Cosmology I and II

Syksy Räsänen

University of Helsinki

Department of Physics and Helsinki Institute of Physics

Practicalities

- Lecturer Syksy Räsänen (A315), teaching assistants Selda Koivula (C304) and Jichao Li (A314). Reachable by email + at our offices.
- Cosmology I is Bachelor level, Cosmology II Master level.
- Up-to-date information is on the course webpage https://www.mv.helsinki.fi/home/syrasane/cosmo/
- Changes are announced via email to registered students.

Cosmology I schedule

- Lectures
  - Monday 14.15-16.00 in Physicum E204
  - Tuesday 14.15-16.00 in Exactum D123
- Exercises
  - Thursday and Friday 12.15-14.00 in Physicum D112
- Assistant help session
  - Wednesday 15.00-16.00, starting on 9.9..
- Exam: Tuesday 20.10. at 13.00-17.00 in Exactum B123

Exercises, exam and grading

- Exercise problems appear on the course webpage on Tuesday (at the latest). They are returned via Moodle by Monday at 14.15.
  - Solutions must be handwritten.
  - Solving problems with AI is forbidden and constitutes cheating.

- Grade is based 1/3 on the exercises and 2/3 on the exam.
  - You need 45% to pass, 85% for 5/5.

Content

Cosmology I

1. Introduction
2. Basics of general relativity
3. Friedmann-Lemaître-Robertson-Walker (FLRW) models
4. Thermodynamics in the expanding universe
5. Big Bang nucleosynthesis
6. Dark matter

Cosmology II

7. Inflation: background
8. Inflation: perturbations
9. Perturbations after inflation, large-scale structure
10. Cosmic microwave background

General Relativity I & II (PAP348) & (PAP 349)

- Essential (at least GRI) if you want to study cosmology further. Also fun.
- If you have taken GRI already, the GR in Cosmology I & II will be easy.
- If you will take GRII after Cosmology I, the cosmology in it will be easy.
- Lectured every spring term by me.
- https://www.mv.helsinki.fi/home/syrasane/gr/

Galaxy Survey Cosmology (PAP352) & Gravitational Lensing (PAP353)

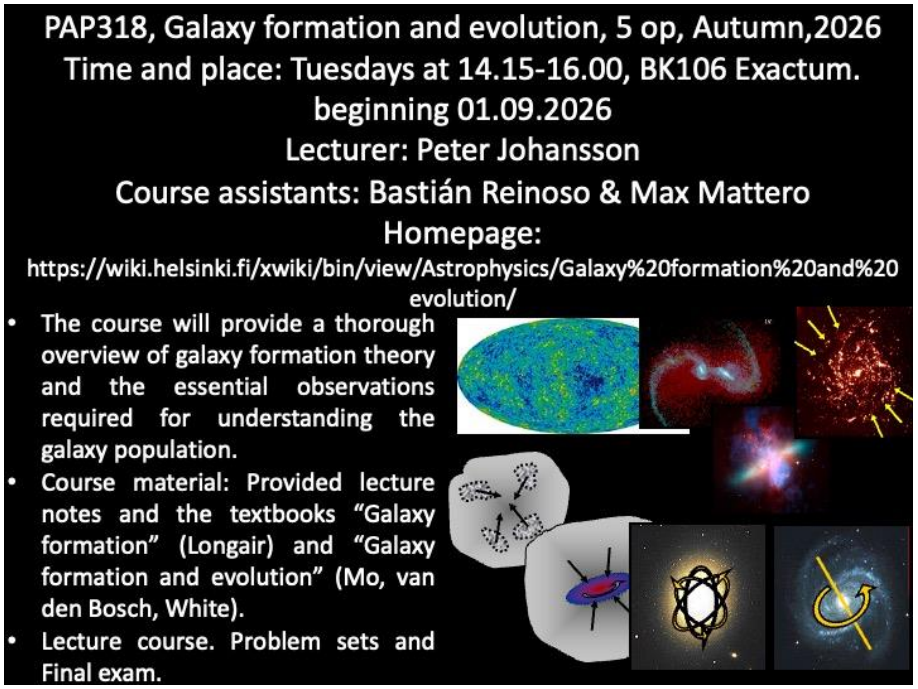
- Motivated by Finnish participation in ESA's Euclid project.

- For Galaxy Survey Cosmology you need Cosmology I & II.
- For Gravitational Lensing you need Cosmology I and General Relativity I.

- Lectured every **odd** spring term, next in 2027 by **Elina Sihonen**.

- https://sisu.helsinki.fi/student/courseunit/otm-ae140c0c-60df-4bea-b04d-1d2189181b07/brochure
- https://sisu.helsinki.fi/student/courseunit/otm-2435dc8f-ff83-4f46-a93d-1908e309f6d6/brochure

Galaxy Formation and Evolution (PAP318)



- Lectured every **even** fall term by **Peter Johansson**. Unfortunately this year on top of these lectures. https://wiki.helsinki.fi/xwiki/bin/view/Astrophysics/Galaxy%20formation%20and%20evolution/#

Galactic Dynamics (PAP317)

PAP317, Galactic Dynamics, 5 op, Spring 2025
Time and place: Tuesdays at 10.15-12.00,
beginning 14.01.2025 in Room D115, Physicum
Lecturer: Peter Johansson
Course assistant: Gábor Rácz & Atte Keitaanranta
https://wiki.helsinki.fi/xwiki/bin/view/Astrophysics/Galactic%20Dynamics/

- The course aims at providing an in-depth overview of galactic dynamics and the role of gravity in shaping the properties of the observed galaxy population.
- Course material: The text book "Galactic Dynamics" by Binney & Tremaine will be extensively used throughout the course, in addition to provided lecture notes.
- Lecture course: Problem sets and the final exam.

