Probing the IMF with HES and SEGUE

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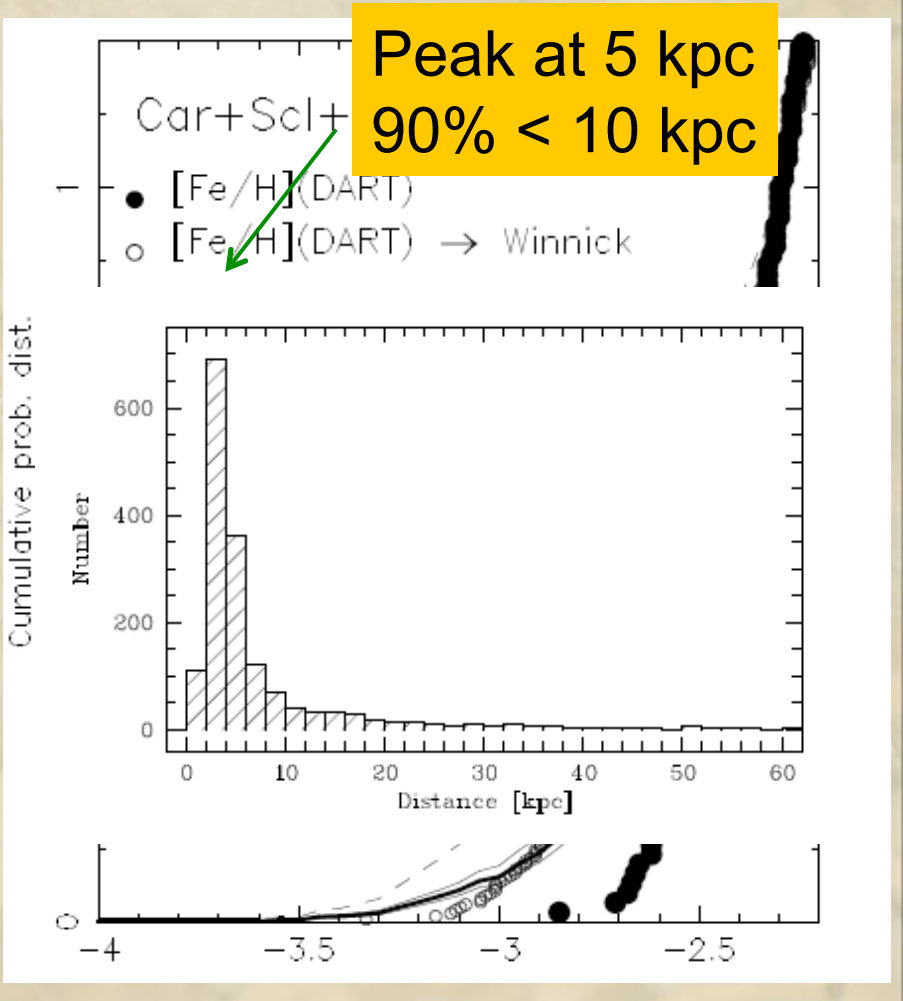
SDSS

Overview

- Direct Constraints, when looking exclusively at the distribution of stellar metallicities, are certain to be rather weak.
- Indirect Constraints, by examination of chemical abundance patterns and frequencies of distinctive objects, are superior in many ways.
- Association of the outer halo with dwarf galaxy (dSph) building blocks provides an important first clue
- Exploration of detailed patterns/frequencies for stars in dSph with outer halo is a promising way forward

Direct Constraints (from HES/HK Surveys)

- Despite heroic efforts over past few decades, total numbers of stars with [Fe/H] < -2.0 were fewer than ~ 3000
- Difficulties in distinguishing “fine structure” at low metallicity due to lack of stars
- Examination of their MDF, although interesting, does not adequately separate unique IMFs
- So, either increase numbers, and hope for the best, or change tactics



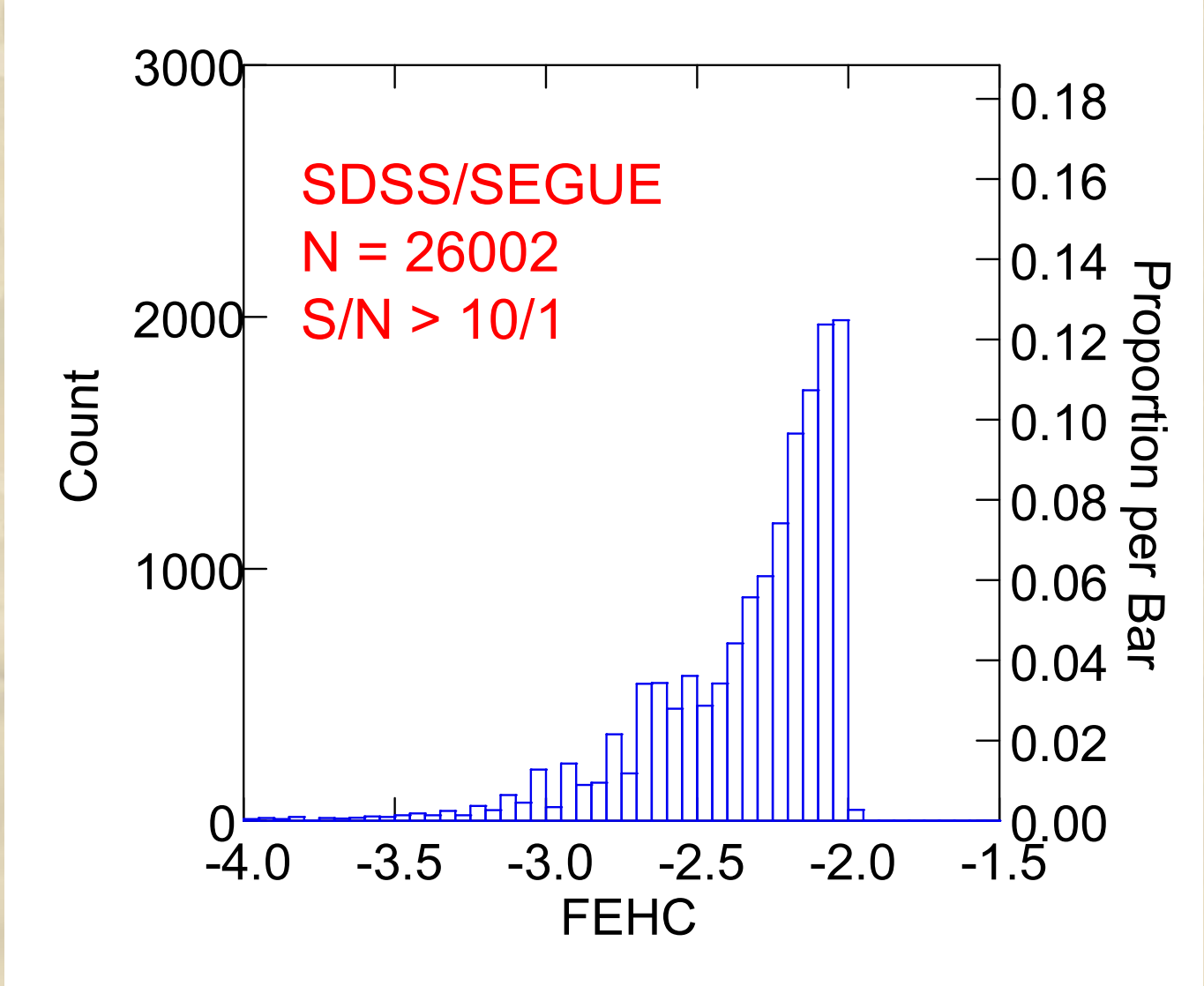
Schoerck et al. (2009)

Known MP Stars – Pre and Post SDSS/SEGUE-1/SEGUE-2

Name	Metallicity	Pre	Post
• Metal-Poor	[Fe/H] < -1.0	15,000	150,000+
• Very Metal-Poor	[Fe/H] < -2.0	3,000	30,000+
• Extremely Metal-Poor	[Fe/H] < -3.0	400	1000+
• Ultra Metal-Poor	[Fe/H] < -4.0	5	5
• Hyper Metal-Poor	[Fe/H] < -5.0	2	2
• Mega Metal-Poor	[Fe/H] < -6.0	0	0

N.B. -- Only includes stars with S/N > 10/1, 4500 < Teff < 7000

Latest and Greatest from SDSS/ SEGUE



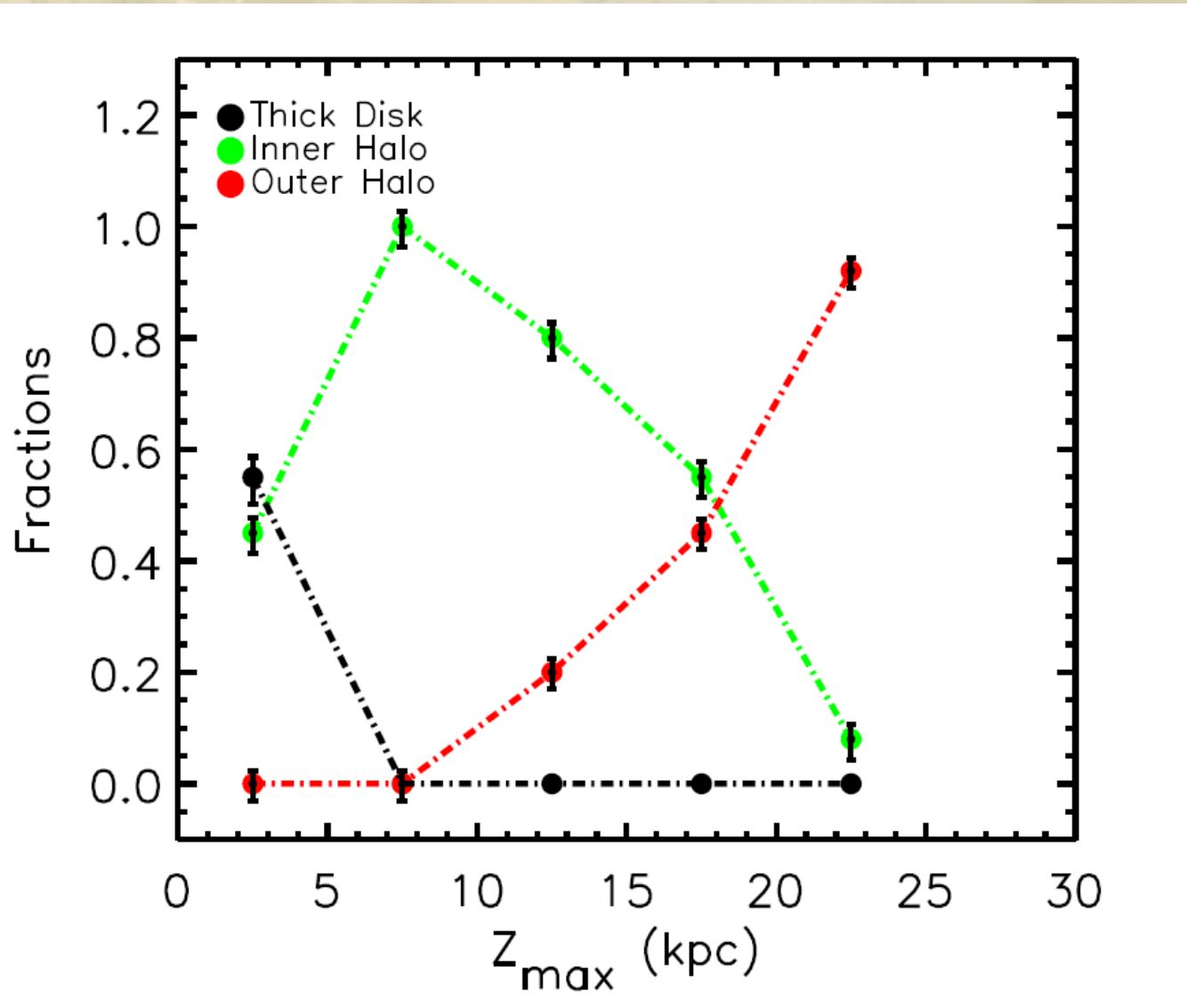
The Impact of SDSS/SEGUE

- Not just that we have many more stars with [Fe/H] < -2, < -3, BUT:
- WE KNOW WHERE TO FIND MORE!

D. Carollo et al. (2010) Kinematic Analysis of DR-7 "Calibration Stars"

- Follow-on of work from D. Carollo et al. (2007), demonstrating existence of inner/outer halo populations, including 32,360 unique calibration stars
- Determination of velocity ellipsoids for thick disk, MWTD, inner, outer halos
- Modeling of fractions of various components in local sample (d < 4 kpc)

