2. Cosmological simulations of galaxy formation

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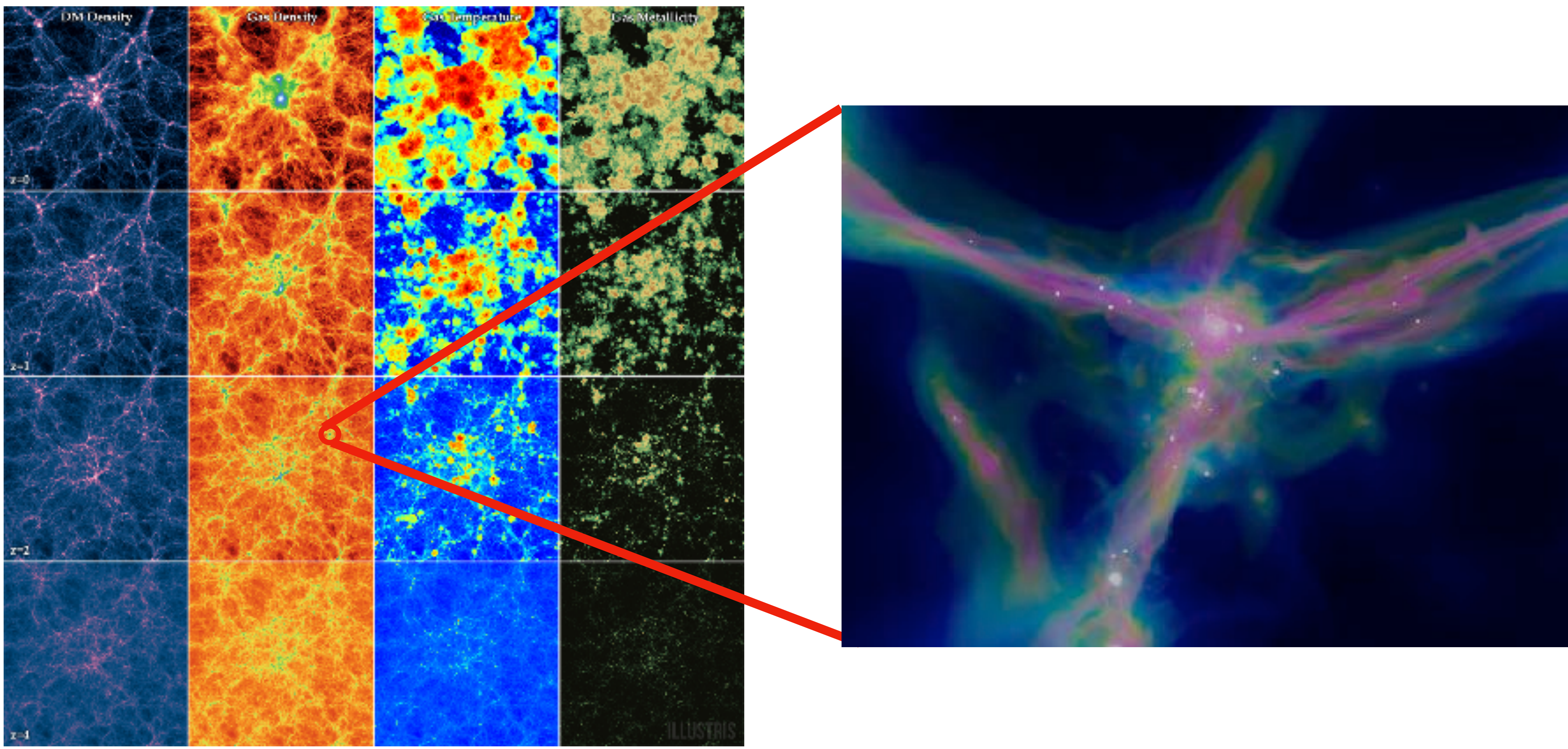
Outline

- introduction of cosmological simulations of galaxy formation
- A crash-course on shock-capturing Eulerian methods

cosmological simulations

- Full-Box: ILLUSTRIS, EAGLE:
- Zoom-in: FIRE, NIHAO, VELA:

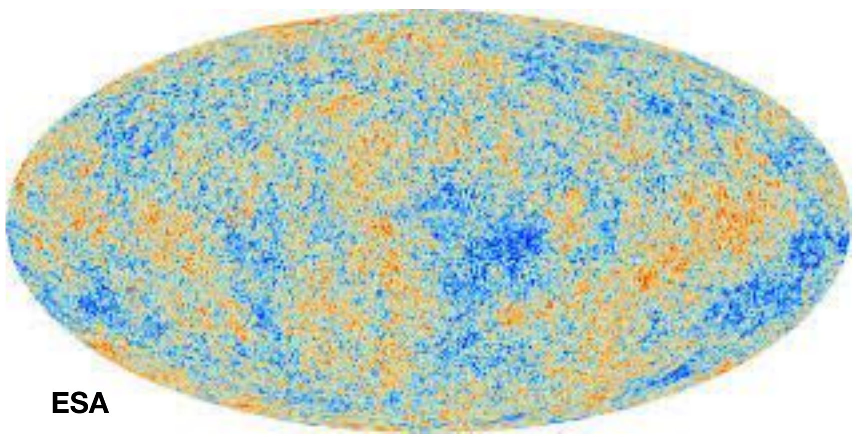


cosmological simulations

- Full Box: ILLUSTRIS, EAGLE:
- full-volume: large sample of galaxies
- low-resolution: ~1 kpc
- ad-hoc simple recipes for complex physical processes: SF, feedback, outflows,…
- calibration against observables like luminosity functions
- little predictive power

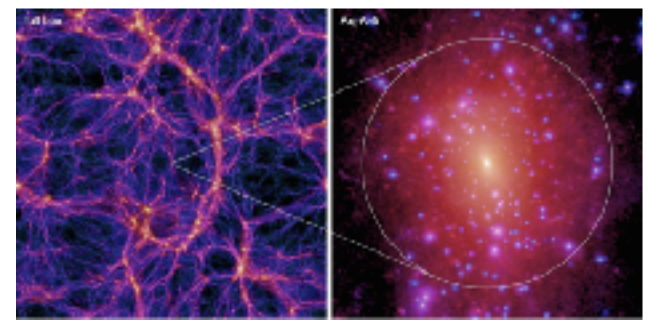
- Zoom-in: FIRE, NIHAO, VELA:
- small samples: selection bias
- high-resolution: ~10 pc
- models of complex (unresolved) processes
- parameters set by physical constraints (energy in a single SN)
- they can fail

