# CAP - report of assignment 4

Lennart van Sluijs, Marco TvdB

December 4, 2017

## 1 Introduction

For assignment 4 we performed several hydrodynamical simulations of the collision of a neutron star ($M_n = 1.3 M_\odot$) with a massive main-sequence star ($M_{MS} = 10$ M$_\odot$) using varying initial conditions. We wonder under what circumstances a Thorne-Zytkov object (neutron star in the core of a main-sequence star) can form and under what circumstances the system becomes a bound binary system.

## 2 Methods

Our default initial setup for all simulations is summarized in Table 1. For every setup we deviate slightly from this initial setup to investigate different parts of the parameter space. First we use a stellar evolution code to create a main-sequence 10 $M_\odot$ star. Then we launch the neutron star into the target and integrate the hydrodynamical simulation for the full simulation lifetime. For every simulation we save a set of final parameters of the system: the number of particles contained within the star, the number of escaped particles, the mass of the stellar object after the merger, the massloss of the original stellar object, the radius of the final stellar object, the kinetic energy of the system and star and neutron star, the potential energy of the system and star and neutron star and finally the position and velocity of the final stellar object and neutron star. We ran simulations with: (i) varying number of SPH particles between $N_{\mathrm{SPH}} \in \{10, 100\}$ (ii) varying impact parameter $b \in \{0, 1\}$ (iii) varying initial velocity $v_{\mathrm{kick}} \in \{50, 1000\}$km/s for an impact parameter $b = 1$ (iv) both the impact parameter and initial kick velocity for the same parameter space as (ii) and (iii). (v) a simulation with an impact parameter $b = 0$ and varying initial velocities between 500-2000 km/s to check which velocity is sufficient for the neutron star to shoot through the main-sequence star.

## 3 Results

Our results are summarized in the Figures below.

| Parameter | Value |
|---|---|
| $M_{MS}$ | 10 $M_\odot$ |
| $M_n$ | 1.3 $M_\odot$ |
| $R_n$ | 10 km |
| $b$ | 0 |
| $v_{\mathrm{kick}}$ | 1000 km/s |
| $t_{\mathrm{sim}}$ | 25 h |
| $\delta t$ | 0.05 h |
| $N_{\mathrm{SPH}}$ | 100 ${M_\odot}^{-1}$ |
| $t_{\mathrm{coll}}$ | 0.01 Myr |

Table 1: Default parameters for all simulations. $b$ indicates the impact parameter. $v_{\mathrm{kick}}$ the velocity in negative x-direction gained after the supernova kick. $t_{\mathrm{sim}}$ the total simulation duration. $\delta t$ time step for the hydrodynamical simulation integrator. $N_{\mathrm{sph}}$ number of particles per unit solar mass. $t_{\mathrm{coll}}$ time to evolve primary target to a main-sequence star using a stellar evolution code.

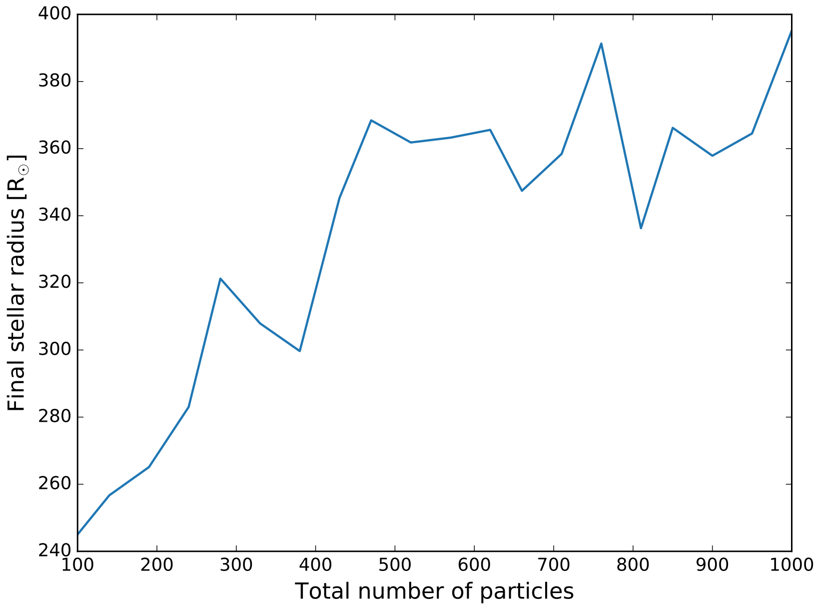


Figure 1: The radius of the final stellar object as a function of the number of SPH particles.

