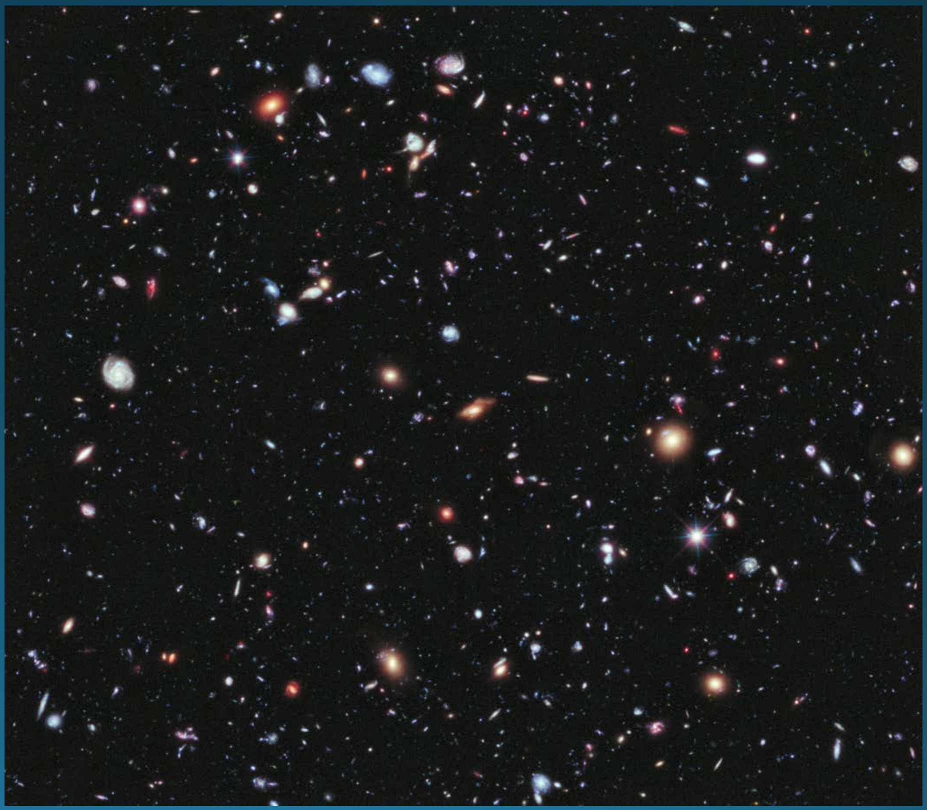
Cosmology 1FA209
2017, 10 credits
Lecture 1: Introduction



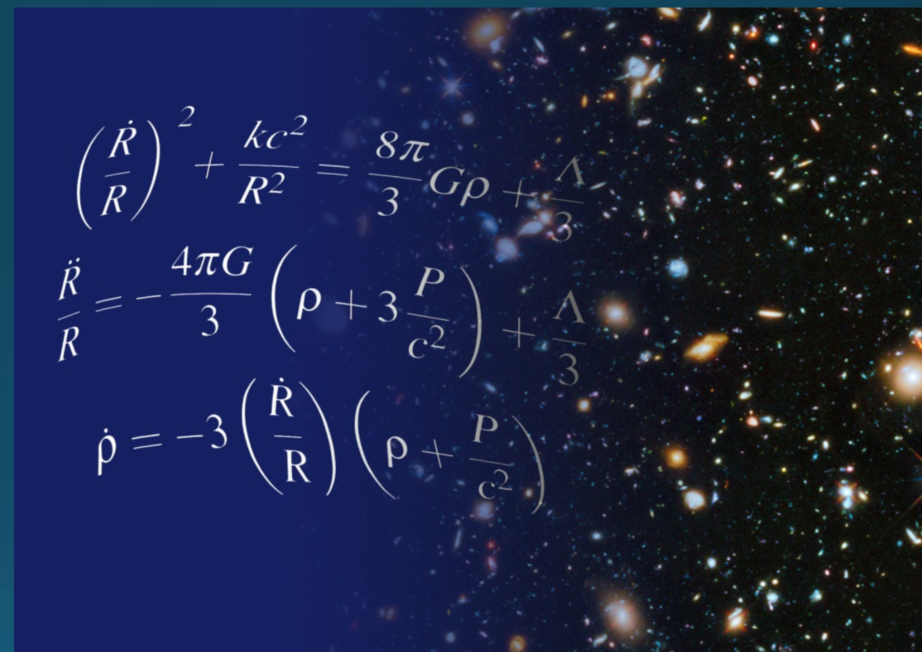
Formal Information

- 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



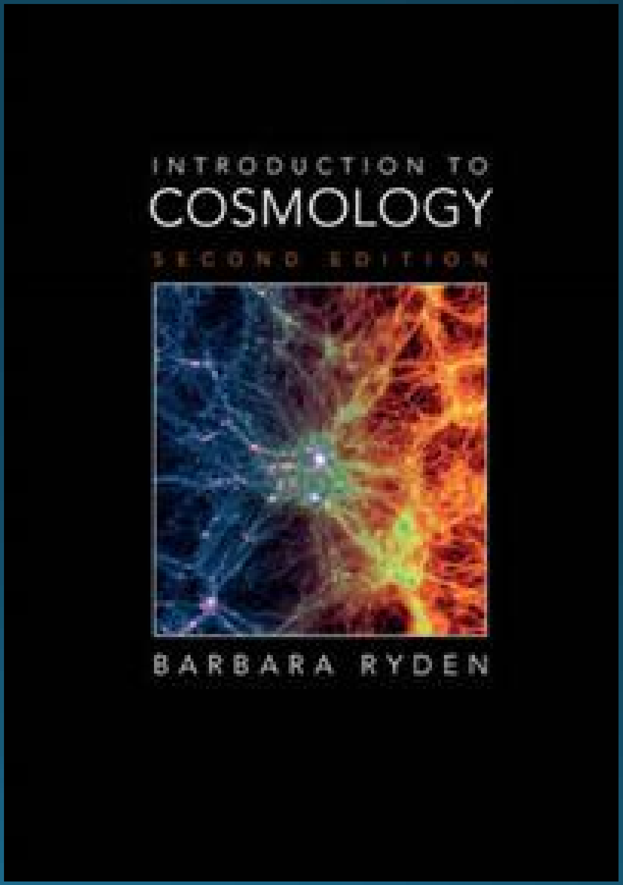

What is this?

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 ($\rightarrow$ 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

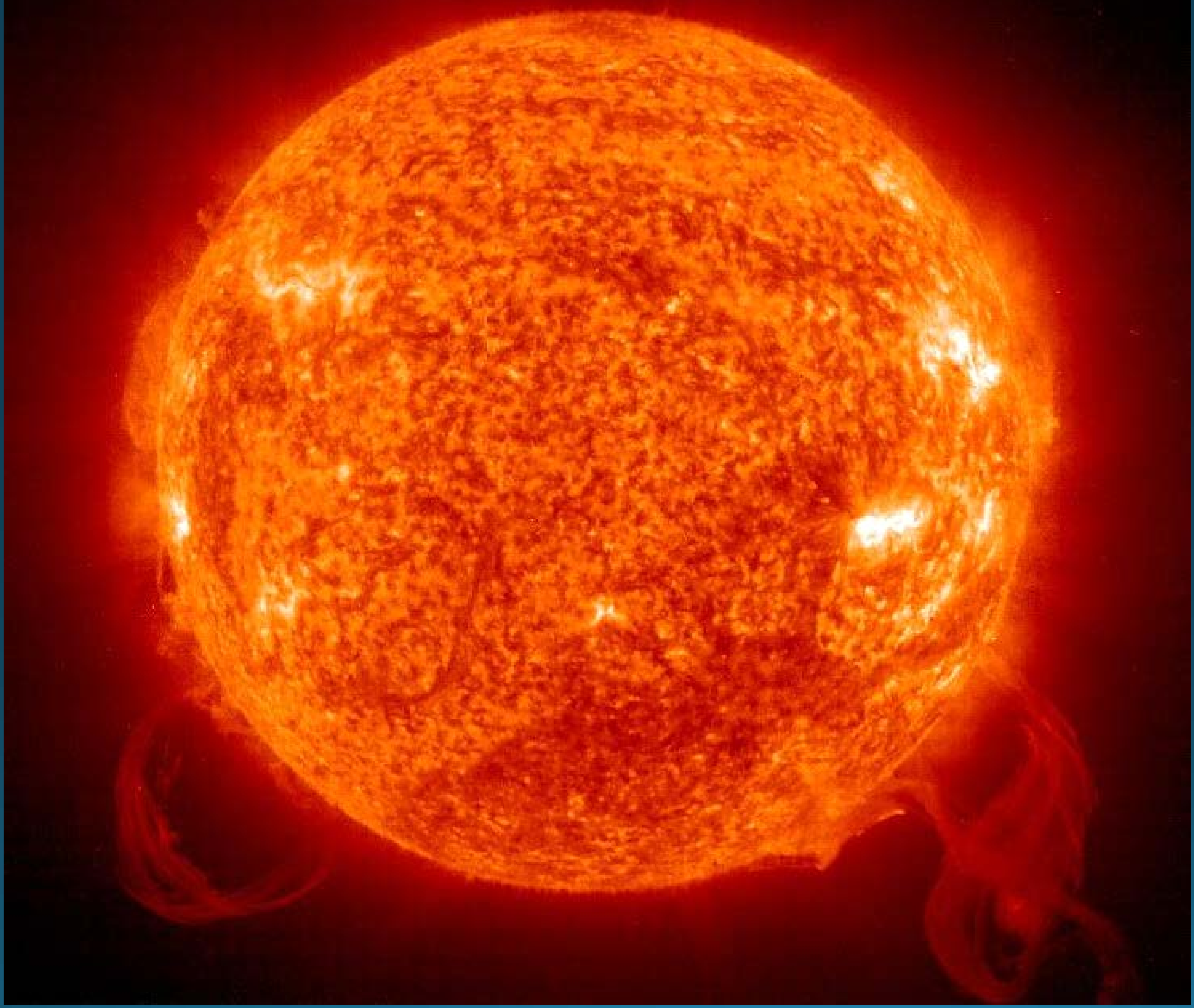
Seminar II

- **Title:** Parallel universes
- **Grade:** Fail, Pass
- Preparation:
  - Read suggested paper
  - Think about ways to explain the four levels of parallel universes and to create vizualations 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 (and will allow for a swifter evaluation), so please consider scanning your solutions (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 $\Omega_{\mathrm{M}} = 0.3$ and $\Omega_{\Lambda} = 0.7$?