The simulation machine

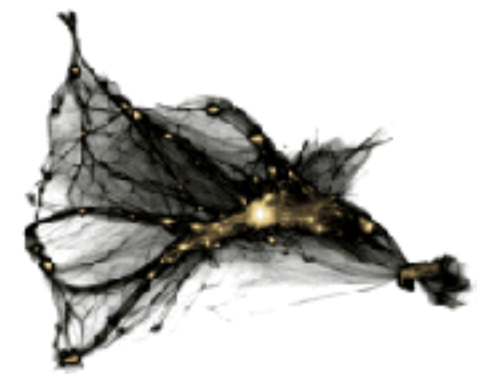


ESA

The Universe Initial Conditions



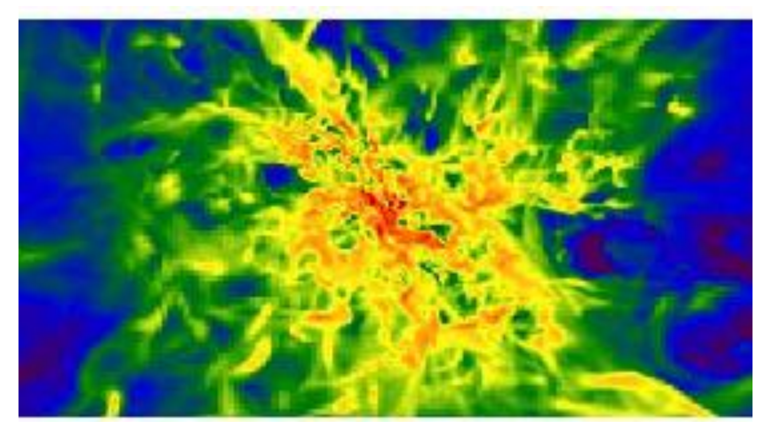
AURIGA



Ralf Kaehler

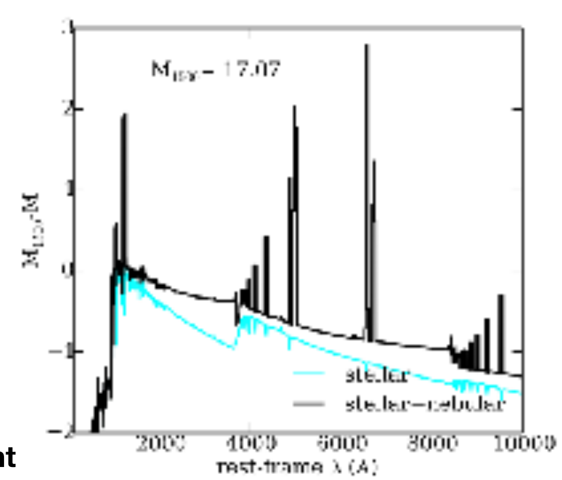
The zoom-in technique

The Run



FirstLight

