Were the HI Grand Design Spiral Arms of M83 Created by a Dark Subhalo?

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Abstract

We investigate whether the HI grand design spiral arms of M83 could be created by the close passage of a dark matter subhalo. We use the AMR code RAMSES to model the HI component of the galaxy, with the initial disk setup in equilibrium (Wang et al. 2010) between the self gravity of the gaseous component, the analytical host halo potential and the gas pressure. Possible subhalo trajectories are investigated by employing a generalized restricted three-body model. We find that a subhalo of mass 1e9 $M_\odot$ (1:1000 M_{sub} / M_{host}) is able to reproduce the morphology and the overdensities observed in the HI THINGS data, if it passes the center of M83 with a pericenter distance of 8 kpc. The wake of the subhalo creates overdensities in the HI extended disk of 20-30 percent compared to the underlying disk density, pointing to a possible channel of star formation in the outer disk.

Numerical Approach

The restricted three body model was one of the first approximations used in modeling the interaction between pairs of galaxies (Toomre & Toomre 1972). The model consists of two massive objects, M and m, with M > m, interacting with each other, and a field of massless test particles, which move in the combined potential of these objects. The particles surround the host galaxies on circular orbits as tracers for the resulting perturbation by the infalling subhalo.

Here, the restricted three body model is extended by replacing the point mass potential representing the two massive objects with potentials of extended mass distributions. This leads to differentially rotating tracer particles as well as significantly altered trajectories of the satellite m. We also include Chandrasekhar's equation (Chandrasekhar 1943) for the dynamical friction caused by the stellar disk, as well as tidal mass stripping with a tidal radius approach.

Equations of Motion:

The motion of the particles and the two objects are governed by the superposed gravitational forces acting between pairs of objects and particles.

$$\ddot{\vec{r}}_m = \ddot{\vec{r}}_m - \ddot{\vec{r}}_M$$
$$= -\nabla\phi_m(r_m) - \nabla\phi_M(r_m)$$
$$\ddot{\vec{r}}_p = \ddot{\vec{r}}_p - \ddot{\vec{r}}_M$$
$$= \nabla\phi_M(r_p) - \nabla\phi_m(r_p - r_m) - \nabla\phi_m(r_m)$$

With the host object at the center of the coordinate system and all motion relative to the origin. There are no restrictions on which potentials may be used.

