The Frontiers of Fundamental Physics

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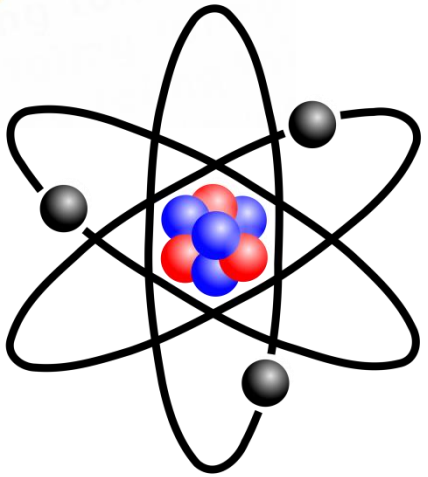
Physics

Physics is about explaining phenomena at all length scales



- Increasingly shorter distances: structure of matter, molecules, atoms, elementary particles…

- Increasingly larger distances: earth, solar system, galaxy, the whole Universe

Unusual and almost unprecedented situation in physics

- Two “Standard Models” describing the shortest and the longest explored distances

- They work extremely well in the range of distances they describe (almost no contradiction).

But

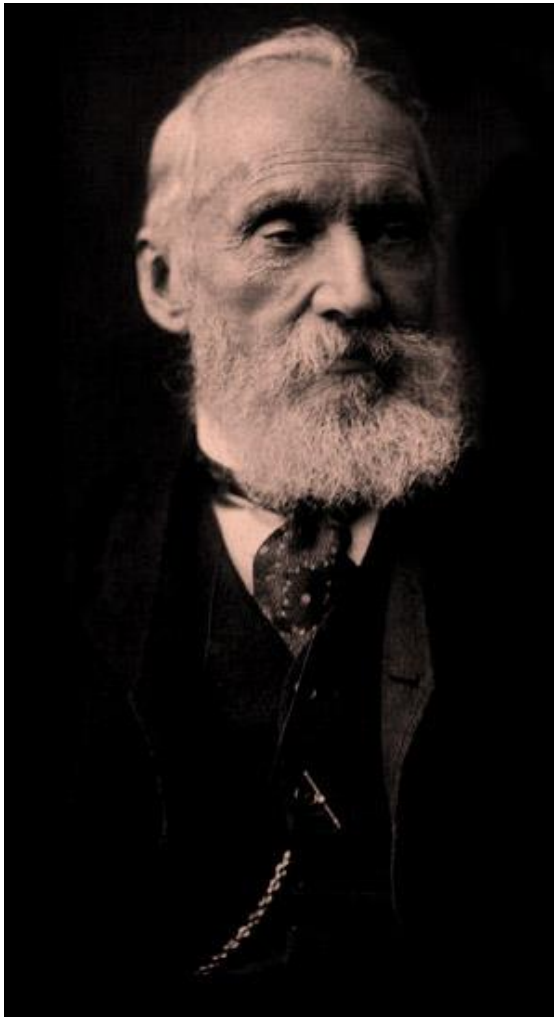
- Excellent arguments that there must be new physics beyond these models

- New experimental input soon.

A similar situation

In 1900, the British physicist Lord Kelvin gave a lecture "Nineteenth-Century Clouds over the Dynamical Theory of Heat and Light."

- Michelson–Morley experiment (eventually led to relativity)
- Black body radiation (one of the roots of quantum theory)