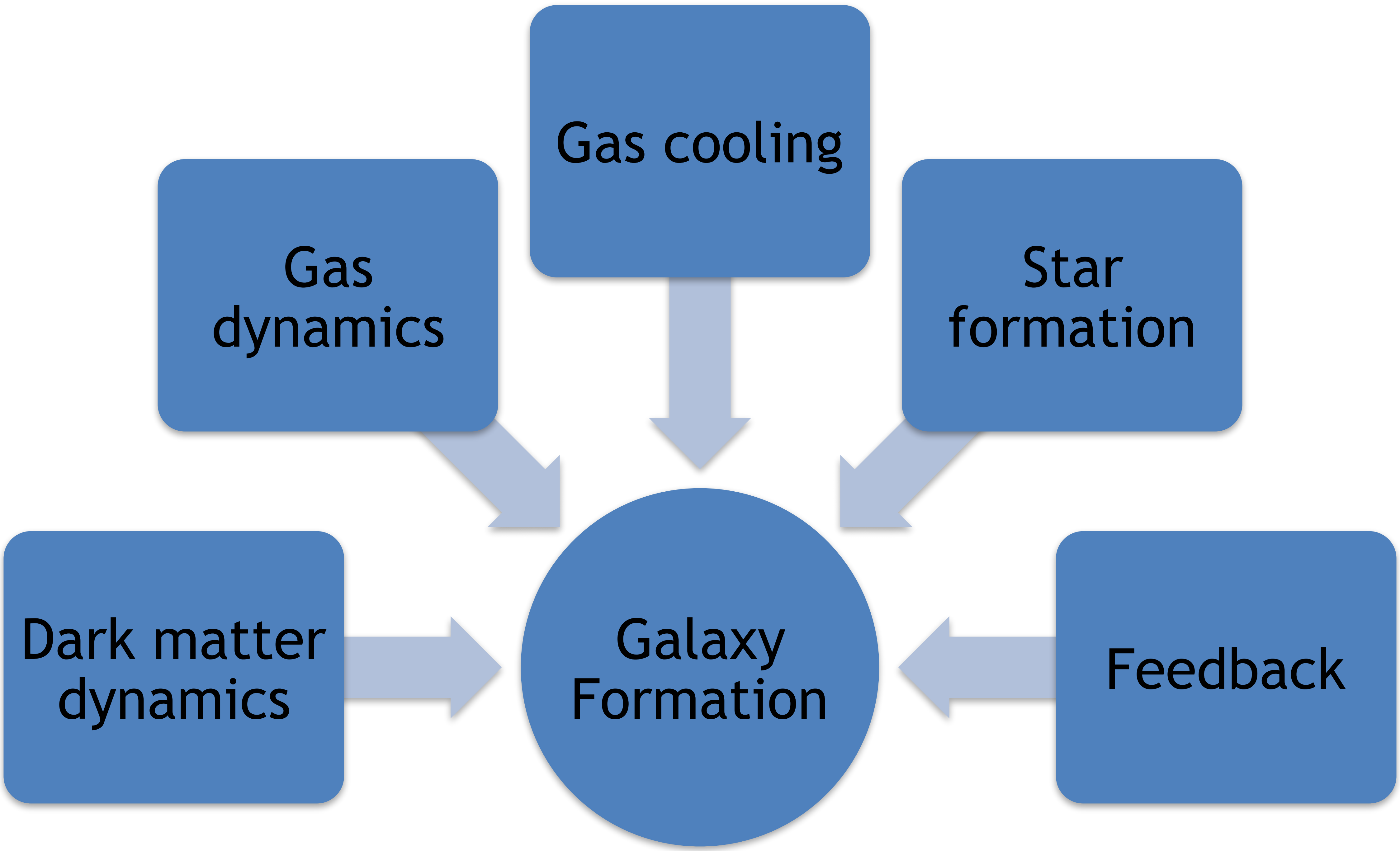
Mock Data



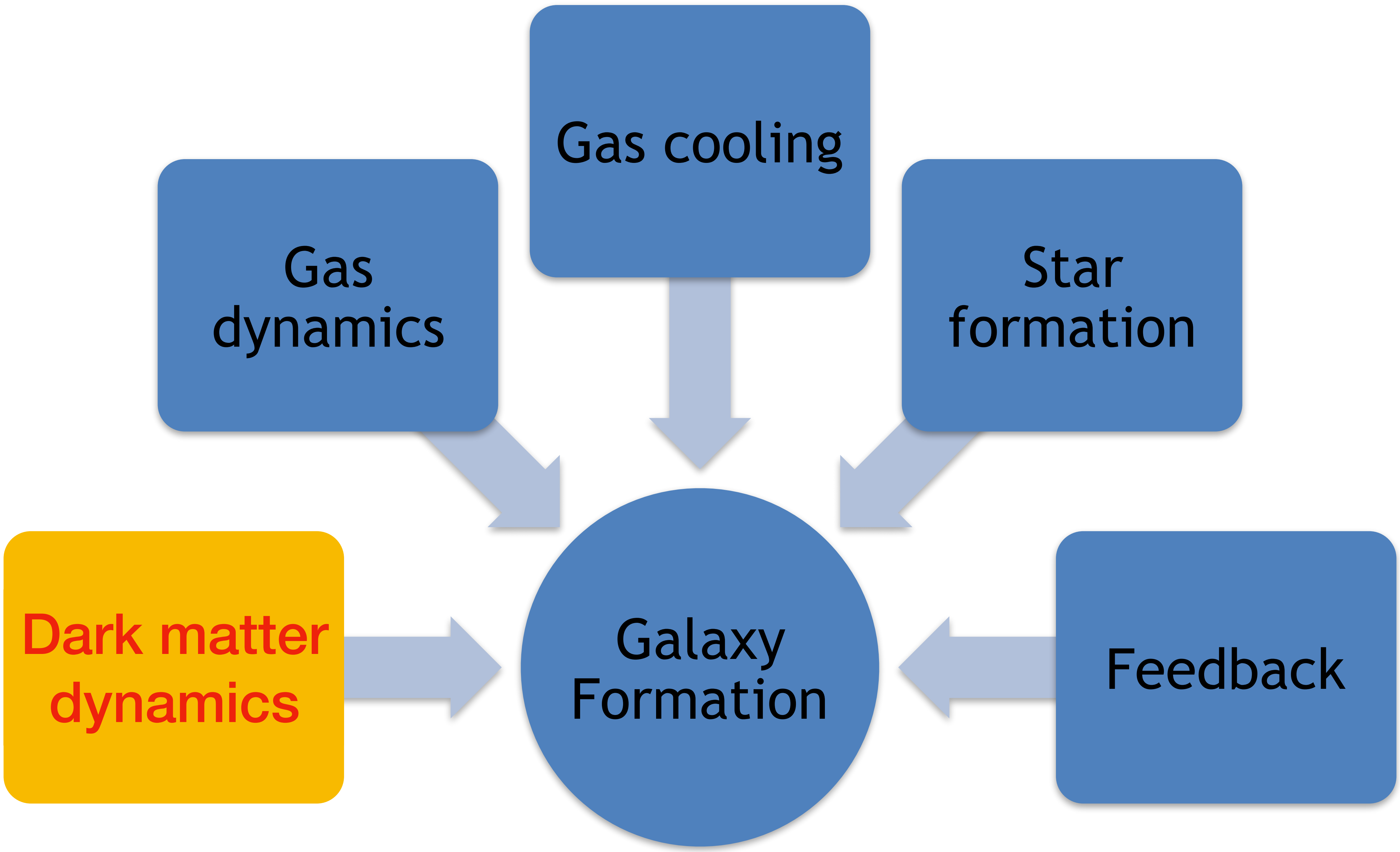
FirstLight


15
10.1
5.85
2.5
0.2
Gas density
time=1

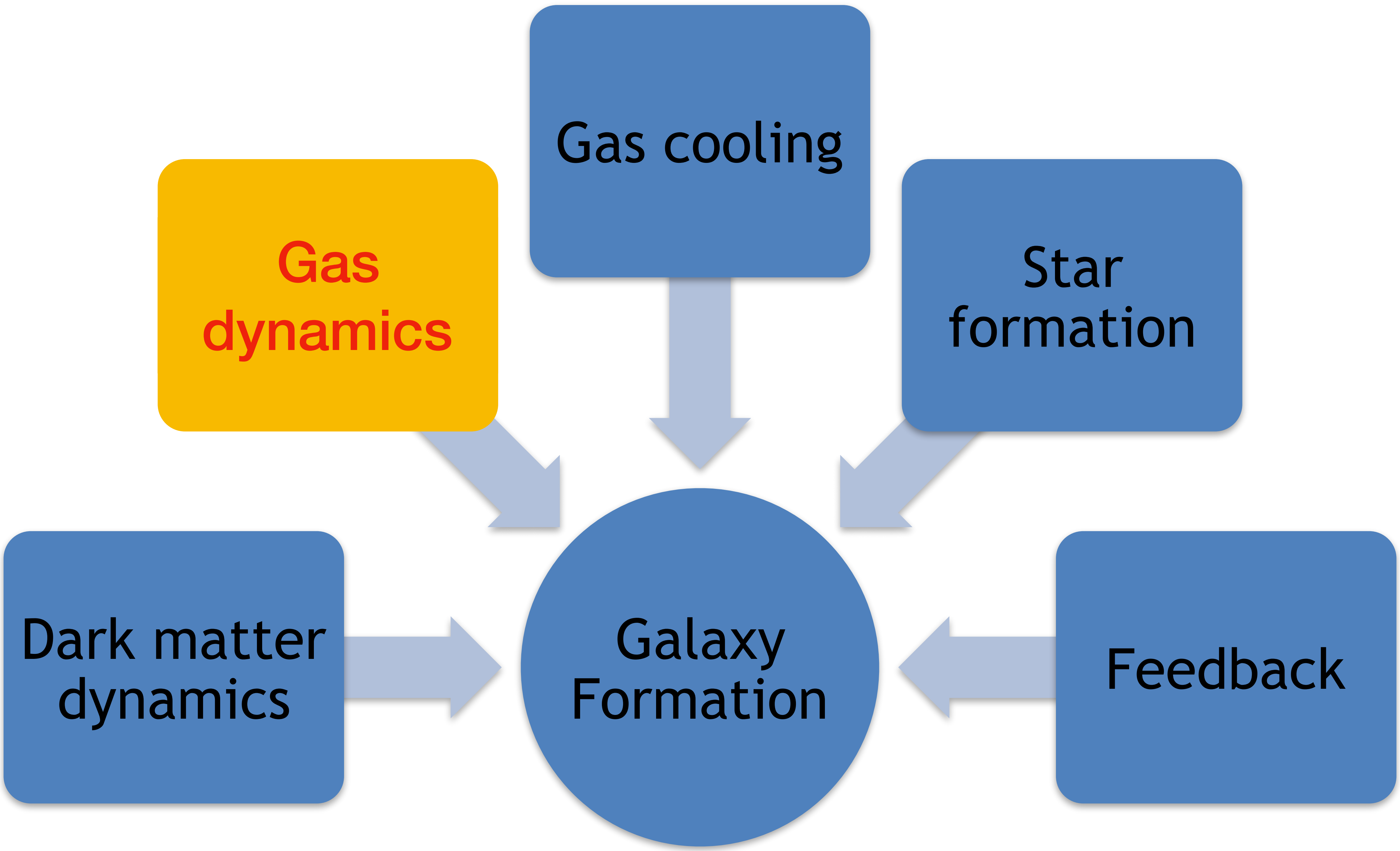
A Physical model for galaxy formation



A Physical model for galaxy formation



