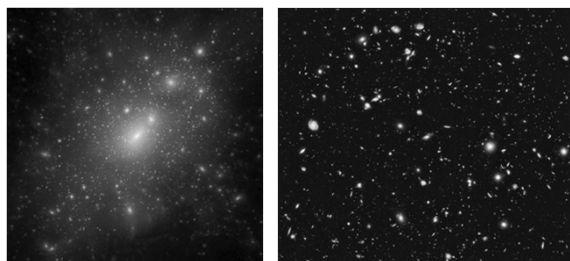


Cosmology 1FA209 2017, 10 credits Lecture 1: Introduction



Formal Information

- Teacher:
 - Erik Zackrisson
 - Office in the astronomy corridor on floor 3 in house 6 – just ring the bell to get in!
 - Telephone: 018-471 5975
 - E-mail: erik.zackrisson@physics.uu.se
- Course homepage:
 - <http://www.astro.uu.se/~ez/kurs/Cosmology17.html>

Outline for today

- Formal Stuff
- Course outline
- Cosmic epochs

$$\left(\frac{\dot{R}}{R}\right)^2 + \frac{kc^2}{R^2} = \frac{8\pi}{3}G\rho + \frac{\Lambda}{3}$$

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}\left(\rho + 3\frac{p}{c^2}\right) + \frac{\Lambda}{3}$$

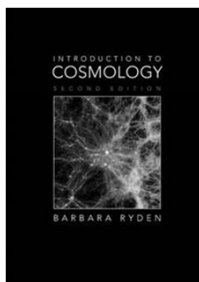
$$\rho = -3\left(\frac{\dot{R}}{R}\right)\left(\rho + \frac{p}{c^2}\right)$$



Course literature

Introduction to cosmology
2nd edition (2017)

Barbara Ryden
Around 360-450 SEK (e.g.
AdLibris, Bokus)



Examination

- Seminars
 - Seminar I: *Common misconceptions of modern cosmology*
 - Seminar II: *Parallel Universes*
 - Seminar III: *Strange Universe*
- Literature exercise
 - Written essay (≈ 3 pages)
 - Oral presentation (≈ 10 minutes)
- Hand-in exercises

Seminars

- Instructions available from course homepage
- Purpose:
 - Practice finding and reading relevant research papers
 - Practice analyzing astronomical data
 - Practice critical thinking
 - Practice scientific creativity
 - Practice illustrating abstract concepts
 - Practice discussing with and in front of others
- What if you cannot attend the seminars?
 - Have to present results in written report before end of course (→ more work!)

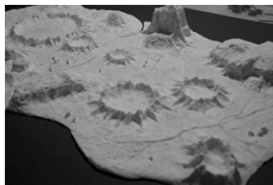
Seminar I

- **Title:** *Common misconceptions about modern cosmology*
- **Grade:** Fail, 3, 4, 5
- Preparation:
 - Read suggested papers + others
 - Answer questions
 - Prepare to present answers and results in class



Seminar II

- **Title:** Parallel universes
- **Grade:** Fail, Pass
- Preparation:
 - Read suggested paper
 - Think about ways to explain the four levels of parallel universes and to create visualizations of these

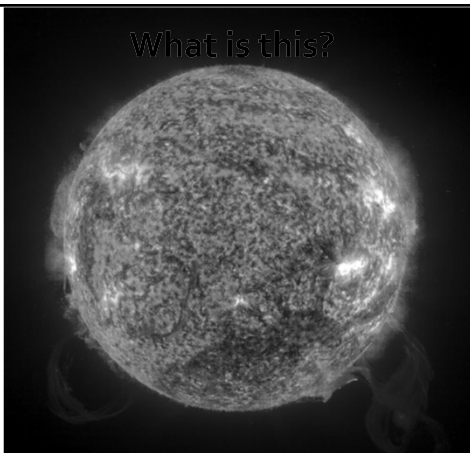


Seminar III

- **Title:** Strange universe
- **Grade:** Fail, 3, 4, 5
- Preparation:
 - Analyze mock data set
 - Prepare to present your findings in class



What is this?