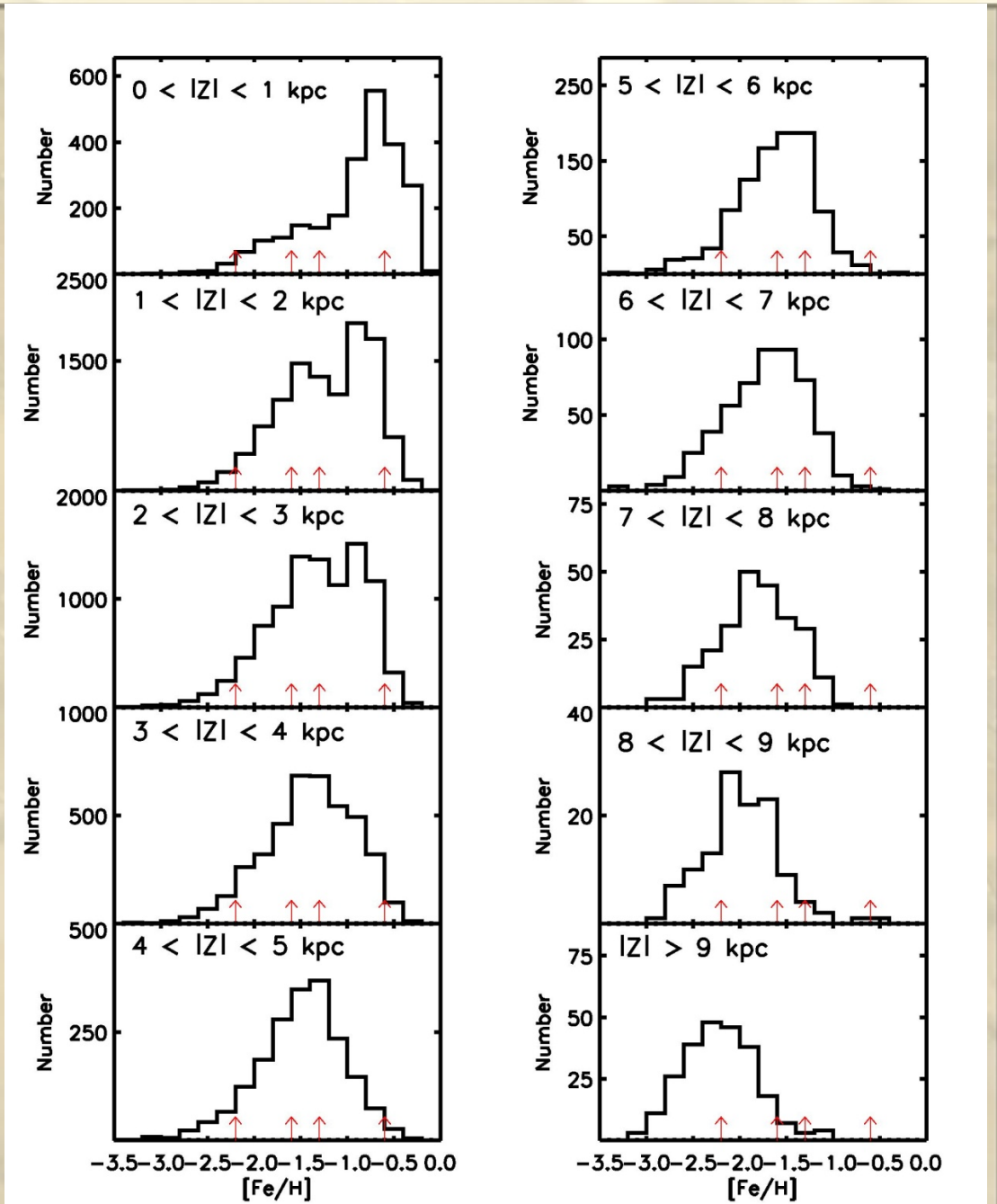
Fractions of Components



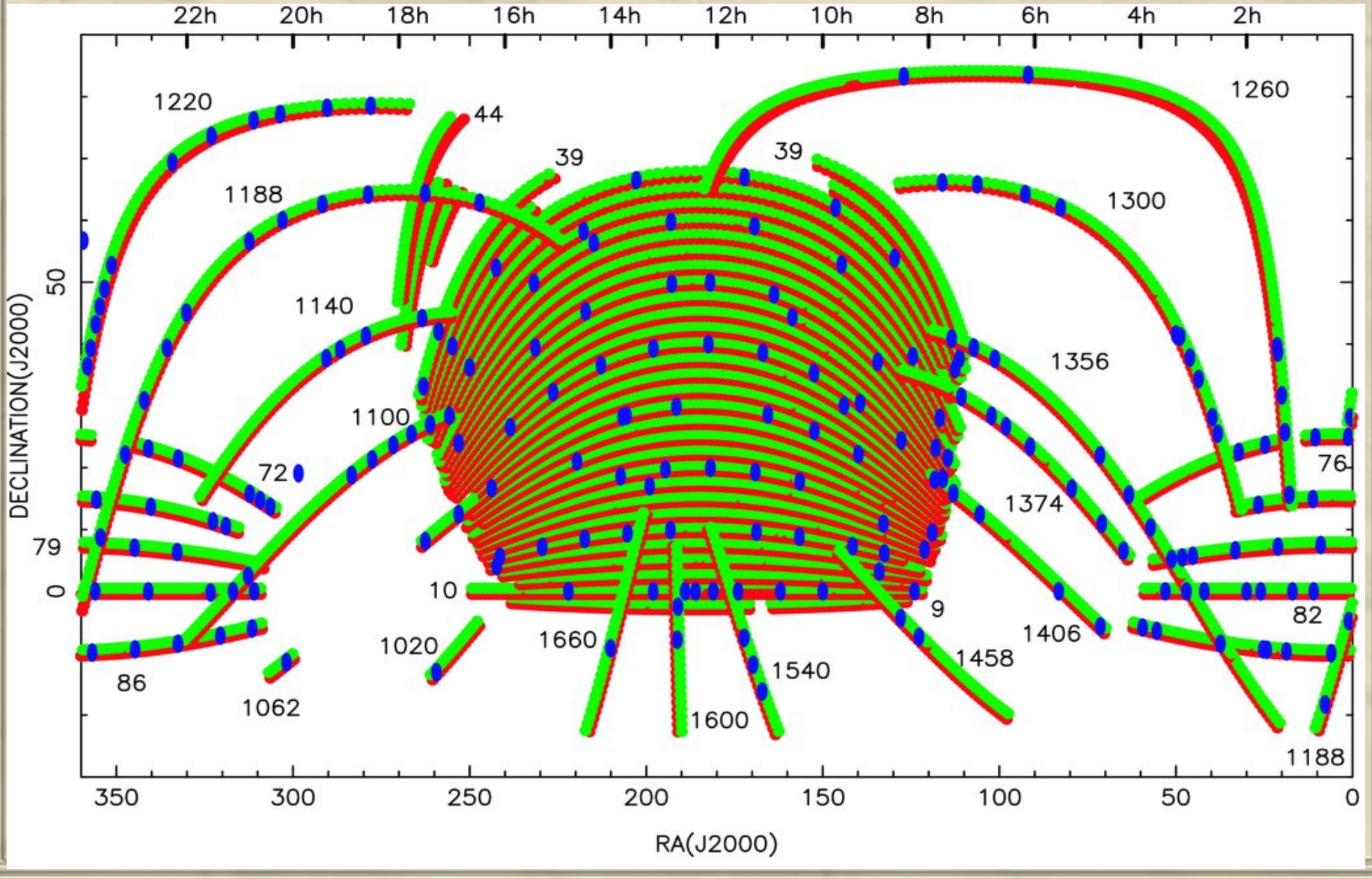
The In-Situ MDF

For the full sample of calibration stars, as one goes from close to the plane to farther away, the nature of the as-observed MDF changes

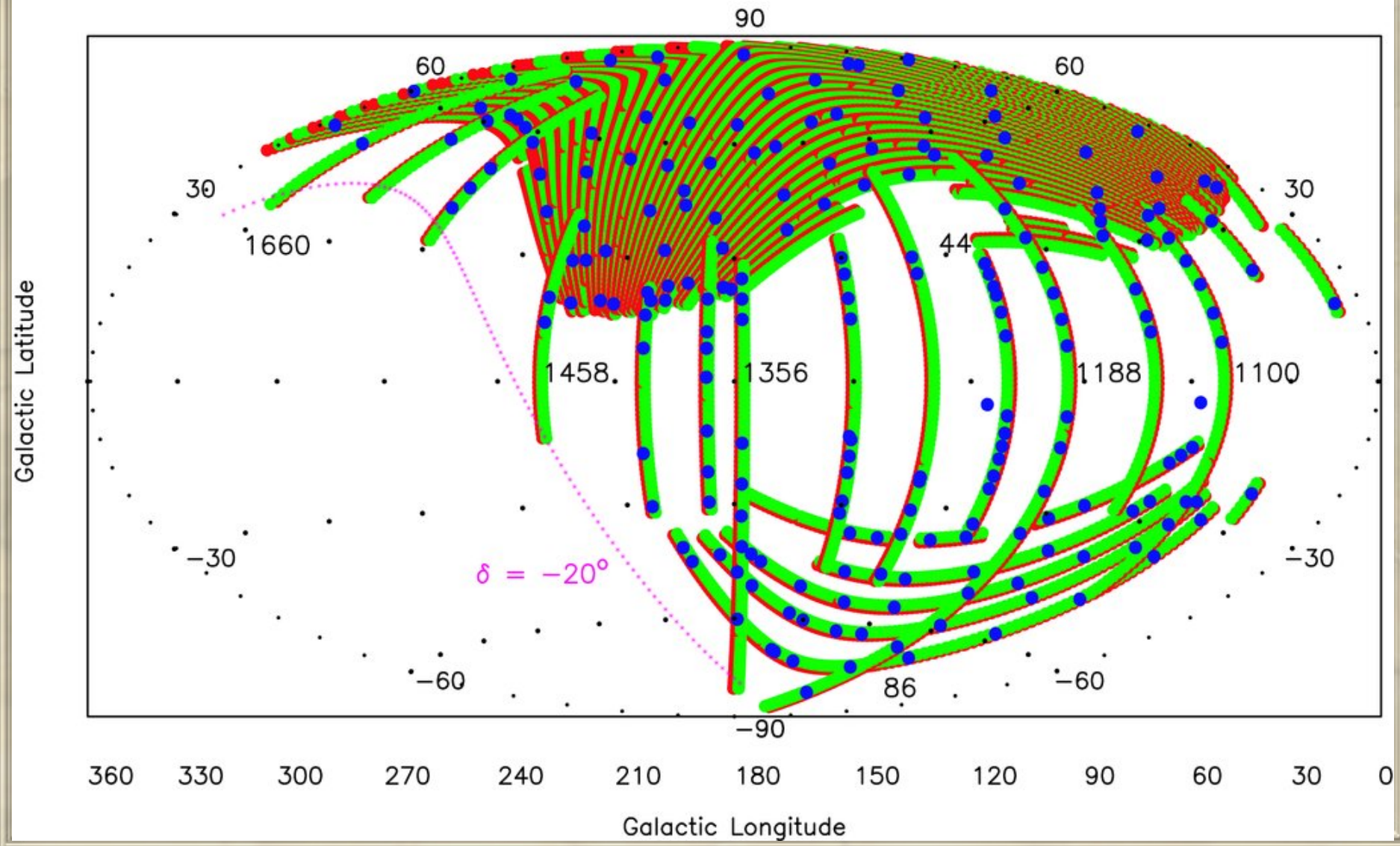
From TD/MWTD to Inner/ Outer Halo



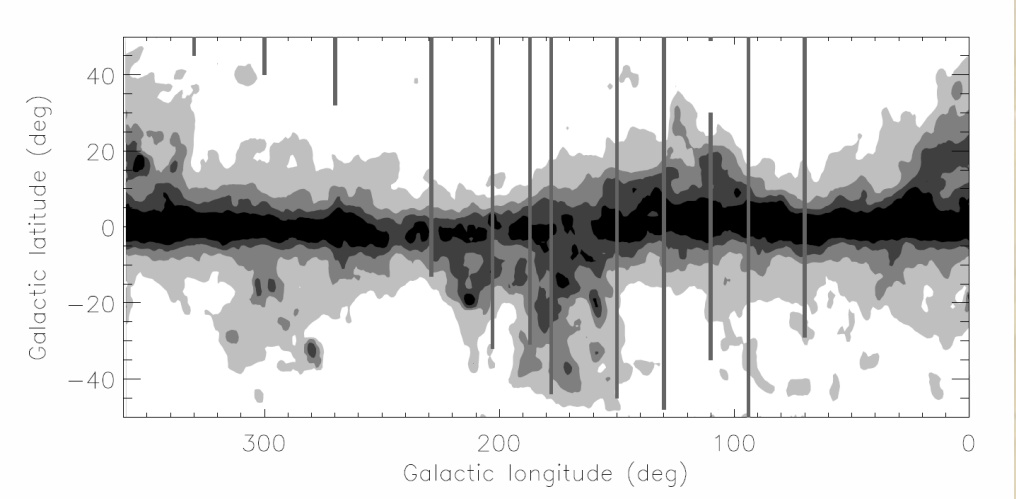
The SDSS/SEGUE Footprint (RA/DEC)



The SDSS/SEGUE Footprint (l, b)



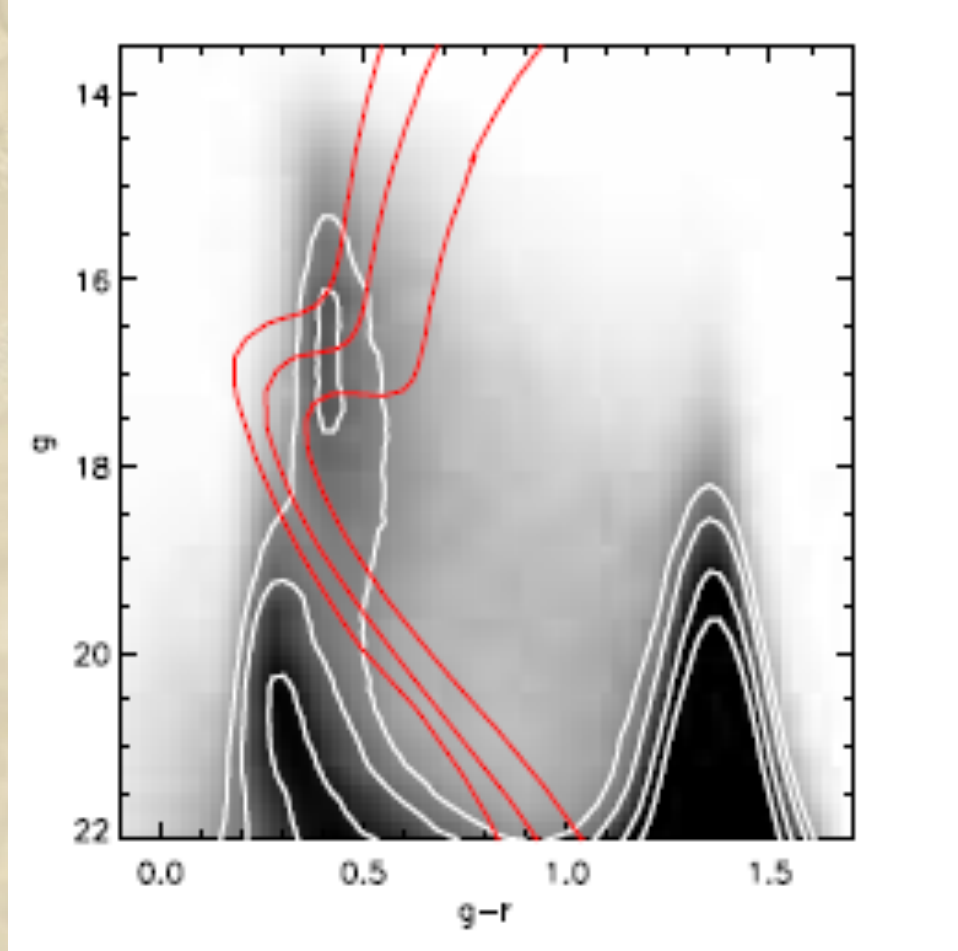
Analysis of SEGUE Vertical Photometry Stripes (De Jong et al. 2010, in press)



- The vertical photometry stripes of SEGUE were obtained in order to sample the transition from disk to halo

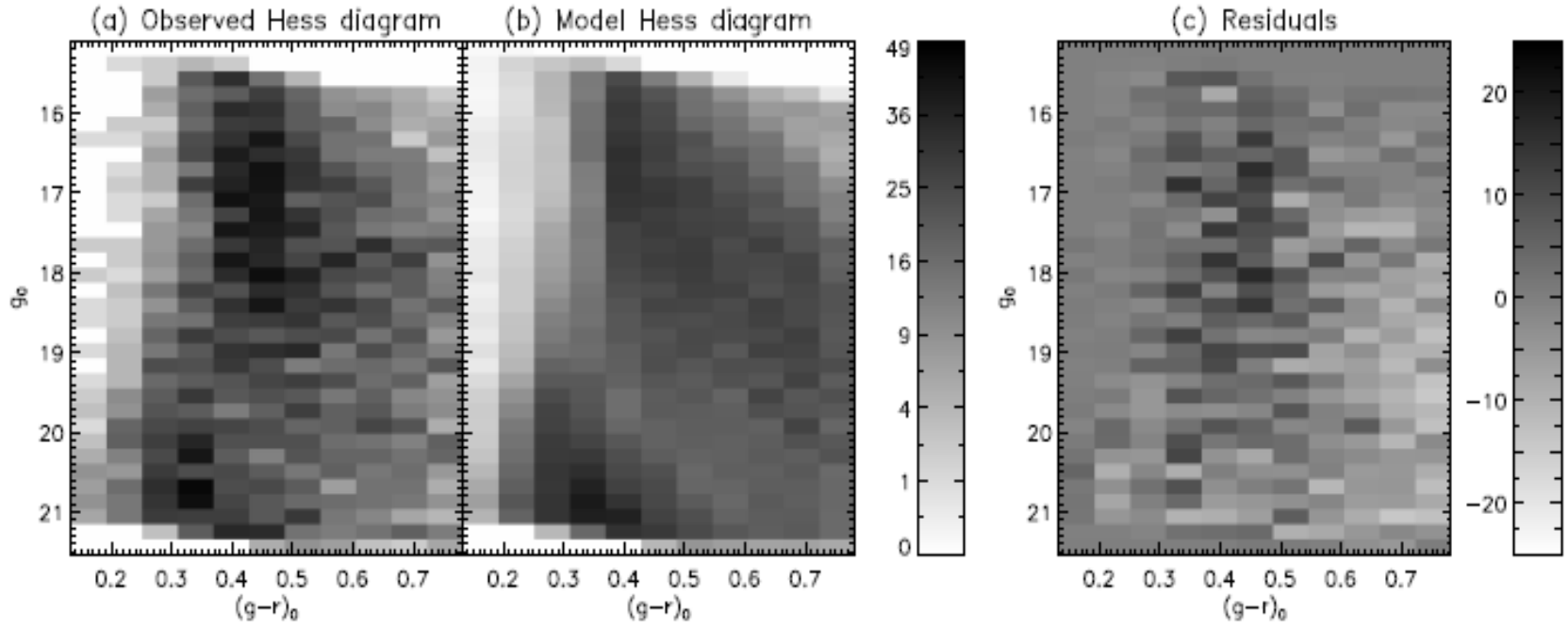
- One can model the number density of stars in these stripes by carving them into small “boxes” in apparent magnitude and color, then fitting them to template isochrones (assuming a constant (old) age, with metallicities fixed to three values typical of the assumed populations

