Binary fractions estimated from LAMOST (dr3)

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OUTLINE

- Introduction
- Method and Data
- Results
- Summary

INTRODUCTION

- Stellar systems constructed with single, double, triple and high-order systems are rightfully regarded as the fundamental building blocks of the milky way.

- Binaries：about 50% of stars （e.g. Gao+2014; yuan+2015, Hettinger+2015, Raghavan+2010）
- Binary stars dominate an important role in formation and evolution of the galaxy, because of its relative high fraction than triple or high-order systems (Raghavan+2010) and material and energy exchange between the numbers of the binary system.

- Understanding the star formation process. e.g. Type Ia SNe: White dwarf with a companion

- Given the light curve or radial velocity variations with time, binary stars provide an independent method to obtain masses and radii using Kepler's third law, which offer exciting opportunities to develop highly constrained stellar models (Gaulme+2016)

- Interpreting stellar population, e.g. IMF, period distribution

- Evolution of the galaxy, e.g. thick/thin disks

Researches about binary fractions

- RV: RV changes with time(phase), e.g. , Hettinger+2010, Gao+2014

- Proper motion(Position): image blinking, common proper motion. e.g. Raghavan+2010

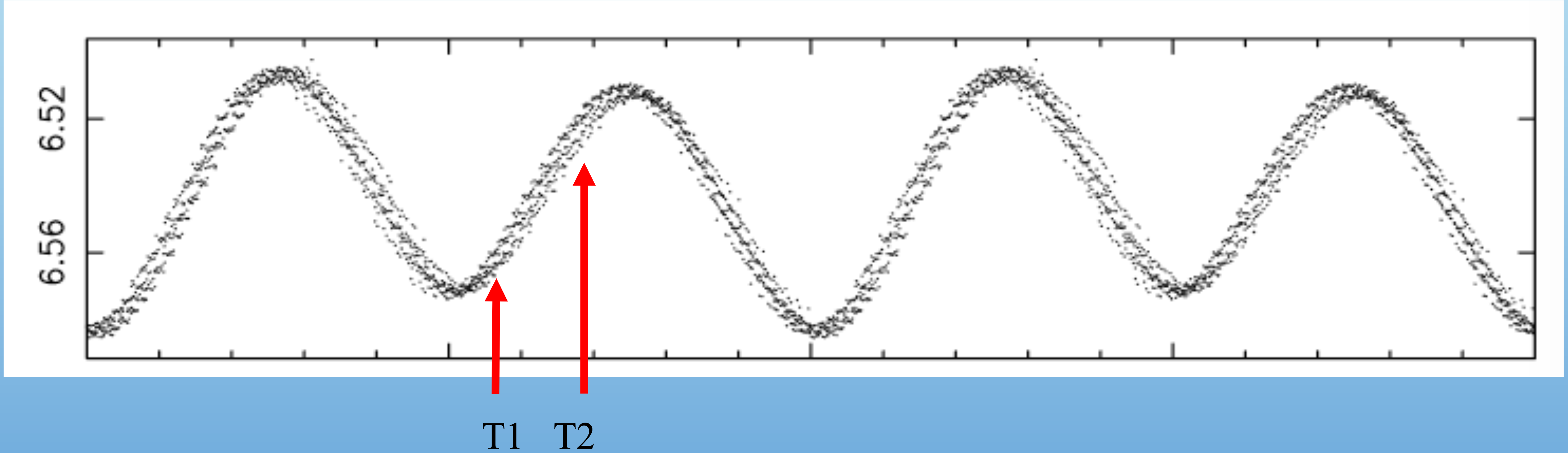
- Based on the difference between single and binary stars, such as colors.

  Distribution of binary stars on color-color diagram deviates from that of single stars. e.g. Yuan+2015

- Light curve, e.g. Kepler eclipsing binaries (Matijevic+ 2012)

Radial Velocity（RV） changes with time/phase

Mass 1 or Mass 2	The mass of each of the two stars.
Separation	The distance between the two stars in solar radii.
Eccentricity	Eccentricity of the orbit
Inclination angle	Angle of the orbital plane of the stars to our line-of-sight. • 0^o - face on • 90^o - edge on Note that this is opposite from the Eclipse simulation - we'll fix this in the future.
Node angle	Angle of the major axis as measured in the orbital plane (see privileged view)



RVs with time fit better for single or binary models?

- Hettinger et al. 2015, ApJL, 806, L2

> The probability of a star having a companion was determined through model comparison using a trans-dimensional, hierarchical, Markov chain Monte Carlo (MCMC) method. Two models were compared: a single-star model $\mathcal{M}_s$, and a binary-star model $\mathcal{M}_b$. The hyperparameter λ, indexes the model choice at each step in the MCMC chain. We evaluated the hierarchical model using the Python package *emcee*, a MCMC ensemble sampler (Foreman-Mackey et al. 2013).

Metal-rich disk stars were found to be 30% more likely to have companions with periods shorter than 12 days than metal-poor halo stars.

Distribution of drv from multi-epoch observations

- Gao et al. 2014, ApJL, 788, L37

THE ASTROPHYSICAL JOURNAL LETTERS, 788:L37 (6pp), 2014 June 20 doi:10.1088/2041-8205/788/2/L37

THE BINARITY OF MILKY WAY F,G,K STARS AS A FUNCTION OF EFFECTIVE TEMPERATURE AND METALLICITY

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ABSTRACT

We estimate the fraction of F,G,K stars with close binary companions by analysing multi-epoch stellar spectra from the Sloan Digital Sky Survey (SDSS) and LAMOST for radial velocity variations. We employ a Bayesian method to infer the maximum likelihood of the fraction of binary stars with orbital periods of 1000 days or shorter, assuming a simple model distribution for a binary population with circular orbits. The overall inferred fraction of stars with such a close binary companion is 43.0% $\pm$ 2.0% for a sample of F,G,K stars from SDSS SEGUE, and 30% $\pm$ 8.0% in a similar sample from LAMOST. The apparent close binary fraction decreases with the stellar effective temperature. We divide the SEGUE and LEGUE data into three subsamples with different metallicity ([Fe/H] < -1.1; $-1.1 <$ [Fe/H] < -0.6; $-0.6 <$ [Fe/H]), for which the inferred close binary fractions are $56 \pm 5.0\%$, $56.0 \pm 3\%$, and $30 \pm 5.7\%$. The metal-rich stars from our sample are therefore substantially less likely to possess a close binary companion than otherwise similar stars drawn from metal-poor populations. The different ages and formation environments of the Milky Way's thin disk, thick disk, and halo may contribute to explaining these observations. Alternatively, metallicity may have a significant effect on the formation and/or evolution of binary stars.

Key words: binaries: close – binaries: spectroscopic – Galaxy: disk – stars: formation – stars: statistics

Online-only material: color figures

$$p(\Delta v) = f_{\rm B}\, p_{\rm B}(\Delta v|\sigma_0, \Delta t, \mathcal{M}_{\mathcal{B}}) + (1 - f_{\rm B})\, p_S(\Delta v|\sigma_0),$$

DATA:

LAMOST DR1 & SDSS DR9

BINARY MODEL:

- IMF Salpeter 1955
- Mass ratio： uniform distribution [0.05,1]
- Period distribution

LOG(P) ~N(5.03,2.28)
Raghavan+2010

- dt from observations

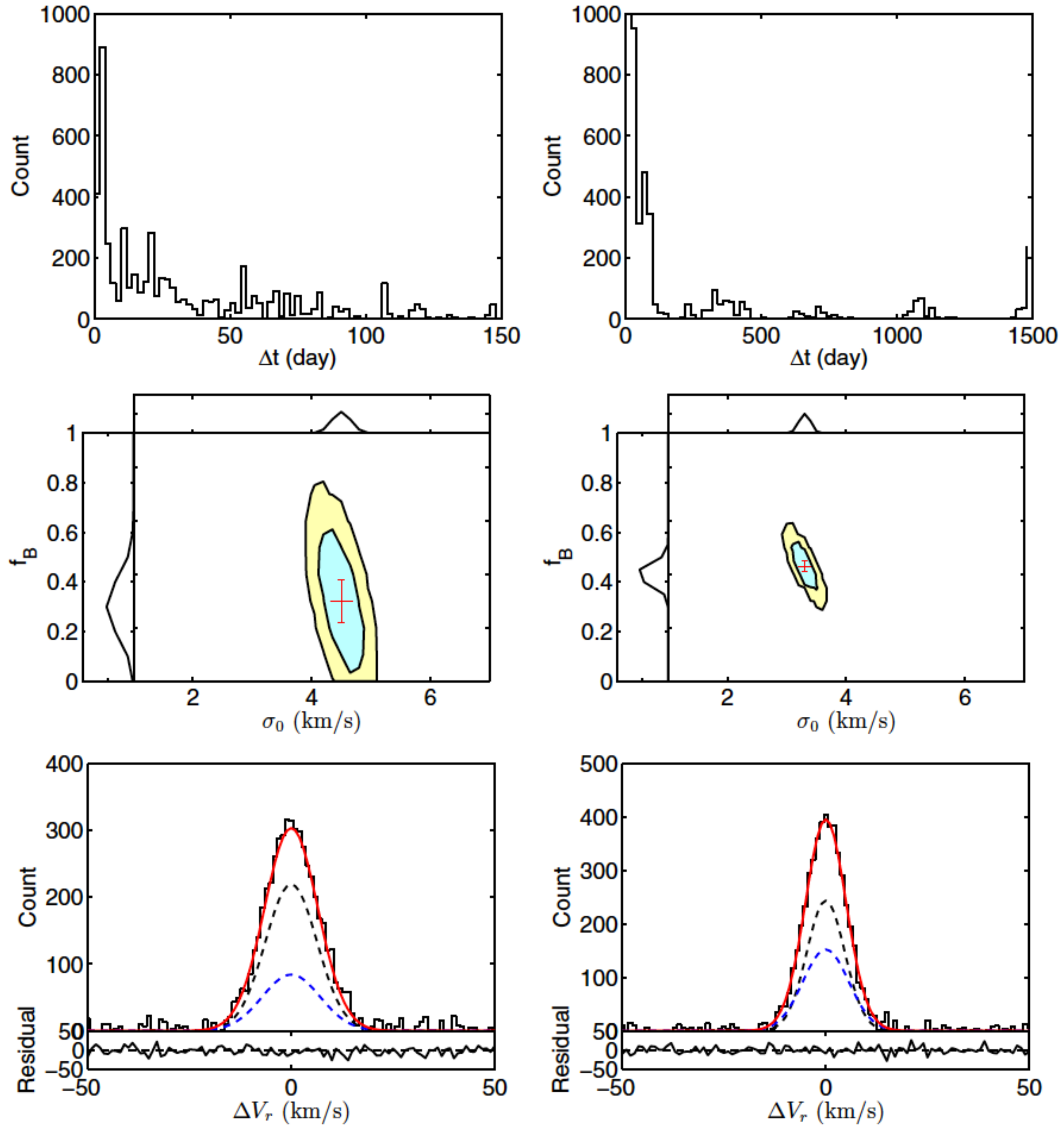


Figure 3. Left panels shows LEGUE information, the right column SEGUE. Top panels: the distributions of time gaps between observations of the same star in the two samples. Middle panels: maps of the posterior PDFs in the plane of σ_0 and f_B. The shaded contours contain σ and 3σ of the cumulative PDF, with marginalized 1D PDFs displayed at the edges of the plane. Bottom panels: the dashed curves show model RV differences for the single and binary components, with the (red) solid curves the combined population. The histograms are the bias-corrected observed profiles.

(A color version of this figure is available in the online journal.)

