Why are there galaxies in the Universe?

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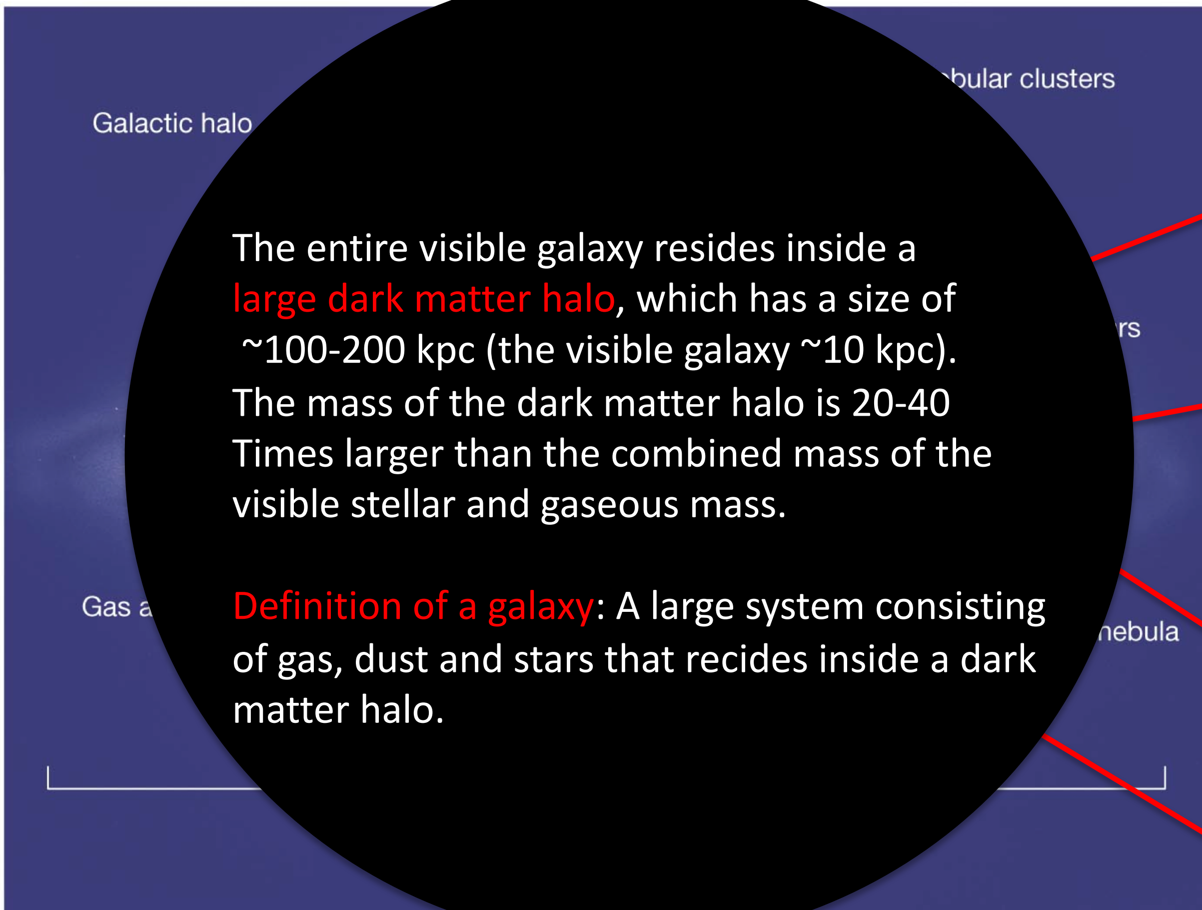
The definition of galaxies



The entire visible galaxy resides inside a large dark matter halo, which has a size of ~100-200 kpc (the visible galaxy ~10 kpc). The mass of the dark matter halo is 20-40 Times larger than the combined mass of the visible stellar and gaseous mass.

Definition of a galaxy: A large system consisting of gas, dust and stars that recides inside a dark matter halo.

