Galaxy formation and evolution
PAP318, 5 op, autumn 2020

on Zoom

Lecture 1: Introduction to galaxy formation, 04/09/2020

Basic information

- Lecturers: Prof. Peter Johansson (Room D311)
  Course assistant: Dr. Stuart McAlpine Room D326)
- Lectures Fridays at 12.15-14.00, in total 14 lectures (last lecture 11.12). All lectures will be given on Zoom.
- Course homepage: https://wiki.helsinki.fi/display/astjourn/Galaxy+formation+and+evolution
- Problem sets will be put on the course homepage every two weeks and a problem solution session will be held after the lectures at 14.00-16.00 on Zoom on the following days 18.9, 2.10, 16.10, 6.11, 20.11 and 4.12.
- In total 6x5=30 questions, **1/3 (10 questions is the minimum requirement)**, surplus points will result in bonus points for the exam.
- The problems consist of regular exercises and questions based on journal articles.
- Course material: Lecture notes provided by the lecturer.
- Preliminary: The final exam will be held on Friday 18.12 at 10-14

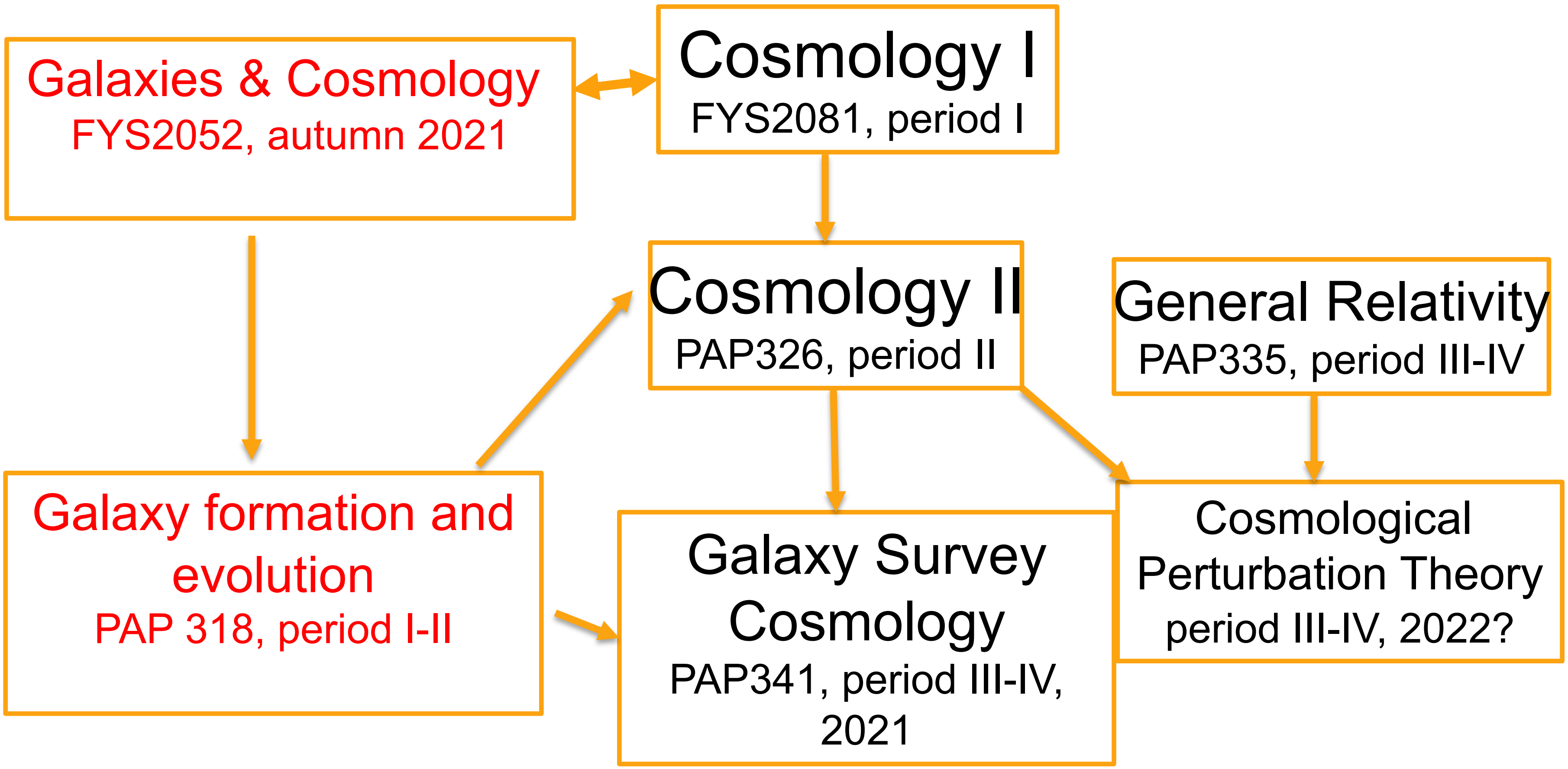
Course material

- The lecture notes will be based on the following two books, which will be extensively used throughout the course.
- H. Mo, F. van den Bosch & S. White: *"Galaxy formation and evolution"*, Cambridge Univ. Press. MBW.
- M.S. Longair: *"Galaxy formation"*, 2nd ed. Springer, 2008. L.
- The total number of pages in these two books is ~1500, thus this course will only cover the most relevant parts for a first course on theoretical galaxy formation.

The relation of this course with other courses taught at the University

- Assumed background: Basic and intermediate level courses in Astronomy, in particular the course: Galaxies and cosmology. Basic and intermediate level studies of theoretical physics recommended.
- Related advanced courses in Astronomy: Advanced dynamics (Spring 2021), Open problems in modern astrophysics (Autumn 2020), High Energy Astrophysics (Spring 2021), Interstellar Medium (Autumn 2020).
- Related advanced courses in theoretical physics: Cosmology I-II, General relativity and Galaxy Survey Cosmology.
- There is also numerous opportunities for writing your M.Sc. thesis on the topics covered in this course. Please, contact the lecturer if you are interested.