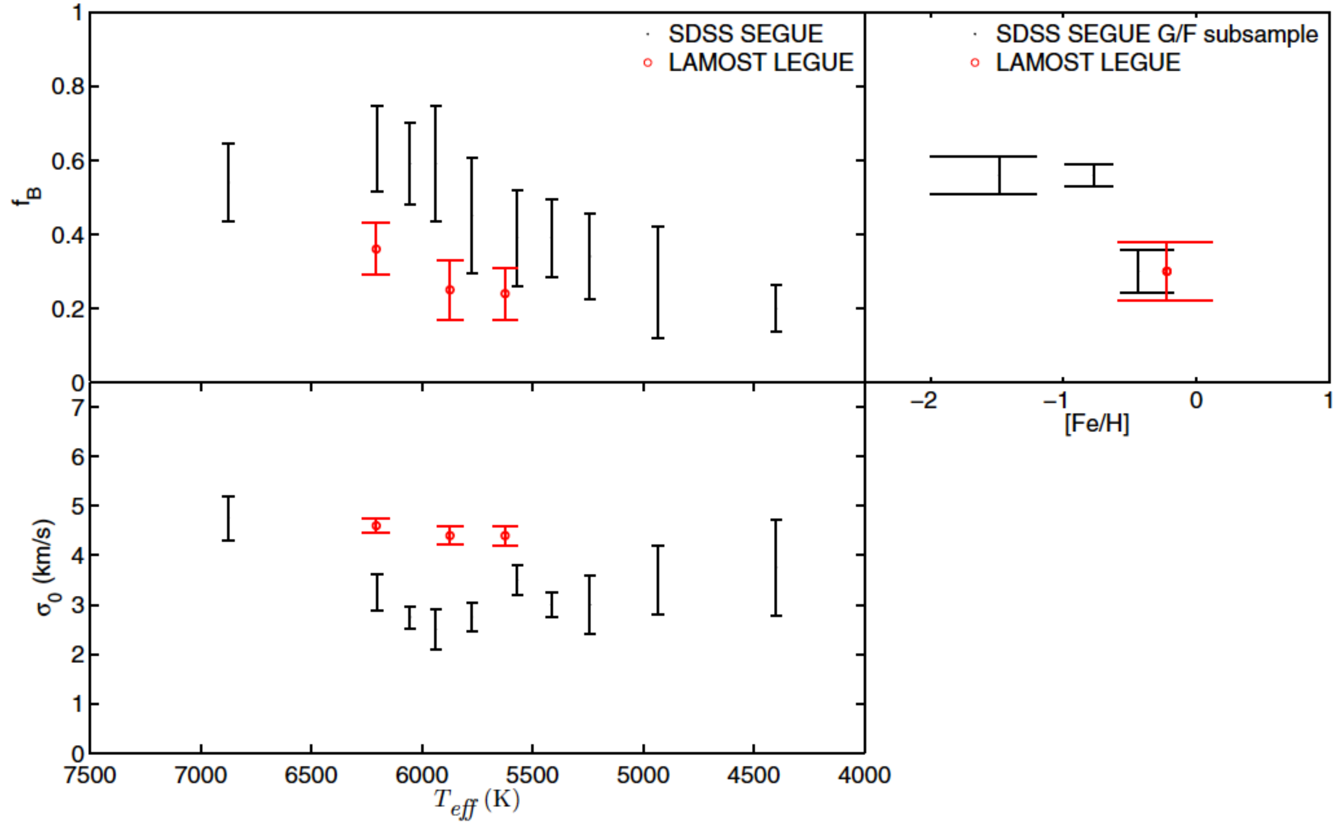


Figure 4. Binary fraction as the function of $T_{\rm eff}$ and [Fe/H]. The binary fraction and RV errors are limited within 10 stellar $T_{\rm eff}$ bins for SEGUE sample, which are shown as black error bars in the upper and lower panels. For LAMOST sample, result based on three bins are shown as red color in panels together. The [Fe/H] function are shown in right panel.

[Fe/H] ↑ , fb ↓

Teff ↑, fb ↑

STELLAR LOCUS

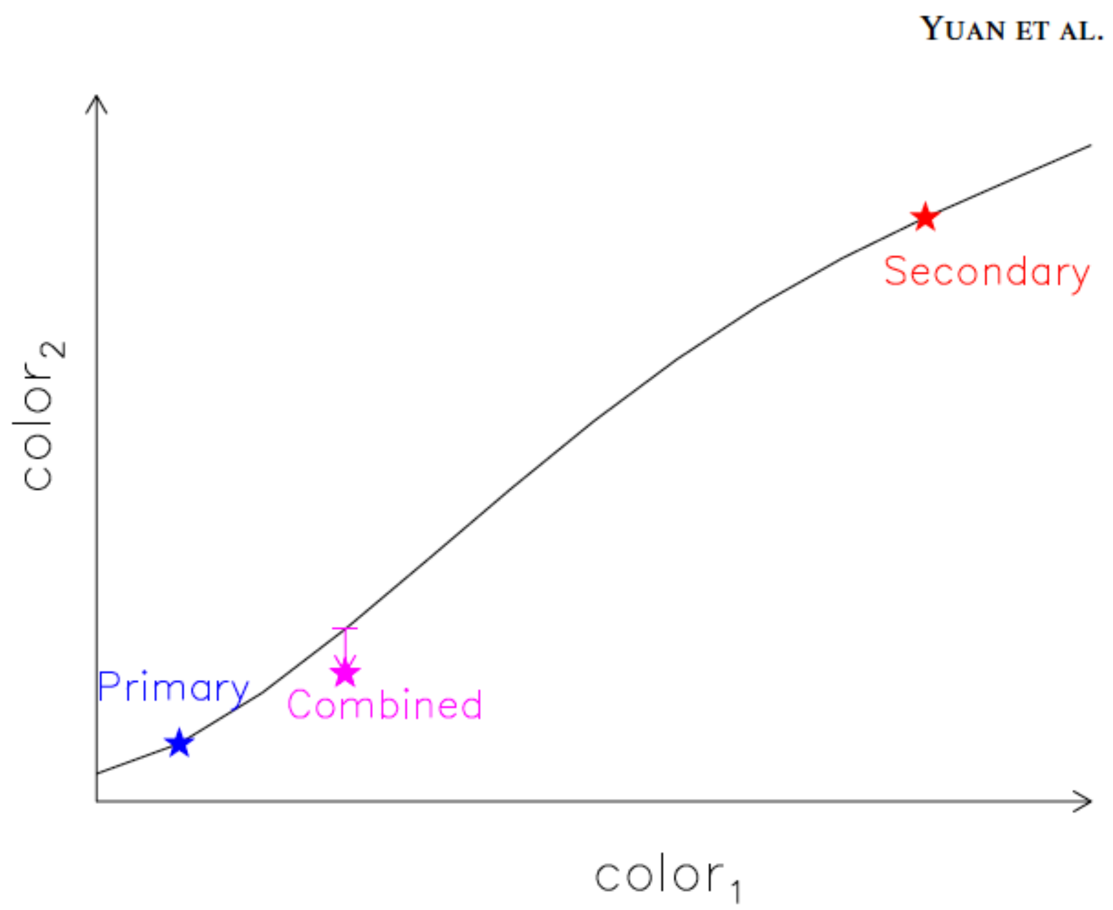


Figure 1. Plot illustrating the SLOT method. The line denotes the stellar locus of MS single stars of a given metallicity. The purple, blue, and red stars denote locations of a binary system and its primary and secondary stars, respectively. The colors of the binary system deviate from the stellar locus, as indicated by the arrow.

The stellar locus outilier (SLOT) method requires a sample of MS stars with accurate photometric colors and well-determined metallicities.

Data:
[Fe/H] from LAMOST&SDSS
Colors from SDSS

Yuan et al. 2015, ApJ, 799, 135

Merits and Demerits?

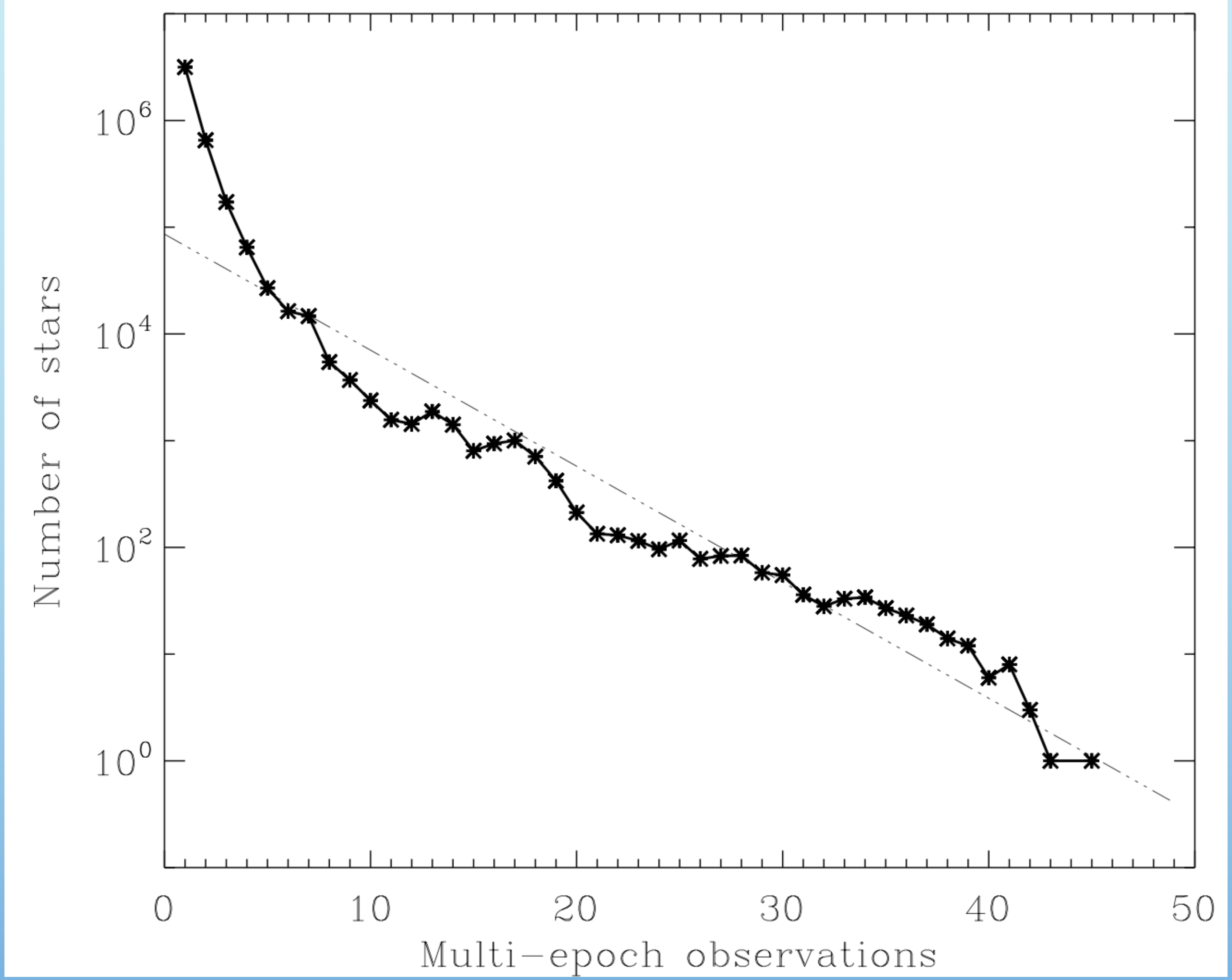
Estimate binary fractions through a sample of identified stars.