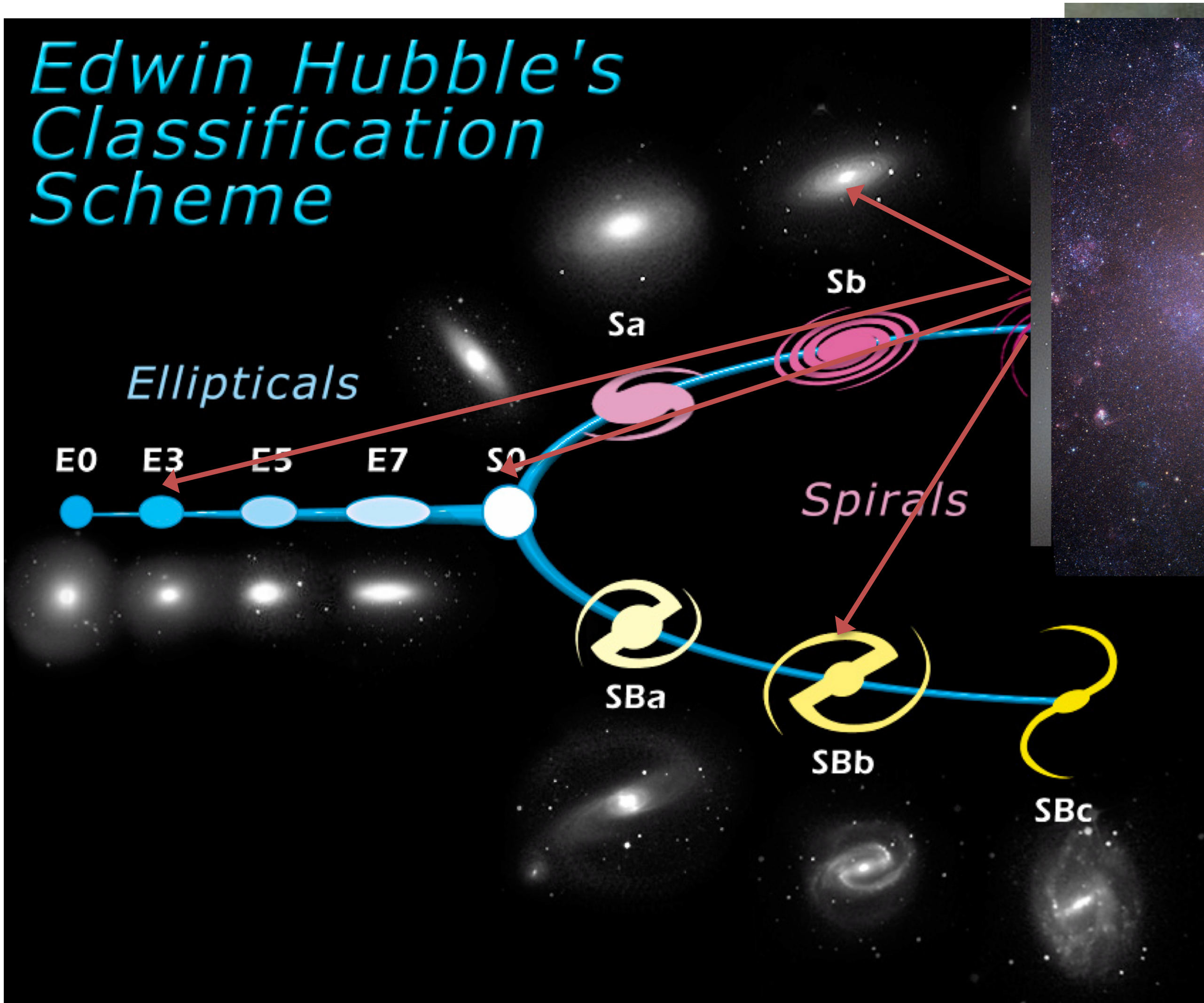
At the centre of a galaxy we often find a central bulge that consists of old stars.

The galactic disc is a flattened structure consisting of gas and young stars.

In the galactic stellar halo we can find very old metal-poor stars and globular clusters.

Typically the very centre of the galaxy contains a supermassive black hole.