CMD of Summed SEGUE Stripes

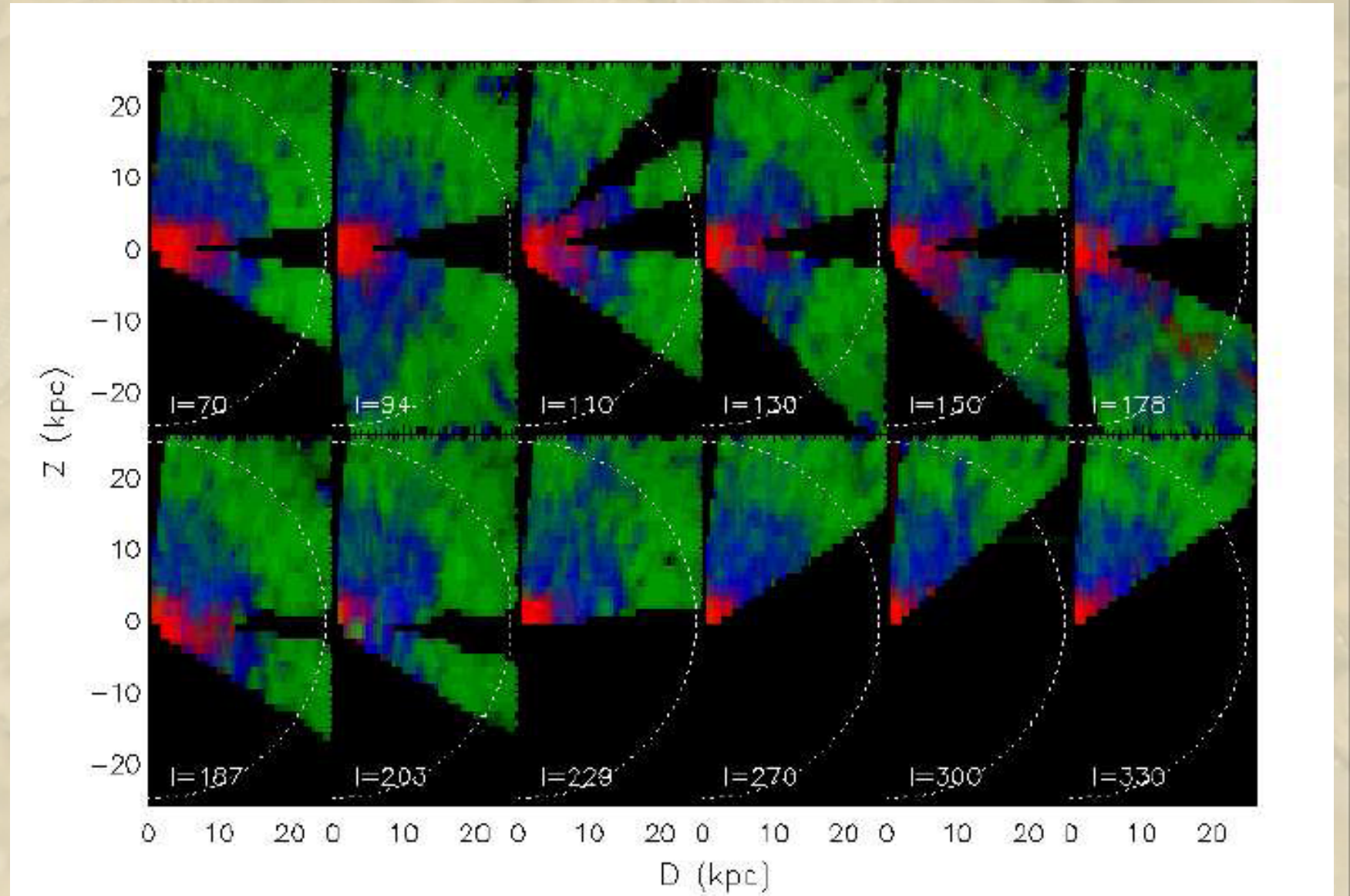


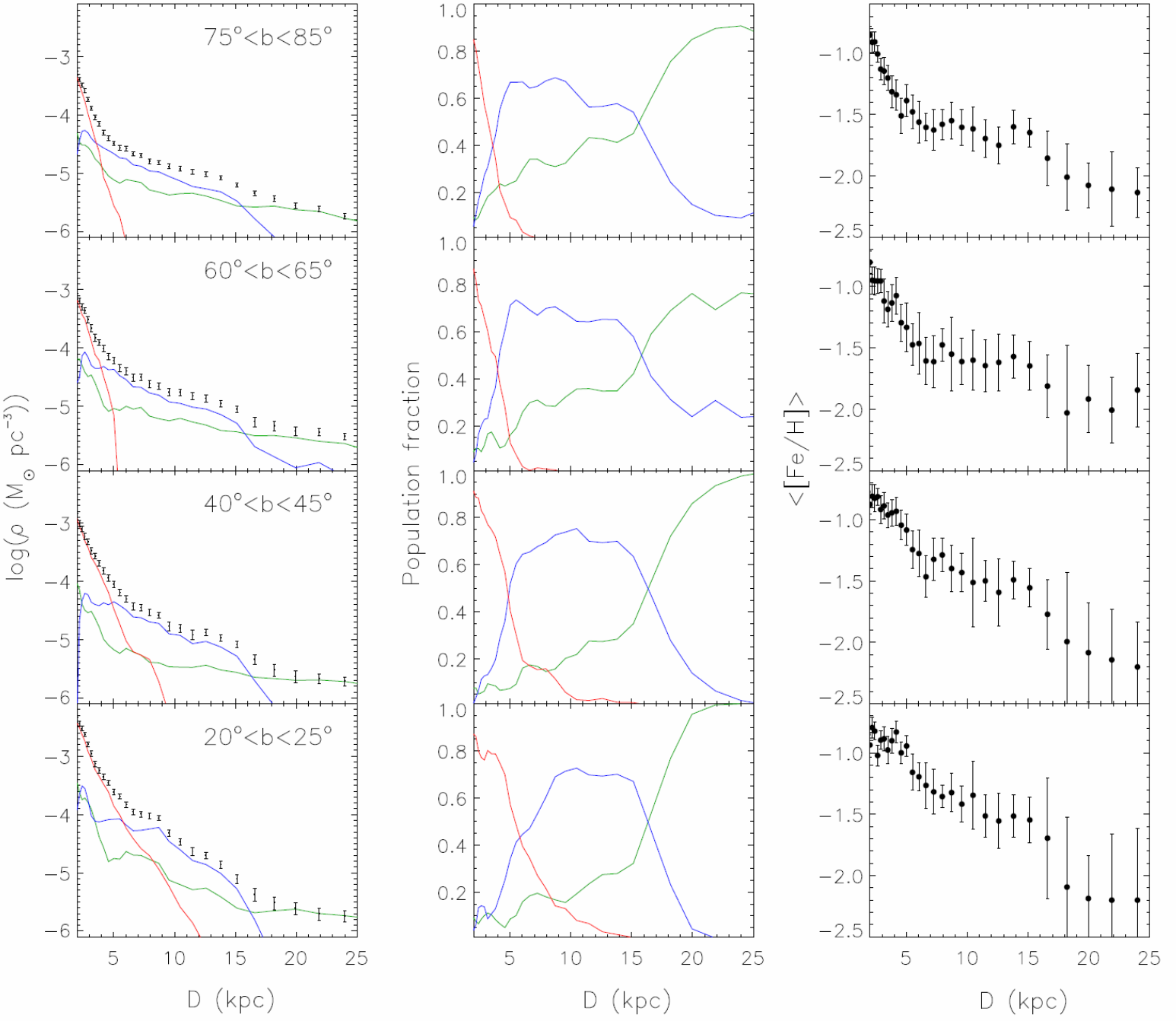
- Thick disk [Fe/H] = -0.6
- Inner halo [Fe/H] = -1.3
- Outer halo [Fe/H] = -2.2

Hess Diagram Models and Residuals



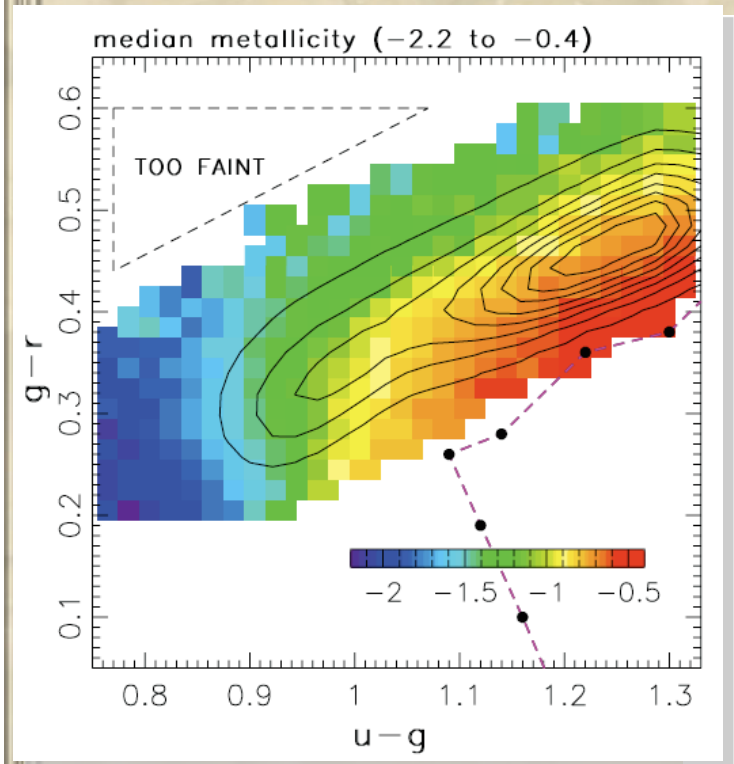
Derived Populations

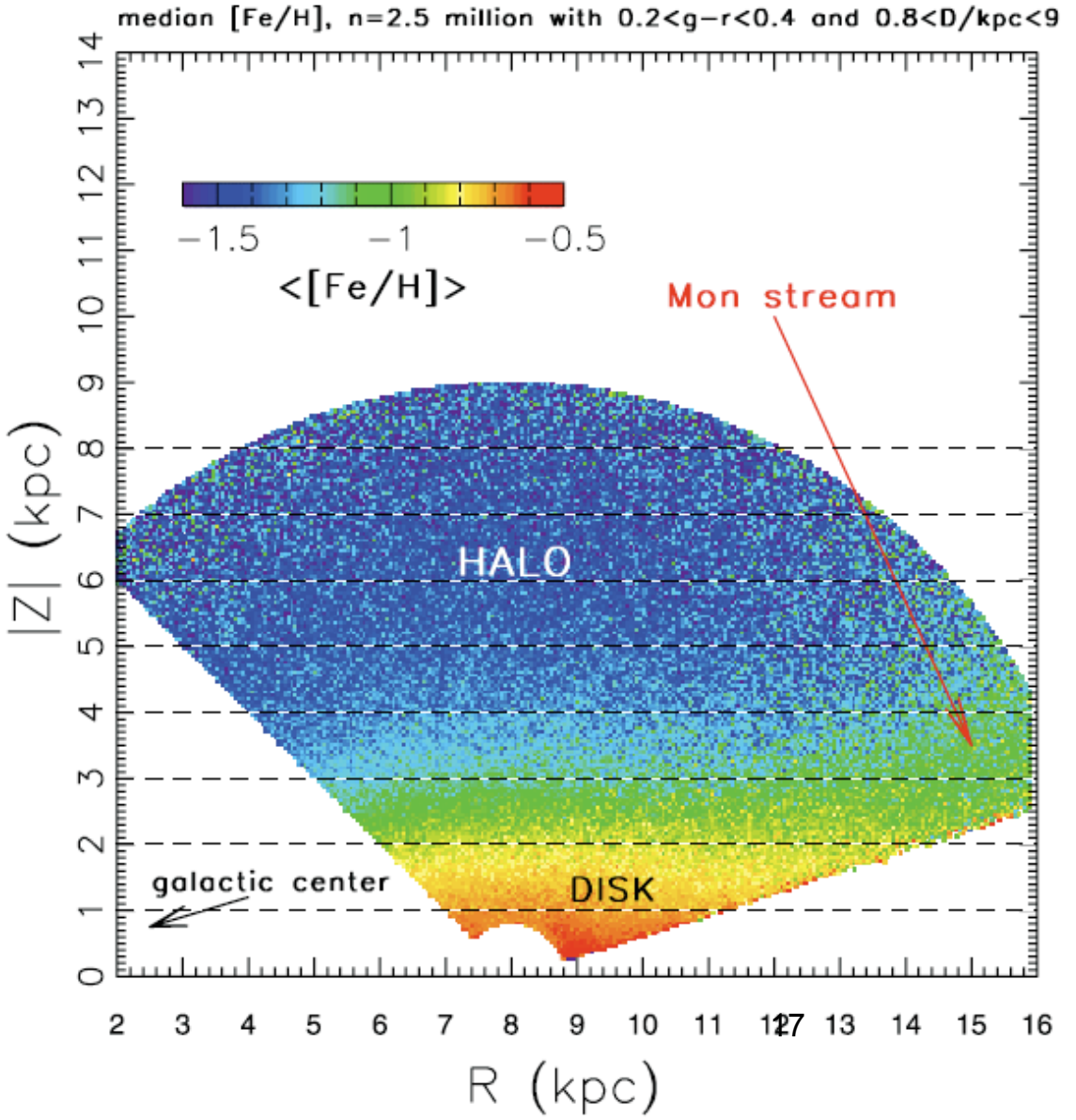



75°<b<85°
60°<b<65°
40°<b<45°
20°<b<25°
log(ρ (M⊙ pc⁻³))
Population fraction
<[Fe/H]>
D (kpc)
D (kpc)
D (kpc)

Photometric Metallicity from *ugr*

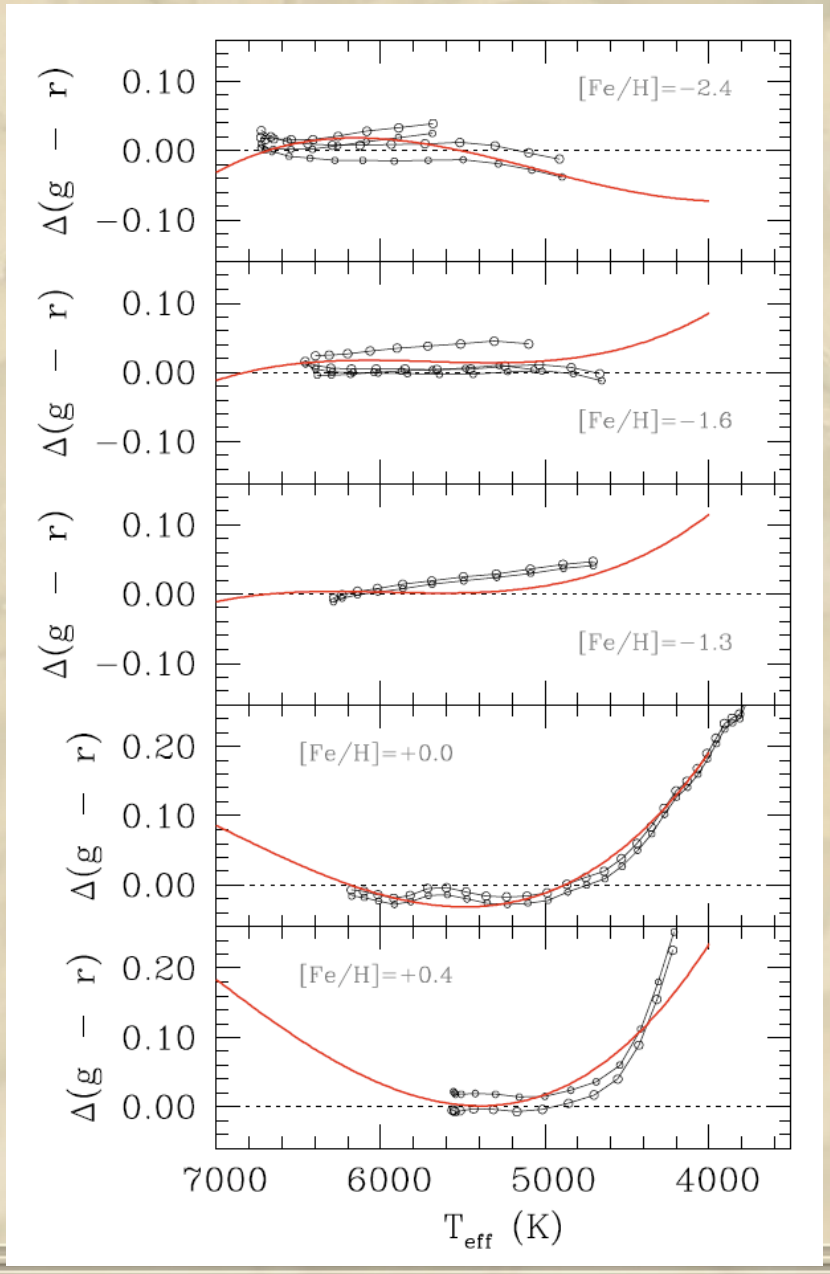
Ivezić et al. 2008





Revised color-T_{eff}-[Fe/H] Corrections

Preliminary



An et al. (in prep)

