Para além do bosão de Higgs

Questões abertas em física das partículas

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Outline of the lecture

The Higgs field

Unsolved mysteries

Beyond the Standard Model

Dark matter and dark energy

What else could we find at LHC?

Particle Physics

Particle physics is a modern name for the centuries old effort to understand the basics laws of physics.

Edward Witten

Aims to answer the two following questions:

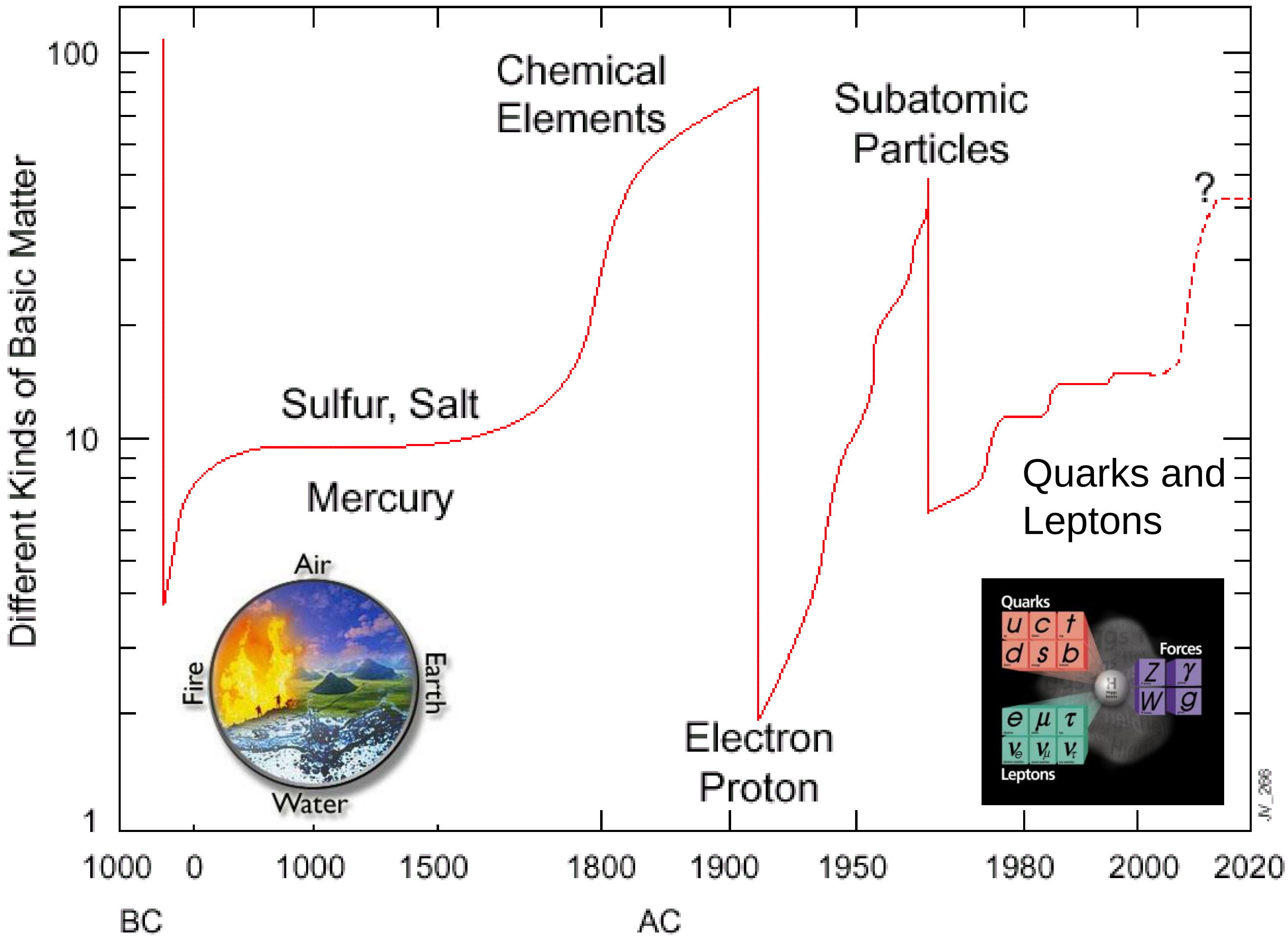
What are the elementary constituents of matter ?

What are the forces that determine their behavior?

Experimentally

Get particles to interact and study what happens

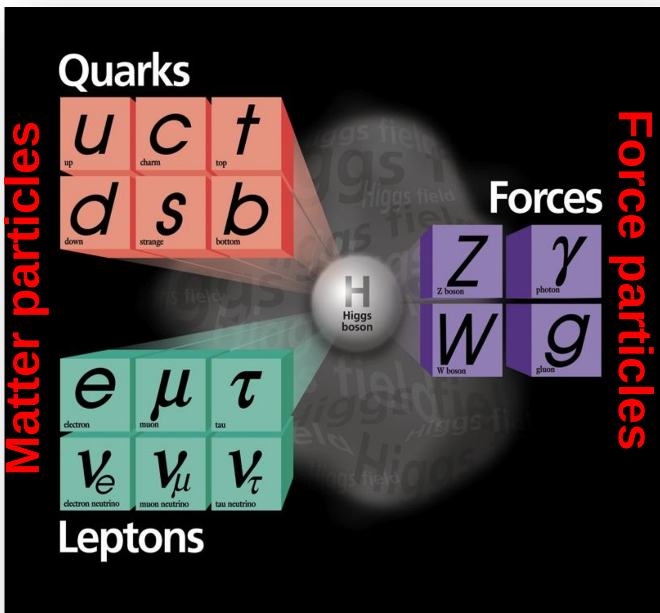
Constituents of matter along History



The Standard Model

Over the last ~100 years: The combination of Quantum Field Theory and discovery of many particles has led to

- The Standard Model of Particle Physics
  - With a new “Periodic Table” of fundamental elements



One of the greatest achievements of 20th Century Science

$$L_H = \frac{1}{2}(\partial_\mu H)^2 - m_H^2 H^2 - h\lambda H^3 - \frac{h}{4}H^4 + \frac{g^2}{4}\left(W_\mu^+ W^\mu + \frac{1}{2\cos^2\theta_W} Z_\mu Z^\mu\right)(\lambda^2 + 2\lambda H + H^2) + \sum_{l,q,q'}\left(\frac{m_l}{\lambda}\bar{l}l + \frac{m_q}{\lambda}\bar{q}q + \frac{m_{q'}}{\lambda}\bar{q}'q'\right)H$$

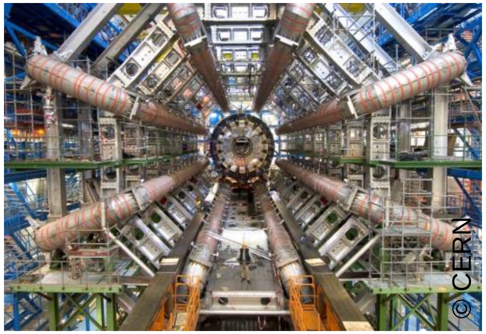
The Higgs boson

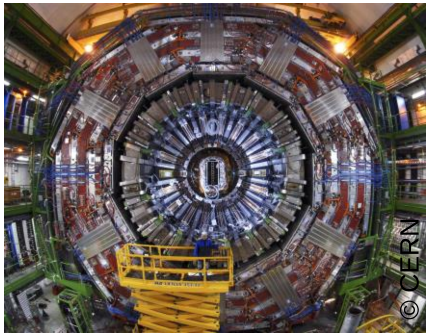
A new force field, the Higgs field, has an *average value in the vacuum* that became non-zero as the early universe cooled.