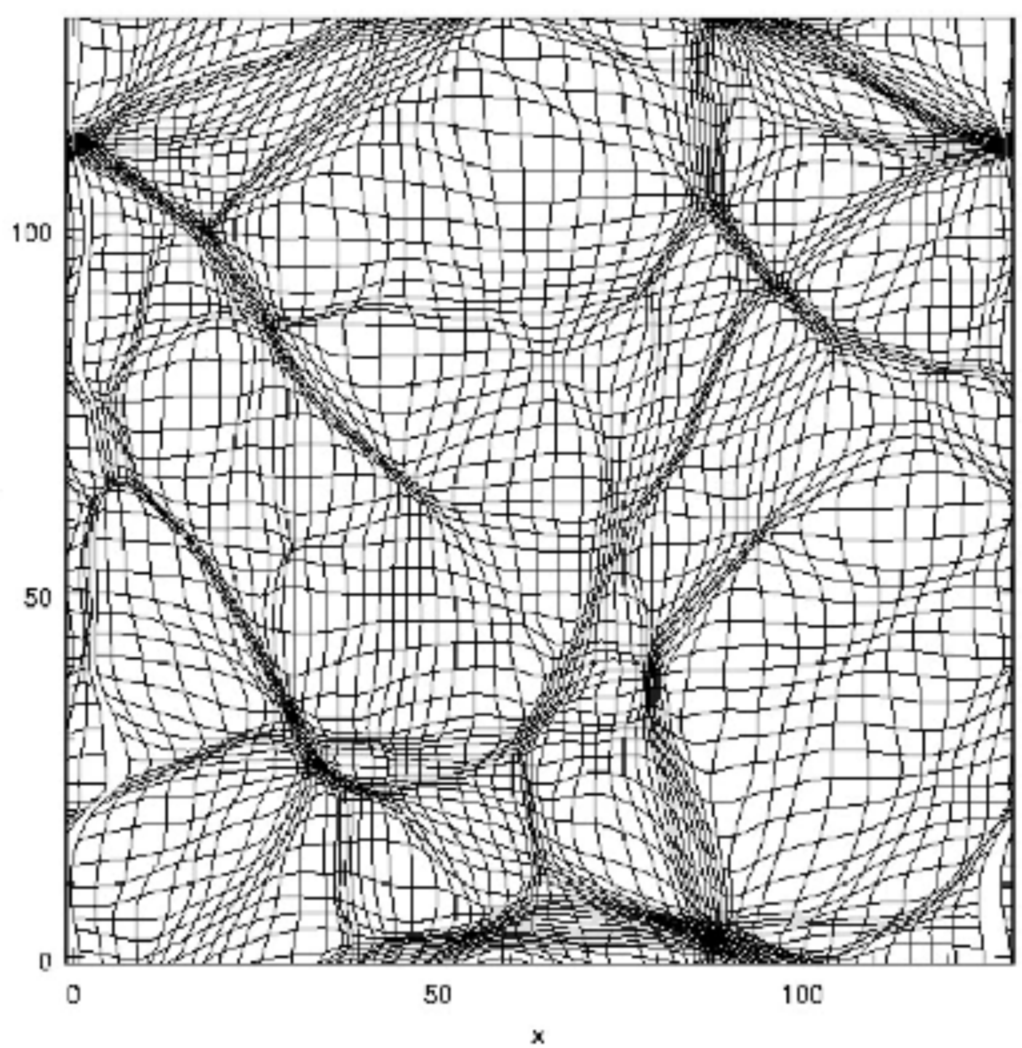
A Physical model for galaxy formation

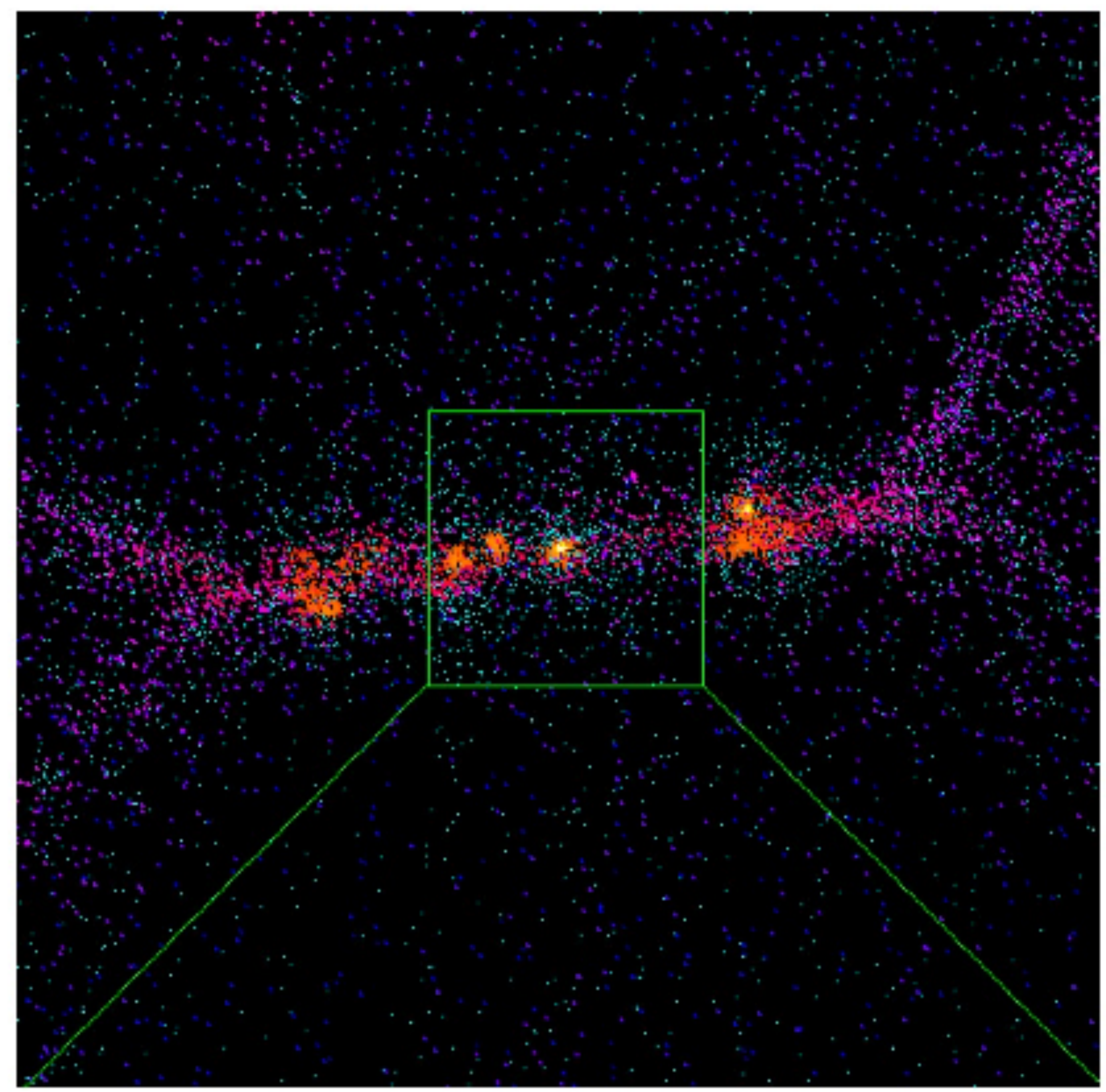


Lagrangian Approach

- Smoothed Lagrangian Hydrodynamics (SLH)
  [Gnedin 1996; Pen 1997]

- Smoothed Particle Hydrodynamics (SPH)





