Presente e Futuro em Física de Partículas

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10ª Escola de Professores em Língua Portuguesa

CERN, Genebra, 2 Setembro 2016

Outline of the lecture

The present in a few words

Unsolved mysteries

Dark matter and dark energy

Beyond the Standard Model

Future accelerators

Particle Physics

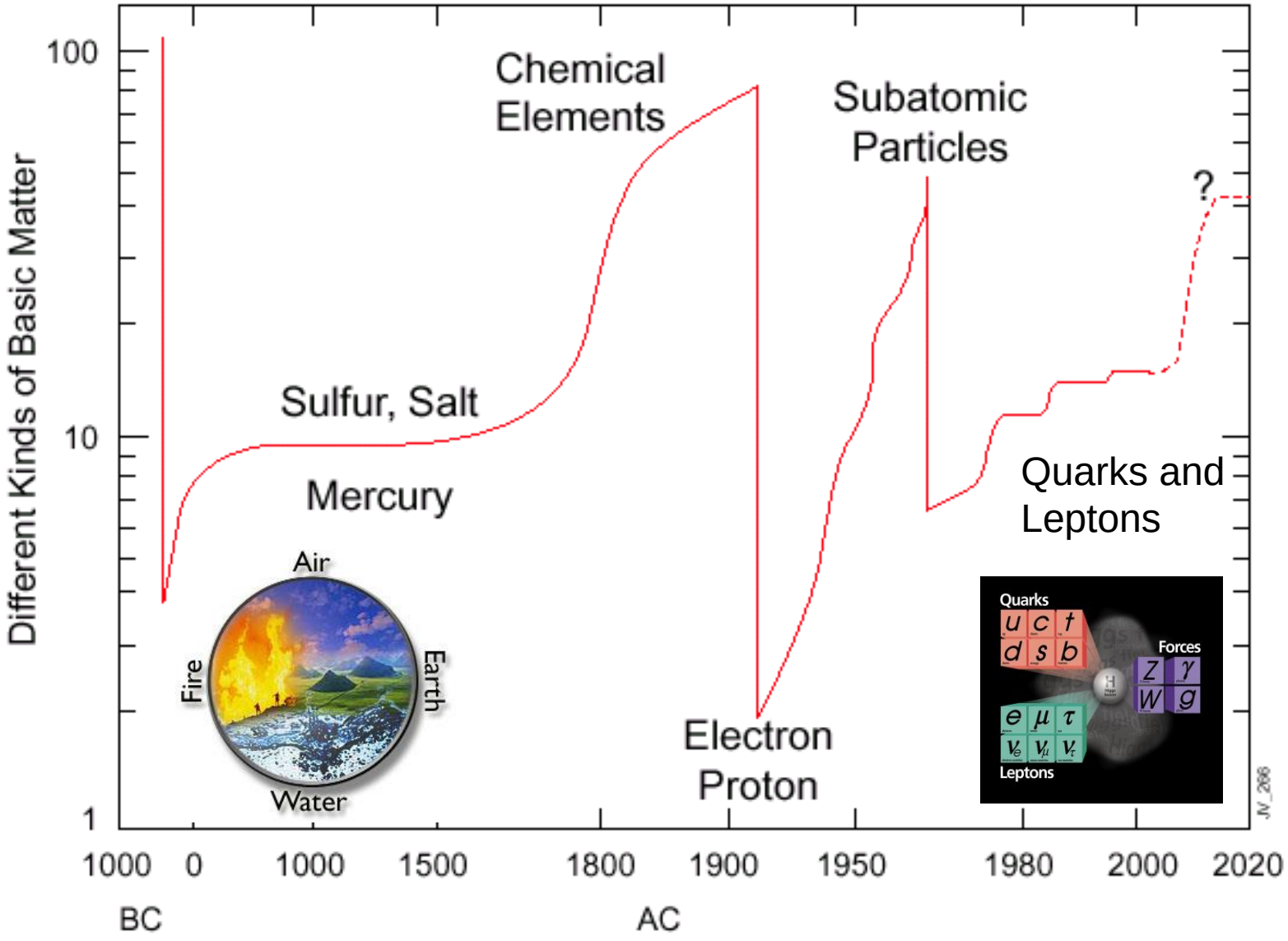
Particle physics is a modern name for the centuries old effort to understand the basics laws of physics.

Aims to answer the two following questions:

What are the elementary constituents of matter ?

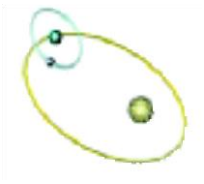
What are the forces that determine their behavior?

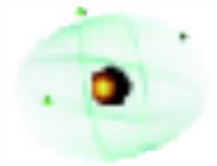
Constituents of matter along History



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

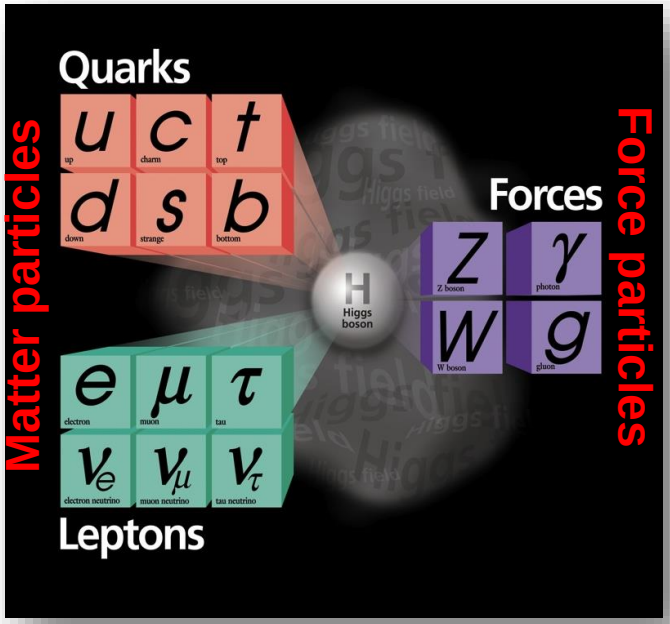
Electron microscope

Accelerator

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

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

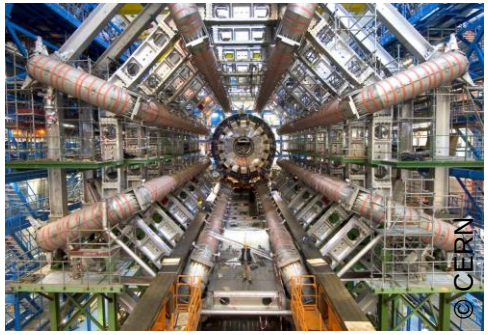
The Higgs boson

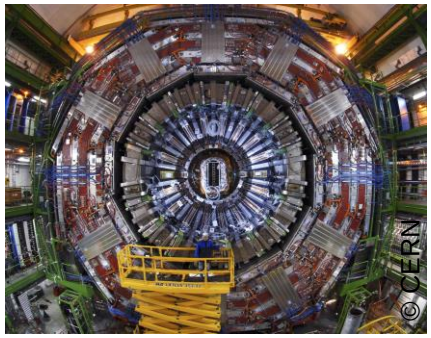
A new force field, the Higgs field, has an *average value in the vacuum* that became non-zero as the early universe cooled.

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.

LHC collider

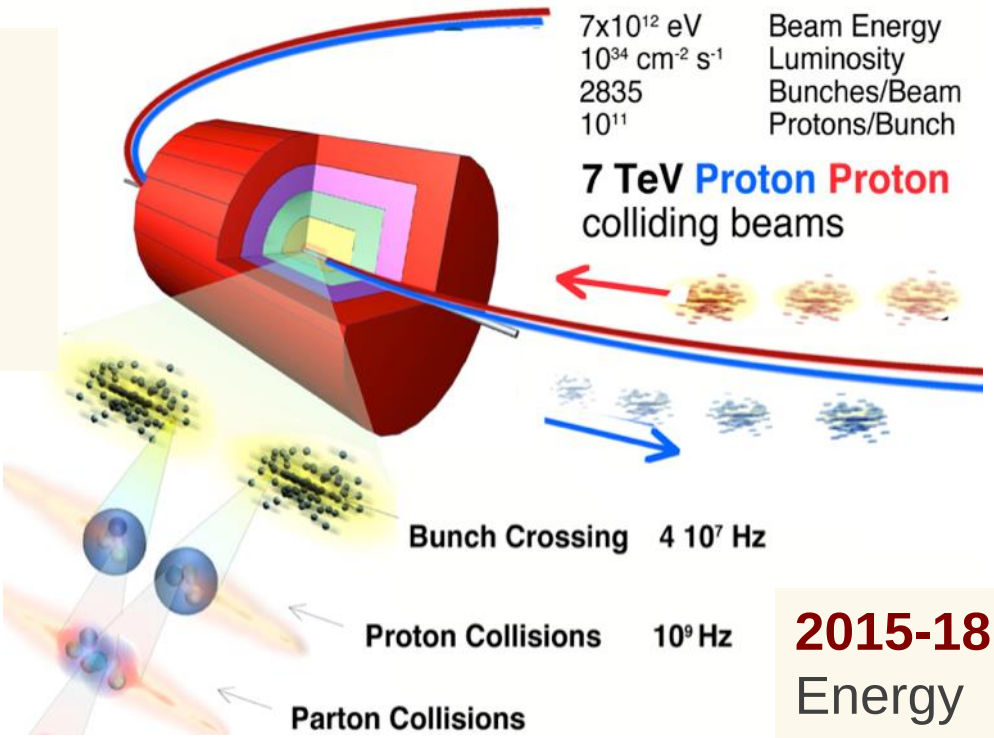
2010-12:

