Astronomical Observations with Implications for Nuclear Astrophysics – Goals, Projects, and Future Efforts

Timothy C. Beers
Department of Physics & Astronomy
Michigan State University
& JINA: Joint Institute for Nuclear Astrophysics

Present JINA Involvements

- SDSS-II (Sloan Extension, from July 2005 to July 2008)
  - SEGUE: Sloan Extension for Galactic Understanding and Exploration
    - Beers @ MSU coordinating JINA involvement
  - Supernova Survey
    - Garnavich @ Notre Dame coordinating JINA involvement)

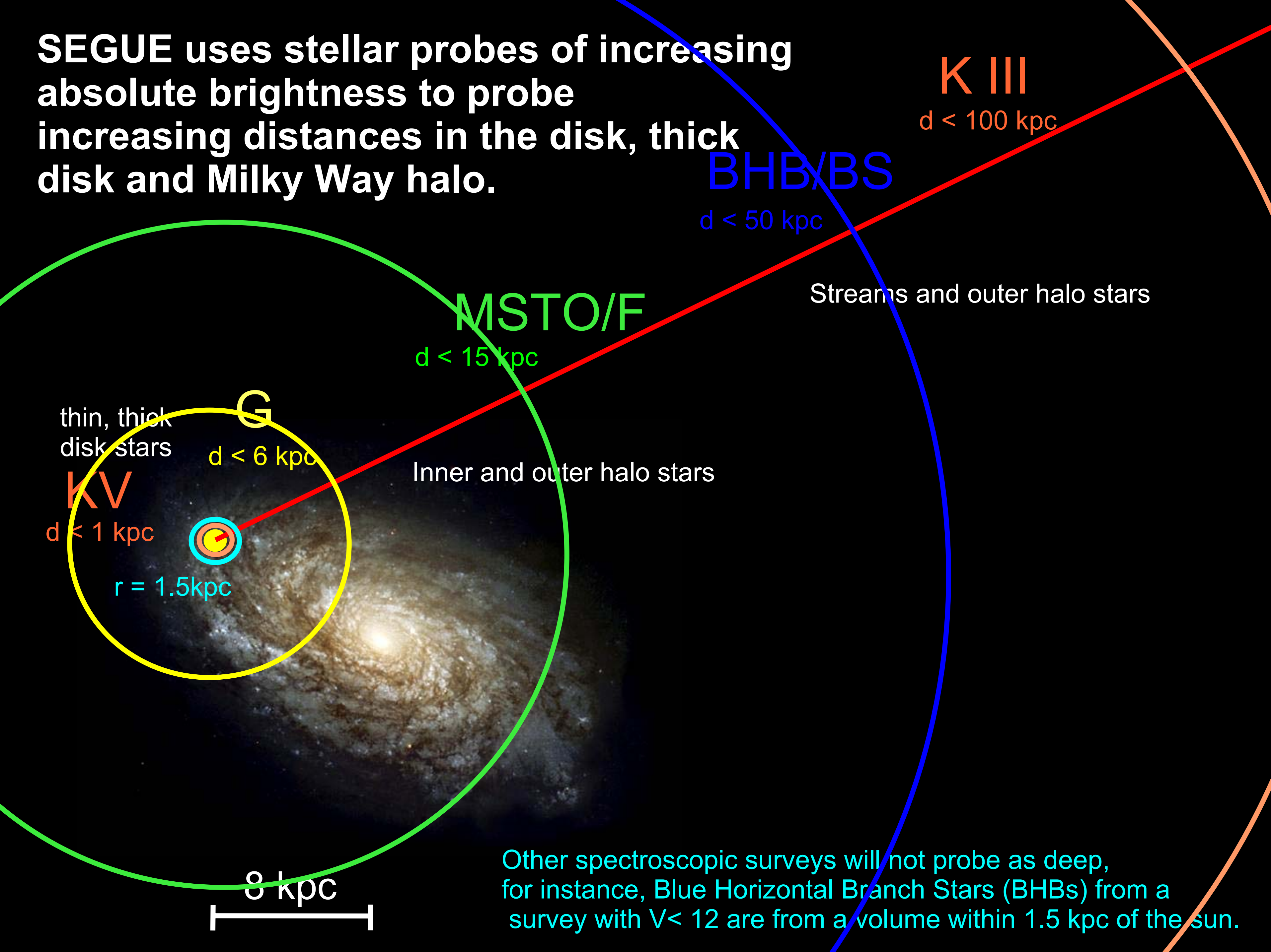
- International Collaborations
  - Australia (ARC grant to Asplund et al. / Skymapper Project)
  - Europe (Marie Curie Foundation CIFIST: Cosmological Impact of the First Stars; Bonifacio et al.)
  - Japan (close collaborations with Aoki et al.)
  - China (beginning collaborations with LAMOST project)

Present Observational Efforts

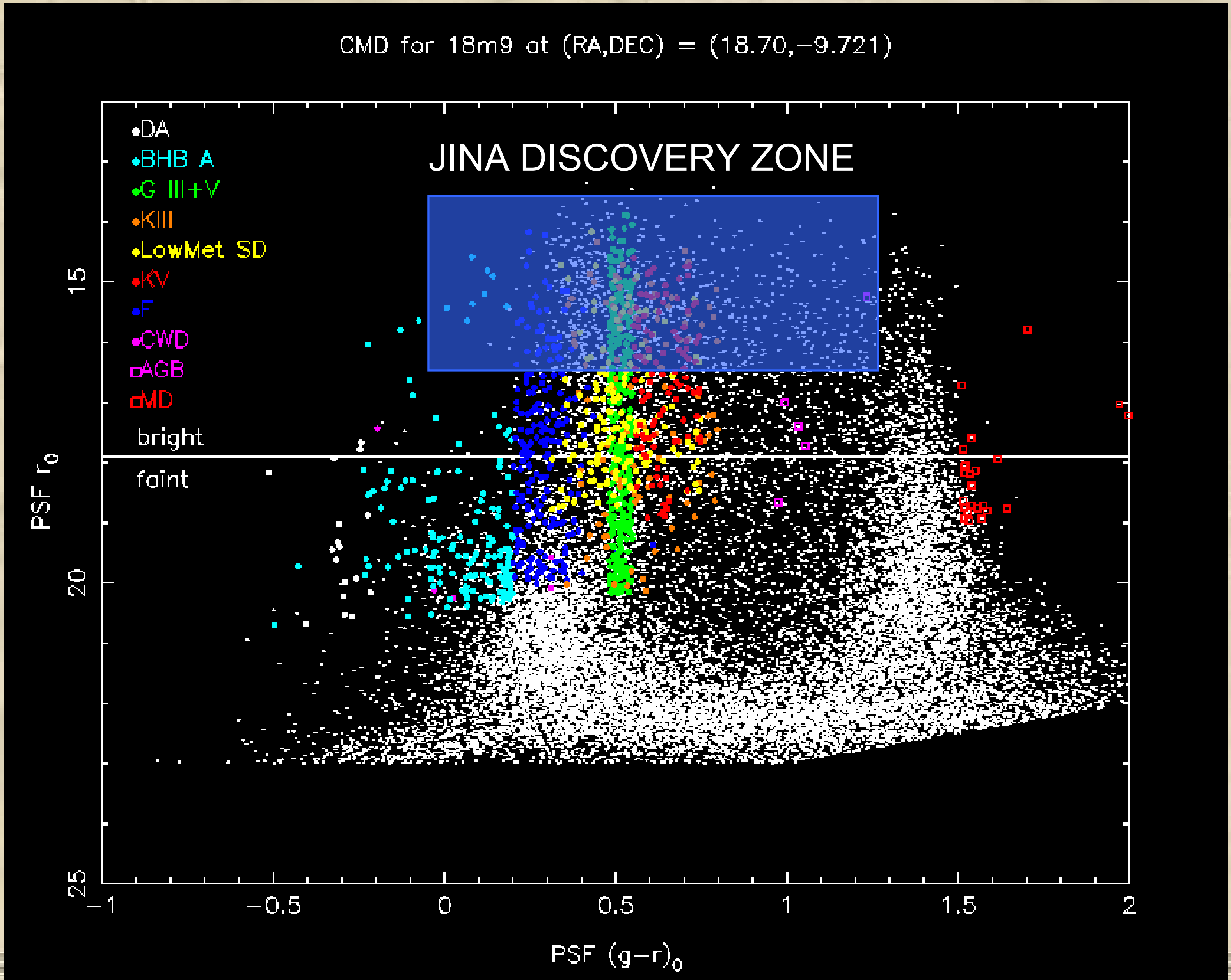
- MSU – Beers, Smith
  - Medium-resolution discovery of VMP ([Fe/H] < -2.0) stars (HK Survey; Hamburg/ESO Survey; SDSS/SEGUE)
  - High-resolution analysis of EMP (< -3.0), UMP (< -4.0), and HMP (< -5.0) stars (VLT; Subaru; Keck)
  - Near-IR observations of Carbon-Enhanced Metal-Poor (CEMP) stars (SOAR 4.1m MSU Partner)
- Notre Dame – Balsara, Garnavich, Howk, Mathews
  - Center for Astrophysics at Notre Dame University (CANDU)
  - Beginning soon (?), access to LBT
  - Observations of VMP stars / Damped Lyman alpha systems

Summary of SEGUE and Supernova Survey

- SEGUE
  - Obtain 3500 square degrees of new ugriz imaging at lower galactic latitude than SDSS-I ($|b| > 40^o$)
  - Obtain medium resolution spectroscopy (2.5 A) of 250,000 optimally selected stars for exploration of galactic structure and chemical evolution
- Supernova Survey
  - Discovery of intermediate redshift ($0.1 < z < 0.3$) Type Ia SN by intensive repeated scans of an equatorial stripe
  - A 2.5 degree wide region along the celestial equator, from roughly -60 < RA < 60, (SDSS Stripe 82) is imaged repeatedly for three months (September, October and November) in each of three years (2005-2007).
  - Confirmation of Type Ia status by (external) spectroscopic follow-up
- JINA's Financial Commitment
  - $250K, comprising $125K from Notre Dame, and $125K of "in kind" development work at MSU
  - MSU In Kind commitment is for development, testing, and refinement of SEGUE spectroscopic analysis pipeline (Teff, log g, [Fe/H])
  - Personnel: Beers (free) + ½ of JINA postdoc (Sivarani) + ½ of JINA grad student (Lee)


SEGUE uses stellar probes of increasing absolute brightness to probe increasing distances in the disk, thick disk and Milky Way halo.
K III
d < 100 kpc
BHB/BS
d < 50 kpc
Streams and outer halo stars
MSTO/F
d < 15 kpc
G
d < 6 kpc
thin, thick disk stars
Inner and outer halo stars
KV
d < 1 kpc
r = 1.5kpc
8 kpc
Other spectroscopic surveys will not probe as deep, for instance, Blue Horizontal Branch Stars (BHBs) from a survey with V< 12 are from a volume within 1.5 kpc of the sun.

