Kinematic imprints from the bar and spiral structure in the galactic disk

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Moving Groups

Stellar streams with no spatial concentration

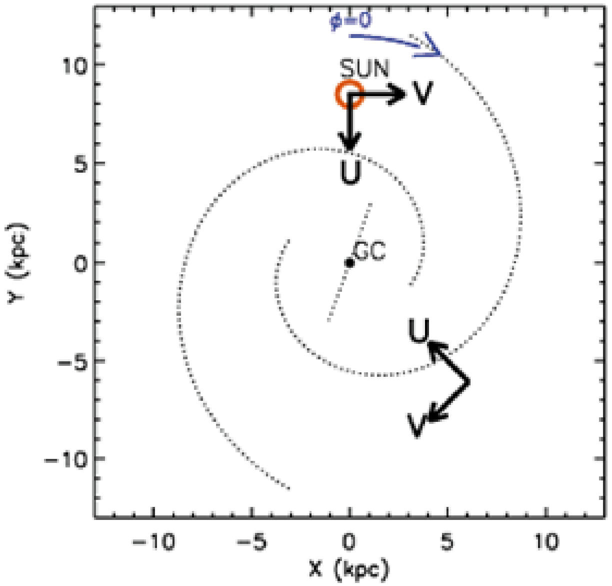
Madler (1846)
Proctor (1869)
→ Eggen (1958 -1996)
→ Hipparcos 1997-
→ Gaia 2015 -

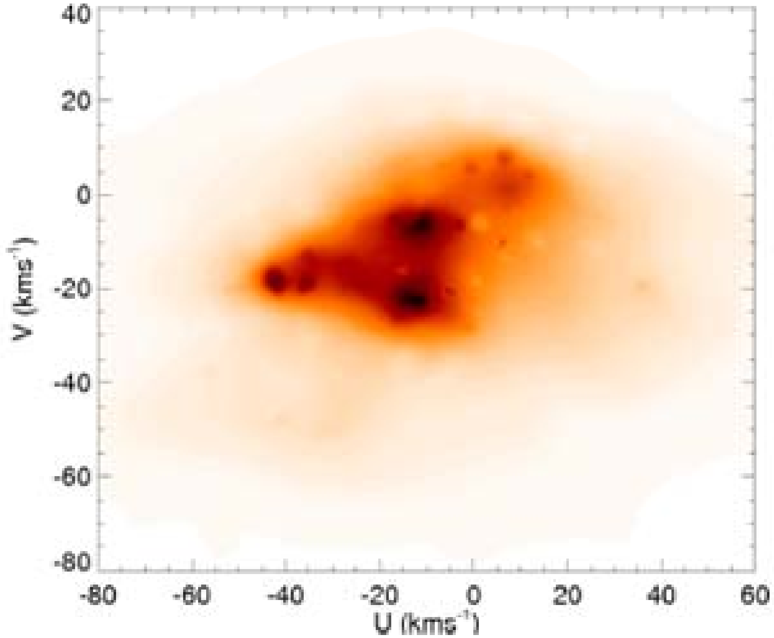
At 140 years of their discovery, these stellar streams are emerging as powerful tools to constrain the models for the spiral arms and the galactic bar in the Gaia era.

Moving Groups

- What we observe
- Origin and evolution: several scenarios
- MG induced by MW spiral arms
- Future Gaia capabilities

MG solar neighbourhood: substructure in the UV space

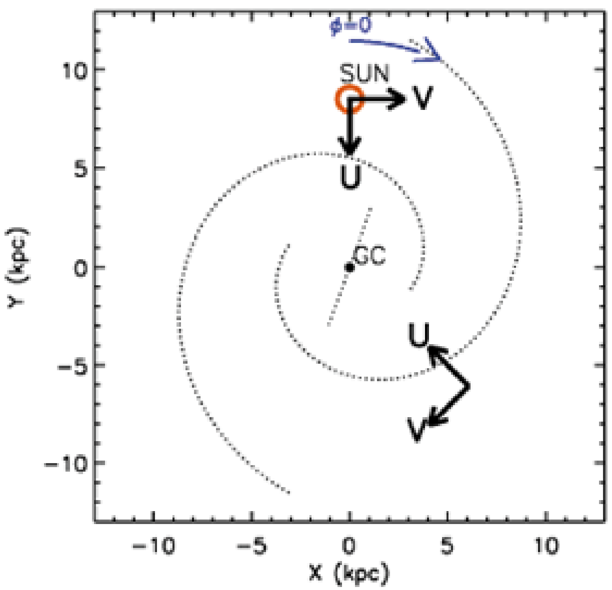


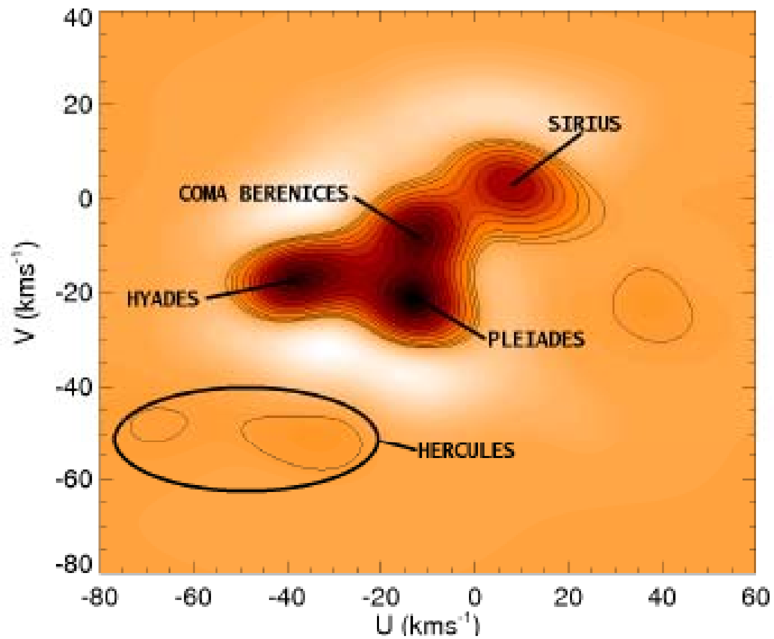


- FGK (Nordström et al. 2004); OB (Asiain et al. 1999a); A (Torra et al. 2000); M (Reid et al. 2002); M (Bochanski et al. 2005); KM giants (Famaey et al. 2005)
- $\sim 200\,\mathrm{pc}$
- 24190 *

Antoja et al. 2008

MG solar neighbourhood: substructure in the UV space





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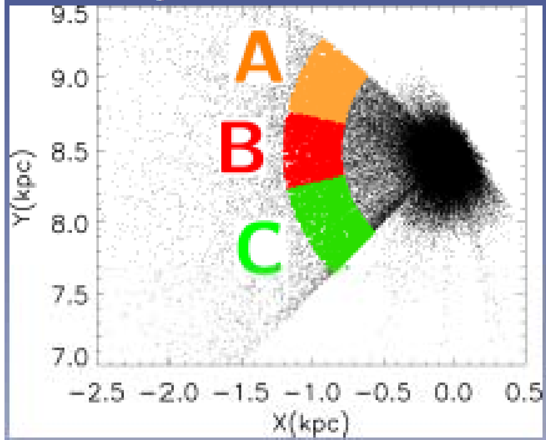
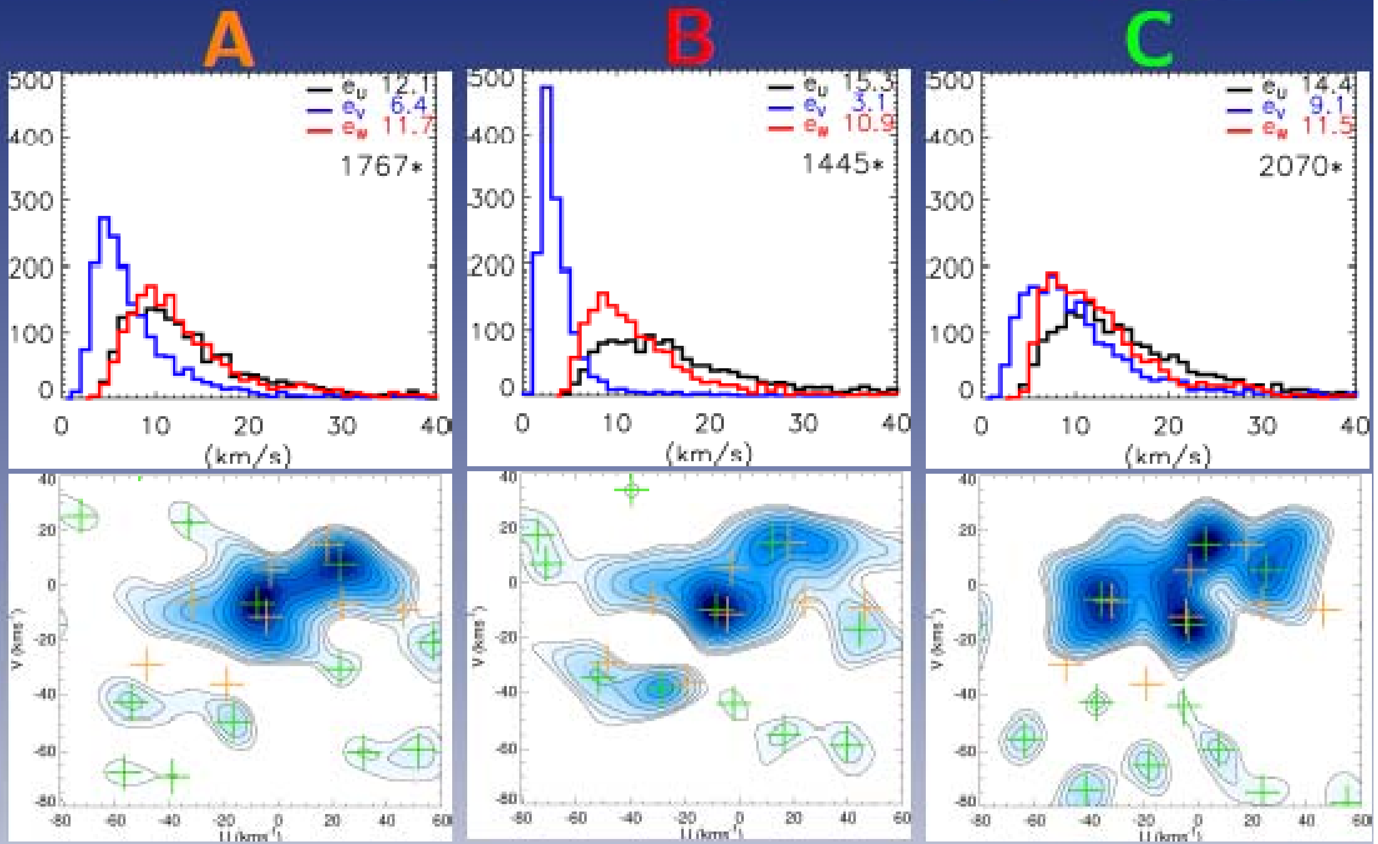
Antoja et al. 2008

