Local halo streamers in the era of Gaia: detection and characterization

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Galactic Surveys: New Results on Formation, Evolution, Structure and Chemical Evolution of the Milky Way

In this talk

↬ New signatures of the MW formation in the local halo & inner-halo streamers in the era of Gaia

★ The context

- ⋆ MW Galactic Halo as testing ground for theories of galaxy formation
- ⋆ Where/How are the signatures?

★ Data: Wide field kinematic survey (SGKS)

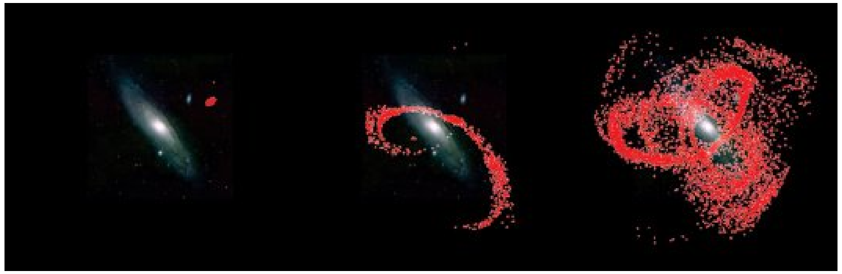
- ⋆ ingredients: survey/data base (SDSS, GSC-II)
- ⋆ preparation (calculation & precision/accuracy):
  - ⇝ proper motions
  - ⇝ astrophysical parameter estimation (e.g. T_{eff}, log g, [Fe/H])
  - ⇝ distance...plus RV: phase-space!
- ⋆ 6D –> 7D (9D)

★ What do we do? Exploiting the results...

- ⋆ Define & describe (kinematic & basic chemical properties) new samples of stellar tracers for Galactic investigations
- ⋆ Kinematic & chemical analysis: search for fossil records in the Milky Way
- ⋆ Comparison to N-body high resolution simulations
- ⋆ Investigate the impact of observational errors

Thank to: Mario G. Lattanzi, Alessandro Spagna, and Anna Curir

Signatures of hierarchical merging



outer Halo: remain spatially and kinematically coherent many Gyr;
inner Halo: detectable as stellar groups of stars with coherent kinematics and metallicities.

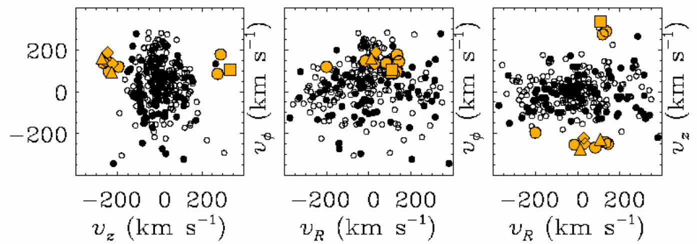
INNER HALO

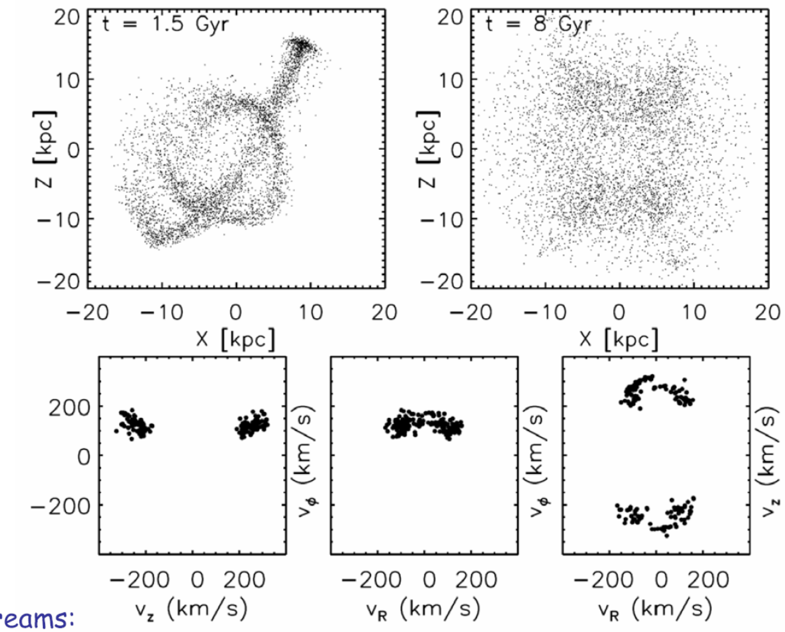
- ★ More interesting:
  - ⋆ location of large majority of stars
- ★ Mixing time scales are short:
  - ⋆ by conservation of volume/density in phase-space

$$dV = d^3x d^3v$$

↬ Debris no longer spatially coherent

↬ Memory is retained in kinematics



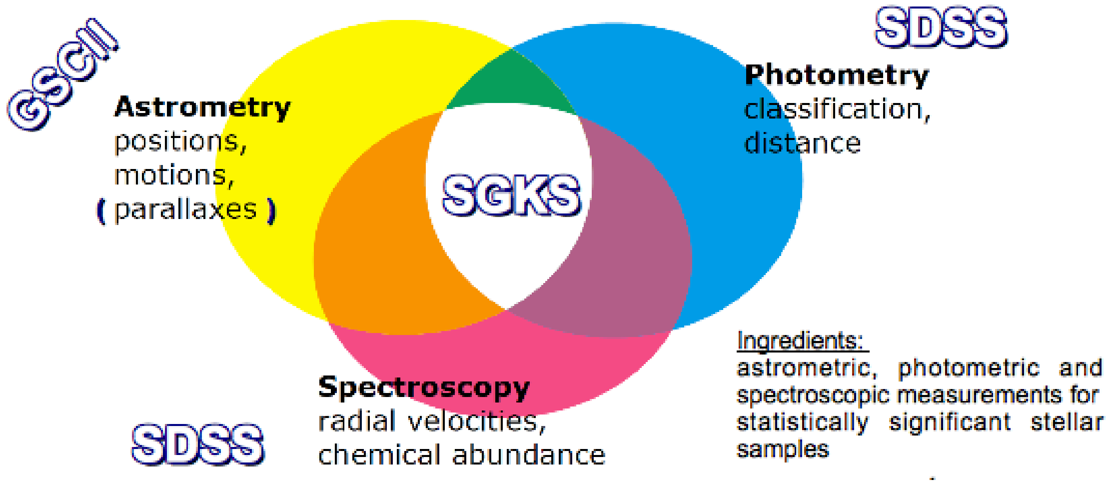


Inner halo streams:

Helmi et al. 1999

The particles might be distributed smoothly in space but their motions be very coherent!

