Numerical Simulations of physical processes driving galaxy evolution

Lecture 1: Backbone Codes

Rhea-Silvia Remus

Canary Islands Winter School, 23.11.2021

Disclaimer

This lecture was designed for presentation with movie media. If no specific URL is provided, movies can be found at

www.usm.uni-muenchen.de/~rhea/teaching/movies

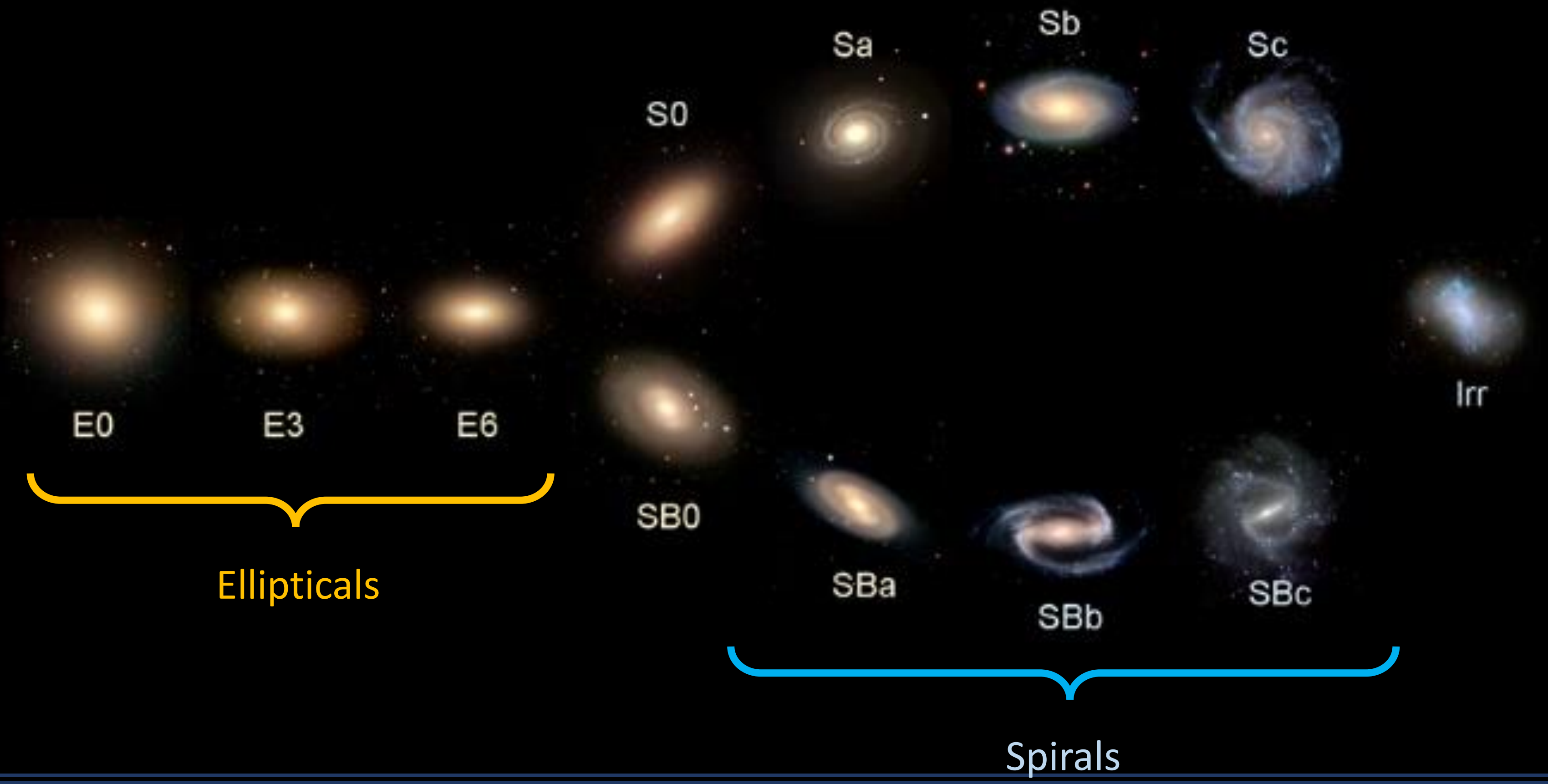
Movies are marked by a *

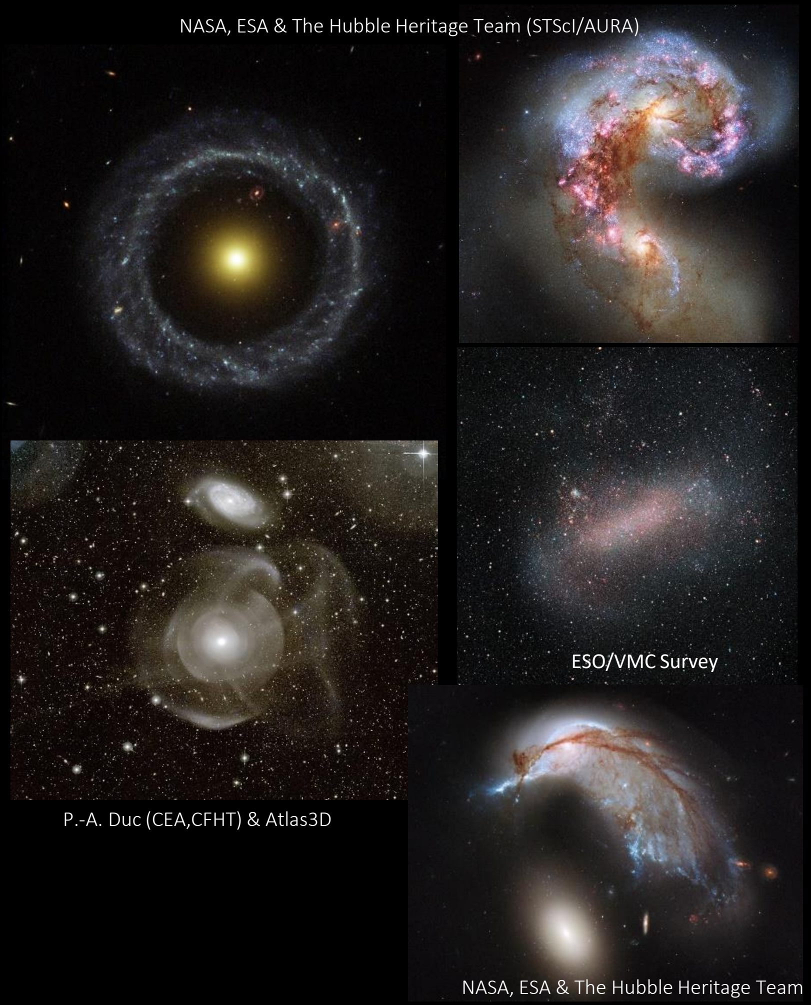
Introduction: This weeks topic?

Numerical Simulations of physical processes driving galaxy evolution

Introduction: why do we care about galaxies?

Galaxies come in many different flavours, not just the well known regular shapes but a multitude of distorted features that need to be explained





NASA, ESA & The Hubble Heritage Team (STScI/AURA)

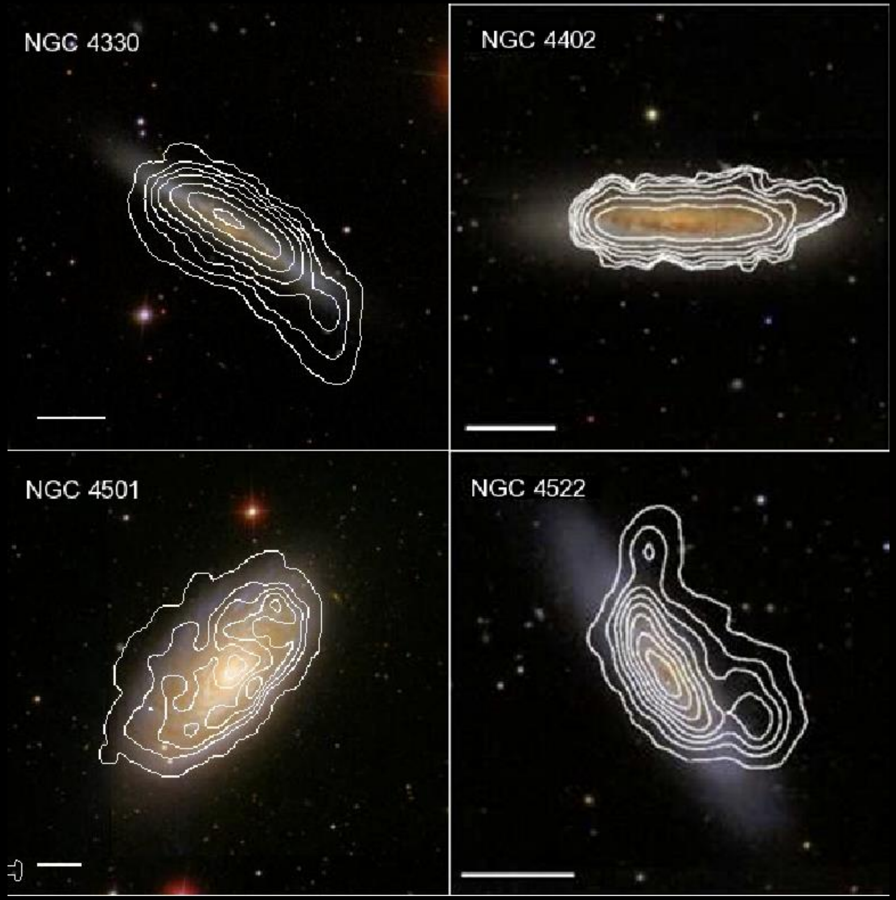
P.-A. Duc (CEA,CFHT) & Atlas3D

ESO/VMC Survey

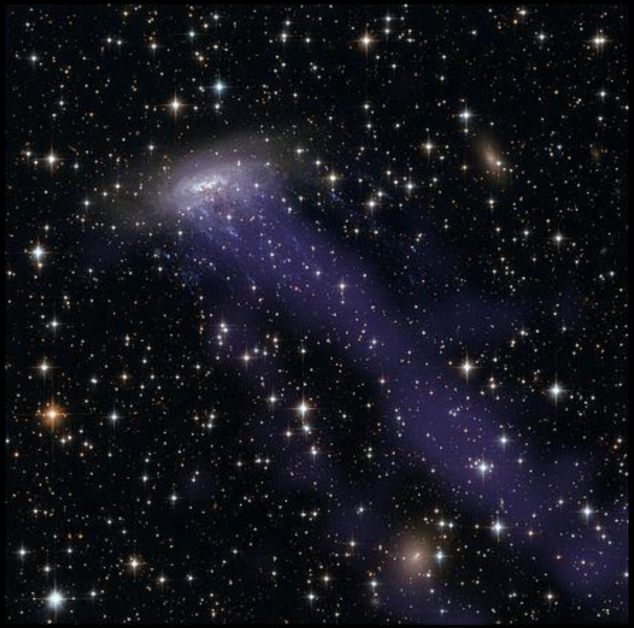
NASA, ESA & The Hubble Heritage Team

Edwin Hubble’s Galaxy Classification

Introduction: why do we care about galaxies?



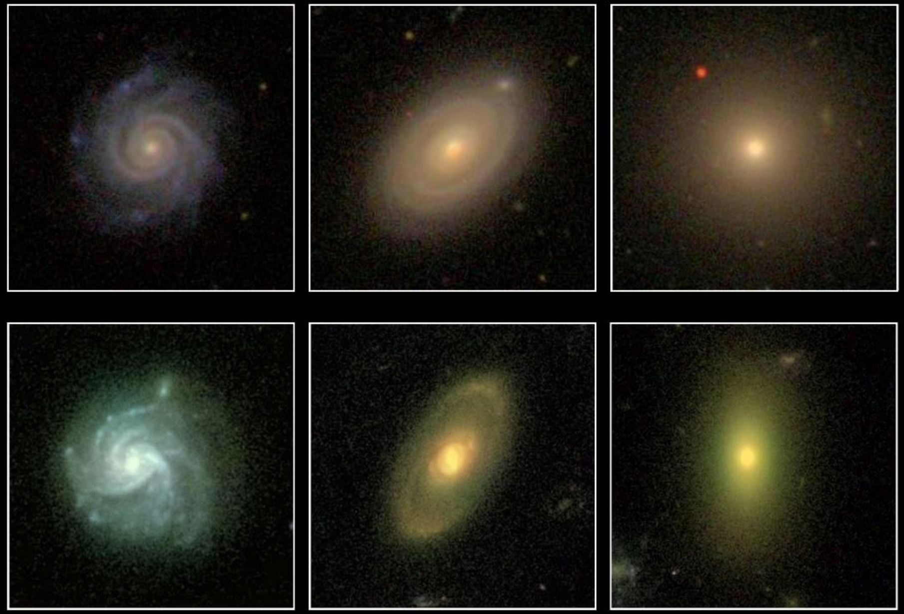
Wong et al., 2014



NASA/ESO

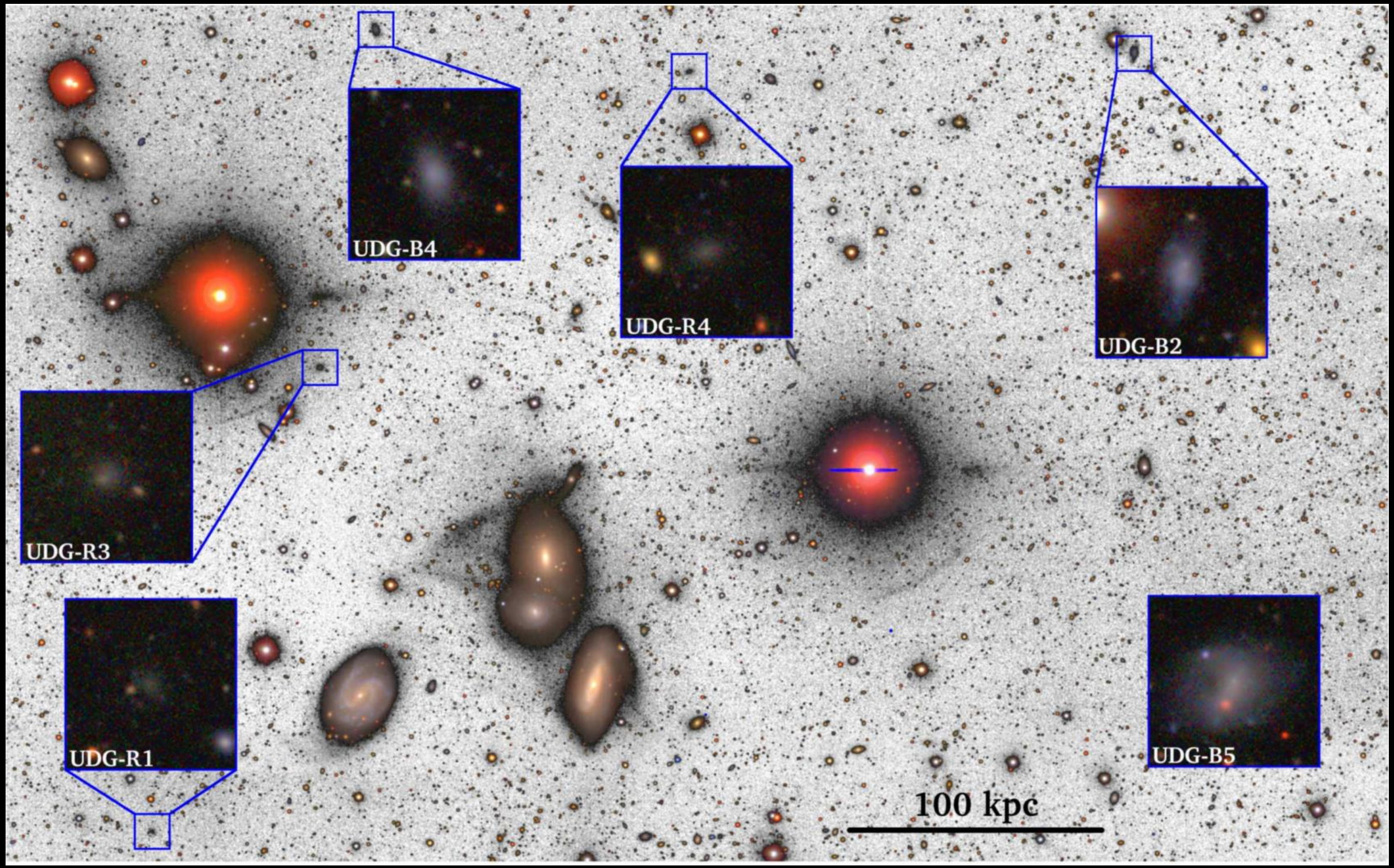
We also see environmental effects work on them, shown in the existence of for example jellyfish galaxies or red spiral galaxies

