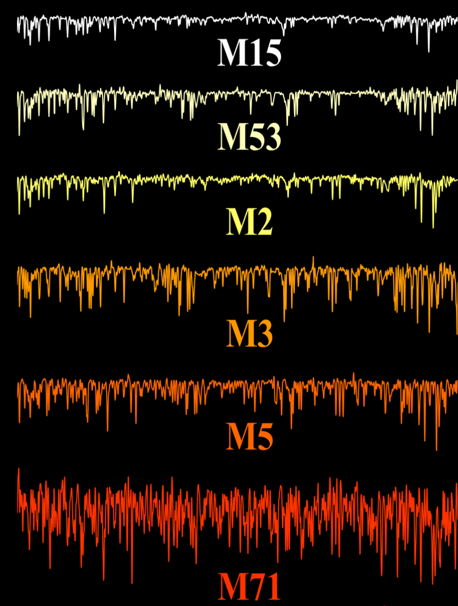
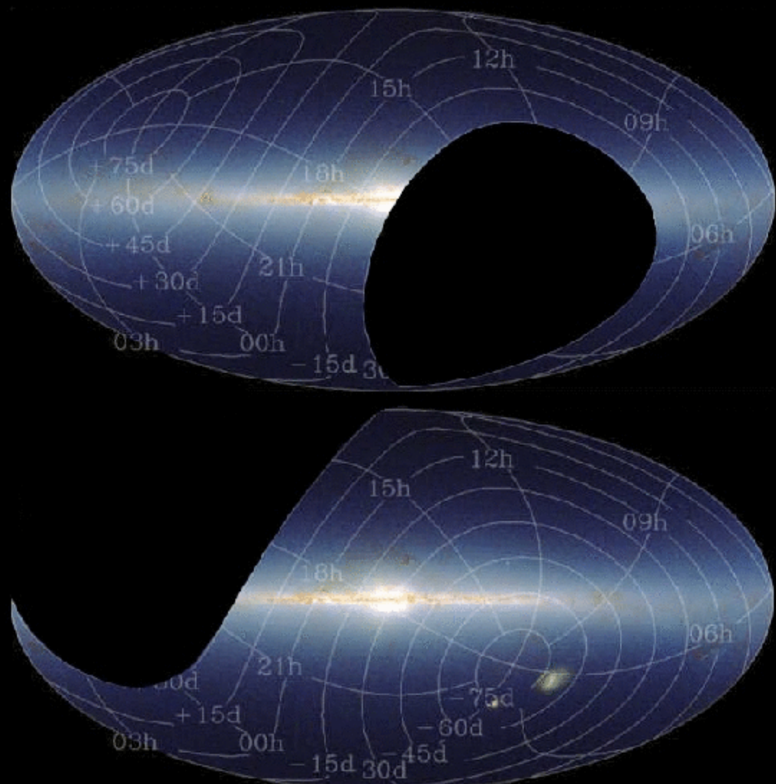
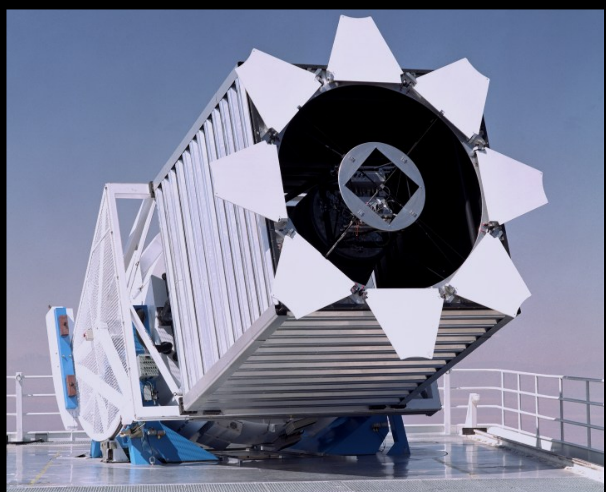
The Apache Point Observatory Galactic Evolution Experiment (APOGEE) and Its Successor, APOGEE-2

M. Schultheis

(Target/Field Analyst for APOGEE-2)







APOGEE-1 at a Glance

SDSS-III -- One of four experiments

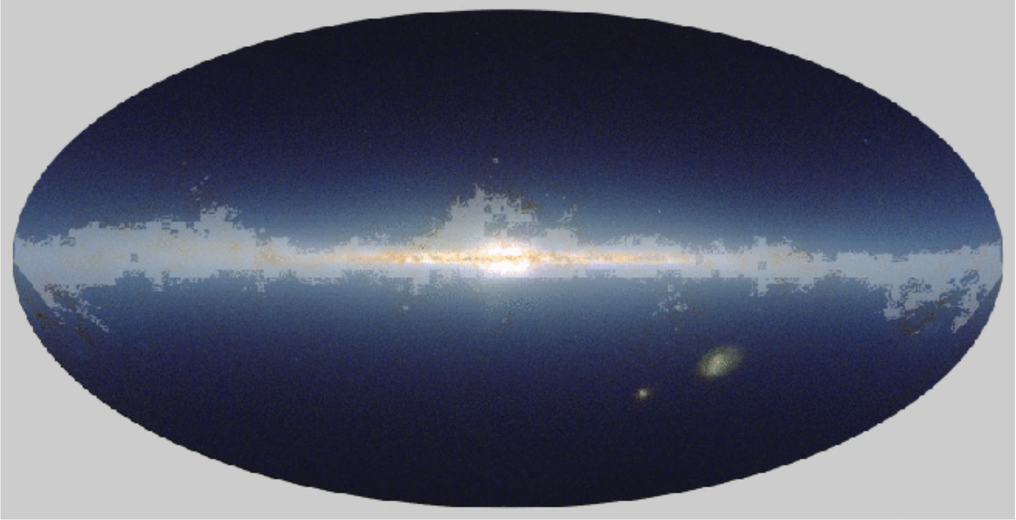
- Bright time 2011.Q2 - 2014.Q2
- 300 fiber, $R \geq 22{,}500$, cryogenic spectrograph, 7 deg^2 FOV
- *H*-band: 1.51-1.69μm $A_H/A_V \sim 1/6$
- $S/N \geq 100$/pixel @ H=12.2 for 3-hr total integration
- RV uncertainty ~100 m/s, 1-hr exposure
- 0.1 dex precision abundances for ~15 chemical elements

  (including Fe, C, N, O, α-elements, odd-Z elements, iron peak elements, neutron capture?)
- $>10^5$ 2MASS-selected giant star candidates 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



grey areas of map have $A_V > 1$

Top Level Science Requirements

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- 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
- Galactic dynamics/substructure with very precise velocities
- order of magnitude leaps:

  ~2-3 orders larger sample than previous high-*R* GCE surveys

  ~2 orders more high *S/N*, high *R* near-IR spectra ever taken

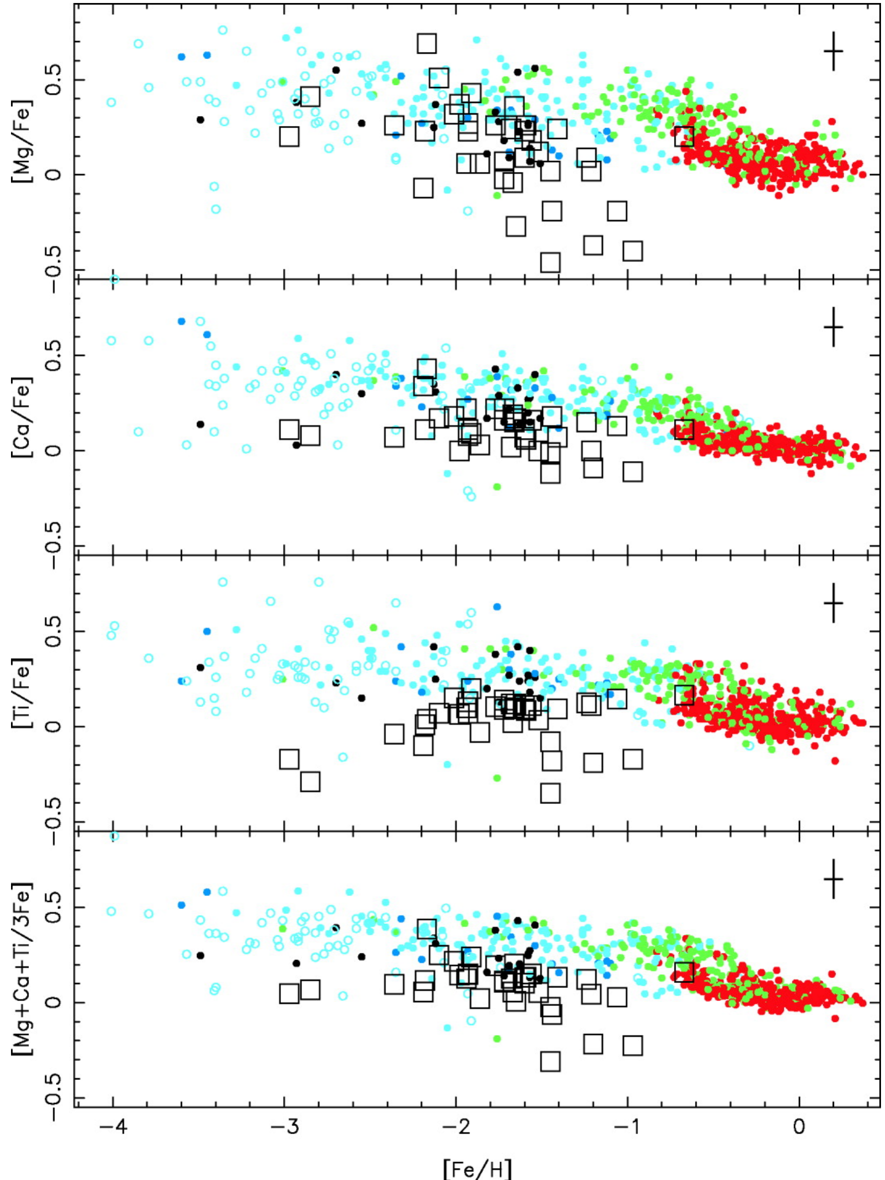
  ~1-2 orders more stars w/high *S/N*, high *R* spectra ever taken

4

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])

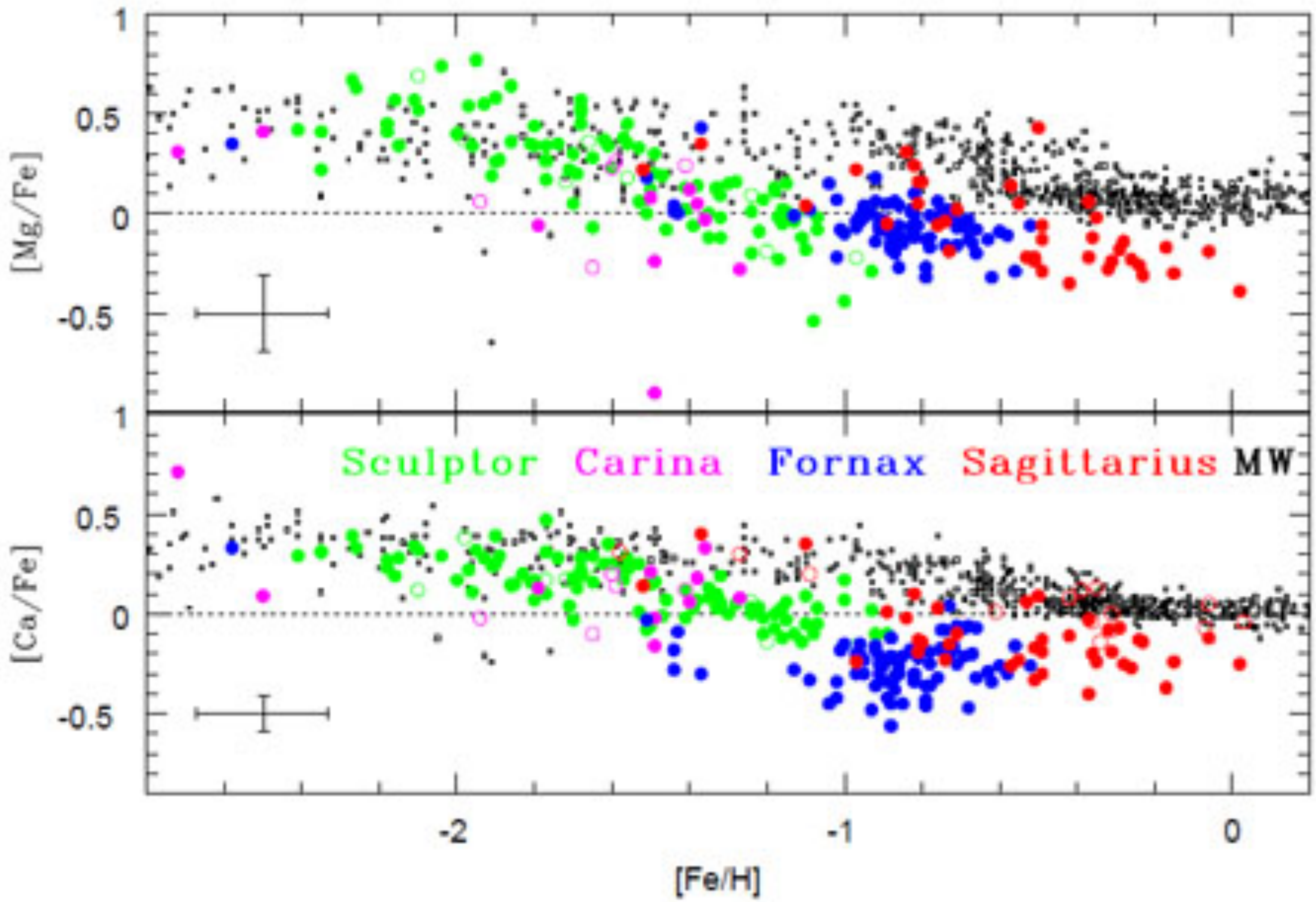


With 10^5 stars, APOGEE seeks to measure similar distributions

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

The Promise of Detailed Galactic Chemical Evolution Studies

Chemical "Fingerprinting"



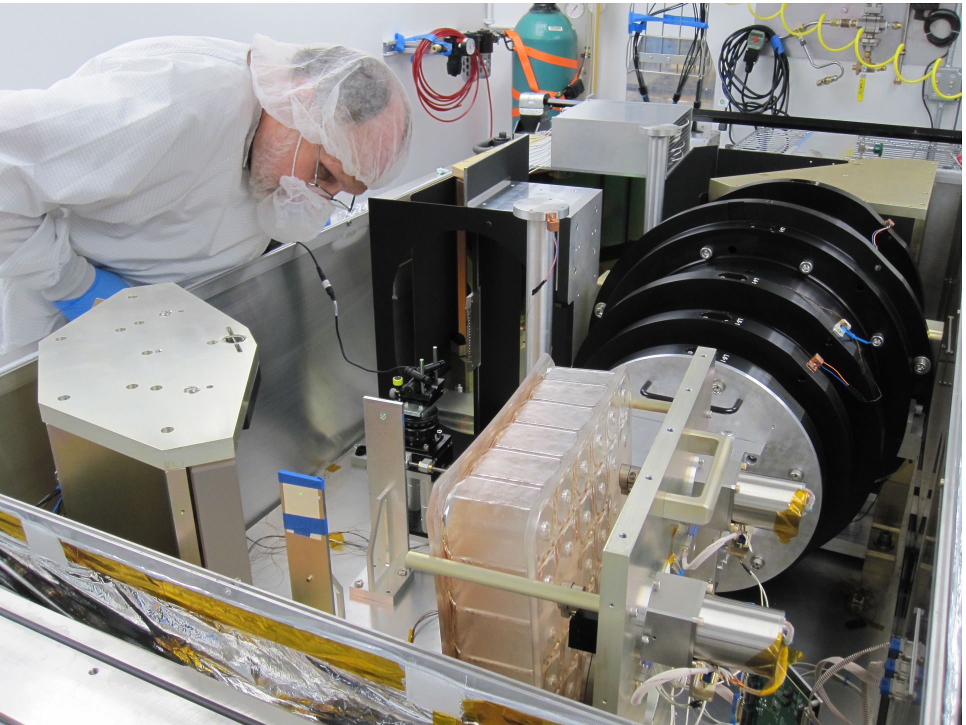
Tolstoy, Hill & Tosi (2009)

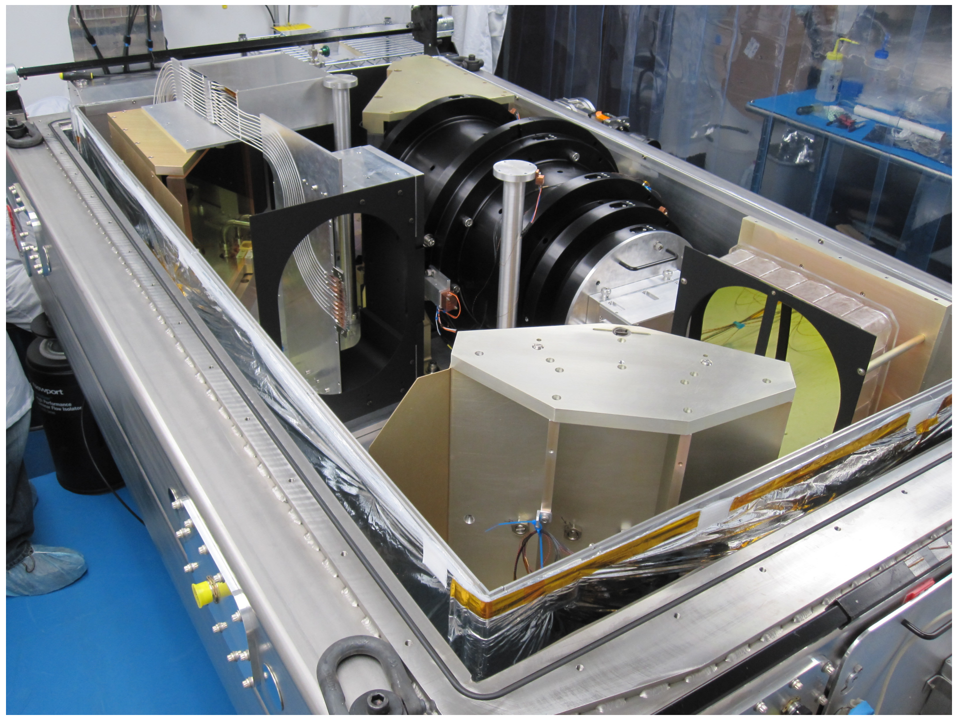
The APOGEE Instrument

- **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.

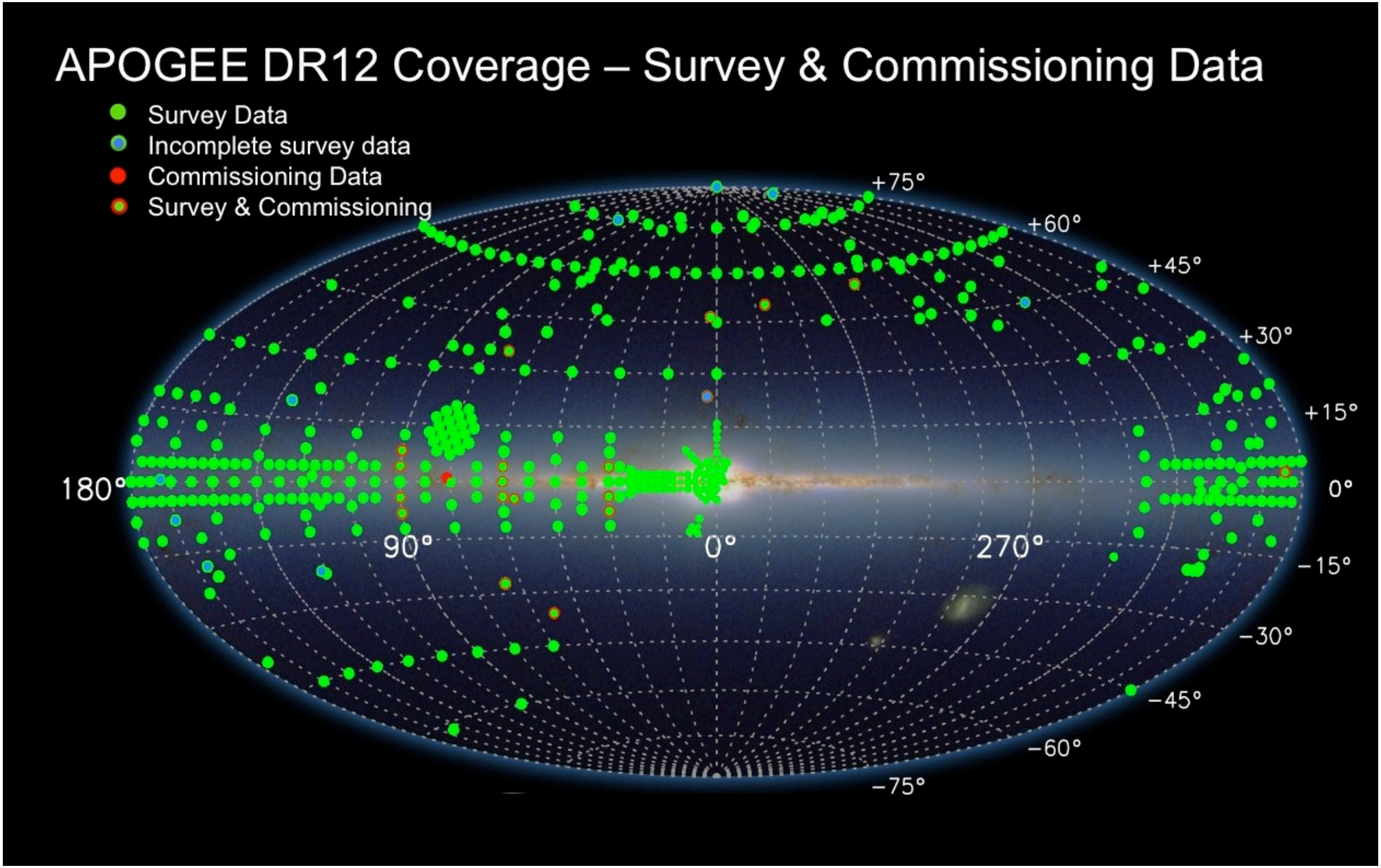




APOGEE First Light

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

APOGEE-1 Coverage



APOGEE-1 Observations

Exceeded goal of >100,000 stars by 2014 Q2:

- >500,000 distinct stellar spectra
- 437 unique field centers, 750 plugplate designs
- >1300 “successful” field visits (~1 hour each)

  (>300 nights w/any data, including commissioning)
- 146,000 stars: 131,000 “science” + 15,000 telluric standards