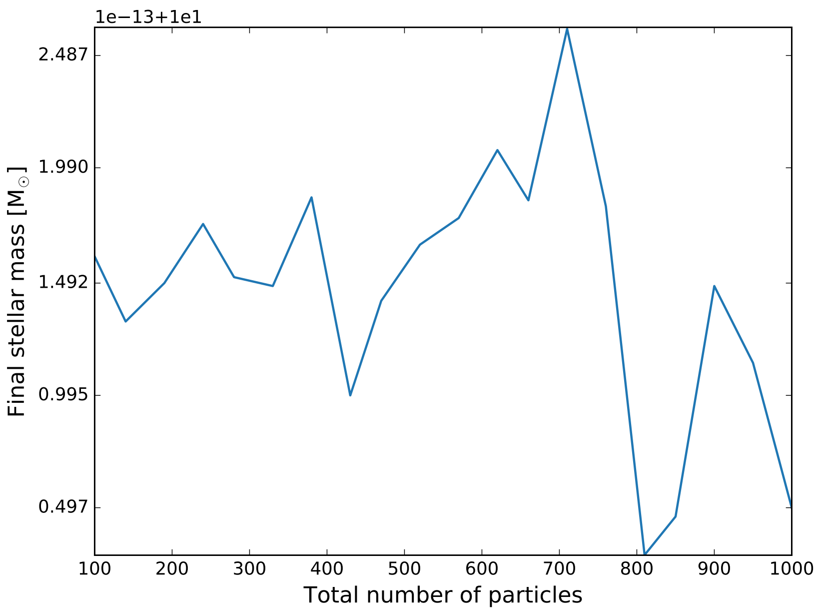


Figure 2: Final stellar mass as a function of the number of SPH particles

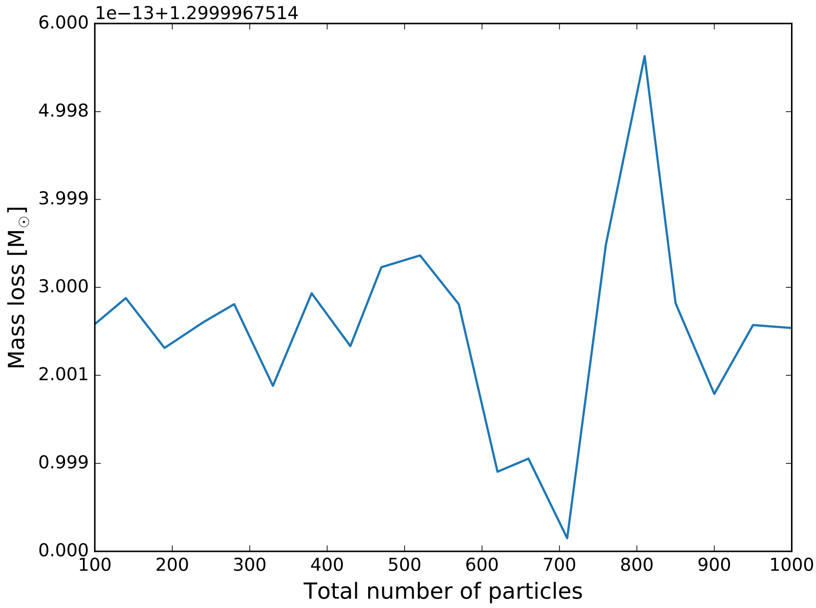


Figure 3: Final mass loss as a function of the number of SPH particles.