Results

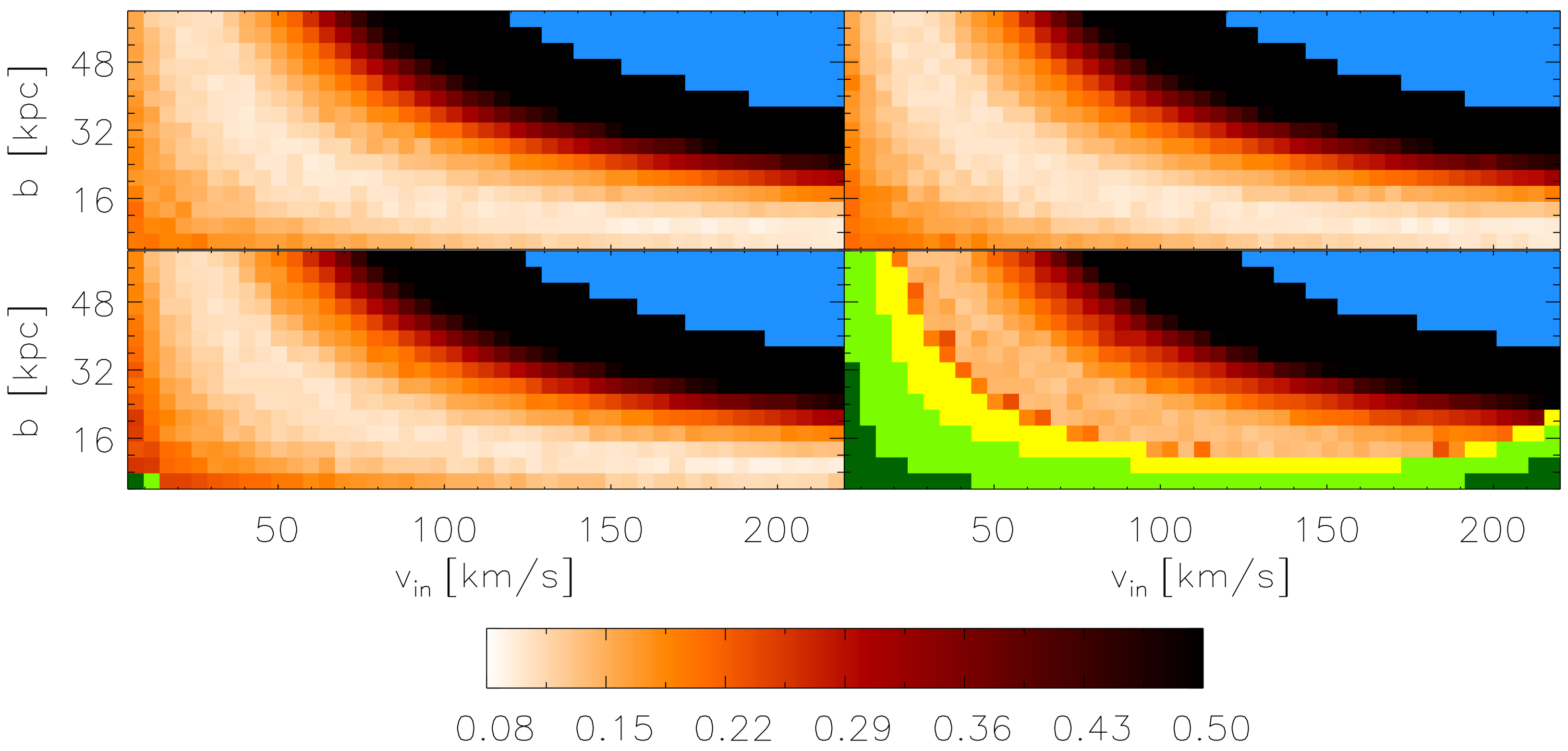

Fig 1: The least squares fitting parameters for the comparison between the spiral arms seen in the THINGS data and the ones obtained from the three body model. Blue, yellow, bright and dark green mark trajectories that failed for various reasons: not enough data points to use in fit, subhalo did not leave the disk, all mass was lost or no tidal radius was found, respectively.

The restricted three body model was used to scan an impact parameter and impact velocity range of 4 - 60 kpc and 0 - 225 km/s, respectively. This velocity range was chosen as the virial velocity at r_{200} of our M83 mass model is 143 km/s ensuring that the most common impact velocities of subhalos were covered.

The generated spiral arm structures were compared to the ones obtained from the THINGS HI map (Walter et al. 2010) with a least squares approach.

For subhalo masses between 1e7 and 1e9 solar masses nearly no mass dependency was found. All three cases have best fit impact parameters of 8 kpc and impact velocities of 170-190 km/s. Only the 1e10 solar mass impact shows significant deviation, which is a result of the more efficient tidal mass stripping leading to the destruction of the subhalo at small impact parameters.

We found two possible ways to create spiral arm with low mass subhalos. Fig 2 shows the more probable scenario where the satellite enters at around virial velocity of the host halo and is deflected during the pericenter passage. Higher deflection angles are more effective in creating symmetric arms, but the shallow halo+stellar potential restrict the deflection angle severely, leading to lopsided arms.

The second mode involves unrealistically high impact velocities at several times the virial host halo velocity. The subhalo shoots nearly un-deflected through the disk and the wake cutting through the disk is sheared away simultaneously at both sides of the galactic center creating nicely symmetric (for small impact parameters) spiral arms. In both cases only prograde trajectories lead to morphologies resembling grand spiral arms.