  15,000 stars in bulge fields

  28,000 stars in halo fields

  1,800 stars in halo stream fields

  55,000 stars in disk fields

  14,000 stars in Kepler/CoRoT fields

  8,000 stars in star cluster fields

  1,200 stars in Sagittarius dSph fields

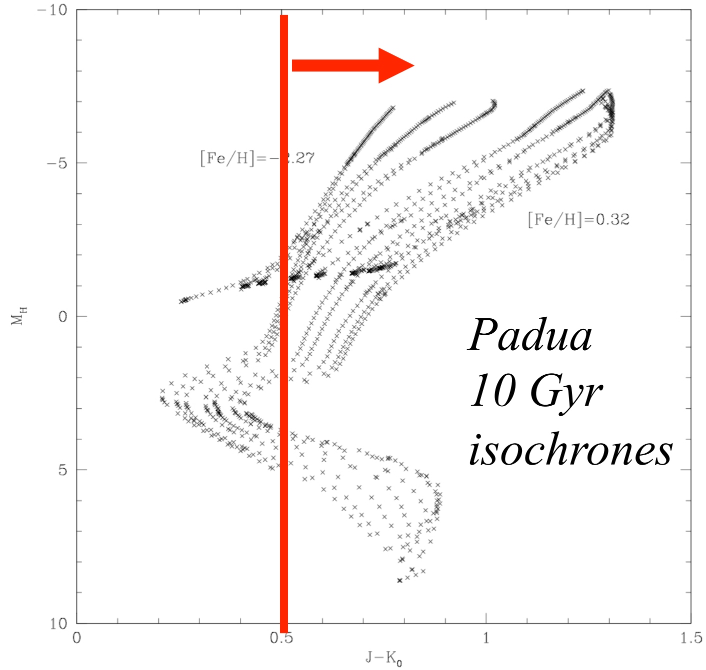
  900 bright stars observed with link to NMSU 1-m telescope

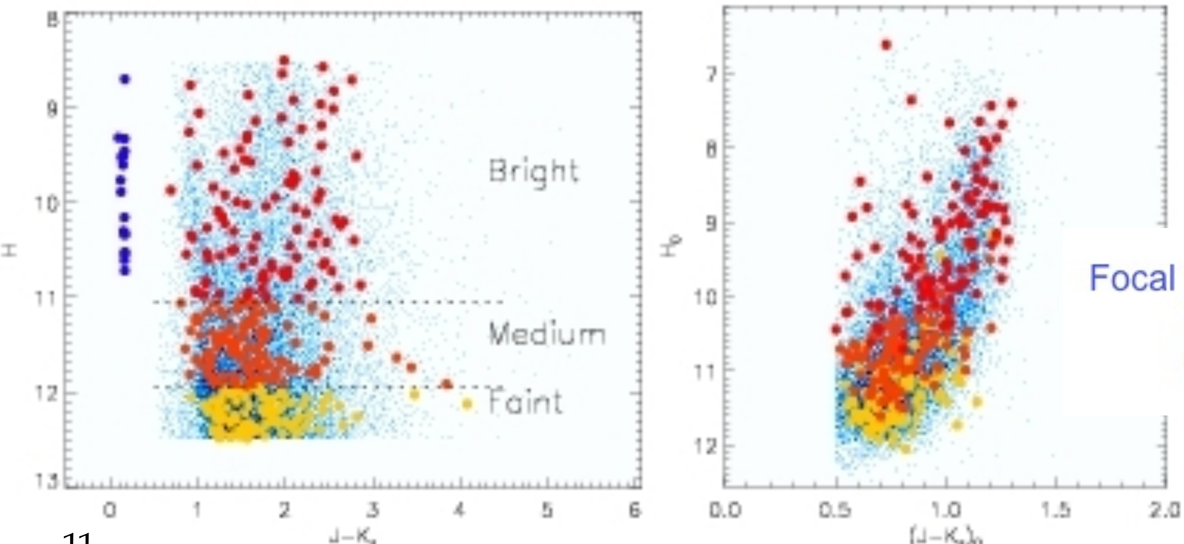
  8,000 objects in Ancillary Science fields

APOGEE Target Selection

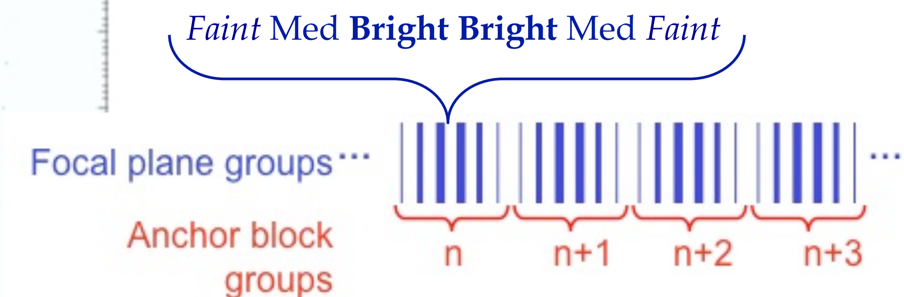
Simple Color & Magnitude Criteria

- Generally only color-selected: $0.5 \leq (J\text{-}K_s)_0$.
- Random sampling by magnitude.
  - Consistent, ~even sampling of fields having different starcount distributions.
- Variable magnitude limits (H < 11-14) for both shallow and deeper probes of MW.





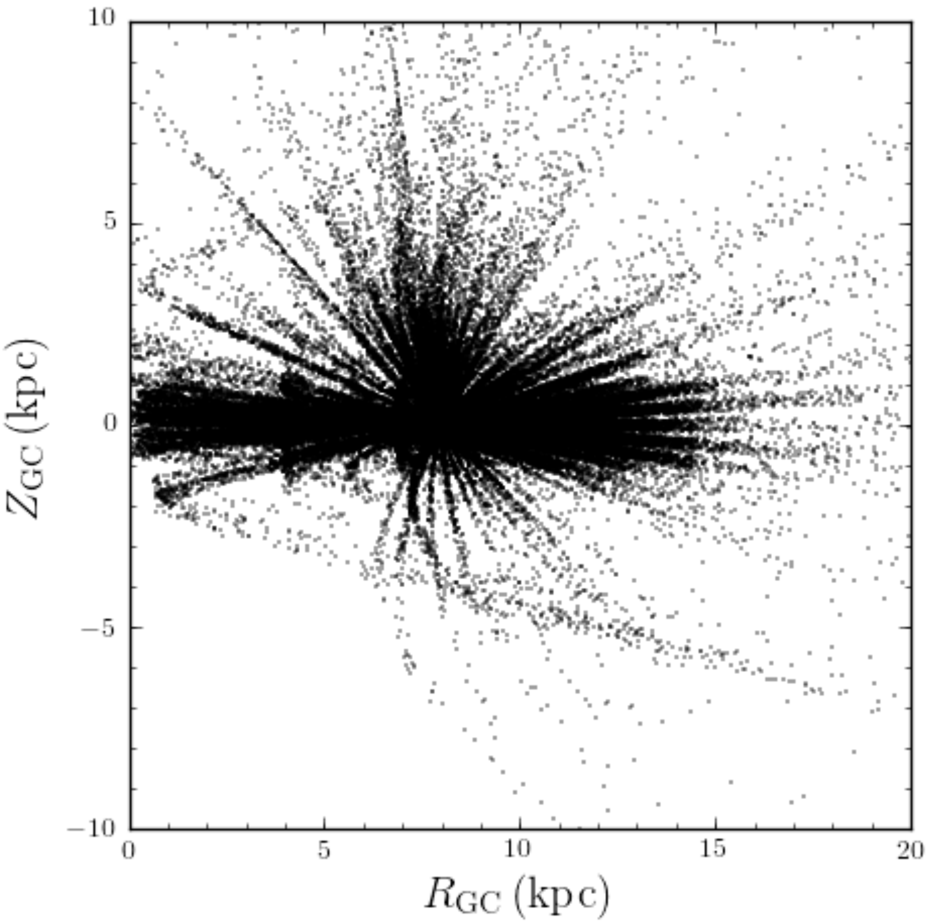
Example selection of *H* < 12.5 fields at (*l*,*b*) = (60,0)°

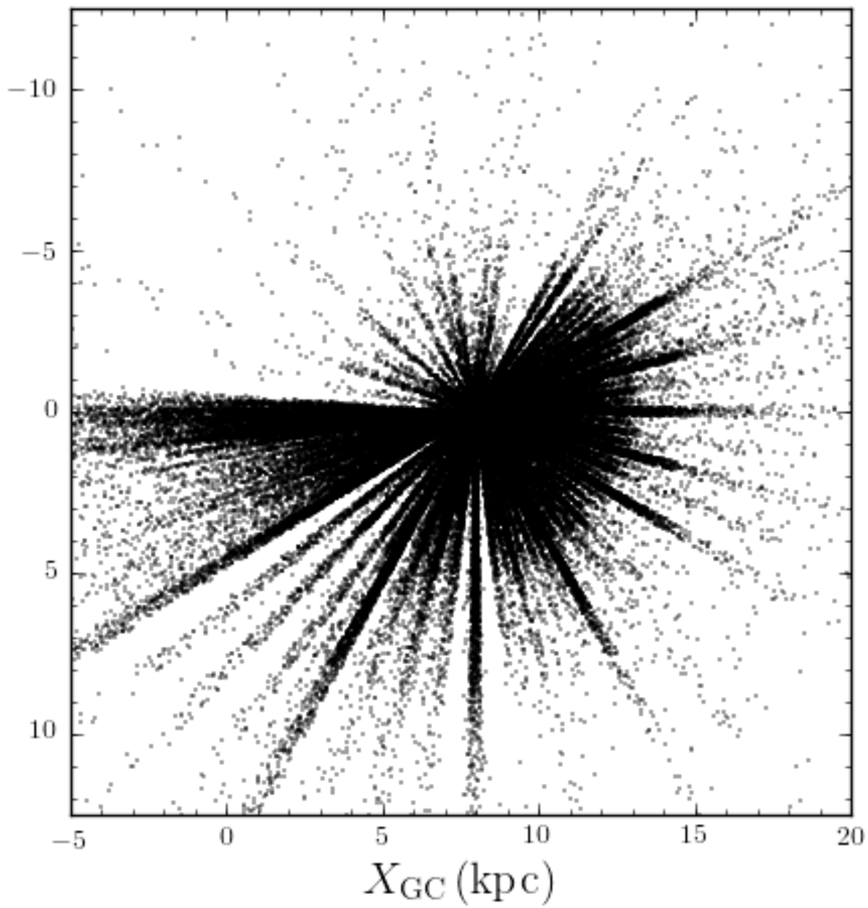


Full details in Zasowski et al. (2013)

APOGEE-1 Spatial Distribution

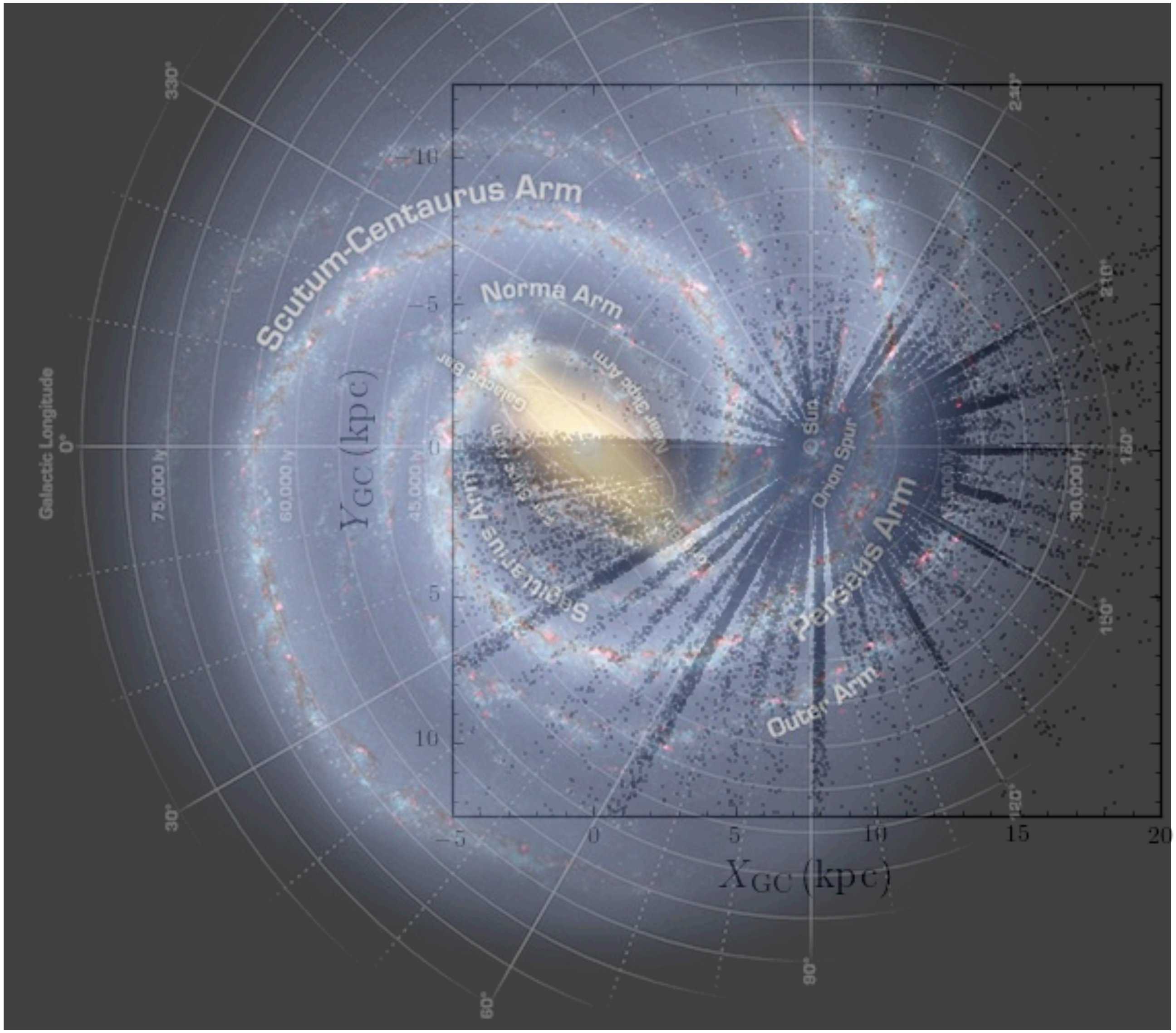
DR12 giant stars





APOGEE-1 Spatial Distribution

DR12 giant stars



Abundances & Stellar Parameters

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

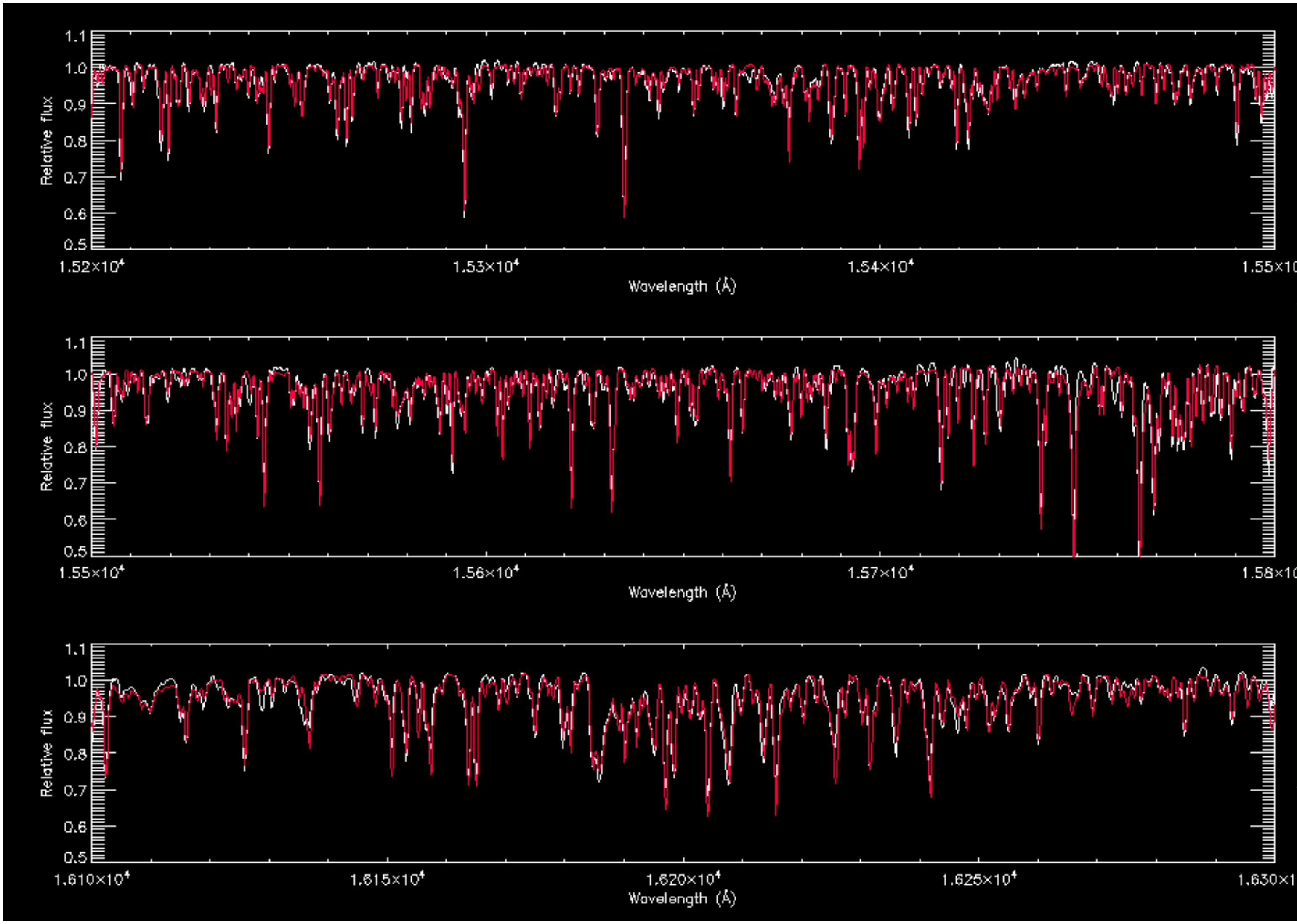
- ASPCAP: χ^2 optimization against synthetic spectral libraries.

  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 …) from narrow, optimal windows for each element.

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

Tying to Sun and Arcturus

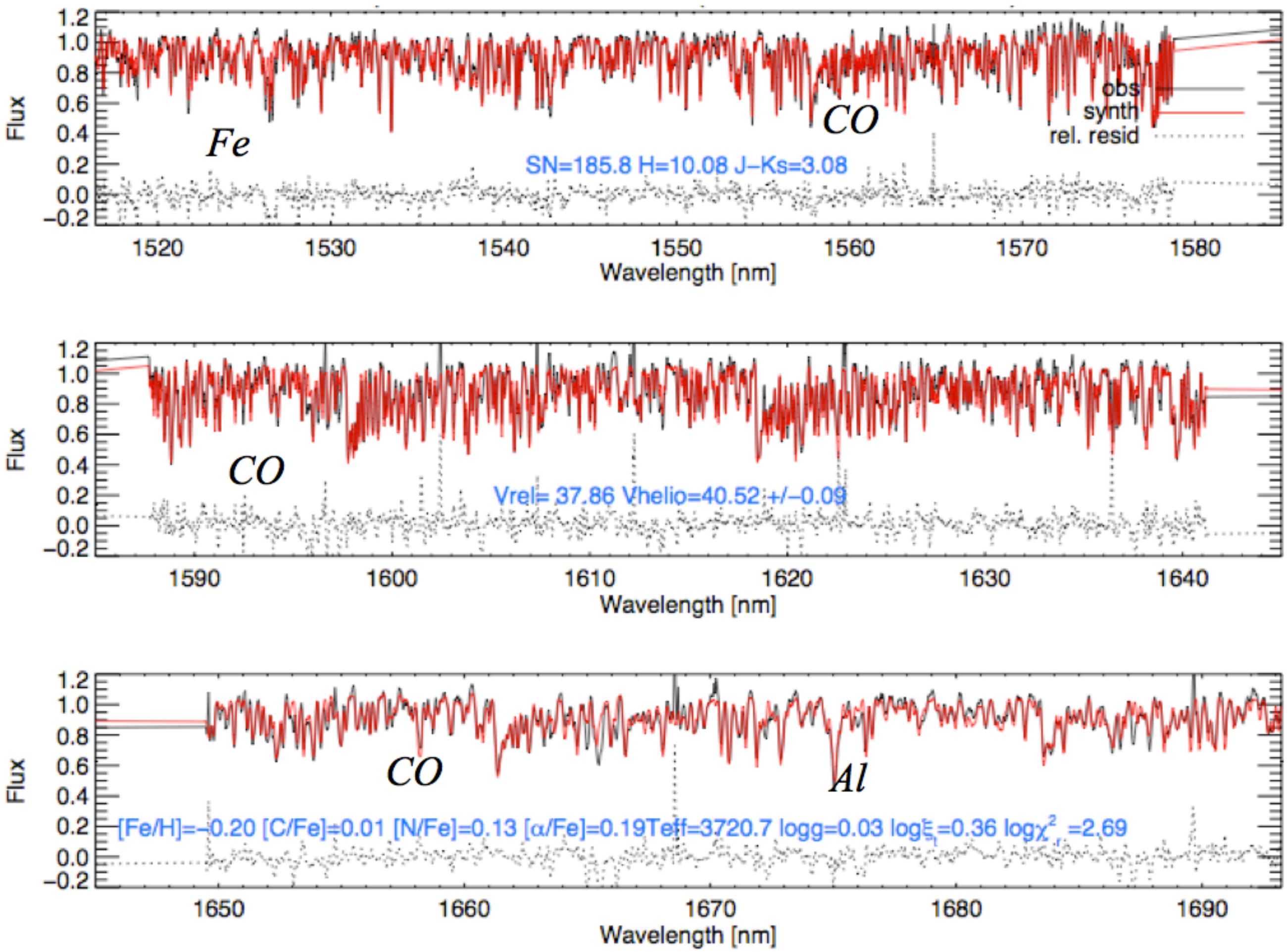


T_{eff}=4408 K
Log g=2.13
$Log_{10}(\xi)$=0.33
[Fe/H]=-0.56
[C/Fe]=+0.44
[N/Fe]=+0.02
[O/Fe]=+0.50

ASPCAP fitting Arcturus spectrum

ASPCAP & Data Release 12

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)

