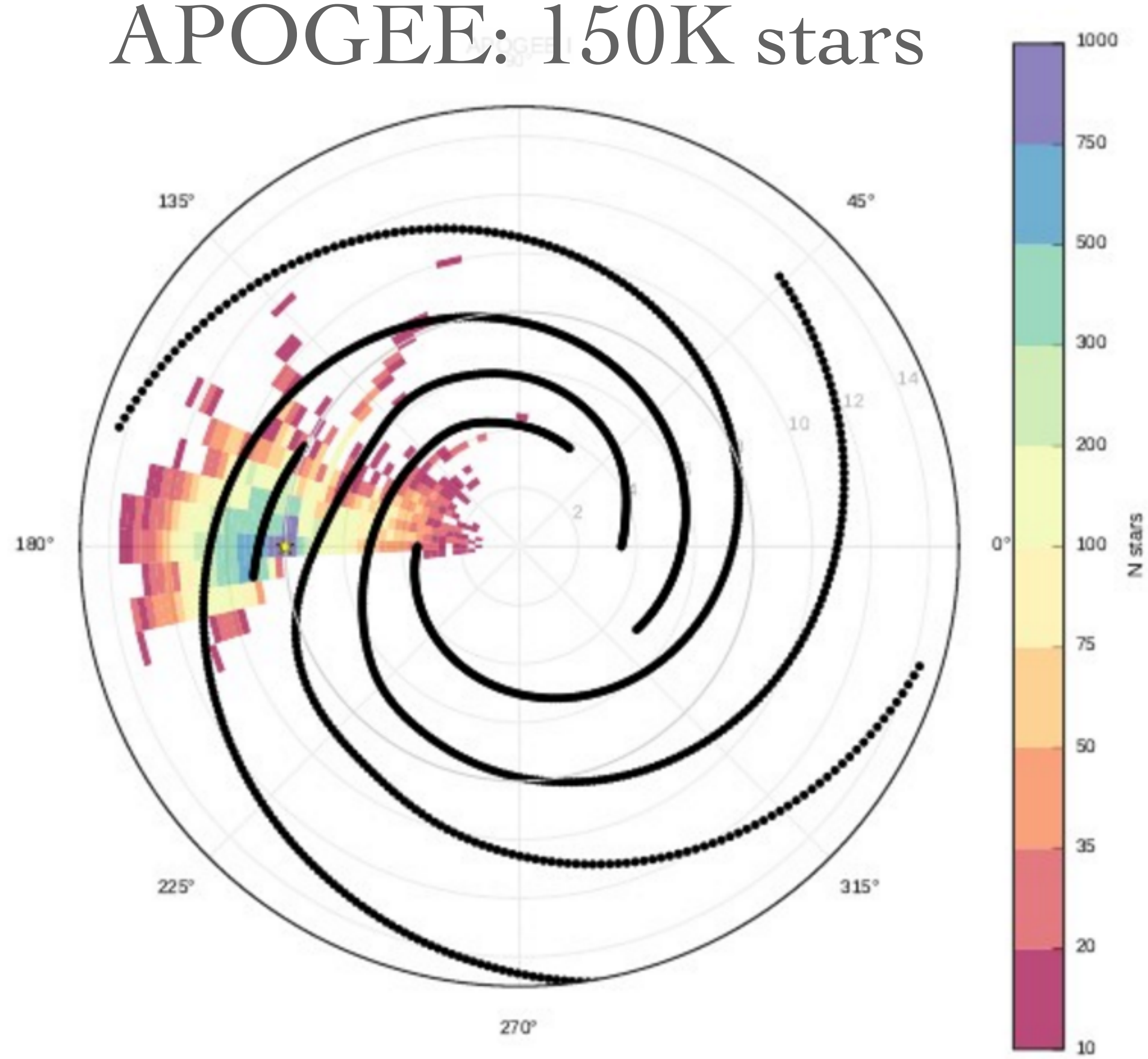
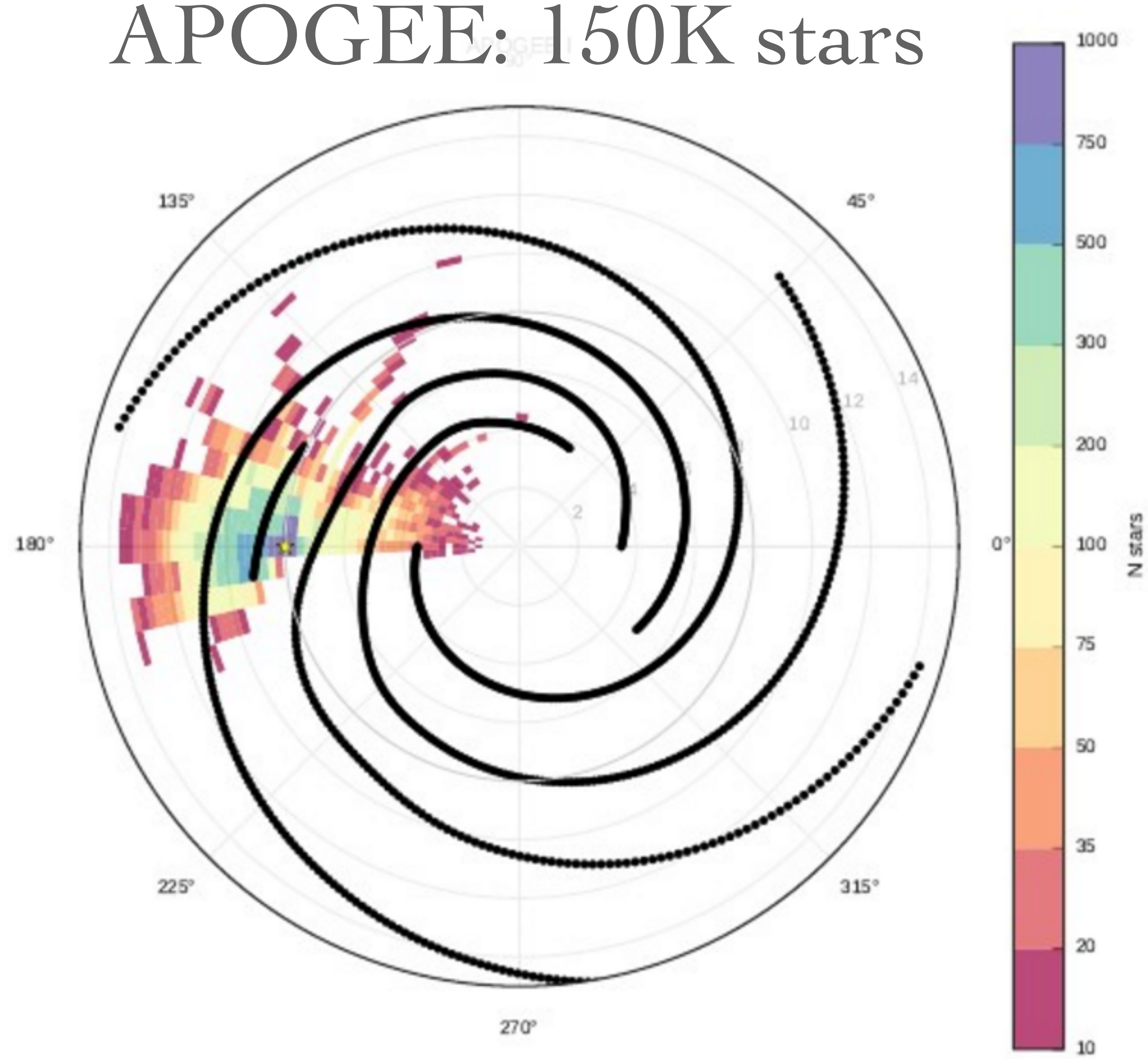
APOGEE: 150K stars



Disco: Proposal submitting this Friday for Sloan V

P.I's Jon Bird & Melissa Ness

APOGEE: 150K stars



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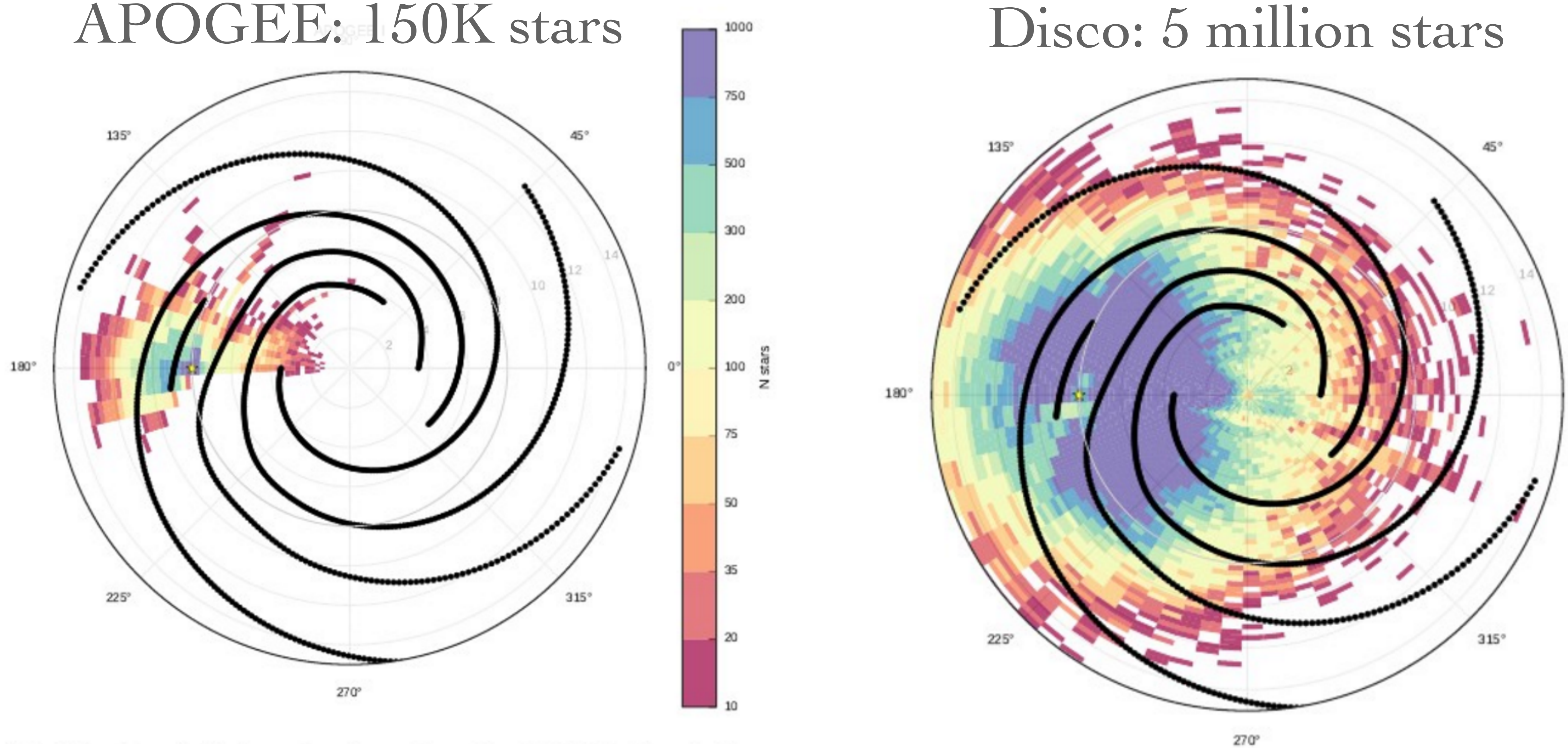
Disco: 5 million stars



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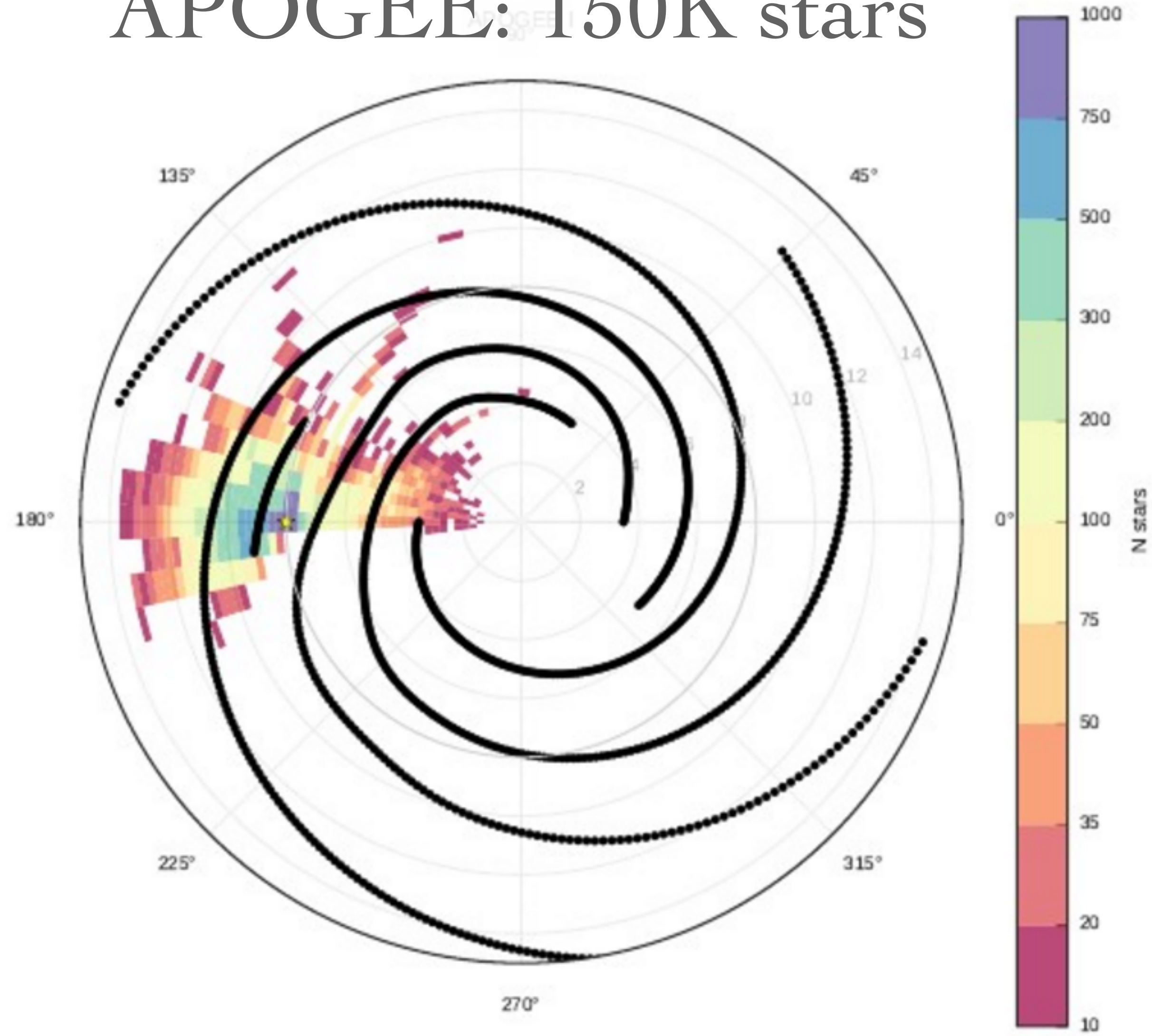

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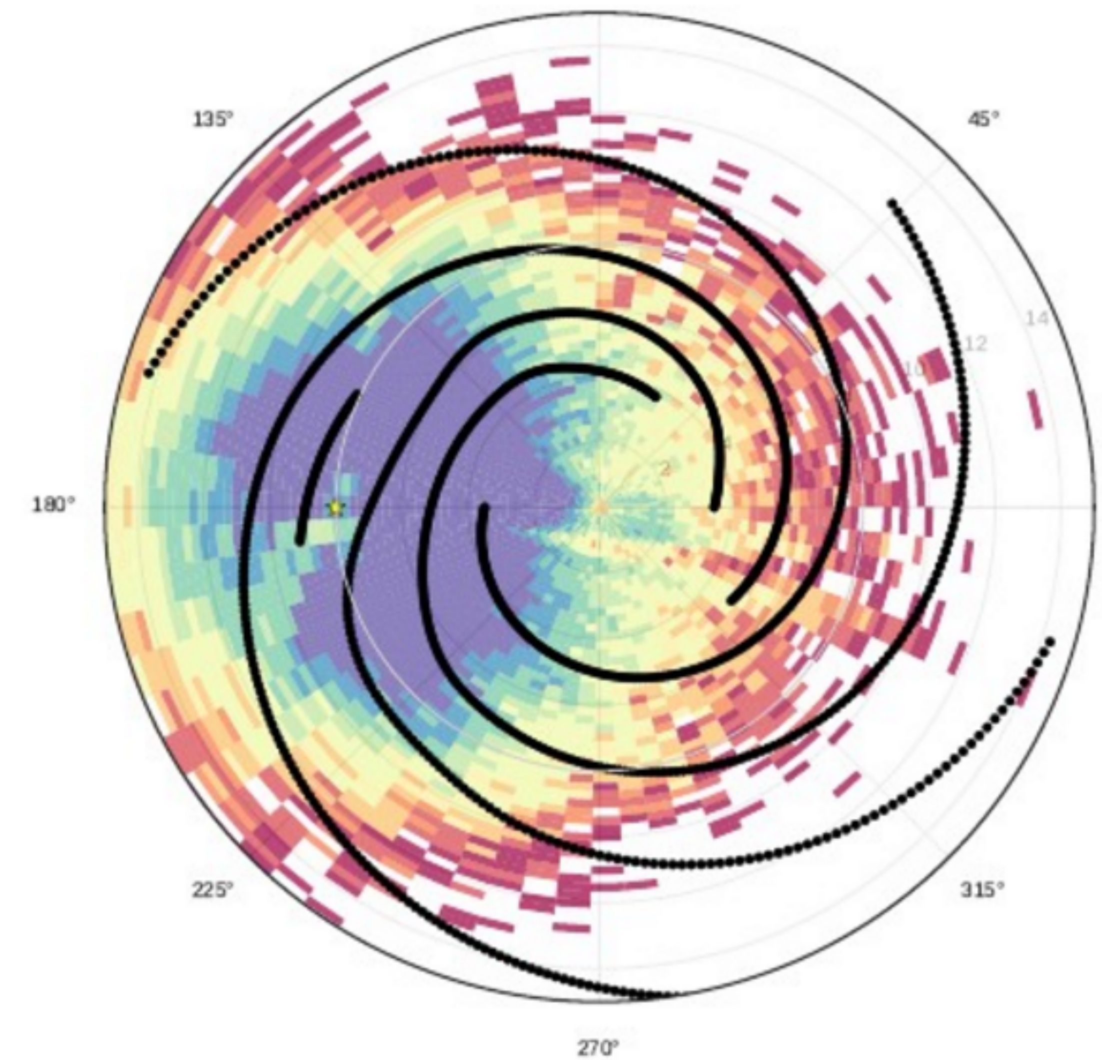
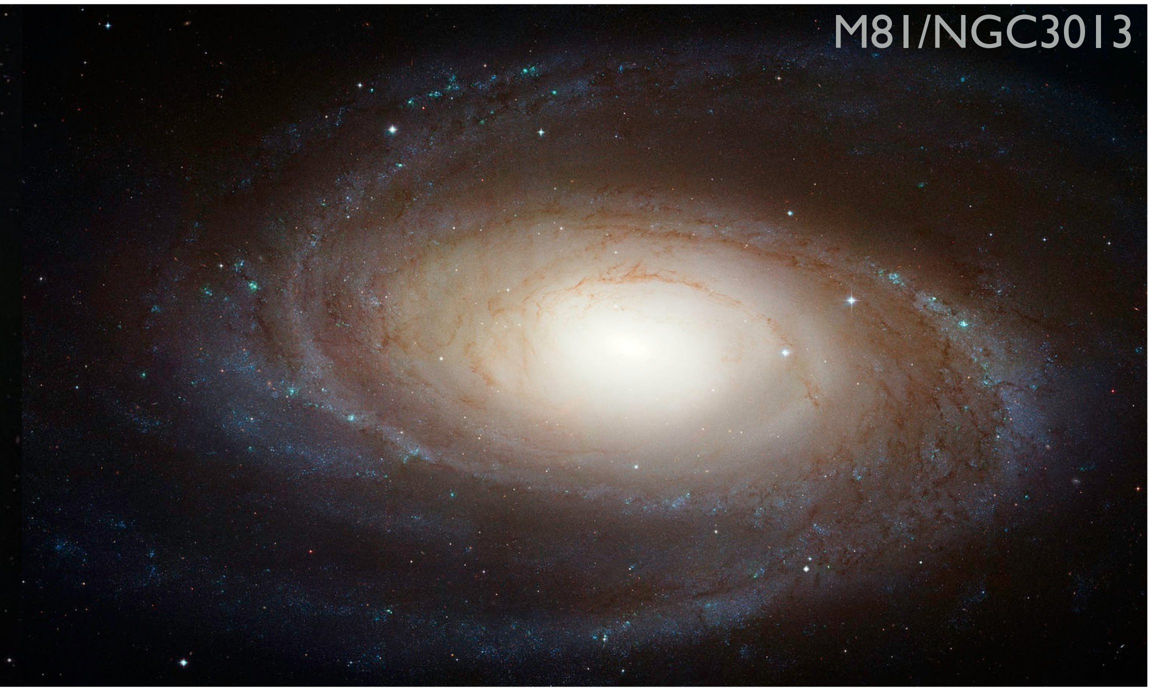


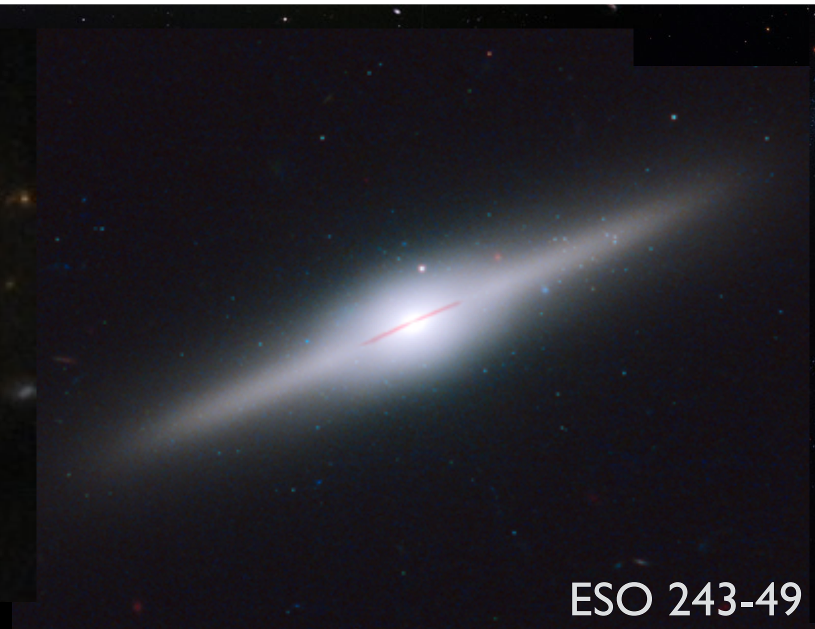
- APOGEE spectrograph: **H-band**
- Measure: radial velocities, stellar parameters & 20 abundances, ages
- **SNR > 40 (10 min. exposures) — precision 0.05 - 0.1 dex** most elements
- **Contiguous complete coverage**: fully sampled **H< 11.3** and 3.7 < G-H < 9.7

Insights from the Galactic Bulge

Melissa Ness, MPIA (Heidelberg, Germany)

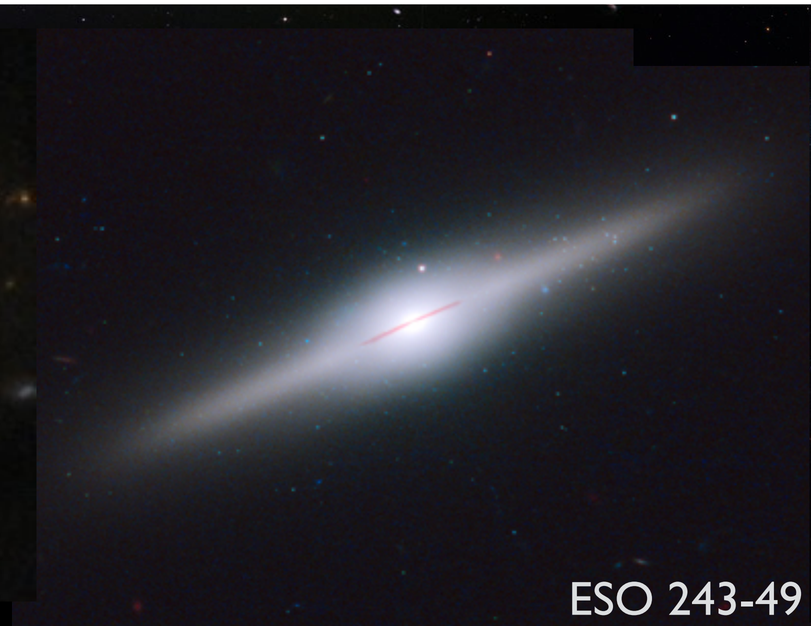
The Milky way and its environment, Paris, September 2016





images courtesy of http://hubblesite.org/gallery/

mergers, hierarchical formation - *classical bulge*



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mergers, hierarchical formation - *classical bulge*

M104/NGC4594

M81/NGC3013

disk instability

NGC5654

ESO 243-49

NGC1300

NGC4013

NGC4710

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Questions

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- What type of bulge does the Milky Way have?
- How and when was the bulge formed?
- How is the bulge related to the Milky Way populations of disk, halo

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Signatures

- Kinematics
- Morphology; density distribution of stars
- Stellar Populations - [Fe/H]

The Milky Way: barred galaxy with boxy/peanut, X-shaped bulge

- Bar-like nature (Okuda et al., 1977), Boxy bulge seen in COBE image (1994)

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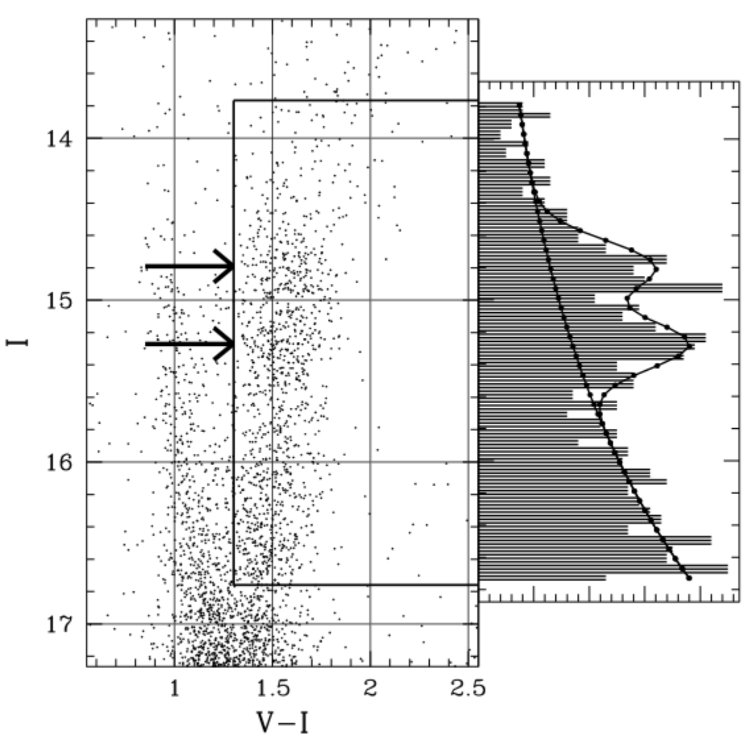

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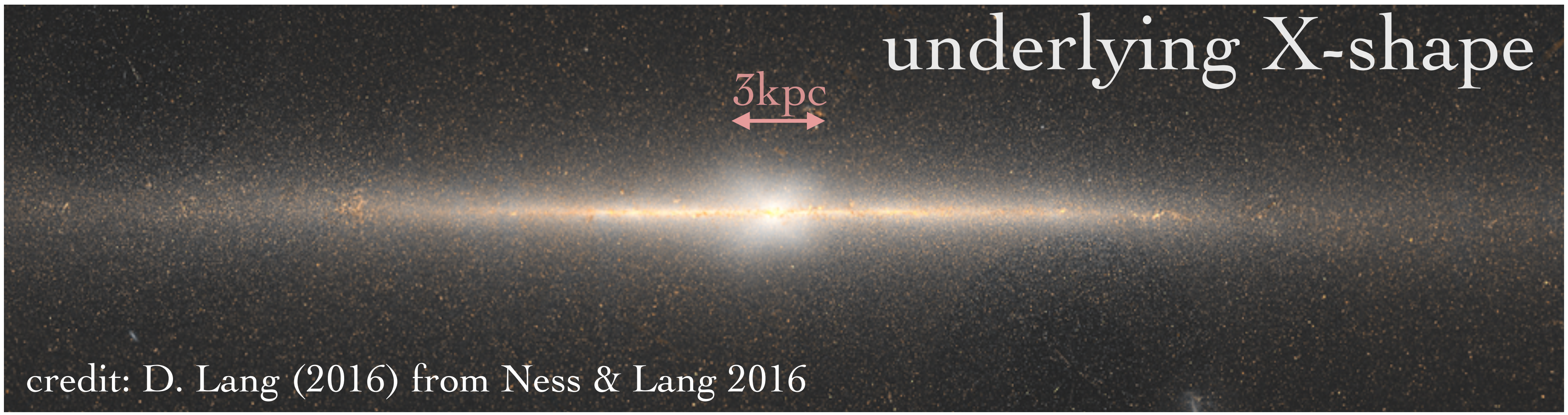

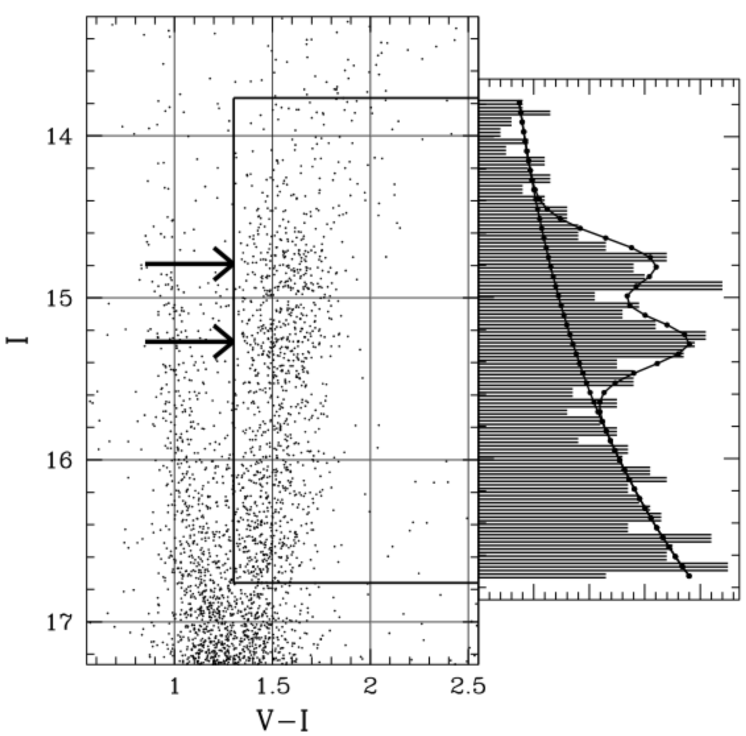

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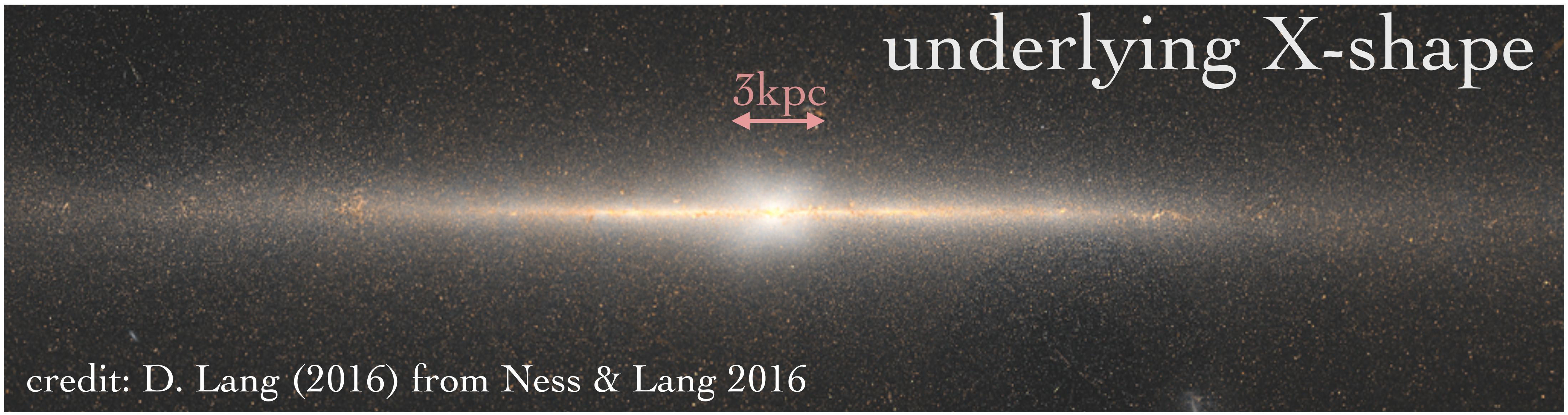

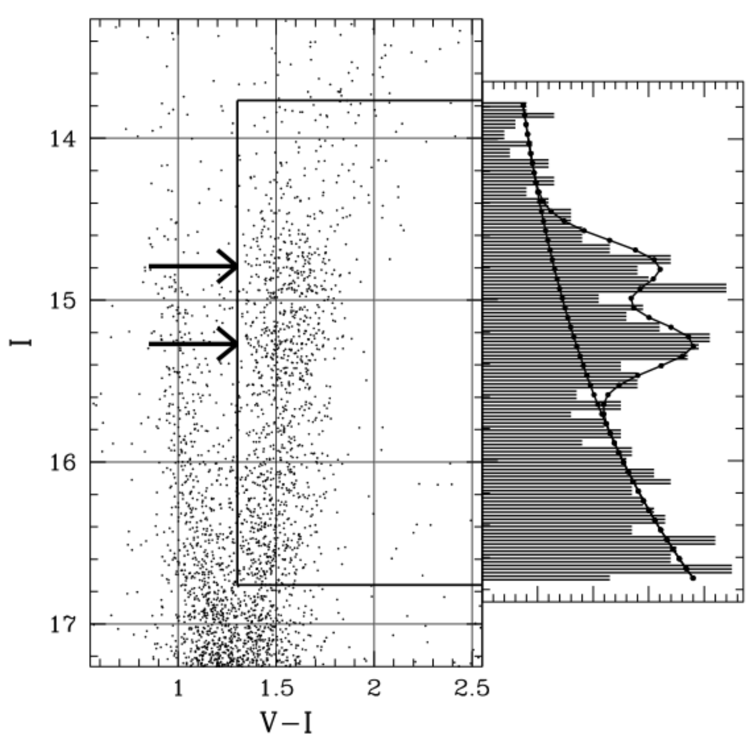

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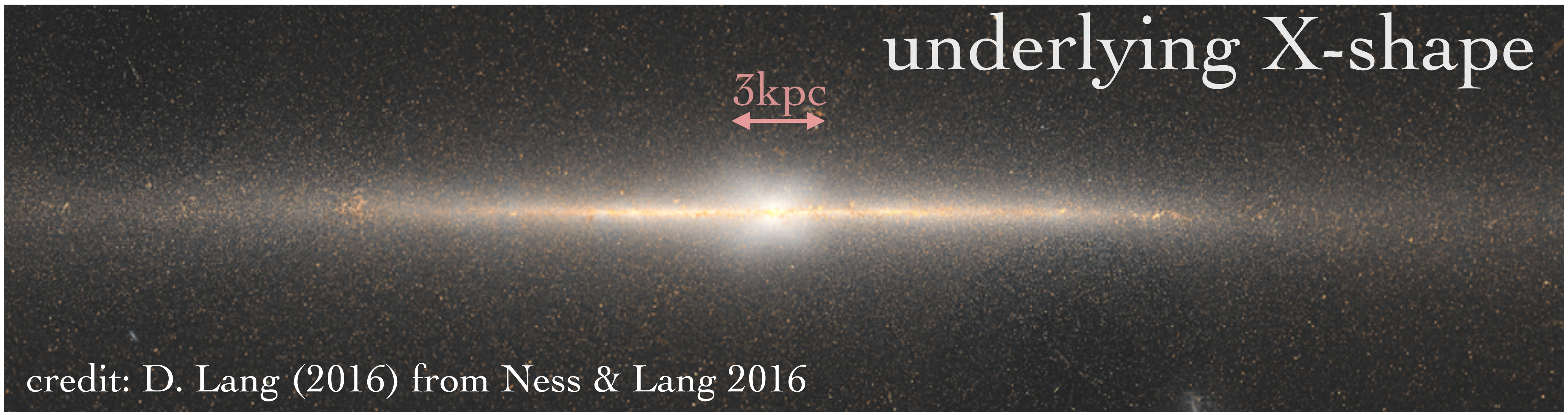

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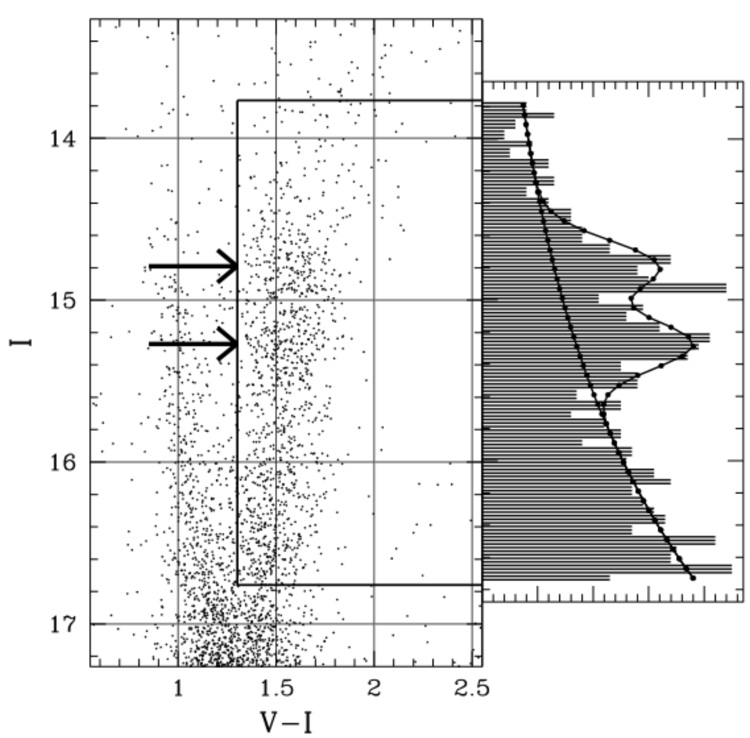

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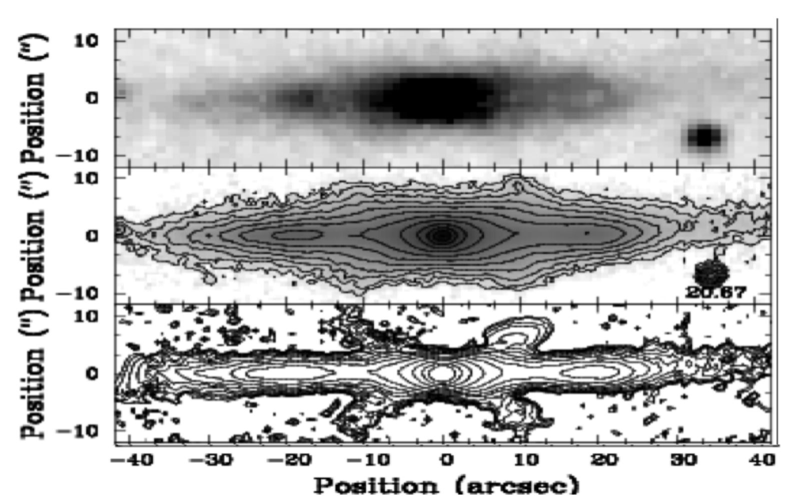
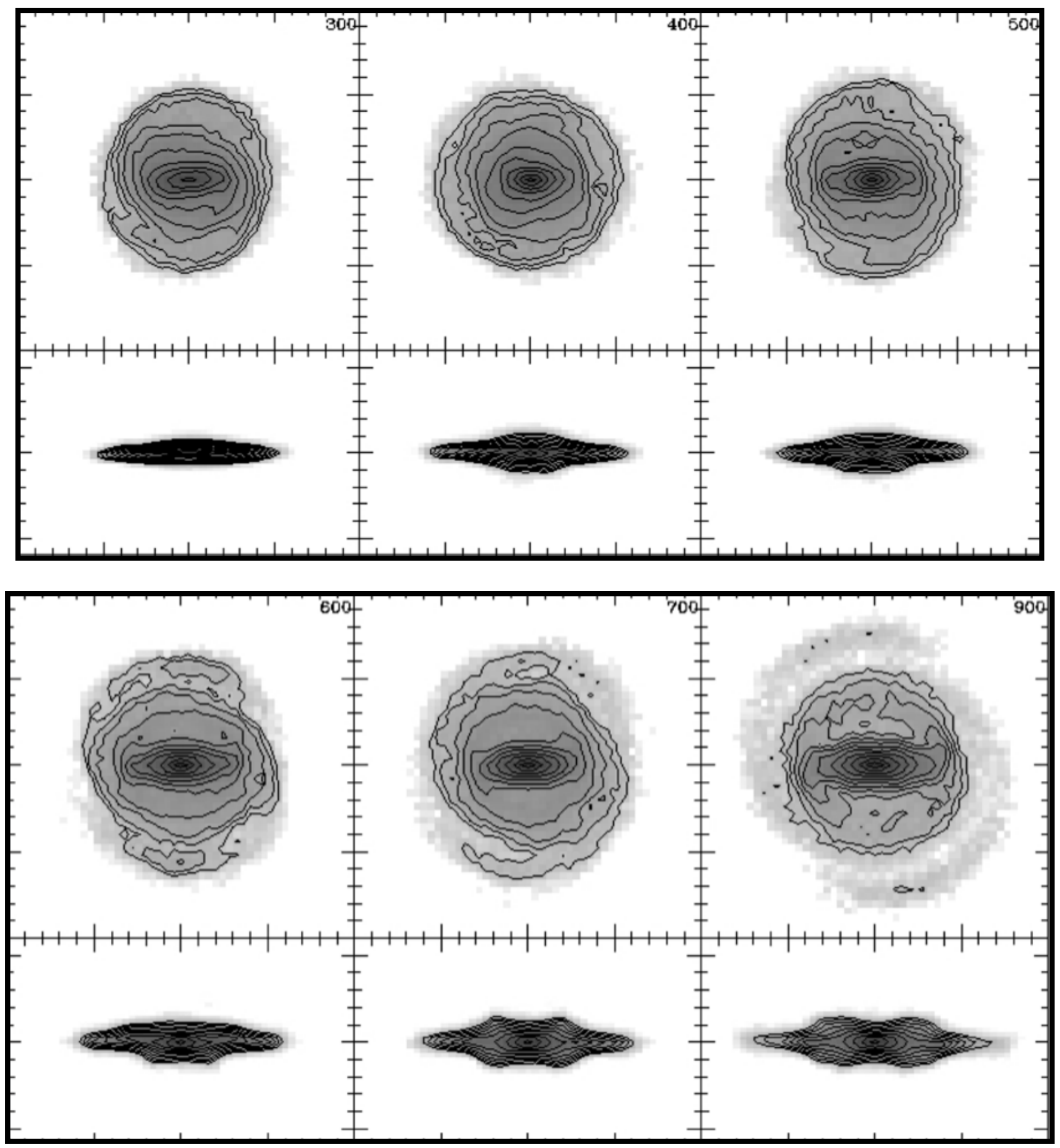


Bureau 2006

- Not atypical

Morphology: signature of formation from the disk

- N-body simulations of disks - form a bar early on ~ 1 Gyr
- bar thickens; buckles & forms a boxy bulge



from Athanassoula (see upcoming talk)

