Newtonian Cosmology

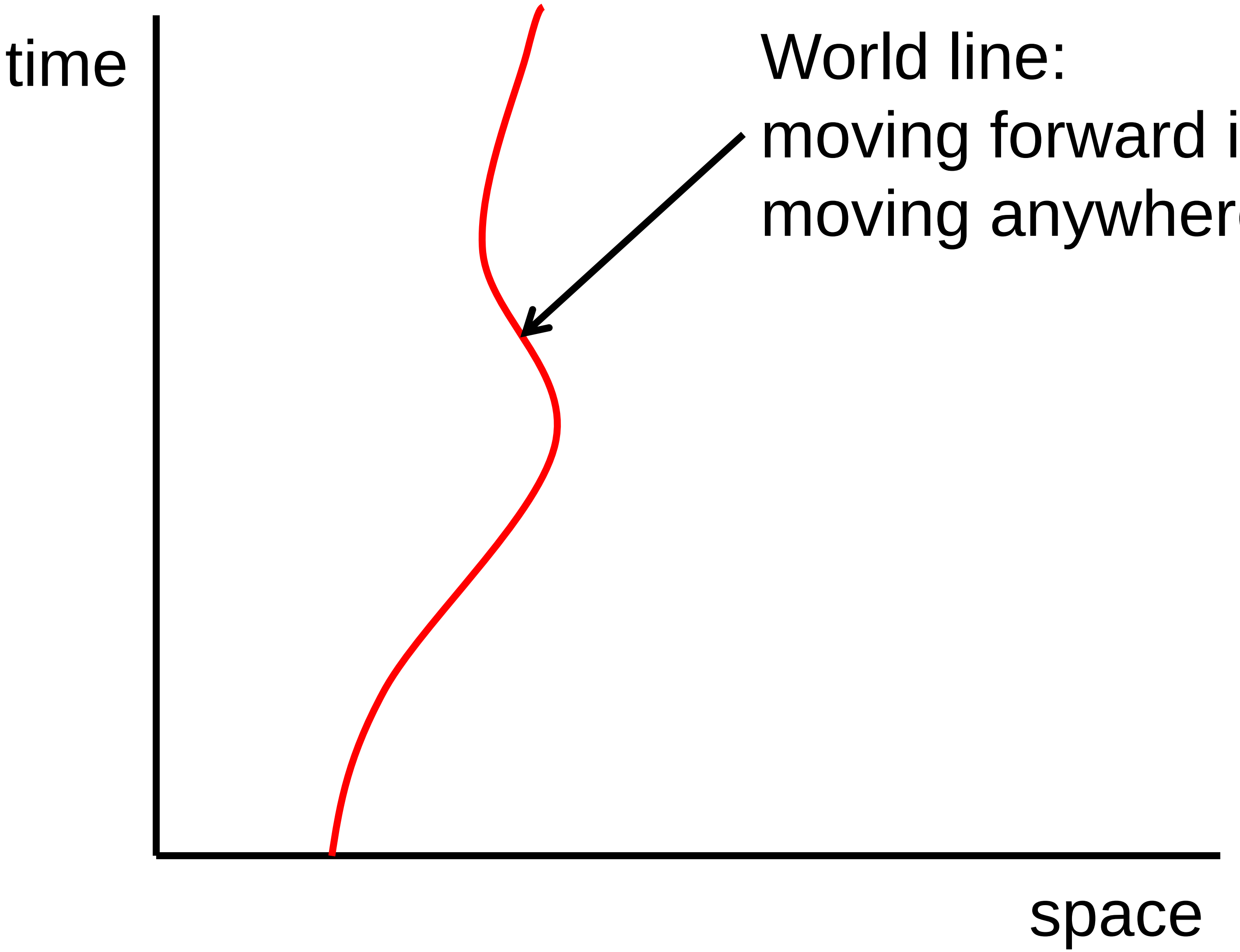
Part I

Building Physical Cosmology

Coordinates

- Science is based upon observations. We can observe space and time by measuring them.
- Any spatial position can be characterized by three numbers - **coordinates**. They are usually denoted by letters *x*, *y*, and *z*. Time is represented by the letter *t*.
- Thus, any point in space at every instant in time - an **event** - can be fully described by four numbers: (*x*,*y*,*z*,*t*).

