Attention !!!

Why the Higgs Is YOUR ultimate Personal Manager !!!

Dr David Cockerill (RAL) Culham 8 Nov 2021

“Why the Higgs boson is YOUR ultimate personal manager”

Plan of the talk

1) The Higgs Boson story
2) The Higgs mechanism
3) The discovery of the Higgs boson at CERN
4) Why the Higgs boson is YOUR ultimate personal manager
5) What next at CERN
6) Conclusions

The Higgs Boson Story

Satyendra Nath Bose at my Father-in-law's joint family home, "Hati Bagan", হাতিবাগান, Kolkata, probably mid 1930s

Responsible for the Mathematics that describe the behavior of particular sub-atomic particles that came to be called **"Bosons"**
This kind of particle was then used by Peter Higgs in his theory in 1964

Peter Higgs

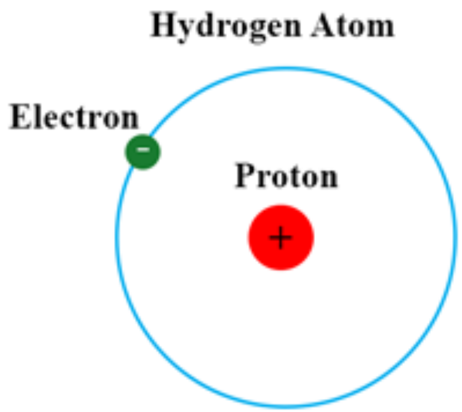
Mathematics to explain **how** sub-atomic particles **obtain mass** through interactions with the so called "**Higgs field**"

Nobel Prize for Physics (2013)
Peter Higgs and François Englert

A big problem in particle physics:

How do fundamental sub-atomic particles get their mass ???

For example, where does the electron's mass come from ?



This question plagued scientist for centuries – until Peter Higgs and others came along in 1964.

They proposed a theory, now called the "Higgs mechanism", which explains how sub-atomic particles get Mass.

The Higgs mechanism

Electrons, and other fundamental sub-atomic particles, get their mass because they (and we) are ALL bathed in the invisible Higgs field that pervades the whole universe.

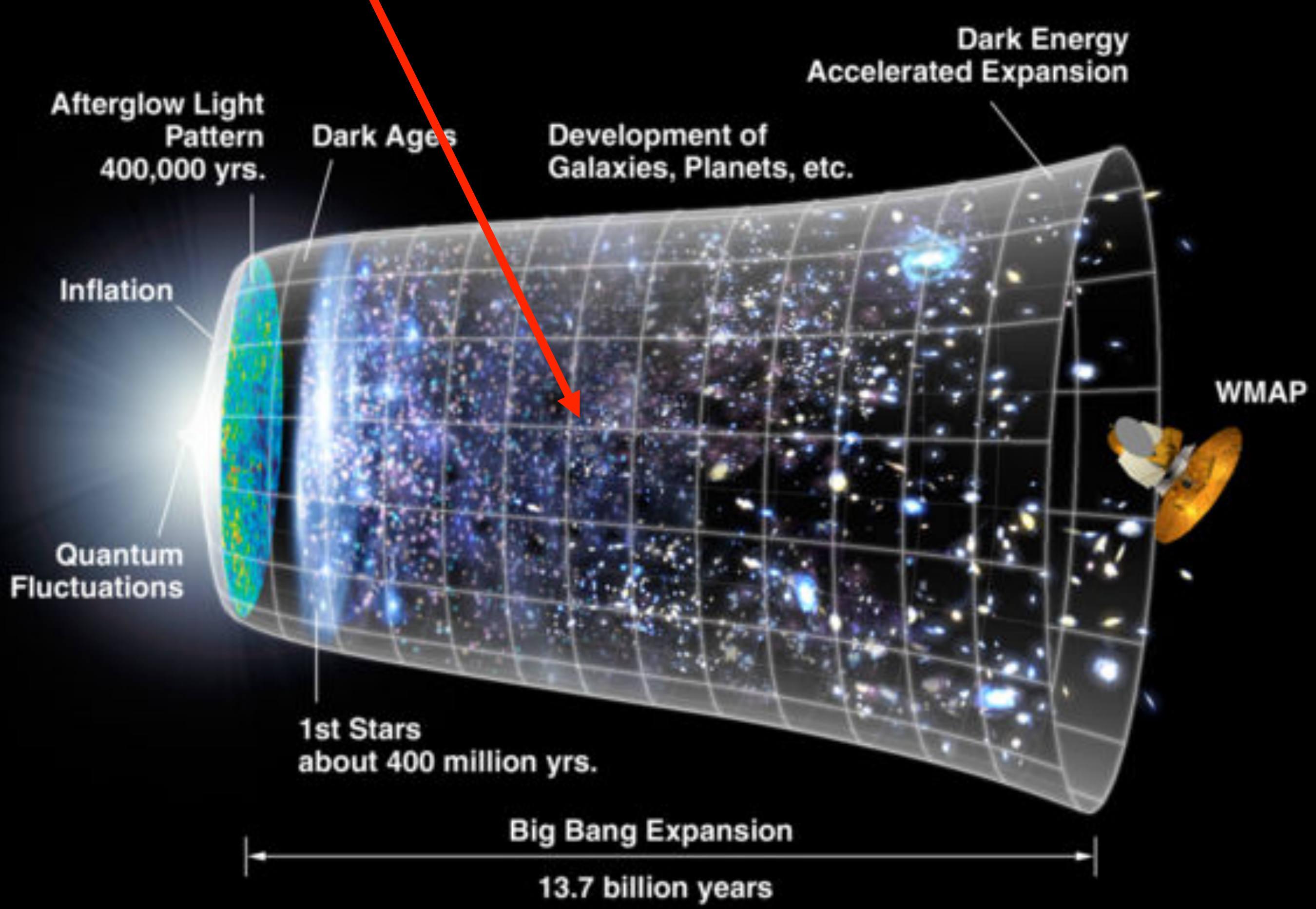
We are also, as it happens, bathed in the earth's gravitational field

A BIG consequence of the theory: if the Higgs field exists, there MUST be a fundamental particle associated with it

This is the famous "Higgs boson".