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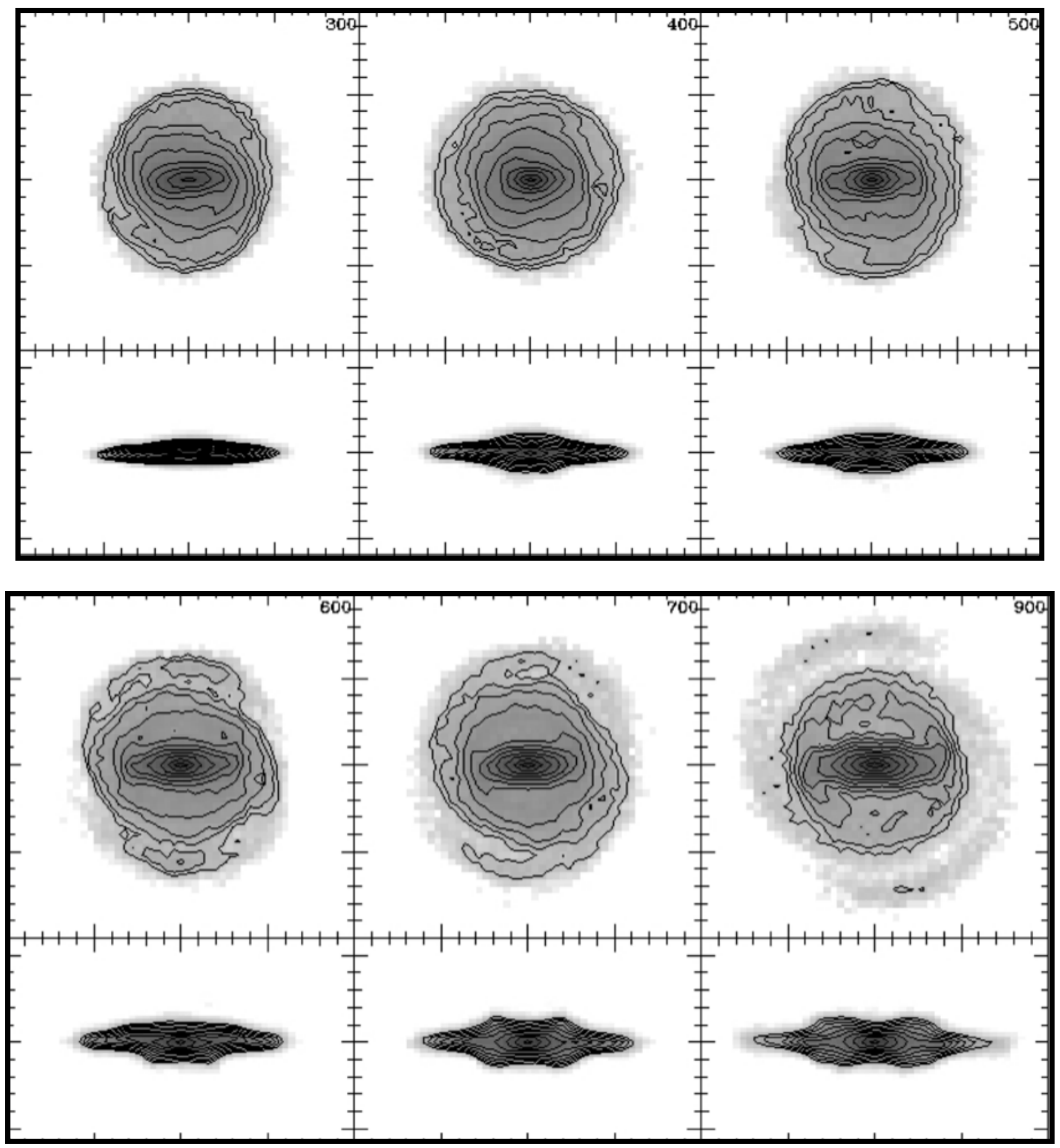

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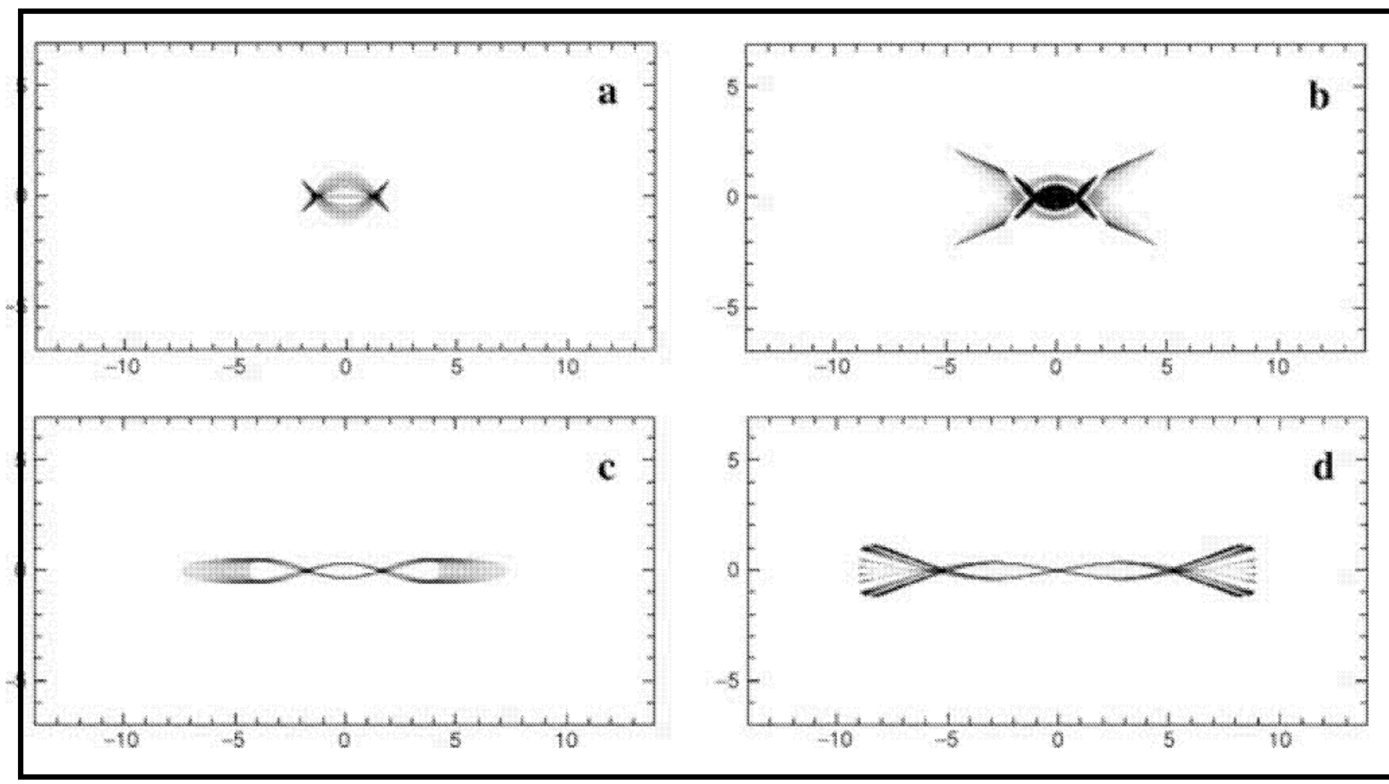

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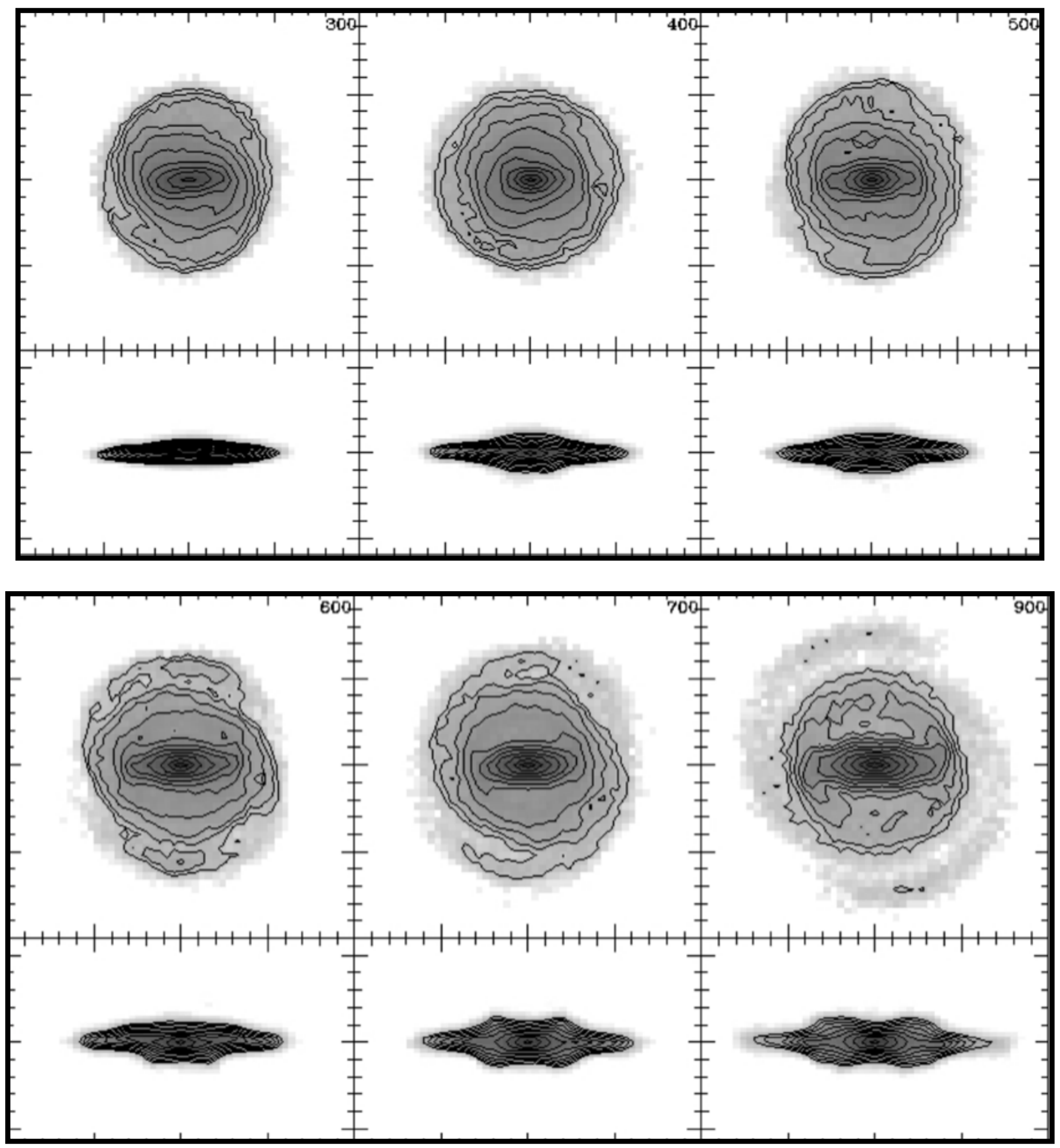

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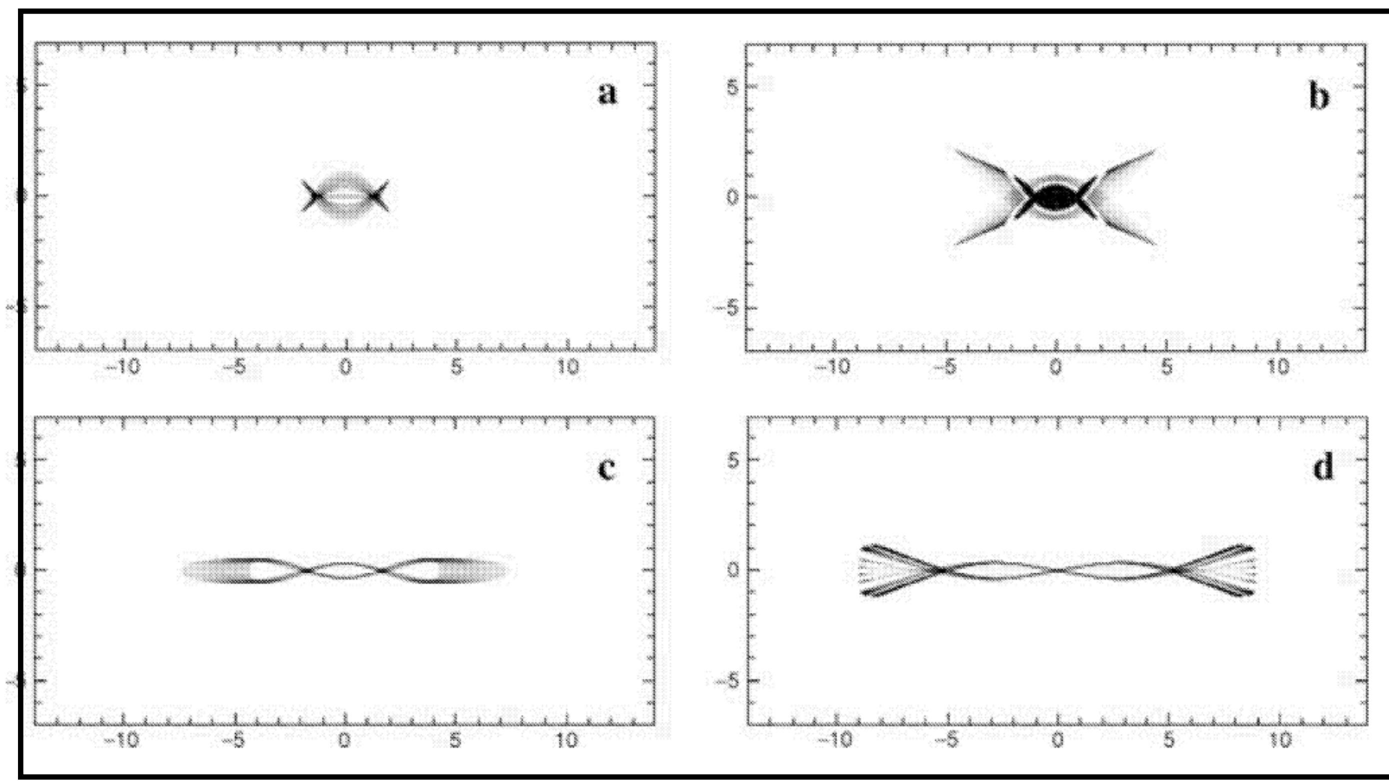
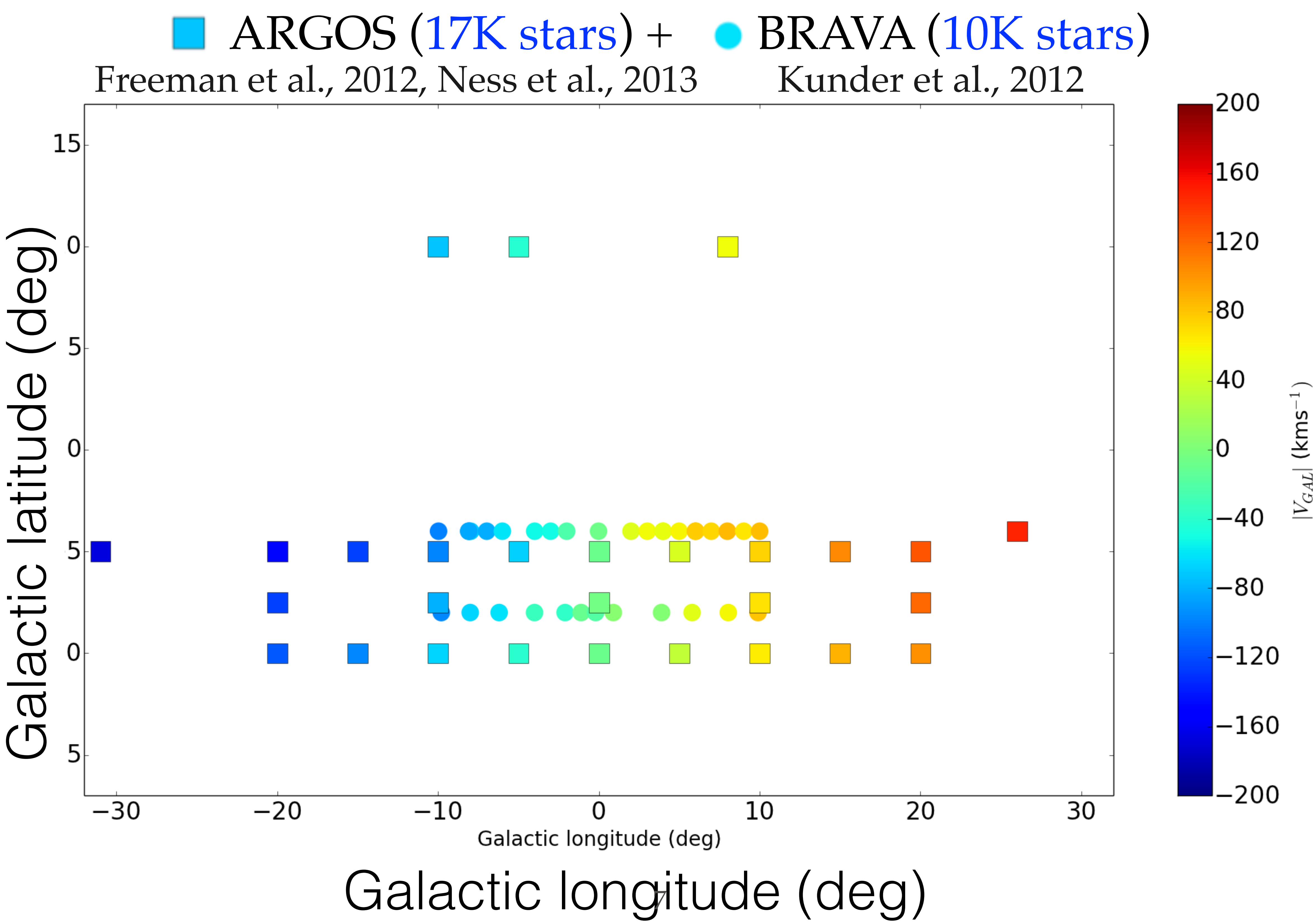


Boxy Bulges have a distinct kinematic profile



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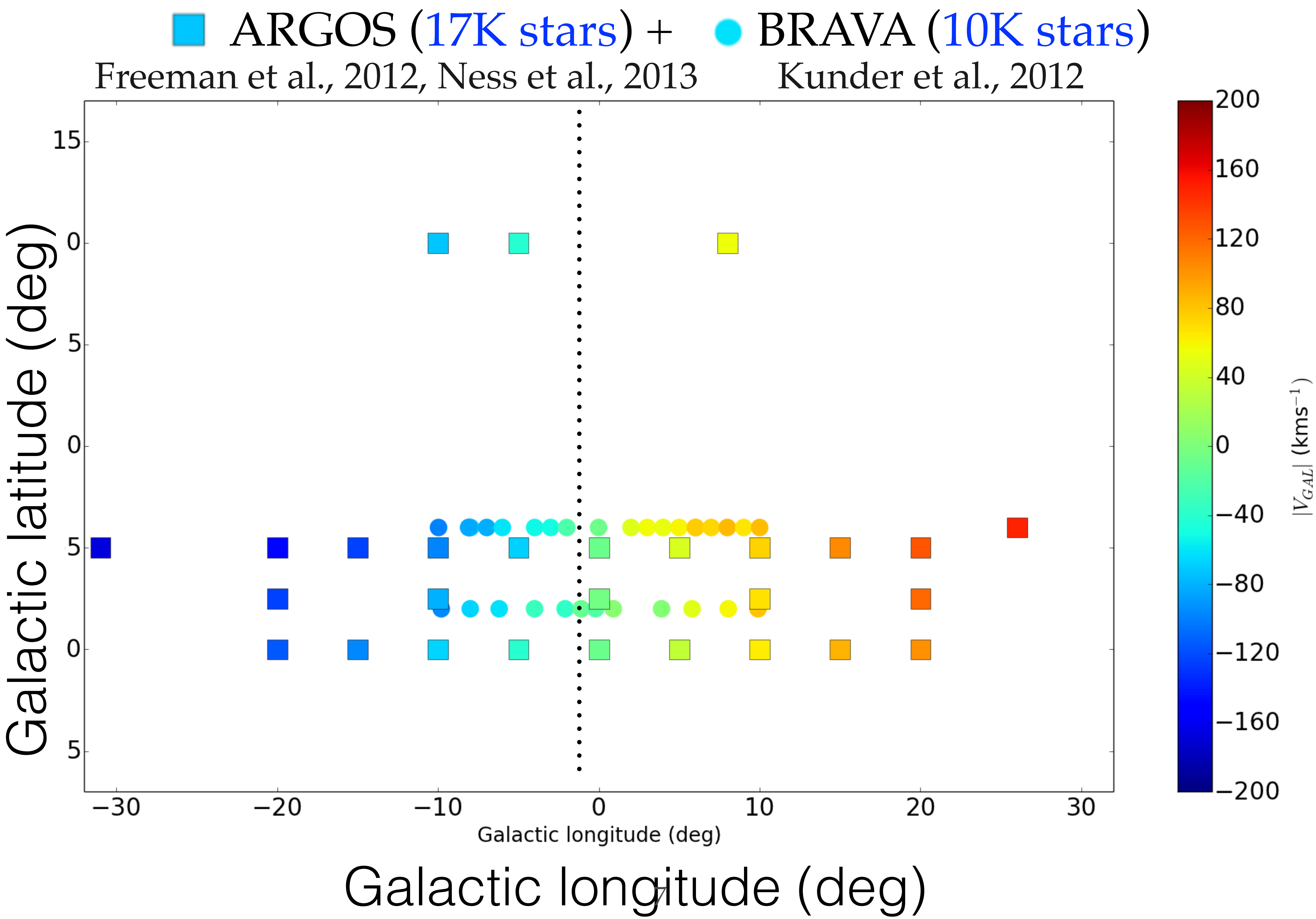

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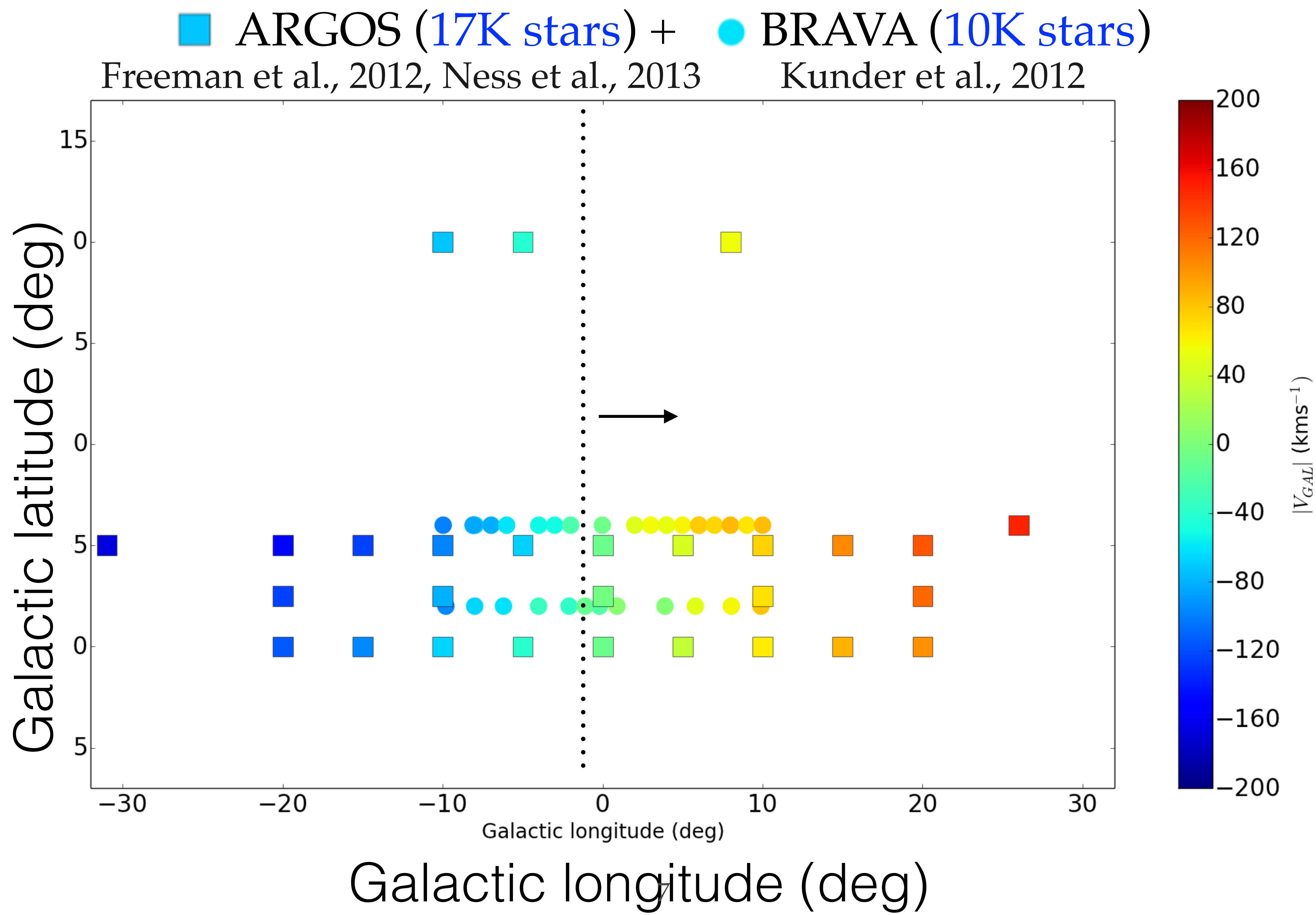
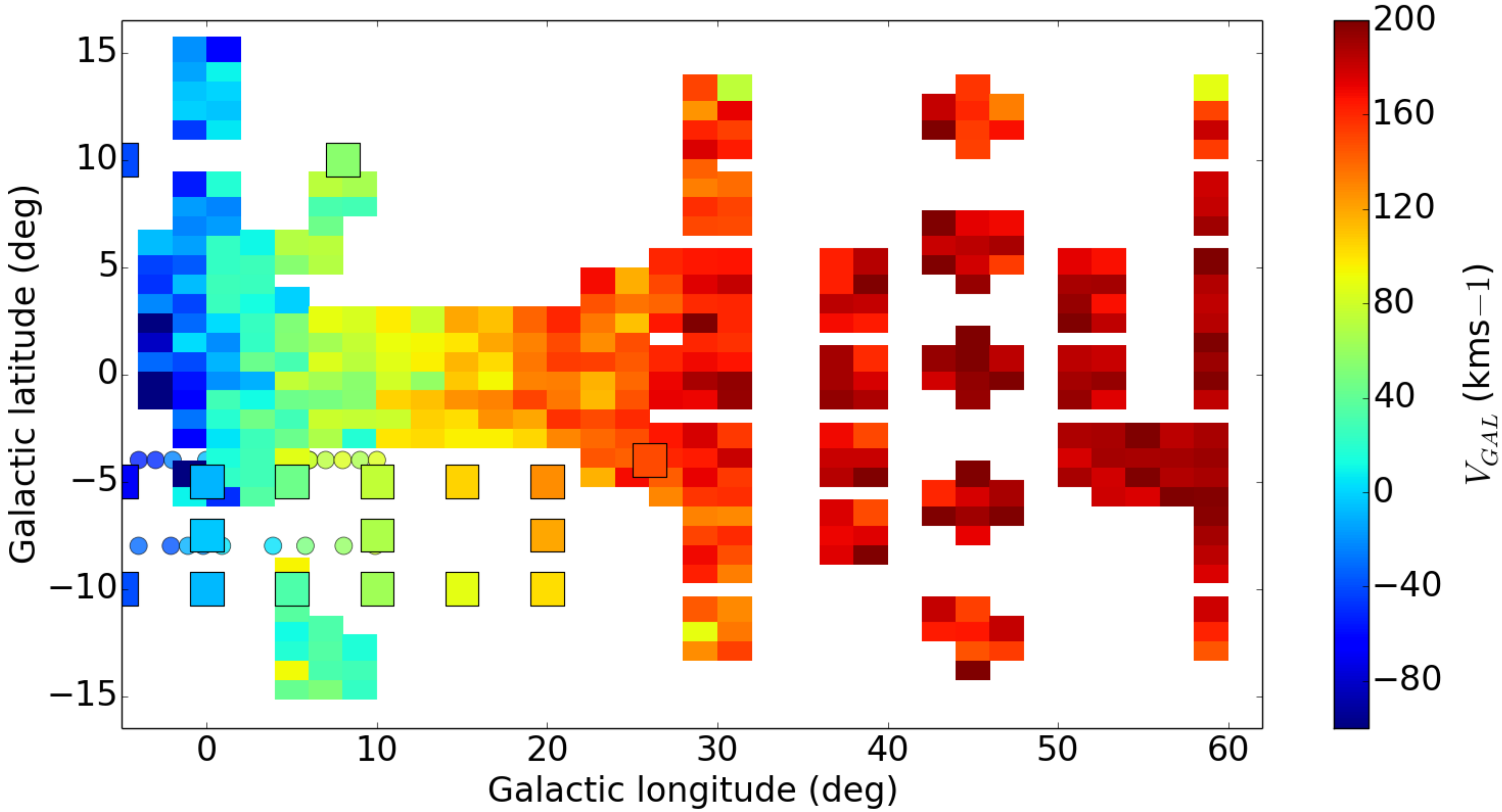


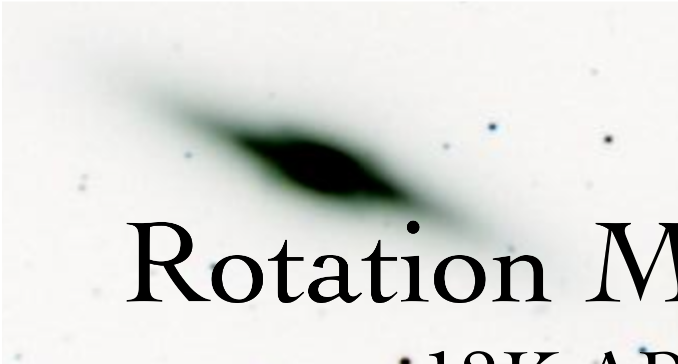
Rotation Map of the MW

12K APOGEE stars
+10K ARGOS stars
+6K BRAVA

4kpc < d < 12 kpc



Ness et al., 2016



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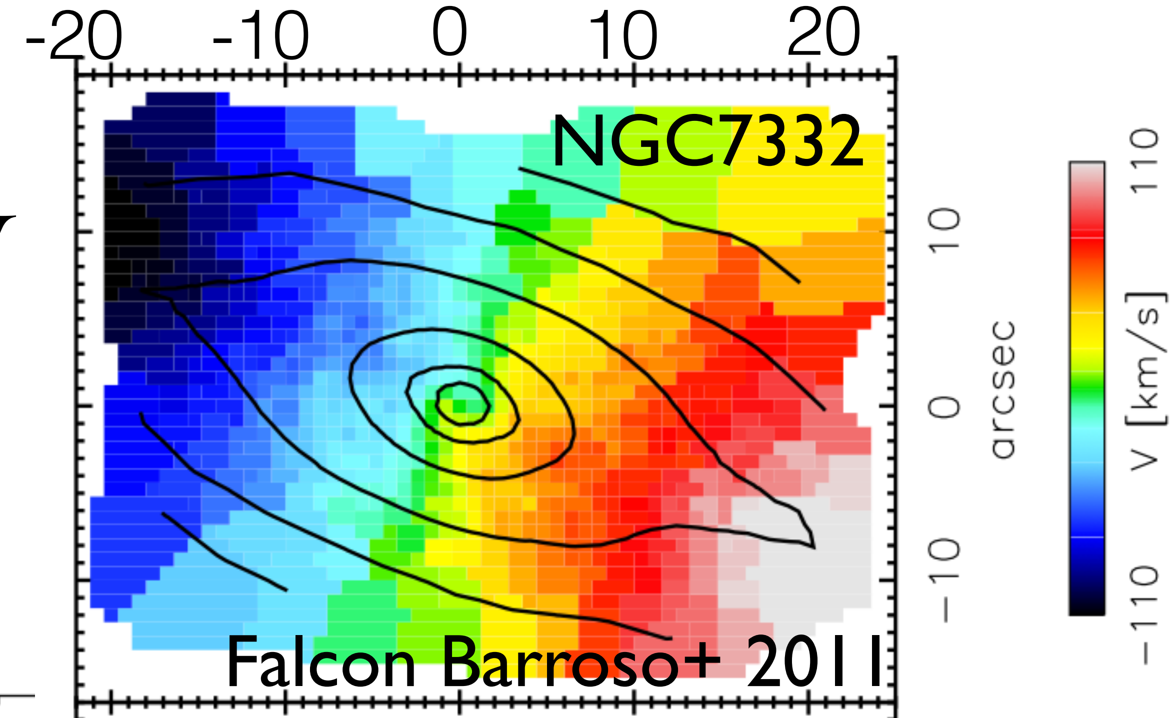
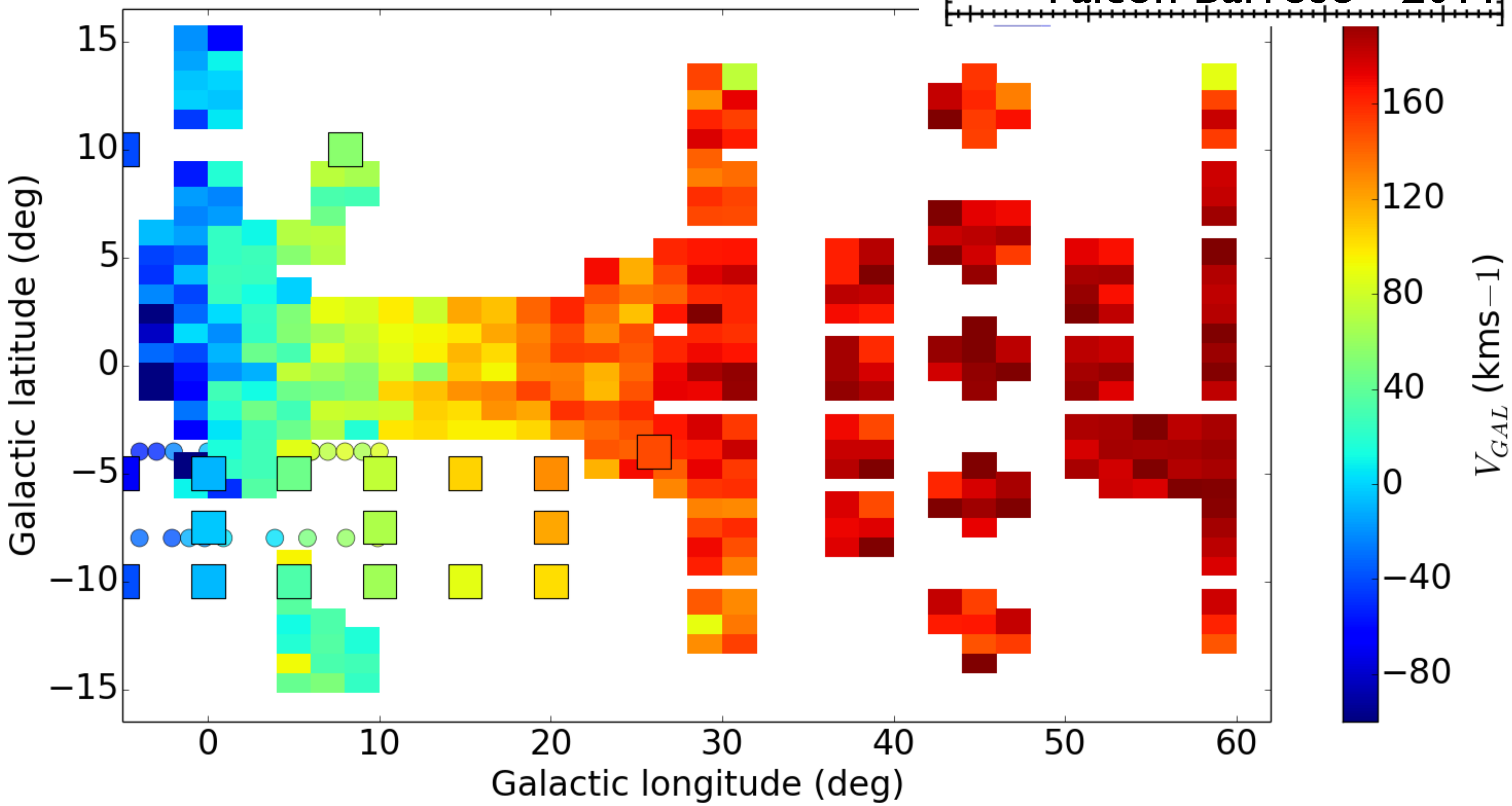
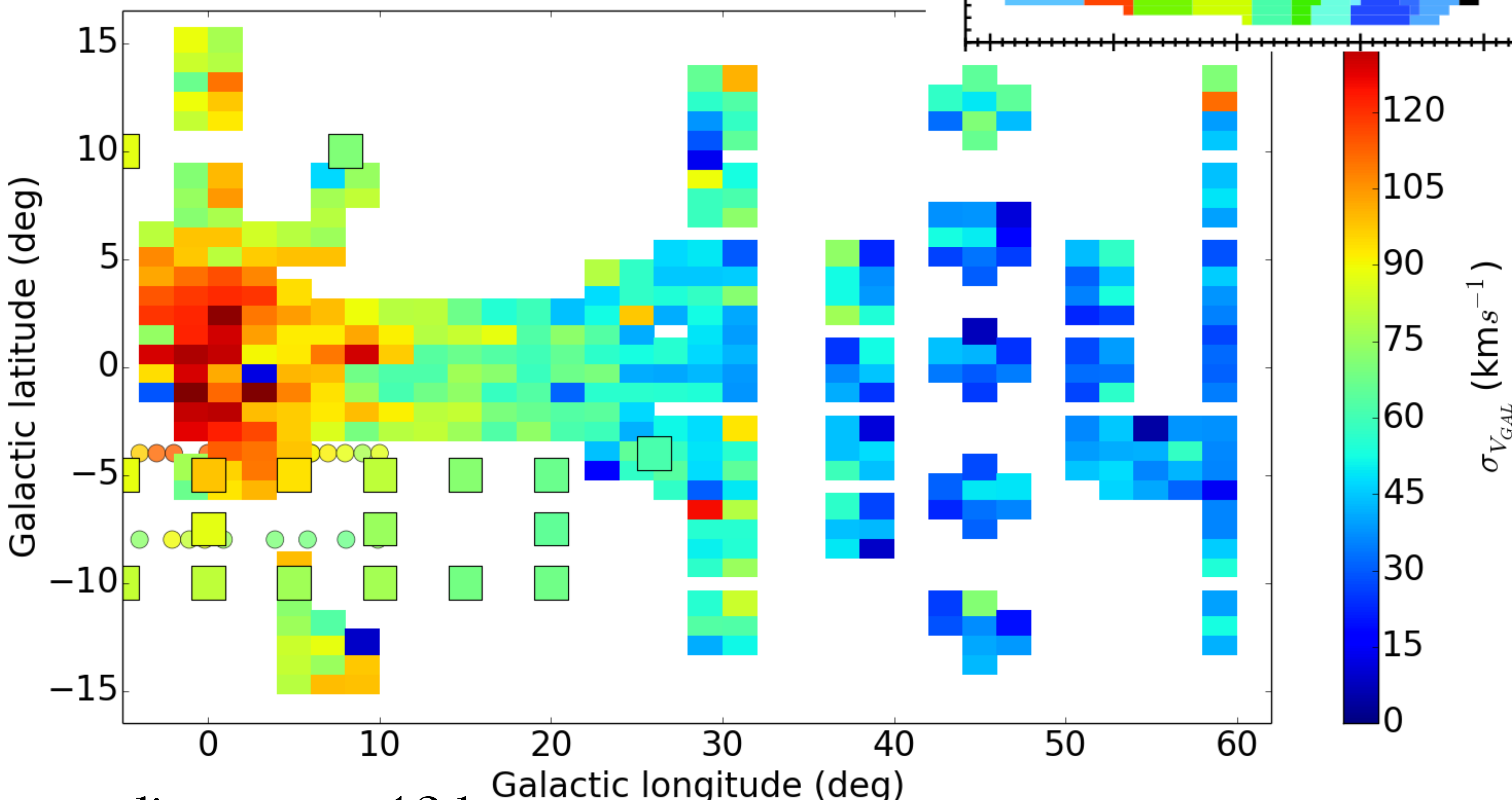
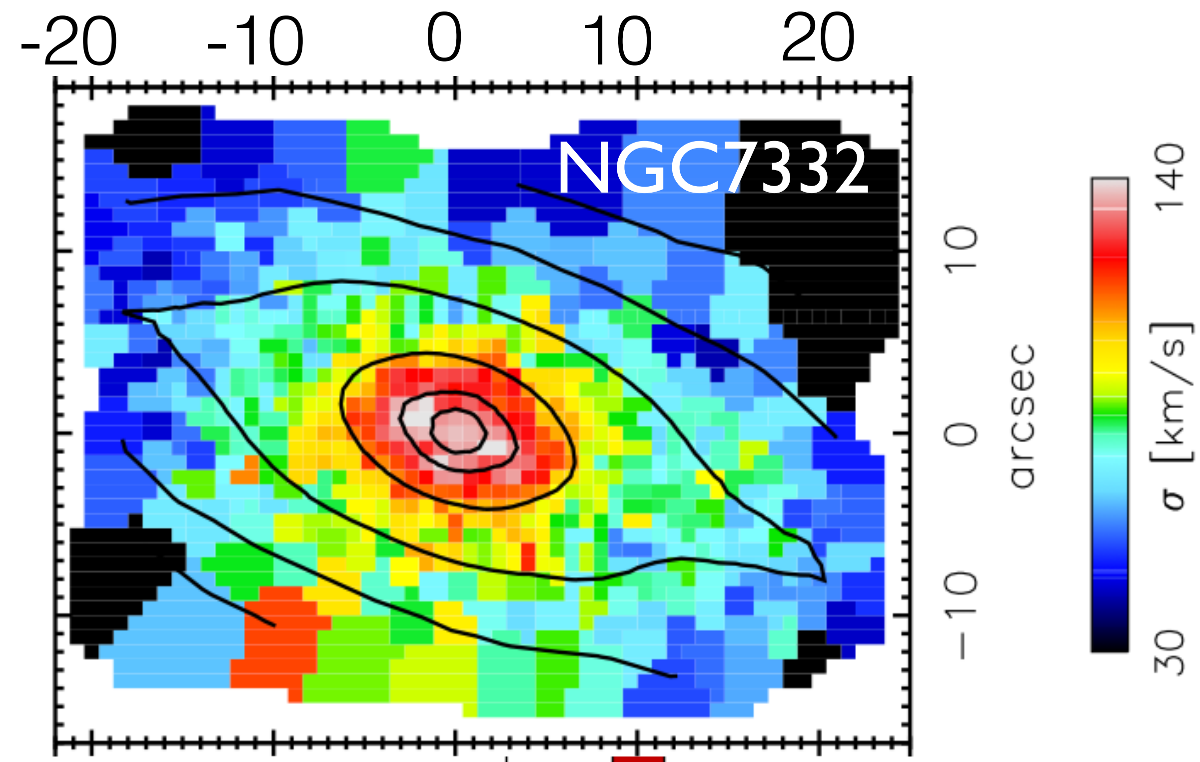




