

Cosmology AS7009, 2010

Lecture 1



Formal Information

- Organizer:
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 - E-mail: ez@astro.su.se
- Course homepage:
 - www.astro.su.se/~ez/kurs/Cosmology10.html

Outline for today

- Formal Stuff
 - Course literature
 - Examination
 - Hand-in exercises
 - Seminars
 - Literature exercise
 - Grades
 - Schedule
- Course outline
- Cosmic epochs

Course literature

Introduction to cosmology

Barbara Ryden (2002)

ISBN 0805389121 or 9780805389128

Around 560 SEK (e.g. AdLibris, Bokus)

Examination

- Hand-in exercises
 - 3 sets X 3 problems each
- Seminars
 - Seminar I: *Common misconceptions in modern cosmology*
 - Seminar II: *Strange Universe*
- Literature exercise:
 - Written essay (≈ 3 pages)
 - Oral presentation (≈10 minutes)

Hand-in exercises I

- 27 exercises downloadable from the course homepage
- Around 18 exercises will be solved (by me) on the blackboard during the tutorials
- Remember: Much easier to grasp the solutions if you have already attempted to solve these, before going to class!

Hand-in exercises II

- 9 of the exercises are hand-in problems:
 - Somewhat similar to those solved on the blackboard
- 3 sets with deadlines: Nov 25, Dec 2, Dec 14
- Access to Matlab, Octave or similar software may be very useful in some cases!

Seminars

- 2 Seminars:
 - Seminar I: *Common misconceptions about modern cosmology*
 - Seminar II: *Strange Universe*
- Instructions available from course homepage
- Seminar I – preparation:
 - Read suggested papers + others
 - Answer questions
 - Prepare to present answers and results in class
- Seminar II – preparation:
 - Analyze data set
 - Prepare to present your findings in class

Seminars II

- Purpose:
 - Practice finding and reading relevant research papers
 - Practice analyzing astronomical data
 - Practice critical thinking
 - Practice scientific creativity
 - Practice discussing in front of audience
- What if you cannot attend the seminars?
 - Have to present results in written report before X-mas (→ more work!)

Seminars III

- Seminar I: Nov 30, 10-12
Common misconceptions about modern cosmology
- Seminar II: Dec 16, 10-12
Strange Universe

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 December 14
- Oral presentation (≈ 10 minutes)
December 20, 13-15
- Note:
 - 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 before X-mas!)
 - But: You will then have to give the oral presentation at one of the Galaxies and Cosmology group meetings (Fridays at 14:00).
This is far scarier! Not recommended!

Suggested topics I

- Parallel Universes
- Topology of the Universe
- CMBR anisotropies
- Observational indications of varying constants
- Wormholes and time travel
- Cosmic antimatter
- The anthropic principle in cosmology
- Brane cosmology

Suggested topics II

- **Off-Broadway:**
 - Alternative theories of gravity – in relation to dark matter
 - Alternative theories of gravity – in relation to dark energy
 - Inhomogeneous models – in relation to dark energy
 - Varying speed of light cosmology
- **Off-off-Broadway:**
 - Quasi Steady-State cosmology
 - Plasma cosmology

But please feel free to suggest other topics!

Grades I

- The total score P_{tot} determines the grade:

A:	$P \geq 90\%$ of $\max(P_{tot})$
B:	$P = 80-89.9\%$ of $\max(P_{tot})$
C:	$P = 70-79.9\%$ of $\max(P_{tot})$
D:	$P = 60-69.9\%$ of $\max(P_{tot})$
E:	$P = 50-59.9\%$ of $\max(P_{tot})$
FX:	$P = 40-49.9\%$ of $\max(P_{tot})$
F:	$P < 40\%$ of $\max(P_{tot})$

Grades II

- P_{tot} is made up of 5 components (with equal weights):

- 1) Hand-in exercises
- 2) Seminar 1
- 3) Seminar 2
- 4) Literature exercise, written report
- 5) Literature exercise, oral report

Note: Failure to meet the deadline for any single component → The contribution from that component is automatically lowered by 20% of the maximum

Grades III

Example:

- 1) Hand-in exercises (max 15 p per set of hand-ins):
5 p, 10p, 12p

But: Set 2 handed in late → Subtract $0.2 \cdot 15 = 3$

Hence: $5p + (10-3)p + 12p = 24p$

Contribution to total: $24/45 \cdot 0.2 \approx 0.11$

- 2) Seminar 1: 3p (out of max 5p)
Contribution to total: $3/5 \cdot 0.2 = 0.12$

- 3) Seminar 2: 4p (out of max 5p)
Contribution to total: $4/5 \cdot 0.2 = 0.16$

- 4) Literature exercise, written report: 2p (out of max 5p)
Contribution to total: $2/5 \cdot 0.2 = 0.08$