Cosmology & galaxy curriculum (astronomy & theoretical physics)



Course syllabus 1

- Lecture 1: 04.09.2020 – Introduction to galaxy formation
- Lecture 2: 11.09.2020 – Observations of galaxies
- Lecture 3: 18.09.2020 – Cosmology and the evolution of small perturbations – P.S. 1
- Lecture 4: 25.09.2020 – Jeans instability and horizons
- Lecture 5: 02.10.2020 – Dark matter and galaxy formation – P.S. 2
- Lecture 6: 09.10.2020 – Correlation functions and the spectrum of the initial fluctuations
- Lecture 7: 16.10.2020 – Non-linear evolution of dark matter haloes – P.S. 3
- Teaching break 23.10.2020

Course syllabus 2

- Lecture 8: 30.10.2020 – Formation and evolution of gaseous haloes
- Lecture 9: 06.11.2020 – Star formation and feedback – P.S. 4
- Lecture 10: 13.11.2020 – Formation of disk galaxies
- Lecture 11: 20.11.2020 – Galaxy interactions and transformations – P.S. 5.
- Lecture 12: 27.11.2020 – Formation of elliptical galaxies
- Lecture 13: 04.12.2020 – Formation of active galaxies – P.S. 6
- Lecture 14: 11.12.2020 – Summary lecture
- Final exam: 18.12.2020

On this lecture we will discuss

1. Galaxy formation as a process and the diversity of the galaxy population.
2. Review of the basic elements of galaxy formation, i.e. overview of what this course is about.
3. Galaxy formation time scales. The dominant process in the life of a galaxy at any time is determined by the process with the shortest time scale.
4. A very brief historical review of the history of structure and galaxy formation.
5. The lecture notes correspond to: MBW: pages 1-24 (§1.1-1.4)
   L: pages 1-25 (§1.1-1.7)

1.1 Galaxy formation as a process I

- Galaxies are dynamically bound systems that consist of a stellar structure embedded in a dark matter halo.
- The Milky Way which is a typical bright galaxy consists of ~200-400 billion stars and has a diameter of ~20 kpc. The number density of stars in a galaxy is 10^7 times higher than the mean number density of stars in the Universe.
- Galaxies are well-defined astronomical identities and they make up the building blocks of the Universe.
- Galaxy formation as a physical process involve two different aspects:

1. Initial and boundary conditions
2. Physical processes, which drive the evolution.

Galaxy formation as a process II

- In order to understand galaxy formation we need to cover the following subjects:

1. **Cosmology:** Galaxies evolve on cosmological time and length scales, thus we need to understand the space-time structure on large scales.
2. **Initial conditions:** These were set by physical processes in the very early Universe and they are beyond current direct astronomical observations. Strong link to particle physics based cosmology.
3. **Physical processes:** The messy astrophysics that is required to understand galaxy formation include general relativity, hydrodynamics, dynamics of collisionless systems, plasma physics, thermodynamics, electrodynamics, atomic and nuclear physics and the theory of radiative processes.

Diversity of the galaxy population I

- Galaxies are diverse objects, meaning a large number of parameters is required to characterize any given galaxy:

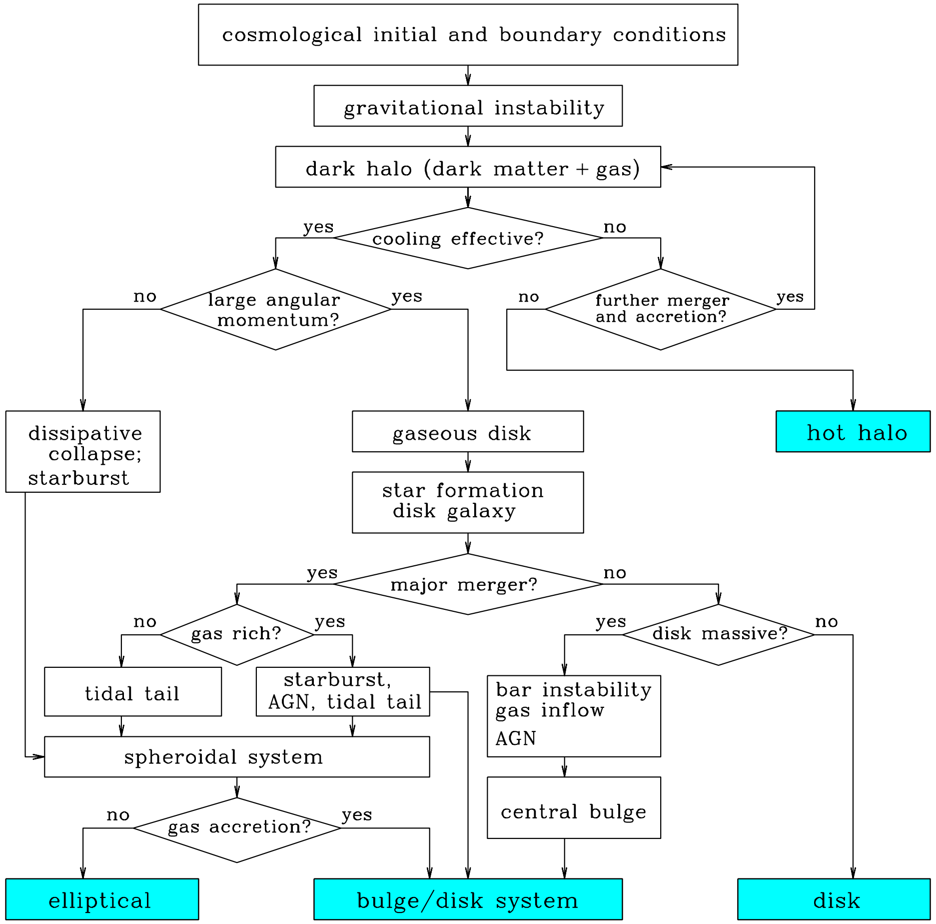
1. **Morphology:** To first approximation there exists only two basic types of galaxies: Elliptical galaxies are mildly flattened, ellipsoidal systems that are mainly supported by random motions of their stars. Spiral galaxies have highly flattened disks that are mainly supported by rotation. The faintest galaxies do not typically fall on the Hubble sequence and they are divided into irregulars and dwarf spheroidals.
2. **Luminosity and stellar mass:** Luminosities of galaxies can range between $\sim 10^3\,L_\odot$-$10^{12}\,L_\odot$. Total luminosity is related to the total number of stars in the galaxy, but with a large scatter due to different stellar populations in different galaxies. The majority of light in the Universe is contributed by Milky-Way type L^* galaxies, which are bright and relatively common.

