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Higher school of applied
physics and space technologies

The Friedmann Universe
and
Modern Cosmology

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1. First scientific concepts of the Universe.

2. Newton’s universal law of gravitation.

3. Einstein’s general relativity theory.

4. Friedmann’s nonstationary solutions.

5. Big Bang.

6. Inflation.

7. Stages of the Universe evolution.

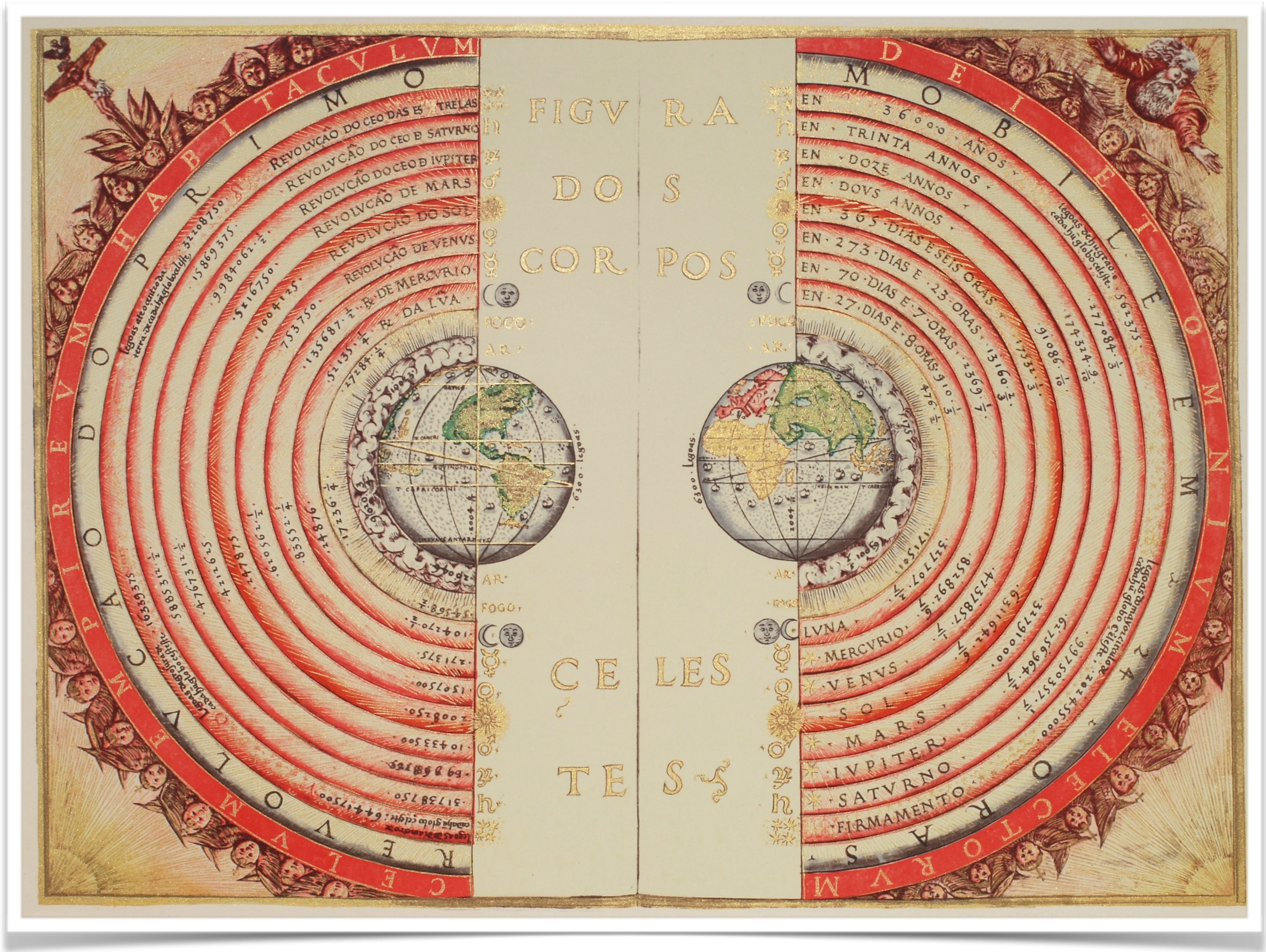
8. Accelerated expansion, dark matter and dark energy.

9. Conclusions.

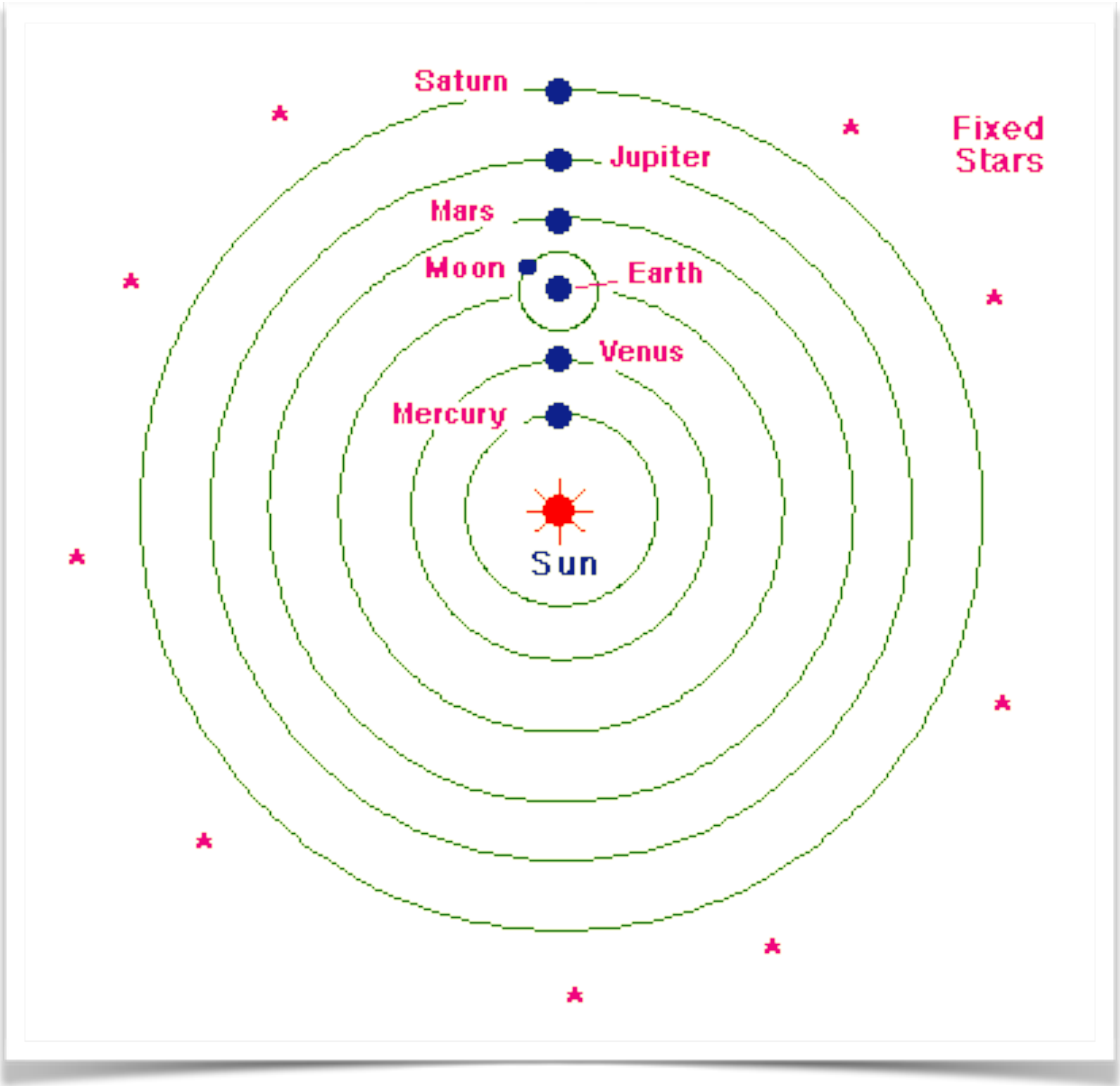
1

First scientific concepts of the Universe

Ptolemy system



Copernicus, Kepler and Galilei system



Both these systems admitted that beyond Saturn there is the firmament with fixed stars which does not obey the same physical laws as all bodies on the Earth.