Improvements over the initial analysis in An et al. (2009):

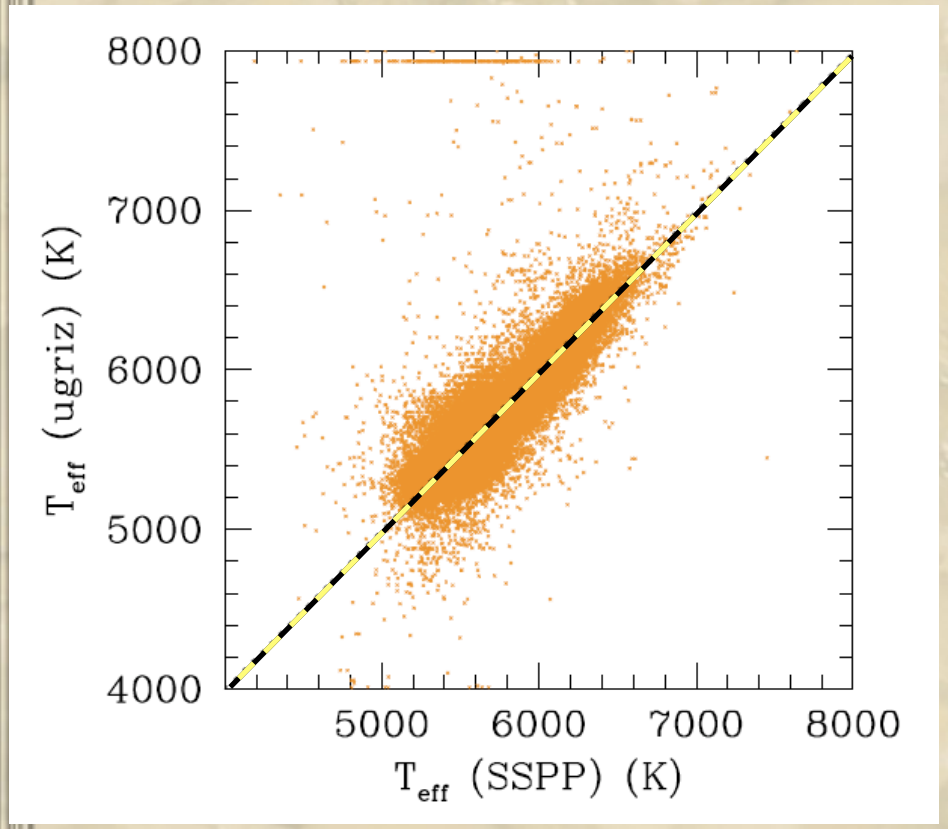
- **Refined color-T_{eff} corrections**

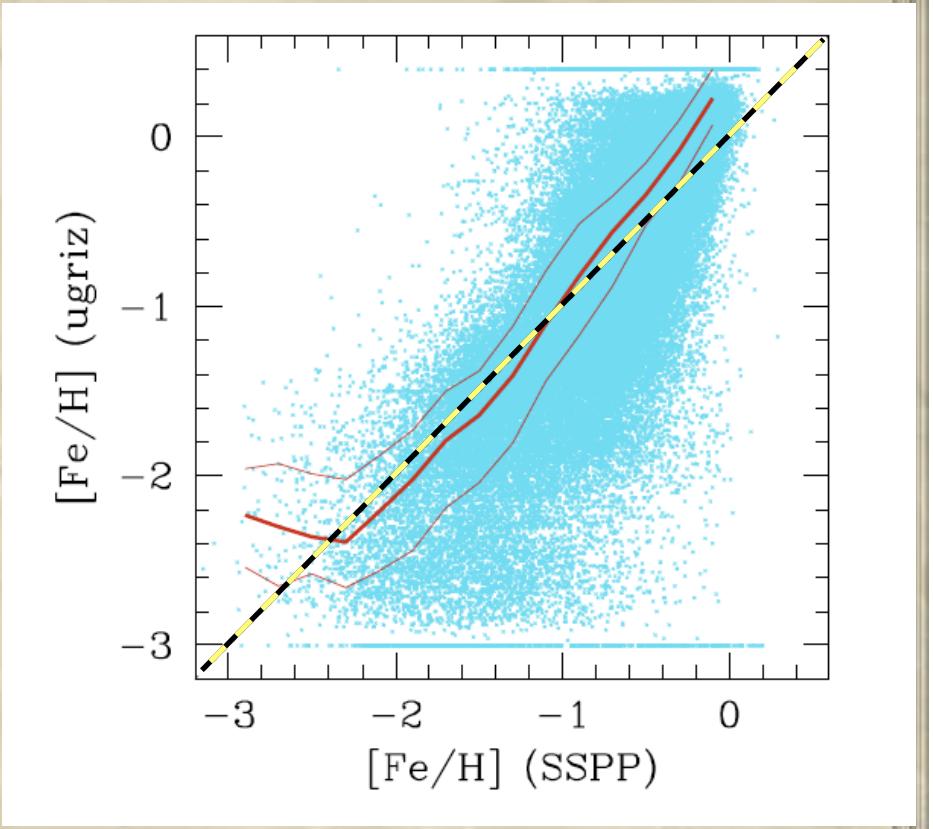
$$\Delta u-g, \Delta g-r, \Delta g-i, \Delta g-z\ (T_{\rm eff}, [Fe/H]) = c_0 + c_1 T_{\rm eff} + c_2 {T_{\rm eff}}^2 + c_3 {T_{\rm eff}}^3 + c_4 [Fe/H] + c_5 [Fe/H]^2 + c_6 [Fe/H]^3 + c_7 [Fe/H] T_{\rm eff} + c_8 [Fe/H] {T_{\rm eff}}^2 + c_9 [Fe/H]^2 T_{\rm eff}$$

- **Inclusion of all *ugriz* bandpass information whenever available**
- **Parameter search in [stellar mass, [Fe/H], stellar age] space.**

Comparison with SSPP

Preliminary





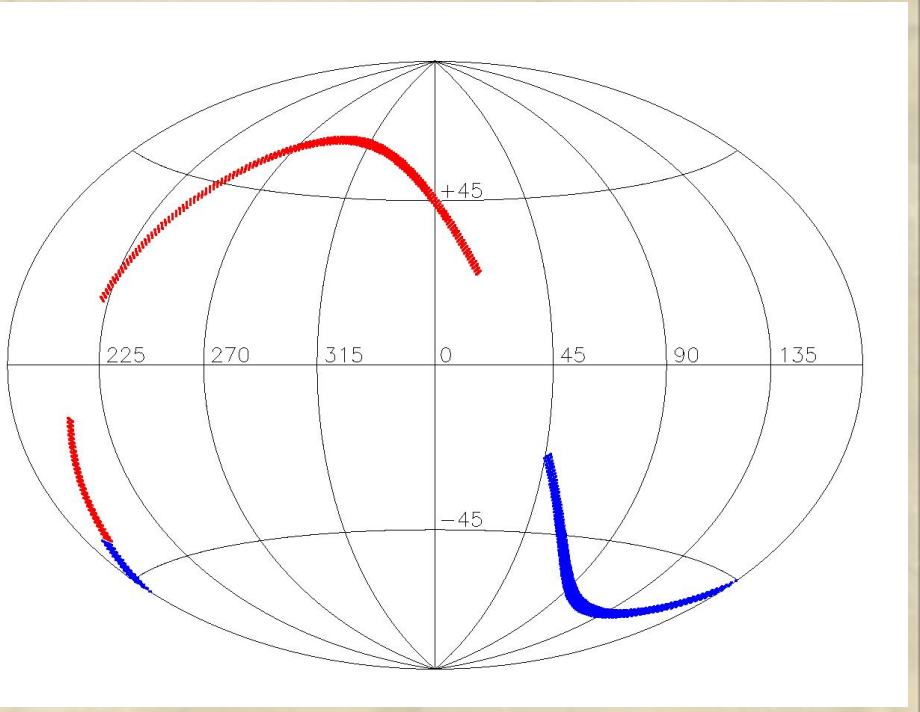
- rms (Carollo et al. sample)=112 K
- rms (FG sample)=130 K

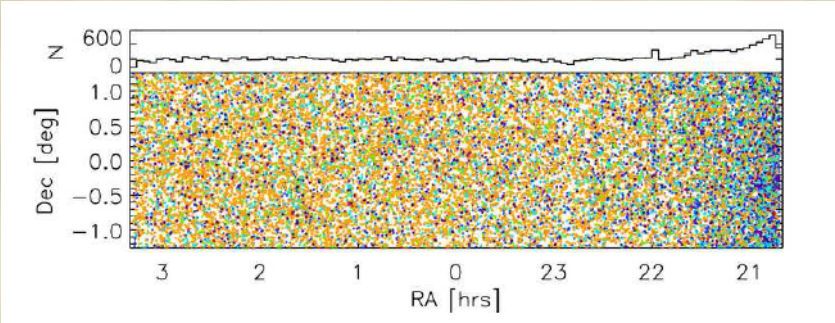
Error in [Fe/H] ~ 0.2-0.4 dex

SDSS Stripe 82

- Multiply imaged during SDSS-II for the Supernova Survey
- Best (yet) ground-based ugriz photometry available
- Errors in all bands

  < 0.01 mags



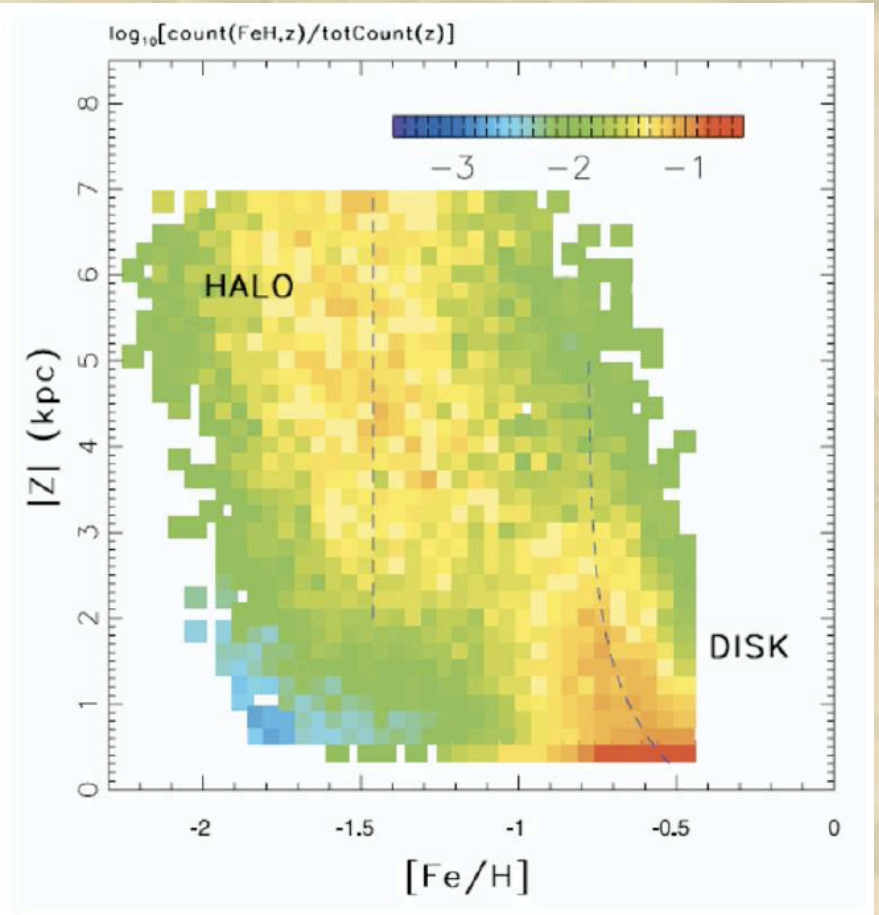


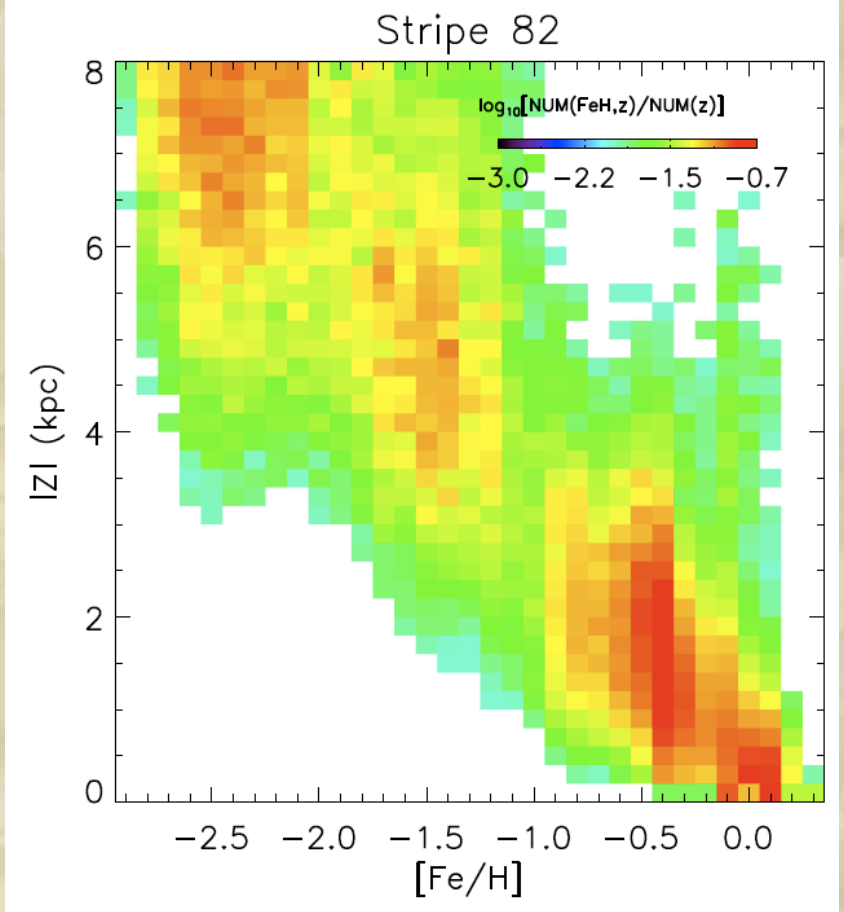
Stripe 82 in BLUE

← Watkins et al. (2009)