Leaving the solar neighbourhood

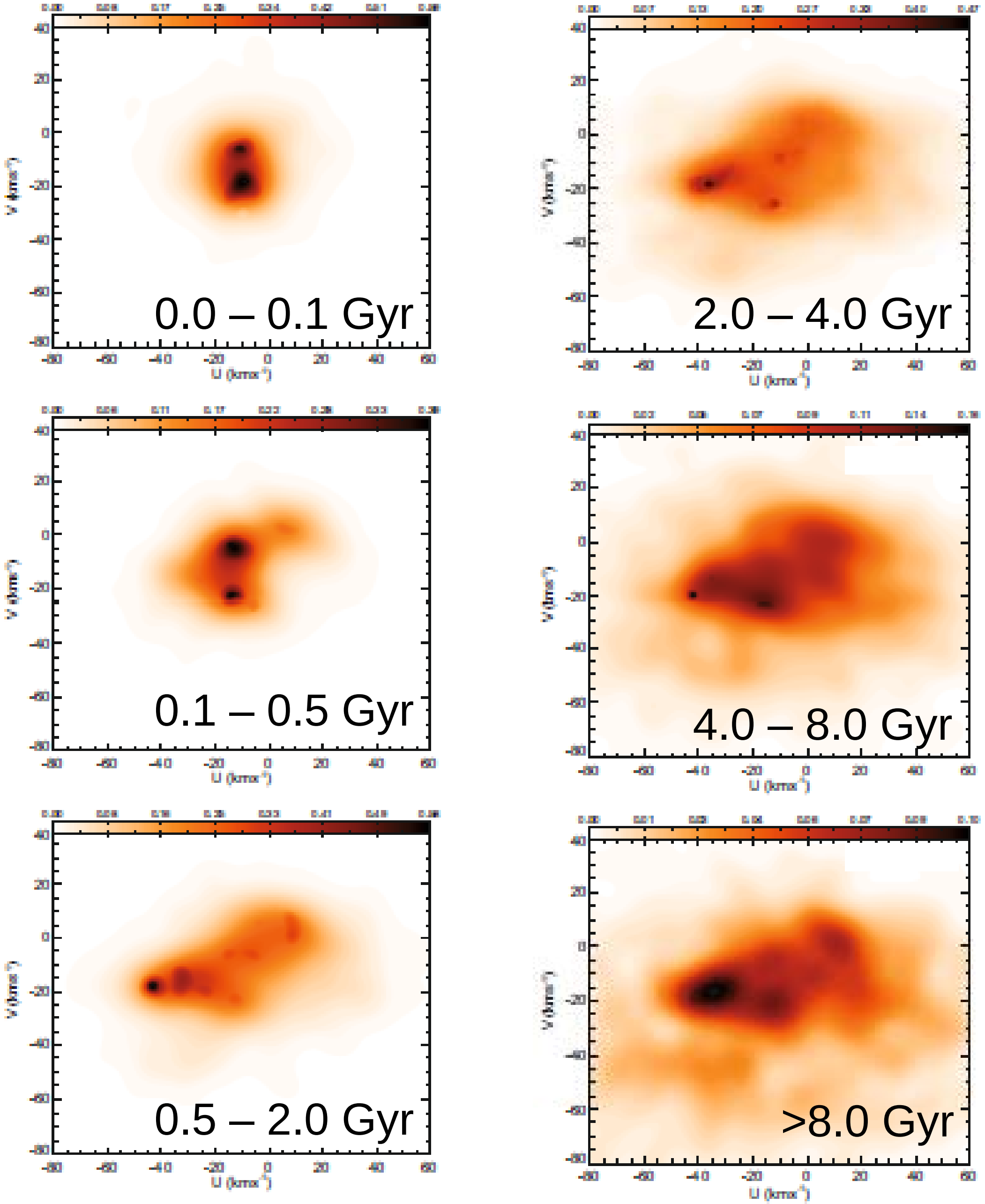
Antoja et al., 2011

d ∼ 1kpc





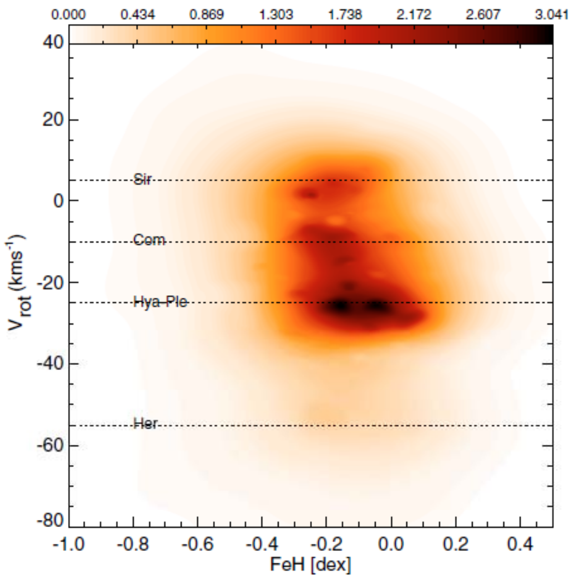
- Some of the main groups still present @1kpc: large scale features
- Hyades-Pleiades & Sirius dominant
- Also Hercules and group at $U \sim 40\,\mathrm{km\,s^{-1}}$!
- More changes when we move in galactocentric radius than in azimuth



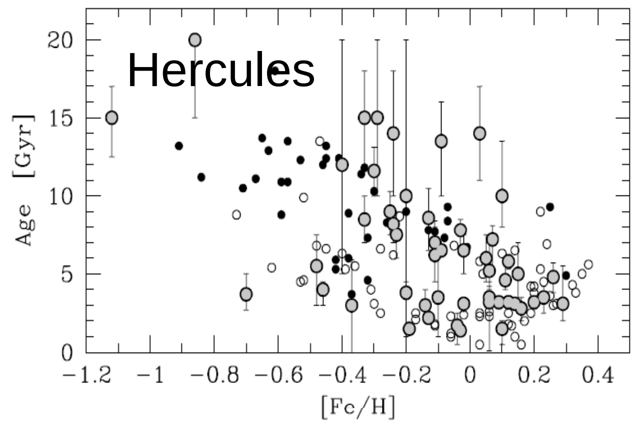
An extended age distribution for moving groups is confirmed

The Bayesian estimation method in Jørgensen & Lindegren (2005) was used for age computation.

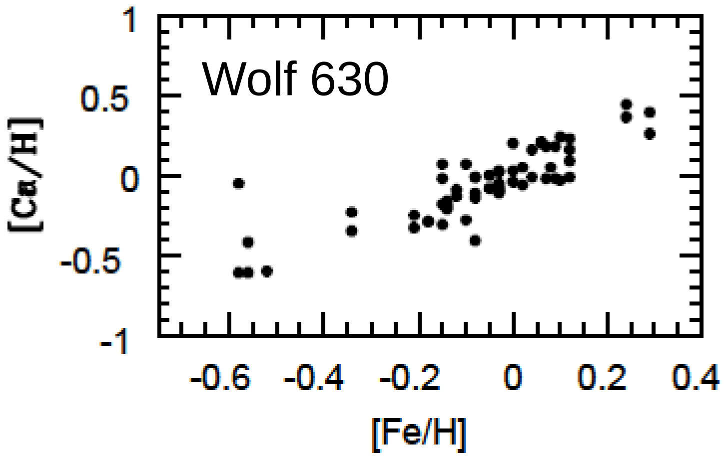
Most groups are chemically inhomogeneous



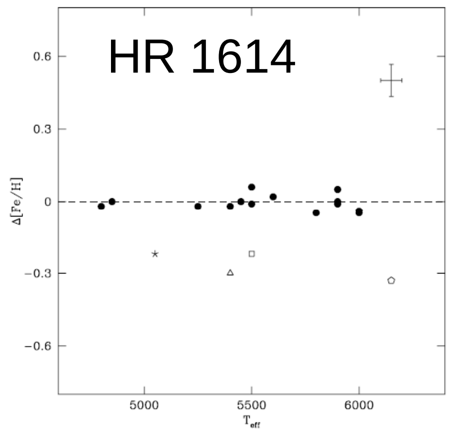
Antoja et al. 2008



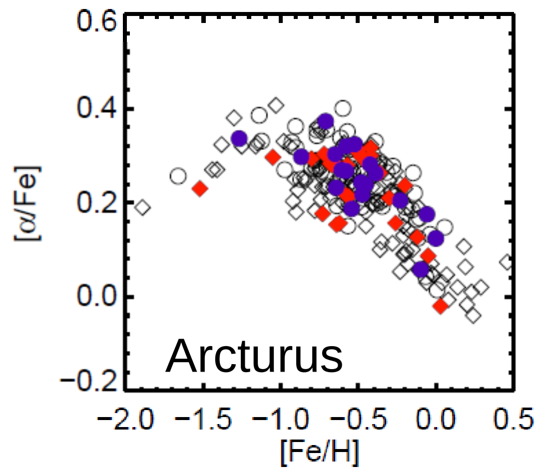
Bensby et al. (2007)



Bubar & King (2010)



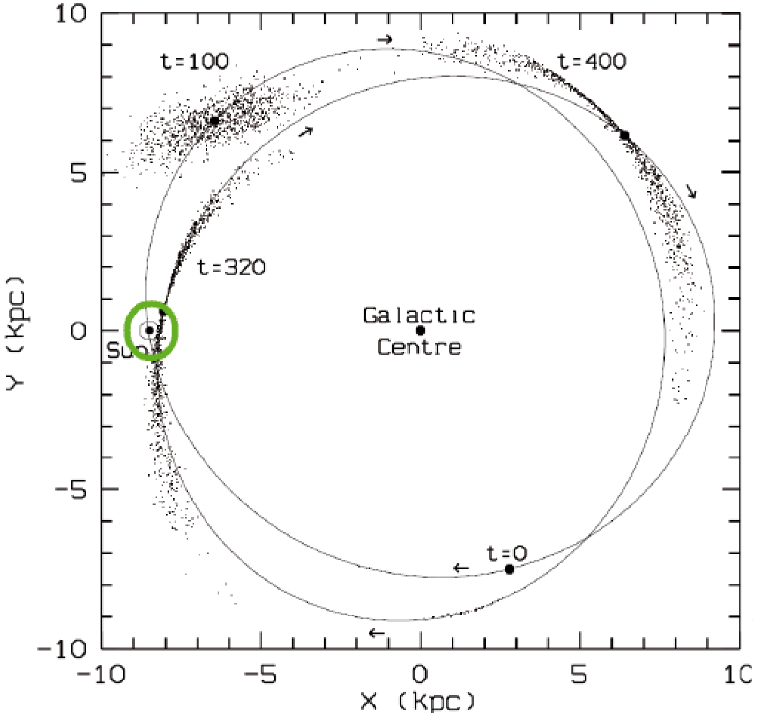
Da Silva et al. (2007)



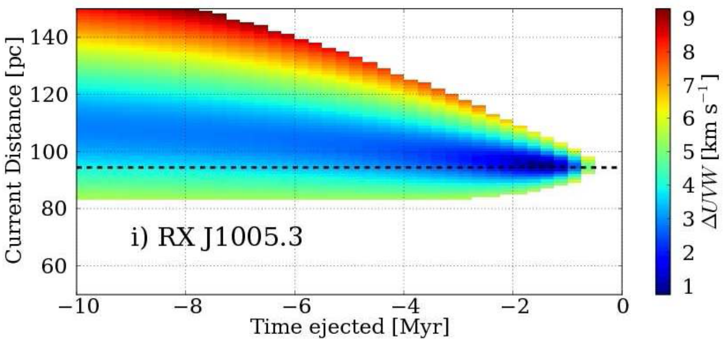
Williams (2009)

Origin of the moving groups

- **Disruption of a stellar cluster**
- Orbital and resonant effects of the MW spiral arms and bar
- Tidal debris of past accretion events
- External dynamical effects on the disc resulting from interaction events



Eggen (1996b), Asiain et al. (1999b), Feltzing & Holmberg (2000), De Silva et al. (2007), Block et al. (2009)



Murphy et al. 2010:

η Chamaeleontis (t~8 Myr,) Members at ϕ=5º, consistent with a dynamical origin for the current configuration of the cluster, without the need to invoke an abnormal Initial Mass Function deficient in low-mass objects

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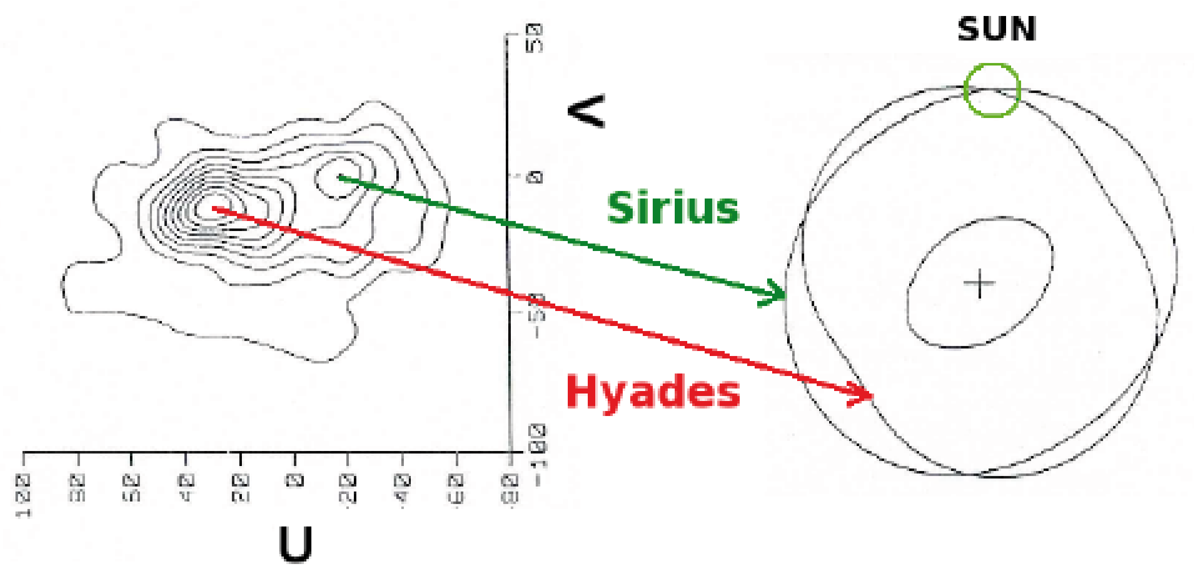

Kalnajs (1991), Dehnen (2000), Fux (2001), De Simone et al. (2004), Quillen & Minchev (2005), Chakrabarty (2007)

Kalnajs (1991): Sun near the outer parts of the bar OLR . Hyades associated to the inner orbits (⊥ bar), Sirius related to the external orbits (|| bar).