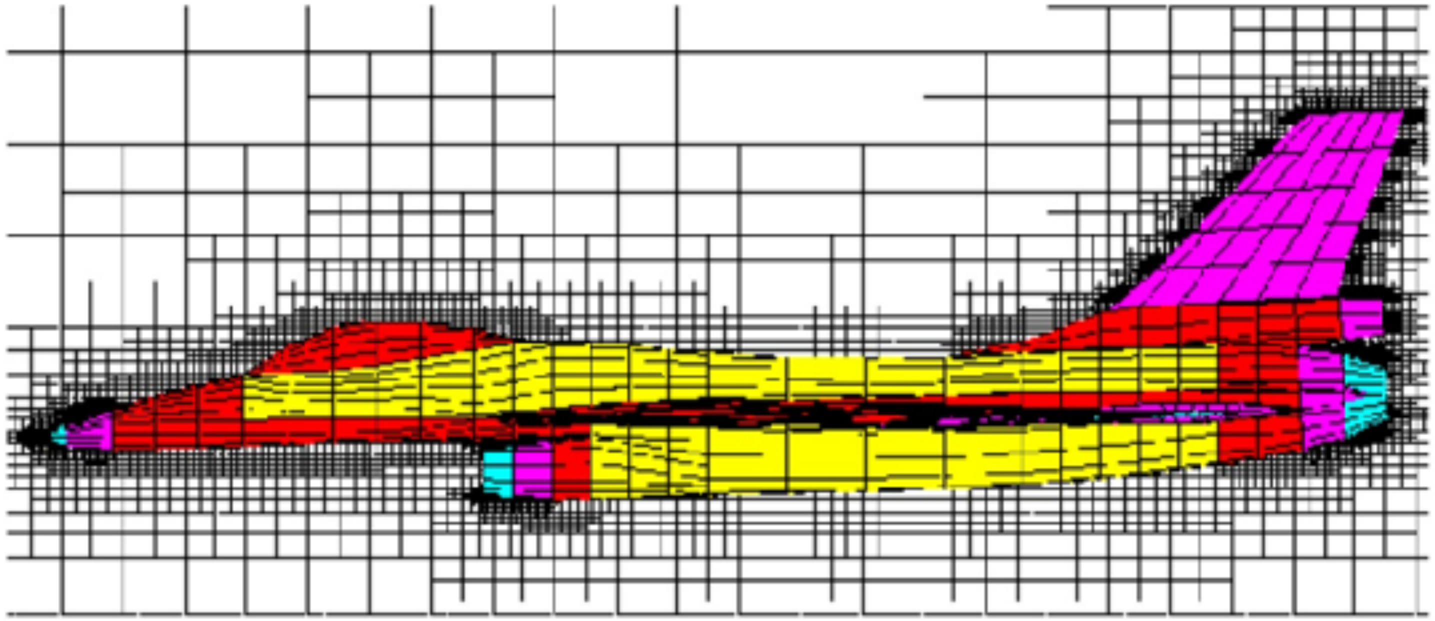
The AMR Approach

- Efficient, reliable finite element methods *for uniform grids* have been developed for solving the Poisson and gasdynamics equations.

- The *Adaptive Mesh Refinement* (AMR) methods increase the dynamic range of grid-based numerical algorithms beyond the limits imposed by existing hardware.

- The methods have numerous applications in different fields of physics, engineering, etc.

- Now gaining popularity in astrophysics and cosmology



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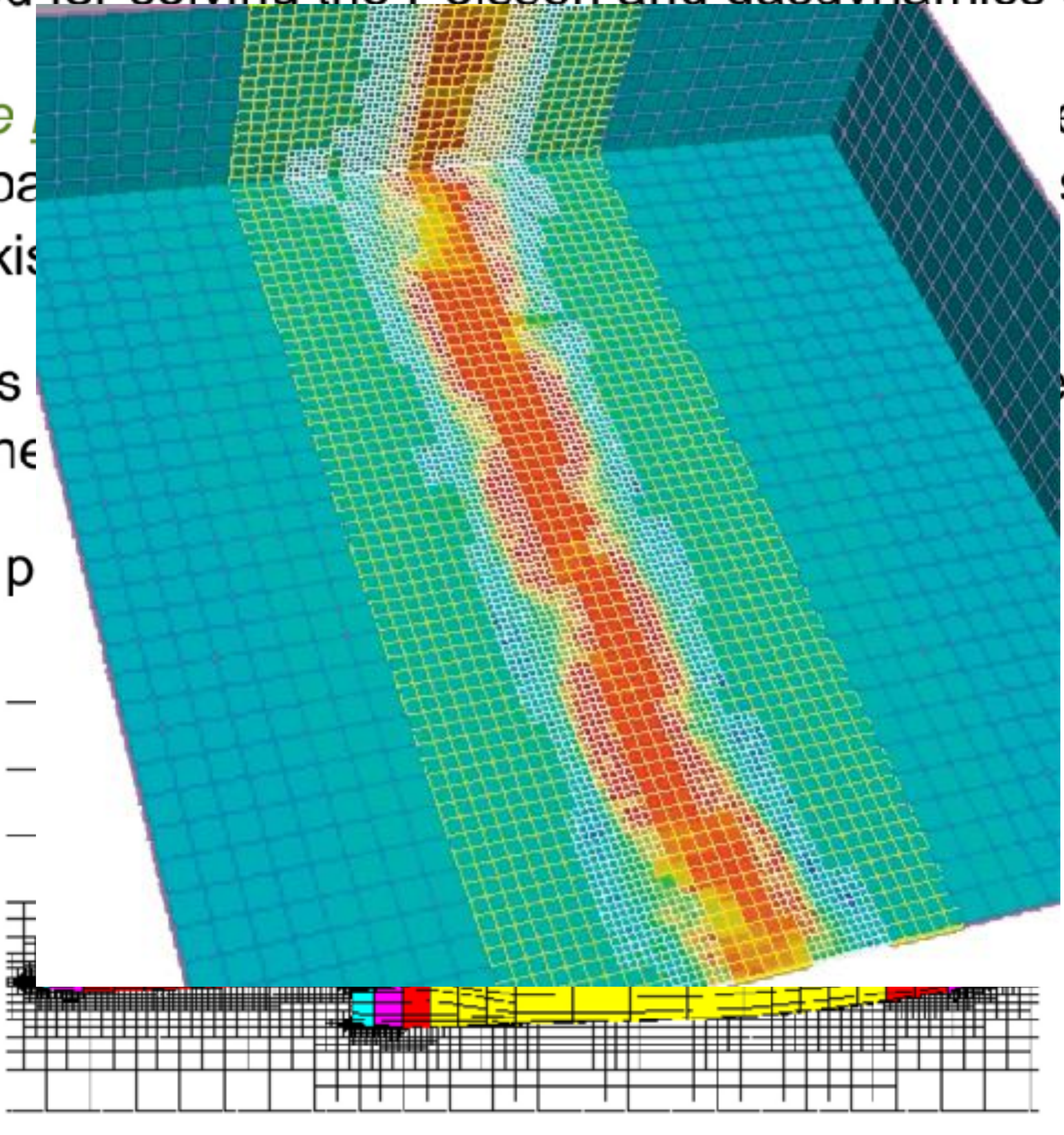

Solving equation of gasdynamics
a crash course in shock-capturing Eulerian methods

$$\frac{\partial \rho}{\partial t} + \nabla \rho \mathbf{u} = 0,$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla \Phi - \frac{\nabla P}{\rho},$$

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E + P)\mathbf{u}] = -\rho \mathbf{u} \cdot \nabla \Phi.$$

- these are equations of Eulerian gasdynamics – they describe evolution of gas properties at a fixed point in space.

- look simple enough – so what is the deal with the vast literature and research on the computational fluid dynamics (CFD) for the past 60 years?