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

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2}\epsilon(t) - \frac{\kappa c^2}{R_0^2 a(t)^2}, \quad (1)$$

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 a 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

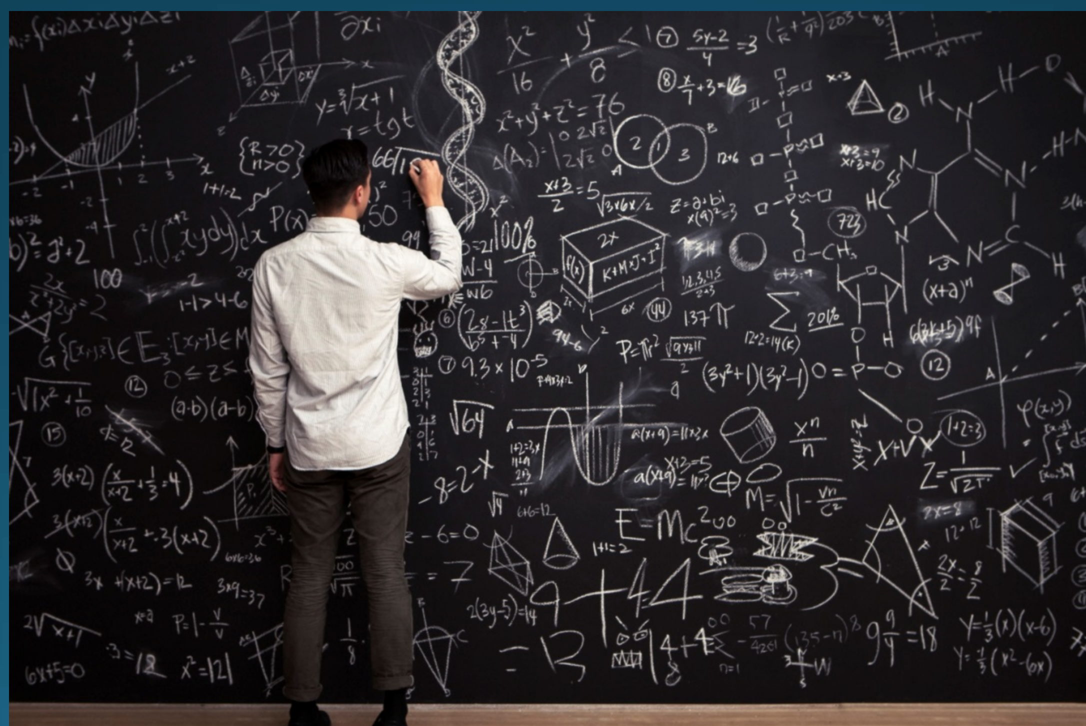
Schedule I

- 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?

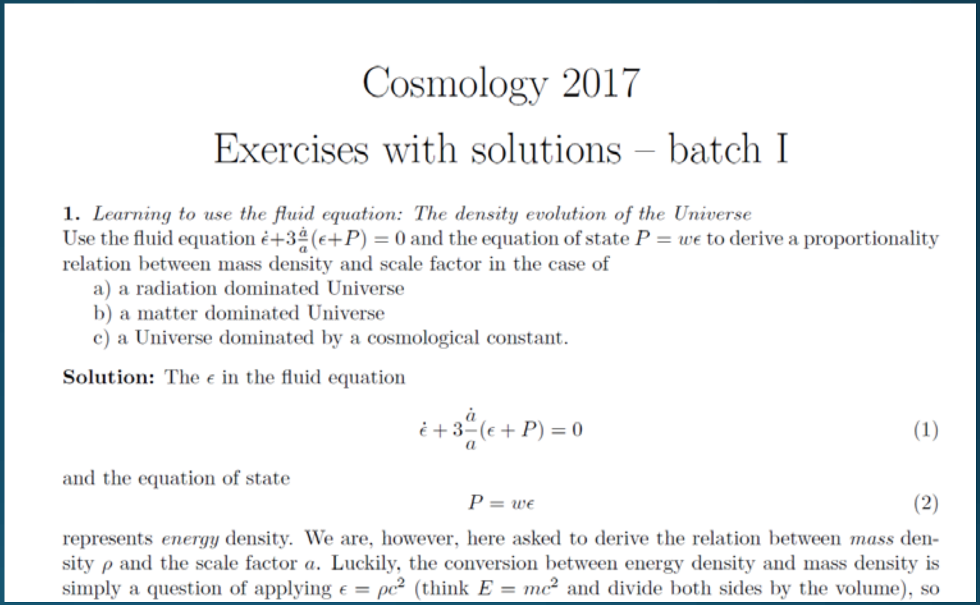
- You solve problems in teams!
- Attendance not compulsory, but actively participating will make it much easier to complete the hand-in problems
- **Suggested preparation:**
  - Study exercises and solutions posted on course homepage for sessions 1-2
  - Bring pen, paper, calculator/computer, textbook 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 fluid equation: The density evolution of the Universe*
Use the fluid equation $\dot{\epsilon}+3\frac{\dot{a}}{a}(\epsilon+P)=0$ and the equation of state $P=w\epsilon$ 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 ϵ in the fluid equation

$$\dot{\epsilon}+3\frac{\dot{a}}{a}(\epsilon+P)=0 \quad (1)$$

and the equation of state

$$P=w\epsilon \quad (2)$$

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

Exercise session 3: Fermi problems

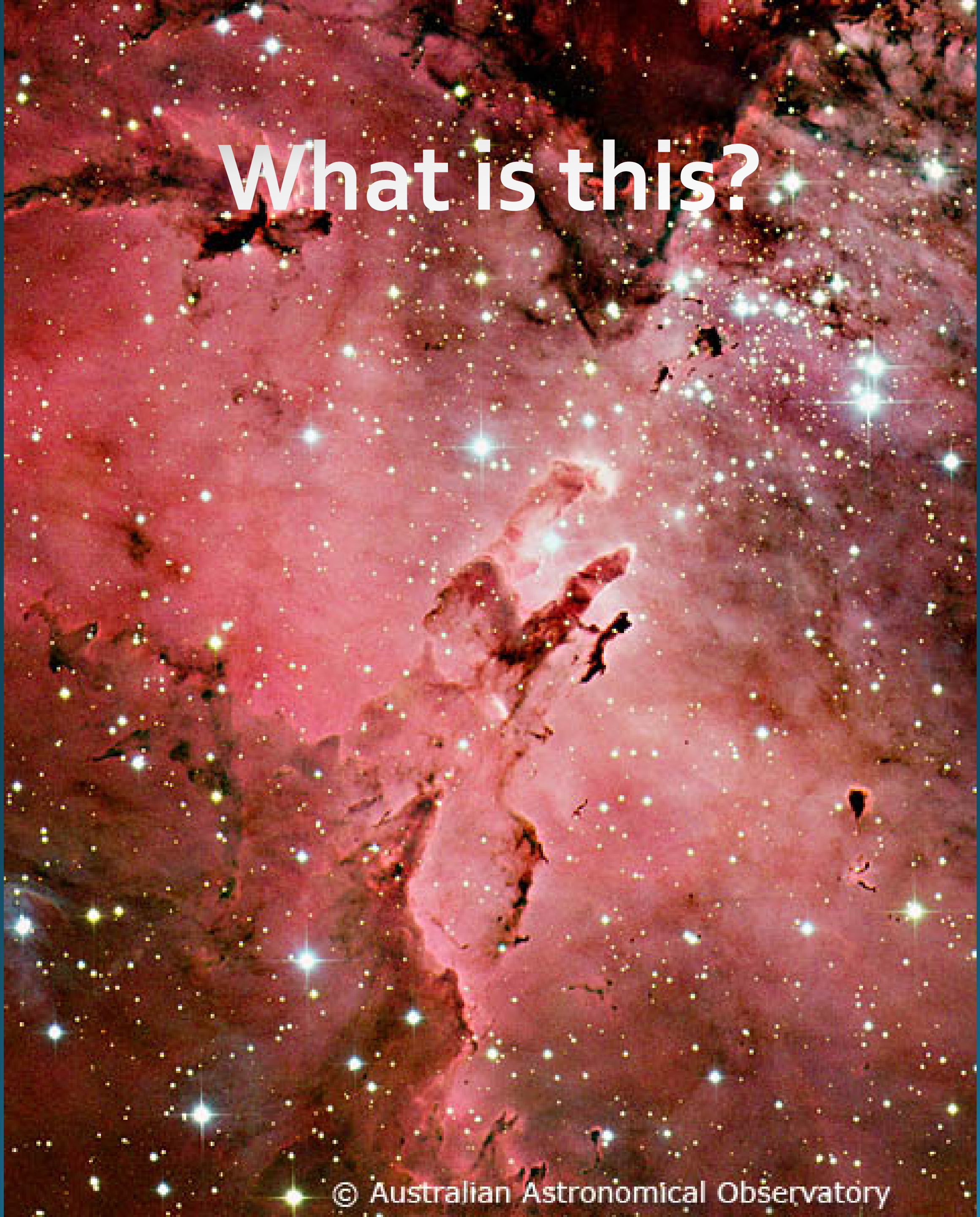
Objective: Gain skill in making back-of-the-envelope calculations

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?



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?

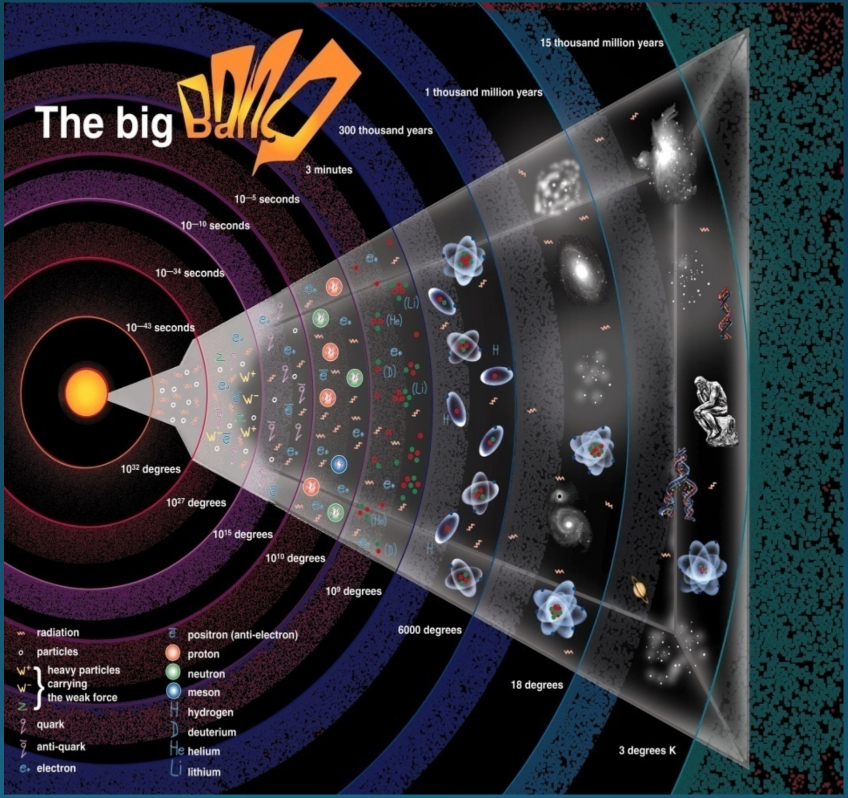
My estimates:

- 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

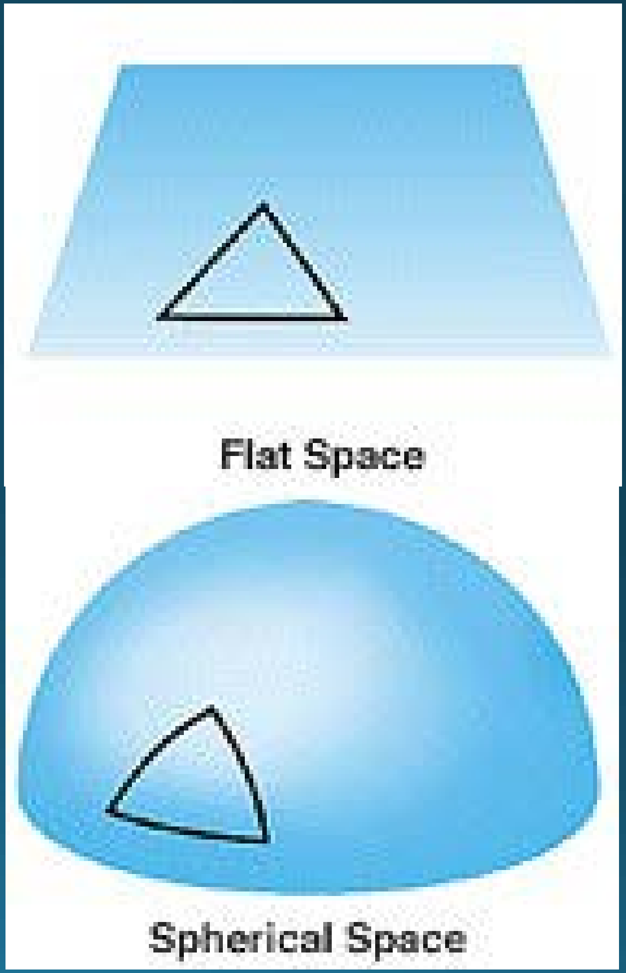
Course Outline

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



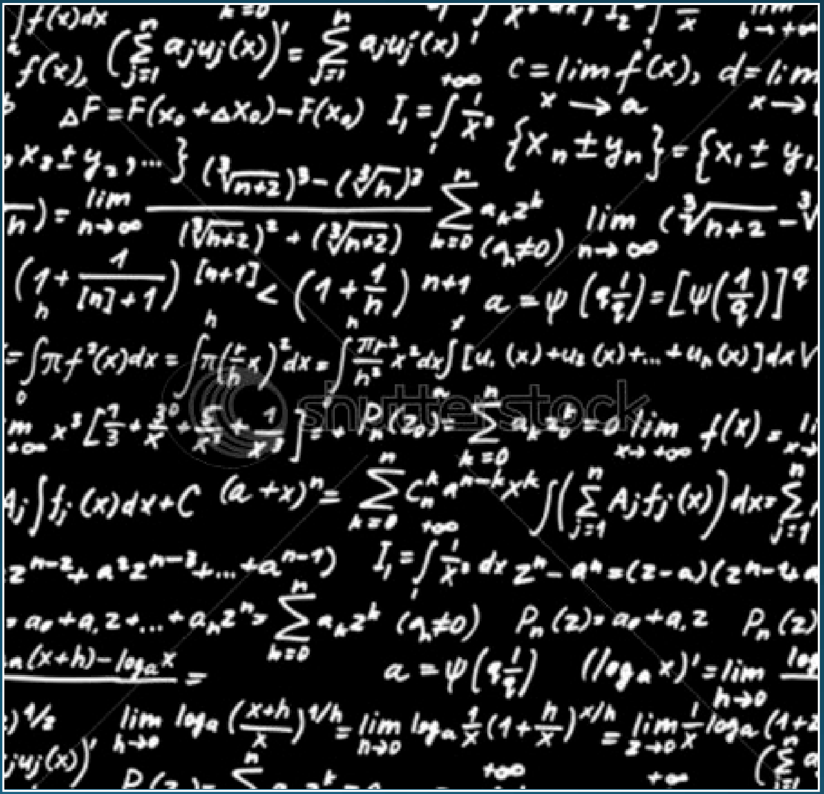
Course Outline

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



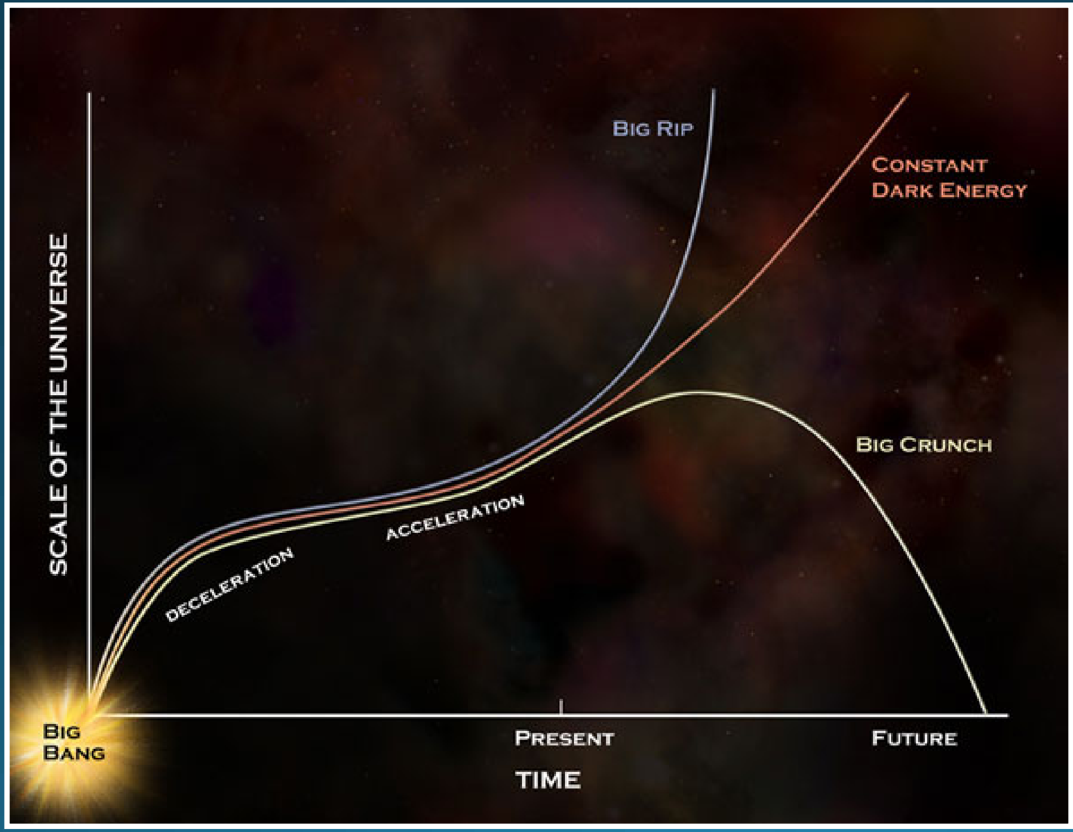
Course Outline

- 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



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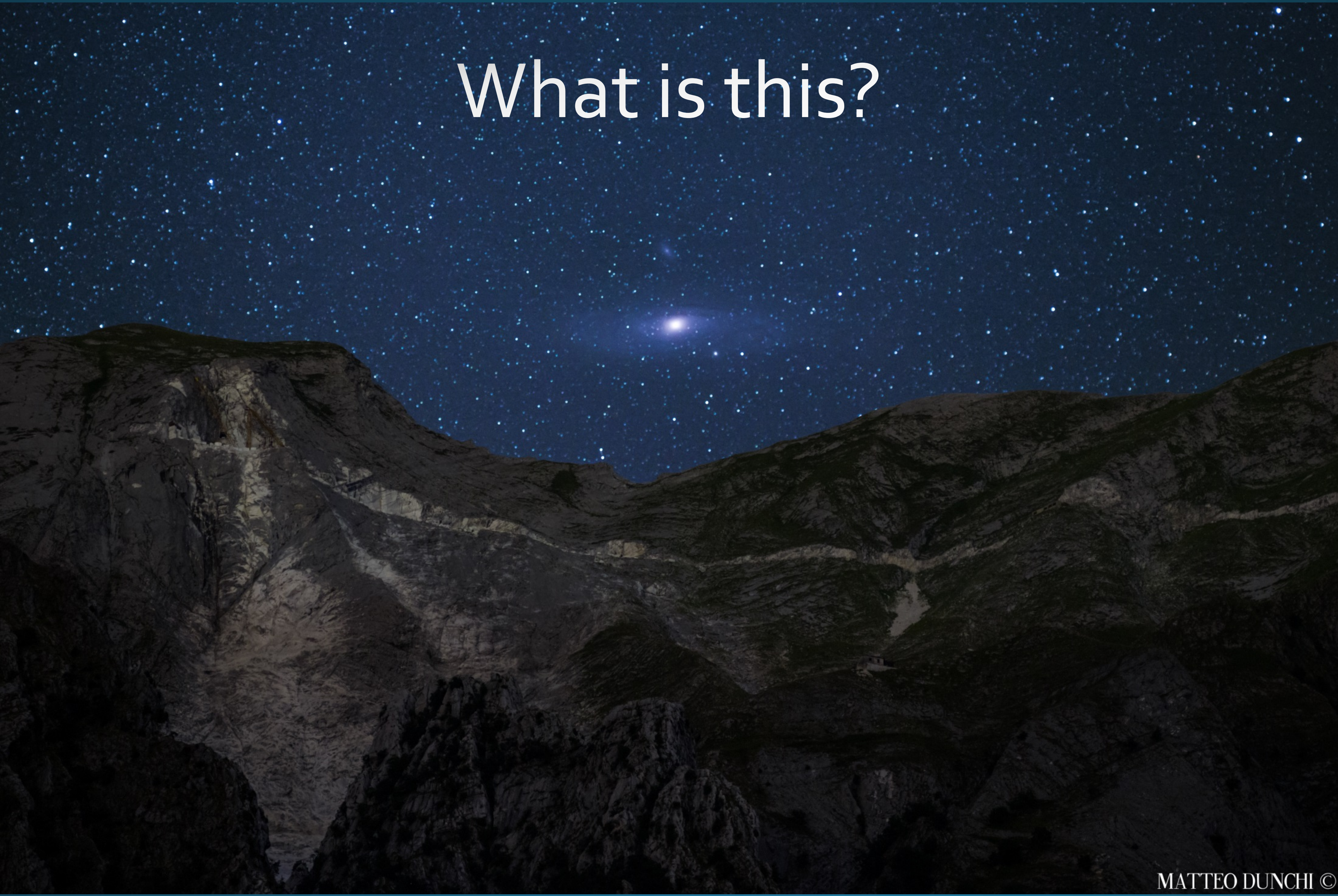
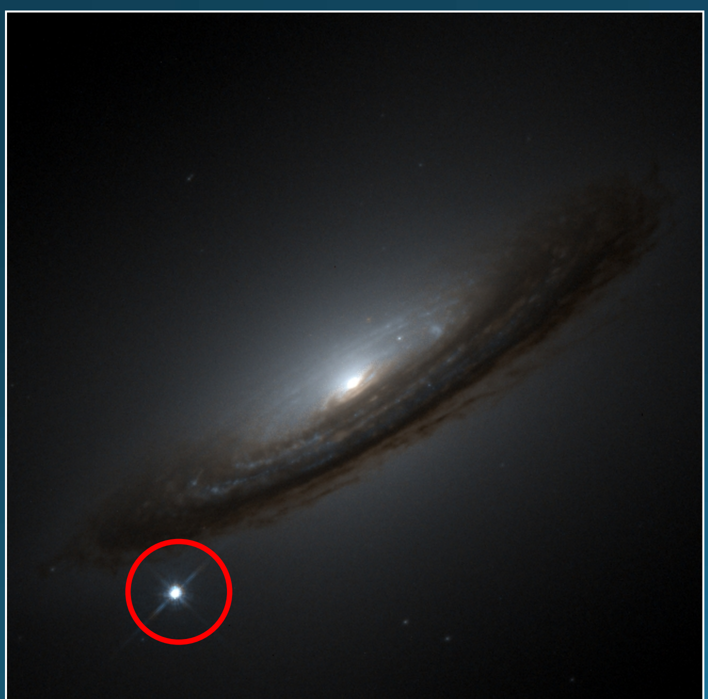


What is this?

