Galaxy Formation and Evolution

Lecture 3:
Galaxy formation in theory

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Lecture 3: learning objectives

- Understanding and knowledge of the main models for galaxy formation and evolution

- Appreciation of the differences between the semi-analytic and fully hydrodynamic approaches to modelling galaxy evolution

- Knowledge of the main physical mechanisms involved in forming galaxies: gravitational accretion, heating, cooling, star formation and feedback

Two main theories of galaxy evolution

- Monolithic collapse. A large gas cloud collapses, and the stars formed as it collapses make up the galaxy halo. Then, as the cloud collapses further conserving angular momentum, the galaxy disk is formed (e.g. Eggen, Sandage & Lynden-Bell 1962). All the galaxy mass is present from the outset in a single unit.

- Hierarchical galaxy formation/evolution. Large galaxies form through successive mergers of smaller galaxies (e.g. White & Rees 1978). This ties in well with our understanding of the formation of structure in a universe with a substantial cold dark matter (CDM) content, and is currently the most widely accepted model of galaxy formation and evolution.

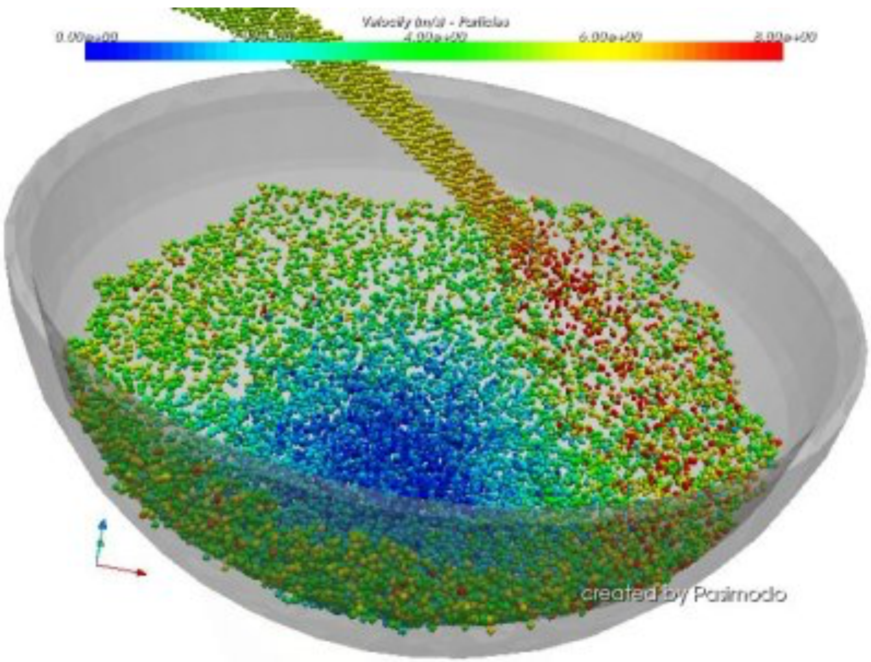
Approaches to modelling galaxy evolution

- Fully hydrodynamic approach. Using numerical simulations to track the detailed evolution of dark matter, stars and gas in mergers, making use of the Smooth Particle Hydrodynamic (SPH) technique. *Useful for predicting the detailed kinematics and structures of galaxies forming in dark matter haloes.*

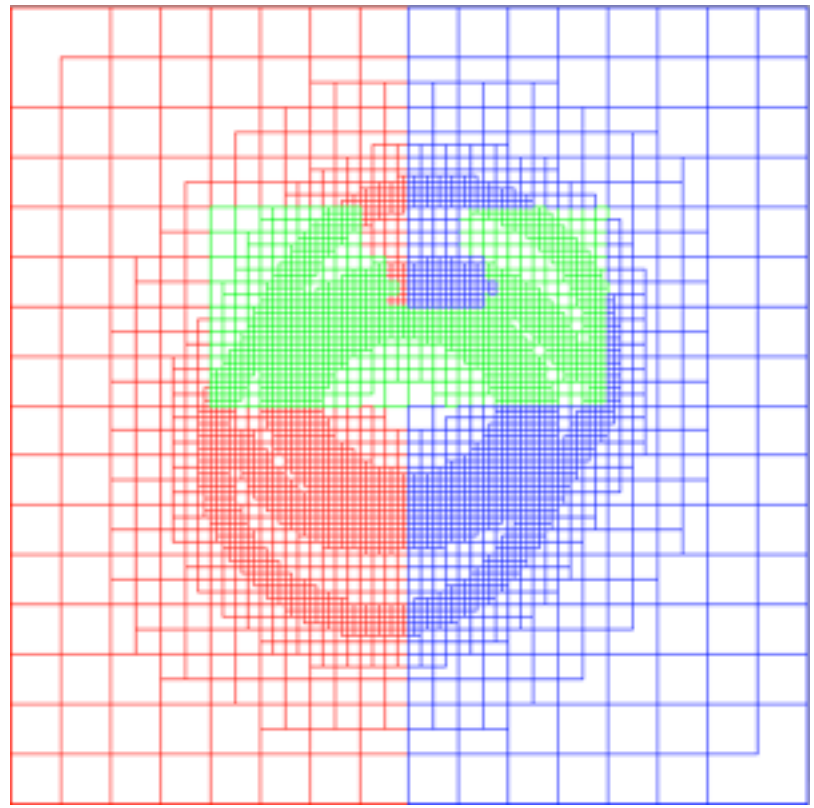
- Semi-analytic approach. Using N-body simulations to track the mergers of dark matter haloes over cosmic time (the "merger tree"). Then using analytic expressions to calculate the cooling of gas, star formation, feedback effects, size and angular momentum of galaxies forming in DM haloes at each timestep. *Useful for predicting the statistical properties of populations of galaxies (e.g. galaxy luminosity function, global star formation rate).*

Lagrangian vs. Eularian

Lagrangian (Smooth Particle Hydro)



Eularian (Mesh)