Galaxy Zoo : SDSS



STAGES : Hubble Space Telescope

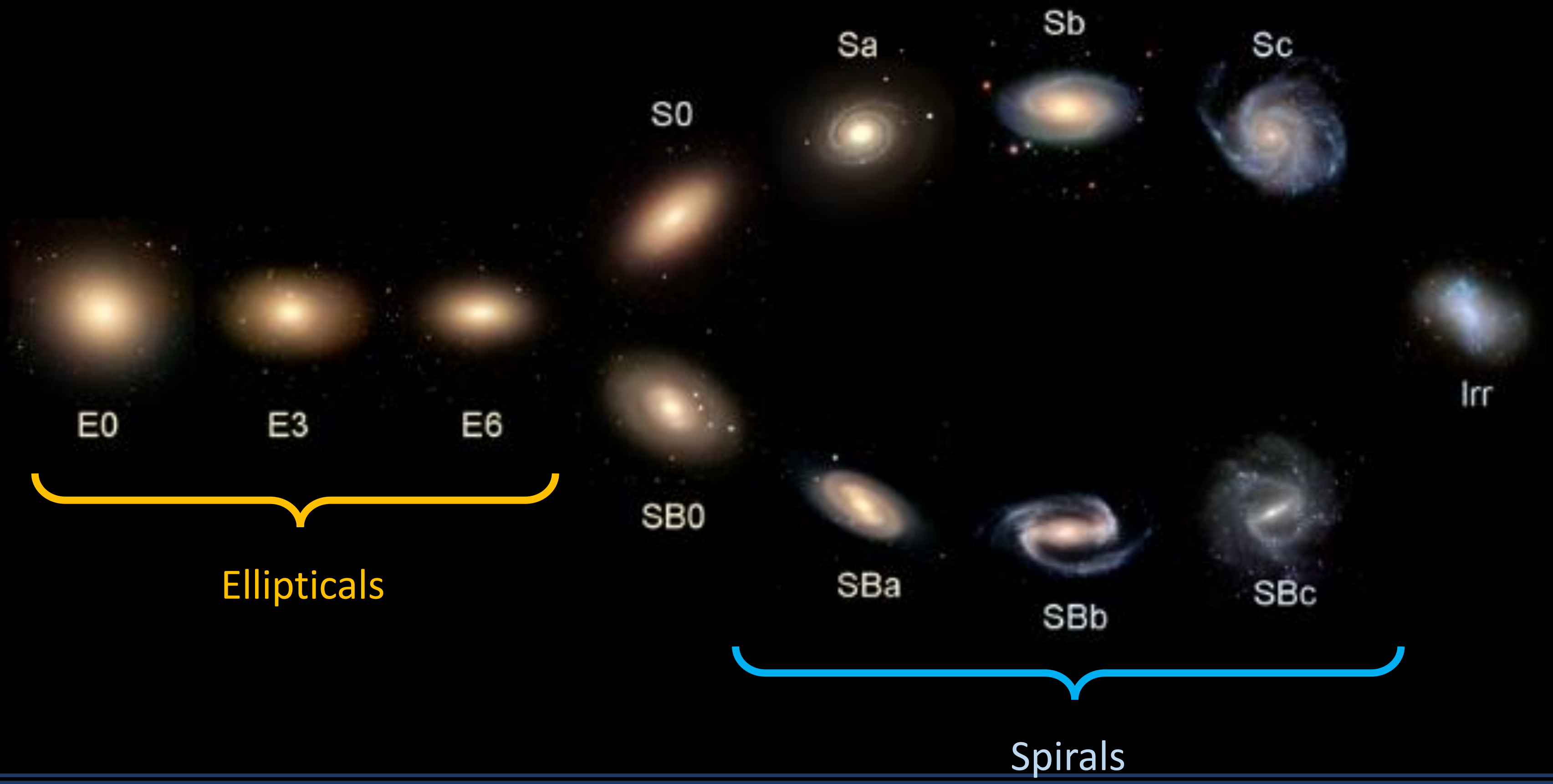
Introduction: why do we care about galaxies?

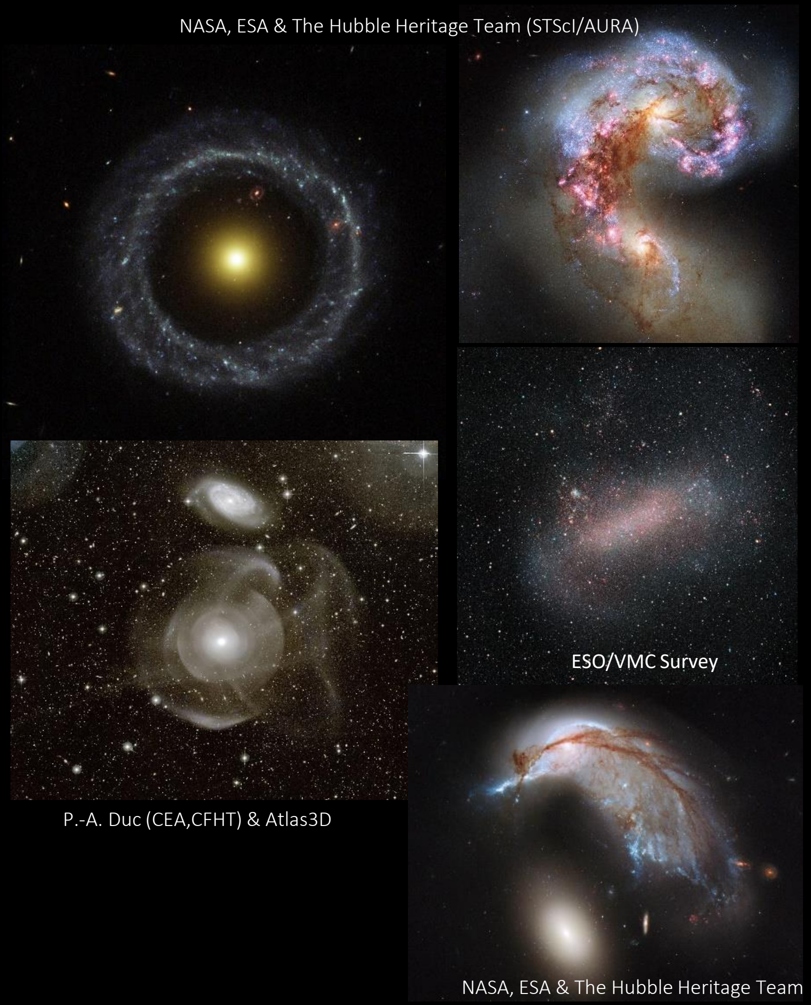


In addition, we find plenty of galaxies in the low-surface brightness regime, among which are the Ultra-Diffuse Galaxies (UDGs) which are especially numerous in the galaxy cluster environment

Roman & Trujillo 2017

Introduction: So how do we make all these different kind of galaxies?





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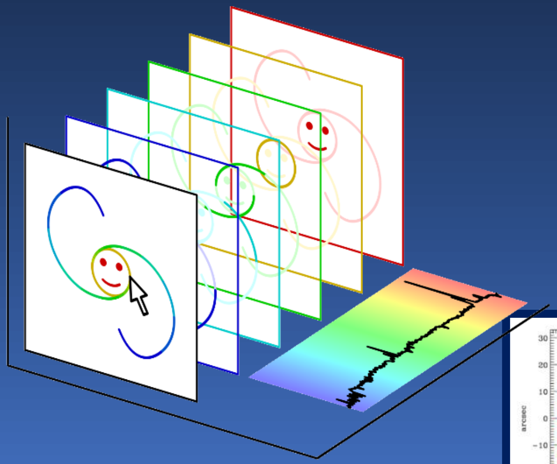
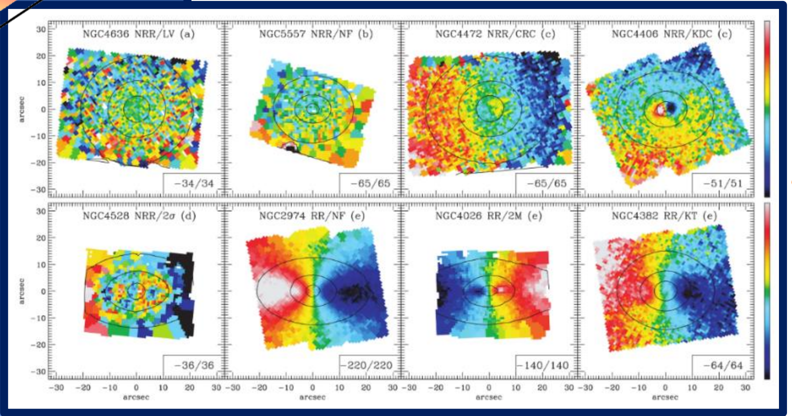
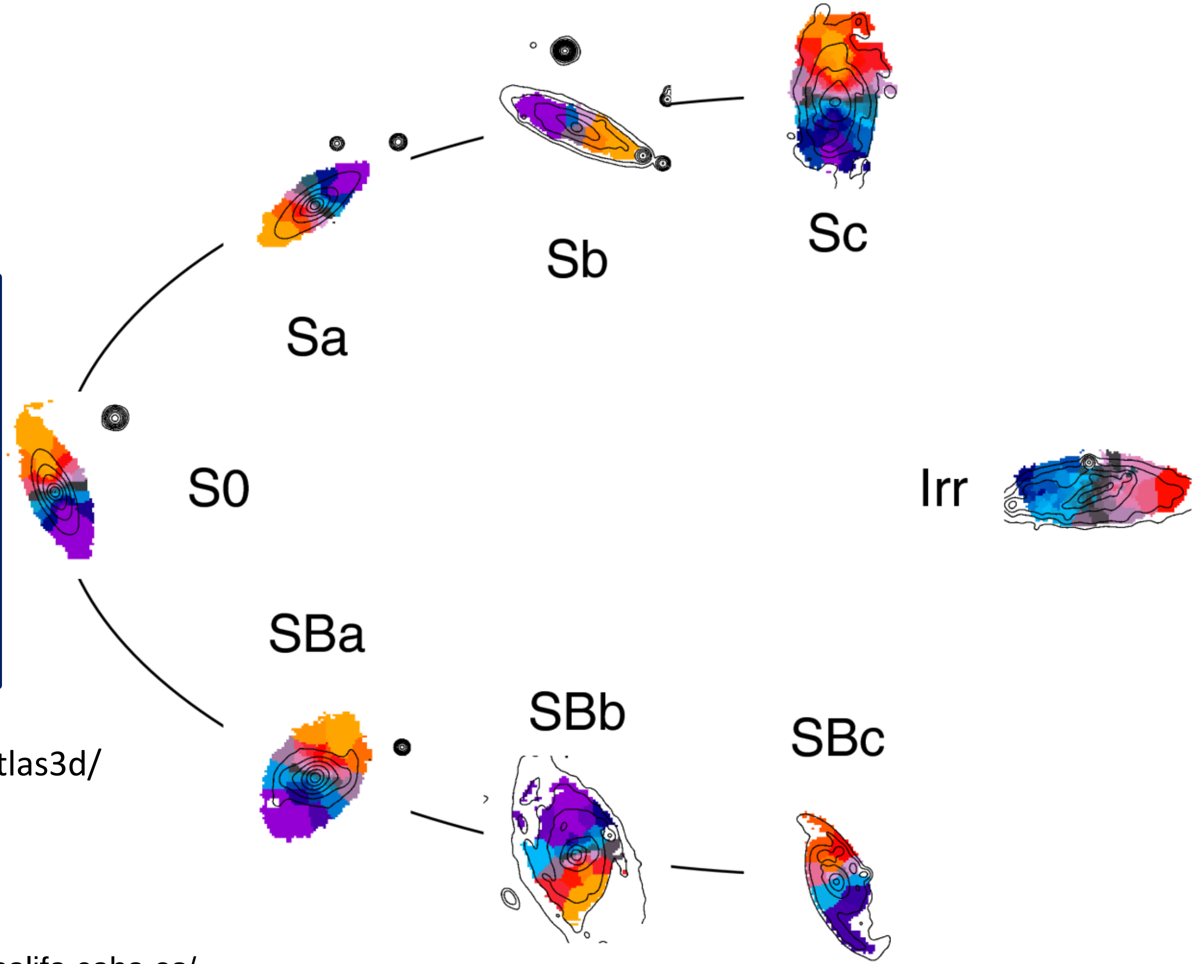


With the advent of Integral Field Spectroscopy, the features known to exist in galaxies were multiplied especially in the realm of quiescent galaxies



Atlas^{3D} Survey: https://www-astro.physics.ox.ac.uk/atlas3d/

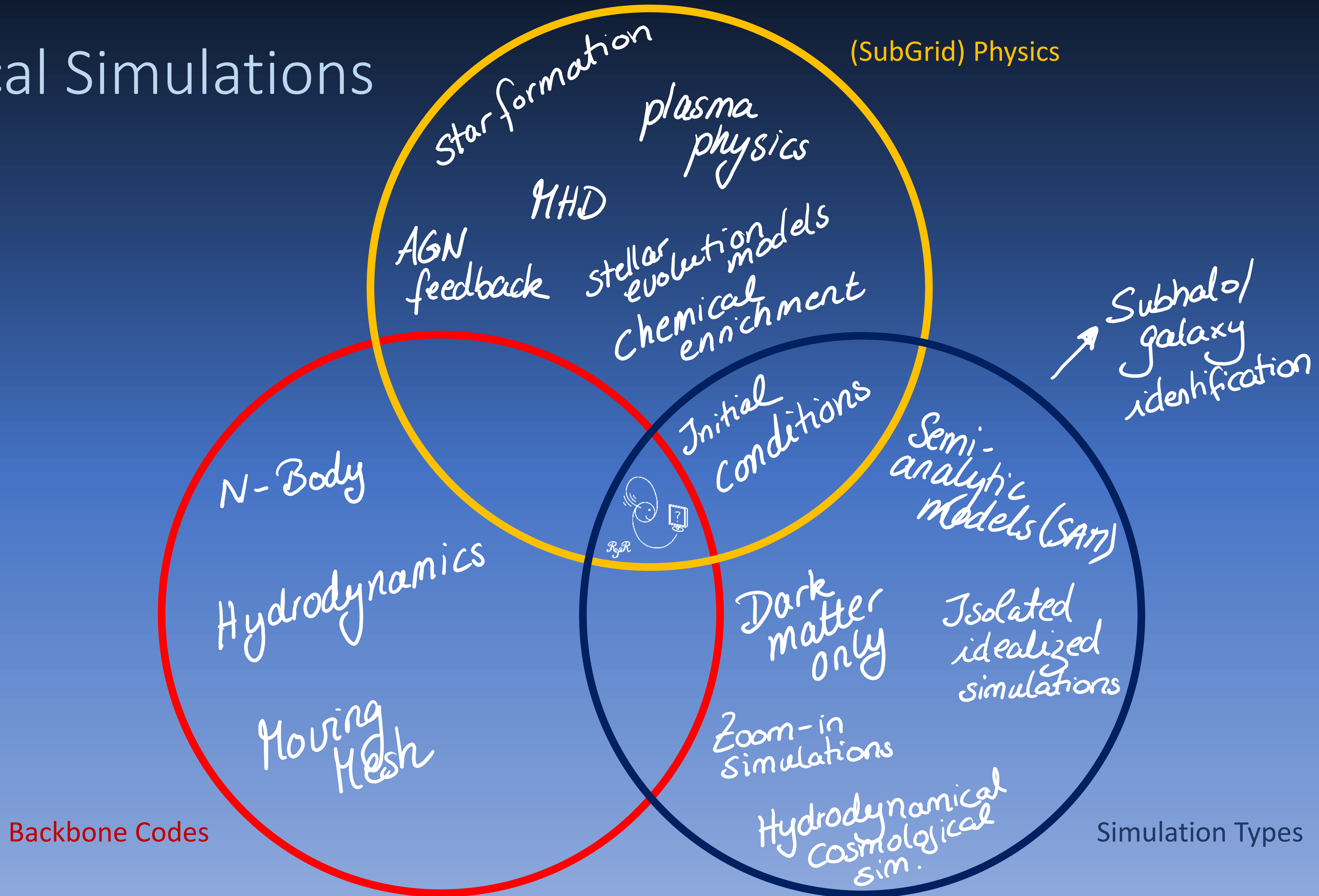


Pictures from the CALIFA survey: http://califa.caha.es/

Introduction: Numerical Simulations

To understand the formation of galaxies, numerical simulations are an excellent tool to study the details of the processed that are responsible for the many faces of galaxies that can be observed. But how does that actually work?