World Lines



World line:
moving forward in time
moving anywhere in space

Frame of Reference

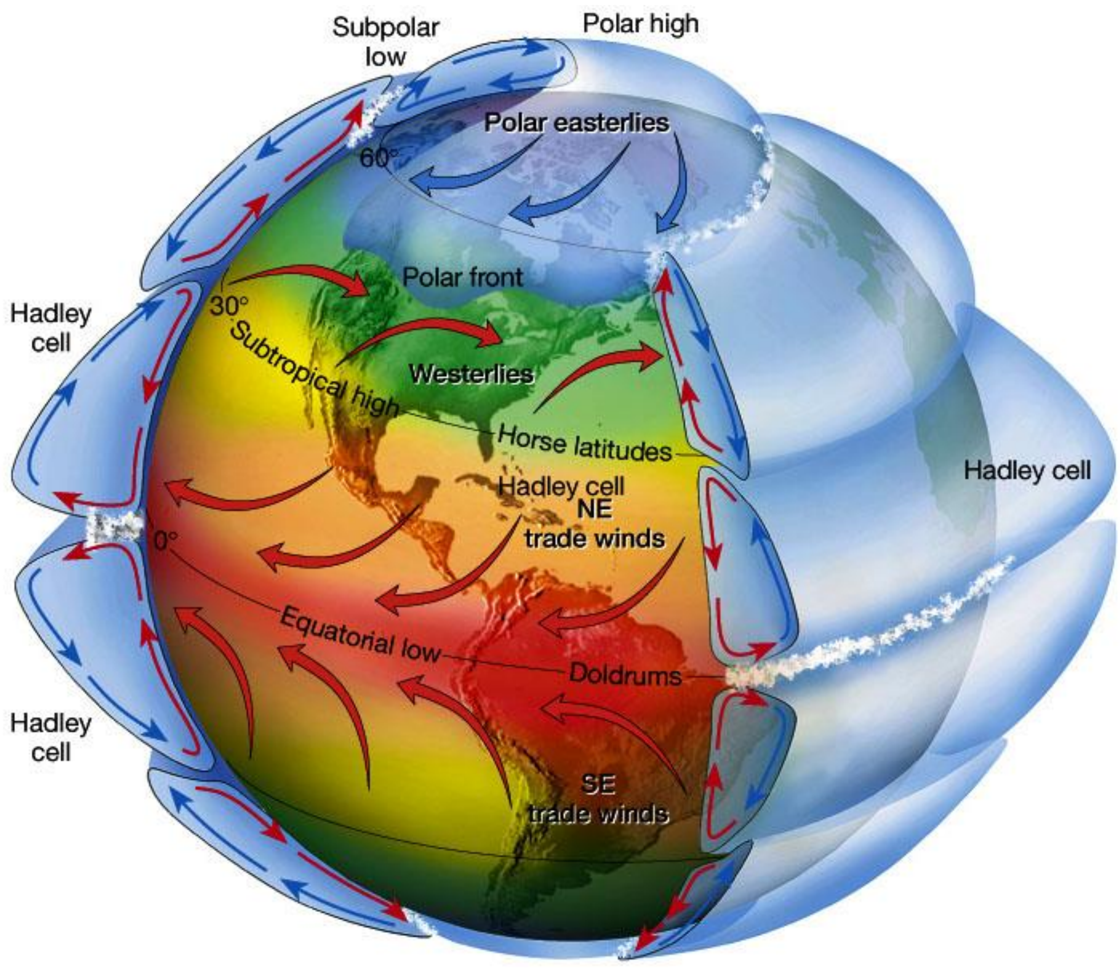
- Different observers may have different sets of coordinates (x,y,z,t). A set of coordinates specific to a particular observer is called a **frame of reference**.
- Not all frames of reference are equal. There is a special subset of all possible frames of reference called **inertial reference frames**. They are associated with observers that move freely, with no external force acting on them.

