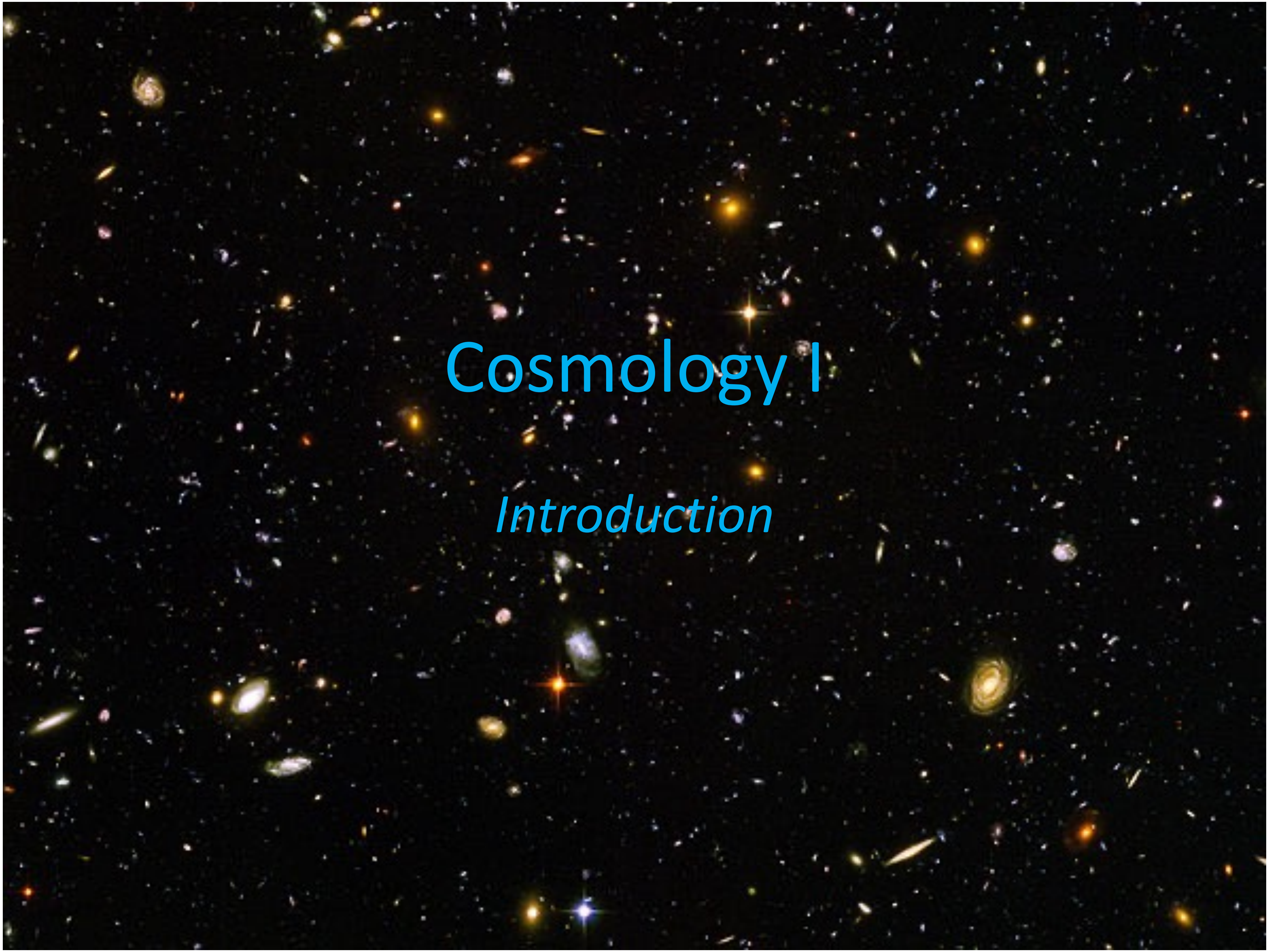
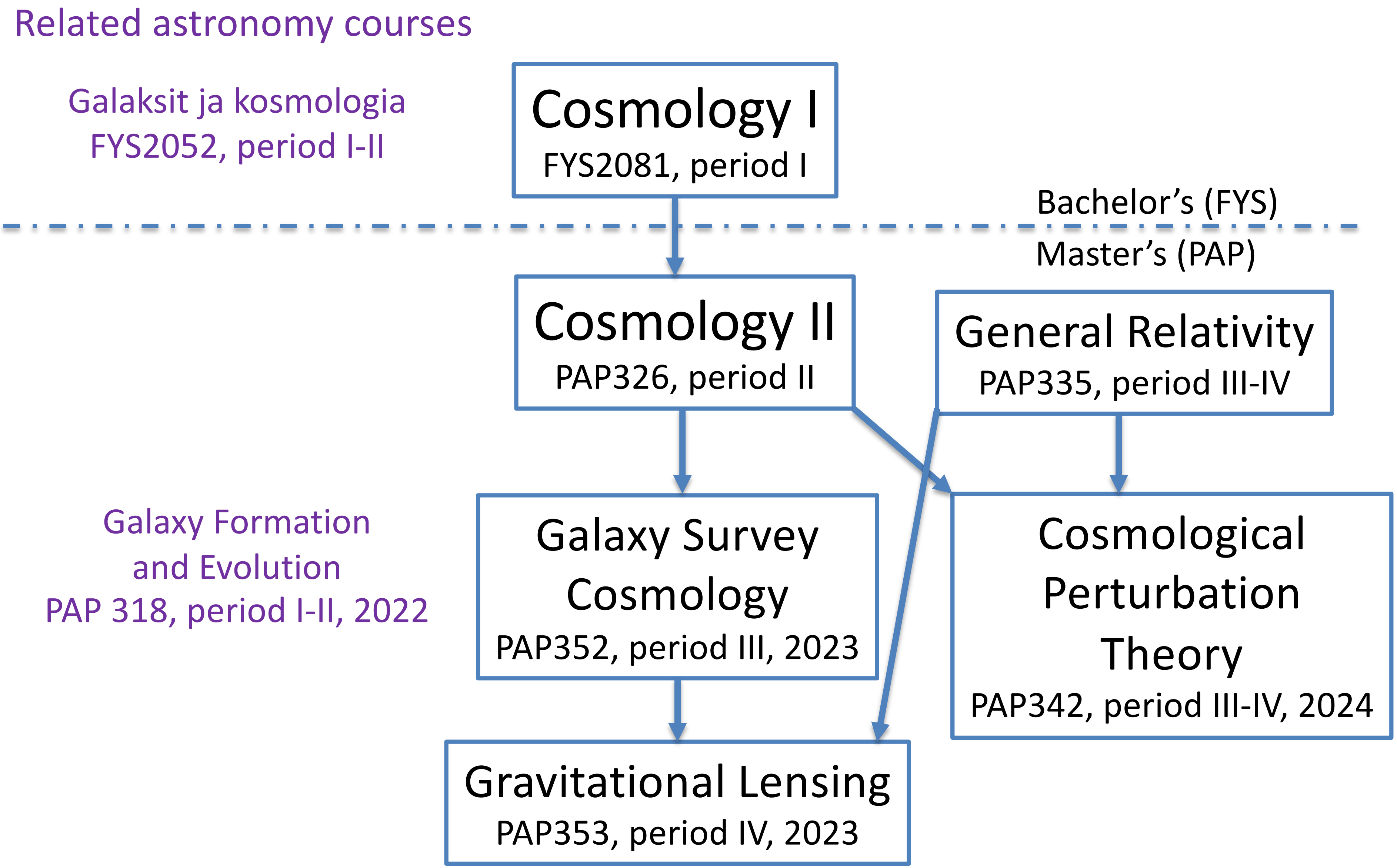