Surveys of galactic stellar populations: SDSS-GSC-II Kinematic Survey (SGKS)



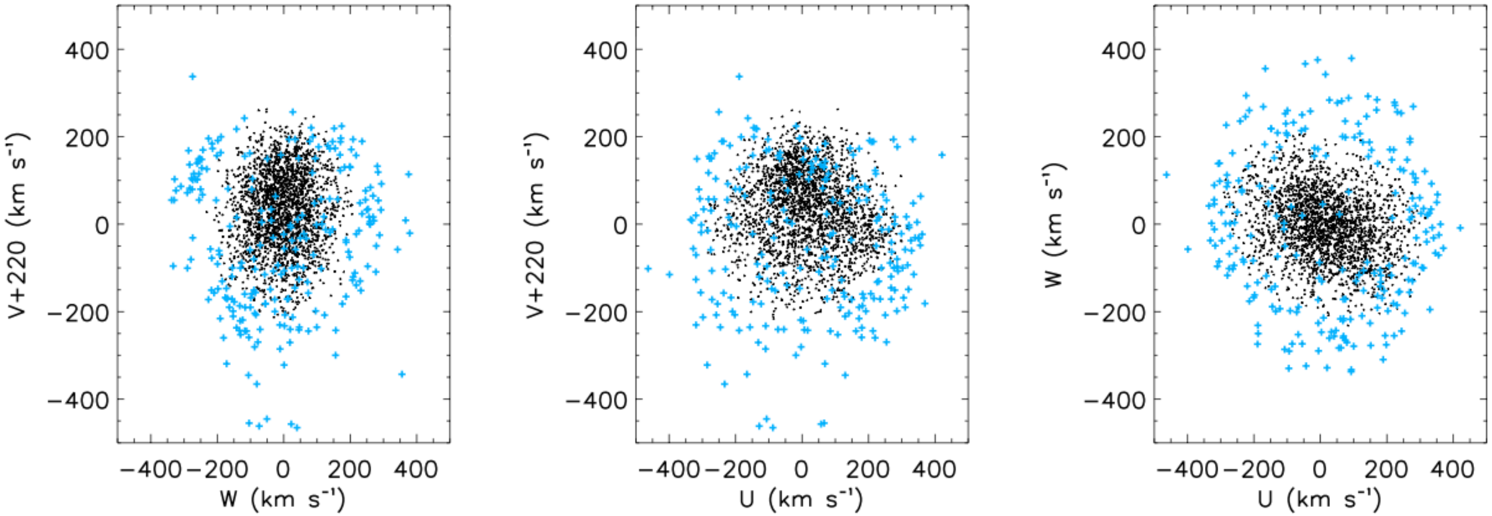
★ Area: 9 000 deg^2

	# Objects	$ugriz$ mag	(μ_α, μ_δ) mas/yr	$T_{\rm eff}$ K	log g dex	[Fe/H] dex	RV km/s	d kpc	UVW km/s
	77 000 000	X	X						
★	**151 000**	X	X	X	X	X	X		
★	**25 000**★	X	X	X	X	X	X	X	X
	Errors		2-3 mas/yr	250 K	0.25 dex	0.20 dex	$\sim$ 10 km/s	20%	$\sim$ 10 km/s

★ FGK dwarfs, kinematic sample:

- ⇝ 4500 K $< T_{\rm eff} <$ 7500 K, log $g >$ 3.5 dex,
- ⇝ [Fe/H] < -0.5 dex, $d <$ 3 kpc

Halo kinematic substructures in the solar neighborhood (d<3 kpc, $|z| > 1$ kpc)



Distribution of nearby halo stars in velocity space for the sample of 2417 FGK subdwarfs, with [Fe/H] < -1.5 and $|z| > 1$ kpc within 3 kpc of the Sun.
The 10% fastest-moving stars (242) are marked as crosses.

HALO VELOCITY PARAMETERS.

$\langle U \rangle$ (km s^{-1})	$\langle V+220 \rangle$ (km s^{-1})	$\langle W \rangle$ (km s^{-1})	σ_U (km s^{-1})	σ_V (km s^{-1})	σ_W (km s^{-1})	ρ_{UV}	ρ_{UW}	ρ_{VW}
15 ± 2	25 ± 2	-4 ± 2	126 ± 1	100 ± 1	91 ± 1	-0.09 ± 0.02	-0.18 ± 0.02	0.05 ± 0.02

$$
\begin{aligned}
f(U,V,W) &= \text{const} \cdot e^{-\frac{1}{2}E(U,V,W)} \\
E(U,V,W) &= \frac{R_{UU}}{R}\left(\frac{U-\langle U\rangle}{\sigma_U}\right)^2 + \frac{R_{VV}}{R}\left(\frac{V-\langle V\rangle}{\sigma_V}\right)^2 + \frac{R_{WW}}{R}\left(\frac{W-\langle W\rangle}{\sigma_W}\right)^2 + \\
& 2\frac{R_{UV}}{R}\left(\frac{U-\langle U\rangle}{\sigma_U}\right)\left(\frac{V-\langle V\rangle}{\sigma_V}\right) + 2\frac{R_{VW}}{R}\left(\frac{V-\langle V\rangle}{\sigma_V}\right)\left(\frac{W-\langle W\rangle}{\sigma_W}\right) + 2\frac{R_{UW}}{R}\left(\frac{U-\langle U\rangle}{\sigma_U}\right)\left(\frac{W-\langle W\rangle}{\sigma_W}\right).
\end{aligned} \tag{1}
$$

Finding the clumps: How can we quantify such substructures?