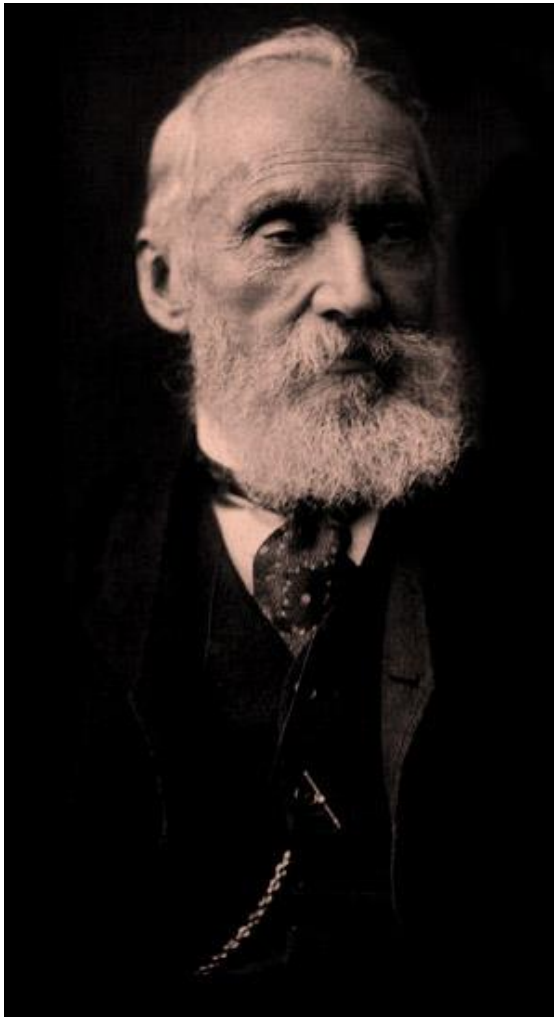


A similar situation

Some people interpreted this to mean that physics was almost over.

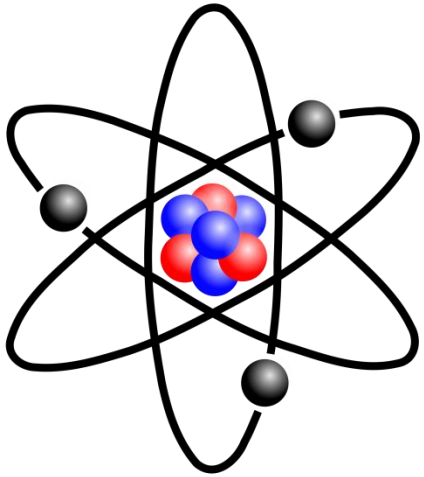
In fact, Kelvin clearly realized the significance of these “clouds.”

We will review the current situation and will discuss today’s clouds.



Two Standard Models

During the past decades two standard models were created:



- In particle physics: a nearly perfect model describing all physics at distances larger than roughly 10^{-19} meters (one tenth of a billionth of a billionth of a meter).

- In cosmology: a nearly perfect model describing all physics at large distances, up to roughly 10^{26} meters – the entire visible Universe. It also describes the early Universe

The Standard Model of particle physics

Describes the elementary particles and the forces acting on them.

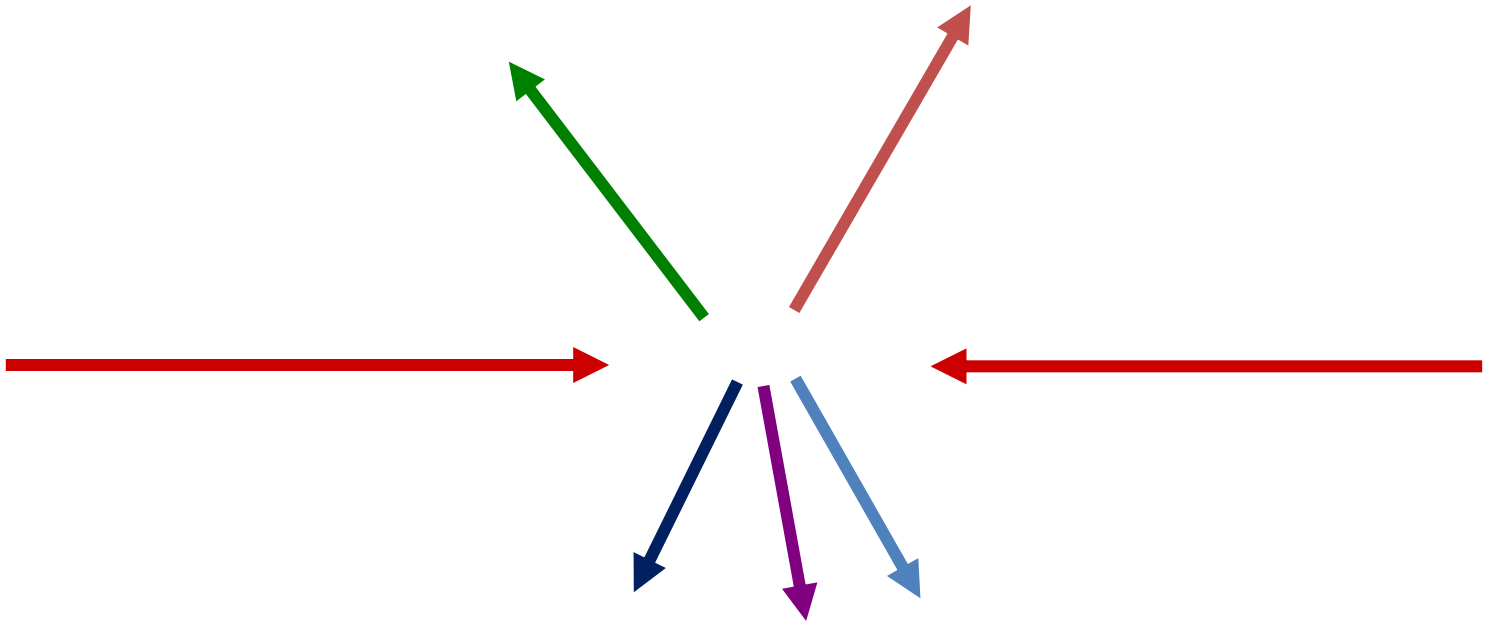
We understand the physical laws and describe them using equations. But in most circumstances we cannot solve these equations.