Cosmology I
Introduction

Cosmology I

- **FYS2081 Cosmology I (Kosmologia I) 5.9-20.10.2023**
- https://moodle.helsinki.fi/course/view.php?id=60341
  - **Lecture notes**
  - **Homework problems**
- Lecturer: Hannu Kurki-Suonio, C329
  Assistants: Jenni Häkkinen, Tiina Minkkinen, C304
- Lectures : Mo 14-16, Tu 14-16 in Physicum A315
  The first lecture is on Tuesday, Sep 5th.
- Homework problem sets given out on Tuesdays, due the following Tuesday
- Exercise sessions: Fr 12-14 and 14-16 in Physicum A315
- The course is lectured in English (I take questions also in Finnish)
- Exam: Monday, Oct 23, 13-17 (TBC)
- Grade: 1/3 from homework, 2/3 from exam

Cosmology curriculum



Introduction

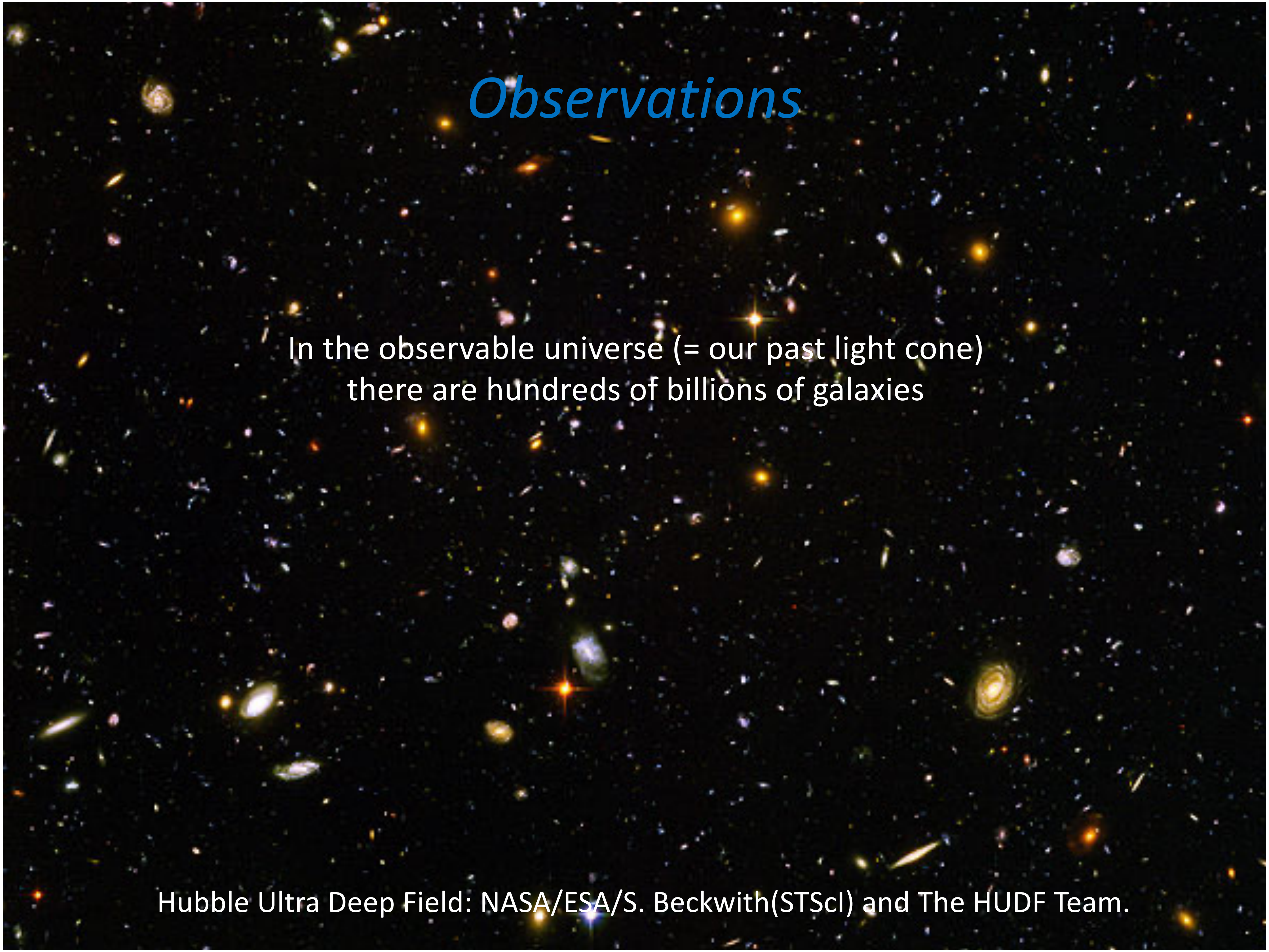
- Cosmology
  - The universe as a whole
    - structure
    - history
- The present universe is a result of evolution
  - expands
  - initial state was very different (”Big Bang")
  - age 13.8 Gyr
- Cosmology is based on
  - Laws of physics (known, hypothetical)
  - Observations
    - Redshift of distant galaxies
    - Primordial abundances of light element isotopes
    - Cosmic microwave background (CMB)
    - Distribution of galaxies (large scale structure)

