Cosmology I and II

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Practicalities

- Lecturer Syksy Räsänen (A315), teaching assistants Jenni Häkkinen (D315) and Lasse Sihvonen. 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 teaching

- Lectures:
  - Monday 14.15-16.00 at Exactum CK112
  - Tuesday 14.15-16.00 at Exactum D122
- Exercises:
  - Friday 12.15-14.00, 14.15-16.00 at Physicum A315.
    (Friday 14.15 session will change next week to Thu 12-14.)
- Assistant help session Tuesday 12.15-13.00, starting on week 37. (Alternating between Jenni's office and the sandbox.)

Exercises, exam and grading

- Exercise problems appear on the course webpage on Tuesday (at the latest). They are returned via Moodle by Monday at 14.00.

- Grade is based 1/3 on the exercises and 2/3 on the exam.

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)

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- Not needed for Cosmology I and II but essential if you want to study cosmology further. Also fun.
- If you have taken GRI already, the GR on Cosmology I & II will be easy.
- If you 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)

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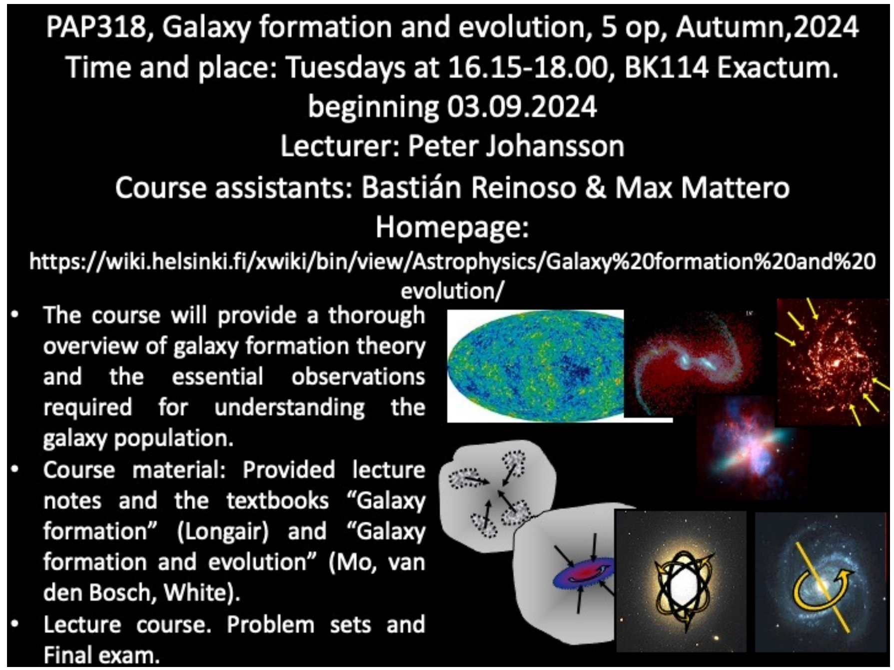
- Motivated by Finnish participation in ESA's Euclid project.
- Study the distribution of galaxies (correlation function and power spectrum) and weak gravitational lensing.
- For Galaxy Survey Cosmology you need Cosmology I & II.
- For Gravitational Lensing you also need General Relativity I and II.
- Lectured every **odd** spring term, next in 2025 by **Elina Keihänen**.
- https://www.mv.helsinki.fi/home/hkurkisu/gsc/

Galaxy Formation and Evolution (PAP318)



- Lectured every **even** fall term, beginning right after this lecture, by **Peter Johansson**.
- https://wiki.helsinki.fi/xwiki/bin/view/Astrophysics/Galaxy%20formation%20and%20evolution/

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Galactic Dynamics (PAP317)

- Detailed course on galactic dynamics.
- Lectured every **odd** fall term, next in 2025 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

Matter particles

Quarks and leptons (3 families)