Ness et al., 2016

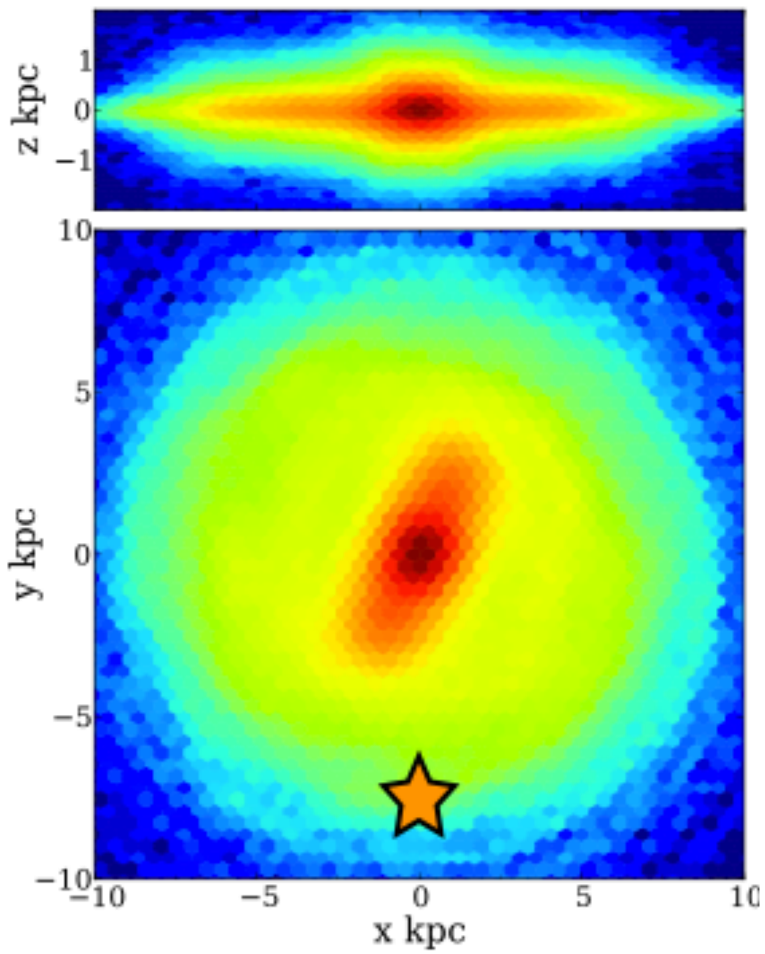
Dispersion Map of the MW





4kpc < distances < 12 kpc

Comparison to N-body models Rotation



model of
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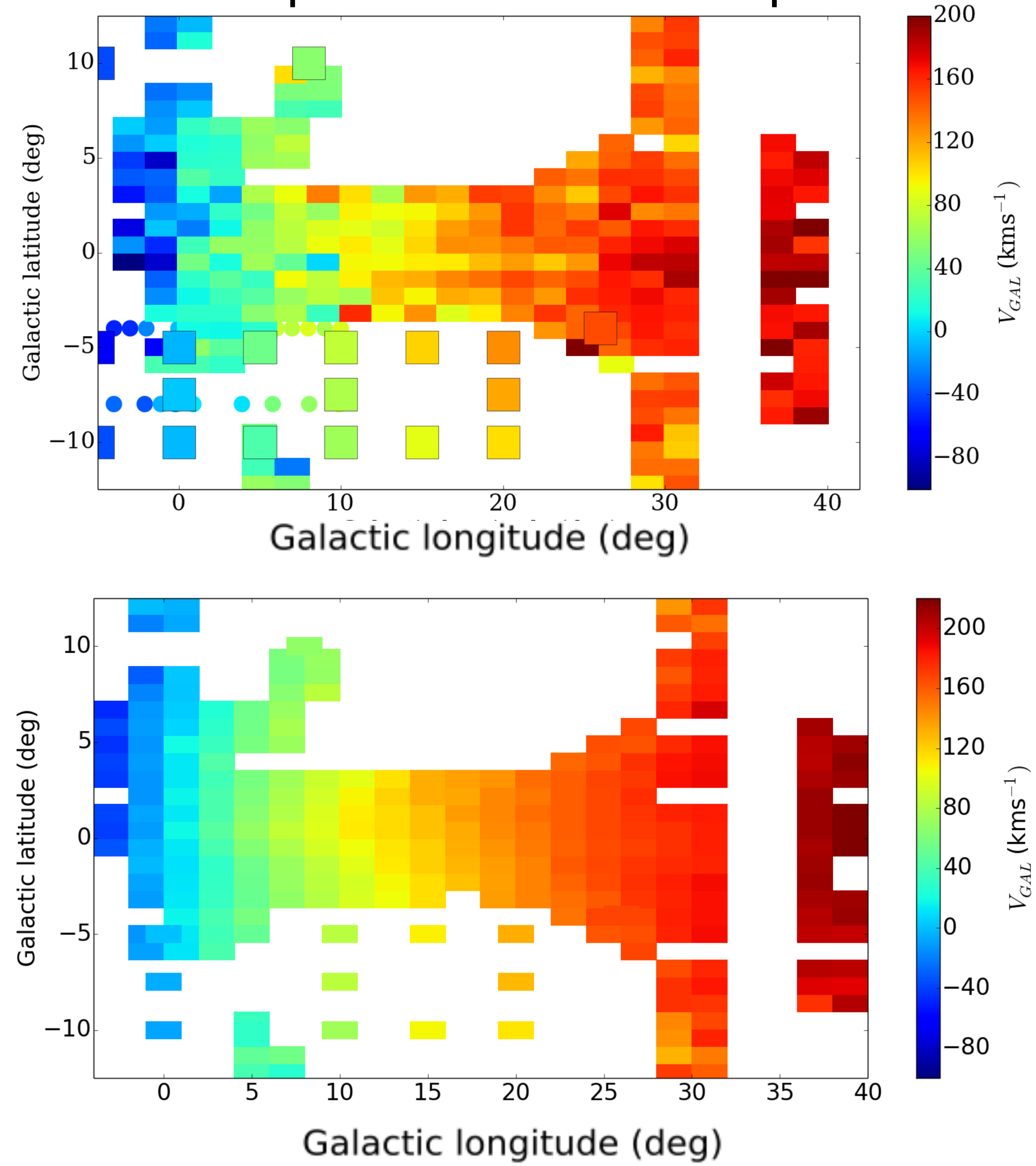

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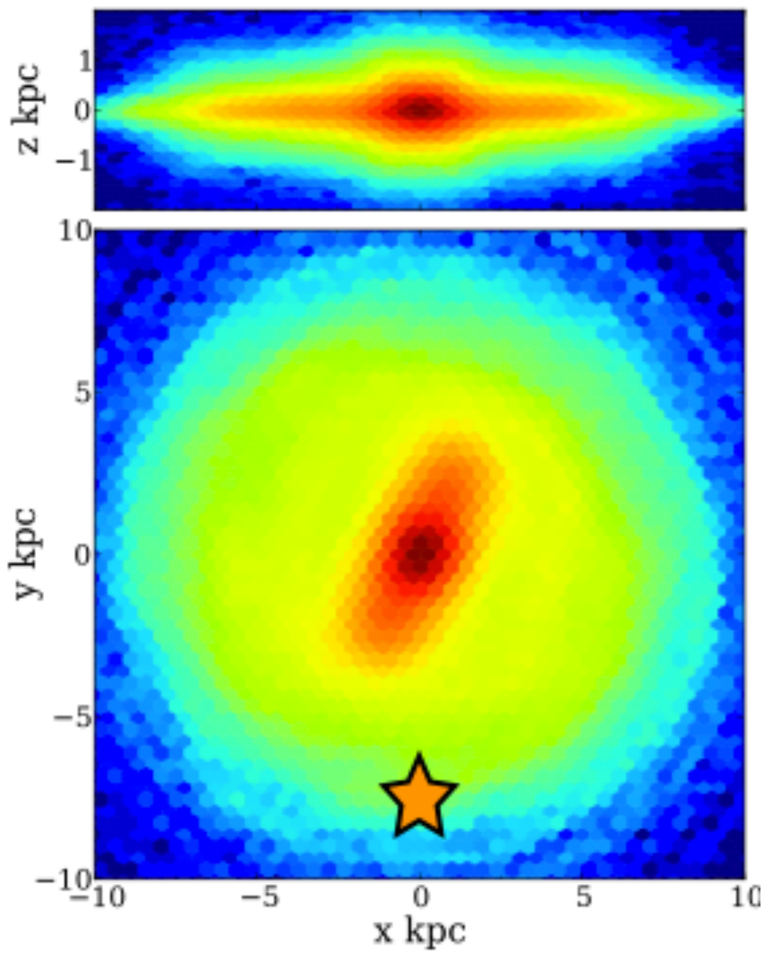

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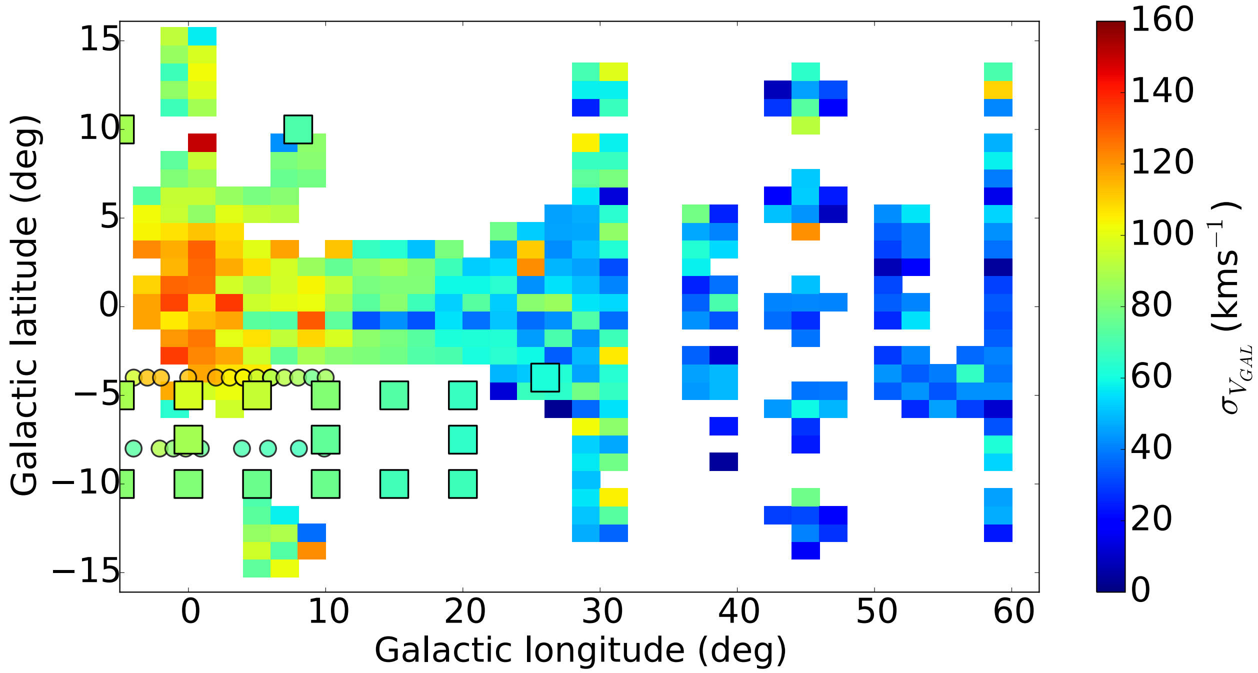

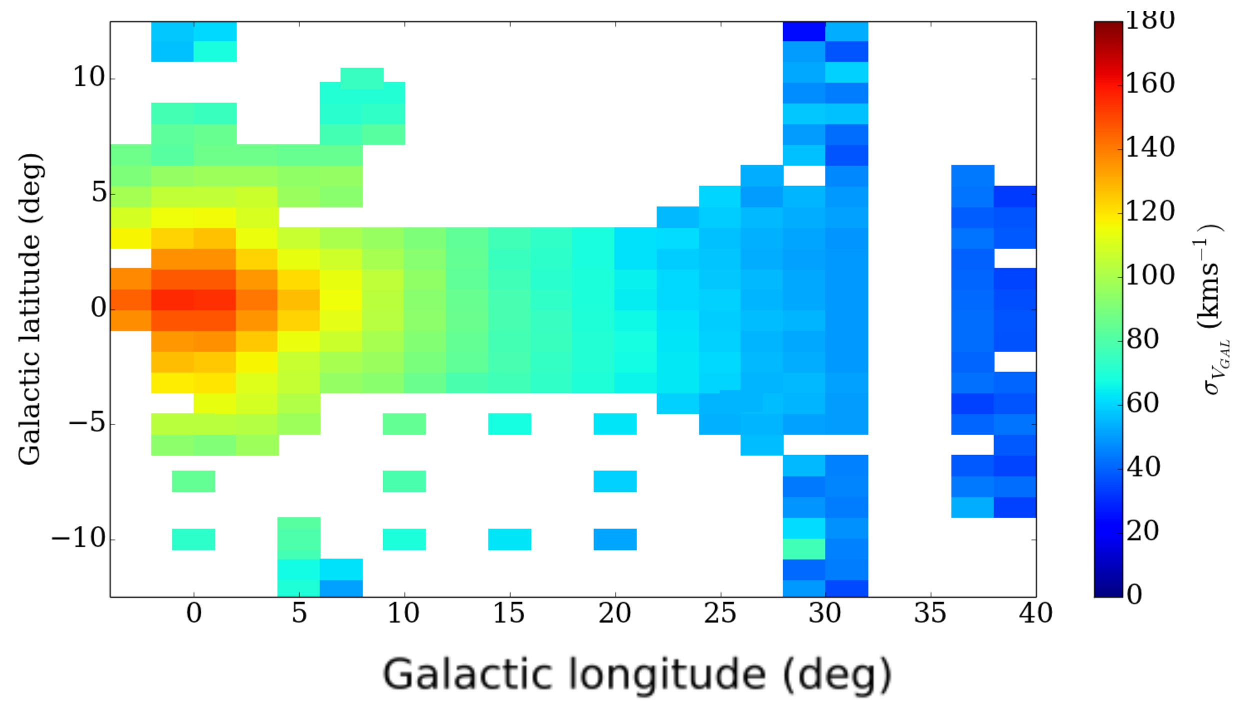

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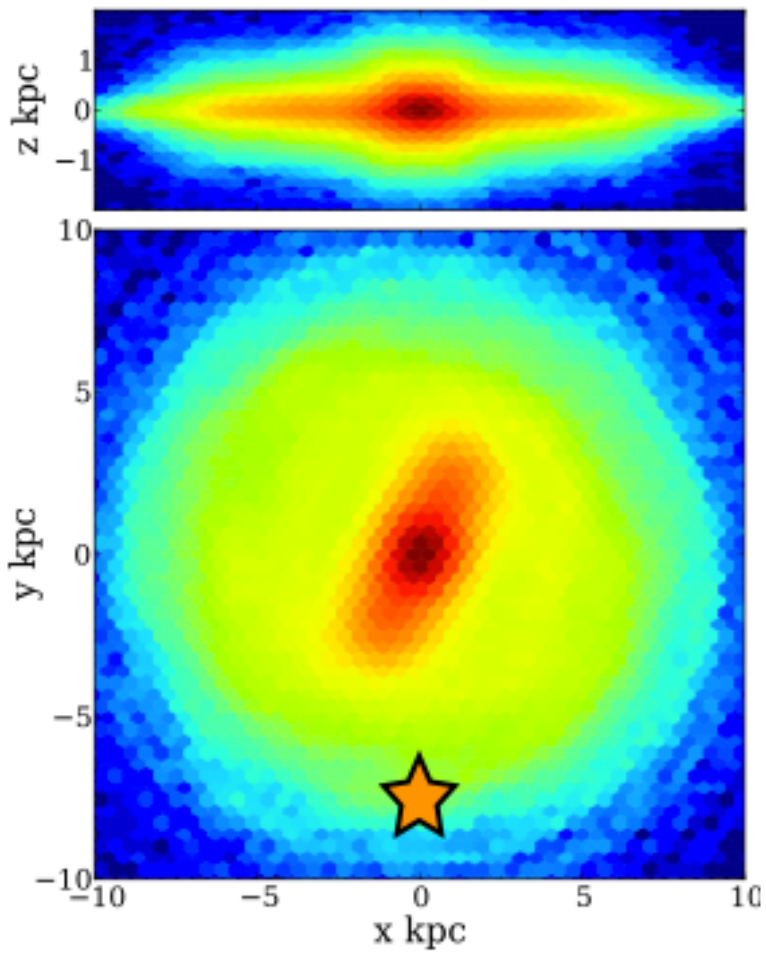

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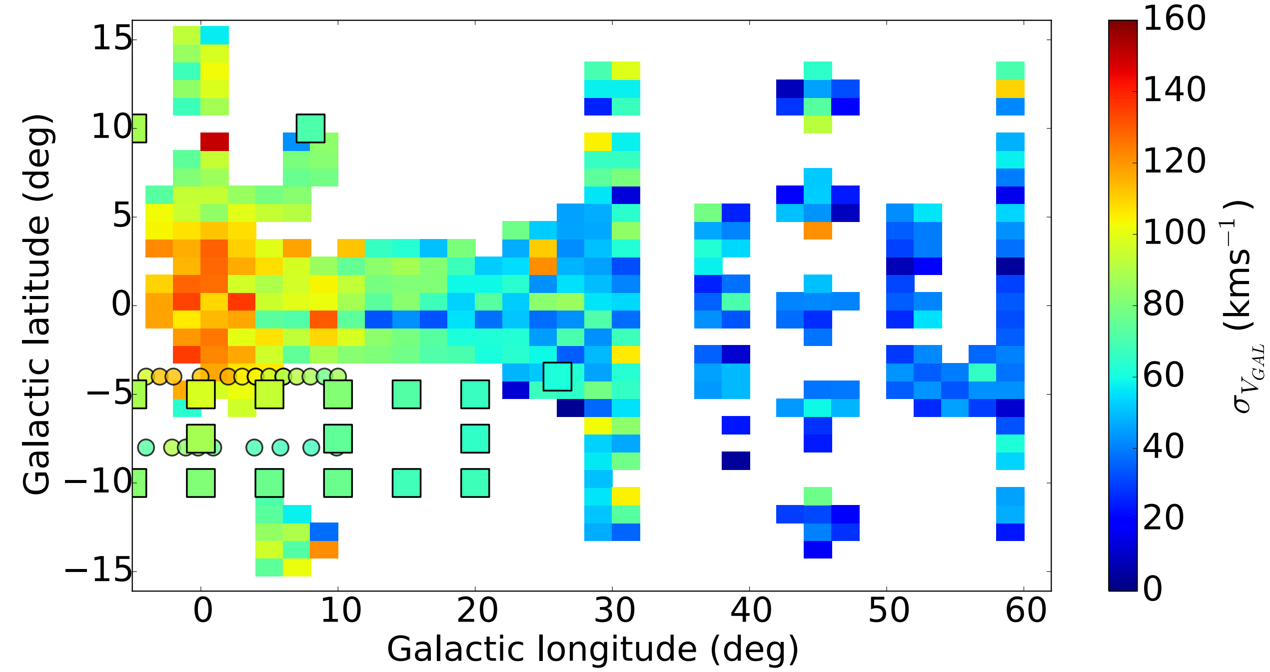

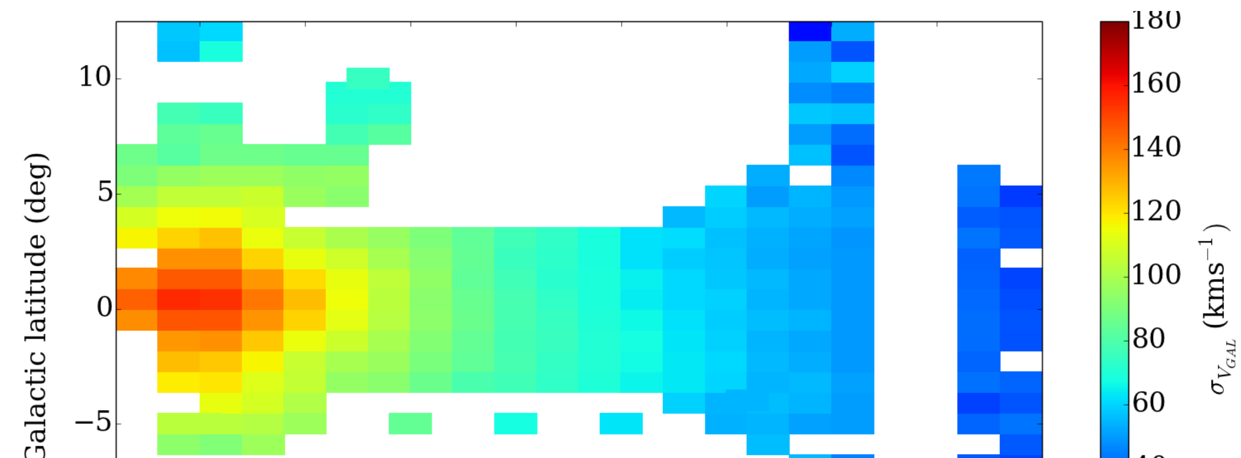

remarkable agreement with N-body models and also kinematic maps of other barred galaxies

Kinematics of all stars constrain properties of the MW

- Shen et al., 2010 -> With BRAVA data: constrained any classical bulge contribution to be < 8% of disk mass

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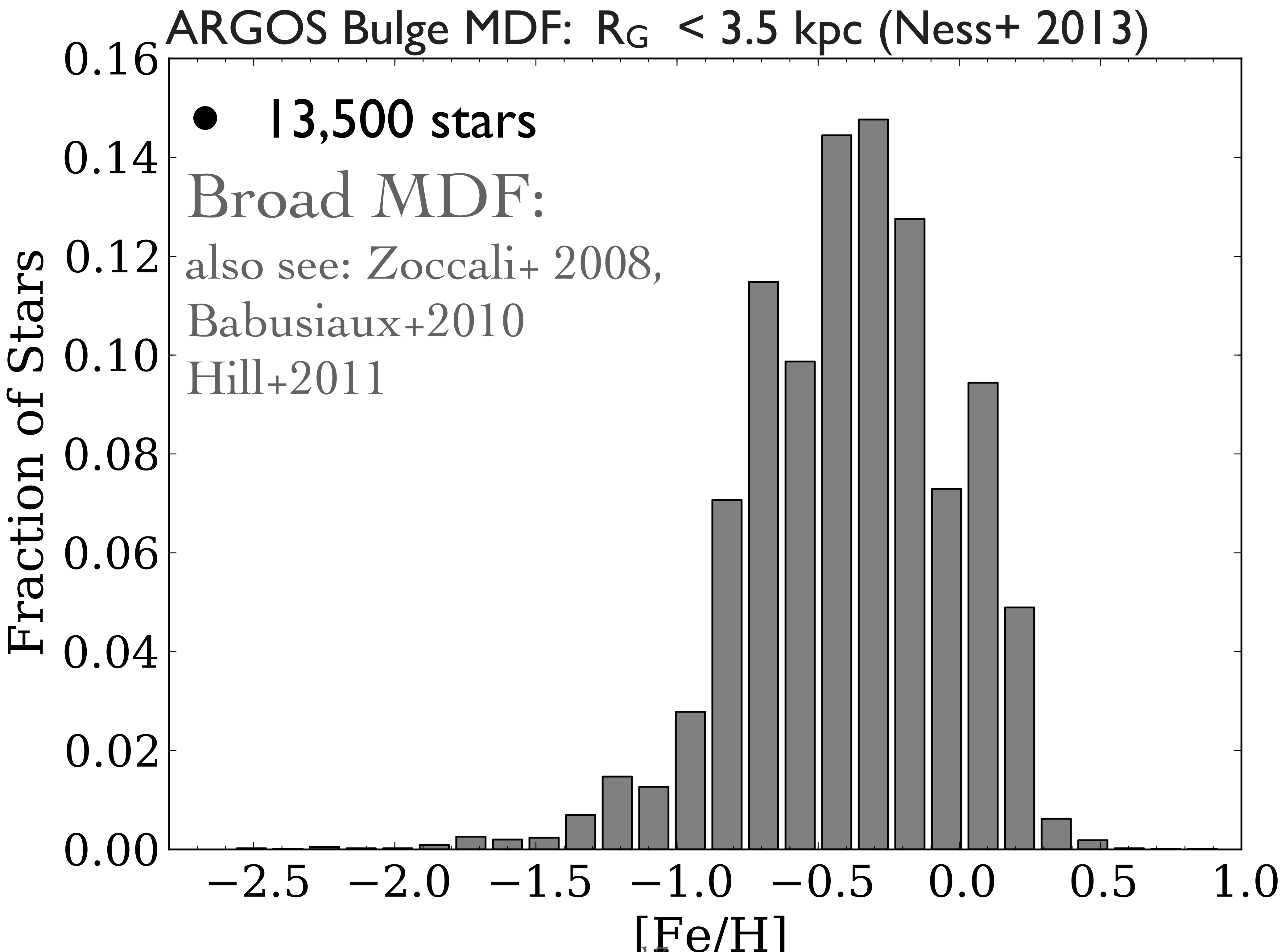
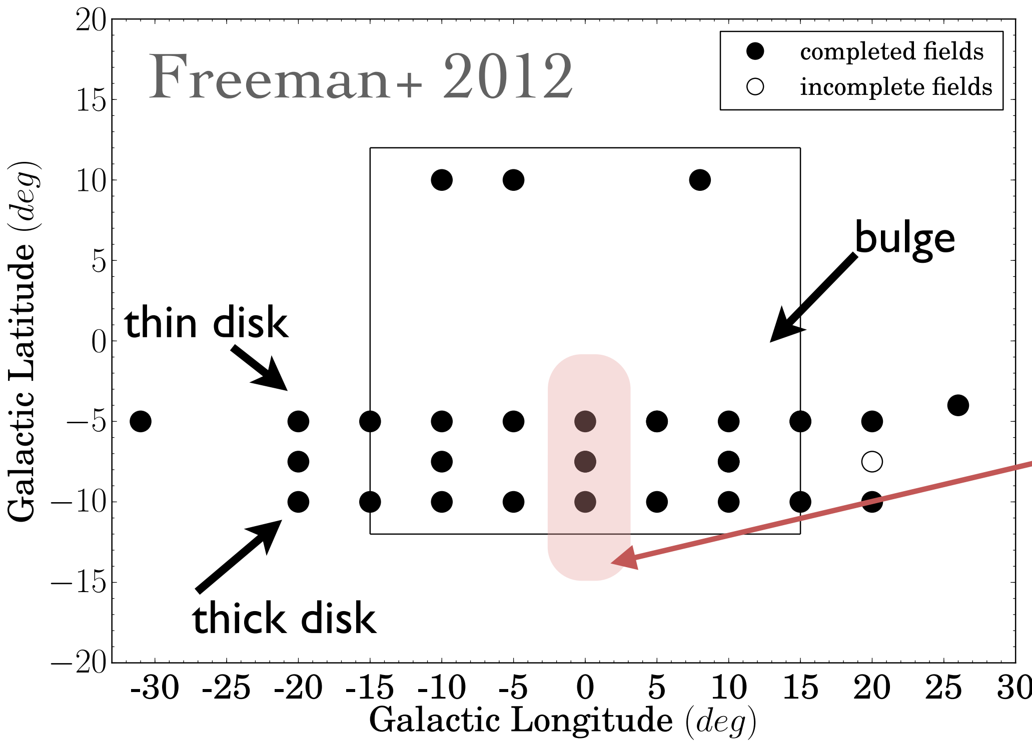
But what about more detailed properties?
What is break up properties of the bulge by [Fe/H]?

Metallicity distribution in the bulge



Morphology is metallicity dependent



ARGOS Survey: 28,000 star survey of bulge R~ 10,000

K-magnitude distribution of red clump stars ƒ[Fe/H]

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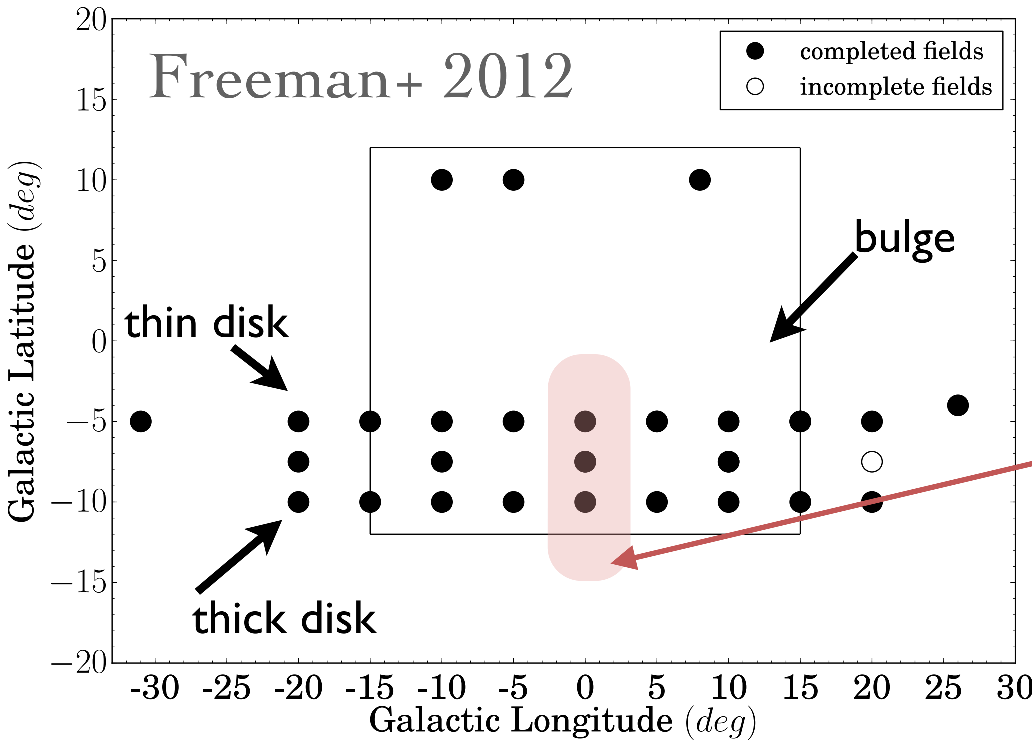

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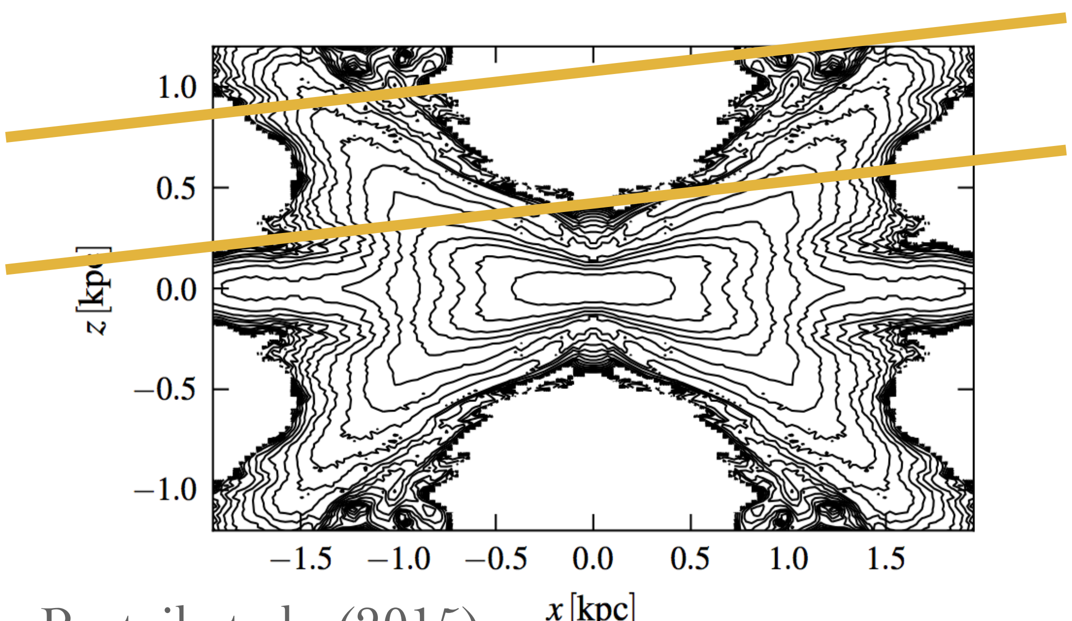

Portail et al., (2015)

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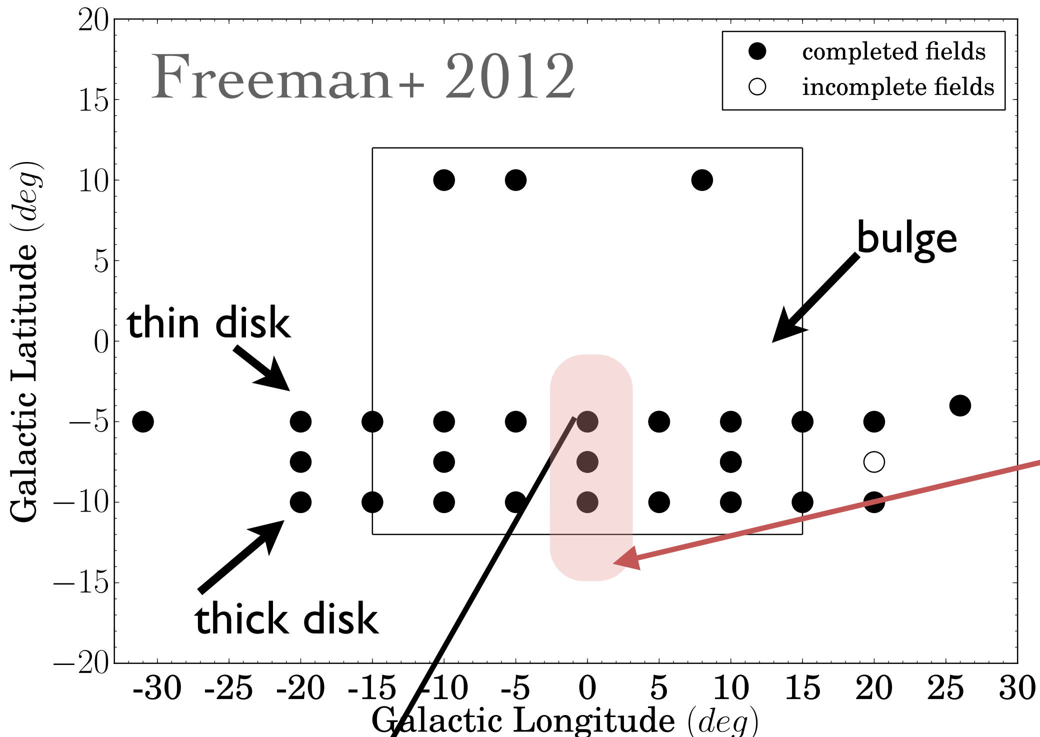

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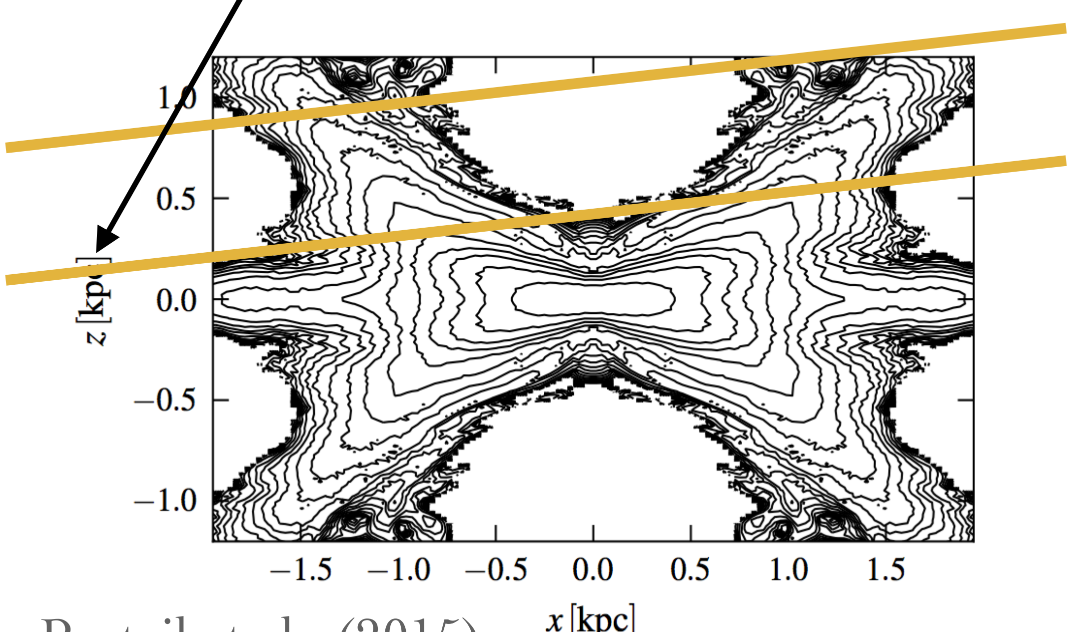

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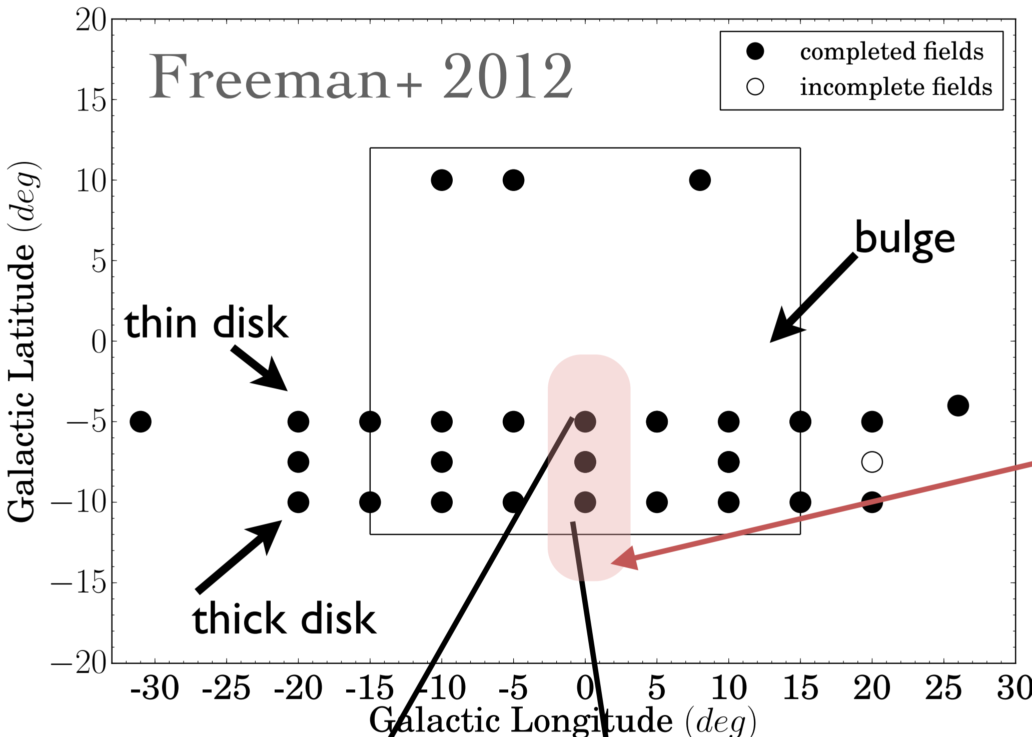

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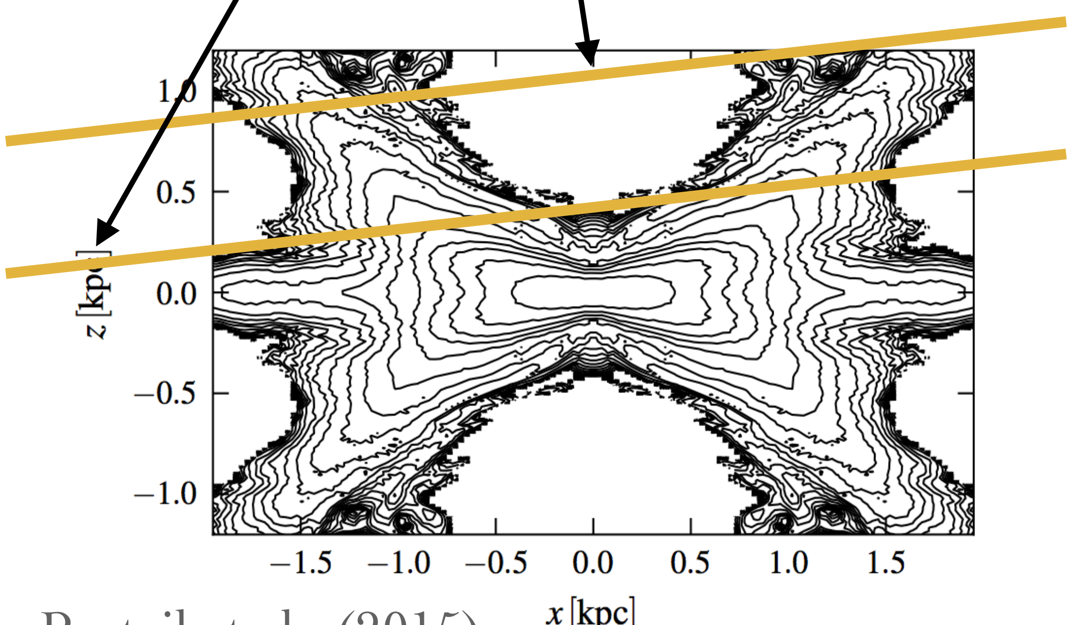

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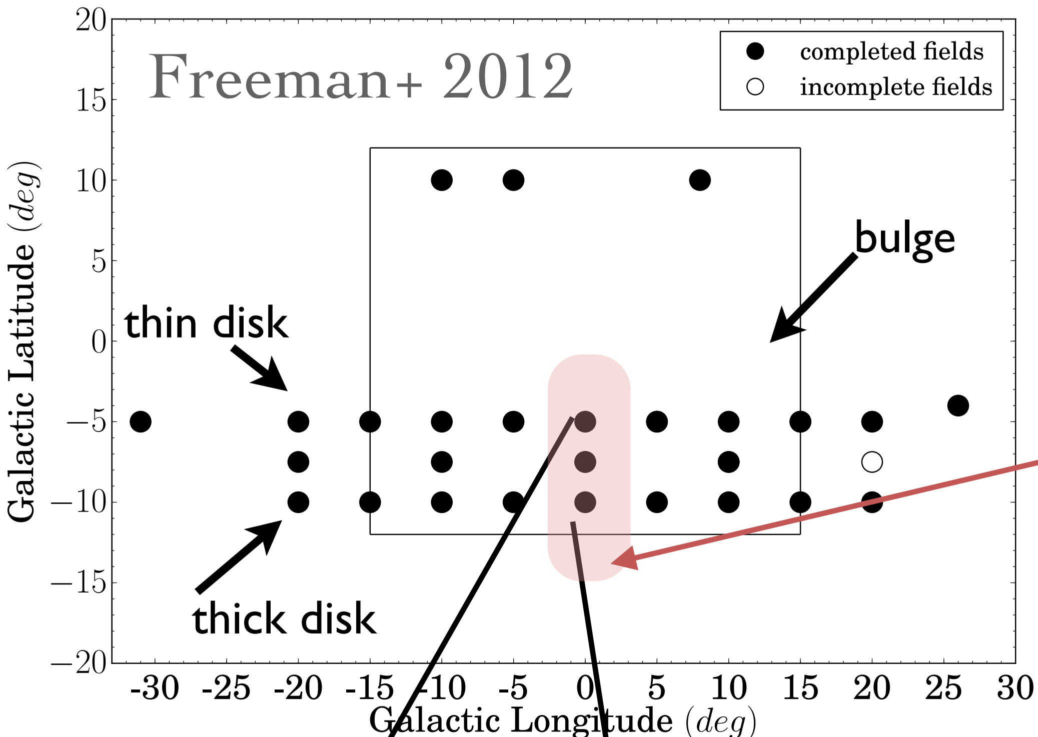