Numerical Simulations



Numerical Simulations: Codes

First Step: Gravity

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Easy method, but computationally expensive

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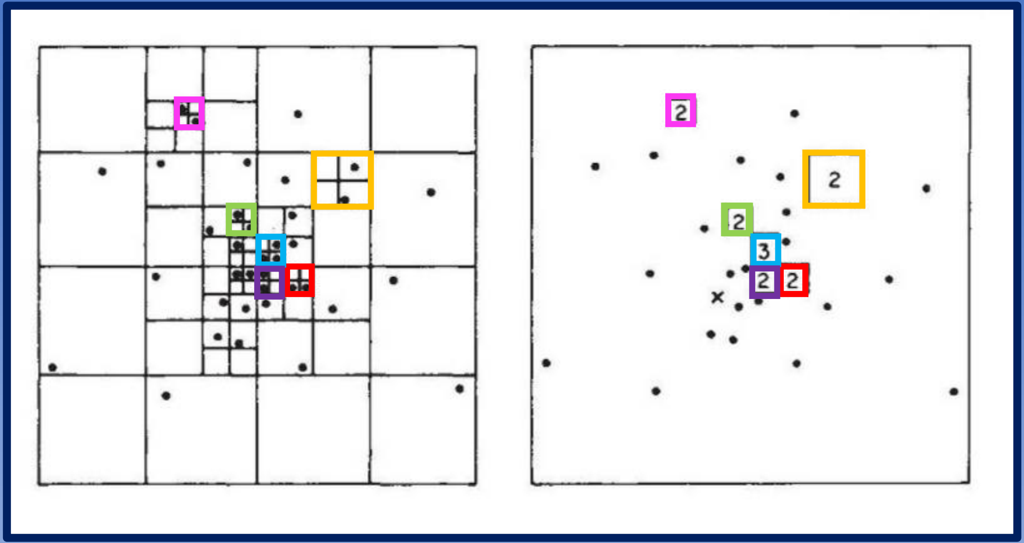
Integrate forces using Leap-Frog, Runge-Kutta, or higher order Integrators and obtain positions and velocities for all particles at every timestep

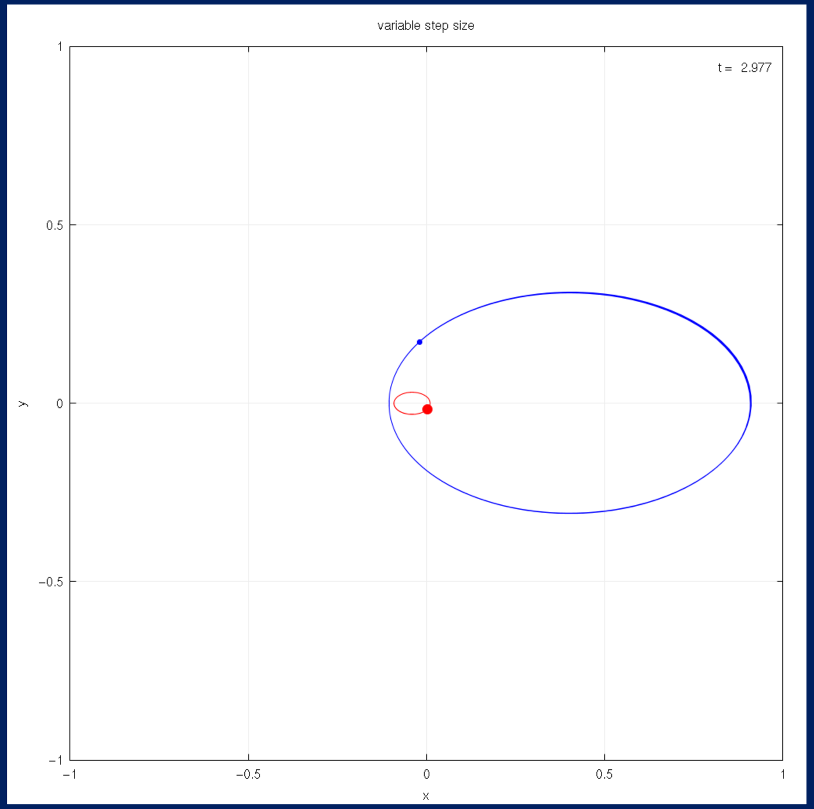
Group together particles that are far away from particle i , and build a tree for the force calculation can limit the computational expense from N^2 to $Nlog(N)$.



Barnes & Hut 1986

N-Body Simulations: Timestep Problem

* Variable timestep



Credit: Tadziu Hoffmann

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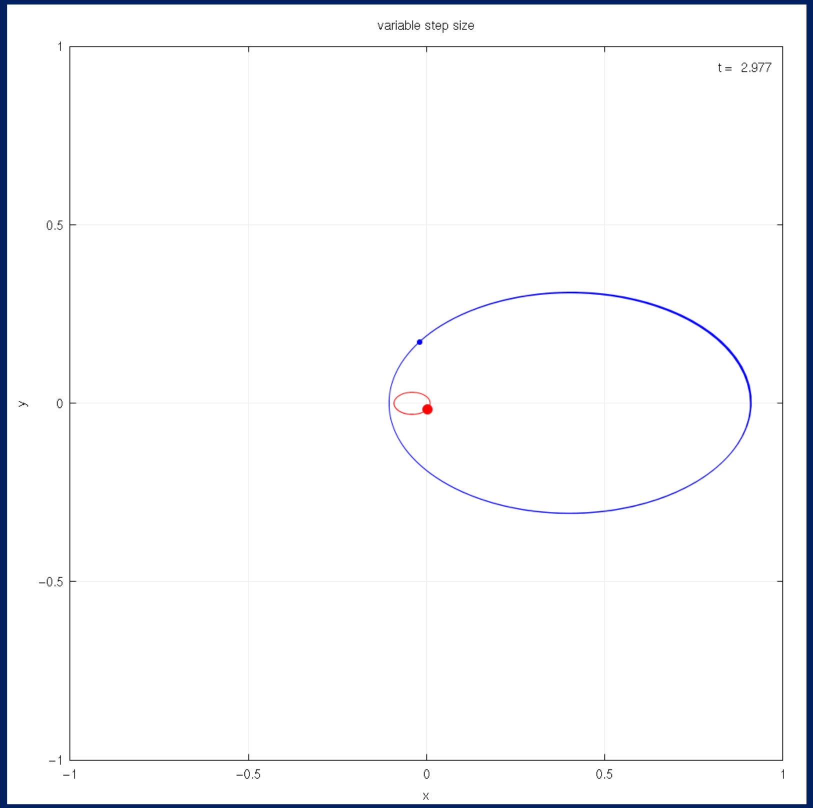
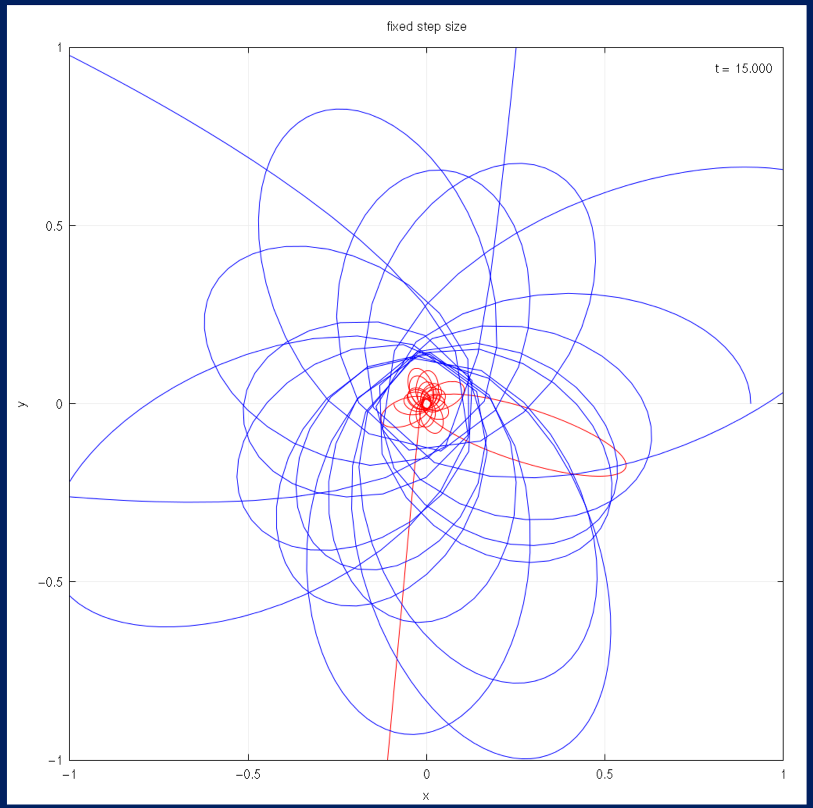


* Fixed timestep



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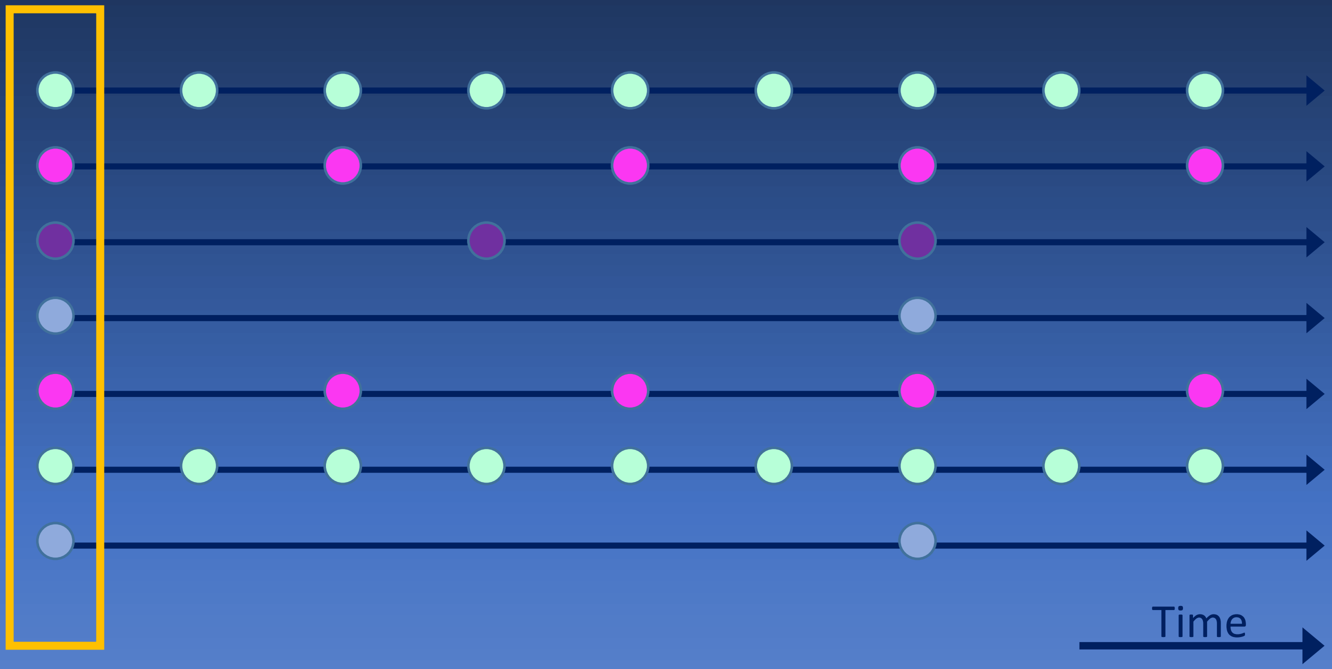
N-Body Simulations: Speedup I: Individual Timesteps



Active Particles

Using individual timesteps means that the Force needs to be calculated only for active particles

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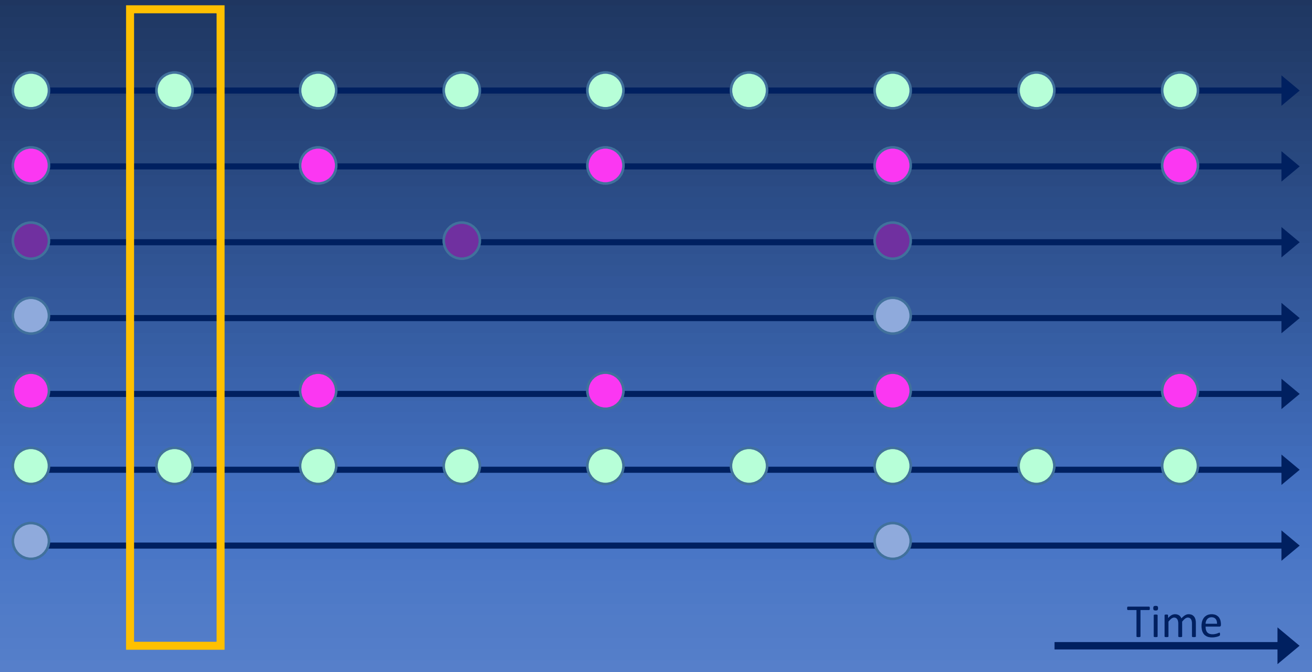

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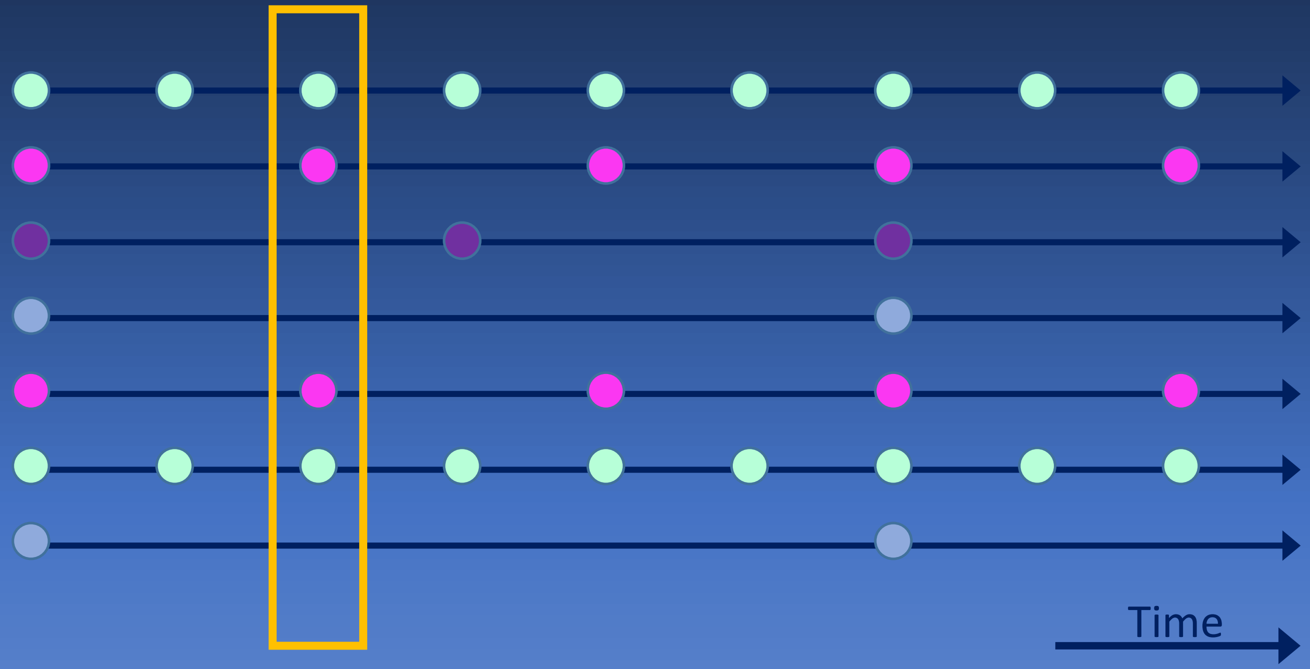

