APOGEE and what comes next

Carlos Allende Prieto

Instituto de Astrofísica de Canarias

APOGEE at a Glance

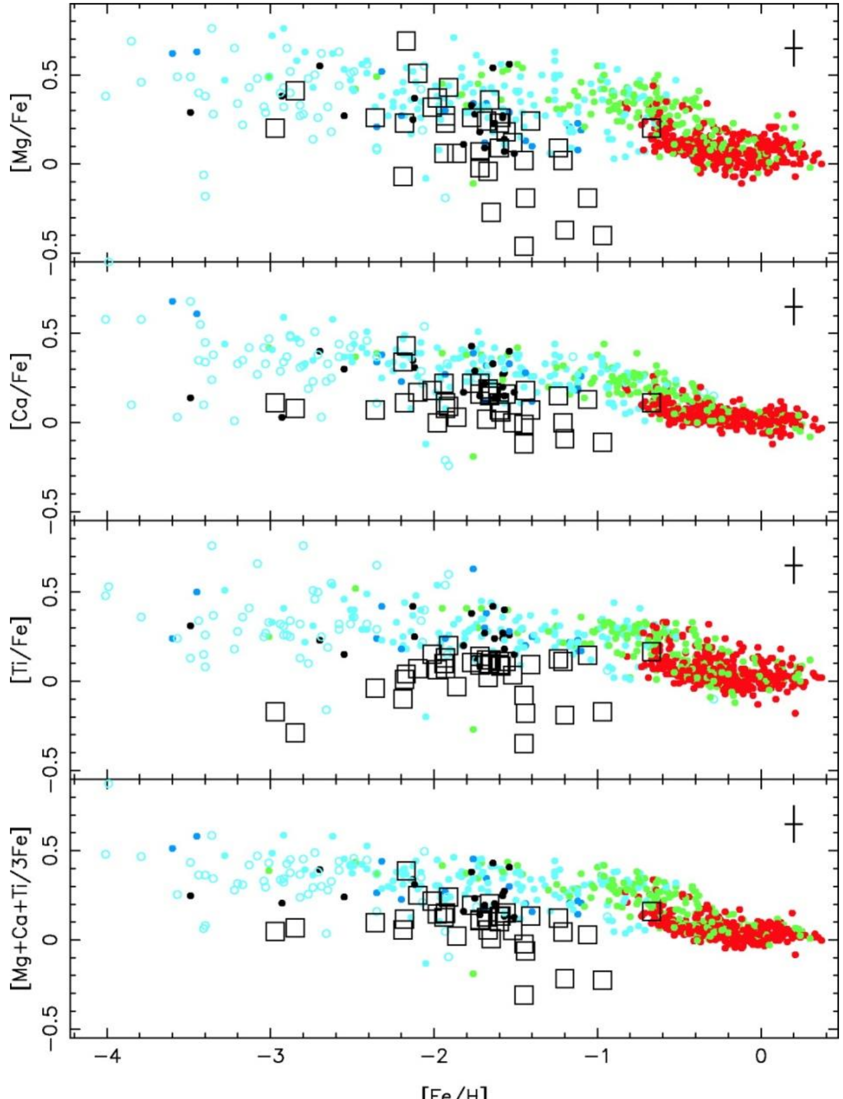
SDSS-III -- One of 4 programs (MARVELS/BOSS/APOGEE)

- Bright time 2011.Q2 - 2014.Q2
- 300 fiber, $R \geq 22{,}500$, cryogenic spectrograph, 7 deg^2 FOV
- *H*-band: 1.51-1.69μm $A_H/A_V \sim 1/6$
- $S/N \geq 100$/pixel @ H=12.2 for 3-hr total integration
- RV uncertainty ~100 m/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)
- 10^5 2MASS-selected giant stars across all Galactic populations.

Top Level Science Requirements

- reliable statistics (= solar neighborhood) in many (R, θ, Z) zones

(E.g., Venn et al. 2004 *compiled* solar neighborhood sample of 781 thin disk, thick disk and halo stars [colored dots] + several dozen dSph stars [boxes])

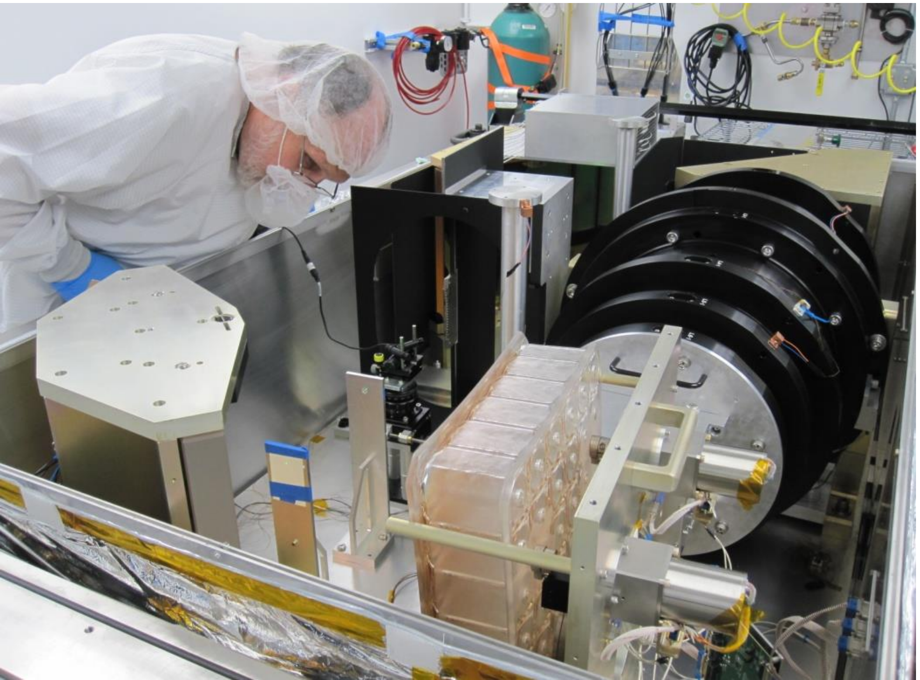


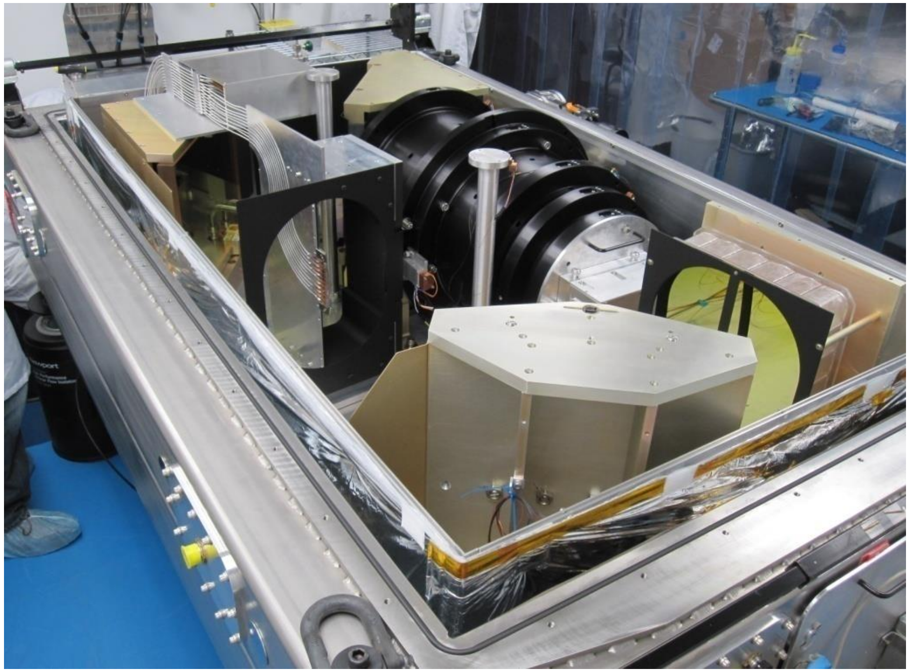
With 10^5 stars, APOGEE seeks to measure similar distributions

- ***for many (~15) elements***
- ***for many other discrete Galactic zones***
- ***across the bulge, disk and halo.***

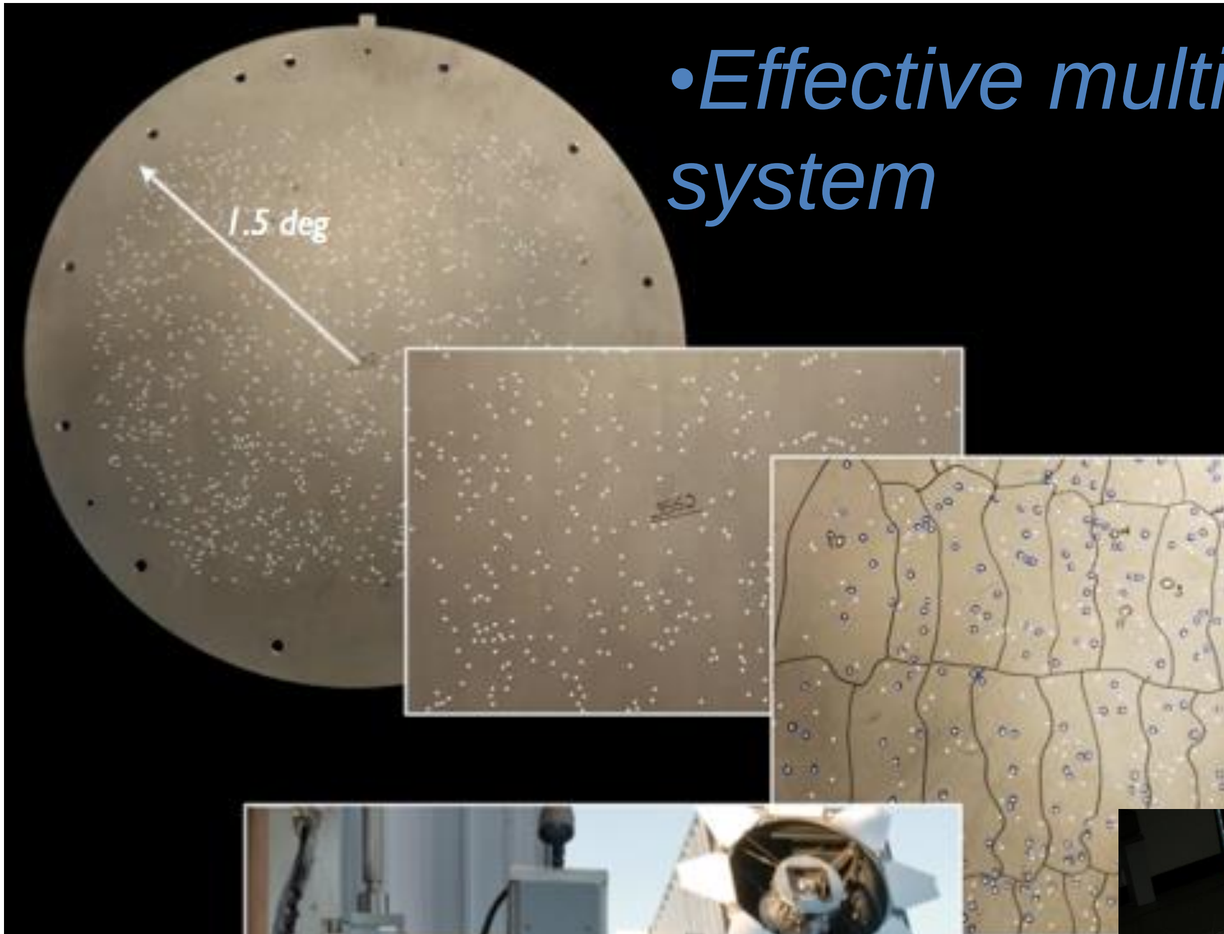
The APOGEE Instrument

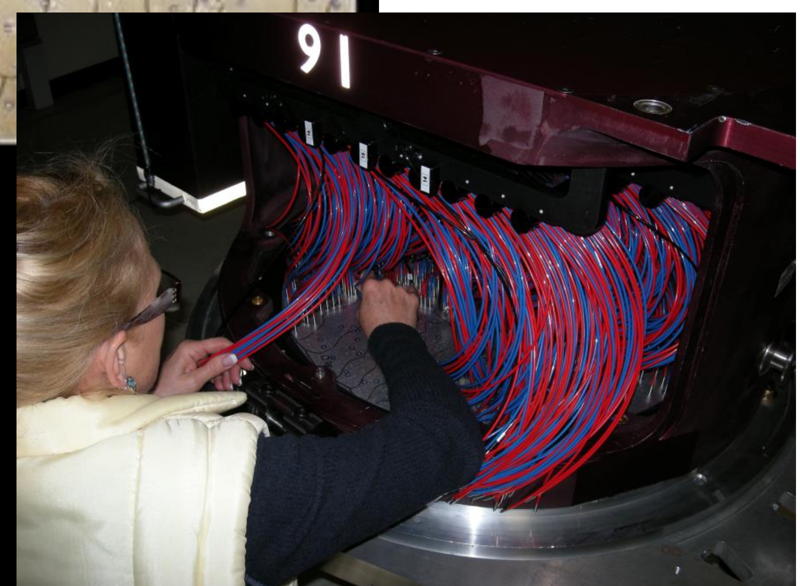
- **Built at the University of Virginia** with private industry and other SDSS-III collaborators.
  - John Wilson: Instrument Scientist
  - Fred Hearty: Project Manager
  - Mike Skrutskie: Instrument Group Leader
- The APOGEE instrument employs a number of **novel technologies** to achieve 300-fiber multiplexing / high resolution / infrared.



