Computational Astrophysics

Lectures every week at Tuesday 12-13:45 in room Y23 G04 at UniZH Irchel campus

Course website under Trello (link and invitation to be given) will contain slides and instructions for projects (later)

Teacher: Prof. Lucio Mayer (lmayer@physik.uzh.ch)

Institute for Computational Science (ICS) Office Y11 F86

Teaching Assistants (offices at F floor of Y11, ICS):

Dr. Clement Surville , Dr, Elisa Bortolas, Mr. Marco Cilibrasi

Mr. Jose Roberto Canivete Cuissa , Mr. Michael Kretschmer

Textbooks: (1) Hockney & Eastwood (Computer Simulation using Particles - partially available at https://books.google.ch/books/)

(2) Saas-Fee Lecture notes by V. Springel (http://arxiv.org/abs/1412.5187)

(3) Galactic Dynamics (Binney & Tremaine 1998, 2008)

Class Assessment

Assessment via computational project to be presented during the exam. Students will write a computer program in a language of choice that implements an important numerical algorithm (or more algorithms) used in modeling of astrophysical systems among those studied in class.

2-3 Projects will be assigned on topics covered during the class.
Tutoring by assistants and by teacher.
Goal; to master the fundamental notions towards creating your first astrophysical simulation.

ECTS and course work

- For 6 ECTS (AST245): complete at least one of the projects.
- For 9 ECTS (AST246): complete the whole project package

Meeting time with teacher/assistants: by appointment, try to arrange well in advance

Outline of Lectures

- Introduction on mathematical models for (astro)physical systems of interacting and non-interacting bodies: from the Vlasov equation to the Euler equation

- Discretization methods and particles: mesh and particles

- Time integration schemes for ODEs

- The gravitational problem: from direct N-body to the treecode

- Astrophysical hydrodynamics: particle-based (SPH) methods

- Astrophysical hydrodynamics: grid-based and lagrangian mesh methods

- Numerical radiative transfer

In modern science, computer simulation has become the 3rd pillar, along with conventional theory and experiment

The advent of high performance parallel computers (hardware) combined with continued development of increasingly accurate and fast algorithms (software) is the reason behind the increasingly central role of computer simulation in science

Initially aimed at increasing accuracy and applicability of theory in the regime of complex systems (many variables and degrees of freedom) it has begun to show ability to predict new phenomena

Computer Simulation in Astrophysics

Astrophysics and Cosmology have always been (since the 70s) ideal research areas where to employ computer simulations because experiments cannot be done in the first place!

Systems under study, like galaxies or stars or extrasolar planets, are indeed too far away and the timescales of processes of interest (eg galaxy rotation or stellar evolution) are too long in human standards (million to billion of years) for any experiment to be possible

Telescopes (from ground and space) do provide data (normally at fixed time, rarely with time-dependent information) to compare theory with but no direct interaction with such data is possible, hence observations cannot replace experiments

Theory , Computation and Astronomical (Telescope) Observation

In the last two decades computational has grown tremendously to the point of becoming a major driver of new theoretical developments as analytical theory has reached the limits of the questions that it can answer in most situations.

For example, the origin of cosmic structure, from small to large scales (from planets to galaxies) is by nature dealing with complex systems described by systems of time-dependent coupled ODEs and PDEs describing gravity,hydrodynamics, radiation and sometimes also magnetic fields (newtonian or relativistic) simultaneously ---> ideal use of large parallel supercomputers

