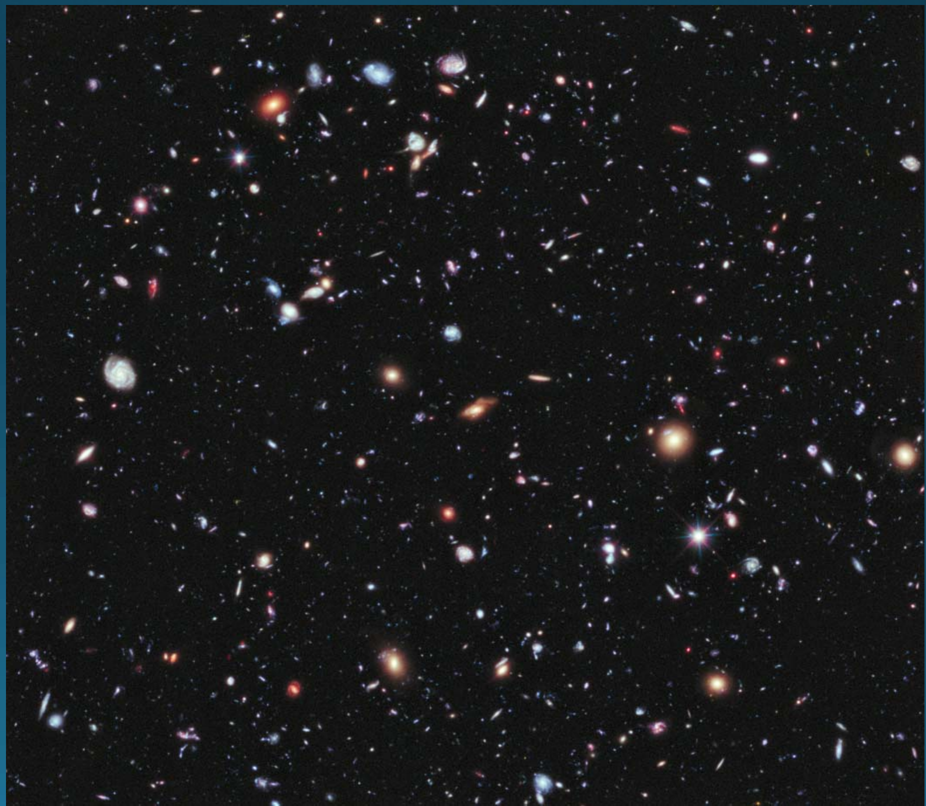
Cosmology 1FA209
2016, 10 credits
Lecture 1: Introduction



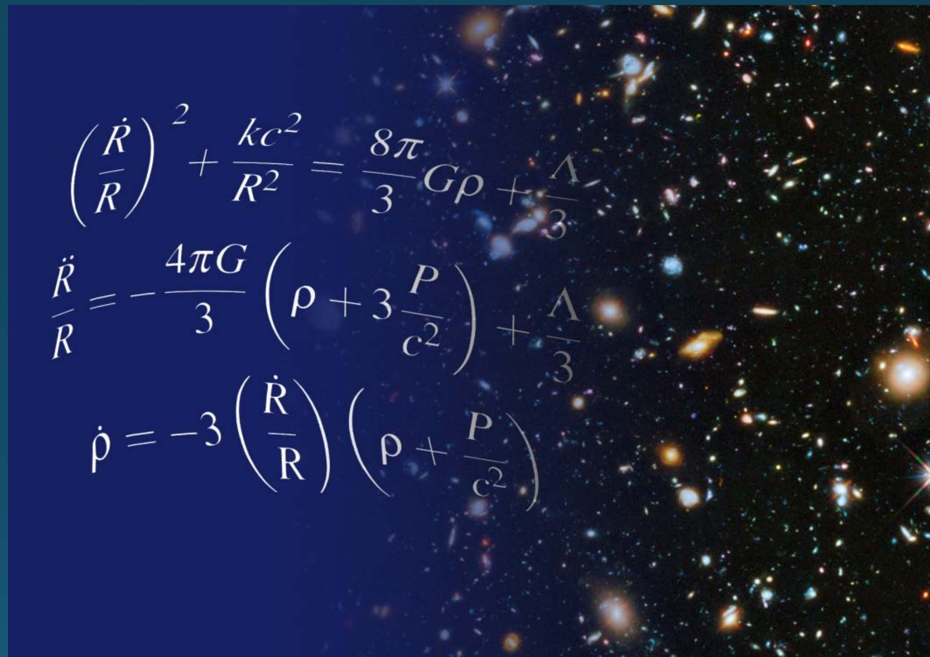
Formal Information

- Teacher:
  - Erik Zackrisson
  - Office in the astronomy corrdinor 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/Cosmology16.html

Outline for today

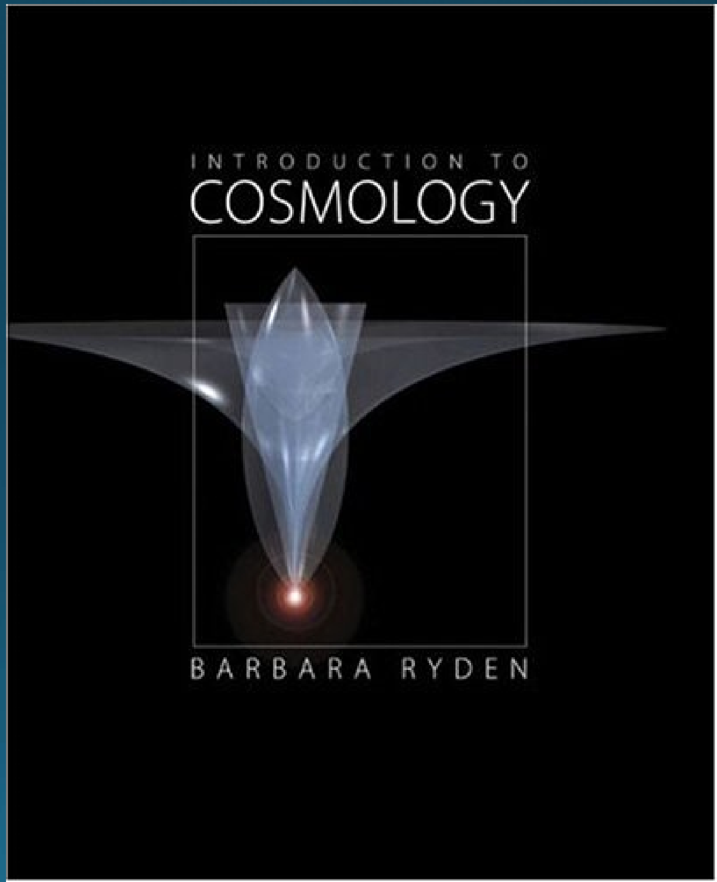
- Formal Stuff
- Course outline
- Cosmic epochs



Course literature

Introduction to cosmology

- Barbara Ryden
- Editions from 2002/2003 & 2013 – both are OK!
- Around 600 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

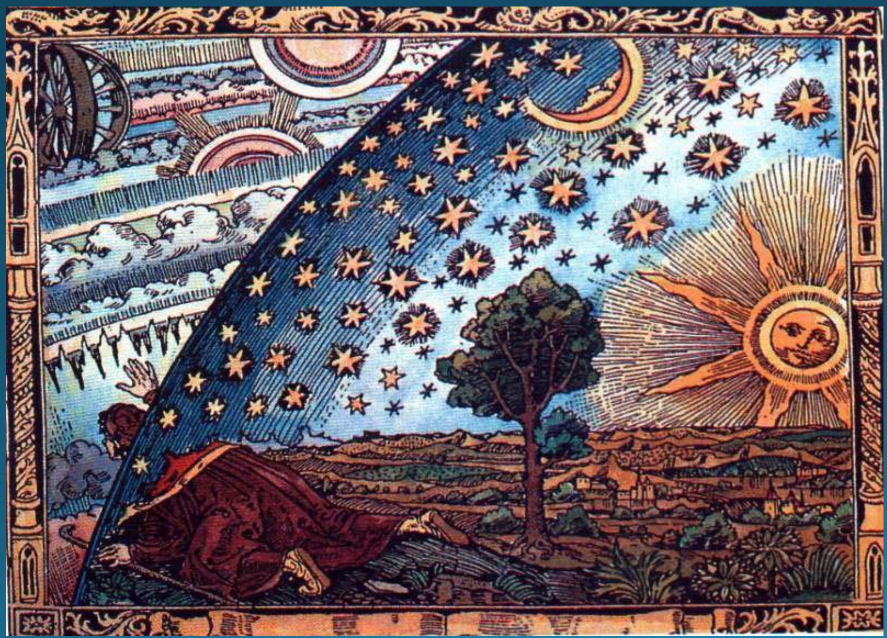
Seminars

- 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

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 January 3
  Grade: Fail, 3, 4, 5
- Oral presentation (≈ 10 minutes)
  Group A: January 10 (13-15)
  Group B: January 11 (10-12)
  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:** January 13
- **Grade:** Fail, 3, 4, 5
- Collaboration OK, but please don't turn in identical solutions!

Hand-in exercises (deadline Jan 13, 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 $\Omega_{\rm M} = 0.3$ and $\Omega_\Lambda = 0.7$?

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

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

demonstrate that a currently expanding, matter-only universe will continue to expand forever if $\Omega_{\rm M} \leq 1$, but not if $\Omega_{\rm M} > 1$.