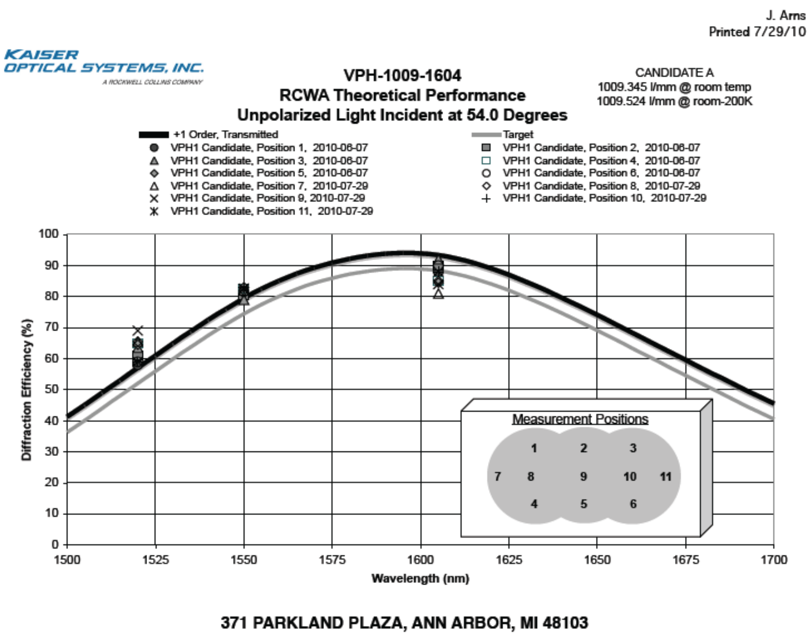


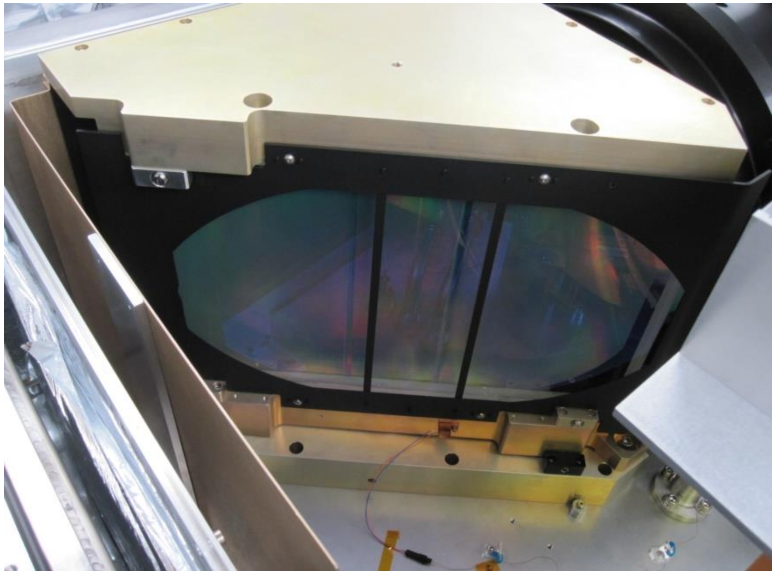
•*Effective multi-fiber plugplate system*

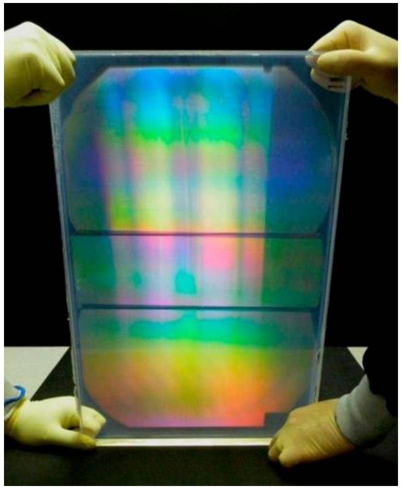


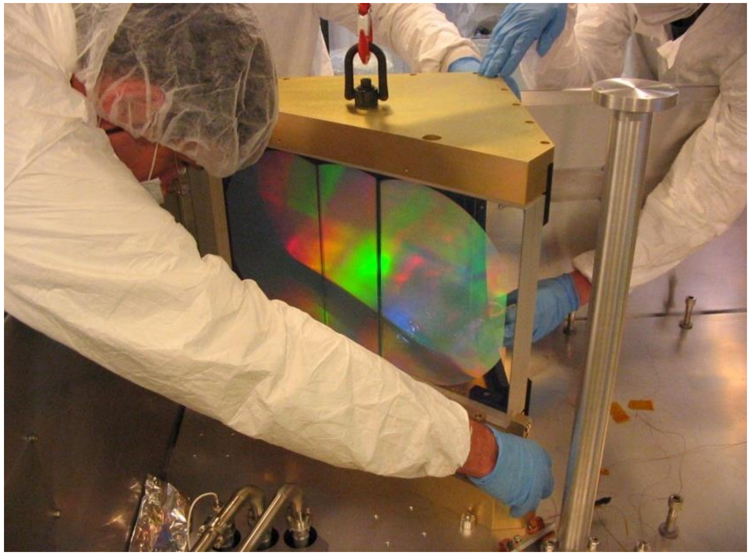


APOGEE Employs Novel Technologies: Largest VPH Grating Ever Deployed

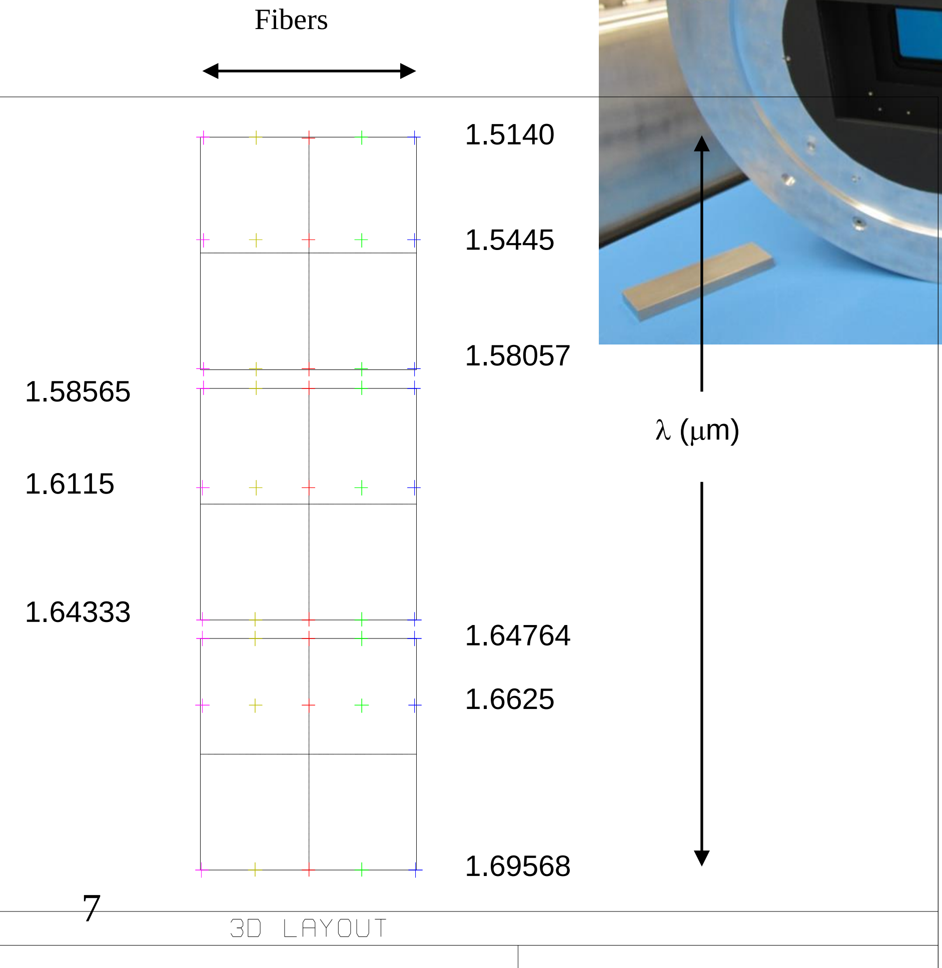


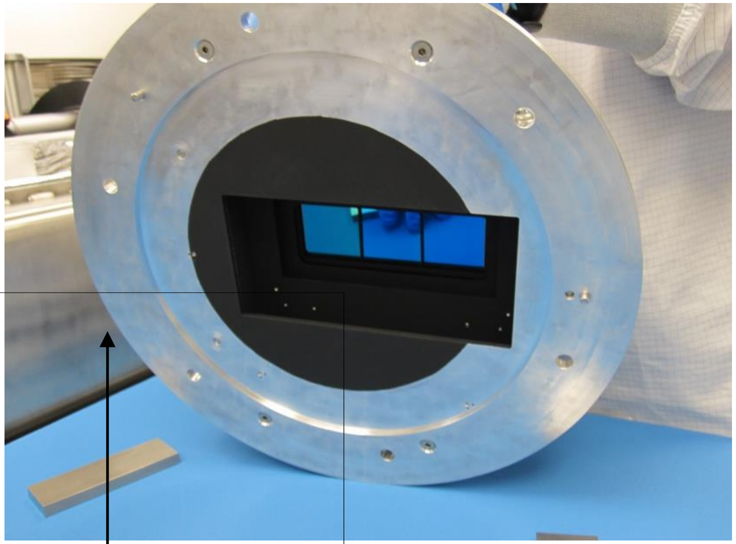


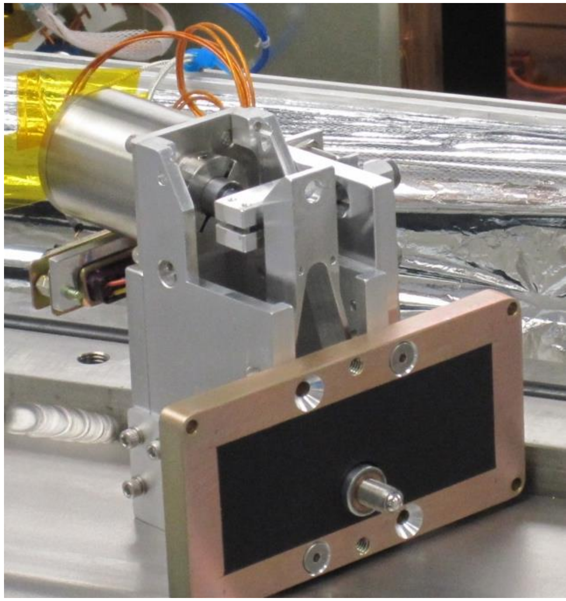


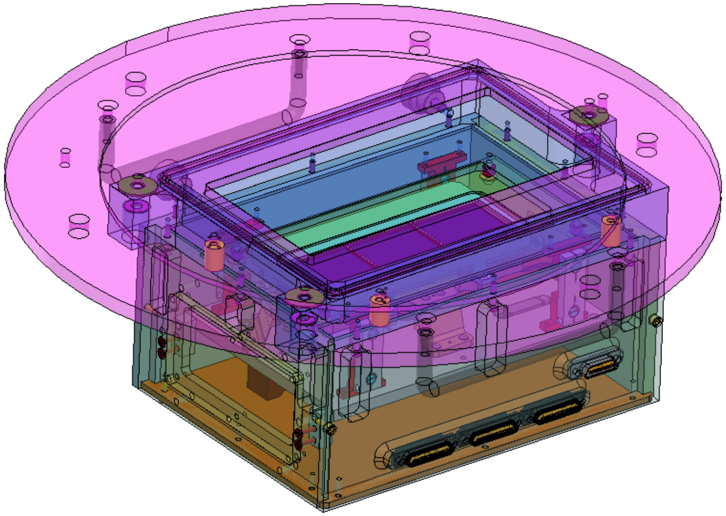


APOGEE Employs Novel Technologies: Pixel-Dithering Detector Mosaic









APOGEE Installation

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



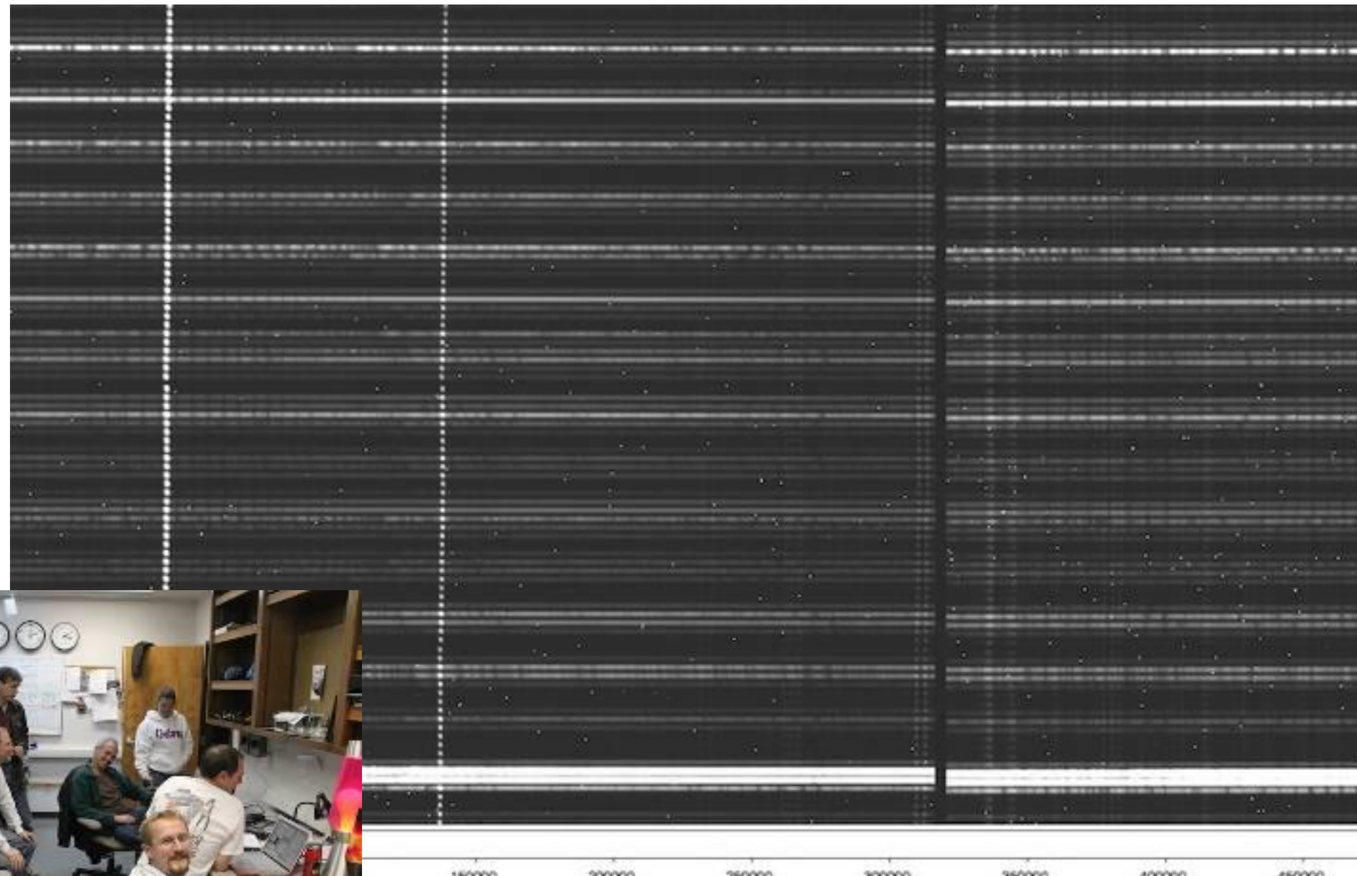


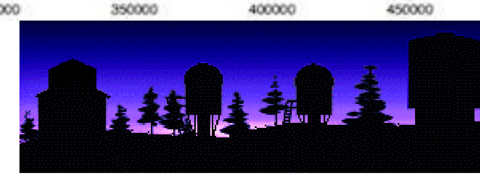


Photos by G. van Doren, D. Long, S. Majewski, O. Malanushenko, M. Nelson, J. Wilson

APOGEE First Light

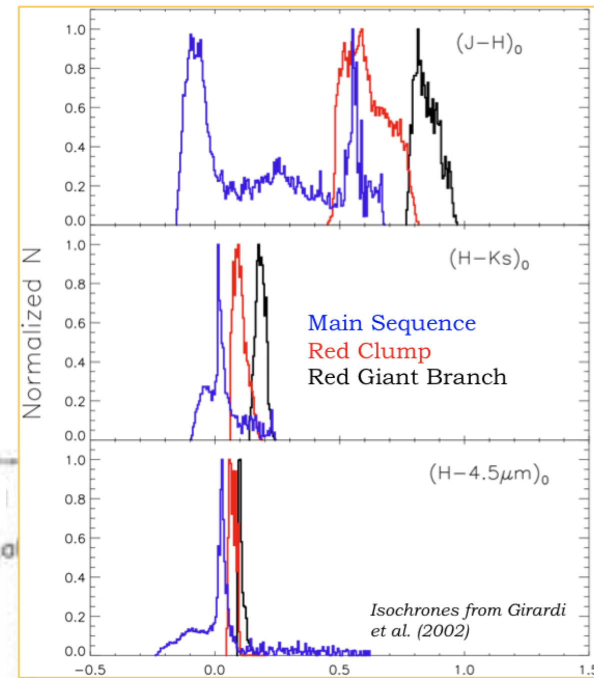
- May 6, 2011: First observations with Sloan 2.5-m telescope.
  - Within weeks (& ~budget) of planned timelines from 2006.