Diversity of the galaxy population II

3. **Size and surface brightness:** Galaxies do not have well defined boundaries, use half-light radius, which encloses half of the total light. For disk galaxies size is a measure of their specific angular momenta and for ellipticals a measure of dissipation during their formation.
4. **Gas mass fraction:** The amount of cold gas: $f_{gas}=M_{cold}/[M_{cold}+M_*]$ is an important parameter. Typically ellipticals have negligibly small cold gas fractions, disk galaxies have typically f_{gas}~0.1 in the local Universe with this fraction approaching unity for very high redshifts.
5. **Colour:** The colour of the galaxy reflects the underlying stellar population in the galaxies. Ellipticals, which have old stellar populations are typically red and disks with younger stellar populations are bluer. Also higher metallicities make galaxies redder, extinction by dust can also make a galaxy appear red.

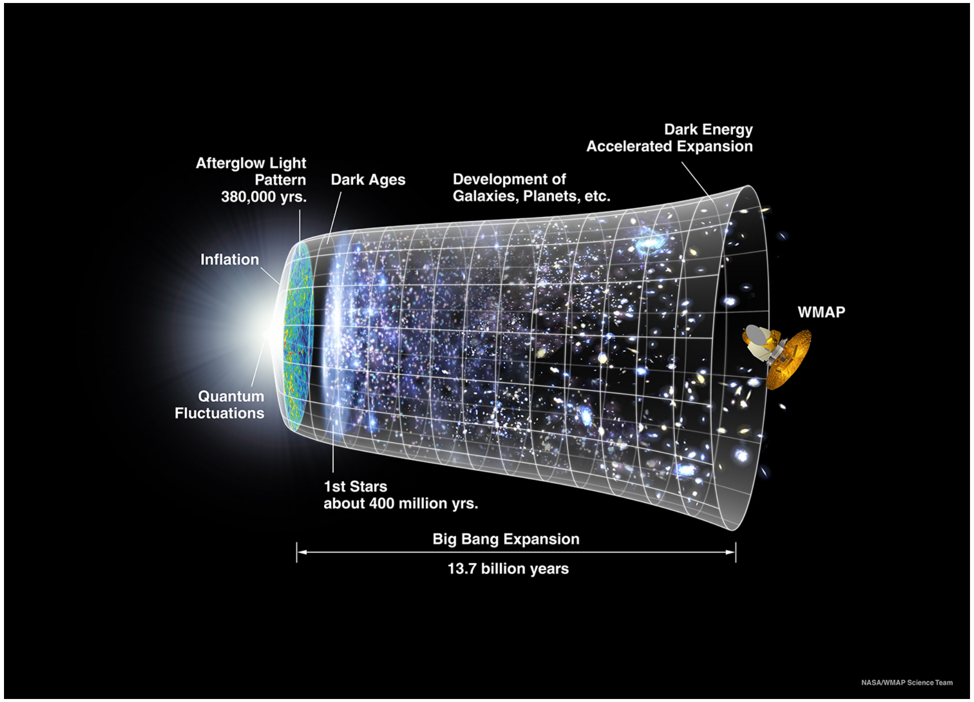
1.2 Basic elements of galaxy formation

- The figure to the right shows a basic logic flowchart for galaxy formation.
- This is only an indicative picture, with the various processes not as neatly separated in reality as indicated in the picture.
- The key astrophysical processes are cooling, star formation and the impact of angular momentum.



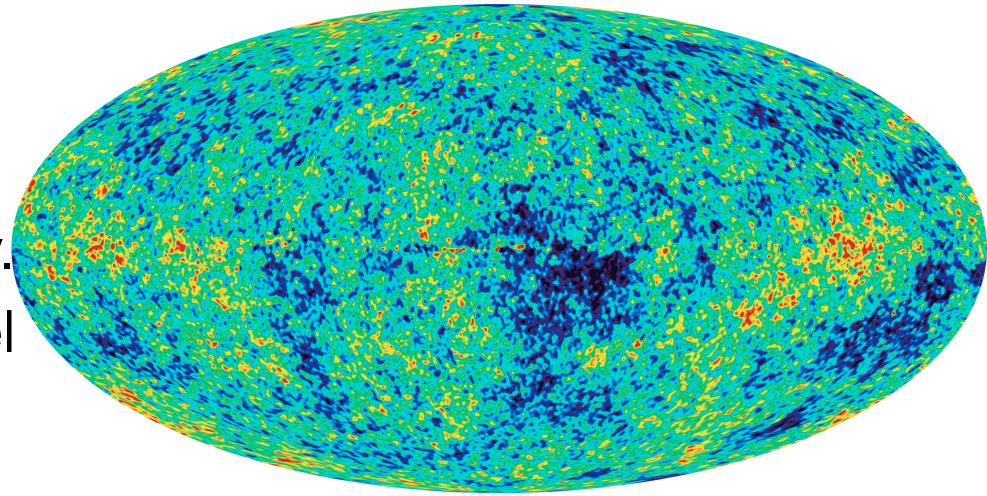
The standard model of cosmology

- Galaxies form on cosmological time and length scales, thus modelling galaxy formation requires a cosmological model.
- The standard model of cosmology is based on general relativity and the hypothesis that the Universe is spatially homogeneous and isotropic.
- The current standard ΛCDM model is sufficiently well constrained to make galaxy formation studies feasible.