Energy

8 TeV

Luminosity

8 10^{33} $cm^{-2}s^{-1}$

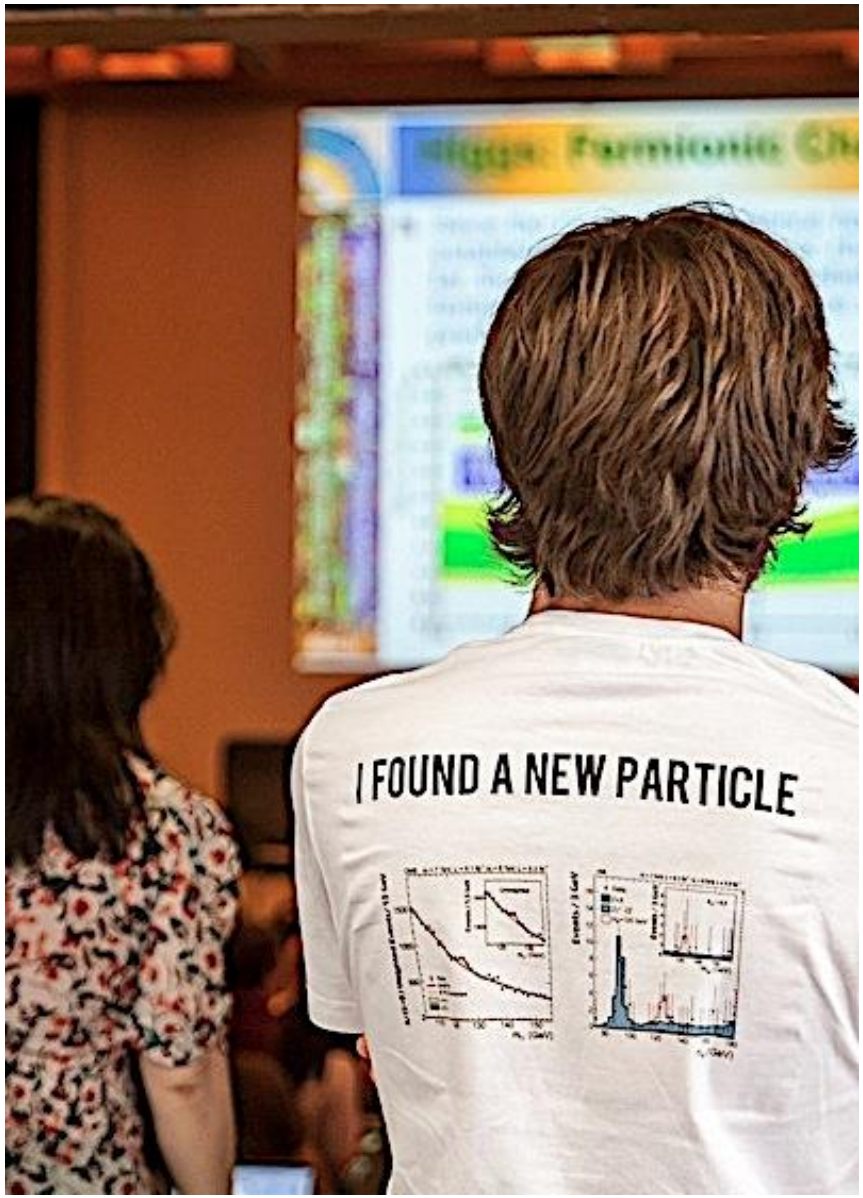


2015-18:

Energy **13 TeV**

Luminosity **2 10^{34} $cm^{-2}s^{-1}$**

2012: A new boson was discovered



A major discovery in physics

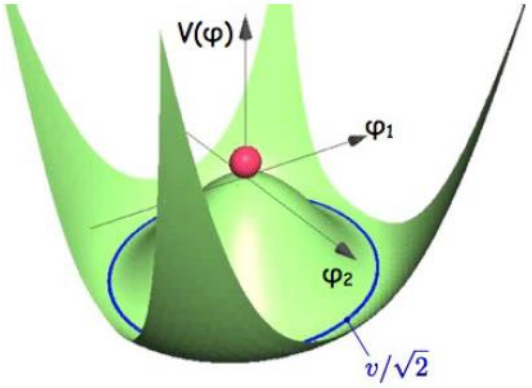
The **new boson** is a Higgs boson.

The **H boson** is not just … “yet another particle”.

The **space is filled with a Higgs field** since the origin of the Universe.

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.

Three generations

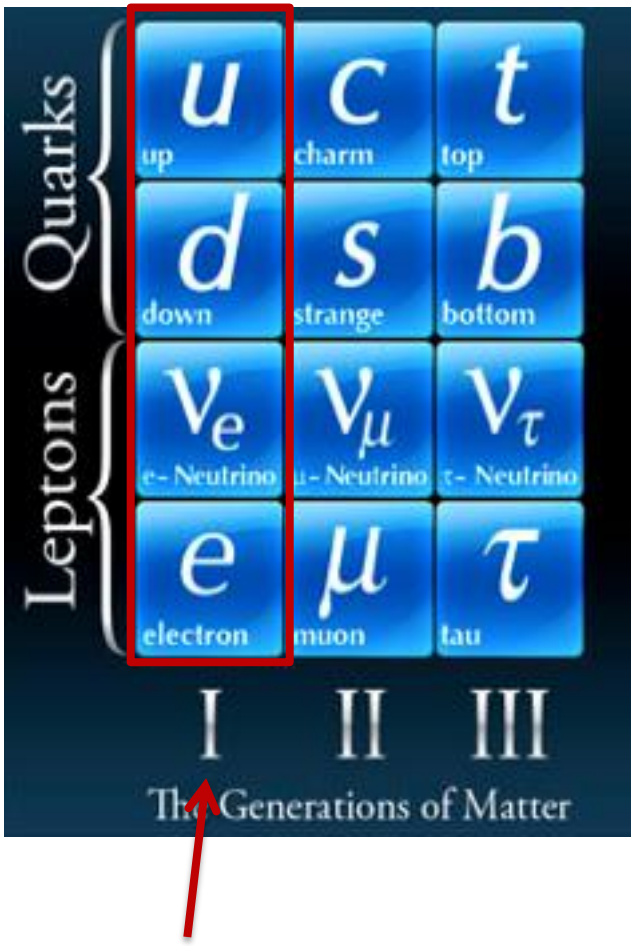
There are three "sets" of quark pairs and lepton pairs, called generations.

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.

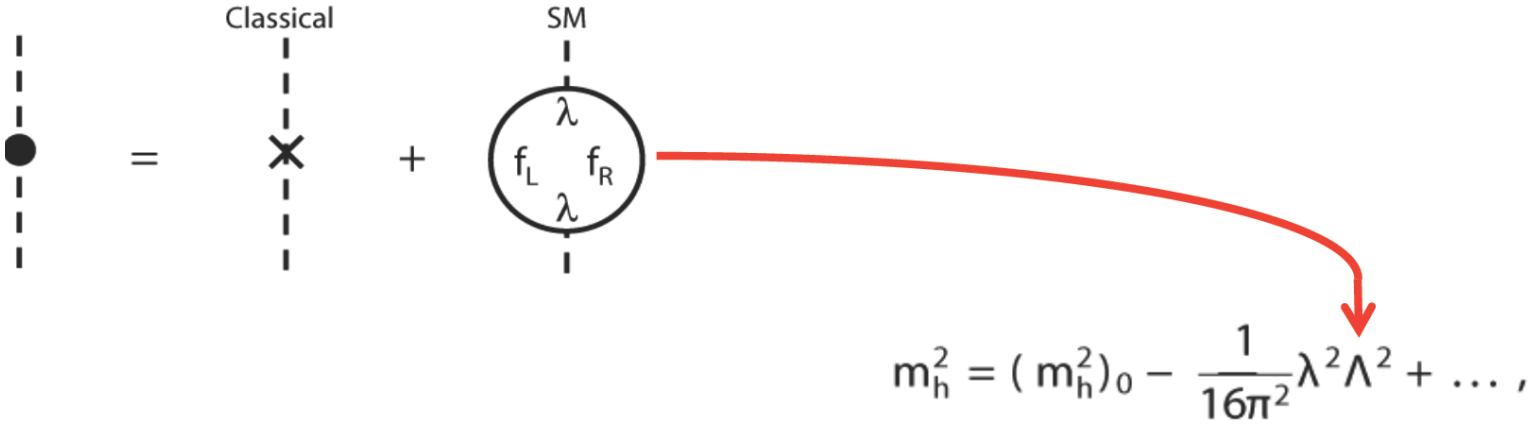
However our observations indicate that we live in a universe of matter, not antimatter.

What happened to the antimatter?

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)
- Miraculous cancelations are needed to keep the Higgs mass ~ 125 GeV