The quantum of the Higgs field is the Higgs boson.

Interaction of particles with the Higgs fiels is at the origin of mass.

Huge instruments in place in Switzerland and France outside Geneva:

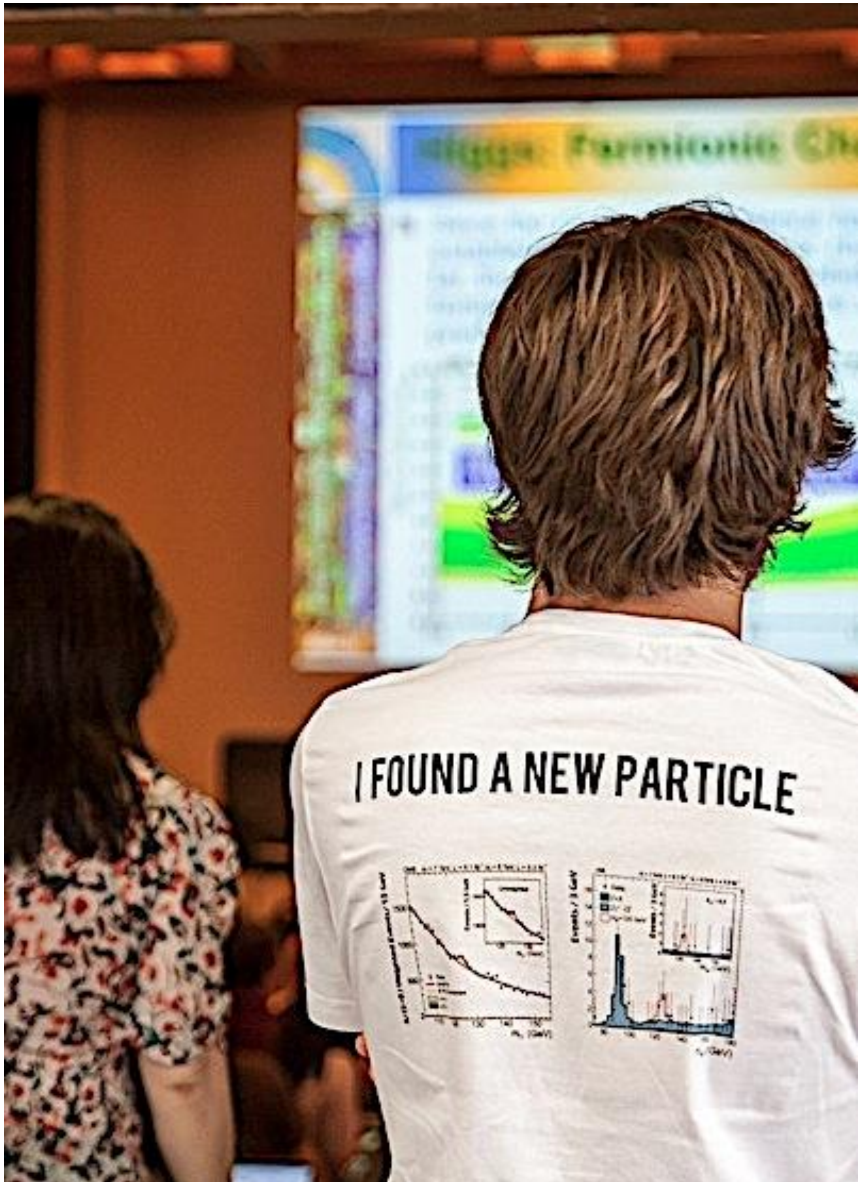




The Large Hadron Collider

Large is an understatement!
Hadrons referred to protons.
Collide is what it does.

A new boson was discovered



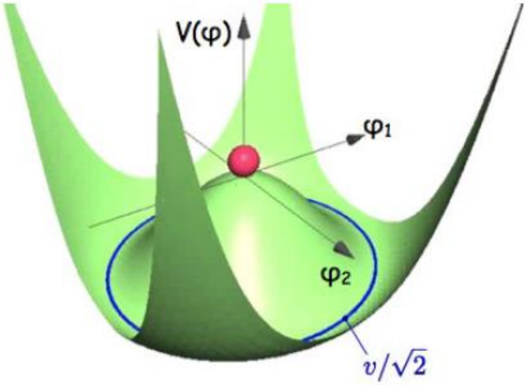
A major discovery in physics

The **new boson** is a Higgs boson.

The hypothesis that the **space is filled with a Higgs field** since the origin of the Universe is a plausible assumption.

A new framework to understand the Universe. Cosmological models become more plausible:

- The Universe inflation after the big-bang
- Energy of a Higgs-like field as the source of all matter in the Universe



Unsolved mysteries

Beyond the standard model

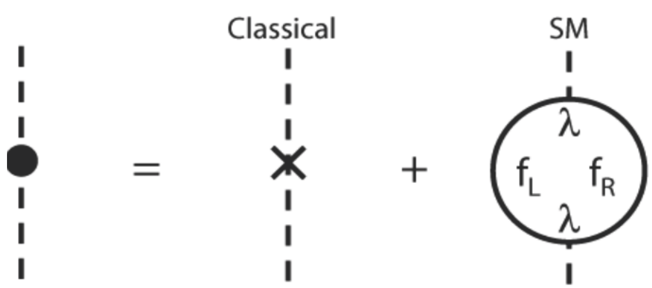
The Standard Model answers many of the questions about the structure of matter.

But the Standard Model is not complete: there are still many unanswered questions.

Higgs and hierarchy problem

In the SM the Higgs mass is a huge problem:

- The calculation of the Higgs mass results in a sum of many terms
- Each term can be as large as the Plank scale (10^{19} GeV)
- Terms can be positive or negative, and may cancel if the constants of nature involved (masses of all other particles) allow it
- Miraculous cancelations are needed to keep the Higgs mass ~ 125 GeV



$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \dots ,$$

This is known as the hierarchy problem

Three generations

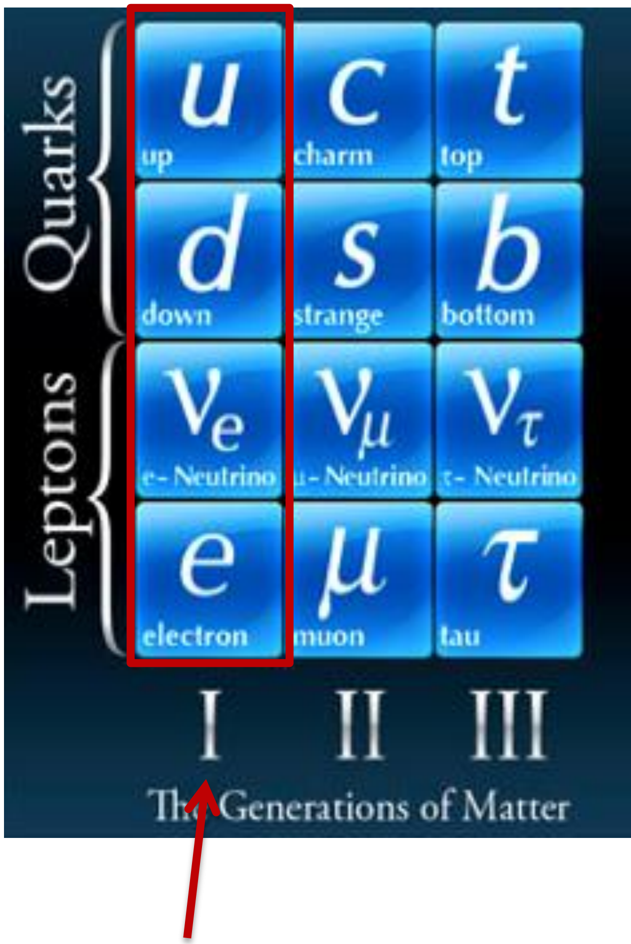
There are three "sets" of quark pairs and lepton pairs, called generations.

