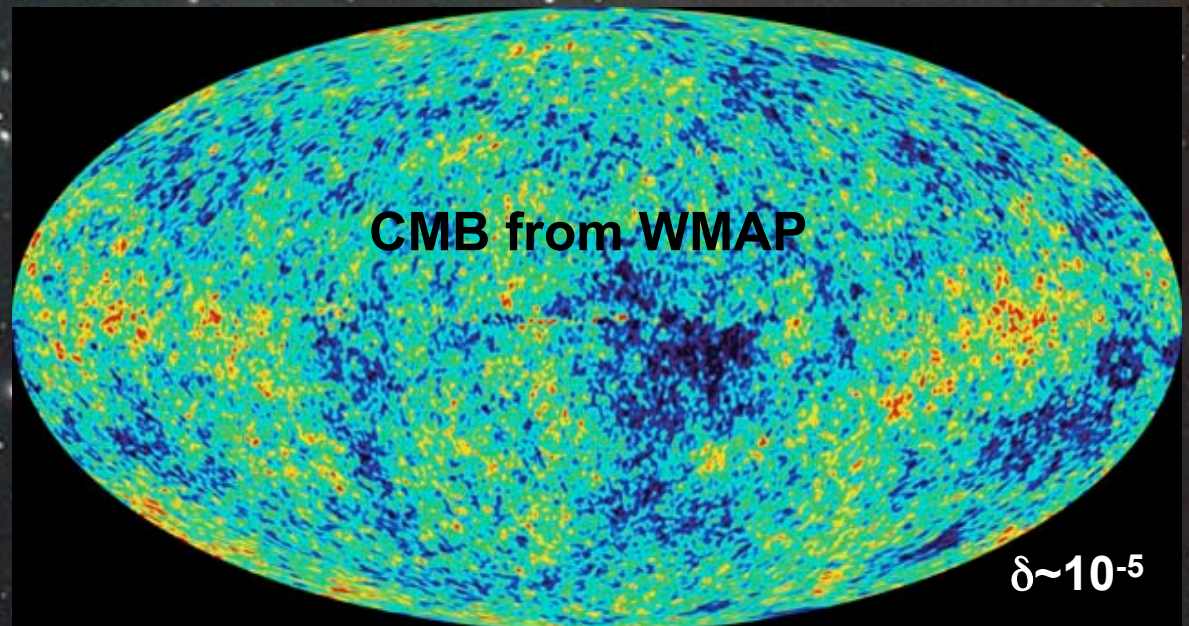


Lecture 3 - Formation of Galaxies

What processes lead from the tiny fluctuations which we see on the surface of last scattering, to the diverse galaxies we see in the Universe today?

The Hydra cluster



Lecture 3 - Formation of Galaxies

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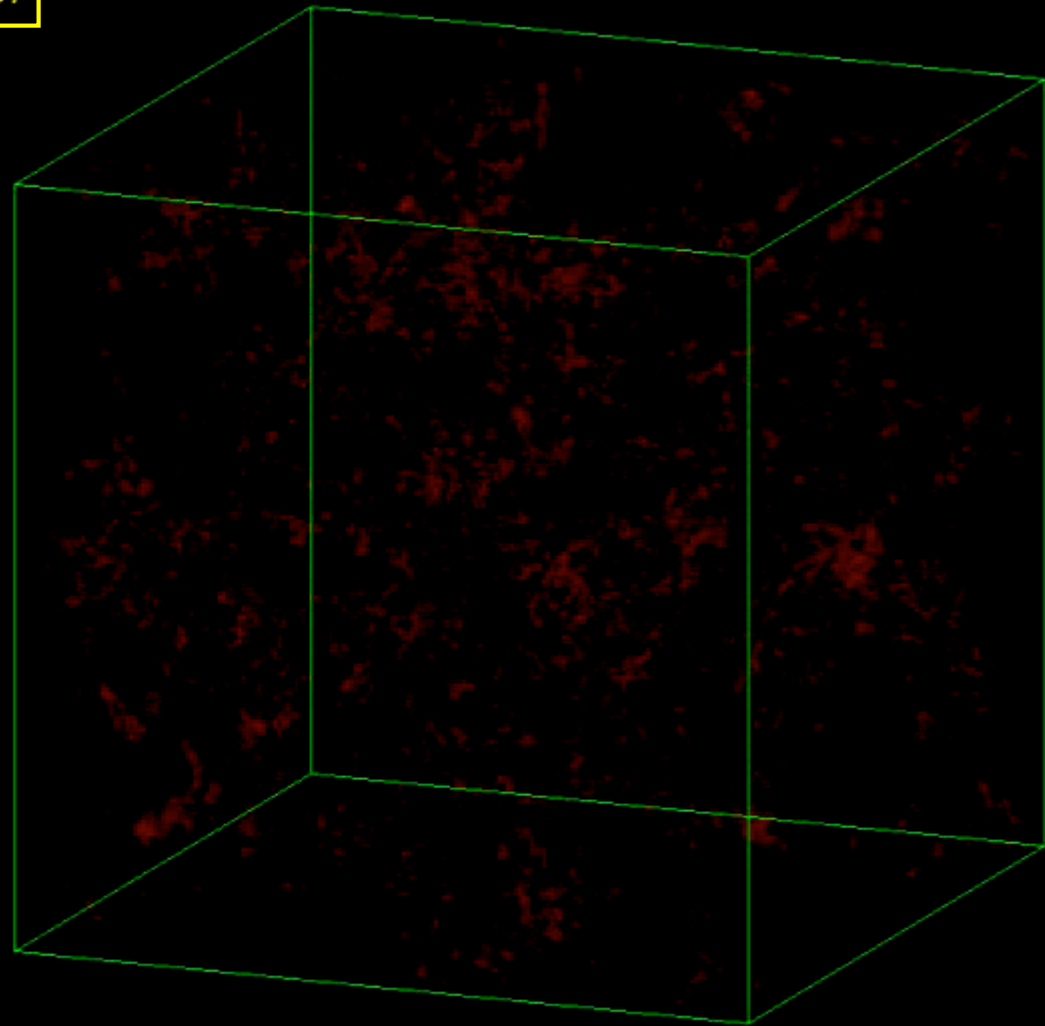
- Growth of structure in the expanding Universe
- Collapse and virialization
- Pressure and the Jeans mass
- Baryon cooling
- Models of galaxy formation
- Some observational tests

Cosmological simulations

Redshift →

15.67

Cosmological simulations can trace the development of dark matter structures from primordial fluctuations in a given cosmology (here Λ CDM).