Initial conditions

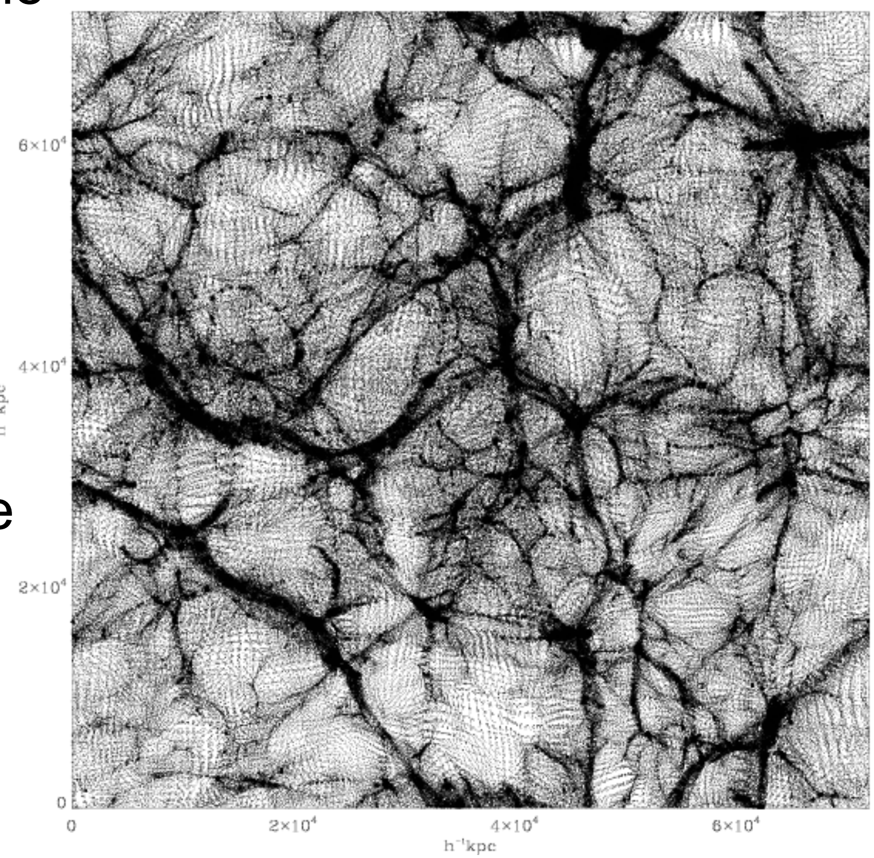
- If the Universe was perfectly uniform and isotropic, there would be no structure formation.
- In order to explain the origin of galaxies, we need some deviations from perfect uniformity.
- The cosmological standard model does not explain the origin of these perturbations.
- Currently the leading theory for the origin of perturbations is quantum fluctuations occurring during inflation in the very early Universe.



The cosmic microwave background (CMB) was formed t=380,000 years after the Big Bang at the so called last scattering surface.

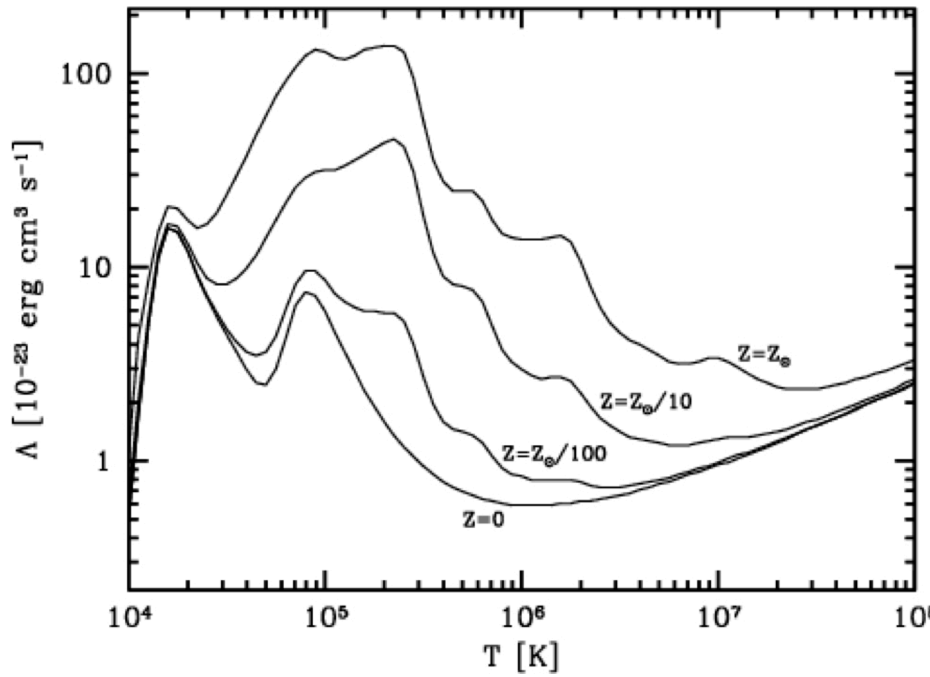
Gravitational instability and structure formation

- Density perturbations grow with time in an expanding Universe. Slightly overdense regions will attract their surroundings more.
- In a static universe $\delta\rho/\rho$ grows exponentially (Jeans collapse, star formation), but in an expanding universe growth is slower $\delta\rho/\rho \propto t^{\alpha}$.
- 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 -> requires numerical simulations.



