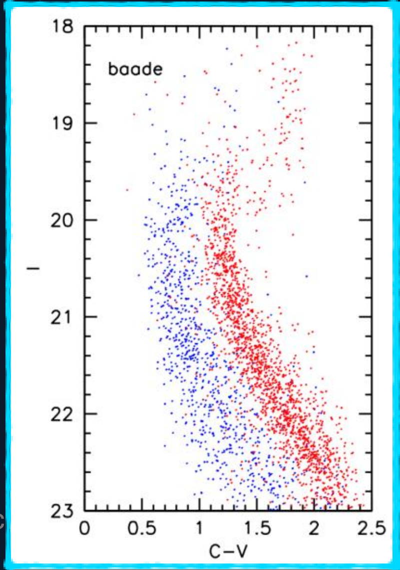
Clarkson et al. 2008, 2011

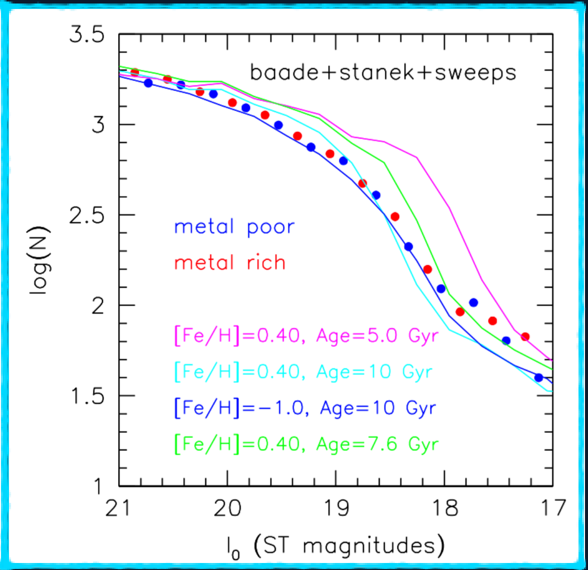
Low Red Fields: -7° < l <10° & -4°<b<-2°

EV et al. 2013



Renzini et al. 2018





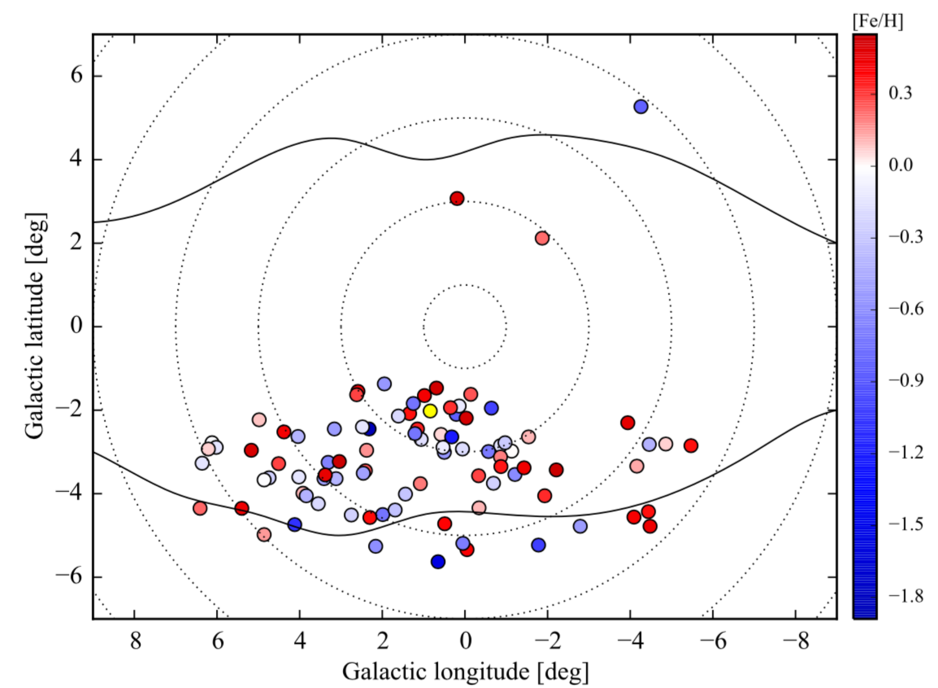
See also i.e., Bergh & Herbst 1974; Terndrup 1988; Ortolani et al. 1995; Feltzing & Gilmore 2000; Kuijken & Rich 2002; Zoccali et al. 2003; Clarkson et al. 2008,2011; EV et al. 2013, Renzini et al. 2018