Inertial Forces

- In the non-inertial frame of reference there appear ***”fictitious” forces*** such as ***centrifugal*** and ***Coriolis*** forces. These forces are called **inertial forces**.

- These forces are fictitious in a sense that there is no physical interaction responsible for these forces. However, a person in a non-inertial frame of reference will feel them quite real!

Coriolis Force



Centrifugal Force

- The Second Law of Newton looks very different in inertial and non-inertial reference frames!
- In the ***inertial*** frame of reference:

$$F_{\mathrm{gr}} = m a_{\mathrm{cp}}$$

- In the non-inertial frame of reference:

$$F_{\mathrm{gr}} = F_{\mathrm{cf}}$$

Kepler's Laws Made Easy

- First Law:

$$m\frac{d^2\vec{r}}{dt^2} = -G\frac{mM}{r^2}\vec{e}_r$$

  - Solution of this equation is the ellipse. There is no deep physics there, just math.
- Second Law:

$$\frac{V^2}{R} = \frac{GM}{R^2}$$

  - When ***R*** is smaller, ***V*** is larger – planets move faster when they are closer to the Sun.

Kepler's Third Law

Period for a circular orbit: $P = {}^{2\pi R}\!/_{V}$

Plug this into the last equation from the previous slide, and we get:

$$P^2 = \frac{4\pi^2}{GM} R^3$$

If we measure **P** in years and **R** in AU, then

$$GM_{\odot} = 4\pi^2$$

What Is Cosmology?

- Cosmology is the science about the universe. In this context the word “universe” means the *physical universe*, the universe of material objects, of energy, of space and time.
- The main proposition of science is that the universe can be understood in terms of natural laws. The origin of these laws is not a subject of modern science, but may become a subject of science some day in the future.
- Scientists call “physical” anything that can be objectively observed or measured (at least in principle).

- Space and time are also physical. Cosmology thus studies space and time as well as material objects, energy, radiation, etc.
- What do you think about questions like:
  - *What happened before the universe existed?*
  - *What is outside of the universe?*
- Your book says these questions are meaningless. Do you agree?
- A related question is whether the universe was created, or existed “forever”.
  - *Can an “existing forever” universe be created?*

Beyond Modern Cosmology

- We also pose questions like:
  - *Why is the universe so big and old?*
  - *Why are the laws of nature such as they are?*
- Even if these questions are scientific, we have no good answers to them now.

Anthropic Principle

- One way to try to answer these questions is the **anthropic principle**. There are two forms of it:
- *Weak anthropic principle* states that the universe must be compatible with our existence. For example, the laws of nature should be such that the universe could become large and cool, and atomic nuclei and molecules could form, and nuclear reactions could proceed in the centers of stars etc.
- *Strong anthropic principle* states that the universe is such as it is because its purpose is to create life. In other words, our presence here and now somehow affected the initial conditions such that we could eventually arise.

Copernican Principle

- If we discard the strong anthropic principle, we must acknowledge that we do not occupy a special place in the universe. This is called the **Copernican principle**. It does not mean that the universe has no center or special places.

- Historically, beginning with Newton, scientists *assumed* that the universe was homogeneous and isotropic on large scales.

Homogeneity and Isotropy

- **Isotropic** means that the universe looks the same in all directions on the sky.

Homogeneity and Isotropy

- **Homogeneous** means that the universe looks the same everywhere on large scales.

Homogeneity and Isotropy

- These two assumptions go well beyond the Copernican principle.
  - Isotropic but not homogeneous means that there is a special place (center).
  - Homogeneous but not isotropic means that there is a special direction (axis).

Cosmological Principle

- Newton based his cosmology on the **cosmological principle**, that asserts that all points and directions in the universe are more or less equivalent on sufficiently large scales. That was a big change from the Ptolemaic/Aristotelian cosmology.
- Cosmological principle does not only tell that the universe looks the same everywhere and in all directions, but it also states that the laws of nature are the same everywhere in the universe.