2

Newton’s concept of the Universe

PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore *JS. NEWTON*, *Trin. Coll. Cantab. Soc.* Mathefeos Profeſſore *Lucaſiano*, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,

Juſſu *Societatis Regiæ* ac Typis *Joſephi Streater*. Proſtat apud plures Bibliopolas. *Anno* MDCLXXXVII.

$$F = \frac{Gm_g M}{r^2}$$

$$F = m_i a$$

$$m_i = m_g$$

Equivalence principle

All bodies on the Earth obey
the same physical laws
as all the celestial bodies.

Newton’s concept

∞ in volume

Homogeneous

Isotropic

∞ age & will exist forever

Contains ∞ stars

Olbers' paradox

If you walk through a forest, you only see trees to the farther distance.

Olbers' paradox

If the Universe is infinite, every direction you look, you should meet a star or a galaxy.

Olbers' paradox

Thus, the night sky should glow like a star, should be as hot as the surface of a star.

Why is this not happening?

3

Einstein’s general relativity theory

Einstein theory

$$R_{ik} - \frac{1}{2}Rg_{ik} + \Lambda g_{ik} = \frac{8\pi G}{c^4}T_{ik}$$

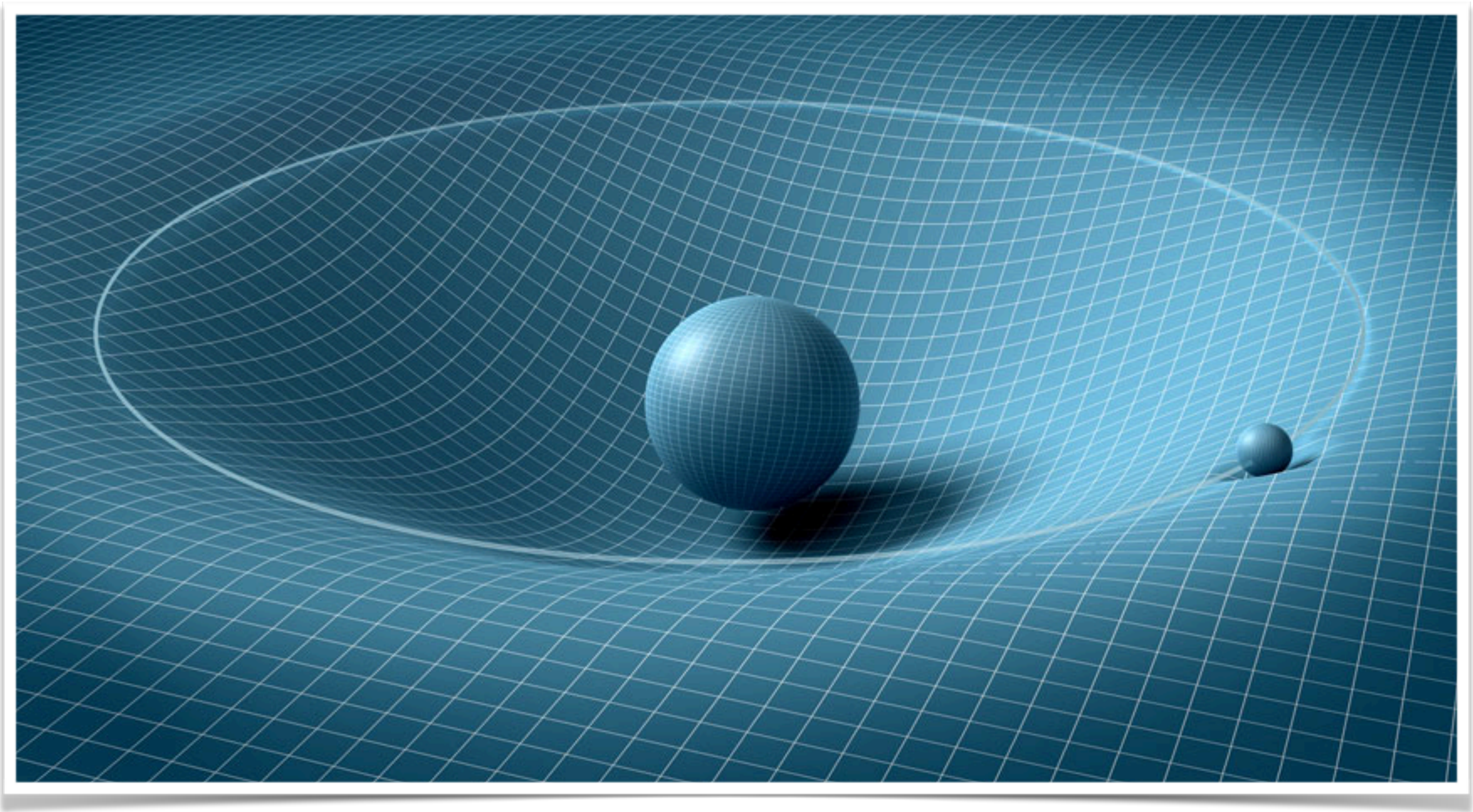
Einstein theory

no attractive gravitational force

massive bodies move free along the shorter lines in curved space-time

acceleration is the same as gravitation

all reference frames are equivalent



Einstein’s concept

static universe with finite spatial volume

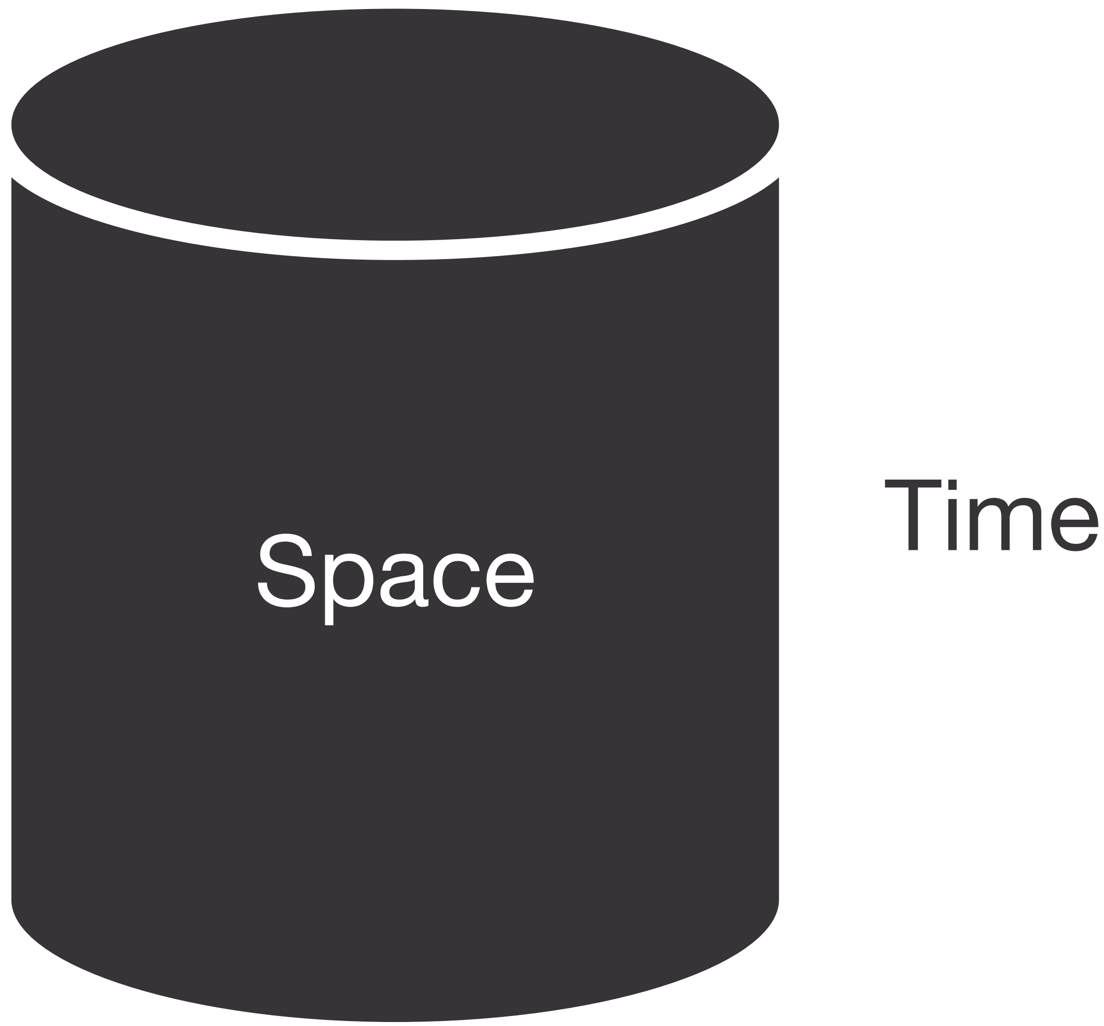
$$\Lambda \neq 0$$

the solution with nonzero cosmological constant

exists forever: never created, will never die

finite number of stars

Einstein's Universe



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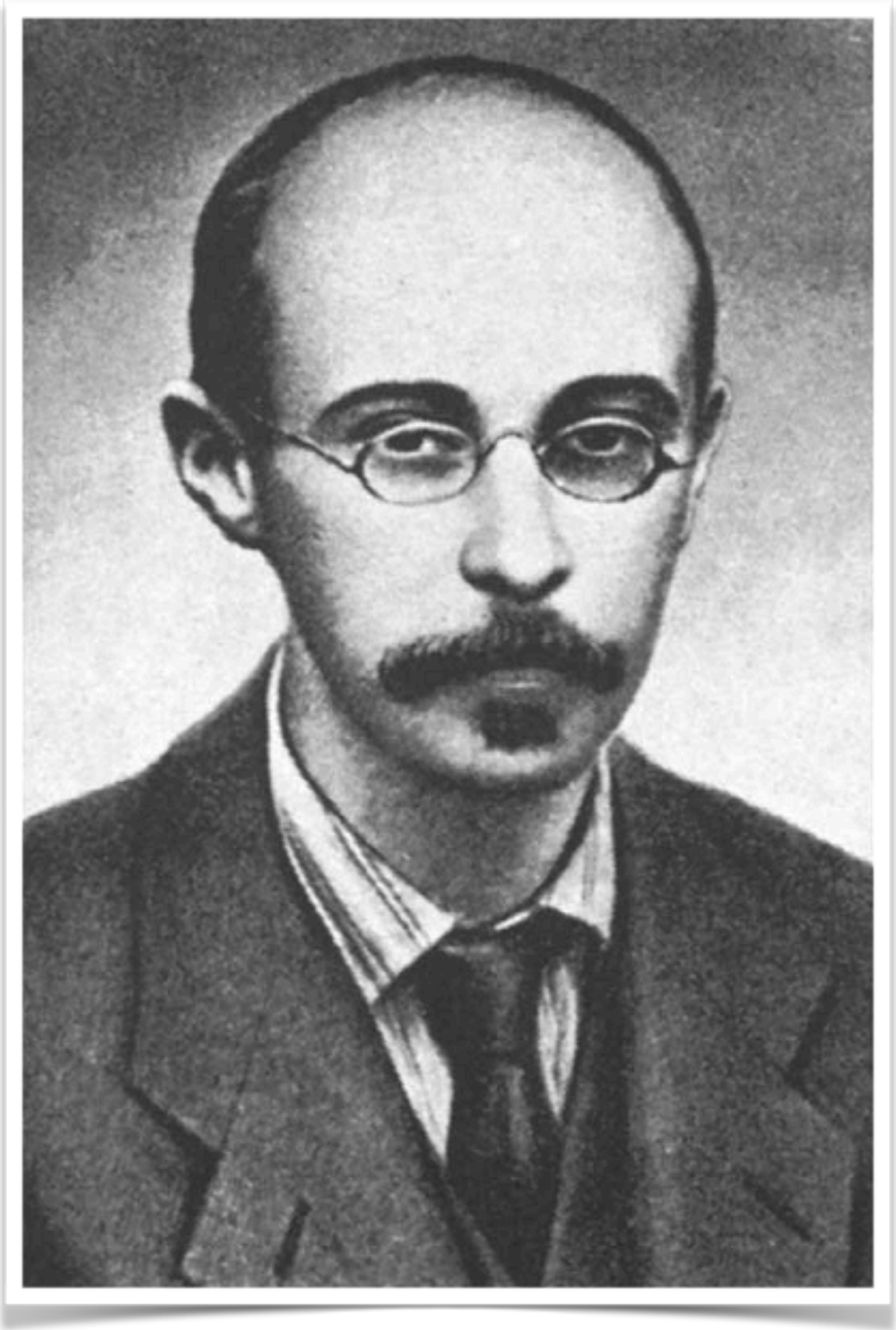
Friedmann’s nonstationary solutions

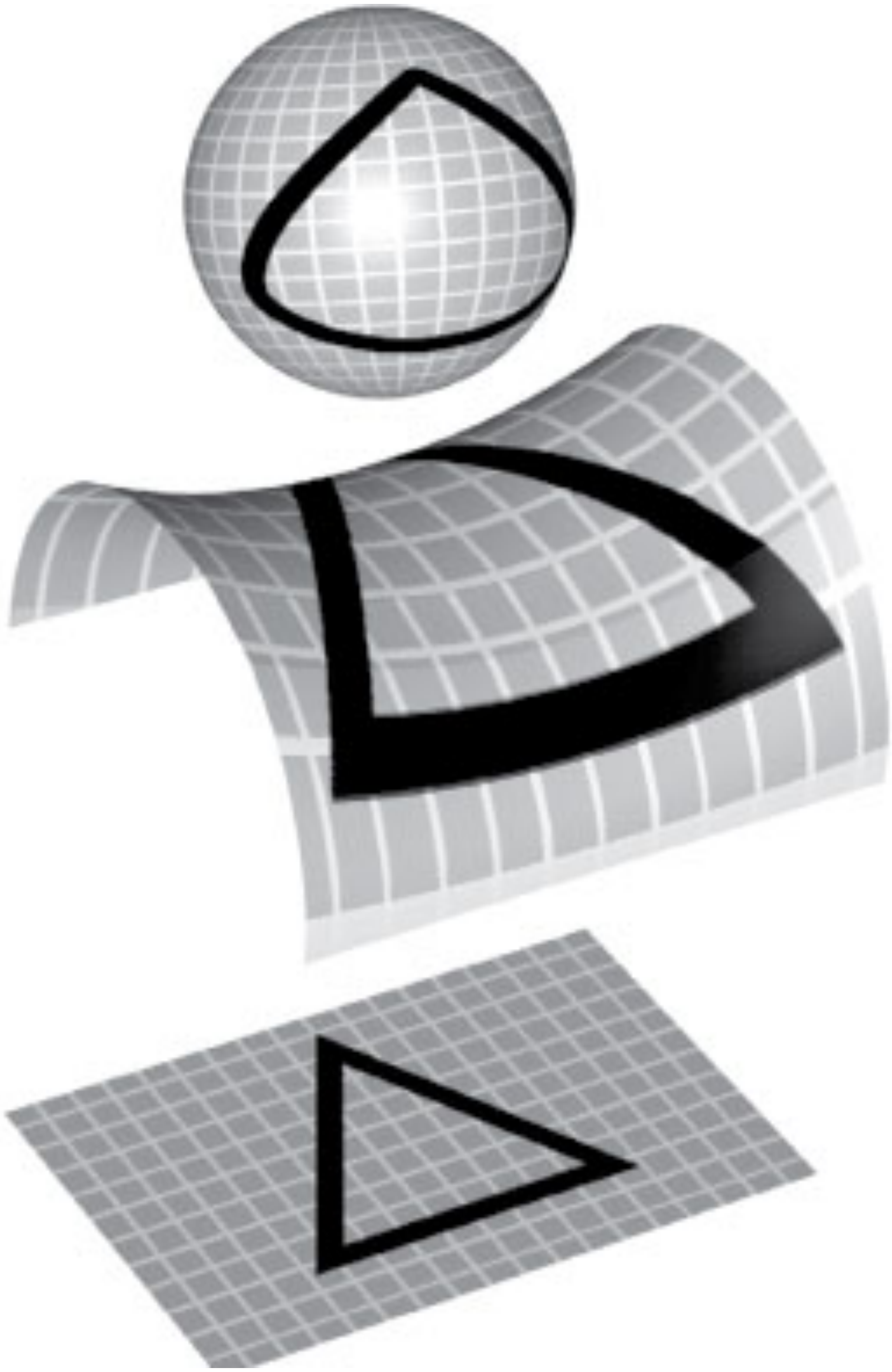


Alexander Friedmann was a professor of Saint Petersburg Polytechnic University from 1920 to his death in 1925

