Galactic Infrared Spectroscopy with APOGEE

SDSS

credit: Gail Zasowski

Jo Bovy (Institute for Advanced Study; Bahcall fellow)
w/ many contributions from the APOGEE team

OVERVIEW

- APOGEE Overview
- APOGEE Science
- APOGEE & WFIRST-AFTA

The APOGEE "Heavy Lifting" Team

The highly-condensed version:

- **PI**: Steve Majewski (UVa)
- **Survey Scientist**: Ricardo Schiavon (Gemini Obs.)
- **Project Manager**: Fred Hearty (UVa)
- **Instrument Scientist**: John Wilson (UVa)
- **Instrument Group Leader**: Mike Skrutskie (UVa)
- **Science Working Group Chair:** Jo Bovy (IAS)

Team meeting, Jan 2012 @ TCU, Fort Worth, TX

- **Data Reduction & Ops S/W**: Jon Holtzman (NMSU), Adam Burton (UVa), Peter Frinchaboy (TCU), David Nidever (UMich)
- **Stellar Params & Abundances**: Carlos Allende Prieto, Szabolcs Meszaros (IAC), Ana Garcia Perez (UVa)
- **Field Selection**: Peter Frinchaboy (TCU), Jennifer Johnson (OSU)
- **Target Selection**: Gail Zasowski, Jennifer Johnson (OSU), Drew Chojnowski (UVa), Peter Frinchaboy (TCU)
- **Plate Design**: Drew Chojnowski (UVa), Gail Zasowski (OSU), Mike Blanton, Demitri Muna (NYU)
- **Lab Data**: Matthew Shetrone (HET), James Lawler (UW), Dmitry Bizyaev (APO)
- **Target Selection Modeling**: Helio Rocha Pinto (U. Rio), Leo Girardi (Padua), Joleen Carlberg (DTM), Annie Robin (Besançon)

- **Fibers/Infrastructure**: UVa IR Lab, Jim Gunn (Princeton)
- **Detector Assembly**: U. Arizona
- **Electronics & Control S/W**: Matt Nelson (UVa), Stephane Beland (UC), Craig Loomis (Princeton)
- **Integration & Testing**: Paul Maseman (Arizona), UVa IR Lab
- **FFP Implementation**: Suvrath Mahadevan, Scott Fleming (PSU), John Wilson, Fred Hearty (UVa)

Slide from Gail Zasowski

APOGEE OVERVIEW

- One of four spectroscopic surveys conducted on the wide-field SDSS 2.5 m telescope at APO, NM over 2008-2014: APOGEE bright time '11-'14

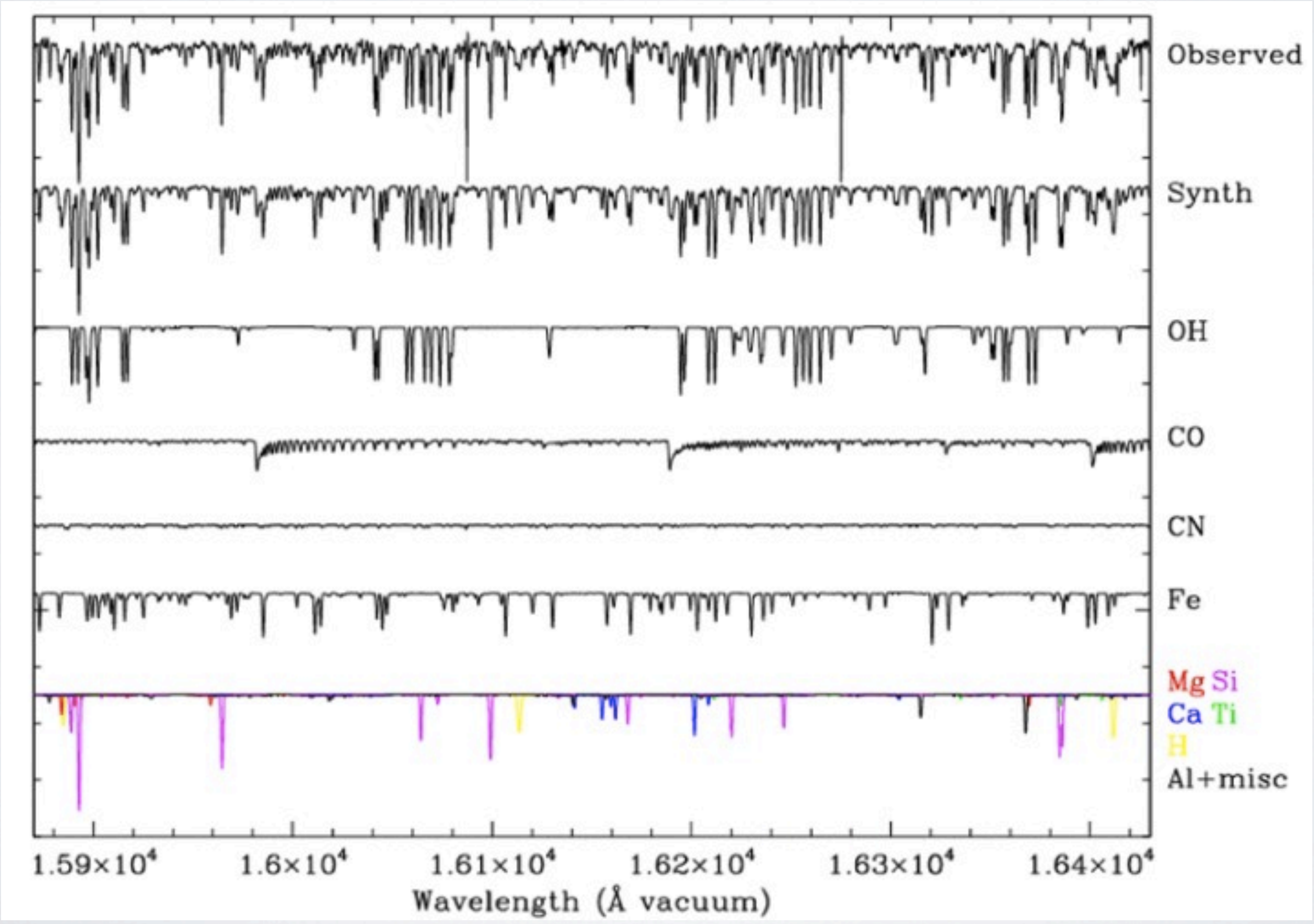
- Continuing for another 6 years (+second instrument on du Pont telescope at LCO Chile) as APOGEE-2

- New instrument for SDSS: 300-fiber, R=~22,500, cryogenic spectrograph operating in the H-band (1.51-1.69**μ**m)

- First high-resolution, high-SNR (SNR ~140 / res. element) instrument at APO 2.5 m

APOGEE HIGH-RESOLUTION SPECTROSCOPY

- H-band chosen because it contains useful lines from ~15 elements (C,N,O,Mg,Si,S,Ca,Ti,V,Mn,Fe,Ni,Na,K,Al) → goal: 0.1 dex precision in each one of these



APOGEE SPECTROGRAPH

- One of the first fiber-fed, multi-object high-resolution spectrographs in the near-infrared

- Fibers: run ~40m from the SDSS 2.5m telescope to the APOGEE instrument in separate building; 300 fibers connected in one step through 'gang-connector' at the telescope and fed into cryostat with vacuum-sealed feed-throughs

- Light dispersed using a mosaic volume-phase grating (first deployed cryogenic VPH in astronomy)

- Detector: 3 2048x2048 HgCdTe H2RG detector arrays

- Wavelength range: At least from K I (1.51631μm) to Al I (1.67634μm); purposefully undersampled at blue end to allow broad wavelength range and dithered in wavelength direction

APOGEE SCIENCE GOALS

- Homogeneous chemical mapping of major components of the Milky Way with large number of elements from different groups: Bulge, Disk, & Halo

- Fine-grained Galactic dynamics: determine axisymmetric potential, deviations from axisymmetry

- Study internal structure of open and globular clusters

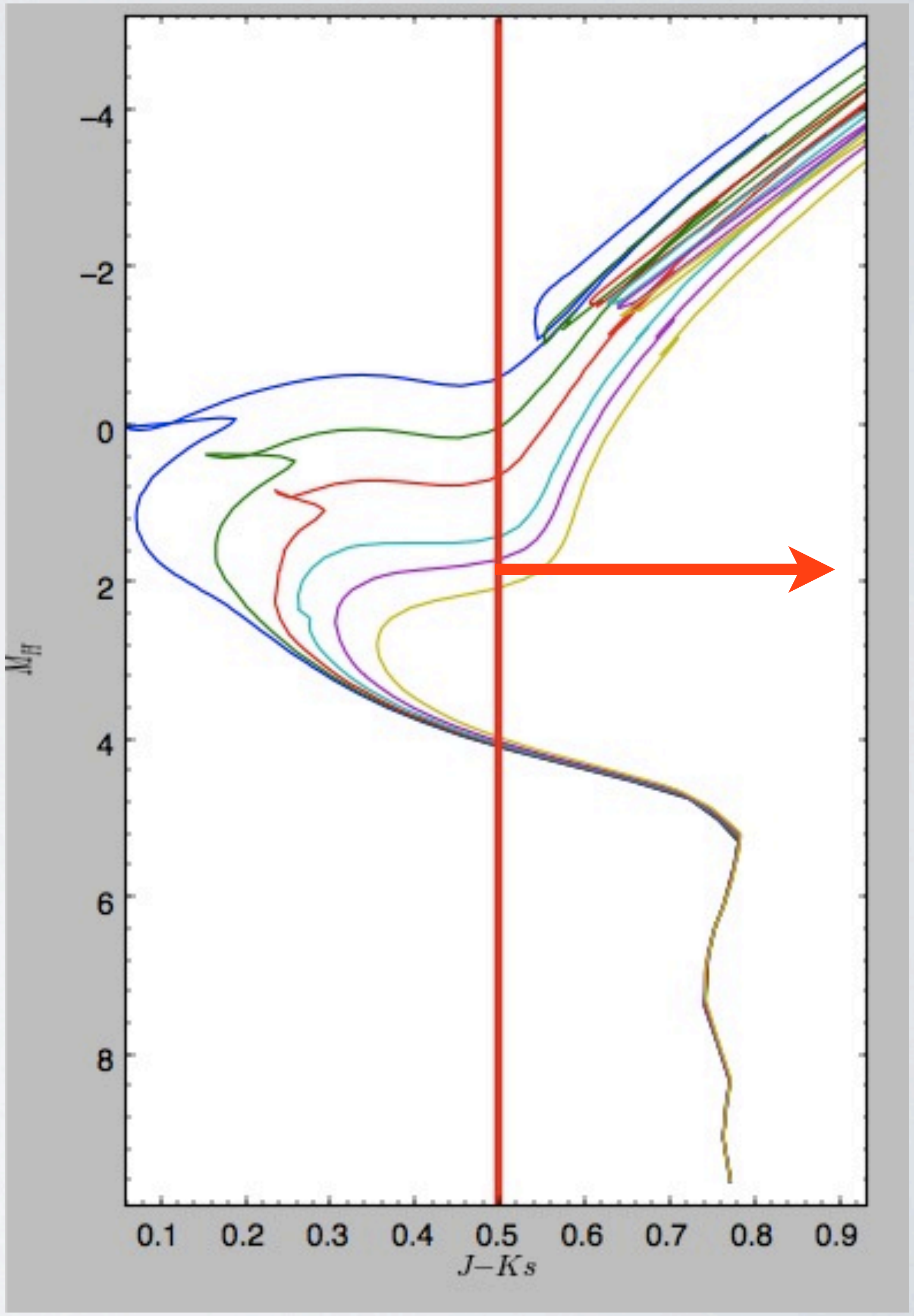
- Stellar physics through combination of spectroscopy and asteroseismology