(Pioneer work by Major (1970): He interpreted the deviation of the vertex of the velocity distribution and the streams in terms of the perturbation by the spiral density wave)

Origin of the moving groups

- Disruption of a stellar cluster
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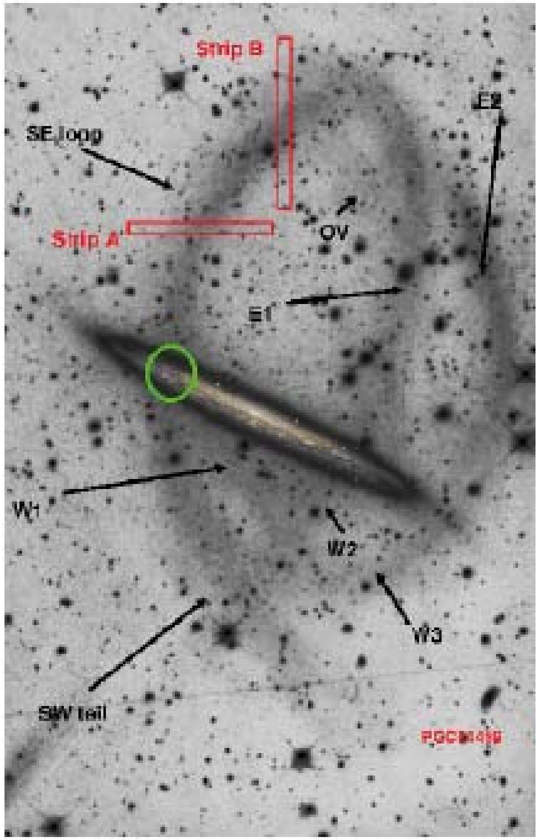
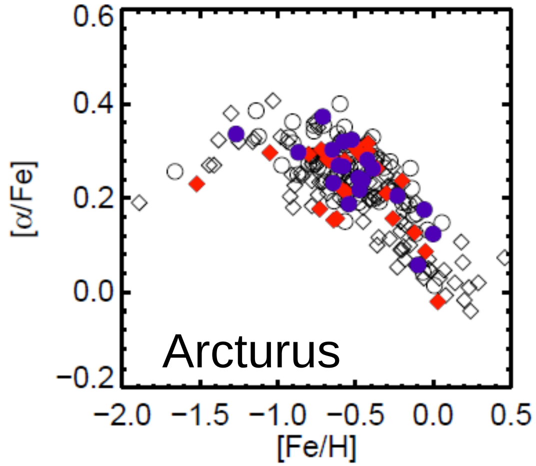


Navarro et al. (2004)

Arcturus



Williams (2009)

Origin of the moving groups

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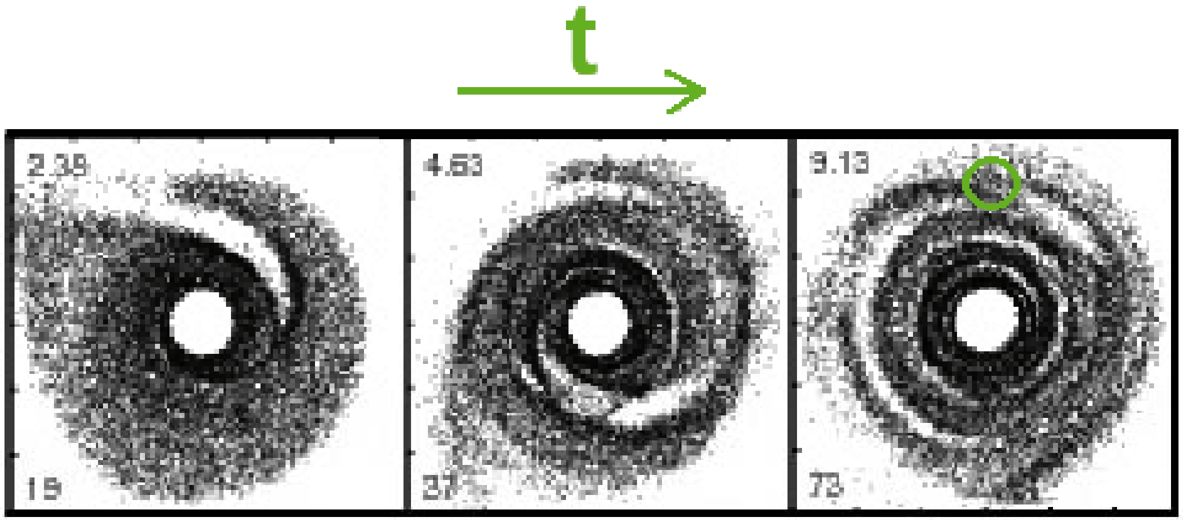


Quillen et al. (2009)

Quillen et al. (2009), Minchev et al. (2009)

Arcturus, HR1614

The velocity distribution in an unrelaxed disc due to, for instance, a recent merger, exhibits waves that travel in the direction of V, associated to observed moving groups of the low L.

Which are the kinematic signatures expected in the solar neighbourhood from the MW spiral arms ?

Which are the conditions that favoured the appearance of the kinematic groups?

Antoja, Figueras, Romero-Gómez et al., 2011, MNRAS (in press)

Two models for the spiral arms (tuned to the observables in the MW):

- Tight-Winding Approximation (TWA) model
- PERLAS, a model with 3D self-consistent material arms , a mass distribution with more abrupt gravitational forces.

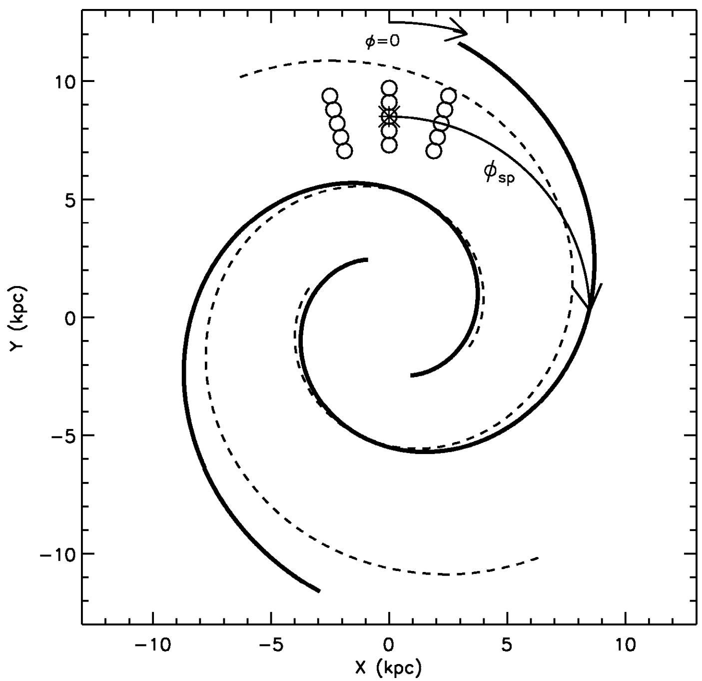
Test particle simulations:

Axisymmetric part (bulge, flattened disc, massive spherical halo) + arms
IC (cold disk) + Particle exposure time to the potential [0, 2] Gyr, random (equivalent to a superposition of stars of different ages)

Property		Value or range
Pitch angle	i (°)	15.5/12.8
Relative spiral phase	$\phi_{sp}(R_\odot)$ (°)	88/60
Pattern speed	Ω_{sp} $(\mathrm{km\,s^{-1}kpc^{-1}})$	15–30
Density contrast	K	1.32–1.6

$K = (\sigma_0 + \delta\sigma)/(\sigma_0 - \delta\sigma)$, where σ_0 is the axisymmetric surface density and = $\delta\sigma$ is the enhancement of density on the spiral arm.

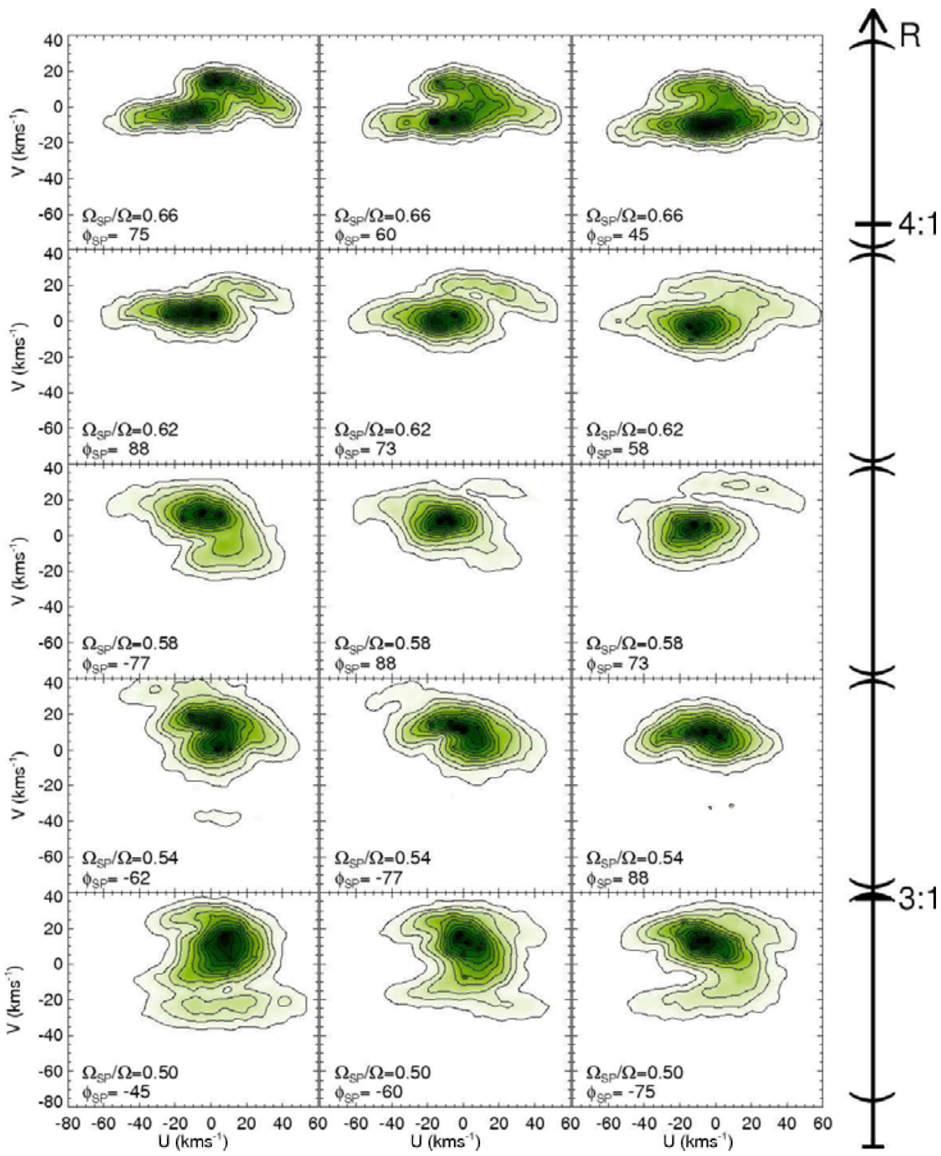
Spiral arms: PERLAS model



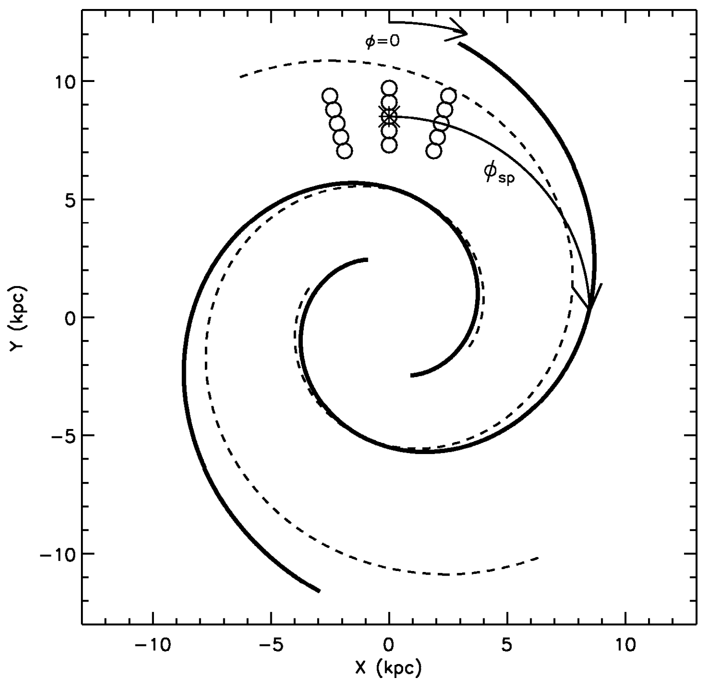
The velocity distribution is:

mostly sensitive to the pattern speed

less sensitive to the relative spiral phase (~2 kpc in azimut are needed)



Ω_p = 15 km/s/kpc



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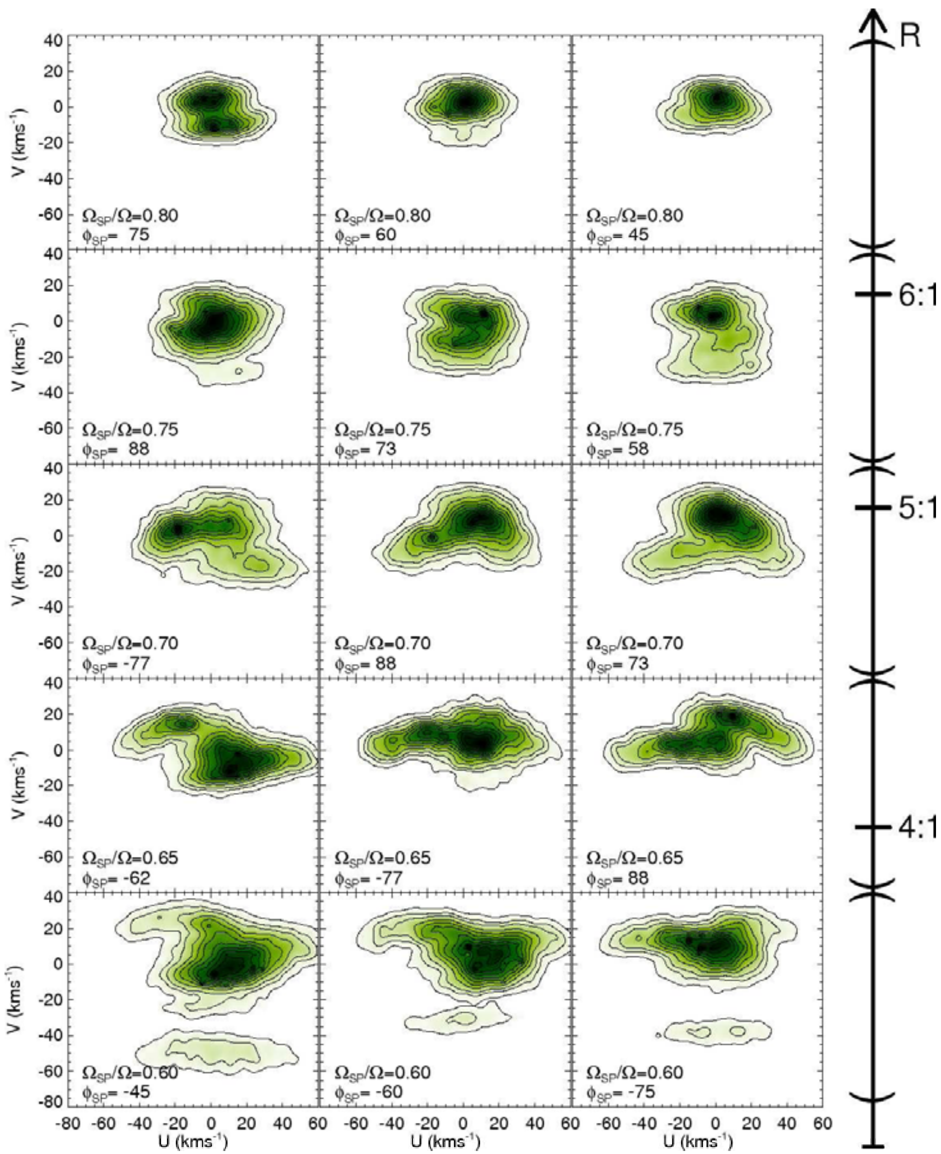
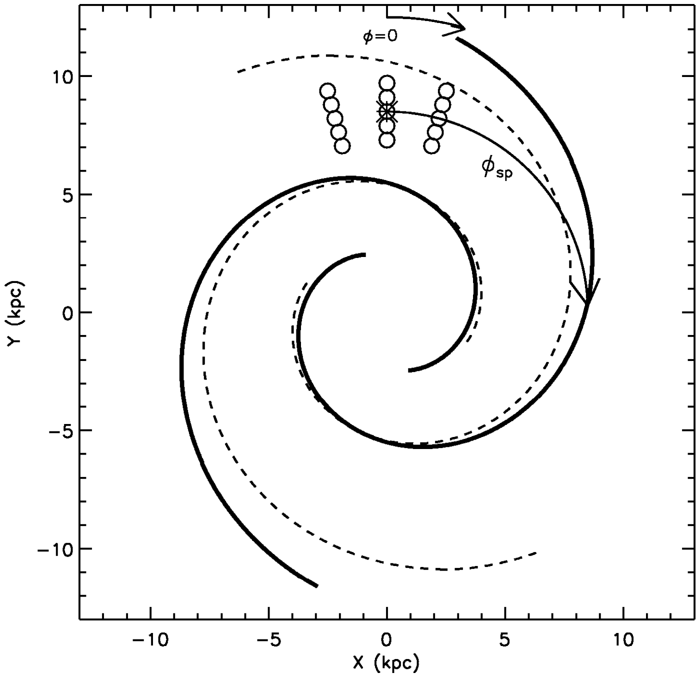
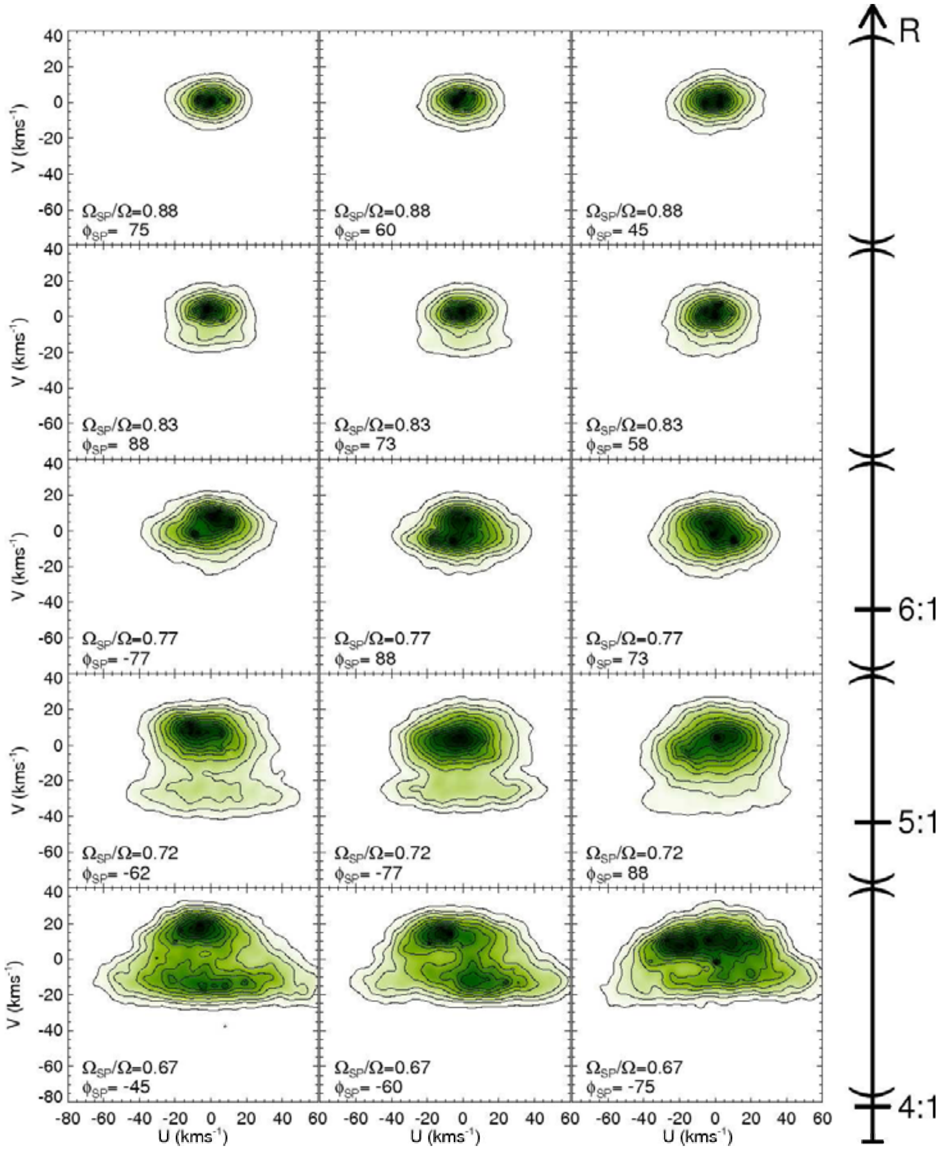
Spiral arms: PERLAS model



Ω_p **= 18 km/s/kpc**

Spiral arms: PERLAS model





The velocity distribution is:

mostly sensitive to the pattern speed

less sensitive to the relative spiral phase (~2 kpc in azimut are needed)

Ω_p = 20 km/s/kpc

In all cases the arms induce strong kinematic imprints in the solar neighborhood for pattern speeds Ω_p ~ [13,19] km/s/kpc (close to the 4:1 inner resonance)

Ωp = [13,19]

- Rich substructure similar to observed

→

Ωp = [20,22]

