The large-scale structure of the Universe

Cristina García Vergara

AstroTwinCoLo (Virtual) School 2020

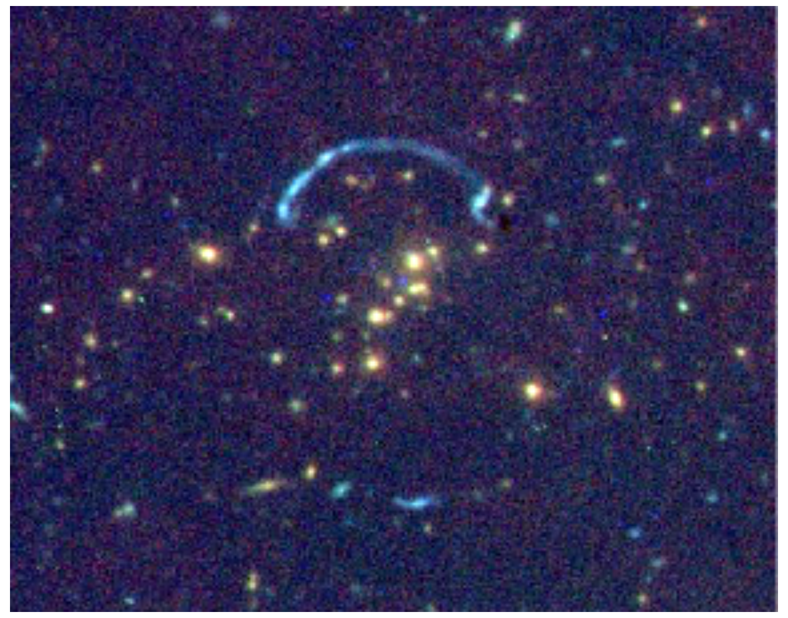
A little bit about myself

A bit of my research

Bachelor in Astronomy at Pontificia Universidad Católica de Chile (PUC)

Prof. Felipe Barrientos

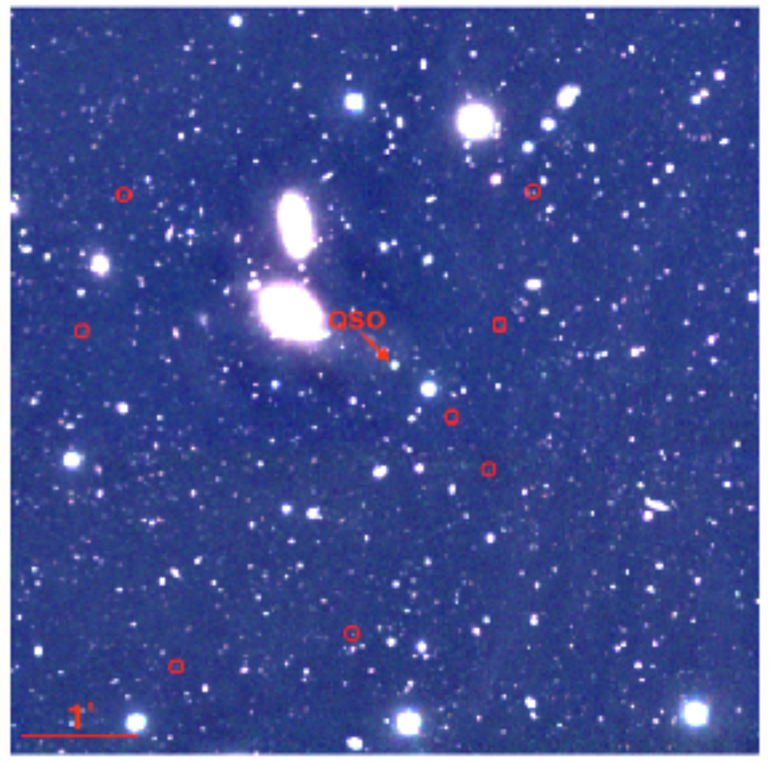
Mass Determination of Galaxy Clusters of RCS2 (Red-Sequence Cluster Survey 2)".

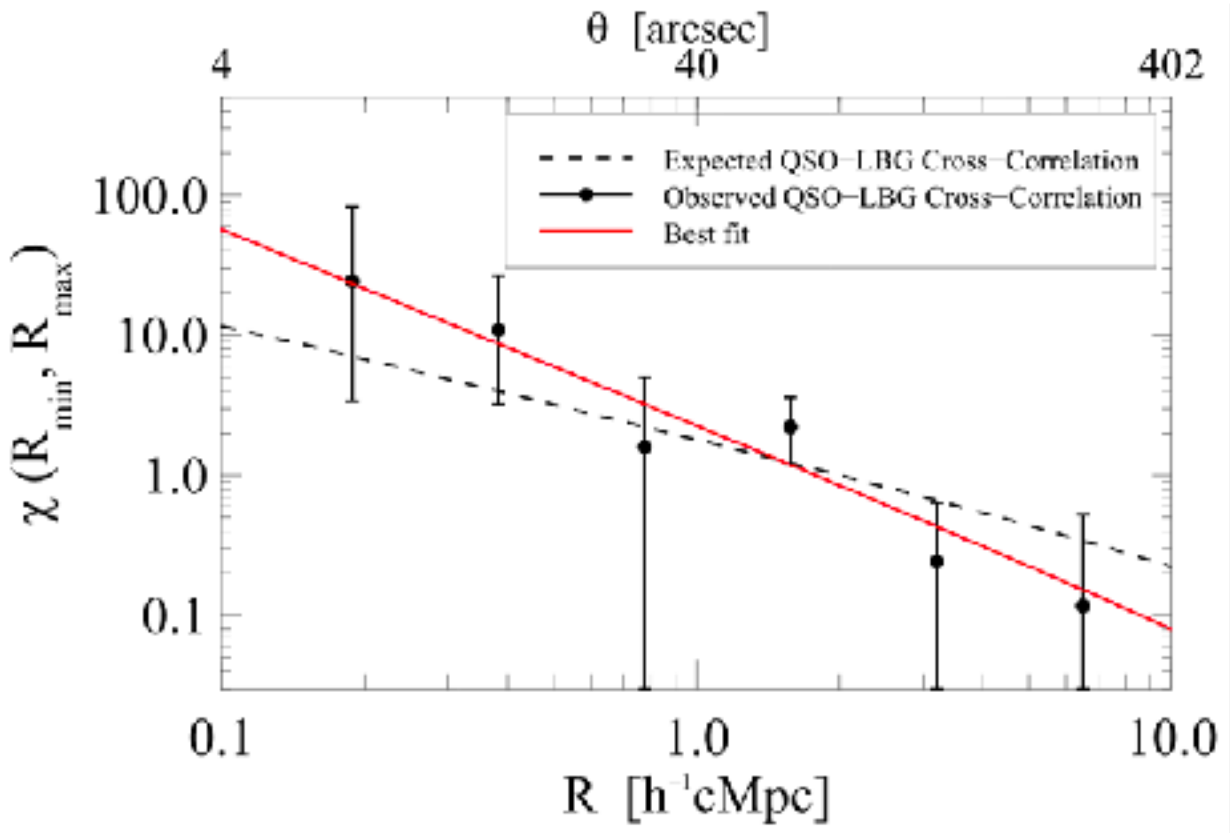


Double **PhD** degree in Astrophysics at PUC and at Max-Planck institute for Astronomy in Germany.

Prof. Felipe Barrientos and Dr. Joseph Hennawi

Quasars Environments at z~4





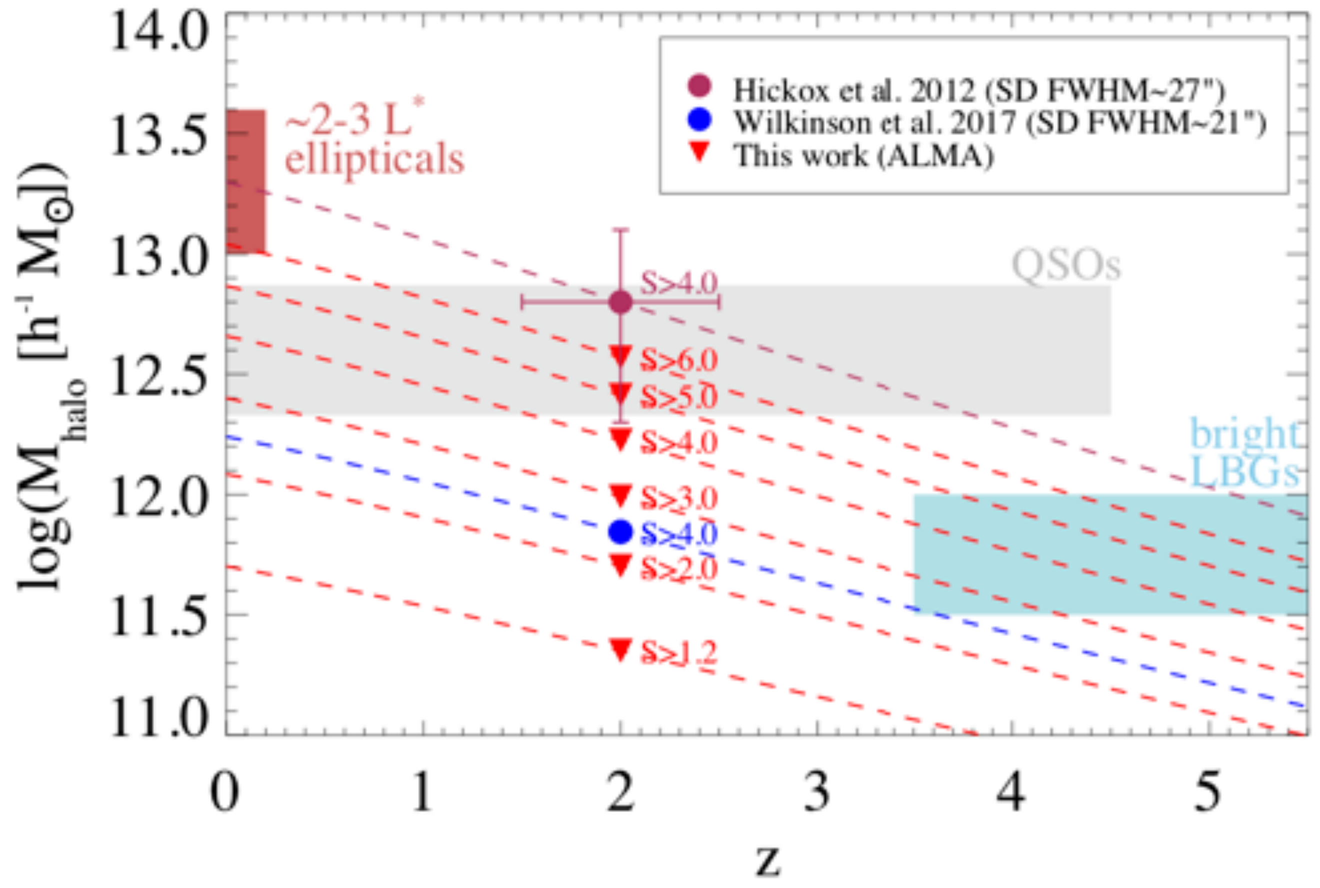
Sterrewacht Leiden

Post-doctoral researcher at Leiden Observatory in the Netherlands since 2016

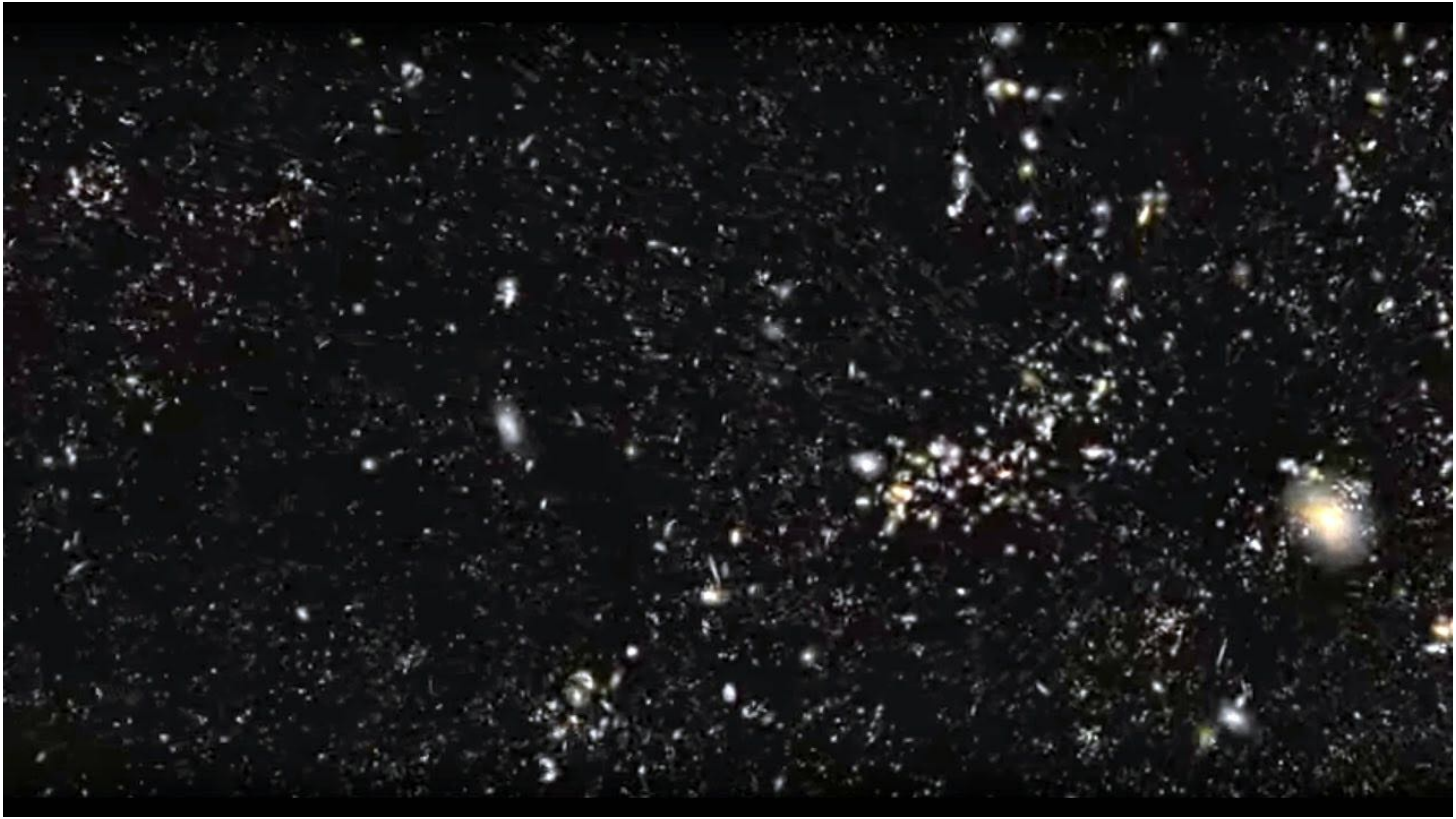
Dr. Jacqueline Hodge and Prof. Huub Röttgering