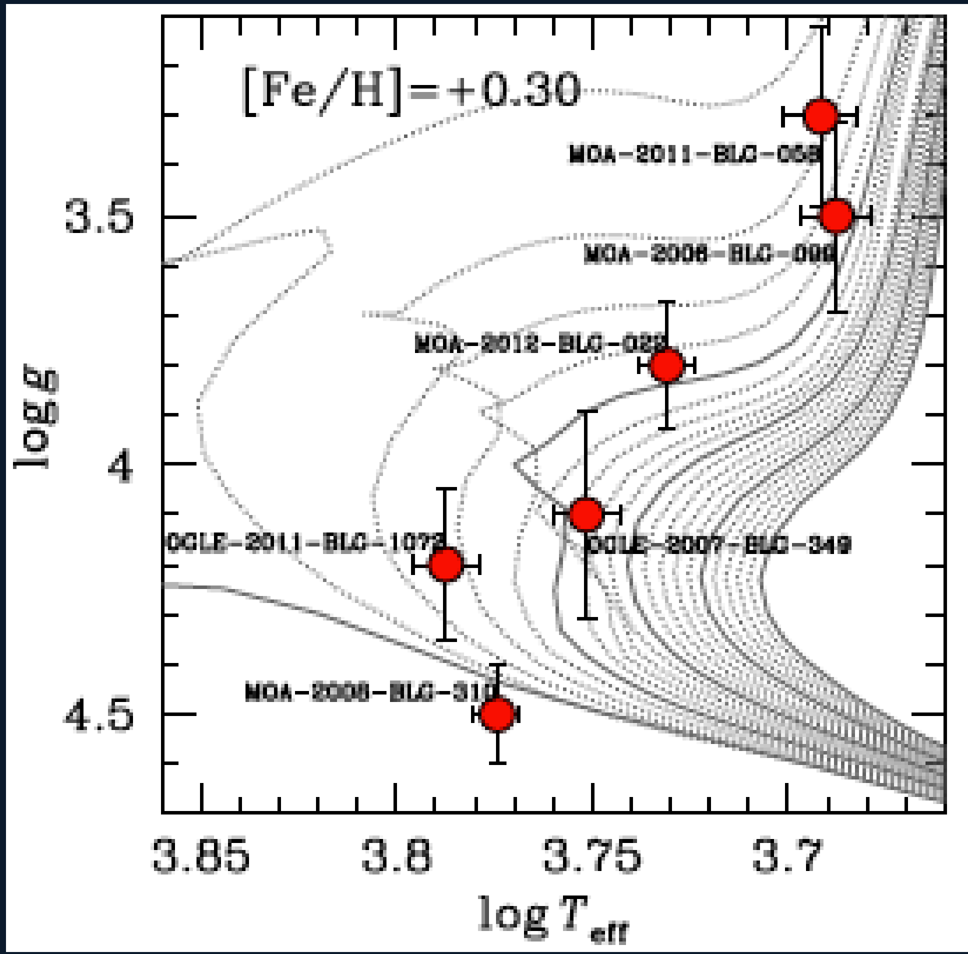
Spectroscopic age determination

UVES@VLT, R>40,000, 90 stars

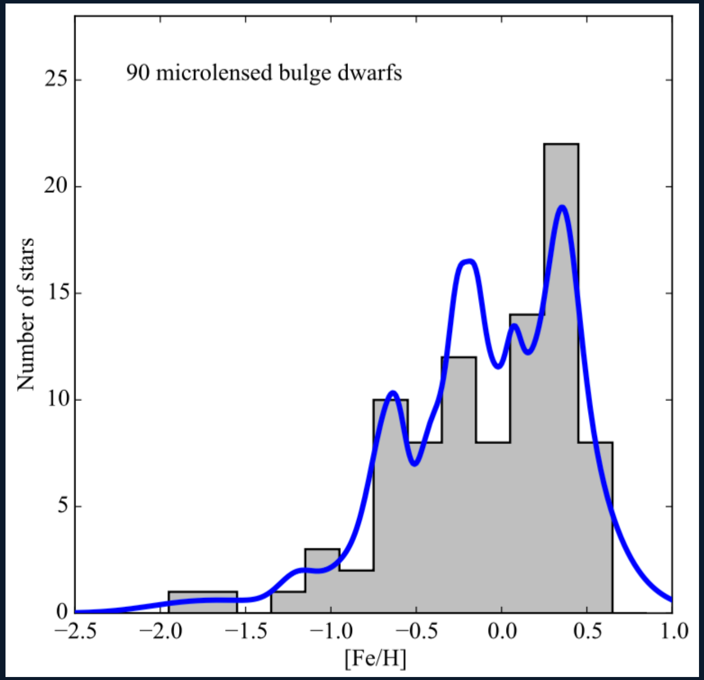
Teff: from excitation balance of abundances from FeI lines
g: from ionization balance between abundances of FeI and FeII lines

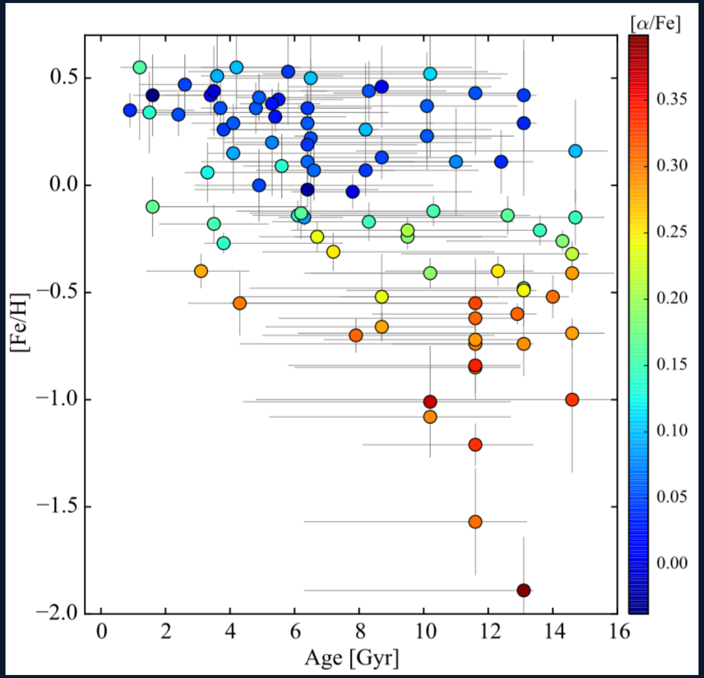
Bensby et al. (2011, 2013, 2017)





Age – Metallicity relation based on dwarfs and sub giants





+ MP stars are mostly old (> 10 Gyr), MR stars show a wide range of ages.

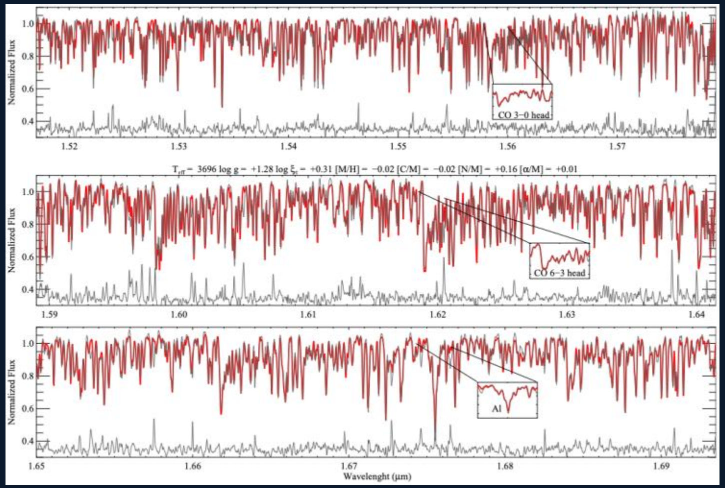
+ At least 18 % of the stars, at all metallicities are young (<5 Gyr).

+ At super-solar metallicities more than 35 % are younger than 8 Gyr.