- 5) Literature exercise, oral report: 5p (out of max 5p)
Contribution to total: $5/5 \cdot 0.2 = 0.2$

Total: $0.11 + 0.12 + 0.16 + 0.08 + 0.2 = 0.67$ (i.e. 67%)
→ Grade D (interval 60-69.9%)

Schedule I

- 10 Lectures
 - L1, Nov 2, 10-12: Course information, course overview
 - L2, Nov 3, 10-12: Fundamentals, Gravity, Curvature (chapters 2-3)
 - L3, Nov 9, 10-12: Metrics, Proper distance, Cosmic dynamics (chapters 3-4)
 - L4, Nov 15, 10-12: Single and Multiple component Universes (chapters 5-6)
 - L5, Nov 16, 10-12: Cosmological parameters and dark energy (chapters 7)
 - L6, Nov 23, 10-12: Dark matter (chapter 8)
 - L7, Nov 25, 10-12: CMBR (chapter 9)
 - L8, Dec 2, 10-12: BBNS and the early Universe (chapter 10)
 - L9, Dec 7, 10-12: Inflation and the very early Universe (chapter 11)
 - L10, Dec 7, 13-15: Structure formation (chapter 12)

Schedule II

- 3 Exercise sessions:
 - E1, Nov 18, 10-12, Exercises 1-6
 - E2, Nov 25, 13-15, Exercises 7-12
 - E3, Dec 8, 10-12, Exercises 13-18

Schedule III

- 2 seminars
 - Seminar I: Nov 30, 10-12
 - Seminar II: Dec 16, 10-12
- Oral presentation of literature review
 - December 20, 13-15

Schedule IV

- Important dates to remember:
 - November 25, Thursday: Deadline hand-ins 1-3
 - November 30, Tuesday 10-12: Seminar 1
 - December 2, Thursday: Deadline hand-ins 4-6
 - December 14, Tuesday: Deadline hand-ins 7-9 & deadline written report
 - December 16, Thursday: Seminar 2
 - December 20, Monday: Oral presentations
- Pretty crowded around Nov 30-Dec 2 and Dec 14-20!
Do as much work as possible during the first four weeks of the course!

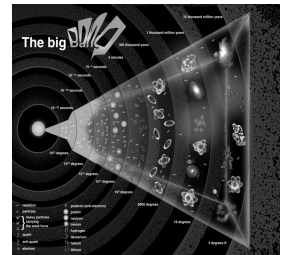
How much time will I have to spend on this course?

My estimates:

- Attending classes: $17 \times 2 \text{ h} = 34 \text{ h} \sim 4 \text{ days}$
 - Studying textbook: 6 days (two chapters a day)
 - Preparing for seminars: 2 days (one day per seminar)
 - Solving exercises (including hand-ins): 9 days (3 exercises a day)
 - Literature exercise: 4 days
- Sum: 25 days, i.e. 5 weeks or 7.5 hp

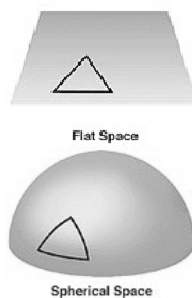
Course Outline

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



Course Outline

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



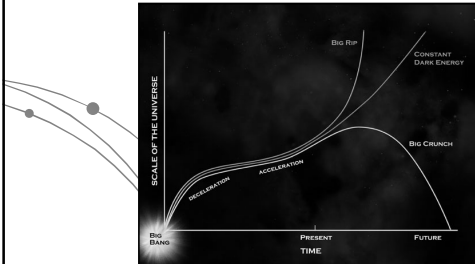
Course Outline

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

$$\begin{aligned} & \frac{d}{dt} \left(\frac{1}{a} \frac{da}{dt} \right) = \frac{1}{a^2} \frac{da}{dt} \left(\frac{da}{dt} - \frac{1}{a} \right) = \frac{1}{a^2} \left(\frac{da}{dt} \right)^2 - \frac{1}{a^3} \frac{da}{dt} \\ & \frac{d}{dt} \left(\frac{1}{a} \frac{da}{dt} \right) = \frac{1}{a^2} \left(\frac{da}{dt} \right)^2 - \frac{1}{a^3} \frac{da}{dt} \\ & \frac{d}{dt} \left(\frac{1}{a} \frac{da}{dt} \right) = \frac{1}{a^2} \left(\frac{da}{dt} \right)^2 - \frac{1}{a^3} \frac{da}{dt} \\ & \frac{d}{dt} \left(\frac{1}{a} \frac{da}{dt} \right) = \frac{1}{a^2} \left(\frac{da}{dt} \right)^2 - \frac{1}{a^3} \frac{da}{dt} \end{aligned}$$