Classification of galaxies

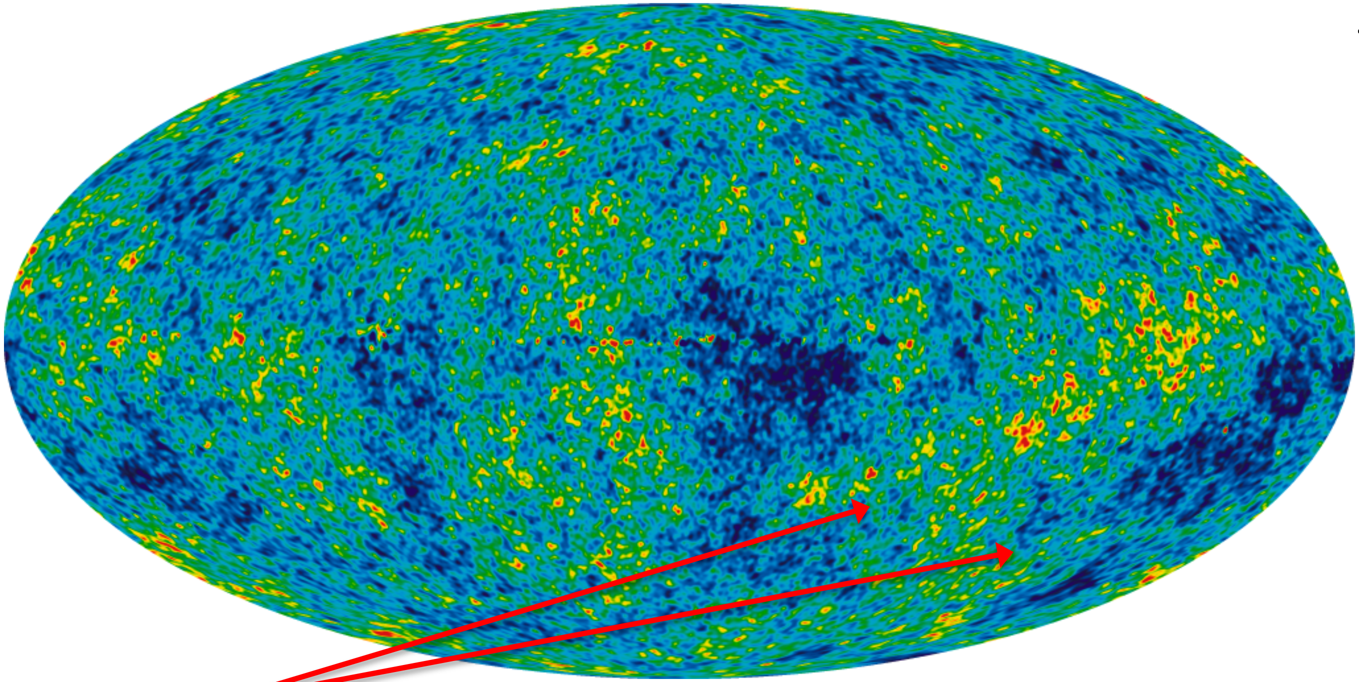


Spiral galaxies have a disk with gas and young blue stars, in the centre a central bulge with old red stars can be found.

Early-type galaxies

Late-type galaxies

The Initial Conditions



The Universe at age 380,000 years, corresponding to z=1100.

$$\frac{\delta T}{T} \sim 10^{-5} \Rightarrow \delta = \frac{\delta\rho}{\rho} \sim 10^{-5}$$

Today galaxies: $\delta \sim 10^6$
and galaxy clusters: $\delta \sim 10^3$

- How did all the structures form from the small density inhomogeneities present in the cosmic microwave background (CMB)?

Gravitational instability and structure formation

$$\frac{d^2\delta_{\bar{k}}}{dt^2} + 2\left(\frac{\dot{a}}{a}\right)\frac{d\delta_{\bar{k}}}{dt} - 4\pi G\bar{\rho}\delta_{\bar{k}} = 0$$

- In the linear regime we can derive the following differential equation, which describes the growth of the density contrast δ in an expanding Universe.
- The second term is the expansion term as it describes the change of the size, a, of the Universe. For an expanding Universe: $\dot{a} > 0$
- Solving this equation we find:

$$\delta_k \propto t^{2/3} \propto a = (1+z)^{-1}$$

- Thus, the density contrast should only grow by a factor of ~1000 from z=1100 to the present day (z=0). And there should be no galaxies in the Universe!!
- At early times the perturbations are still linear $\delta\rho/\rho \ll 1$. Once the perturbation reaches $\delta\rho/\rho \sim 1$ it becomes non-linear and breaks away from the expansion and collapses rapidly, but how can we achieve $\delta\rho/\rho \sim 1$??

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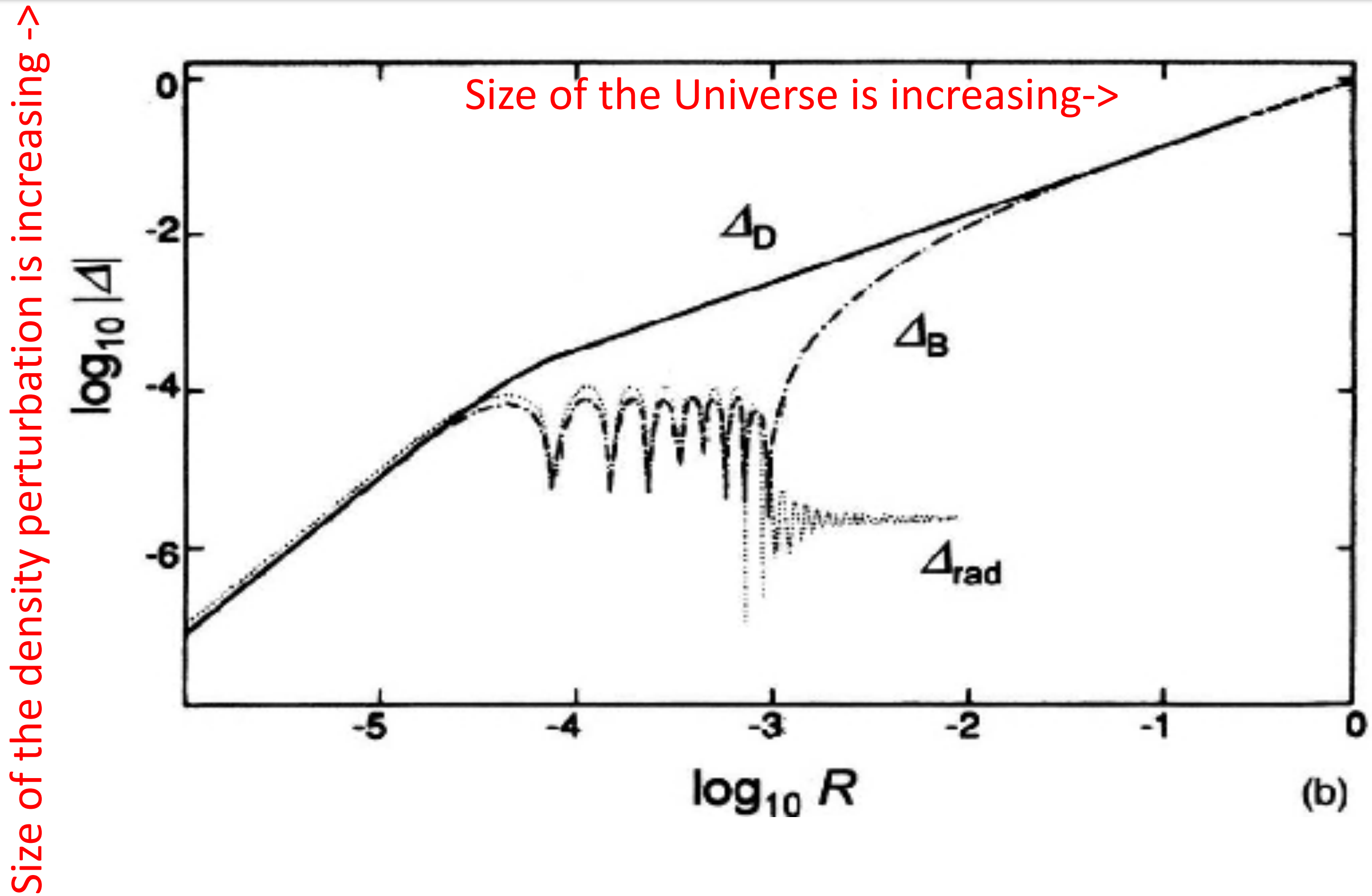
Dark matter and galaxy formation



