Origin of Phase Space Spirals in Gaia DR2

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Spirals in Gaia DR2

Following the release of Gaia DR2, Antoja et al. (2018) found striking spirals in various projections of the phase space of solar neighborhood stars. These spirals are shown below in Figure 1. Although the (z,v_z) density spiral in Figure 1 (left) can be explained by kinematic phase wrapping, the spirals in mean v_R and v_φ shown in Figure 1 (center and right) do not have as obvious an explanation.

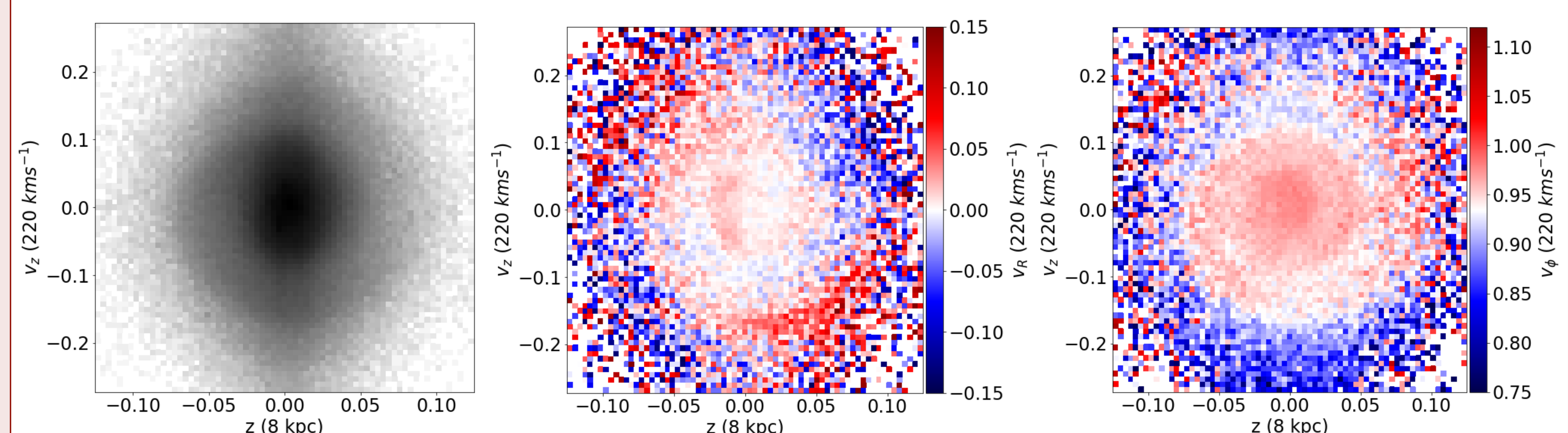

Figure 1: From left to right: (z,v_z) density, mean $v_R(z,v_z)$, mean $v_\varphi(z,v_z)$. Same projections as Antoja et al. (2018). Note that all numerical values are in natural units, that is 220 kms^{-1} = 8 kpc = 1.

We hypothesize that:

- These spirals arise naturally from vertical bending oscillations in a galactic disc.
- Coupling between vertical and in plane motion is needed to understand them.
- Self gravity plays a role in their evolution.

Objectives

We hope to understand the cause of these spirals through use of simulations, both by integrating orbits of test particles in a time independent potential and using a self consistent N-body code.

We take the viewpoint that the spirals in v_R and v_φ arise due to coupling between vertical and in plane motion, in particular between R and z, which is inherent to realistic models of components of the Milky Way potential, such as the Miyamoto Nagai disc. We investigate this by studying the effect of a cubic coupling term in a toy model potential, and comparing these results to simulations in more realistic models.