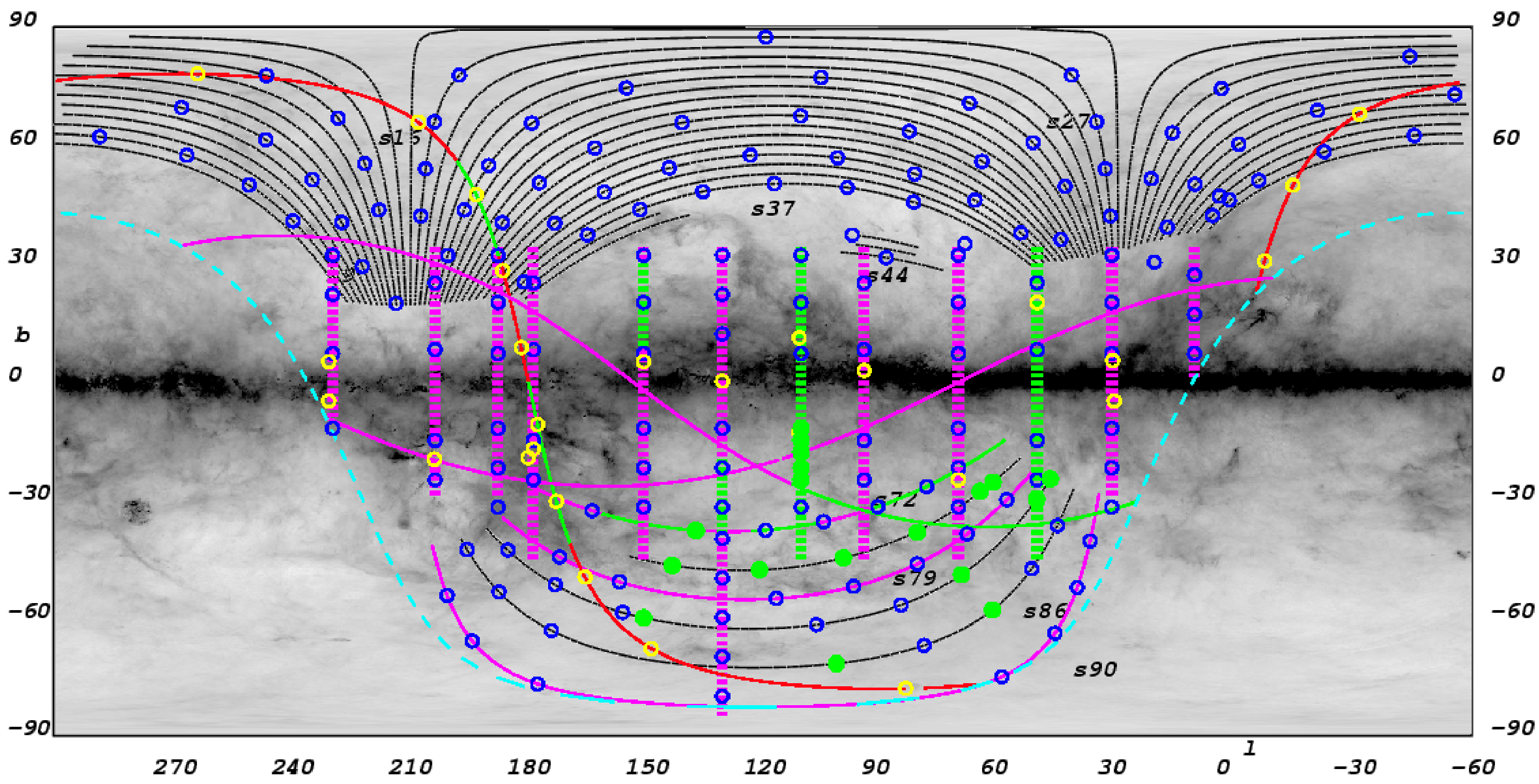
SEGUE Target Selection– “JINA-fied”



Present Status of SEGUE and Supernova Survey

- SEGUE
  - Tests of target selection algorithms carried out fall 2004 and spring 2005
  - Began taking “real” data in July 2005
  - To date, approximately 2/3 of imaging (2300 square degrees) and over 1/3 of spectroscopy (95,000 stars) observed – first public release of SEGUE data (year 1) in June 2007
  - Essentially final version of SEGUE Spectroscopic Parameter Pipeline completed
  - High-resolution follow-up of SEGUE stars for validation and refinement of spectroscopic pipeline underway (HET / Subaru / Keck)
- Supernova Survey
  - Tests of cadence, rapid processing (at APO) carried out fall 2004
  - Completed two of three planned sets of scans of Stripe 82 fall 2005, fall 2006, final sets expected fall 2007
  - Discovery of over 250 confirmed Type Ia supernovae

SEGUE observing plan and status as of Mar 2007



SDSS Imaging scan

Declination = -20 degrees

Planned SEGUE scan (3500 sq deg)

Planned SEGUE grid pointings (200)

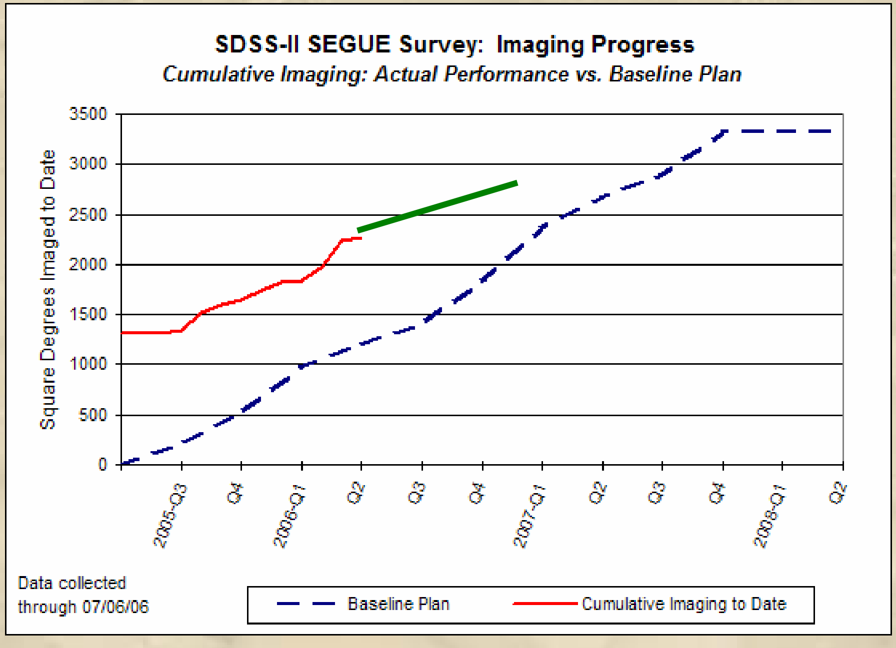
Sgr stream planned scan

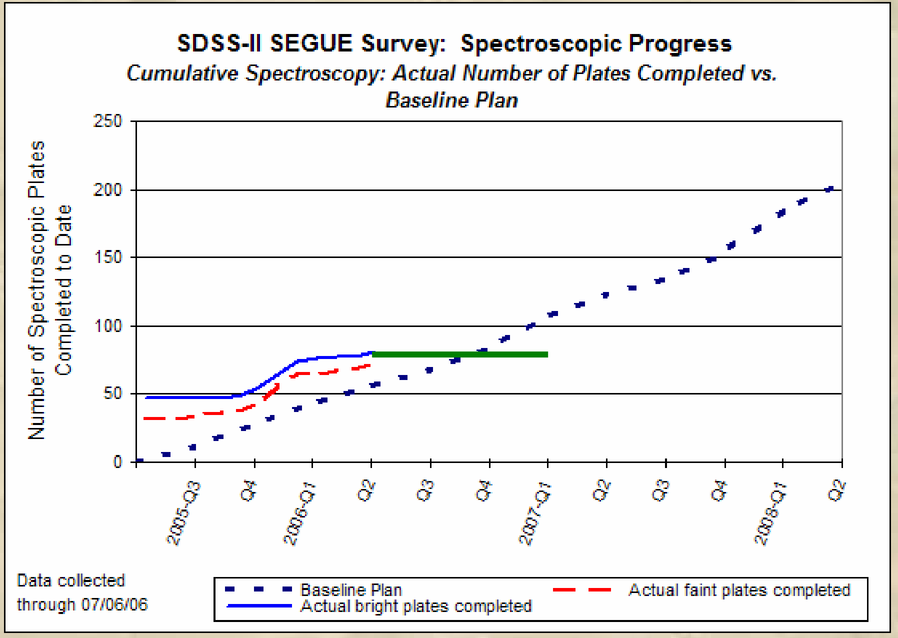
Planned targeted SEGUE pointings(60)

Completed SEGUE imaging

Completed SEGUE plate pointing

SEGUE Imaging and Spectroscopy Status





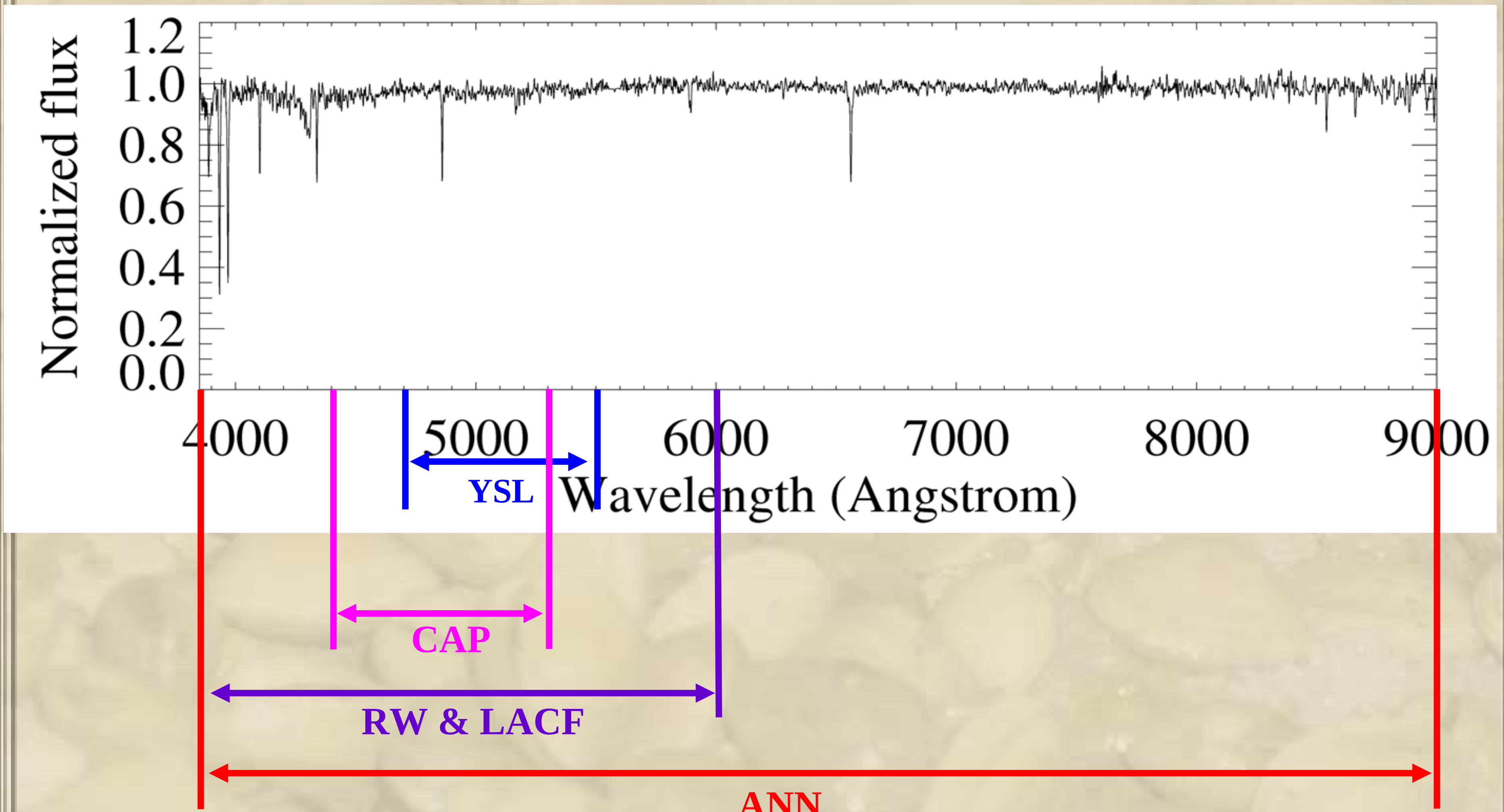
- Plans above indicate the present status of SEGUE imaging and spectroscopic followup. Imaging is ahead of schedule, spectroscopy expected to increase this spring.

Highlights of SDSS-I/SEGUE

- Development / Validation of SEGUE Spectroscopic Parameter Pipeline software (SSPP)
- Discovery of large numbers of MP stars
- Discovery of large numbers of CEMP stars
- Discovery of new dwarf galaxy interactions with MW, and new debris streams
- Discovery of Dichotomy of Halo – Inner Halo/ Outer Halo

SSPP - Methodology I

There are 9 methods for determining [Fe/H], 7 for log g, and 5 for T_{eff}. Each approach makes use of different wavelength coverage or line bands for estimating parameters.