The clustering of submillimeter galaxies detected with ALMA

The dependence of the clustering of radio sources with their physical properties using LOFAR



The large-scale structure of the Universe



Sloan Digital Sky Survey (SDSS) Data Release 7

Some interesting questions

- What is large-scale structure?
- How the matter is distributed in the universe?
- Have some regions in the universe more matter than other regions?
- Does the matter distribution evolve over time?
- How can we “measure” and quantify the distribution of matter over a volume?
- Why is it important to quantify?
- What information can we get from studying the matter distribution?
- Can we really learn about galaxy evolution with this?

Measuring The large-scale structure of the Universe

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This course

Monday General background: Filaments, nodes, and voids.

Tuesday The two-point correlation function.

Wednesday The dependence of clustering on galaxy properties.

Thursday Galaxy bias and dark matter halo masses.

Friday Using clustering to study galaxy evolution.

This course

Schedule:

(Colombian time)

8:00am - 9:00am: Lecture

9:15am - 10:00am: Lecture

10:25am - 11:15am: Exercises and practical applications

11:30am - 12:00am: Exercises and practical applications

Online class: Ask questions at any time, participate in quizzes (kahoot)

Website of this curse: https://home.strw.leidenuniv.nl/~garcia/#Teaching

Slides will be posted after each lecture

Questions by email: garcia@strw.leidenuniv.nl

General References

- Books:

Schneider, P., 2015: Extragalactic Astronomy and Cosmology (chap. 7 and 8).

Peebles, 1980: The large-scale structure of the universe.

Padmanabhan, T., 1993: Structure formation in the universe.

- Invited contribution:

Coil, A., 2012: Large Scale Structure of the Universe, https://arxiv.org/abs/1202.6633

More specific references mentioned in the slides.

The large-scale structure of the Universe

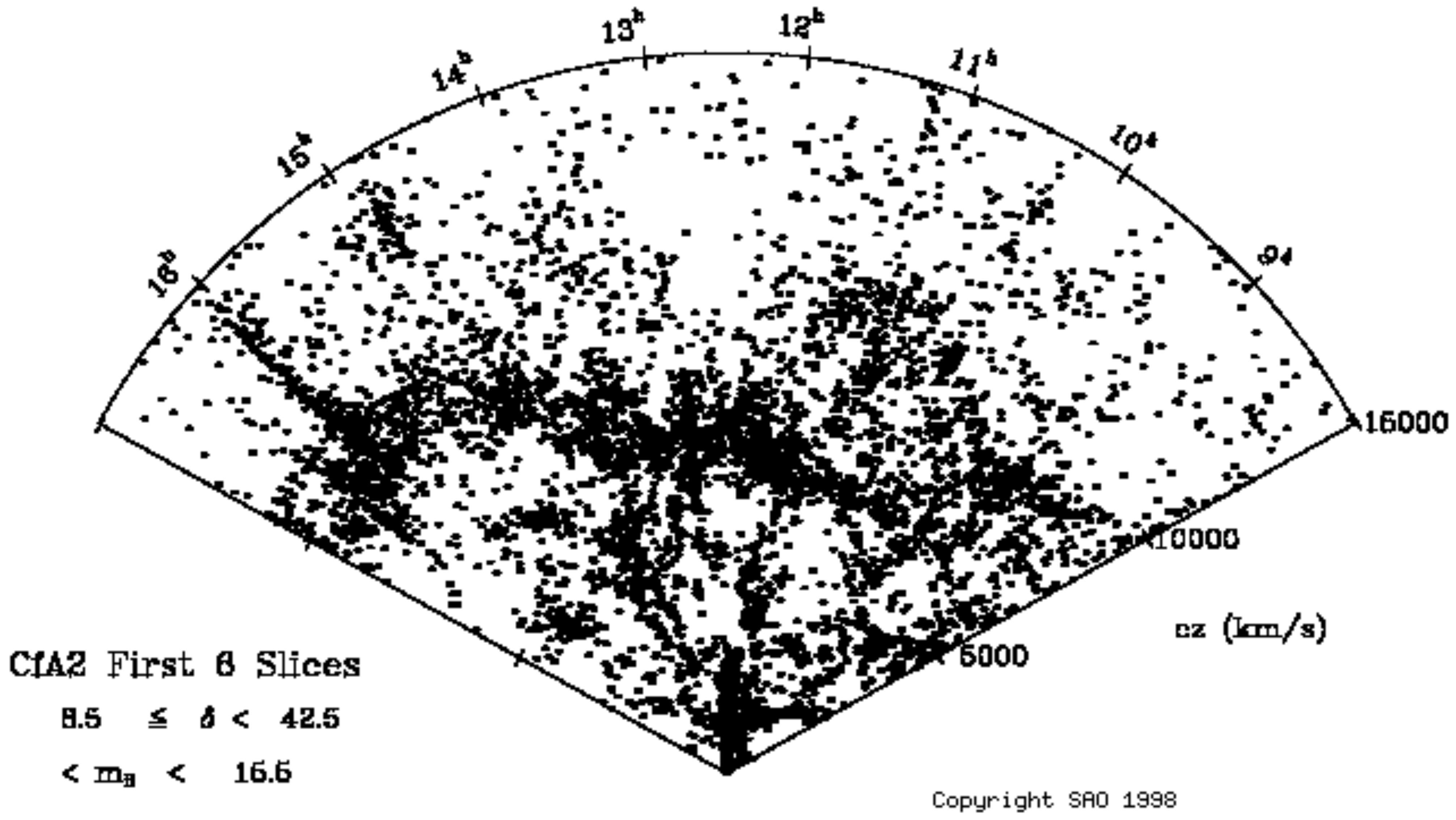
General background: Filaments, nodes, and voids

- General definition: The large-scale structure are all the structures bigger than individual galaxies.

- Galaxy surveys (3D positions of galaxies) allow us to make a map of the large scale-structure.
  - CfA survey carried out in the 1980s: Clearly revealing non-uniform structure.
  - SDSS extended the map up to considerably larger distances. The eBOSS was completed in March 2019.

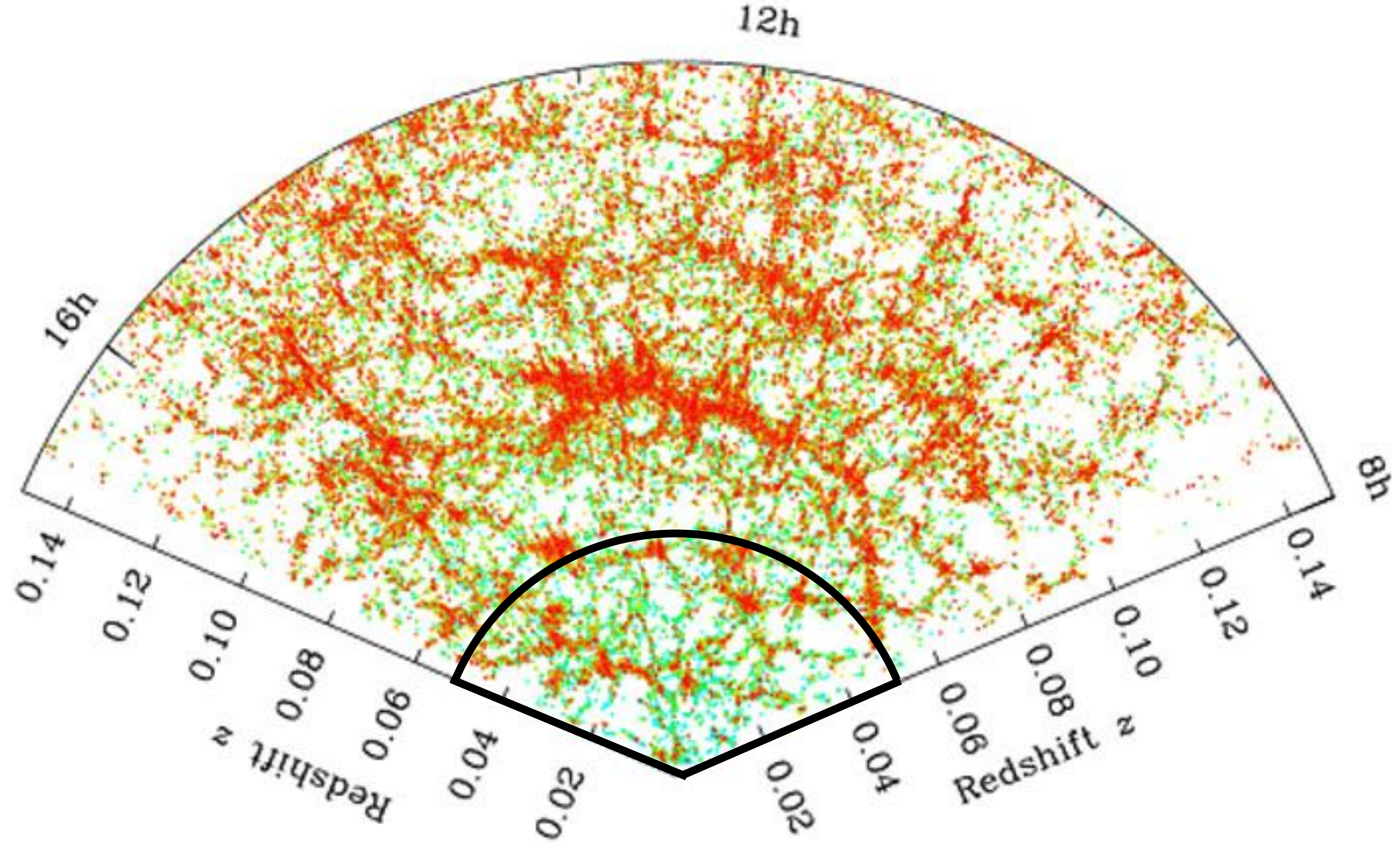
Galaxies are not randomly distributed in the universe, but they tend to be grouped forming a filamentary and clumpy structure.

