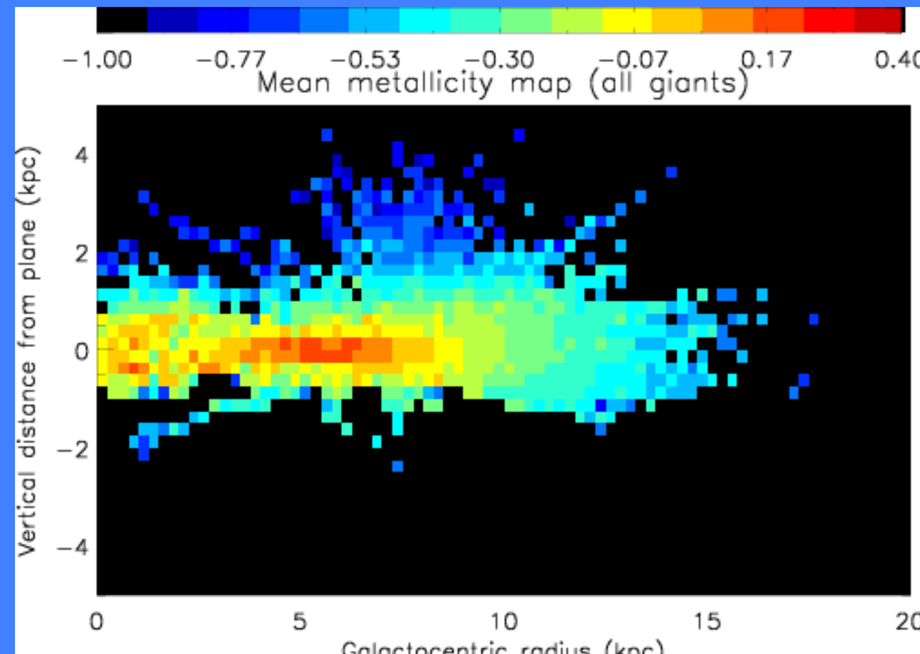
Chemical Cartography with SDSS/APOGEE



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with the SDSS-III/APOGEE collaboration

(see Hayden et al, AJ, astro-ph 1311.4569,

also Anders et al, A&A, astro-ph 1311.4549)

APOGEE at a Glance

SDSS-III -- One of four experiments (BOSS/APOGEE until 2014)

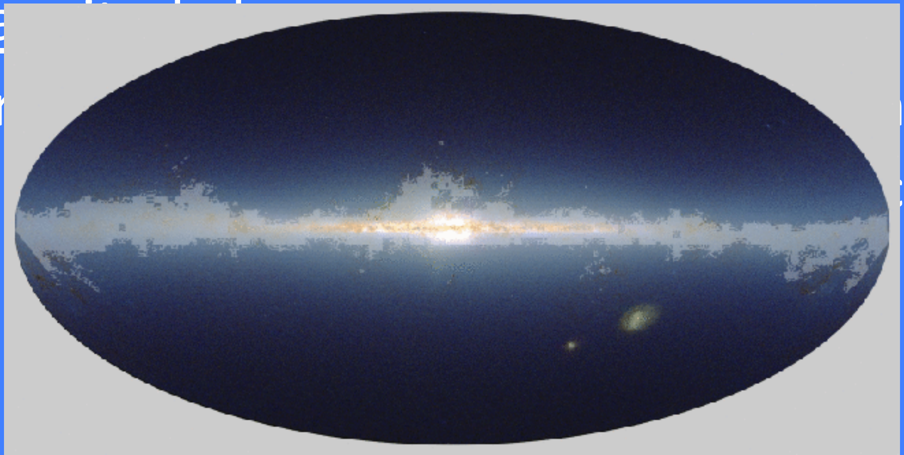
- Bright time 2011.Q2 - 2014.Q2
- 300 fiber, $R \geq 22{,}500$, cryogenic spectrograph, 7 deg^2 FOV
- H-band: 1.51-1.69μm $A_H/A_V \sim 1/6$
- $S/N \geq 100$/pixel @ H=12.2 for 3-hr total integration
- RV uncertainty spec. < 0.5 km/s, 3-hr; *actual* <~100 m/s, 1-hr
- 0.1 dex precision abundances for ~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.

APOGEE Science Goals

- **First large scale, systematic, uniform spectroscopic study of *all* major Galactic stellar populations/regions 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
  - Galactic dynamics/substructure with very precise velocities
  - order of ma

