# Kinematic constrains to the Milky Way evolution and structure (moving groups, spiral arms, pattern speeds, high order moments of the distribution function ...)

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# Aims

- Measure and study the value of velocity distribution function moments in simulated galactic disks.
- Find relations between galactic large scale structures (bars, arms, ...) and high order moments of stellar velocity distribution function. What is the nature of spiral arms on barred and unbarred galaxies?
- Study and interpretation of the kinematic substructures (moving groups) on U-V space of simulated galactic disks. Possible connection with galactic formation and bar and spiral arms evolution.
- Fit a range for the values of observables (mean velocities, vertex deviation, ...) that let us, using observations, characterize properties of the Milky Way large scale structures.
- Are this quantities a diagnostic for structures in the galactic disk (bar, spiral arms, ...)?

# Introduction

Observed moving groups on the solar neigbourhood (orange) and simulated (green).

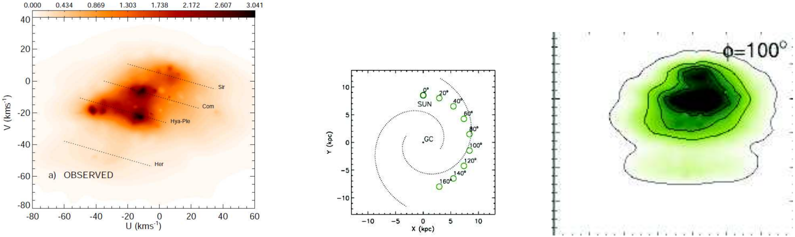



Figure: Antoja, T. PhD Thesis, 2010

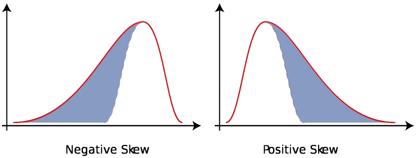
# Introduction

Velocity distribution function moments.

$$l_v = \frac{1}{2}\arctan\left(\frac{2\sigma^2_{R\varphi}}{\sigma^2_{RR} - \sigma^2_{\varphi\varphi}}\right)$$

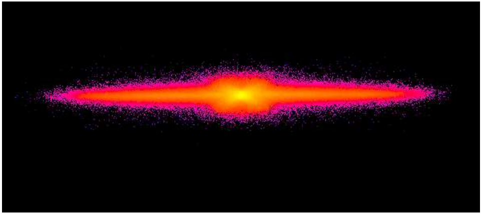
$$\sigma_{RRR} = \frac{\iiint_\infty (U - \langle U\rangle)^3 f \quad dUdVdW}{N} = \mu_{300}$$

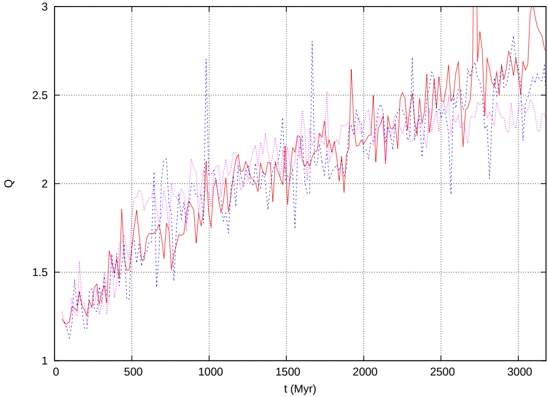
$$\sigma_{\varphi\varphi\varphi} = \frac{\iiint_\infty (V - \langle V\rangle)^3 f \quad dUdVdW}{N} = \mu_{030}$$

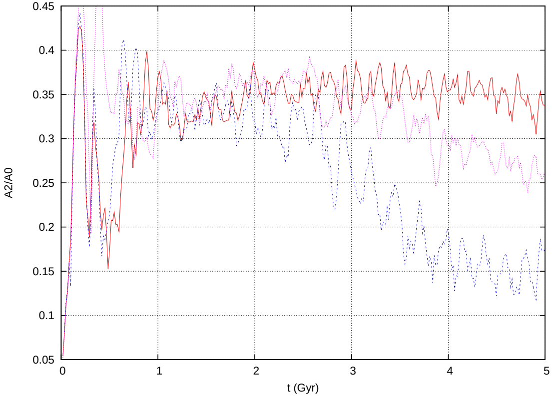


# N-body simulations I

- We have several Milky Way like simulations with various values for $M_{disk}/M_{halo}$ relation, particle number, and spatial and temporal resolutions. This simulations are pure N-body simulations, they have no gas.
- We have done several convergence tests to the problem we are studying (the code, ART, is well tested yet).