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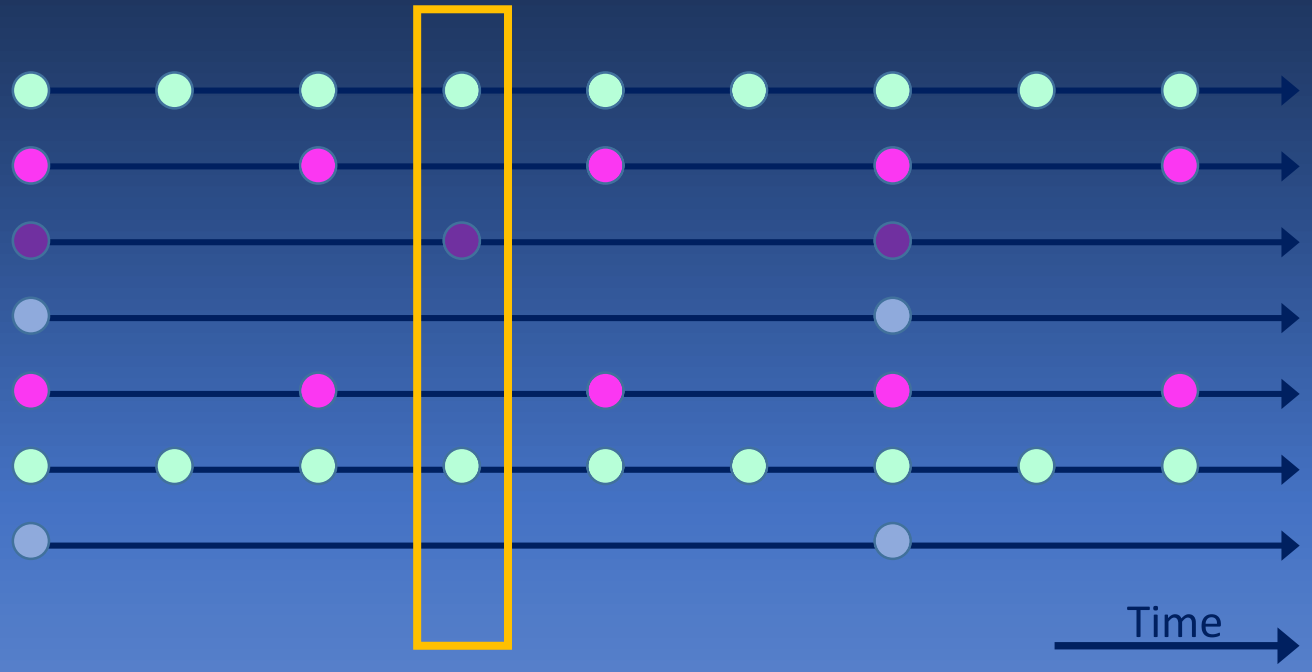

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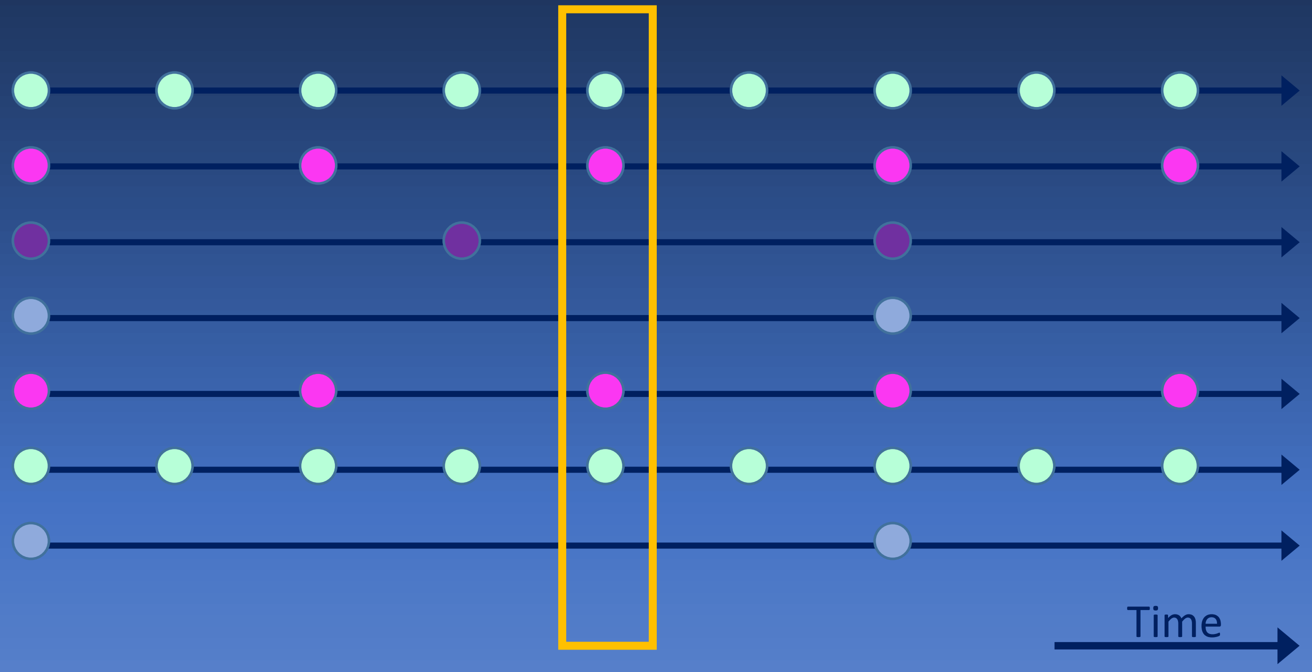

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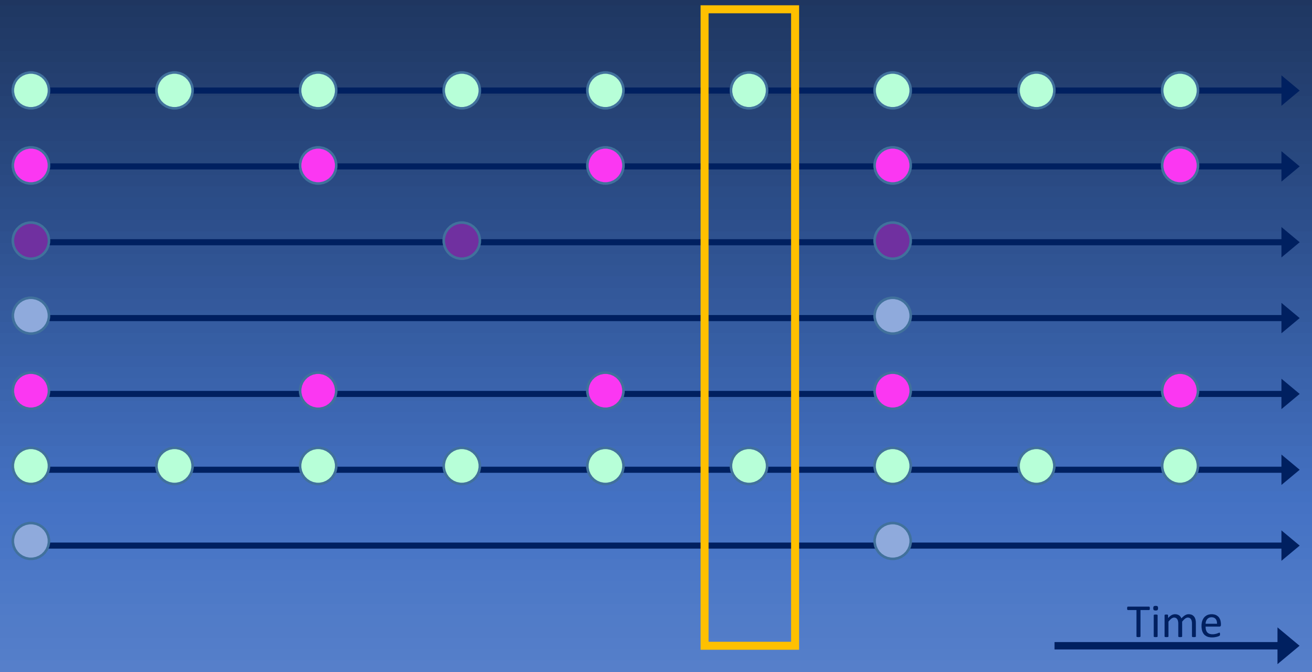

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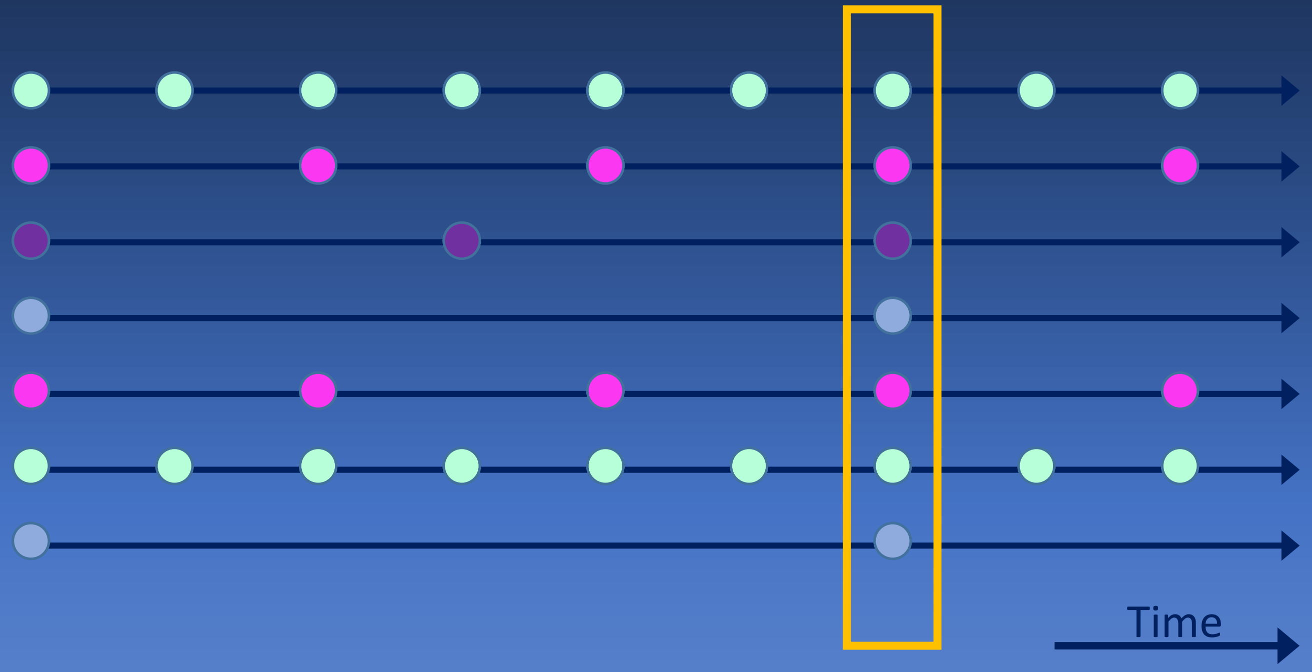

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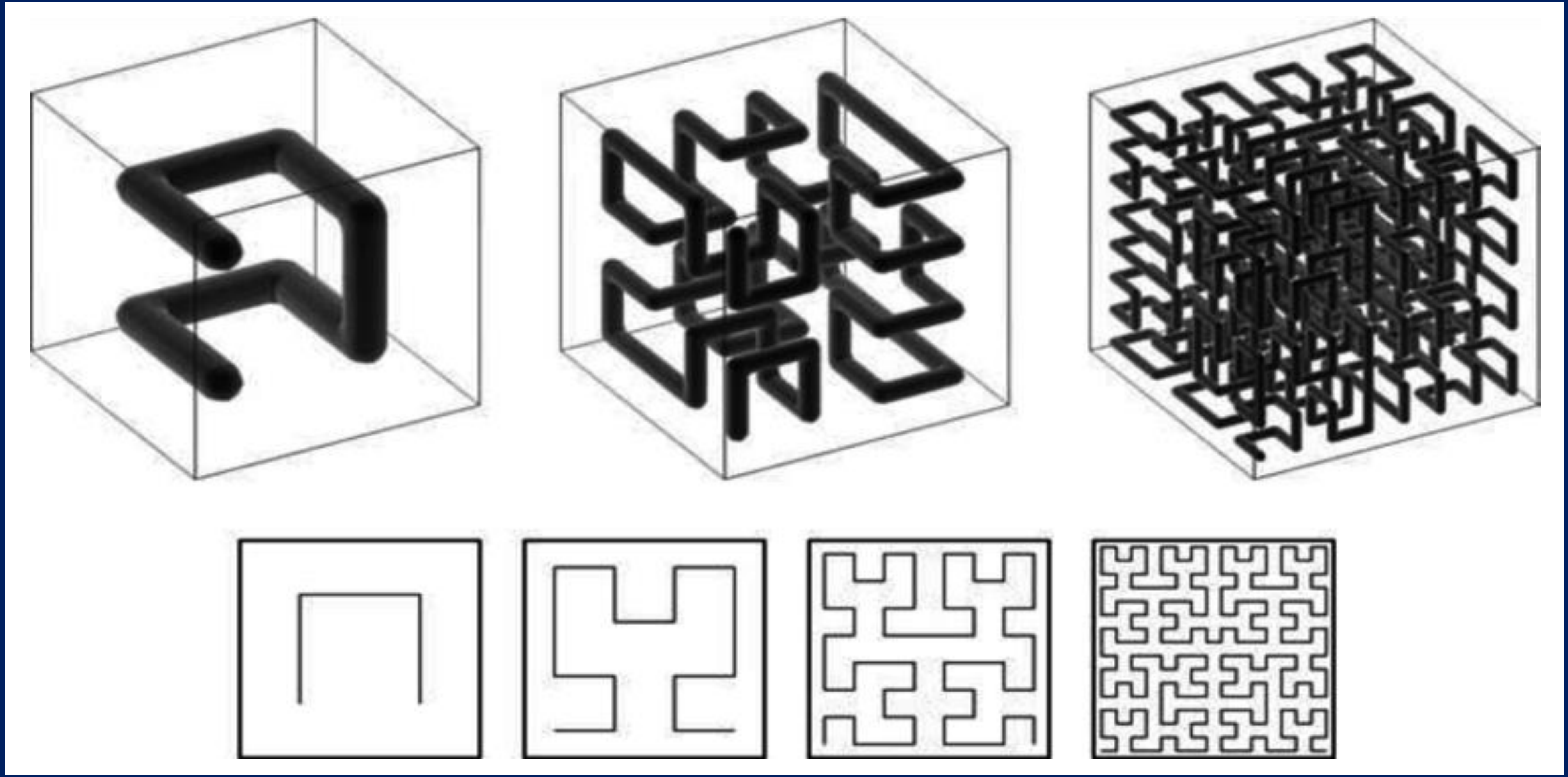
N-Body Simulations: Speedup II: Parallelize



Borovska & Ivanova 2015

Peano-Hilbert Curve

Distributing particles (memory) and work load (balance) simultaneously

N-Body Simulations: Softening

Two Problems depending on the simulation setup, one solution:

1) In a `real particle simulation': If particles get very close, the timesteps are getting extremely short, causing numerical problems

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2) If the particles are actually not a representation of one object but a group of objects, they should not be able to collide.

N-Body Simulations: Softening

Two Problems depending on the simulation setup, one solution:

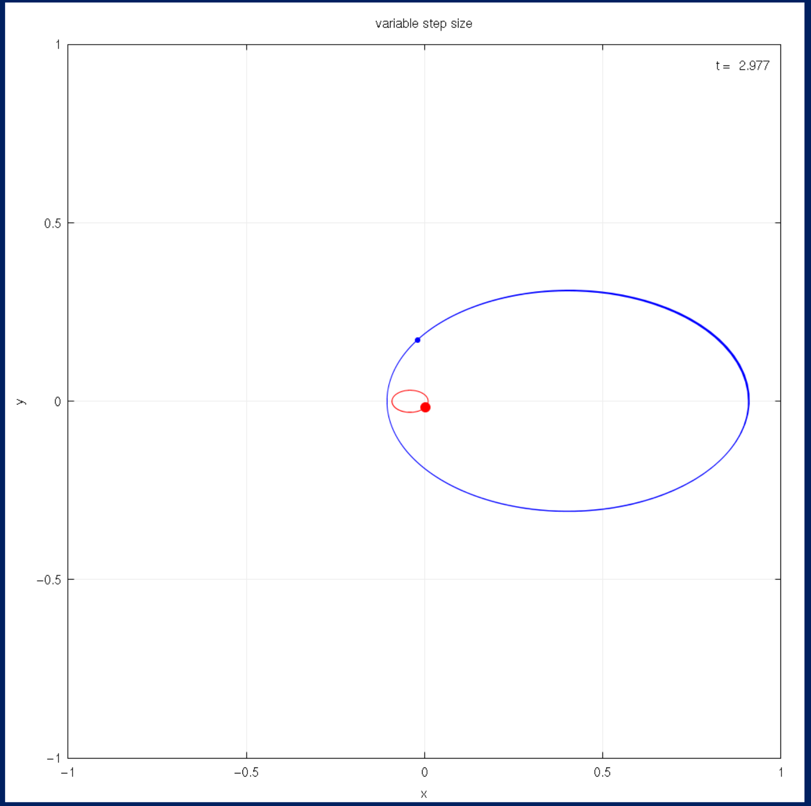
1) In a `real particle simulation': If particles get very close, the timesteps are getting extremely short, causing numerical problems
2) If the particles are actually not a representation of one object but a group of objects, they should not be able to collide.