ONLY Peter Higgs, in his 1964 paper, explicitly mentioned that the Higgs field has a fundamental particle associated with it

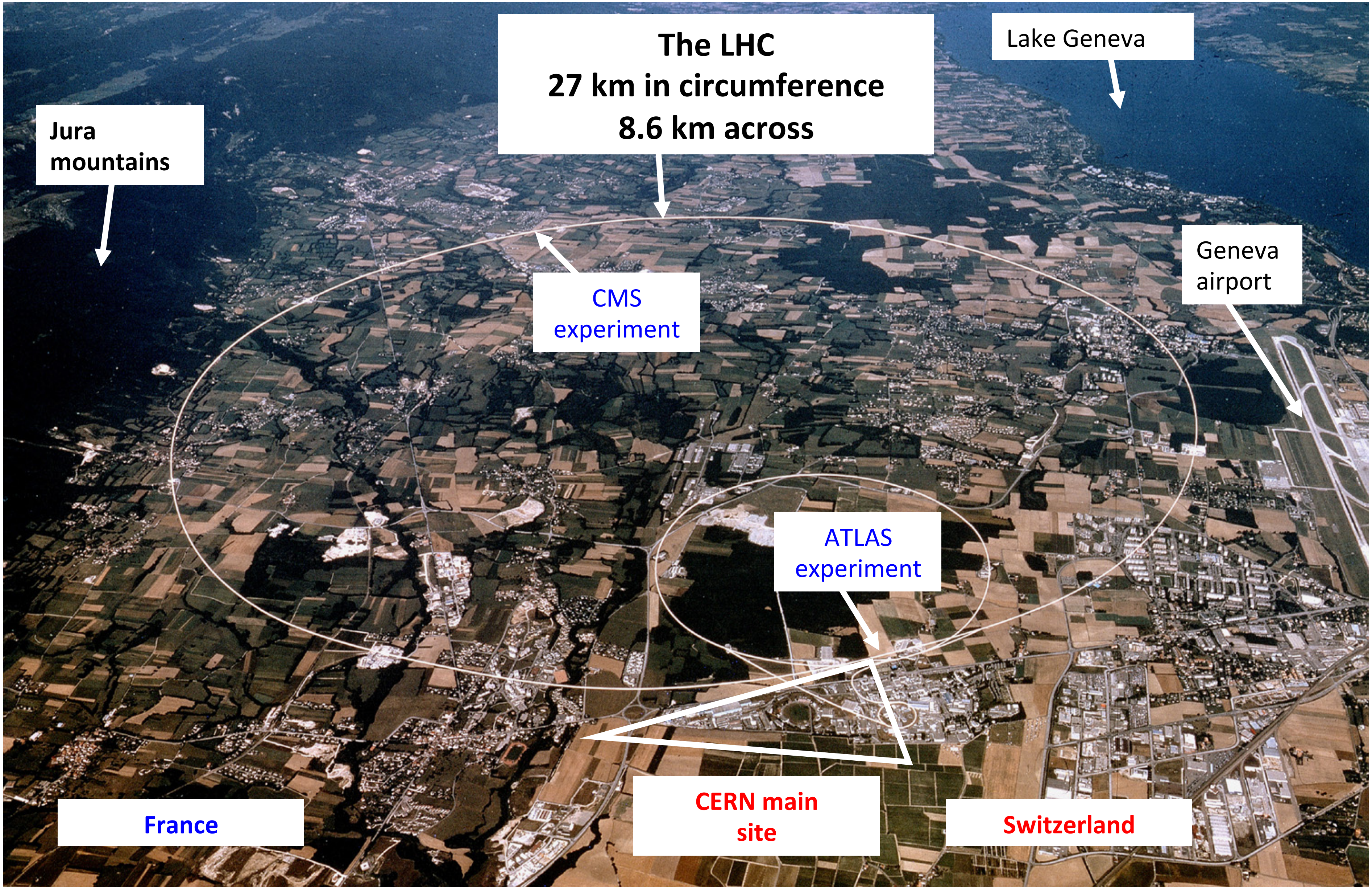
The Higgs field: same "strength" throughout space, unlike a gravitational field which gets weaker with distance