SSPP - Methodology II

YSL (Lee et al. 2007, submitted)

- **uses χ^2 minimization with synthetic templates over the wavelength range of T_{eff} (4700-5500Å), log g(5150-5220 Å), [Fe/H] (5220-5500 Å, 3900-4000 Å)**
- **grid of synthetic spectra :**
  T_{eff} = 3500~10000 K(Δ 250 K), log g =0.0 ~ 5.0(Δ 0.5), [Fe/H]=-4.0 ~ +0.5(Δ 0.5)

ANN (Re Fiorentin et al. 2007, submitted)

- **trains network on SEGUE spectra with previously estimated parameters and estimates T_{eff}, log g, and [Fe/H]**

RW (Wilhelm et al. 1999)

- **fits Balmer lines with Voigt or Gaussian profiles for T_{eff}, the G-band for log g, and the Ca II K line and other metallic indices for [Fe/H]**
- **grid of synthetic spectra :**
  T_{eff} = 3500~9750 K(Δ 250 K), log g =1.0 ~ 4.5(Δ 0.5), [Fe/H]=-3.0 ~ +0.0(Δ 0.5)

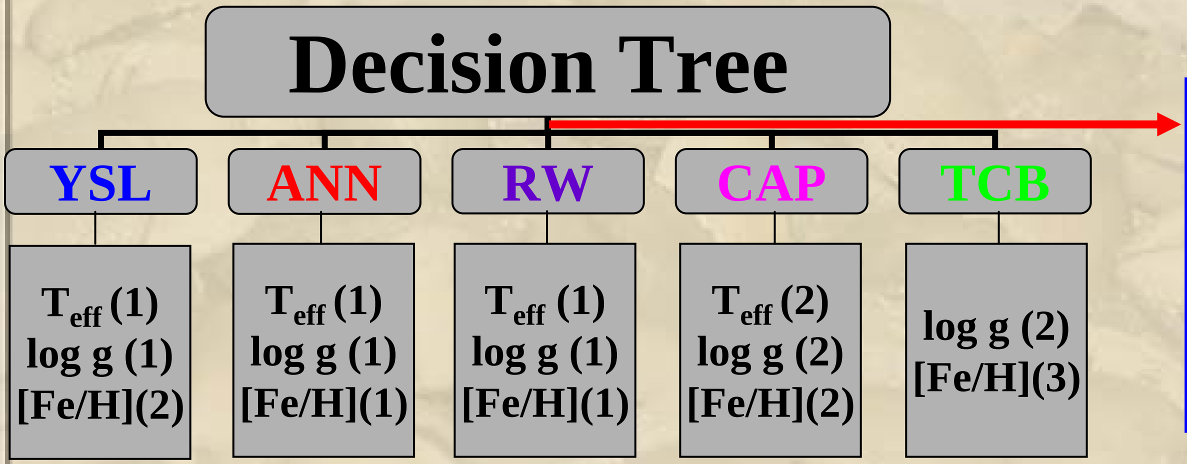
CAP (Allende-Prieto et al. 2006)

- **uses χ^2 minimization with different synthetic spectral templates (k24 and ki13) over (4400 – 5300 Å) for T_{eff}, log g, and [Fe/H]**
- **grid of synthetic spectra (k24) :**
  T_{eff} = 4500~9250 K(Δ 500 K), log g =1.5 ~ 5.0(Δ 0.5), [Fe/H]=-4.83 ~ +0.63(Δ 0.5)
- **grid of synthetic spectra (k24) :**
  T_{eff} = 4500~7750 K(Δ 500 K), log g =1.0 ~ 5.0(Δ 0.5), [Fe/H]=-3.83 ~ +0.63(Δ 0.5)

TCB (Beers et al. 1999)

- **uses (*B-V*)/Ca II K (3933 Å), Ca II Triplet (around 8550 Å) line index, and LACF for [Fe/H] and Ca I (4227 Å) and MgH (around 5170 Å) line index for log g.**

SSPP - Methodology III

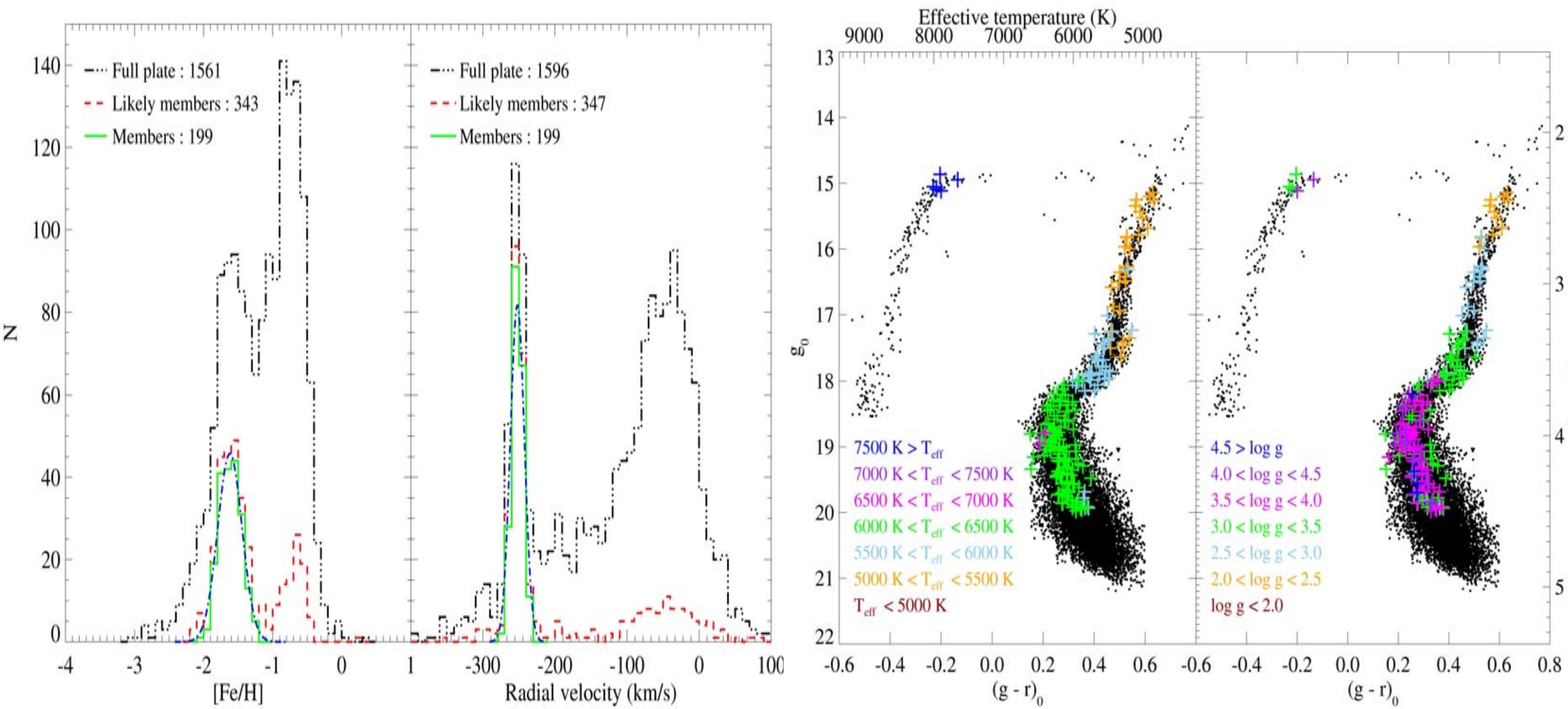


Determine which method is available, mostly depending on T_{eff}, and calculate robust mean from available parameters.

(The number in parenthesis is the number of estimates.)

Validation with Globular Clusters

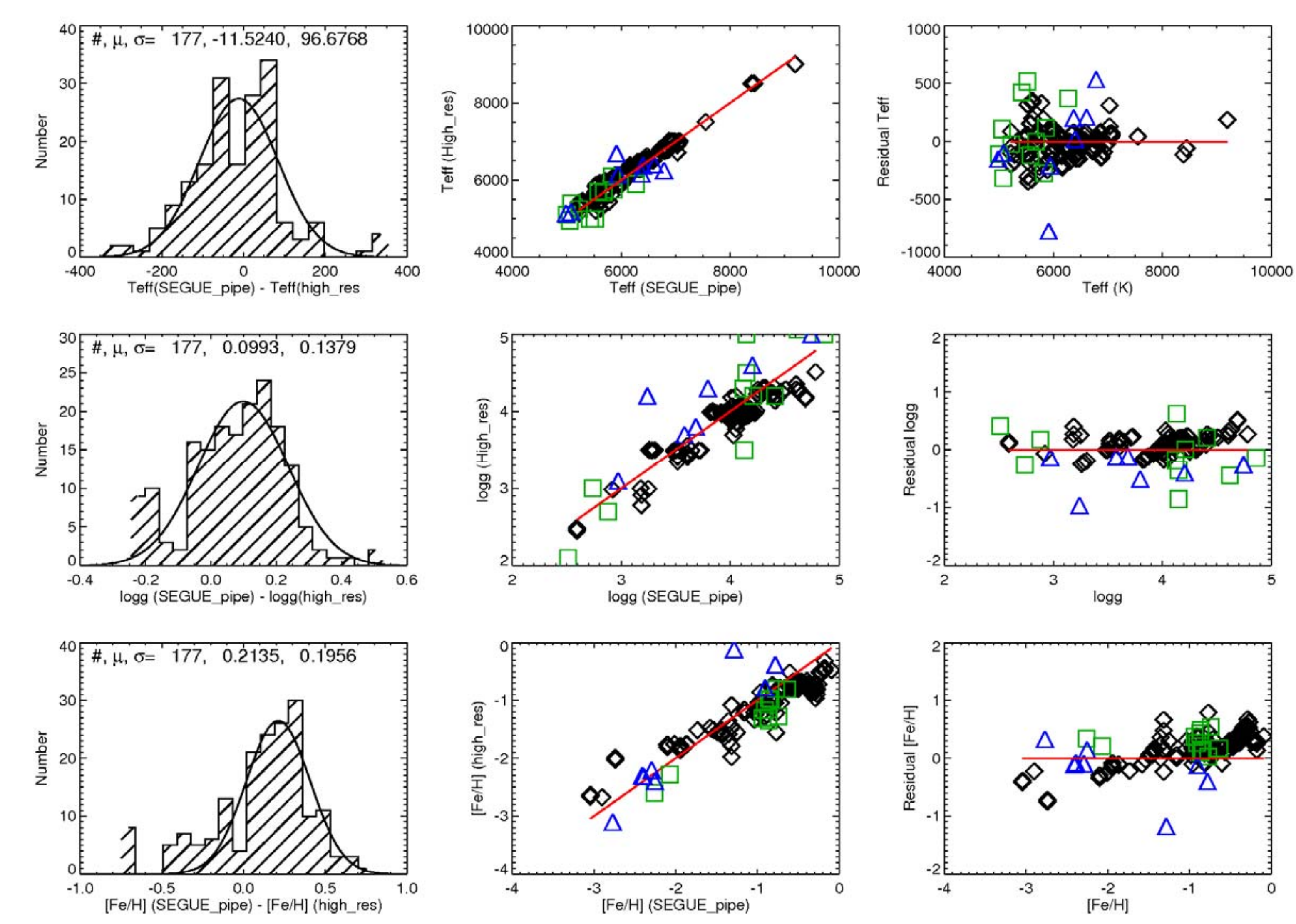
After selecting member stars of M 13, the cluster metallicity is calculated by fitting a Gaussian (left panel). We obtained [Fe/H] = -1.62 (-1.63, Kraft & Ivans 2003) with σ=0.18. We also examined T_{eff} and log g distribution of the members on CMD (right panels). Note how well the temperature and gravity are estimated along the CMD (see Lee et al. 2007 for more clusters and details).