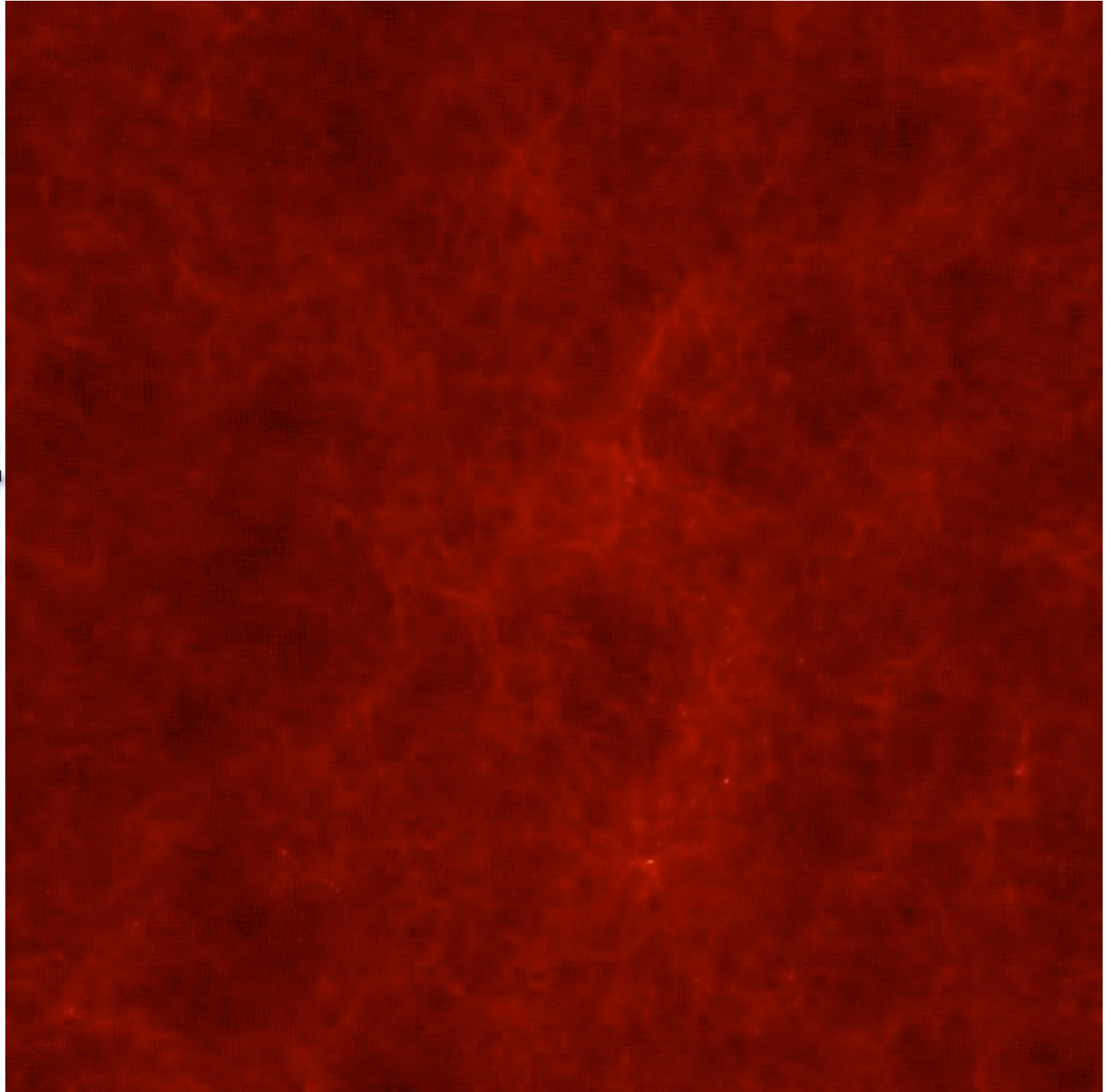


$z=9.00$

(comoving)