- Ancillary science on a variety of topics

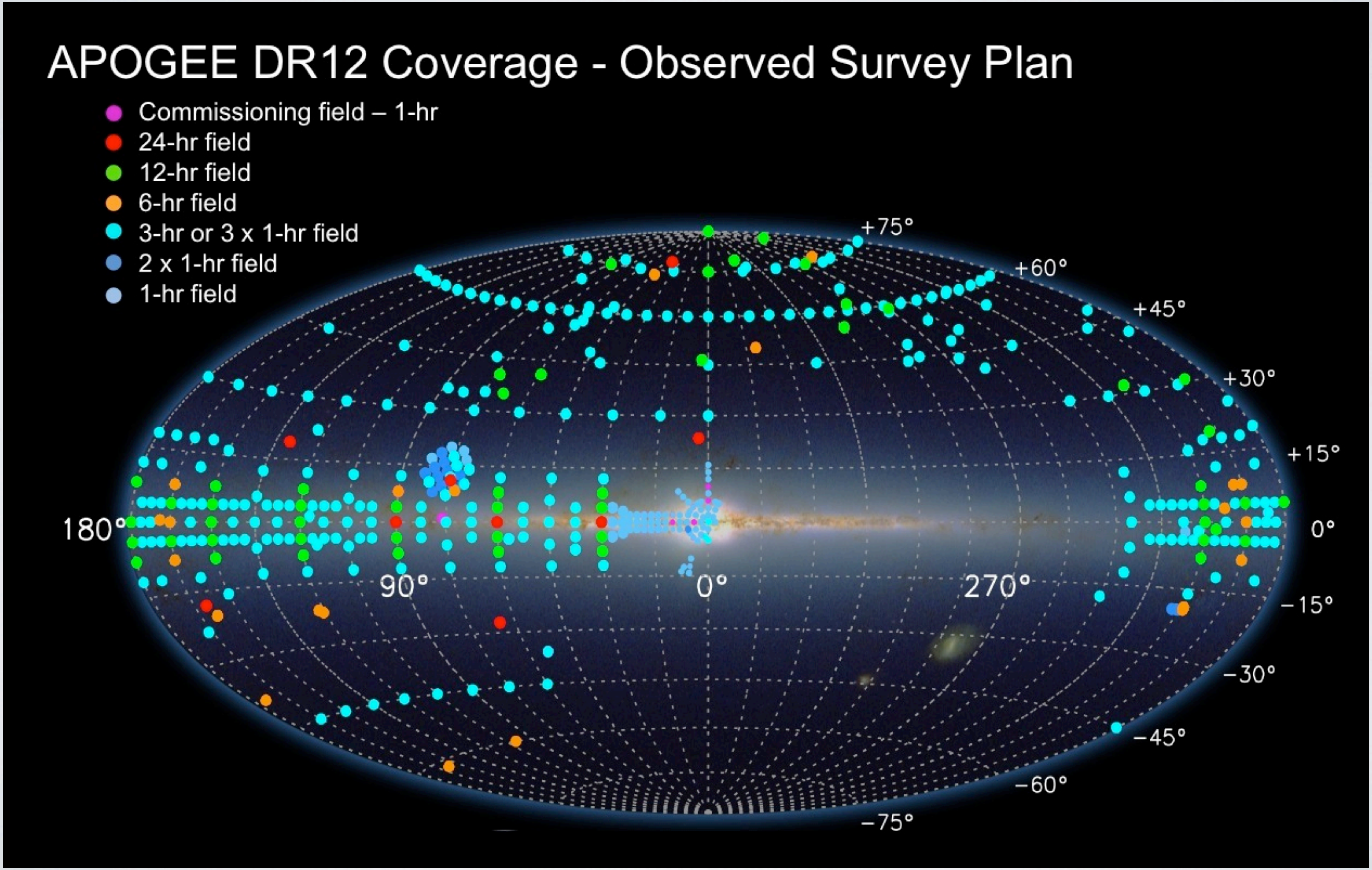
- and more

APOGEE TARGET SELECTION

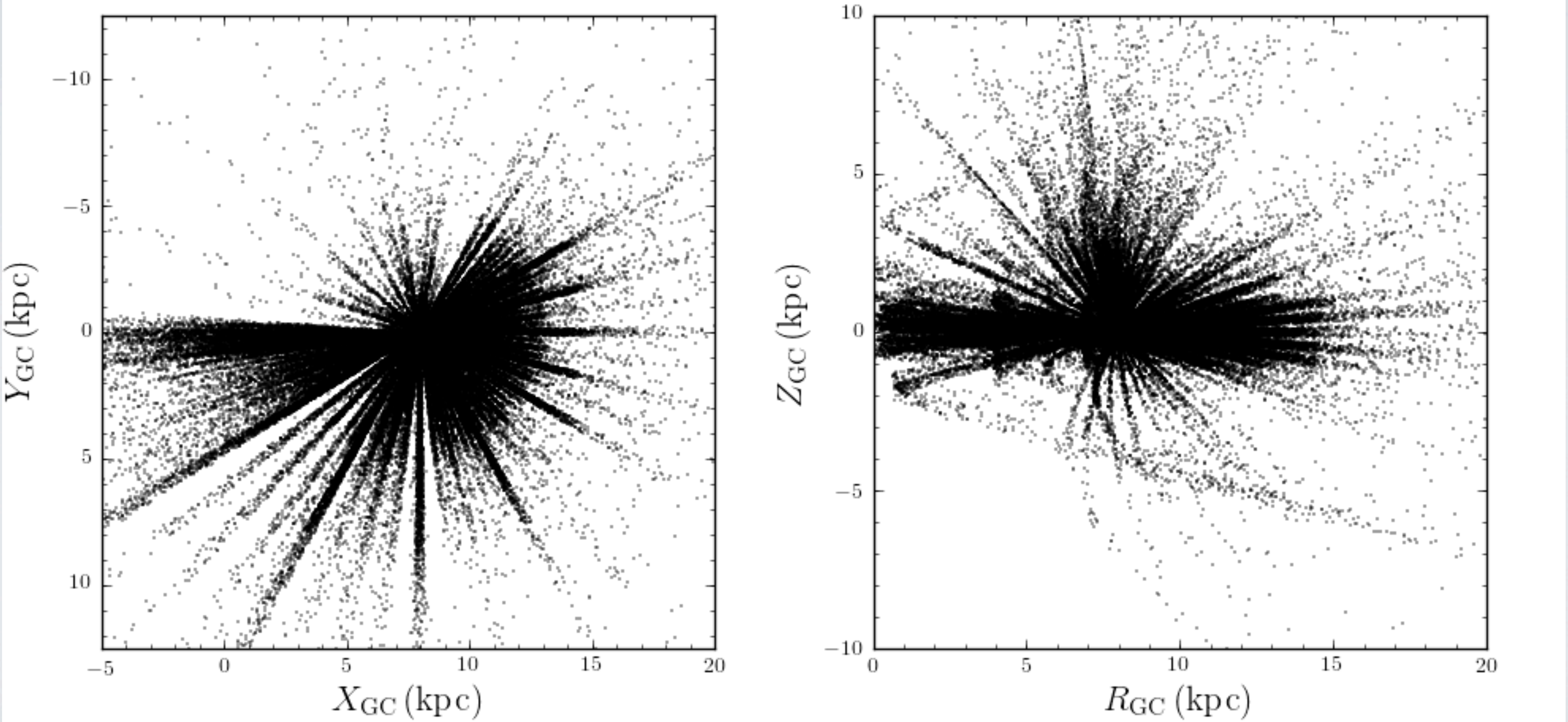
- Main sample 2MASS selected: $(J\text{-}K_s)_0 \geq 0.5$, magnitude limits from H=11 to H=13.8 →mainly luminous K and M giants, RC and RGB
- Open and globular cluster targets for calibration and open-cluster studies; whole host of ancillary target classes
- Goal was: 100,000 stars, mainly in the disk, some in bulge, halo
- Full details in Zasowski et al. (2013)



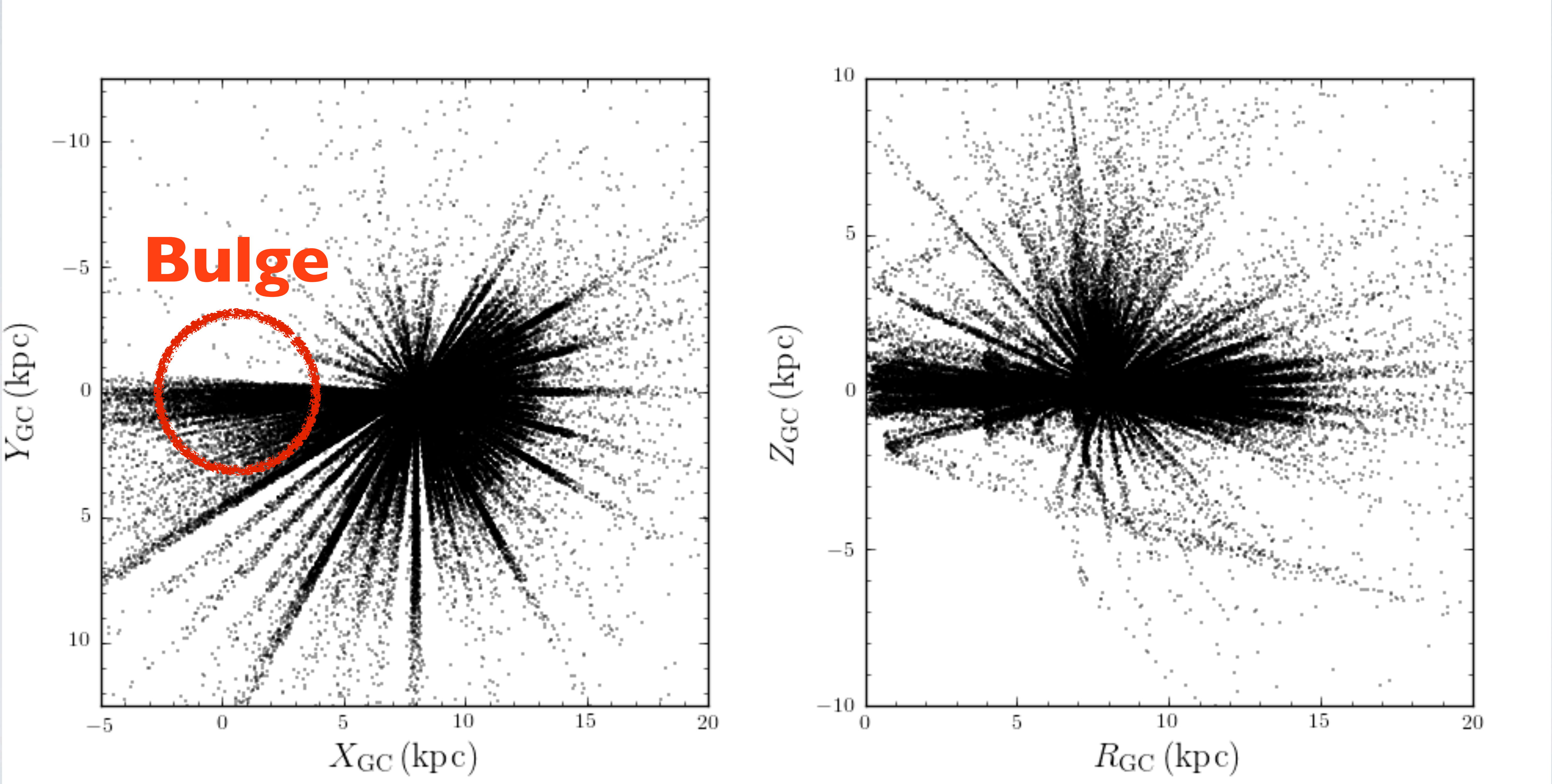
APOGEE-1 COVERAGE



APOGEE-1 SPATIAL COVERAGE



APOGEE-1 SPATIAL COVERAGE



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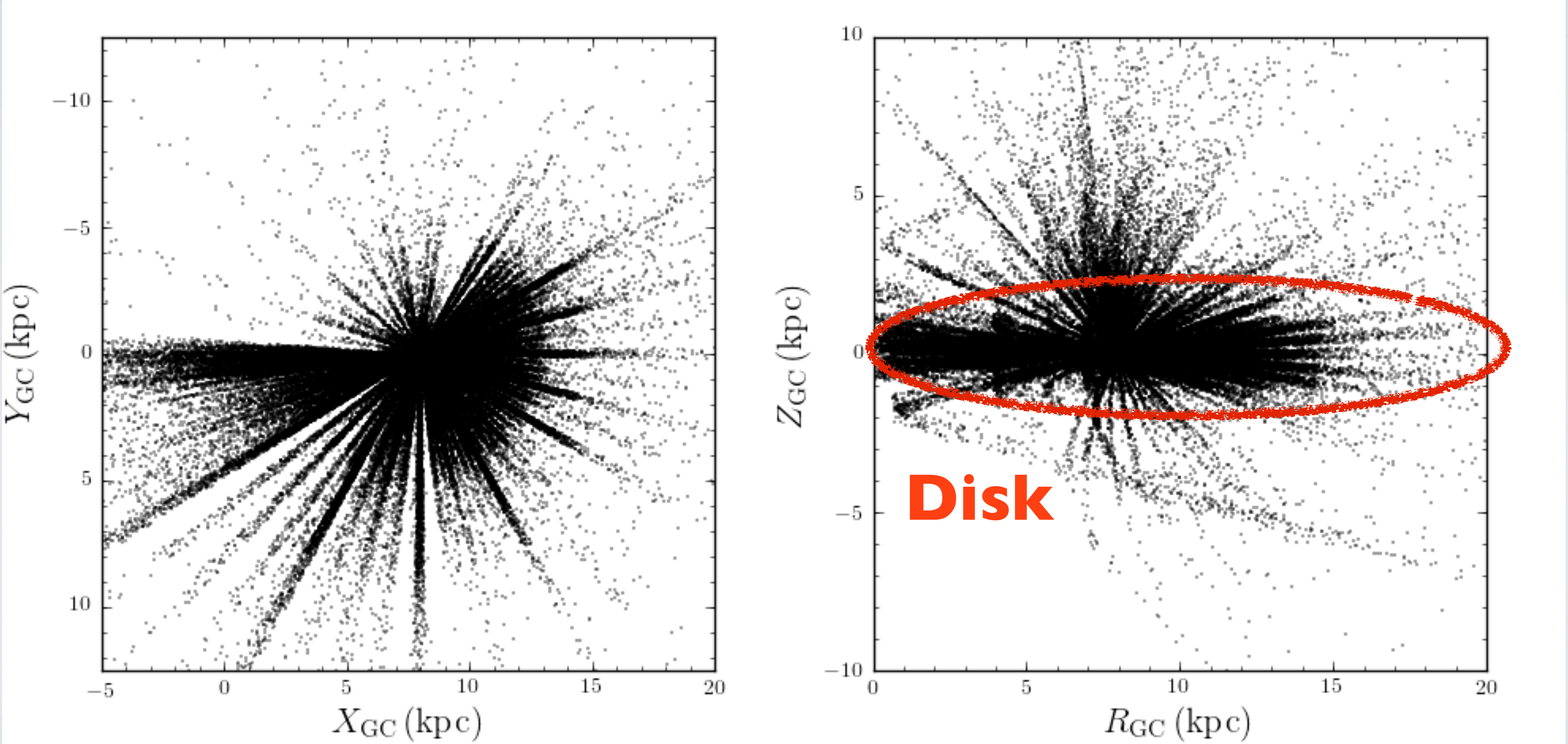


APOGEE PERFORMANCE

- Obtained ~130,000 survey-quality SNR>100 observations by the end of the survey, *30,000 more than goal!*

- RV precision ~ 0.1 km/s, zero-point accuracy ~-1 km/s (cf. M3, M13, M15, M92)

- Current pipeline precision: T_{eff} ~ 100 K , logg ~ 0.15 dex, [Fe/H] ~ 0.03 to 0.08 dex, [a/Fe] ~ 0.03 dex; calibration described in Meszaros et al. (2013), Holtzman et al. (2014, in prep.)

