Course on Physics at the LHC

LIP Lisbon, March - May 2017

The standard model of Particle Physics, J. Varela, 6-7-8 March

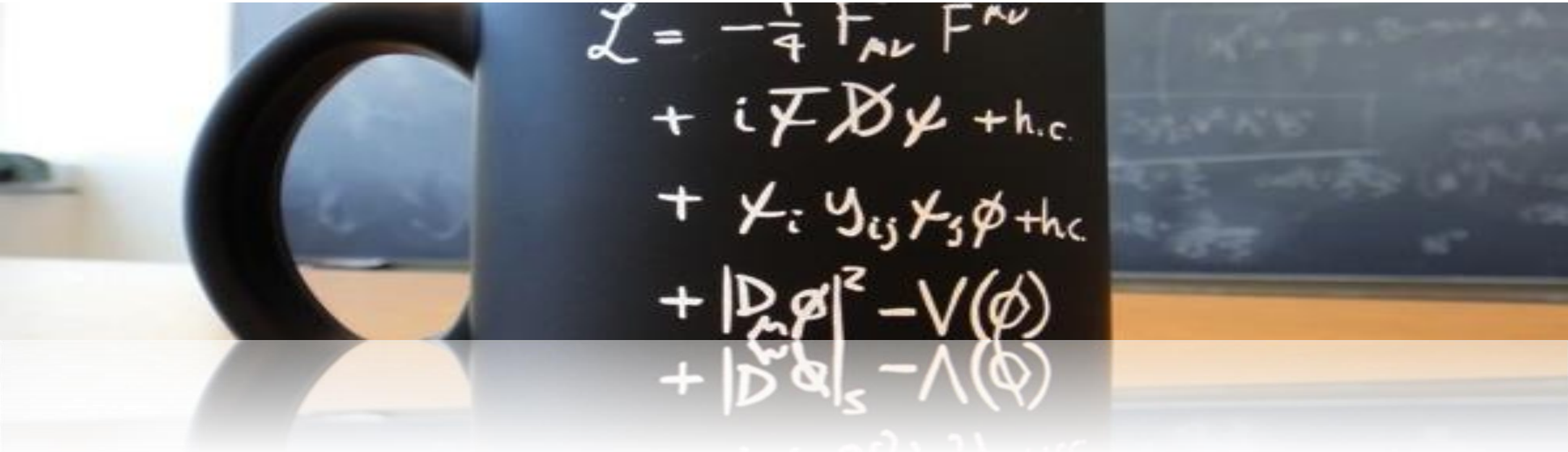
Detector physics and experimental methods	Michele Gallinaro (LIP), Pedro Silva (CERN)	13, 15 March
Statistical methods in data analysis	Pietro Vischia (Univ. Oviedo)	20 March
Top quark physics	Michele Gallinaro (LIP), António Onofre (LIP, UM)	22, 27, 29 March
Standard model Higgs and beyond	Ricardo Gonçalo (LIP), Patricia Muiño (LIP), Pedro Silva (CERN), Michele Gallinaro (LIP)	3, 5, 10, 12 April
Supersymmetry	Pedrame Bargassa (LIP)	19, 26 April
Exotica and Dark Matter	Michele Gallinaro (LIP)	3 May
B physics and rare decays	Nuno Leonardo (LIP)	8 May
Heavy ions, polarization	João Seixas (LIP, IST)	10 May

The lectures will take place 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/2017_lhc_physics

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

The LHC physics case



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:

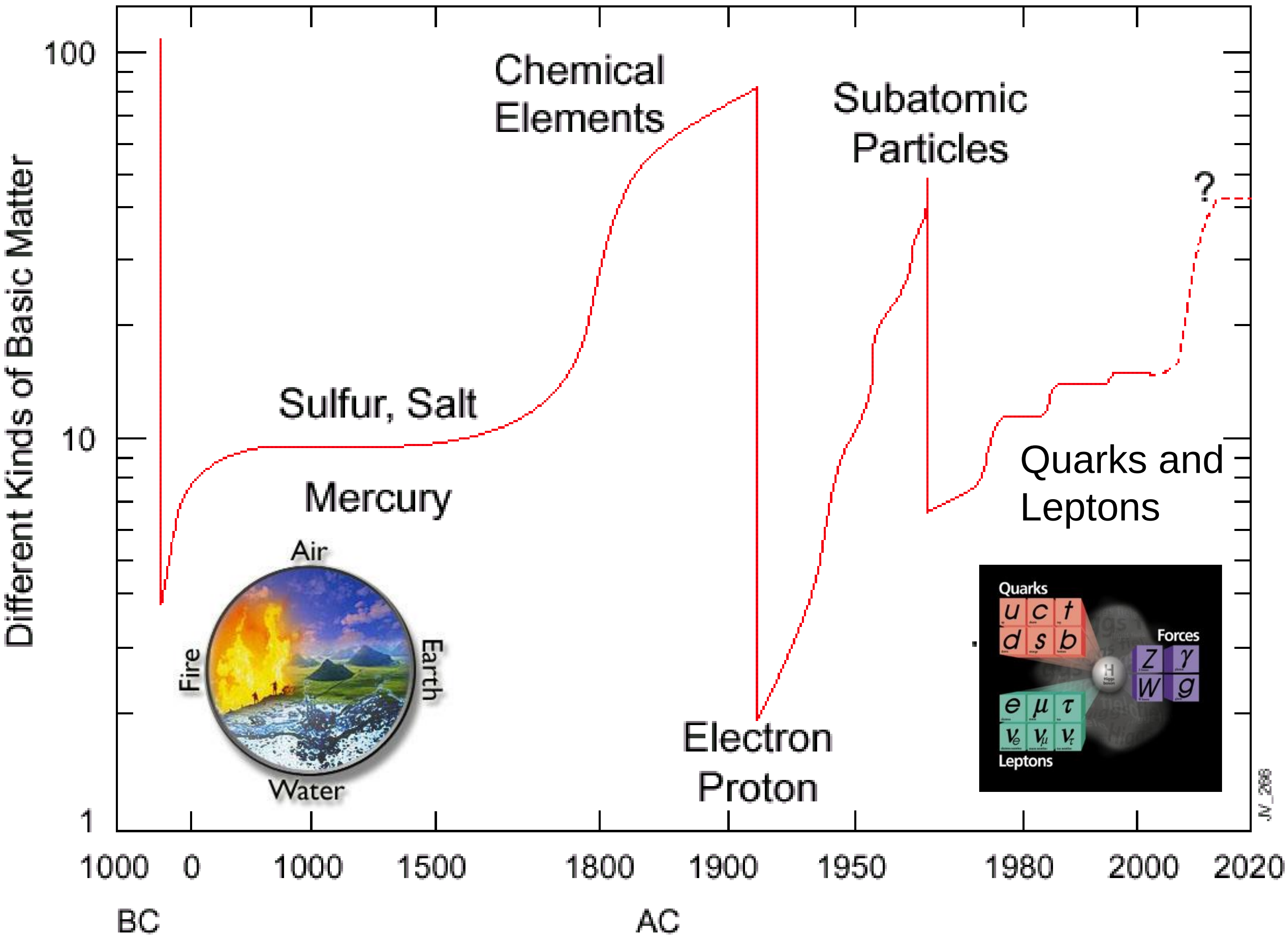
What are the elementary constituents of matter ?

What are the forces that determine their behavior?

Experimentally

Get particles to interact and study what happens

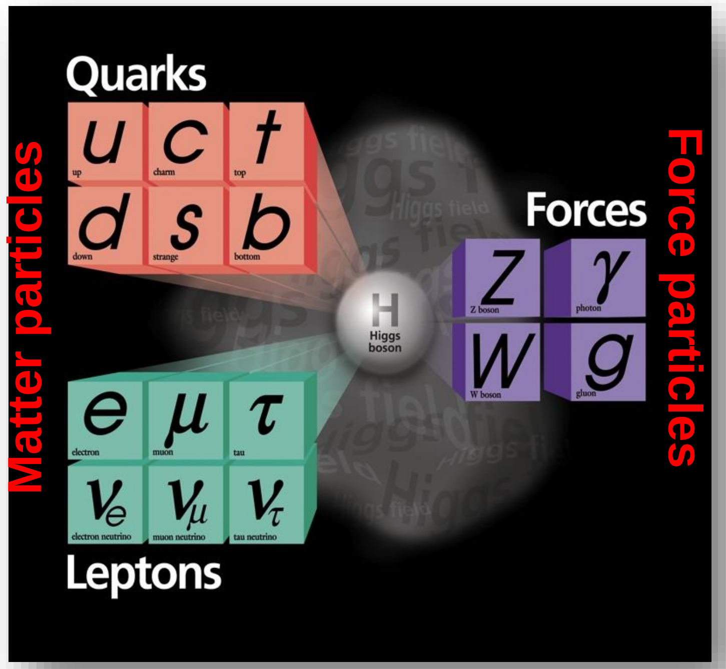
Constituents of matter along History



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



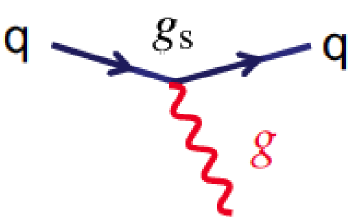
One of the greatest achievements of 20th Century Science

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

Standard model interactions

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

STRONG



Only quarks

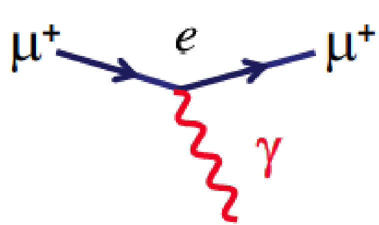
Never changes flavour

$\alpha_S \sim 1$

Gluons

massless

EM



All charged fermions

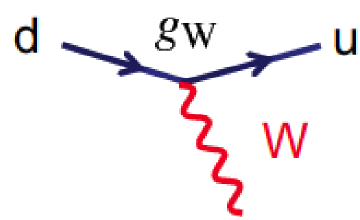
Never changes flavour

$\alpha \simeq 1/137$

Photon

massless

WEAK CC



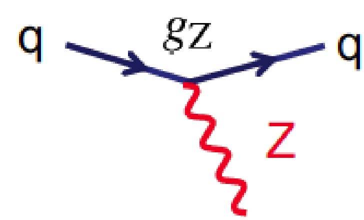
All fermions

<u>Always</u> changes flavour

W+, W-

very massive

WEAK NC



All fermions

Never changes flavour

$\alpha_{W/Z} \sim 1/40$

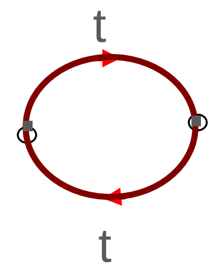
Z^0

very massive

Quantum field theory

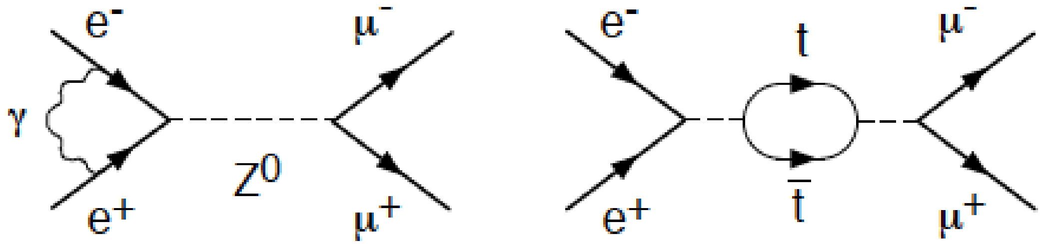
A particle-antiparticle pair can pop out of empty space ("the vacuum") and then vanish back into it

These are *Virtual* particles.



