Exploring the Galactic bulge/bar with APOGEE and APOGEE-South

David Nidever
University of Virginia

Outline

I. Introduction to APOGEE

II. First results on Galactic bulge kinematics

III. After Sloan-III and APOGEE-South

I. Introduction to APOGEE

APOGEE at a Glance

- Part of Sloan Digital Sky Survey (SDSS)-III
- Bright time 2011.Q2 - 2014.Q2
- 300 fiber, $R \geq 22{,}500$, cryogenic spectrograph
- *H*-band: 1.51-1.68μ ($A_H/A_V \sim 1/6$)
- Goal: *S/N* = 100/pixel @ *H*=12.2 for 3-hr total integration
- Goal RV uncertainty < 0.5 km/s
- 0.1 dex precision abundances for ~15 chemical elements

  (including Fe, C, N, O, α-elements, odd-Z elements,

  iron peak elements, possibly even neutron capture)
- 100,000 2MASS-selected giant stars across all Galactic populations.

Top Level Science Requirements

First large scale, systematic, uniform spectroscopic study of *all* major Galactic stellar populations to understand:

- chemical evolution at precision, multi-element level
  (including preferred, most common metals CNO)
  -- sensitivity to SFR, IMF
- tightly constrain GCE and dynamical models (bulge, disk, halo)
- access typically ignored, dust-obscured populations

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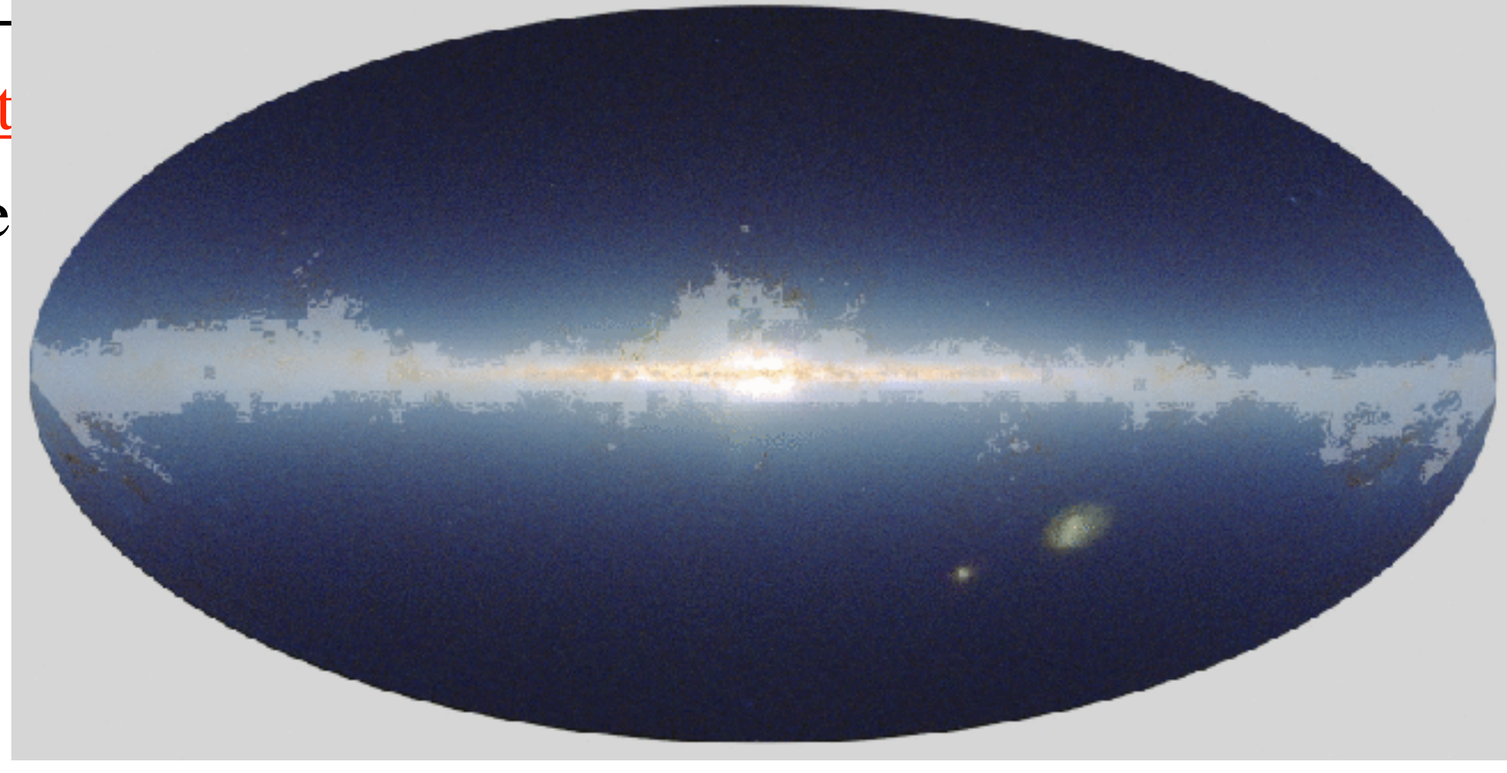

grey is $A_V > 1$

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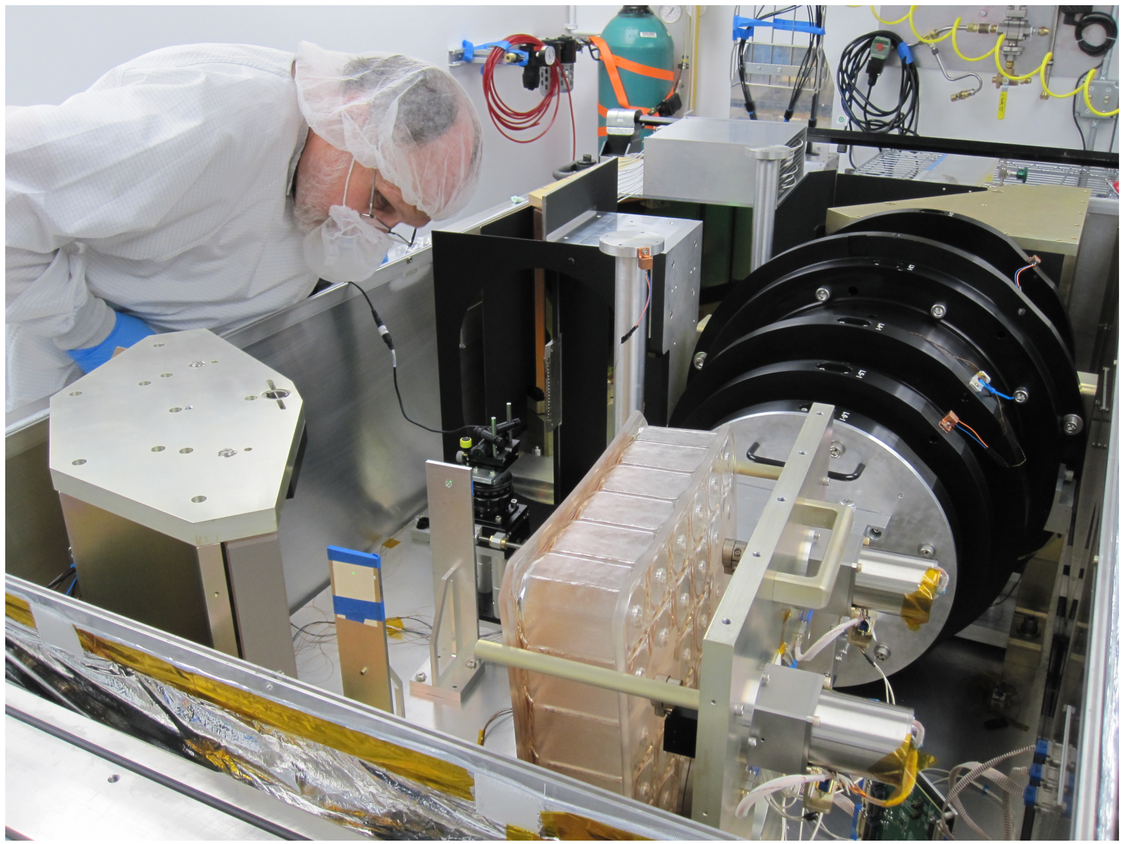
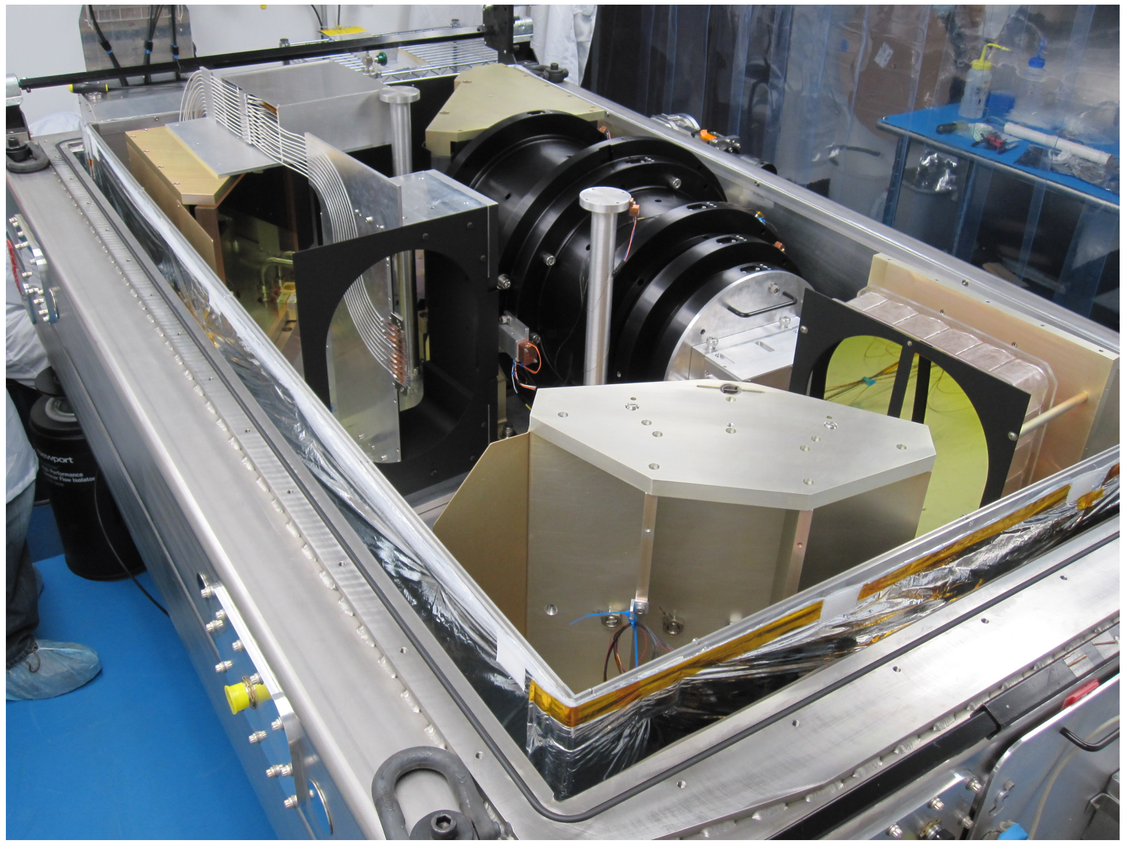
  (including preferred, most common metals CNO)
  -- sensitivity to SFR, IMF
- tightly constrain GCE and dynamical models (bulge, disk, halo)
- access typically ignored, dust-obscured populations
- Galactic dynamics/substructure with very precise velocities
- order of magnitude leaps:
  ~2-3 orders larger sample than previous high-*R* GCE

The APOGEE Instrument

- Built at the University of Virginia with private industry and other SDSS-III collaborators.
- The APOGEE instrument employs a number of novel technologies to achieve 300-fiber multiplexing / high resolution / infrared.





Photos by S.R. Majewski

APOGEE Employs Novel Technologies: Holographic Optic

- Mosaiced Volume Phased Holographic grating on single substrate.
- Largest VPH grating ever deployed in astronomical instrument.

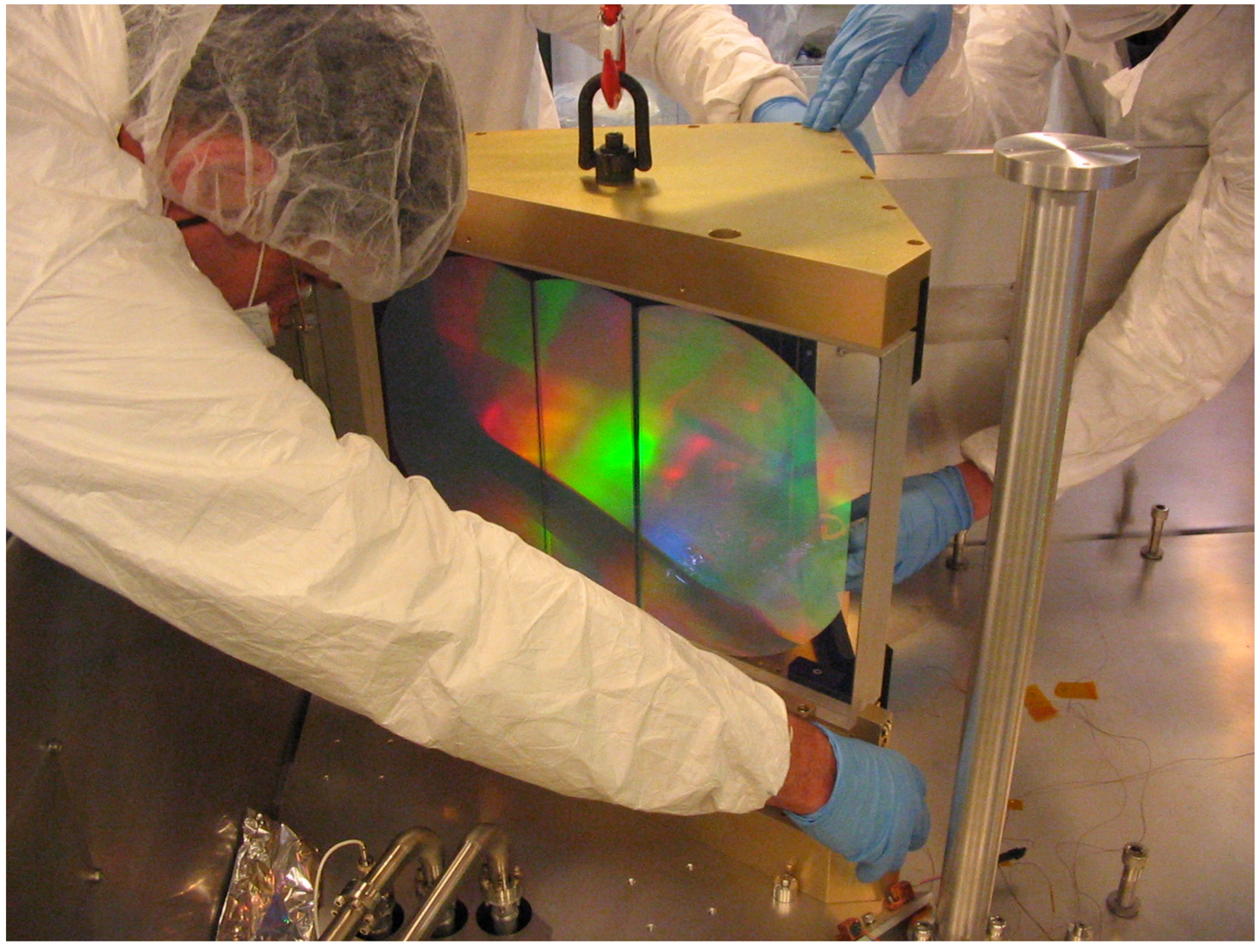
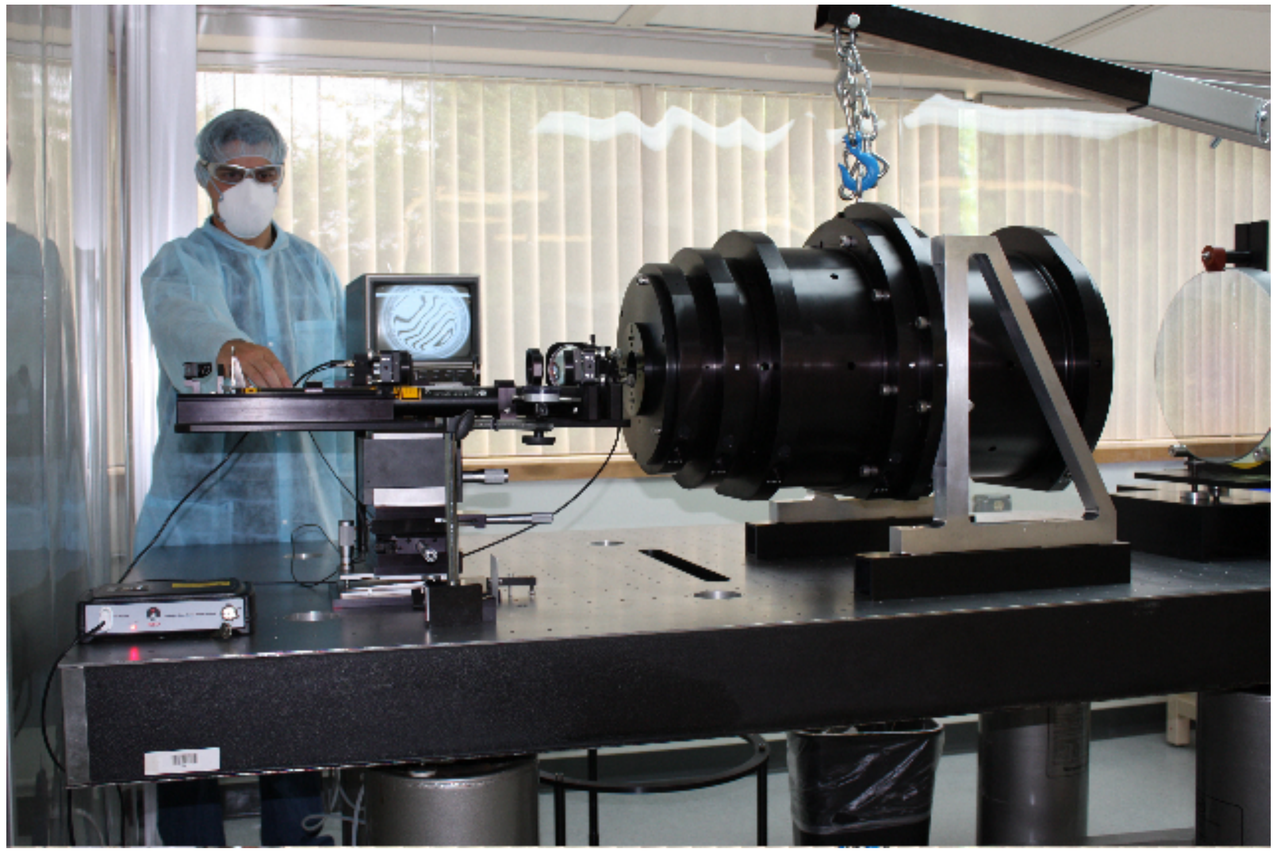


Photo by S.R. Majewski

APOGEE Employs Novel Technologies: Large Camera with Silicon Lenses

- The 250 lb, 6-element camera includes 4 pure silicon and 2 fused silica lenses as large as 16-inches in diameter.
- Only 1 aspheric surface.



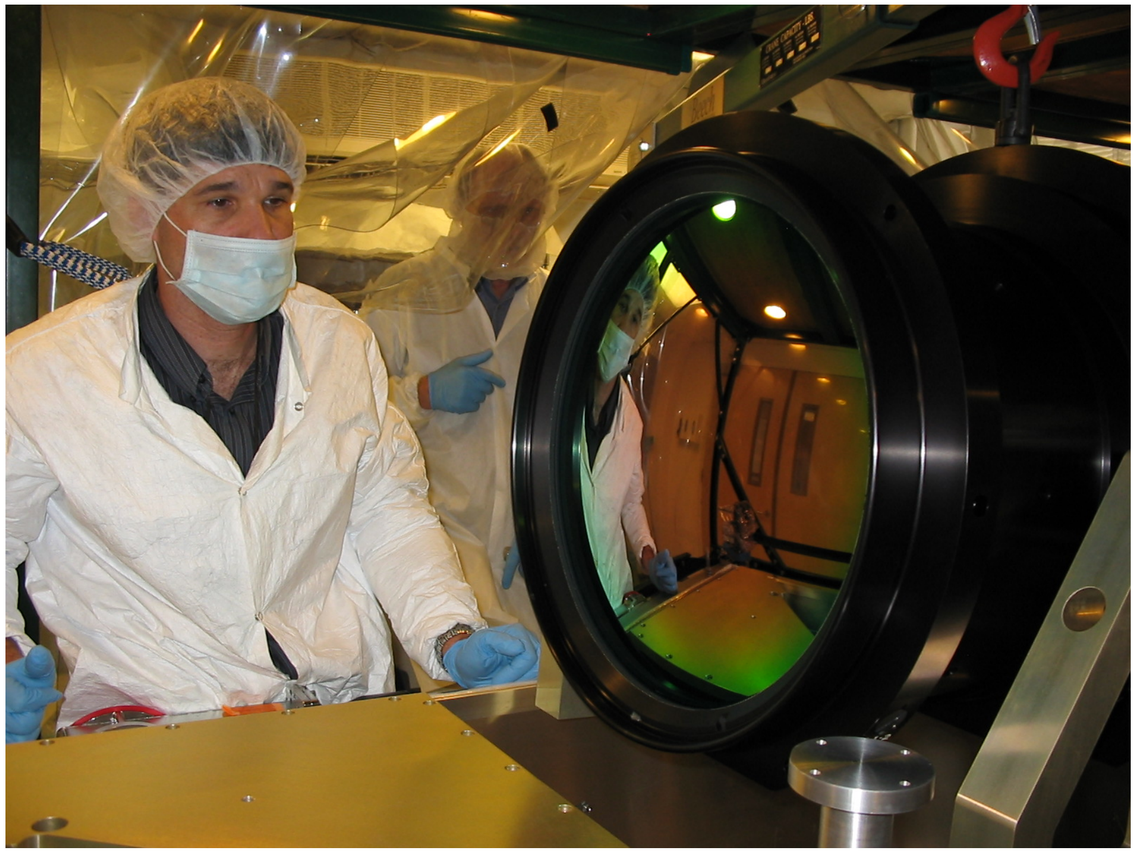


Image by New England Opical Systems.