65 Mpc

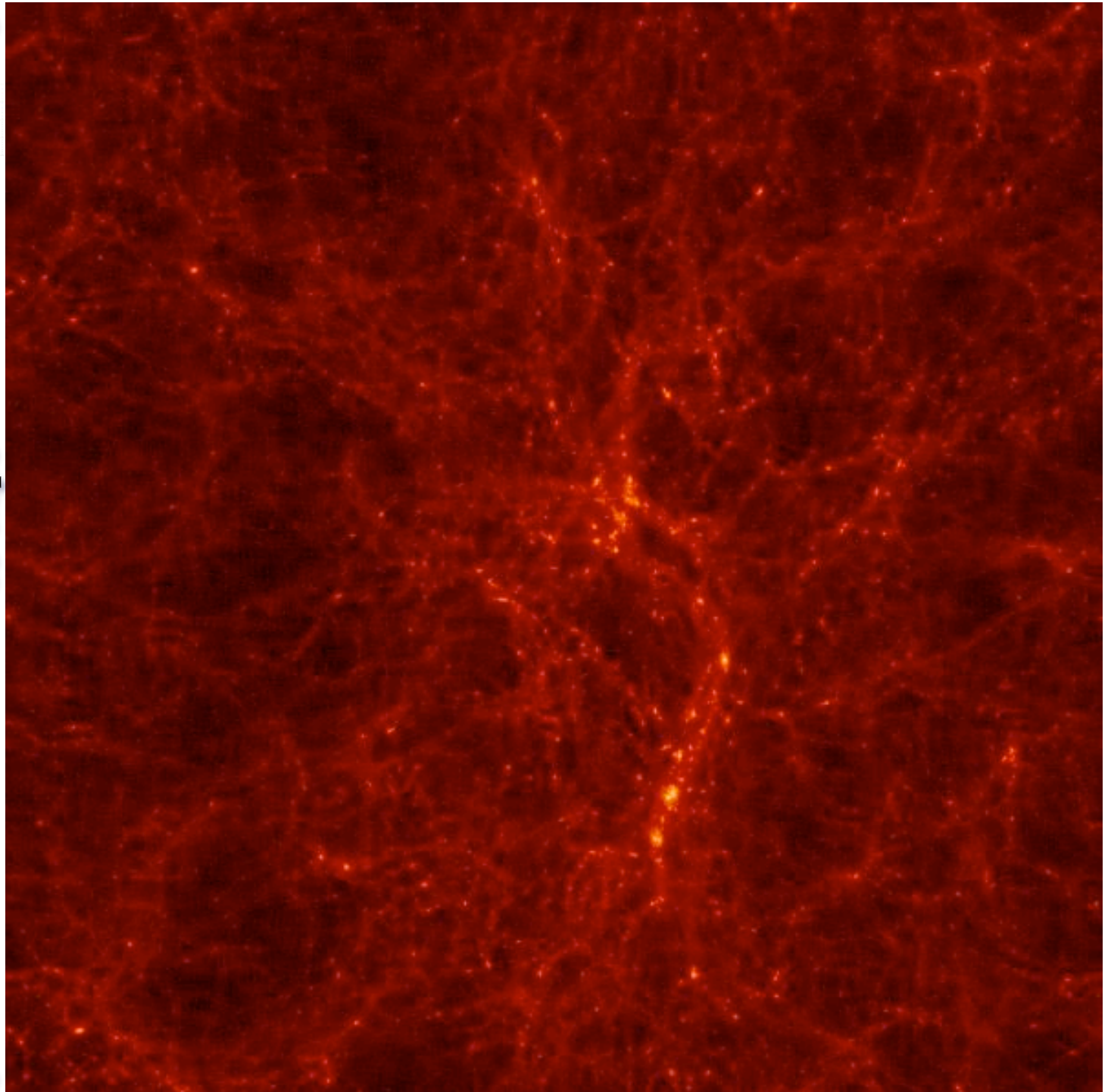
50 million
particle
N-body
simulation



$z=4.00$

65 Mpc

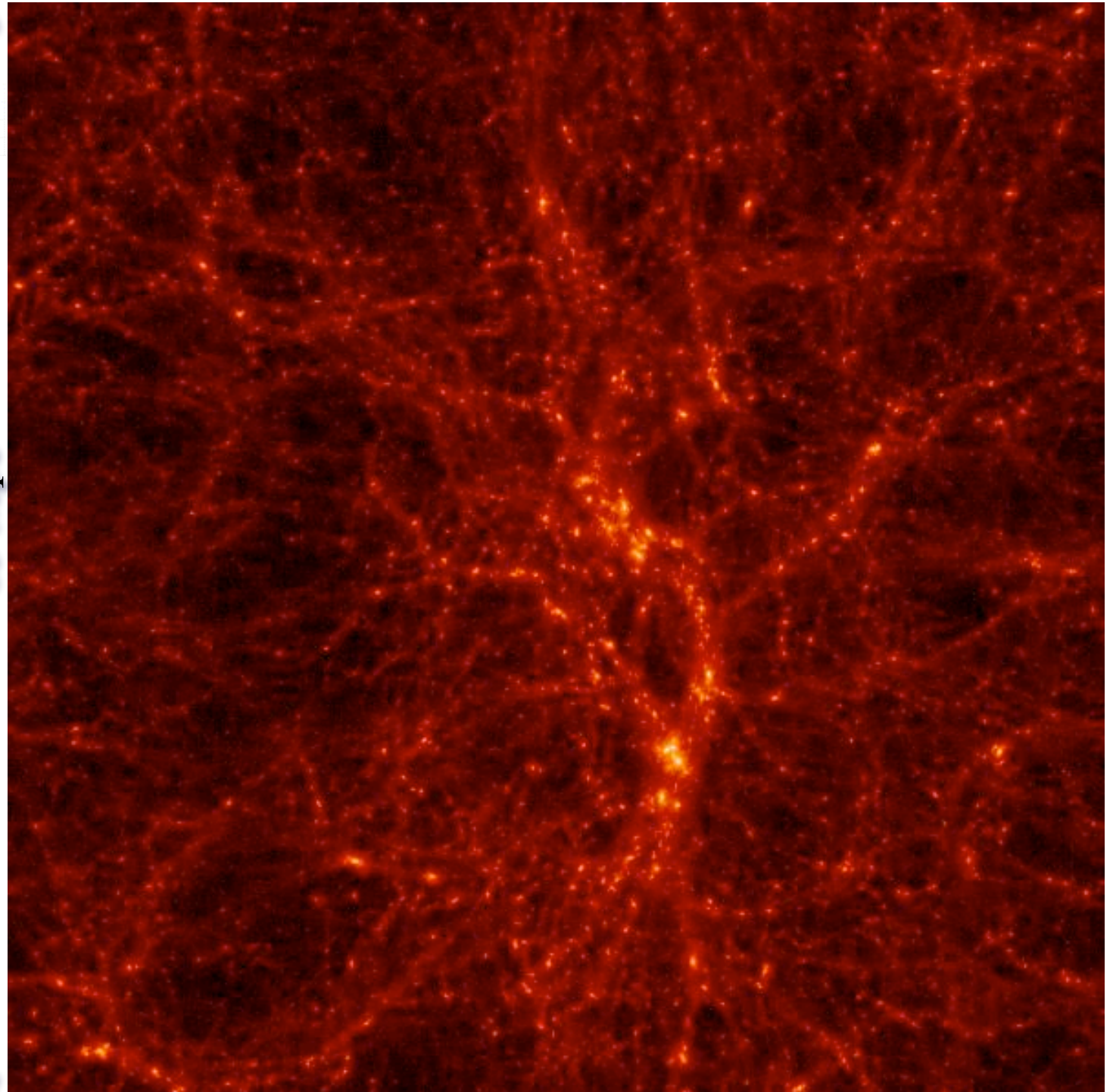
50 million
particle
N-body
simulation



$z=2.33$

65 Mpc

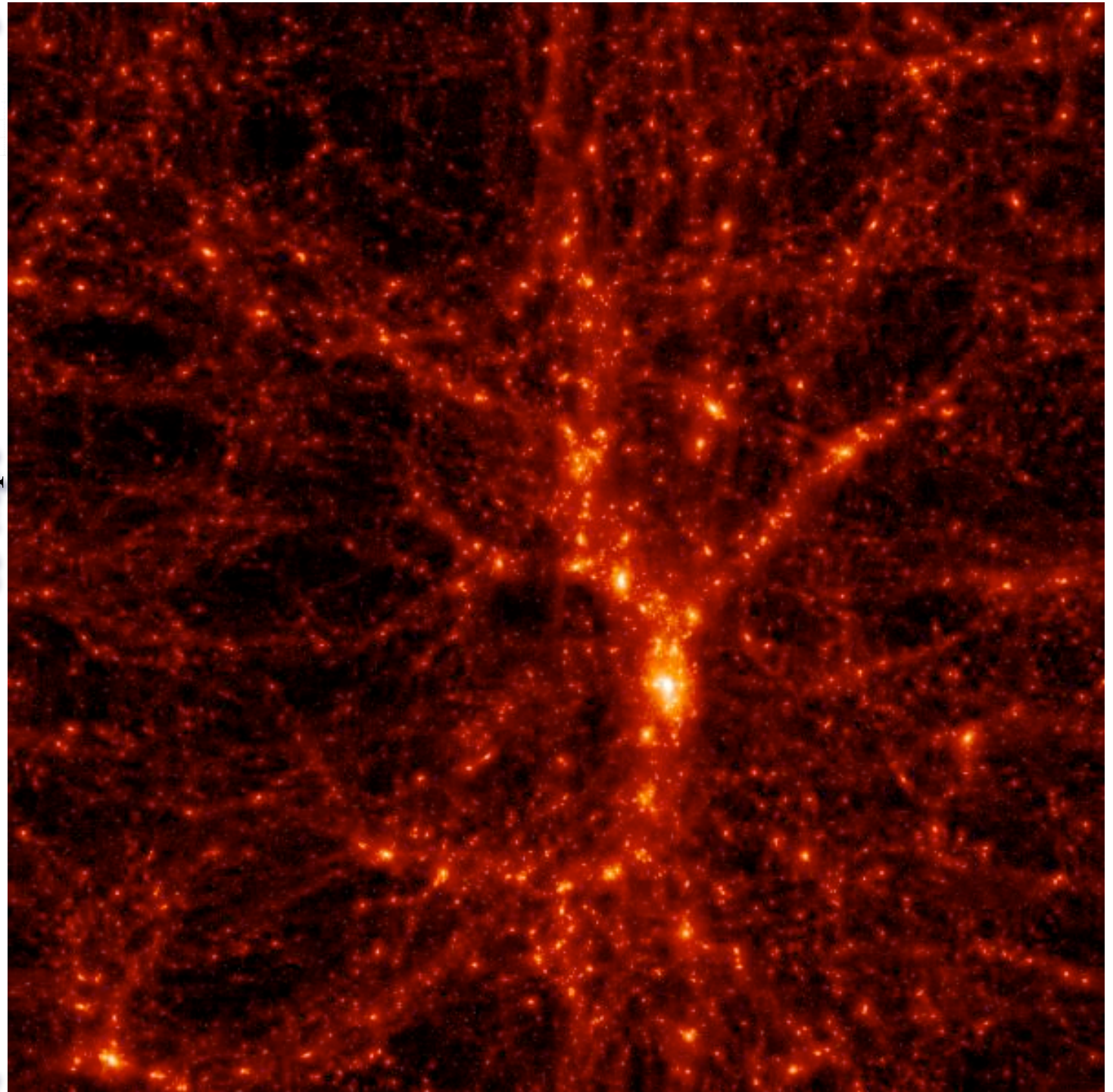
50 million
particle
N-body
simulation



$z=1.00$

65 Mpc

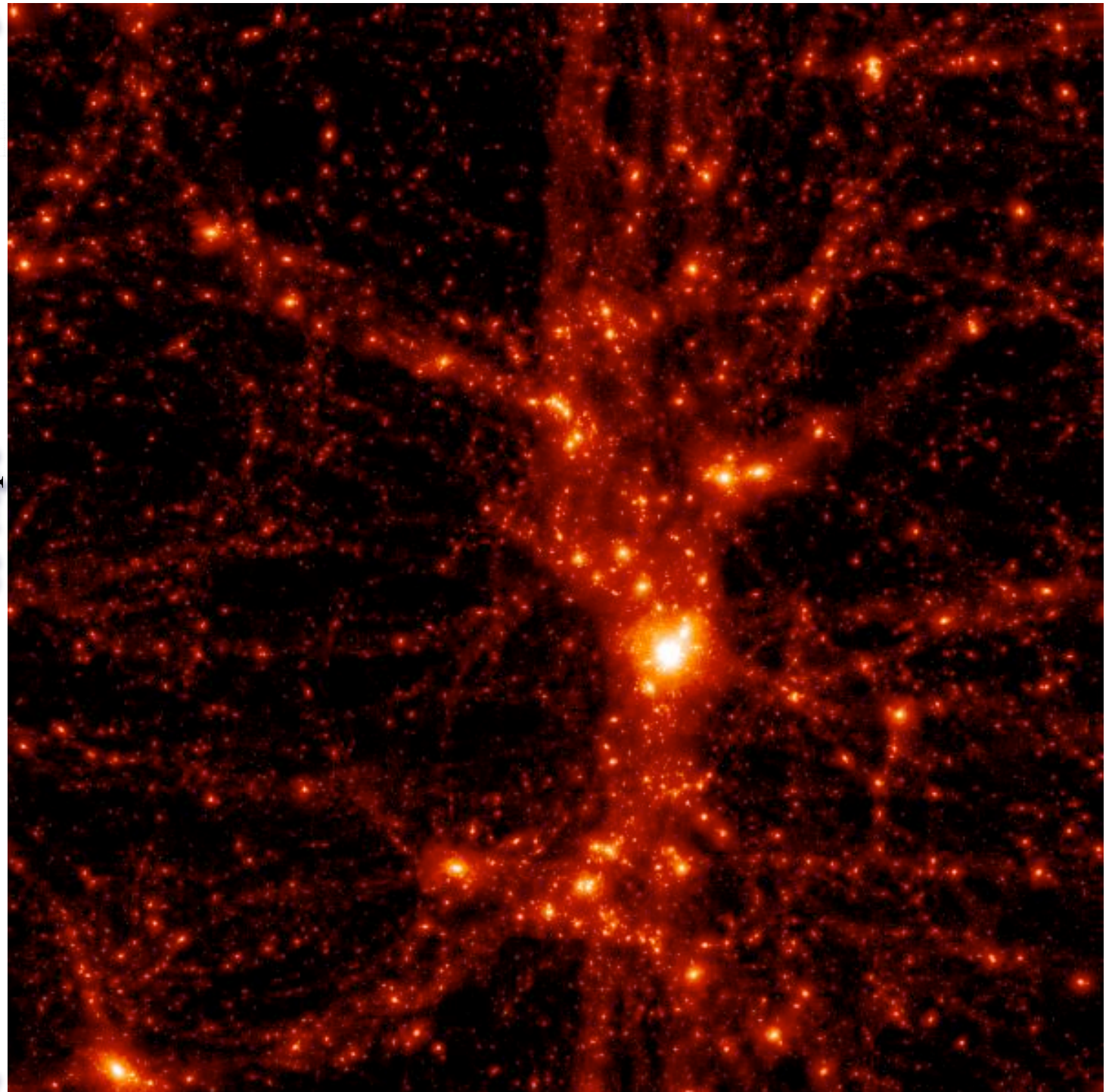
50 million
particle
N-body
simulation



$z=0.00$

65 Mpc

50 million
particle
N-body
simulation



Evolution of Structure

- Small fluctuations in the mass density are seen in the CMB fluctuations, at a level