Friedmann's equation

$$\Lambda = 0, \qquad \frac{3}{a^2}\left(\frac{\dot{a}^2}{c^2} + \kappa\right) = \frac{8\pi G}{c^4}\epsilon, \qquad \kappa = 0, \pm 1$$

*discussion with Einstein



Closed

Open

Flat

Modern epoch

$$a \sim t^{2/3}$$

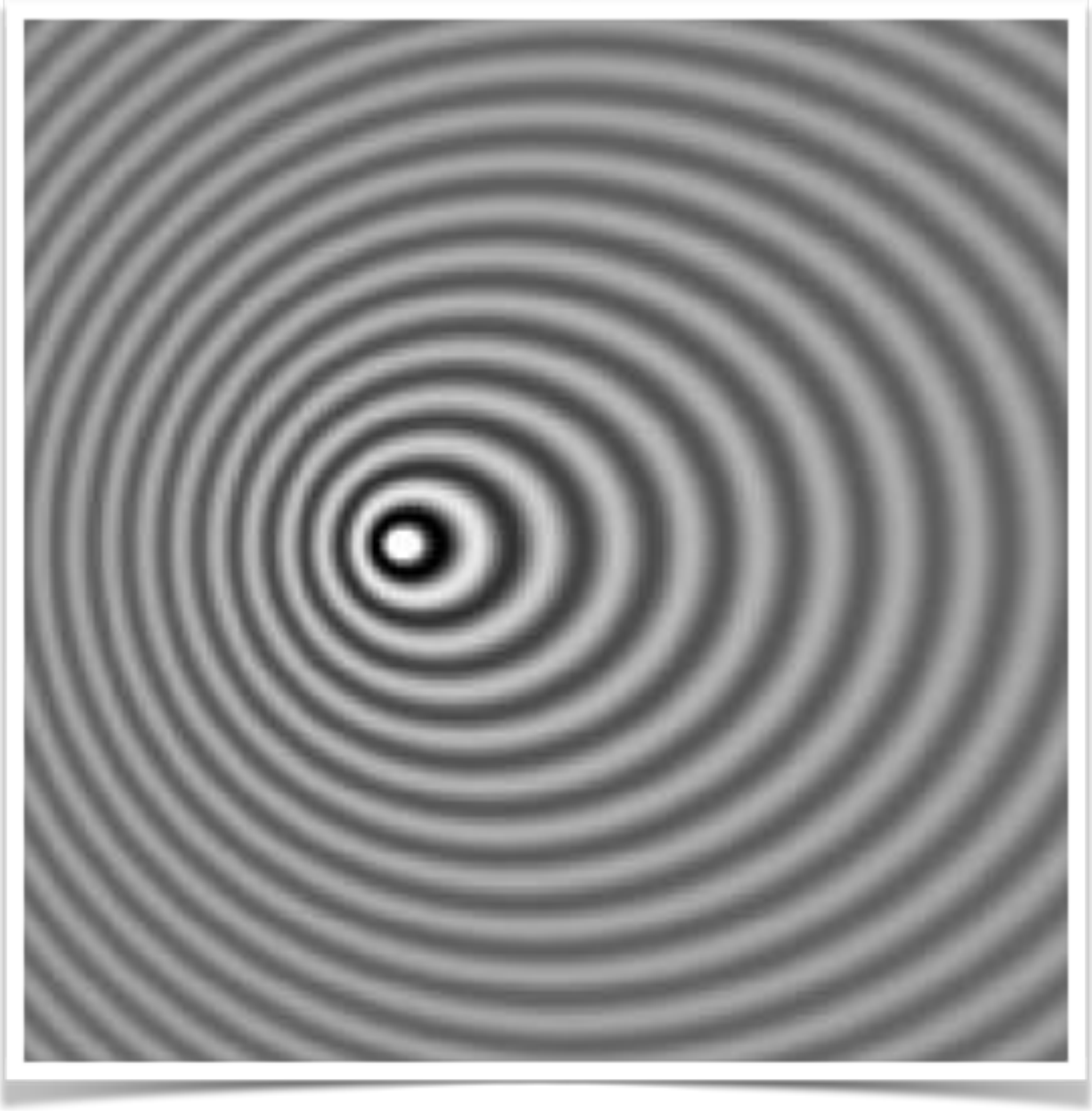
Epoch of small time

$$a \sim \sqrt{t}$$

According to the Friedmann's solution, the Universe is nonstationary and there is the cosmological singularity.

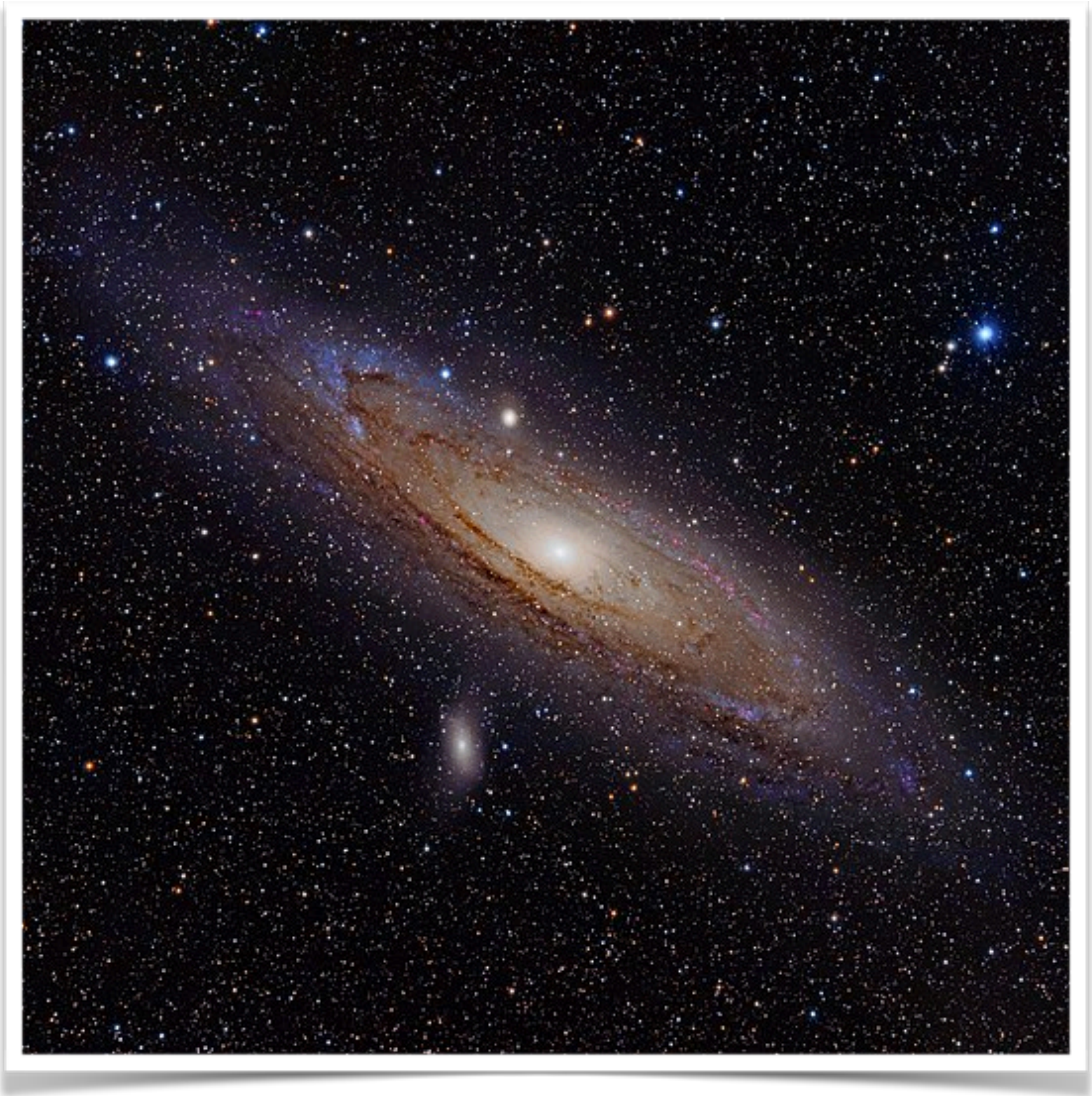
5

Big Bang



Doppler effect: if the source of waves is moving away from the observer, the wave frequency is reduced.