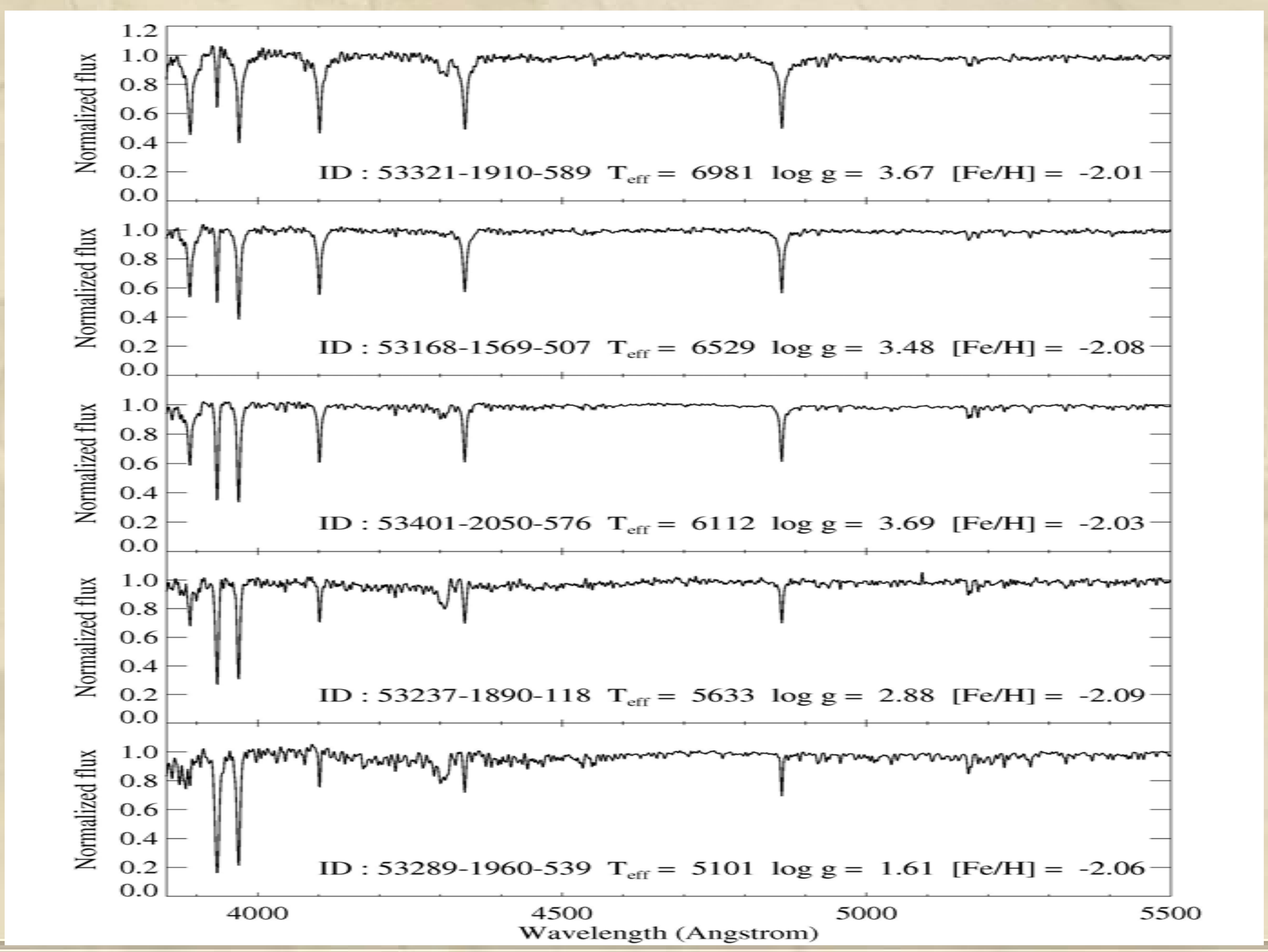
High-Res Observations To Date

Telescope	Instrument	Resolution R=λ/Δλ	Wavelength Coverage Å	No. stars
HET	HRS	15000	4500 - 7000	112
Keck	HIRES	45000	3000-10000	24
Keck	ESI	6000	3000-10000	27
Subaru	HDS	45000	3000-5800	11

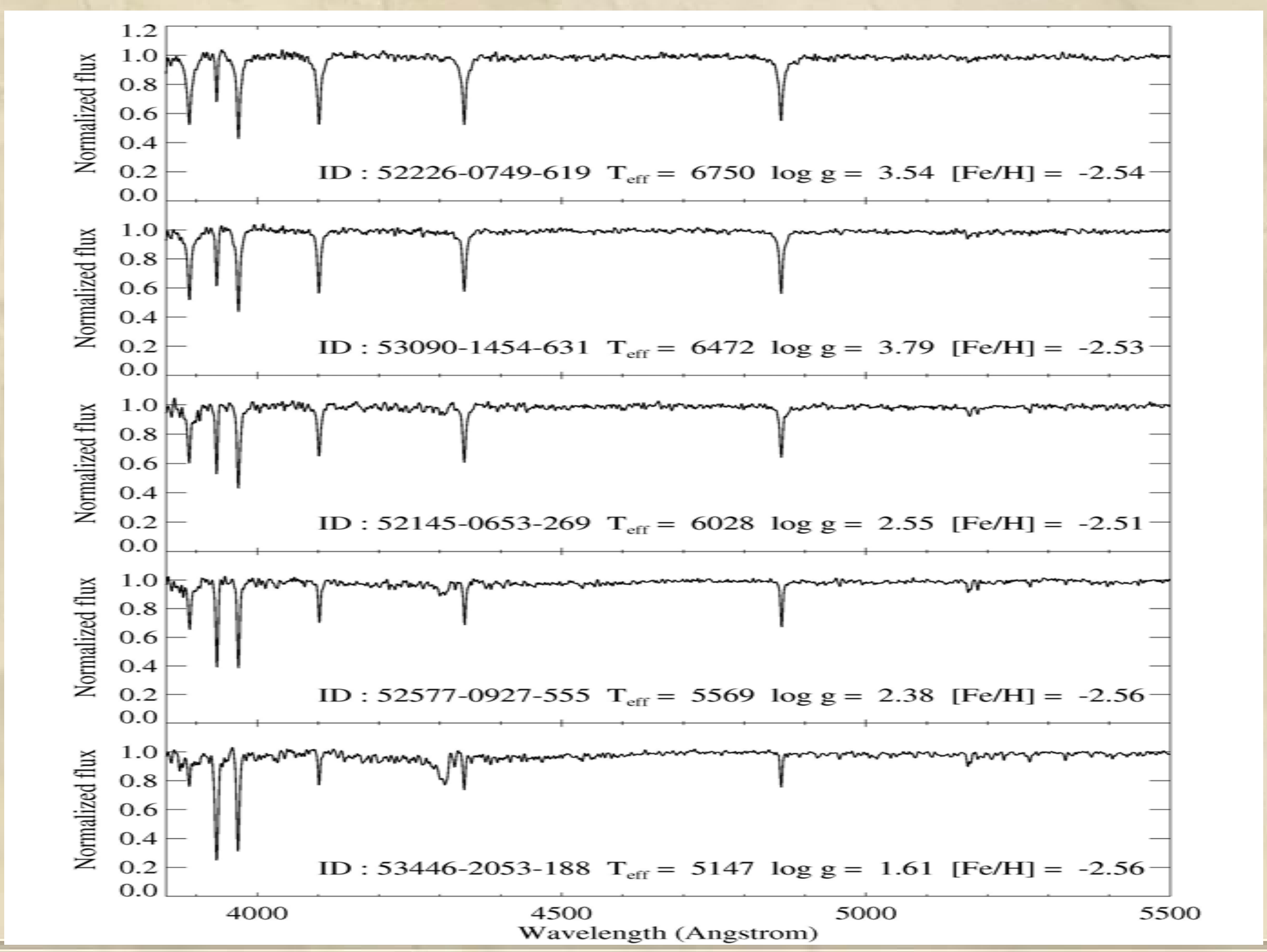
RESULTS OF HIGH-RES COMPARISONS TO DATE



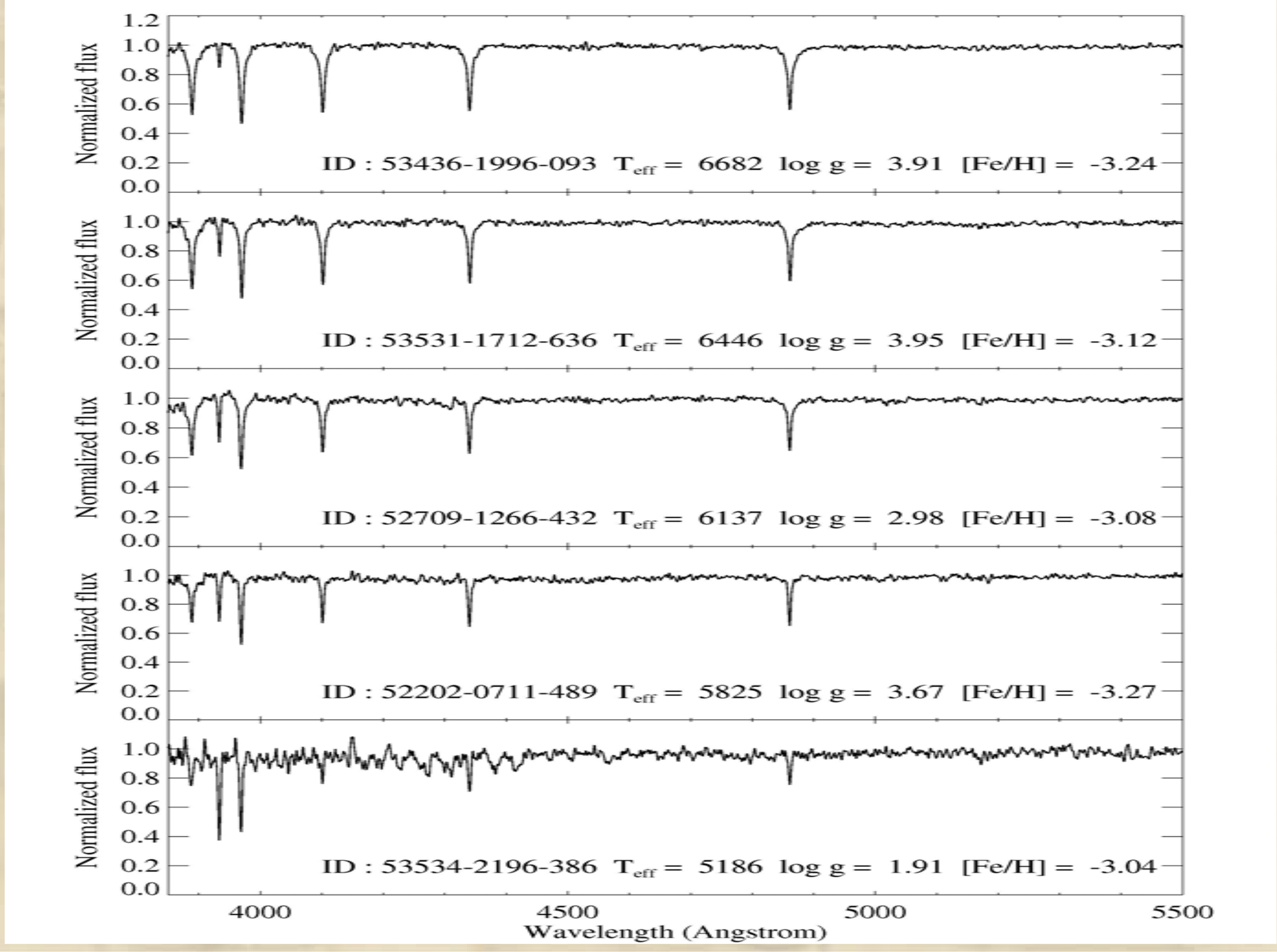
Sample SDSS-I Spectra with [Fe/H] ~ −2.0



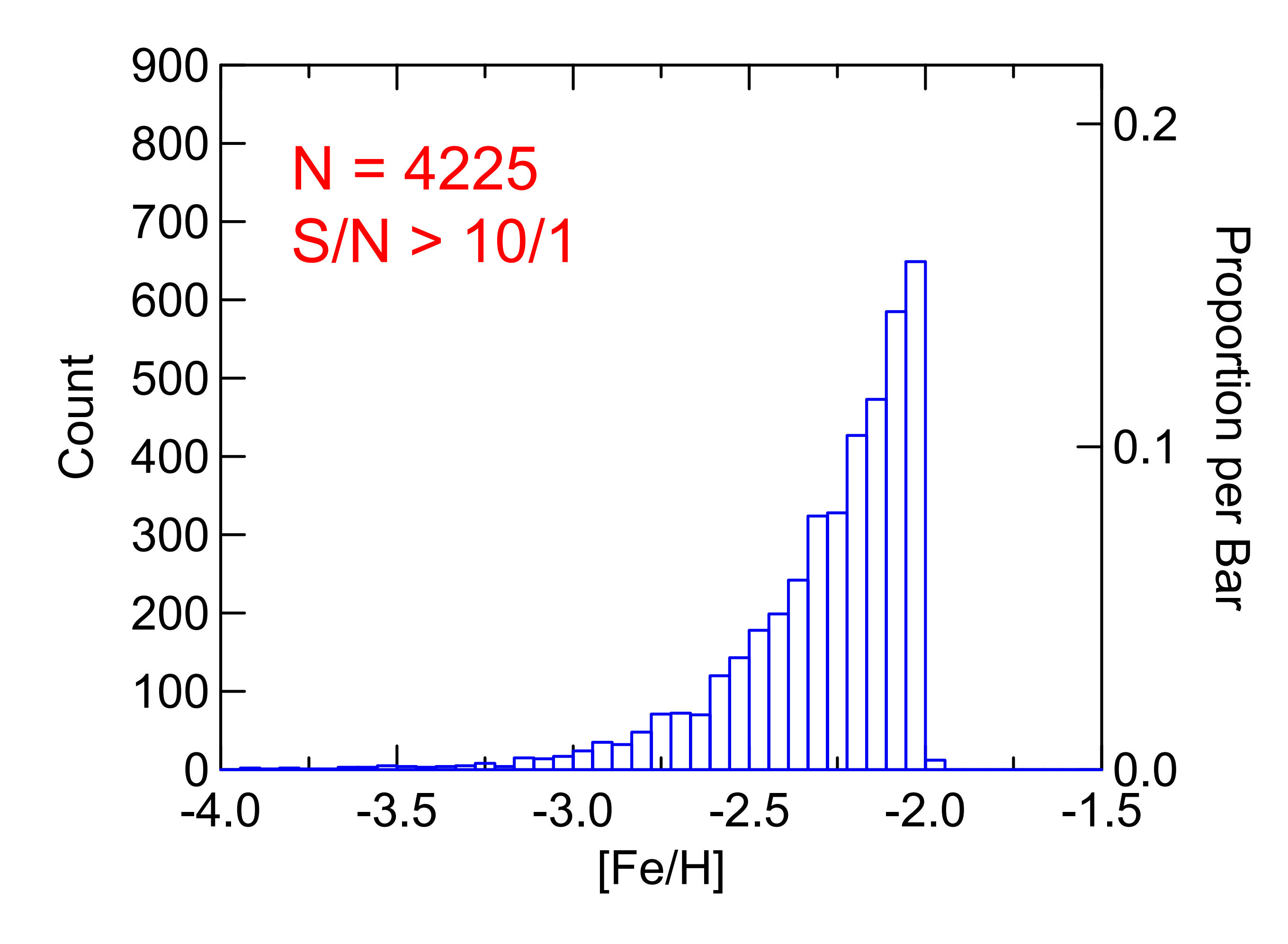
Sample SDSS-I Spectra with [Fe/H] ~ −2.5



