Course on Physics at the LHC

LIP Lisbon, February - June 2016

IDPASC

LIP

Program

The standard model of particle physics	João Varela (LIP, IST)	22, 24, 26 February
Detector physics and experimental methods	Michele Gallinaro (LIP), Pedro Silva (CERN)	29 February, 7 March
Statistical methods in data analysis	Pietro Vischia (LIP)	14 March
Top quark physics	Michele Gallinaro (LIP), António Onofre (LIP, UM))	21 March, 4, 11 April
Standard model Higgs and beyond	Pedro Silva (CERN), André David (CERN), Patricia Muino (LIP), Ricardo Gonçalo (LIP)	18 April 2, 10, 16 May
Supersymmetry	Pedrame Bargassa (LIP)	23, 30 May
B physics and rare decays	Nuno Leonardo (LIP)	6 June
Heavy ions, polarization	João Seixas (LIP, IST), Pietro Faccioli (LIP)	13 June

The lectures will take place on Mondays, between 17:00 and 18:30 at LIP,
Av. Elias Garcia, 14 r/c, 1000 Lisbon - Portugal

More info at
http://idpasc.lip.pt/LIP/events/2016_lhc_physics

Course coordinator: João Varela, Michele Gallinaro (LIP, IST)

Introduction

Specialized course on the Physics at the Large Hadron Collider organized by LIP in the framework of IDPASC.

The objective of the Course is to introduce the physics, analysis methods and results on the physics of the LHC experiments.

Emphasis is placed on the search for new physics.

Benchmark channels in proton-proton collisions will be discussed in detail:
- identification of the objects involved
- signal and background properties
- background estimation and S/B discriminants
- estimation of systematical errors
- extraction and interpretation of the final results

Required background

The course is intended for under-graduate or graduate students having basic training in Particle Physics:

Basic concepts
Elementary constituents of matter and interactions. Quantum numbers and conservation rules. Spin and symmetry groups. Relativistic kinematics. Cross-section. Natural units. Mass and lifetime. Resonances.

Structure of matter
Elastic scattering and form factors. Inelastic scattering experiments. Nucleon structure functions. Scale invariance. Quark model. Parton distribution functions. Introduction to QCD.

Fundamental interactions
Introduction to QED. Fermi interaction. Parity violation. Currents V-A and weak doblets. W and Z bosons. Cabibbo angle. Neutral currents. Electroweak interaction. Gauge symmetries. The Higgs mechanism. Weinberg-Salam model. CP violation.

Background bibliography

F. Halzen and A.D.Martin, ' Quarks and Leptons ', John Wiley and Sons (1984)

D. Griffiths, ' Introduction to Elementary Particles ', John Wiley and Sons (1987)

B.R.Martin, G. Shaw, ' Particle Physics ', John Wiley and Sons (1999)

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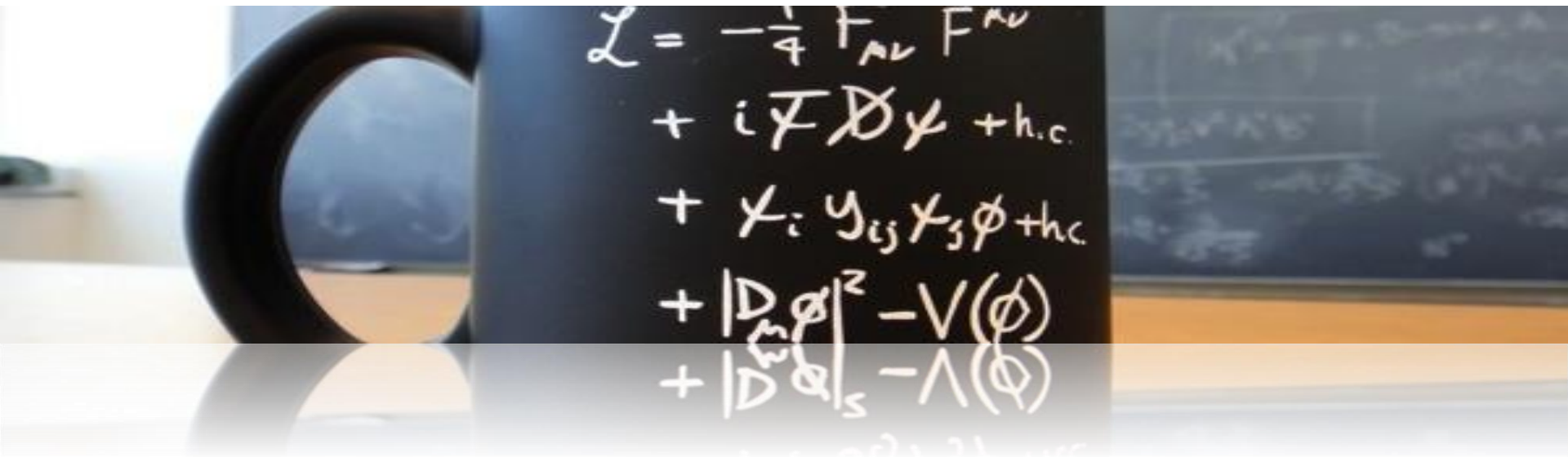
Particle physics is a modern name for the centuries old effort to understand the basics laws of physics.

Edward Witten

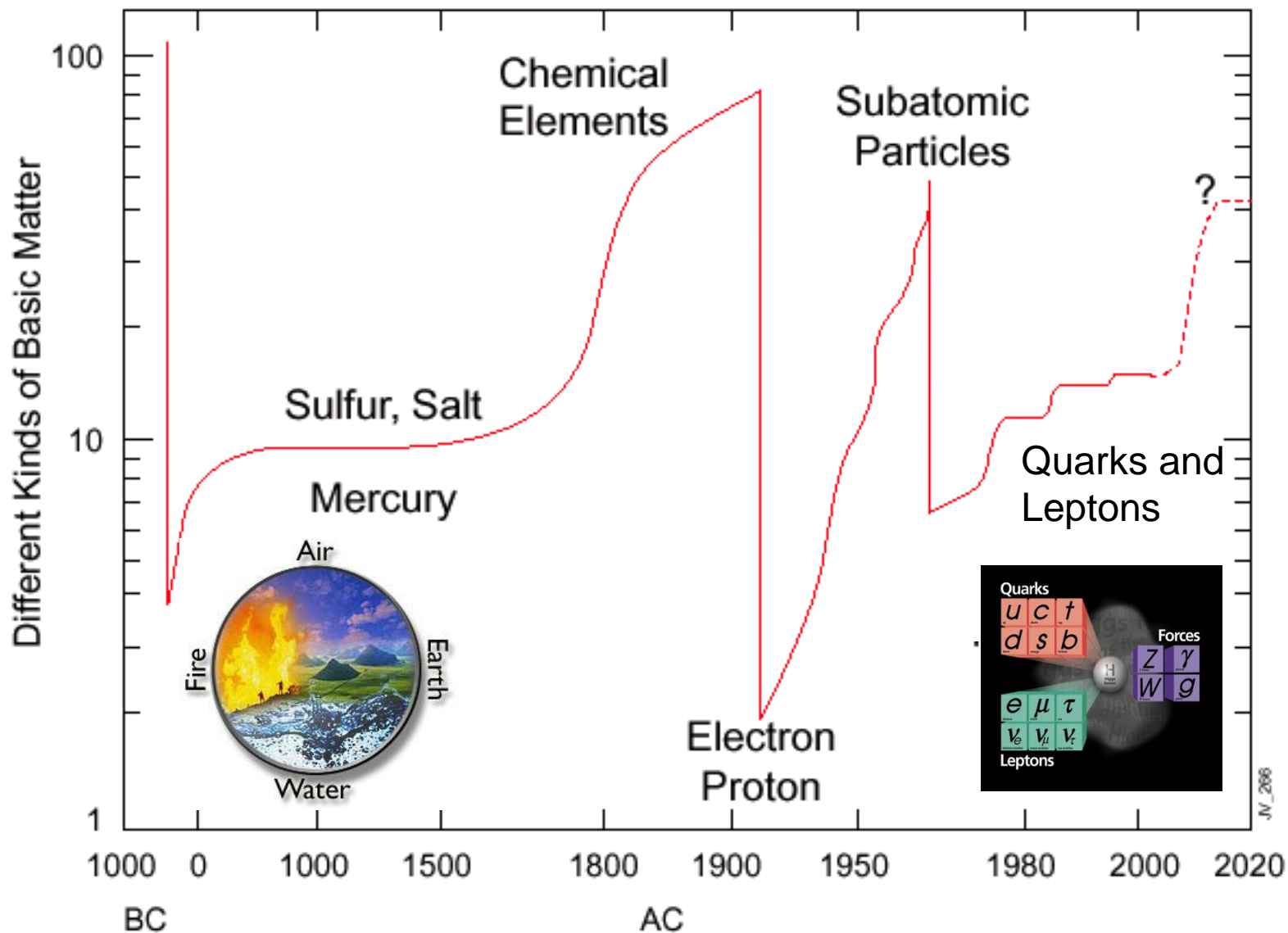Aims to answer the two following questions:

What are the elementary constituents of matter ?

What are the forces that determine their behavior?

Experimentally
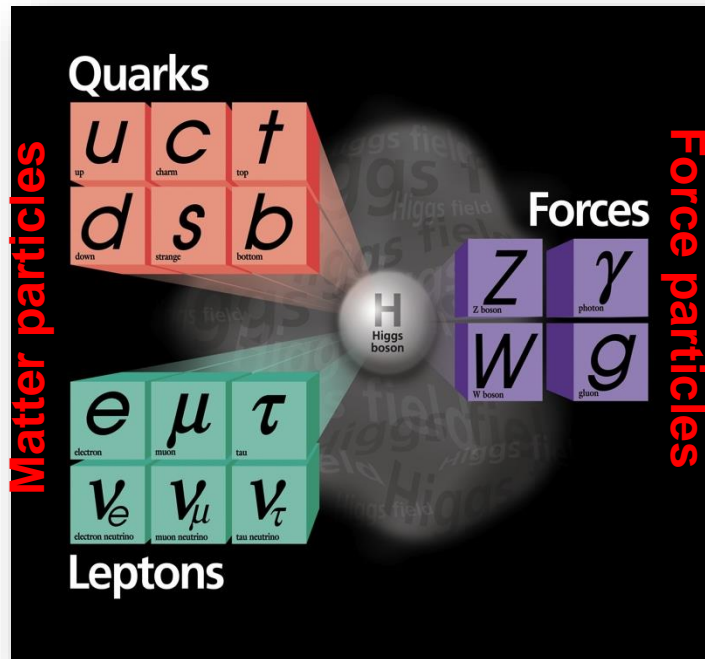   Get particles to interact and study what happens