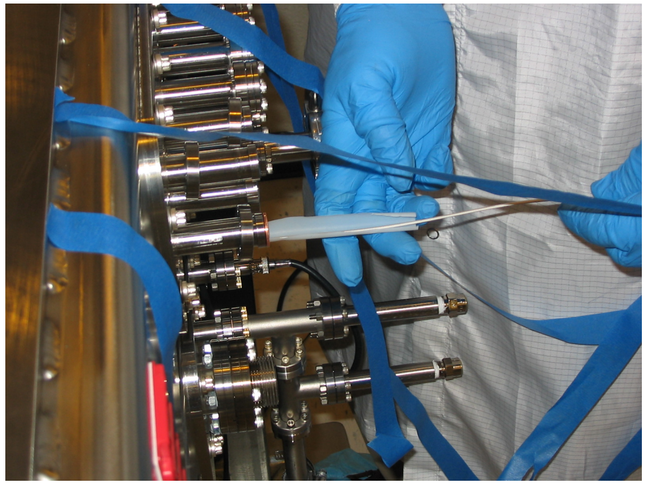
APOGEE Employs Novel Technologies: Optical Fiber System

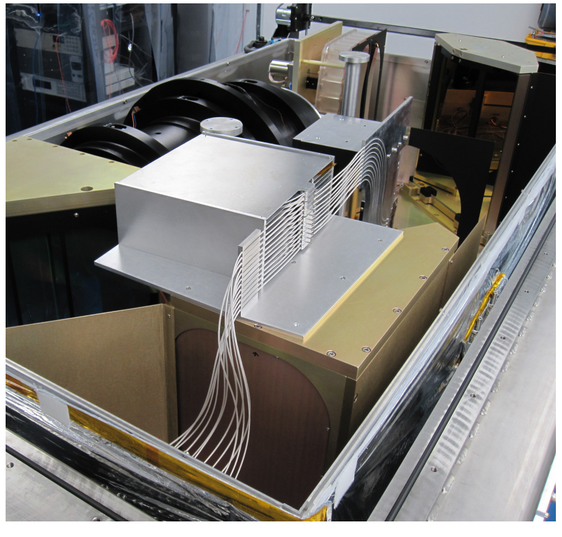
2.5-meter Sloan Telescope

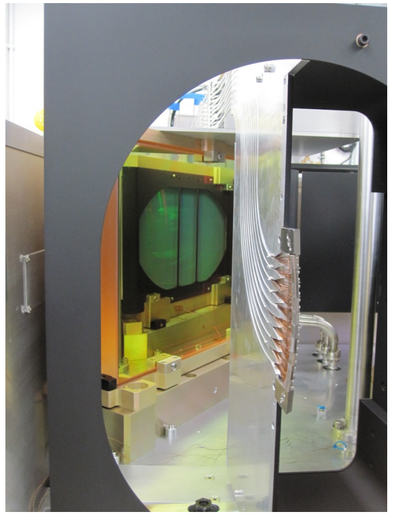
Three hundred, 40-meter-long optical fibers connect the telescope to the APOGEE instrument.

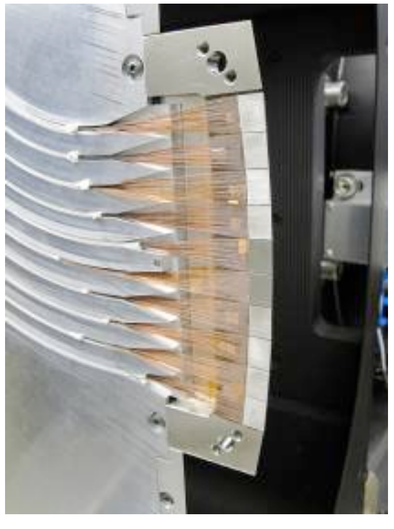
APOGEE Employs Novel Technologies: Optical Fiber System

- Fibers channel light from 300 stars into cryogenic, vacuum chamber enclosing APOGEE optics.









Photos by S.R. Majewski

APOGEE Installation

•April 25, 2011: Instrument arrives at Apache Point Observatory.







Photos by G. van Doren, D. Long, S. Majewski, O. Malanushenko, M. Nelson, J. Wilson

APOGEE First Light

- May 6, 2011: First observations with 2.5-m telescope.
  - Within weeks (& ~budget) of planned timelines from 2006.

Observations to Date

May-March "Science" Observations:

~495 "successful" visits (~1 hour each)

~220 separate plates

~140 unique fields (24 one-visit bulge fields "completed")

~64,000 science spectra (S/N > 60)

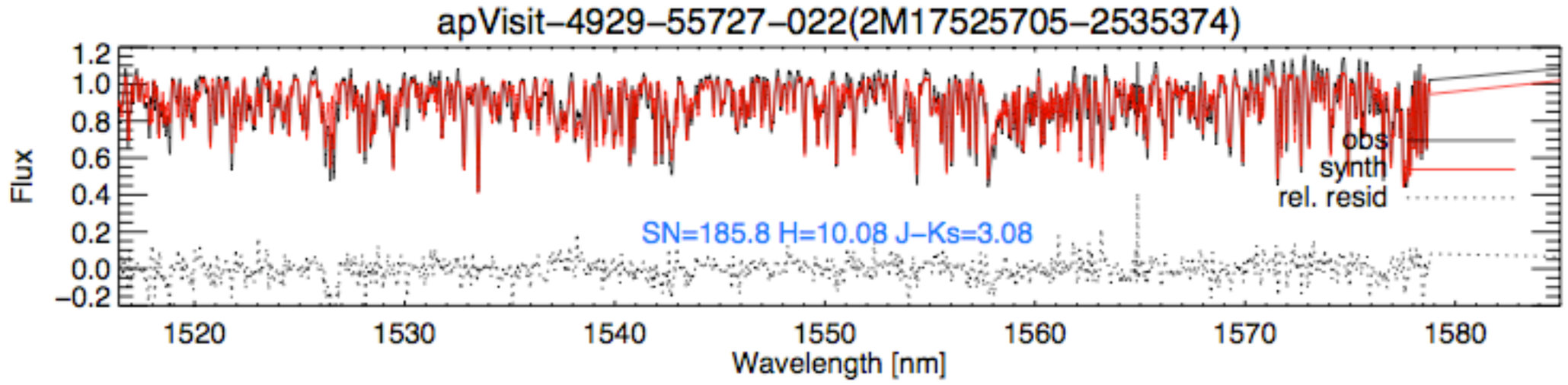
> ~40,000 unique stars observed:

~5,000 tellurics (OBA stars)

~35,000 calibration and science targets

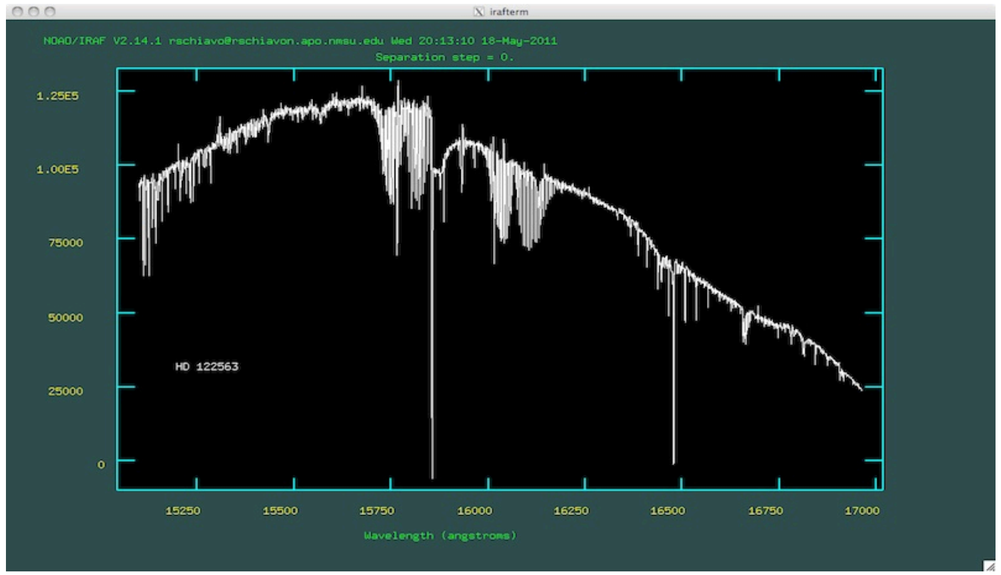
~5,000 stars on bulge plates

bulge star, [Fe/H] ~ -0.2

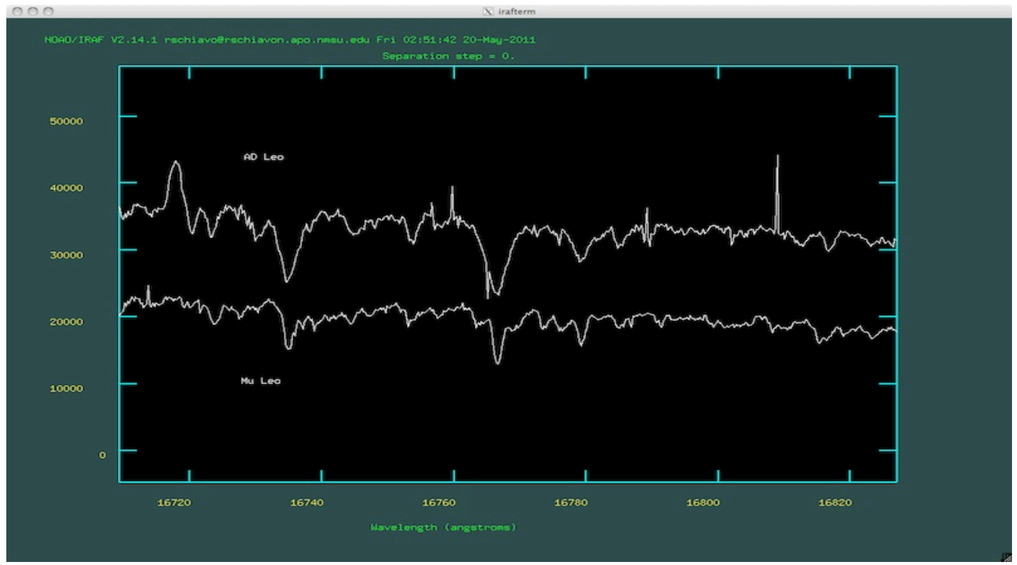


Example Spectra

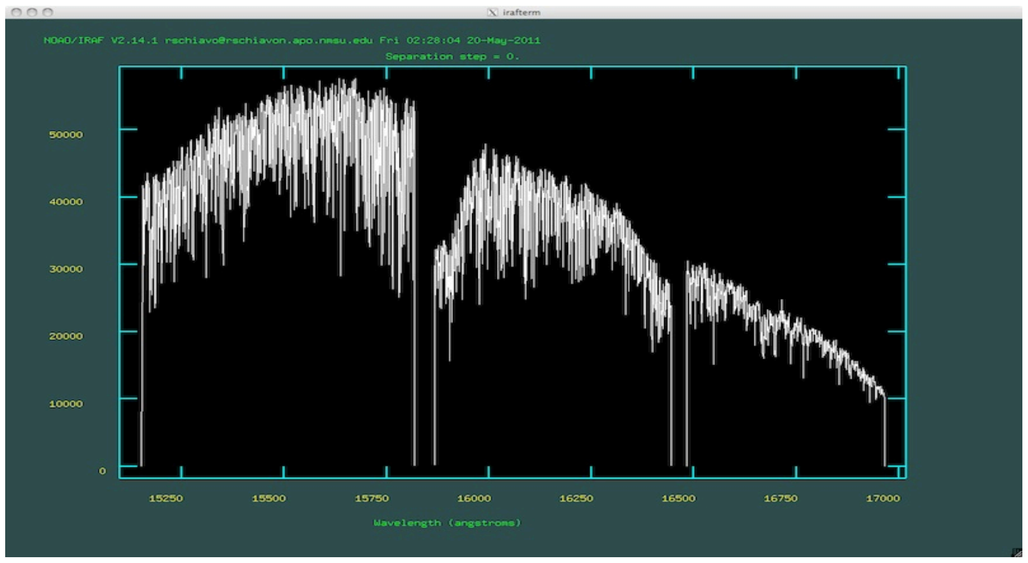
- May 11-22: First full APOGEE bright run -- rogue's gallery raw spectra.



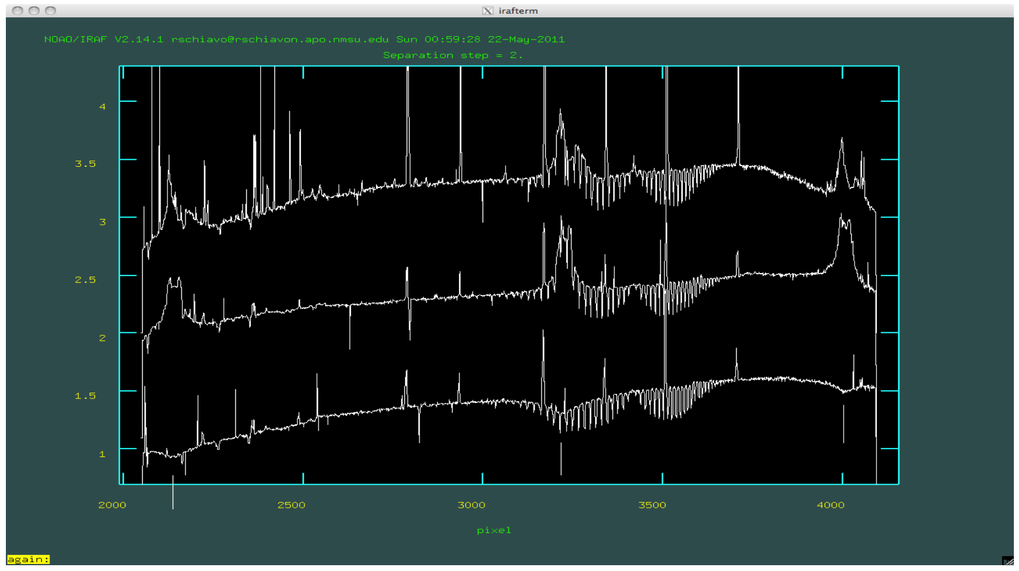
High S/N (>100) exposure of the very metal poor star HD 122563.



Zoomed in comparison of M dwarf (AD Leo) and M giant (μ Leo).



μ Leo, a metal-rich M giant star.



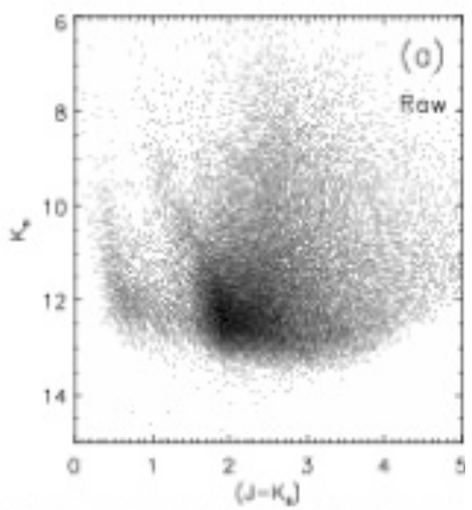
Some newly discovered Be stars (note Keplerian profile).

APOGEE Target Selection

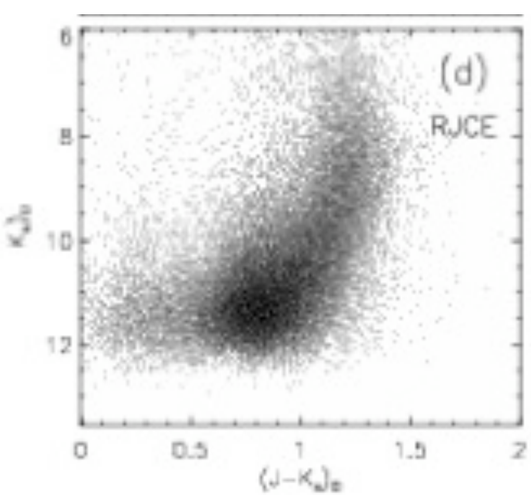
Dereddening:

- NIR+MIR color-excess dereddening by RJCE method (Majewski, Zasowski & Nidever 2011).
- Calculated on a star-by-star basis.
- $\sigma(A_{Ks}) < 0.1$ mag
- $A(K_s)$ from 2MASS+IRAC where available (higher resolution), fill in rest with WISE.

