Simulation of a double degenerate (WDWD) binary system with FLASH

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Goals of the project

1. Simulate the Roche lobe overflow of a double degenerate binary system (WDWD) in 2D using the grid-based FLASH code.

2. Compare our results with particle-based simulations in the literature.

White Dwarfs

* End point of stellar evolution for most stars.

* Supported by electron-degeneracy pressure.

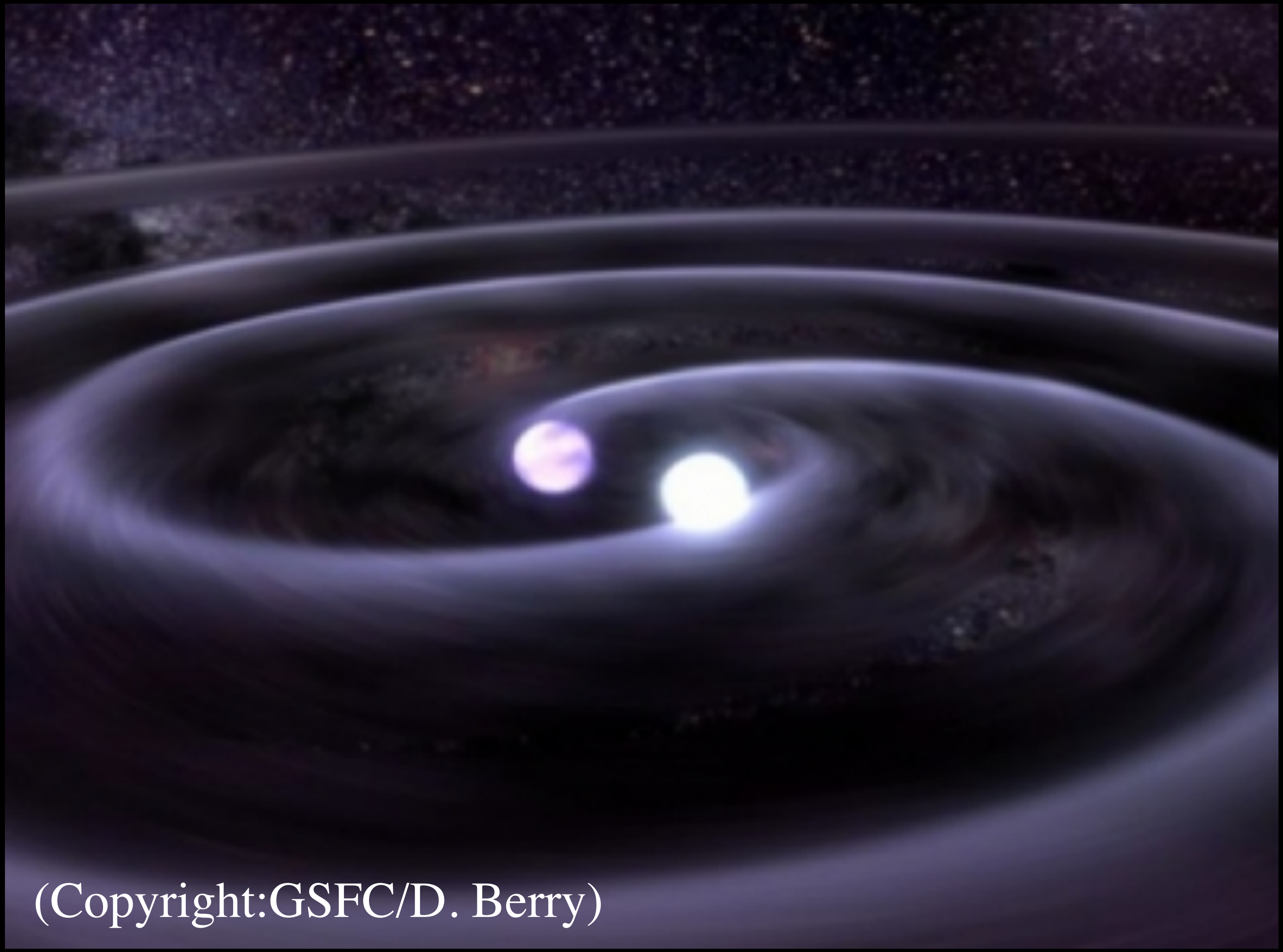
$$P_{deg} \propto \rho^{5/3}$$

* This pressure prevents the gravitational collapse of WDs bellow the Chandrasekhar mass limit (~ 1.44 $M_{\odot}$)

- ⋆ Earth-sized and almost as massive as the Sun.
- ⋆ One of the densest forms of matter. We are surrounded by ~ 10^{10} of them in the Milky Way.

Original image by ESA/Hubble

Double degenerate (DD) systems



The study of DD binaries is crucial

Because:

1. At least two phases of mass transfer: good tests for binary evolution theories.

2. If a WD accretes matter from companion, a type 1a Supernova may occur, whose explosion mechanism is still under debate.