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- naïve discretization of these equations does not work because flows often develop discontinuities and numerical derivatives “blow up”

- one can introduce artificial viscosity to “smear” the discontinuities, the price is the loss of accuracy and resolution

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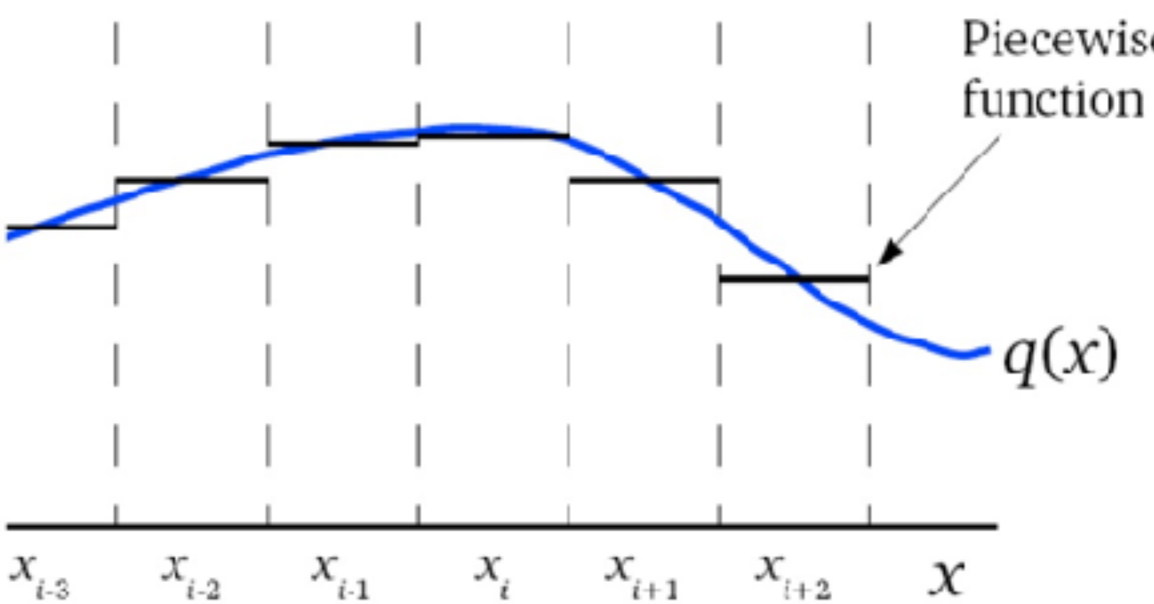
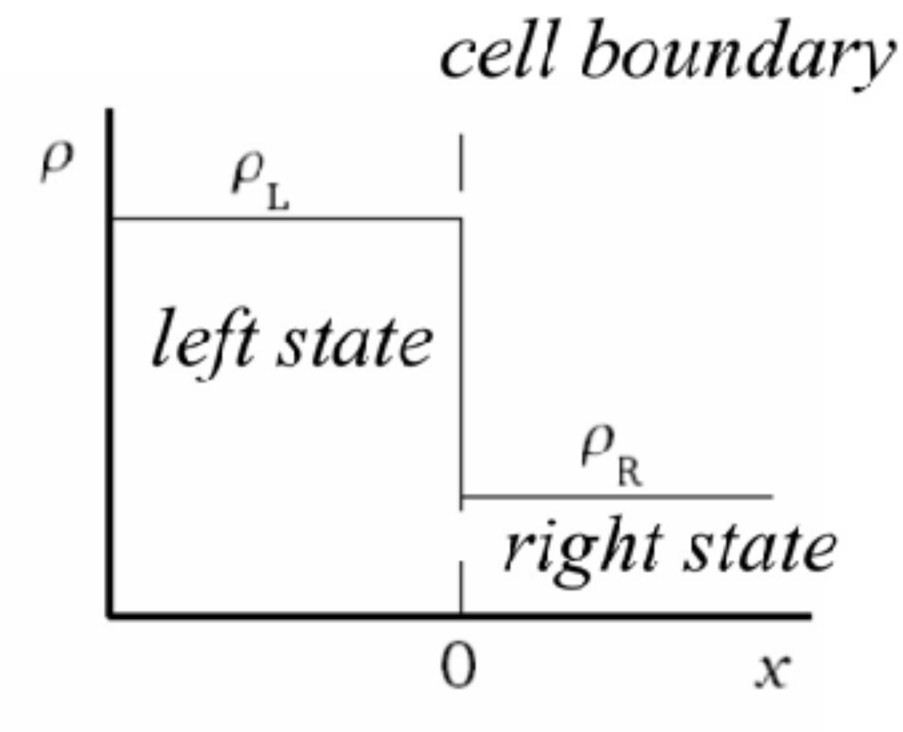


- Some other schemes (e.g., Lax-Wendroff) were proposed but none were really satisfactory
- In 1959, Godunov proposed a radically different scheme for solving these equations
- In the original Godunov's method variables were assumed to be constant in each cell.
- At each cell interface the fluxes of variables are computed by solving the Riemann boundary problem

Solving equation of gasdynamics



variable, flux, source

$$\frac{\partial \mathcal{U}}{\partial t} = \frac{\partial \mathcal{F}}{\partial x} + \mathcal{S}$$

$$\mathcal{F} = (\rho v_x, (E+P)v_x, \rho v_x^2, \rho v_x v_y, \rho v_x v_z)$$

$$\mathcal{S} = (0, \rho v_x g_x, \rho g_x, 0, 0)$$

- Find a set of intermediate states (one for each characteristic) that connect left and right states and satisfy physical conditions (e.g., shock jump conditions)

- solve for conservation equations for the fluxes through cell interface given the boundary conditions on the left and on the right of the interface

- update physical variables in cells around the interface

$$\bar{\boldsymbol{q}}_i^L = \boldsymbol{q}_i^L + \frac{\Delta t}{2 \Delta x}[\boldsymbol{F}(\boldsymbol{q}_i^L) - \boldsymbol{F}(\boldsymbol{q}_i^R)]$$

$$\bar{\boldsymbol{q}}_i^R = \boldsymbol{q}_i^R + \frac{\Delta t}{2 \Delta x}[\boldsymbol{F}(\boldsymbol{q}_i^L) - \boldsymbol{F}(\boldsymbol{q}_i^R)]$$

Solving equation of gasdynamics

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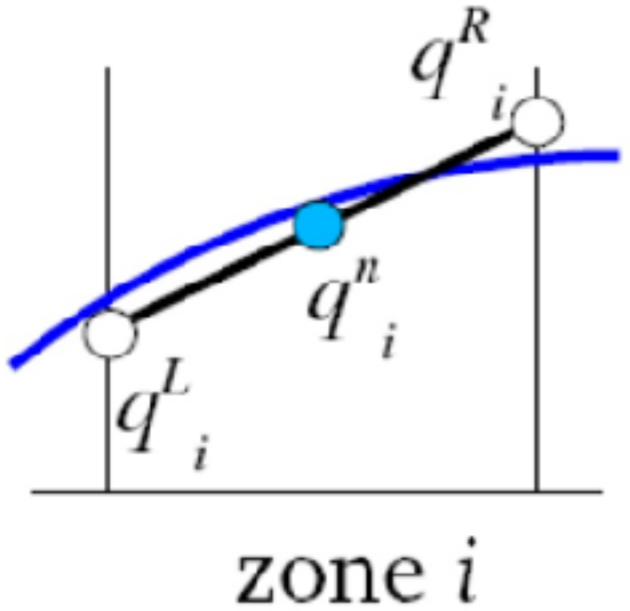

variable → $\frac{\partial \mathcal{U}}{\partial t}$, *flux* → $\frac{\partial \mathcal{F}}{\partial x}$, *source* → $\mathcal{S}$