3. *The era of dark-energy domination*
Estimate the redshift at which the Universe became dark-energy dominated, assuming $\Omega_{\rm M} = 0.3$ and $\Omega_{\rm DE} = 0.7$ today, and that the dark energy has an equation of state ($p = wc^2\rho$):
a) $w = -1.0$ (i.e. a cosmological constant)
b) $w = -1.5$

4. *Dark energy and supernovae type Ia*
The redshifts and apparent magnitudes of a small sample of supernovae type Ia are listed in Table 1. Use this data to determine which of the following three cosmological models is the most likely:

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

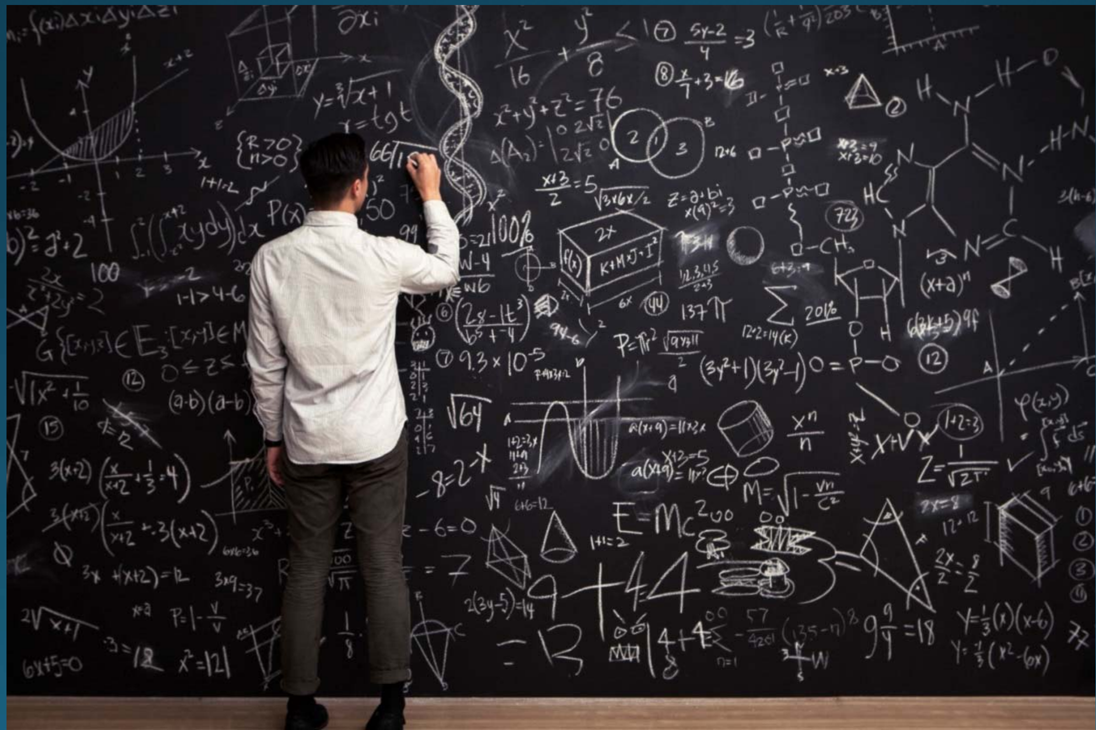
Schedule I

- 9 Lectures
  - L1, Oct 25, 13-15: Course information, course overview
  - L2, Oct 28, 13-15: Fundamentals, Gravity, Curvature (chapters 2-3)

  - L3, Nov 15, 15-17: Metrics, Proper distance, Cosmic dynamics (chapters 3-4)
  - L4, Nov 17, 13-15: Single and Multiple component Universes (chapters 5-6)
  - L5, Nov 21, 10-12: Cosmological parameters and dark energy (chapters 7)
  - L6, Dec 2 13-15: Dark matter (chapter 8)
  - L7, Dec 6, 13-15: CMBR (chapter 9)
  - L8, Dec 7, 13-15: BBNS, the early Universe, inflation (chapter 10, 11)
  - L9, Dec 20, 13-15: Structure formation (chapter 12)

Schedule II

- 2 Exercise sessions:
  - E1, Nov 24, 15-17
  - E2, Dec 13, 13-15



What happens in the exercise sessions?

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

Exercises and solutions on the course homepage

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

The problems we solve in class will be similar.

[2] "Fun" with the fluid equation

Ryden uses energy density (ε), wheras I will here use mass density (ρ): $\rho c^2 = \varepsilon$

The fluid equation:

$$\dot{\rho} c^2 + 3\frac{\dot{a}}{a}(\rho c^2 + P) = 0 \qquad (1;\ 4.39 \text{ in Ryden})$$

Equation of state:

$$P = w\rho c^2 \qquad (2;\ 5.3)$$

(2) in (1) $\Rightarrow$

$$\dot{\rho} = -\frac{3\dot{a}}{a}(1+w)\rho \qquad (3)$$

Want ρ as a function of a!

Rewrite (3):

$$\frac{\dot{\rho}}{\rho} = -3(1+w)\frac{\dot{a}}{a} \qquad (4)$$

Integrate both sides! (Ph.H p370: $\ln f(x)$ is the primitive function of $\frac{f'(x)}{f(x)}$)

$$\Rightarrow \ln \rho = -3(1+w)\ln a + \text{const}$$

Exponentiate both sides $\Rightarrow$

$$\rho = \underbrace{e^{-3(1+w)\ln a}}_{e^{\ln a^{-3(1+w)}} = a^{-3(1+w)}} \cdot \underbrace{e^{\text{const}}}_{\text{const (other)}}$$

$$\therefore \boxed{\rho = \text{const} \cdot a^{-3(1+w)}} \qquad (5)$$

Schedule III

- 3 seminars
  - Seminar I: Nov 28, 15-17 (group A)
    Nov 29, 13-15 (group B)
  - Seminar II: Dec 16, 13-16
  - Seminar III: Dec 21, 13-15 (group A)
    Dec 22, 15-17 (group B)

- Oral presentation of literature review
  - Jan 10, 13-15 (group A)
  - Jan 11, 10-12 (group B)

- Spare slot (in case something else gets cancelled): Jan 12, 13-15

Schedule IV

- Important dates to remember:
  - November 28/29: Seminar 1
  - December 16: Seminar 2
  - December 21/22: Seminar 3
  - January 3: Deadline for written literature report
  - January 10/11: Oral presentations
  - January 13: Deadline for hand-in exercises

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

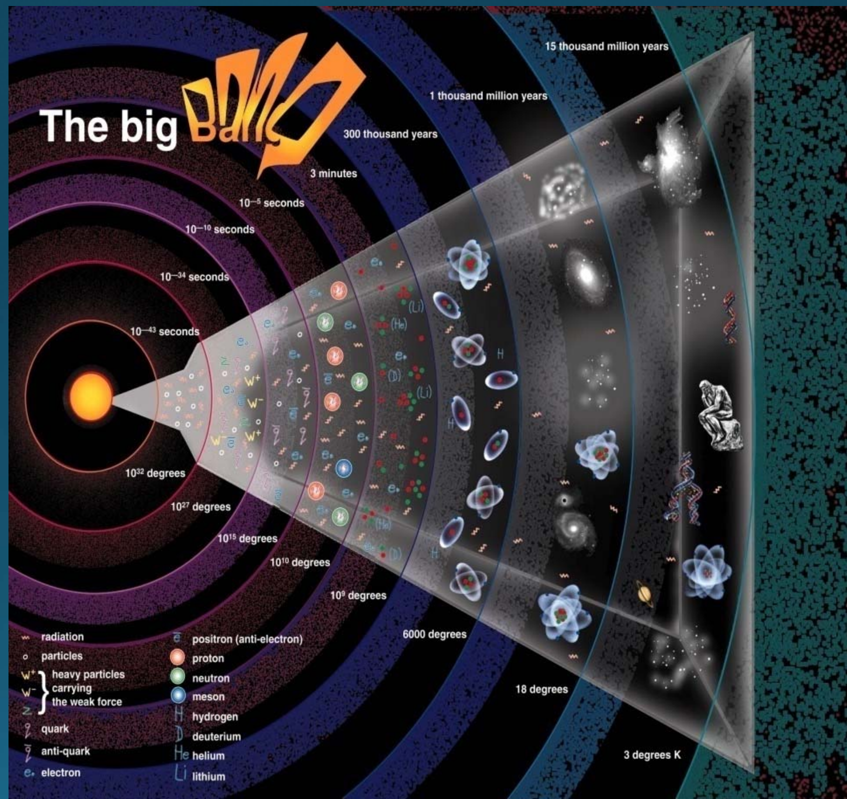
My estimates:

