What’s next?

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Disclaimer

We do not know what will be discovered.

- This is the reason we perform experiments.
- This is the reason scientific research is exciting.

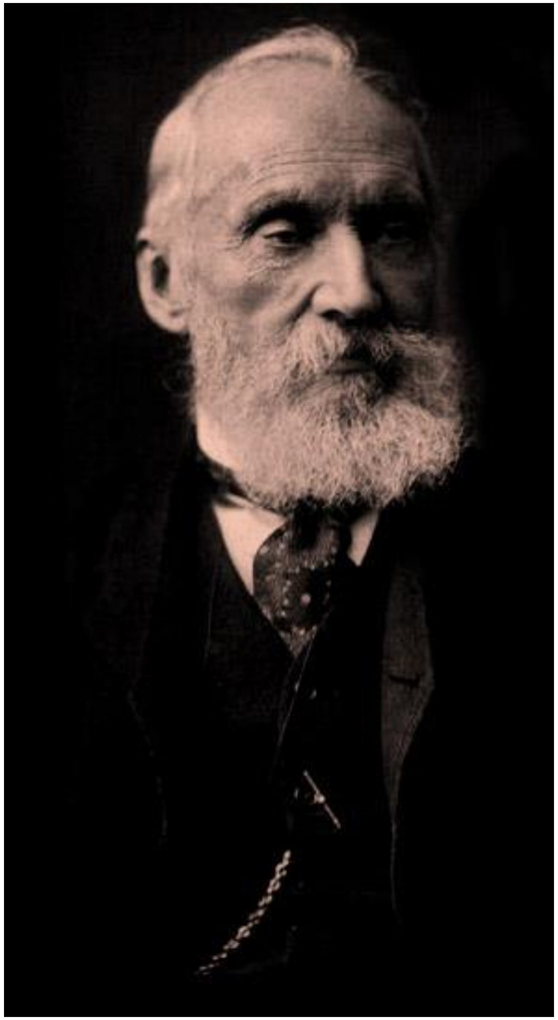
Today we will review the past and the present and suggest some possibilities for the future.

- An 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 (no contradiction).
- Excellent arguments that there must be new physics beyond these models

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)

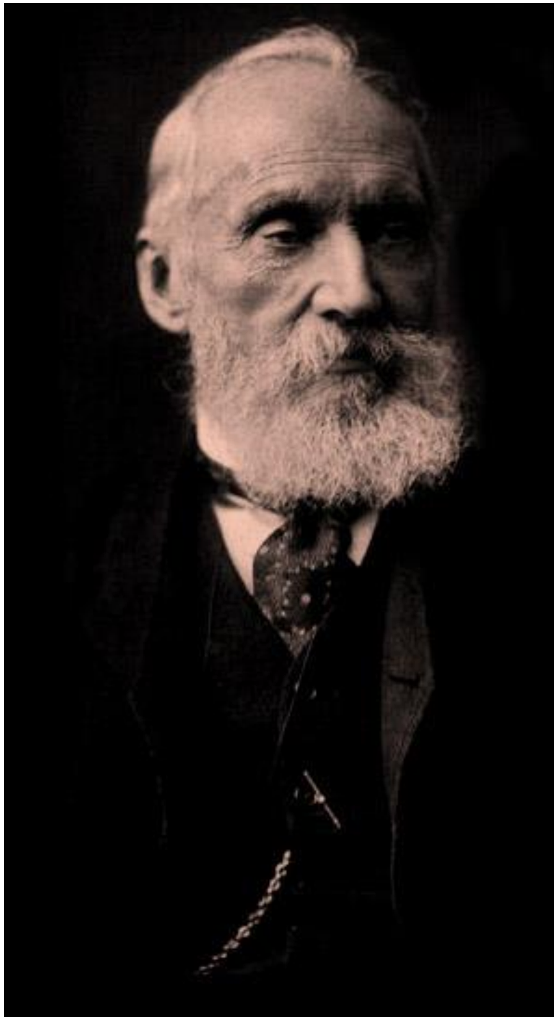


A similar situation

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

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

Here we will discuss today's clouds.

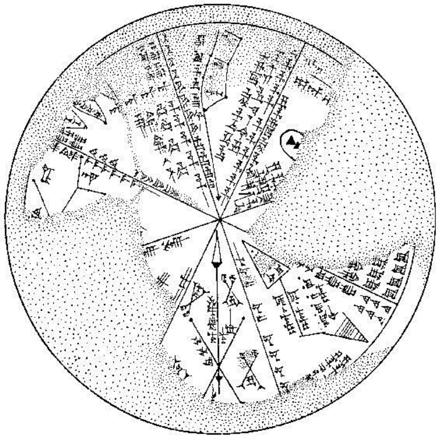


Often research progresses in steps

- Collect data
- Find a pattern – explain a lot of data using fewer numbers (parameters).
- Understand the underlying reason – the origin of the pattern.
- Explore the remaining parameters.
- Collect more data