The generations increase in mass.

Higher generation particles decay into lower generation particles.

We do not know why there are three generations.

We do not have an explanation for the observed mass pattern



Every-day world

What happened to the antimatter?

Experiments tell us that for every fundamental particle there exists an antiparticle.

The big bang almost certainly produced particles and antiparticles in equal numbers.

However our observations indicate that we live in a universe of matter, not antimatter.

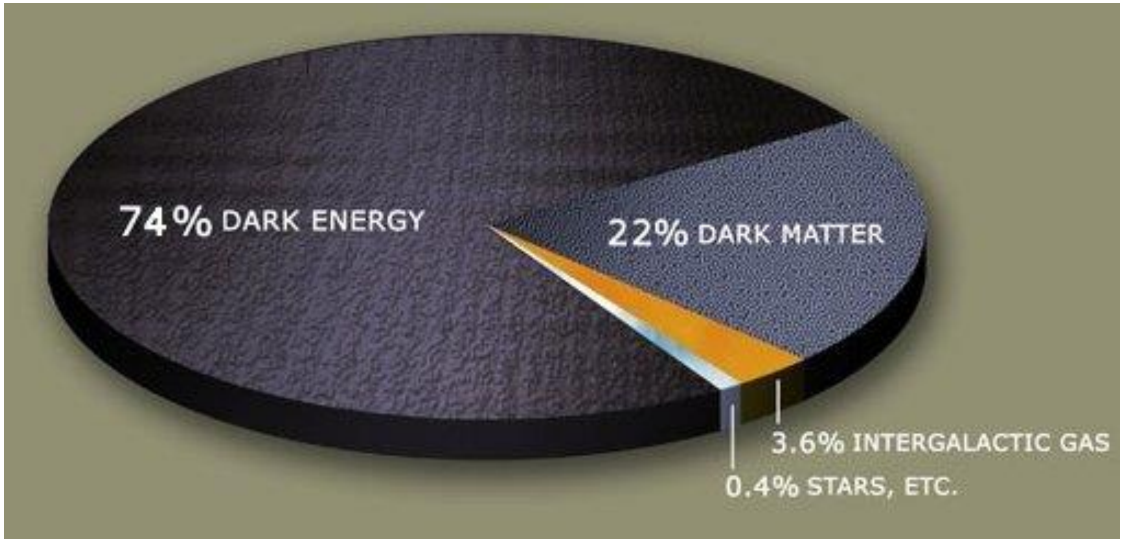
What happened to the antimatter?

Dark matter and energy

What is the Universe made of? Stars and other visible matter account for 0.4%. Intergalactic gas is 3.6%.

What is the dark stuff which accounts for 96% of the Universe? Nobody knows.

It is one of the greatest mysteries of science

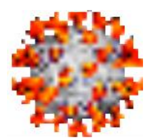
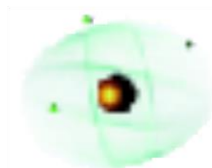


Beyond the Standard Model

Fundamental forces

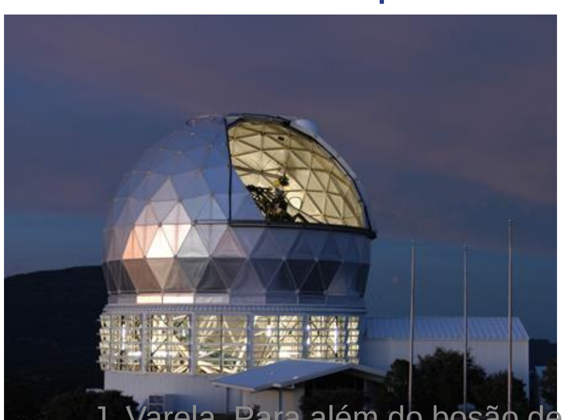
	Gravity	Electromagnetic force	Strong force	Weak force
Strength:	10^{-40}	10^{-2}	1	10^{-6}
	Planets, stars, galaxies	Atoms, molecules, electromagnetic waves	Atomic nuclei	Radioactive decays



Distances	10^{6} - 10^{26}	10^{-6} - 10^{-10}	10^{-14} - 10^{-15}	$<10^{-18}$	m

Telescope



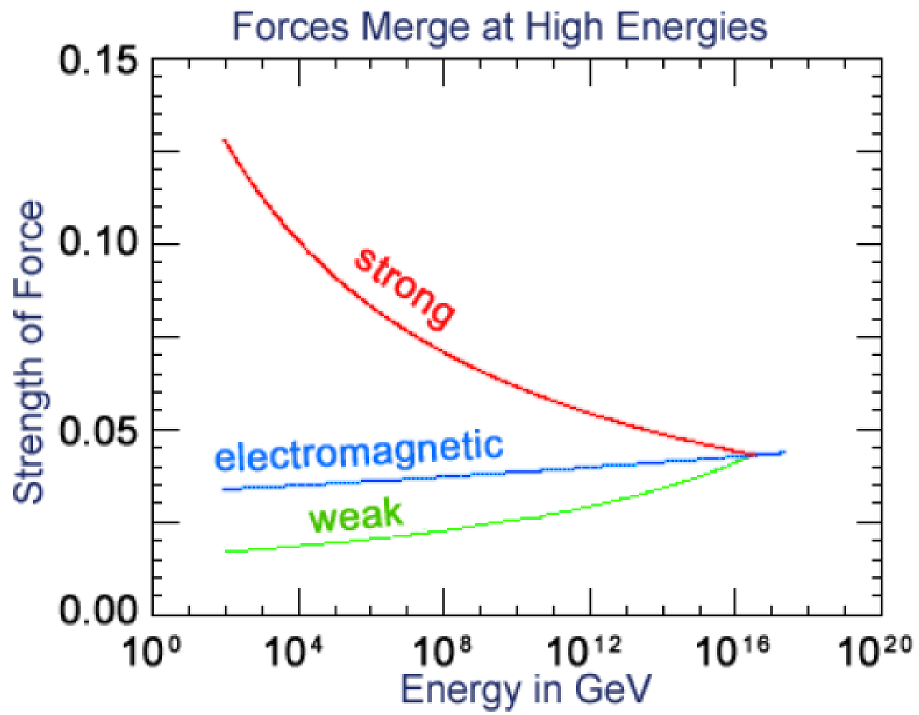
Microscope

Electron microscope

Accelerator

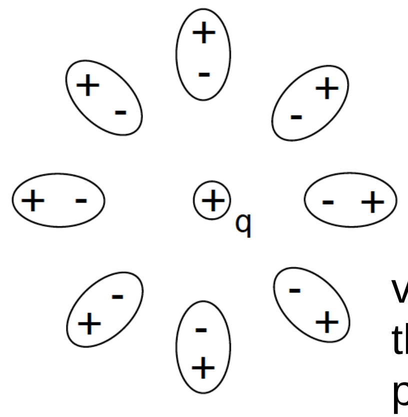
Forces and the Grand Unified Theory

Physicists hope that a Grand Unified Theory will unify the strong, weak, and electromagnetic interactions.