- Attending classes:
  15*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

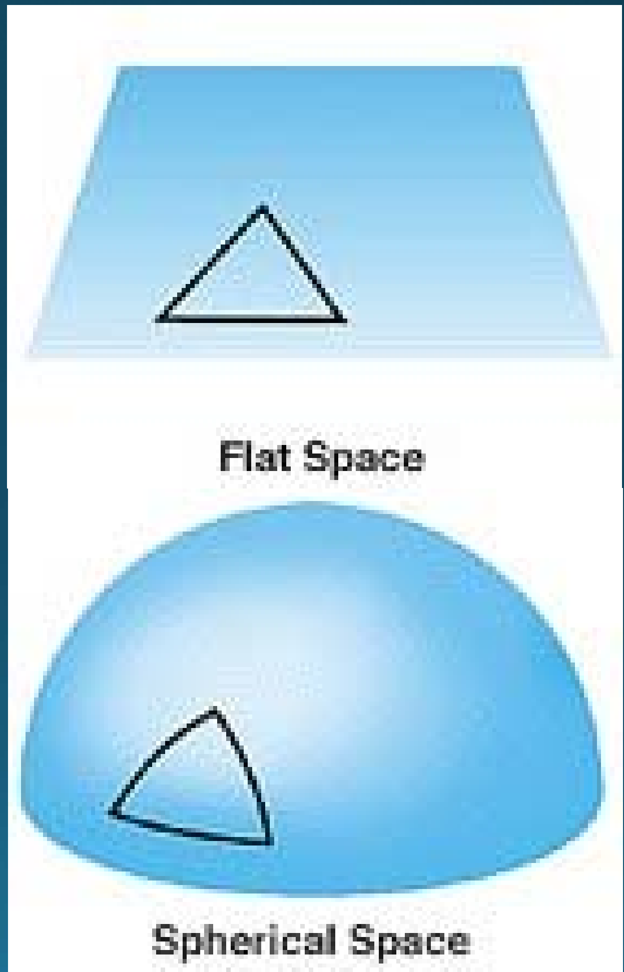
Course Outline

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



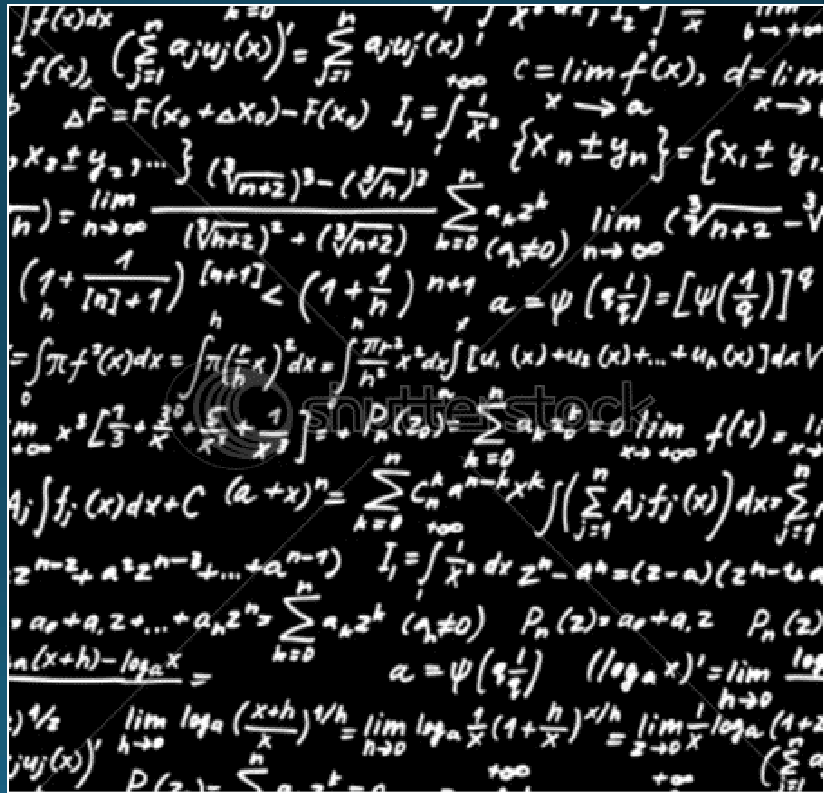
Course Outline

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



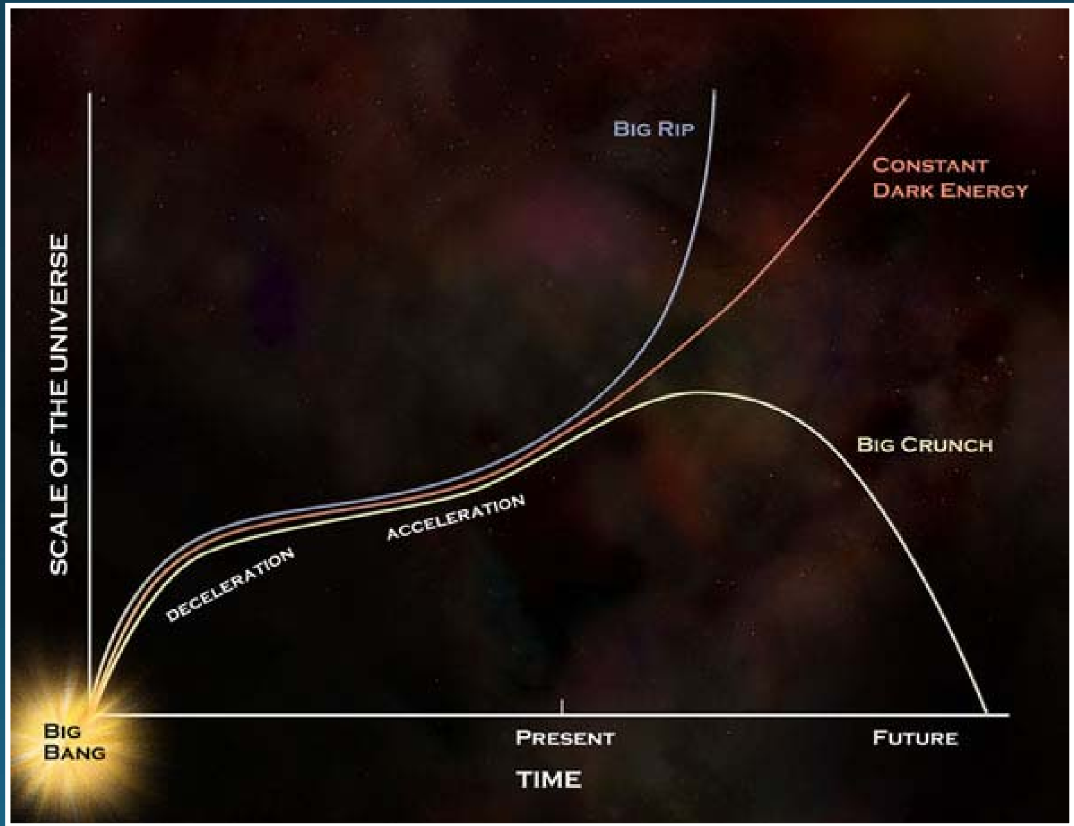
Course Outline

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



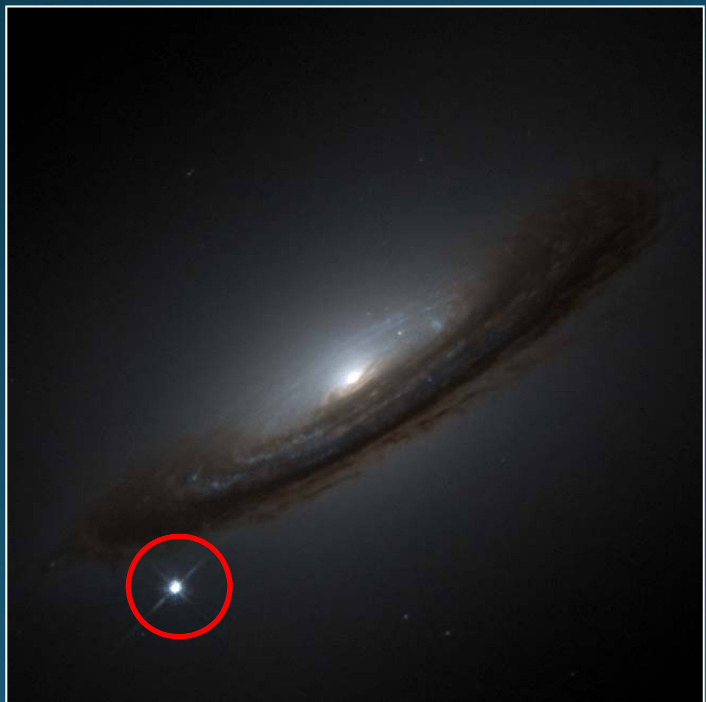
Course Outline

- 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



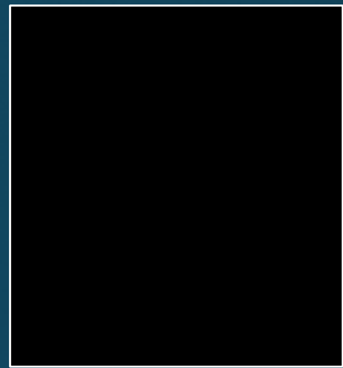
H_0 q_0 w_{DE}

Ω_Λ Ω_γ κ

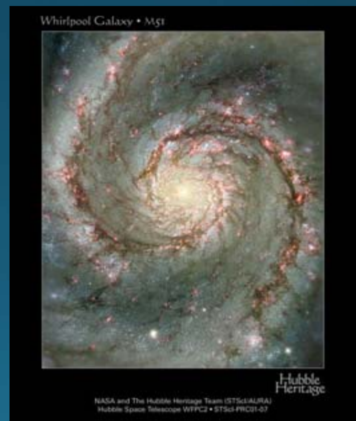
Ω_M

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



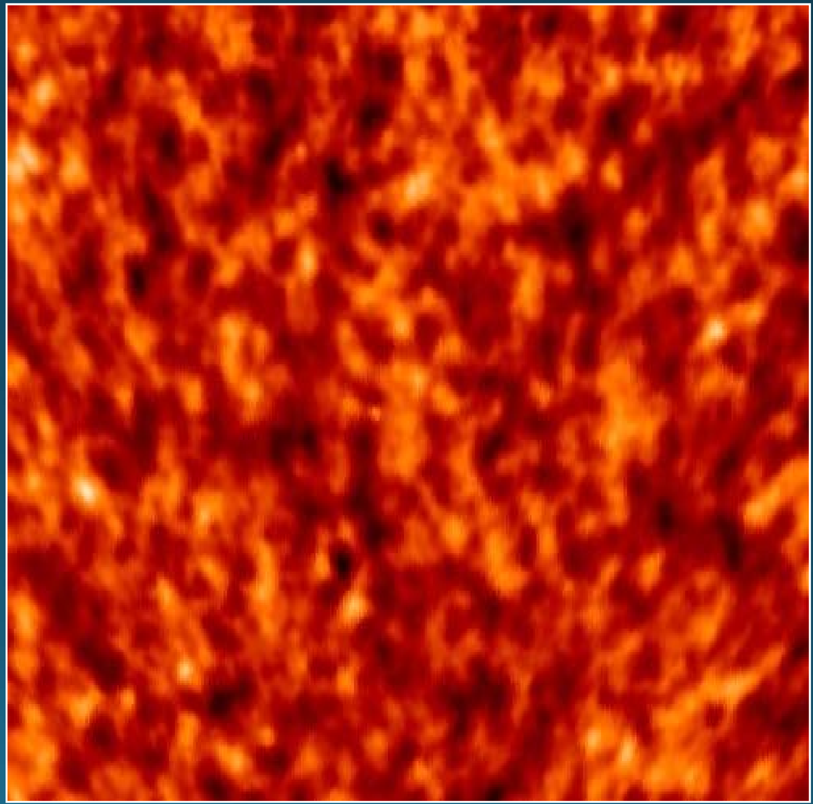