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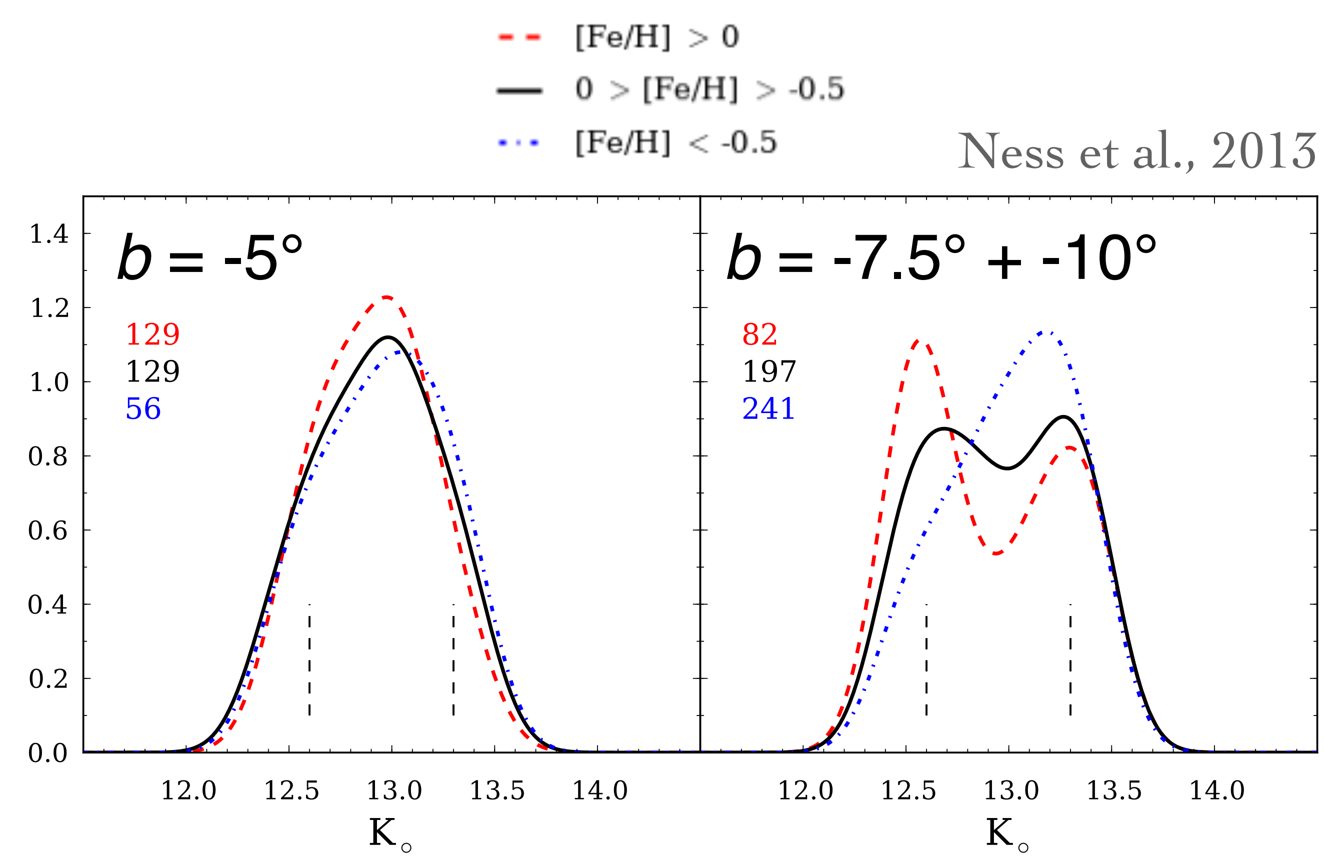
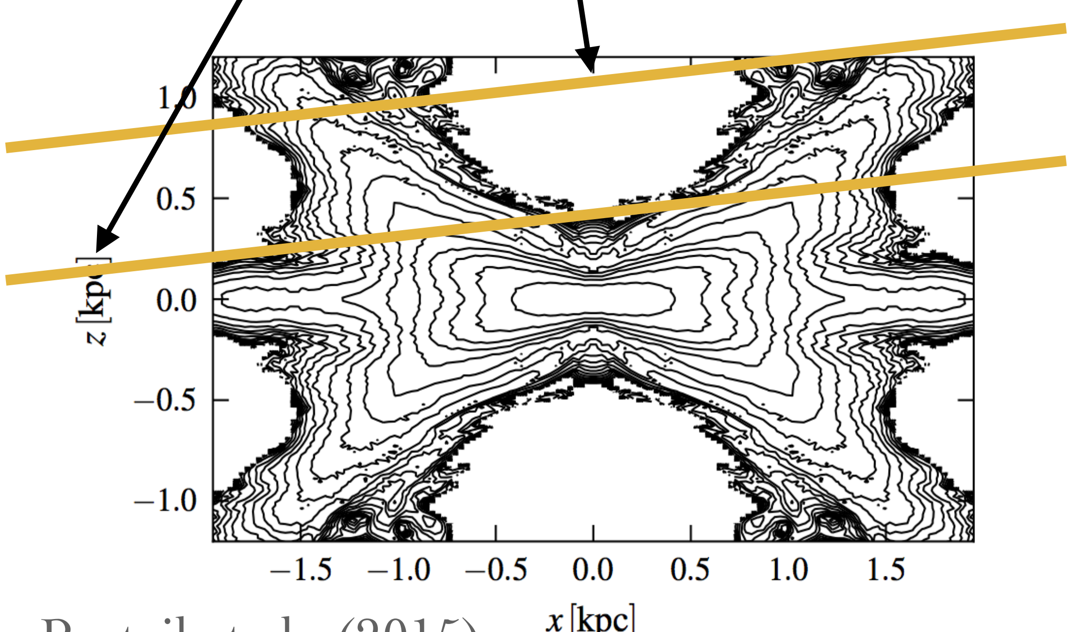


Ness et al., 2013

Bimodality for stars [Fe/H] > -0.5



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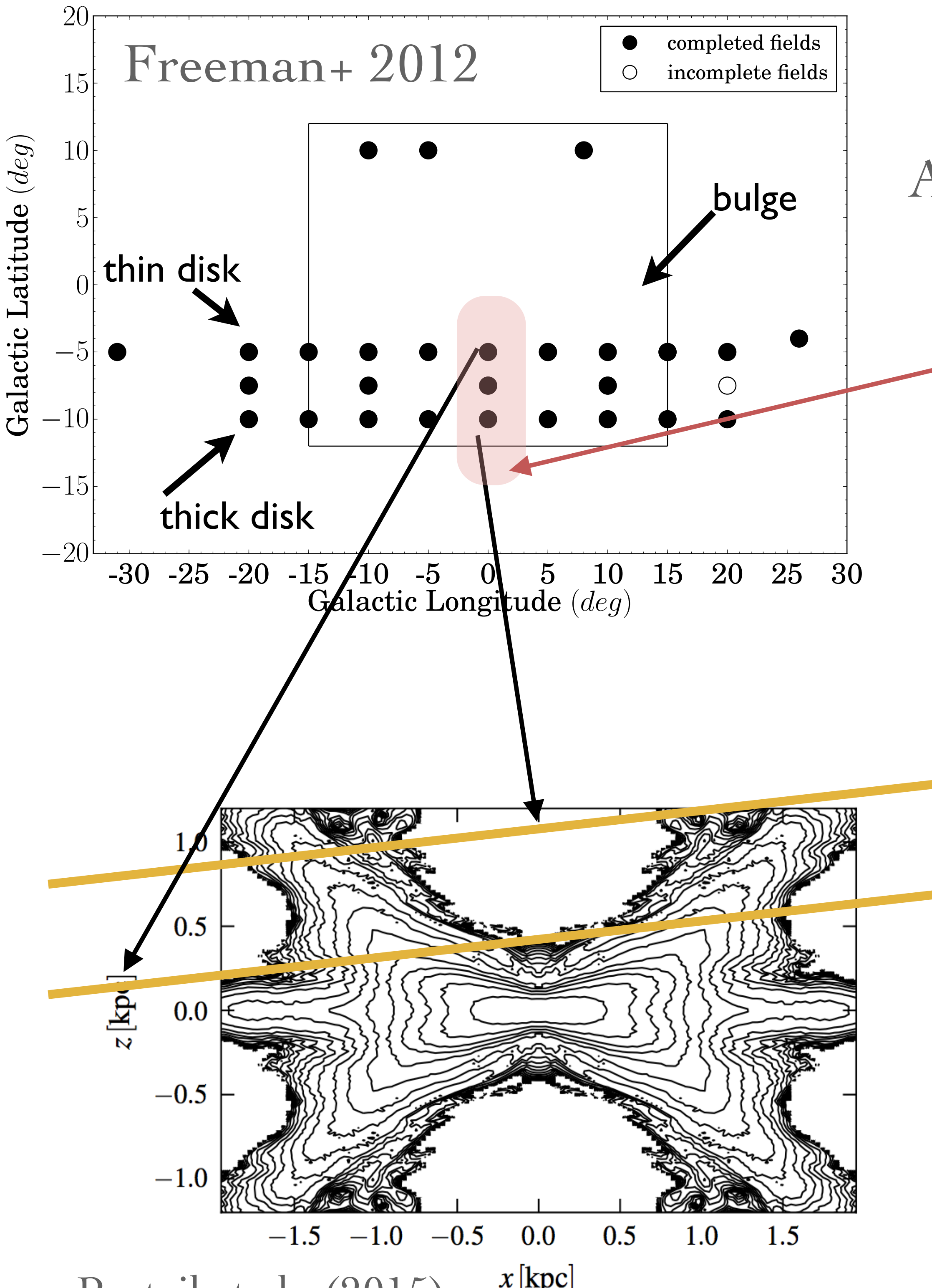

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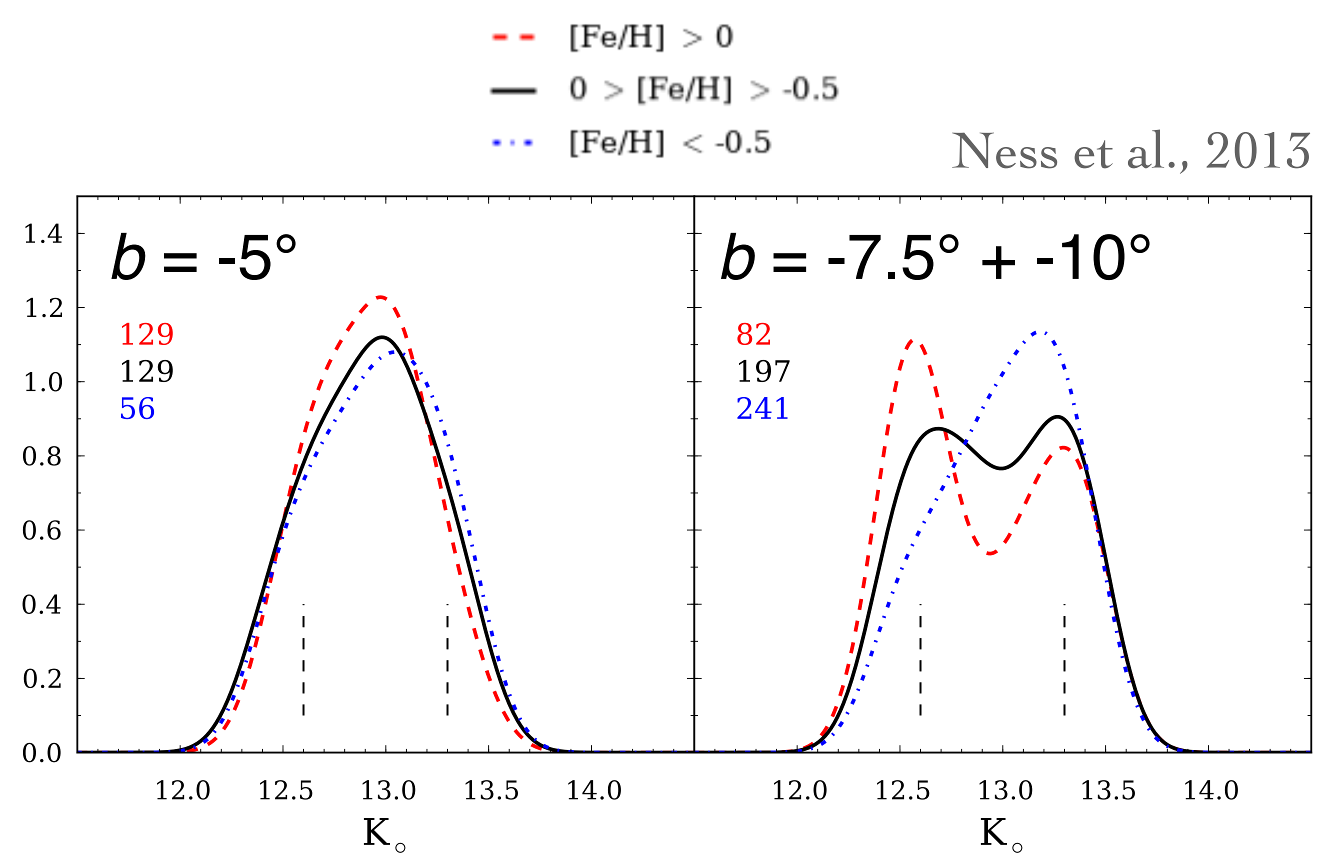
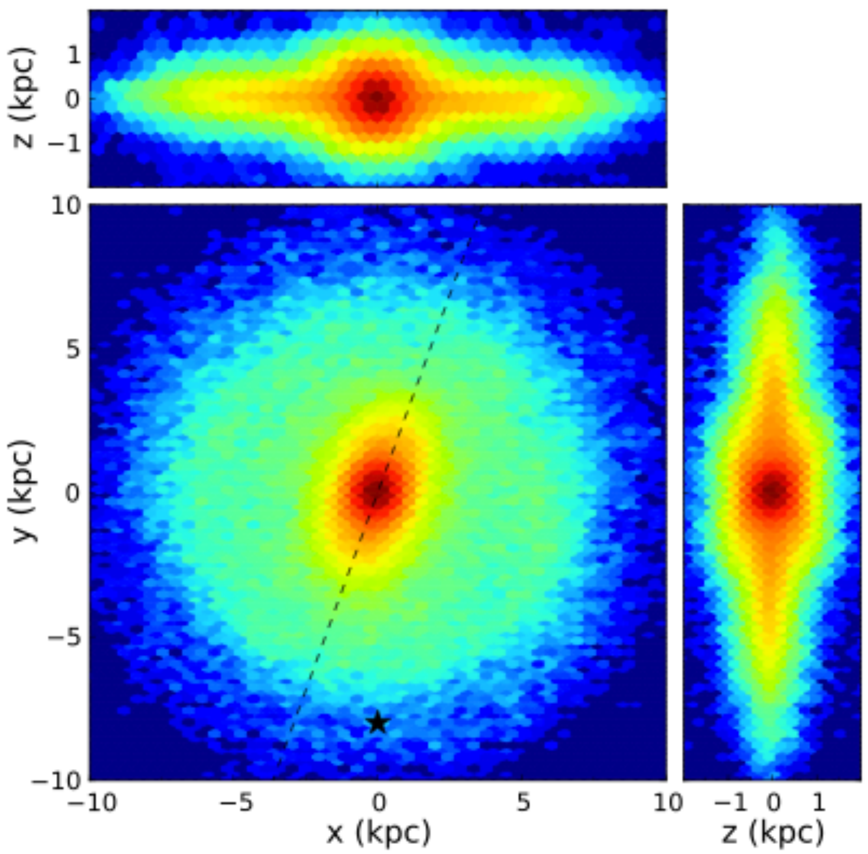


Bimodality for stars [Fe/H] > -0.5

Only the stars with [Fe/H] > -0.5 are part of the boxy/peanut

Bimodality in N-body models



Ness, Athanassoula+ 2012

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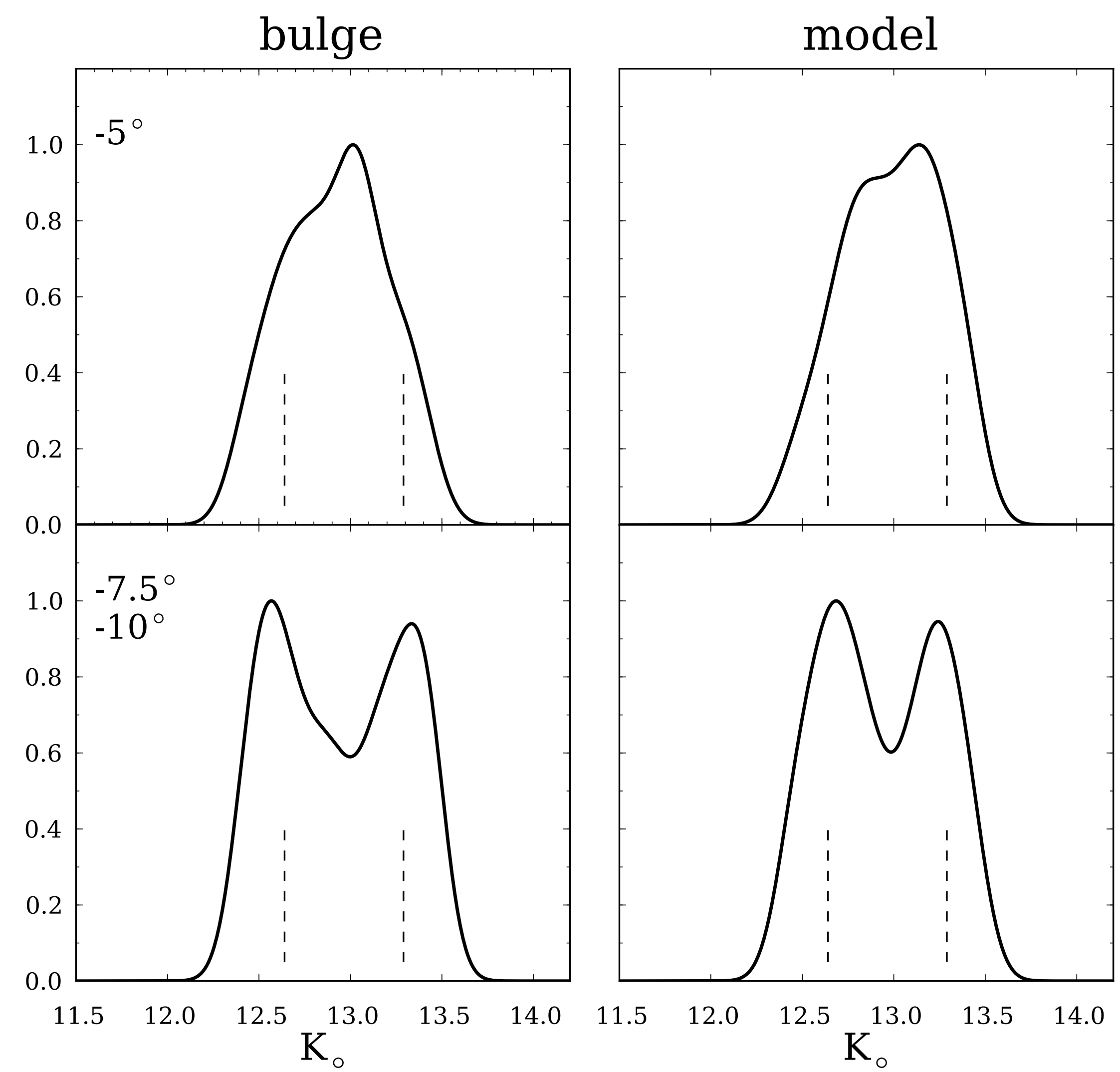
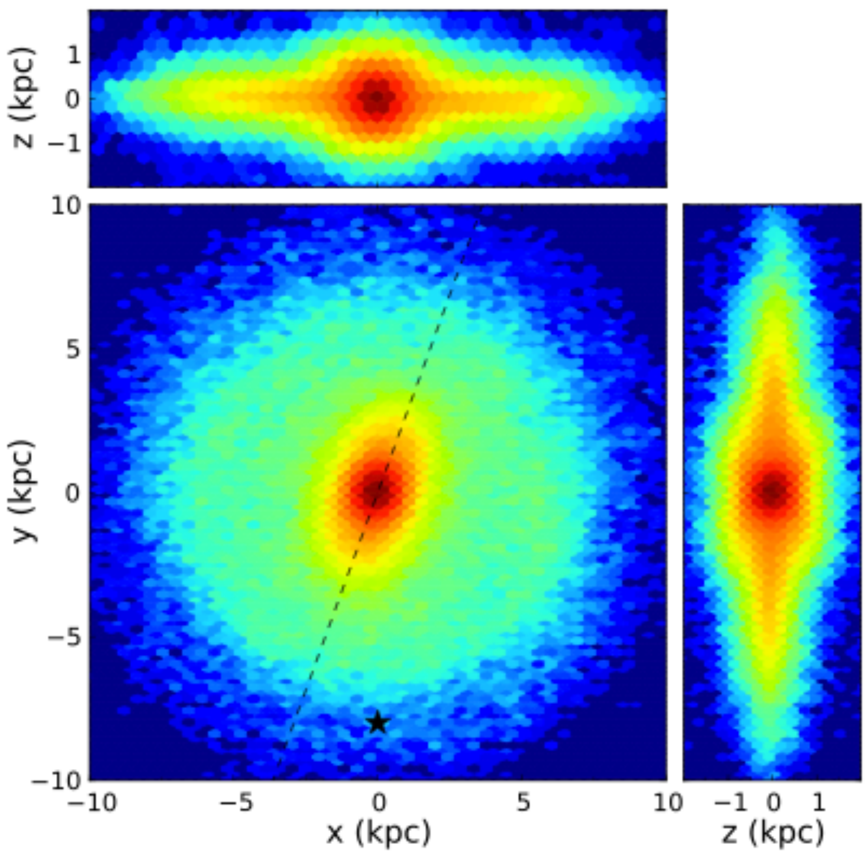


Conclusion - the split is generic to the N-body models of boxy/peanut bulges.

Bimodality in N-body models



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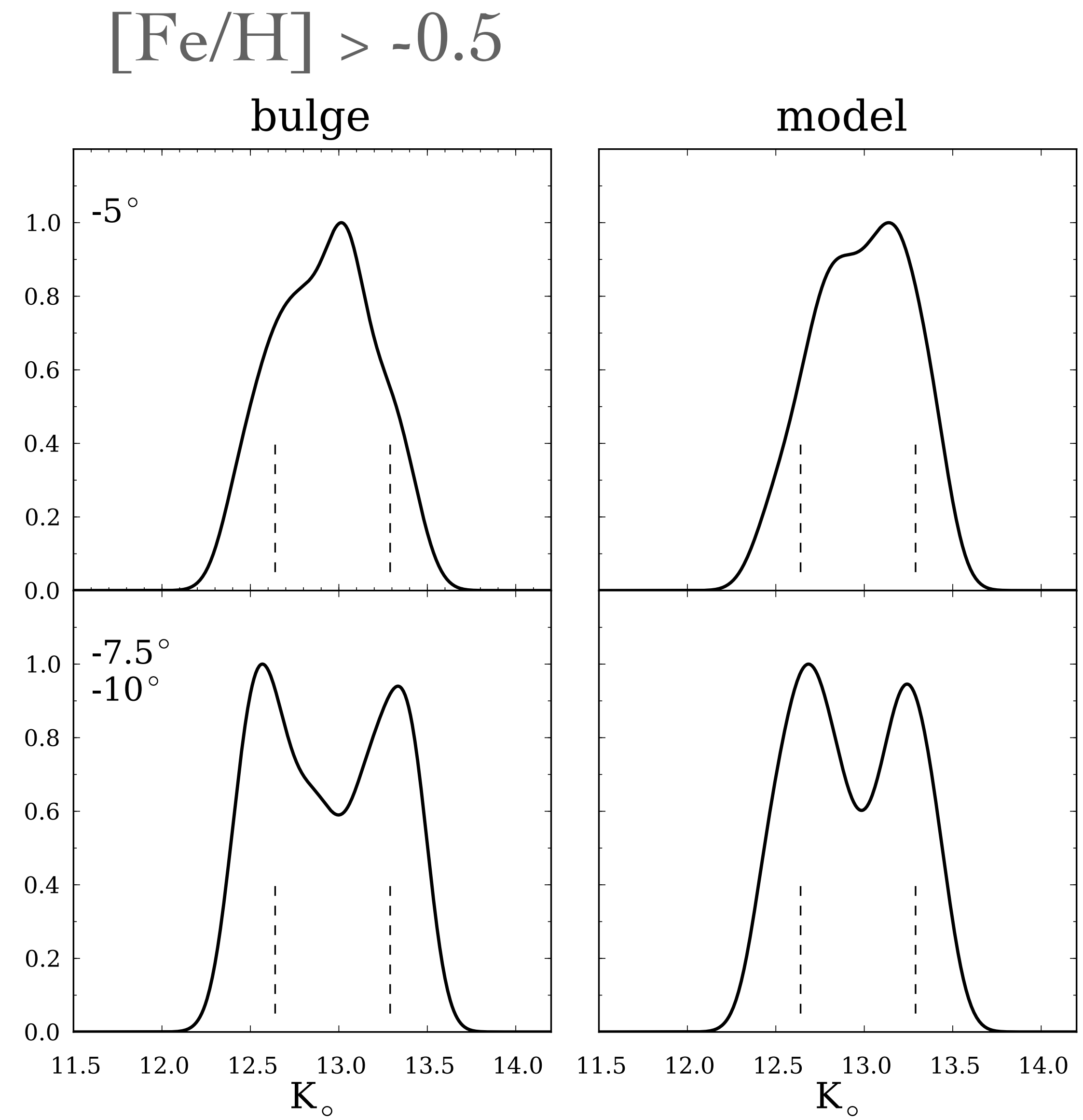
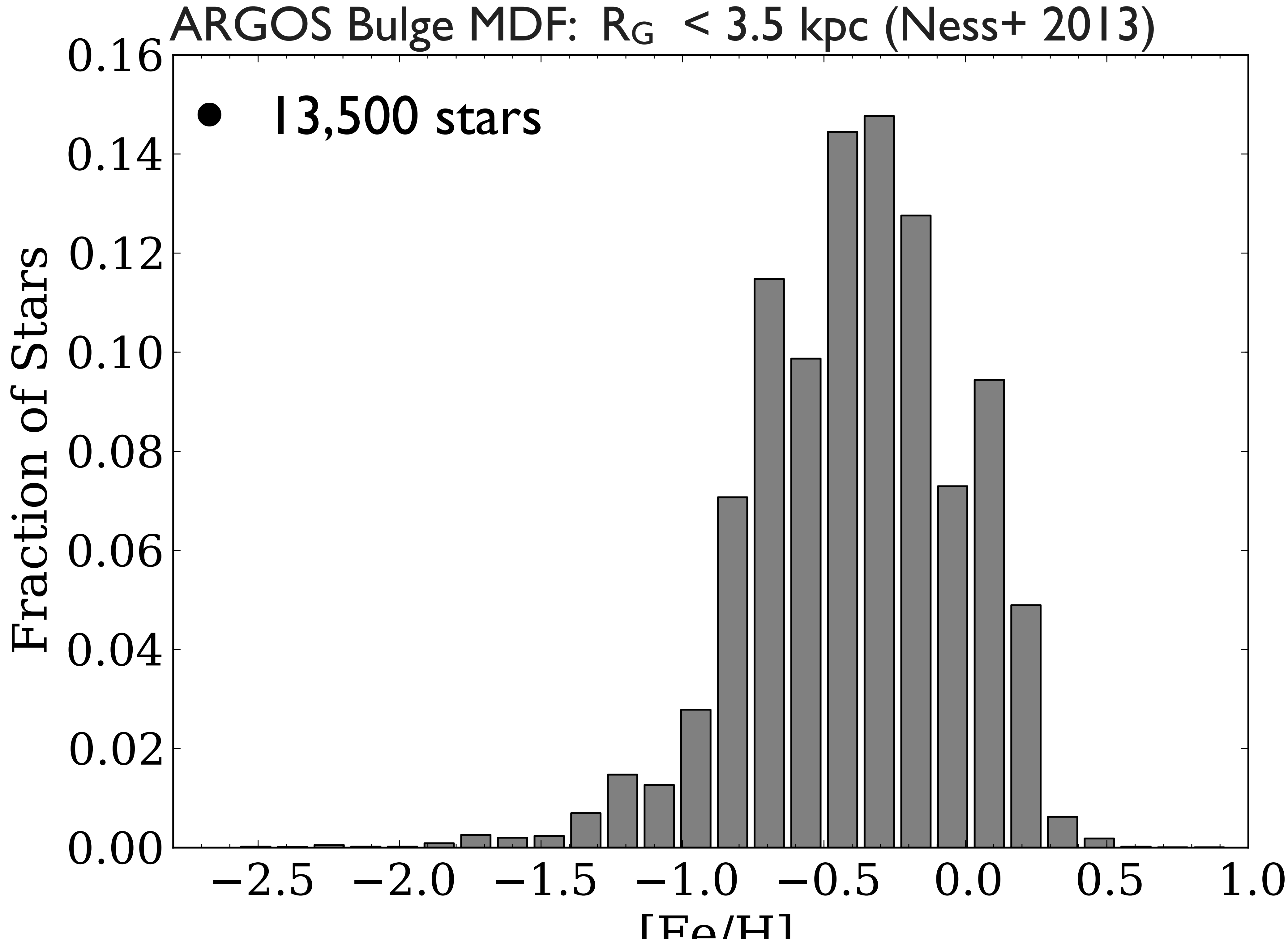


Conclusion - the split is generic to the N-body models of boxy/peanut bulges.

Split is not seen in the metal-poor bulge population

Metallicity distribution in the bulge



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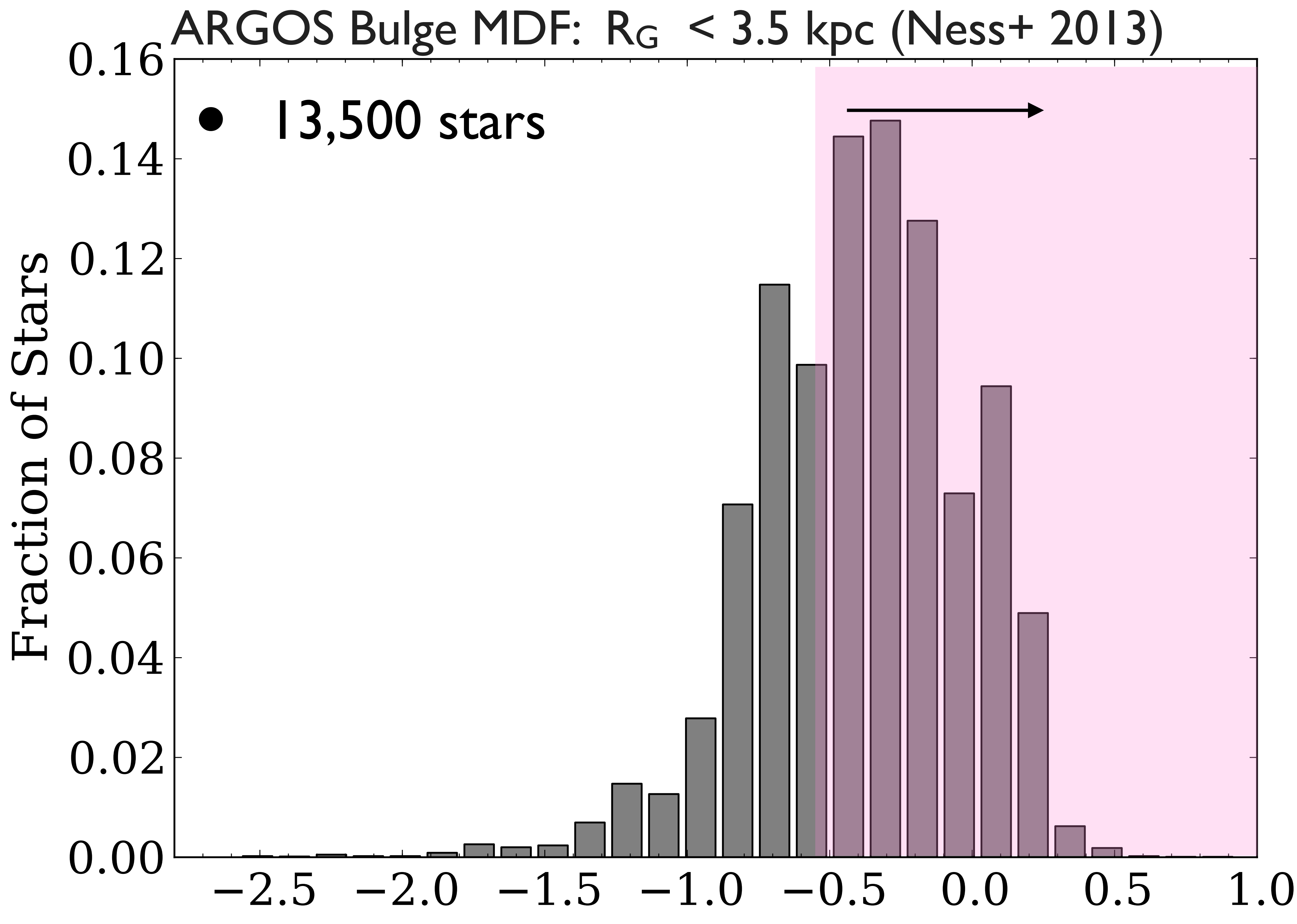
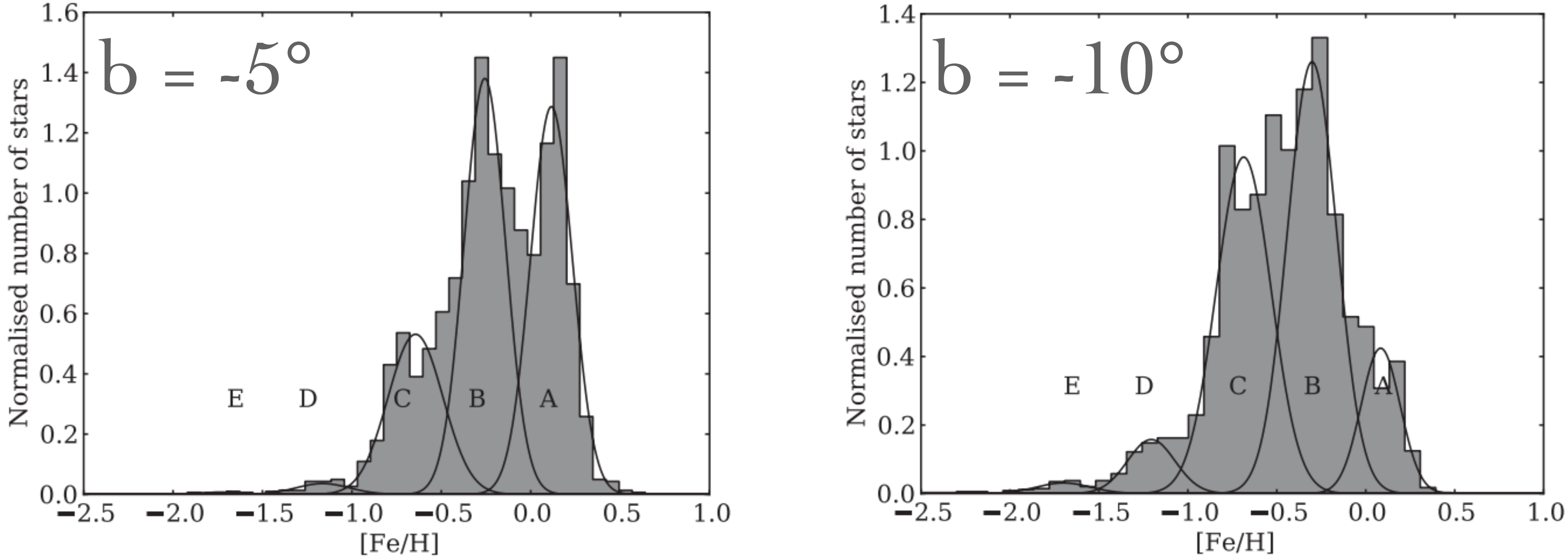


Multiple populations in the bulge



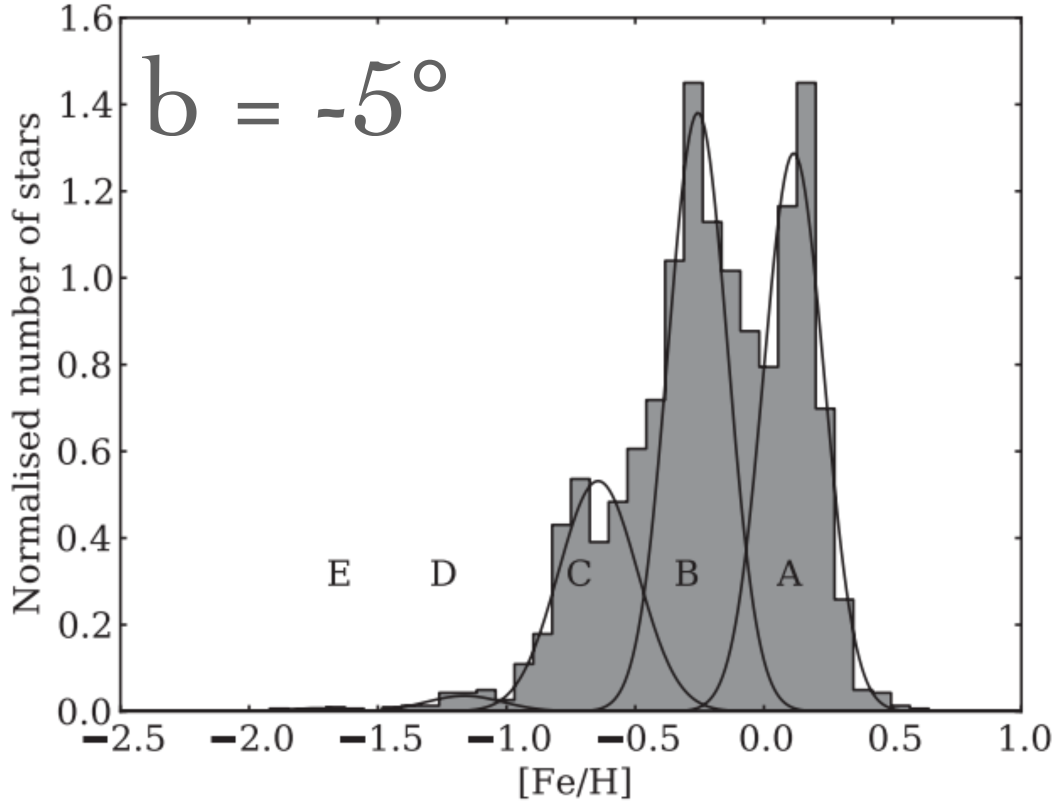
(a) $l \pm 15°, b = -5°$

(c) $l \pm 15°, b = -10°$

A: young thin disk
B: old thin disk
C: thick disk
D: metal-poor thick disk+halo
E: halo

Ness+ 2013

Multiple populations in the bulge



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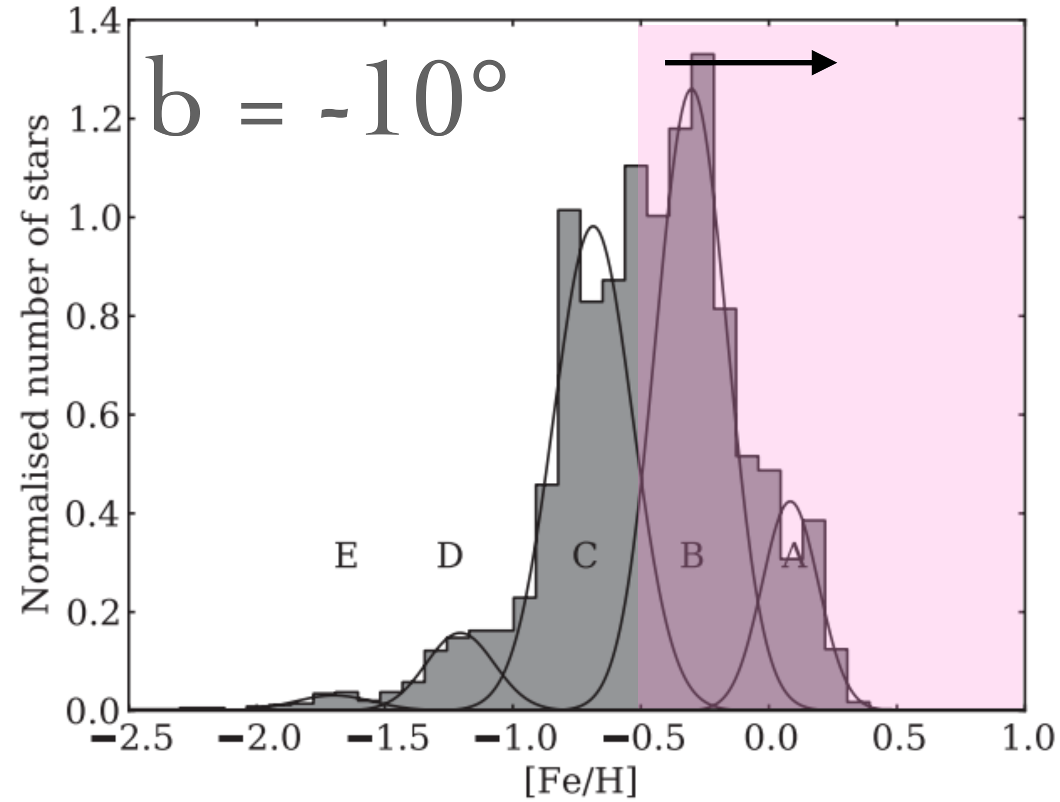

(c) $l \pm 15°, b = -10°$

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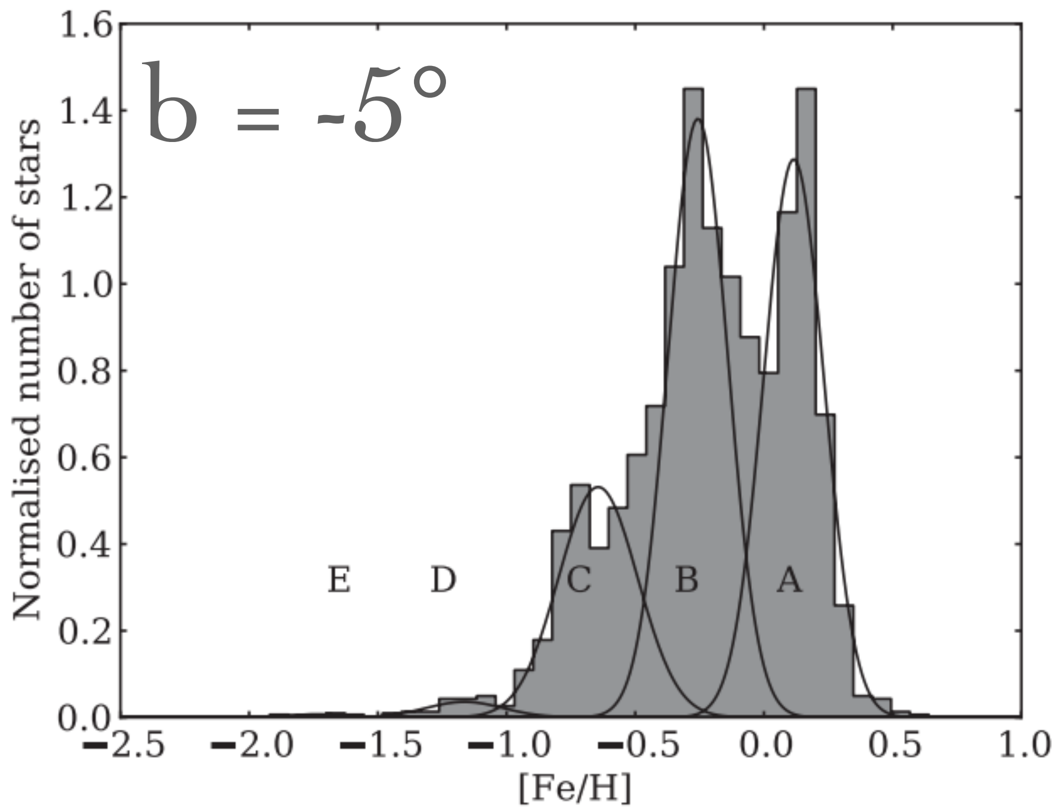
E: halo

Ness+ 2013

in talk by K. Freeman

Multiple populations in the bulge



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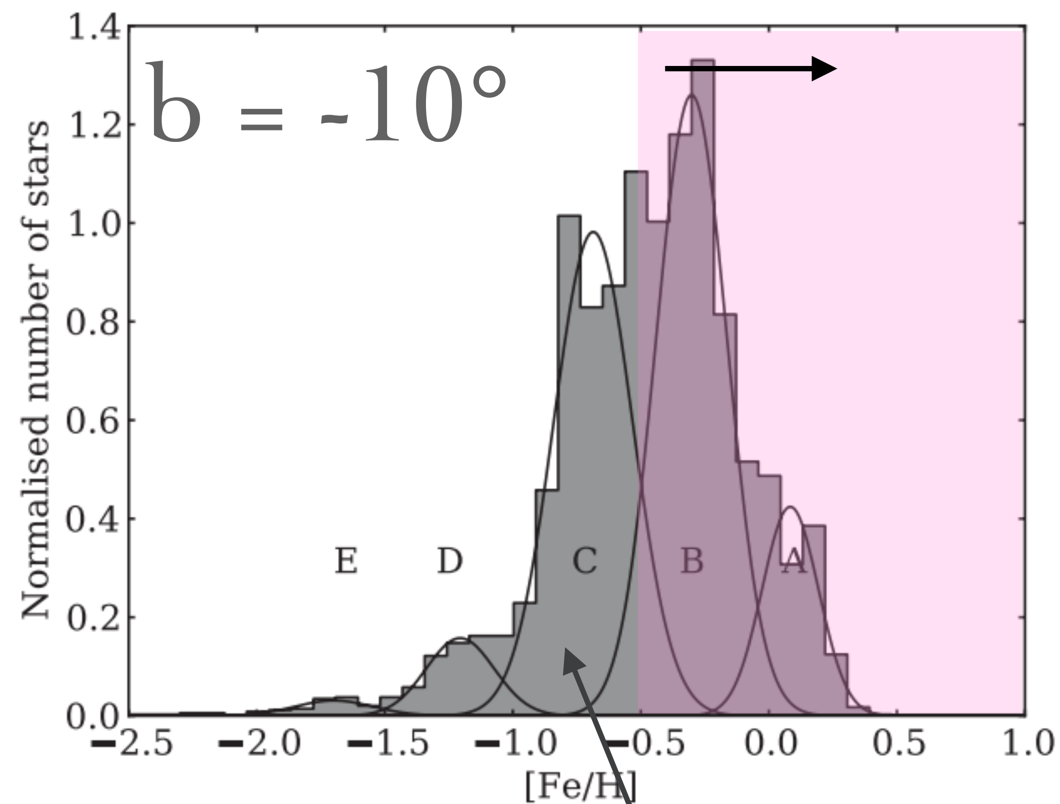