3. Low frequency gravitational waves.

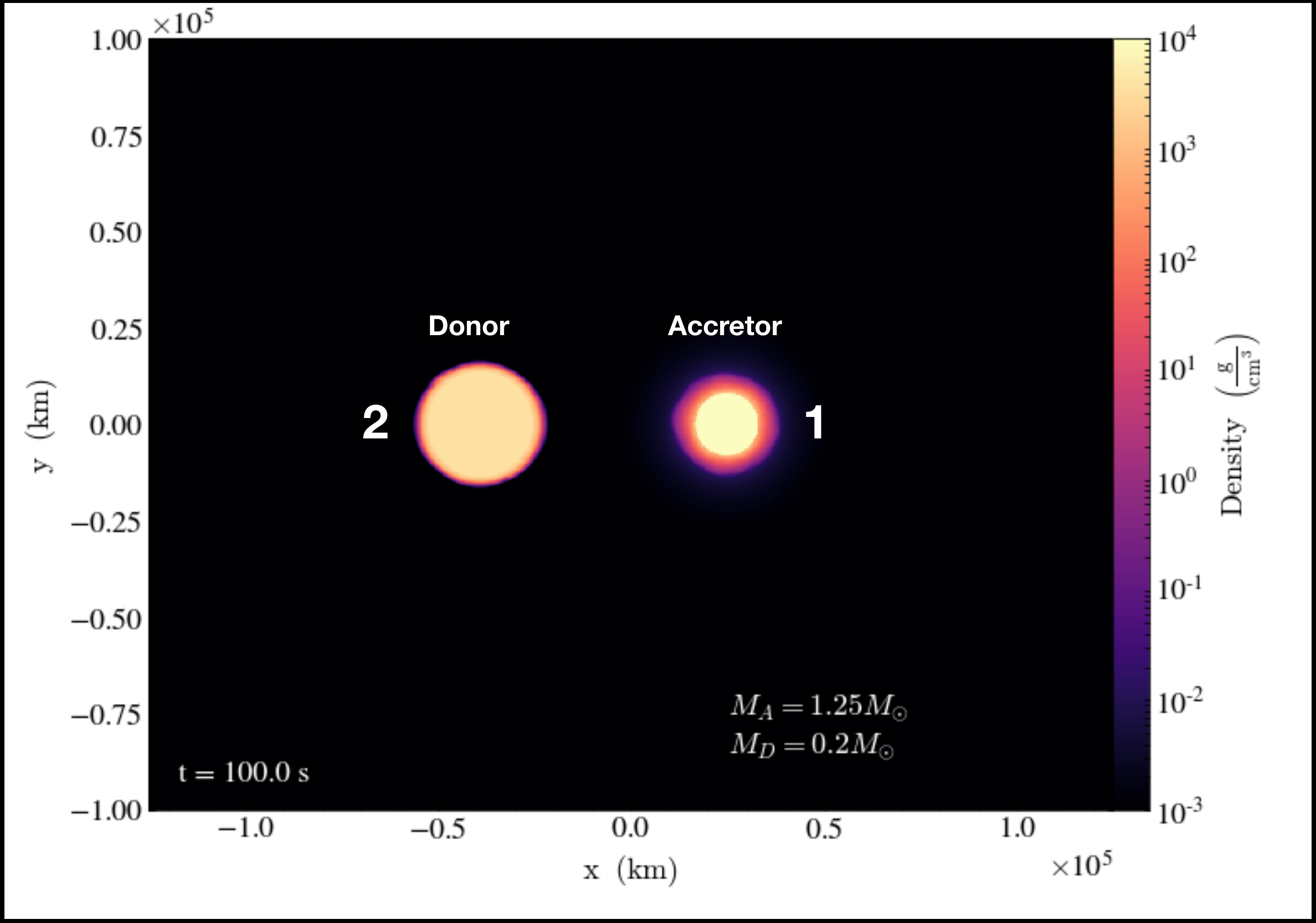
4. Sources of super-soft X-rays if nuclear burning ignited.

The FLASH simulation

1. Initializing simulation

- Primary and secondary WD initially at hydrodynamical equilibrium. Very well described by spherical polytropes of n = 1.5.

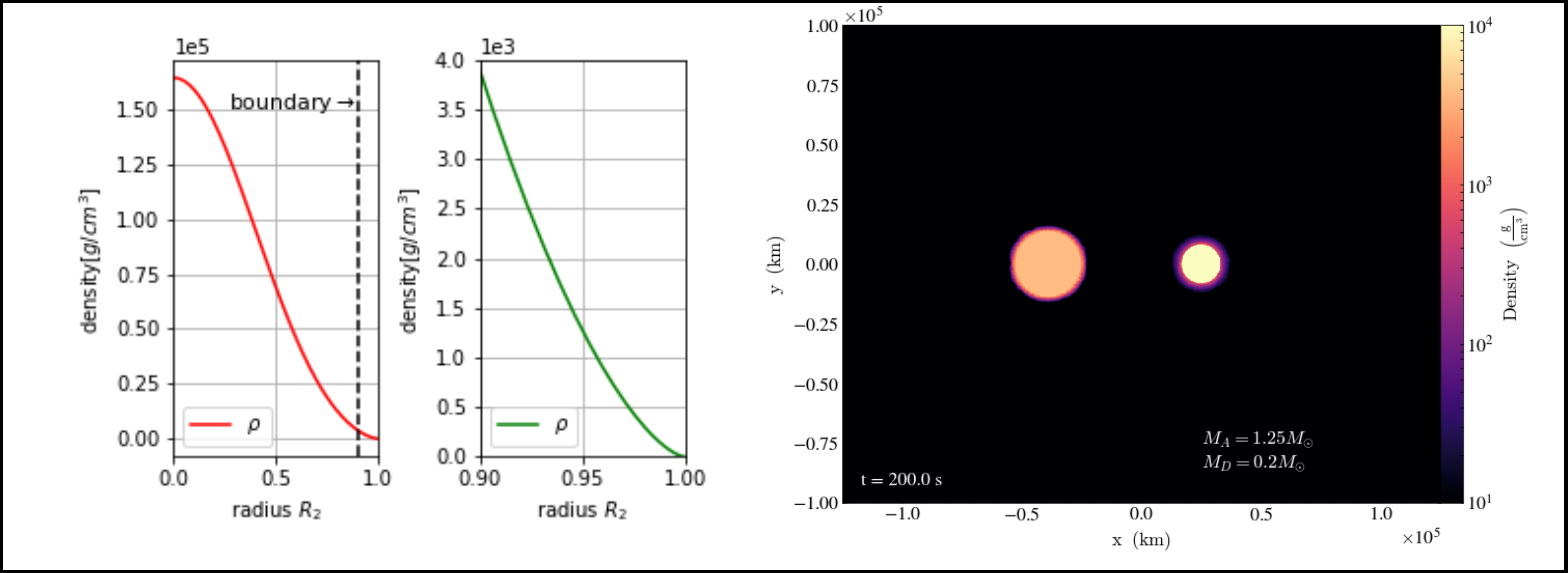
- Solutions mapped into the x-y plane. Hydrodynamical equations not solved along the z-direction.