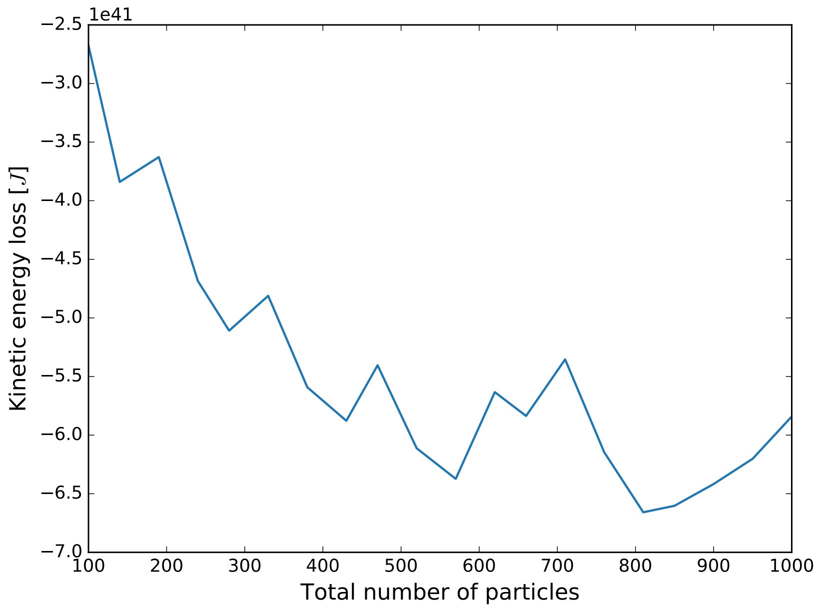


Figure 4: Distance of the neutron star to the final stellar object's center and the radius of the final stellar object.

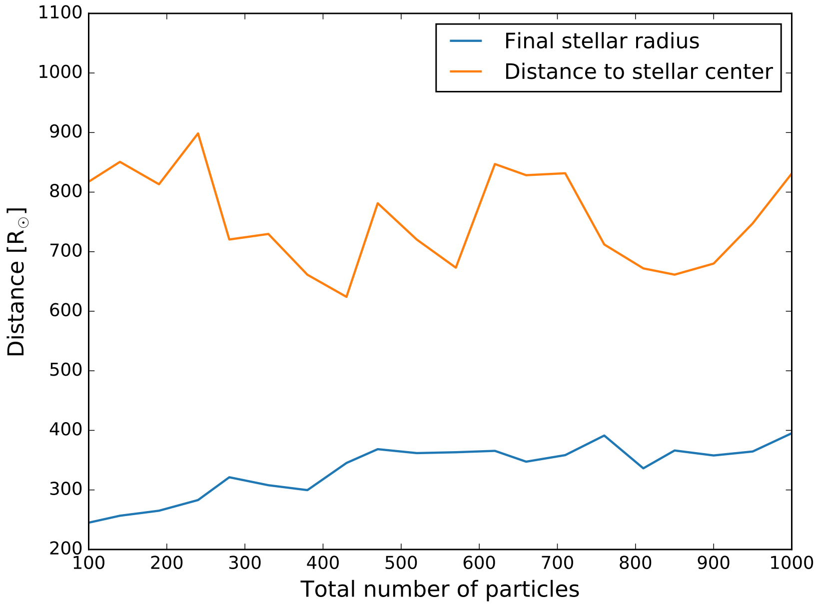


Figure 5: Distance of the neutron star to the final stellar object's center and the radius of the final stellar object as a function of the number of SPH particles.

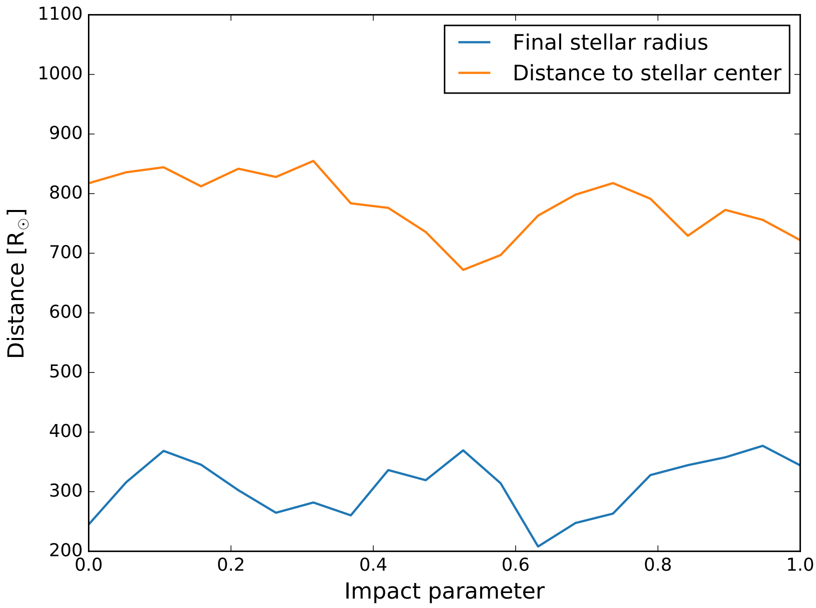


Figure 6: Distance of the neutron star to the final stellar object's center and the radius of the final stellar object as a function of the impact parameter.