To avoid this, we introduce an additional term into our force calculations, called softening:

$$m_i \frac{d^2 r_i}{dt^2} = \sum_{\substack{j=1 \\ i \neq i}}^{n} \frac{G m_i m_j \left(r_j - r_i\right)}{\left(\left\|r_j - r_i\right\|^2 + \varepsilon^2\right)^{3/2}}$$

N-Body Simulations: Softening

* Variable timestep



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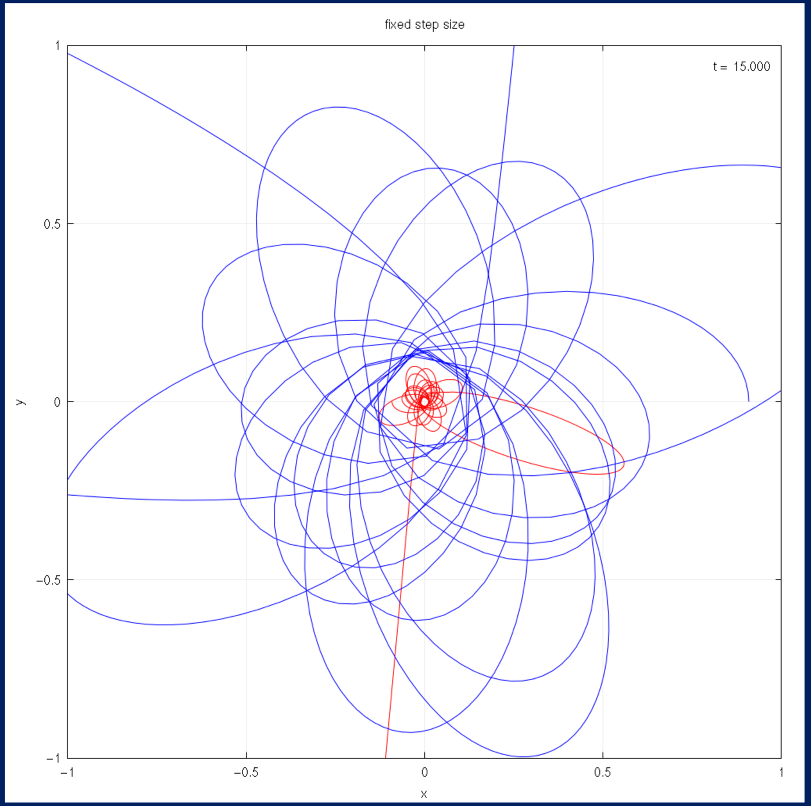
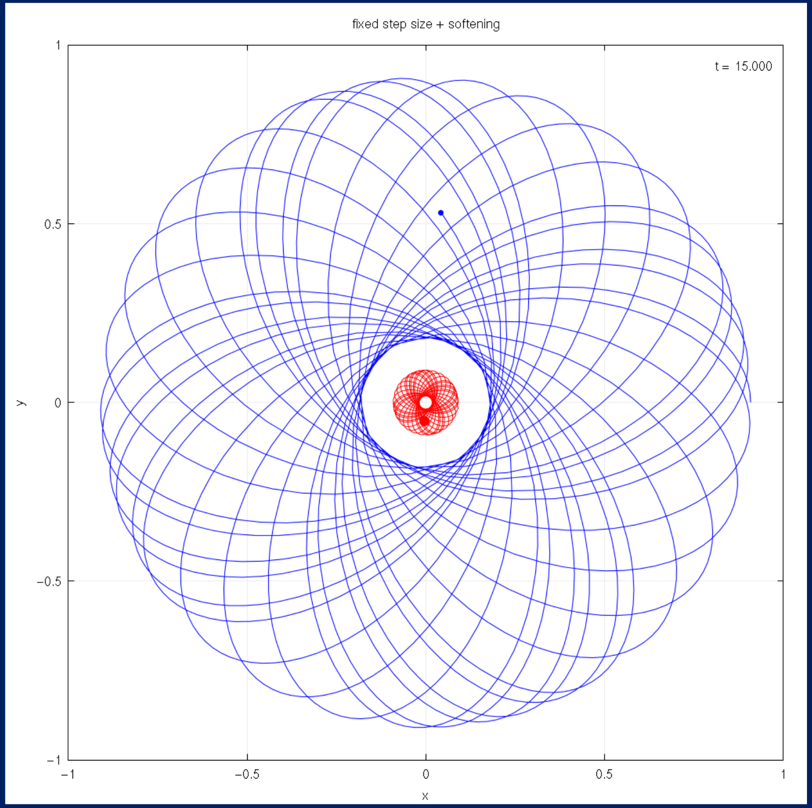


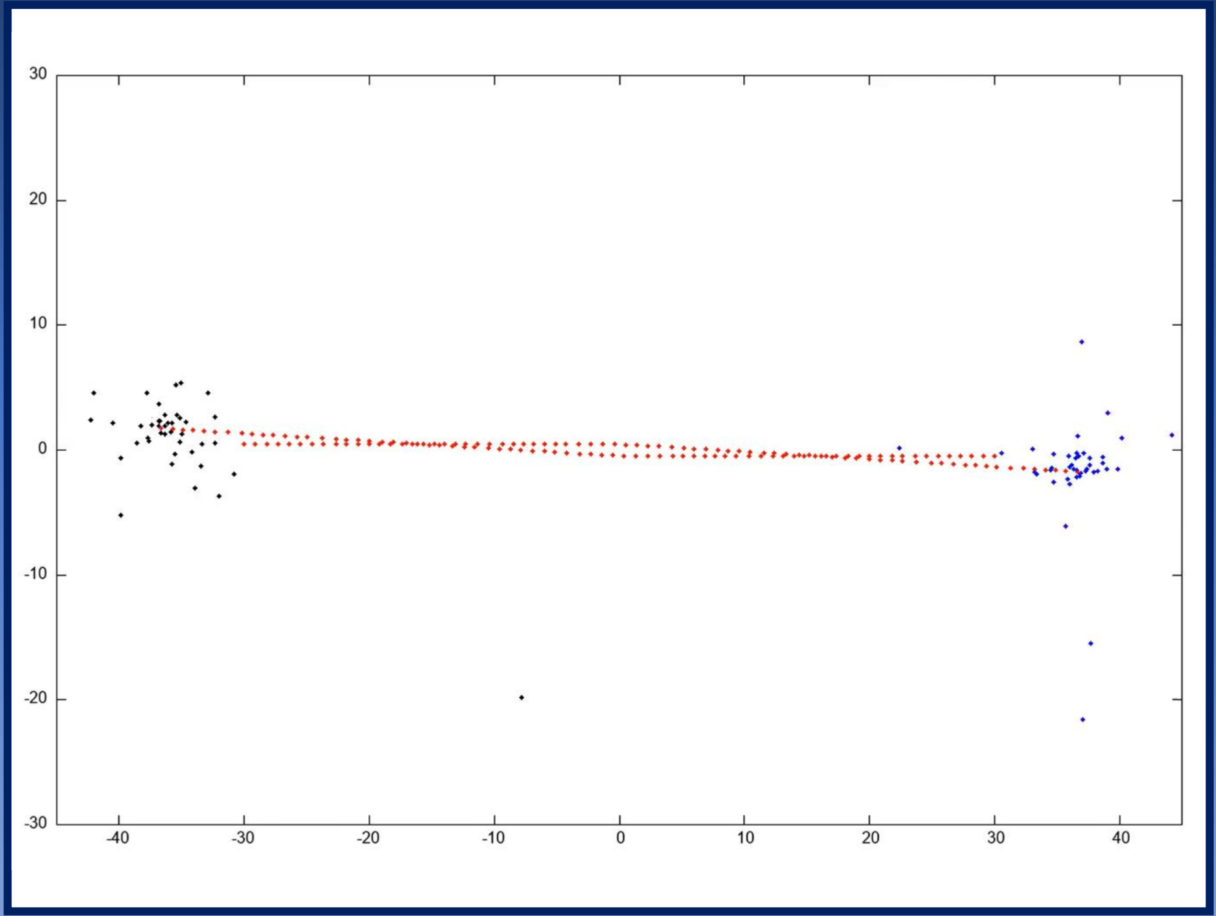
* With softening



Credit: Tadziu Hoffmann

Softening

Collision with Point Particles



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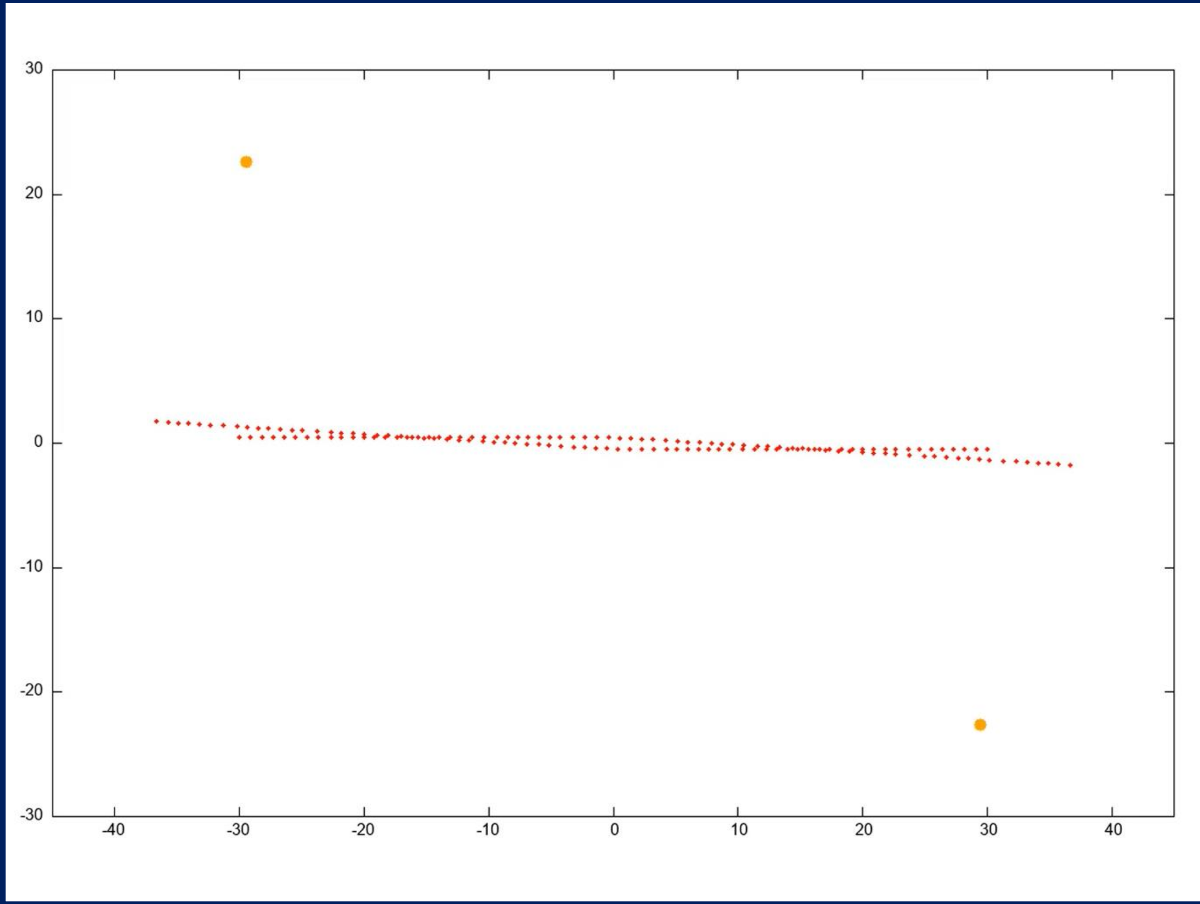
Red line: Movement of the centre of mass for both particle clouds

Credit: Lucas Valenzuela

Softening

Collision with Macro Particles, No softening



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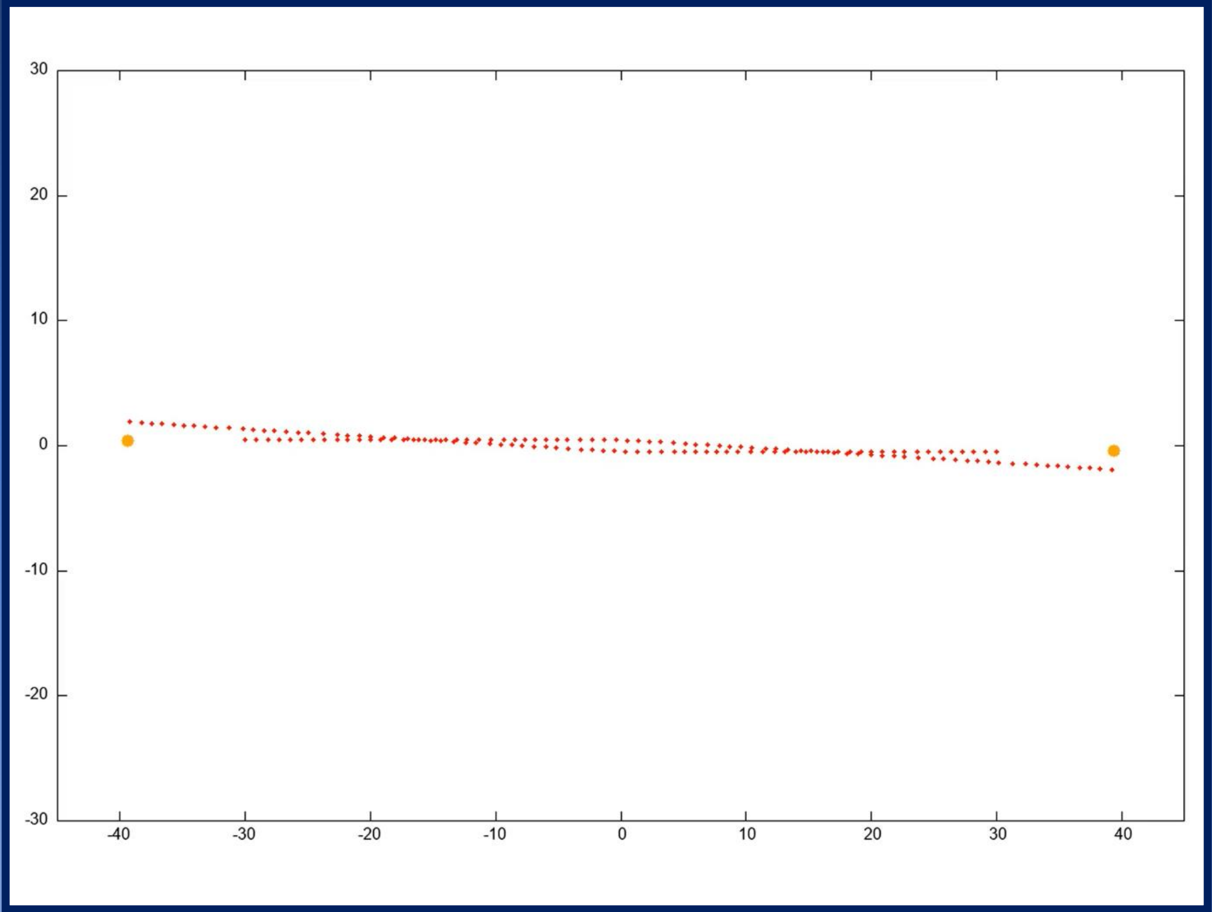
Red line: Movement of the centre of mass for original particle clouds

Yellow dots: New Macro Particles representing the point cloud

Credit: Lucas Valenzuela

Softening

Collision with Macro Particles, High softening ($\varepsilon = 5$)



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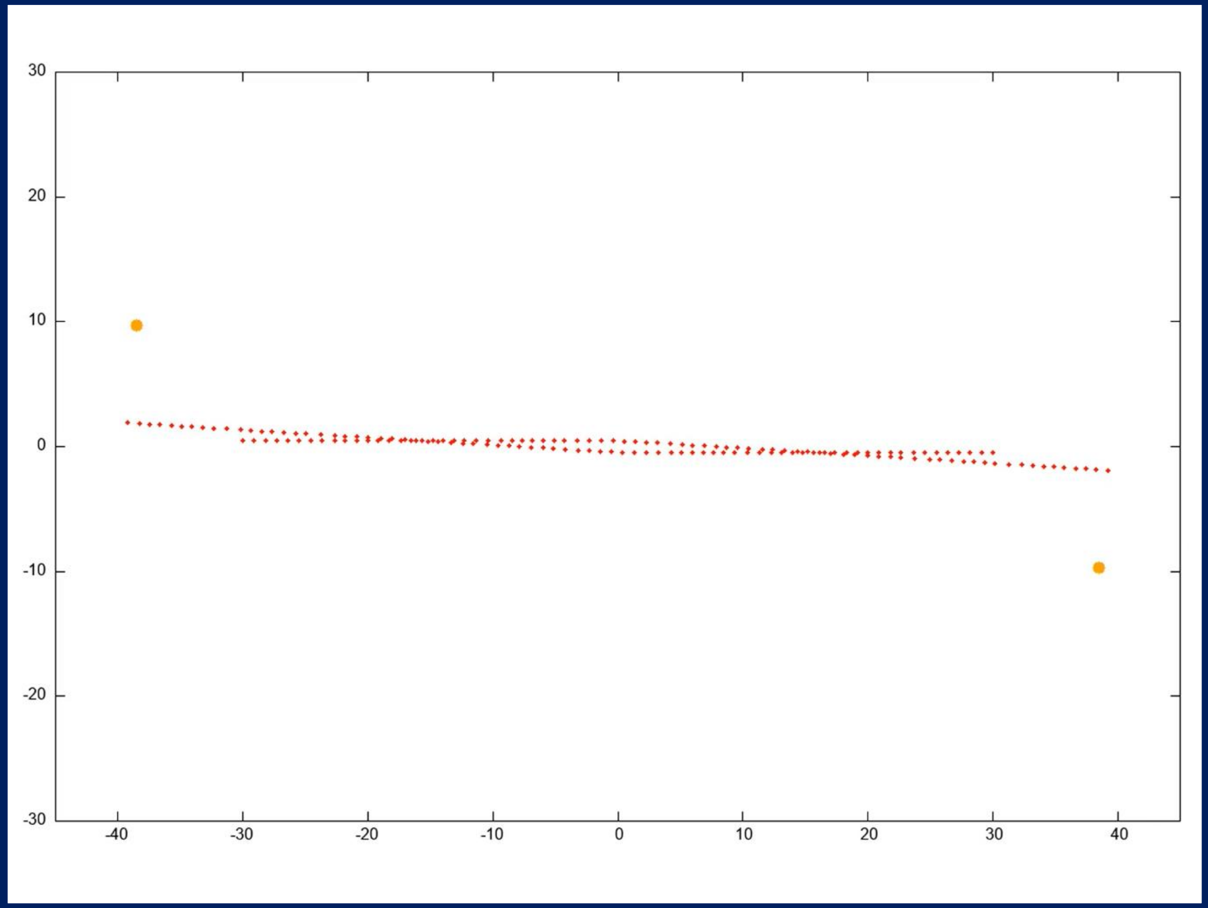
Softening

