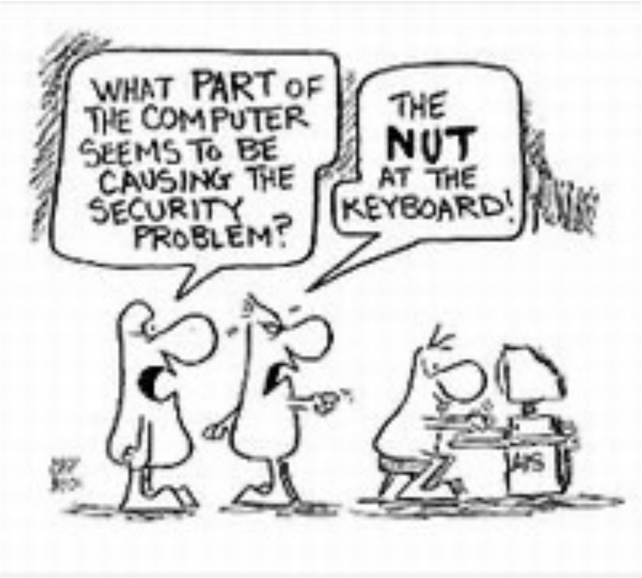
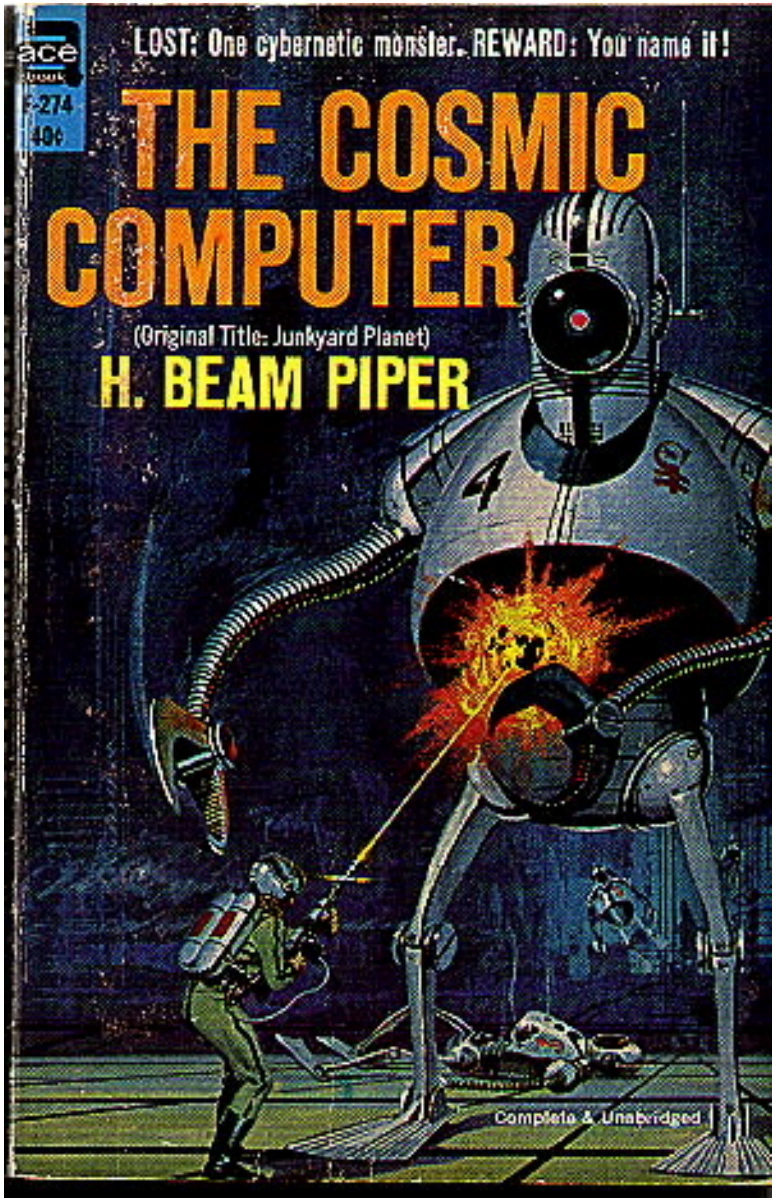
Alexander Knebe, *Universidad Autonoma de Madrid*



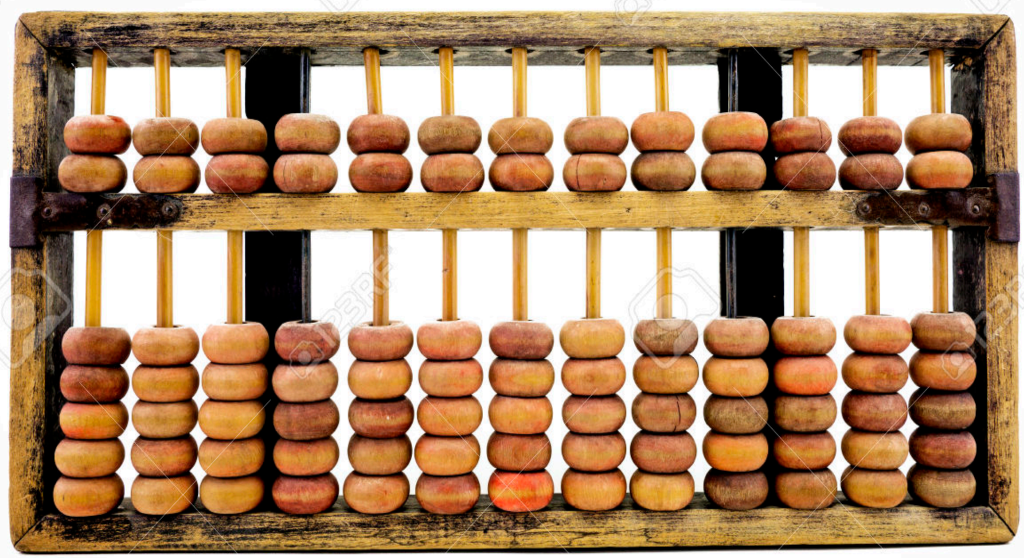
- supercomputing
- numerical modelling



how and when did it all begin?

Eurasia

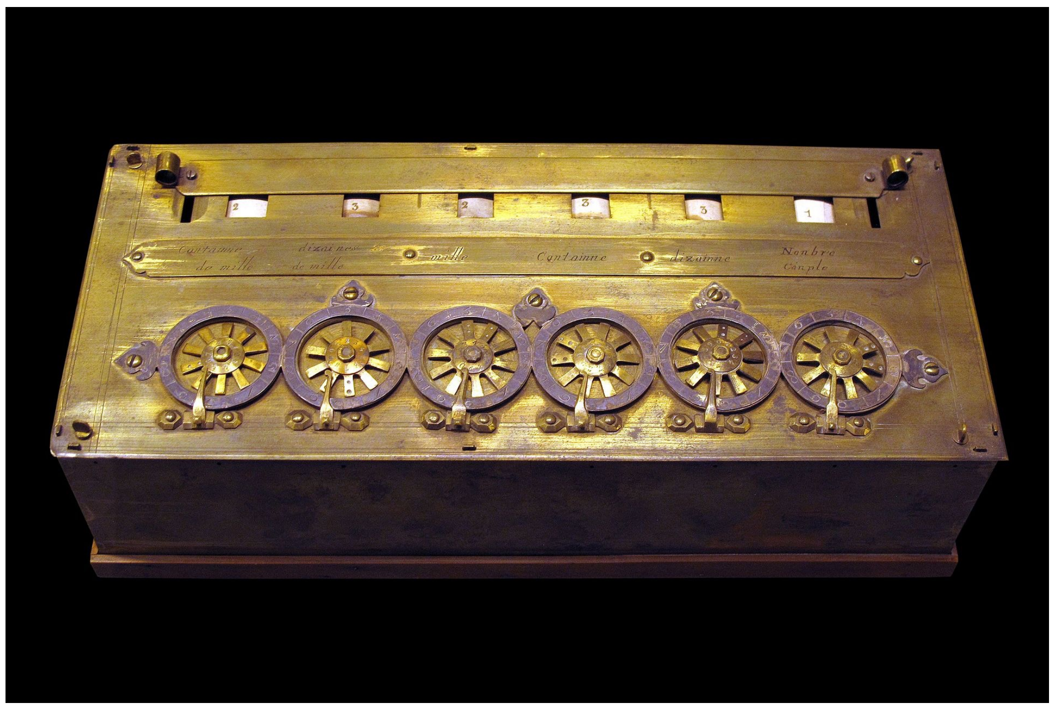
- suitable for any base system
- developed all across the Eurasian continent thousands of years BC

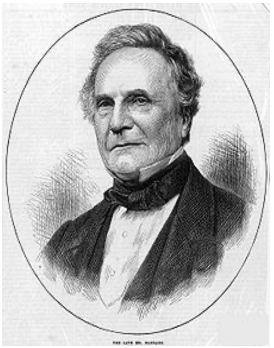


Abacus

Blaise Pascal

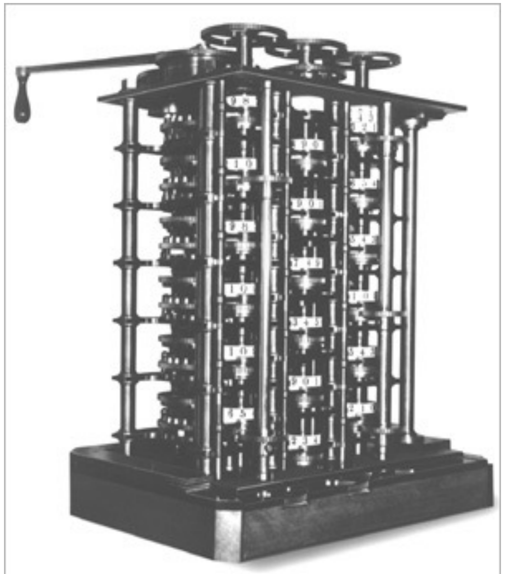
- mechanical calculator
- addition/subtraction
- multiplication/division by successive addition/subtraction
- 5 digit accuracy





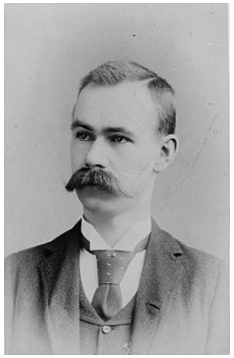
Charles Babbage

- 4000 parts
- 3 tons
- 3m x 2 m
- 31 digits accuracy
- steam driven
- "difference engine":
  - designed to tabulate polynomials
  - calculates 2nd order differences



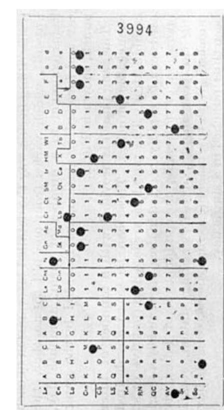
Courtesy IBM (www.ibm.com)

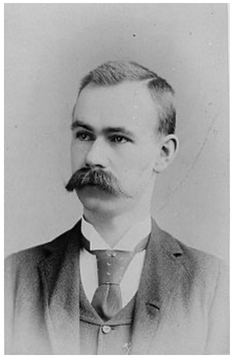
Part of one of Babbage's Difference Engines



Herman Hollerith

- developed a machine to read punch cards
- machines was used for 1890 census in the USA
- census took only one year to evaluate (prev. 8 years!)
- company: *Computing Tabulating Recording Corporation*





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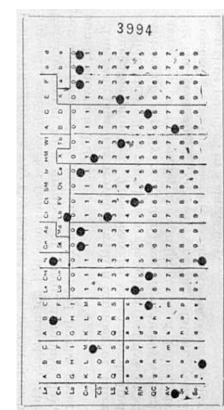

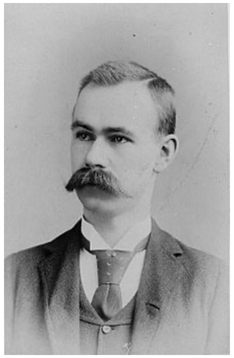

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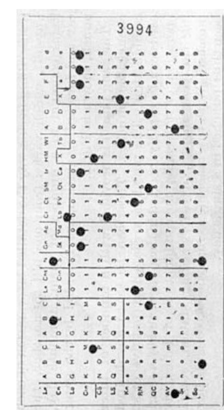
- renamed in 1924 to ... **International Business Machines (IBM)**



Arthur Scherbius

- Enigma:
  - merely a cipher device
  - heavily used by the Germans during World War II

Arthur Scherbius

- Enigma:
  - merely a cipher device
  - heavily used by the Germans during World War II
    - → movie right about that application:

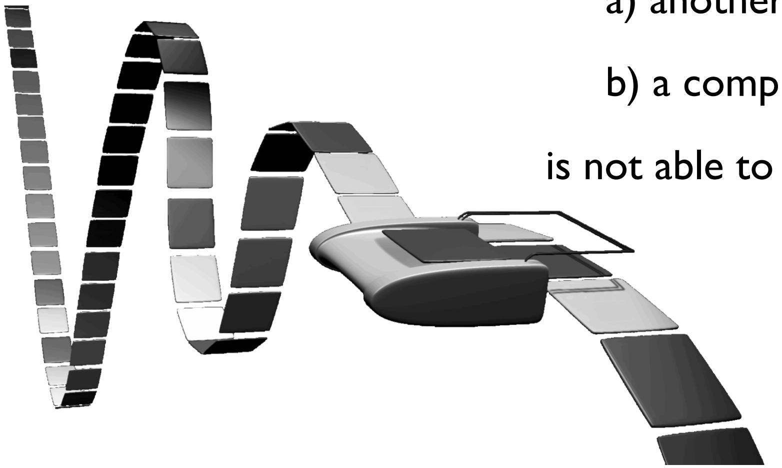
Alan Turing

- Turing Machine:
  - theoretical concept only:
    - reading instructions from printed symbols on a tape
    - result printed on back of tape
  - foundation for theories about computing, however...
  - based upon sequential memory (instead of random-access memory)
- Turing Test:
  - if a human interacting with

    a) another human

    b) a computer

  is not able to tell the difference, the computer is said to "think"



Alan Turing

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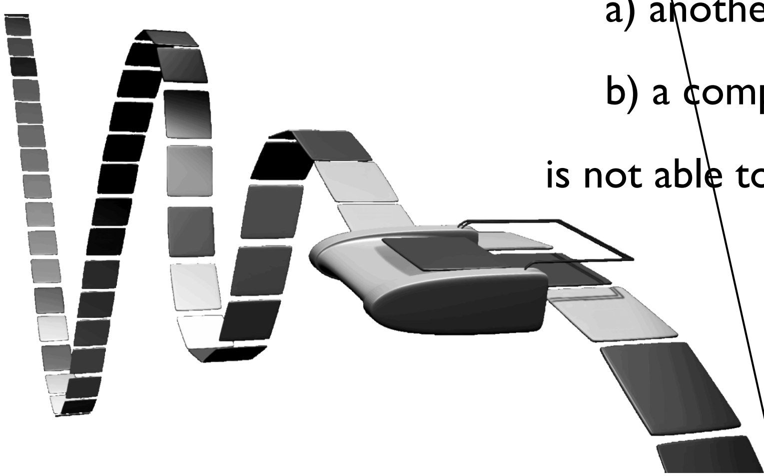
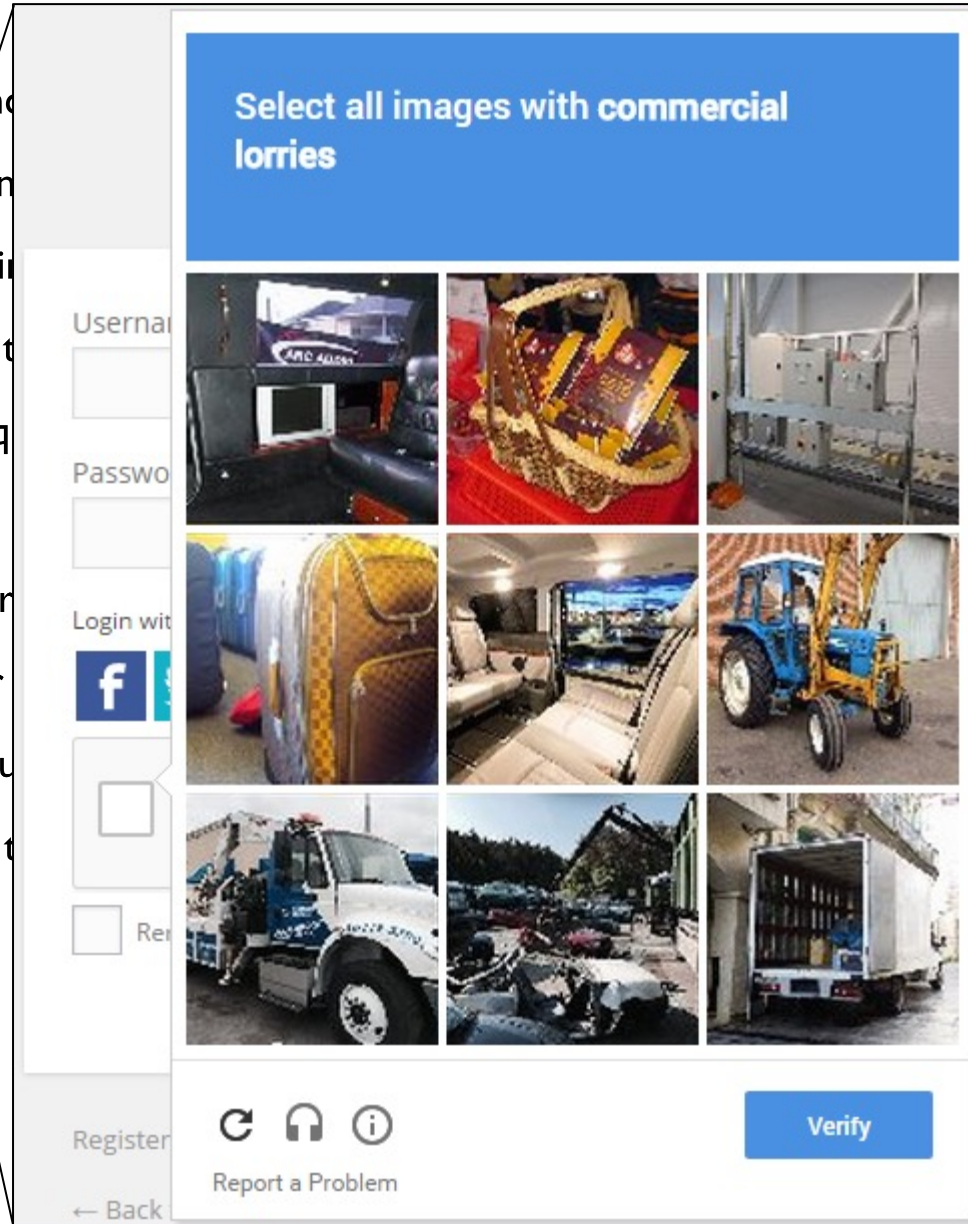
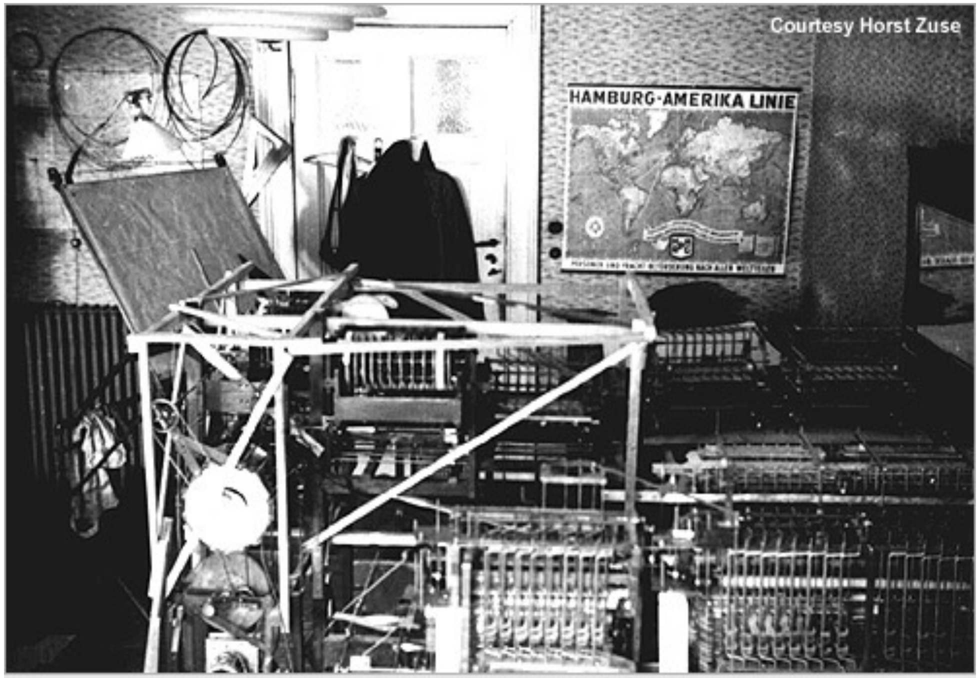




Konrad Zuse

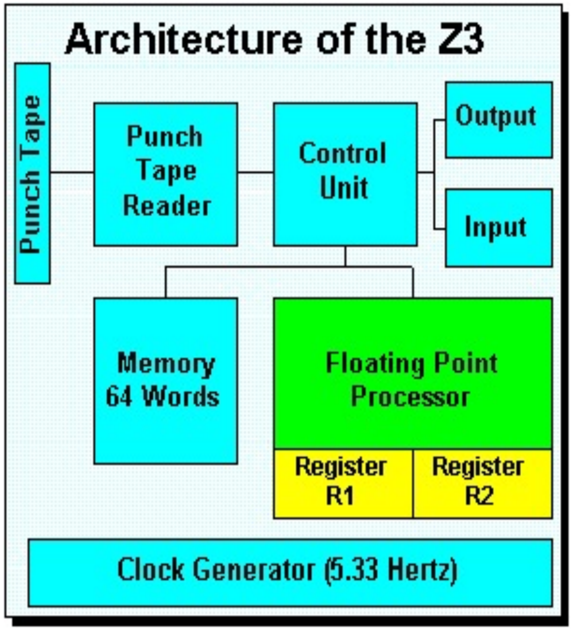
- Z1:
  - 30000 parts
  - calculations were performed in binary
  - input and output in decimal system though
  - floating point operations
  - freely programmable via punch cards

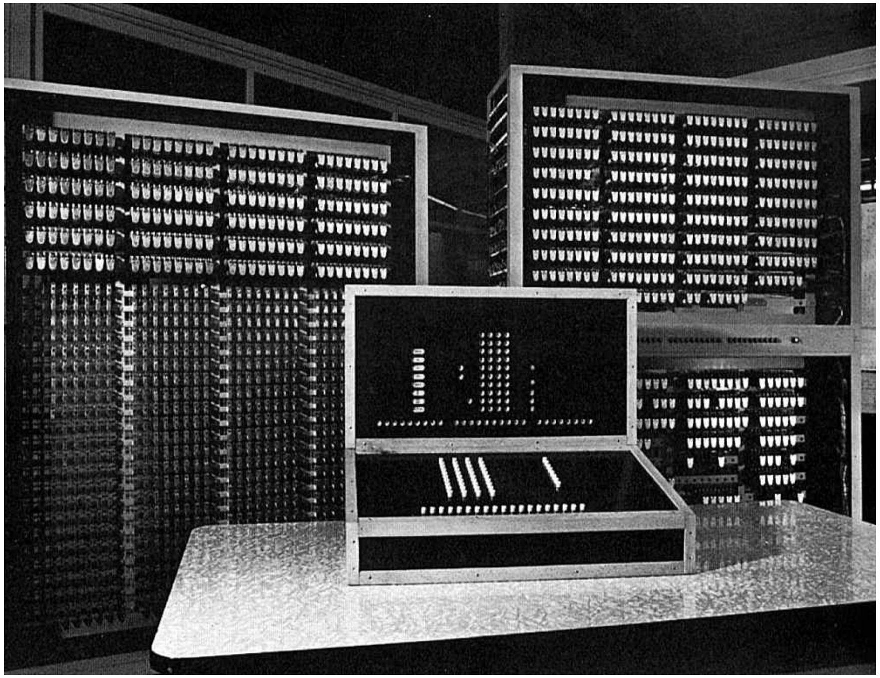


The original Z1 in Konrad's parent's living room circa 1938

Konrad Zuse

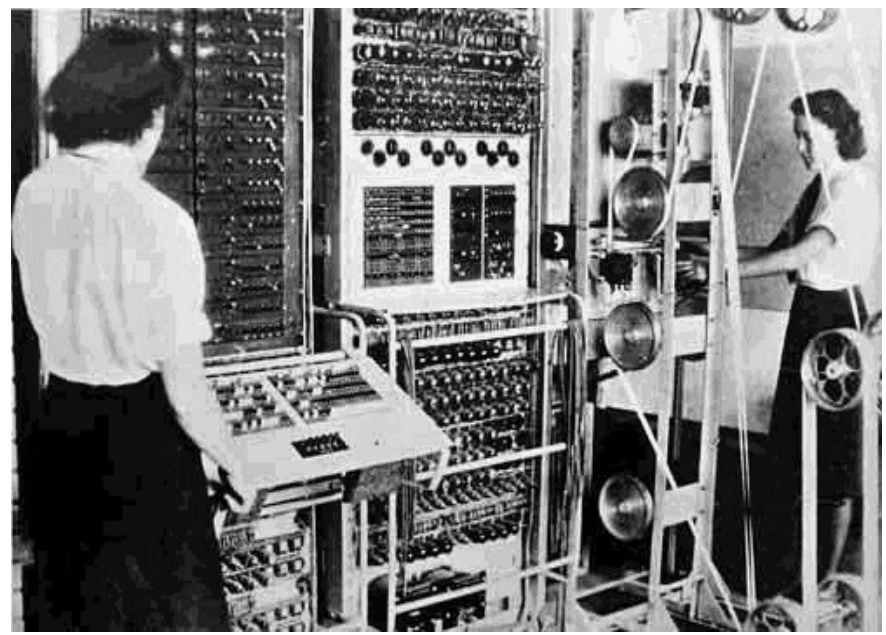
- Z3:
  - 5.3 Hz, 22bit, 176 bytes memory, 2600 relays
  - speed: 0.8sec/+ and 3sec/* (=0.333 flops)
  - floating point operations
  - freely programmable via punch cards