- Minor groups or only small deformation of a unique clump

→

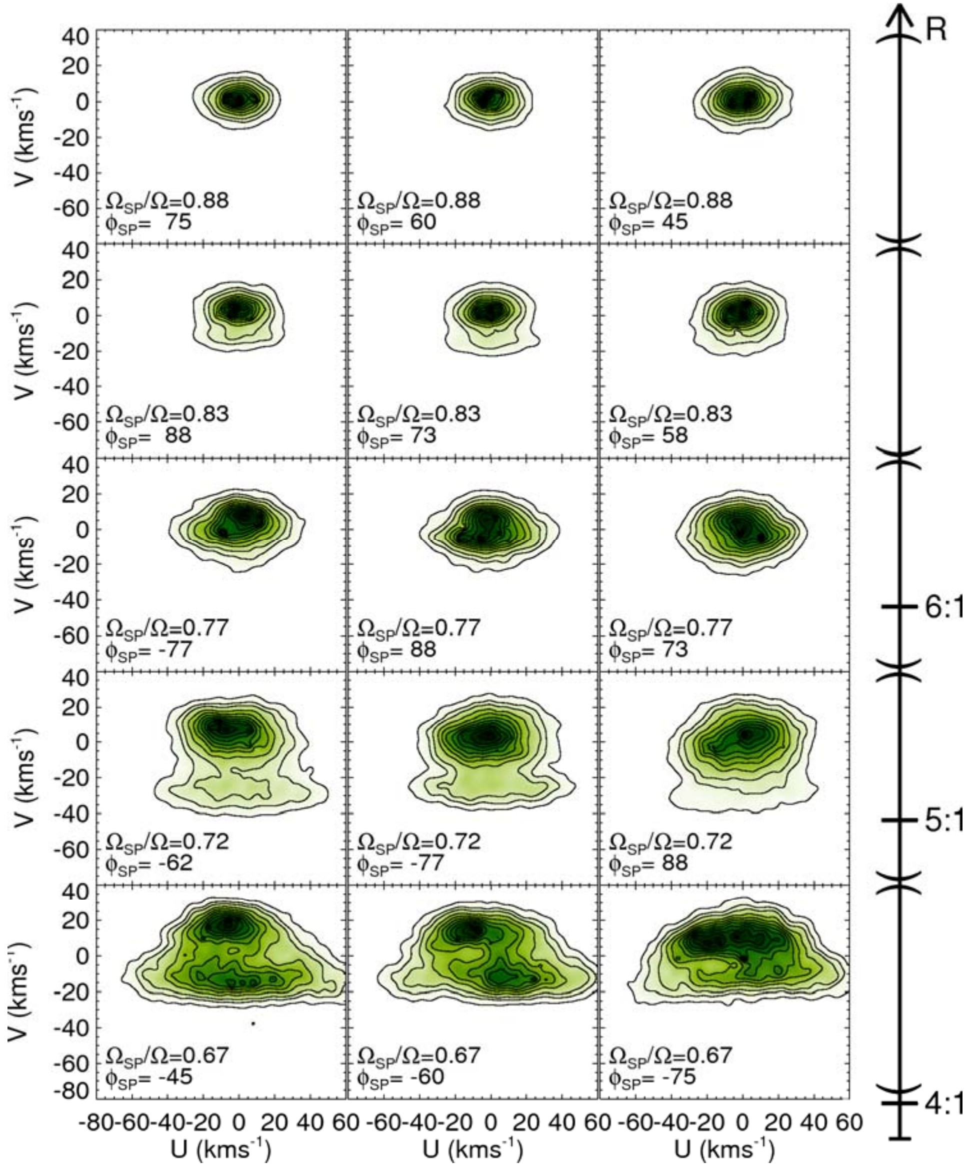
Ωp = [23,30]

- No substructure at all

No substructure is induced close to corotation or higher order resonances (m>6) which, in the solar neighborhood, corresponds to pattern speeds of 20-30 km/s/kpc

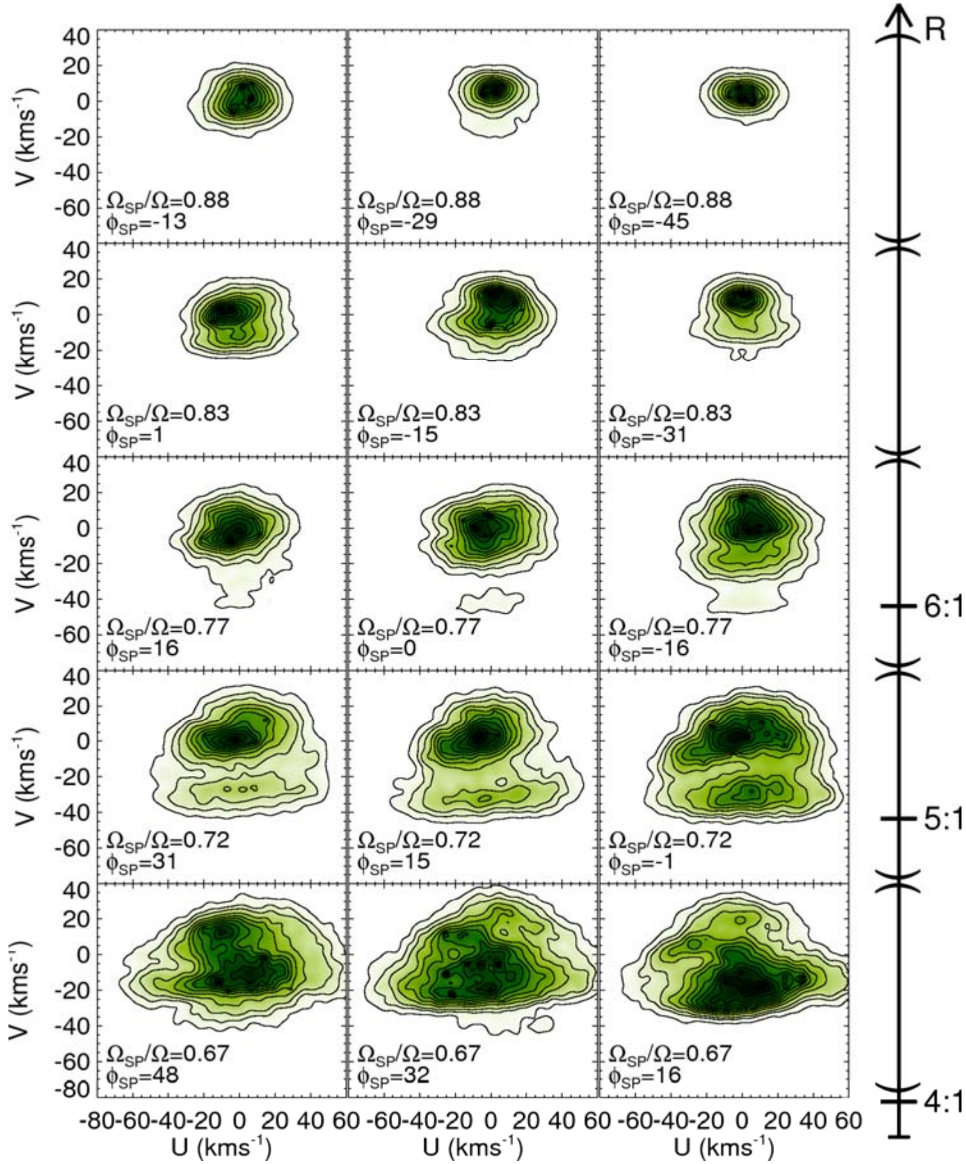
Solar Neighbourhood

Stronger effects near the arms



Near the arm

Stronger effects near the arms

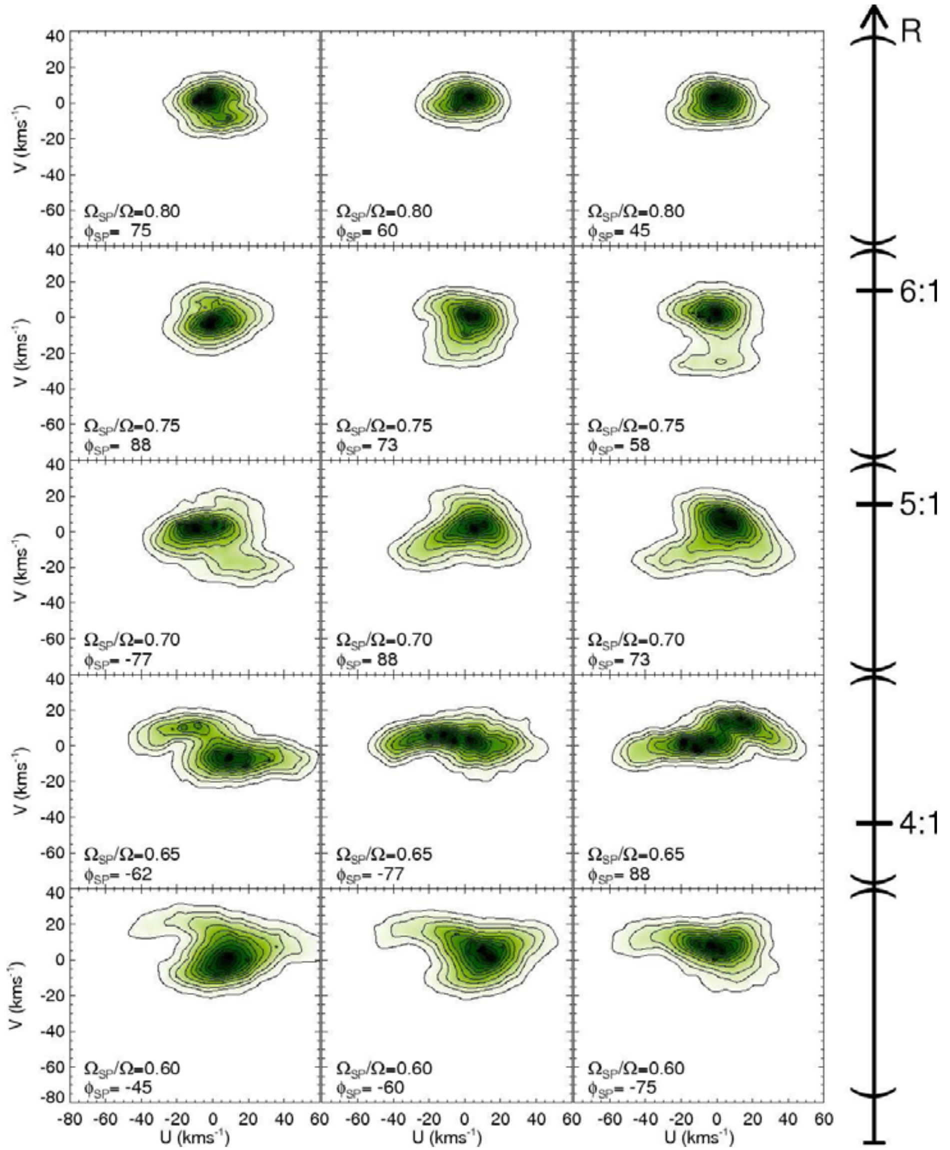


Small density contrast (K=1.16)

Changes in the spiral strength produce no significant differences in most cases

Higher density contrast increase the dispersion but maintain the geometry of the kinematic substructure

Spiral strength: a parameter difficult to constrain from MG



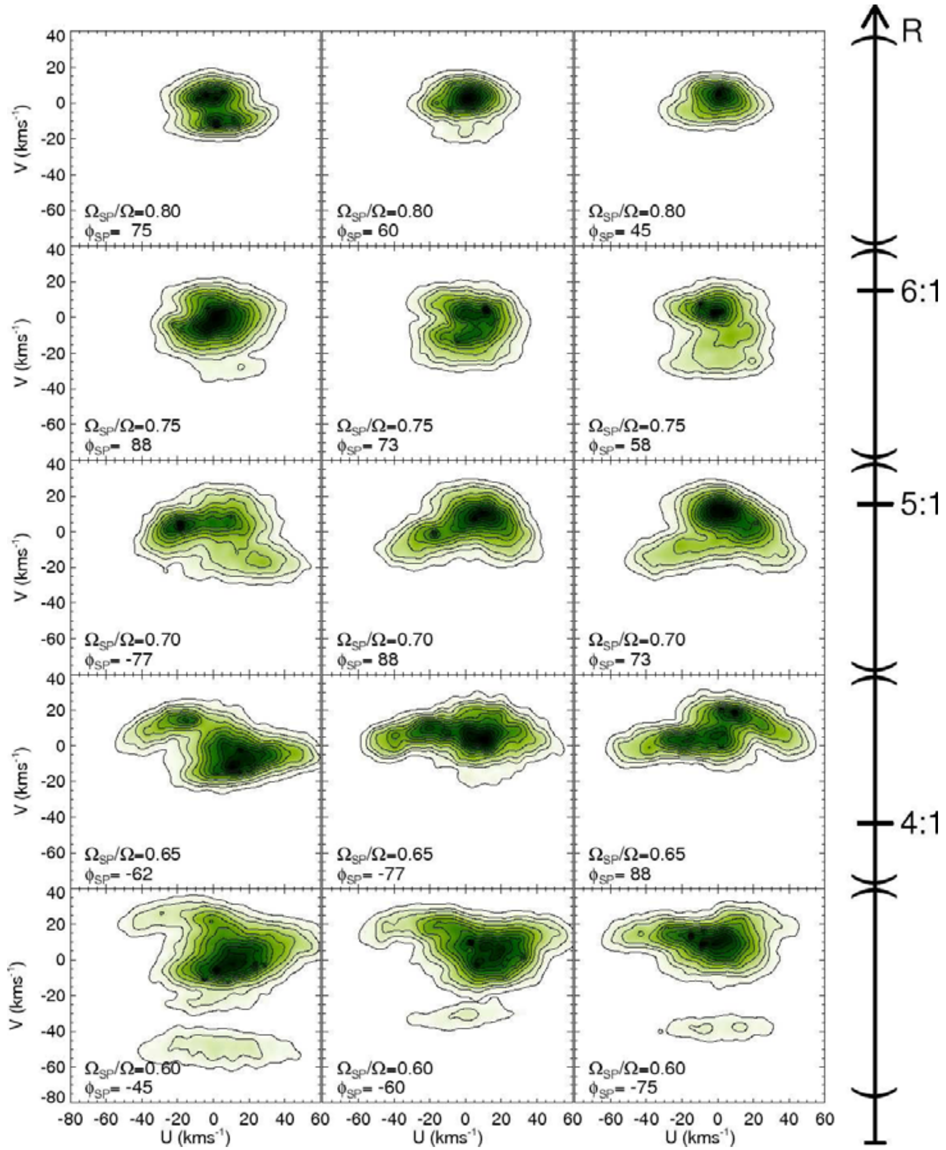
K = $(\sigma_0 + \delta\sigma)/(\sigma_0 - \delta\sigma)$, where σ_0 is the axisymmetric surface density and = $\delta\sigma$) is the enhancement of density on the spiral arm.