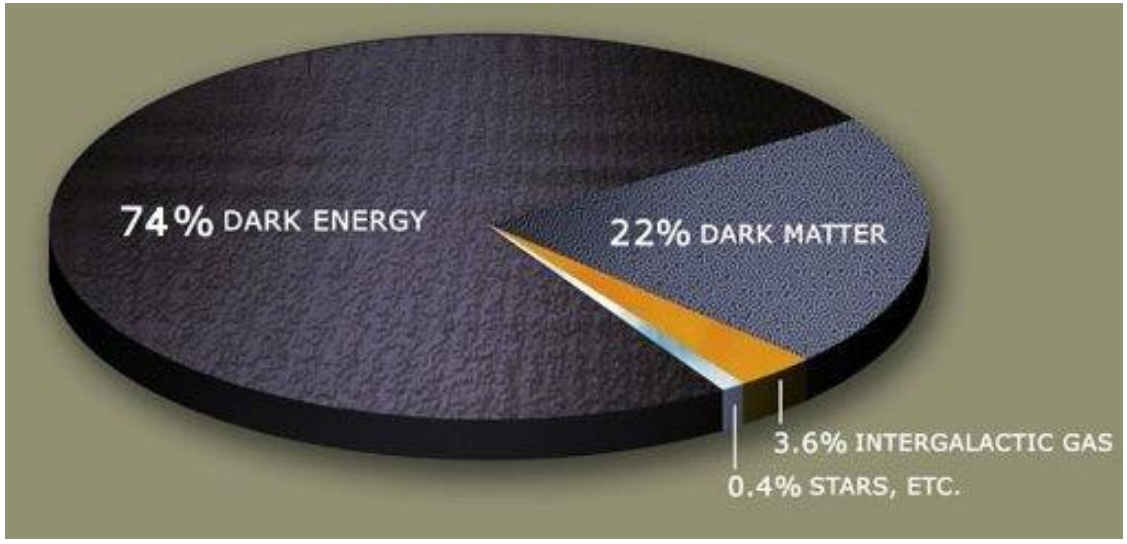
This is known as the hierarchy problem

Dark matter and energy

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

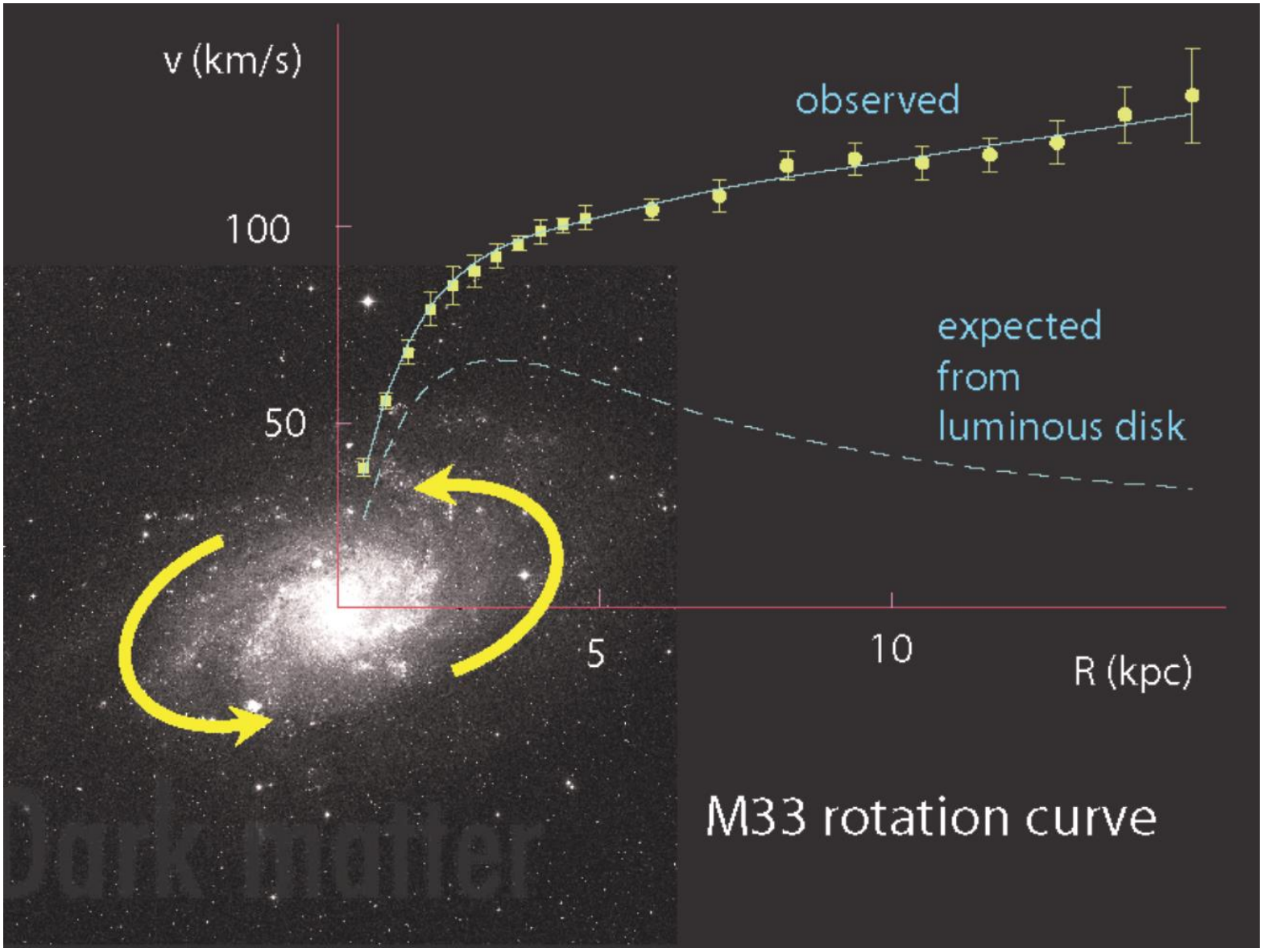
What is the dark stuff which accounts for 96% of the matter-energy of the Universe? Nobody knows.

It is one of the greatest mysteries of science



Dark matter and dark energy

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.

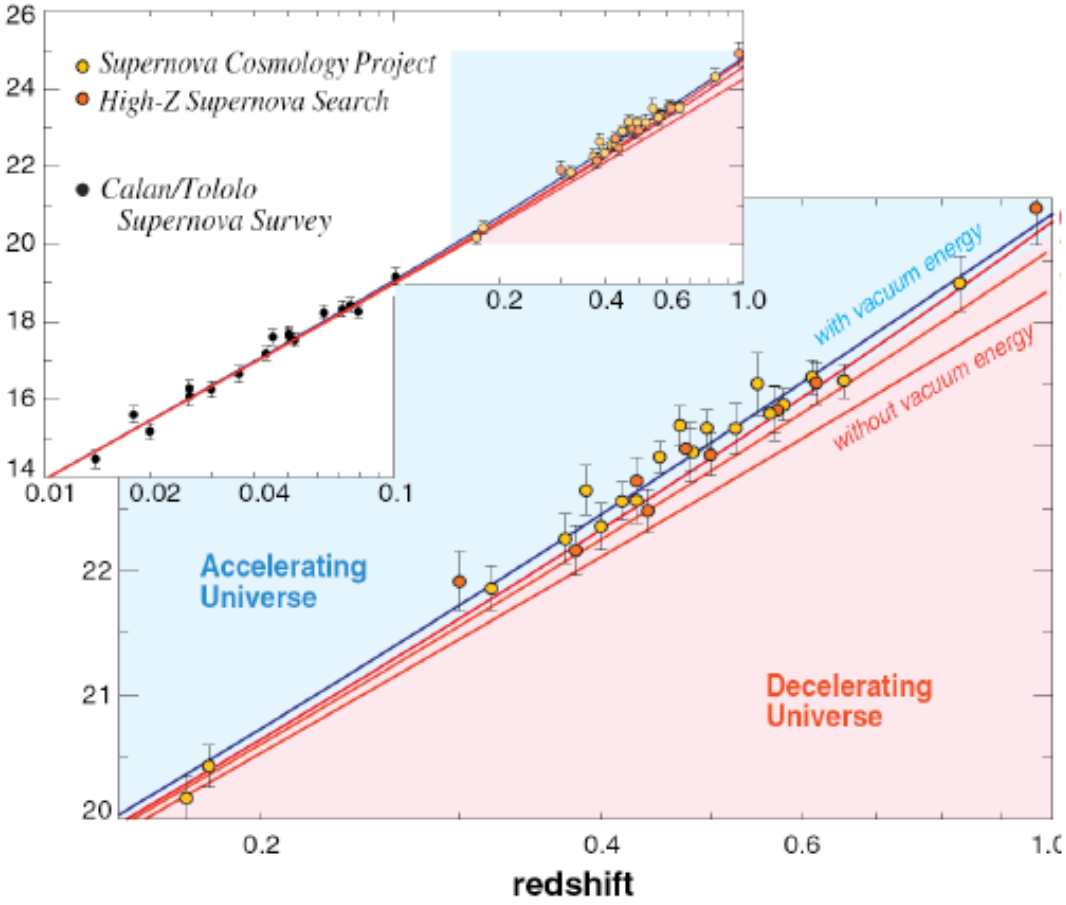
The rest is something else!

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)

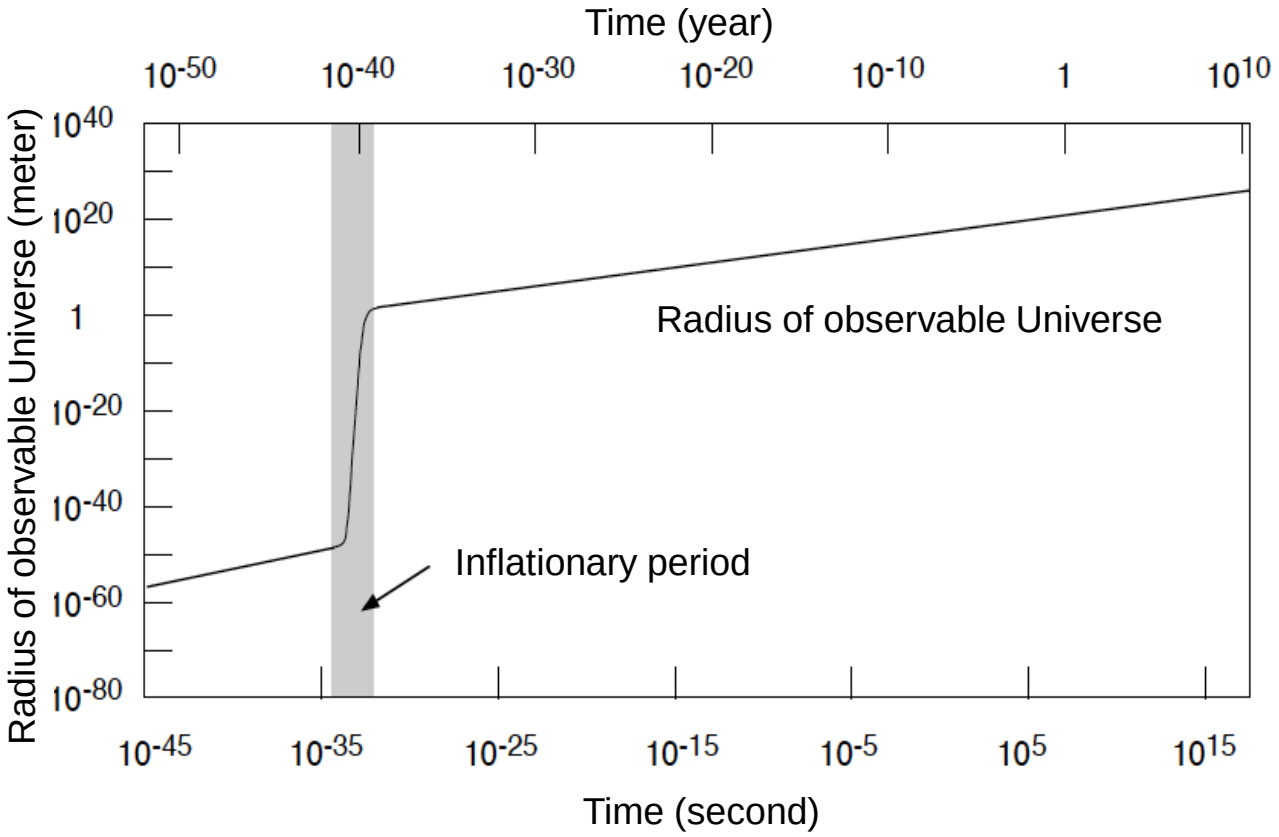
They got the same result:
The Universe expansion is accelerating