- In an expanding Universe with only baryons (i.e. ordinary matter) the density perturbation $\delta=\Delta$ does not have enough time to grow to the galaxies we see today -> we must have dark matter to explain the existence of galaxies.

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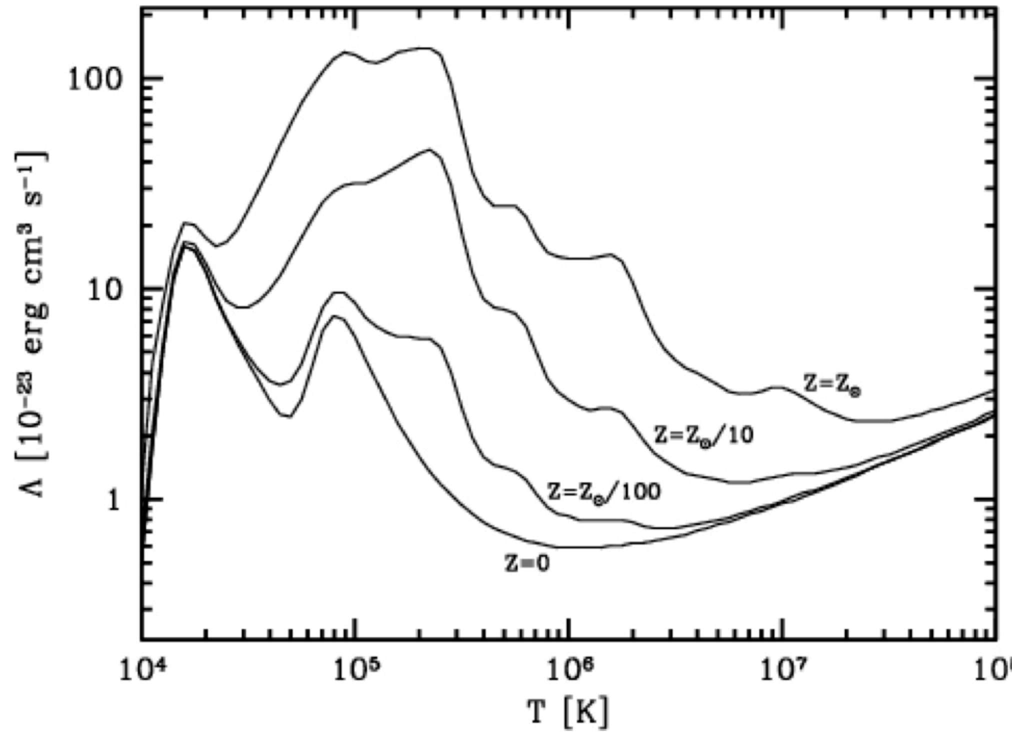
Gas cooling

- Cooling is a crucial ingredient of galaxy formation. Gas cools and collapses, whereas dark matter cannot cool.
- Cooling is general strong at $T>10^4$ K, below this temperature gas is mostly neutral and the cooling rate drops by orders of magnitudes. A higher gas metallicity always increases the cooling rates.
- The emission of photons is isotropic and thus the angular momentum is conserved. -> Formation of disks.

Cooling curve, showing the cooling rate as a function of temperature.



Cooling $\propto \rho^2$

Heating $\propto \rho$

For high densities cooling always wins.

The Astrophysics of galaxy formation

- Star formation is a crucial, but badly understood aspect of galaxy formation, especially the stellar initial mass function (IMF) is unknown.
- In order to avoid excessive cooling galaxy formation models must include energetic feedback from supernovae, supermassive black holes and a photo-ionising background.
- In the standard LCDM model all galaxies are assembled by hierarchical merging of lower-mass objects.