- Pipeline in place to measure individual elements from spectral windows; precision ~0.1 dex for all 15 elements

APOGEE SCIENCE

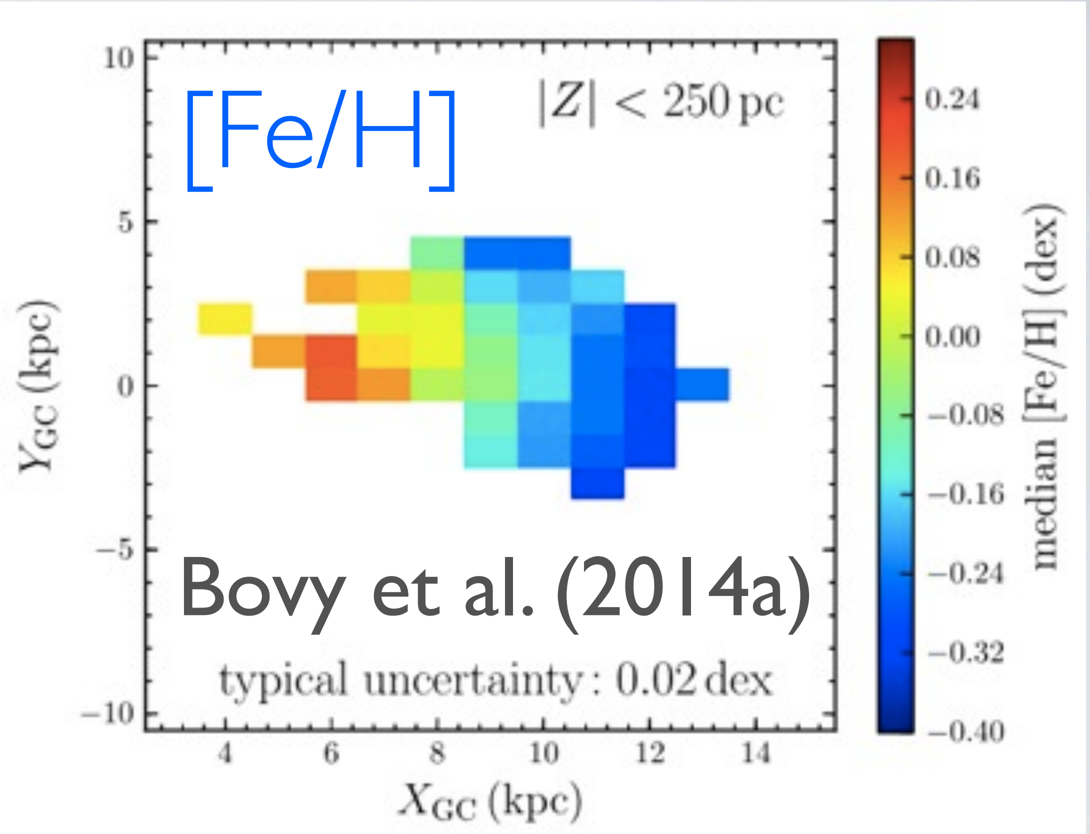
APOGEE SCIENCE

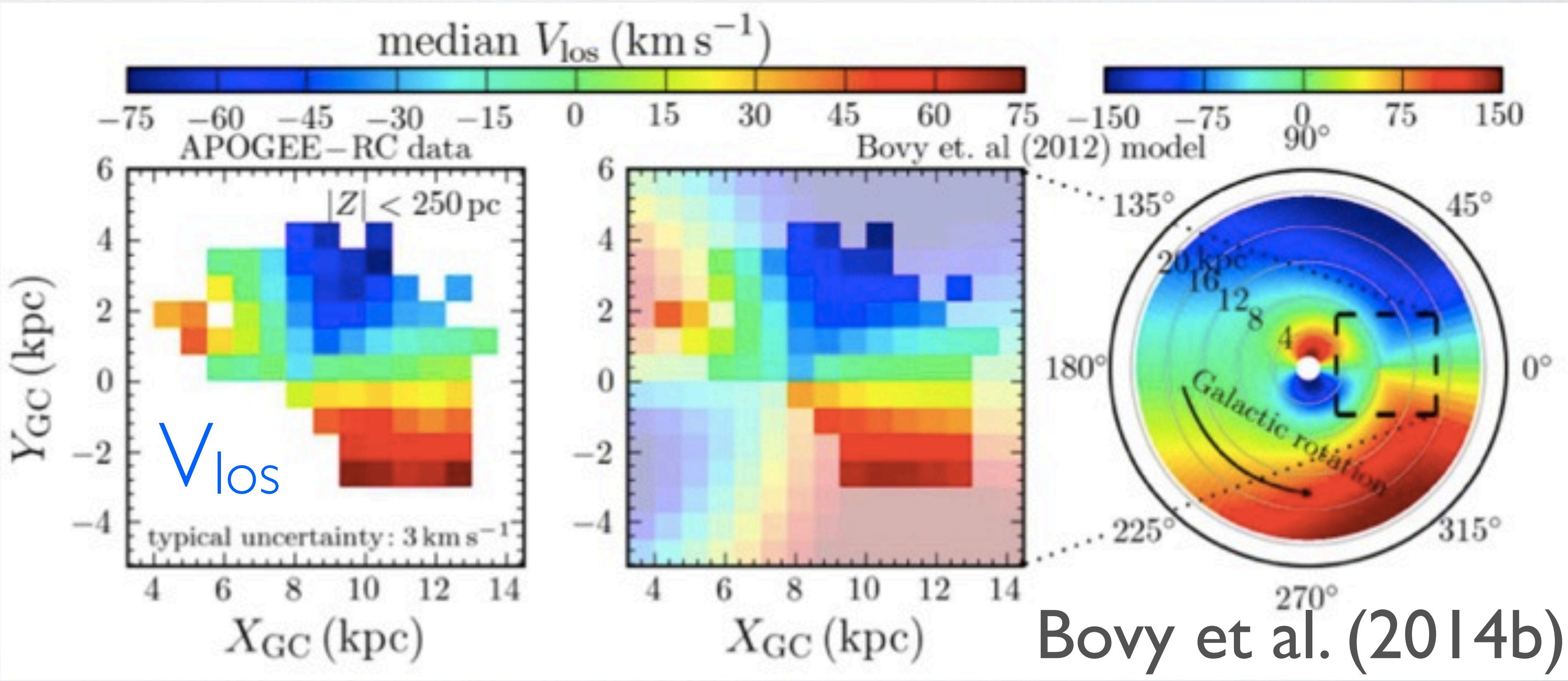
- ★ Galactic dynamics: circular velocity (Bovy et al. 2012), bar kinematics (Nidever et al. 2012), non-axisymmetric streaming motions (Bovy et al. 2014)
- ★ Disk abundances: Mean metallicity over large part of the disk (Hayden et al. 2014), metallicity gradients (Anders et al. 2014), [a/Fe] vs. [Fe/H] abundance distribution (Nidever et al. 2014), MDFs over the entire radial range of the disk (Hayden et al. in prep.)
- ★ Bulge studies: metal-poor stars in the bulge (Garcia Perez et al. 2013), bulge MDF (Garcia Perez et al. in prep.), bulge kinematics (Ness et al. in prep.), bulge extinction maps (Schultheis et al. 2014)
- ★ Tracing the ISM with diffuse interstellar bands (Zasowski et al. 2014)
- ★ Open cluster survey OCCAM: Year 1: Frinchaboy et al. (2013), more to come
- ★ Northern globular clusters: Abundance (anti-)correlations and multiple populations (Meszaros et al. in prep.)
- ★ Large overlap with Kepler asteroseismology: Year 1 catalog (Pinnsoneault et al. 2014), asteroseismic scaling relations at low [Fe/H] (Epstein et al. 2014), solar neighborhood MDF with young secondary-red-clump stars (Epstein et al. in prep.), ages for stars in the Kepler field (Martig et al. in prep.), seismic distances (Rodrigues et al. 2014)
- ★ Large sample of Be stars among hot tellurics (Chojnowski et al. 2014), including rare fast-rotating highly-magnetized Be stars (Eikenberry et al. 2014)
- ★ IN-SYNC: large program to study the dynamics of young clusters (Cottaar et al. 2014, Da Rio et al.)
- ★ and much more

RED-CLUMP CATALOG

Bovy et al. (2014ab)

- New method for selecting red-clump stars based on T_{eff}-logg-[Fe/H]-$(J-K_s)_0$
- Catalog of ~20,000 stars with distances accurate to ~5%, contamination ≲5%
- Allows fine-grained investigation of spatial trends in kinematics, metallicity, other abundances

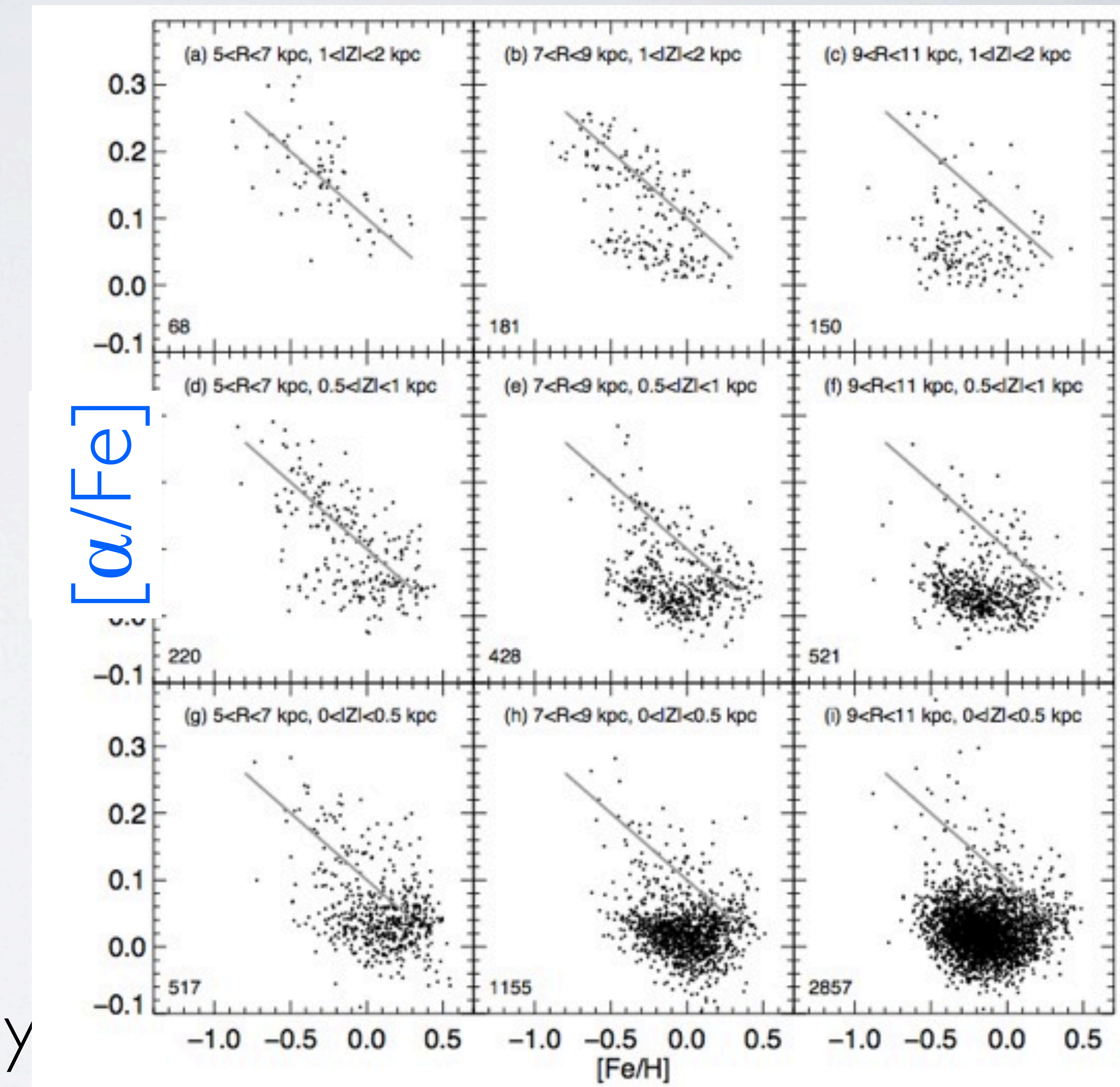




[FE/H] -- [α/FE] DISTRIBUTION

Nidever, Bovy, et al. (2014)

- First large-sample, high-resolution [Fe/H] -- [α/Fe] distribution away from the solar neighborhood
- Cover 5 ≤ R ≤ 12 kpc, |z| ≤ 2 kpc
- Find highly uniform high-[α/Fe] sequence with R, indicative of uniform early enrichment



[Fe/H]