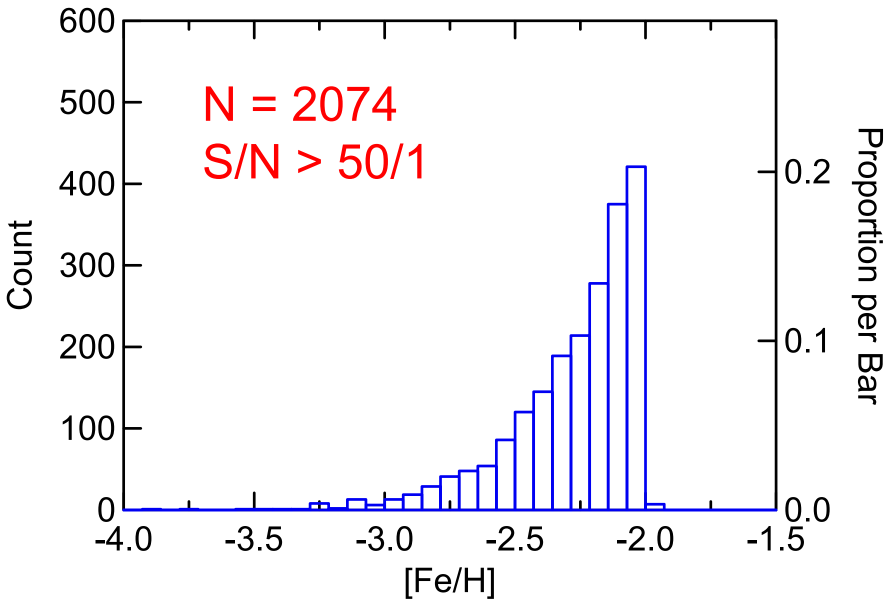
Sample SDSS-I Spectra with [Fe/H] < −3.0

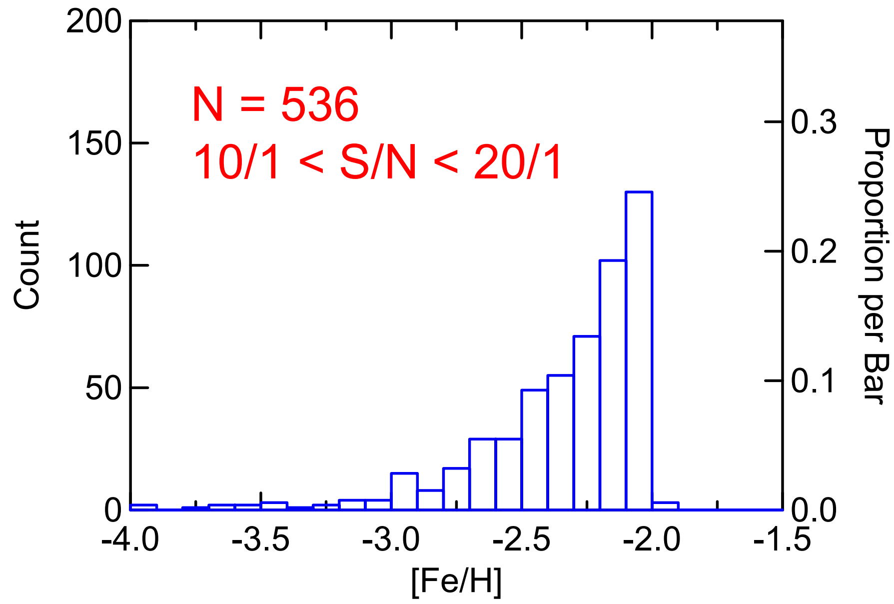


The Low-Metallicity Tail of the Metallicity Distribution Function of SDSS-I Stars



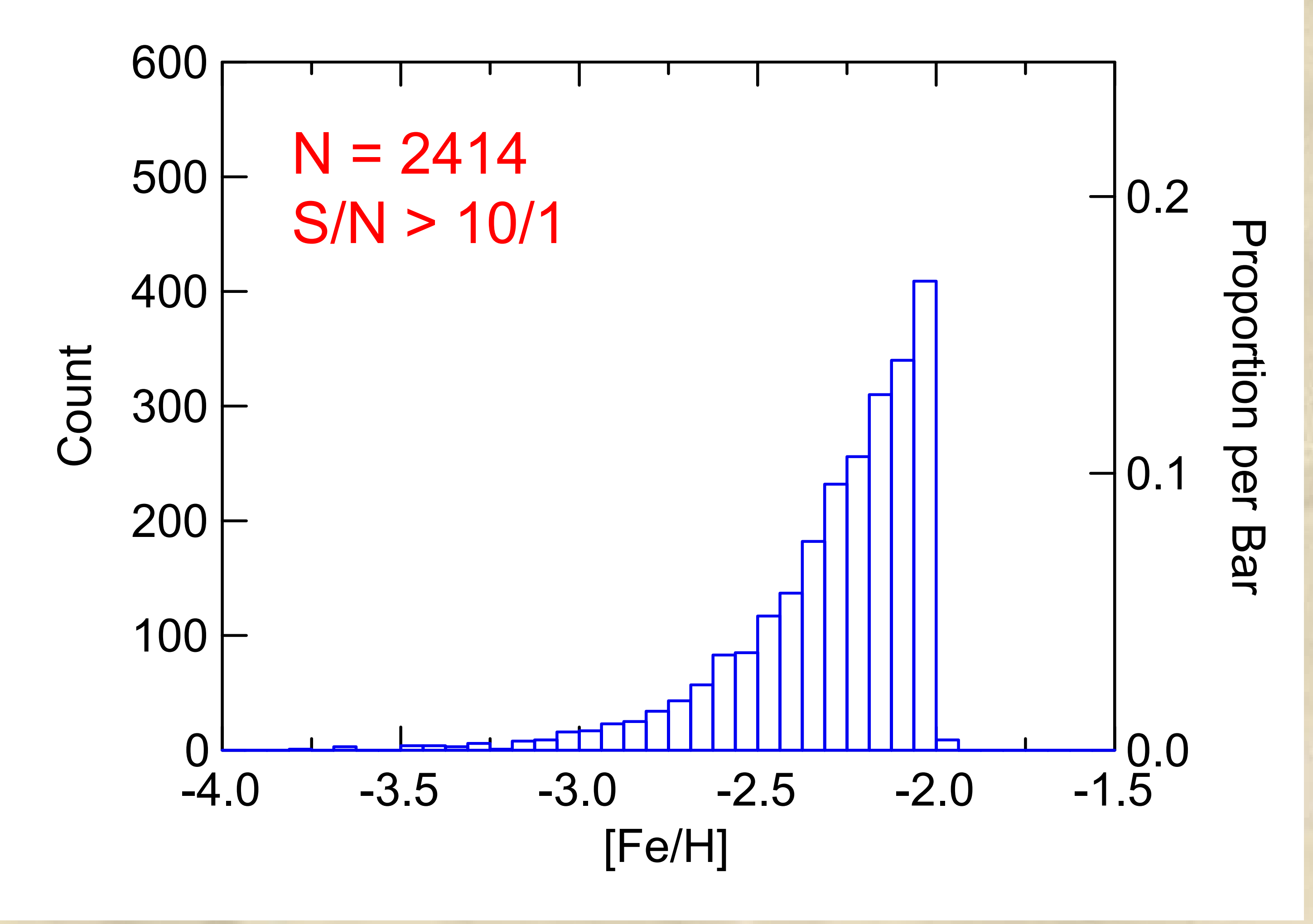
Comparison of HI and LOW S/N MDFs – SDSS-I



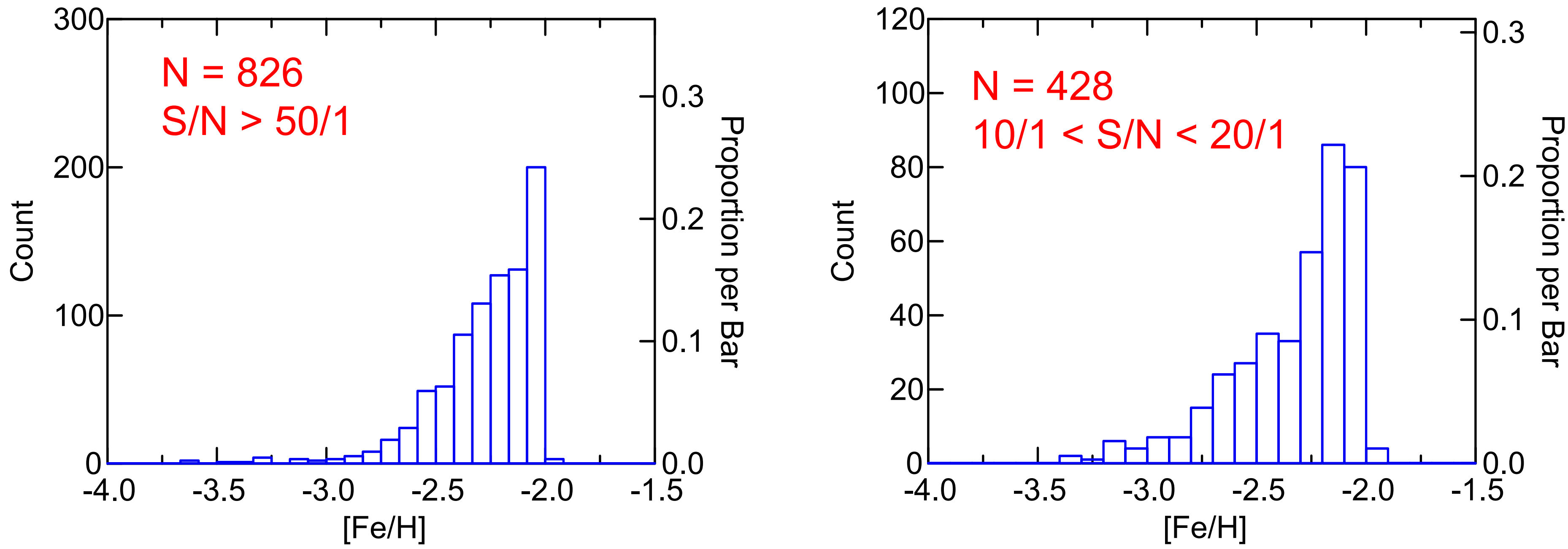


Note that the lower S/N sample includes a number of likely spurious results for [Fe/H] < −3.0.