Gas cooling

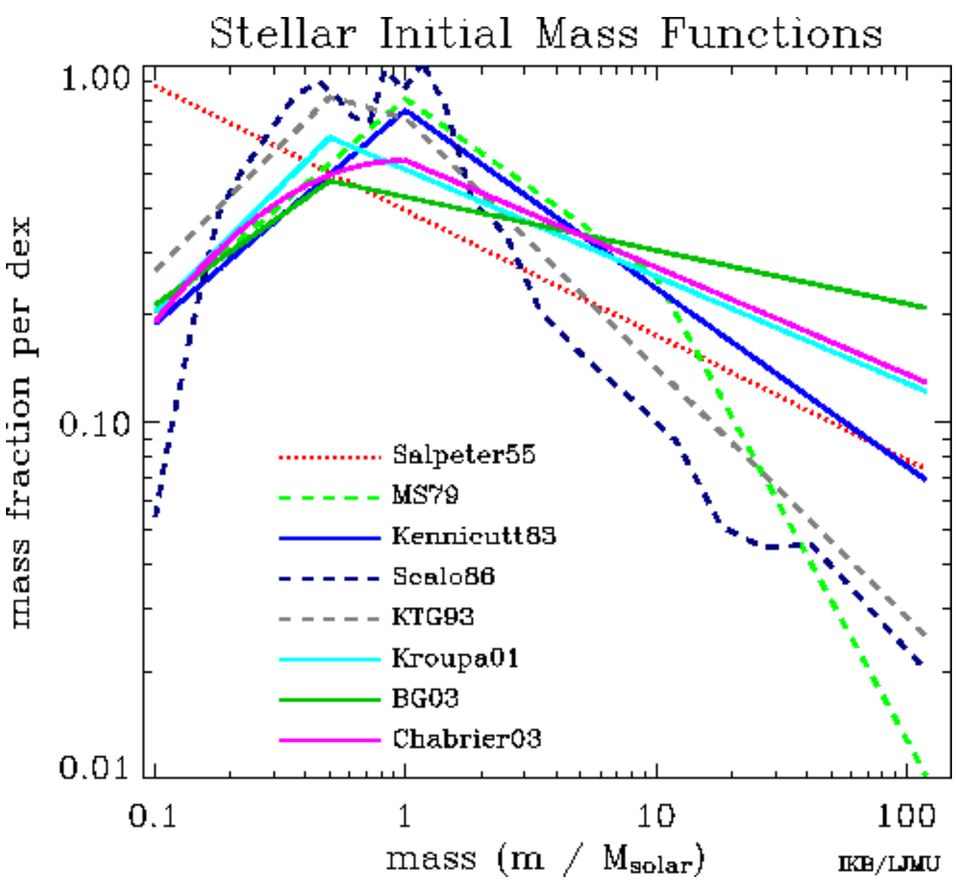
- Cooling is a crucial ingredient of galaxy formation. Gas cools and collapses, whereas dark matter cannot cool.
- Cooling is general strong at $T>10^4$ K, below this temperature gas is mostly neutral and the cooling rate drops by orders of magnitudes. A higher gas metallicity always increases the cooling rates.
- Cooling involves in general two particles, whereas heating only involves one particle.



Cooling $\propto \rho^2$
Heating $\propto \rho$
For high densities cooling always wins!

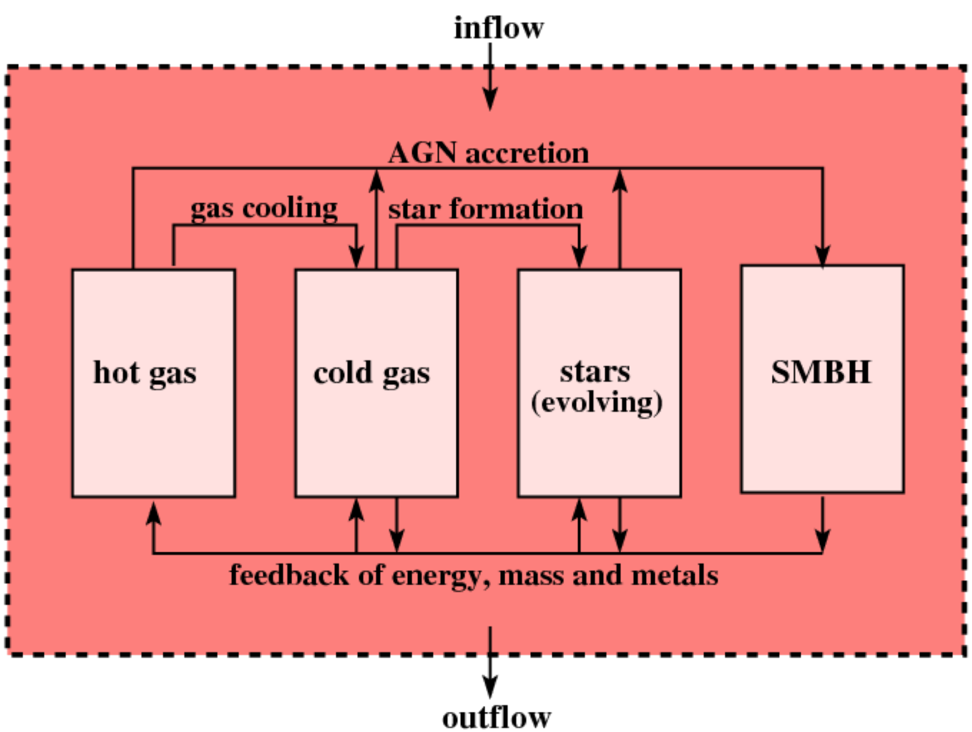
Star formation

- As gas in dark matter haloes cools and flows inwards, its self-gravity will eventually dominate and catastrophic collapse ensues.
- During the runway collapse the cloud may fragment into small, high-density molecular cores, where stars will be formed.
- The details of star formation and in particular the initial mass function (IMF) is currently not well understood.
- In general we can distinguish between quiescent star formation in disks and "starbursts" caused by mergers.