[FE/H] -- [α/FE] DISTRIBUTION

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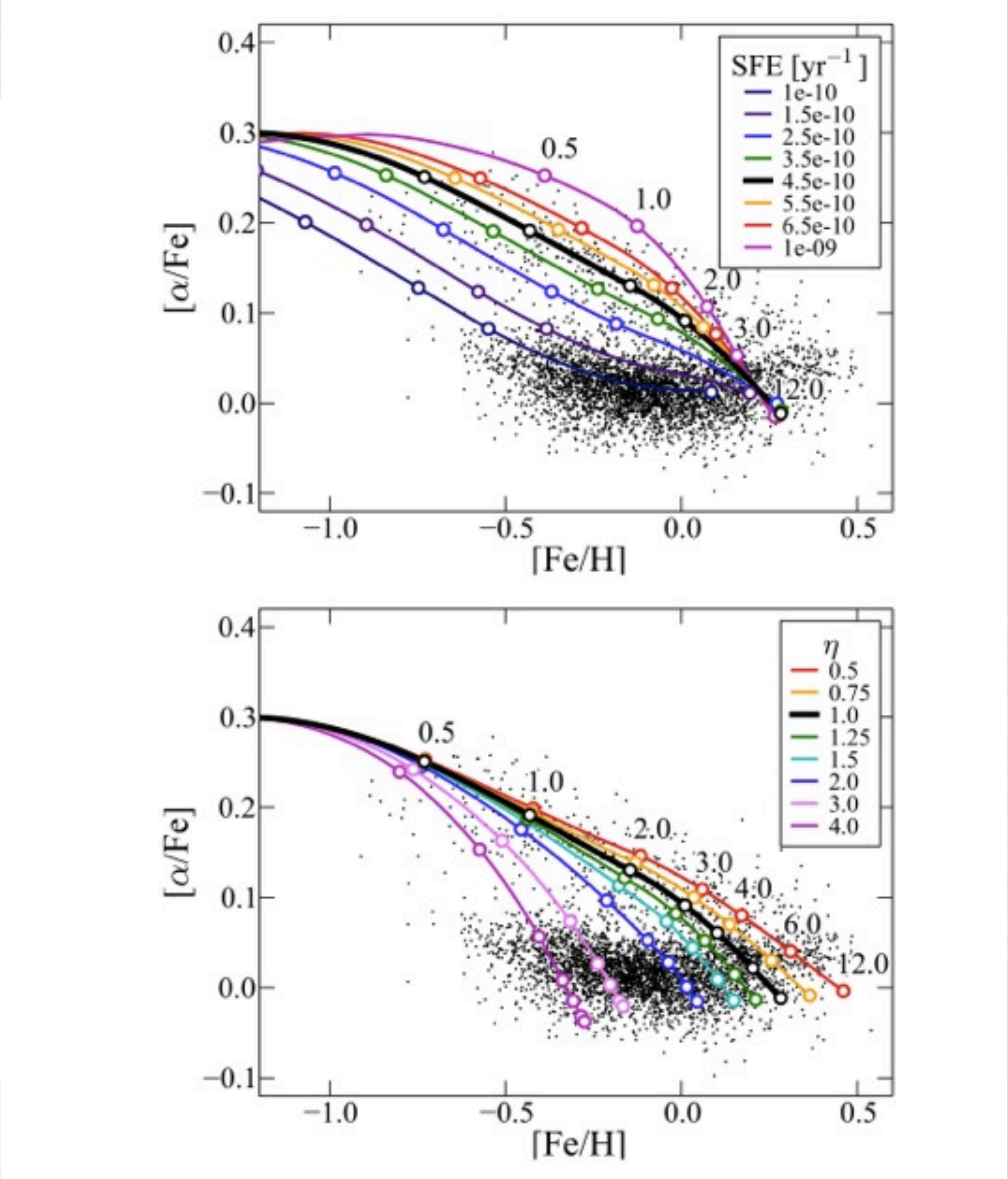
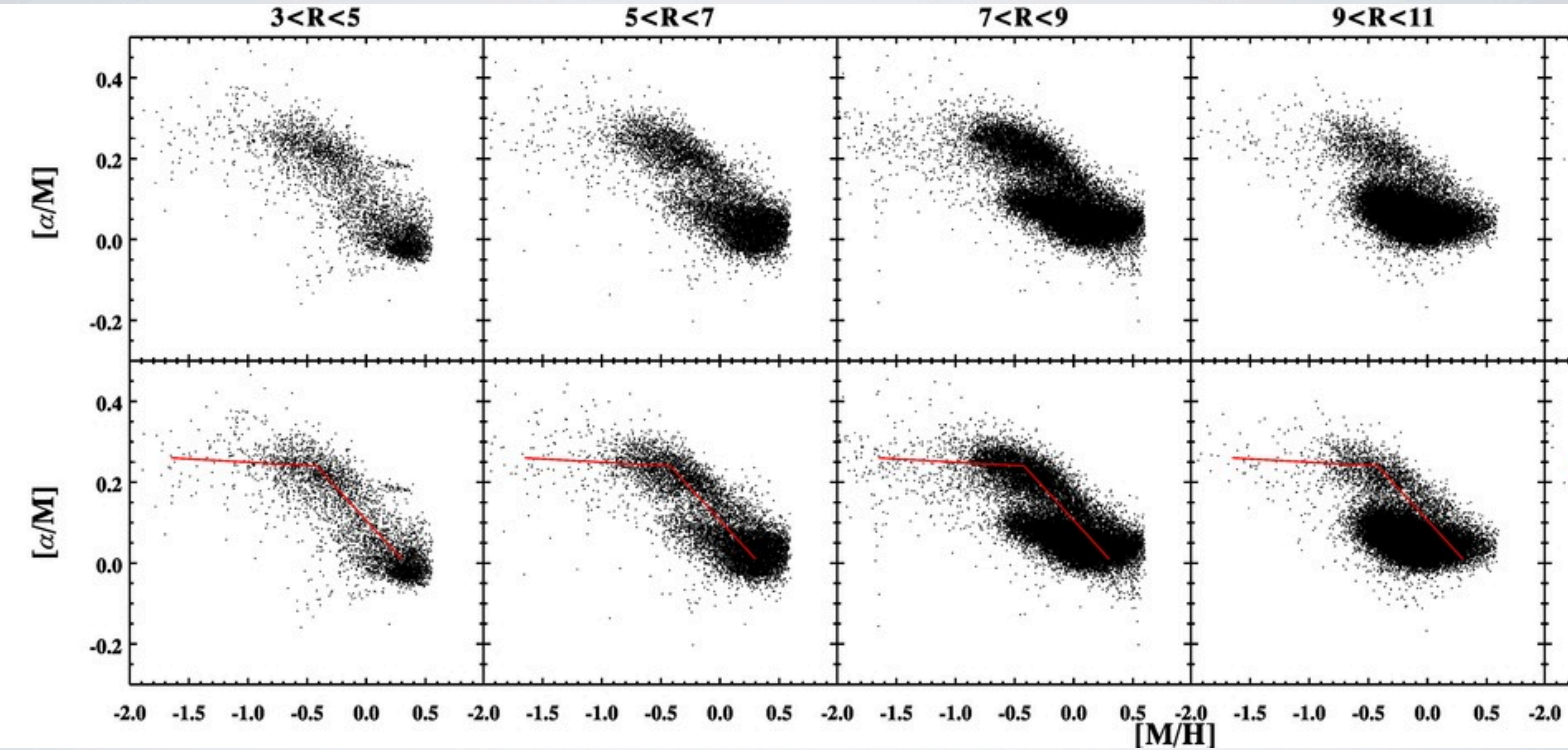


LARGER-SCALE ABUNDANCE DISTRIBUTION

Hayden et al. (in prep.)



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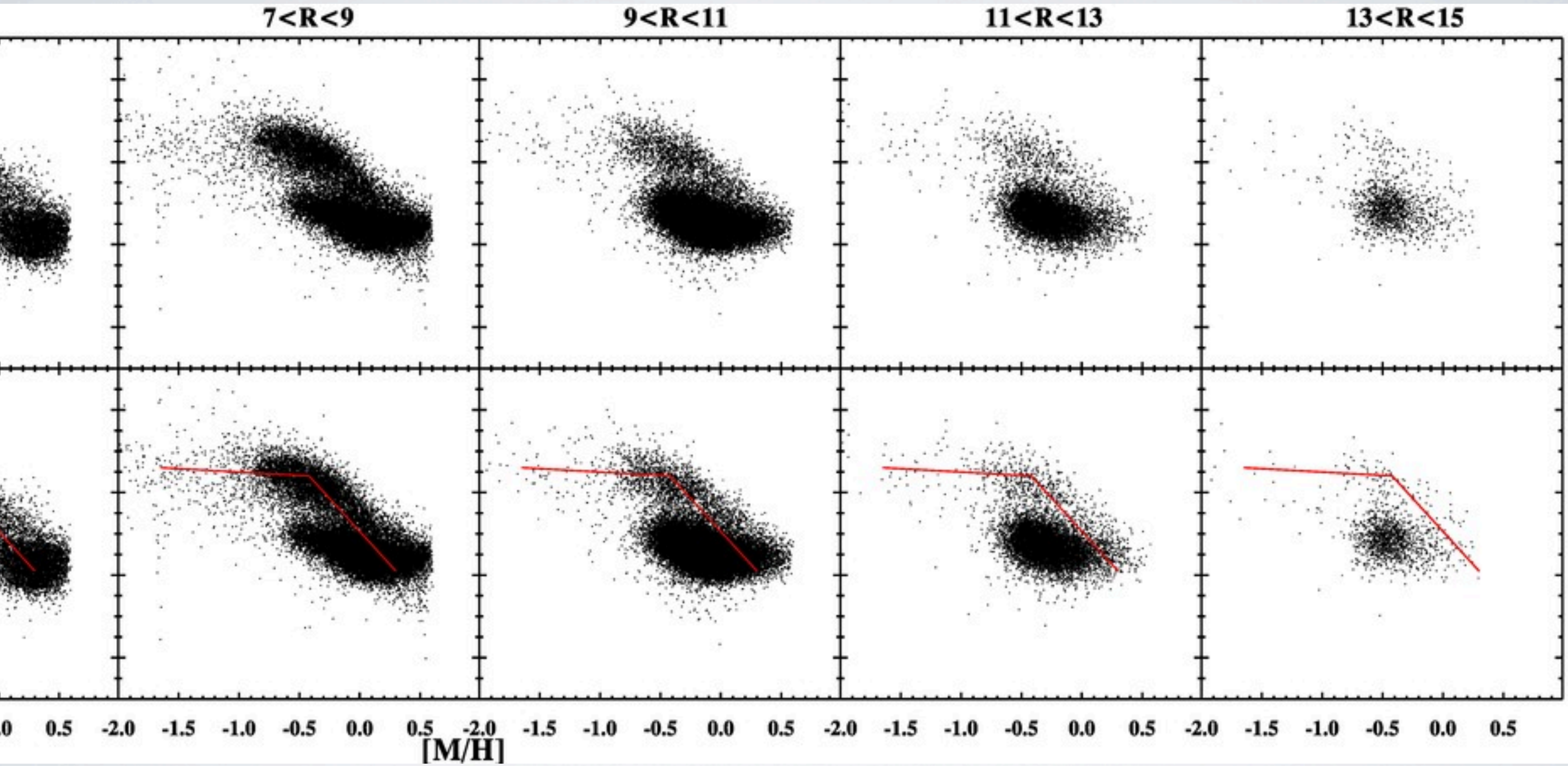


APOKASC: APOGEE AND KASC KEPLER SEISMOLOGY COLLAB.

- ~10,000 stars in Kepler field targeted by APOGEE; 2,540 observed in year 1 → DR10 APOKASC catalog (Pinsonneault et al. 2014) to be released w/ DR12
- Catalog contains:
  - APOGEE spec. parameters
  - Seismic analysis ν_{max} and $\Delta\nu$, seismic classifications
  - Masses, radii, and logg from seismic scaling relations and grid-based seismic modeling
- Work in progress on deriving ages for RGB stars from seismic masses and [Fe/H]
- Useful for calibration of logg, improving stellar models, stellar pops. in Kepler field

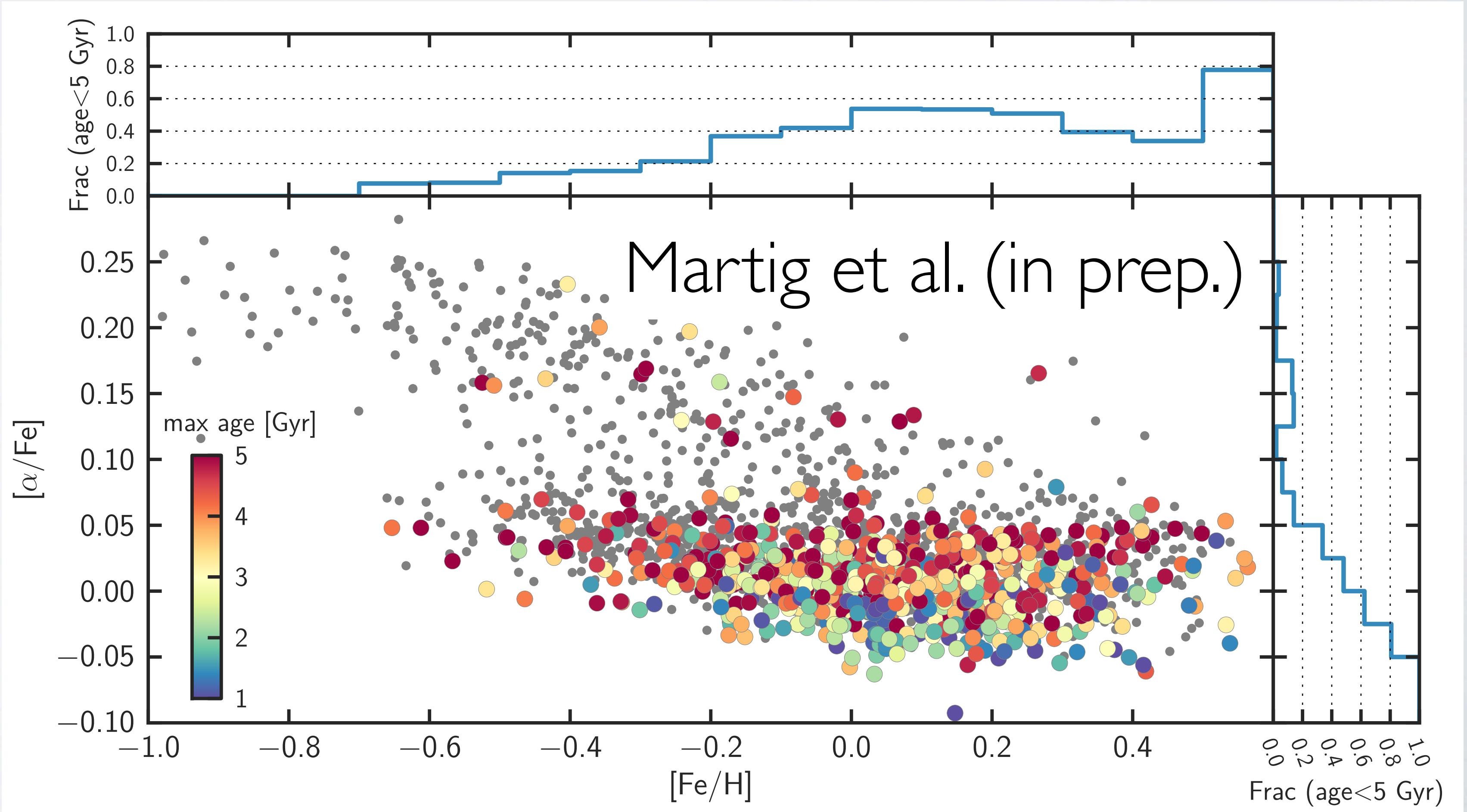
AGE--[FE/H] -- [α/FE] DISTRIBUTION

Martig, et al. (in prep.)