Dark matter



Luminous matter

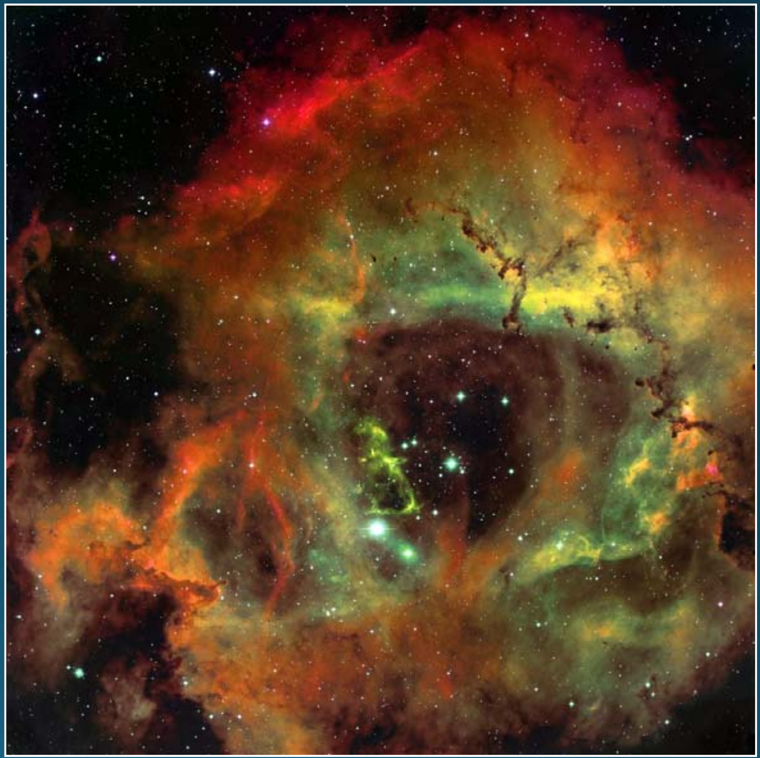
Course Outline

- 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



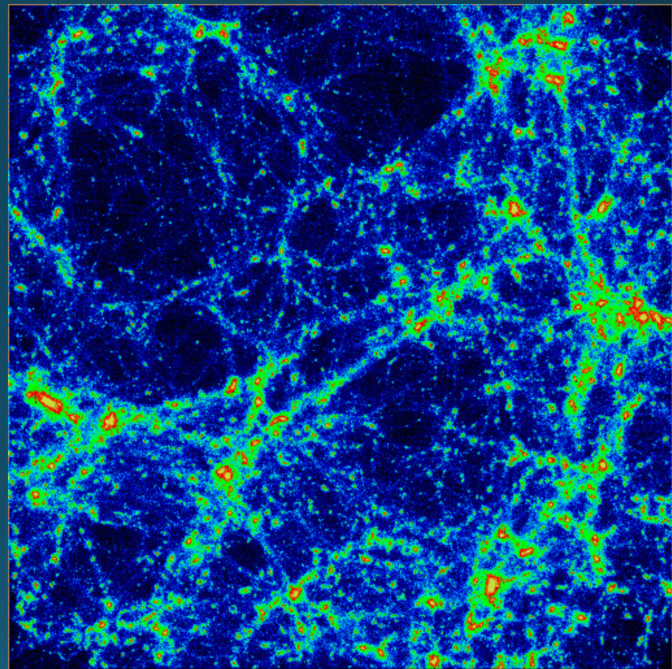
Course Outline

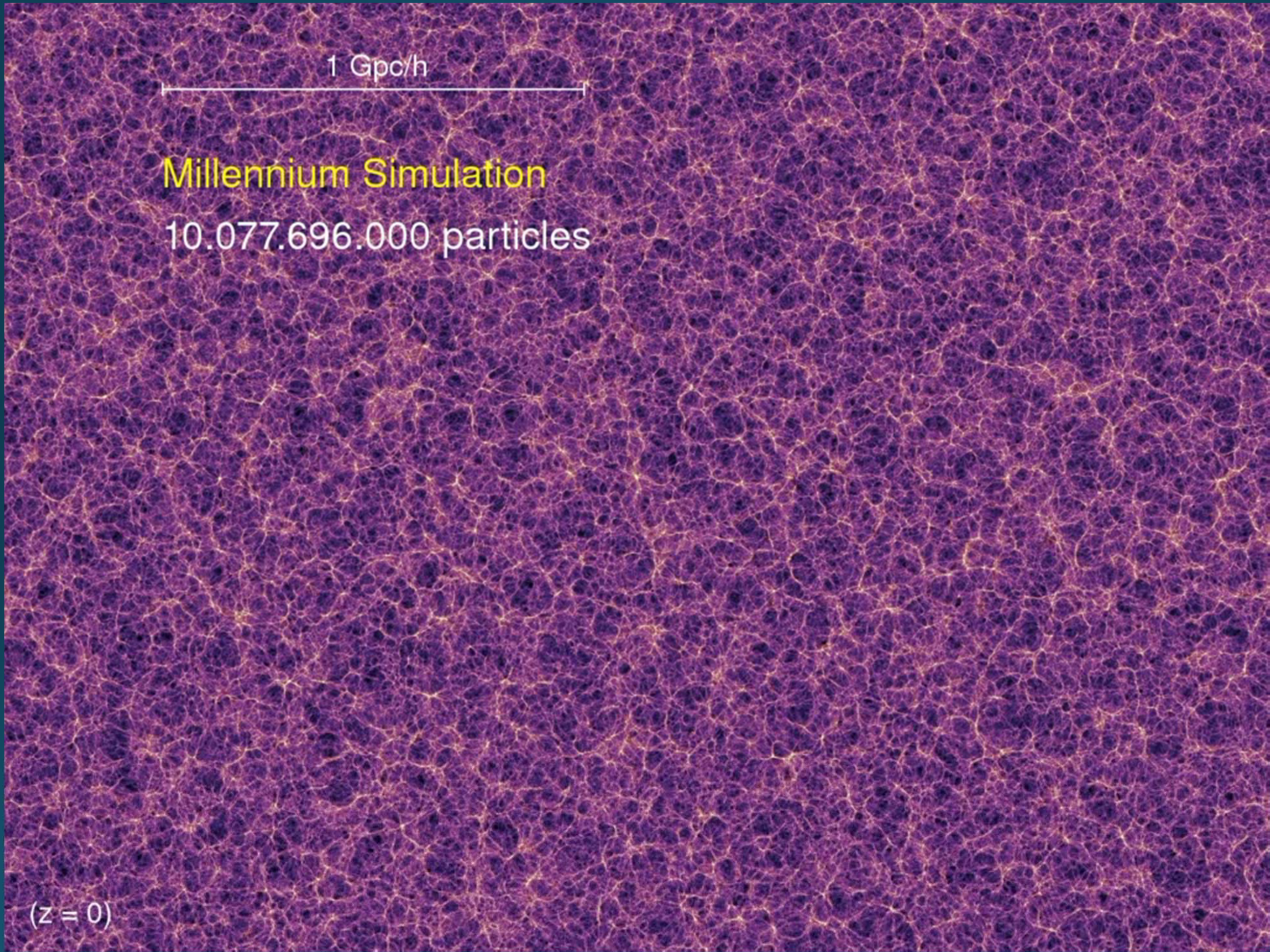
- Lecture 8: Big Bang Nucleosynthesis, the early Universe, cosmic inflation
  - BBNS
  - Measuring primordial abundances
  - What happened to the antimatter?
  - Problems with a non-inflationary Big Bang
  - Inflation
  - Grand Unified Theories



Course Outline

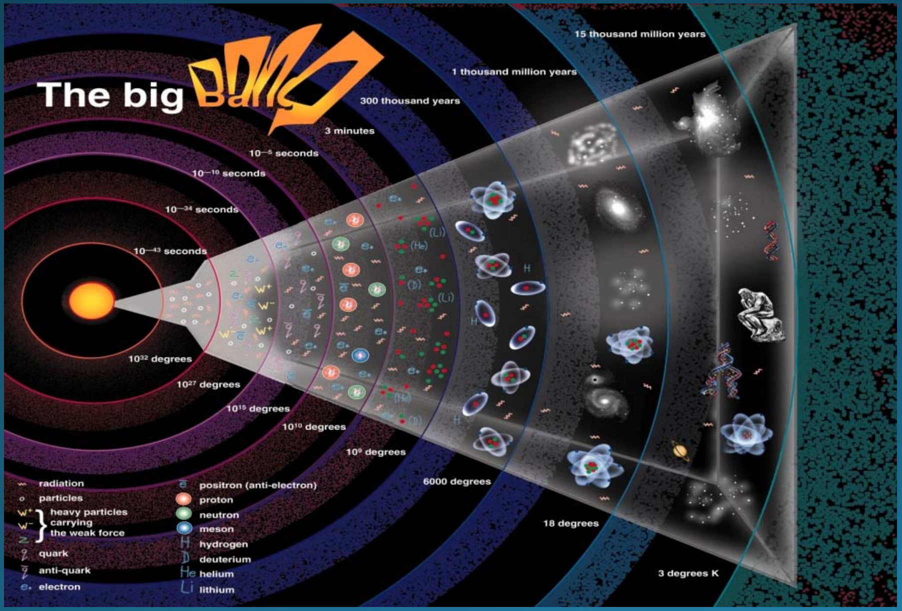
- Lecture 9: Structure formation
  - Perturbation spectrum
  - Jeans mass, Jeans length
  - Hot vs. cold dark matter
  - First light
  - Large scale structure
  - Cosmic reionization