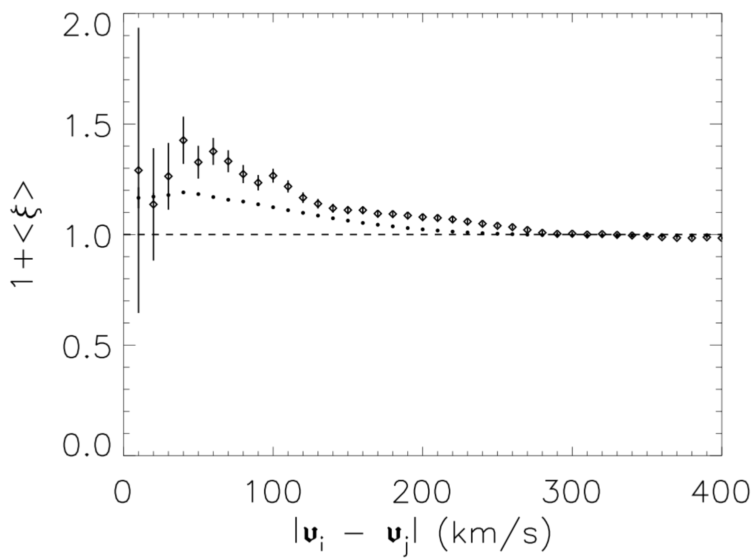
★ Two-Point Correlation function

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

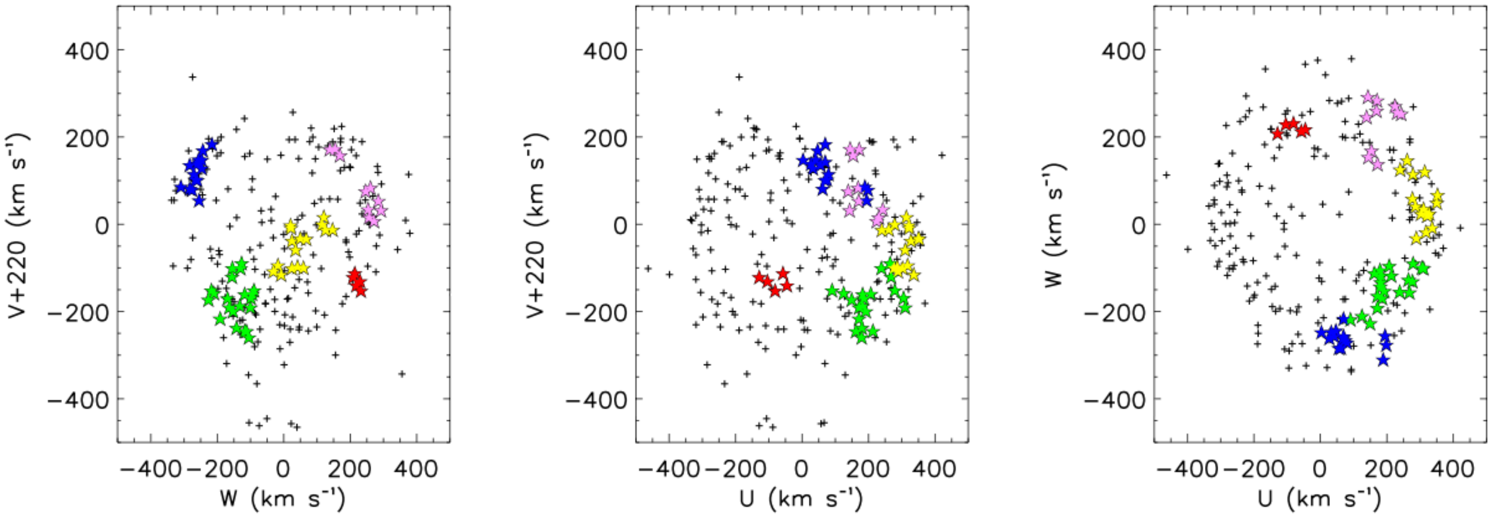
$< RR >$ number of pairs of random particles with velocity difference less than *that* given value



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

Assigning Membership I

★ $|\mathbf{v}_i - \mathbf{v}_j| < 40$ km/s & exclude isolated pairs; objs: 242 → 67



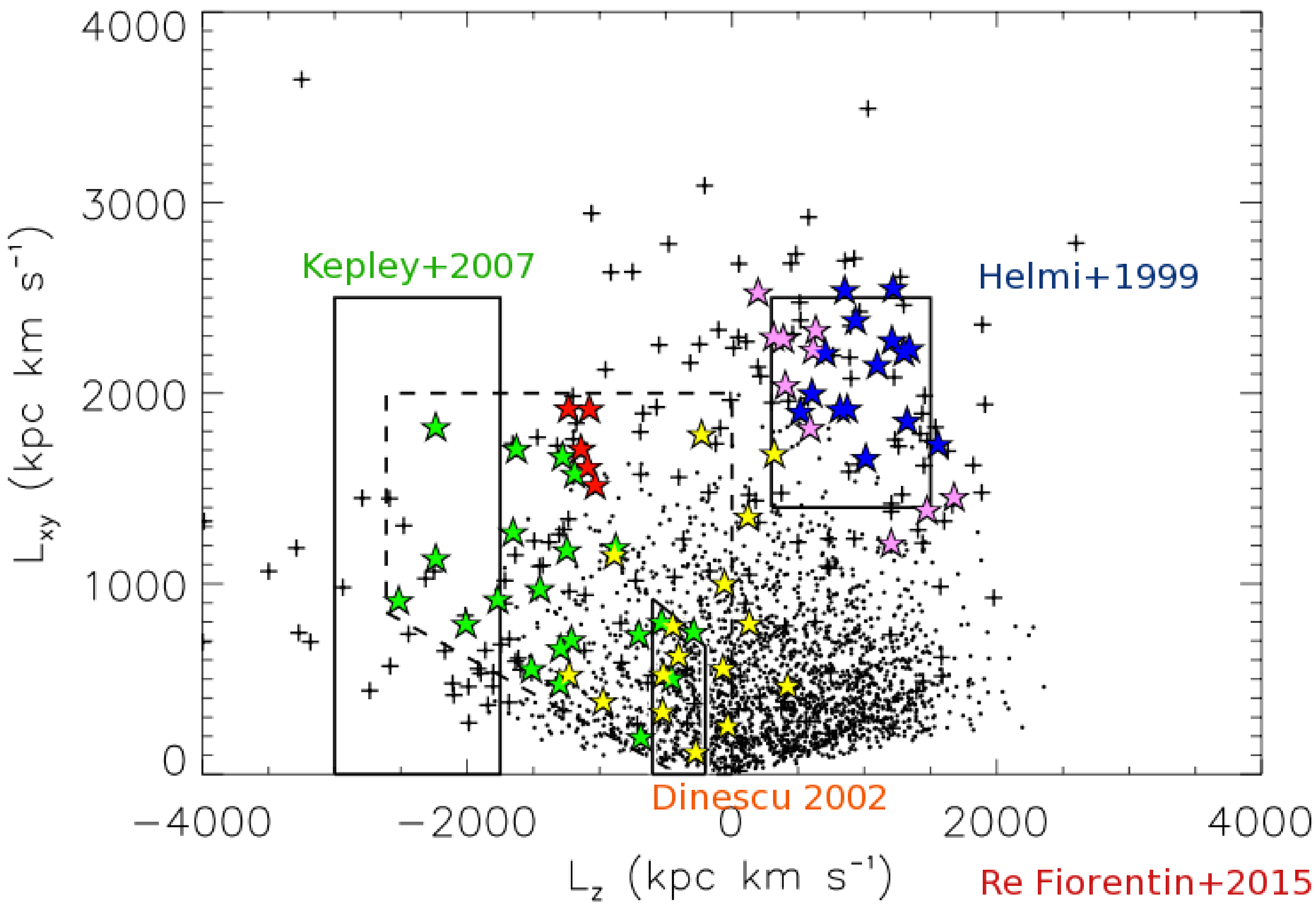
★ K-medoids clustering: to group data into a pre-specified number of clusters that minimizes the rms of the distance to the center of each cluster