Edwin Hubble observed many remote stars and found that they do not belong to the Milky way and their spectra are shifted to the red. Thus, they go away from us.

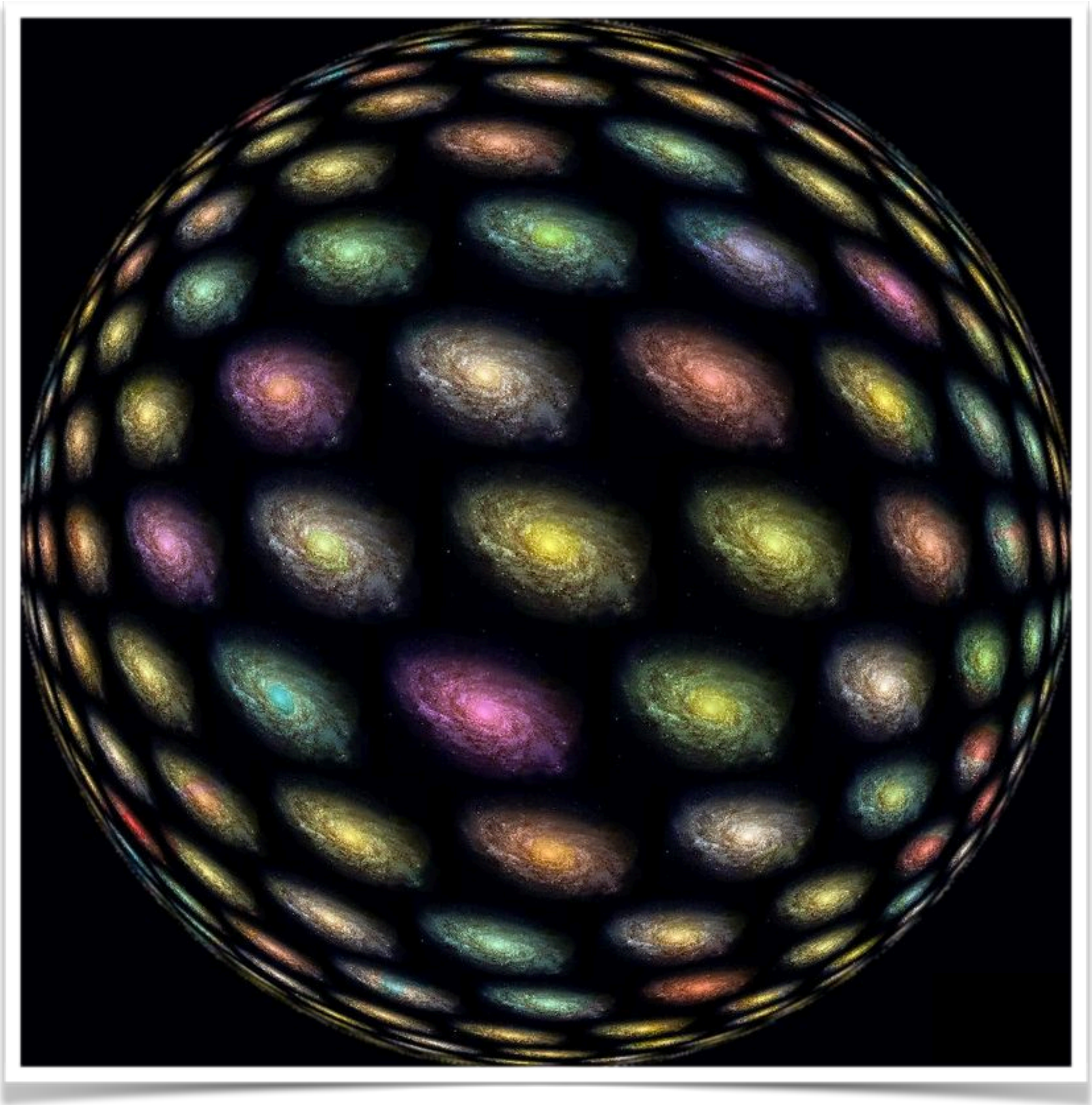


Hubble found that many objects previously thought as clouds of dust and gas were other galaxies beyond our Galaxy (the Milky way).

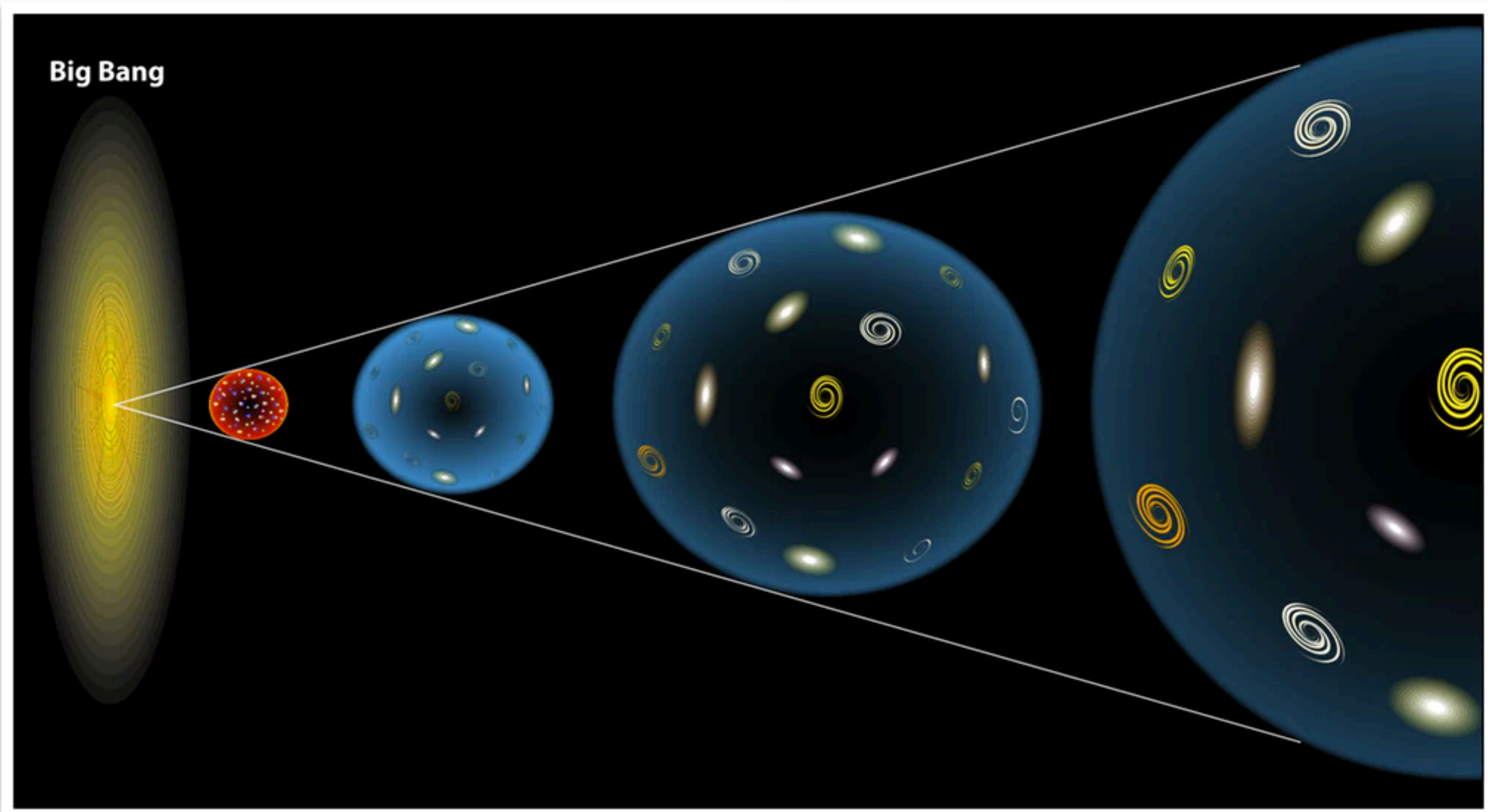
Hubble’s law

$$v = HL$$

Hubble discovered that the velocity of a galaxy increases with its distance from the Earth.