At least in principle all nuclear physics, atomic physics, chemistry, even biology, etc. follow from this model.

Sources of data

Mostly from accelerators

Collide protons or electrons and examine the debris.



Sources of data

Protons move in a tunnel. It is about 100m below ground and its circumference is 27Km (17miles).

The Standard Model of particle physics

- Principles: quantum mechanics, special relativity
- Matter particles: electrons, quarks…
- Forces: electromagnetic force, strong nuclear force, weak nuclear force
- Parameters: masses of particles, strength of forces

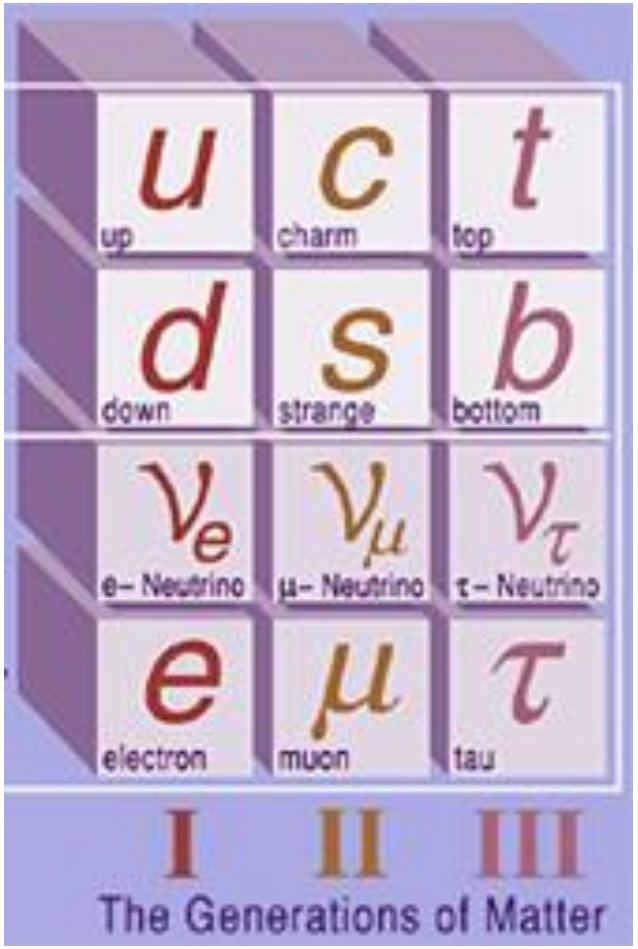
Matter particles

The protons and neutrons are made of quarks.

There are several different species of quarks.