However, how can this be the case if strong and weak and electromagnetic interactions are so different in strength and effect?

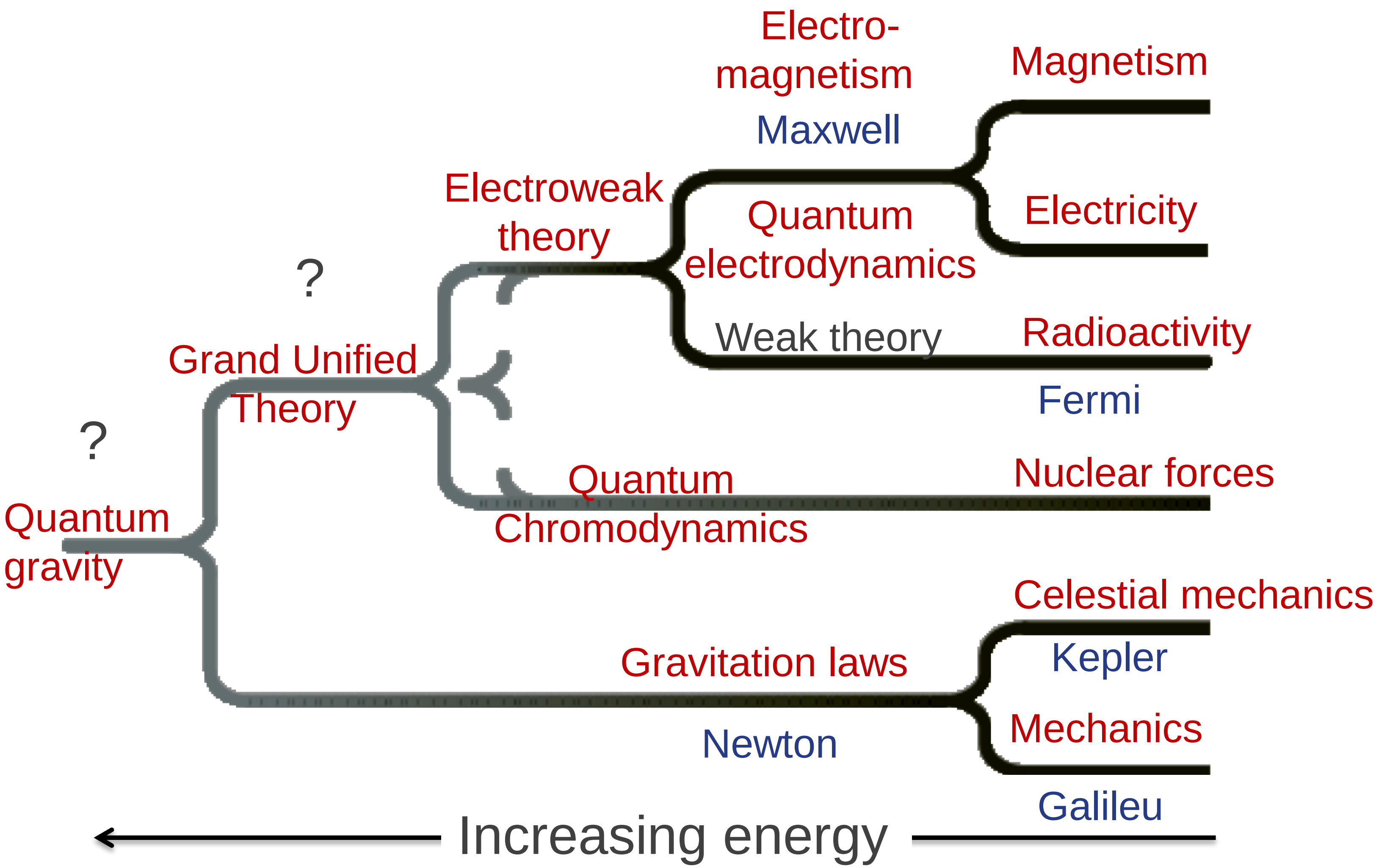
Strangely enough, current data and theory suggests that these varied forces merge into one force when the particles being affected are at a high enough energy.



Vacuum polarization

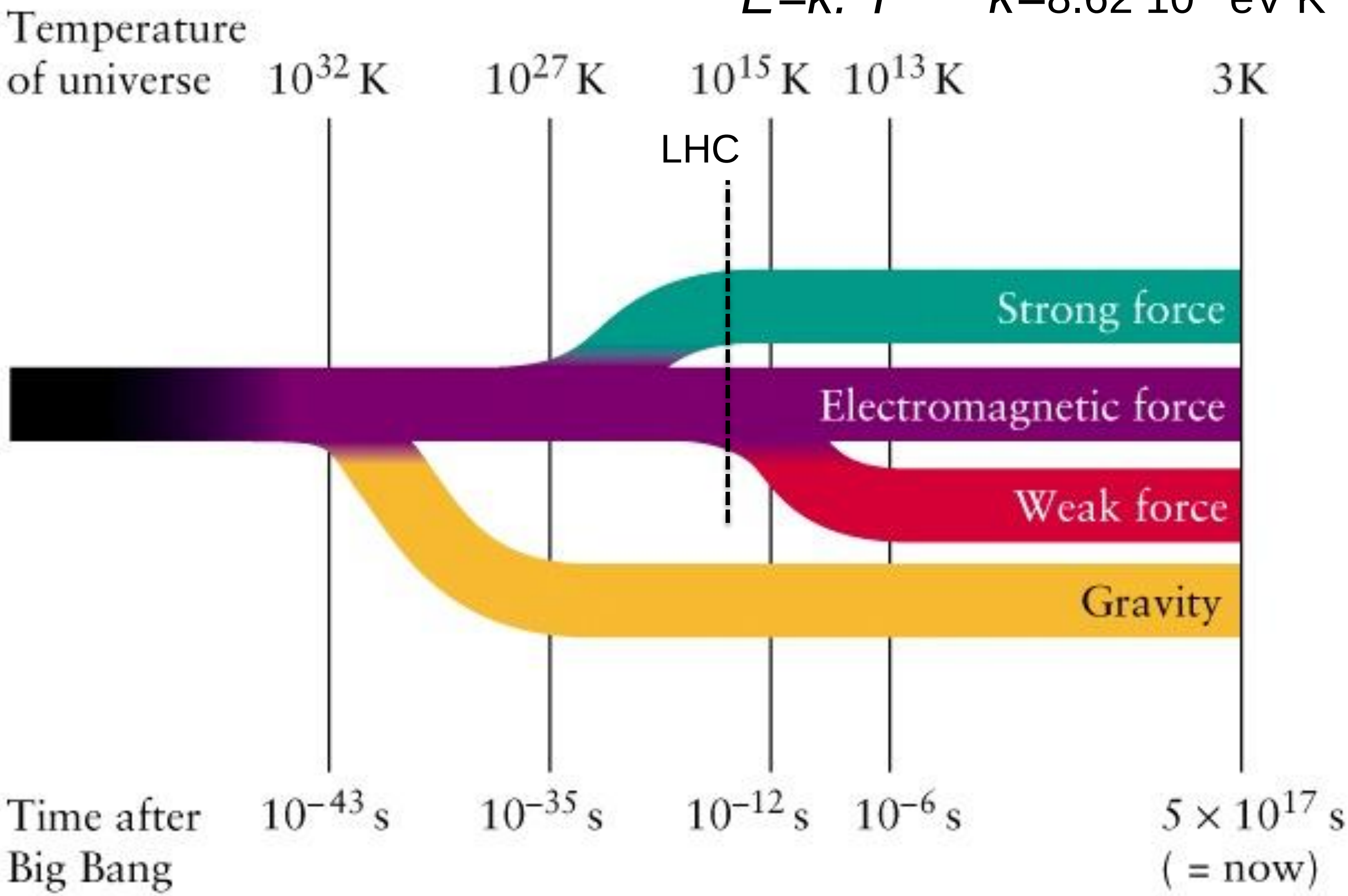
virtual pairs around the charge q are polarized