Data Products – DR12&DR13

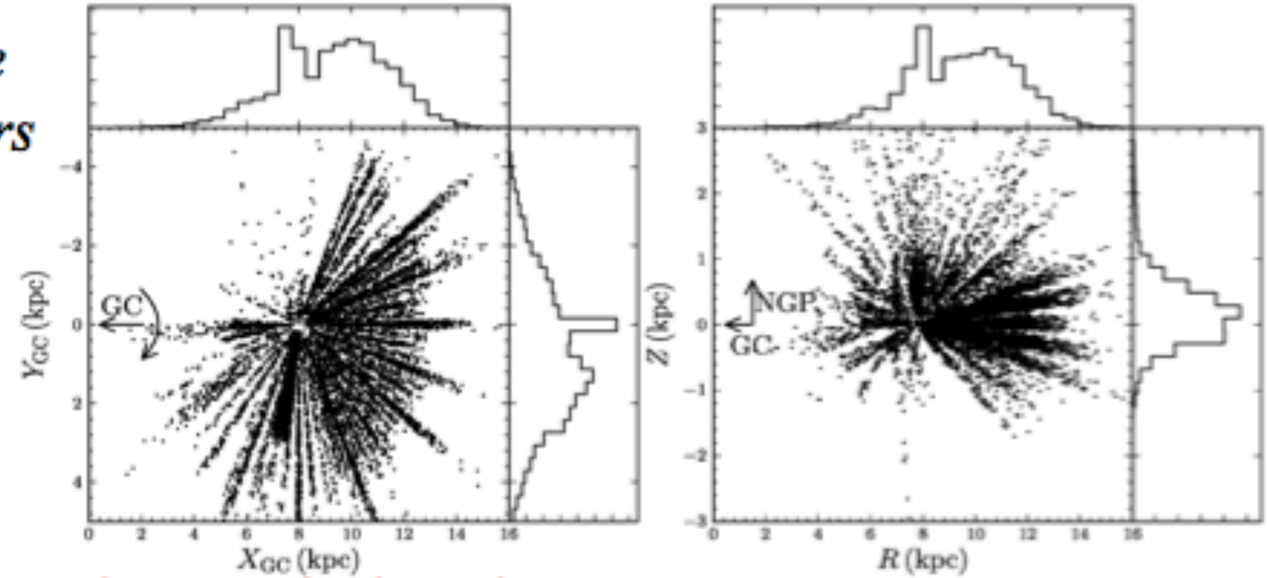
- DR12 (http://www.sdss.org/dr12/irspec/):
  - Target selection information
    - Sufficient to reconstruct sampling functions
  - Spectra across full APOGEE spectral window (1.51-1.69 μm)
    - Reduced, calibrated 1-D spectra with errors, pixel flag, LSF vectors
    - $S/N > 100$ per pixel (Nyquist limit)
  - Velocity data (< ~100 m/s precision)
    - Radial velocities, RV variability information (multiple epochs), errors
  - Stellar atmospheric parameters from matches to synthetic libraries
    - Via simultaneous 6-D optimization of T_{eff}, log *g*, [Fe/H], [C-N-O/Fe]
    - Uncertainties, covariances, error flags
  - Chemical abundances (~ 0.1-0.2 dex internal accuracy)
    - C, N, O, Na, Mg, Al, Si, S, K, Ca, [Ti], [V], Mn, Fe, Ni

DR13 (Summer 2016, same targets, new reductions):

Value-Added Catalogs

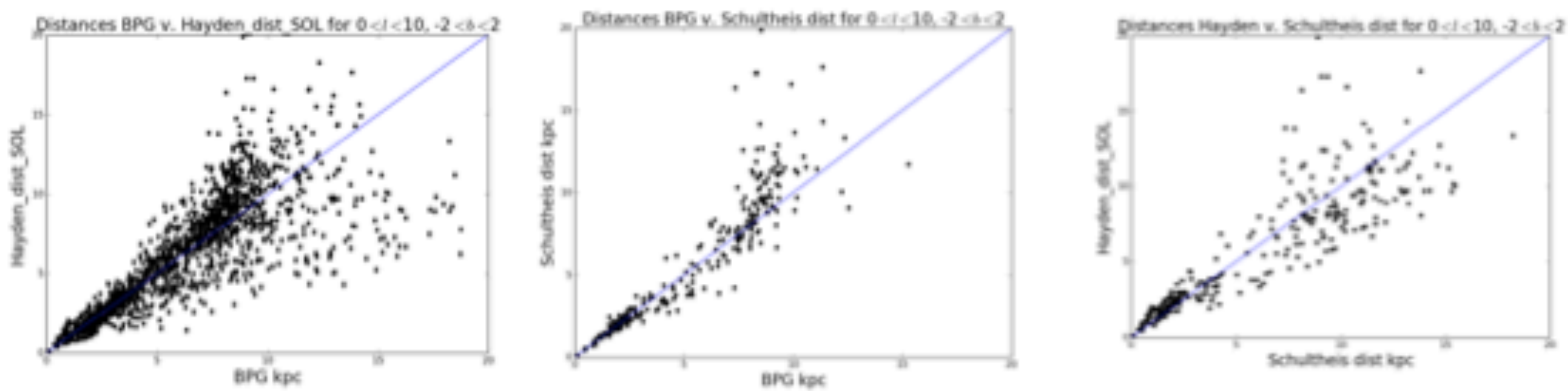
- Red Clump Catalog (see Bovy et al. 2014 ApJ, 790, 127):

very pure (95%) sample of 20,000 DR12 RC stars with 5-10% distances



- RGB distances – 4 estimates in hand:

(Hayden et al., Santiago et al., Schultheis et al., Ness et al.



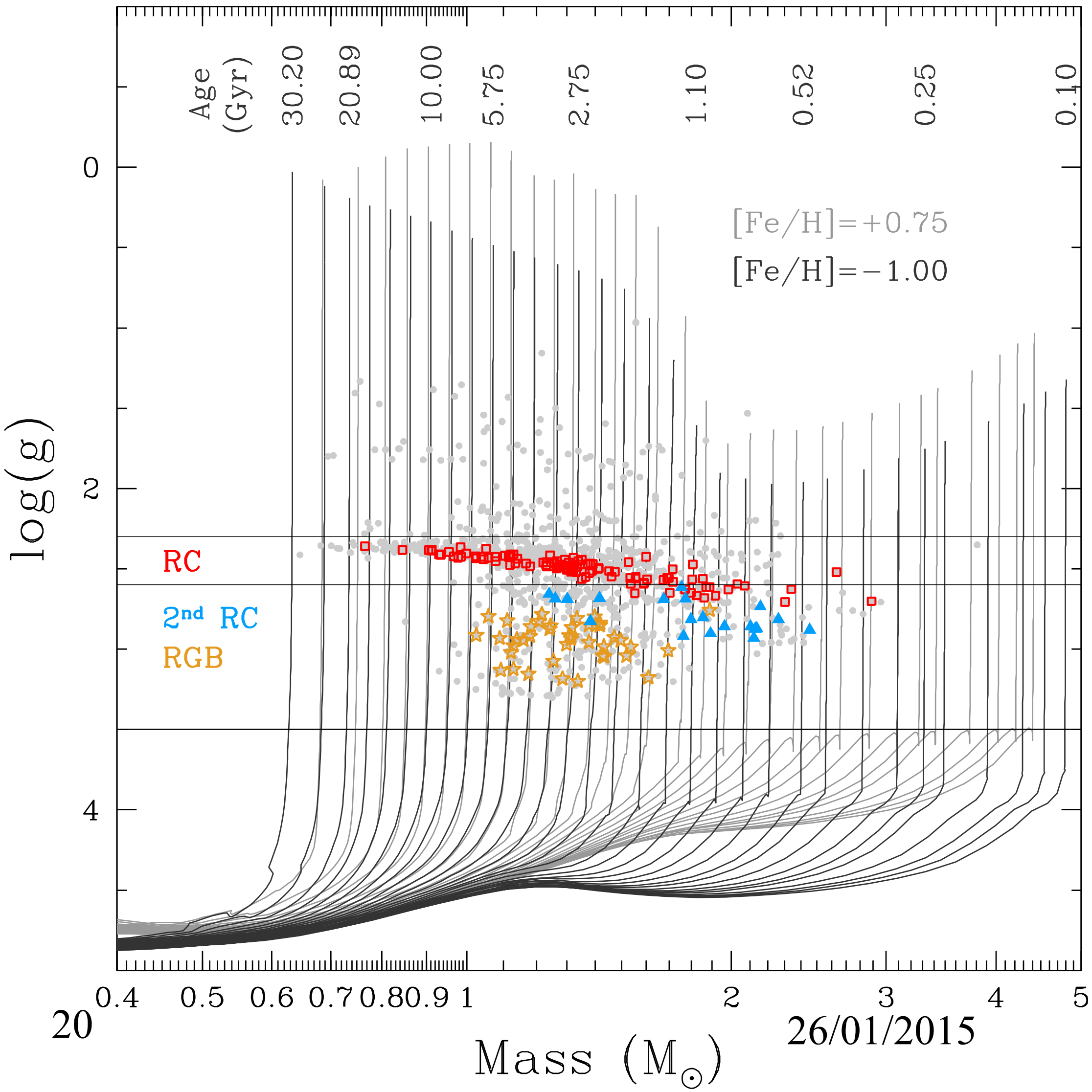
Technical Papers

- Stellar atmospheric models (Meszaros et al. 2012, AJ, 144, 120)
- Test of APOGEE linelist (Smith et al. 2013, ApJ, 765, 16)
- Targeting paper (Zasowski et al. 2013, AJ, 146, 810)
- Star cluster calibration (Meszaros et al. 2013, AJ, 146, 133)
- APOGEE-KASC (Pinsonneault et al. 2014, ApJS, 215, 19)
- Reduction pipeline (Nidever et al. 2015, AJ 150, 173)
- Data Release 12 products (Holtzman et al. 2015, AJ150, 148)
- Test of element abundances (Cunha et al.,ApJ 798, 41)
- Stellar spectral libraries (Zamora et al. 2015, AJ 149, 181)
- Overall survey (Majewski et al., submitted)
- ASPCAP (Garcia Perez et al., 2016, AJ 151, 144)
- Linelist creation (Shetrone et al.,2015, ApJS, 221, 24)
- Instrument (Wilson et al., in preparation)

APOGEE-Kepler Asteroseismology Collaboration (APOKASC)

• Stellar ages from APOKASC

- *To date, ~10,000 Kepler stars (mostly asteroseismology giants) observed by APOGEE.*



- *Critical log g measures for pipeline calibration.*
- *Catalog in Pinnsoneault et al. (2014, ApJ)*

26/01/2015

ASPCAP & Data Release 12

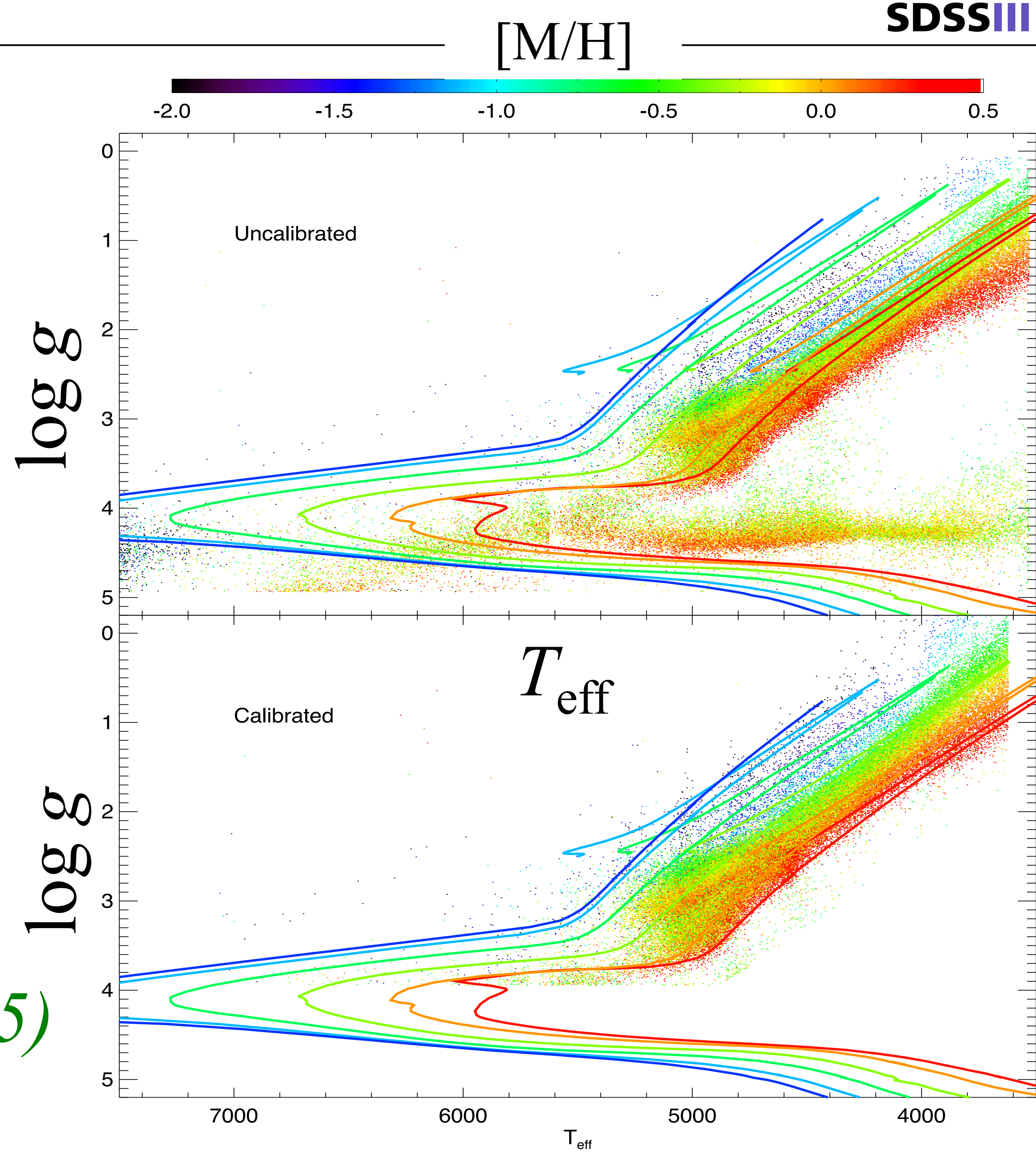
<u>Calibration:</u>

T_{eff} = IRFM

log *g* = seismic

[M/H] = clusters

4 Gyr isochrone (Bressan et al. 2012) comparison (Holtzman et al. 2015)



Age-[Fe/H] - [α/Fe] Distribution

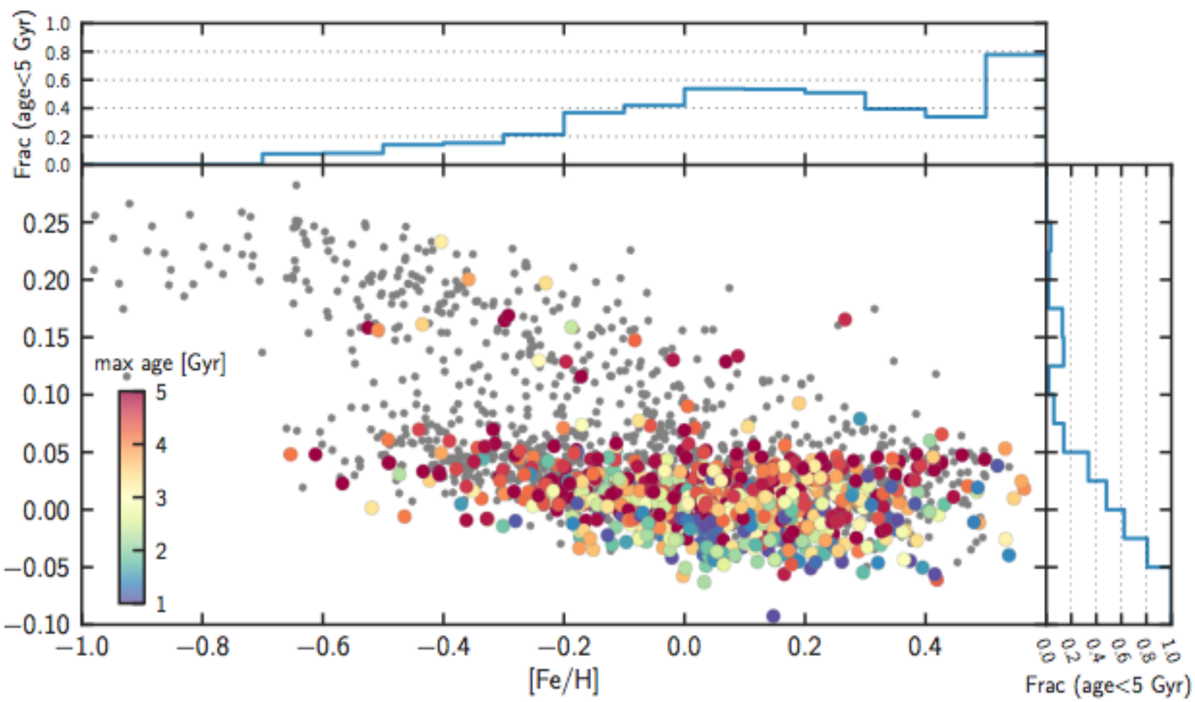
Martig, et al. (2015) for Kepler

Chiappini et al. (2015) for CoRoT

Asteroseismology+APOGEE allows masses and ages to be determined for red giants:

$$\frac{M}{M_\odot} \simeq \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right)^3 \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-4} \left(\frac{T_{\text{eff}}}{T_{\text{eff},\odot}}\right)^{3/2}$$

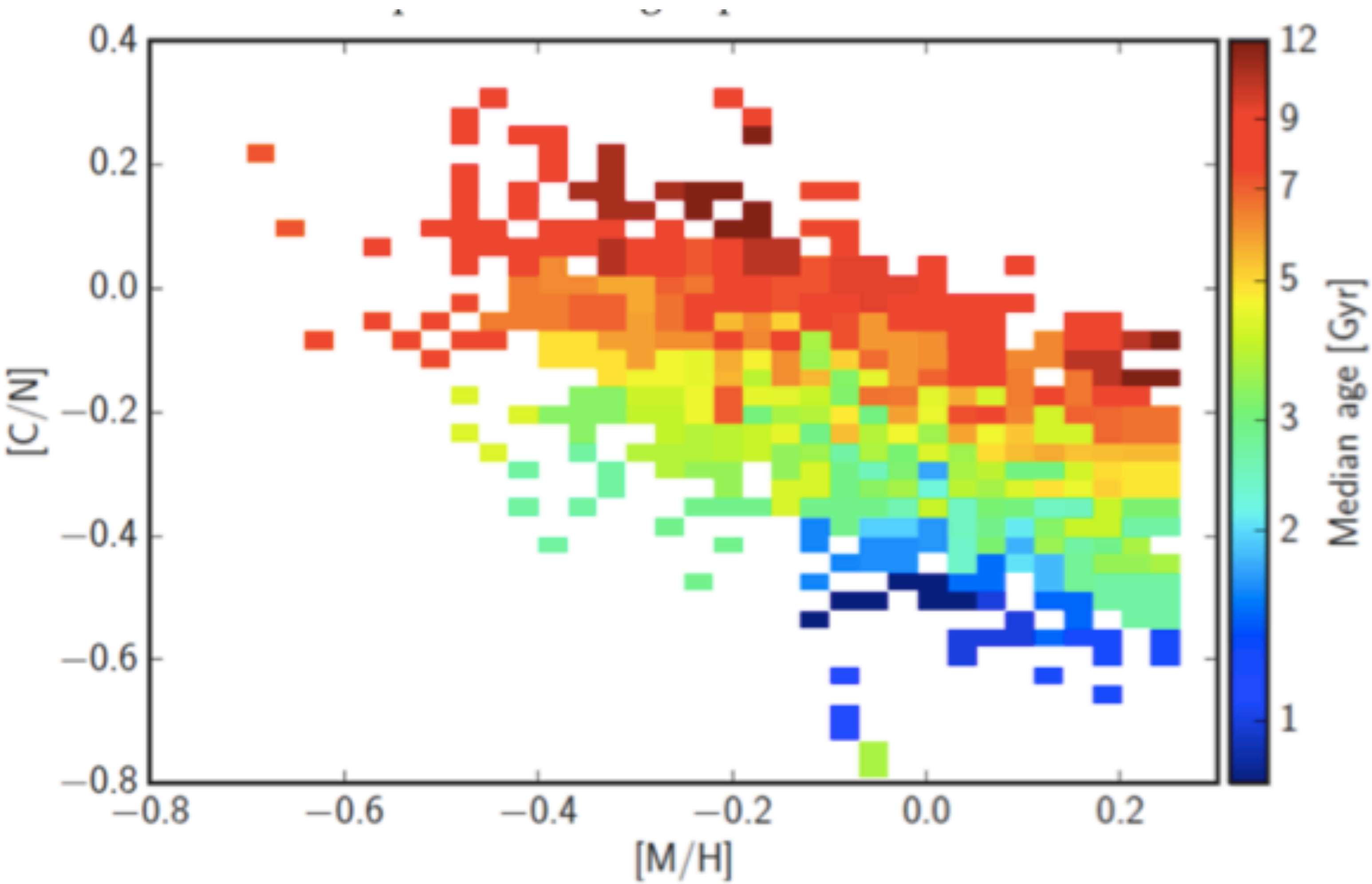
- Maximum ages (minimum masses) are very robust → can investigate what fraction of stars are young.
- Fraction ↑ for [α/Fe] ↓.
- Some young stars at high [α/Fe].