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
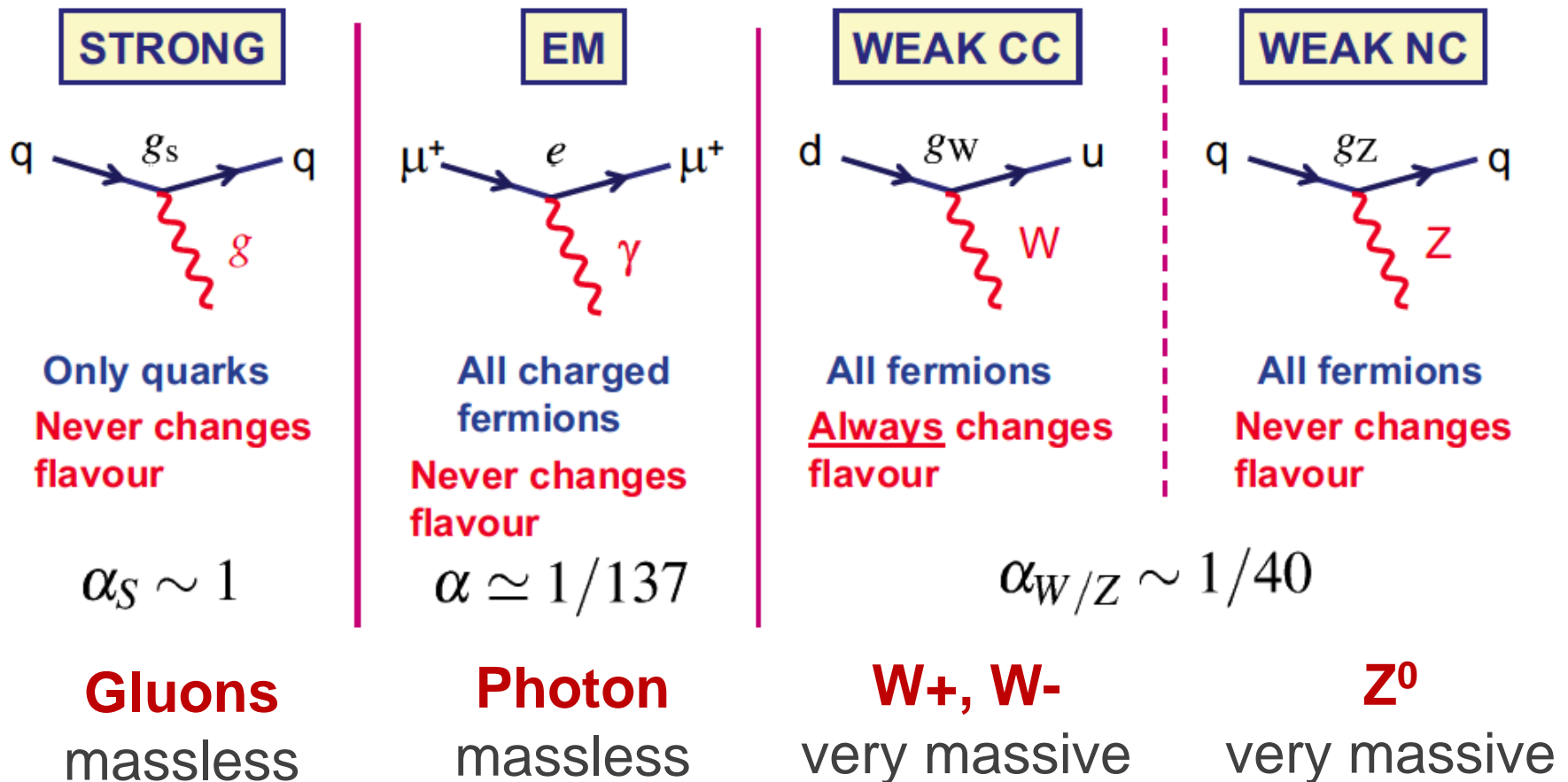

One of the greatest achievements of 20th Century Science

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

Standard model interactions

The interaction of gauge bosons with fermions is described by the Standard Model

| STRONG	EM	WEAK CC	WEAK NC
$q \xrightarrow{g_s} q$ with g	$\mu^+ \xrightarrow{e} \mu^+$ with γ	$d \xrightarrow{g_W} u$ with W	$q \xrightarrow{g_Z} q$ with Z
Only quarks	**All charged fermions**	**All fermions**	**All fermions**
Never changes flavour	**Never changes flavour**	**Always changes flavour**	**Never changes flavour**
$\alpha_S \sim 1$	$\alpha \simeq 1/137$	$\alpha_{W/Z} \sim 1/40$	
Gluons massless	**Photon** massless	**W+, W-** very massive	**Z^0** very massive

Quantum field theory

A particle-antiparticle pair can pop out of empty space ("the vacuum") and then vanish back into it

These are *Virtual* particles.
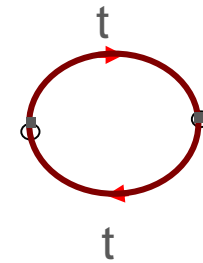
Vacuum Fluctuation
Involving top quarks

Other examples of Virtual particles:
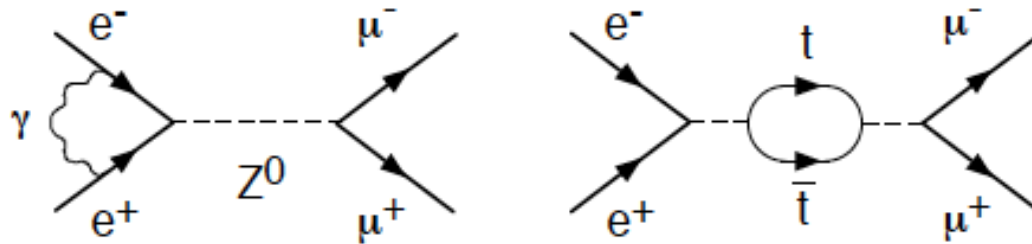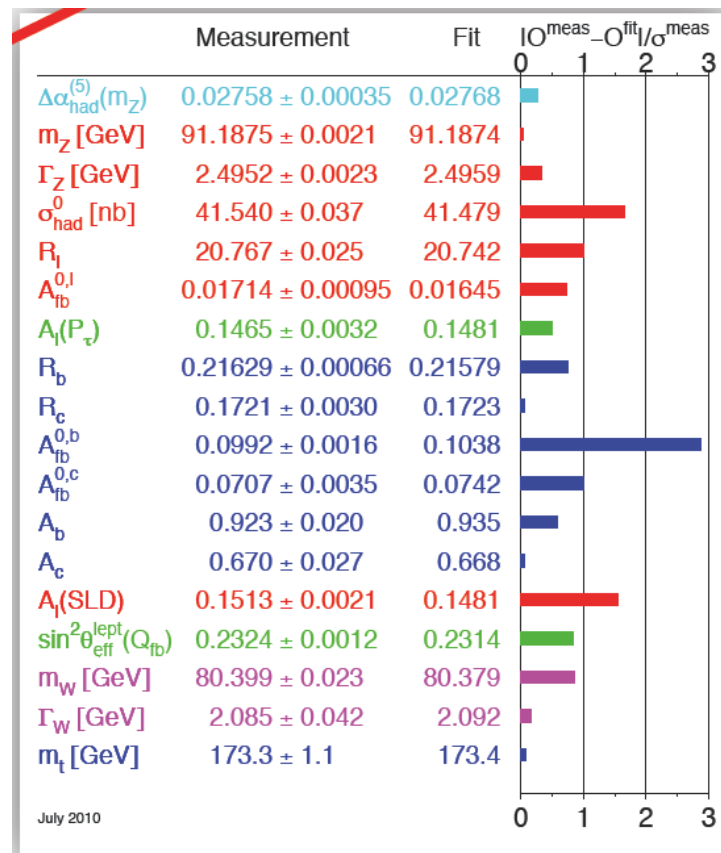

This has far-reaching consequences

The structure of the universe depends on particles that ***don't exist in the usual sense***

SM confirmed by data

STANDARD MODEL OF ELEMENTARY PARTICLES

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \slashed{D} \psi + h.c.$$

	Measurement	Fit	$|O^{meas}-O^{fit}|/\sigma^{meas}$ 0 1 2 3
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959	
σ_{had}^{0} [nb]	41.540 ± 0.037	41.479	
R_l	20.767 ± 0.025	20.742	
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481	
R_b	0.21629 ± 0.00066	0.21579	
R_c	0.1721 ± 0.0030	0.1723	
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038	
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
$A_l(SLD)$	0.1513 ± 0.0021	0.1481	
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.399 ± 0.023	80.379	
Γ_W [GeV]	2.085 ± 0.042	2.092	
m_t [GeV]	173.3 ± 1.1	173.4	

July 2010

Confirmed at sub 1% level!

A "funny" thing happened on the way to the modern theory of quarks, leptons, force fields, and their quanta:

The equations only made sense if all the bosons, and all the quarks and leptons, had no mass and moved at the speed of light!

In the simplest model the interactions are symmetrical and particles do not have mass

The symmetry between the electromagnetic and the week interactions is broken:
- Photon do not have mass
- W, Z do have a mass ~ 80-90 GeV

Higgs mechanism:
mass of W and Z results from the interactions with the Higgs field

Non-zero average value of the Higgs field can also give masses to the quarks, electrons and muons – to all point-like particles.

Old theoretical problem affecting the quantum theory of the weak force :

the probability of two W's interacting becomes larger than 1 at high energies (> 1 TeV).

This is solved by the Higgs field!

$$\lim_{E \to \infty} \mathcal{A} \propto E^2$$

+

$$\lim_{E \to \infty} \mathcal{A} \propto \text{const.}$$
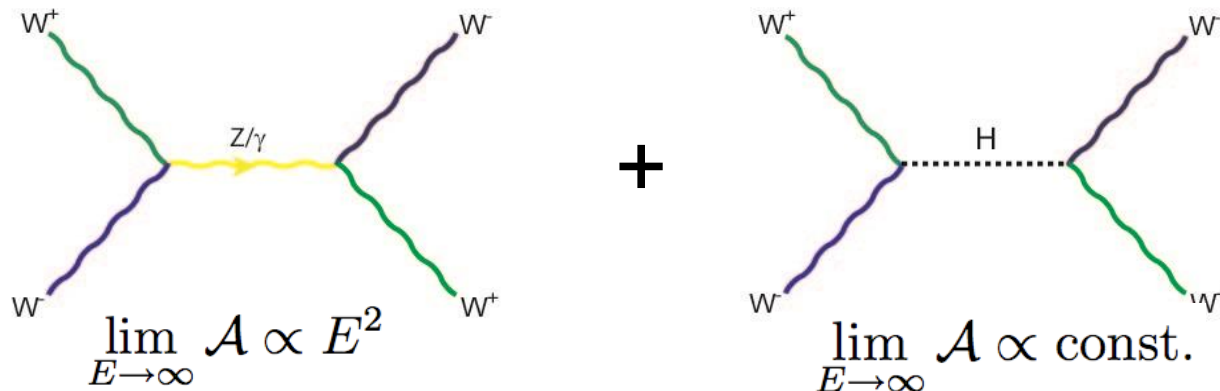
Beyond the standard model

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.

Why do we observe matter and almost no antimatter if we believe there is a symmetry between the two in the universe?

What is this "dark matter" that we can't see that has visible gravitational effects in the cosmos?

Are quarks and leptons actually fundamental, or made up of even more fundamental particles?

Why are there three generations of quarks and leptons? What is the explanation for the observed pattern for particle masses?

How does gravity fit into all of this?

Forces and expansion of the Universe

$E = k \cdot T$ $k = 8.62 \; 10^{-5}$ eV K^{-1}

Temperature
of universe 10^{32} K 10^{27} K 10^{15} K 10^{13} K   3 K

LHC

Strong force

Electromagnetic force

Weak force

Gravity

Time after
Big Bang 10^{-43} s 10^{-35} s 10^{-12} s 10^{-6} s 5×10^{17} s
(= now)
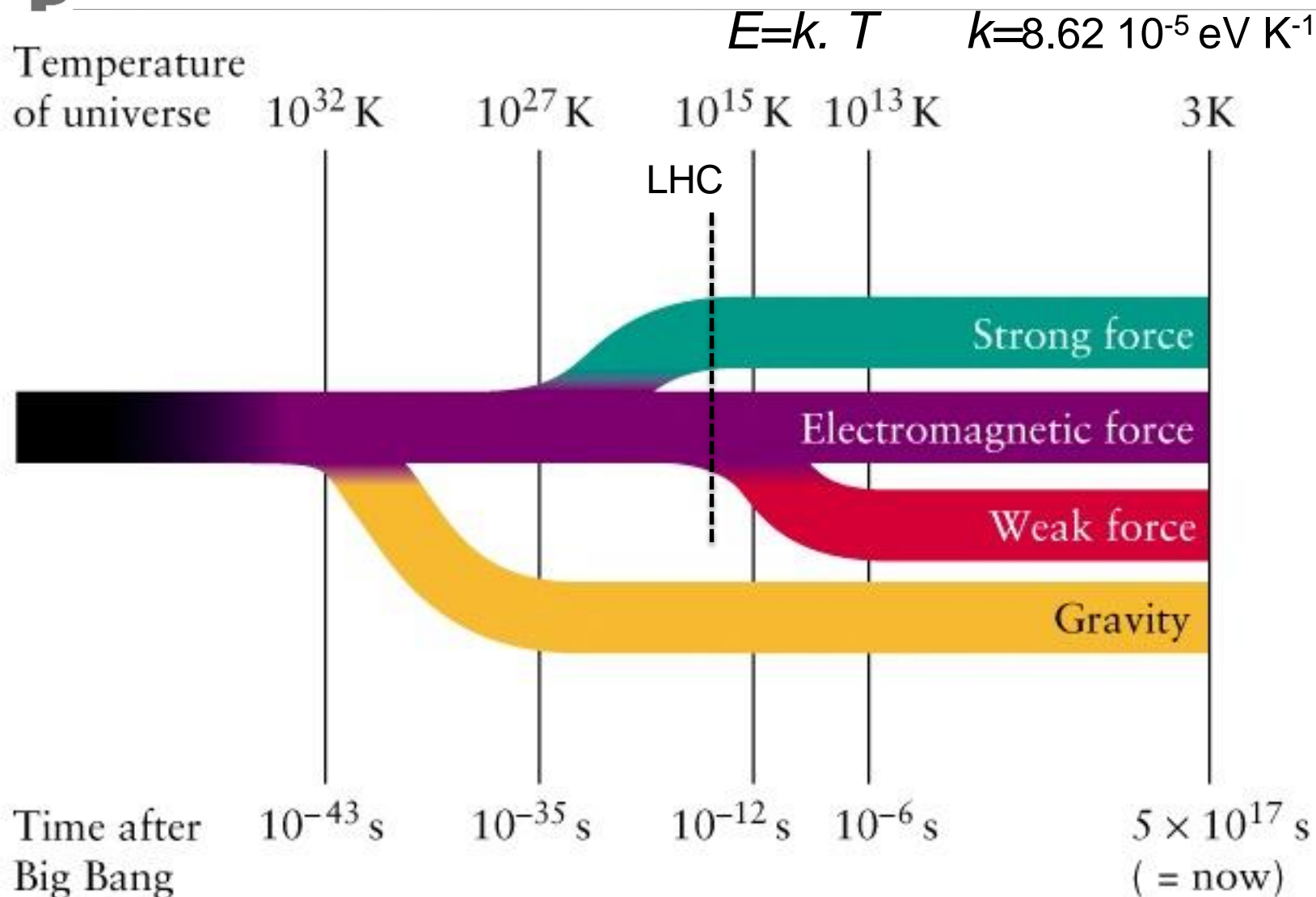
The dark side of the Universe

Long standing problem:

We know that ordinary matter is only ~4% of the matter-energy in the Universe.

