# Warped galaxies and the dark matter connection

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## Summary

50 years have passed since the first HI observation of the Milky Way warp. If during this time, numerous hypothesis have been proposed to explain this galactic common phenomenon, none of them was able to clearly satisfying all the constraints provided by the observations. Most of the works on the topic are based on the assumption of a spherical or triaxial dark matter halo as predicted by the CDM theory. In this poster, we point out some problems arising with a dynamically hot dark matter halo and explore the hypothesis of a heavy self-gravitating warped disk. For such a model, periodic orbits which form the backbone of the galaxy are described and are confronted with N-body simulations.

## The shape of the dark matter

### Observed properties of warps

Global properties of warps can be summarized in for rules :

1. Warps are a common phenomenon and thus must be either long-lived or continuously generated
(Bosma [2]; Reshetnikov & Combes [9]).
2. Warps are generally pronounced outside $R_{25}$ (radius at the 25 mag arcsec$^{-2}$) (Briggs [3]).
3. The line of nodes (LON) is straight inside radius $R_{26.5}$ (Briggs [3]).
4. Outside $R_{26.5}$ the LON forms a leading spiral (Briggs [3]).

### Interest of the heavy disk

In the context of the warps, the heavy disk assumption, which implies a strong rotational support, is attractive for several reasons :

- The radical change of the dynamic between the inner flat disk and the outer warp is hardly explained by a hot halo which imposes a uniform dynamic over a large scale. In contrast, such a change appears to be natural for a heavy disk.
- The straight LON can result of a slow diffusion of angular momentum which is a quasi conserved quantity. Thus, a strong rotational support in the dark matter will be more prone to keep the LON straight than a spherical component. The angular momentum can be deposited, for example, by an accretion event.

### More arguments

Moreover, other arguments play in the favor of the heavy disk assumption. Unlike the CDM scenario, heavy disks are consistent with the galactic center which seems to be dominated by baryons (Gerhard [6]). The cold flaring $H_2$ disk model (Pfenniger et al.[8]) is in agreement with the observed constant ratio between the DM and HI surface density (Bosma [1]). Recently, B stars have been detected in the outer disk of M31, where no star formation were expected to exist (Cuillandre et al. [5]). Such observations reveal that molecular gas must be present in abundance in the outer disk of galaxies.

## Semi-analytical model

Because periodic orbits are the backbone of the galaxies, it is first useful to study the assumption of a heavy self-gravitating disk in the context of the warps, by determining its periodic orbits. The latter orbits are then found and compared in a more realistic N-body simulation.

In a previous paper (Revaz & Pfenniger [10]), an analytical warped model based on a superposition of three Miyamoto-Nagai potentials has been proposed. The determination of the periodic orbits reveal that the well known circular orbit family survives the warp and becomes quasi-annular with a tilt corresponding to the warped galactic disk. Its stability is also preserved.

## N-body model

A similar study has been performed in an N-body disk model of $10^6$ particules. The galaxy is composed of 3 components, the bulge, the visible exponential disk and the heavy disk of dark matter. This latter, which contains about 3/4 of the total mass, is a flaring disk. As it can be expected from HI observations (Burton [4]) the flaring is an exponential function of the radius. The total rotation curve is thus straight well after 30 kpc.

### Creating the warp

In order to get a warp, the galactic disk is embedded in a non-rotating warped potential. The potential, calculated with a grid code, is a deformation of the potential of the initially flat disk. The warp is obtained by including a term in the vertical coordinate : $z \rightarrow z - wR^2 \cos\phi$, where $\phi$ is the azimuthal angle and $w$, the warp parameter. To warp adiabatically the disk, the outer potential is flat at $t = 0$ and warps slowly in function of the time, rising the maximum deformation with $w = 0.005\,\mathrm{kpc}^{-1}$ at $t = 1200$ Myr. For this time, on Fig. 1., the amplitude of the imposed deformation is marked with a blue line. The mass ration between the outer potential and the disk grows proportionally to $w$. The disk deformation is then comparable to the Milky Way warp. Between $t = 1200$ and $t = 1500$, the contribution of the potential decreases and after $t = 1500$ the galaxy is self-gravitating.