Literature exercise

- Choose topic individually
- Find suitable articles
 - Published papers (ADS abstract service)
 - http://adsabs.harvard.edu/abstract_service.html
 - Preprints:
 - <http://www.arxiv.org>
- Written report (≈ 3 pages), deadline October 15
 - Grade:** Fail, 3, 4, 5
- Oral presentation (≈ 10 minutes)
 - Group A: October 19 (10-12)
 - Group B: October 19 (13-15)
 - Grade:** Fail, 3, 4, 5

Hand-in exercises

- 6 hand-in problems available from course homepage
- These are fairly similar to the ones solved during the exercise sessions
- **Deadline:** October 29
- **Grade:** Fail, 3, 4, 5
- Collaboration OK, but please don't turn in identical solutions!

Cosmology 1FA209
Hand-in exercises 2017

Instructions: Hand-written solutions are quite acceptable, but submission via email is highly encouraged (we will allow for a smaller evaluation), so please consider scanning your solution (or taking photos of them) and submitting them in electronic format. The deadline for handing in solutions to these problems is **October 29, 2017**.

1. *Hubble's law and luminosity distance*
A galaxy is observed at a redshift of $z = 0.25$. How distant is this object according to Hubble's law? How accurate is Hubble's law for estimating the luminosity distance at this redshift, under the assumption of a cosmological model with $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$?

2. *Rate of the Universe*
Starting from the Friedmann equation

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{c^2}{R_0^2 a^2} + \frac{\Lambda}{3} \quad (1)$$

Literature exercise

If you cannot meet the deadlines for the written report or the oral presentation, you may hand the report in at some later time

But: You will then have to give the oral presentation at one of the Galaxies and Cosmology group meetings.



***This is far scarier!
Not recommended!***

Suggestions for topics I

- Topology of the Universe
- Strange CMBR anisotropies
- Dark flow
- Varying constants of nature
- Alternative theories of gravity
- Alternative cosmologies
- Wormholes and time travel
- The anthropic principle in cosmology
- Gravitational waves

But please feel free to suggest other topics!

Grading

- The final grade will be the mean grade from:
 - Seminar 1
 - Seminar 3
 - Written report on literature exercise
 - Oral presentation of literature exercise
 - Hand-in exercises
- No final grade will be computed until you have reached a passing grade (3 or higher) for each of these
- Please note that you also need a passing grade from seminar 2 to complete the course

Potential bonus exercise (still tentative): Virtual reality in the cosmology classroom



Not compulsory, but can boost final grade!
Deadline: Nov 5

Schedule I

- 9 Lectures
 - L1, Aug 30, 10-12: Course information, course overview
 - L2, Aug 31, 15-17: Fundamentals, Gravity, Curvature (chapters 2-3)
 - L3, Sept 4, 13-15: Metrics, Proper distance, Cosmic dynamics (chapters 3-4)
 - L4, Sept 8, 10-12: Single and Multiple component Universes (chapters 5)
 - L5, Sept 8, 13-15: Cosmological parameters and dark energy (chapters 6)
 - L6, Sept 11, 10-12: Dark matter (chapter 7)
 - L7, Sept 18, 8-10: CMBR (chapter 8)
 - L8, Oct 6, 10-12: BBNS, the early Universe, inflation (chapter 9, 10)
 - L9, Oct 11, 8-10: Structure formation (chapter 11-12)

Schedule II

- 3 Exercise sessions:
 - E1, Sept 27, 8-10
 - E2, Oct 9, 8-10
 - E3, Oct 13, 15-17



What happens in the exercise sessions?

- You solve problems in teams!
- Attendance not compulsory, but actively participating will make it much easier to complete the hand-in problems
- **Suggested preparation:**
 - Study exercises and solutions posted on course homepage for sessions 1-2
 - Bring pen, paper, calculator/computer, textbook and exercise solutions

Exercises and solutions on the course homepage for sessions 1 & 2

Please try to understand the solutions before coming to the exercise session!