+ Several episodes of SF occurred 3, 6, 8 and 12 Gyr ago

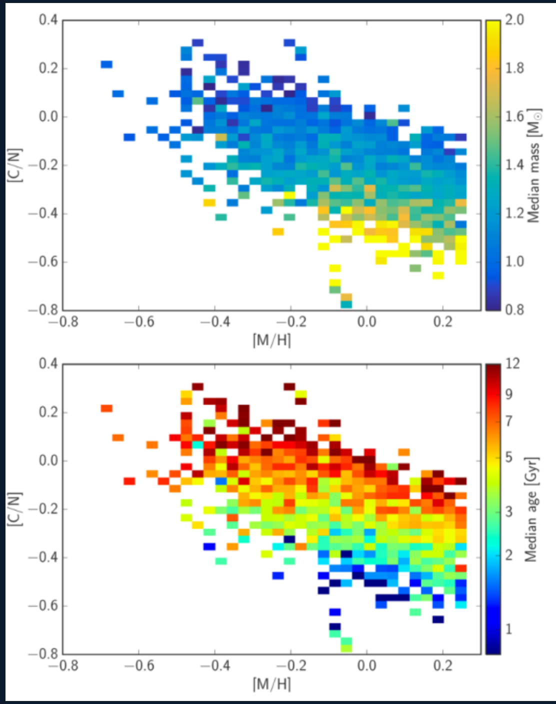
Stellar ages in the spectroscopic survey's era: stellar label and [C/N] abundance

APOGEE Spectra bright RGB
H-band, R~22,500
—> [C/N]