Collision with Macro Particles, Low softening ($\varepsilon = 1$)



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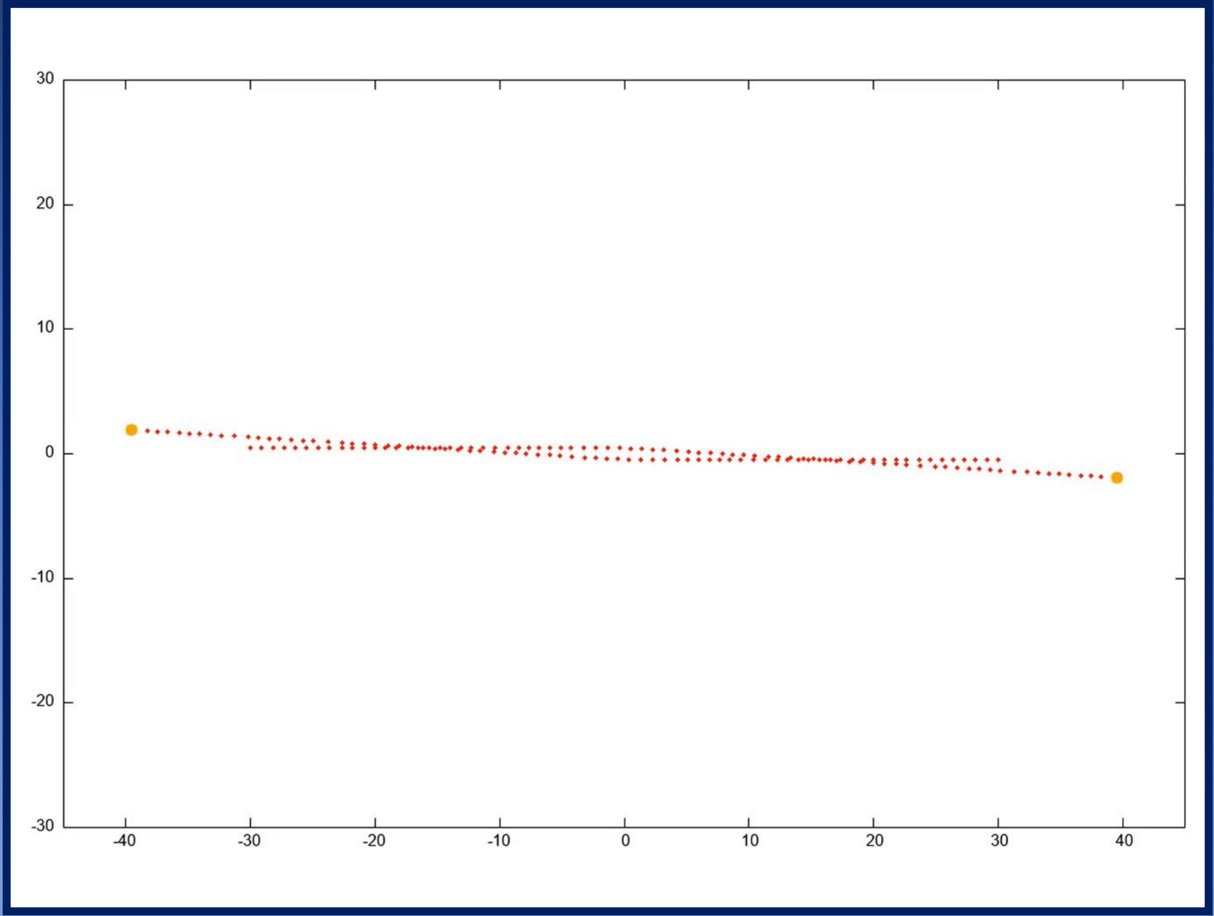
Softening

Collision with Macro Particles, perfect softening ($\varepsilon = 2.8$)



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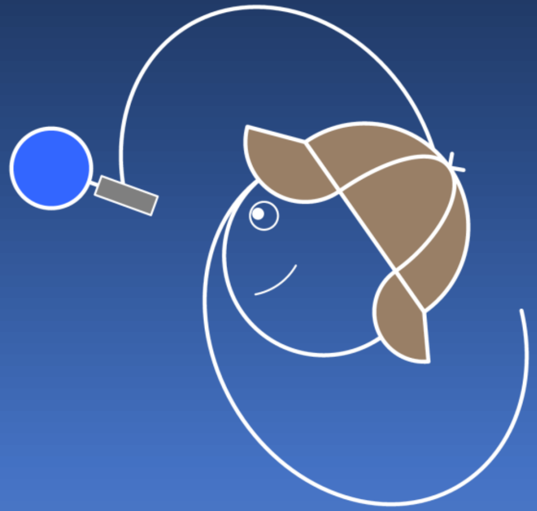
Take a Break: Riddle!

I am the reason you stir your coffee,
I am what keeps the plane in the air.
I caused Mark Antony to lose his last battle,
Leading to an epic love affair.
Without me
There would be
No light in the Universe.

Who am I?



Problems with the Gas!

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Including Hydrodynamics

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While Stars and Dark Matter can be described to our current knowledge well as point particles, for gas this is more of an issue, as gas is a much more diffuse component where the hydrodynamical equations become important.

Problems with the Gas!

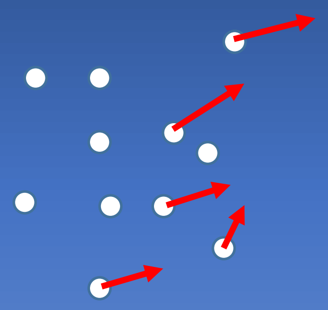
While Stars and Dark Matter can be described to our current knowledge well as point particles, for gas this is more of an issue, as gas is a much more diffuse component where the hydrodynamical equations become important.

Two ways to treat gas:

1) discretize mass
2) discretize space

Problems with the Gas!

Treat gas as discretized particles:
Smoothed Particle Hydrodynamics
(Lagrangian method)



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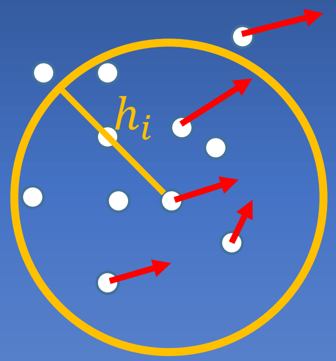

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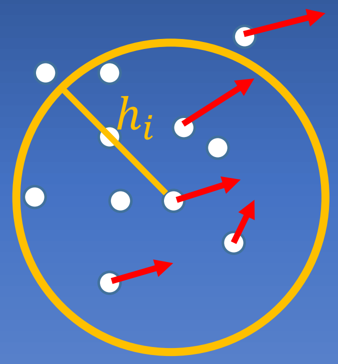

Discretizing mass means that the errors in the density filling results in errors in the volume measure. However, both the equations and the discretization are Galilei-invariant

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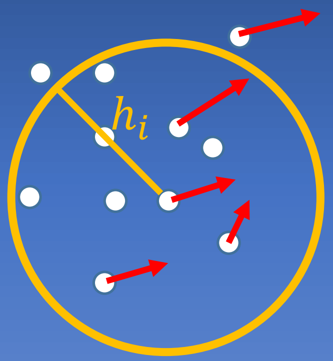

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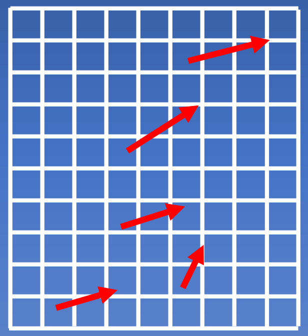
Discretize space: Treat gas within a grid: Mesh Hydrodynamics (Eulerian method)



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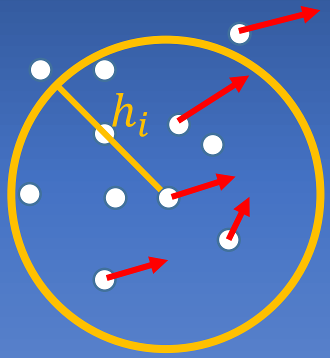

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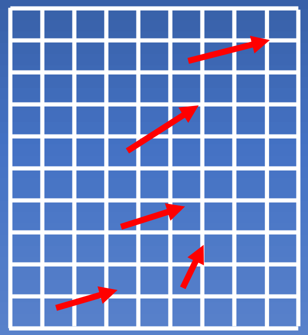
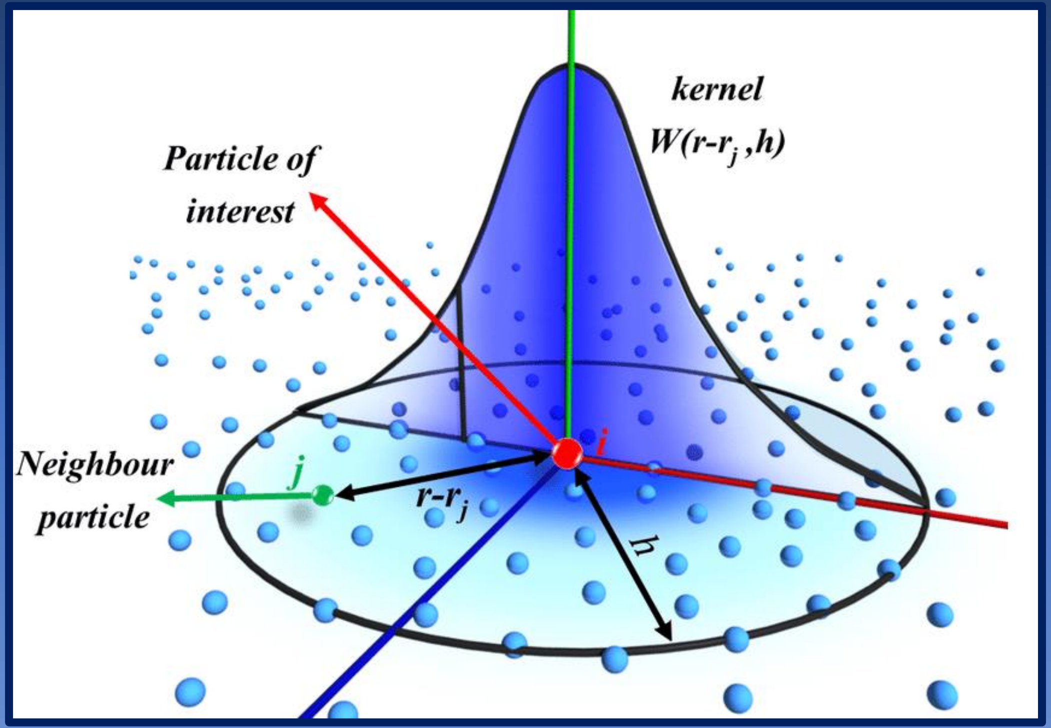


Discretizing space means that volume is fixed and errors in the density results in mass loss of growth. While the equations here are also Galilei-invariant, the discretization is not!

SPH

Smoothed Particle Hydrodynamics



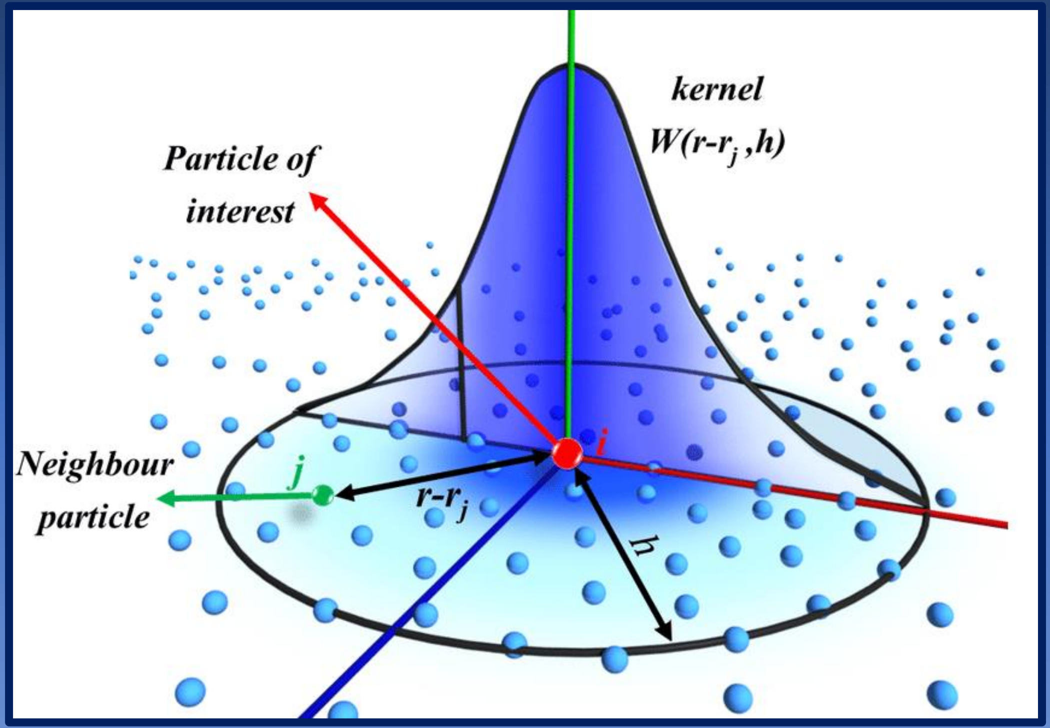
PhD Thesis Giuseppe Giorgi

$$\langle A(\boldsymbol{r})\rangle = \int W(\boldsymbol{r}-\boldsymbol{r}', h)A(\boldsymbol{r}')d^3r'$$

$$\langle A_i\rangle = \sum_{j=1}^{N} \frac{m_j}{\rho_j} A_j W(\boldsymbol{r}_{ij};\, h_i)$$

AMR

Smoothed Particle Hydrodynamics



PhD Thesis Giuseppe Giorgi

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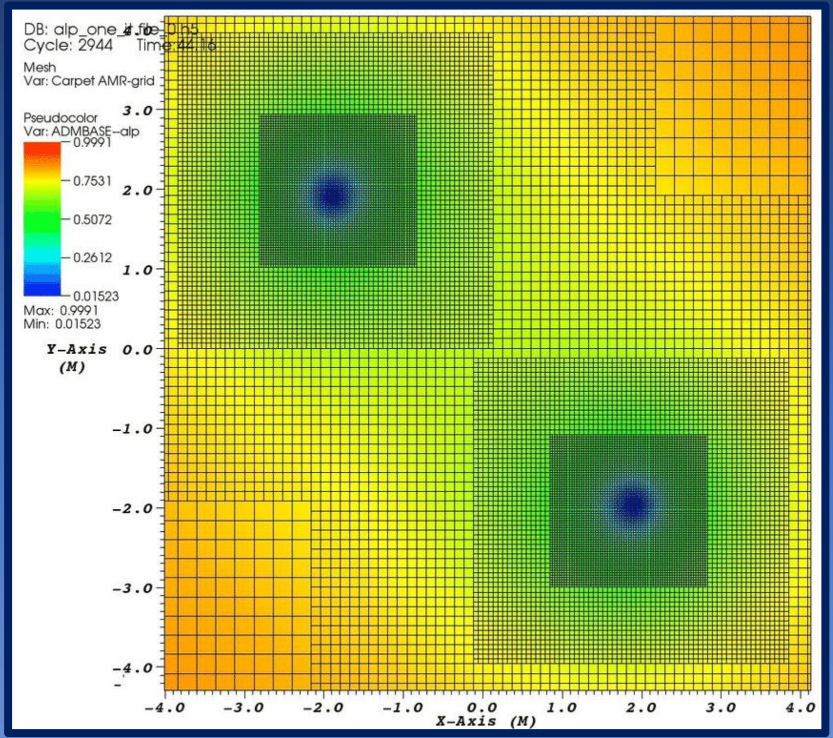
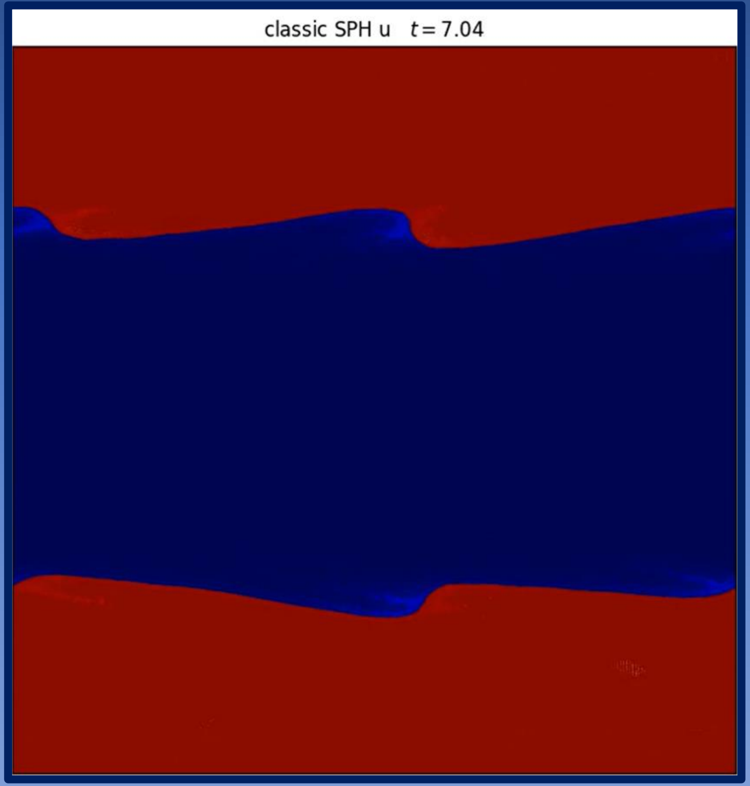
Adaptive Mesh Refinement



