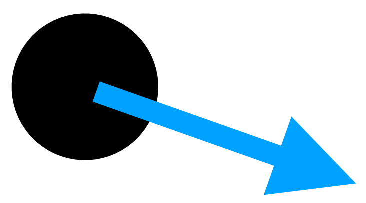
Particle-based simulations in Astrophysics

The N-body problem

The one body problem

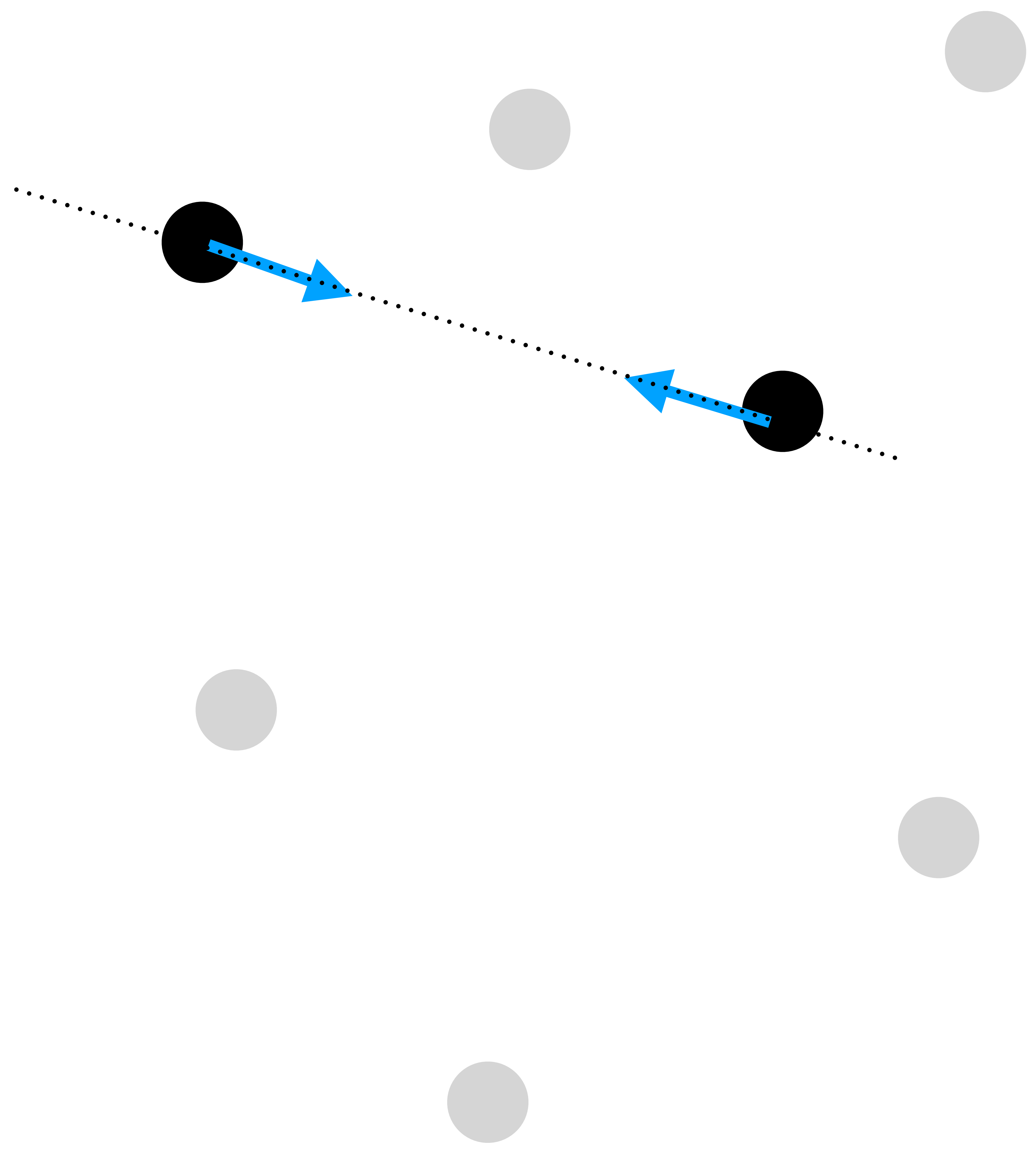
Consider one particle subjected to a force. How do you integrate its equation of motion numerically?



onebody.py

The N-body problem

Consider a set of N interacting particles. Each particle produces a force on each one of the rest. How would you integrate the equations of motion of each particle?