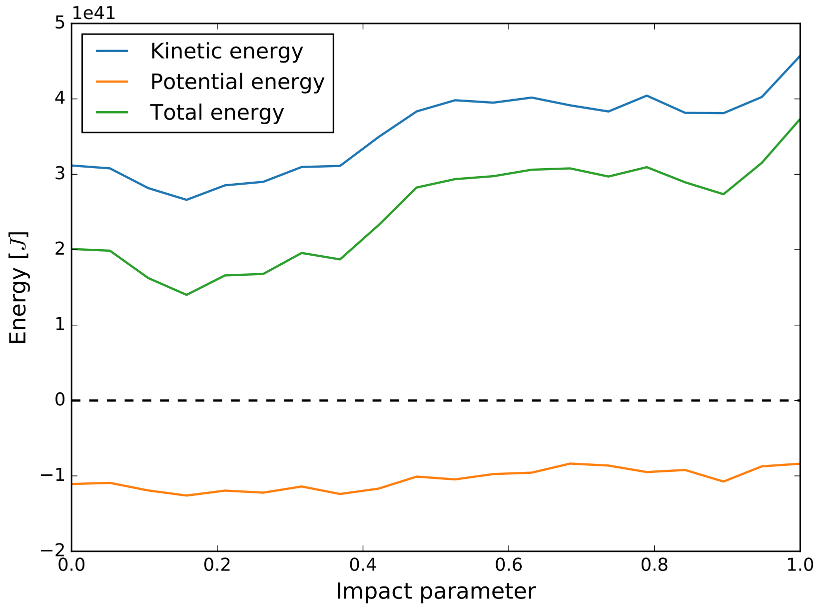


Figure 7: Energy as a function for different impact parameters.

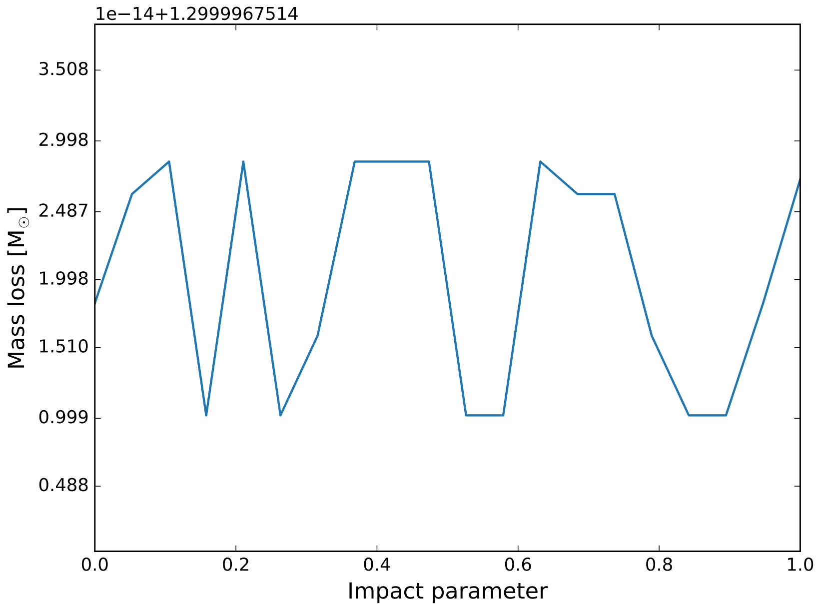


Figure 8: Mass loss as a function of the impact parameter.