Metallicity Distribution

Preliminary





Ivezic et al. (2008)

u g r i z

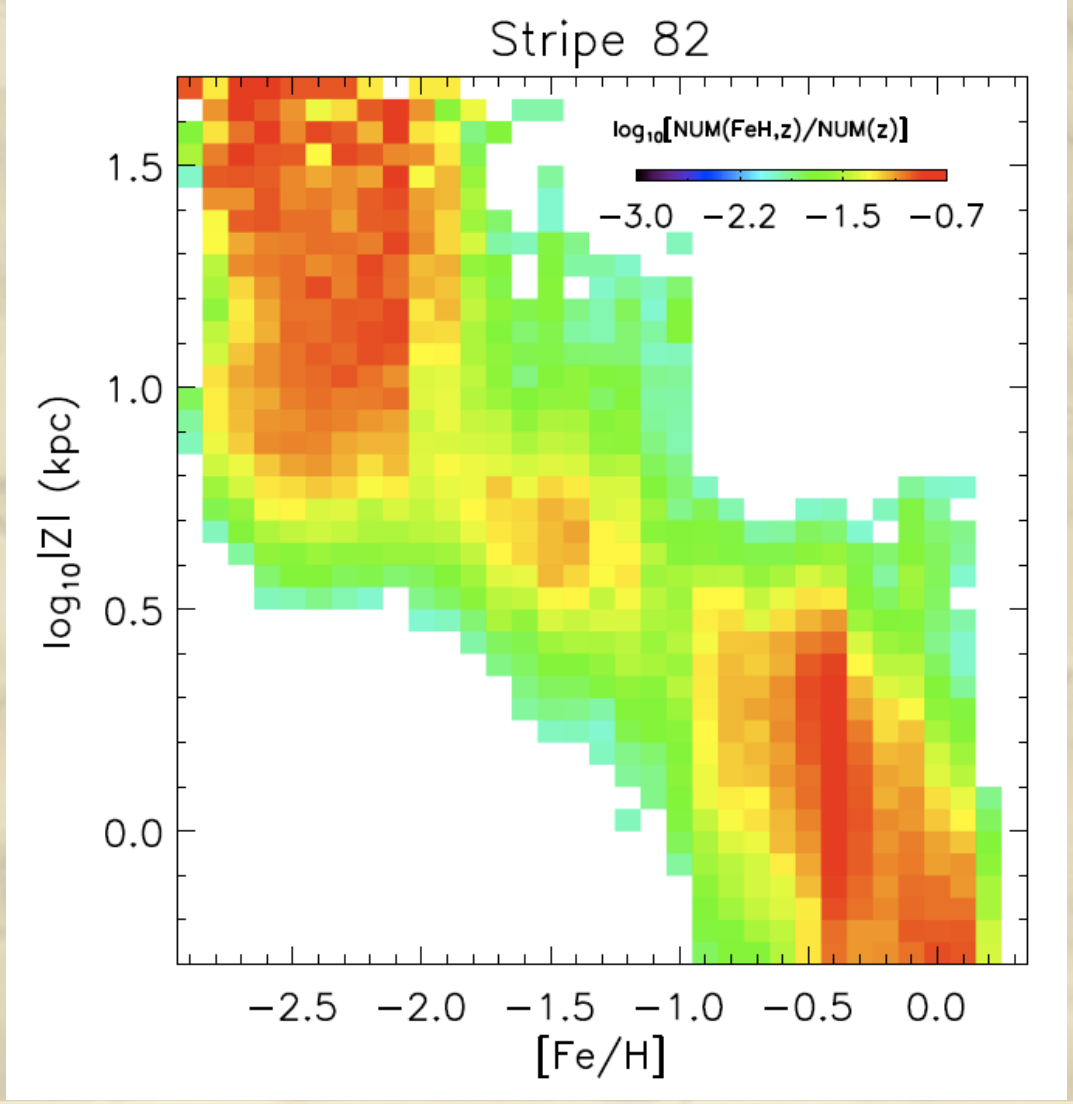
***Recalibrated* isochrones**

u g r i z

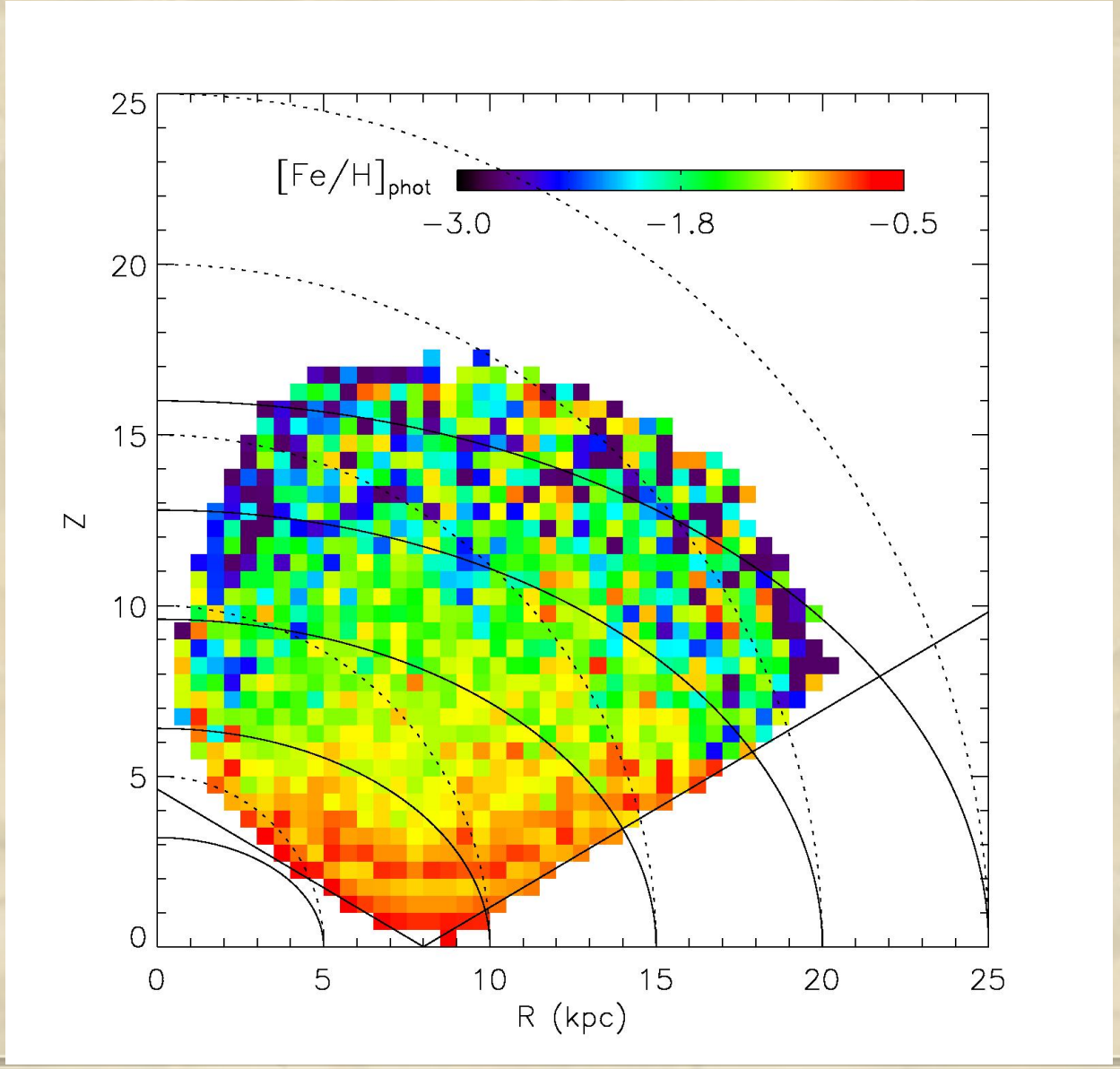
Metallicity Distribution to 30 kpc

Preliminary

u g r i z



A *gri* Map to 20 kpc

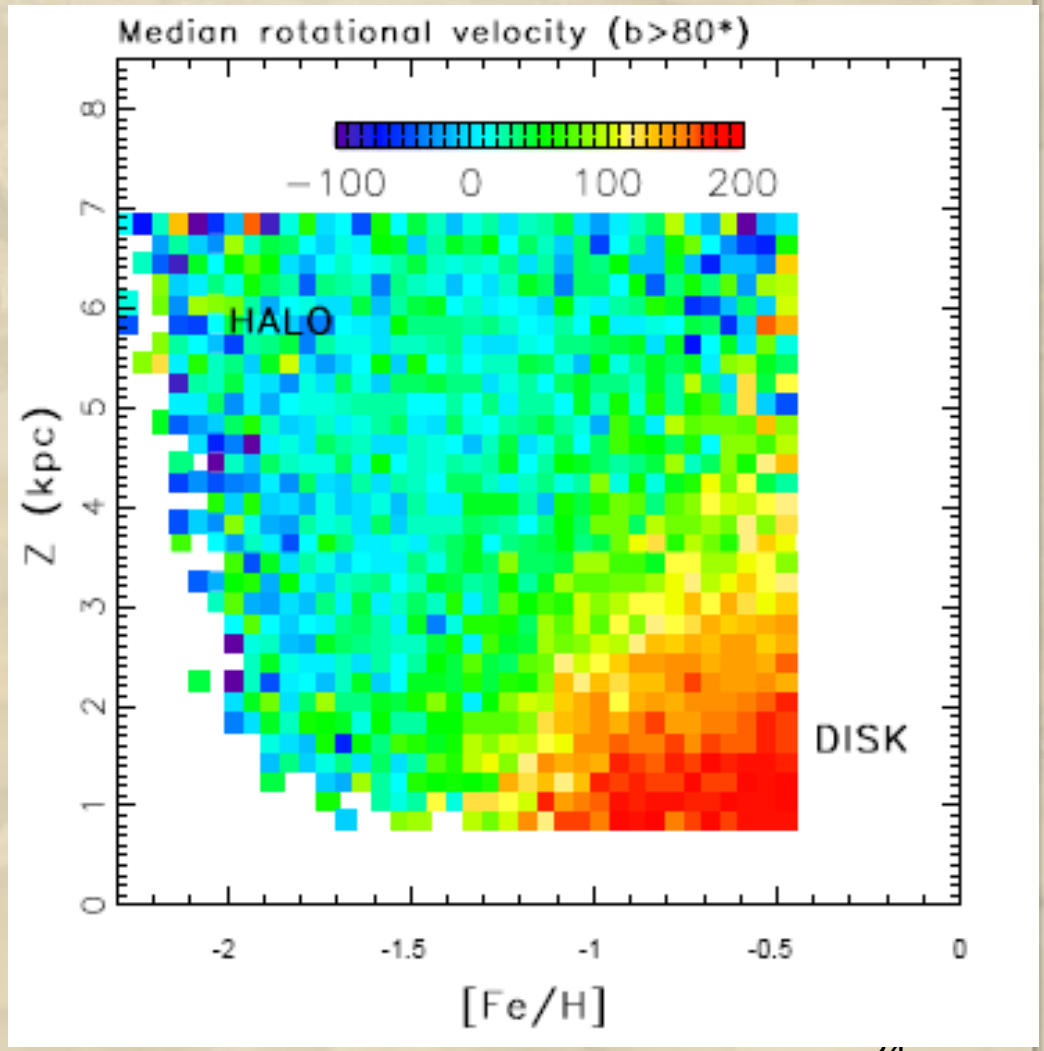


Kinematics at the NGP

By choosing directions close to the NGP, the proper motions (obtained from a re-calibration of the USNO-B catalog) sample only the U and V velocity components.

This enables determination of the rotational properties for Galactic components as a function of distance and metallicity

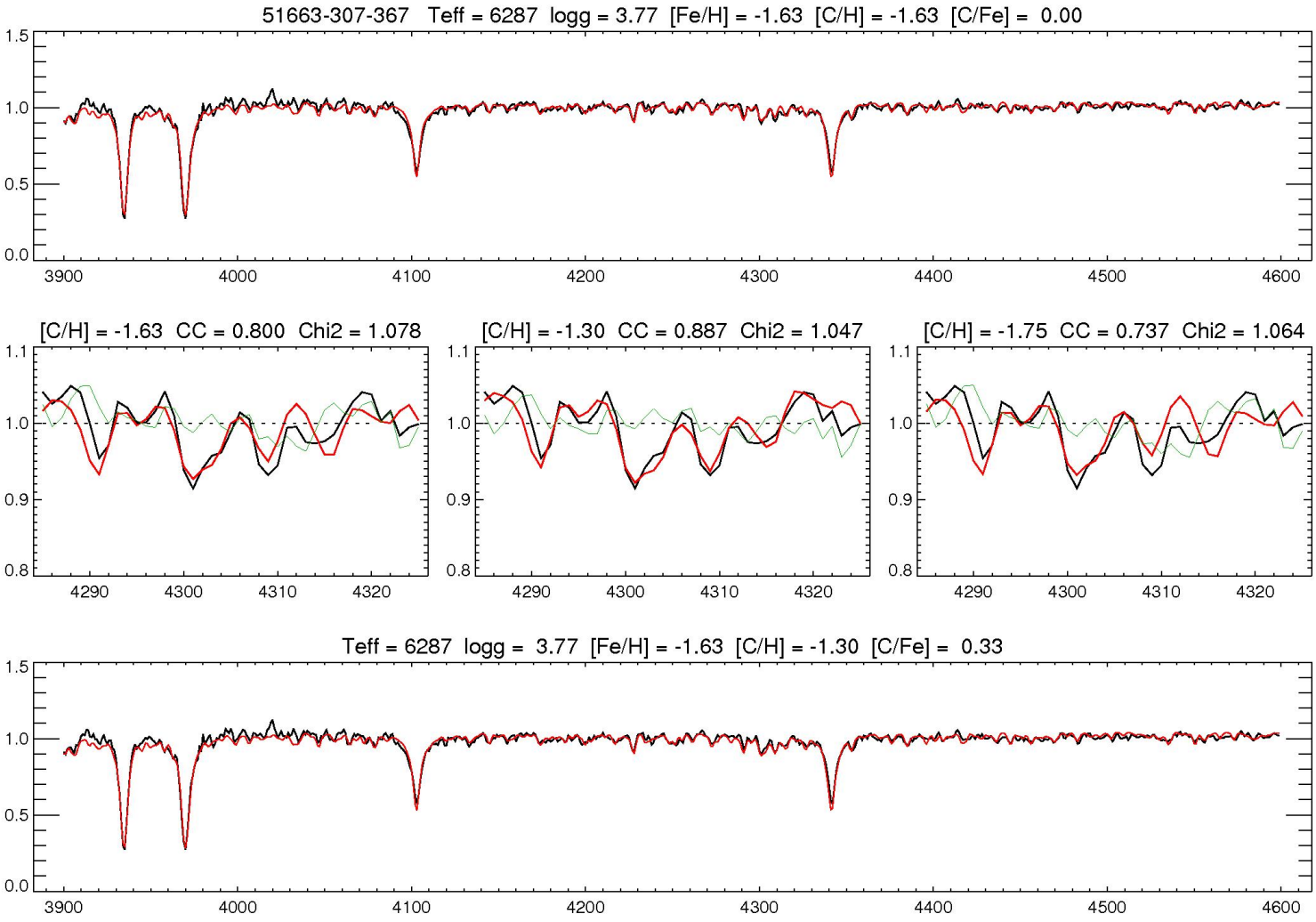
This map shows results for some **60,000** stars.