Vacuum Fluctuation
Involving top quarks

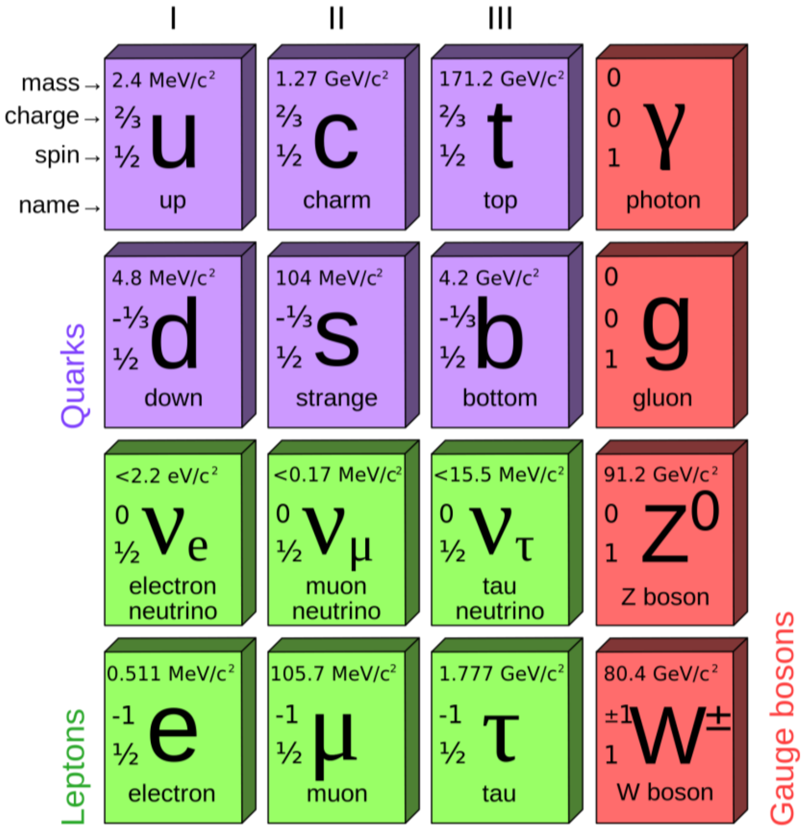
Other examples of Virtual particles:



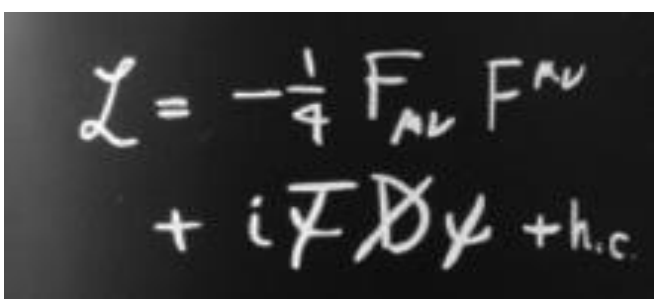
This has far-reaching consequences

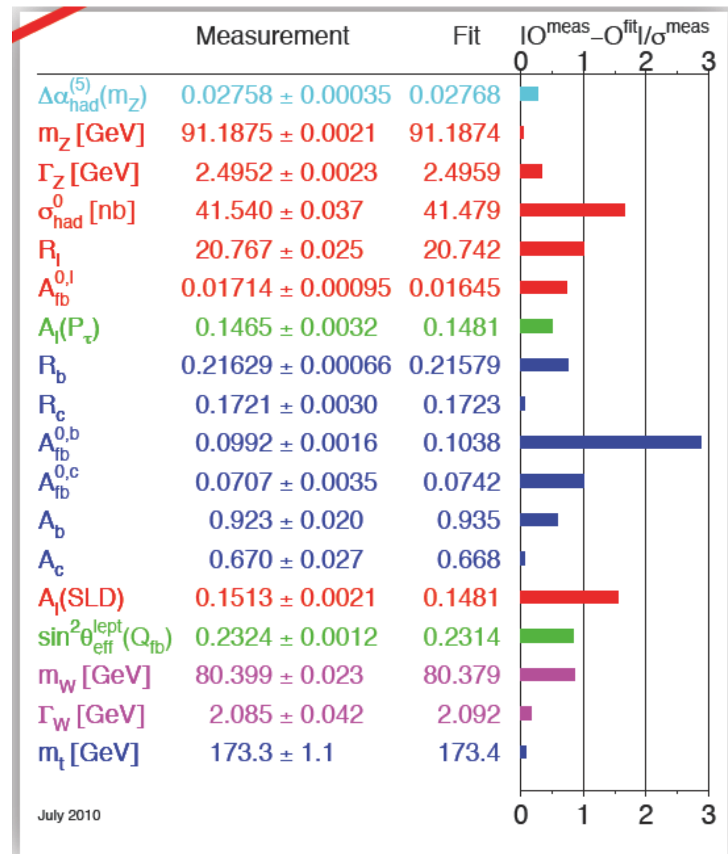
The structure of the universe depends on particles that ***don't exist in the usual sense***

SM confirmed by data



STANDARD MODEL OF ELEMENTARY PARTICLES





	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	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

Confirmed at sub 1% level!

What's missing?

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!

The Higgs

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

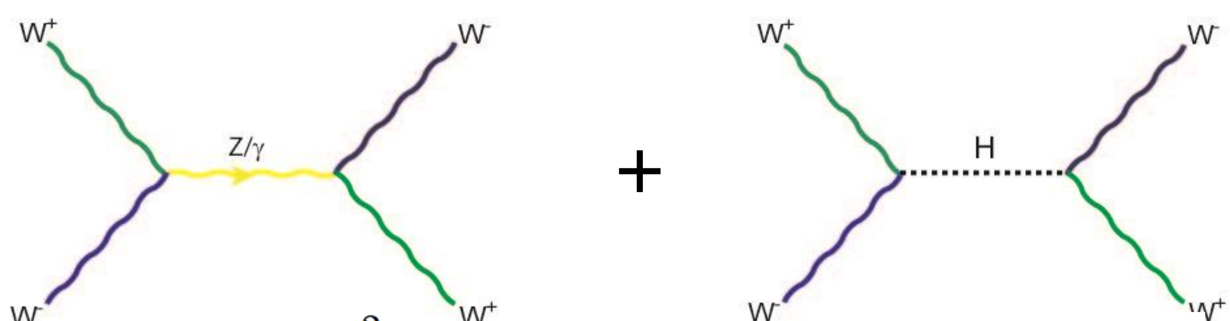
Added bonus

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!



$$\lim_{E\to\infty} \mathcal{A} \propto E^2 \qquad \lim_{E\to\infty} \mathcal{A} \propto \text{const.}$$

The Terascale

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

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?

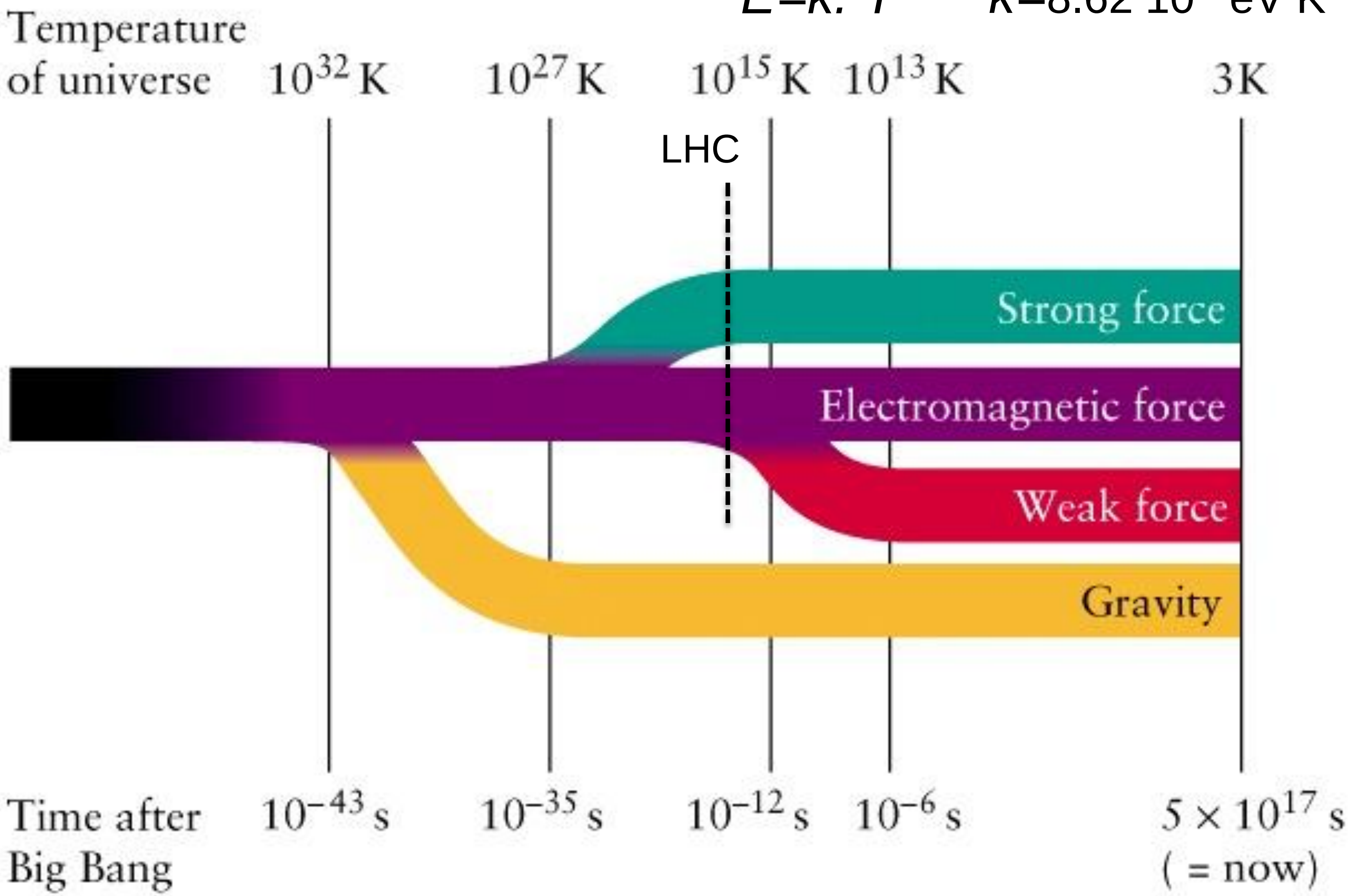
Are quarks and leptons actually fundamental, or made up of even more fundamental particles?