Fully hydrodynamical approach

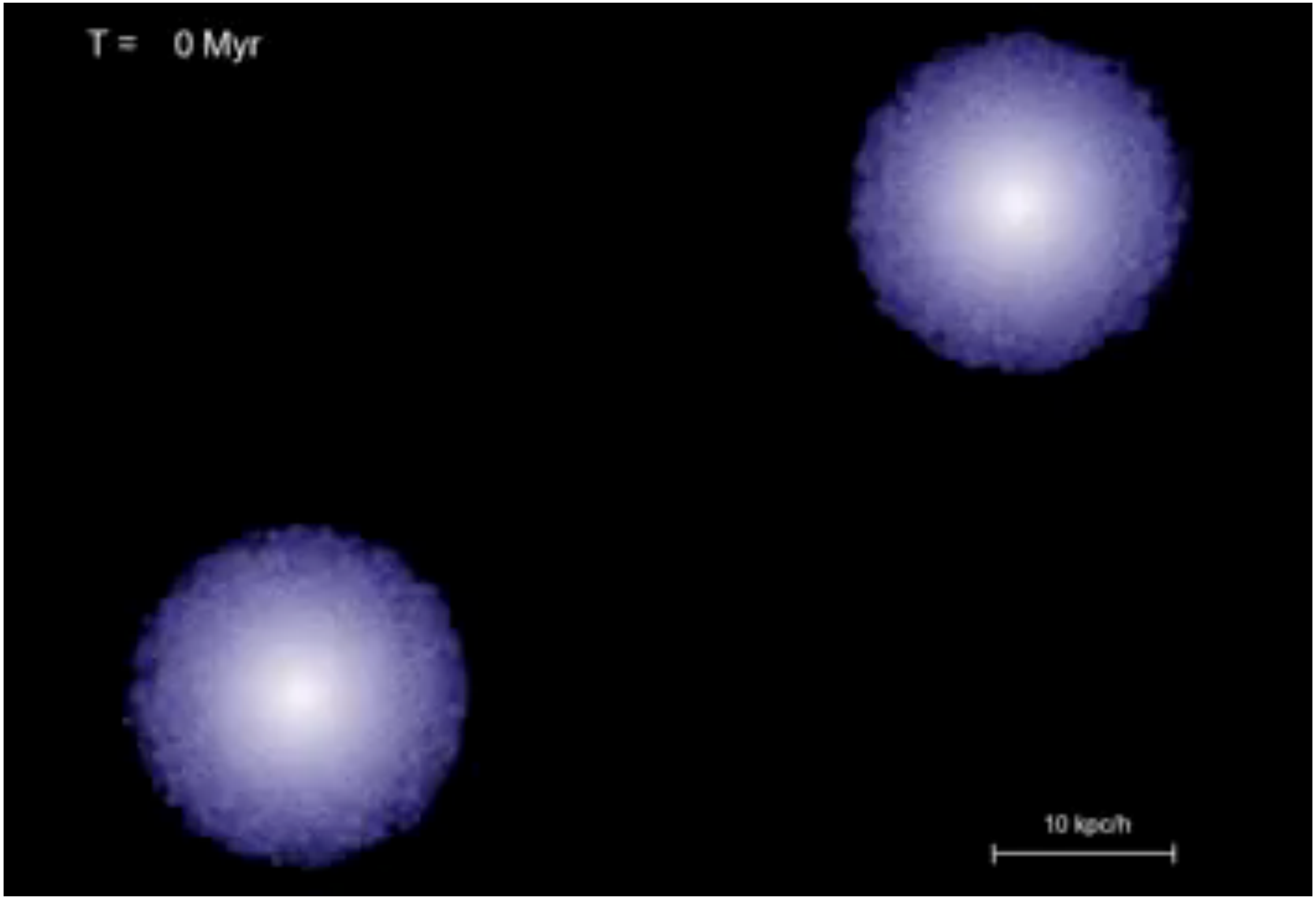
- Dark matter and stars are *collisionless* and relatively easy to treat using standard N-body techniques.
- The gas, is *highly dissipational* and must be treated separately using a hydrodynamical approach.
- In SPH the physical conditions of the gas (T, P etc.) are computed for each gas element at each timestep, and compared with the spatially smoothed conditions in the surrounding gas elements.
- Taking full account of the gravity of all the mass components, the hydrodynamic equations of motion are solved and the subsequent motion each gas element predicted.
- The amount of cooling, heating, star formation and feedback for each element is also calculated at each timestep for each element using analytic expressions.

Processes to take into account

- Initial conditions, mass distribution and kinematics of all components in dark matter halo.
- Gravitational forces due to all mass components
- Gas hydrodynamics
- Physics of gas heating/cooling (sub-element)
- Star formation (sub-element)
- Feedback from supernovae and AGN (sub-element)

Hydrodynamic approach example

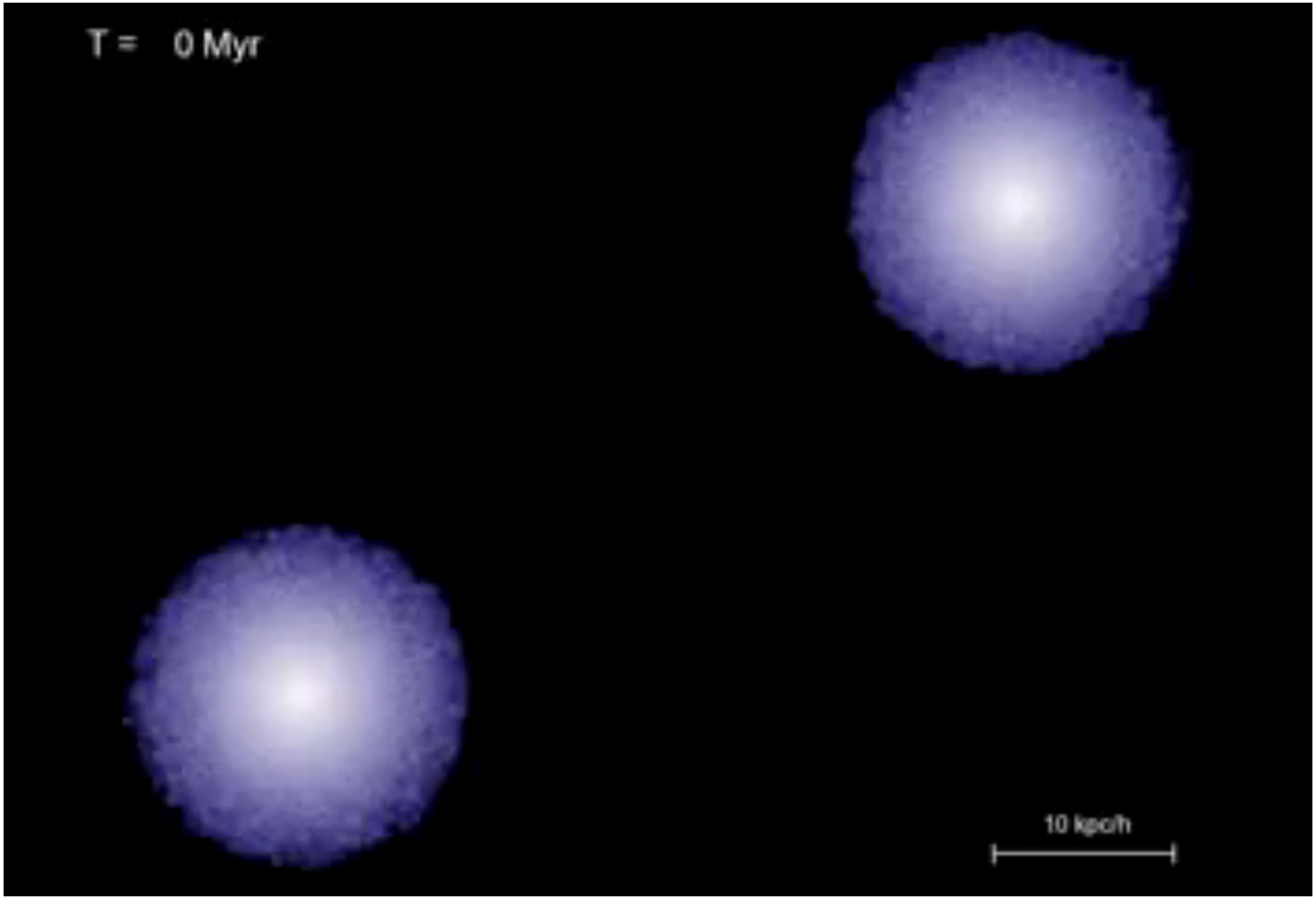
The merger of two spiral galaxies



di Matteo et al. (2005)