Unification of the Forces



Forces and expansion of the Universe

$E = k.\ T \qquad k = 8.62\ 10^{-5}\ \text{eV K}^{-1}$



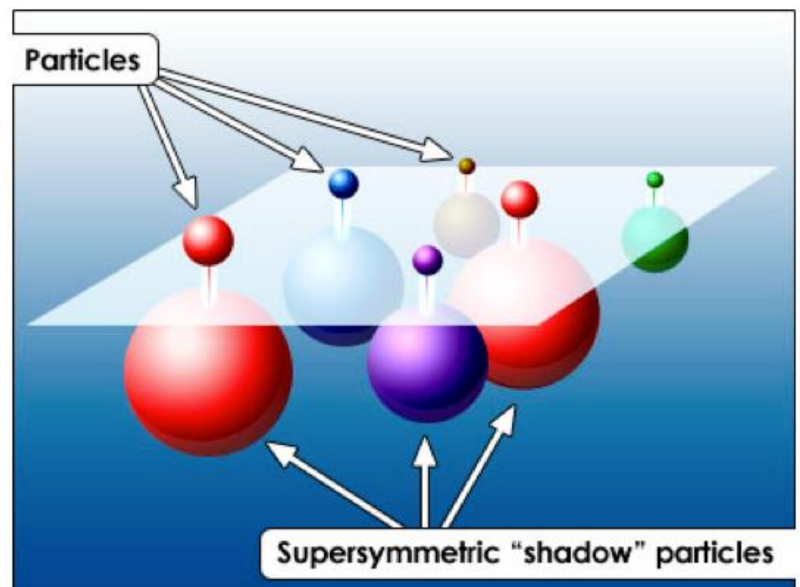
Supersymmetry

Some physicists attempting to unify gravity with the other fundamental forces have proposed a new fundamental symmetry:

- Every fundamental matter particle should have a massive "shadow" force particle,
- and every force particle should have a massive "shadow" matter particle.

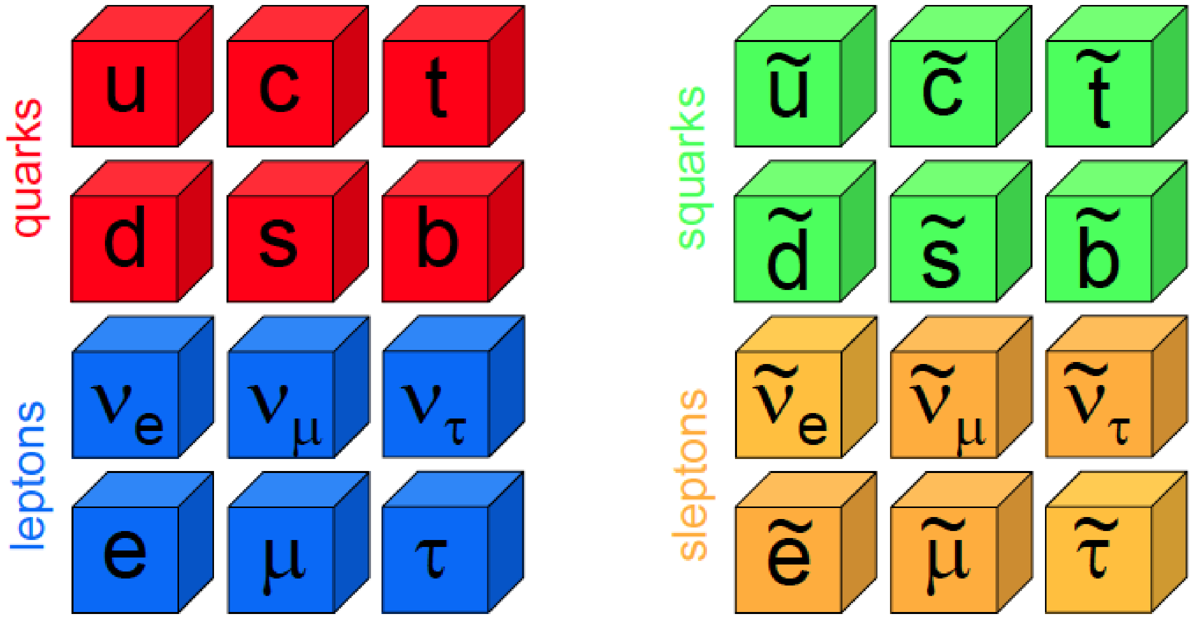
This relationship between matter particles and force carriers is called supersymmetry (**SUSY**)

No supersymmetric particle has yet been found, but experiments are underway at CERN to detect supersymmetric partner particles.



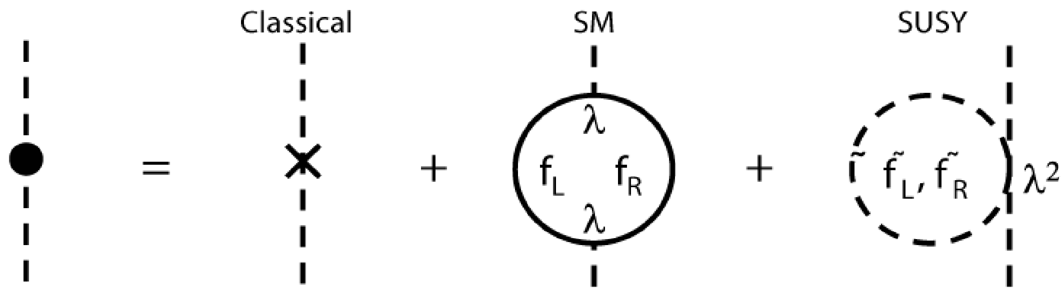
Supersymmetry

Double the whole table with a new type of matter?



Heavy versions of every quark and lepton
Supersymmetry is broken

SUSY and the Higgs mass



$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \ldots ,$$

Natural cancellation

$$\begin{aligned} m_h^2 &= (m_h^2)_0 \boxed{- \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2} + \ldots \\ &\approx (m_h^2)_0 + \boxed{\frac{1}{16\pi^2}(m_{\tilde f}^2 - m_f^2)\ln(\Lambda/m_{\tilde f})} , \end{aligned}$$

Higgs mass:

- correction has quadratic divergence!
  - Λ a cut-off scale – e.g. Planck scale

Superpartners fix this:

- Need superpartners at mass ~1-2 TeV
  - Otherwise the logarithmic term becomes too large, which would require more fine-tuning.