Laws of Physics

- General relativity (GR) – theory of gravitation
- $SU(3) \otimes SU(2) \otimes U(1)$ quantum field theory (standard model of particle physics)
- Nuclear and atomic physics
- Thermodynamics

Observations

In the observable universe (= our past light cone)
there are hundreds of billions of galaxies

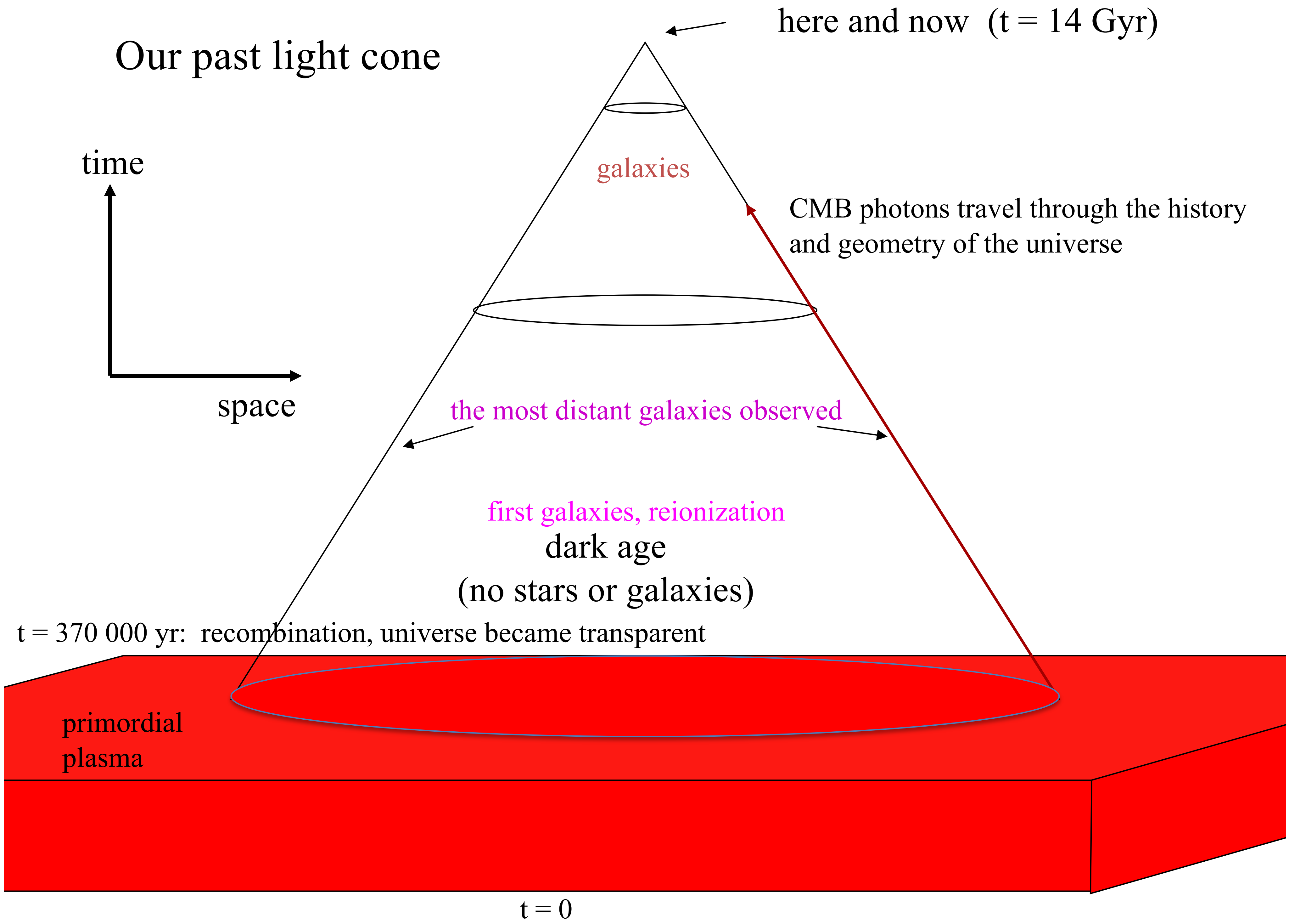


Hubble Ultra Deep Field: NASA/ESA/S. Beckwith(STScI) and The HUDF Team.