$$\sum_{j \in C_i} d(i,j)$$

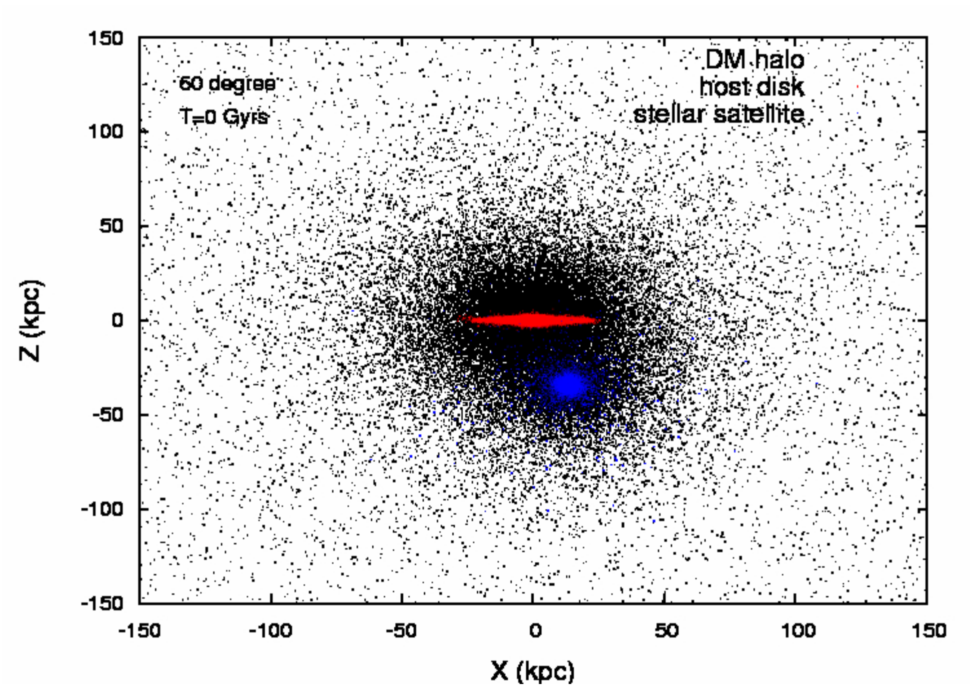
1. Choose k objects at random to be the initial cluster medoids.
2. Assign each object to the cluster associated with the closest medoid.
3. Recalculate the positions of the k medoids.
4. Repeat Steps 2 and 3 until the medoids become fixed.

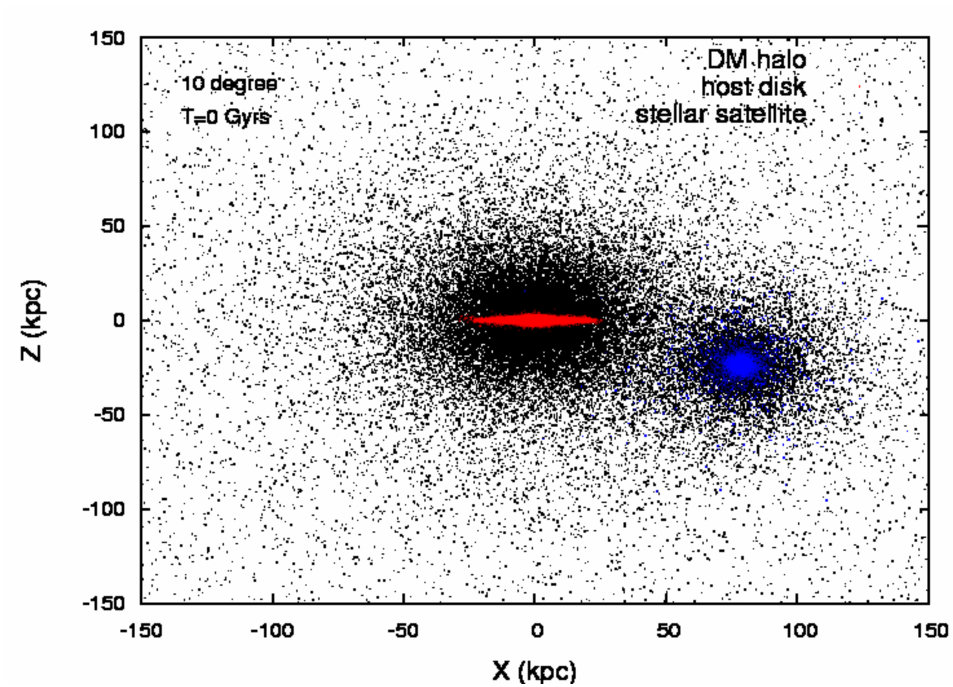
Assigning Membership II

★ Angular Momentum and Orbital Properties



High Resolution N-body Simulation (Murante+2010)