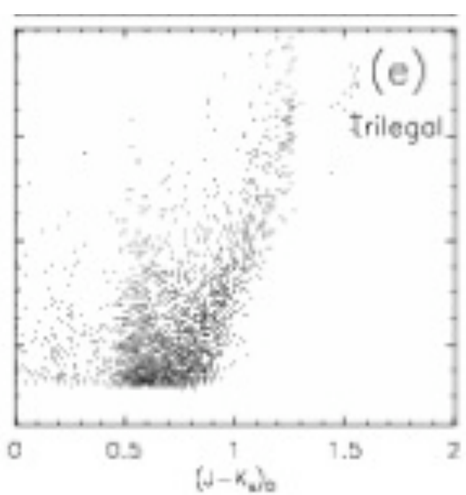
Observed 2MASS, (42,0)°



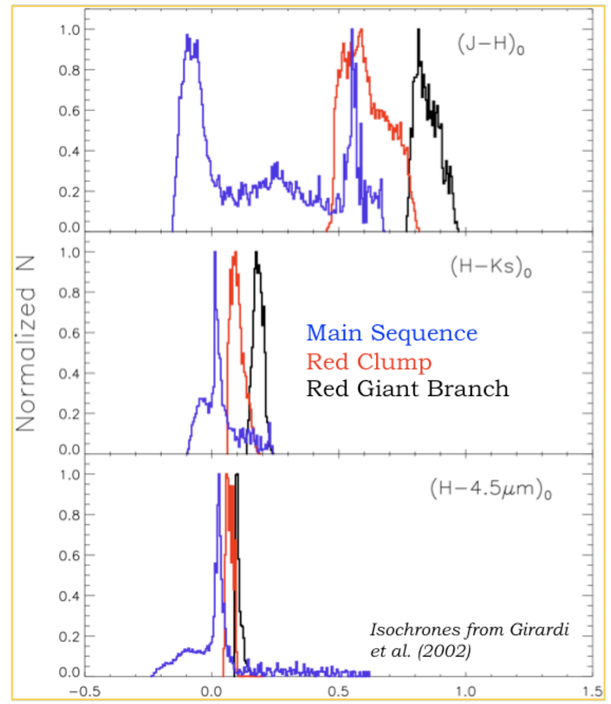
Corrected 2MASS



TRILEGAL model

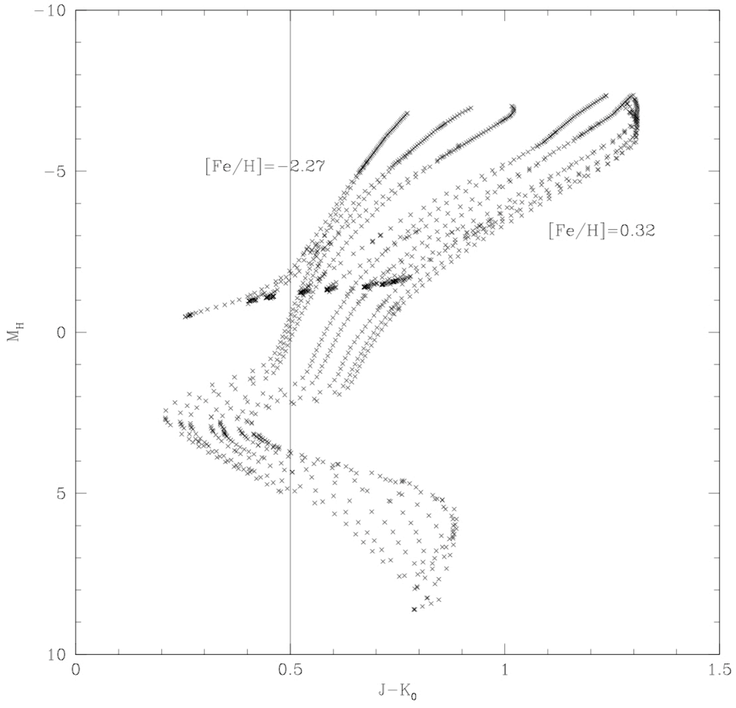


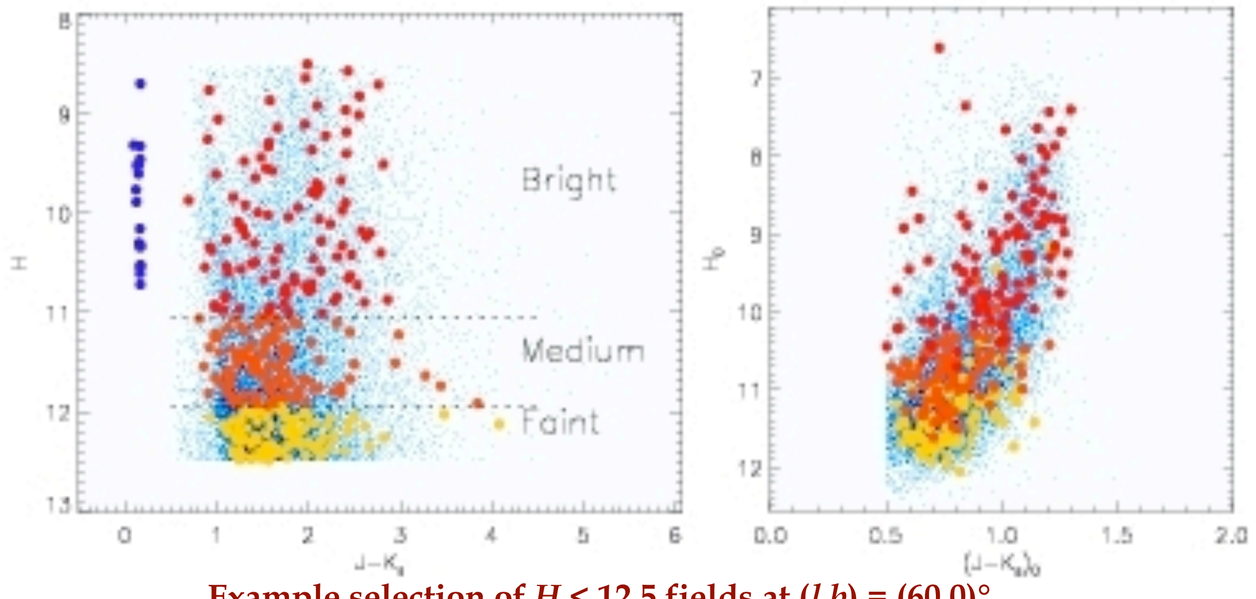
Isochrone Colors



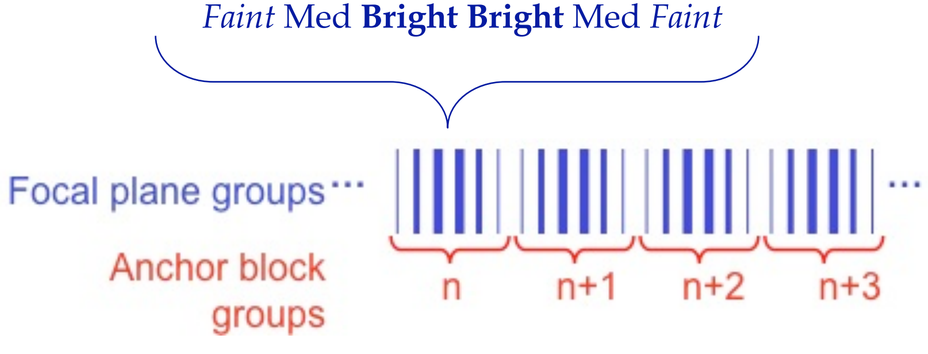
APOGEE Target Selection

- Science targets
  - Generally only color-selected: $(J\text{-}K_s)_0 \geq 0.5$
  - Variable magnitude limits (H < 11-14) for both shallow and deeper probes of MW.
  - 3 flexible magnitude divisions:
    - Consistent, ~even sampling of fields having different starcount distributions.
    - Aids in fiber brightness management.





Example selection of H < 12.5 fields at (l,b) = (60,0)°

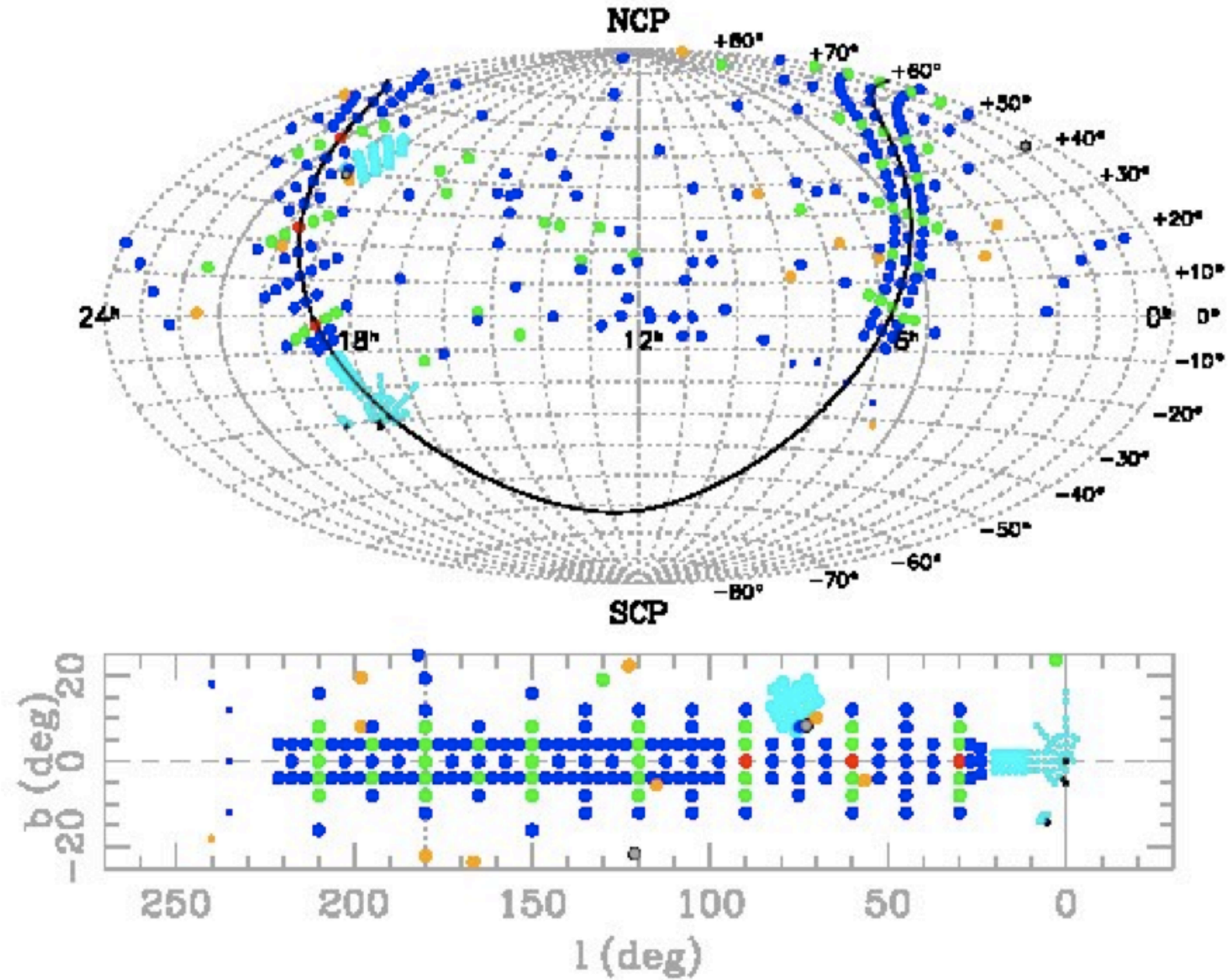


Field Selection

Field Center Plan:

24 hour
12 hour
3 hour (science)
3 hour (calibration)
1 hour

~343 fields
~600 star clusters
~116,000 science stars
Kepler fields

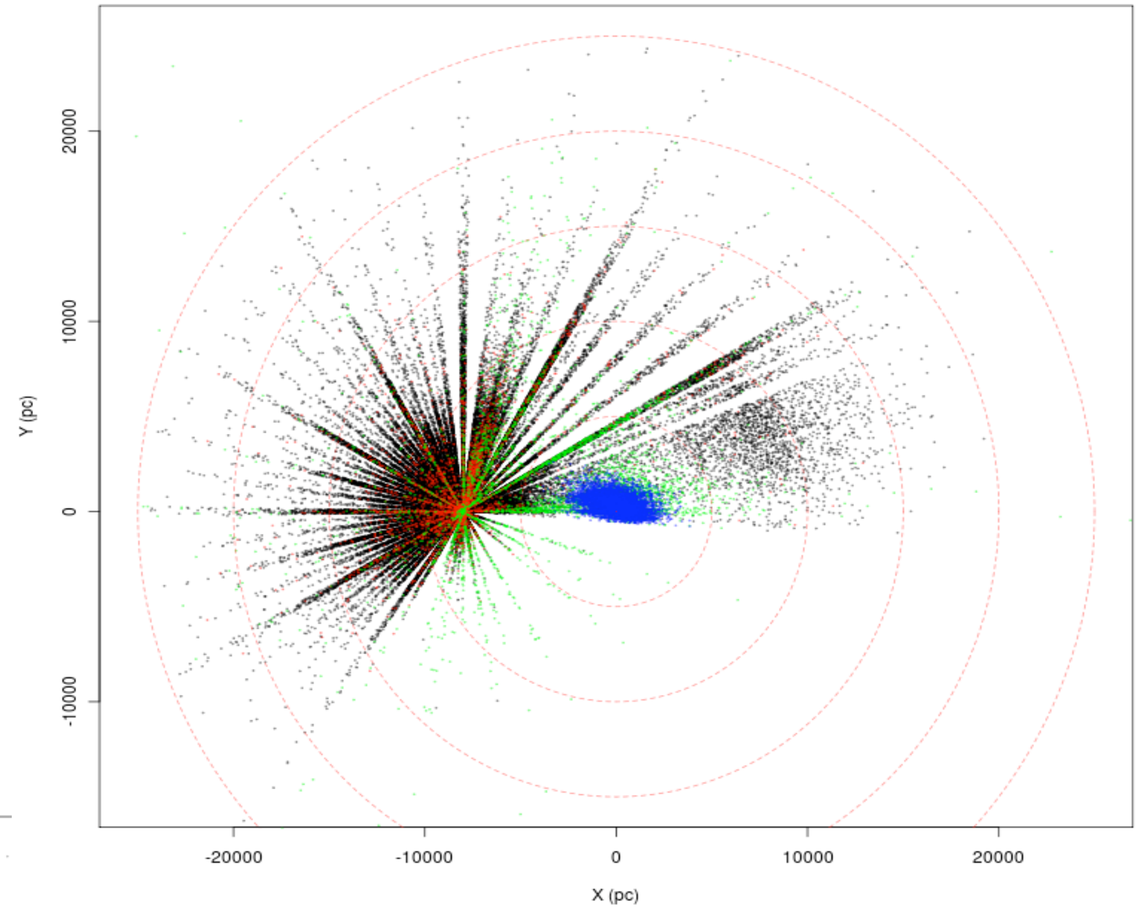


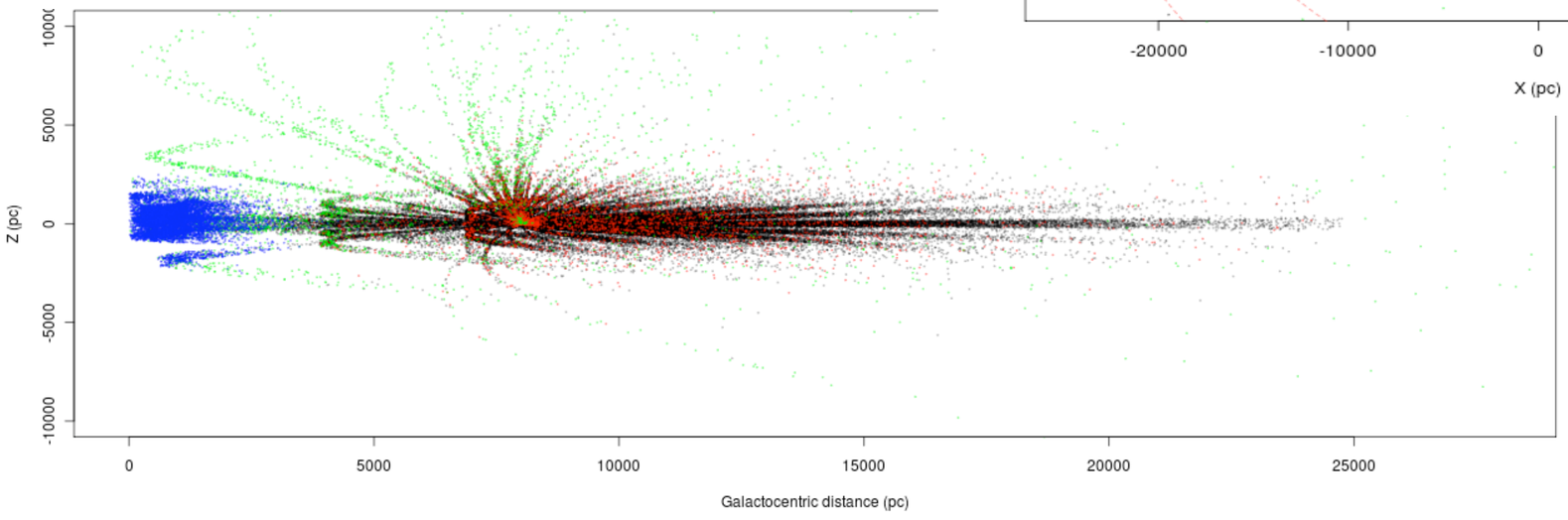
Anticipated Spatial Distribution

For currently selected fields

Bulge	*8000 stars*
Thin disk	*84100 stars*
Thick disk	*4300 stars*
Halo	*4500 stars*

79% giants





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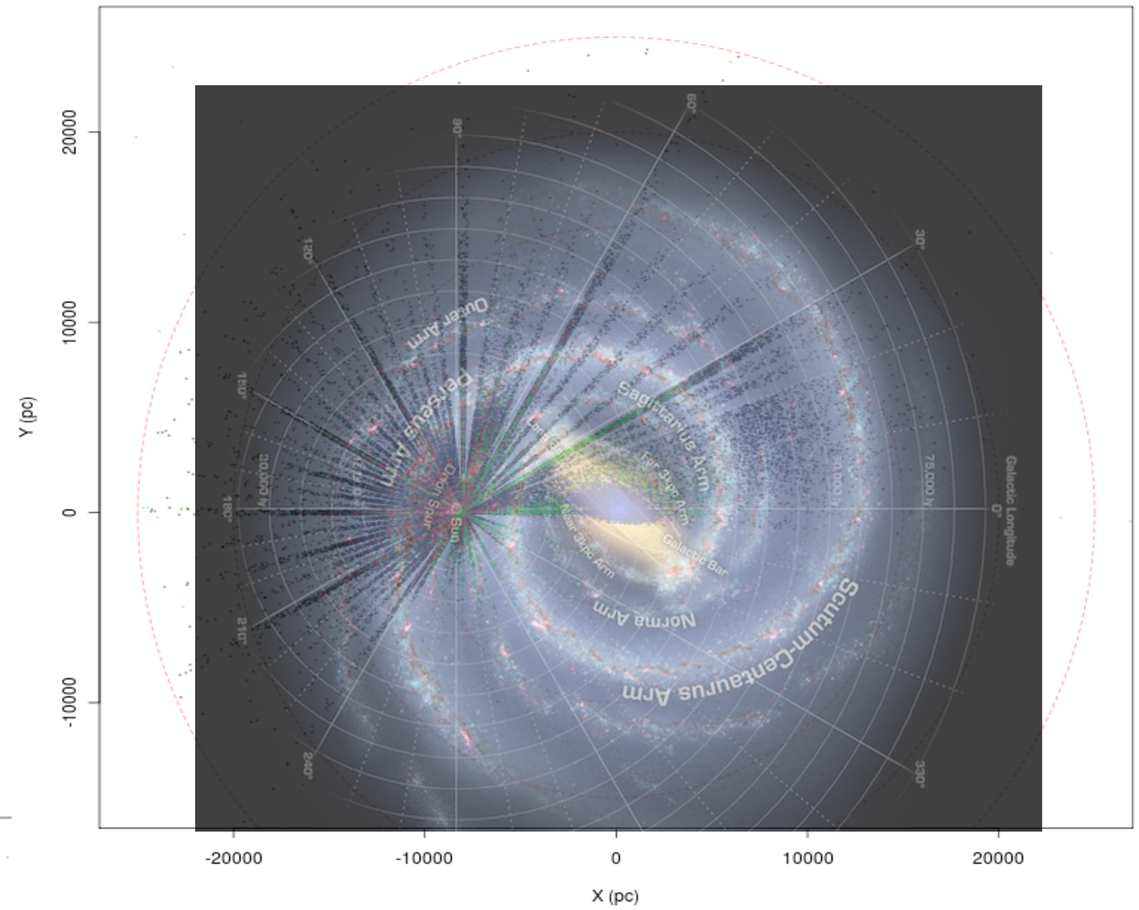
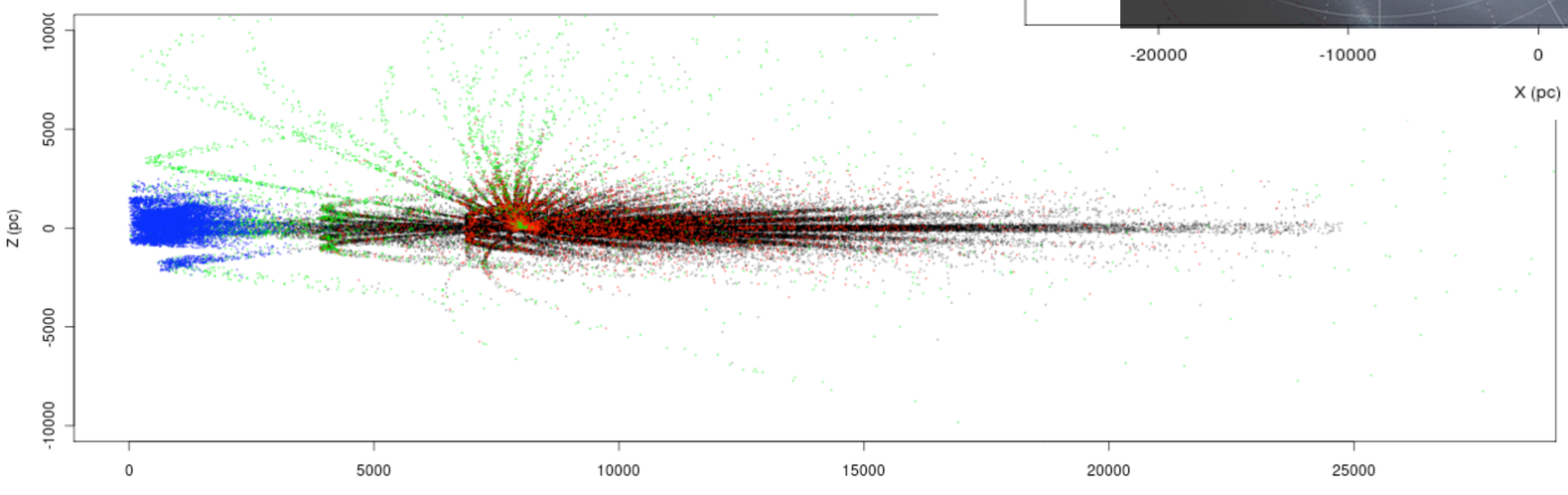




Reduction Pipeline

AP3D

Collapse 3D datacube of reads to 2D

- Dark subtract
- Flatfield
- Linearity correction
- Detect and fix CRs
- Fix saturated pixels

AP2D

Extract the fiber spectra

- Use Trace file to extract all 300 spectra

AP1DVISIT

Calibrate and combine visit frames

- Wavelength calibrate
- Sky subtraction
- Telluric correction
- Dither combination
- Flux calibrate
- Measure RV for each spectrum

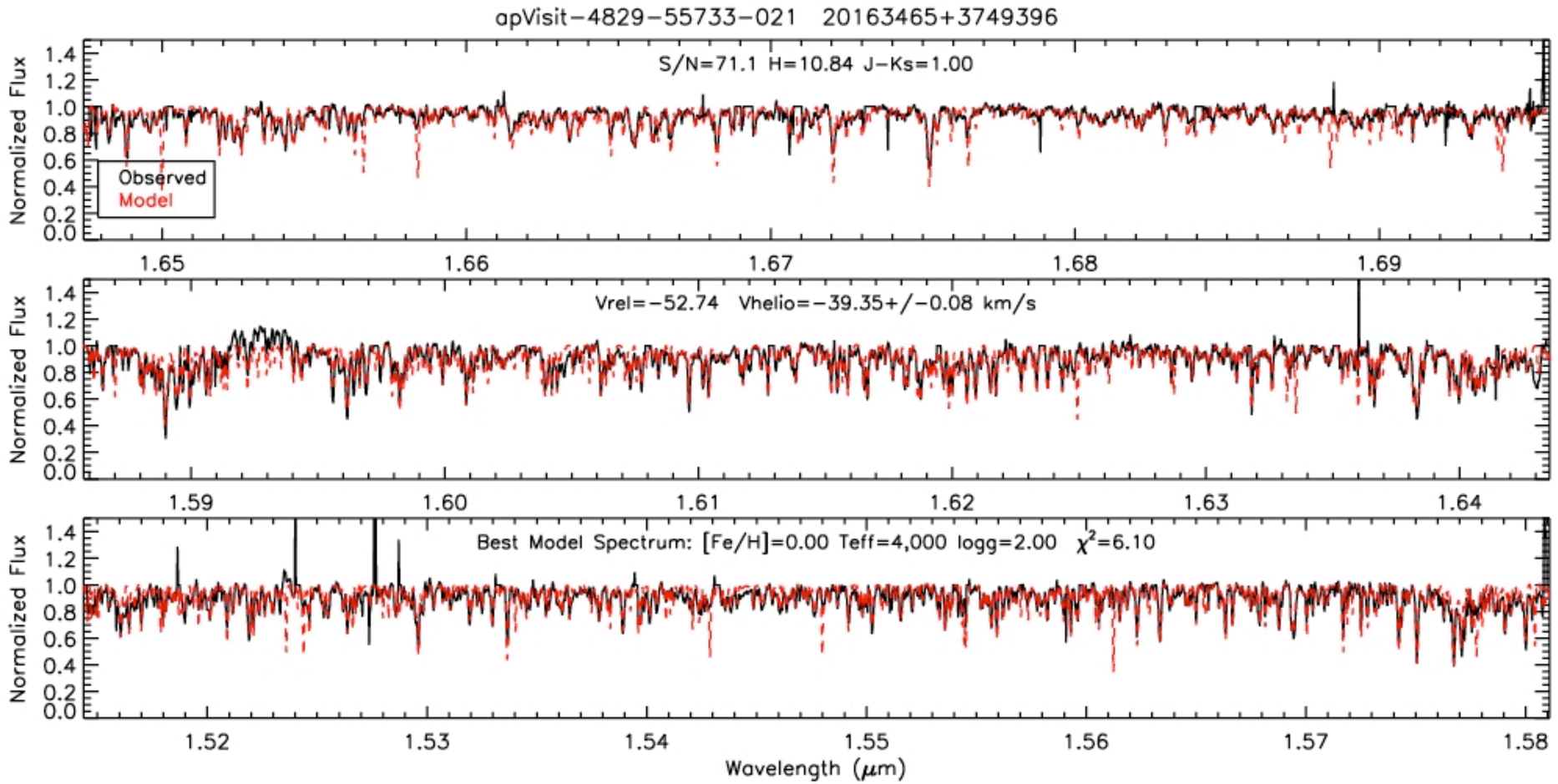
APCOMBINE

- Combine visit spectra to create final spectrum

- ~120 new programs
- ~20,000 lines of code

Nidever et al. (2012), in prep.