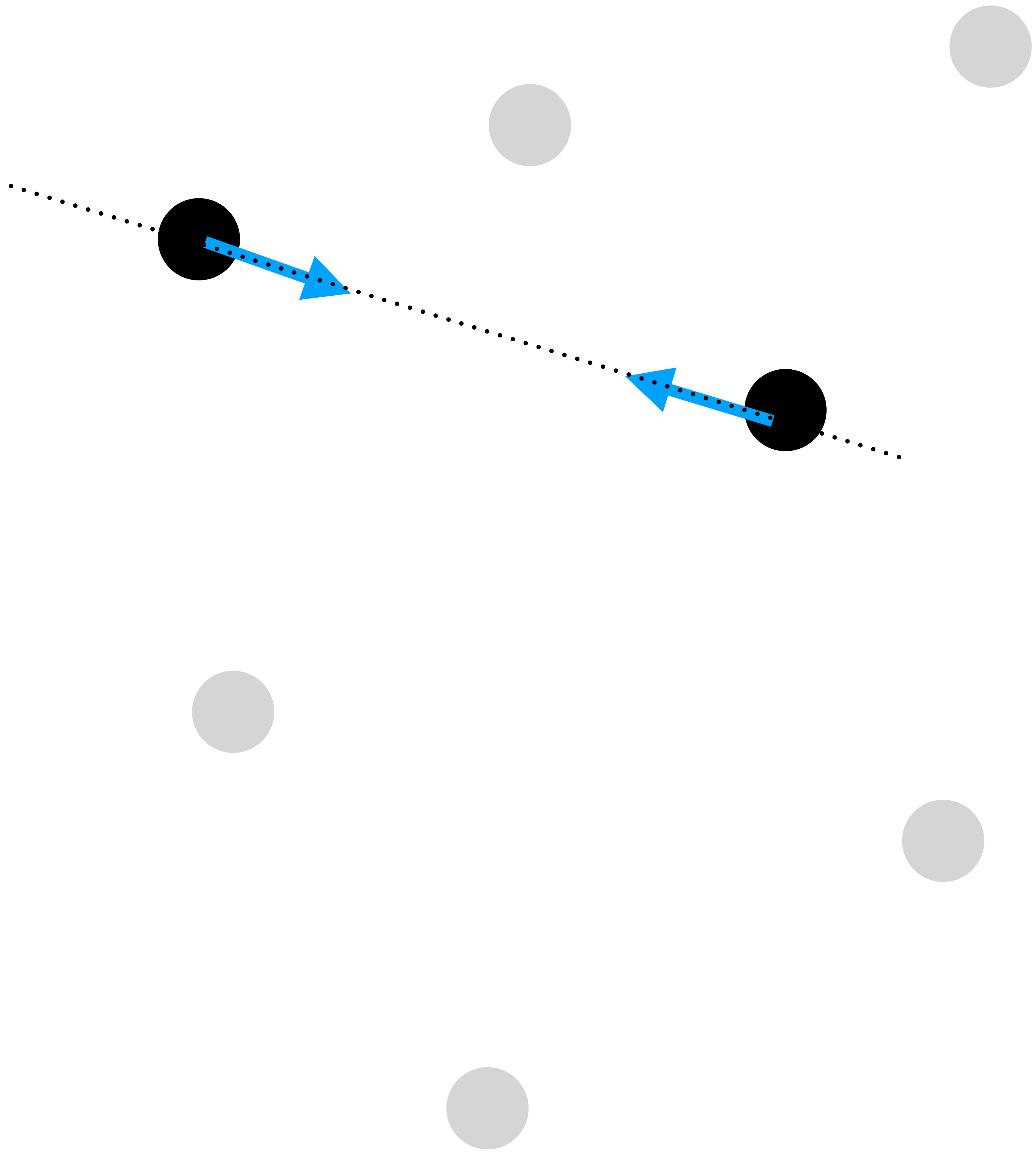


simplenbody.py

Problems with the N-body problem

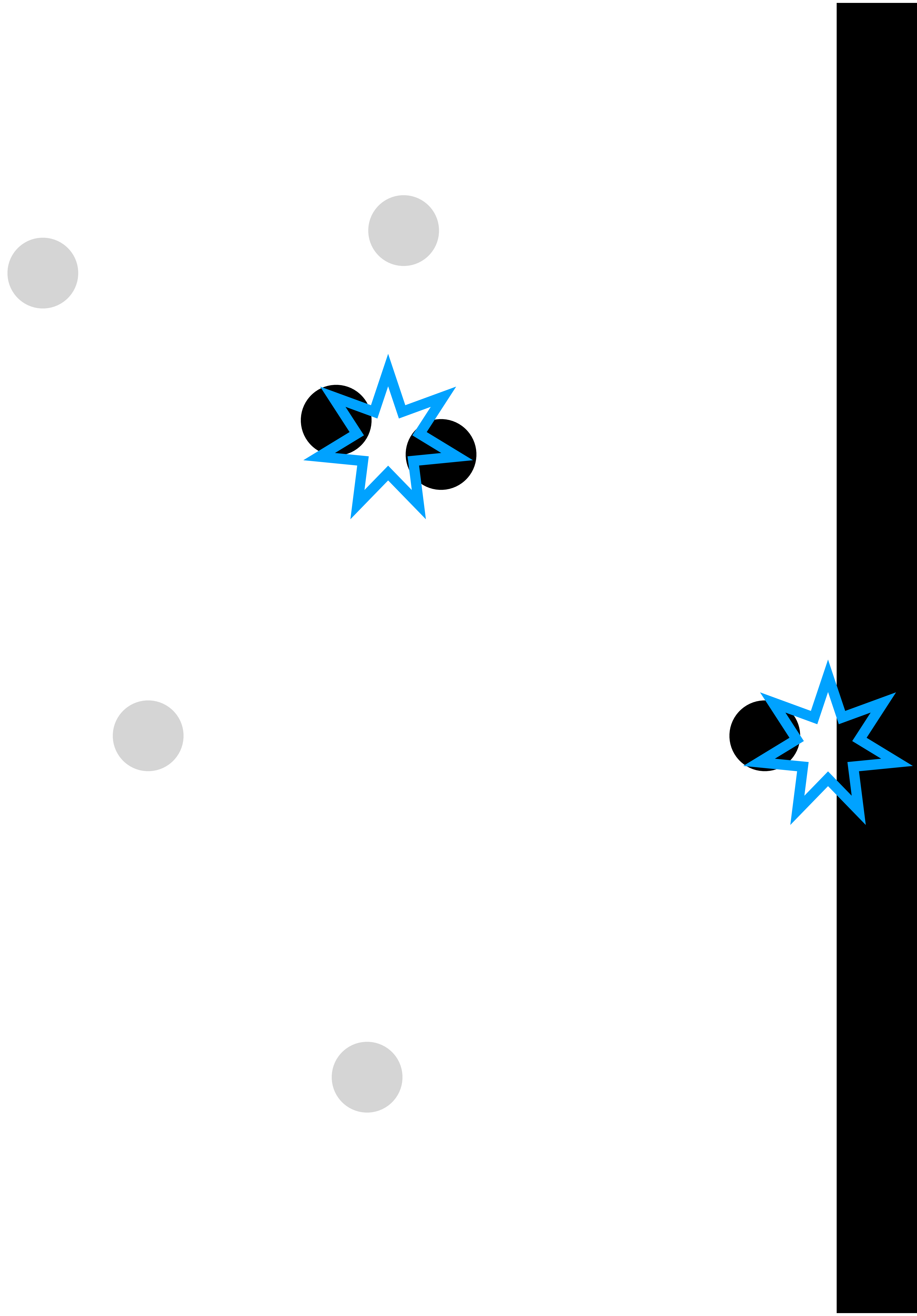
- What happens when two particles come very close to each other?
- What happens when we include a lot of particles?

simplenbody.py



The ideal gas

In this example, we handle elastic collisions between particles and elastic collisions against a wall.



idealgas.py

Rebound

This is a proper N-body integration library. It can be used to study, for example, perturbations in the orbits of a (forming) planet.