~2-3 order -*R* GCE surveys

~2 orders tra ever taken



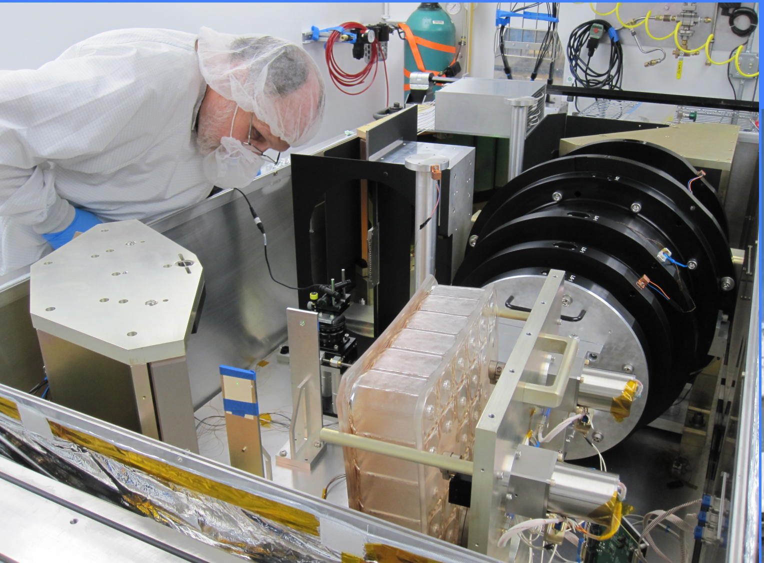
grey areas of map have $A_V > 1$

APOGEE Instrument

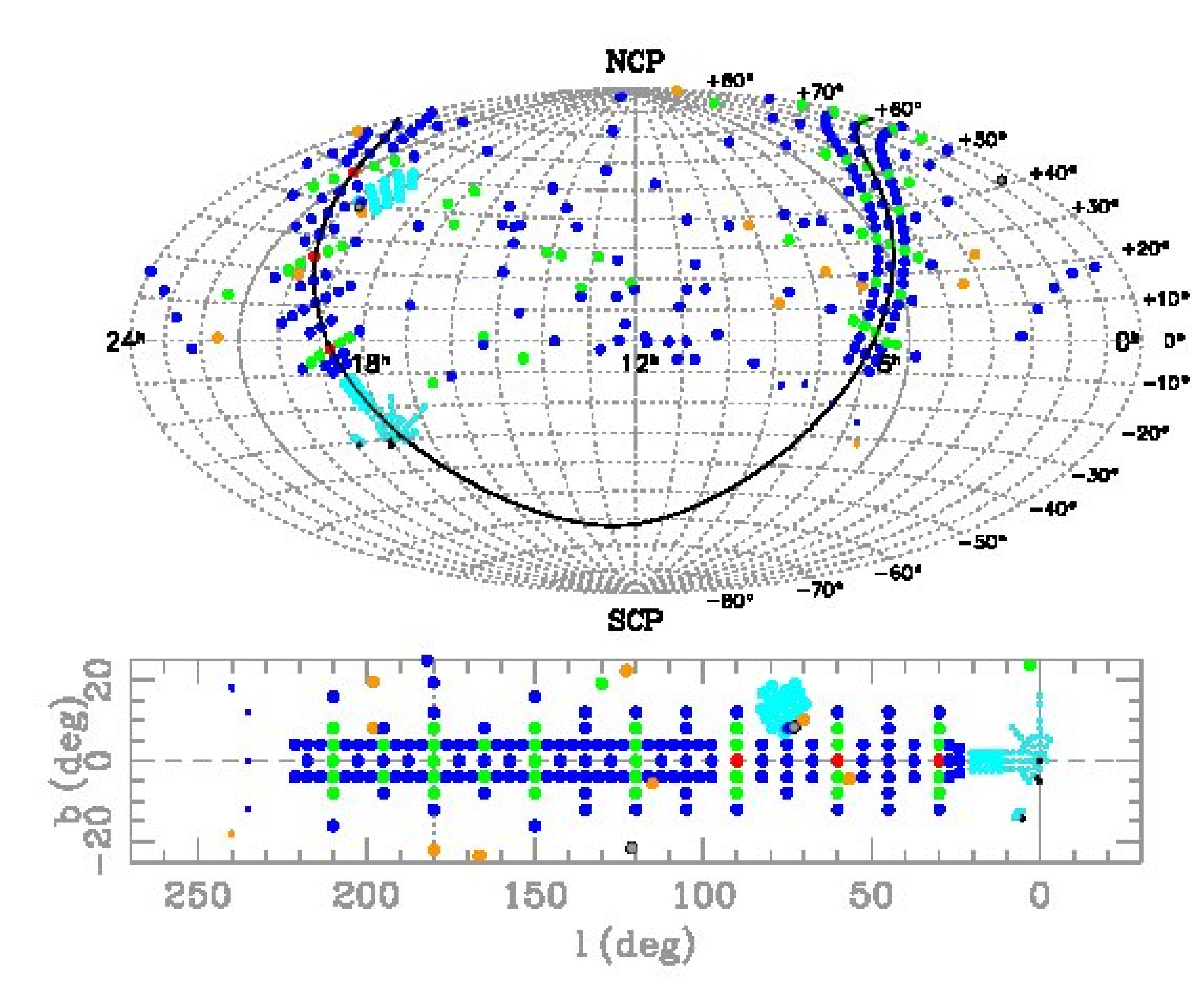
- Built at the University of Virginia with private industry and other SDSS-III collaborators. John Wilson: Instrument Scientist; Fred Hearty: Project Manager; Mike Skrutskie: Instrument Group Leader

- The APOGEE instrument employs a number of **novel technologies** to achieve 300-fiber multiplexing / high resolution / infrared.

- Integrated into fiber plugplate system of Sloan 2.5-m telescope (Spring 2011).