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

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

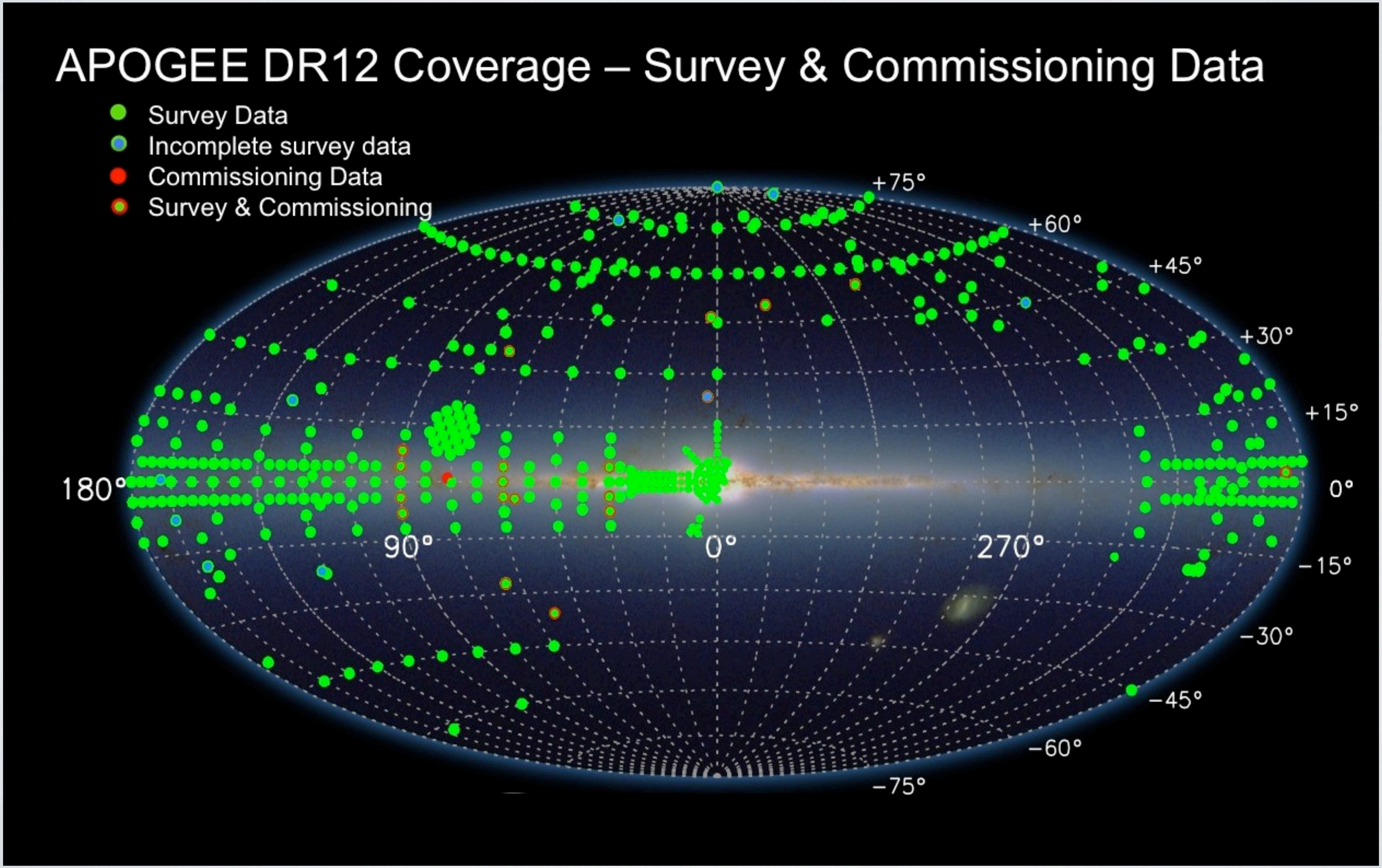
- Maximum ages (minimum masses) are very robust → can investigate what fraction of stars are young
- Fraction ↑ for [α/Fe] ↓
- Some young stars at high [α/Fe]



APOGEE-2

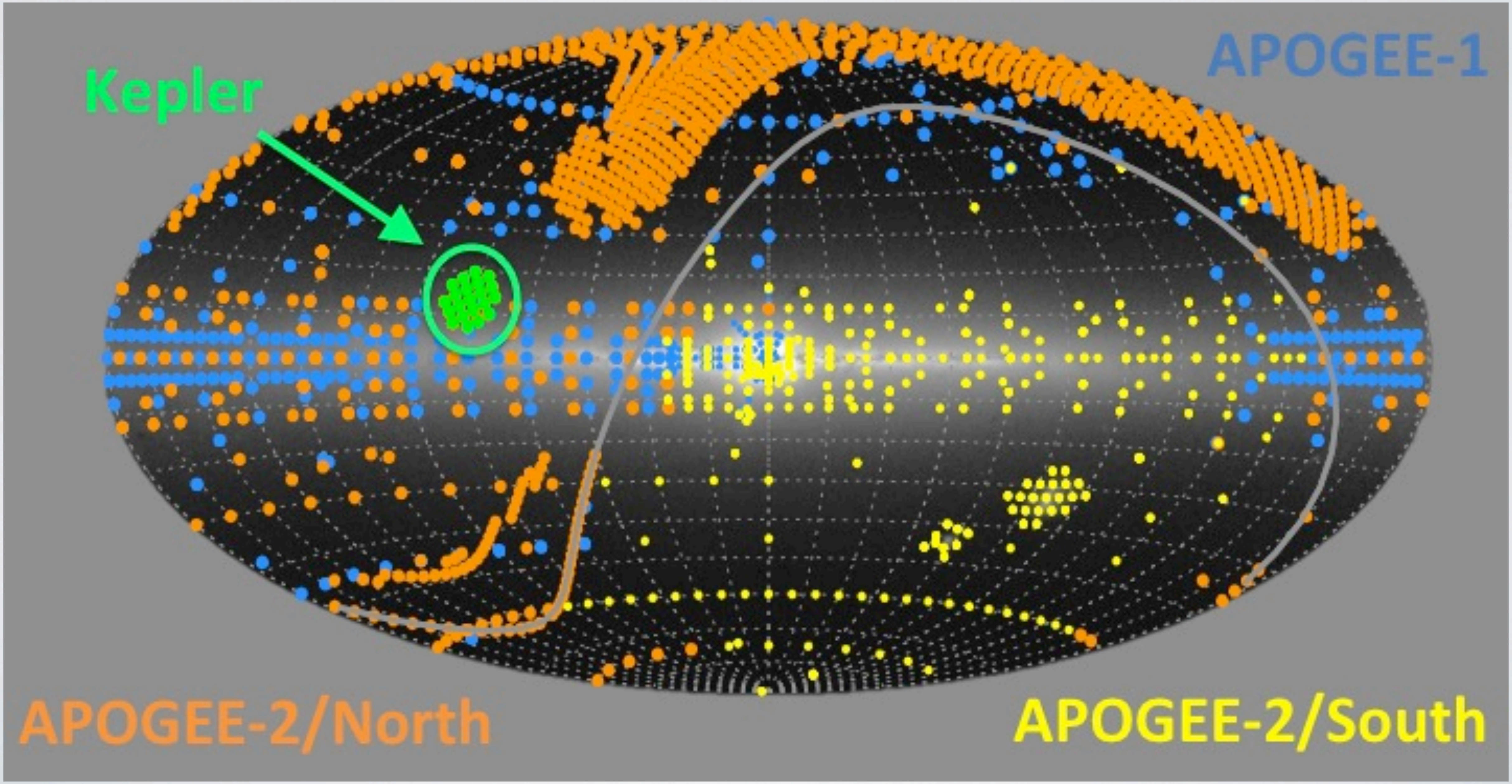
- Building on the success of APOGEE-1, more fully and additionally pursue:
  - Bulge, bulge-disk interface
  - Disk: new areas and larger distances
  - Halo: vastly expand the current small sample, really open up halo
  - Open and globular clusters: vastly expand sample
  - Satellite galaxies: dwarf spheroidals, Magellanic clouds, Sgr and its stream
  - Stellar ages and physics from asteroseismology and gyrochronology
- Dual-hemisphere survey: continue at APO with current APOGEE instrument, build second spectrograph for du Pont telescope in Chile

APOGEE-2 COVERAGE



APOGEE-2 COVERAGE

- Much finer sampling of all major components
- Note large shallow halo sample due to co-observing with Manga!