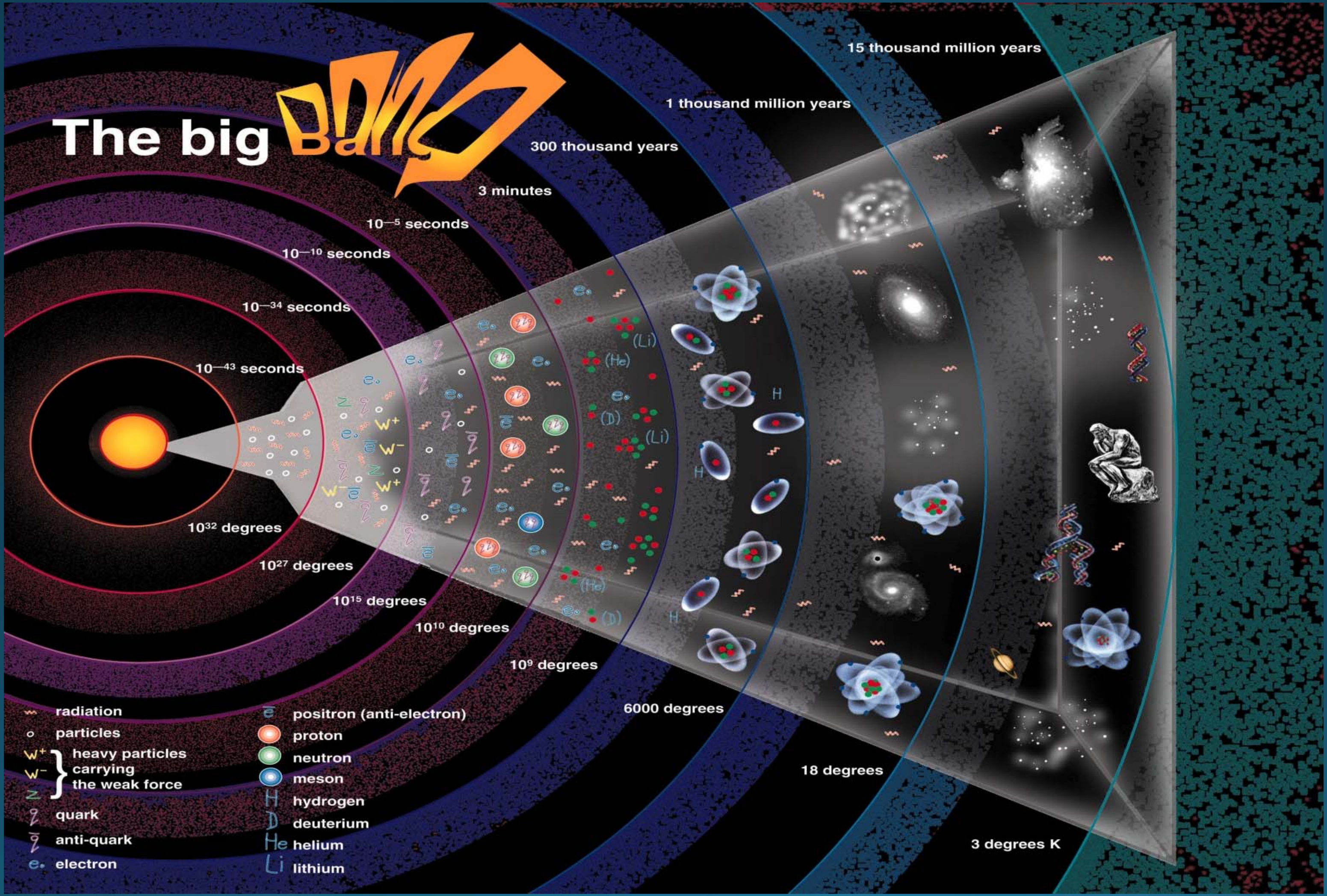

1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)

The Big Bang Scenario

- The part of the Universe <u>observable to us today</u> was extremely hot, dense and small ≈ 14 Gyr ago
- The Universe expanded and cooled →
  cosmic epochs and events



Cosmic epochs



The Planck time

- In extremely early Universe, gravity and quantum effects operate on same scale $\rightarrow$

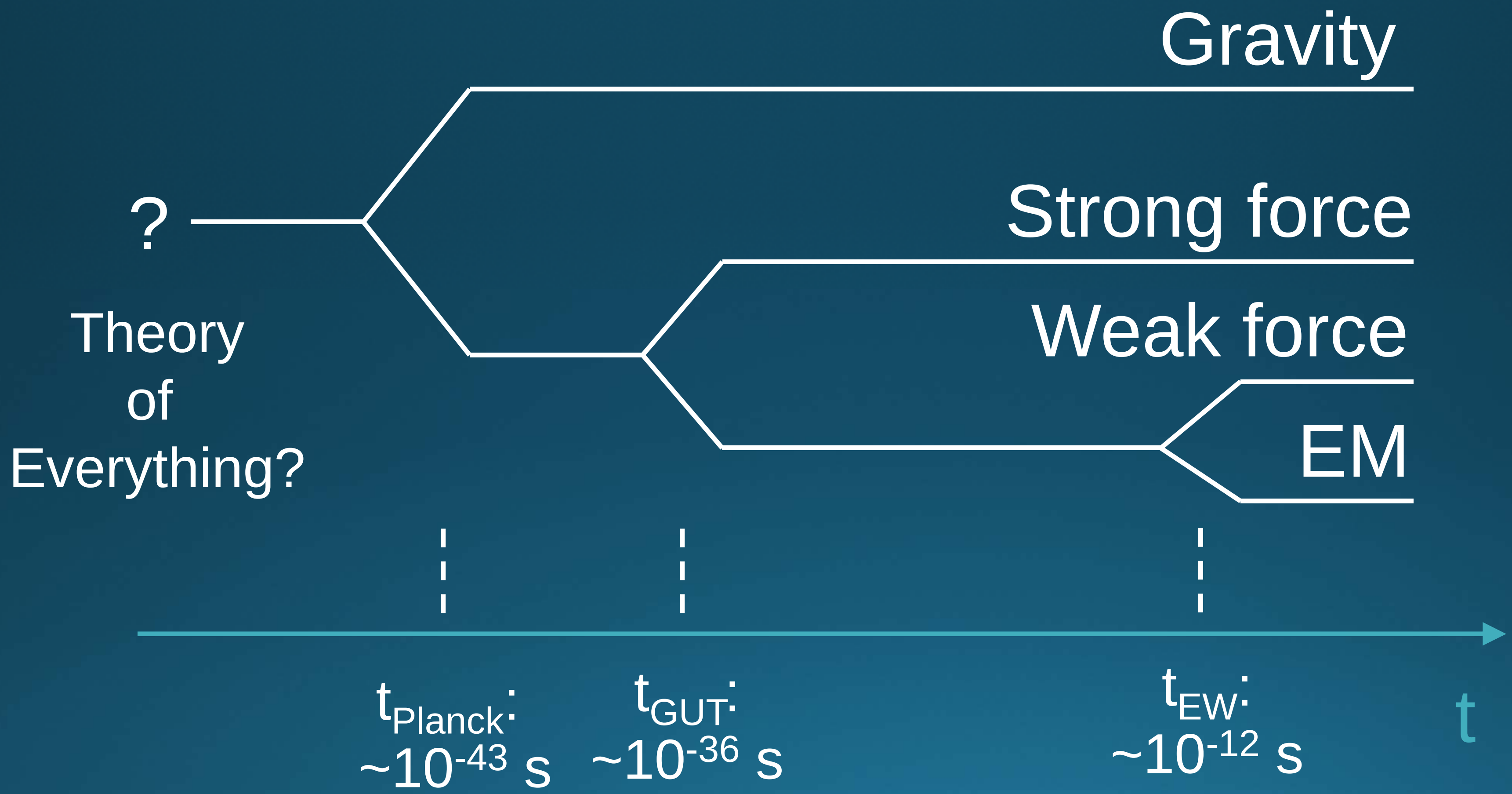
  General relativity no good anymore! Theory of quantum gravity necessary!

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

Prior to the Planck era:
? ? ? ?

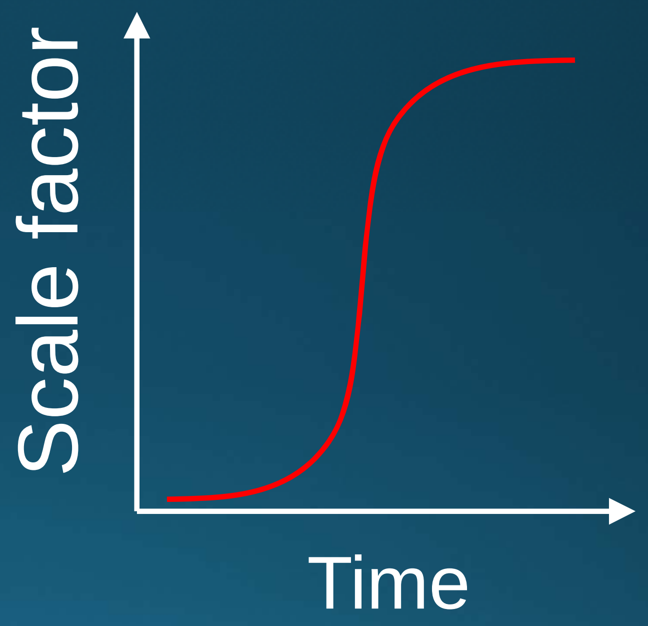
Current Big Bang theory only describes what happens at $t > t_{Planck}$

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 → seeds for large-scale structure formation later on