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

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

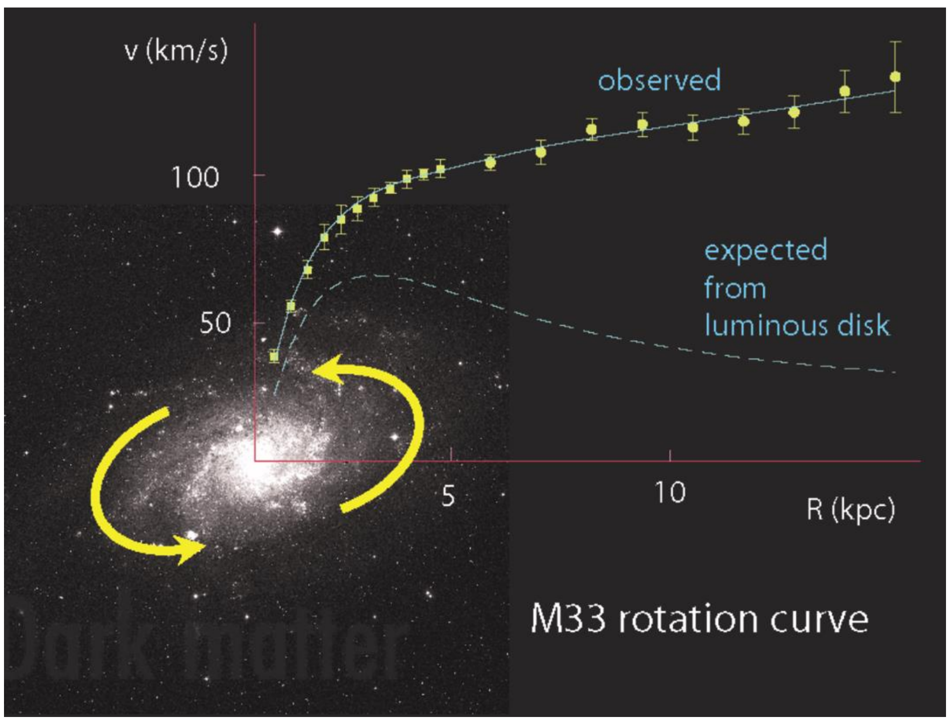


The dark side of the Universe

Long standing problem:

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

What is the remaining 96%?

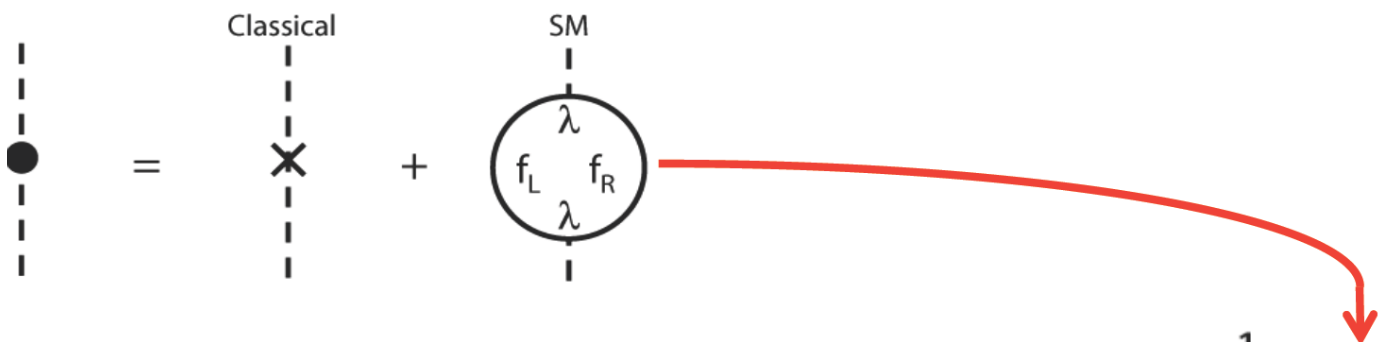


The LHC may help to solve this problem, discovering **dark matter**

Higgs and hierarchy problem

In the SM the Higgs mass is a huge problem:

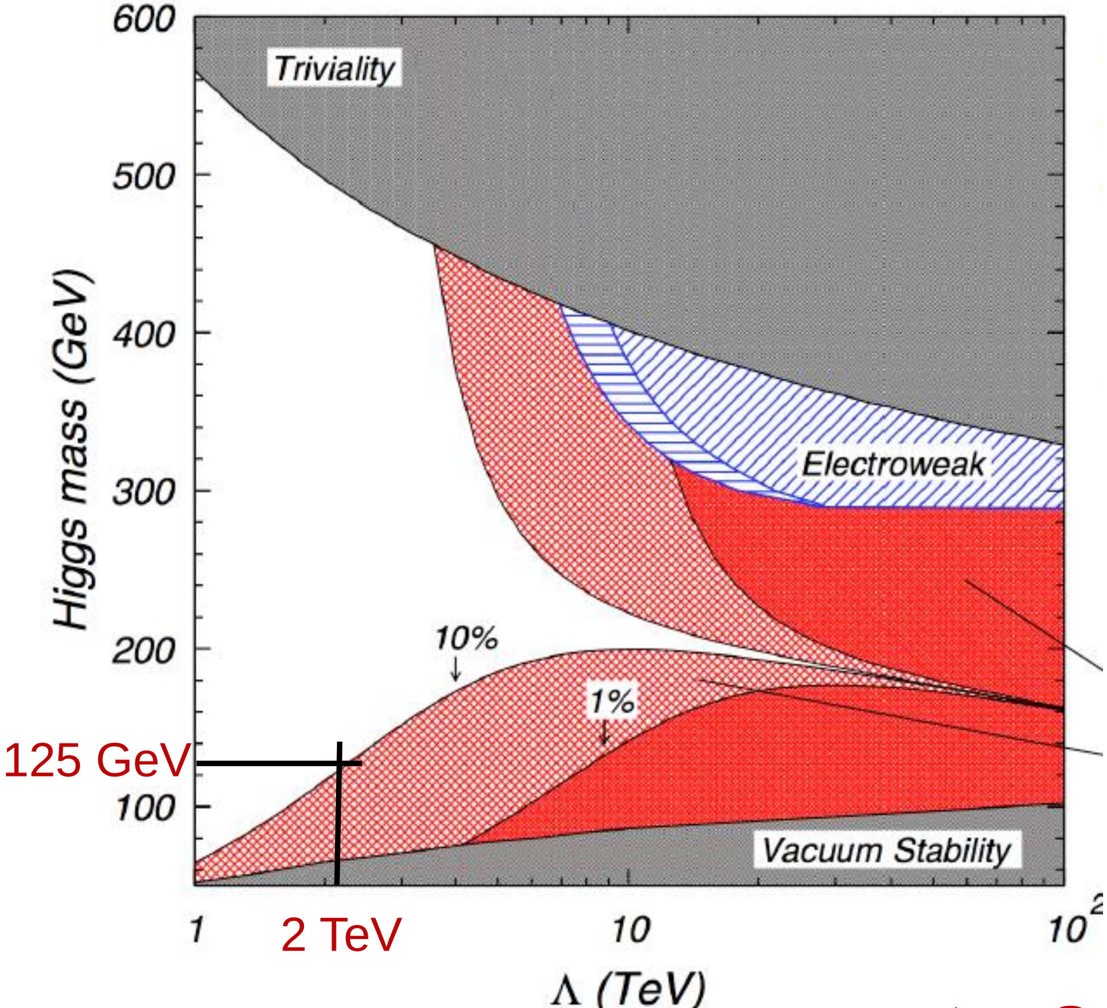
- Virtual particles in quantum loops contribute to the Higgs mass
- Contributions grow with Λ (upper scale of validity of the SM)
- Λ could be huge – e.g. the Plank scale (10^{19} GeV)
- Miraculous cancelations are needed to keep the Higgs mass < 1 TeV



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

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

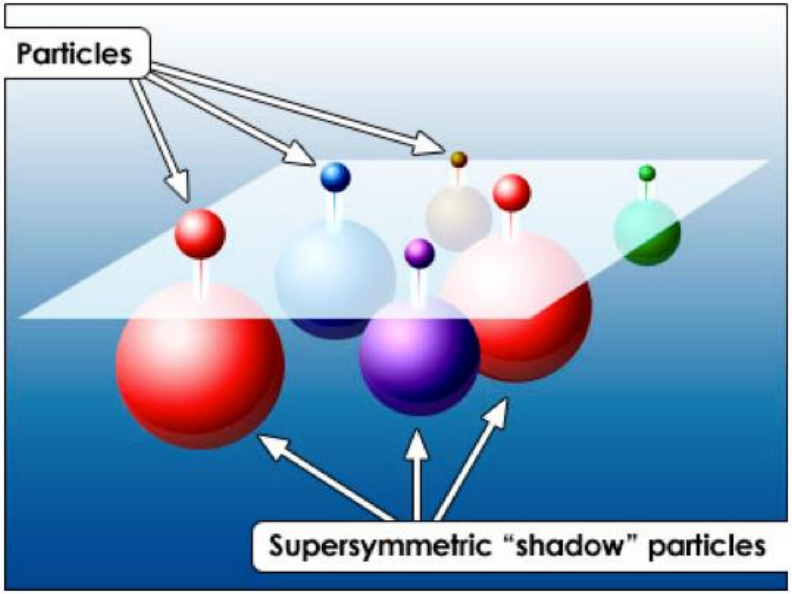
Supersymmetry

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.

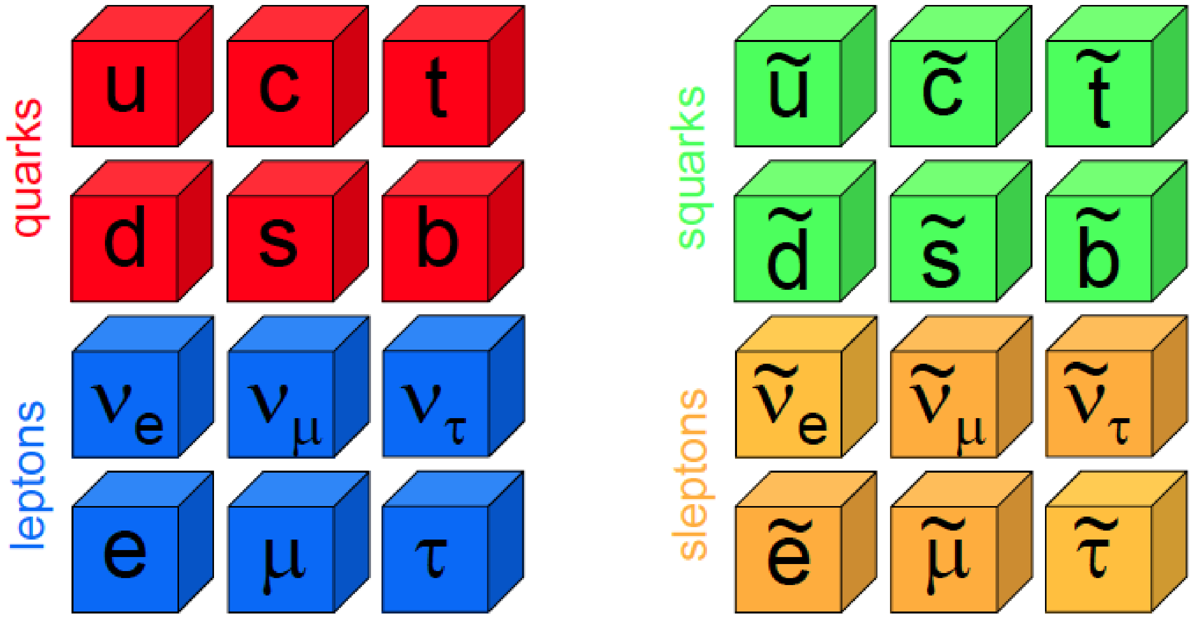
This relationship between fermions and bosons is called supersymmetry (SUSY)

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



Supersymmetry

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?

