THE MILKY WAY BULGE

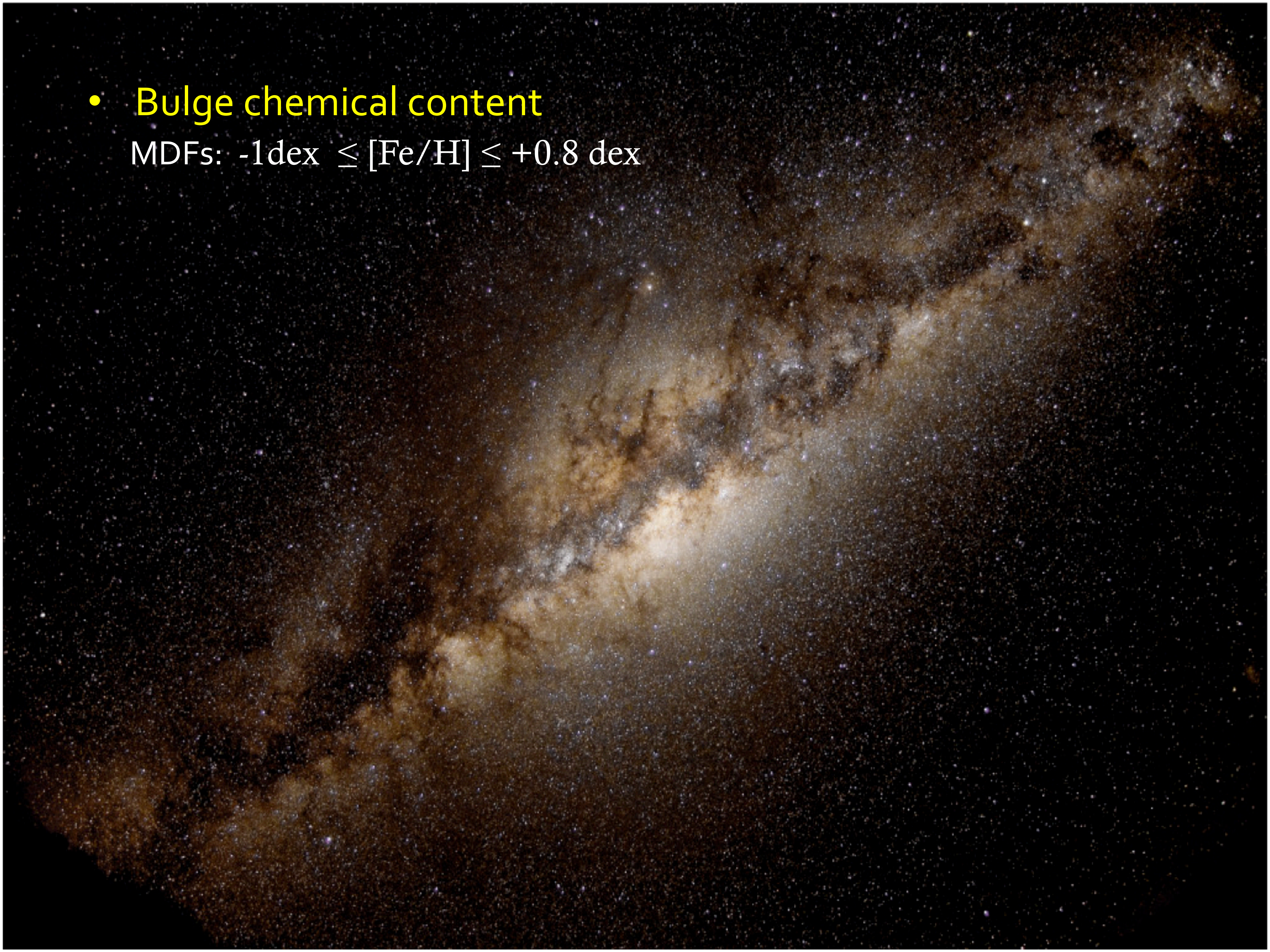
Elena Valenti (ESO)

How do galaxies form and evolve?
How did the Milky Way form and evolve?

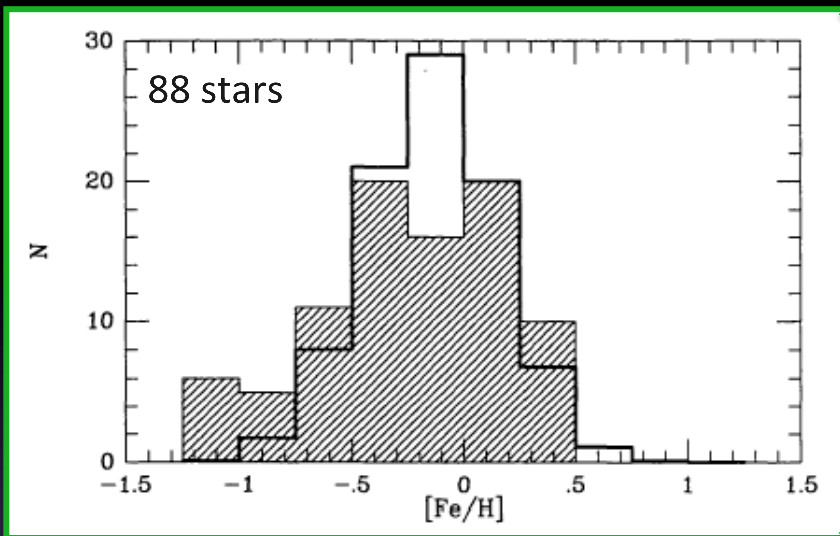
The relative role and timing of processes (i.e merging, instabilities, dynamical friction ..) in establishing the galactic bulges we observe today is yet to be assessed!

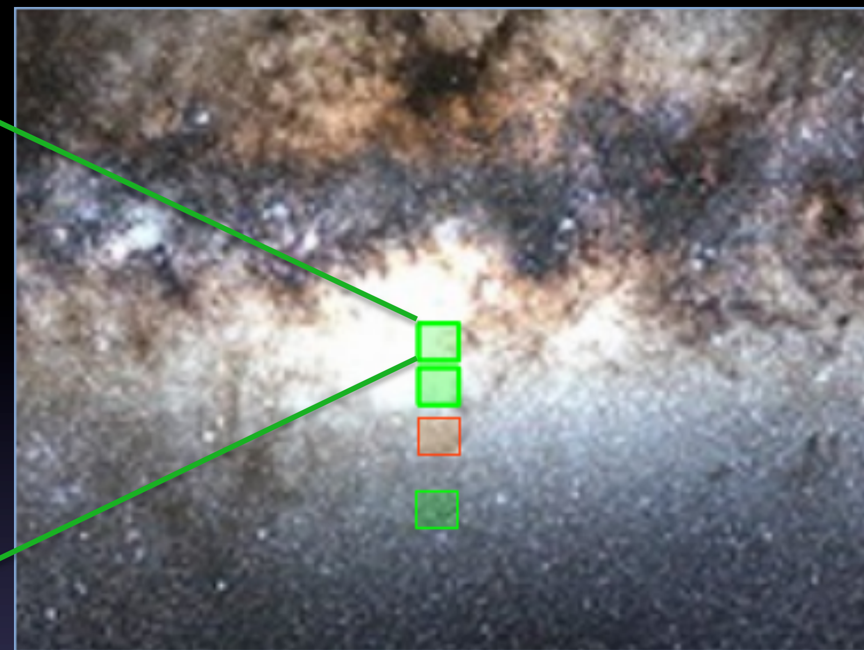
- Bulge chemical content

MDFs: -1dex $\leq$ [Fe/H] $\leq$ +0.8 dex



Chemical Abundances in the MW bulge



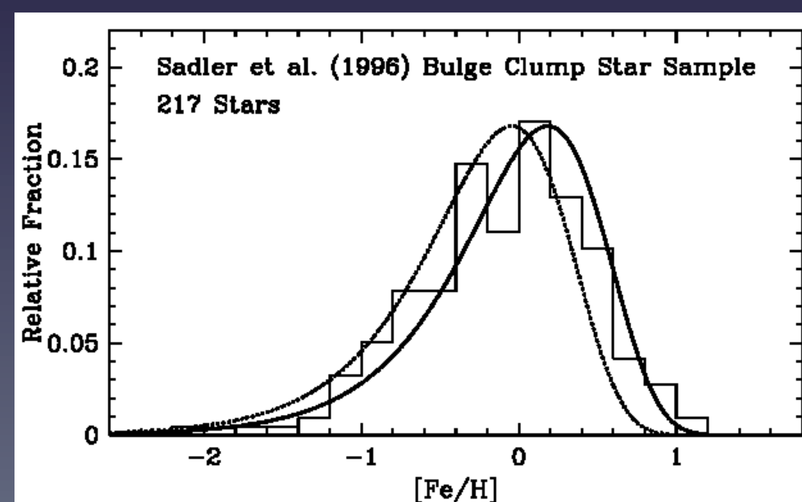


McWilliam & Rich (1994)

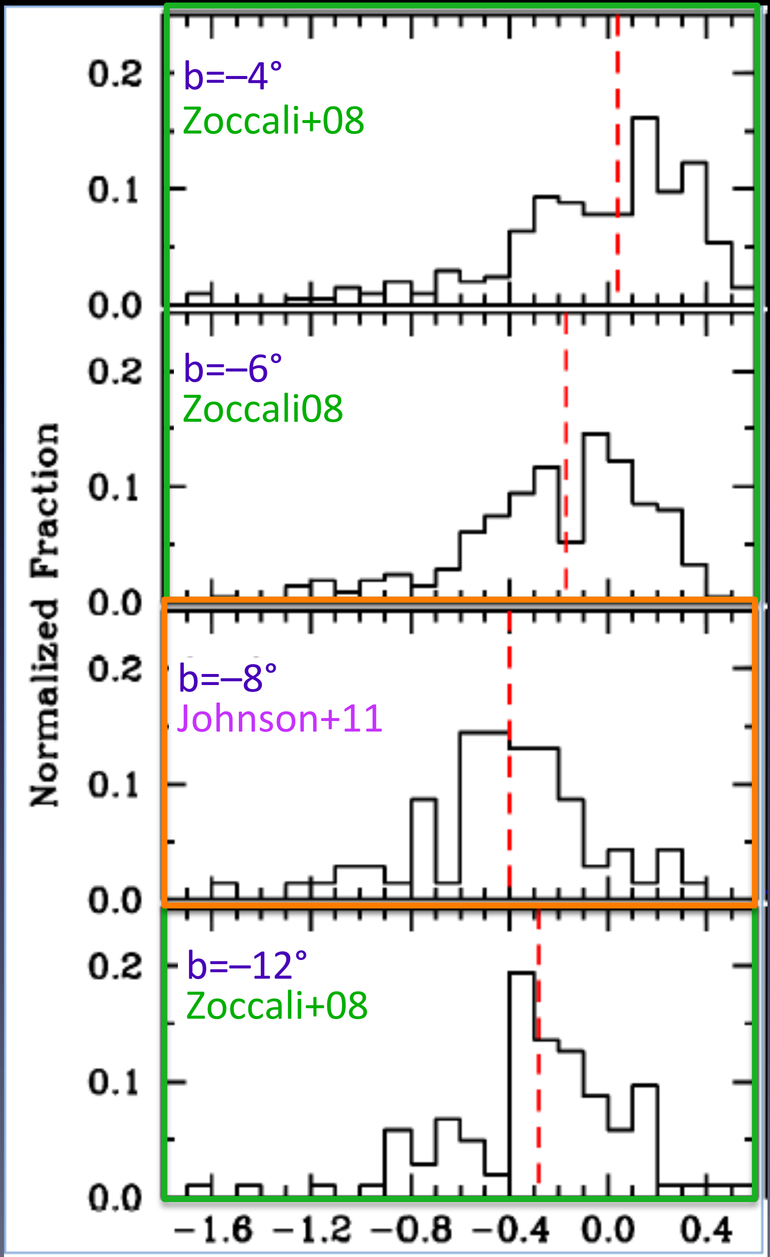
11 calibrating stars at R=17,000

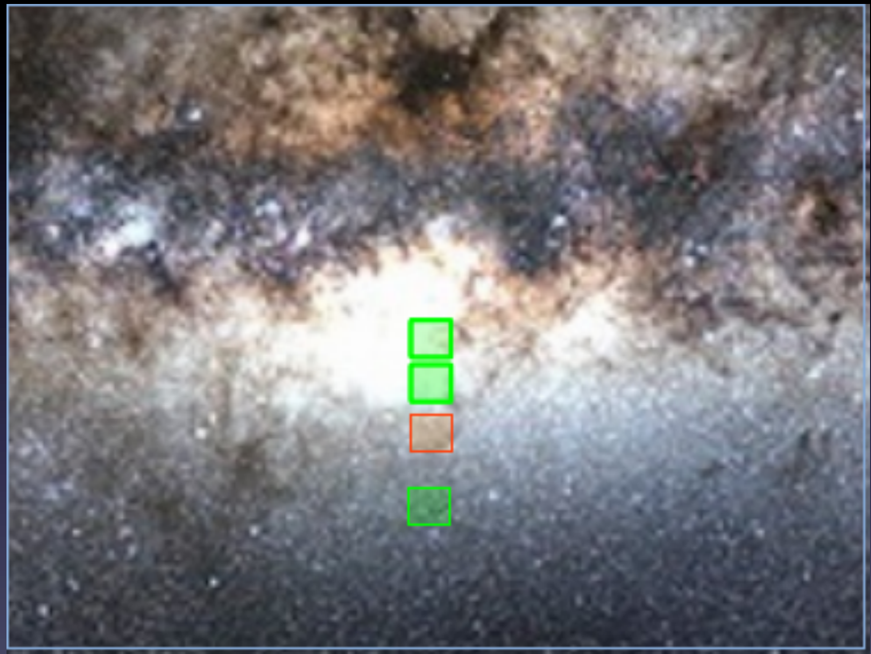
Fulbright et al. (2006)