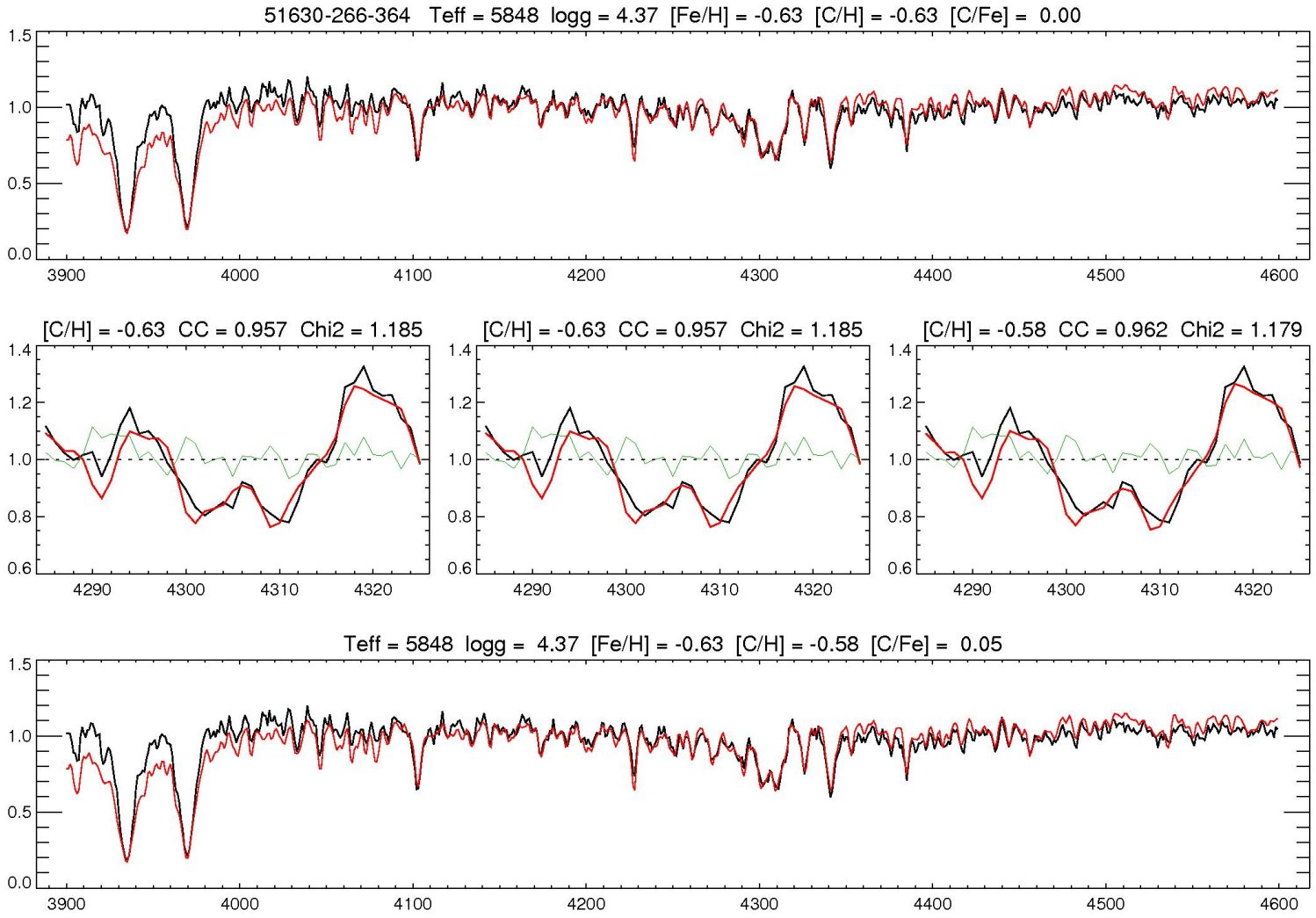


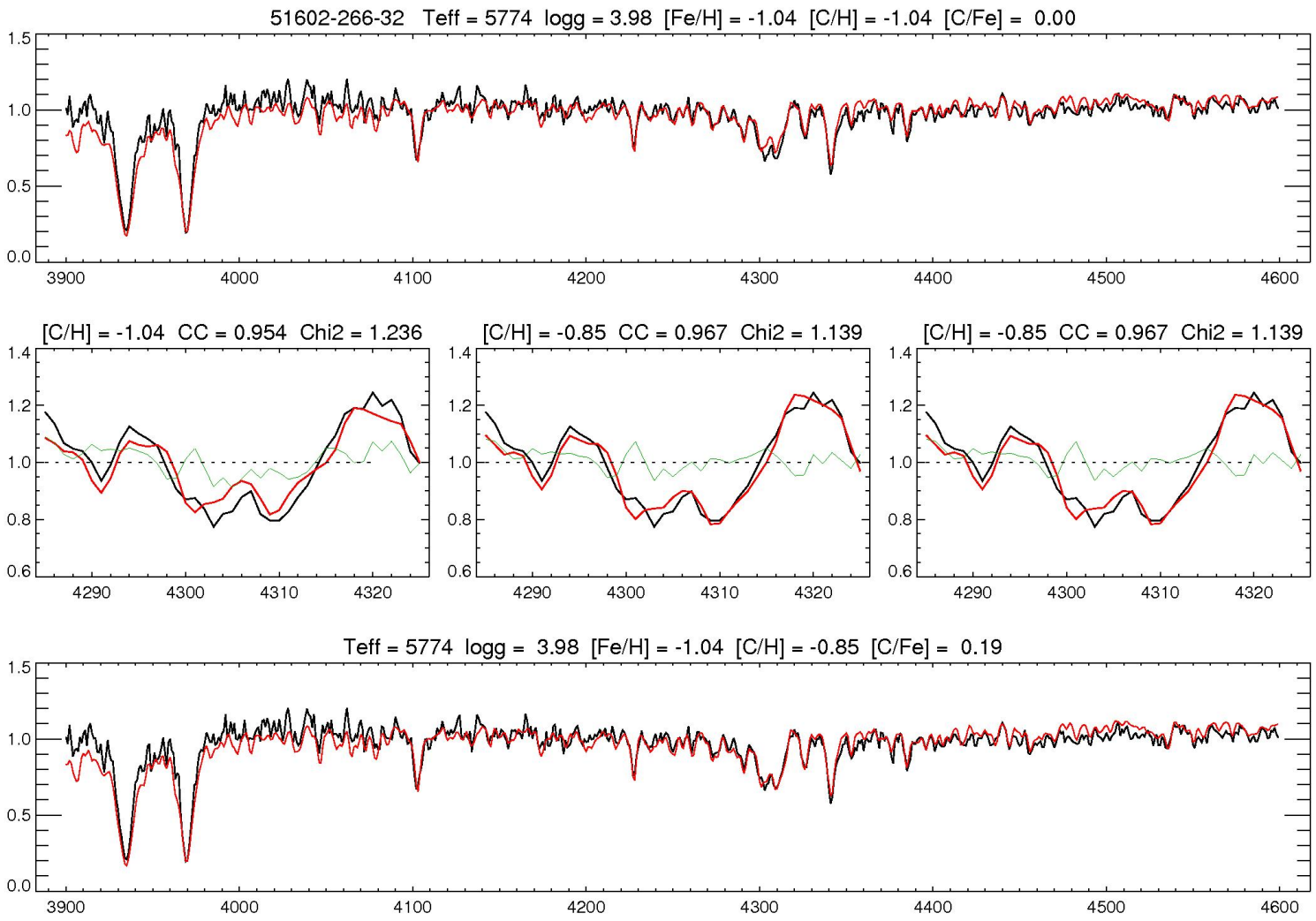
Indirect Constraints – [C/Fe] for SDSS/SEGUE Stars

- Determination of Teff, logg, [Fe/H] from SSPP
- Grids of [C/H] for to cover a wide range of parameter space (-0.5 < [C/Fe] < +4.0)
- Chi-square minimization search with techniques to avoid local minima
- Evaluation of best fit

Example Fits




51630-266-364 Teff = 5848 logg = 4.37 [Fe/H] = -0.63 [C/H] = -0.63 [C/Fe] = 0.00
[C/H] = -0.63 CC = 0.957 Chi2 = 1.185
[C/H] = -0.63 CC = 0.957 Chi2 = 1.185
[C/H] = -0.58 CC = 0.962 Chi2 = 1.179
Teff = 5848 logg = 4.37 [Fe/H] = -0.63 [C/H] = -0.58 [C/Fe] = 0.05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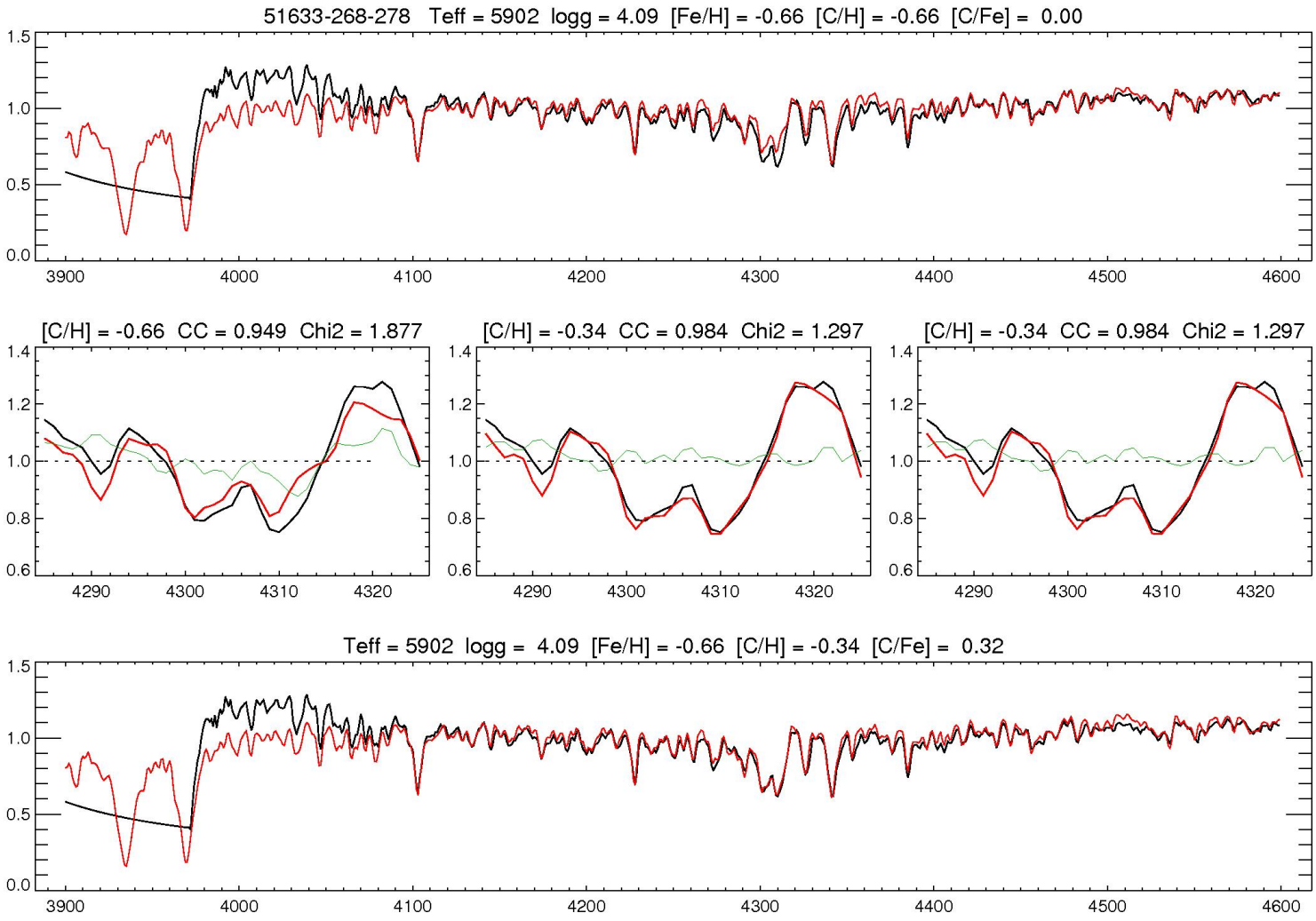
[C/H] = -1.04 CC = 0.954 Chi2 = 1.236
[C/H] = -0.85 CC = 0.967 Chi2 = 1.139
[C/H] = -0.85 CC = 0.967 Chi2 = 1.139
Teff = 5774 logg = 3.98 [Fe/H] = -1.04 [C/H] = -0.85 [C/Fe] = 0.19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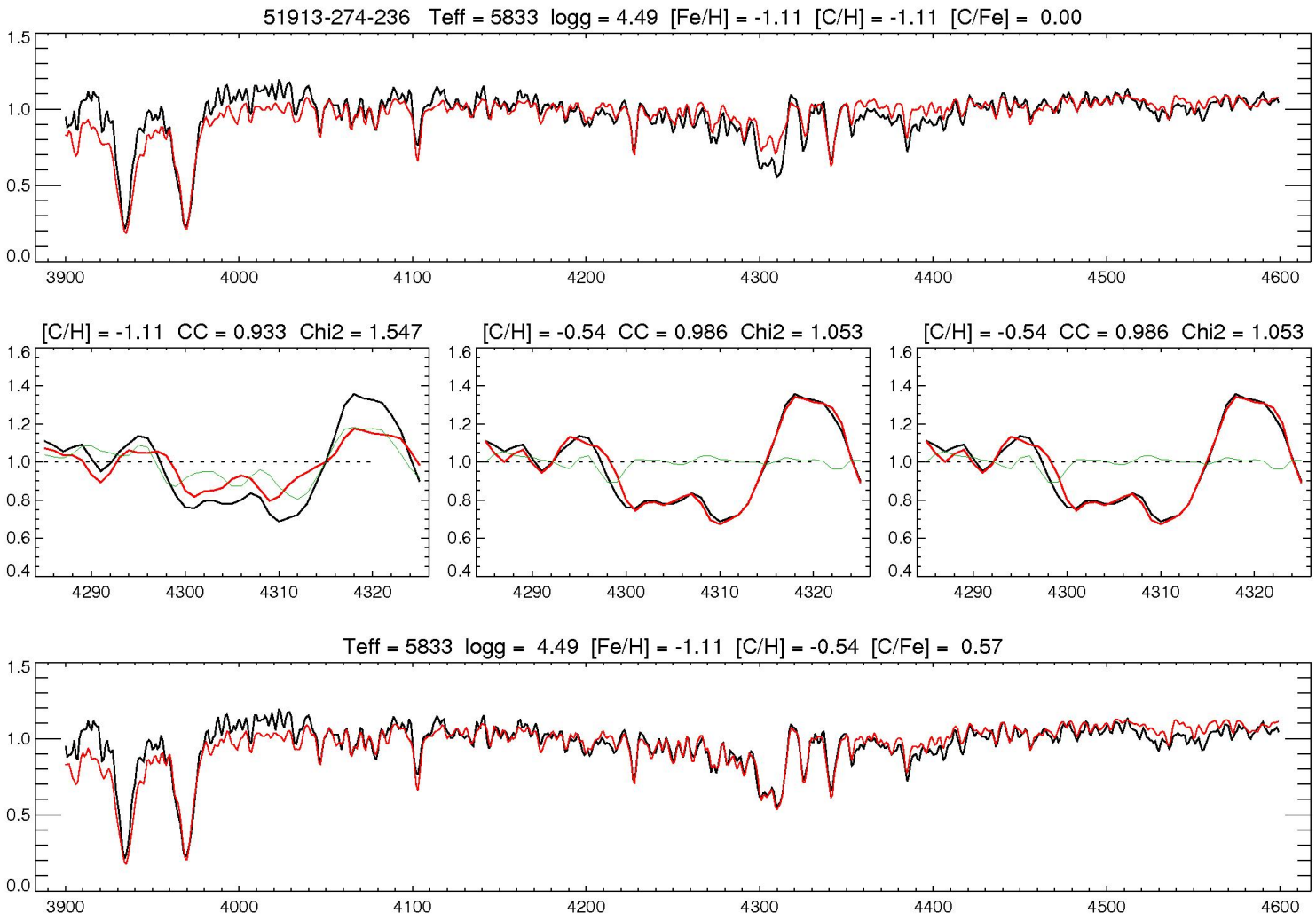
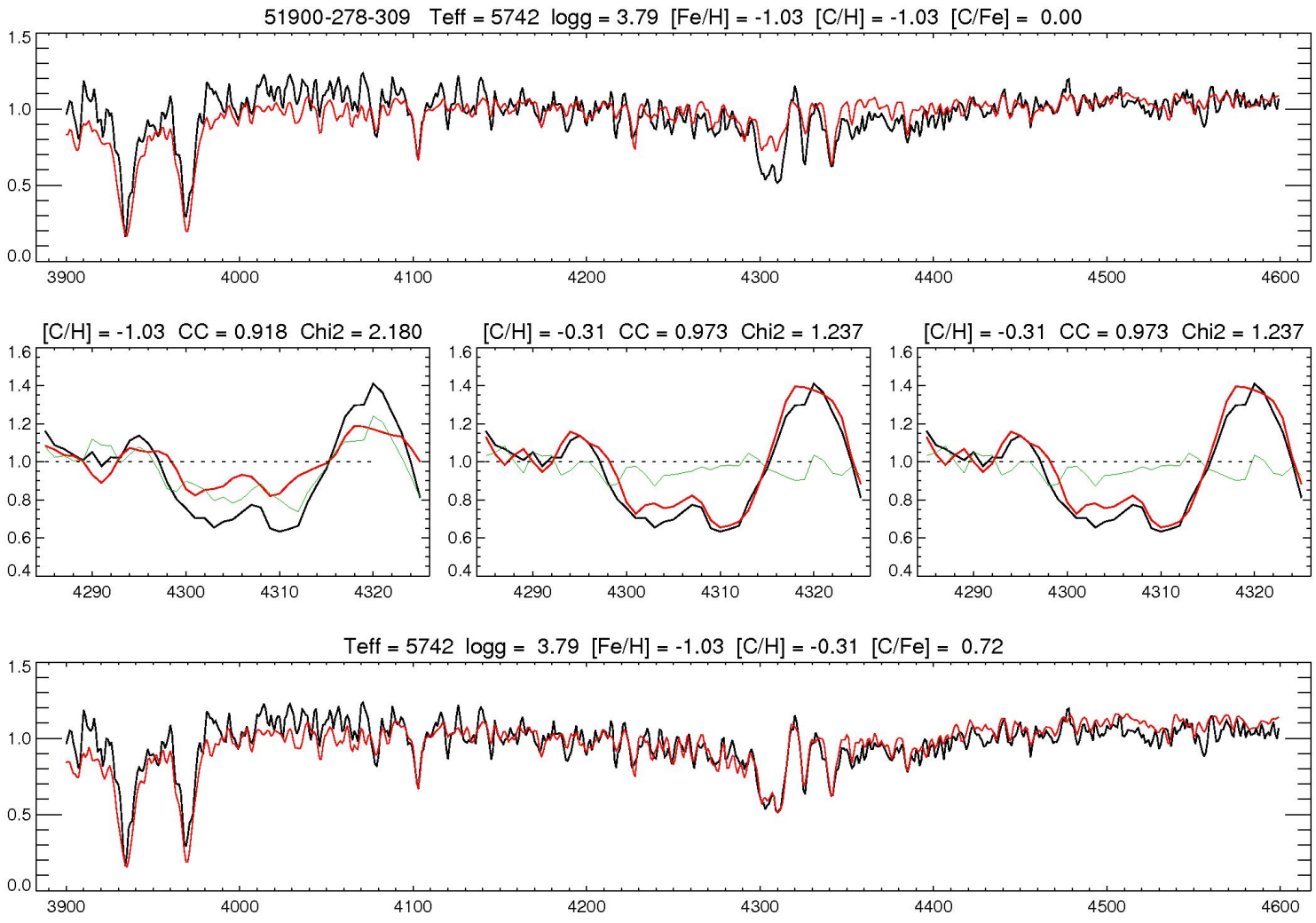
[C/H] = -0.66 CC = 0.949 Chi2 = 1.877
[C/H] = -0.34 CC = 0.984 Chi2 = 1.297
[C/H] = -0.34 CC = 0.984 Chi2 = 1.297
Teff = 5902 logg = 4.09 [Fe/H] = -0.66 [C/H] = -0.34 [C/Fe] = 0.32