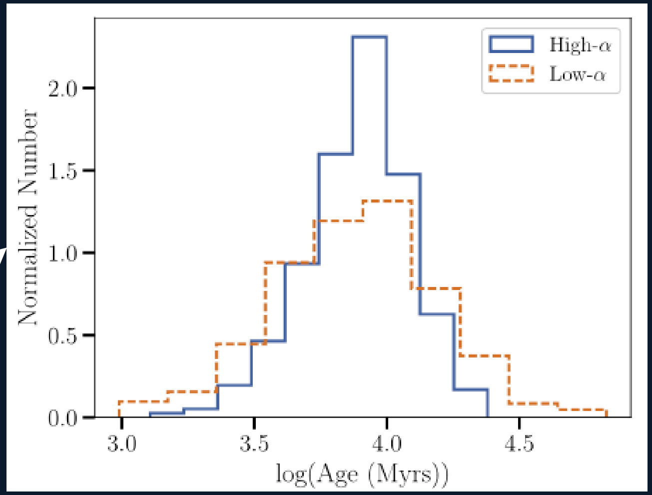


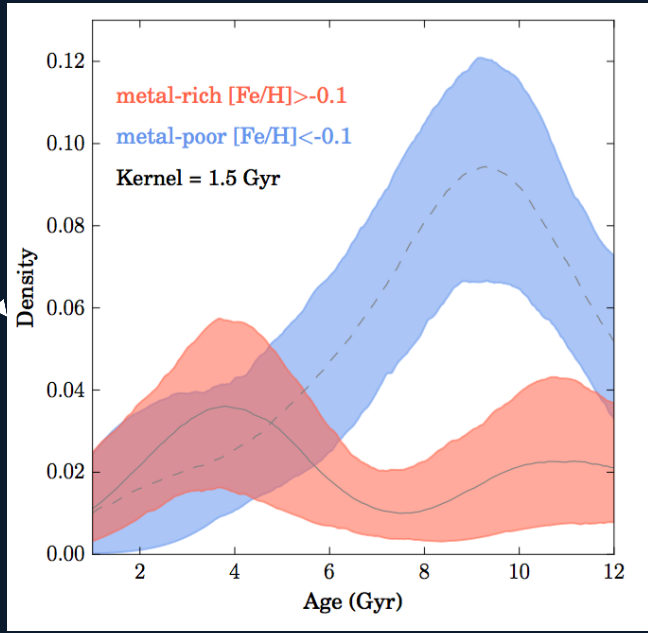
X

APOKASP, APOKASP2
Mass from asteroseismology



Sit & Ness 2020



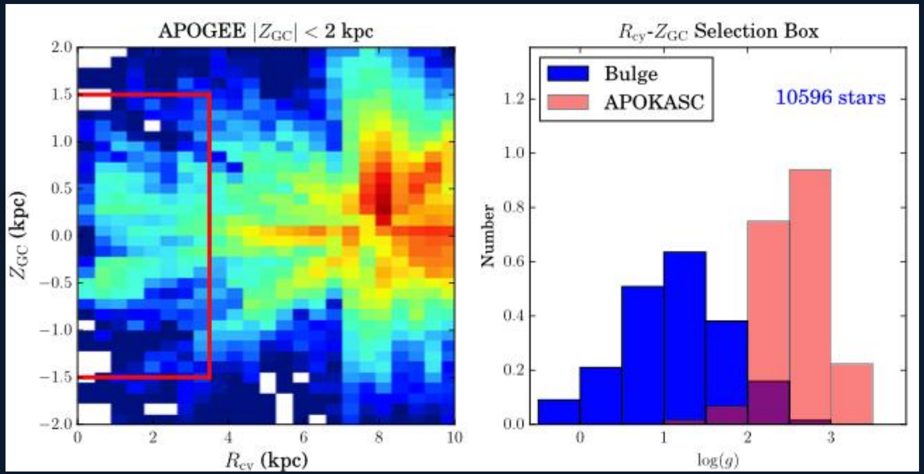


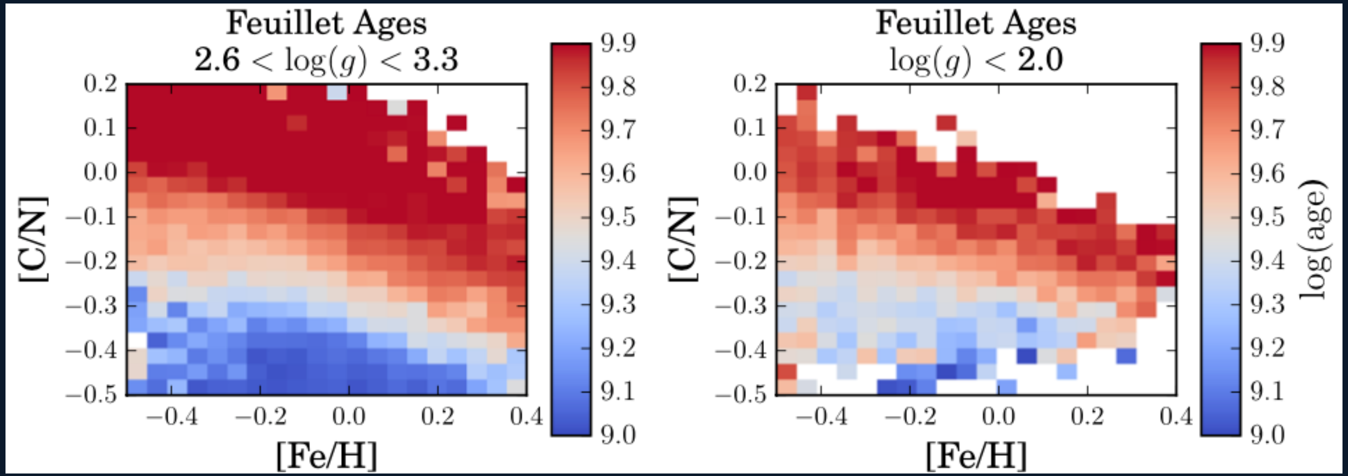
Schultheis et al. 2017

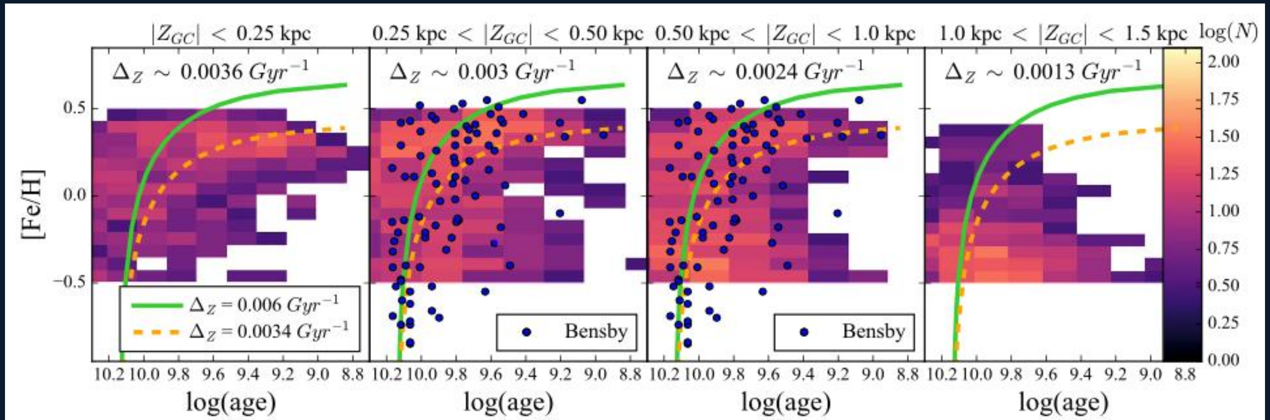
The Bulge is primarily old (>8Gyr) BUT
its age distribution shows a tail of young stars (~2Gyr)

Tension between spec and phot age remains!

APOGEE (~6000 bright RGB; -0.5<[Fe/H]<+0.5) + Feullet Age training sample (Age vs [C/N]) + TheCannon







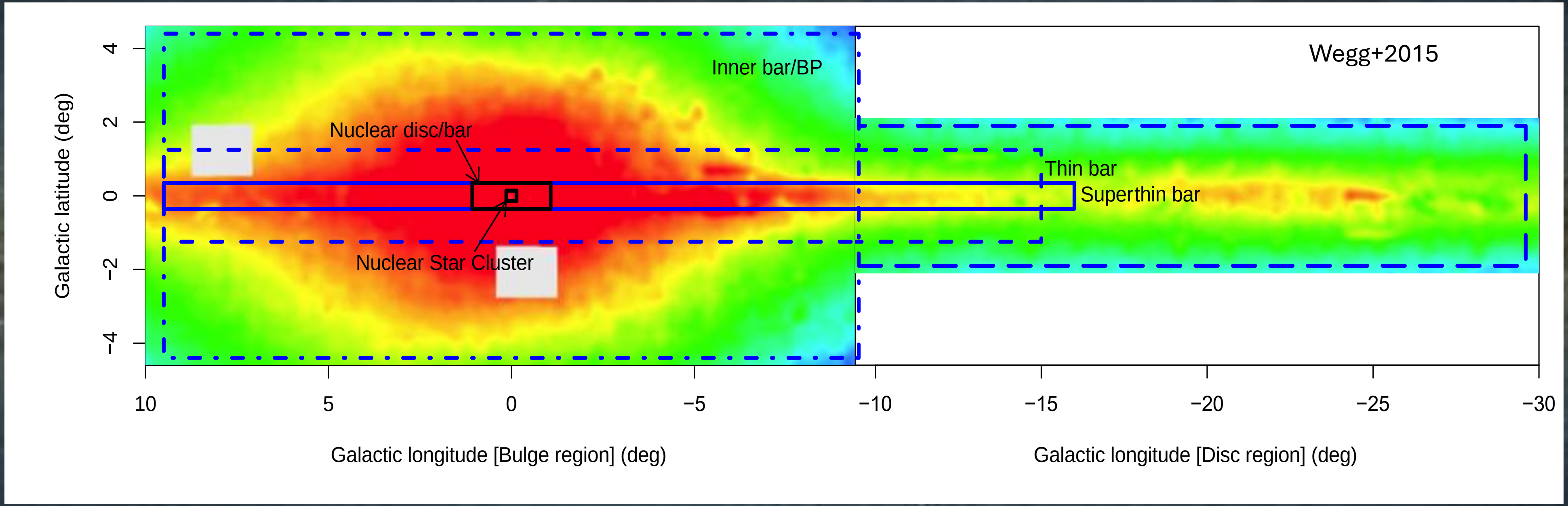
AMR suggests that the Bulge is NOT uniformly old, with stars as young as ~1-2Gyr at [Fe/H]>0.1 & $|Z_{Gal}|$<0.25kpc