Q
t (Myr)
0
500
1000
1500
2000
2500
3000
1
1.5
2
2.5
3


A2/A0
t (Gyr)
0
1
2
3
4
5
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45

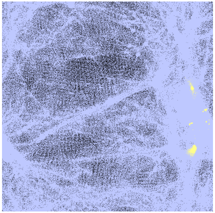
# N-body simulations II: Cosmological case

We need cosmological simulations:

- Our galaxy is not isolated.
- We have kinematic imprints of galaxy formation processes (mergers, flybys, ...) on disk kinematics.
- Galaxies obtained in cosmological simulations have the assembling imprints. This imprints let us evaluate the strategy to make galactic archaeology.

We are running a cosmological simulation with gas, star formation, chemical tagging, cooling, feedback, etc.

HART code uses an eulerian method with no artificial viscosity and with adaptative mesh. It is also well tested.

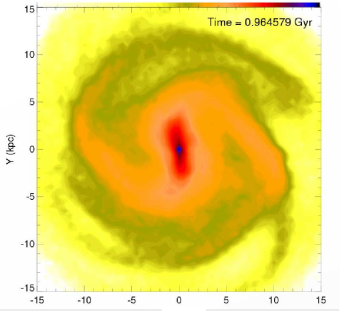


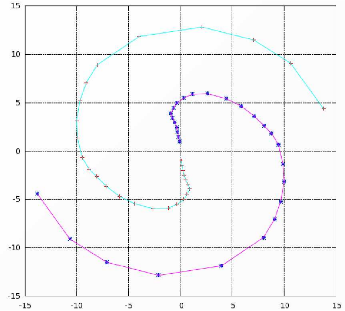
# Work in progress

- Vertex deviation as an indicator of arms nature.
- Study of differences in spiral pattern velocity, according to the arms origin.
- Fourier modes to study simulated and observed spiral galaxies.
- Characterization of the third order moments in pure N-body simulations.

# Tools

- Velocity distribution function moments (calculated in cubic cells of 250 pc).
- Fourier modes m=0,10 (calculated in rings of variable width).



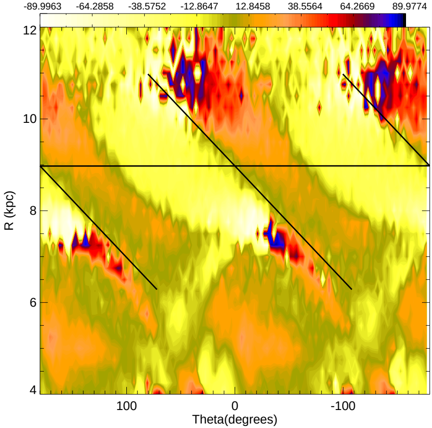



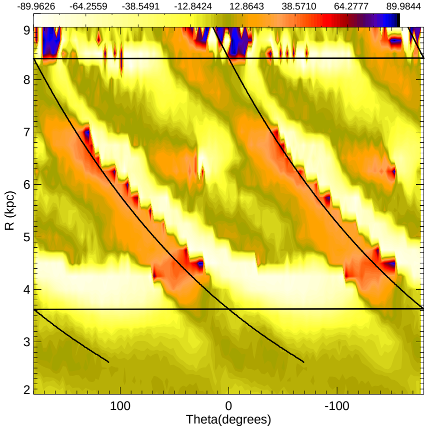
# Vertex deviation as an indicator of arms nature

After analyse several N-body and test particle simulations (Antoja, T. et al. 2008) we have found that radial gradients of vertex deviation, that can be observed when crossing spiral arms density structure, have different sign in response arms than in case of imposed arms.

We are starting new tests to determine the origin of this deviations.