51913-274-236 Teff = 5833 logg = 4.49 [Fe/H] = -1.11 [C/H] = -1.11 [C/Fe] = 0.00
[C/H] = -1.11 CC = 0.933 Chi2 = 1.547
[C/H] = -0.54 CC = 0.986 Chi2 = 1.053
[C/H] = -0.54 CC = 0.986 Chi2 = 1.053
Teff = 5833 logg = 4.49 [Fe/H] = -1.11 [C/H] = -0.54 [C/Fe] = 0.57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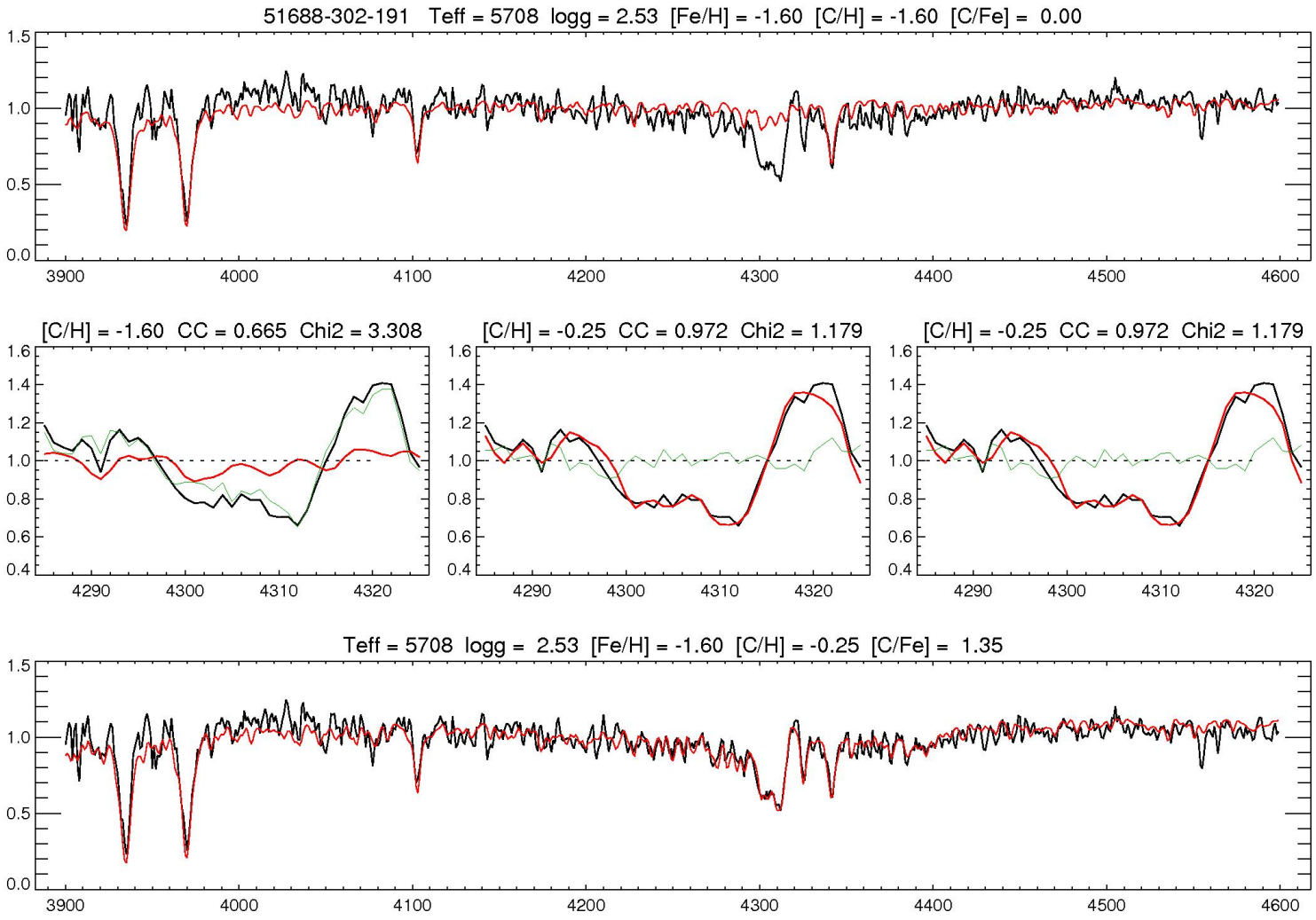
[C/H] = -1.03 CC = 0.918 Chi2 = 2.180
[C/H] = -0.31 CC = 0.973 Chi2 = 1.237
[C/H] = -0.31 CC = 0.973 Chi2 = 1.237
Teff = 5742 logg = 3.79 [Fe/H] = -1.03 [C/H] = -0.31 [C/Fe] = 0.72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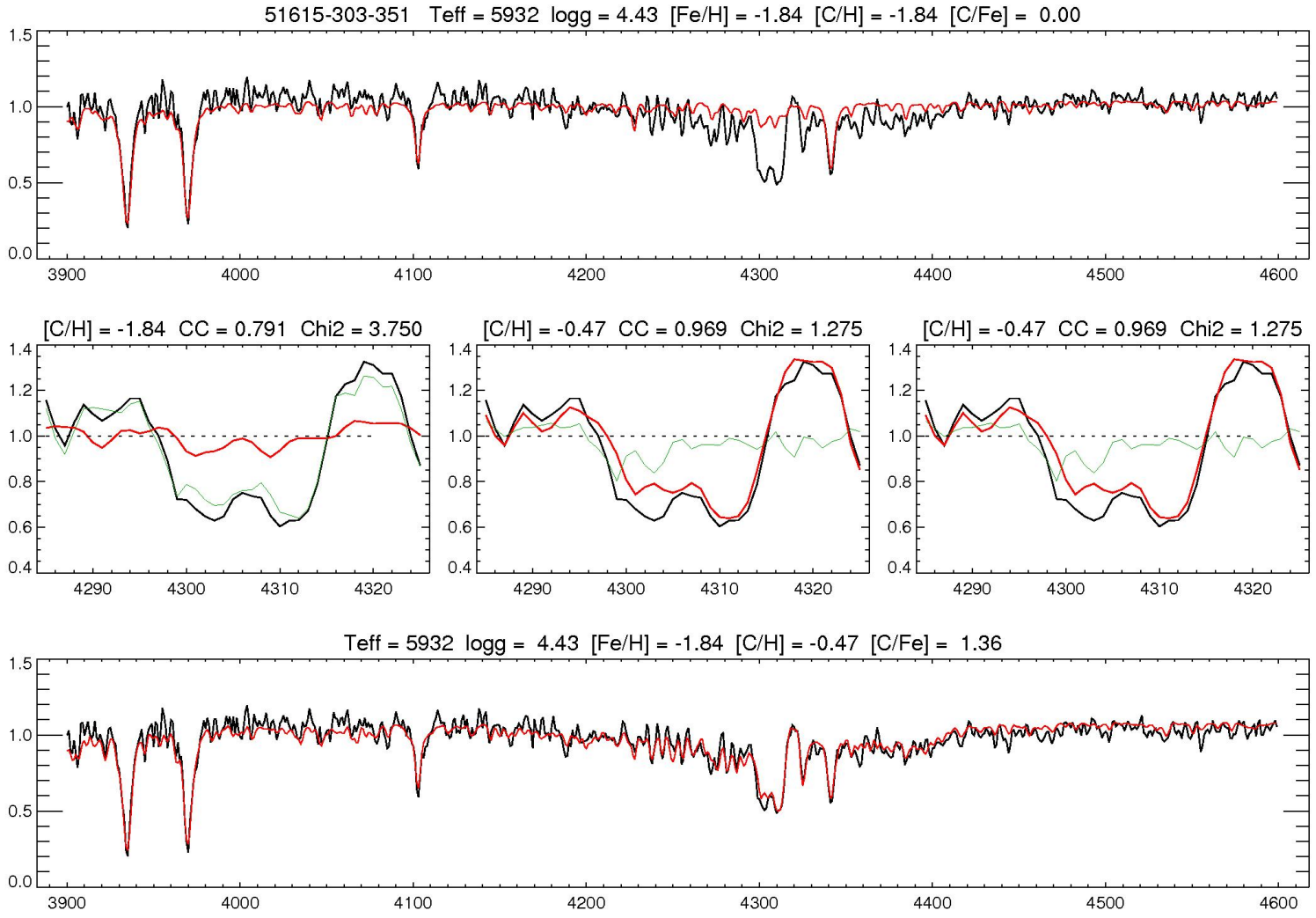
[C/H] = -1.60 CC = 0.665 Chi2 = 3.308
[C/H] = -0.25 CC = 0.972 Chi2 = 1.179
[C/H] = -0.25 CC = 0.972 Chi2 = 1.179
Teff = 5708 logg = 2.53 [Fe/H] = -1.60 [C/H] = -0.25 [C/Fe] = 1.35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[C/H] = -0.47 CC = 0.969 Chi2 = 1.275
[C/H] = -0.47 CC = 0.969 Chi2 = 1.275
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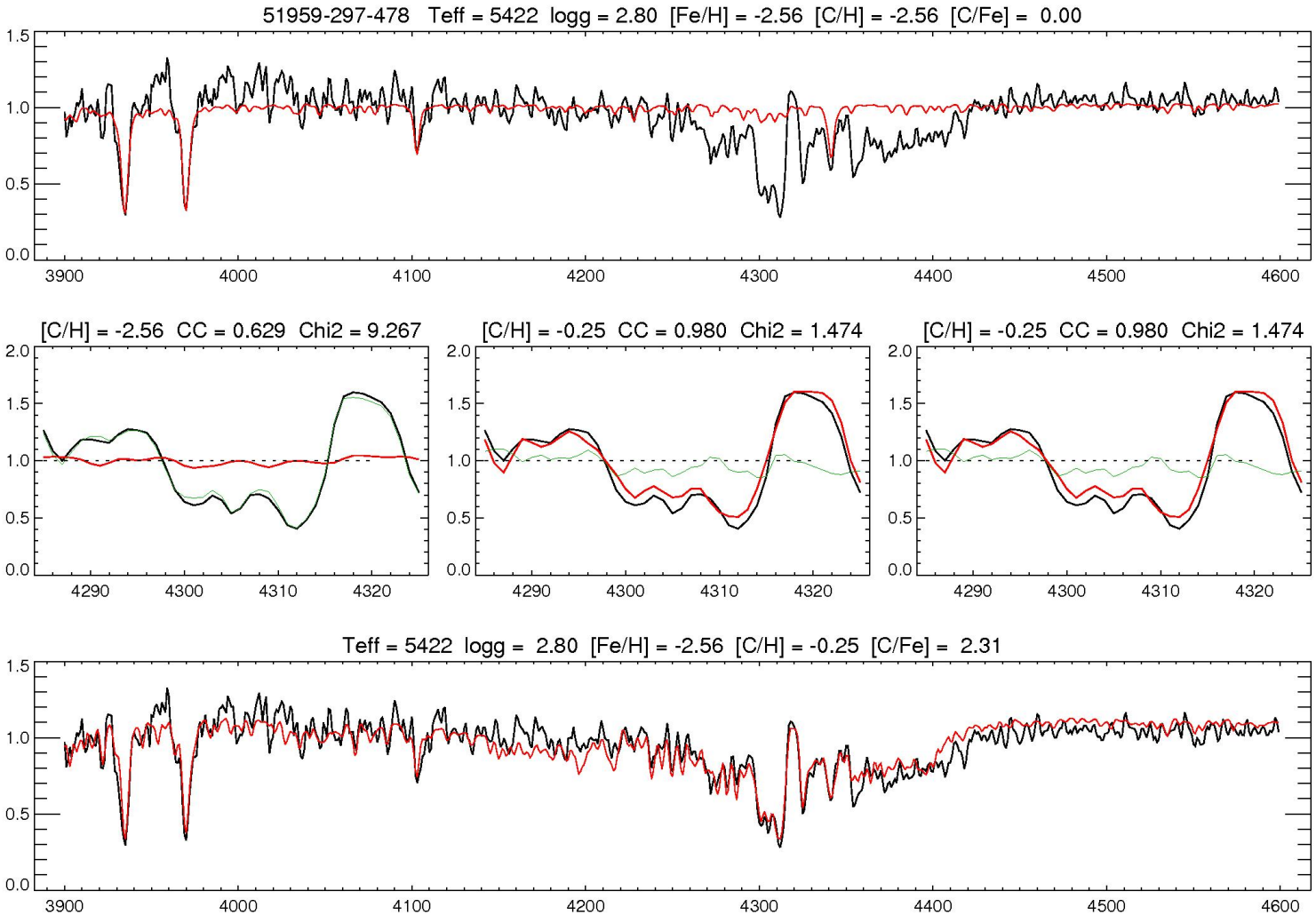
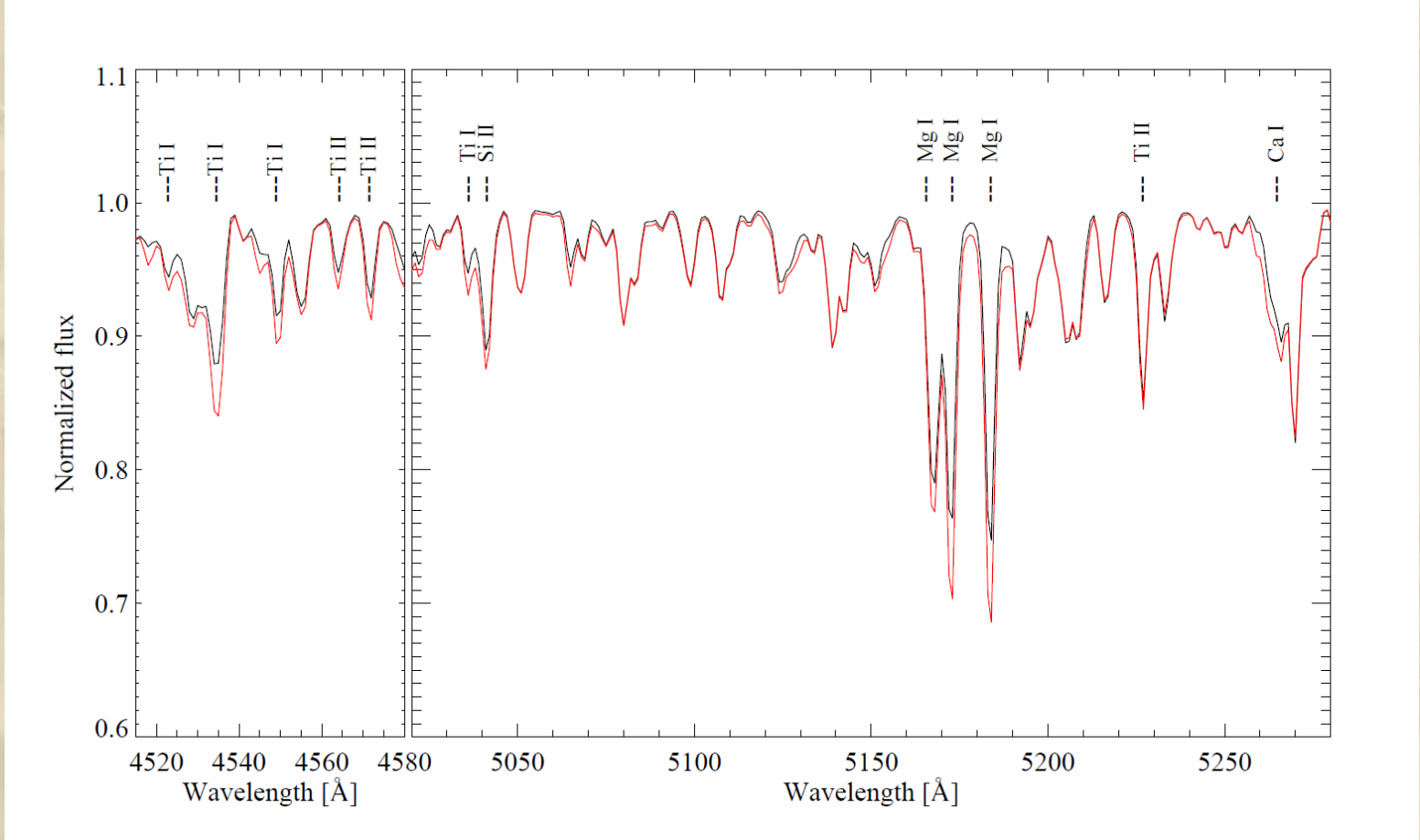