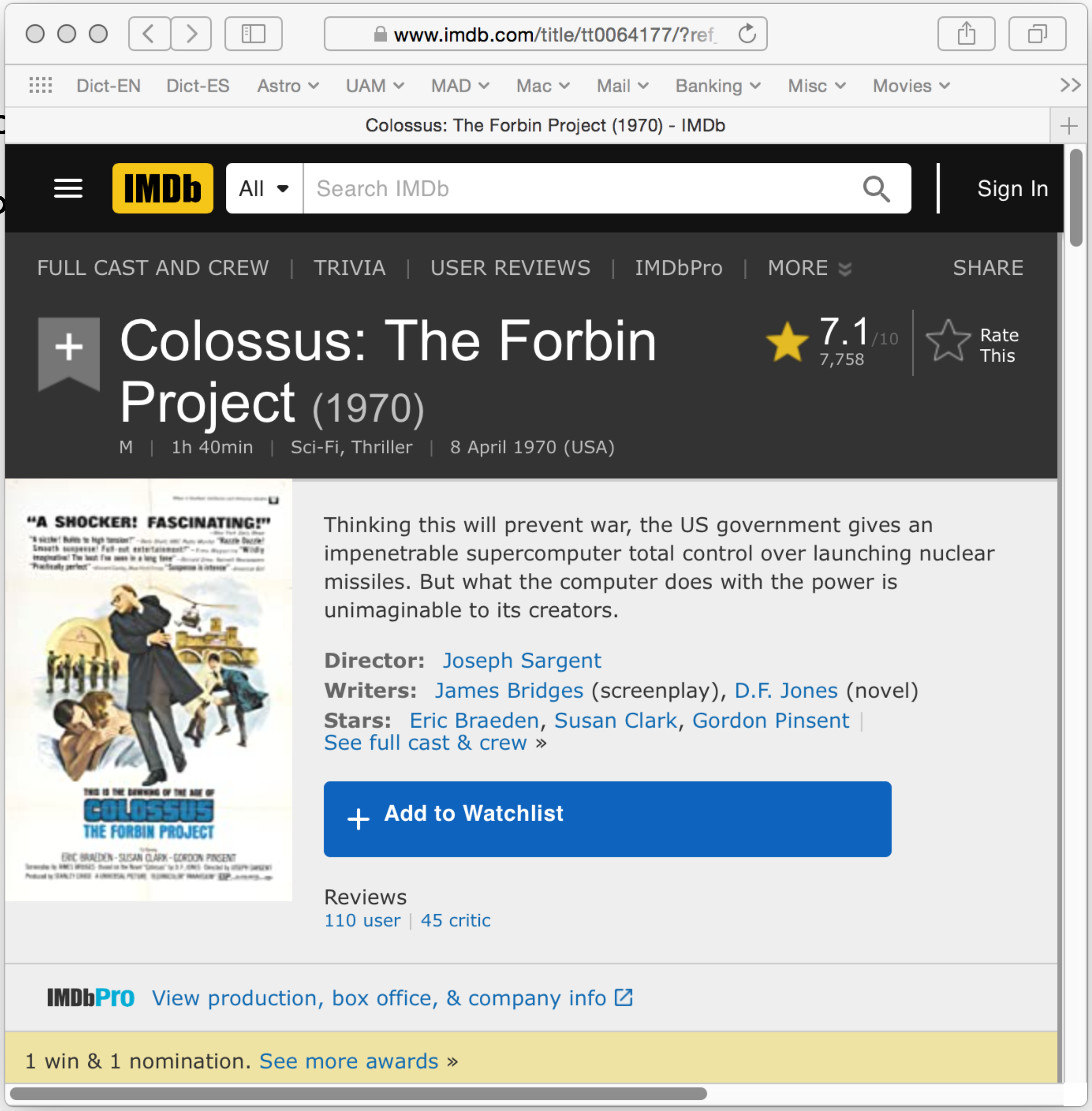

Post Office Research Station

- Colossus:
  - first "commercial" computer
  - five parallel processors
  - developed in order to decrypt German messages (see Enigma)
  - freely programmable via tape



Post Office Research Station

- Colossus:
  - first “c
  - develo
  - freely



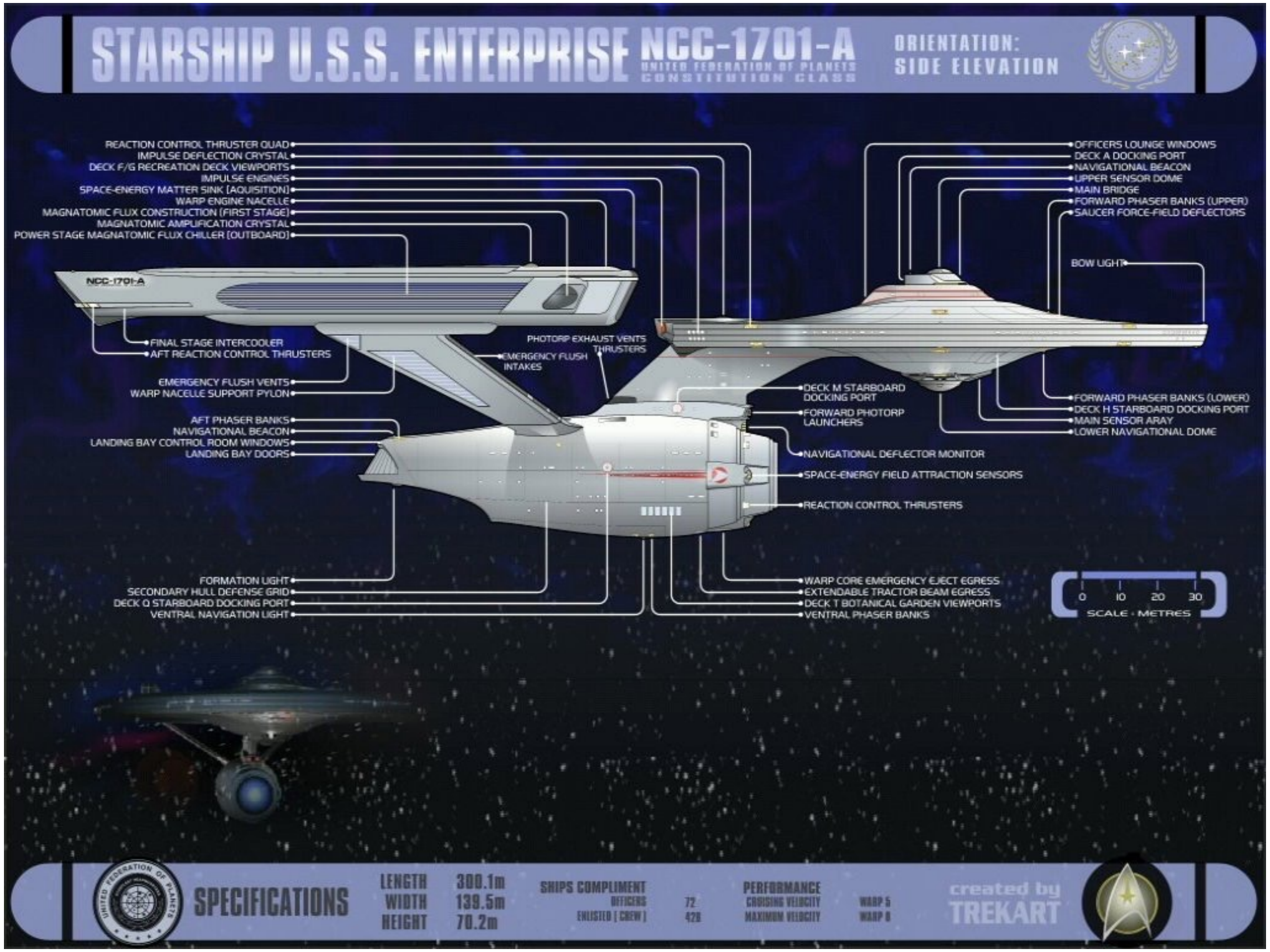
and what about today?

- Fugaku “Mount Fuji” (Japan), #1 in 11/2020:
    - 7,630,848 cores, 5000TB RAM
    - speed: 440 x 10^{15} flop/s (= 440 PetaFlops)
    - freely programmable (not via punch cards...)
    - operation system: Linux (Red Hat)

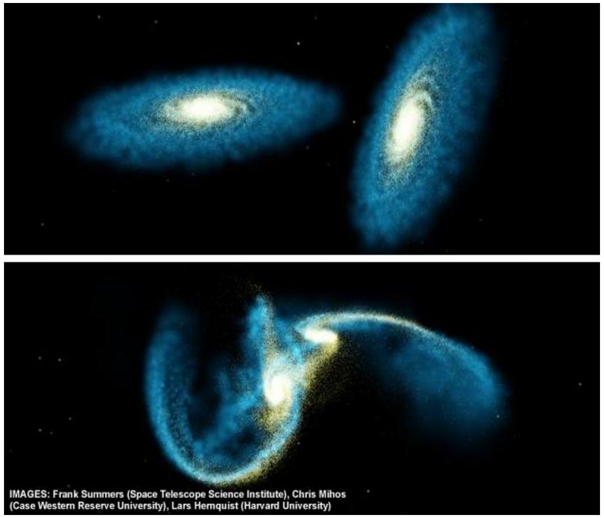
RIKEN Center for Computational Science in Kobe

- MareNostrum (Spain), #42 in 11/2020:
  - 153.216 cores, 41TB RAM
  - speed: 7 Pflop/s
  - operating system: Linux (Suse)

Torre Girona Chapel, Barcelona

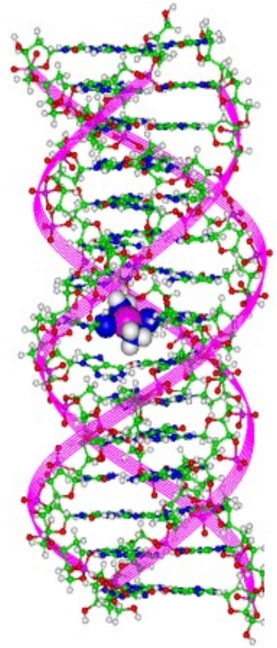


...but what about the science?



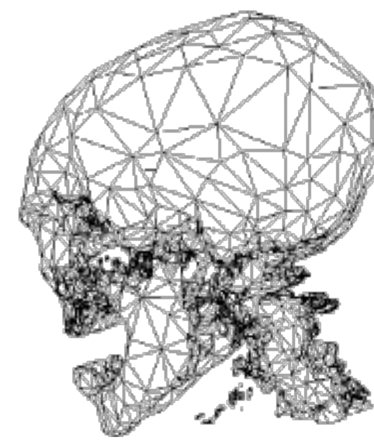
astrophysics

biology

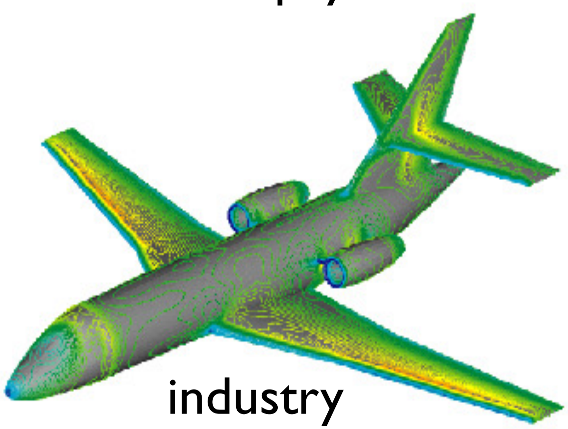


stock market

entertainment

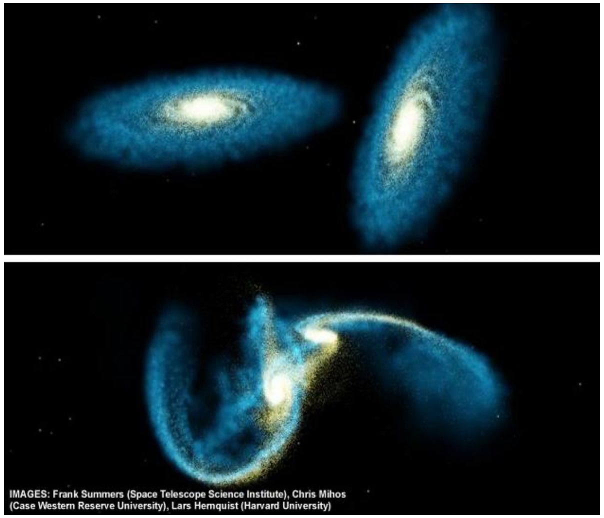


medicine



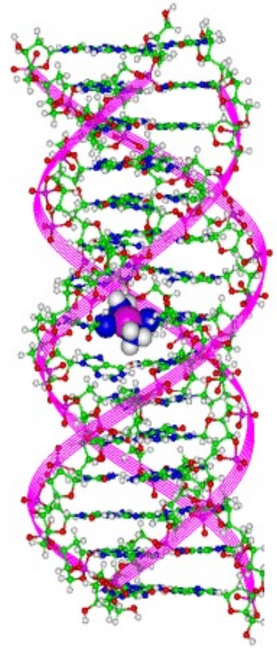
industry

artificial intelligence



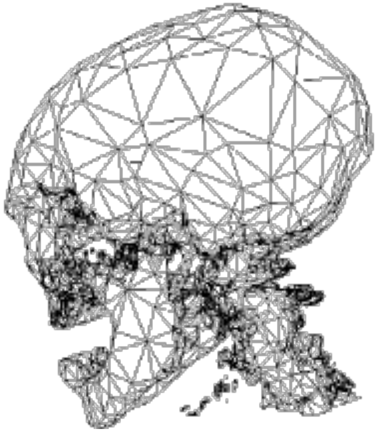
astrophysics

biology



stock market

entertainment



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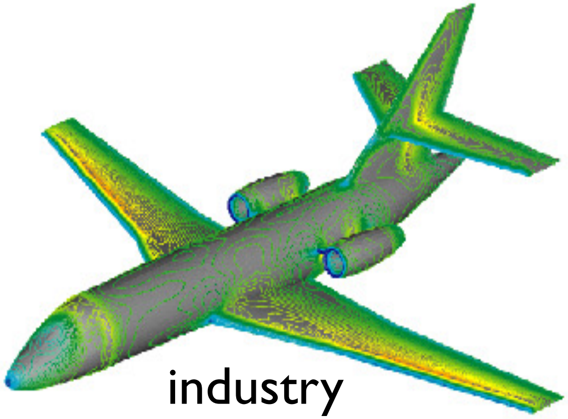
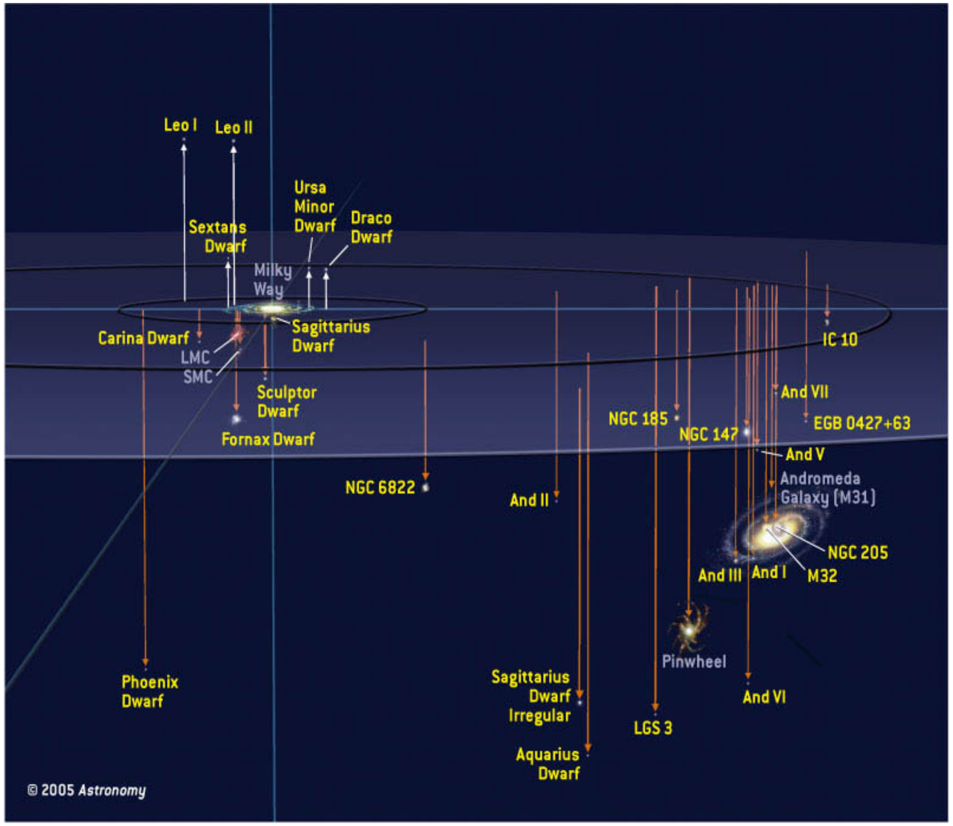


industry

artificial intelligence

The collision of our Milky Way with the Andromeda Galaxy!



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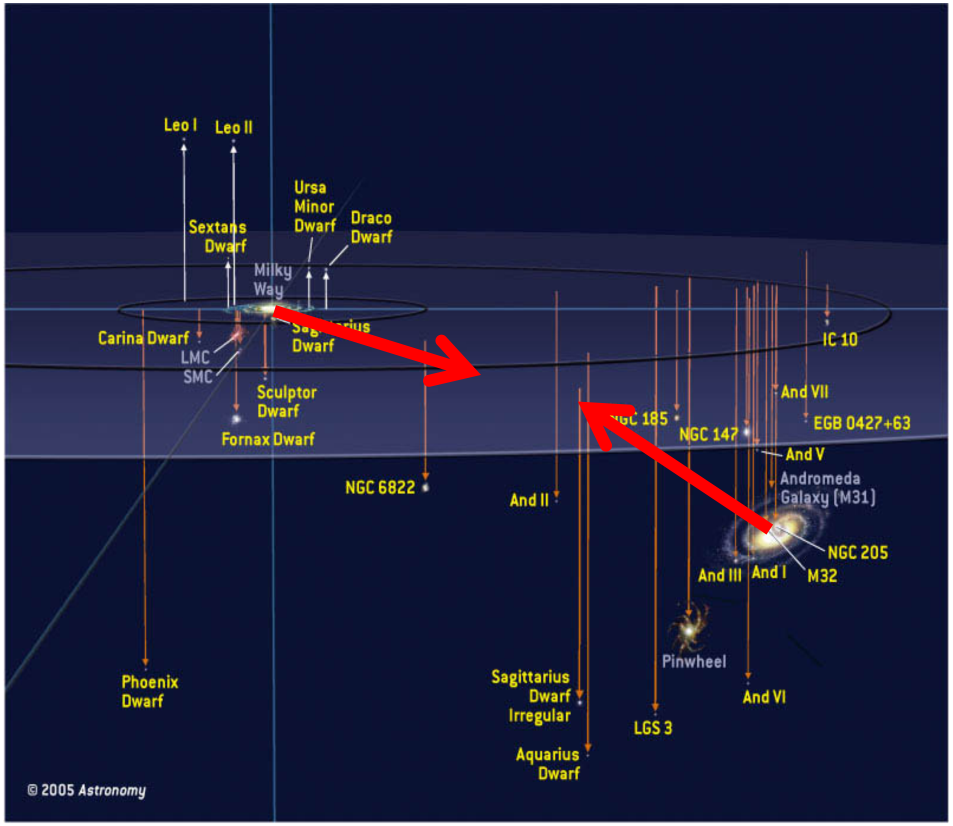

The collision of our Milky Way with the Andromeda Galaxy!

(courtesy Arman Khalatyan, www.clues-project.org)

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Erik Holmberg

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 94 NOVEMBER 1941 NUMBER 3

ON THE CLUSTERING TENDENCIES AMONG THE NEBULAE

II. A STUDY OF ENCOUNTERS BETWEEN LABORATORY MODELS OF STELLAR SYSTEMS BY A NEW INTEGRATION PROCEDURE

ERIK HOLMBERG

ABSTRACT

In a previous paper[1] the writer discussed the possibility of explaining the observed clustering effects among extragalactic nebulae as a result of captures. The present investigation deals with the important problem of whether the loss of energy resulting from the tidal disturbances at a close encounter between two nebulae is large enough to effect a capture. The tidal deformations of two models of stellar systems, passing each other at a small distance, are studied by reconstructing, piece by piece, the orbits described by the individual mass elements. The difficulty of integrating the total gravitational force acting upon a certain element at a certain point of time is solved by replacing gravitation by light. The mass elements are represented by light-bulbs, the candle power being proportional to mass, and the total light is measured by a photocell (Fig. 1). The nebulae are assumed to have a flattened shape, and each is represented by 37 light-bulbs. It is found that the tidal deformations cause an increase in the attraction between the two objects, the increase reaching its maximum value when the nebulae are separating, i.e., after the passage. The resulting loss of energy (Fig. 6) is comparatively large and may, in favorable cases, effect a capture. The spiral arms developing during the encounter (Figs. 4) represent an interesting by-product of the investigation. The direction of the arms depends on the direction of rotation of the nebulae with respect to the direction of their space motions.

I. THE EXPERIMENTAL ARRANGEMENTS

The present paper is a study of the tidal disturbances appearing in stellar systems which pass one another at small distances. These tidal disturbances are of some importance since they are accompanied by a loss of energy which may result in a capture between the two objects. In a previous paper[1] the writer discussed the clustering tendencies among extragalactic nebulae. A theory was put forth that the observed clustering effects are the result of captures between individual nebulae. The capture theory seems to be able to account not only for double and multiple nebulae but also for the large extragalactic clusters. The present investigation tries to give an answer to the important question of whether the loss of energy accompanying a close encounter between two nebulae is large enough to effect a capture.

A study of tidal disturbances is greatly facilitated if it can be restricted to only two dimensions, i.e., to nebulae of a flattened shape, the principal planes of which coincide with the plane of their hyperbolic orbits. In order to reconstruct the orbit described by

[1] *Mt. W. Contr.*, No. 633; *Ap. J.*, **92**, 200, 1940.

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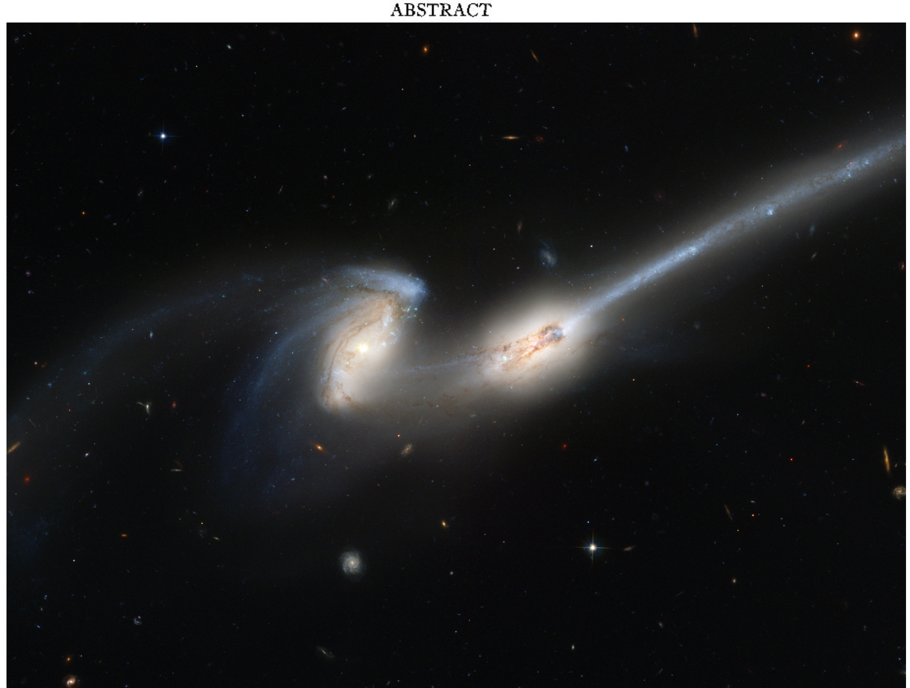
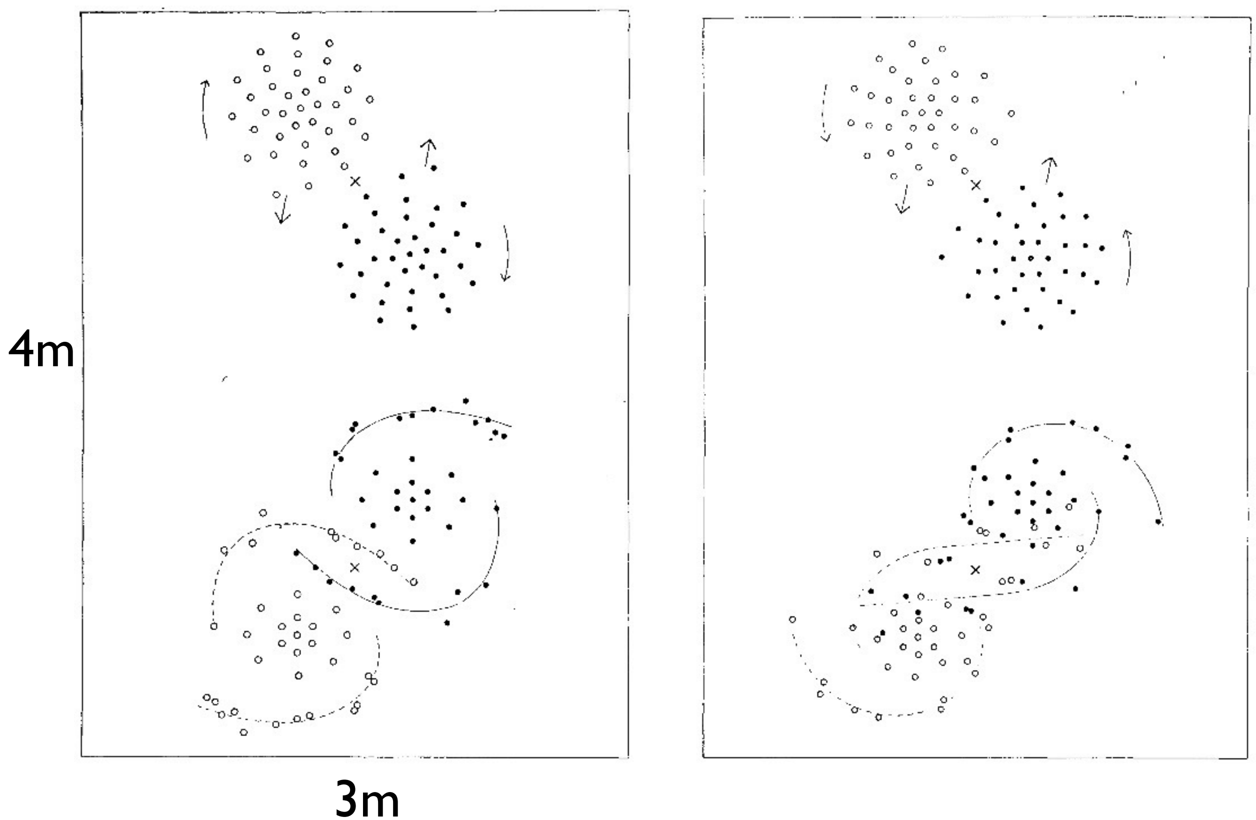