$$\delta(x) = \frac{\rho(x) - \bar{\rho}}{\bar{\rho}} \sim 10^{-5}$$

- In a static medium, such density fluctuations grow exponentially due to gravitational instability if they are not opposed by pressure forces. However, in an expanding medium it can be shown that the growth is linear:

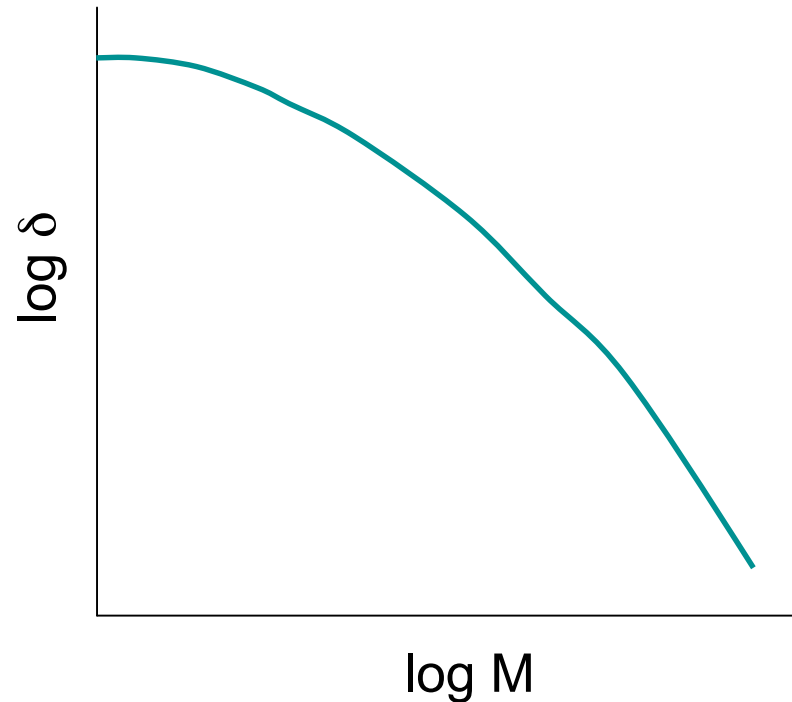
$$\delta(t) \propto a(t) \propto 1/(1+z)$$

- Such density perturbations in the dark matter (which is pressureless, since d.m. particles interact only via gravity) grow until $\delta \sim 1$, and the evolution becomes non-linear.