The problems we solve in class will be similar.

Note: No preparations necessary for session 3

Cosmology 2017
Exercises with solutions – batch I

1. Learning to use the Fried equations: The density evolution of the Universe. Use the Fried equations $\dot{a} = H_0 a$ and the equation of state $P = w\rho c^2$ to derive a proportionality relation between mass density and scale factor in the case of

(a) a radiation dominated Universe
(b) a matter dominated Universe
(c) a Universe dominated by a cosmological constant.

Solution: The \dot{a} in the Fried equation $\dot{a} + \frac{1}{a} \frac{da}{dt} = H_0$ is 0

$$\dot{\rho} + \frac{1}{a} \frac{d\rho}{da} = 0 \quad (1)$$

and the equation of state $P = w\rho c^2$

$$P = w\rho c^2 \quad (2)$$

represents energy density. We are, however, here asked to derive the relation between mass density ρ and the scale factor a . Luckily, the connection between energy density and mass density is simply a question of applying $E = \rho c^2$ (think $E = mc^2$ and divide both sides by the volume), so

Exercise session 3: Fermi problems

Objective: Gain skill in making back-of-the-envelope calculations

Examples:

- What is the mass of a sky scraper?
- How many atoms are there in the observable Universe?



Compete in teams - win marvelous prizes!

What is this?



© Australian Astronomical Observatory

Schedule III

- 3 seminars
 - Seminar I: Oct 2, 10-12 (group A)
Oct 3, 10-12 (group B)
 - Seminar II: Oct 12, 12-15
 - Seminar III: Oct 18, 8-10 (group A)
Oct 18, 15-17 (group B)
- Oral presentation of literature review
 - Oct 19, 10-12 (group A)
 - Oct 19, 13-15 (group B)

Schedule IV

- Important dates to remember:
 - October 2/3: Seminar 1
 - October 12: Seminar 2
 - October 15: Deadline for written literature report
 - October 18: Seminar 3
 - October 19: Oral presentations
 - October 29: Deadline for hand-in exercises
 - Nov 5: Deadline bonus exercise

How much time will I have to spend on this course?

My estimates:

- Attending classes: 17*2 h = 30 h ~ 4 days
- Studying textbook: 12 days (one chapter a day)
- Preparing for seminars: 6 days (two days per seminar)
- Solving exercises (in-class exercises + hand-ins): 6 days
- Literature exercise: 5 days (3 days for written report + 2 for oral presentation)

Sum: 33 days, i.e. 6.6 weeks or 10 ECTS

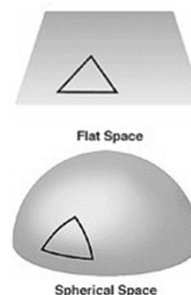
Course Outline

- Lecture 1: Introduction
 - Formal stuff
 - Course outline
 - Cosmic epochs



Course Outline

- Lecture 2: Basics
 - Cosmological principle
 - Cosmic expansion
 - Newton versus Einstein
 - Gravity = curvature
 - Metrics

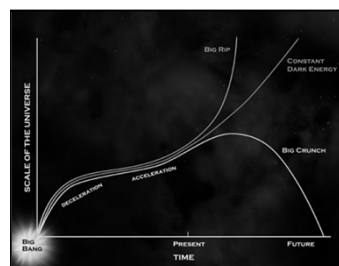


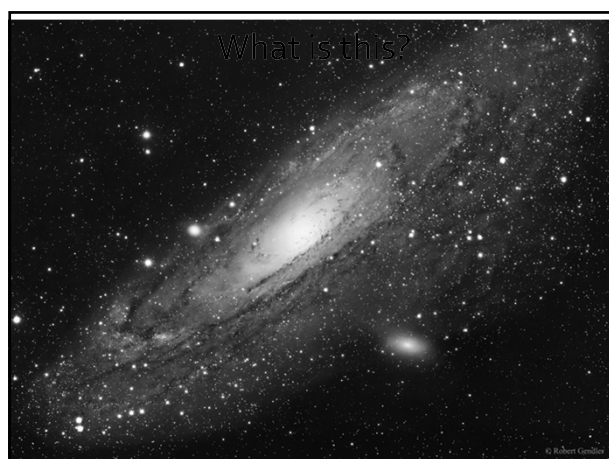
Course Outline

- Lecture 3: Dynamics
 - Robertson-Walker metric
 - Proper distance
 - Computational tools:
 - Friedmann equation
 - Fluid equation
 - Acceleration equation
 - Equation of state
 - Cosmic dynamics

