A new kinematic survey
(from SDSS-DR7 & GSC-II)
to search for fossil records in the Milky Way

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Gaia: at the frontiers of Astrometry @ Sevres - 9 June 2010

The beginning...

To determine the intrinsic properties of individual objects observed by Galactic Surveys (e.g., RAVE and SDSS)

- ★ discrete source classification
  - ⇝ star, binary, etc.
  - ⇝ identification of new types of objects
- ★ (stellar) astrophysical parameter estimation
  - ⇝ $T_{\rm eff}$, log g, [Fe/H], ([α/Fe], $V_{\rm rot}$, A_V,...)
- ★ learning from (astronomical) data, e.g. spectra: kNN, ANN, SVM, PCA

↬ Catalog with astrophysical information (e.g. A new kinematic survey!)

Thank to: Tomaž Zwitter & RAVE Collaboration; Coryn Bailer-Jones & CU8, Tim Beers & SEGUE Collaboration; B. Bucciarelli, R.E. Drimmel, M.G. Lattanzi, R.L. Smart, A. Spagna (OATo team)

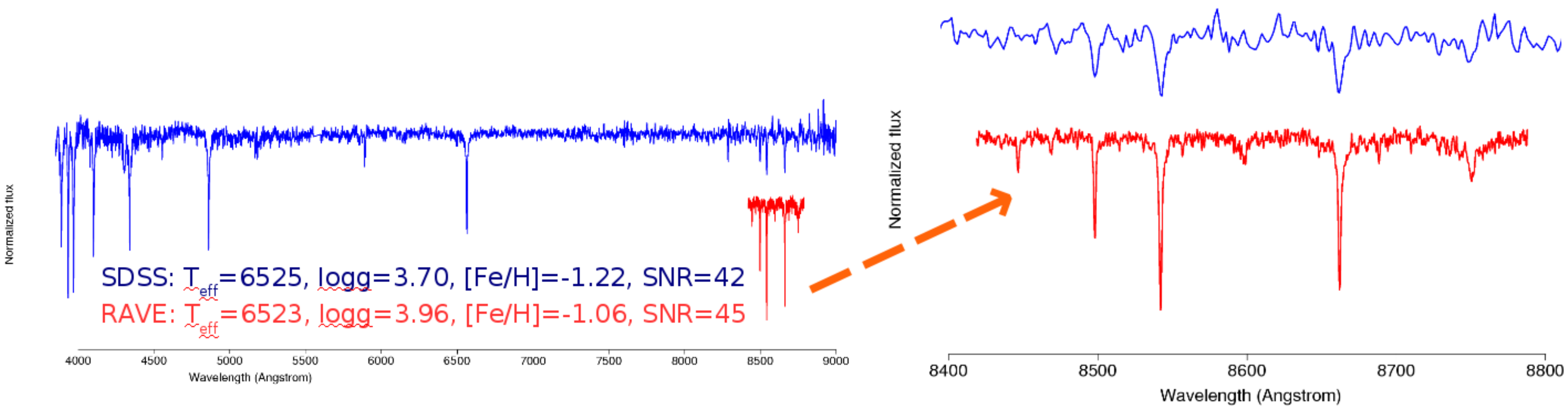
Galactic Surveys

★ **SDSS-II/SEGUE: The Sloan Digital Sky Survey**
northern hemisphere, one-quarter of the sky in 2008 (CCD camera on the 2.5-m telescope on Apache Point, New Mexico)

- $11\,663\,\mathrm{deg}^2$ of imaging data (position and multicolor photometry, $14.0 \leq g \leq 20.5$) of ~ 357 million stars; including data ($3500\,\mathrm{deg}^2$) at lower Galactic latitudes ($|b| < 40^o$),
- Spectra ($\lambda\lambda$ 3850–9000 Å) with R=2000 for approximately $\sim 300\,000$ Galactic stars,
- Radial velocities with typical accuracy of $10\,\mathrm{km\,s}^{-1}$.

★ **RAVE: The RAdial Velocity Experiment**
southern hemisphere, ~ 1 million bright stars by 2010 (6dF multi-object spectrograph on the 1.2-m UK Schmidt Telescope of the Anglo-Australian Observatory)

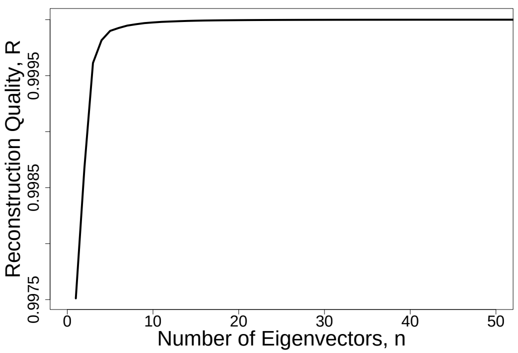
- Spectra ($\lambda\lambda$ 8410–8795 Å) with R=7500 for approximately $\sim 350\,000$ Galactic stars off the Milky Way plane ($|b| > 25^o$),
- Radial velocities accuracy better than $2\,\mathrm{km\,s}^{-1}$ (RV: $\sharp 50\,k/\sim 150\,k$; APs: $\sharp 25\,k/\sim 100\,k$),
- cross-identification with photometric ($9 \leq I \leq 12$) and astrometric catalogues.



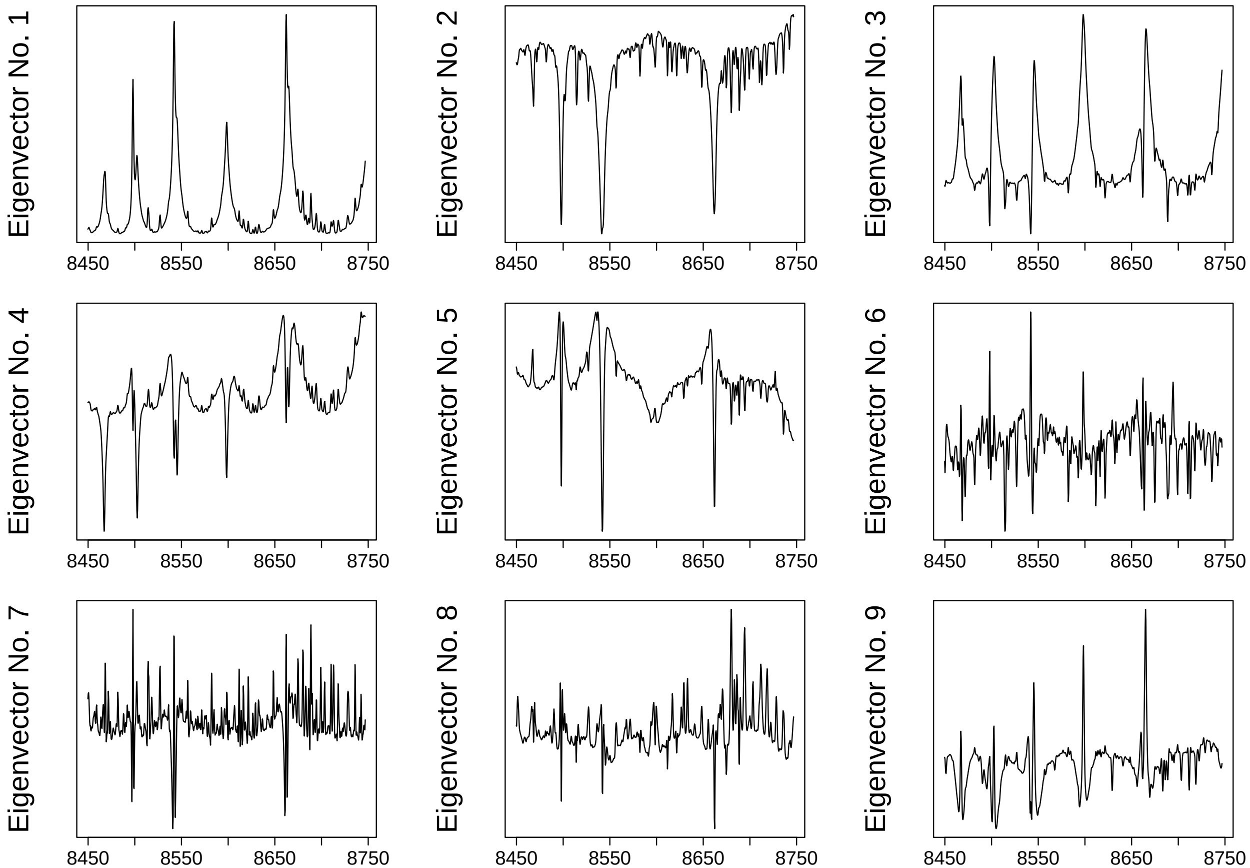
Dimensionality reduction: Principal Components Analysis

Represent a set of $N(788)$-dimensional data ($\mathbf{x}_p$) by means of their projection (a_{kp}) onto a set of $r < N$ optimally defined axes ($\mathbf{u}_k$).

- admixture coefficients:
  $$a_{kp} = \mathbf{x}_p \cdot \mathbf{u}_k$$
- reduced reconstruction:
  $$\mathbf{y}_p = \sum_{k=1}^{k=r} a_{kp}\mathbf{u}_k$$
  $$r < N$$
- reconstruction quality:
  $$R = \frac{\sum_{k=1}^{k=r} \lambda_k}{\sum_{k=1}^{k=N} \lambda_k}$$

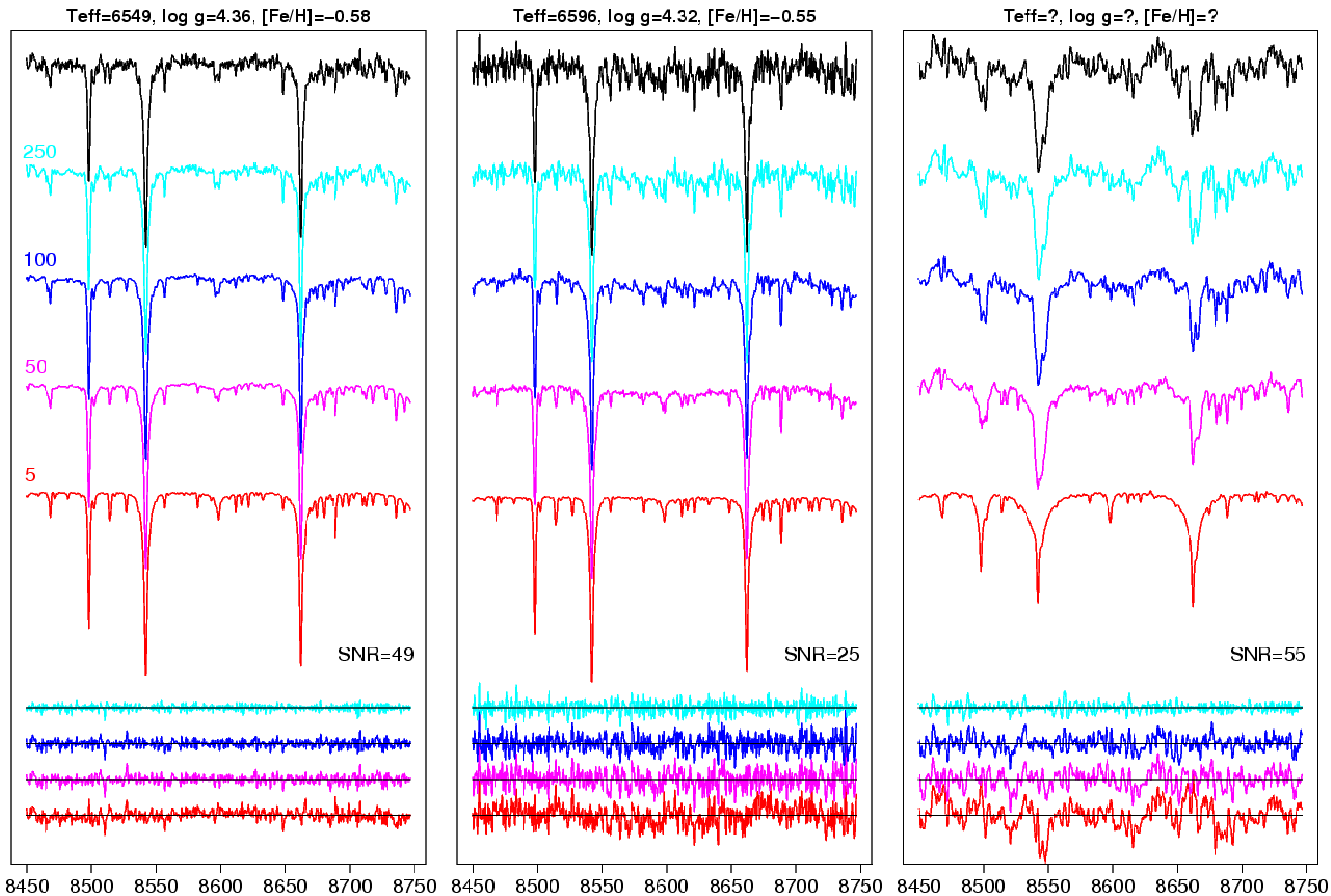


Removal of noise/rare features!