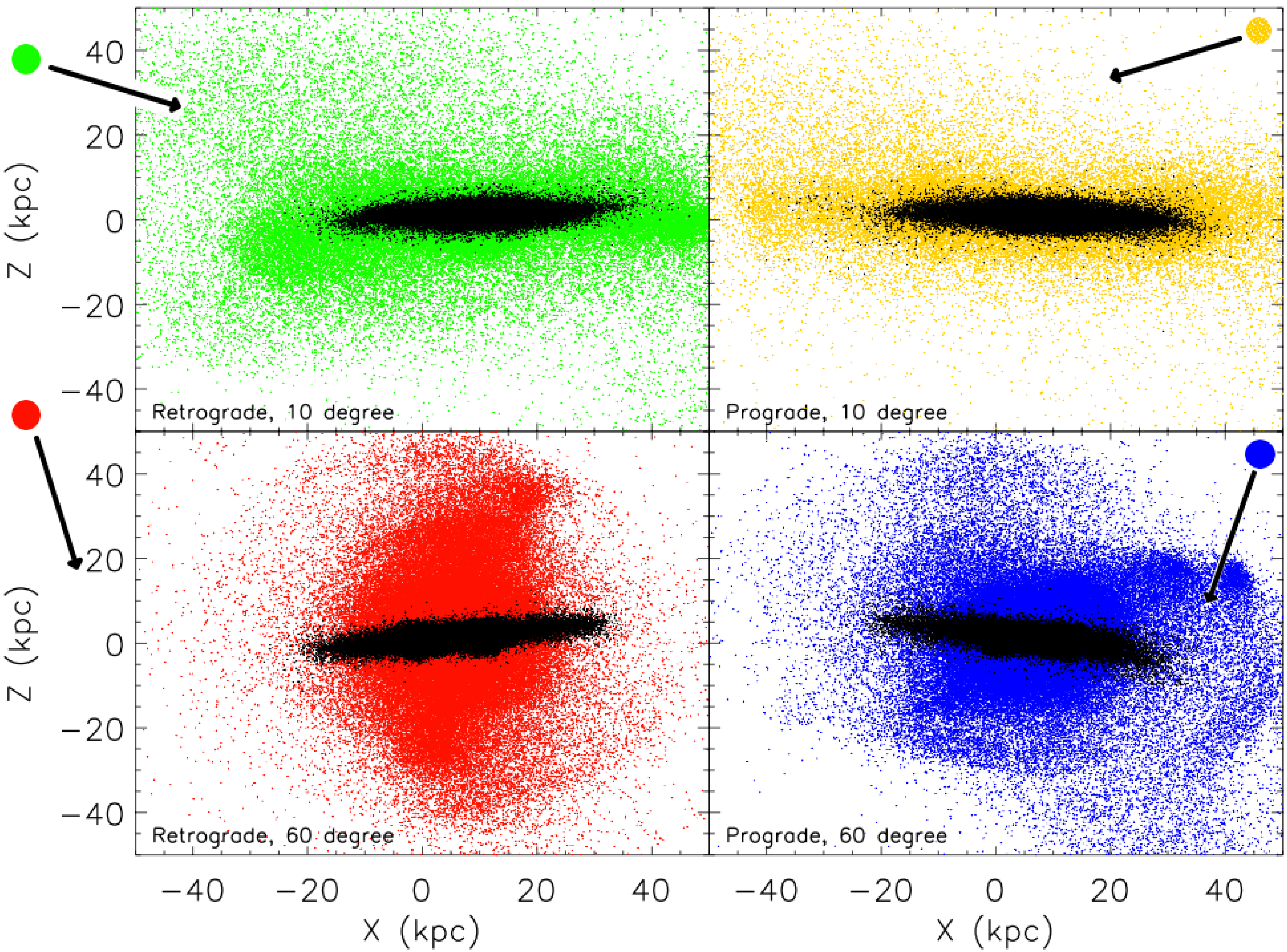
	disk	satellite
r_0 (kpc)	4	0.709
r_{disk} (kpc)	20	
M_{DM} $(M_\odot)$	10^{12}	$2.4 \cdot 10^{10}$
M_* $(M_\odot)$	$5.7 \cdot 10^{10}$	$2.4 \cdot 10^{09}$
N_{DM}	10^{06}	$1.1 \cdot 10^{05}$
N_*	10^{06}	10^{05}

$$F_d = -\frac{4\pi G^2 M_s^2 \rho_f(< v_s) \ln \Lambda}{v_s^2}$$

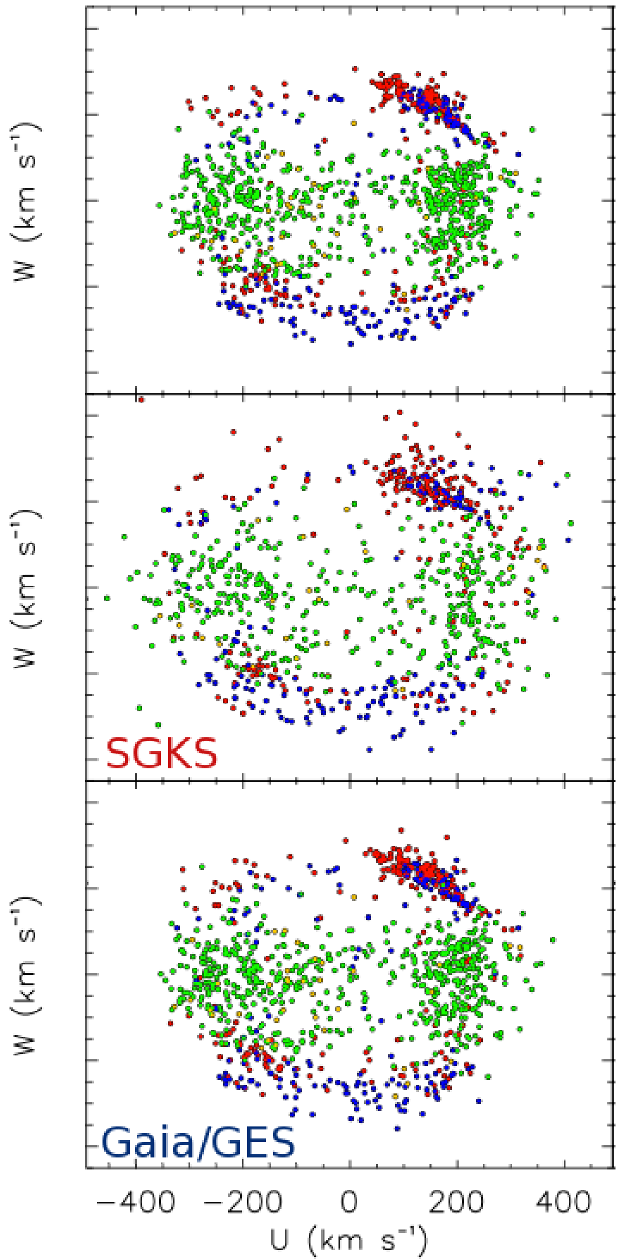
Time of simulation: $t = 4.63$ Gyrs

Any satellite is slowed down by dynamical friction exerted on it by disk and halo particles.