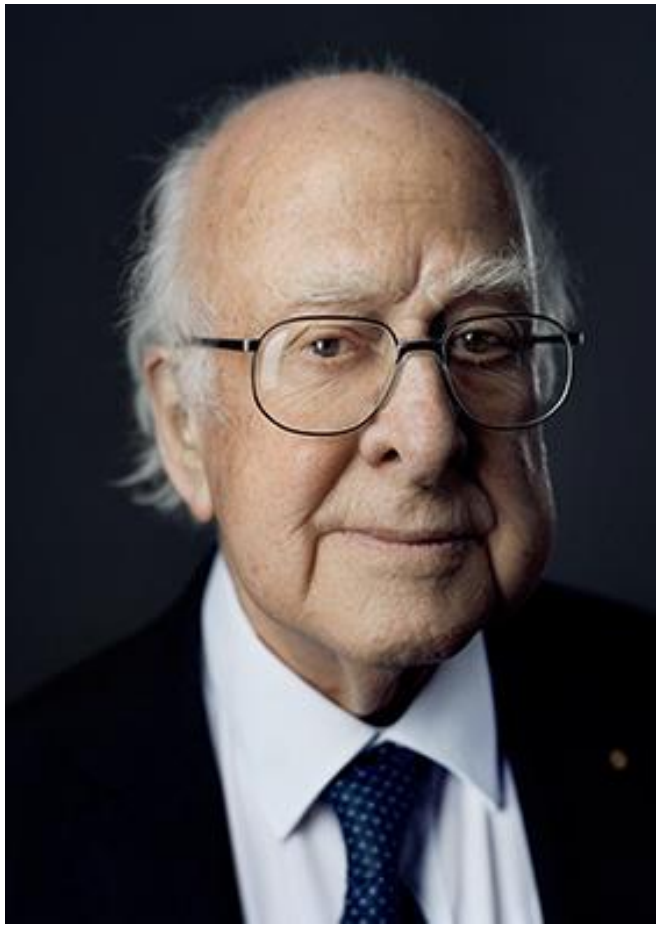
The electron is a member of a larger family of particles.

Need to explain the pattern



The "periodic table" of matter particles

The Higgs Boson



Peter Higgs

Satyendra Nath Bose

The Higgs Boson

- This particle gives mass to matter particles and to the particles of the weak force.
- In 2012 the Higgs Boson was discovered at the LHC.
- This was the last discovered element of the Standard Model.

Englert and Higgs

The Standard Model is extremely successful

- Small number of parameters (like particle masses) explain many experimental results.
- It is not contradicted by any known experiment!
- Unprecedented success
  - some quantities can be computed and measured with accuracy of 10 significant digits!

Open problems

- The standard model exhibits a pattern. It should be explained.
  - Origin of the particles, the “periodic table”, etc.
  - Origin of the forces, their number, their strengths, etc.
  - Origin of the parameters like masses of particles

- The model is incomplete (more technical)
  - The Higgs Boson mass is unstable
  - Neutrino masses
  - Quantum gravity (more below)

More data soon

The LHC has just been upgraded

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More data soon

- Roughly twice the energy and larger intensity
- More detailed information with higher resolution
- Can expect new exciting discoveries

Standard model of cosmology

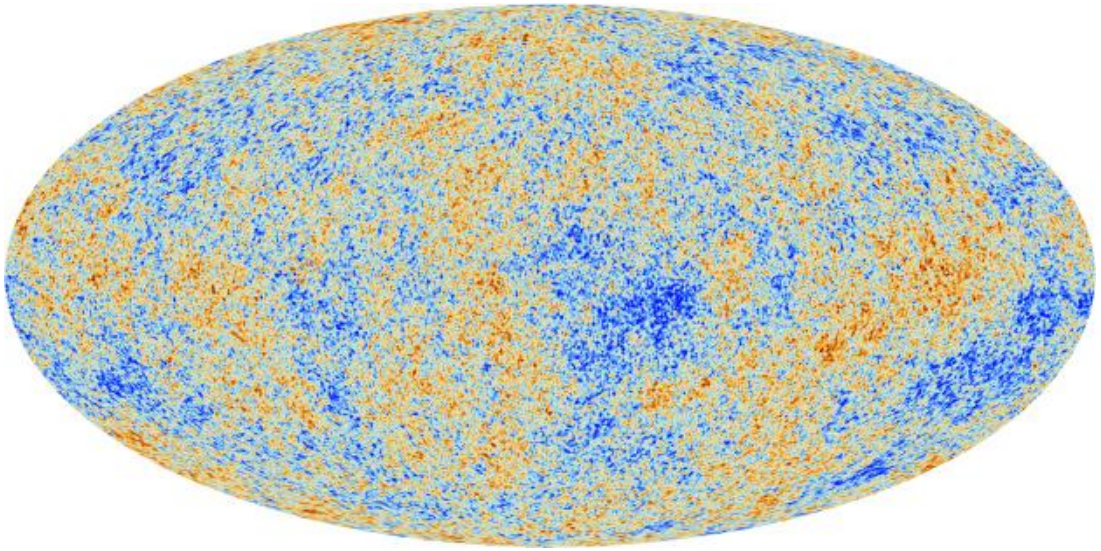
It describes the whole Universe and its origin.