Extra dimensions

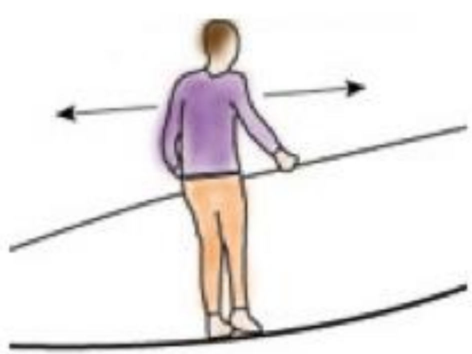
Space-time could have more than three space dimensions. The extra dimensions could be very small and undetected until now.

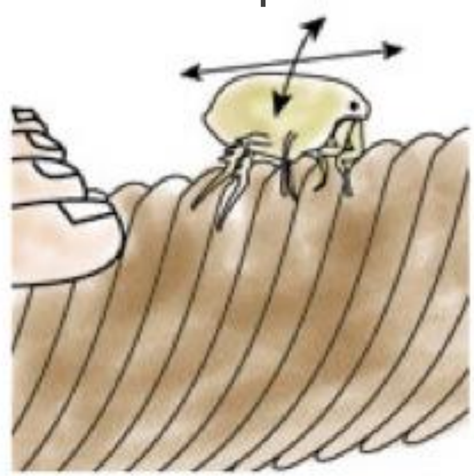
How can there be extra, smaller dimensions?

The acrobat can move forward and backward along the rope: **one dimension**

The flea can move forward and backward as well as side to side: **two dimensions**

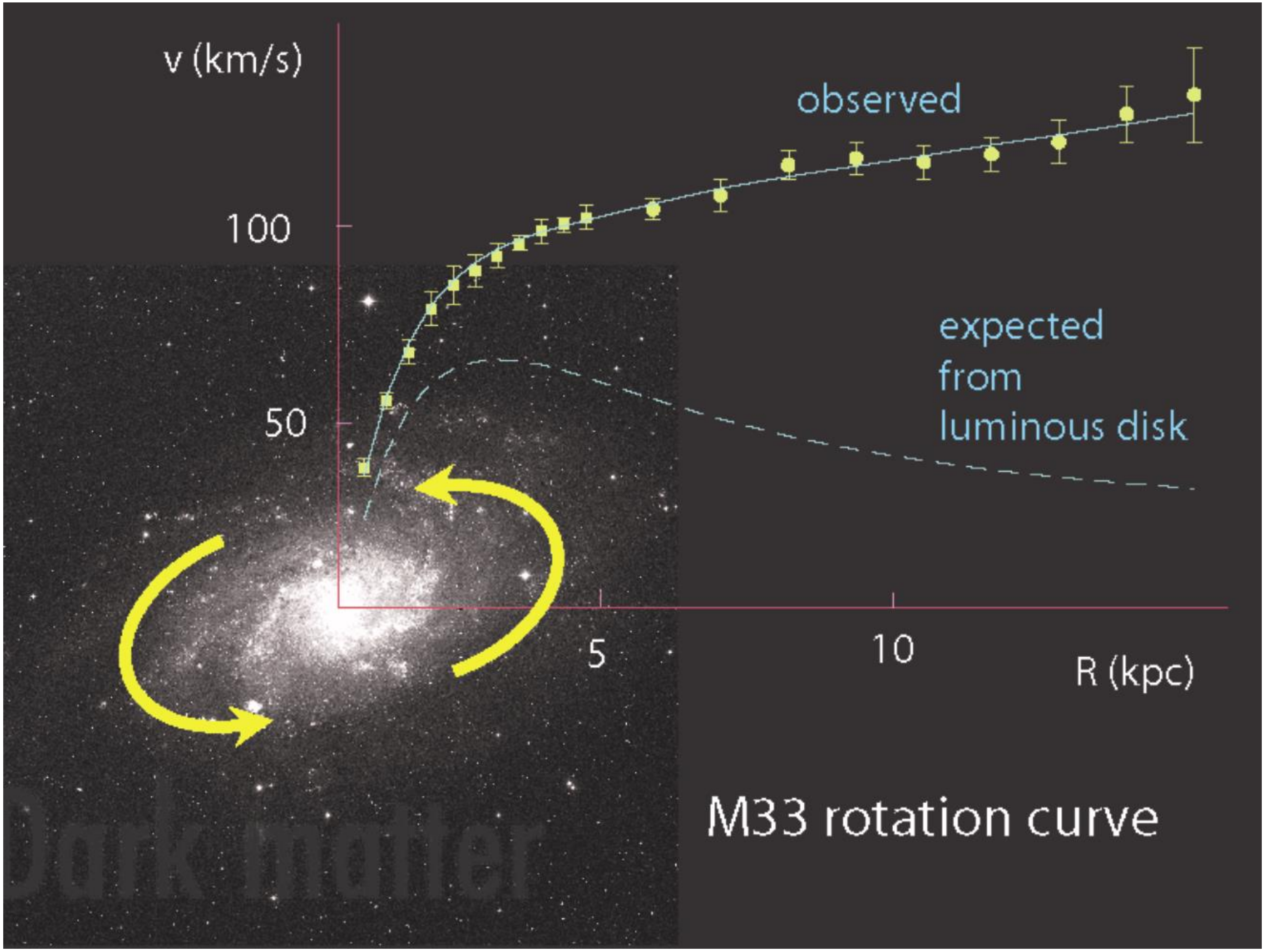
But one of these dimensions is a small closed loop.





Dark matter

The dark matter problem



What is the dark matter?

Must be invisible matter ("dark matter") to account for these observations.

What in the world (out of this world?) is that?

After 40 years, answer still unknown.

"Ordinary matter" makes up only about 1/6 of the matter in the universe.

The rest is something else!