Useful historical examples: 1. Motion of planets

- Collect data



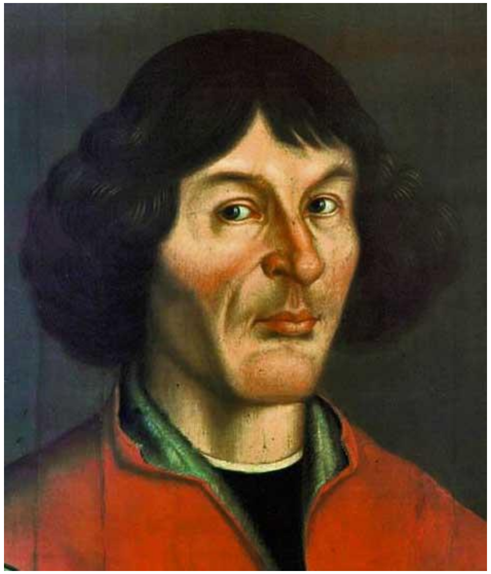
Assyrian star map from Nineve

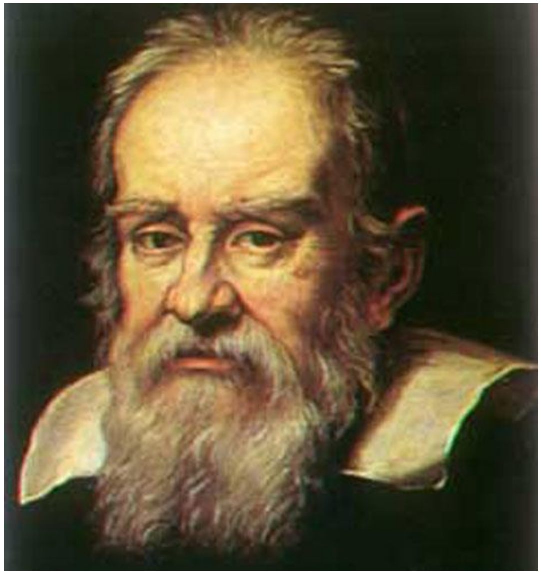
Ptolemaeus

Hipparchus

Motion of Planets

- Find a pattern: heliocentric model
  - Sun in the center, the orbits are ellipses
  - The parameters are the radii


Copernicus

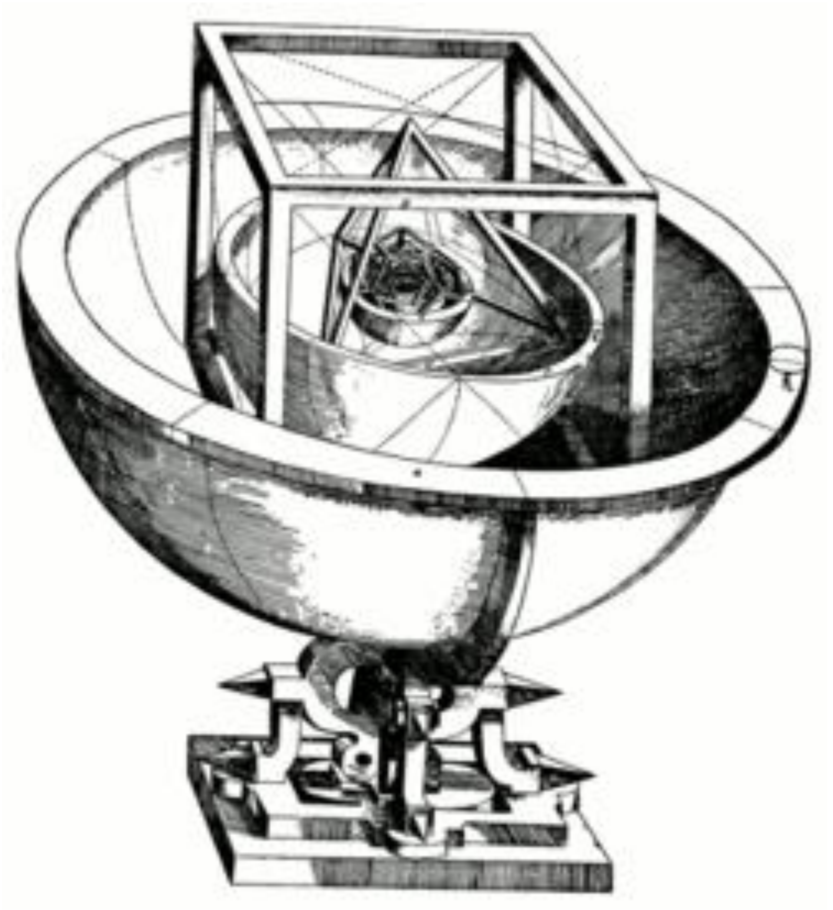

Galileo


Kepler

Motion of planets
Looking for a pattern in the parameters

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.



Motion of planets

- Underlying principle: Classical mechanics (Newton…)

Motion of planets
Are the remaining parameters stable?

- Newton was concerned that the solar system was unstable.

- Historian Michael Hoskin about Newton's view: "God demonstrated his continuing concern for
his clockwork universe by entering into what we might describe as a permanent servicing contract" for the solar system.