Gauge bosons

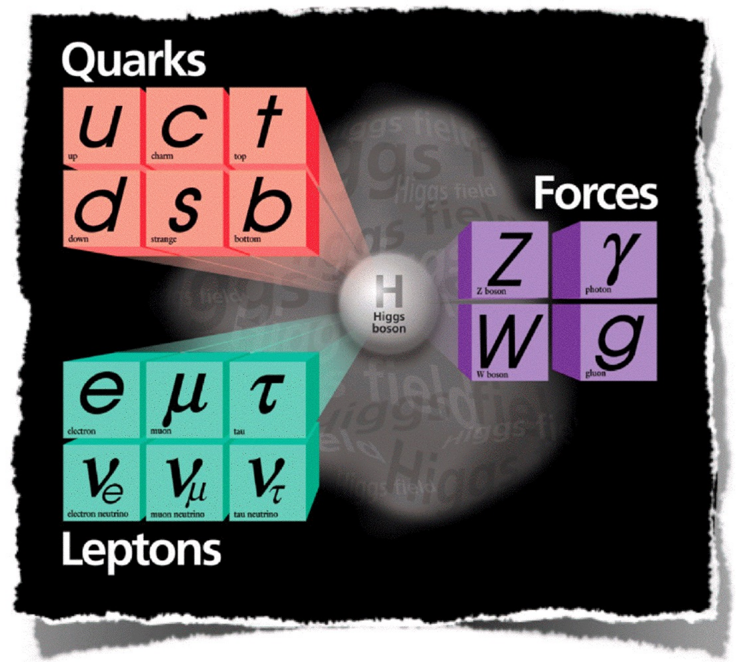
Photon: EM interaction

Gluons (8): strong interaction

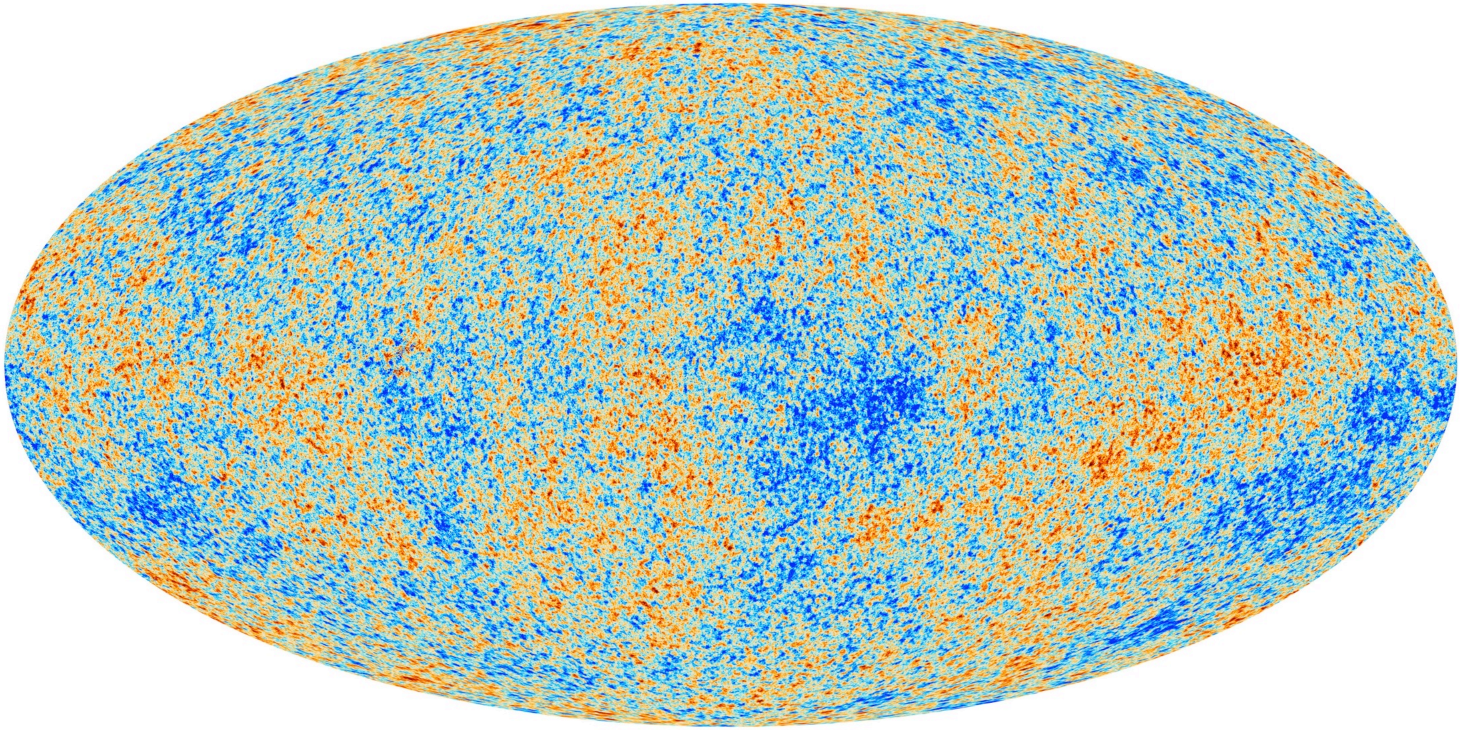
W^+, W^-, Z: weak interaction