rebound_earthsun.ipynb

rebound_jupiter.ipynb

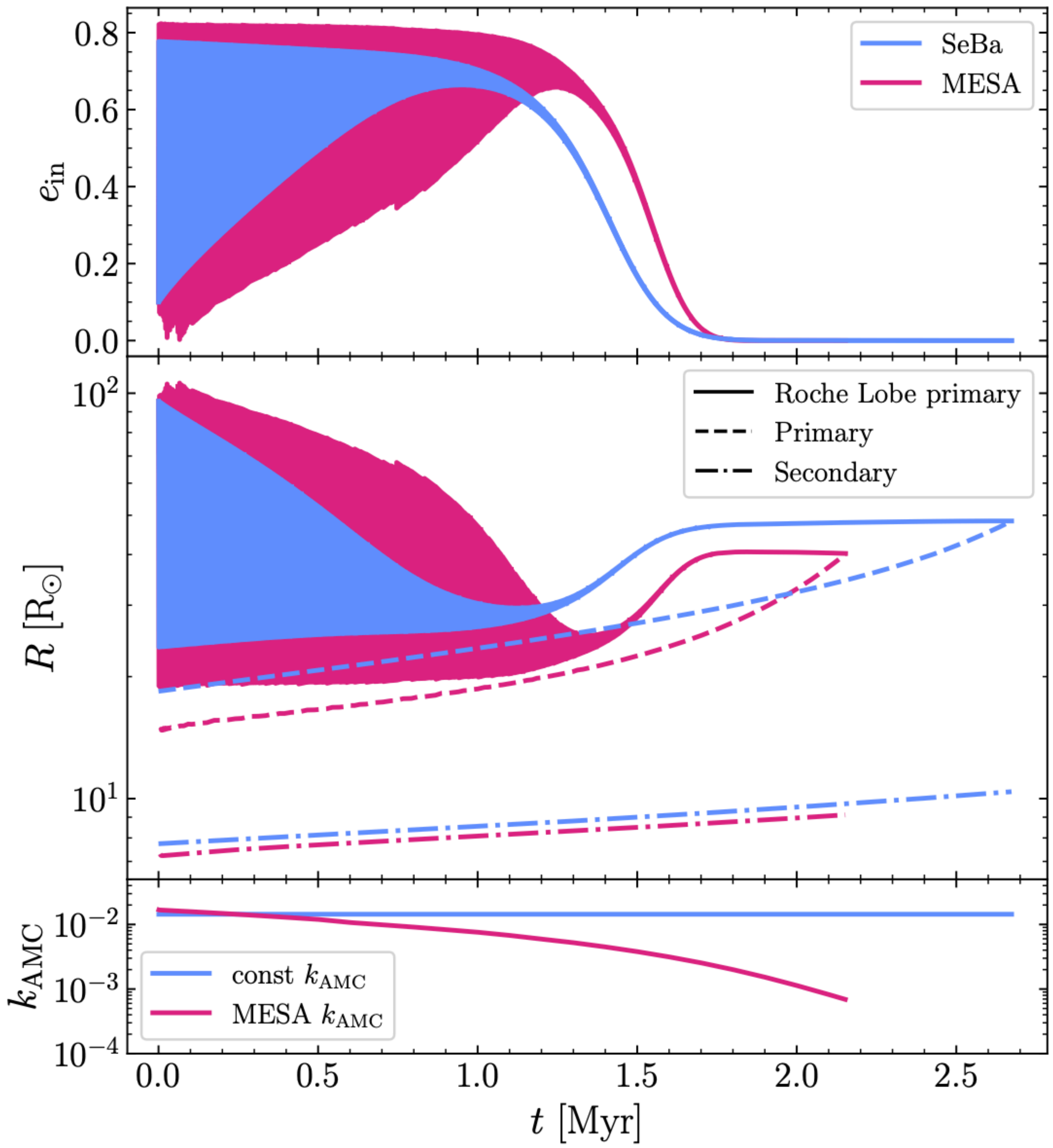
EccentricComets.ipynb

example from research

Stellar evolution of triple stars

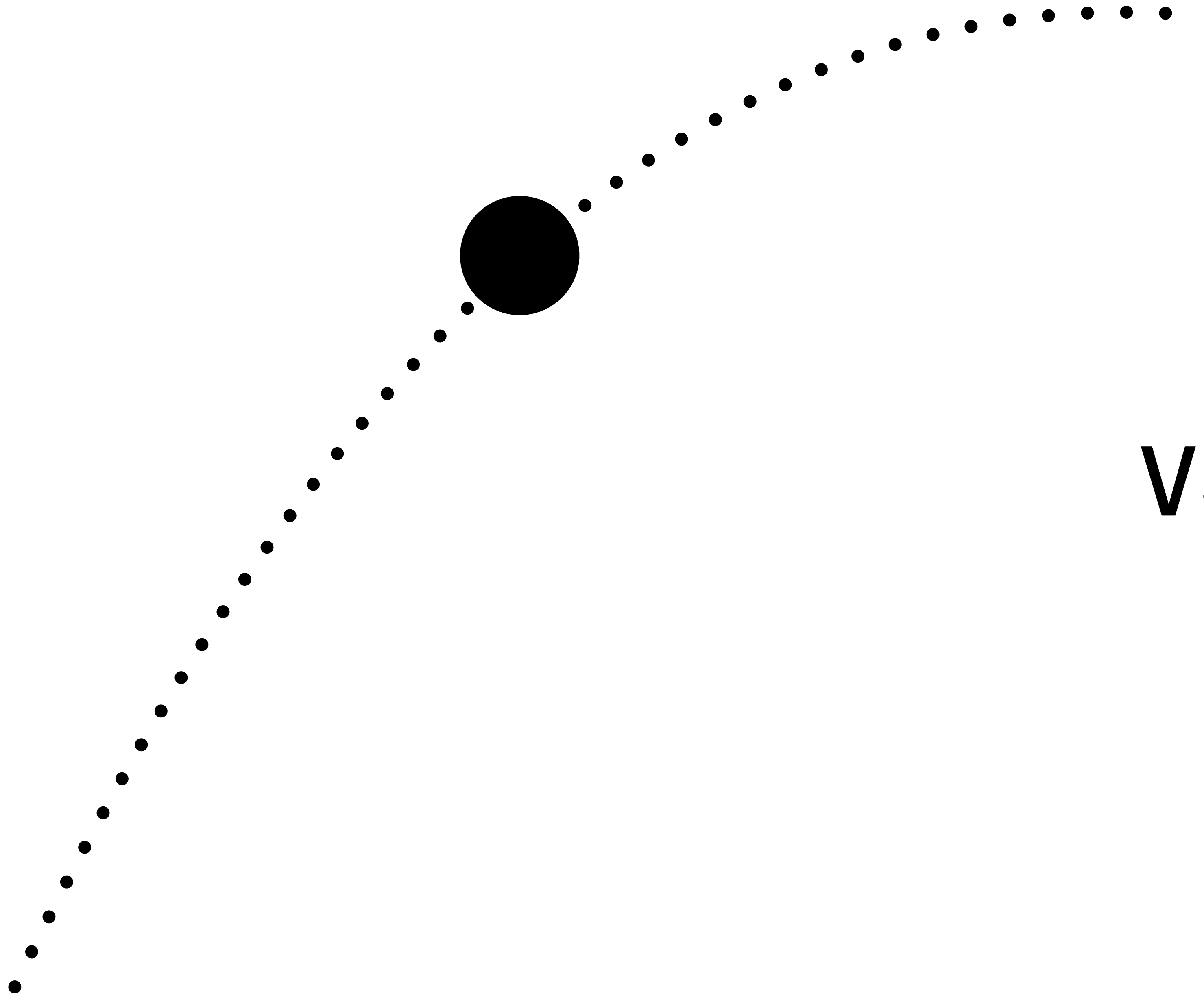
In this article, the researches have combined a three-body code (which integrates the orbits of stars treating the third star as a perturbation) and a stellar evolution code to see how the interior of the star reacts to eventual mass transfers between the stars. The model system is η -Carinae for this figure. The top panel shows the evolution of the inner eccentricity (product of the n-body code), and the middle panel shows the evolution of the radius of the star (product of the stellar evolution code).