- Identify each star (or measure the probability of a star having a companion)
- require: high quality data, long-term observations
- Underestimate the fractions of binary stars (especially for long-period binaries)

Statistical analysis

- Can’t measure the probability of a star having a companion(do not depend on each identification)
- Dependent on binary period distributions…
- Apply to a huge sample of data

DATA: LAMOST DR3



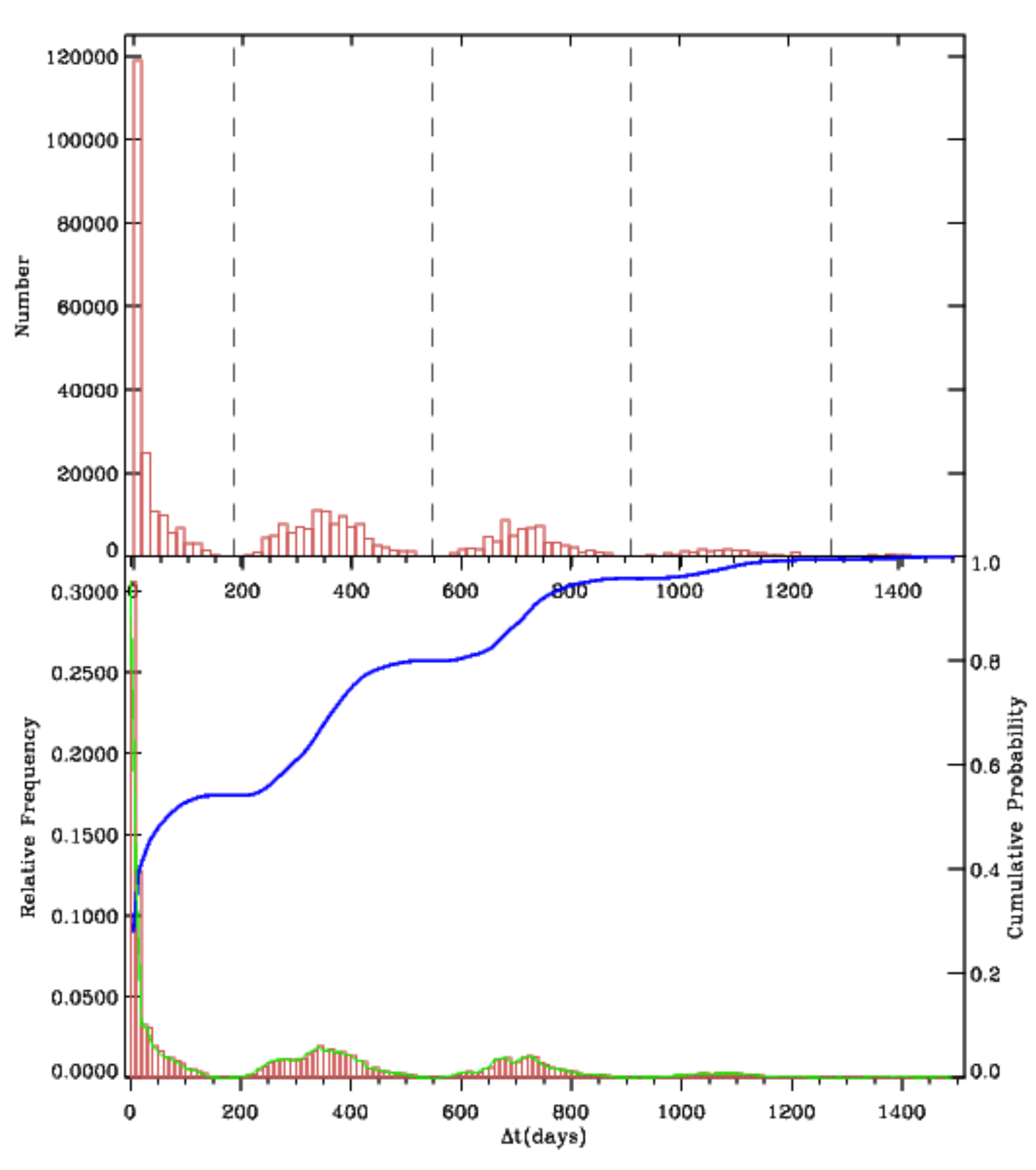
Dr3(Data before Nov, 2015): 5.6 millions spectra (SNR ge 10)

2.6 million (45%) stars with multi-epoch observations

唯一源：4 millions

具有重复观测的唯一源数量：934965

TIME INTERVALS DISTRIBUTIONS



~2.6 million stars with multi-epoch observation

Data selected with dt greater than 1 day

The observations at the same night probably share the similar environments(e.g. seeing, skylight, flat…), while most of observations with dt greater than one day do have different observation environments.

METHOD

- Based on Gao+2014

$$p(\Delta v) = f_{\mathrm{B}}\, p_{\mathrm{B}}(\Delta v|\sigma_0, \Delta t, \mathcal{M}_{\mathcal{B}}) + (1 - f_{\mathrm{B}}) p_S(\Delta v|\sigma_0),$$

- (1) the observed RVs for binary stars are contributed from the main stars of binary system which are during the main sequence;
- (2) we adopt the masses distribution of main stars from isochrones fitting, rather than adopt Salpeter initial mass function (Salpeter 1955);
- (3) the mass-ratio distribution shows a preference for like-mass pairs (Raghavan et al. 2010), the mass ratio between the secondary to the primary stars follow the uniform distribution between 0.3 and 1;

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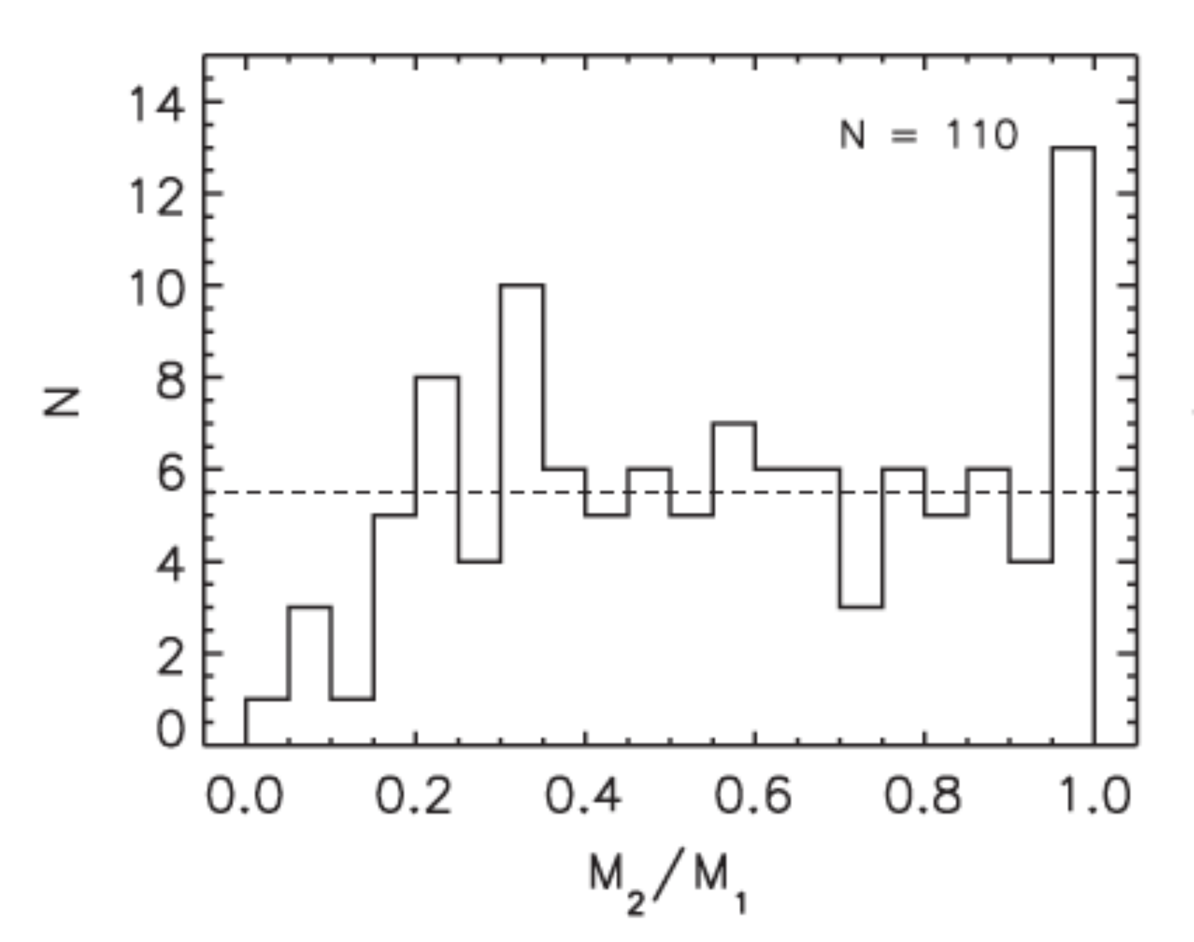
A complete sample

within 25pc



Based on a complete sample of dwarfs and subdwarf stars.

- (4) the orbital periods following the log-normal distribution proposed by Raghavan et al. (2010);

Log(P) ~N(5.03, 2.28)

Mean(log(P)) 300 yrs

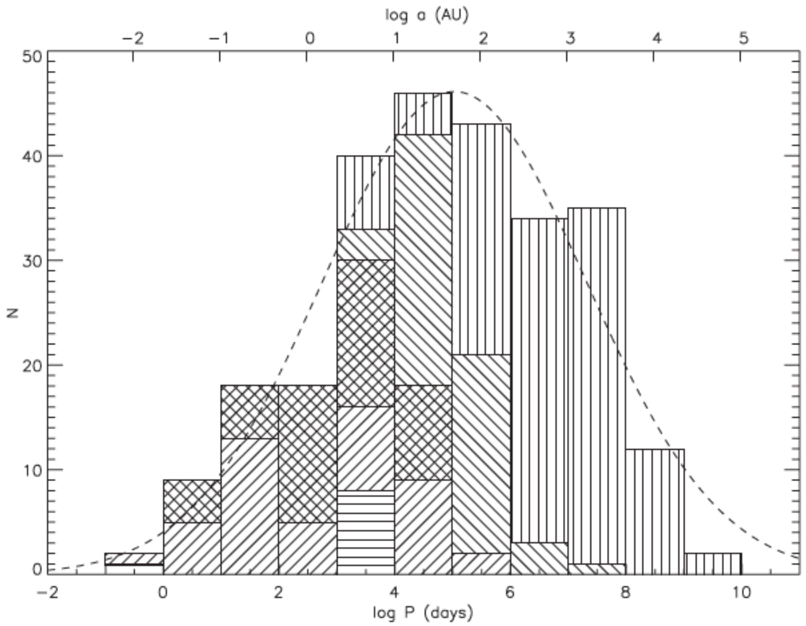
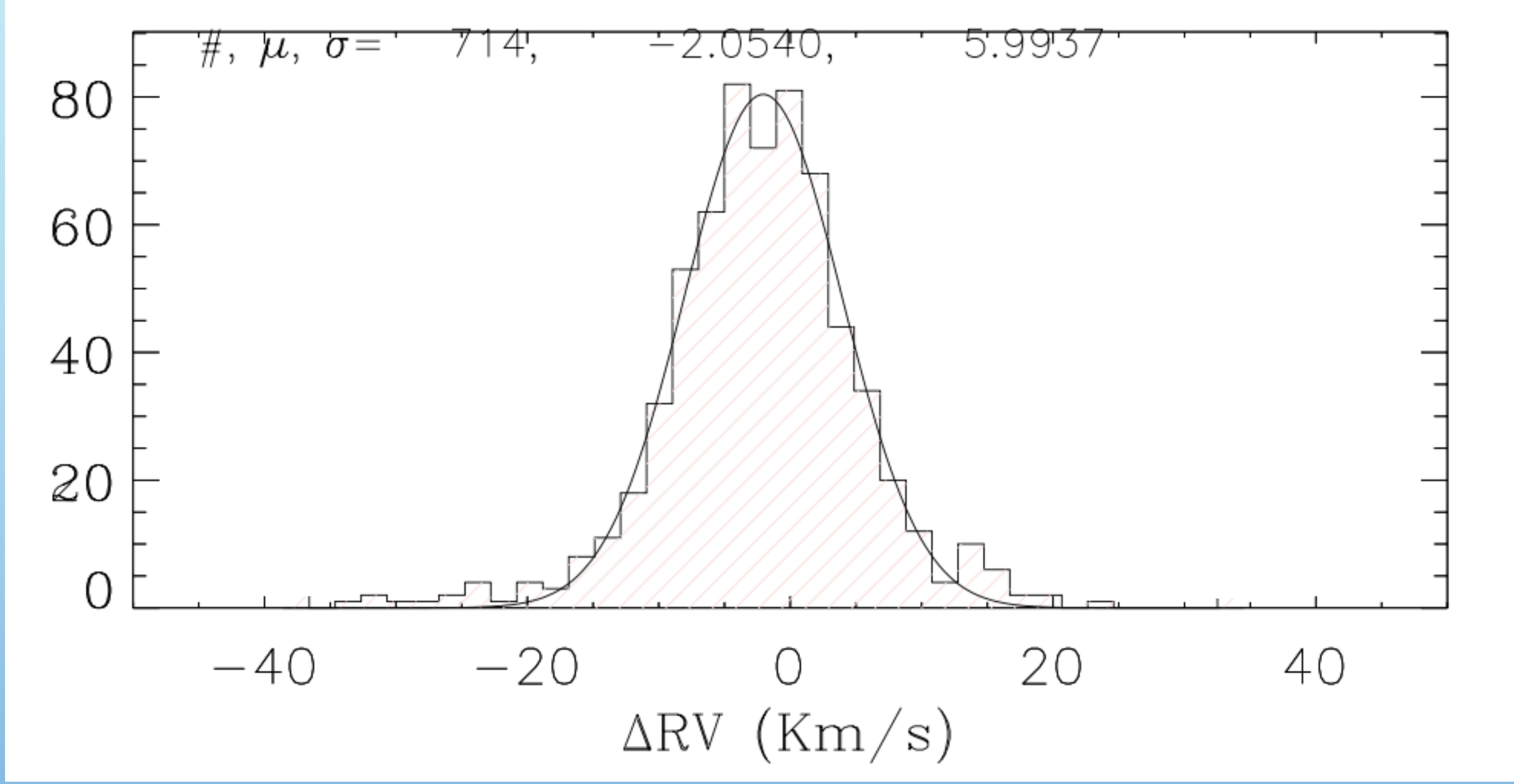