(Ian P.)

- To prevent FLASH from refining uninteresting regions, we replace fractions of primary and secondary with a constant density (boundary condition).

(Ian P.)



1D initial condition for a polytrope (secondary WD)

Simulation domain

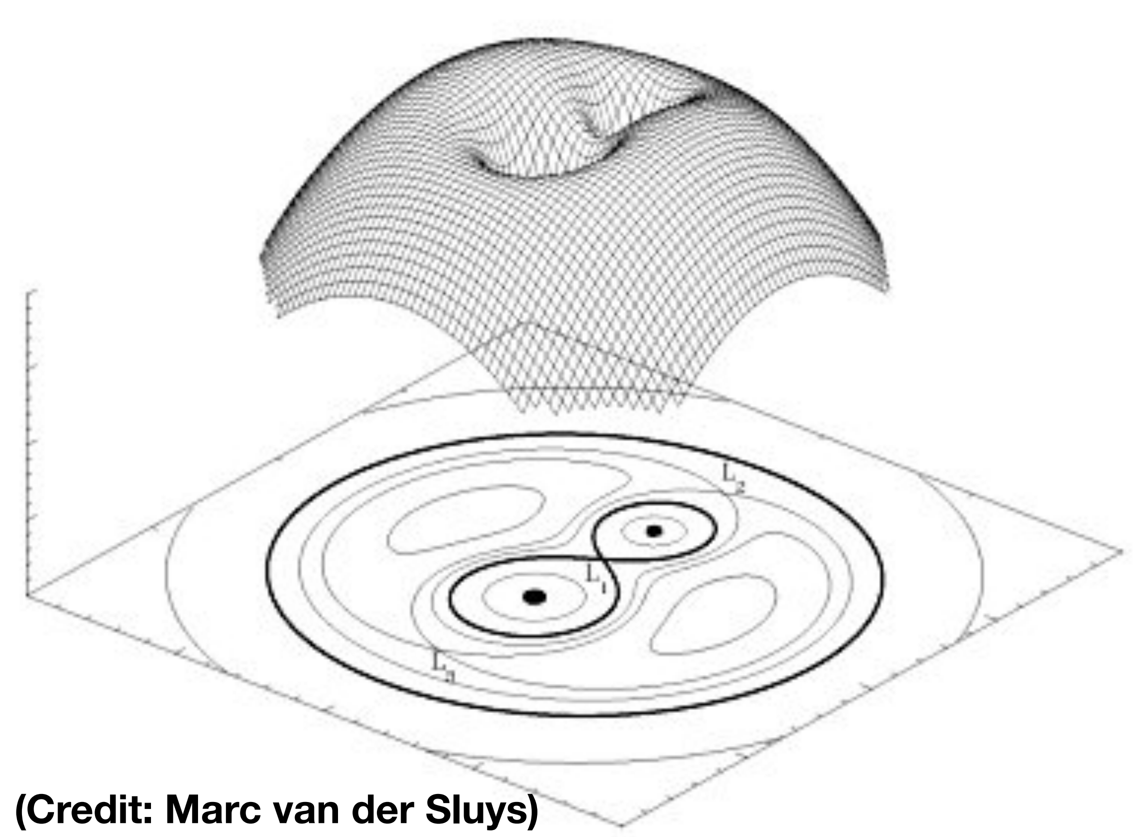
- Binary separation is such that secondary completely fills its Roche lobe.

Eggleton's approx.