### Evolution

In order to determine the characteristics of the warped disk, we have decomposed it between 0 to 50 kpc, in a family of 25 concentric rings. The evolution of the disk is then followed by the evolution of these rings. The *tilt* plots represent the polar angle $\theta$ of a ring vs the radius $R$, while the *tip-LON* plots (Briggs [3]) is a polar projection of the normal vector defining each ring. $\phi$, the azimuth angle, is read along the circles from 0 to 360°, while $\theta$ is read perpendicularly to those circles between the range 0 to 10°. Fig. 1. presents the evolution of the model. Each snapshot is described by a set of five plots : an edge-on and face-on surface density, a 3D model of rings, and a *tilt* and *tip-LON* plot. In order to increase the effect of the warp, in the 3D model the polar angle is multiplied by 3.

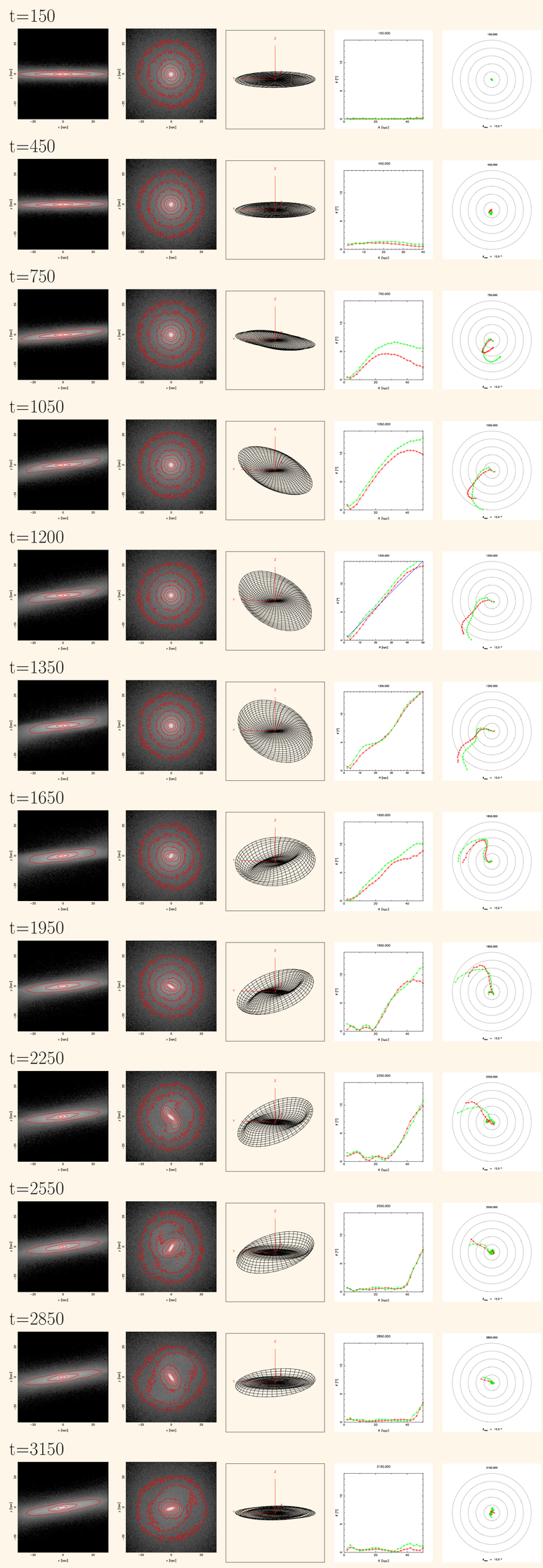


**Fig. 1.** Evolution of the warped N-body galaxy model between $t = 450$ and $t = 2100$ Myr. For the *tilt* and *tip-LON* plots, points in red (resp. green) are determined by the positions (resp. velocities) of particules.

- From $t = 450$ the disk begin to warp and reaches its maximum deformation at $t = 1200$. Tip-LON plots show clearly a leading LON.
- Between $t = 1200$ and $t = 1500$ the outer potential is slightly removed and at $t = 1500$ the disk becomes self-gravitating. From $t = 1200$ to $t = 1650$ the LON rotates. The disk is precessing differentially clock-wise, with a maximum frequency around $R = 30$ kpc.
- At $t = 1650$ the center of the galaxy has formed a small new tilted disk. This can be seen on the corresponding *tilt* graph where $\theta$ is constant between 0 and 5 kpc.
- During the following 1500 Myr the inner disk grows while the LON straightens. At $t = 3150$ the galaxy is flat, up to 50 = kpc.