Figure 13. Period distribution for the 259 confirmed companions. The data are plotted by the companion detection method. Unresolved companions such as proper-motion accelerations are identified by horizontal line shading, spectroscopic binaries by positively sloped lines, visual binaries by negatively sloped lines, companions found by both spectroscopic and visual techniques by crosshatching, and CPM pairs by vertical lines. The semimajor axes shown in AU at the top correspond to the periods on the *x*-axis for a system with a mass sum of 1.5 $M_\odot$, the average value for all the pairs. The dashed curve shows a Gaussian fit to the distribution, with a peak at log P = 5.03 and standard deviation of $\sigma_{\log P} = 2.28$.

- (5) the orbital orientations in 3D space and initial phase in the range of [0, 2π] follow uniform distributions.

We ignored the binaries merger during the main sequence and we selected dwarfs stars with $log g > 3.75$ in this study.

dt → 0 DISTRIBUTION → GAUSSIAN ERROR(OR MULTI-GAUSSIAN)



Errors are related with seeing, attitude, SNR and so on.

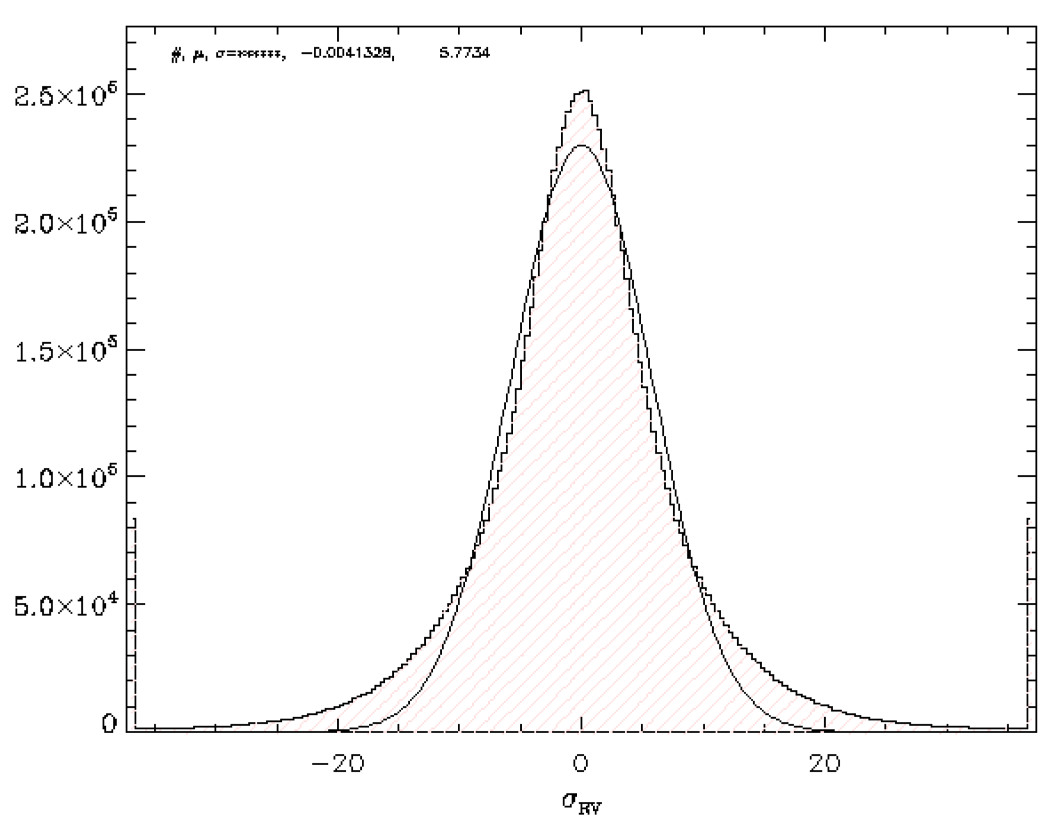
RANDOM UNCERTAINTIES FOR A STAR FOLLOW A GAUSSIAN DISTRIBUTION

ONE GAUSSIAN PROFILE + ANOTHER GAUSSIAN PROFILE ≠ A GAUSSIAN PROFILE

FWHM=2.3

FWHM=4.6

FWHM=6.9



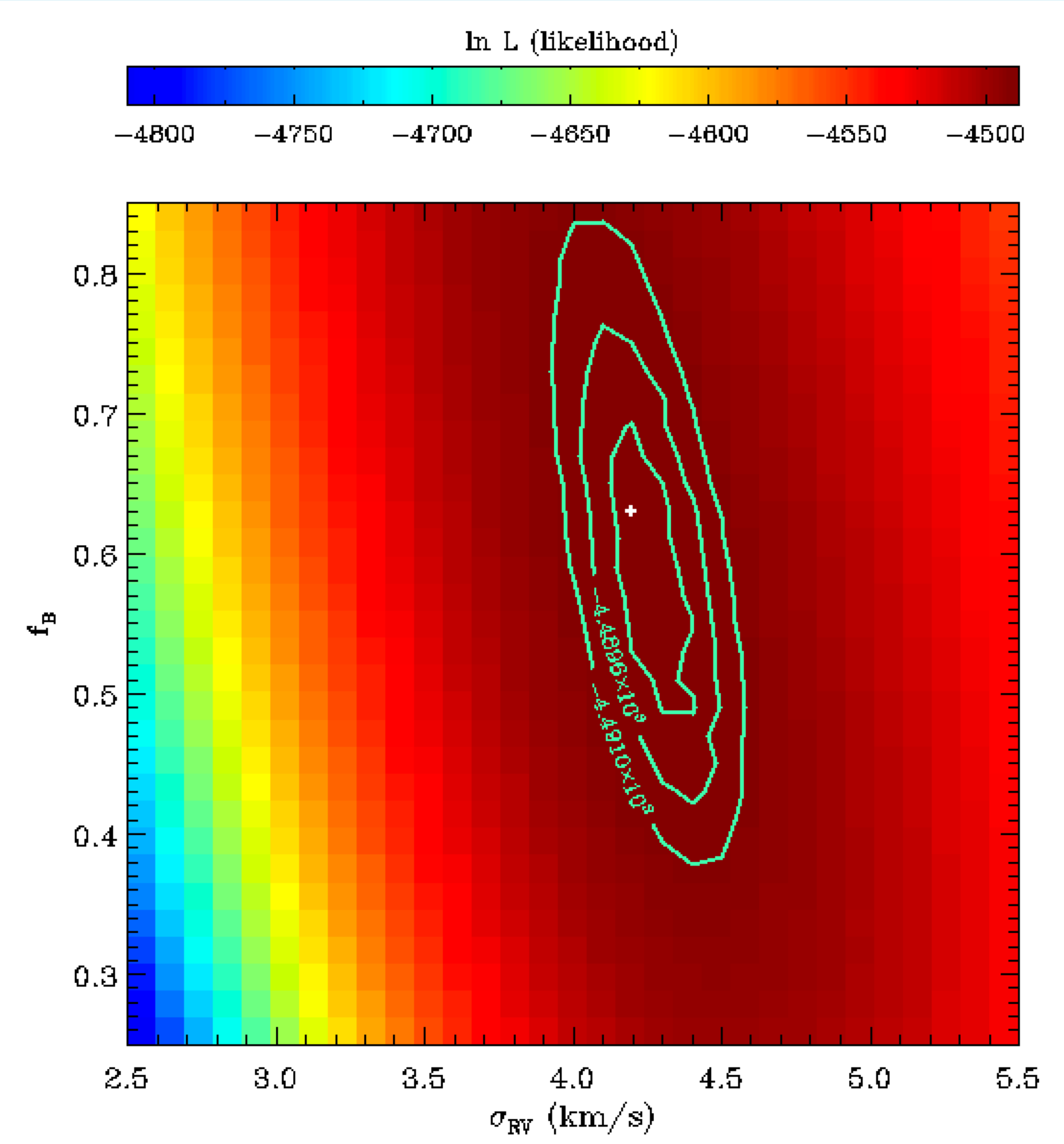
Wings of the distribution maybe from the combination of RV with different uncertainties

WINGS affect the determination of binary fraction

BINs

- RV error is a function of snr, teff, logg. (Xiang+2015)
- The combination of dRV with different RV errors could deduce the wing over a Gaussian profile.