27 calibrating stars at R=60,000

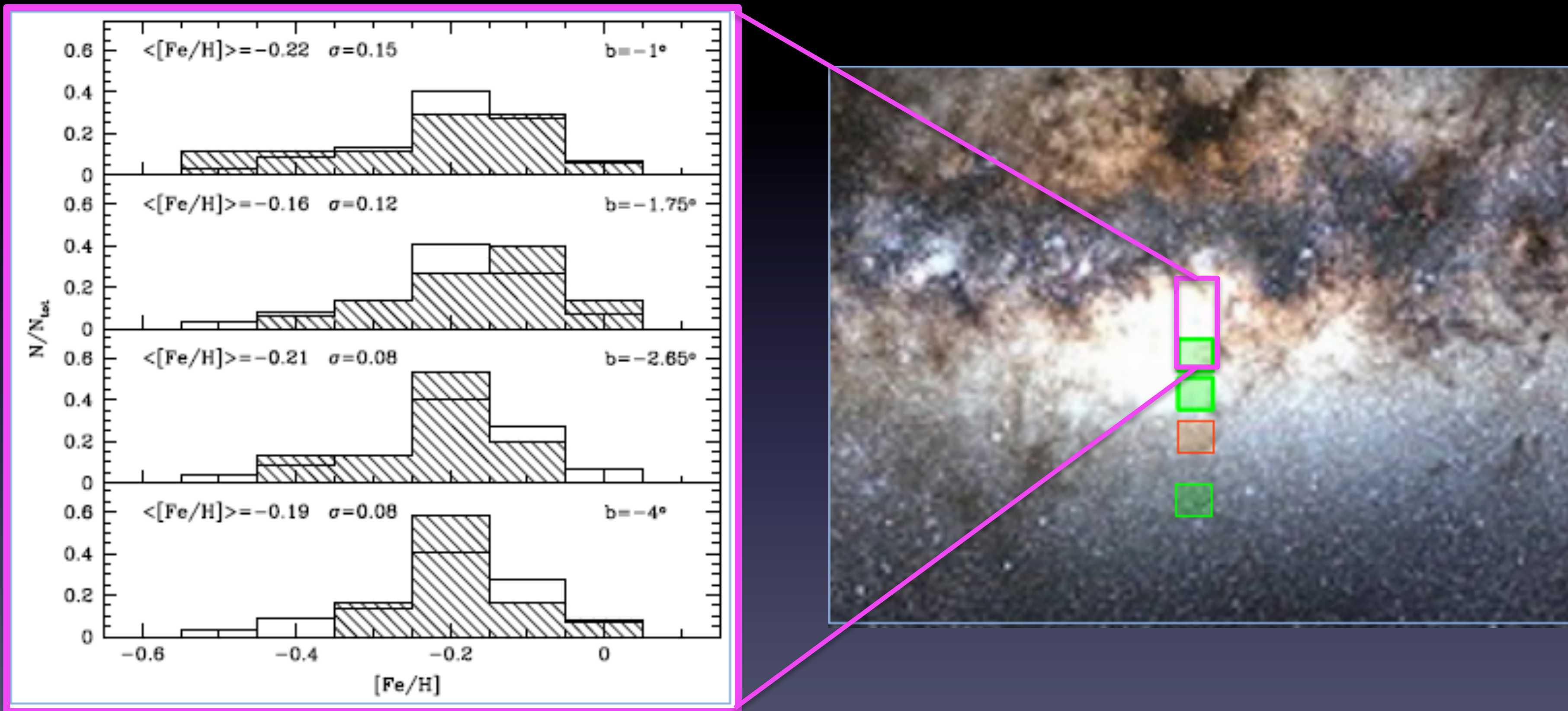


Bulge MDF from high-res. Spectroscopy



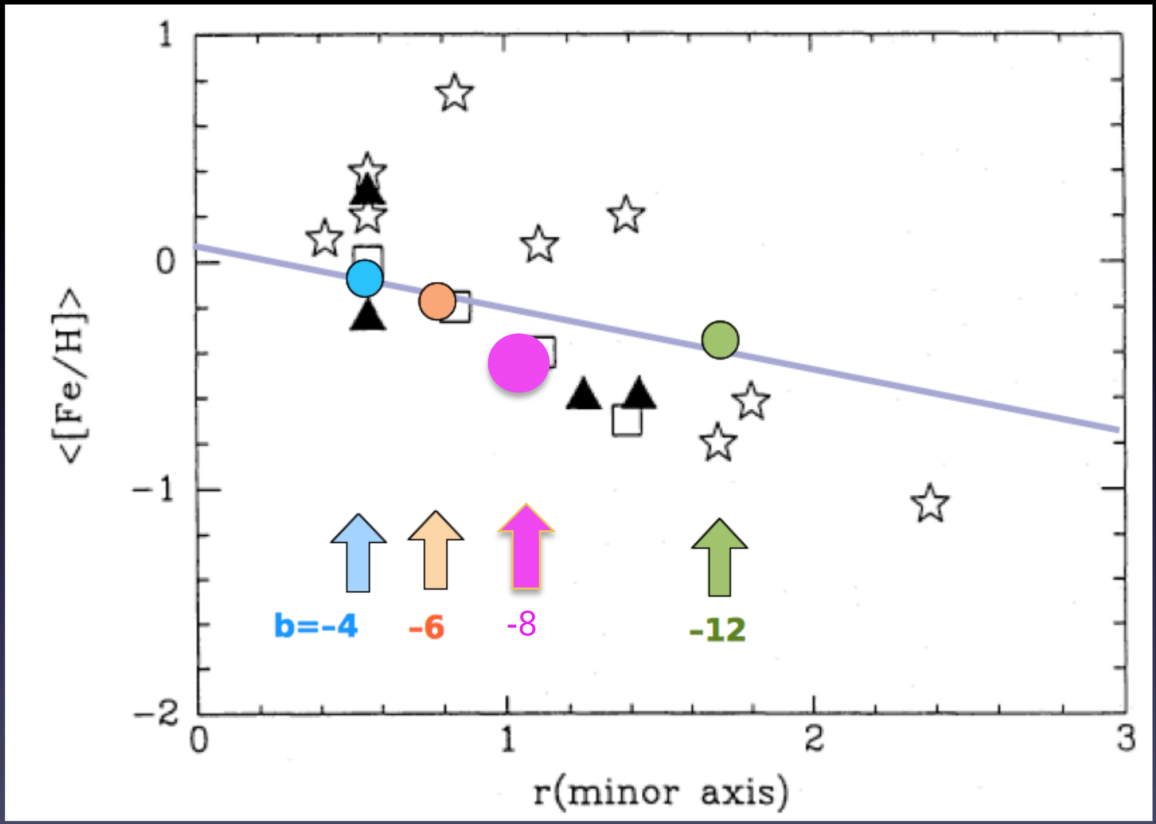


Bulge MDF from high-res. Spectroscopy



Rich, Origlia & Valenti (2007, 2011)

Bulge radial metallicity gradient

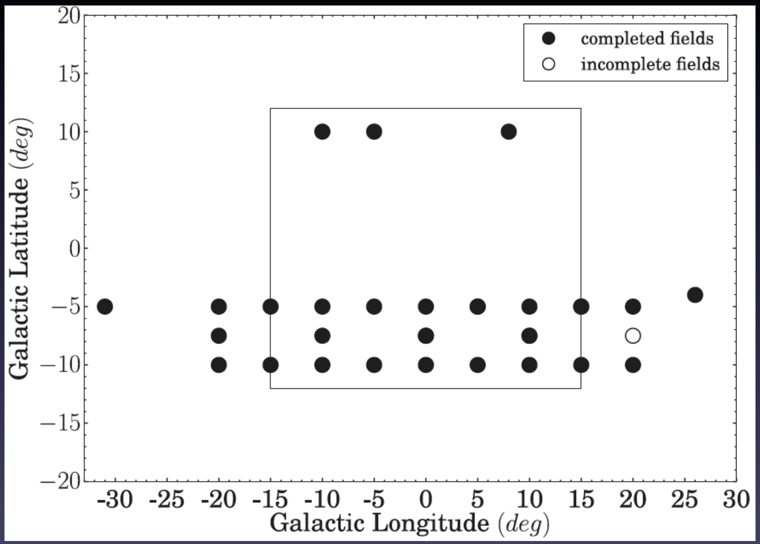


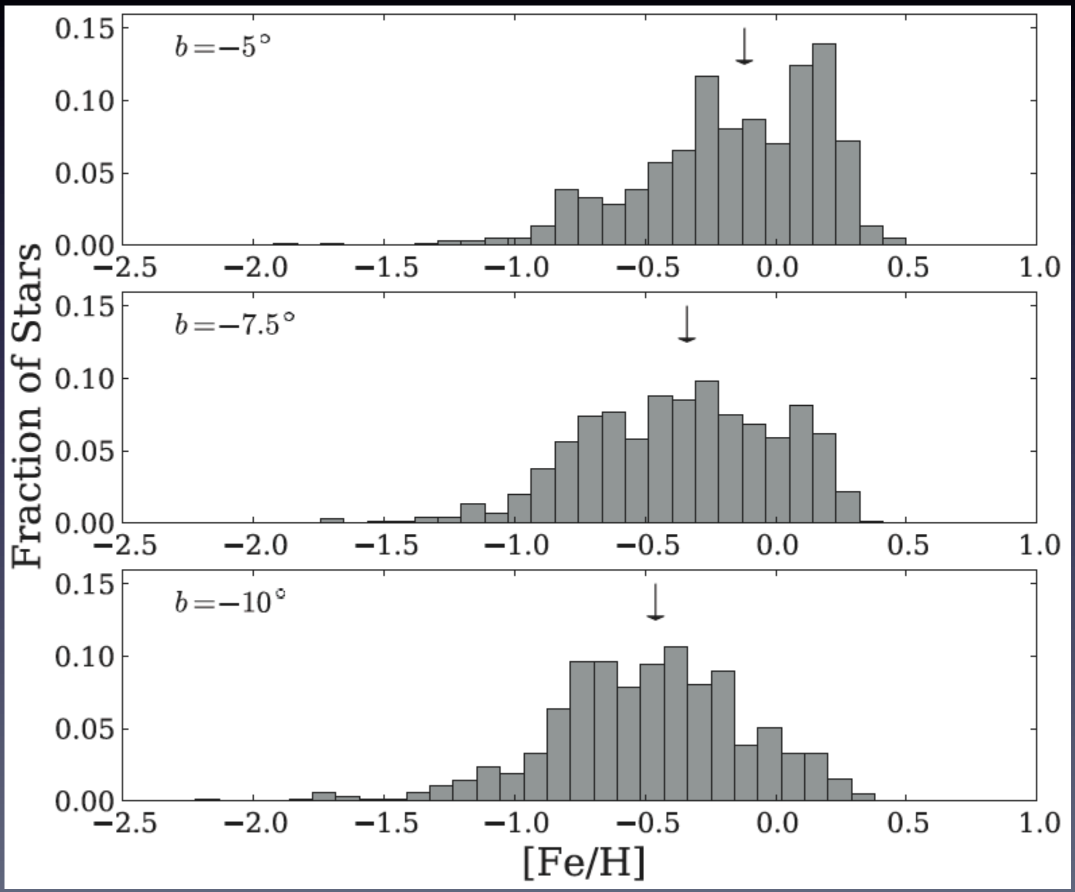
Zoccali+08

~0.6 dex/Kpc for |b| > 4° along the minor axis

The ARGOS Survey

ARGOS Survey
28,000 stars 14,150 stars within 3.5 kpc from the Galactic center
R=11,000

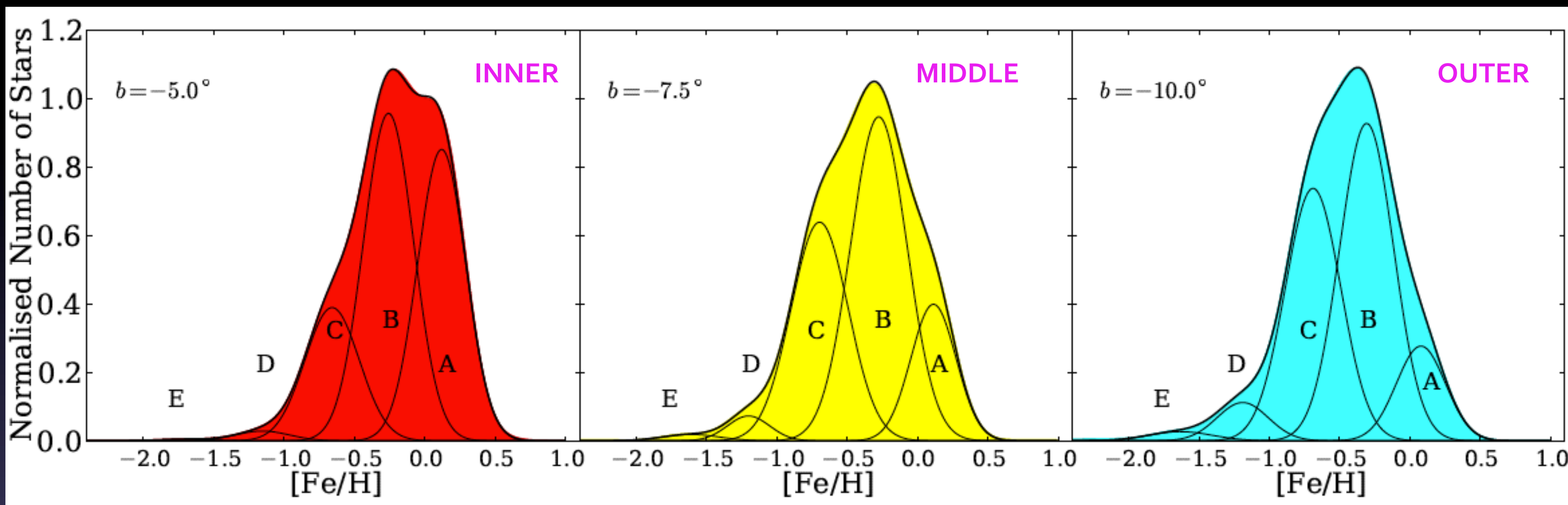




Freeman et al. (2012)
Ness et al. (2013a, 2013b)

The ARGOS Survey

Ness et al. (2013a)



A: The metal rich boxy/peanut bulge <[Fe/H]>∼+0.15

B: The vertically thicker boxy/peanut bulge <[Fe/H]>∼−0.25

C: The Inner thick disk <[Fe/H]>∼−0.70

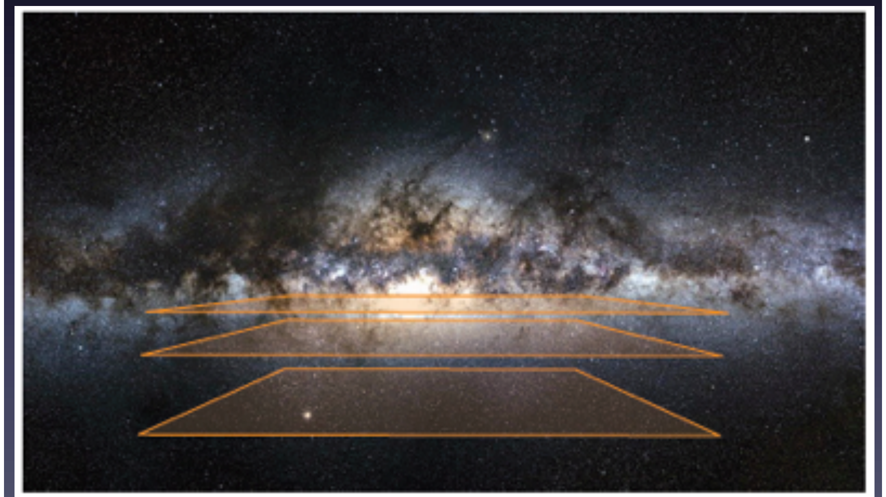
D: The Metal weak thick disk <[Fe/H]>∼−1.20