Sciarini et al 2025 A&A 698 A240



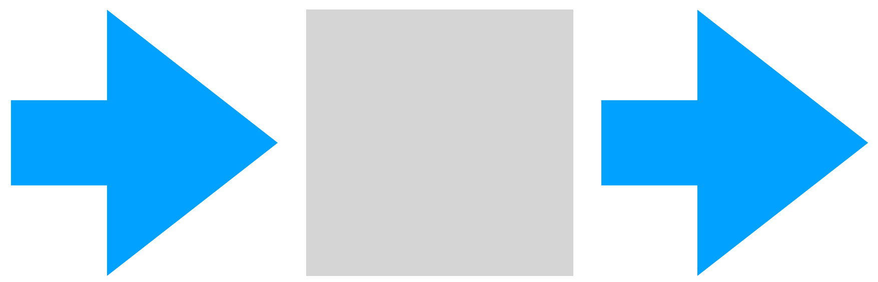
Smoothed Particle Hydrodynamics

Lagrangian



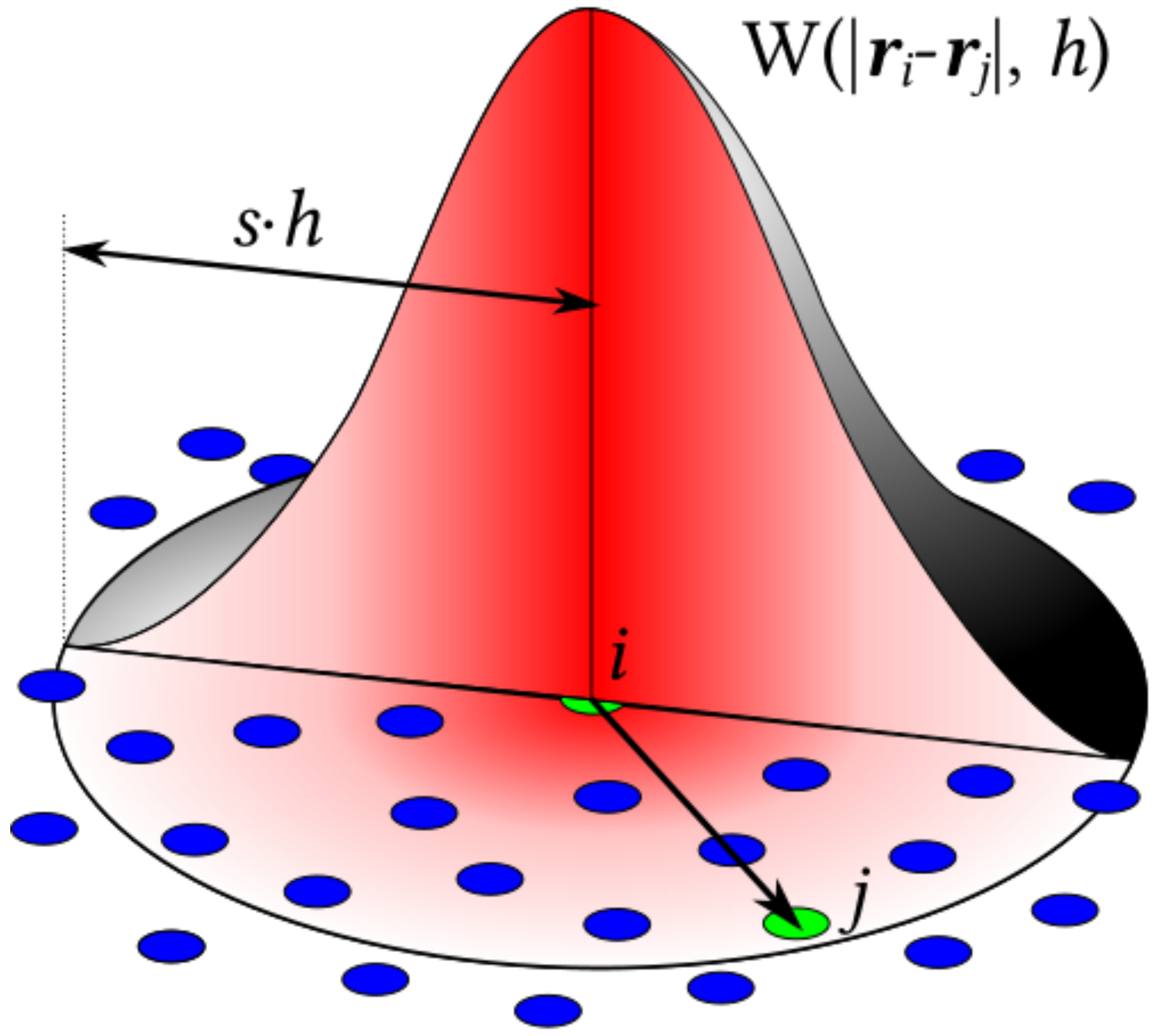
vs

Eulerian codes



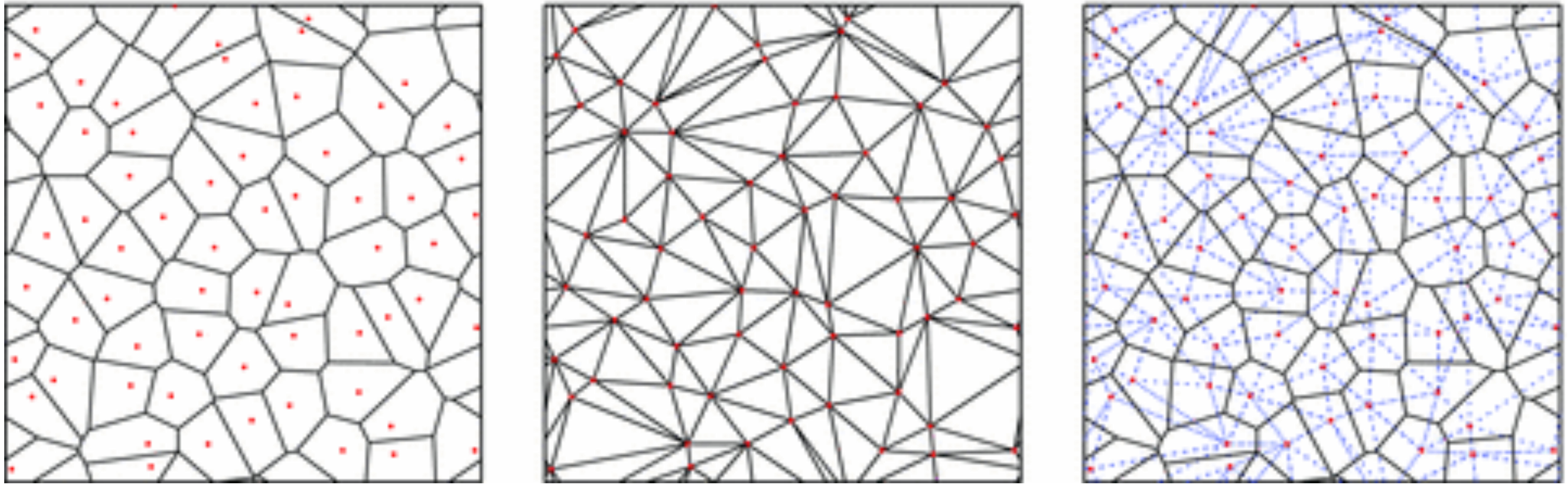
Introduction to SPH

- Dividing a fluid into particles
- The kernel and smoothing length
- Limitations of SPH



The middle ground: moving mesh codes

Voronoi grids



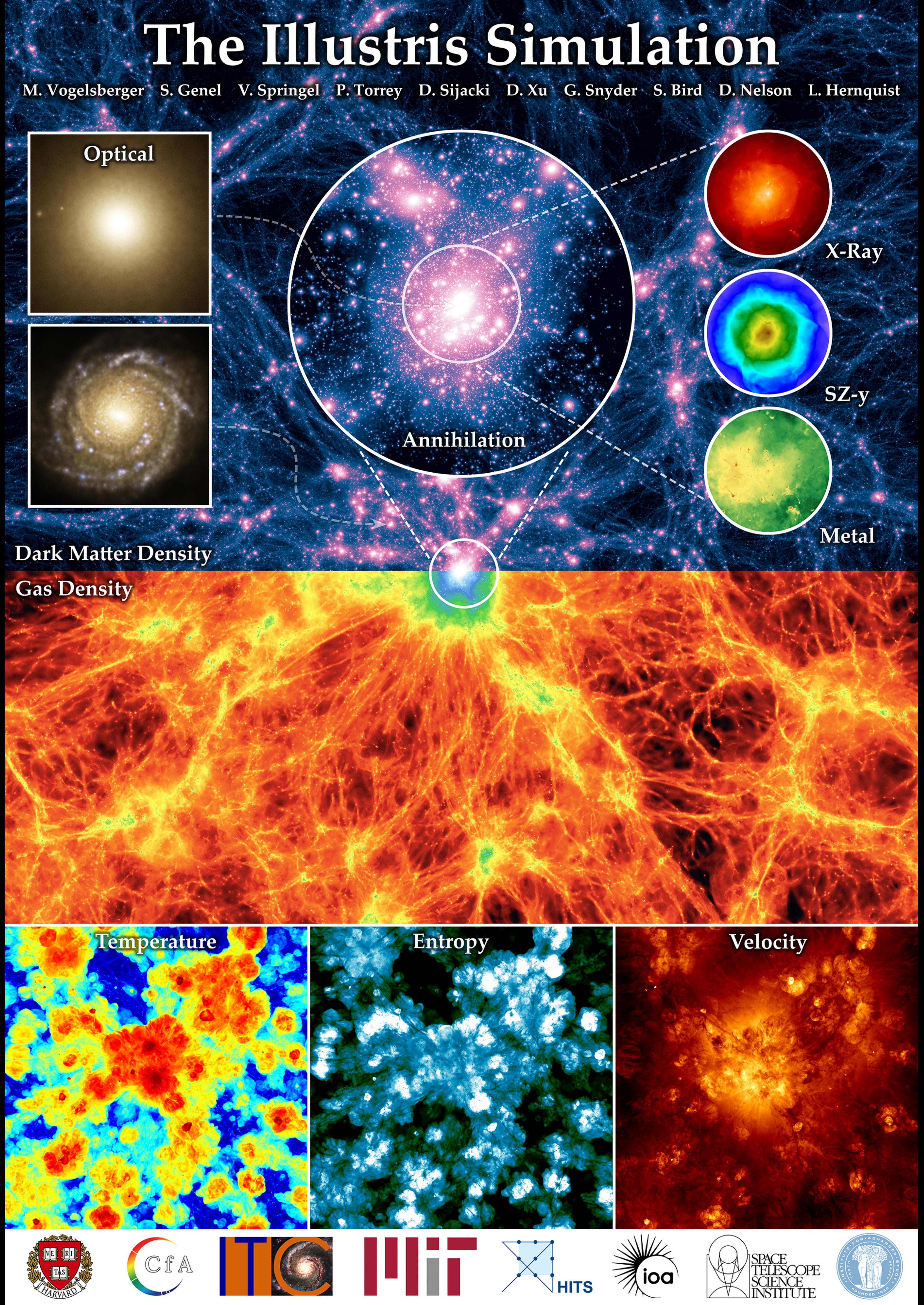
Springel 2010 MNRAS 401 791

example from research

Cosmological simulations

The Illustris simulation uses the moving mesh code AREPO to study structure formation in the Universe. They follow a section of the universe as its different components (matter, dark matter, dark energy, radiation) form galaxies. A moving mesh approach as used in Illustris refines the grid with increased density, which allows the researches to track the formation of structures at very different spatial scales.