Higgs boson

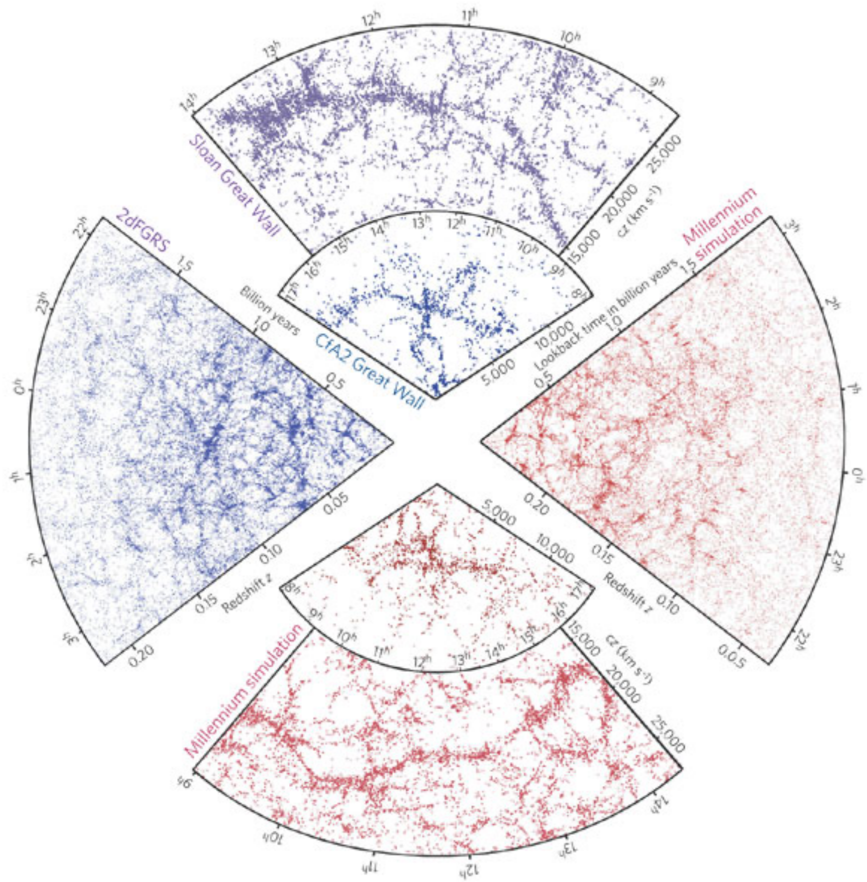
Gives masses to *W, Z,* and fermions



Homogeneity and isotropy: observations

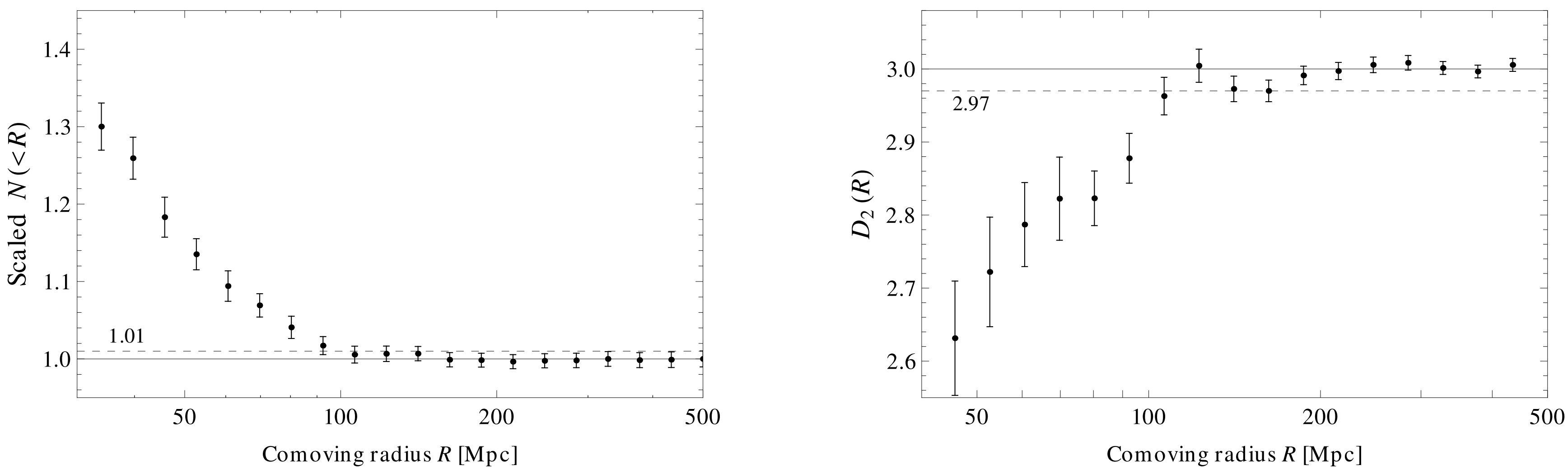


Homogeneity and isotropy: observations



https://arxiv.org/abs/astro-ph/0604561

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 $a \to 0$, $\rho \to \infty$, $T \to \infty$.