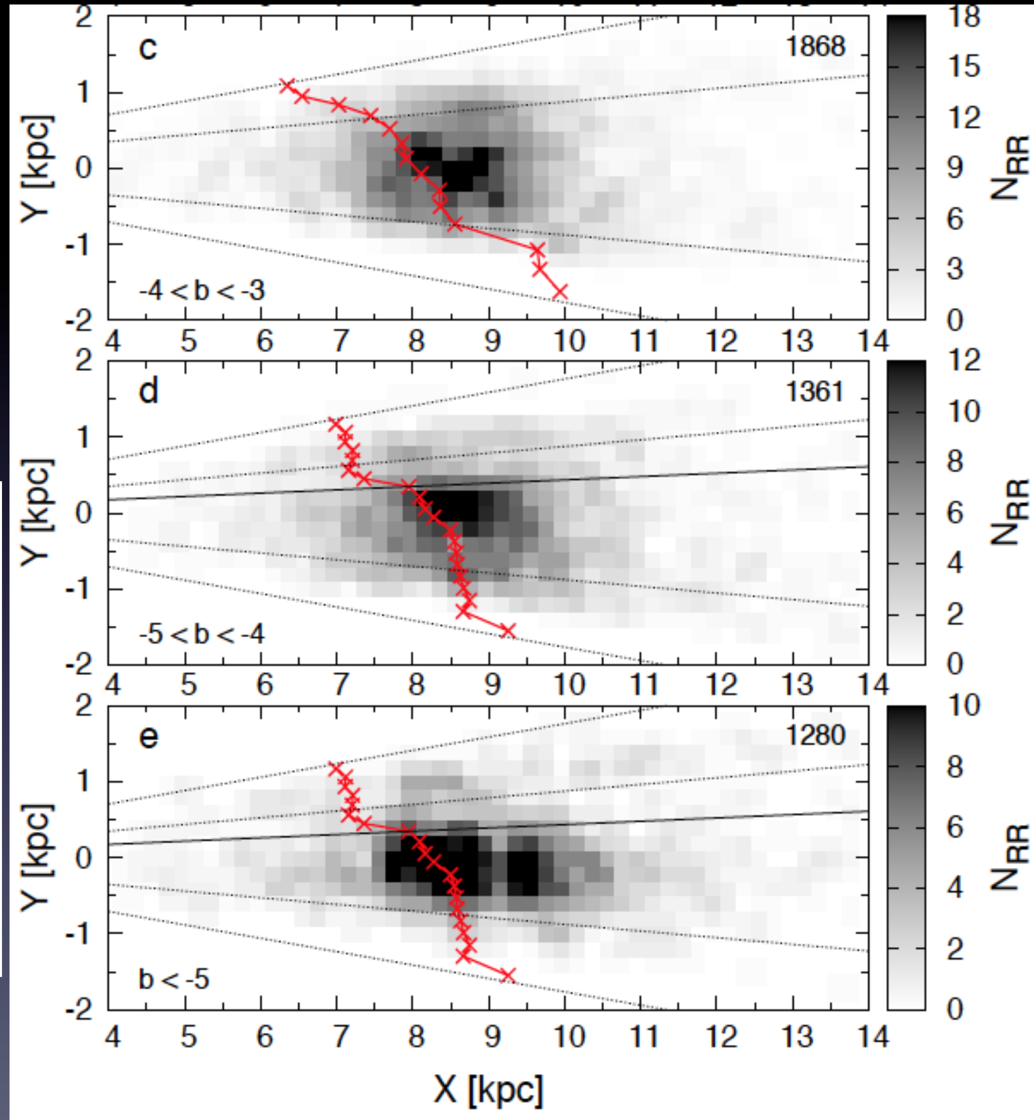
E: The Halo

The 3D map from RR Lyrae

a two-component bulge

RR Lyrae stars do not show the bar traced by RC stars



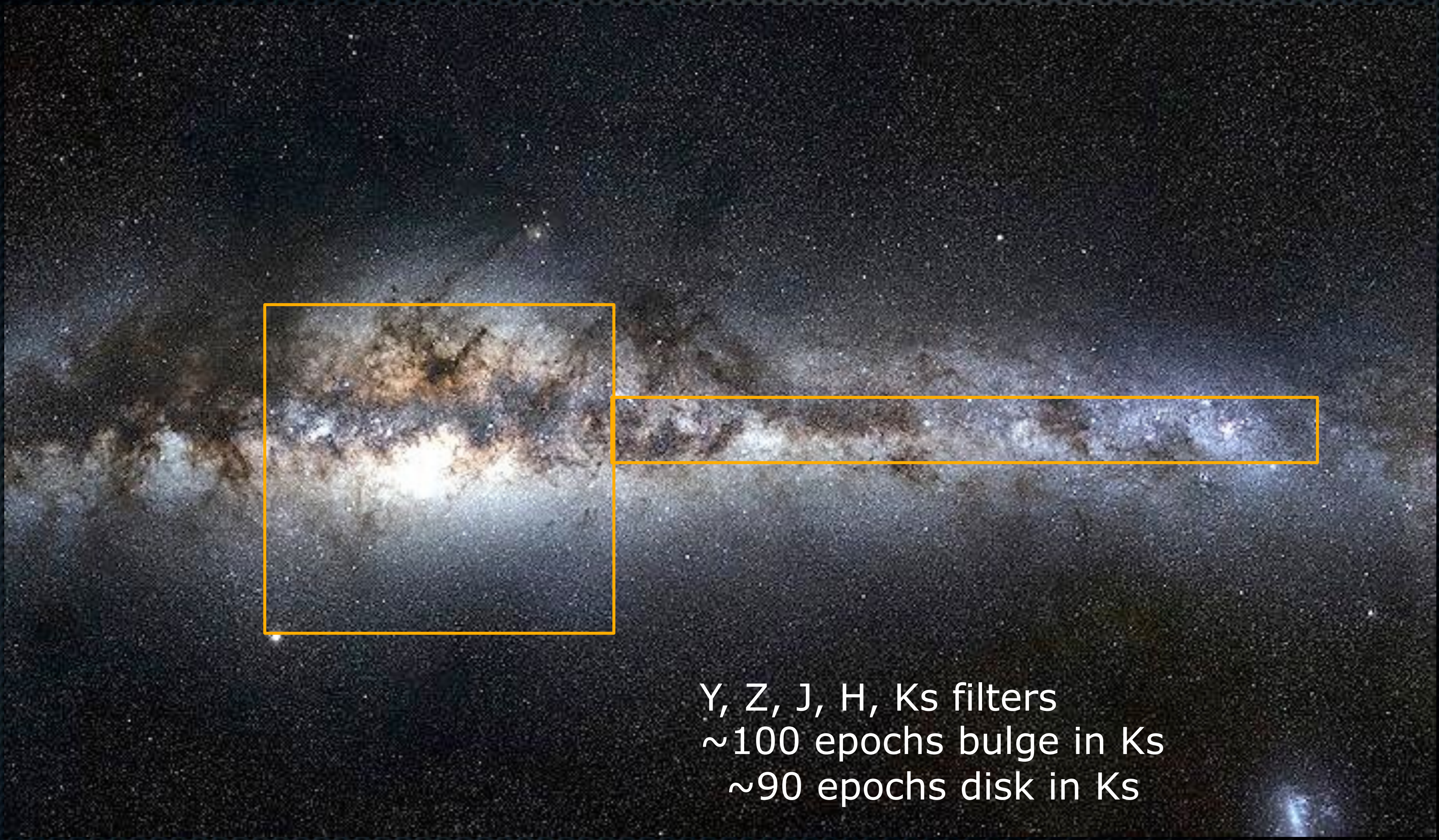


Dékány et al. (2013, *ApJL*)

The **V**ISTA **V**ariables in the **V**ía Láctea survey (VVV)