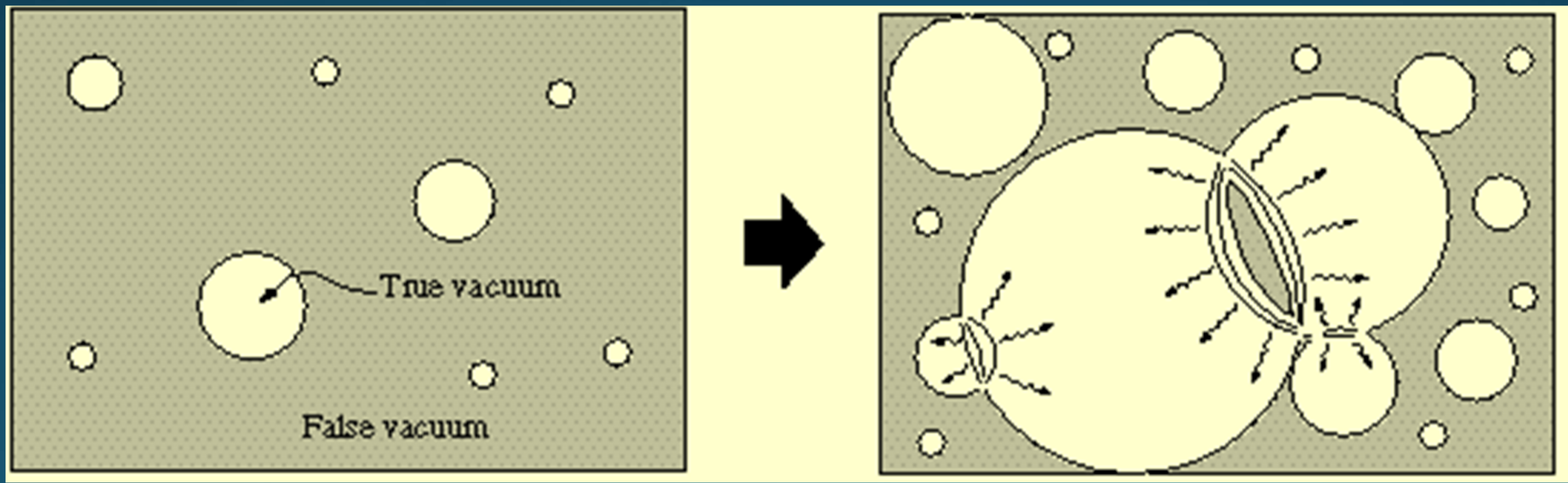
Phase transitions

Transitions:

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

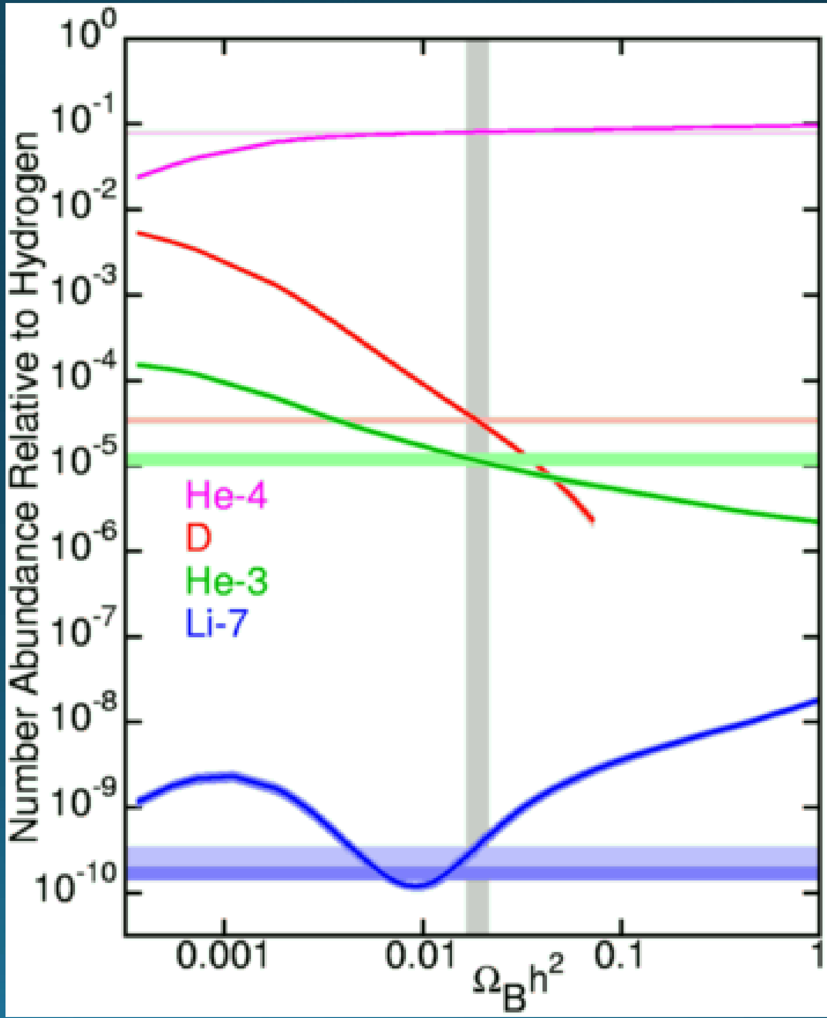
Defects may have formed:

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

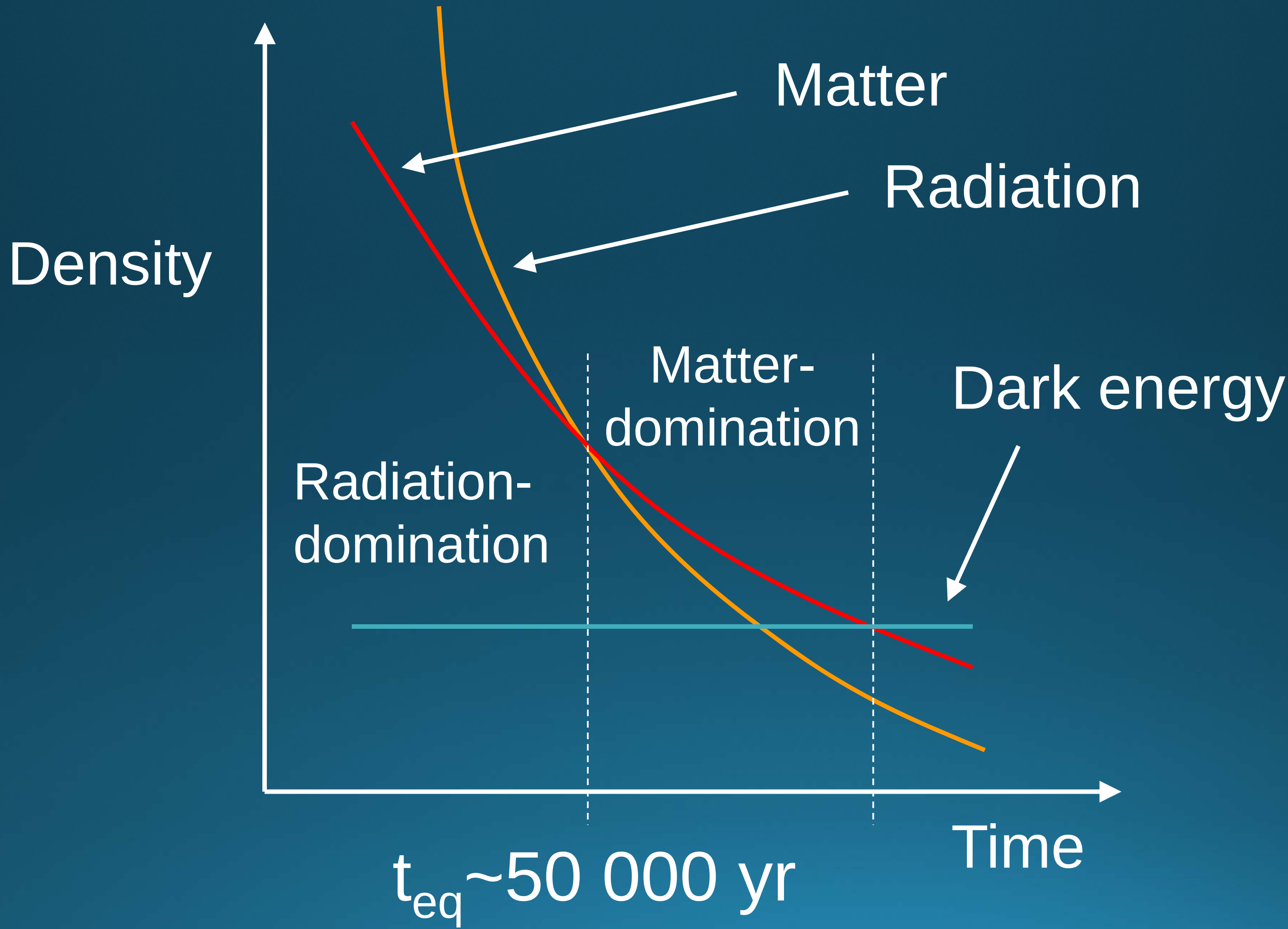


Big Bang Nucleosynthesis

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

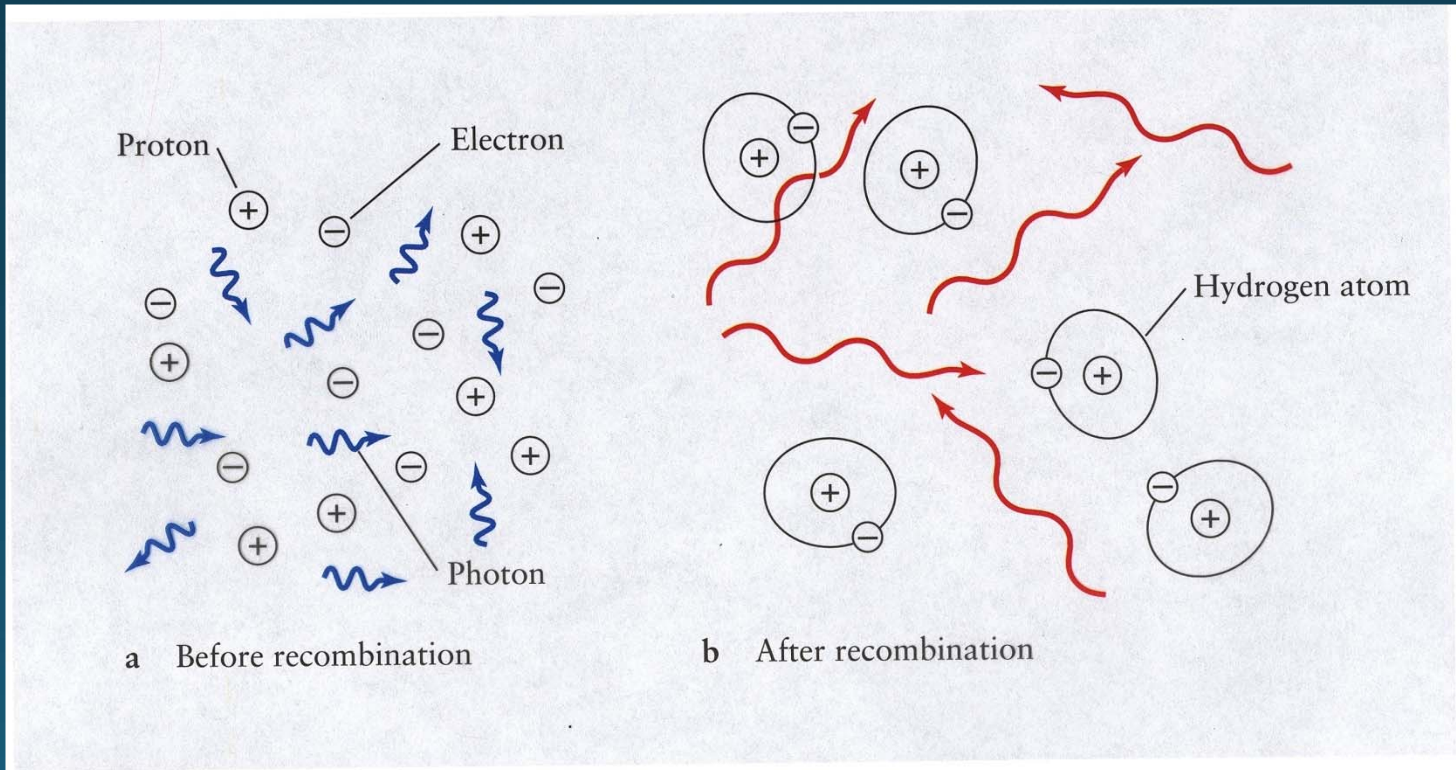


Radiation-dominated era ends and the matter-dominated era begins

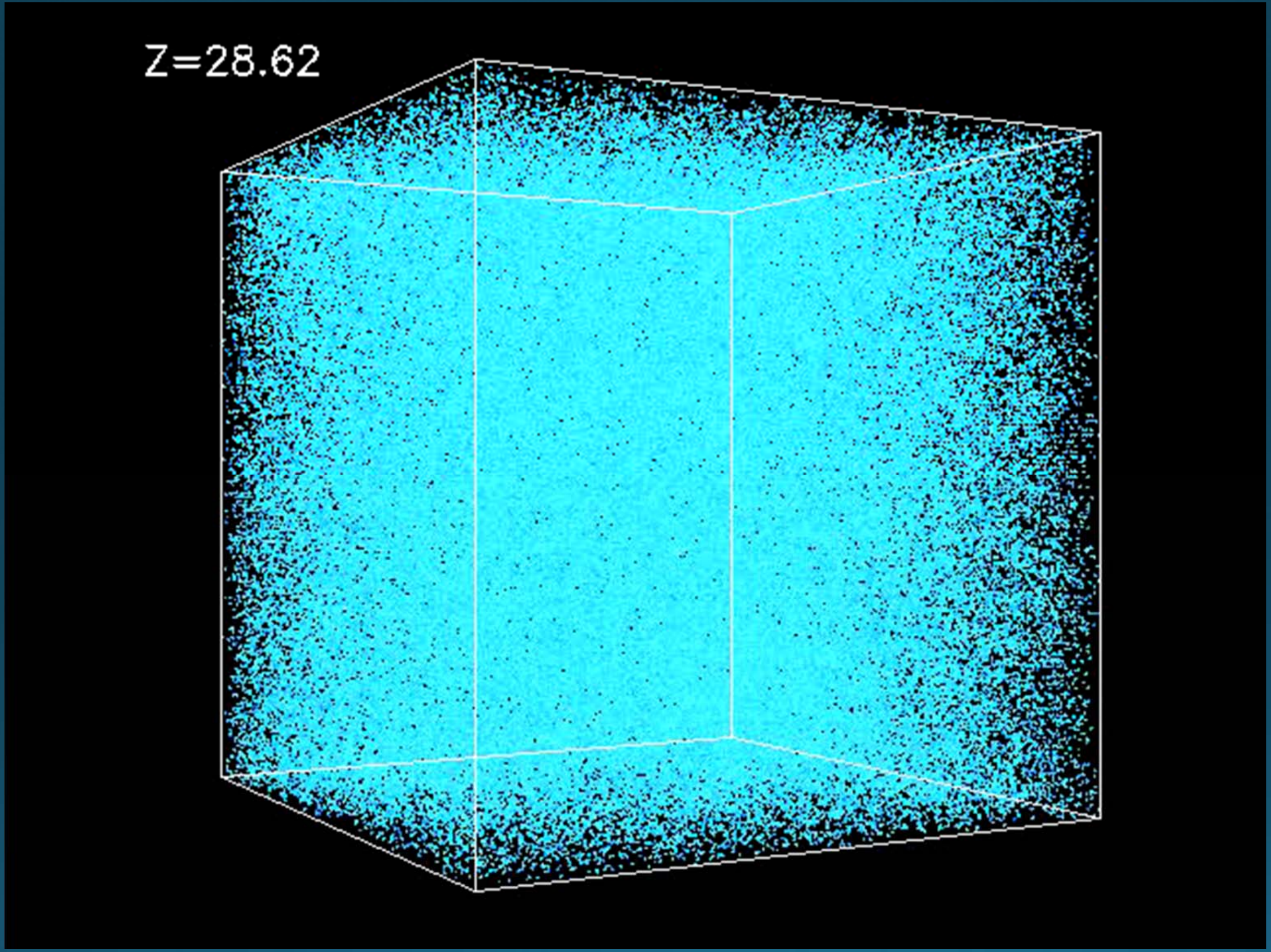


Recombination →
Cosmic Microwave Background Radiation

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



Structure formation I

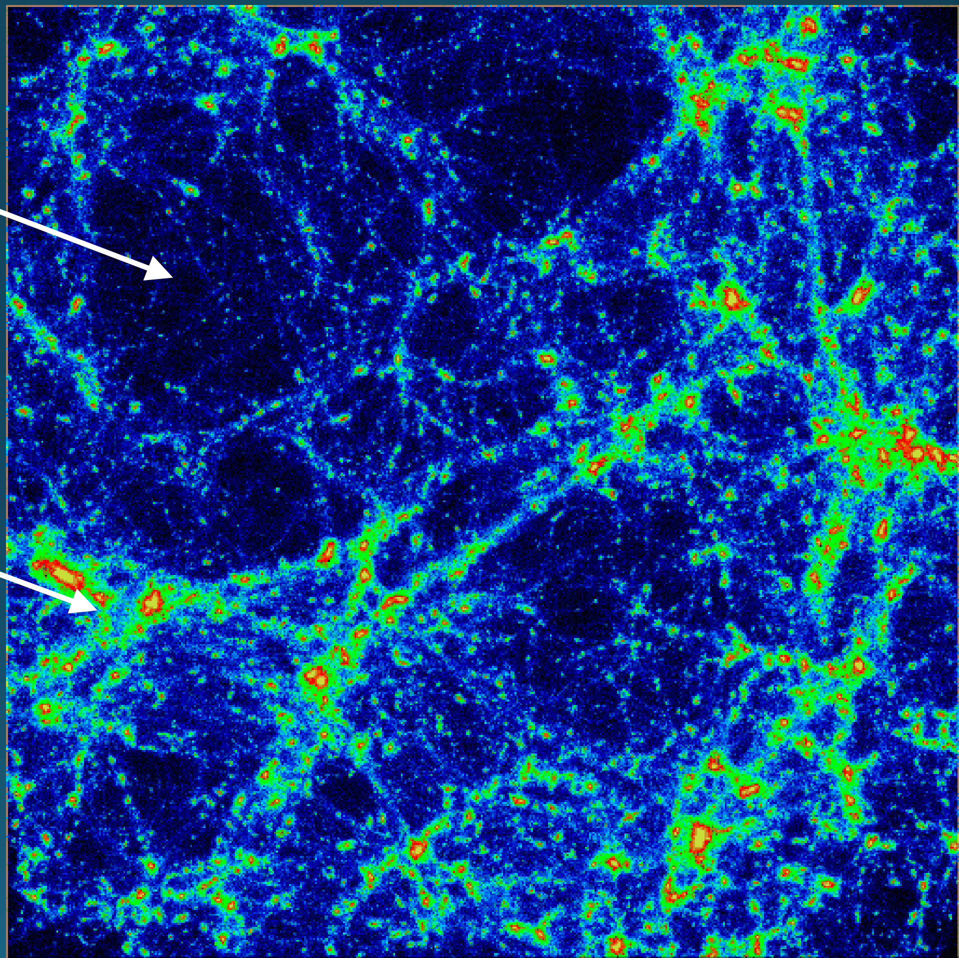