Feedback processes

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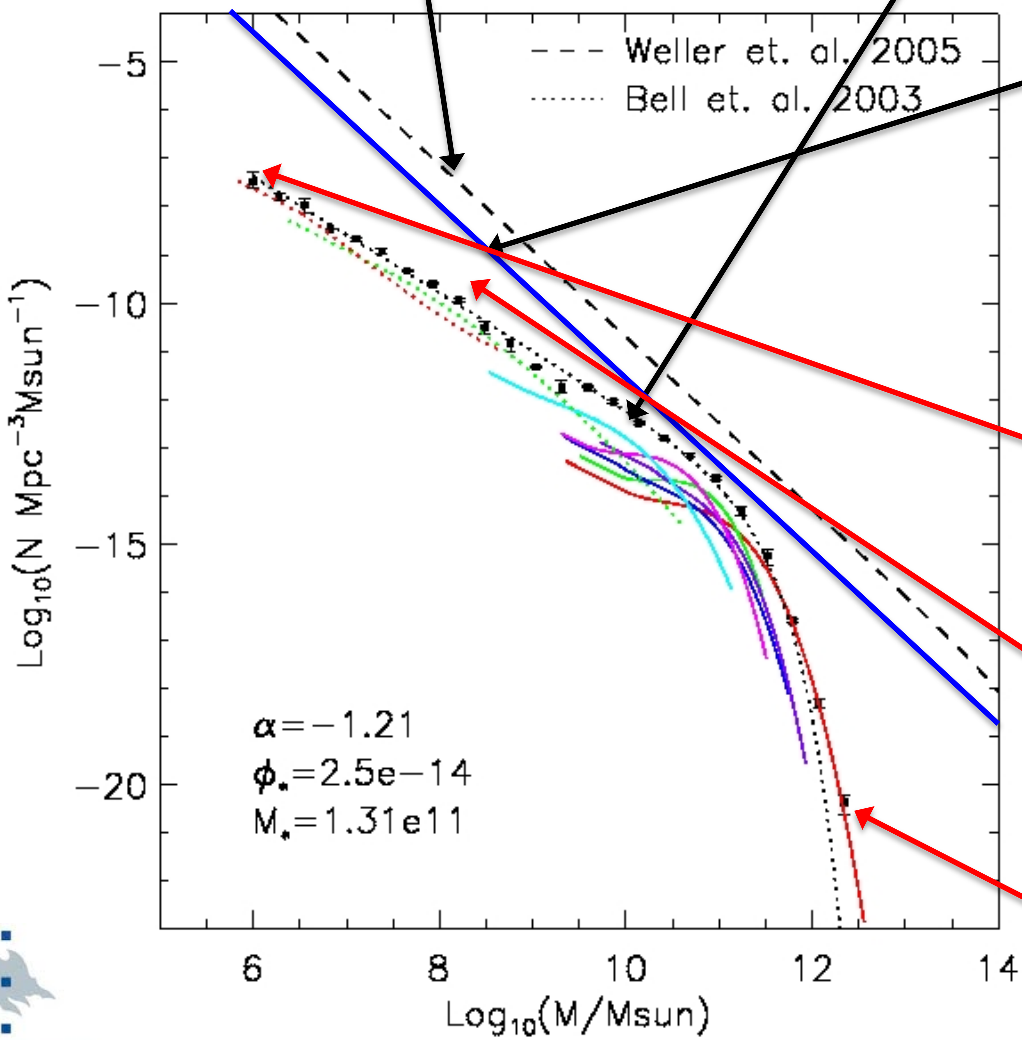
The masses of galaxies

The dark matter halo function.

The galaxy mass function



If the galaxy formation efficiency would be the same in all haloes: -> x Ω_b/Ω_m=0.2

The visible parts of a galaxy are formed when the gas settles in a dark matter halo, cools and forms stars.

1. Heating from the epoch of reionisation prevents gas from cooling in very small dark matter haloes, $M_{DM}<10^7\ M_\odot$.

2. Explosive feedback from super-novae drives out gas from galaxies.

3. The radiation and feedback from supermassive black holes at the centers of galaxies may set limits on the maximum mass of galaxies.