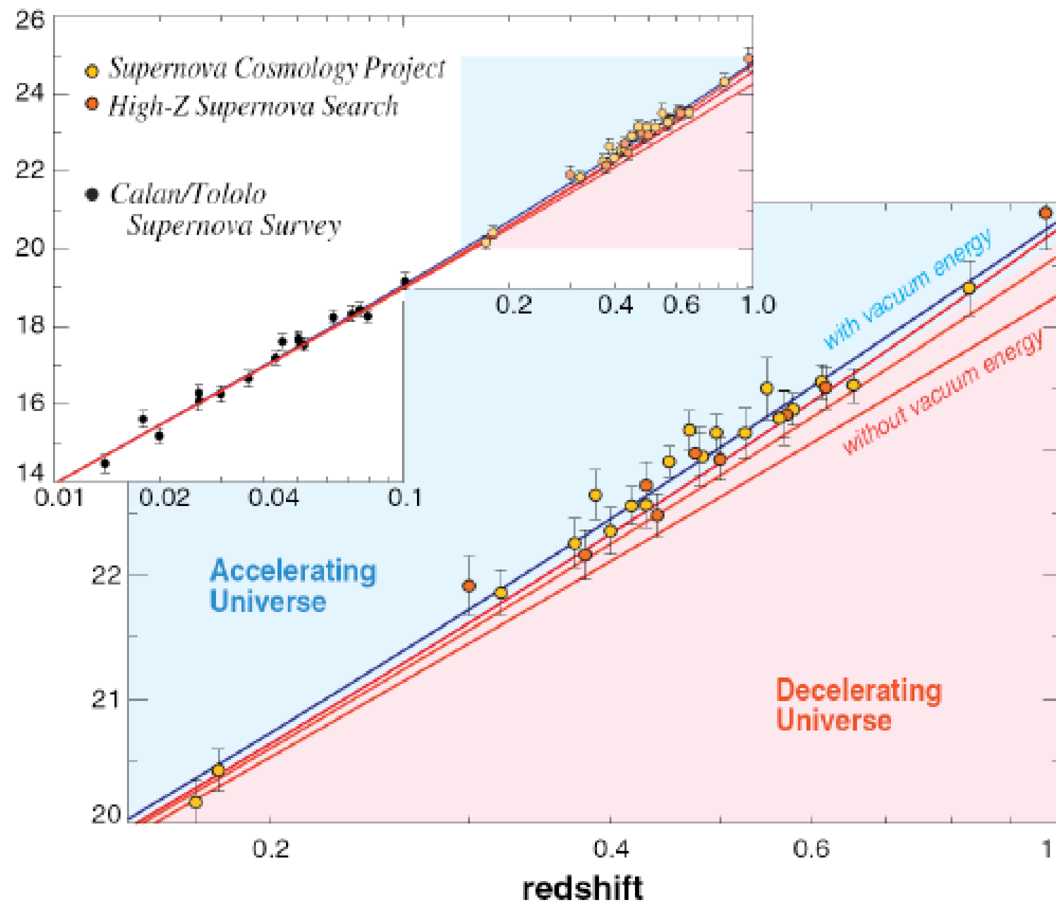
Dark energy

The Universe expansion is accelerating

In 1998, two groups used distant Supernovae to measure the expansion rate of the universe.
(Supernova Cosmology Project and High-z Supernova Team)

They got the same result:
The Universe expansion is accelerating

Some form of energy (dark energy) fills space

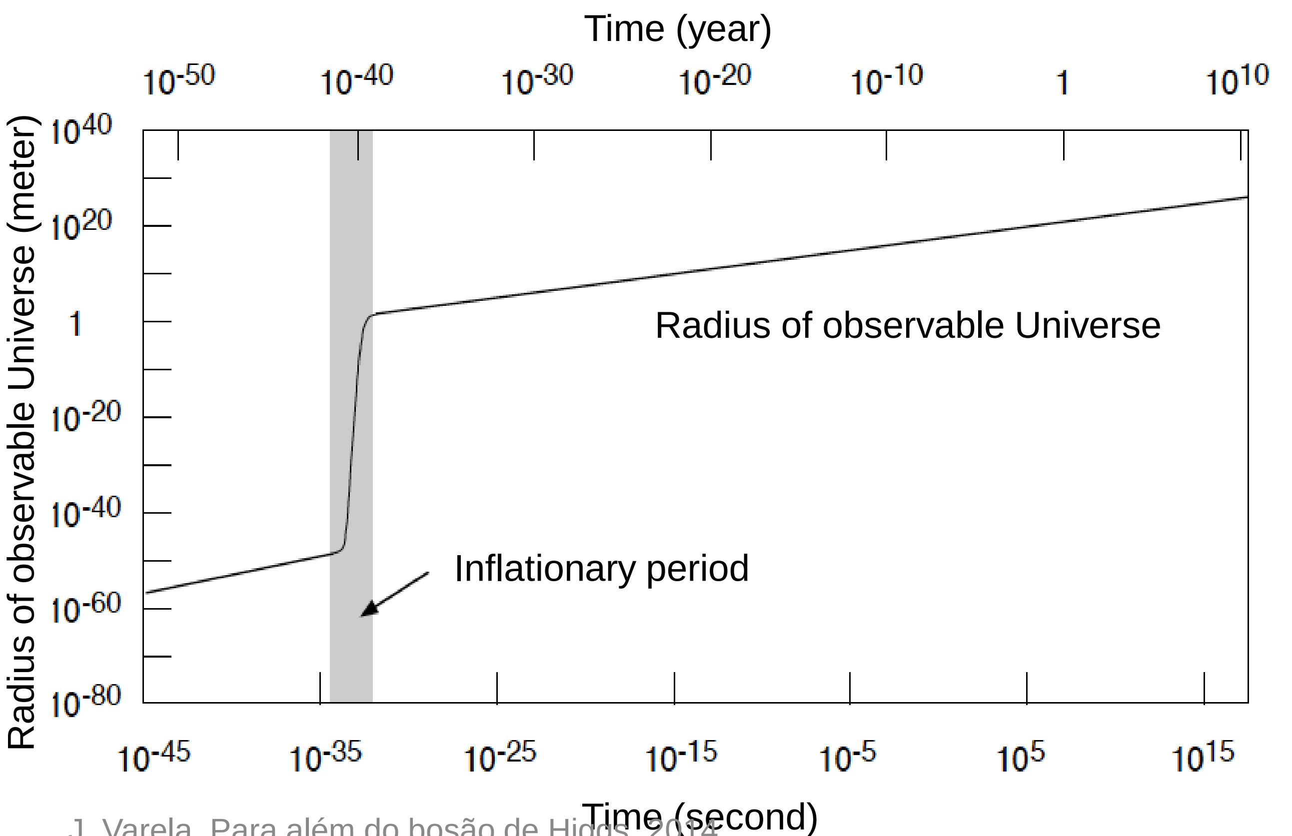


Cosmological inflation

In the very early universe, the physical vacuum undergoes a transition from a high energy state to a low energy state.

The resulting energy shift drives a dramatic exponential expansion.

Explains why the Universe has a uniform Temperature (3 K)

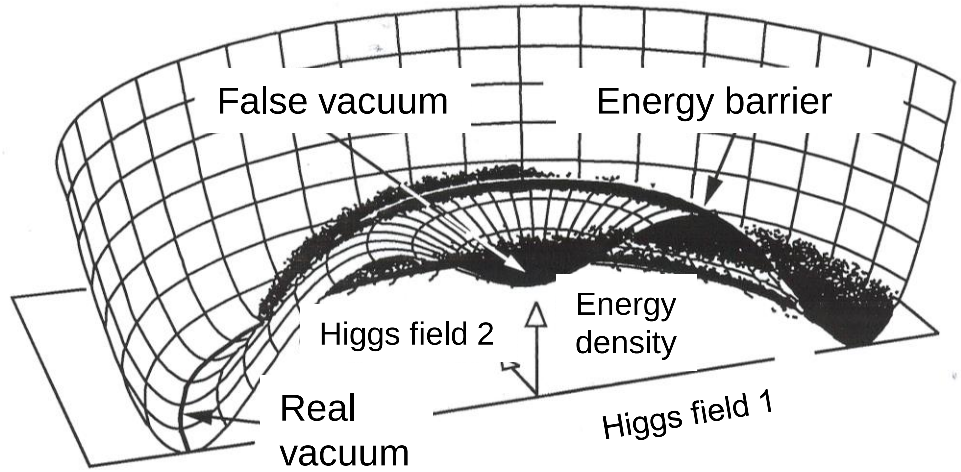


The inflation theory was developed independently in the late 1970's by Alan Guth, Alexey Starobinsky, and others

Higgs field and inflation

Before the inflation (10^{-34} s), the Higgs-like field is trapped is a state of false vacuum.

While the energy density of the Higgs field is positive, the Universe expands at accelerated rate (inflation) and the energy stored in the Higgs field increases.