General Relativity requires that some form of energy fills space (cosmological constant) to justify accelerated expansion



Cosmological inflation

- **Inflation theory:** in the very early universe, the Universe went through a dramatic exponential expansion.
- It explains why the Universe has a uniform Temperature (3 K) and has a flat geometry

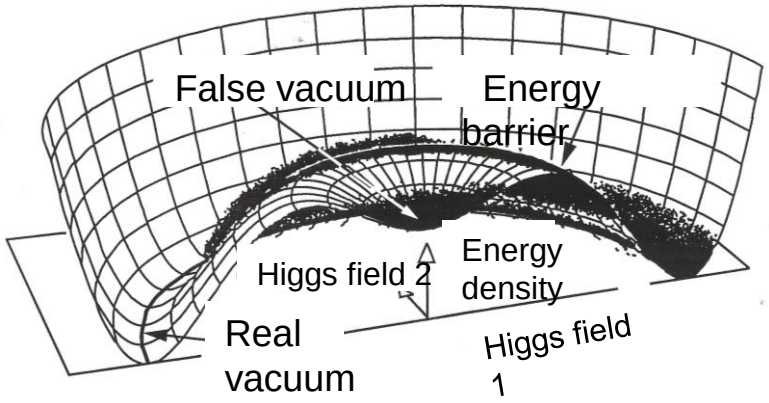


The inflation theory was developed independently in the late 1970's by Alan Guth, Alexey Starobinsky, and others

Higgs field and inflation

Inflation models require a Higgs like field filling the whole space

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



Inflation stops when the Higgs field decays to the minimum energy density.

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

Is Dark Energy due to some kind of Higgs field?

Estimate of vacuum energy density from the SM is 10^{120} times larger than the measured cosmological constant!

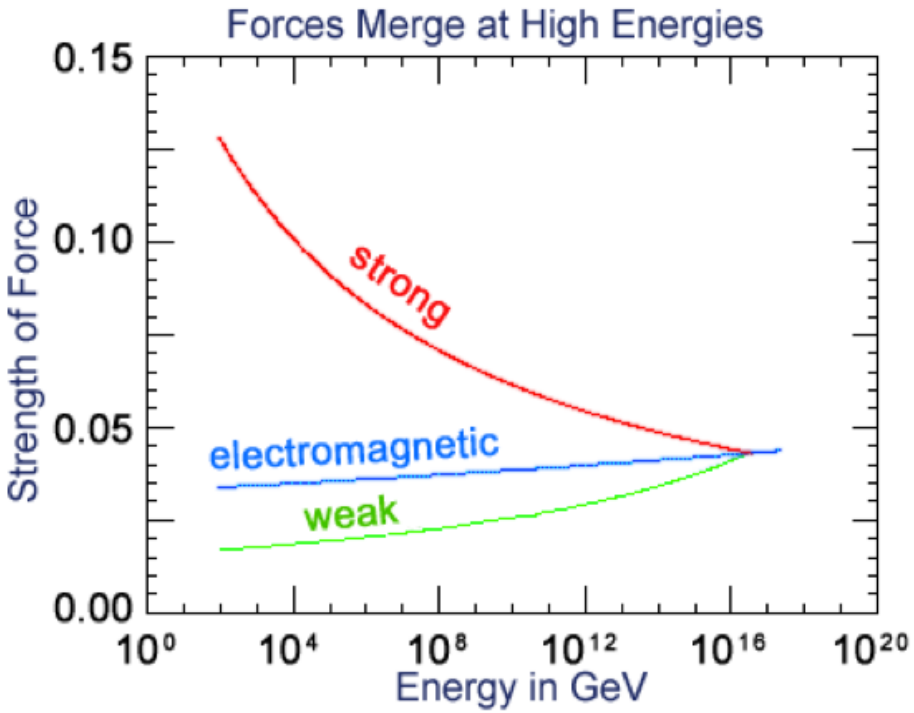
Clearly there is something that we don't understand!

Beyond the Standard Model

Forces and the Grand Unified Theory

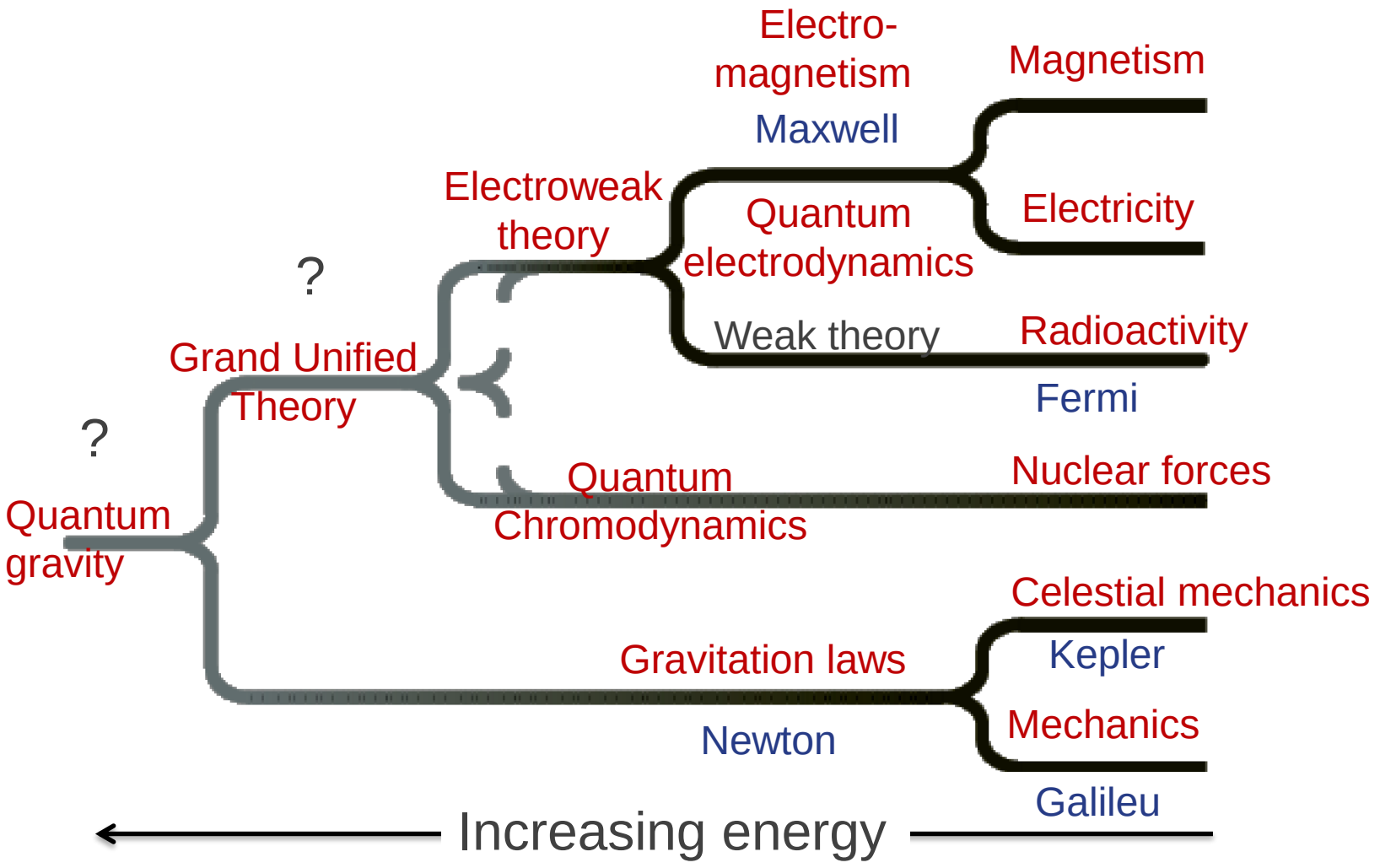
Physicists hope that a Grand Unified Theory will unify the strong, weak, and electromagnetic interactions.