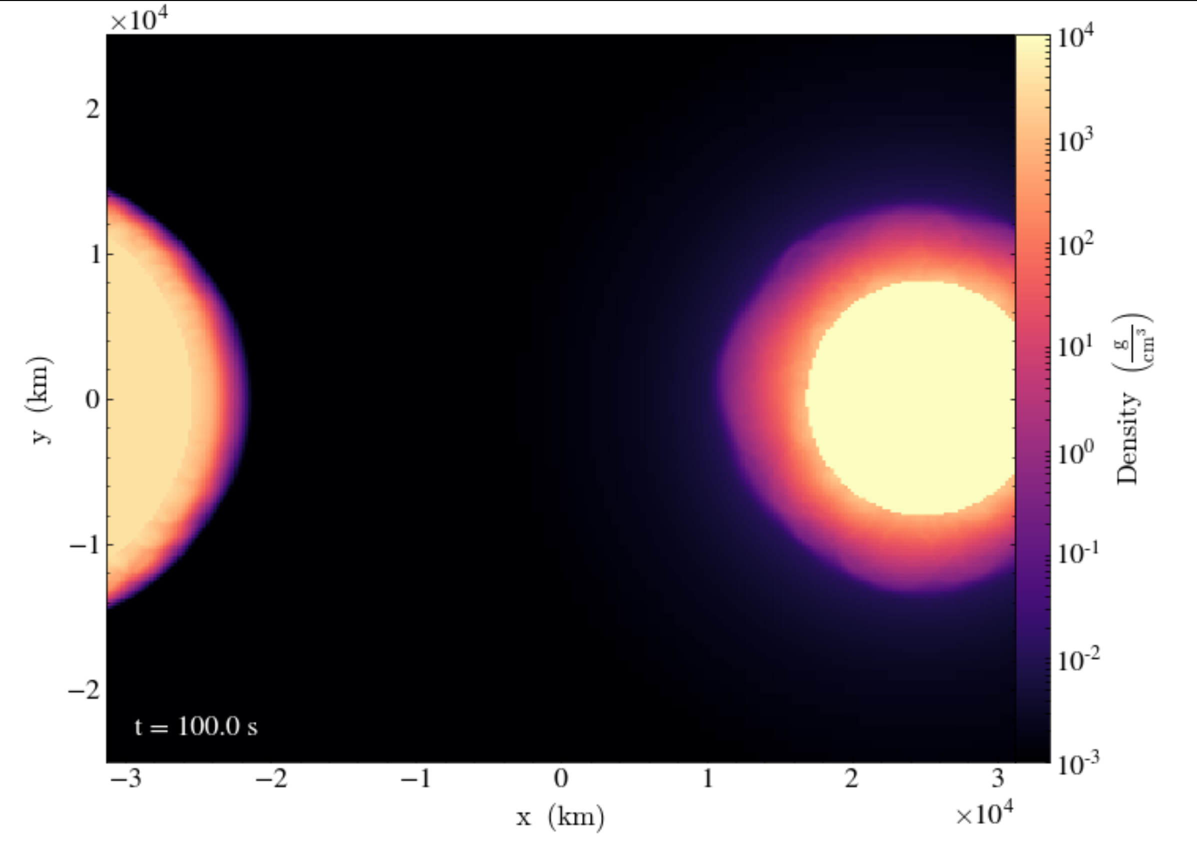
$$\frac{R_L}{a} = \frac{0.49q^{\frac{2}{3}}}{0.60q^{2/3} + \log(1 + q^{\frac{1}{3}})}$$

$$q = \frac{M_2}{M_1}$$

$$R_L = R_2$$



(Credit: Marc van der Sluys)