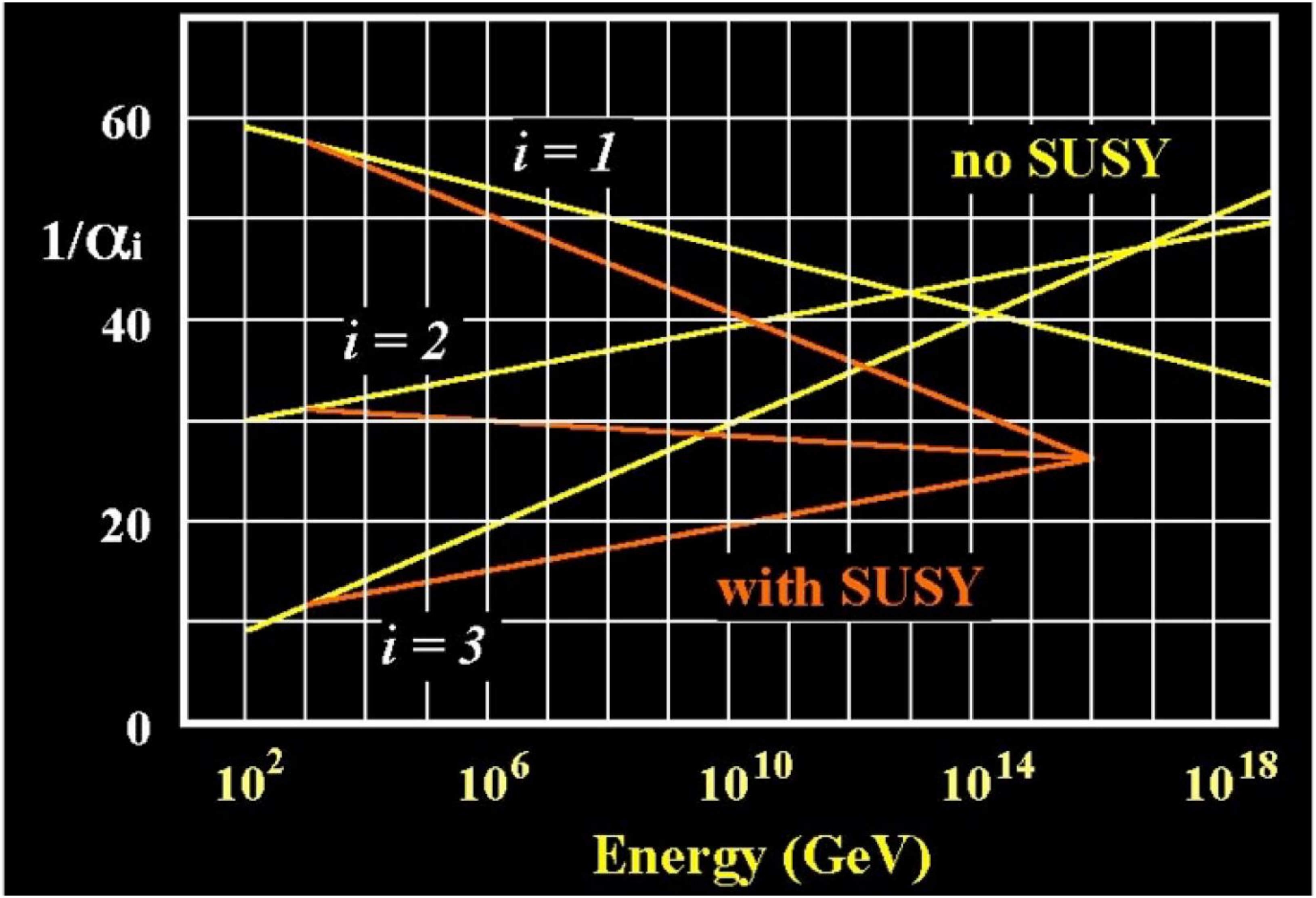
For every “normal” force quanta (boson), there are supersymmetric partners:

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

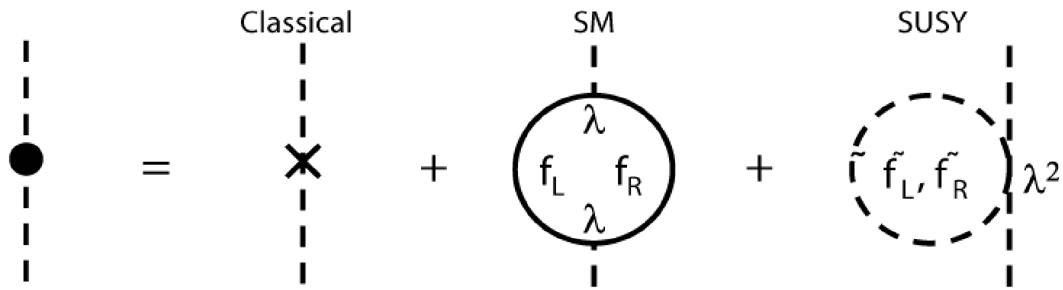
These “…inos” are prime suspects to be the galactic dark matter!

Relics from the Big Bang!

The temptation unification



SUSY and the Higgs mass



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

Higgs mass:

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

Cancellation

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

Superpartners fix this:

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

Extra dimensions

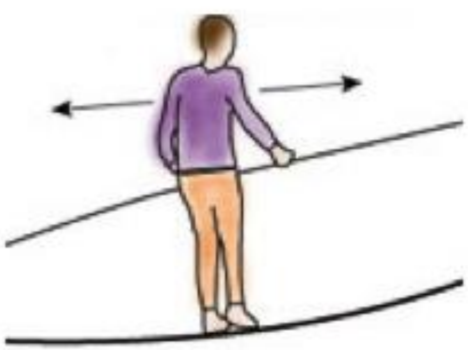
Space-time could have more than three space dimensions. The extra dimensions could be very small and undetected until now.

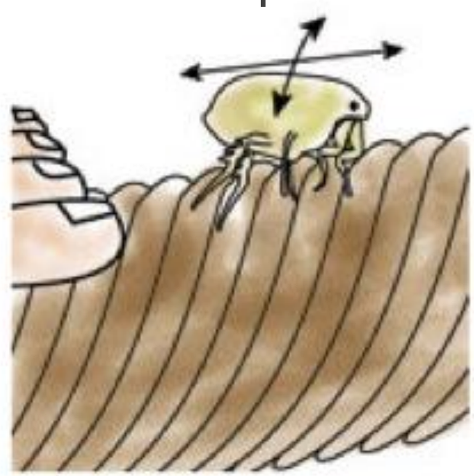
How can there be extra, smaller dimensions?

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.