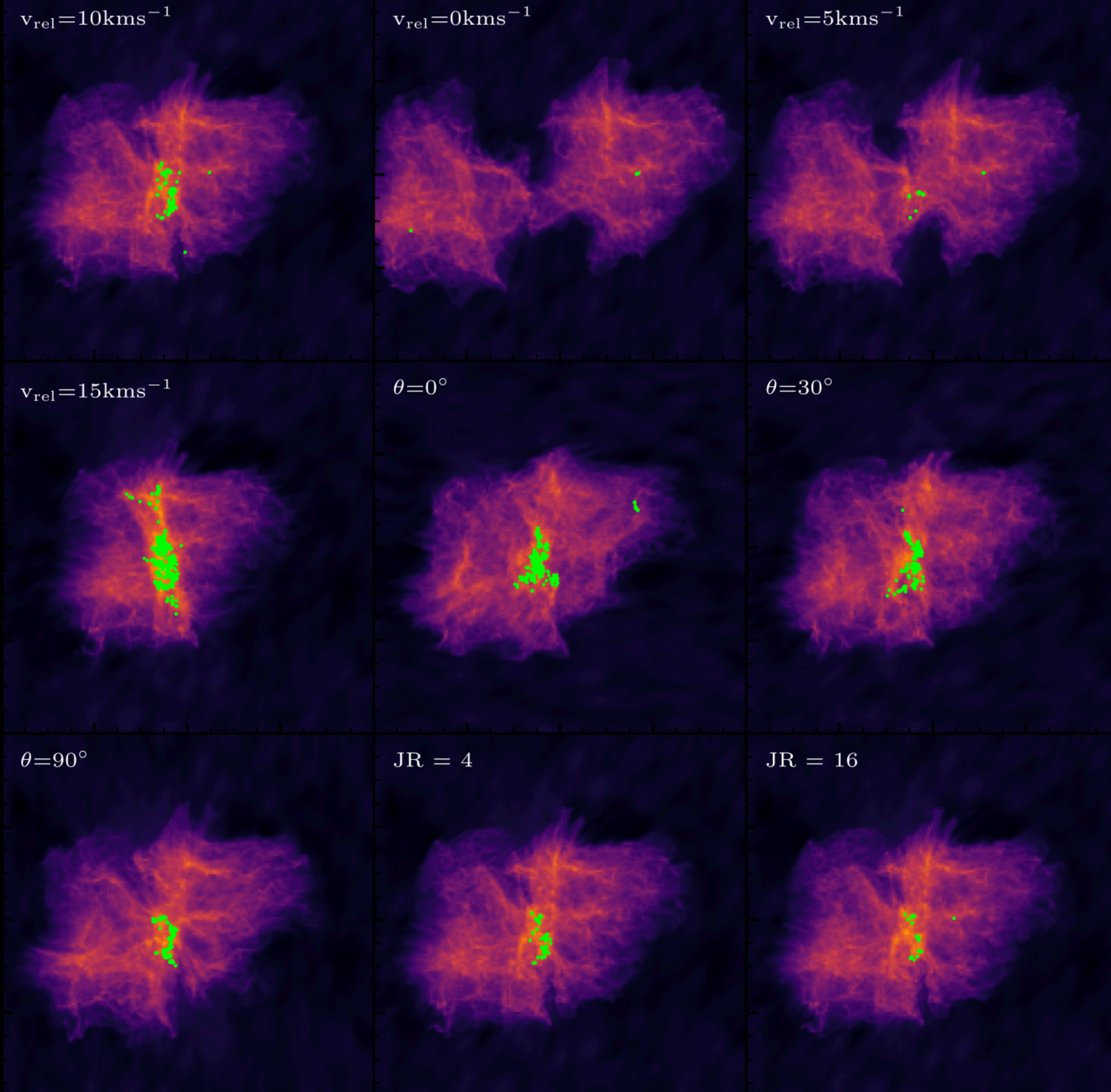
illustris-project.org



example from research

Simulations of molecular clouds

This is another use for AREPO: the study of how the collisions of two molecular clouds can give rise to the formation of massive stars. The plots on the right show different simulations with different initial conditions, all at the same instant in time. The background colors are density, and the green dots are possible new stars.



Hunter et al 2023 MNRAS 519 4152