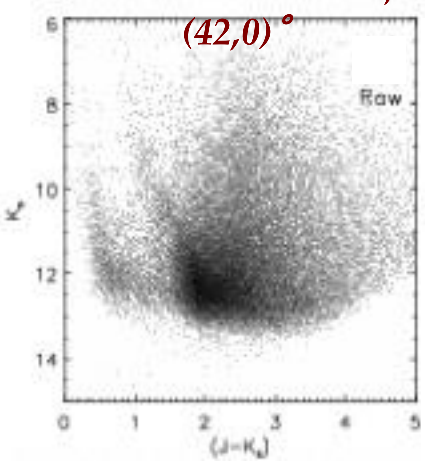


APOGEE Target Selection
Science Target Dereddening

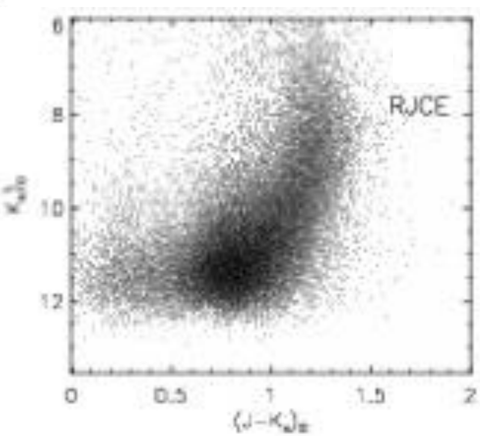
- NIR+MIR color-excess dereddening by RJCE method (Majewski et al. 2011).
- Calculated on a star-by-star basis.
- $\sigma(A_{Ks}) < 0.1$ mag
- $A(K_s)$ from IRAC+2MASS where available (higher resolution), fill in rest with WISE.



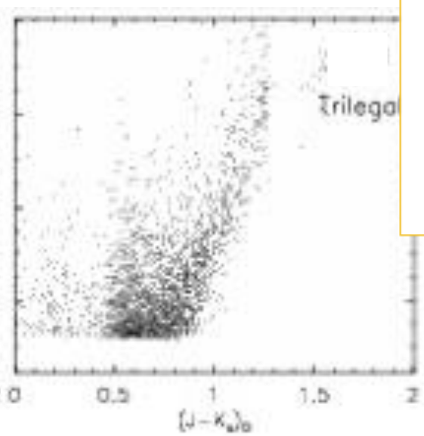
Observed 2MASS, (42,0)°



Corrected 2MASS



TRILEGAL model

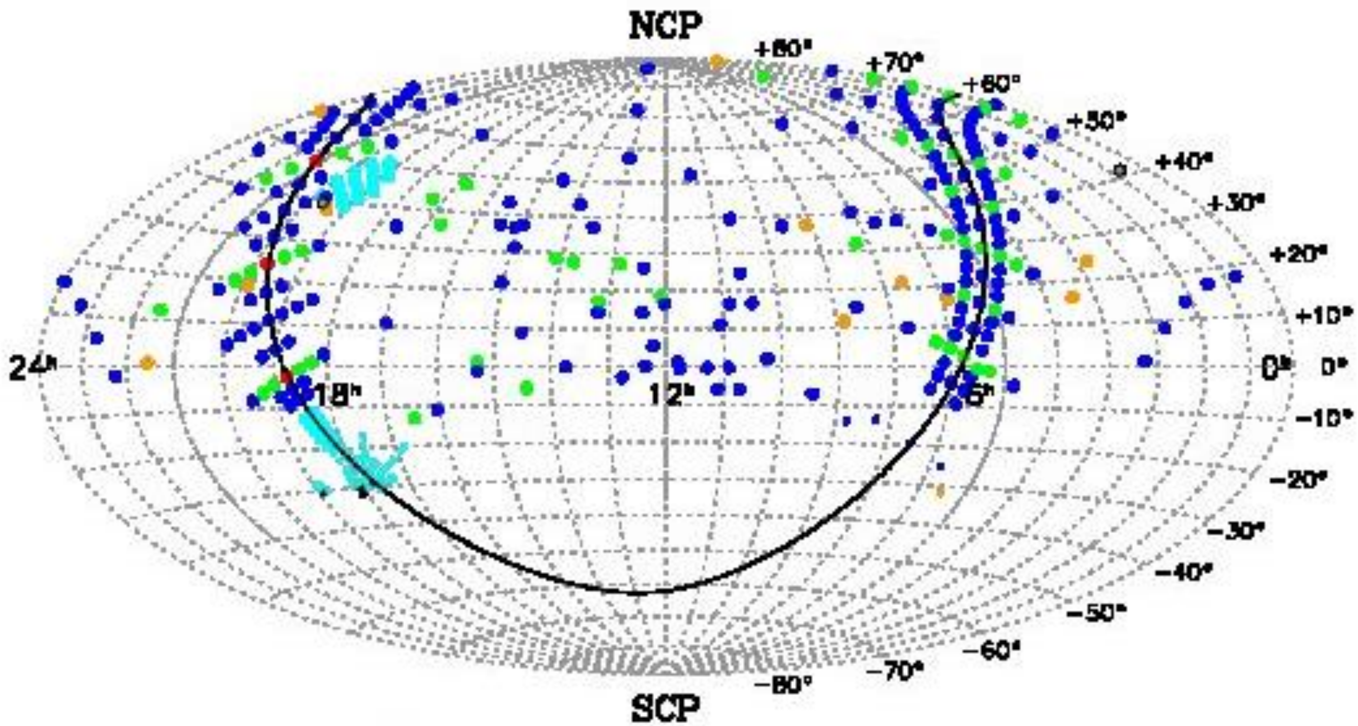


$(J-Ks)_o > 0.5$

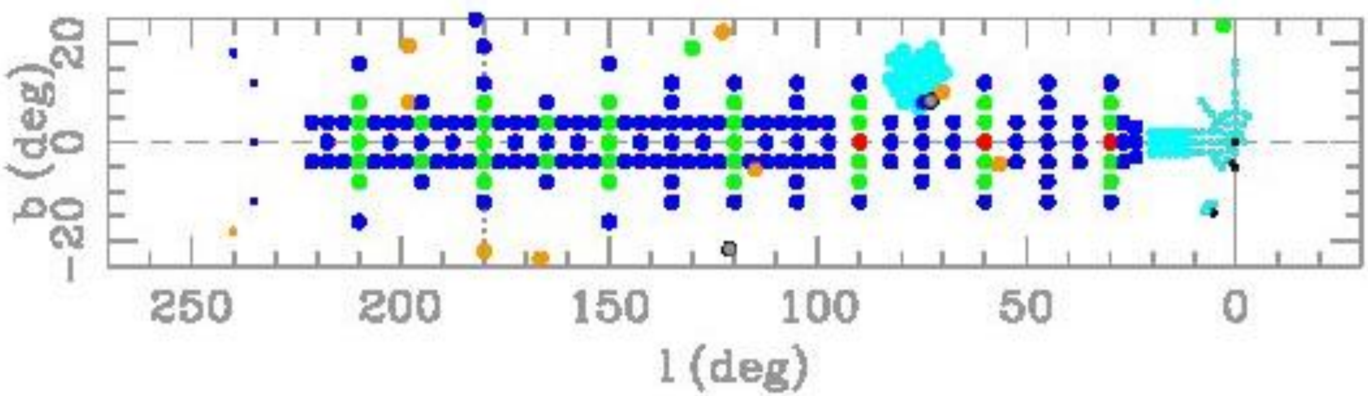
Field Selection

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

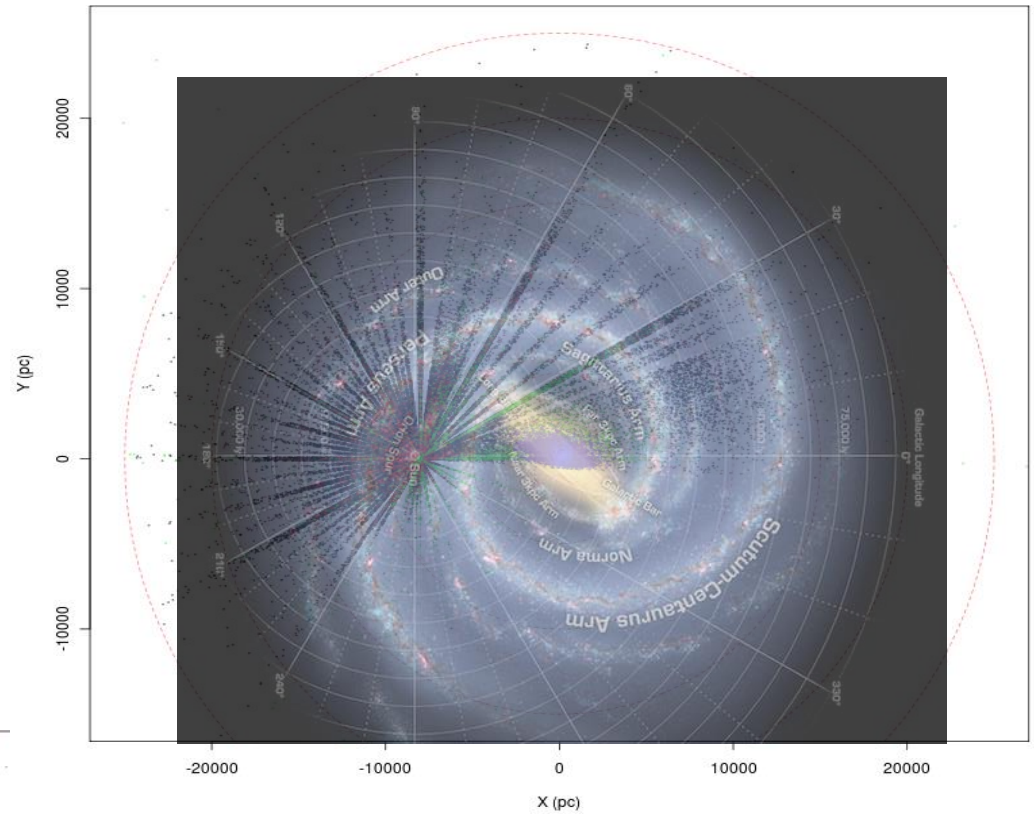


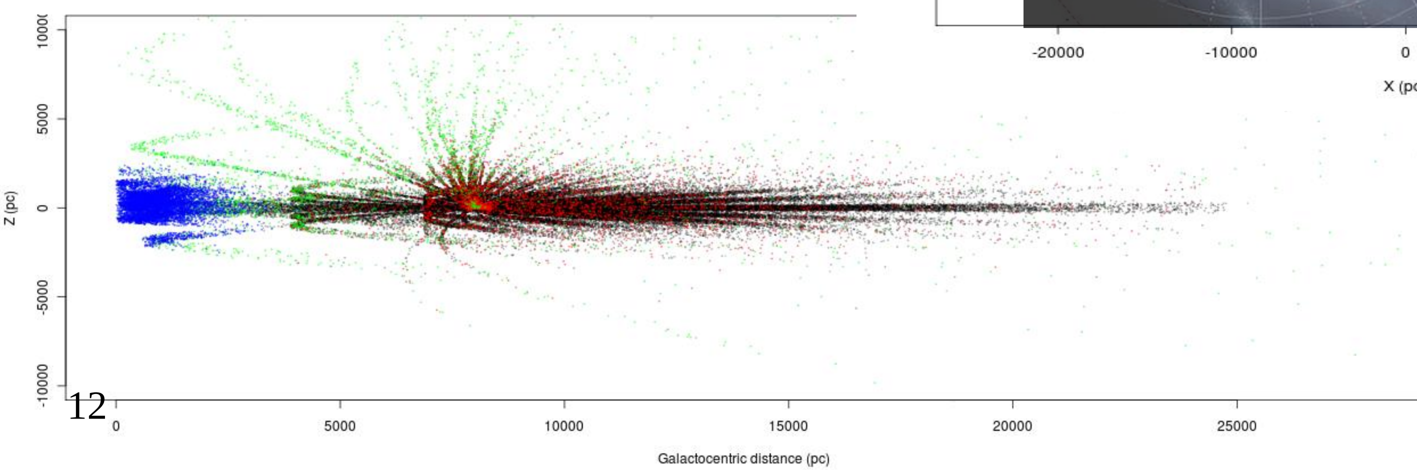
Anticipated Spatial Distribution

For currently selected fields

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

79% giants





Data Reduction Pipeline

- APOGEE has a custom-built data reduction pipeline (main responsible people Jon Holtzman and David Nidever)
- IR arrays read in a non-destructive way every few seconds
- Pipeline software goes from data cubes to fully reduced calibrated spectra
- Data cubes to extracted spectra, dither combine, wavelength calibrated, flux calibrated
- Modeling and subtraction of telluric lines (CO_2, CH_4, H_2O) using
- Cleaning up of sky (OH) lines
- Pipeline also measures radial velocities (multiple methods)

Abundances & Stellar Parameters

- 1.5 million elemental abundances to 0.1 dex internal accuracy: unprecedented, very challenging, must be done automatically… uncharted territory!

- ASPCAP: χ^2 optimization against synthetic spectral libraries.

1. Fundamental parameters (e.g., T_{eff}, log g, [Fe/H], C/Fe, N/Fe, O/Fe, ξ) using full APOGEE spectral window (1.51-1.69 μm).

2. Derivation of other elemental abundances (Na, Mg, Al, Si, S, K, Ca, Ti, V, Mn, Co, Ni) from narrow, optimal windows for each element.