Hydrodynamic approach example

The merger of two spiral galaxies



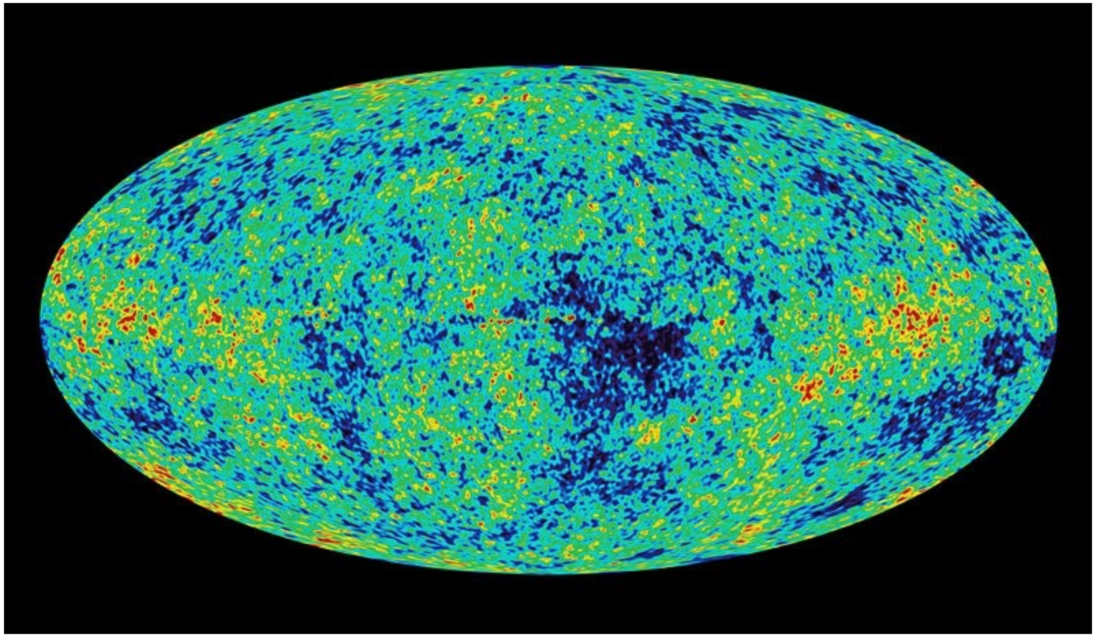
di Matteo et al. (2005)

Semi-analytic models: ingredients

- Initial spectrum of primordial density fluctuations (usually assumed Guassian).
- Merger tree from N-body simulation showing evolution of dark matter haloes as they evolve hierarchically.
- Prescription for the cooling of the gas falling ino the merged haloes.
- Prescription for star formation (e.g. Schmidt-Kennicutt law).
- Prescription for feedback processes (e.g. SN, AGN feedback).
- Prescription for determining final size and angular momentum of the forming galaxy.

Semi-analytic models – Step 1

Assume spectrum of primordial density fluctuations



WMAP image of the microwave background showing large-scale fluctuations

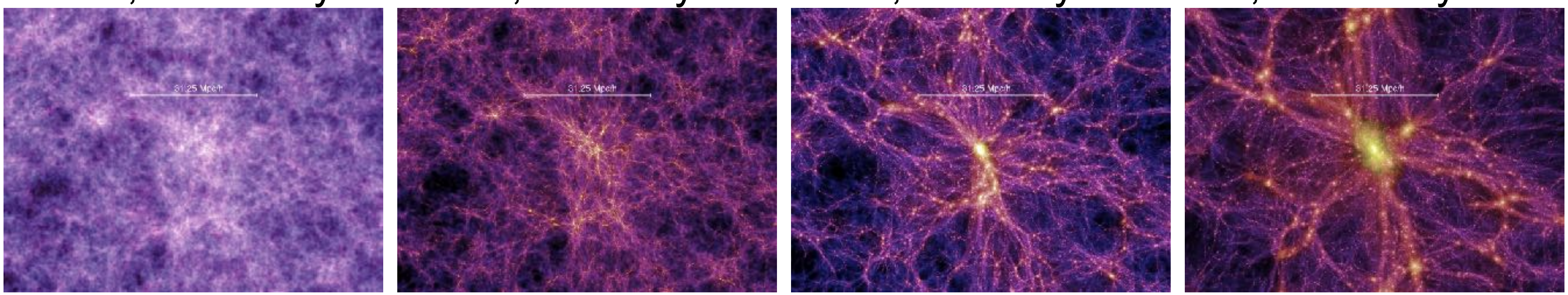
Probability of density fluctuation δ assumed to be given by Gaussian field:

$$p(\delta) = \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left(-\frac{\delta^2}{2\sigma^2}\right)$$