Age Maps

Based on C/N abundances   Martig et al. (2016)

Mass dependent dredge up -> alters CN abundances



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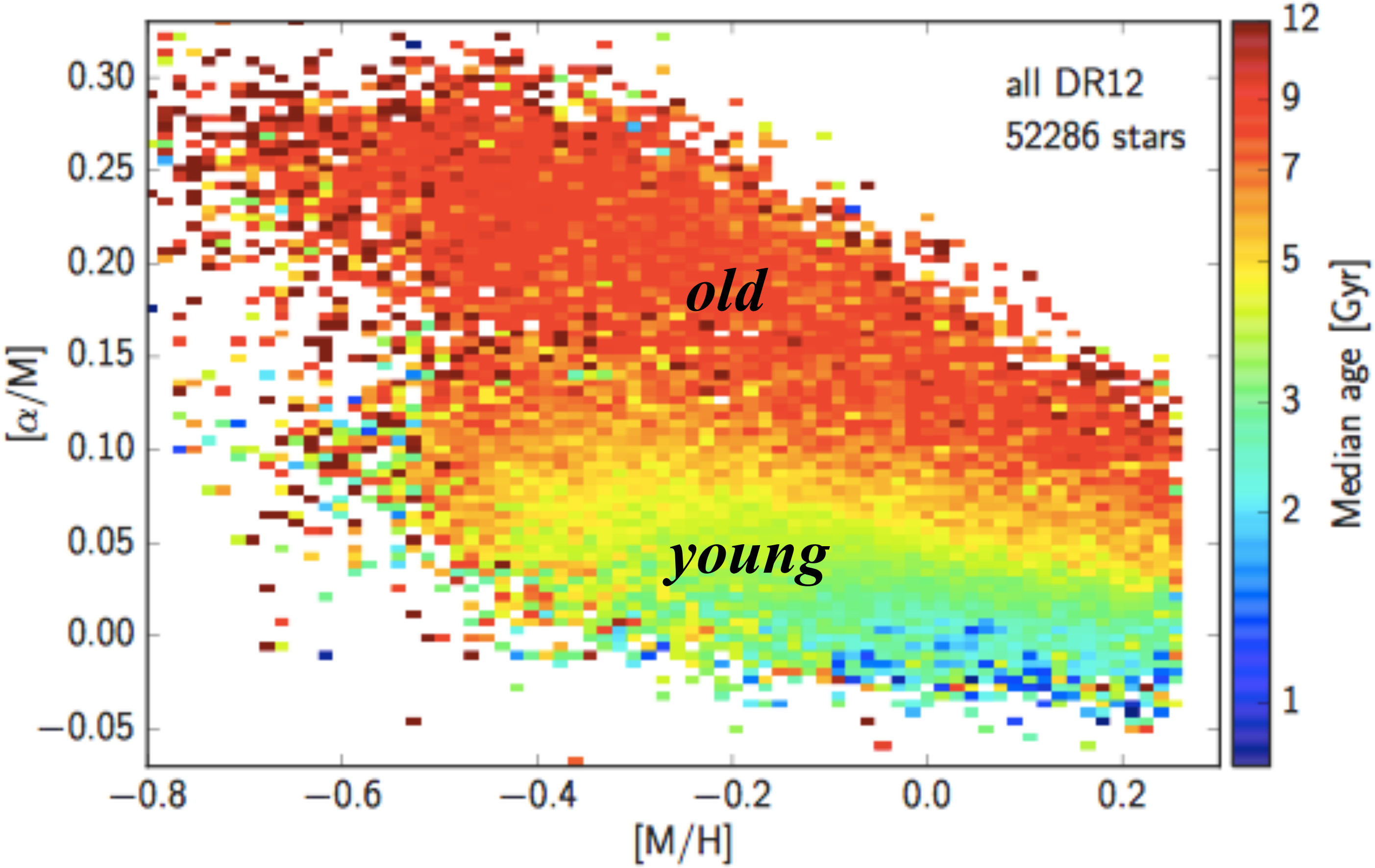
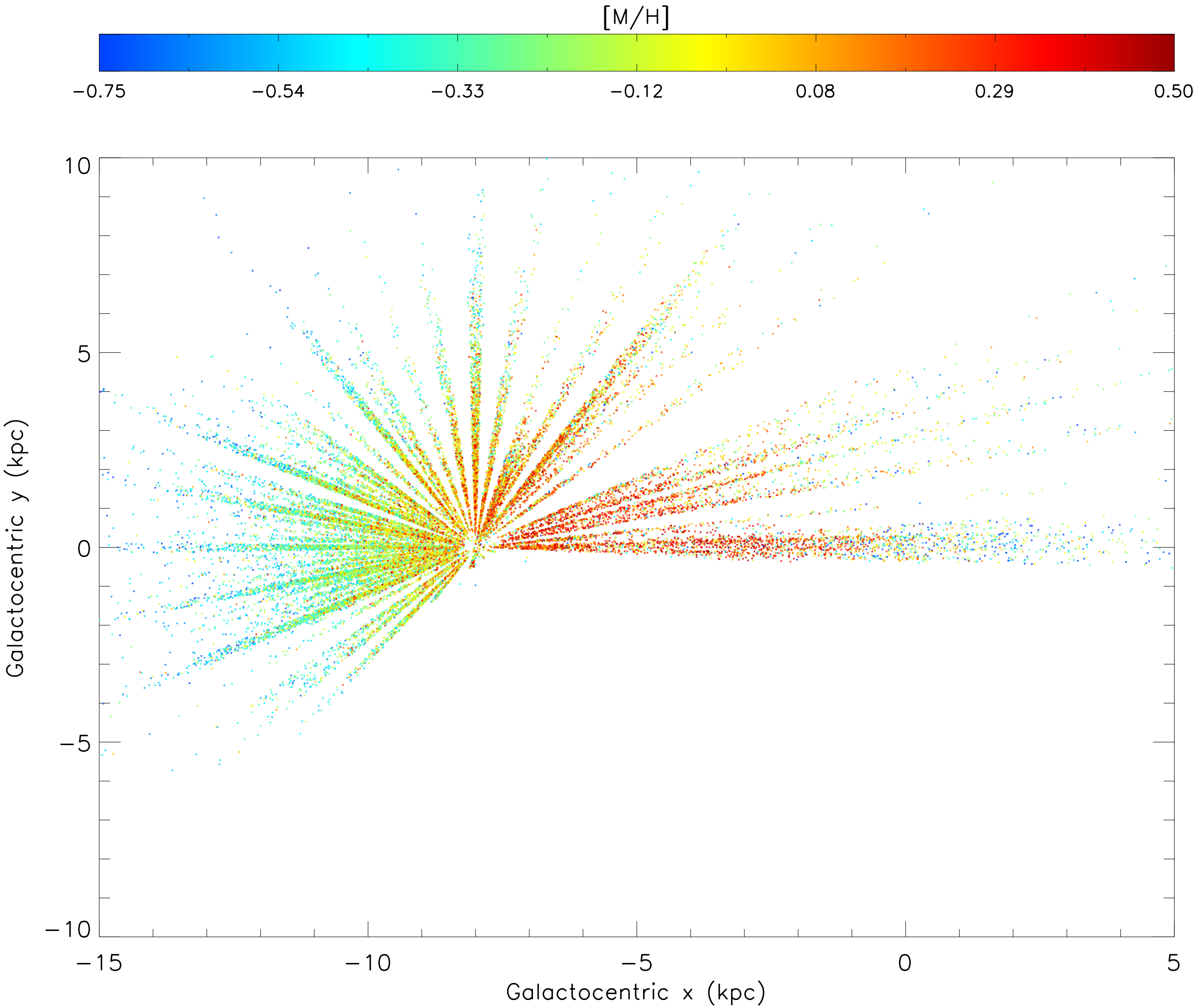


SCIENCE with APOGEE

Metallicity Gradients

(Hayden et al. 2015)



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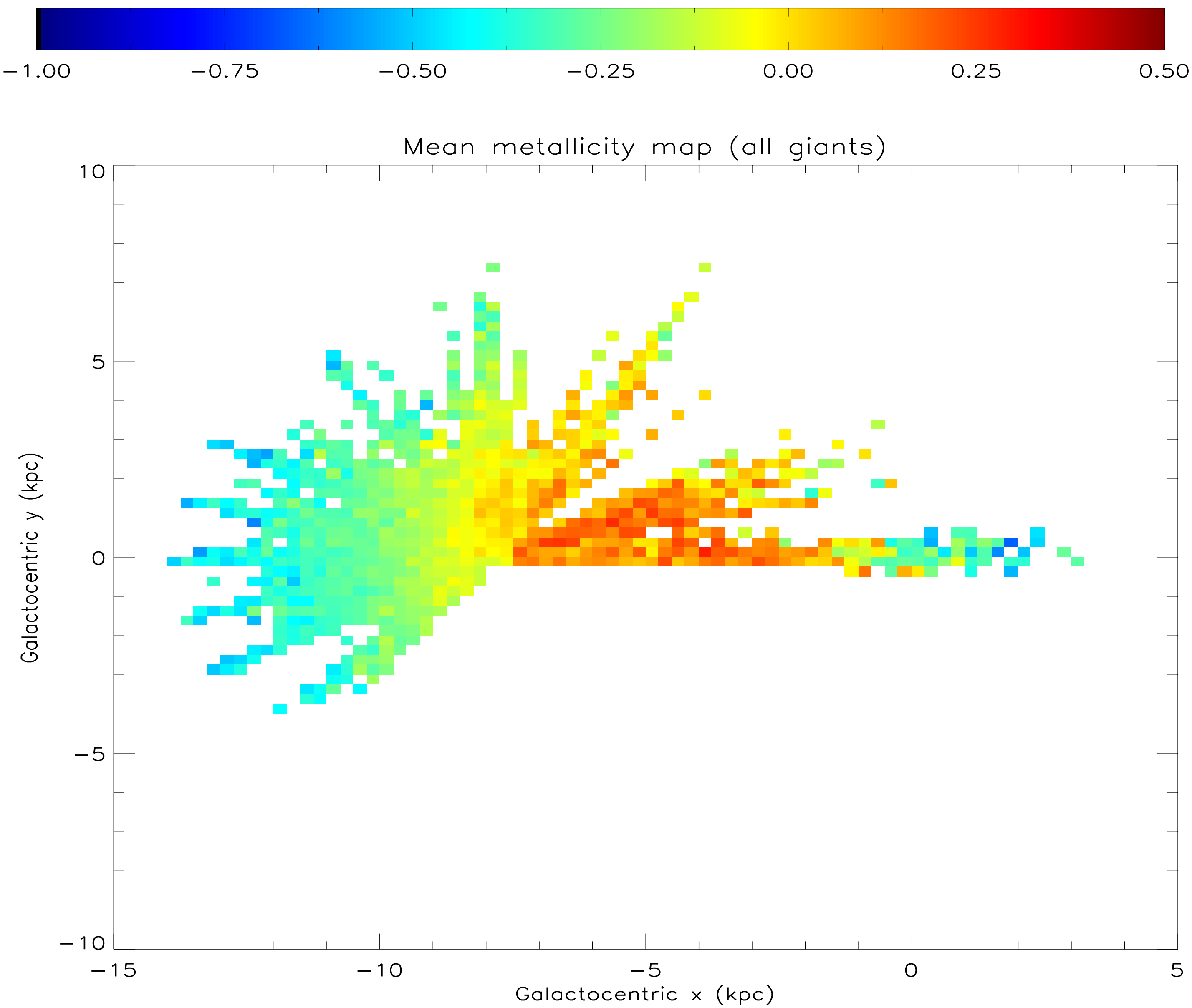
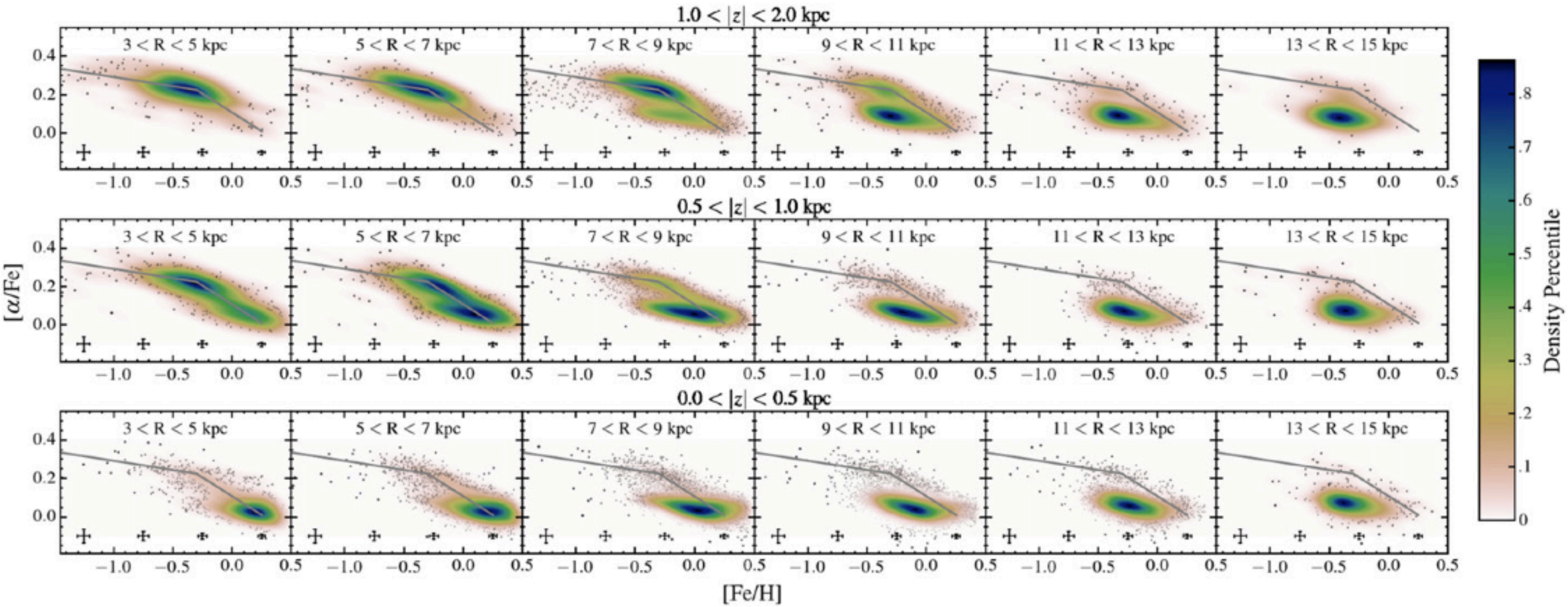


[α/Fe] Patterns

(Hayden et al. 2015)

Fraction of low-alpha and high alpha varies as a function of R,z

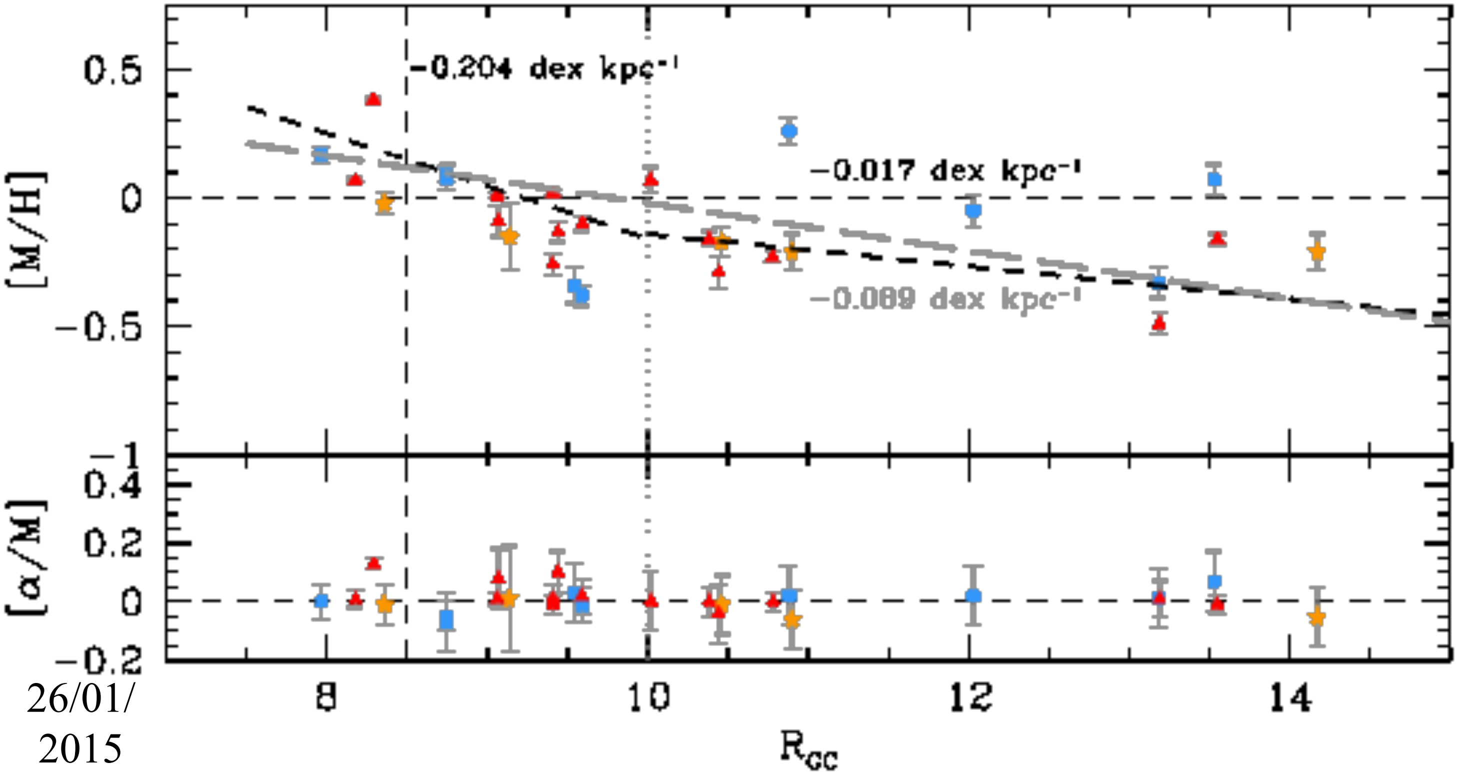


Galactic Abundance Gradients Using Open Star Clusters

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, ApJL, 777, L1*):

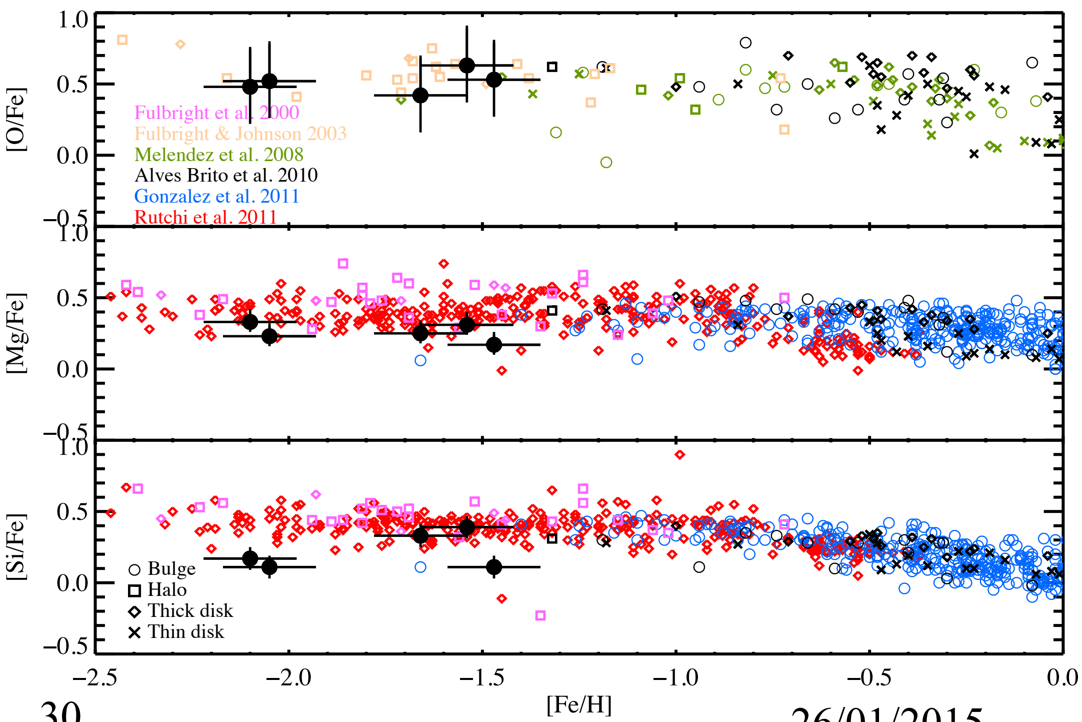
- 141 stars in 28 clusters
- **MW [Fe/H] radial gradient seen,** evidence for flattening R > 10 kpc.
- **No mean [α/Fe] gradient.**

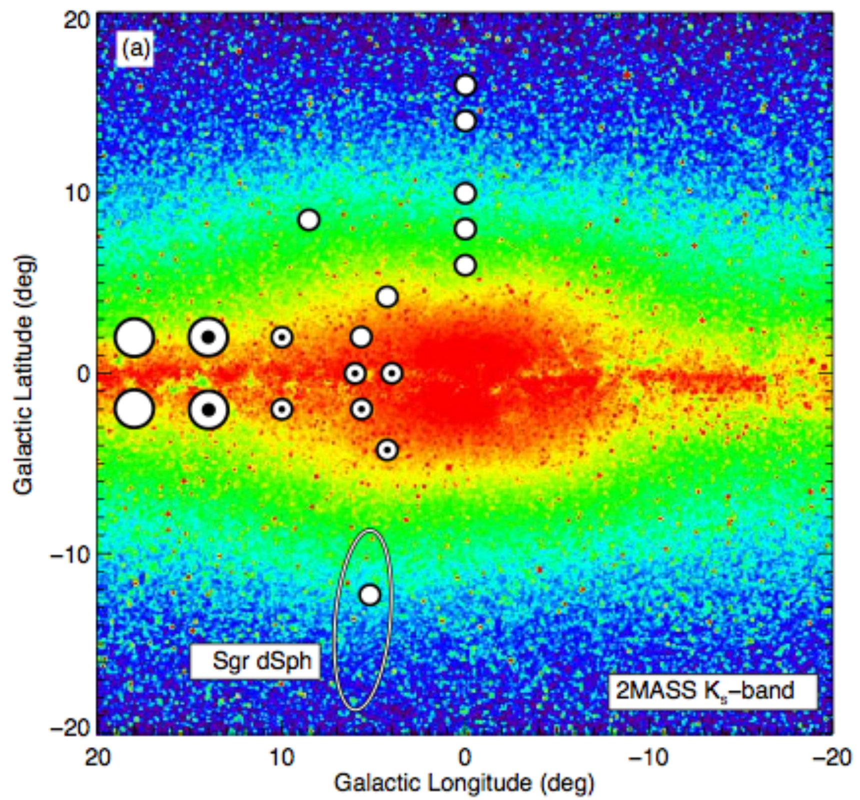


log(*age*) < 8.5
8.5 < log(*age*) < 9
log(*age*) > 9

Galactic Bulge

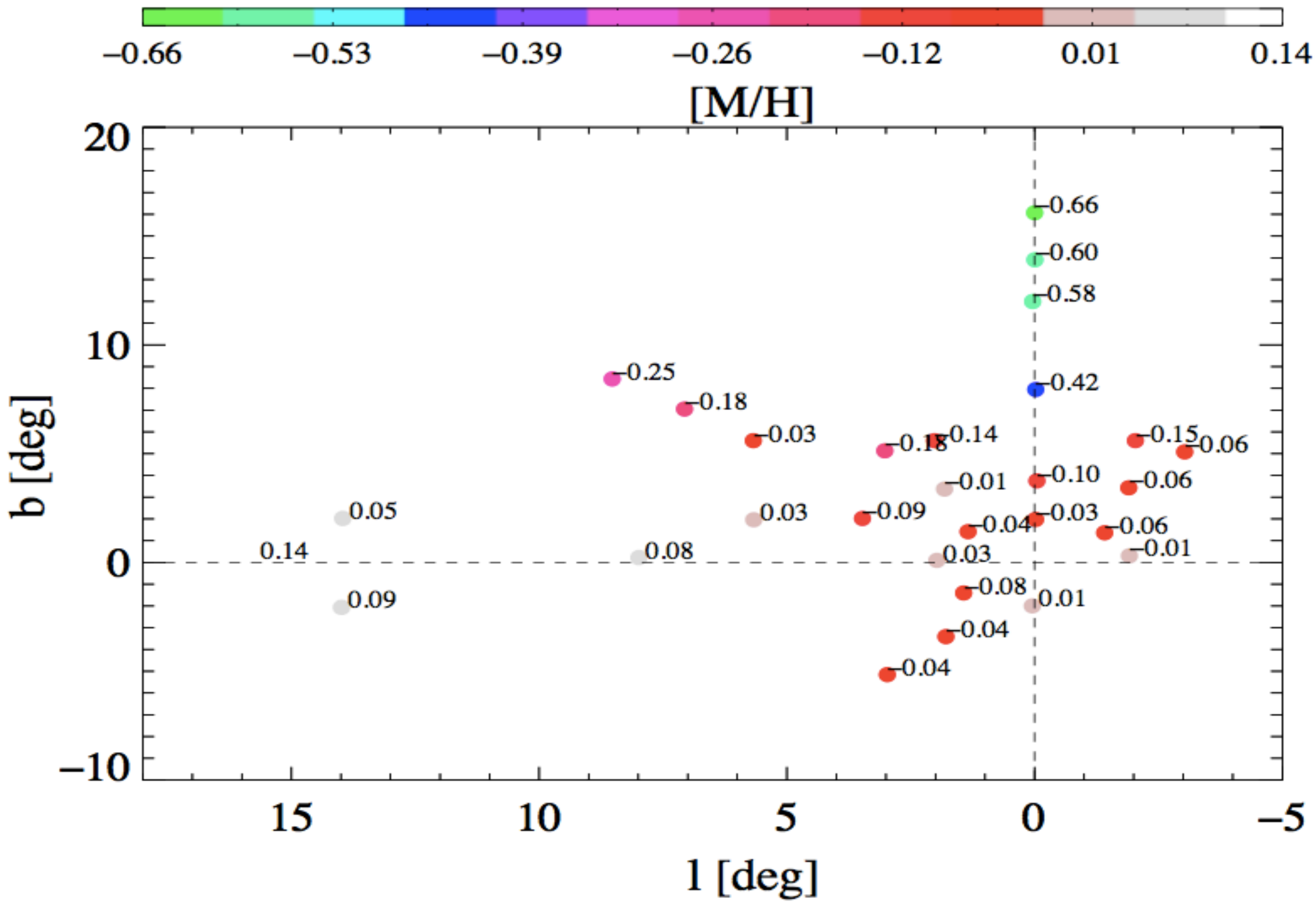
- Metal-poor stars in Galactic bulge (*Garcia-Perez et al. 2013, ApJ, 767, L9*)
- 5 stars with [Fe/H] < ~-1.5 within a few kpc from MW center, from commissioning data only.
- [α/Fe] patterns similar to metal-poor part of disk.