Distribution of galaxies from the CfA survey carried out in the 1980s



Geller and Huchra 1989

Distribution of galaxies from the SDSS

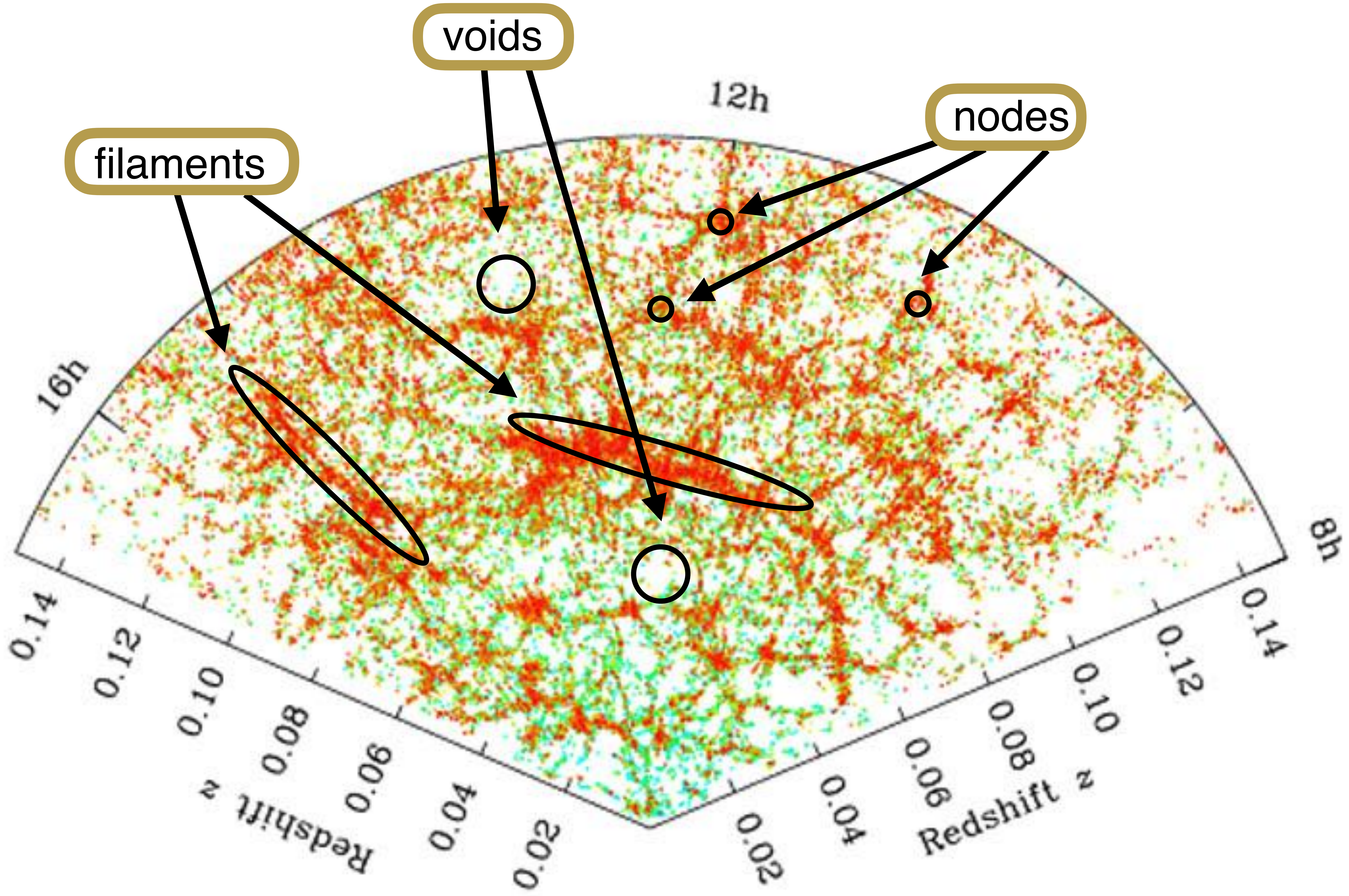


The large-scale structure of the Universe

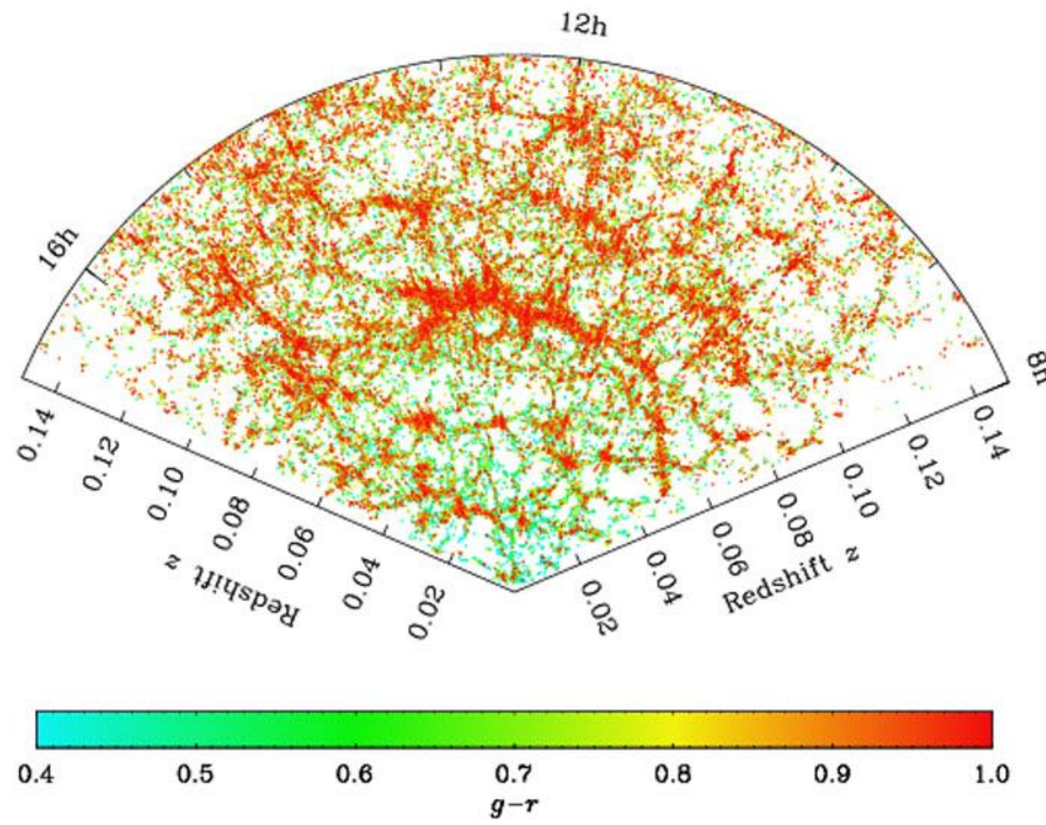
General background: Filaments, nodes, and voids

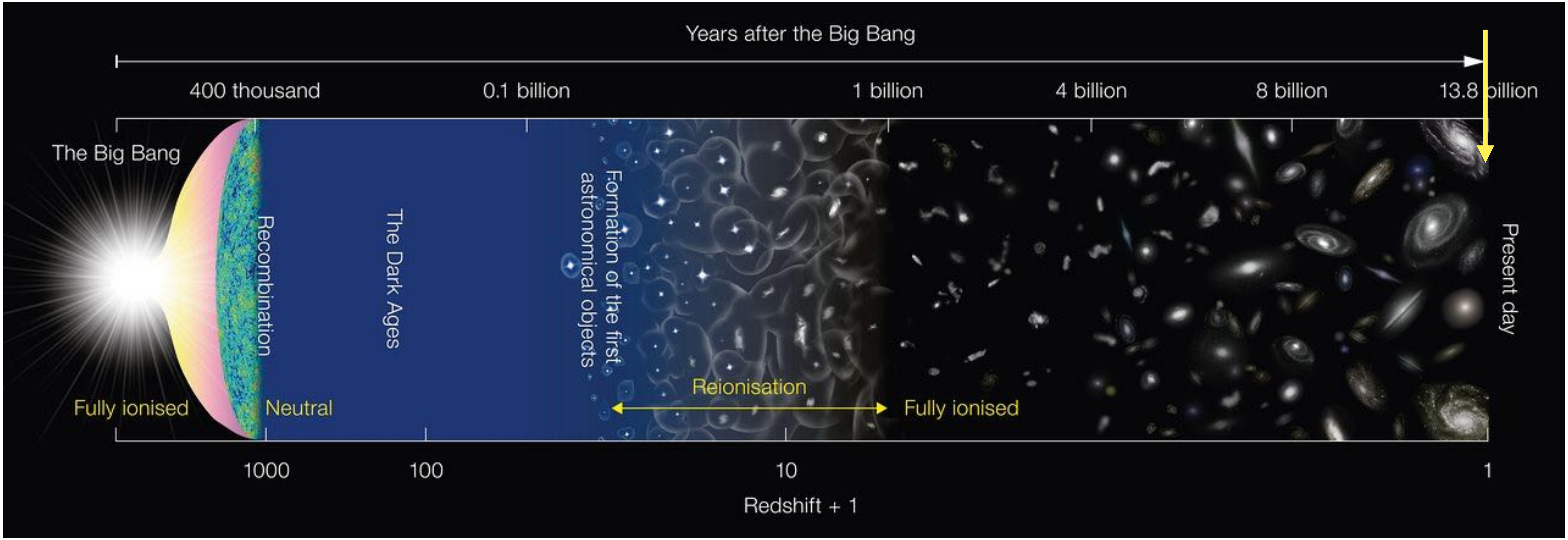
- We can recognize filaments, nodes and voids.
- Galaxies trace dark matter distribution (assume this for now, more details on Lecture 4).
- The density field is inhomogeneous. There are matter overdensities and matter underdensities.
- But, these are observations of the local universe. Did those inhomogenities exist at earlier times in the Universe?

Distribution of galaxies from the SDSS



Structure formation in the Universe





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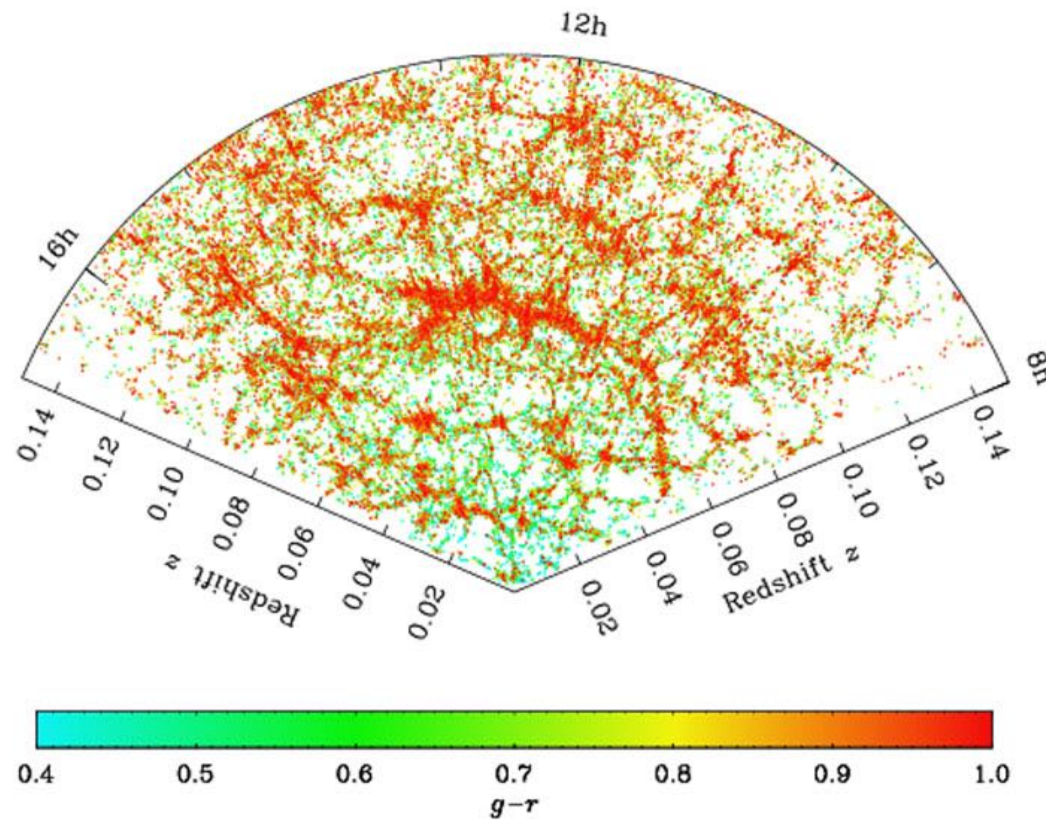
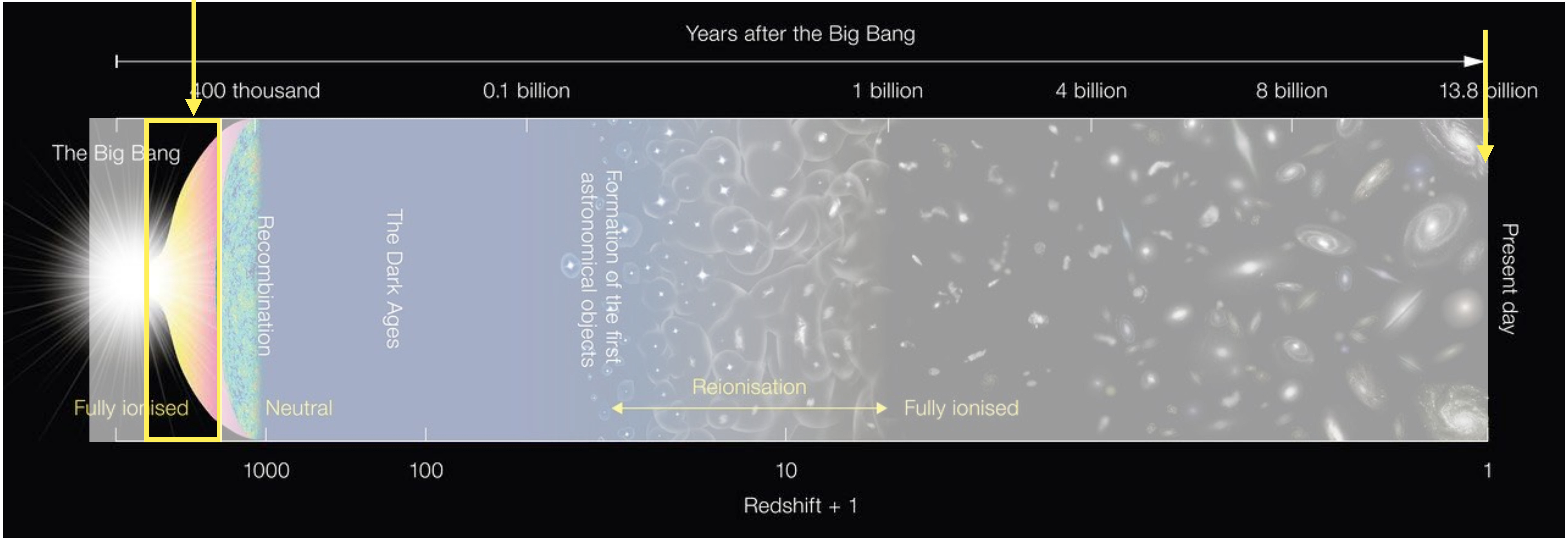


