APOGEE: 150K stars
Disco: Proposal submitting this Friday for Sloan V
P.I’s Jon Bird & Melissa Ness

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**APOGEE**: 150K stars

**Disco**: 5 million stars
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APOGEE: 150K stars

• 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 $3.7 < G-H < 9.7$

Disco: 5 million stars

• Measurement of 5 million stars
• 150K stars with APOGEE spectrograph
• Contiguous complete coverage

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**Images:**

- Left: APOGEE spectrograph map
- Right: Disco coverage map

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**Legend:**

- Color scale indicating star density
- Contiguous complete coverage marked

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**Notes:**

- Precision and coverage details for both projects
- Collaboration and proposal highlights

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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

disk instability

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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
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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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$(l,b) = (0.0, -6.3)$, Nataf et al. 2011, McWilliam & Zoccali (2011)
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- Bulge is 8kpc away, 27 deg wrt line of sight (Wegg+ 2013)
- Bar extends to 5kpc in the plane (Wegg+ 2015)
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- Bulge is 8kpc away, 27 deg wrt line of sight (Wegg+ 2013)
- Bar extends to 5kpc in the plane (Wegg+ 2015)
- Not atypical

$(l,b) = (0.0, -6.3)$, Nataf et al. 2011,
McWilliam & Zoccali (2011)

Bureau 2006
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)
Morphology: signature of formation from the disk

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from Athanassoula (see upcoming talk)
Boxy Bulges have a distinct kinematic profile

ARGOS (17K stars) + BRAVA (10K stars)

Freeman et al., 2012, Ness et al., 2013
Kunder et al., 2012
Boxy Bulges have a distinct kinematic profile

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ARGOS (17K stars) + BRAVA (10K stars)

Freeman et al., 2012, Ness et al., 2013

Kunder et al., 2012
Rotation Map of the MW
12K APOGEE stars
+10K ARGOS stars
+6K BRAVA
4kpc < d < 12 kpc

Ness et al., 2016
Rotation Map of the MW

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

Ness et al., 2016
Dispersion Map of the MW

4kpc < distances < 12 kpc
Comparison to N-body models Rotation

model of Athanassoula (2008)

Ness et al., (2016)
Comparison to N-body models Dispersion

4kpc < d < 12 kpc

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Comparison to N-body models Dispersion

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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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- Portail et al., 2016: Constrain pattern speed at 39km/s/kpc ± 3.5 (see talk by M.Portail)
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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

ARGOS Bulge MDF: $R_G < 3.5$ kpc (Ness+ 2013)

- 13,500 stars

Broad MDF:
also see: Zoccali+ 2008, Babusiaux+2010, Hill+2011

Fraction of Stars

[Fe/H]
Morphology is metallicity dependent

ARGOS Survey: 28,000 star survey of bulge R~ 10,000
K-magnitude distribution of red clump stars $\int [\text{Fe/H}]$
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ARGOS Survey: 28,000 star survey of bulge R~10,000
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Bimodality for stars [Fe/H] > -0.5

Ness et al., 2013

Portail et al., (2015)
Morphology is metallicity dependent

ARGOS Survey: 28,000 star survey of bulge R~ 10,000 K-magnitude distribution of red clump stars $f([\text{Fe/H}]$) 

Only the stars with $[\text{Fe/H}] > -0.5$ are part of the boxy/peanut

Portail et al., (2015)

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Bimodality for stars $[\text{Fe/H}] > -0.5$

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Only the stars with $[\text{Fe/H}] > -0.5$ are part of the boxy/peanut
Bimodality in N-body models

Ness, Athanassoula+ 2012

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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![Metallicity distribution in the bulge](chart.png)
Metallicity distribution in the bulge

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• 13,500 stars
Multiple populations in the bulge

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

(a) $l \pm 15^\circ, b = -5^\circ$

(b) $b = -10^\circ$

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

Ness+ 2013

in talk by K. Freeman
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\[ b = -5^\circ \]

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\([\text{Fe/H}] < -0.5\] classical bulge: very different formation history

Ness+ 2013
MDF gradient & disk-instability formation
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Observations

Gonzalez et al., 2013
MDF gradient & disk-instability formation

Observations

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
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 $[\alpha/Fe]$ from inner to outer region
Chemical enrichment of the bulge in context

70,000 giants from Hayden, M from APOGEE

- smooth transition in $[\alpha/Fe]$ from inner to outer region
- narrow high-$\alpha$ in inner region — star formation and chemical evolution rate was high in the early epoch in the disk
Kinematics of Multiple populations

Ness et al., 2013
Kinematics of Multiple populations

Ness et al., 2013
Kinematics of Multiple populations

A. [Fe/H] > 0
B. 0 > [Fe/H] > -0.5
C. -0.5 > [Fe/H] > -1.0
D. [Fe/H] < -1.0

Ness et al., 2013
Kinematics of Multiple populations

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Kinematics of Multiple populations

A

B

C

D/E

Ness et al., 2013
Kinematics at $[\text{Fe/H}] < -0.5$ not well reproduced

- Latitude-independent dispersion can not be reproduced in instability models (di Matteo+ 2015)
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\[
\begin{align*}
\text{B} & \quad \text{Latitude-independent dispersion cannot be reproduced in instability models (di Matteo+ 2015)} \\
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Interpret different populations within instability formation
Debattista, (2016), submitted (also see di Matteo 2015)
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- Pure N-body (no gas) simulation with 5 stellar populations
- Motivation: to understand the more complicated evolution of a system with gas, feedback, chemistry.
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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
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Simulation after 5 Gyr
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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
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Model explains split clump $f[\text{Fe/H}]$

Convolved with a $\sigma = 0.17$ mag RC width

Debattista, (2016), submitted
Model explains split clump $f([\text{Fe/H}]$)

Debattista, (2016), submitted

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

Convolved with a $\sigma = 0.17$ mag RC width

![Graph showing distribution of stars in different age groups]
Model explains split clump $f[\text{Fe/H}]$

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Kinematics as $f([\text{Fe/H}])$

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- 5% hot population required to reproduce population C in ARGOS $\text{[Fe/H]} < -0.5$

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

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V$_{\text{GC}}$ [kms$^{-1}$]  σ$_{\text{GC}}$ [kms$^{-1}$]

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D,E

500 stars (28%)

[Fe/H] < -1.0

Galactic Longitude (deg)
Kinematics as $f([\text{Fe/H}])$

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All stars $\quad$ Fe/H > -0.5 $\quad$ [Fe/H] < -0.5 $\quad$ [Fe/H] < -0.5

A,B $\quad$ C $\quad$ C+spheroid

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 $f[\text{Fe/H}]$

Debattista, (2016), submitted
Model explains split clump $f[\text{Fe/H}]$

younger: 6-7 Gyr (6%)
older: 9-10 Gyr (60%)

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Model explains split clump f[Fe/H]

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Model explains split clump $f[\text{Fe/H}]$

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Debattista+ 16

Convolved with $\sigma = 0.17$ mag RC width

Raw

With better distance estimates:

1) It is possible to observe splits also in old populations
2) In relatively younger stars, the branches do not overlap

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Model explains split clump $f([\text{Fe/H}]$)

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  1. It is possible to observe splits also in old populations
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\[\sigma = 0.17 \text{ mag RC width}\]

\[\text{Youngest stars: 6-7 Gyr (6\%)} \quad \text{Younger stars: 6-7 Gyr (6\%)} \quad \text{Older stars: 9-10 Gyr (60\%)} \quad \text{Oldest stars: 9-10 Gyr (60\%)}\]
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