Janiuk & Charzynski 2016

SPH

Treat gas as discretized particles:
Smoothed Particle Hydrodynamics
(Lagrangian method)



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Courtesy
M. Niemeyer,
K. Dolag

AMR

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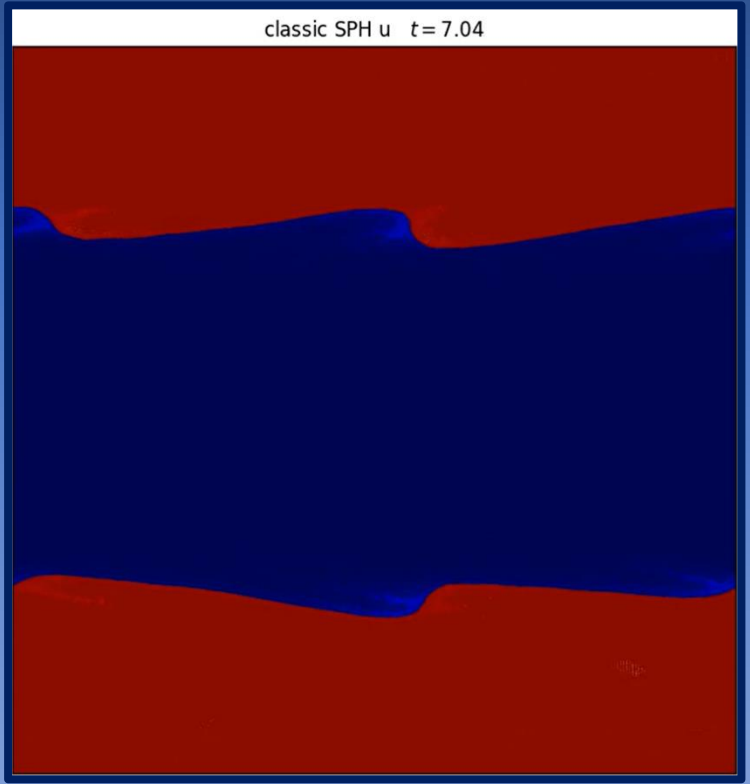

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Courtesy
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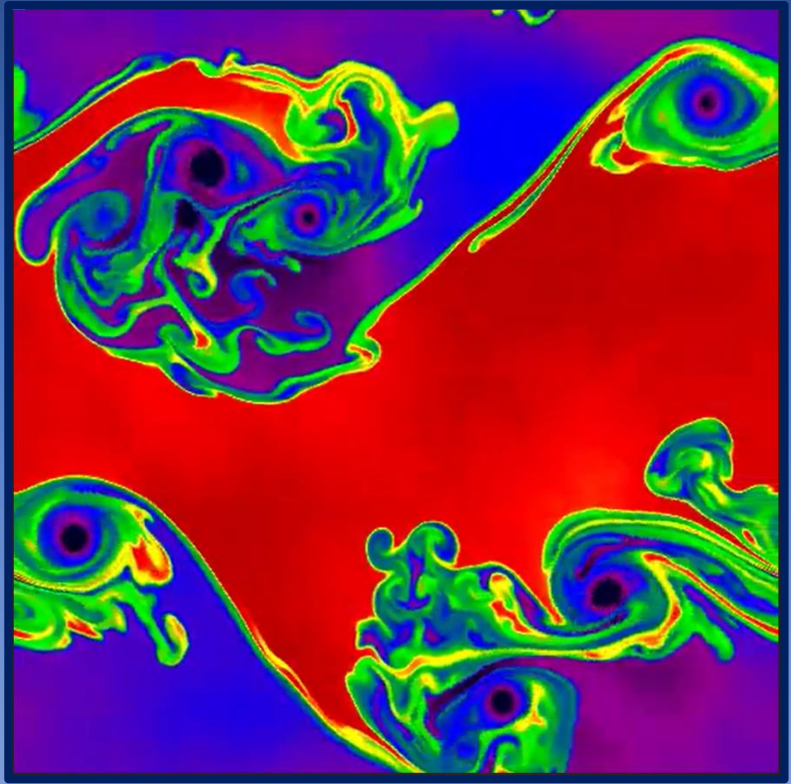
K. Dolag

Discretize space: Treat gas within a grid: Adaptive Mesh Hydrodynamics (Eulerian method)



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https://www.astro.princeton.edu/~jstone/Athena/tests/kh/kh.html

SPH versus Grid Codes

Treat gas as discretized particles: Smoothed Particle Hydrodynamics (Lagrangian method)

- ✓ Very good conservation properties (mass, momentum, total energy, angular momentum, entropy)
- ✓ shape invariant

- Instabilities do not grow sufficiently
- Mixing behind shocks not sufficient

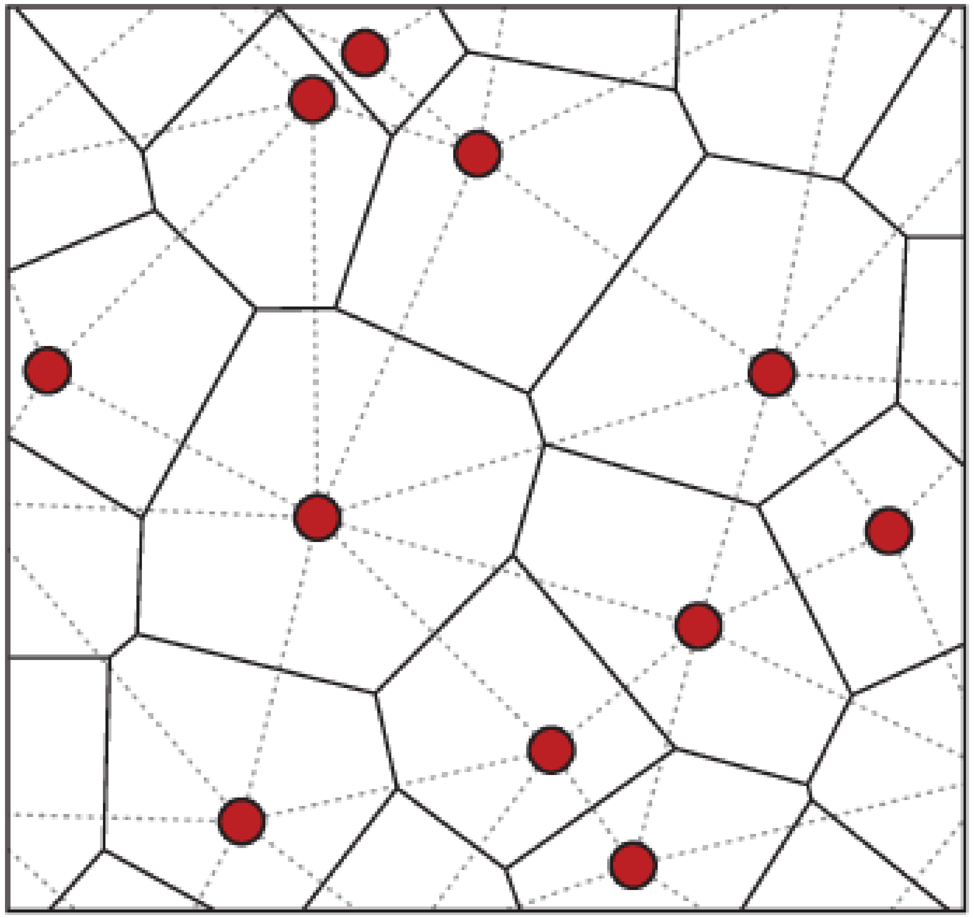
Discretize space: Treat gas within a grid: Adaptive Mesh Hydrodynamics (Eulerian method)

- ✓ Instabilities nicely grow
- ✓ Mixing between phases works well

- Energy conservation issues (especially for fast moving elements)
- Flow over cell boundaries becomes an issue for adaptive meshs
- Not shape invariant

Merging Particle and Grid code: Moving Mesh

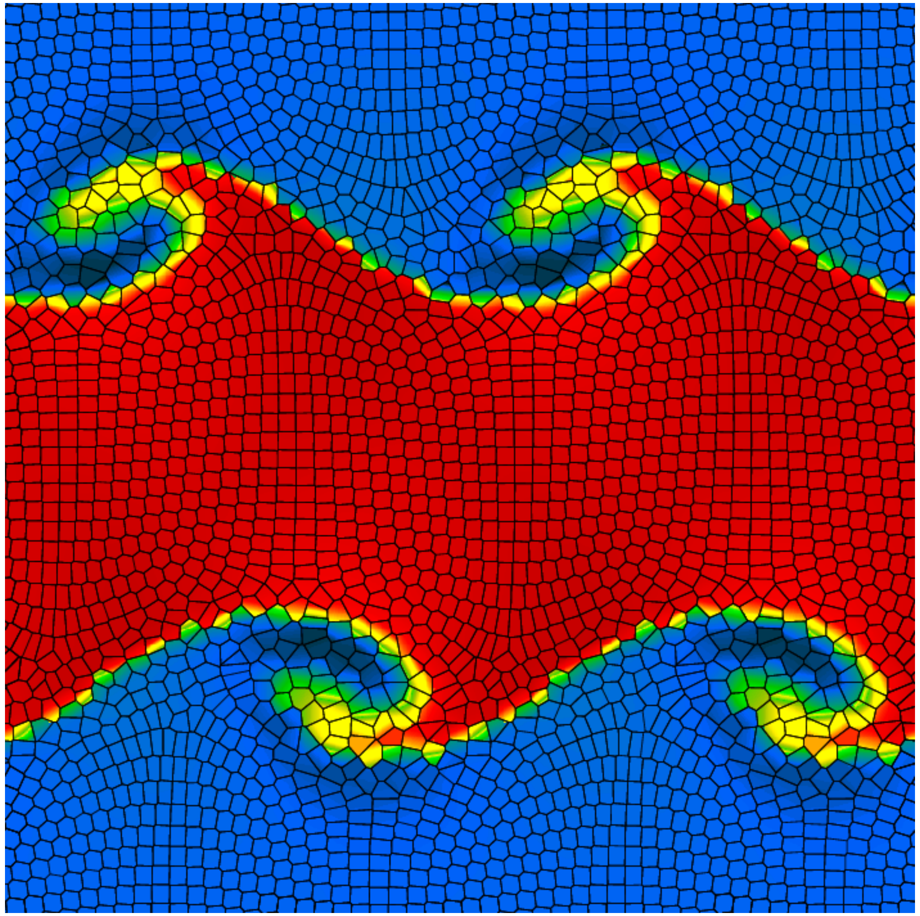
Moving Mesh Codes: Gas flows through cells, but has particle properties as well: Cells are Voronoi-tessellated