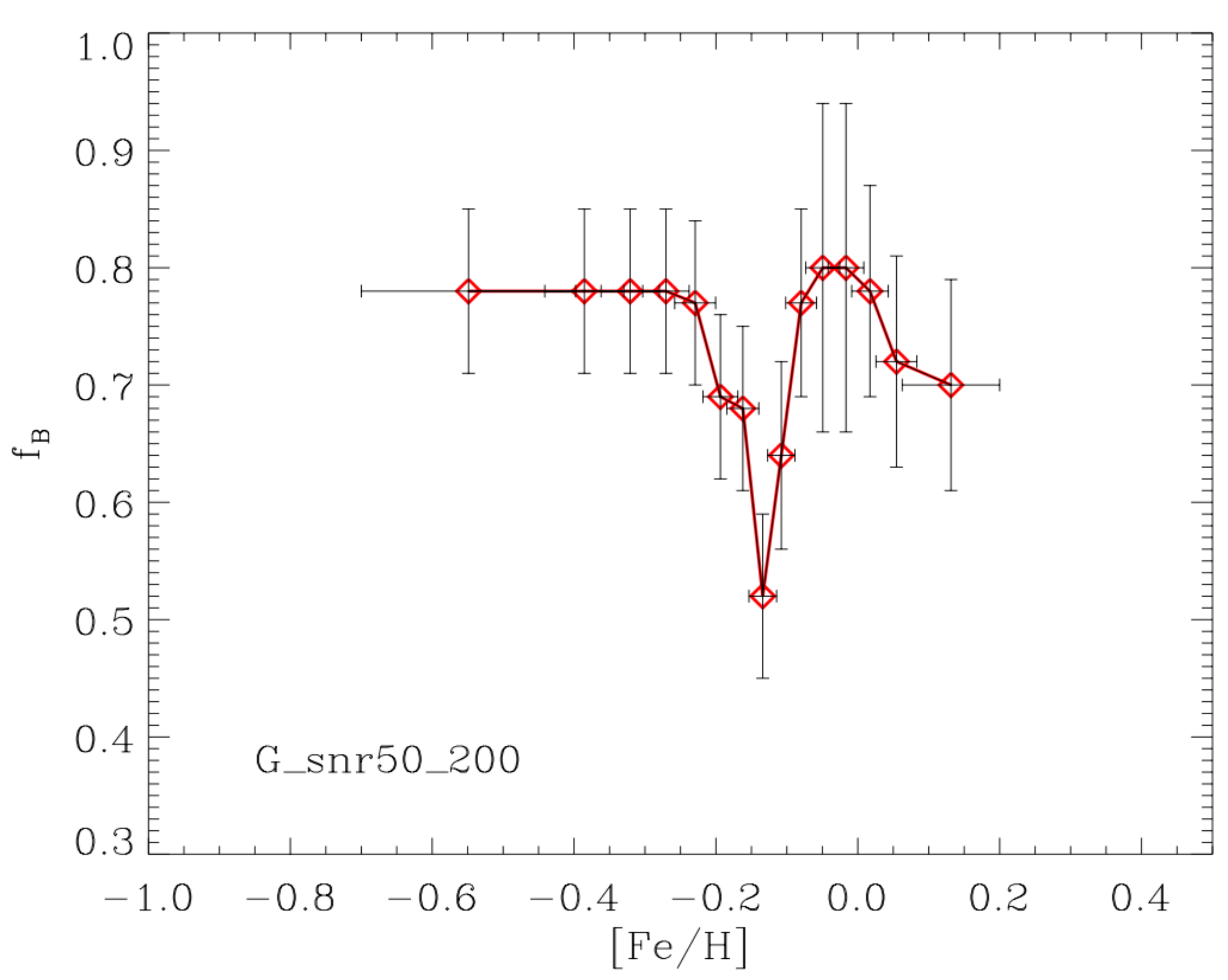
- F、G、K main sequence stars (logg >3.75)
- SNR:[50,200]
- [Fe/H]: 3000 stars in each bin, with a overlap of 1000.

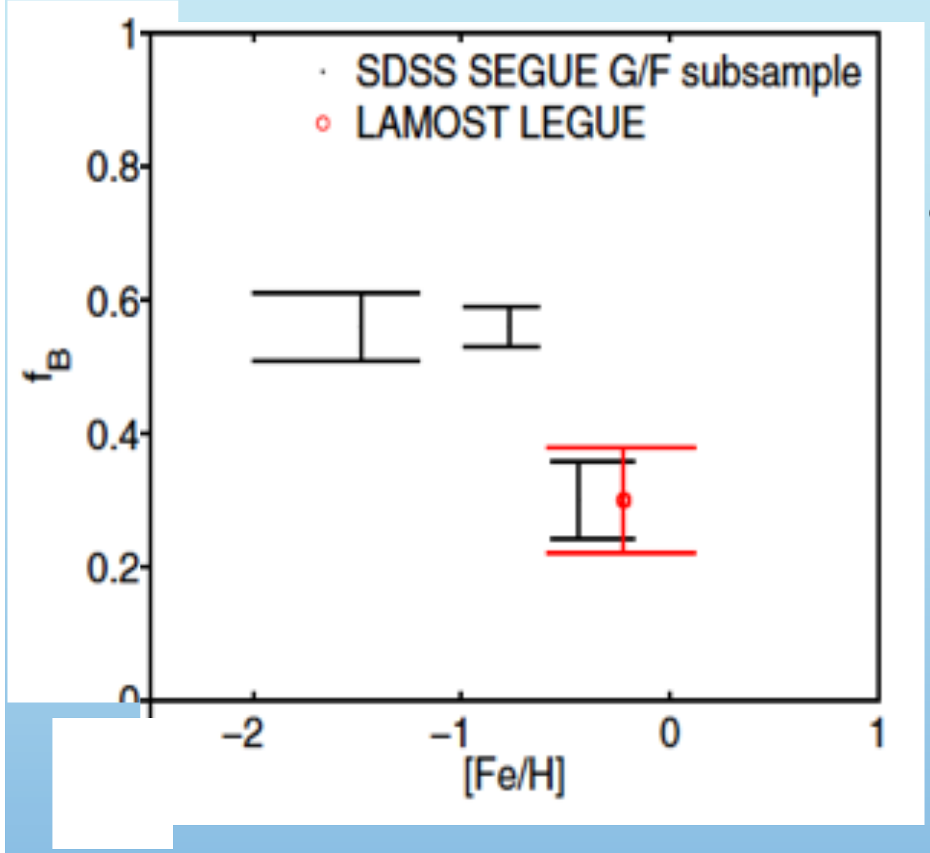


G-type
SNR:50_200
[Fe/H]:0.032_0.082

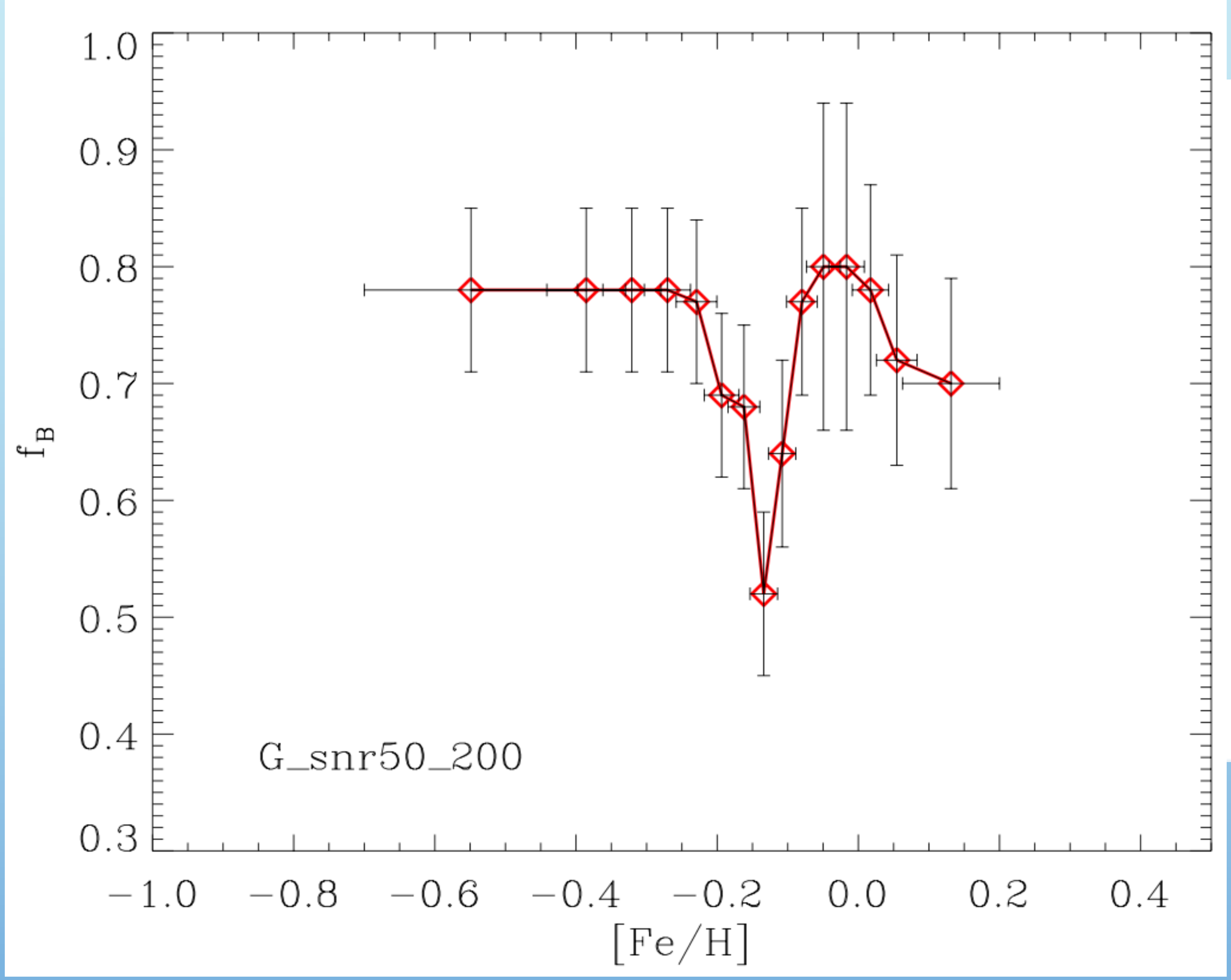
G-TYPE STARS, SORTED BY [Fe/H]

3000 STARS IN EACH BIN WITH A OVERLAP OF 1000 STARS

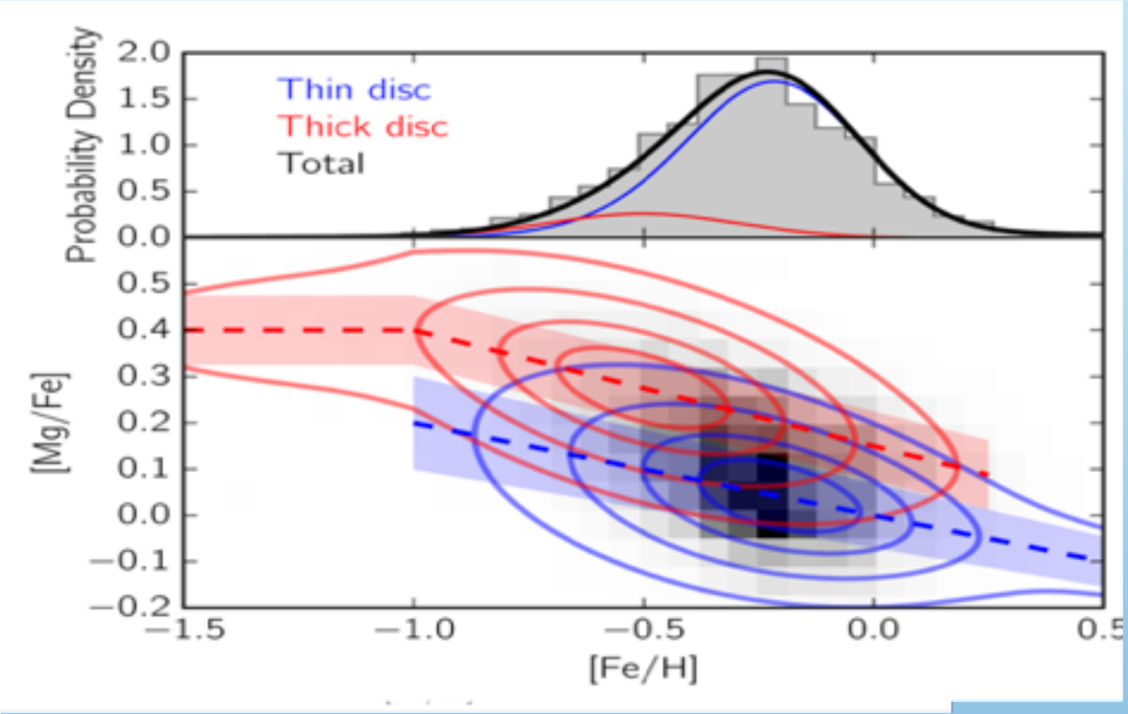




Gao+2014



1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
f_B
G_snr50_200
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
0.2
0.4
[Fe/H]