Field selection



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

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

Power of Chemistry

- Abundances provide record of conditions under which stars form
- Distributions of abundances contain information about gas inflow/outflow (e.g. G dwarf "problem")
- Detailed abundances provide a chemical "clock" (e.g. [α/Fe] ratios)
- Very detailed abundances may provide information about star formation site
- For lighter elements (e.g., CNO) abundances provide information about mixing processes in evolved stars

Disk structure and assembly

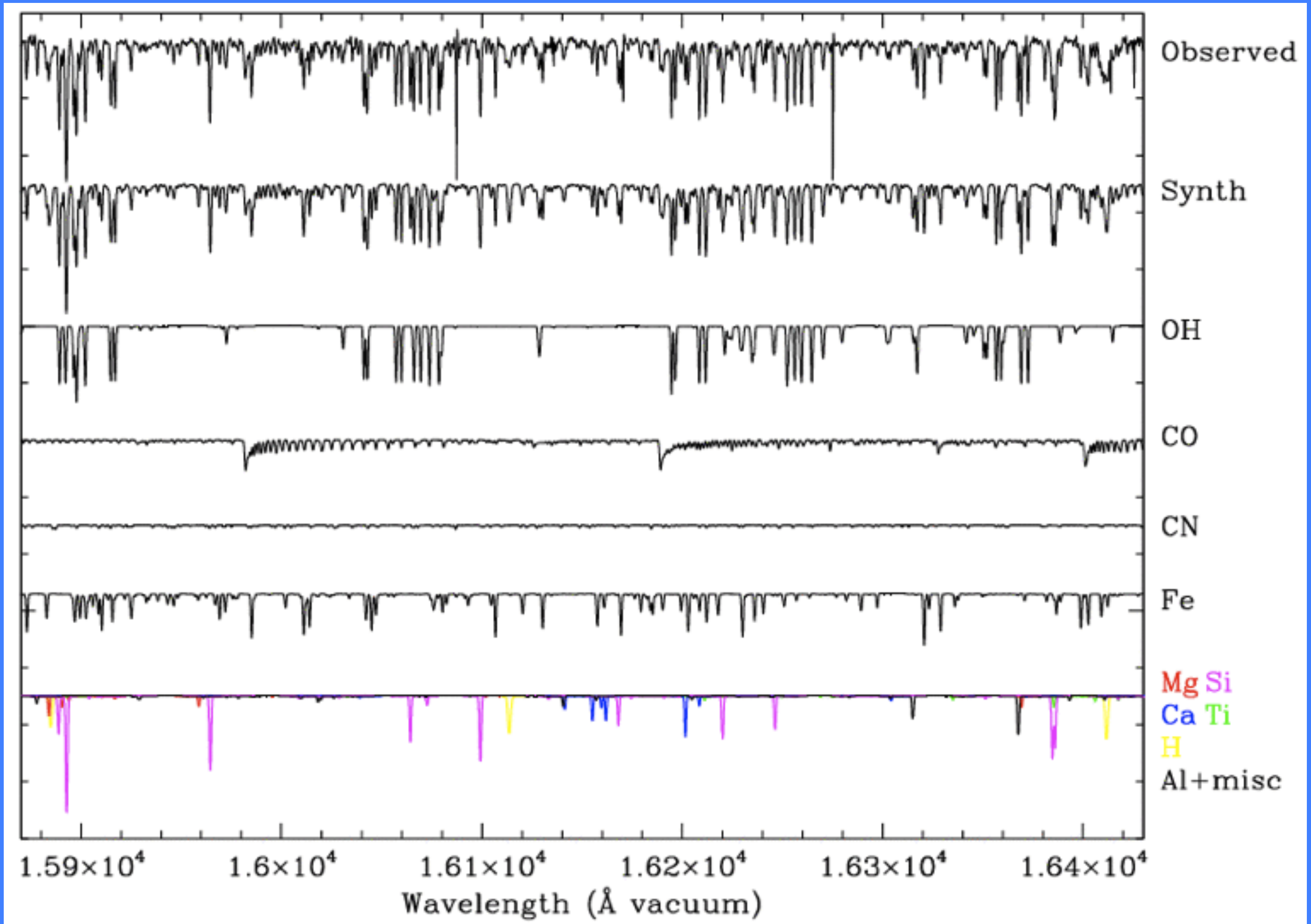
- Galaxy contains multiple stellar components: bulge/bar, thick/thin disk, halo
  - Disks form as gas accretes and cools within halos, generally thought to happen "inside-out", with possible contribution from stellar mergers dynamical instabilities can occur
  - Bulge may form from early mergers and/or from subsequent "secular" evolution
  - Thick disk : multiple possible formation mechanisms (external perturbation, disk thickness evolution, massive disk instabilities, radial migration)
- Would like to observationally constrain the importance of these processes
- Variation of abundance and abundance distribution with location and time provide key constraints
  - Chemical evolution models generally predict radial gradients but vary on how they evolve with time
  - Radial migration may affect gradients
  - Varying disk structure may affect gradients