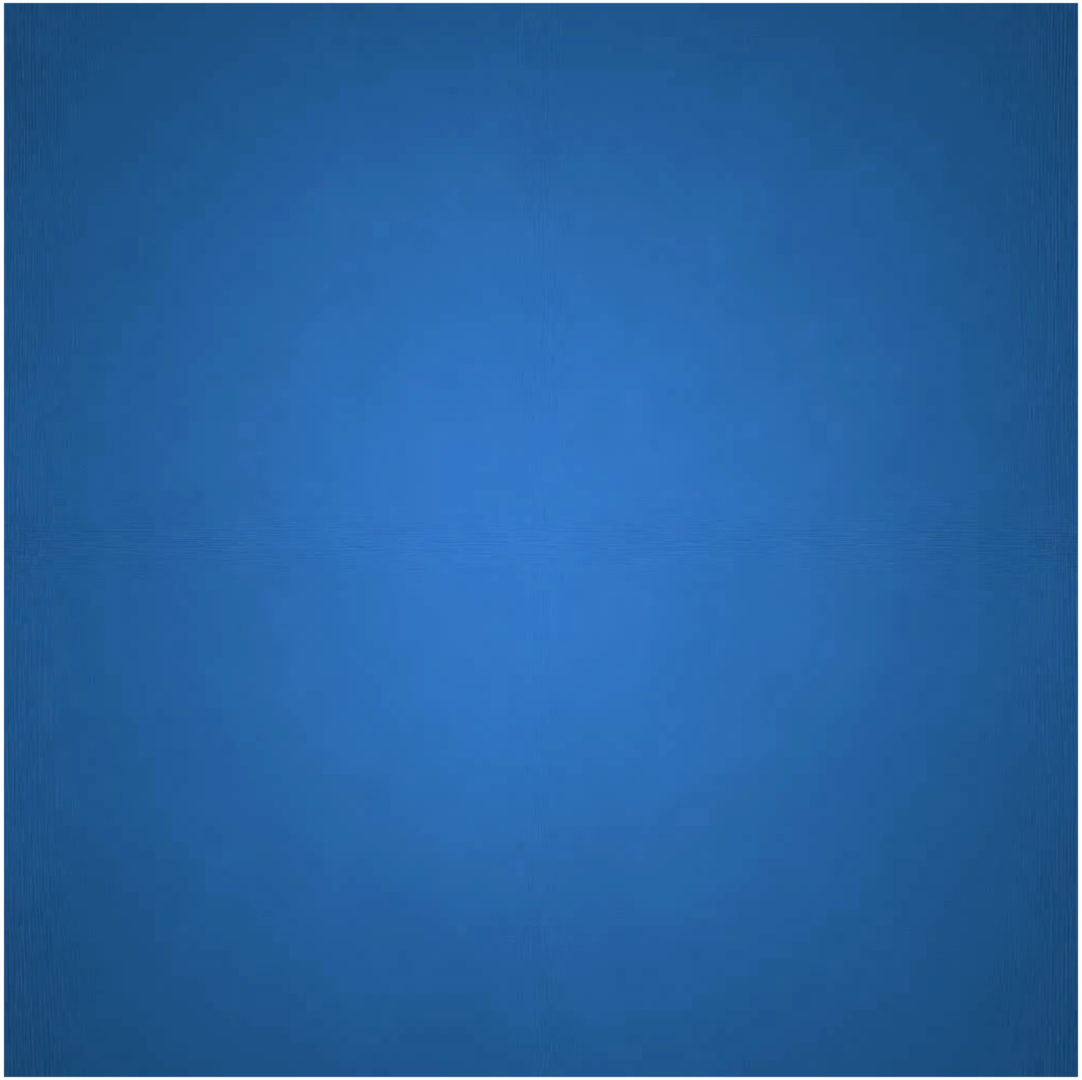
N = 2x 37

Erik Holmberg

- replacing gravity by light (same $1/r^2$ law)
- formation of tidal features

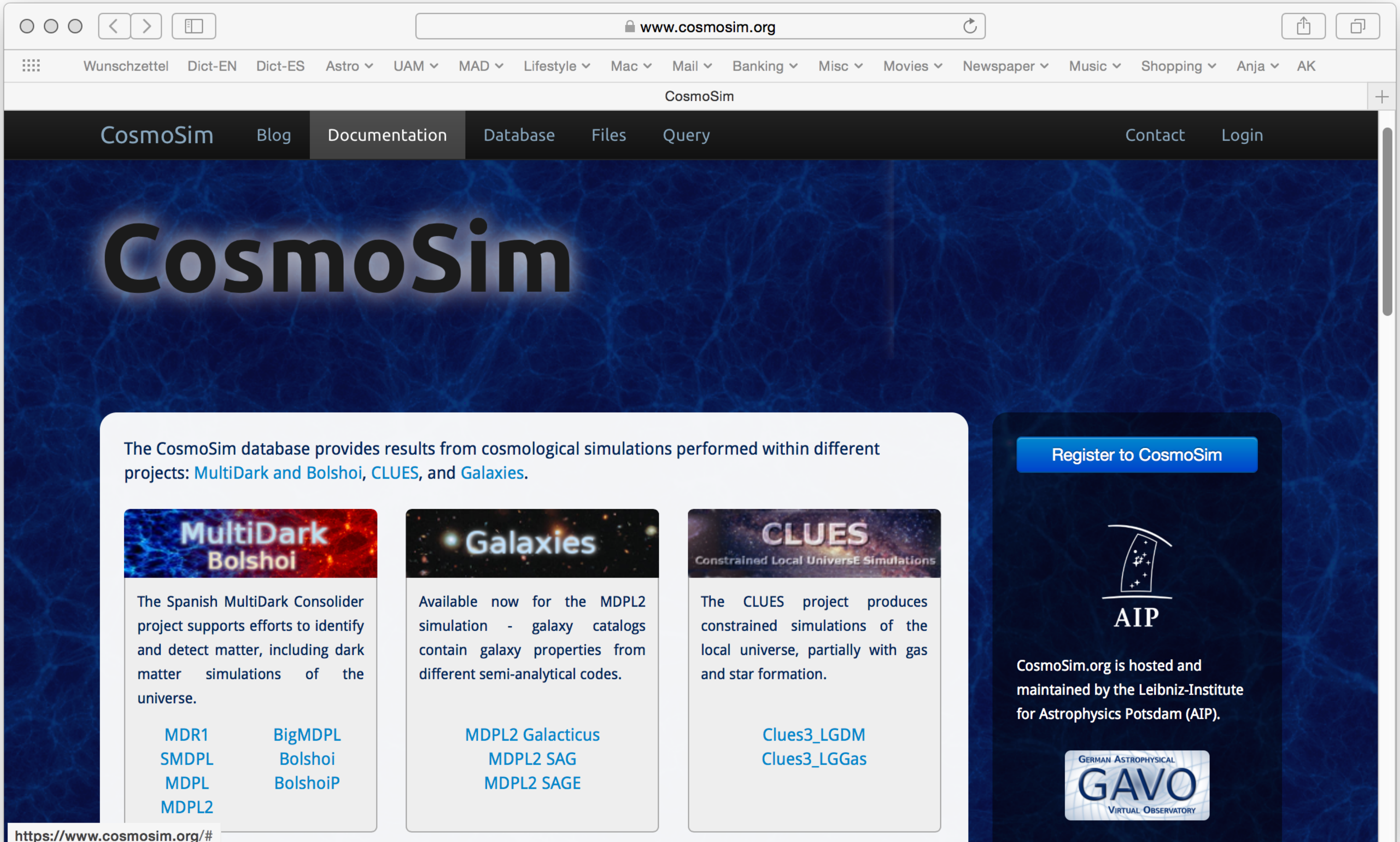


the formation of our Local Group within full cosmological context



(www.clues-project.org)

www.cosmosim.org



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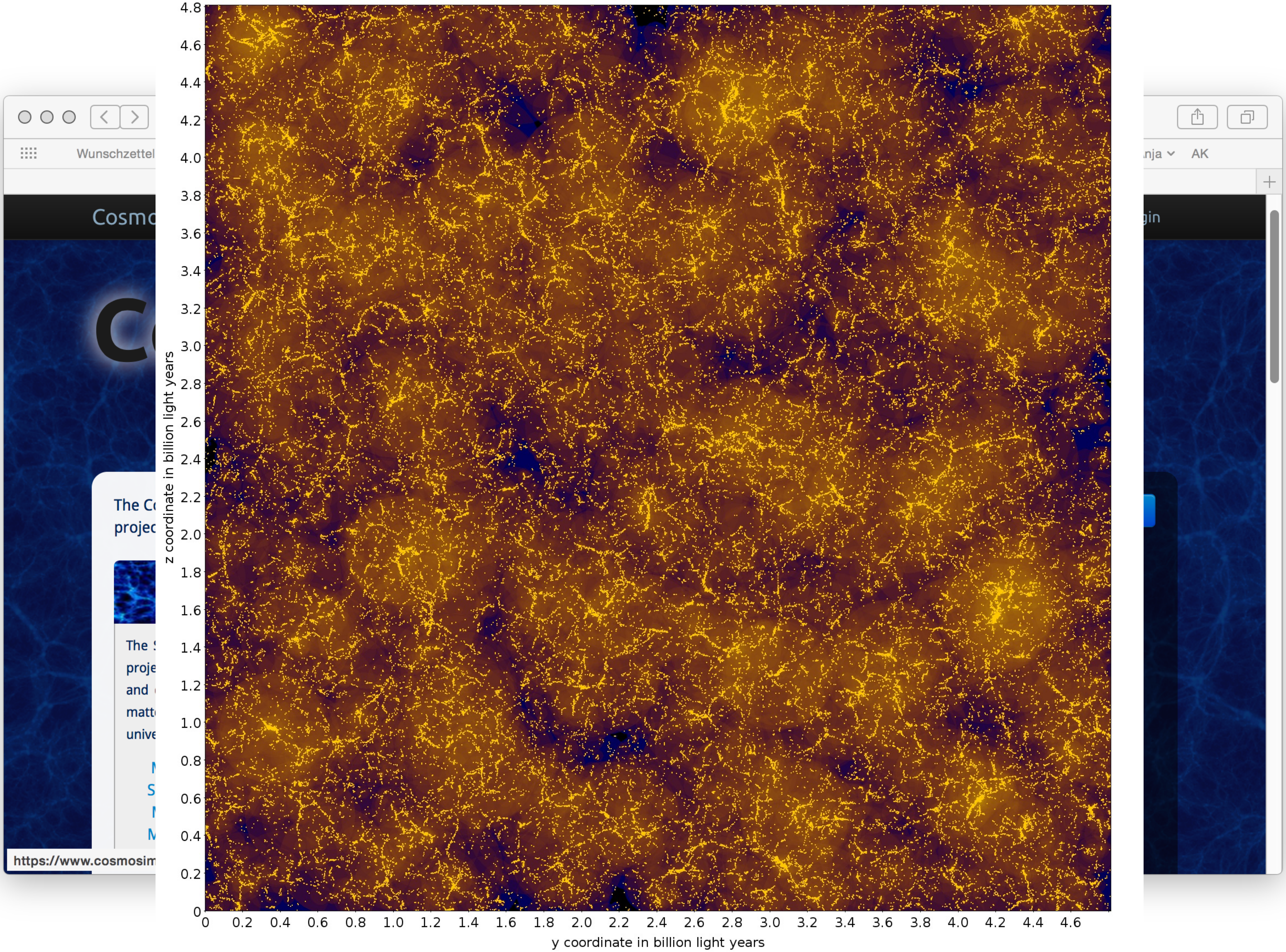
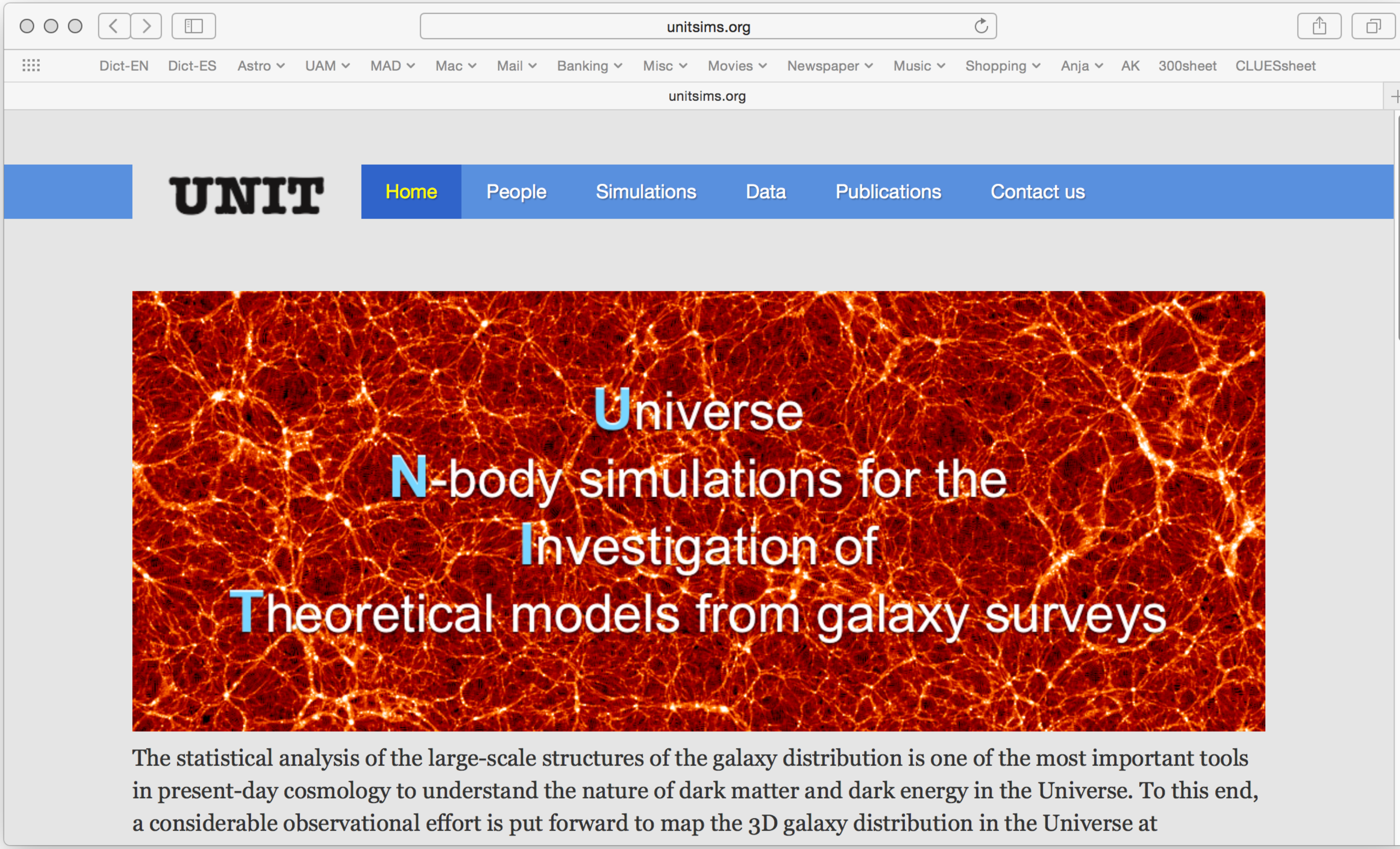
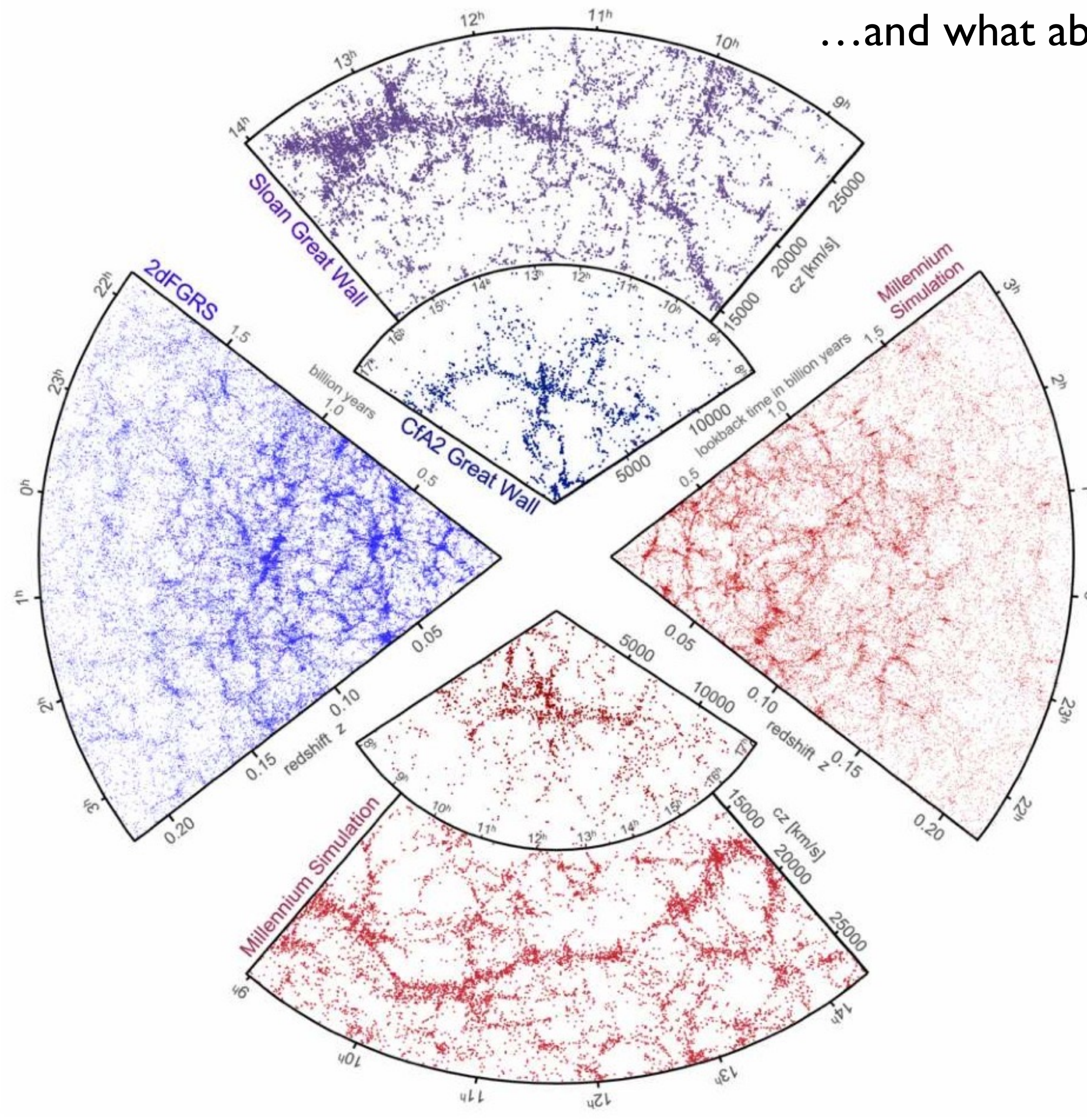
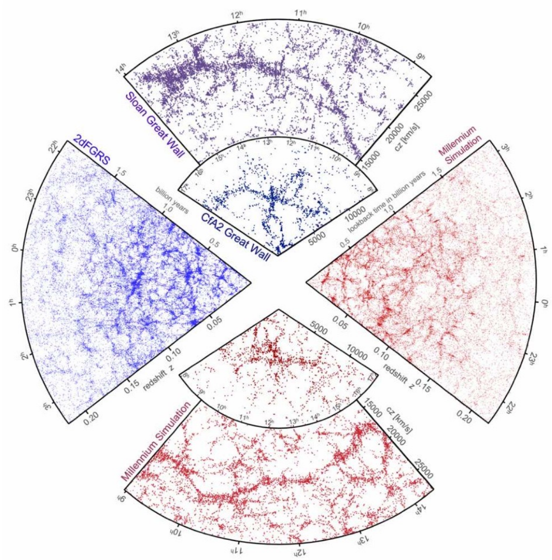

Wunschzettel
AK
z coordinate in billion light years
y coordinate in billion light years

www.unitsims.org



…and what about the results?





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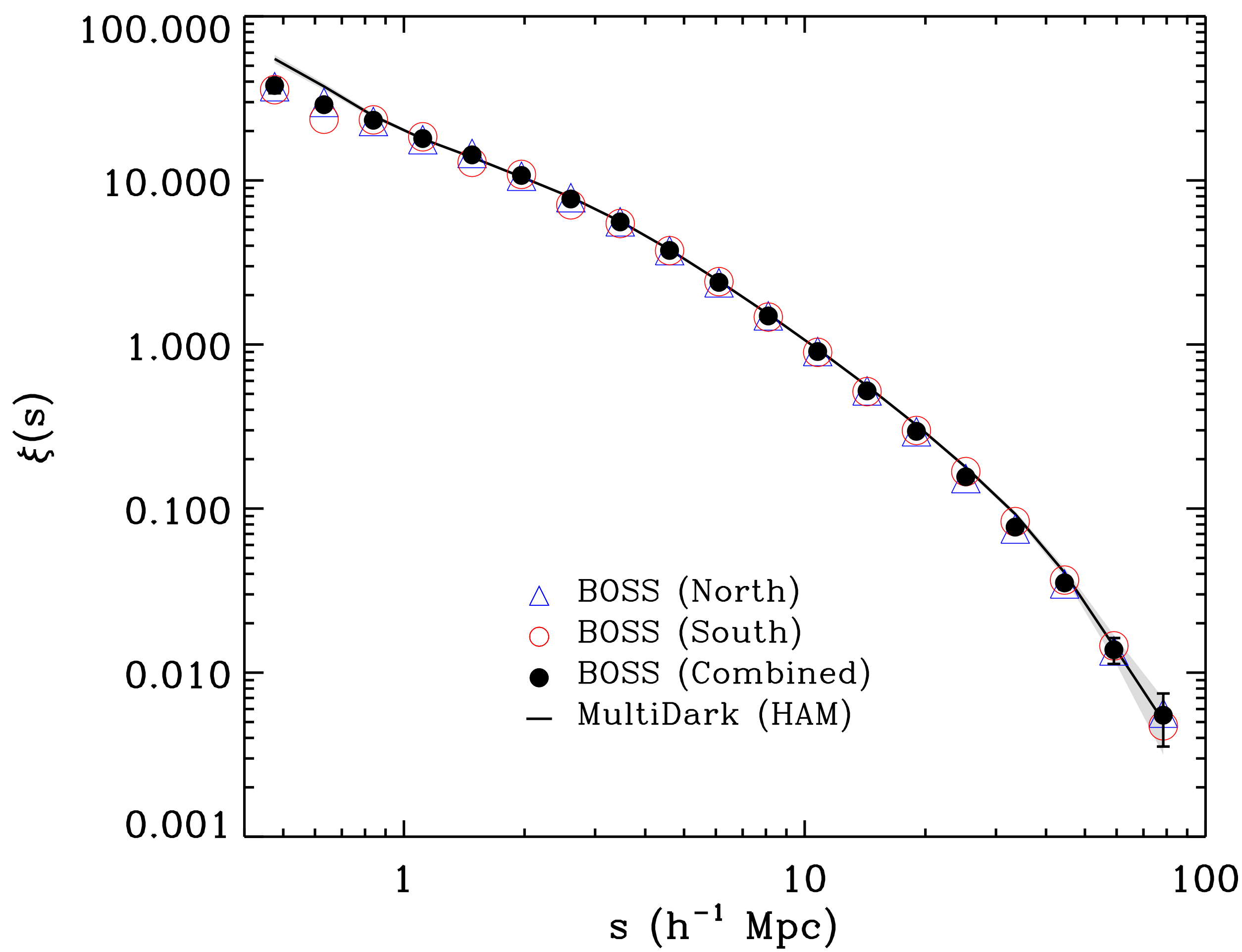
two-point correlation function



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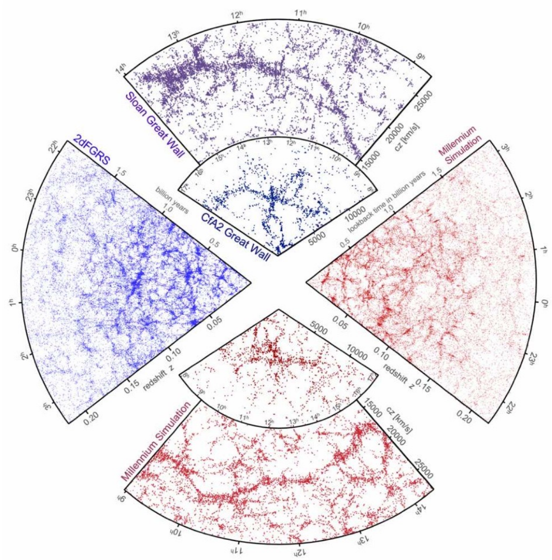