Evolution of Structure

Since density perturbations grow linearly, the first objects to go non-linear (i.e. to reach $\delta \sim 1$) will be those which had highest initial amplitudes. Whether this is high or low mass objects, is determined by the *spectrum of initial fluctuations*.

In practice, cold dark matter models predict that δ will be largest for *low* mass objects. At high masses (corresponding to size scales ~ 1000 Mpc at $z=0$), the spectrum tends to a power law form $\delta \propto M^{-2/3}$, whilst on smaller scales, the spectrum flattens due to the fact that even *cold* dark matter particles can move fast enough to blur out small scale fluctuations in the early Universe.



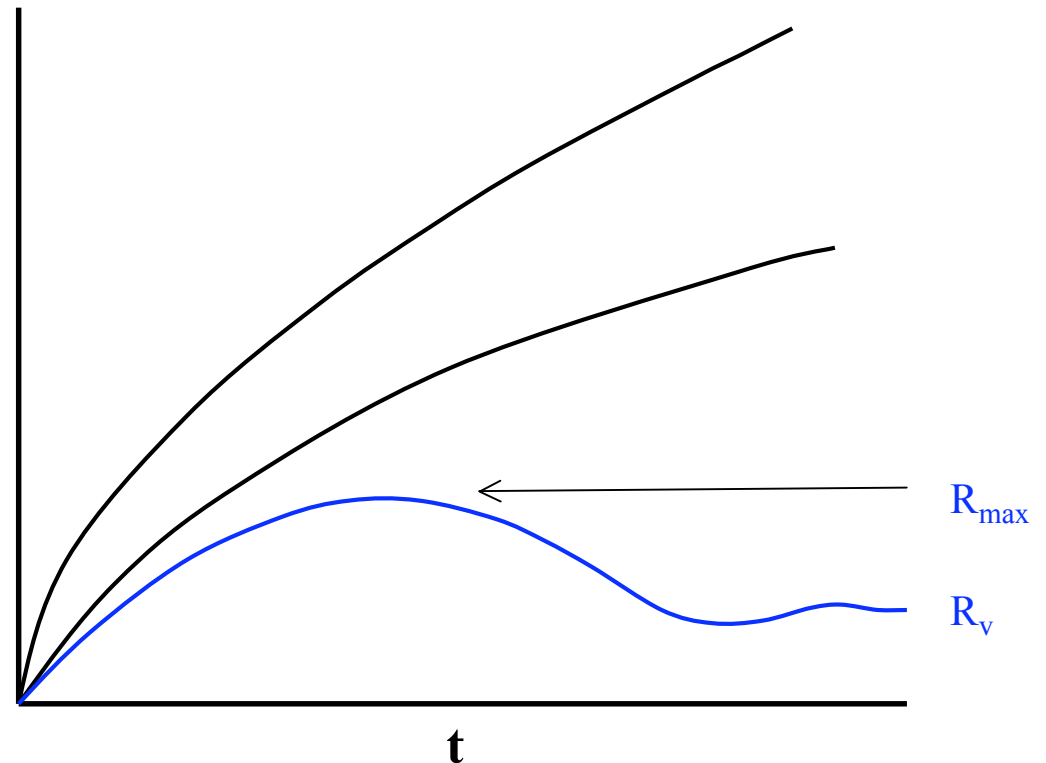
Evolution of Structure

Non-linear density perturbations separate out from the Hubble flow when their mean density exceeds ρ_c - they then collapse and virialize.

Since $E=K+V$ (k.e.+p.e.) is conserved during this collapse, and $2K=-V$ for a virialized system, it follows that $R_v=R_{\max}/2$.

It can be shown that the radius within which the system is virialized (i.e. no net inward or outward particle motions) is that within which the mean density is $\sim 200 \rho_c$, often denoted R_{200} .

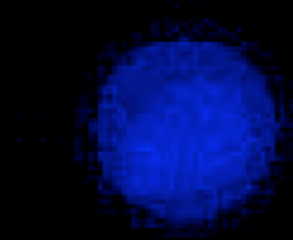
Evolution of radii of concentric shells near a spherical overdensity.



Hierarchical structure formation

The result of these processes is the development of structure through a process of *hierarchical structure formation*, as perturbations on progressively larger scales go non-linear, and smaller virialized masses find themselves incorporated into larger structures through repeated mergers.

$z=49.000$



Response of the baryons - pressure

The above applies to the dark matter, which dominates the mass - however, the behaviour of the baryons is more complex:

- Pressure forces will tend to prevent baryons from collapsing into overdensities with mass less than the Jeans Mass:

$$M_J = \left[\frac{5kT}{G\mu m_H} \right]^{3/2} \left[\frac{3}{4\pi\rho} \right]^{1/2}$$

- Before recombination, baryonic matter is supported by the high radiation pressure, and $M_J > 10^{16} M_\odot$, so that the baryons do not collect in the developing dark matter potentials wells.
- After recombination, radiation pressure no longer supports the baryons, M_J drops abruptly to $\sim 10^6 M_\odot$, and the baryons are able to collapse into galaxy-sizes structures. This accounts for why virialized ($\delta \gg 1$) objects have been able to develop from such low amplitude ($\delta \sim 10^{-5}$) baryon fluctuations since $z \sim 1000$.

Response of the baryons - cooling

In addition to feeling the effect of pressure, baryonic material can also lose energy through radiation, which can have a profound effect on subsequent events. To investigate this, we need to know the temperature of the gas which collects in the forming cosmic structures.

The virial theorem tells us that $2K = -V$, where the kinetic energy of a system of mass M scales as

$$K \sim NkT \sim MkT/m,$$

where N is the total number of particles, of mean mass m .

Since the gravitational potential energy scales as $V \sim -GM^2/R$, it follows from the V.T. that $T \sim M/R$.

We have already seen that a virialised system (whatever its mass) has a mean density which is $\sim 200 \rho_c$, so that systems which virialize at a given epoch should have the same mean density, and hence $M \sim R^3$.