Useful historical examples: 2. Chemistry

- Collect data (many people including the alchemists)

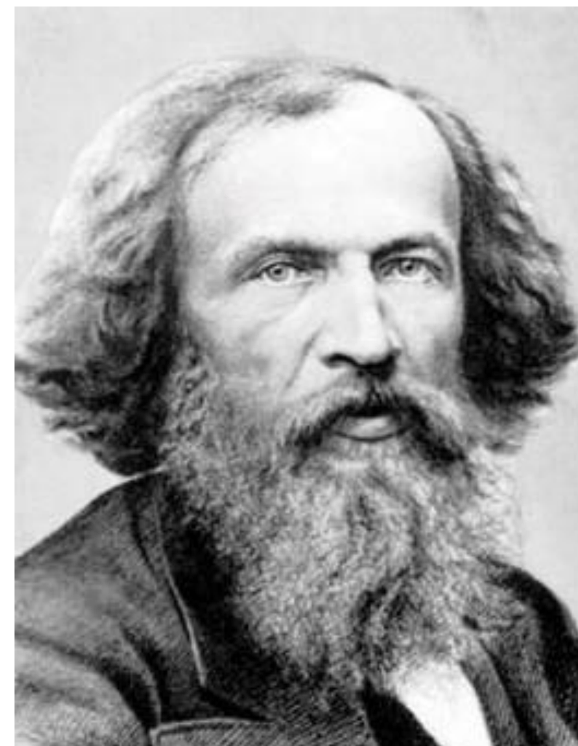
Chemistry

- The pattern – the periodic table (Mendeleev)

Periodic Table of the Elements

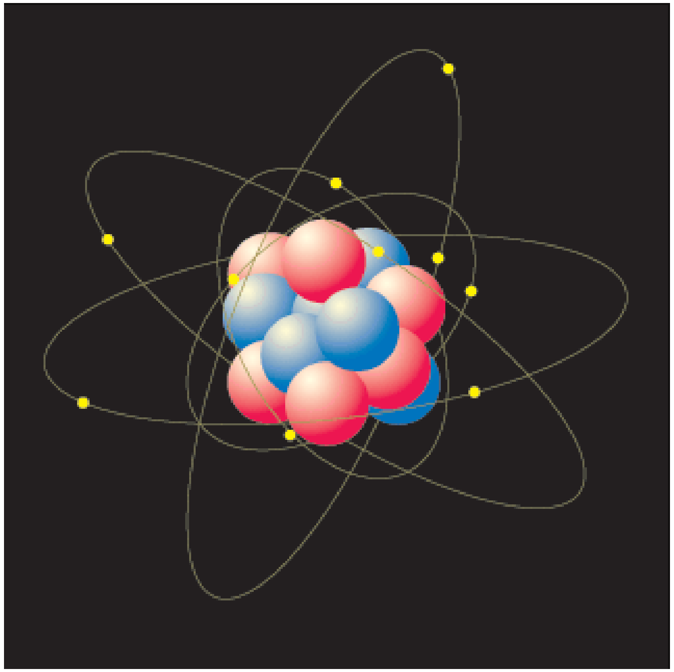
I	II											III	IV	V	VI	VII	VIII
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H 1.008																	2 He 4.003
3 Li 6.941	4 Be 9.012											5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.180
11 Na 22.990	12 Mg 24.305											13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.066	17 Cl 35.453	18 Ar 39.948
19 K 39.098	20 Ca 40.078	21 Sc 44.956	22 Ti 47.88	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.847	27 Co 58.933	28 Ni 58.69	29 Cu 63.546	30 Zn 65.39	31 Ga 69.723	32 Ge 72.61	33 As 74.922	34 Se 78.96	35 Br 79.904	36 Kr 83.80
37 Rb 85.468	38 Sr 87.62	39 Y 88.906	40 Zr 91.224	41 Nb 92.906	42 Mo 95.94	43 Tc (98)	44 Ru 101.07	45 Rh 102.906	46 Pd 106.42	47 Ag 107.868	48 Cd 112.411	49 In 114.82	50 Sn 118.710	51 Sb 121.757	52 Te 127.60	53 I 126.905	54 Xe 131.29
55 Cs 132.905	56 Ba 137.327	71 Lu 174.967	72 Hf 178.49	73 Ta 180.948	74 W 183.85	75 Re 186.207	76 Os 190.2	77 Ir 192.22	78 Pt 195.08	79 Au 196.967	80 Hg 200.59	81 Tl 204.383	82 Pb 207.2	83 Bi 208.980	84 Po (209)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra 226.025	103 Lr (260)	104 Rf (261)	105 Db (262)	106 Sg (263)	107 Bh (262)	108 Hs (265)	109 Mt (268)	110 (269)	111 (272)							

57 La 138.906	58 Ce 140.115	59 Pr 140.908	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.965	64 Gd 157.25	65 Tb 158.925	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.934	70 Yb 173.04
89 Ac 227.028	90 Th 232.038	91 Pa 231.036	92 U 238.029	93 Np 237.048	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)