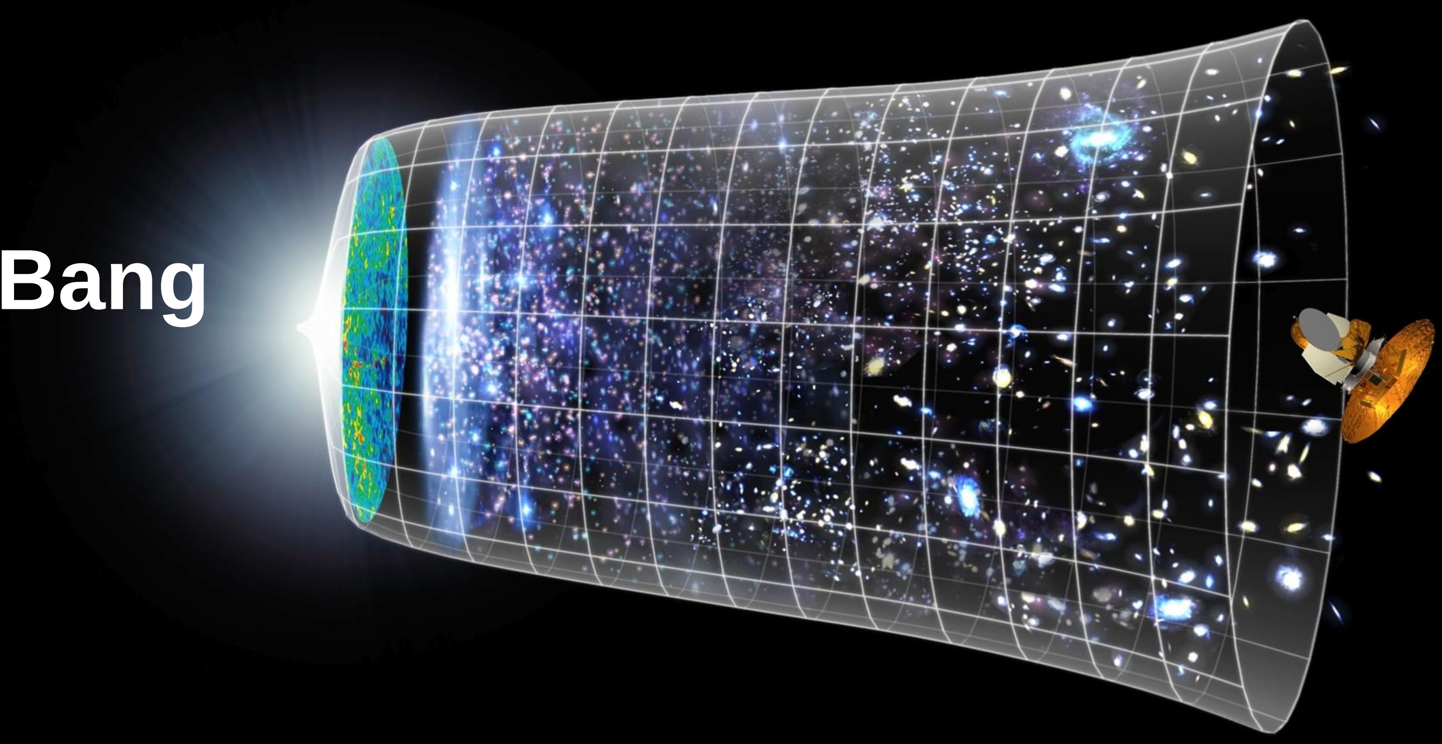




Timeline of the Universe

13.7 billion years

Big Bang

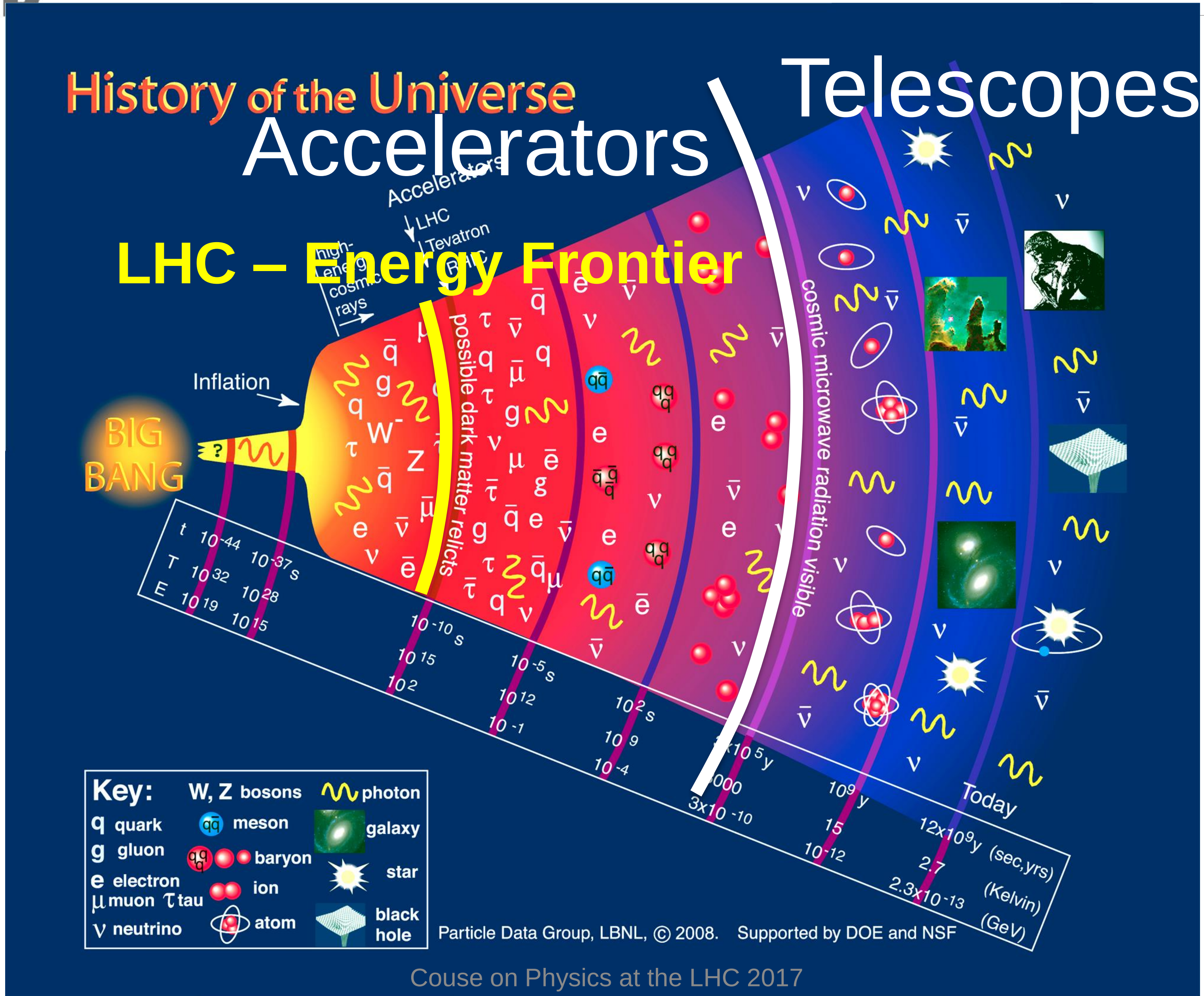


Today

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

NASA/WMAP Science Team

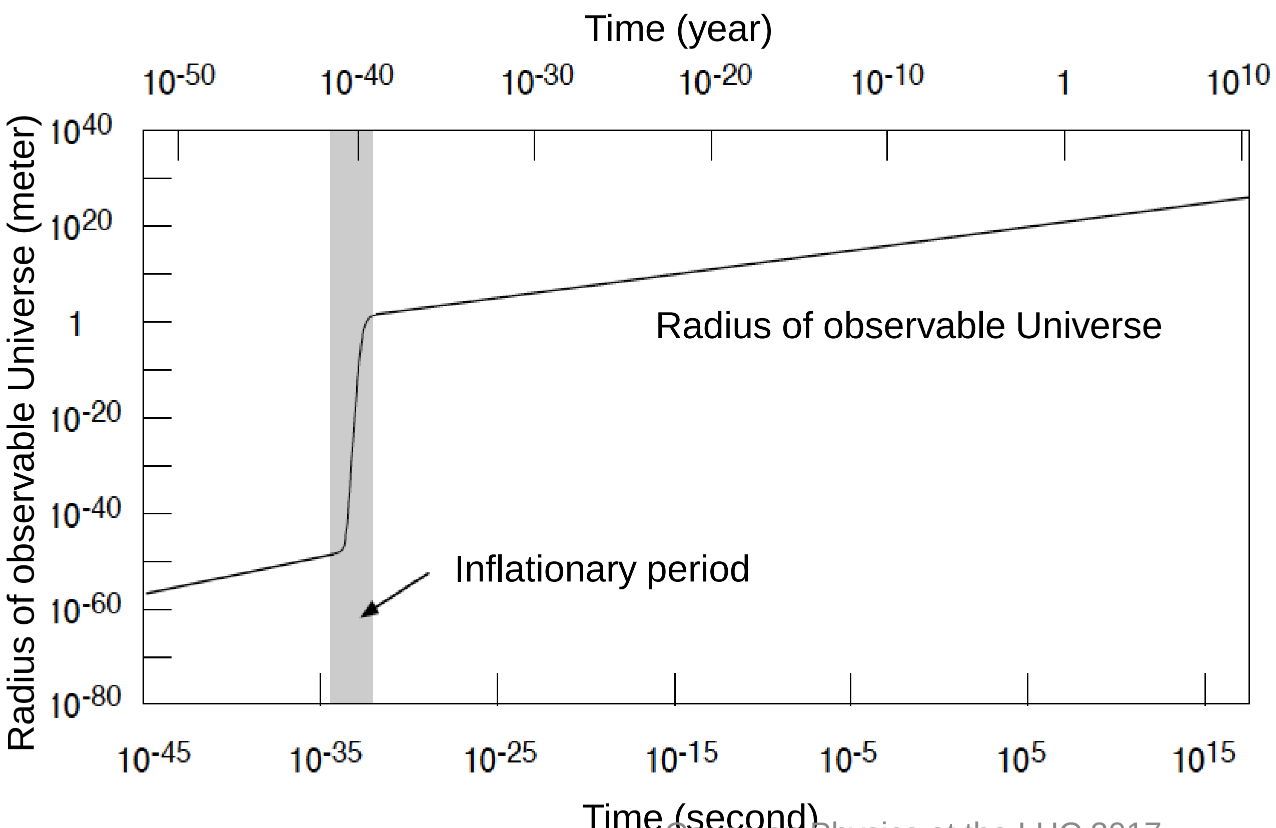
Understanding the Universe



Cosmological inflation

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

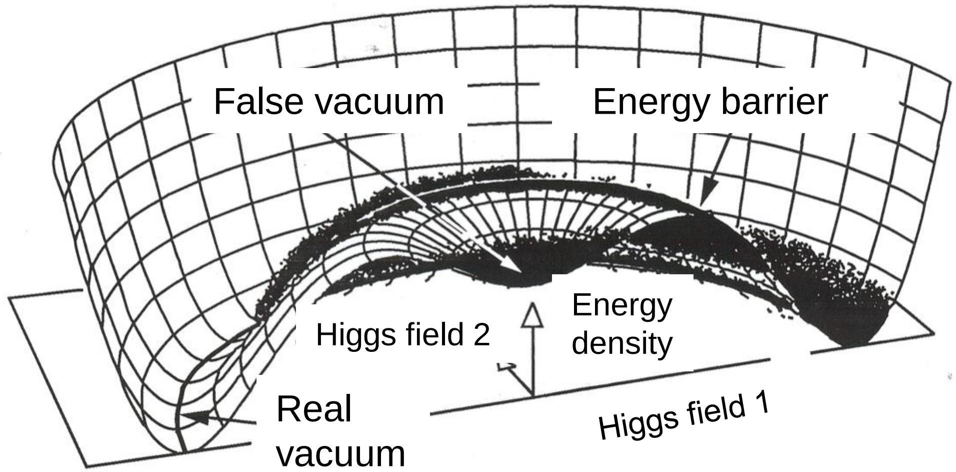
Explains why the Universe has a uniform Temperature (3 K) and why space-time has a flat geometry



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

Higgs like field and inflation

At the origin of the Universe, the energy density of a Higgs-like field is positive.



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.

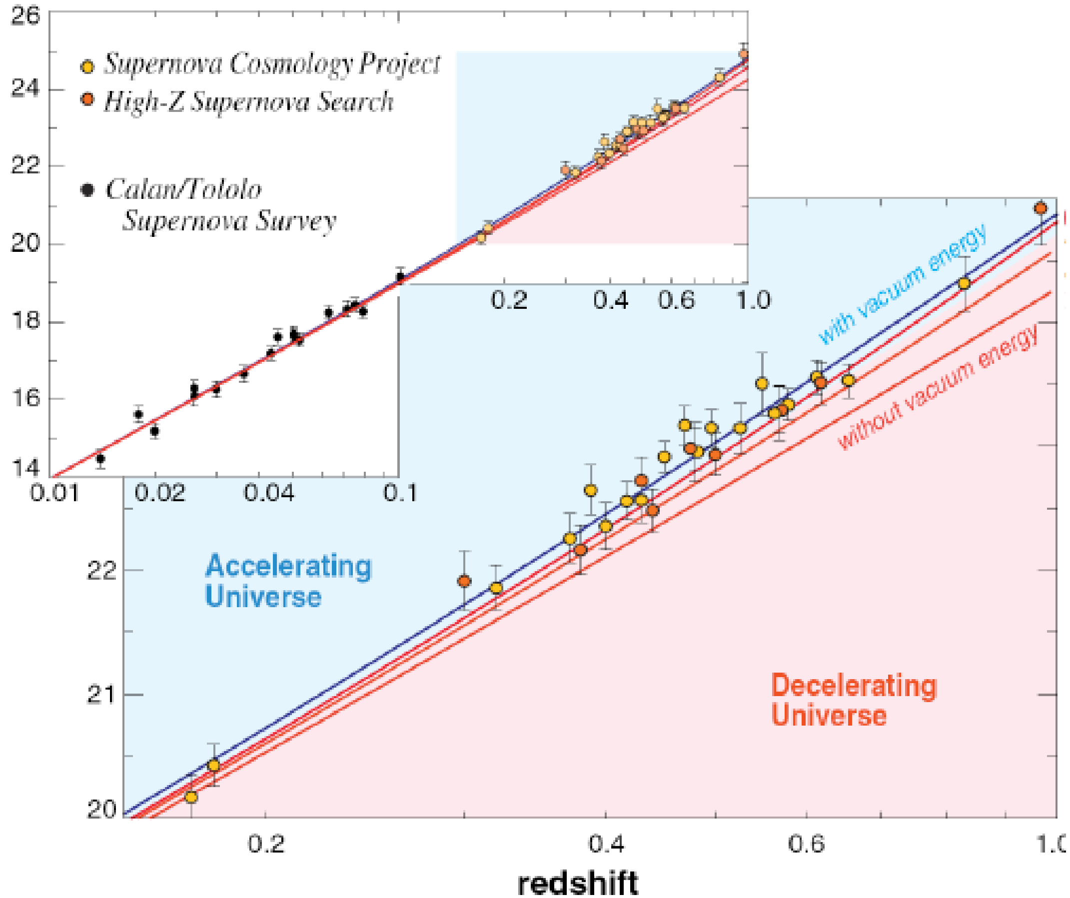
The energy released by the Higgs field is converted into matter particles.