Measuring Radial Velocities

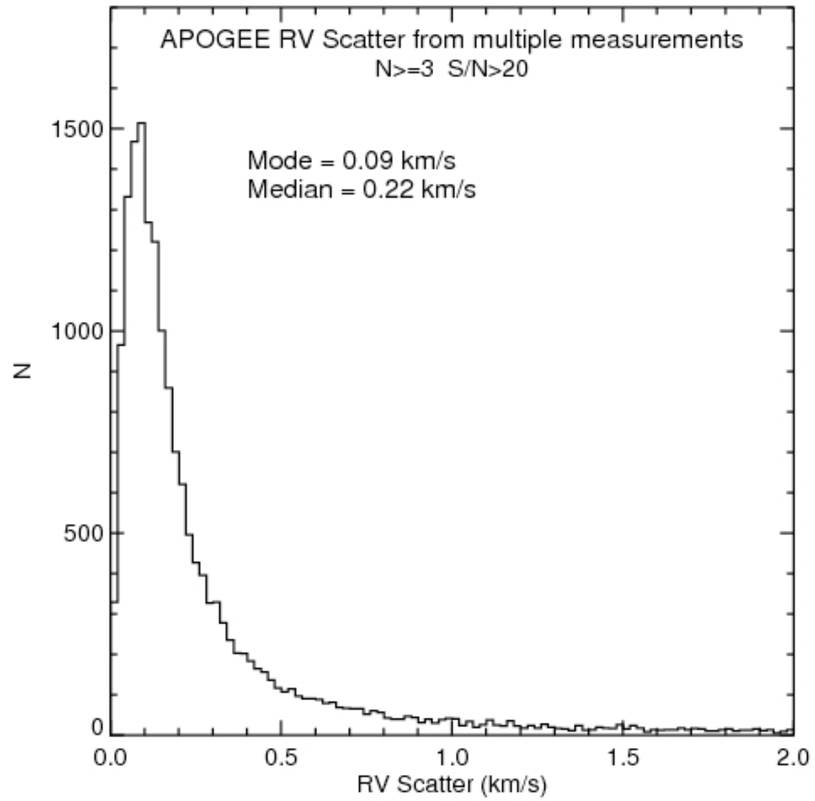


- *Example reduced spectrum and best-fitting RV template*

Velocity Uncertainties

Velocity Uncertainty

- Scatter from multiple measurements
- Some real variability
- Peak RV scatter = ~0.2 km/s



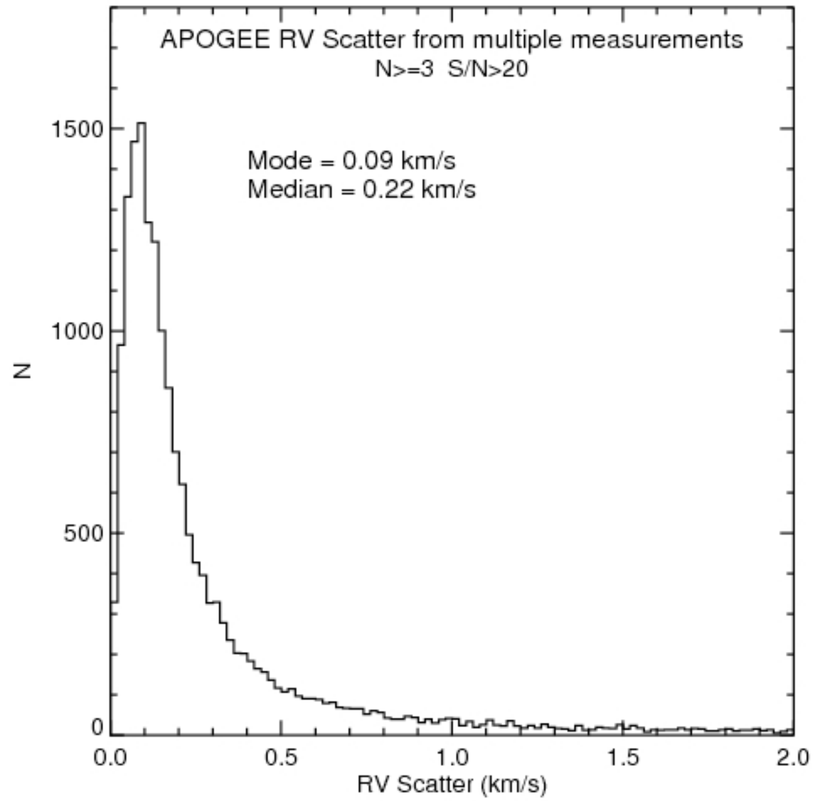
Velocity Uncertainties

Velocity Uncertainty

- Scatter from multiple measurements
- Some real variability
- Peak RV scatter = ~0.2 km/s

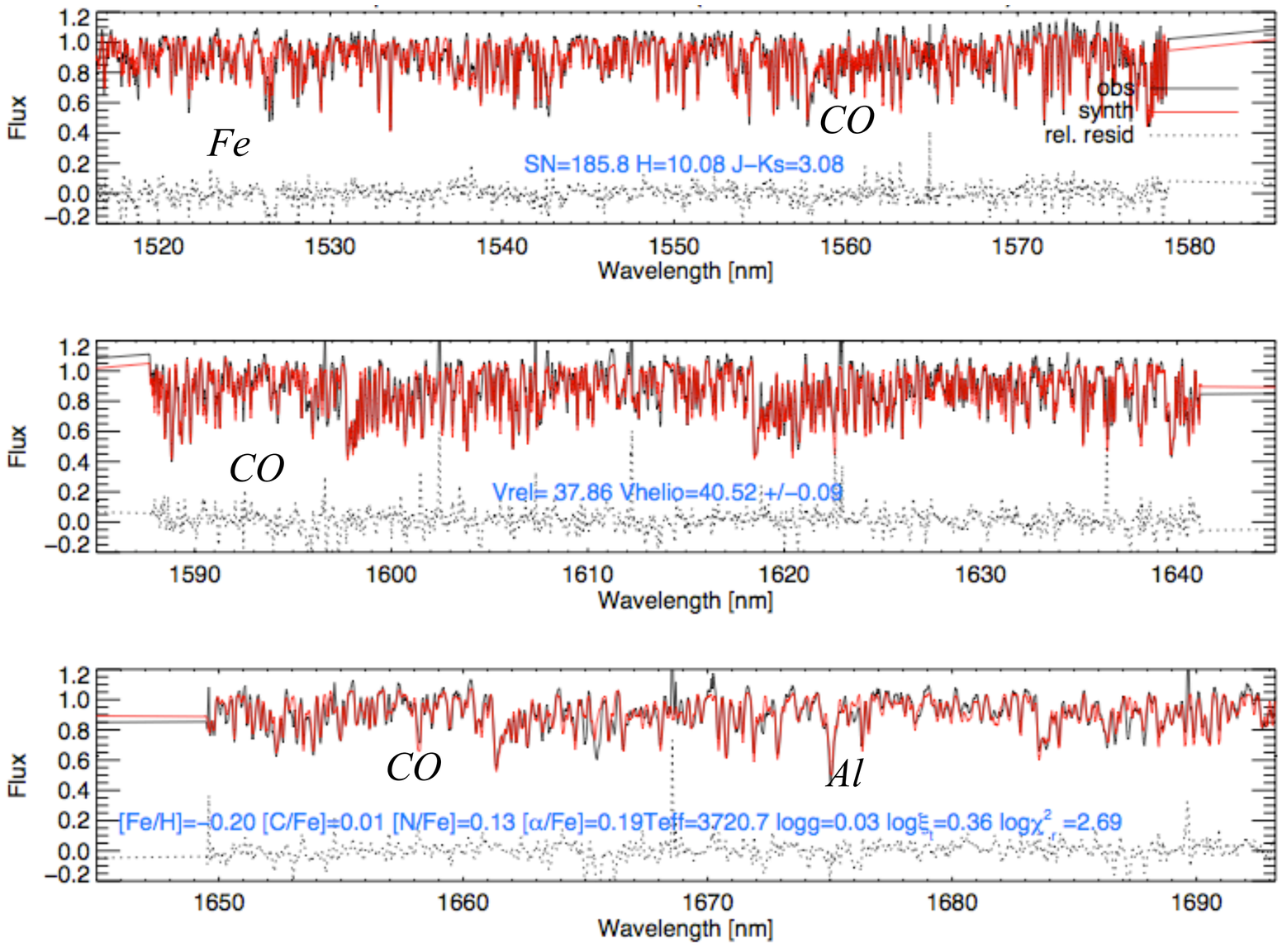
Velocity Zeropoint

- Comparison to globular cluster RVs (M3, M13, M15)
- RV Offset (Lit - APG) = -0.26 +/- 0.2 km/s



Chemical Abundance Determination

Bulge [Fe/H]~-0.2

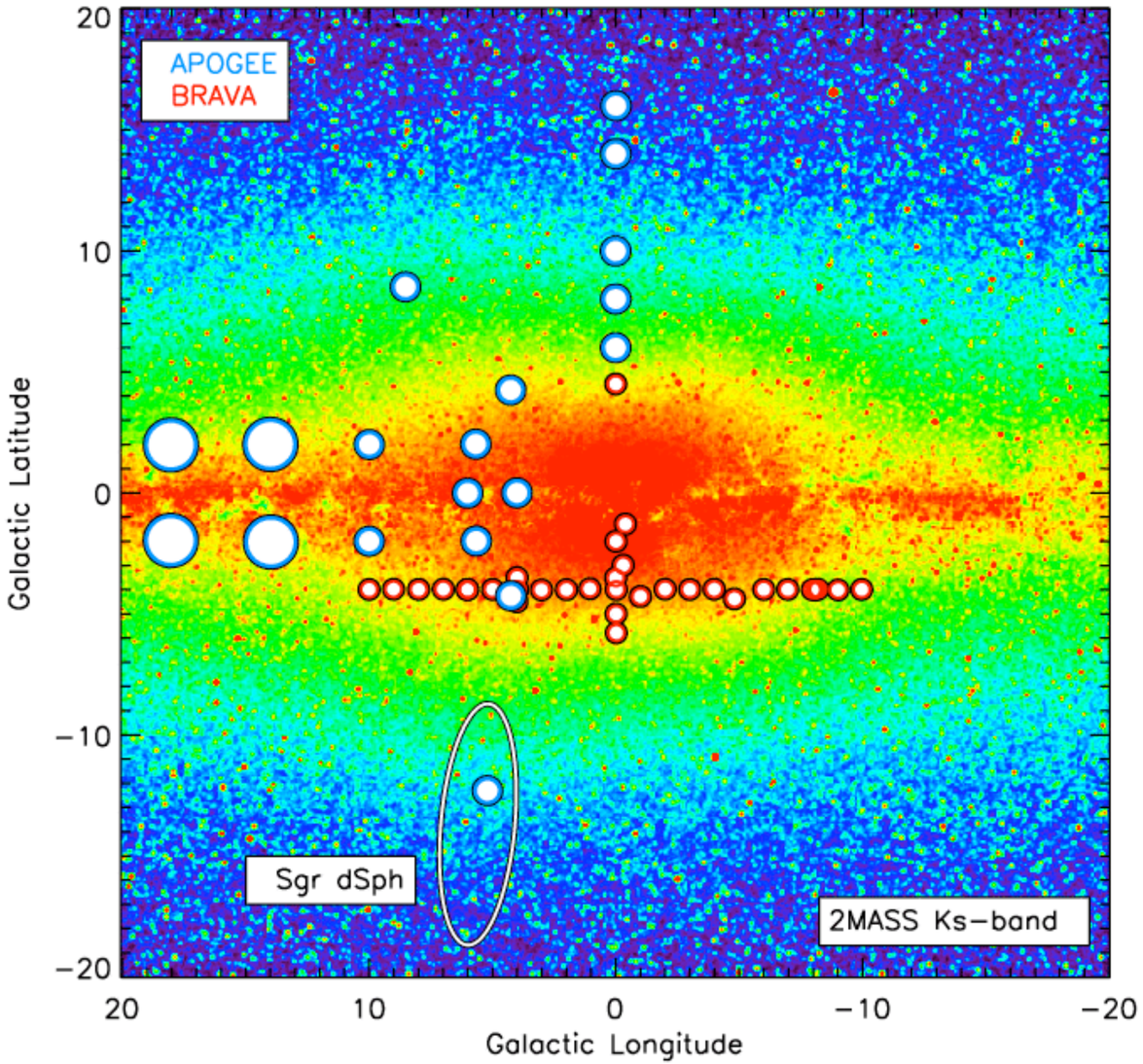


Abundance Pipeline

- χ^2 optimization against large library of synthetic spectra
- First find stellar parameters (Teff, logg, [Fe/H], micro, ...)
- Then find individual abundances (15)

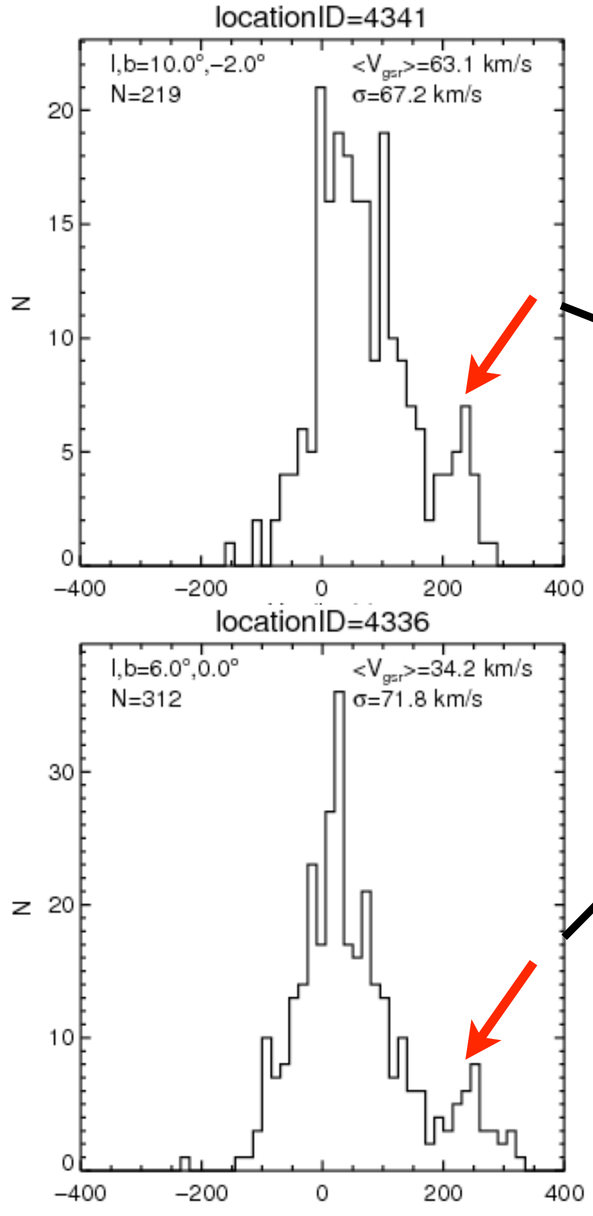
II. First results on Galactic bulge kinematics

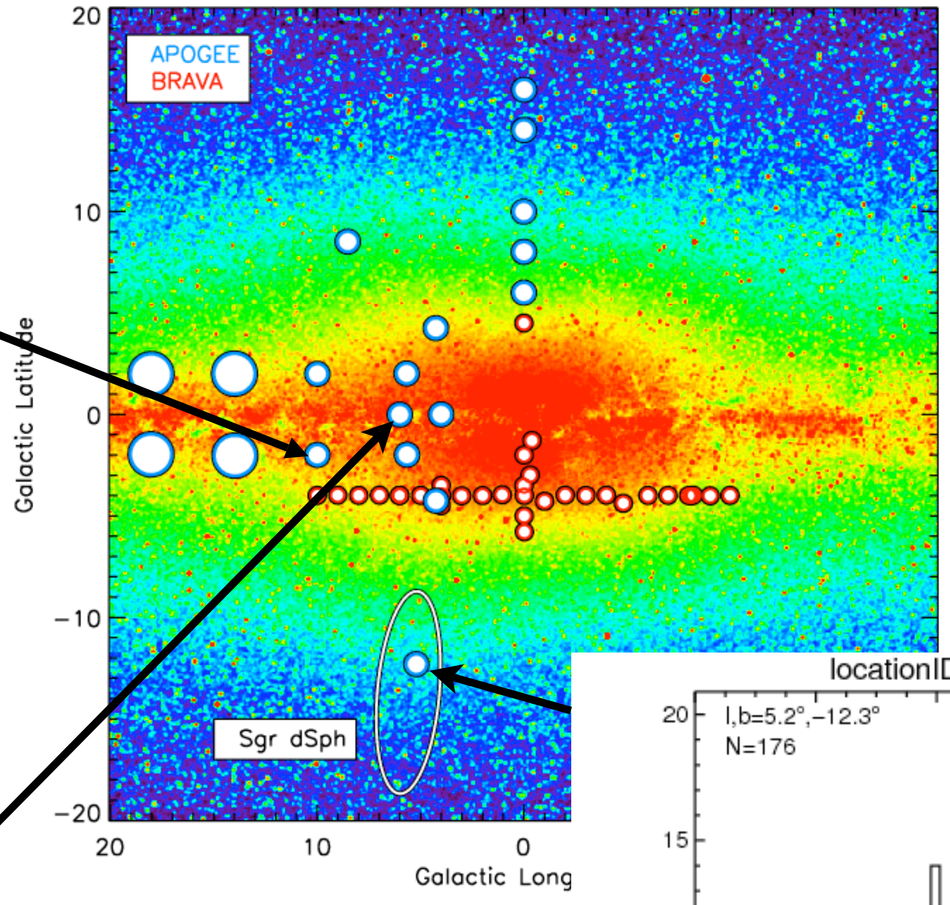
Early APOGEE Bulge Kinematics

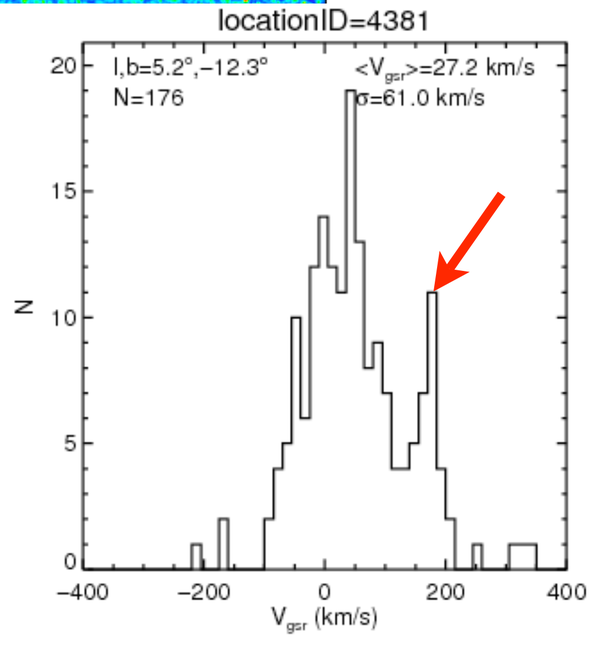


- First APOGEE bulge data
- June/July bright runs
- 19 fields, ~4700 stars
- Radial velocities
- ~0.1-0.2 km/s uncertainties