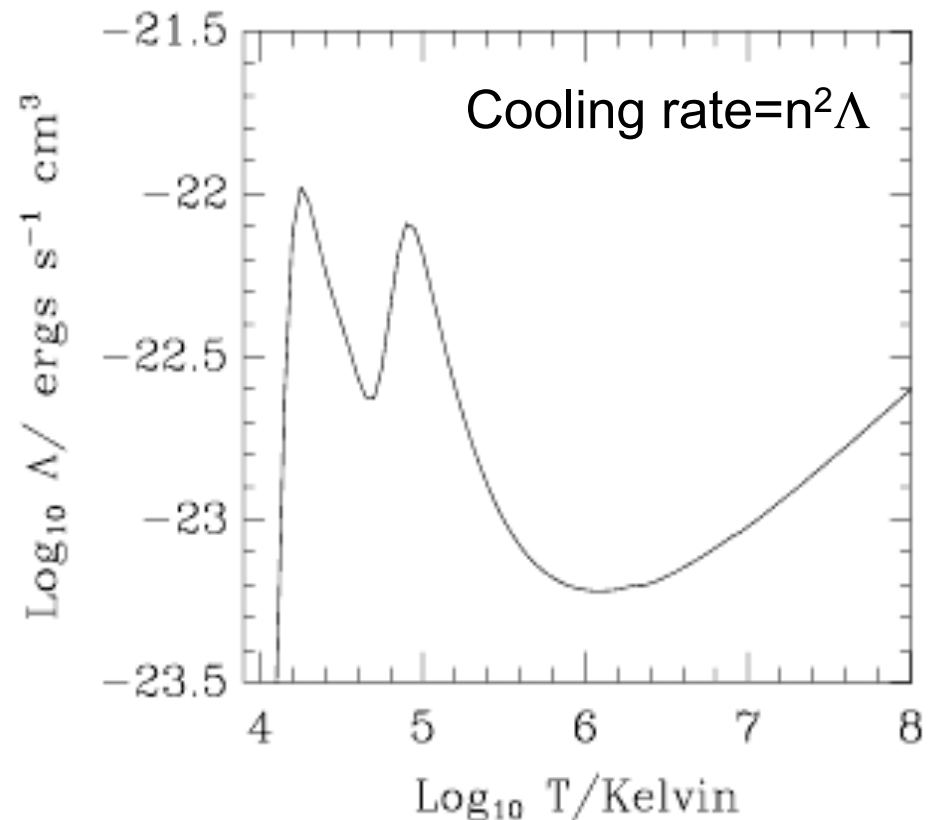
It follows that the characteristic virial temperature of a collapsed system scales with mass as $T \sim M^{2/3}$ - i.e. massive systems are hotter.

Response of the baryons - cooling

In practice, the ability of gas to cool is a strong function of temperature, since at $T \gg 10^5$ K atoms are mostly ionized, reducing their ability to radiate.

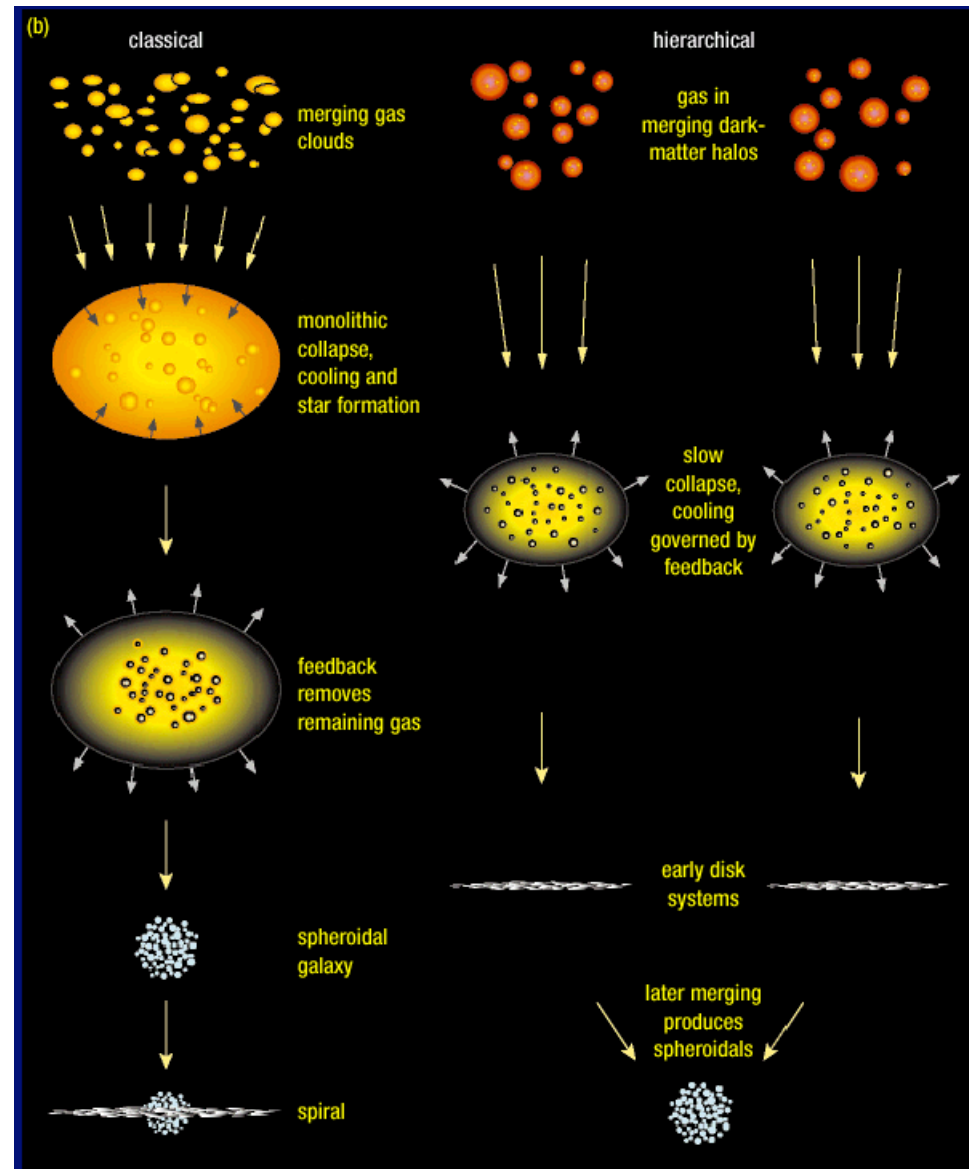
Though it may appear from the cooling function plot that gas at $T > 10^6$ K radiates more effectively, the cooling time $\tau = nkT/n^2\Lambda$, is actually *longer* at high T , since the thermal energy per particle is higher.

The result is that gas in halos with masses greater than about $10^{12} M_\odot$ is unable to cool effectively. This sets a natural upper limit to the mass of galaxies. In lower mass systems, gas is able to cool and form stars, whilst in more massive halos most of the baryons remain in the form of hot intergalactic gas.