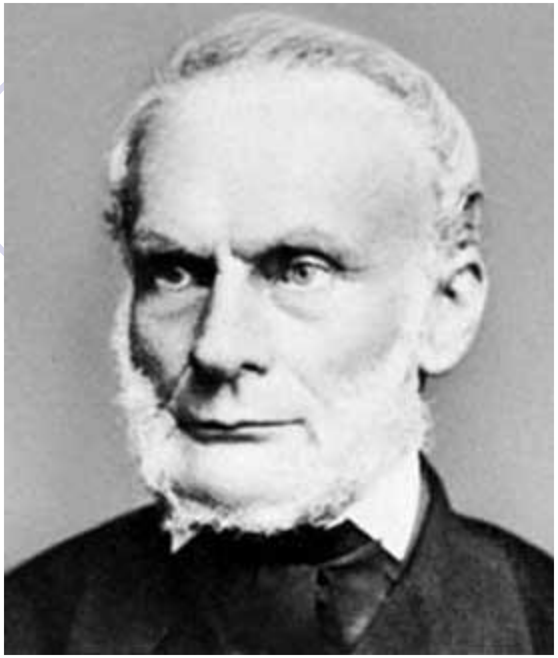
- Newton's universe was infinite and consisted of stars filling the space more or less uniformly.
- But he left Aristotelian time intact. In Newton's cosmology the time is infinite too, and the universe always was and always will be as it is now. This latter proposition is called the **perfect cosmological principle**.
- The perfect cosmological principle states that the universe looks the same at every place in space and at every moment in time (on large scales).

- Newtonian cosmology envisions the universe as a huge clock mechanism, which operates indefinitely. The role of Creator was in creating the laws and setting the machine in motion, after that it operated by itself. This type of theology is called *deism*. To a large extent this is still the theology of science.
- In Newton's cosmology space and time are absolute. They exist independently of the material world and are both infinite in every possible direction.

Problems with Newtonian Cosmology

- Gravitational interaction extends instantaneously to infinite distances
- Such a universe cannot exist - it is unstable!
- Problem with **entropy**

Layover: Entropy


Rudolf Clausius
(1822-1888)

- The concept of entropy has been understood since XVIII century, but the mathematical formulation and name was invented by Rudolf Clausius in 1865.
- Entropy is related to the concept of a “state” for some matter (gas, fluid, solid, anything). One state is a specific distribution of molecules in some volume, plus the values of their velocities.

Number of States

- The number of states for any measurable volume of matter is humongous (there are 10^{25} molecules in our classroom).
- Entropy is a measure of the number of states of matter under given conditions (density, temperature, pressure, etc). Since that number is so huge, it is actually a logarithm of that number:

$$S = k_B \log(N)$$

Ludwig Boltzmann (1844-1906)

- Here $k_B = 1.3806488(13) \times 10^{-23} \mathrm{J/sec}$ is the *Boltzmann constant*.
- Several other important things in physics are named after him.
- Was so famous at the end of his life, the Austrian Emperor send him a personal invitation.
- His life story emphasizes a danger of using pink slips.

Second Law of Thermodynamics

- The second law of thermodynamics states that *the entropy of a closed system is never decreasing*.
- It is extremely unlikely for air molecules in the classroom to randomly assemble in its front half.
- It is equally unlikely that all the molecules in the room will be flying towards the lake (rather than flying randomly in all possible directions).
- Since the entropy increases in some places, the universe cannot be infinitely old.