Course Outline

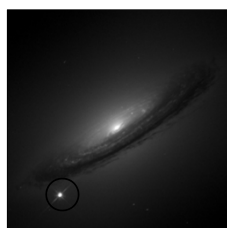
- Lecture 4: Towards a realistic cosmology
 - Dynamics with single and multiple components
 - Concordance cosmology (Benchmark model)
 - Fate of the Universe





Course Outline

- Lecture 5: Cosmological parameters
 - Measuring cosmological parameters
 - Dark energy



$$H_0 \quad q_0 \quad w_{DE}$$

$$\Omega_\Lambda \quad \Omega_\gamma \quad \kappa$$

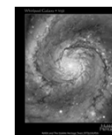
$$\Omega_M$$

Course Outline

- Lecture 6: Dark matter
 - Evidence for dark matter
 - Baryonic and non-baryonic dark matter
 - Spatial distribution
 - Cold dark matter (CDM)
 - Problems with CDM
 - Dark matter candidates
 - Possible detections
 - Alternatives to dark matter



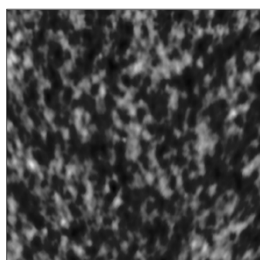
Dark matter



Luminous matter

Course Outline

- Lecture 7: The Cosmic Microwave Background Radiation
 - Origin of the CMBR
 - The dipole anisotropy
 - Recombination and decoupling
 - Temperature fluctuations
 - Cosmological information extracted from the CMBR



Course Outline

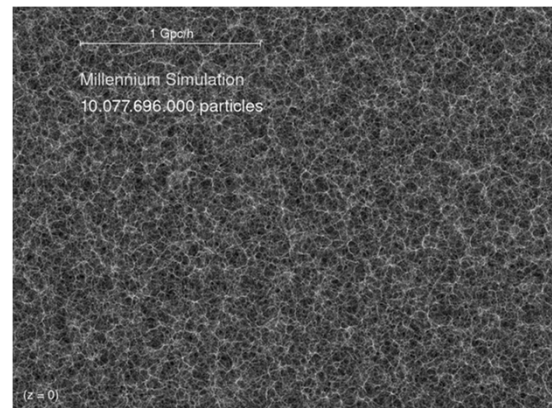
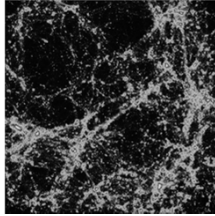
- Lecture 8: Big Bang Nucleosynthesis, the early Universe, cosmic inflation
 - BBNS
 - Measuring primordial abundances
 - What happened to the antimatter?
 - Problems with a non-inflationary Big Bang
 - Inflation
 - Grand Unified Theories



Course Outline

•Lecture 9: Structure formation

- Perturbation spectrum
- Jeans mass, Jeans length
- Hot vs. cold dark matter
- First light
- Large scale structure
- Cosmic reionization

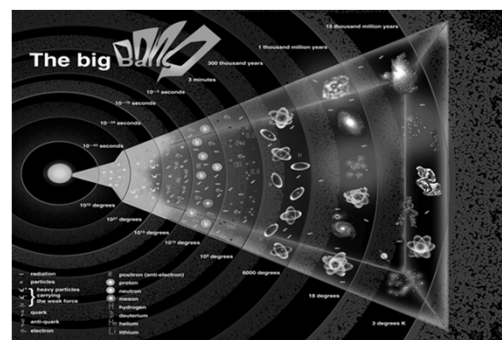


The Big Bang Scenario

- The part of the Universe observable to us today was extremely hot, dense and small ≈ 14 Gyr ago
- The Universe expanded and cooled \rightarrow cosmic epochs and events



Cosmic epochs



The Planck time

- In extremely early Universe, gravity and quantum effects operate on same scale \rightarrow General relativity no good anymore! Theory of quantum gravity necessary!