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

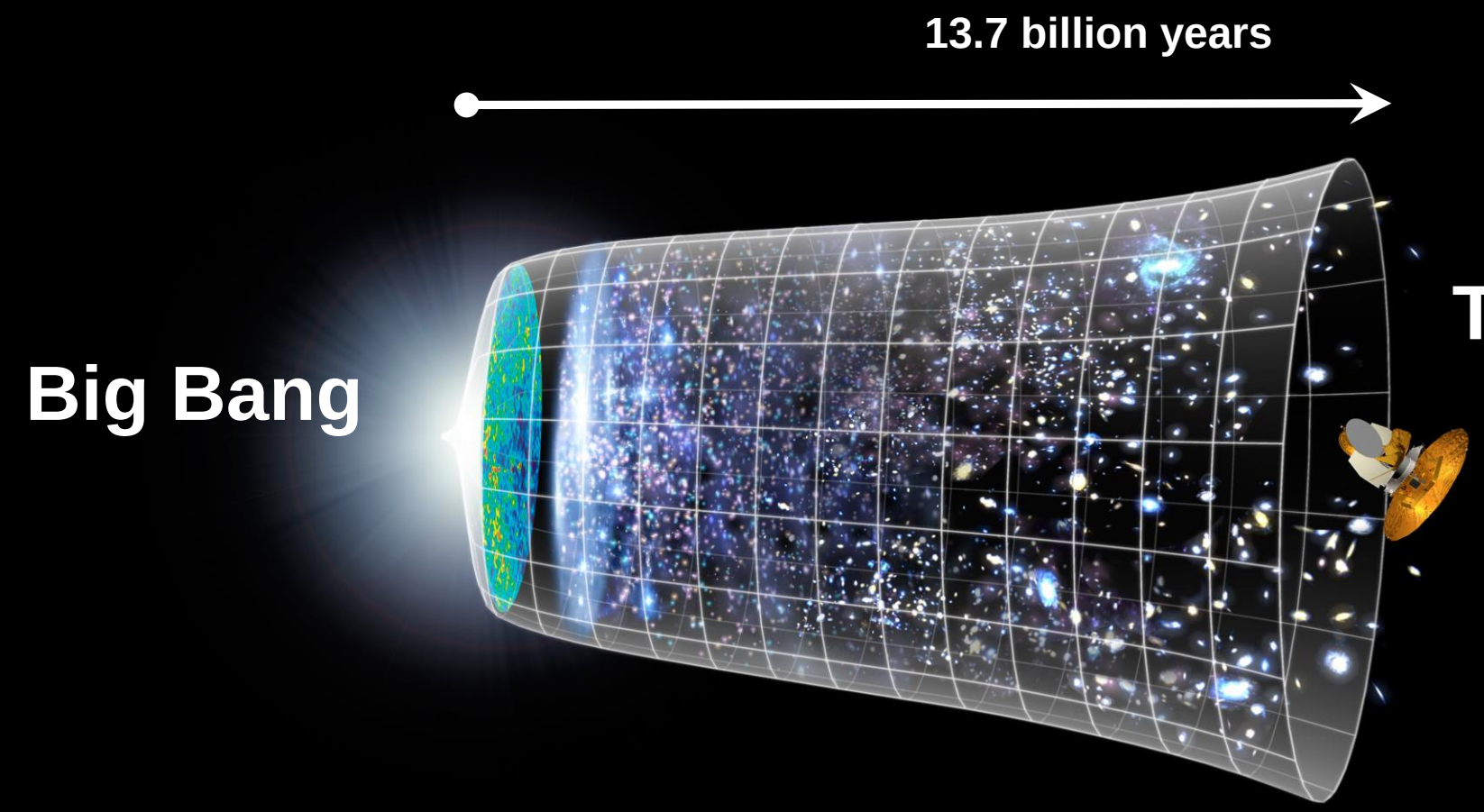


Strangely enough, current data and theory suggests that these varied forces merge into one force when the particles being affected are at a high enough energy.

Unification of the Forces



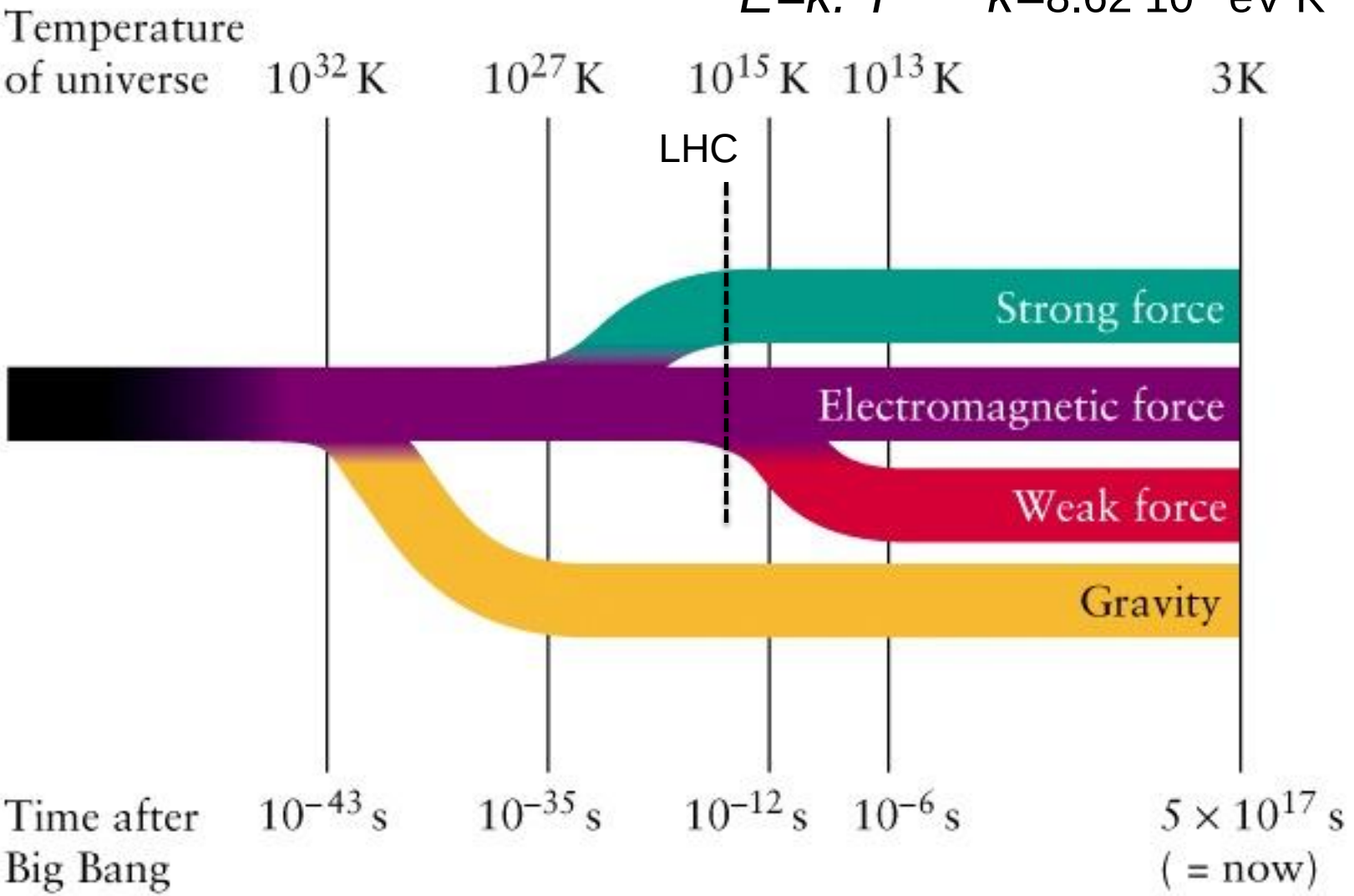
Timeline of the Universe



LHC recreates the conditions one billionth of a second after Big Bang

Forces and expansion of the Universe

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



Supersymmetry

Some physicists have proposed a new fundamental symmetry:

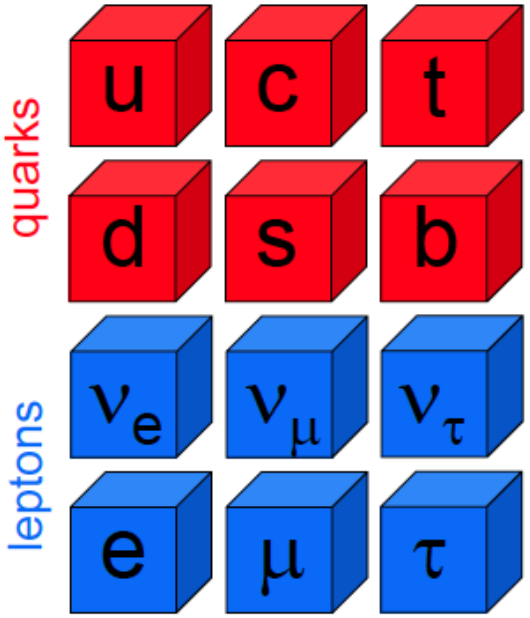
- Every fundamental matter particle should have a massive force particle partner
- Every force particle should have a massive matter particle partner

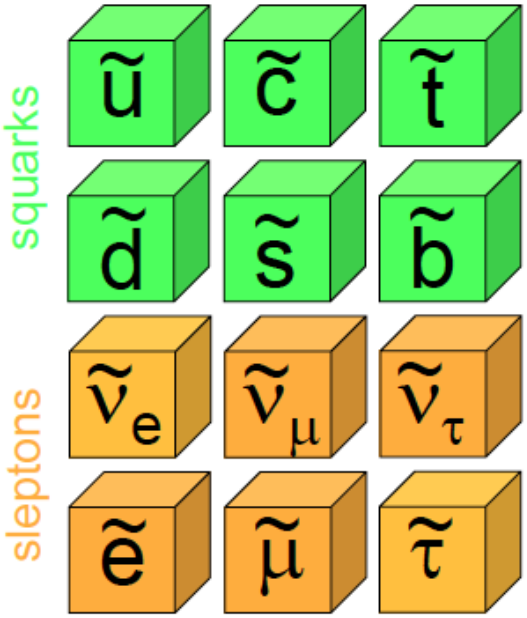
This relationship between matter particles and force carriers is called supersymmetry (**SUSY**)

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?

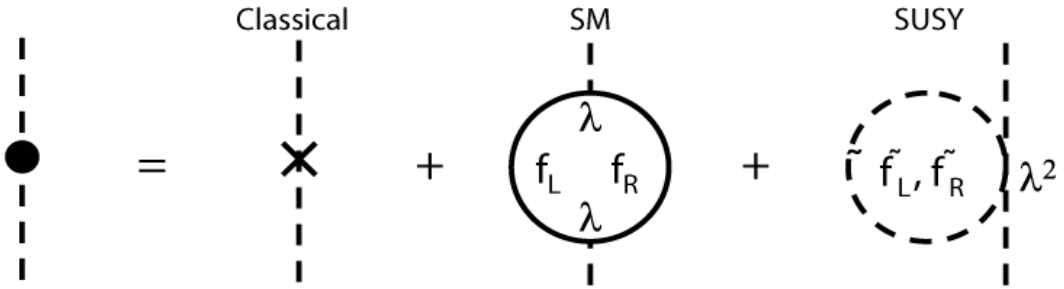




Heavy versions of every quark and lepton
Supersymmetry is broken

The Lightest Susy Particle (LSP) is a candidate to explain Dark Matter.