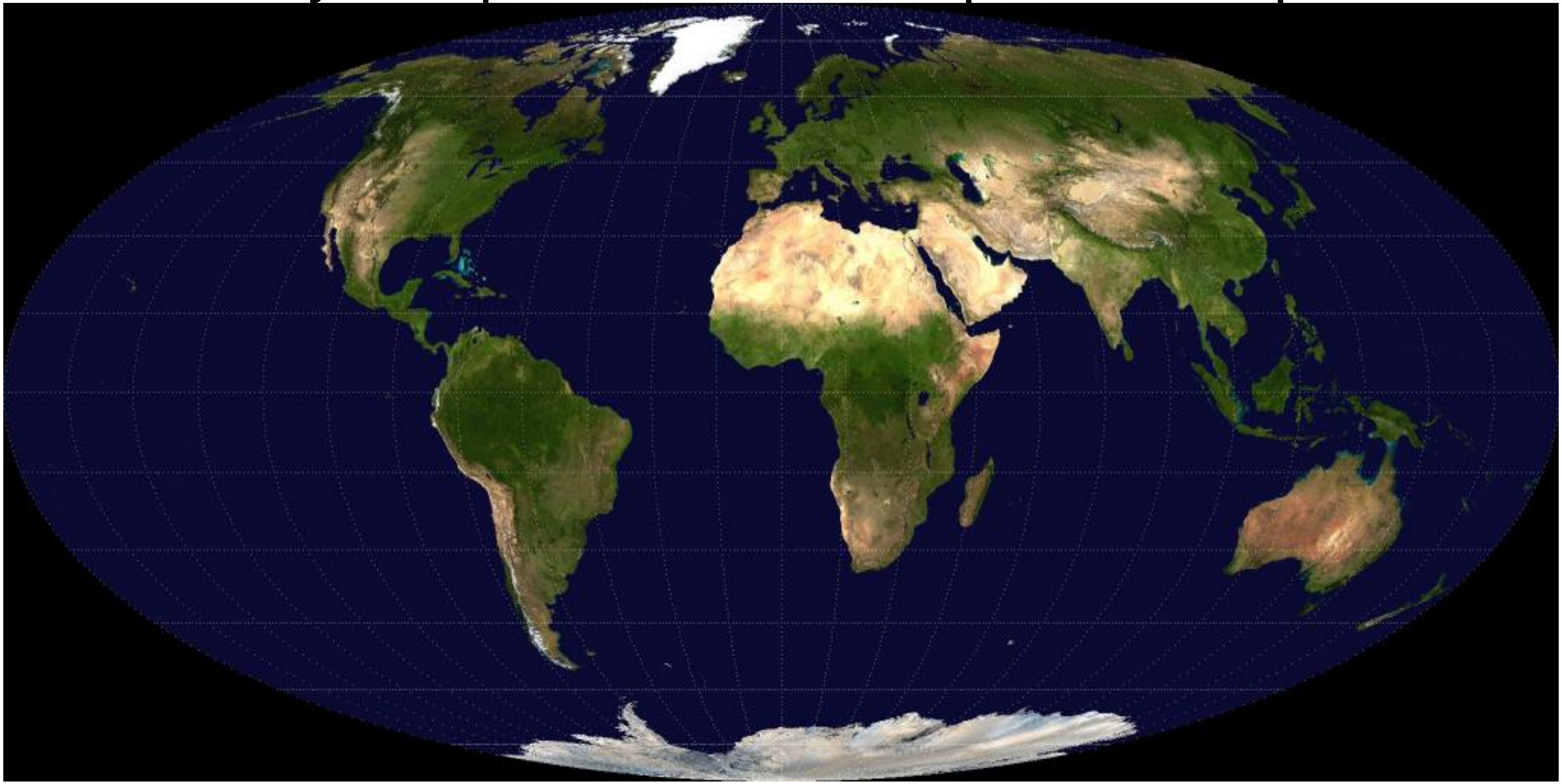
Testing Cosmological Principles

- Cosmological principles were formulated as pure guesses, or, at best, plausible assumptions. However, science is developing, and today we can gather observational data about what yesterday was only a guess. In particular, we can *test* cosmological principles observationally.
- *Observational data available now strongly contradict the perfect cosmological principle: for example, galaxies are observed to evolve strongly; some 10 billion years ago there existed no galaxies similar to those around us.*