The meaning of Big Bang

- The early universe was:
  - Hot
  - Dense
  - Rapidly expanding

- Homogeneity and isotropy + thermal equilibrium ⇒ easy to calculate

- High T ⇒ high energy ⇒ quantum field theory

Timeline of the universe

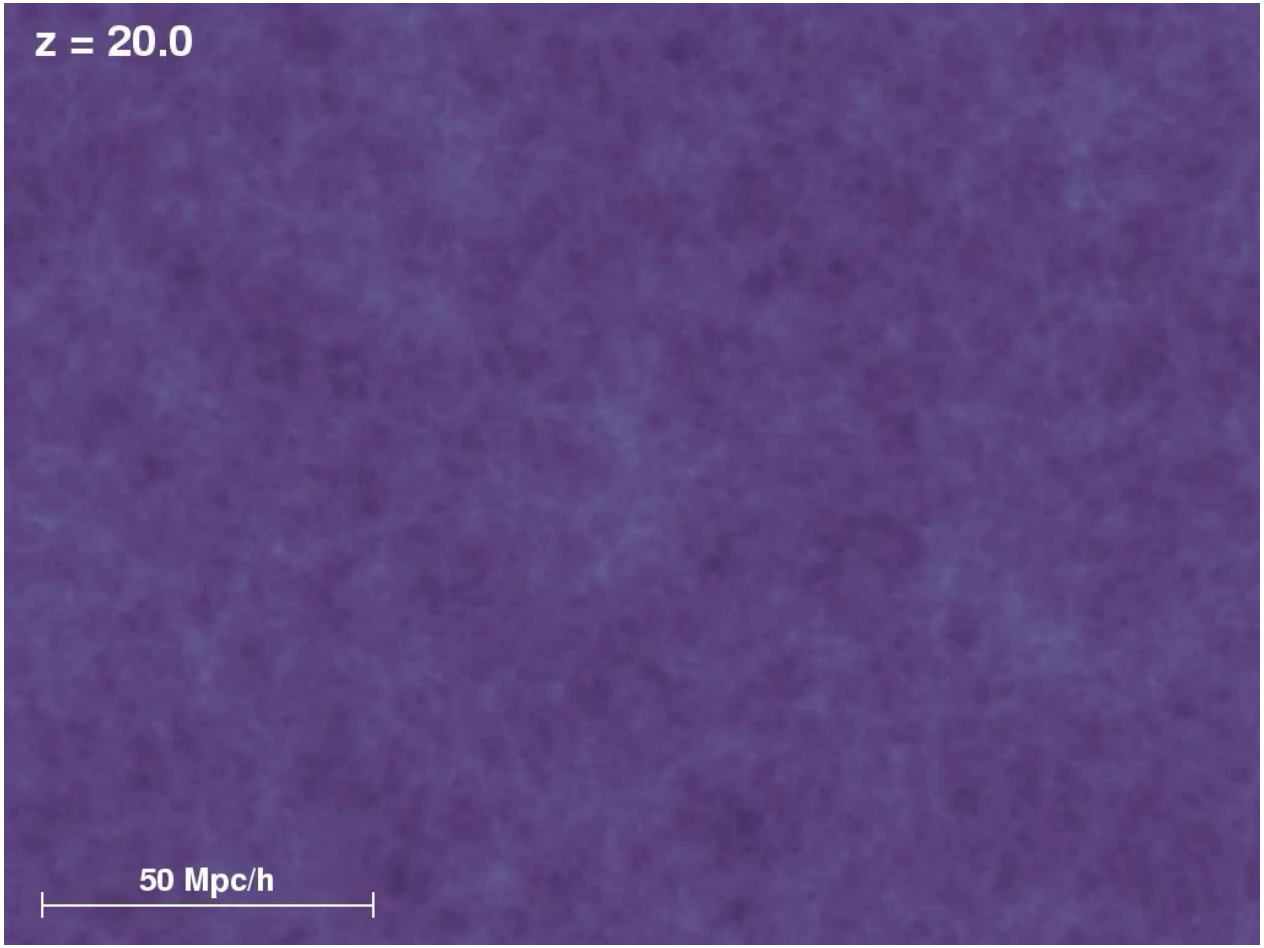
t $(\propto E^{-2})$	E	Event
14 Gyr	10^{-3} eV	present day
8 Gyr	10^{-3} eV	expansion accelerates
100 Myr	10^{-2} eV	reionisation
40 Myr	10^{-2} eV	first structures form
380 000 yr	0.1 eV	atoms and the CMB form
50 000 yr	1 eV	matter overtakes radiation
3-30 min	0.1 MeV	Big Bang Nucleosynthesis
1 s	1 MeV	neutrino decoupling
10^{-5} s	100 MeV	QCD transition (?)
10^{-11} s	100 GeV	electroweak transition (?)
$10^{-11}\ldots10^{-36}$ s	$10^{3}\ldots10^{16}$ GeV	baryogenesis?
$10^{-13}\ldots10^{-36}$ s	$10^{3}\ldots10^{16}$ GeV	inflation?
$10^{-13}\ldots10^{-42}$ s	$10^{3}\ldots10^{18}$ 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.