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)

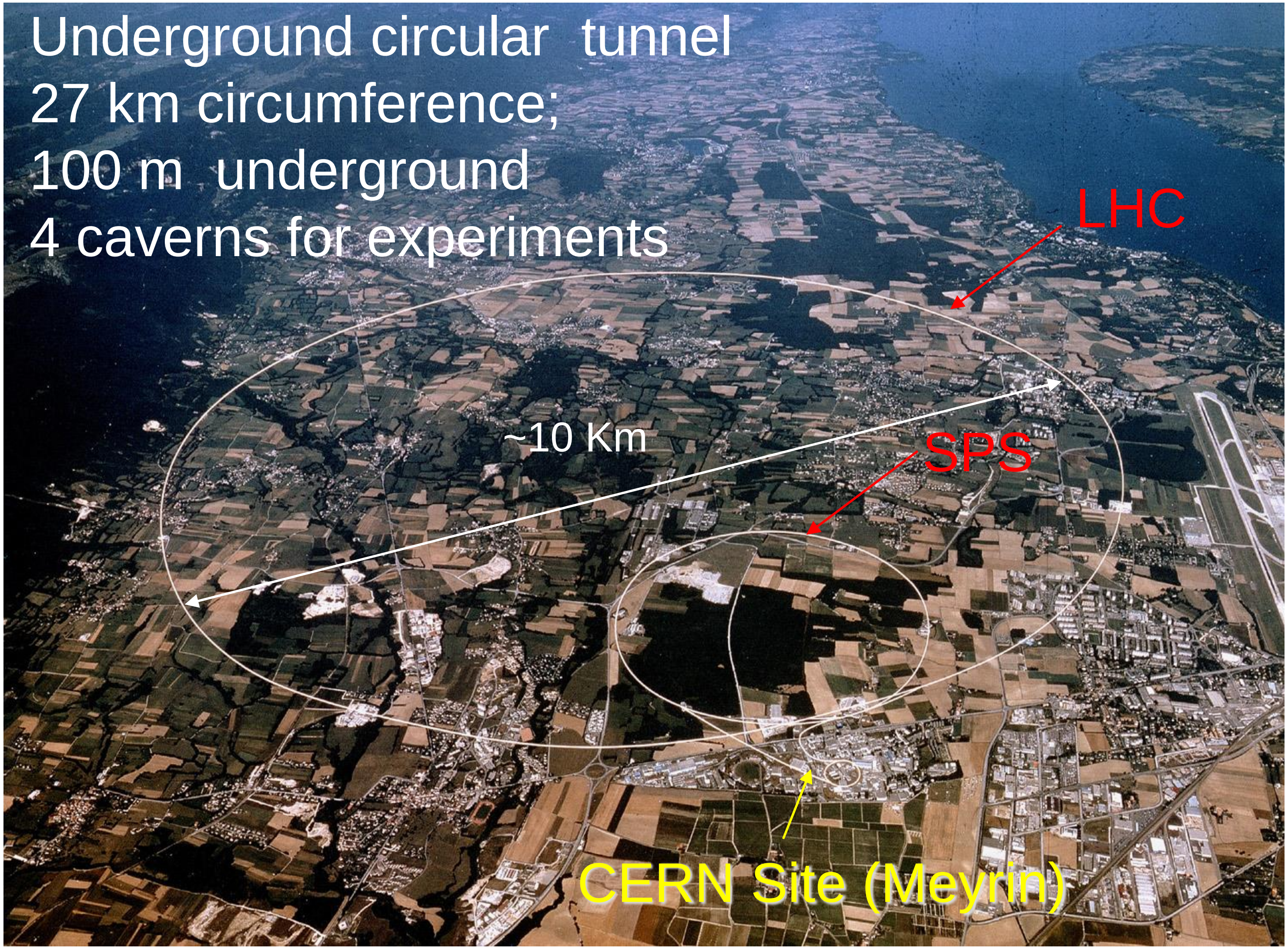
They got the same result:
The Universe expansion is accelerating

Some form of energy (dark energy) fills space

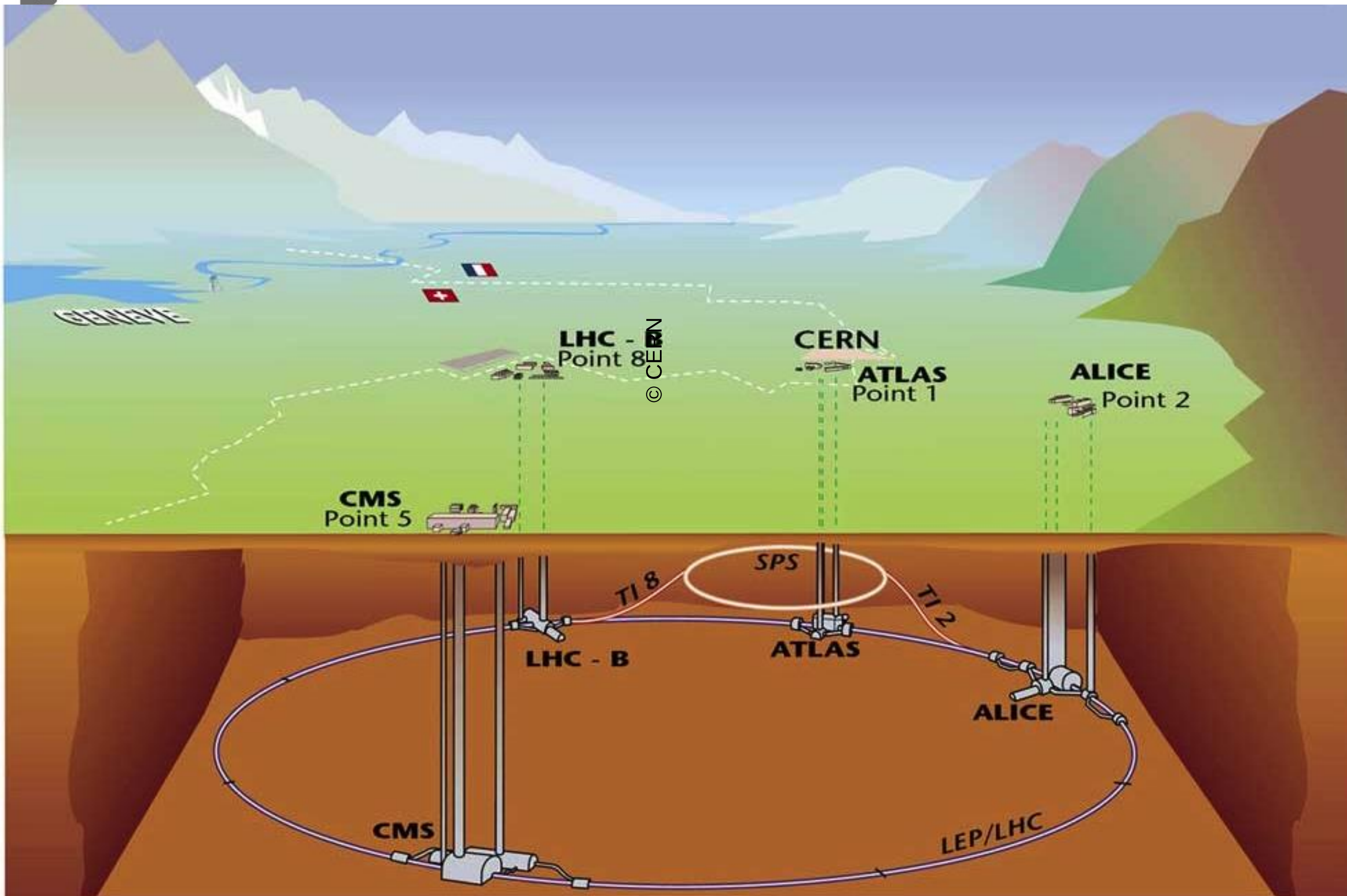


The LHC proton collider

Accelerator and Experiments



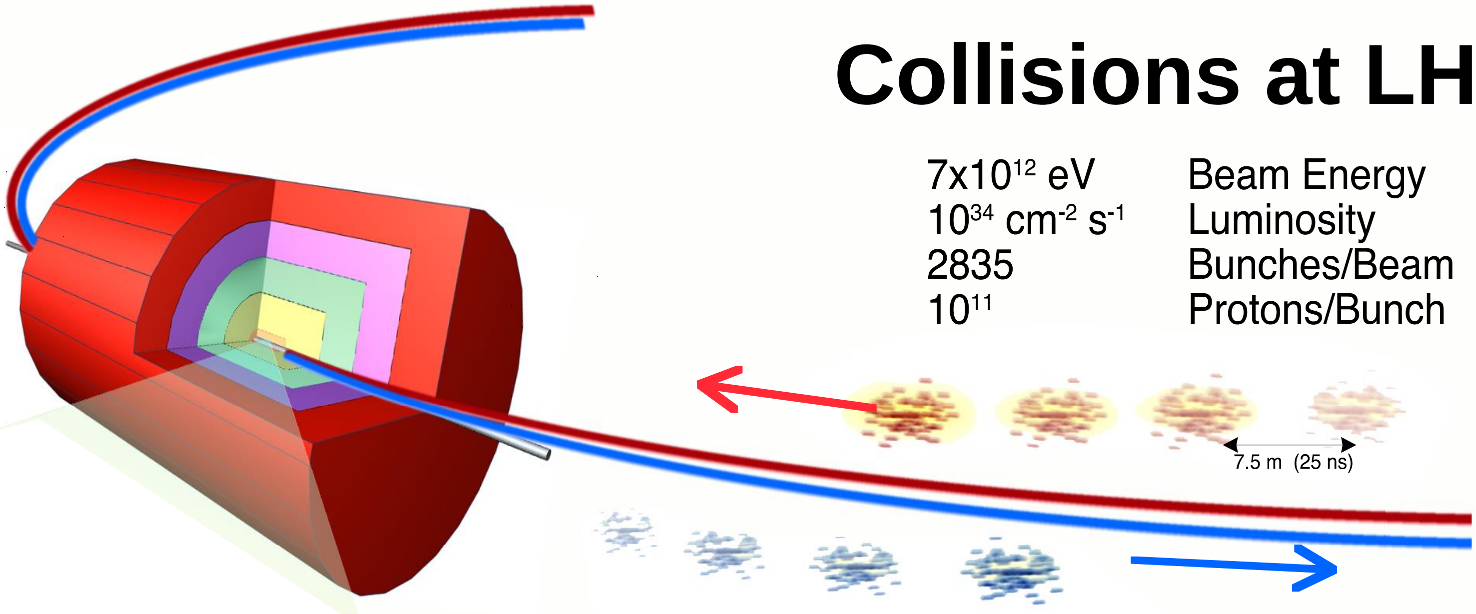
Accelerator and experiments layout



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 TeV Proton Proton
colliding beams