Inflation



Structure formation in the Universe

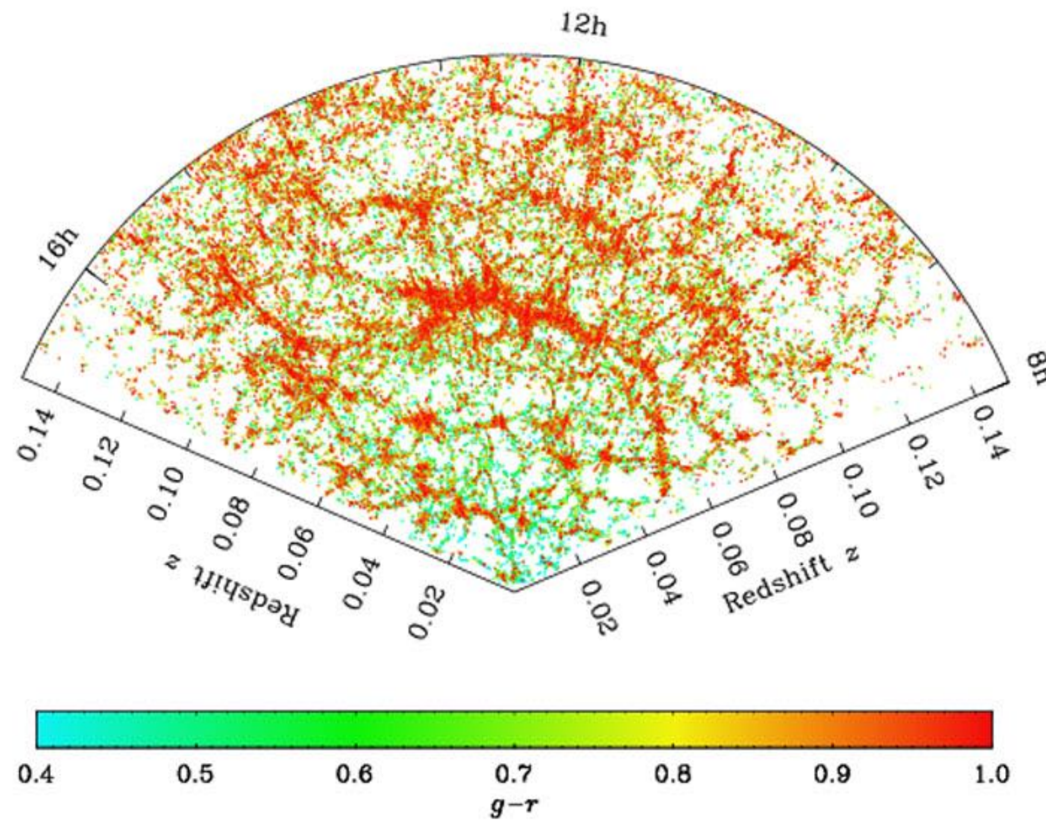
Inflation

- Just after big-bang: Matter distribution cannot be fully homogeneous, but it is subject to small quantum fluctuations (quantum mechanics).

- **Inflation:** An extremely rapid exponential expansion of the universe. The universe increased its volume by a factor of at least 10^{78} in ~10^{-32} secs!

- According to the model of inflation, quantum fluctuations were amplified and formed the seed of all current observed structure.

Structure formation in the Universe



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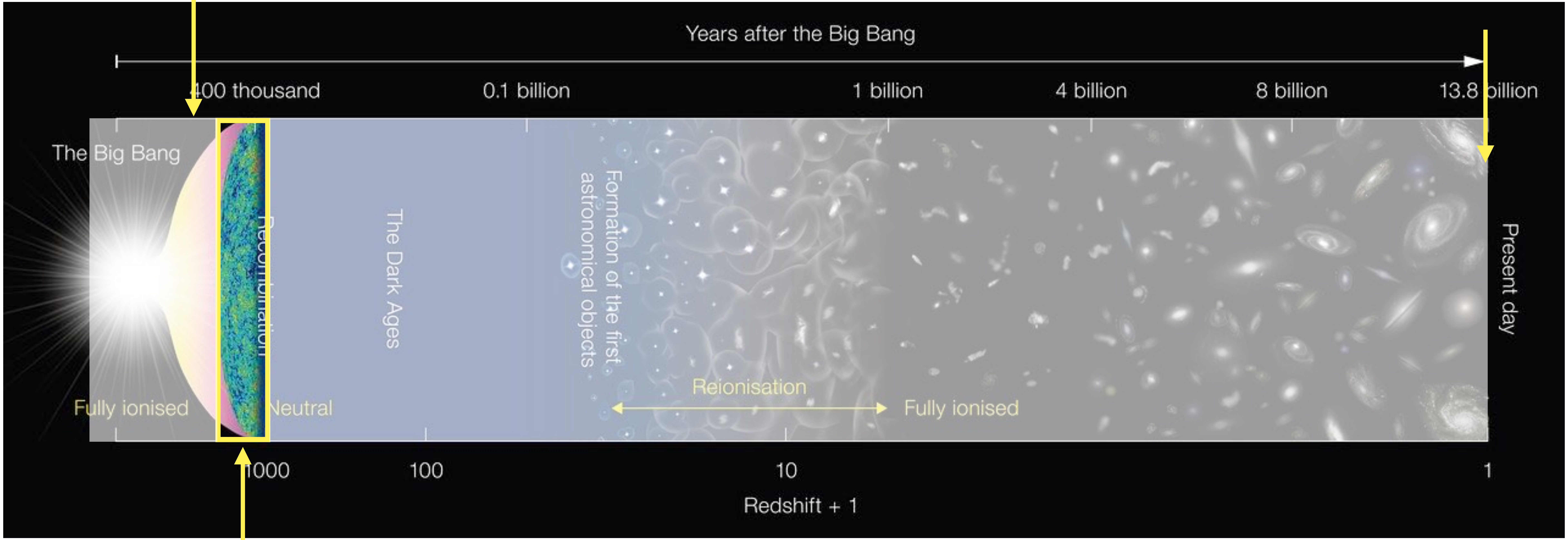
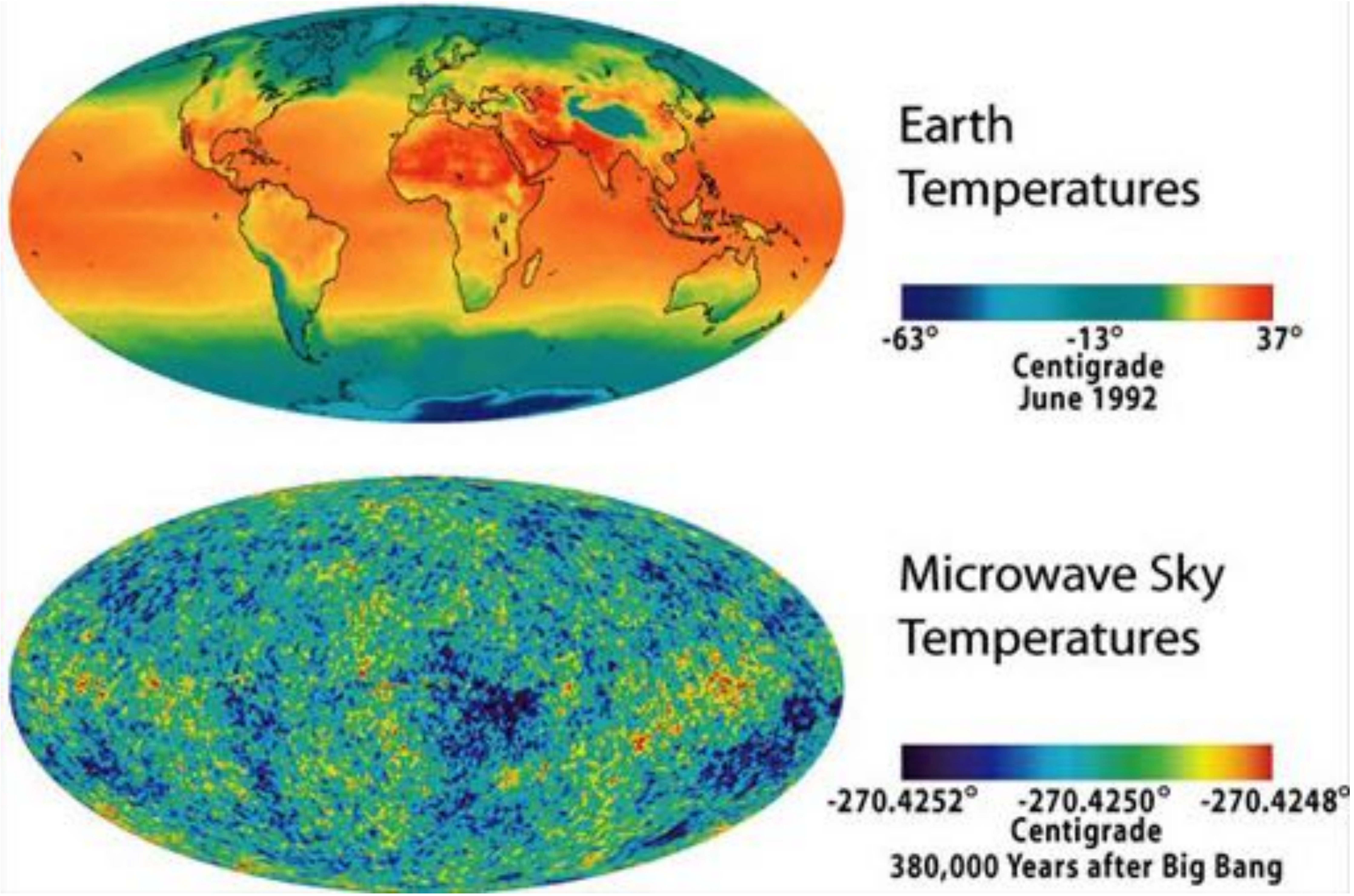


CMB

Structure formation in the Universe: Cosmic microwave background (CMB)

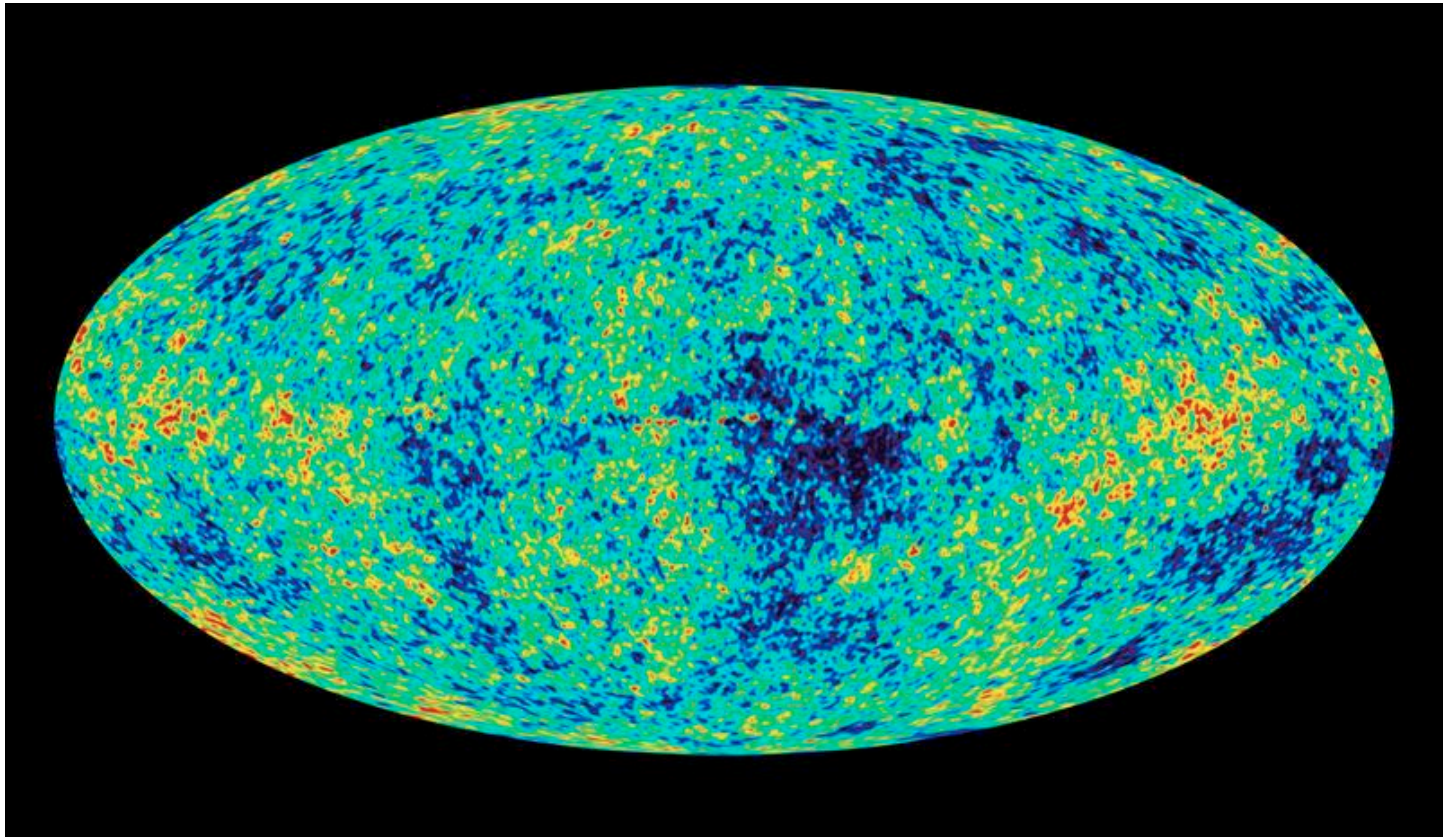


Structure formation in the Universe: Cosmic microwave background (CMB)