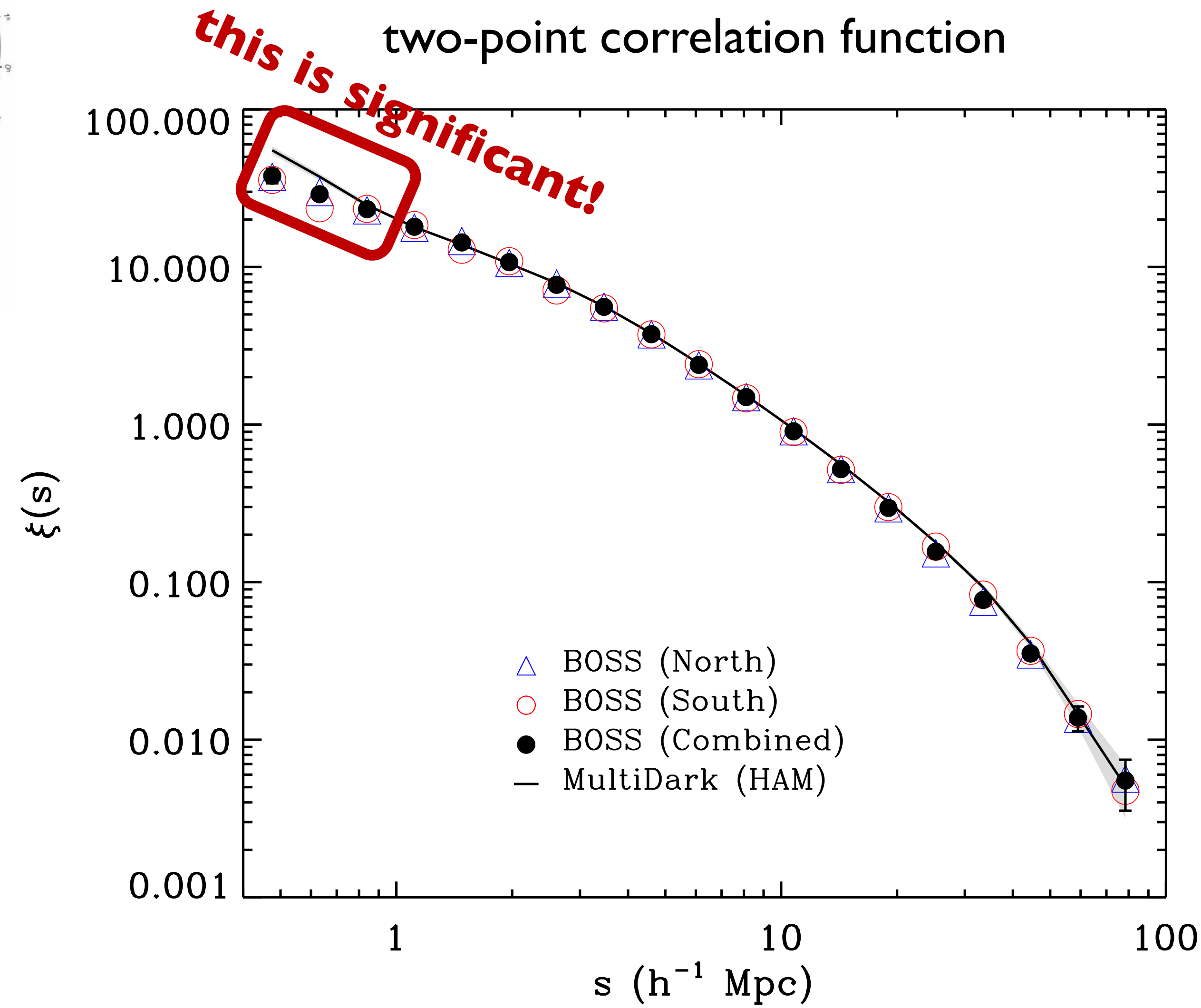

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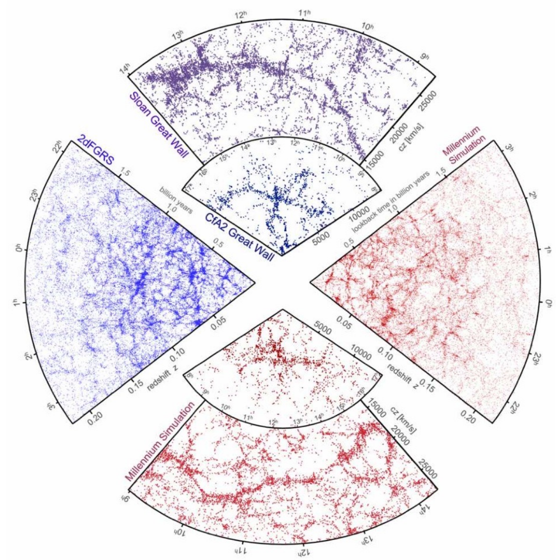

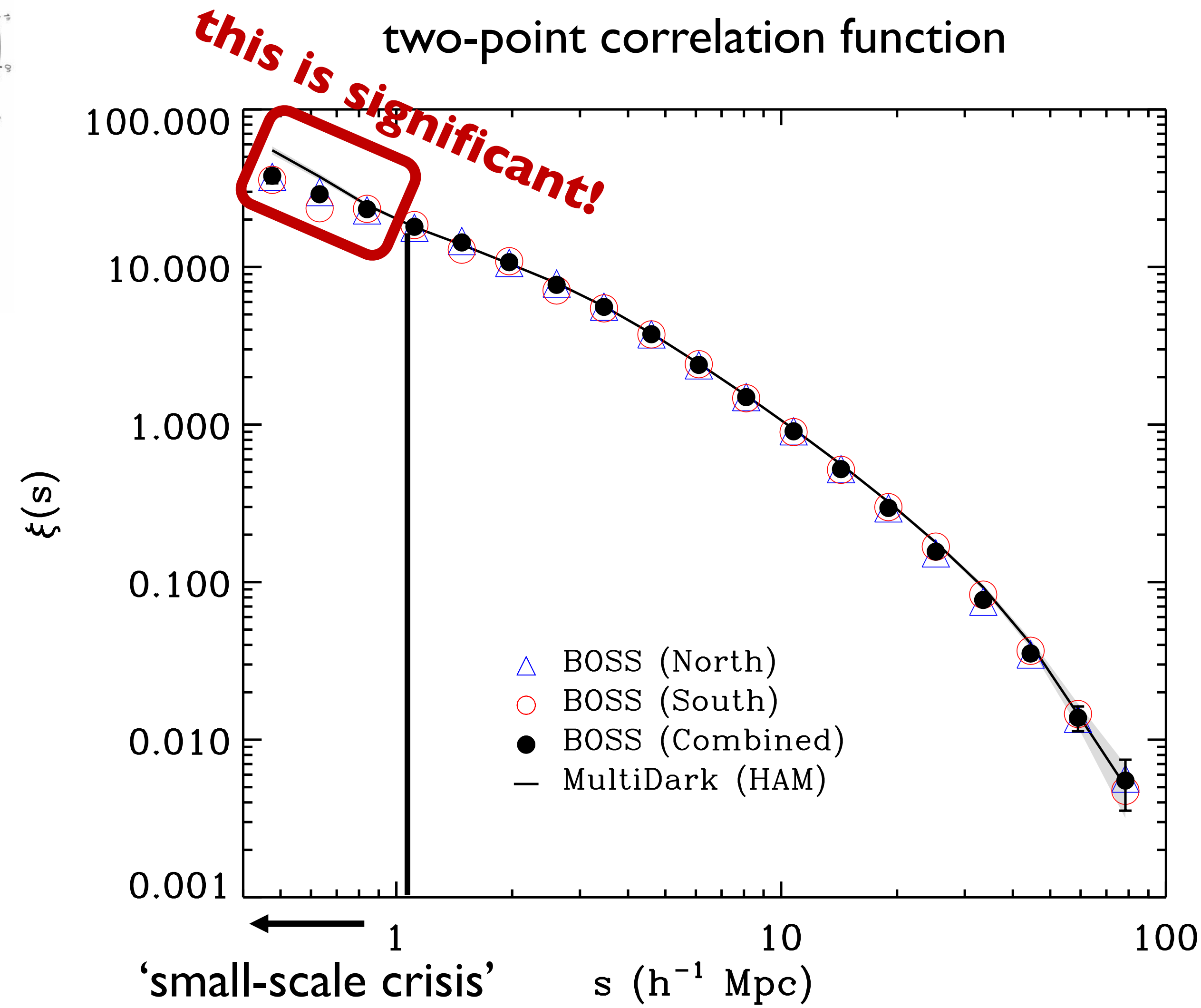

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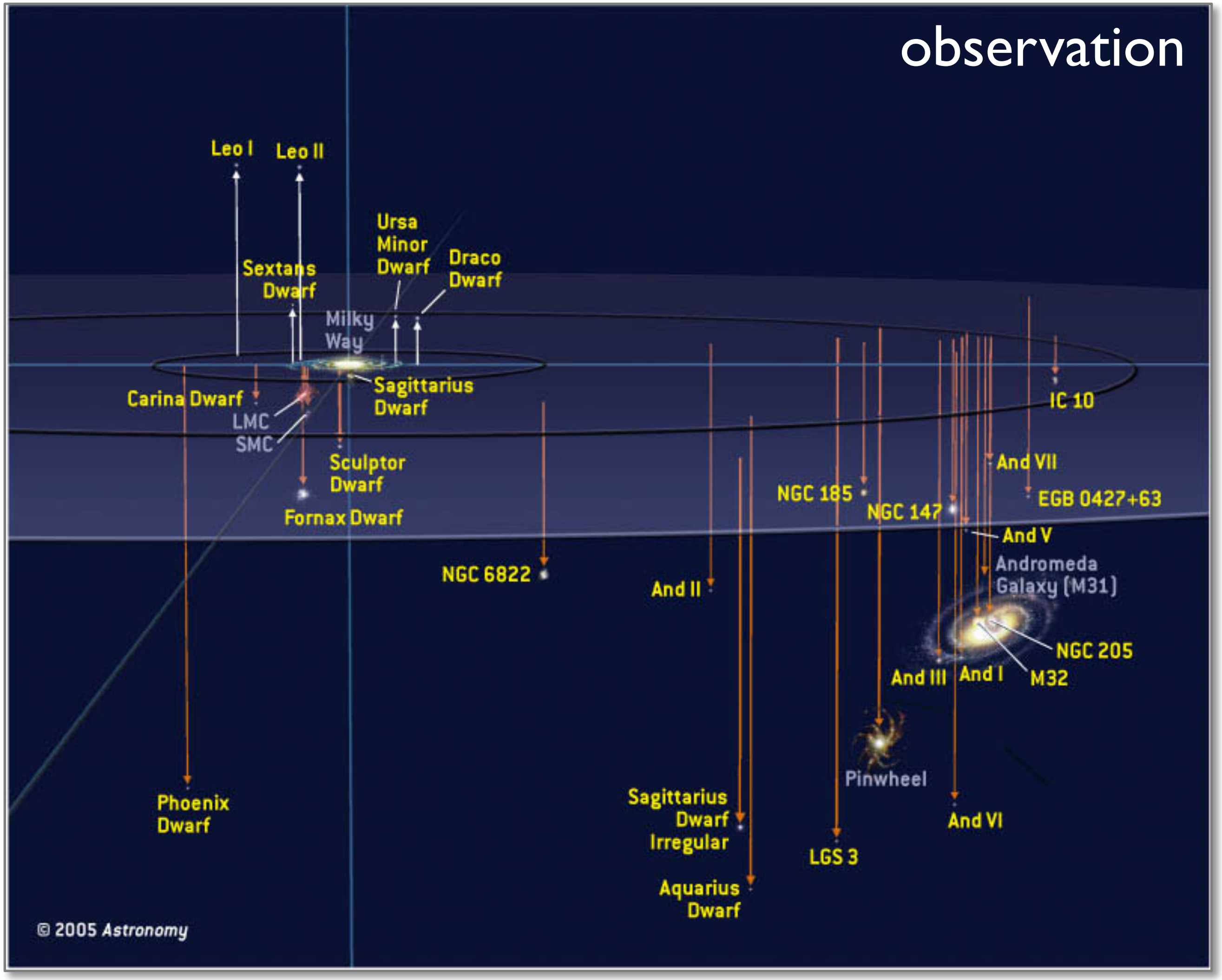

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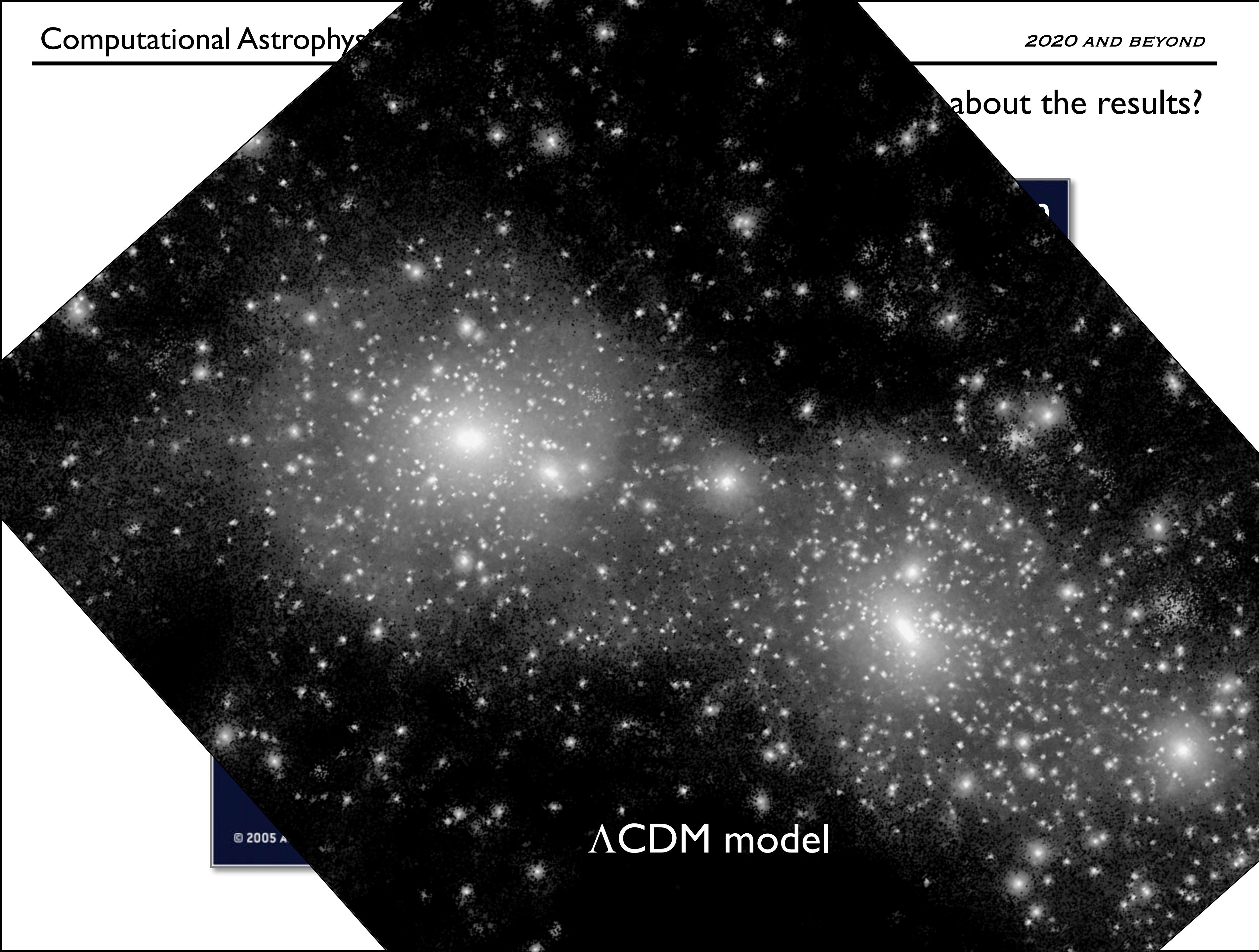

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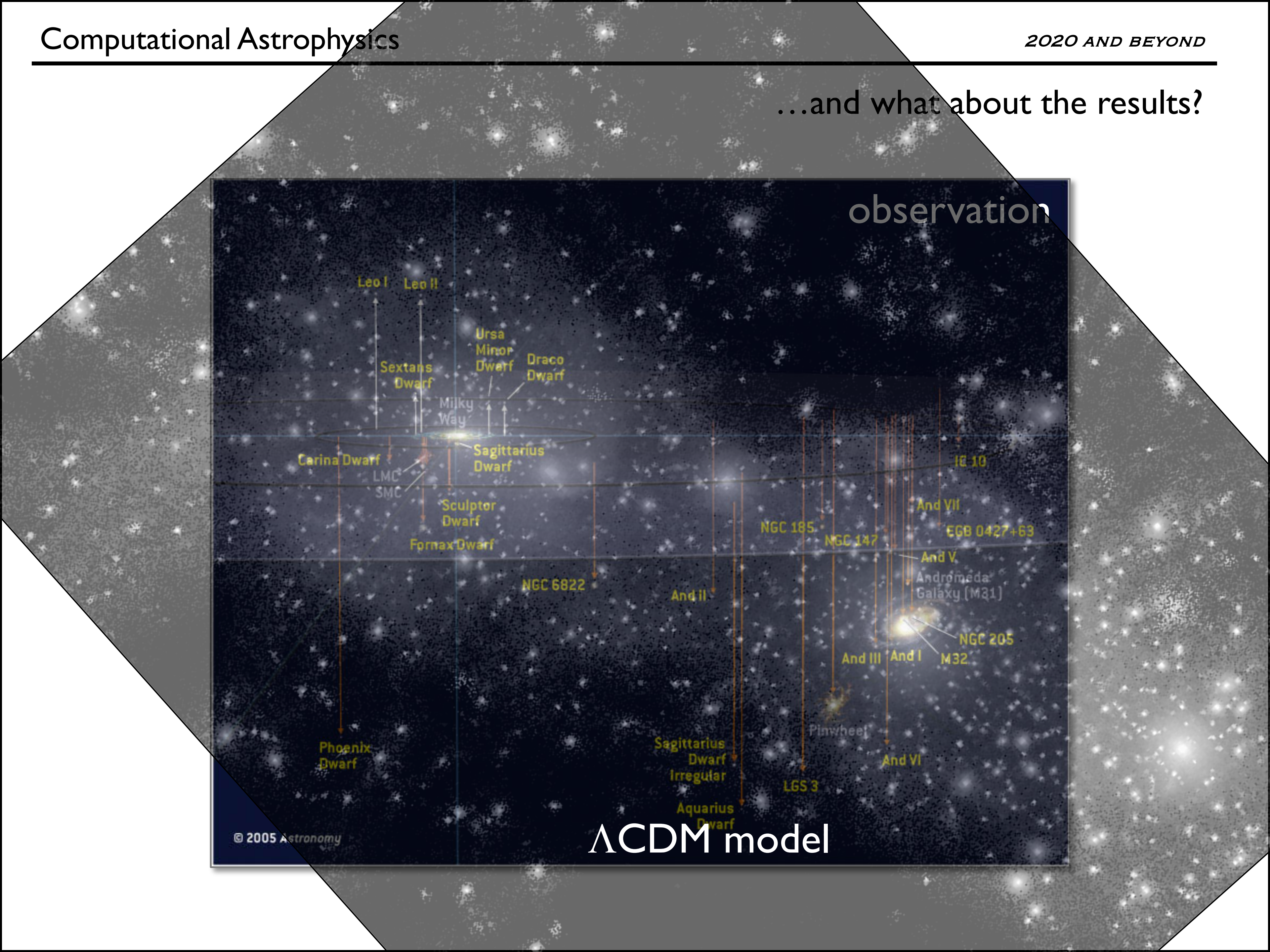

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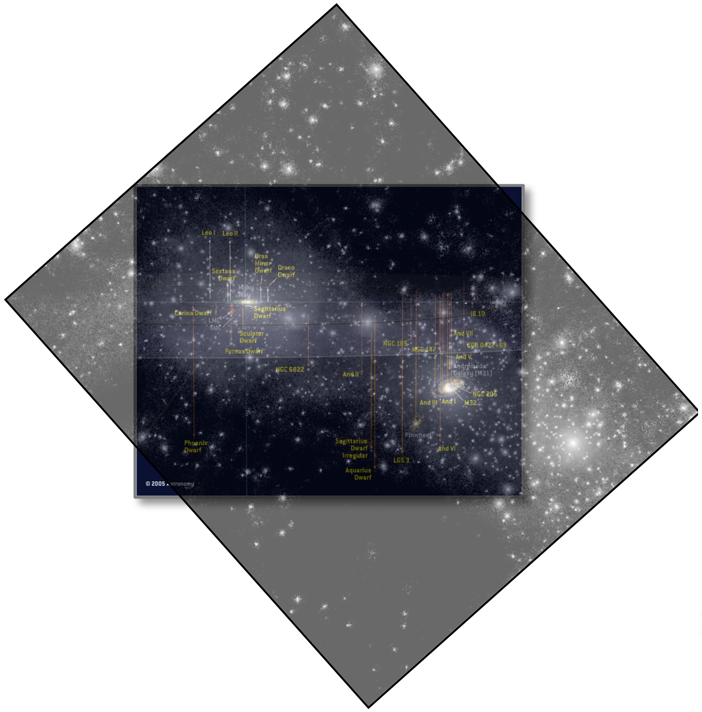

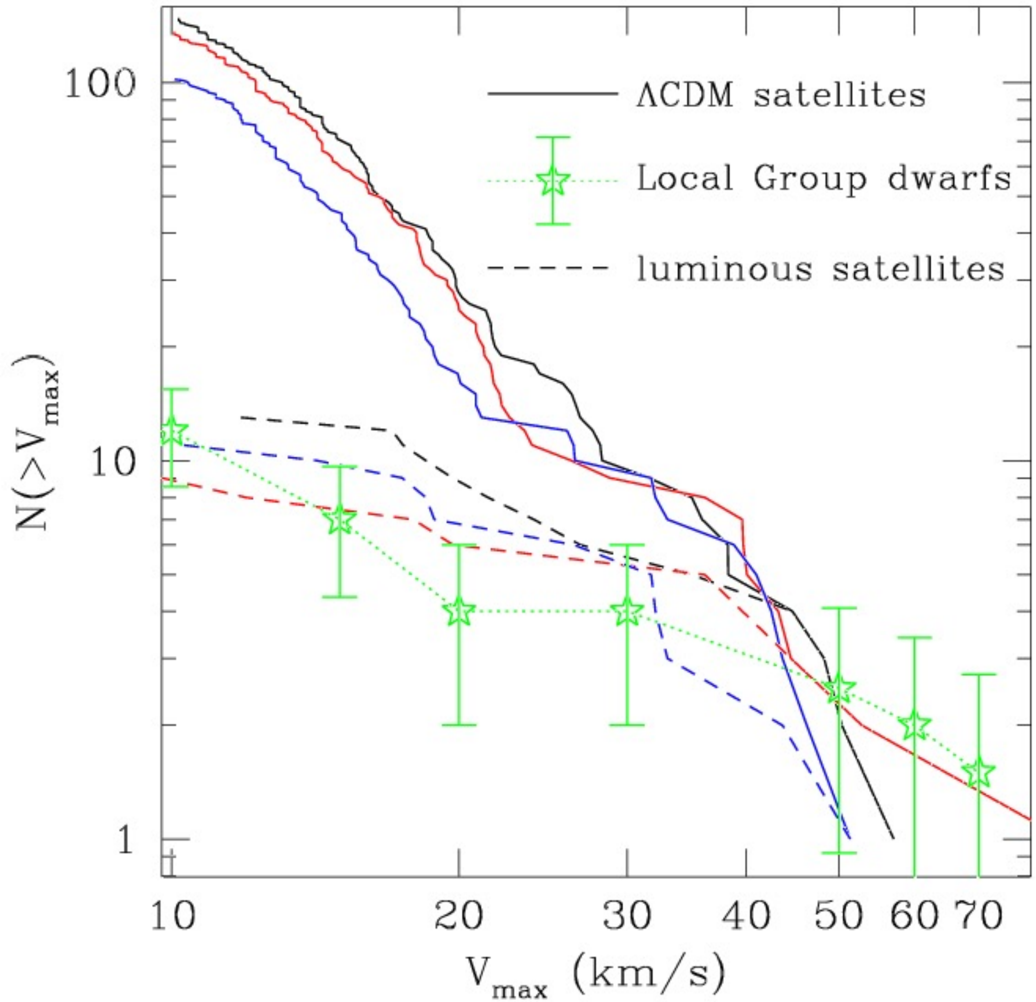

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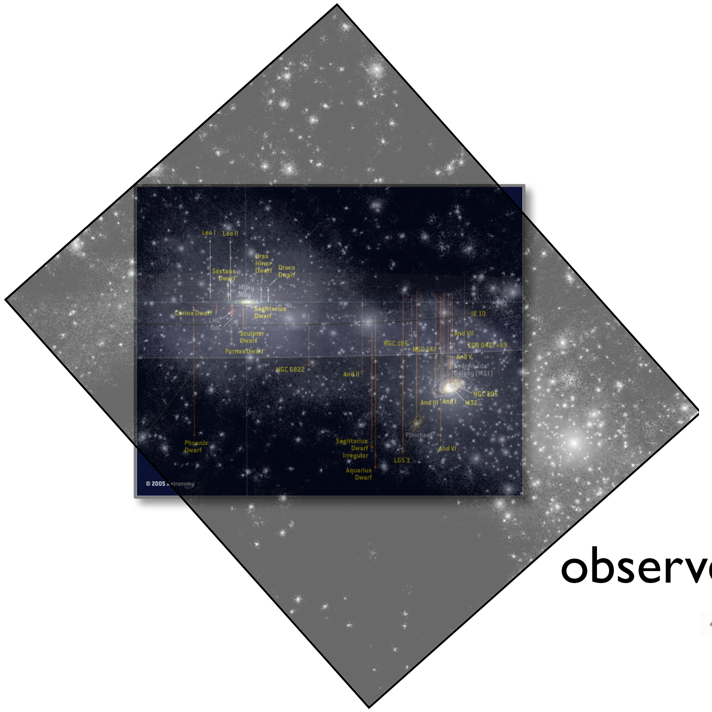
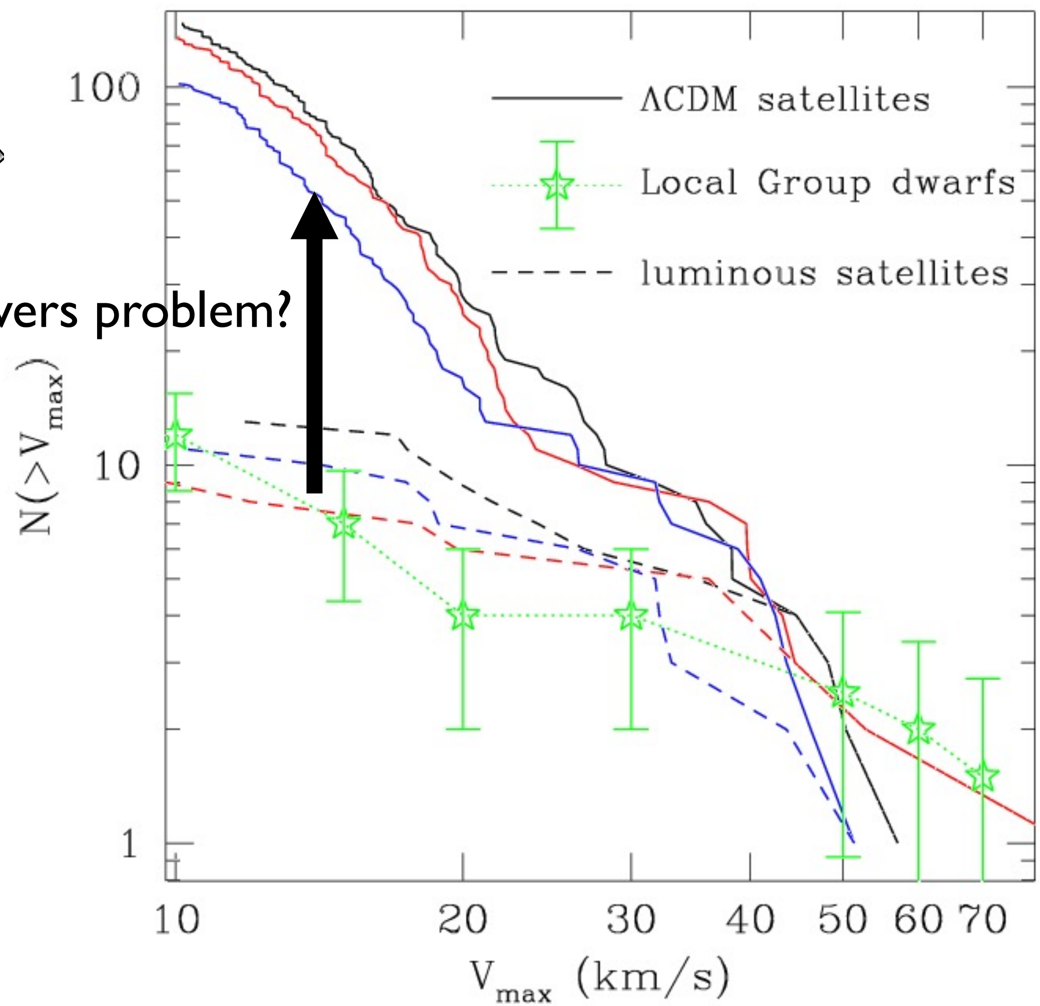


observers problem?