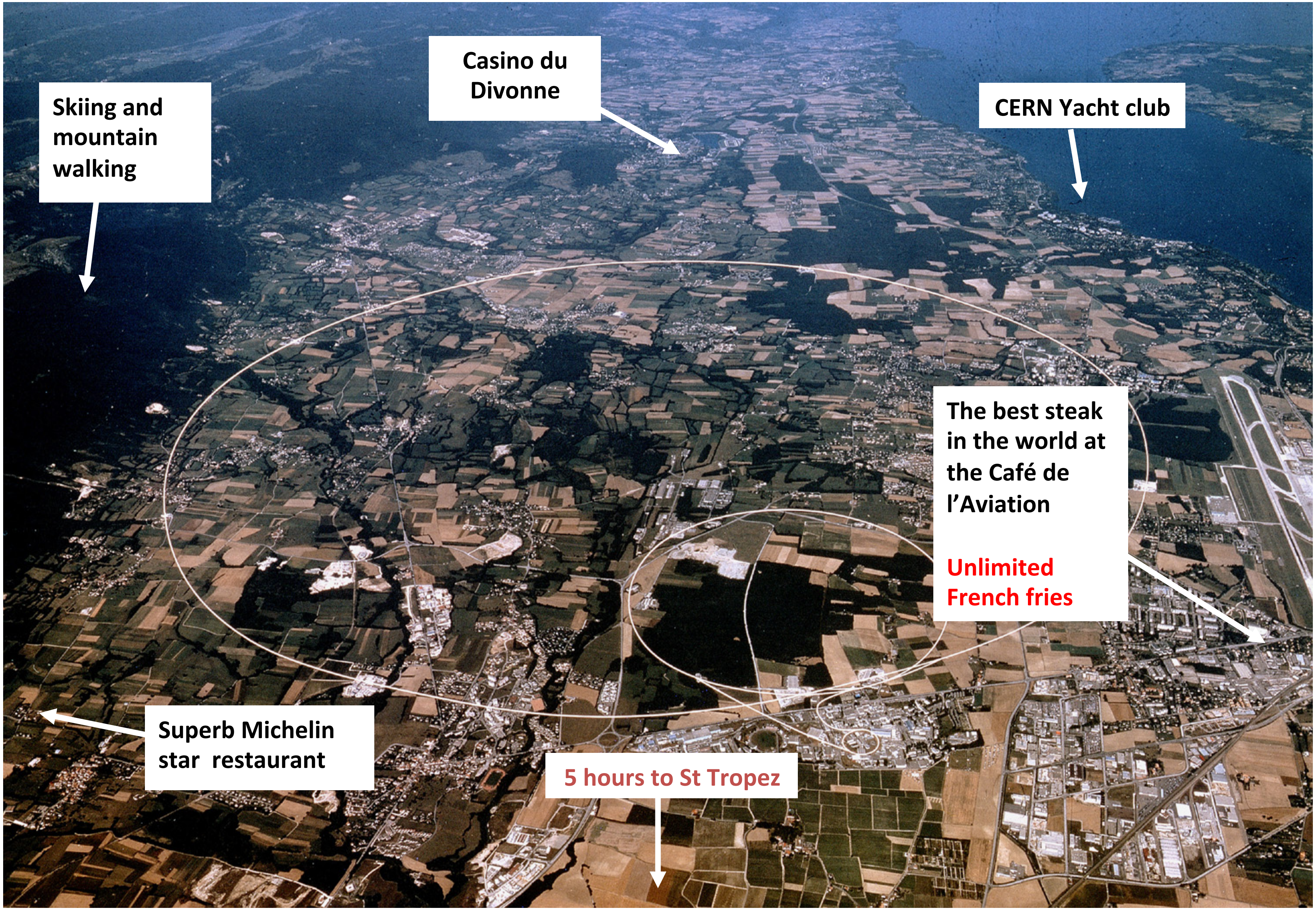
We are COMPLETELY in this Higgs field right now (and wherever we go, even to the toilet) !!

To Create and Detect the Higgs boson

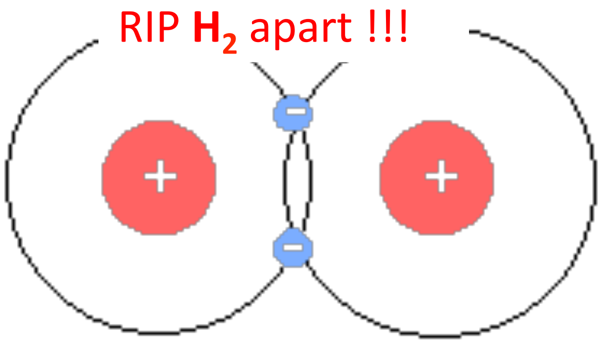
Enter: The Large Hadron Collider (LHC) at CERN



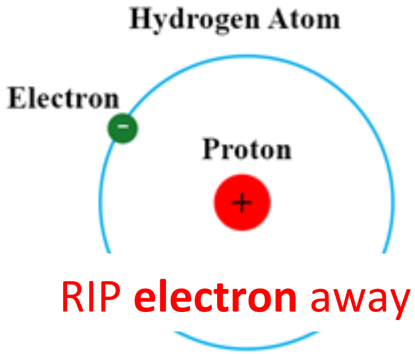
The Large Hadron Collider (LHC) – a challenging environment:



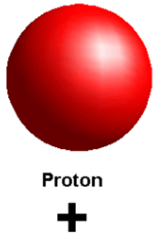
From Protons to Higgs at the Large Hadron Collider, the LHC



Hydrogen molecule, H_2



Just one ordinary cylinder of hydrogen (hydrogen = "watermaker" in Greek)