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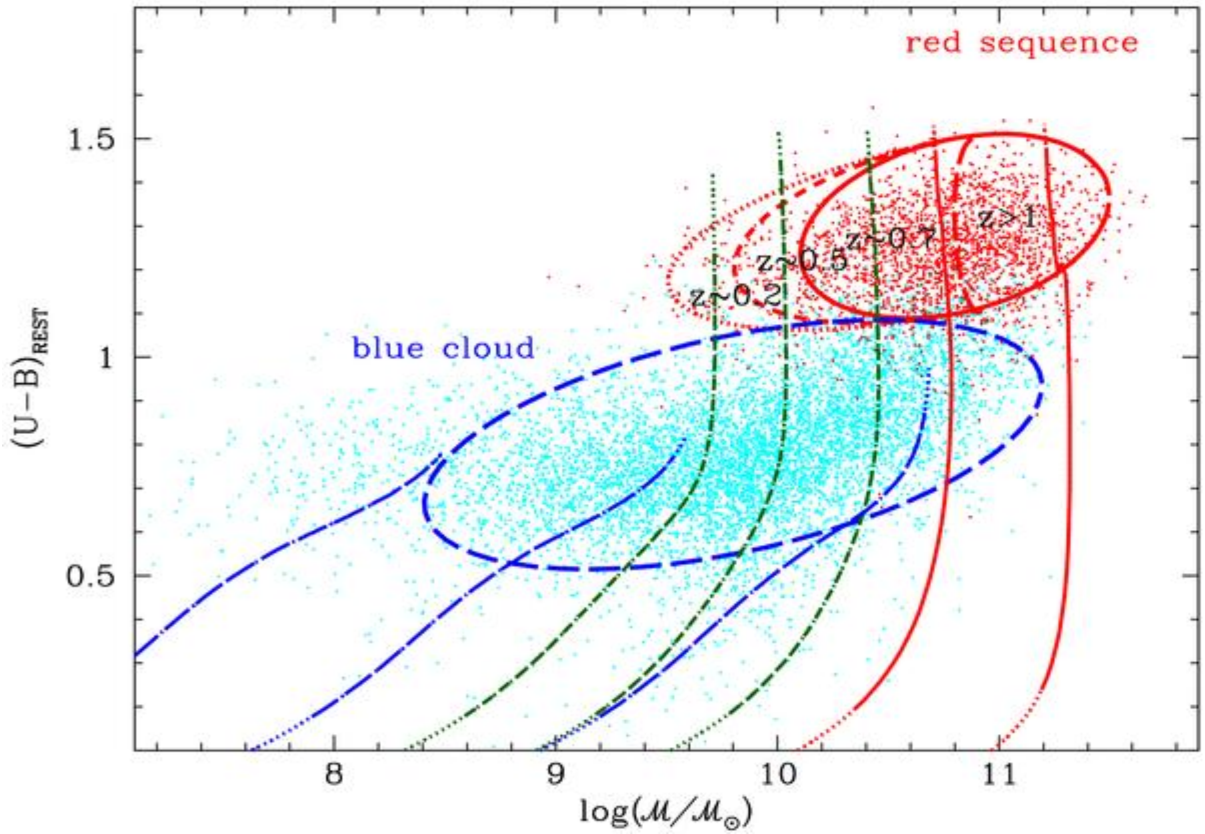
Bimodality of the galaxy population

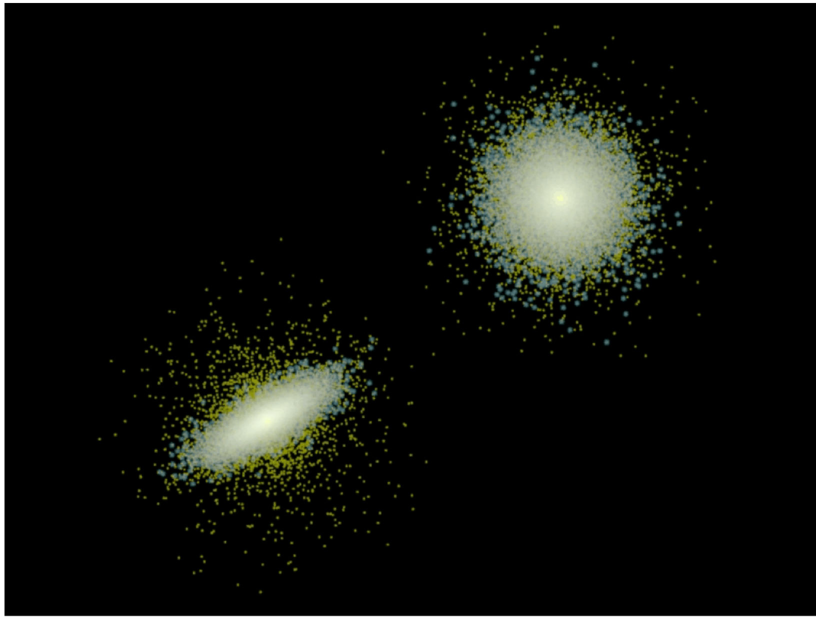


Bimodality of the galaxy population.
Pozetti et al. (2010)

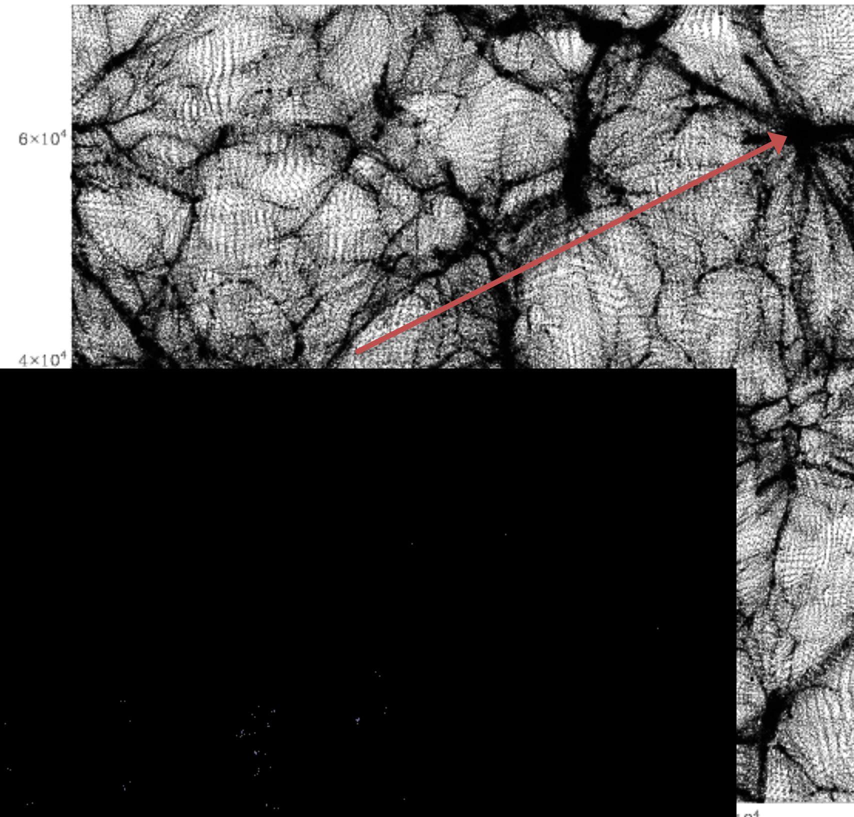
- The local galaxy population is observed to be bimodal: Galaxies above ≈Milky Way mass are red spheroidal systems and below blue, star-forming disk galaxies.
- Some mass-dependent process must turn off star formation and make the galaxies dead and red.