A minute/star/processor (4.4 days on 16 processors for 100,000 stars)

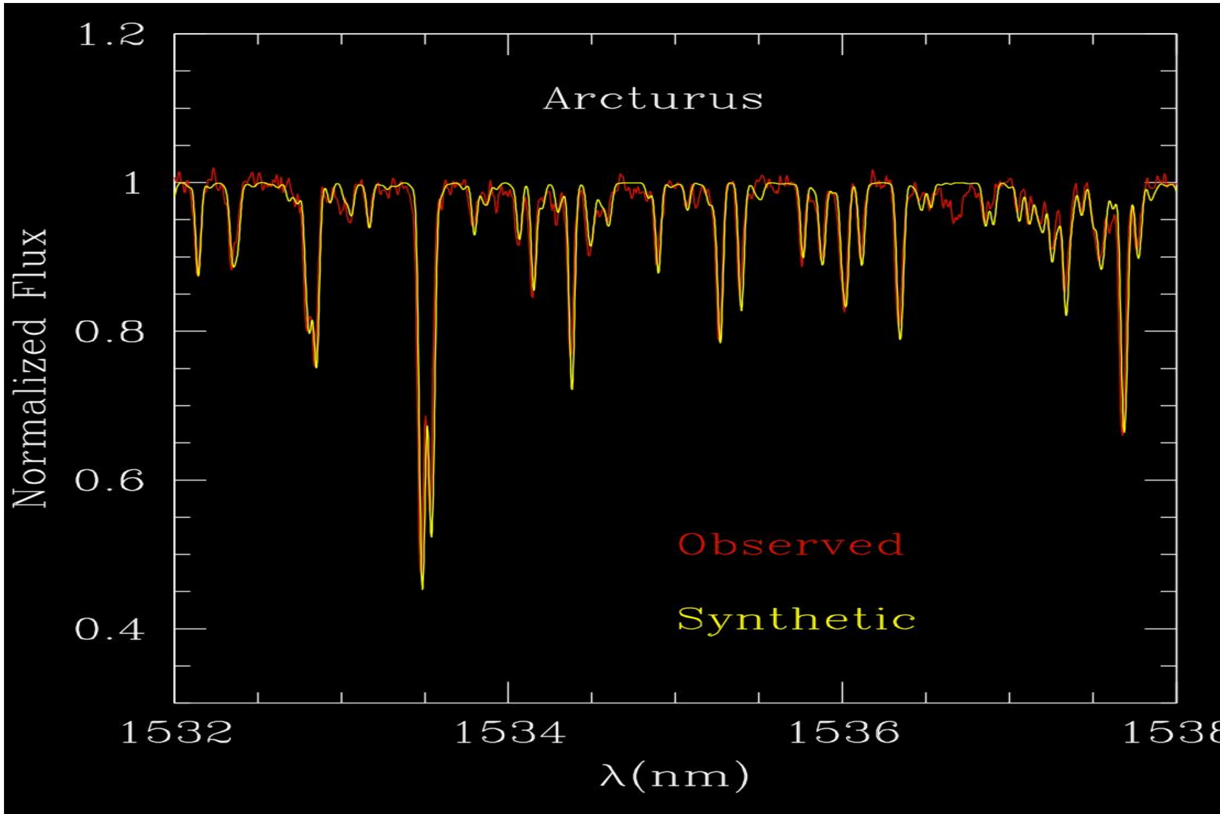
Laboratory Line Data

Three parallel efforts to develop and test linelists:

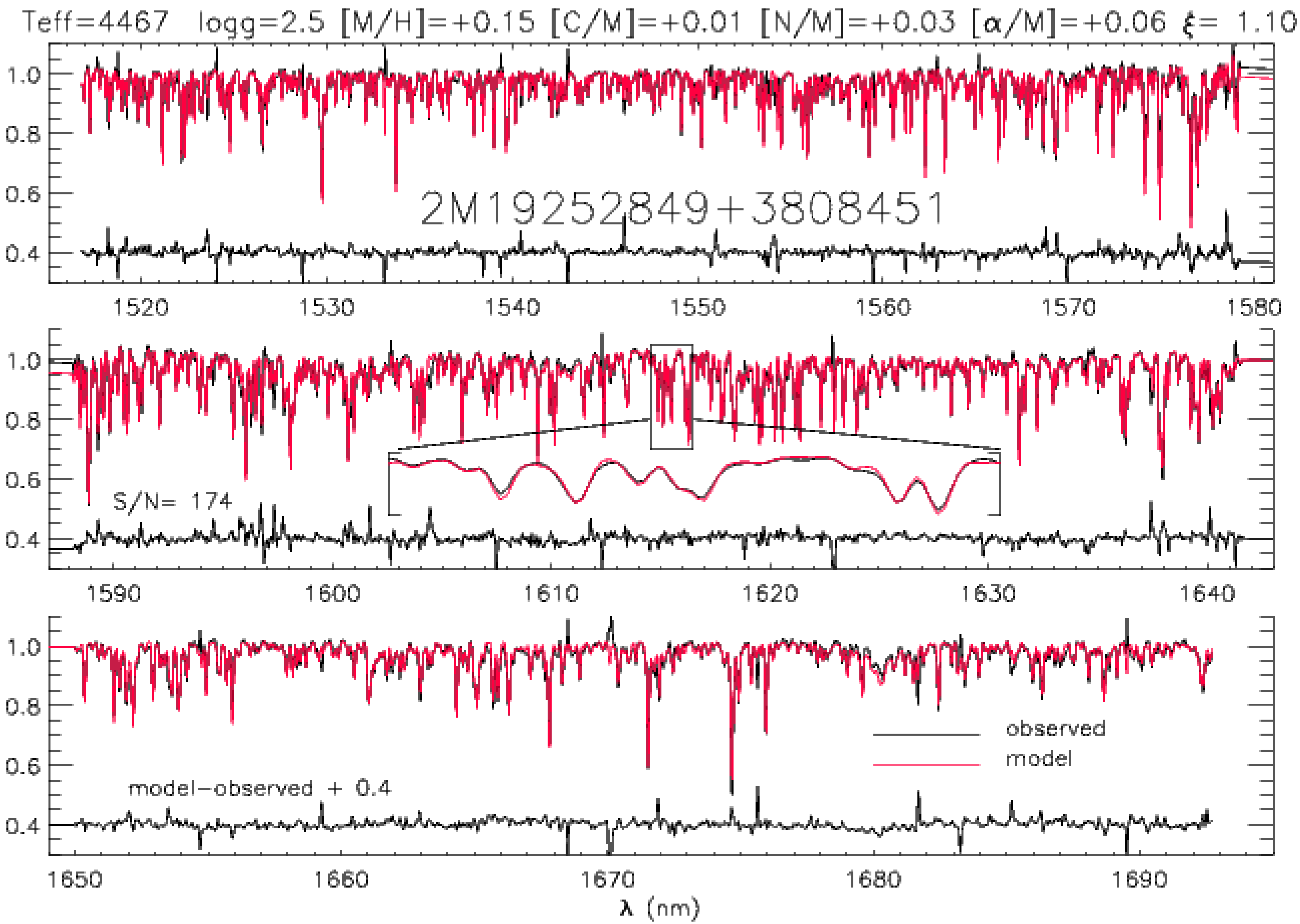
- Laboratory efforts to refine key elements parameters
  - Wisconsin Atomic Transition Probability Program
  - Imperial College group
- Basic linelist construction from critical evaluation of lab λ and gfs.
- Astrophysical gf-values from spectral synthesis of Sun and Arcturus.

Discovery of Ge I, Rb I and Ce III lines.

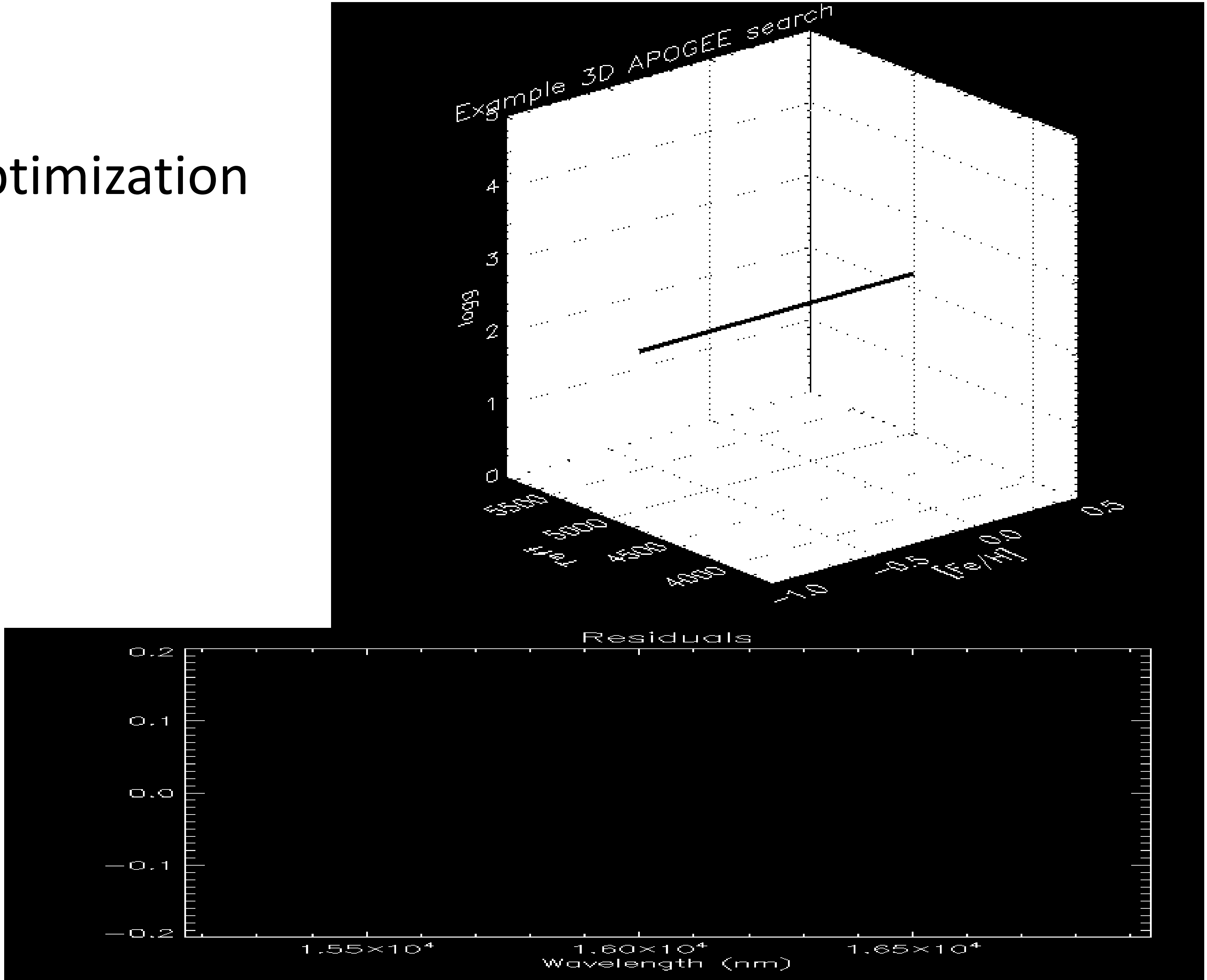
Regenerated Arcturus spectrum from our current linelist. →



ASPCAP fittings



optimization



Data Products

– APOGEE data releases include:

- Target selection information
  - – Sufficient to reconstruct sampling functions
- Spectra across full APOGEE spectral window (1.51-1.69 μm)
  - – Reduced, calibrated 1-D spectra with error, pixel flag, LSF vectors
  - – *S/N* > 100 per pixel (Nyquist limit)
- Velocity data (< 150 m/s precision)
  - – Radial velocities, *v* sin*i*, variability information (multiple epochs), errors
- Stellar atmospheric parameters from matches to synthetic libraries
  - – Via simultaneous 7-D optimization of T_{eff}, log *g*, [Fe/H], [C-N-O/Fe], ξ
  - – Uncertainties, covariances
- Chemical abundances (≤ 0.1 dex internal accuracy)
  - – C, N, O, Na, Mg, Al, Si, S, K, Ca, Ti, V, Mn, Fe, Co, Ni, (neutron capture?)

APOGEE Data Products

• DR10: 1st APOGEE data release (summer 2013).

APOGEE release (***www.sdss3.org***) includes:

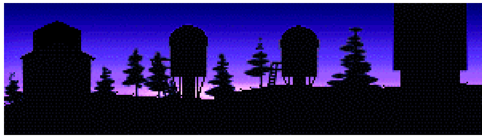
- 178,000 high resolution, *H*-band spectra on ~60,000 stars
- from 710 visits in 170 fields
- ASPCAP results for ***~48,000 stars***

•DR12: 2nd APOGEE data release (Jan 2015).

APOGEE release (***www.sdss.org***) includes:

- >500,000 high resolution, *H*-band spectra for ~150,000 stars
- from 710 visits in 170 fields
- ASPCAP results for ***~120,000 stars***

Technical papers coming out… (look for them on astro-ph)

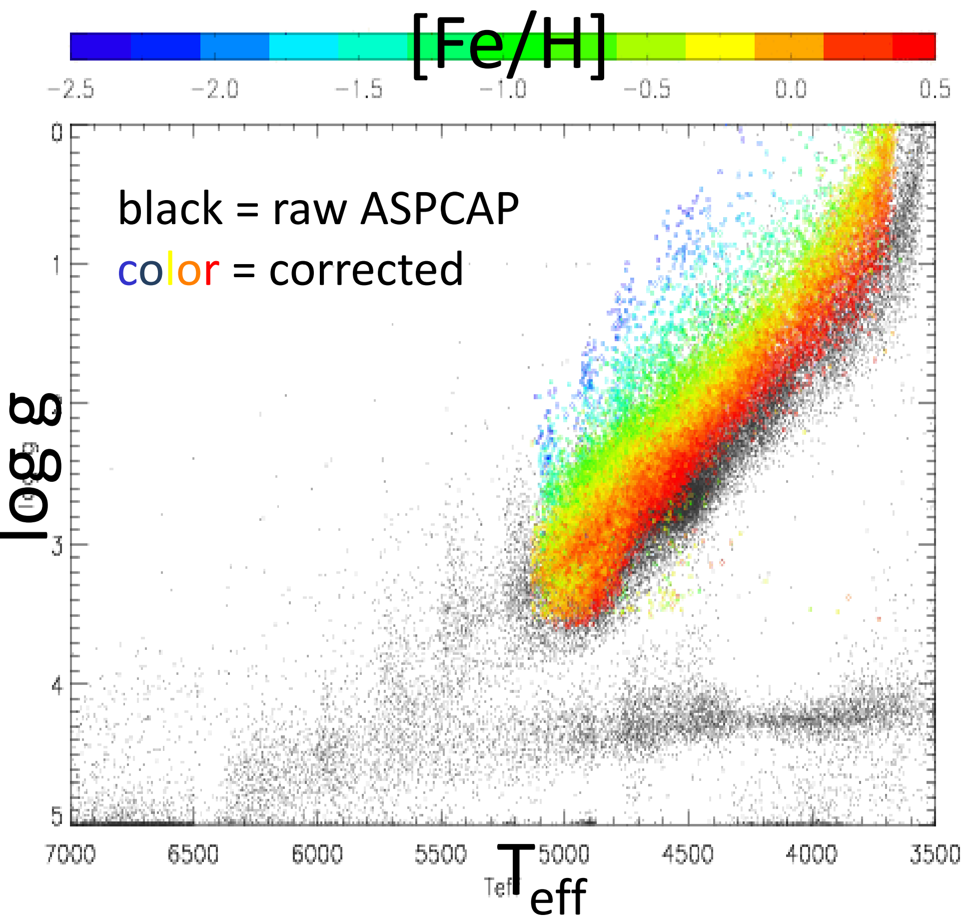


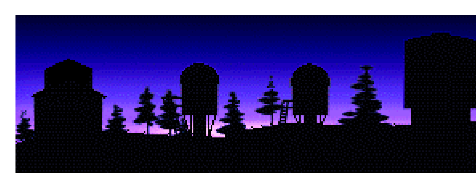
ASPCAP & Data Release 10

Year 1 (Sep 2011-July 2012) + Commissioning "Science" Data

(ASPCAP = APOGEE Stellar Parameters & Chemical Abundances Pipeline)

APOGEE = 48,000 stars in DR10.