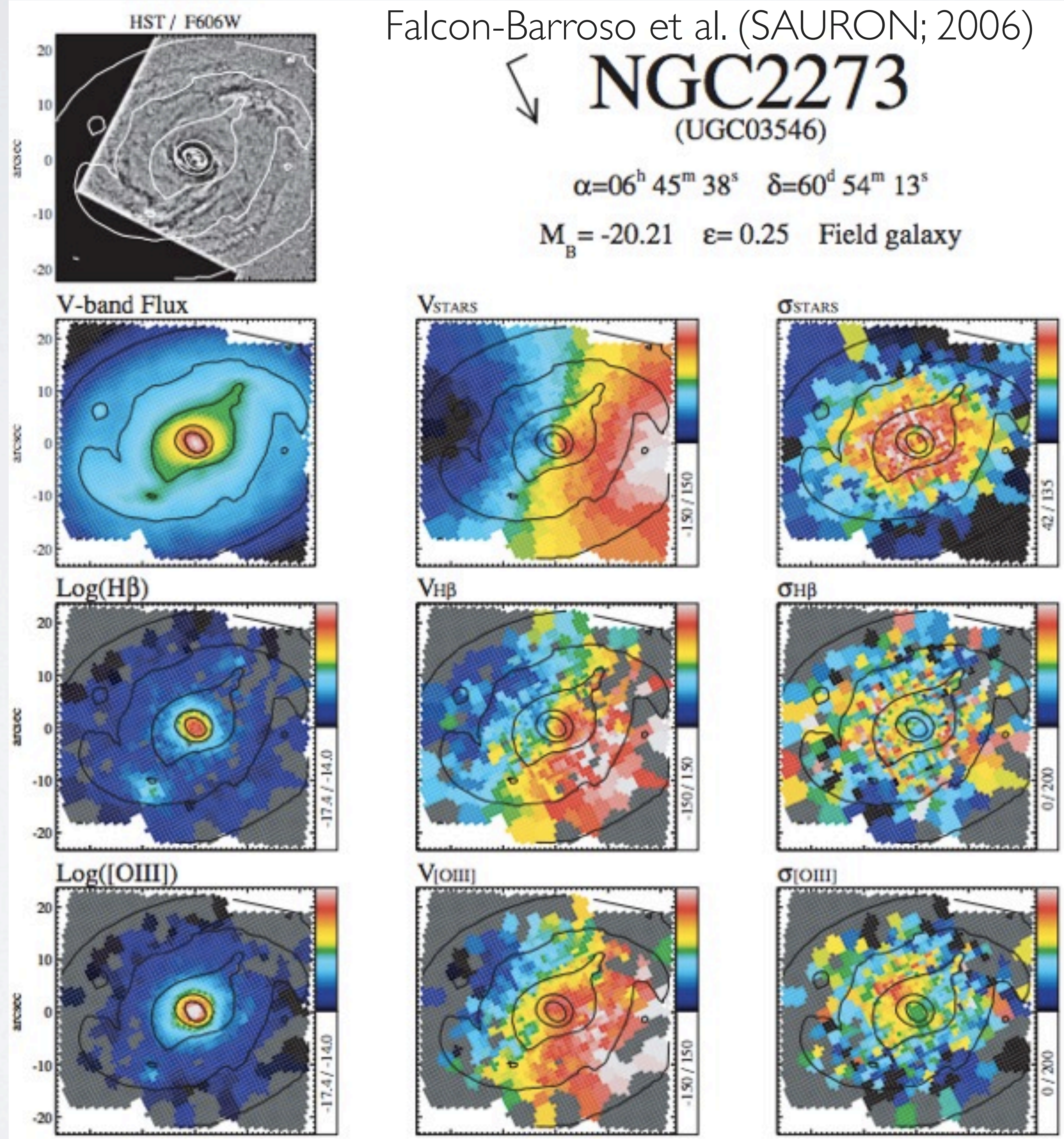


APOGEE & WFIRST-AFTA

THE MW DISK & WFIRST-AFTA

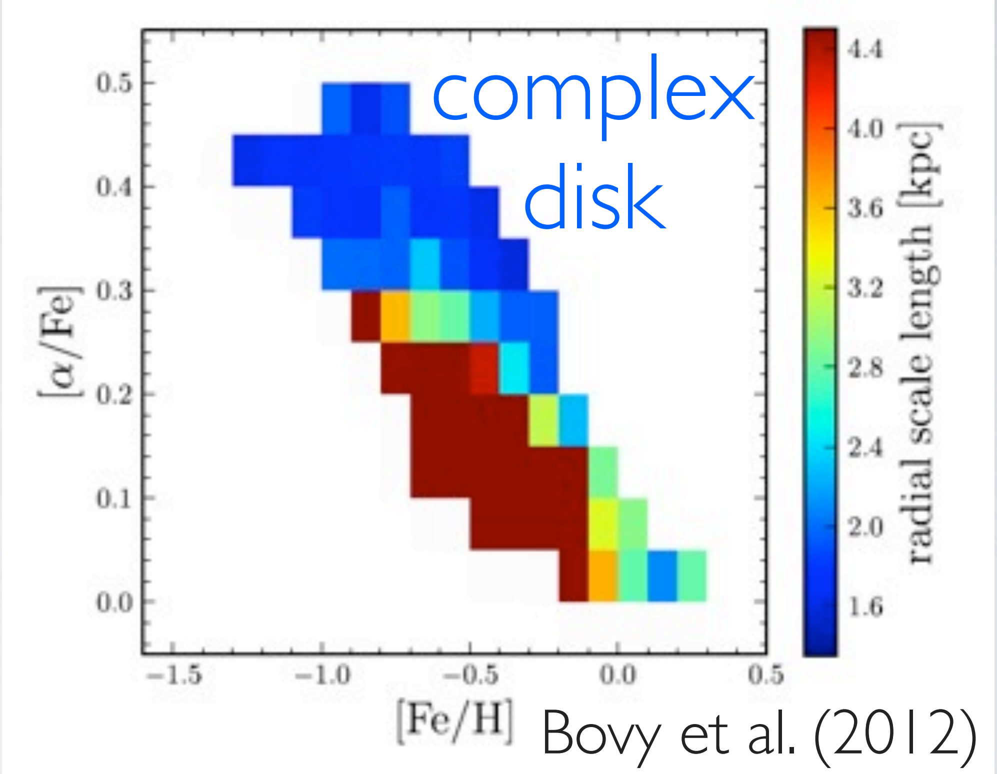
- Many IFU instruments conducting large surveys of spiral galaxies, providing detailed internal structure for the population (CALIFA, MaNGA, SAMI, ... + MUSE)
- WFIRST-AFTA can really help with creating full picture of the MW disk and bulge region
- 'Direct' comparison between MW and MW-like galaxies
- Much more detailed view of MW helpful in interpreting external galaxies

Falcon-Barroso et al. (SAURON; 2006)

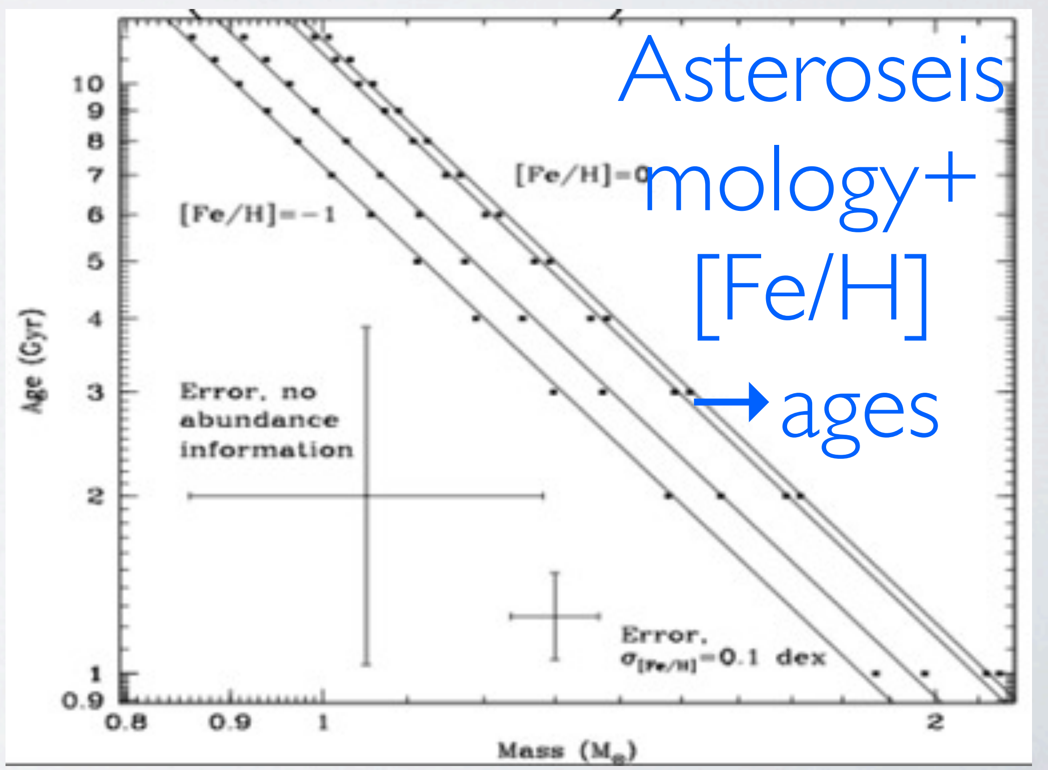


APOGEE & WFIRST-AFTA

- Full picture of the Milky Way's stellar DF(**x**,**v**,age,[Fe/H],[X/Fe]) needs spectroscopy: v_{los}, spectrophotometric distances, abundances
- Asteroseismology in bulge microlensing field: stellar modeling improved with [Fe/H], other abundances; need [Fe/H] to turn RGB asteroseismology into ages
- Many optical, multi-object spectrographs available, but for follow-up in heavily extincted regions need IR follow-up
- APOGEE instrument(s): existing (or soon existing) near-IR spectroscopic facility
- APOGEE: step toward similar instrumentation on larger telescope, larger multiplexing, ...

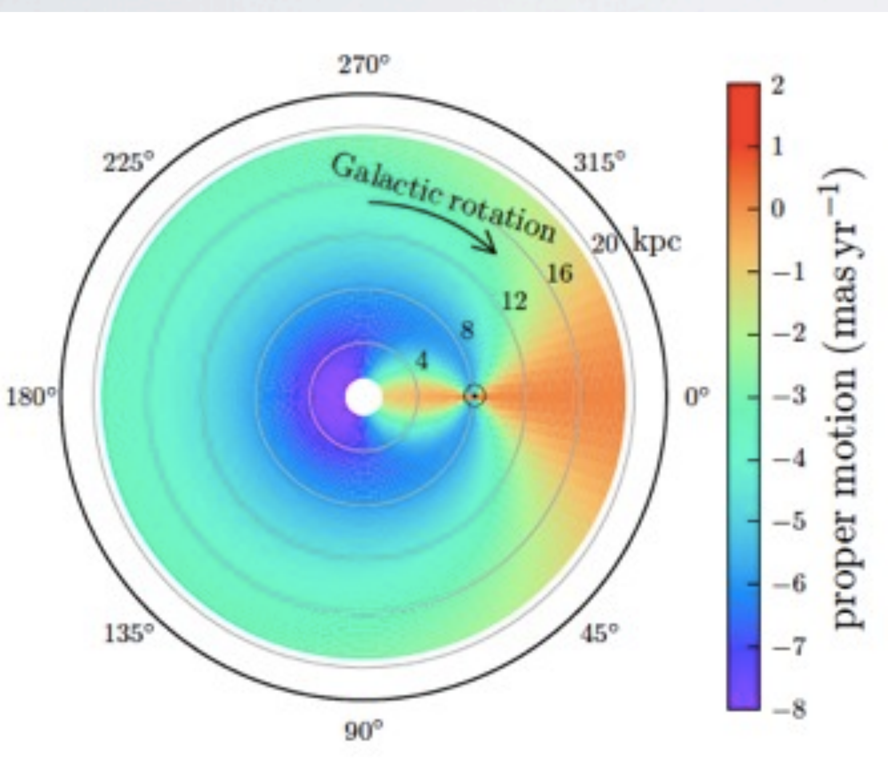


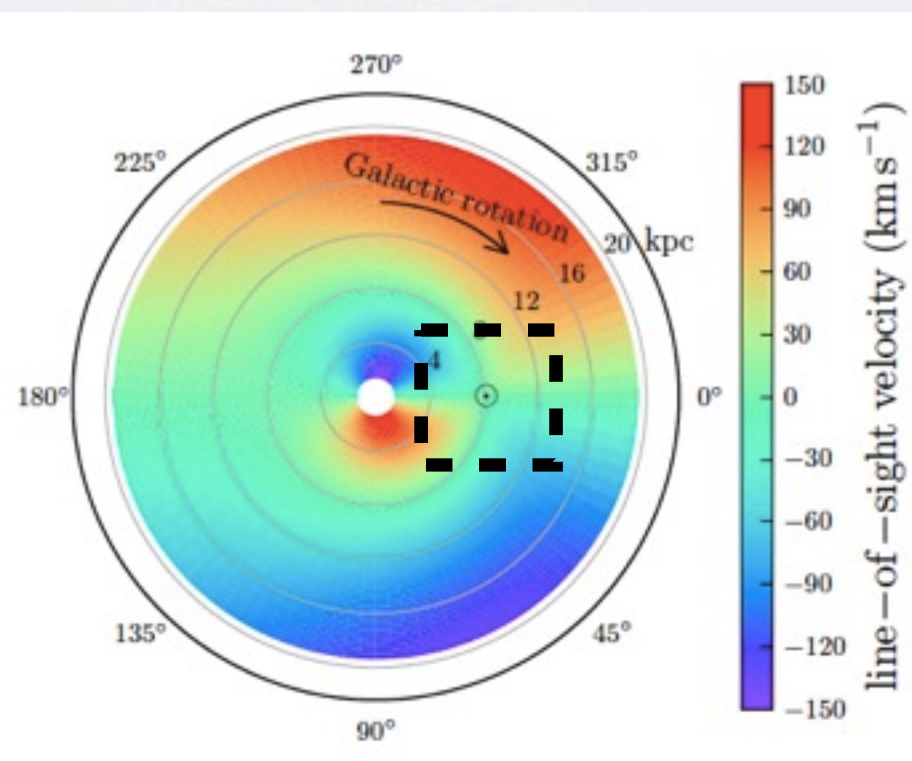
Bovy et al. (2012)

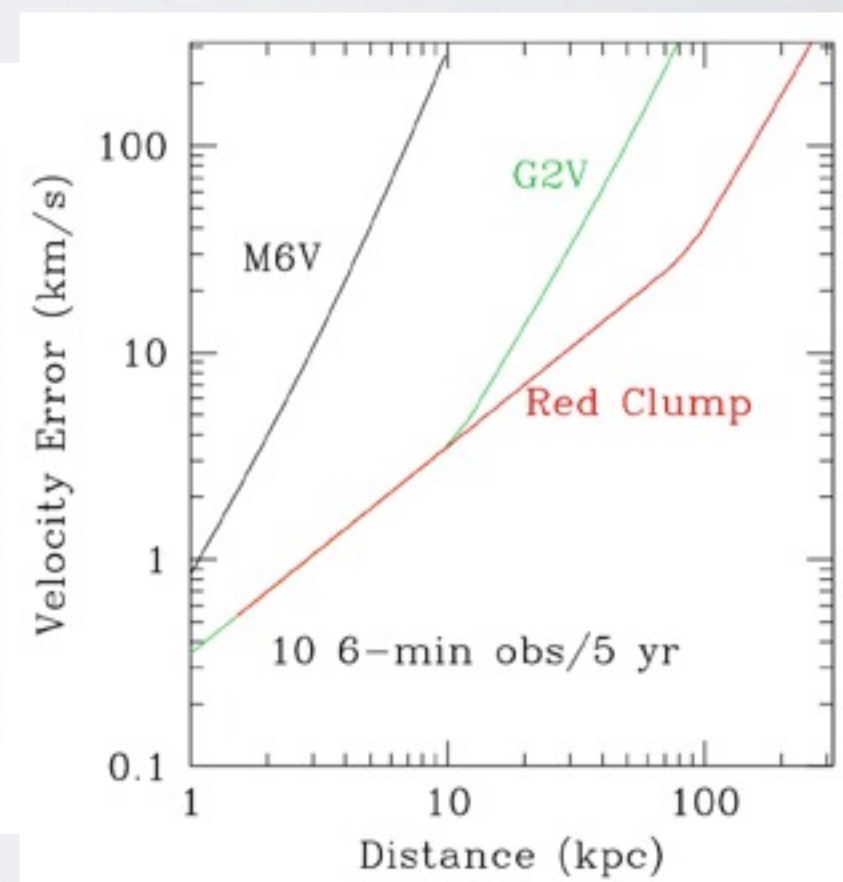


APOGEE & WFIRST-AFTA SEEING THE WHOLE DISK

- Proper motions:
  - pm from Galactic rotation easily measurable over the entire disk (few mas/yr) *if you can detect sources*
  - velocity DF: (10 km/s) / 4.74 / 16 kpc =~ 130 μas/yr → detect non-axisymmetric streaming, resonances; measure mass distribution using vertical dynamics
- v_{los} necessary to complement the dynamical picture
- v_{tan}: need precise distances, e.g., spectroscopic RC







MOONS

- Proposed near-IR medium- and high-res spectrograph on the VLT
- Aim is to be operational in 2019 and go about 4.5 mag deeper than APOGEE

Parameter	Requirement
Telescope	VLT
Field of View	500 square arcmin
Multiplex	1000 fibers, with possibility to deploy in pairs (500 obj+500 sky)
Sky-projected diameter of single fiber	1.2 arcsec
Wavelength coverage	0.8μm-1.8μm
Observing mode	medium resolution (MR) and high resolution (HR)
Simultaneous λ-coverage in MR	0.8μm-1.8μm
Simultaneous λ-coverage in HR	[0.8μm-0.9μm] + [1.17μm-1.26μm] + [1.52μm-1.63μm]
Resolving power in MR	R~ 4,000 – 6,000
Resolving power in HR	R≥7,000 (around CaII triplet); R≥20,000 (in the J and H bands)