This was direct experimental confirmation of the Friedmann's discovery that our Universe is not static but **expanding**.



During the Big Bang our Universe was expanding starting from the state of very high temperature and density.

Penzias and **Wilson** detected the homogeneous and isotropic **relic radiation** of photons with T=2.7K which is observed presently as evidence of that epoch.

400 — 500 photons/cm^3

6

Inflation

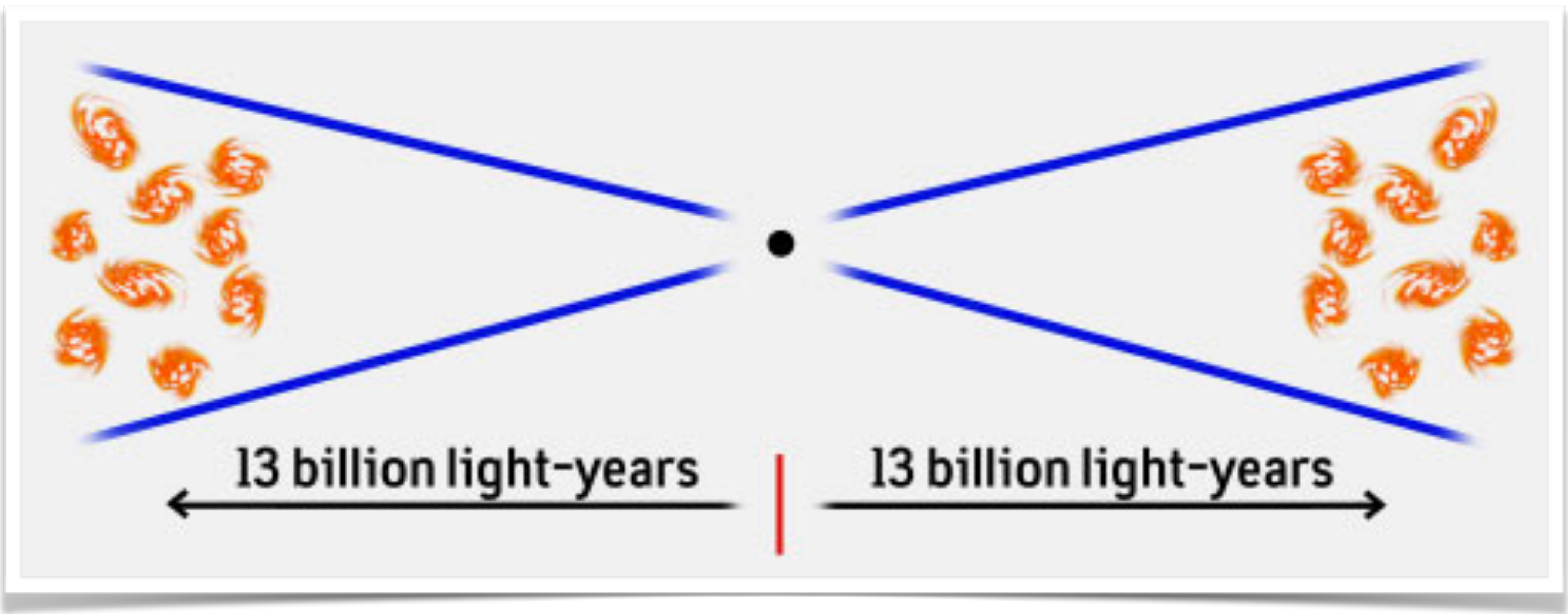
Planck time

$$t_{\mathrm{P}} = \sqrt{\frac{\hbar G}{c^5}} = 5.39 \times 10^{-44}\ \mathrm{s}$$

Planck length

$$l_\mathrm{P} = \sqrt{\frac{\hbar G}{c^3}} = 1.62 \times 10^{-33}\ \mathrm{cm}$$

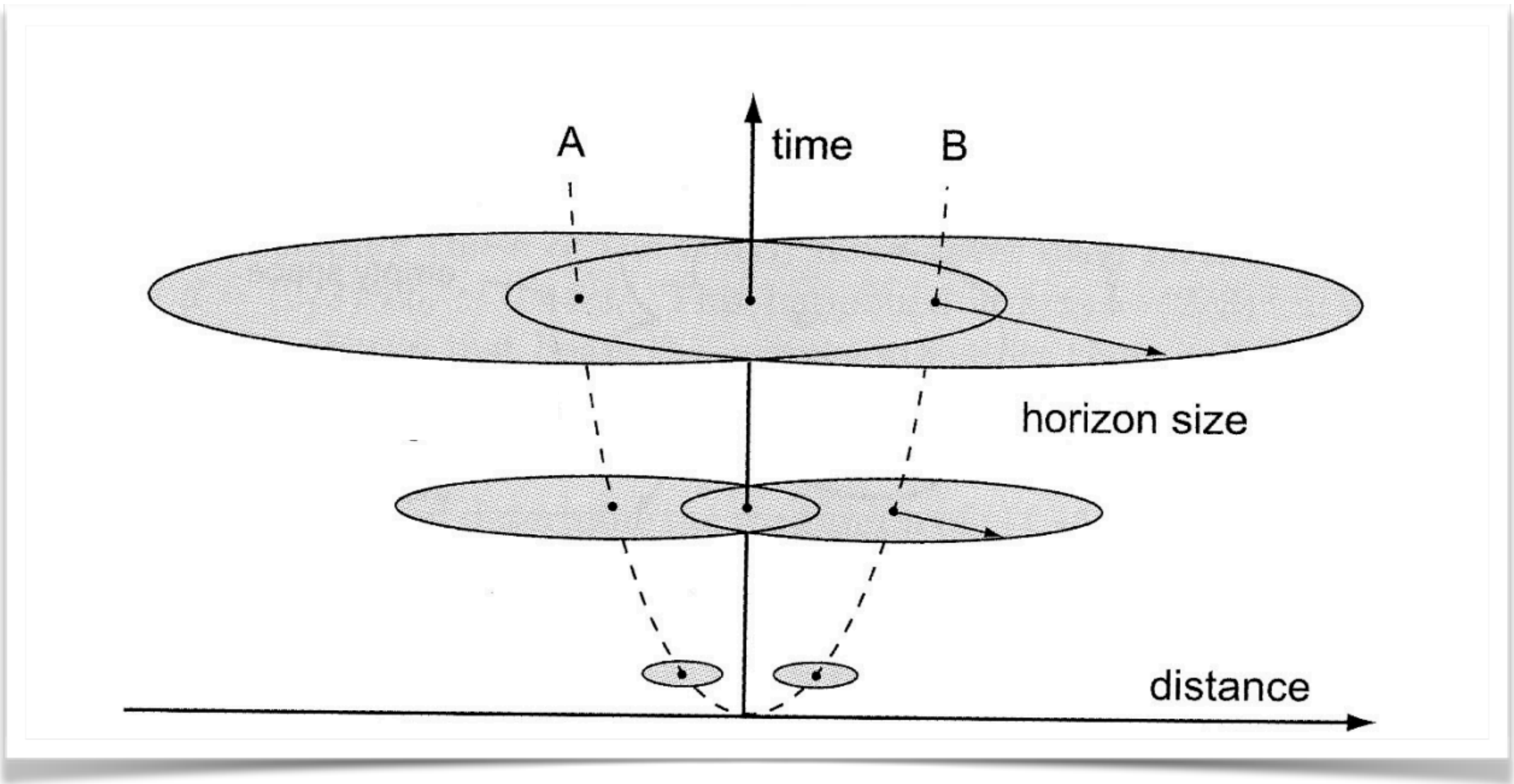
Horizon problem



$$a(t_{\rm P}) \sim 10^{-3}\ \text{cm}$$

$\sim 10^{89}$ causally disconnected regions

Horizon problem



Alan Guth proposed the inflationary stage of the Universe in order to solve the causality problem.