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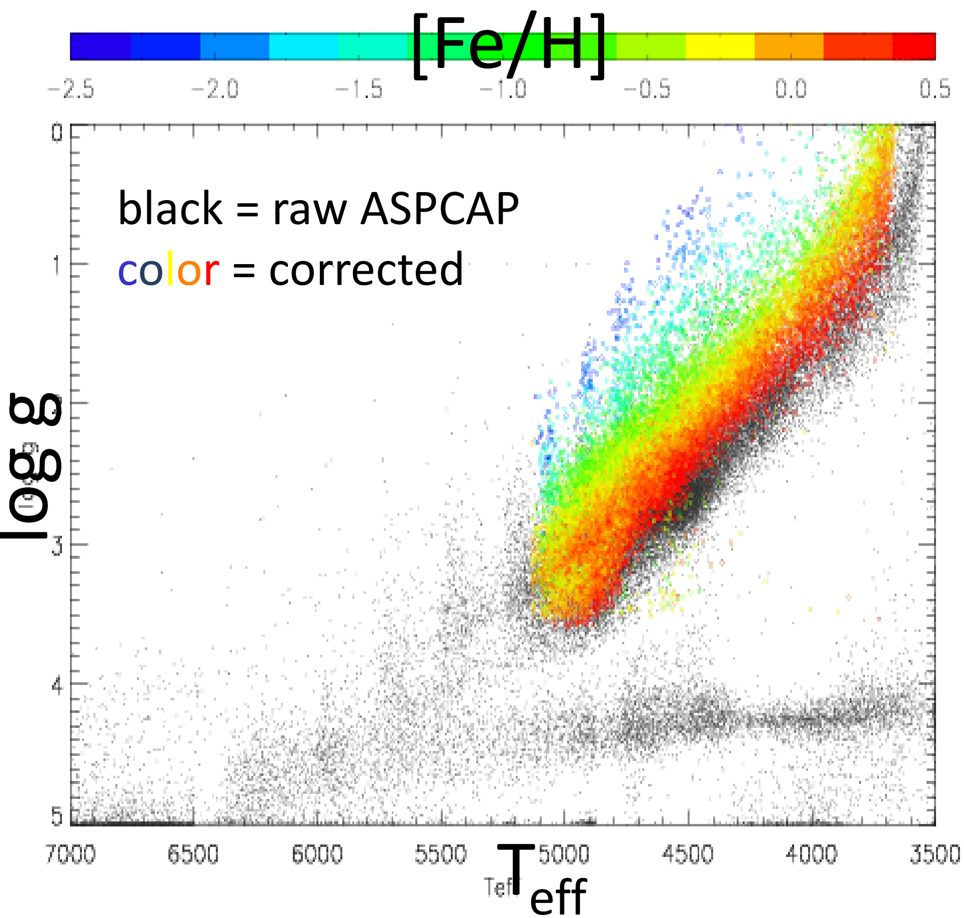
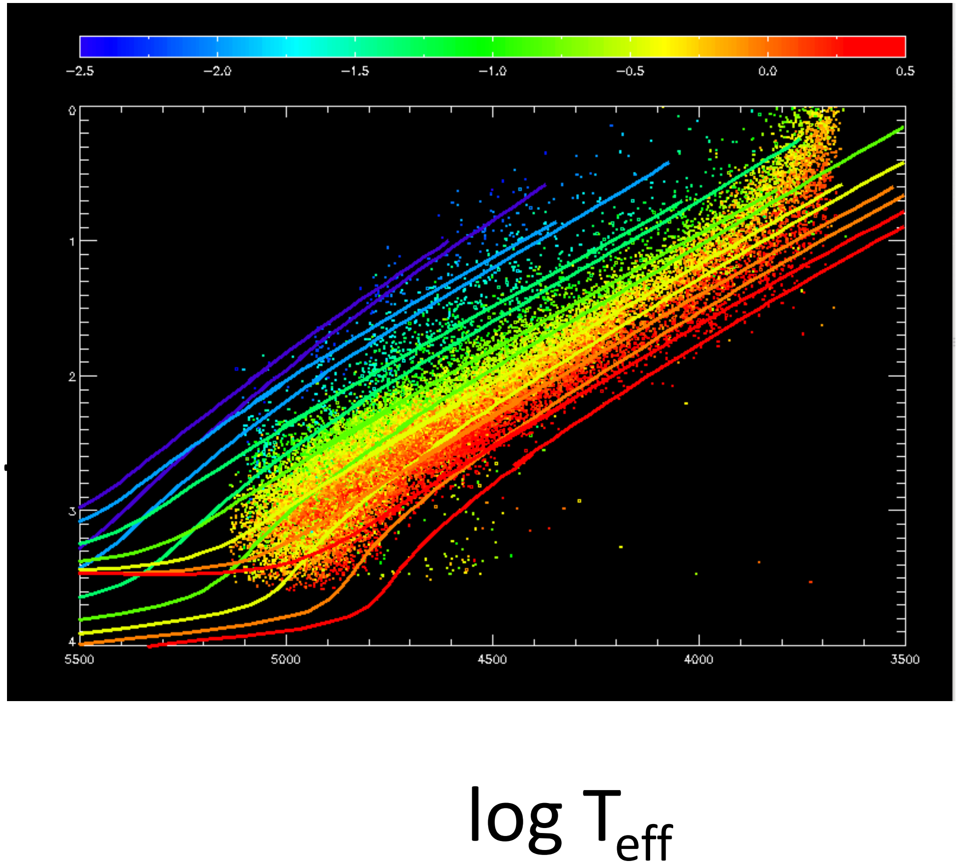




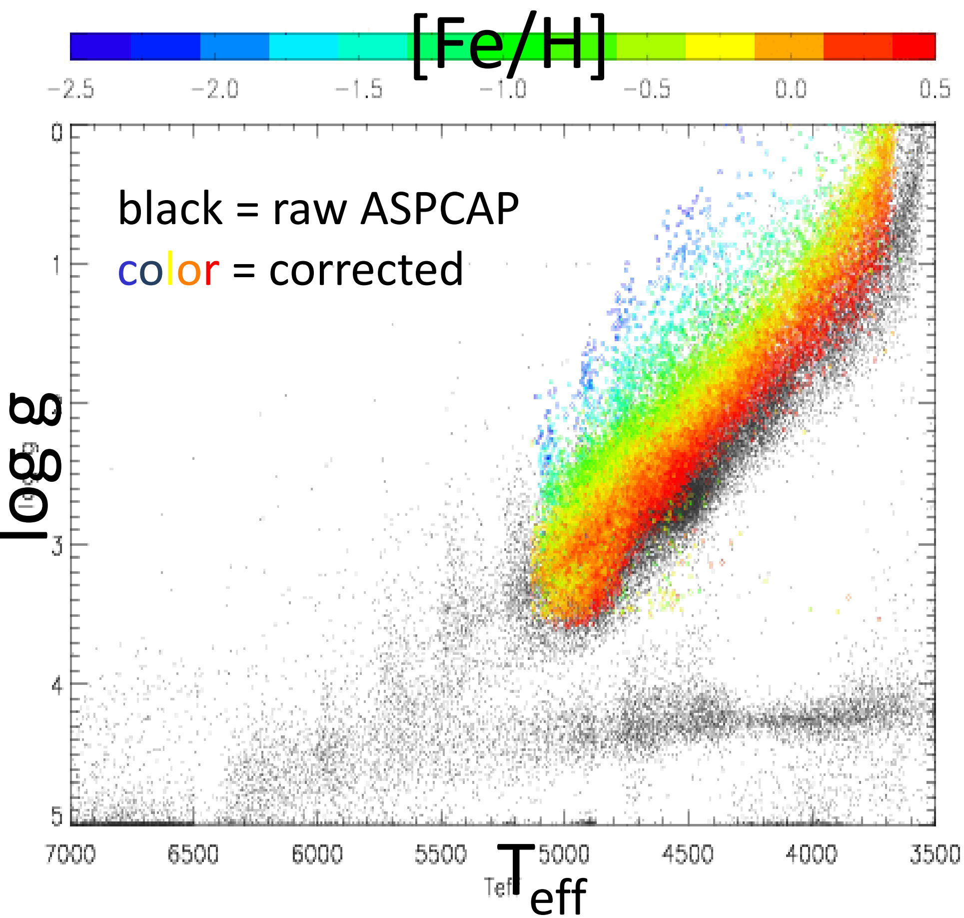
ASPCAP & Data Release 10

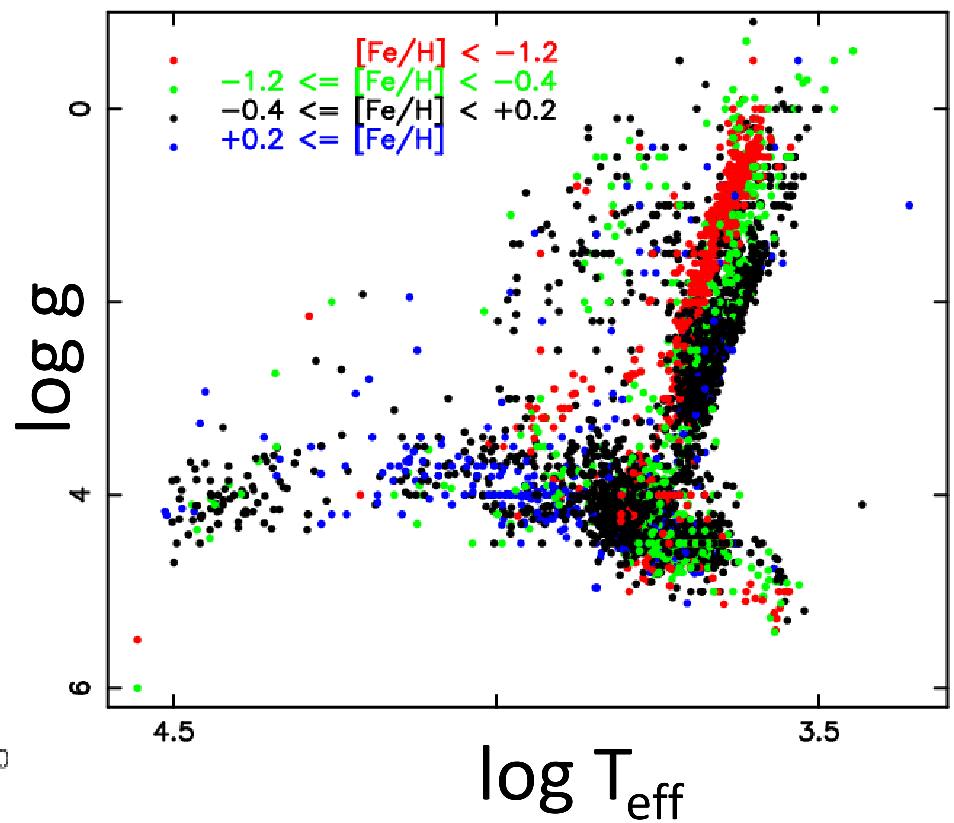
Year 1 (Sep 2011-July 2012) + Commissioning "Science" Data

(ASPCAP = APOGEE Stellar Parameters & Chemical Abundances Pipeline)

APOGEE = 48,000 stars in DR10.

Soubiran+ (2010) compilation of all previous 6,000 stars having high resolution [Fe/H] (JUST metallicity).

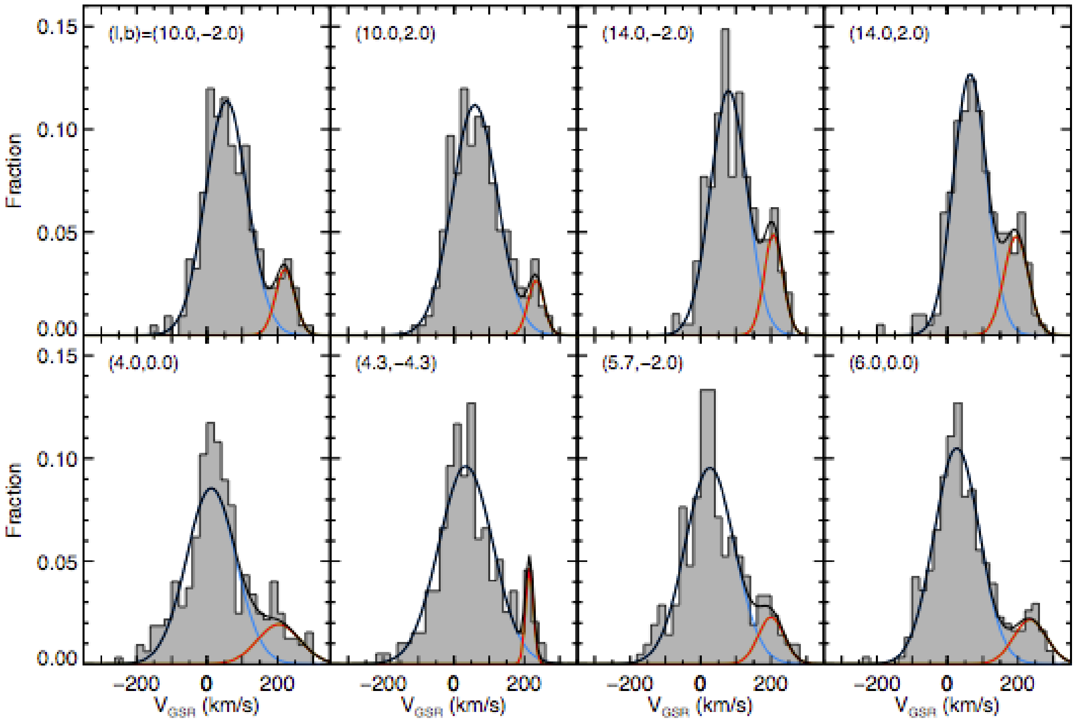




Published Science Highlights

- Detection of high velocity stars in Galactic bulge/bar

(Nidever/Zasowski et al. 2012)



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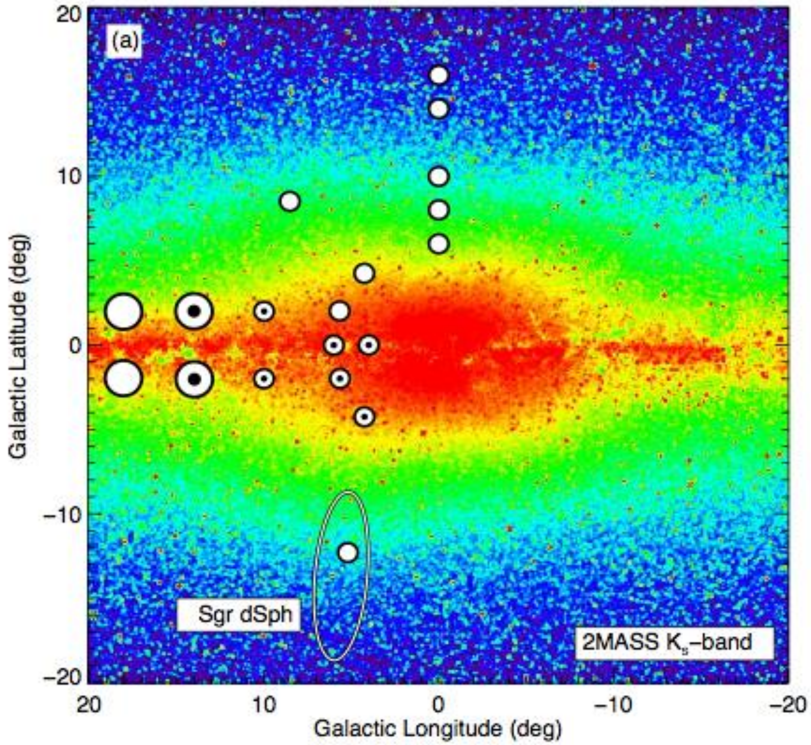
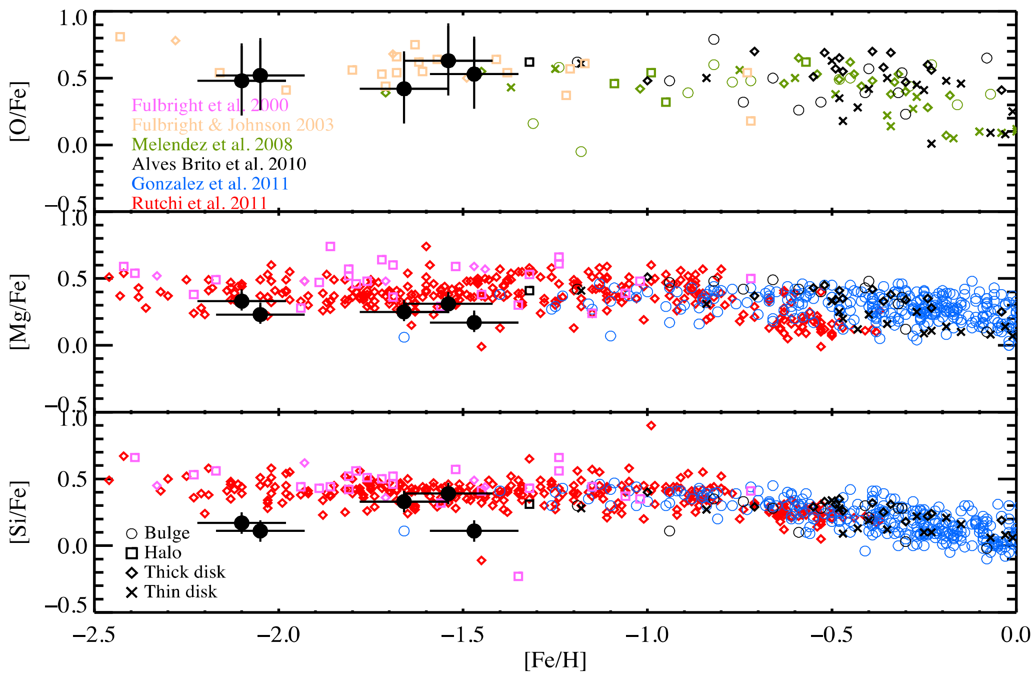