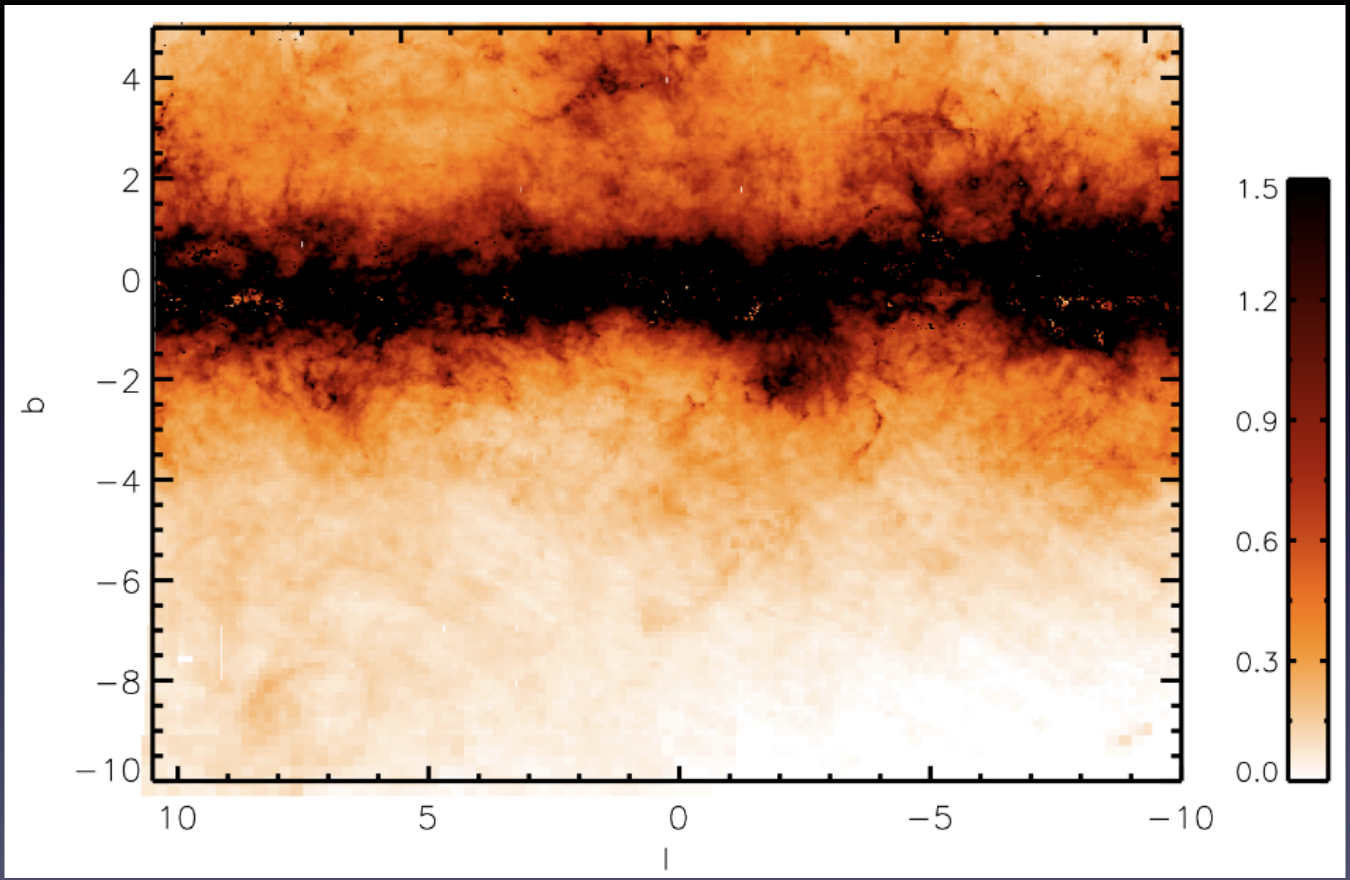
PIs: Minniti, Lucas

DR2: http://archive.eso.org/cms/eso-data/eso-data-products



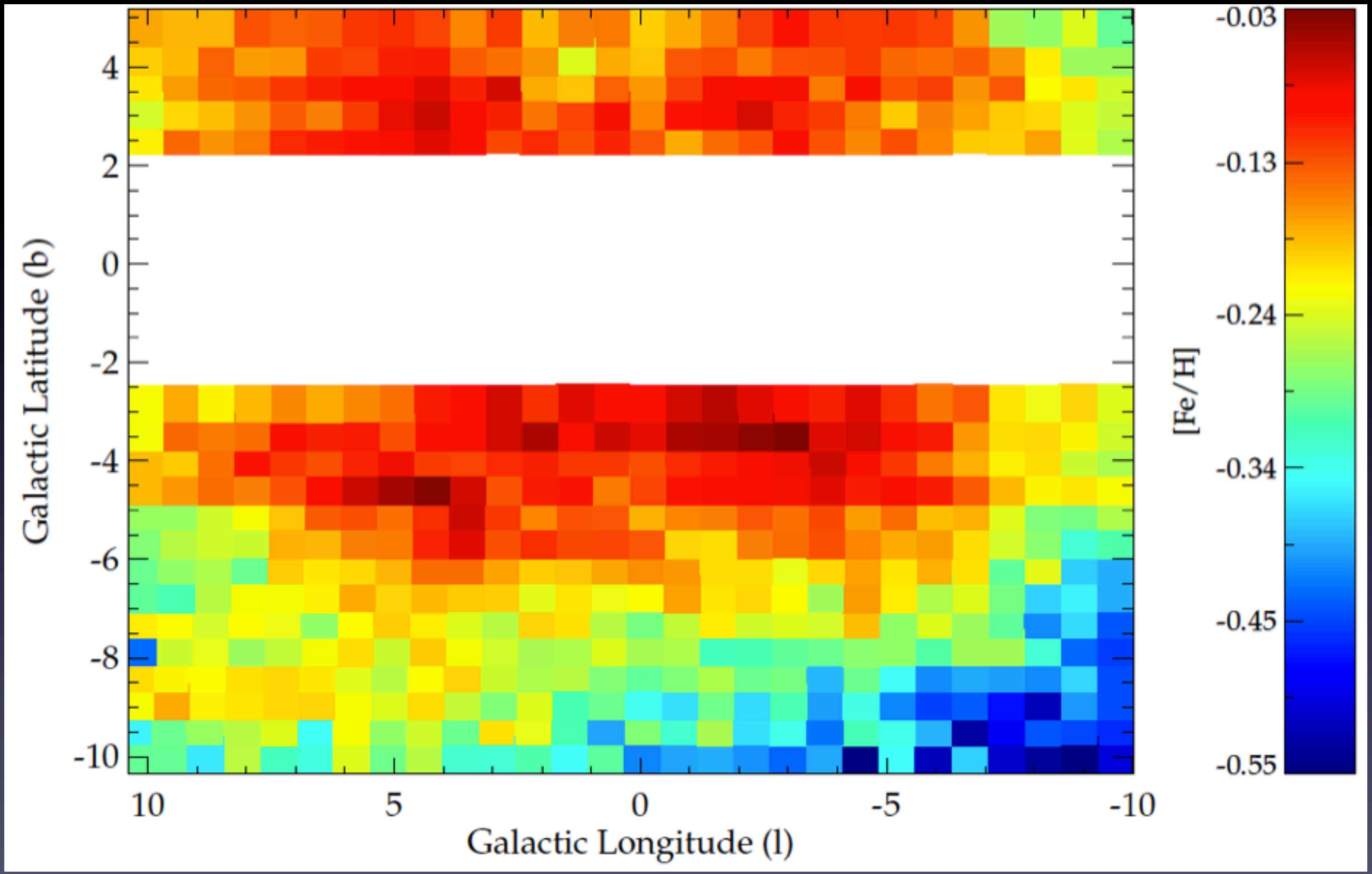
VVV: Bulge complete reddening map

http://mill.astro.puc.cl/BEAM/calculator.php



Gonzalez+12

VVV: Bulge complete photometric metallicity map

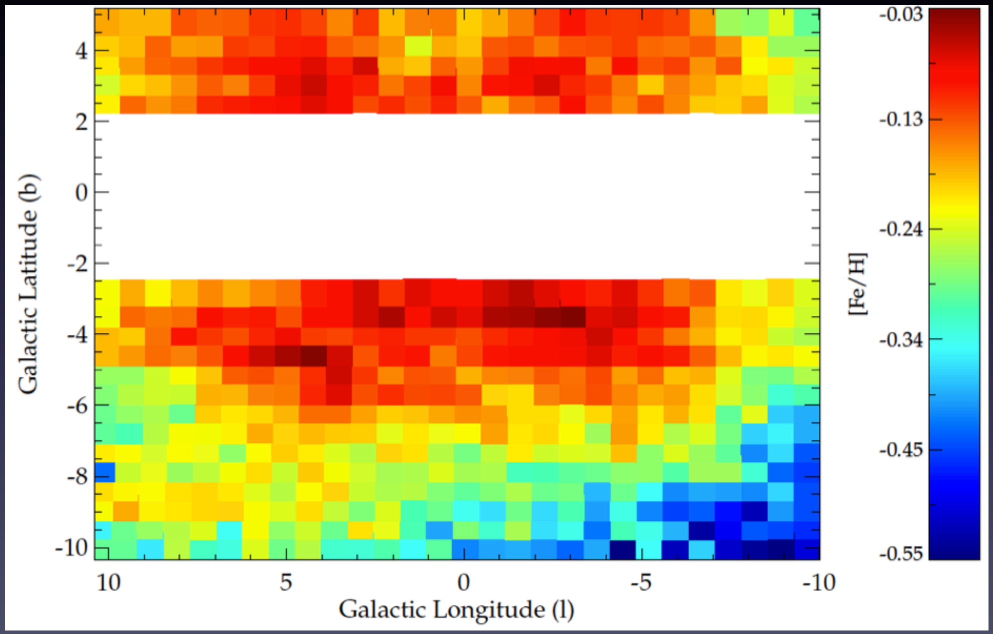


Gonzalez+12

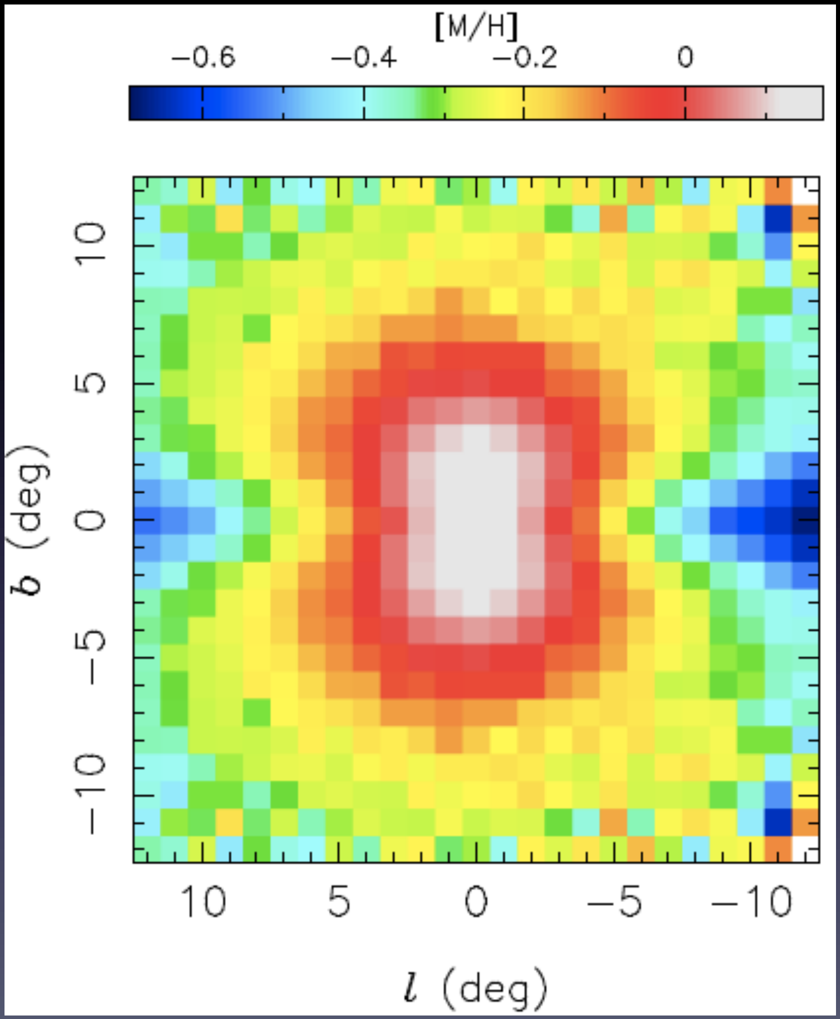
The Bulge radial metallicity gradient

Observed

Model



Gonzalez et al. 2012



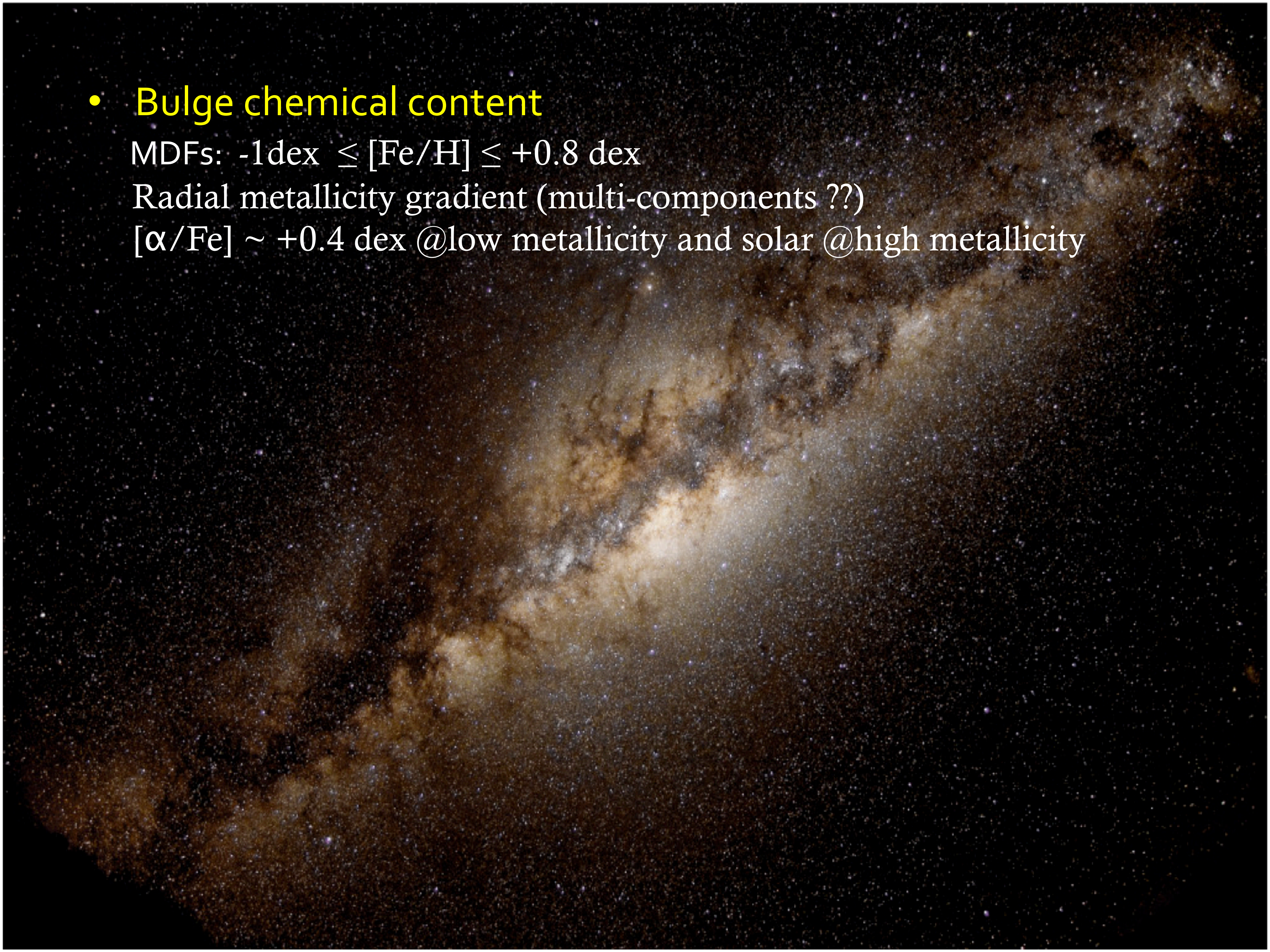
Martinez-Valpuesta & Gerhard 2013

- Bulge chemical content

MDFs: -1dex $\leq$ [Fe/H] $\leq$ +0.8 dex

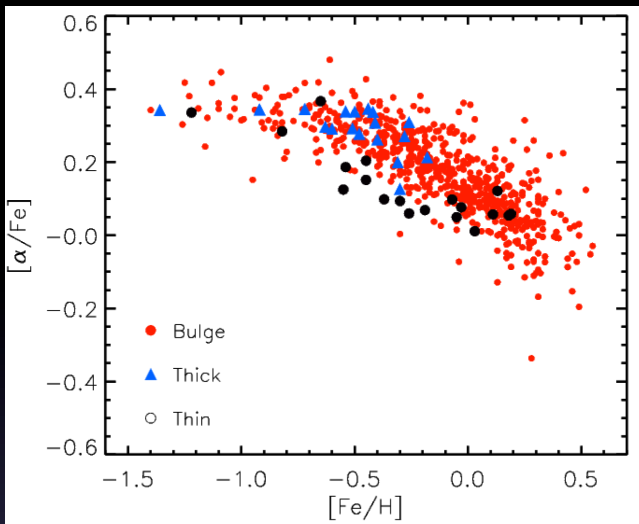
Radial metallicity gradient (multi-components ??)

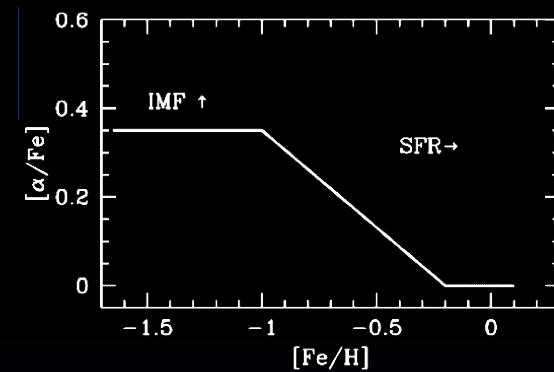
[α/Fe] ~ +0.4 dex @low metallicity and solar @high metallicity



Alpha element ratios

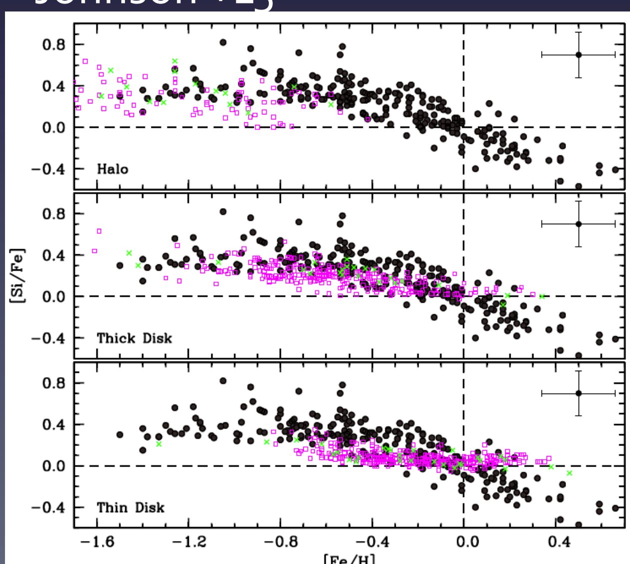
Gonzalez +11



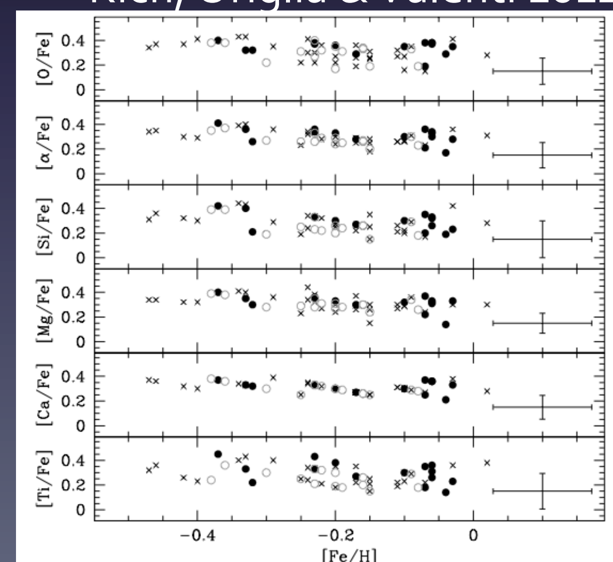


Rich & Origlia 05
Zoccali +06
Cunha & Smith 06
Fulbright +07
Lecureur +07
Rich, Origlia, Valenti 07
Melendez +08
Ryde +09
Ryde +10
Alves-Brito +10
Bensby +10
Bensby +11
Rich, Origlia & Valenti 11
Gonzalez +11
Johnson +13

Johnson +13



Rich, Origlia & Valenti 2011



- Bulge chemical content

  MDFs: -1dex ≤ [Fe/H] ≤ +0.8 dex

  Radial metallicity gradient

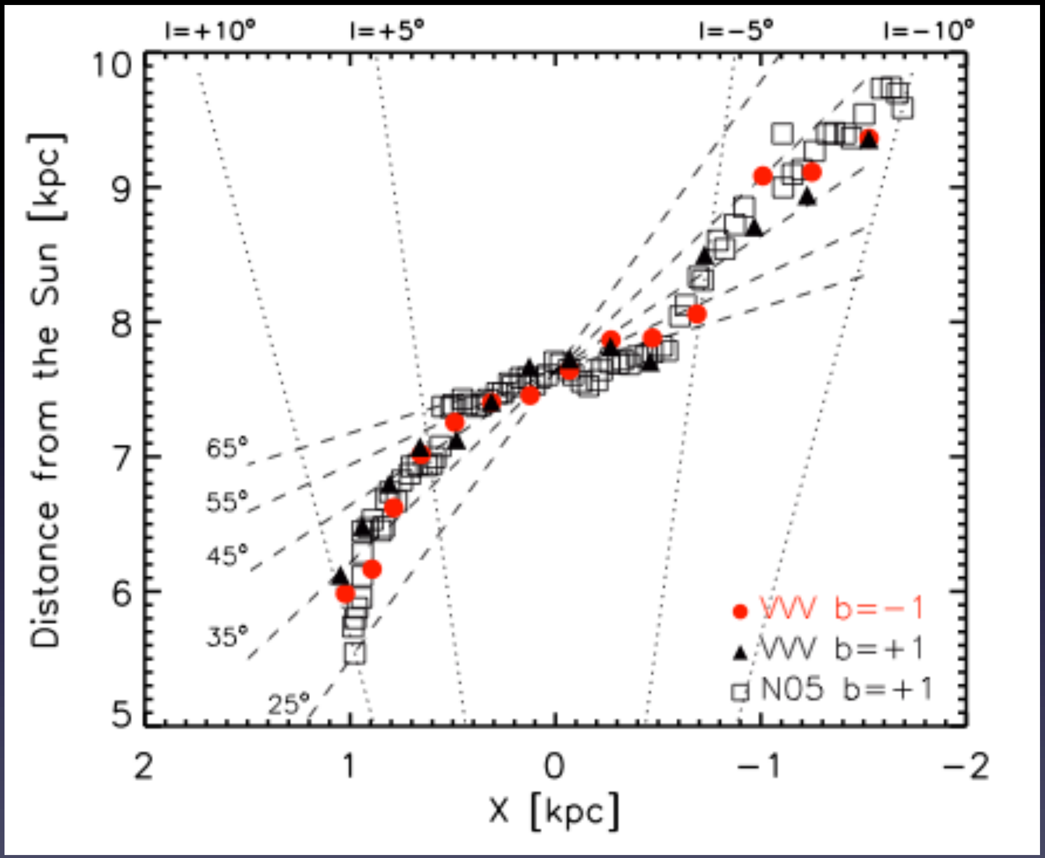
  [α/Fe] ~ +0.4 dex @low metallicity and solar @high metallicity

  Rapid formation scenario, similar to thick disk but faster than thin disk

- Bulge structure and morphology?

Bar structure

Gonzalez +12



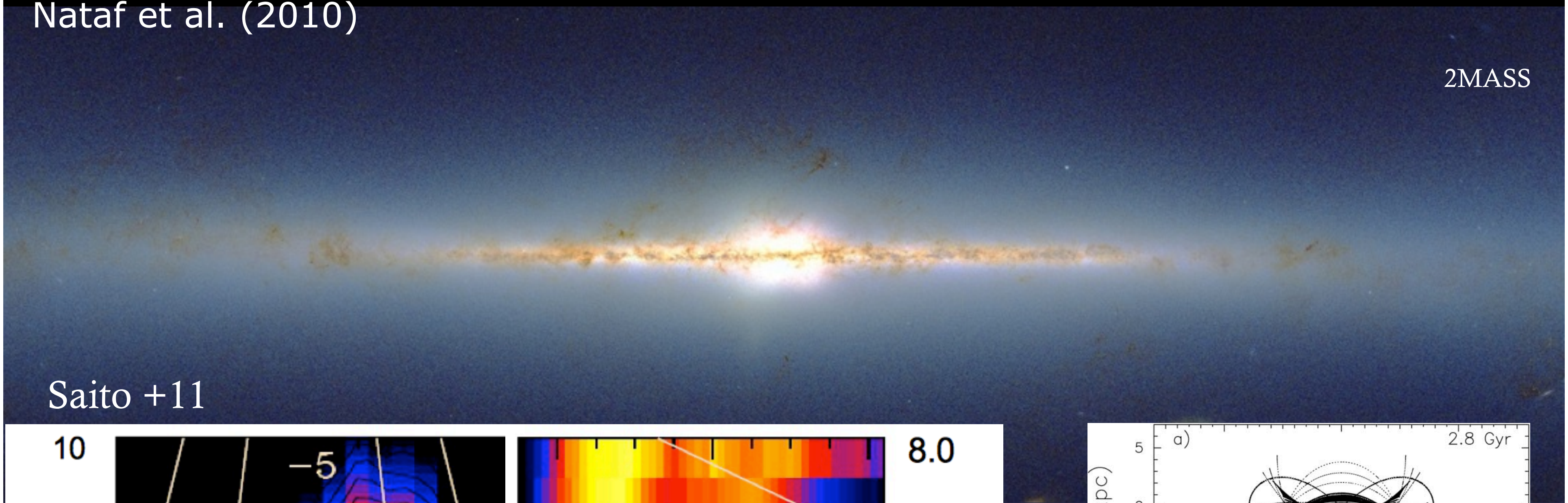
Methods:
Radial velocity
surface brightness
star counts
microlensing

Binney +91
Blitz & Spergel +91
Nakata +91
Stanek +94
Uldaski +94
Dwek +95
Bissantz & Gerhard 02
Babusiaux & Gilmore 05
Lopez-Corredoira +05
Rattenbury +07
Gonzalez +12
Cao +13

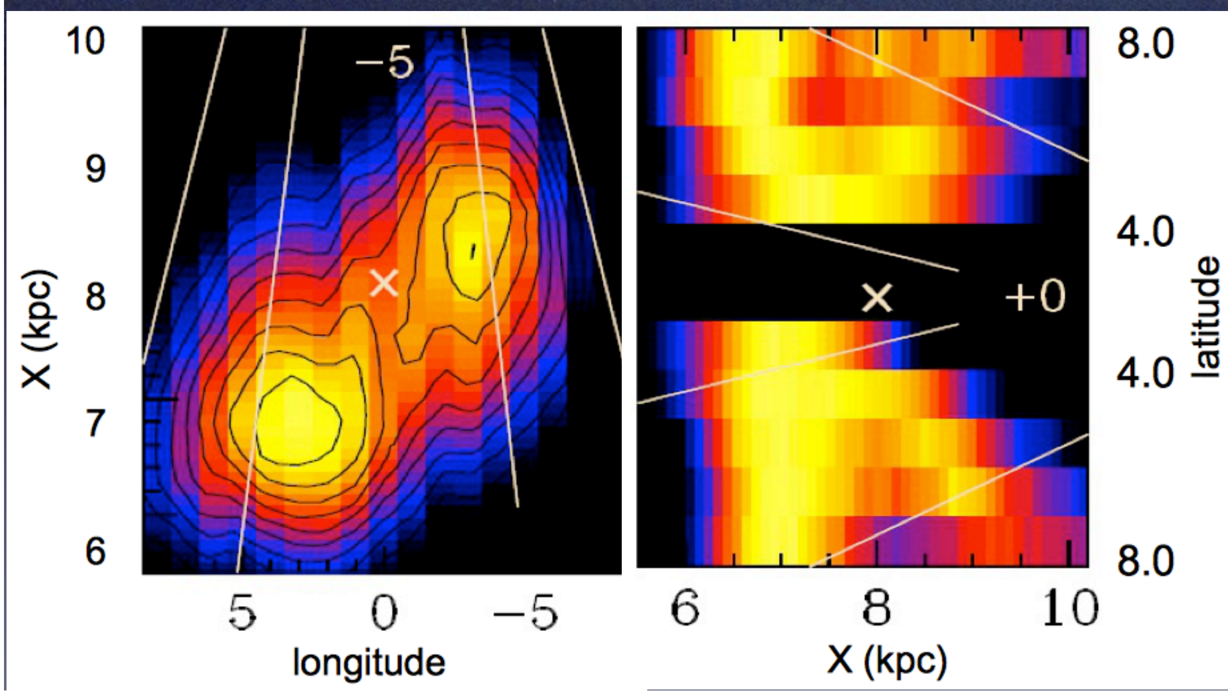
Inclination: 15° - 45°
Axial ratios: 1 : 0.41 : 0.38
(Cao +13)

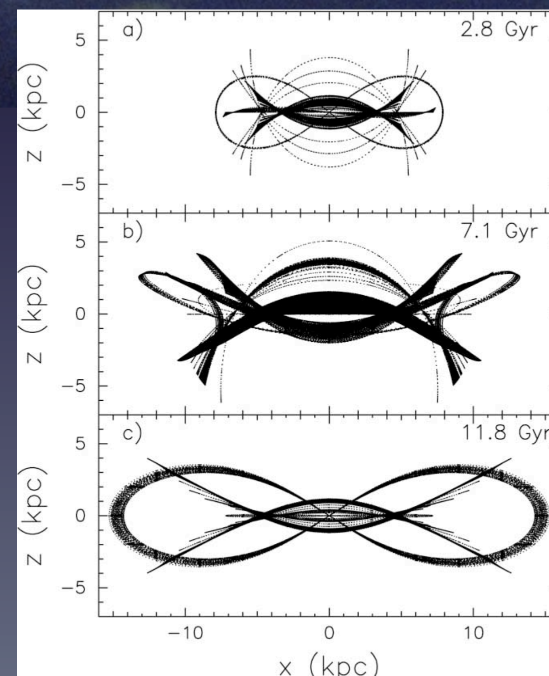
Boxy Peanut and X-Shape

McWilliam & Zoccali (2010)
Nataf et al. (2010)



Saito +11





- Bulge chemical content

MDFs: -1dex ≤ [Fe/H] ≤ +0.8 dex
Radial metallicity gradient
[α/Fe] ~ +0.4 dex @low metallicity and solar @high metallicity
Rapid star formation similar to thick disk