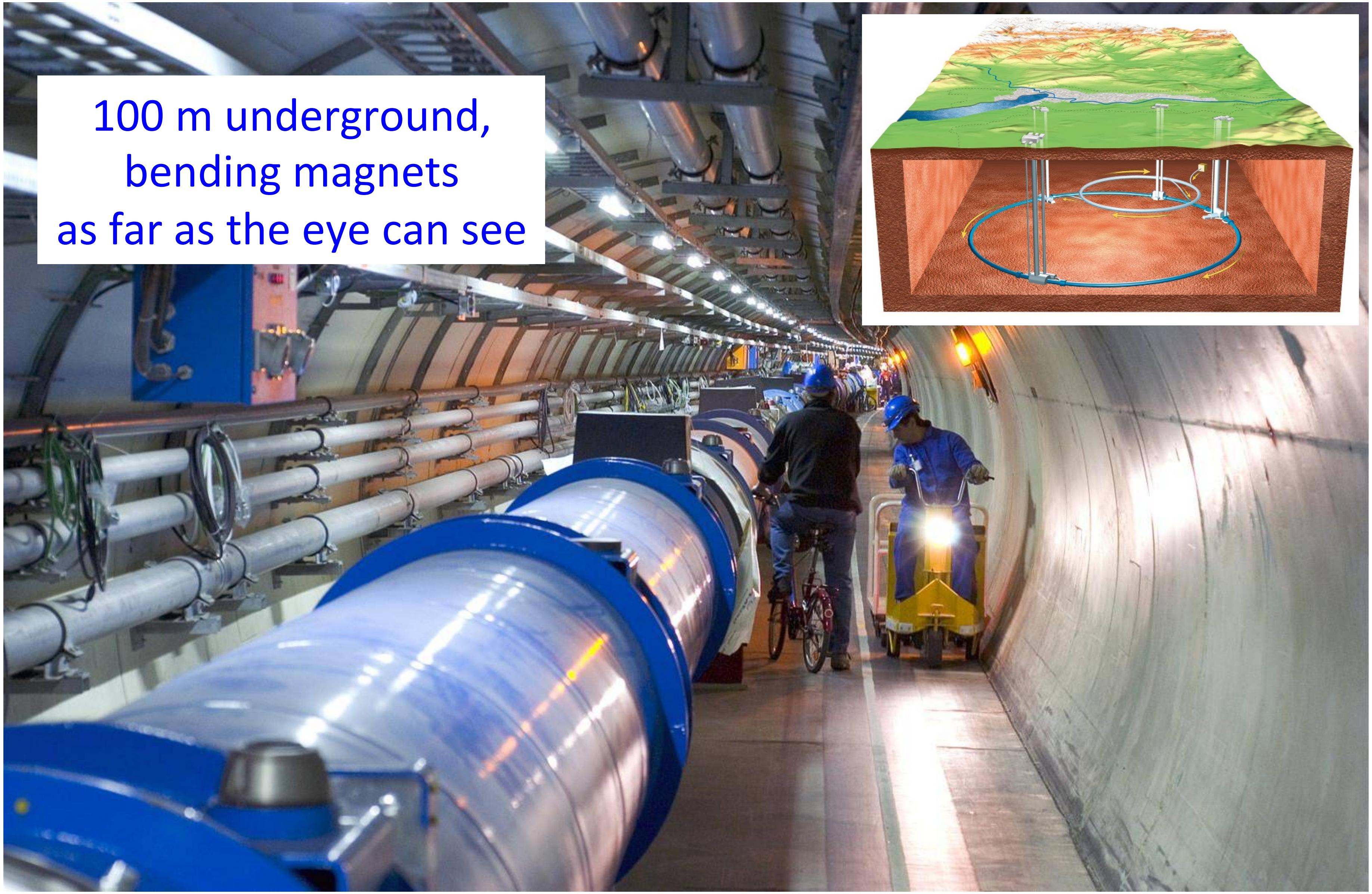
STUFF the proton into the LHC (and 2.10^{12} others), collide, and find the Higgs !!!

Could do this on your kitchen table

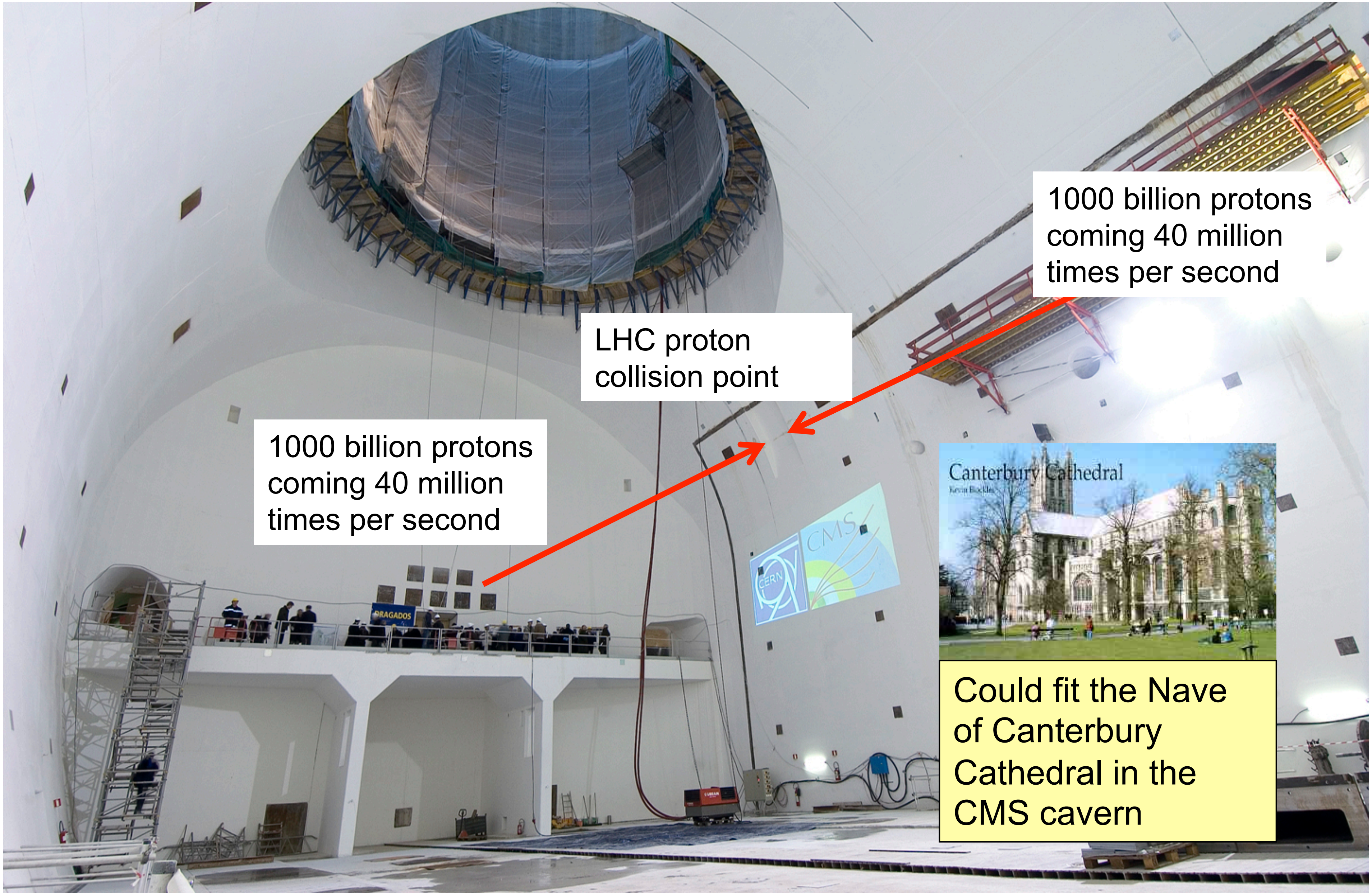
Accelerate the protons to 7 TRILLION (7.10^{12}) e-VOLTS of energy