Cold dark matter scenario

Structure formation II

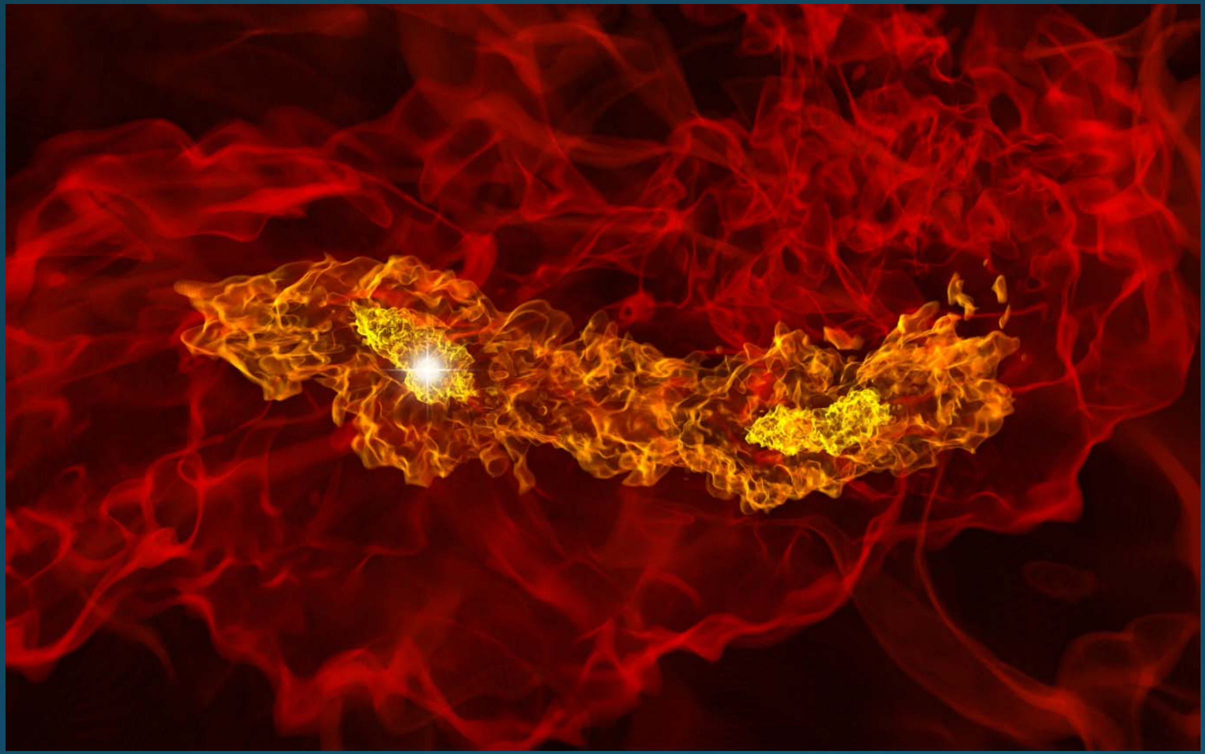
Low-density region

High-density region (site of star formation)



Voids, walls and filaments

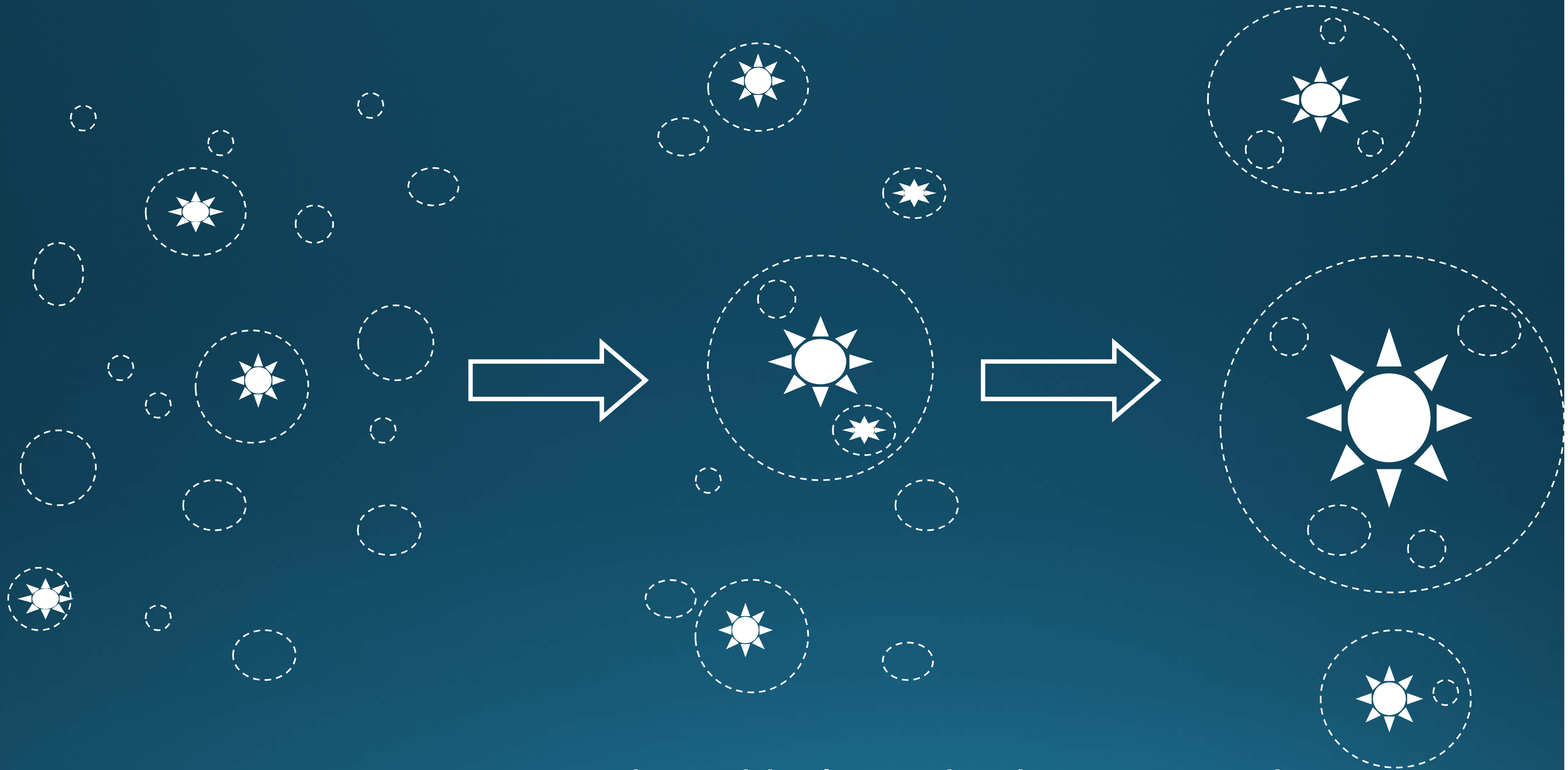
First stars and reionization



© Kaehler, Turk and Abel

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

Hierarchical galaxy formation

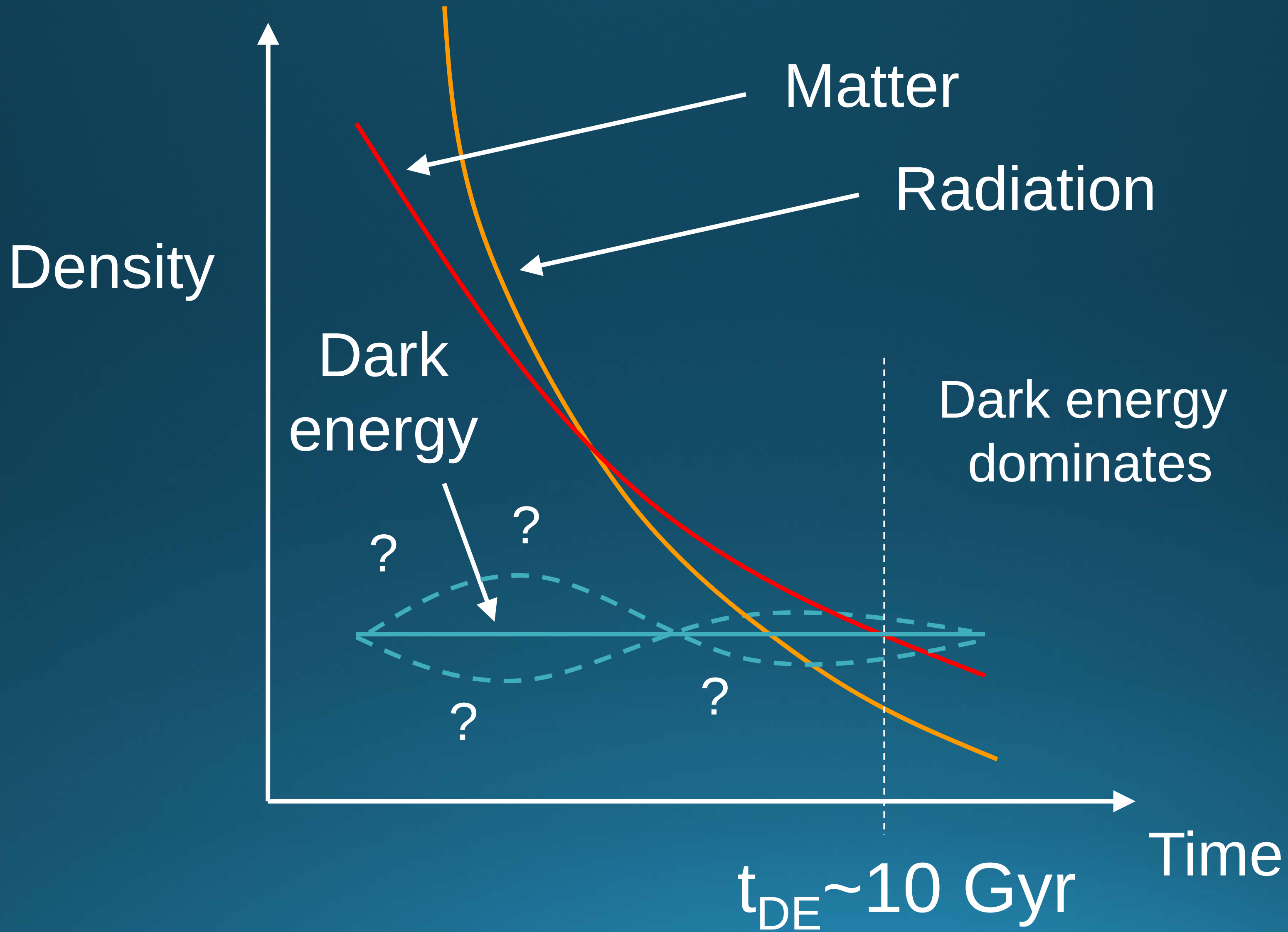


Dark matter halos
with some star formation

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?