Semi-analytic models – Step 2

Generate merger tree using N-body simulations of merging DM haloes

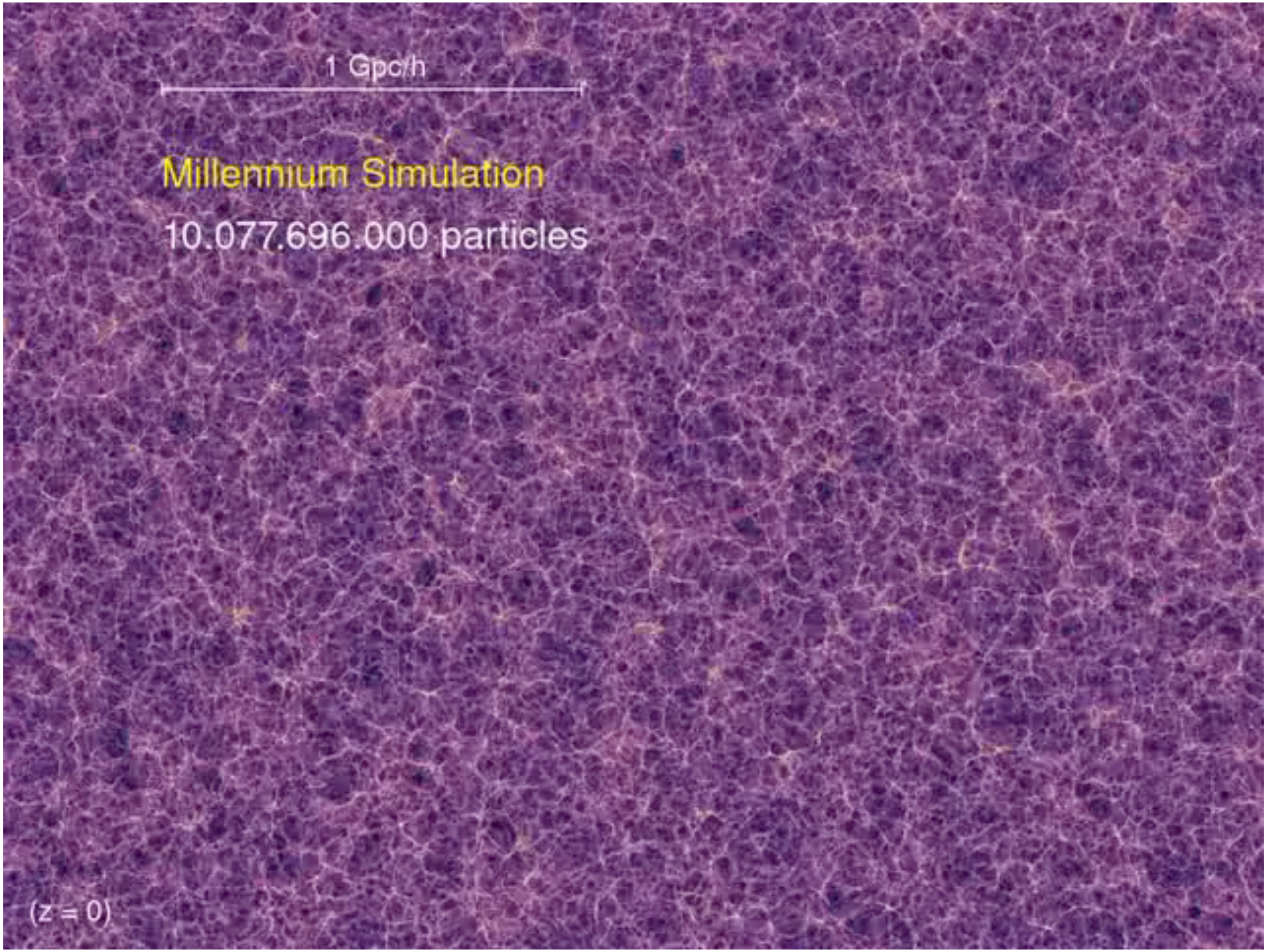
z=18.7, t=0.21 Gyr z=5.7, t=1.0 Gyr z=1.4, t=4.7 Gyr z=0, t=13.6 Gyr



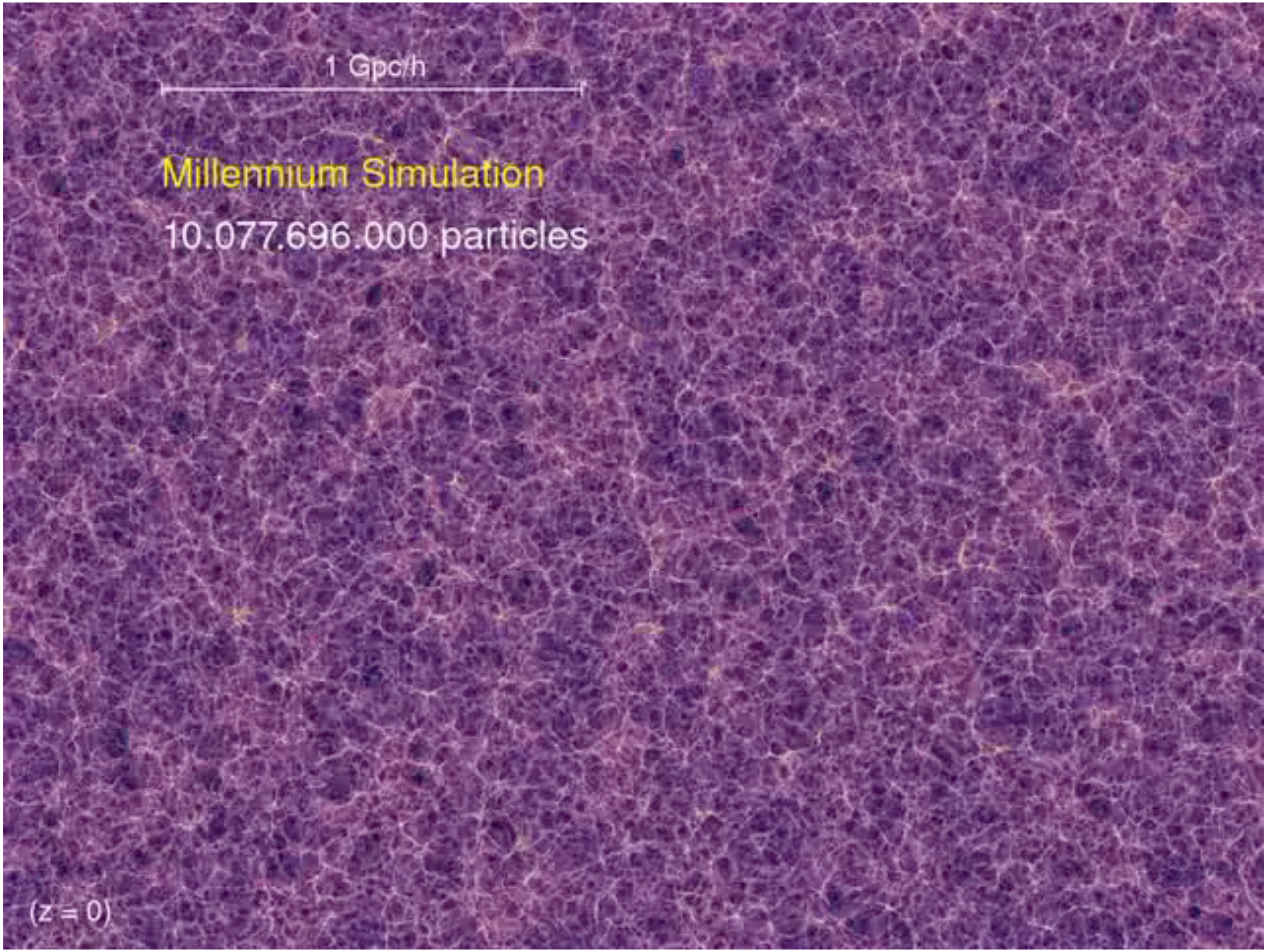
30 Mpc

Millennium Project simulation of the growth of large-scale structure in dark matter haloes via mergers as a function of cosmic time/redshift