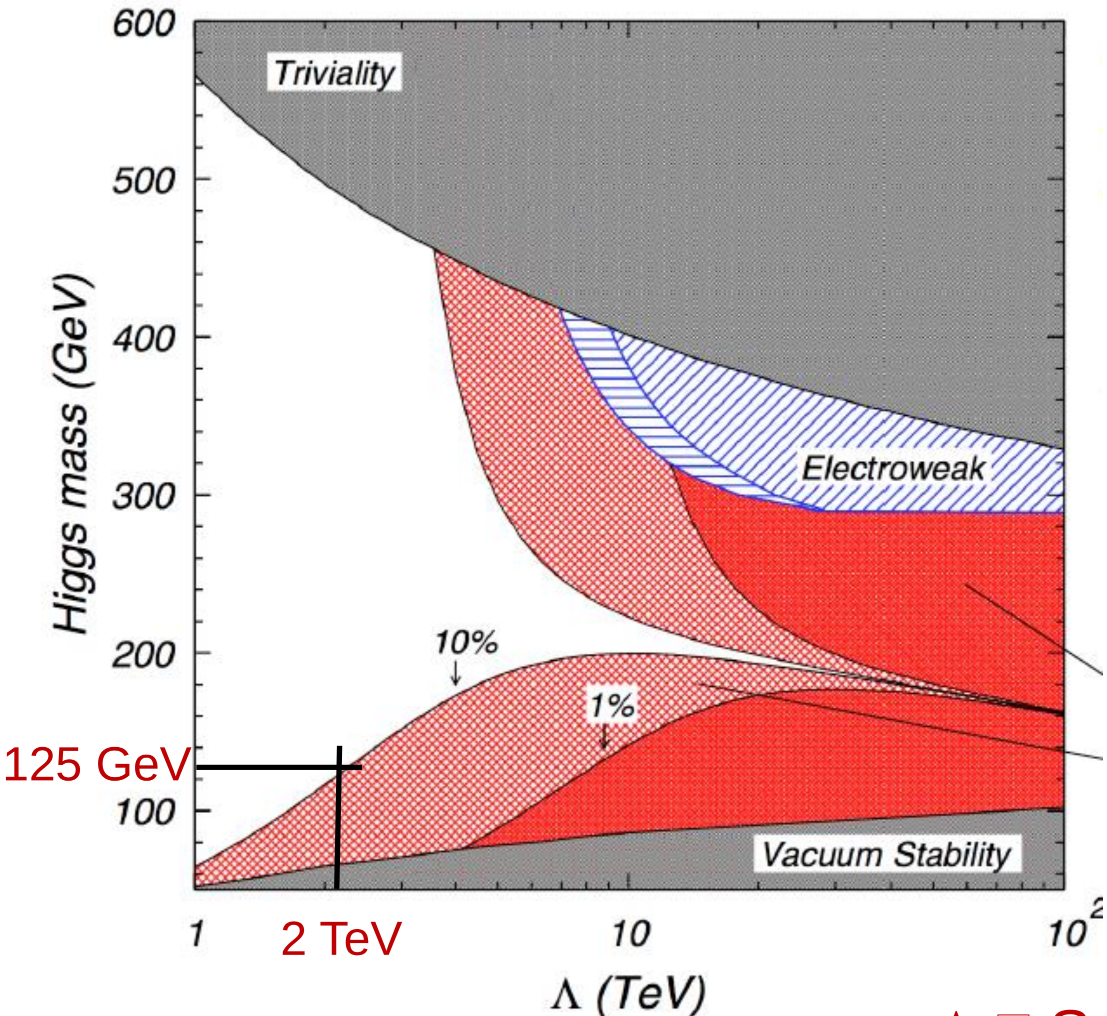


Inflation stops when the Higgs field decays to the real vacuum.

The energy released by the Higgs field is converted into matter particles.

What else could we find at LHC?

New physics at a few TeV?



Naturalness implies Supersymmetry or another 'New Physics' below ~ 2 TeV

Excluded to avoid fine-tuning

Λ Scale of New Physics

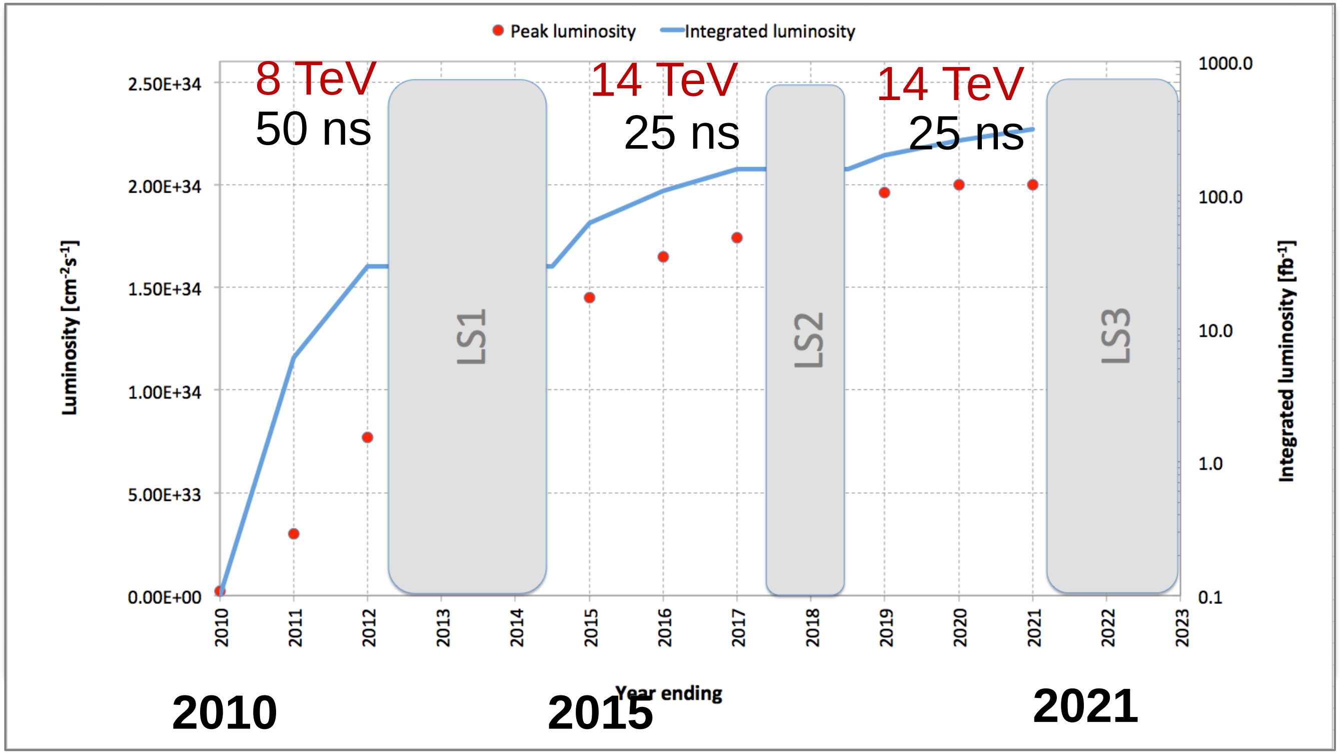
Many possible theories

There are a large number of models which predict new physics at the TeV scale accessible at the LHC:

- Supersymmetry (SUSY)
- Extra dimensions
- Extended Higgs Sector e.g. in SUSY Models
- Grand Unified Theories (SU(5), O(10), E6, …)
- Leptoquarks
- New Heavy Gauge Bosons
- Technicolour
- Compositeness

Any of this could still be found at the LHC

LHC projections



14 TeV

HL-LHC

Luminosity-leveled at $5x10^{34}$ Hz/cm^2

2023

30 fb^{-1} **300 fb^{-1}** **3000 fb^{-1}**

CMS Detector Upgrades:

Phase 1 Upgrade

Phase 2 Upgrade

End