Our Past Light Cone

- We can see the history of the universe
  - speed of light = 300 000 km/s = 1 light year / year
  - we see distant objects in the past:
    - Sun: 8 minutes
    - Sirius: 8.6 years
    - Andromeda galaxy: 2 million years
    - Distant galaxies: billions of years
- Age of the universe ~14 billion years

  => The maximum distance we can see is the distance light travelled in this time (horizon)
  - At which distance we see the big bang (cosmic microwave background)

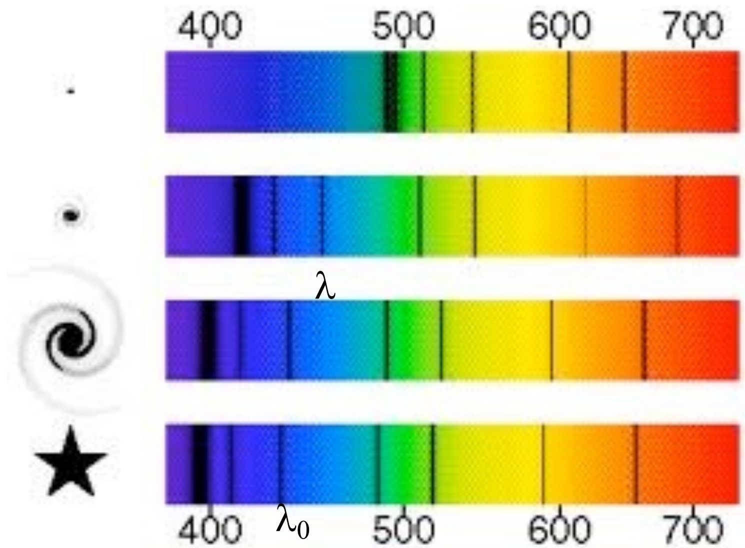


here and now (t = 14 Gyr)
Our past light cone
time
space
galaxies
CMB photons travel through the history
and geometry of the universe
the most distant galaxies observed
first galaxies, reionization
dark age
(no stars or galaxies)
t = 370 000 yr: recombination, universe became transparent
primordial
plasma
t = 0

Expansion of the universe

- Edwin Hubble (1929): Redshift of distant galaxies

http://www.astro.ucla.edu/~wright/doppler.htm



$$z = \frac{\lambda - \lambda_0}{\lambda_0} \qquad \text{or} \qquad 1 + z = \frac{\lambda}{\lambda_0}$$

Hubble law $\quad cz = H_0 r$

Hubble constant

Possible interpretation: Doppler effect
galaxy is receding with velocity v = cz
=> v = H_0r

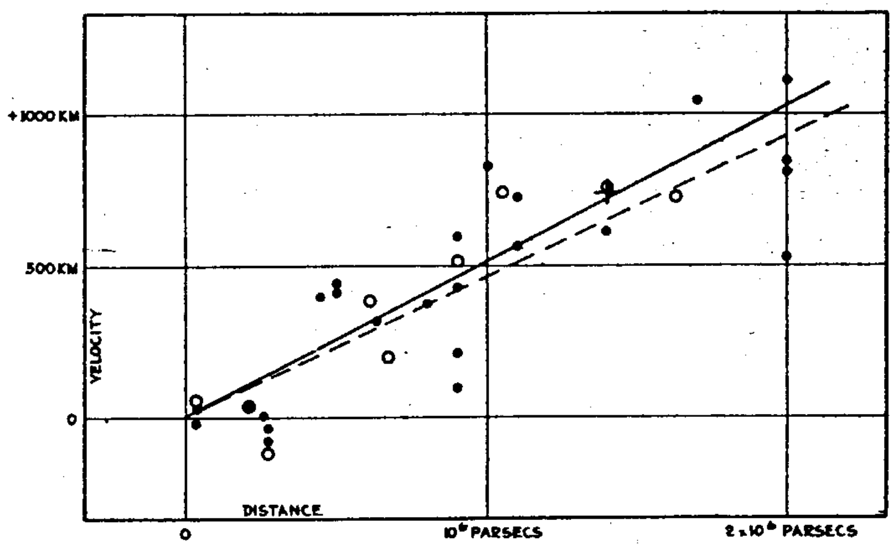
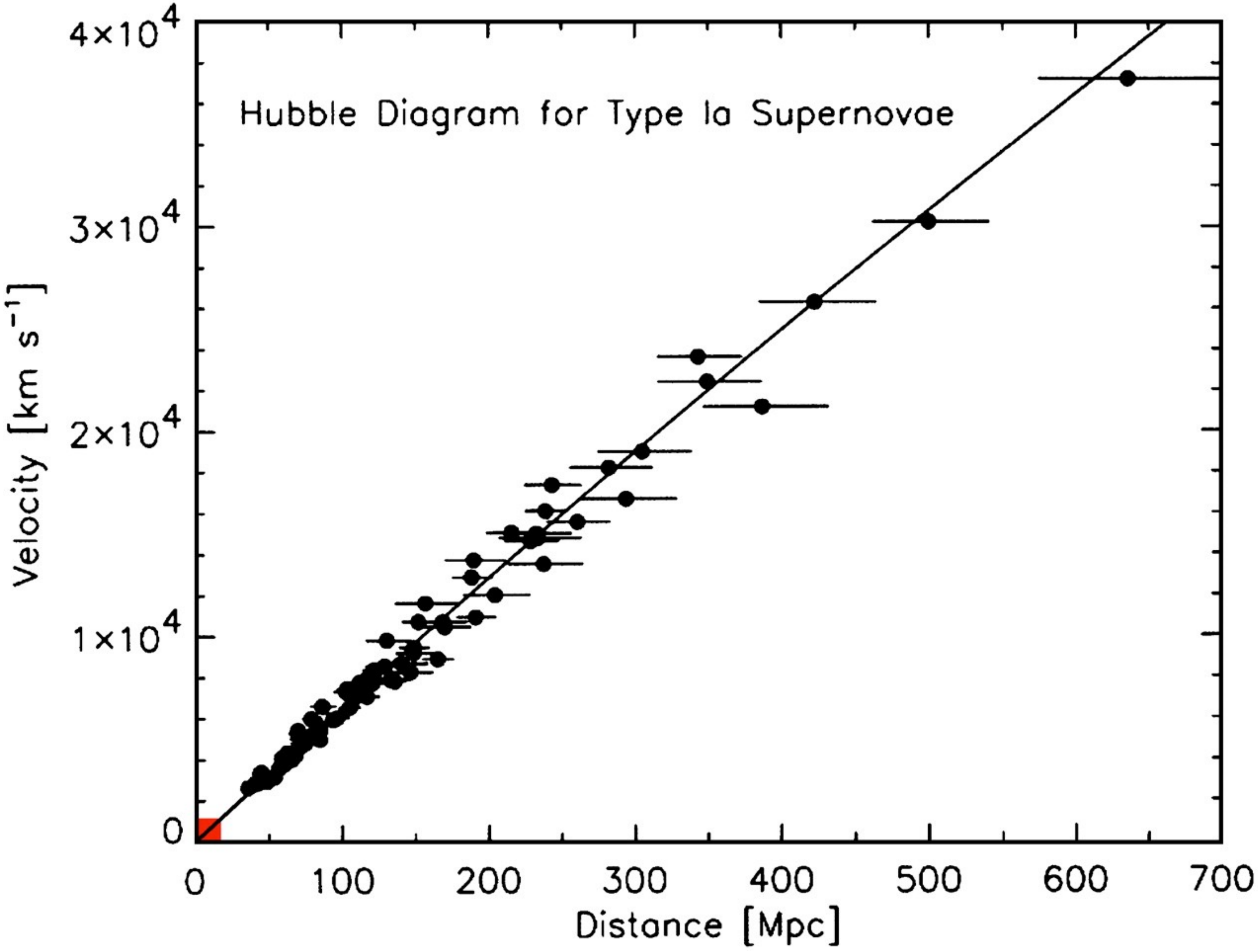