Hesselquist et al. 2020

To recap ……

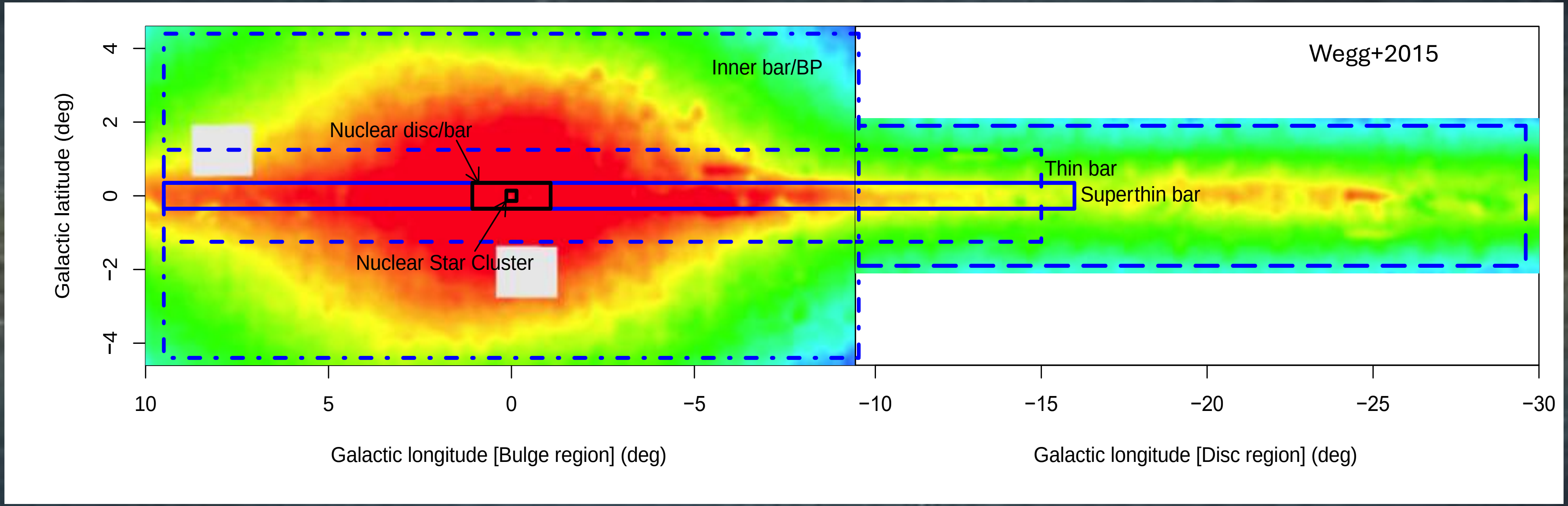
- The bulge is a massive Galactic component ($M = 1.7\text{-}2 \times 10^{10} M_\odot$ in stars and remnants)
- The bulge is a bar with a pivot angle ~27°, and has a B/P/X-shape in the outer regions
- Globally, the bulge rotates cylindrically → product of disk evolution
- The observed MDF is bimodal → m-poor and m-rich component whose relative fraction changes across the bulge producing the observed global gradient
- M-poor and m-rich stars show different kinematics, spatial distribution and abundances:
  - M-poor SP is α-rich and spherically distributed, m-rich stars are α–poor and arranged as a bar
- The bulk of the SP is old (~10Gyr)

Open Questions



- How many components coexist in the MW inner region?
- What is the nature of the super thin-bar and its connection to the Bar and B/P bulge?
- What is the connection between the Bulge and its Nuclear region?
- What are the properties (i.e., kinematics, abundances) of the RRL pop?
- What is the age of the m-rich component?

Open Questions

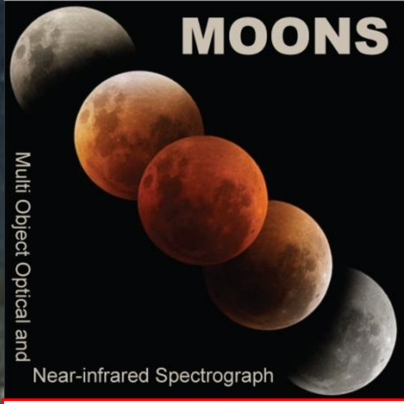


- How many components coexist in the MW inner region?
- What is the nature of the super thin-bar and its connection to the Bar and B/P bulge?
- What is the connection between the Bulge and its Nuclear region?
- What are the properties (i.e., kinematics, abundances) of the RRL pop?
- What is the age of the m-rich component?

→ Comprehensive chemo-dynamical map of its stellar populations

Multi-Object Optical and Near-IR Spectrograph

PI: M. Cirasuolo



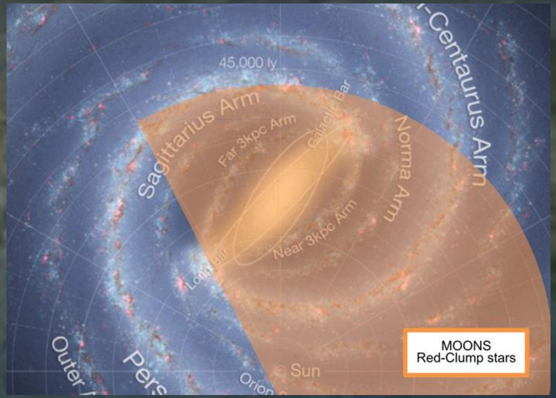
- Multiplexing: 1000 fibers per pointing
- FoV: 500 $arcmin^2$
- Medium and High spectral resolution
- Wavelength coverage: 0.65 – 1.8 μm
- 2 observing modes (MR, HR), each providing 3 channels

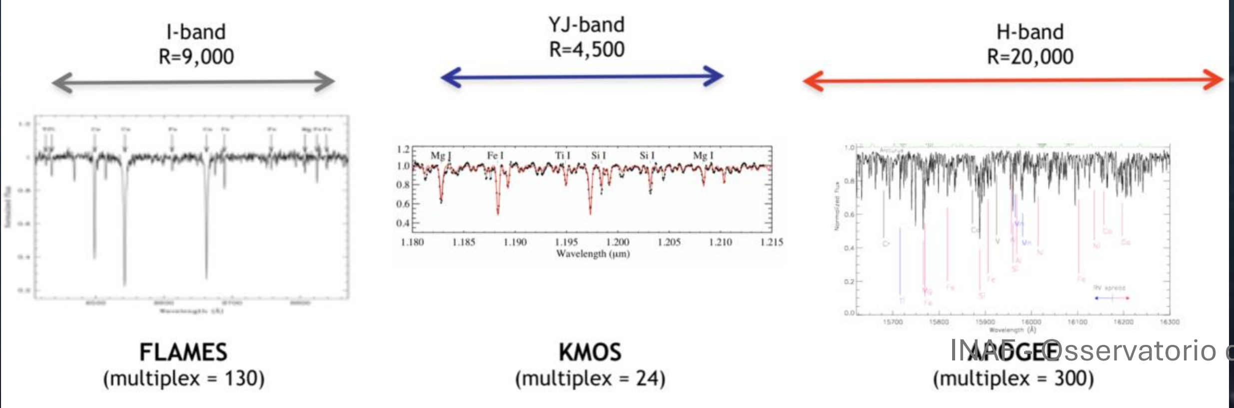
1st Comm: Q1 2026

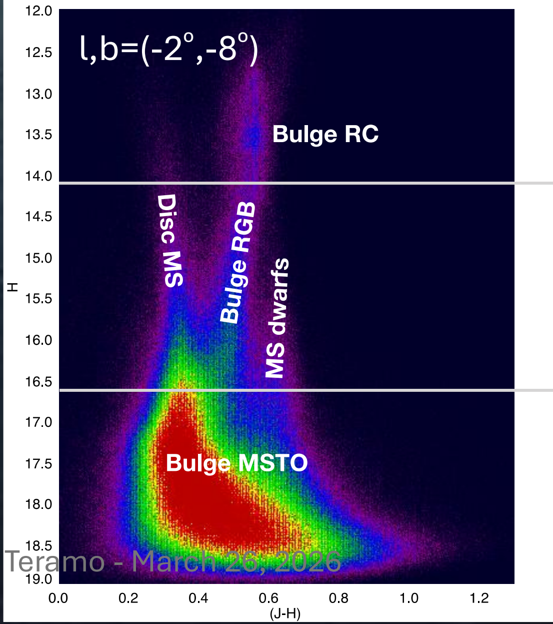
	Observing Mode / Band	Spectral coverage	R (at central lambda)
MR mode	MR-RI	0.647 - 0.955	4,100
	MR-YJ	0.934 - 1.350	4,300
	MR-H	1.452 - 1.800	6,600
HR mode	HR-I	0.765 - 0.898	9,200
	MR-YJ	0.934 - 1.350	4,300
	HR-H	1.521 - 1.641	18,300