- Big bang
- The evolution of the Universe starting when it was only a fraction of a second old
- Origin of the matter in the Universe
- Galaxies, stars, etc.

Sources of data

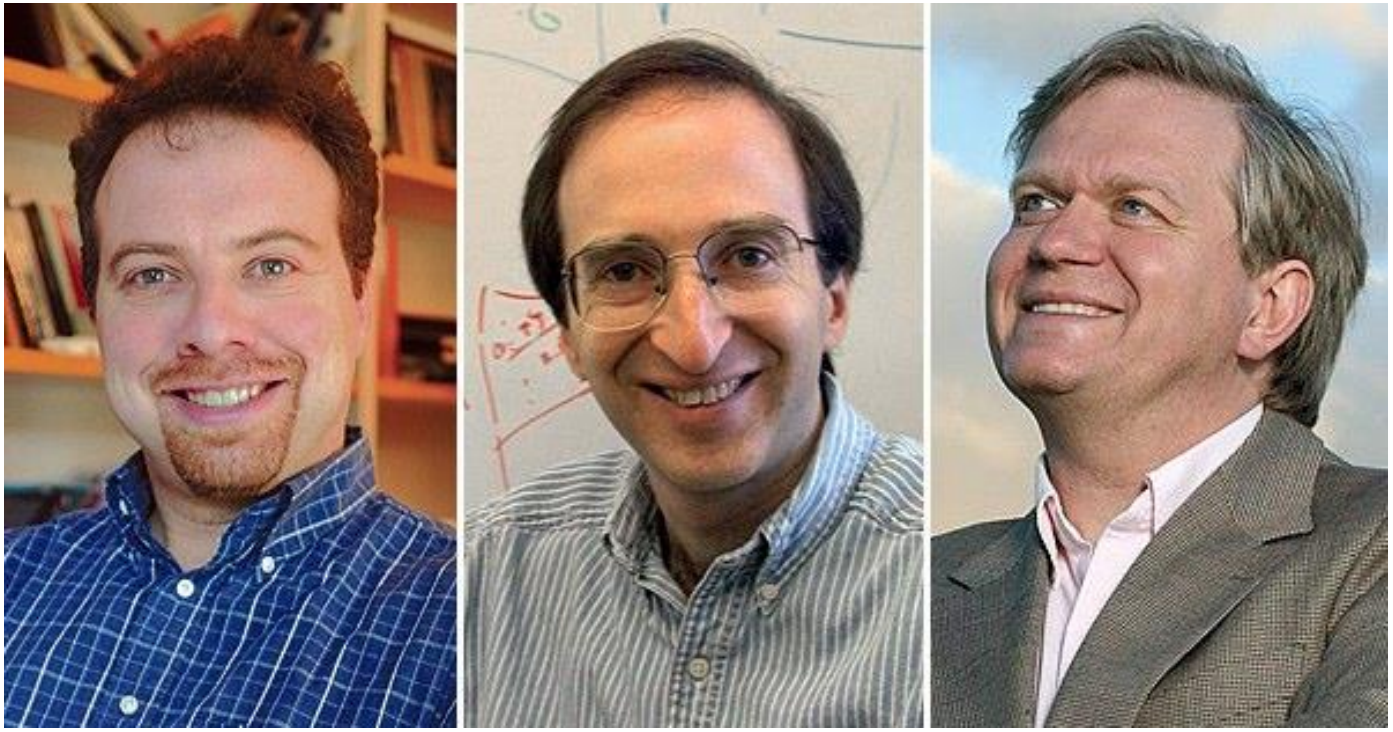
Two main sources

- Measure the microwave radiation emitted in the early universe – afterglow of the big bang.
  - Cosmic Background Explorer (COBE), ... , Planck space telescope