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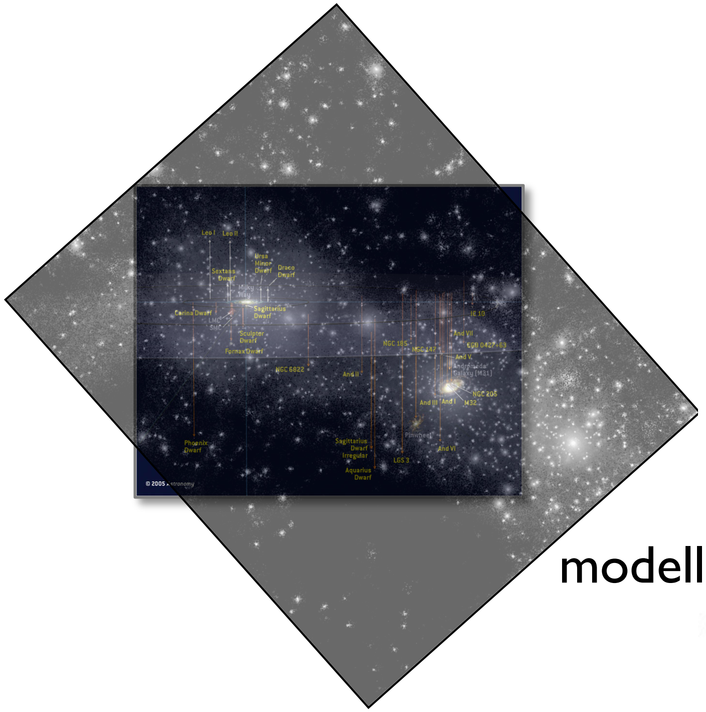
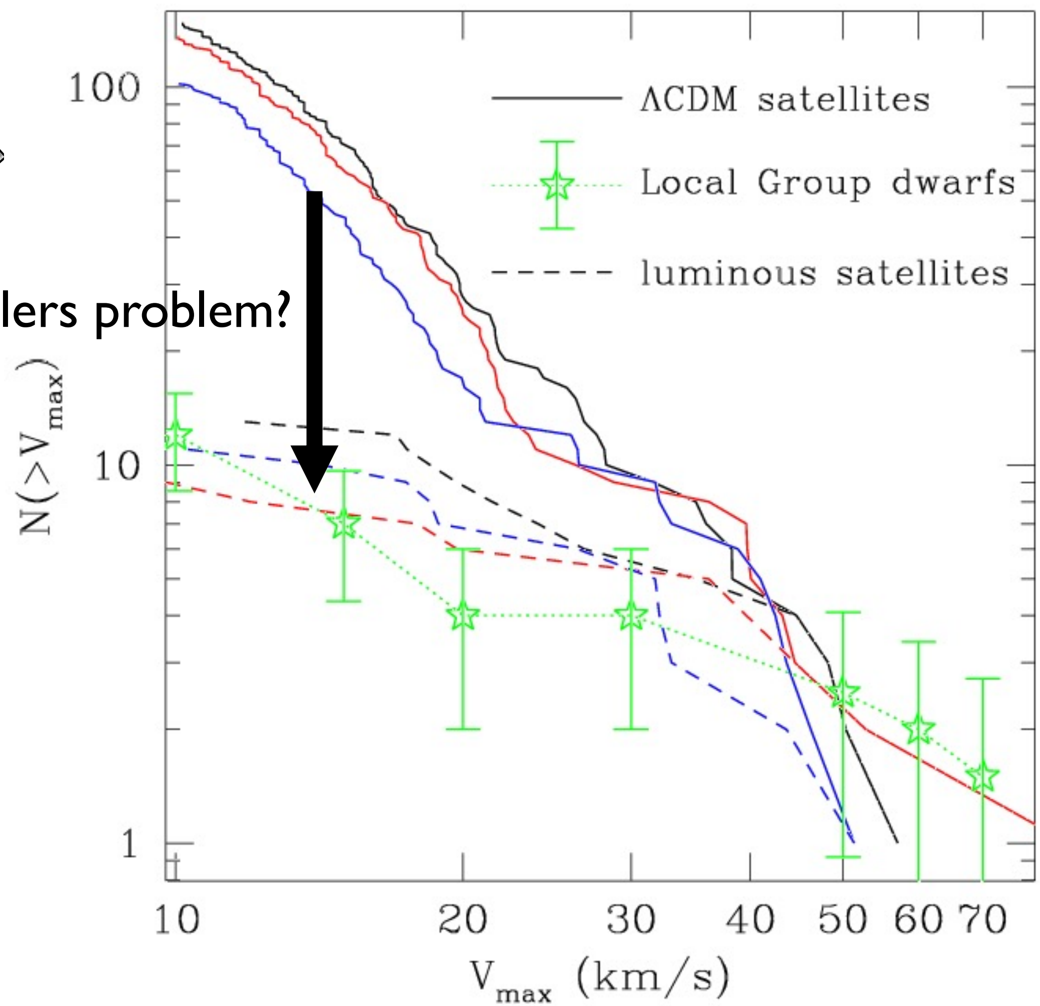
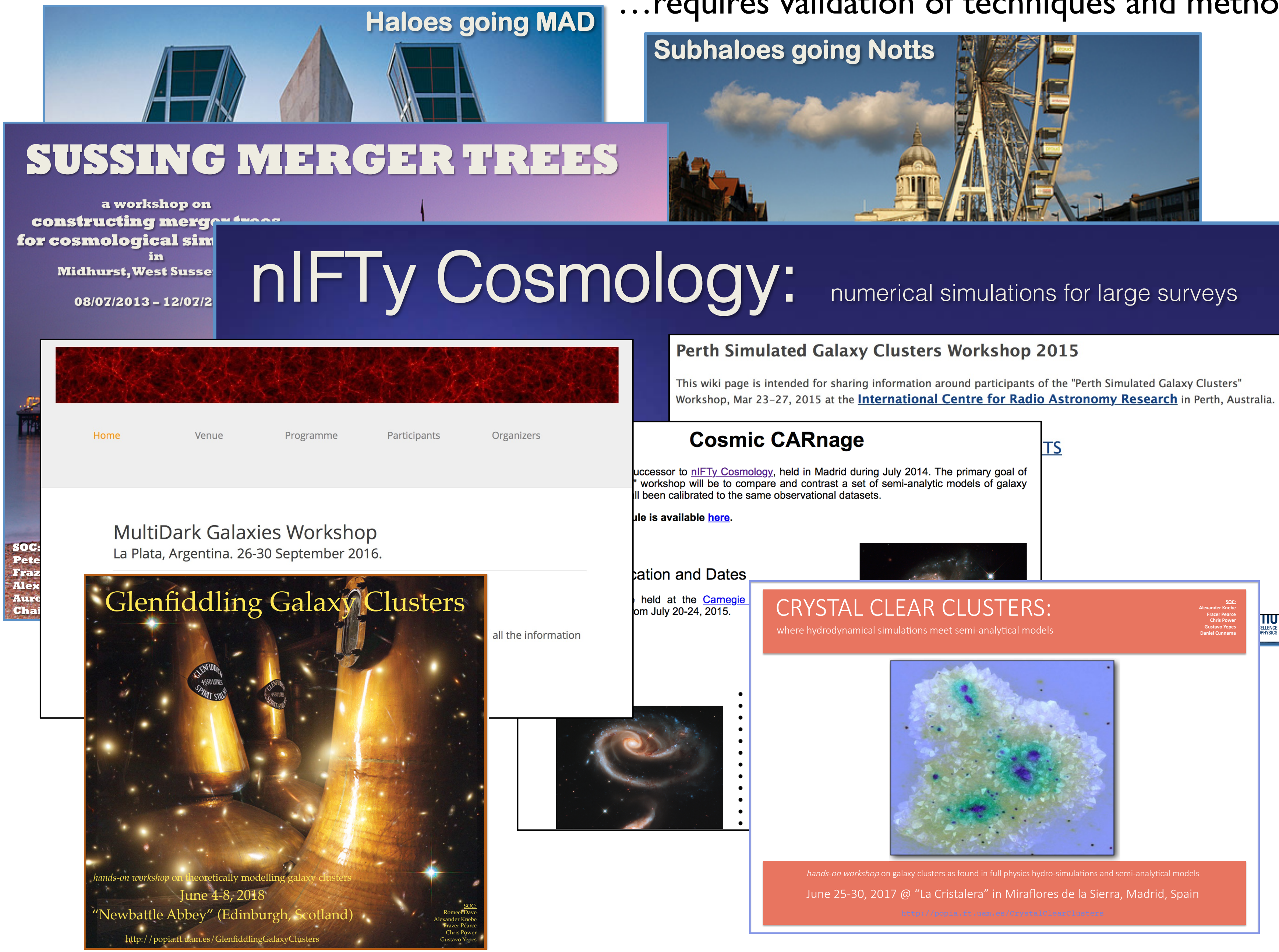


modellers problem?



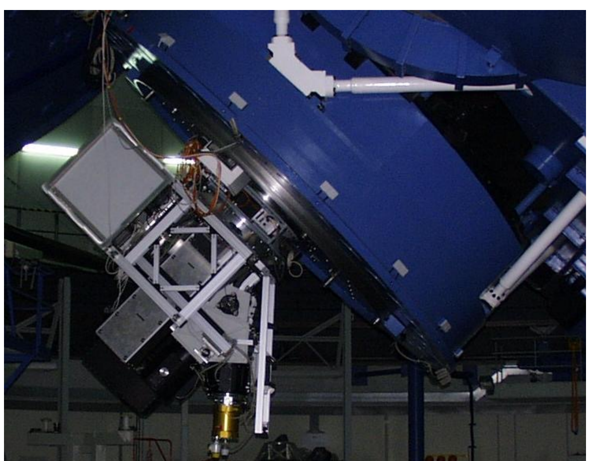
…requires validation of techniques and methods!

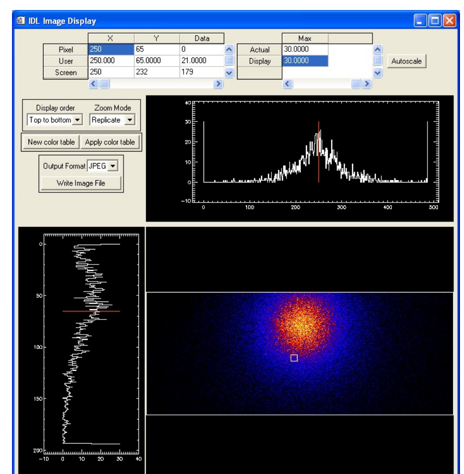


- supercomputing
- **numerical modelling**

Numerical Modelling (in Astrophysics)

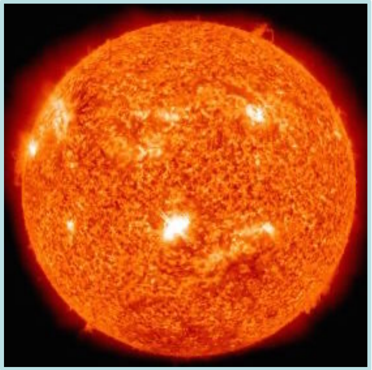
observation via telescope ⇔ modelling via supercomputers





physical phenomenon

physical phenomenon

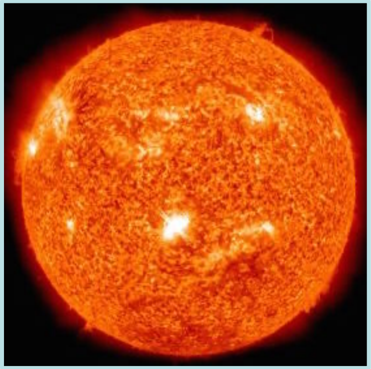


- what is the physical process we aim at modelling?

physical phenomenon

⇩

mathematical model



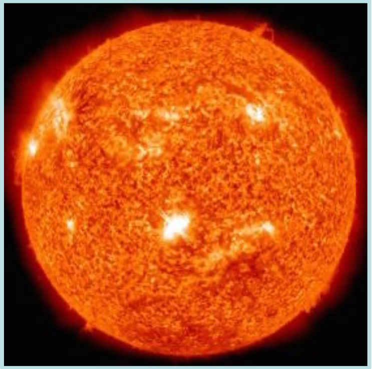
- the governing equations

$$
\begin{aligned}
\frac{\partial \rho}{\partial t} &+ \nabla \cdot \left(\rho \vec{v}\right) &&= 0 \\
\frac{\partial \left(\rho \vec{v}\right)}{\partial t} &+ \nabla \cdot \left(\rho \vec{v} \otimes \vec{v} + \left(p + \frac{1}{2\mu} B^2\right)\vec{1} - \frac{1}{\mu}\vec{B} \otimes \vec{B}\right) &&= \rho \ \left(-\nabla \phi\right) \\
\frac{\partial \left(\rho E\right)}{\partial t} &+ \nabla \cdot \left(\left[\rho E + p + \frac{1}{2\mu} B^2\right]\vec{v} - \frac{1}{\mu}\left[\vec{v} \cdot \vec{B}\right]\vec{B}\right) &&= \rho \vec{v} \cdot \left(-\nabla \phi\right) + \left(\Gamma - L\right) \\
\frac{\partial \vec{B}}{\partial t} &+ \nabla \times \left(-\vec{v} \times \vec{B}\right) &&= 0 \\
& \Delta \phi &&= 4\pi G \rho
\end{aligned}
$$

physical phenomenon

⇧

mathematical model



- the governing equations

$$\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\vec{v}) = 0$$

$$\frac{\partial(\rho\vec{v})}{\partial t} + \nabla\cdot\left(\rho\vec{v}\otimes\vec{v} + \left(p + \frac{1}{2\mu}B^2\right)\vec{1} - \frac{1}{\mu}\vec{B}\otimes\vec{B}\right) = \rho\ (-\nabla\phi)$$

$$\frac{\partial(\rho E)}{\partial t} + \nabla\cdot\left(\left[\rho E + p + \frac{1}{2\mu}B^2\right]\vec{v} - \frac{1}{\mu}\left[\vec{v}\cdot\vec{B}\right]\vec{B}\right) = \rho\vec{v}\cdot(-\nabla\phi) + (\Gamma - L)$$

$$\frac{\partial\vec{B}}{\partial t} + \nabla\times\left(-\vec{v}\times\vec{B}\right) = 0$$

$$\Delta\phi = 4\pi G\rho$$

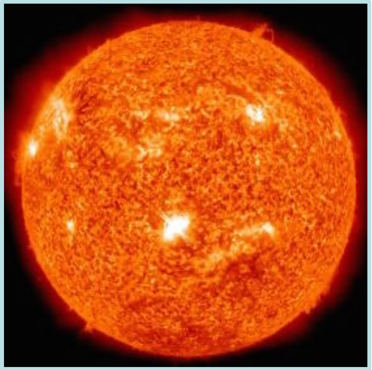
this is what we want in the end:

a model that explains the phenomenon!

physical phenomenon

⇕

mathematical model



- the governing equations

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\frac{\partial \vec{B}}{\partial t} &+ \nabla \times \left(-\vec{v} \times \vec{B}\right) &&= 0 \\
& \Delta \phi &&= 4\pi G \rho
\end{aligned}
$$

...details in lecture

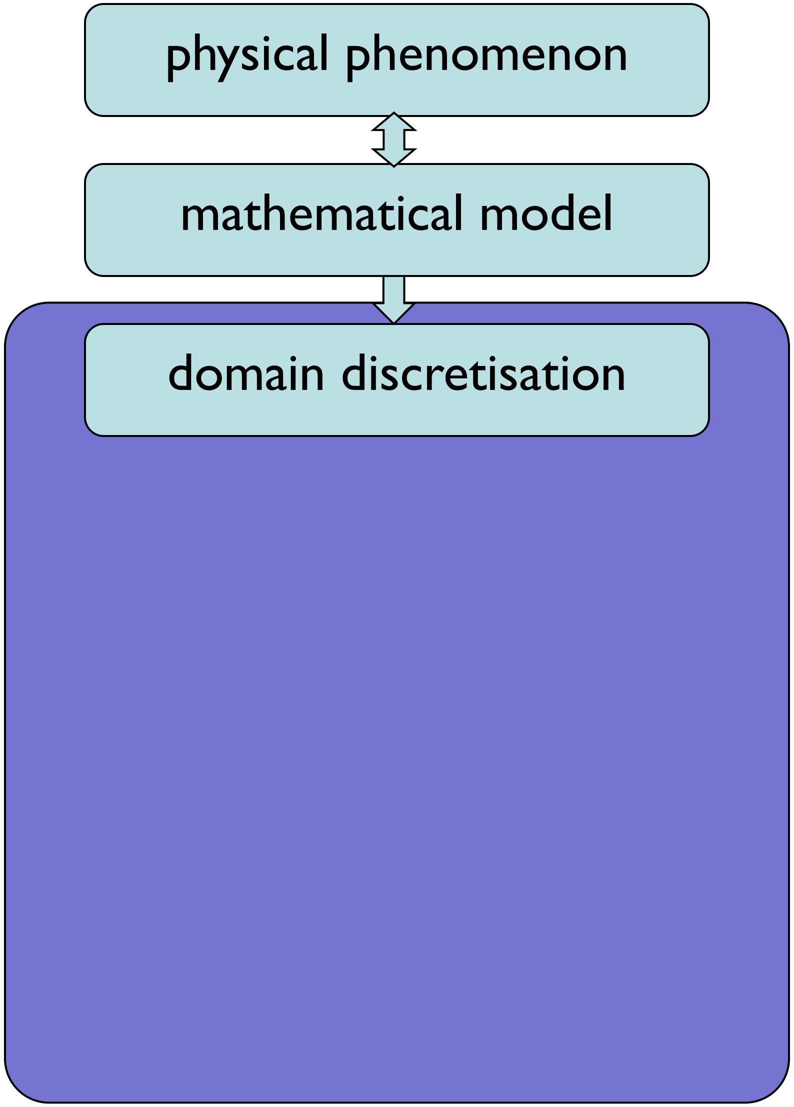
"astrophysical processes"

physical phenomenon

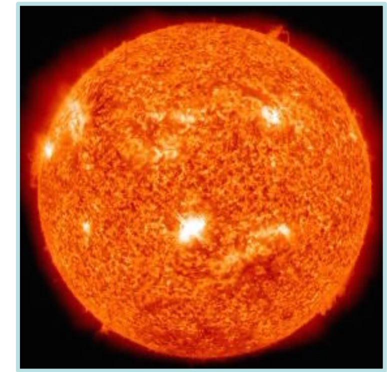
↕

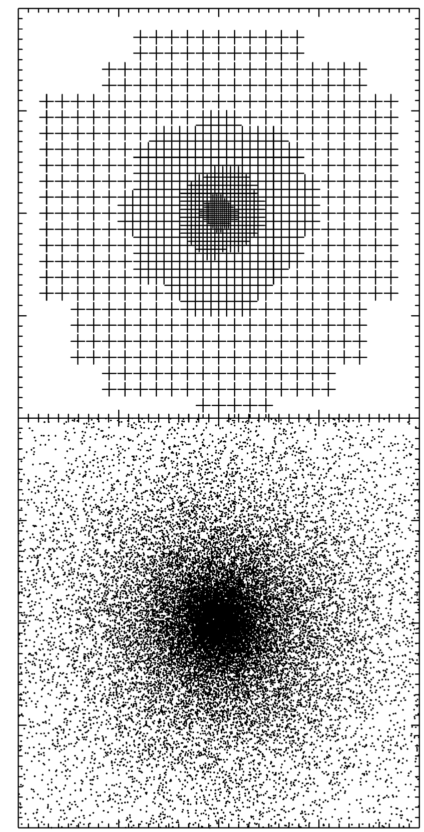
mathematical model

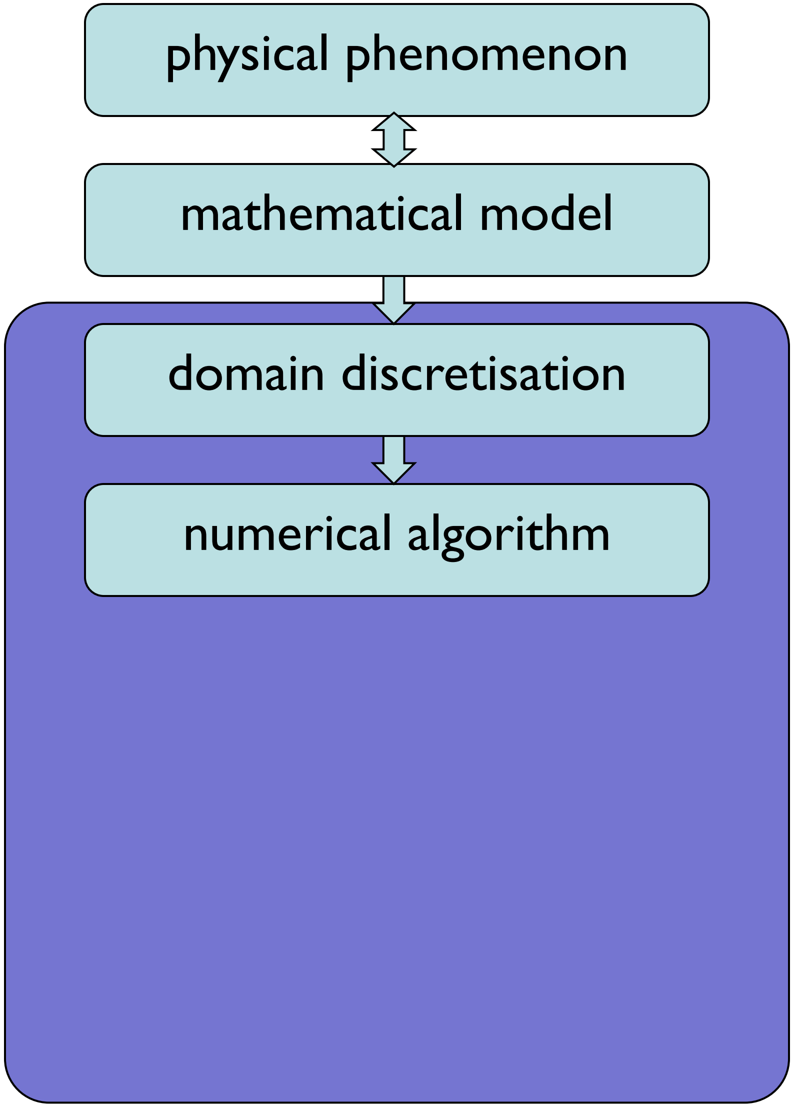
use a numerical simulation to verify the model...



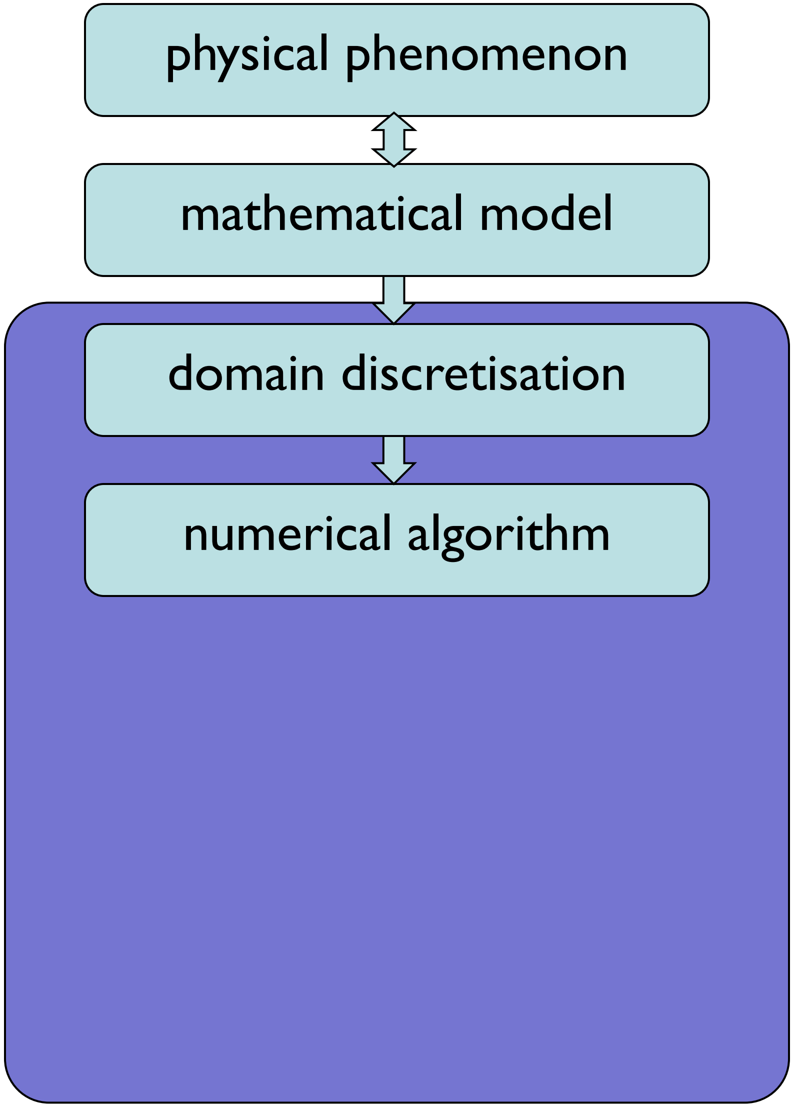
- grid introduction
- particle sampling
- ...