New Kinematical Substructure

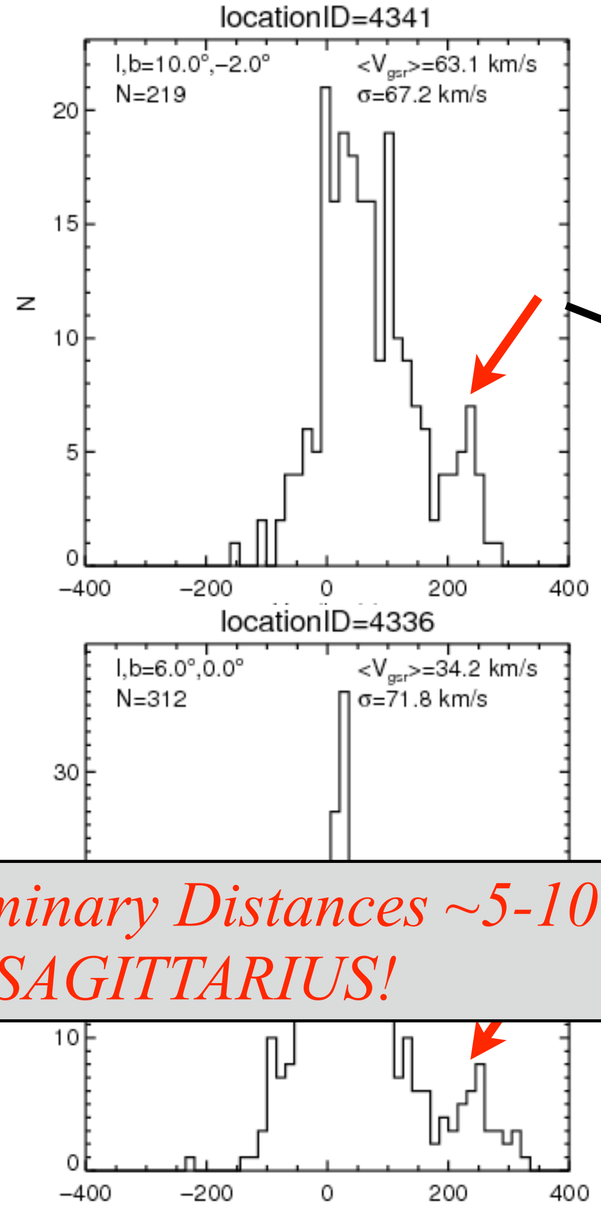


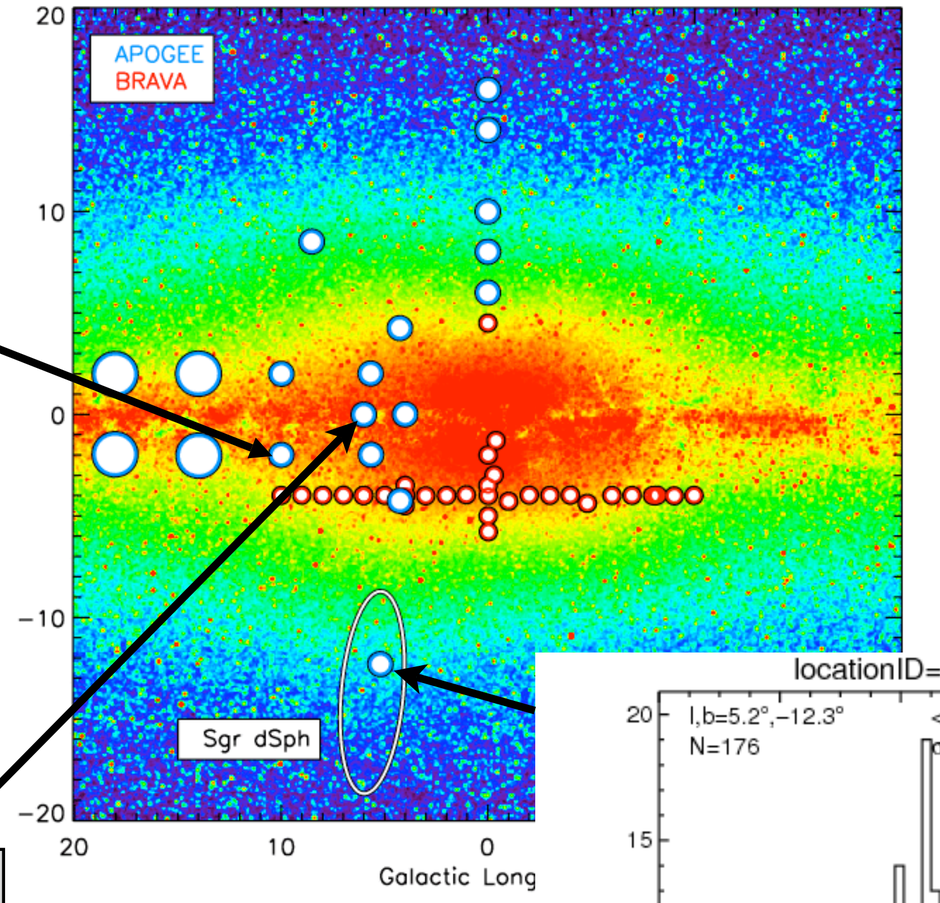


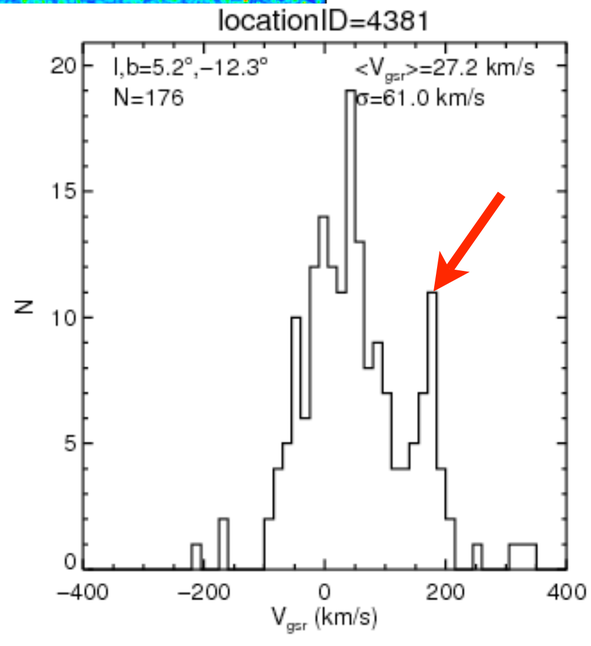


Sgr dSph

New Kinematical Substructure







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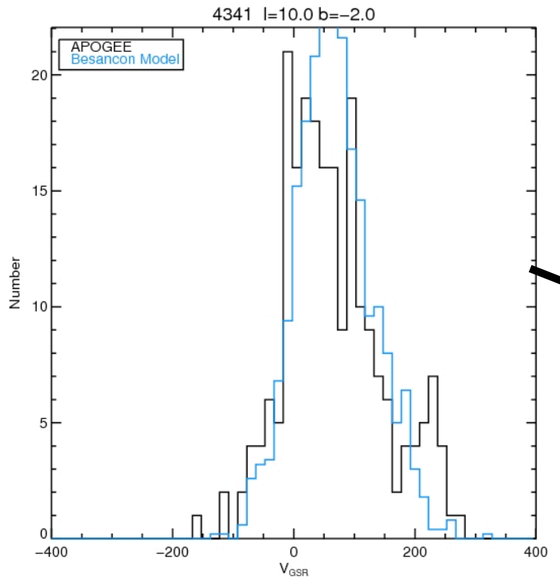
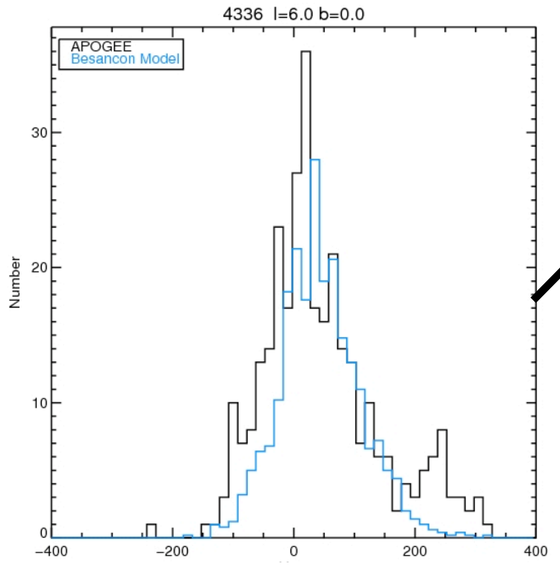
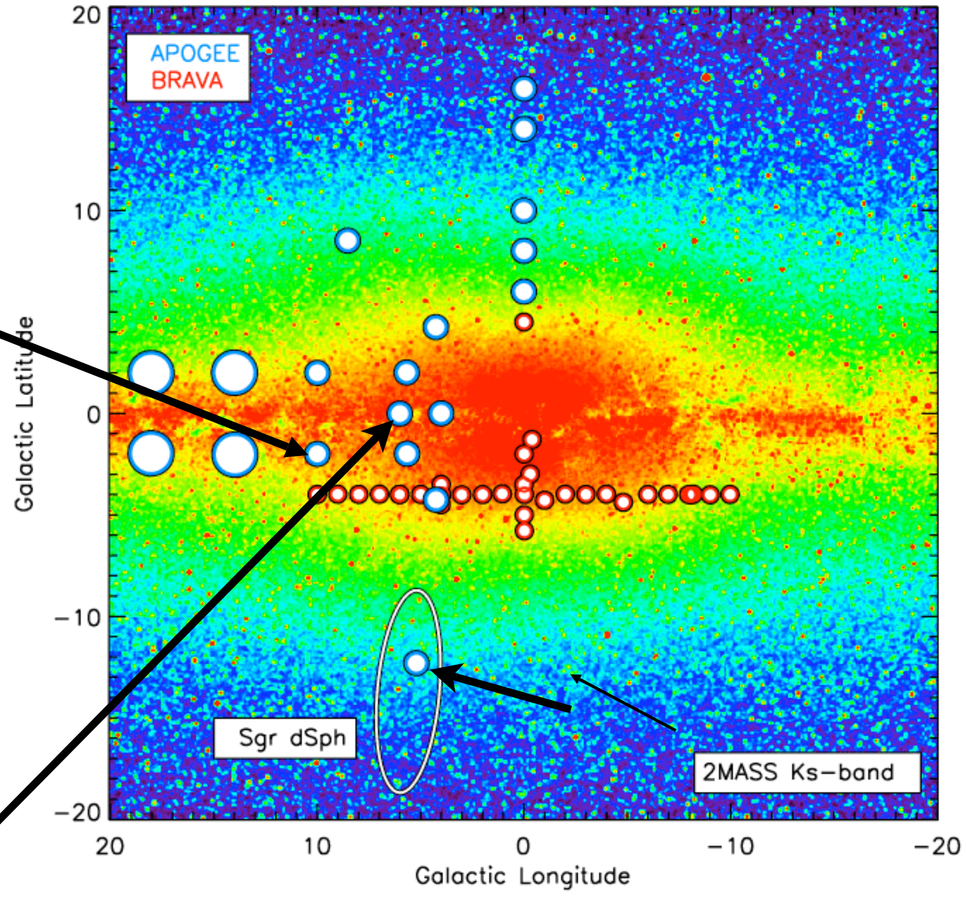






Besancon Galaxy Model

Robin et al. (2012)

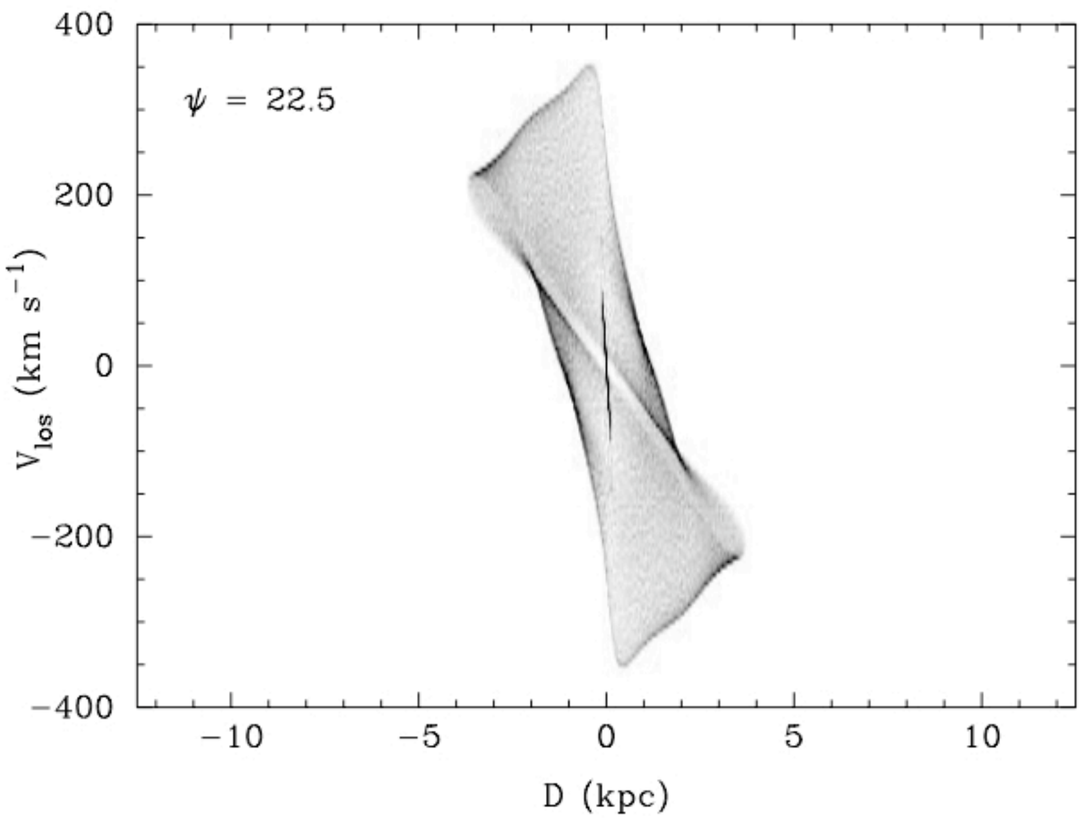
New Kinematical Substructure

Could this be new substructure/stream?

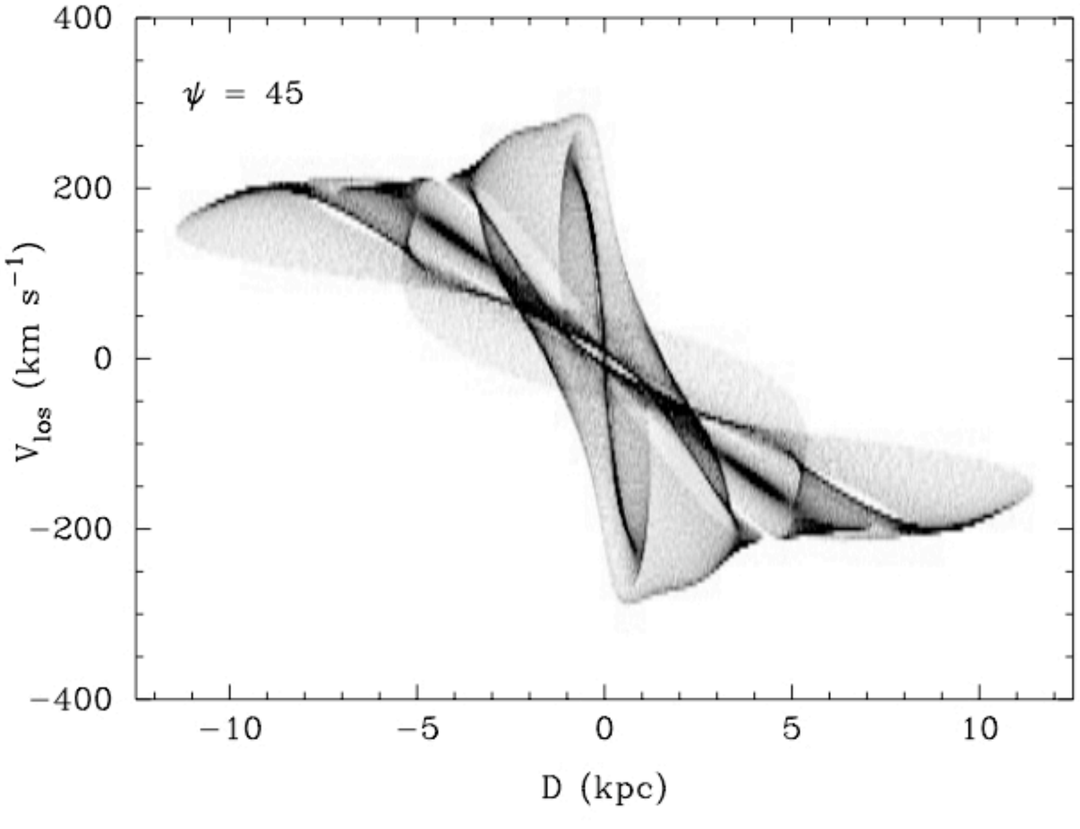
- Are the stars tightly clumped in distance or metallicity? NO
- Look very similar (distance/metallicity) to rest of stars in field which should be dominated by bulge/bar

Bar Orbit Families

Orbits along major axis



Many Orbit Families



Bureau & Athanassoula (1999)

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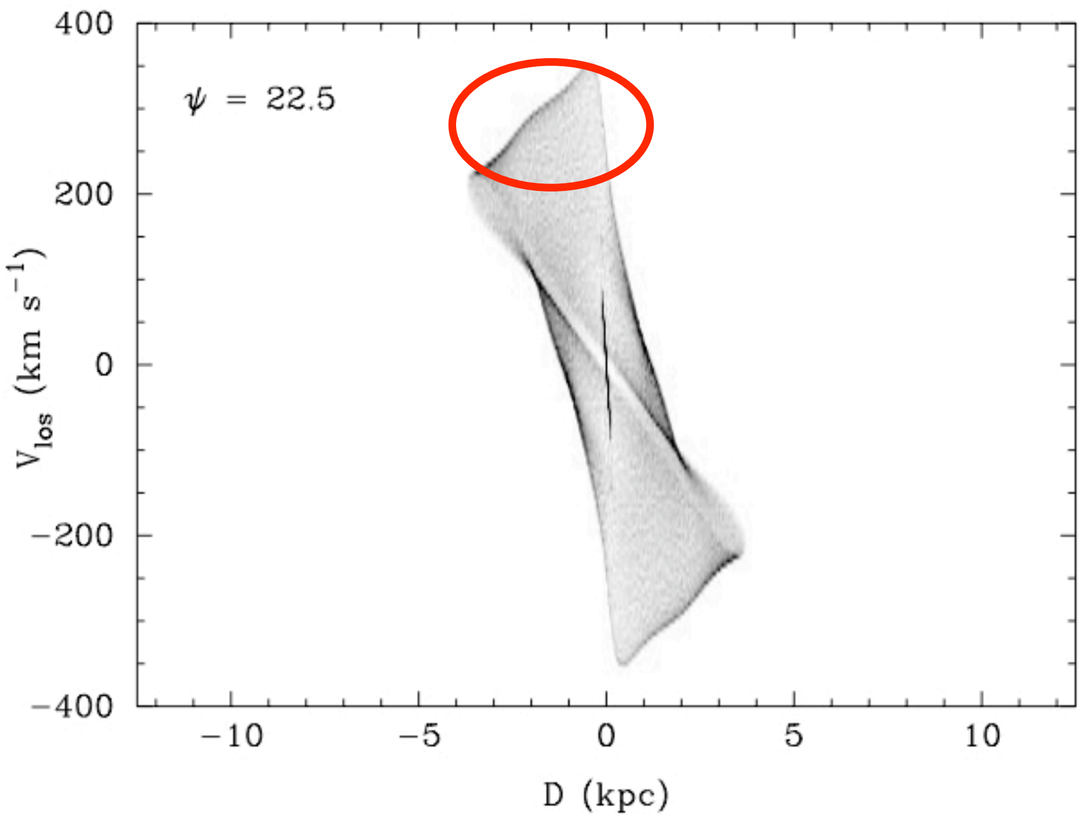