Sources of data

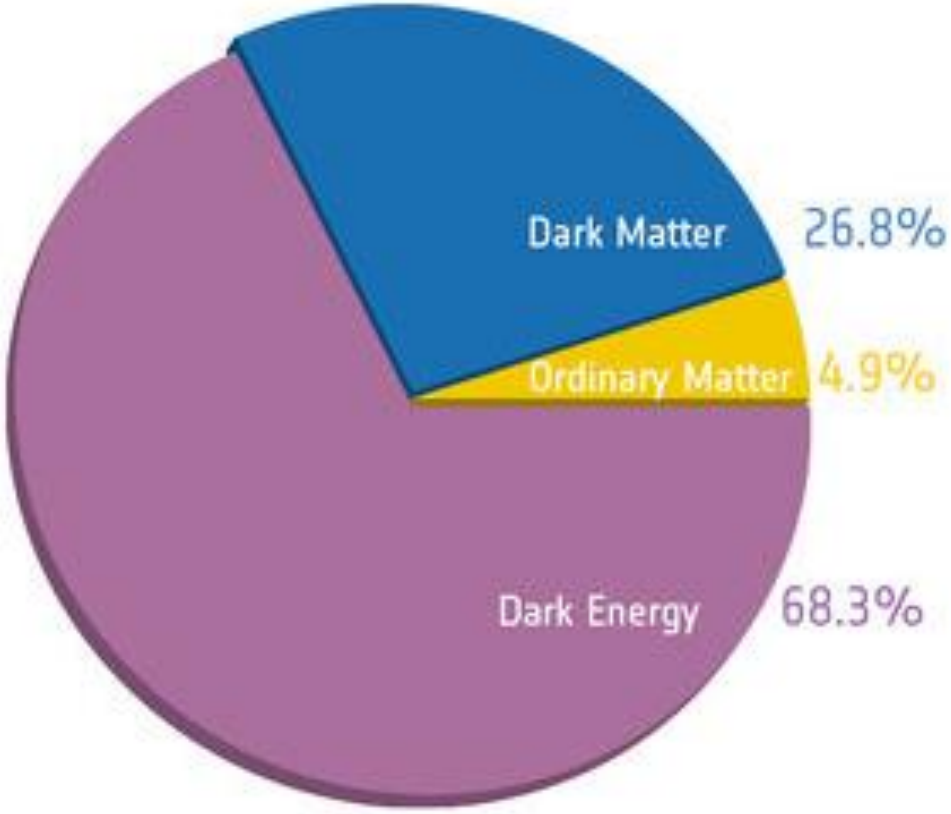
- Survey of supernovae



Riess Perlmutter Schmidt

Standard model of cosmology

- The principles: General relativity (gravity), big bang
- Composition of the Universe
  - Ordinary matter
  - Dark matter
  - Dark energy