FIGURE 1

Modern value:
$H_0 \approx$ 70 km/s/Mpc
(1 Mpc = 3.26 million light years)

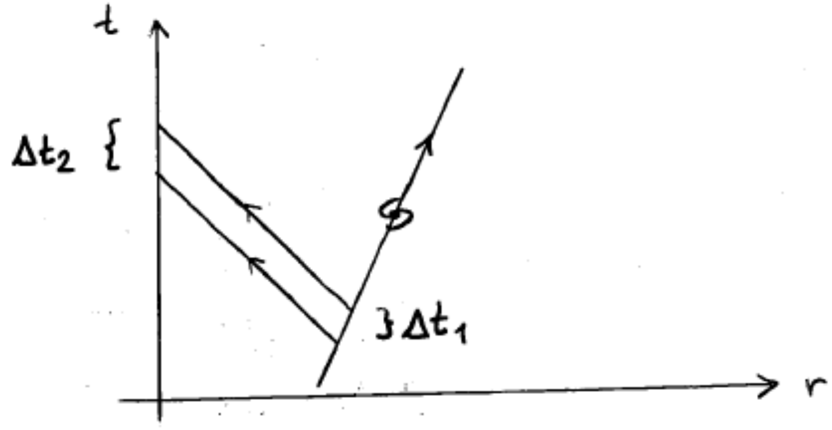
h = H_0 / (100 km/s/Mpc) ≈ 0.7

A modern Hubble diagram



[R.P. Kishner, PNAS 101, 8 (2004)]

- Everything appears to slow down (e.g., supernova lightcurves)