High density contrast (K=1.32)

Changes in the spiral strength produce no significant differences in most cases

Higher density contrast increase the dispersion but maintain the geometry of the kinematic substructure

Spiral strength: a parameter difficult to constrain



$K = (\sigma_0 + \delta\sigma)/(\sigma_0 - \delta\sigma)$, where σ_0 is the axisymmetric surface density and = $\delta\sigma$) is the enhancement of density on the spiral arm.

Can we find evidences of the spiral lifetime in the velocity distribution?

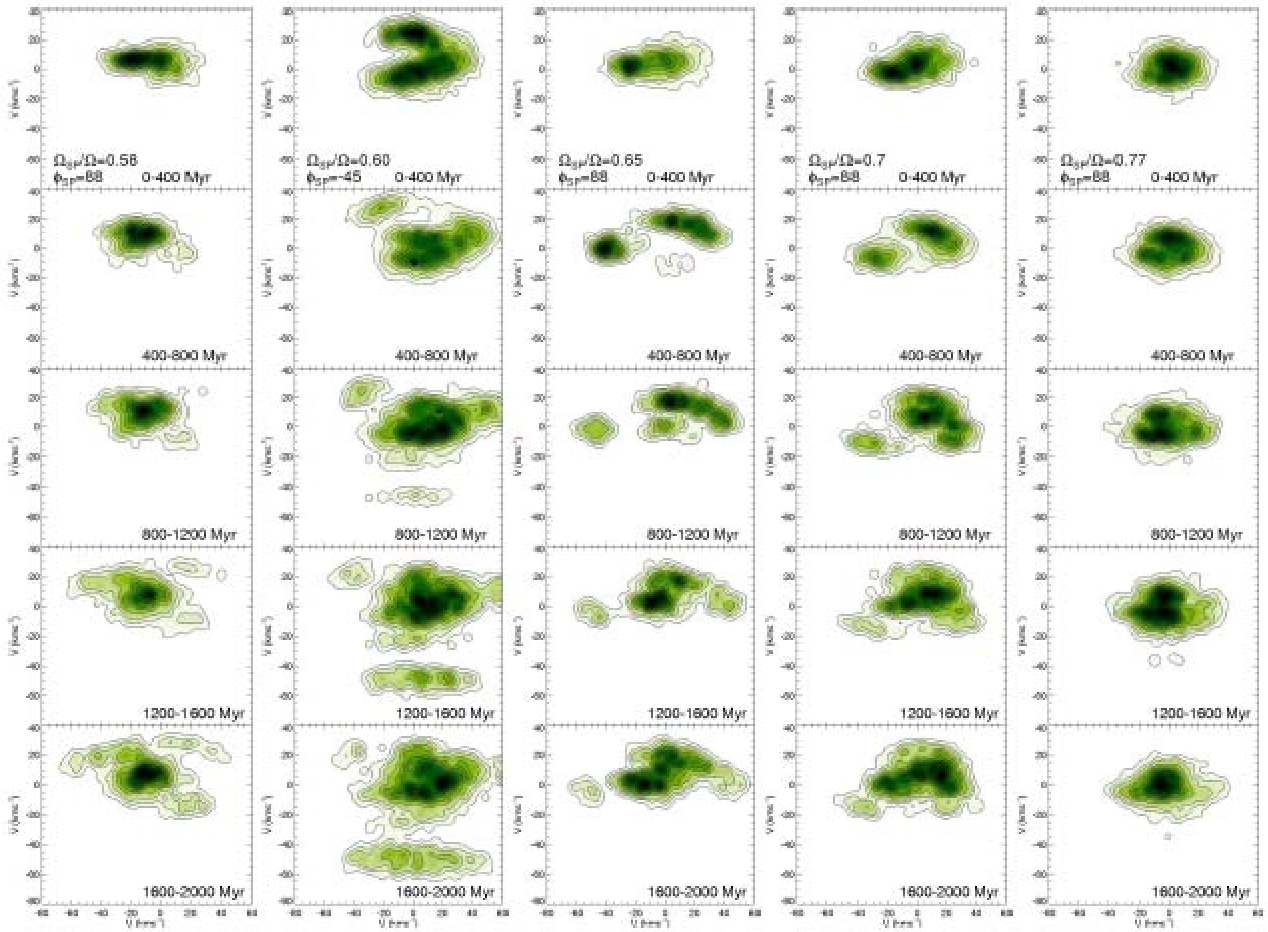
0 – 400 Myr

400 – 800 Myr

800 – 1200 Myr

1200 – 1600 Myr

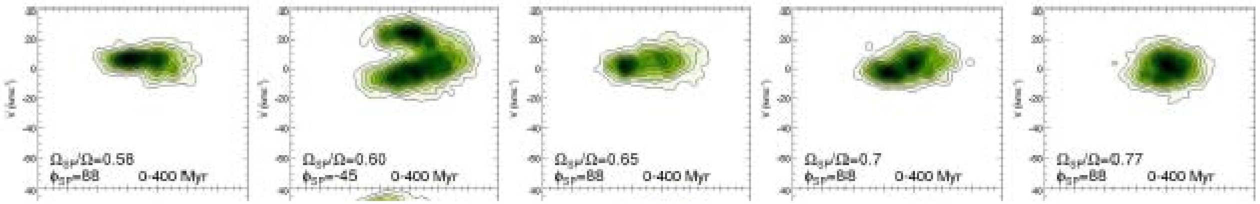
1600 – 2000 Myr



Particle exposure time to the potential

Can we find evidences of the spiral lifetime in the velocity distribution?

0 – 400 Myr



Recent spiral arms (< 400 Myr) can produce strong kinematic structures

Can we find evidences of the spiral lifetime in the velocity distribution?

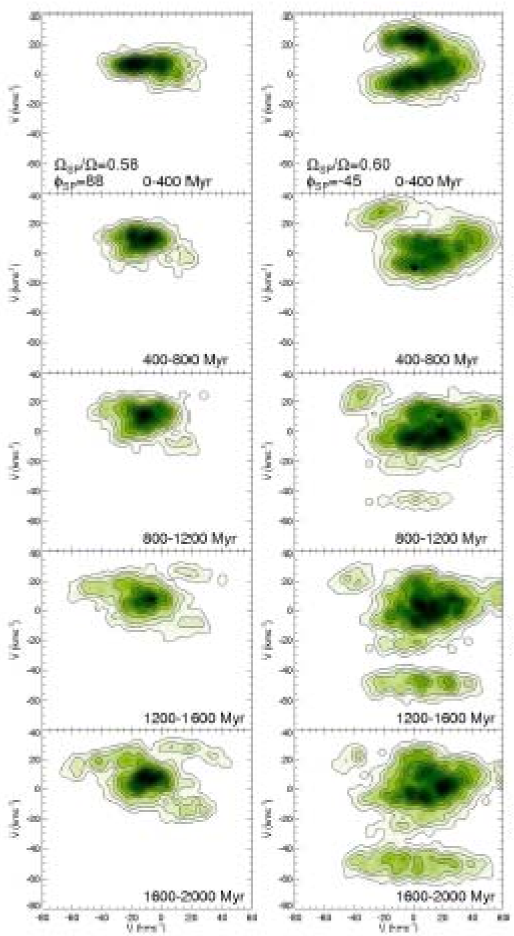
0 – 400 Myr

400 – 800 Myr

800 – 1200 Myr

1200 – 1600 Myr

1600 – 2000 Myr



Structures at low V require more integration time, i.e., a larger spiral lifetime

(more eccentric orbits and larger radial excursions, more time to reach the region)

Can we find evidences of the spiral lifetime in the velocity distribution?

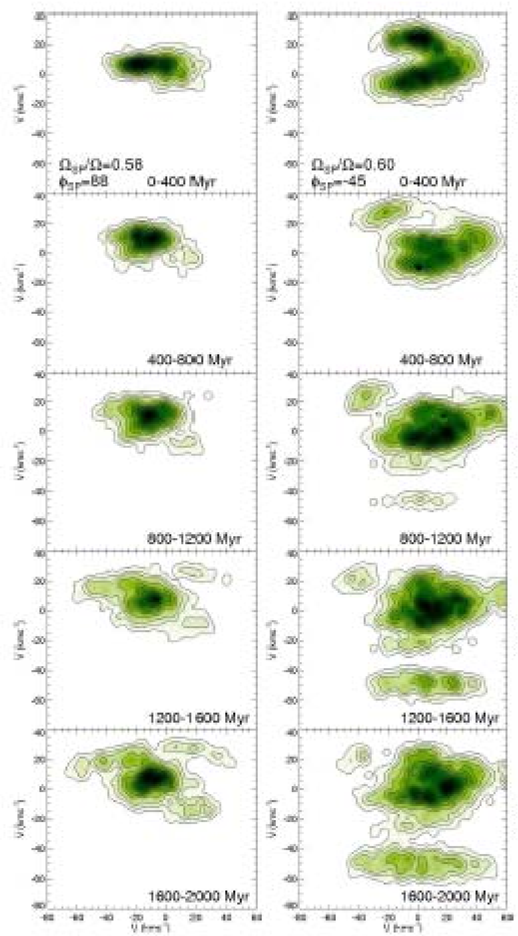
0 – 400 Myr

400 – 800 Myr

800 – 1200 Myr

1200 – 1600 Myr

1600 – 2000 Myr



The time of appearance is different for each group, ranging from 0 – 1200 Myr

After 1200 Myr, the UV plane becomes stationary

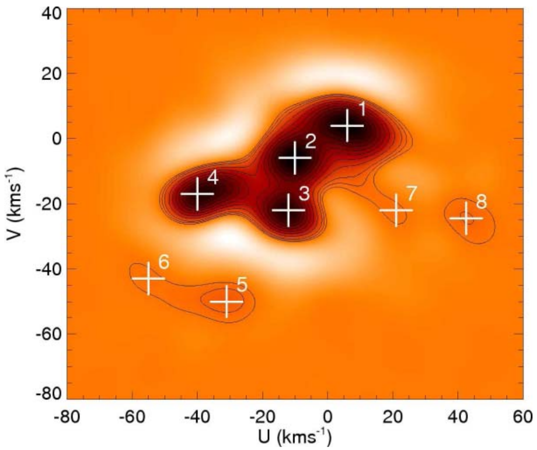
First conclusion

Yes, MW Spiral Arms - in the range of observed spiral arms parameters - favours the triggering of kinematics groups such us the ones observed in the solar neighbourhood

Both, PERLAS and TWA models induce several and rich kinematic substructure near the solar position (in PERLAS, more abrupt force features thus more kinematic substructure)

But, can we at present constrain the spiral arms from MGs?