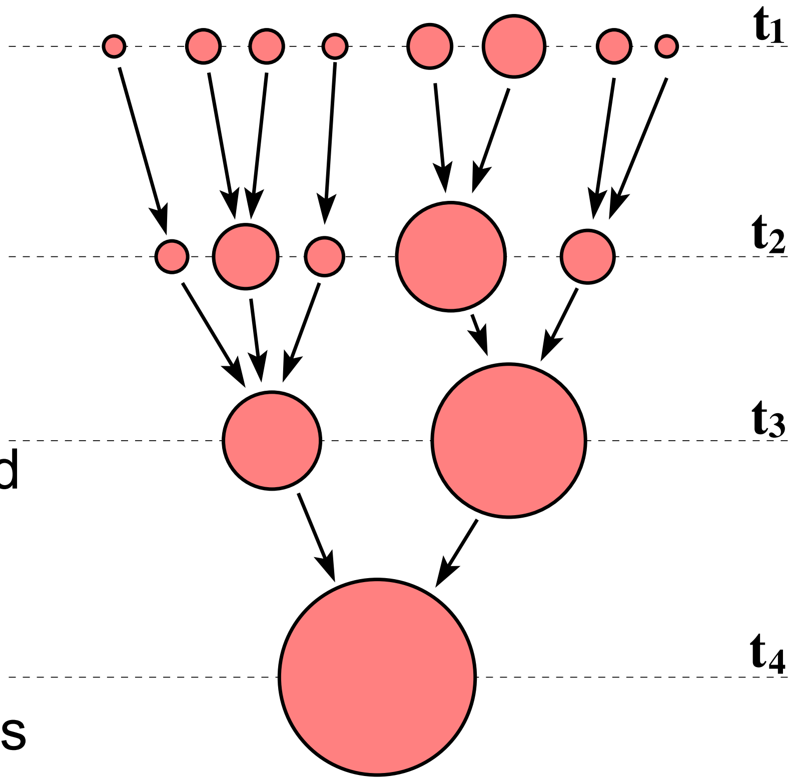
Feedback processes

- Early galaxy formation models showed that too much gas would cool rapidly and form too many stars compared to the observations -> cooling disaster.
- The solution lie in energetic feedback from supernovae and supermassive black holes (AGN) that are able to heat and in some instances expel the gas from galaxies.
- Feedback is a crucial, but badly understood aspect of galaxy formation theory.



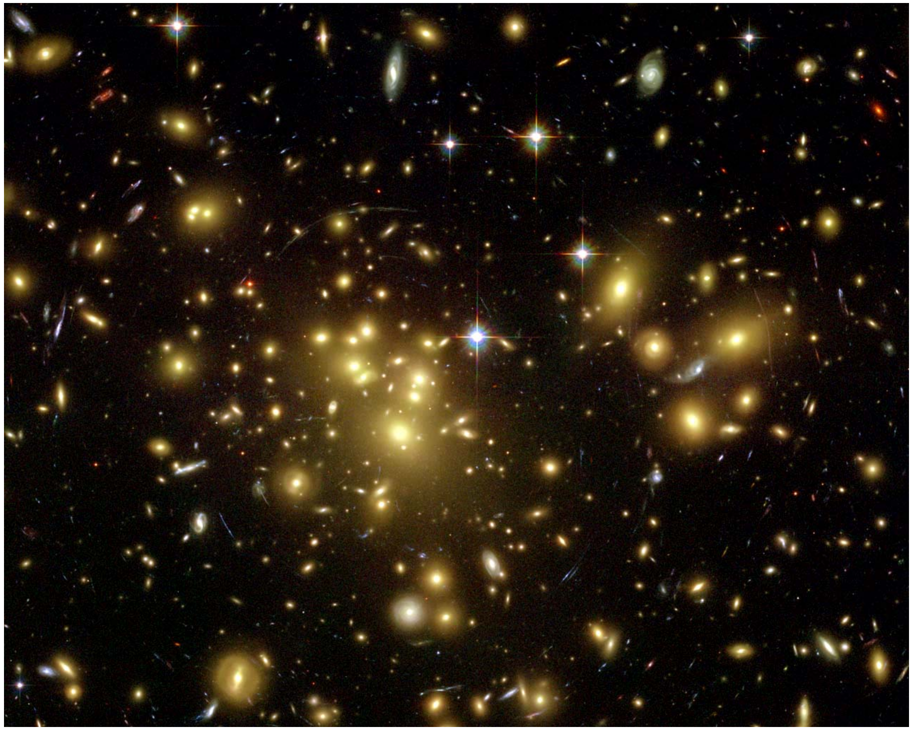
Mergers

- In the current standard ΛCDM model galaxy formation proceeds bottom-top, with the initial fluctuation having larger amplitudes for smaller mass objects.
- All galaxies are then assembled by the hierarchical merging of lower-mass objects, i.e. bottom-up.
- A gas-rich merger might be accompanied by strong star formation and/or AGN activity.
- Dynamical friction scales with the mass squared of the objects. Low mass objects may end up orbiting the main galaxy instead of merging –> galaxy clusters.



Dynamical evolution

- **External processes:** Satellite galaxies orbiting within dark matter haloes experience tidal forces that can remove dark matter, stars and gas from the galaxy.
- In addition, galaxies moving through hot gas in haloes can have their gas removed through ram-pressure stripping.
- **Internal processes:** Internal (secular) dynamical processes can cause bar-instabilities in disk galaxies and potentially lead to bulge formation.