Equivalent to using 4.6 TRILLION 1.5 V torch batteries

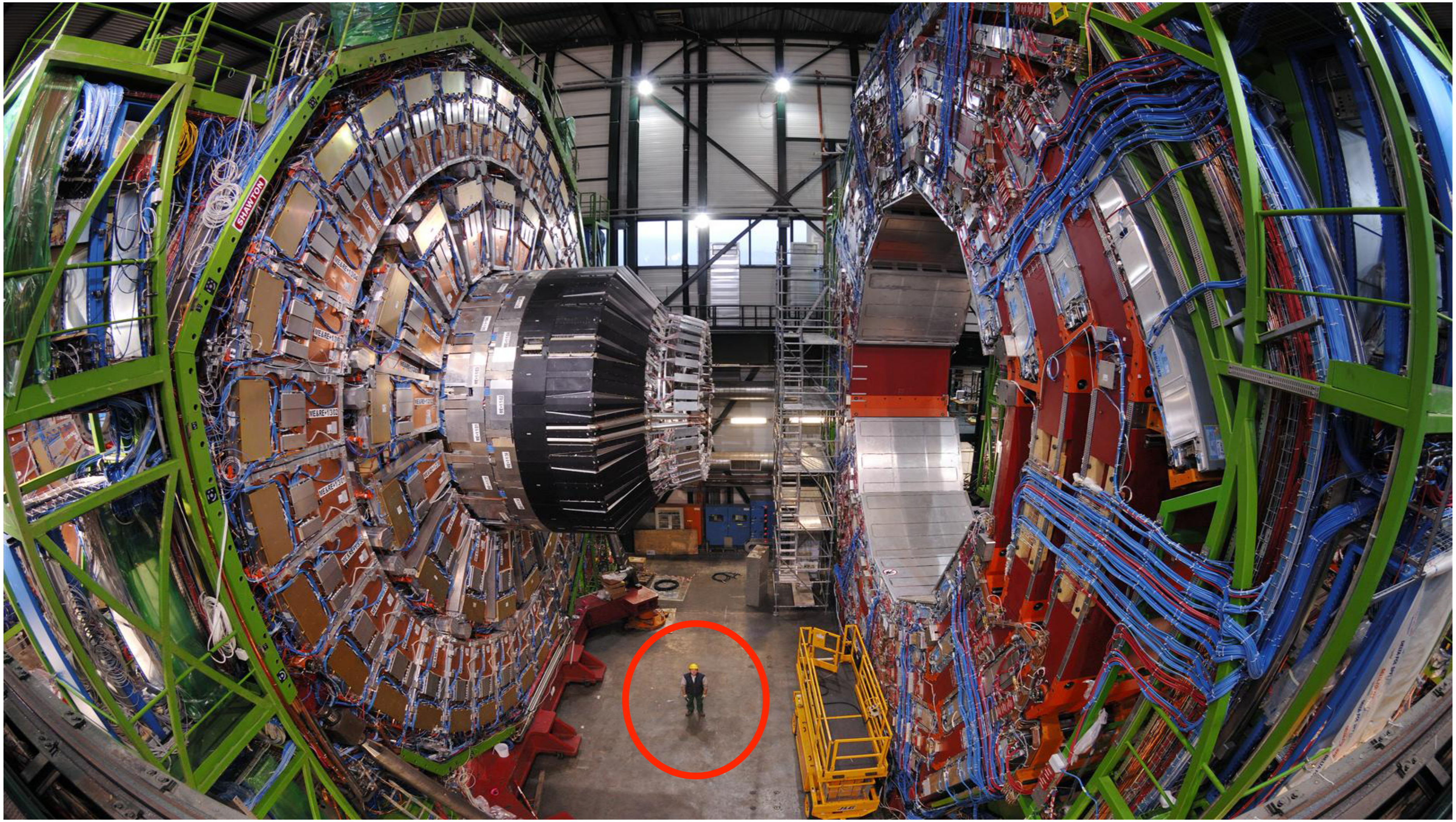
Protons at 99.99999% the speed of light



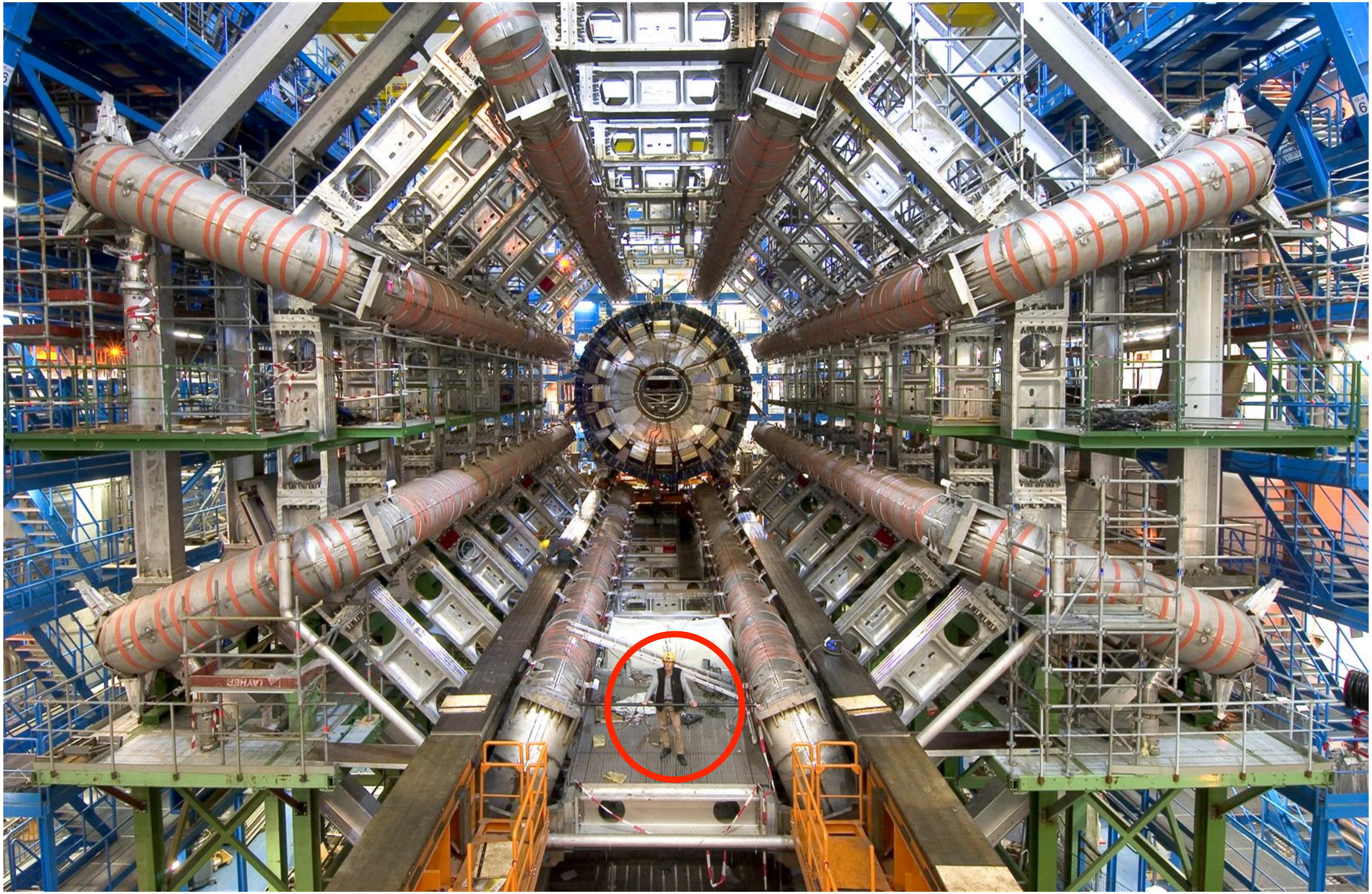
The experimental underground cavern for CMS – the Compact Muon Solenoid detector



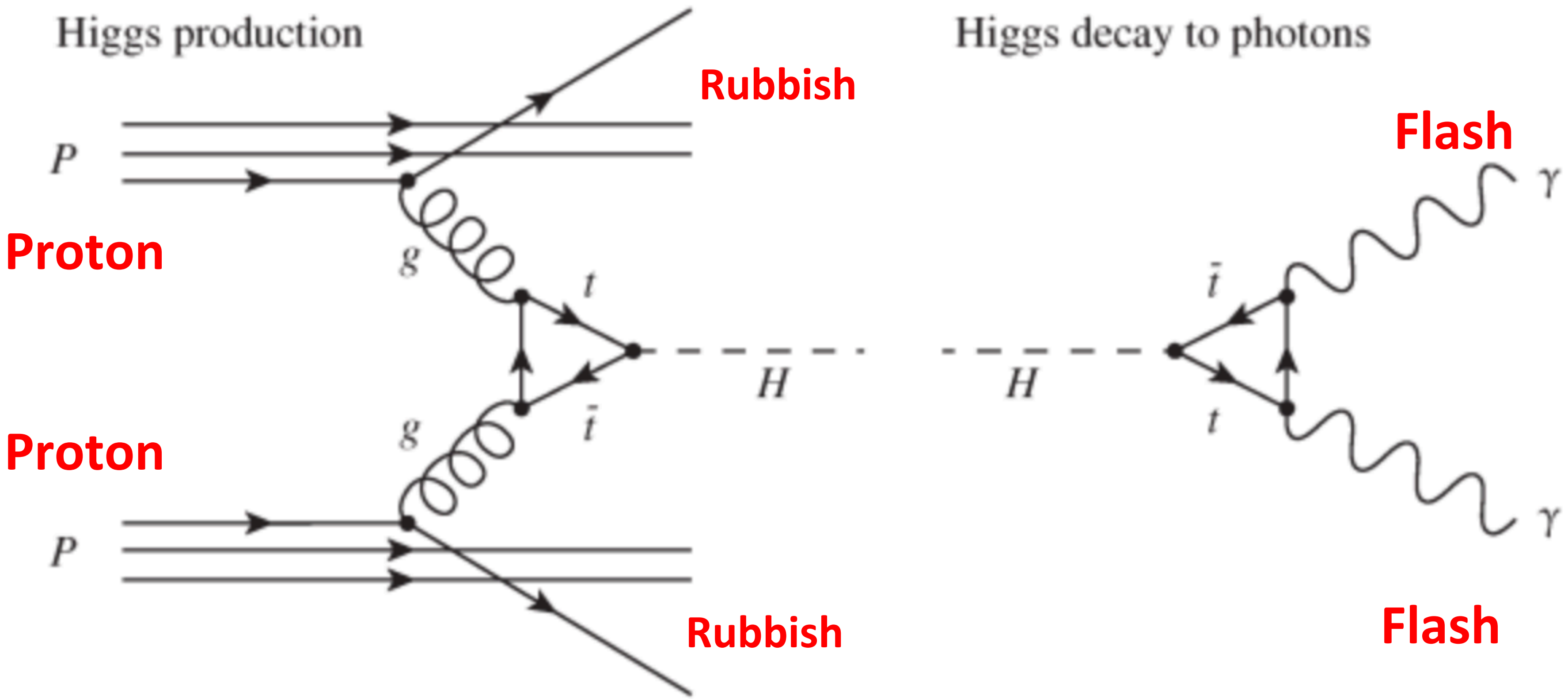
The CMS experiment just before moving the "endcap" section on the left towards the "barrel" section on the right, to close-up the detector