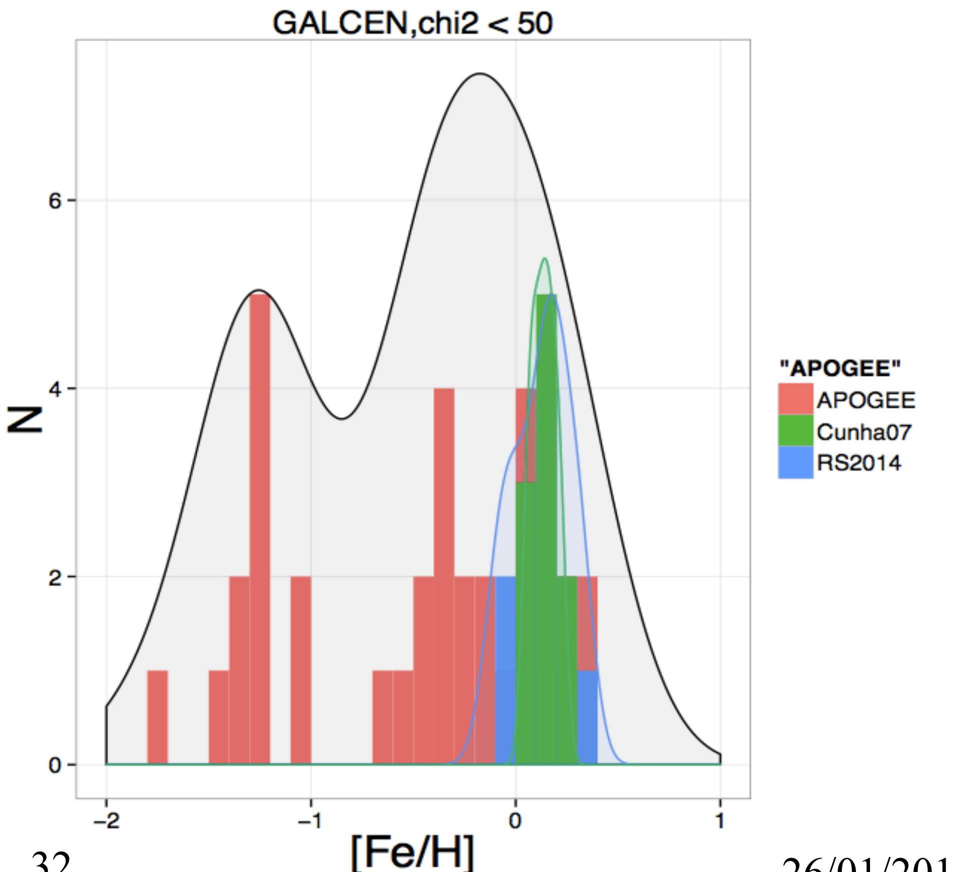
Bulge Metallicities

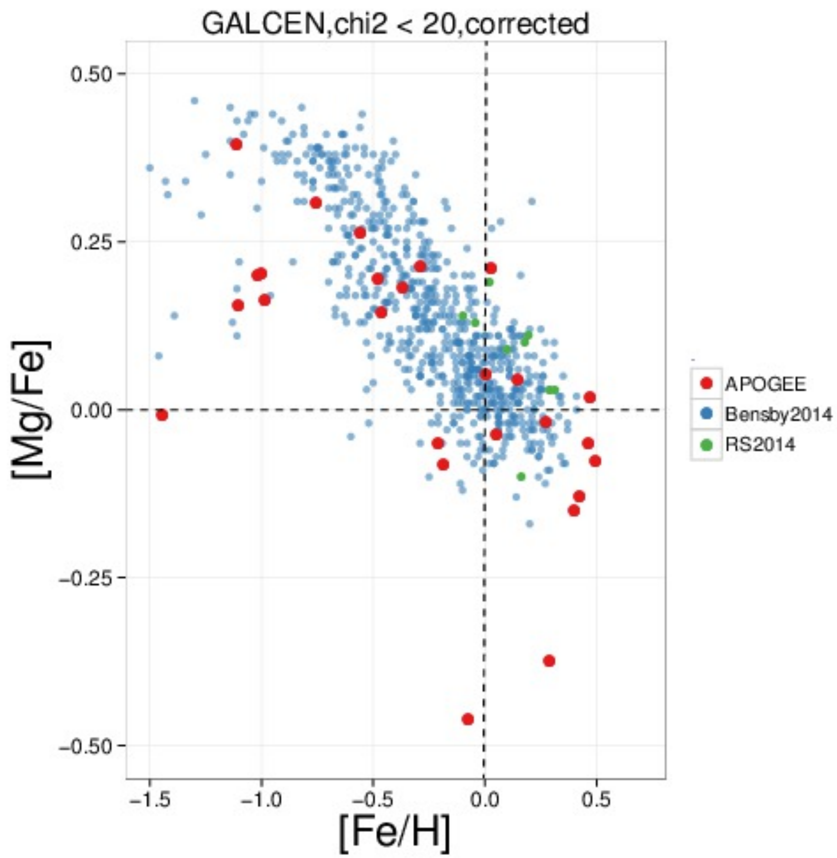
Garcia-Perez et al. 2016



Galactic Center

- Dedicated observations in the Galactic Center *(Schultheis et al. 2015.)*
- Due to high extinction most of the stars are AGBs, supergiants
- Detailed analysis of 30 RGB stars in the galactic Center region

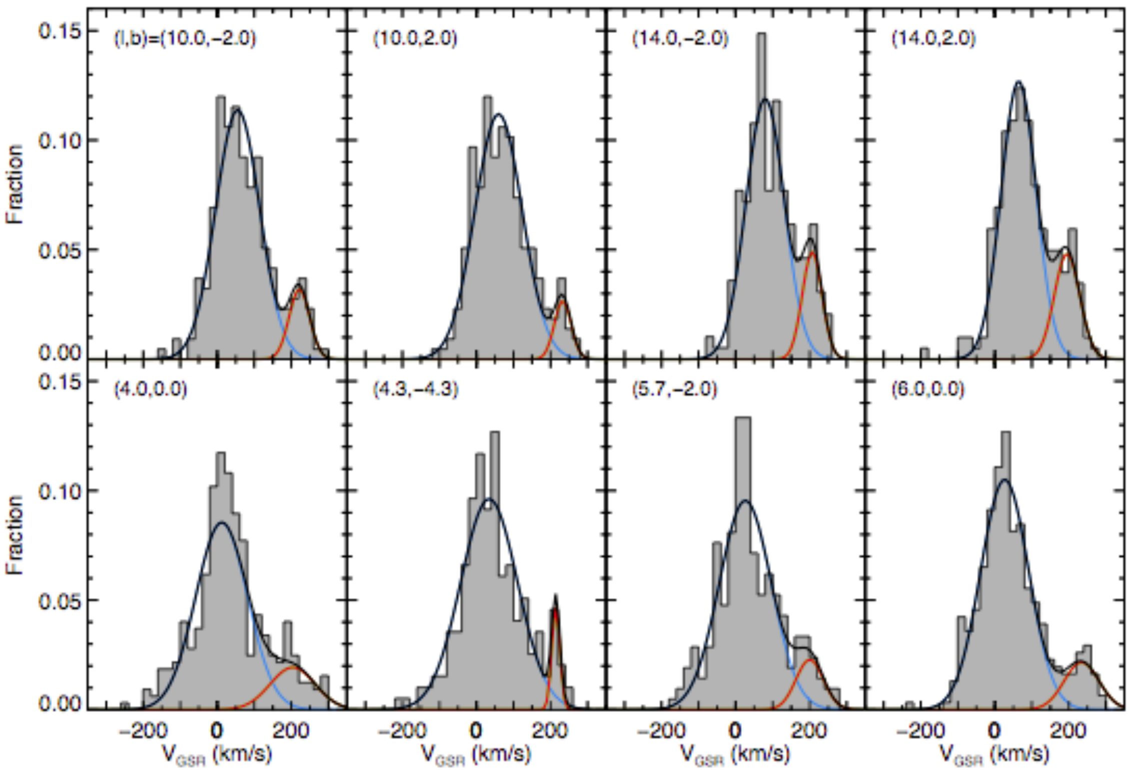


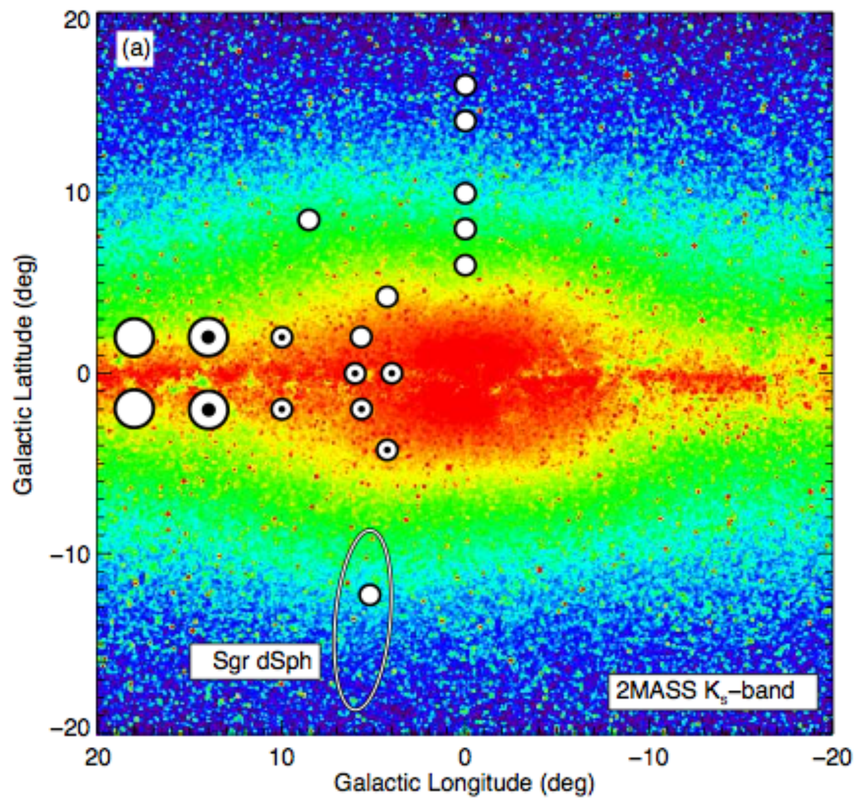


Galactic Dynamics

Nidever et al. (2012, ApJ, 755, L25) – Commissioning data.

- Detection of high velocity stars in Galactic bulge/bar.
- Likely due to dynamical effect of the bar.

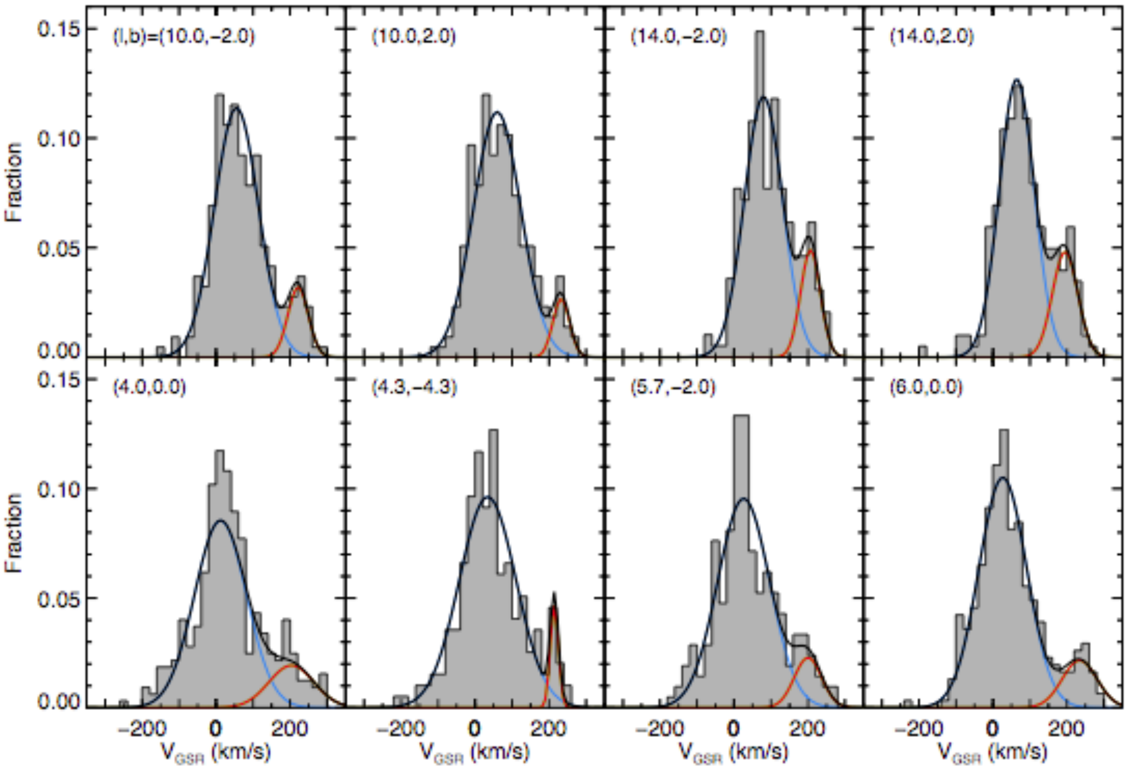


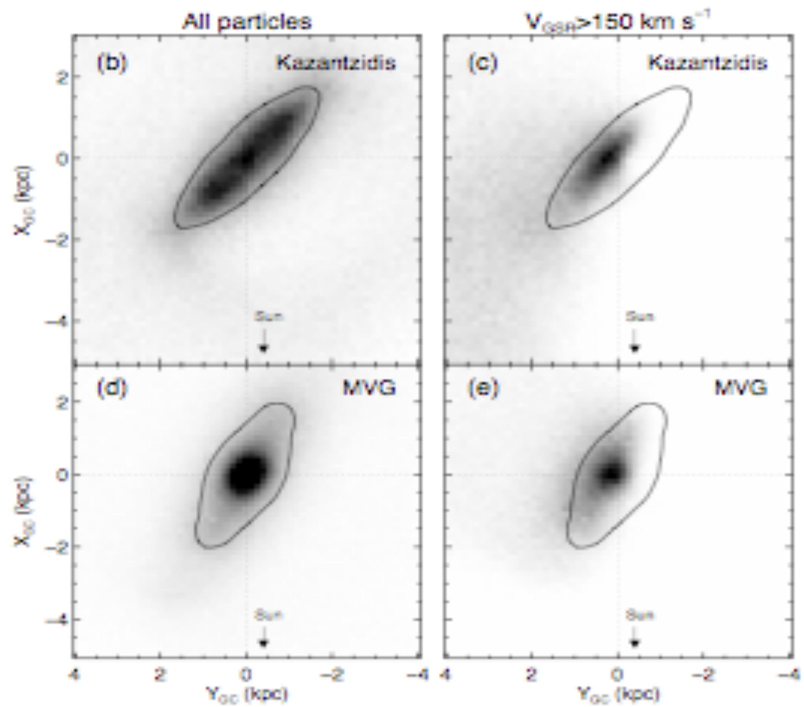


Galactic Dynamics

Nidever et al. (2012, ApJ, 755, L25) – Commissioning data.

- Detection of high velocity stars in Galactic bulge/bar.
- Likely due to dynamical effect of the bar.
- May be a family of stars on leading edge of bar.

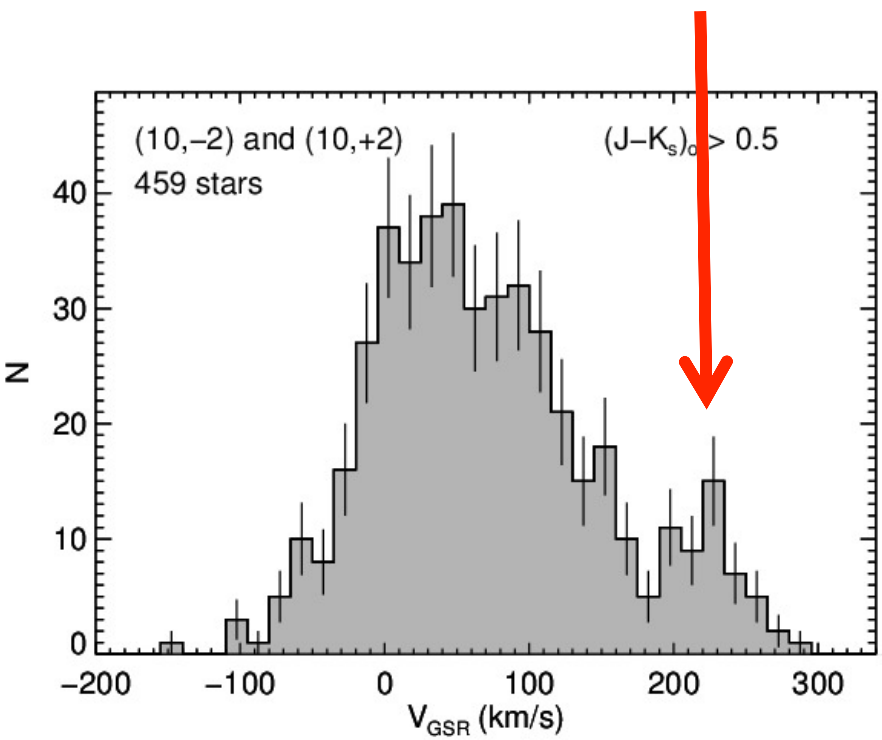


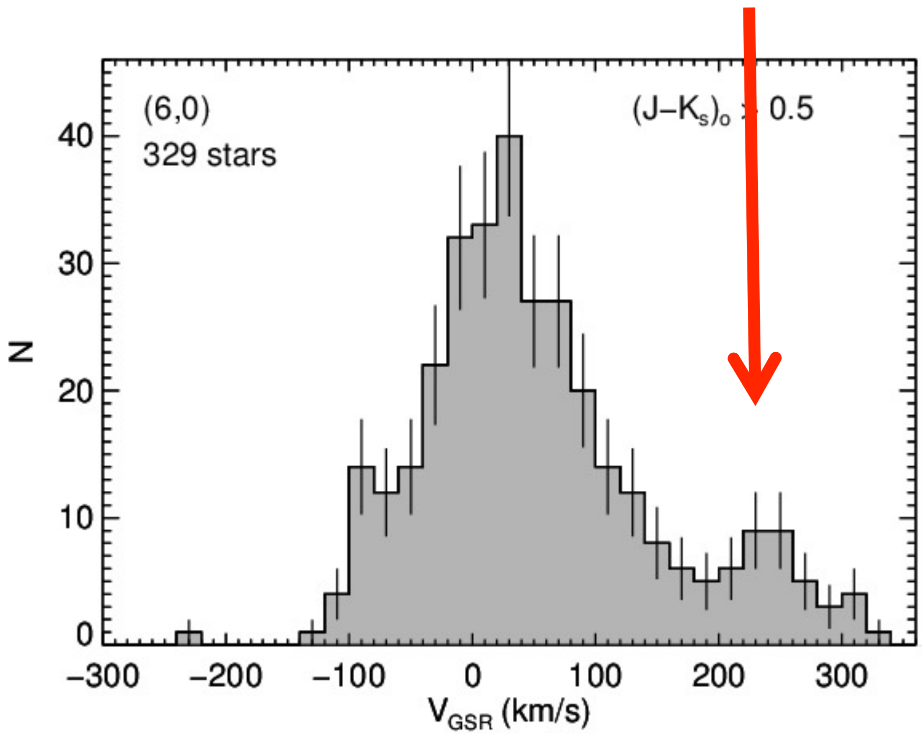


Galactic Dynamics

Nidever et al. (2012, ApJ, 755, L25) – Commissioning data.