The Low-Metallicity Tail of the Metallicity Distribution Function of SEGUE Stars



Comparison of HI and LOW S/N MDFs -- SEGUE



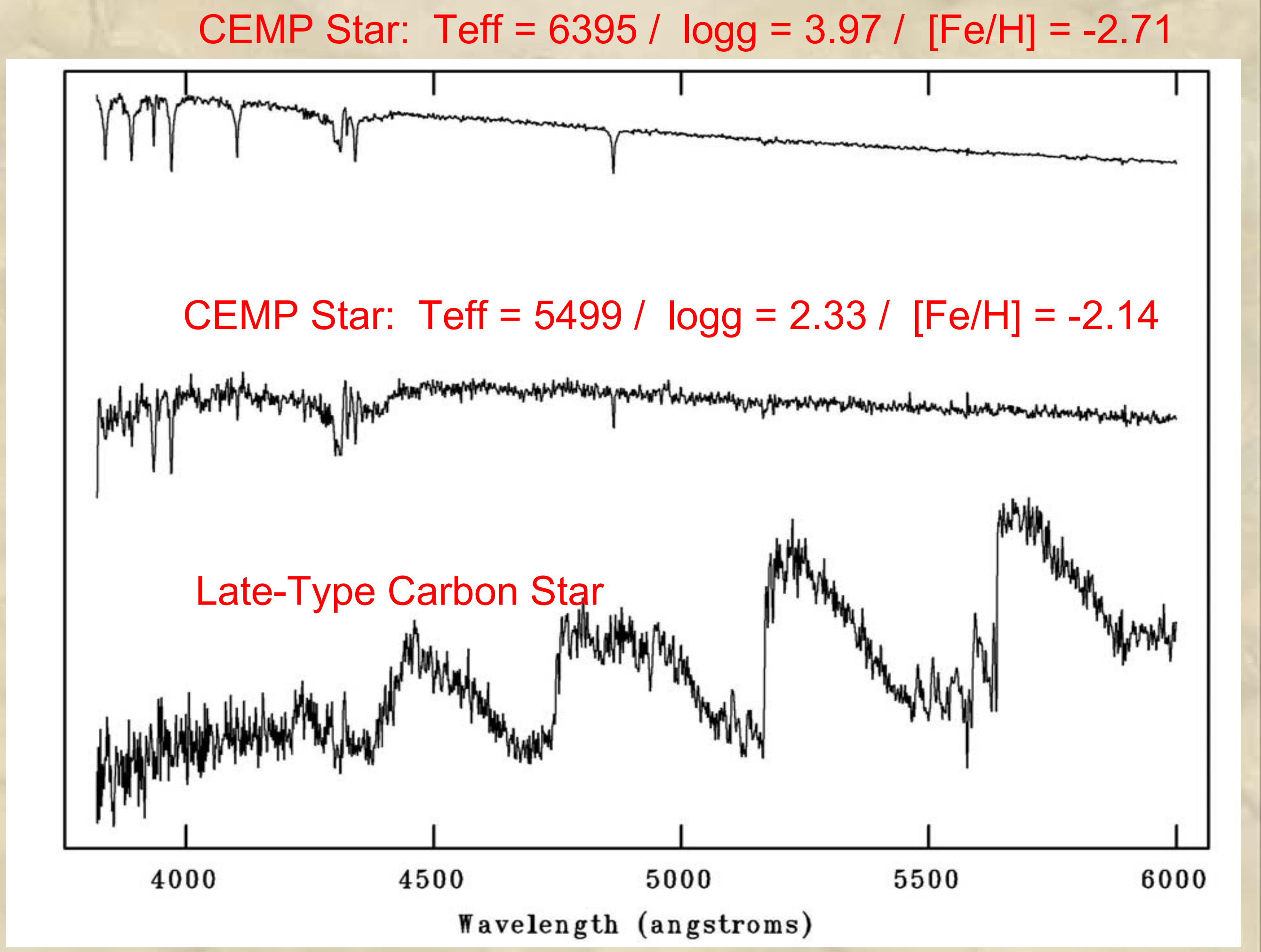
Note that the lower S/N sample includes a number of likely spurious results for [Fe/H] < −3.0.

Likely Numbers of Detected MP Stars from SEGUE

- Actual numbers will depend on the shape of the halo Metallicity Distribution Function
  - [Fe/H] < -2.0 ~ 20,000 (VMP)
  - [Fe/H] < -3.0 ~ 2,000 (EMP)
  - [Fe/H] < -4.0 ~ 200 ? (UMP)
  - [Fe/H] < -5.0 ~ 20 ? (HMP)
  - [Fe/H] < -6.0 ~ 2 ? (MMP)
- Tests indicate we expect to find ~ 5000 CEMP stars among the SEGUE sample of MP stars

Example Spectra – Carbon-Enhanced Metal-Poor (CEMP) Stars

- Three spectra are shown, non-continuum normalized
- Upper two panels are examples of CEMP stars of different Teffs
- Lower panel is a late-type carbon star



The Zoo of CEMP Stars

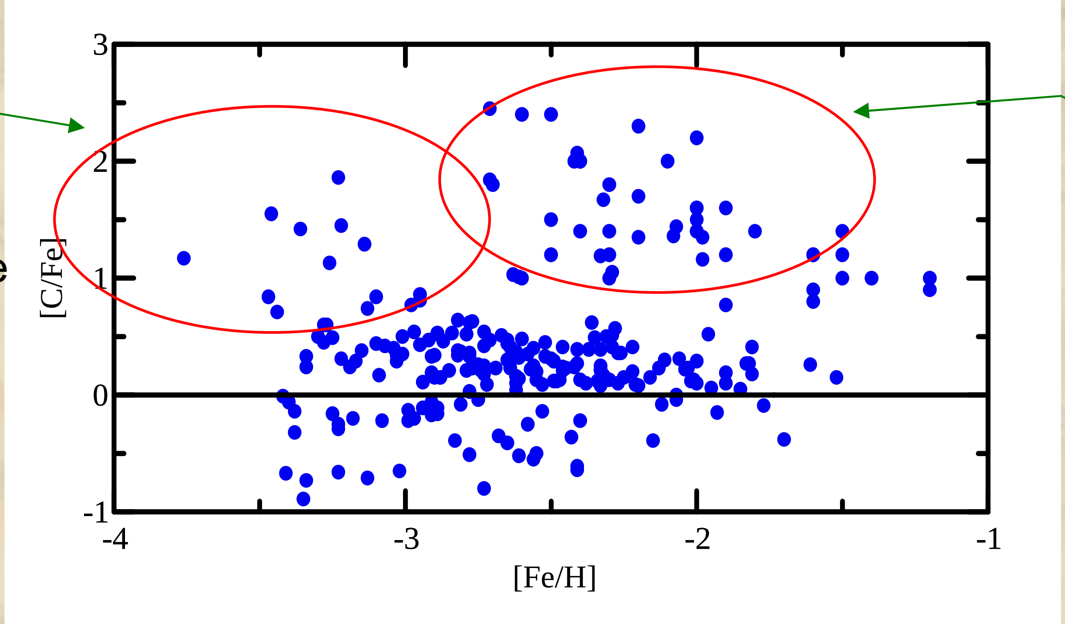
CLASS	ABUNDANCE PATTERN (Beers & Christlieb 2005)
CEMP	[C/Fe] > +1.0
CEMP-r	[C/Fe] > +1.0 and [Eu/Fe] > +1.0
CEMP-s	[C/Fe] > +1.0, [Ba/Fe] > +1.0, and [Ba/Eu] > +0.5
CEMP-r/s	[C/Fe] > +1.0 and 0.0 < [Ba/Fe] < +0.5
CEMP-no	[C/Fe] > +1.0 and [Ba/Fe] < 0

Carbon Often Associated with Interesting Neutron-Capture Elements

The Origin of Carbon in the Universe – New Insights from Carbon-Enhanced Metal-Poor Stars

Among the most metal-deficient (iron-poor) stars in the Galaxy, JINA scientists have discovered that a large fraction of them – on the order of 20-25% -- exhibit strong absorption lines due to the presence of molecular carbon. CH, CN, and C_2 bands are quite prominent in medium-resolution optical spectra of these objects.

Carbon in these stars is likely created by massive first-generation stars in the early Universe

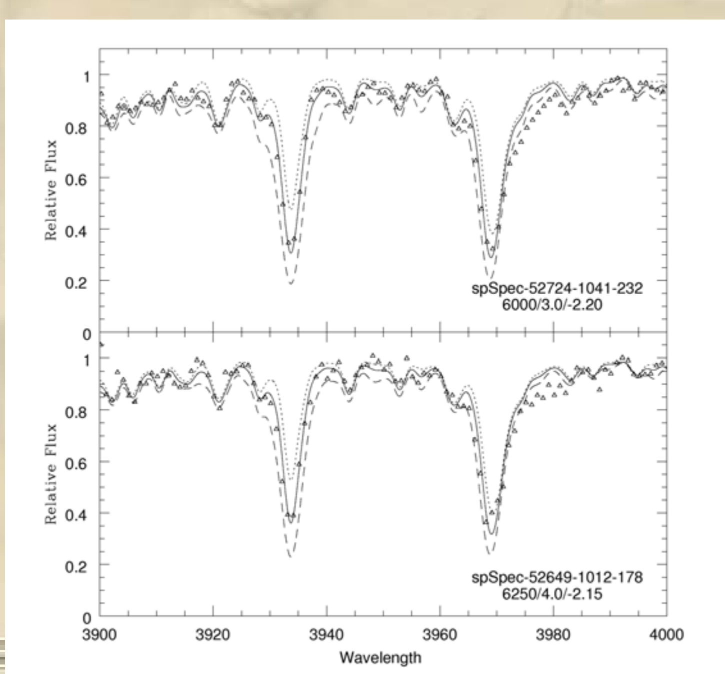


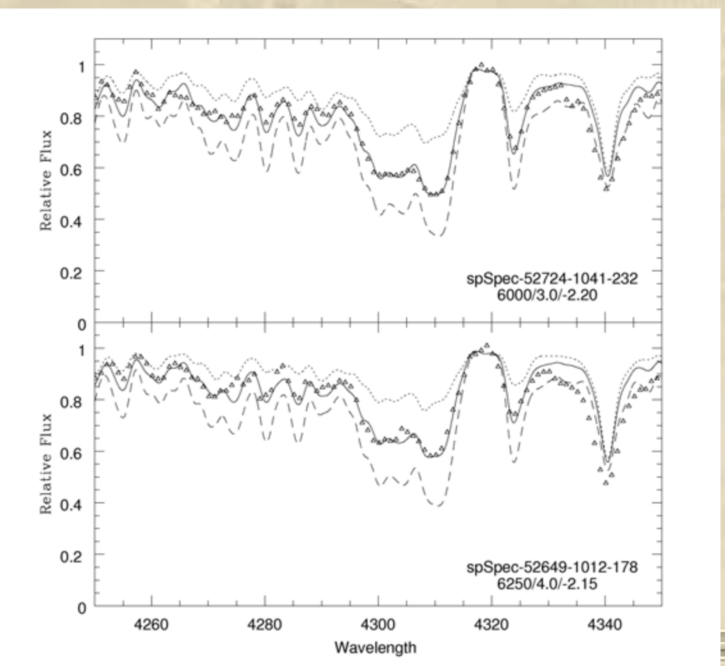
Carbon in these stars is likely created by nucleosynthesis in intermediate mass Asymptotic Giant Branch stars

High resolution spectroscopy with the European VLT 8m telescope has been used to verify the carbon abundances of these stars, and to produce a sample from which the absolute frequency of their occurrence can be derived as a function of metallicity, [Fe/H]. The observed distribution of [C/Fe] vs / [Fe/H] is shown above, based on work by Barklem et al. (2005).

New CEMP Stars Selected from SDSS-I FTO Sample (5700 K < Teff < 6700 K)

- MP FTO stars targeted during normal SDSS operation as spectrophotometric flux calibrators (PHO: 8 per plug-plate / reasonably bright, g < 16.5)
- [Fe/H] from spectroscopic pipeline (5 estimators) [C/Fe] estimated using [C/Fe] = f (GP,KP) and spectral synthesis
- Through DR-5: N (PHO; [Fe/H] < -1.0) = 5321





Measurements of Oxygen in Carbon-Enhanced Stars

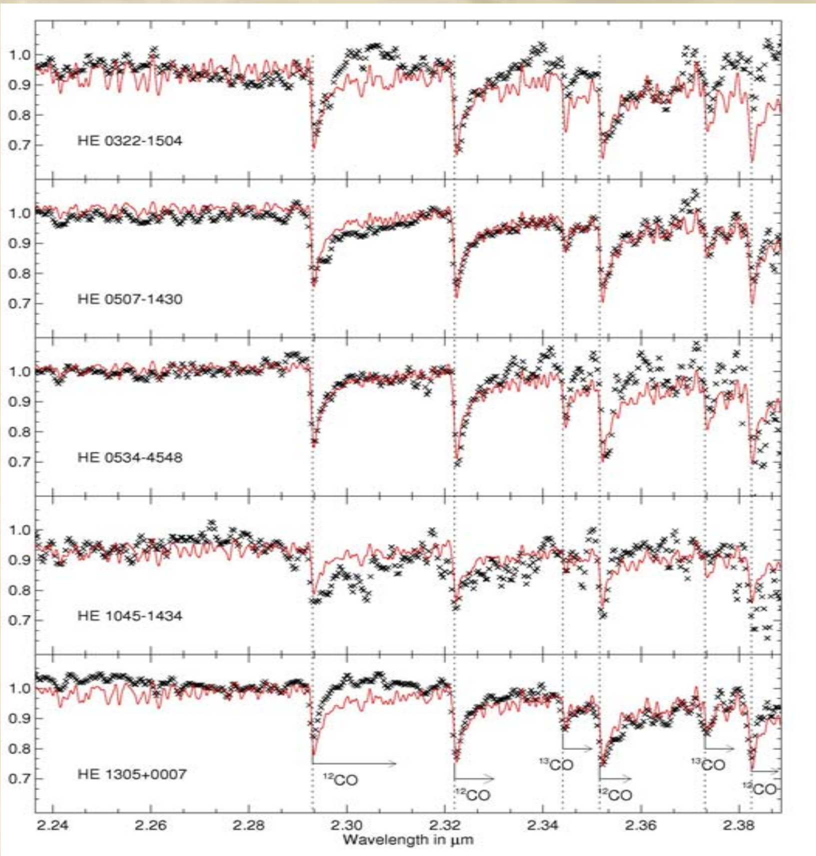
JINA scientists and their international colleagues are using the new SOAR 4.1m telescope in Chile, along with the OSIRIS near-infrared spectrograph, in order to make measurements of the abundance of the important elements C and O in the atmospheres of ancient, metal-poor stars.