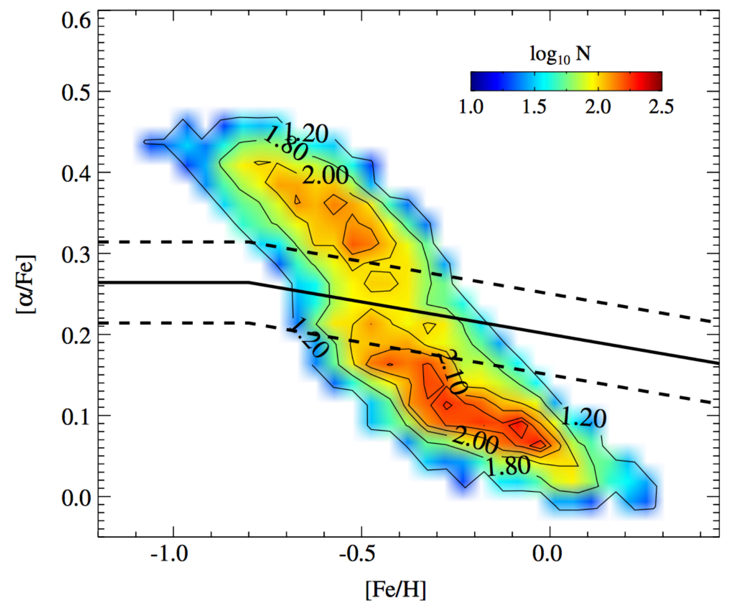


Probability Density
Thin disc
Thick disc
Total
[Mg/Fe]
[Fe/H]

Wjono+2016

DISTRIBUTION OF THIN/THICK DISKS, IN [FE/H]-[A/FE] PLANE

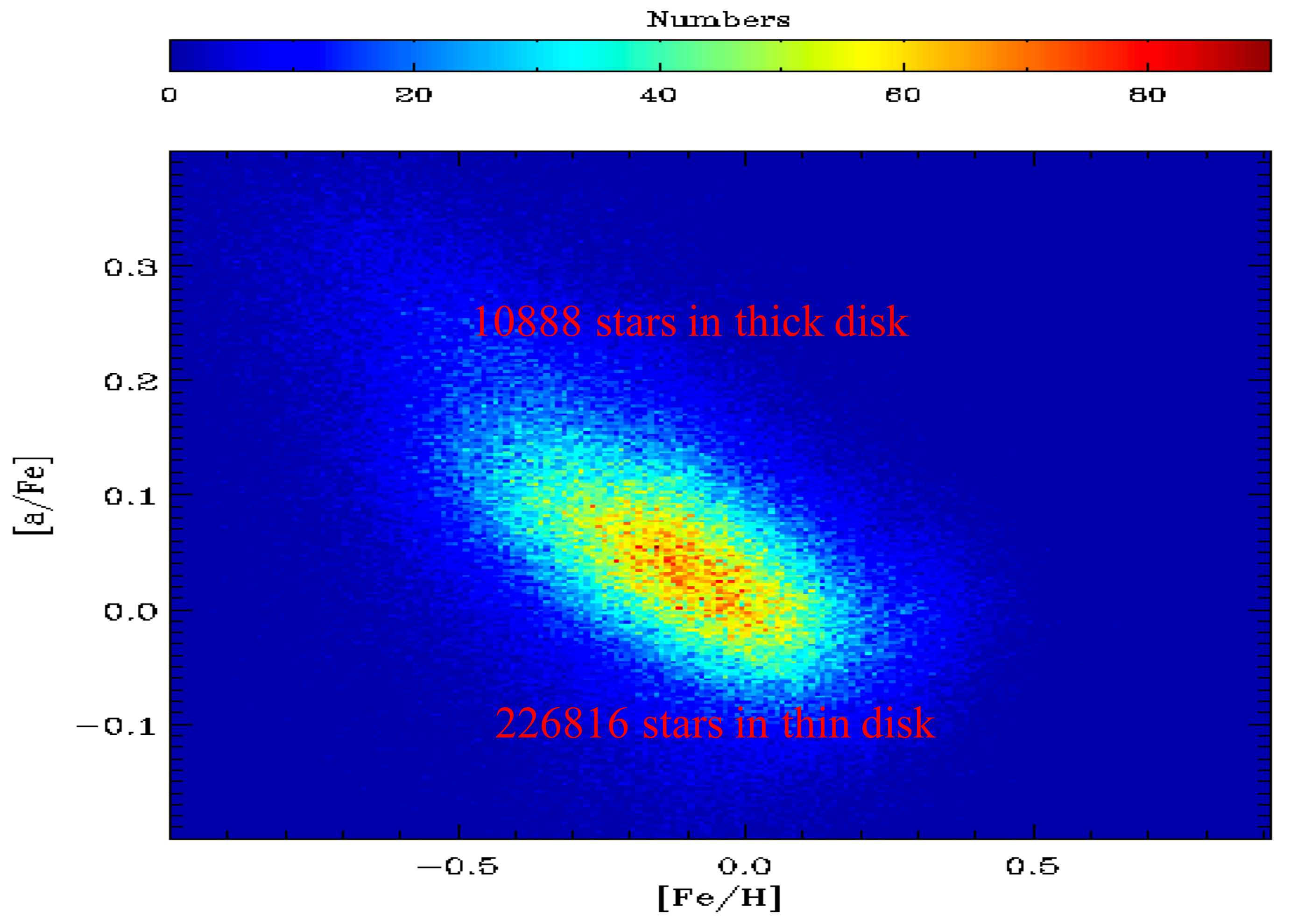
THE ASTROPHYSICAL JOURNAL, 738:187 (17pp), 2011 September 10



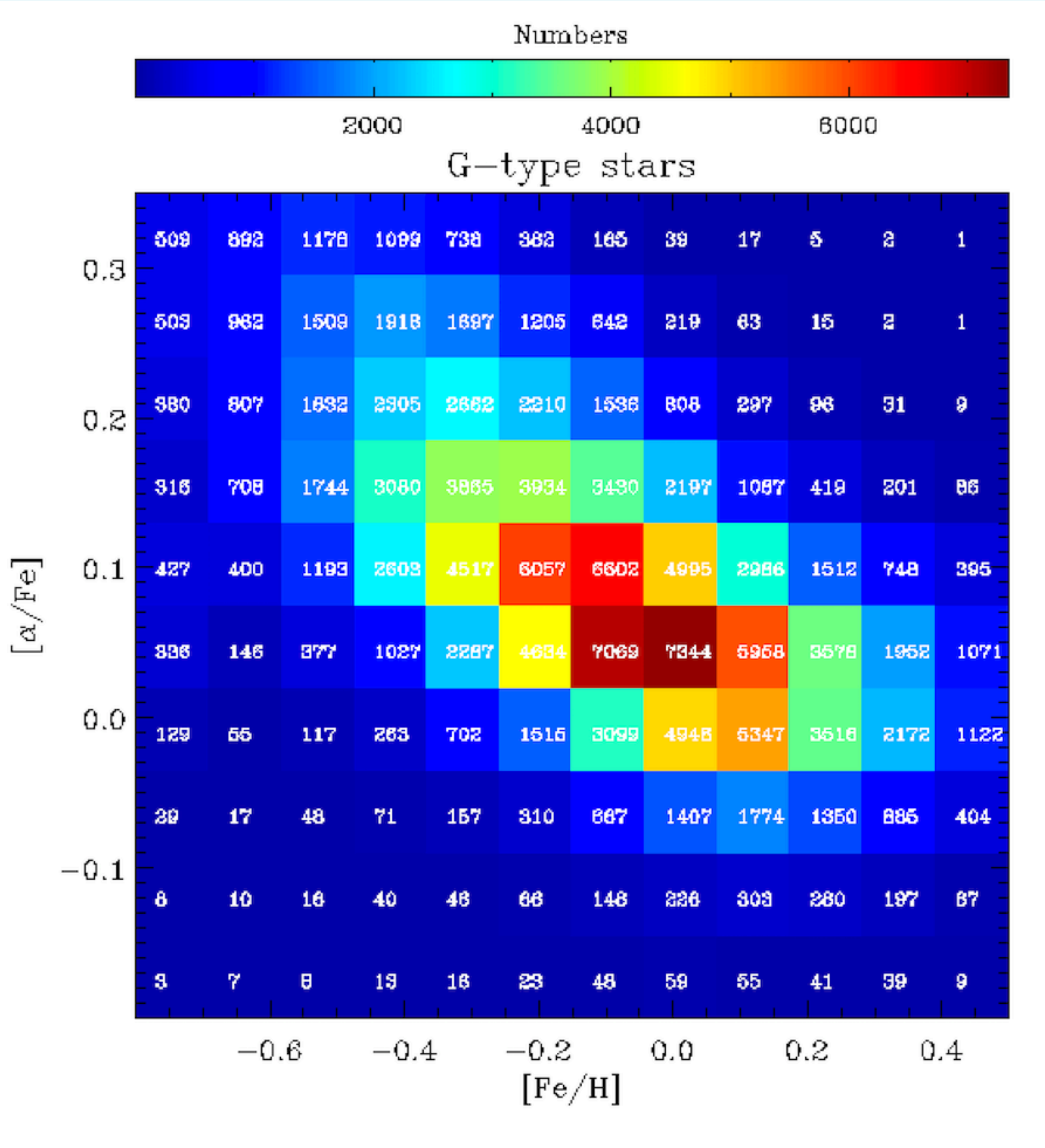
For the purpose of the present analysis, our dwarf sample is split into likely thin-disk (with low $[\alpha/\mathrm{Fe}]$) and thick-disk (with high $[\alpha/\mathrm{Fe}]$) populations, based on the following scheme.