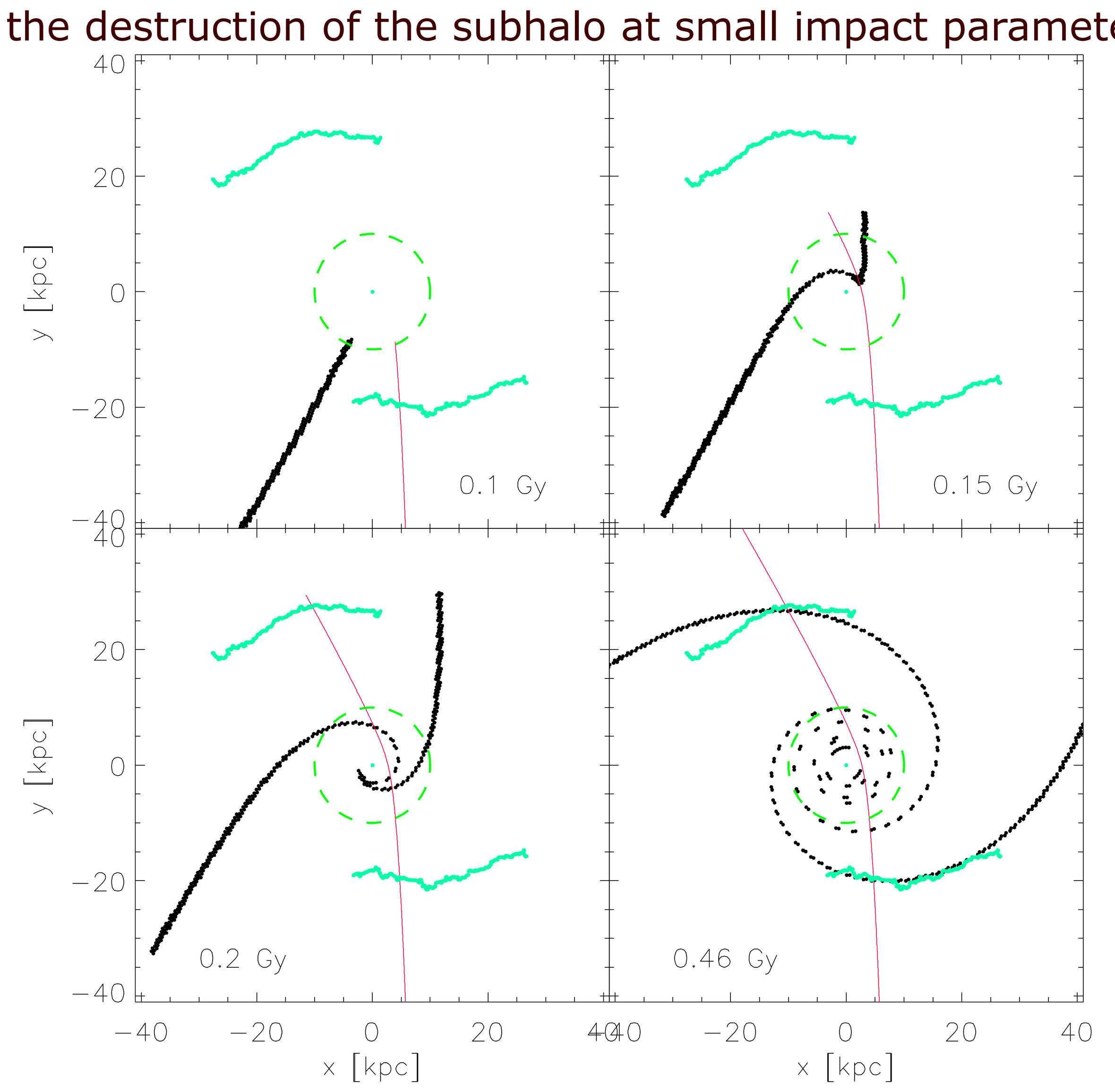

Fig 2: Several snapshots in time of the spiral arm creation by a 1e9 solar mass subhalo. The time stamps show the time after entering the extended HI disk. The deflected tracer particles are shown in black, the trajectory of the subhalo is shown in red and the M83 spiral arms as well as the optically visible disk (dashed line) in teal.