What is the remaining 96%?

M33 rotation curve
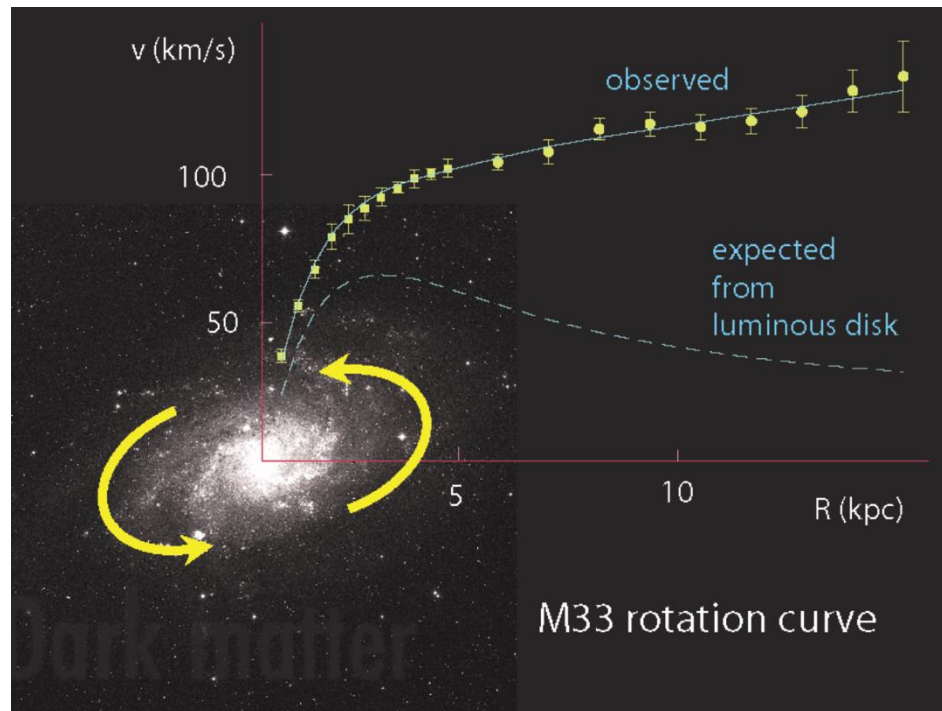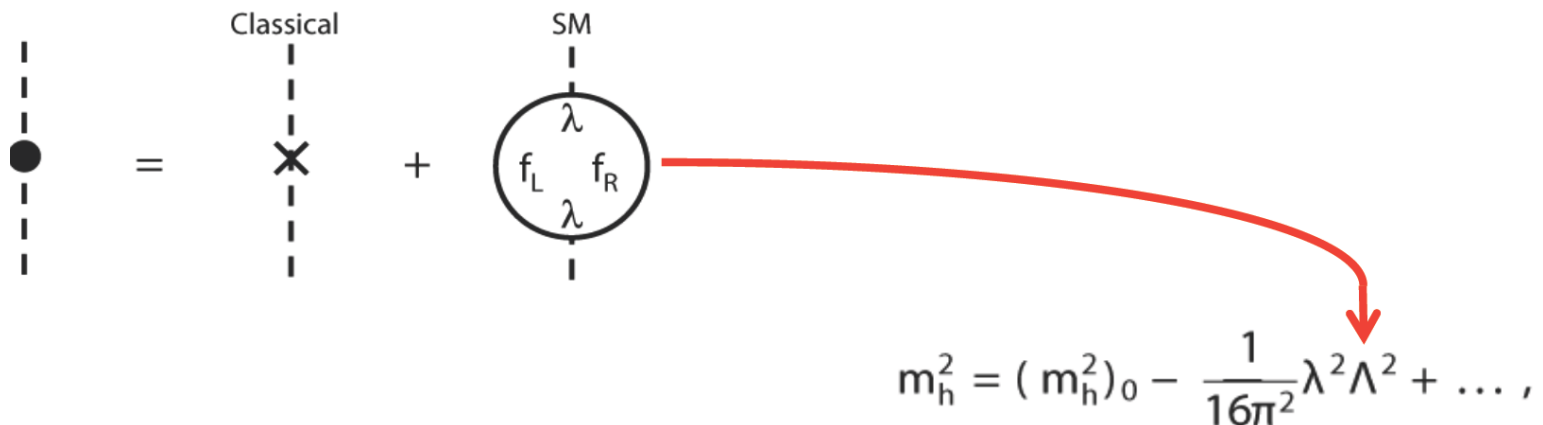
The LHC may help to solve this problem, discovering **dark matter**

Higgs and hierarchy problem

In the SM the Higgs mass is a huge problem:

- Virtual particles in quantum loops contribute to the Higgs mass
- Contributions grow with Λ (upper scale of validity of the SM)
- Λ could be huge – e.g. the Plank scale (10^{19} GeV)
- Miraculous cancelations are needed to keep the Higgs mass < 1 TeV

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

This is known as the hierarchy problem

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
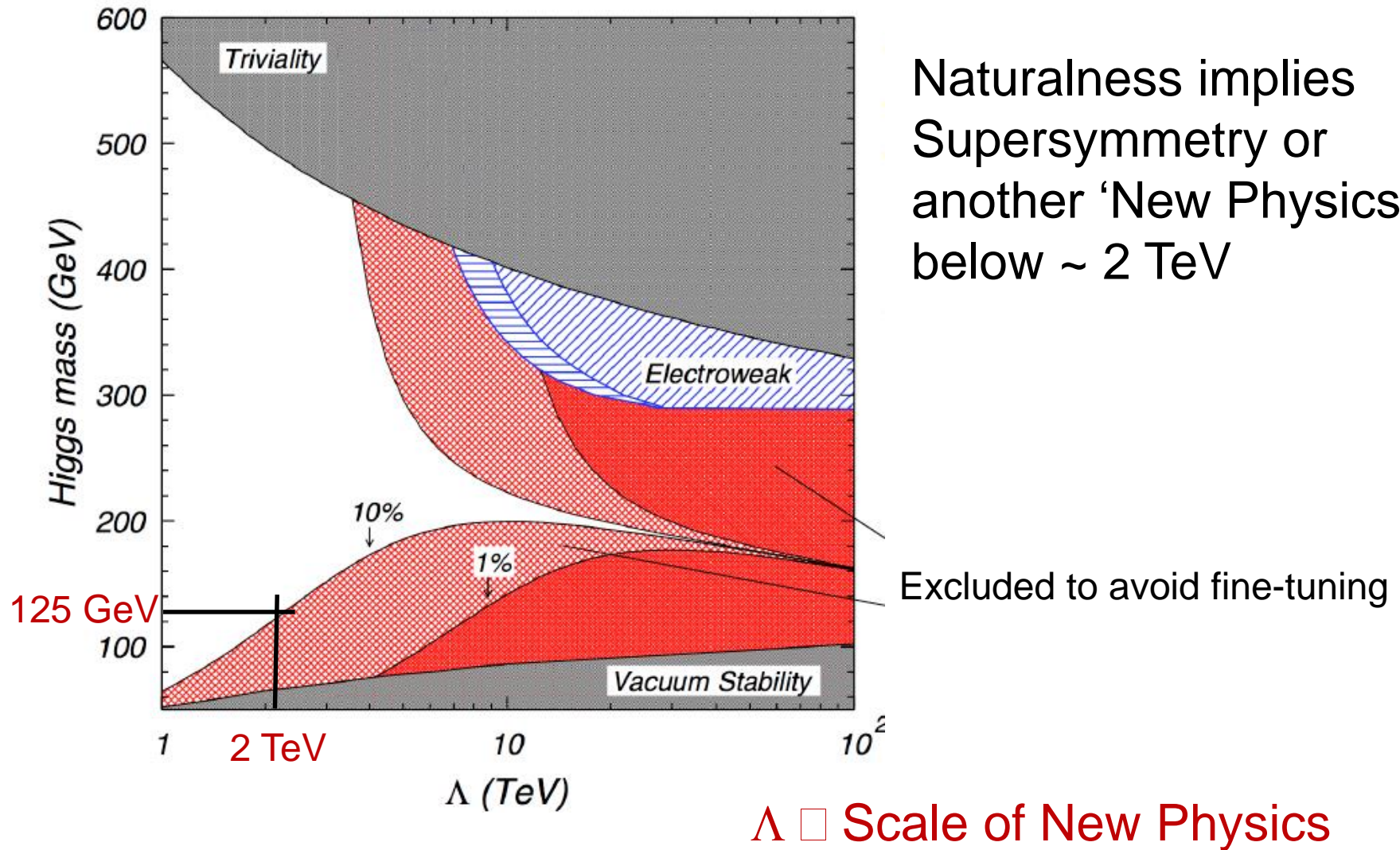
Many possible theories

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
- Compositeness

Any of this could still be found at the LHC

Supersymmetry

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

- Every fermion should have a massive "shadow" boson
- Every boson should have a massive "shadow" fermion.

This relationship between fermions and bosons is called supersymmetry (SUSY)

No supersymmetric particle has yet been found, but experiments at LHC could detect supersymmetric partner particles.

Particles
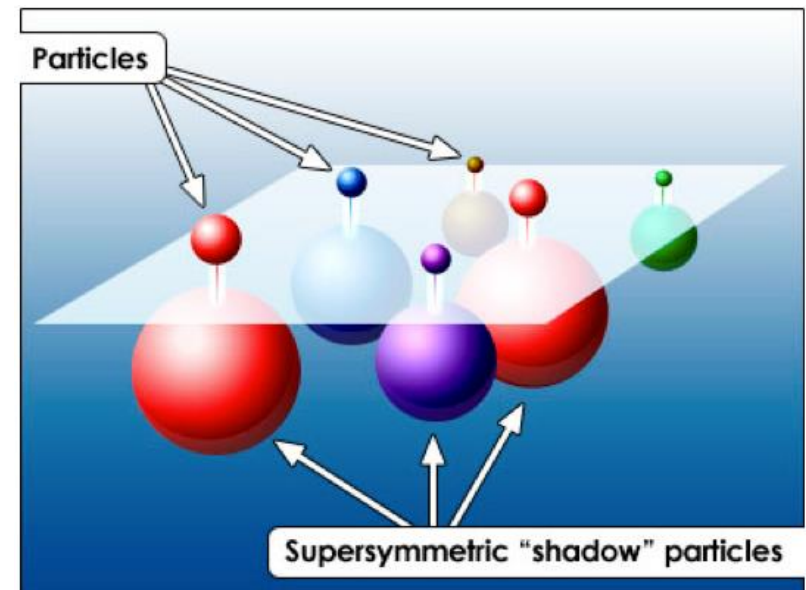
Supersymmetric "shadow" particles