SUSY and the Higgs mass



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

Natural cancellation

Higgs mass:

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

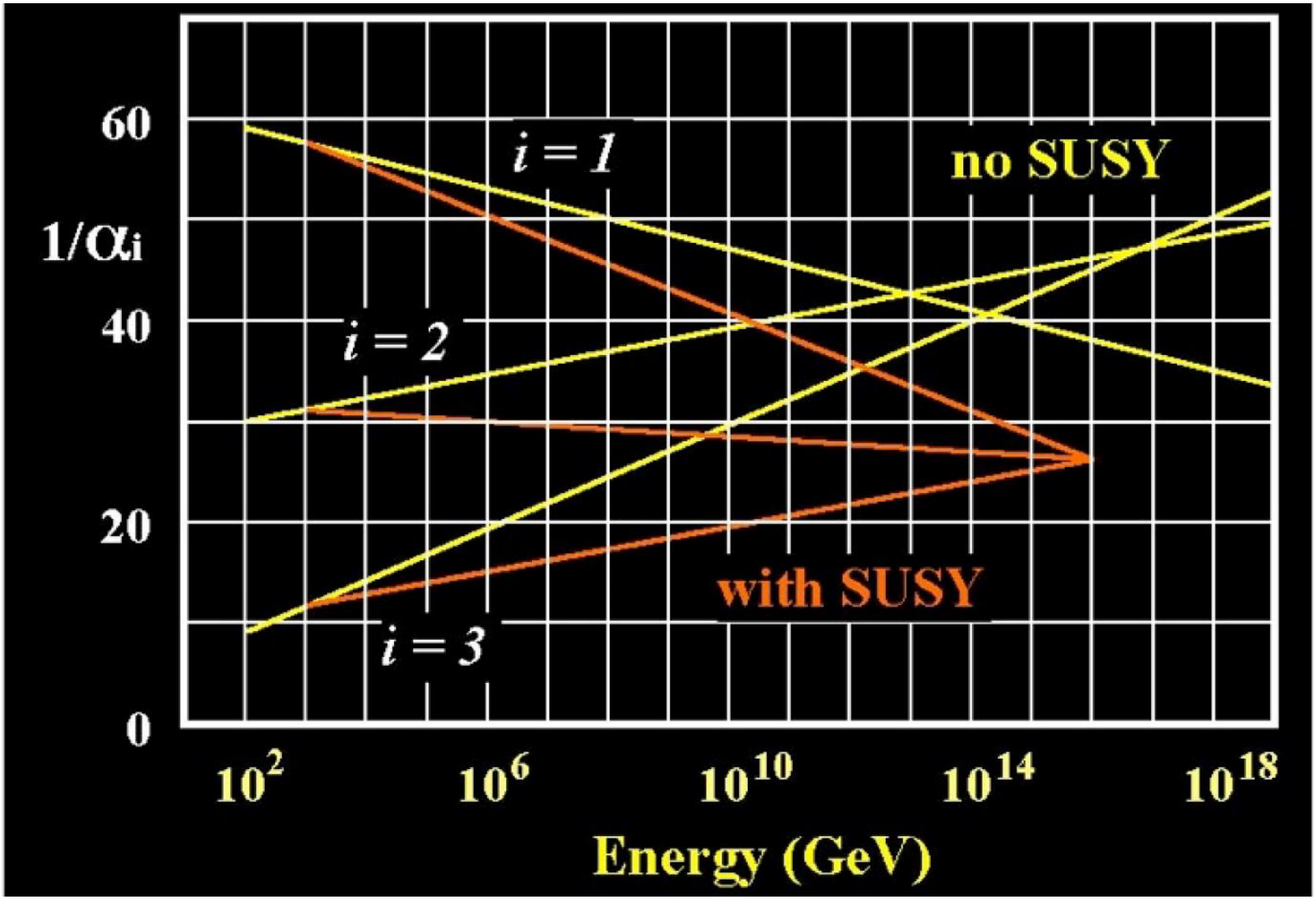
$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \dots$$

$$\approx (m_h^2)_0 + \frac{1}{16\pi^2}(m_{\tilde{f}}^2 - m_f^2)\ln(\Lambda/m_{\tilde{f}}) ,$$

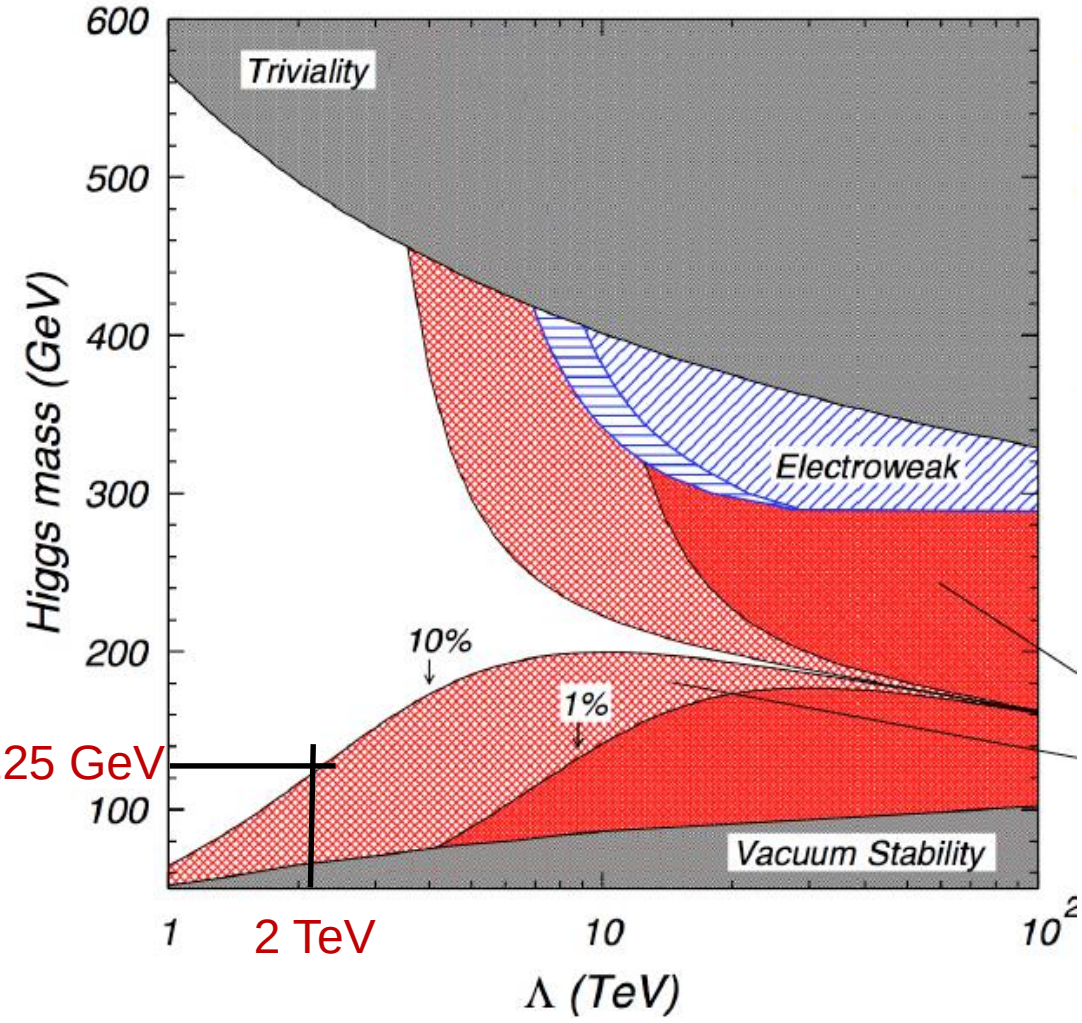
Superpartners fix this:

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

The temptation unification



New physics at a few TeV?



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

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

Still no sign of new physics at LHC…

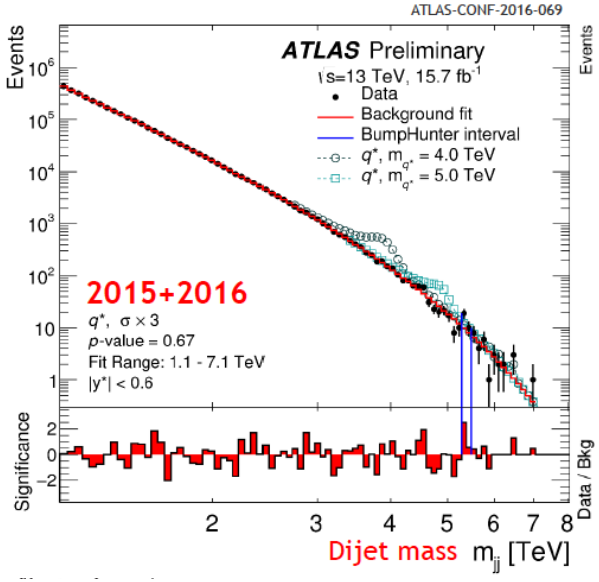
Λ □ Scale of New Physics

No new bumps…

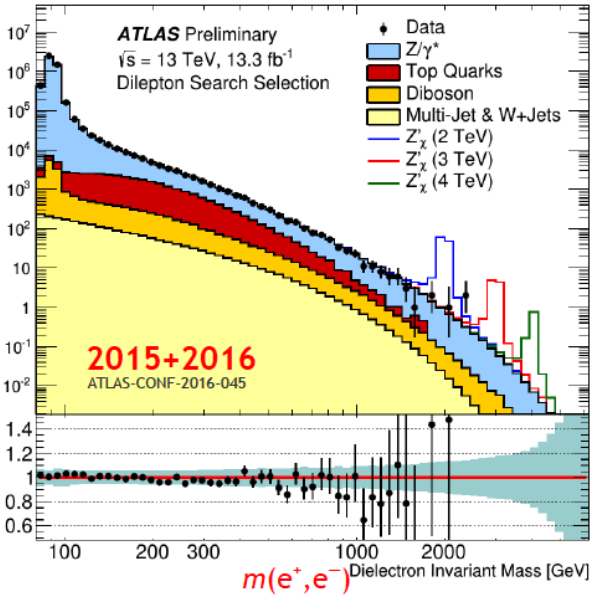
New particles could decay in pairs of quarks (jets), leptons or photons, among others.