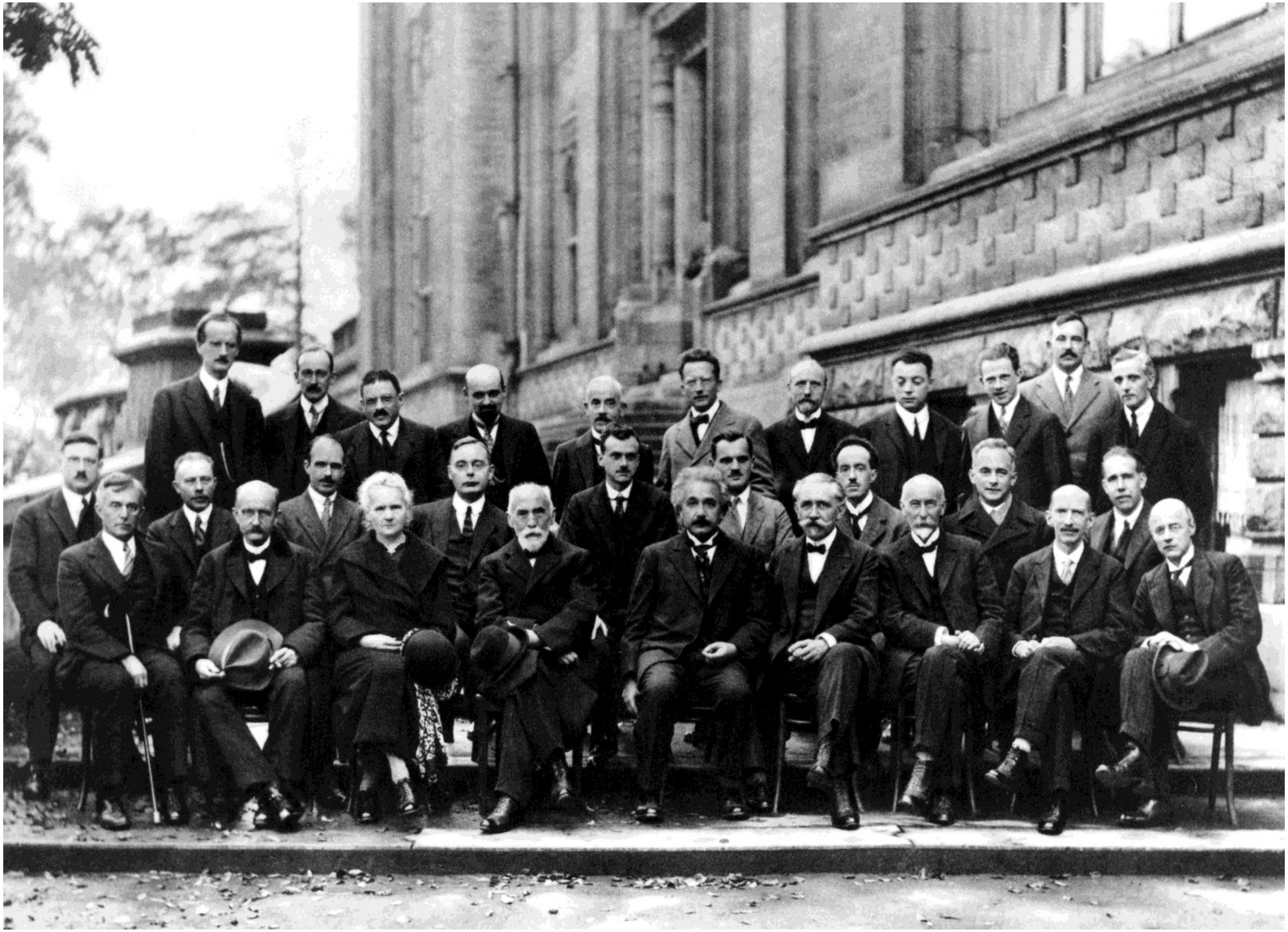


Chemistry

Underlying reason – structure of atoms, quantum mechanics



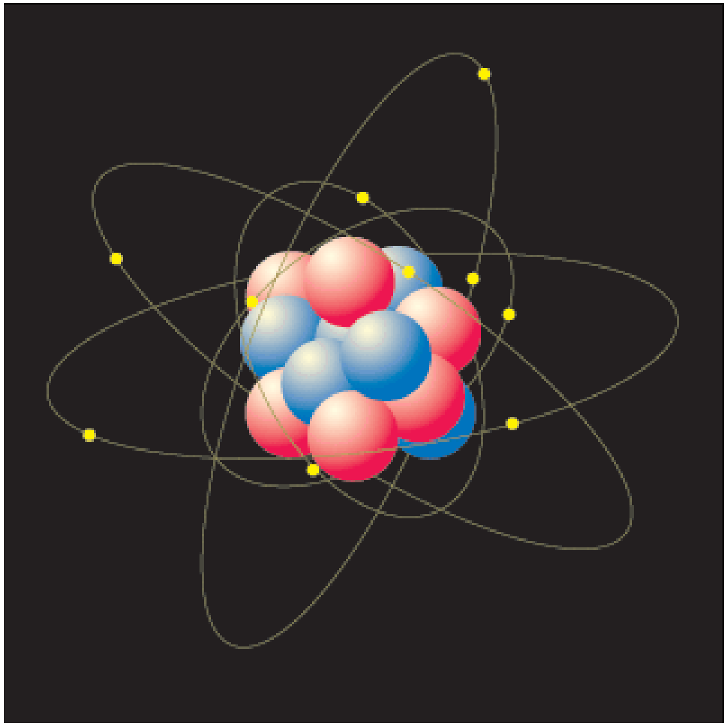
The first Solvay Conference (1911)



Solvay Conference (1927)

Chemistry

- Remaining parameters to explain: mass of the electron, masses of nuclei, …



Two Standard Models

During the past decades two standard models were found:

- In particle physics: a nearly perfect model describing all physics at distances larger than roughly 10^{-19} (one tenth of a billionth of a billionth) meters .
- In cosmology: a nearly perfect model describing all physics at large distances, up to roughly 10^{26} meters – the entire visible Universe.