Millennium Project Simulation

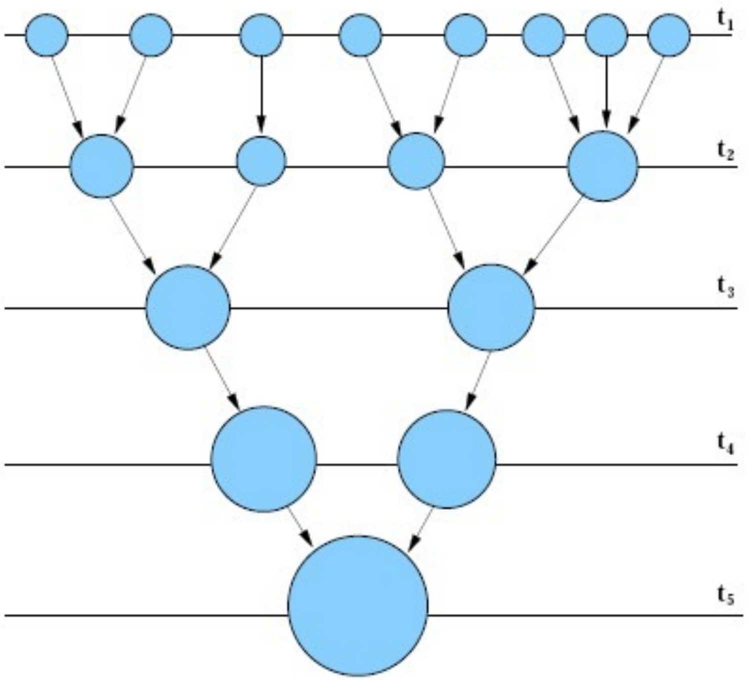


Millennium Project Simulation



Semi-analytic models – Step 2

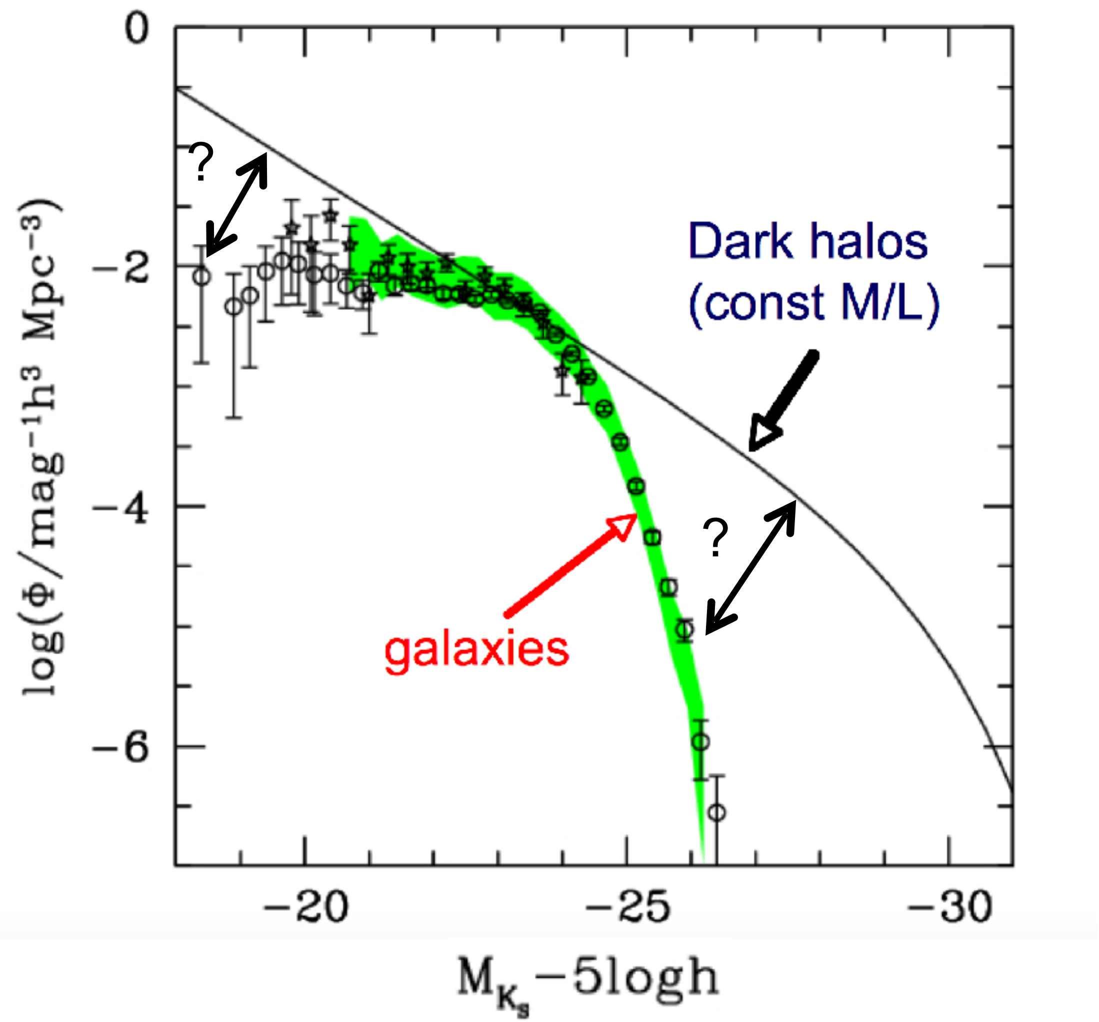
Generate merger tree using N-body simulations of merging DM haloes



Merger tree generated using N-body simulation, showing the growth of dark matter haloes via mergers

Dark matter halos to galaxies

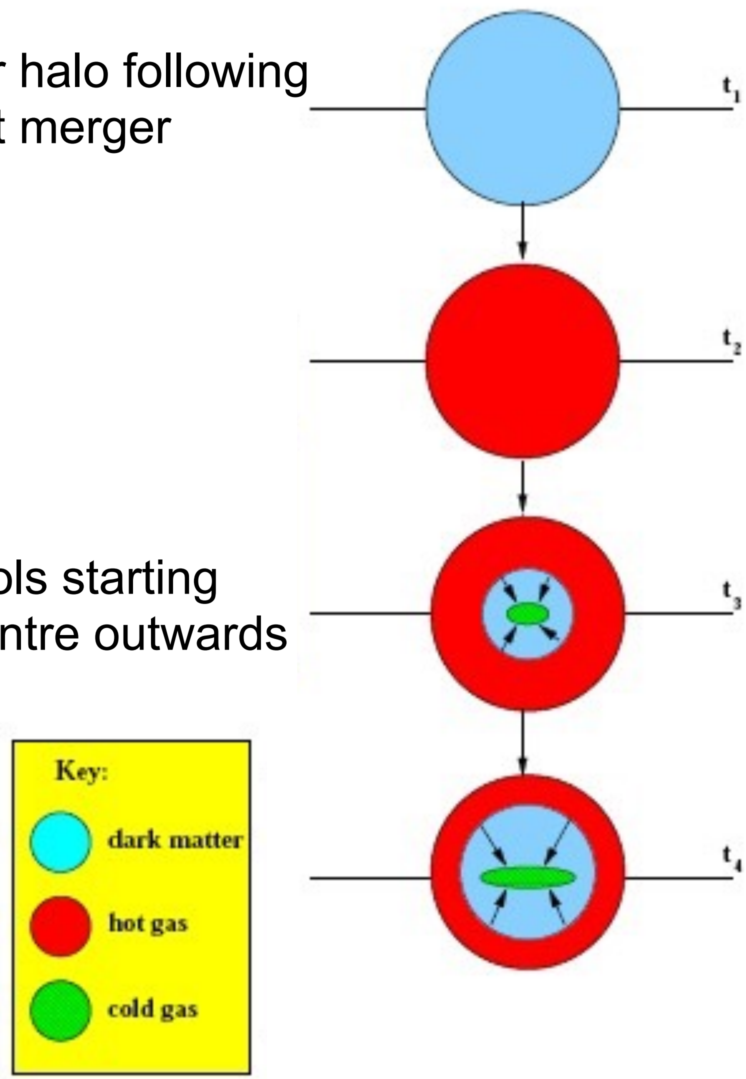
How does it happen?