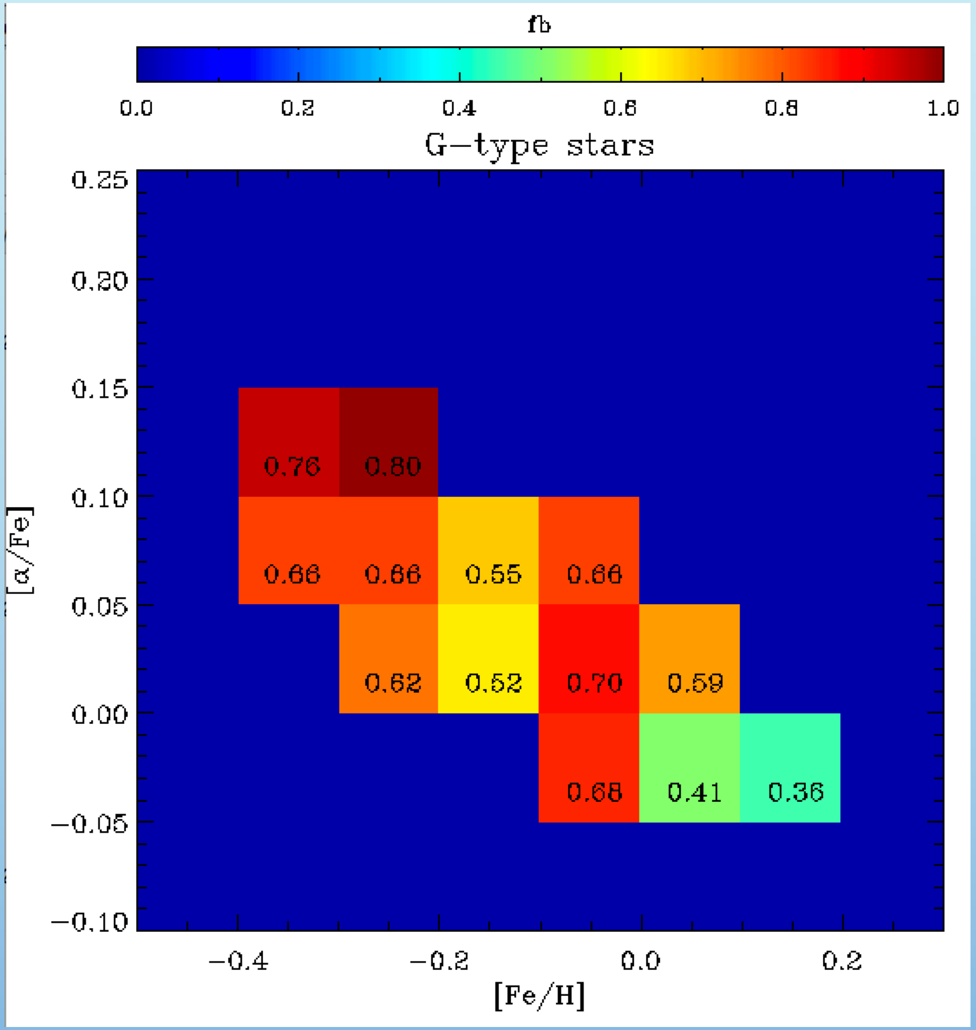
1. For stars with $[\mathrm{Fe/H}] \geqslant -0.8$
   (a) thin disk, if $[\alpha/\mathrm{Fe}] < -0.08 \cdot [\mathrm{Fe/H}] + 0.15$
   (b) thick disk, if $[\alpha/\mathrm{Fe}] > -0.08 \cdot [\mathrm{Fe/H}] + 0.25$.
2. For stars with $[\mathrm{Fe/H}] < -0.8$
   (a) thin disk, if $[\alpha/\mathrm{Fe}] < +0.214$
   (b) thick disk, if $[\alpha/\mathrm{Fe}] > +0.314$.

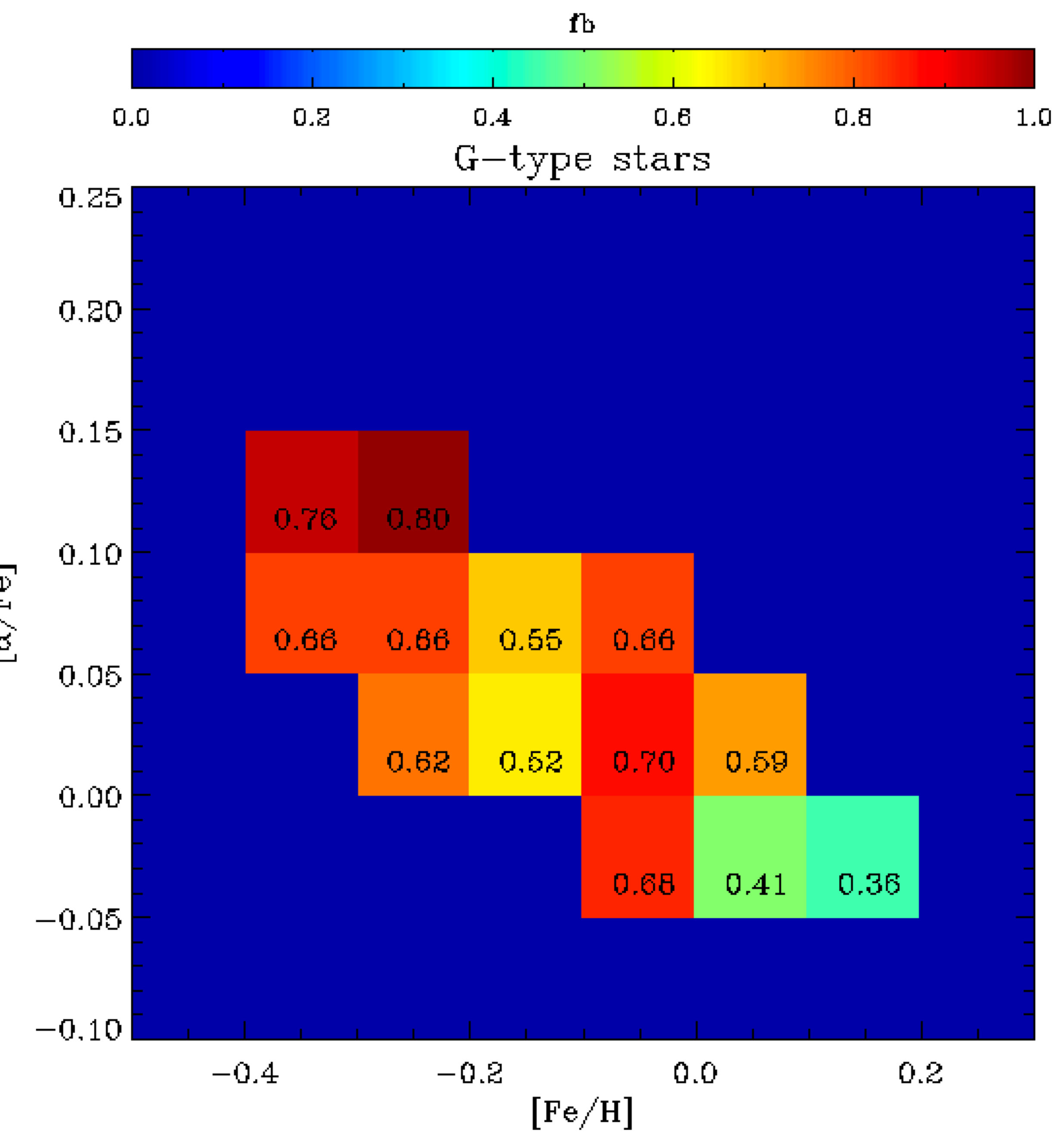
Young Sun LEE et al. 2011, ApJ, 738:187



[a/Fe] from Xiang et al. 2016, submitted


Numbers
2000 4000 6000
G−type stars
509 892 1178 1099 738 382 165 39 17 5 2 1
503 962 1509 1918 1697 1205 642 219 63 15 2 1
380 807 1632 2305 2662 2210 1536 808 297 96 31 9
316 708 1744 3080 3865 3934 3430 2197 1067 419 201 86
427 400 1193 2603 4517 6057 6602 4995 2986 1512 748 395
336 146 377 1027 2287 4634 7069 7344 5958 3576 1952 1071
129 55 117 263 702 1515 3099 4948 5347 3516 2172 1122
29 17 48 71 157 310 667 1407 1774 1350 885 404
8 10 16 40 46 66 148 226 303 280 197 67
3 7 8 13 16 23 48 59 55 41 39 9
0.3 0.2 0.1 0.0 −0.1
[α/Fe]
−0.6 −0.4 −0.2 0.0 0.2 0.4
[Fe/H]


fb
0.0 0.2 0.4 0.6 0.8 1.0
G−type stars
0.76 0.80
0.66 0.66 0.55 0.66
0.62 0.52 0.70 0.59
0.68 0.41 0.36
0.25 0.20 0.15 0.10 0.05 0.00 −0.05 −0.10
[α/Fe]
−0.4 −0.2 0.0 0.2
[Fe/H]


fb
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G−type stars
0.25
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−0.10
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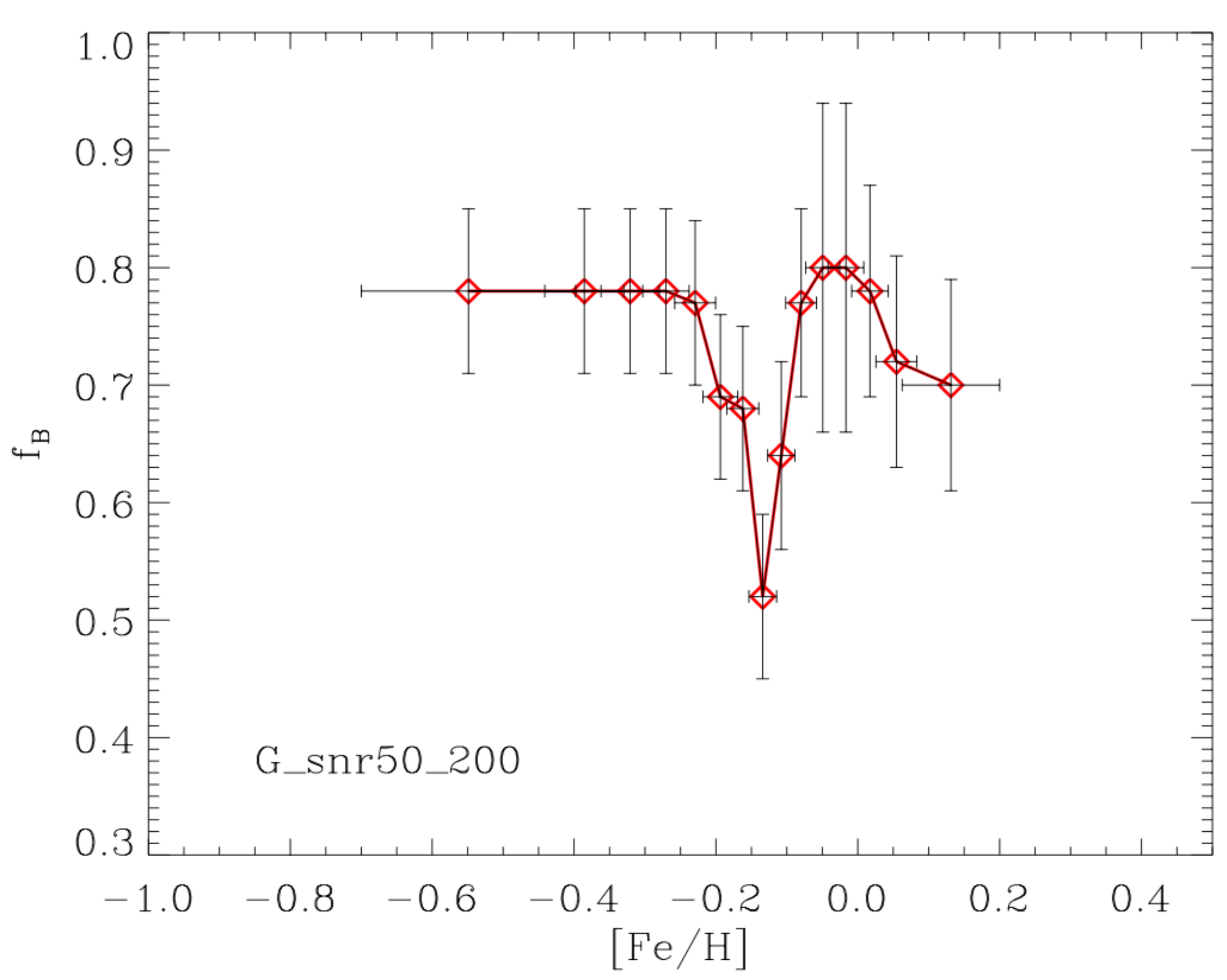
0.36
−0.4
−0.2
0.0
0.2
[Fe/H]


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
f_B
G_snr50_200
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
0.2
0.4
[Fe/H]