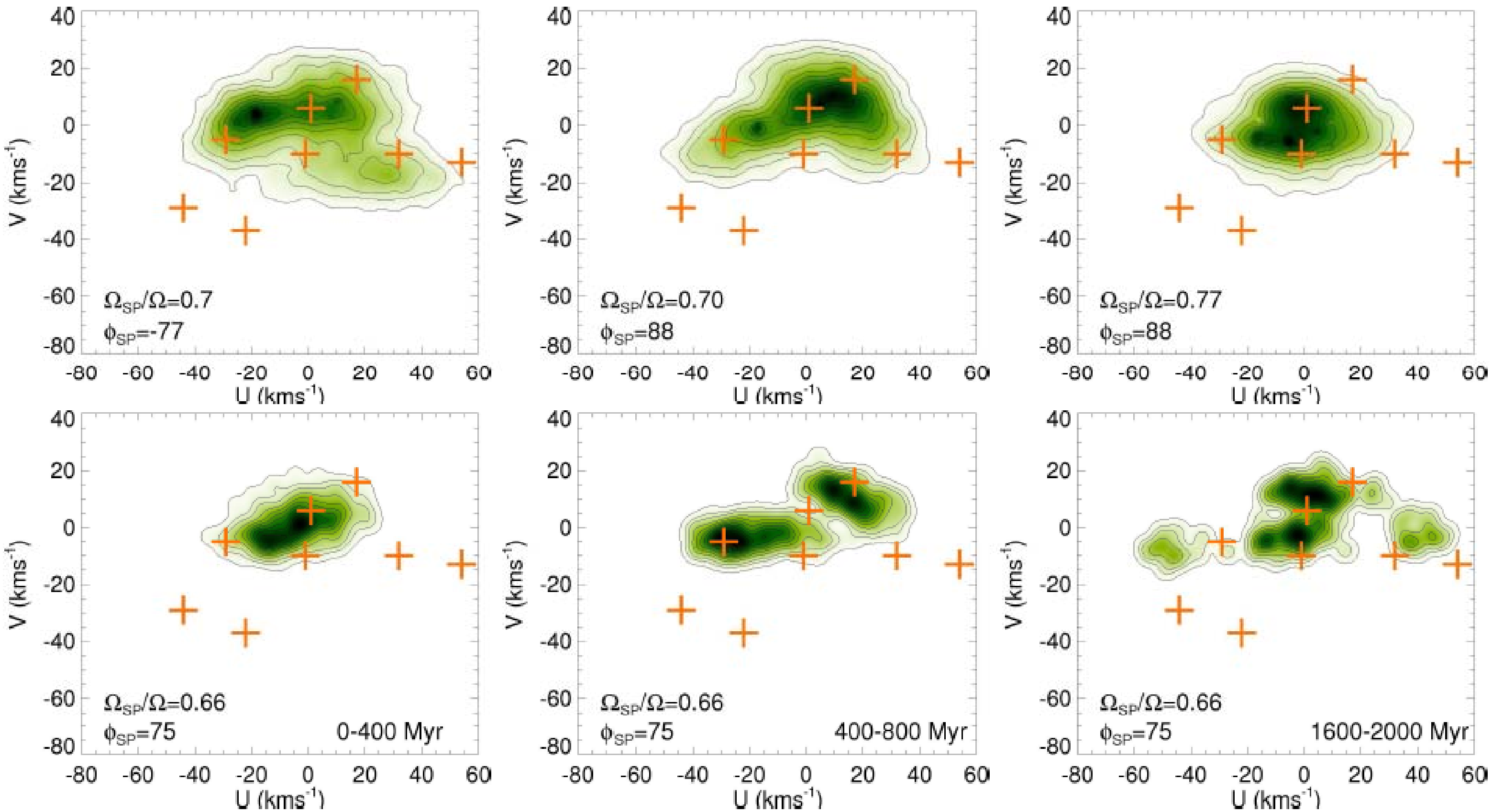
Groups such as the observed ones in the solar vicinity can be reproduced by different parameter combinations.



Degeneracy:

- Several models with the established range of MW spirals fit some of the observed groups

- One particular group can be induced by different parameter combination



Furthermore …

Other processes my influence the local velocity distribution:

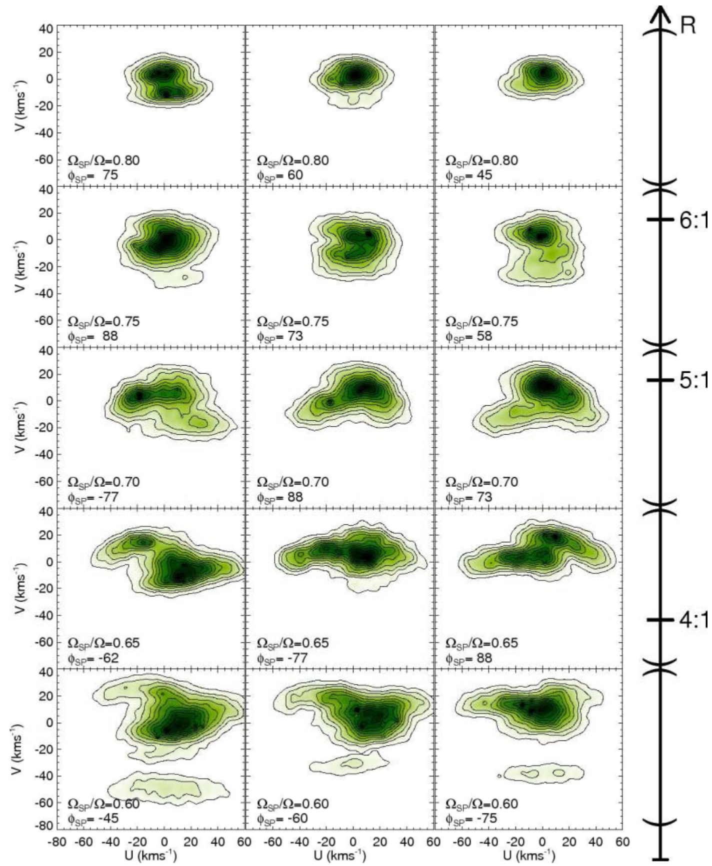
- The galactic bar (models with spirals + bar: checked that individual imprints can still be identified)
- External processes (i.e. accretion events, …)
- Internal disk processes (i.e star formation burst, GMC, …)

Thus …

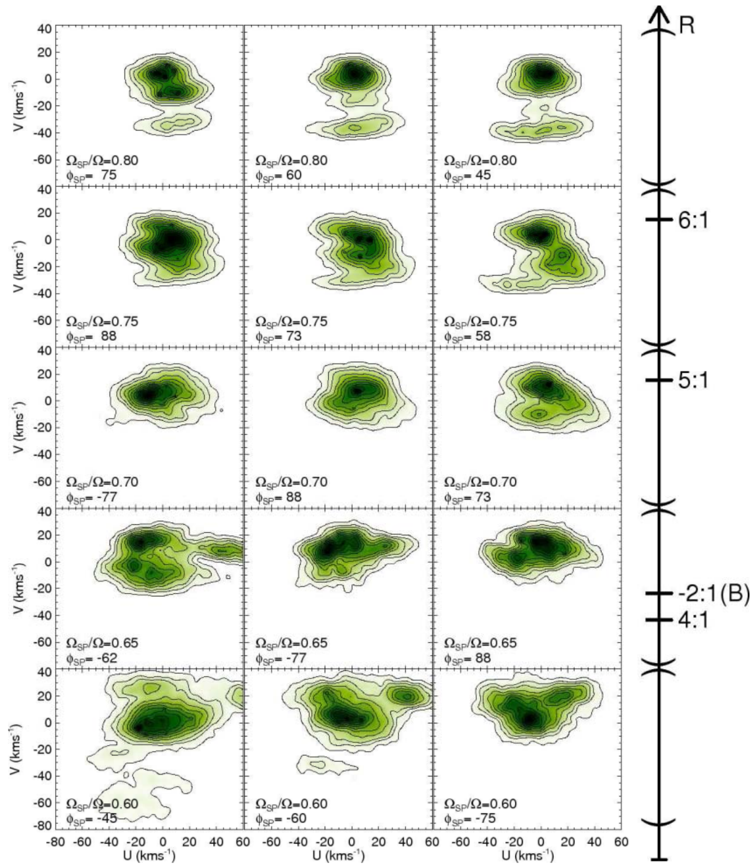
Data from velocity distributions at larger distances are needed for a definitive constraint.

When both the spiral arms and the bar are included, individual imprints of the bar and the arms can still be identified in the final velocity distribution

Spirals



Spirals + bar



The significant group in V= -40 (first row) also appears in only bar

The central regions (second row) is rather similar to the spiral only case

Significant differences (fourth row) in the resonance overlap case (chaos)

Exercise: Simulating Gaia data near the Scutum-Centaurus tangency (~ 6 kpc)

Will Gaia provide precise enough velocity distributions at different regions to be compared with our models?

How far is Gaia going to go in providing precise 3D velocity distributions?

Table 1. Gaia magnitude and accuracies[1] for different types of stars at the Scutum-Centaurus tangency and the Perseus arm in the anti-centre direction.

ST	G	$e_{\pi}(\mu as)$	$e_{\mu\alpha}(\mu as/yr)$	$e_{\mu\delta}(\mu as/yr)$	$e_{v_r}(\mathrm{km\,s^{-1}})$
K5 III @Scutum-Cent.	18	90	53	48	-
B5 V @Perseus	13	8	5	4	10
K5 III @Perseus	13	8	5	4	1
A5 V @Perseus	15	23	13	12	20

Antoja, Figueras, Monguió, 2010

GAIA: Scutum Centaurus tangency (l=305º, ~7 kpc)

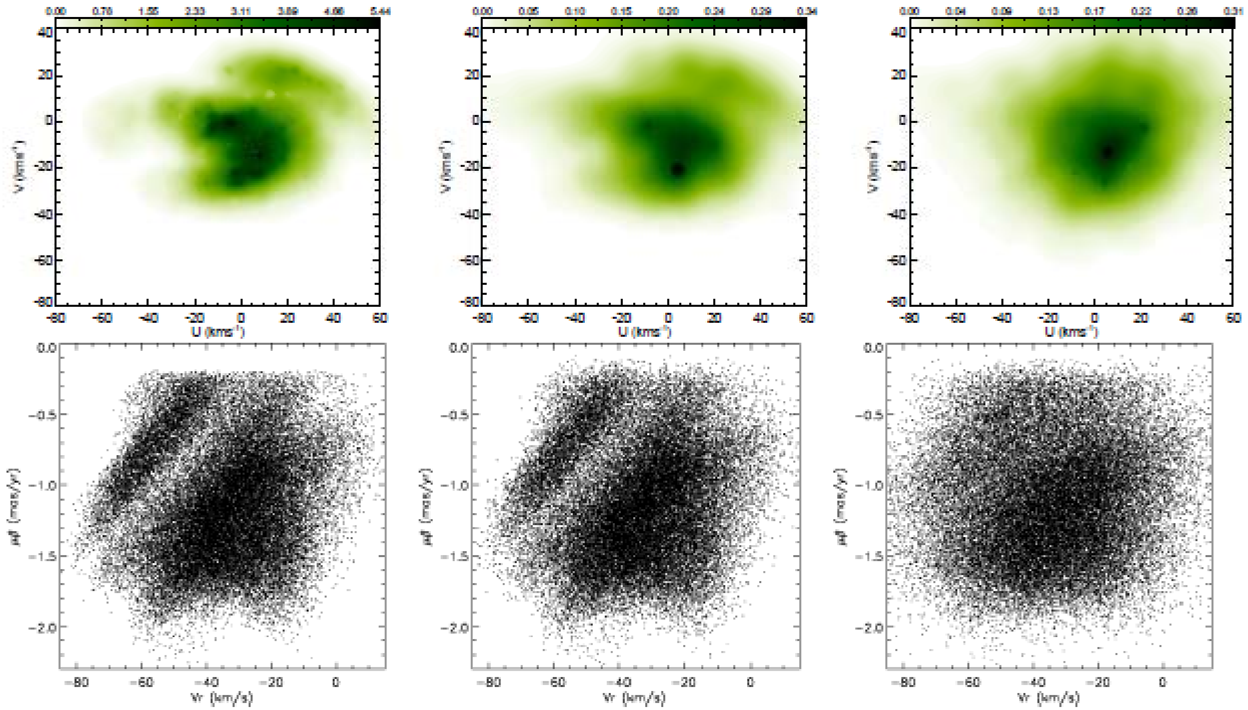


Fig. 1. Left column: simulated U-V (top) and $v_r - \mu_\delta$ (bottom) planes without errors in the Scutum-Centaurus tangency. Middle column: same as left column but including Gaia astrometric errors and radial velocities errors of $\sim 2\,\mathrm{km\,s^{-1}}$ from a hypothetical additional survey. Third column: same as middle column but with $\sim 10\,\mathrm{km\,s^{-1}}$.