Semi-analytic models – Step 3

Cooling of gas within DM haloes

1. Dark matter halo following most recent merger



2. Gas falling into DM halo is shocked and heated up to virial temperature:

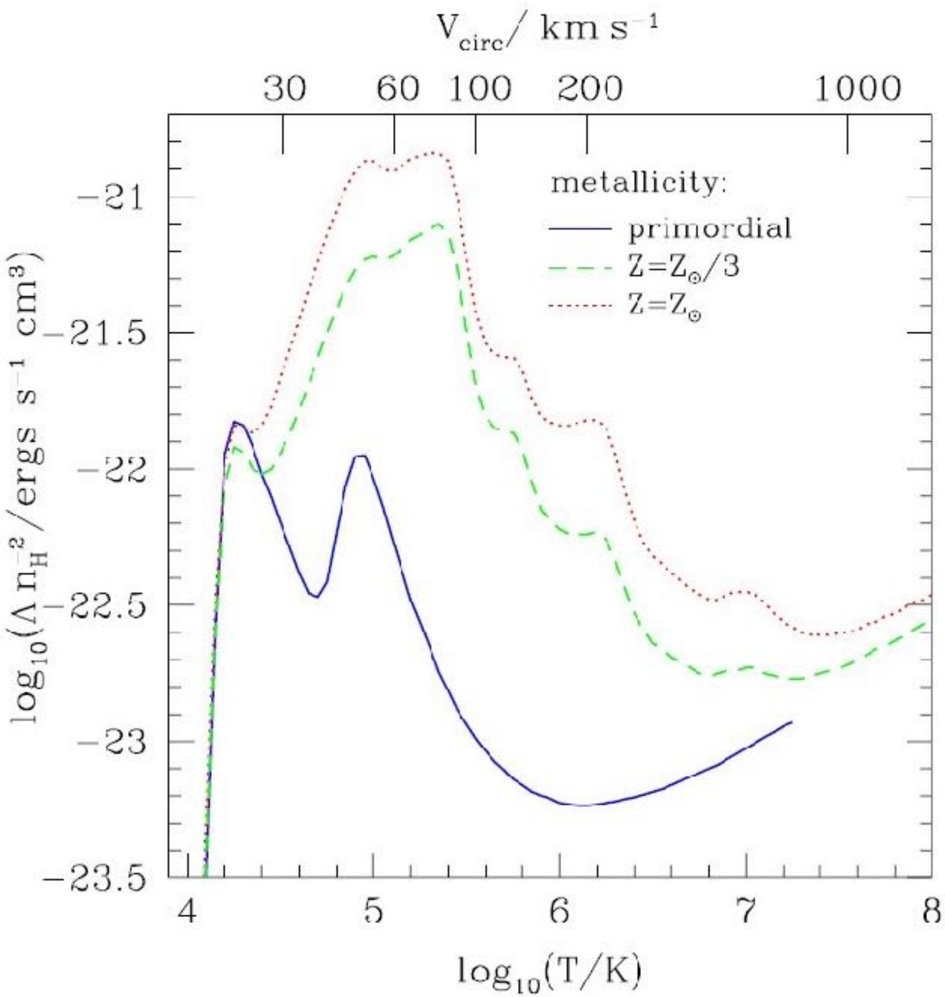
$$T_{vir} = \frac{1}{2}\frac{\mu m_H}{k}\frac{GM_{tot}}{r_{vir}}$$

3. Hot gas cools starting from the centre outwards

4. A disk will be formed at the centre of halo if angular momentum conserved during collapse

Semi-analytic models – Step 3

Cooling curves

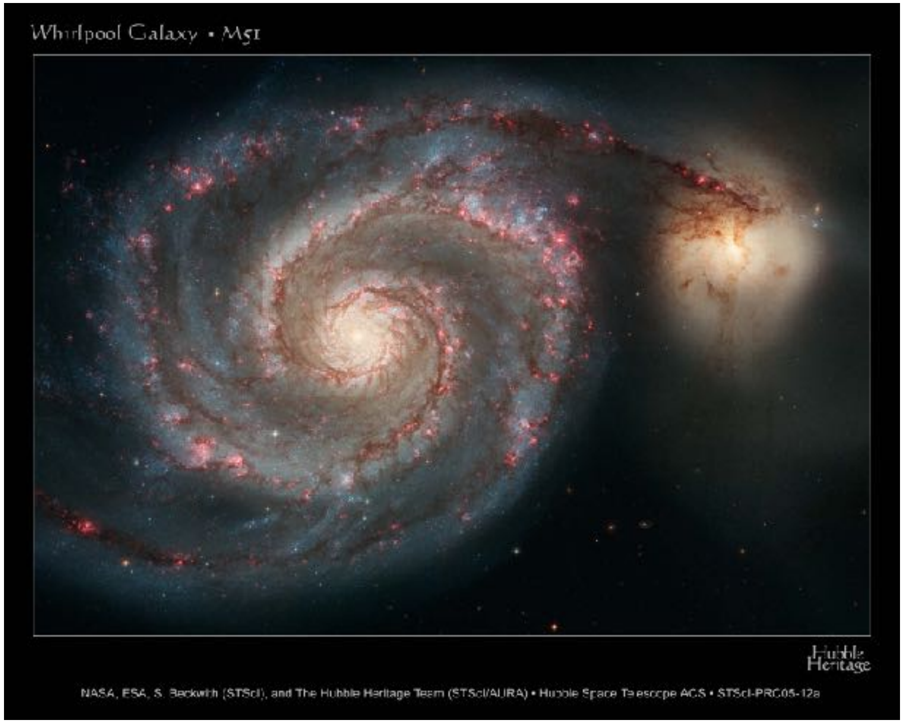


The cooling curve depends strongly on detailed physics, and varies strongly with temperature:

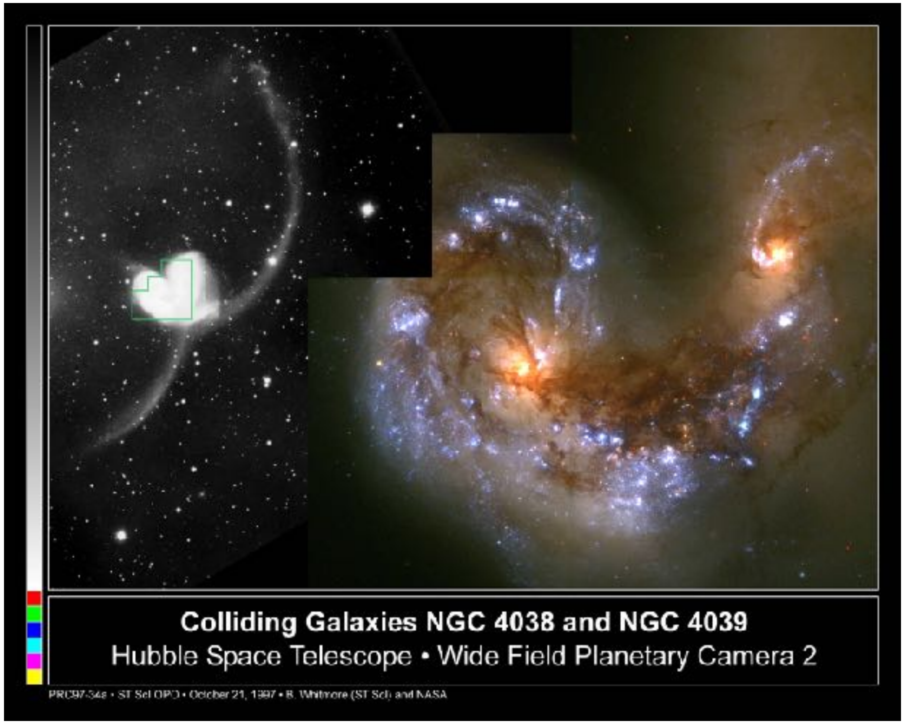
- at high temperatures it's dominated by thermal Bremsstrahlung;
- at lower temperatures it is dominated by collisional excitation and radiative de-excitation of energy levels in H, He and metal atoms/ions.

The rate of cooling depends strongly on metallicity and hence redshift.

Two modes of star formation in galaxies



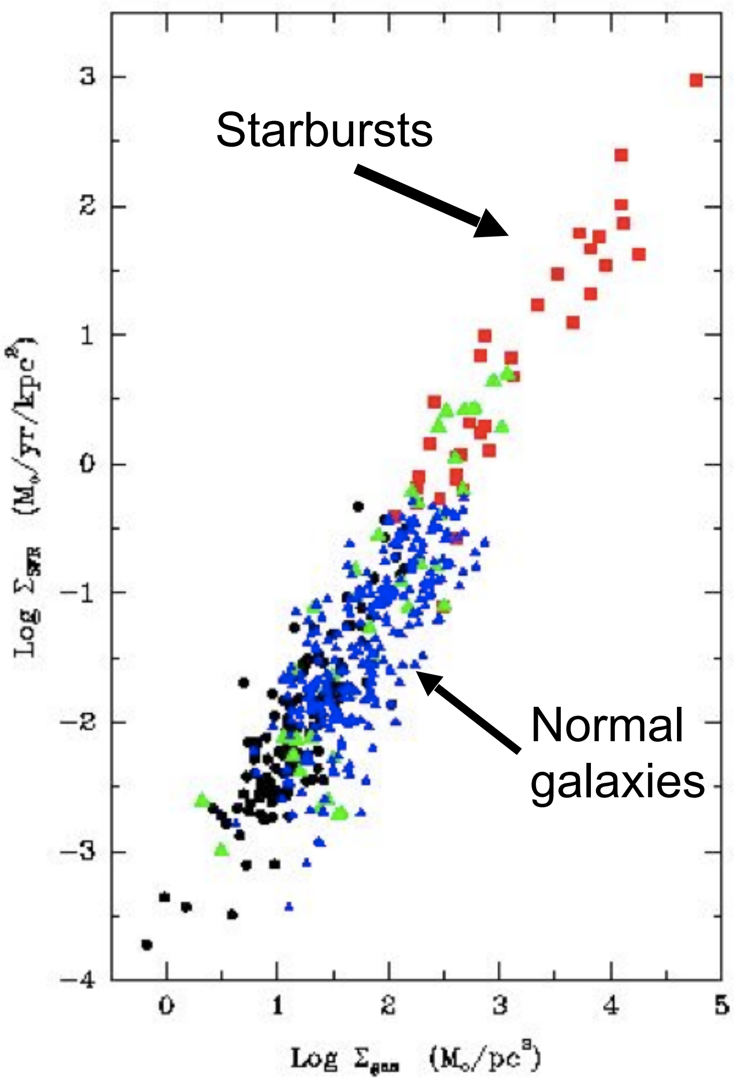
Normal formation of stars
in galaxy disks (secular evolution)



Merger-induced star formation in
galaxy mergers

Semi-analytic models - Step 4

Calculate the rate of formation of stars



In the absence of a complete theory of star formation that encompasses a range of environments, metallicity etc. it is common to use one of the observationally-derived scaling laws. For example:

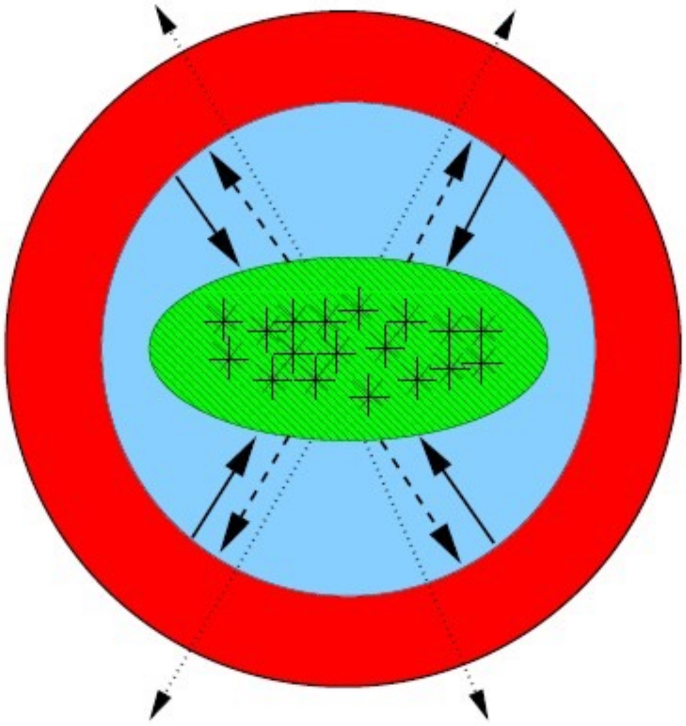
$$\Sigma_{SFR} = (2.5 \pm 0.7) \times \left(\frac{\Sigma_{gas}}{1 M_{sun}\, pc^{-2}} \right)^{1.4 \pm 0.15}$$

Where the Σs correspond to disk - averaged SFR and gas surface densities (e.g. Kennicutt 1998).

The Schmidt-Kennicutt law appears to apply to a wide range of environments from mergers to galaxy disks

Semi-analytic models – Step 5

Take into account heating/feedback processes



Major sources of feedback include supernovae and AGN, which tend to heat and expel gas from the central regions, countering the cooling of gas from the dark matter haloes.

Full hydrodynamical approach

Advantages:

- Can track the *detailed* evolution of gas and star motions, star formation, feedback etc. as galaxies evolve via mergers in dark matter haloes (making “movies”).
- Makes fewer simplifying assumptions than other approaches.