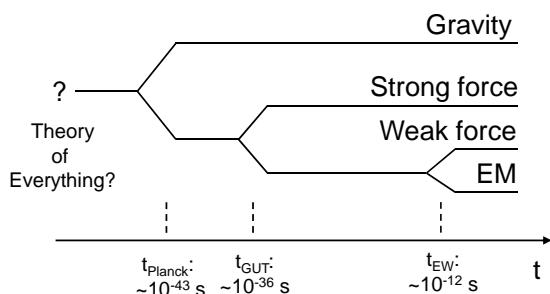
$$t_{\text{Planck}} \sim 10^{-43} \text{ s}$$

Prior to the Planck era:
? ? ?

Current Big Bang theory only describes what happens at $t > t_{\text{Planck}}$

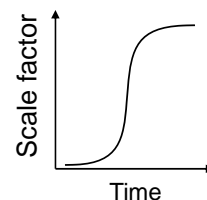
What is this?

Grand Unification



Inflation

- Universe quickly expands by factor $\sim 10^{30}$
- Inflation finished by $t \sim 10^{-32} \text{ s}$
- Solves the flatness, isotropy (horizon) and magnetic monopole problems of the standard Big Bang model
- Quantum fluctuations blown up to cosmic scales \rightarrow seeds for large-scale structure formation later on



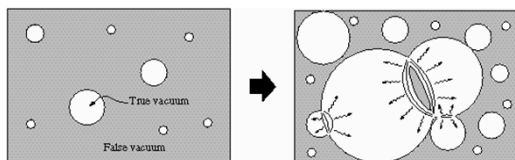
Phase transitions

Transitions:

- Grand unification transition: $t \sim 10^{-36} \text{ s}$
- Electroweak phase transition: $t \sim 10^{-12} \text{ s}$
- Quark-hadron transition: $t \sim 10^{-6} \text{ s}$

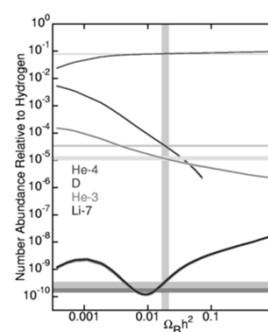
Defects may have formed:

- Domain walls
- Cosmic strings
- Monopoles
- Textures
- Primordial black holes
- Quark nuggets

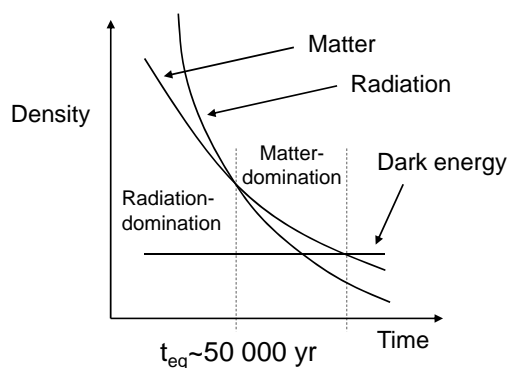


Big Bang Nucleosynthesis

- $t_{\text{BBNS}} \sim 100 \text{ s}$
- Primordial abundances of D, ^3He , ^4He , ^6Li , ^7Li , ^7Be established



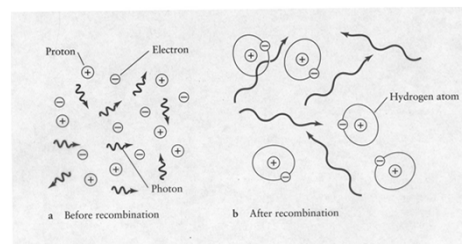
Radiation-dominated era ends and the matter-dominated era begins