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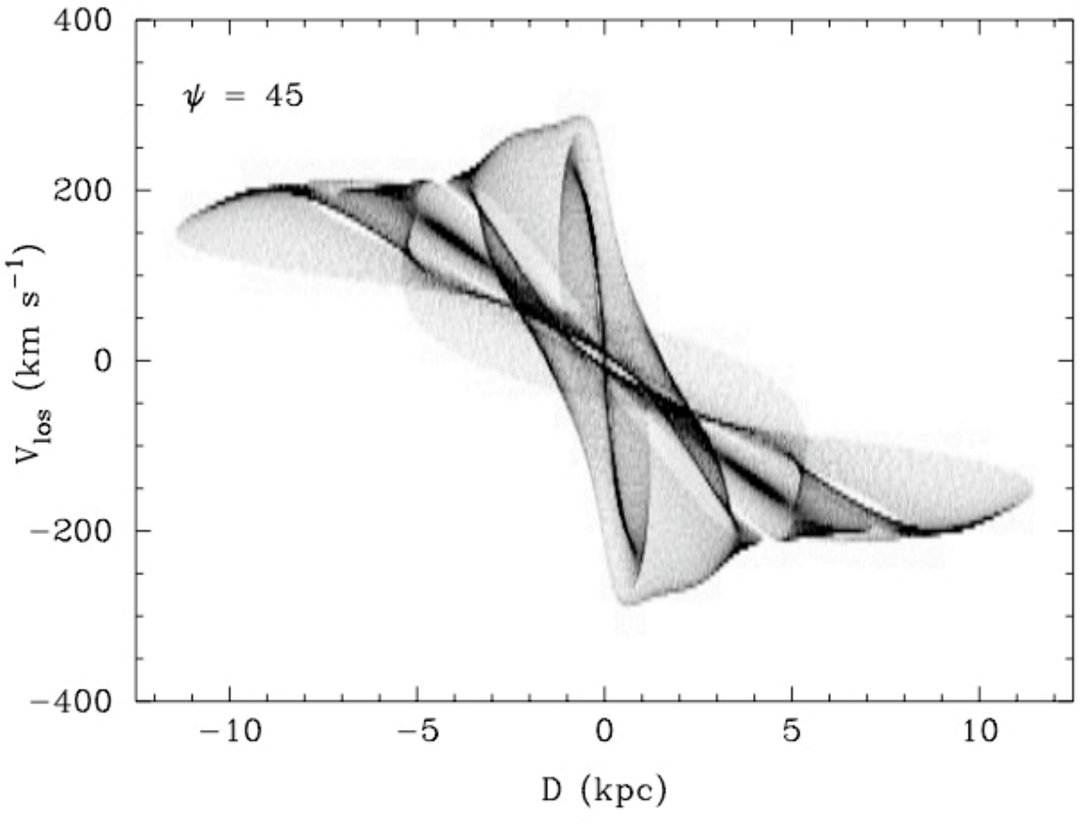
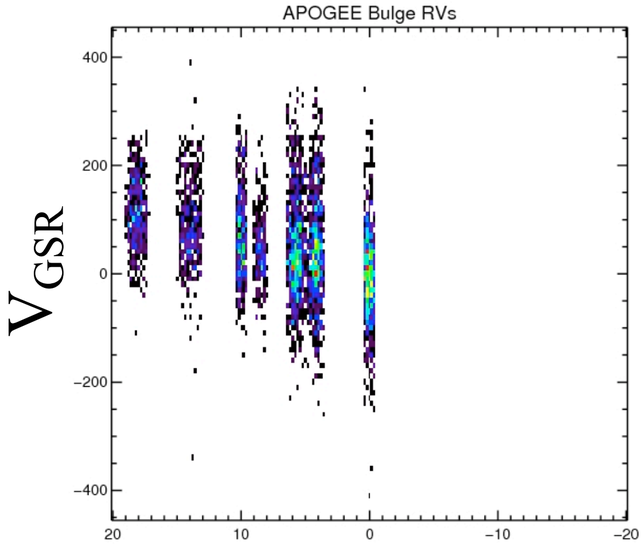


Bureau & Athanassoula (1999)

Position-Velocity Diagrams

APOGEE data



Position-Velocity Diagrams

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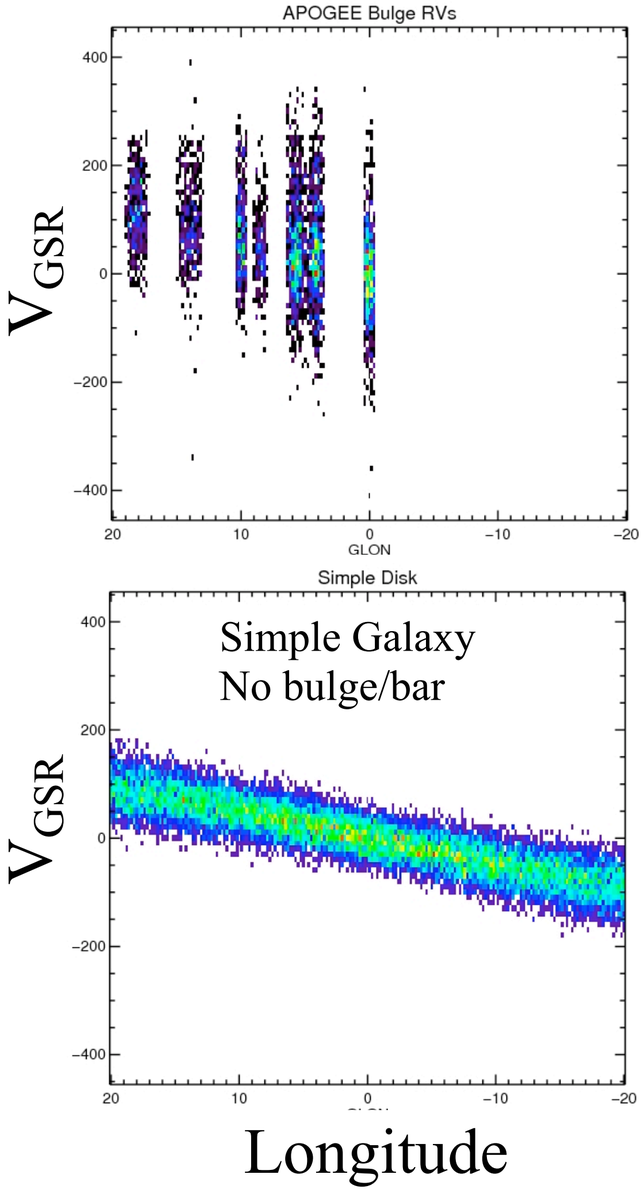
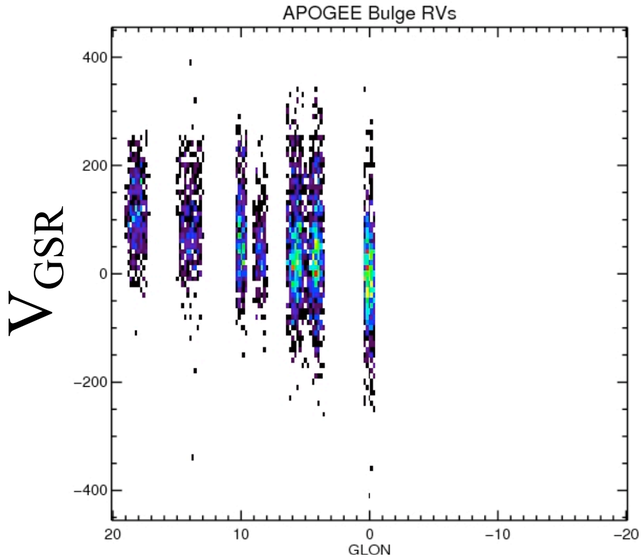
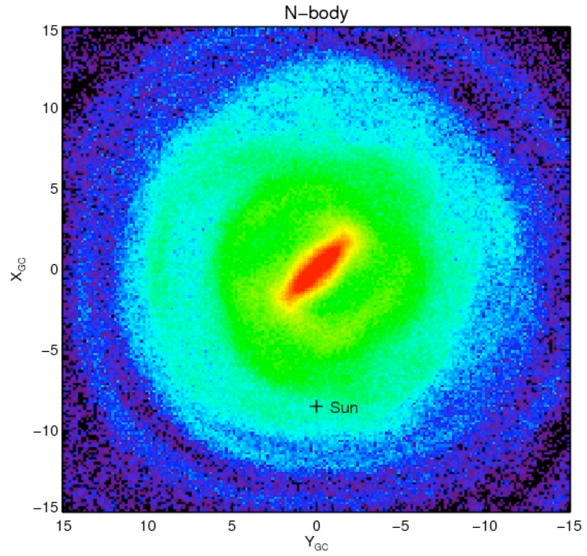


N-body Model

APOGEE data

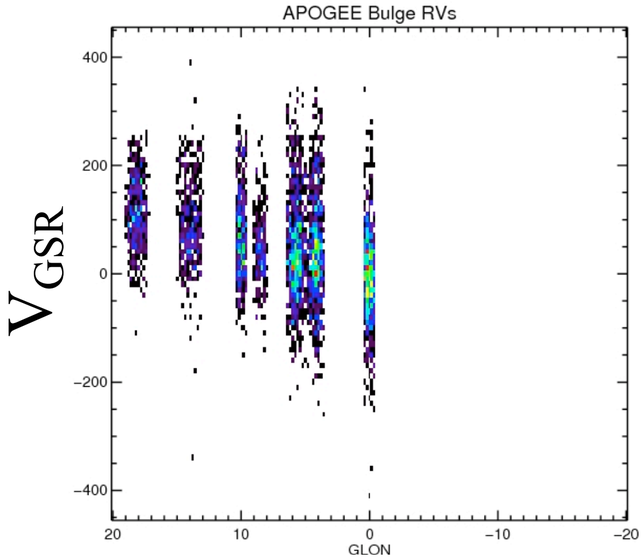


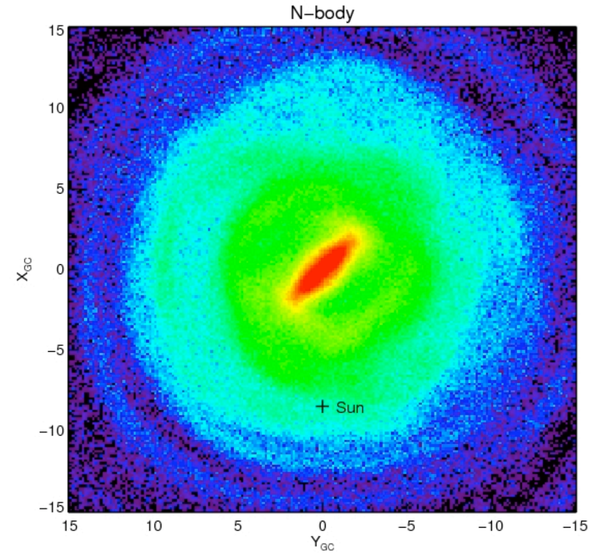


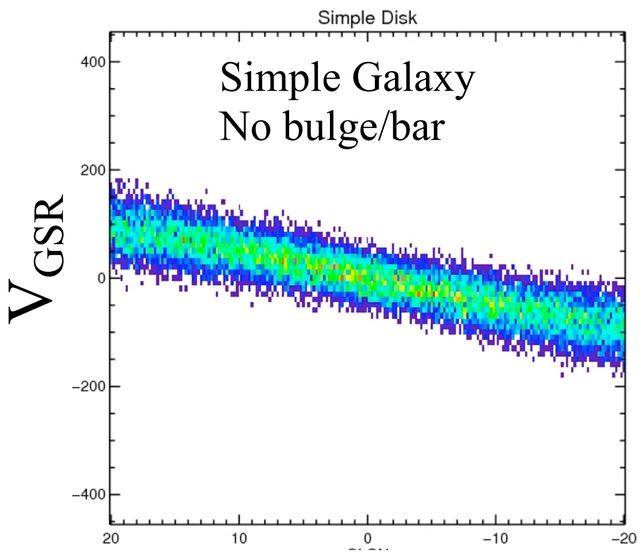
- 400 pc initial scale height
- Subjected to cosmologically motivated satellite accretion history
- Bar is from the outcome of satellite perturbations
- Kazantzidis et al. (2008), Bird et al. (2011)