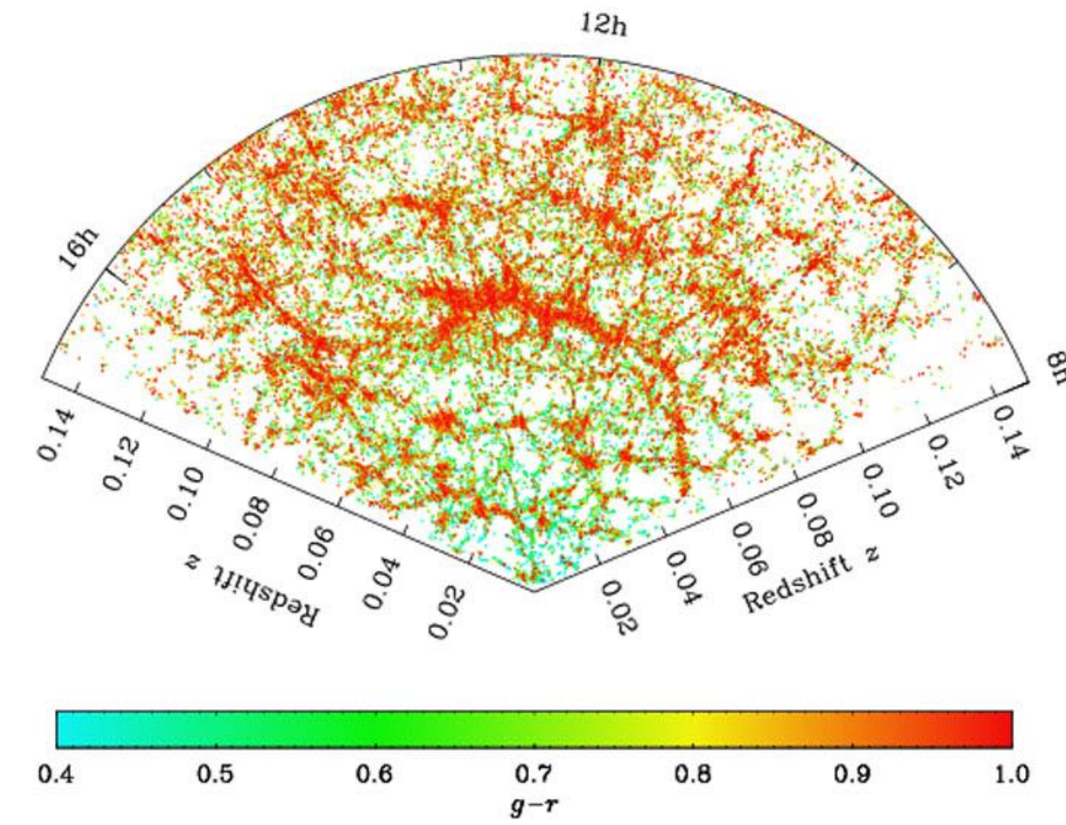
CMB: Cosmic microwave background

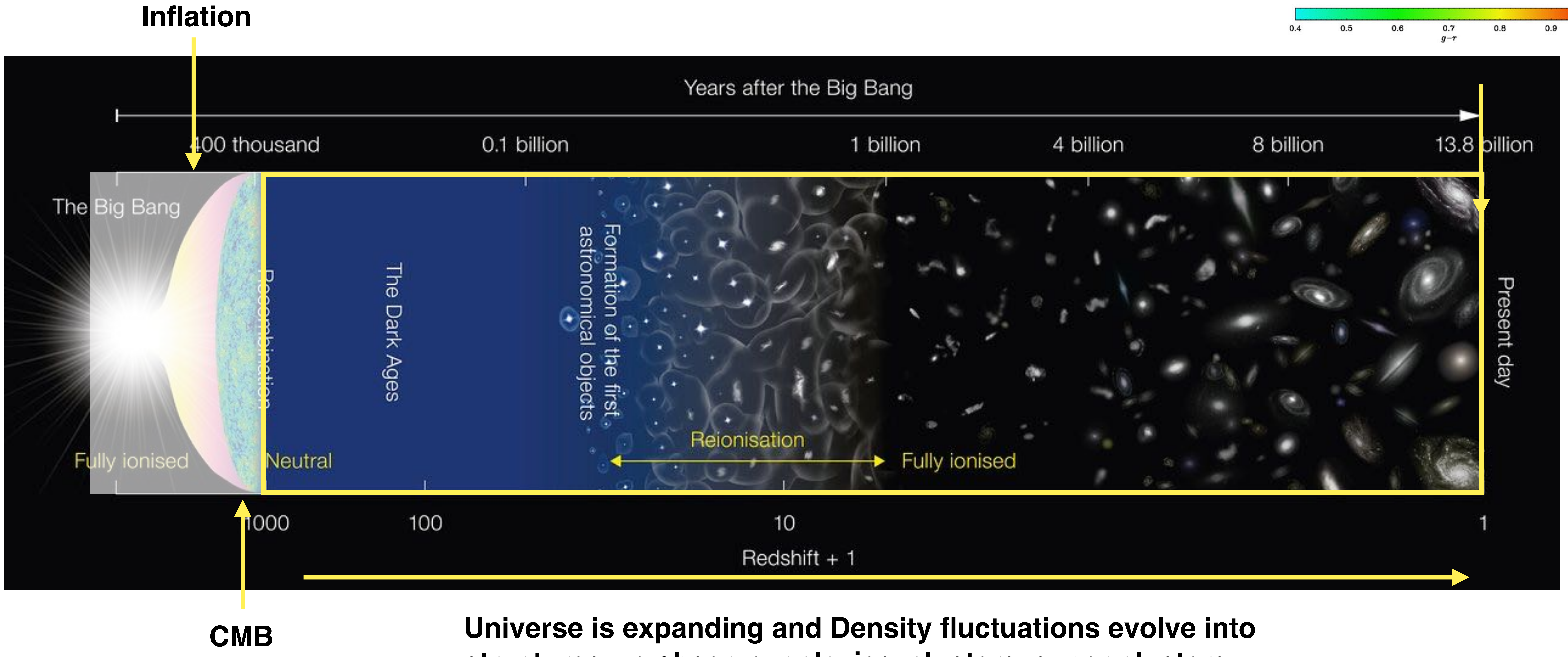
- It is a thermal radiation coming from $z \sim 1100$.
- Firstly observed by Penzias and Wilson in 1965.
- The universe seems to be homogeneous at large scales, but is clumpy at smaller scales.
- Relative temperatures fluctuations of $\Delta T/T \sim 10^{-5}$, which indicates that the Universe already showed small inhomogenities at $z \sim 1100$.

CMB is the observational evidence of the existence of matter inhomogeneities in the early universe



Structure formation in the Universe

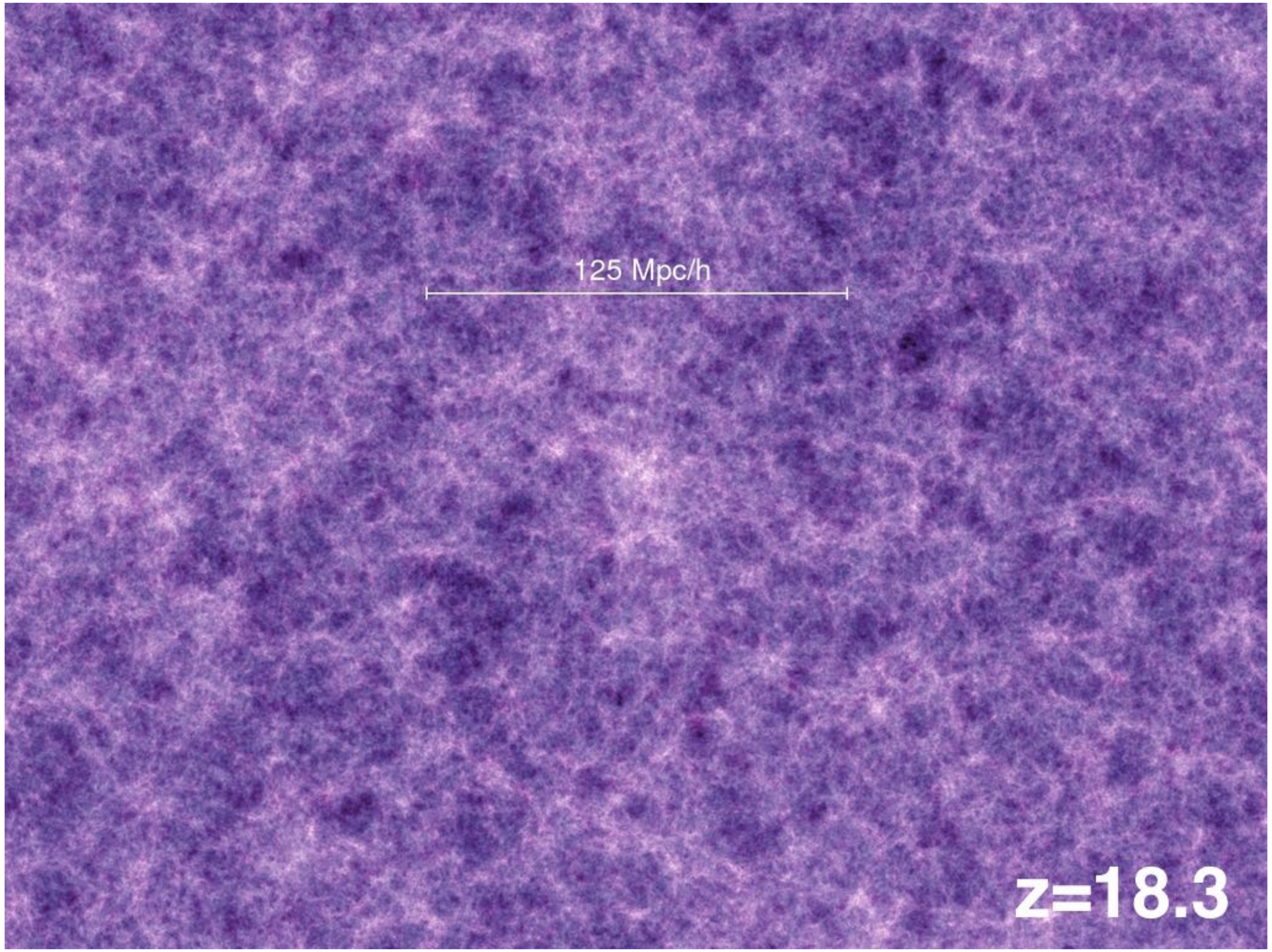




Universe is expanding and Density fluctuations evolve into structures we observe: galaxies, clusters, super-clusters.

Structure evolution in the Universe: Small fluctuations in the density field grow over time

Dark matter distribution in the universe

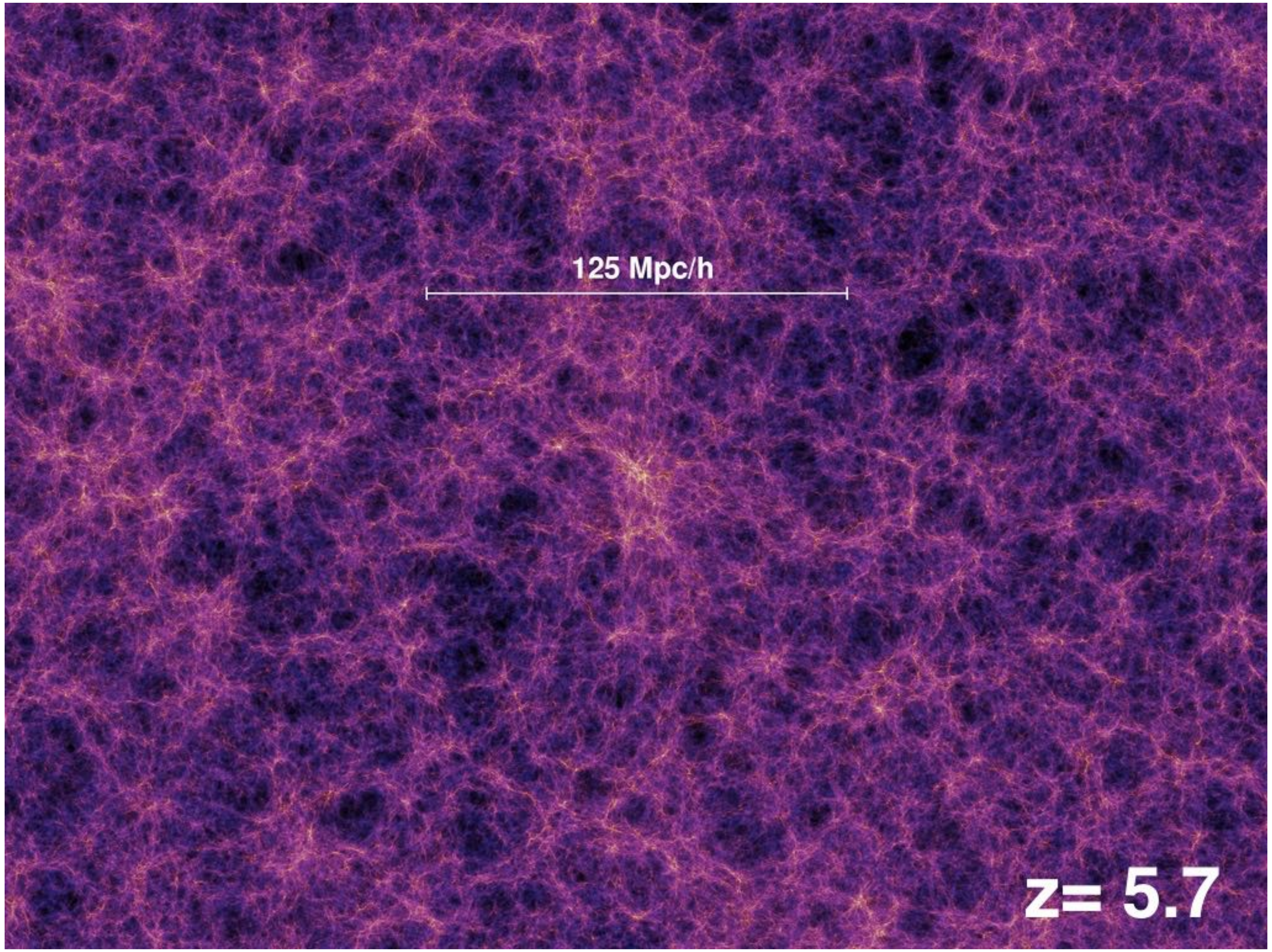


(Springel et al. 2005, Millennium Simulation)

In the standard scenario for the structure formation, it is suggested that structures grow hierarchically through gravitational instability.