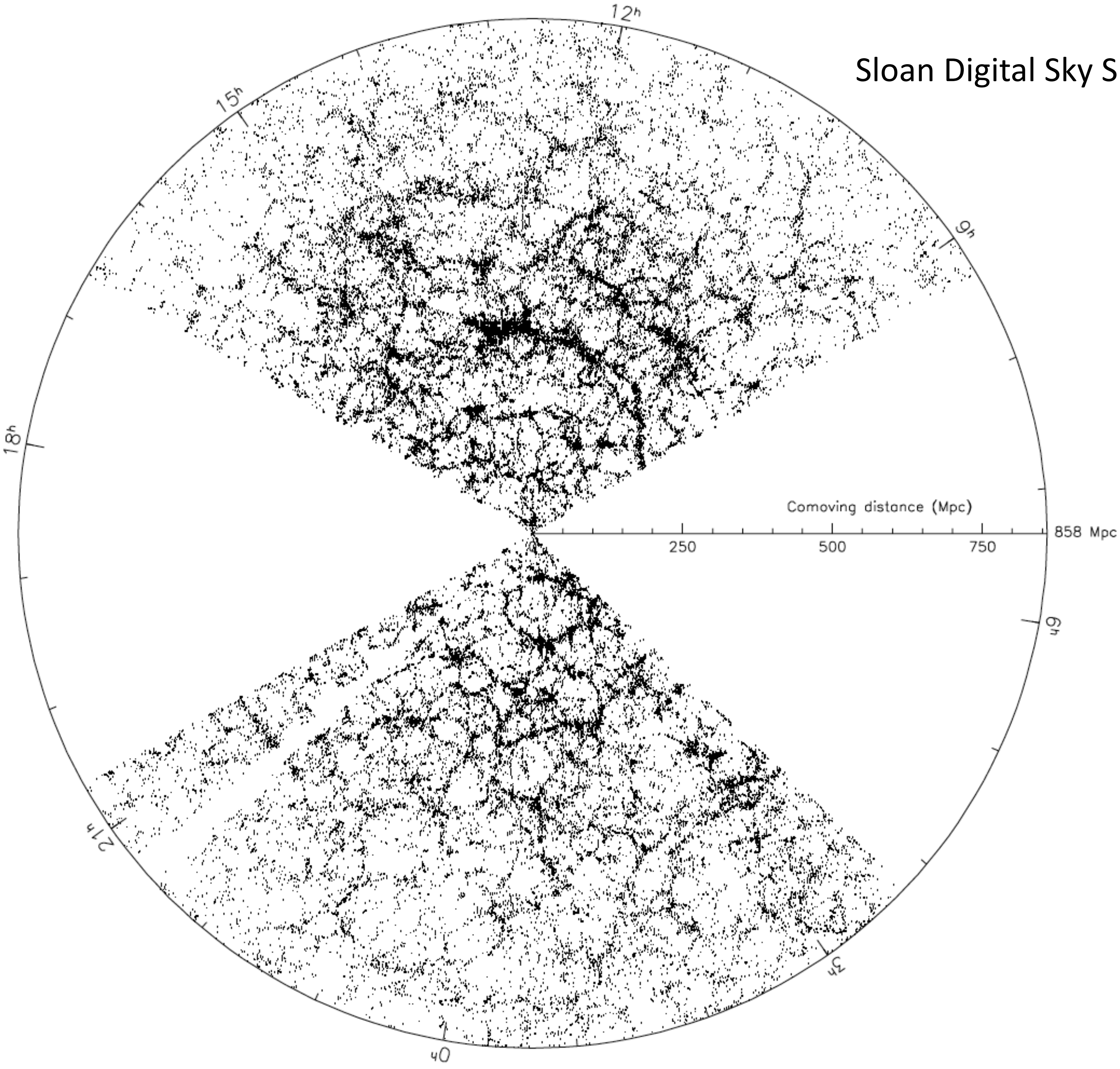


- General relativity (Einstein): the galaxies are not moving, but the space between them is expanding
  - Wavelength expands with the universe

$$1 + z \equiv \frac{\lambda_2}{\lambda_1} = \frac{\delta t_2}{\delta t_1} = \frac{a(t_2)}{a(t_1)}$$

- Redshifts can be measured accurately
  - The Hubble law then gives a distance estimate
  - Large redshift surveys (2DFGRS, SDSS) map the 3-dimensional distribution of galaxies

Sloan Digital Sky Survey



- Redshift

  => distances between galaxies are increasing

  => the universe is expanding

- GR: $a(t)$ scale factor increases with time
- Going back in time:

  $a(t) \rightarrow 0$

  $\rho \rightarrow \infty$ $\sim 14 \times 10^9$ years ago

  $T \rightarrow \infty$

- Planck time $\rho \approx \rho_{Pl} \approx 5 \times 10^{96}$ kg/m^3

  $T \approx T_{Pl} \approx 1.4 \times 10^{32}$ K

~~GR~~ $\rightarrow$ Quantum gravity

Big Bang

- The universe was once
  - very hot
  - very dense
  - expanding fast
- Homogeneous & in thermal equilibrium

  => simple, we can calculate
- High T => high energies => particle physics

Natural units: $c = k_B = \hbar = 1$

- Relativity: space and time unified into spacetime: use same units for time and distance
  - 1 s = 299 792 458 m, 1 year = 1 light-year, $c = 1$
  - Velocity is dimensionless, < 1 for massive particles
  - Same units for energy and mass
- Measure temperature in energy units: $k_B T = T$
  - 1 K = 1.38×10^{-23} J
  - 1 eV = 11600 K = 1.78×10^{-36} kg = 1.60×10^{-19} J
- Quantum physics: energy related to time
  - Energy of photon related to its angular frequency: $E = \hbar\omega = \omega$
  - 1 eV = 1.52×10^{15} s^{-1}

The Standard Model of particle physics

$SU(3) \otimes SU(2) \otimes U(1)$ (symmetries)

Electroweak theory (EW)

Quantum chromodynamics (QCD)

- T > 100 GeV:

Fermions:	Quarks:	d u s c b t
(matter)	Leptons:	e^- ν_e μ^- ν_μ τ^- ν_t
Gauge bosons:	8 gluons	
(interactions)	W^+ W^- W^0 B	

These are all massless

Higgs boson H

Short history of the universe I

Time	Energy	
10^{-42} s	10^{19} GeV	Planck time ?
	10^{18}	
		Inflation ?
10^{-36} s	10^{15}	GUT era ?
		Inflation ?
10^{-30} s	10^{12}	
		DESERT ?
10^{-24} s	10^{9}	
10^{-18} s	10^{6}	
10^{-12} s	10^{3} GeV	**$SU(3) \otimes SU(2) \otimes U(1)$**

Matter-antimatter asymmetry ?
Topological defects ?
(monopoles, cosmic strings,
domain walls)

Supersymmetry ?

Short history of the universe II

10^{-12} s — TeV

Electroweak (EW) transition
Fermions, W^+, W^-, Z^0 become massive
γ massless

Matter-antimatter asymmetry?