Double the whole table with a new type of matter?
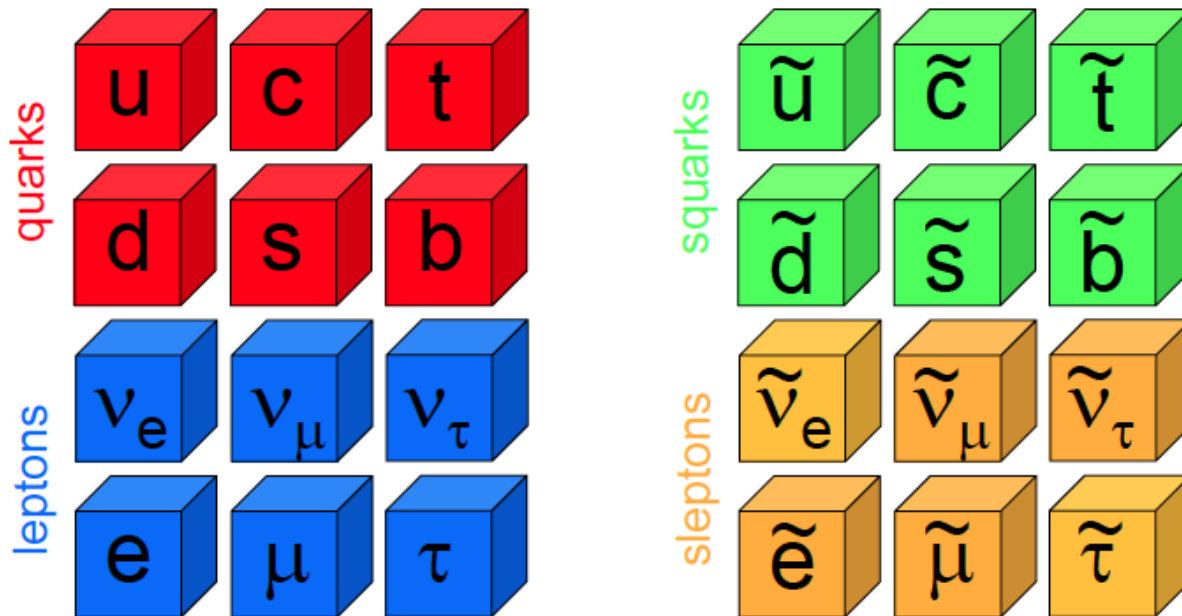
Heavy versions of every quark and lepton
Supersymmetry is broken

Could DM be SUSY particles?

For every "normal" force quanta (boson), there are supersymmetric partners:

photon	photino
W, Z bosons	Wino, Zino
gluon	gluino
Higgs boson	higgsino

These "…inos" are prime suspects to be the galactic dark matter!

Relics from the Big Bang!

The temptation unification
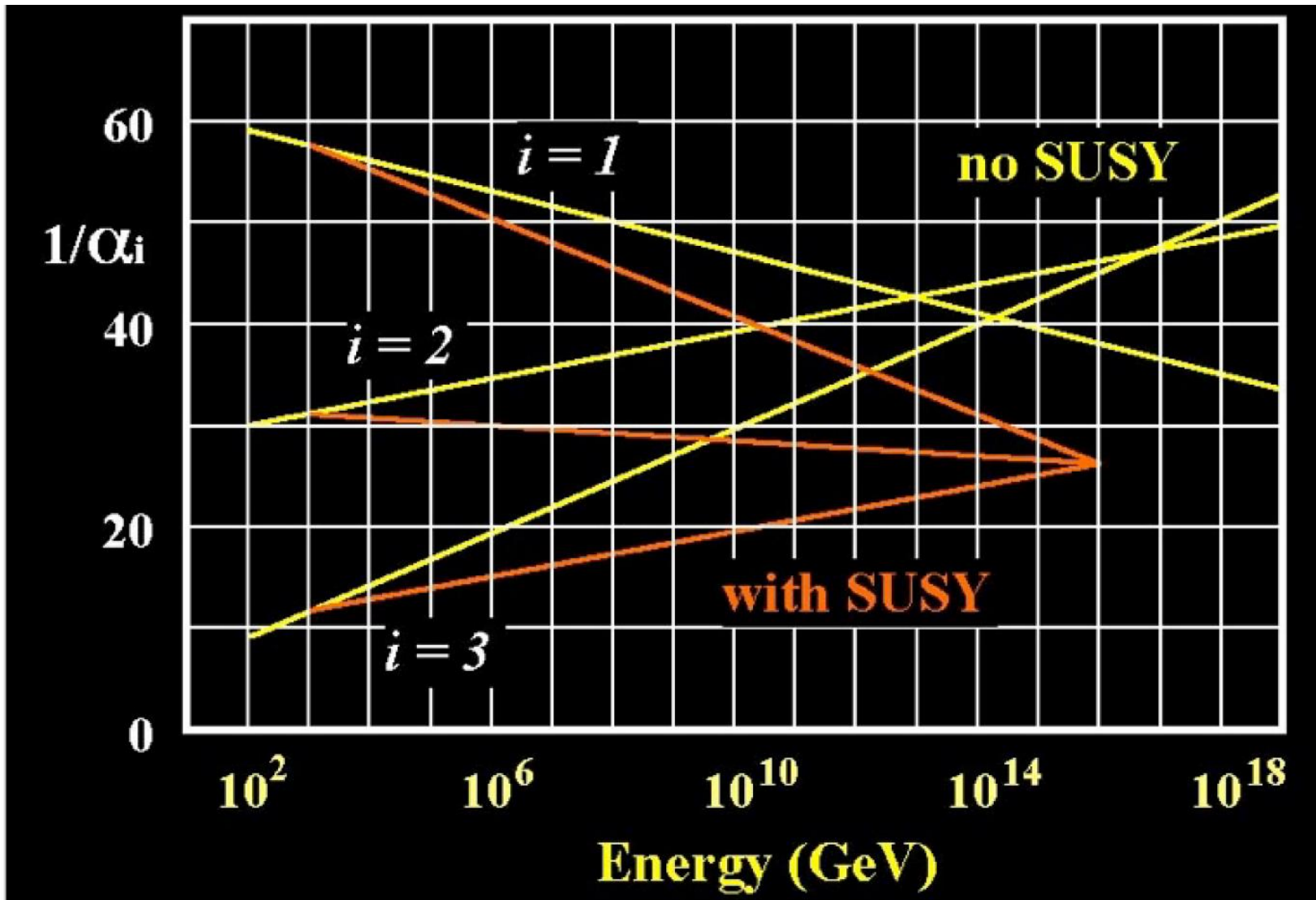
SUSY and the Higgs mass

Classical   SM   SUSY

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

Cancellation
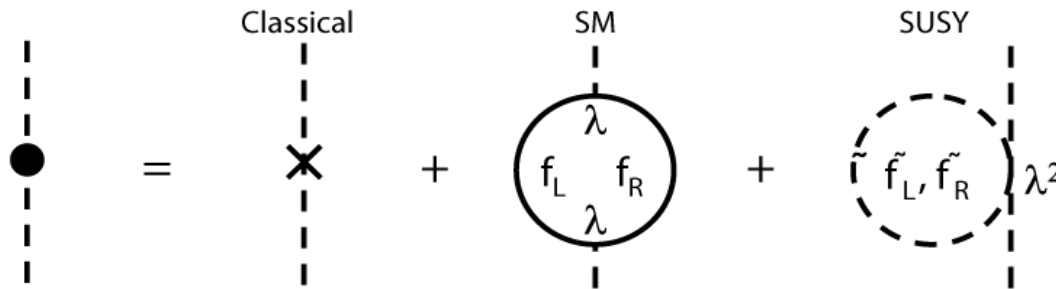
Higgs mass:

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

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

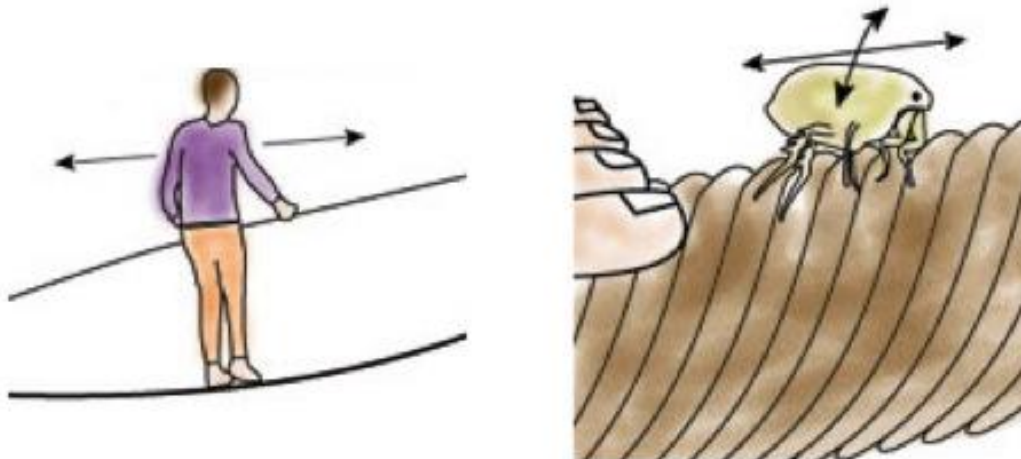$$\approx (m_h^2)_0 + \frac{1}{16\pi^2}(m_f^2 - m_{\tilde{f}}^2)\ln(\Lambda/m_{\tilde{f}}) ,$$

Superpartners fix this:

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

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.