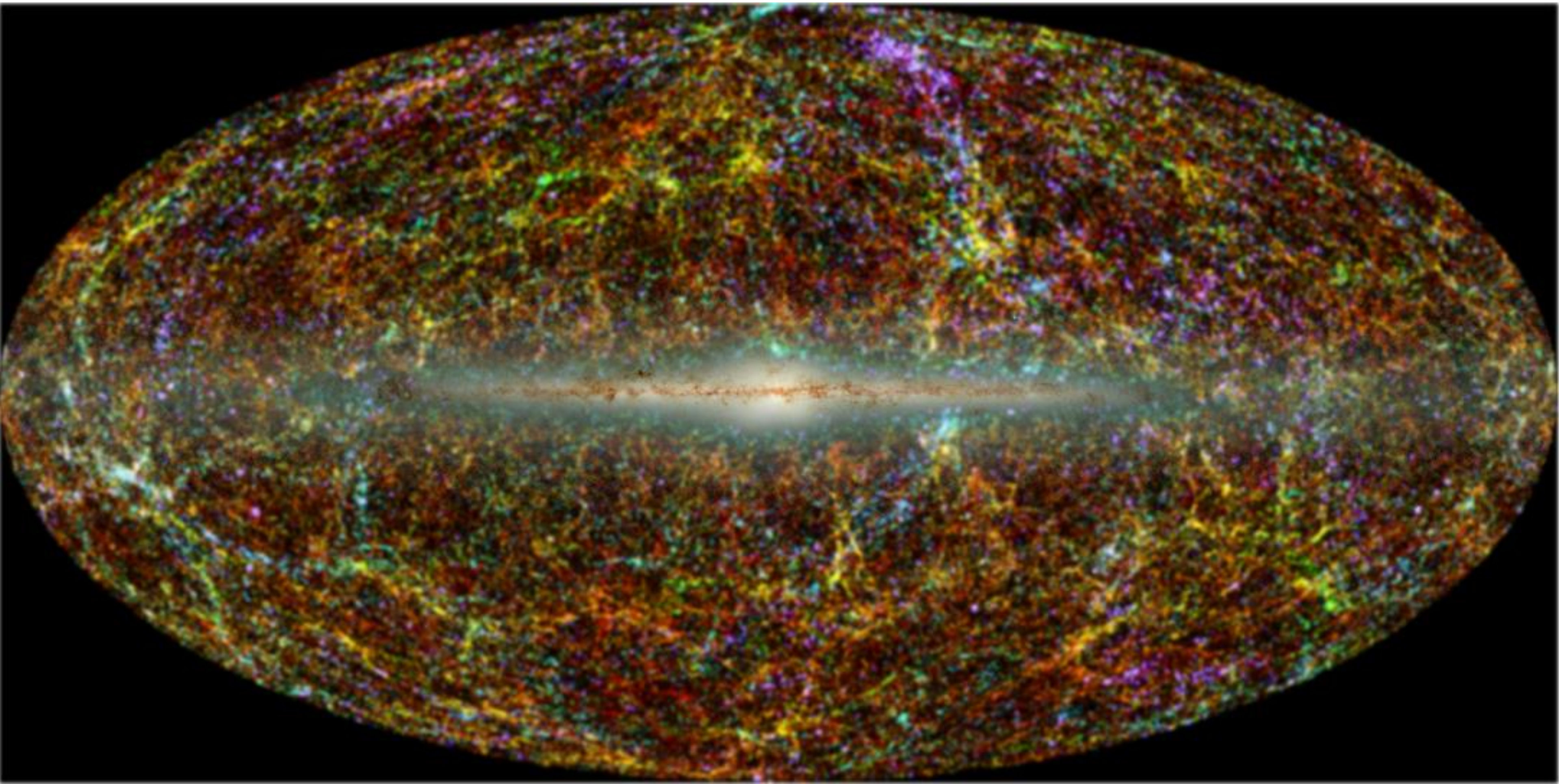
- *Observational data support the cosmological principle per se. This support is based on two pieces of evidence:*
  - Universe is highly isotropic around us. This is demonstrated by distribution of galaxies, Cosmic Microwave background (abbreviated to CMB), gamma-ray bursters etc.
  - Universe is isotropic to about 10% level around another distant point in space. This is enough to prove that the universe is homogeneous on large scales (to about 10%).