Carbon, Nitrogen, and Oxygen are among the most basic elements required in order for life to exist. Hence, the identification and measurement of C, N, and O in old stars helps elucidate the picture of how the Universe created the conditions for life to emerge.

Estimates of the C and N abundances can often be obtained from observations in the optical region using moderate-sized telescopes, but O measurements in the optical usually requires 8m-10m class telescopes. By observing in the near-infrared with SOAR/OSIRIS, the abundance of O can be inferred due to its influence on the strong CO molecular bands that are visible in this portion of the spectrum.

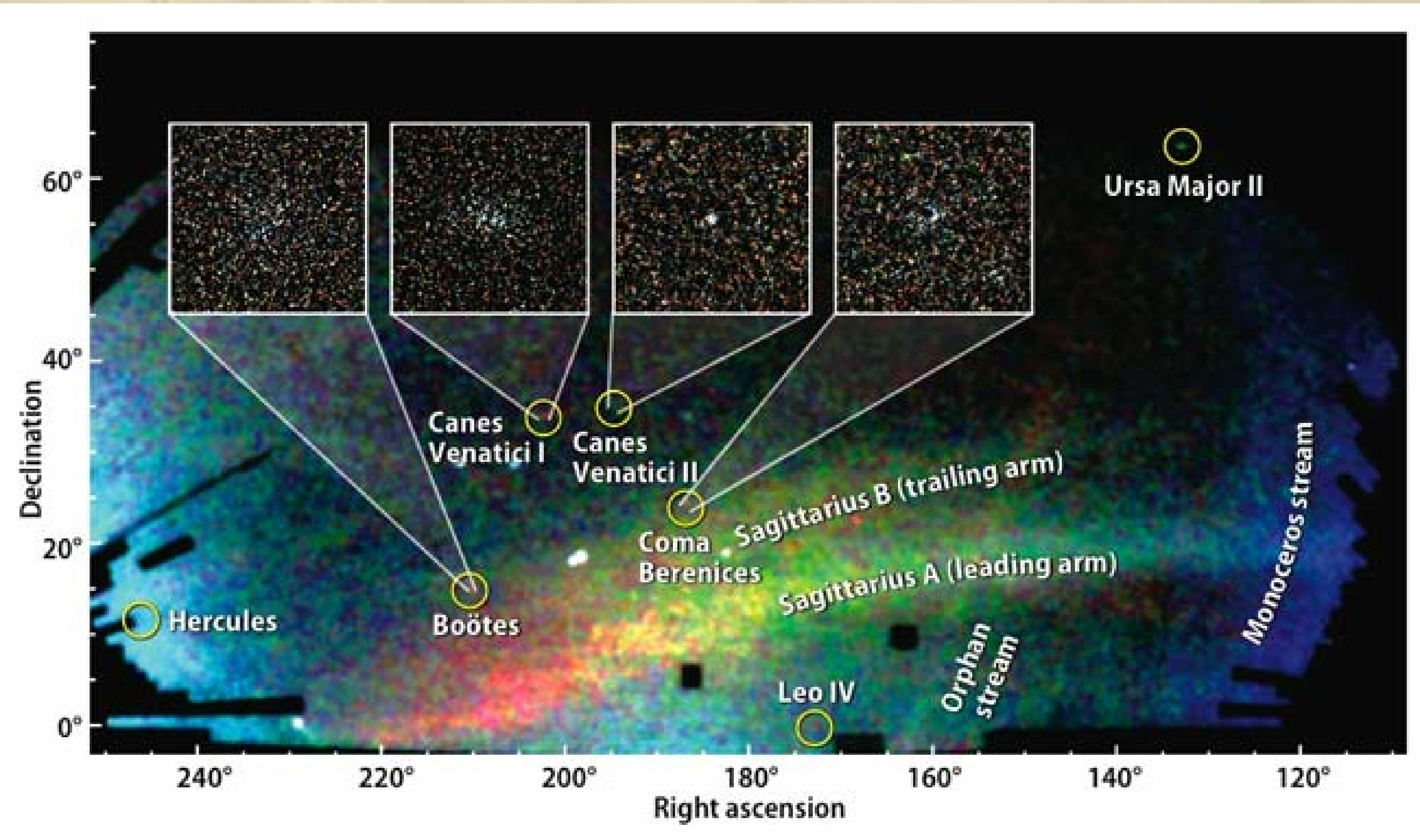
Timothy Beers (Professor of Astronomy at MSU), and his JINA-supported post-doctoral fellow Sivarani Thirupathi, and JINA-supported graduate students Young Sun Lee and Brian Marsteller, and their other colleagues, present these results in a paper to in the March 2007 issue of The Astronomical Journal. This study reveals that the ration of O relative to Fe in these stars is over 10 times the solar value.

See the preprint -- http://arxiv.org/abs/astro-ph/0611827



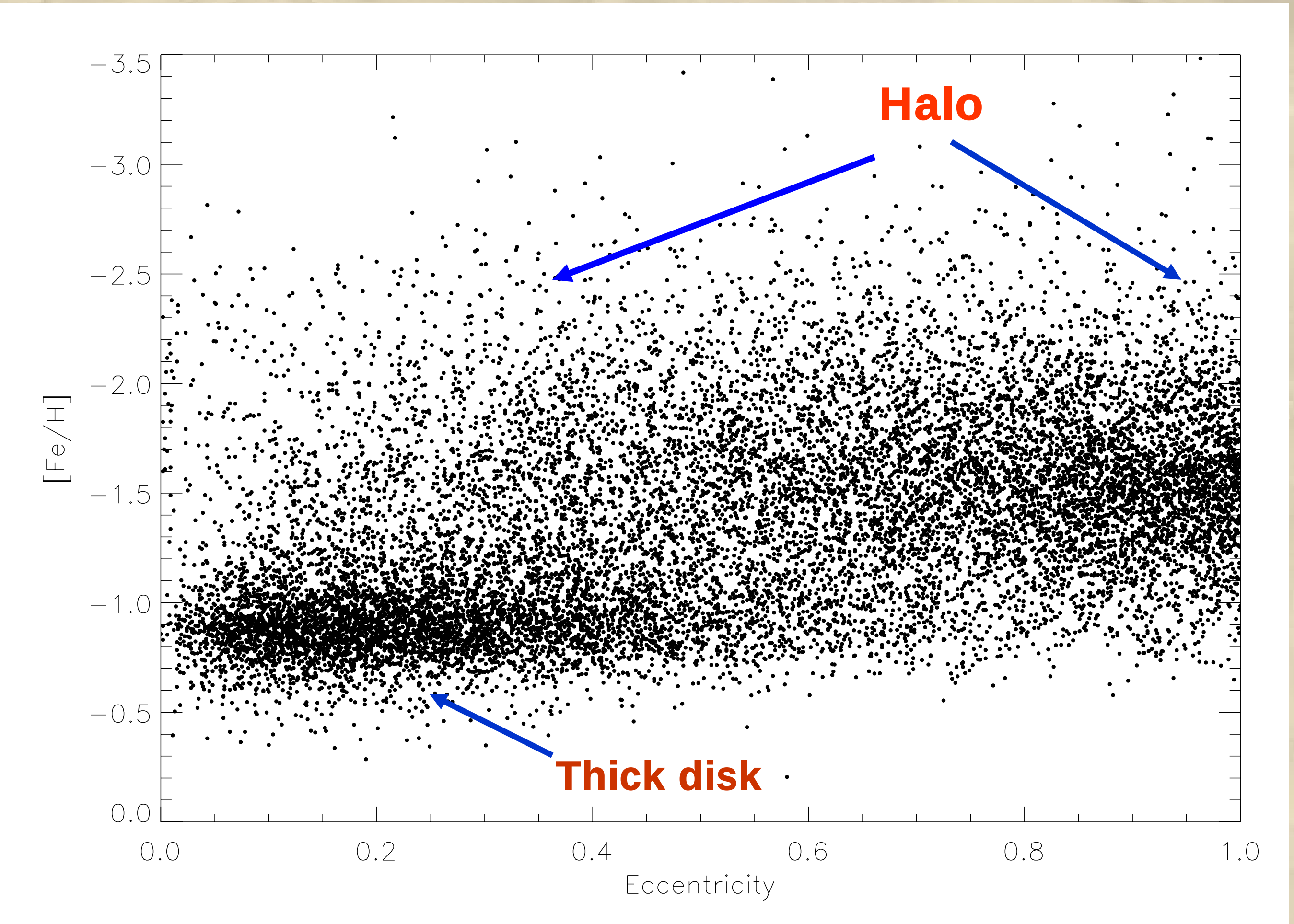
Near-infrared medium-resolution spectra of very metal-poor stars obtained with the SOAR 4.1m telescope. All of these stars have heavy element abundances less than 1% of the solar value. The strength of the CO bands can be modeled in order to estimate the abundance of O.

The Field of Streams and Discovery of New Dwarf Galaxies in the Milky Way from SDSS-II



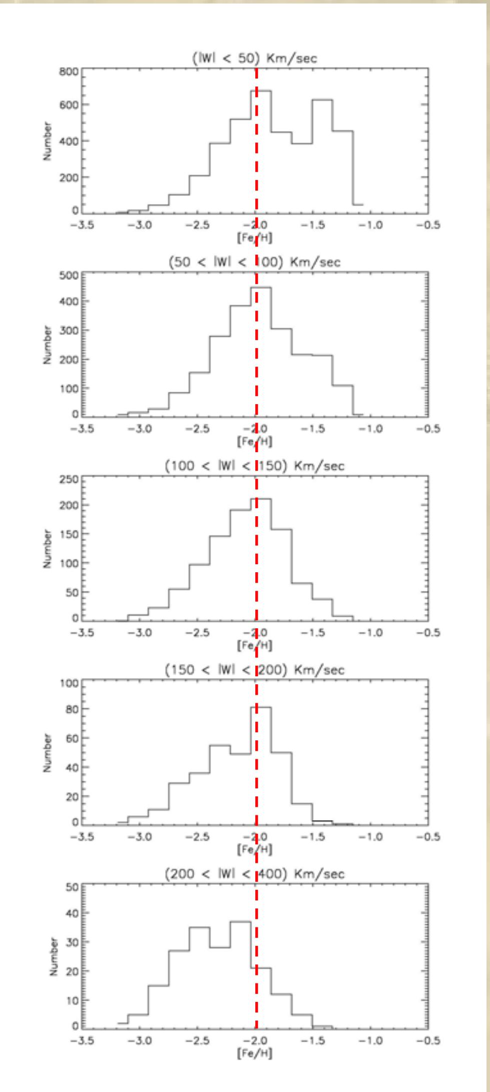
Researchers from the Sloan Digital Sky Survey (SDSS-II), along with their JINA collaborators, recently announced the discovery of eight new dwarf galaxies, seven of them satellites orbiting the Milky Way. They resemble systems cannibalized by the Milky Way billions of years ago and help close the gap between the observed number of dwarf satellites and theoretical predictions. Also shown above are streams of debris that are likely to have been stripped from other dwarfs or globular clusters that have interacted with the Milky Way in the past few billion years. These discoveries have been described in a series of articles appearing in the Astrophysical Journal Letters.