(c) $l \pm 15°, b = -10°$

A: young thin disk
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E: halo

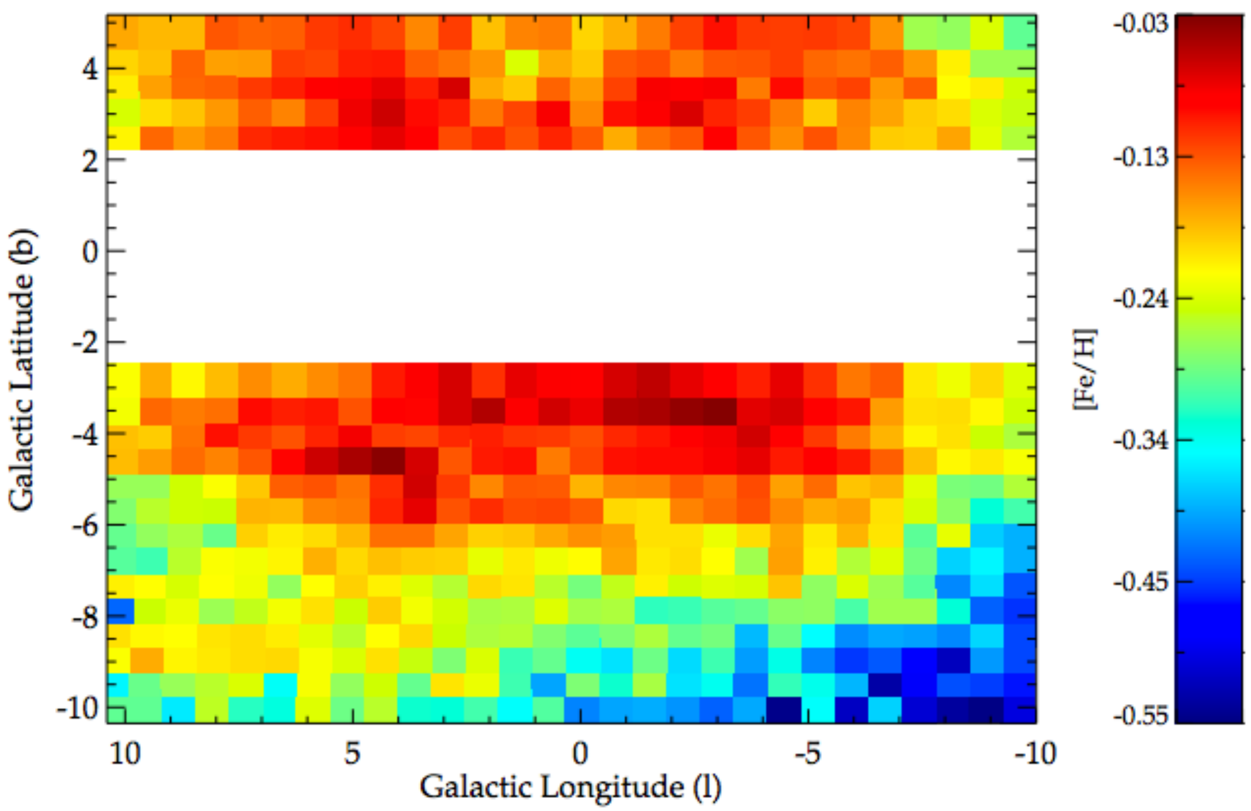
[Fe/H] < -0.5 classical bulge: very different formation history

Ness+ 2013

MDF gradient & disk-instability formation

MDF gradient & disk-instability formation

Observations



Gonzalez et al., 2013

MDF gradient & disk-instability formation

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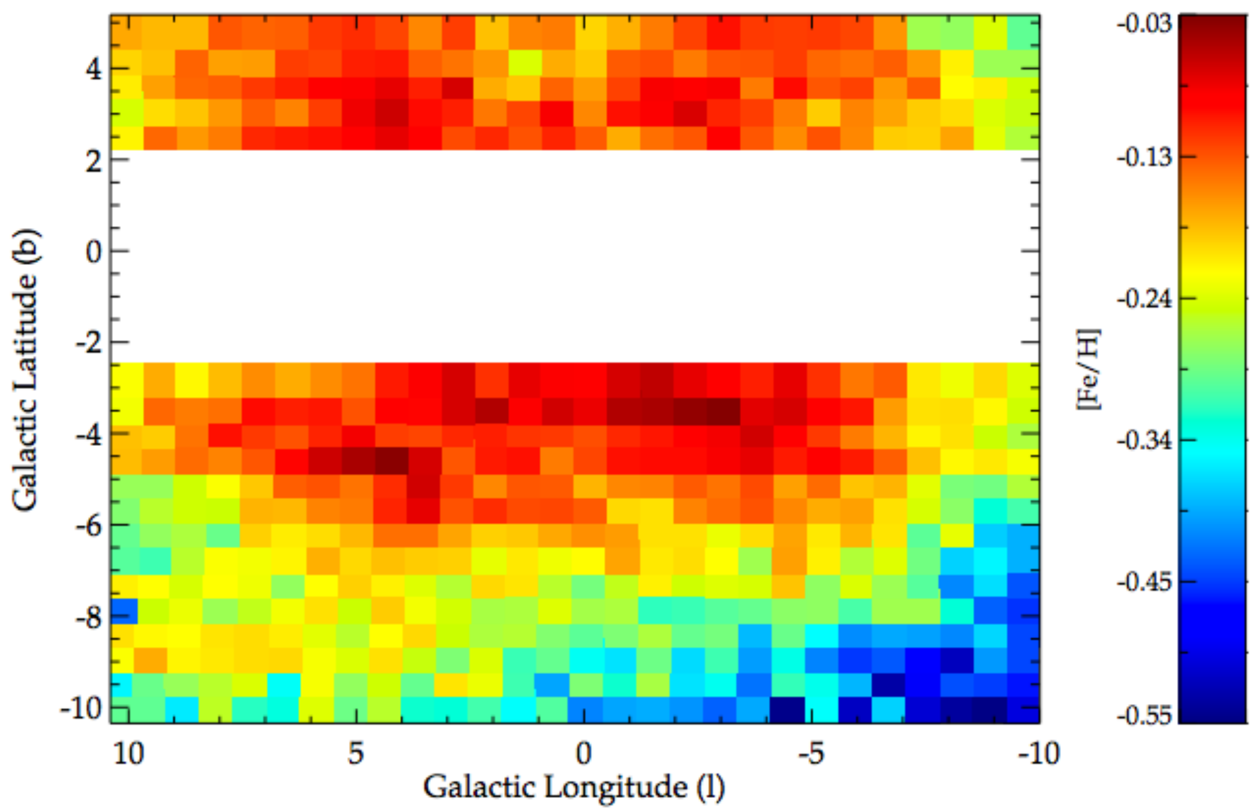
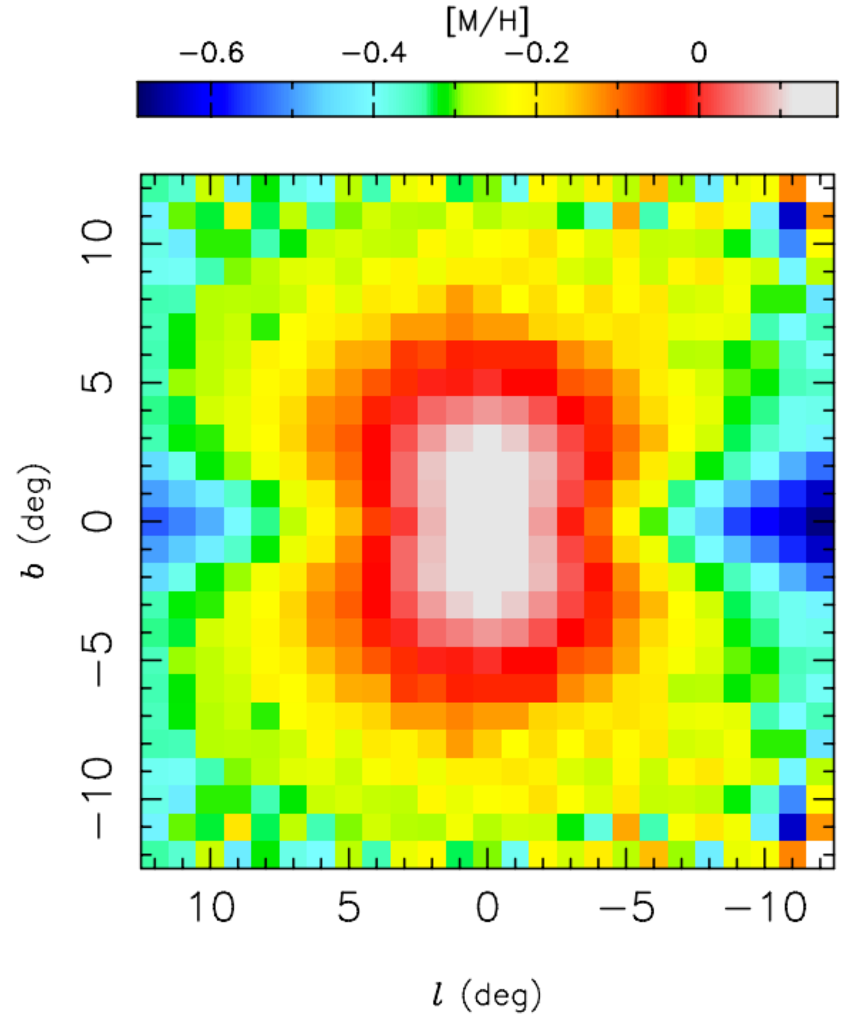


Gonzalez et al., 2013

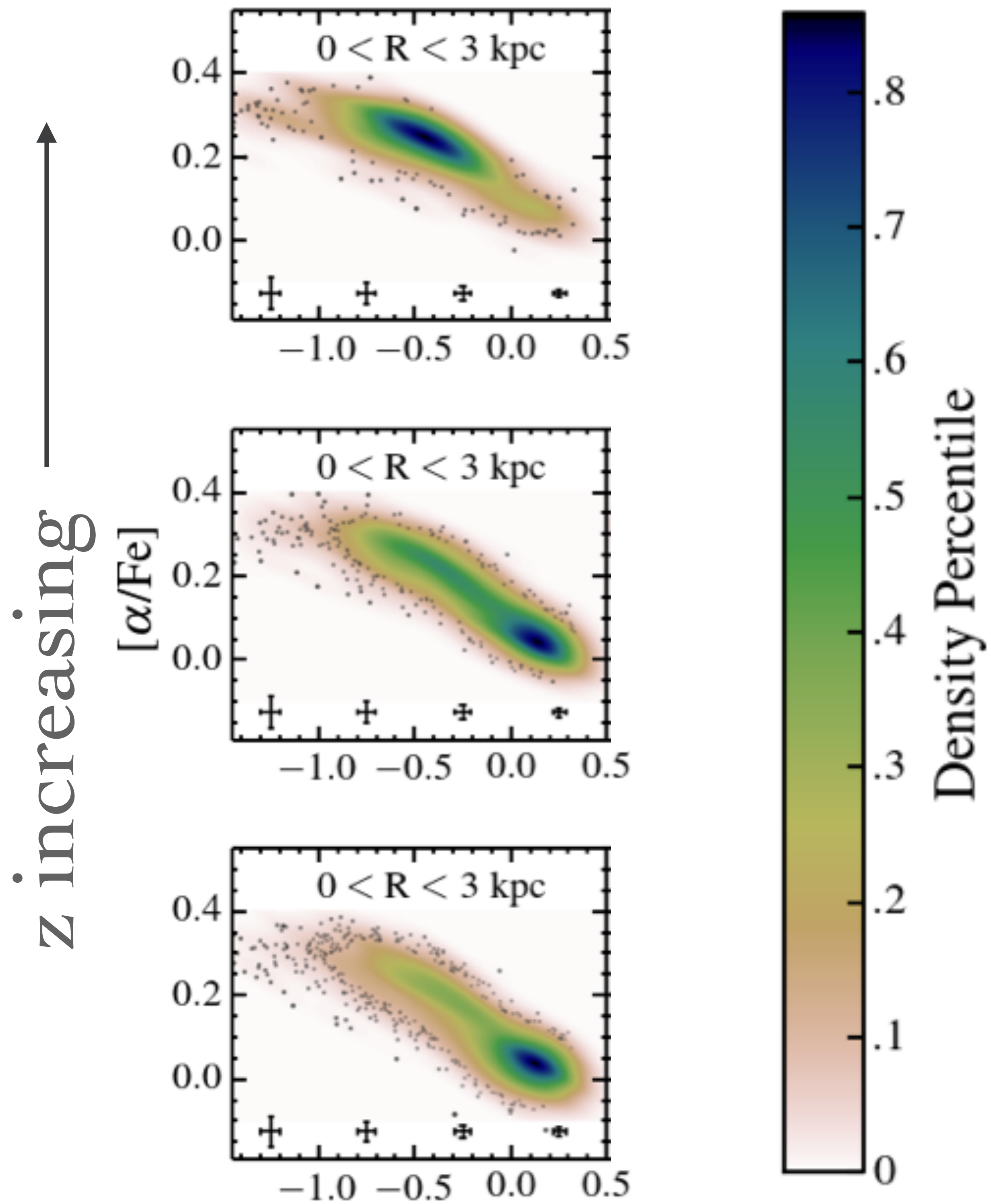
Simulation

Disk instability bulge formation: Initial radial metallicity gradient is mapped into the bulge

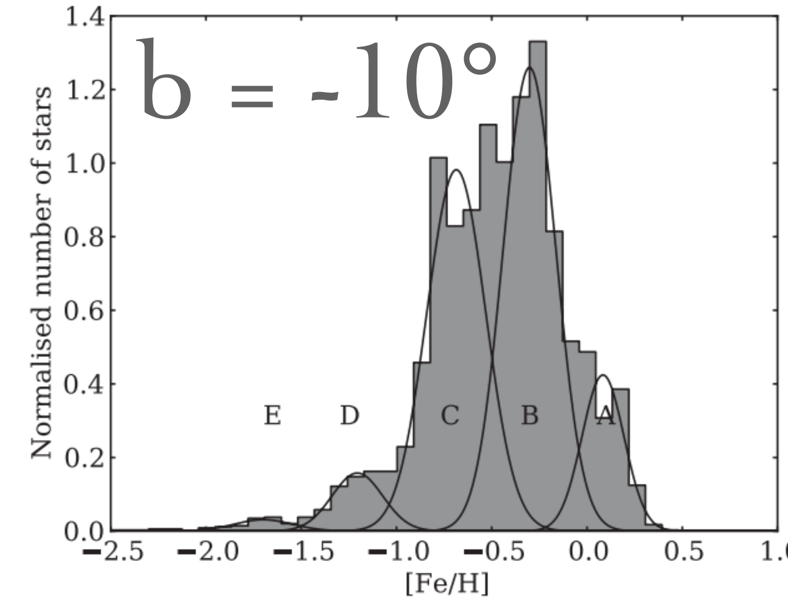


Martinez-Valpuesta+ 2013

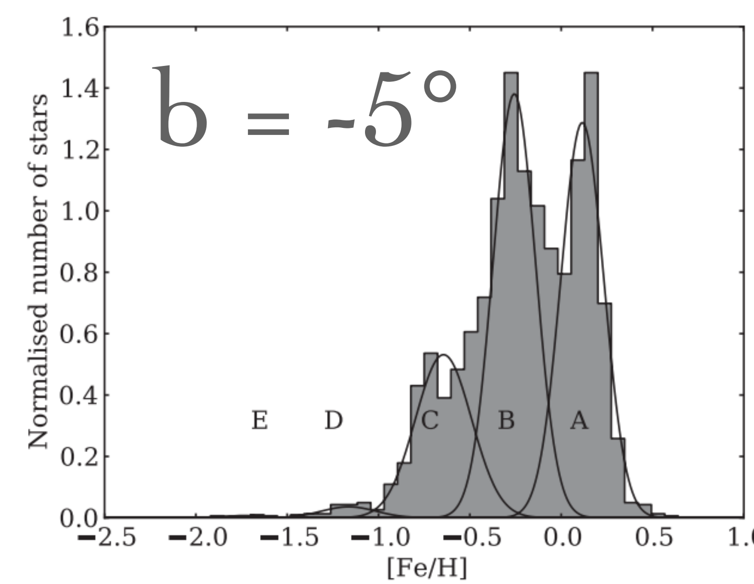
Chemical enrichment of bulge from APOGEE



from Hayden,M



(c) $l \pm 15^\circ, b = -10^\circ$



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Chemical enrichment of the bulge in context

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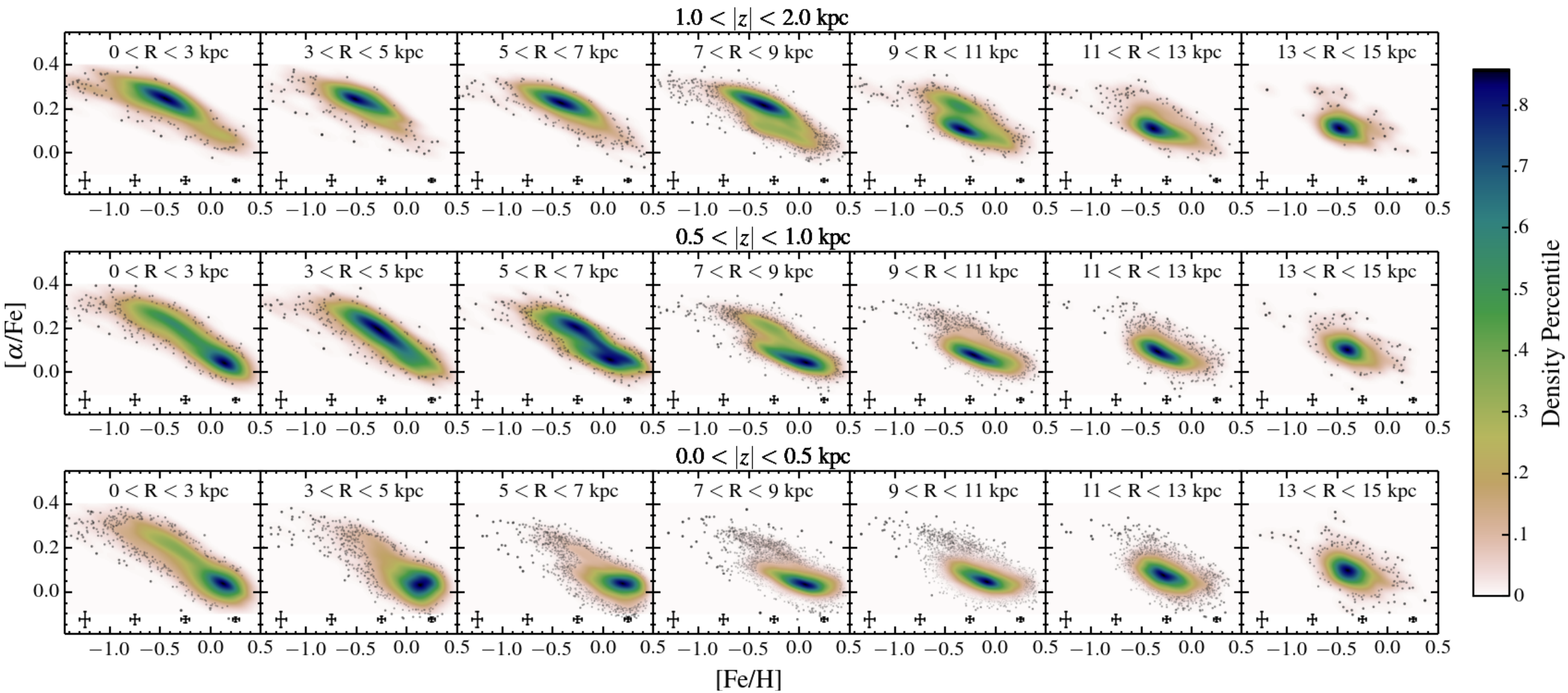
70,000 giants from Hayden,M from **APOGEE**



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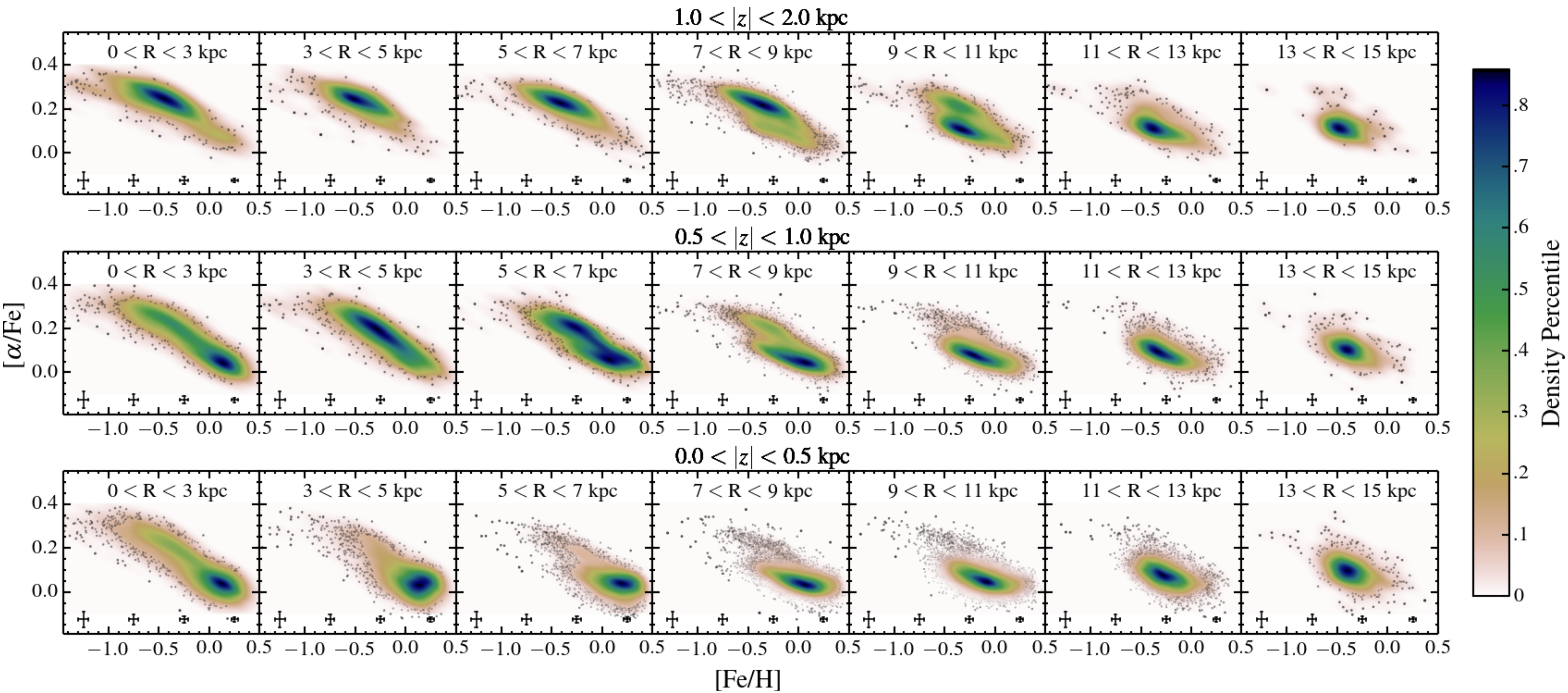

- smooth transition in [α/Fe] from inner to outer region

Chemical enrichment of the bulge in context

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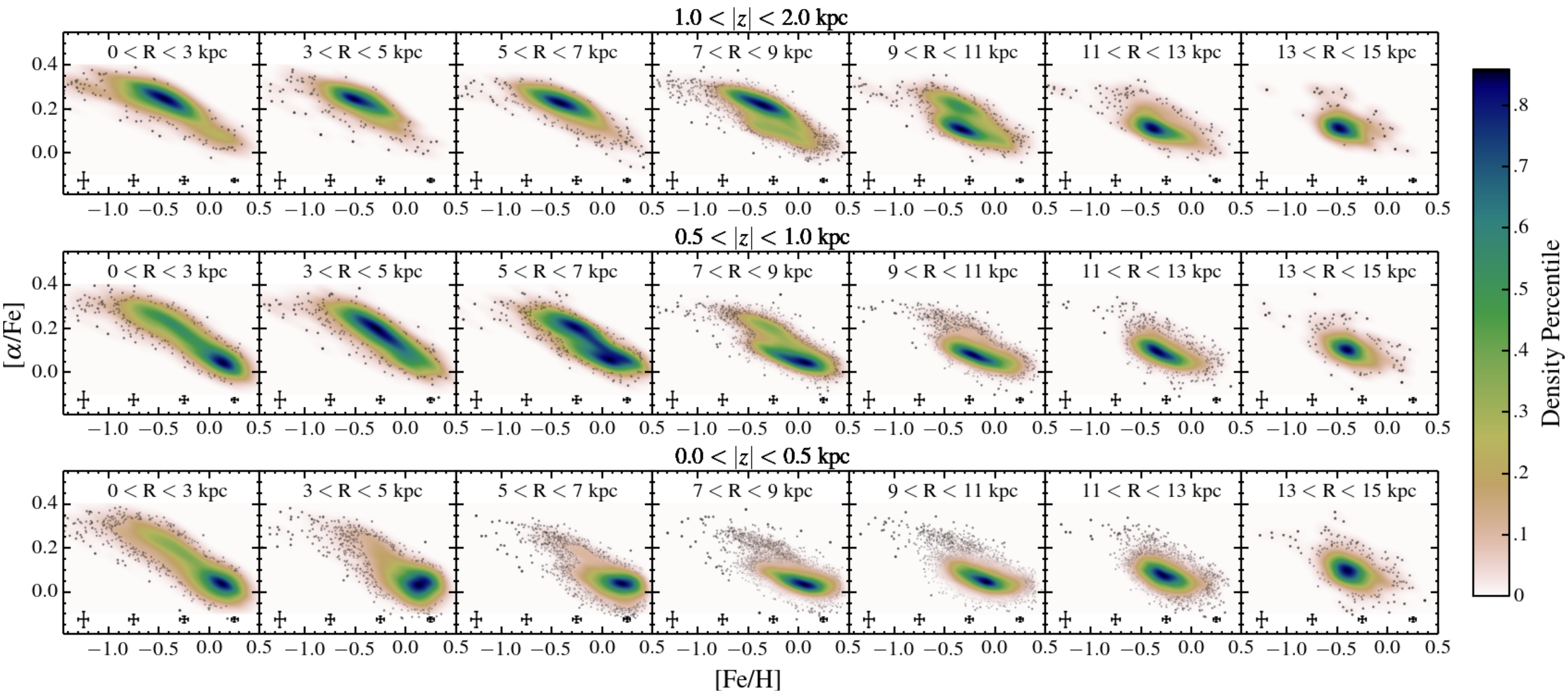
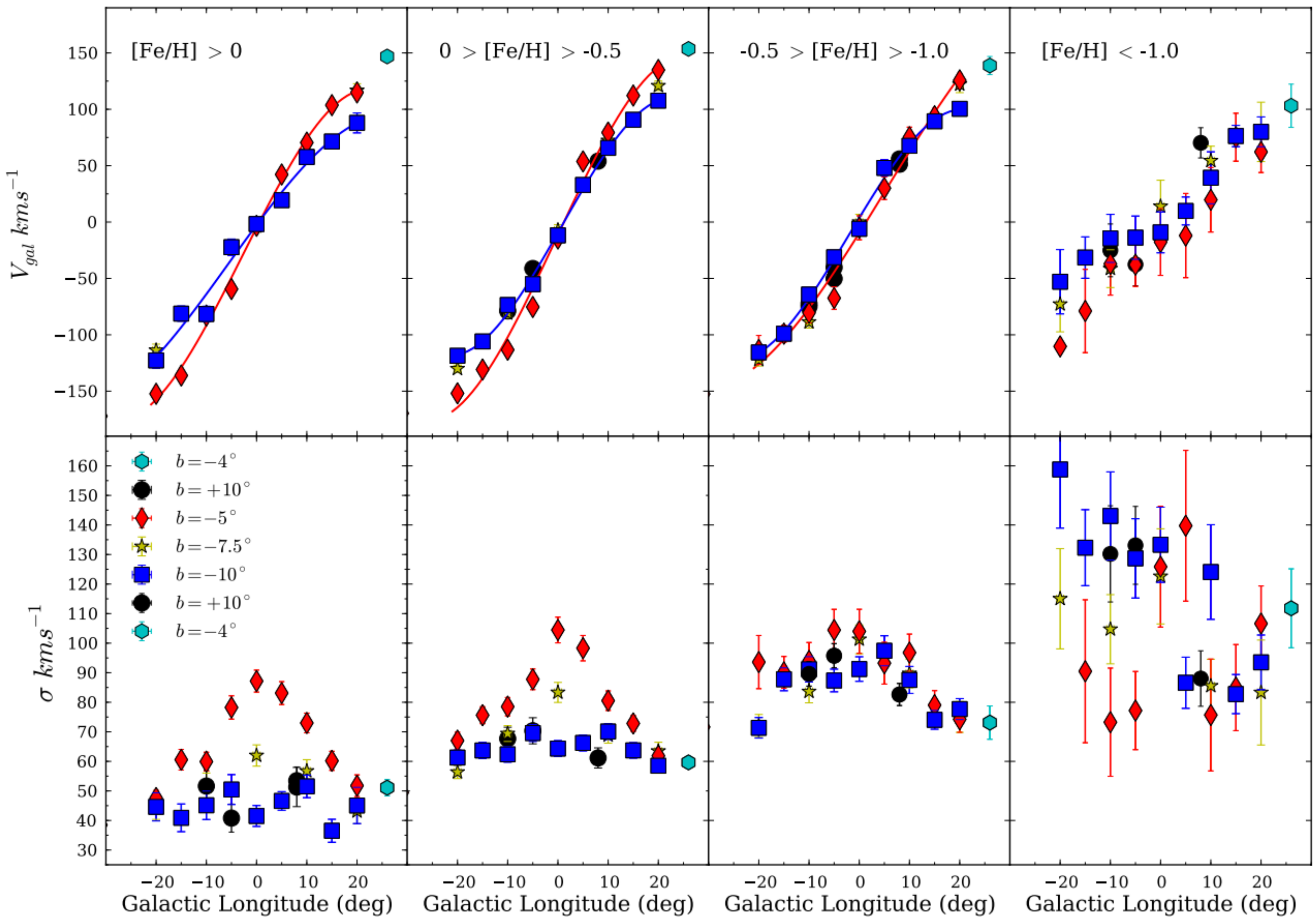
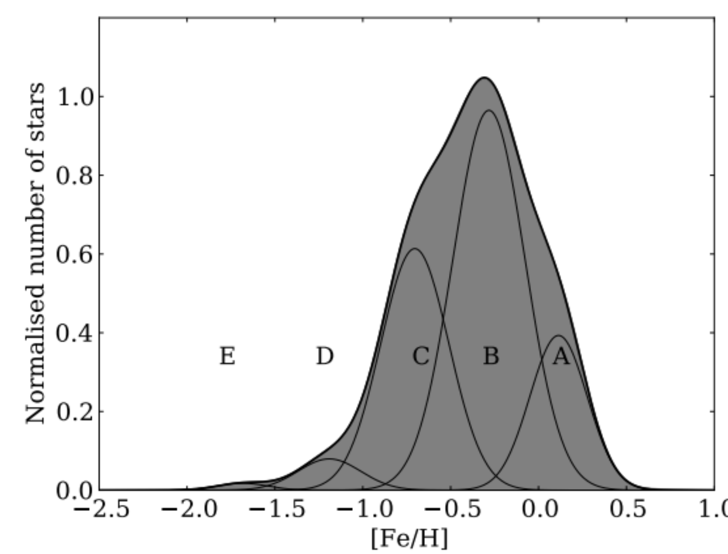


- smooth transition in [α/Fe] from inner to outer region
- narrow high-α in inner region — star formation and chemical evolution rate was high in the early epoch in the disk

Kinematics of Multiple populations

A B C D/E





Ness et al., 2013

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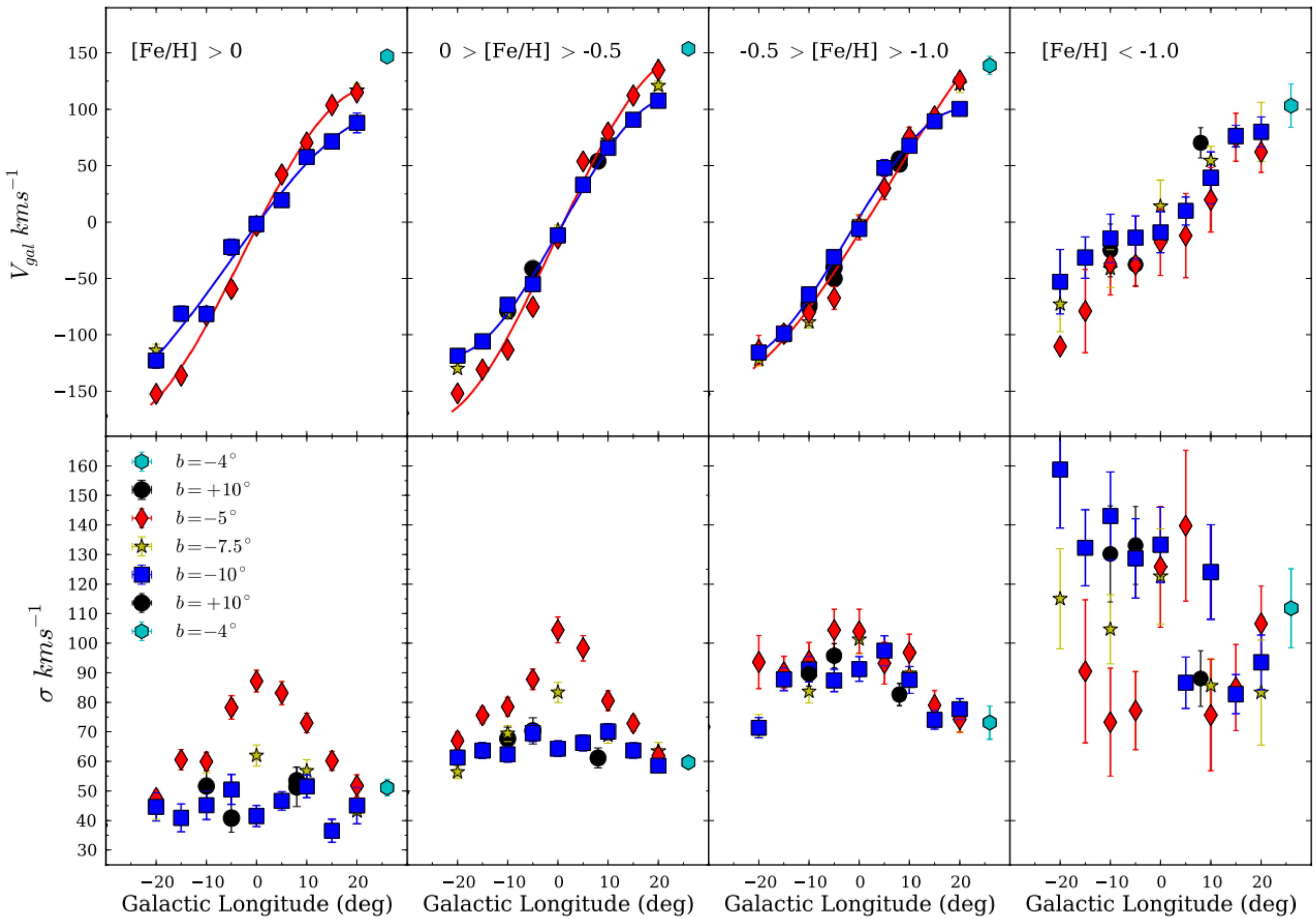

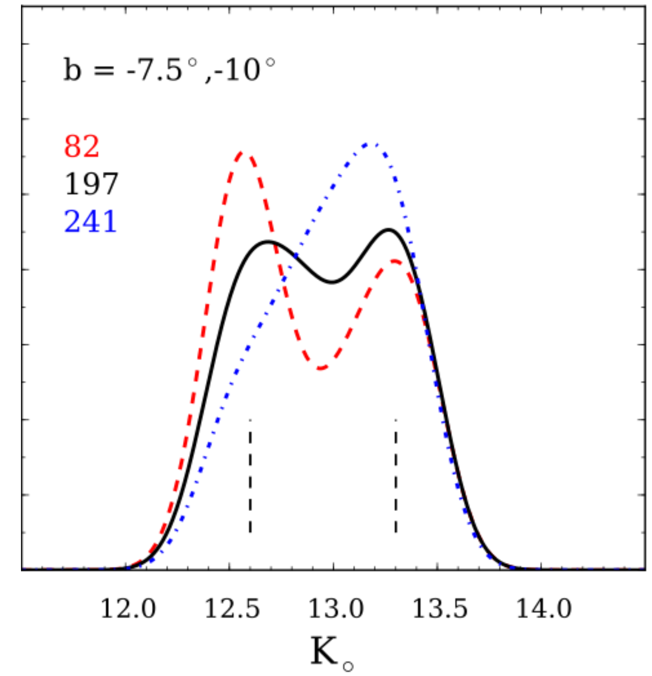

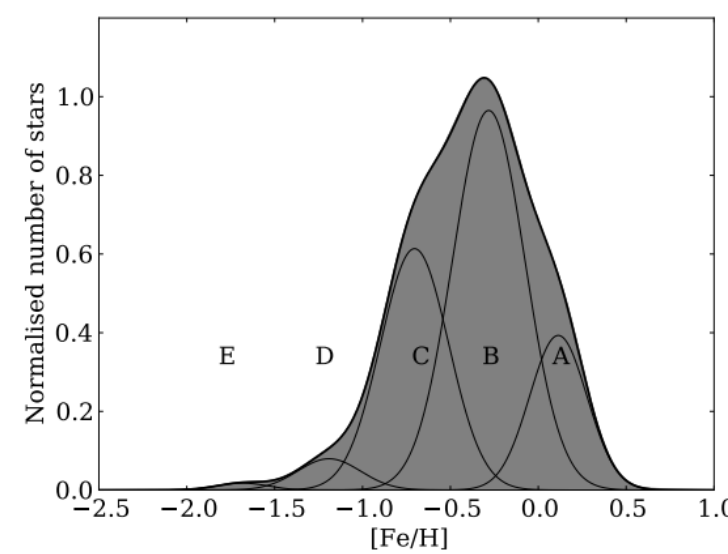

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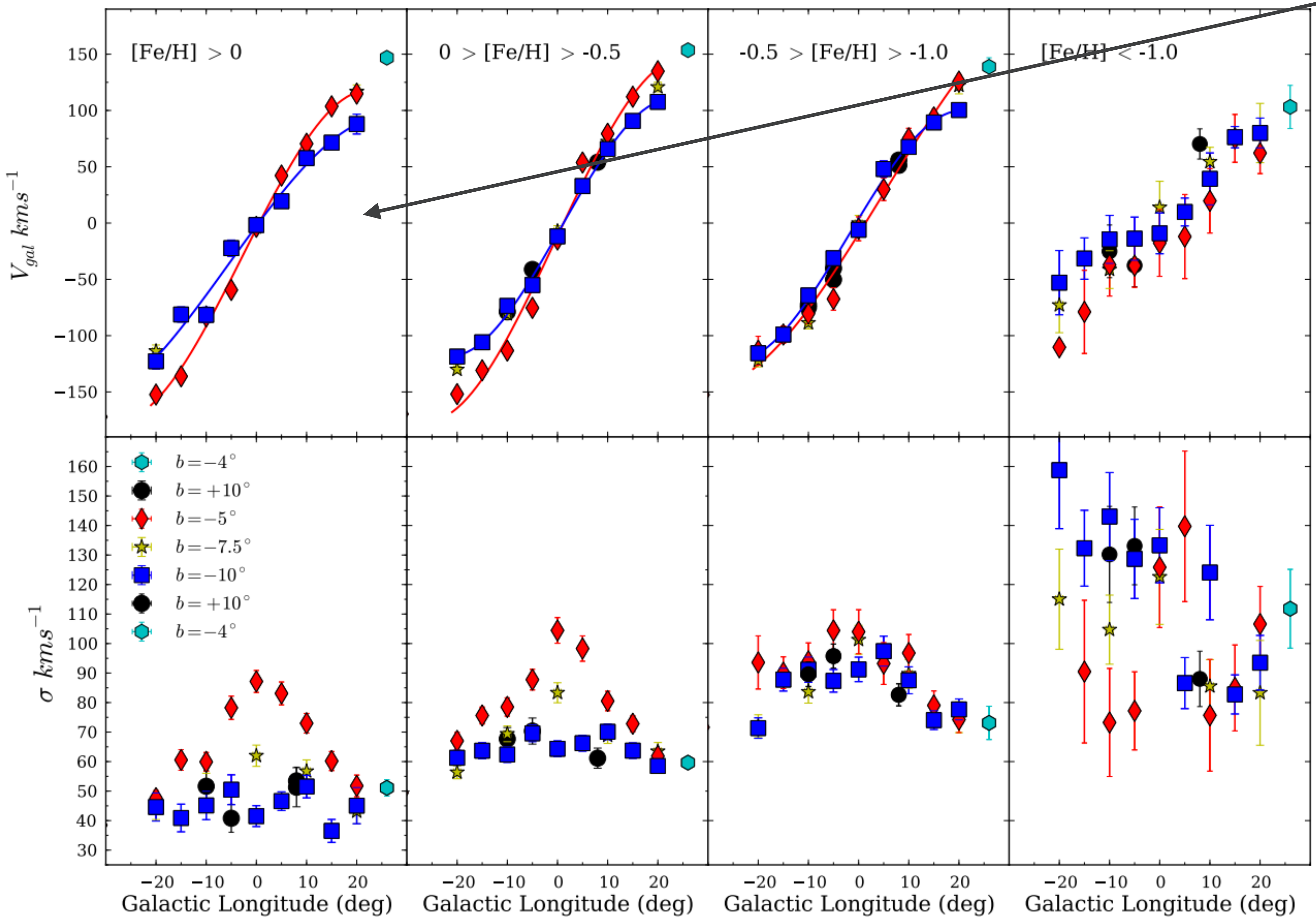