Mollweide Projection

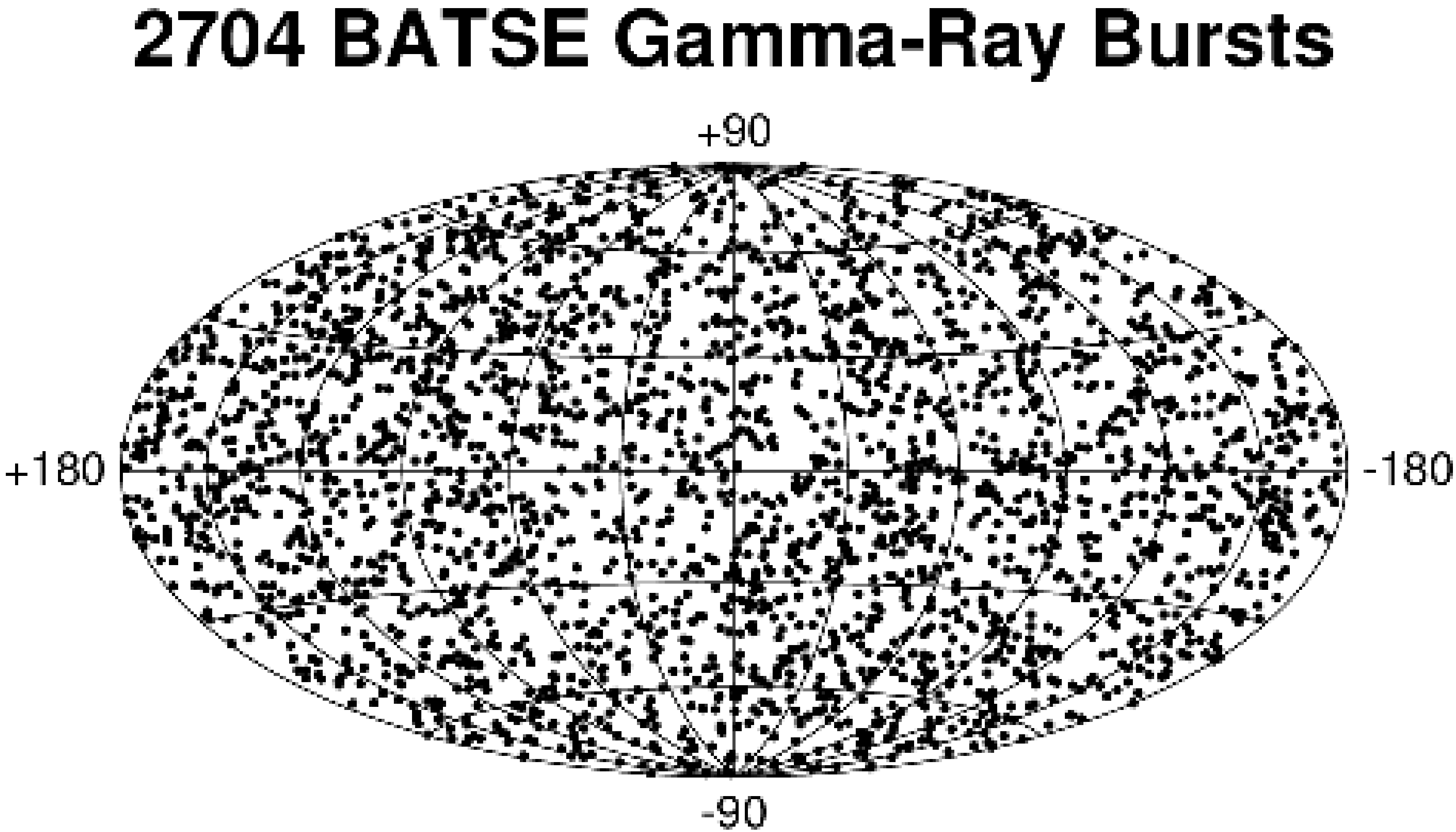
- A way to represent a whole sphere on a plane.