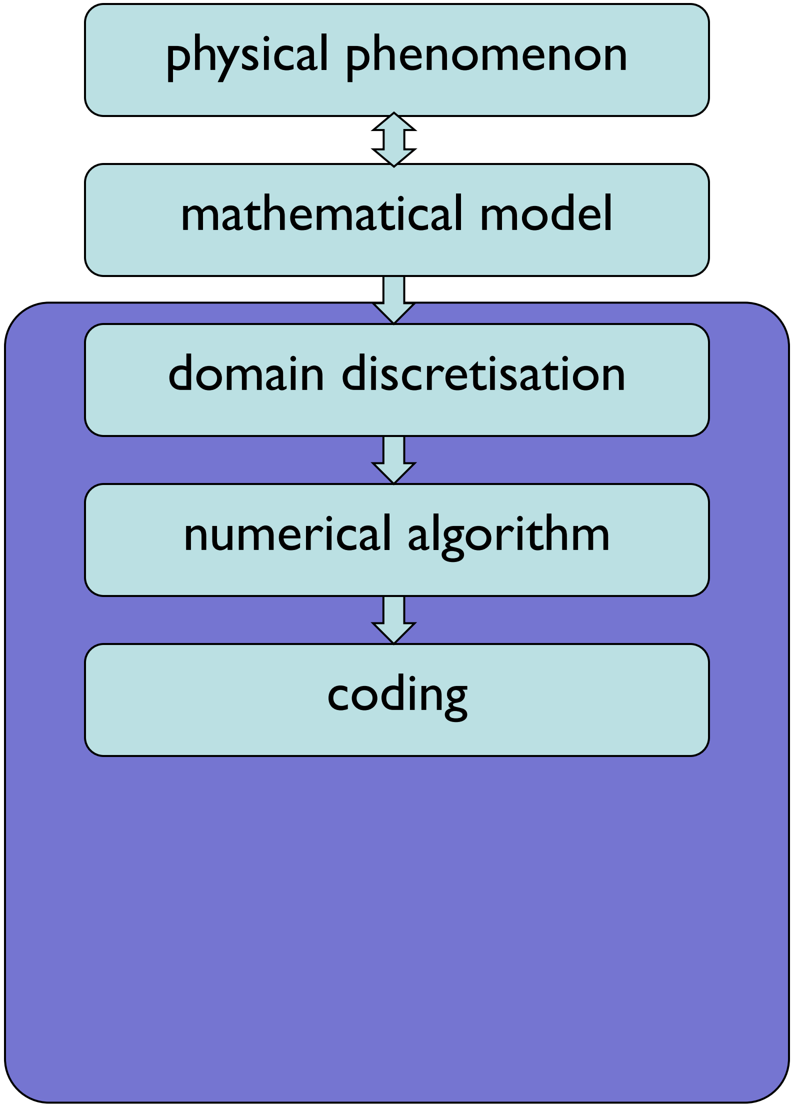


$$I = \int_a^b f(x)\,dx \quad \Rightarrow \quad \sum_{i=1}^{N-1} \frac{f(x_{i+1}) + f(x_i)}{2} (x_{i+1} - x_i)$$

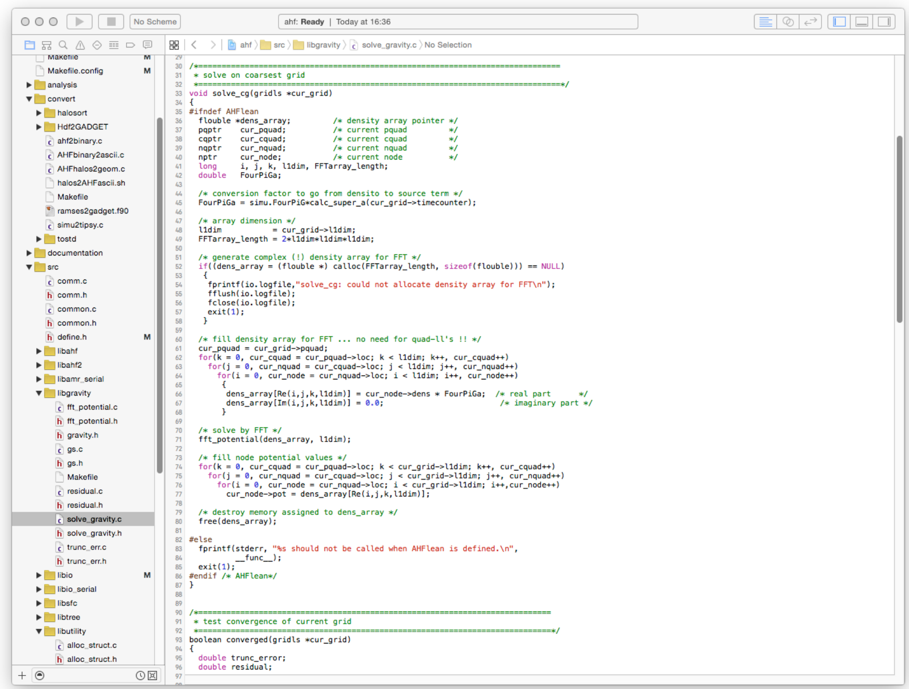


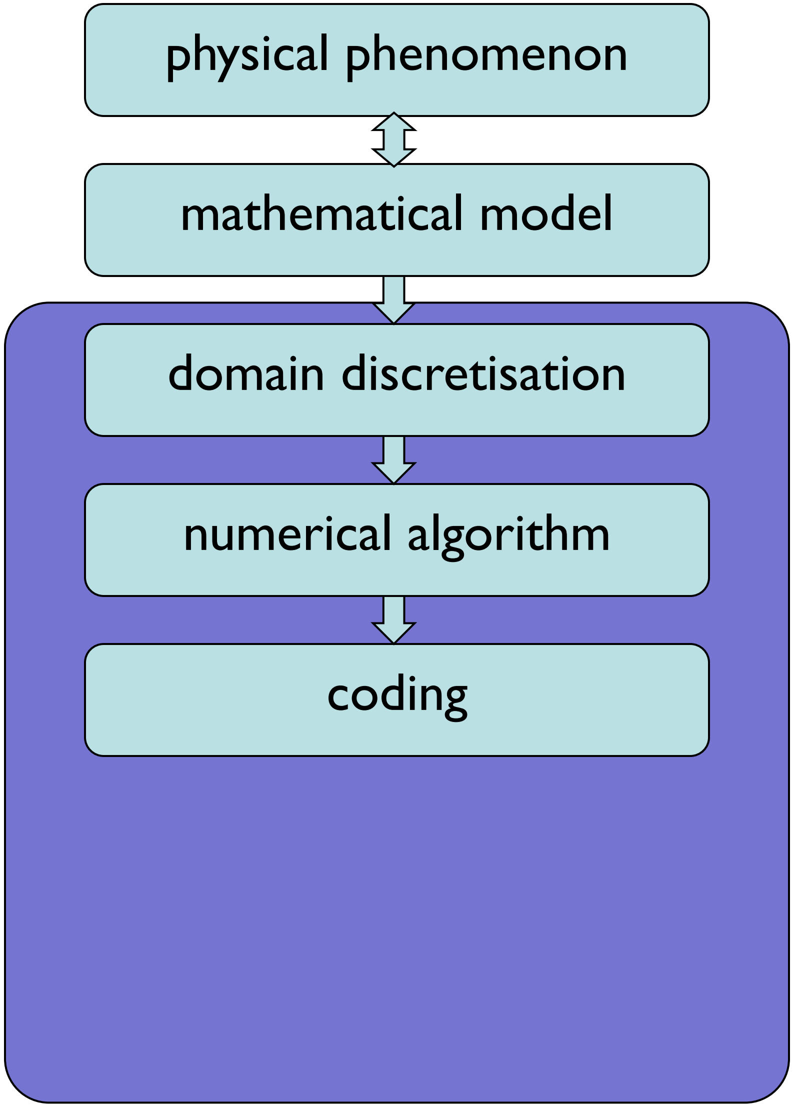
$$I = \int_a^b f(x)\,dx \quad \Rightarrow \quad \sum_{i=1}^{N-1} \frac{f(x_{i+1}) + f(x_i)}{2}(x_{i+1} - x_i)$$

...lots of details later!

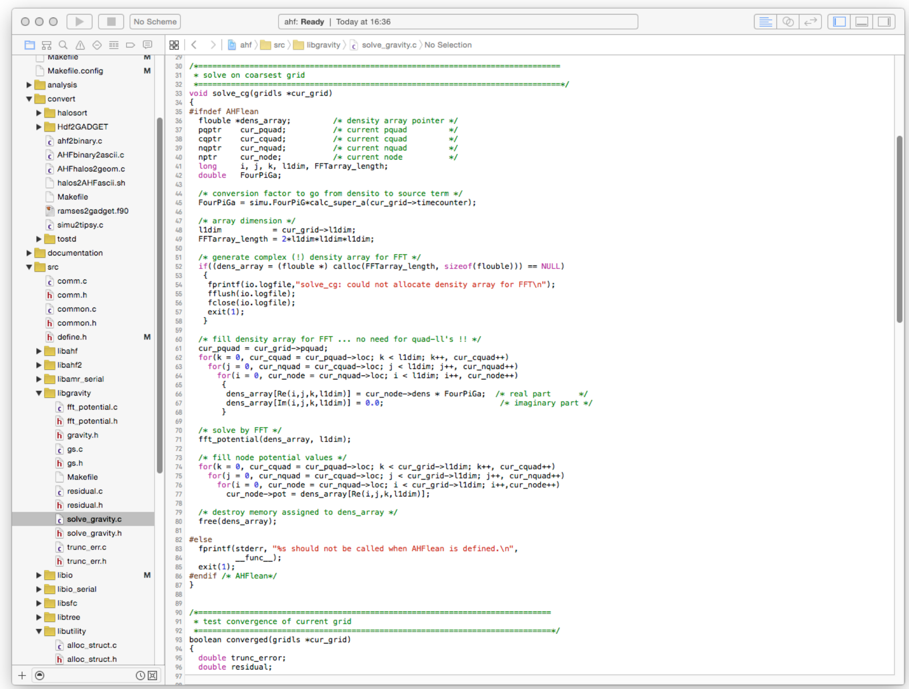

physical phenomenon
mathematical model
domain discretisation
numerical algorithm
coding

the fun part ;-)

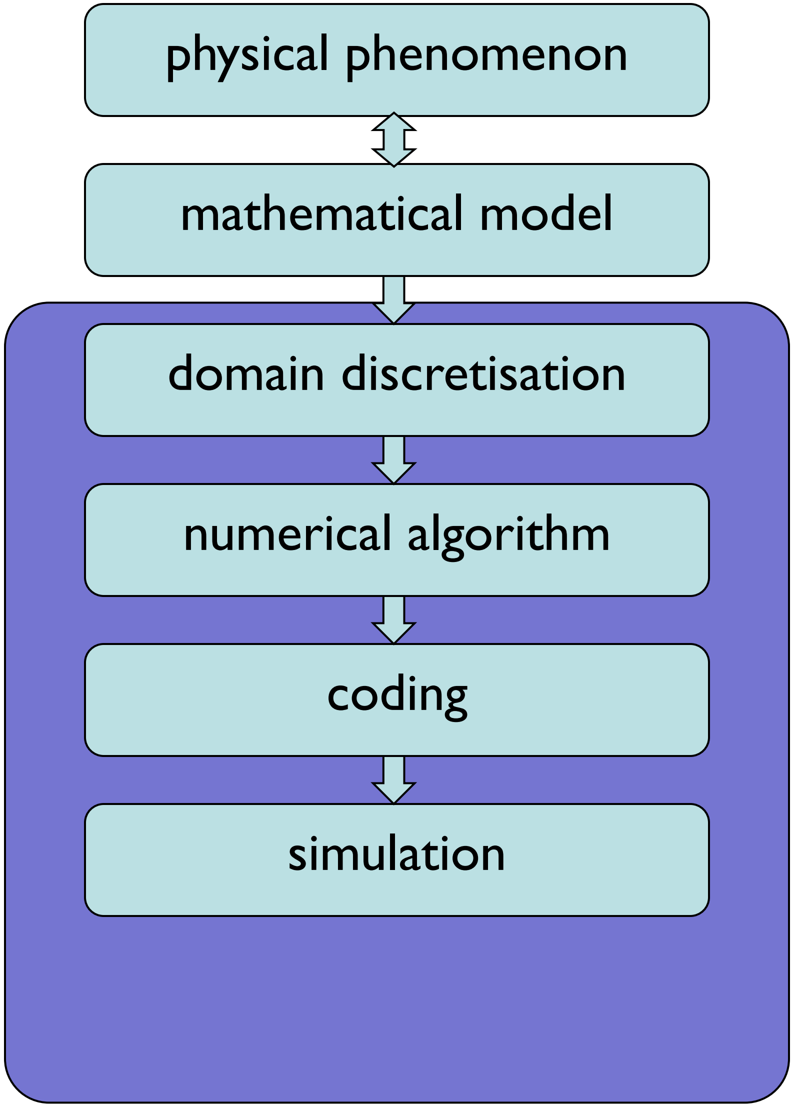




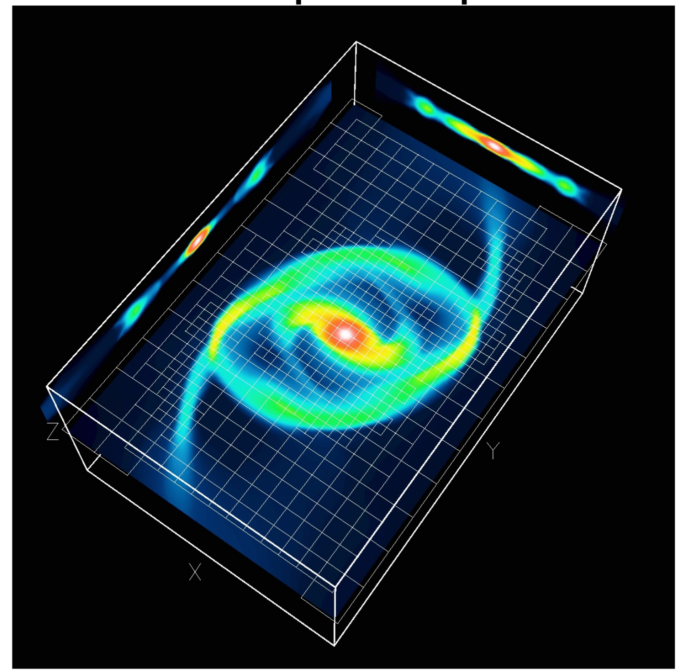
the fun part ;-)