We have seen regions near the arms are particularly rich in resonant kinematic structure
But ... more accurate radial velocities are needed (Gaia - ESO survey 2011-2014)

K giants: Relative error in parallax: 60%, photometric parallax needed

Exercise: Simulating Gaia data at the anticenter direction – Perseus (~ 2 kpc)

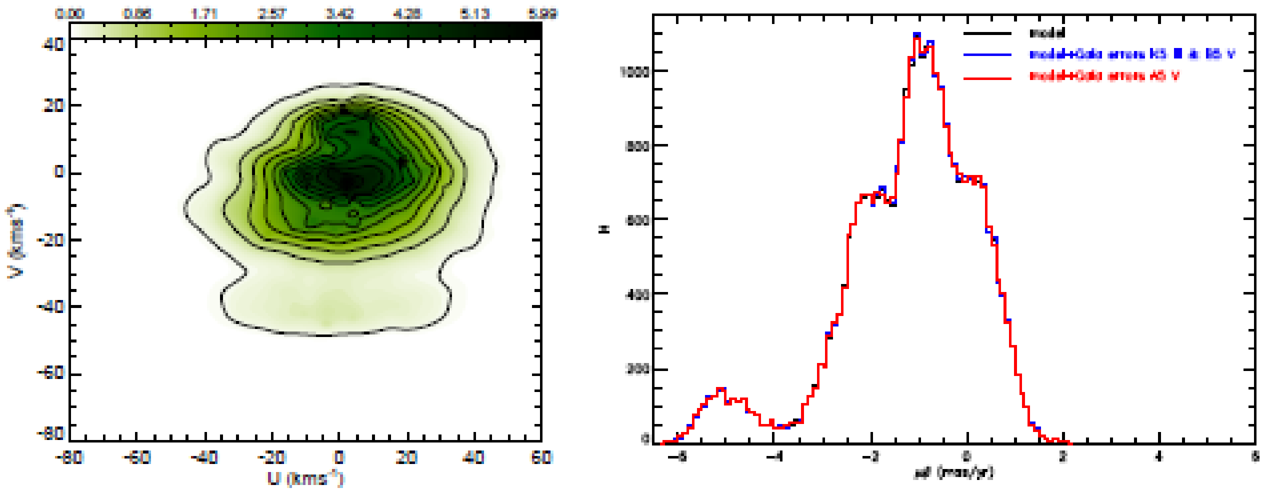


Fig. 2. Left column: simulated U-V velocity distribution without errors in the Perseus arm in the anti-centre direction. Second column: simulated distribution of the proper motion without errors (black line) and with Gaia astrometric errors (blue and red lines).

The unprecedented Gaia accuracy in proper motions hardly changes the μ_δ distribution

Relative error in parallax: < 5%

Yes, **the stellar streams are emerging as powerful tools to constrain the models for the spiral arms and the galactic bar in the Gaia era.**

It is mandatory to analyze carefully our modelled velocity distributions at large scale in the galactic disk so as to find strategic places where the kinematic structures are particularly rich to discriminate among models and to constrain the spiral arm and galactic bar parameter space.

Thanks for the attention

TWA vs PERLAS:

Up to know, spiral arms modelled following TWA, here the 2 approaches compared

Observational evidences for the MW spiral arms (density contrast and pitch angle) suggest assumptions for self-consistency of the TWA model is doubtfully satisfied

PERLAS: a independent 3D mass distribution, not local approximation

- PERLAS tangential and radial forces are more abrupt features

- PERLAS model induce kinematic structure where the TWA model does not

- TWA give substructure or a smaller range of pattern speeds

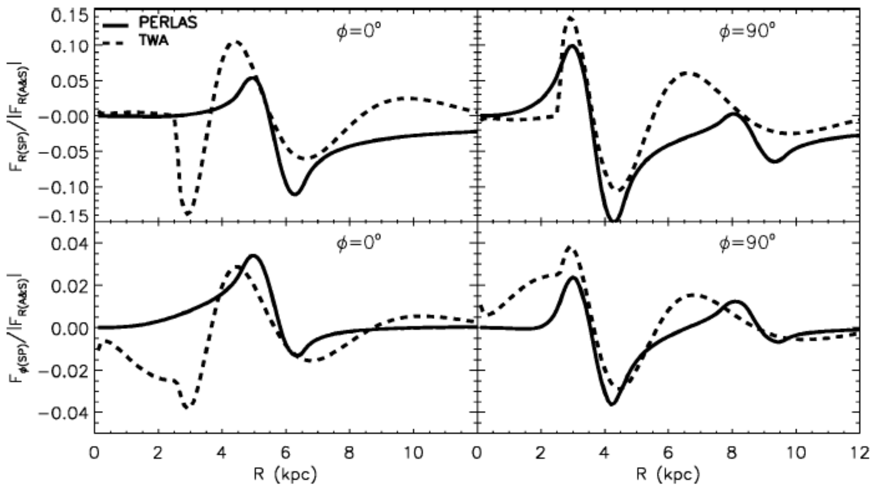
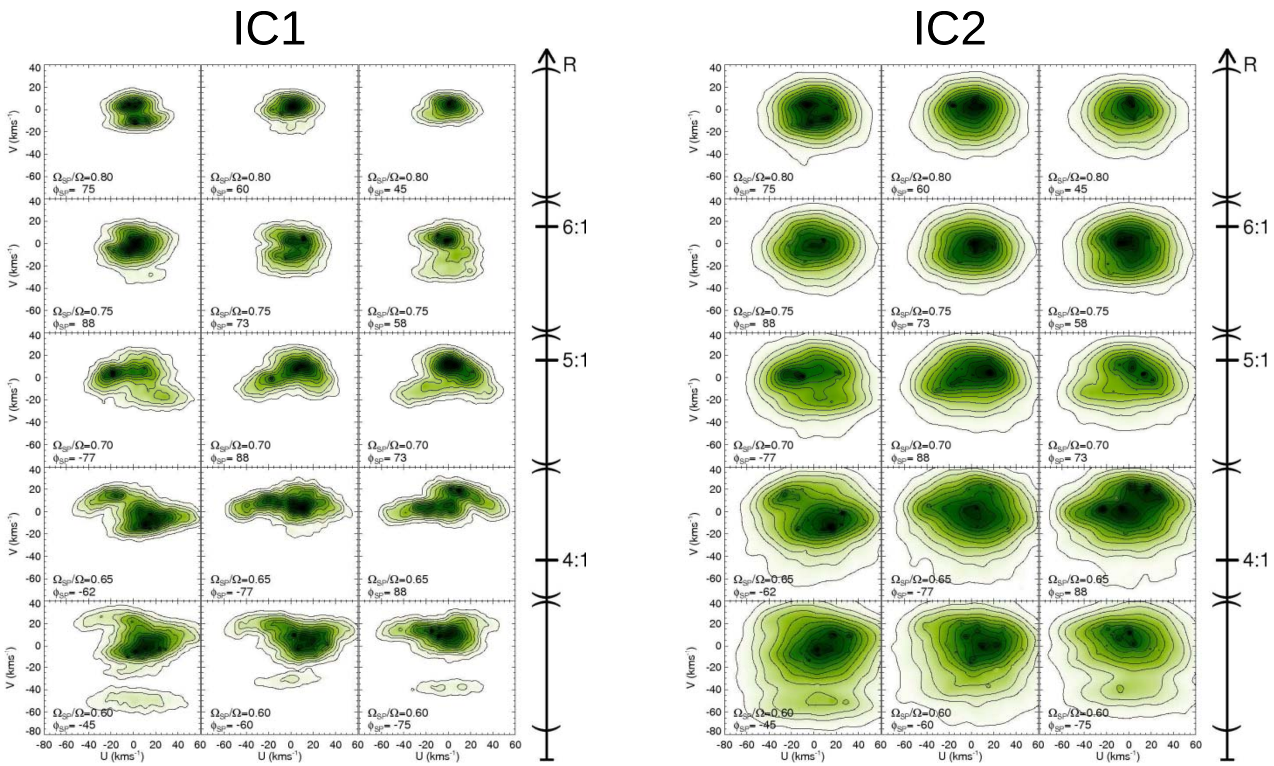


Figure 7. Radial force (top) and tangential force (bottom) as a function of radius for two different azimuths ϕ for the TWA and PERLAS model. The forces are scaled to the A&S radial axisymmetric force.

Changing the initial conditions

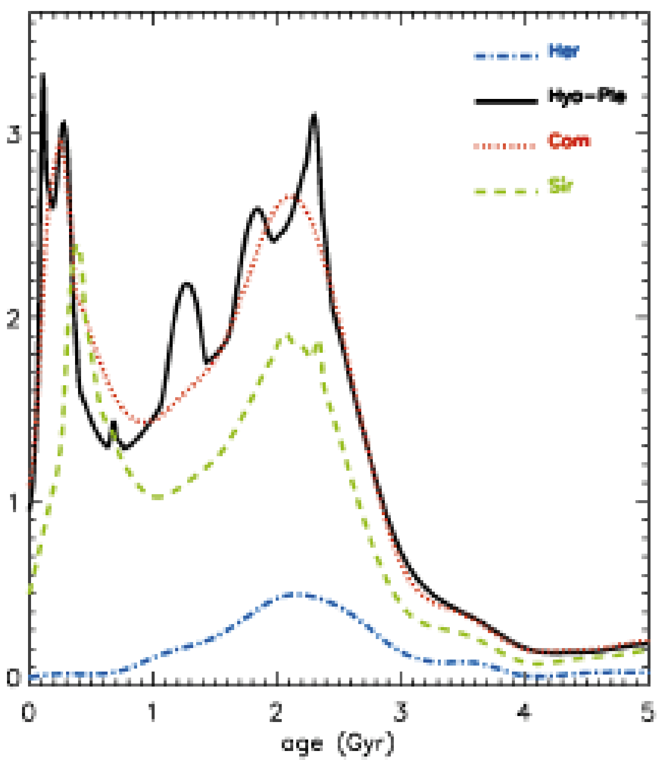


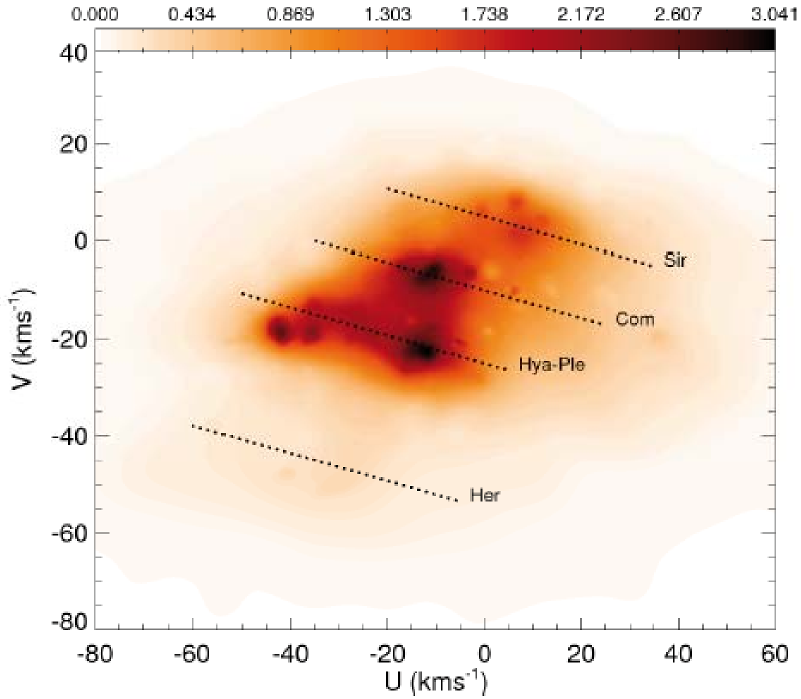
As expected the hotter population (IC2) does not respond so strongly to the spiral perturbation

The main groups are still observed (as there is no change in the orbital structure)

MG solar neighbourhood: substructure in the UV space

ONLY $\epsilon_{age} \leq 30\%$





⇨ Large spread in ages