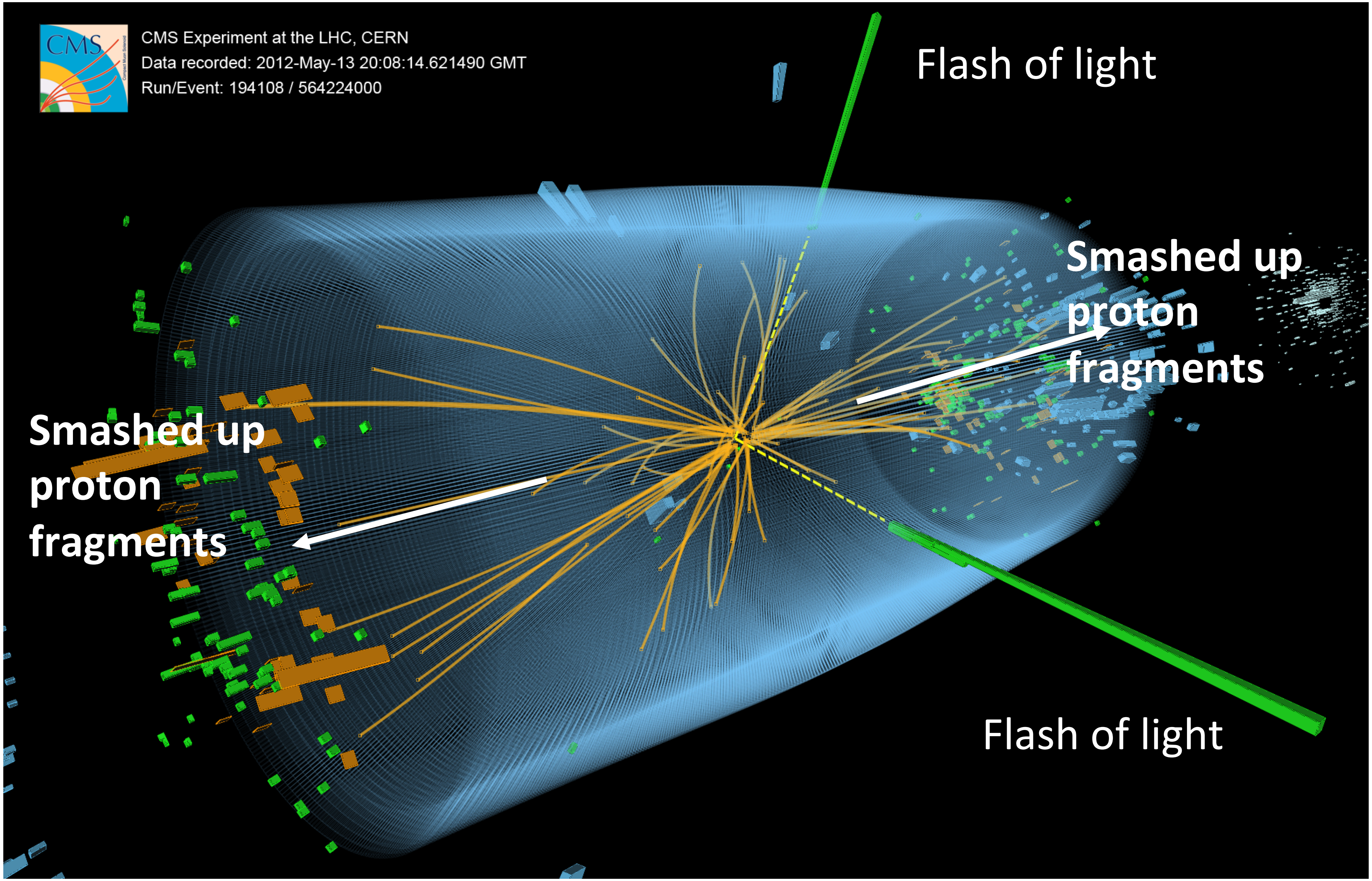
ATLAS: A Toroidal LHC ApparatuS
the huge sister experiment to CMS



The creation of a Higgs boson at the LHC and its signature decay to 2 flashes of light