APOGEE data

- First two years of data provide data for ~75000 giants
  - First year of data is public in SDSS DR10
- Abundance pipeline (ASPCAP) currently providing stellar parameters, overall metallicity ([M/H]), and [α/M] ratios
- Abundances have been validated/calibrated using cluster observations (Meszaros et al. 2013)

Abundances & Stellar Parameters

ASPCAP fitting to M3 giant spectrum



Distances

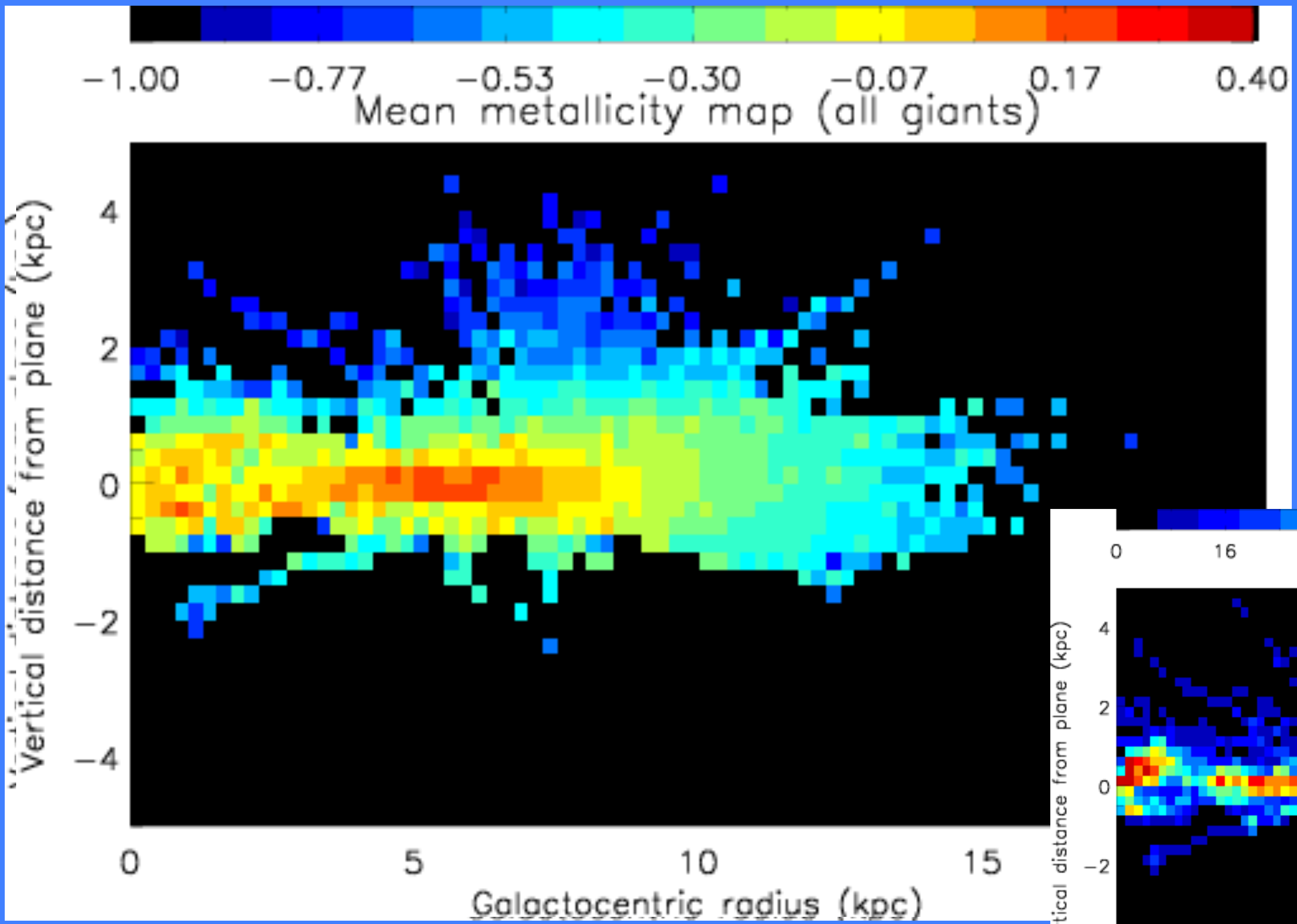
- Obtain distances using APOGEE/ASPCAP parameters and isochrones
  - What distance is most probable given observed magnitude, metallicity, surface gravity and temperature, given the relation between these (ncluding relative numbers) as given by our understanding of stellar evolution?
  - Alternatively, what mass is most probable given observed parameters? Given this mass, what distance is implied by observed parameters?
  - Can also include priors on distances, e.g. from expected density distribution
  - See, e.g., Burnett&Binney 2010, Binney et al 2014, Santiago et al 2014)
- Need extinction estimate: provided star-by-star using near-IR + mid-IR color (RJCE method; Majewski et al. 2011)