MOONS: Unique facility for MWB systematic studies

- IR coverage:
  - Overcoming dust extinction → most central regions
- Multiplexing + simultaneous wavelength coverage
  - High observing efficiency → large number statistics
- HR mode:
  - Chemical abundances (α, light, iron-peak, neutron-capture elements)
  - Kinematics
  - Xcalibration with complementary surveys (e.g., Gaia RVS)
- VLT collecting area
  - Faintest RC → surveys depth & reliable selection function

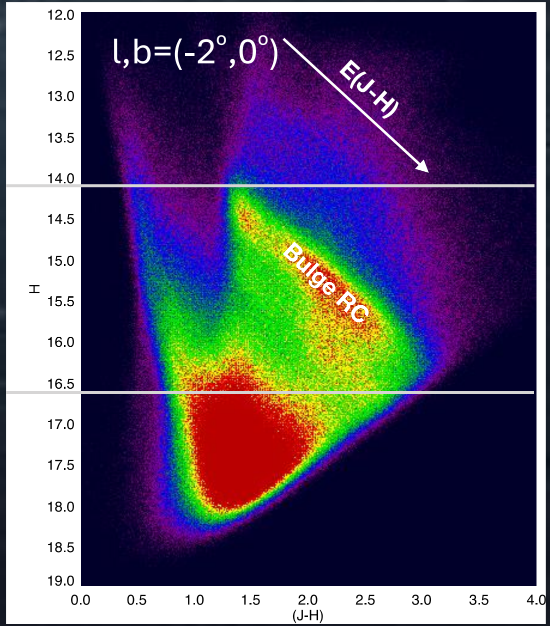






APOGEE
Mag limit

MOONS
1hr, S/N~60










MOONS
Galactic Team














MOONS GTO Galactic Surveys

GOAL: Comprehensive chemo-dynamical map of the resolved stellar populations in the MW, and closest satellites, focusing on those environments/populations poorly - if any - sampled by previous/ongoing/future spectroscopic surveys (e.g., Gaia, GES, GIBS, WAVE, APOGEE, 4MOST)

I. **The Reddened MW Survey** [~70 nights, PI: O.A. Gonzalez]:
- The Nuclear Region [Resp: L. Origlia]
- The bulge/bar/disk @ low latitude [Resp: O.A. Gonzalez]
- The Boxy/Peanut bulge. [Resp: M. Zoccali]
- Inner Bulge GCs [Resp: P. Di Matteo]
- Young star clusters [Resp. S. Randich]
- Very metal poor stars [Resp. E. Caffau]

II. **The MW Satellites Survey** [~30 nights, PI: A. Mucciarelli]:
- Magellanic Clouds and Sagittarius Chemistry [Resp. A. Mucciarelli]
- Magellanic Clouds and Sagittarius Kinematics [Resp. E. Dalessandro]

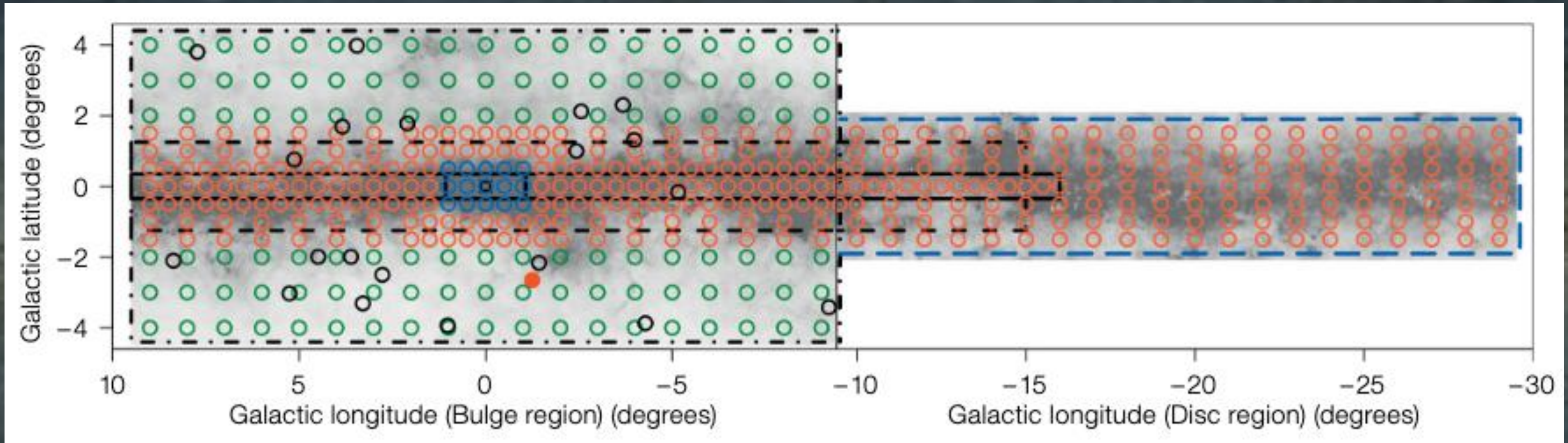
MOONS GTO Galactic Surveys

GOAL: Comprehensive chemo-dynamical map of the resolved stellar populations in the MW, and closest satellites, focusing on those environments/populations poorly - if any - sampled by previous/ongoing/future spectroscopic surveys (e.g., Gaia, GES, GIBS, WAVE, APOGEE, 4MOST)

I. **The Reddened MW Survey** [~70 nights, PI: O.A. Gonzalez]:
- The Nuclear Region [Resp: L. Origlia]
- The bulge/bar/disk @ low latitude [Resp: O.A. Gonzalez]
- The Boxy/Peanut bulge. [Resp: M. Zoccali]
- Inner Bulge GCs [Resp: P. Di Matteo]
- Young star clusters [Resp. S. Randich]
- Very metal poor stars [Resp. E. Caffau]