Disadvantages:

- Resolution relatively poor ~20 - 100pc
- Considerable uncertainties about detailed physics, much of which takes place at a sub-element level
- Many free parameters that can be tuned to match observational results

Semi-analytic models

Advantages:

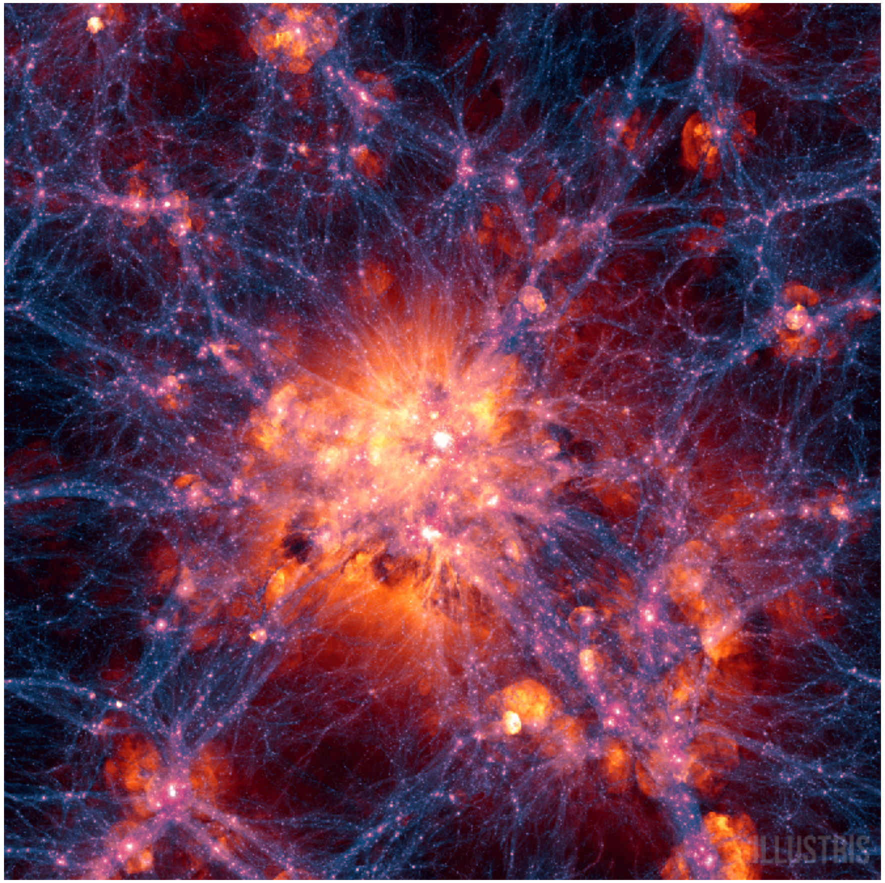
- Good for tracking the statistical properties of galaxy populations as they evolve across cosmic time.

Disadvantages:

- Don’t track in detail the structures and kinematics of individual galaxies (no movies)
- Many free parameters that can be “tuned” to match observed properties
- Uncertain physics for some of the steps

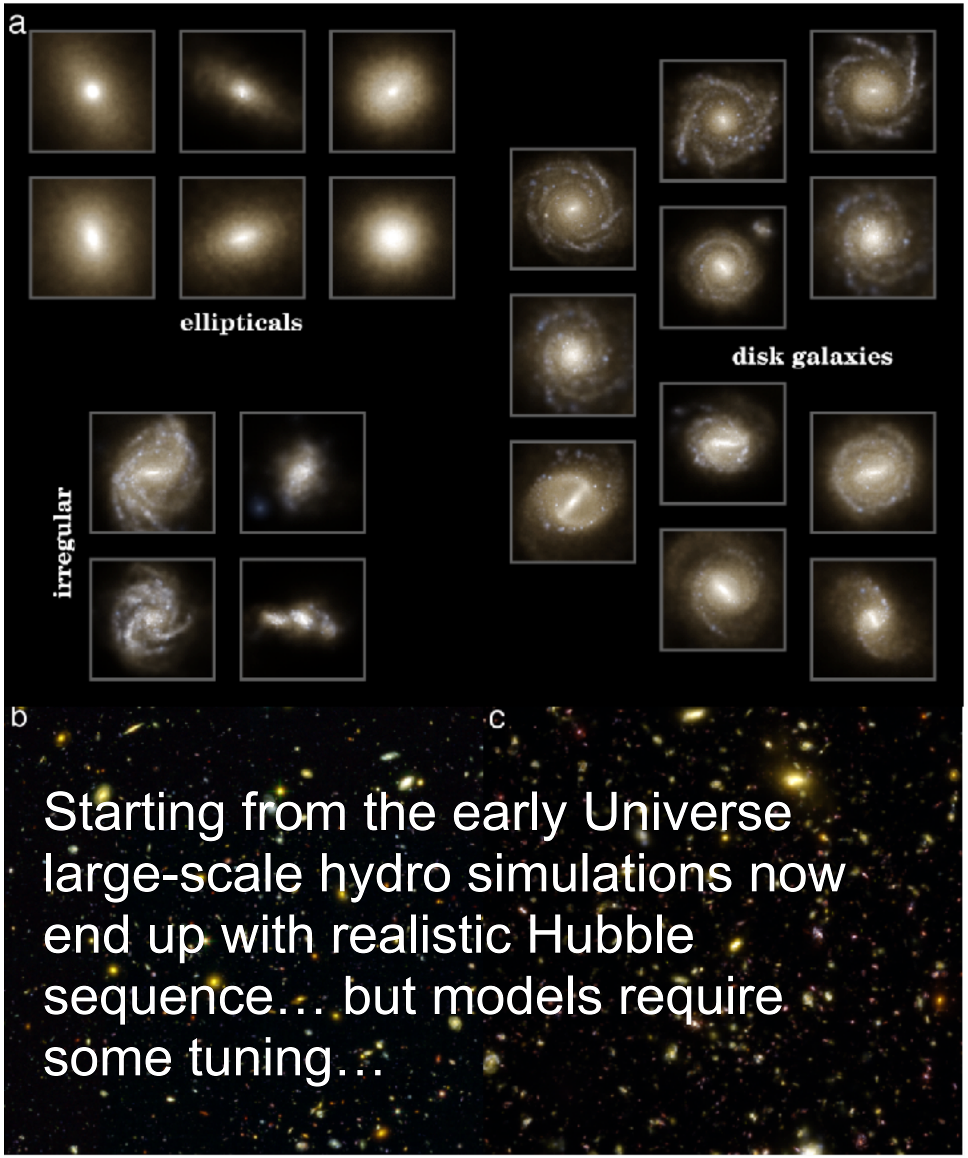
The state of the art:

Large-scale hydrodynamic simulations



Illustris simulation: 12 billion particles; $(107\ \text{Mpc})^3$; 50pc resolution (Vogelsberger et al. 2014)

Illustris simulations results



Starting from the early Universe large-scale hydro simulations now end up with realistic Hubble sequence… but models require some tuning…

Vogelsberger et al. (2014)

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