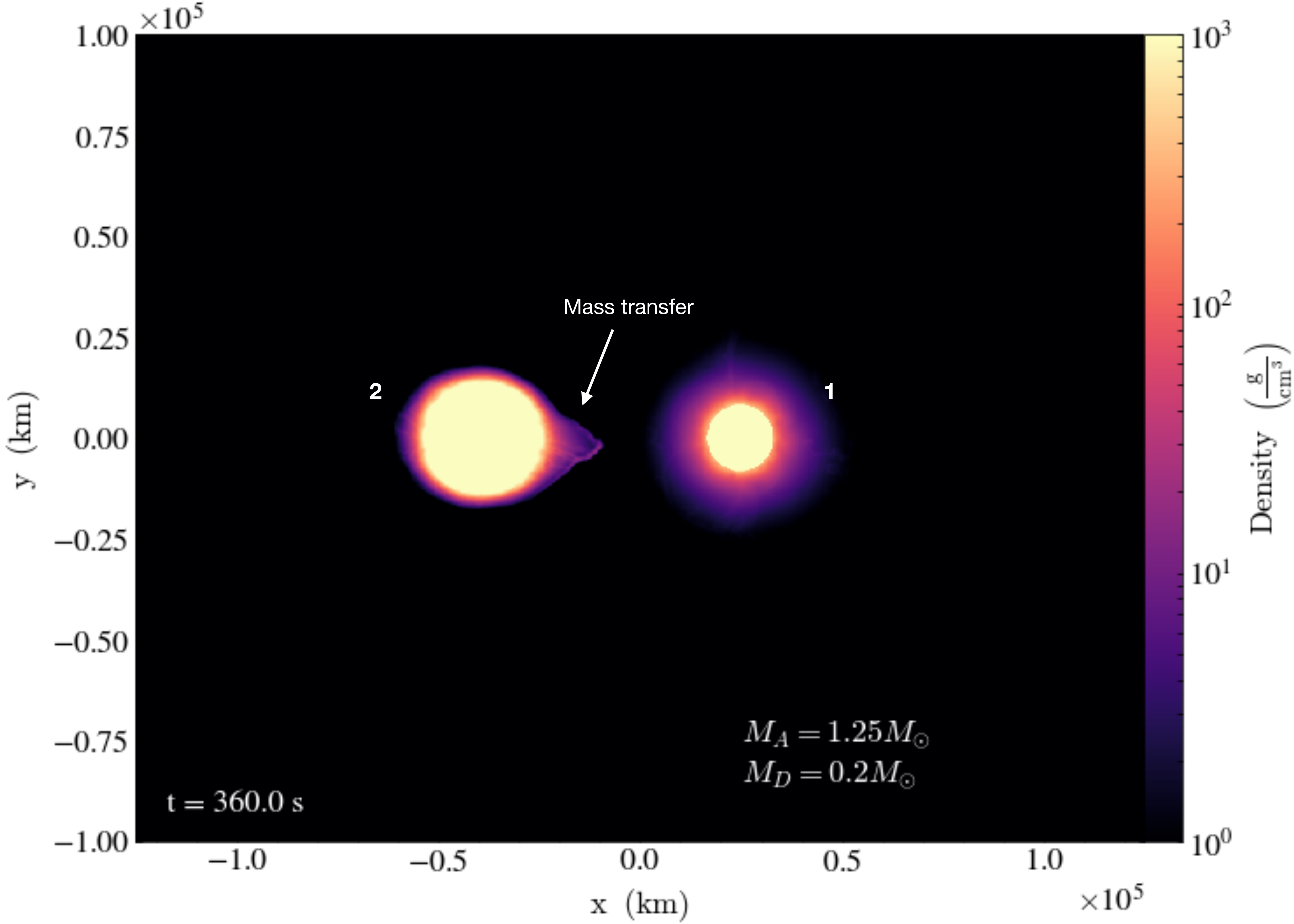


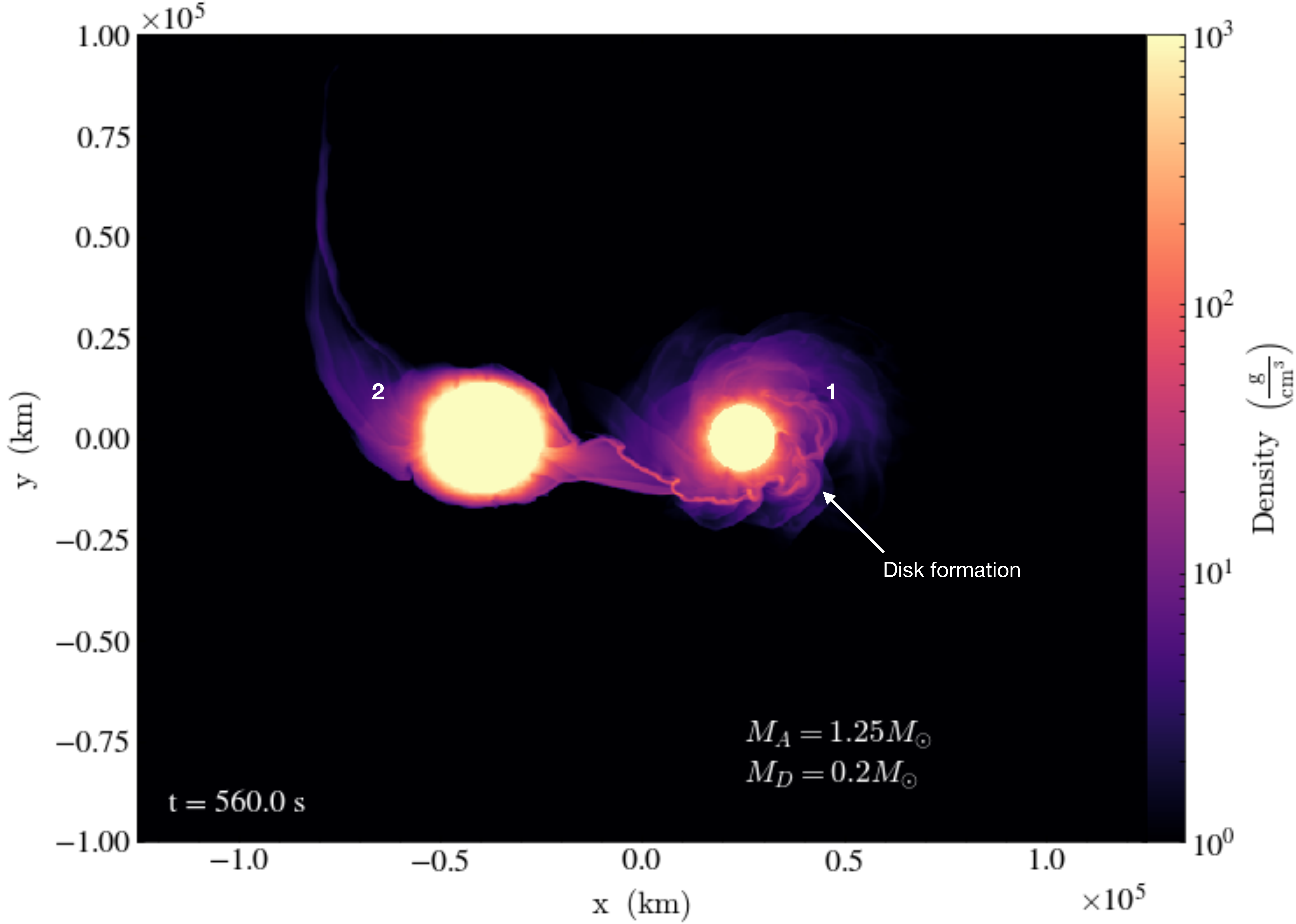
(Ian P.)