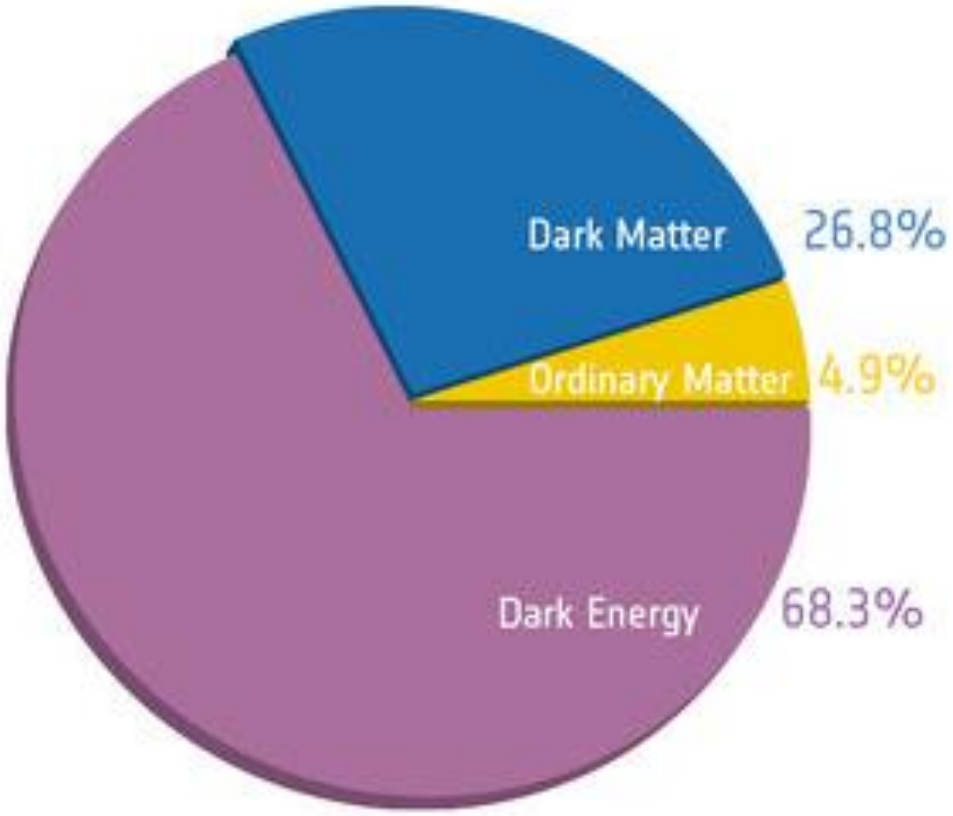


Standard model of cosmology

These principles together with a small number of accurately measured parameters beautifully explains all measurements.

No contradiction.

A beautiful and coherent picture of the Universe.



Open problems

We need to understand:

- What is the dark matter?
- What is the dark energy?
- Origin of parameters (explain the pattern)
- Origin of the Universe and its fate in the far future

Cosmic inflation:

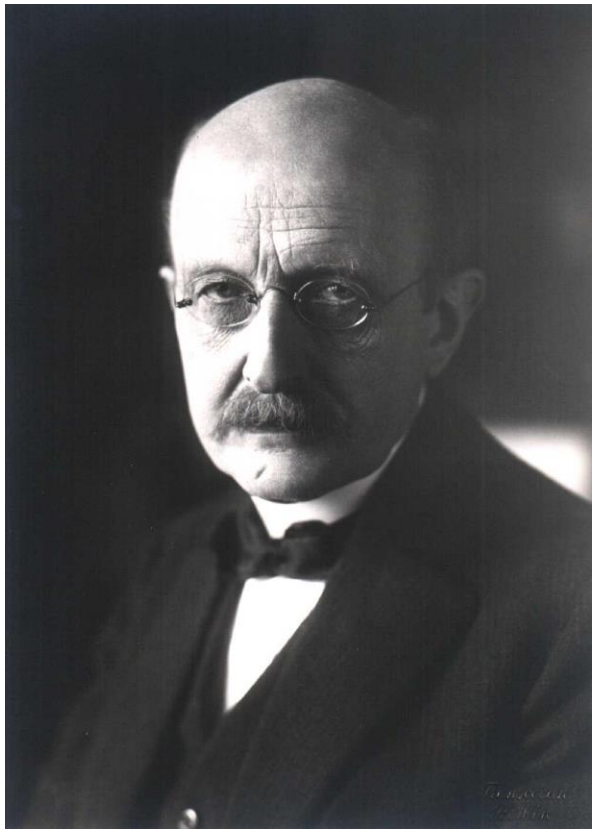
- Early period of extremely rapid expansion
- It explains some of the pattern
- Supported by a lot of evidence
- But there are still many puzzles.

More data soon

The frontier: measure the polarization of the primordial radiation

The biggest conceptual question

- Merge the two Standard Models
- Combine quantum mechanics and general relativity (gravity)
- Quantum gravity is most relevant at the Planck scale – the basic scale of Nature
  - 10^{-35} meters
  - 10^{-43} seconds
- Should address the structure of the Universe when it was 10^{-43} seconds old – origin of the Universe



Best candidate: string theory

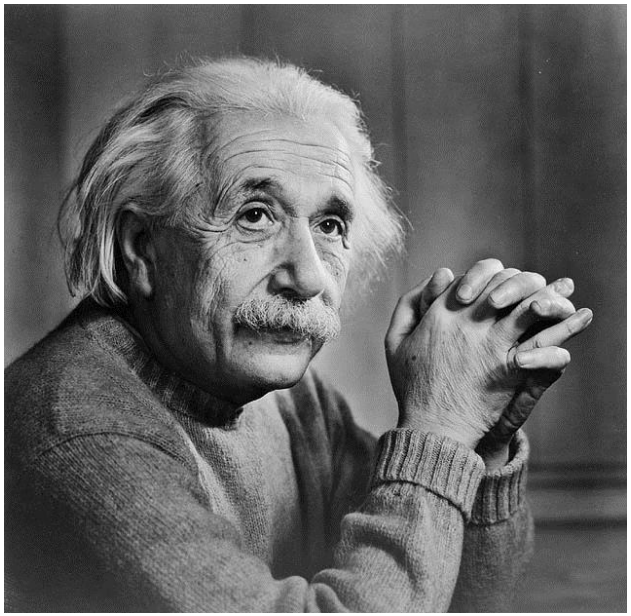
Enormous and exciting progress with amazing new insights during the past decades

Deep physics with surprising impact on mathematics and other branches of physics.