Final distribution.



Final distribution. Zooming at the Sun...



Simulation & Observed Simulations:

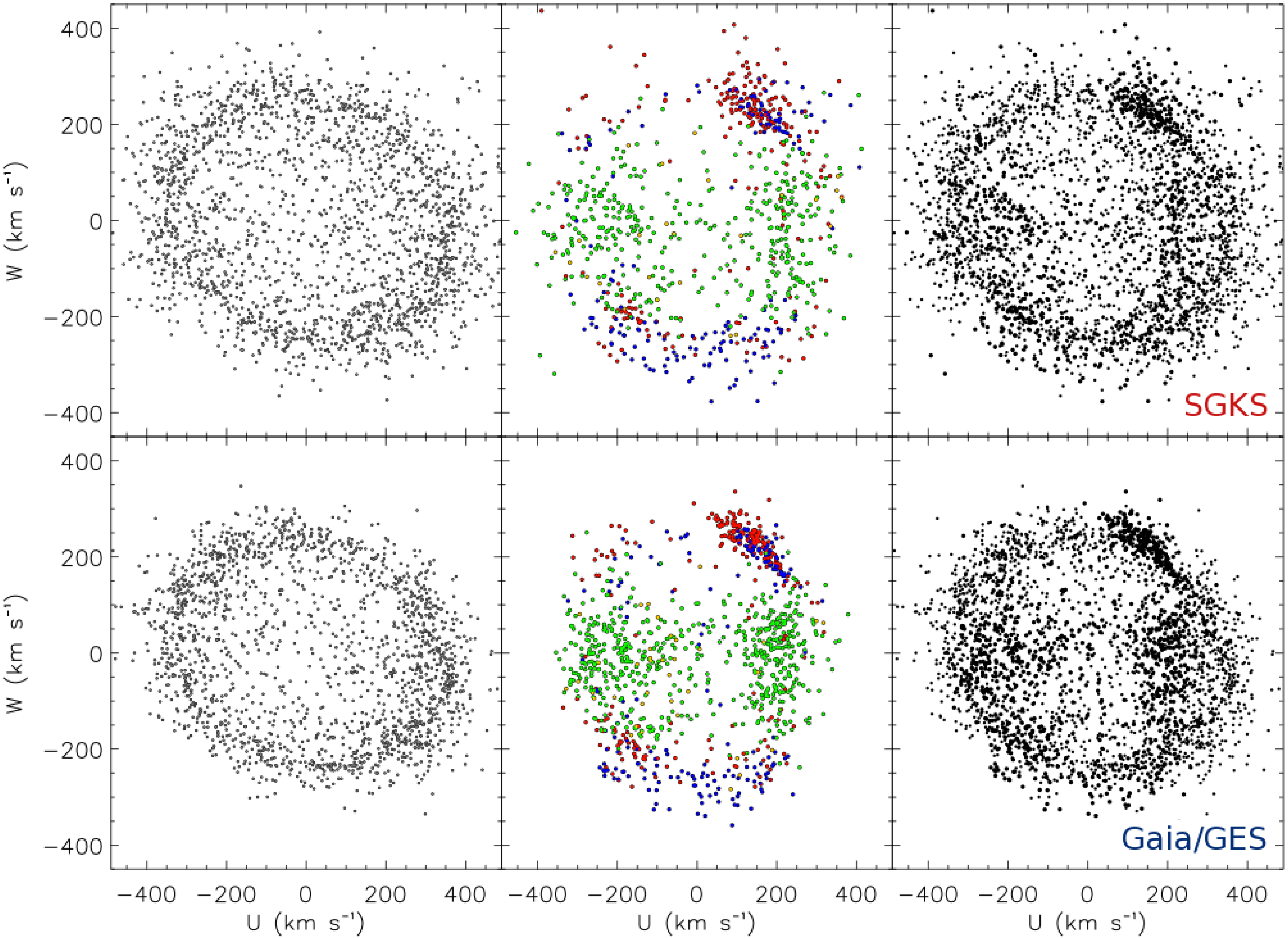
ESTIMATED/EXPECTED ERRORS FOR THE SGKS AND GAIA CATALOGUES.

Catalogue	distance	proper motion (μas yr^{-1})	radial velocity (km s^{-1})
SGKS	$\sigma_{m-M} = 0.4$ mag	2000	10
Gaia/GES	$\sigma_\pi = 20$ μas	20	1