Inflation

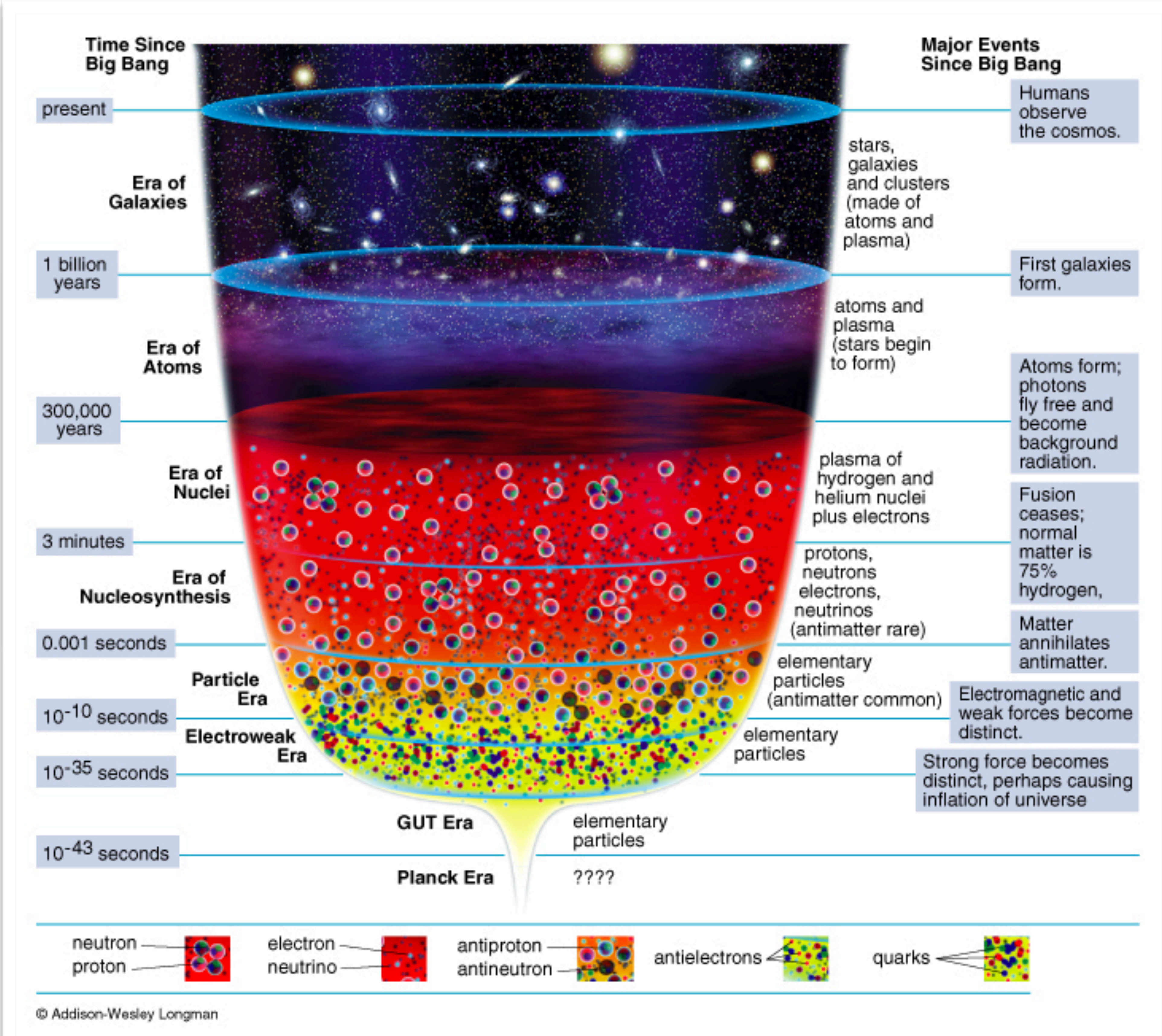
$$a(t) \sim e^t$$

$$t \sim 10^{-33}\ \mathrm{s}$$

Inflation from the inflaton field;
Inflation from the vacuum polarization of quantized fields.

7

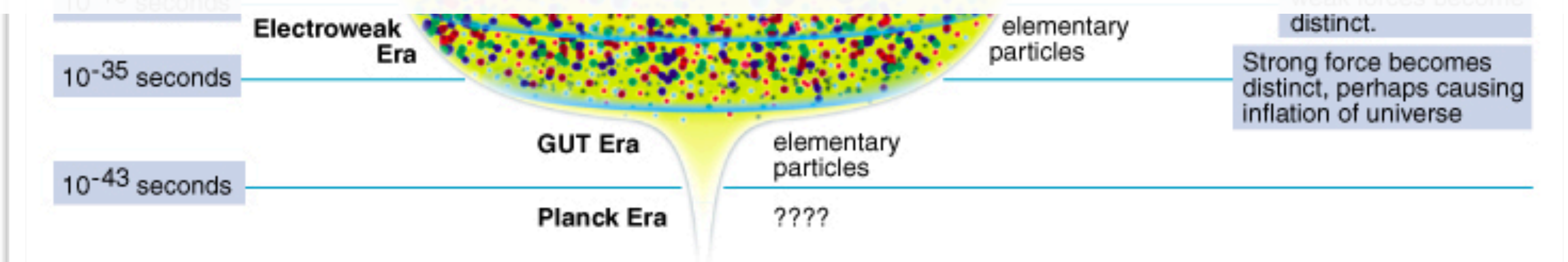
Stages of the Universe evolution



Time Since Big Bang
Major Events Since Big Bang
present
Humans observe the cosmos.
stars, galaxies and clusters (made of atoms and plasma)
Era of Galaxies
1 billion years
First galaxies form.
atoms and plasma (stars begin to form)
Era of Atoms
Atoms form; photons fly free and become background radiation.
300,000 years
Era of Nuclei
plasma of hydrogen and helium nuclei plus electrons
Fusion ceases; normal matter is 75% hydrogen,
3 minutes
Era of Nucleosynthesis
protons, neutrons electrons, neutrinos (antimatter rare)
Matter annihilates antimatter.
0.001 seconds
Particle Era
elementary particles (antimatter common)
Electromagnetic and weak forces become distinct.
10^{-10} seconds
Electroweak Era
elementary particles
Strong force becomes distinct, perhaps causing inflation of universe
10^{-35} seconds
GUT Era
elementary particles
10^{-43} seconds
Planck Era
????
neutron
proton
electron
neutrino
antiproton
antineutron
antielectrons
quarks
© Addison-Wesley Longman

At the very beginning…

— In the “primordial soup” temperatures are enormous.
— All four forces are “unified” into one.
— Matter/antimatter and energy are in constant interaction.
— Particles are very elementary: quarks, electrons and their antimatter counterparts.

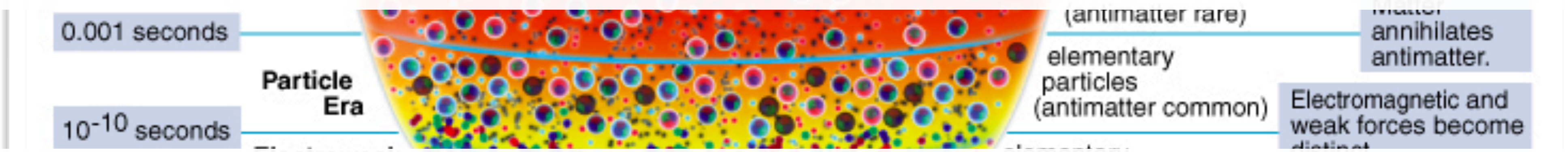


The particle era

— The 4 fundamental forces are separated.

— Particles are created and destroyed with equal efficiency.

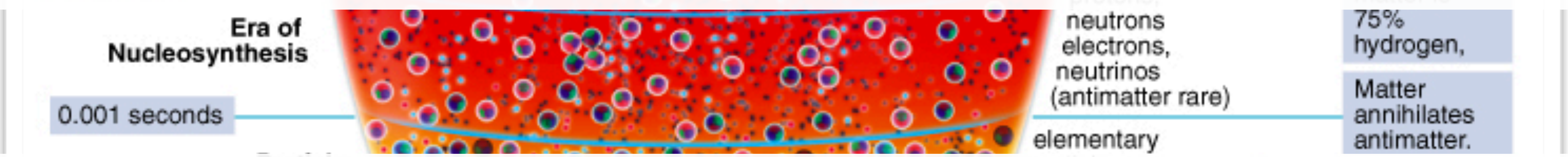
— At the end of this time, it is no longer hot enough to spontaneously produce protons and antiprotons.



—Because of symmetry breaking for every 1 billion antiprotons, there were 1 billion + 1 protons. All antiprotons annihilated with protons to produce photons.