II. **The MW Satellites Survey** [~30 nights, PI: A. Mucciarelli]:
- Magellanic Clouds and Sagittarius Chemistry [Resp. A. Mucciarelli]
- Magellanic Clouds and Sagittarius Kinematics [Resp. E. Dalessandro]

The MOONS **RED**dened Milky **WAY** survey



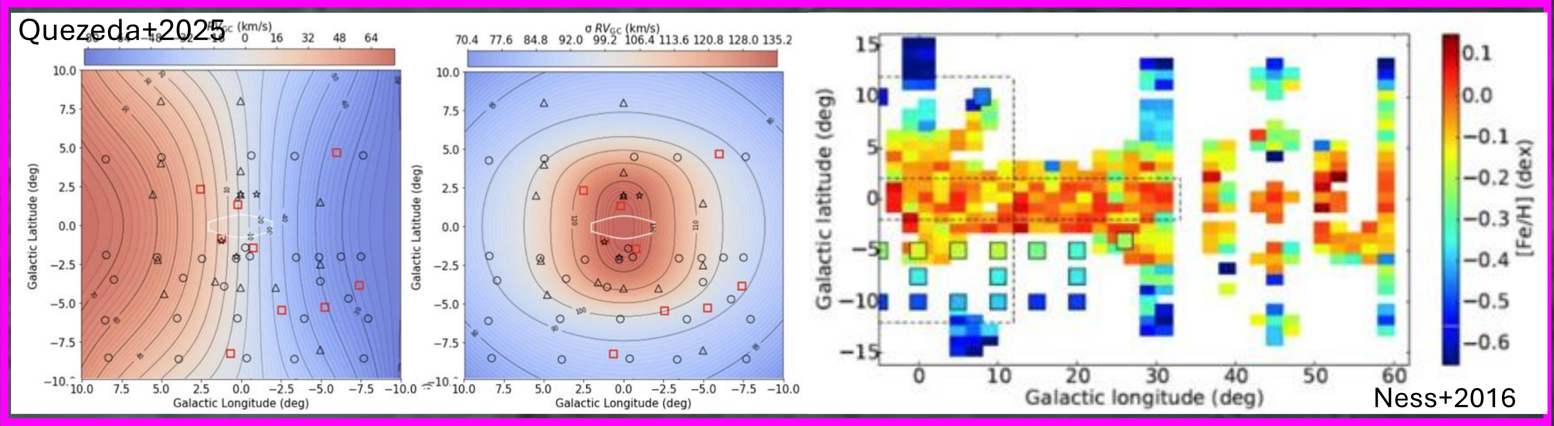
- **Nuclear region:** RCs, RGBs, $|l| \leq 1^{\circ}$, $|b| \leq 0.5^{\circ}$, 15 fields, **~14K stars**
- **Bulge/bar/disk at low latitude:** RCs, $-30^{\circ} \leq l \leq 10^{\circ}$, $|b| \leq 1^{\circ}$, >500 fields, **~0.5M stars**
- **Boxy/Peanut Bulge:** RCs, RRL , $|l| \leq 10^{\circ}$, $2^{\circ} \leq |b| \leq 4^{\circ}$, ~115 fields, **~100K stars**

Setup: HR mode, SNR>60 (per pixel)
Target Selection: 13 < H < 17 (VVV phot catalog, PMs from Gaia & VVV)
Accuracy: $\Delta t_{eff} < 100K$, $\Delta logg < 0.3dex$, $\Delta RV < 1km/s$, $\Delta[Fe/H] < 0.1dex$, $\Delta[X/Fe] < 0.15dex$
X=C, N, O, Mg, Al, Si, S, Ca, Ti, Ni, Cr, Co, Cu, V