↫ vs SDSS-GSC-II accuracy

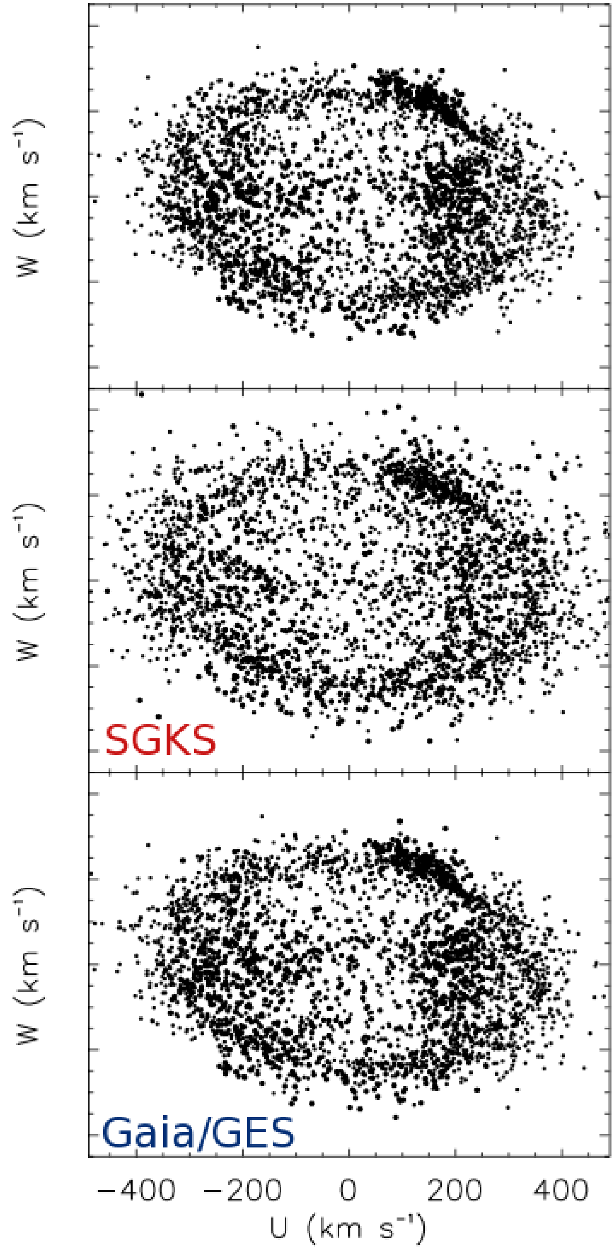
↫ vs Gaia + Gaia ESO Survey accuracy

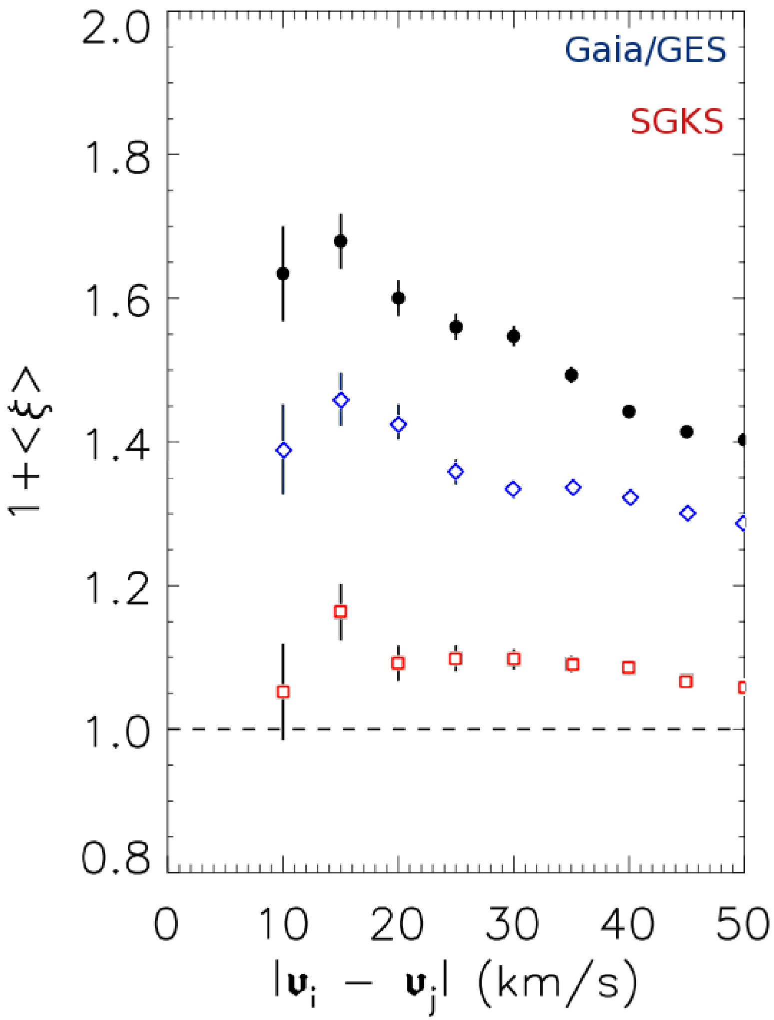
The Inner Halo Model



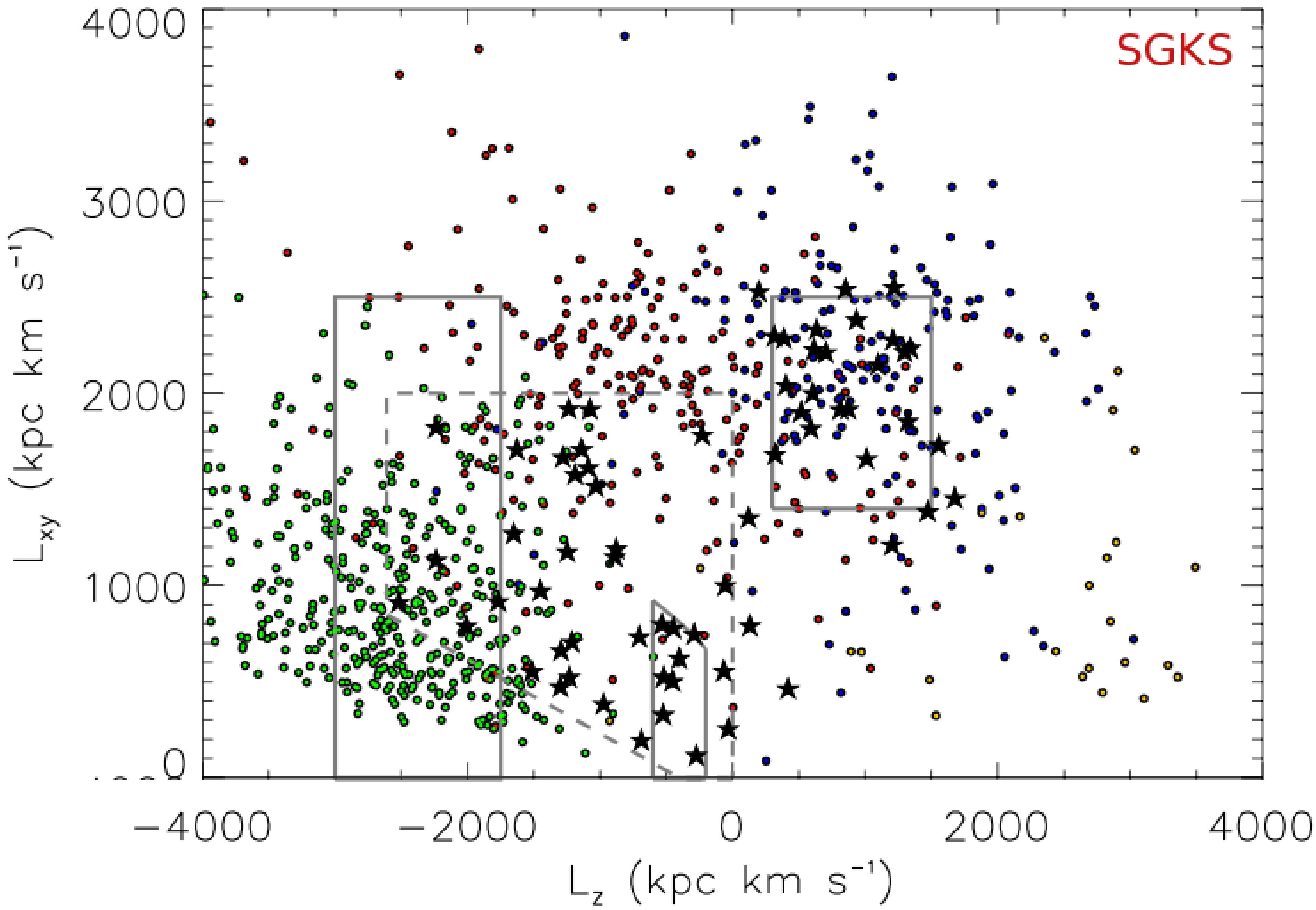
Substructures in the Correlation Function