Structure evolution in the Universe: Small fluctuations in the density field grow over time

Dark matter distribution in the universe



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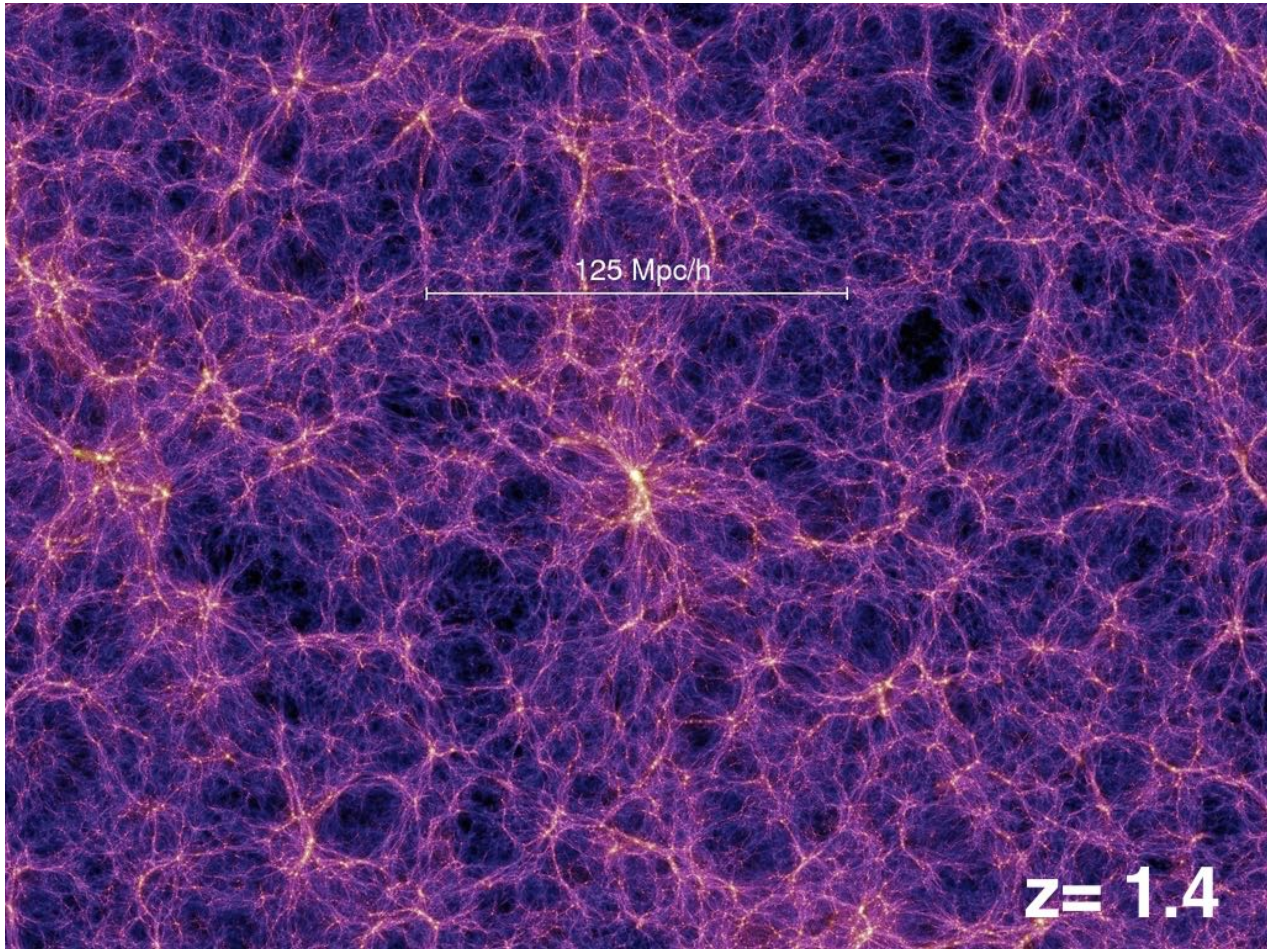

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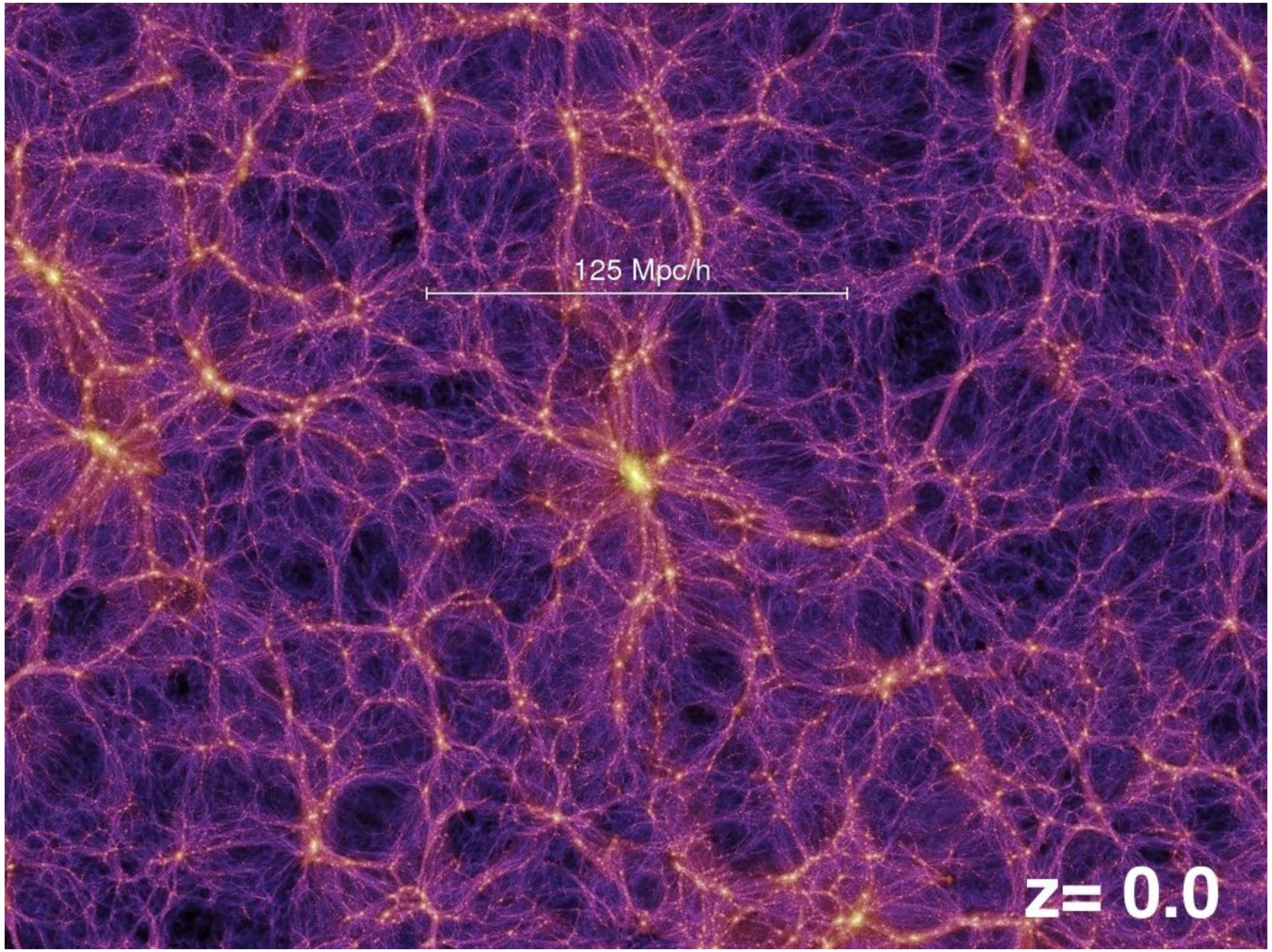
Structure evolution in the Universe:
Small fluctuations in the density field grow over time

Dark matter distribution in the universe



(Springel et al. 2005, Millennium Simulation)

In the standard scenario for the structure formation, it is suggested that structures grow hierarchically through gravitational instability.

Structure evolution in the Universe: Gravitational instability (qualitatively*)

* The mathematical description of the growth of density perturbations will not be covered in this course

Dark matter distribution

Some definitions:

- Density field
- $\rho(r,t)$ matter density in a specific time t and position r in the Universe.
- $\bar{\rho}(t)$ mean matter density in the Universe at time t.
- Relative density contrast (matter overdensity):

$$\delta(r,t) = \frac{\rho(r,t) - \bar{\rho}(t)}{\bar{\rho}(t)} \longrightarrow$$

Homogeneous fields: $\delta(r,t) = 0$

Small inhomogenities: $|\delta(r,t)| \ll 1$

Large inhomogenities: $|\delta(r,t)| \gg 1$

Structure evolution in the Universe: Gravitational instability (qualitatively)

The Hubble expansion is controlled by the average gravitational field, which depends on $\overline{\rho}(t_1)$. → As long as the universe expands, the average density $\overline{\rho}(t)$ decrease.

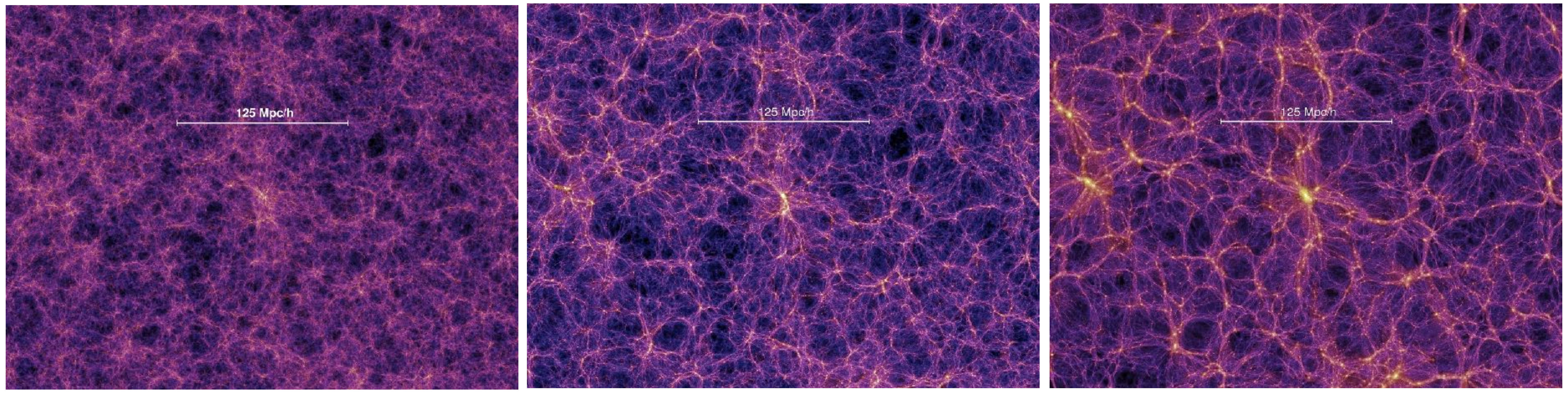
In an overdensity the gravitational field is stronger than the average. → This region will expand slower than the average Hubble expansion, and the density here will decrease slower than the average density. Therefore, the density contrast in this region increase.

$$\delta_1(r,t_1) = \frac{\rho(r,t_1) - \overline{\rho}(t_1)}{\overline{\rho}(t_1)} \quad < \quad \delta_2(r,t_2) = \frac{\rho(r,t_2) - \overline{\rho}(t_2)}{\overline{\rho}(t_2)} \quad < \quad \delta_3(r,t_3) = \frac{\rho(r,t_3) - \overline{\rho}(t_3)}{\overline{\rho}(t_3)}$$

Structure evolution in the Universe: Gravitational instability (qualitatively)

Gravitational instability leads to an increase of density fluctuations with increasing time. Overdense regions become more overdense and underdense regions (voids) become more underdense.