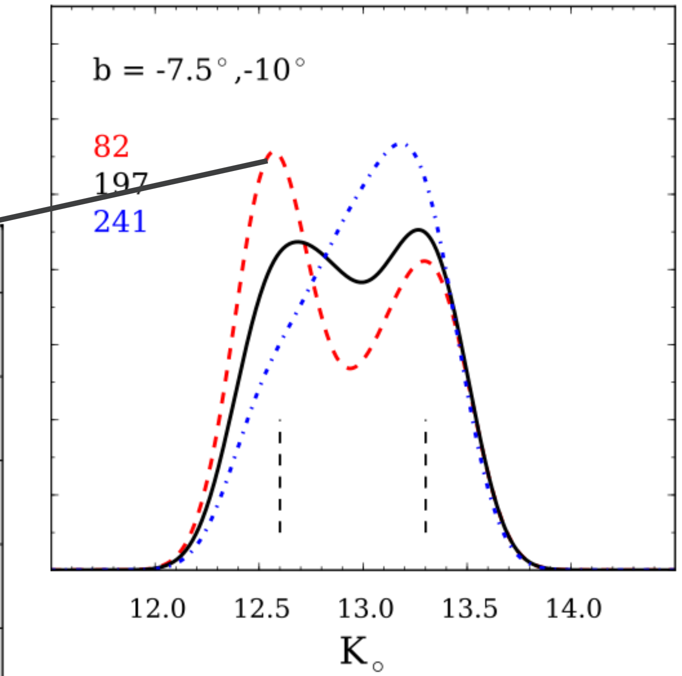

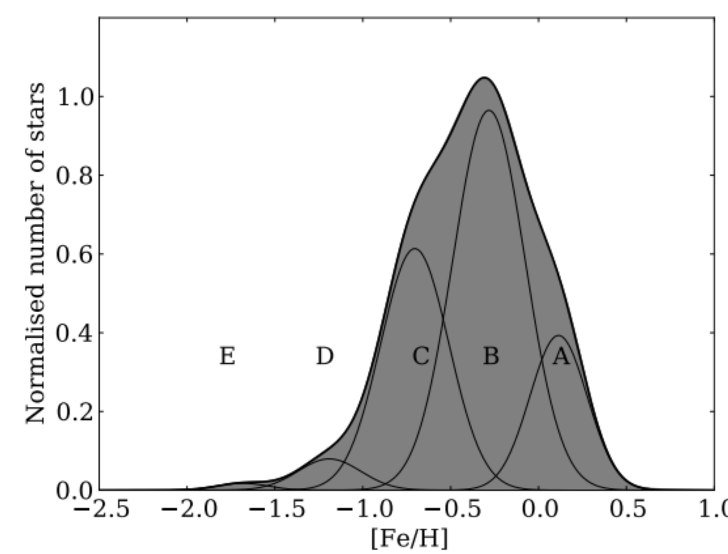

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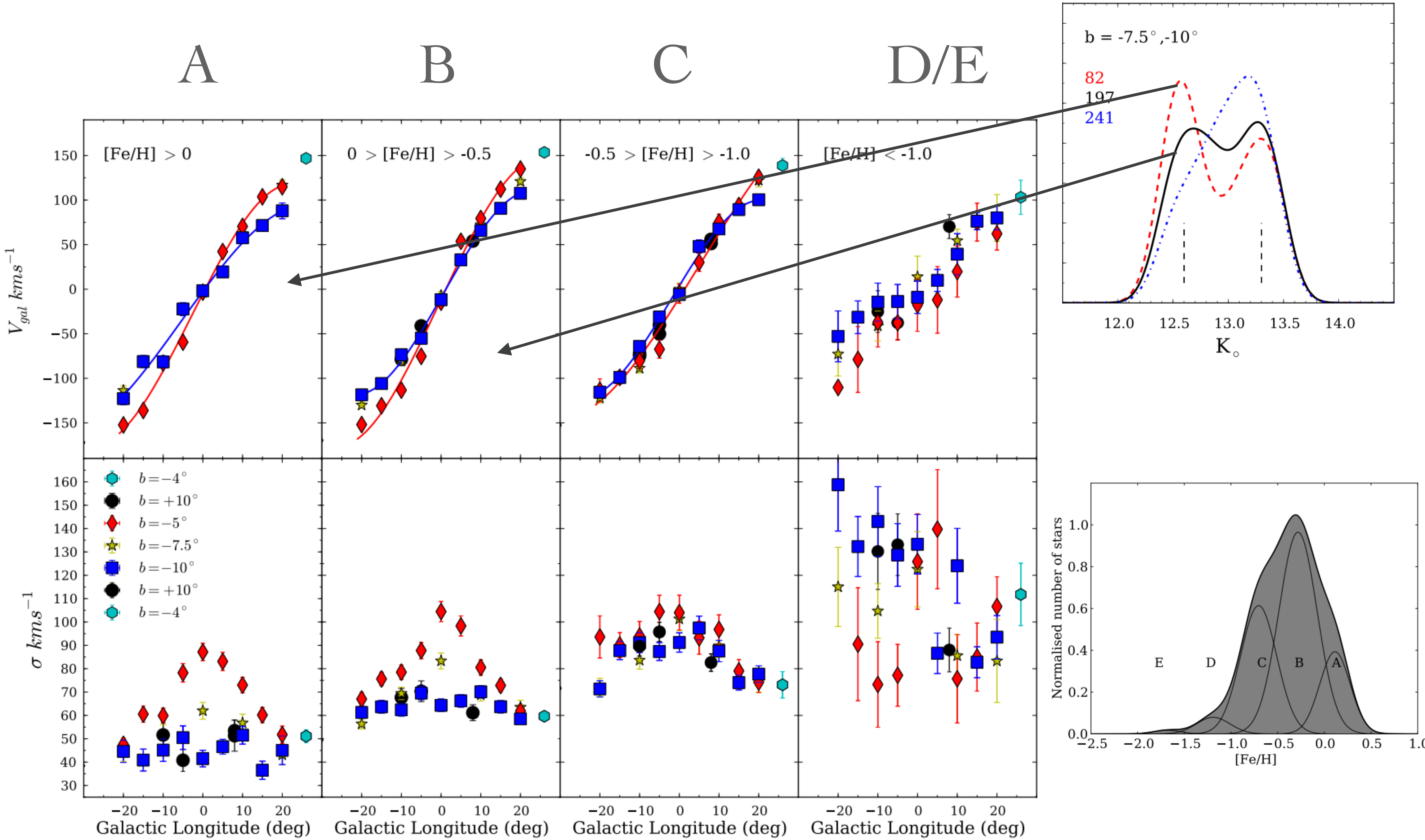

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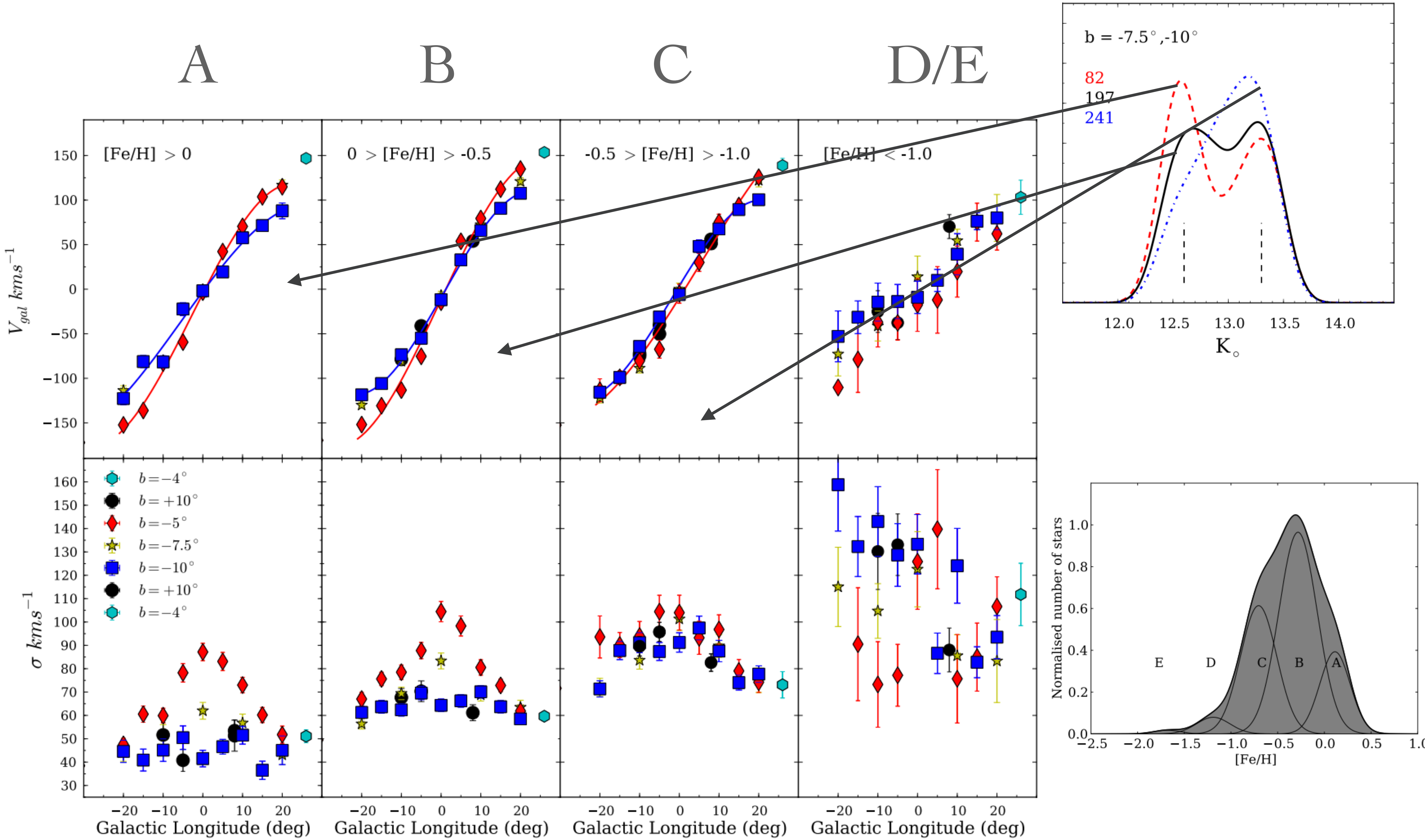


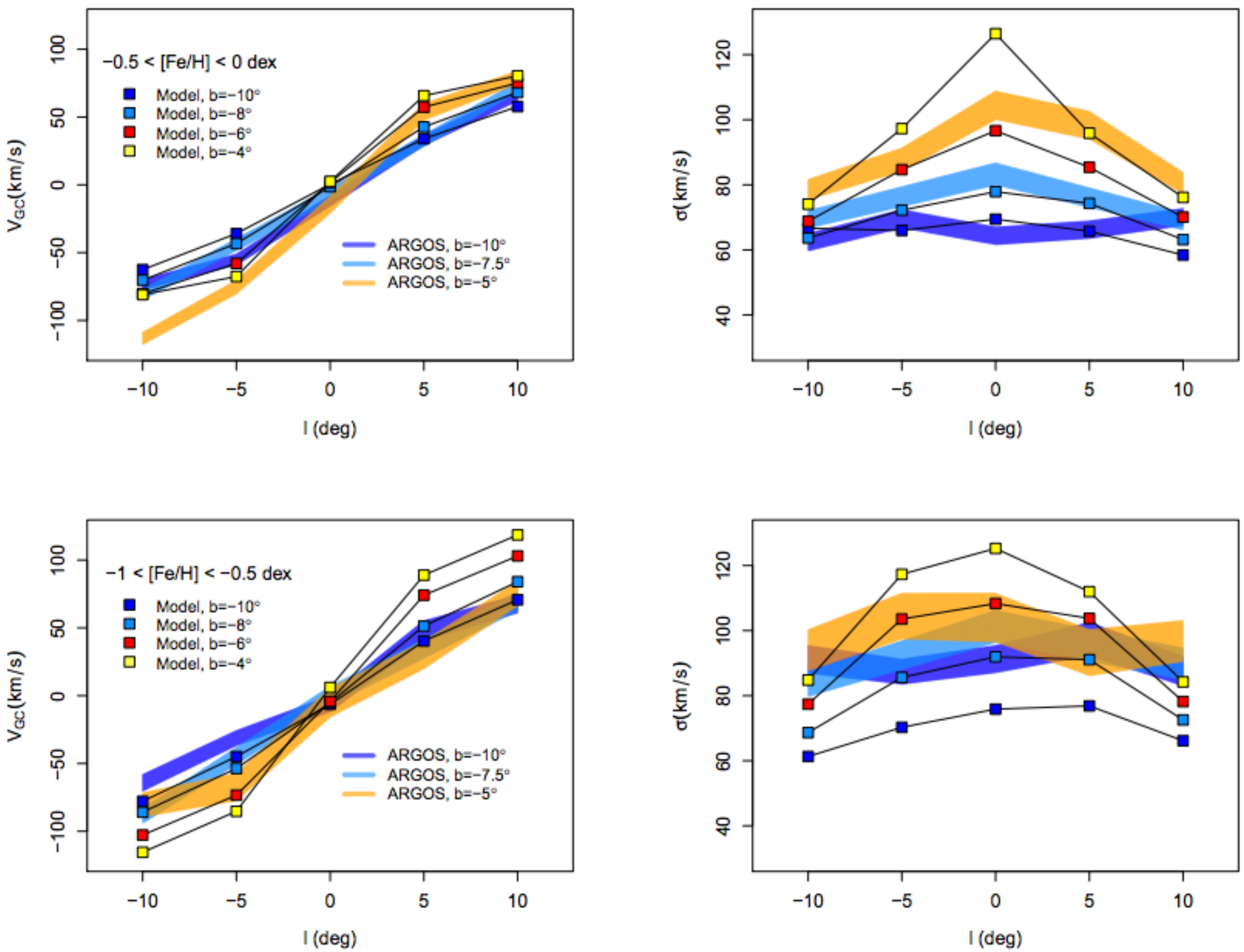
Ness et al., 2013

Kinematics at [Fe/H] < -0.5 not well reproduced

- Latitude-independent dispersion can not be reproduced in instability models (di Matteo+ 2015)

B ✓

C



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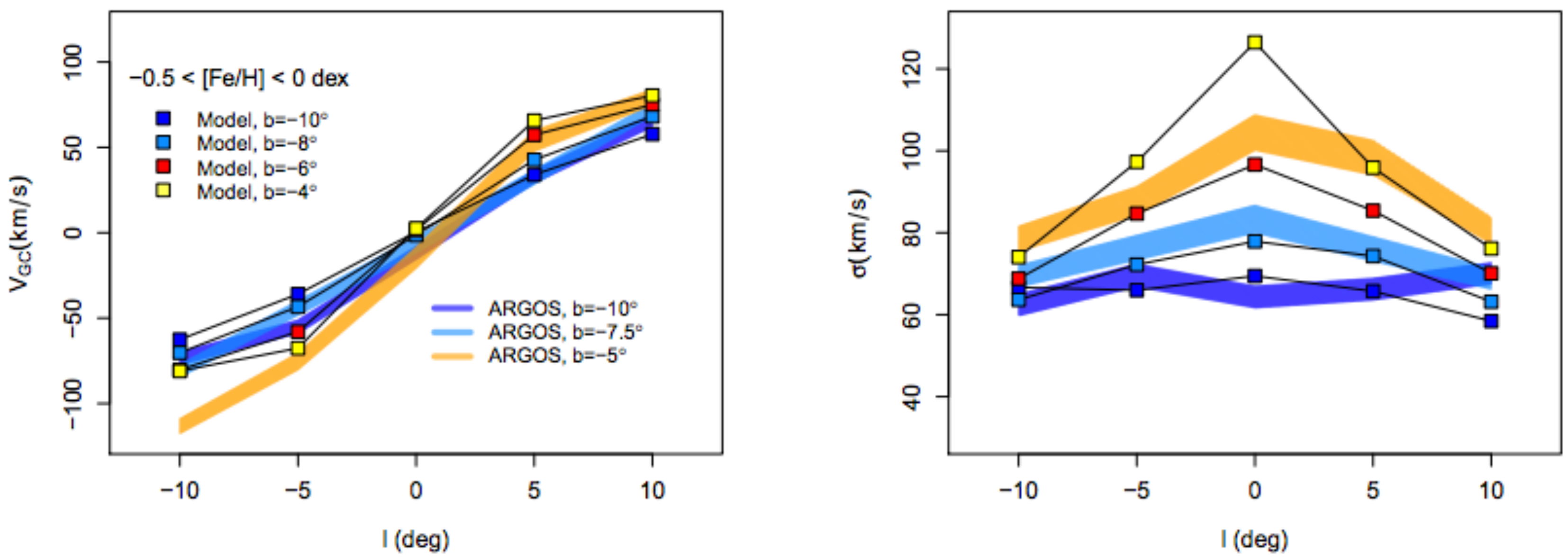
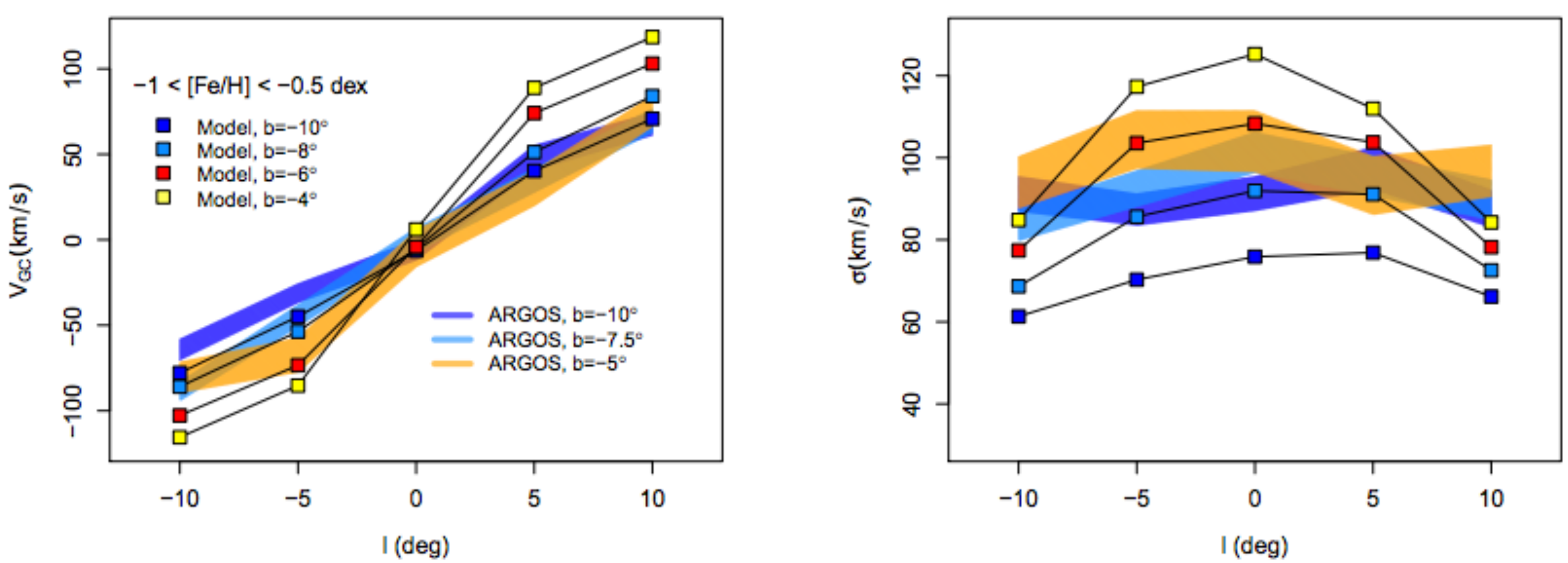


✓

C



di Matteo+ 2015

Interpret different populations within instability formation

Debattista, (2016), submitted (also see di Matteo 2015)

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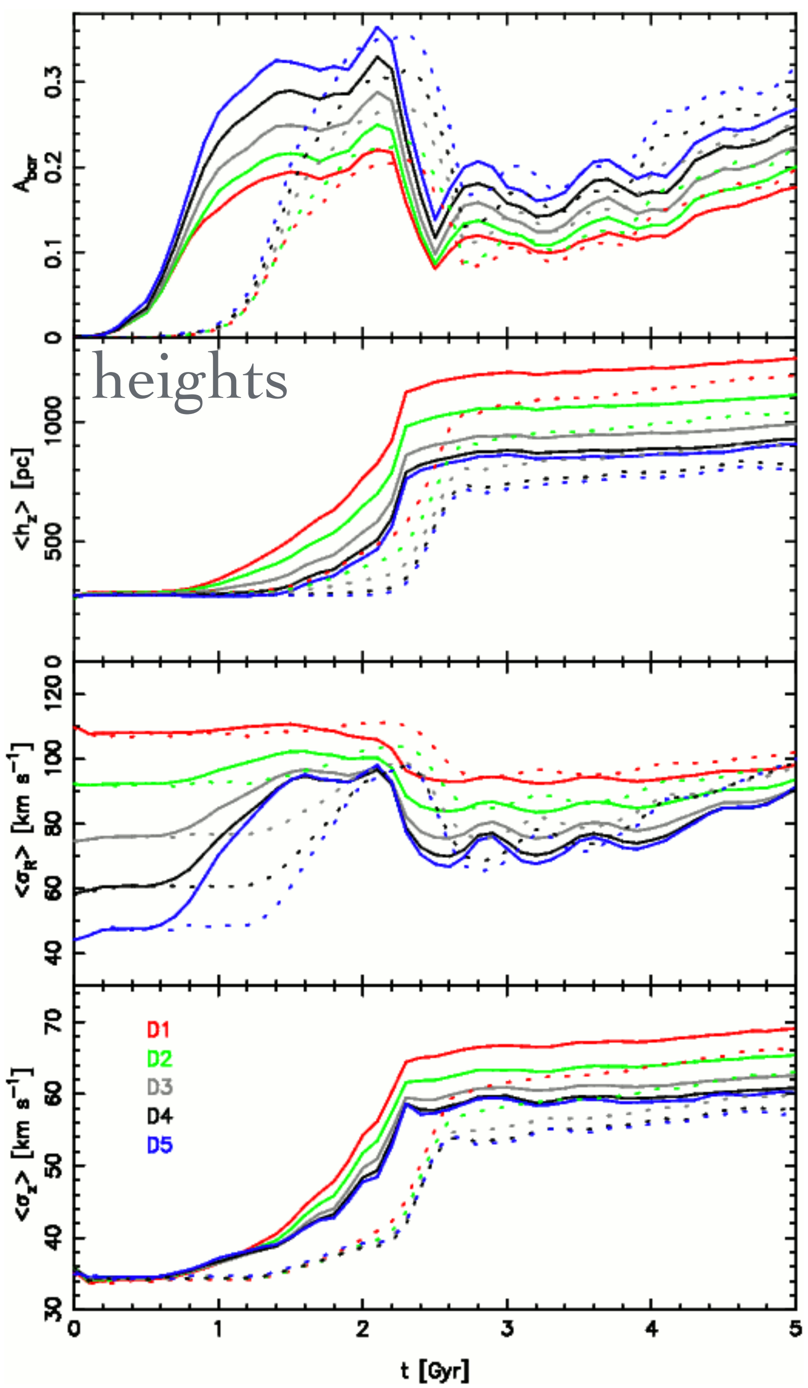
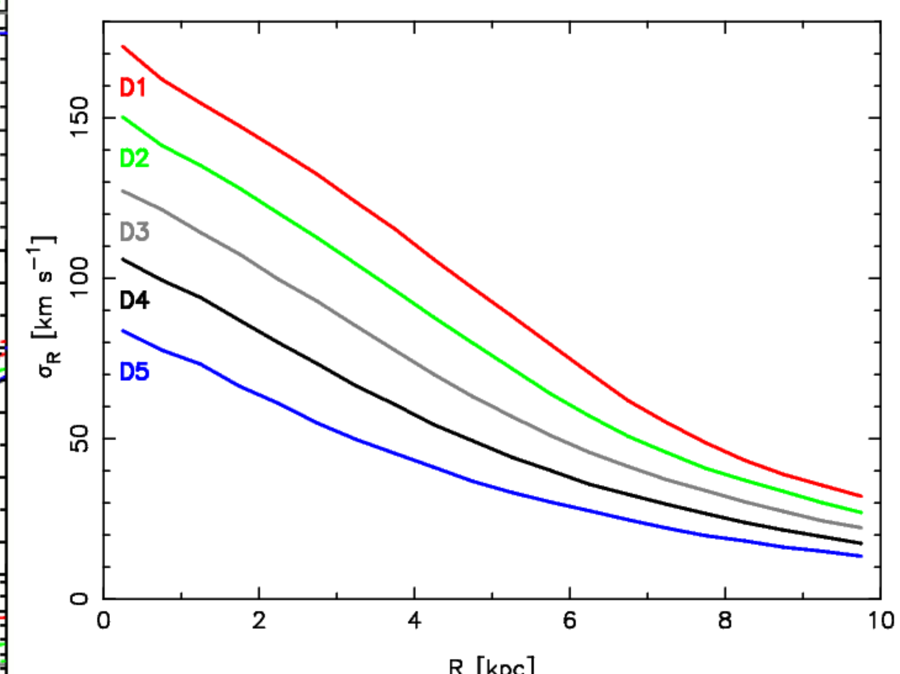
bar amplitudes

average radial velocity dispersion





average vertical velocity dispersion

Initially co-incident populations - separated by the bar

- Kinematic fractionation (Debattista et al., 2016 - submitted)

- radially cool populations form a strong bar, vertically thin & peanut shaped
- hotter populations form a weaker bar & become a vertically thicker box

Simulation after 5 Gyr

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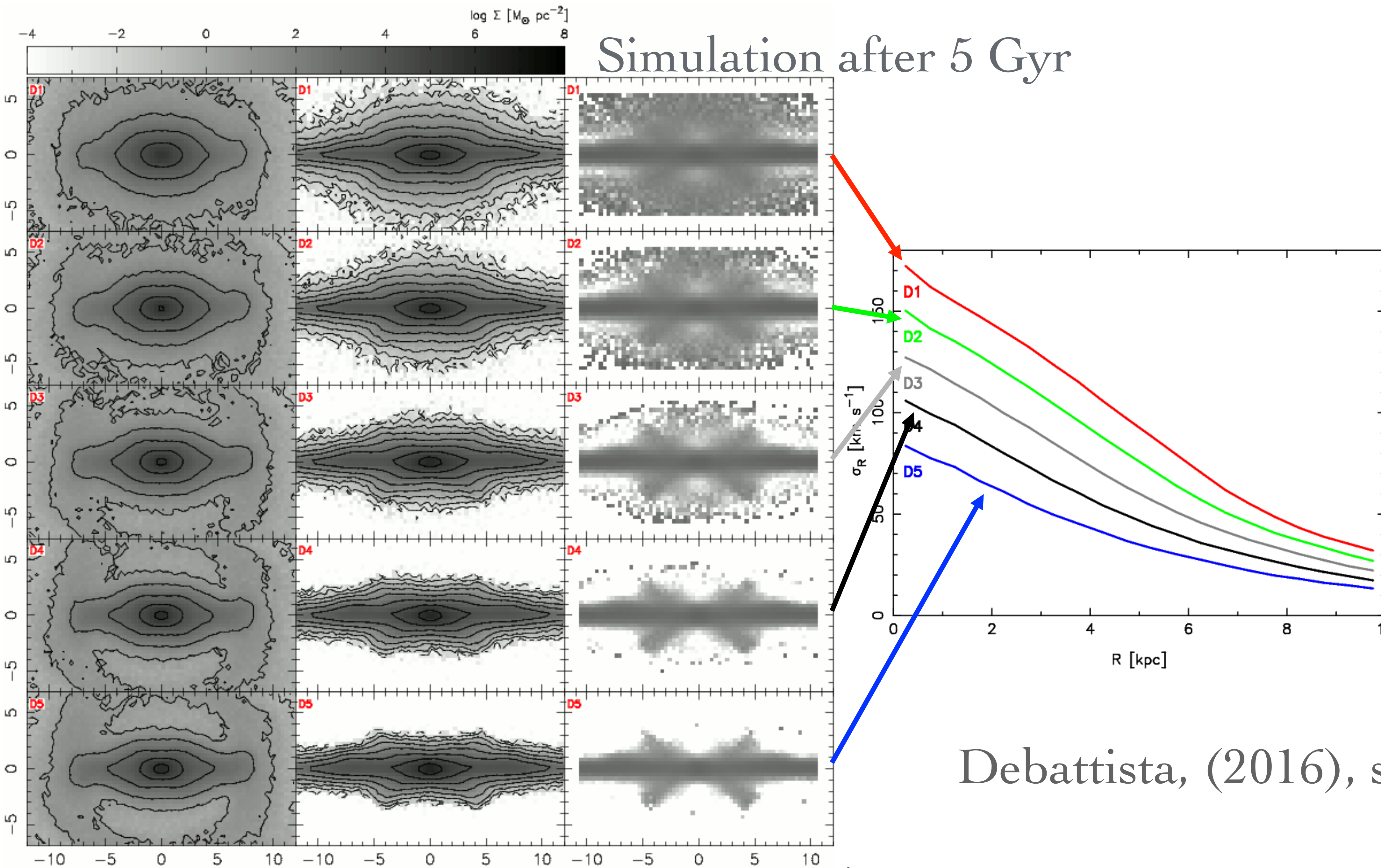
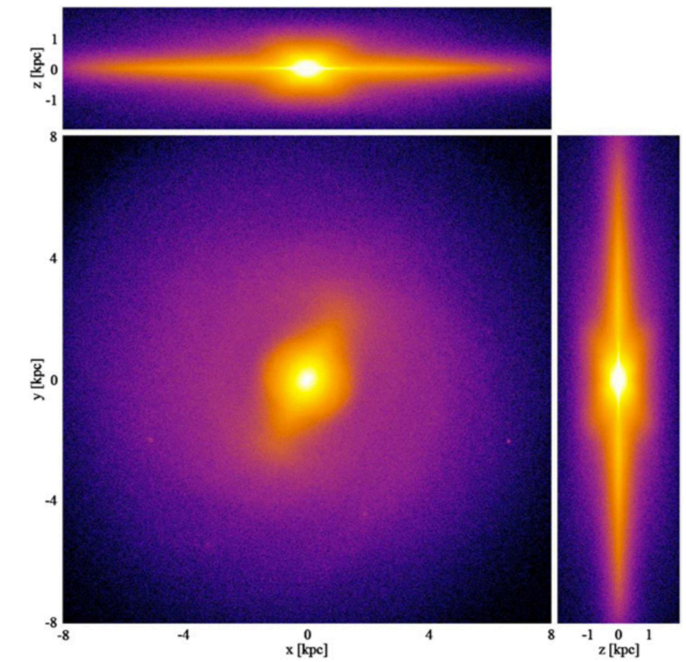


Debattista, (2016), submitted

Now a more sophisticated simulation



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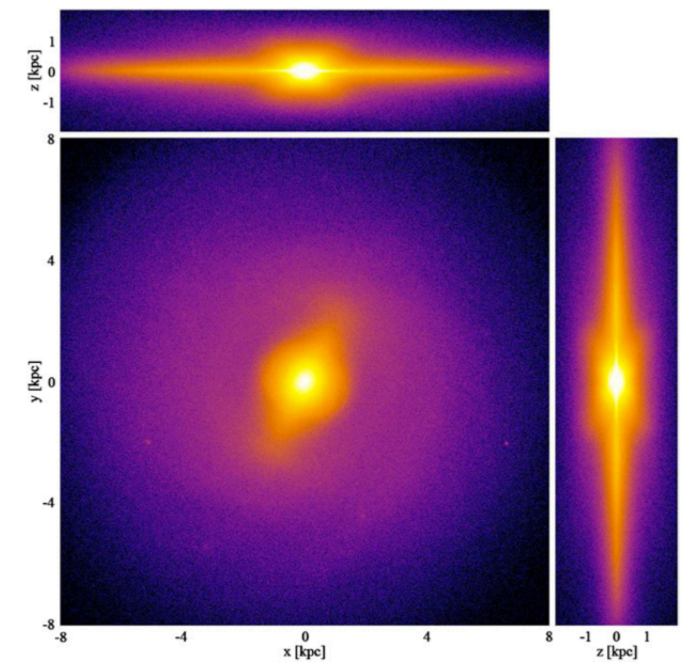
- Use this idea to examine a high-resolution simulation with gas, continuous star formation, feedback, chemistry



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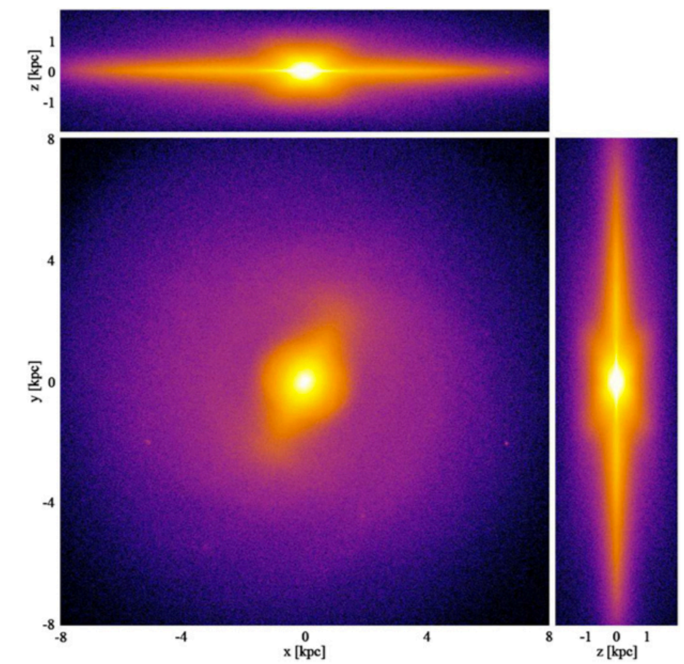

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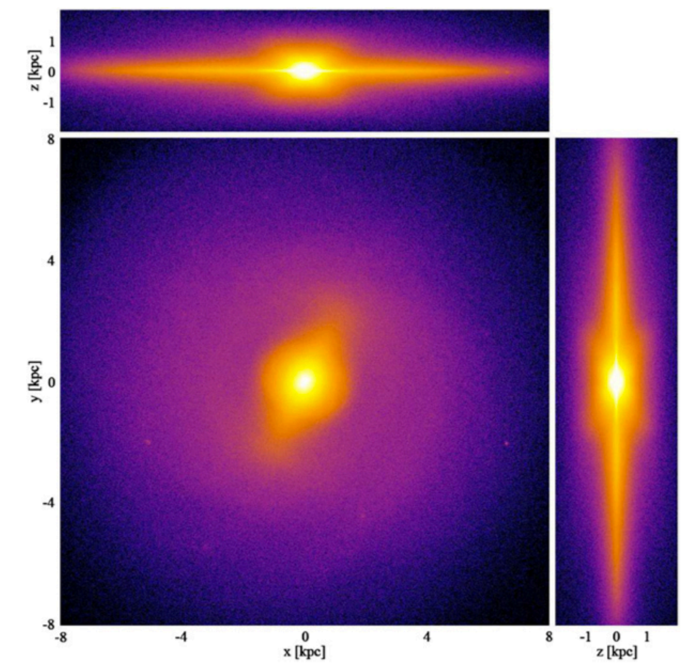

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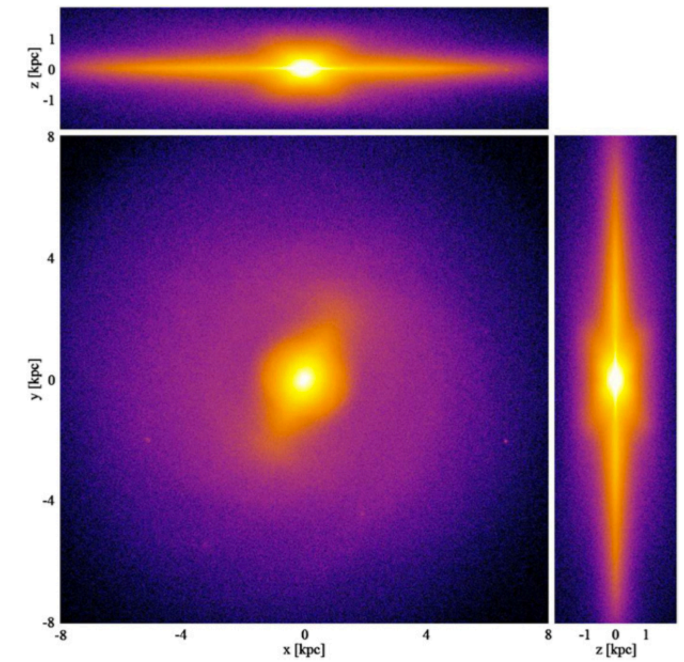
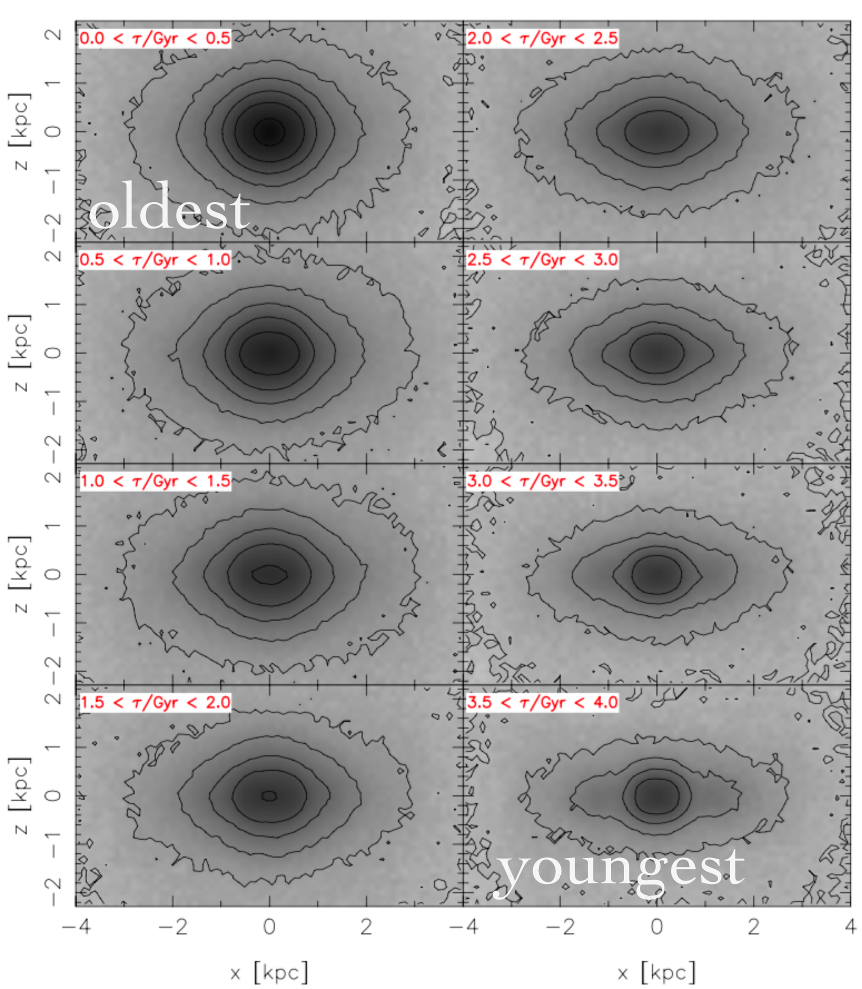
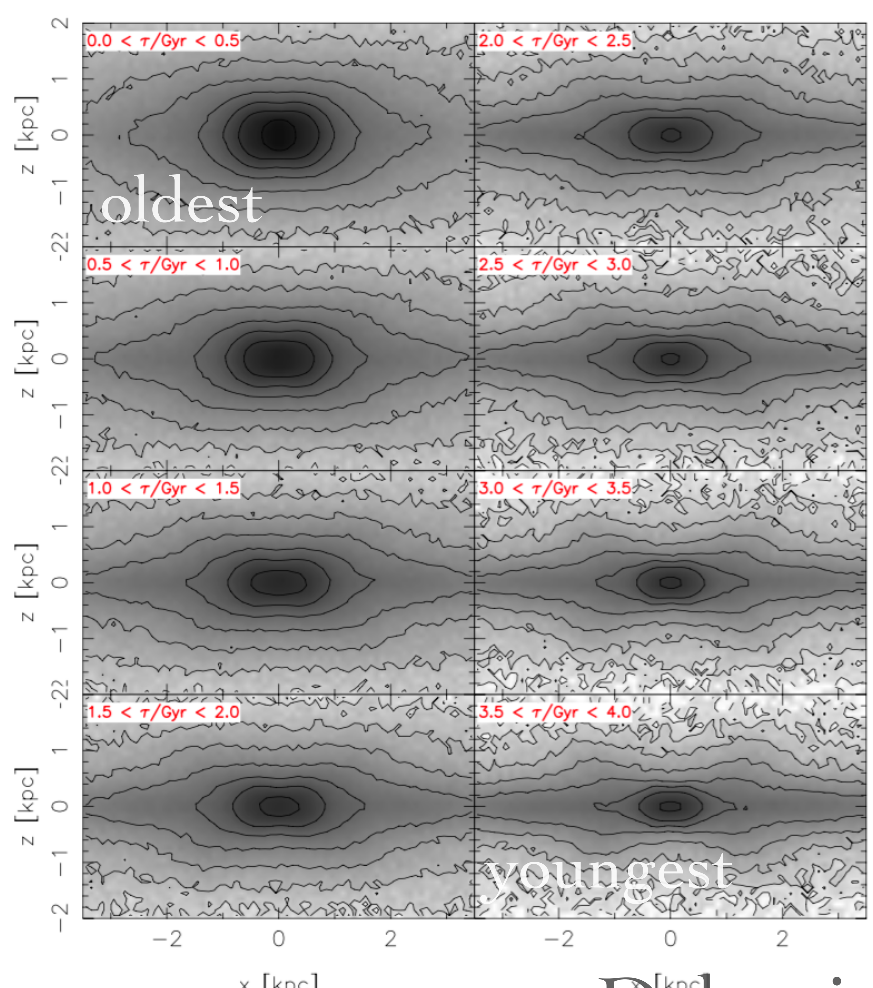


Ness+ 2014





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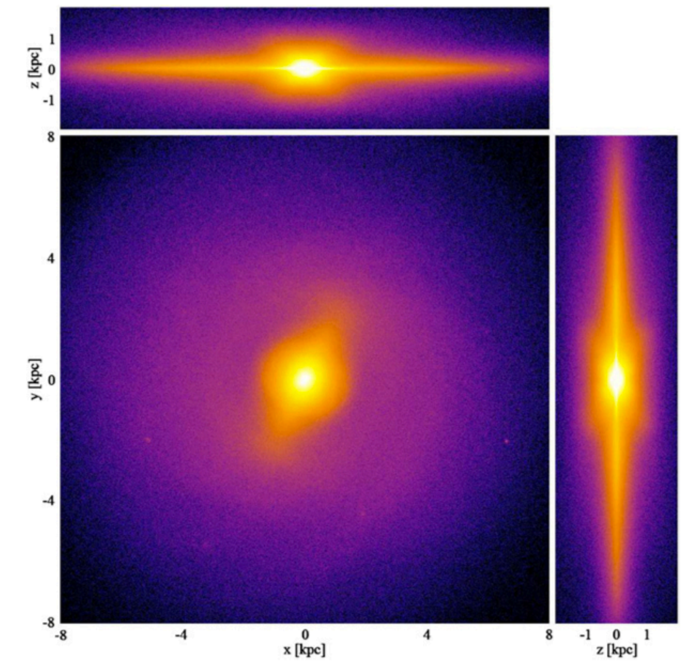