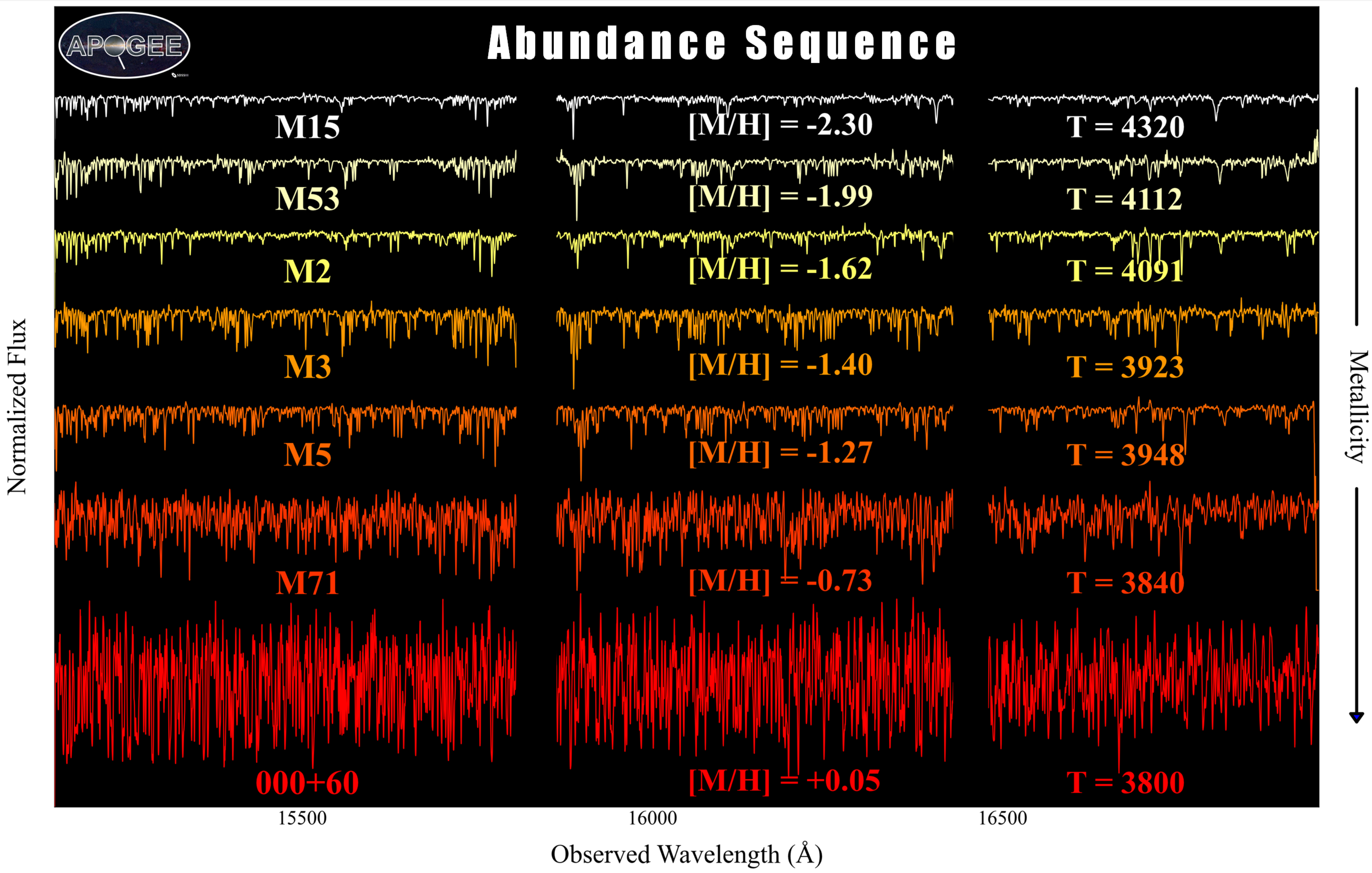
- Detection of high velocity stars in Galactic bulge/bar.
- Verified by later *more and survey quality* data (DR11, DR12).





Globular Cluster Studies

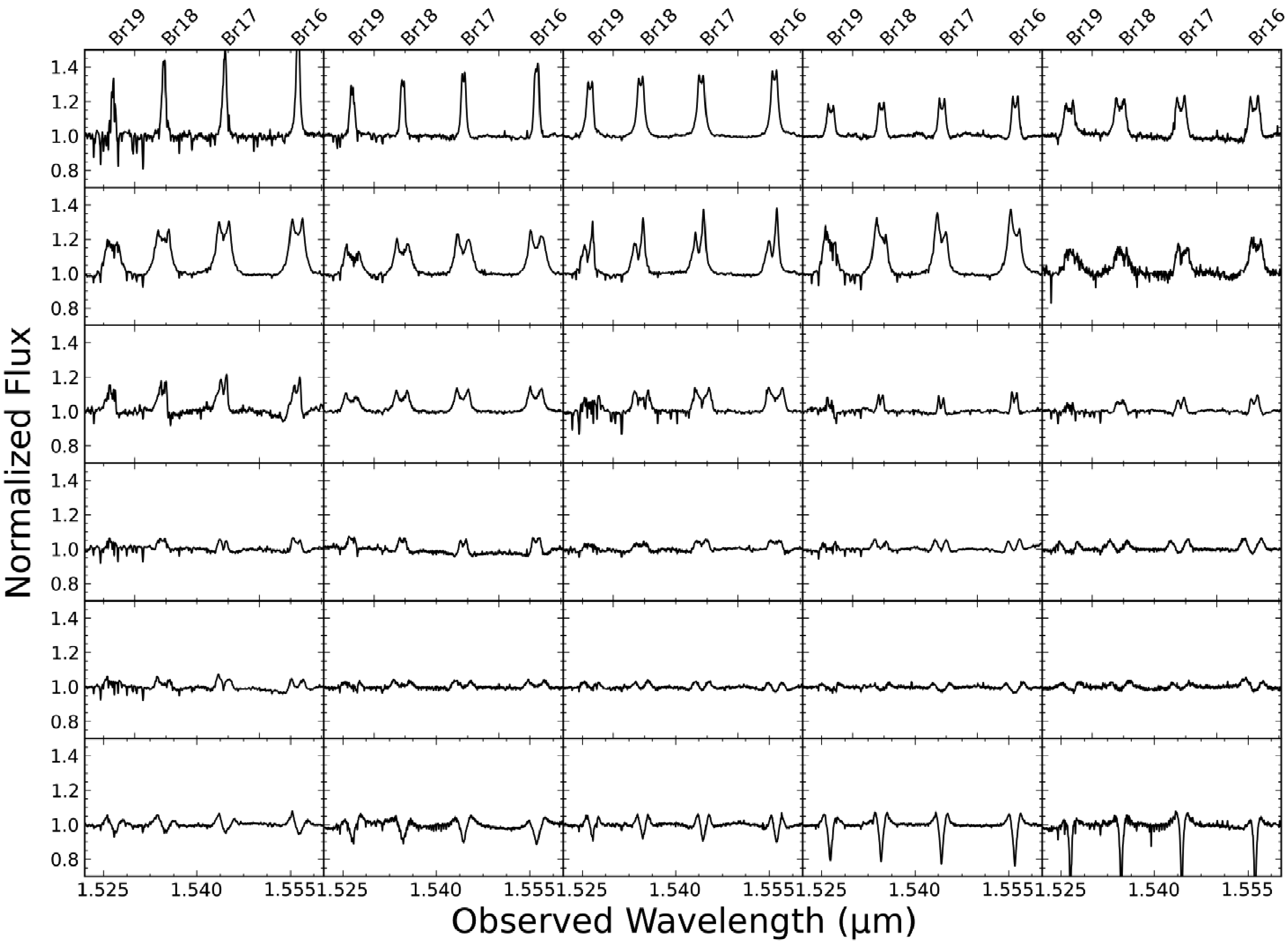
- Globular clusters stars are both science and calibration targets.

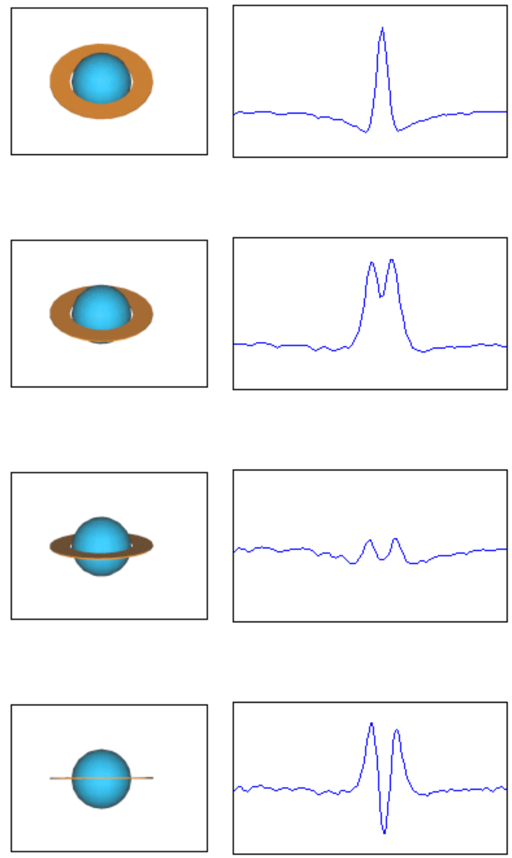


(Image by Drew Chojnowski)

Unanticipated Science
Emission Line Stars in APOGEE

- Be stars found among telluric standards



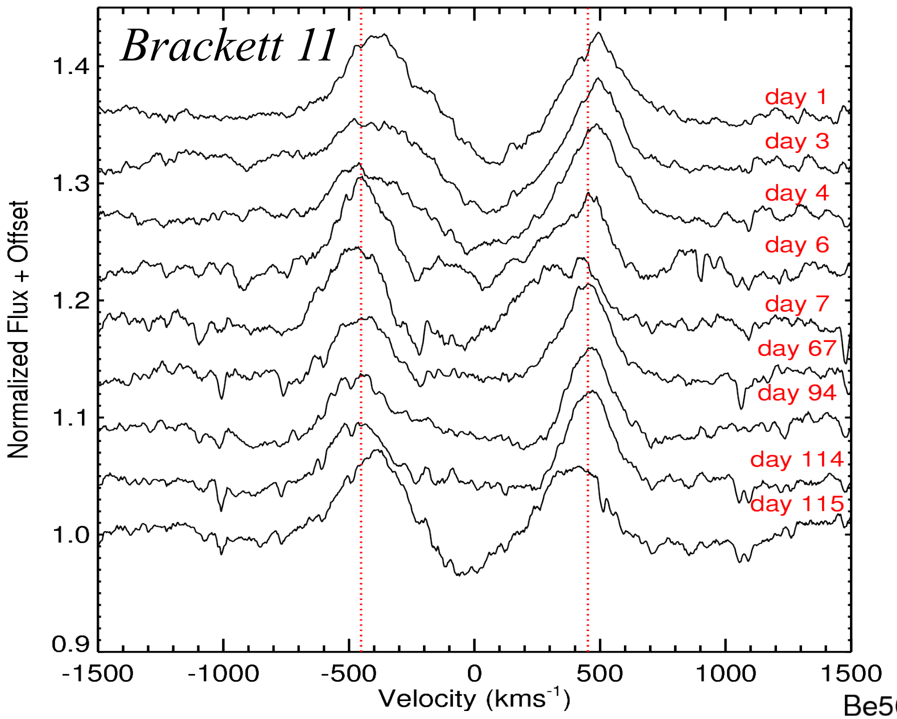


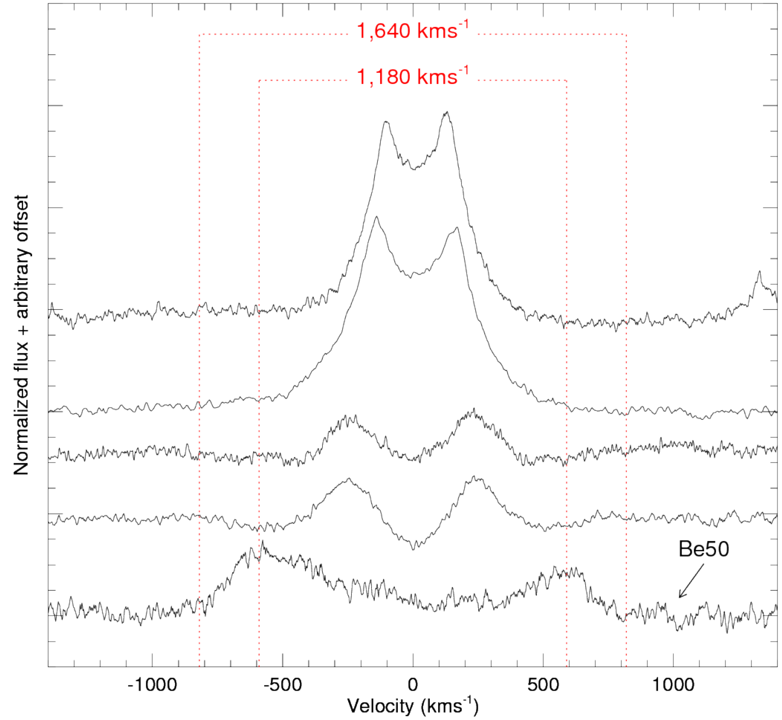
Brackett Line Emission

(Chojnowski et al. 2014, in press)

Unanticipated Science
Emission Line Stars in APOGEE

- Unusual species & spectral variability

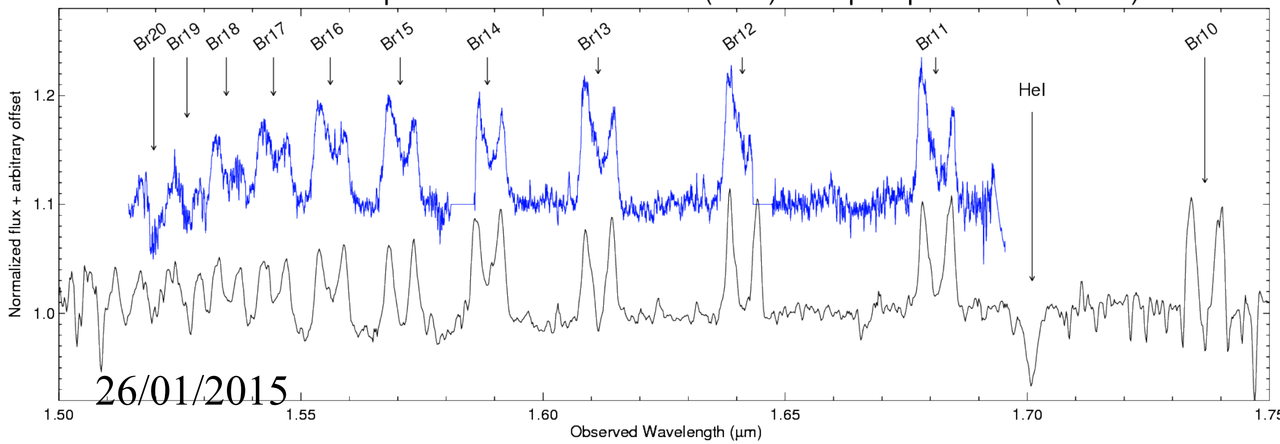




E.g., Rare, highly magnetized, rapidly rotating σ Ori E stars

(Eikenberry et al. 2014, ApJ, 784, L30)

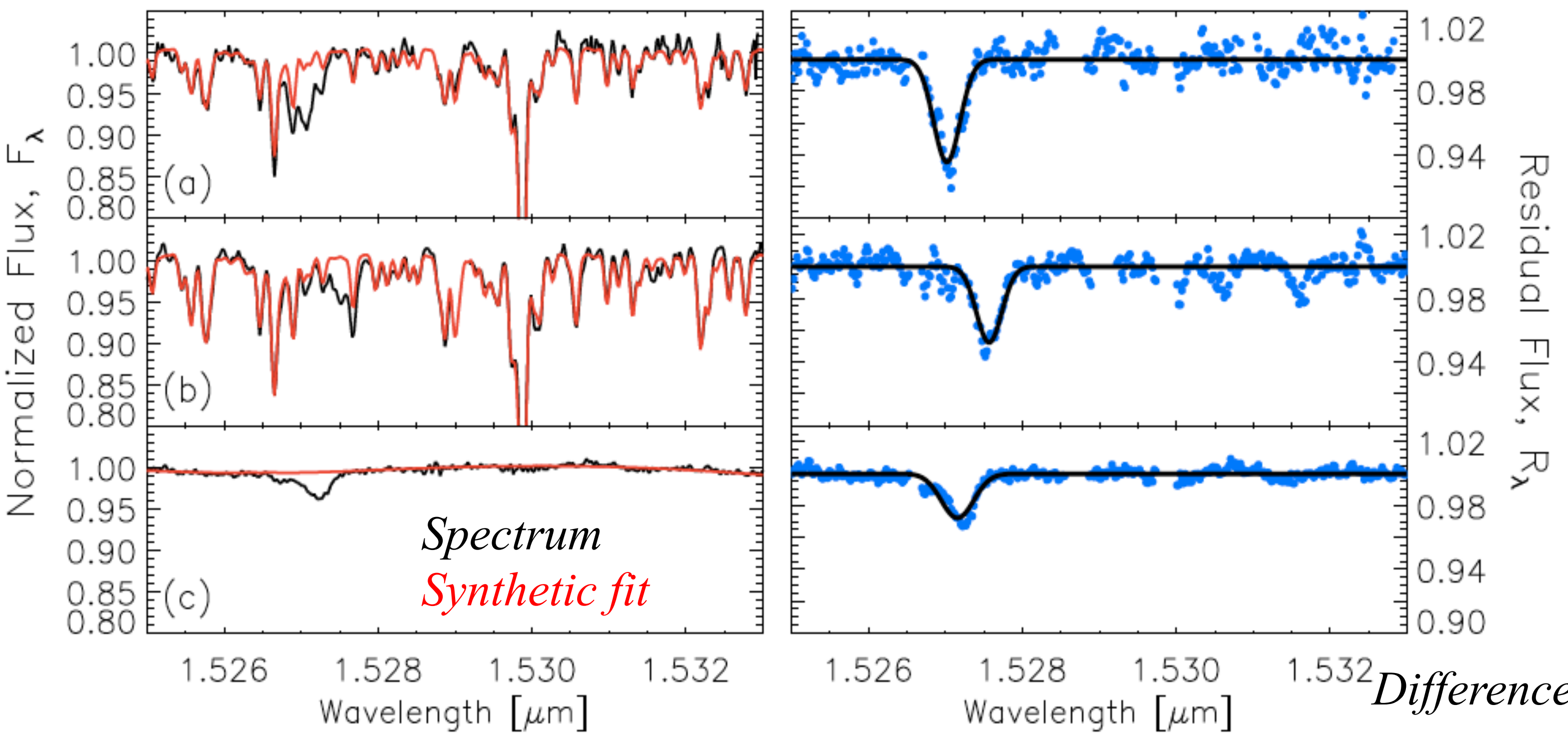
Be50 H-band spectra: APOGEE 9/3/11 (blue) & TripleSpec 9/2/12 (black)



“Bonus” Science: Diffuse Interstellar Bands

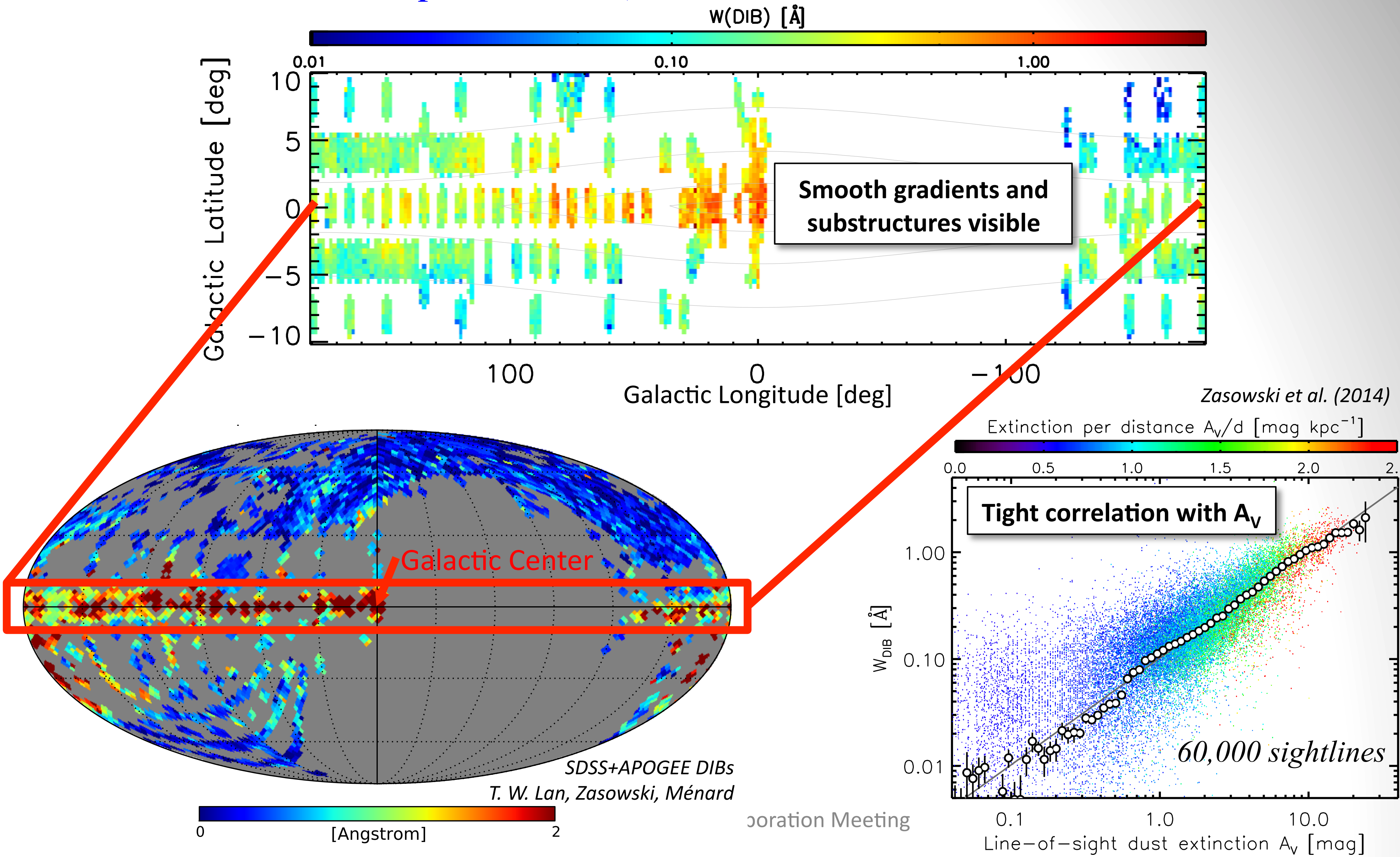
(Zasowski et al. 2015, ApJ, 798, 35)

- Recently identified *H*-band DIBs (Geballe et al. 2011)
- Seen as residuals to APOGEE fits.
- Detected in majority of |b|<10 stars.