Initial Conditions

We set up our test particle simulations by sampling initial conditions from a distribution function (DF) constructed from the vertical and in-plane energies, and angular momentum. These quantities are exact integrals of motion for a separable potential, and approximate integrals of motion in the non-separable case. Similarly to Kuijken and Dubinski (1995) we take the DF to have the form

$$f(E_z, E_p, L_z) \propto \frac{g(L_z)}{\sigma_z(L_z)\sigma_R^2(L_z)} e^{-(E_p - E_c(L_z))/\sigma_R^2(L_z)} e^{-E_z/\sigma_z^2(L_z)}$$

where E_c is the in plane energy of a circular orbit with angular momentum L_z, and $g(L_z)$ is a function describing the distribution in L_z. We require the initial conditions to have a mixture of multiple angular momenta due to the implicit coupling between the in-plane and vertical velocities through their mutual dependence on L_z. We use the simplest form to achieve this, in particular

$$g(L_z) = \alpha_1 \delta(L_z - L_{z1}) + \alpha_2 \delta(L_z - L_{z2})$$

For each simulation we perturb the initial conditions in v_z by 30 kms^{-1}, and evolve the perturbed distribution for 300 Myr.

Realistic Milky Way Model

We first consider a realistic Milky Way potential consisting of 3 Miyamoto Nagai discs, a NFW halo, and a bulge modeled by the Hernquist potential. The result in Figure 2 shows that spirals appear in v_R and v_φ, although with notably richer features than can be seen in Gaia DR2.

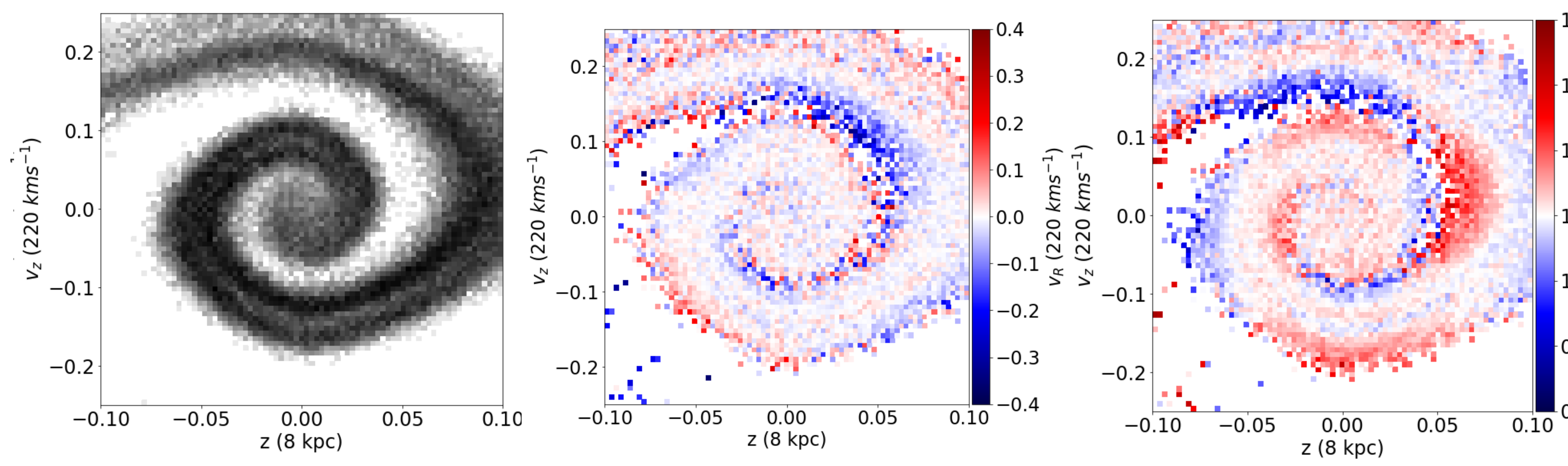

Figure 2: Same projections as Figure 1, but for simulated test particles in the realistic Milky Way potential.

Separable Toy Model

To study the effect of coupling, we consider a separable toy model on which we can add a coupling term to study the direct effect of coupling. We start with the simple form

$$\Phi(R, z) = \psi(R) + \chi(z)$$

where

$$\psi(R) = \frac{v_o^2}{2} \ln\left(R^2 + R_0^2\right) \quad \text{and} \quad \chi(z) = ab^2\sqrt{\frac{z^2}{b^2} + 1} + cz^2$$

and the parameters of the model are determined by minimizing the mean squared error (MSE) between the toy model and the realistic Milky Way model.