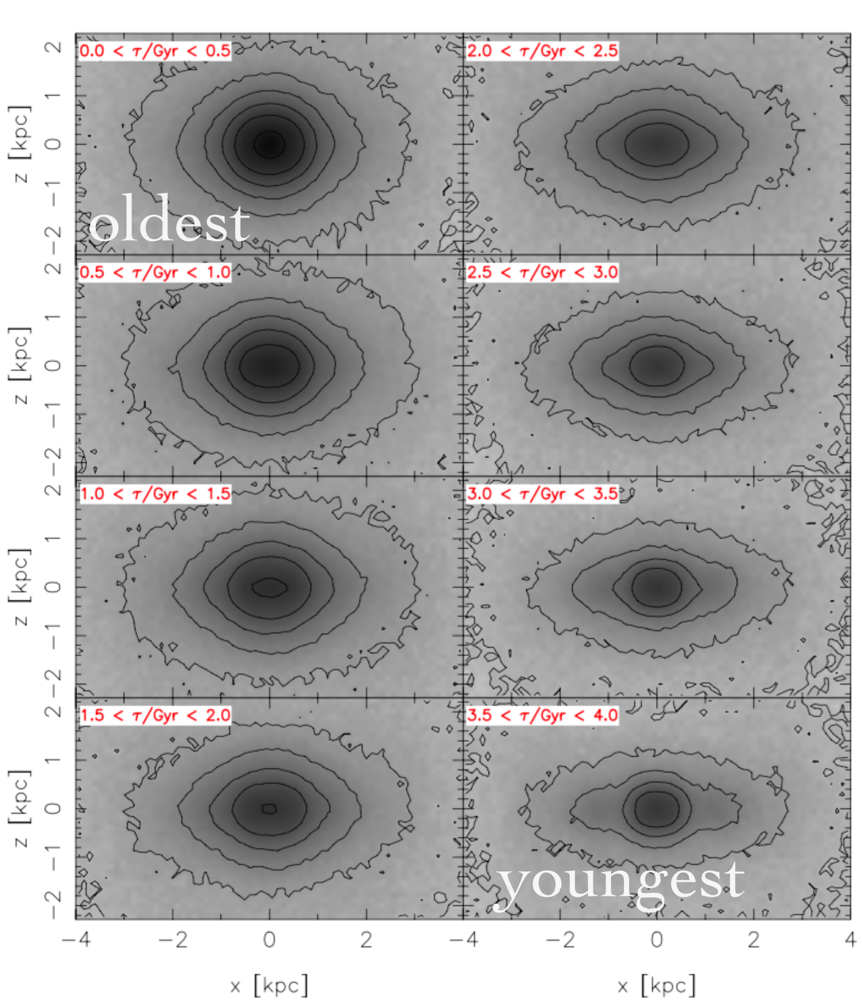

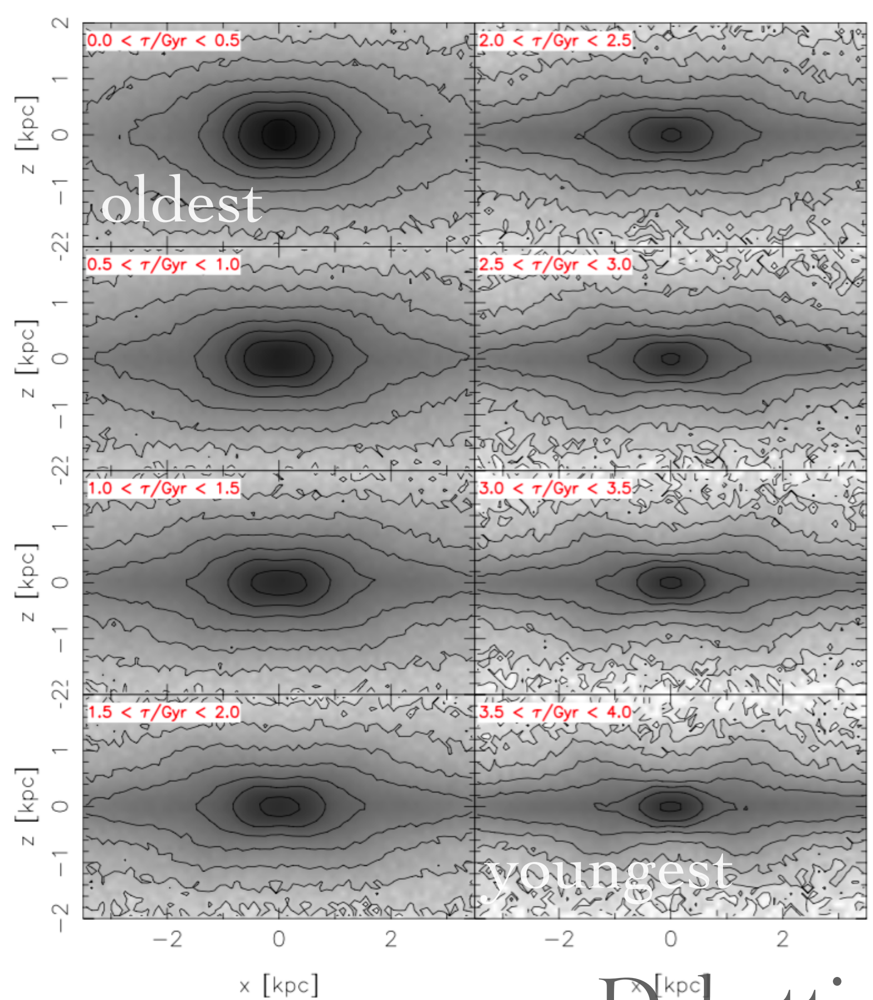

- oldest population thick disk

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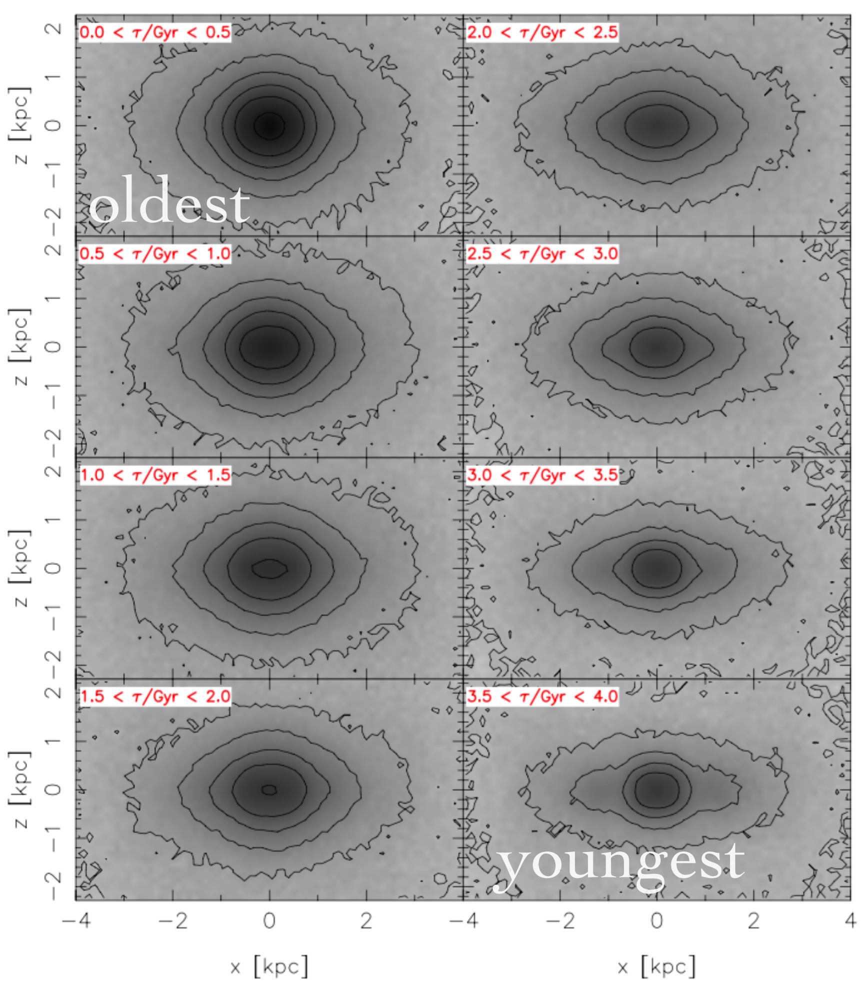
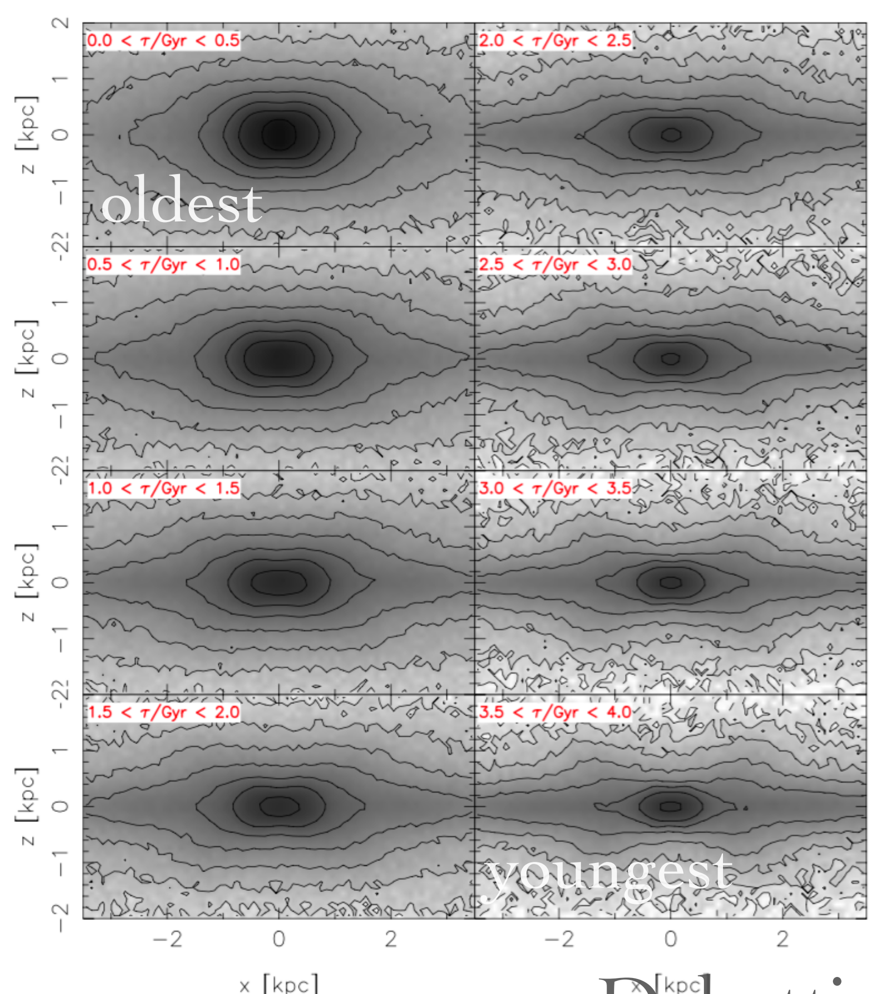
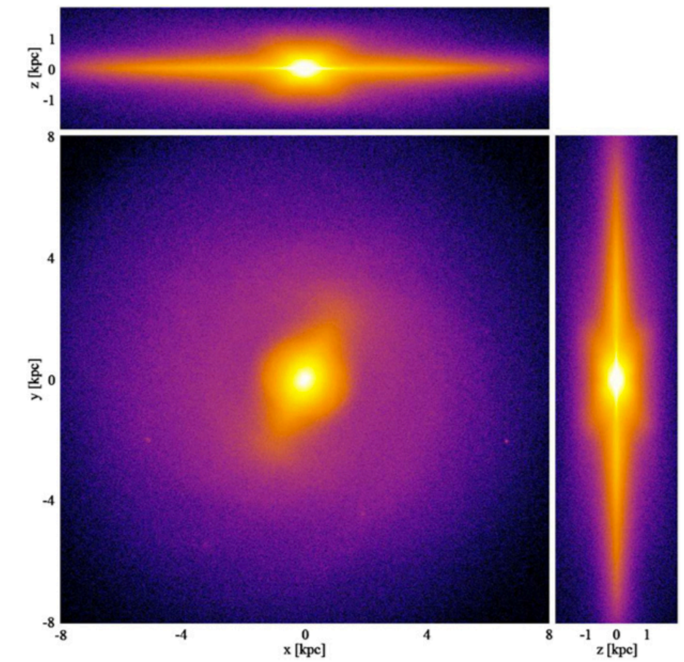






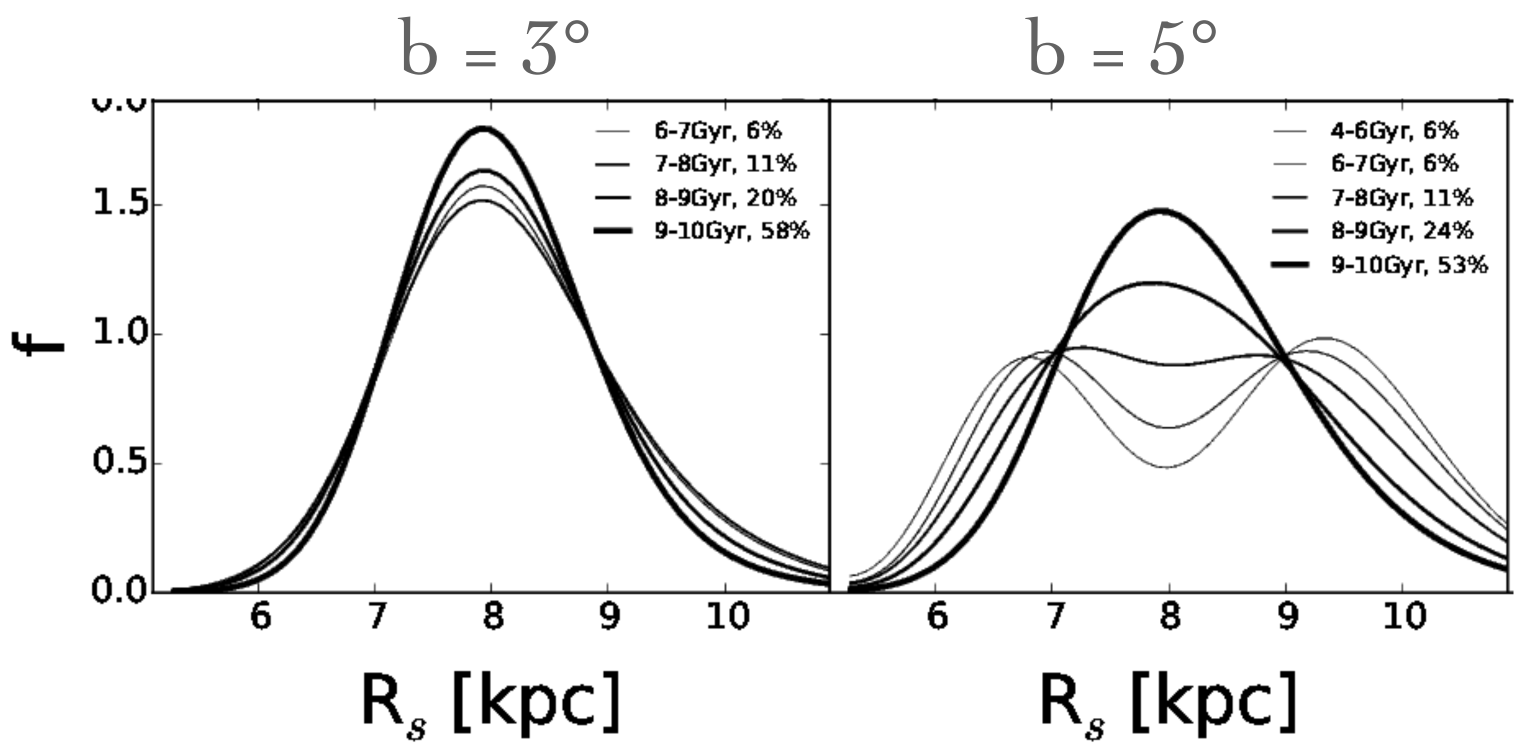
Ness+ 2014

- oldest population thick disk
- younger population barred and boxy

Debattista, (2016), submitted

Model explains split clump f[Fe/H]

Convolved with a σ = 0.17 mag RC width



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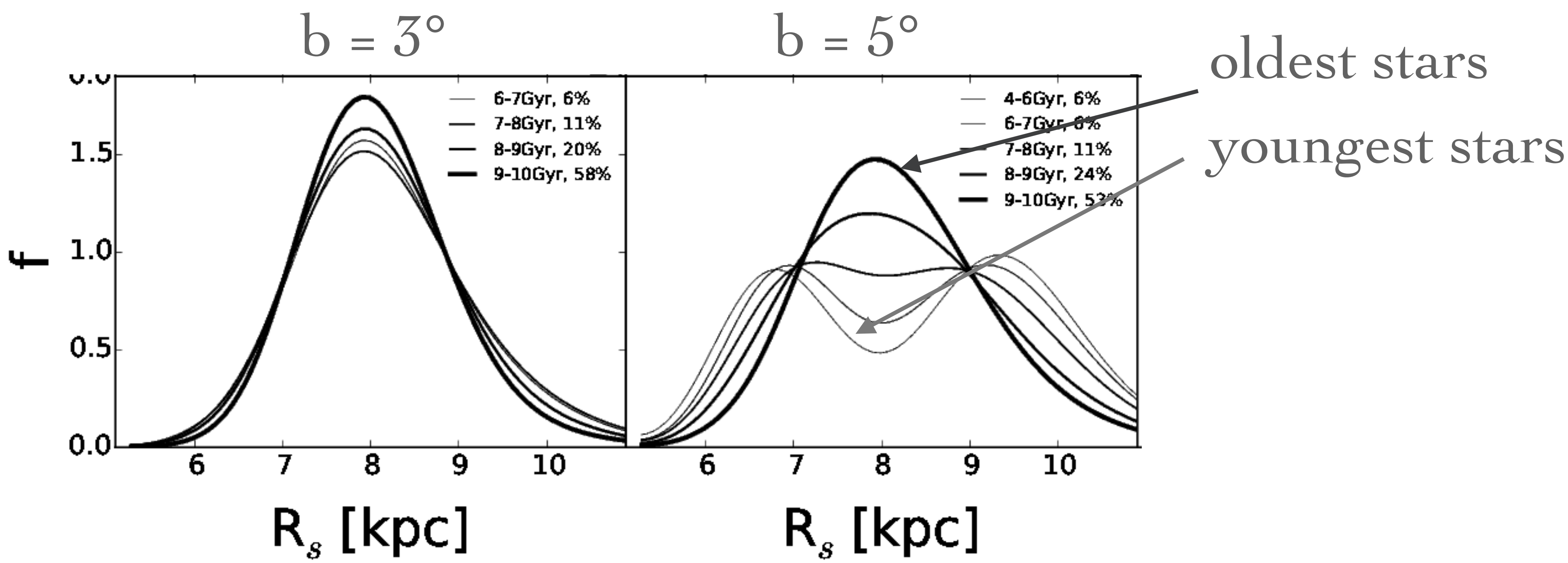

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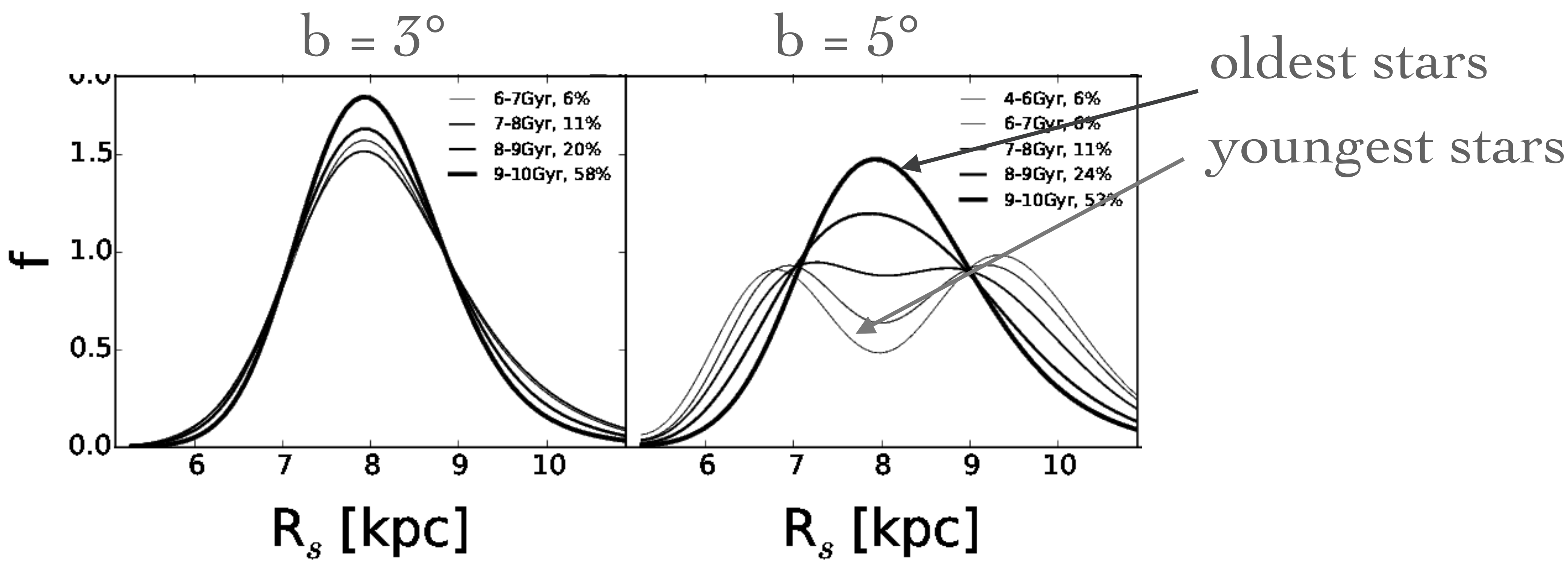

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- Younger stars are split in their distribution, older stars are not

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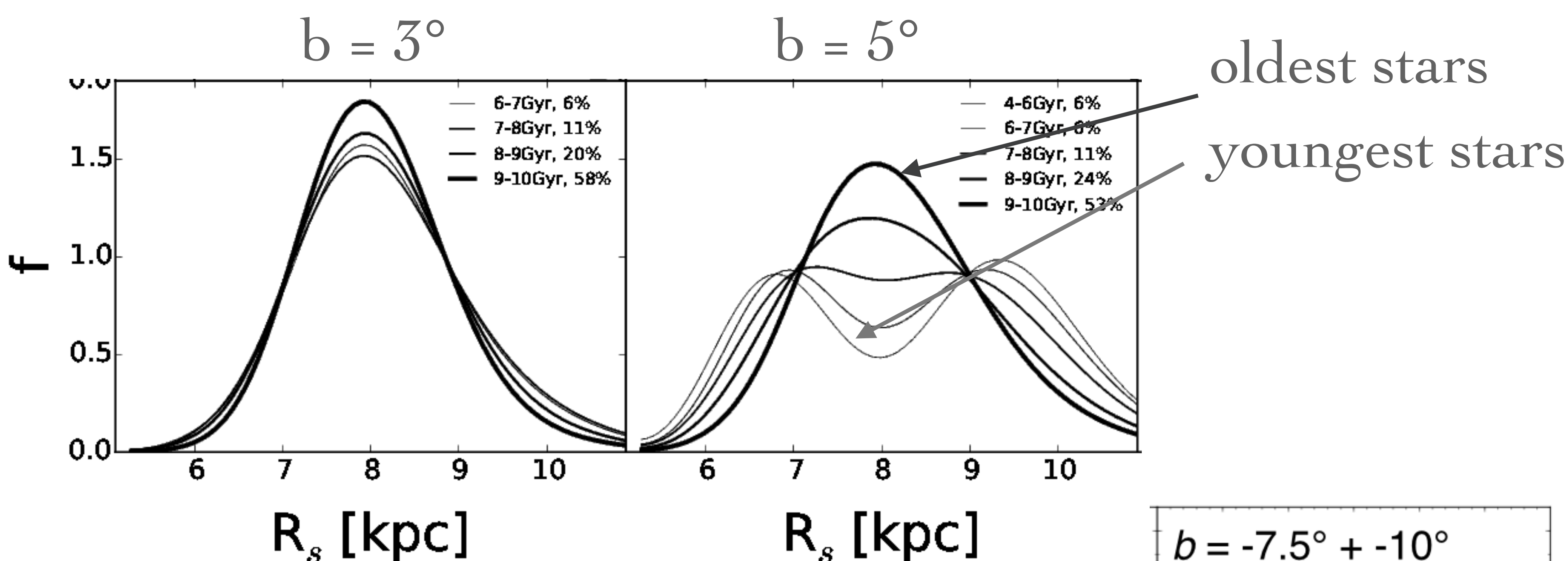

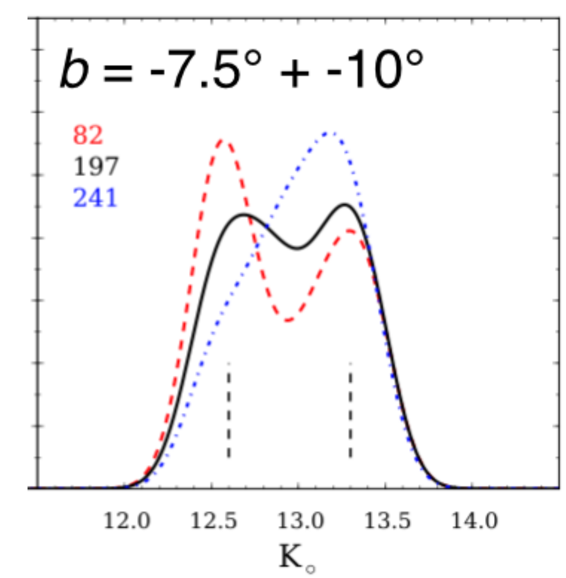

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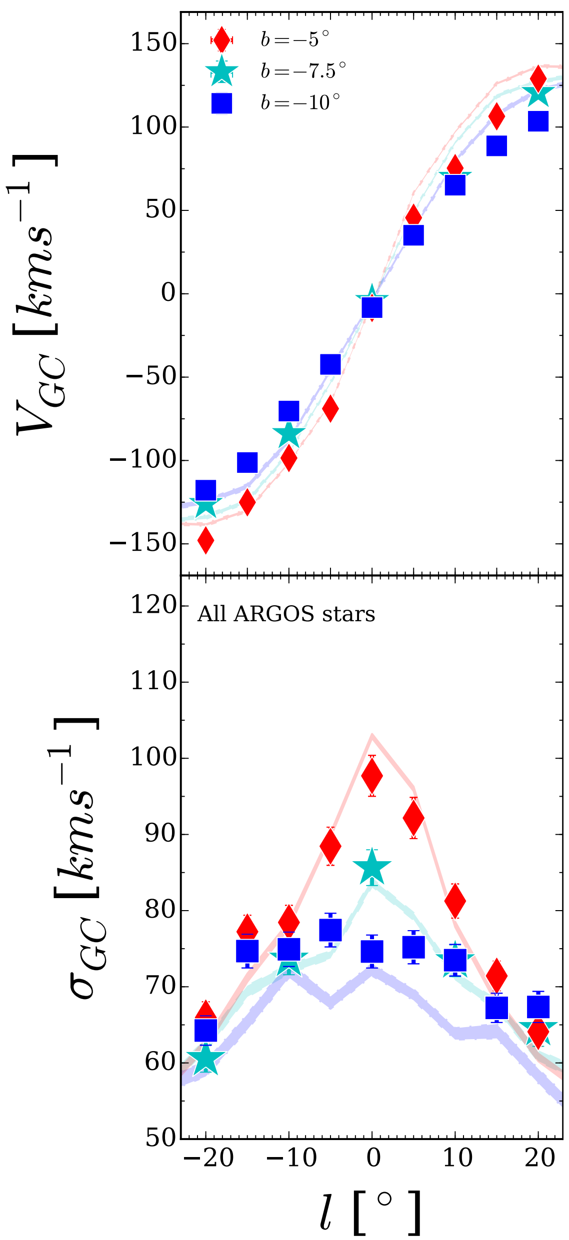
Kinematics as f([Fe/H])

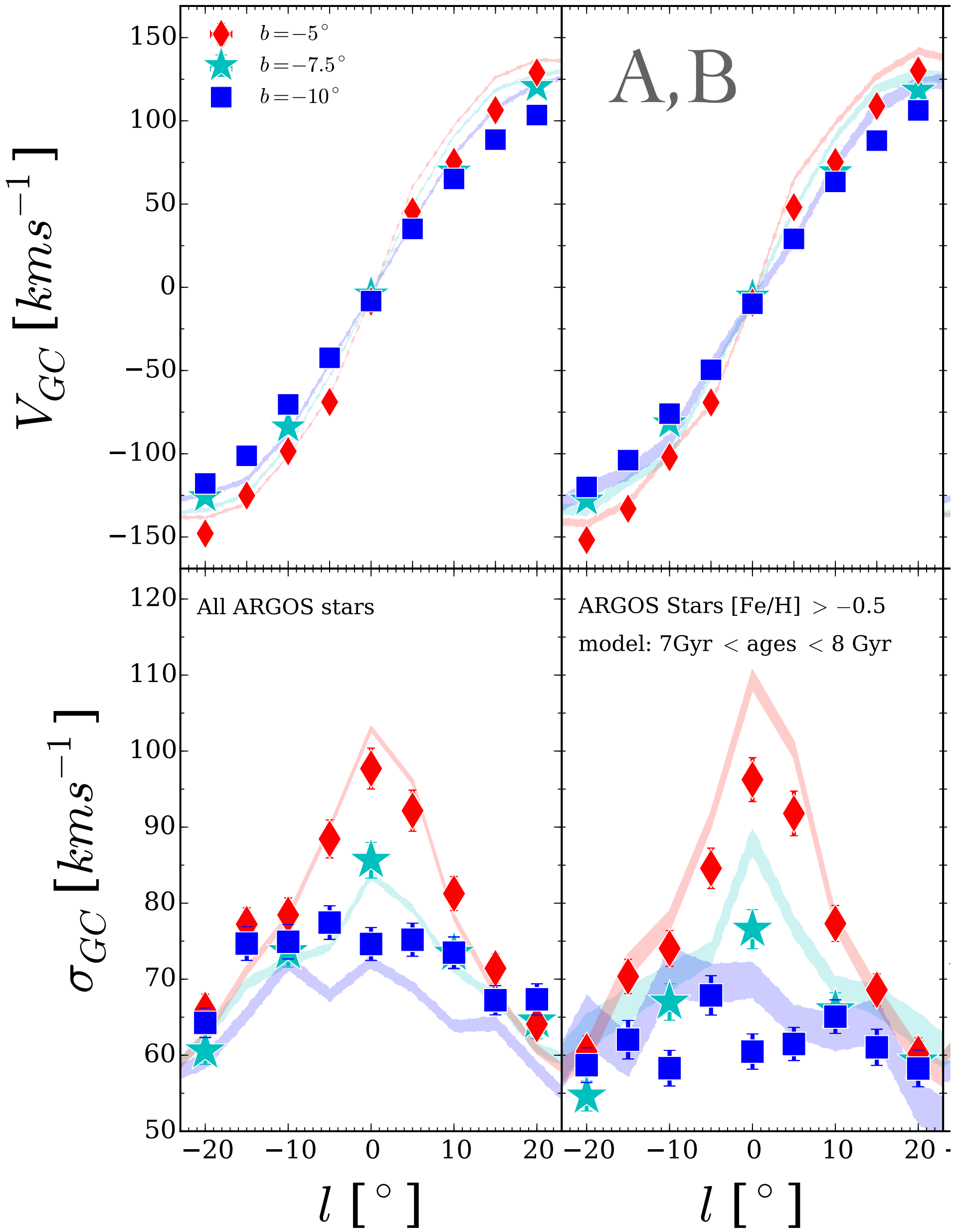
All stars



Debattista, (2016), submitted

Kinematics as f([Fe/H])

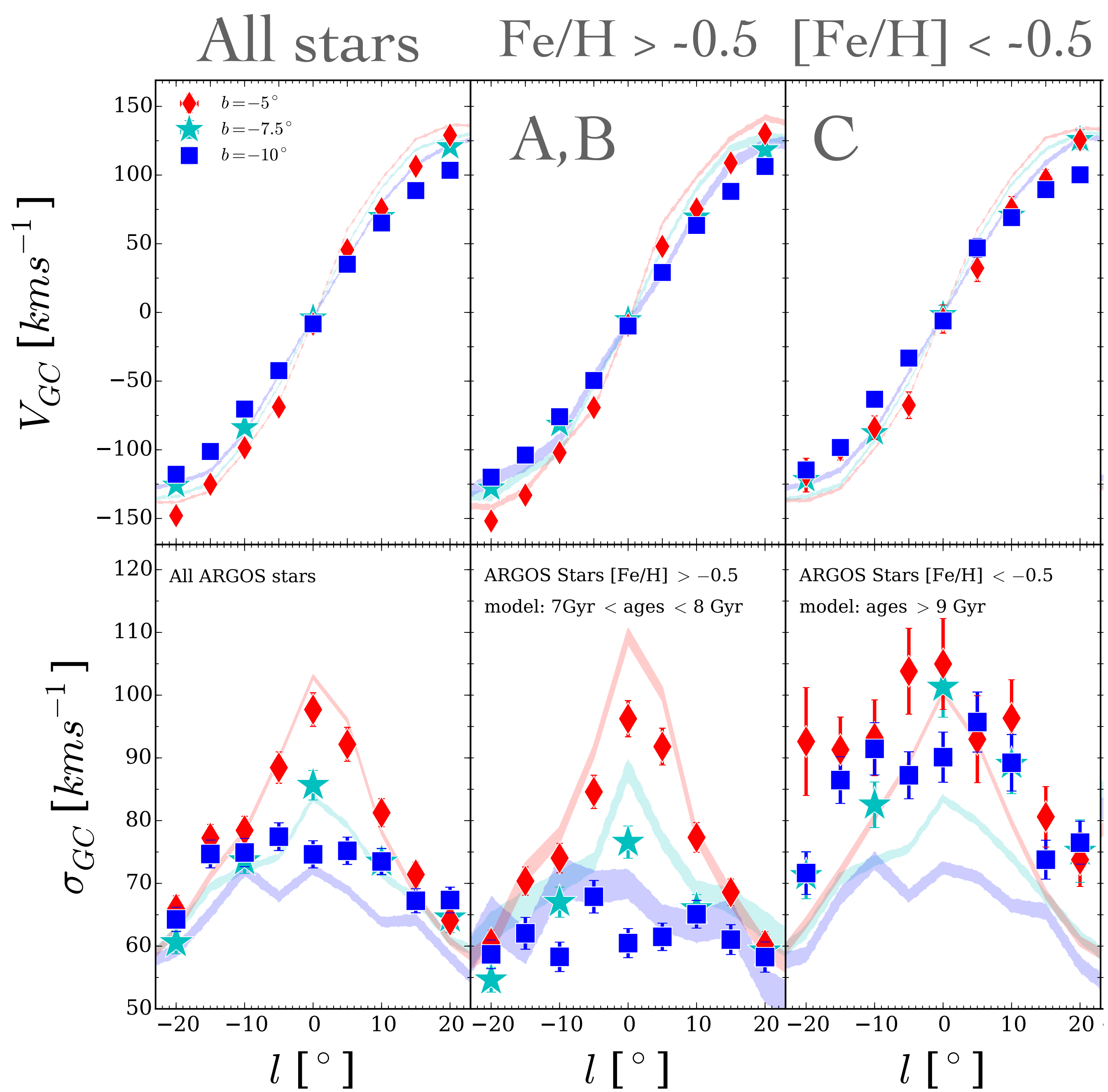
All stars Fe/H > -0.5



Debattista, (2016), submitted

Kinematics as f([Fe/H])

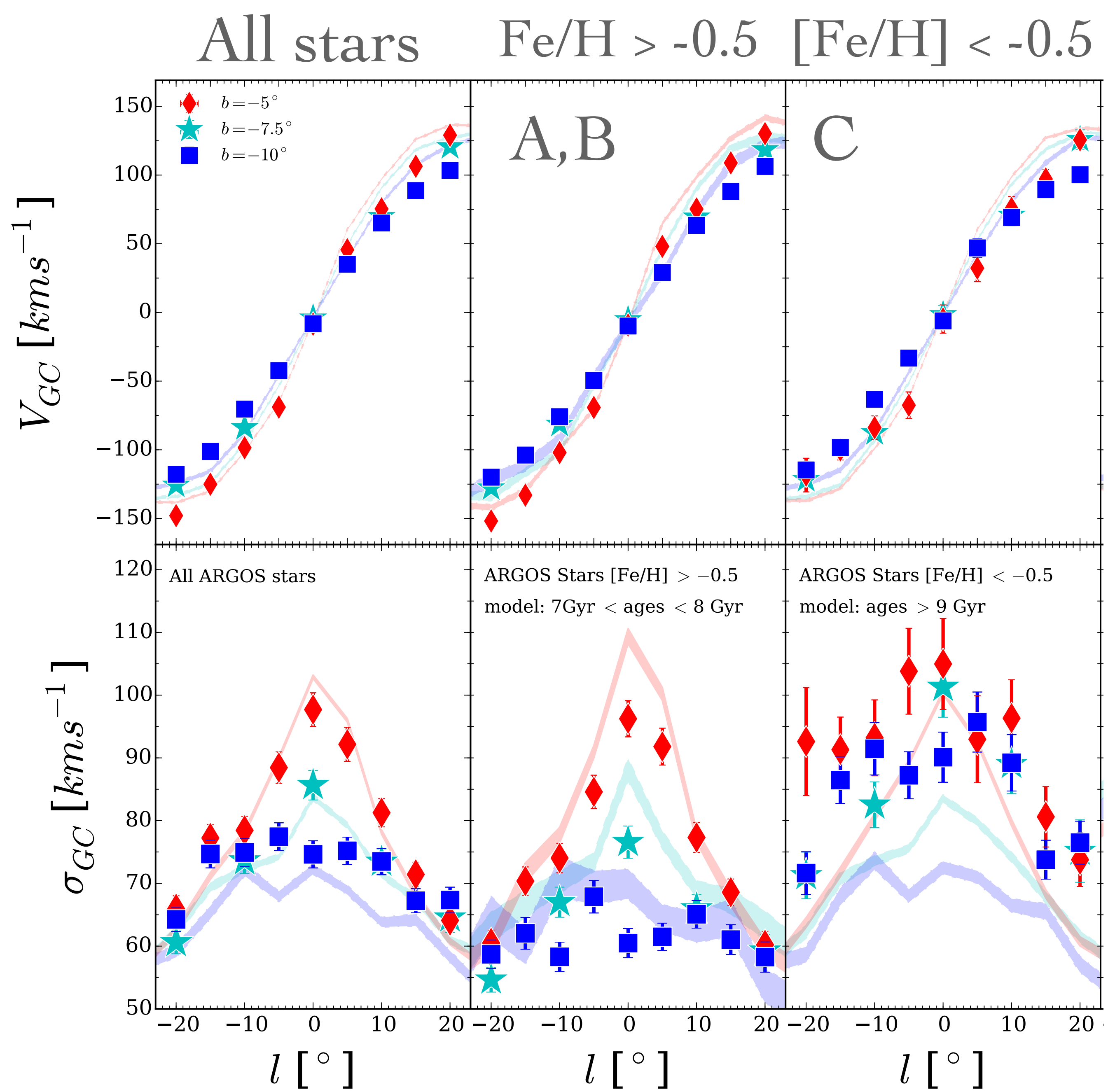
D,E



Kinematics as f([Fe/H])

D,E

- 5% hot population required to reproduce population C in ARGOS [Fe/H] < -0.5



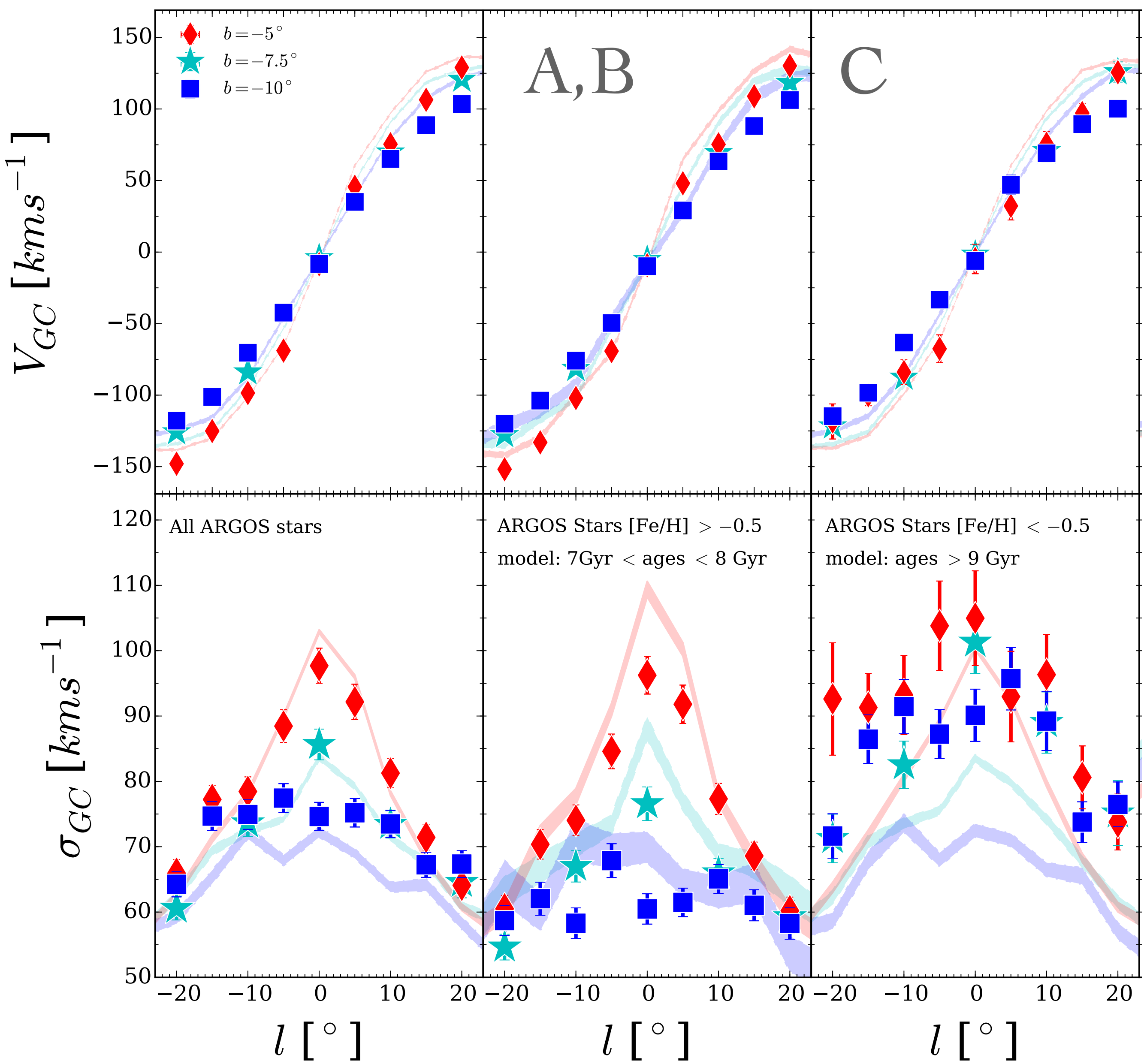
Kinematics as f([Fe/H])

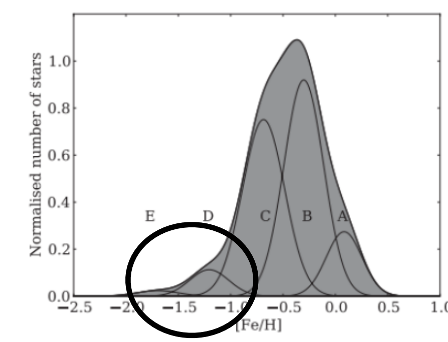
D,E

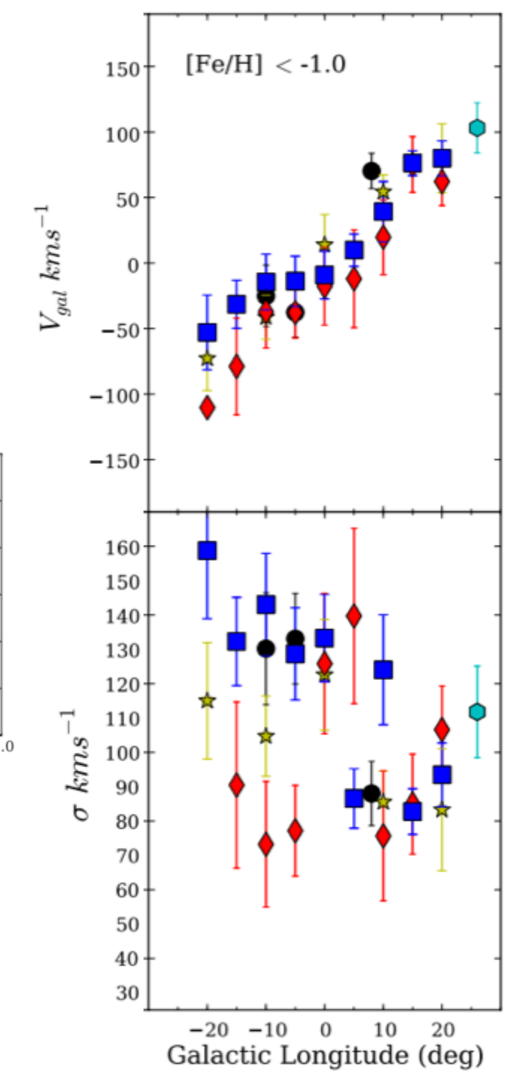
500 stars (28%)