$$\frac{\partial \mathcal{U}}{\partial t} = \frac{\partial \mathcal{F}}{\partial x} + \mathcal{S}$$

$$\mathcal{F} = (\rho v_x, (E+P)v_x, \rho v_x^2, \rho v_x v_y, \rho v_x v_z)$$

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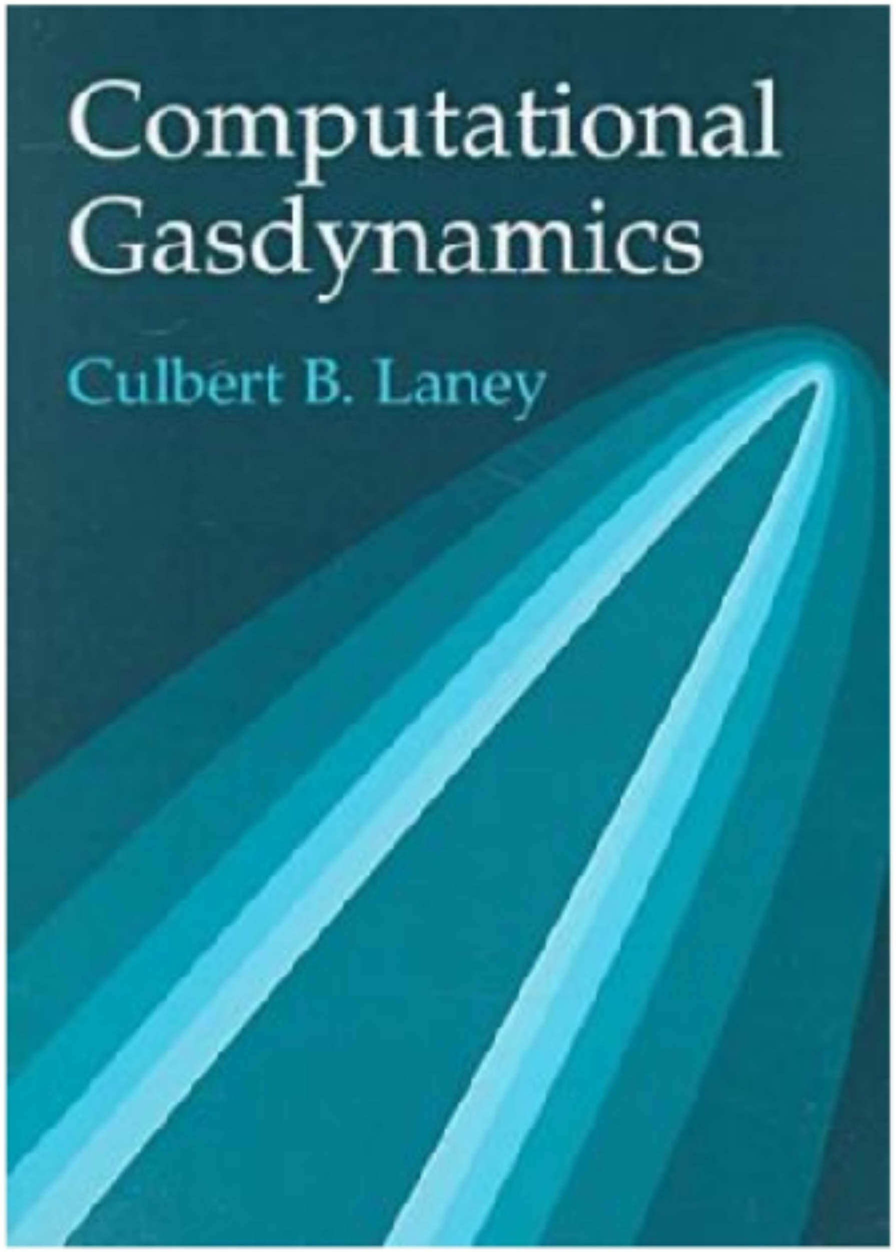
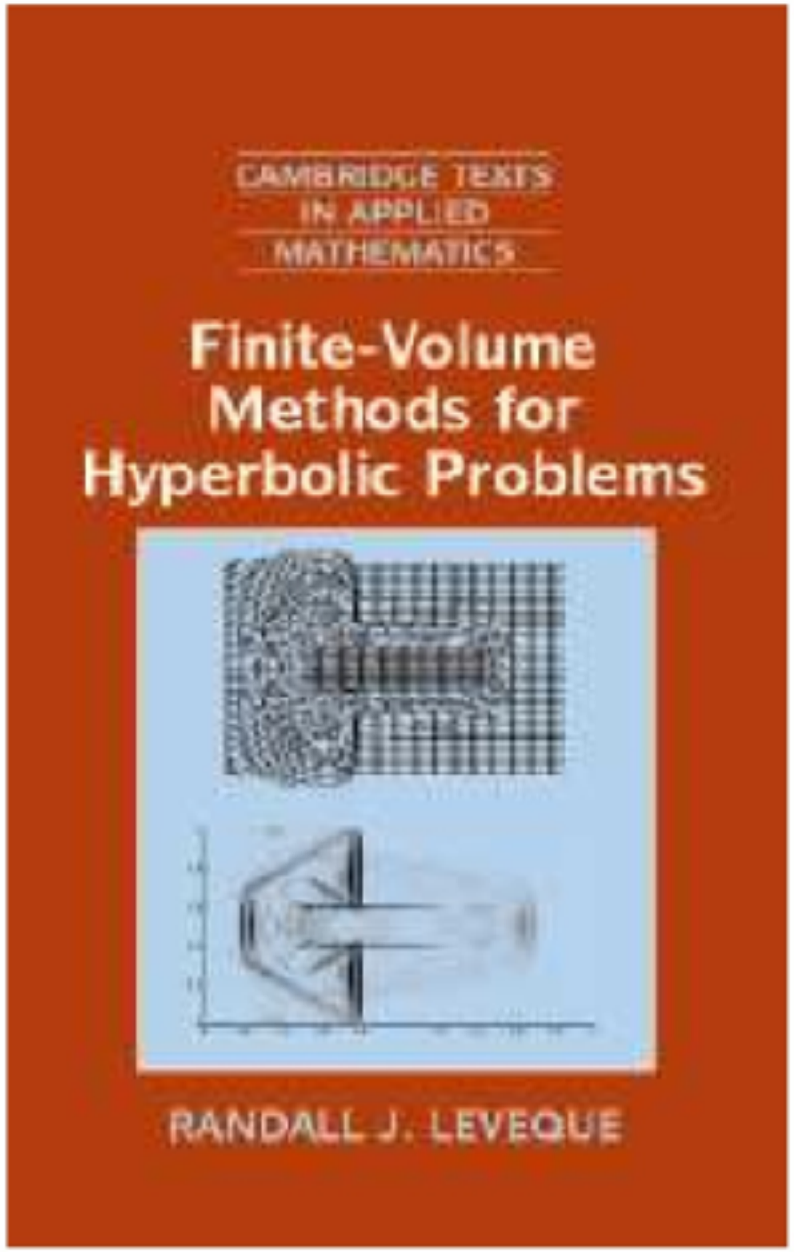
- In the ART code the left and right states are constructed by linear extrapolation (the change of variables is represented by piecewise linear function) and exact Riemann solver is used

- higher order reconstruction is possible (e.g., piecewise parabolic method – PPM)