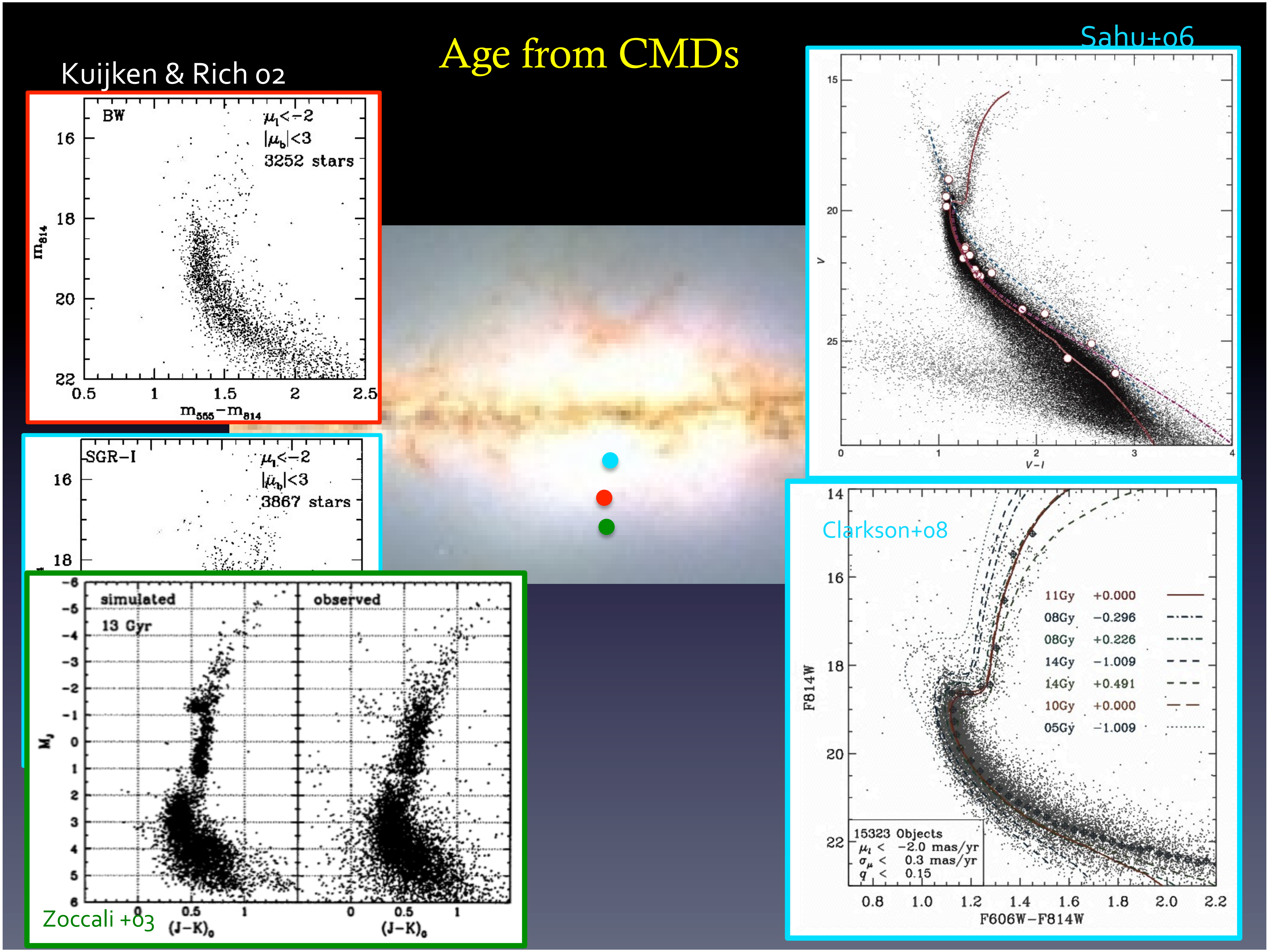
- Bulge structure and morphology

central Bar
Boxy peanut and X-shape

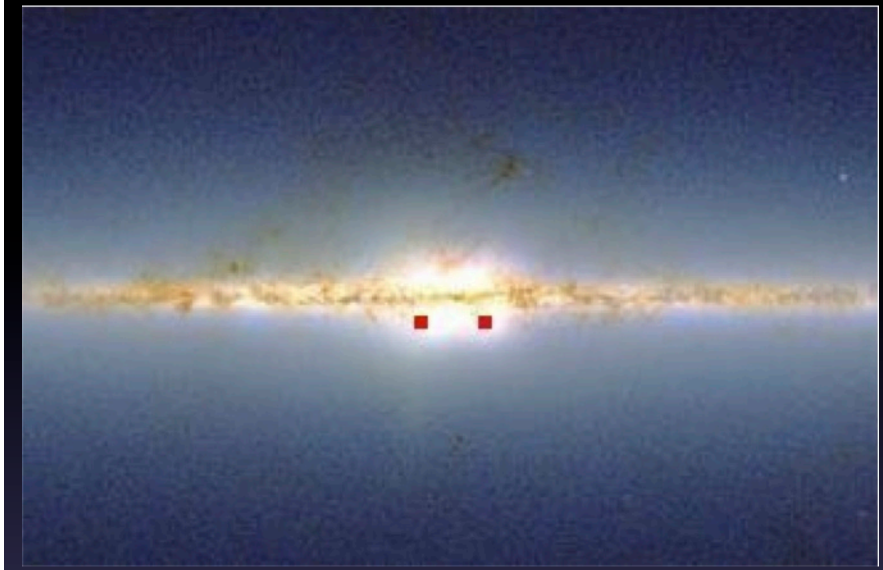
- Age

CMDs: SP along the minor axis is virtually coeval and OLD (> 10 Gyr)

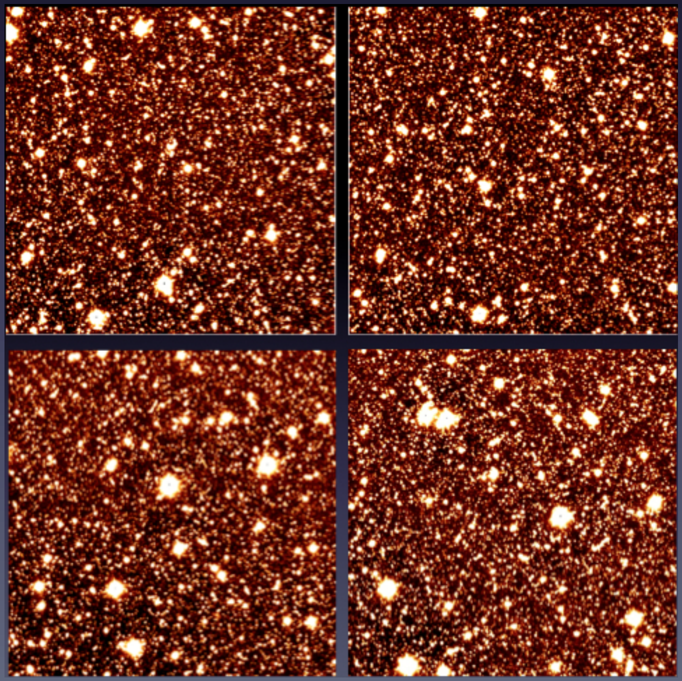
Age from CMDs



HAWK-I IR DATA



Name	l°	b°	Filter	ExpTime (sec)	FWHM
BUL-SC29	10.3	-4.2	J	3120	0.6”
			Ks	10920	0.7”
BUL-SC9	-6.8	-4.7	J	1560	0.6”
			Ks	10920	0.4”



4 Hawaii 2RG detectors Mosaic

FoV = 7.5’ x 7.5’

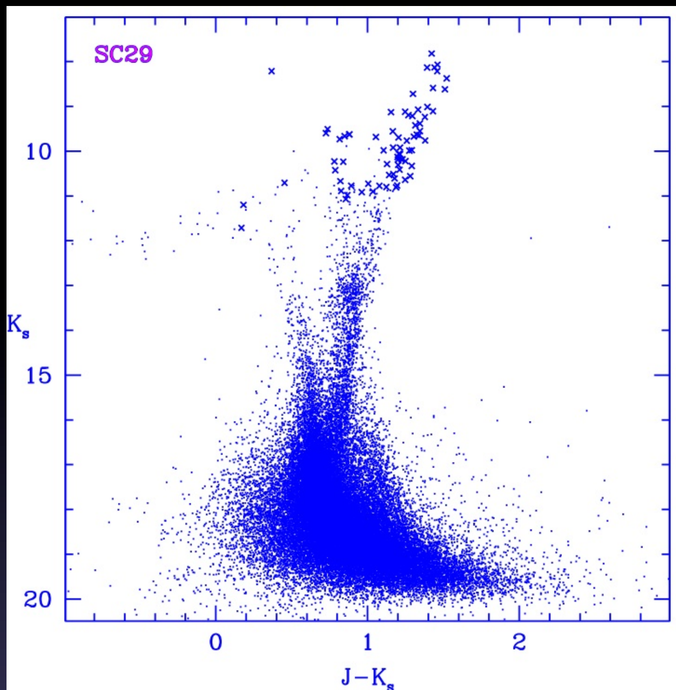
Pixel scale: 0.106”/pix

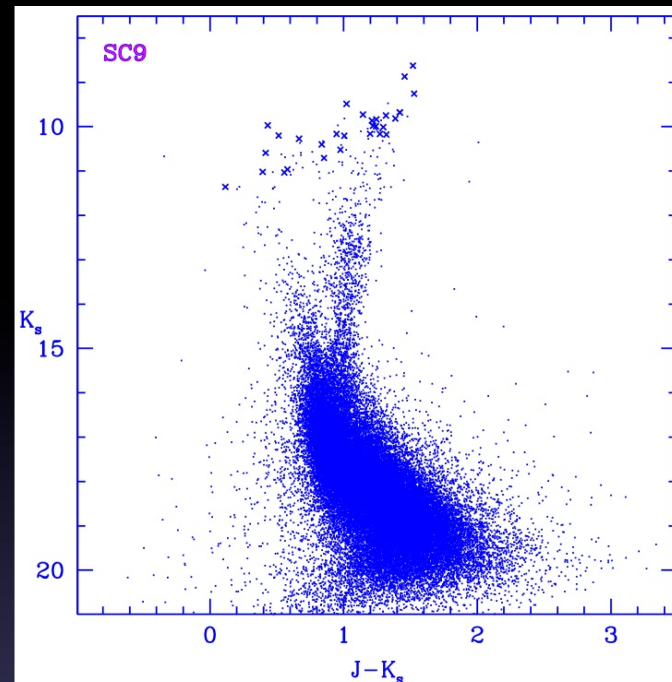
Wavelength range: 0.85 – 2.5 μm

BB filters: Y, J, H, K_s (VISTA)

NB filters: Brγ, CH4, H2, 1.161μm, 1.187μm, 2.090μm

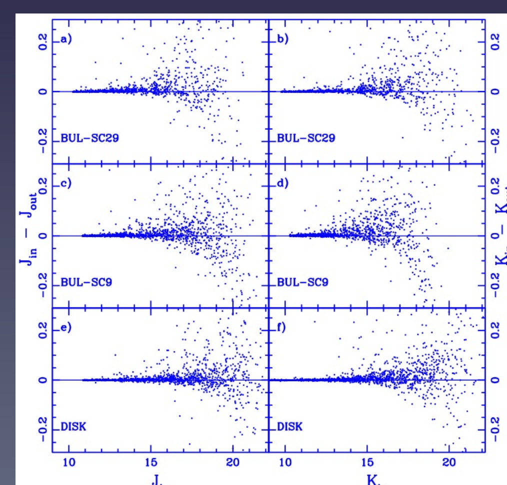
Derived CMDs





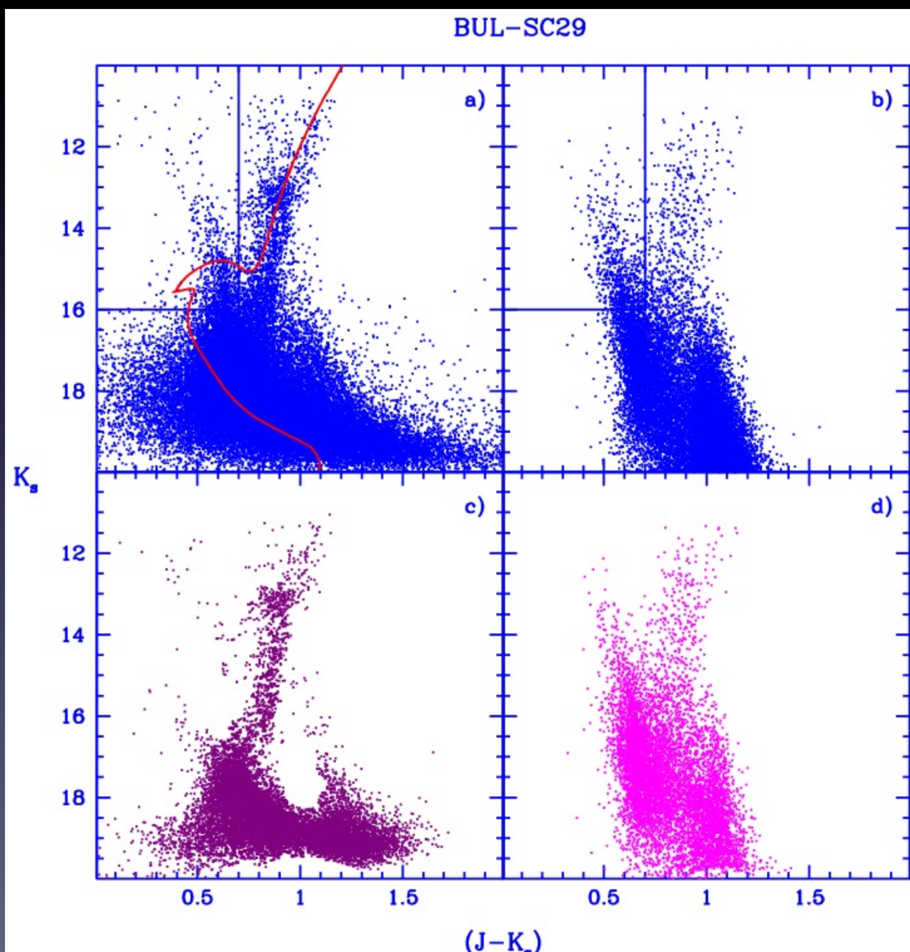
Artificial stars experiment

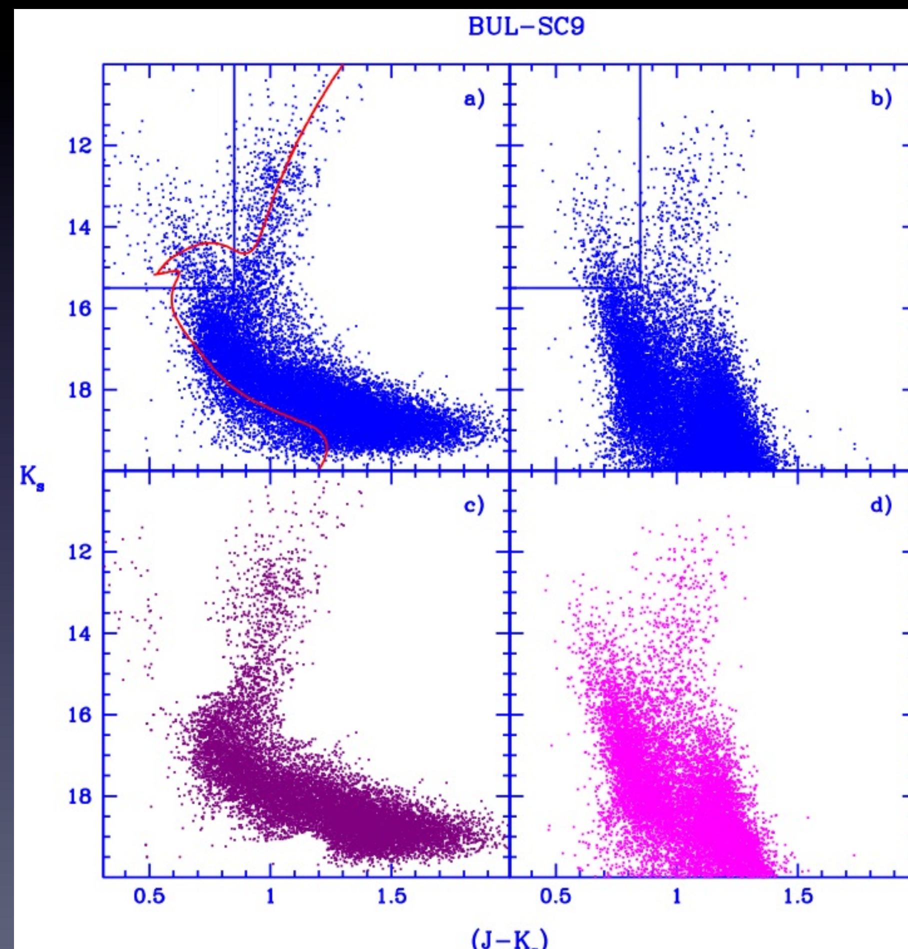
- Completeness: 50% above J~20 and K_s~19
- Error estimates