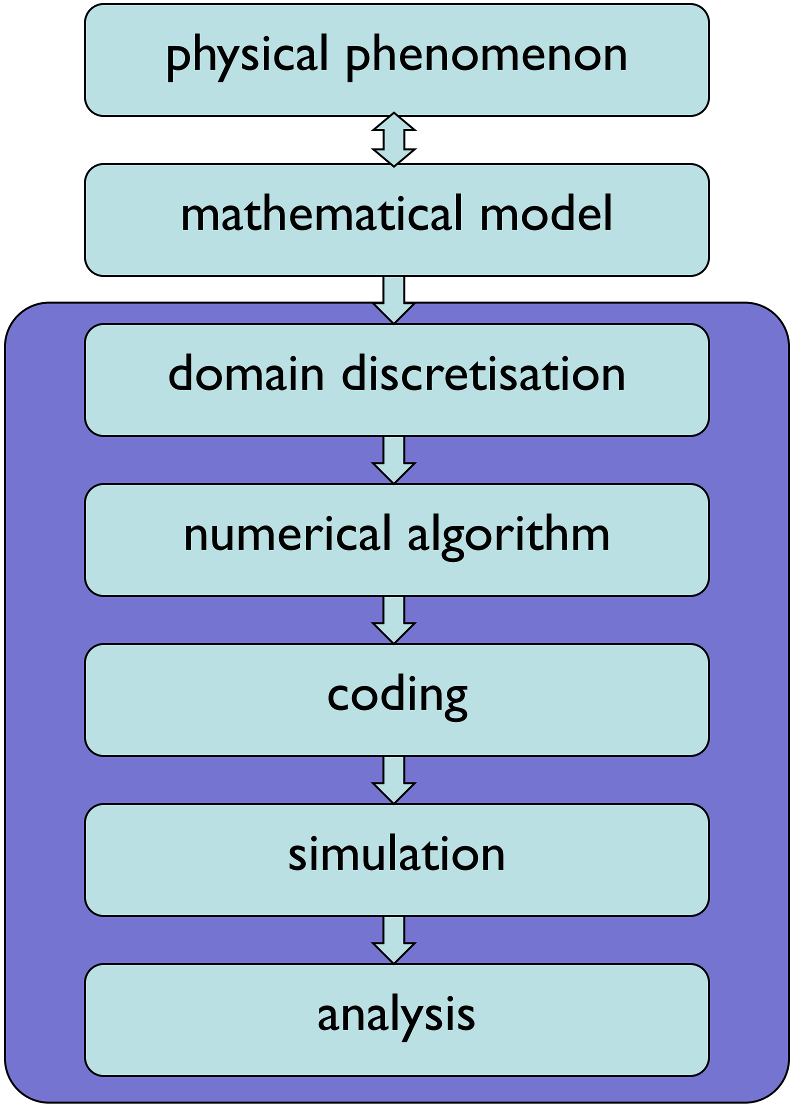


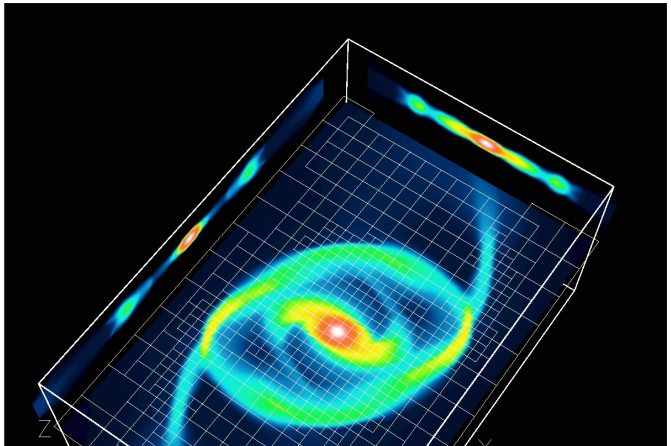
Friday's hands-on coding…



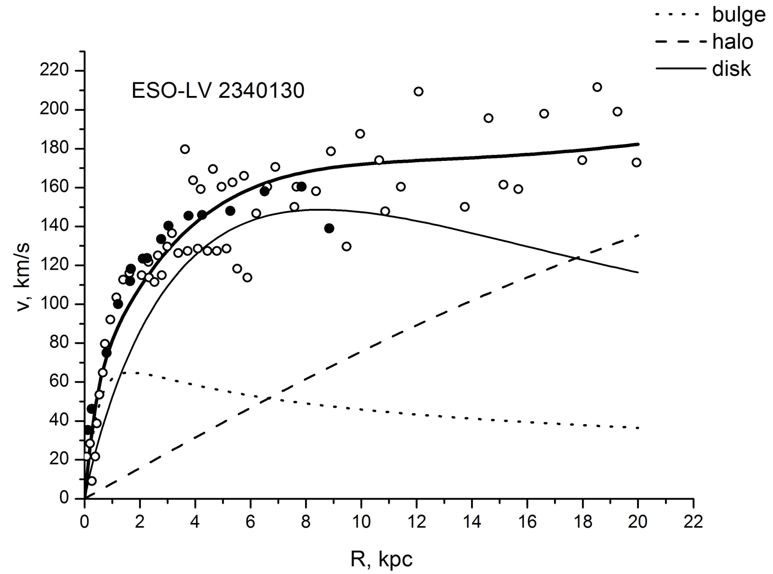
find a supercomputer

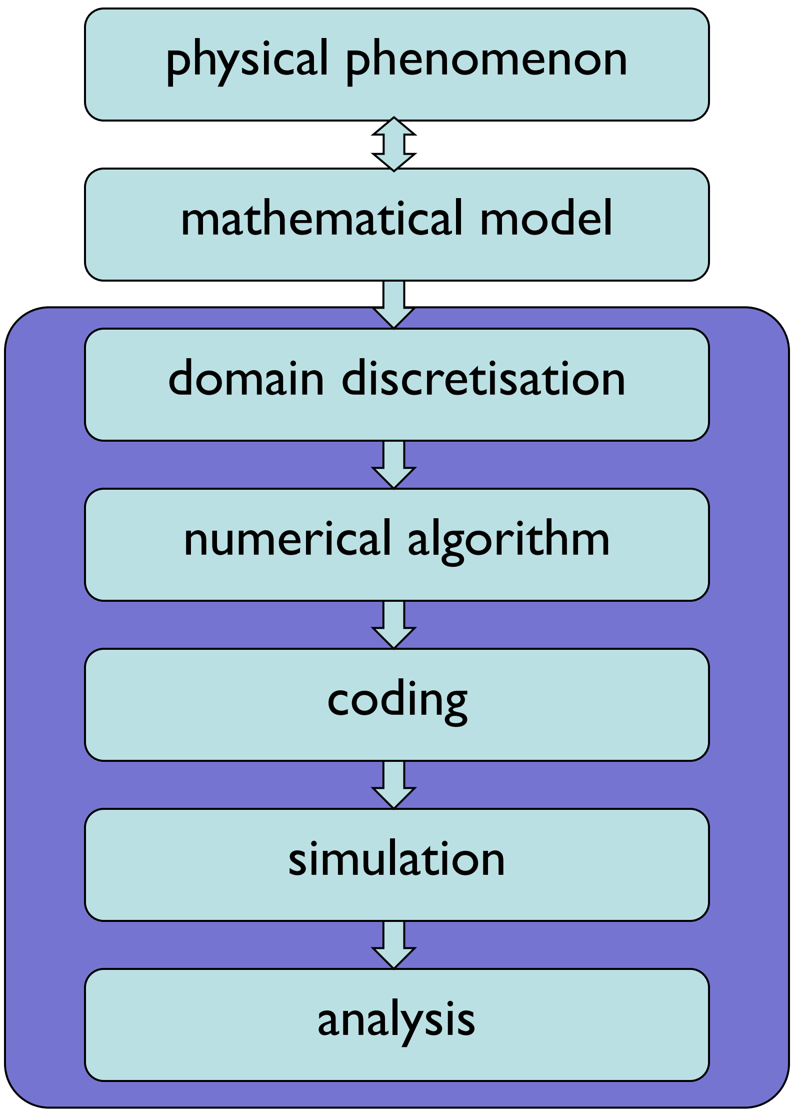




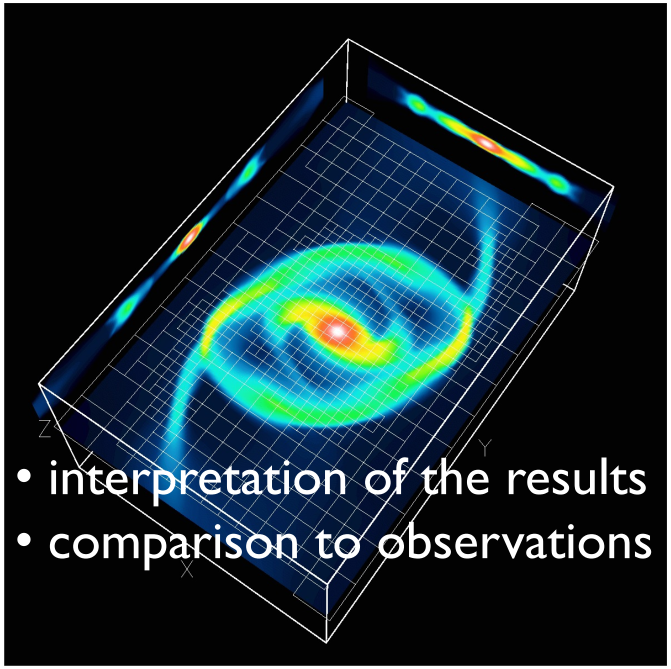


- interpretation of the results
- comparison to observations

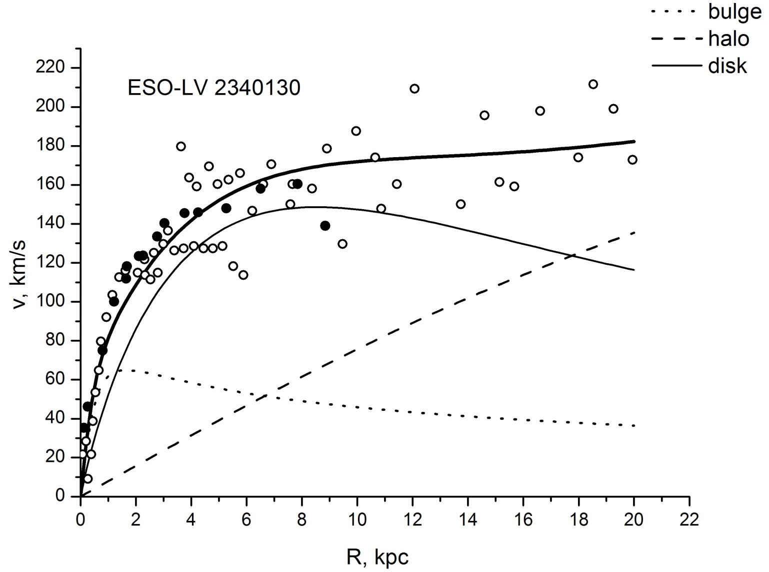


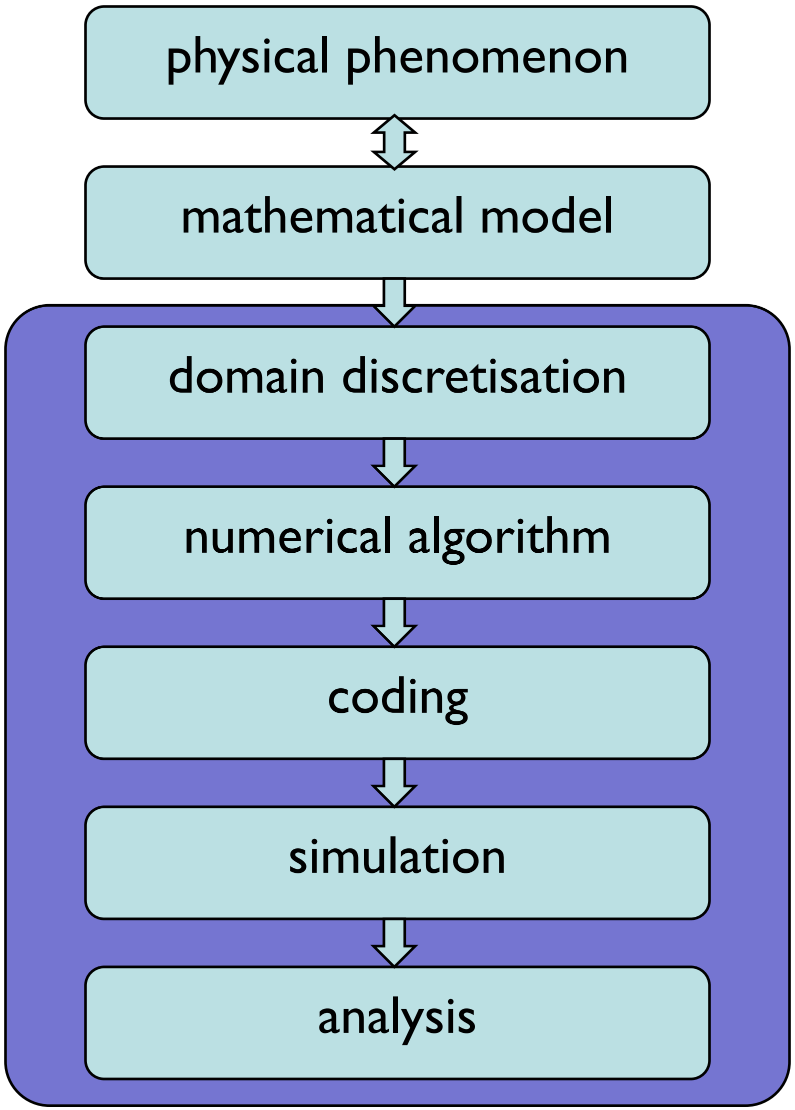


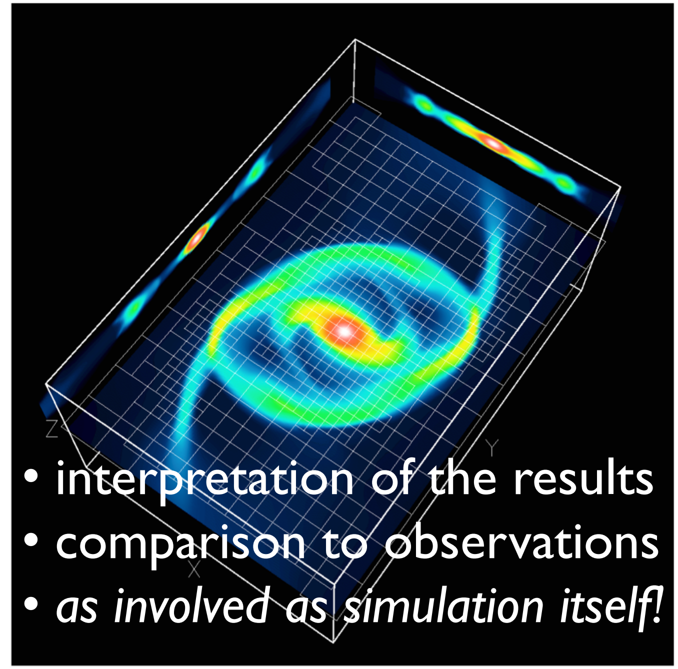
... end-of-course projects

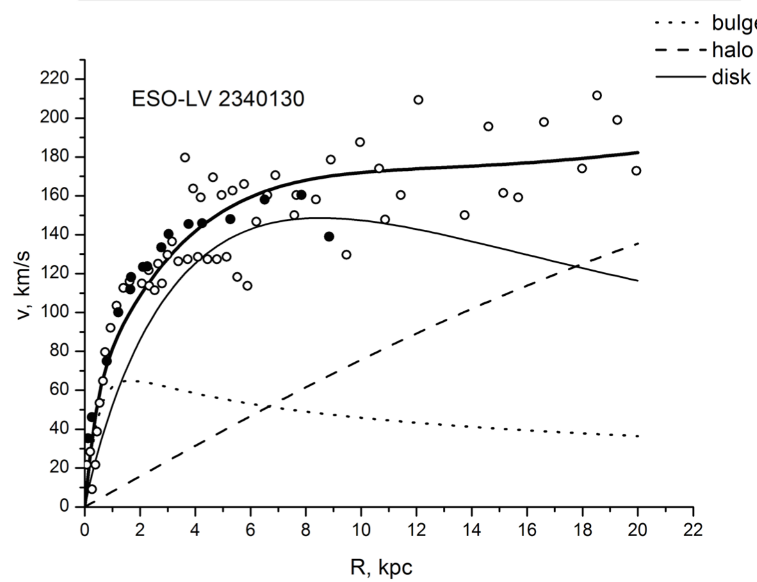


- interpretation of the results
- comparison to observations

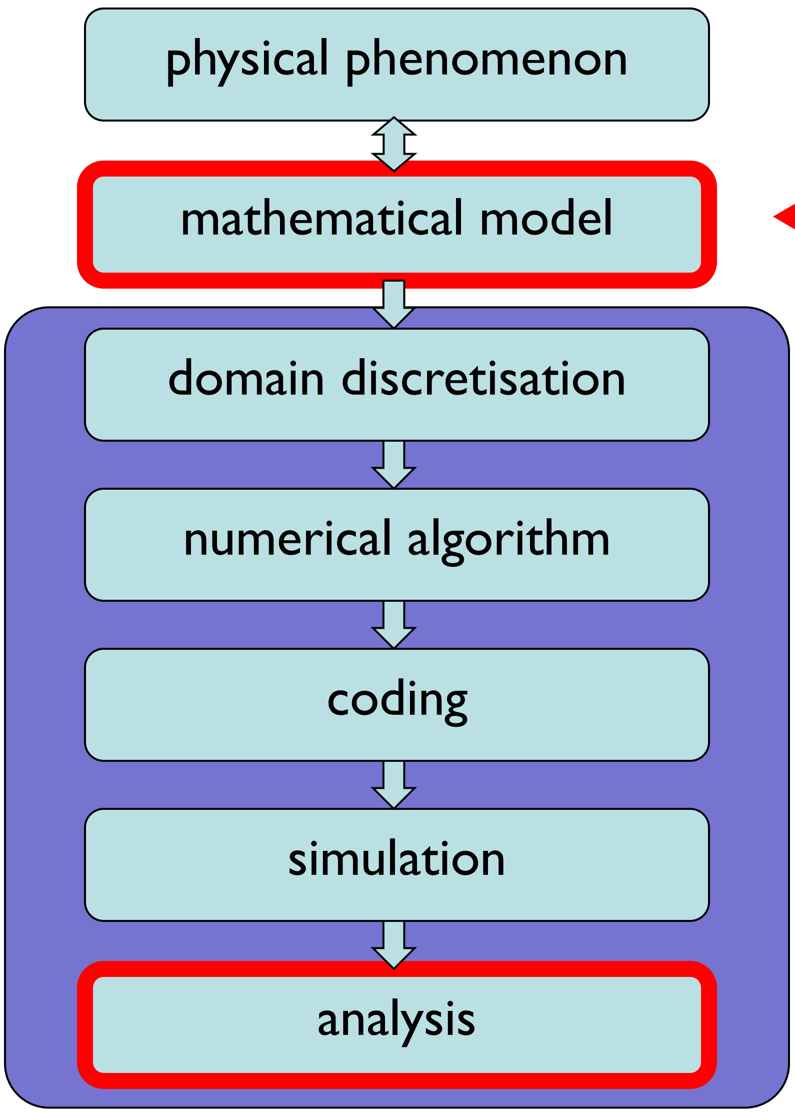



physical phenomenon
mathematical model
domain discretisation
numerical algorithm
coding
simulation
analysis

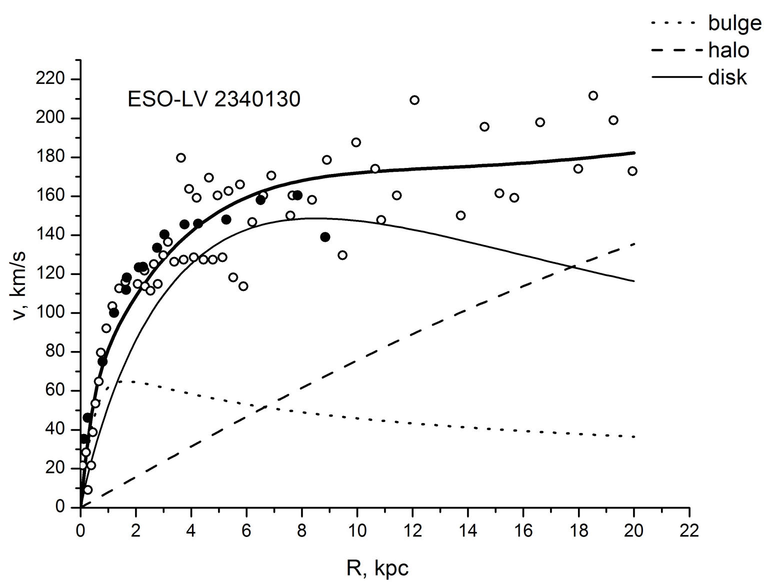

Z
Y
X
• interpretation of the results
• comparison to observations
• *as involved as simulation itself!*


bulge
halo
disk
ESO-LV 2340130
v, km/s
R, kpc
0
20
40
60
80
100
120
140
160
180
200
220
0
2
4
6
8
10
12
14
16
18
20
22

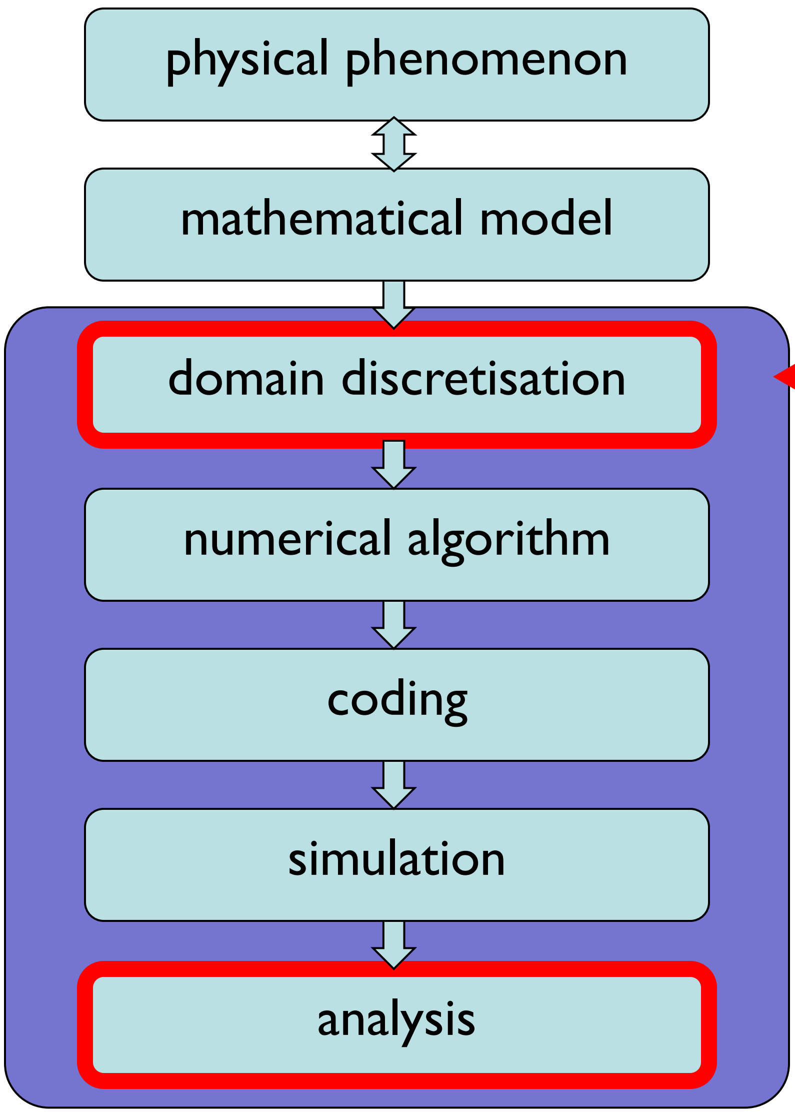
feedback loop:



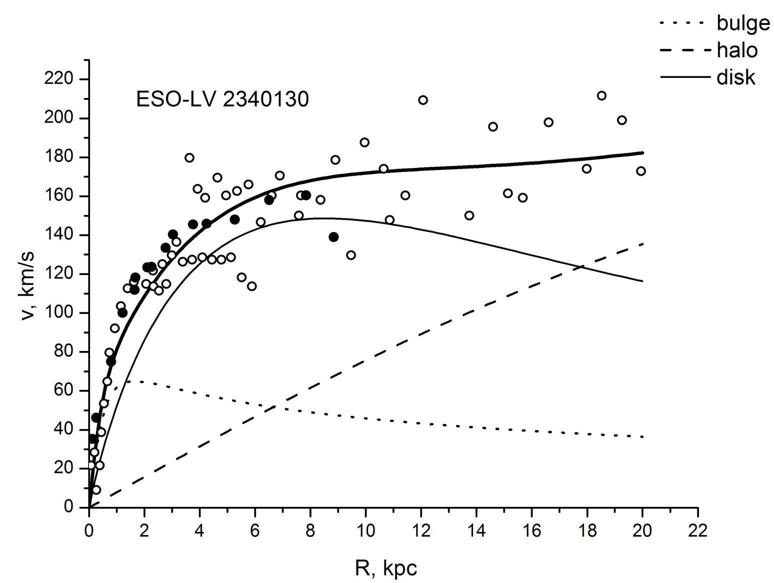
adjustments to the model?



feedback loop:



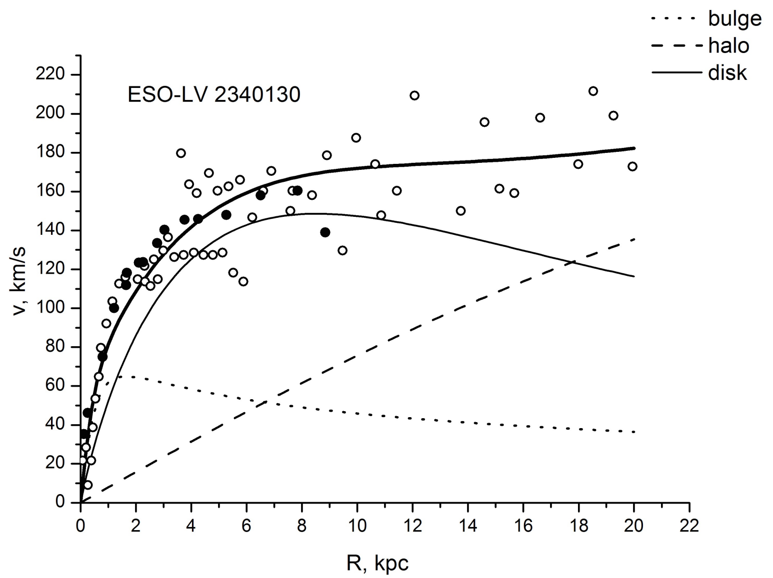
wrong domain discretisation?



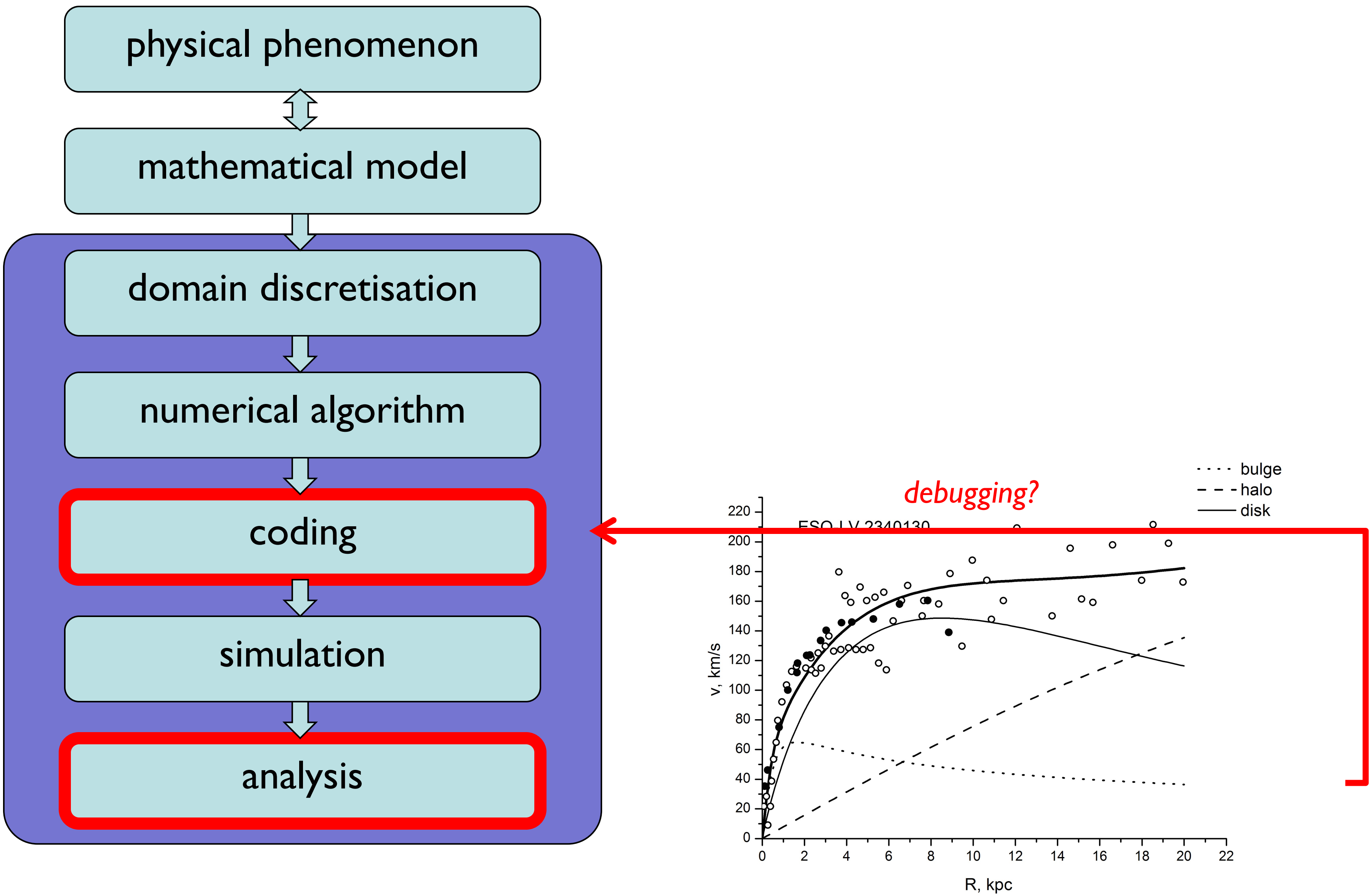
feedback loop:

- physical phenomenon
- mathematical model
- domain discretisation
- **numerical algorithm**
- coding
- simulation
- **analysis**

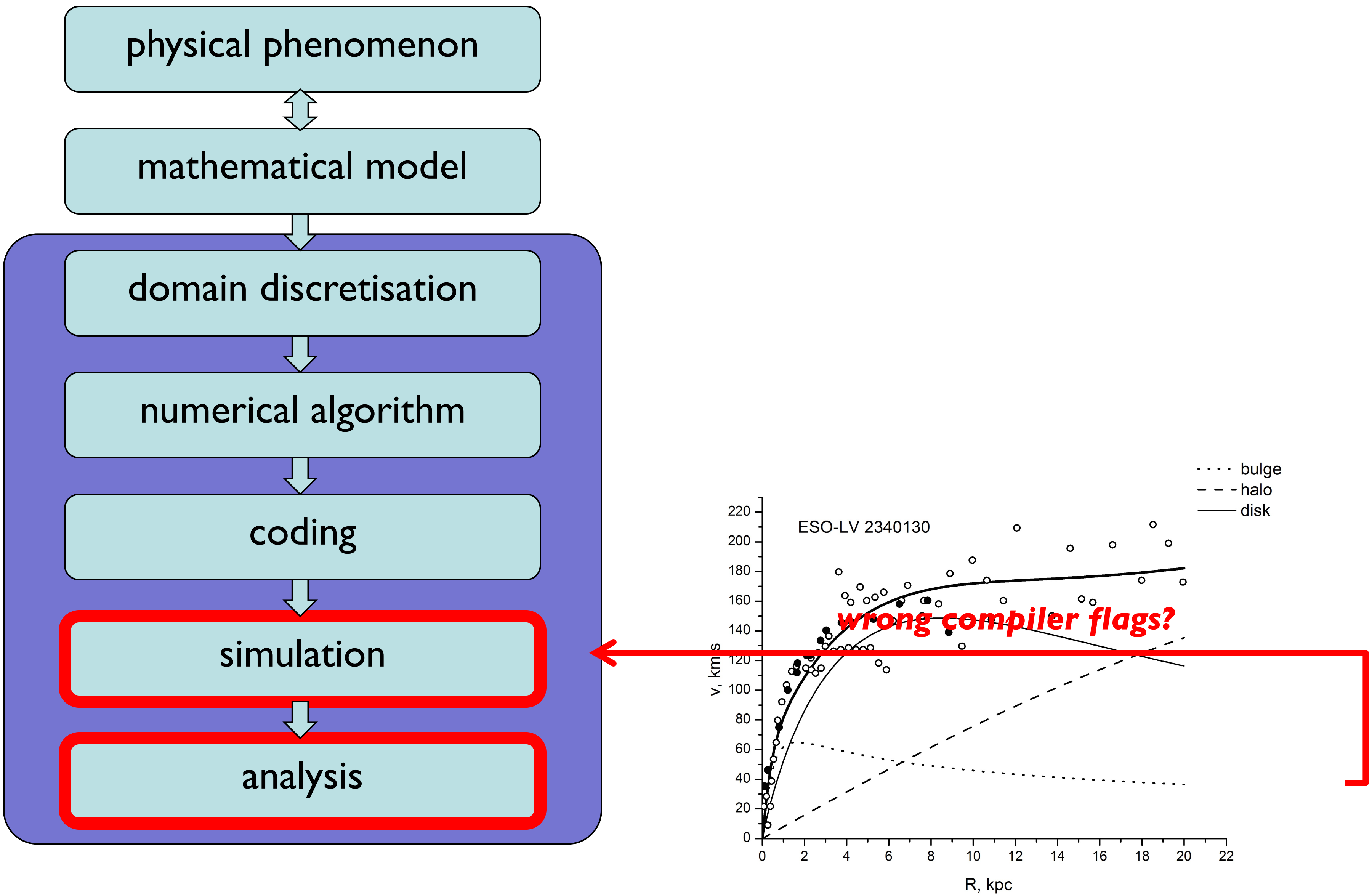
better suited algorithm possible?

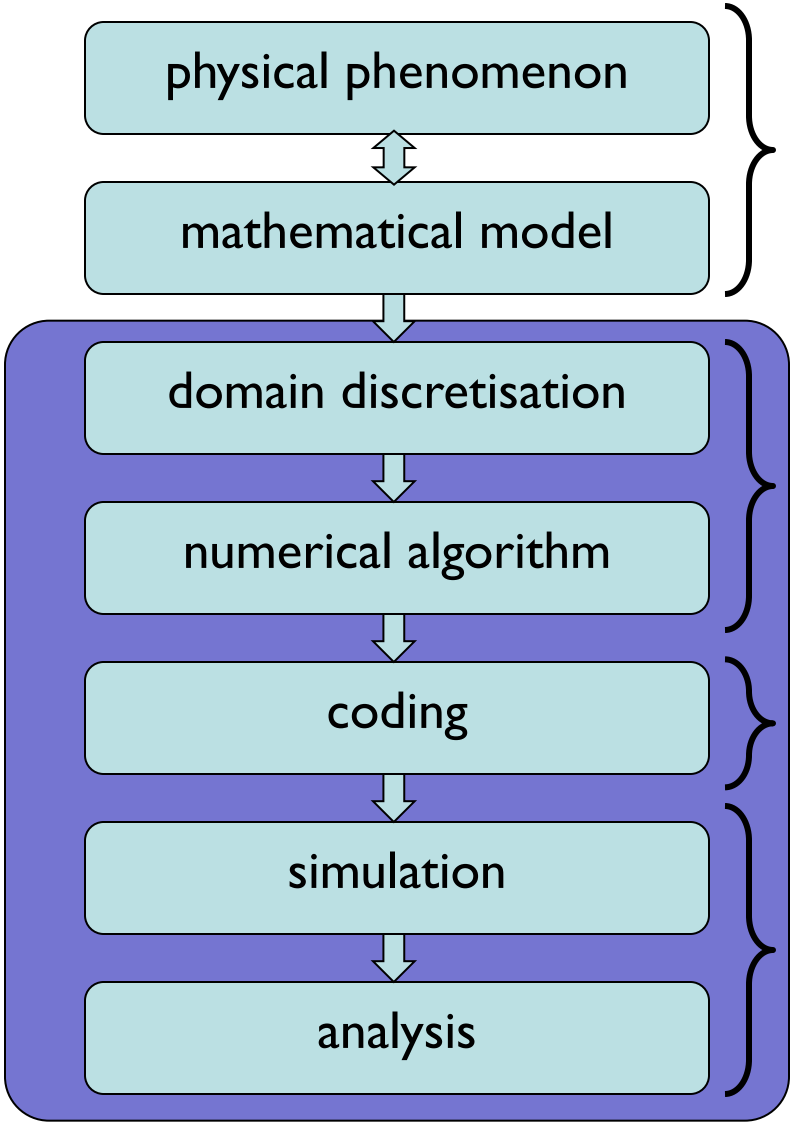


feedback loop:

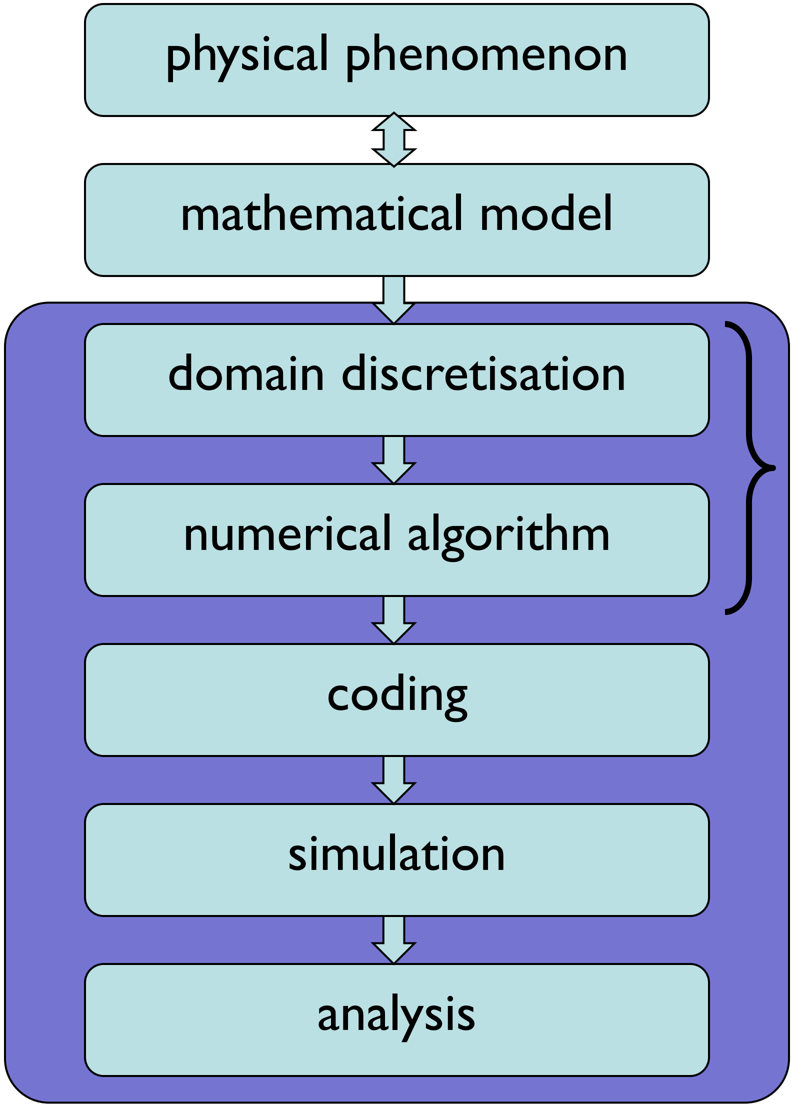


feedback loop:



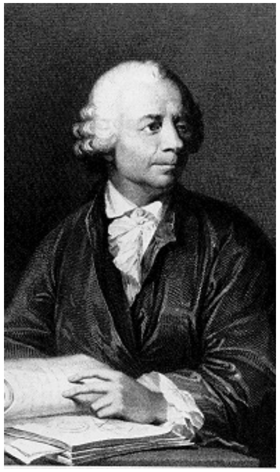


- lecture “astrophysical processes”
- all remaining lectures
- practical lessons
- exercises & projects



- a few introductory words already now...