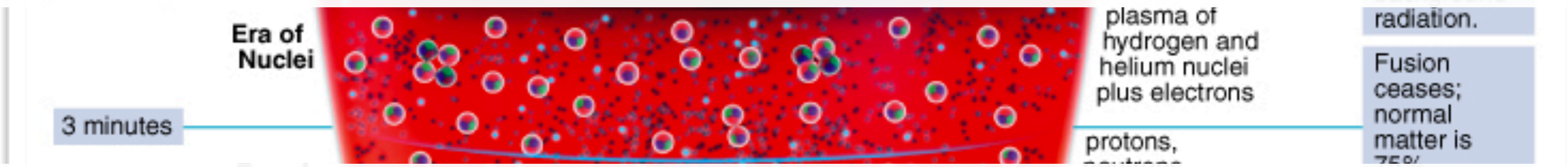
The era of nucleosynthesis

— Hydrogen is fused into helium and a small amount of deuterium and lithium.
— At the end of this time, the Universe was too cool for any more fusion.



The era of nuclei

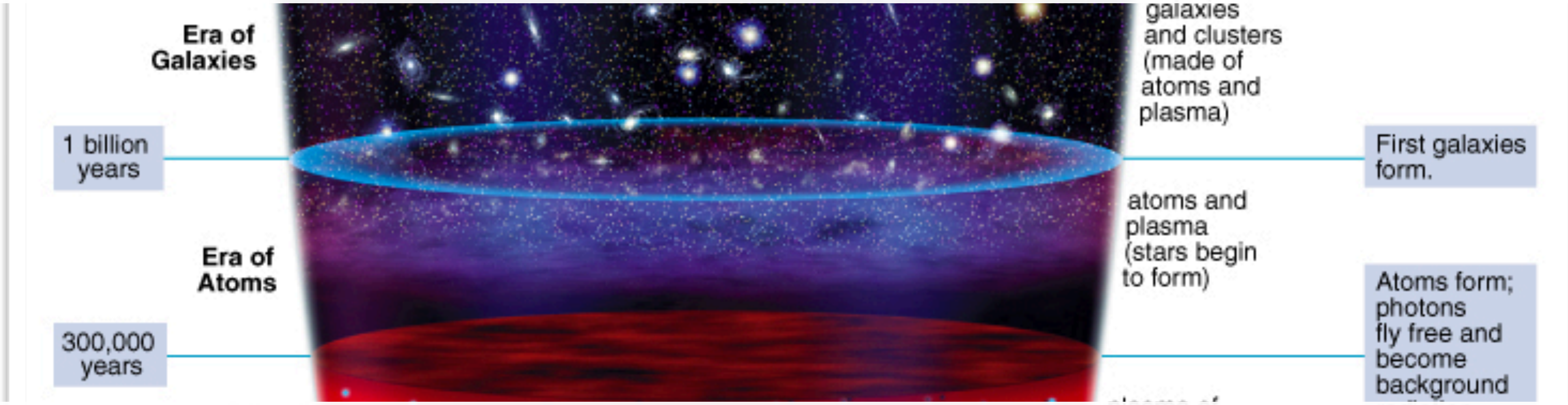
– The Universe is opaque.



– Hydrogen is fused into helium and a small amount of deuterium and lithium.

– At the end of this time, the Universe was too cool for any more fusion.

The era of atoms & galaxies



— The Universe in no longer hot enough to keep matter ionised.
— Structure formed and here we are.

8

Accelerated expansion, dark matter and dark energy

Dark matter $\neq$ Dark energy

Dark matter

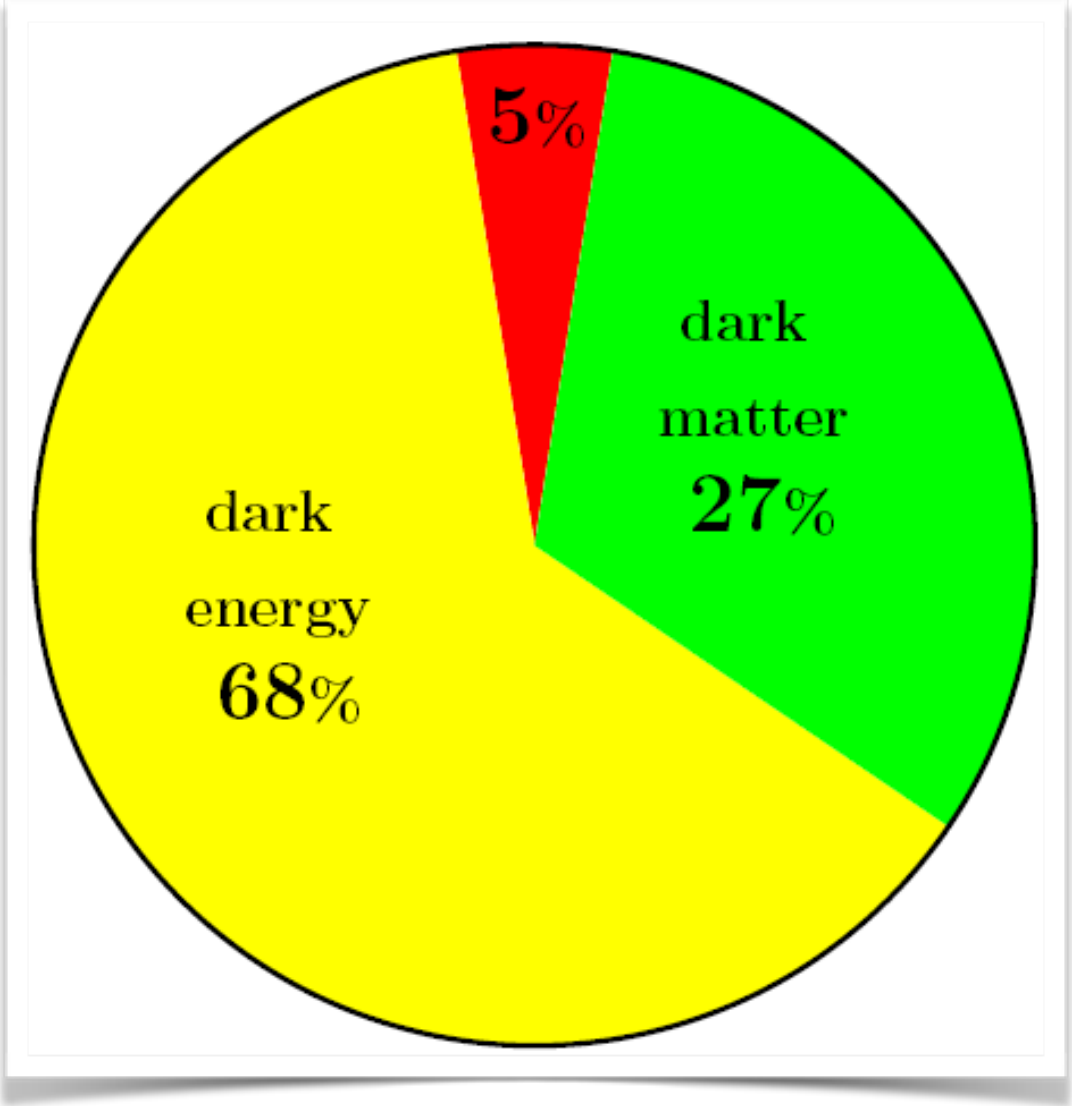
J. Oort (1932) studied stellar motion in the neighbourhood of a galaxy and found that the galaxy mass must be larger than that of visible matter;

F. Zwicky (1933) applied the virial theorem to the Coma cluster of galaxies and found that the total cluster mass is much larger than that determined from the number of galaxies and their brightness.

Dark energy

M. Turner (1998) introduced this term for the form of energy which permeates all of space and is responsible for the accelerated expansion of our Universe confirmed by many independent observations.

Fractions of dark matter and dark energy in the energy of the Universe



9

Conclusions

1

According to modern picture of the world, our Universe is expanding starting from the singular state.

2

This discovery made by Alexander Friedmann has changed completely all the previous concepts by Ptolemy, Copernicus, Galilei, Newton, and Einstein.

3

The age of the Universe is of about 13.7 billion years.

4

The expansion of the Universe is accelerating.

5

Many problems, such as the origin of singularity, nature of dark matter and dark energy, remain to be solved.

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