Course Outline

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



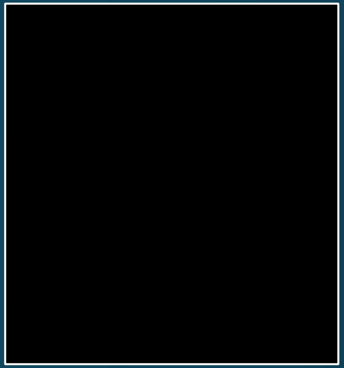
H_0 q_0 w_{DE}

Ω_Λ Ω_γ κ

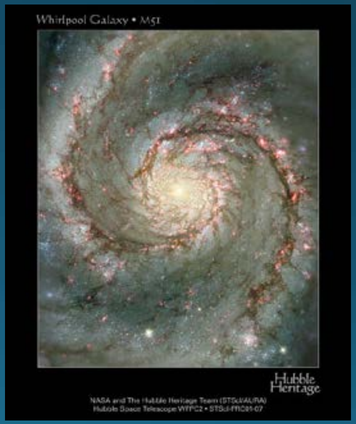
Ω_M

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



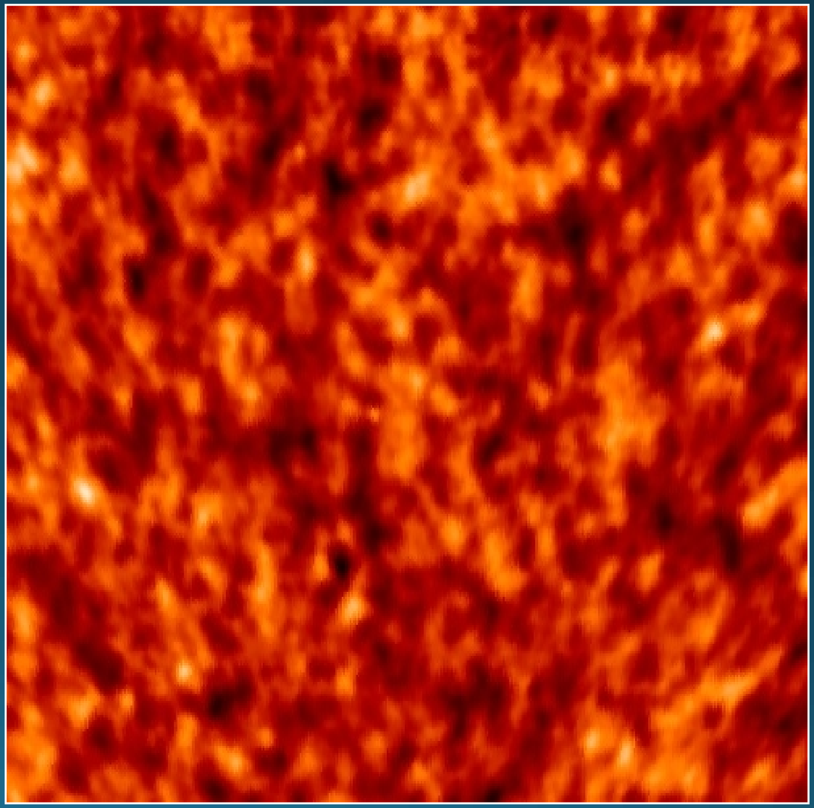
Dark matter



Luminous matter

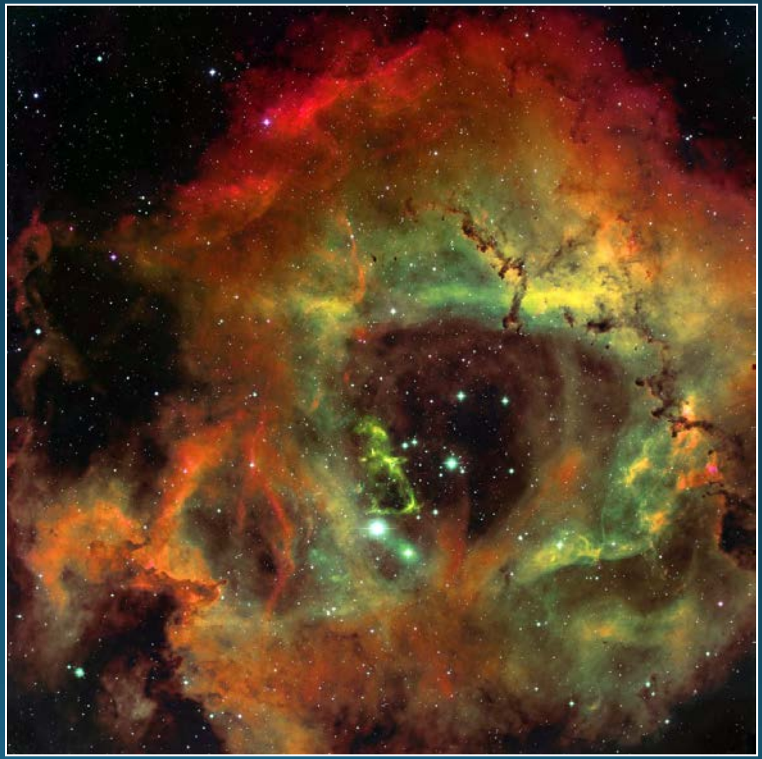
Course Outline

- 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



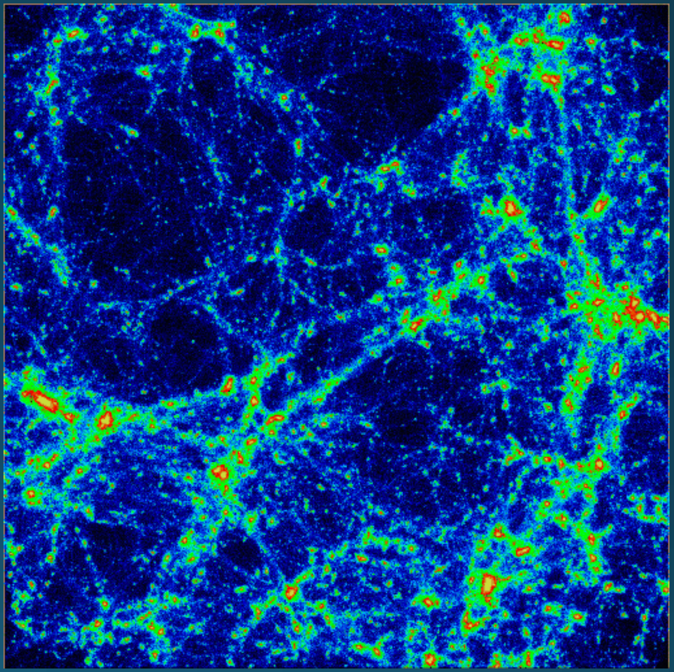
Course Outline

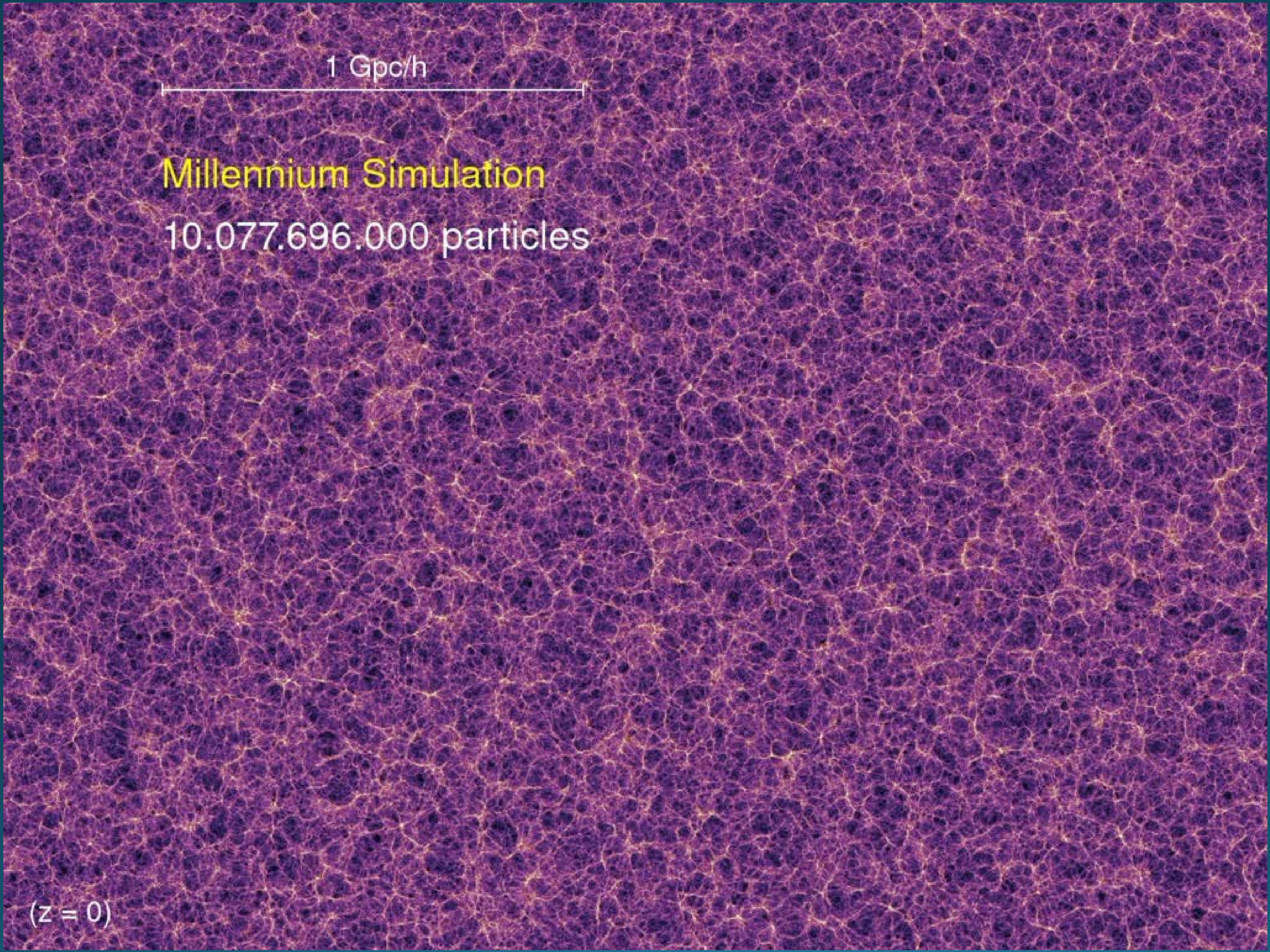
- Lecture 8: Big Bang Nucleosynthesis, the early Universe, cosmic inflation
  - BBNS
  - Measuring primordial abundances
  - What happened to the antimatter?
  - Problems with a non-inflationary Big Bang
  - Inflation
  - Grand Unified Theories



Course Outline

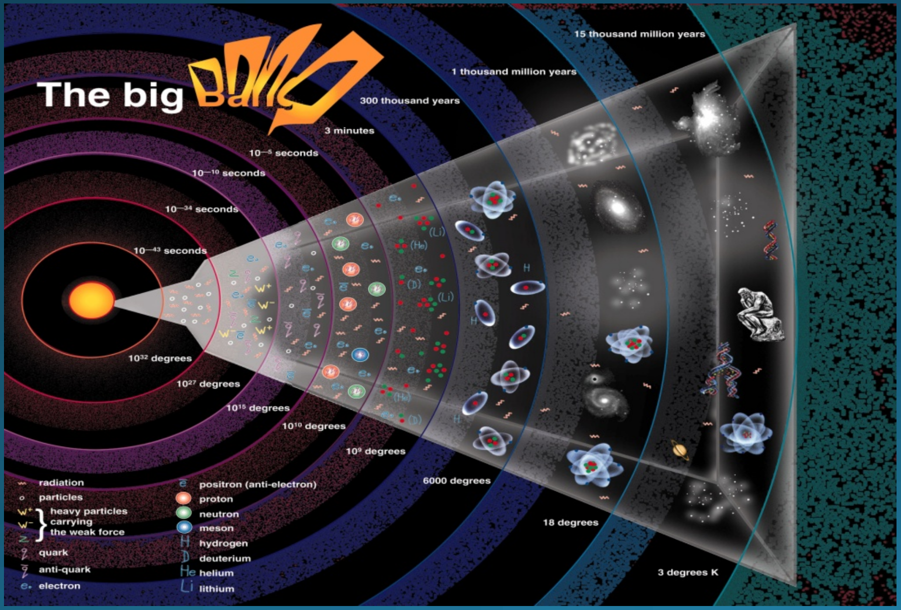
- Lecture 9: Structure formation
  - Perturbation spectrum
  - Jeans mass, Jeans length
  - Hot vs. cold dark matter
  - First light
  - Large scale structure
  - Cosmic reionization



