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# The time evolution of gaps in tidal streams in axisymmetric potentials

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**Abstract.** Our goal is to understand the evolution and properties of gaps produced by dark matter subhalos in stellar tidal streams. Here we explore how gaps grow in spherical potentials in comparison to axisymmetric potentials. We develop a model that uses the divergence of two orbits, one on each side of the gap, to describe the size of the gap and how this varies with time and depends on the characteristics of the encounter with the dark subhalo. To this end we use a formalism based on action-angle variables.

**Keywords.** Galaxy: halo, Galaxy: structure, Galaxy: kinematics and dynamics

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## 1. Introduction & Motivation

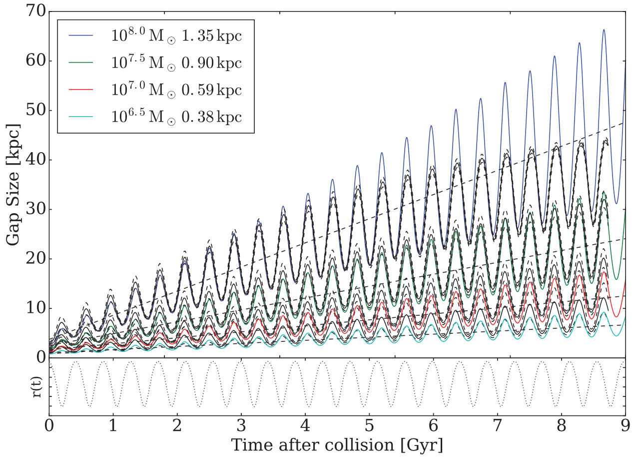
$\Lambda$CDM simulations typically predict thousands of satellites orbiting the Milky Way to be completely dark matter dominated (Springel *et al.* 2008). Possibly interesting objects to probe this population of (otherwise invisible) dark satellites are tidal streams. We thus aim to infer the properties of the dark matter satellites from the properties of the gaps formed as a dark subhalo comes sufficiently close to a tidal stream. Modeling the evolution of a gap as the divergence of two orbits has shown good agreement with N-body experiments carried out in a spherical host potential (Helmi & Koppelman, 2016). We present here the results obtained for a more realistic Stäckel Galactic potential, now including a disk and a halo component.

## 2. Model

Building on Helmi & Koppelman (2016) we model the size of the gap as the separation of two orbits A & B which correspond to particles in the stream that have been perturbed the most because of the interaction with the subhalo. To obtain the initial separation of these two orbits we use the impulse approximation (Erkal & Belokurov, 2015). By assuming a Plummer profile for the dark matter we can obtain analytic expressions for their separations in phase-space, $\Delta X_0$ and $\Delta V_0$. This initial separation can be transformed to a separation in action-angle space with a matrix: $M_0 = \partial(\Theta, J)/\partial(X, V)$, which is the Jacobian of the coordinate transformation. In action-angle space, time evolution is simple: $\Delta\Theta(t) = \Delta\Theta_0 + \Omega(J)t$, where $\Omega(J)$ are the frequencies of motion, and $J(t) = J_0$. We encode this evolution in a matrix $\Omega^{'} = \begin{bmatrix} I_3 & \partial\boldsymbol{\Omega}/\partial\mathbf{J}t \\ {[0.3em]0} & I_3 \end{bmatrix}$. At each timestep the separation vector in action-angle space is transformed back locally to Cartesian coordinates with matrix $M_t^{-1}$. For a schematic overview of the model see Fig.1a.

$$\begin{tikzcd}
\begin{bmatrix}\Delta\mathbf{X}_0\\ \Delta\mathbf{V}_0\end{bmatrix} \arrow[r, "M_0"] & \begin{bmatrix}\Delta\mathbf{\Theta}_0\\ \Delta\mathbf{J}_0\end{bmatrix} \arrow[d, "\Omega'"] \\
\begin{bmatrix}\Delta\mathbf{X}_t\\ \Delta\mathbf{V}_t\end{bmatrix} & \begin{bmatrix}\Delta\mathbf{\Theta}_t\\ \Delta\mathbf{J}\end{bmatrix} \arrow[l, "M_t^{-1}"']
\end{tikzcd}$$

(a)



(b)

Figure 1: Panel (a): A schematic overview of the model. First we calculate the initial size of the gap from the impulse approximation, then we evolve this separation in time using actions and angles. Panel (b): Gaps growing in tidal streams. The colored lines show the predicted sizes of the gaps from our model, the solid black lines show the size measured in N-body experiments. The fitted dashed lines show the linear rate of growth of the size of the gap with time for these experiments run in a realistic (axisymmetric) Galactic potential.

## 3. Results & Conclusions

Fig. 1b shows the evolution in time of the four different gaps produced by encounters with different mass subhalos. The solid colored lines show the prediction for the size of the gap from our model, the solid black lines are the measured size of the gaps in the corresponding N-body experiments. The fitted dashed lines show that a linear fit to the growth of the gap size in time works well on average. The oscillations seen depend on the orbital phase of the gap in the stream.

Our model thus shows very nice agreement with gap sizes measured in the N-body experiments. The rate of growth is dependent on the properties of the dark matter subhalo, e.g. its mass and scale radius, on the geometry of the impact, and on the age of the stream. The latter two have not been varied for the results shown in Fig. 1b. The evolution in time of the size of a gap is thus linear, also in the case of an axisymmetric potential.

## References

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