Mathematical description of growth and evolution of structure



Theory of lineal perturbation

Main equations of motion:

Matter conservation (Continuity equation)

Conservation of momentum (Euler equation)

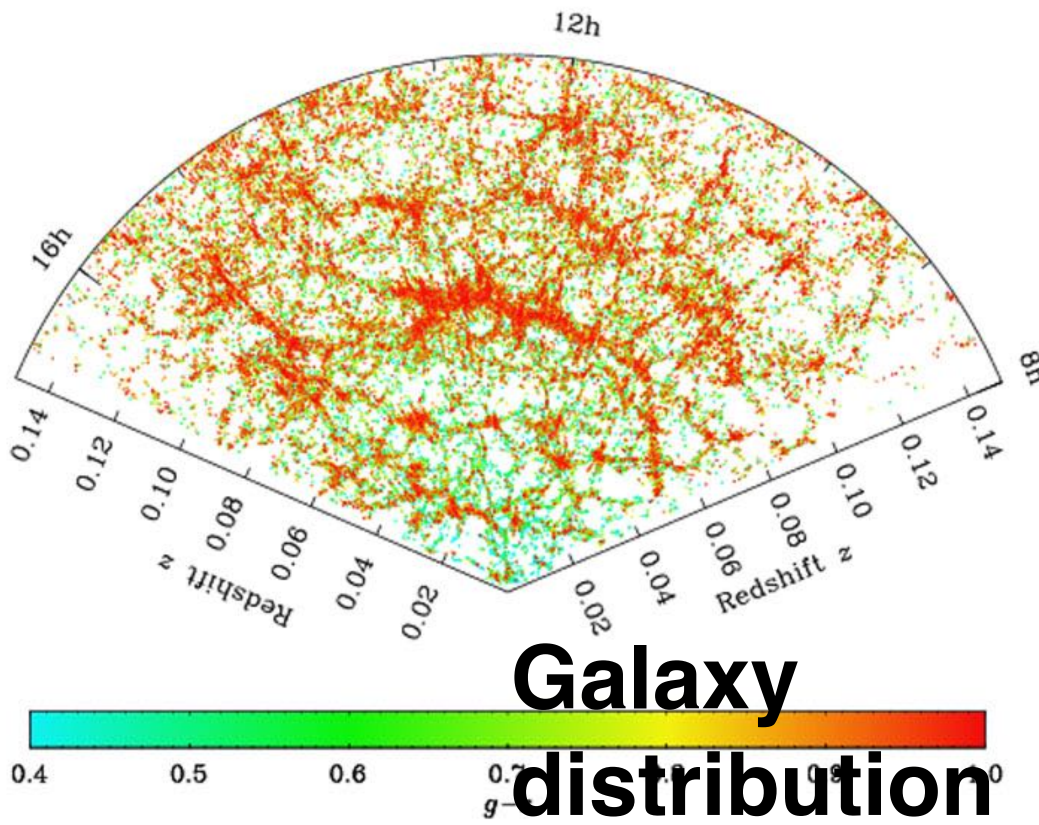
Gravitational field (Equation of poisson)

These are non-linear equations

If we only consider first-order terms in these equation and ignore the others, these can be linearized (and can be solved analytically). If we work at large scales (where the perturbations are small, and delta is small), we can actually ignore these terms.

More details in the books!

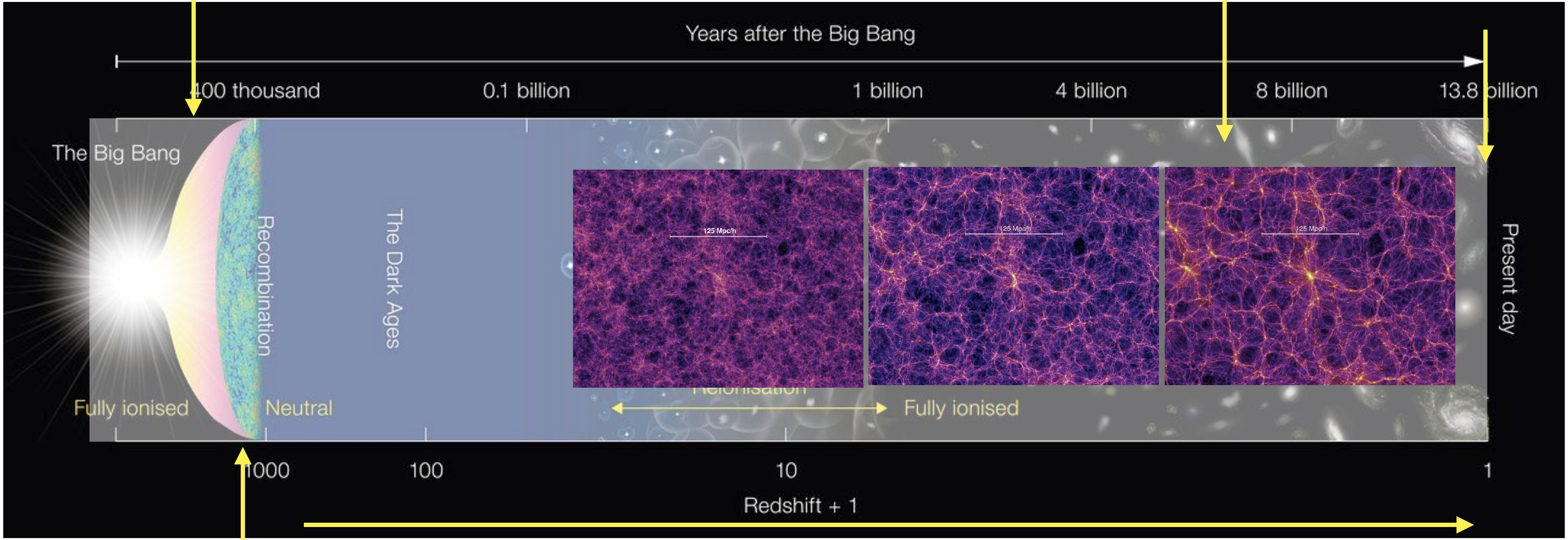
Structure formation in the Universe



Dark matter distribution

Galaxy distribution

Inflation



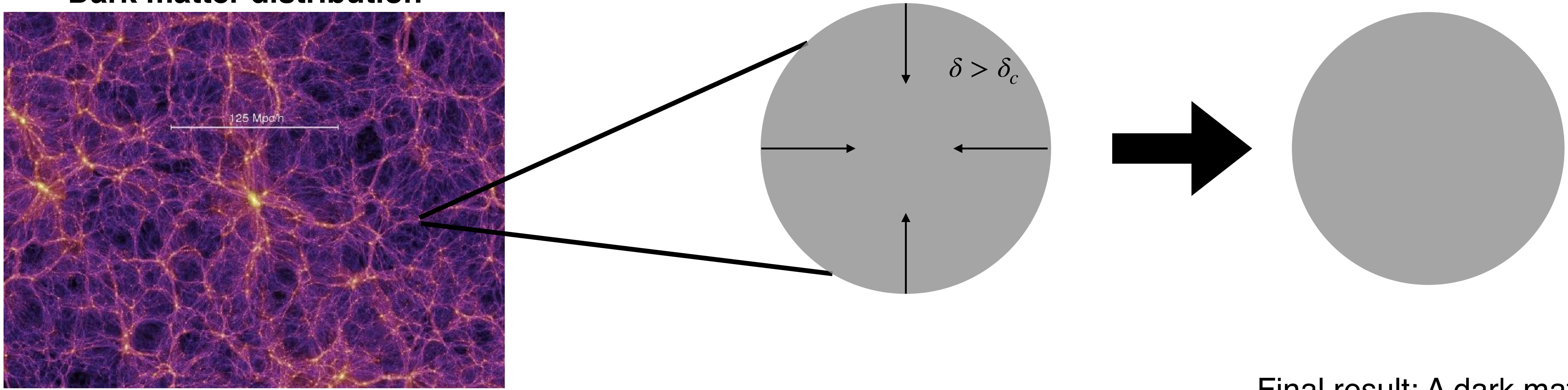
CMB

Universe is expanding and Density fluctuations evolve into structures we observe: galaxies, clusters, super-clusters.

Dark matter halos

Overdensities will not growth their radius infinitely, they growth linearly, but because as their mass is also growing, at some point (density threshold) this will re-collapse to form a dark matter halo (spherical collapse model).

Dark matter distribution



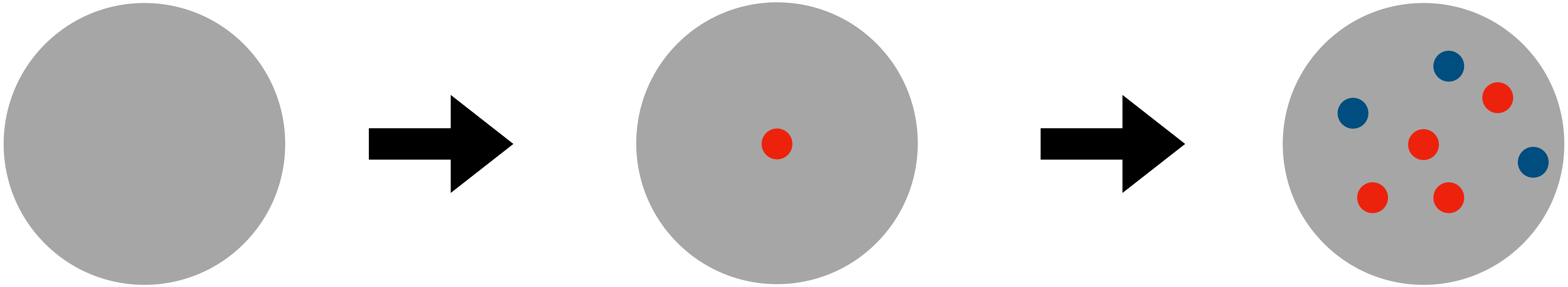
Final result: A dark matter halo in equilibrium.

If the density contrast δ is greater than a certain threshold over a certain volume, then the overdensity will start to collapse (local gravity strongly dominate over the universe expansion)

Dark matter halos are collapsed overdensities in the dark matter distribution with density ~200 times the mean density in the universe, inside of which all mass is gravitationally bound.

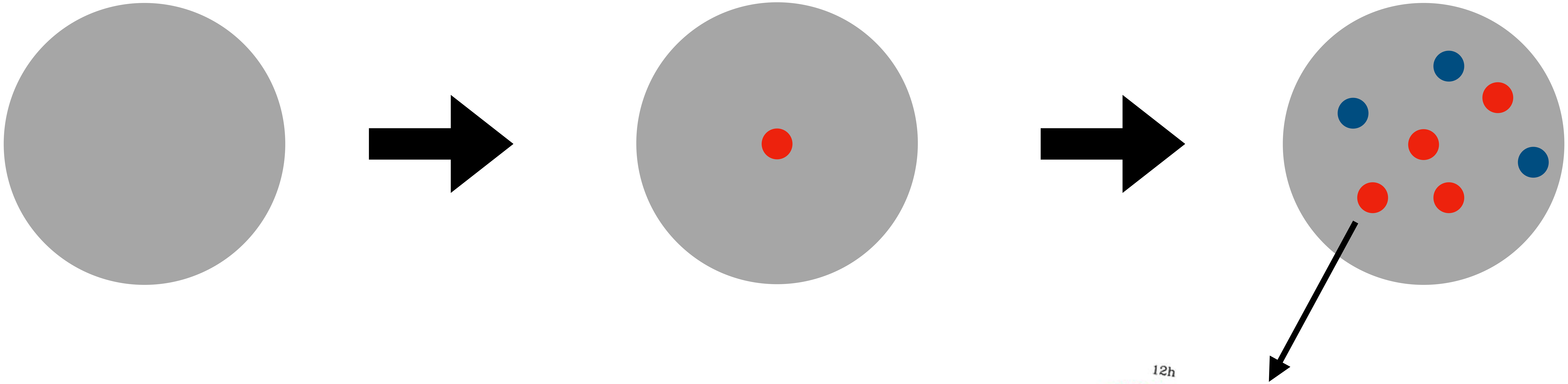
Dark matter halos

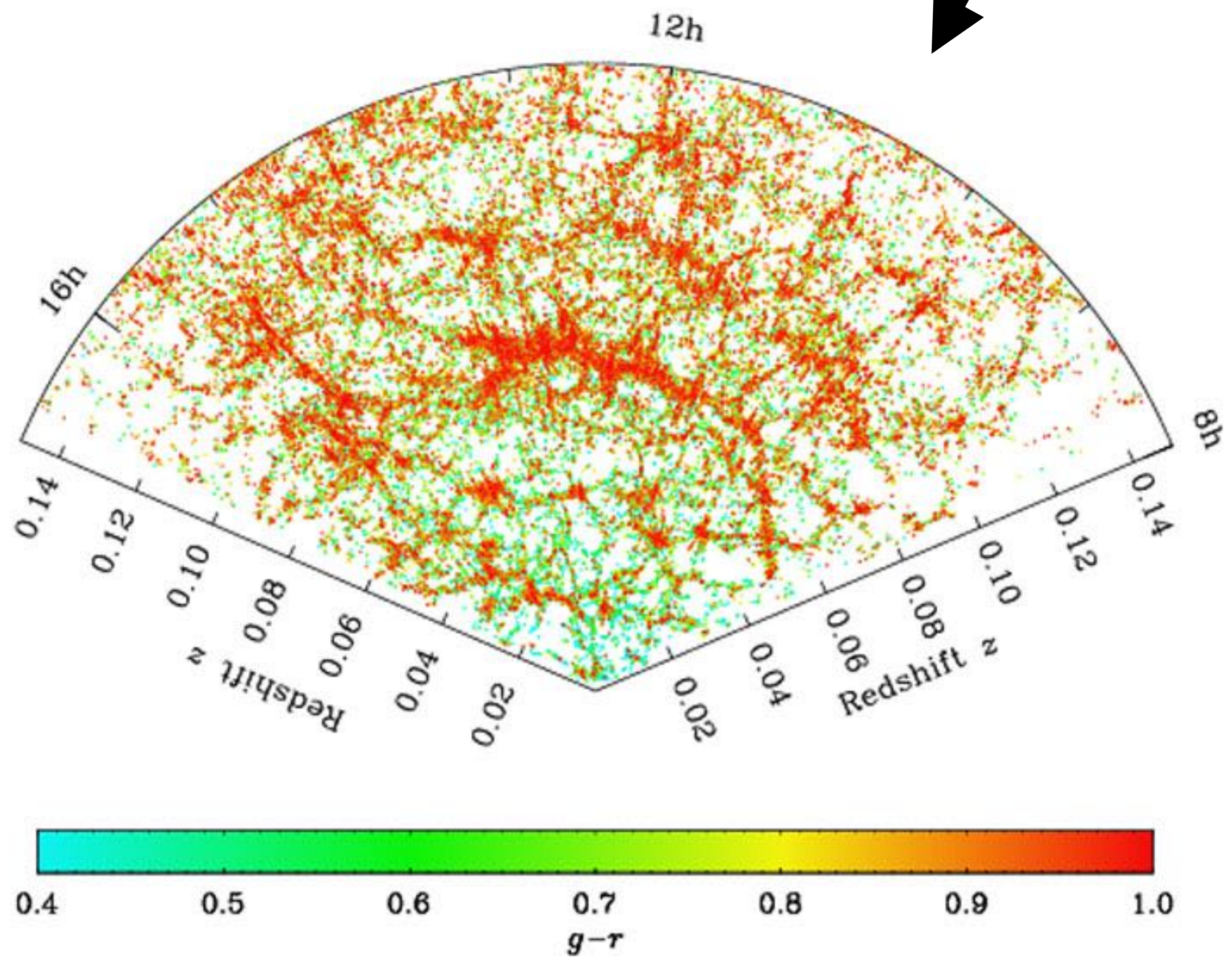
- Galaxies form in the center of the larger dark matter halos.
- To understand how galaxies form we need to understand galaxy formation models (not covered in this course).