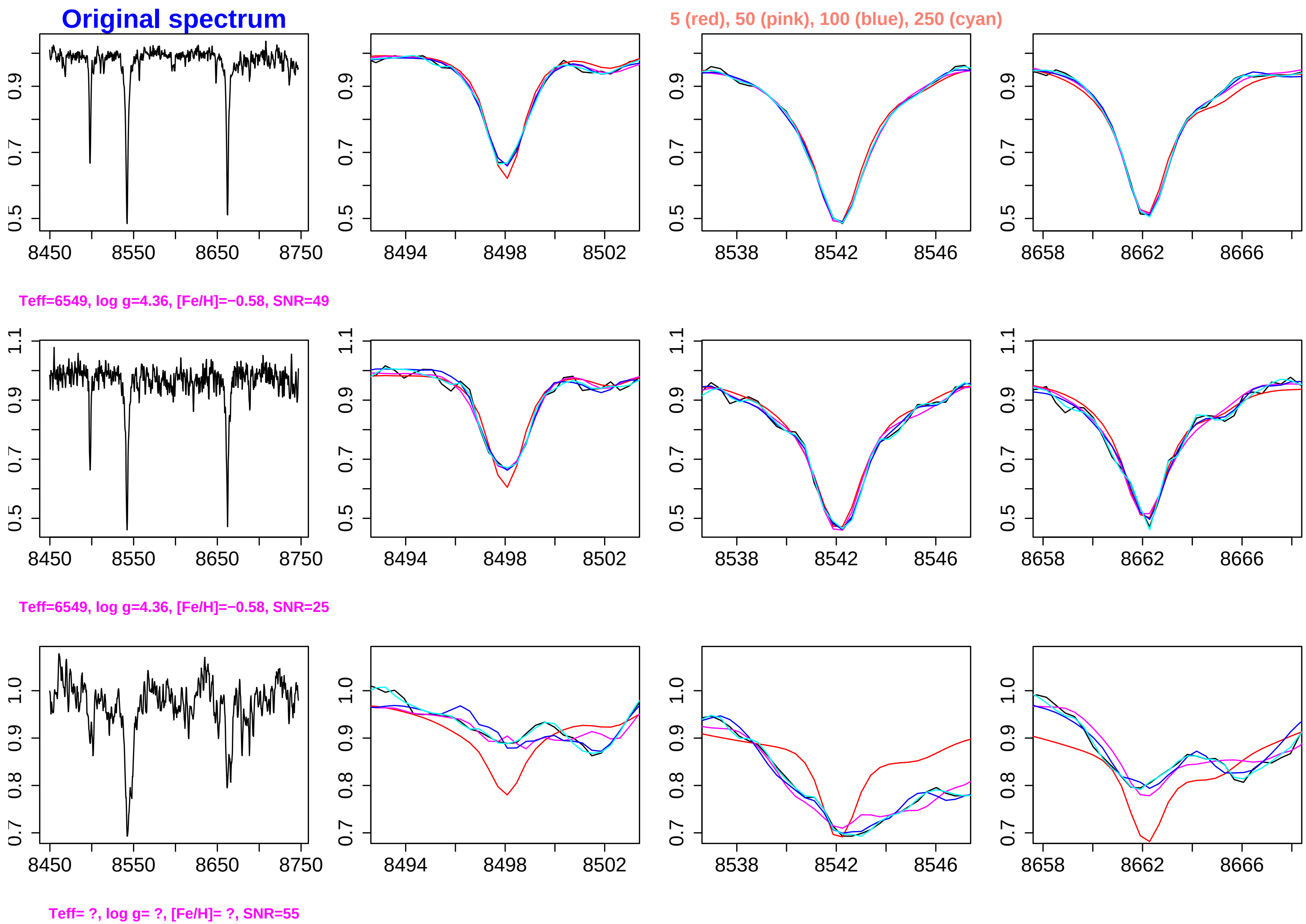


1:9 PCs (eigenvectors plotted against wavelength) of the spectra in training set.

Constructing RAVE spectra by projection onto the synthetic PCs



Constructing RAVE spectra by projection onto the synthetic PCs

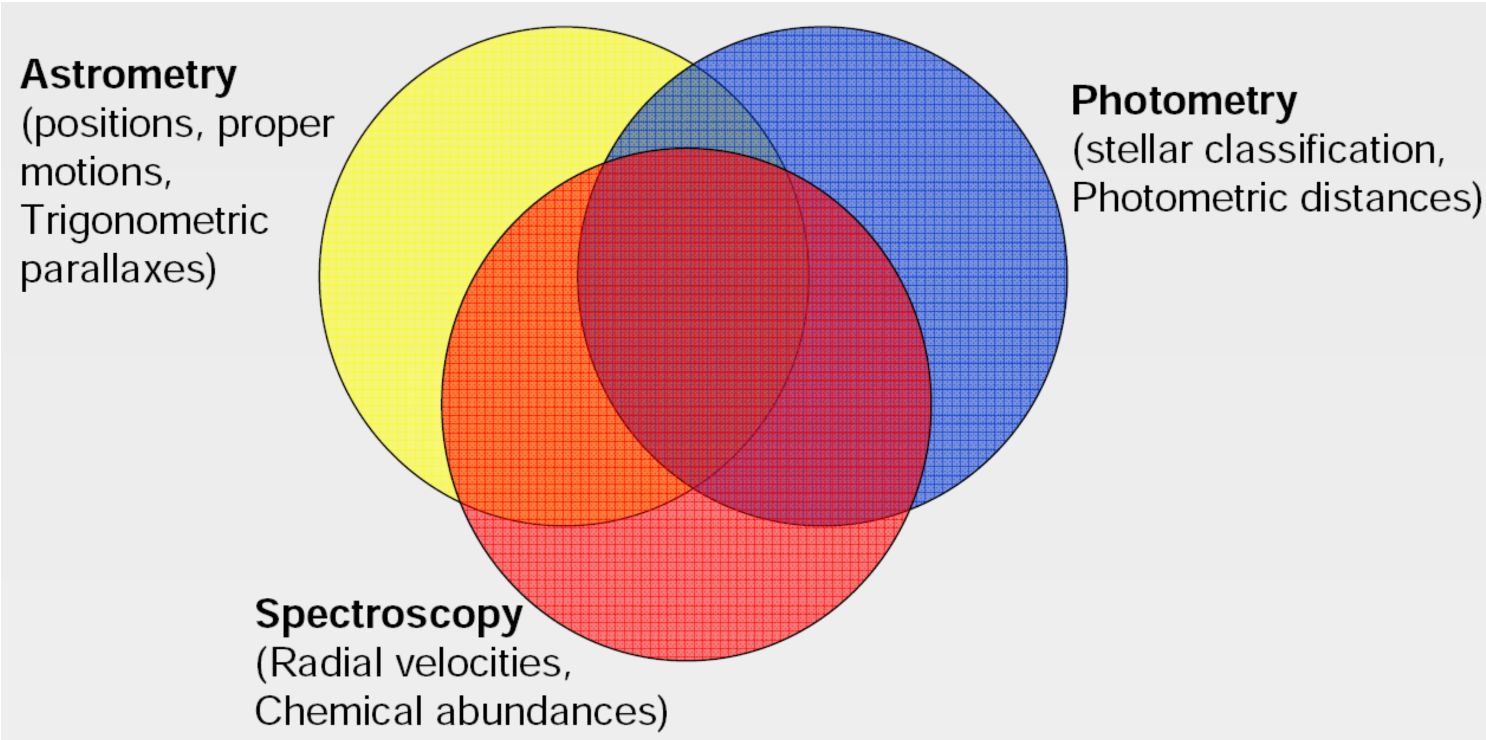


RAVE spectra. Zooming in around CaII triplet, color coded lines indicate the number of eigenvectors used to reconstruct the spectrum.

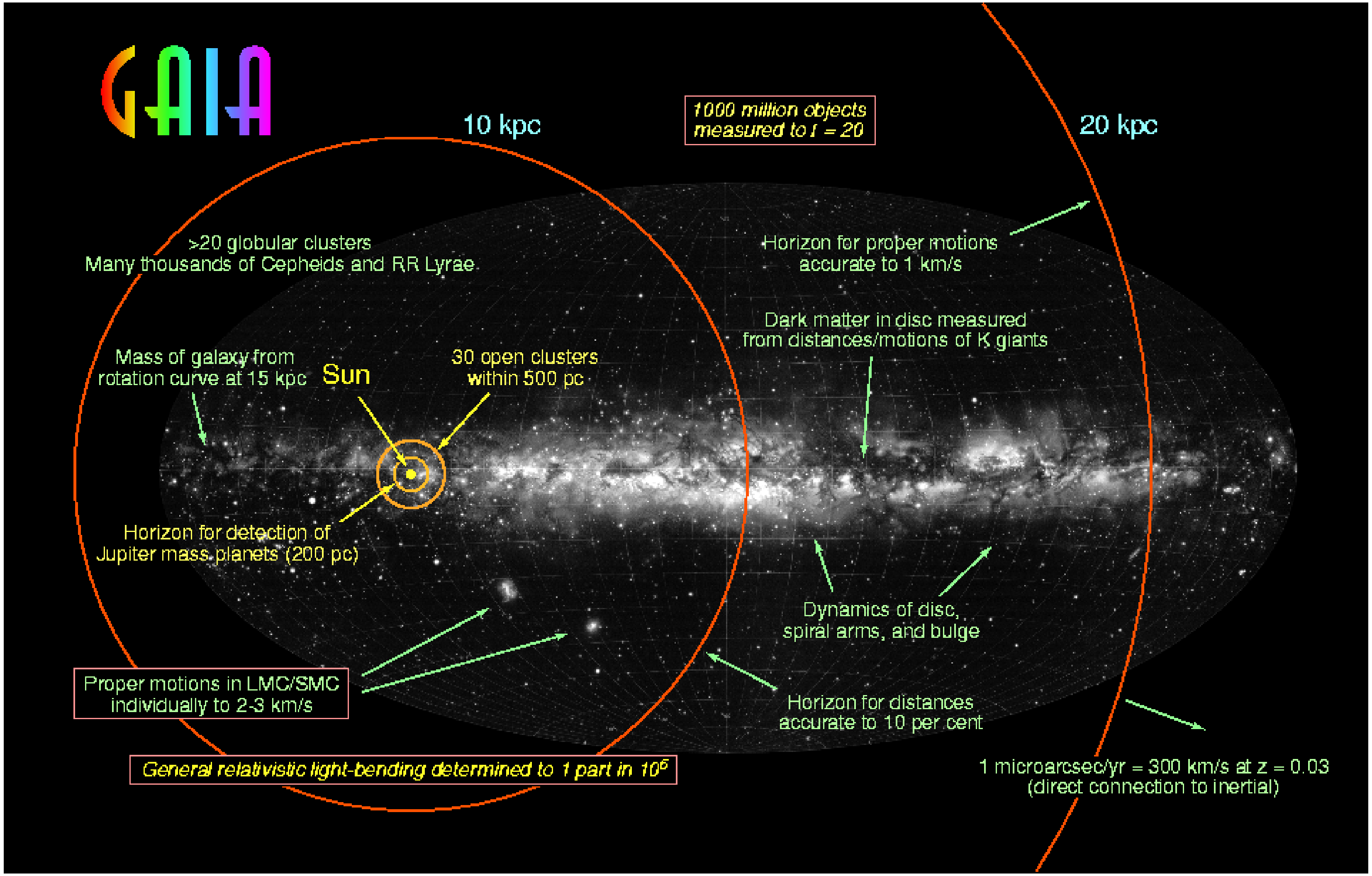
In this talk...