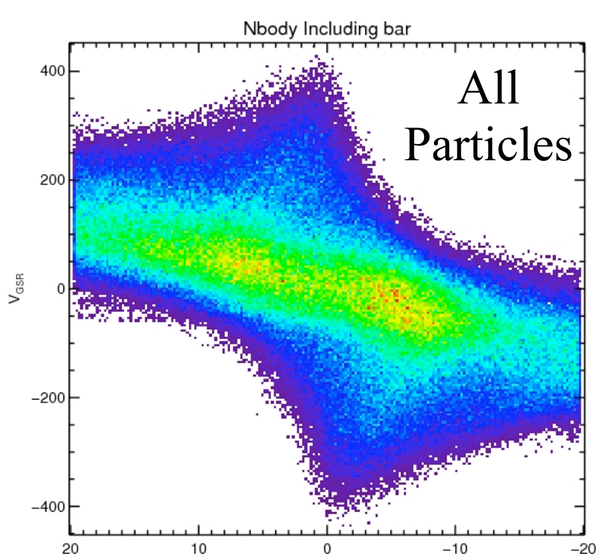
N-body Model

APOGEE data







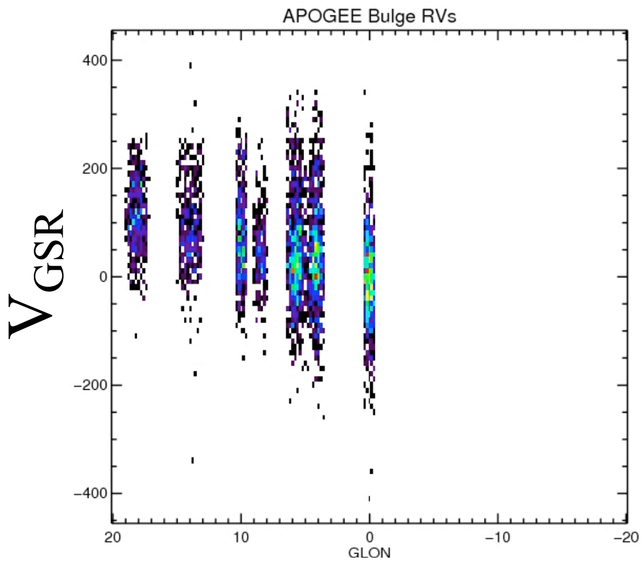


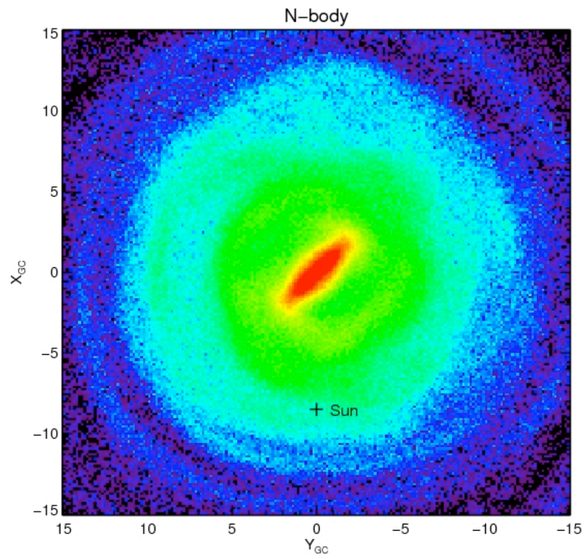
Longitude

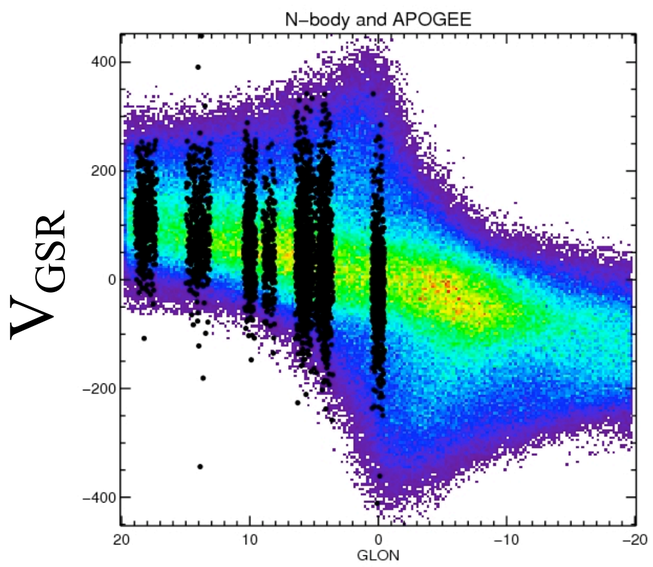
Longitude

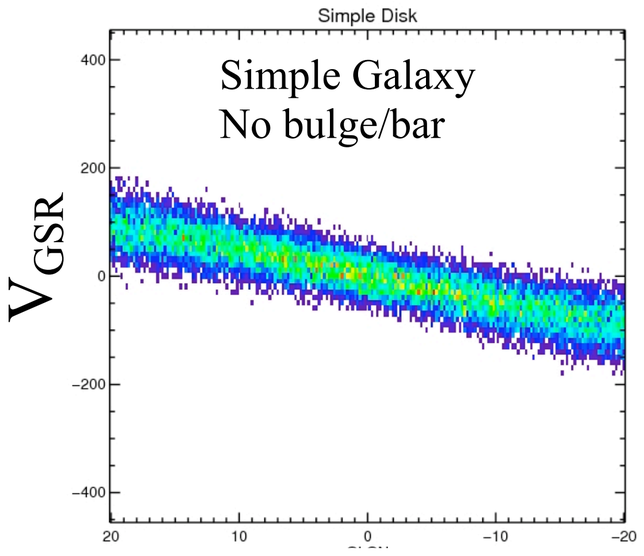
N-body Model

APOGEE data

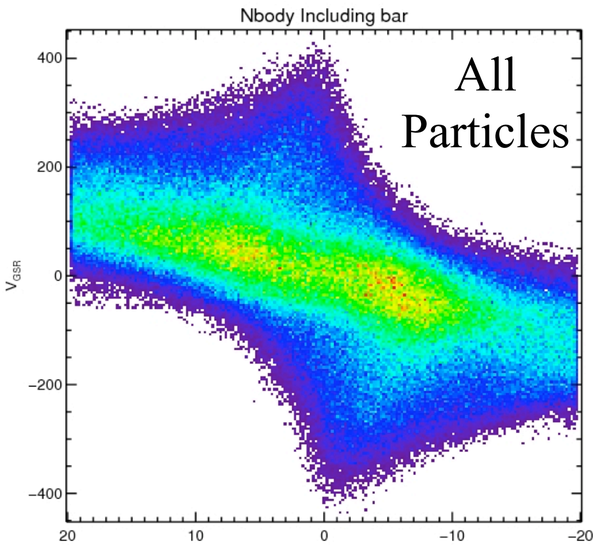








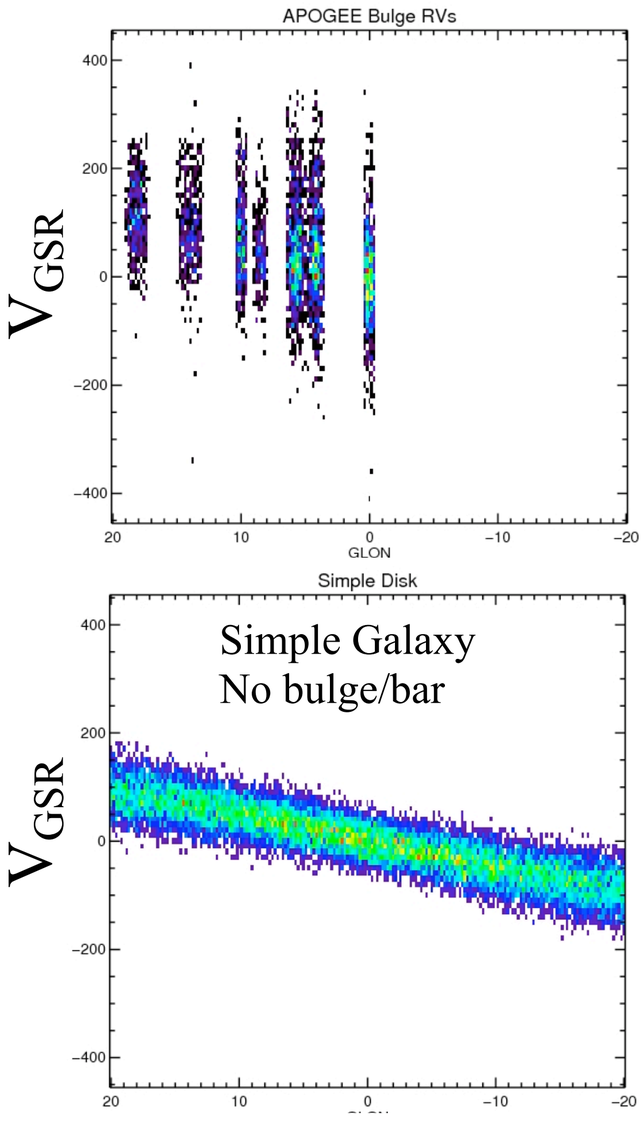
Longitude

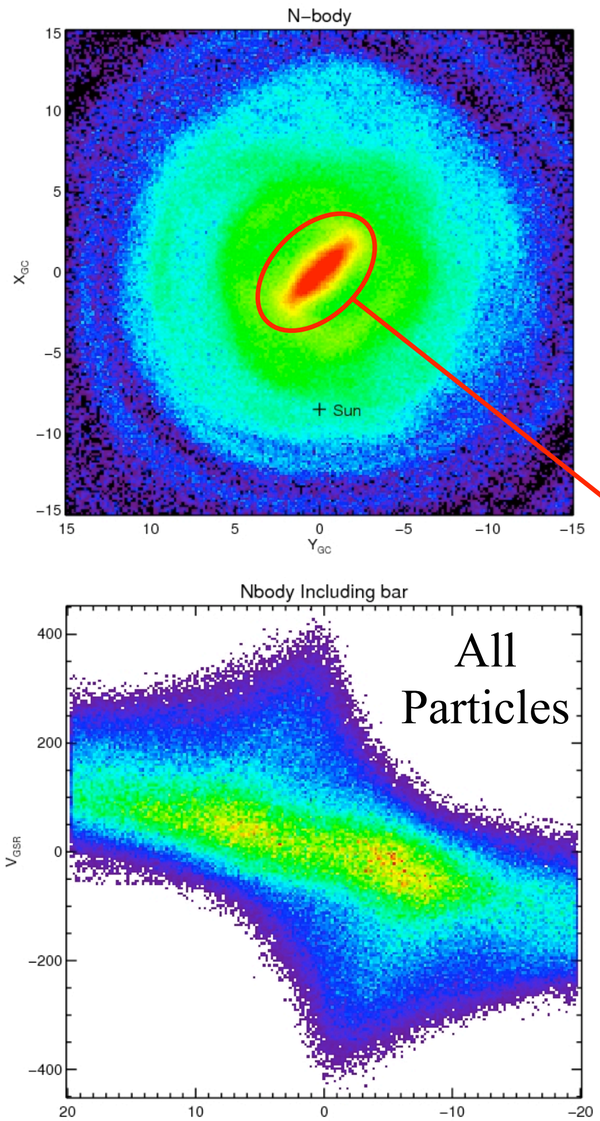


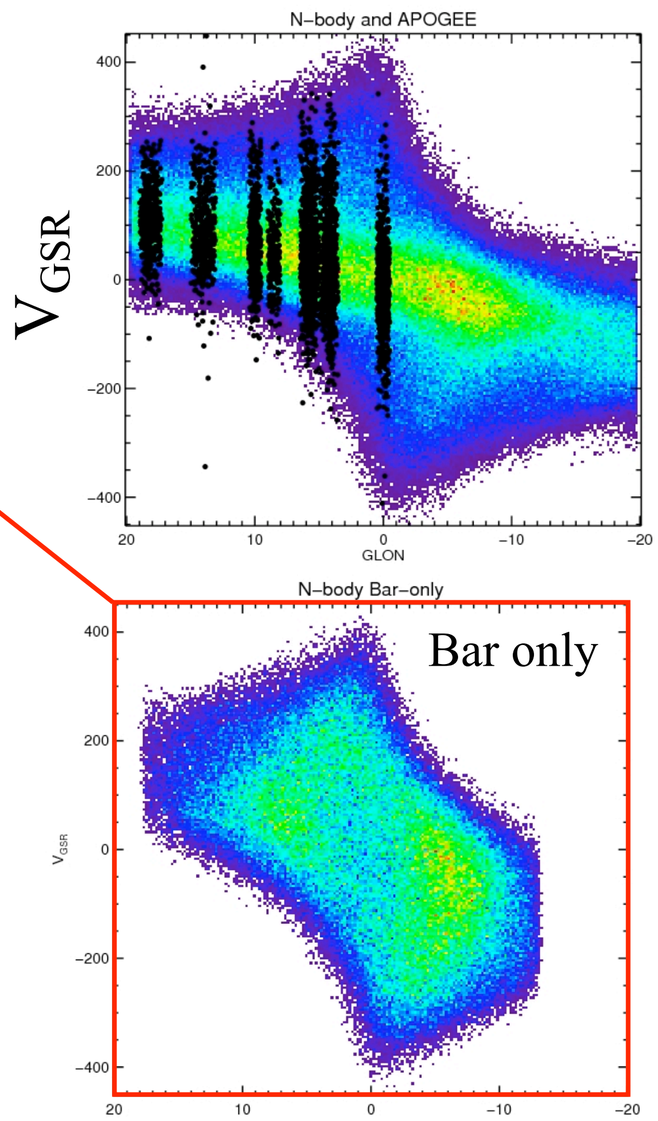
Longitude

N-body Model

APOGEE data

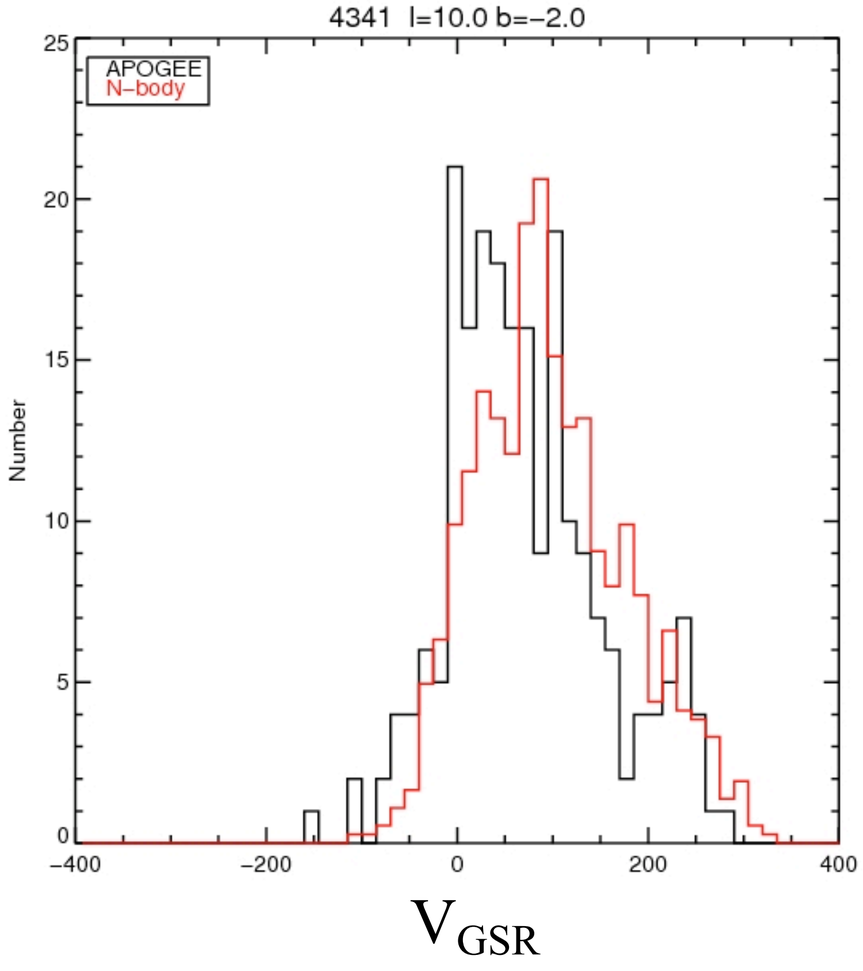


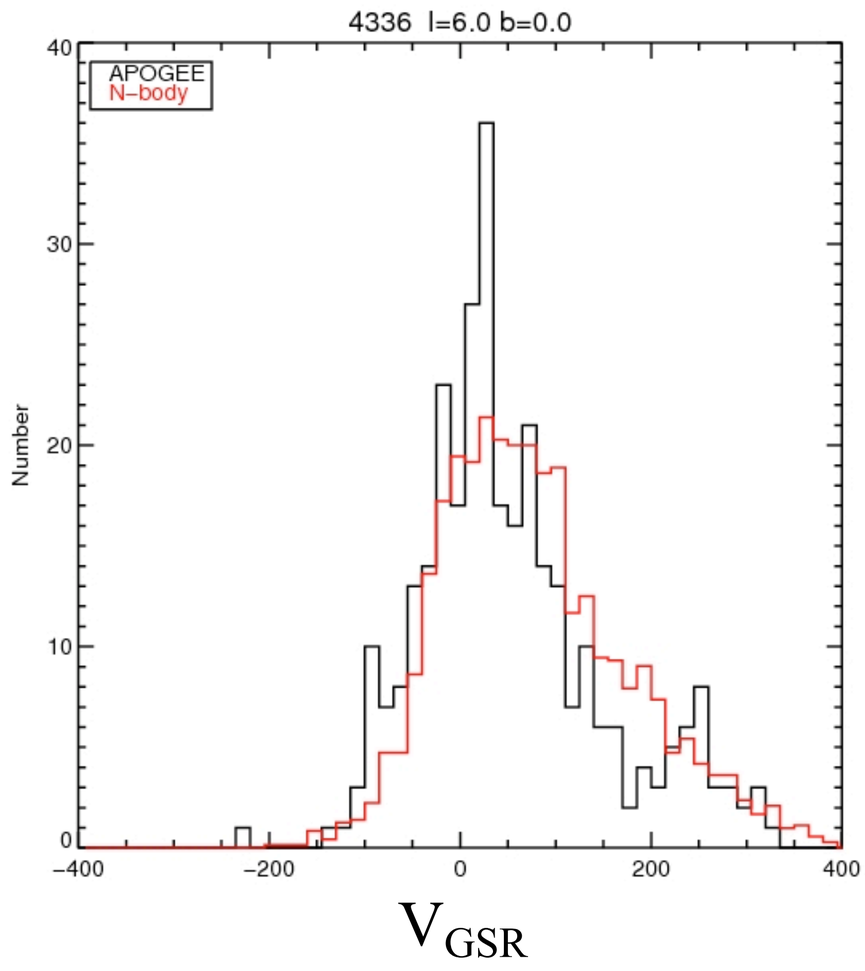




RV Histograms

APOGEE + Kazantzidis N-body





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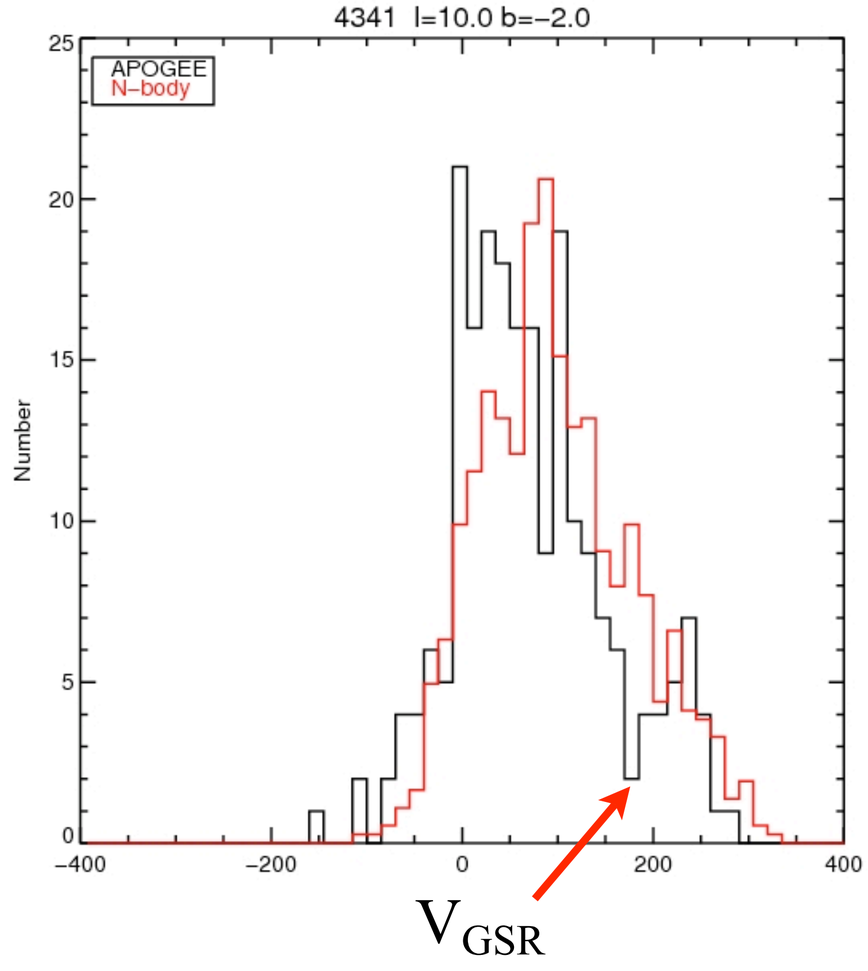
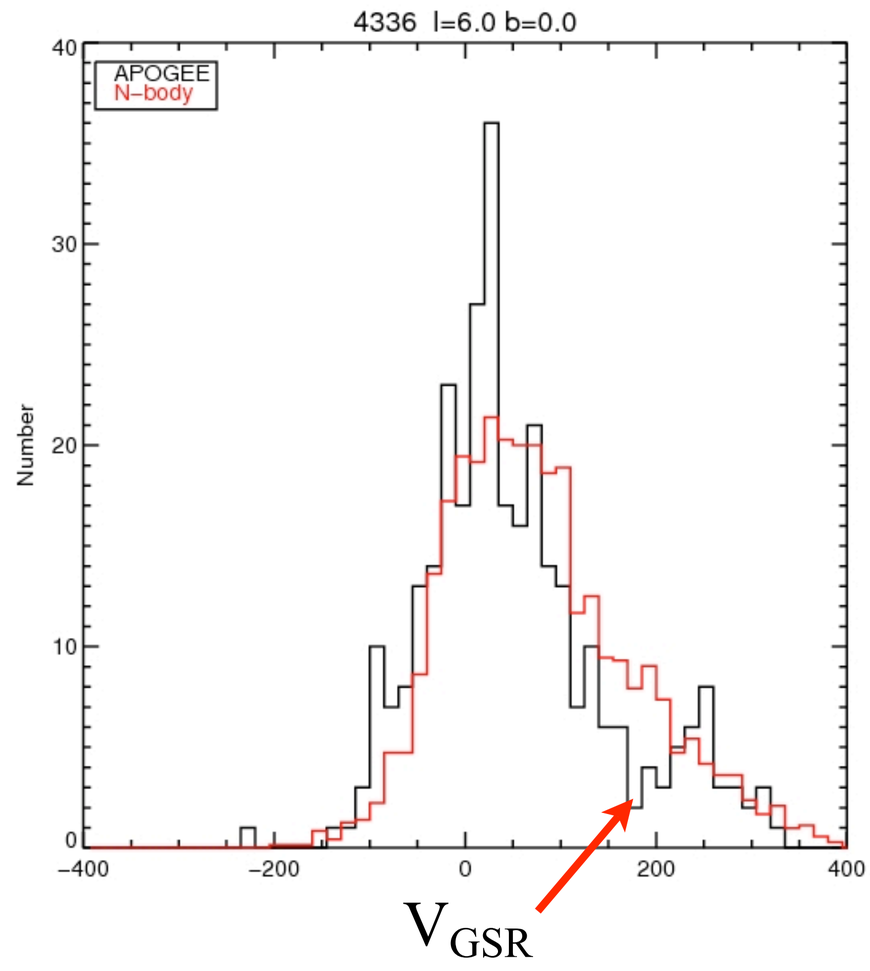
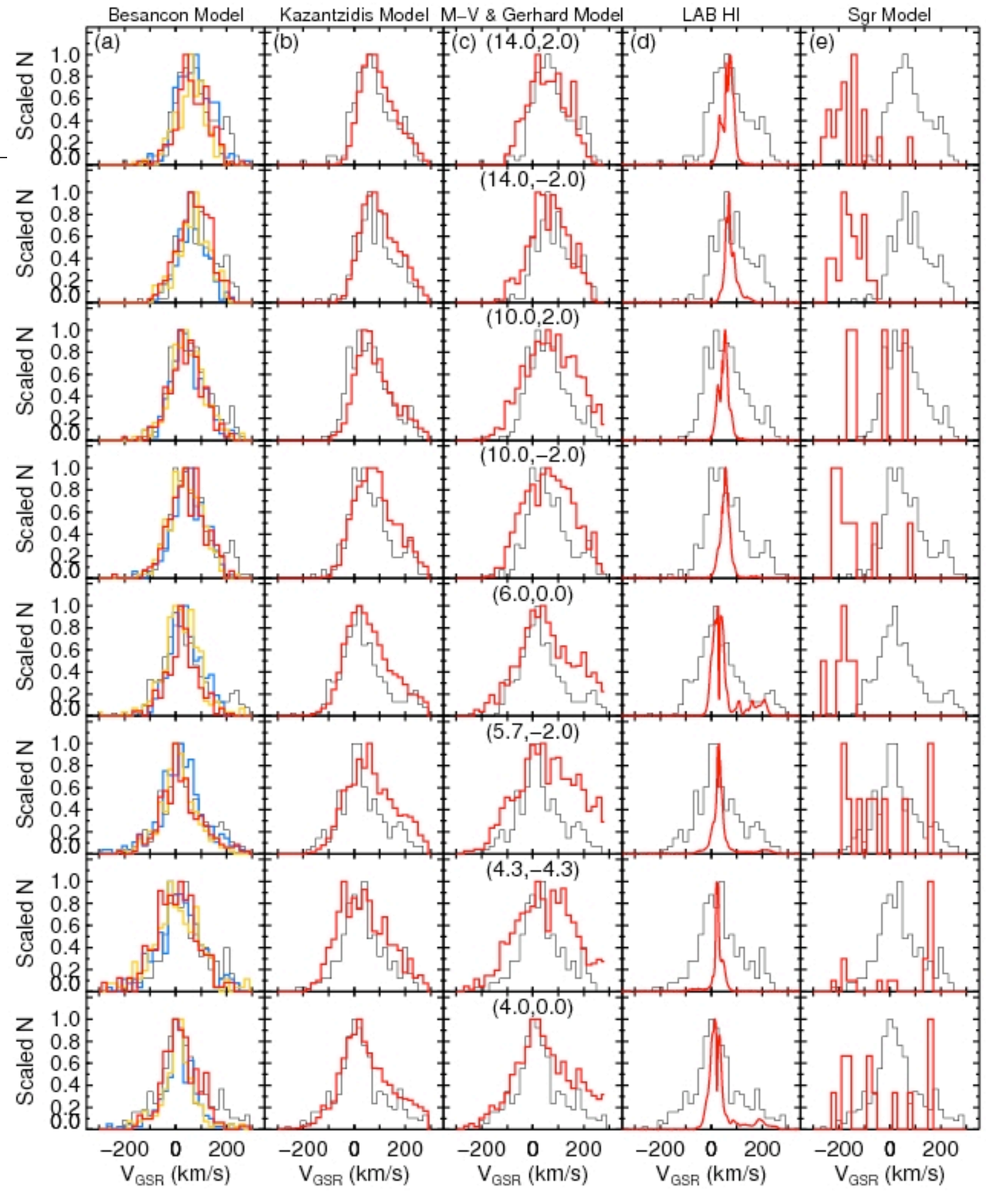




- N-body reproduces high-velocity features
- But no trough!

Nidever et al. (2012), in prep.



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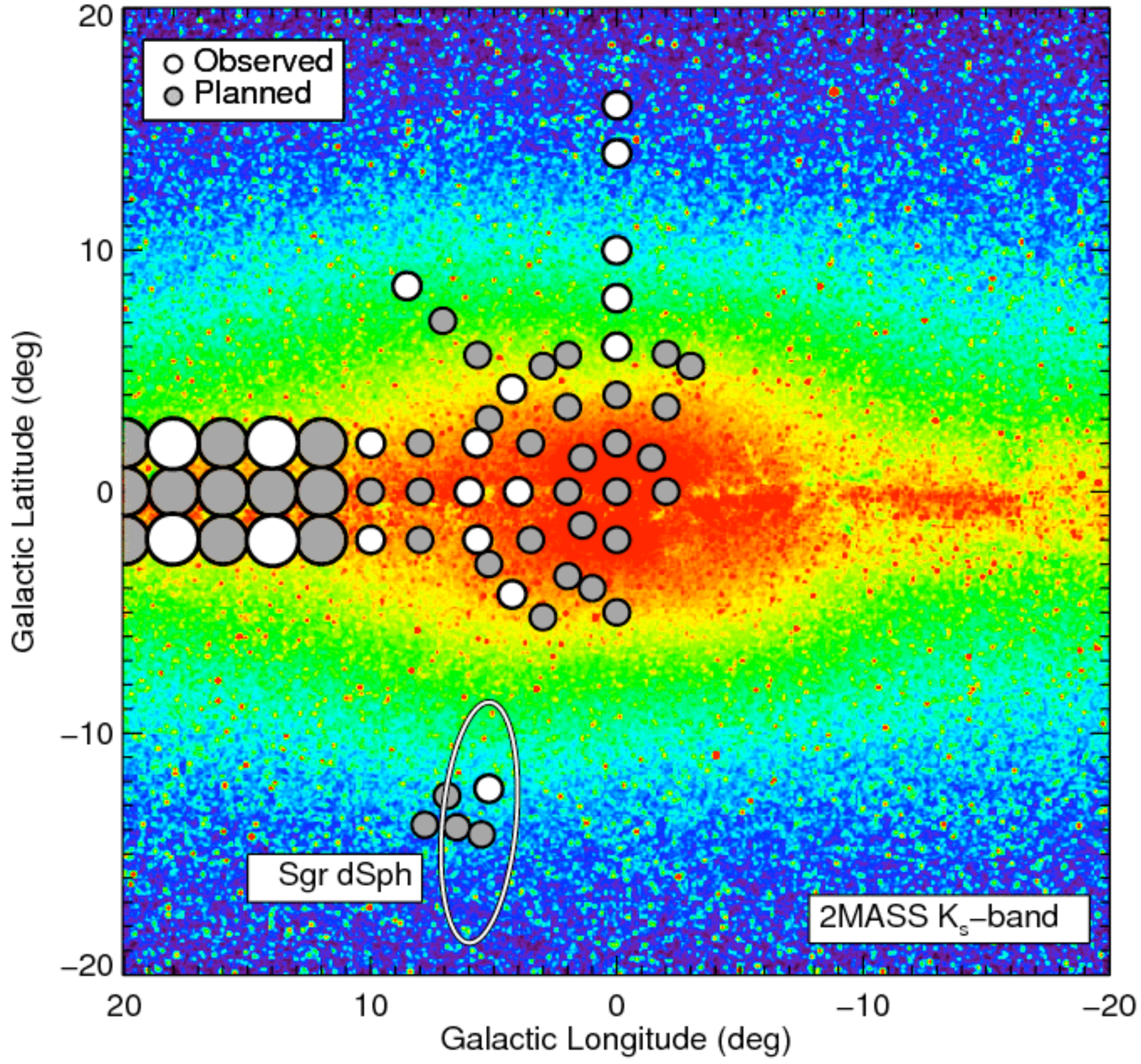
All APOGEE Bulge Fields



III. After Sloan-III and APOGEE-South

Observing the Central Milky Way with APOGEE+Sloan 2.5-m

First APOGEE+Sloan 2.5-m observations of Galactic bulge, May 2011.
(in full moon, at >2 airmasses, and towards lights of El Paso).