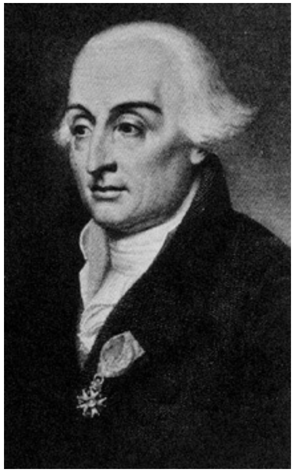
- domain discretisation



L. P. Euler
1707-1783

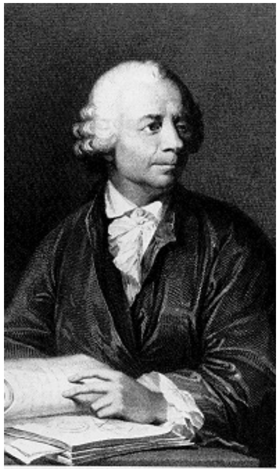
vs.

J.-L. Lagrange
1736-1813



two fundamentally different approaches to solving the same equations

- domain discretisation



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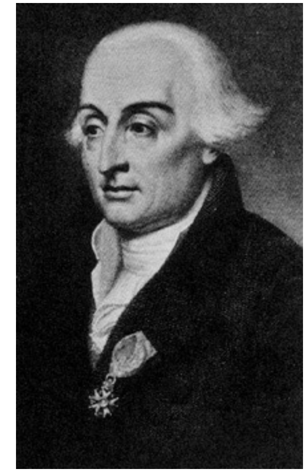
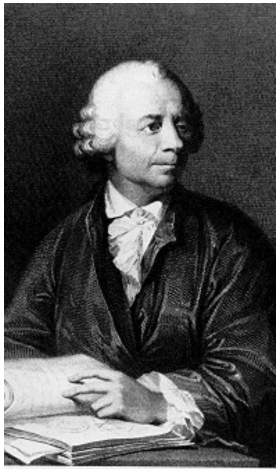


$\frac{\partial \rho}{\partial t} + v_i \frac{\partial \rho}{\partial x_i} = -\rho \frac{\partial v_i}{\partial x_i}$	mass conservation	$\frac{D\rho}{Dt} = -\rho \frac{\partial v_i}{\partial x_i}$
$\frac{\partial v_i}{\partial t} + v_i \frac{\partial v_j}{\partial v_i} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i}$	momentum conservation	$\frac{Dv_i}{Dt} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i}$
$\frac{\partial e}{\partial t} + v_i \frac{\partial e}{\partial x_i} = -\frac{p}{\rho} \frac{\partial v_i}{\partial x_i}$	energy conservation	$\frac{De}{Dt} = -\frac{p}{\rho} \frac{\partial v_i}{\partial x_i}$

- domain discretisation



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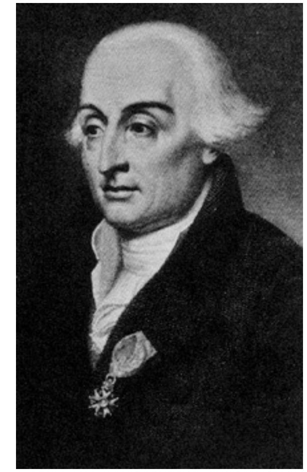


$\partial/\partial t$ = rate of change at a fixed point in space

D/Dt = rate of change following a mass element

$$\frac{\partial\rho}{\partial t} + v_i \frac{\partial\rho}{\partial x_i} = -\rho \frac{\partial v_i}{\partial x_i}$$

mass conservation

$$\frac{D\rho}{Dt} = -\rho \frac{\partial v_i}{\partial x_i}$$

$$\frac{\partial v_i}{\partial t} + v_i \frac{\partial v_j}{\partial v_i} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i}$$

momentum conservation

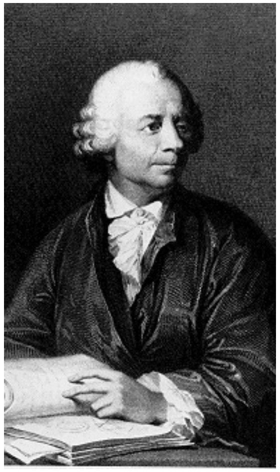
$$\frac{Dv_i}{Dt} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i}$$

$$\frac{\partial e}{\partial t} + v_i \frac{\partial e}{\partial x_i} = -\frac{p}{\rho} \frac{\partial v_i}{\partial x_i}$$

energy conservation

$$\frac{De}{Dt} = -\frac{p}{\rho} \frac{\partial v_i}{\partial x_i}$$

- domain discretisation



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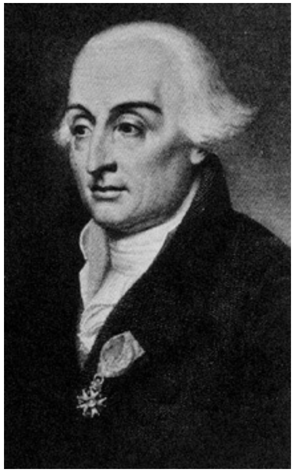

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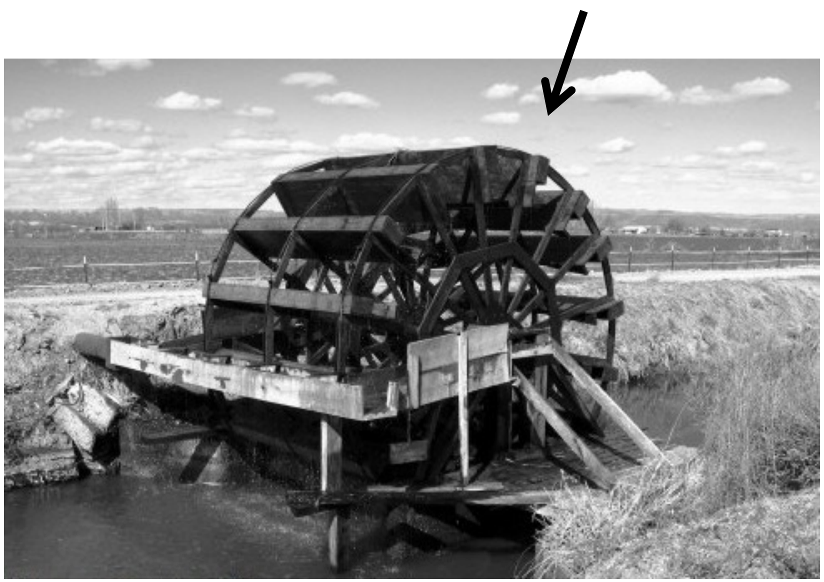
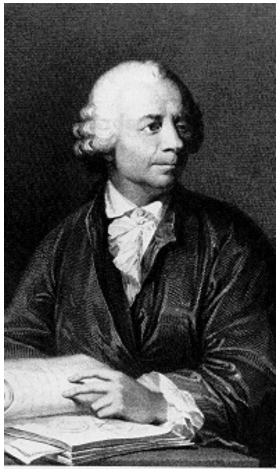


- domain discretisation



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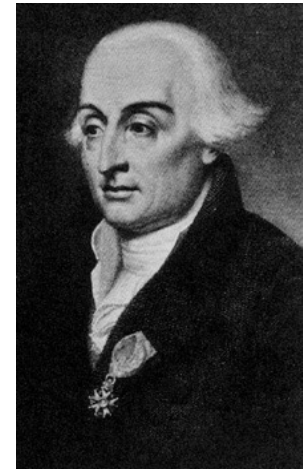

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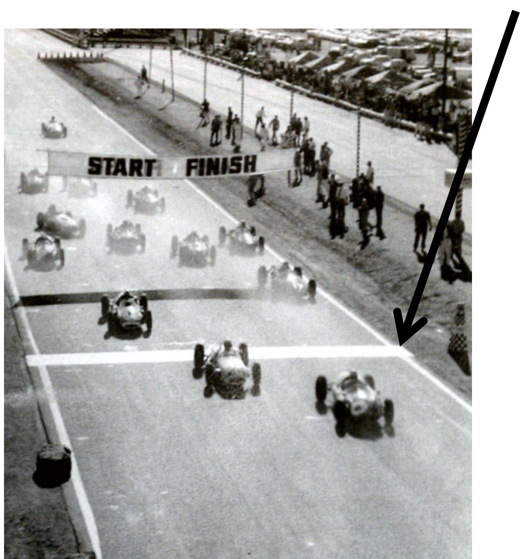
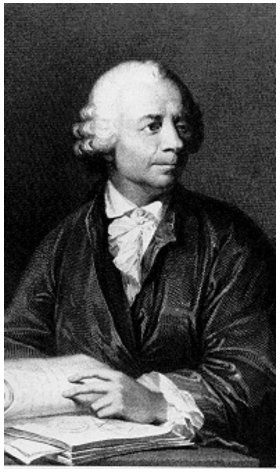


- domain discretisation



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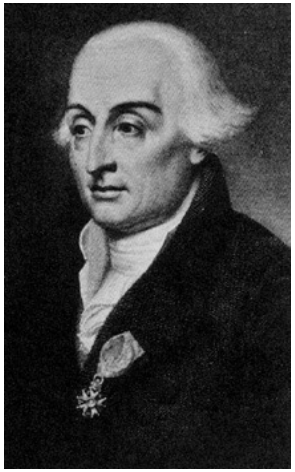
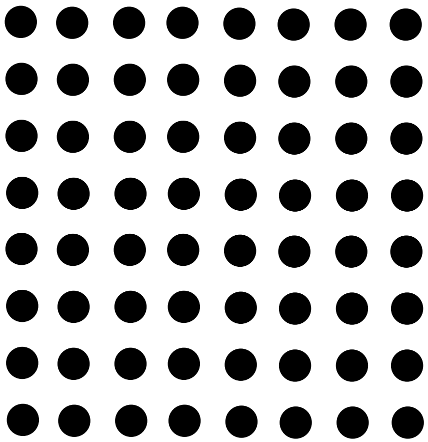
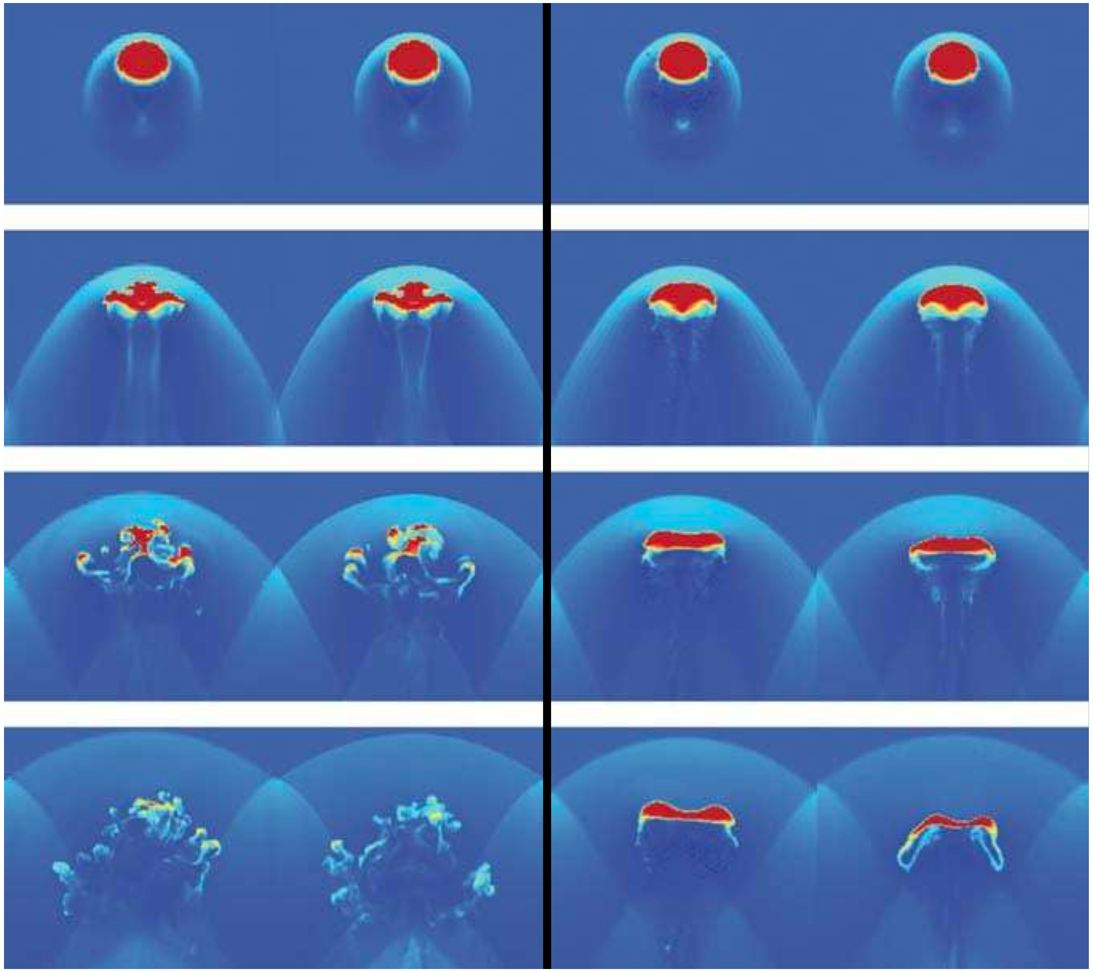




grid-based methods vs. particle-based methods

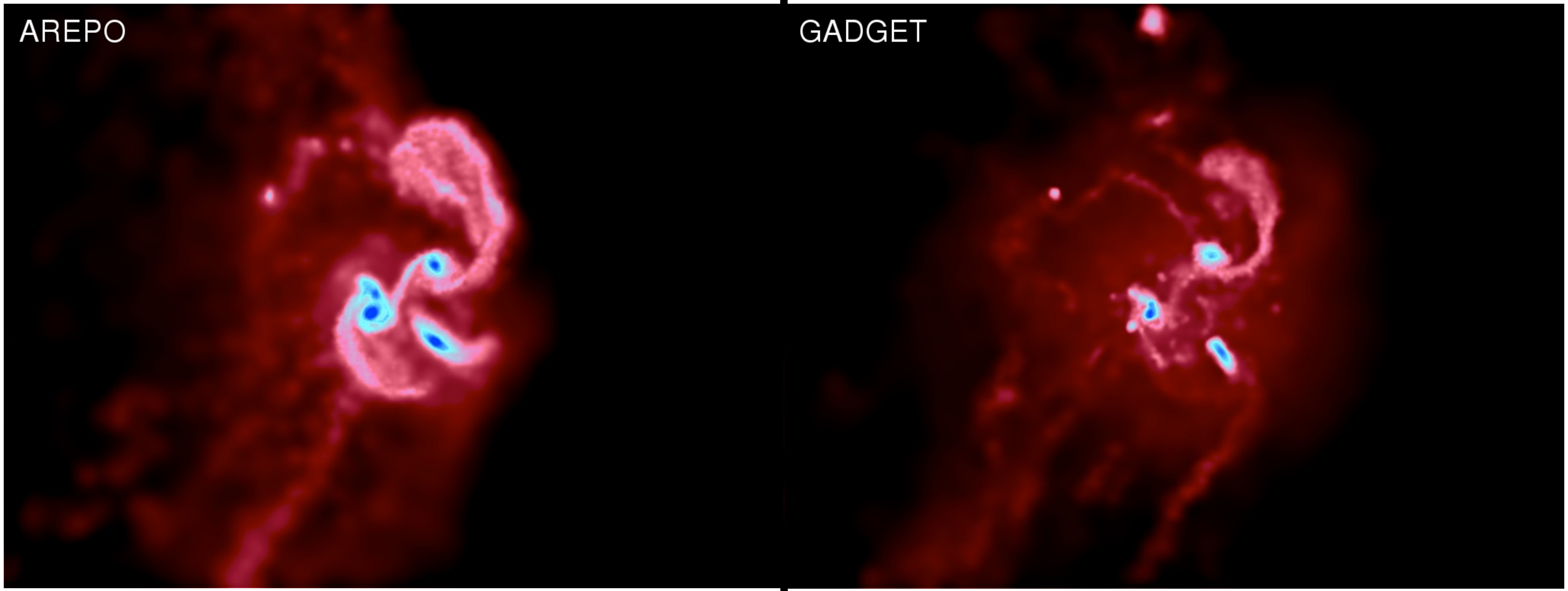
- domain discretisation



Agertz et al. (2007)

grid-based methods vs. particle-based methods

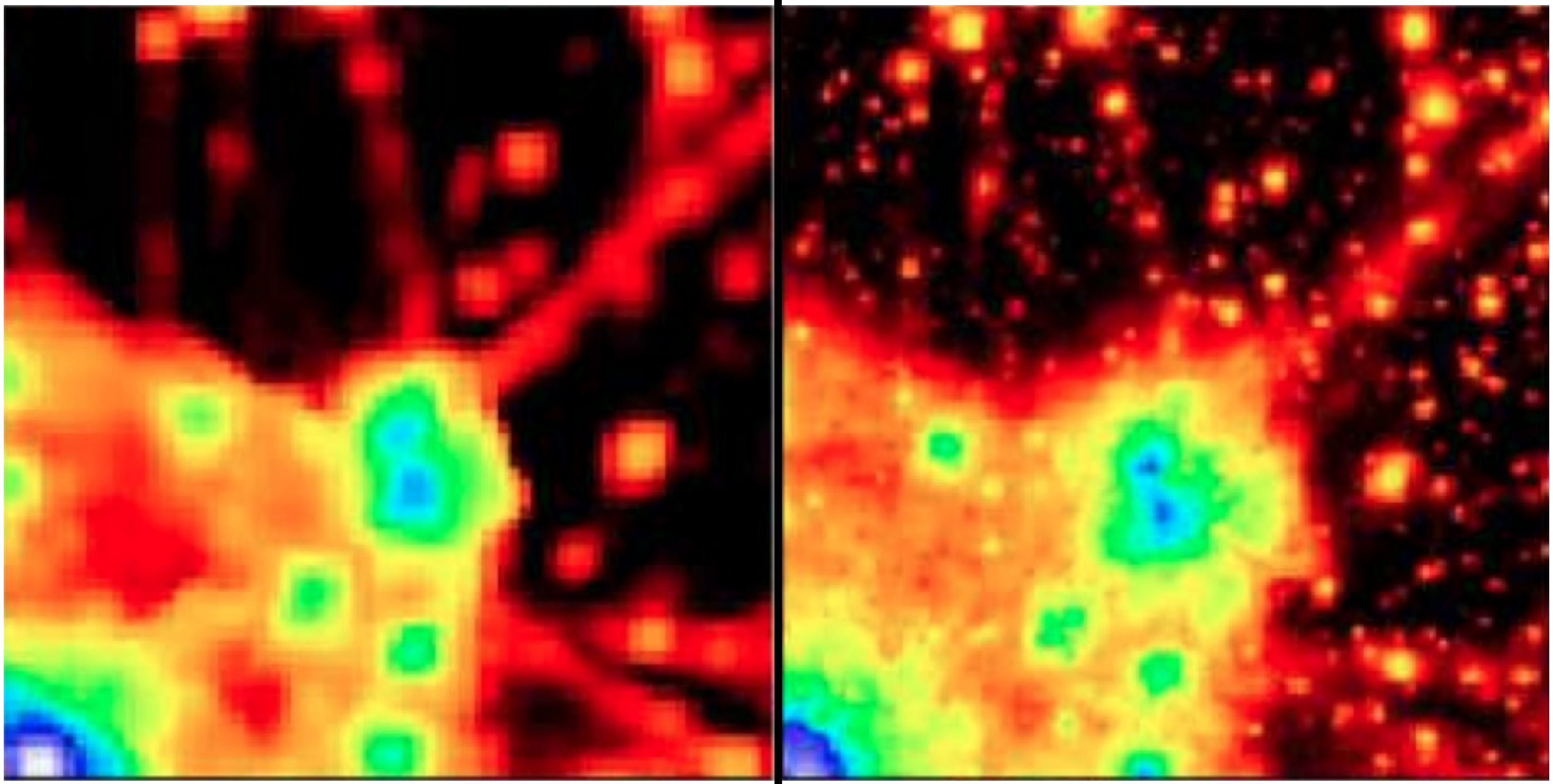
- domain discretisation



Keres et al. (2011)

grid-based methods vs. particle-based methods

- domain discretisation



Vazza et al. (2011)

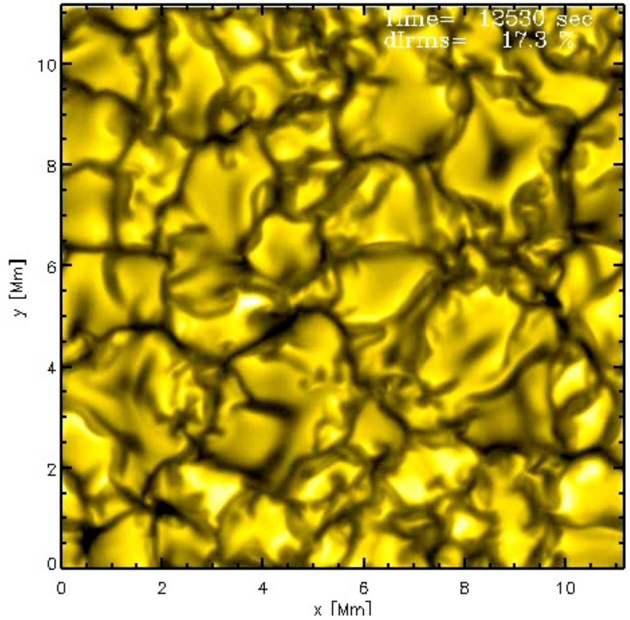
grid-based methods vs. particle-based methods

- domain discretisation

grid-based methods	vs.	particle-based methods
• originate from fluid dynamics		• originate from plasma physics

- domain discretisation

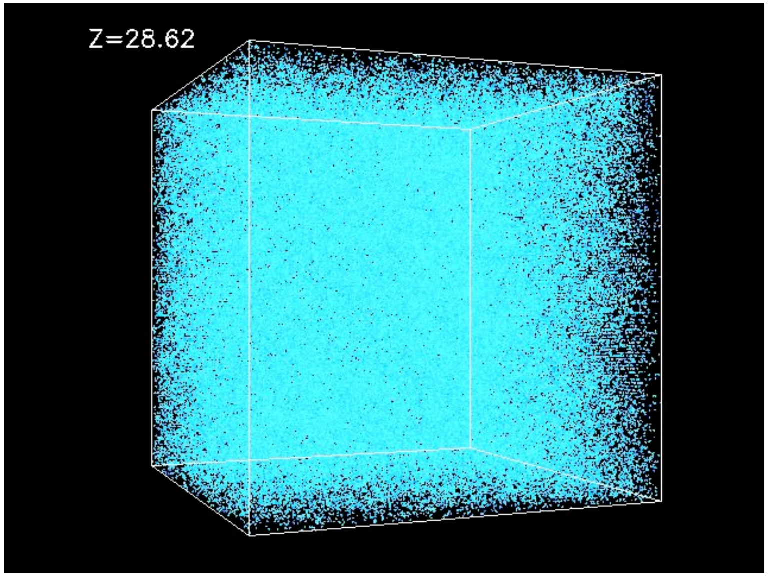
  - originate from fluid dynamics
  - in astrophysics primarily used for stellar evolution



grid-based methods

vs.

  - originate from plasma physics
  - in astrophysics primarily used for cosmology



particle-based methods

- domain discretisation

both methods have their merits and shortcomings...
...and the verdict (if any) is still out there

grid-based methods vs. particle-based methods

Alexander Knebe, *Universidad Autonoma de Madrid*