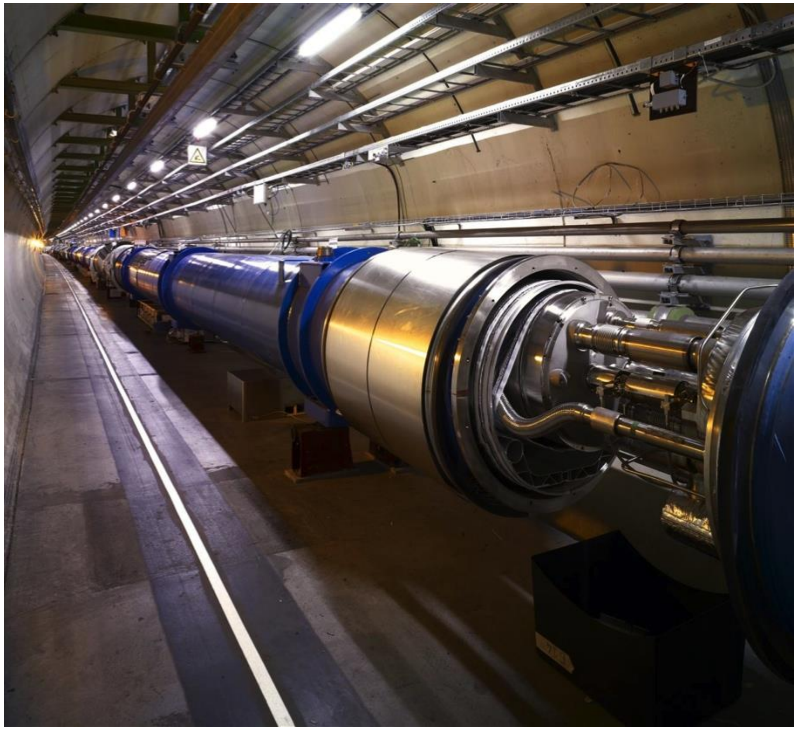
Accelerator challenges

Relative to Tevatron (Fermilab, USA)

Energy (14 TeV) x 7

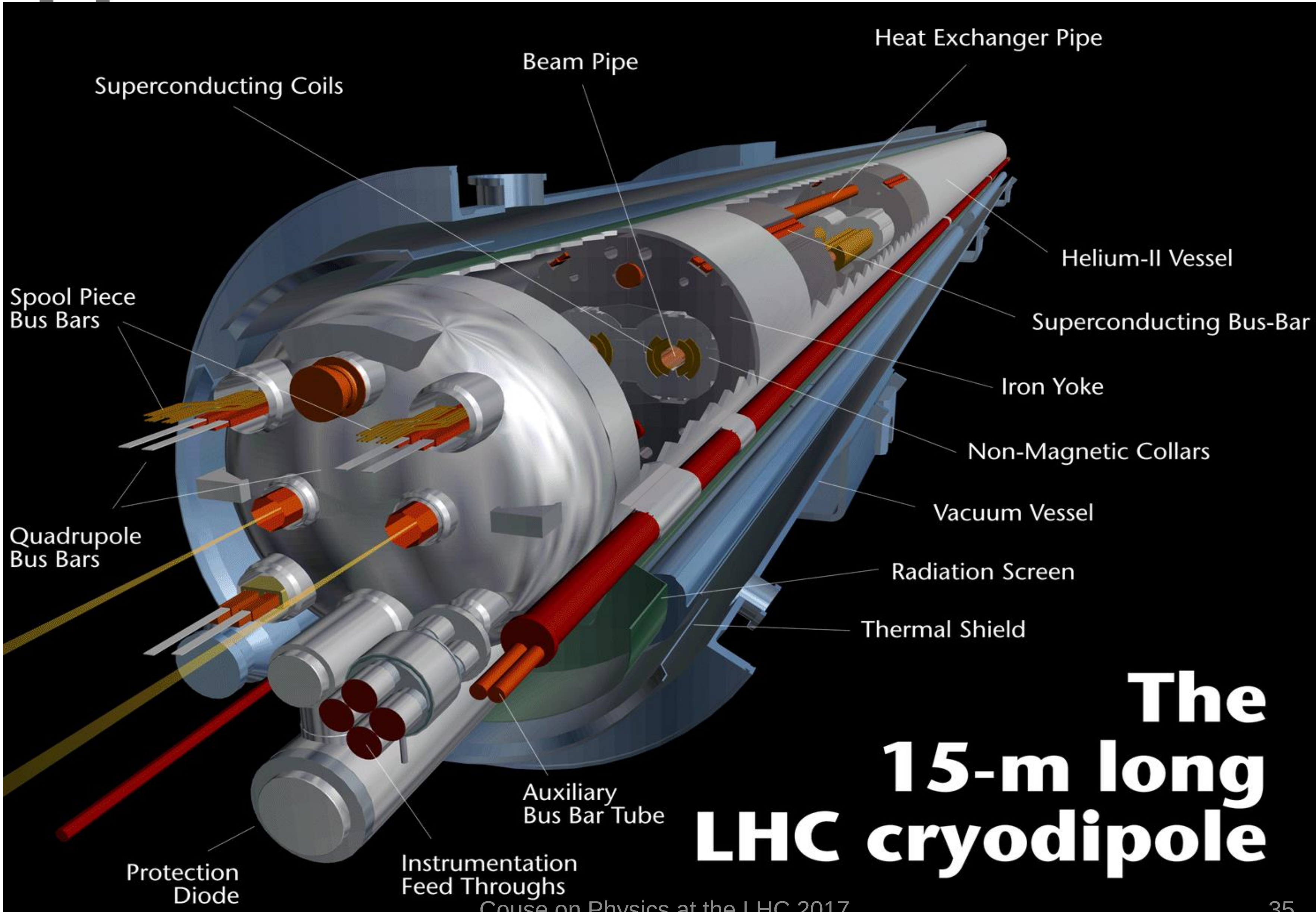
Luminosity ($10^{34} cm^{-2} s^{-1}$) x 30