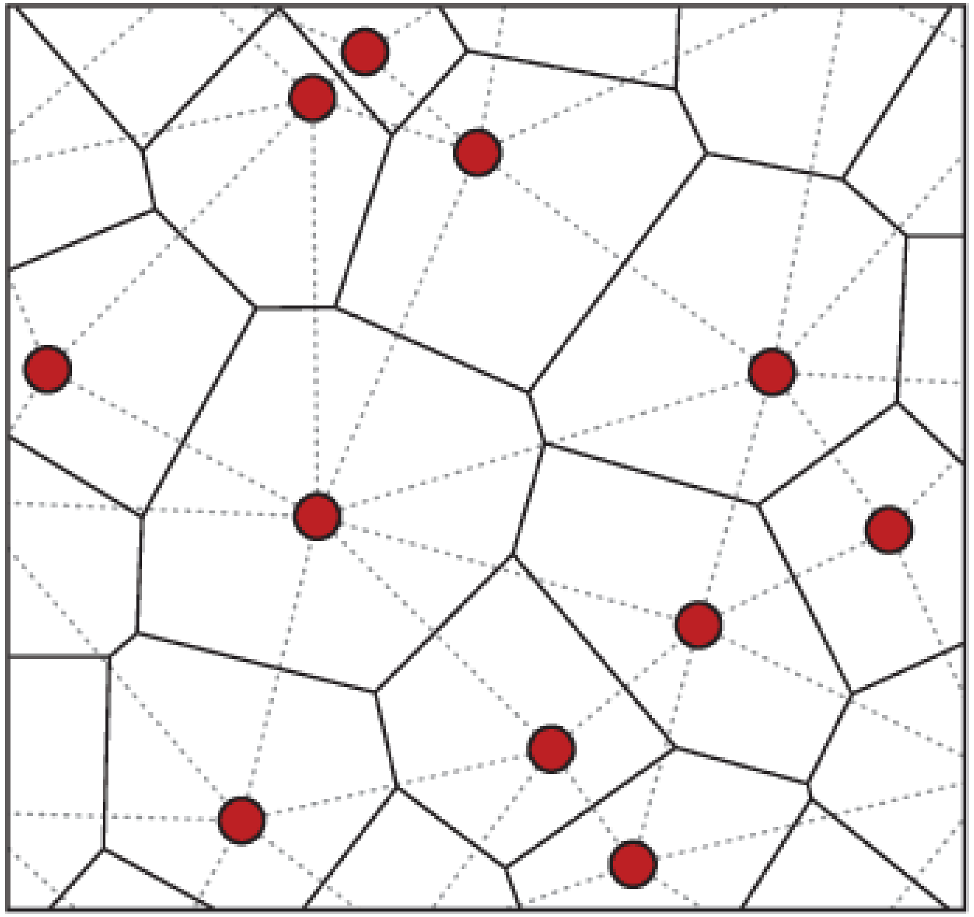


Springel et al., 2015

Merging Particle and Grid code

AREPO Code
by V. Springel





Springel et al., 2015

Merging Particle and Grid code

AREPO Code
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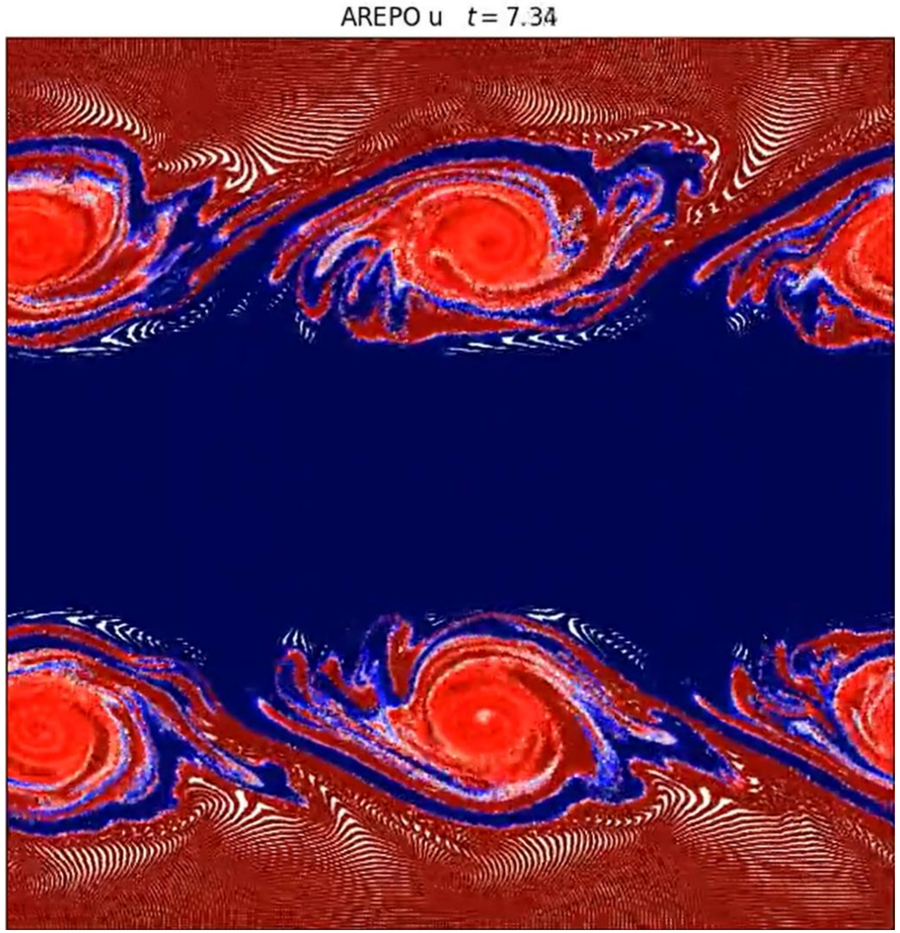
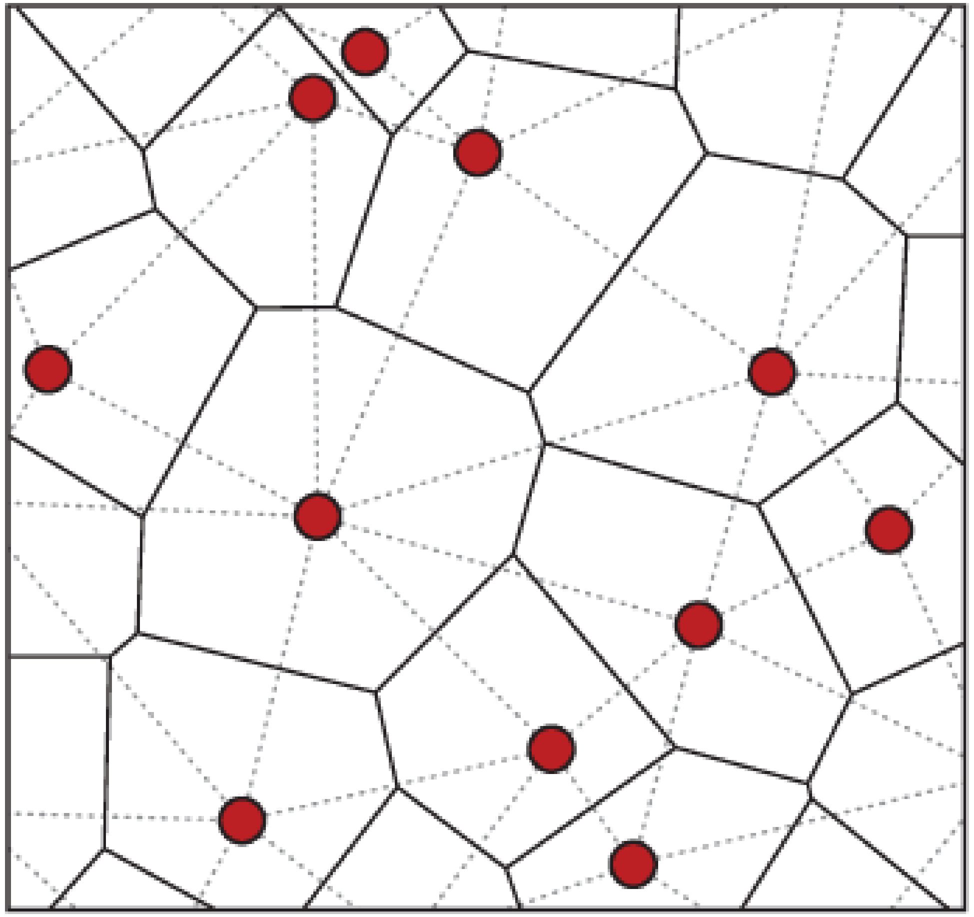
*



Courtesy M. Niemeyer, K. Dolag

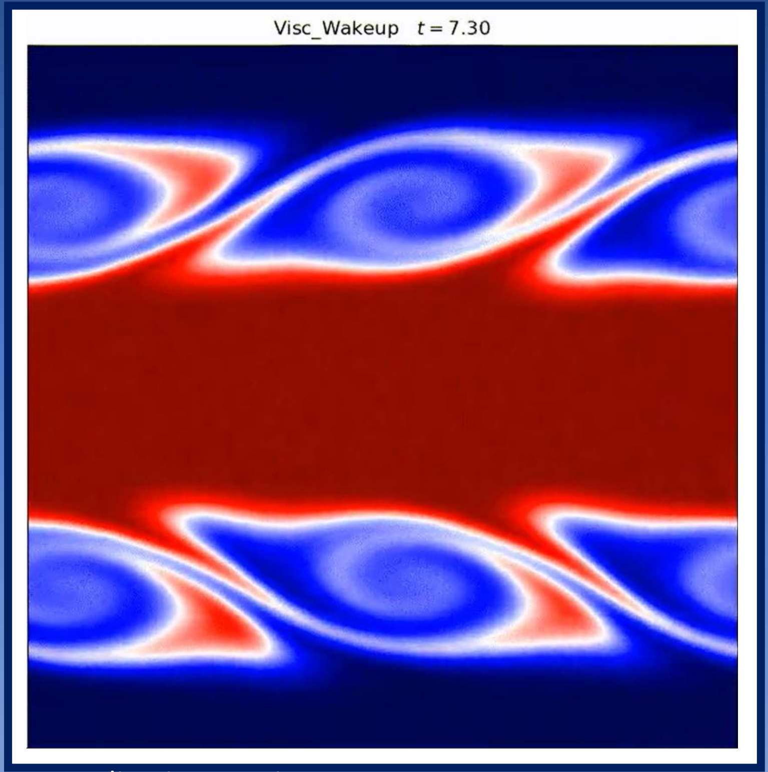


Springel et al., 2015

What can we do about SPH?

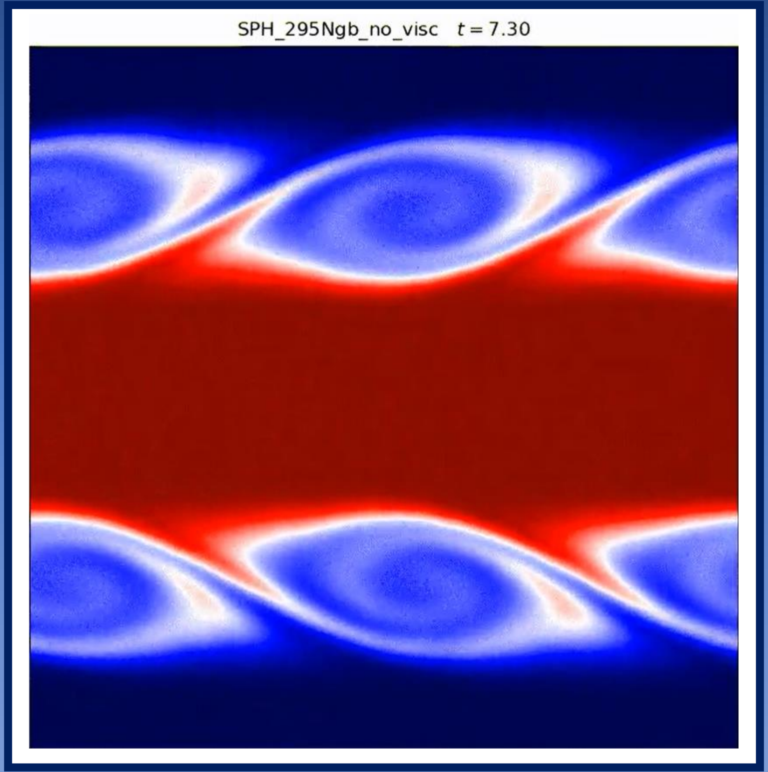
Introducing Artificial Viscosity and Conductivity

* Artificial Viscosity and Conductivity



* Artificial Viscosity only

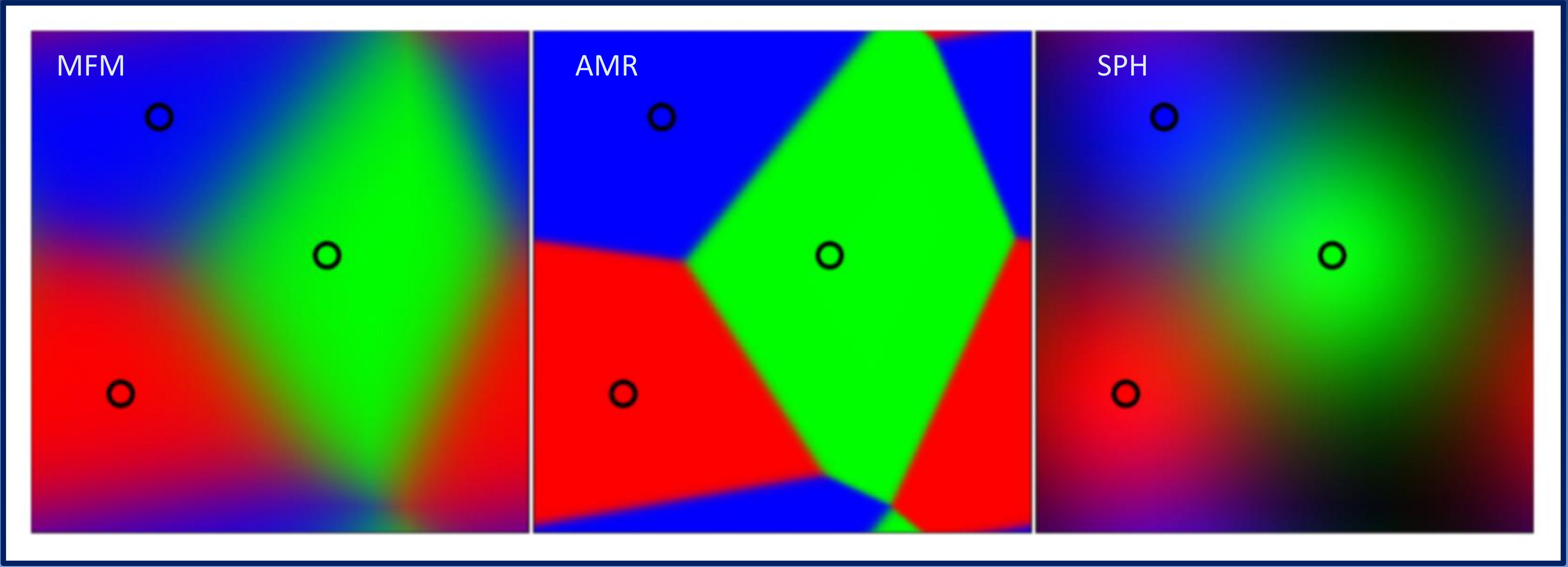
* Conductivity only



Credit: Tirso Marin

What can we do about SPH?

Meshless Finite Mass (MFM): The best of both worlds

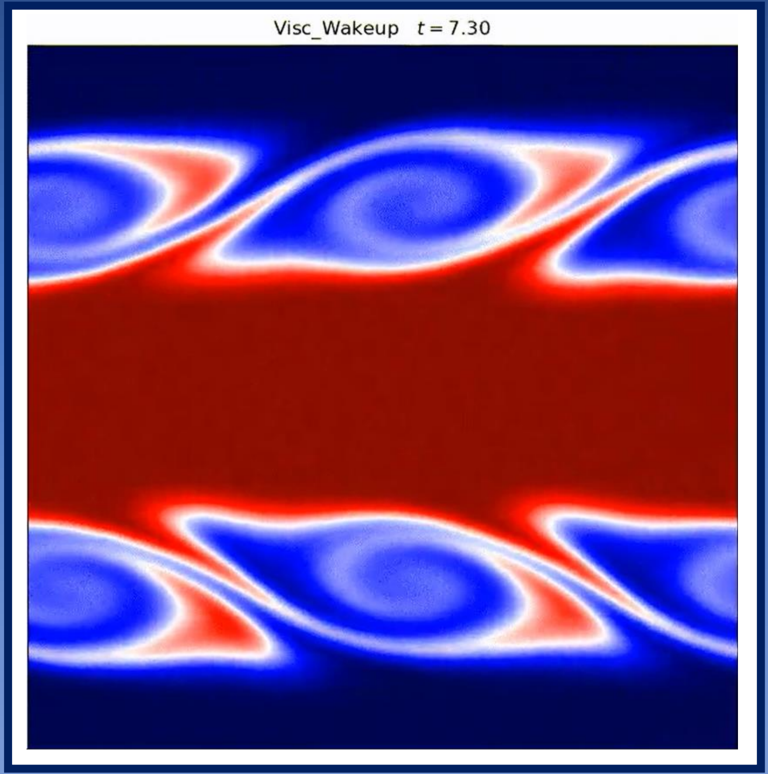


Credit: Hopkins et al 2015

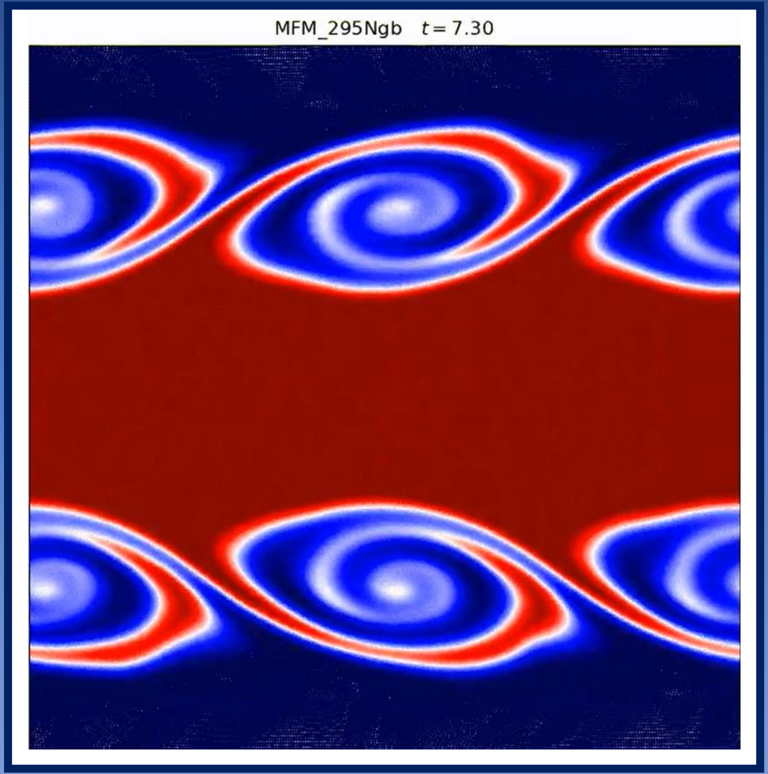
What can we do about SPH?

Meshless Finite Mass (MFM): The best of both worlds

* Artificial Viscosity and Conductivity



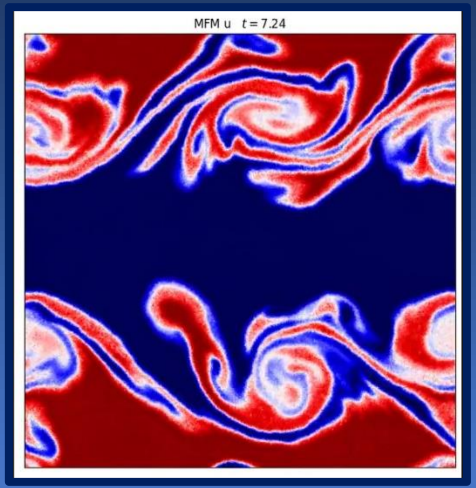
* MFM



Credit: Tirso Marin

Summary: Computational Methods

Smooth Particle Hydrodyn.

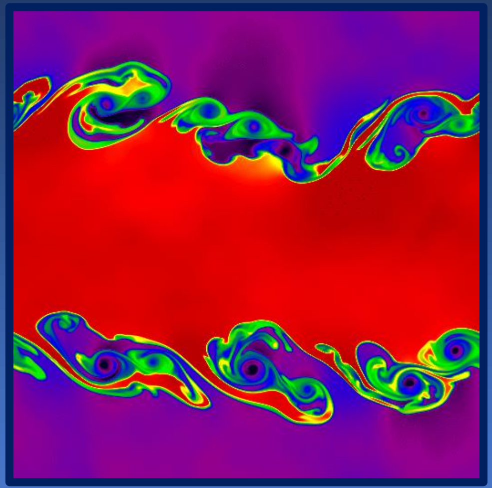


Courtesy
M. Niemeyer, K. Dolag

- ✓ Very good conservation properties (mass, momentum, total energy, angular momentum, entropy)
- ✓ shape invariant

- \- Instabilities do not grow sufficiently
- \- Mixing behind shocks not sufficient
- \- Shocks captured by artificial viscosity

Adaptive Mesh Refinement

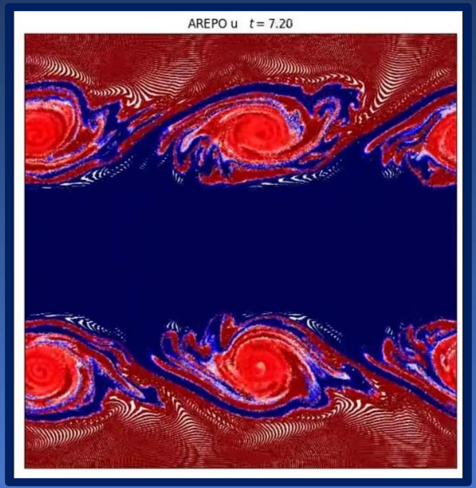


https://www.astro.princeton.edu/~jstone/Athena/tests/kh/kh.html

- ✓ Instabilities nicely grow
- ✓ Mixing between phases works well

- \- Energy conservation issues (especially for fast moving elements)
- \- Flow over cell boundaries becomes an issue for adaptive meshs
- \- Not shape invariant

Moving Mesh



Courtesy
M. Niemeyer, K. Dolag

- ✓ All good things from the other two

- \- Flow over cell boundaries (only pseudo-Lagrangian)