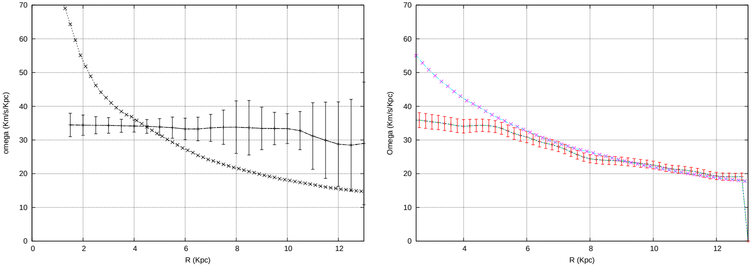
For that study it has a special importance the analysis of simulations with hidrodynamics. It is because the gas let us obtain simulations with autogravitant and maybe longlived arms.



# Study of differences in spiral pattern velocity according to their origin

After analyse several simulations we have seen that spiral arms rotation is clearly different in the case of they are a response to a bar, than what we observe when they have grown from an intrinsic perturbation in the disk ( poisson noise).




Roca-Fàbrega et al. (2012) in preparation

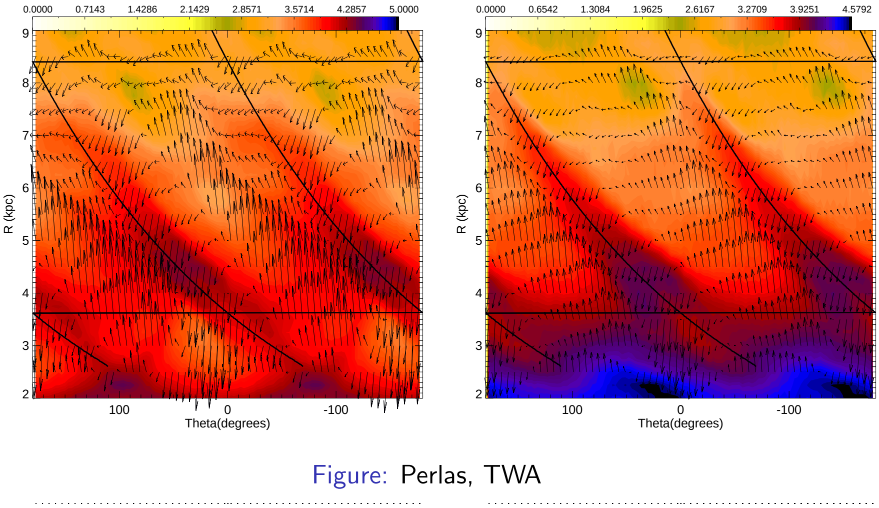



Figure: Perlas, TWA

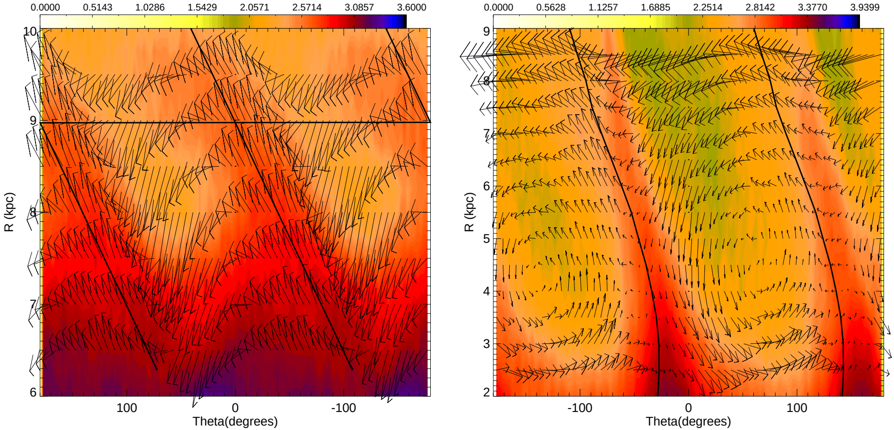


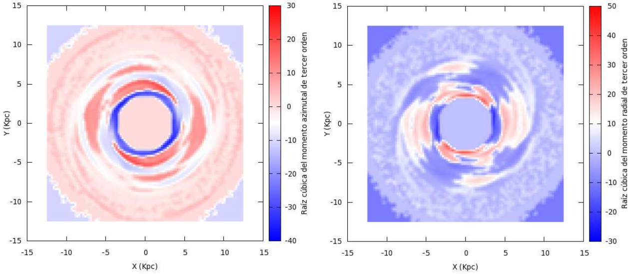

Figure: Quadrupole, N106 N-body simulation

# Fourier modes to study simulated and observed spiral galaxies

We are starting the analysis of fourier modes up to m=10 in spiral galaxies, both simulated and observed.
We are searching parameters that let us classify galaxies according their large scale structures (arms connected to the bar, unconnected arms, arms without a bar, bar without arms, ...), automatically.
This work is in an initiall fase and we want to carry on it in collaboration with Hector Toledo (IA-UNAM).

# Characterization of the third order moments in pure N-body simulations

Starting with the results obtained in the master thesis S. Roca-Fàbrega, 2010, we want to study the possiblity that third order moments can give us information about galactic potential.



# Future work

- New N-body simulations using different initial parameters.
- Analyse arms and bars formed after a satellite flyby.
- Halo fourier modes.
- Study why the arms break and lose their connection with the bar (study the breaking point and moment).
- Run and analyse new cosmological simulations using different parameters (Warm dark matter, ...).