The results for the separable model are shown in Figure 3, where we see that the features in the v_R and v_φ spirals have been lost.

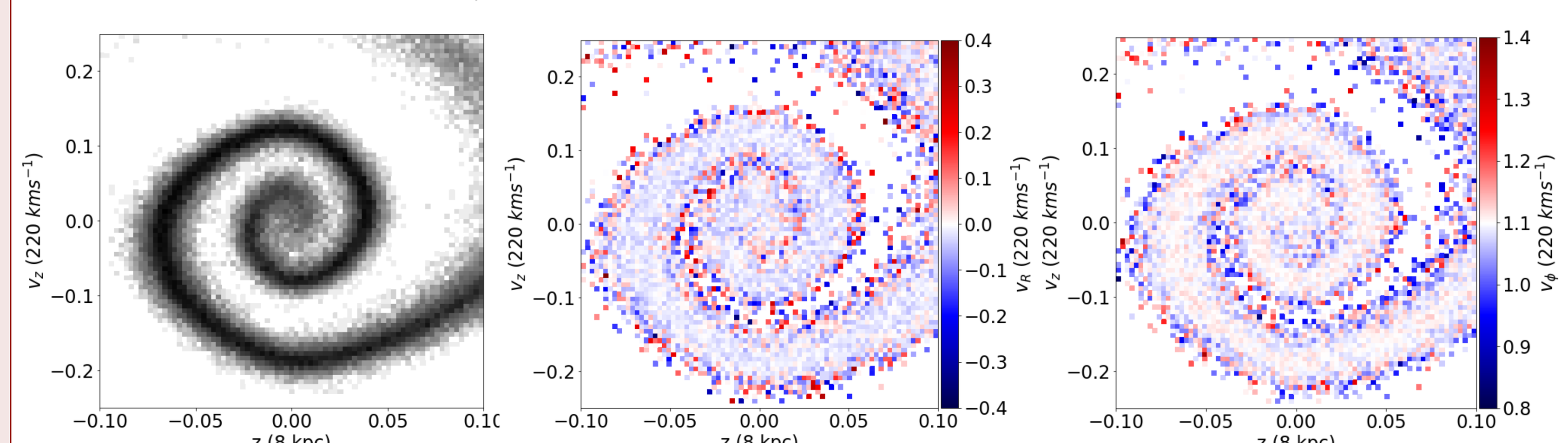

Figure 3: Same projections as Figure 1, but for simulated test particles in the separable toy potential.

Coupled Toy Model

To motivate the form of the coupled toy model, we consider the effective potential for the realistic Milky Way model for a given angular momentum. The guiding radius of this potential can be determined numerically. If one then derives a Taylor series about the guiding radius and z=0 up to order three, a cubic coupling term of the form $(R-R_g)z^2$ with a non-zero coefficient arises. We take this to motivate consideration of a toy model of the form

$$\Phi(R, z) = \psi(R) + \chi(z) + \xi(R - R_s)z^2$$

Where again we determine the parameters by minimizing the MSE between this model and the realistic Milky Way model.