“Bonus” Science: Diffuse Interstellar Bands

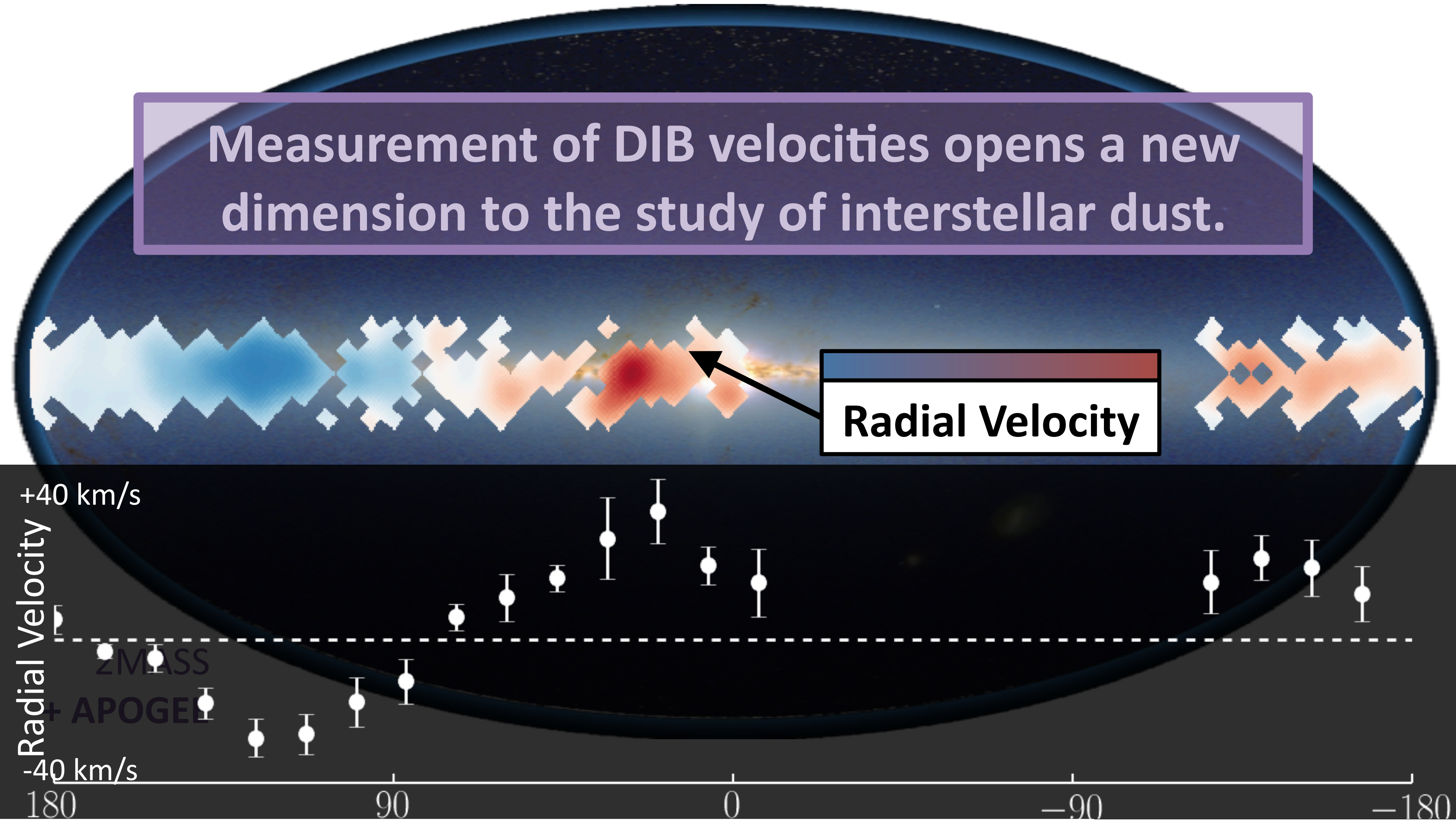
(Zasowski et al. 2015, ApJ, 798, 35)



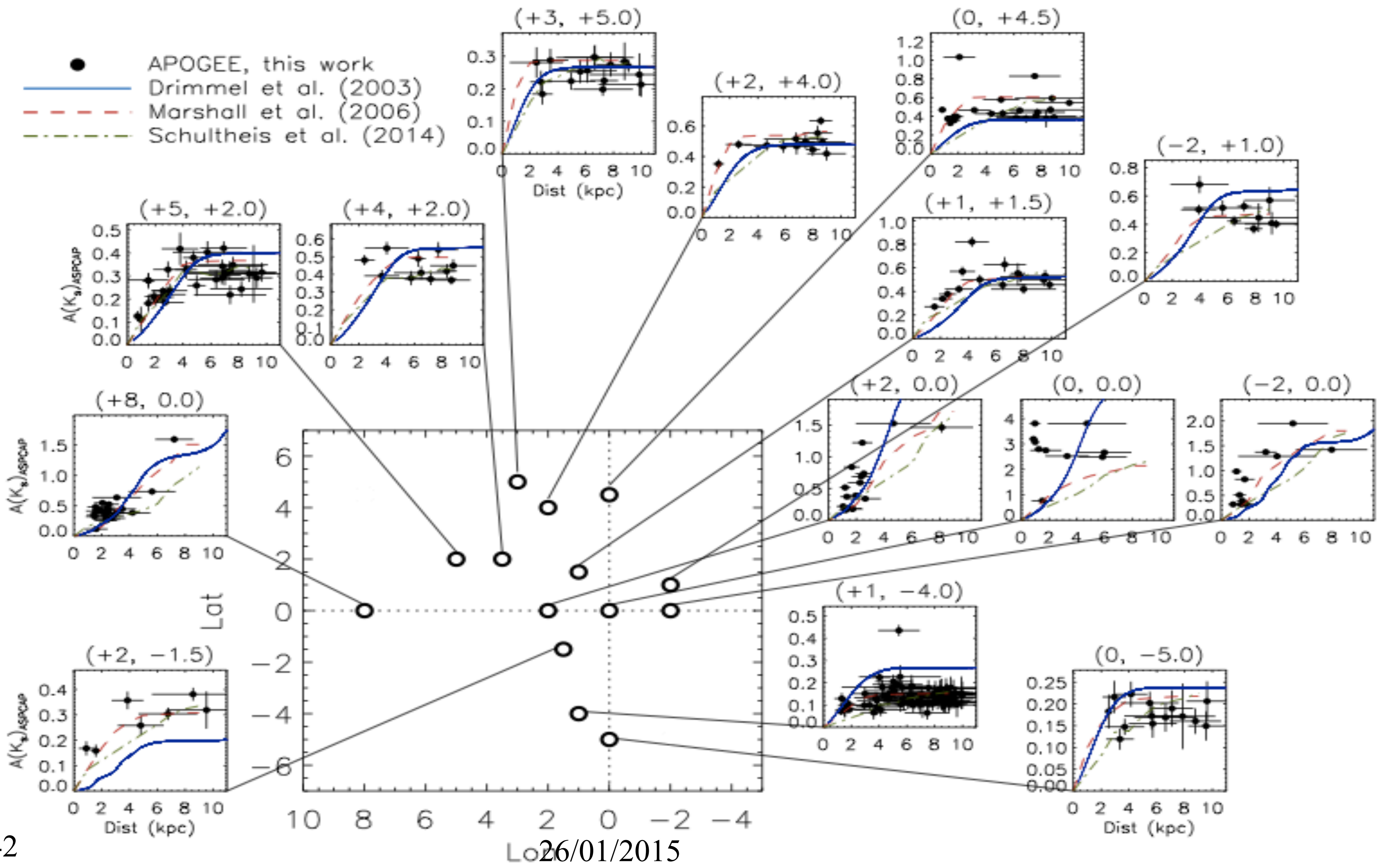
oration Meeting

“Bonus” Science: Diffuse Interstellar Bands

Measurement of DIB velocities opens a new dimension to the study of interstellar dust.



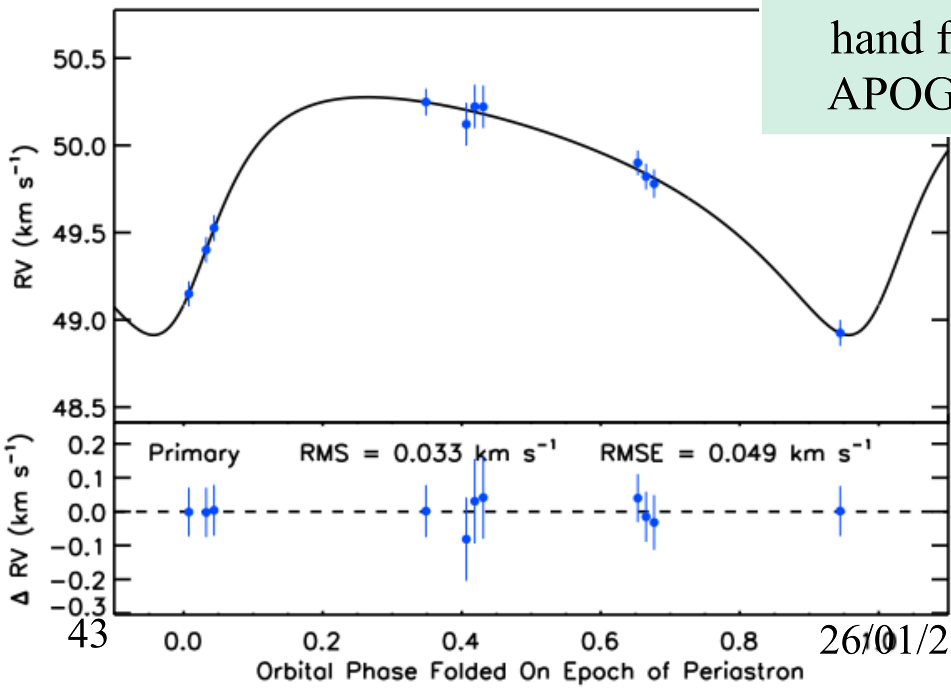
Unanticipated Science: Tracing 3D interstellar extinction



Unexpected Capabilities, New Opportunities: Exoplanets/Brown Dwarfs

- (Re-)Detection of exoplanet around HD114762 (*Nidever et al.*)
  - Originally discovered by Latham et al. (1989).
  - 11 APOGEE visits.
  - TODCOR fit gives RMS = 33 m/s.

source	*K* *(m/s)*	*P* *(days)*	*e*	*Ω* *(deg)*	$M_2 sini$ (M_{jup})
published	616	83.9	0.34	202	11
automated fitting APOGEE data	590	77.9	0.01	176	14
hand fitting of APOGEE data	682	81.7	0.44	221.8	



- One of about 130 planet/brown dwarf candidates flagged in analysis of ~1300 stars with at least 8 APOGEE visits.

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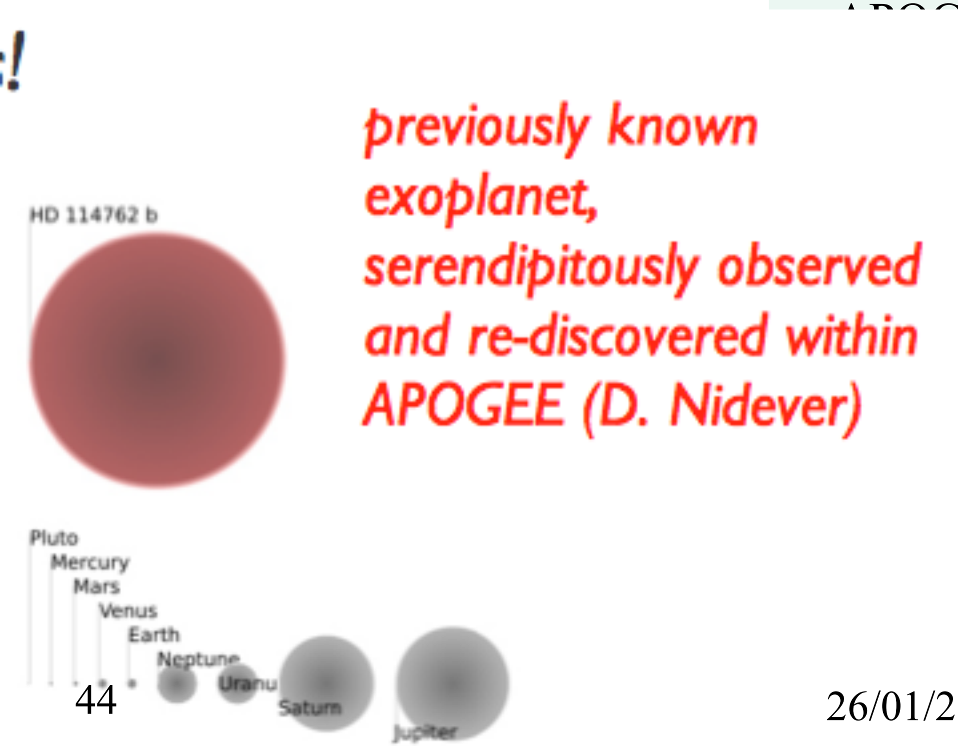

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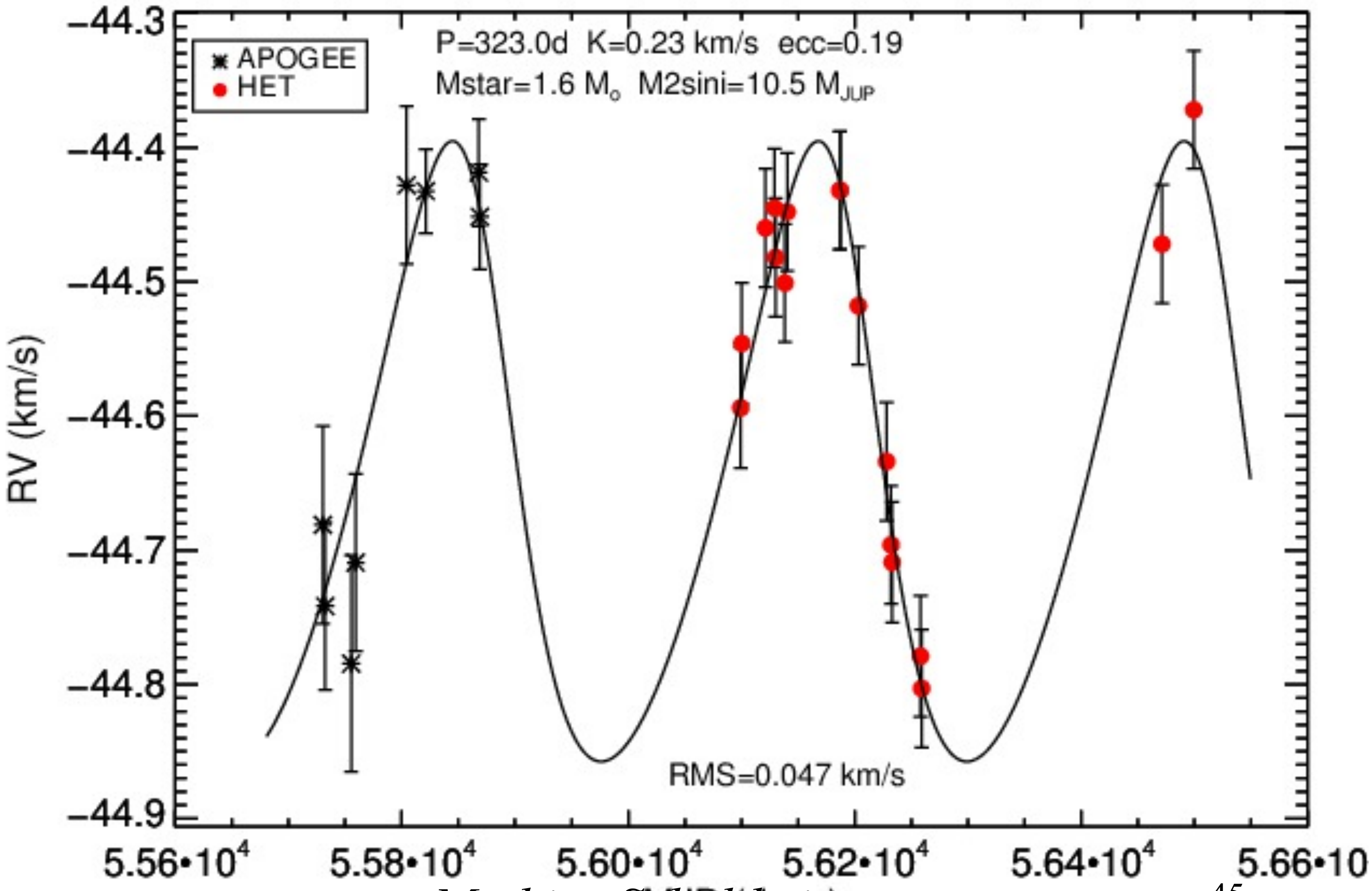
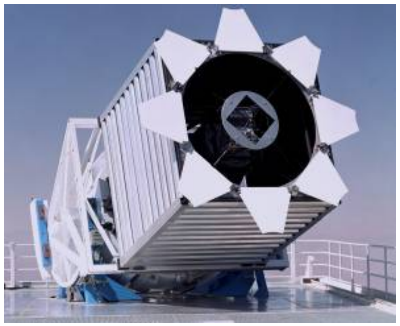


APOGEE^2

SDSS

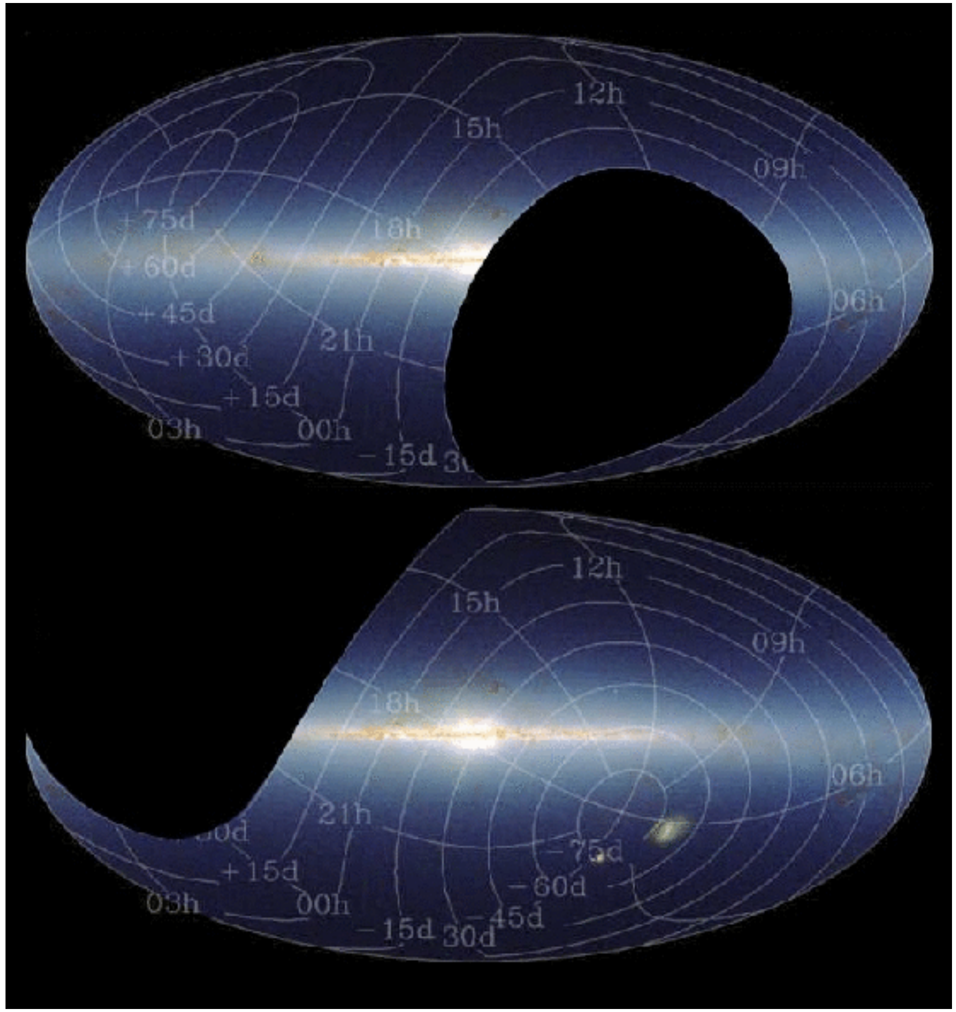
SDSS-IV/ APOGEE-2: 2014-2020
Dual Hemisphere Observations

Apache Point Observatory



Las Campanas Observatory

Sky above 2 airmasses at each site



- Carnegie Observatories collaboration, ≥ 75 nights per year.
- Strong participation from seven Chilean universities.