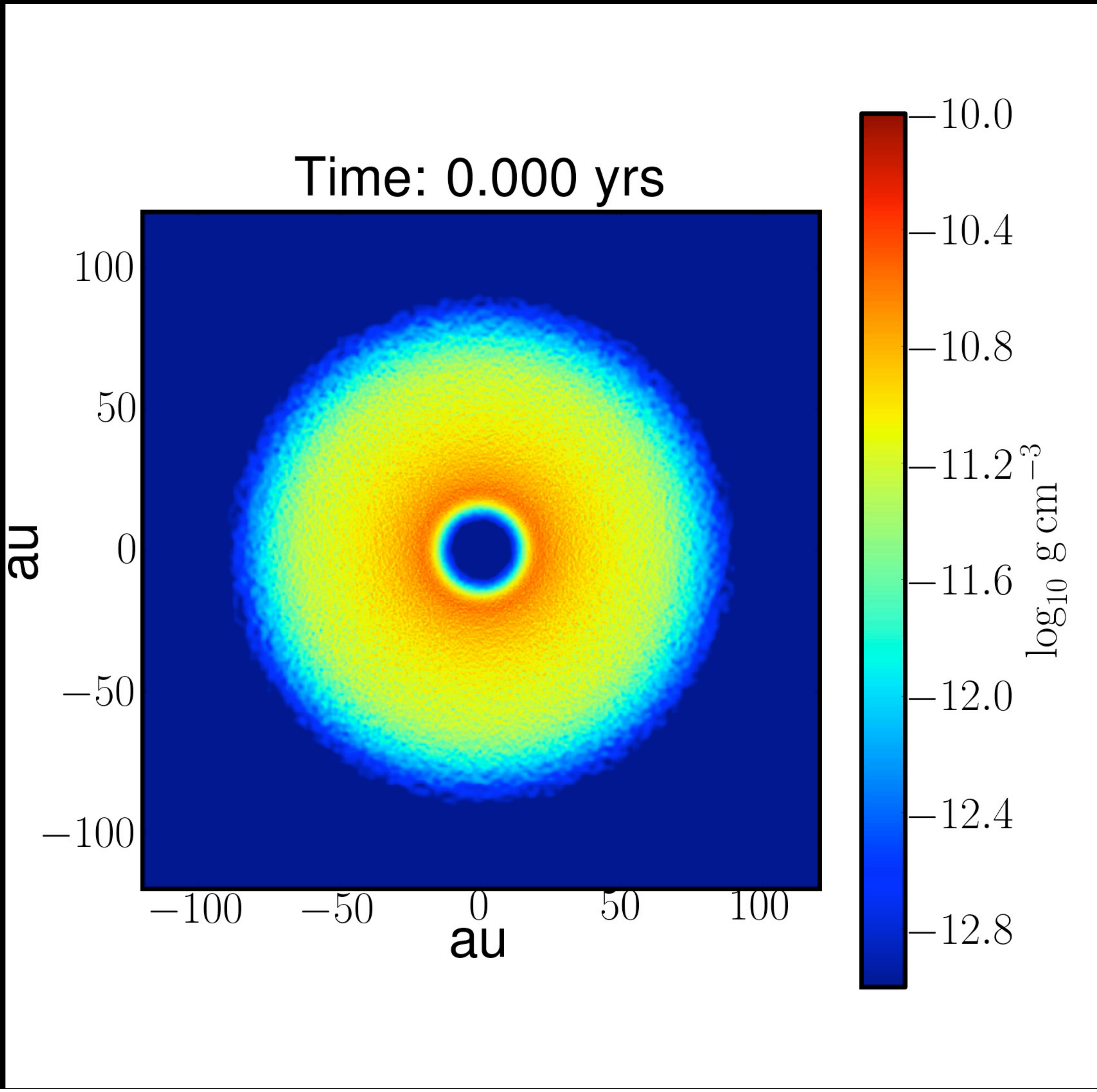
Cosmological simulation of cold dark matter halo:
fly-through into halo

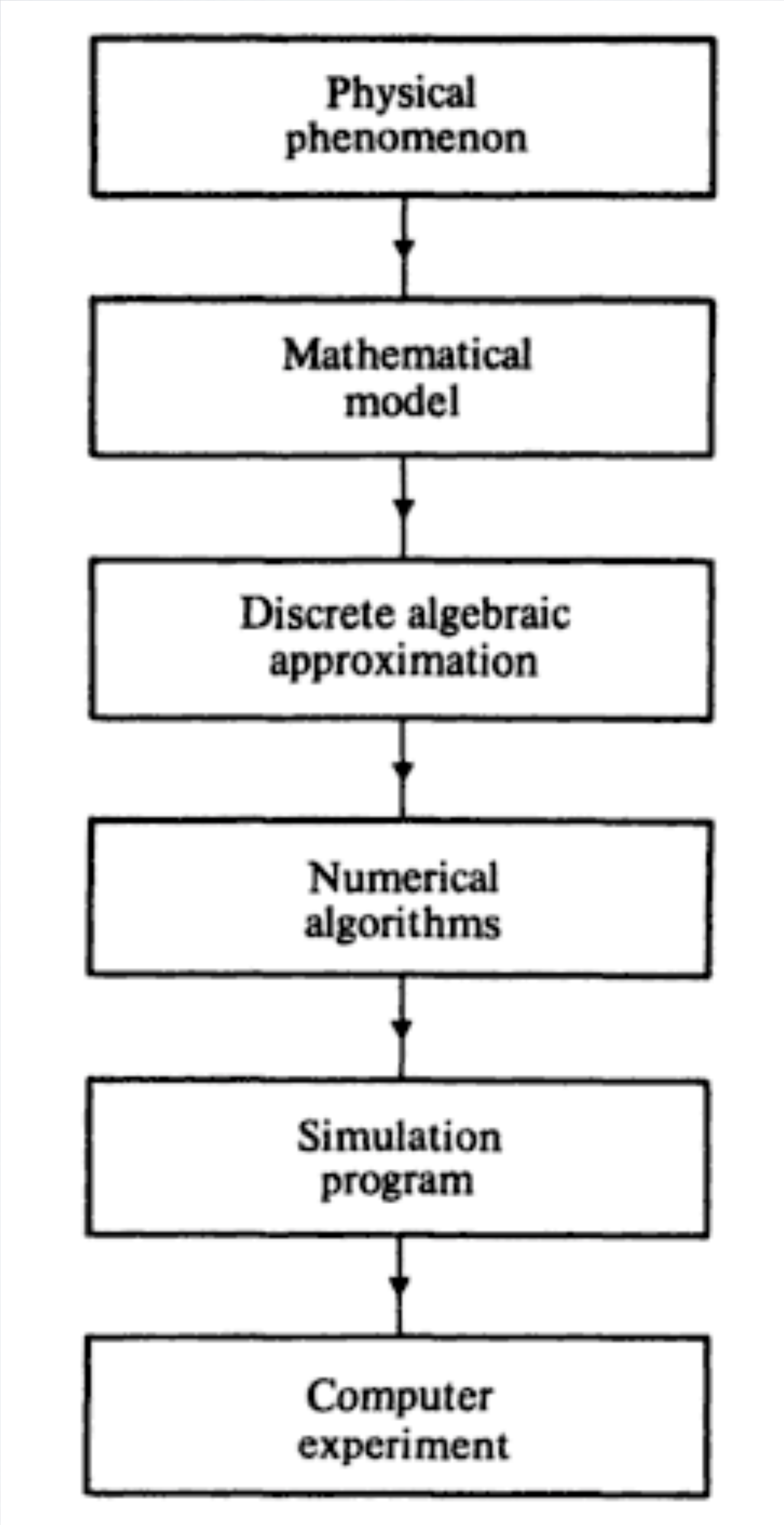
Via Lactea II:
hi-res
cosmological
simulation of
Milky Way-
sized
dark matter
halo
(Diemand et
al. 2008)