The new particle would be revealed by peaks appearing in the mass distribution of the pair.

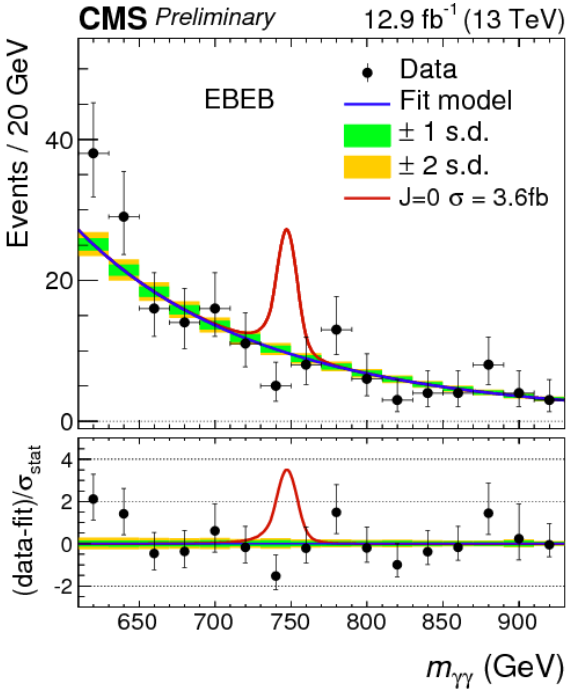
Di-jets



Di-leptons



Di-photons



Future accelerators

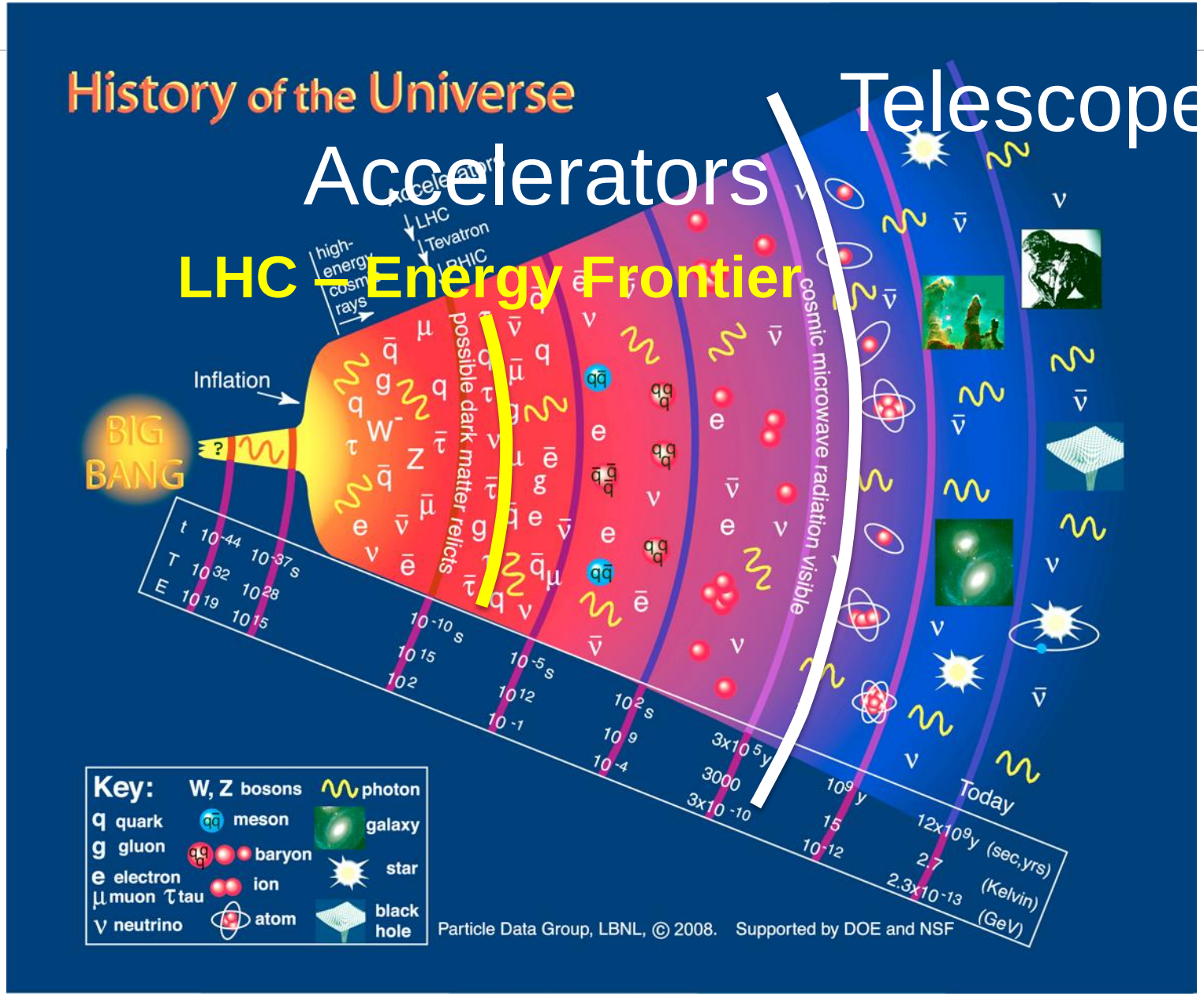
Particle physics is big science

Can't we do this research without increasingly more powerful accelerators?

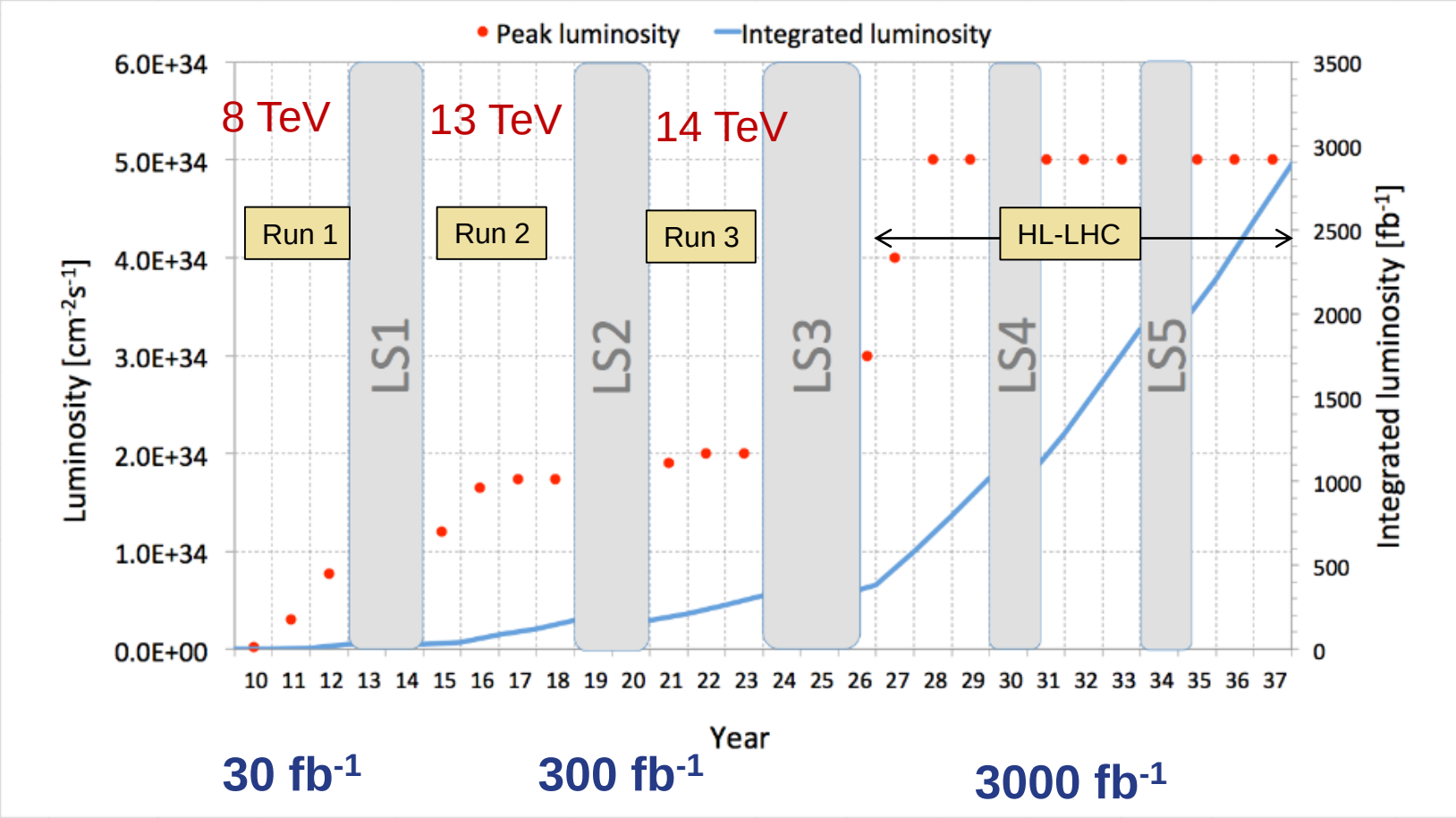
Aren't there subtler ways to unveil the mysteries of Nature?

Unfortunately, to the best of our knowledge the answer to both questions is NO.

Before some unexpected breakthrough(s) happens, this tendency will remain.