- ★ What do we do? A new wide field kinematic survey
  - ⋆ ingredients: survey/data base (SDSS, GSC-II)
  - ⋆ preparation:
    - ⇝ proper motions (calculation & precision/accuracy)
    - ⇝ astrophysical parameter estimation (e.g. $T_{\rm eff}$, log g, [Fe/H] & validation/improvement)
    - ⇝ distance...plus RV: phase-space!
  - ⋆ 6D −> 7D (9D)
- ★ Where do we go from here? Exploiting the results...
  - ⋆ Define & describe (kinematic & chemical properties) new samples of stellar tracers for Galactic investigations
  - ⋆ Kinematic & chemical analysis: search for fossil records in the Milky Way

Surveys of galactic stellar populations: basic ingredients



- ...Crucial points!
  - ⇝ identification of stellar populations (Halo, Disk);
  - ⇝ investigation of methods for estimating stellar parameters from photometric and spectroscopic data, e.g. [Fe/H];
  - ⇝ distance estimate: e.g. photometric, trigonometric;
  - ⇝ combination of astrometric data, in order to derive velocities and remove degeneracies;



Illustrative summary of the primary Gaia scientific goals, superimposed on the Lund map of the MW and Local Group galaxies. From Gilmore et al. 1998, SPIE 3350, 541

⇝ large samples of astrometric and spectro-photometric data: e.g. GSC-II, SDSS-I, & SDSS-II/SEGUE (SDSS-III/SEGUE), RAVE, Gaia (spring 2012).

The Sloan Digital Sky Survey

★ **SDSS-I & SDSS-II/SEGUE (DR7)−> III**
northern hemisphere, one-quarter of the sky (CCD camera on the 2.5-m telescope on Apache Point, New Mexico)

- ⇝ 11 663 $\deg^2$ of imaging data (position and multicolor photometry, $14.0 \leq g \leq 20.5$) of $\sim$ 357 million stars; including data (3500 $\deg^2$) at lower Galactic latitudes ($|b| < 40^o$),
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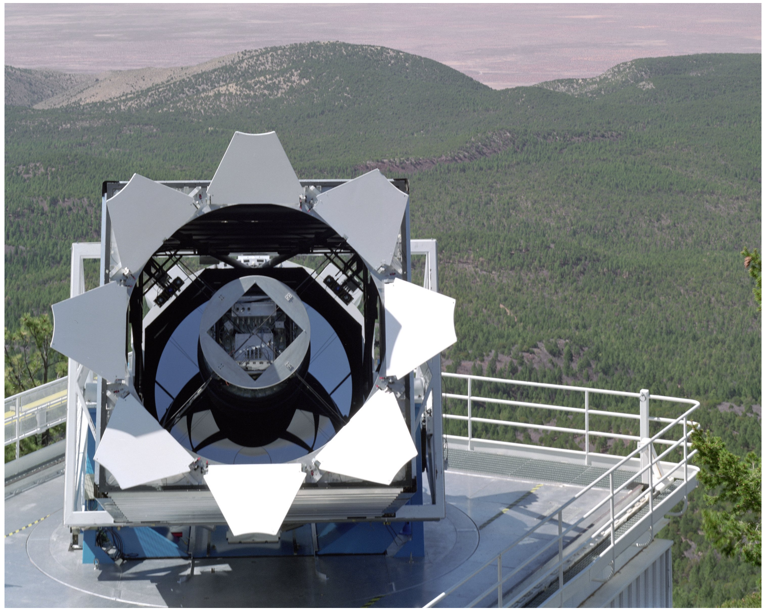
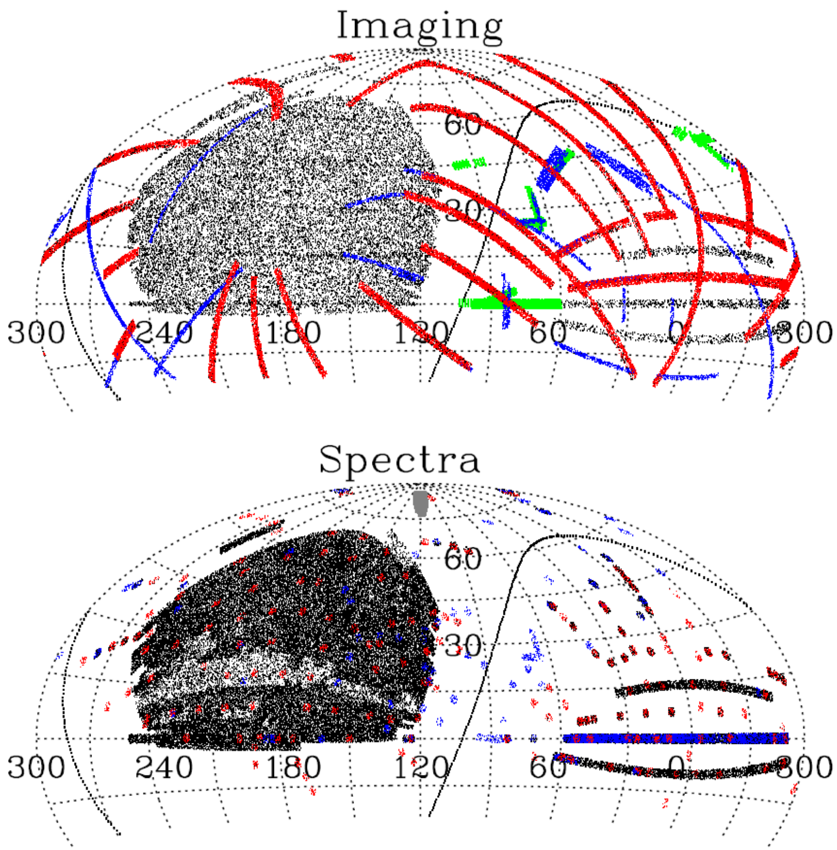




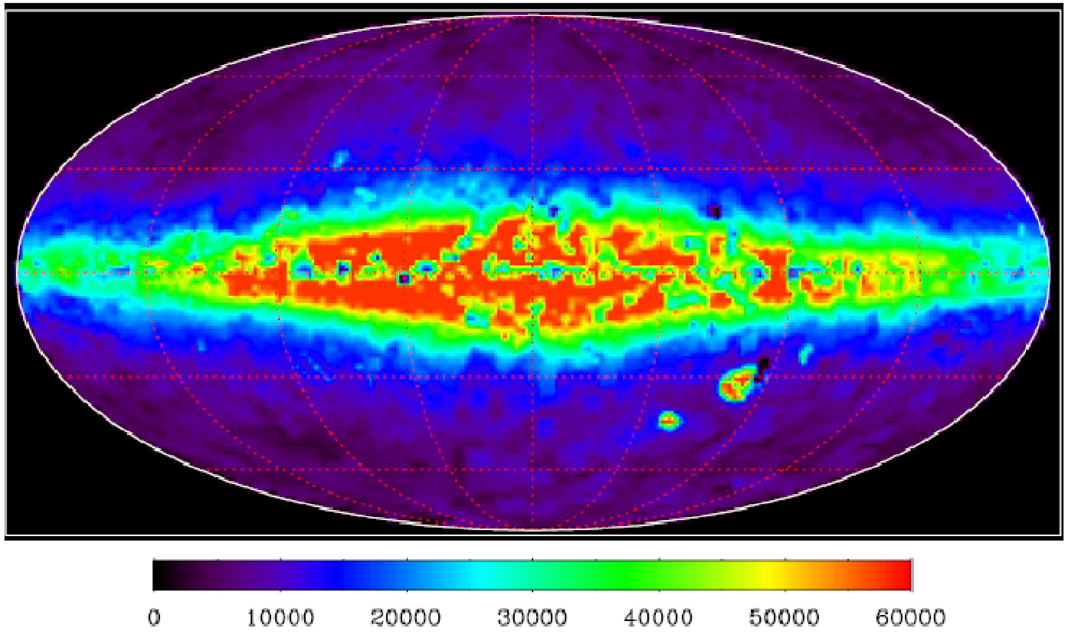
e.g., Abazajian+2008, ApJS 175, 297; Abazajian+2009, ApJ in press; Yanny+2009, AJ 137, 4377

The Second Guide Star Catalog

★ GSC-II (OATo & STScI)

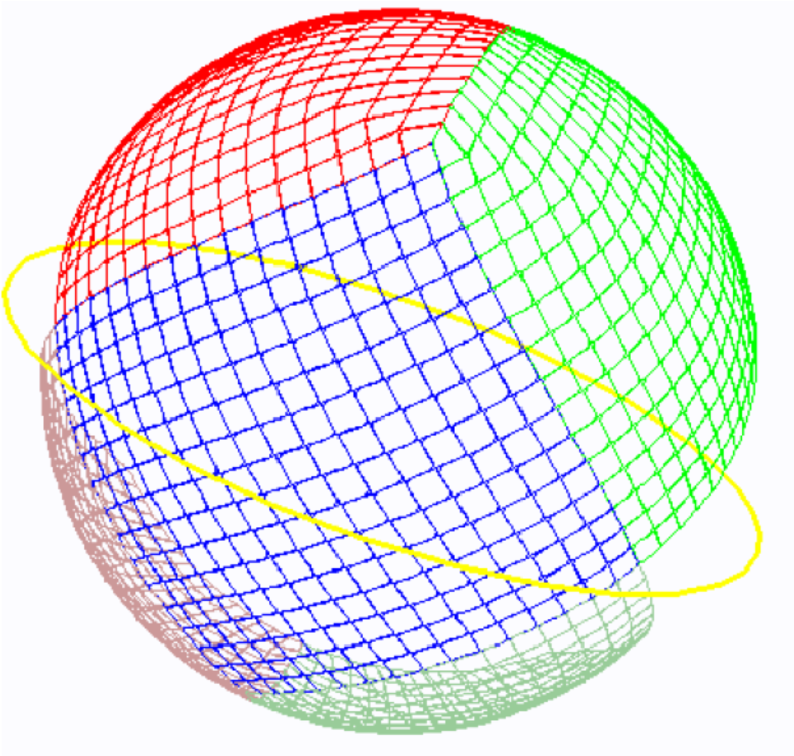
- All-sky database, compiled from Schmidt plate surveys (AAO, POSS-I and POSS-II), from which the GSC 2.2 (2001) and GSC 2.3 (2007) have been exported.
- $\sim$ 1 billion objects down to $B_J < 22.5, R_F < 20.5$ and $I_N < 19.5$.
- Multi-epoch positions (0.2–0.3$''$ accuracy) and multicolor photographic photometry (0.15–0.20 mag accuracy).
- Object Classification.