- Lectured every **odd** spring term, next in 2027 by **Peter Johansson**. https://wiki.helsinki.fi/xwiki/bin/view/Astrophysics/Galactic%20Dynamics/

Observations: fundamentals

- Electromagnetic radiation
  - Radio – Microwaves – IR – Visible – UV – X-Rays – Gamma rays
- Massive particles
  - Cosmic rays (protons, antiprotons, heavy ions, electrons, antielectrons)
  - Neutrinos
- Gravitational waves (since 2015)
- Composition of the solar system

Observations in practice

- Motion of galaxies
- Distribution of galaxies (large scale structure)
- Abundance of light elements
- Cosmic microwave background
- Luminosities of distant supernovae
- Number counts of galaxy clusters
- Deformation of galaxy images (lensing)
- Gravitational wave signals
- Pulsar timing
- ...

Laws of physics

- General relativity
- Quantum field theory
  - Atomic physics, nuclear physics, Standard Model of particle physics, and beyond
- Statistical physics and thermodynamics

The Standard Model

HELSINKI INSTITUTE OF PHYSICS

Matter particles

Quarks and leptons (3 families)

Gauge bosons

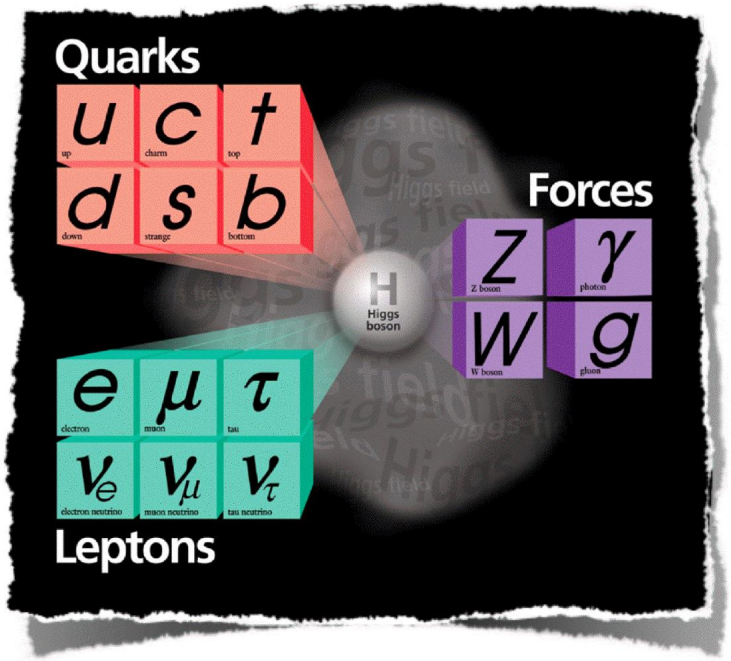
Photon: EM interaction

Gluons (8): strong interaction

W^+, W^-, Z: weak interaction

Higgs boson

Gives masses to W, Z, and fermions

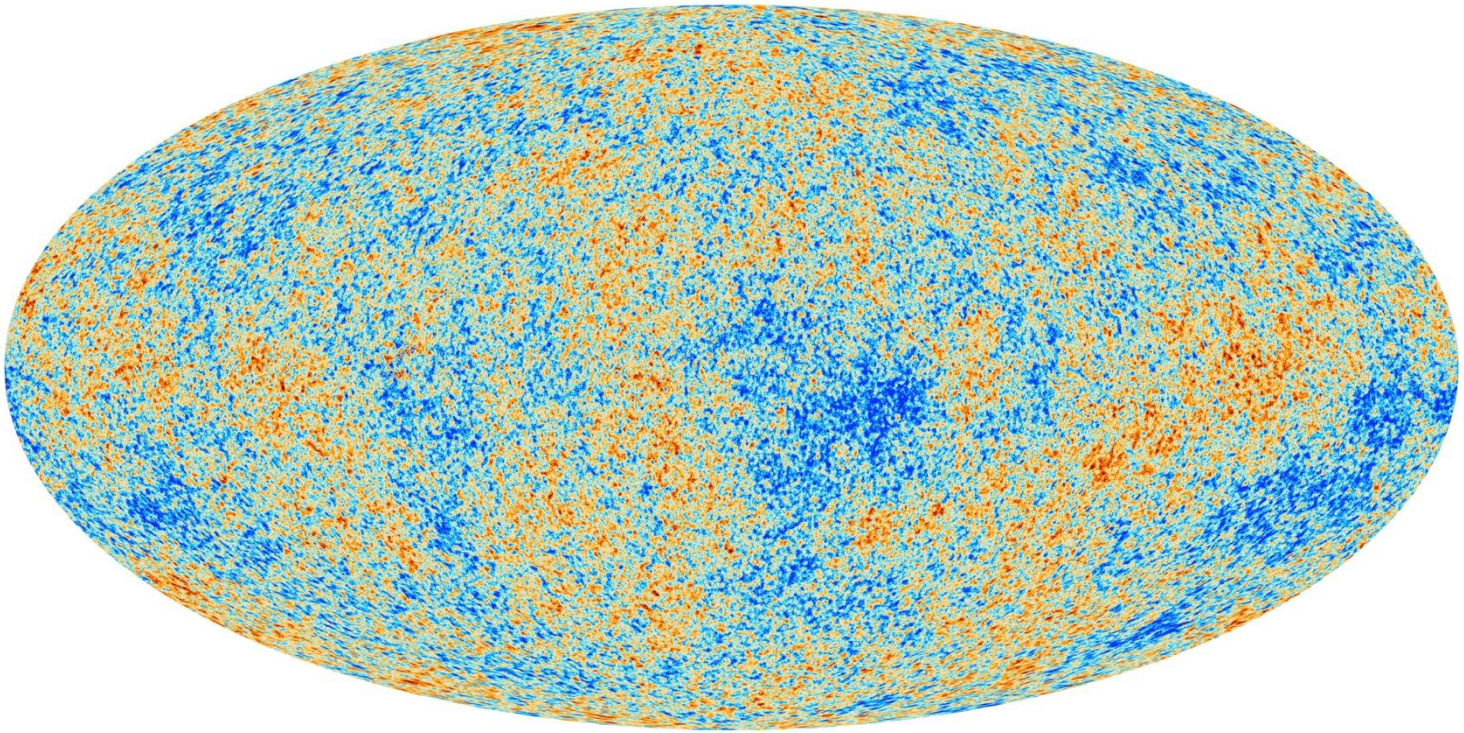


Why is the universe understandable?

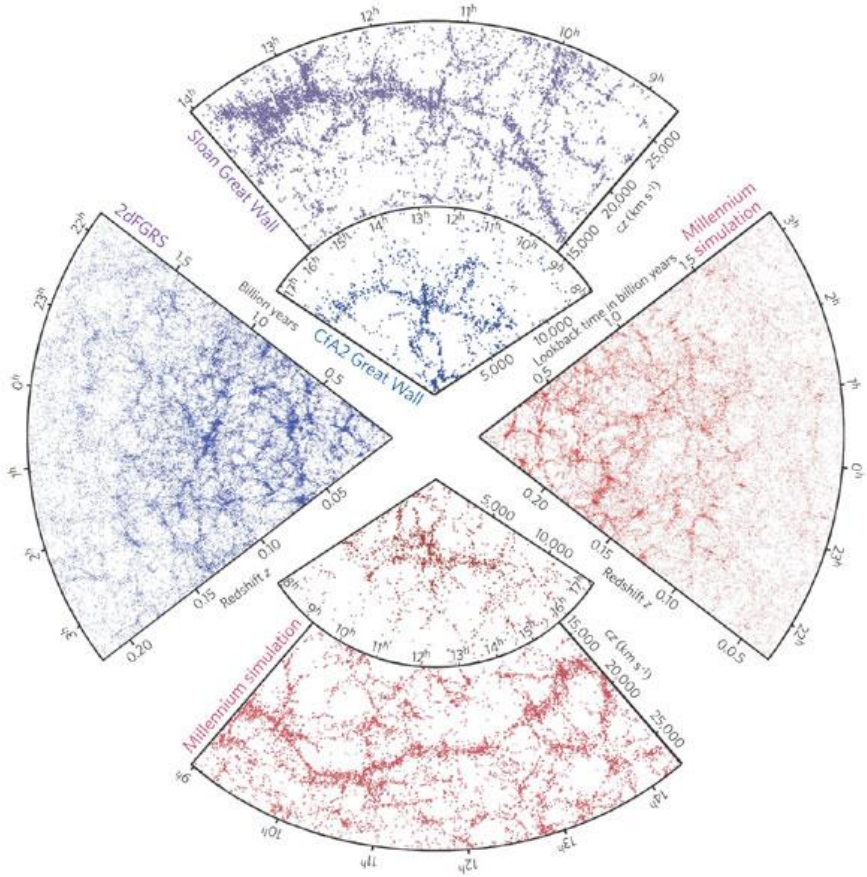
- Cosmology is feasible because of two key properties of the universe:

1. Homogeneity & isotropy
2. Thermal equilibrium

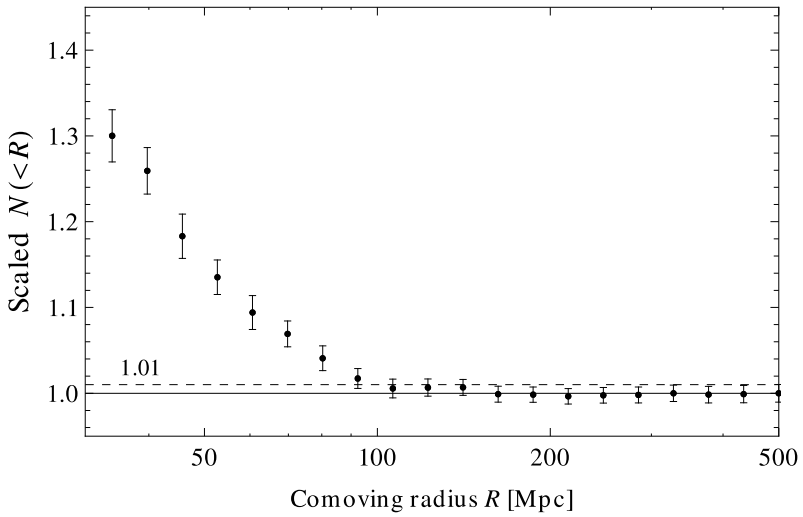
Homogeneity and isotropy: observations

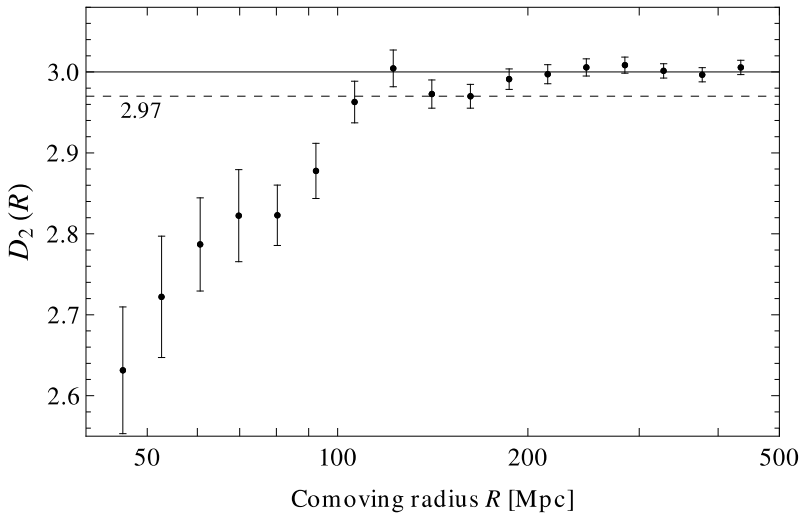


Homogeneity and isotropy: observations



Homogeneity and isotropy: observations





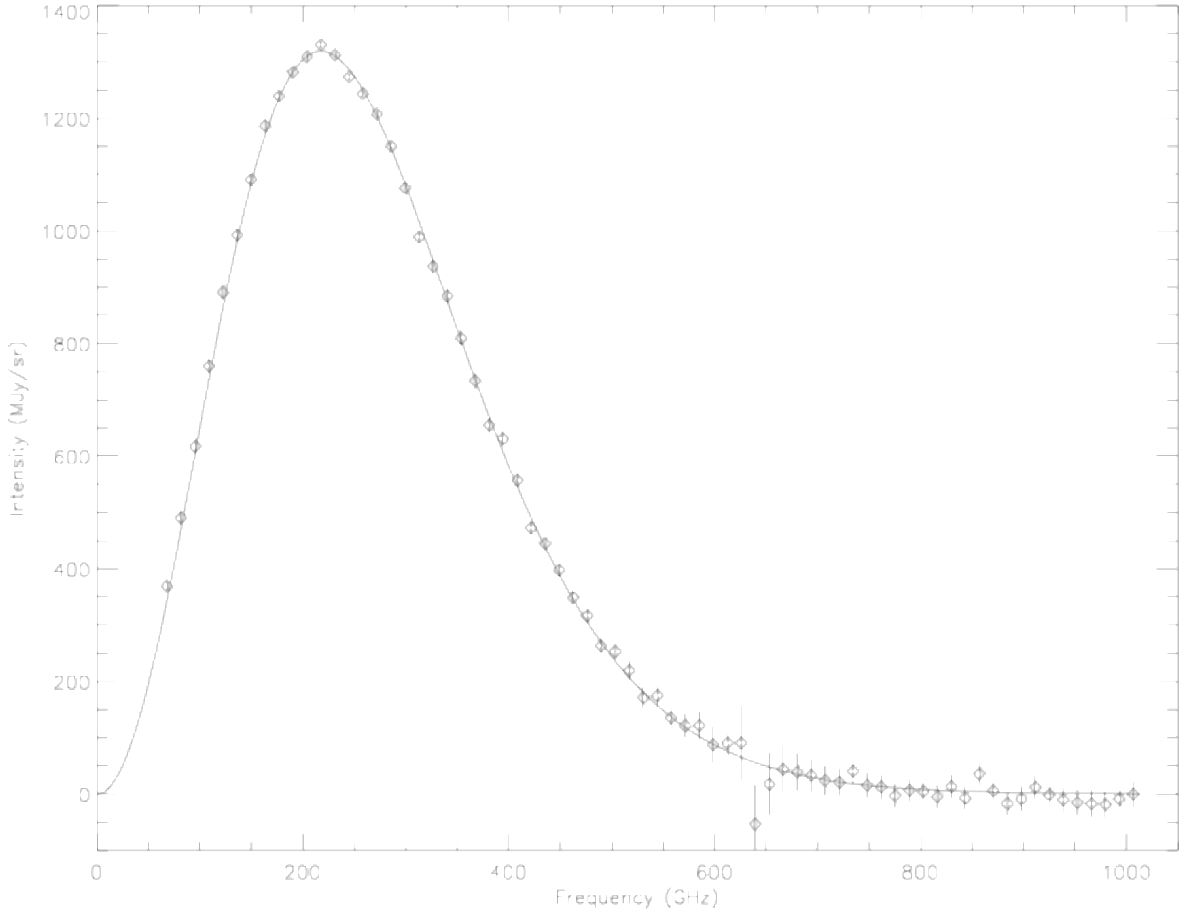
Homogeneity and isotropy: theory

- Observed **statistical** homogeneity and isotropy motivates theory with **exact** H&I: Friedmann-Lemaître-Robertson-Walker (FLRW) models.

- The expansion of the universe is described by the scale factor *a(t).*

- Extrapolating the known laws of physics, 14 billion years ago $a \to 0$, $\rho \to \infty$, $T \to \infty$.

Thermal equilibrium: observations



https://arxiv.org/abs/0911.1955

Thermal equilibrium: theory

- The early universe was:
  - Hot (high T)
  - Dense (large ρ)
  - Rapidly expanding

- High $T \Rightarrow$ high energy $\Rightarrow$ quantum field theory

- With time, T and ρ go down: particles fall out of equilibrium and form bound states.