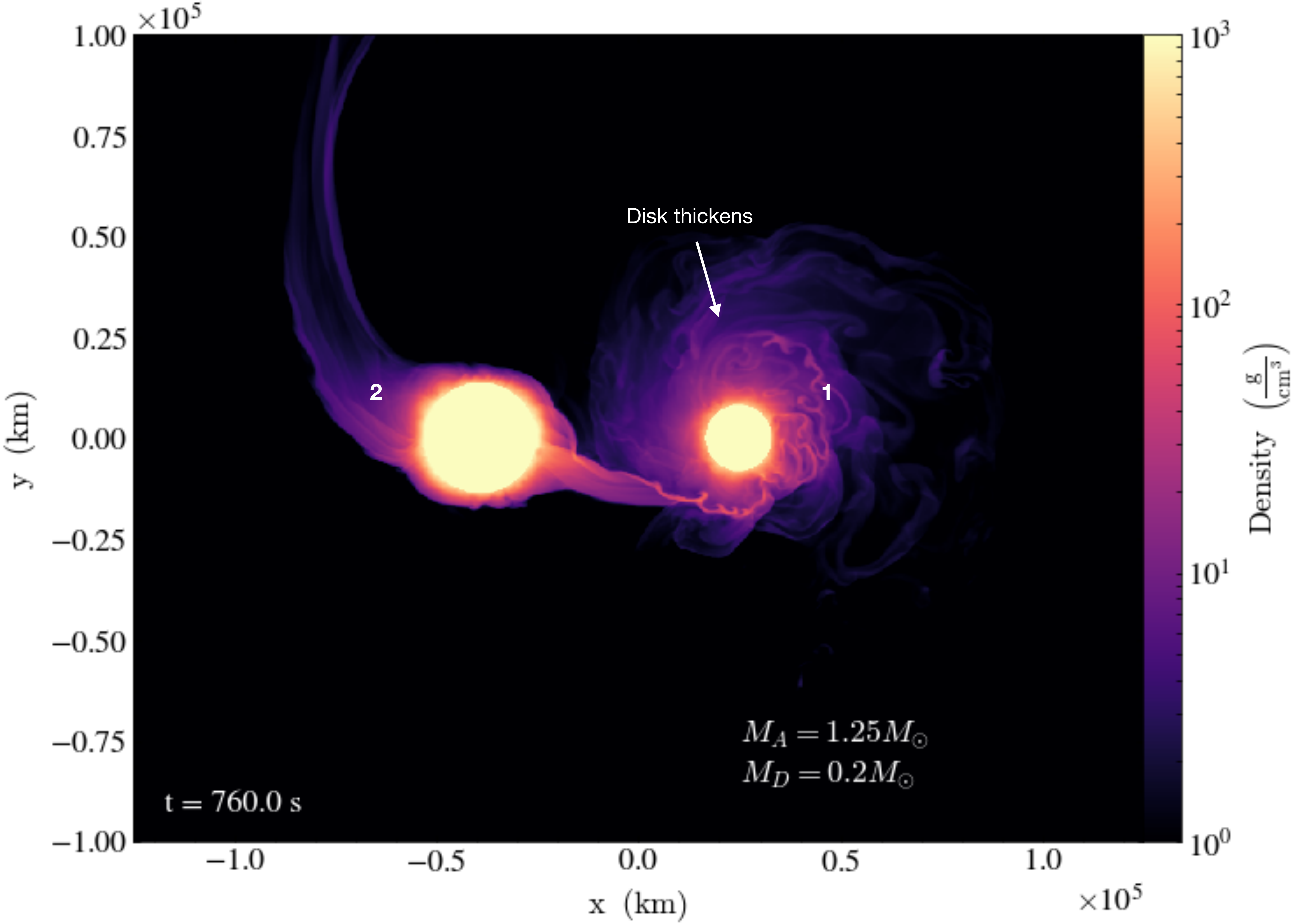
2. Evolving simulation

- The choice of (co-rotating) frame and the presence of companion affect the hydrostatic configuration: Let them relax!
- After many dynamical time scales (350 s), we stop the relaxation routine.
- Gravitational field accounts for point-mass-, coriolis- and centrifugal forces.
- Temperatures are computed using the ideal-gas equation of state.