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



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

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

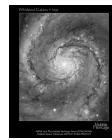
$$\Omega_M$$

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



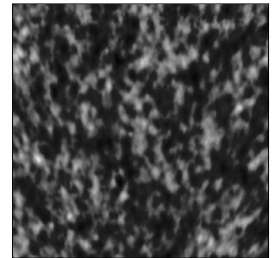
Dark matter



Luminous matter

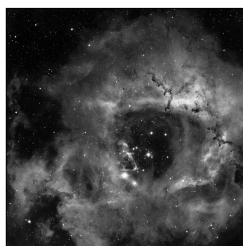
Course Outline

- 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



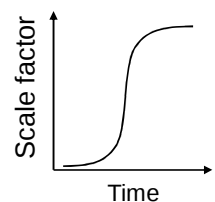
Course Outline

- Lecture 8: Big Bang Nucleosynthesis and the early Universe
 - BBNS
 - Measuring primordial abundances
 - What happened to the antimatter?



Course Outline

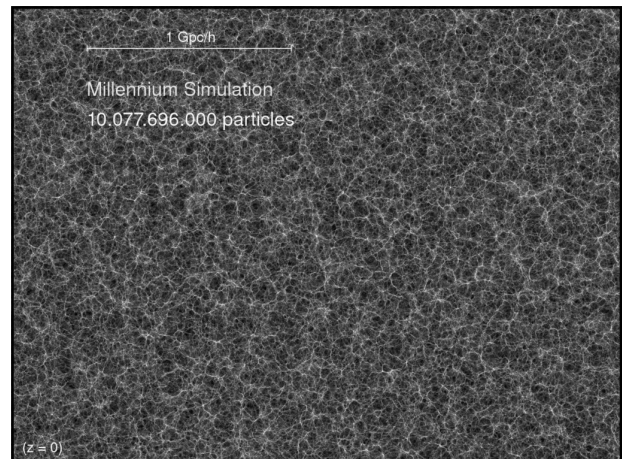
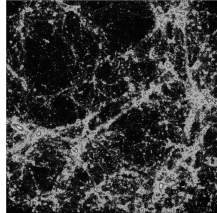
- Lecture 9: Inflation and the very early Universe
 - Problems with a non-inflationary Big Bang
 - Inflation
 - Grand Unified Theories
 - Phase transitions



Course Outline

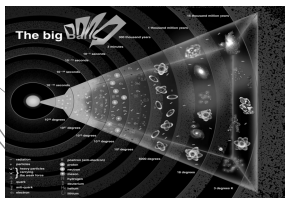
- Lecture 10: Structure formation

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

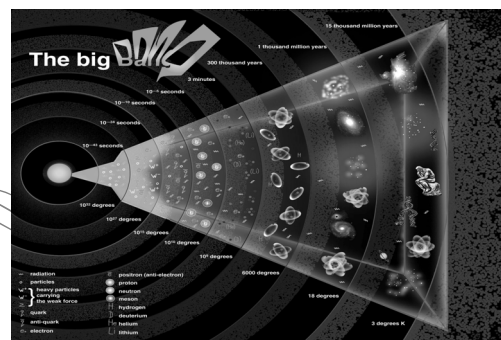


The Big Bang Scenario

- 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

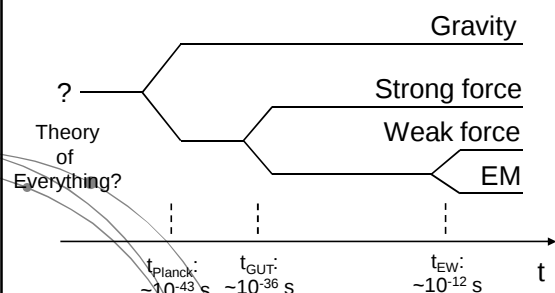
- In extremely early Universe, gravity and quantum effects operate on same scale $\rightarrow$ General relativity no good anymore! Theory of quantum gravity necessary!

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

Prior to the Planck era:
????

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

Grand Unification



Inflation

- Universe quickly expands by factor $\sim 10^{30}$
- Inflation finished by $t \sim 10^{-32}$ 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

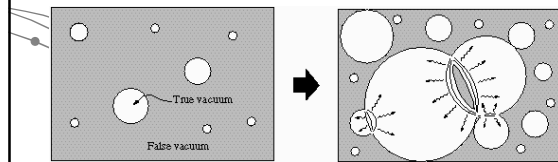
Phase transitions

Transitions:

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

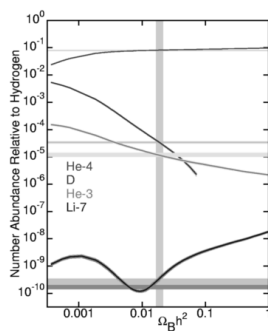
Defects may have formed:

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

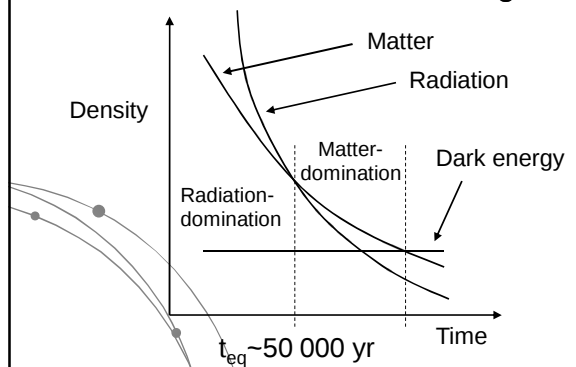


Big Bang Nucleosynthesis

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



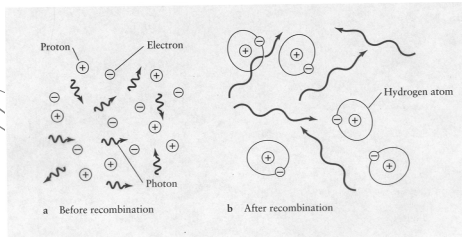
Radiation-dominated era ends and the matter-dominated era begins



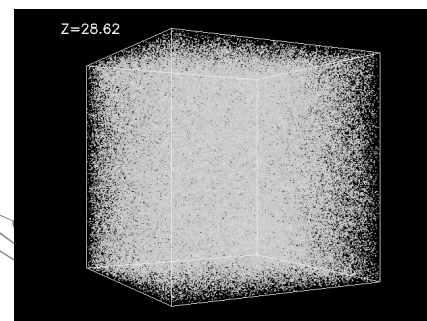
Recombination $\rightarrow$

Cosmic Microwave Background Radiation

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



Structure formation I

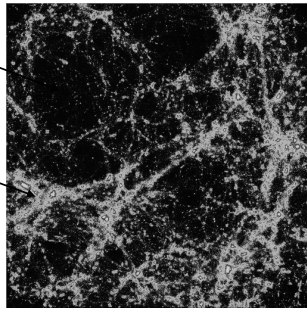


Cold dark matter scenario

Structure formation II

Low-density region

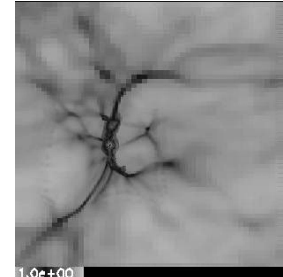
High-density region
(site of star formation)



Voids, walls and filaments

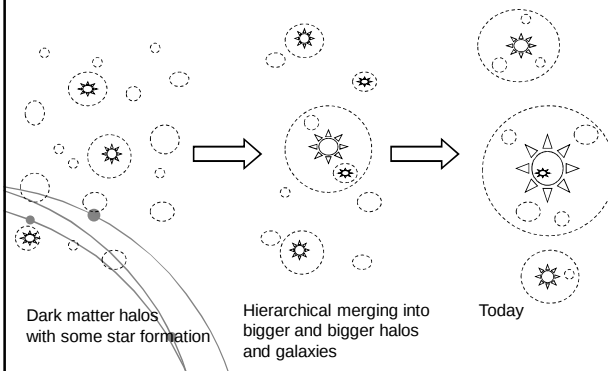
First stars and reionization

- $t_{\text{stars}} \sim 100 \text{ Myr}$
- $t_{\text{reionization}} \sim 100 - 500 \text{ Myr}$

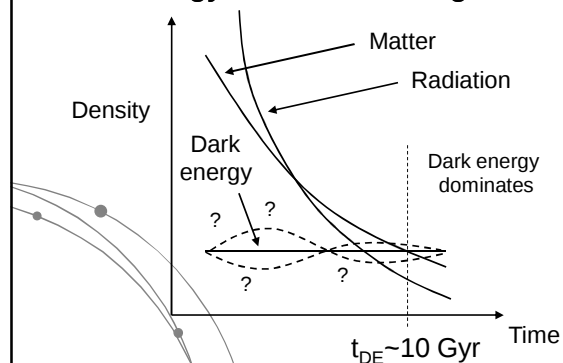


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Hierarchical galaxy formation

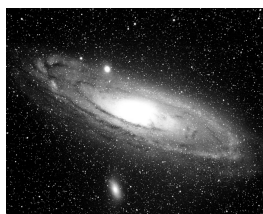


Matter-domination ends and dark energy-domination begins



Today

- $t_0 \approx 13.7 \text{ Gyr}$
- 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?