Avoiding biases

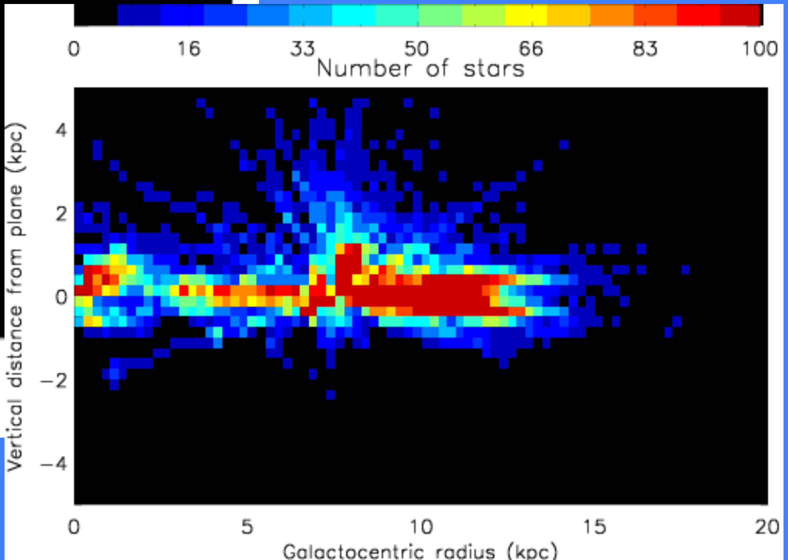
- Need to consider potential biases in observed metallicity distribution functions (MDFs)
  - Sample selection: APOGEE-1 color cut gives little biases for giants based on models (e.g., TRILEGAL)
  - Abundance analysis bias: currently no results for T<3500: biases against metal-rich stars at top of giant branch
    - Assess by comparing MDFs with various gravity cuts
    - Cut to log g > 0.9 avoids this except for the most-metal populations
  - Distance bias: beware of using metallicity-dependent variables as priors in distance determination!