The Standard Model of particle physics

- Principles: quantum mechanics, special relativity. Combined into quantum field theory
- Matter particles: electrons, quarks…
- Forces: electromagnetic force, strong nuclear force, weak nuclear force
- The parameters: masses of particles, strength of forces

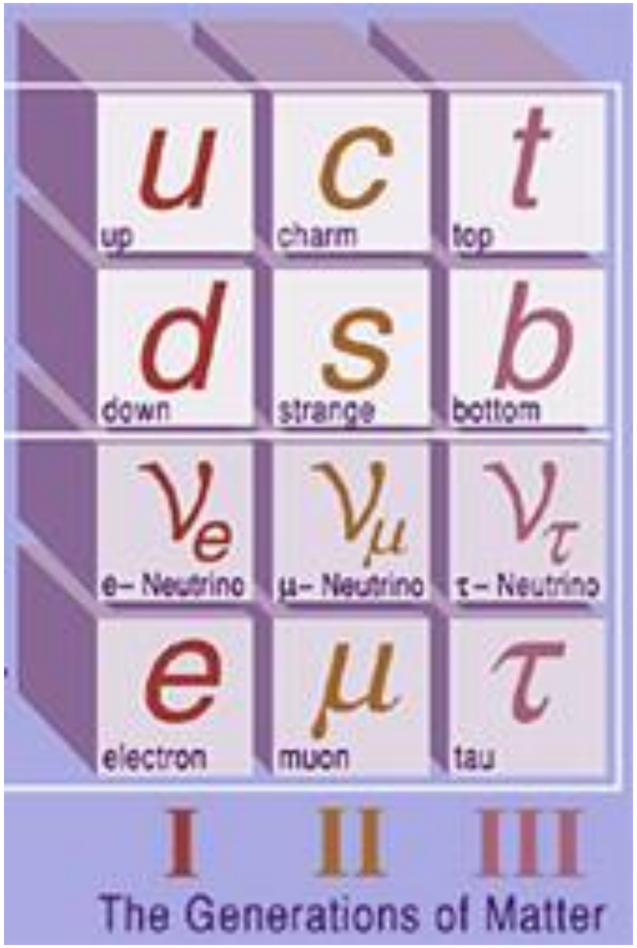
Matter particles

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.

New pattern to explain



The "periodic table" of matter particles

The Higgs particle

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

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

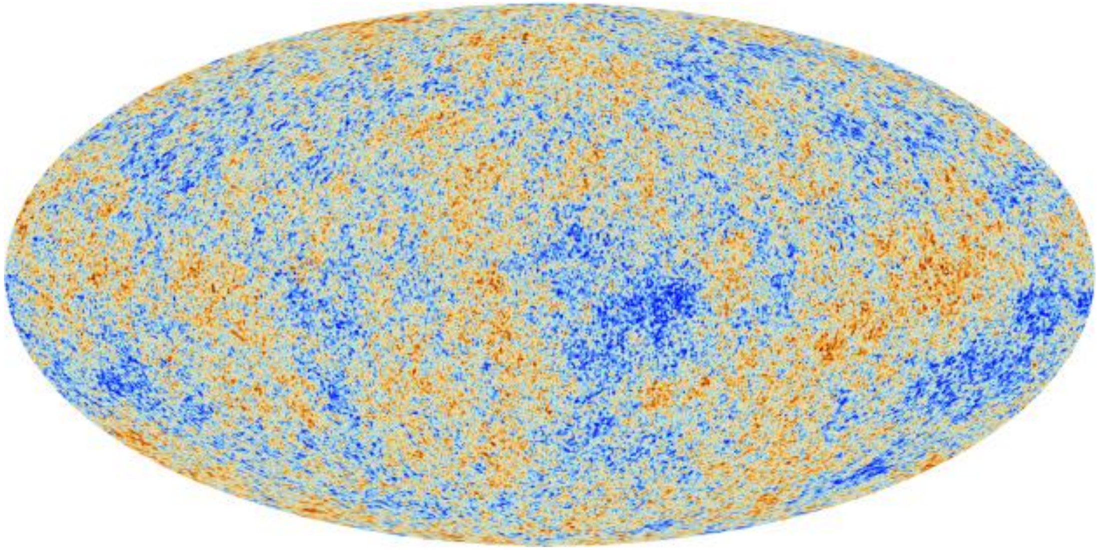
- The standard model exhibits a pattern. It should be explained
  - Origin of particles, the “periodic table”, etc.
  - Origin of forces, their number, their strengths, etc.
  - Origin of the parameters like masses of particles
- The Higgs particle mass is unstable (more later)

- Neutrino masses
  - Zero in the Standard Model
  - Experiment: they are nonzero, but extremely small
  - The relevant new physics is at much shorter distances.

Standard model of cosmology

The best current data from:

- Wilkinson Microwave Anisotropy Probe (WMAP), Planck space telescope

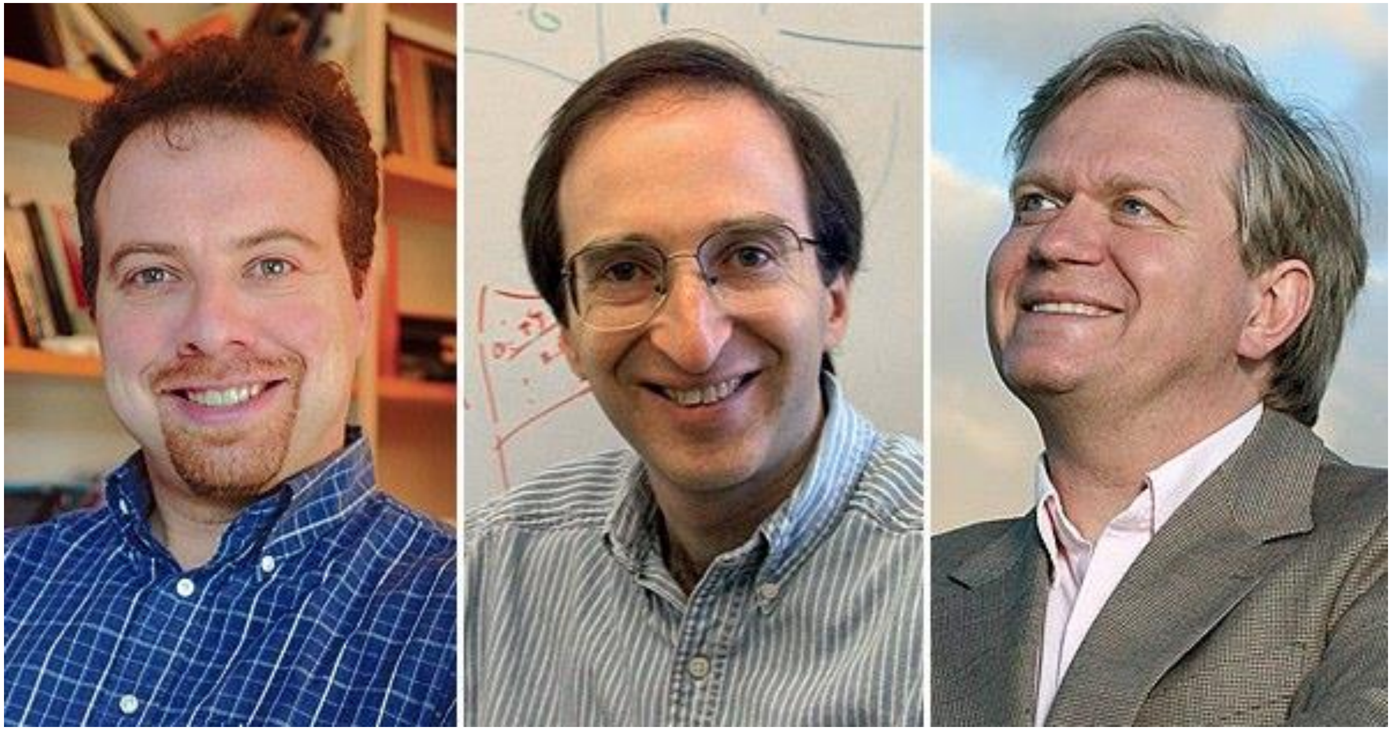


- Survey of supernovae…

Standard model of cosmology

The best current data from:

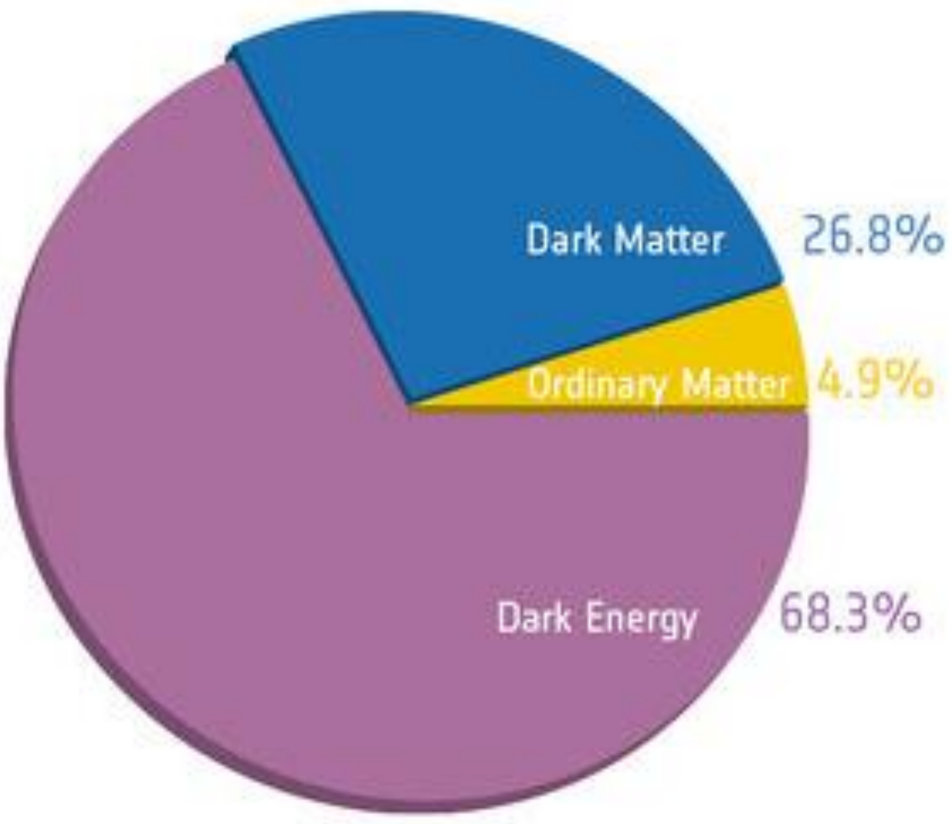
- Survey of supernovae



Riess Perlmutter Schmidt

Standard Model of cosmology

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

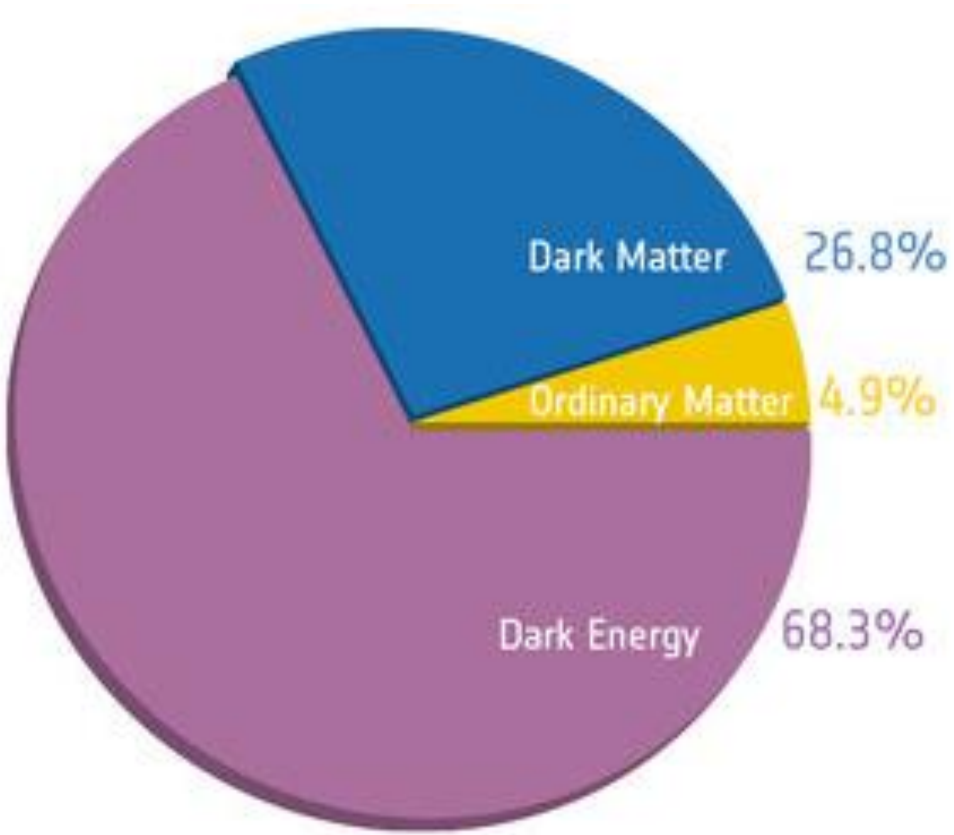


Standard model of cosmology

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.



Standard model of cosmology

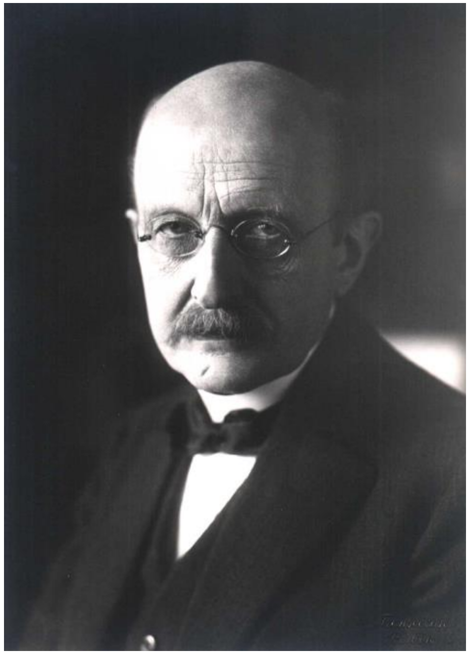
We need to understand:

- What is the dark matter?
- What is the dark energy?
- Origin of parameters (explain the pattern)

- Cosmic inflation?

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^{18} times the proton mass
  - 10^{-34} meters
- Should address the structure of the Universe when its size was only 10^{-34} meters – origin of the Universe



Best candidate: string theory

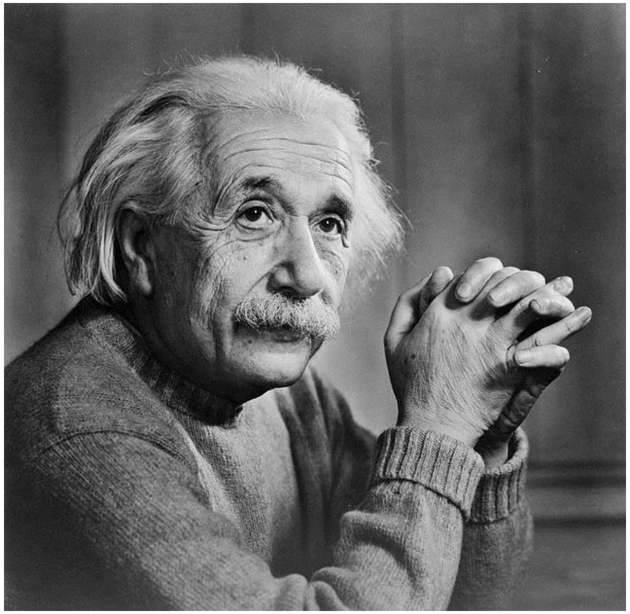
Challenges:

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

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

Explain the remaining parameters of these Standard Models

- The existence of these parameters points to a deeper truth.
- Look for new models with fewer parameters that explain/predict the parameters of the current Standard Models.
- Ultimately, we hope to find a fundamental theory that explains everything with no input parameters.