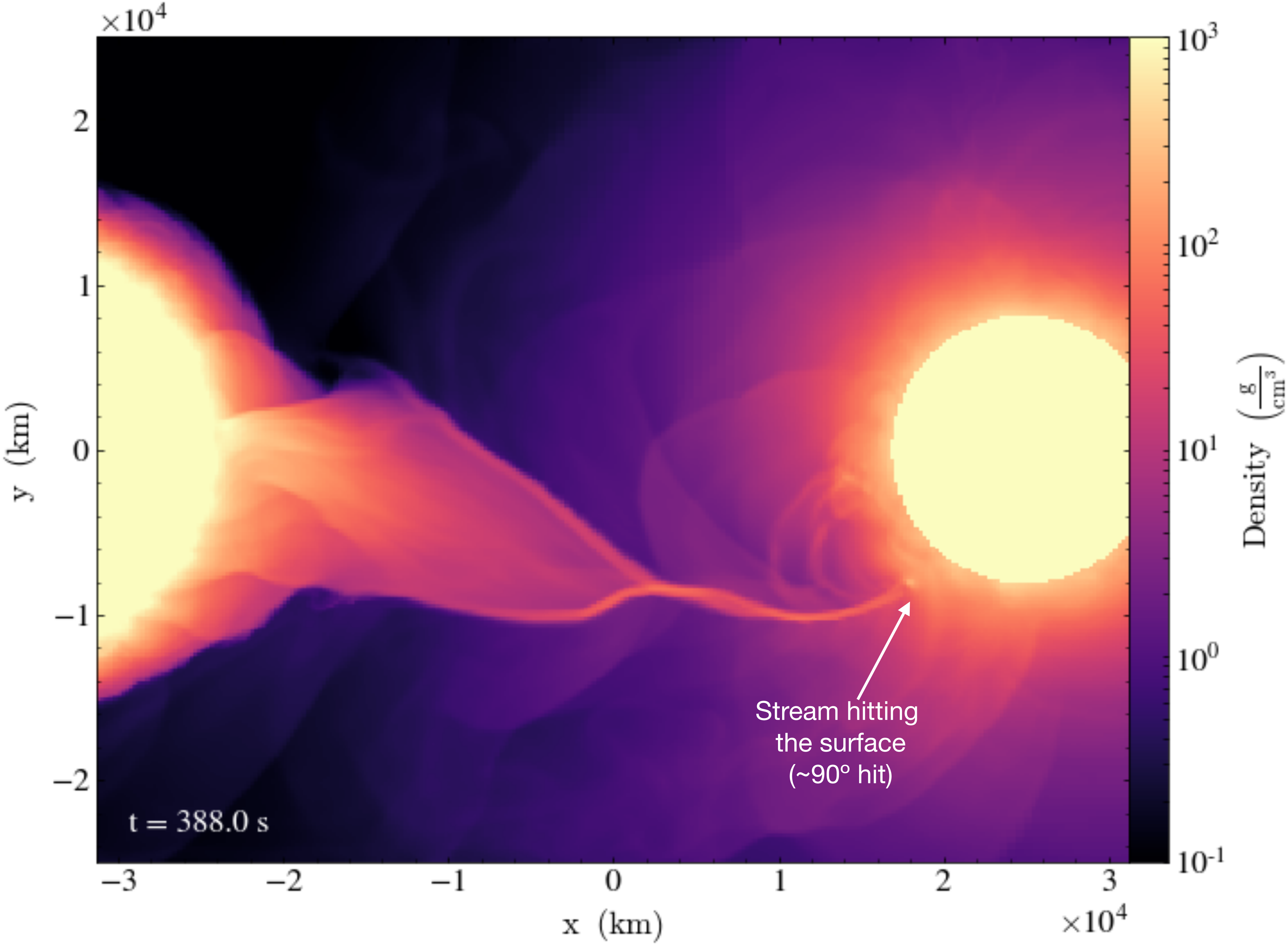
3. Results


Mass transfer
2
1
$M_A = 1.25 M_\odot$
$M_D = 0.2 M_\odot$
t = 360.0 s
x (km)
y (km)
Density $\left(\frac{g}{cm^3}\right)$

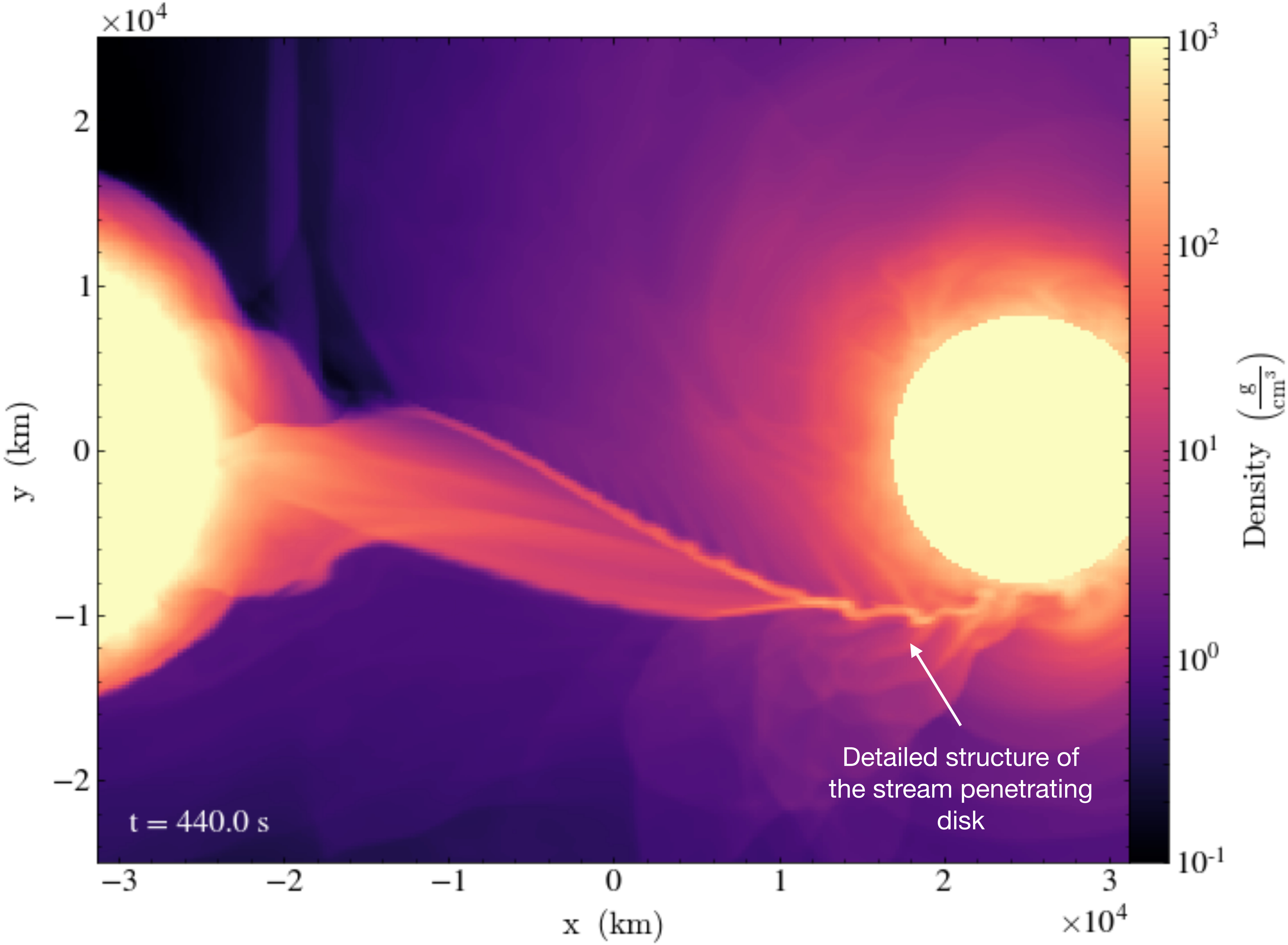

×10^5
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
y (km)
−1.0
−0.5
0.0
0.5
1.0
x (km)
×10^5
2
1
Disk formation
$M_A = 1.25 M_\odot$
$M_D = 0.2 M_\odot$
t = 560.0 s
10^3
10^2
10^1
10^0
Density $\left(\frac{g}{cm^3}\right)$