Timeline of the universe

$t \quad (\propto E^{-2})$	E	Event
14 Gyr	10^{-3} eV	present day
8 Gyr	10^{-3} eV	expansion accelerates
100 Myr	10^{-2} eV	reionisation
40 Myr	10^{-2} eV	first structures form
380 000 yr	0.1 eV	atoms and the CMB form
50 000 yr	1 eV	matter overtakes radiation
3-30 min	0.1 MeV	Big Bang Nucleosynthesis
1 s	1 MeV	neutrino decoupling
10^{-5} s	100 MeV	QCD transition (?)
10^{-11} s	100 GeV	electroweak transition (?)
10^{-11}…10^{-36} s	10^{3}…10^{16} GeV	baryogenesis?
10^{-13}…10^{-36} s	10^{3}…10^{16} GeV	inflation?
10^{-13}…10^{-42} s	10^{3}…10^{18} GeV	quantum gravity?

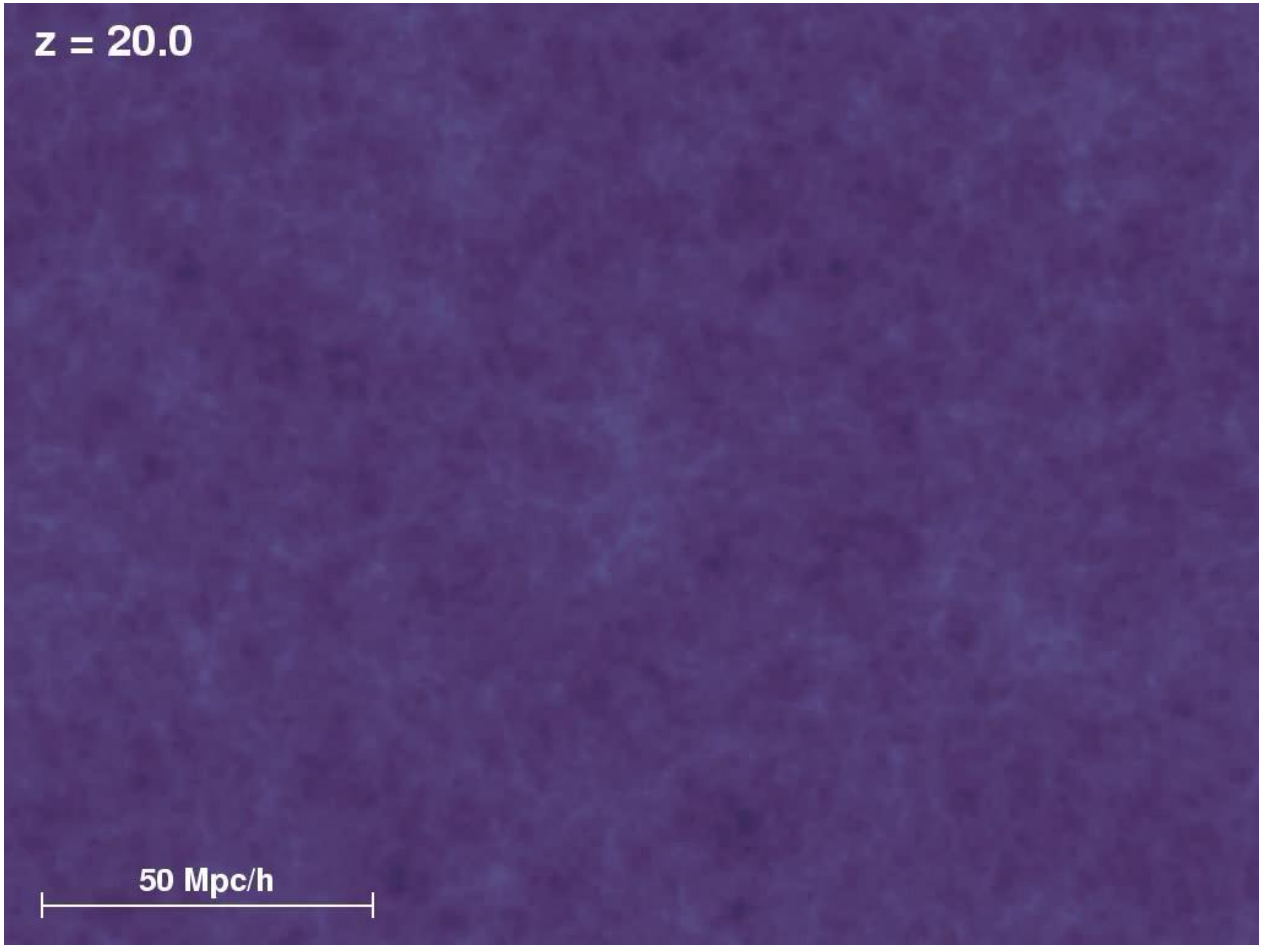
Structure formation

- CMB shows the initial conditions
  - The early universe is exactly homogeneous except for small perturbations of 10^{-5}.
  - Seeds of structure.