Einstein

"…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)."

Explain the remaining parameters Hierarchy problems

The first parameters to explain are the overall scales:

- In particle physics:
  - Why is the scale of particle physics, so much smaller than the Planck scale (a factor of 10^{-16})?
- In cosmology:
  - Why is the observable Universe so much larger than the Planck length (a factor of 10^{60})?
  - Equivalently, why is the amount of dark energy density so small relative to the Planck scale?

Stability of the hierarchy

First, we should understand the origin of these hierarchies between widely different scales.

Second, we should ensure the stability of the hierarchies.

- Recall Newton's concern about the stability of the solar system (and his idea about the need for divine intervention).
- Ensure that small changes in the short distance description does not make a huge difference in the results.
- Some parameters in the Standard Model seem fine tuned.

Instability?

- This structure is not likely to be found in nature
  - it is unstable.
- If we do find this structure, we should look for an explanation; e.g. the rocks are connected …

Stability of the hierarchy

- Many effects contribute to the masses of particles and the dark energy density.
- All of them are of the same order of magnitude, the Planck scale, but they have different signs.
- In particle physics these effects must cancel out to 32 decimal points.
- In cosmology they must cancel out to 120 decimal points.

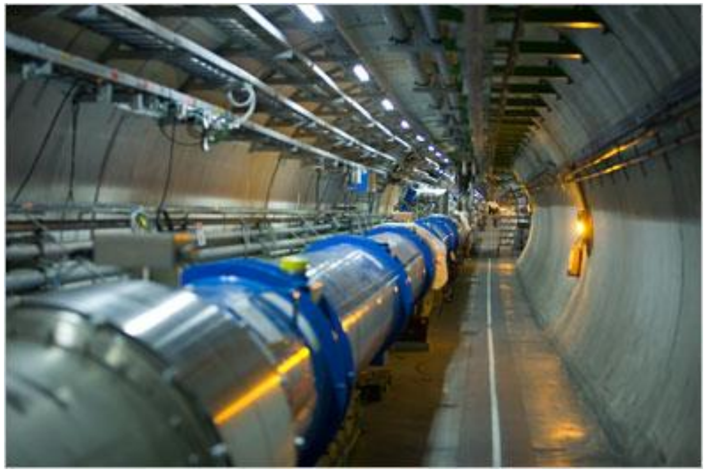
- These delicate cancellations seem unnatural.
- The hierarchies are unstable – small changes ruin the cancellation and thus ruin the hierarchy.

Hierarchy problems – possible answers

- Our reasoning is wrong
  - Recall Newton and the stability of the solar system
- A new stabilizing mechanism
  - Recall the connected rocks
- This is the wrong question
  - These parameters are environmental
  - Recall Kepler's Platonic solids

A new stabilizing mechanism

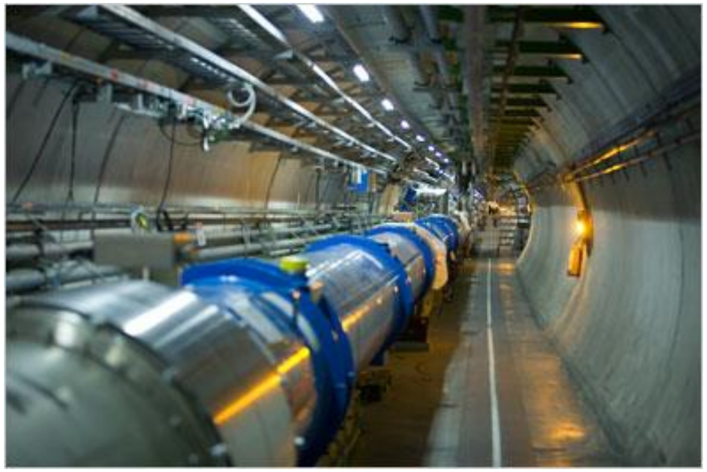
- A stabilizing mechanism is expected to act at energies close to the energies of the standard model.
- It should lead to new particles in the current and future experiments (in particular the LHC).



- Leading candidate is supersymmetry. Alternatively, something else we have not yet thought about.

A new stabilizing mechanism

- So far there is no experimental sign of any of new particle beyond the Standard Model.
- Perhaps something will be found in the next run of the LHC.



- If no discrepancy with the Standard Model, it is likely that there is no stabilizing mechanism.

This is the wrong question

- 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 dimensions

The multiverse

If true, this is a revolution of the scale of the Copernican revolution.

Not only isn't the earth special.

Even our universe is not special.

Obviously, many physicists are reluctant to accept it.

How should we think about physics in such a setup?

- What are the right questions in this case?
- Is it meaningful to discuss other unobservable universes?
- Our universe is not special. What principle selects it?
  - It does not have to be governed by generic laws of physics (values of parameters).
  - It might not even be the most likely universe.
  - Perhaps we should argue that of all possible universes we live in the one that can support life (anthropic reasoning).

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: we should explain the parameters of these models.

Summary

- Some of these parameters are unstable.
- The LHC is going to give some input into this question soon.
- One option is that experiments in the near future will find a mechanism to stabilize some of these parameters.
- Alternatively, some physicists believe that some of these parameters are environmental.
  - Their values are accidents specific to our universe.
  - They are different in other universes.

We asked: What’s next?

We do not know, but it is guaranteed to be exciting.

Thank you for your attention!