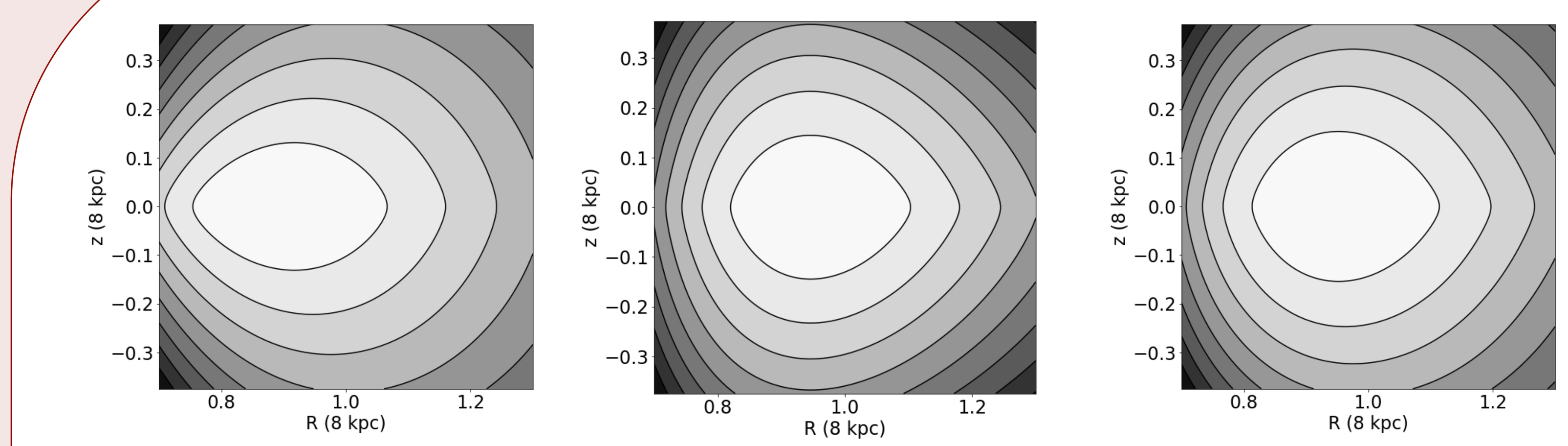

Figure 4: Effective potentials given L_z=1 from left to right: realistic Milky Way model, separable toy mode, and coupled toy model

We have shown contour plots of the effective potentials given L_z=1 for the three potential models in Figure 4. This shows how the addition of the coupling term brings the toy model closer to the realistic Milky Way potential.

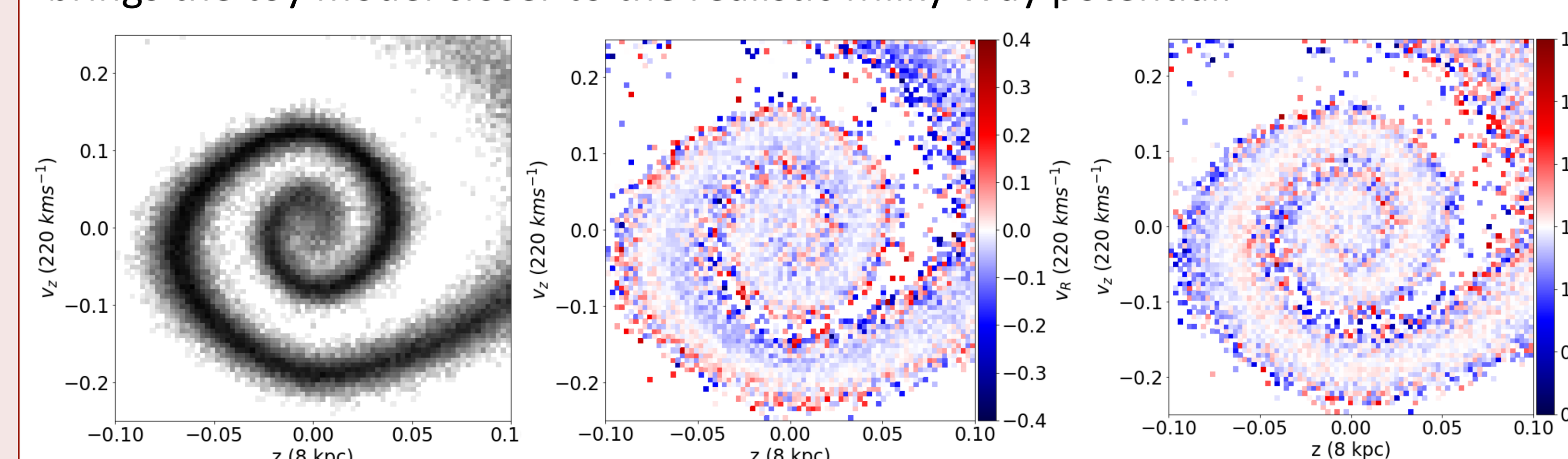

Figure 5: Same projections as Figure 1, but for simulated test particles in the coupled toy potential.