- Gravity is attractive

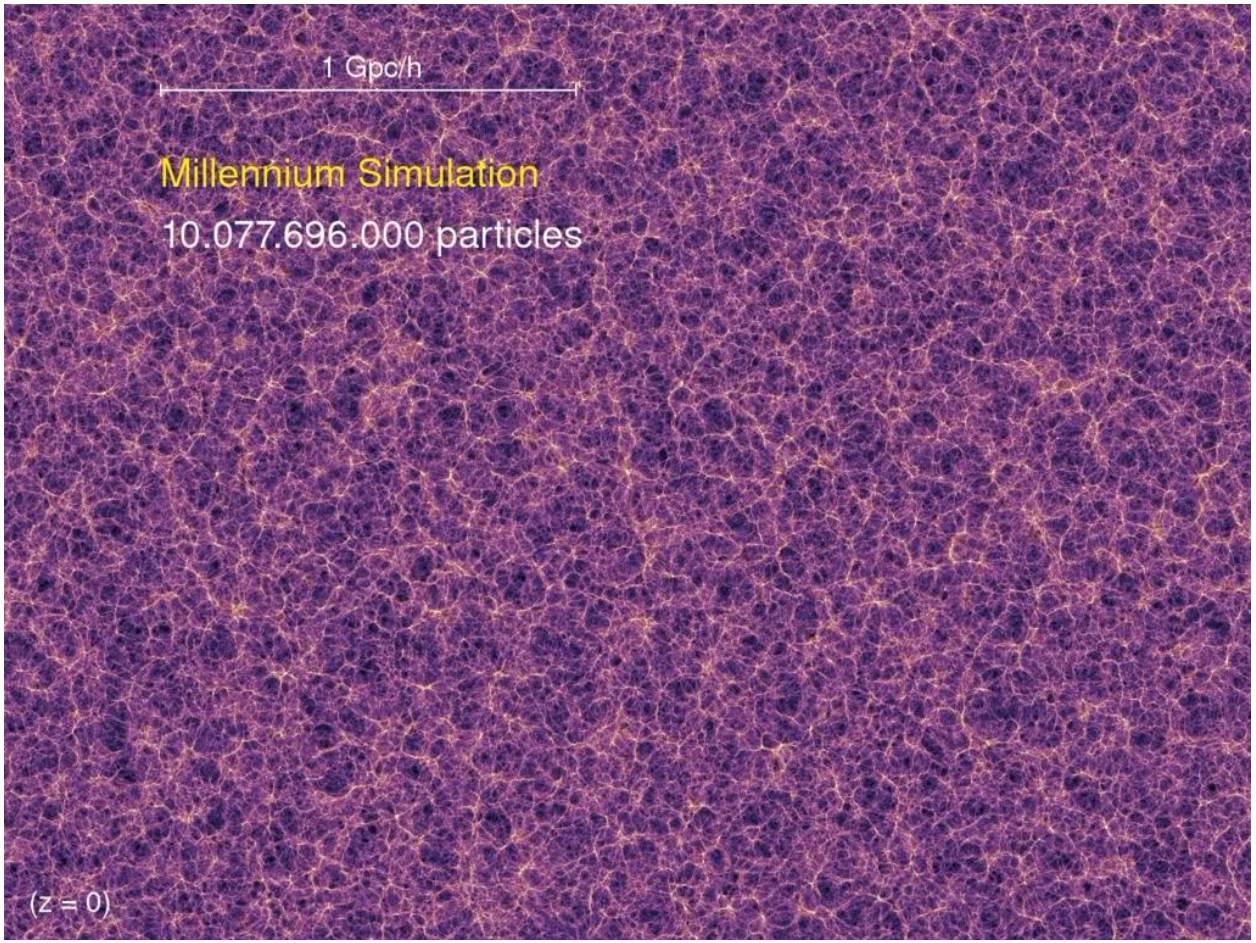
⇒ fluctuations grow into galaxies, clusters of galaxies, filaments, walls and voids, which form the large-scale structure of the universe