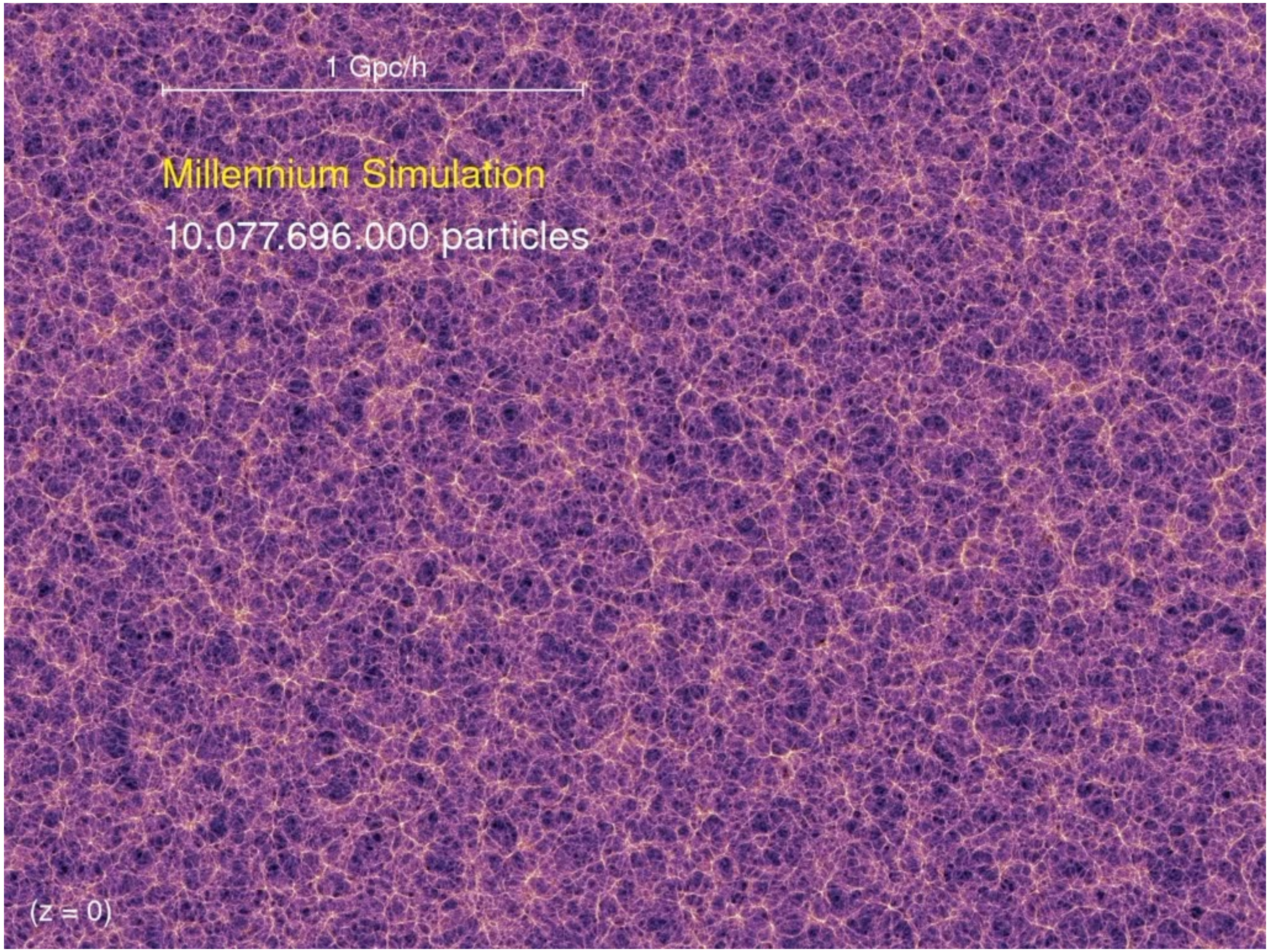
- Gravity is attractive
  - ⇒ fluctuations grow into galaxies, clusters of galaxies, filaments, walls and voids, which form the large-scale structure of the universe