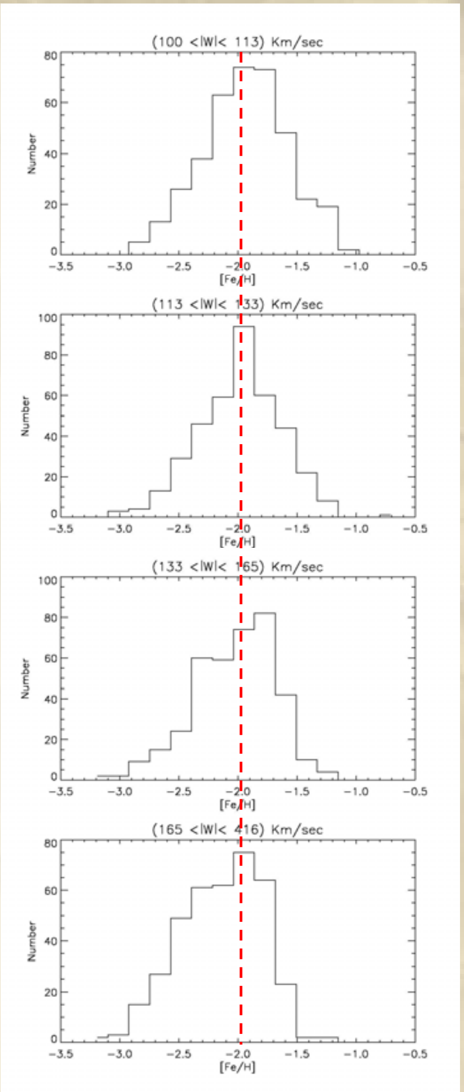
Abundance as a Function of Orbital Eccentricity

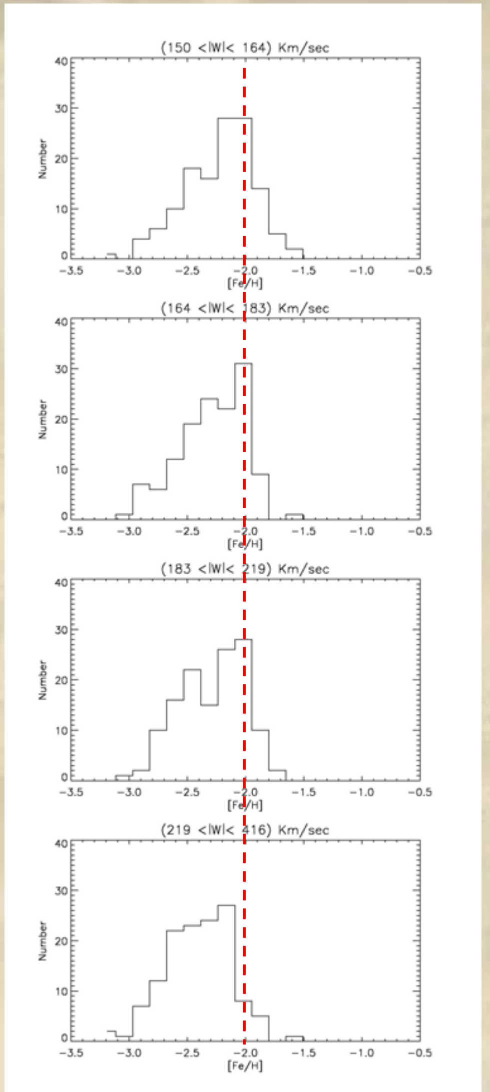


The orbital parameters were evaluated adopting a Galactic potential of the Stackel form (Chiba & Beers 2000 for details). There is NO clear correlation, as would have been predicted from the ELS monolithic collapse model. Also, for the first time we can clearly distinguish the presence of the thick disk (and MWTD) population as a separate entity from the local halo stars.

Distribution of [Fe/H] as a function of the Vertical Velocity W



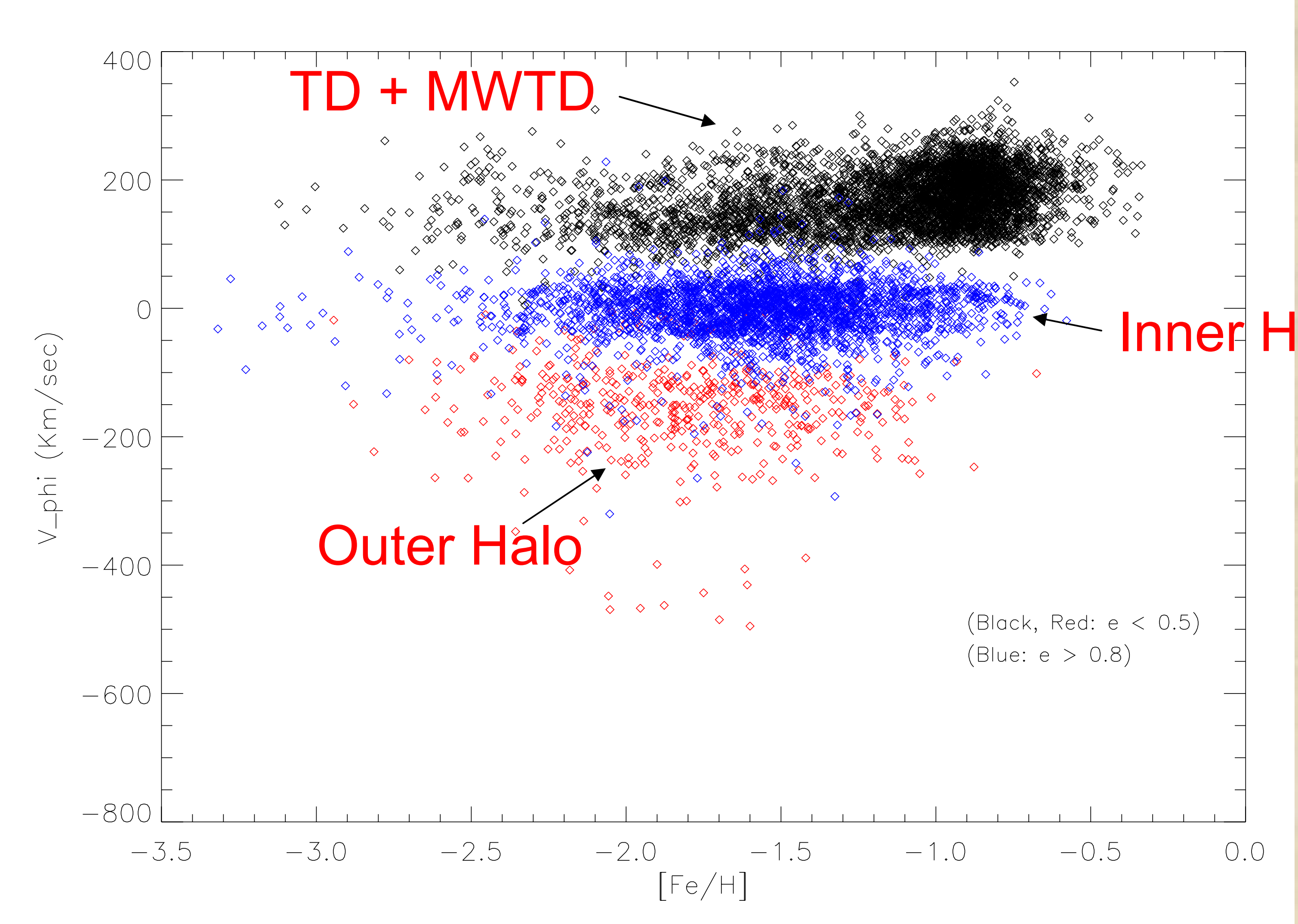




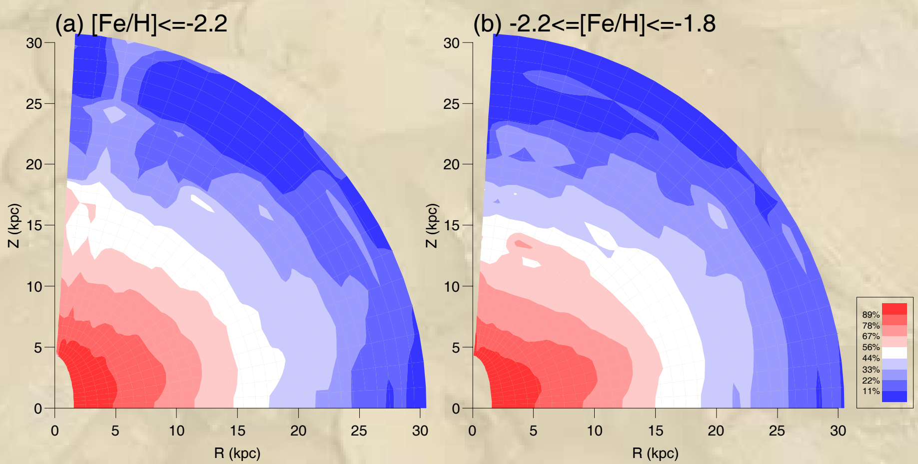
Left panel: Note the obvious presence of the MWTD component in the upper two plots.

The remaining plots: distribution for |W| > 100 Km/sec (middle) and |W| >150 Km/sec. Note the lack of stars around [Fe/H] ~ -2! At very high |W| velocity. **This suggest a shift in the observed Metallicity Distribution Function (MDF) of the pure halo stars as |W| increases!**

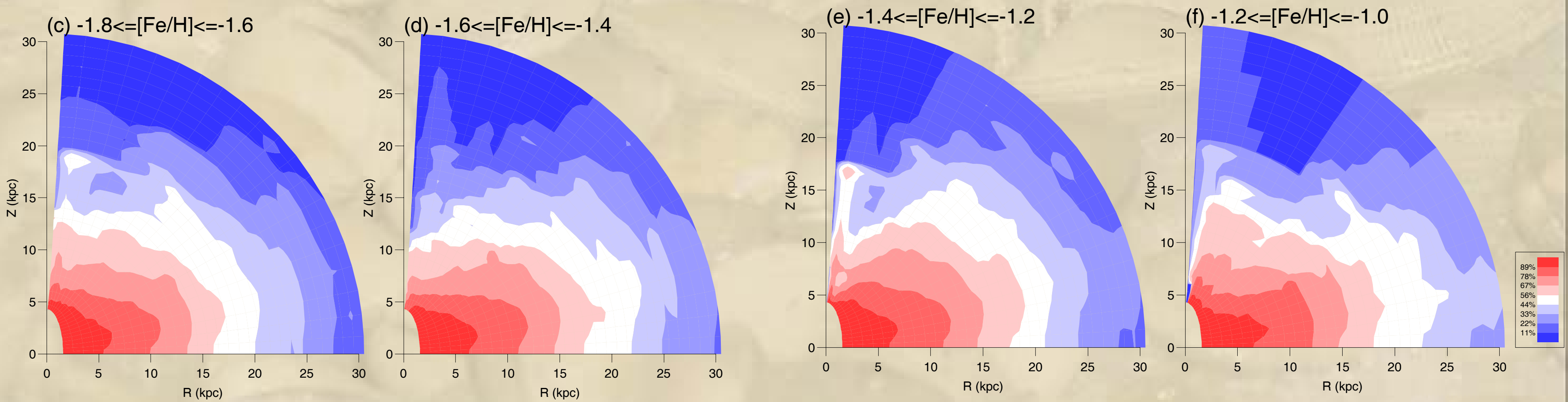
Split of TD/MWTD/Inner Halo/Outer Halo



Inversion from Kinematics to Density Prediction



By making simplifying assumptions about nature of galactic potential, one can invert motions to recover density field. Note progression from spherical to flattened with increasing metallicity.



Plans for Near Future

- Sep 2006: Initiate VLT survey (in collaboration with CIFIST) of additional EMP stars for extended studies of Li abundances (recently completed)
- Sep 2006: Initiate SOAR/OSIRIS survey of ~ 50 CEMP stars in near-IR, in order to obtain C, O, and 12C/13C abundances (recently completed)
- Dec 2006: Complete HET / Subaru / Keck high-resolution spectroscopic study of ~ 150 SEGUE stars, in order to validate assignment of atmospheric parameters (recently completed)
- Jan 2007: Initiate HET-RES survey of 1000 brighter (g < 16) stars with [Fe/H] < -2.0, in hopes of finding ~ 50-100 r-II stars (100 stars observed so far)
- June 2007: Produce “value added” catalog of SDSS-I and SEGUE Year 1 stellar parameters, based on final SEGUE Spectroscopic Parameter Pipeline (a total of over 200,000 stars)

Plans for Moderate Future

- June 2007: DR6 public release (1st public release of SEGUE/Legacy data)
- June 2007: Value added catalog of stellar parameters to accompany SEGUE/Legacy releases
- July 2008: DR7 public release, and additional value added catalog
- July 2008: End of SDSS-II
- July 2008: Beginning of SDSS-III – Instrumentation and efforts being discussed NOW
  - ASEPS: All Sky Extra Solar Planet Search (piggy back fibers)
  - SEGUE-II: (Additional 250,000 spectra in one year)
  - APOGEE: Near IR R=10,000 stellar spectroscopy survey
  - BOSS: Baryon Oscillation Observational Survey
- July 2009: DR8 public release, and final value added catalog

Plans to Consider for JINA-II

- Involvement with SDSS-III, in particular SEGUE-II, APOGEE, and ASEPS

- Involvement with LAMOST = Large Aperture Multi-Object Spectrographic Telescope (China) Survey – up to 10 Million stellar spectra, similar resolution as SEGUE

- Involvement with WFMOS = Wide-Field Multi-Object Spectrograph Gemini/Subaru) – Up to 1 Million high-resolution stellar spectra