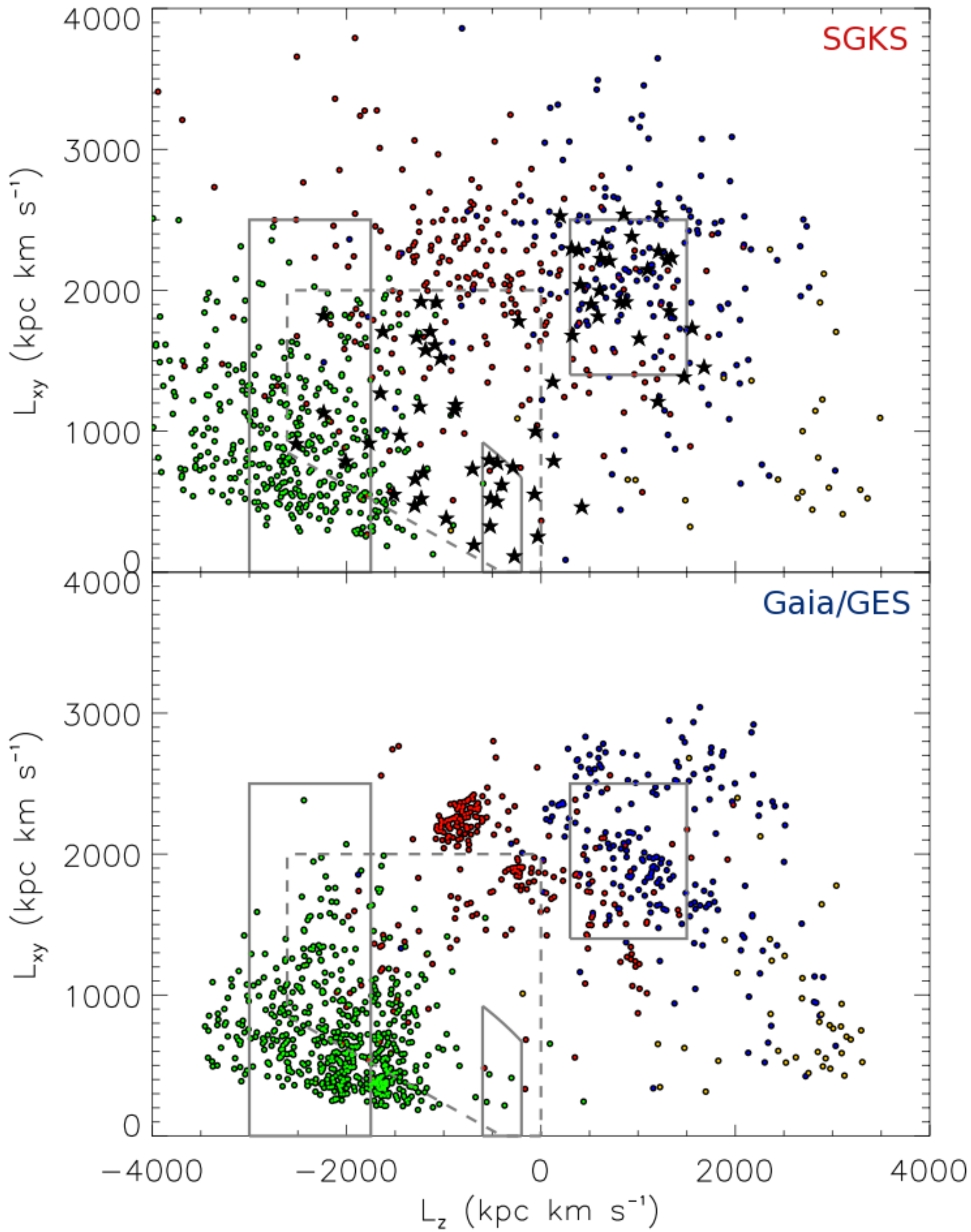
Sample: three synthetic catalogs of 2874 fastest-moving particles, i.e.





Angular Momentum...





Re Fiorentin+2015

Accurate data provided by future surveys can improve detection & characterization

Summary

Objective: Unravelling the formation of the Milky Way

- ★ In the solar neighbourhood ($d < 3$ kpc), from the SGKS, we have selected and analysed halo stars ([Fe/H] < -1.5, $|z| > 1$ kpc).

- ★ We have found statistical evidence of substructure in the space motions of the fastest moving stars, due to five moving groups that are clustered also in the angular momentum phase space. Of these five streamers torn from satellites,
  - ⇝ two appear to be associated, yelding twenty-one additional MS members, with the stream of Helmi et al. (1999) that owr analysis confirms on high inclination prograde orbit;
  - ⇝ the three newly identified kinematic groups could be associated with the retrograde streams detected by Dinescu (2002) and Kepley et al. (2007); whatever their origin, the progenitor(s) would be on retrograde orbit(s) and inclination(s) within the range $10^\circ \div 60^\circ$.

- ★ We have compared this result to high resolution N-body numerical simulations of (four) minor merger of orbiting satellites.
  - ⇝ In the velocity distribution and the angular momentum phase space of the local halo, satellites do appear very coherent.
  - ⇝ Among the subsample of the fastest objects, the regions of high inclination / low inclination retrograde orbits are populated consistently to observed data, according the mechanism of dynamical friction and indicating its important role in the accretion events.
  - ⇝ Convolving true/simulated data with different error distributions according to the accuracy of SGKS and the accuracy predicted for Gaia/GES these findings are confirmed.

- ★ Space astrometric missions, such as Gaia/GES, will collect samples of millions of stars with very accurate positions and kinematics which will dramatically improve the reliability of such conclusions.