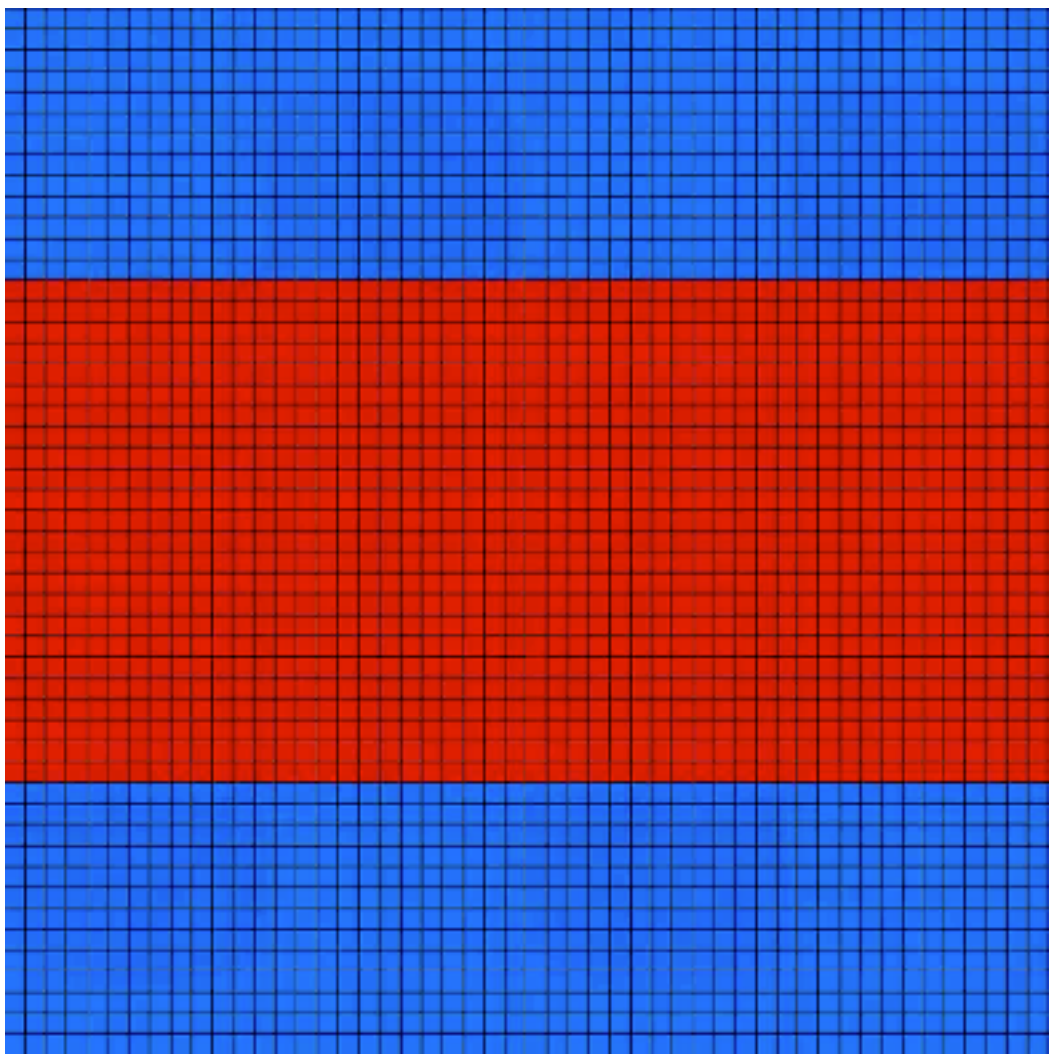
- however, advatantage of higher order with AMR is dubious (e.g. Zhang & McFadyen 2006)

good books on Eulerian gasdynamics methods:





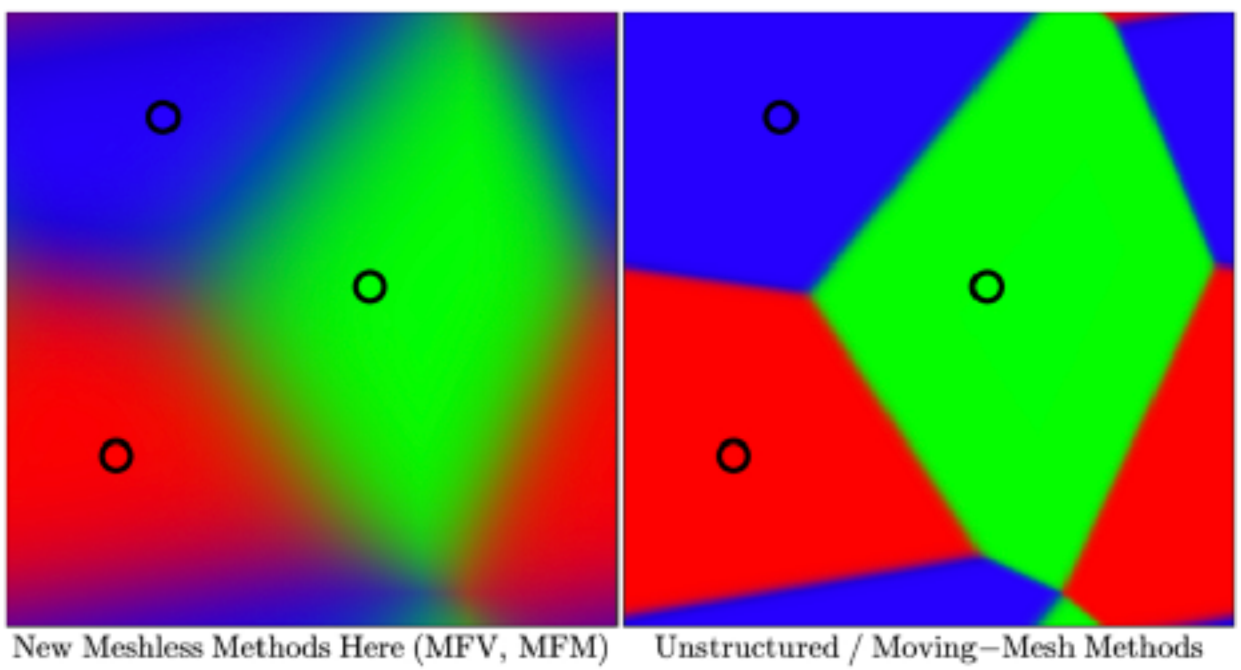
Other discretization methods in computational astrophysics



Springel et al. 2010

- AREPO: a fully dynamic unstructured (Voronoi) mesh (moving mesh)

Other discretization methods in computational astrophysics



- GIZMO: Meshless Methods, using Weighting functions W

Hopkins (2015)

Three take-home messages

- Simulations are numerical experiments (machines) for testing theory (physical models)
- zoom-in simulations of galaxy formation have the highest resolution and include the most accurate models of gas physics
- There is a diversity of techniques for solving the equations of gasdynamics

THANKS

Second Tutorial Section

List of projects

- 1. Accretion rate onto halos and onto galaxies: DM, gas, stars
- 2. Interaction of cold flows and Disk.
- 3. Angular momentum: in cold flows vs disk
- 4. Basic Structure of galaxies: Density profiles of gas, stars, DM. f_b?
- 5. Kinematics of gas: disk rotation curve, velocity dispersion
- 6. Kinematics of stars: bulge/disk decomposition
- 7. Gas outflows