Growth of the cosmic web



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

From clusters to large-scale structure



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

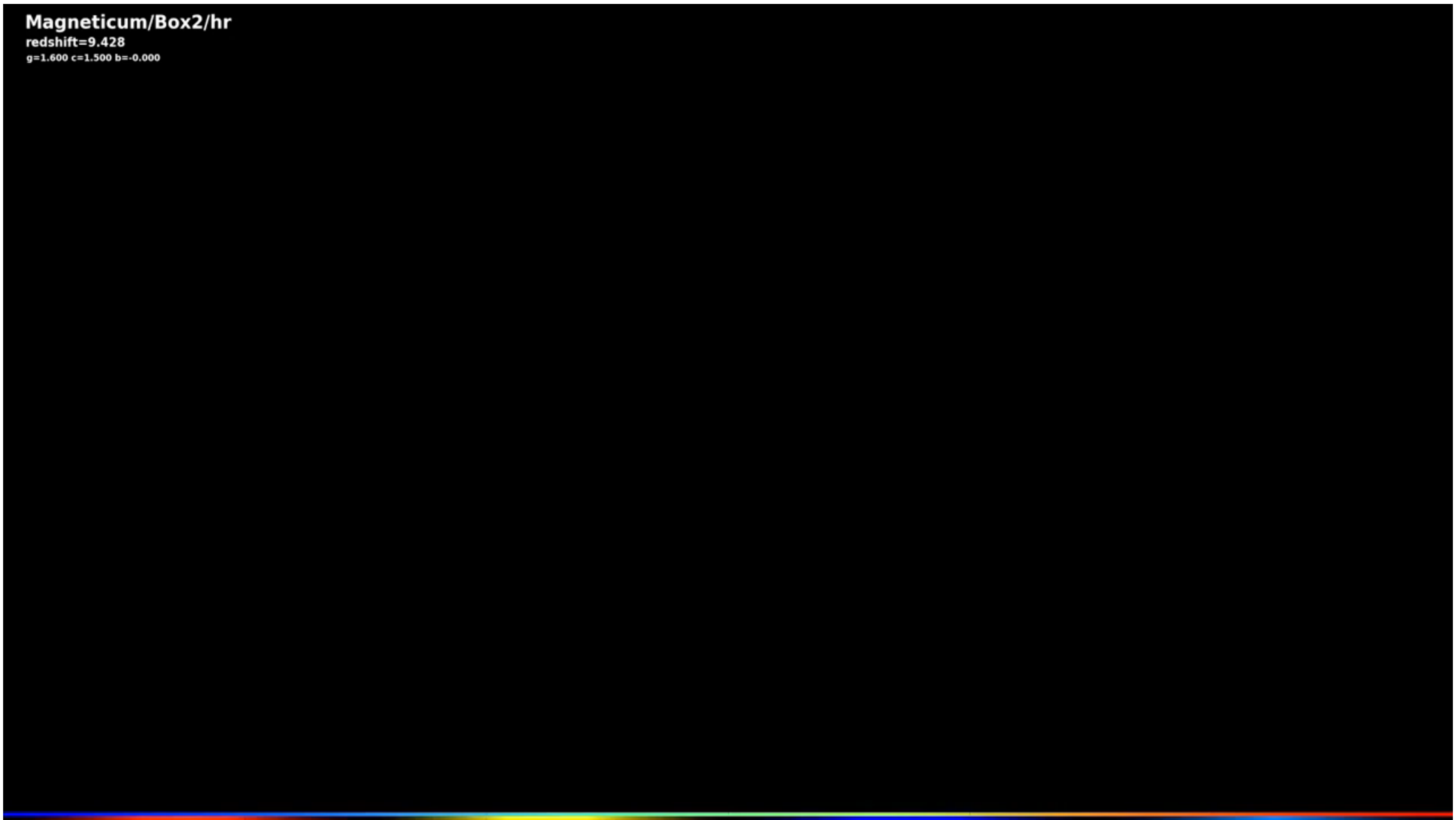
A rich cluster

https://wwwmpa.mpa-garching.mpg.de/galform/virgo/millennium/#movies

Birth of the Milky Way

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

- Has large negative pressure.
- Is smoothly distributed.
- Has an 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 26 years.
  - Challenged by discrepancies in measurement of H_0 (Hubble tension).