- 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

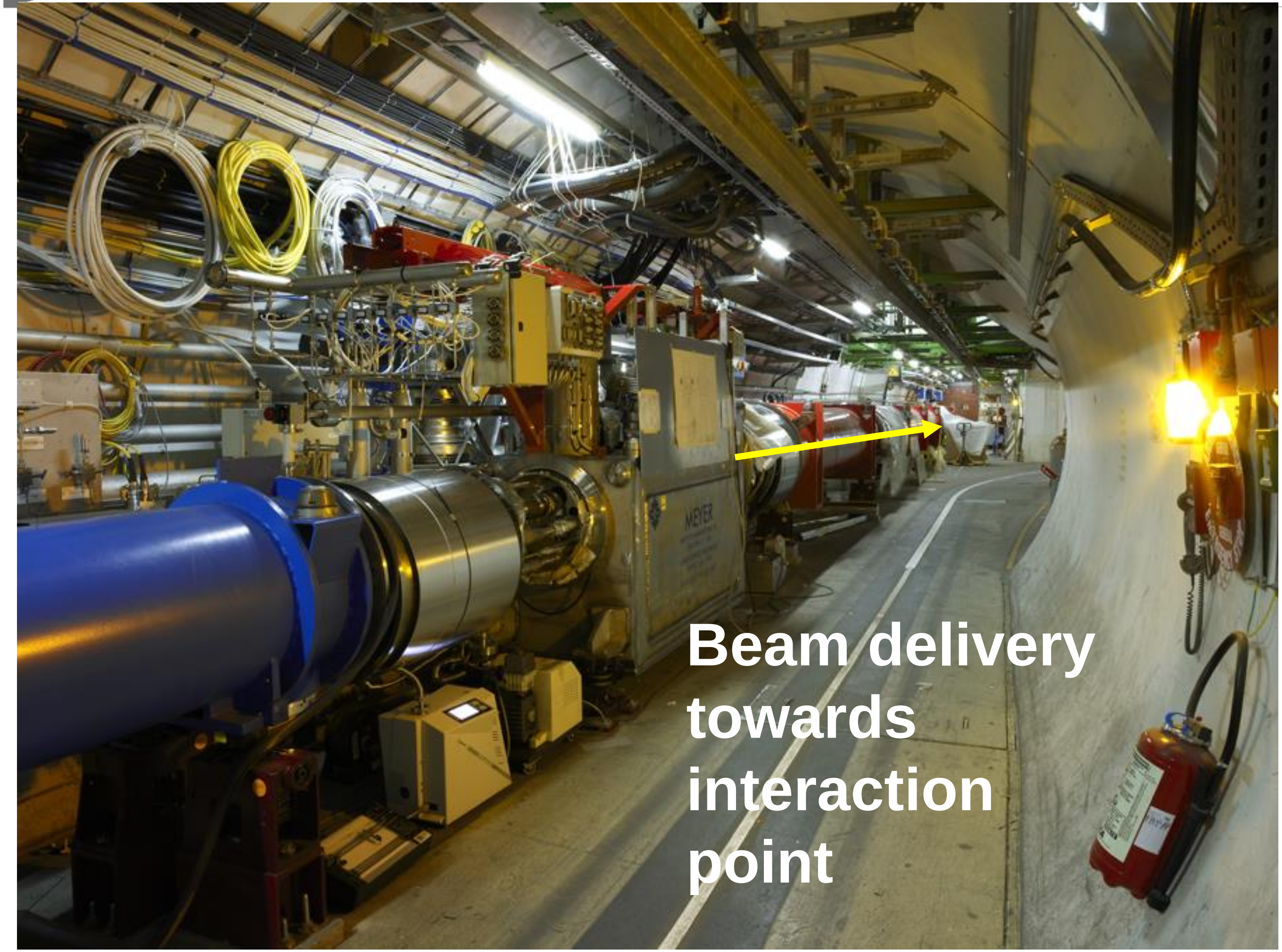


- More than 2000 dipoles
- 100 ton liquid helium
- LHC power consumption 120 MW

Superconducting magnetic dipole

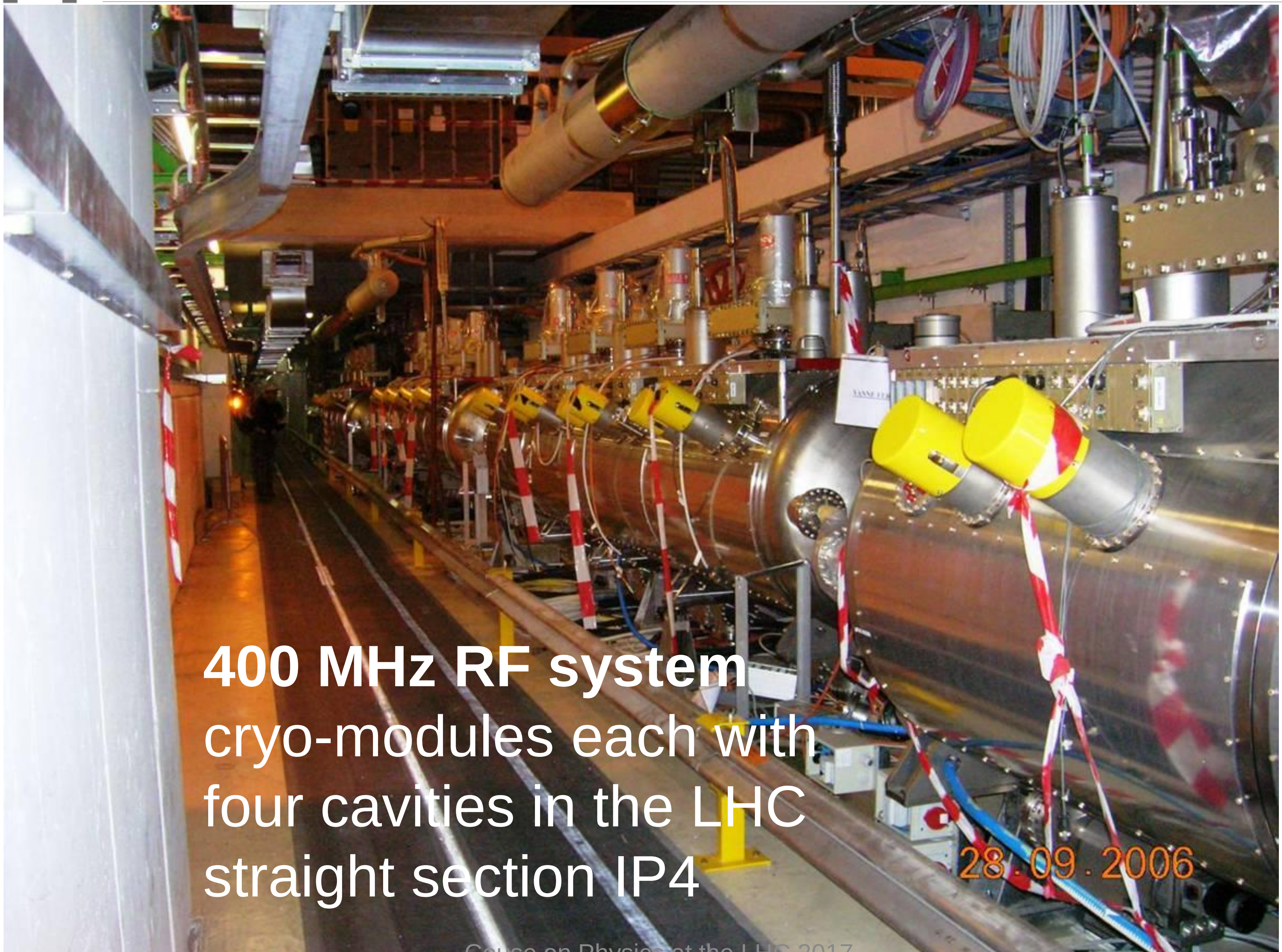


In the tunnel



Beam delivery towards interaction point

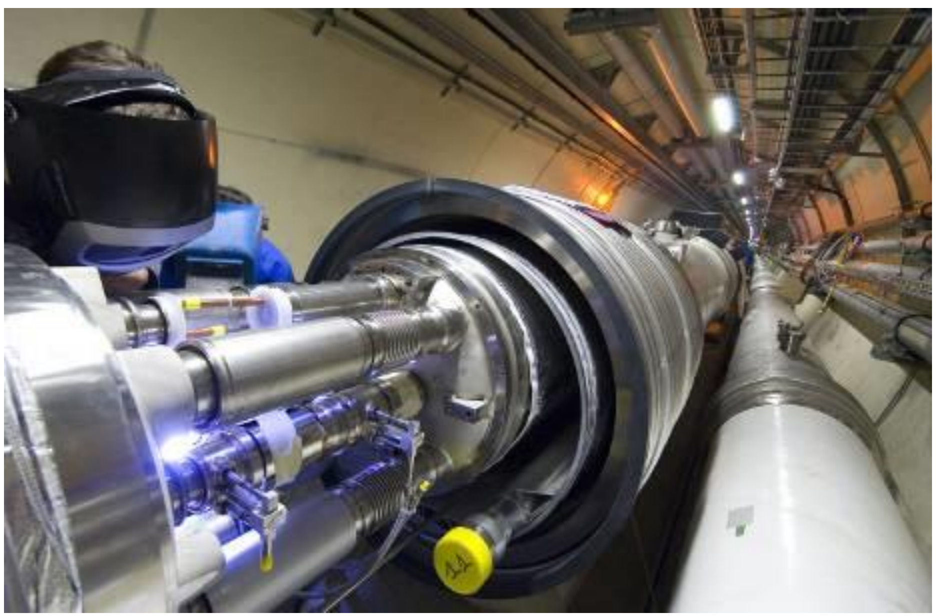
In the tunnel

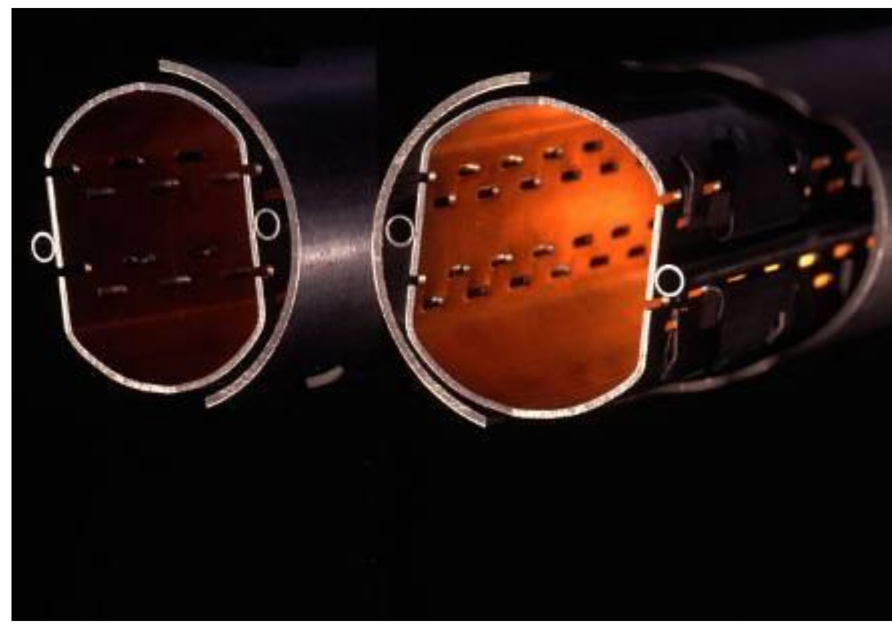


400 MHz RF system
cryo-modules each with four cavities in the LHC straight section IP4

It’s empty!

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



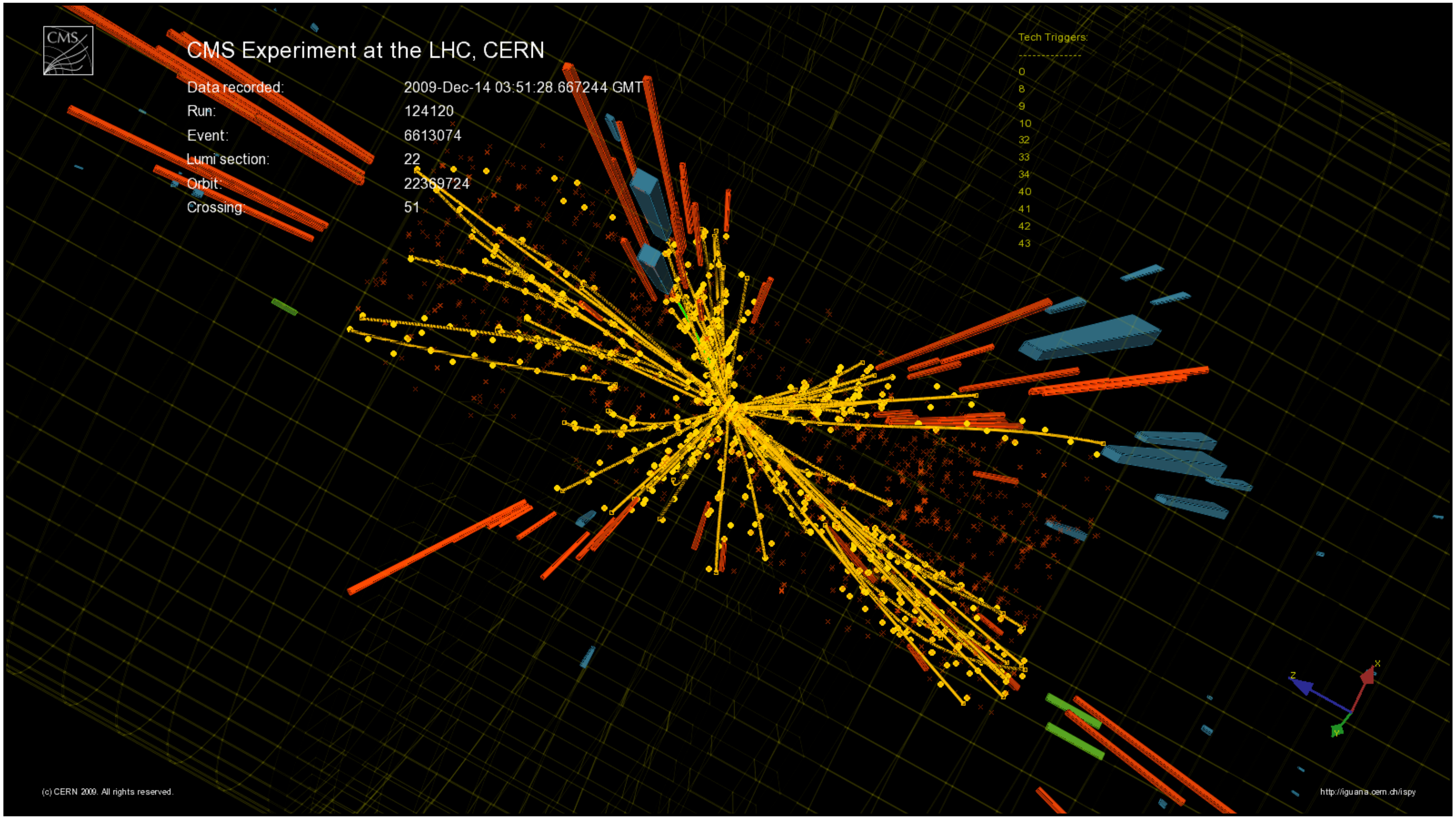


It’s cold!

27 Km of magnets are kept at 1.9 ºK, 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