GSC 2.3 counts: objects per deg^2 down to $R_F = 20$



Lasker, Lattanzi, McLean et al. 2008, AJ 139, 735

Proper motions - I

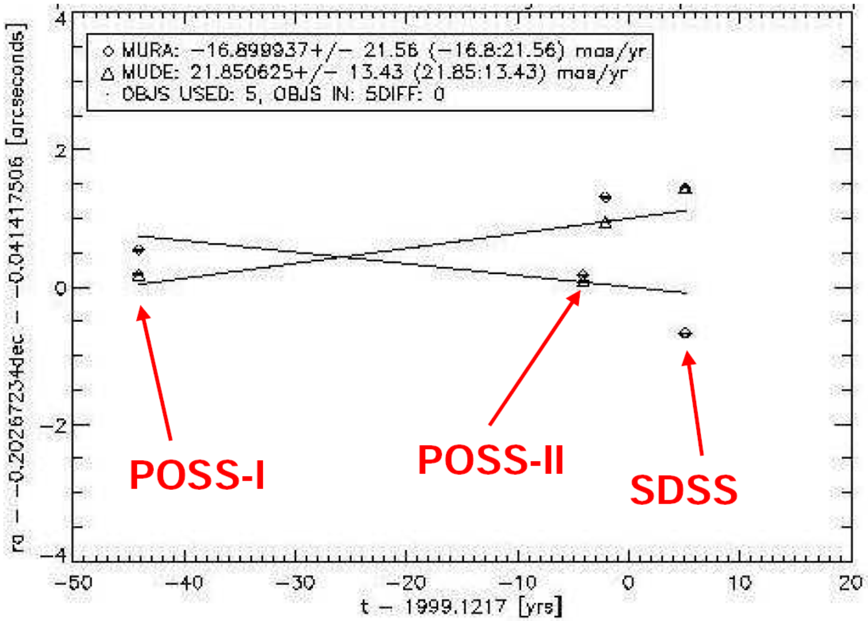


Spagna et al. 1996, A&A 311, 758

- ★ Multi-epoch positions from SDSS and GSC-II (mainly POSS-I and POSS-II) available in the GSC-II DB mirror in Torino
- ★ Database structure: HEALPix tesselation level 6, i.e. 49 152 regions (0.839 deg^2)
- ★ Transformations from (X, Y) plate coordinates to standard coordinates (ξ, η) computed for HEALPix level 7 (27'x27')
- ★ Relative proper motions
- ★ Absolute proper motions computed with zero-point derived from extra-galactic sources (SDSS classification adopted)

Proper motions - I

$\Delta\alpha\&\Delta\delta$ (arcsec) vs. Δt (yr)



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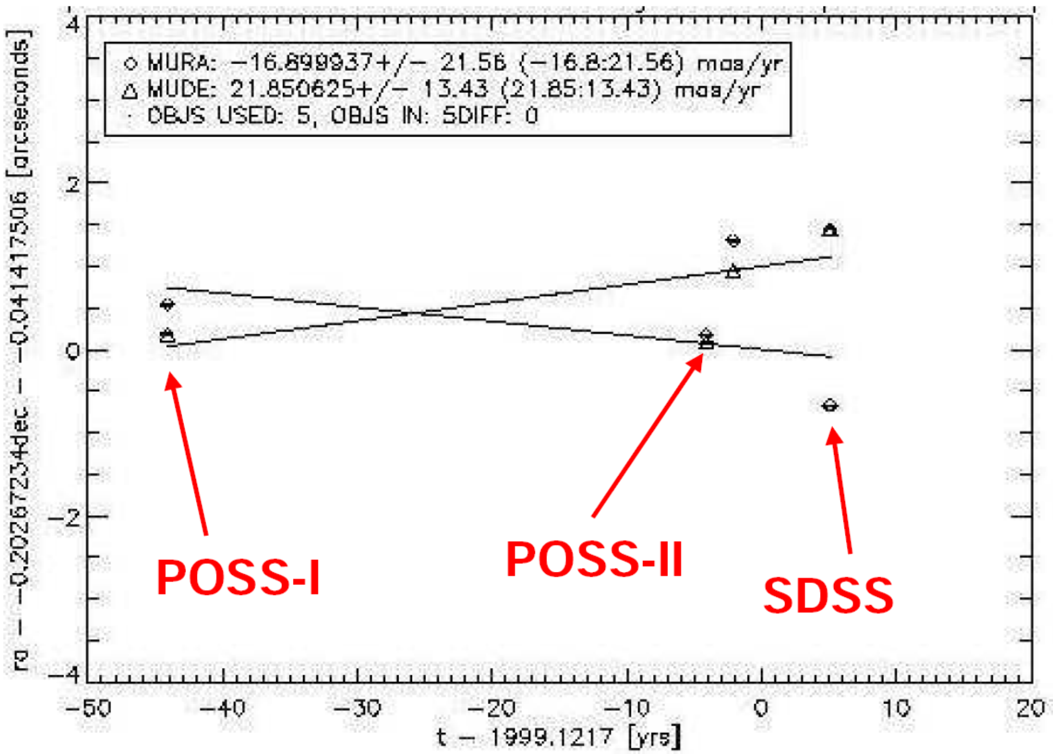
Spagna et al. 1996, A&A 311, 758

Proper motions - II

$\Delta\alpha \& \Delta\delta$ (arcsec) vs. Δt (yr)



★ Proper motion formal errors
$\sigma(\mu) = 2 - 3$ mas/yr

★ Proper motion accuracy
235 QSOs ▷ galactic anticenter:

⋆ GSC-II catalog

⇝ $< \mu_{\alpha \cos\delta} >= 0.13 \pm 0.20$ mas/yr
⇝ $< \mu_{\delta} >= 0.10 \pm 0.18$ mas/yr
⇝ $\sigma(\mu_{\alpha \cos\delta}) = 3.0$ mas/yr
⇝ $\sigma(\mu_{\delta}) = 2.7$ mas/yr

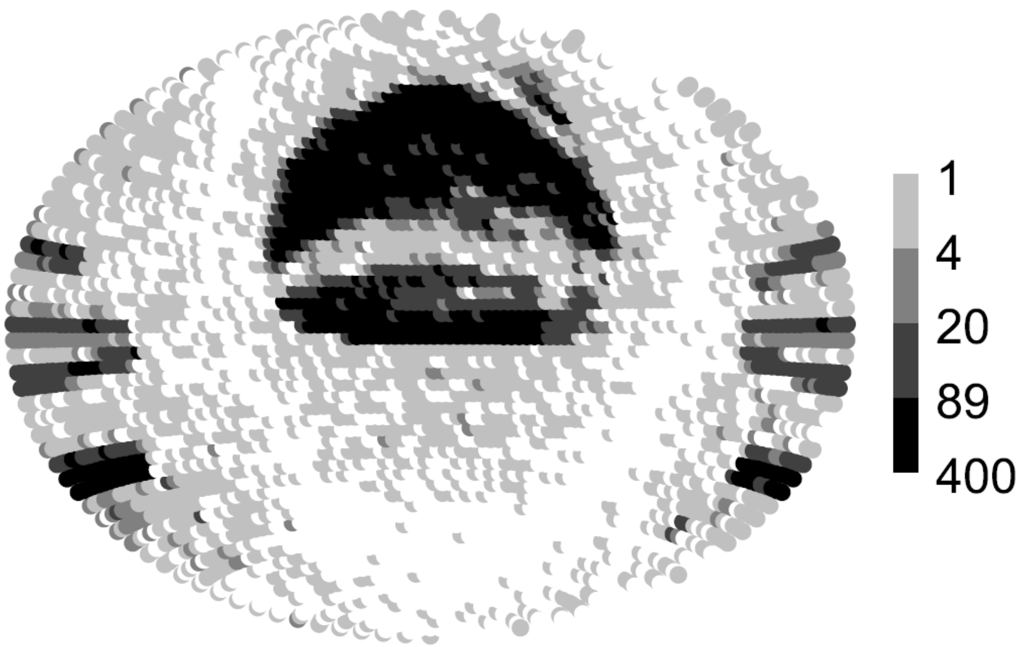
⋆ Munn's catalog

⇝ $< \mu_{\alpha \cos\delta} >= 0.07 \pm 0.29$ mas/yr
⇝ $< \mu_{\delta} >= 1.07 \pm 0.31$ mas/yr
⇝ $\sigma(\mu_{\alpha \cos\delta}) = 4.5$ mas/yr
⇝ $\sigma(\mu_{\delta}) = 4.8$ mas/yr

Proper motions - III

★ Proper motion accuracy, test based on $\sim 80\,000$ QSOs:

g	$<\mu_\alpha \cos\delta>$ GSC-II	Munn	$\sigma(\mu_\alpha \cos\delta)$ GSC-II	Munn	$<\mu_\delta>$ GSC-II	Munn	$\sigma(\mu_\delta)$ GSC-II	Munn
14	0.20 ± 0.60	-1.90 ± 0.53	5.04	4.34	-0.30 ± 0.57	-0.20 ± 0.78	4.83	6.35
15	0.20 ± 0.19	-0.90 ± 0.25	3.28	4.33	-0.10 ± 0.20	1.20 ± 0.27	3.56	4.61
16	-0.20 ± 0.08	-0.20 ± 0.10	2.92	3.69	-0.30 ± 0.08	0.50 ± 0.10	2.95	3.60
17	-0.30 ± 0.04	0.20 ± 0.04	2.86	3.25	-0.30 ± 0.04	0.20 ± 0.04	2.96	3.23
18	-0.10 ± 0.02	0.30 ± 0.02	3.43	3.37	0.10 ± 0.02	0.20 ± 0.02	3.56	3.39
19	-0.10 ± 0.03	0.30 ± 0.03	4.83	4.36	0.00 ± 0.03	0.00 ± 0.03	4.90	4.43
20	-0.30 ± 0.08	0.00 ± 0.07	6.61	6.18	0.10 ± 0.08	0.00 ± 0.07	6.59	6.17
21	mas/yr	mas/yr	mas/yr	mas/yr	mas/yr	mas/yr	mas/yr	mas/yr



Sky distribution of the quasars found in the GSC2.3 catalog. The highest density region marks the SDSS contribution. The scale represents the number of sources in regions of 9 deg^2 shown on the plots.

Andrei et al. 2009, A&A, in press

Proper motions - III

★ Proper motion accuracy, test based on $\sim 80\,000$ QSOs:

g	$<\mu_\alpha \cos\delta>$		$\sigma(\mu_\alpha \cos\delta)$		$<\mu_\delta>$		$\sigma(\mu_\delta)$	
	GSC-II	Munn	GSC-II	Munn	GSC-II	Munn	GSC-II	Munn
14	0.20 ± 0.60	-1.90 ± 0.53	5.04	4.34	-0.30 ± 0.57	-0.20 ± 0.78	4.83	6.35
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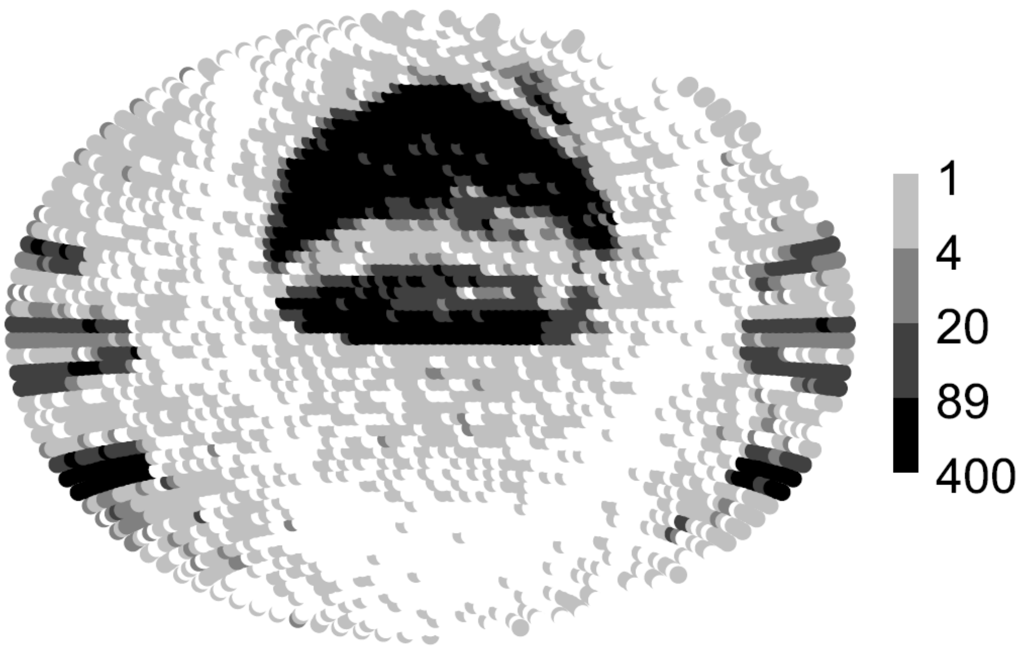
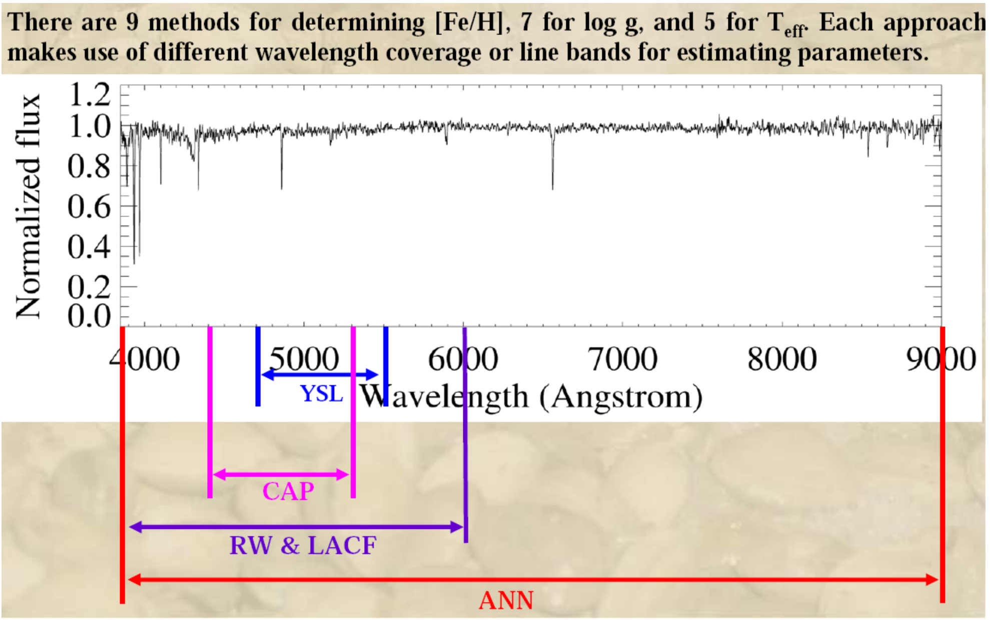


Sky distribution of the quasars found in the GSC2.3 catalog. The highest density region marks the SDSS contribution. The scale represents the number of sources in regions of 9 deg^2 shown on the pl ots.

Andrei et al. 2009, A&A, in press

Stellar astrophysical parameters (e.g. $T_{\rm eff}$, log g, [Fe/H])

★ SSPP - Methodology



- ⋆ SDSS pipeline (SSPP)
  Lee et al. 2008, AJ 136, 2022
- ⋆ Supervised feedforward neural network (ANN)
  Re Fiorentin et al. 2007, A&A 467, 1374

★ SSPP - Precision

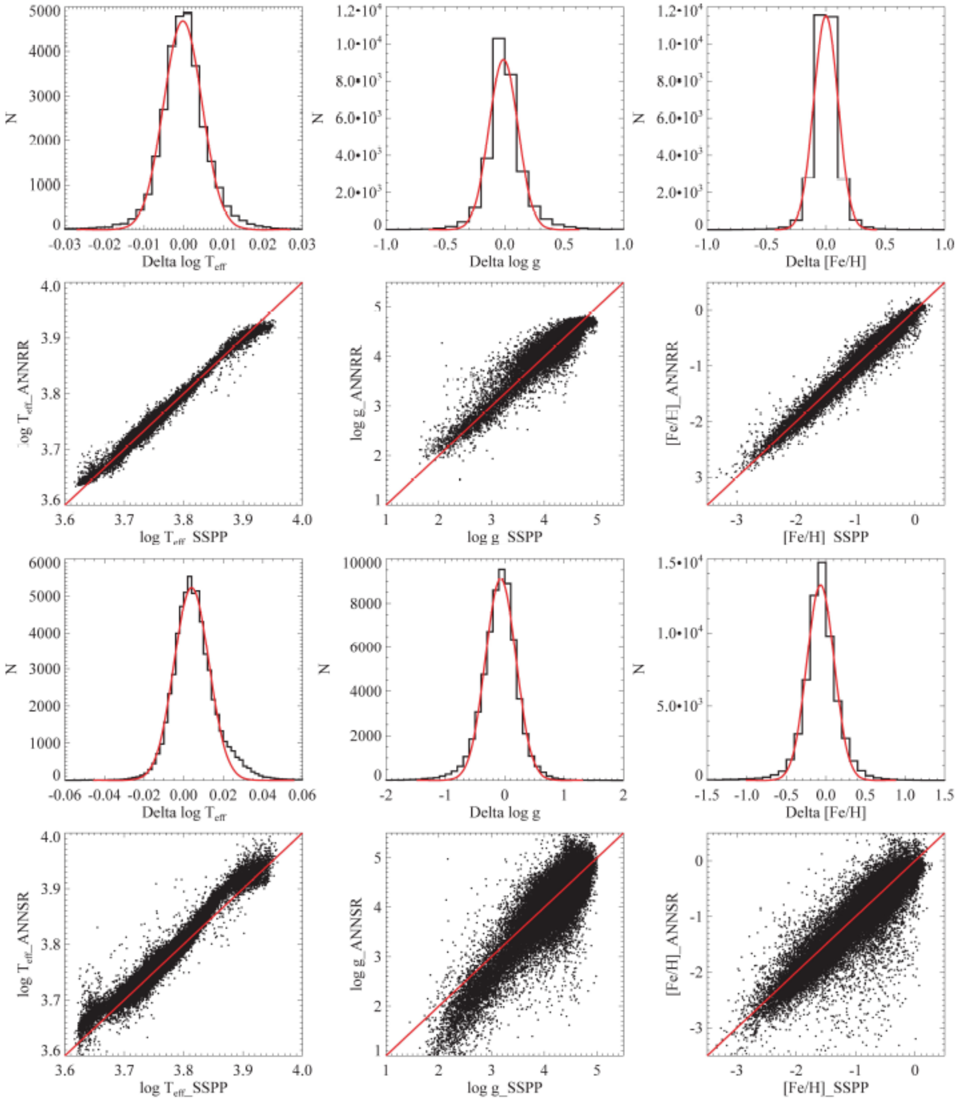
- ⋆ 4500 K $< T_{\rm eff} <$ 7500 K, SNR>15:
  $\sigma(T_{\rm eff}) = 150$ K, $\sigma(\log\ g) = 0.25$ dex, $\sigma([{\rm Fe/H}]) = 0.20$ dex
- ⋆ over 125 F,G stars (HET spectra, high quality):
  $\sigma(T_{\rm eff}) = 130$ K, $\sigma(\log\ g) = 0.21$ dex, $\sigma([{\rm Fe/H}]) = 0.11$ dex
- ⋆ over G;OC (M13,M15,M2; NGC2420,M67):
  $\sigma(T_{\rm eff}) < 200$ K, $\sigma(\log\ g) \leq 0.40$ dex

(e.g. Allende Prieto et al. 2008, AJ 136, 2070; Lee et al. 2008, AJ 136, 2050)

Stellar astrophysical parameters

Precision/Accuracy improved by further development of ANN, improved stellar models, better data calibration... (e.g. Re Fiorentin et al. 2008, AIPC 1082, 76)

★ RR



★ SR

Accuracy estimate:

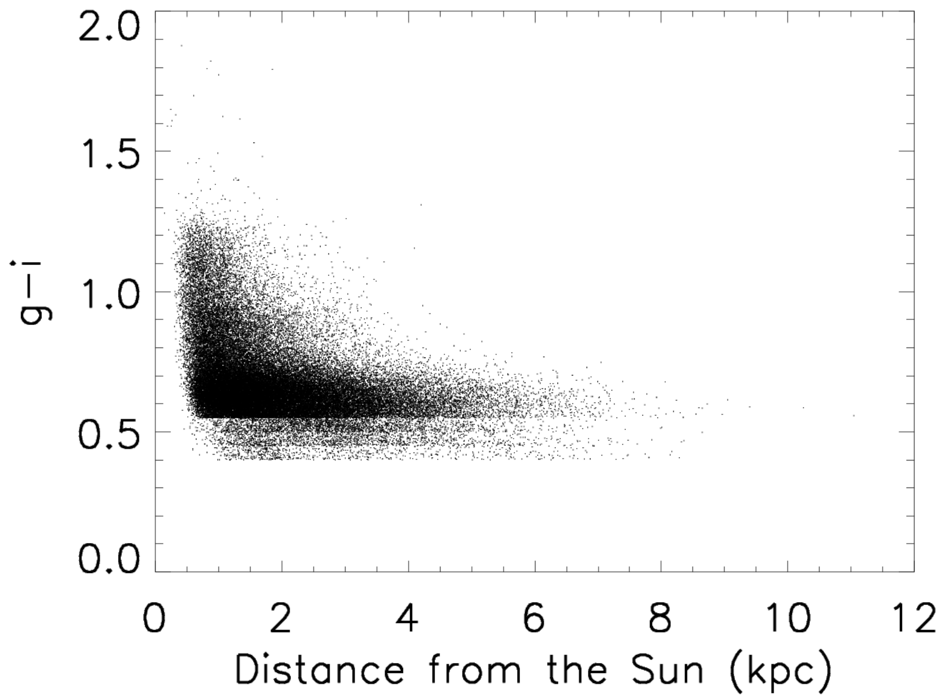
$$E = \frac{1}{P}\sum_{p=1}^{P} |C(p) - T(p)|$$

Model	$\log\ T_{\rm eff}$	$E_{\log\ g}$	$E_{\rm [Fe/H]}$
RR	0.0058	0.11	0.0879
SR	0.0083	0.3105	0.2456

currently SNR>10; and lower?