- Almost all the dark matter halos, contain a galaxy in their center (central galaxy).
- Dark matter halos can also contain more than one galaxy (satellite galaxies).
- The most massive dark matter halos can contain a lot of satellite galaxies (for example cluster of galaxies).

Dark matter halos





This result i the galaxy distribution I show before (not exactly the same as dark matter distribution (More details in Lecture 4)

Mathematical description of growth and evolution of structure

More details in the books!

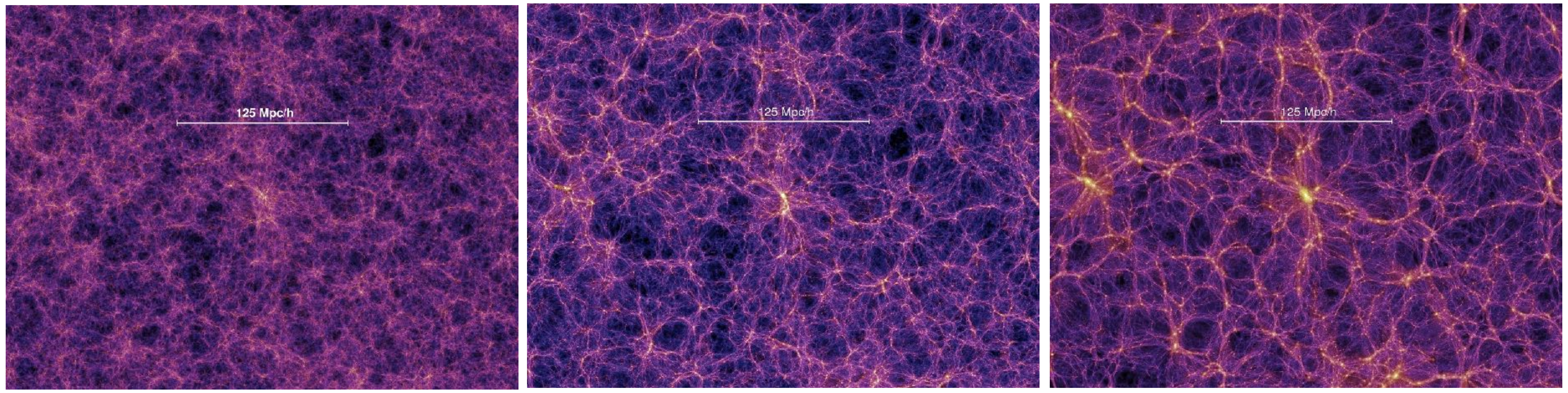
Main equations of motion:

Matter conservation (Continuity equation)

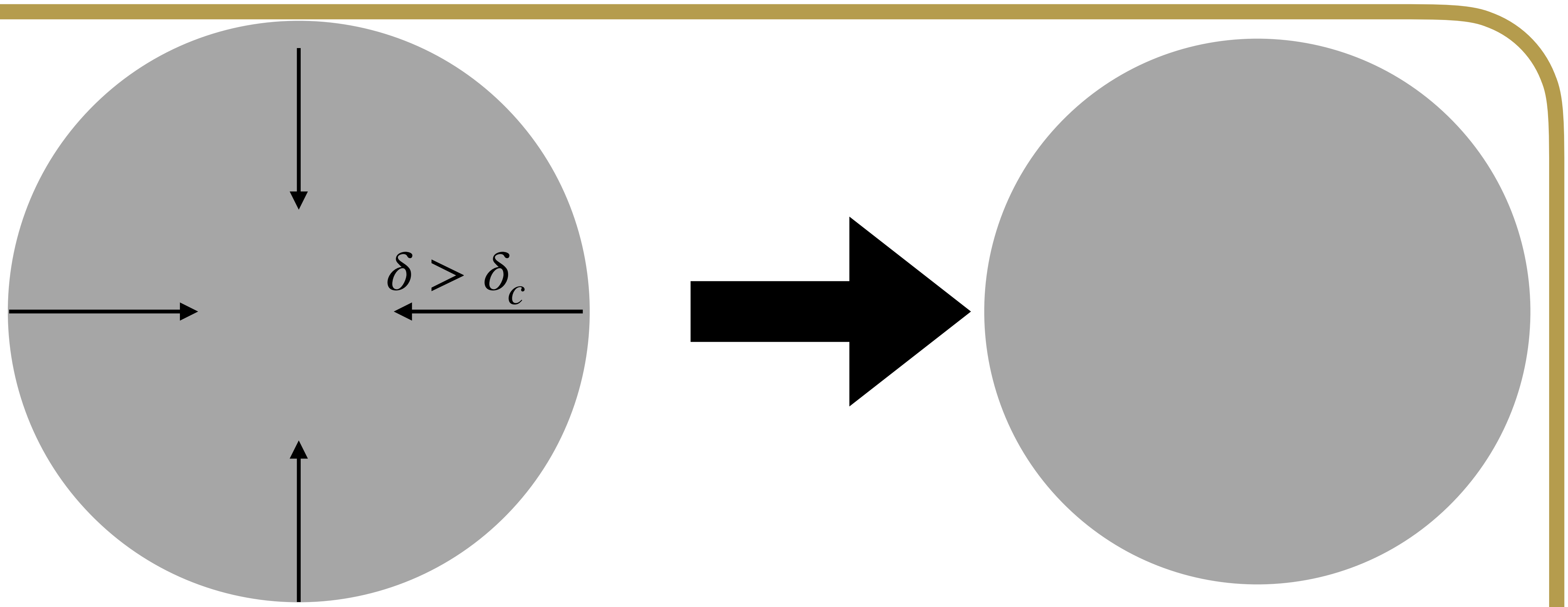
Conservation of momentum (Euler equation)

Gravitational field (Equation of poisson)

These are non-linear equations



Theory of lineal perturbation



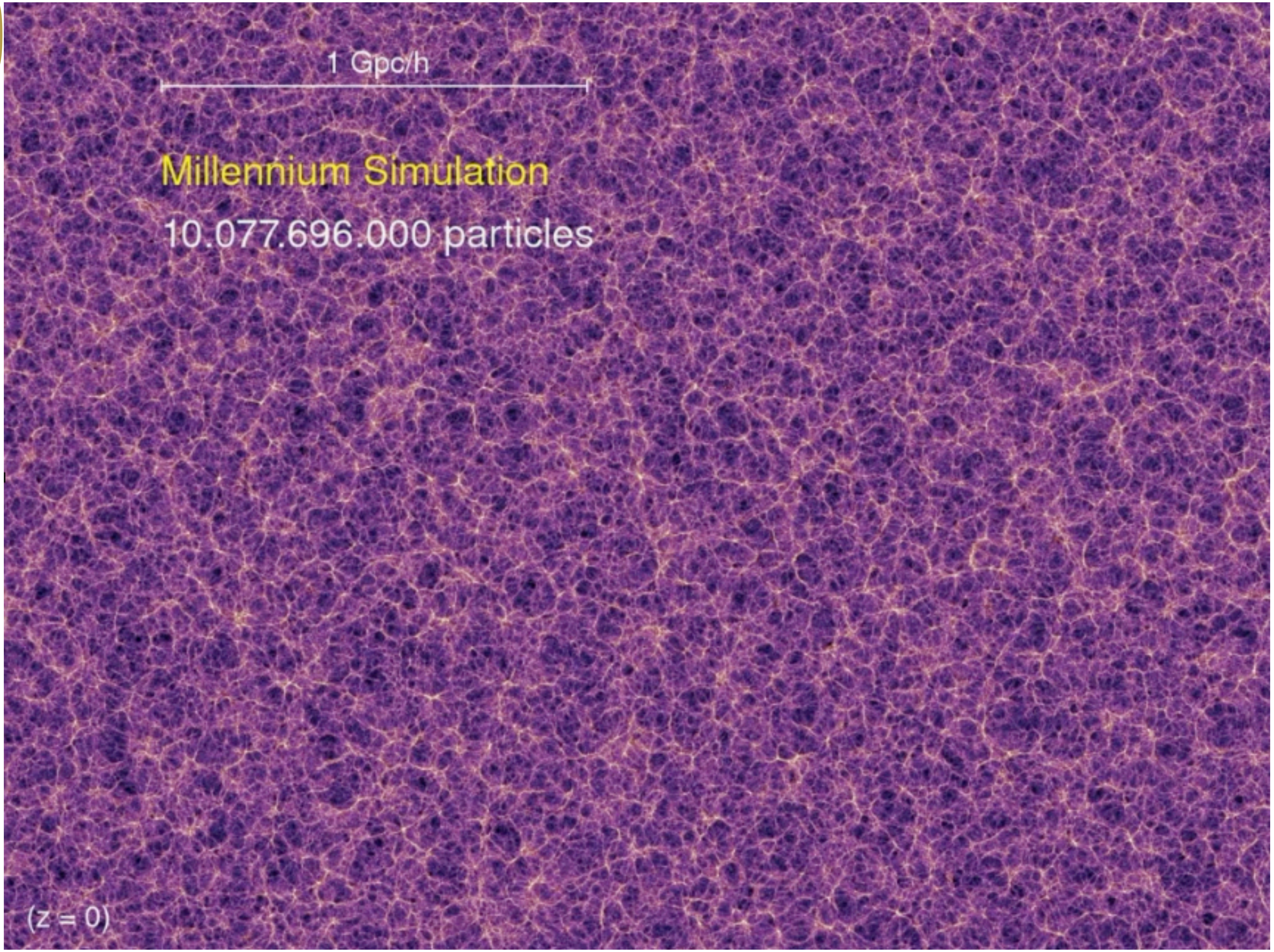
Non-linear structure evolution

If we only consider first-order terms in these equation and ignore the others, these can be linearized (and can be solved analytically). If we work at large scales (where the perturbations are small, and delta is small), we can actually ignore these terms, but at smaller scales (dark matter halo scales and smaller) these terms start being important, and the equations can not be linearized (numerical solution only).

But remember: The universe is homogeneous at large scales

Millennium Simulation: Dark matter distribution in the local universe at different physical scales.

Video of the millennium simulation available to download here: https://wwwmpa.mpa-garching.mpg.de/galform/virgo/millennium/



Why is important to trace and quantify the LSS?

Visually we can see and detect structure, but we need a mathematical formalism to quantify the density fluctuations and the level in which the matter is grouped.

Details of LSS depends on:

- Initial conditions (characteristics of the initial density field): CMB
- Cosmological parameters (matter density at each epoch, dark energy, etc).
- Formation and evolution of structure.
- Physical processes involved in the growth and evolution of individual galaxies.

Measurements of the large scale structure in combination of theoretical models allow us to constrain both cosmology and physics of galaxy evolution.

Statistical characterization of the LSS are needed to test models of structure formation and evolution, and models are needed to interpret LSS observations.

How can we quantify the non-uniform distribution of matter on the sky?

In general, the way that we use to quantify any deviation from a uniform distribution is through a measurement of the clustering signal. Mathematically, the clustering can be quantified through the “two-point correlation function”, which can be defined as:

$$\xi(r) = \langle \delta_x \delta_y \rangle$$

where

$$\delta_i = \frac{\rho_i - \bar{\rho}}{\bar{\rho}}$$

Is the overdensity of matter in a position i in the universe

and r is the distance between the positions x and y

(More details in Lecture 2)

The measurement of the clustering of a population can teach us about the dark matter halos in which galaxies live (more details in Lecture 4).

Next class

- What is clustering?
- How can we measure clustering?
- The two-point correlation function
- Practical guide to measure clustering from observations

Take home message

- Gravitational instability leads to an increase of density fluctuations with increasing time. Overdense regions become more overdense and underdense regions (voids) become more underdense.
- At some point, when the overdensity is massive enough it collapse to form a dark matter halos, where galaxies can form.
- Measurements of the large scale structure in combination of theoretical models allow us to constrain both cosmology and physics of galaxy evolution.
- We quantify the large scale structure through the measurement of the clustering of galaxies.

Important equations:

Matter overdensity:

$$\delta(r,t) = \frac{\rho(r,t) - \overline{\rho}(t)}{\overline{\rho}(t)}$$

The two-point correlation function:

$$\xi(r) = \langle \delta_x \delta_y \rangle$$