51959-297-478 Teff = 5422 logg = 2.80 [Fe/H] = -2.56 [C/H] = -2.56 [C/Fe] = 0.00
[C/H] = -2.56 CC = 0.629 Chi2 = 9.267
[C/H] = -0.25 CC = 0.980 Chi2 = 1.474
[C/H] = -0.25 CC = 0.980 Chi2 = 1.474
Teff = 5422 logg = 2.80 [Fe/H] = -2.56 [C/H] = -0.25 [C/Fe] = 2.31

[C/Fe] For SDSS/SEGUE Stars

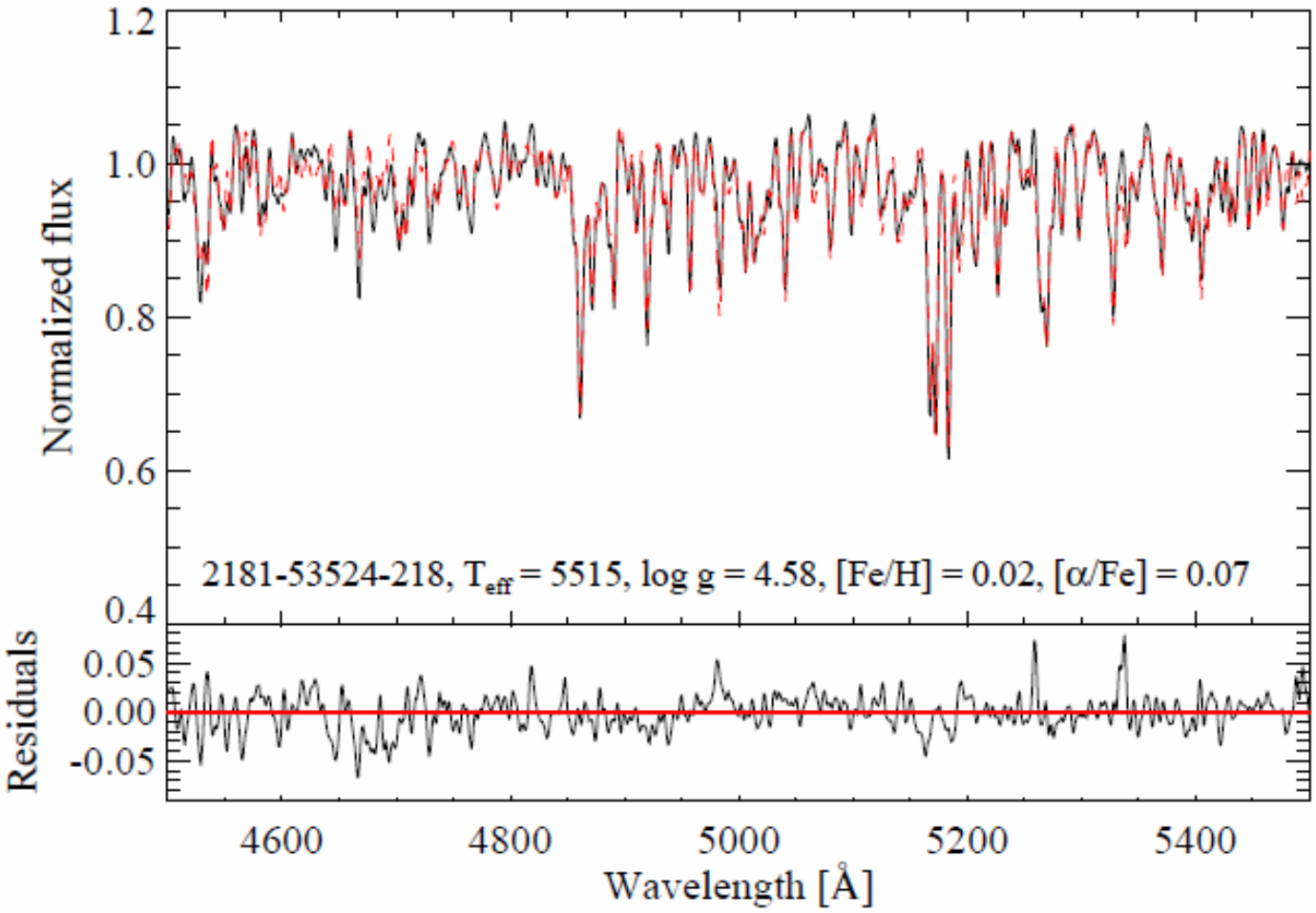
- [C/Fe] can probe the IMF / binarity fraction of progenitors of Milky Way components – distribution and frequency may vary between, e.g., inner/outer halo, TD and MWTD
- Global frequency as a f([Fe/H]) provides constraints on AGB models and non-AGB sources of carbon
- C-rich stars may include additional EMP/UMP/ HMP stars
- Now have detections for > 200,000 SDSS/ SEGUE stars, limits for many more

[α/Fe] for SEGUE Stars

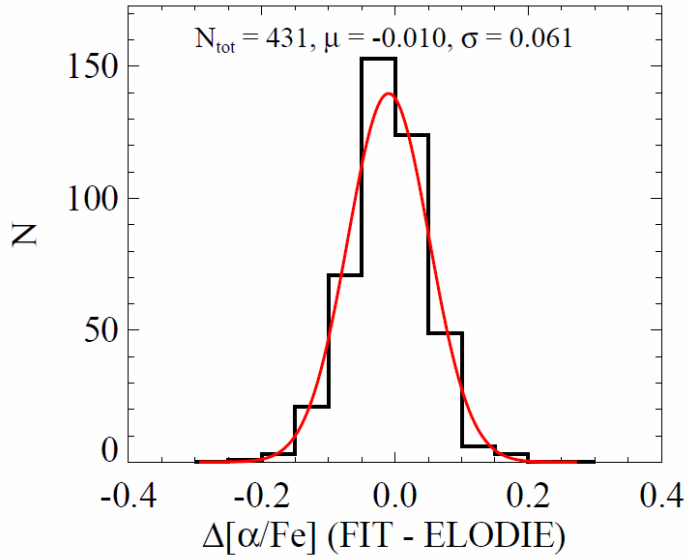


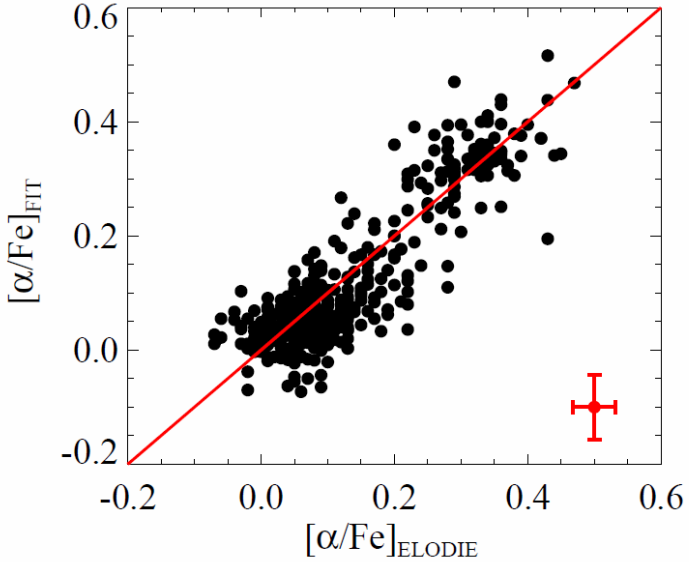
Lee et al. (in prep)

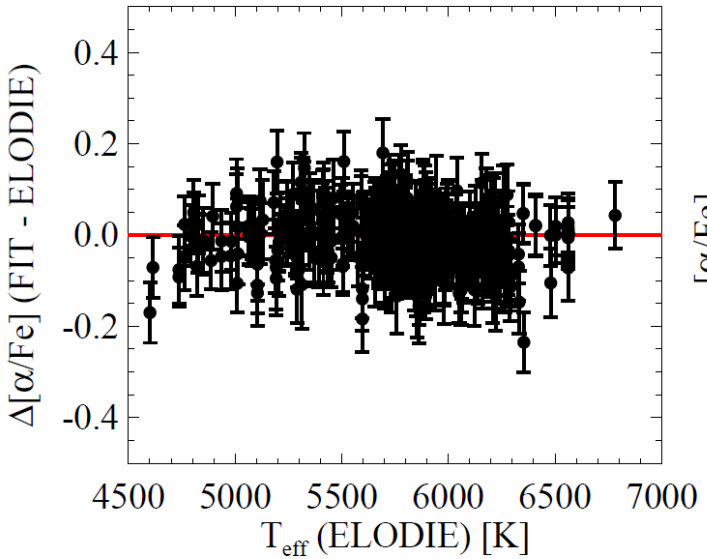
Example Fits

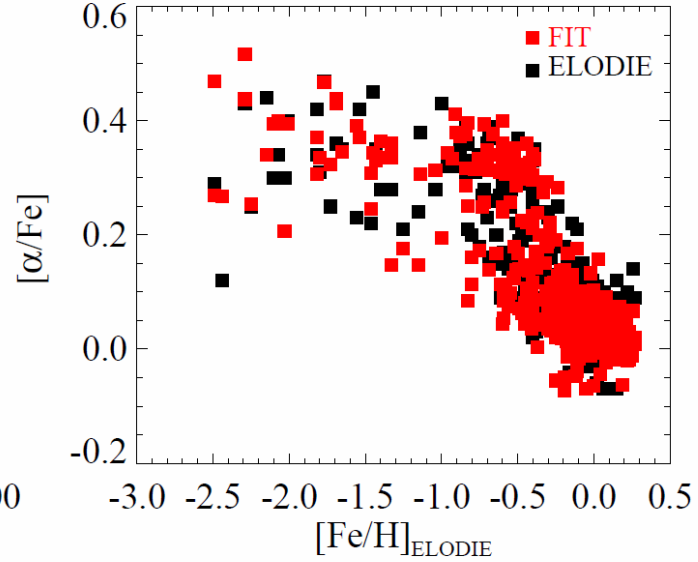


[α/Fe] for SDSS Comparison with Elodie Library



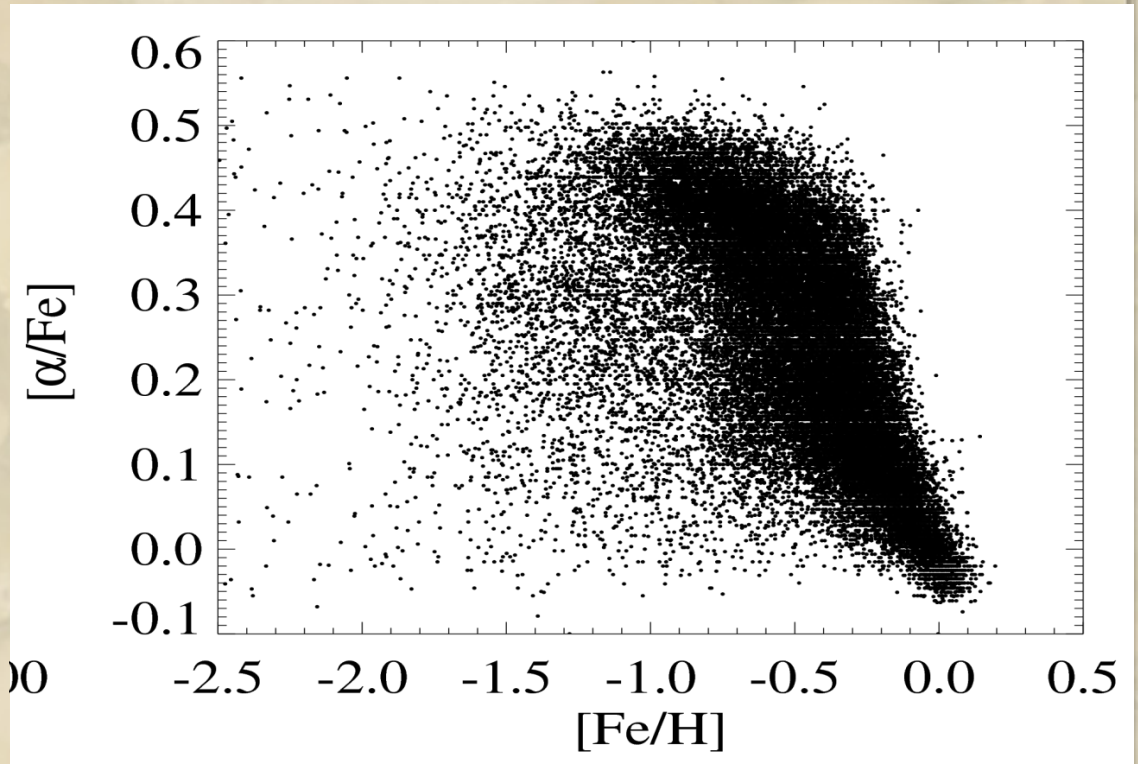






[α/Fe] for SDSS/SEGUE Stars

- [α/Fe] ratios are critical probes of the environment in which metal-poor stars were born (masses of parent sub-halos)
- [α/Fe] ratios are critical probes of the accretion history of the Galaxy (Johnston et al. 2008)
- Can estimate to < 0.1 dex for stars in SDSS/SEGUE with S/N > 20/1 (Lee et al. 2010, in prep)

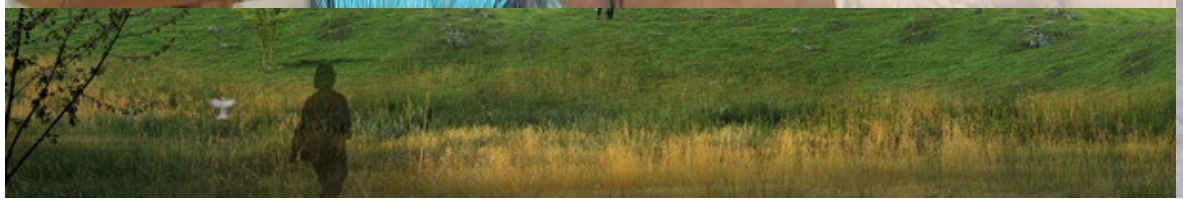


Roughly 70,000 G dwarfs, S/N > 20/1

Looking Forward

- MDF of "halo" stars will "break up" into a component obviously associated with the inner halo, and one (at lower [Fe/H]) associated with the outer halo
- Need to consider the CDF ("Carbonicity" -- [C/Fe] -- Distribution Function) of the components of the Galaxy
- Need to consider the ADF ("Alphanicity" -- [α/Fe] -- Distribution Function) of the components of the Galaxy
- Ultimately, will require similar data for many individual elements (in particular n-capture)

LAMOST



Numbers With LAMOST Upon Completion of 5 Million Star Survey

- 300,000 stars with [Fe/H] < -2
- 10,000 with [Fe/H] < -3
- 2,500,000 stars with [C/Fe]
- 1,500,000 stars with [α/Fe]