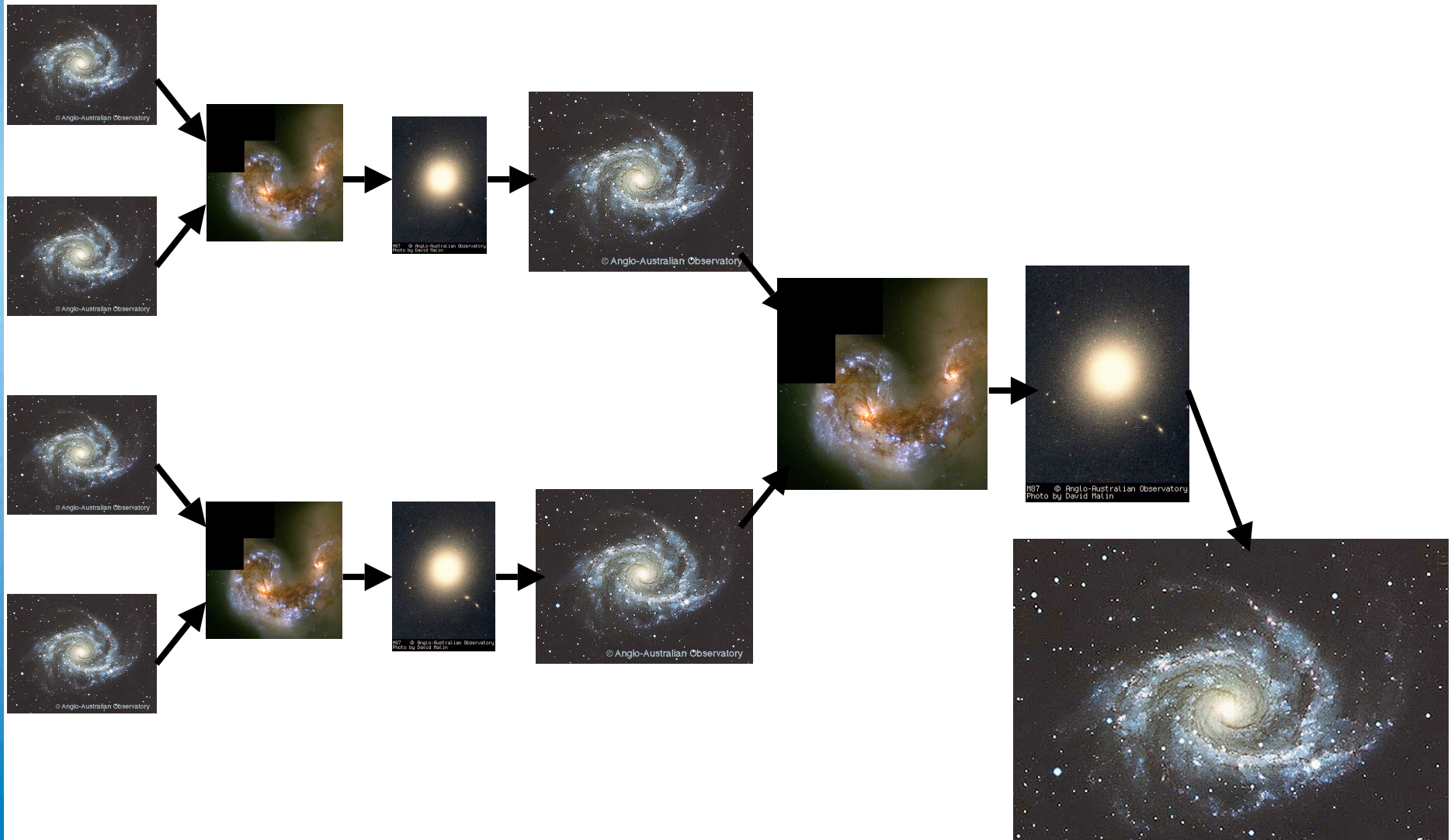
Cooling function for a cosmic abundance H+He mixture.

Galaxy formation - two models



Hierarchical galaxy formation

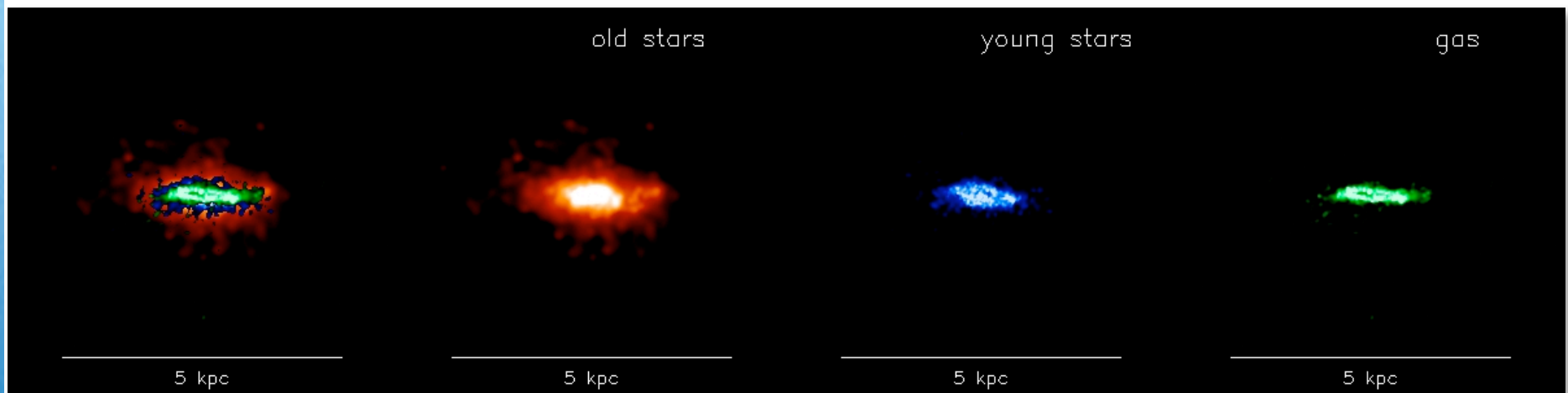
The hierarchical assembly picture, whereby galaxies grow by mergers and gas cooling, is the most popular today.



Direct simulations of galaxy formation

Galaxy formation is very difficult to simulate, since it involves processes which take place over a very wide range of spatial scales. The following slides show one recent attempt to do this.