History of the Universe
Accelerators
Telescope
LHC – Energy Frontier
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
Today
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
star
e electron
ion
μ muon τ tau
atom
black hole
ν neutrino
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

LHC projections



HL-LHC: High Luminosity LHC

Motivations for HL-LHC

LHC is the highest Energy and highest Luminosity operational collider

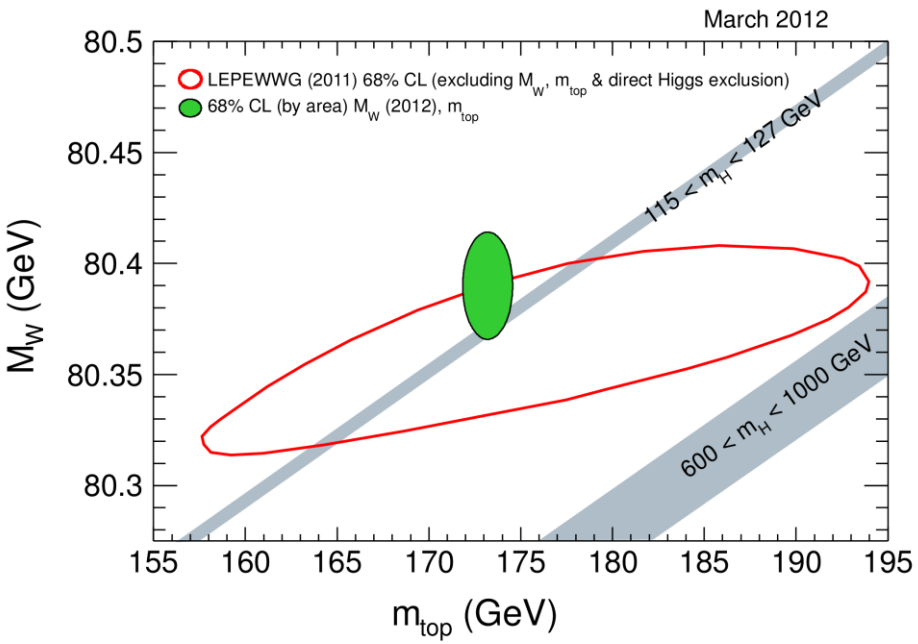
→ full exploitation (E~ 14 TeV, 3000/fb) is mandatory

- ❑ If new physics discovered in Run 2-3:
  - first detailed exploration of new physics with well understood machine and experiments
- ❑ If no new physics in Run 2-3:
  - extend direct discovery potential by ~ 20-30% (up to Mass ~ 8 TeV)
  - In either case: measure Higgs properties to few percent
  - Deviations relative to the SM may point direction to New Physics

The power of precision measurements

The SM establishes a precise relation between the masses of the Higgs, the Top quark and the W boson.

Even before the Higgs discovery the precision measurements of W and Z bosons done in e+e- collisions at LEP and of top quark at the Tevatron had pointed towards a light Higgs.



Measuring deviations of Higgs properties relative to the prediction of the SM provides powerful guidance towards Physics Beyond the SM.

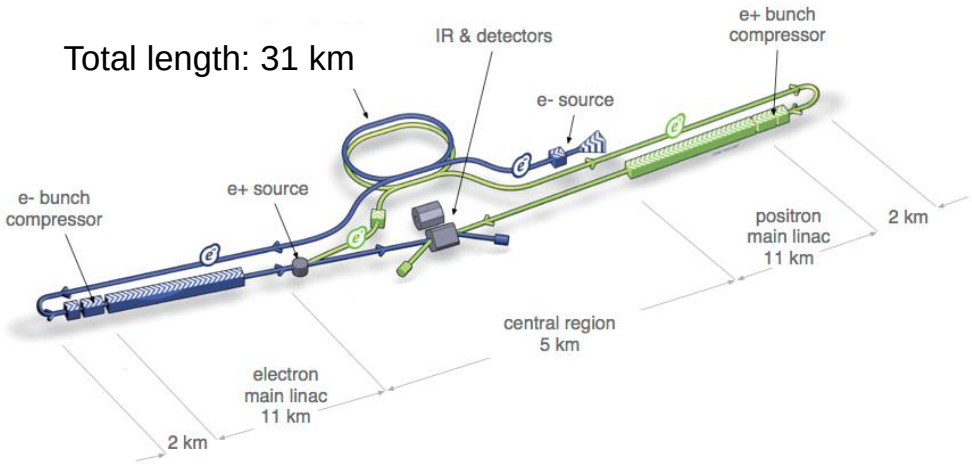
A precision of the order of 0.1-1% will be needed! High luminosity will be needed.

Linear e+e- colliders

International Linear Collider (ILC)

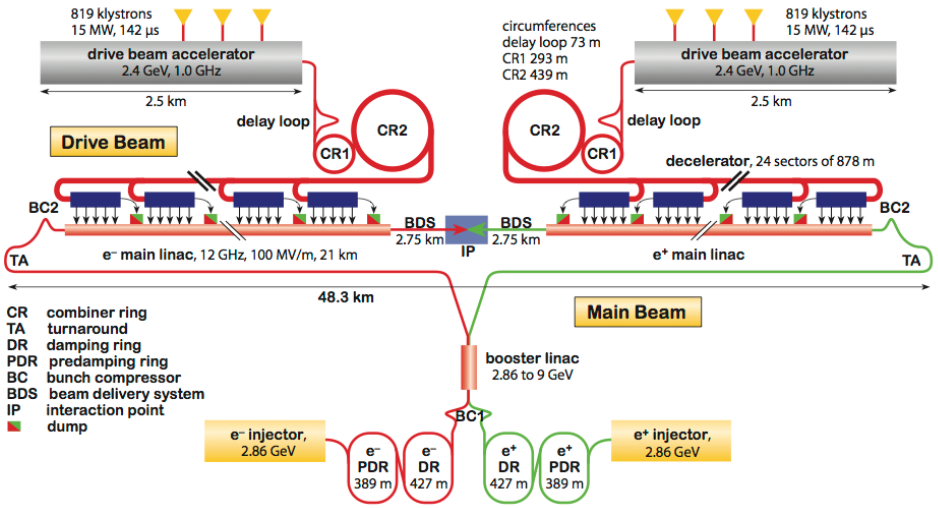
- ❑ 500 GeV machine: ~ 15000 SCRF cavities, 31.5 MV/m
- Mature technology (20 years of R&D experience worldwide).
- Challenges: positron source; final focus (nm-size beams)

- ❑ Prospects
- Japan interested to host
- Construction duration ~10 years → physics could start ~2030



Compact Linear Collider (CLIC)

- ❑ 100 MV/m accelerating gradient needed for compact (50 km) multi-TeV (up to 3 TeV) collider
- ❑ Power consumption (600 MW at 3 TeV): reduction under investigation



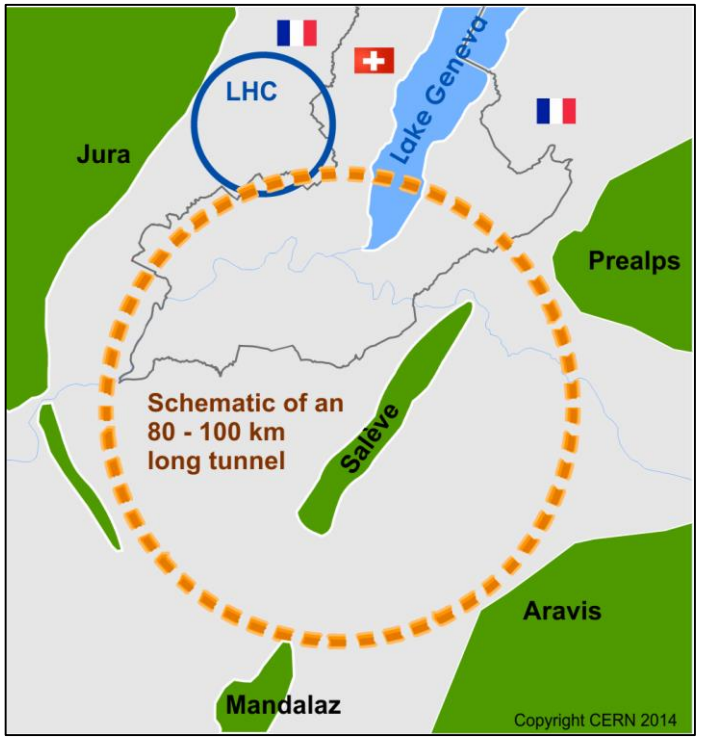
The CERN FCC project

Future Circular Collider in a ~100 km ring:

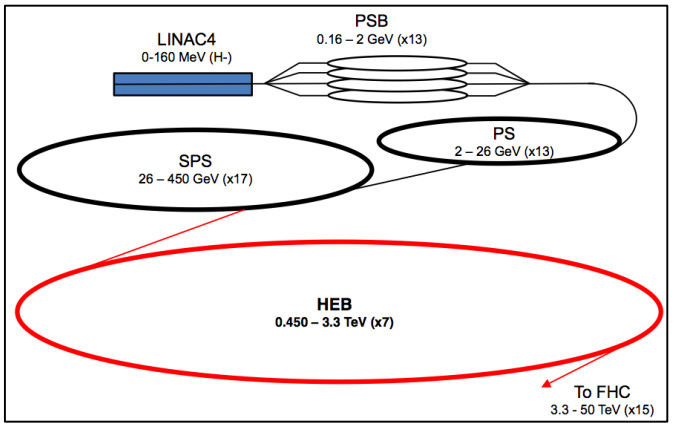
- pp, E = 100 TeV, L~2.5x10^{35}
- intermediate step: e^+e^- (FCC-ee)
  - E=90-350 GeV L=2x10^{36}-2x10^{34}

- Conceptual Design Report in ~2018

- FCC at CERN would greatly benefit from existing infrastructure
- FCC injector chain would be based on existing accelerator complex



90-100 km ring fits geology in Geneva area



Many big technical challenges:

- technology of bending dipoles
- synchrotron radiation
- stored beam energy

Final comments

- The discovery of the Higgs boson opens new paths of exploration and a very broad and challenging experimental program
- New physics: hiding well or beyond present reach ?
- Hadron colliders permit direct exploration of the “energy frontier”
- Precision measurements at High-Luminosity LHC and at future e+e- colliders have great potential to uncover physics beyond the SM
- The full exploitation of the LHC, as well as future high-energy/intensity colliders, are necessary to advance our knowledge of fundamental physics

End