Numerical simulations of galaxy formation

Galaxy Merger simulations:



Cosmological galaxy simulations:



Examples of research performed at the University of Helsinki.

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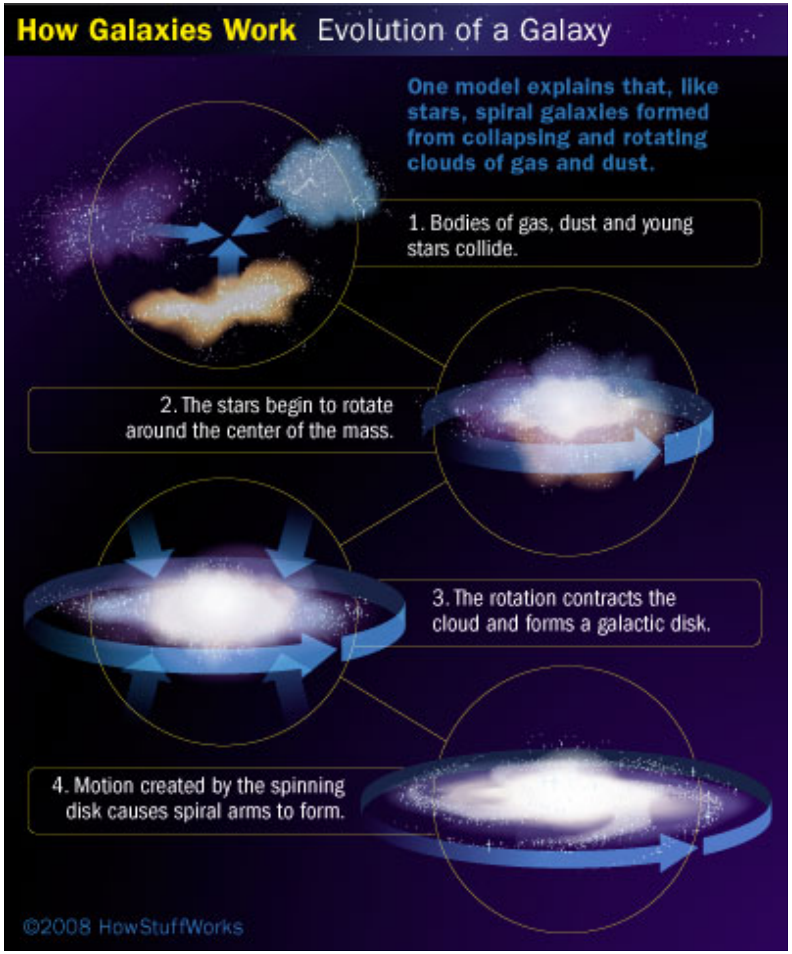
Formation of disk galaxies

- Definition: Disk galaxies are stable rotationally supported galaxies with relatively high current star formation rates.
- Formation scenario:

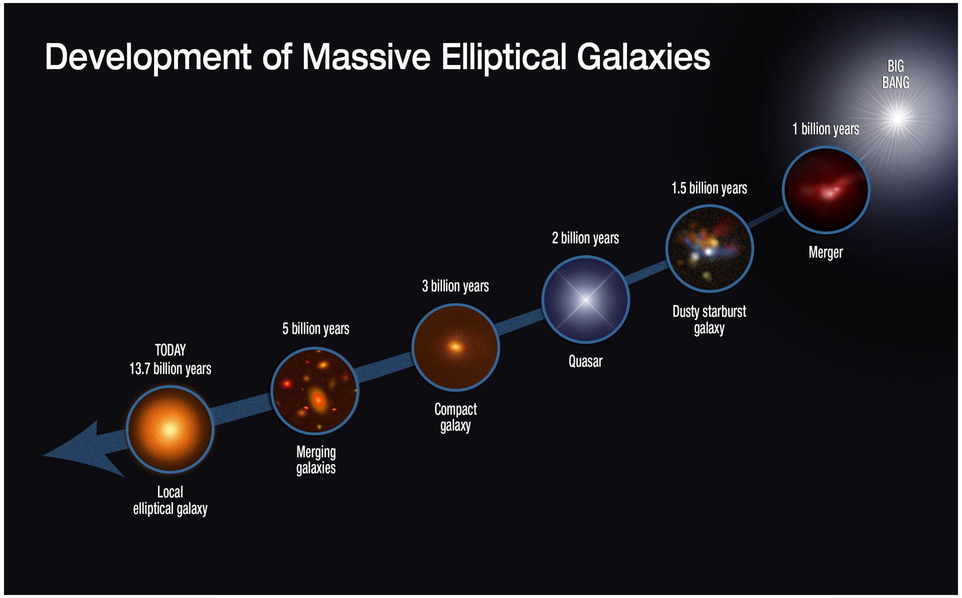
1. Hot shock-heated gas inside a dark matter halo cools radiatively.
2. As gas cools, its pressure decreases causing the gas to contract.
3. The emission of photons is isotropic and thus the angular momentum is conserved.
4. The gas sphere contracts, spins up and flattens.
5. The surface density of the disk increases, at some point the critical threshold for star formation is reached and a disk galaxy is born.