In conclusion, the galaxy needs more than 1500 Myr to loose its warp up to a radius of $R = 50$ kpc (850 Myr at $R = 30$ kpc). The growth of the inner disk seems to be rawly proportionnal to the rotational period at a given radius. A leading LON is initially formed which straightens after the perturbation. This can be the result of angular momentum diffusion through the galactic disk.

## Periodic orbits

In order to find periodic orbits in our N-body model, we have used a grid code to compute the corresponding potential at a given time. The periodic orbits are determined by numerically finding the fixed points of the 4D Poincaré map at $y = 0$, $\dot{x} < 0$ generated by the equations of motion. A complete description of the procedure is exposed in Pfenniger & Friedli [7].

Five families have been found in our model :

- family $p$ is the correspondent of the circular family in an axisymmetry disk. Except at resonances, it is always stable.
- families $s2+$ and $s2-$ are vertical 2:1 resonances. They cross the $p$-family at at the line of node. They are unstable.
- families $t2+$ and $t2-$ are similar to the $s2+$ and $s2-$ but are rotated for 45° in the azimuth. (These families are called $sz+$ and $sz-$ in Revaz & Pfenniger [10]). They are always stable.

In an axisymmetric potential, families $s2+$,$s2-$ and $t2+$,$t2-$ are degenerated. Fig 2. and 3. show the set of these five families around $R = 10$ kpc computed at time $t = 1650$ Myr. On fig. 2., the $z$ coordinate is traced in function of the azimuth $\phi$ while a 3D representation is shown on Fig 3.

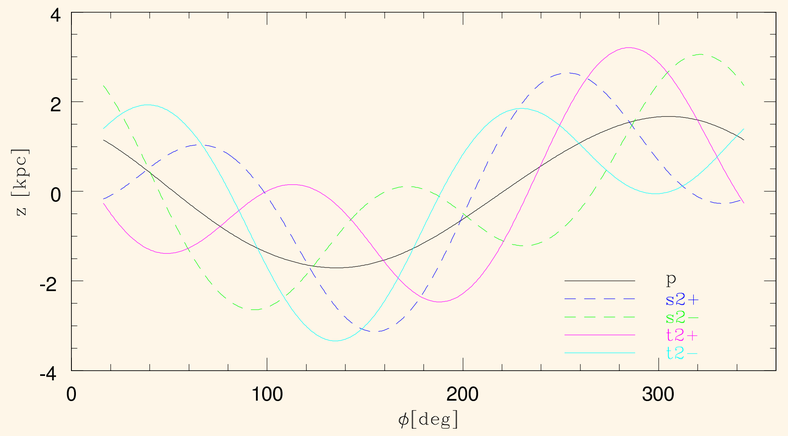


**Fig. 2.** Five families populating the heavy disk model at $R = 10$ kpc, $t = 1650$ Myr. Solid lines (resp. dashed) represent stable (resp. unstable) orbits.

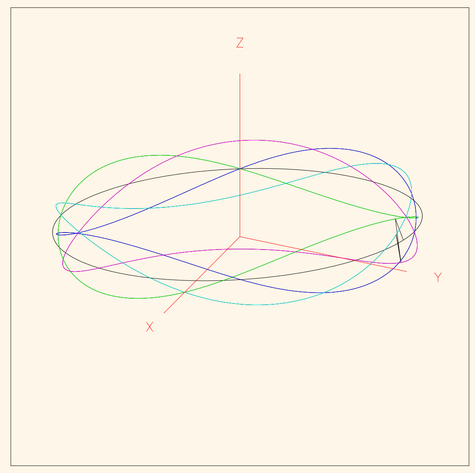


**Fig. 3.** 3D representation of the five families populating the heavy disk model ($R = 10$ kpc, $t = 1650$ Myr).

## Conclusion

Numerical simulations of warped heavy disks reveal the consistency of such models with the available observations. During the galaxy evolution, the LON straightens and a flat disk develops at the center. A detailed study of the orbits reveals the existence of quasi-circular stable orbits. This study confirms the intuitive idea that orbits follow the warp and justify the use of the ring models. Finally, such model underlines the viability of the heavy disk hypothesis in the context of dark matter.

## References

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