Mean metallicity map

< [M/H] >

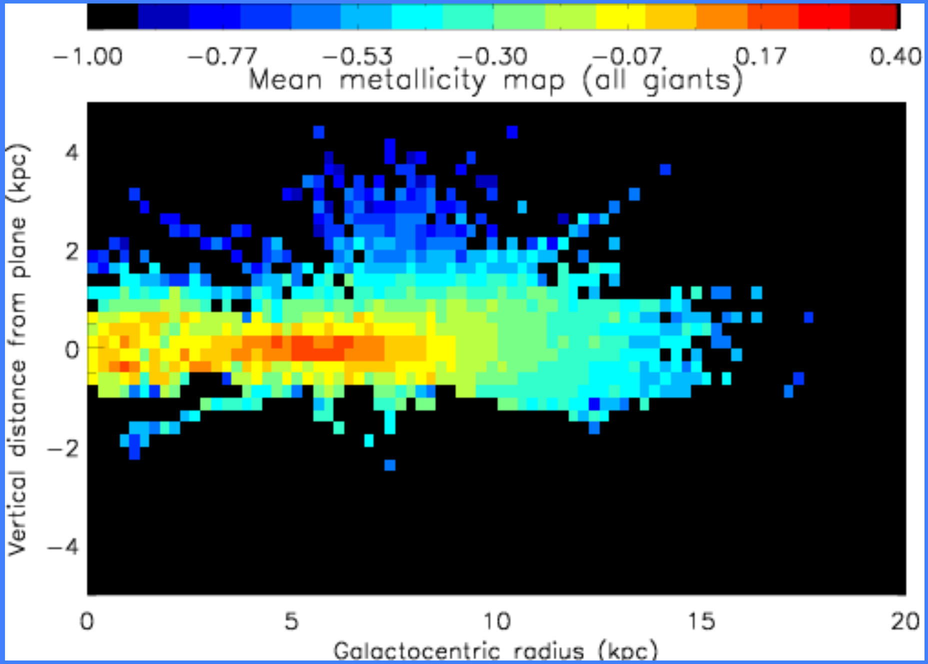


Number of stars



Mean metallicity map

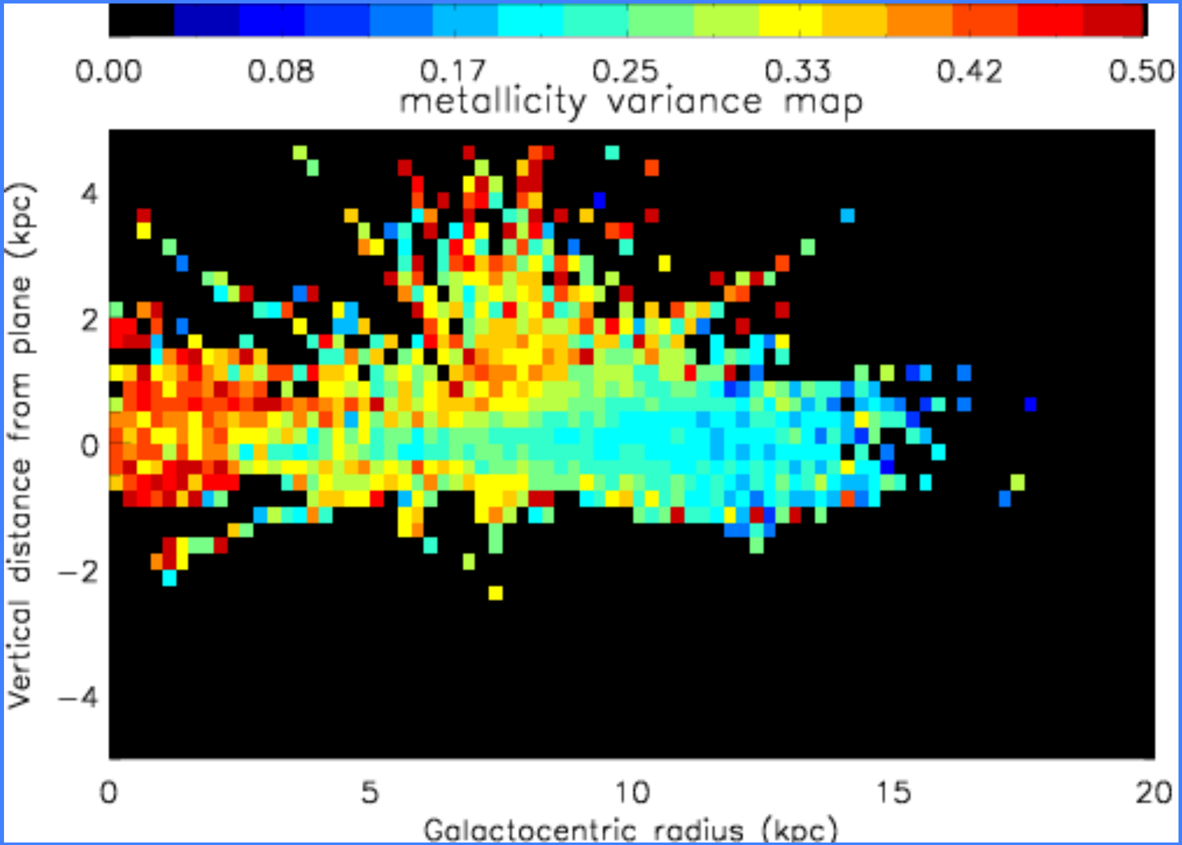
- Radial and vertical metallicity gradients are obvious
- Radial gradient flattens in inner regions
- In outer regions, gradient flatten above the plane
- Vertical gradients flatten with increasing Galactocentric radius



Results are generally consistent with previous results from numerous varied techniques, but have extended coverage, with more stars: in particular, inner disk

Metallicity spread

- Number of stars allows determination of metallicity spread
- At all locations, spread is larger than analysis uncertainties
- Metallicity spread varies with location



Additional information available in full shape of MDF!

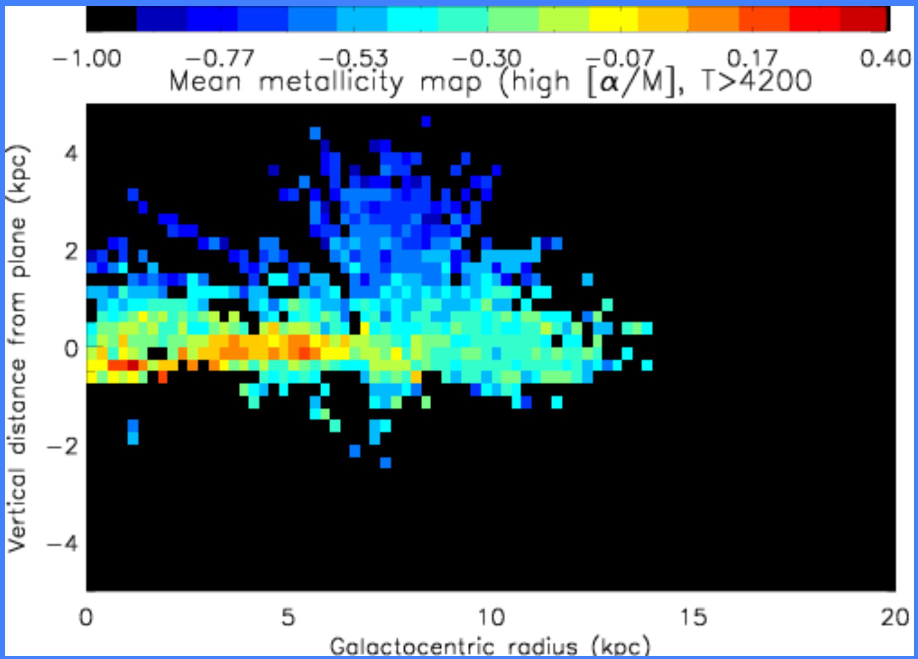
Red giant sample

- APOGEE targets are giants, which cover a wide range of ages
  - Typical ages of red clump stars ~2 Gyr
  - Typical ages of more luminous giants ~4 Gyr