Disk decontamination

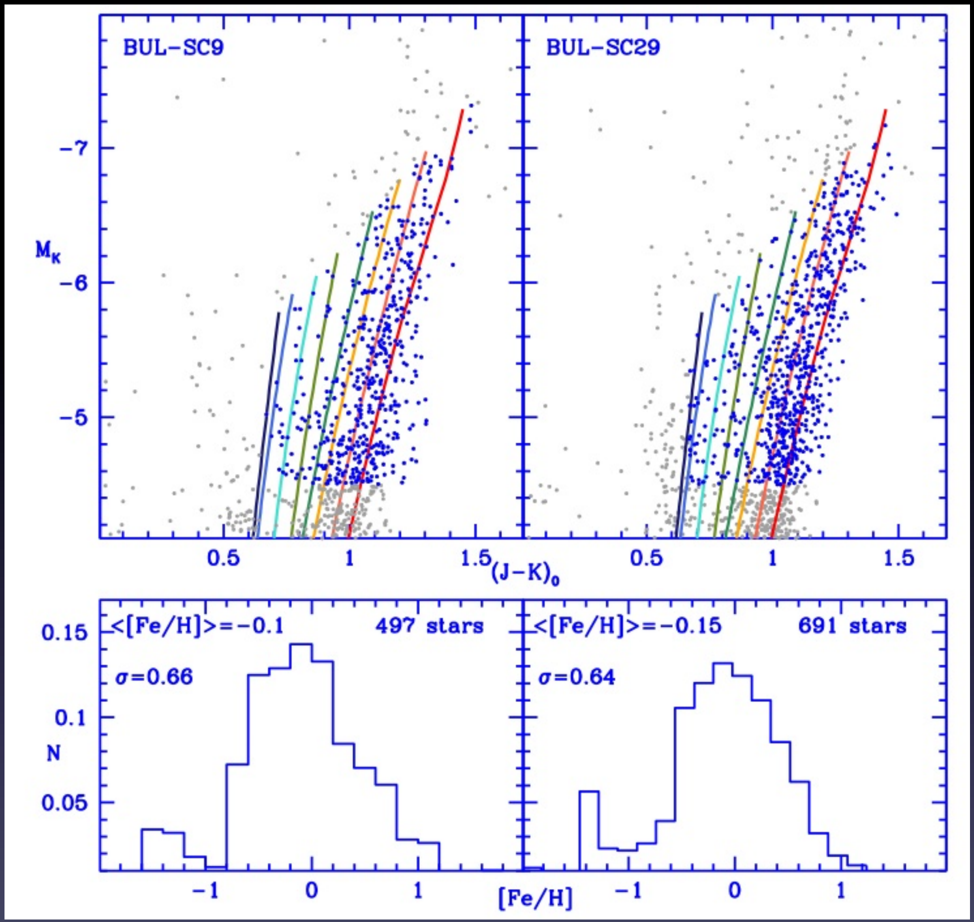
Name	l°	b°	Filter	ExpTime (sec)	FWHM
Disk	29.9	-3.9	J	3120	0.5”
			Ks	9360	0.4”





Photometric MDFs

Empirical templates
Globular Clusters
(Valenti+04a)
M92: [Fe/H]= -2.1
M55: [Fe/H]= -1.61
NGC6752: [Fe/H]= -1.42
NGC362: [Fe/H]= -1.15
M69: [F/H]= -0.68
NGC6440: [Fe/H]= -0.50
NGC6528: [Fe/H]= -0.17
Open Cluster
(Origlia+06)
NGC6791: [Fe/H]= +0.35

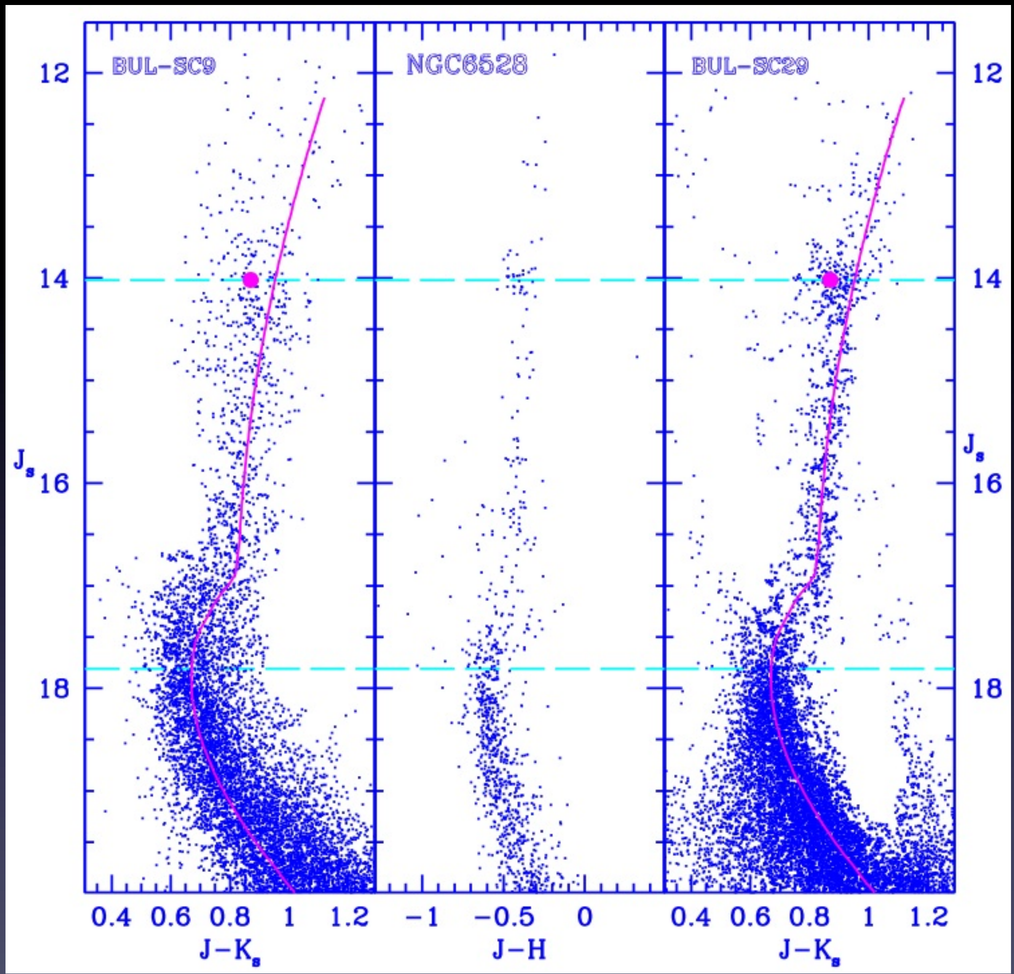


All 2MASS stars (FoV=30'x30'):

- Fainter than RGB-Tip (Valenti+04b)
- M_k< -4.5
- $(J-K_s)_0$>0.7

Both fields have very similar MDF
The bulk of SP has metallicity in the range -0.8 dex < [Fe/H] < +0.6 dex
Mean peak around [Fe/H] = -0.1 dex

Relative Age: Fields vs Cluster



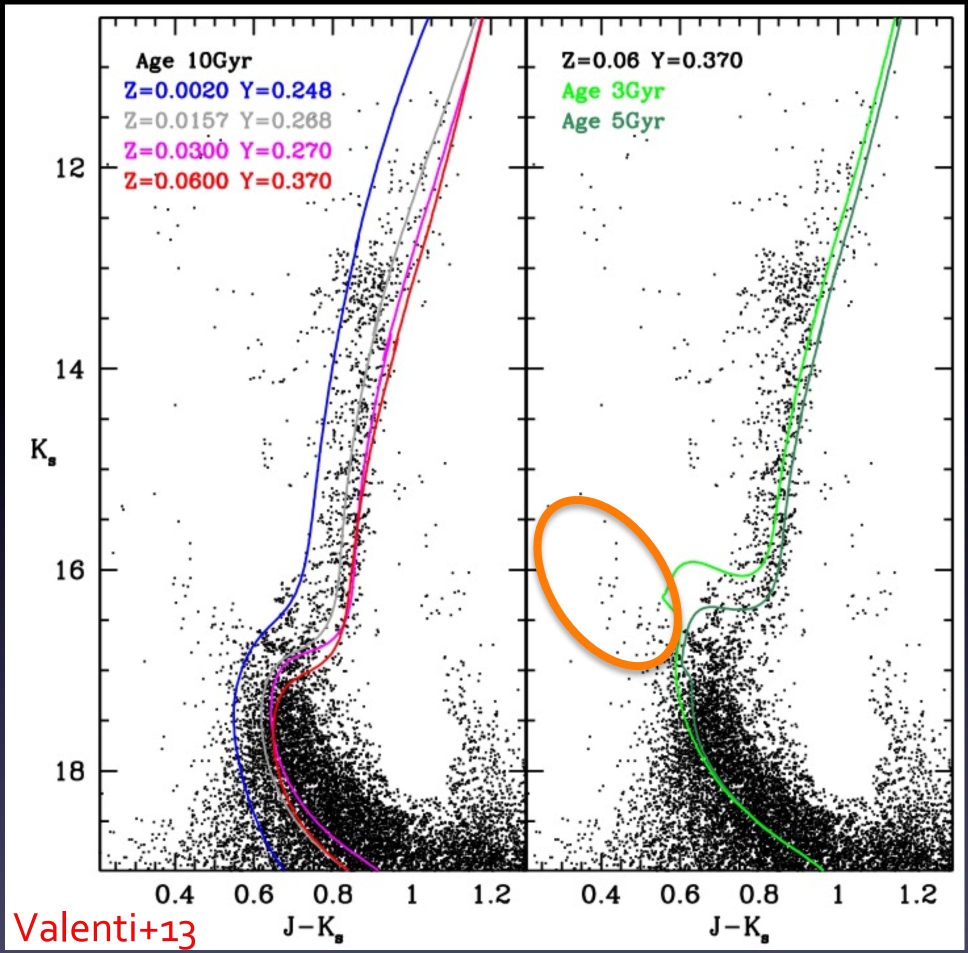
Age of NGC6528 from HST:

13 Gyr	(Ortolani +01)
11 Gyr	(Feltzing & Johnson 02)
12.6 Gyr	(Momany +03)
12.5 Gyr	(Brown +05)

$\Delta J^{RC-HB}|_{MS-TO}$ ➔ Two Bulge fields and NGC6528 have essentially the same age within better than 20%

Absolute Age

Theoretical isochrones from Valcarce +12



Clarkson+11

- **The bulk of the Bulge stellar population has an age ≥ 10 Gyr**
- **Very little room left for the presence of intermediate age population**

Age-Metallicity relation from microlensed dwarfs

Bensby +13

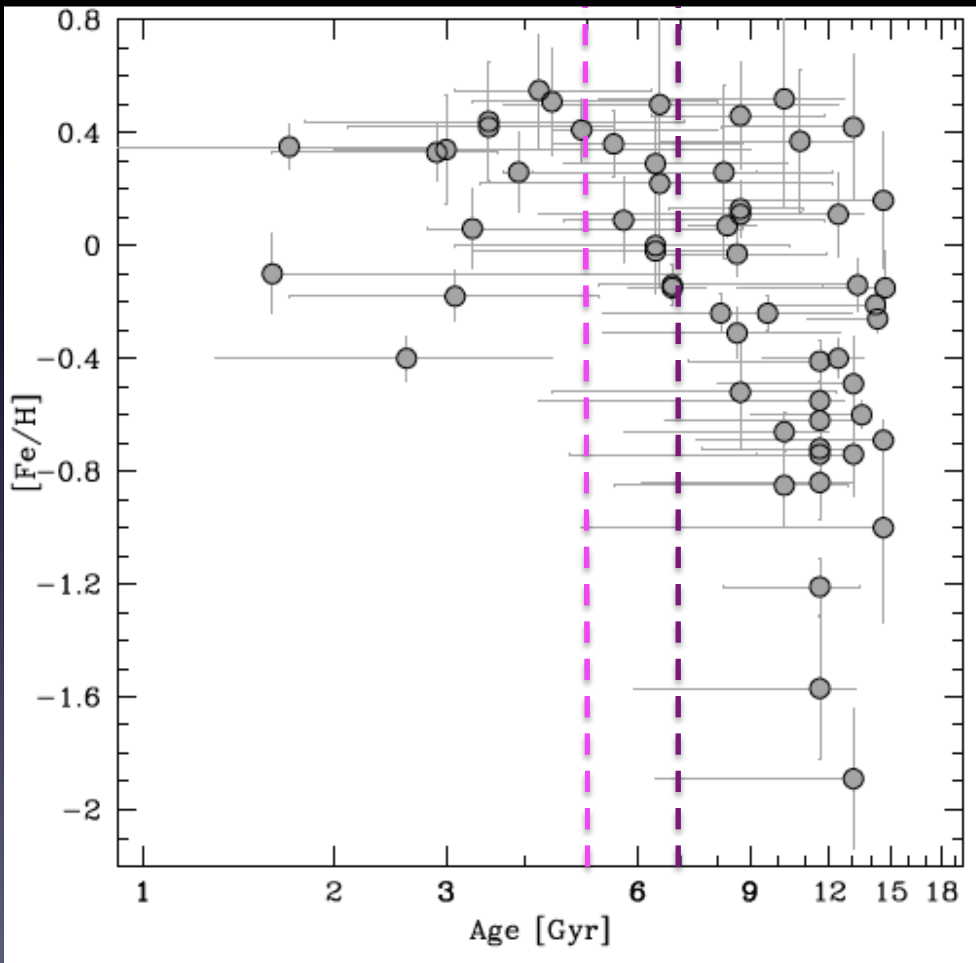
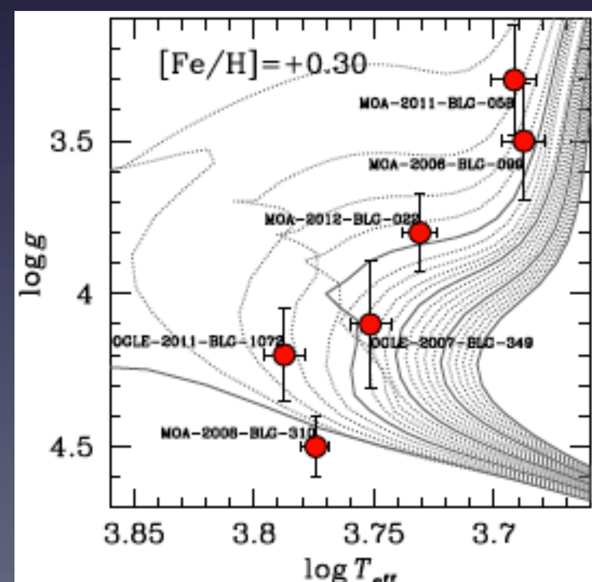


Fig. 15. Age versus [Fe/H] for the microlensed dwarf sample.

~30% of
the microlensed dwarfs
have ages < 7 Gyr, 20% younger than
5 Gyr, with a few as young as 1.5 Gyr.



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  Radial metallicity gradient
  [α/Fe] ~ +0.4 dex @low metallicity and solar @high metallicity
  Rapid star formation similar to thick disk

- Bulge structure and morphology

  central Bar
  Boxy peanut and X-shape

- Bulge Age

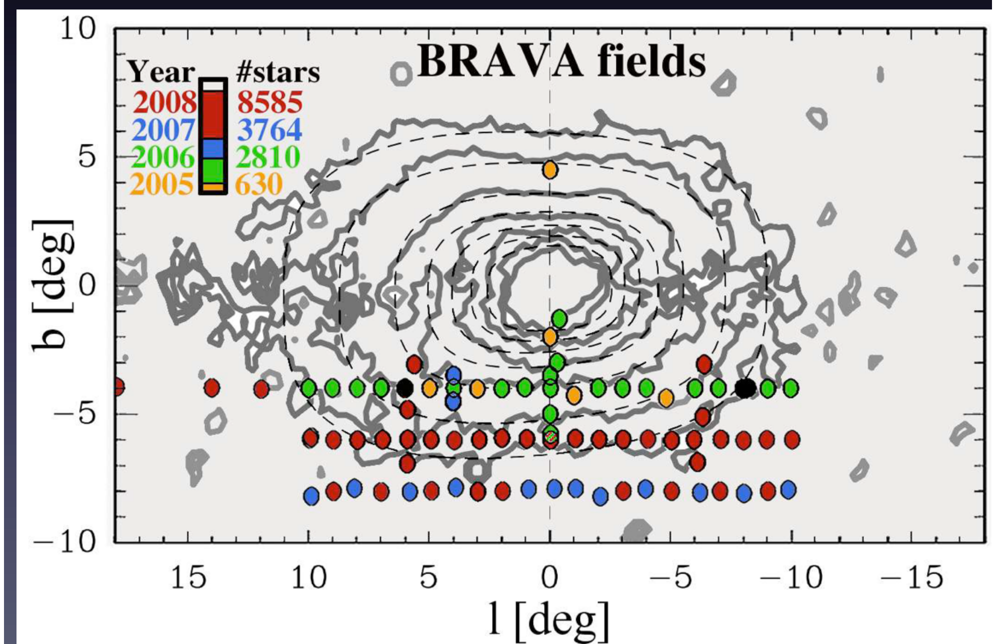
  CMDs: SP along the minor axis and at the edge of the bar is virtually coeval and OLD (> 10 Gyr)
  Most MR stars might have formed over a slightly longer timescale
  So far age-metallicity gradient only from dwarfs