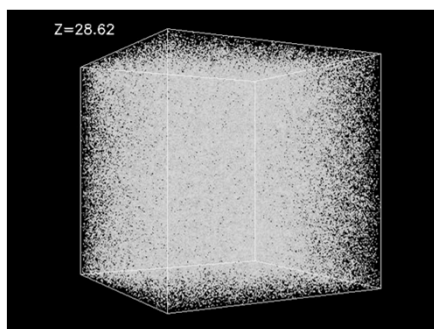
Recombination \rightarrow

Cosmic Microwave Background Radiation

- $t_{\text{recomb}} \sim t_{\text{CMBR}} \sim 0.3 \text{ Myr}$
- $T_0 \approx 2.73 \text{ K}$, Black-body spectrum
- Temperature anisotropies on $\Delta T \sim 10^{-5} \text{ K}$ scale



Structure formation I

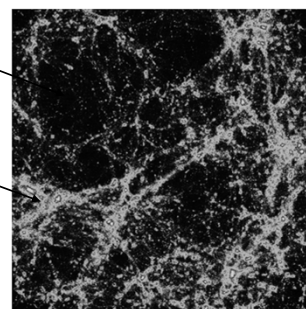


Cold dark matter scenario

Structure formation II

Low-density region

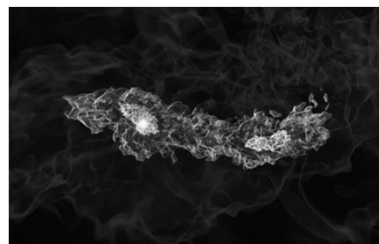
High-density region
(site of star formation)



Voids, walls and filaments



First stars and reionization

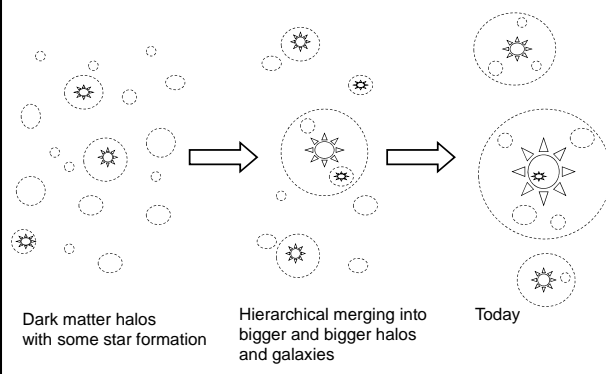


© Kaehler, Turk and Abel

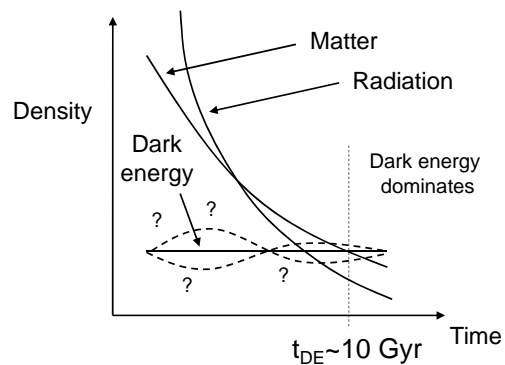
• $t_{\text{stars}} \sim 0.1 \text{ Gyr}$

• $t_{\text{reionization}} \sim 0.1-1 \text{ Gyr}$

Hierarchical galaxy formation



Matter-domination ends and dark energy-domination begins



Today

- $t_0 \approx 13.8$ Gyr
- Astronomical objects up to $z \approx 10$ have been detected
- The cosmic microwave background radiation has $z \approx 1100$



Quite a few unsolved problems...

- What drove inflation?
- What is the dark matter?
- What is the dark energy?
 - How will the Universe end?
- What were the initial conditions?
 - Why is the Universe expanding?
 - Why is there something instead of nothing?
- Why is there more matter than antimatter?
- Is the Universe spatially infinite?
- What caused reionization?
- What came before the Big Bang?
- Are there parallel Universes?