Heavy particles annihilate or decay unless protected by conserved number

10^{-6} s — GeV

QCD transition: quarks → p, n, π
π annihilation
μ annihilation

p, n, π
e, μ, ν, γ

ν decoupling
e annihilation
n/p ~ 1/6

1 s — MeV

Big bang nucleosynthesis (BBN)
^{2}H, ^{3}He, ^{4}He, ^{7}Li

1 h

Short history of the universe III

1 a — keV

10^6 a — eV

Recombination => atoms

The universe becomes transparent (γ decoupling)

Cosmic Microwave Background (CMB)

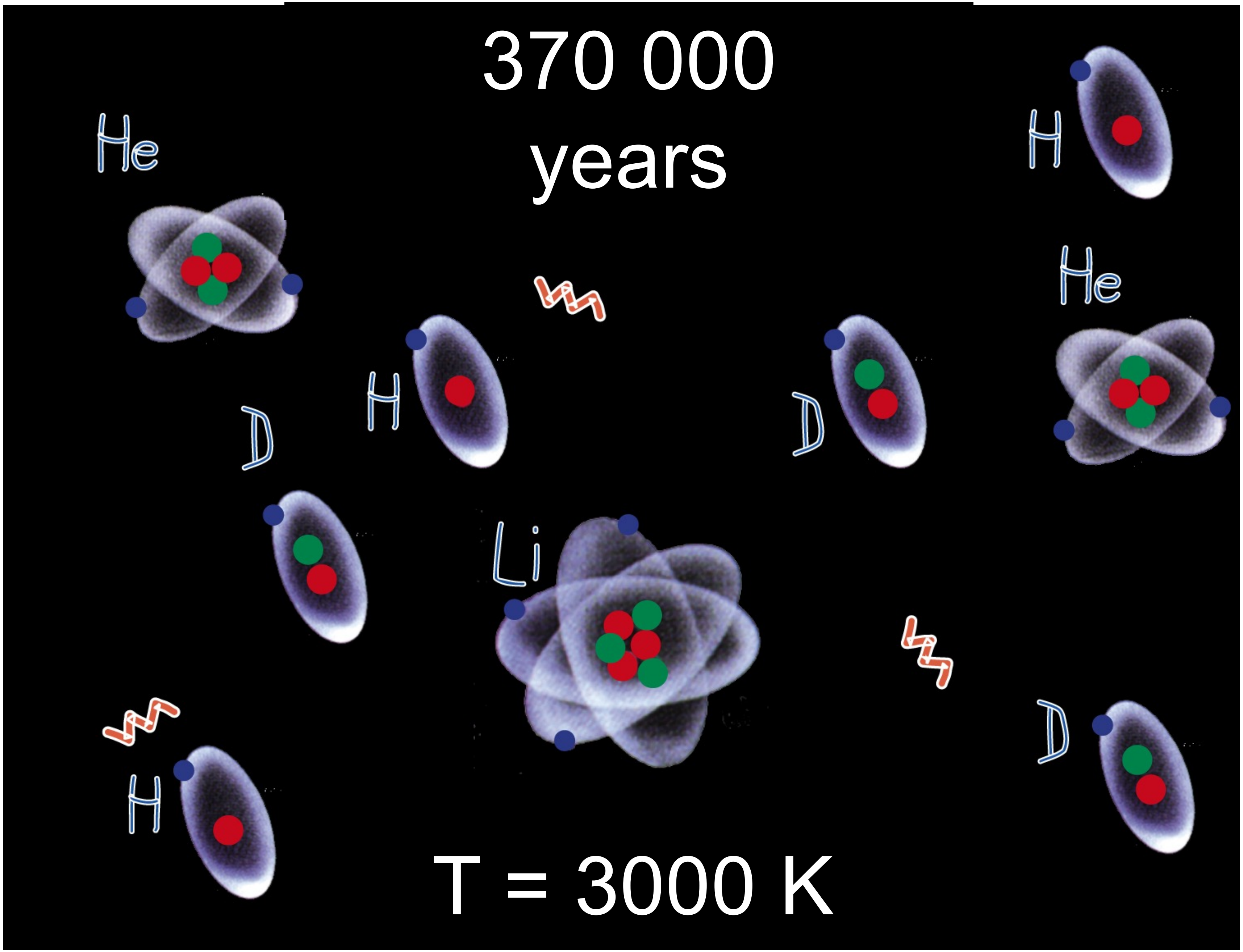
Dark age

Structure formation

Formation of galaxies, first stars

meV — 10^{10} a

Now



Atoms formed in recombination

Structure formation

- Cosmic microwave background

  => early universe was homogeneous

  few x 10^{-5} density fluctuations = seeds of galaxies

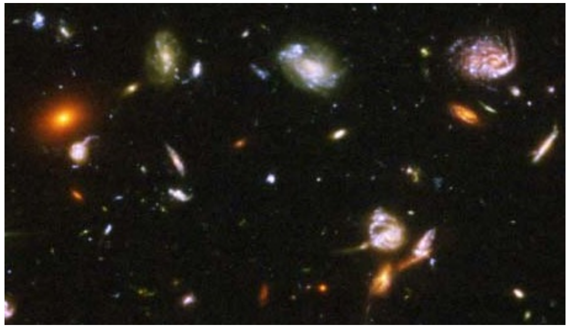
- Gravity => fluctuations grow

  => galaxies,

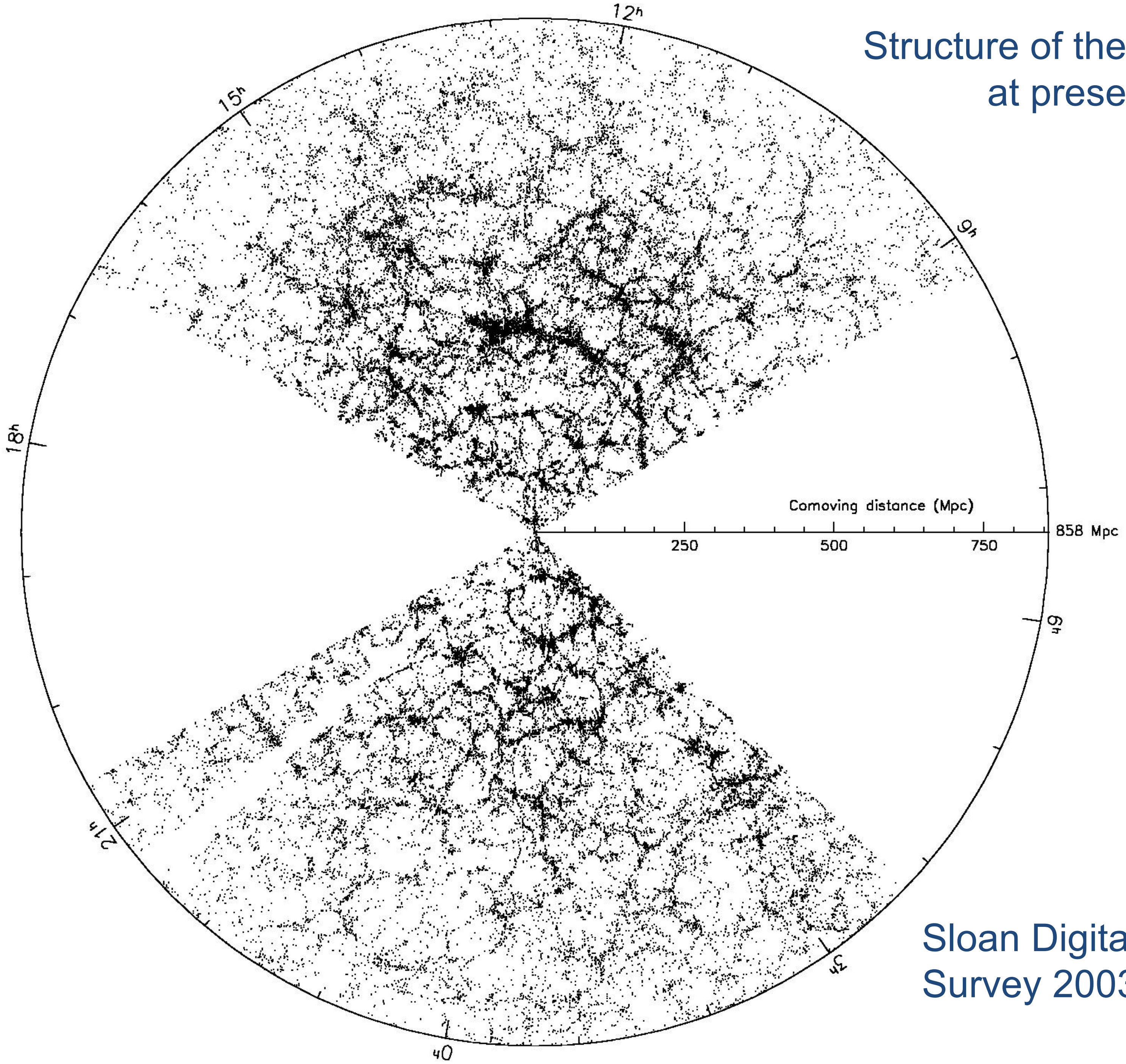
  clusters of galaxies,

  superclusters, ”walls”, ”voids”

  = large scale structure of the universe



Structure of the universe
at present



Sloan Digital Sky
Survey 2003

Structure formation

1. Origin of fluctuations
   - Inflation ? +
   - Cosmic strings ? -
2. Growth of fluctuations
   - Caused by gravity
   - Depends on composition / nature of matter
   - Dark matter ?

Dark matter ?	Baryonic dark matter	-
	Hot dark matter	-
	Cold dark matter	+

Dark matter

- ”Luminous” matter: stars, gas, dust
- Motions of galaxies => there’s more matter (gravity) => dark matter

1. Ordinary = baryonic, dark matter (BDM): ”jupiters”, brown dwarfs, intergalactic gas