Published Science Highlights

- Metal-poor stars in outer Galactic bulge

(Garcia-Perez et al. 2013)



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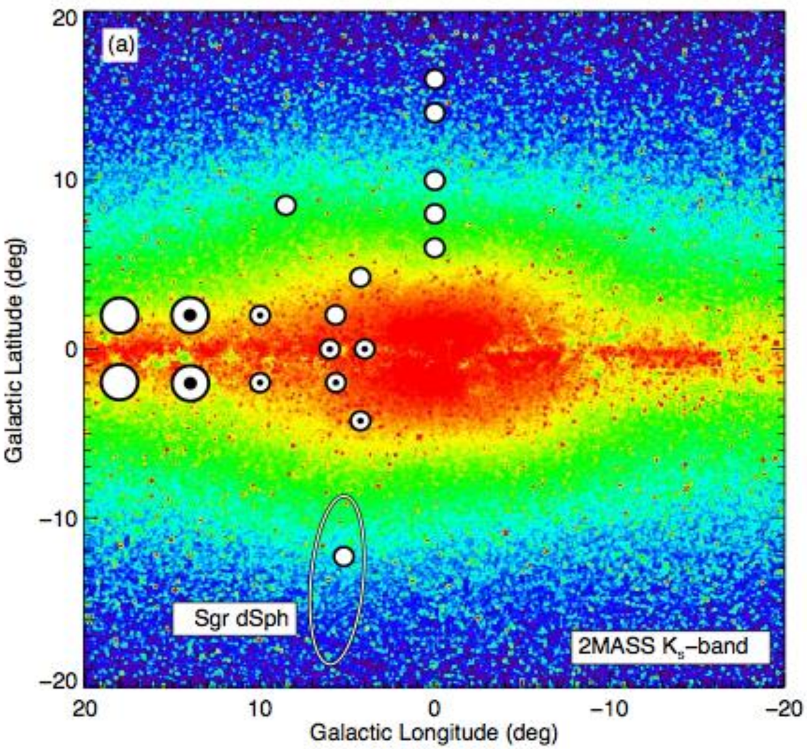
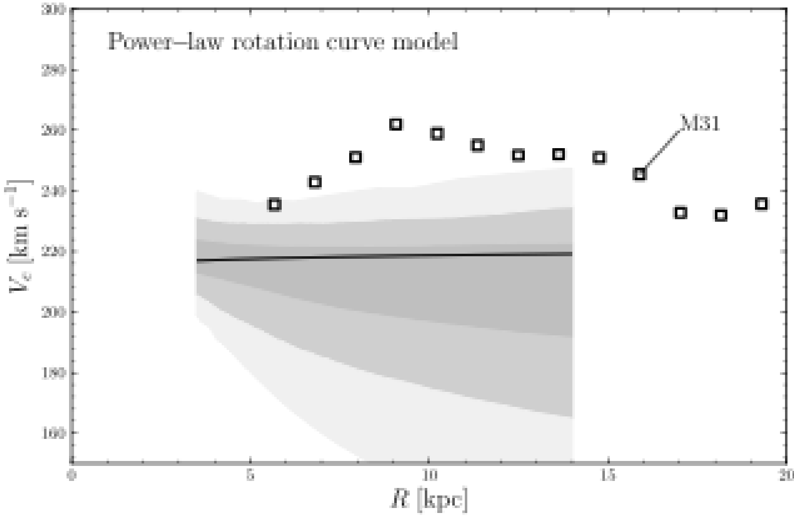
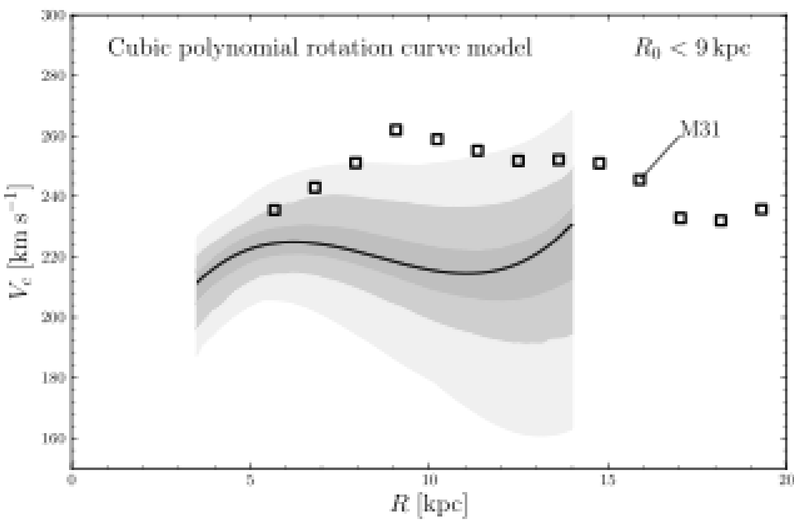


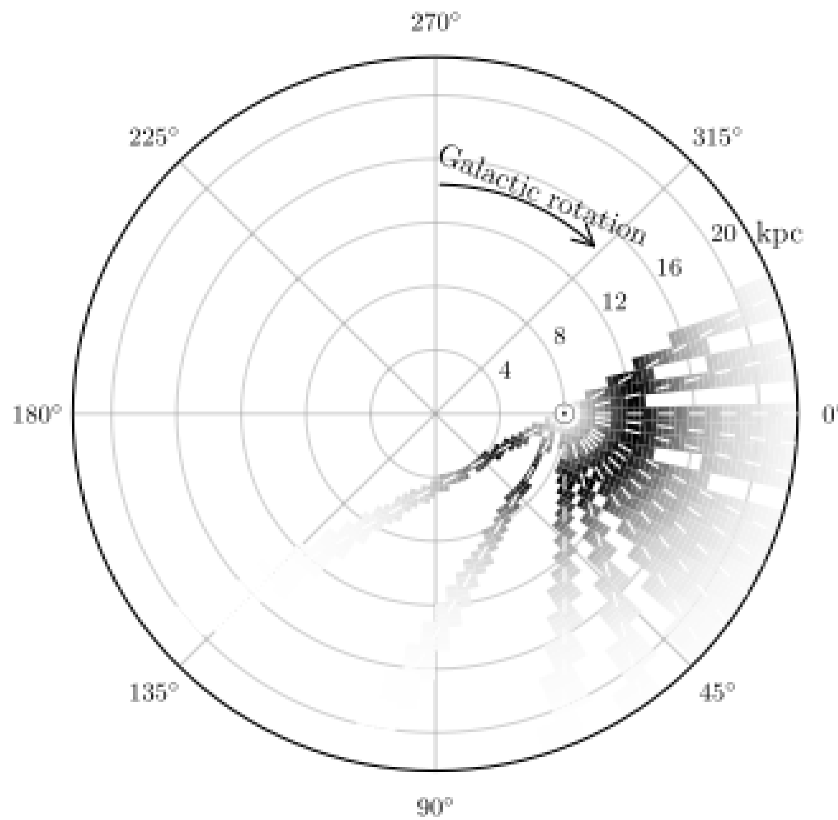
Published Science Highlights

- Milky Way circular velocity curve from 4-14 kpc

(*Bovy et al. 2012*)





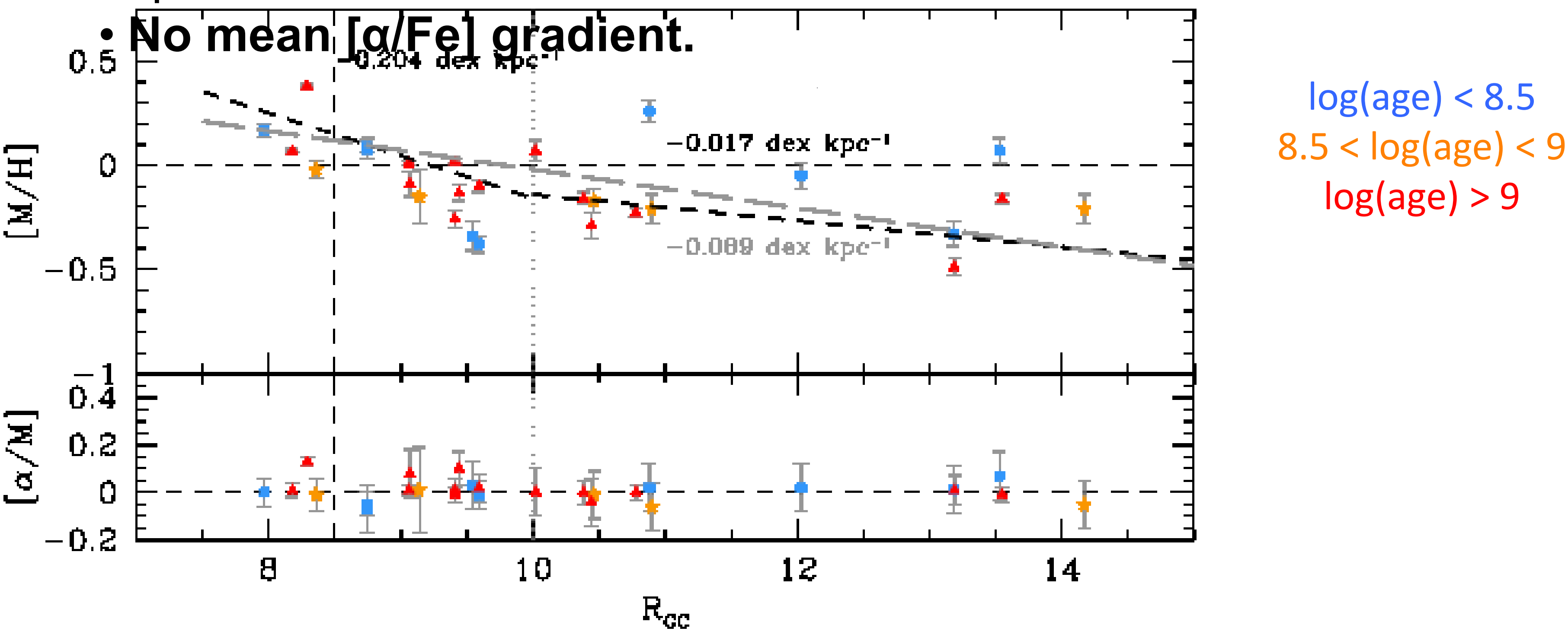


Galactic Abundance Gradients Using Open Star Clusters

Best previous compilation of high res abundances for open clusters is Yong et al. (2012): 68 stars in 49 clusters, North & South Hemisphere

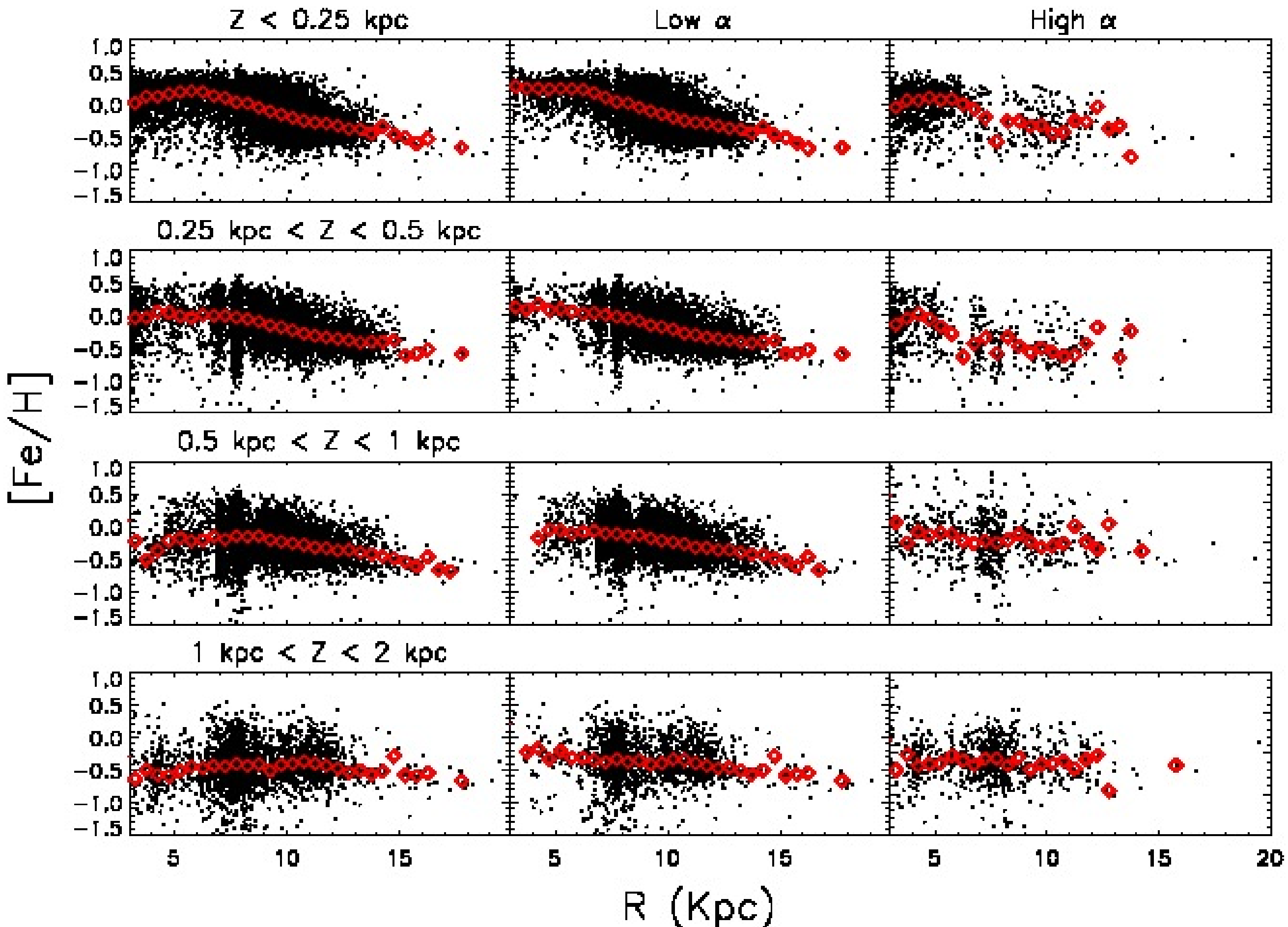
APOGEE DR10 Sample (Frinchaboy et al. 2013):

- 141 stars in 28 clusters
- **MW [Fe/H] radial gradient seen,** evidence for flattening R > 10 kpc.
- **No mean [α/Fe] gradient.**



Chemical Cartography with APOGEE

(Hayden, Holtzman et al.)