SNR	$T_{\rm eff}$	$E_{\log\ g}$	$E_{\rm [Fe/H]}$
10	0.68%	0.1591	0.1040
5	0.93%	0.1897	0.1312
1	2.04%	0.3280	0.2766

Photometric distances



Method:

1. Magnitude correction: extinction maps by Schlegel et al. (1998)

2. Photometric parallax: absolute magnitude by Ivezic et al. (2008), calibrated for FGK (sub)dwarfs with [Fe/H] < -0.5

$$M_r(g-i, \text{[Fe/H]}) = M_r^0(g-i) + \Delta M_r(\text{[Fe/H]})$$

Schlegel et al. 1998, ApJ 500, 525; Ivezic et al. 2008, AJ 684, 287

SDSS-GSC-II catalog

★ Area: 9 000 deg^2

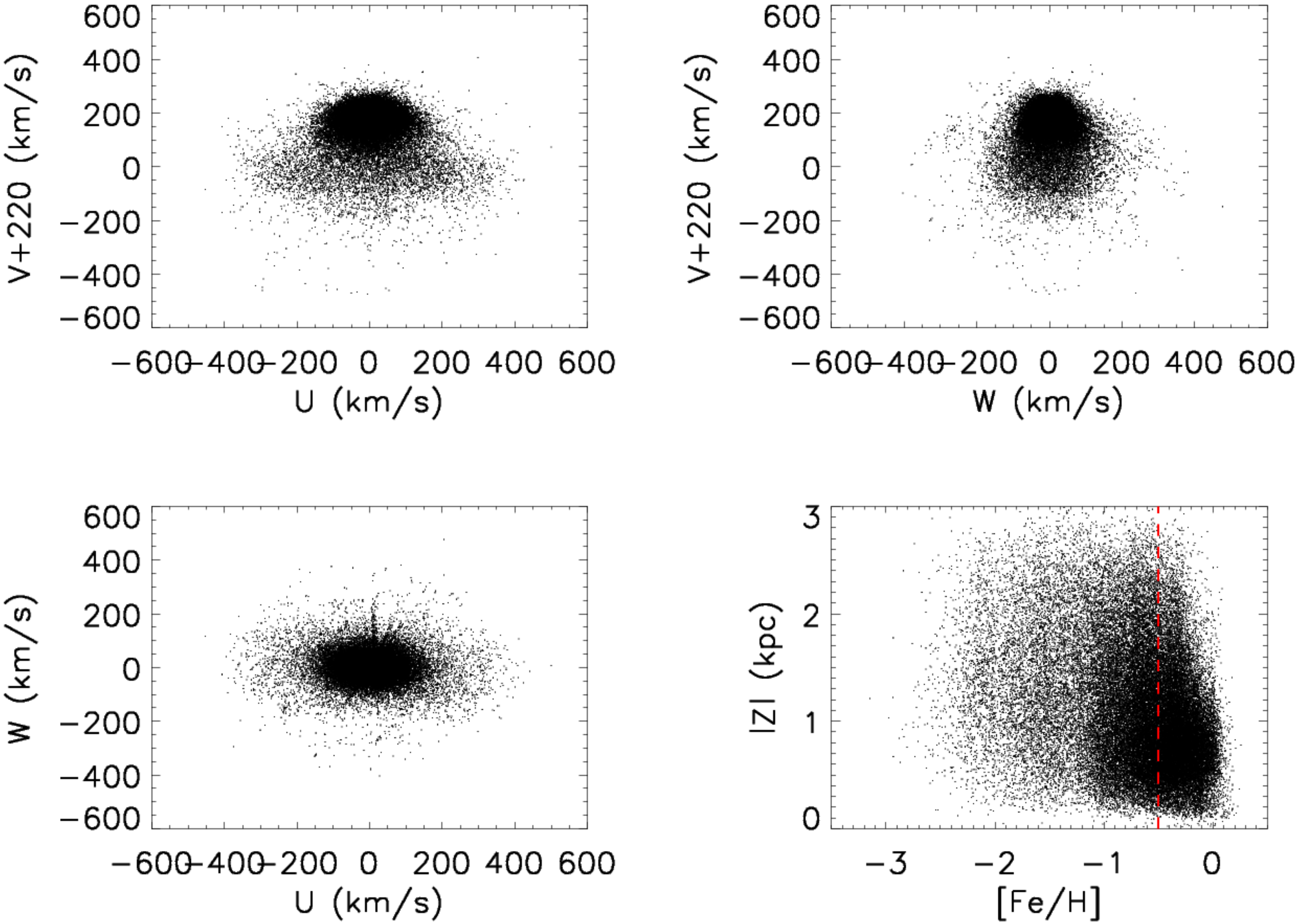
	# Objects	$ugriz$ mag	(μ_α, μ_δ) mas/yr	T_{eff} K	log g dex	[Fe/H] dex	RV km/s	d kpc	UVW km/s
	77 000 000	×	×						
★	**150 000**	×	×	×	×	×	×		
★	**27 000**★	×	×	×	×	×	×	×	×

★ FGK dwarfs, kinematic sample:

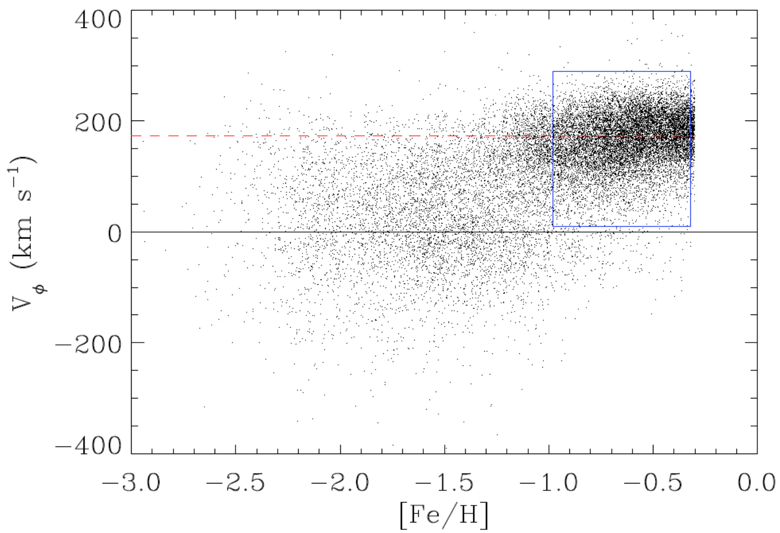
⇝ 4500 K $< T_{\text{eff}} <$ 7500 K, log $g >$ 3.5 dex,

⇝ [Fe/H] < -0.5 dex, $d <$ 3 kpc

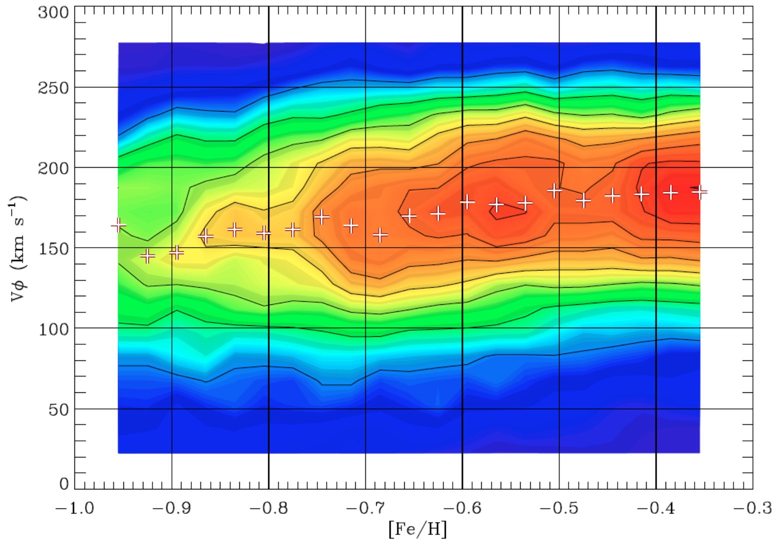
Kinematics & Chemical properties: overview



Evidence of a thick disk rotation-metallicity correlation: $dV_\phi/dz \sim 40 - 50$ km/s per dex



V_ϕ vs [Fe/H]. Stars with $|z| = 1.0 - 3.0$ kpc and [Fe/H] < -0.3. Dashed line is the thick disk rotation, 173 km/s.The box defines the region in which the thick disk population dominates.



Zooming, iso-density contours.
Ridge line of the maximum likelihood marked.

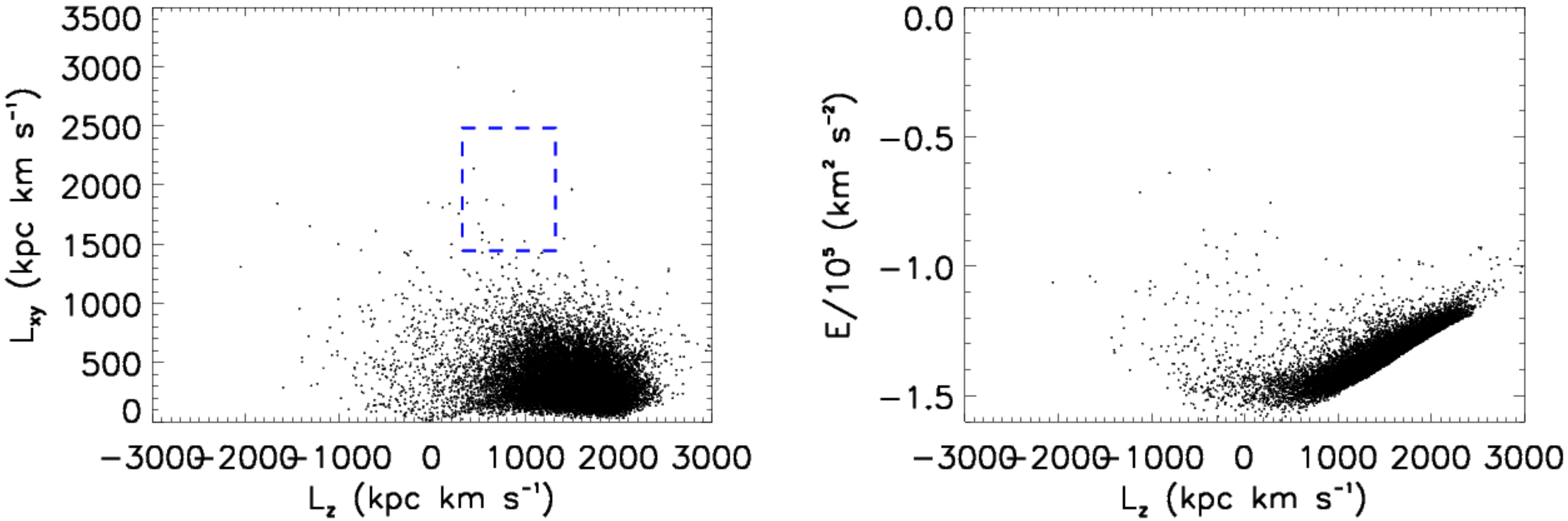
$\langle\lvert z\rvert\rangle$ (kpc)	N_{tot}	N_{used}		$\partial\langle V_\phi\rangle/\partial$[Fe/H] (km s^{-1} dex^{-1})		ρ_s ($\times10^{-2}$)	
		3σ	2σ	3σ	2σ	3σ	2σ
1.23	3994	3672	2915	50 ± 5	39 ± 5	17 ± 2	15 ± 2
1.73	2641	2348	1715	54 ± 6	35 ± 5	18 ± 2	16 ± 2
2.37	2194	1768	1131	35 ± 8	33 ± 5	10 ± 2	14 ± 3

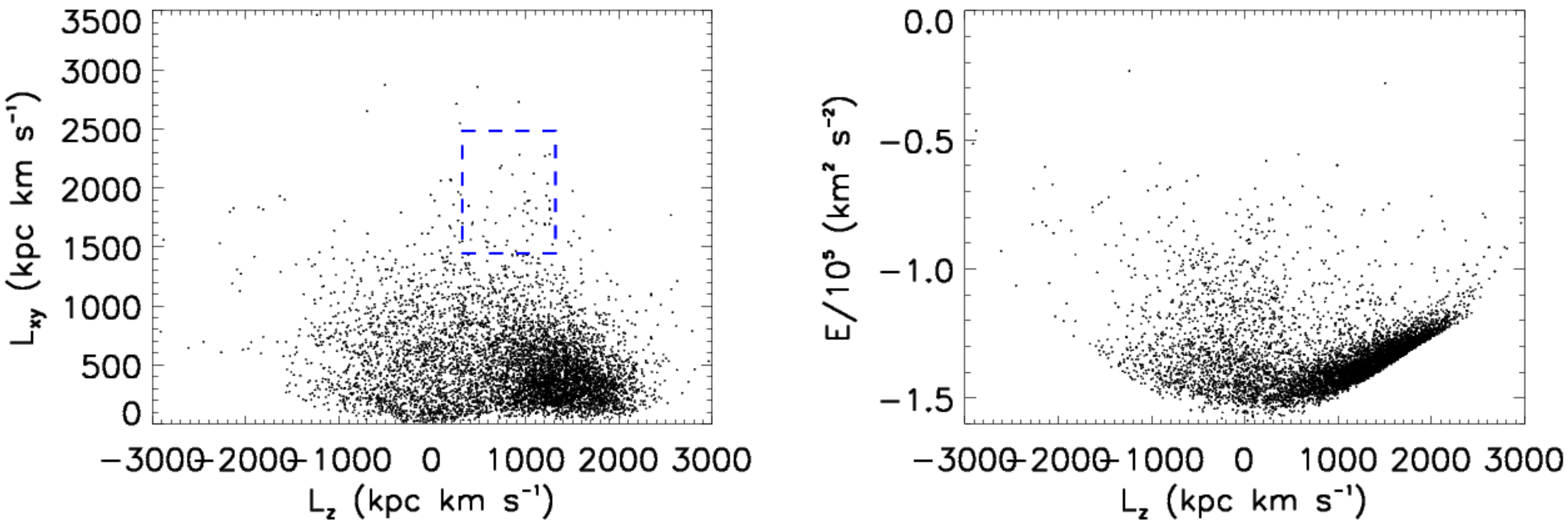
Kinematics-metallicity correlation of thick disk stars with -1.0<[Fe/H]< -0.5 @ height intervals.