Need to avoid disk destroying major mergers.

Formation of elliptical galaxies

- Definition: Elliptical galaxies are typically very massive, have old stellar populations and are supported by anisotropic velocity dispersion.



The formation of ellipticals require very rapid star formation at high redshifts.

- Formation scenario:

1. The two-phased formation model developed by Naab, Johansson Ostriker explains the formation of ellipticals as a combination of the monolithic and merger scenarios.
2. The core (r<1 kpc) of ellipticals is assembled rapidly at high redshifts (z~4-6) in dissipational collapse and multiple mergers.
3. The later assembly (z≤2-3) proceeds then by the accretion of gas-poor minor galaxies that build the outer envelope of the ellipticals.

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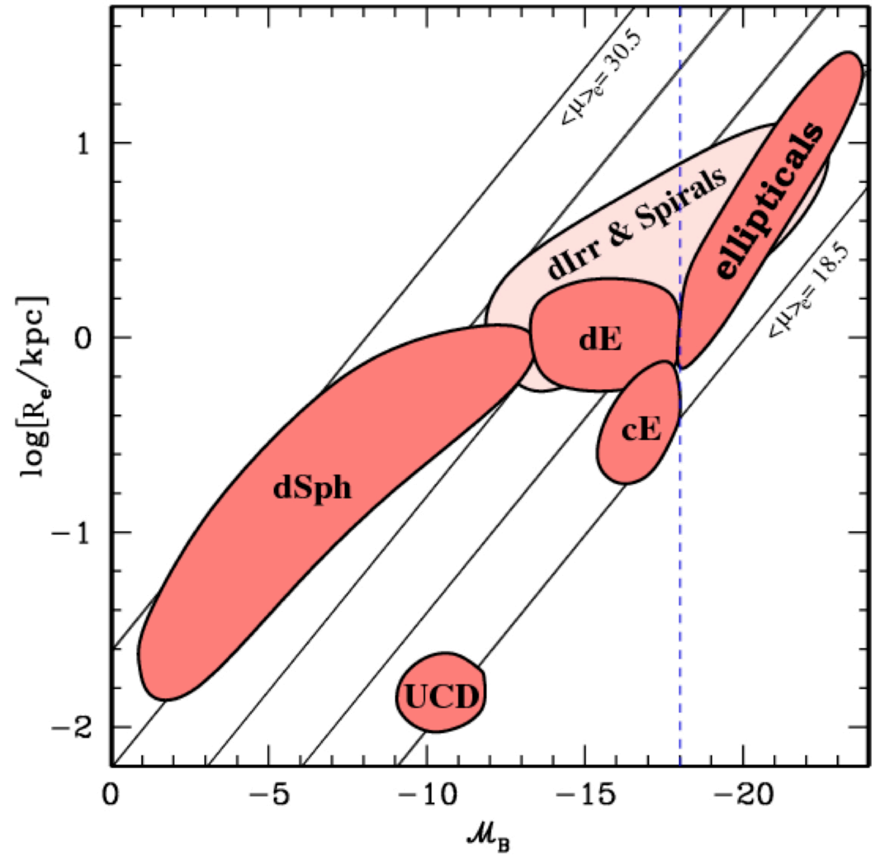
Formation of dwarf galaxies

- Definition: Low mass galaxies that are either rich in gas (irregular galaxies) or gas-poor (dwarf spheroidal galaxies).
- Formation scenario:

1. Dwarf irregulars are an extension of disk galaxies, with irregular morphologies and high specific star formation rates.
2. Dwarf spheroidals are typically very faint and compact, almost failed galaxies, as the first population of stars has probably ejected most of the gas in these systems.



Dwarf galaxies are very sensitive to both external (reionisation, ram-pressure stripping) and internal processes (supernova feedback).

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Why are there galaxies in the Universe?

1. Galaxies are able to form because of dark matter. Without dark matter there would simply not be enough time for the small density perturbations observed in the cosmic background radiation to grow into galaxies during the lifetime of the Universe.
2. Galaxies form because gas is able to cool in dark matter haloes, leading to star formation and the build-up of their stellar components. The role of feedback is crucial for regulated star formation, otherwise all stars would have already formed in the Universe.

- Galaxy formation is not solved! – Open question include:
- Why are both disk and elliptical galaxies forming in the same Universe?
- What exactly is the role of the supermassive black holes in galaxies?
- Can observations and modelling of dwarf galaxies reveal the true nature of dark matter?