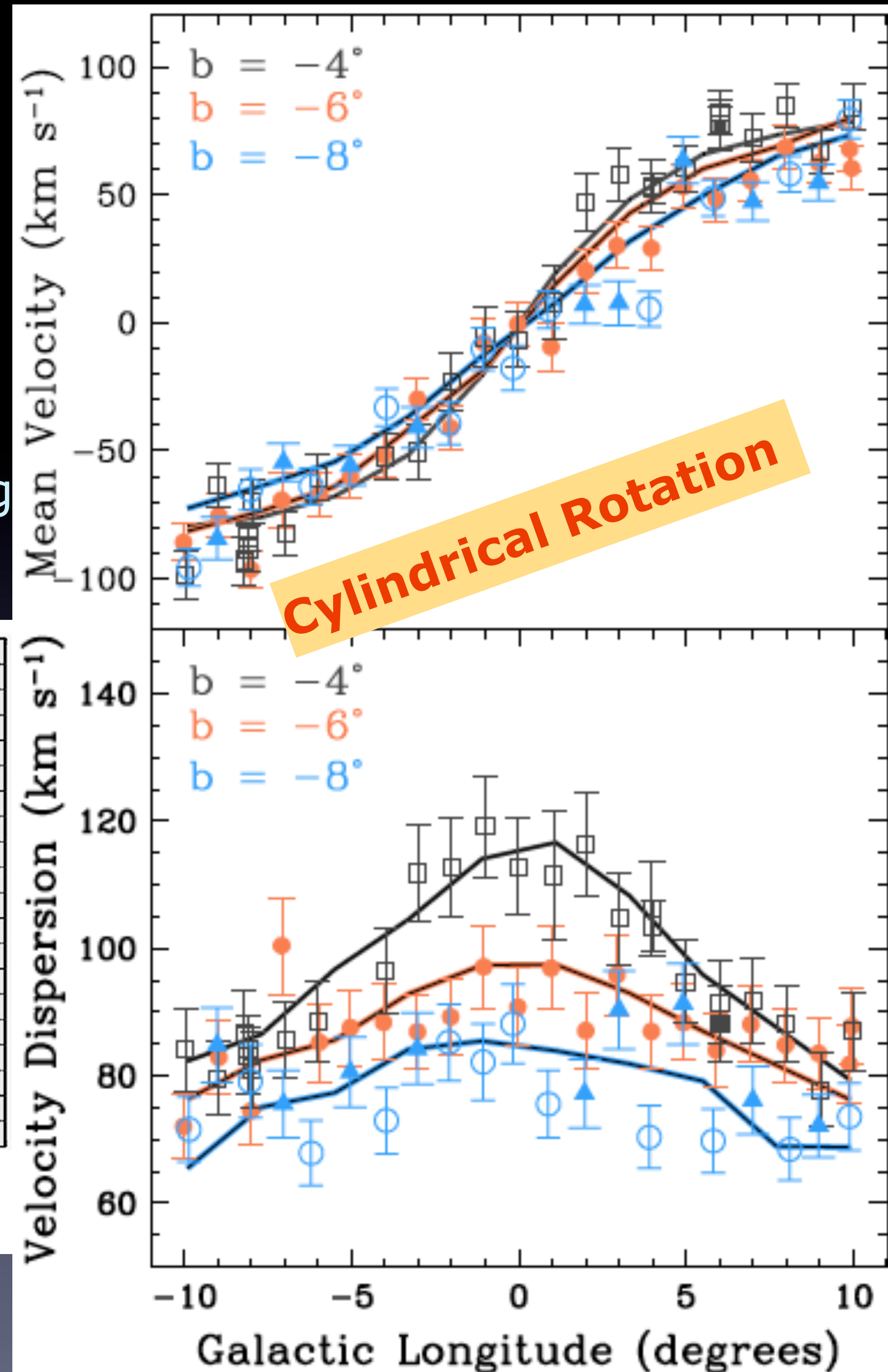
- Bulge kinematics?

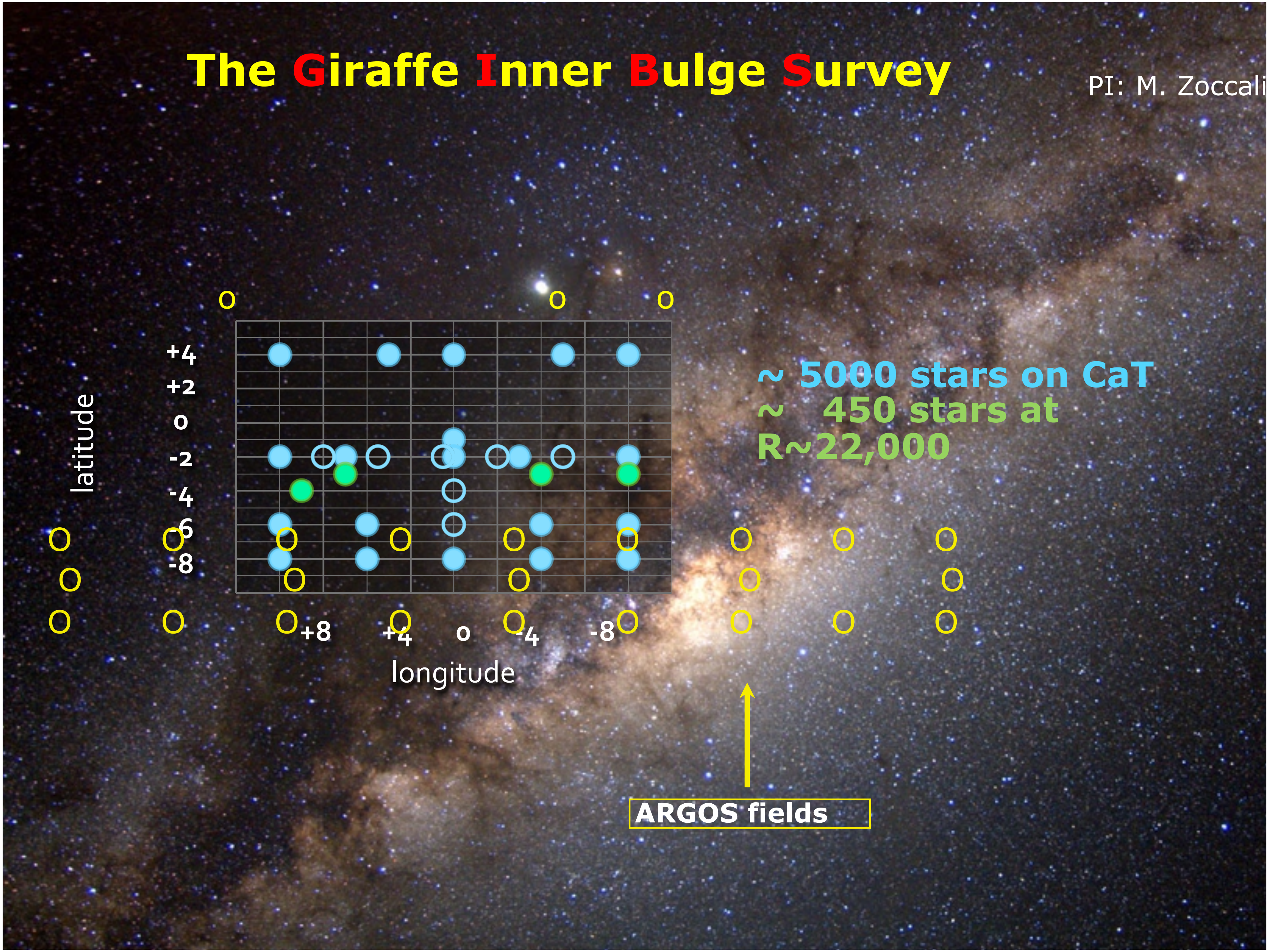
The BRAVA Survey

Rich et al. (2007)
Howard et al. (2009)
Shen et al. (2010)
Kunder et al. (2012)

Radial Velocities for 10,000 bulge M g

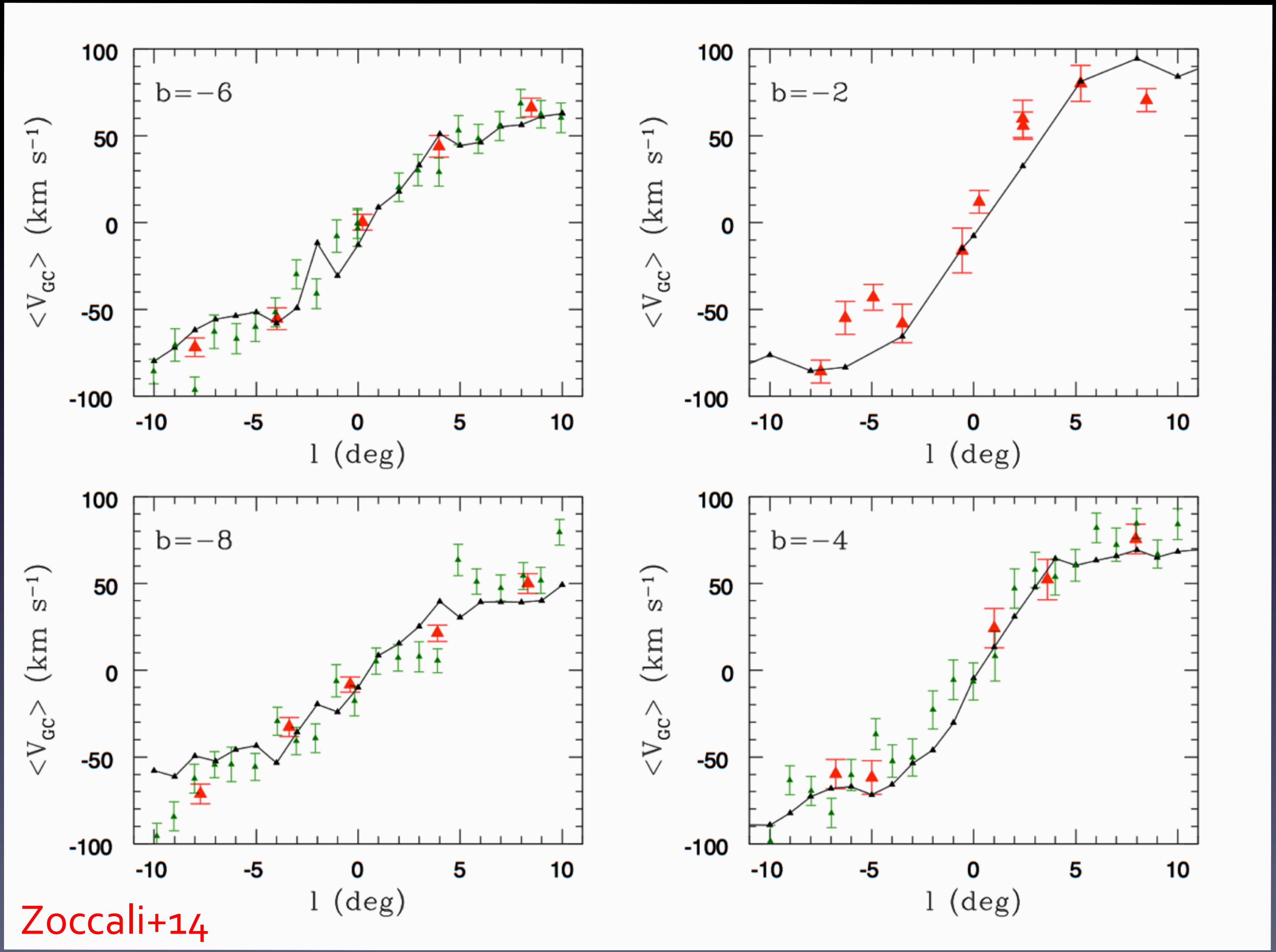





The Giraffe Inner Bulge Survey
PI: M. Zoccali
~ 5000 stars on CaT
~ 450 stars at R~22,000
latitude
+4
+2
0
-2
-4
-6
-8
+8
+4
0
-4
-8
longitude
ARGOS fields

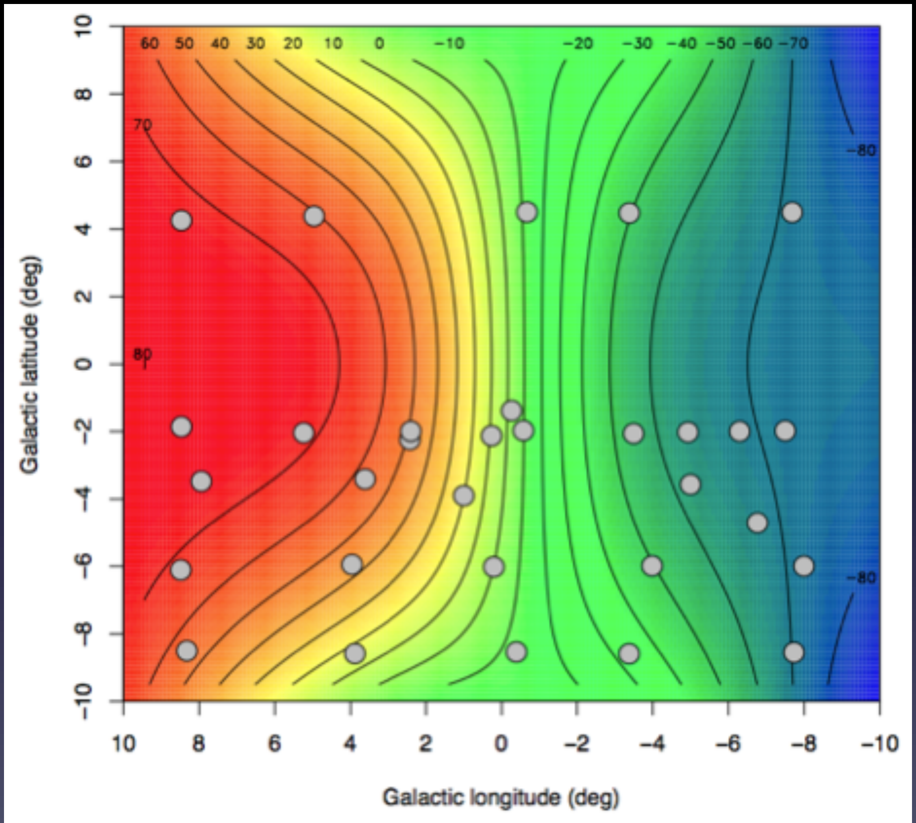
GIBS: Radial velocities across the bulge area

Cylindrical rotation confirmed

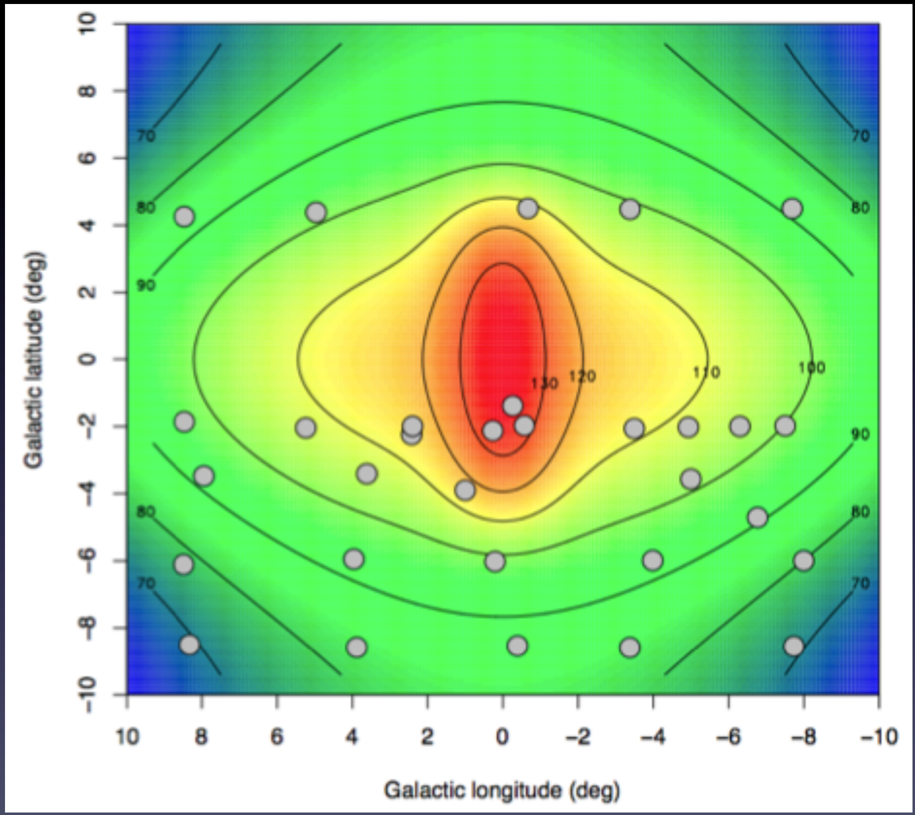


GIBS: kinematical maps

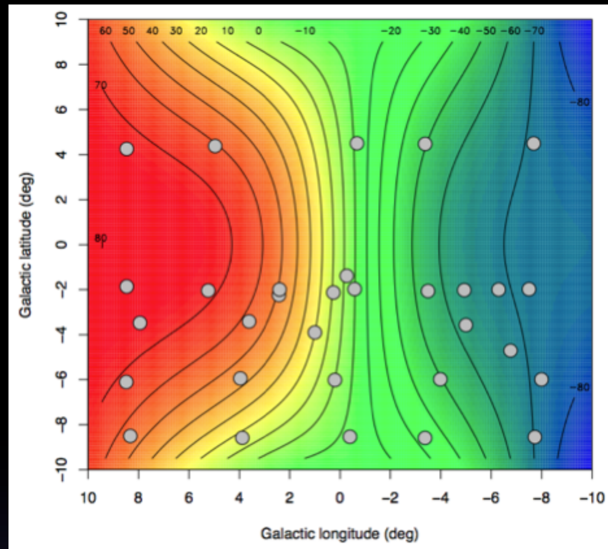
Radial Velocity

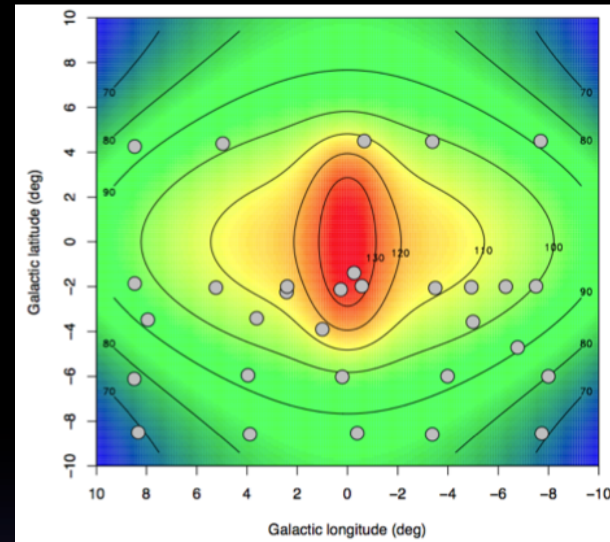


Velocity dispersion



Zoccali+14


Galactic latitude (deg)
Galactic longitude (deg)