(see poster, Spagna et al. 2010)

Kinematics & Chemical properties: overview

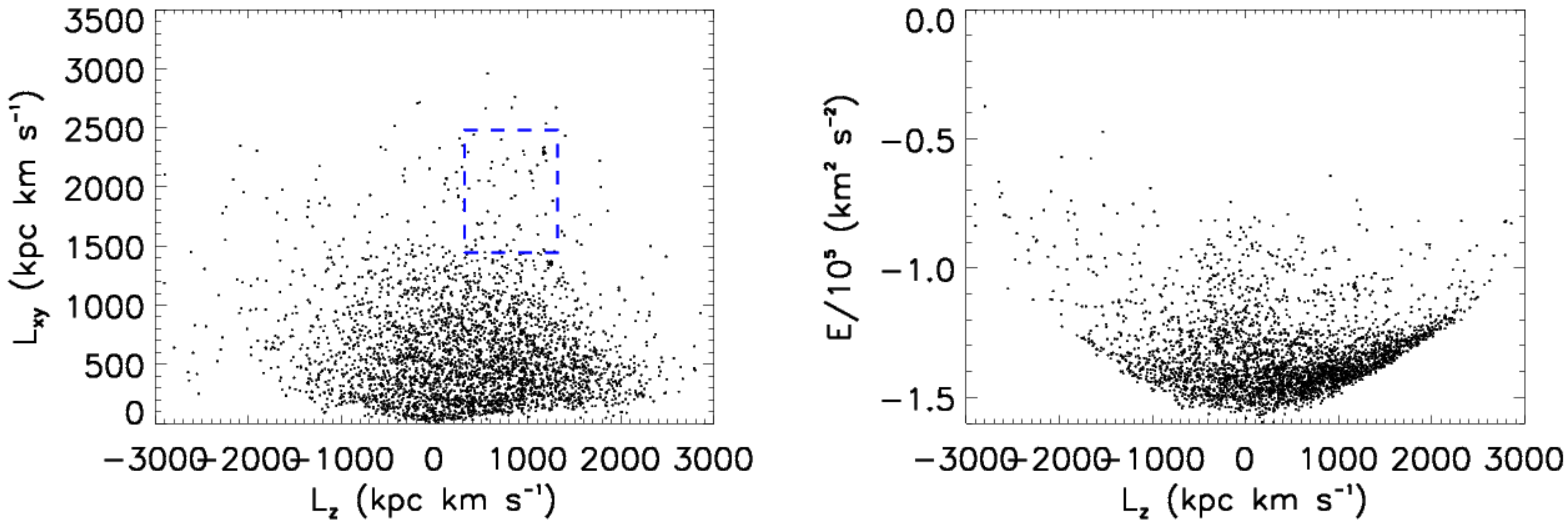
★ $-1.0 < [Fe/H] < -0.5$

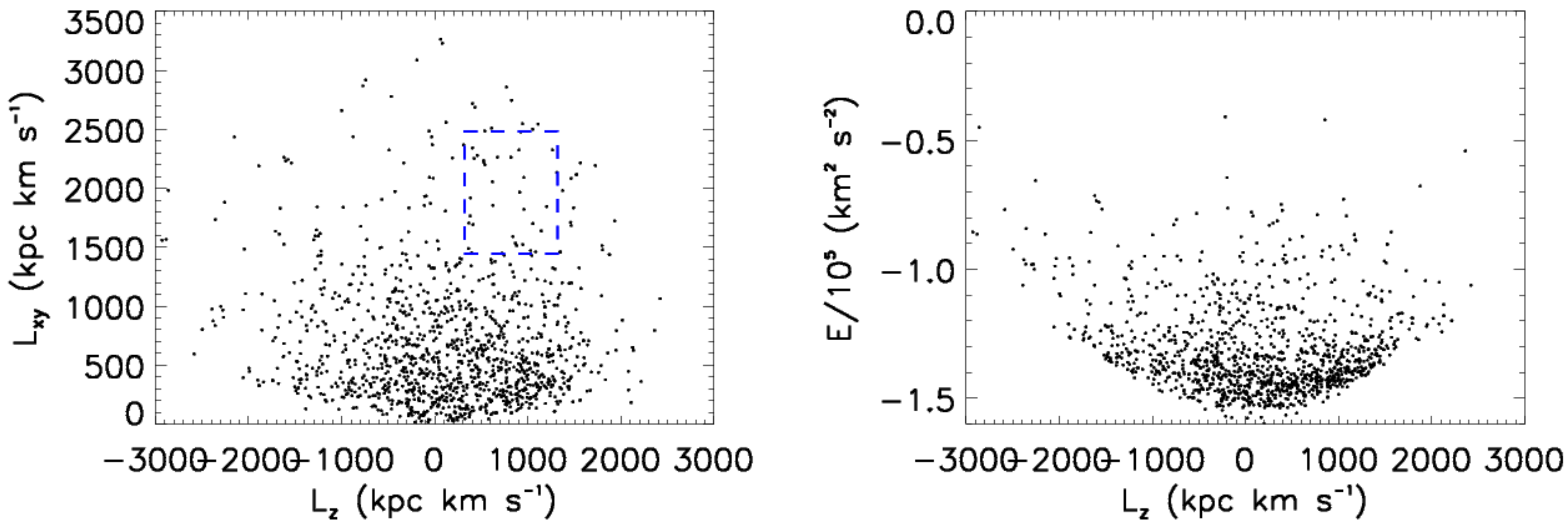




★ $-1.5 < [Fe/H] < -1.0$

★ $-2.0 < [Fe/H] < -1.5$

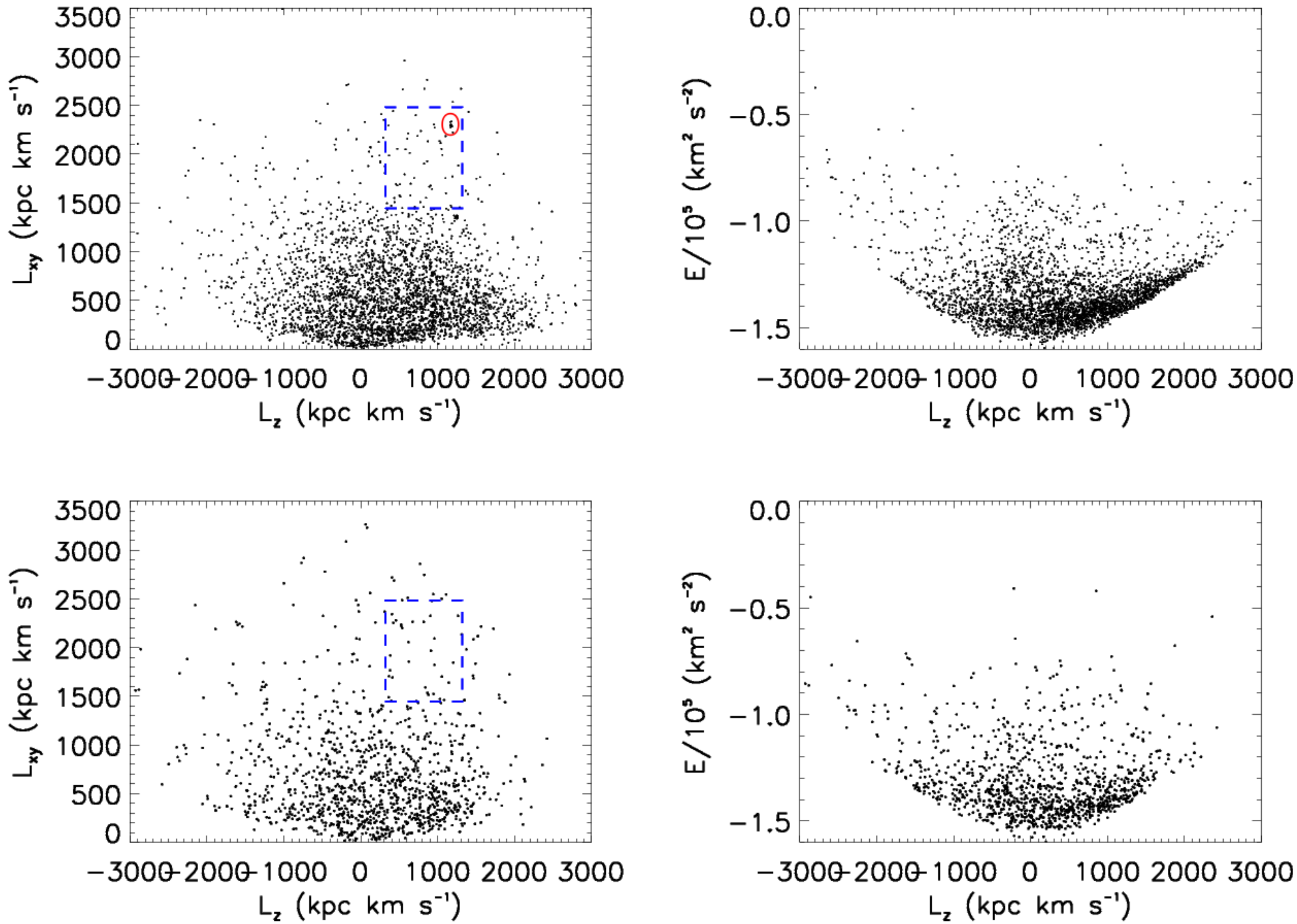




★ $[Fe/H] < -2.0$

Kinematics & Chemical properties: overview

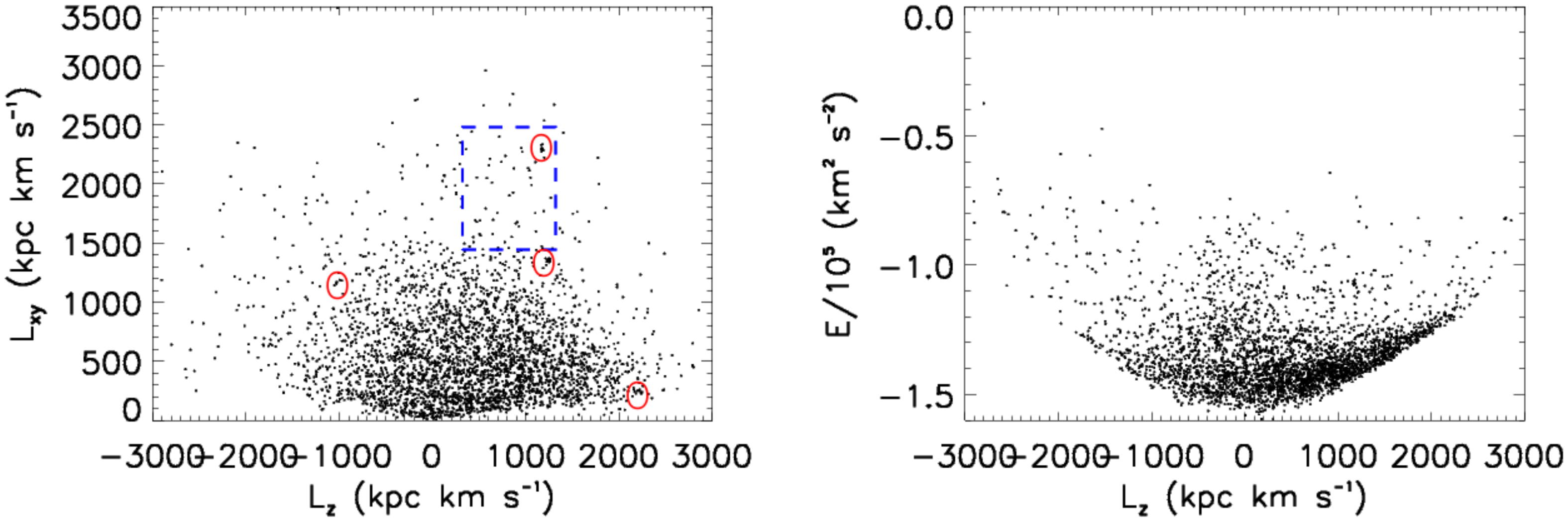
★ $-2.0 < [\mathrm{Fe/H}] < -1.5$

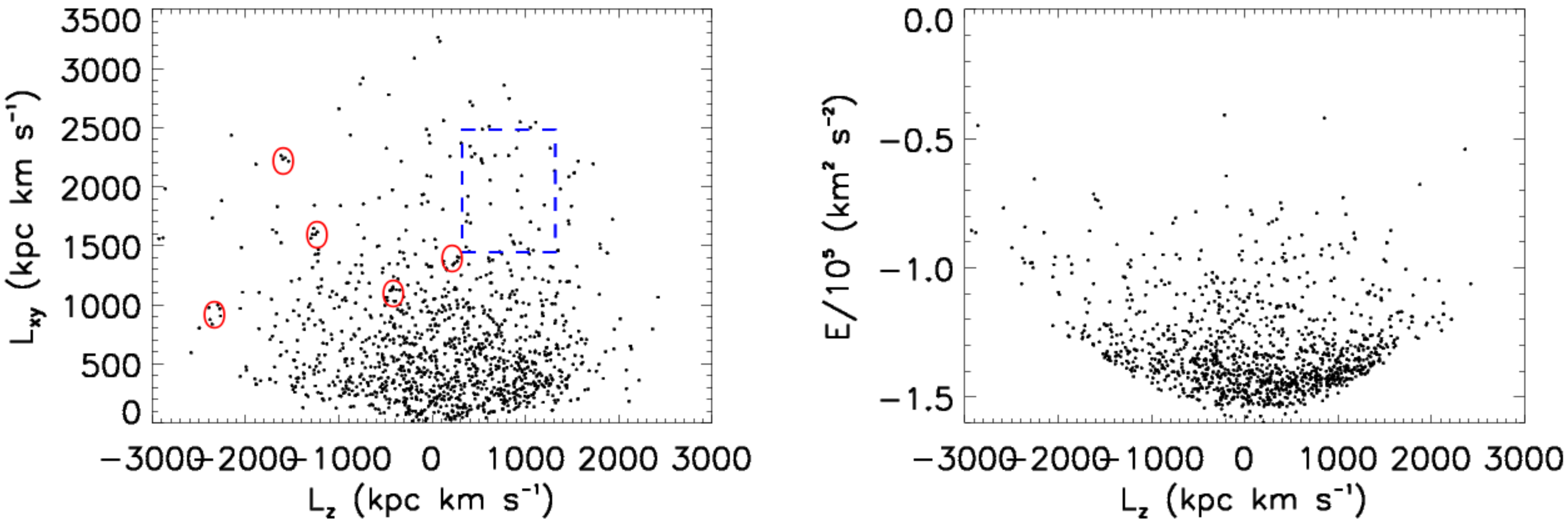


★ $[\mathrm{Fe/H}] < -2.0$

Kinematics & Chemical properties: overview

★ $-2.0 < [Fe/H] < -1.5$





★ $[Fe/H] < -2.0$

How can we quantify such substructures?

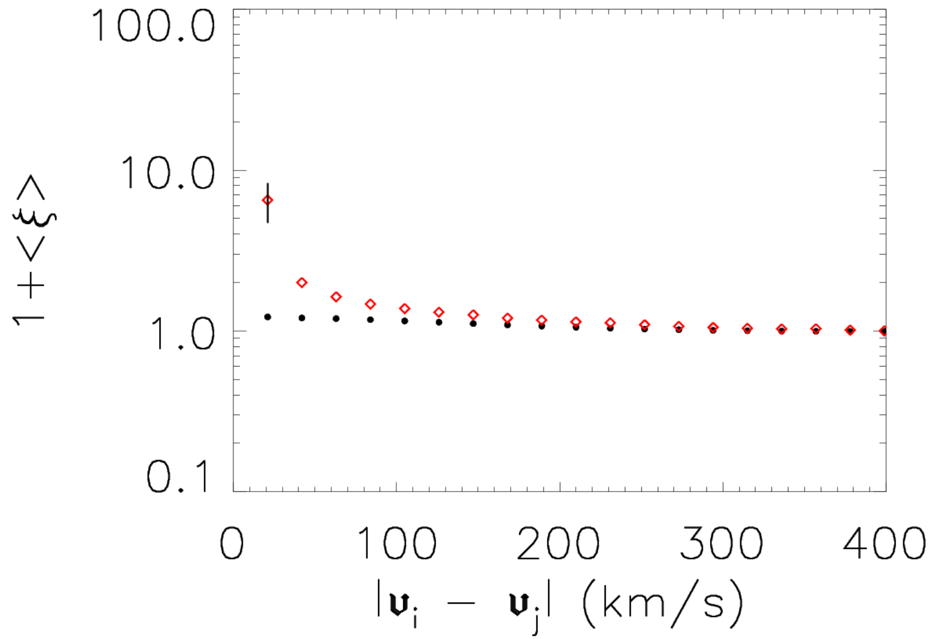
★ Two-Point Correlation function

Clustering method for uncovering (new) structures in data sets

$$\xi = \frac{< DD >}{< RR >} - 1$$

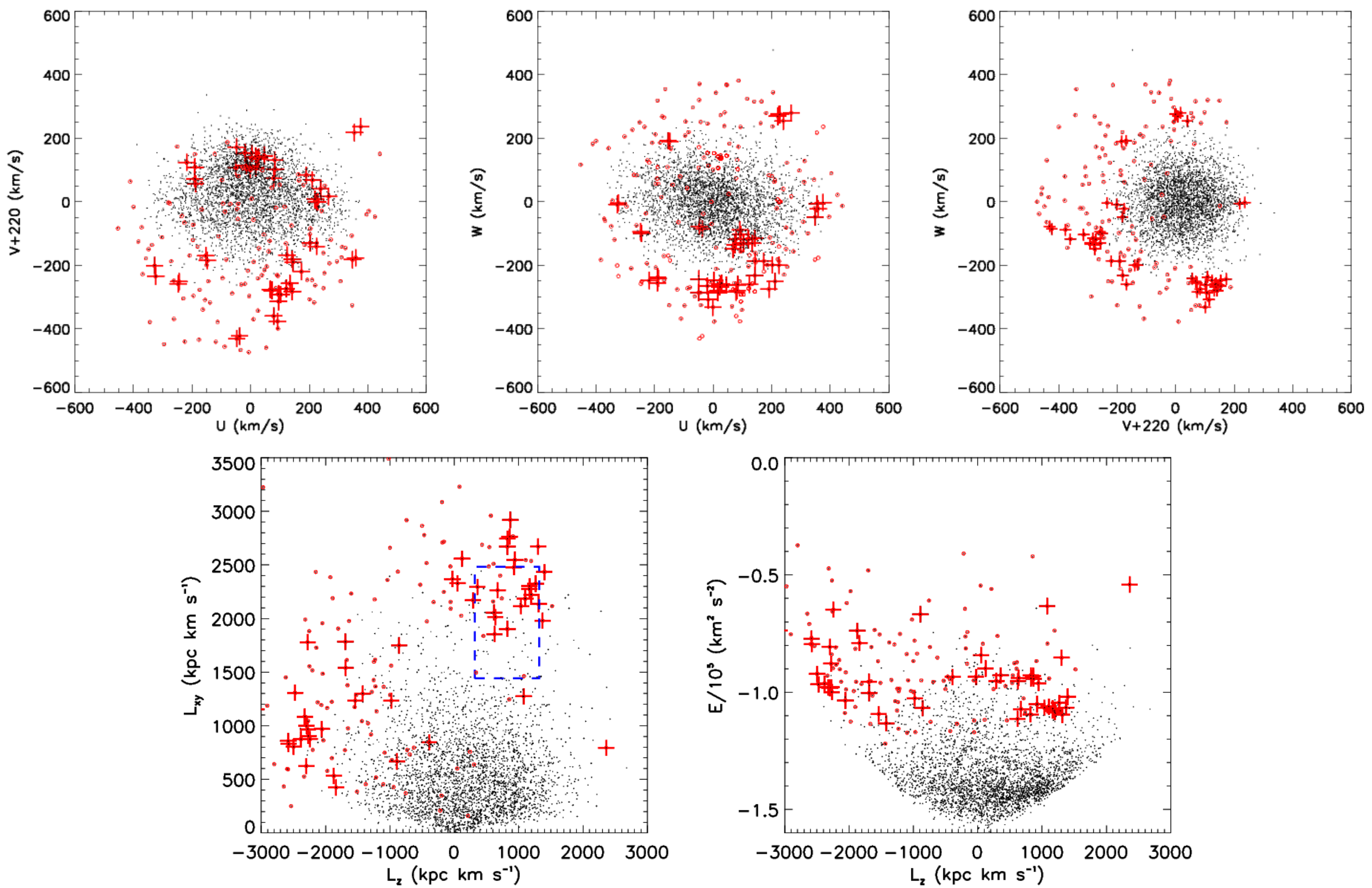
$< DD >$ number of pairs of particles in our data with velocity difference less than a given value

$< RR >$ number of pairs of random particles with velocity difference less than *that* given value



★ ξ measure the excess of pairs of stars moving with given velocity difference, above that expected from a random sample.

Kinematic substructures