Challenges:

- We do not understand the principles.
- We need experimental confirmation.
- It might take a long time to reach any of these goals.

Einstein's dream

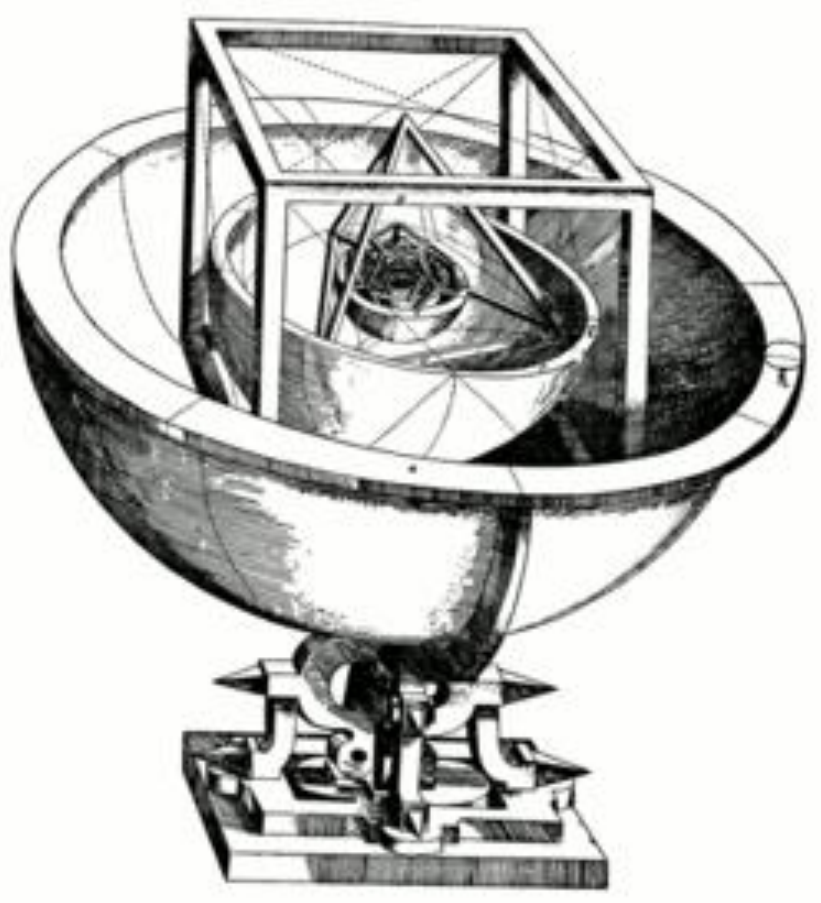


"…there are no arbitrary constants ... nature is so constituted that it is possible logically to lay down such strongly determined laws that within these laws only rationally determined constants occur (not constants, therefore, whose numerical value could be changed without destroying the theory)."

A cautionary historical example

Kepler had a beautiful mathematical description of the sizes of the orbits in terms of the 5 Platonic solids.

This turned out to be the wrong question.



A possible paradigm change
The Multiverse

- The Universe is much larger than we think – many universes
- Different laws of physics in the other universes
  - Different mass for the electron, strength for the electric forces, etc.
  - Different elementary particles
  - Different number of space dimensions
- Some of the parameters we want to explain are not fundamental – they are specific to our region

Summary

- We have two extremely successful Standard Models
  - Particle physics – short distances
  - Cosmology – the whole Universe
- It is clear that there must be new physics beyond these models.
- One challenge is to unify them – quantum gravity.
- Perhaps a simpler problem: explain the observed patterns and the parameters of these models.
- Fortunately, new input into these questions will come very soon.

The future is guaranteed to be exciting.

So stay tuned.

Thank you for your attention!