Galactic latitude (deg)
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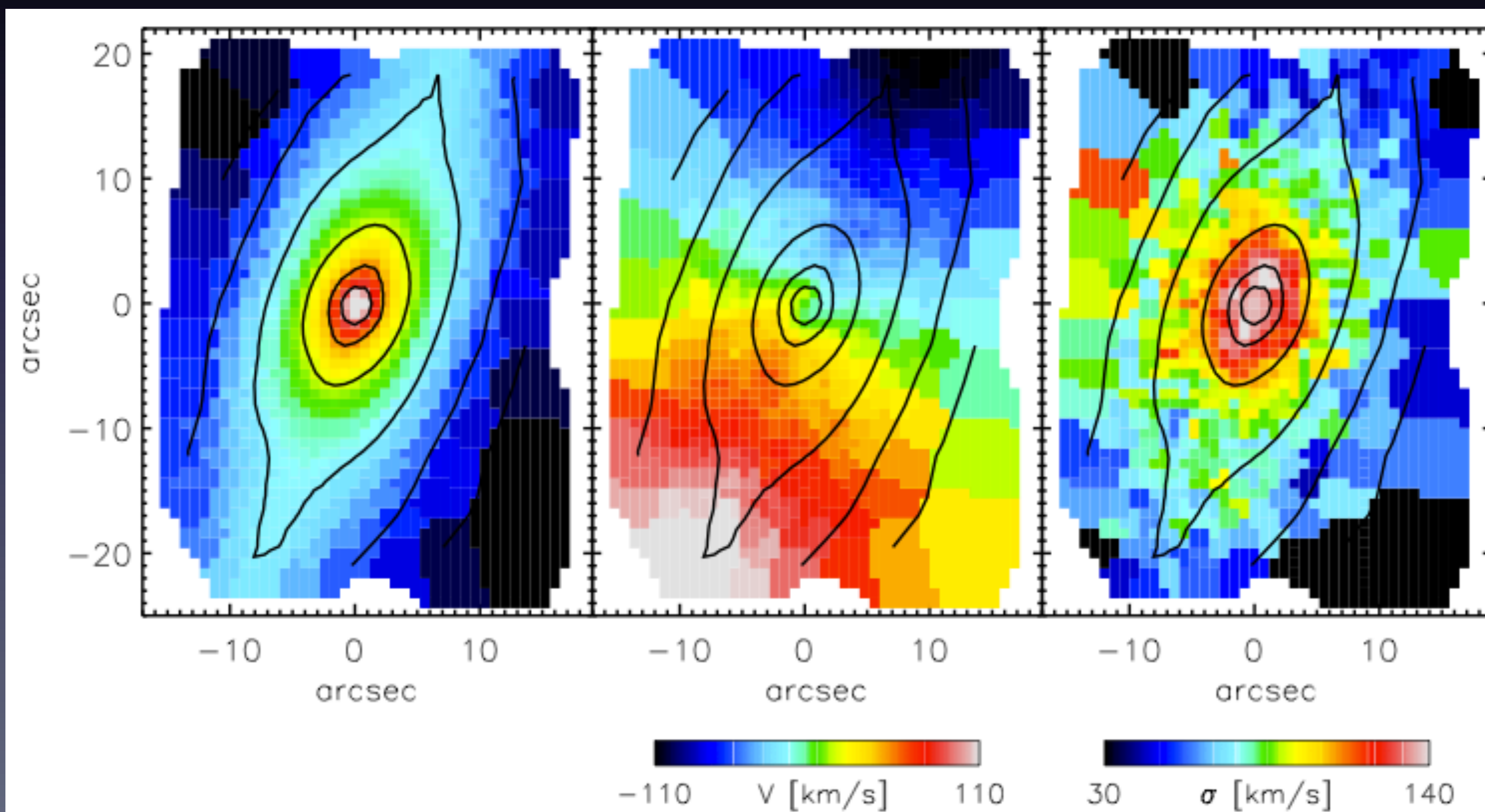
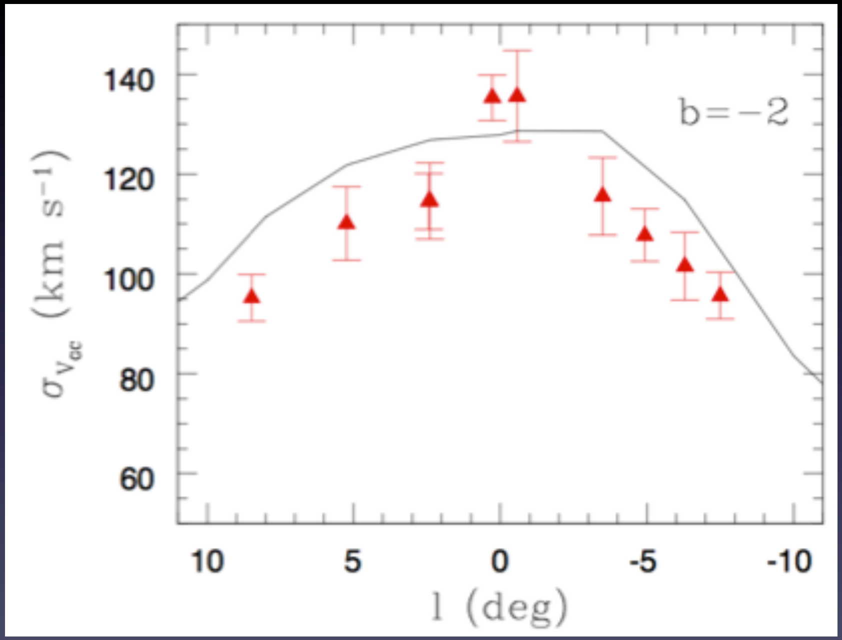
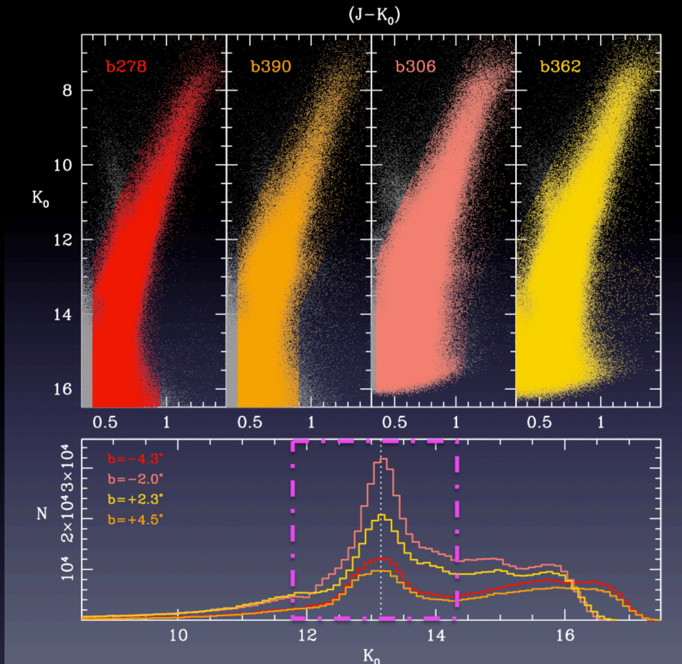

arcsec
arcsec
arcsec
arcsec
−110 V [km/s] 110
30 σ [km/s] 140

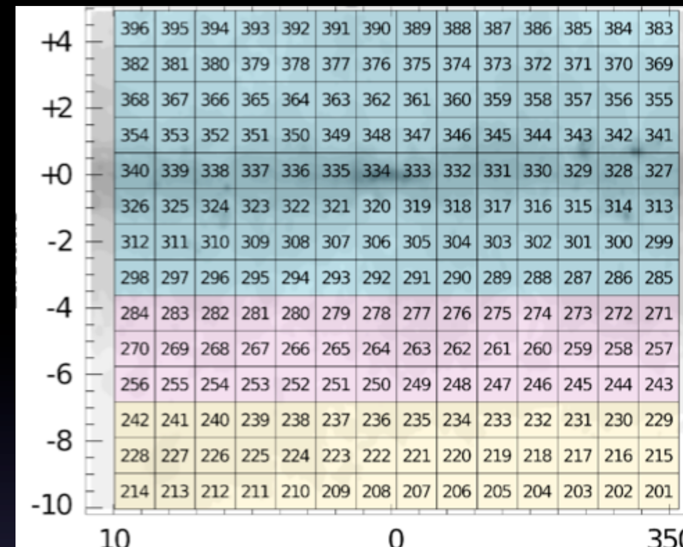
GIBS and VVV: Kinematics and Mass

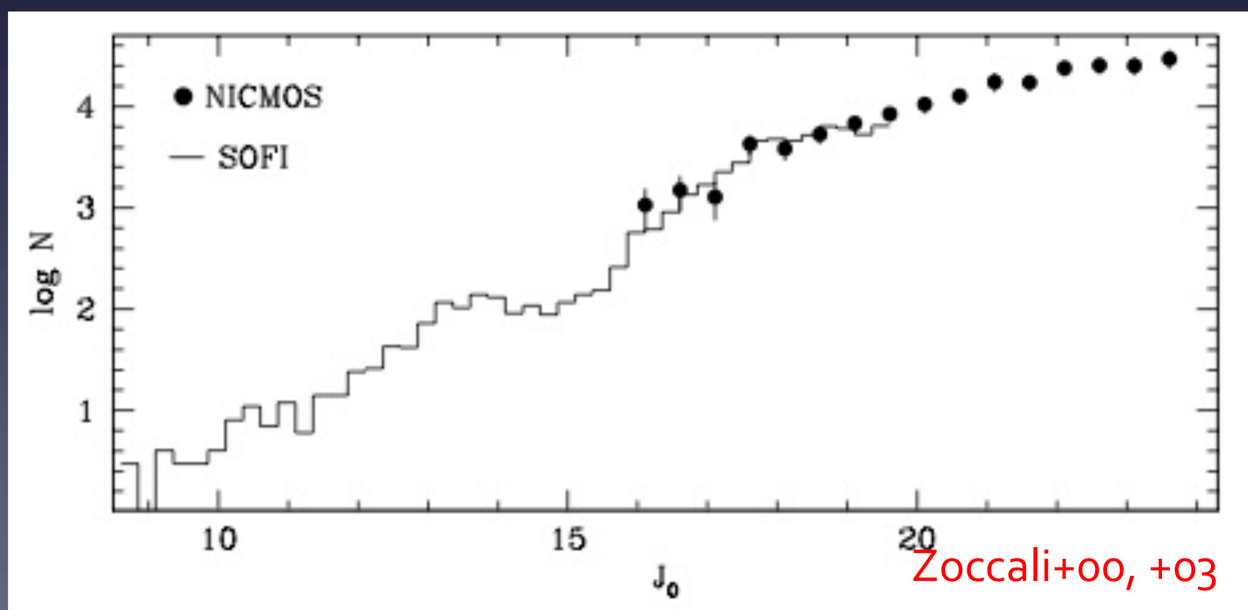
σ-peak in the center ~2°



GIBS and VVV: Kinematics and Mass



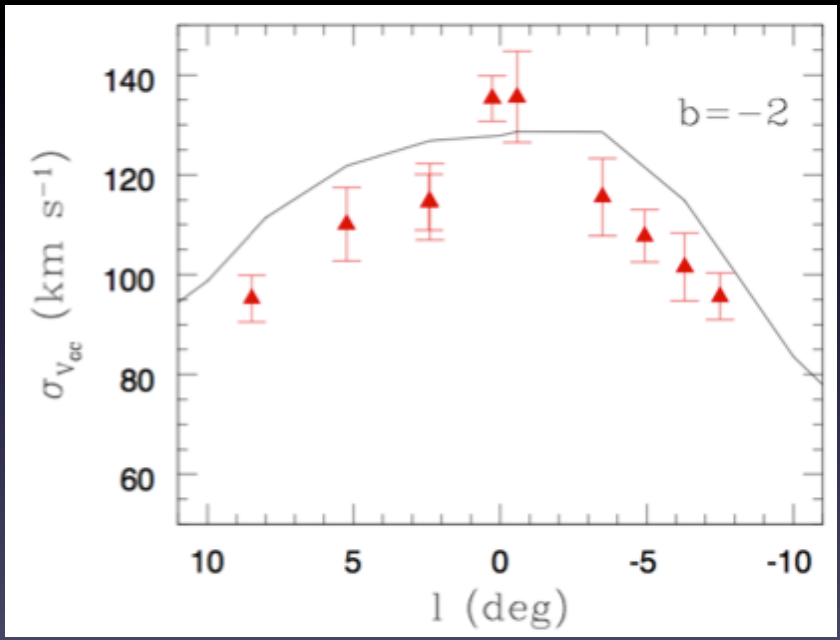




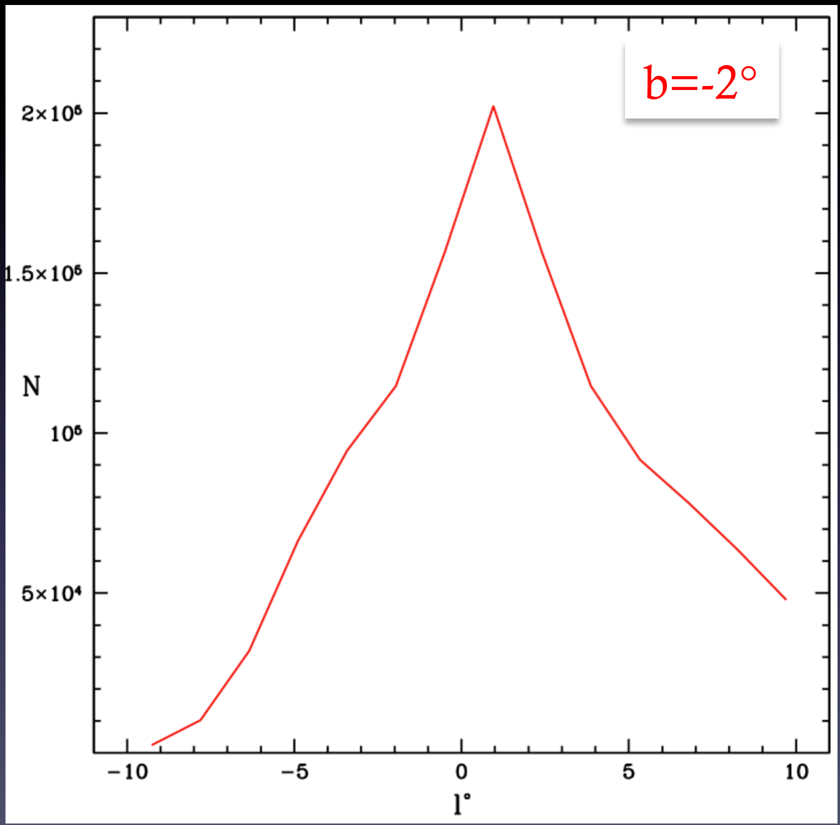
Zoccali+00, +03

GIBS and VVV: Kinematics and Mass

σ-peak in the center ~2°



Zoccali+14



Valenti+14 (in prep)

SUMMARY

the Galactic Bulge is very complex ......

- The Bulge hosts a boxy/peanut structure
- Several independent observations suggest the presence of 2 components
  'classical bulge' + bar ??
- A metallicity gradient, in the outer bulge, follows the B/P structure
  What about the inner bulge ? Challenge for dynamical models
- Bulge stars are old and MR, with [α/Fe] similar to thick disk
  Rapid star formation occurred ~10Gyr ago with a short (< 1 Gyr) timescale
  Most MR stars might have formed over a slightly longer (~ 3 Gyr) timescale
- A simple B/P model is suff. to reproduce the Bulge kinematics
- Presence of a high density mass in the inner ~ 2 degrees ???


THANKS !