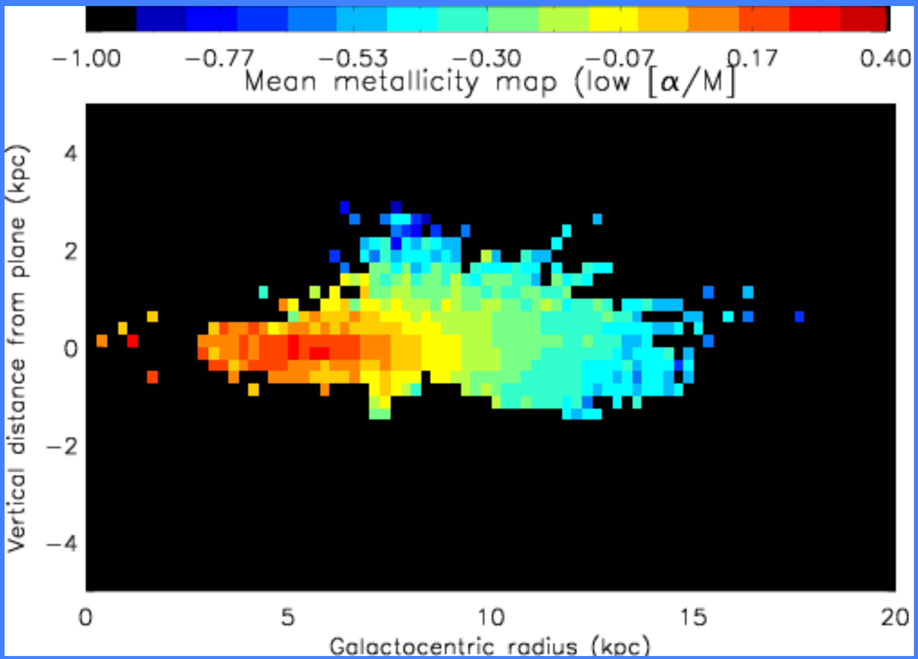
(but both depend on SF history)

Using [α/Fe] as an age proxy

High α/M stars

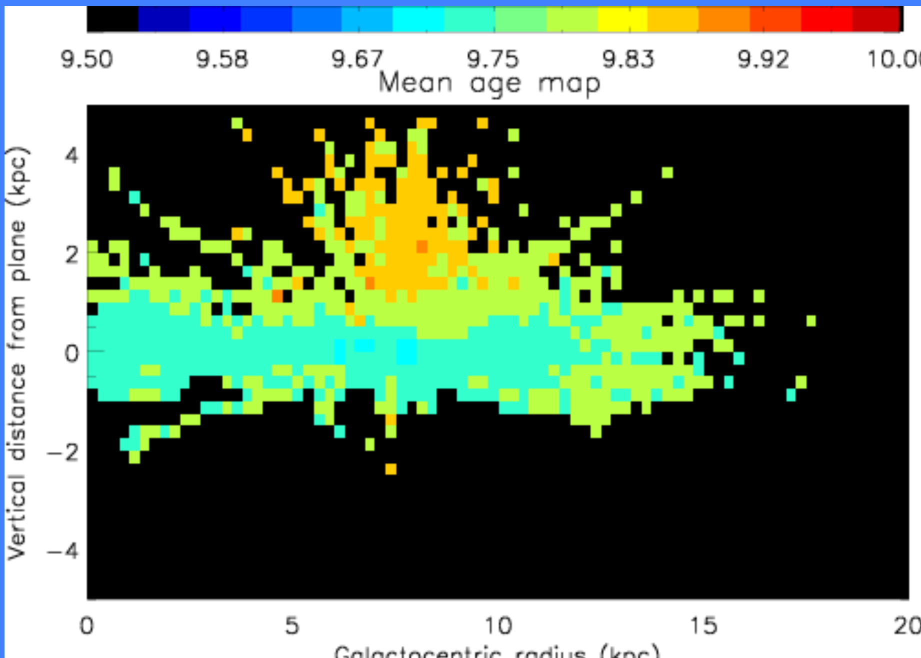


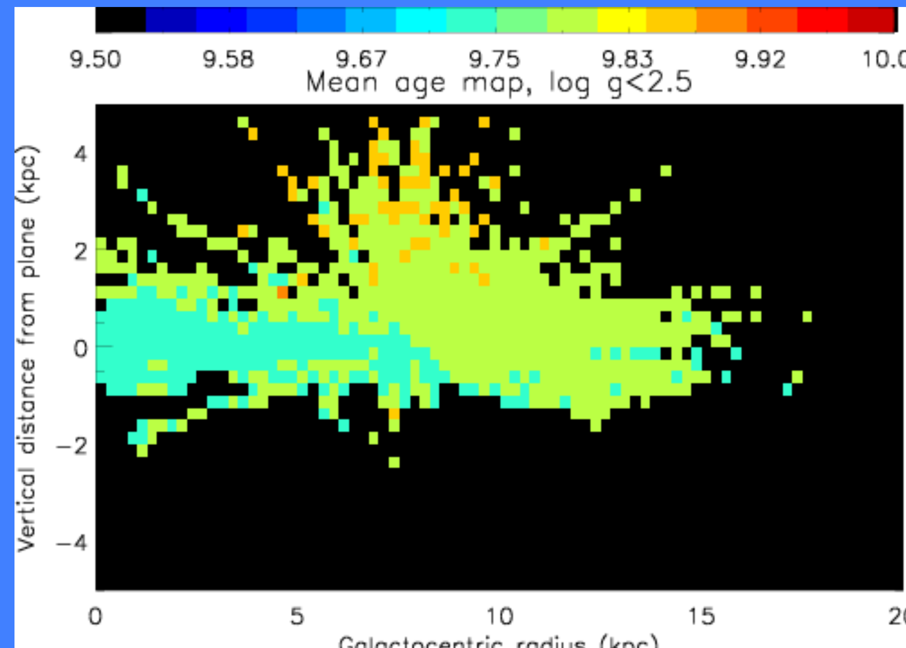
Low α/M stars



- Radial gradient significantly flatter for high [α/M] stars
- Radial gradient non-existent above plane for high [α/M] stars, but not for low [α/M] stars