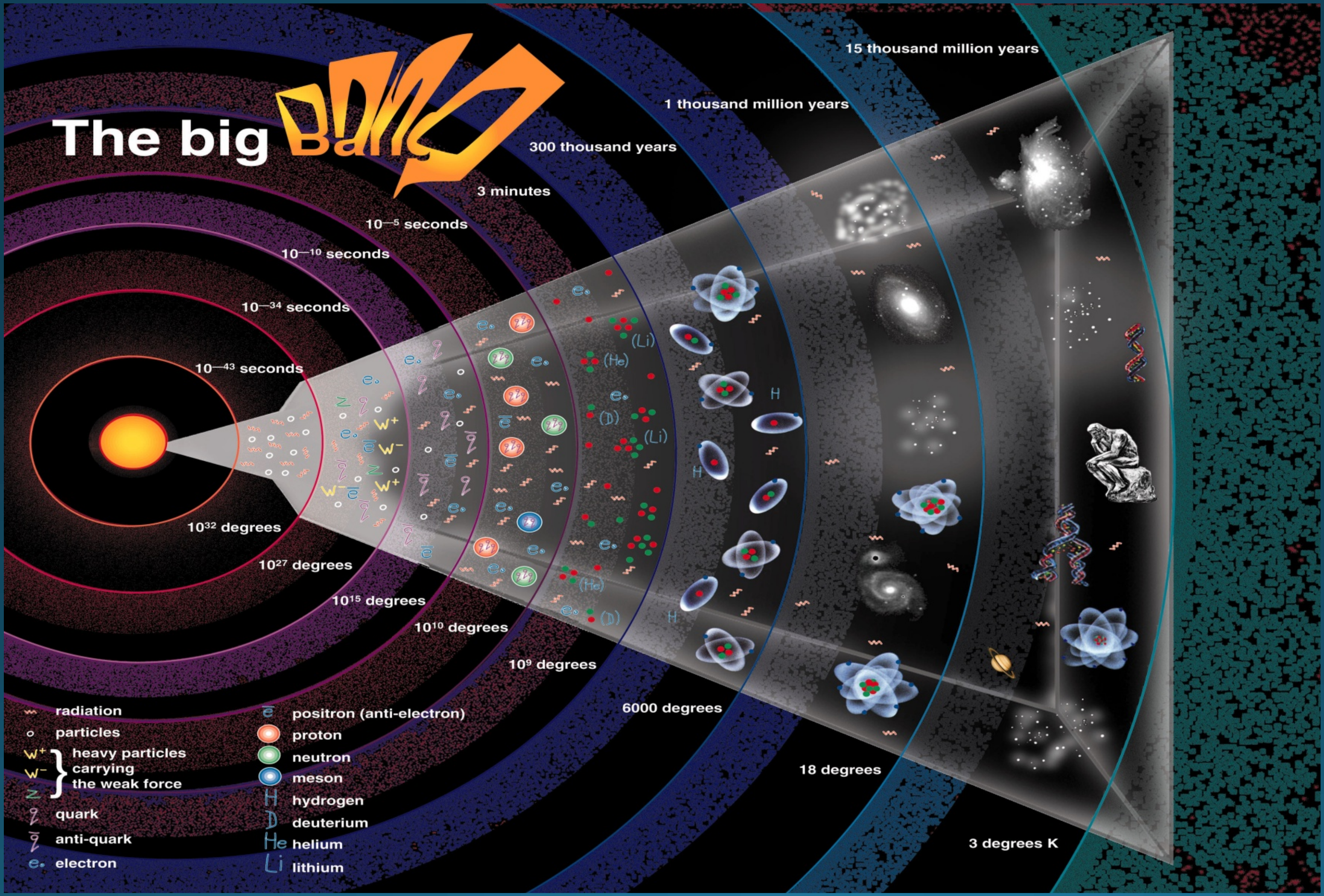

1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)

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 $\rightarrow$

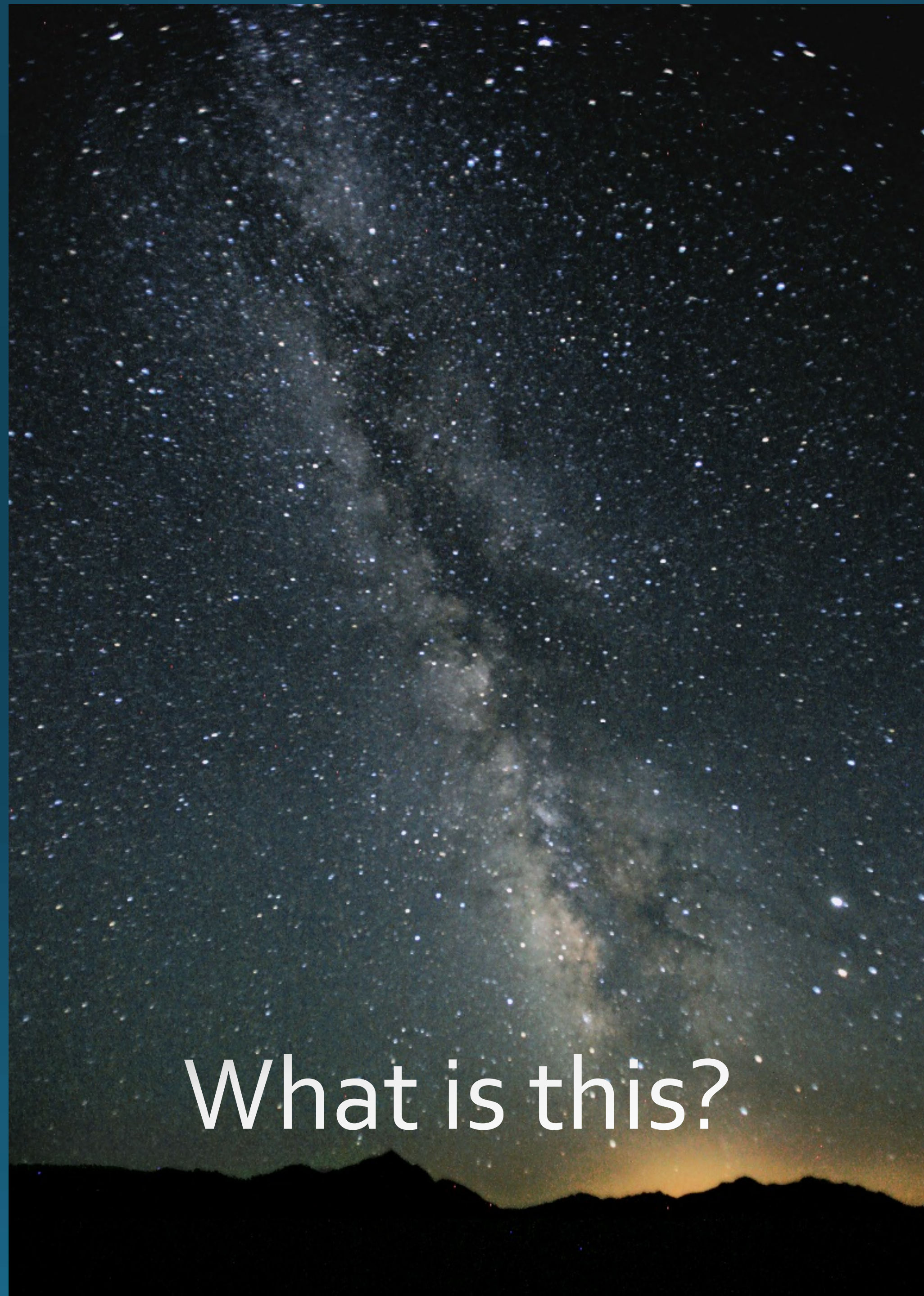
  General relativity no good anymore! Theory of quantum gravity necessary!

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

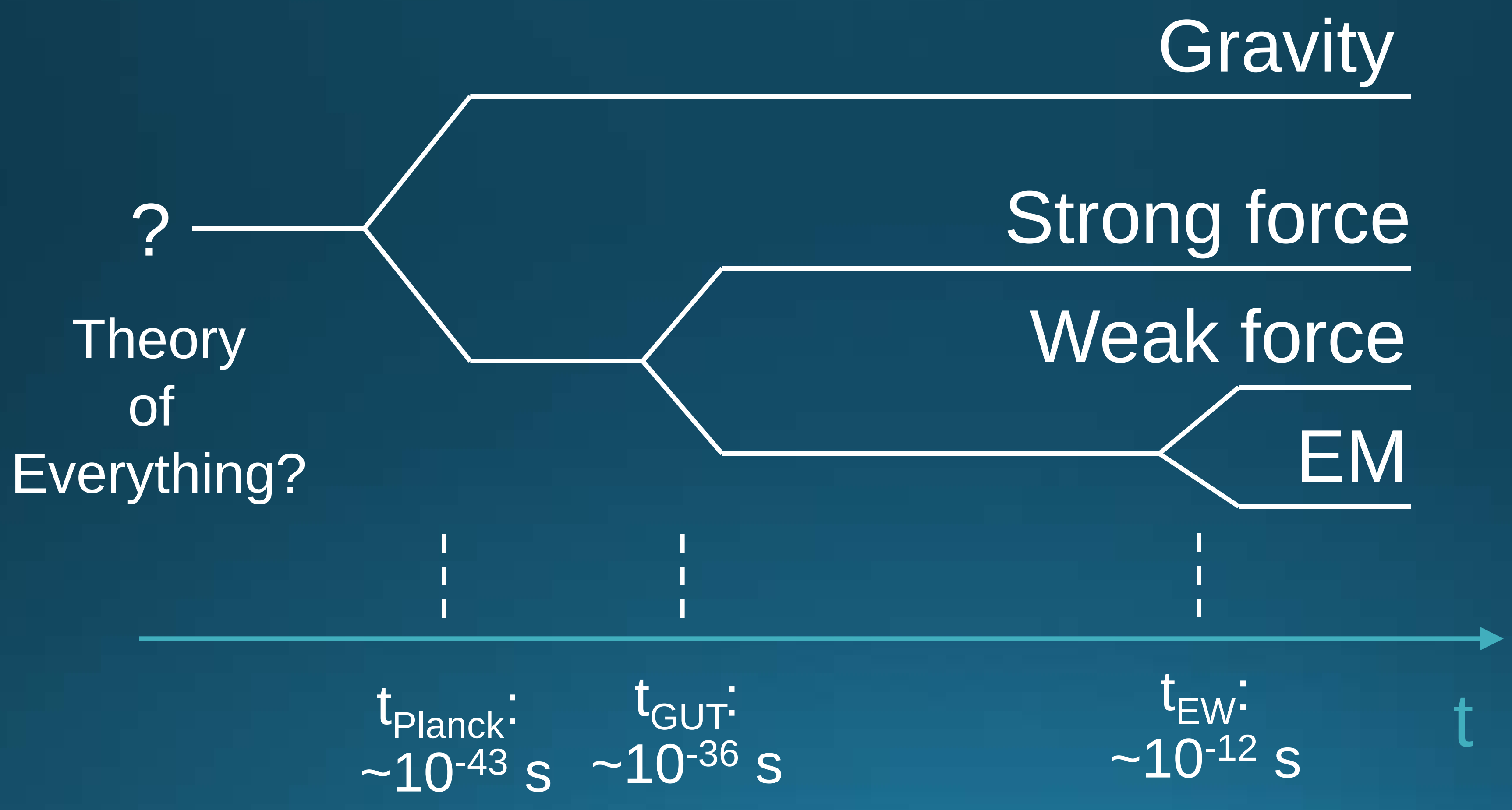
Prior to the Planck era:

? ? ? ?