2. Non-baryonic dark matter
    1. Hot dark matter (HDM): neutrinos m ~ 1 eV
    2. Cold dark matter (CDM): ”exotic” particles, e.g., axions, neutralinos

- Need both baryonic and non-baryonic dark matter
    - Big bang nucleosynthesis
    - Galaxy motions
    - Structure formation

Dark Energy

GR: gravity depends on both energy density and pressure

- source of gravity = $\rho + 3p$
- equation of state $\rho(p)$ expansion law
- distance-redshift relation of supernovae

  => expansion is accelerating => $\rho+3p < 0$

  => a negative pressure component

- > 2/3 of total energy density
- uniformly distributed
- large negative pressure
- Possibilities:
  - vacuum energy (cosmological constant)
  - scalar field (quintessence)

Cosmological principle

- Copernican principle: We do not occupy a privileged position in the universe
- Cosmological principle: The universe is homogeneous and isotropic (at large scales)
  - The evidence for isotropy (as seen from our location) is stronger than for homogeneity
  - Copernican principle => should be isotropic as seen from other locations also
  - Isotropic from everywhere => homogeneous
- These principles are invoked to arrive at plausible models, which are then tested against observation

Cosmology I

1. Introduction
2. General relativity (brief introduction)
3. Friedmann-Robertson-Walker (FRW) universe
4. Thermal history of the early universe
5. Big bang nucleosynthesis (BBN)
6. Dark matter

Cosmology II

7. Inflation
8. Structure formation
9. Cosmic microwave background (CMB) anisotropy

THE END