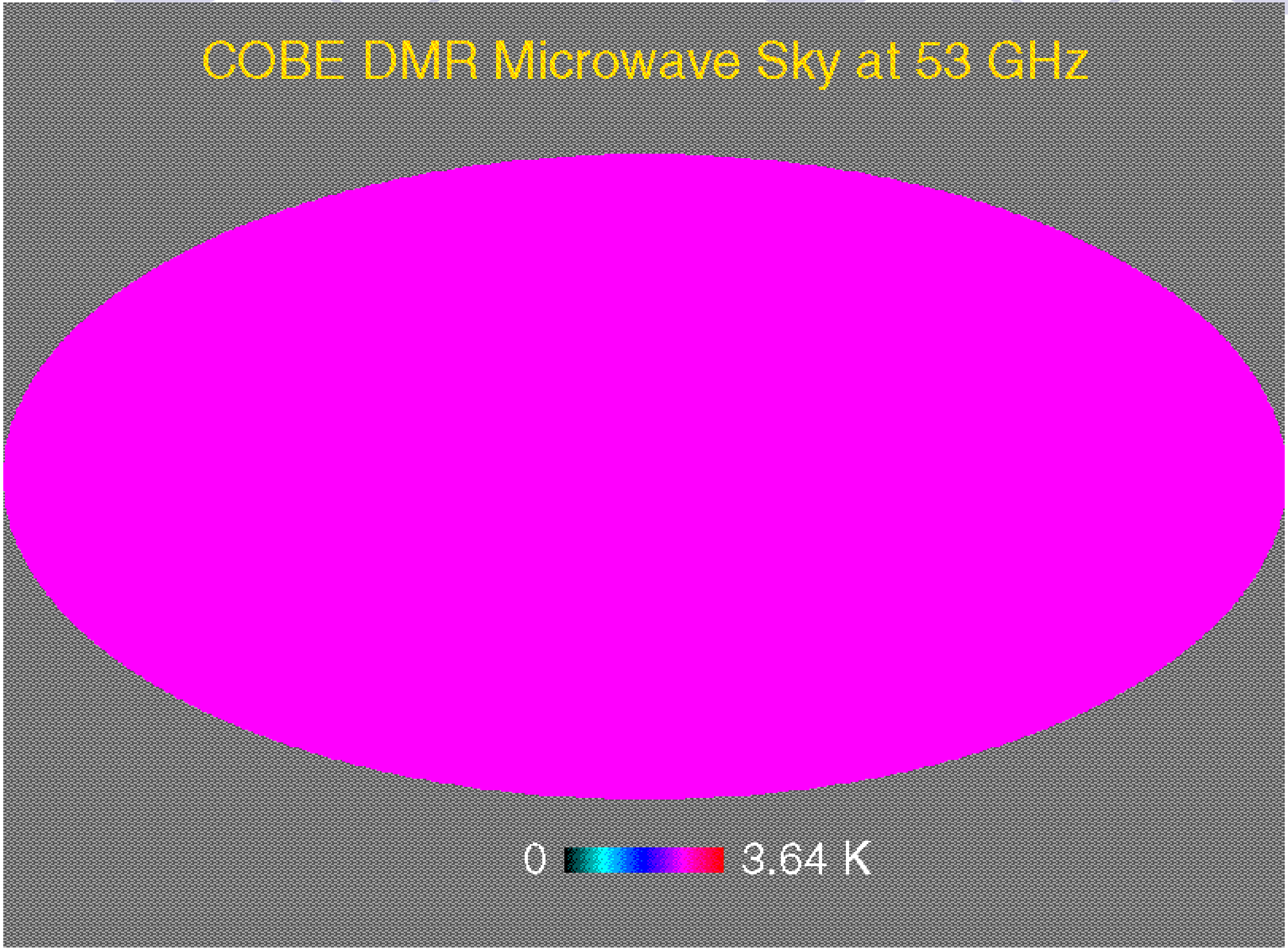
Galaxies on the Sky



Gamma-ray Bursts



Cosmic Microwave Background



Homogeneity of the Universe Can Be Tested!

- Observed isotropy + Copernican Principle = Homogeneity

- Observed Isotropy (place #1) + Observed Isotropy (place #2) = Homogeneity