At a Crossroad
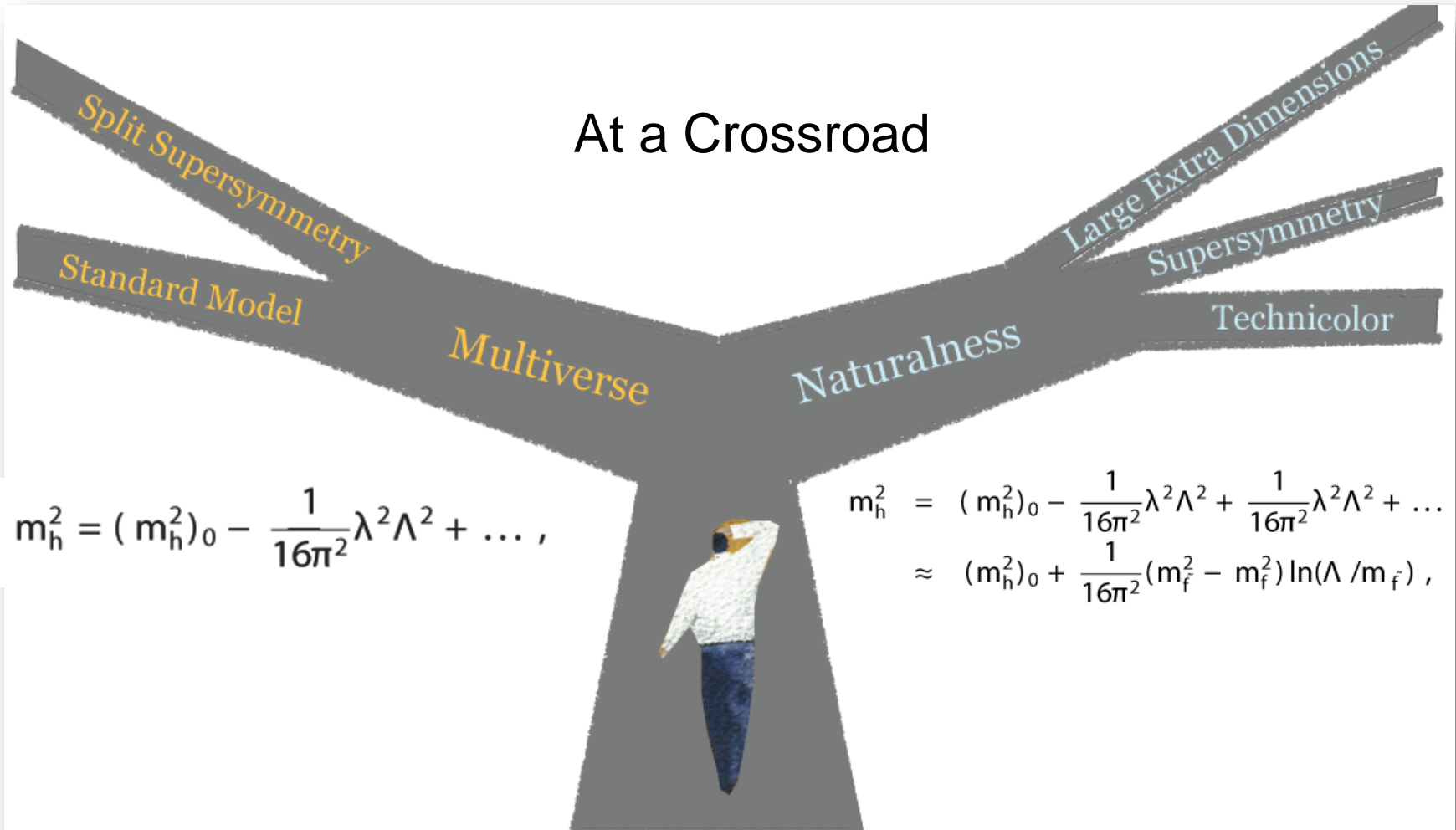
Split Supersymmetry

Large Extra Dimensions

Supersymmetry

Standard Model

Technicolor

Multiverse

Naturalness

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

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

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

Savas Dimopoulos, CERN Colloquium, Sep 20, 2012

Timeline of the Universe

13.7 billion years

Big Bang
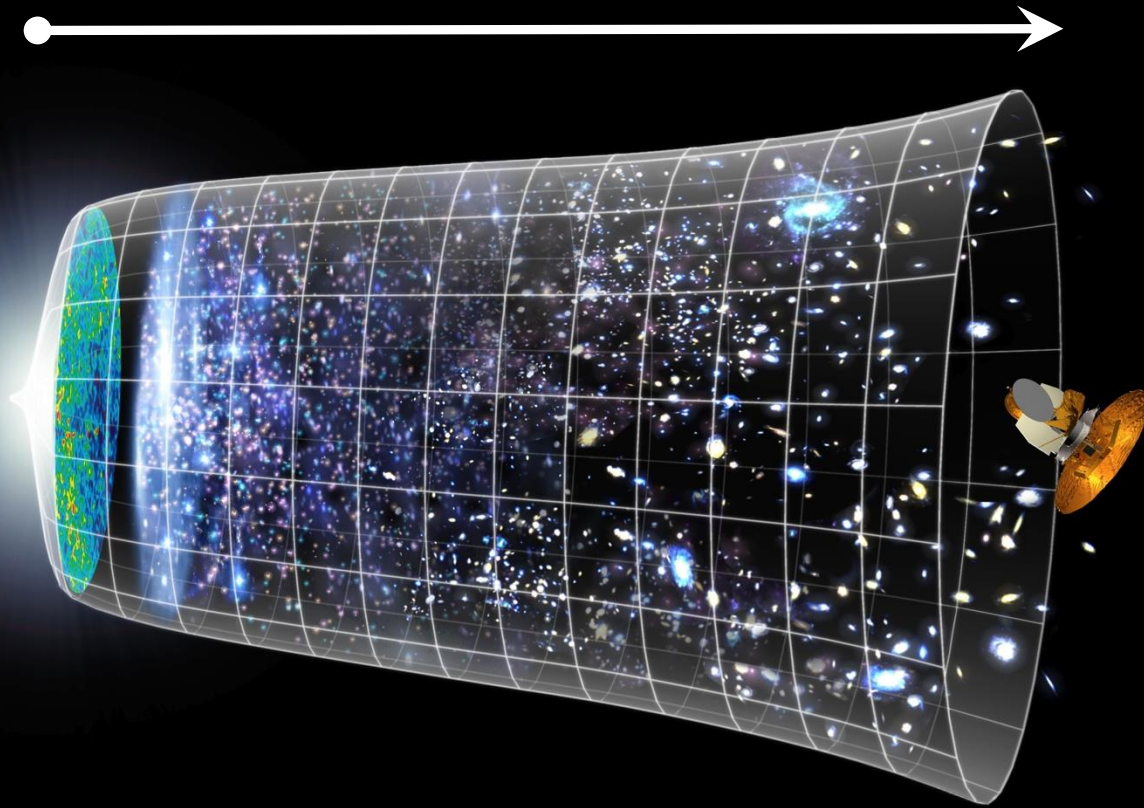
Today

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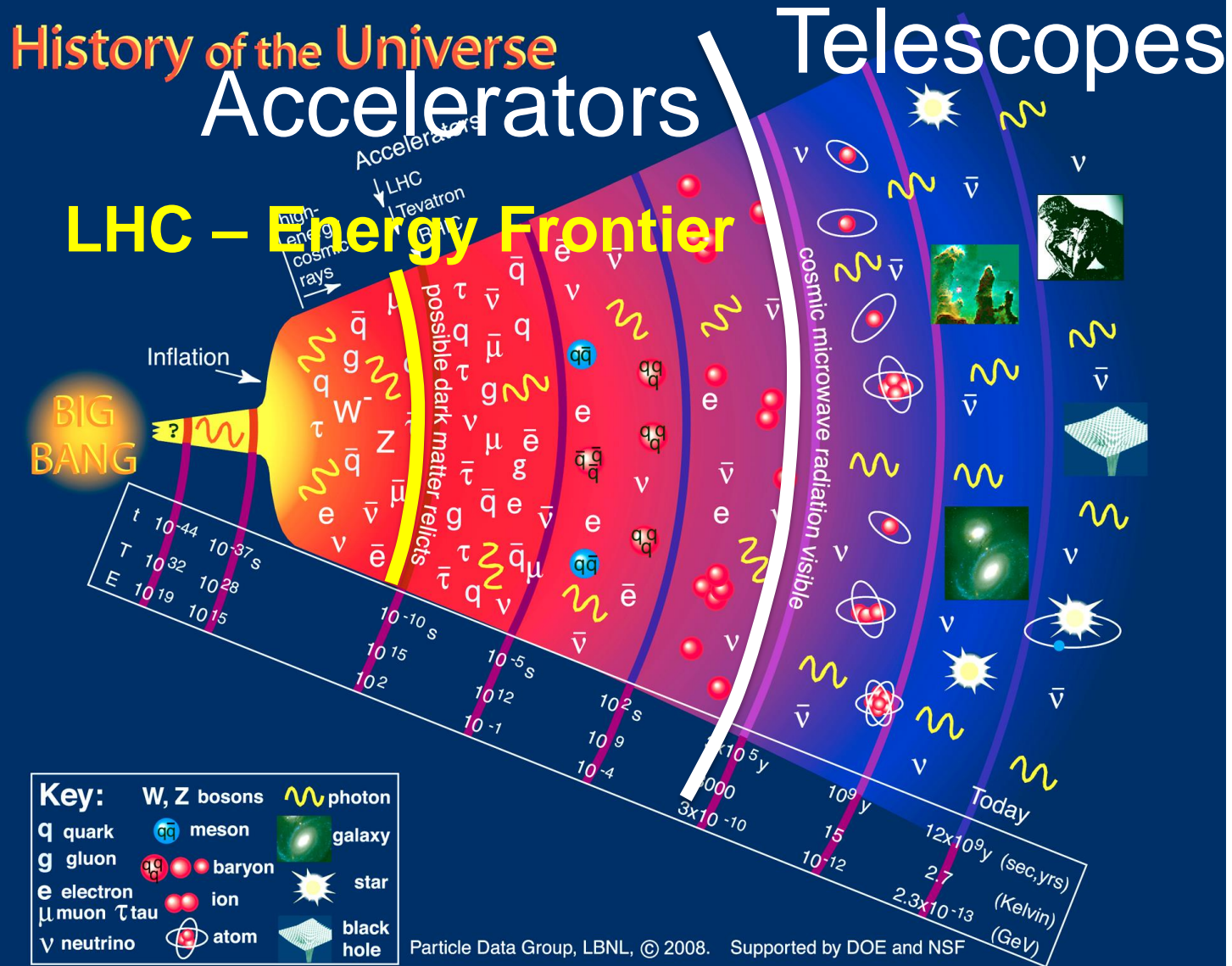
Cosmological inflation

In the very early universe space undergoes a dramatic exponential expansion.

Explains why the Universe has a uniform Temperature (3 K) and why space-time has a flat geometry
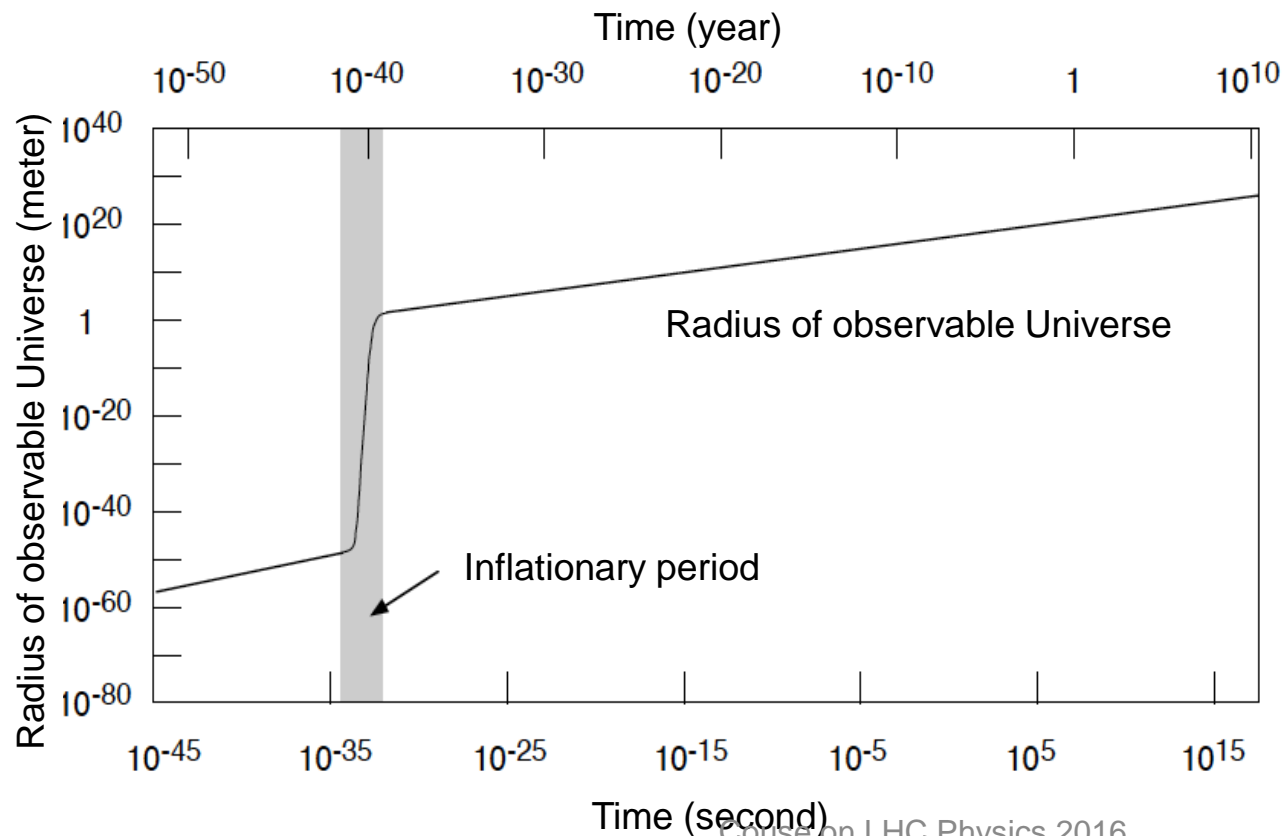
The inflation theory was developed independently in the late 1970's by Alan Guth, Alexey Starobinsky, and others

Higgs like field and inflation

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

False vacuum   Energy barrier

Energy density

Higgs field 2

Real vacuum
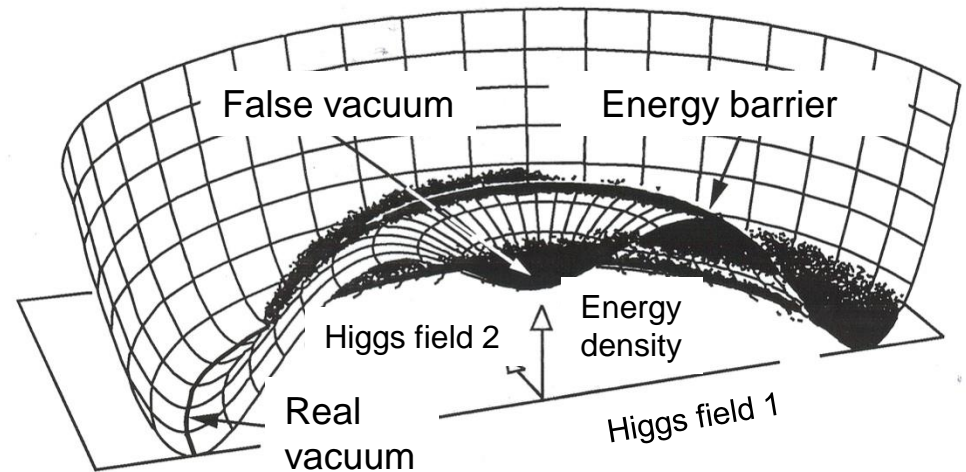
Higgs field 1

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 real vacuum.