3D simulation of a turbulent gas cloud - dense regions collapse and generate stars. Evolution followed for about 100.000 yr

ERIS (Guedes et al. 2011): first cosmological simulation with dark matter and baryons that produced a spiral galaxy analogous to our Milly Way

3D simulation of gaseous protoplanetary disk showing gravitational collapse into gas giant planets along spiral arms (Galvagni & Mayer 2014)





Conventional scheme of a computational experiment.

Note: mathematical model is usually some set of ordinary or partial differential equations that describe a physical system

It is a "model" because such equations are often based on some approximation (eg the fluid approximation to describe interstellar gas in galaxies or the behaviour of dark matter)

Systems of interacting and non-interacting particles:
I - direct simulations vs. simulation of a model

Examples: molecular dynamics or star cluster (A) dynamics vs. galactic dynamics (B)

In (A) we can simulate directly a bunch of molecules or stars by using "particles" obeying the relevant physical laws, normally expressed by a field equation.
No discretization of the system necessary.

Note: Star clusters contain $N_p \sim 10^4$-10^6 particles interacting via gravity - computing mutual forces is possible with such low N_p on modern computers.
Note2: in this case the governing field equation is the Poisson equation

In (B) we would have to compute gravitational interactions between Np ~ 10^{11} stars, which is too much even for modern parallel computers!

So we have to discretize, creating "superparticles" or "mesh points" each of which represents a cluster of stars of, say, 10^4-10^5 Mo.
Now we can do the computation (a galaxy is more than just a collection of stars as it contains interstellar gas and dark matter, but for the moment we will forget about it).

The discretized model, to be physically meaningful, has to be based on a robust mathematical model of the system under study. As we will see, the physical nature of a galaxy is such that it can be correctly described using a discretized model due to the low interaction rate of stars (-->> collisionless systems)

II - Towards a general mathematical model for astrophysical systems: the notion of distribution function f (**x,v**,t)

Any system of particles or superparticles can be described by a distribution function which expresses the probability density to have a particle or superparticle with position between **x** and **x + dx** and velocity between **v** and **v + dv** at time t.
In other words it describes how phase space (**x,v**) is filled at any given time, by "real" particles or superparticles.

Next question is: how does f evolve in time? Or equivalently, how particles/superparticles evolve in phase-space?

First we must specify a field by which these particles interact (eg gravity or electromagnetic field, so we give them a mass or a charge),then find the dynamical equation that f obeys under the action of such field.

Uncorrelated and correlated systems

Consider a trivial system made of two particles
If the particles are *uncorrelated*, namely the evolution of one particle in phase space is independent from that of the other particle, at any given time t the state of the system is fully specified by the two-particle distribution function f_2:

$$f_2 = f_1\,(\mathbf{r},\mathbf{v},t)\; f_1\,(\mathbf{r'},\mathbf{v'},t)$$

which can be extended to N particles-system as:

$$f_N = f_1\,(\mathbf{r_i},\,\mathbf{v_i},\,t)\ldots f_1(\mathbf{r_n},\,\mathbf{v_n},\,t)$$

and holds when the direct interaction between particles (through whatever force field) is negligible. We will see that for gravitational systems this means the acceleration induced by *individual* particles is negligible, yet particles will still respond to the *mean gravity field*