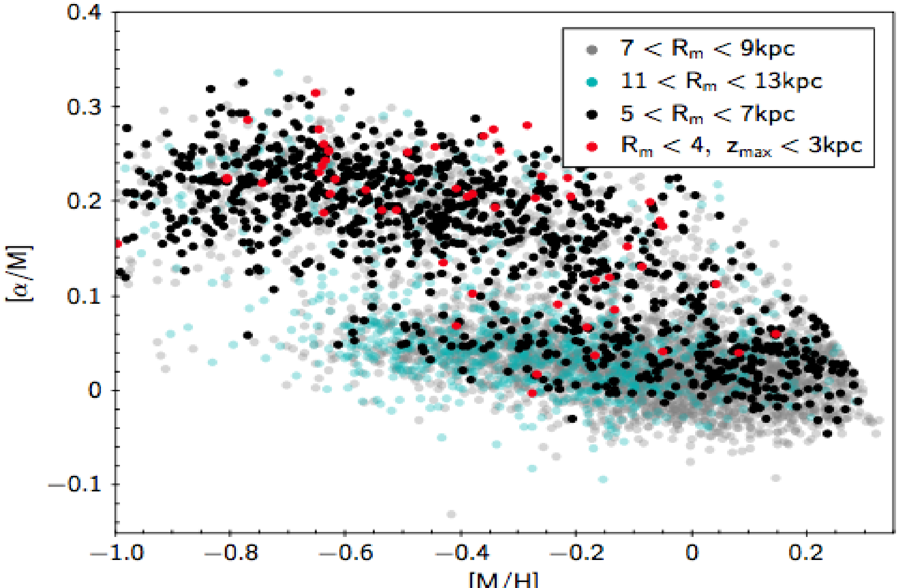


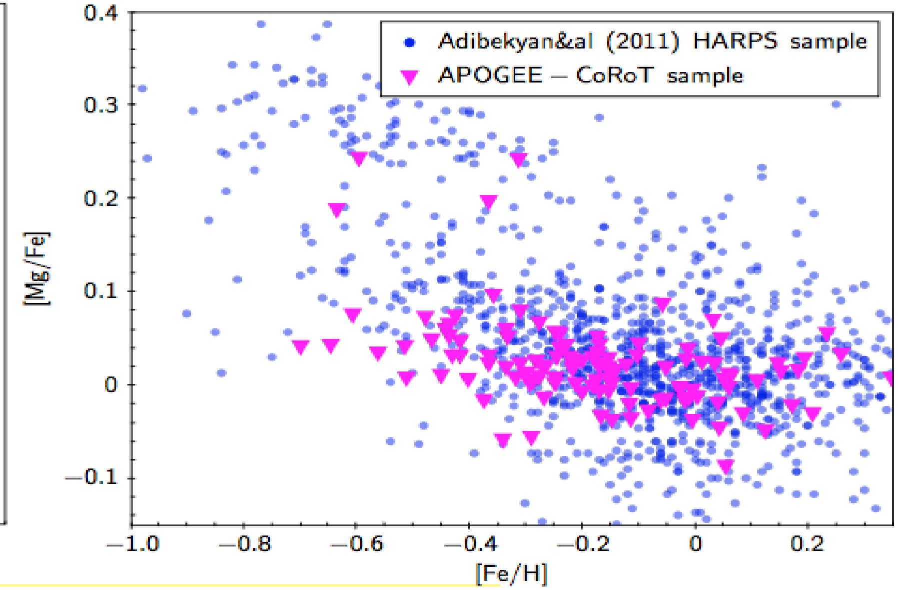
- Observe metallicity gradients in the radial and vertical directions for R_{GC} > 3 kpc.
- Using >25,000 giant stars with S/N > 80.
- Find steep gradients for low α stars in plane of galaxy, which flatten as Z increases.
- Gradient also flattens in plane for R < ~6 kpc.

New Observational Constraints to Chemodynamical Models

Chiappini, Anders, Santiago, Girardi et al.)

- APOGEE data show a clear gap in [α/Fe], as seen in other high res samples.
- CoRoT Ira01 field: as expected, mostly thin disk and just few percent thick disk.
- [α/Fe] > 0.1 stars seen in all mean radius bins (even outer disk).
- Local sample (7 < Rm < 9 kpc) extends to low metallicity.
- Outer sample contributes to extend low metallicity end of thin disk (as shown by Haywood), but other mean radius bins contribute as well.
- Favorable comparison to HARPS high res, high S/N sample.

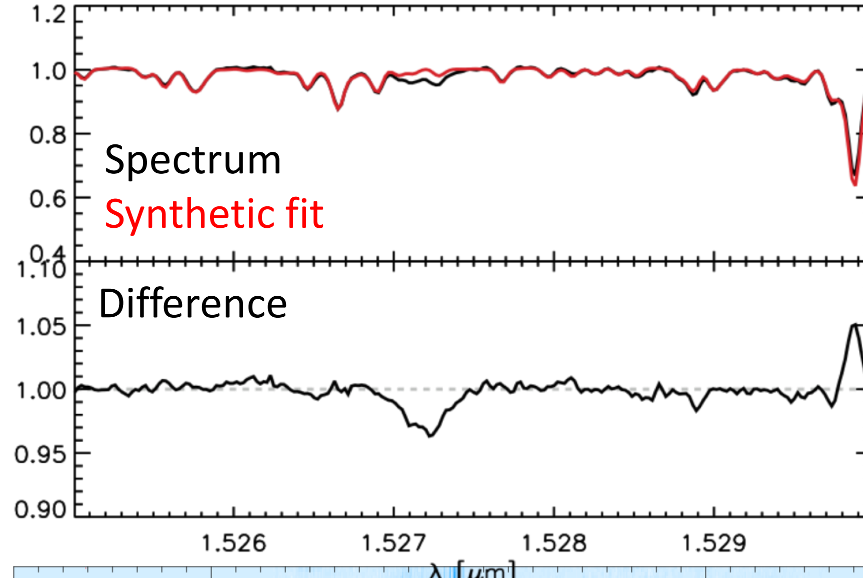


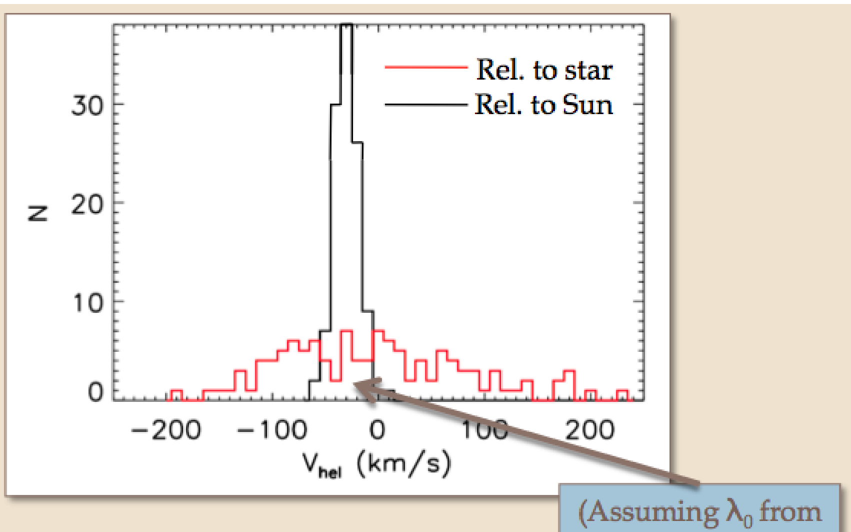


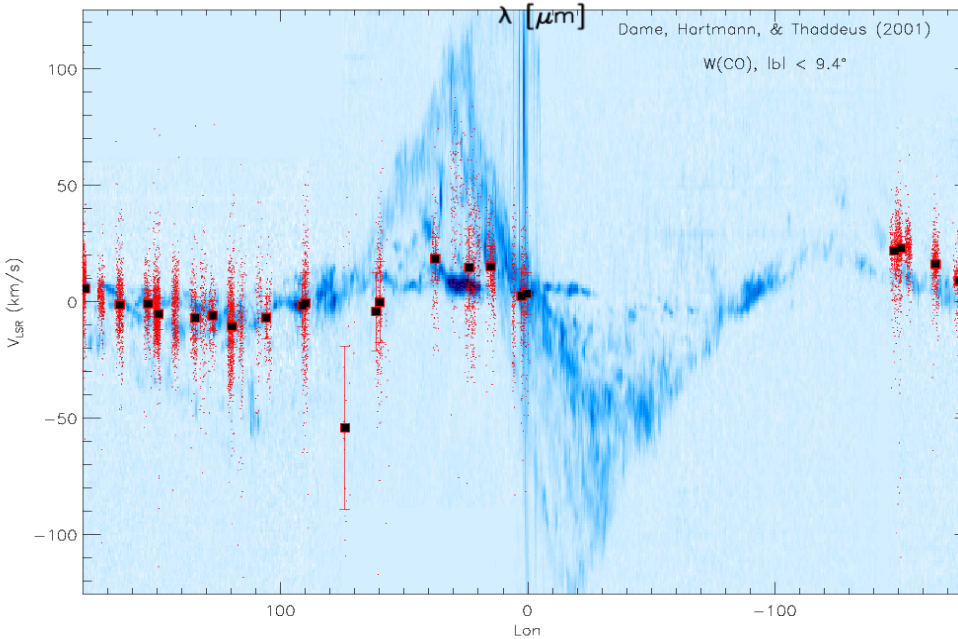
Unanticipated Science: Diffuse Interstellar Bands

(Zasowski et al.)

- Recently identified *H*-band DIBs (Geballe et al. 2011)
- Seen as residuals to APOGEE fits!
- Detected in 60% of |b|<10 stars.
- Narrow velocity range uncorrelated with stars but correlated with CO.



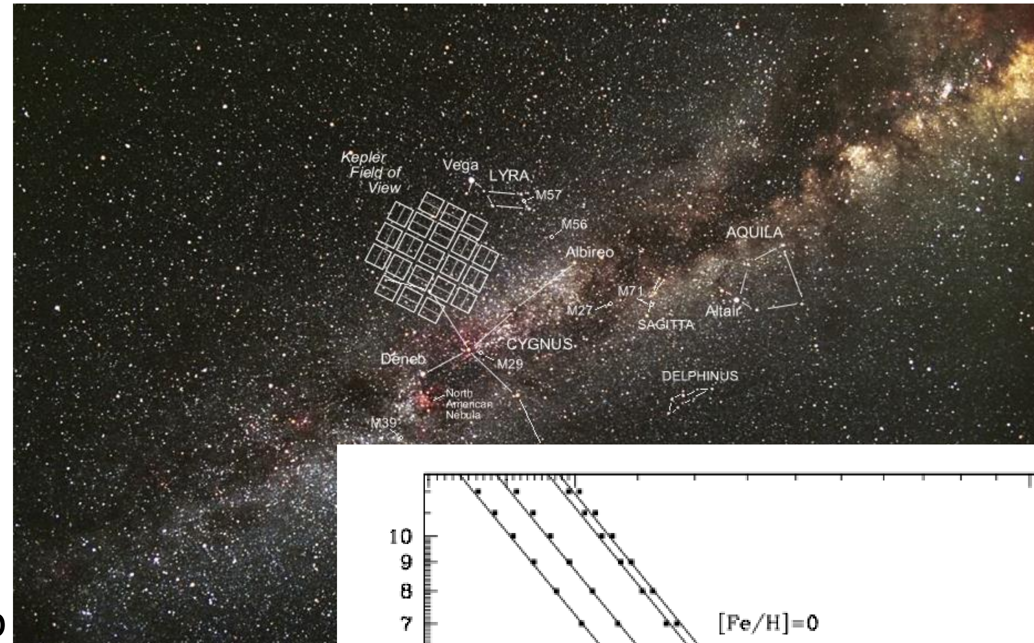




APOGEE-Kepler Asteroseismology Collaboration (APOKASC)

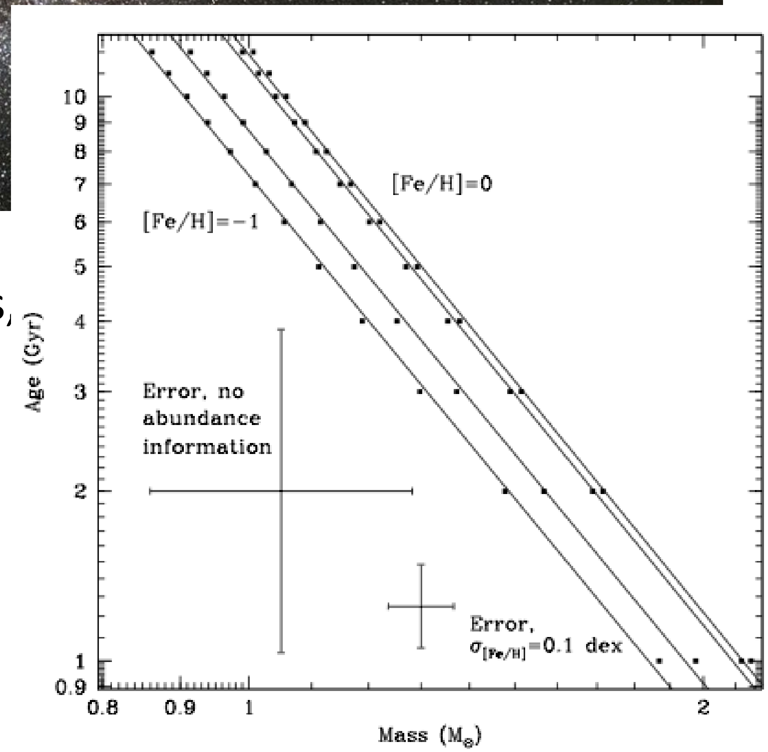
APOGEE Kepler field visits

- 21 x 2 visits, ~10,000 stars



- Kepler measures asteroseismic frequencies for ~10k giants:
  - gravity
  - radius
  - mass
- APOGEE provides abundances:
  - Combined w/asteroseismic info ages to 18% for field stars 1-5 kpc away!
  - Strict constraints on chemical evolution models, beyond solar neighborhood.
  - Also observing CoRoT targets.
  - Calibrate APOGEE pipelines.

APOGEE also observing eclipsing binaries, transit hosts in Kepler field.