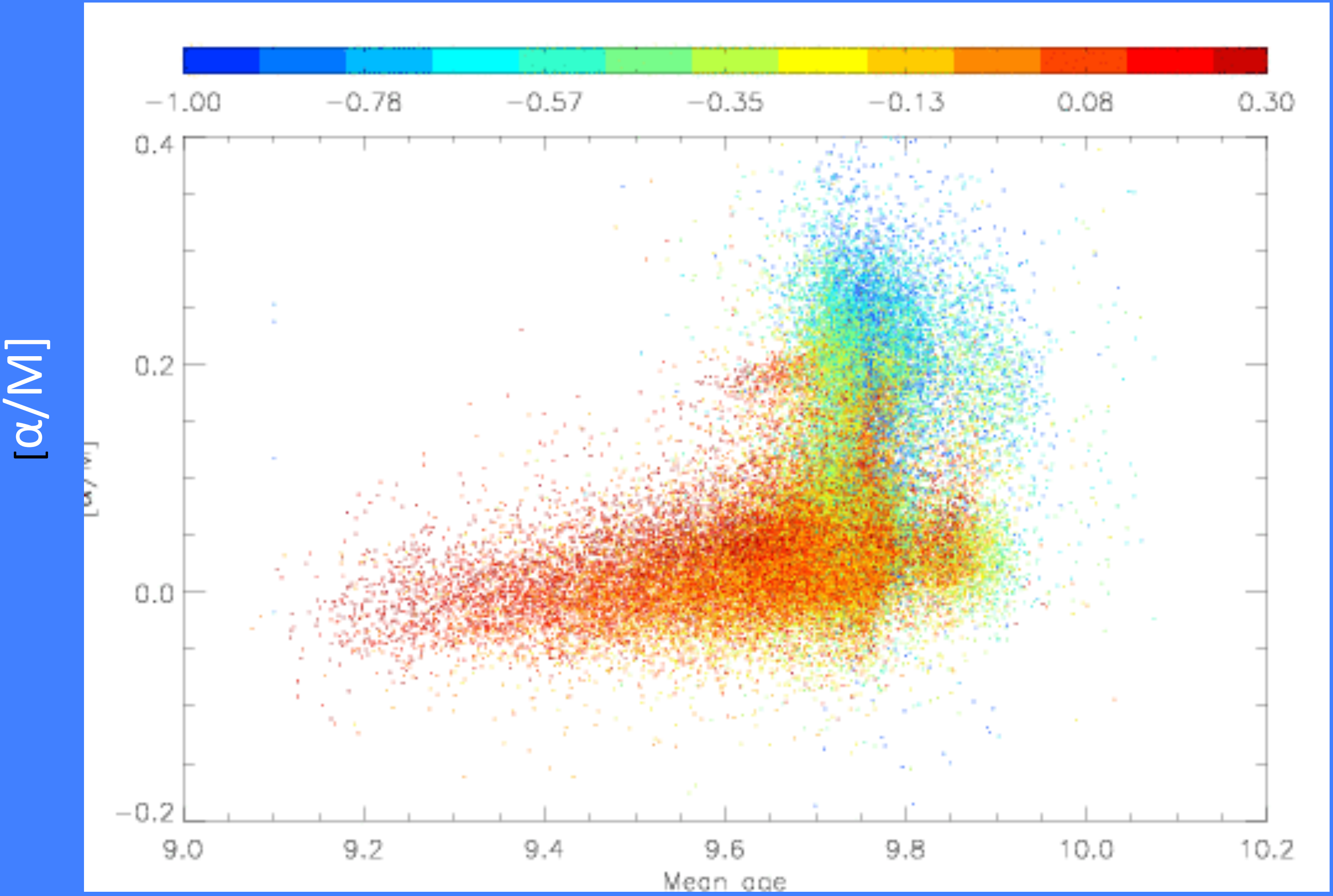
Direct age estimates





- Limited information on stellar ages is available via temperature of giant branch at given metallicity, but perhaps statistically contain information
- Different sampling at different distances needs to be considered
- Results depend on isochrone and may be sensitive to abundance ratio variations

Direct age estimates



Age estimate

Conclusions/Future work

- APOGEE is providing homogeneous chemistry information across much of the Galactic disk
- Many future directions:
  - MDFs
  - Individual element abundances
  - Kinematics / chemodynamics
  - Comparison with models, c.f. Minchev et al. 2013, Bird et al 2013

(for more details on work on DR10 sample,
see Hayden et al, AJ, astro-ph 1311.4569,
also Anders et al, A&A, astro-ph 1311.4549)