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

The Universe expansion is accelerating

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

They got the same result:
The Universe expansion is accelerating

Some form of energy (dark energy) fills space
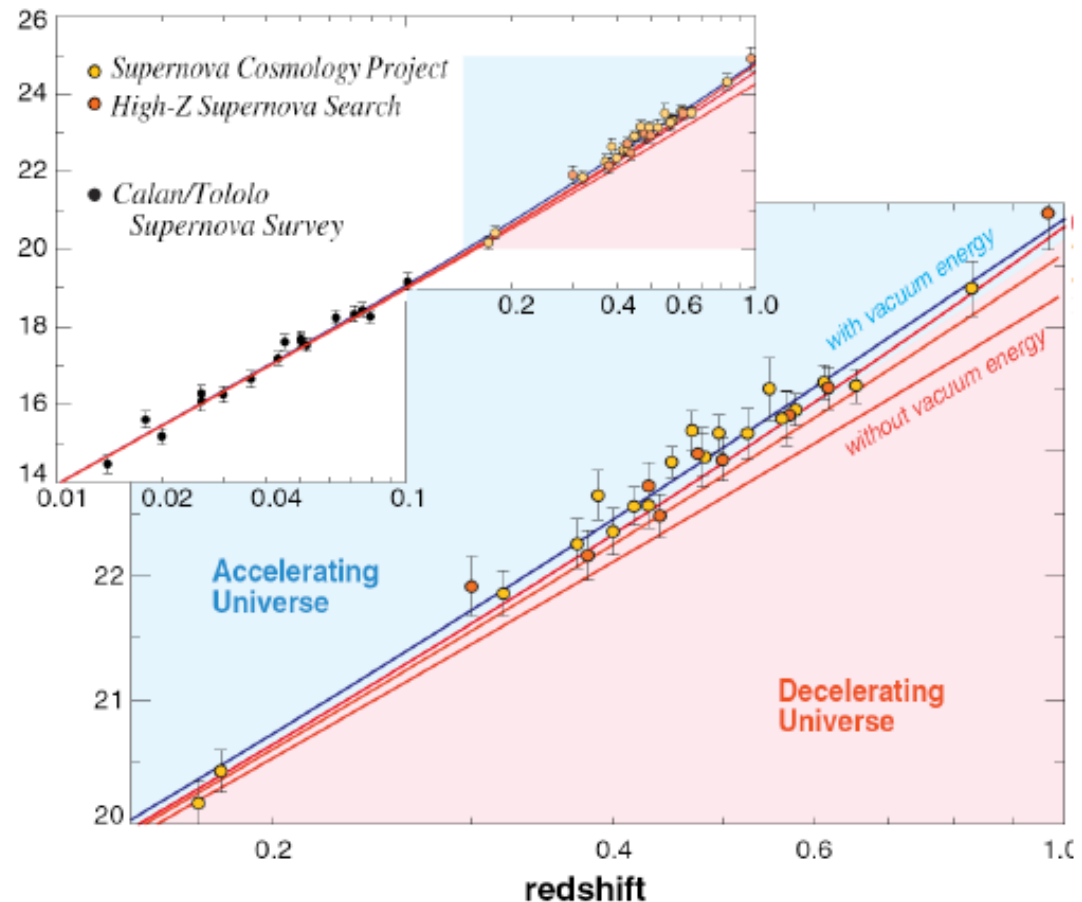
Vacuum energy density

Dark energy responsible for acceleration of expansion is very small

From particle physics we know that Vacuum has energy:
- potential energy of scalar fields
- energy of quantum fluctuations as predicted by quantum mechanics

This vacuum energy is 100 orders of magnitude larger than dark energy!

This huge discrepancy is known as the vacuum catastrophe.

The Standard Model would fail at high energy without the Higgs particle or other 'new physics'

Based on the available data and on quite general theoretical insights it was expected that the **'new physics'** would manifest at an energy around
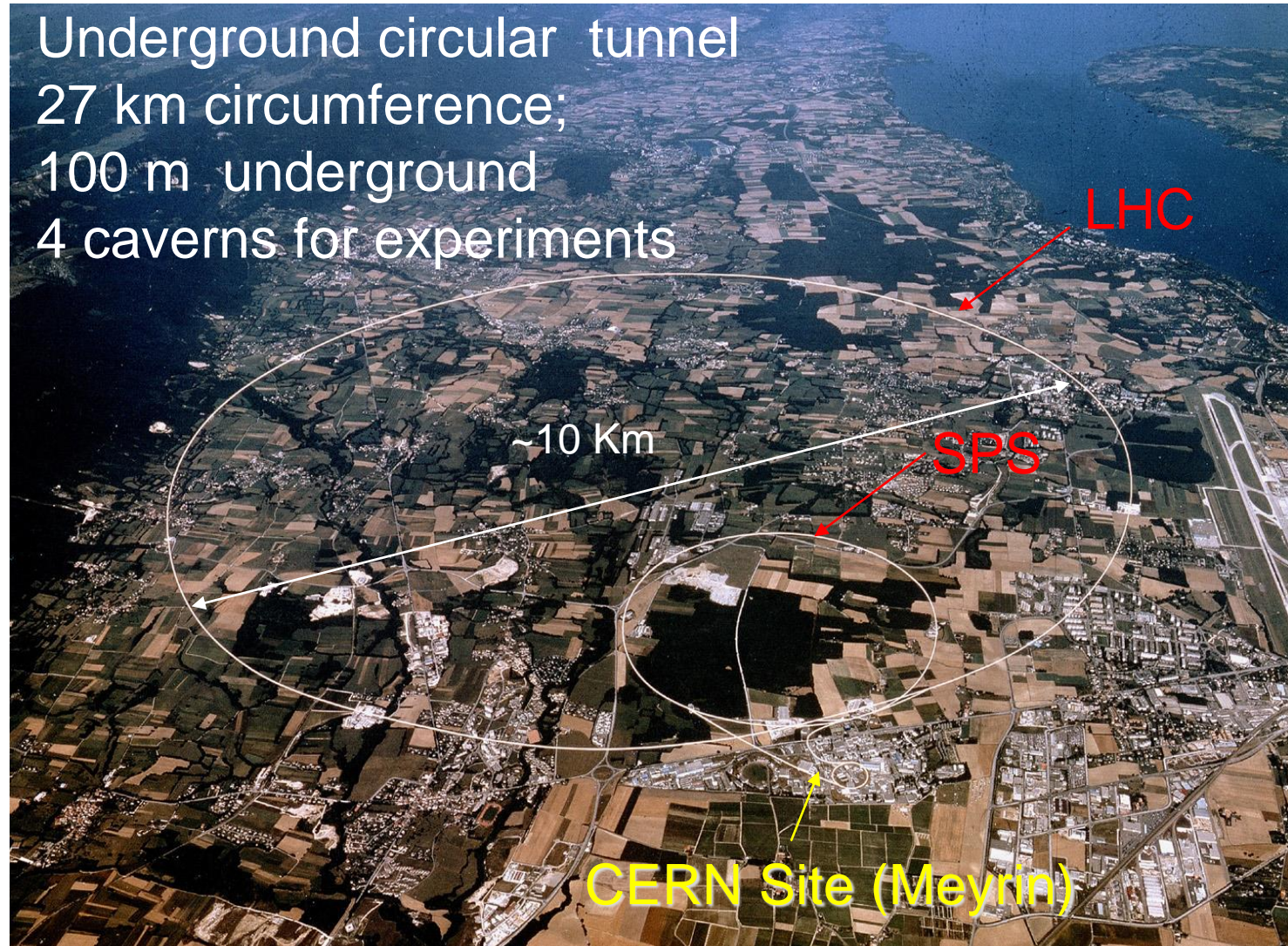
1 Tera-electronVolt = 10^{12} electronVolt

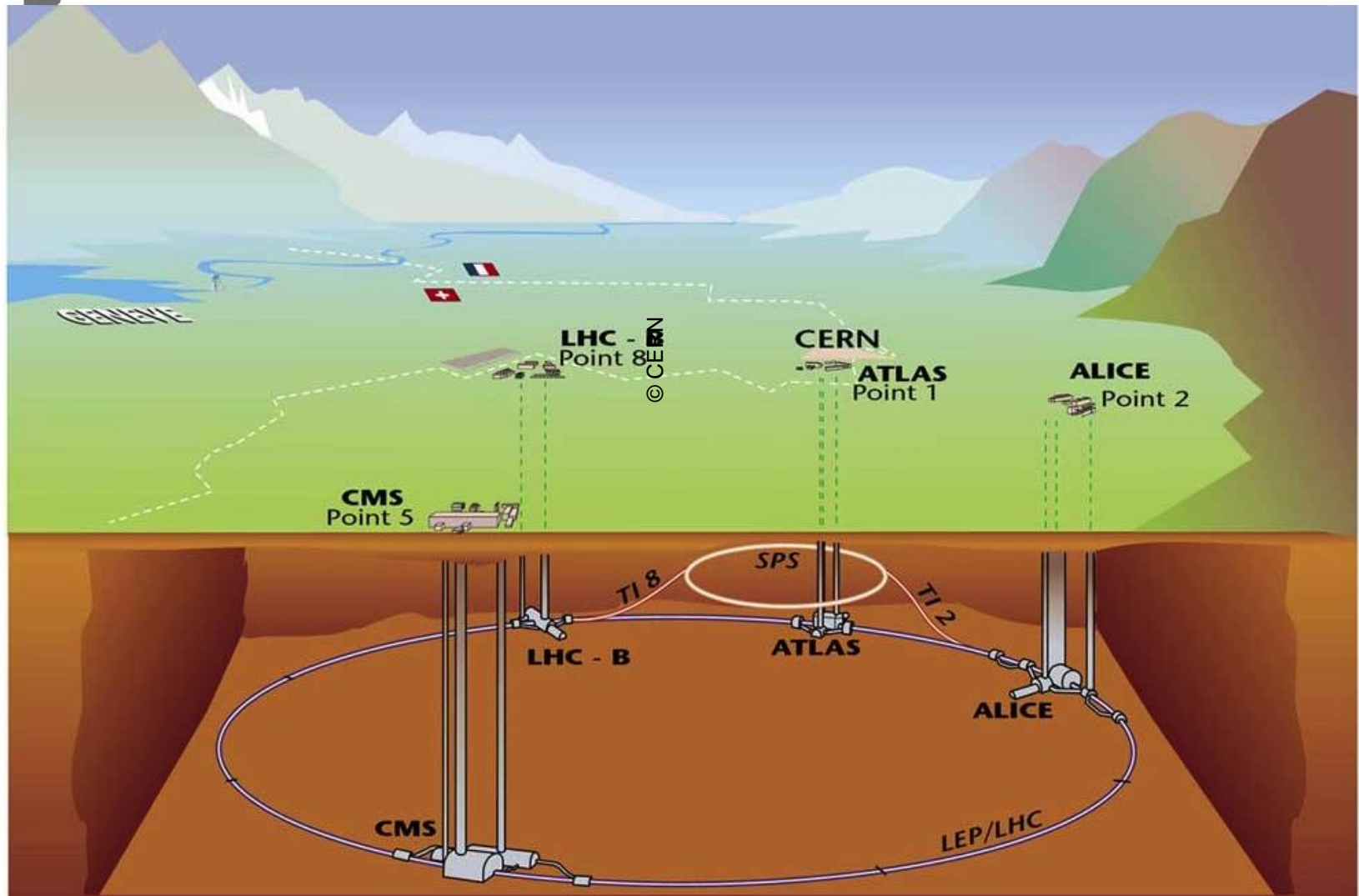accessible at the LHC for the first time

The LHC proton collider

Underground circular tunnel
27 km circumference;
100 m underground
4 caverns for experiments