BINARY FRACTIONS FROM YUAN+2015

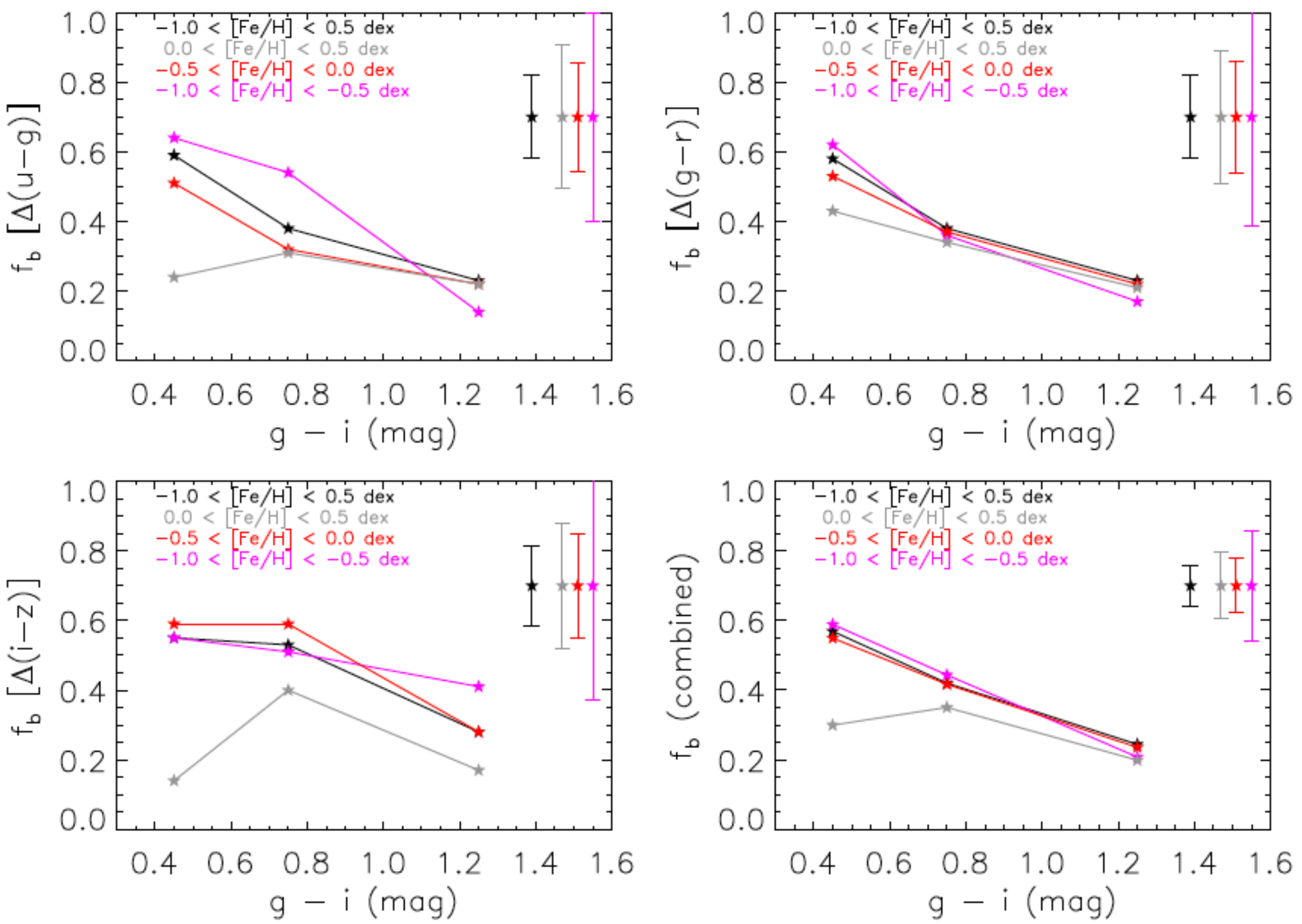
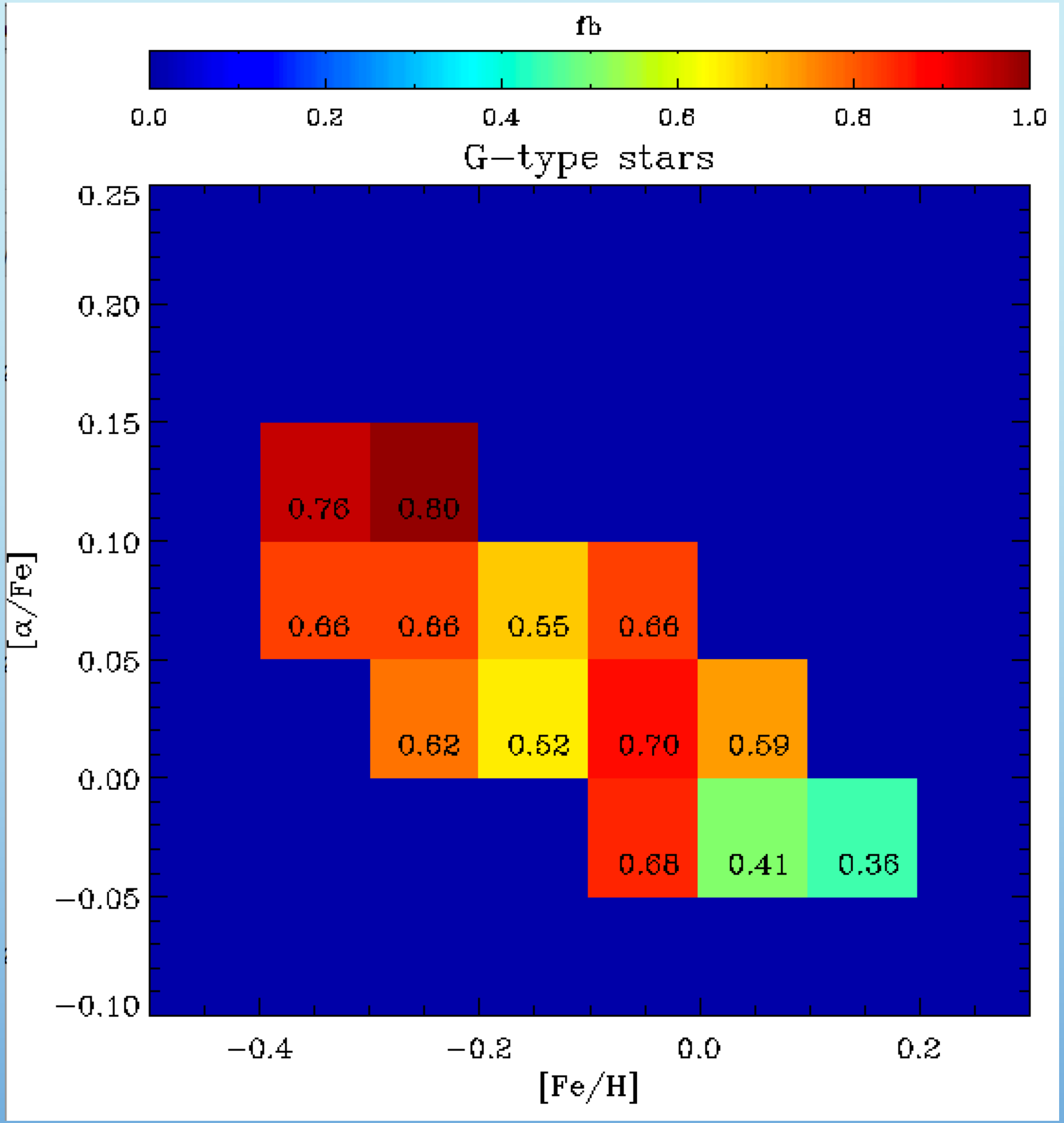
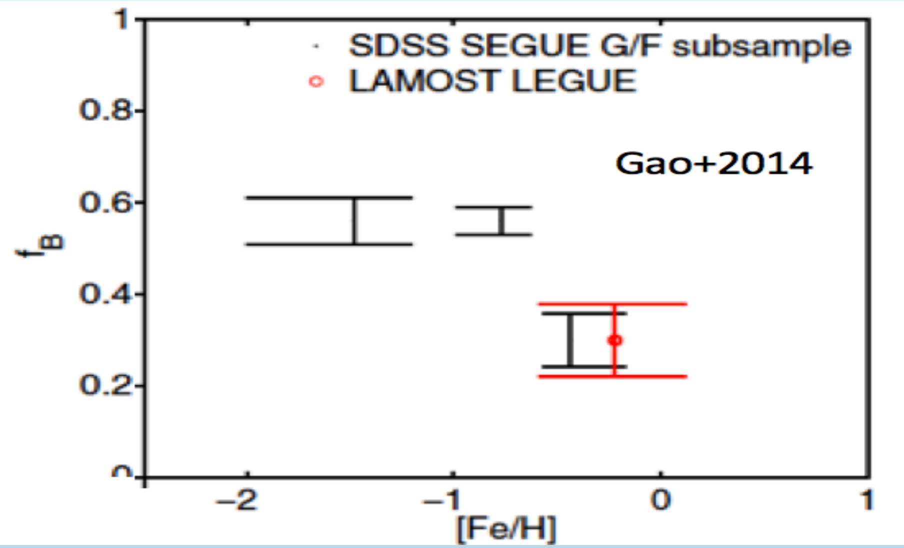
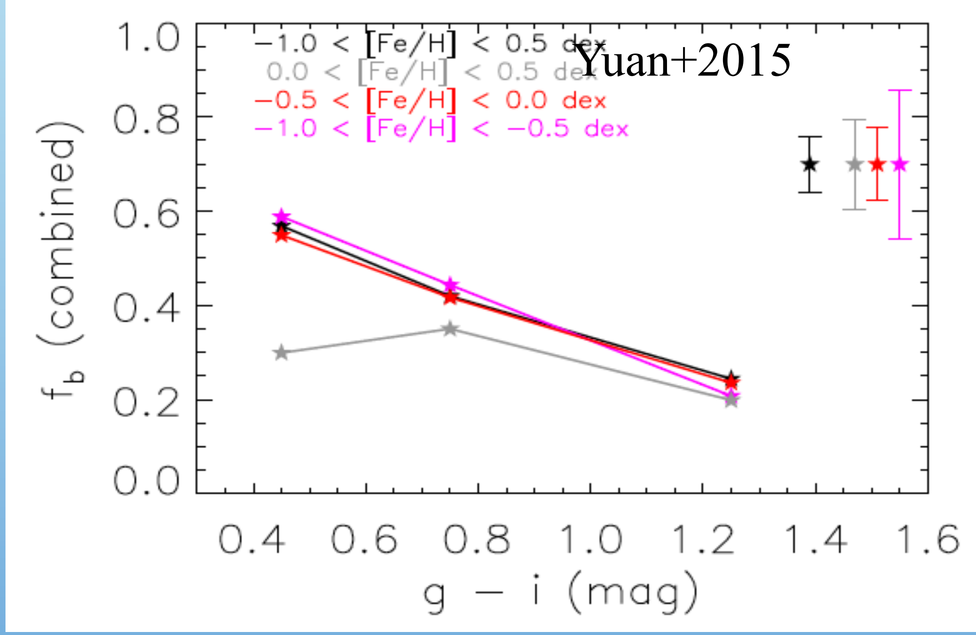


Figure 20. Binary fractions derived from the residuals in colors $u-g$ (top left), $g-r$ (top right), $i-z$ (bottom left), and the combined data of all three colors (bottom right) for field FGK stars of the LAMOST sample, plotted against $g-i$ color for the individual bins of color and metallicity. The typical error bars are marked in the top right corner of each panel.

OUR RESULTS VS GAO+2014/YUAN+2015







SUMMARY

- This Method relays on mass ratios, period distributions, given the distribution of mass and dt.
- The Trend In Our Work Is Coincident With Gao+2014, Yuan+2015;
- Thick/Thin Disk Stars May Have Different Binary star distributions (e.g.. IMF, Period Distribution …)
- Fb Is Relatively Flat With [Fe/H] ([a/Fe]), Especially For Thick Disk Stars;
- The trend is dominated with thick/thin disks;
- Binary Fraction = Birth Rate – Dissipation Rate

Thanks