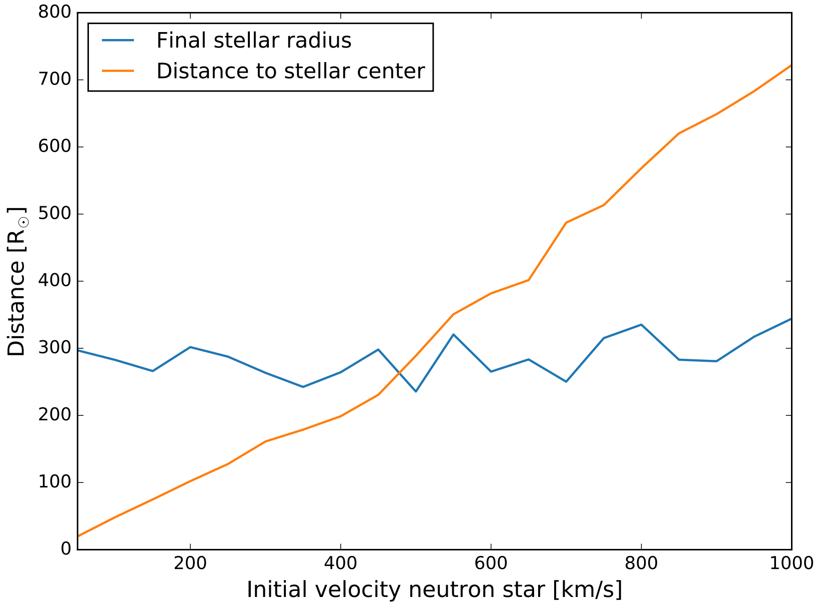


Figure 9: Final stellar radius and distance to stellar center of the neutron star for different initial kick velocities.

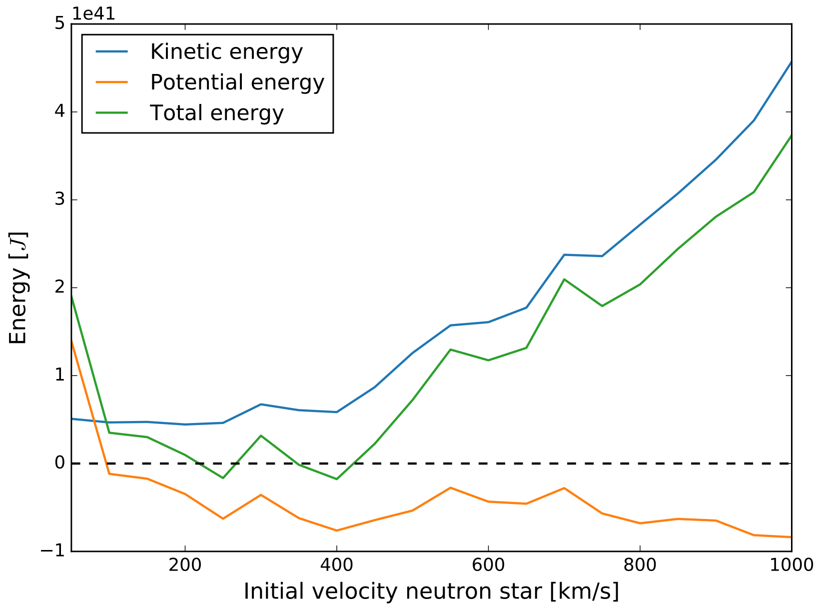


Figure 10: Energy as a function for different initial kick velocities for $b = 1$.