LHC

~10 Km
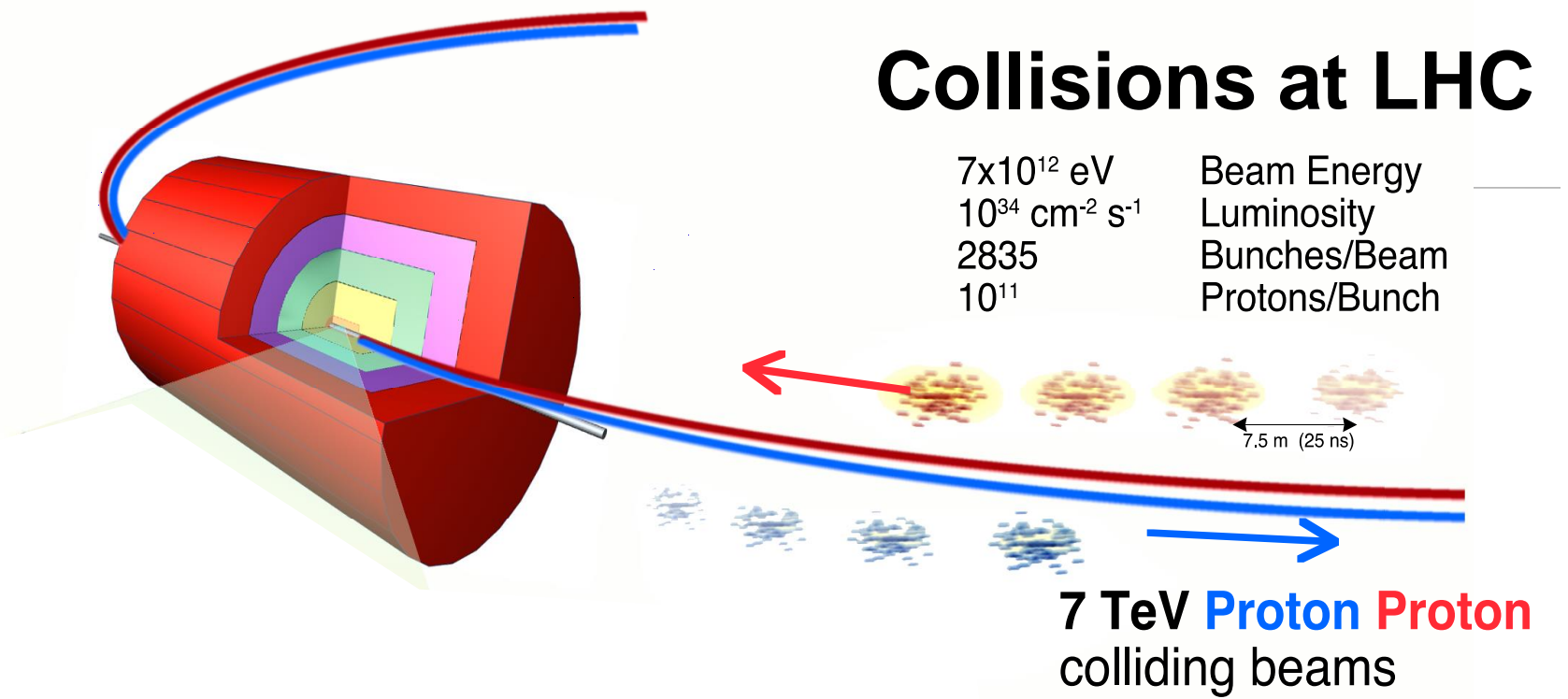
SPS

CERN Site (Meyrin)

Accelerator and experiments layout

**Tiny bunches of counter-circulating protons.
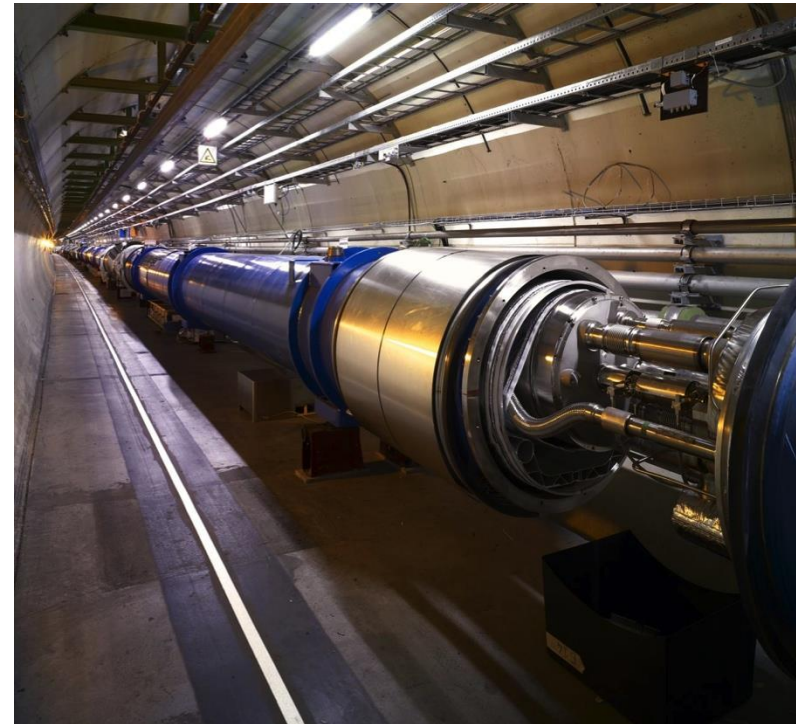Colliding head-on 40 million times each second.**

Collisions at LHC

7×10^{12} eV	Beam Energy
10^{34} cm^{-2} s^{-1}	Luminosity
2835	Bunches/Beam
10^{11}	Protons/Bunch

7.5 m (25 ns)

7 TeV Proton Proton
colliding beams

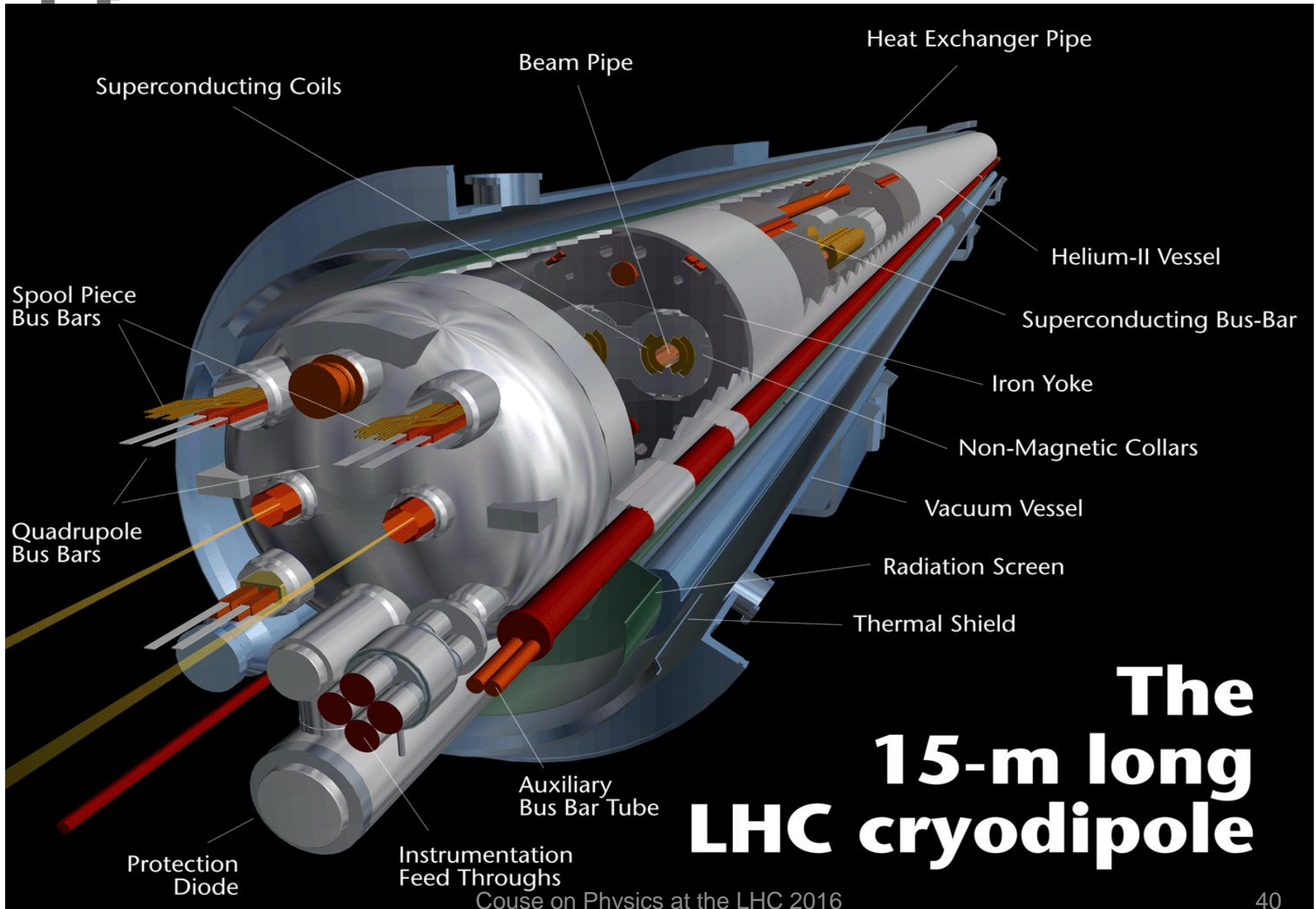# **Accelerator challenges**

Relative to Tevatron (Fermilab, USA)

Energy (14 TeV) x 7
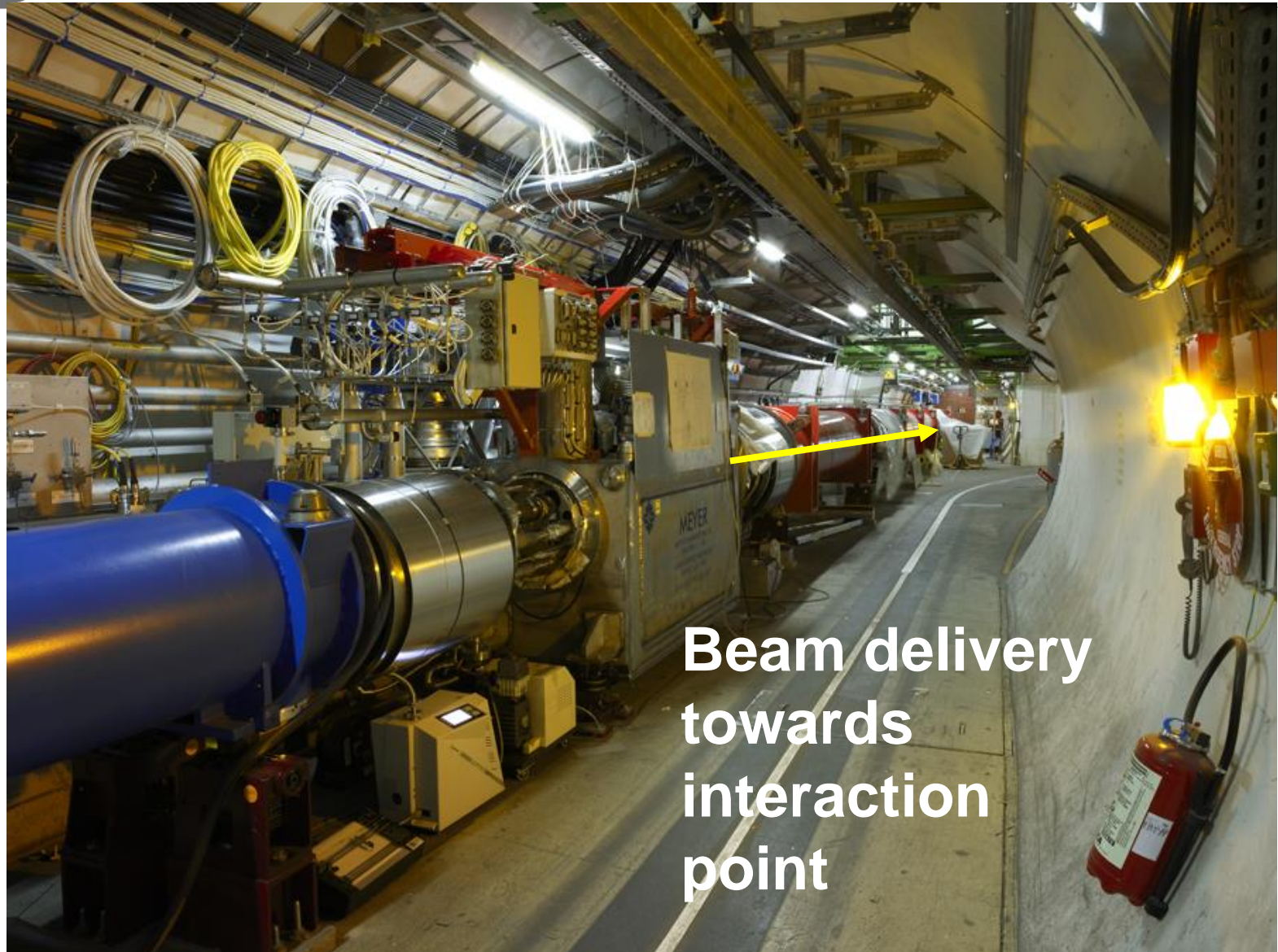
Luminosity (10^{34}cm^{-2}s^{-1}) x 30