Photo by S.R. Majewski

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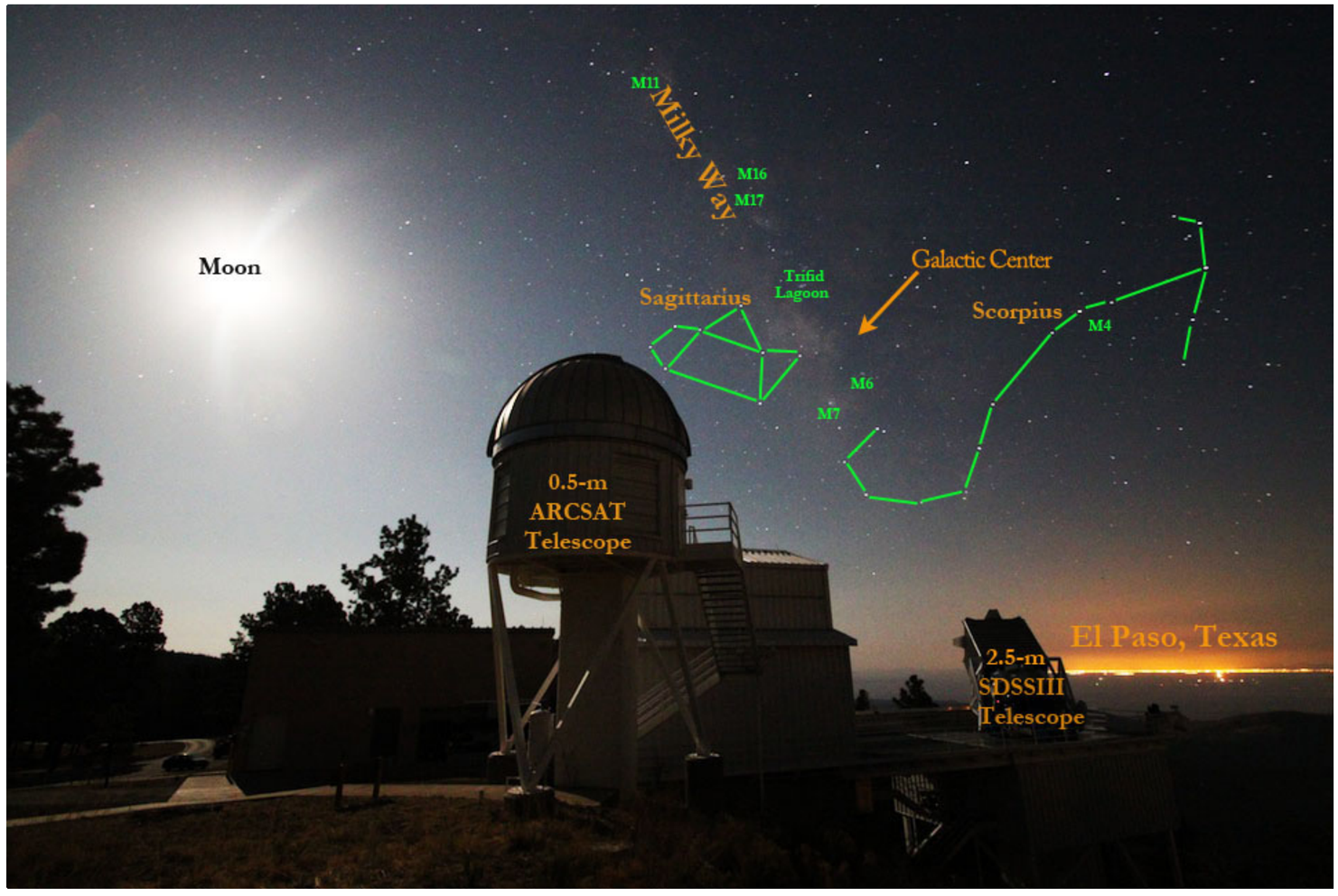


Photo by S.R. Majewski

Observing the Central Milky Way with APOGEE+Sloan 2.5-m

From Apache Point Observatory:

Sgr center culmination @ altitude = 27˚ (airmass = 2.2!)

Galactic center culmination @ altitude = 28˚ (airmass = 2.1)

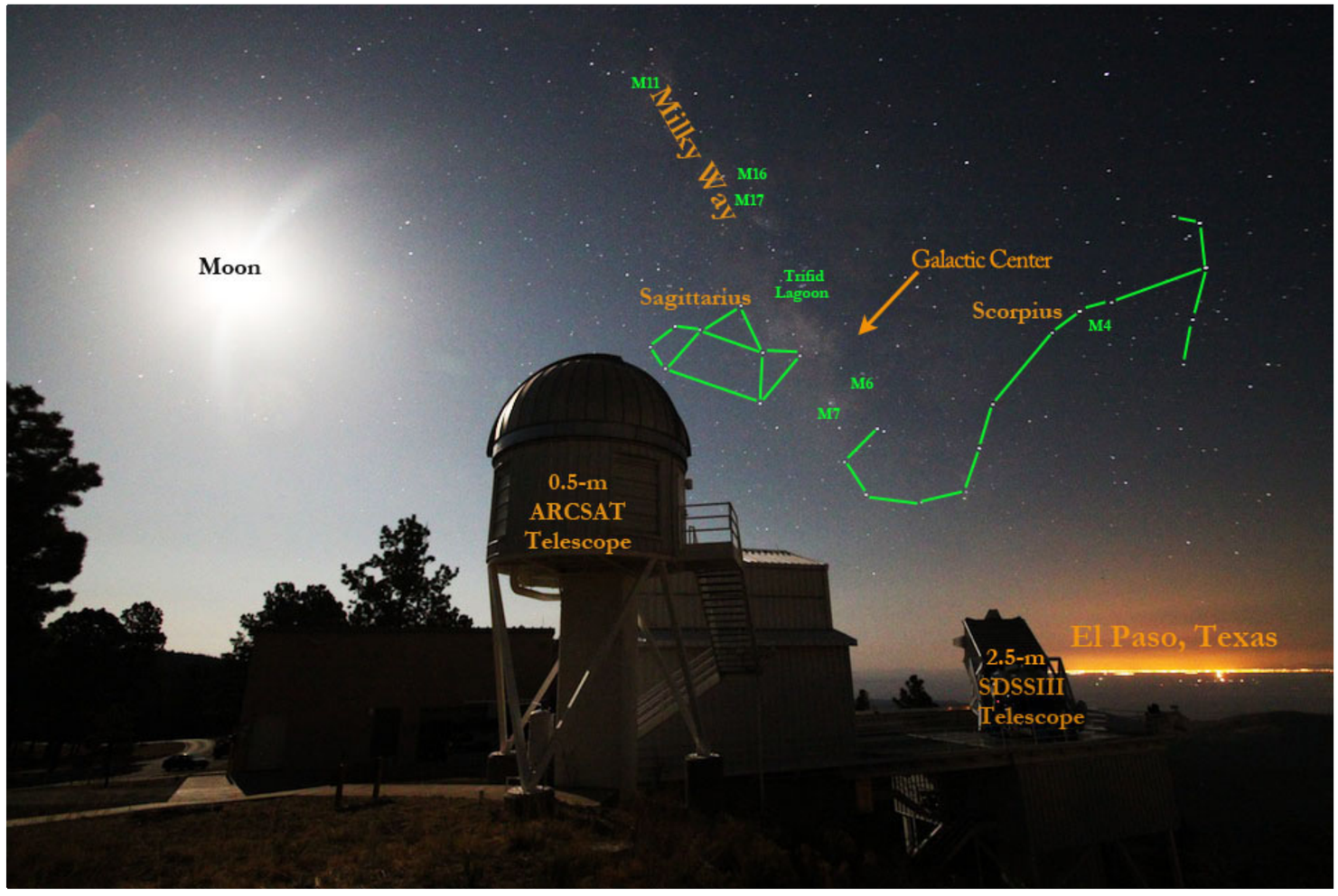


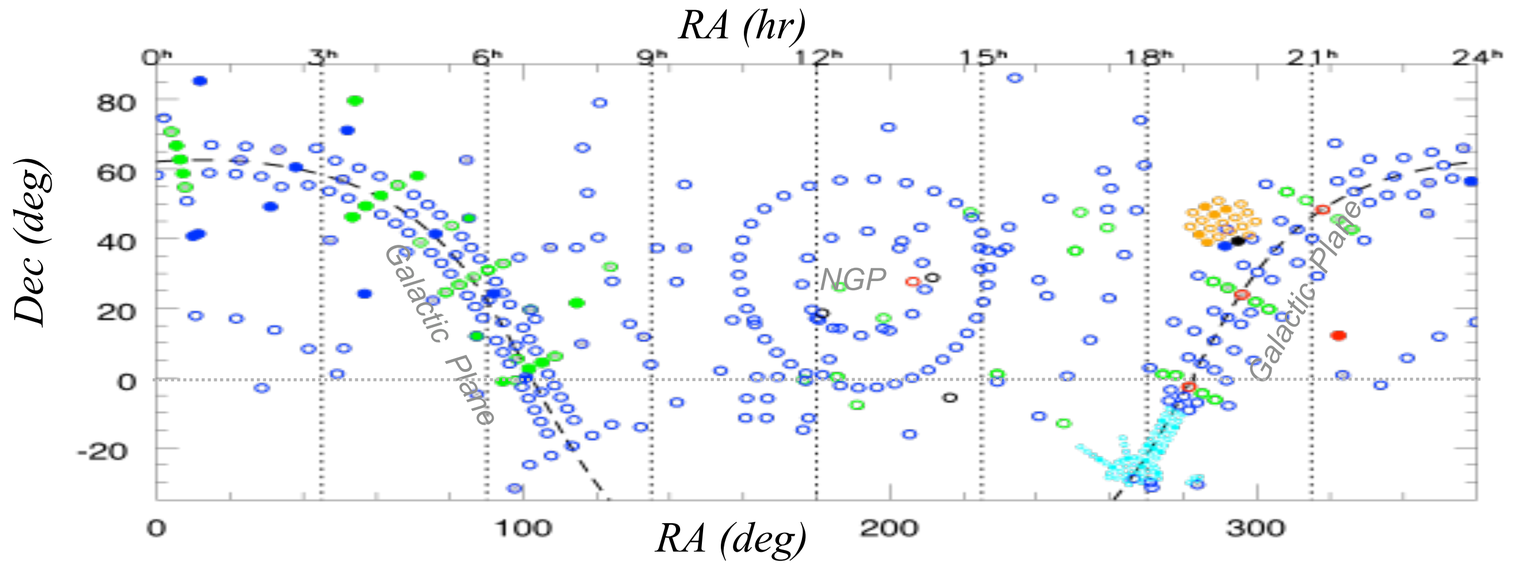
Photo by S.R. Majewski

Extending APOGEE

SDSS3/APOGEE Survey ends June 2014

SDSS3: Resulting 10^5 sample very large, but still scratching surface:

- Halo sample relatively small (~4,500 stars).
- Bulge will be relatively "meagerly" sampled (~8,000 stars).
- Bulge, bar and inner disk hard to do from APO!!
  – high airmass reduces FOV due to differential refraction effects
  – only partial bulge coverage
  – pile-up of inner Galaxy longitudes over small range of RA



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APOGEE extension for "After Sloan-III":

- APOGEE-II (North) significantly increase sample by factor of several.
  - Instrument ready from the start -- another ~250,000 stars.
- APOGEE-South, cloned instrument on Du Pont 2.5-m at LCO.

Science of an APOGEE-South

- Large chemical and kinematical study of the Galactic bulge

  - >65,000 stars & ~15 elements
    - Significantly sample low end of MDF.
    - Increase chance of seeing first stars (Tumlinson 2010) …
      ...or constrain Pop III nature from abundance imprint on succeeding generation (Eckstrom et al. ‘08).
    - X-shaped bulge (McWilliam & Zoccali 2010, De Propris et al. 2011)
    - Sample other rare stellar types
      (e.g., C-stars, CN-strong stars, S-type, Mira, very young stars?)
    - Center of halo and disk distributions
    - Exploring bar

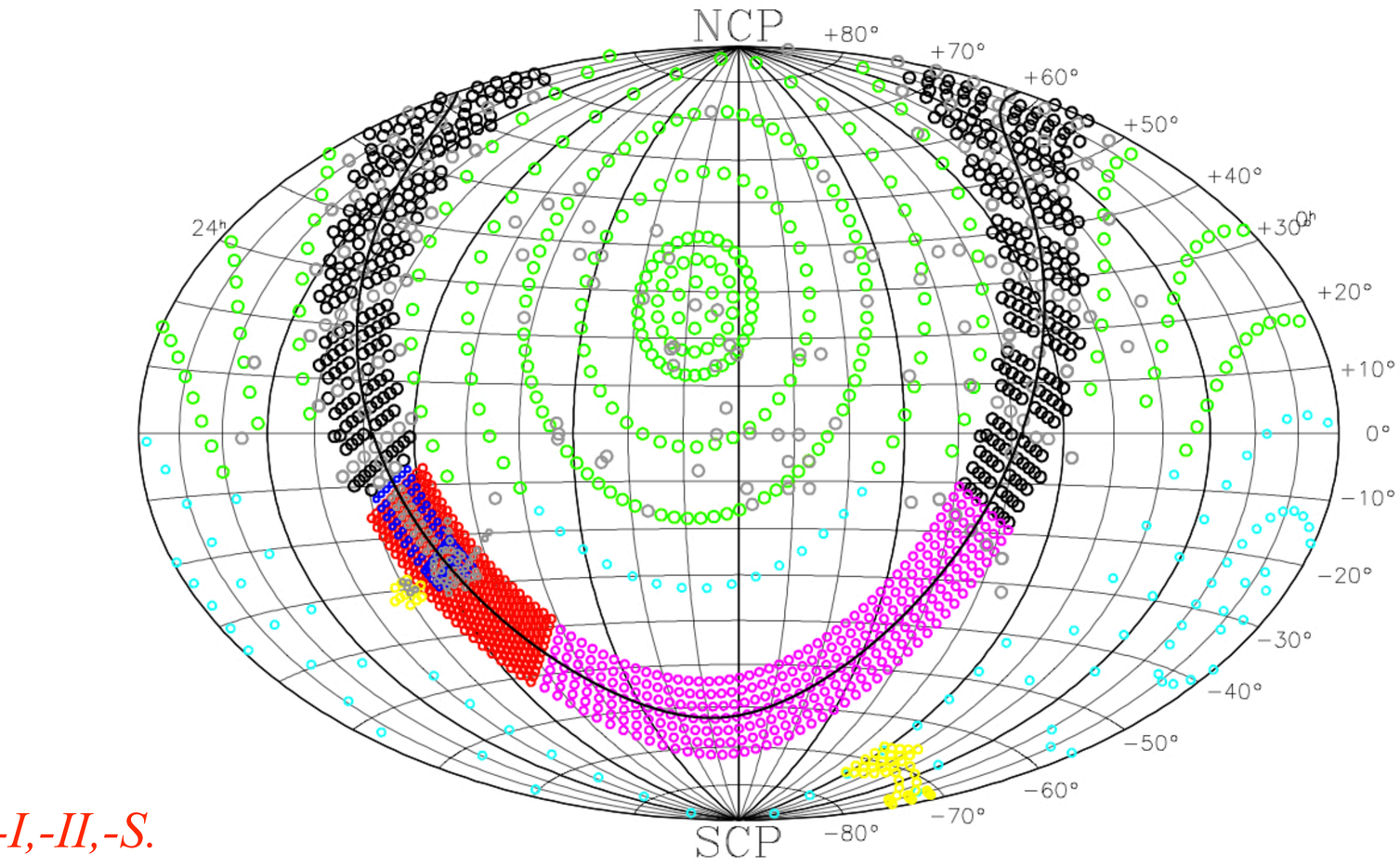
Science of an APOGEE-South

- Significant/homogeneous surveys of 4 other Local Group galaxies:
  - Large and Small Magellanic Clouds, Sagittarius, ω Centauri

- Halo/disk substructure
  - Disk/bar/spiral arm symmetry by inclusion of III and IV quadrants.
  - Clear views of Monoceros/Canis Major/Argo (warp or tidal stream?).
  - Disk warp and disk edge/truncation.
  - Far side of the disk, beyond bulge.
  - Follow-up for southern hemisphere photometric surveys *(VVV* and *SkyMapper)*.

- Star cluster chemistry
  - Definitive metal-rich bulge/disk clusters study (not possible in north).
  - Important targets:
    e.g., ω Cen, 47 Tuc, NGC 288/362, N6338/N6441, Sgr & Magellanic clusters.
  - Integrated light in Magellanic clusters.

APOGEE-II/-S Sky Coverage



Approaching 10^6 stars in combined APOGEE-I,-II,-S.

Opportunities for Collaboration

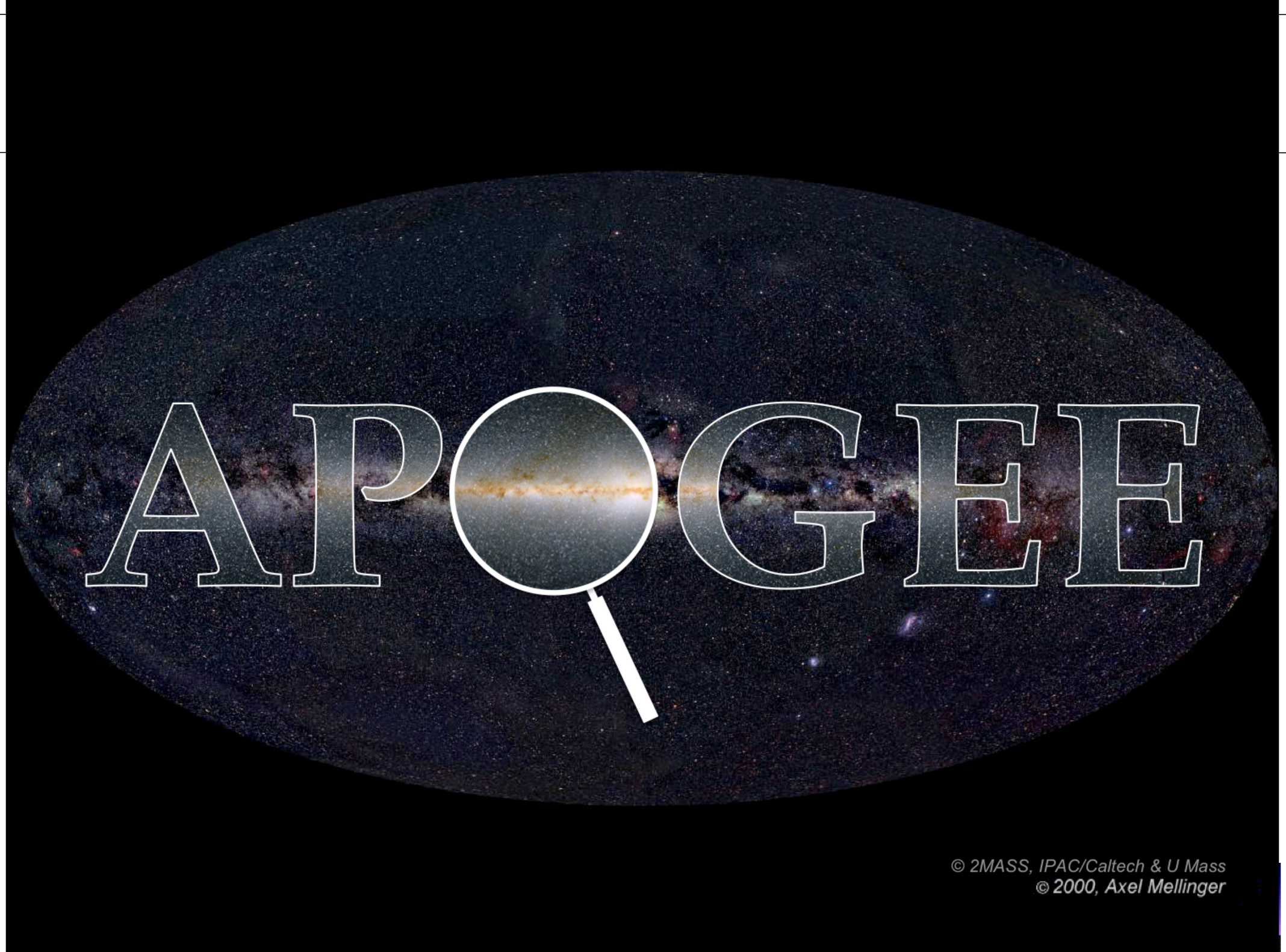
Anticipate a "Sloan-like" organization:

- Interested parties/institutions join "SDSS-IV"

  -- presently called "After Sloan-III (AS3)" --

  which would operate like previous SDSS collaborations.

- Talk to any APOGEE team member if you are interested in joining us!


APOGEE
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