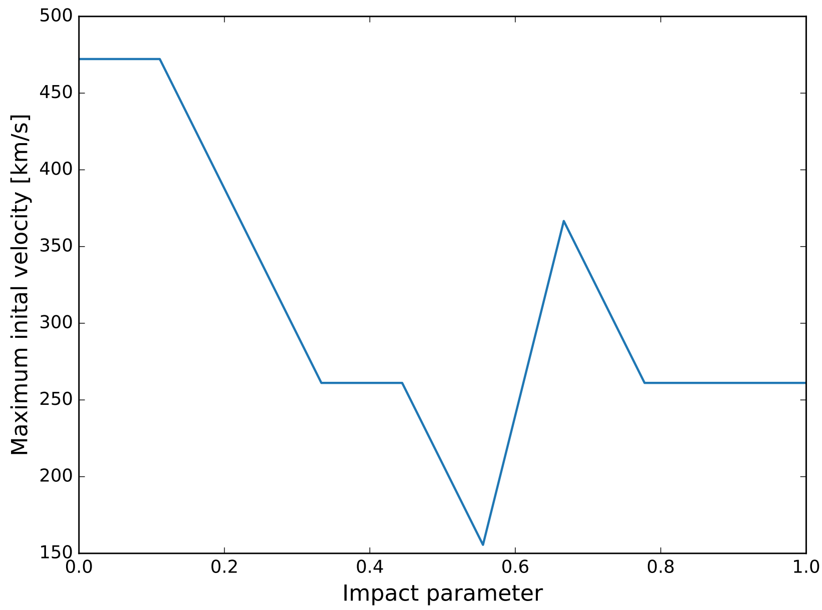


Figure 11: Maximum velocity for which the system becomes bound as a function of the impact parameter.

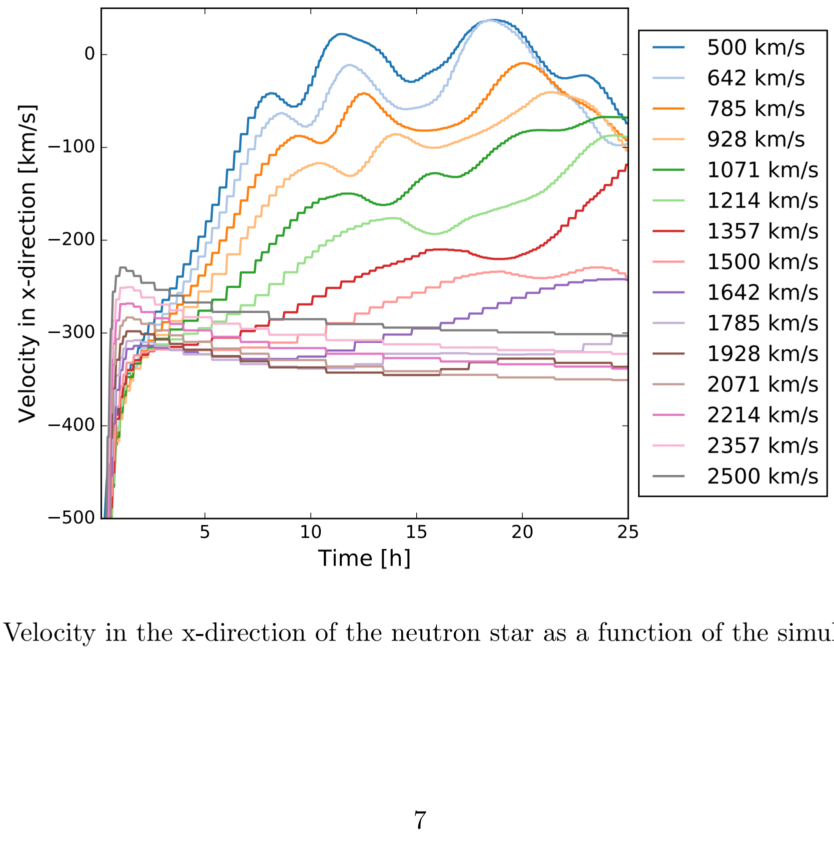


Figure 12: Velocity in the x-direction of the neutron star as a function of the simulation time.

We calculate the three orbital parameters semi-major axis, eccentricity and inclination for the bound system using the AMUSE Kepler code *get_ elements()*. Since we take the plane spanned by the star and the neutron star as the orbital plane vector, the relative inclination is zero degrees. Furthermore, we get a semi-major axis of 0.56 AU and an eccentricity of 0.99.

# 4 Discussion

Figures 1, 2, 3 and 4 show the results from simulation (i) where the number of particles varies. In Figure 1 we for simulations with $>$ 500 particles the radius of the final stellar object stays about constant. This suggest convergence of the simulation for $\sim$ 500 particles. Figure 2 and Figure 3 show both the mass of the final stellar object and mass loss are quite stable, no matter the amount of particles. Therefore, the final radius of the object is most-likely a better estimate whether convergence happened already or not. This hypothesis is supported by Figure 4 which shows the kinetic energy loss stabilizes as well around $\sim$ 500 particles. Figure 5 shows the distance of the neutron star with respect to final stellar object as well as again the final stellar object radius. Here we will assume the simulation ran sufficiently long such that if the neutron star is closer than the stellar radius to the center of the final stellar object the two objects have 'merged'. However, we see this is never the case for our initial setup during simulation (i). Most likely the velocity is too large for the neutron star to merge with the final stellar object. Therefore no Thorne-Zytkov object is formed.