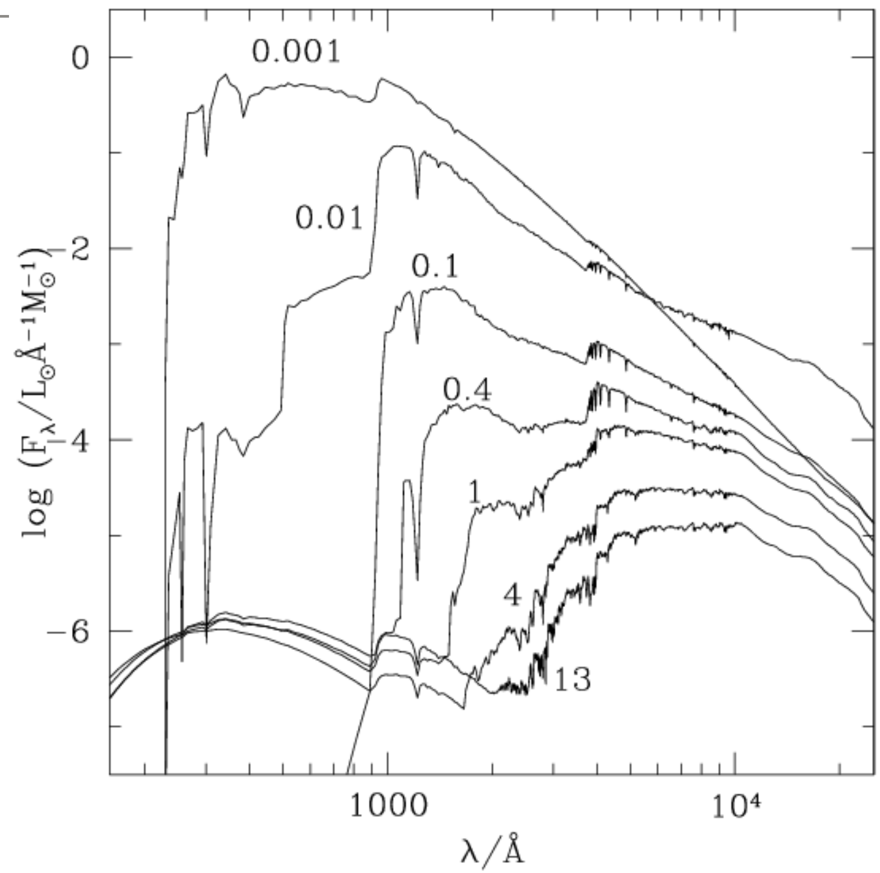
Chemical evolution

- Only hydrogen and helium and small traces of lithium were formed in the Big Bang. All other elements have been later synthesized in stars.

1. The Luminosity and colour of galaxies depend on their metallicity.
2. Cooling processes are very sensitive to the gas metallicity.
3. Dust grains consist of heavy elements (C, O, Si, etc.) and depend on the metallicity. Higher amount of dust cause higher levels of extinction.

Stellar population synthesis

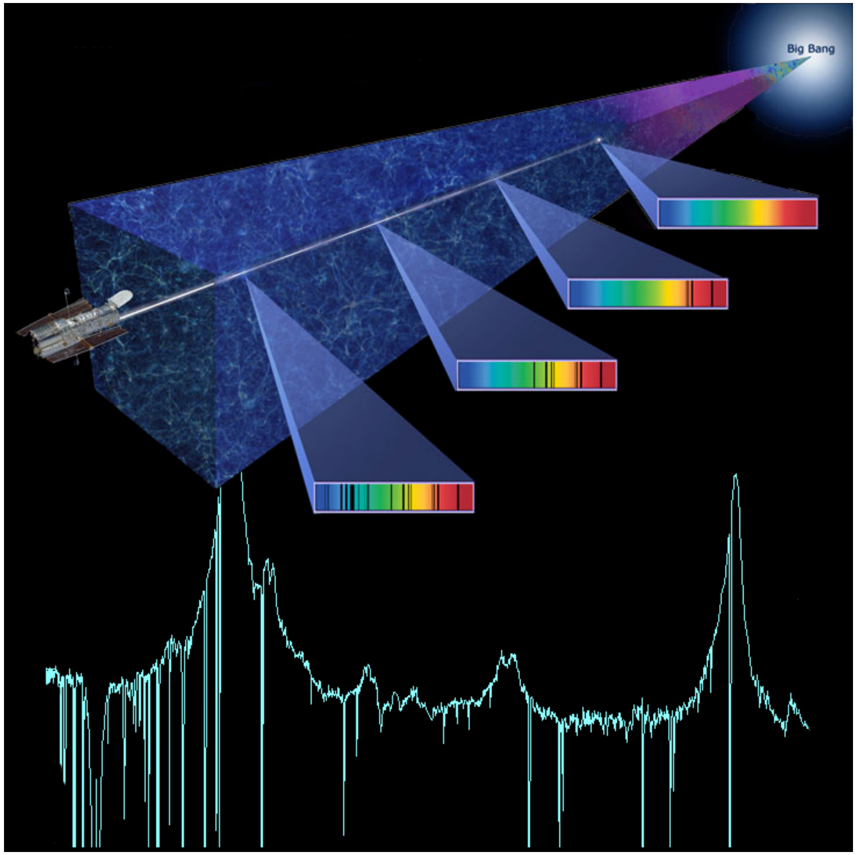
- The stellar light from a galaxy is the sum of the light of all its stars.
- Unlike galaxy formation, the theory of stellar evolution is relatively well understood.
- If we know the star formation history and IMF of a galaxy we can then synthesize its spectrum at any given time.
- Most of the normal stellar light is produced in the optical. Very young stars emit in the UV and dusty objects in the infrared.