The simulation results for the coupled toy model are shown in Figure 5. Here we see that some of the features in v_R and v_φ are recovered with the addition of the coupling term. We note that the features are not as rich as in Figure 2, which at this point we take to be due to the fact that we are ignoring higher order coupling terms.

N-body Simulations

We also run a similar simulation with the same velocity perturbation and evolution time, with a self consistent N-body code. The results are shown in Figure 6, where we see weak features reminiscent of those visible in the coupled toy model results. At this point it is unclear if the weakness of the features means the spirals do not persist as well in a self gravitating system, or if we are losing detail due to insufficient resolution.

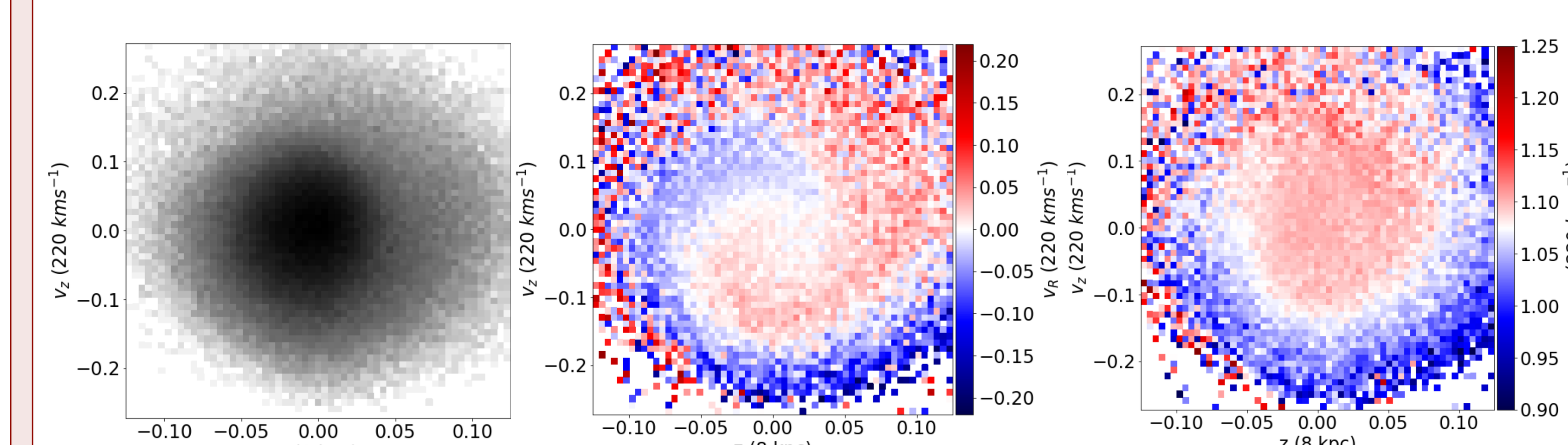

Figure 6: Same projections as Figure 1, but for the self consistent N-body simulation.

Conclusions

We have shown that the addition of a cubic coupling term to a separable toy model results in features reminiscent those appearing in both recent observations and more accurate simulations. This may mean that R-z coupling is necessary to understand the morphology of phase space spirals. This consequently means that observed phase space spirals may be a strong probe for the Milky Way potential.

References:
1. Antoja T., et al., 2018, preprint, (arXiv:1804.10196)
2. Kuijken K. and Dubinski J., 1995, MNRAS 277 1341
3. Widrow L.M. and Dubinski J., 2005, ApJ 631 838
4. Kuijken K., and Gilmore G., 1989 MNRAS 239 571