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

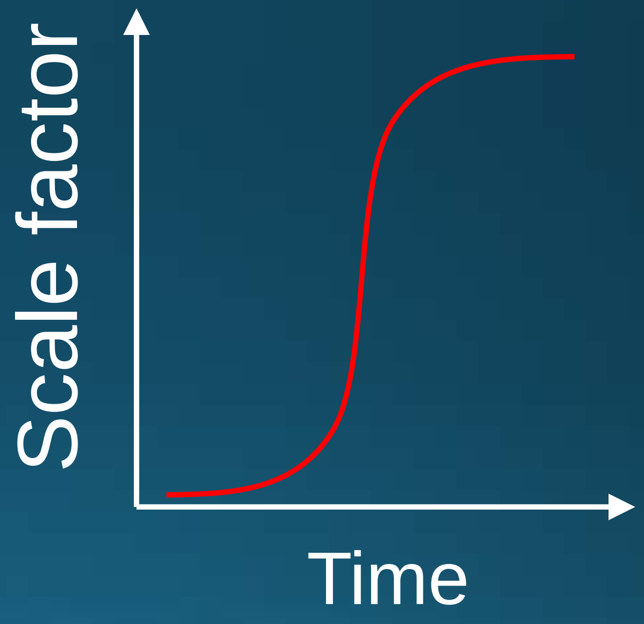

What is this?

Grand Unification



Inflation

- Universe quickly expands by factor ~ 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



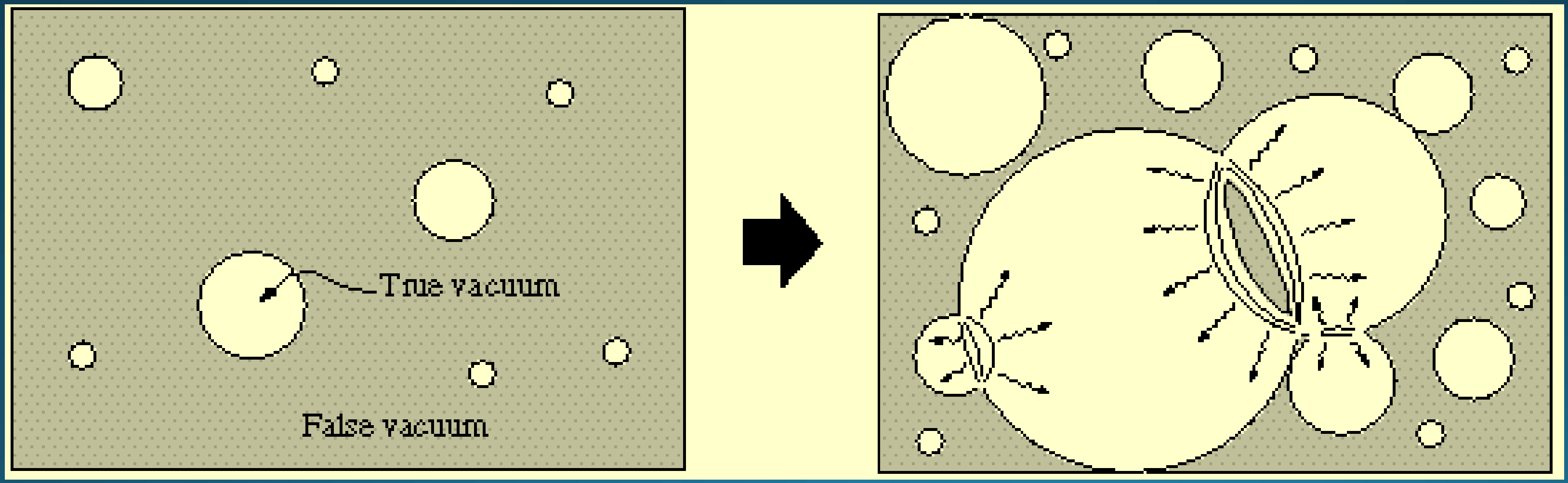
Phase transitions

Transitions:

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

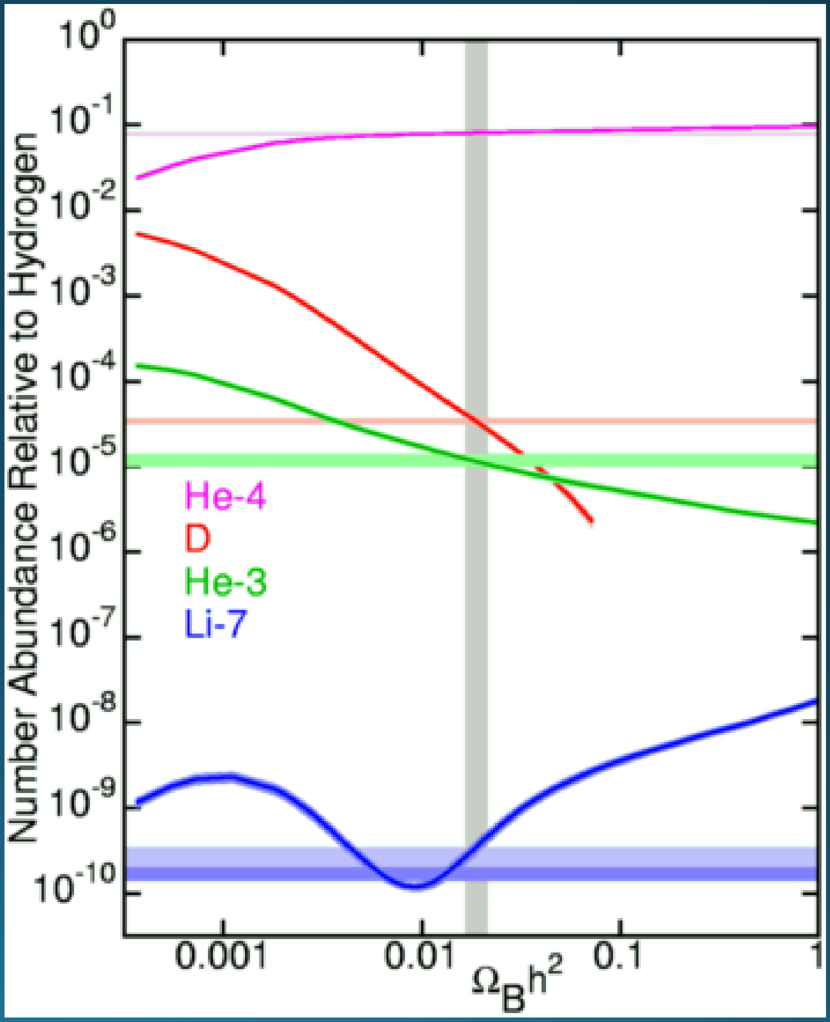
Defects may have formed:

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

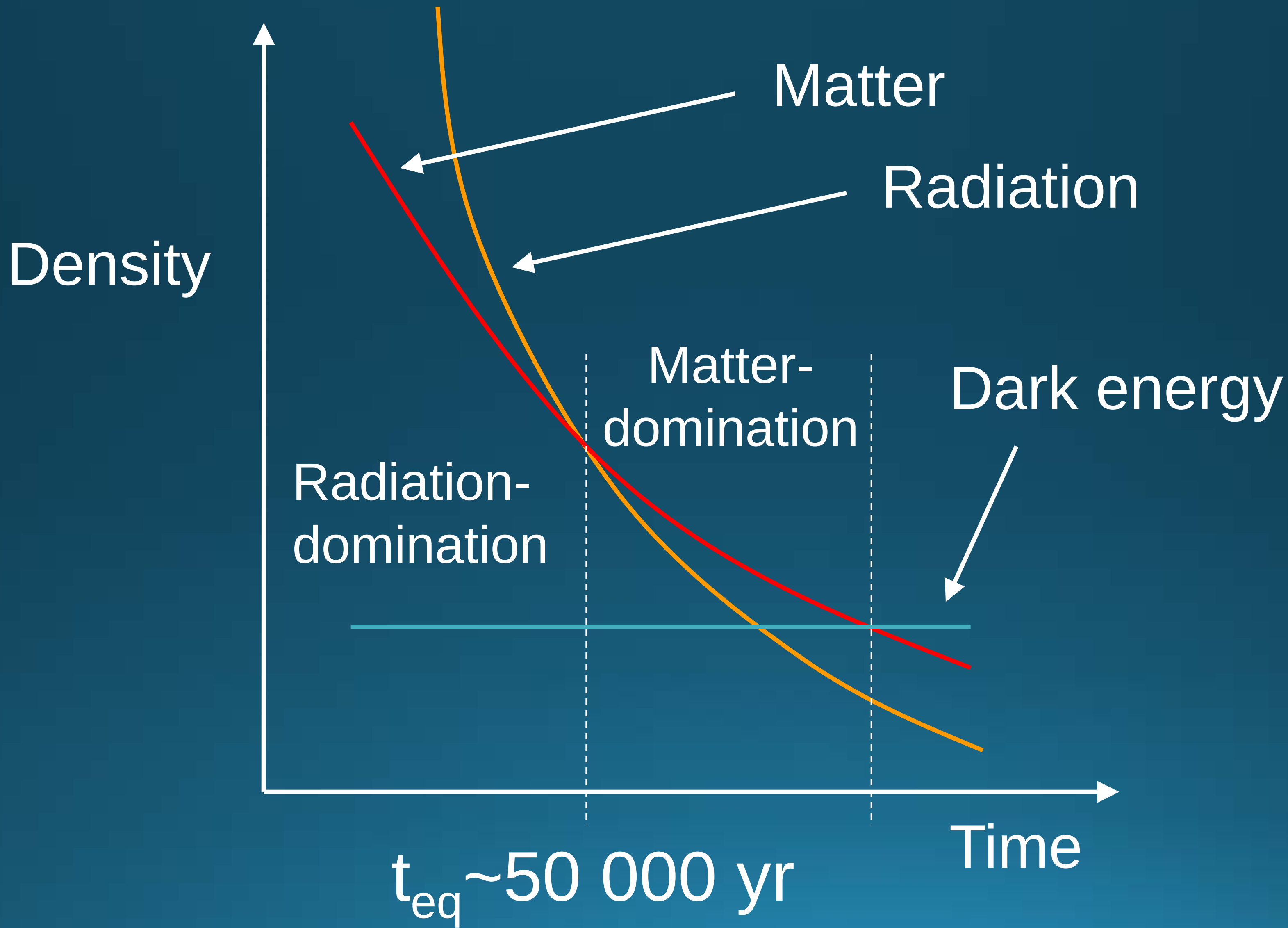


Big Bang Nucleosynthesis

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

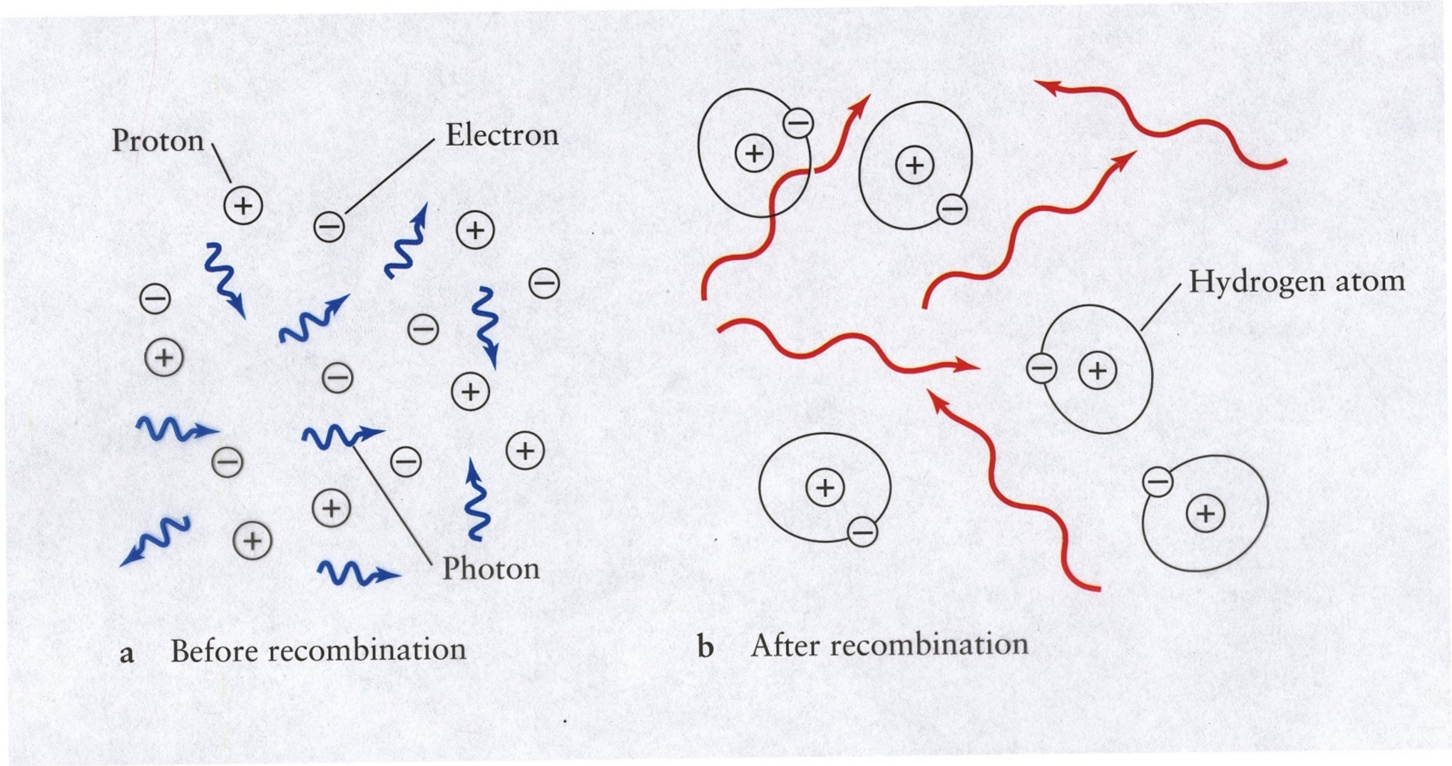


Radiation-dominated era ends and the matter-dominated era begins

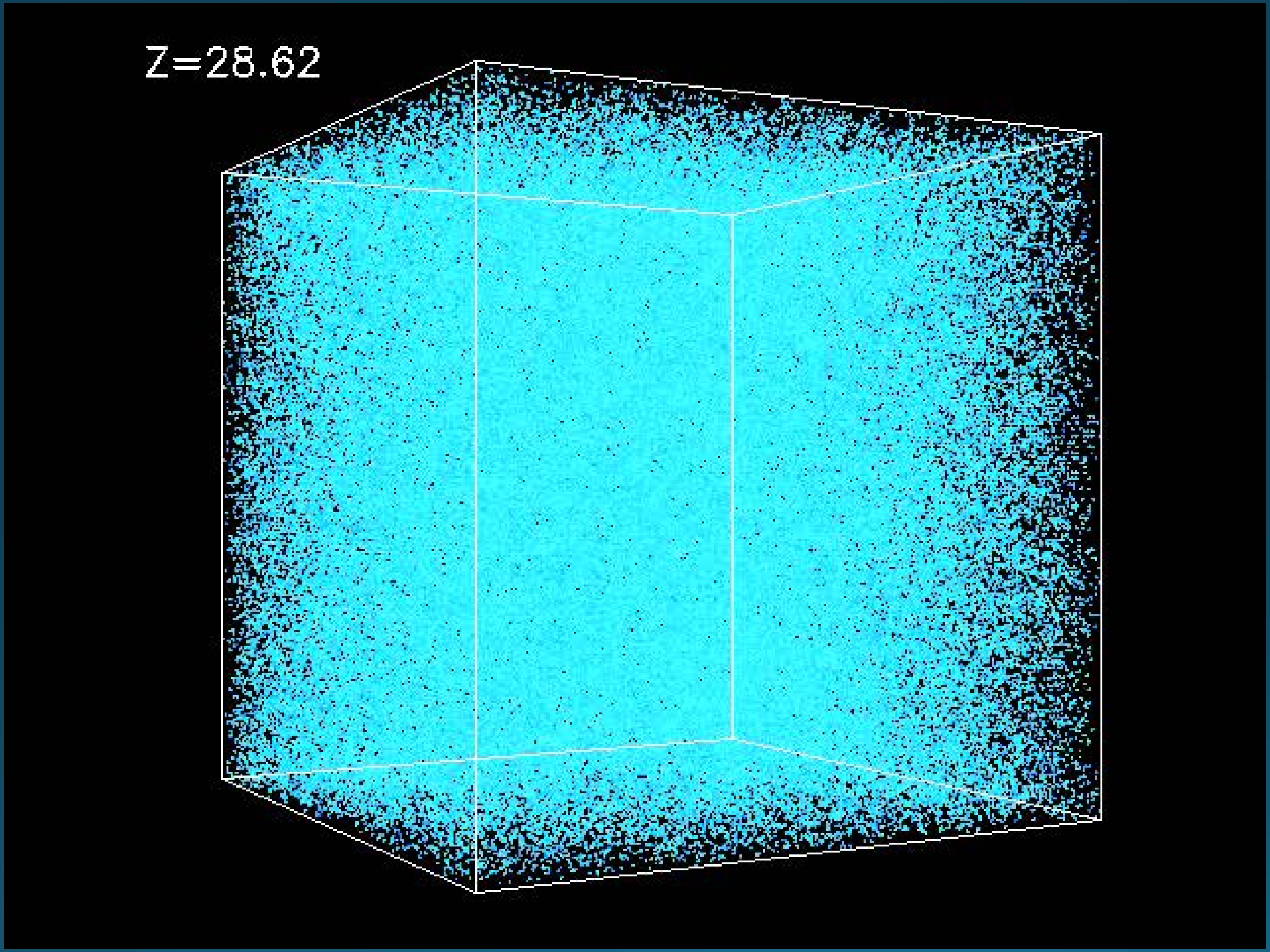


Recombination →
Cosmic Microwave Background Radiation

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



Structure formation I

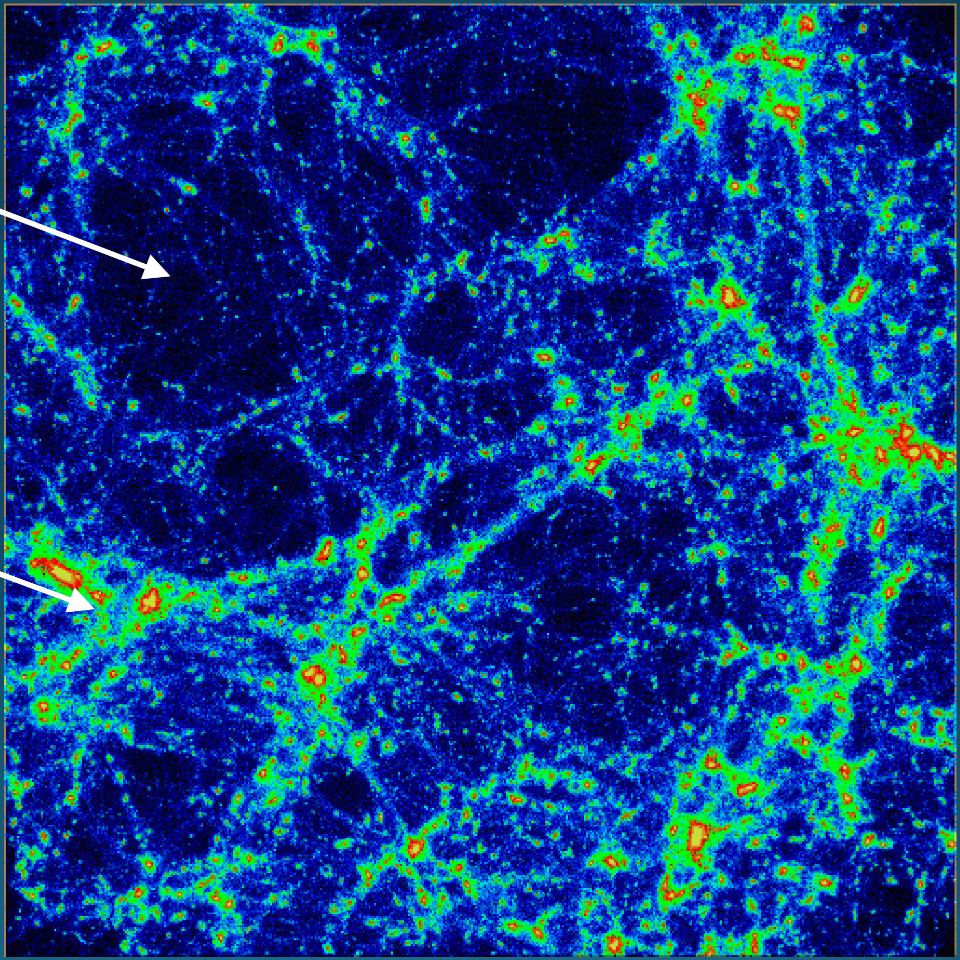


Cold dark matter scenario

Structure formation II

Low-density region