Distribution of the halo subsample (3337 stars with [Fe/H]< -1.5 and $d < 3$ kpc). The 5% fastest are highlighted (circles). Among them, the crosses identify groups with velocity difference less than 42 km/s. The box shows the locus of the halo stream discovered by Helmi et al. 1999.

Summary

Objective: A new kinematic survey from SDSS-DR7 & GSC-II

- ★ We have produced a new proper motion survey covering 9 000 deg^2 based on the multi-epoch positions derived SDSS-DR7 combined with the plate material from the GSC-II database.

- ★ Accurate absolute proper motions (μ_α, μ_δ) have been computed for 40 million sources down to magnitude $g \sim 22$ ($r \sim 20$). Proper motions errors attain 2-3 mas/yr.

- ★ Stellar astrophysical parameters (T_{eff}, log g, [Fe/H]) have been (re)estimated for the SDSS spectroscopic sample by means of updated ANN models.

- ★ Full *astrometric, photometric, and spectroscopic measurements* are available for 150 000 stars.

- ★ Photometric distances and 3D velocities (UVW) have been computed for FGK (sub)dwarfs with [Fe/H] < -0.5.

- ★ A kinematic sample of 30 700 tracers within 3 kpc from the Sun has been extracted and will be used to

  - ⇝ study the kinematic properties of the thick disk and inner halo:

  - ⇝ search for members of known/new kinematic substructures produced by past mering events.

↬ to study the kinematic and chemical properties of stellar populations and to search for fossil records in the Milky Way