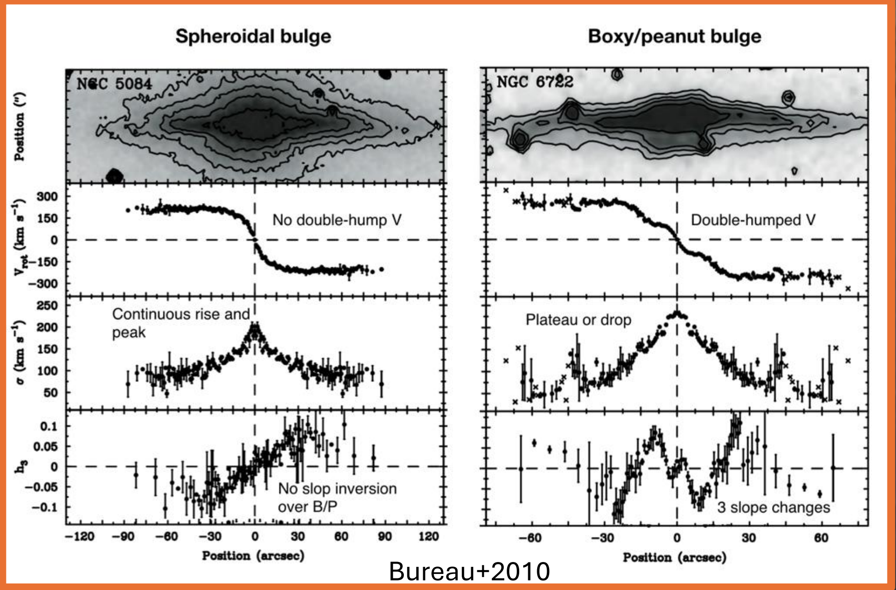
O.A.Gonzalez

REDWAY: Bulge/Bar/Disk @low latitude

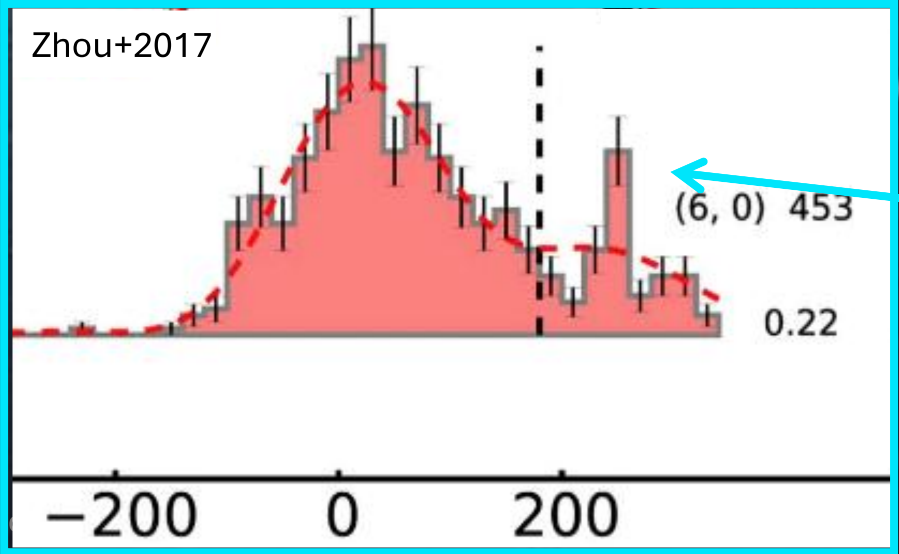
Chemo-dynamics of the in-plane Bulge



Bar/Disk connection



Bar LOS-V distribution



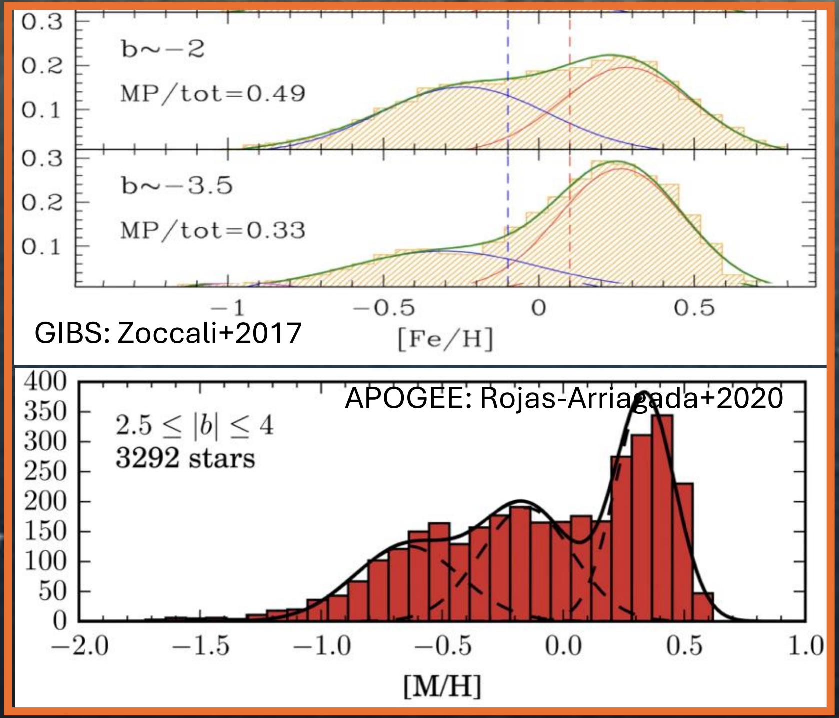
Nuclear Disk
or
Ring??

Robust Statistics is crucial!

M.Zoccali

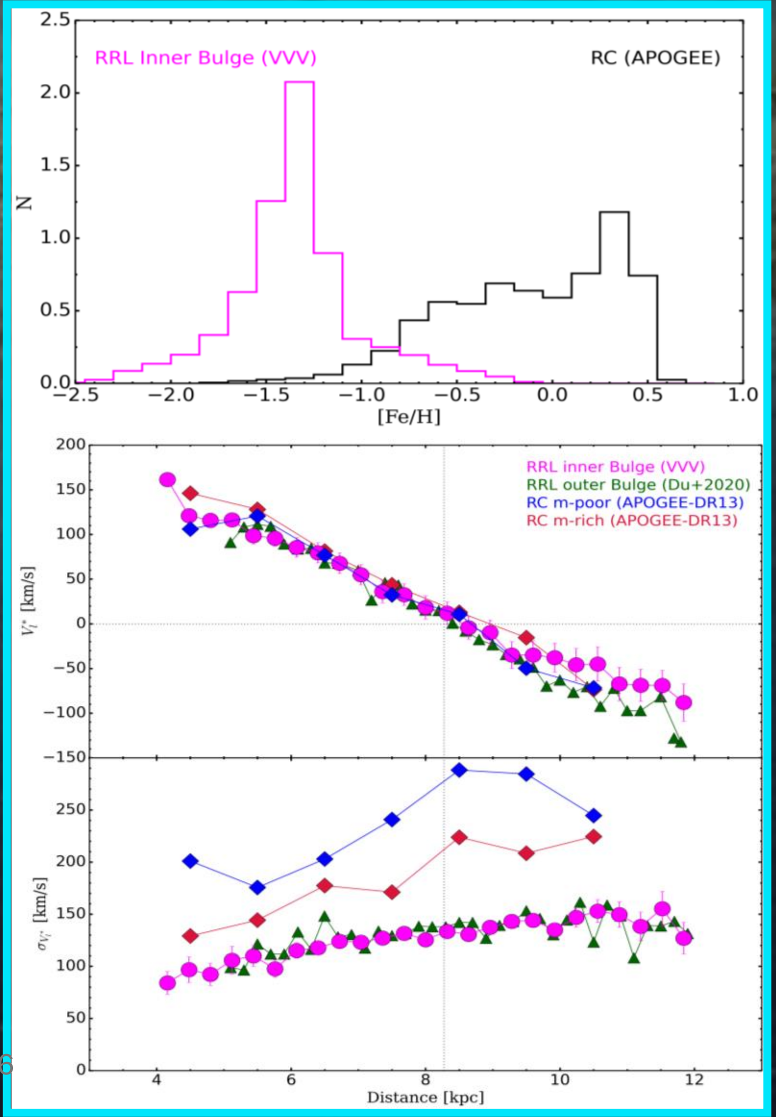
REDWAY: Boxy/Peanut Bulge

Chemo-dynamical separation of bulge components



RRL

Valenti+2026, in prep



The oldest Bulge component

Summary

- **MOONS** is a unique facility for systematic studies of the Milky Way central regions
- **MOONS REDWAY** survey will soon revolutionize our current understanding of the Milky Way by providing a comprehensive chemo-dynamical map of the MW inner bulge and disk based on ~0.7 millions stars
  - Identifying possible distinct large-scale inner structures (e.g., inner/nuclear bar, m-poor central spheroids)
  - Characterization of Nuclear bulge
  - Galactic disk – bar transition
  - Complete the global/detailed view of the Boxy/Peanut bulge
  - Unique benchmark for comparisons with extragalactic bulges and to constraint galaxy evolution models
- **MOONS REDWAY** is highly complementary to ongoing/future spectroscopic facilities/surveys (e.g., Gaia, 4MOST, WAVE…)

THANK YOU!