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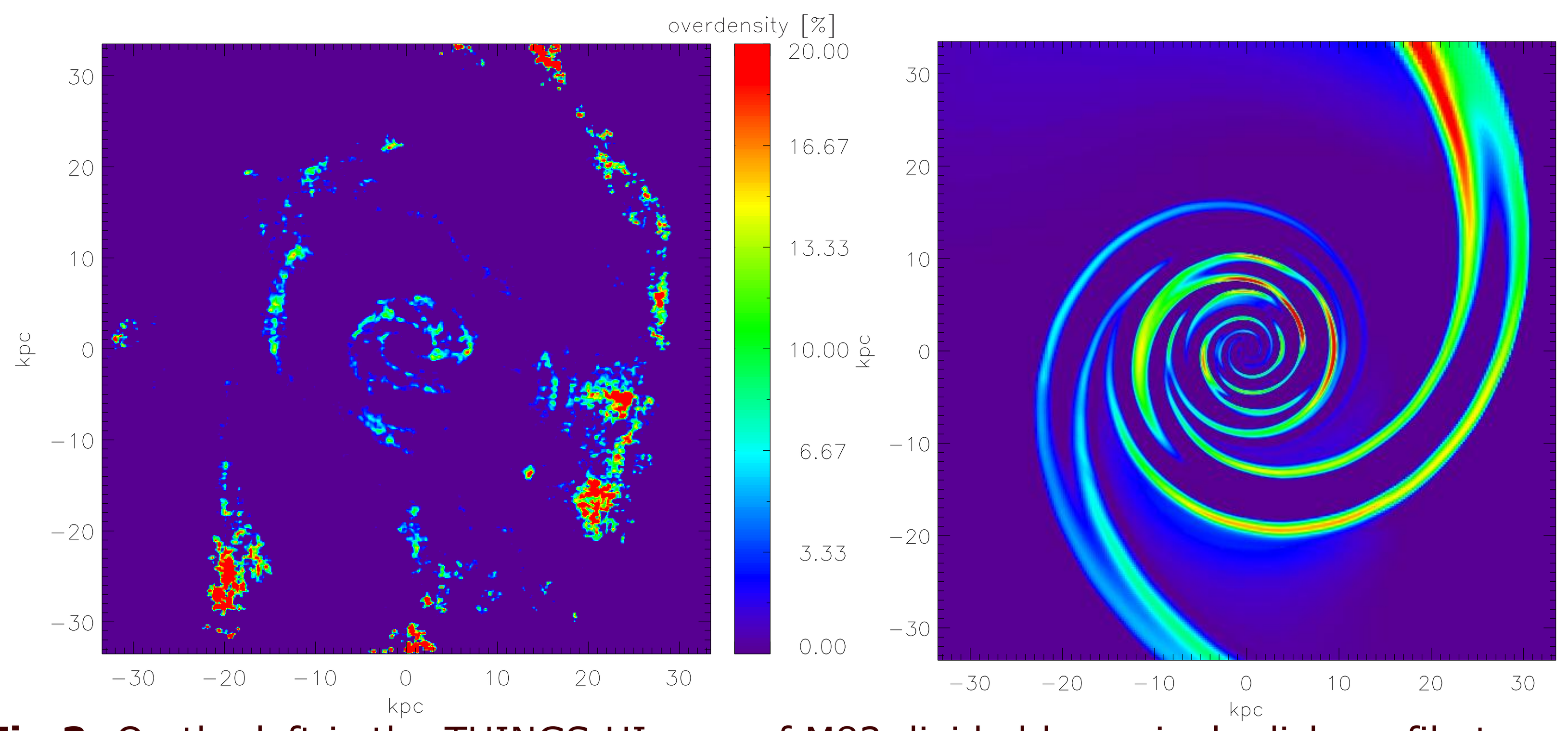

Fig 3: On the left is the THINGS HI map of M83 divided by a single dish profile to gain the observed overdensities in the arms. On the right is the 1e9 $M_\odot$ subhalo RAMSES simulation at the best fit time of 0.46 Gy. The optically visible disk has a radius of 10 kpc and would mask the wound up spirals in the center seen on the right.

To break the mass degeneracy (see Fig 1) full 3d hydrodynamic simulations were performed with a live HI disk embedded in the same analytical halo+stellar potential that was used in the three body study. The same prescription for the dynamical friction and tidal mass loss was employed additionally. Fig 3 shows the 1e9 solar mass subhalo simulation in comparison with the HI THINGS data. We find good agreement in the generated overdensities and the overall morphology. The bifurcation seen in the simulation stems from the subhalo losing mass rapidly during its pericenter passage, leading to the division of the wake as the it becomes too light to hold onto all of the wake.

Conclusions and Speculation

- Low mass subhalo impacts can create grand design spiral arms.
- The extended HI disk could be used as a detector for small mass subhalos if more massive pert-urbers are absent.
- As there is a high number (100s) of 1:1000 M_{sub}/M_{host} subhalos, impacts on the extended disk are likely.
- Subhalos are able to create wakes in extended HI disks that might lead to enhanced localised star formation.

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