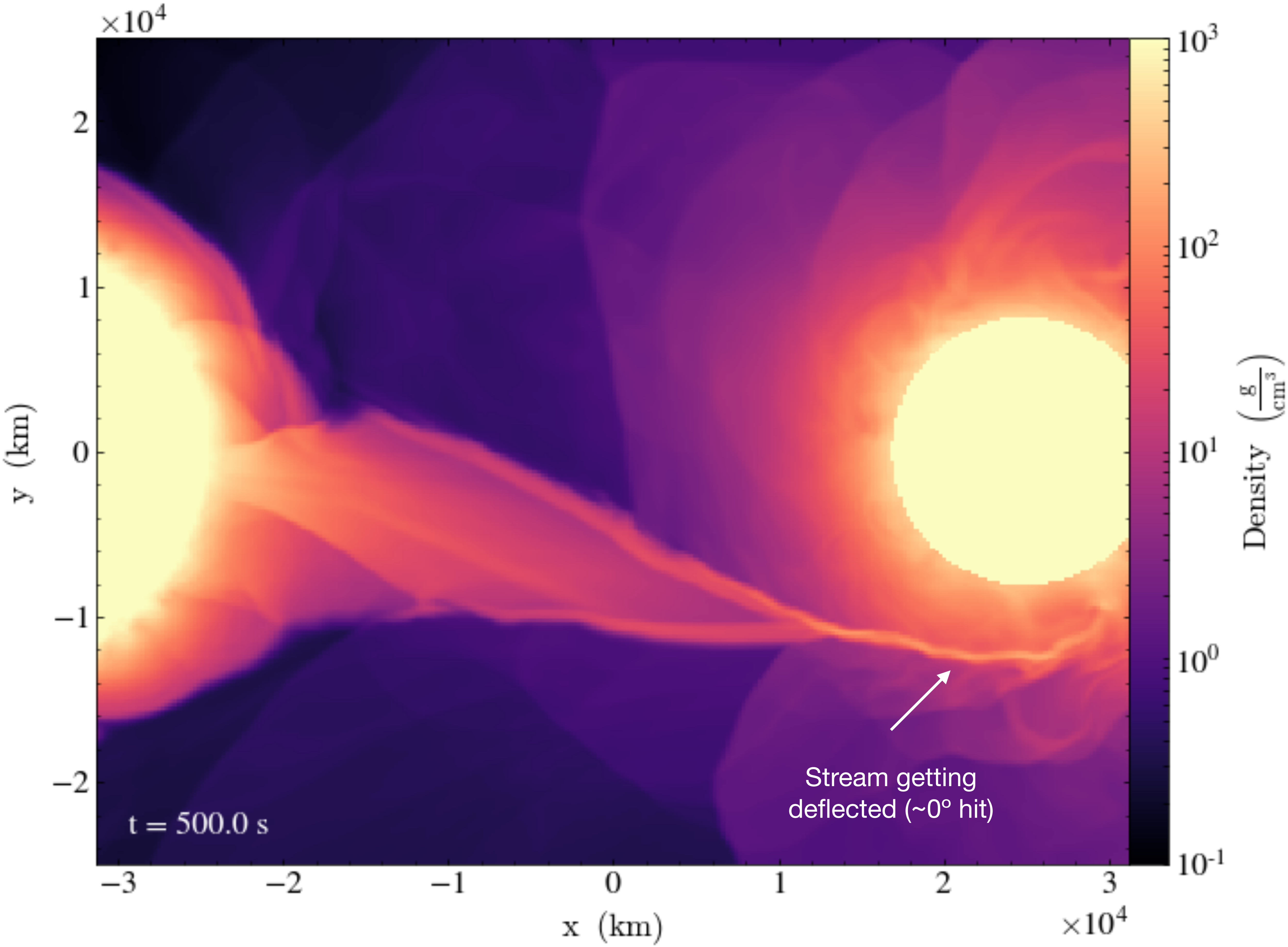
$\times 10^5$
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
y (km)
−1.0
−0.5
0.0
0.5
1.0
x (km)
$\times 10^5$
Disk thickens
2
1
$M_A = 1.25 M_\odot$
$M_D = 0.2 M_\odot$
t = 760.0 s
10^3
10^2
10^1
10^0
Density $\left(\frac{g}{cm^3}\right)$



×10^4
2
1
0
−1
−2
y (km)
t = 388.0 s
−3
−2
−1
0
1
2
3
x (km)
×10^4
10^3
10^2
10^1
10^0
10^-1
Density (g/cm^3)
Stream hitting the surface (~90° hit)



$\times 10^4$
2
1
0
−1
−2
y (km)
t = 440.0 s
−3
−2
−1
0
1
2
3
x (km)
$\times 10^4$
10^3
10^2
10^1
10^0
10^{-1}
Density $\left(\frac{g}{cm^3}\right)$
Detailed structure of the stream penetrating disk



×10^4
t = 500.0 s
Stream getting deflected (~0° hit)
y (km)
x (km)
×10^4
Density (g/cm^3)
10^3
10^2
10^1
10^0
10^-1

Conclusions

1. This simulation is a first step towards:

    A. Investigating the mass transfer of a DD binary.

    B. Studying the distribution of total angular momentum between the orbit and the spins of primary and secondary WD.

    C. Exploring direct impact and disk formation scenarios.

    D. Understanding the orbital evolution of the binary (controlled by GW emission) which leads to a merger and a possible explosive disruption.

Future work

A. Add chemical composition to WDs.

B. Explore parameter space to determine which binaries are prone to a thermonuclear explosion just prior to merger.

References and acknowledgments

1. J. Guillochon, M. Dan, E. Ramirez-Ruiz & S. Rosswog, 2009, arXiv:0911.0416.

2. W.P. Hawley, T. Athanassiadou, F.X. Timmes, 2012, arXiv:1209.3749.

3. M. Dan, S. Rosswog, J. Guillochon, E. Ramirez-Ruiz, 2012, arXiv:1201.2406.

4. The software used in this work was in part developed by the DOE NNSA-ASC OASCR Flash Center at the University of Chicago.

5. Special thanks to P. Macias and R. Navarrete at UCSC.