- Superconducting dipoles 8.3 Tesla
- Operating temperature 1.9K (-271 C)
- Stored energy per beam 350 M Joule
  - energy of a train of 400 tons at 150 Km/h

- More than 2000 dipoles
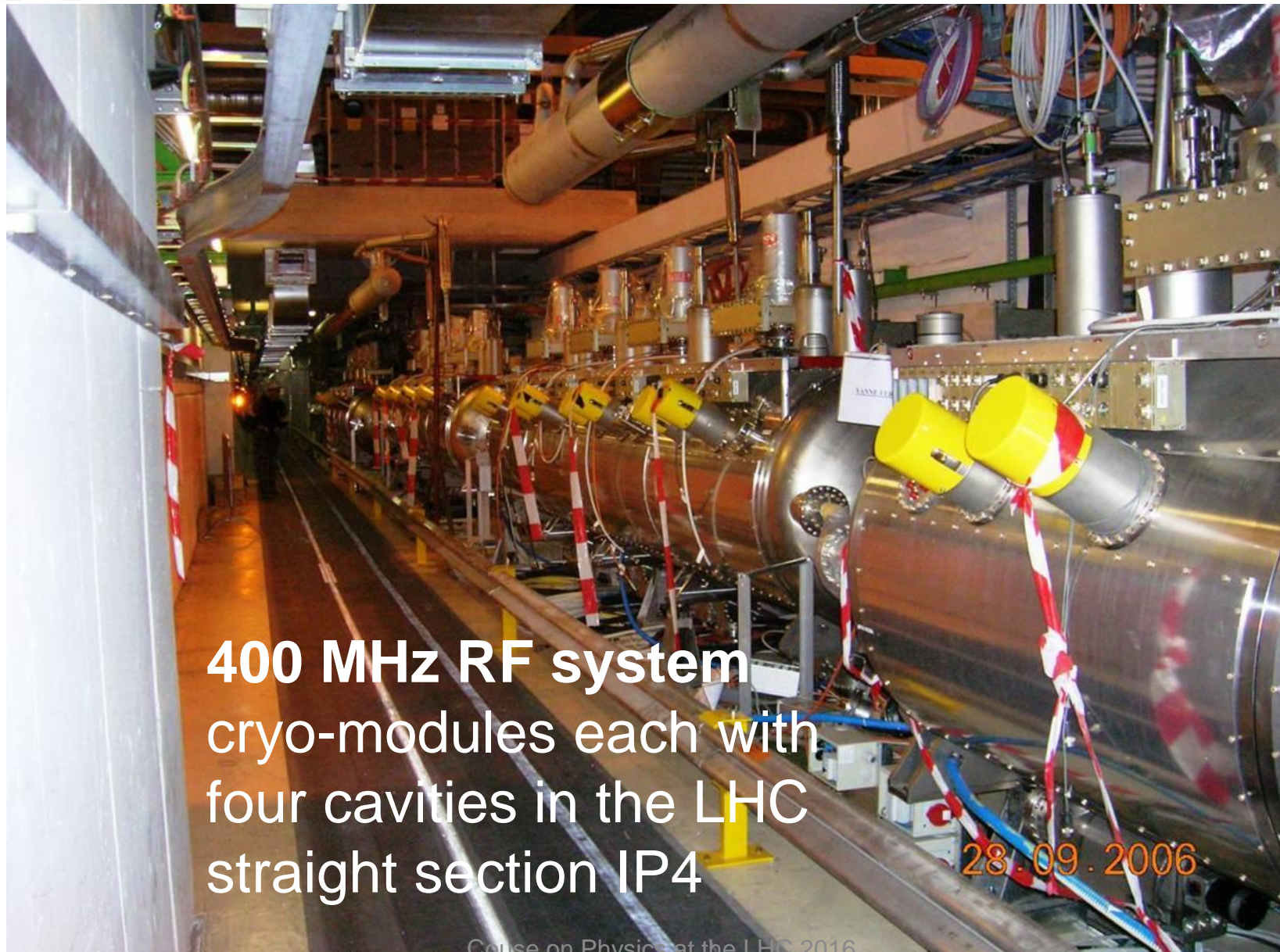- 100 ton liquid helium
- LHC power consumption 120 MW

Superconducting magnetic dipole

Beam Pipe

Heat Exchanger Pipe

Superconducting Coils

Helium-II Vessel

Spool Piece
Bus Bars

Superconducting Bus-Bar

Iron Yoke

Quadrupole
Bus Bars

Non-Magnetic Collars

Vacuum Vessel

Radiation Screen

Thermal Shield

The 15-m long LHC cryodipole

Protection
Diode

Instrumentation
Feed Throughs

Auxiliary
Bus Bar Tube

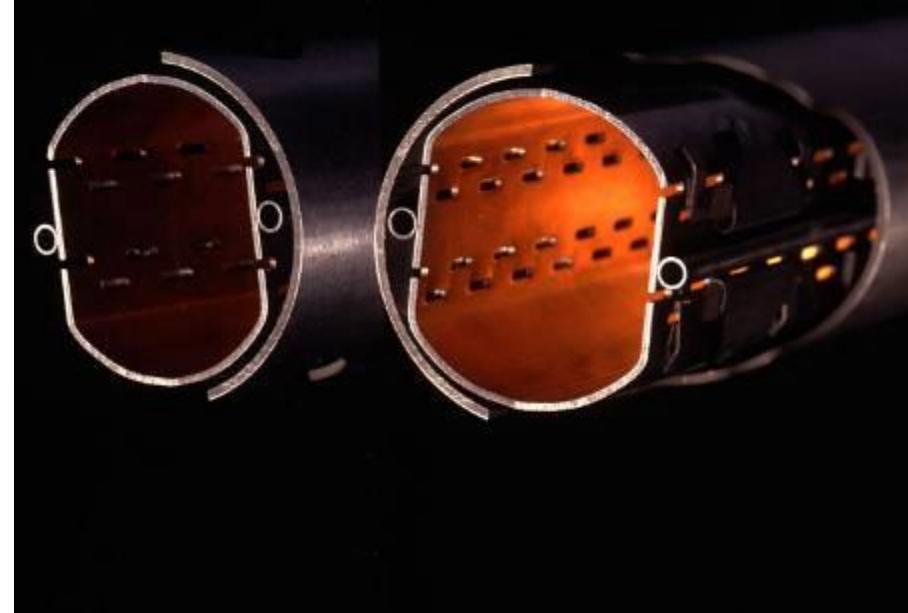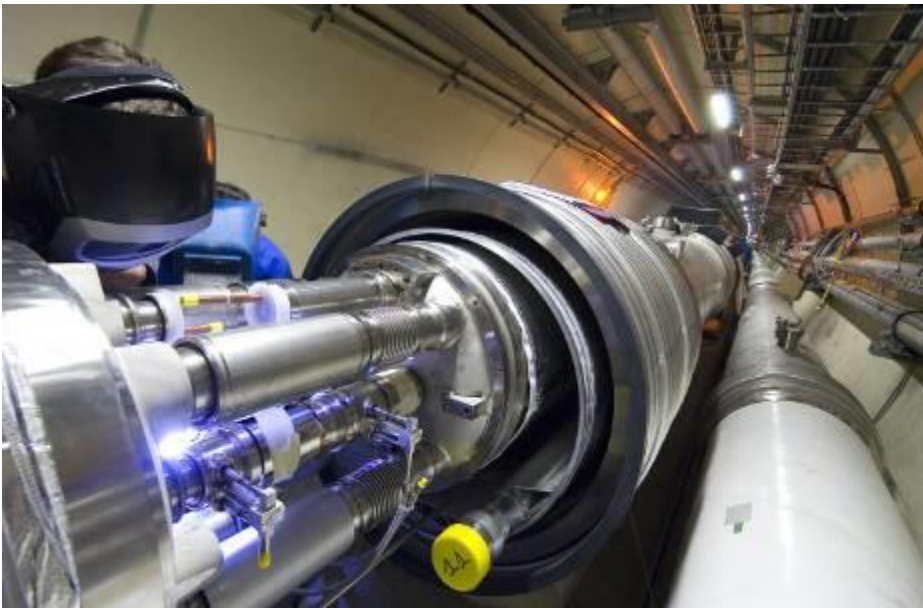**Beam delivery towards interaction point**

400 MHz RF system
cryo-modules each with
four cavities in the LHC
straight section IP4

28.09.2006

It's empty!

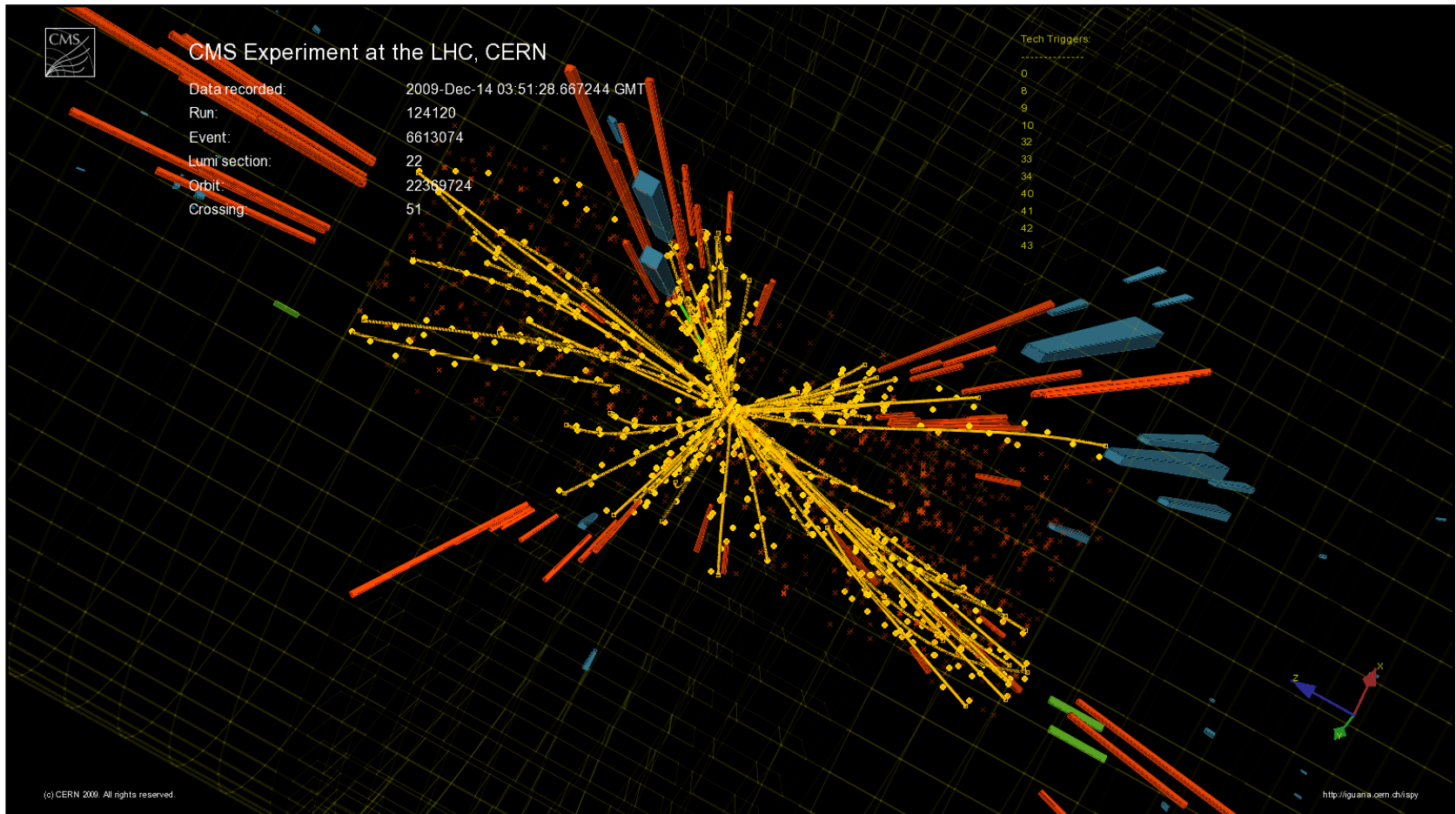Air pressure inside the two 27Km-long vacuum pipes (10^{-13} atm) is lower than on the moon.

It's cold!

27 Km of magnets are kept at 1.9 °K, colder than outer space, using over 100 tons of liquid helium.

It's Hot!

In a *tiny* volume, temperatures one billion times hotter than the center of the sun.

End of Lecture 1