Other Science examples

- Li-rich stars (Carlberg et al. 2014)
- Globular clusters (Meszaros et al. 2015)
- Nd abundances in Saggitarius stars (Hasselquist et al. 2014)
- Young high-[α/Fe] stars (Martig et al. 2014; Chiappini et al. 2015)
- Be stars idenfied from their Paschen lines in emission (Eikenberry et al. 2013)
- Clump stars tracing the chemical trends in the thin and thick disks (Bovy et al. 2014; Nidever et al. 2014)
- …

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

From Apache Point Observatory:

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

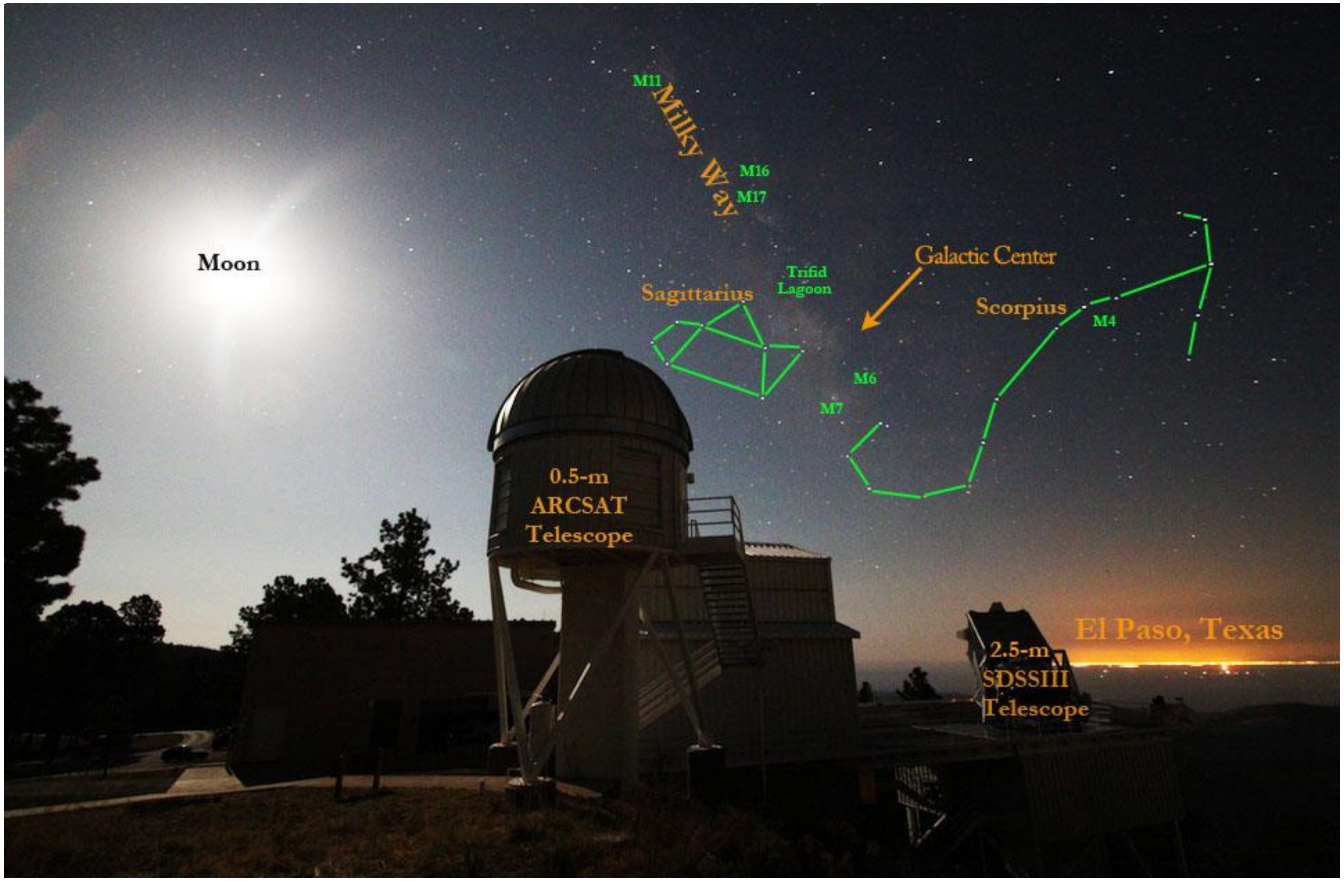


Photo by S.R. Majewski

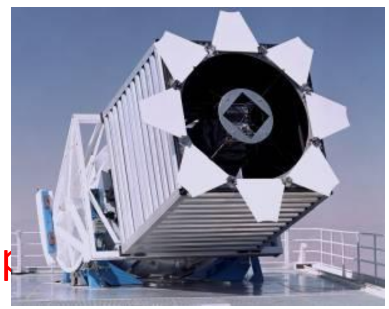
Observing the Central Milky Way with APOGEE+Sloan 2.5-m

From Apache Point Observatory:

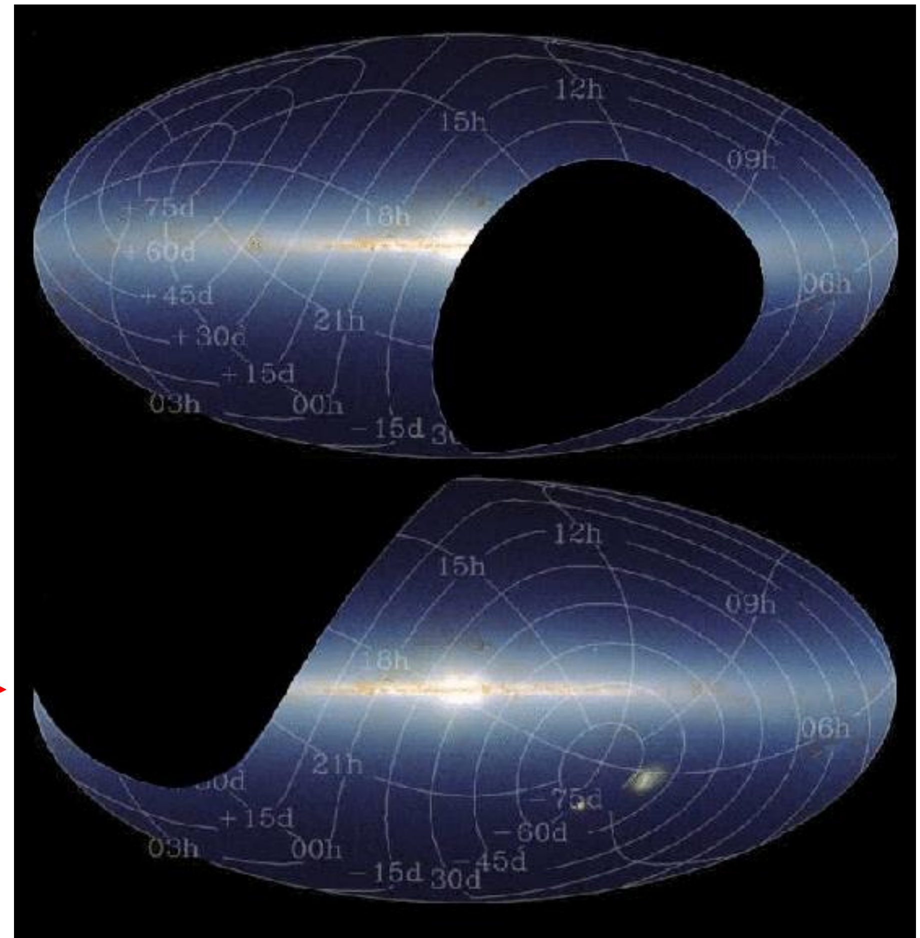
Galactic center culmination @ altitude = 28˚ (airmass = 2.1!)

Sky above 2 airmasses:

Apache Point Observatory



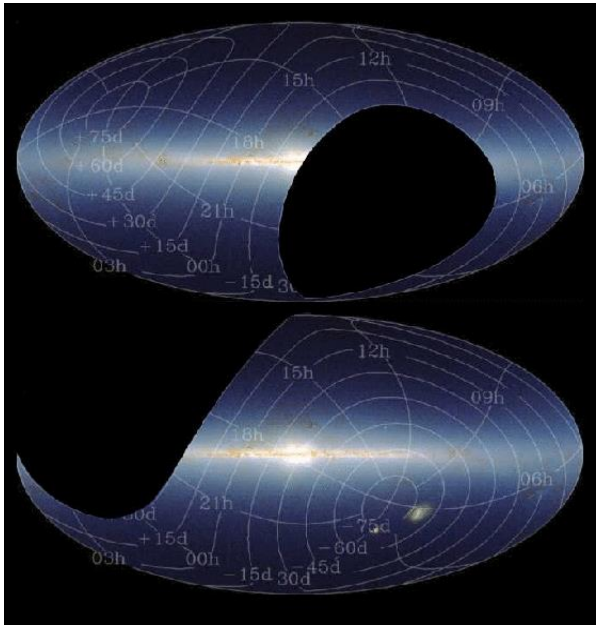
Las Camp



- Carnegie is committed to the project, contributing significant # of nights.

APOGEE-2

- **First high resolution, spectroscopic survey of the entire Milky Way.**
- **Legacy contributions to:**
  - Galactic structure
  - Stellar populations
  - Galactic dynamics
  - Galaxy assembly and evolution
  - Origin and evolution of the elements
  - Fundamental stellar astrophysics

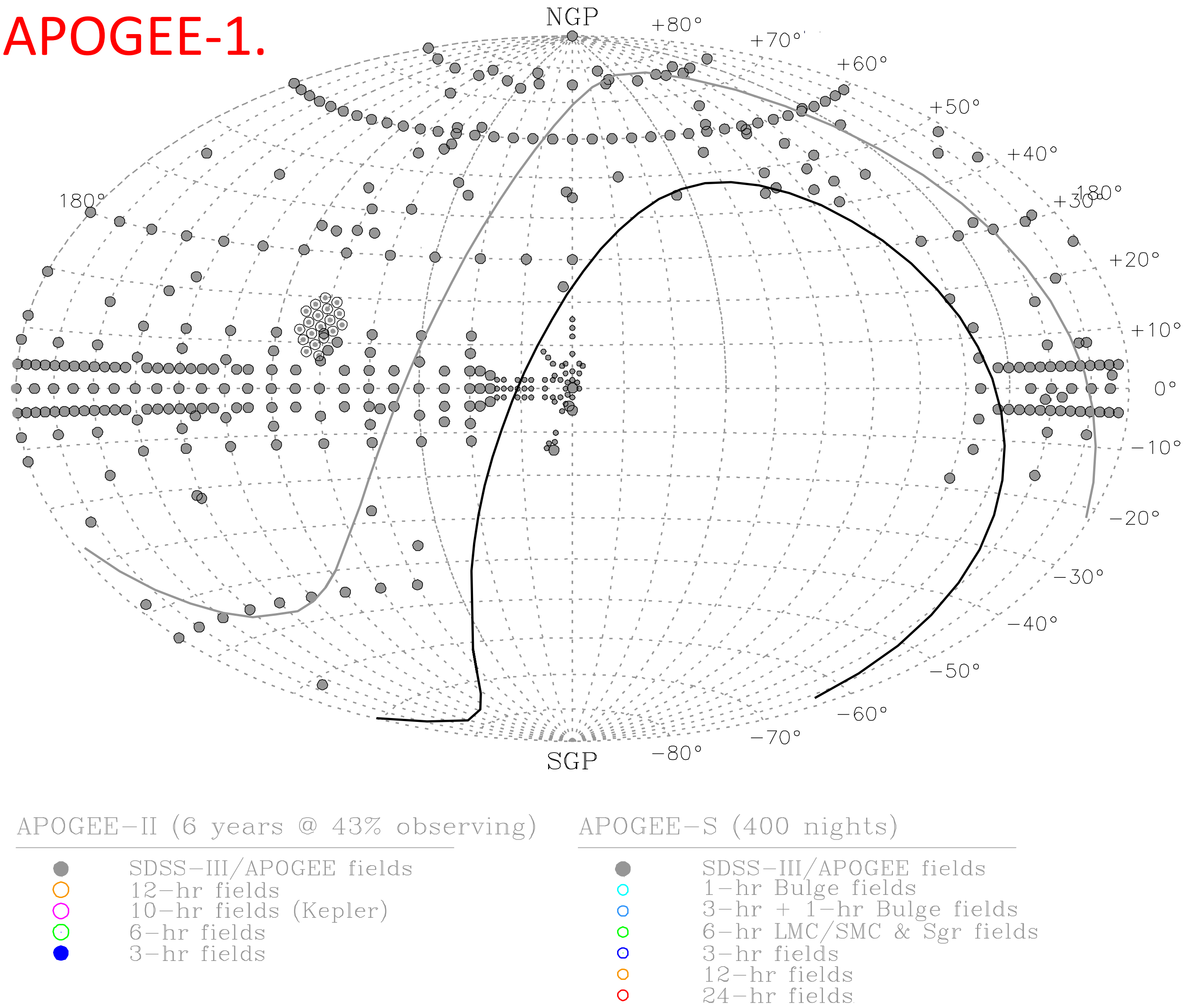


- **Expanding Sloan's horizons:**

  Science, technology, global collaboration

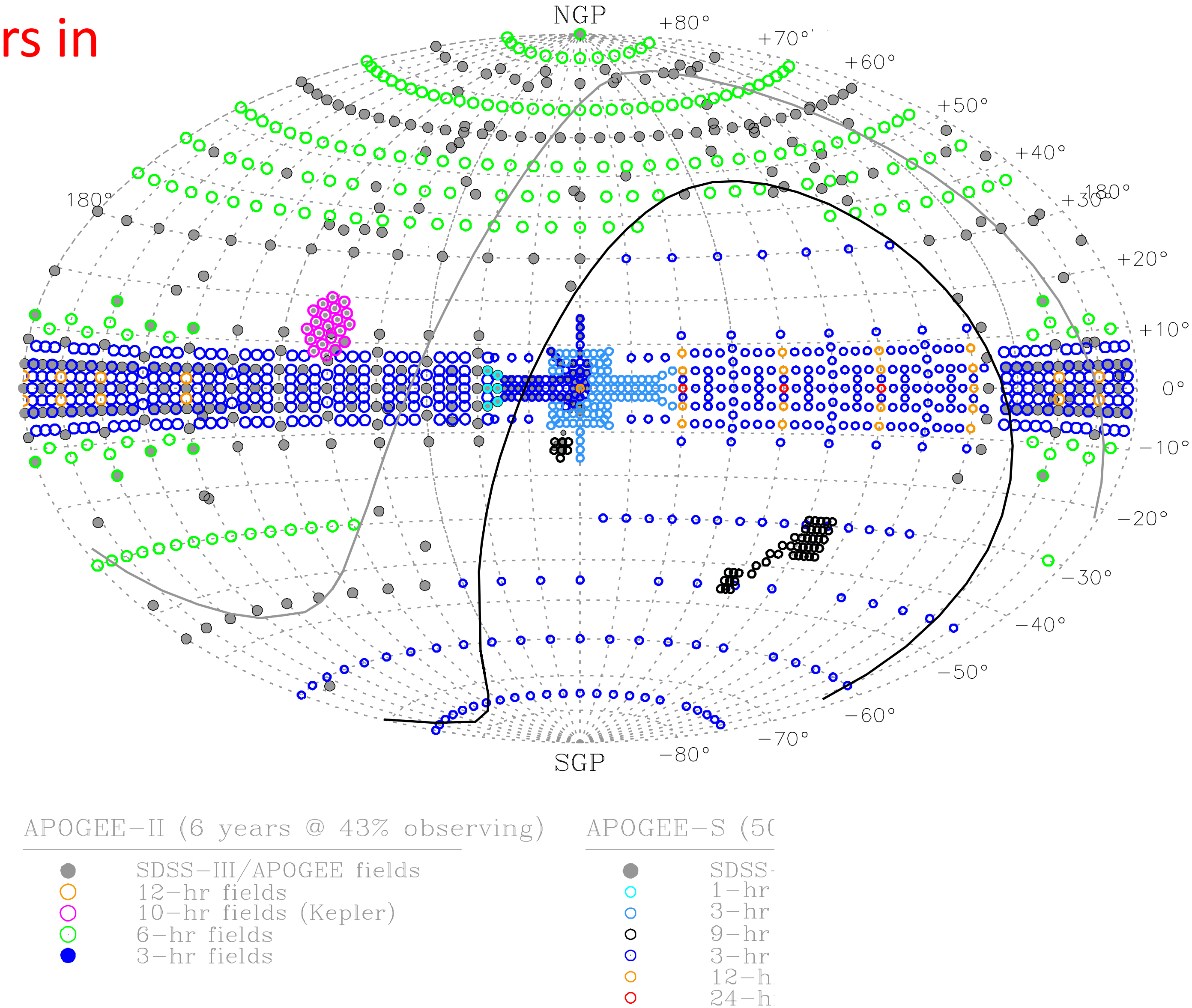
APOGEE-1 Sky Coverage

~140,000 stars in APOGEE-1.



APOGEE-2 Sky Coverage

Over 300,000 stars in combined APOGEE-1 & -2.



APOGEE

SDSS III

Logo by Gail Zasowski.