Figure 6 shows if the neutron star and main-sequence star merged for varying impact parameters for simulation (ii). Even with varying $b$ nowhere does the neutron star get swallowed by the main-sequence star. This is probably due to the large initial velocity which prevents a merger even for larger $b$ values. Figure 8 shows the mass loss as a function of the impact parameter which is again quite stable for all impact parameters. Figure 7 shows the total, kinetic and potential energy at the final state for different impact parameters. As in agreement with Figure 6 the total energy is never negative, meaning the system never becomes bound. Again this is likely due to the large initial kick velocity.

Figure 9 shows distance to the final object's center of the neutron star as a function of the initial kick velocity for simulation (iii). We see for a velocity of about 470 km/s the neutron star sticks to the companion star and thus forms a Thorne-Zytkov object. Figure 10 shows the total, kinetic and potential energy at the final state for different initial kick velocities. We see around $\sim$ 400km/s the total energy becomes negative, implying the system is bound. This is slightly lower than the velocity in Figure 9, but both are of the same order of magnitude.

Figure 11 shows the maximum initial kick velocity for the system to remain bound as a function of the impact parameter as found after simulation (iv). This velocity was calculated as the maximum velocity for which the final total energy of the system is negative implying the system is bound. This velocity slowly decreases as a function of impact parameter. This is as expected since the neutron star is slowed down much more when hitting the main-sequence star head-on then at an angle.

Figure 12 shows the results of simulation (v). As can be seen for low initial velocities the neutron star becomes bound and the velocity starts to oscillate towards zero. However, after some critical initial velocity the pattern changes and the velocity never slows down anymore. This can be seen in Figure 12 as two sets of curves: one with velocities $<$ 1500 km/s and one with velocities $\geq$ 1500 km/s. Thus the critical velocity is $\sim$1500 km/s. This can be understood since the escape velocity given by

$$v_{\text{esc}} = \sqrt{\frac{2GM}{R}}, \tag{1}$$

equals about 1544 km/s $\approx$ 1500 km/s for an object with the mass and radius of our main-sequence star. We need exactly to overcome the potential of this object to escape, thus we indeed expect the velocity to shoot through the main-sequence star to be around this value.

In reality however the neutron star hits the primary star from it's orbit. Our primary star has a radius of 1.6 $R_\odot$. Now assume that our original secondary star orbits this star at a 1 au distance. This means the angle $\theta$ that the radius of the star fills equals

$$\theta = \arctan \frac{1.6 R_\odot}{1\text{au}} = 0.426\,\text{deg}. \tag{2}$$

Now the whole star fills a cone with angle $2\theta$ on the sky and the solid angle $\Omega$ is given by

$$\Omega = 2\pi(1 - \cos\theta) = 0.000173 \text{ sr}. \tag{3}$$

The total sky fills $4\pi$ sr, so the ratio of the two indicates the probability the neutron star will hit the primary target assuming it is launched into every direction with equal probability. This gives a probability of $\sim 0.01\%$ of hitting the primary star, thus a very small probability. Therefore, Thorne-Zytkov object will be rare since both the right initial conditions have to be satisfied, but the kick has also a very small possibility of being directed into the right direction.

# 5 Conclusions

Our main conclusions are:

- Our simulations suggest $\sim$500 SPH particles are sufficient to simulate the collision of a neutron star and main-sequence star to determine if the system becomes a bound system or if a Thorne-Zytkov object will be formed.
- The initial velocity and impact parameter are of crucial importance whether or not the system stays bound, unbound or whether a Thorne-Zytkov object is formed.
- Lower initial kick velocities are allowed at higher impact parameters for the system to stay bound.
- Only for sufficiently low velocities a Thorne-Zytkov object can be formed. Lower impact parameters increase this possibility.
- The velocity needed to shoot through the main-sequence star is about equal to the escape velocity of this object.
- A theoretical calculation suggest the actual number of neutron stars that are kicked into their main-sequence binary companion is very low, because the probability of the neutron star being directed into the right direction is very low.