APOGEE-2 at a Glance

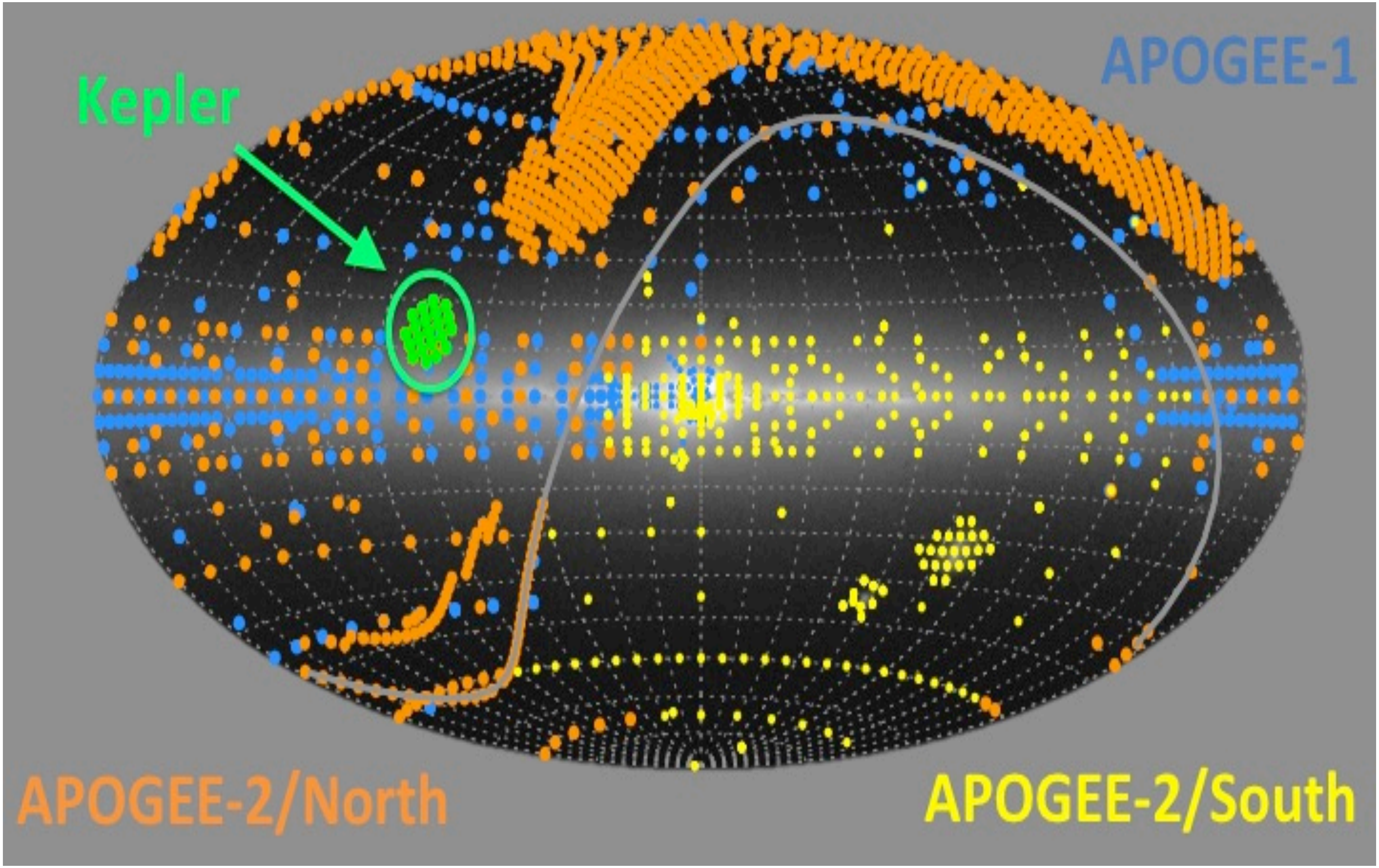
SDSS-IV -- One of three major experiments (w/ eBOSS, MaNGA)

- 5-6 year campaign (compared to 3 years for APOGEE-1).
- *BOTH* bright *and* dark time (75% of time on Sloan 2.5-m).
- *DUAL* spectrographs: Sloan *and* du Pont 2.5-m's.
    - 2nd instrument under construction, aiming for June 2016.
    - Similar instrument performance and survey characteristics.
- APOGEE-2N observations already under way (Sept. 2014).
- APOGEE-2S observations in 2016Q4 (75 nights/year).
- Goal of *half million* 2MASS-selected giant star candidates

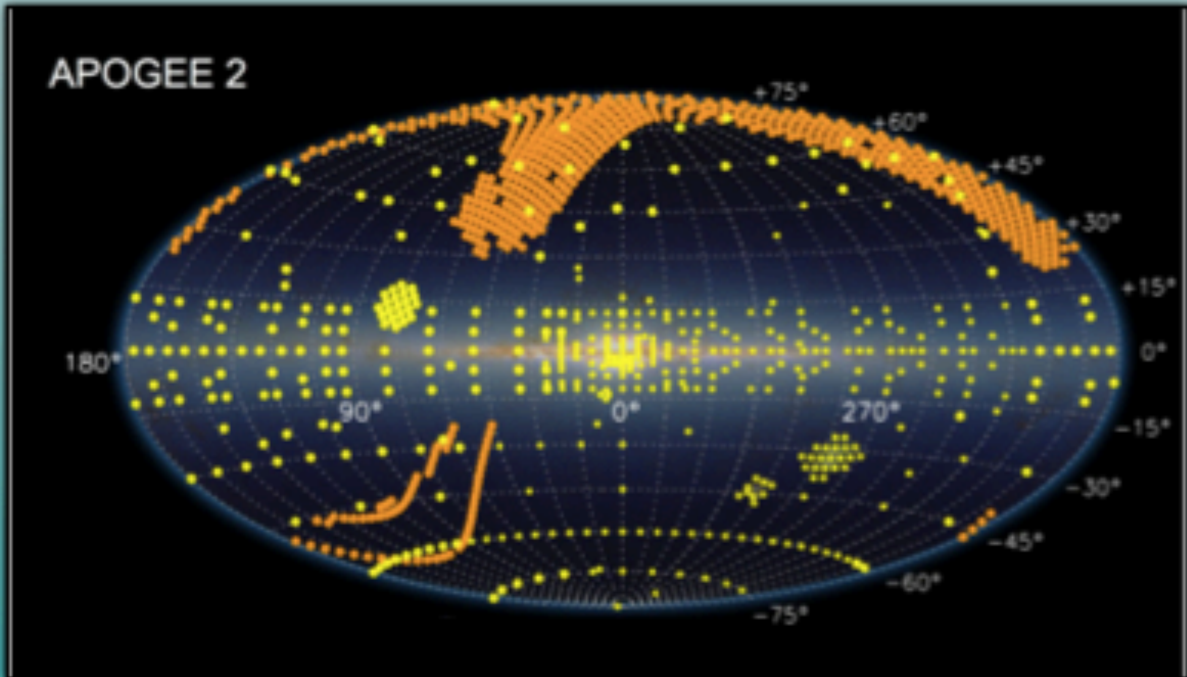
  not only sampling all Galactic populations, but

  probing all parts of the Milky Way (APOGEE-1 + 2)

APOGEE-2 Target Plan



CORE SCIENCE DRIVERS



BULGE

DISK

HALO

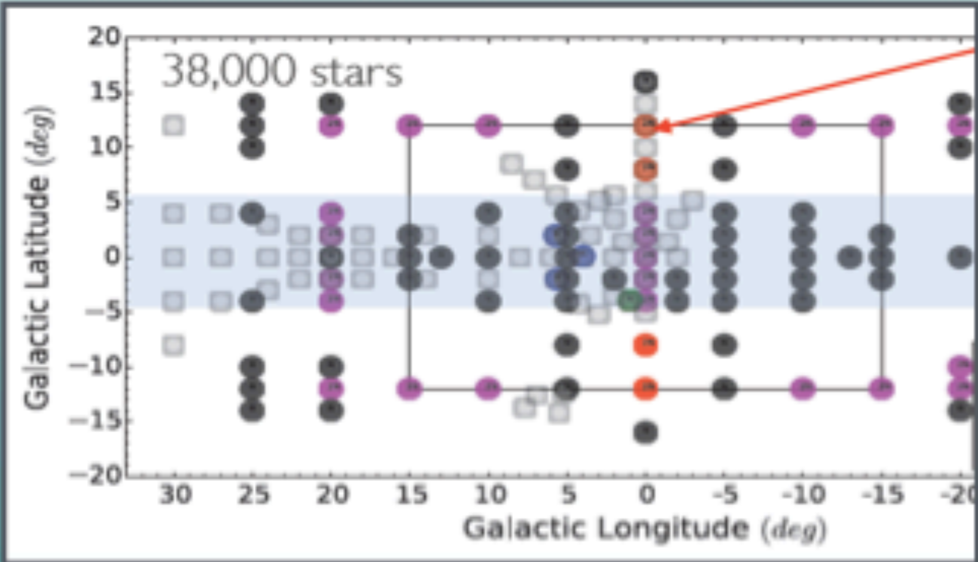
GLOBULAR + OPEN CLUSTERS

APOKASC

SATELLITE GALAXIES

CORE SCIENCE DRIVERS

BULGE



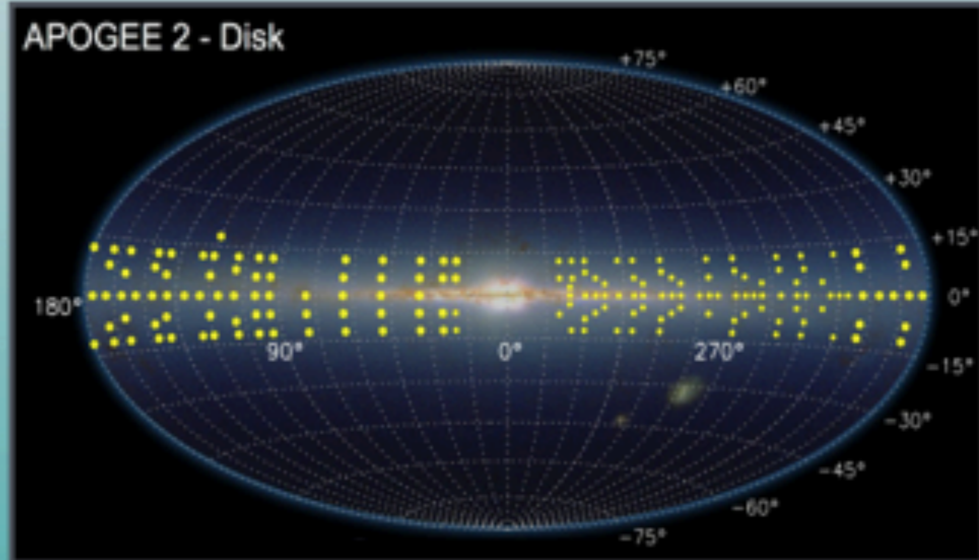
SCIENTIFIC OBJECTIVES:

- Formation mechanism (mergers, accretion, secular)
- X-Shaped Structure
- Origin of metal-deficient population
- Young bulge stars
- Transition regions/interfaces

APOGEE-2 PLANS+ CURRENT STATUS:

- APOGEE-2N Planned Visits: 24
- APOGEE-2S Planned Visits: 286
- Bulge Novel Probes (RC, RRL; test plates)

DISK



SCIENTIFIC OBJECTIVES:

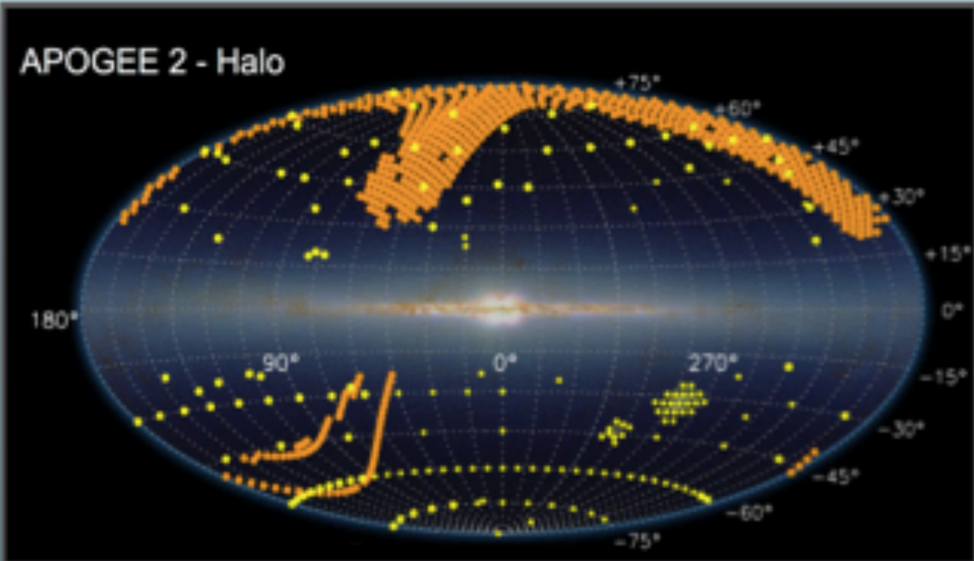
- Spiral Structure
- Axi-symmetric Perturbations (presence of bar)
- Disk-Bulge Interface (bulge formation role)
- Radial Gas Flows and Radial Migration
- Accreted Substructure
- Outer Disk (Warp, Monoceros Stream)

APOGEE-2 PLANS+ CURRENT STATUS:

- APOGEE-2N Planned Visits: 627
- APOGEE-2S Planned Visits: 372
- Two Color Cuts

CORE SCIENCE DRIVERS

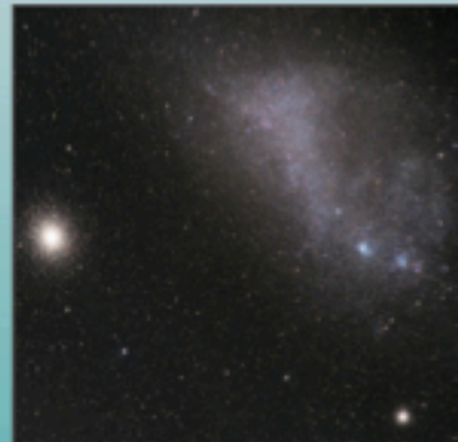
HALO



SCIENTIFIC OBJECTIVES:
- Formation Mechanism (in situ, early mergers, tidal stripping,...)
- Galactocentric Distance Variation (inner v. outer)
- Resident Stellar Population Comparison
- Streams (GD-1, Pal5, Orphan, TriAnd, Sgr)

APOGEE-2 PLANS + CURRENT STATUS:
- APOGEE-2N Planned Visits: 990 (w/o MaNGA)
- APOGEE-2S Planned Visits: 108
- 24-hr Deep Fields
- Bluer color cut

SATELLITE GALAXIES

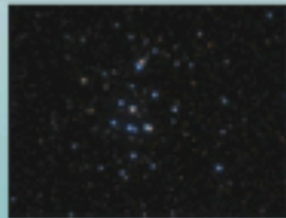


SCIENTIFIC OBJECTIVES:
- Star Formation History (density, dark matter fraction)
- Chemical Evolution (density, dark matter fraction, SFR)
- Hierarchical Formation (galactic morphological types)
- Binarity fraction
- Disk and bar comparisons (MC)
- Tidal disruption (Sgr)

APOGEE-2 PLANS + CURRENT STATUS:
- APOGEE-2N Planned Visits: 72
- APOGEE-2S Planned Visits: 339
- 6 dSph (Ursa Minor, Sculptor, Sextans, Bootes I, Draco, Carina)
- UMi Test Plates

CORE SCIENCE DRIVERS

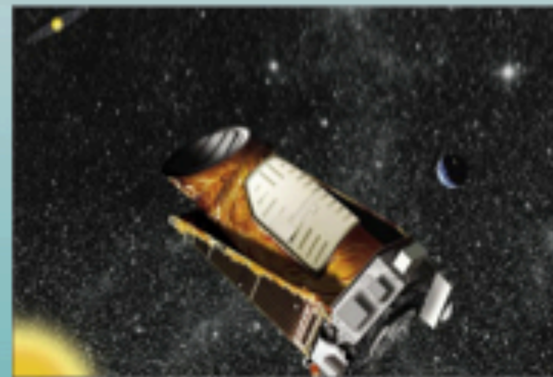
GLOBULAR+OPEN CLUSTERS


SCIENTIFIC OBJECTIVES:
- Calibration (internal, inter-survey, external survey)
- Star Formation History
- Galactic Chemical Evolution
- Stellar Evolutionary Processes (dredge-up, nucleosynthesis)
- Binarity
- Internal Cluster Dynamics
- Multiple Stellar Generations (**GC**)
- Radial Migration, Disk Resonances+Structure (**OC**)

APOGEE-2 PLANS + CURRENT STATUS:
- APOGEE-2N Planned Visits: 48 (GC), 15 (OC;*dedicated)
- APOGEE-2S Planned Visits: 133 (GC), 25 (OC;*dedicated)
- **GC** Targets: 5 North; 15 South
- **OC** Targets: 120 North; 150 South

APOKASC



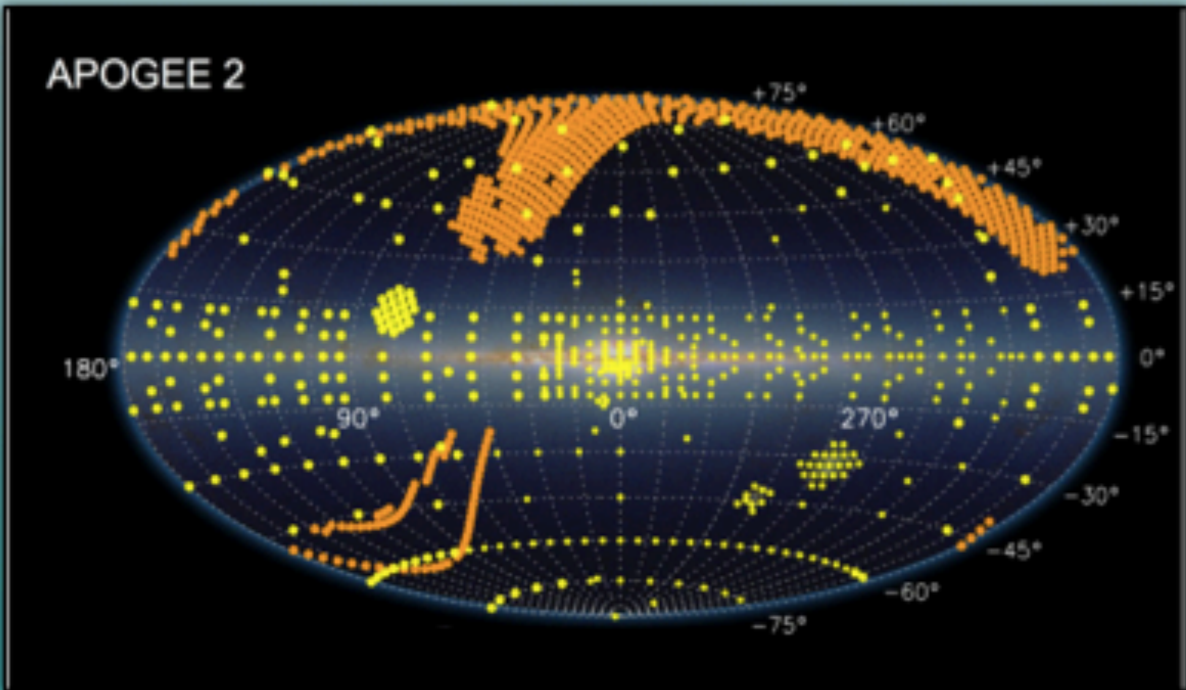
Kepler

SCIENTIFIC OBJECTIVES:
- Age Determinations Via Asteroseismology (pulsation) and Gyrochronology (spin-down)
- Rotation-Mass-Absolute Age (dwarfs)
- Mass-composition-Absolute Age (giants)
- Age-Metallicity Relations
- Stellar Photospheric Model/Theory
- Stellar Interior Models
- Stellar Pulsation Theory
- Evolutionary State Determinations (RGB/RC)
- Extrasolar Planet Host Characterization

APOGEE-2 PLANS + CURRENT STATUS:
- APOGEE-2N Planned Visits: 56

ANCILLARY SCIENCE DRIVERS

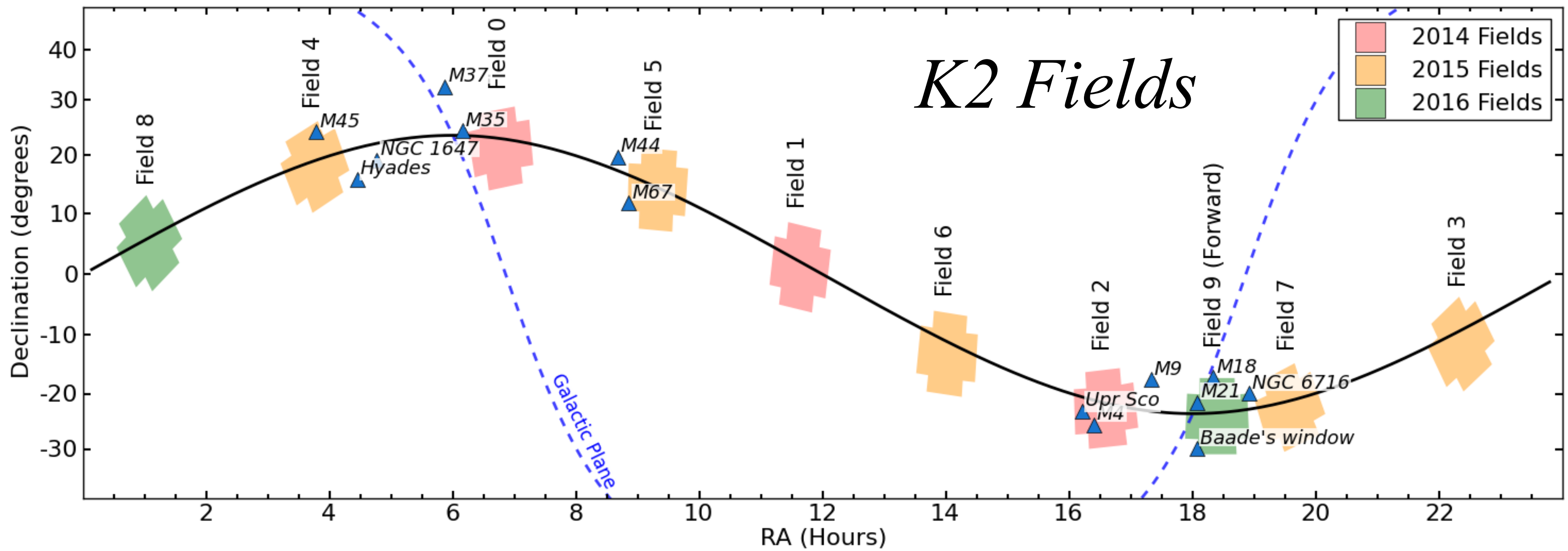
NON APOKASC-FIELD PROPOSALS



- Deep Disk
- Calibration+Reference Objects
- Extinction
- QSO
- Young Moving Groups
- AGB Stars
- Cepheid Stars
- W3/4/5 Star Forming Regions
- Hot Emission Line Stars
- Evolved Massive Stars

APOGEE-Kepler Asteroseismology Collaboration (APOKASC)

- Some challenges moving forward:
  - New opportunity of more distant giants in Kepler field (increase radial coverage of disk).
  - How to capitalize on growing/future samples of extremely valuable stars with asteroseismological/gyrochronological/flicker ages?
  - Anticipate Gaia database in optimal way.



APOGEE 2

SDSS

What did we learn from…

- ASPCAP pipeline took several years –still problems (e.g. Ti, some heavy elements, metal rich stars)… → **a lot of effort and extensive testing is still needed !!**
- **Calibration!** Too few calibration stars in general. For validation we need to cover a larger fraction of stars in Teff, logg, [Fe/H] space.
- In general very few stars in common between **APOGEE, GES, ARGOS → we need to improve that!**
- APOGEE aims in getting high S/N of at least 100. Some tendancy to go to lower S/N ratio… -while this might work for some elements it is not true **for all elements**!
- Target selection should be **as simple as possible** (Colour,mag cuts)