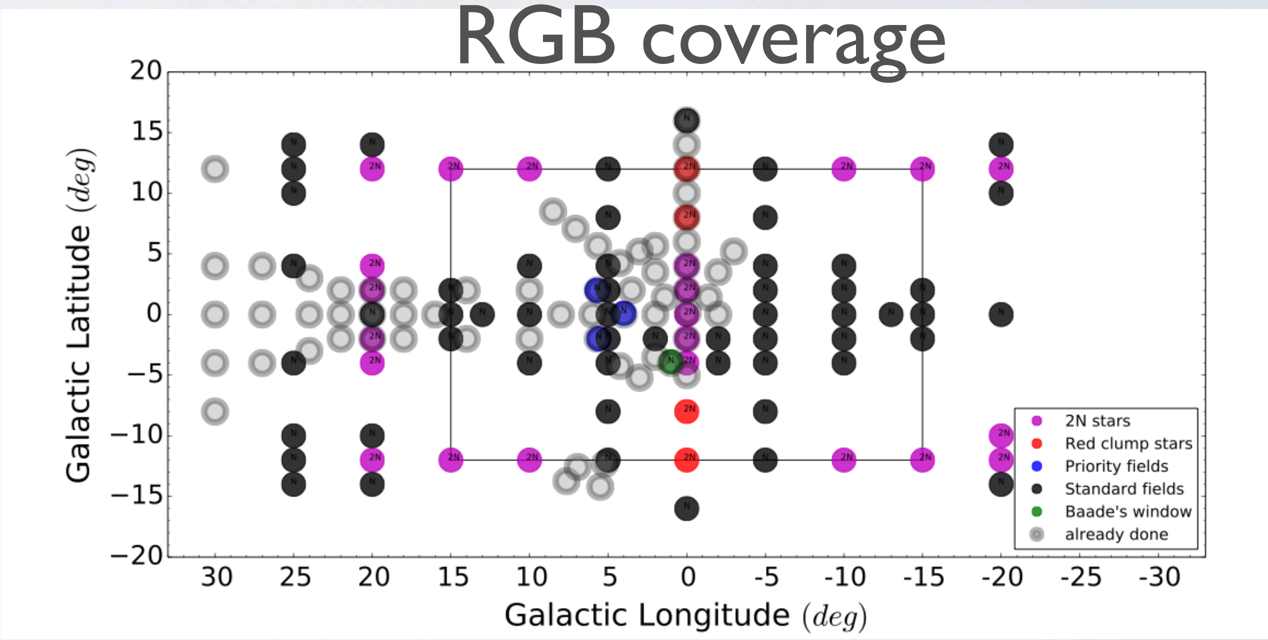
CONCLUSIONS

- APOGEE: near-IR, multi-object spectrograph currently doing large survey of all MW components
- WFIRST+near-IR spectroscopy: full picture of the disk

EXTRA

APOGEE-2 BULGE

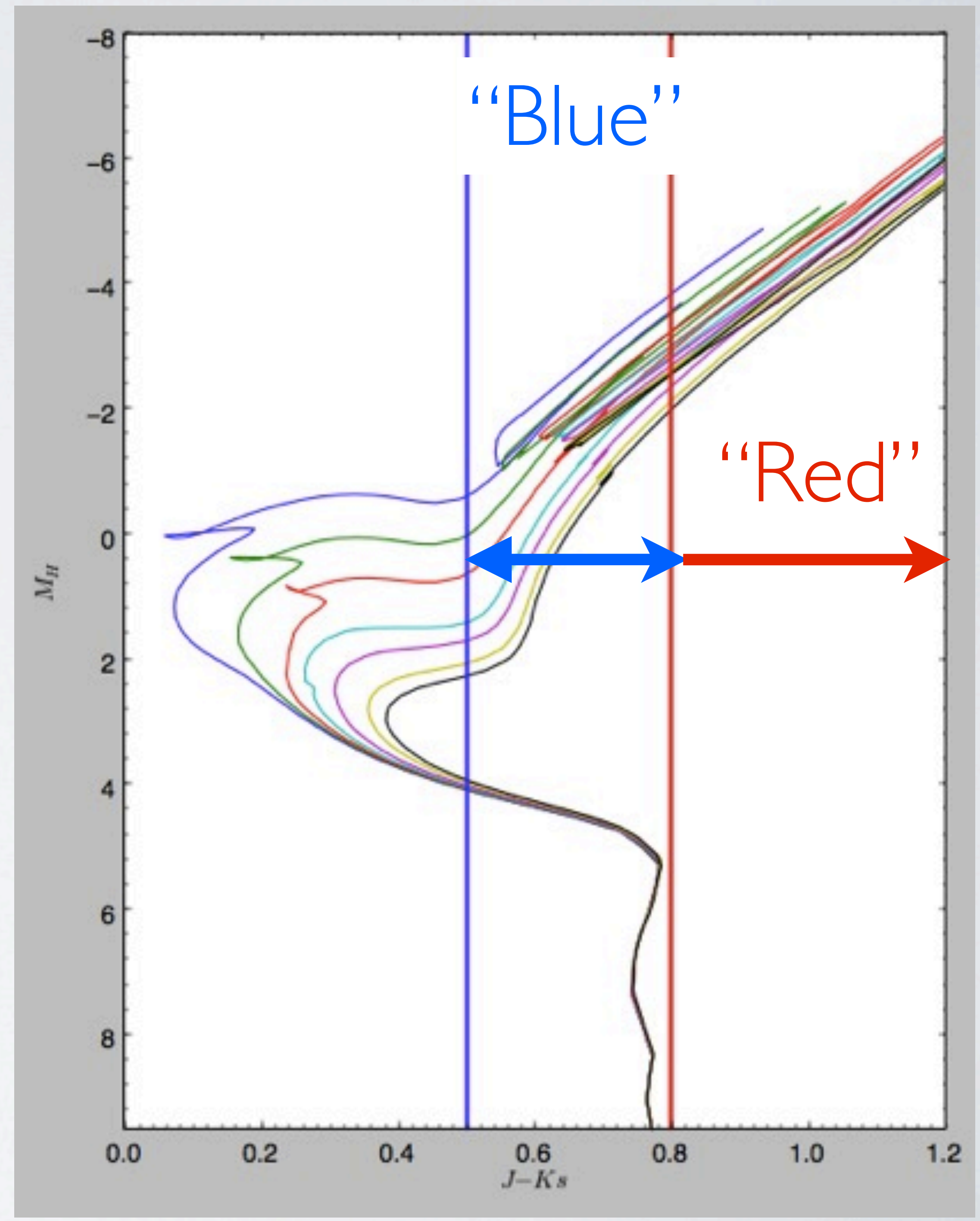
- Much better access to the bulge from the South
- In depth chemo-dynamical mapping with red giants and red clump:
  - Origin of bulge? Did the bulge form through a disk instability and if yes, at what time?
  - Extent of disk into the inner Galaxy
  - Substructure



- Low-metallicity mapping with RR Lyrae:
  - Precise distances (~2%) from IR Spitzer program
  - Proper motions from OGLE; RV from APOGEE: full 6D information

APOGEE-2 DISK

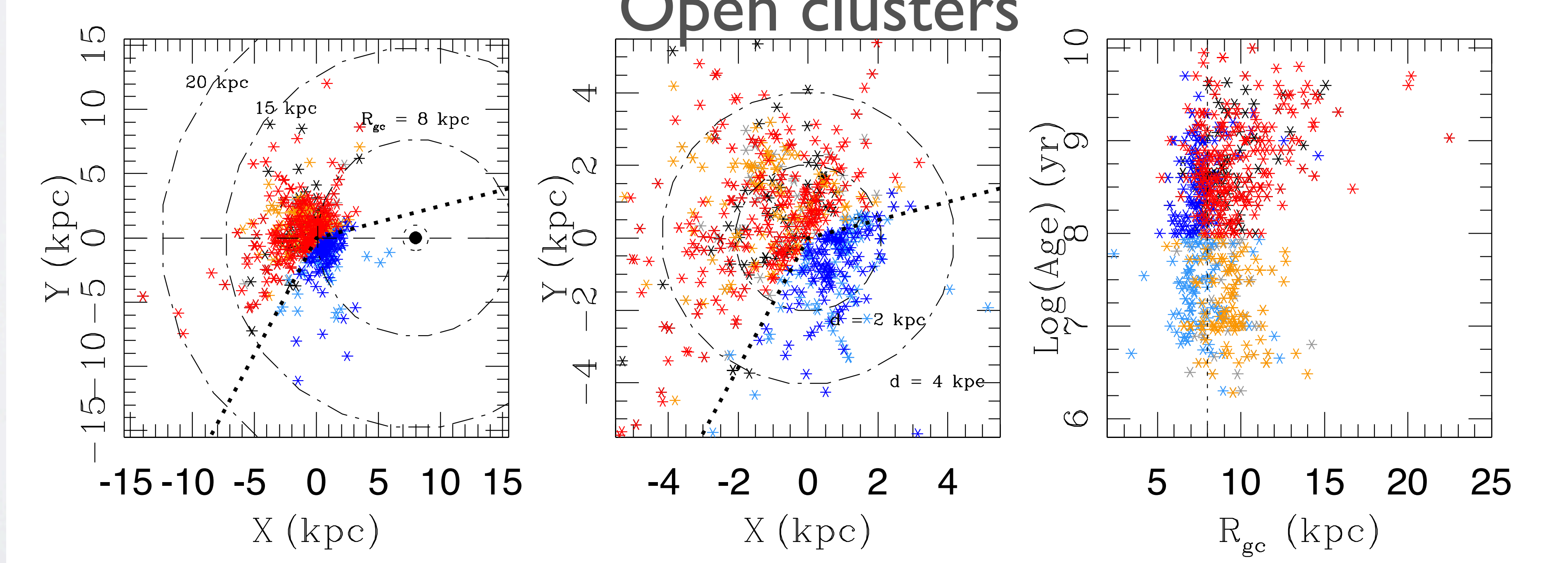
- Extend current disk sampling to investigate:
  - Chemical evolution of the Disk
  - Disk dynamics and asymmetries, in particular with 4th quadrant ($l > 270°$)
  - Disk/bulge/bar interface
  - In-depth investigation of the outer disk: flare, warp, substructure
- Modified targeting scheme to reach larger distances:
  - Blue: $0.5 < (J\text{-}K_s)_0 < 0.8$
  - Red: $0.8 < (J\text{-}K_s)_0$



APOGEE-2 CLUSTERS

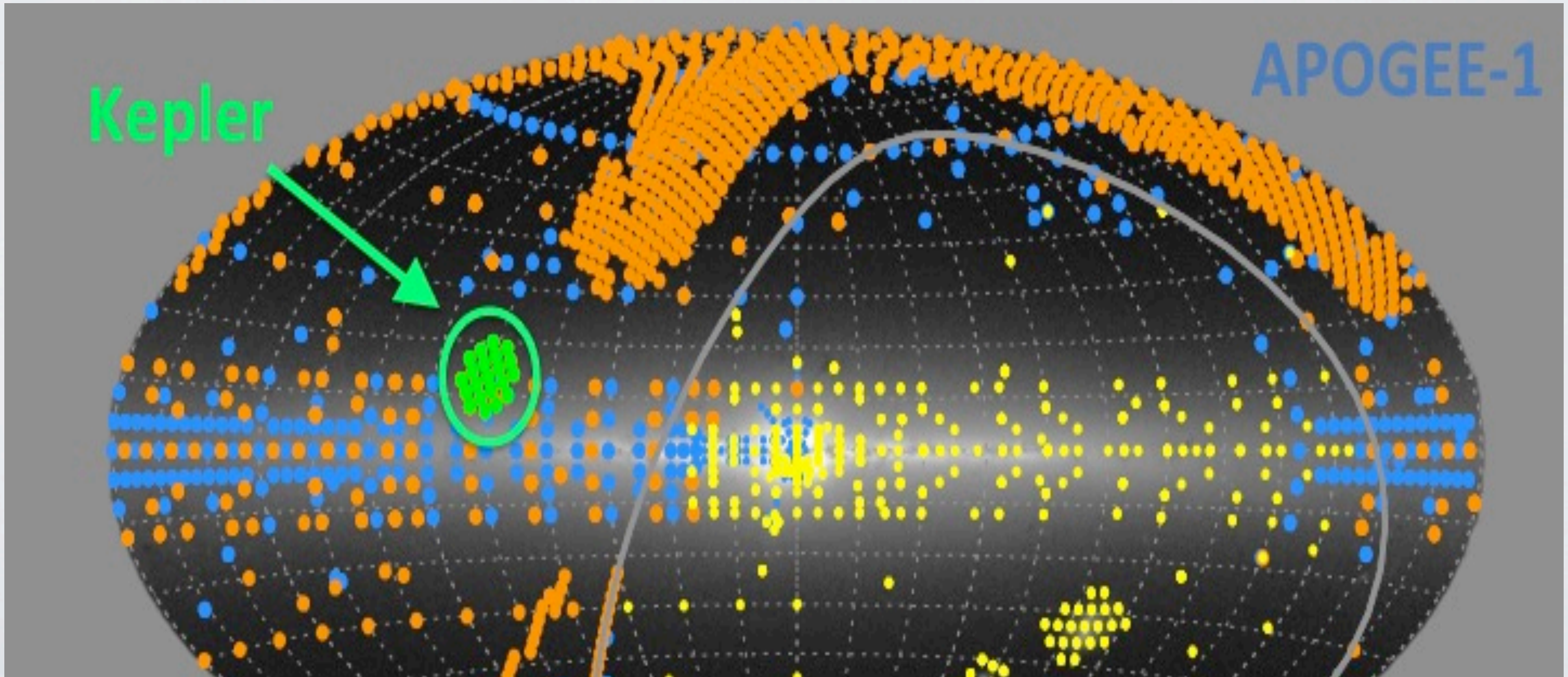
- Hundreds of open clusters in APOGEE-2 disk and bulge fields
- Used for calibration, cross-calibration between APOGEE-1, -2N, and -2S, and other surveys
- Chemical and kinematic trends with open cluster ages
- 20 globular clusters planned over wide range of [Fe/H], age, ...
- Homogeneous investigation of multiple populations crucial to understanding GC formation with many chemical species relevant to this question (C,N,O,Al,Mg,Na)