Phase I: Formation of First Galactic Disks (1Gyr)

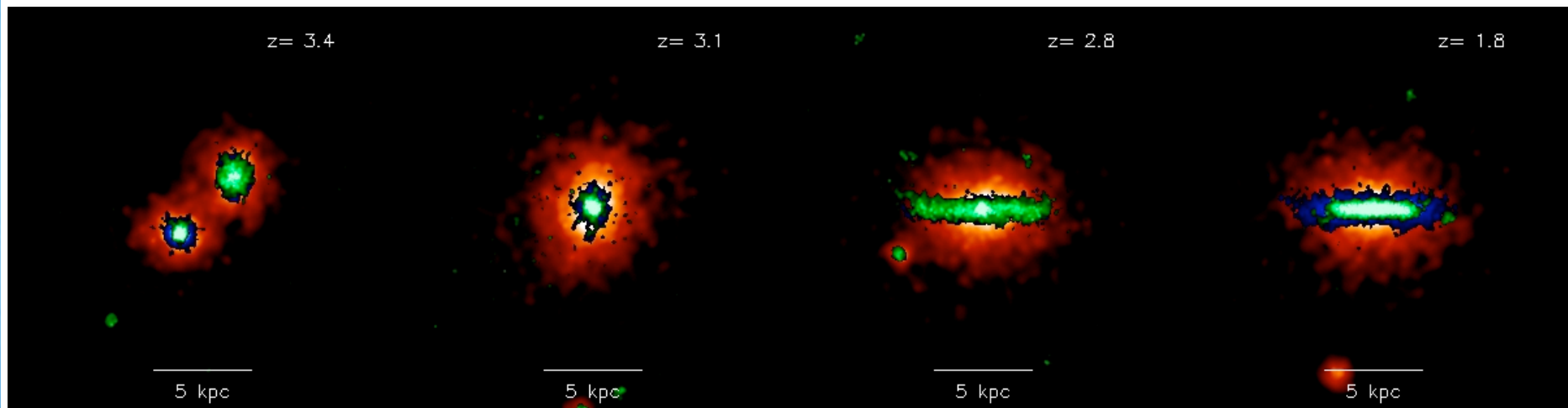


- first relaxed small disks

Matthias Steinmetz

Direct simulations of galaxy formation

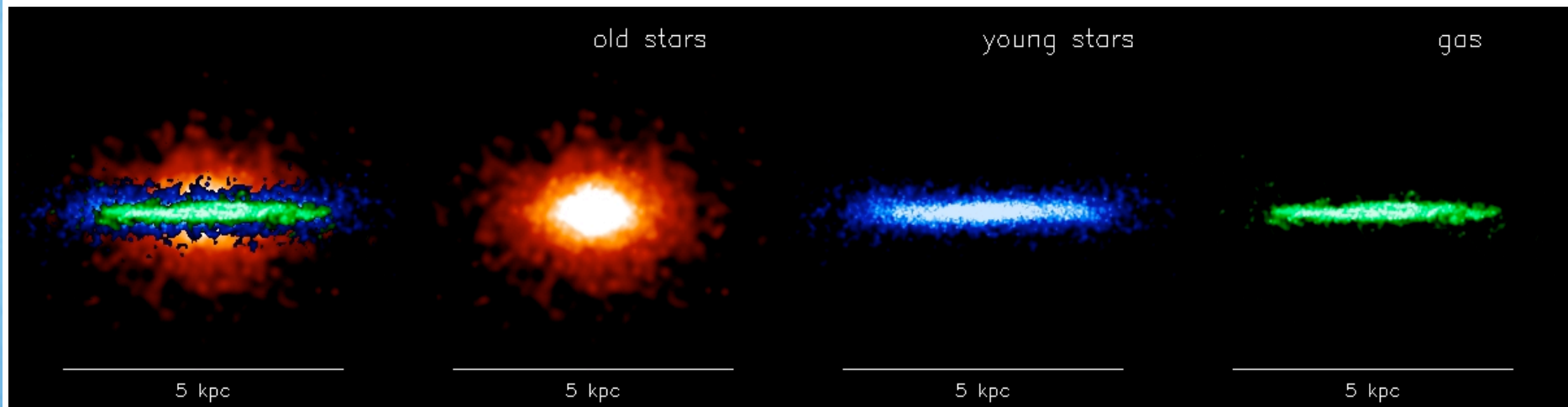
Phase II: Bulge Formation and Disk Reassembly (2 Gyr)



- disks are destroyed by merging, formation of an elliptical
- later on: disk reassemble

Direct simulations of galaxy formation

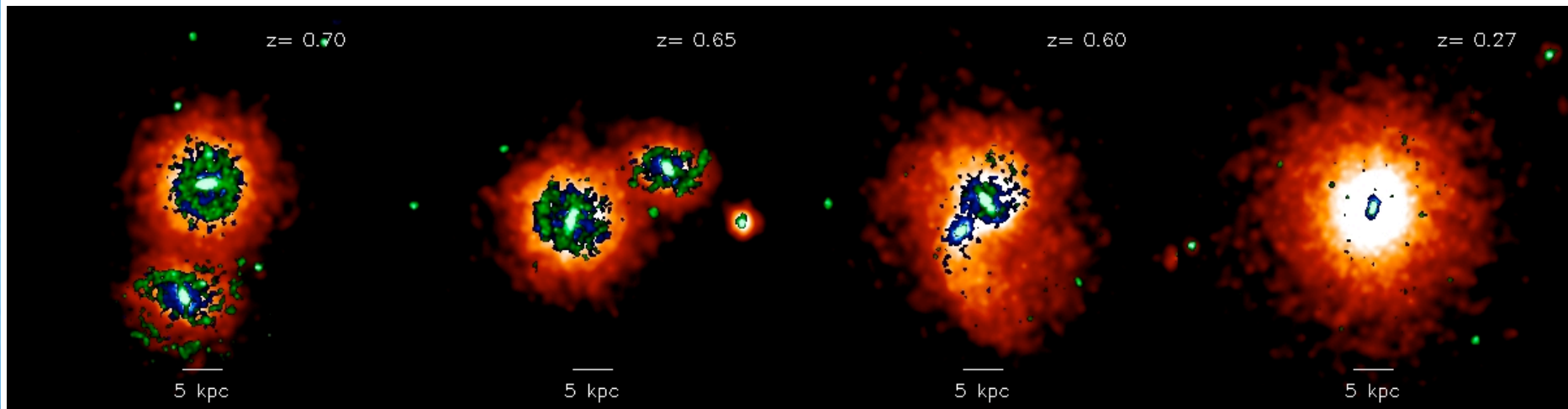
Phase III: Well Developed Disk+Bulge Structure (3 Gyr)



- slowly growing disk
- young stars and gas in thin disk, bulge of old stars

Direct simulations of galaxy formation

Phase IV: Formation of a Giant Elliptical (7 Gyr)



- nuclear star burst consumes nearly all remaining gas

Models vs. observations

Models of structure formation attempt to reproduce a variety of observed features of the Universe:

- Fraction of cooled baryons $\sim 10\%$ - difficult
- Spatial distribution of galaxies - OK
- Luminosity function of galaxies - difficult at high L
- Structure (e.g. disk size) and colours of galaxies - problems with disk radii
- Star formation history - OK? (obscuration problems)

Many of the remaining problems arise from the difficulty in treating feedback - i.e. energy returned to the baryonic component by supernovae and AGN.

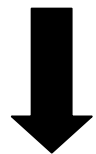
Summary

Dark Matter



Virialized Halos
(Hierarchical Growth)

Intergalactic Medium



Galaxies and Stars