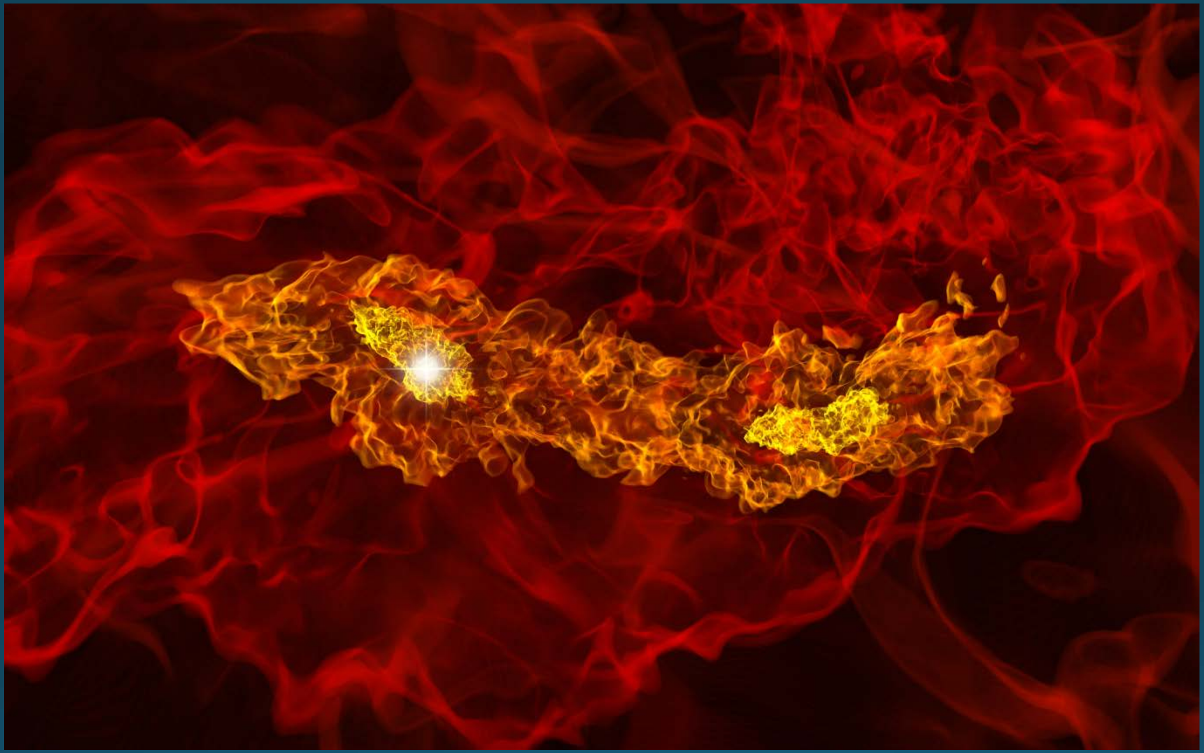
High-density region (site of star formation)



Voids, walls and filaments

What is this?

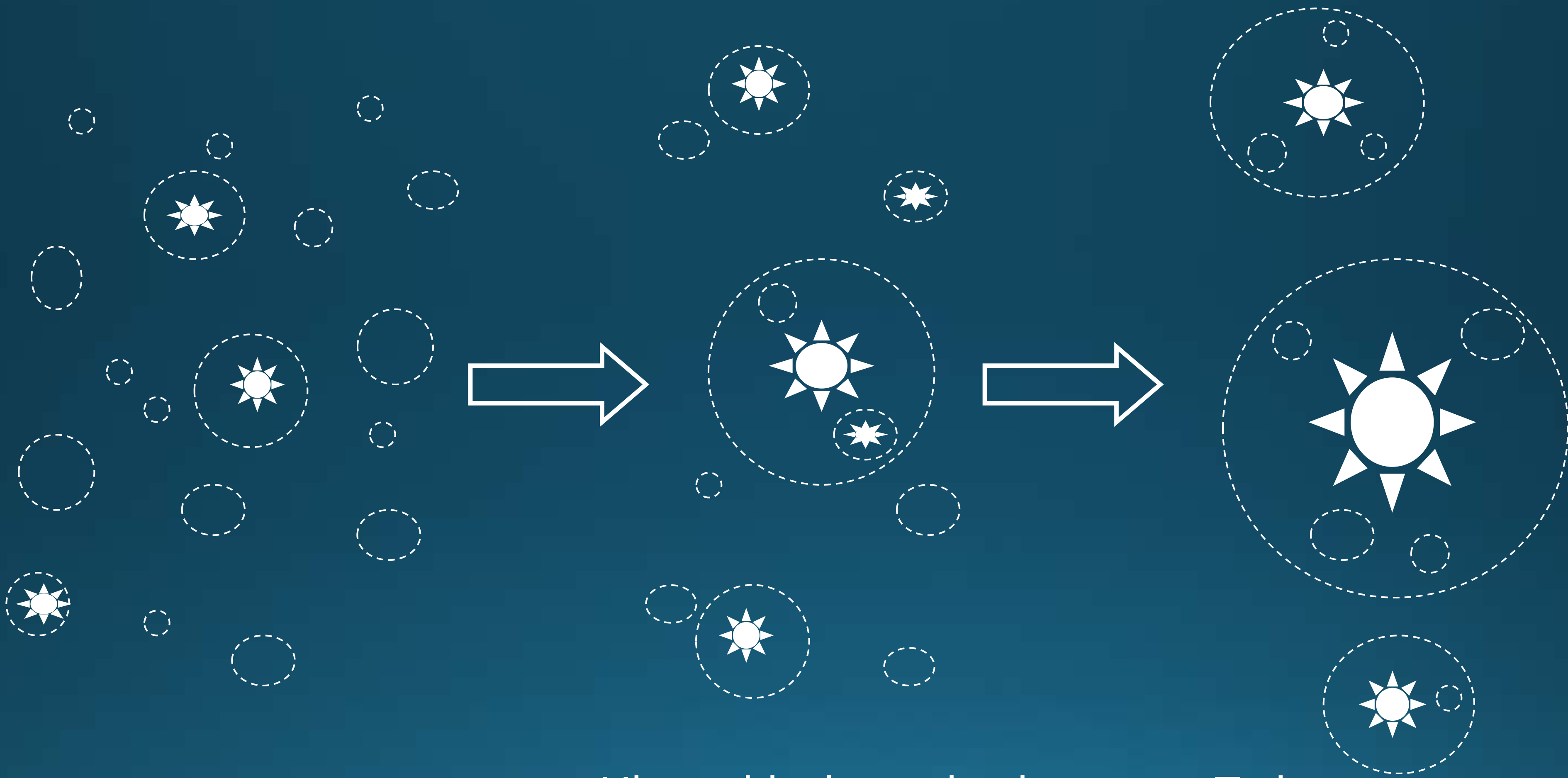
First stars and reionization



© Kaehler, Turk and Abel

- t_{stars}~0.1 Gyr
- $t_{reionization}$~ 0.1-1 Gyr

Hierarchical galaxy formation

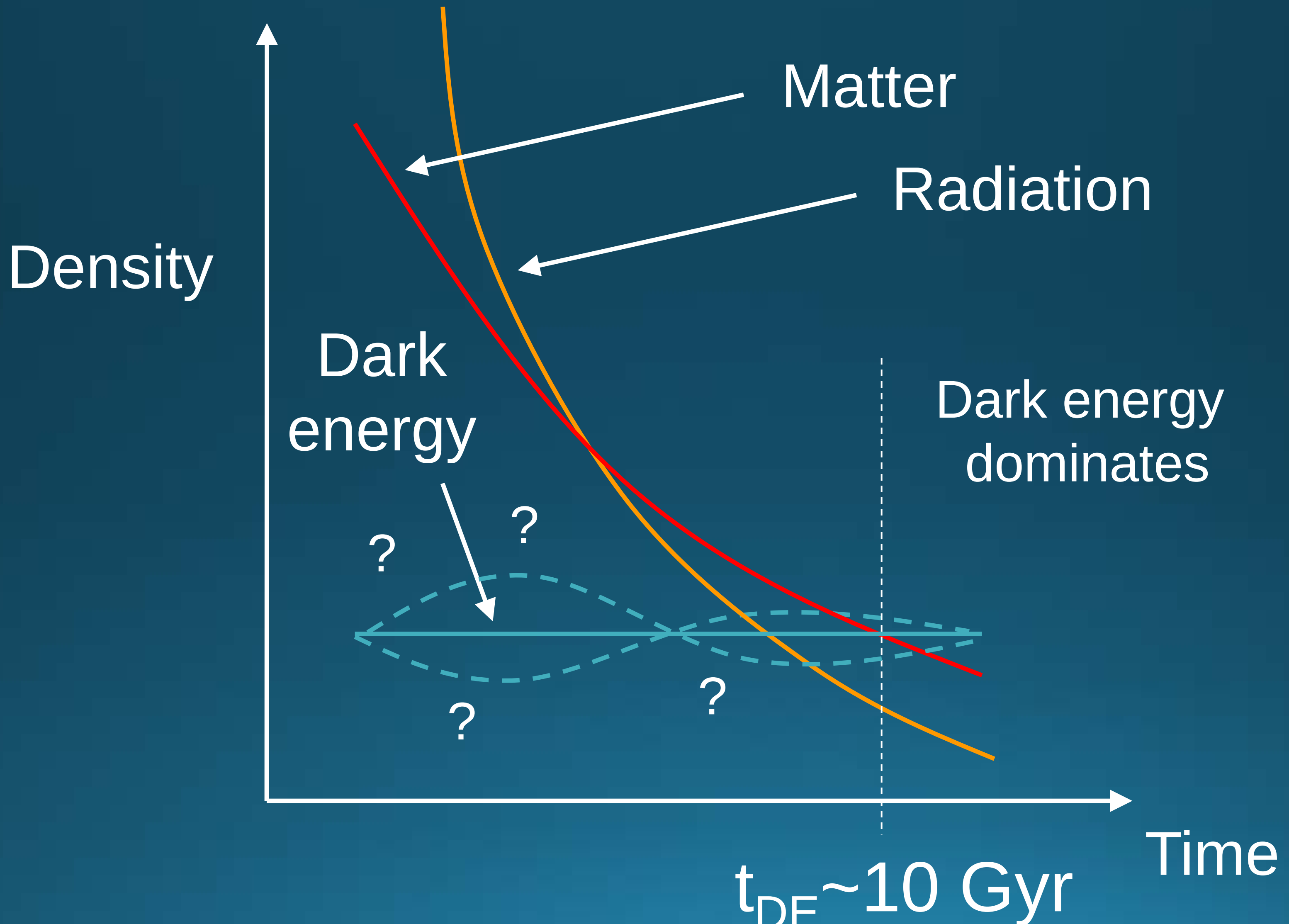


Dark matter halos
with some star formation

Hierarchical merging into
bigger and bigger halos
and galaxies

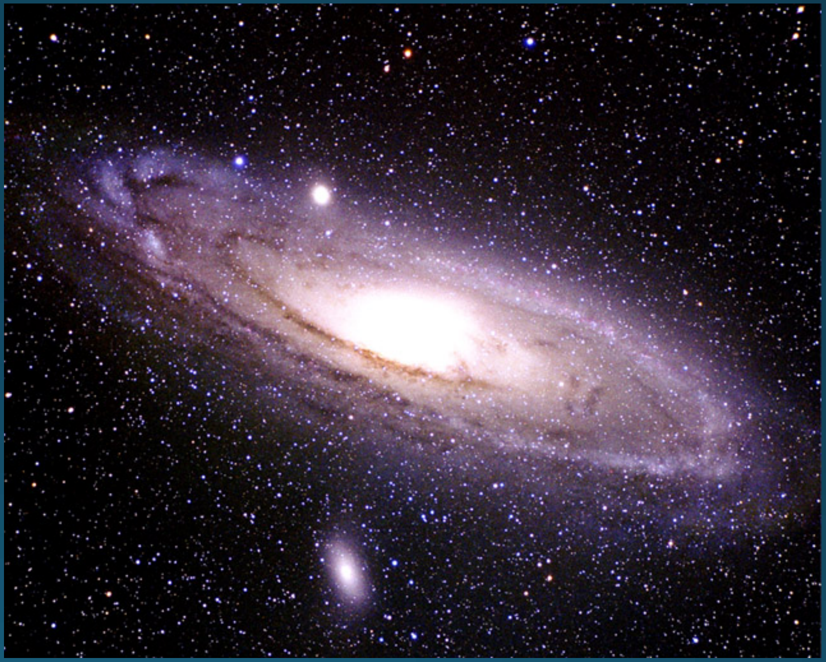
Today

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?