Open clusters



APOGEE-2 HALO

- Detailed investigation of the Galactic halo:
  - 23 deep (24-hour) fields down to H=13.5 mag; additional fields on satellites and streams
  - $(J\text{-}K_s)_0 > 0.3$ color cut + Washington+DDO photometry to exclude dwarfs where available
  - +huge shallow survey due to Manga co-observing



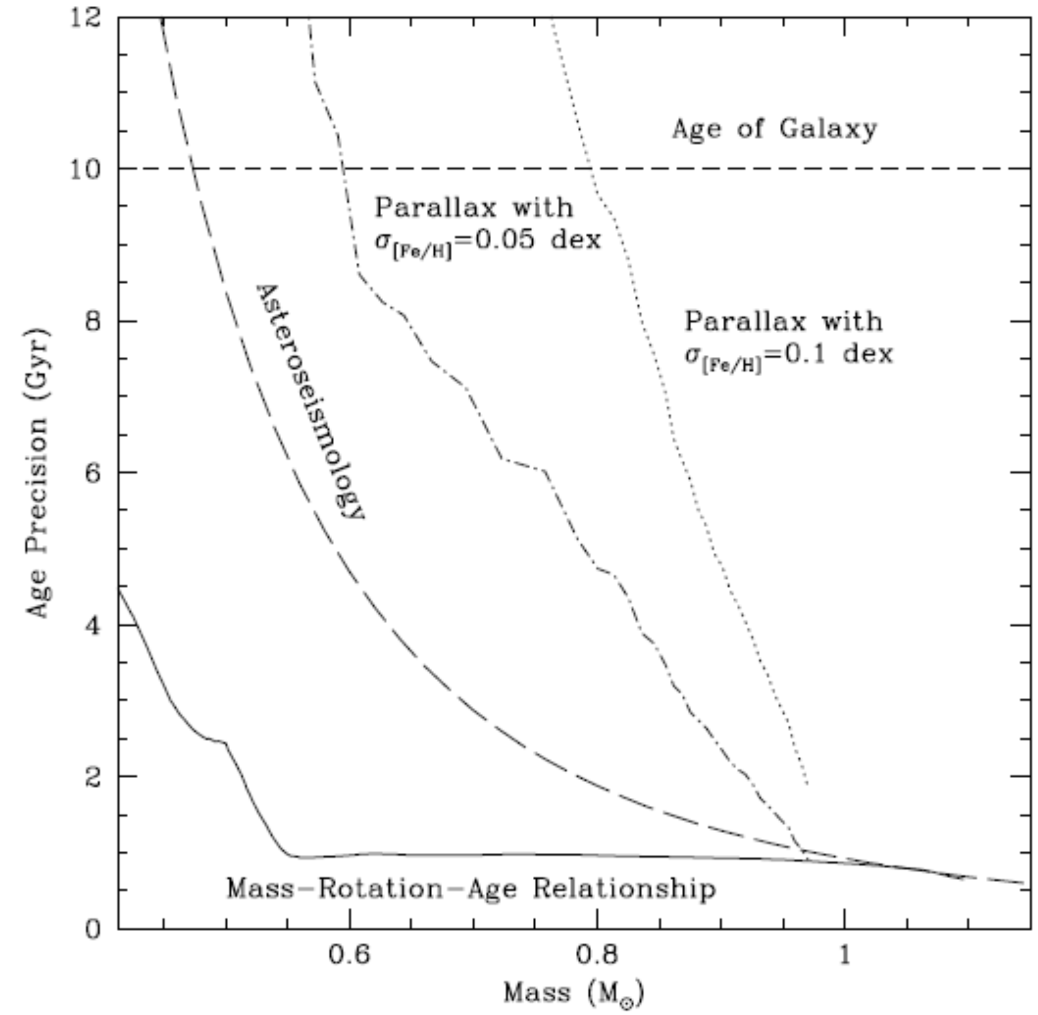
APOGEE-2 SATELLITES

- Magellanic clouds: RGB, AGB, and main-sequence targets in 30 LMC and SMC fields; trace chemistry of the clouds
- Dwarf spheroidals:
  - very few dSphs have been studied in detail in high-resolution
  - Need to push deeper than for regular APOGEE targets: H down to 15 mag and lower S/N; aim for S/N > 50 out to the tidal radius
  - Aiming for at least Al, Mg, Si, and Fe, but more in brighter stars
  - Determine chemical building blocks of the halo
- Sgr: Increase APOGEE-1 sample on Sgr dSph by factor of 5; detailed chemical enrichment history, variations with radius, ...
- Sgr stream: Explore chemical make-up of various parts of the stream

APOGEE-2 STELLAR PHYSICS AND AGES

- Extend current APOKASC (APOGEE+*Kepler*) sample: double RGB sample, making selection function simpler (but still complex *Kepler* selection function)
- Also targets *K2* stars, many of which are selected in a more homogeneous manner
- Gyrochronology: measure ages from rotation periods of low-mass stars, explore trends in rotation with [Fe/H]

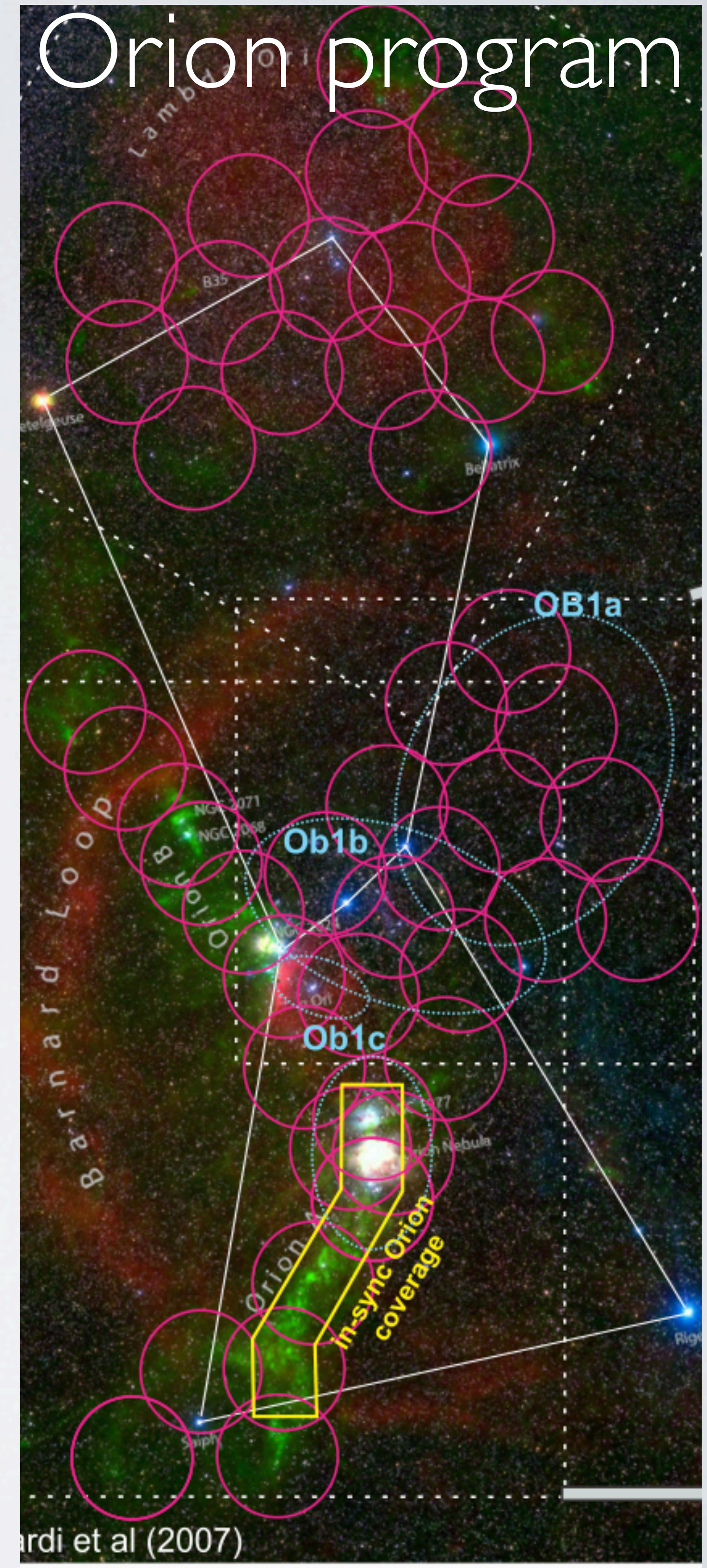
Gyrochronology: precise ages for dwarfs



Epstein & Pinsonneault (2014)

FURTHER APOGEE-2 TOPICS ("GOAL SCIENCE")

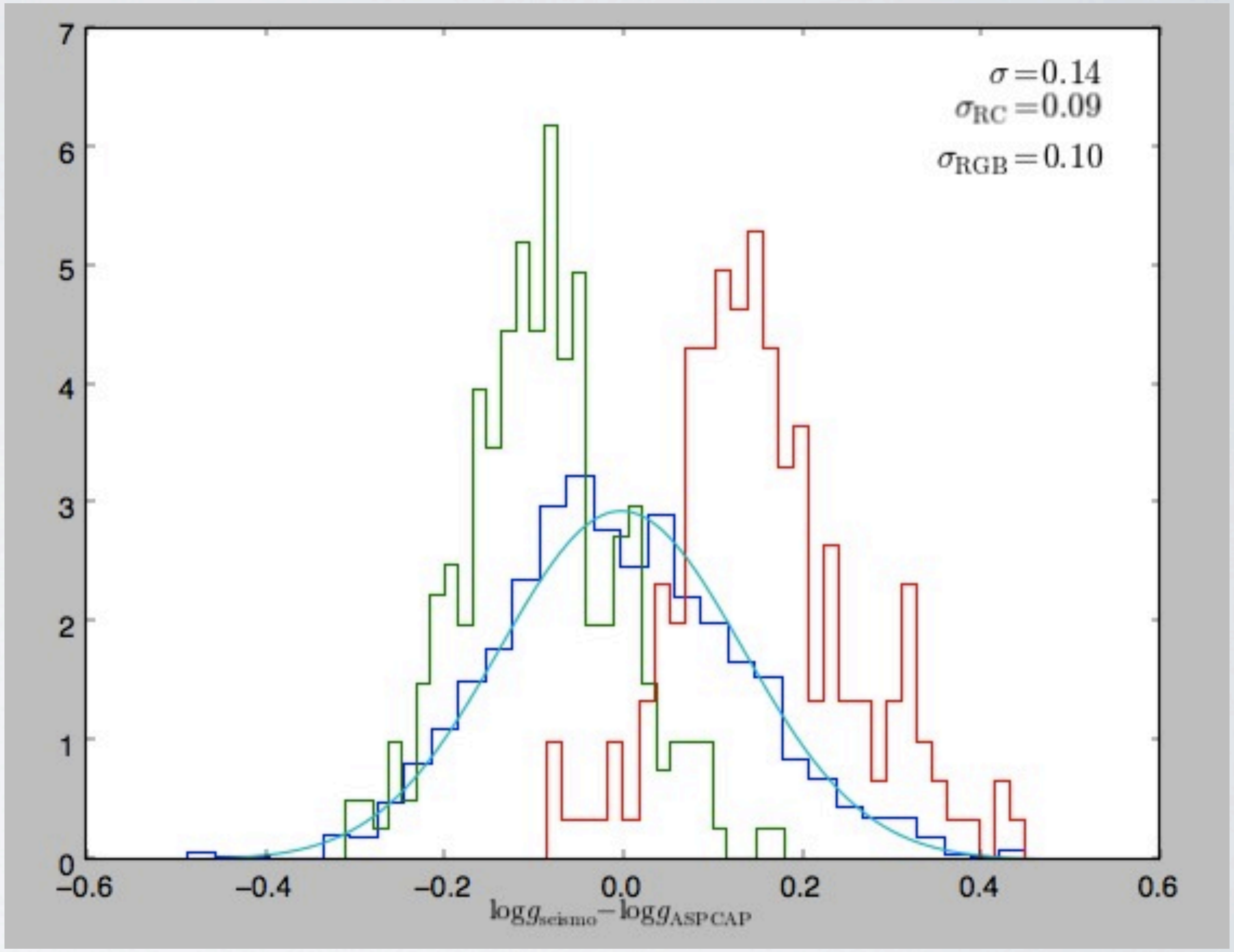
- If possible (likely) the following will also be observed:
  - Eclipsing binaries: high precision masses for stellar-mass -- radius relationship, ...
  - M dwarfs: metallicity calibration, spectral type, improve existing models
  - Young star clusters: Internal dynamics, binary frequency, star formation histories
  - Substellar companions: explore substellar companions in giants and across environments, chemical trends
  - *Kepler* objects-of-interest (KOIs) and control sample: binarity, abundance trends in planet-host vs. no-host



EXTRA SLIDES

LOGG ERRORS

- Extremely precise (~1%) seismic logg useful for calibrating log g and assessing errors
- Currently, ~Gaussian log g uncertainties with σ = 0.15 dex (RC region shown on right)
- Slight relative log g bias for RGB and RC



TRACING THE ISM W/ DIFFUSE INTERSTELLAR BANDS

Zasowski et al. (2014, in prep.)