Growth of the cosmic web

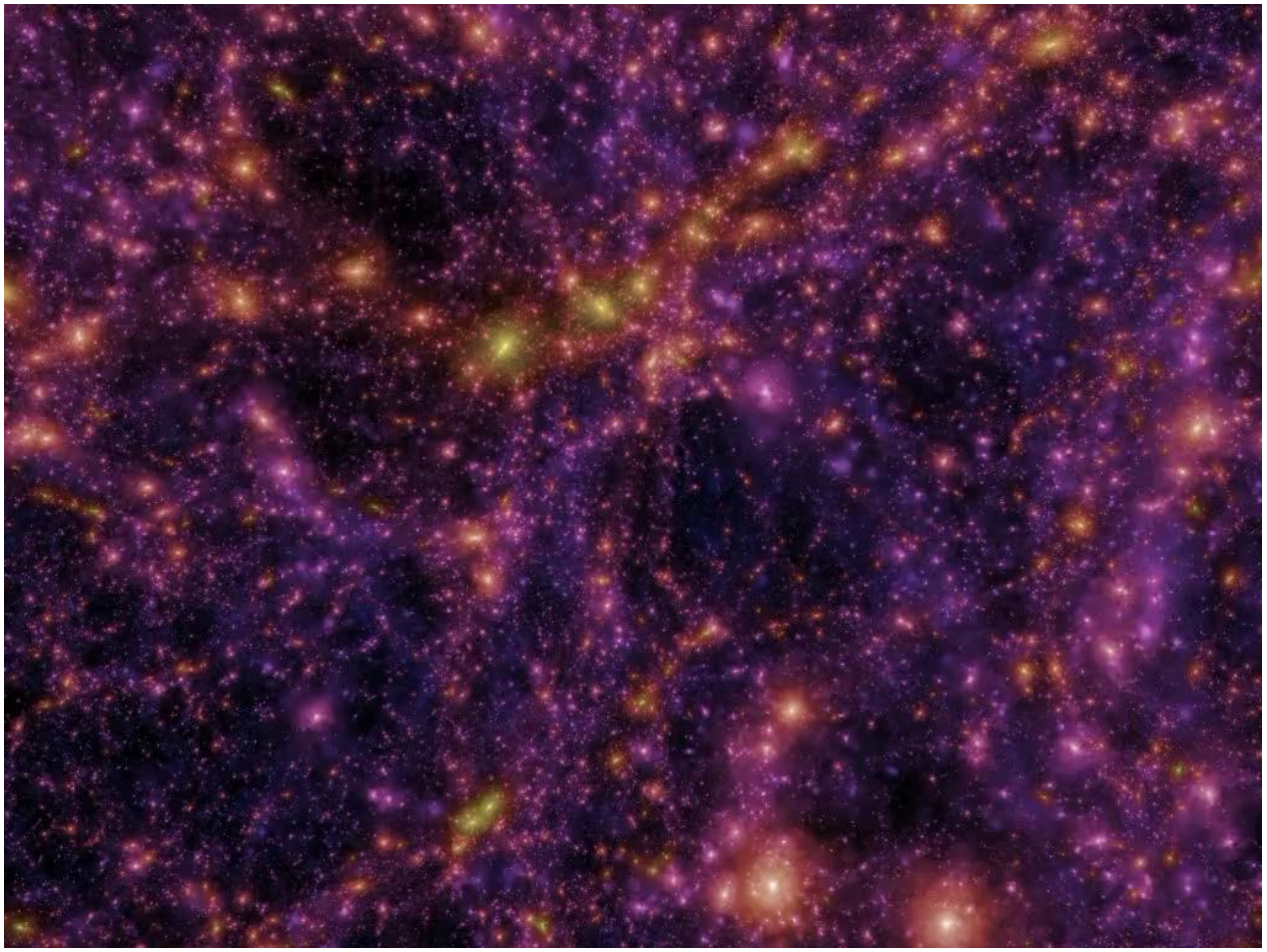


http://wwwmpa.mpa-garching.mpg.de/galform/data_vis/index.shtml

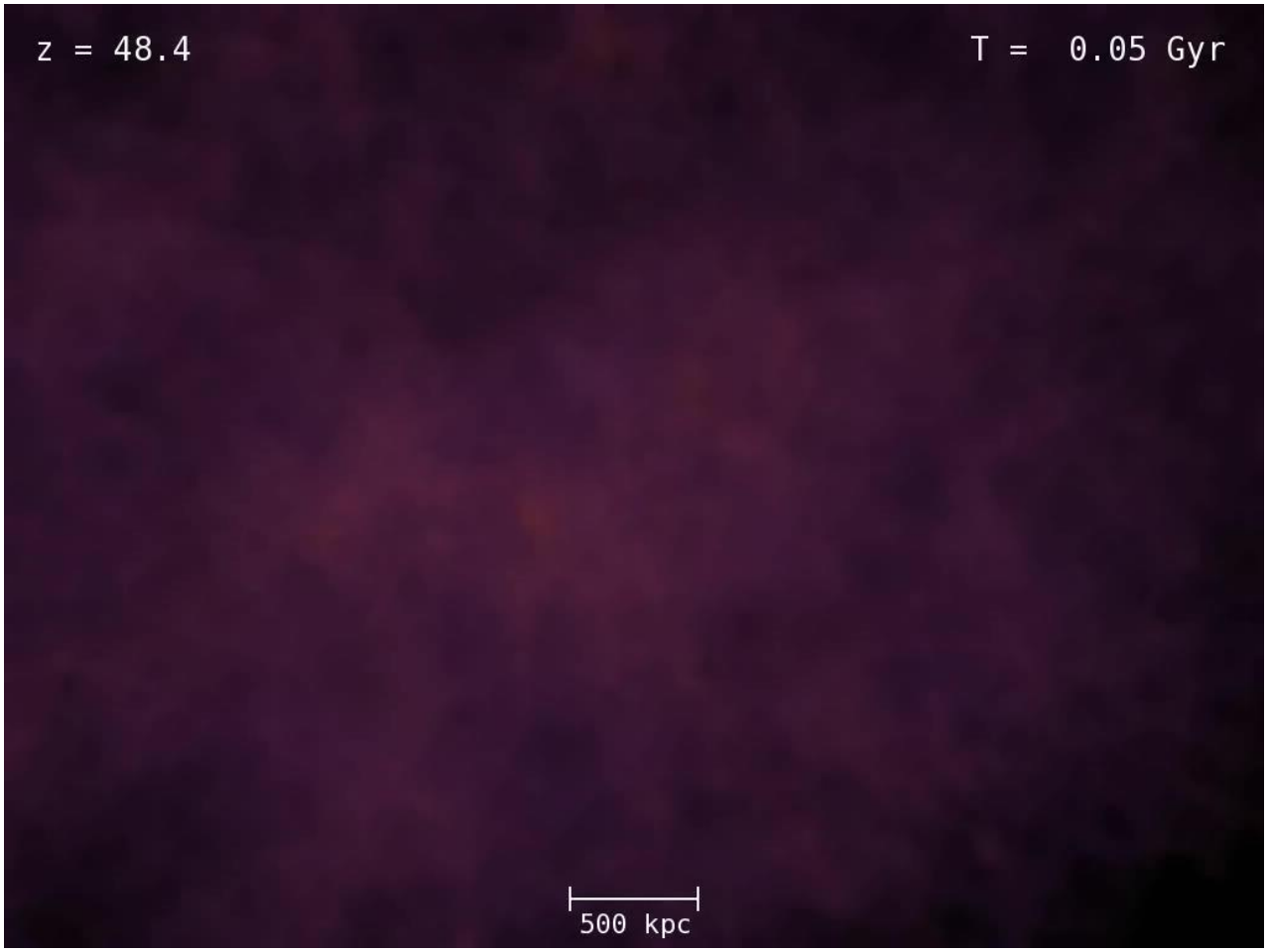
From clusters to large-scale structure



A rich cluster



Birth of the Milky Way: all matter

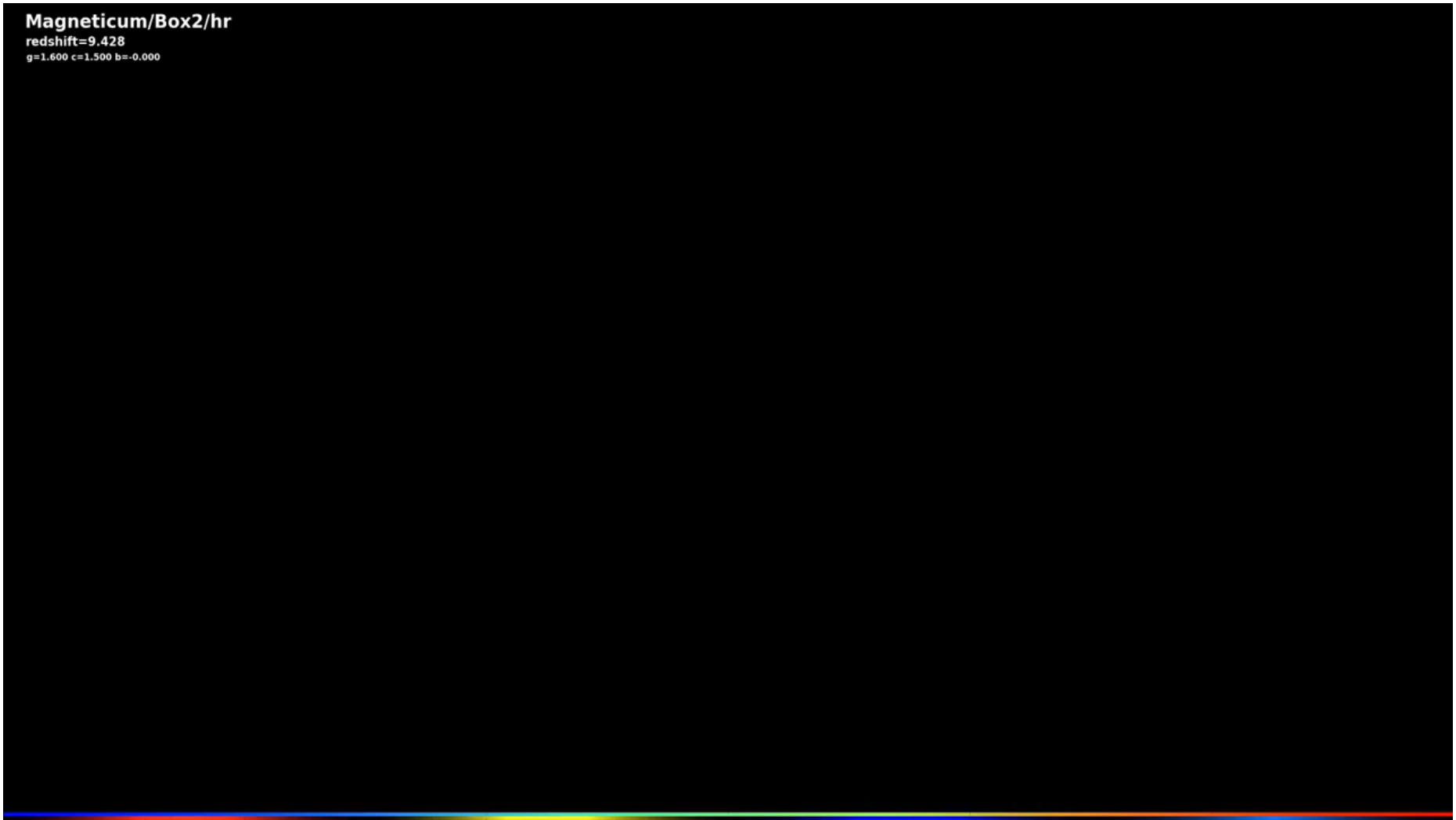


http://wwwmpa.mpa-garching.mpg.de/aquarius/

The birth of a galaxy: gas

Large-scale structure and the birth of galaxies

http://www.magneticum.org/media.html#MOVIES



Dark matter

- Large-scale structure, CMB anisotropies, motions of stars in galaxies & galaxies and gas in clusters, gravitational lensing, BBN, ...

  ⇒ most matter does not consist of Standard Model particles

- Either:
  - new massive particle(s) that have no electric charge, live long and move slowly, or
  - primordial black holes.

- Many candidates: neutralinos, technicolor dark matter, axions, right-handed neutrinos, ...

Accelerated expansion

- Exactly homogeneous and isotropic models with baryonic and dark matter don't agree with observations.
- Distances and the expansion rate are larger than expected by a factor of about 2.
  - Expansion has accelerated in the past 5 billion years.
- Most successful explanation is dark energy.
  - Other possibilities are modified gravity or effect of structures.

Dark energy

- Large negative pressure.
- Smoothly distributed.
- Energy density about three times that of baryonic plus dark matter today.

- The simplest candidate is vacuum energy.
  - Has explained and predicted observations successfully for 27 years.
  - Challenged by discrepancies in the measurement of H_0 (Hubble tension) and hints of change in the dark energy density.