The numbers in the plot indicate the age of the simple stellar population in Gyr.

The intergalactic medium

- The intergalactic medium is the baryonic material that lies between galaxies.
- This is and has always been the dominant baryonic component in the Universe and the material from which galaxies form.
- Galaxies do not evolve as closed boxes, but affect the properties of the IGM through exchanges of mass, energy and heavy elements caused by feedback processes.



1.3 Timescales I

- The galaxy formation process is a competition among different processes, such as the collapse of dark matter, gas cooling, star formation etc. The relative importance of the various processes at various stages in a galaxies life is determined by whichever timescale is shortest and thus dominates:
- **Hubble time:** Time scale at which the Universe as a whole evolves, $t=H(z)^{-1}$.This is the time scale on which substantial evolution of the galaxy population takes place.
- **Dynamical time:** This is the time required to orbit across an equilibrium dynamical system: For a uniform, pressureless sphere of mass M and radius R:

$$t_{\rm dyn} = \sqrt{\frac{3\pi}{16G\bar{\rho}}}, \quad t_{\rm ff} = t_{\rm dyn}/\sqrt{2}$$

Timescales II

- **Cooling time:** This is the ratio between the thermal energy content and the energy loss rate through cooling for the gas component.
- **Star-formation timescale:** This is the ratio between the cold gas content of a galaxy and the star-formation rate.
- **Chemical enrichment time:** This is a measure for the time scale on which the gas is enriched by heavy elements. In general different for different elements.
- **Merging time:** The typical time a galaxy must wait before experiencing a merger with an object of similar mass.
- **Dynamical friction time:** The timescale on which a satellite object in a large halo loses its orbital energy and spirals to the centre. It is proportional to the mass ratio M_{sat}/M_{main}.

Implications of the timescales

- Processes for which the timescale is longer than the Hubble time can usually be ignored. For example the dynamical friction times for low mass galaxies in galaxy clusters is longer than the Hubble time, thus galaxy clusters with separate galaxies exist.
- If the cooling time is longer than the dynamical time, the hot gas will typically be in a hydrostatic equilibrium. In the opposite case the gas cools and collapses to the centre on the free fall time.
- If the star formation time is comparable to the dynamical time, the gas will turn into stars during its initial collapse -> elliptical. If the star formation time is much longer than the dynamical and cooling time, the gas will first form a centrifugally supported disk before SFR -> disk.
- If the chemical evolution is longer than the star-formation time, little metal enrichment will occur during star formation -> same initial metallicity.

1.4 Brief history of galaxy formation

- The ideas of gravitational instability was developed by Jeans (1902) for a static Universe and Gamow & Teller (1939) and Lifshitz (1946) for an expanding medium.
- Most of the early models of structure models assumed that the Universe consists of two components: ordinary baryonic matter and radiation.
- Two distinct models for the perturbations were considered:

1. Adiabatic models: All matter and radiation fields are perturbed in the same way so that the total density (or local curvature) varies, but the ratio of photons and baryons are spatially invariant.
2. Isothermal (or isocurvature) models: Correspond to initial perturbations in the ratio of the mass components, but with no associated spatial variation in the total density or curvature.

Predictions of the first models

- In the adiabatic case, the perturbations can be considered as applying to a single fluid. Radiation and matter remain tightly coupled and the Jeans' mass is very large and small-scale perturbations execute acoustic oscillations. Furthermore, photon diffusion (Silk dampening) damps small scale oscillations below 10^{12}-10^{14} $M_{\odot}$. After recombination structure must form top-down, i.e. large structure form first followed by smaller structures.
- In the isothermal case, the pressure is spatially uniform and there is no acoustic oscillations. If the initial perturbation include small-scale structure this survives until after the recombination epoch, when baryon fluctuations can collapse. In this model structure forms bottom-top, i.e. small structures form first followed by larger structures.

Dark matter and galaxy formation I

- A fundamental problem in structure formation models without dark matter is the fact that the observed density perturbations in the CMB are of the order $\delta\rho/\rho \sim 10^{-5}$ at z~1100. However, in an expanding Universe the perturbations can only grow by a factor of ~1100 and galaxies would not have enough time to form.
- Observations in the 1970s , together with numerical stability models made it increasingly clear that galaxies must contain unseen non-baryonic dark matter.
- **Hot dark matter models:** The first DM candidate was neutrinos, which would be hot relativistic dark matter meaning that their high thermal motions would result in the first objects being very massive (10^{14}-10^{15} $M_\odot$) as predicted in the Zeldovich pancake theory.

Dark matter and galaxy formation II

- **Cold dark matter models:** In these models the dark matter particles are weakly interacting massive particles (WIMPs, e.g. the supersymmetric neutralino, an axion or something similar).
- The lower thermal velocities result in the survival of fluctuations of galactic scale and the DM particles decouple from the radiation field long before the recombination, so perturbations in their density can grow at early times to be substantially larger than the fluctuations visible in the CMB. After recombination the baryonic matter then falls into the potential wells formed by the CDM perturbations.
- This picture together with the ΛCDM cosmology is currently our best model for structure, although note that the true nature of both Λ and CDM are currently not known.

What have we learned today?

1. In order to understand galaxy formation we have to know 1) the cosmological background model, 2) the initial conditions and 3) the relevant astrophysical processes.
2. Galaxy formation is a series of “messy” astrophysical processes taking place on vast length and time scales. The key steps include gravitational instability and collapse of dark matter haloes, followed by gas cooling, star formation and feedback processes.
3. Galaxies do not evolve in isolation as closed boxes. Mergers and inflow/outflow from/to the intergalactic medium play a crucial role in their evolution.
4. The details of the current standard cold dark matter model have only been established in the last 30 years. In this model structure form bottom-top, i.e. small galaxies form first and then merge to form larger galaxies.