- 5% hot population required to reproduce population C in ARGOS [Fe/H] < -0.5

All stars   Fe/H > -0.5   [Fe/H] < -0.5







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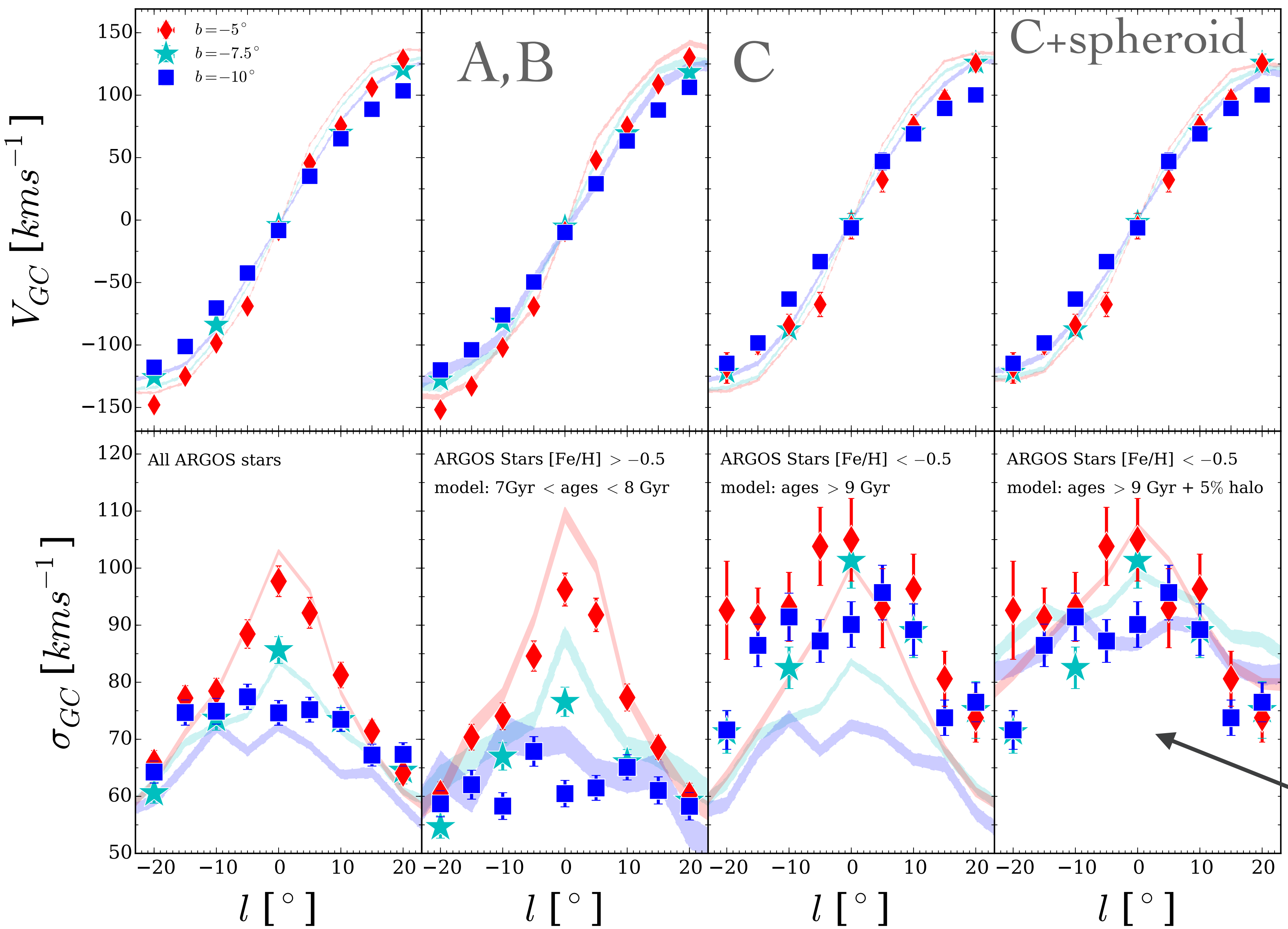
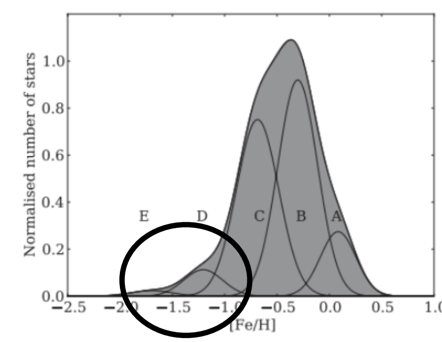
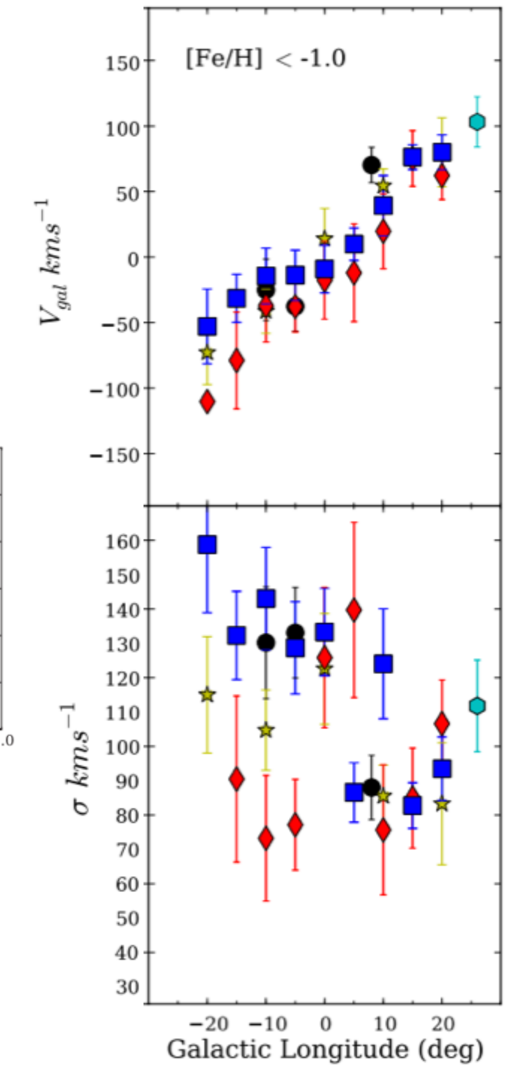




D,E

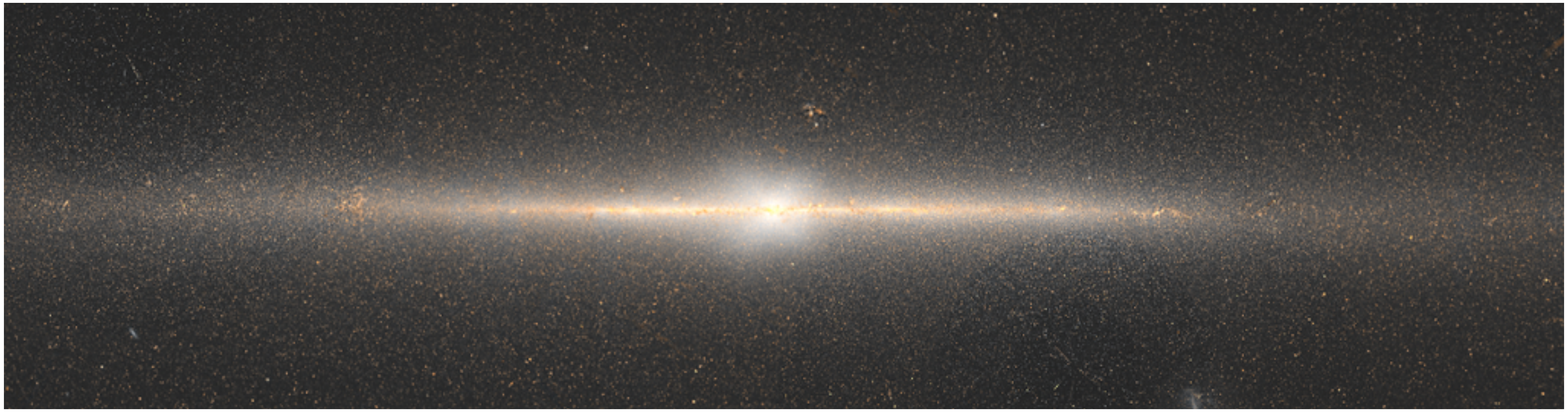
500 stars (28%)



+5% hot population

Debattista, (2016), submitted

The Milky Way bulge has (largely ~ 95%) formed from the disk



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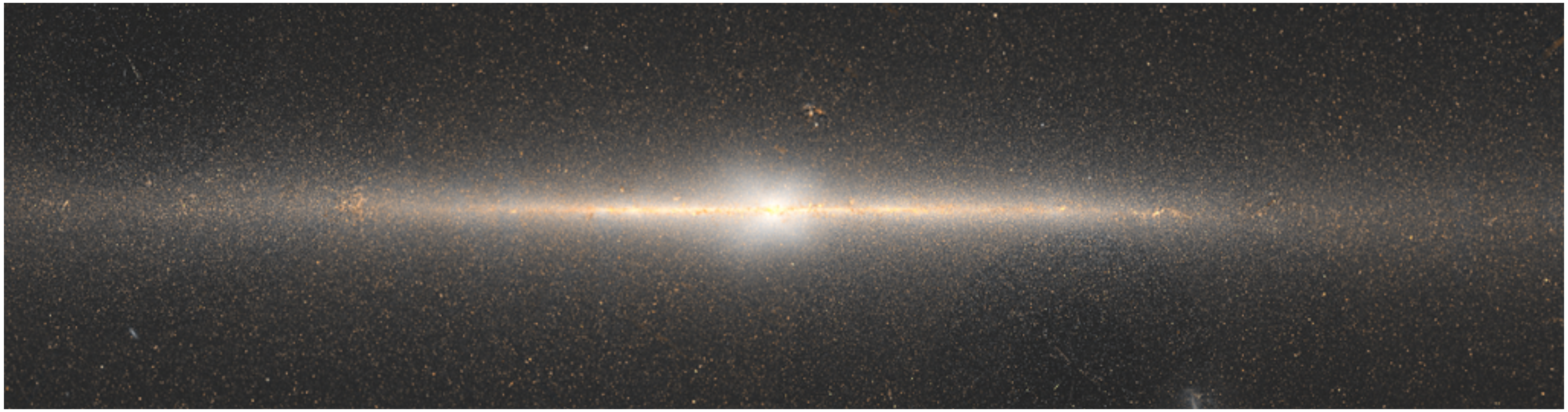


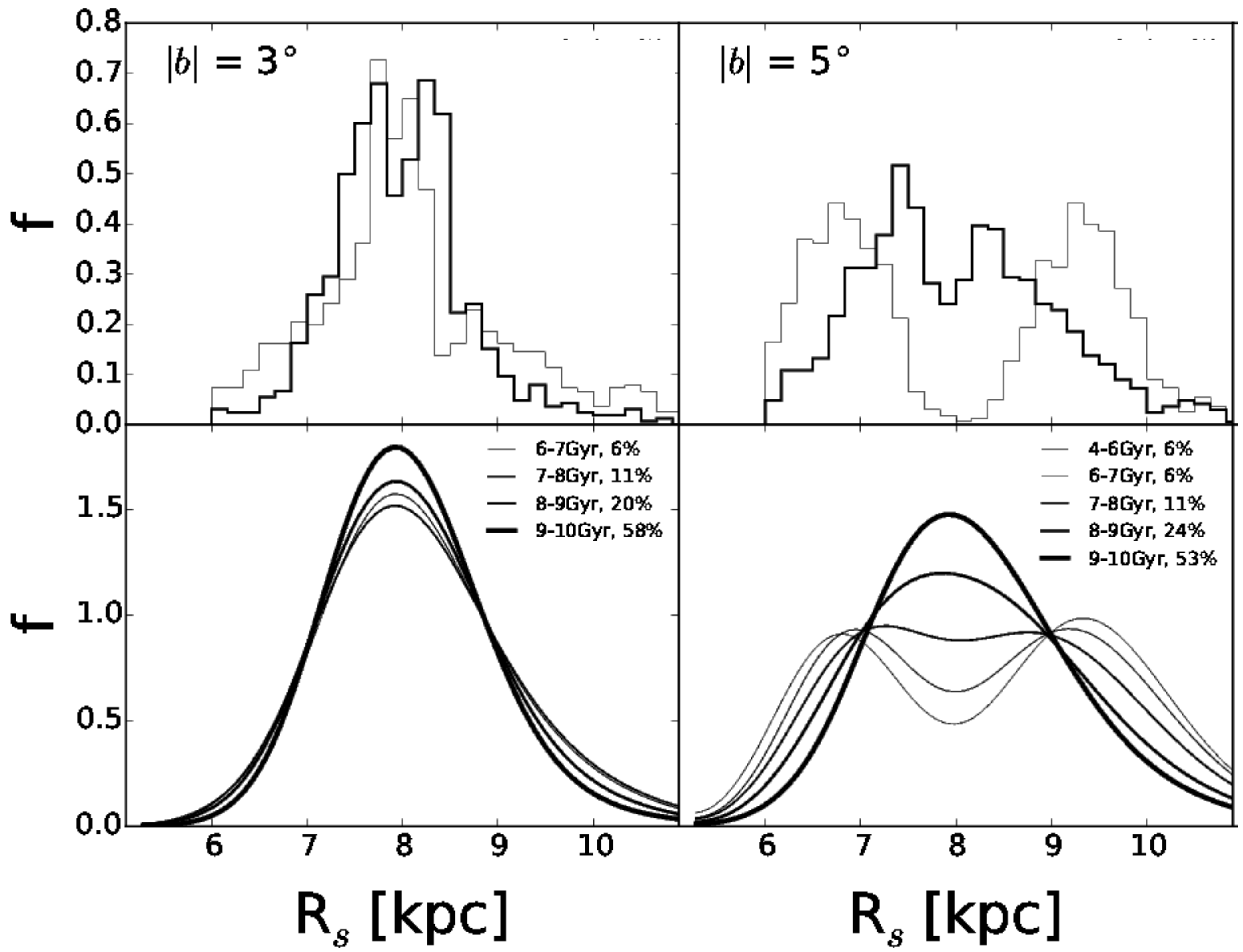
- MW bulge is not atypical — indicative of a quiet life for many spirals
- Instability formation — not all stars participate in X — youngest stars most strongly split — oldest stars thick disk
- Can not explain latitude independent velocity dispersion [Fe/H] < -0.5 by disk formation alone — need a 5% kinematically hot population — not part of disk formation - early merger origin? halo?

extra

Model explains split clump *f*[Fe/H]

Raw

Convolved with a σ = 0.17 mag RC width



Debattista, (2016), submitted

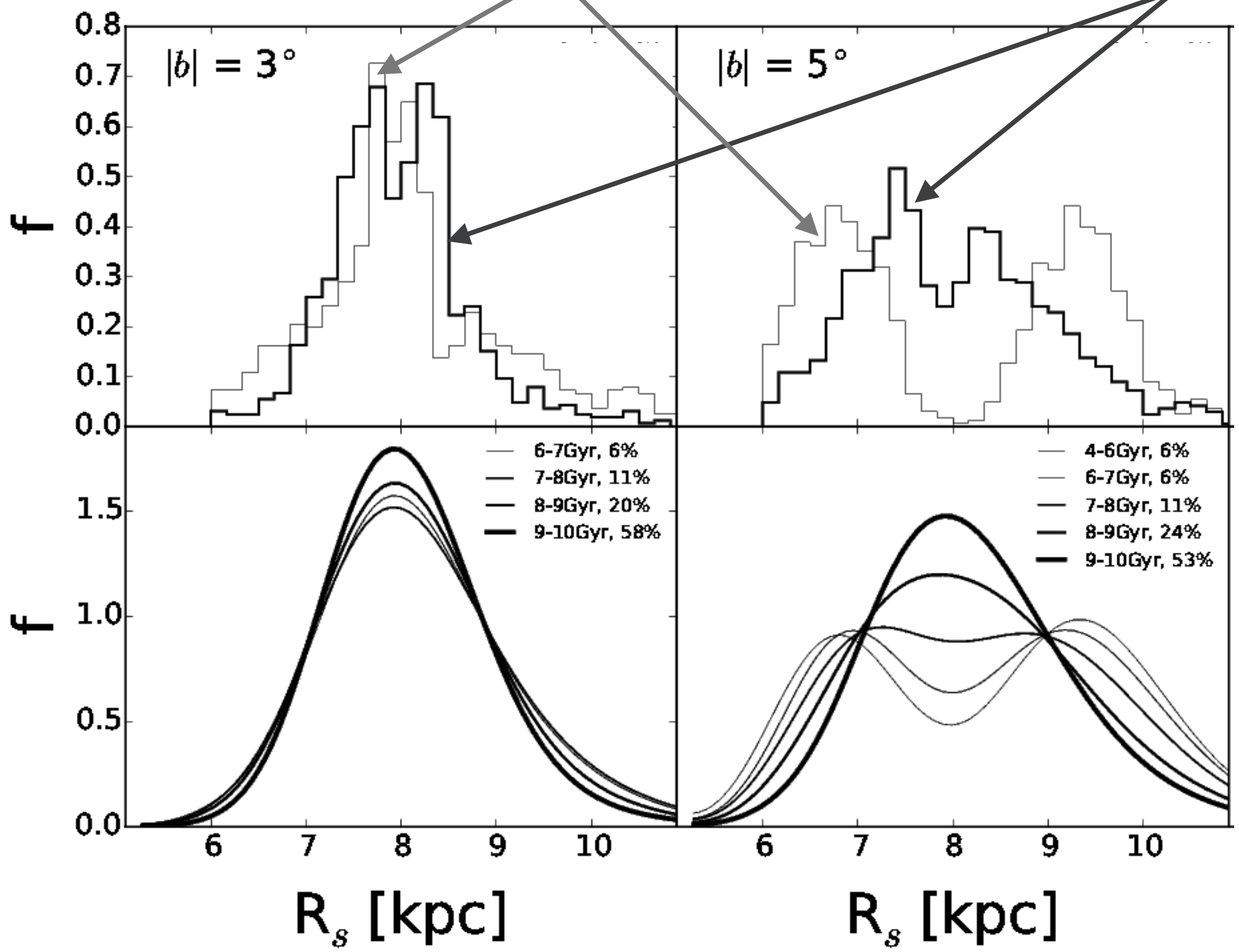
Model explains split clump f[Fe/H]

younger: 6-7 Gyr (6%)

older: 9-10 Gyr (60%)

Raw

Convolved with a σ = 0.17 mag RC width



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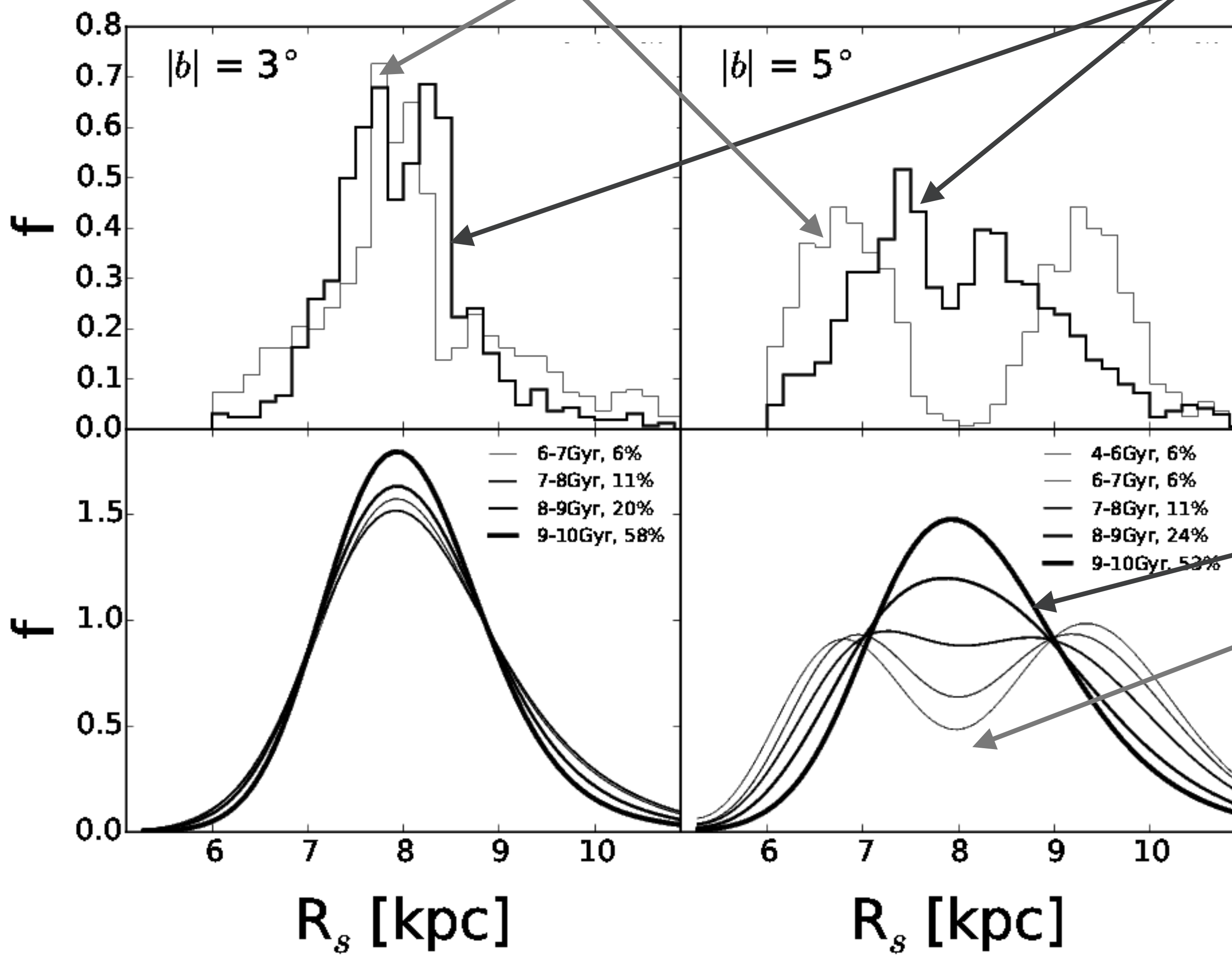

oldest stars

youngest stars

Debattista, (2016), submitted

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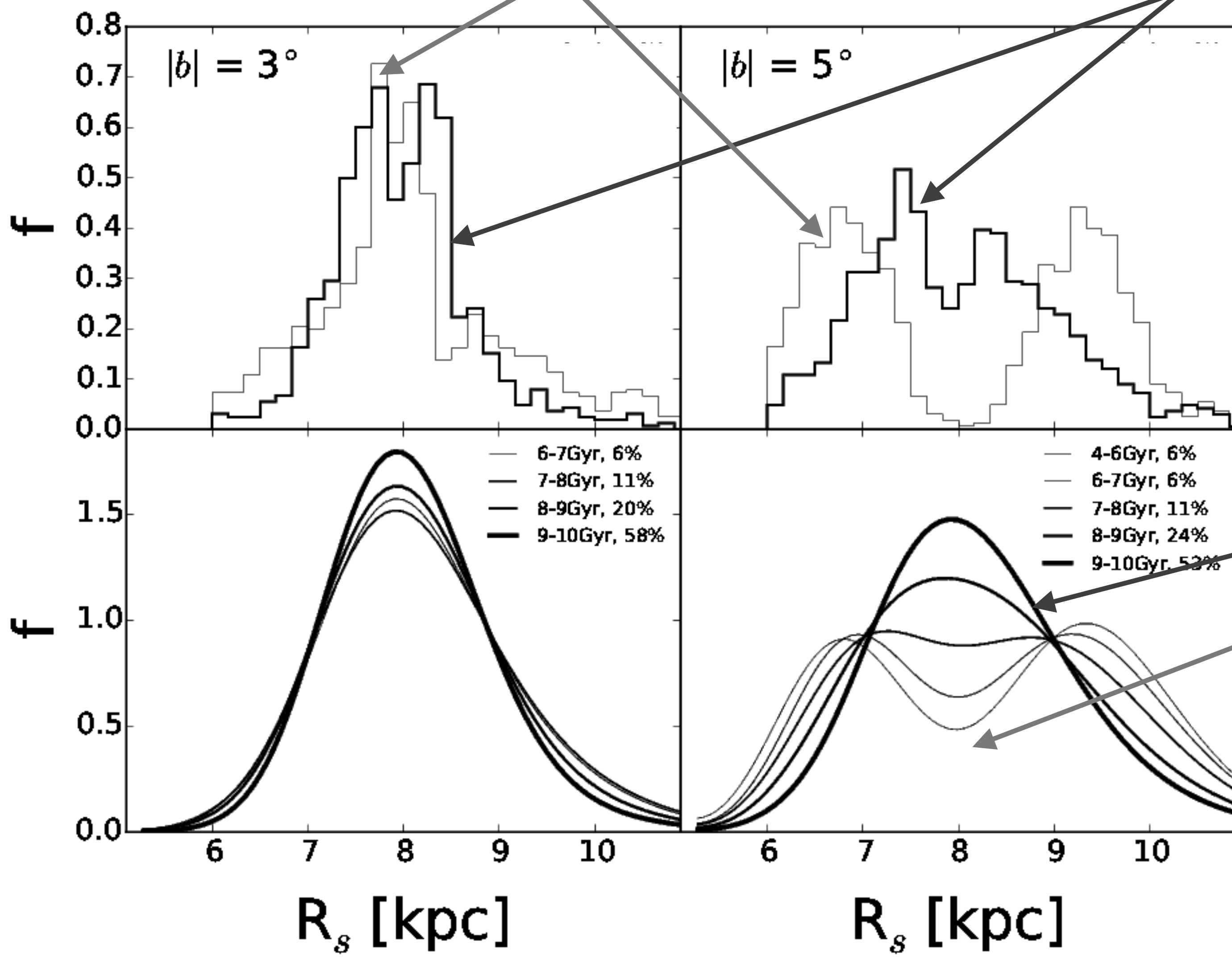

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Debattista, (2016), submitted

- Younger stars are split in their distribution, older stars are not

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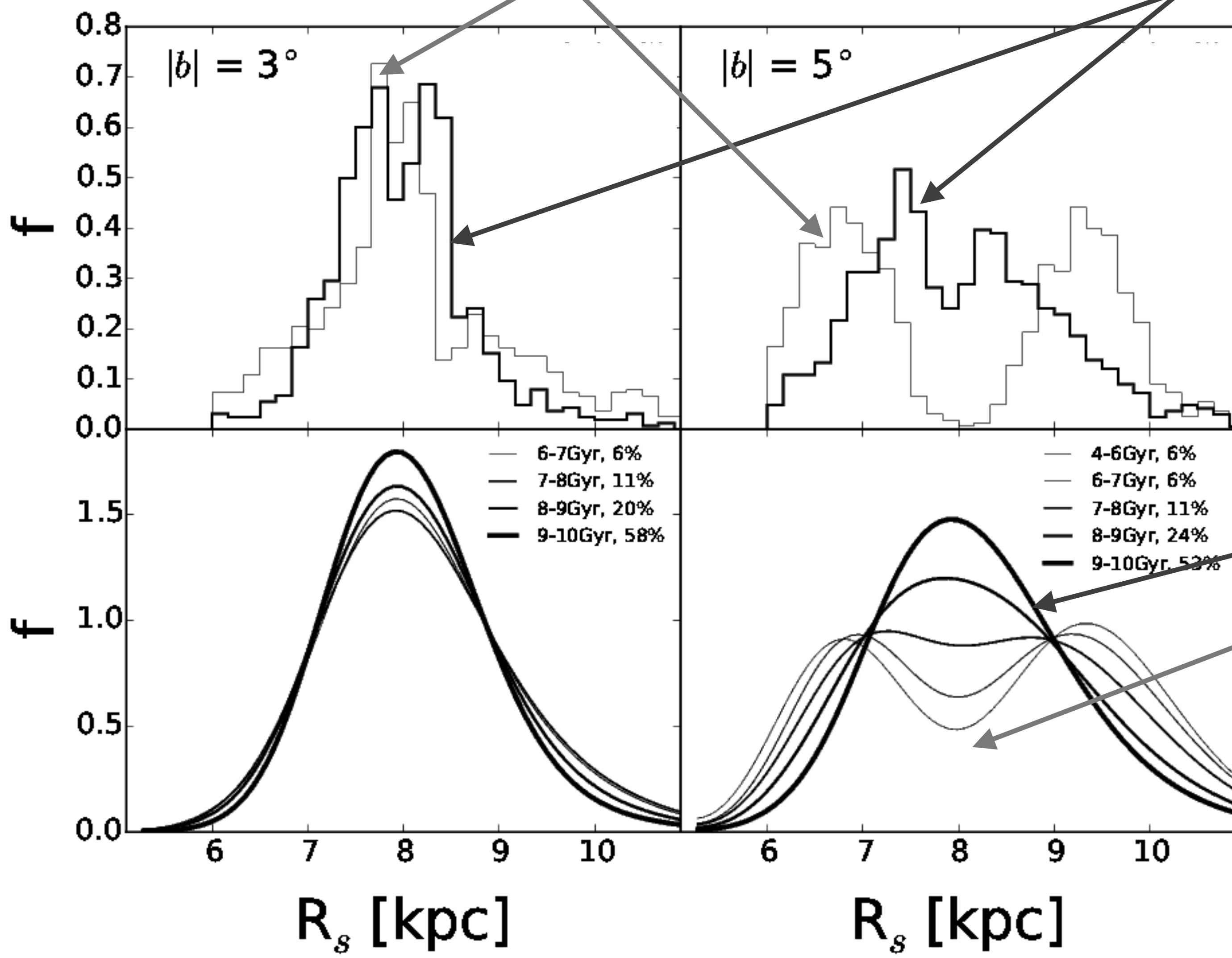
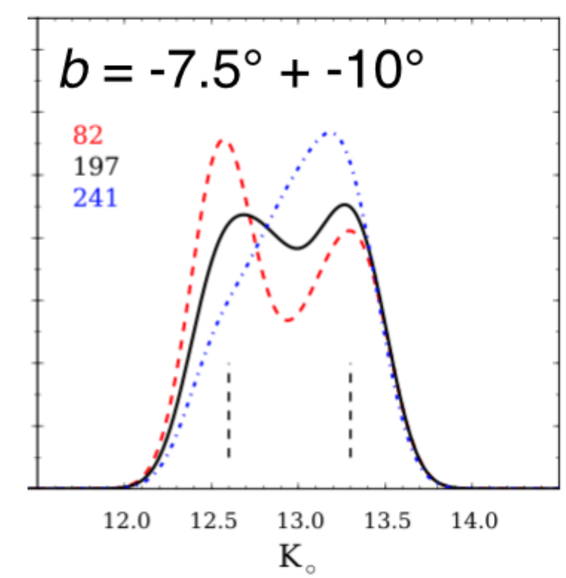


oldest stars

youngest stars



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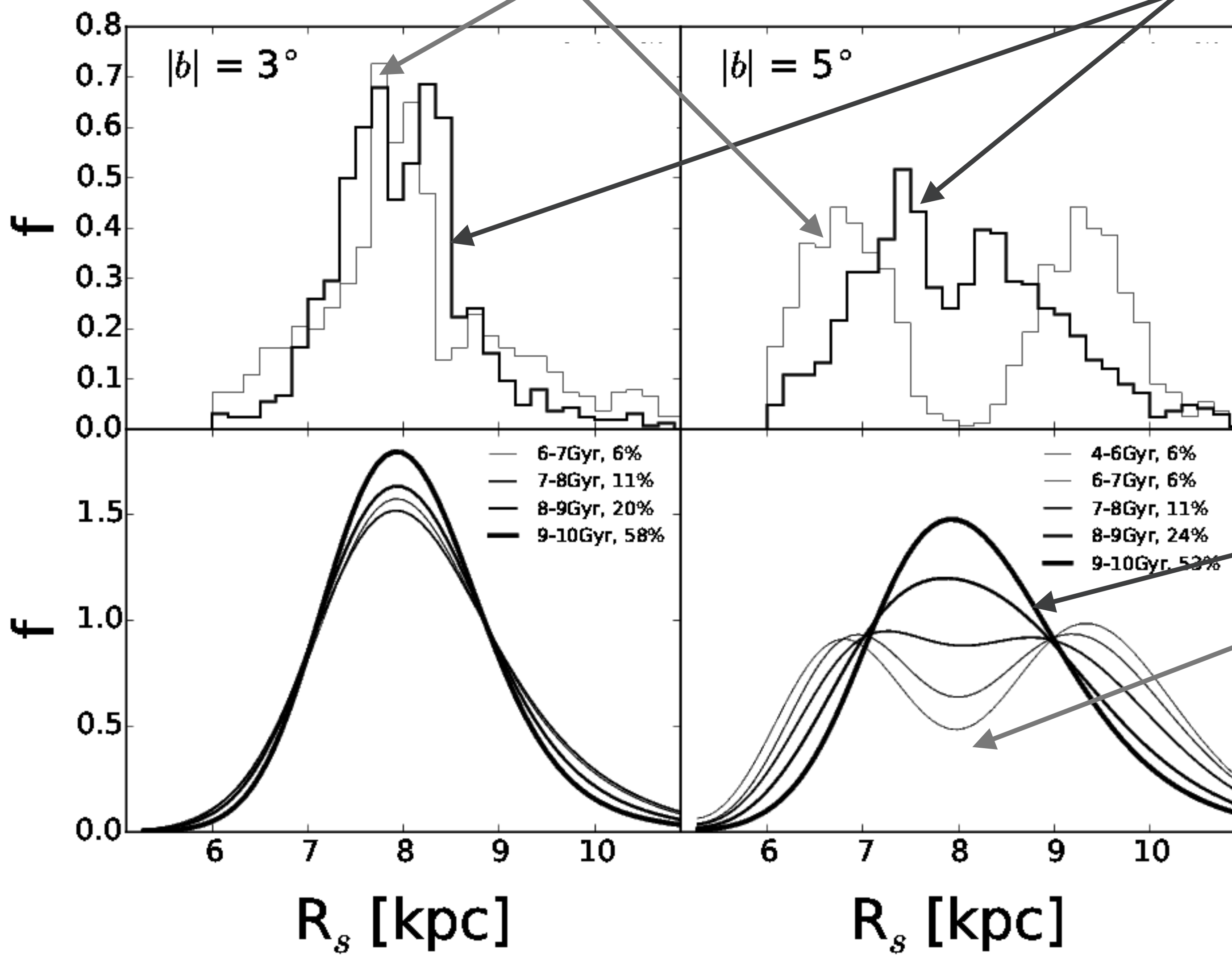
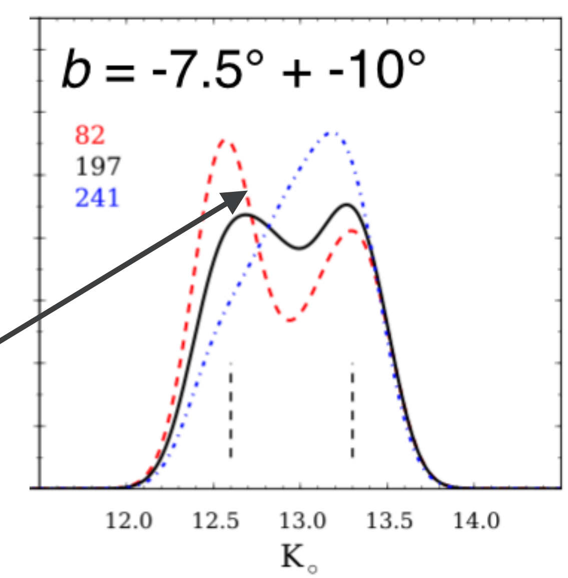


oldest stars

youngest stars



Debattista, (2016), submitted

young-thin disk

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Model explains split clump *f*[Fe/H]

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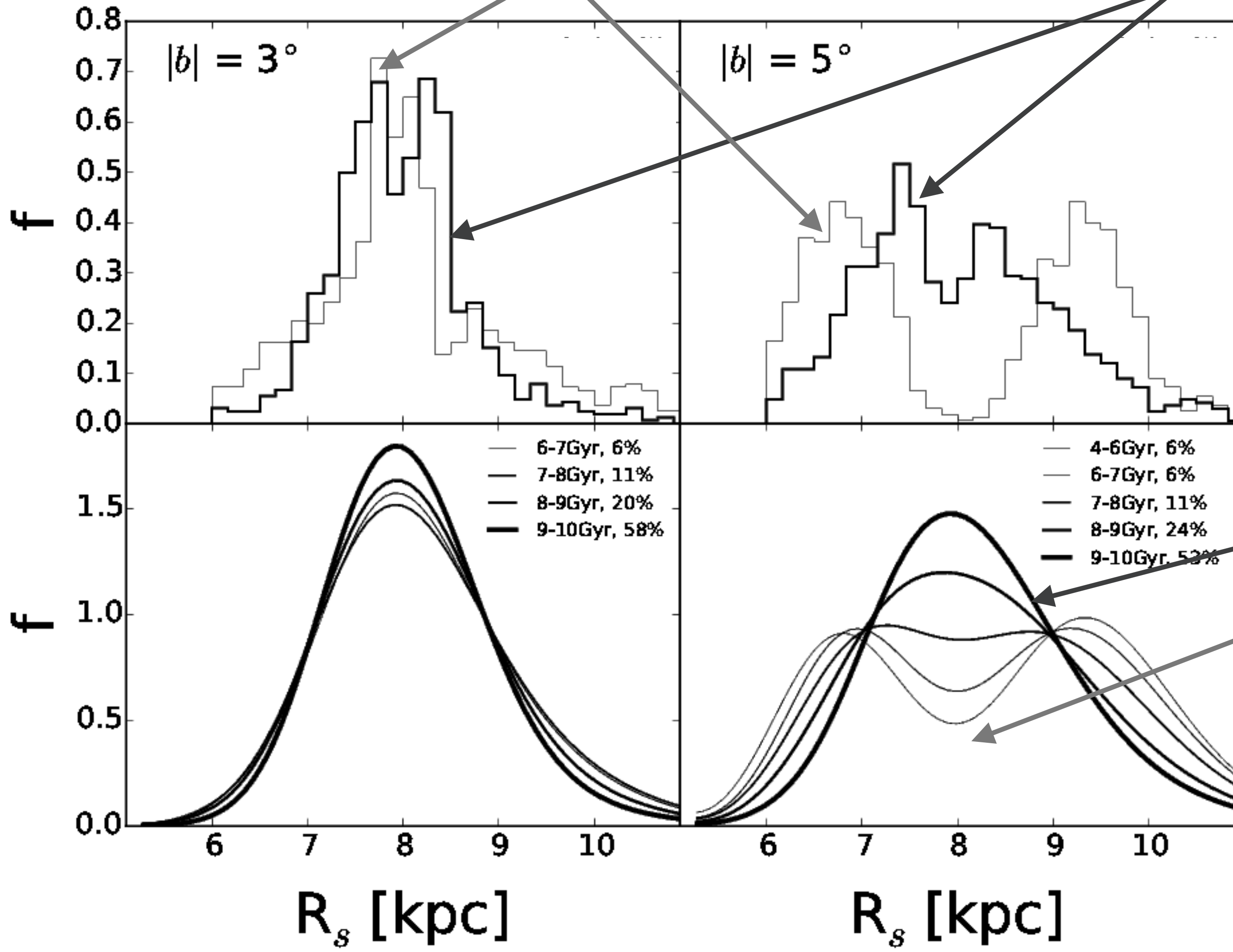
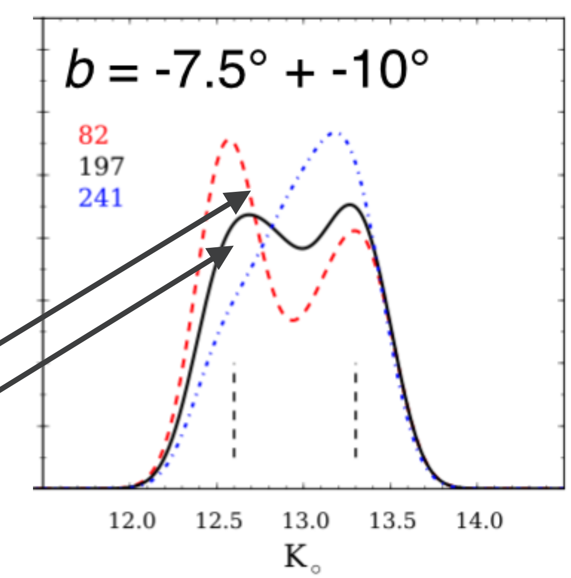
Raw

Convolved with a σ = 0.17 mag RC width



oldest stars

youngest stars



Debattista, (2016), submitted

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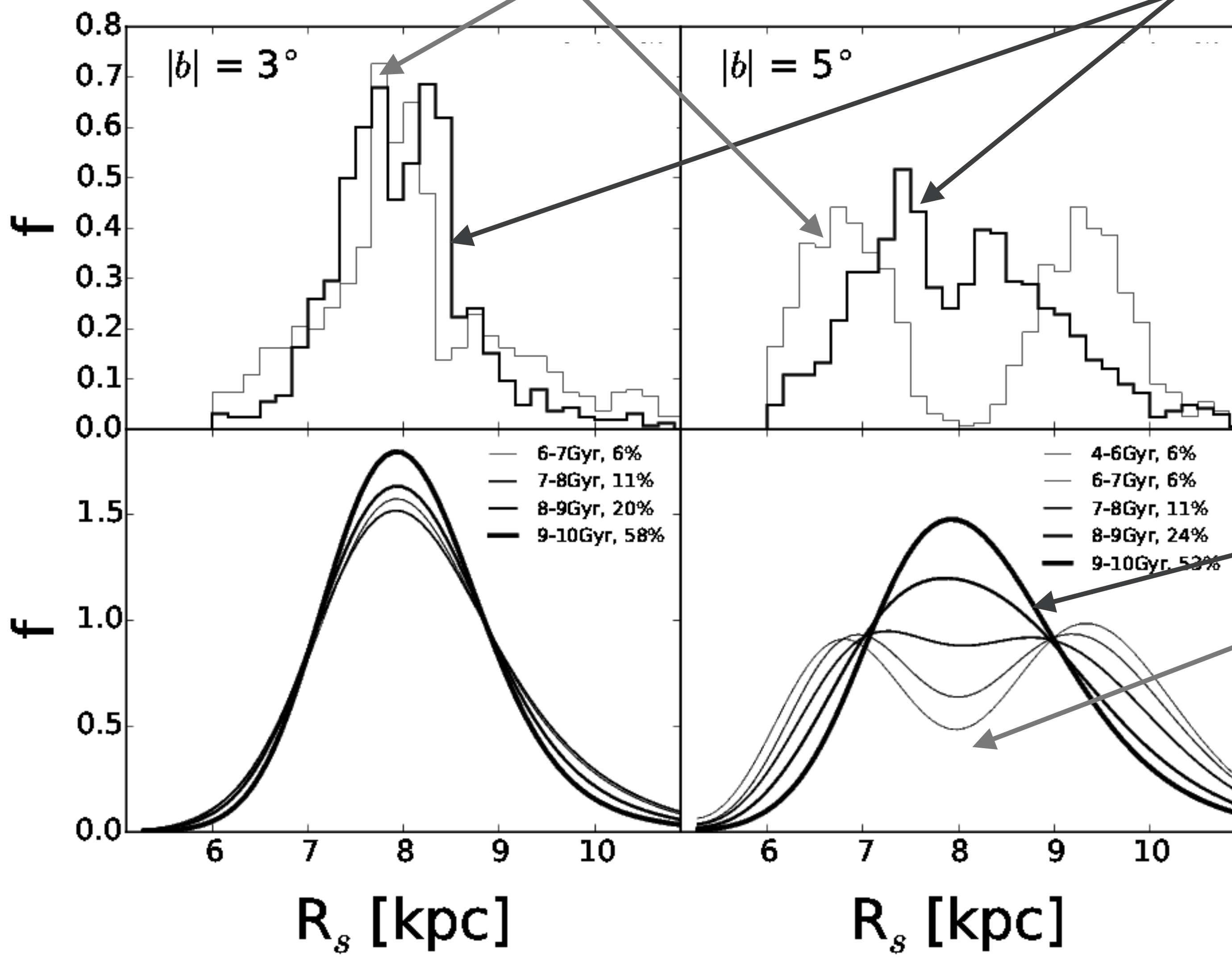
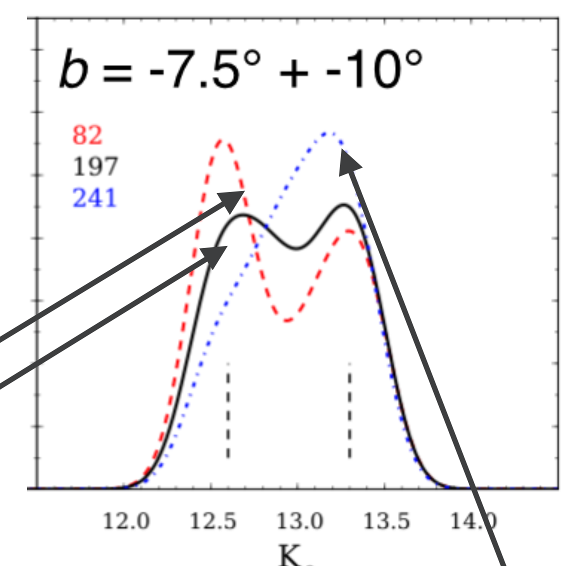


Convolved with a σ = 0.17 mag RC width

oldest stars

youngest stars



Debattista, (2016), submitted

young-thin disk

old-thin disk

thick disk

- Younger stars are split in their distribution, older stars are not