| Parameter | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $C_7$ | $S_1$ | $S_2$ | $F_1$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Disk mass ($10^{10} M\odot$) | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 3.75 | 3.75 | 3.75 |
| Total mass ($10^{12} M\odot$) | 1.43 | 1.43 | 1.43 | 1.43 | 1.43 | 1.43 | 1.43 | 1.5375 | 1.5375 | 1.5375 |
| $R_d$(kpc) | 3.86 | 3.86 | 3.86 | 3.86 | 3.86 | 3.86 | 3.86 | 4.0 | 4.0 | 4.0 |
| $z_{d0}$ | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| $R_{dtrunc}$(kpc) | 19.3 | 19.3 | 19.3 | 19.3 | 19.3 | 19.3 | 19.3 | 19.3 | 19.3 | 19.3 |
| Toomre parameter Q | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| Halo NFW $R_s$(kpc) | 29.186 | 29.186 | 29.186 | 29.186 | 29.186 | 29.186 | 29.186 | 16.614 | 16.614 | 16.614 |
| Halo concentration C | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 18 | 18 | 18 |
| $R_{htrunc}$(kpc) | 291.86 | 291.86 | 291.86 | 291.86 | 291.86 | 291.86 | 291.86 | 299.05 | 299.05 | 299.05 |
| Number of disk part. ($10^5$) | 2.0 | 2.0 | 2.0 | 2.0 | 10.0 | 10.0 | 50.0 | 2.0 | 10.0 | 2.0 |
| Total number of part. ($10^6$) | 1.63 | 1.63 | 1.63 | 1.63 | 8.14 | 8.14 | 38.23 | 1.81 | 11.07 | 1.88 |
| Star particle mass ($10^5 M\odot$) | 2.5 | 2.5 | 2.5 | 2.5 | 0.5 | 0.5 | 0.1 | 1.875 | 0.375 | 1.875 |
| Number of DM species | 6 | 6 | 6 | 6 | 6 | 6 | 7 | 6 | 6 | 6 |
| Minimum time step ($10^4$ yr) | 7.9 | 31.5 | 3.2 | 3.2 | 7.9 | 3.2 | 1.6 | 3.2 | 7.9 | 0.8 |
| Resol. (2 grid cells) (pc) | 11.0 | 44.0 | 44.0 | 176.0 | 11.0 | 44.0 | 11.0 | 44.0 | 11.0 | 22.0 |
| Lenght of box (Mpc) | 1.429 | 1.429 | 1.429 | 1.429 | 1.429 | 1.429 | 1.429 | 1.429 | 1.429 | 2.857 |
| Satellite mass ($10^9 M\odot$) | | | | | | | | | | 1.43 |
| Num. of sat. part. ($10^5$) | | | | | | | | | | 0.76 |
| Sat. x,y,z: (Kpc) | | | | | | | | | | x: 85.7 |
| Sat. $V_x$,$V_y$,$V_z$: (Km/s) | | | | | | | | | | $V_y$: -100 |

Table: Simulation parameters