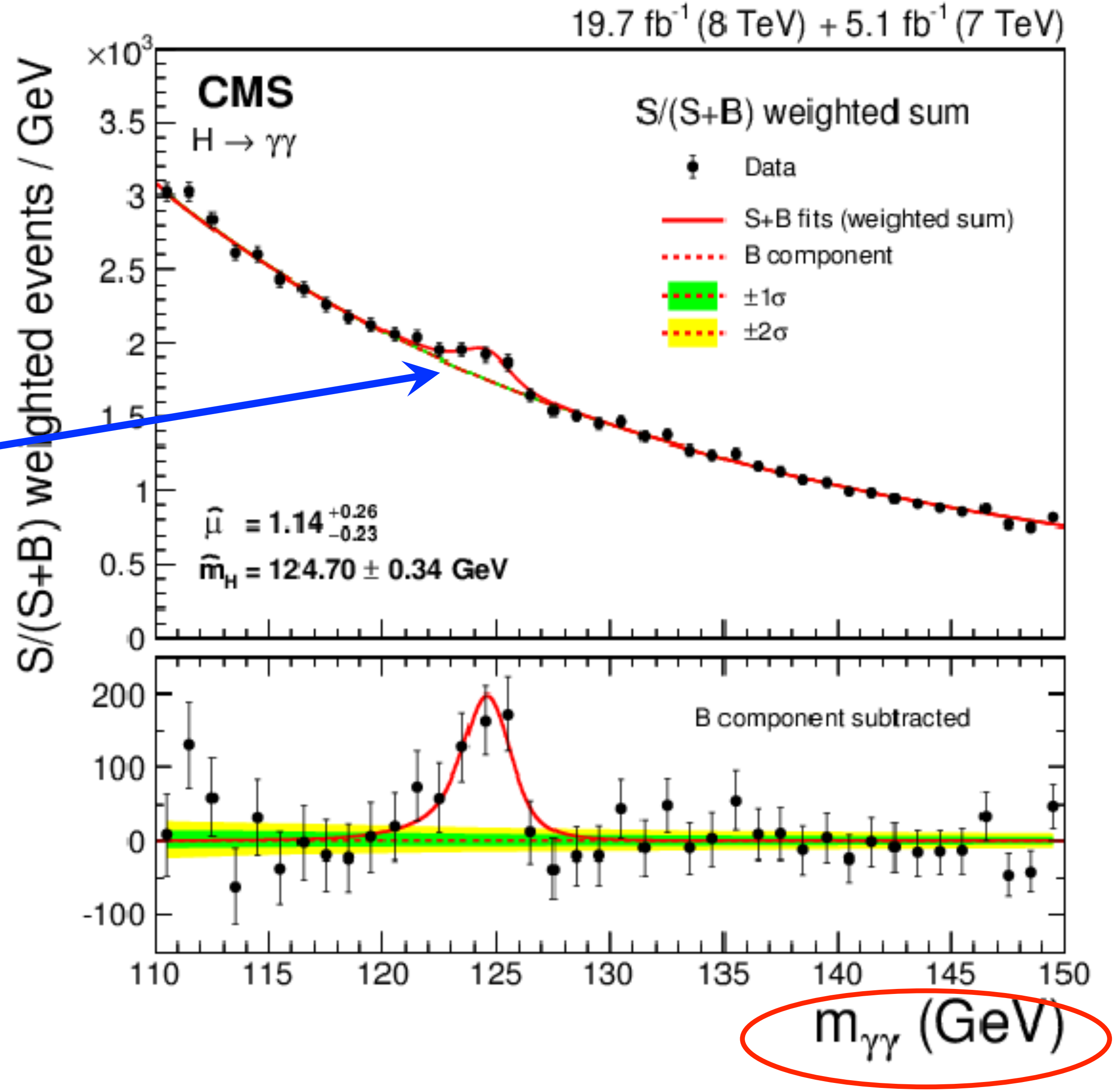
A dramatic proton-proton collision on 13 May 2012, with the possible creation of a Higgs particle and its decay



The final NOBEL prize winning plot with the Higgs signal !!!!!

Only the Higgs decays give 2 flashes of light that add up to a unique energy

(smeared due to limited detector resolution)



At CERN on 4 July 2012, the ATLAS and CMS collaborations presented evidence in the LHC data for the Higgs boson

On 8 October 2013 the **Nobel prize** awarded jointly to **François Englert and Peter Higgs**

"…for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles…."

An aside: A WARNING ON HOW (not) TO WRITE A PAPER

Other theorists, in 1964, said that the consequent existence of the Higgs boson was too obvious to mention, in connection with the Higgs field

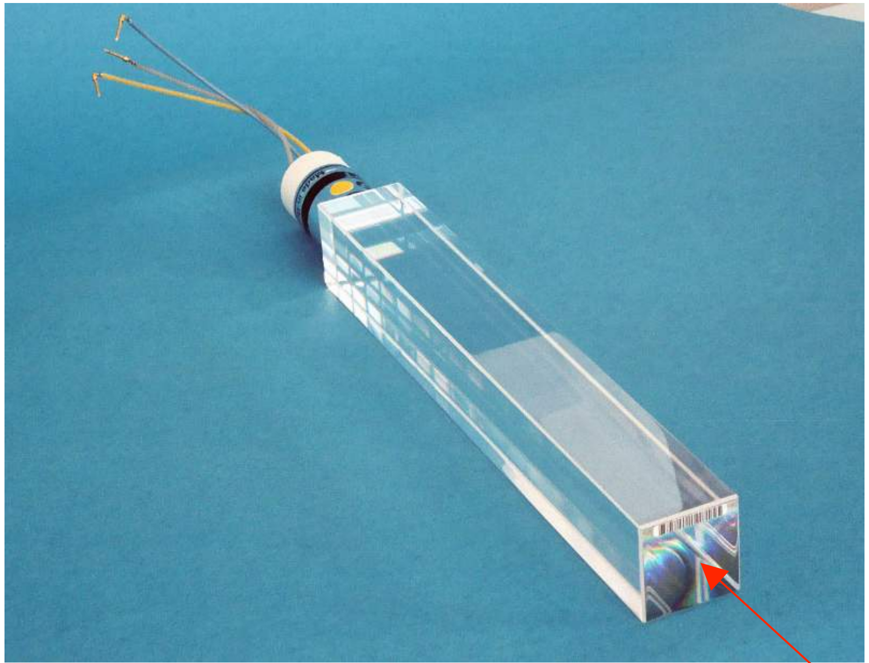
This resulted in only Peter Higgs having the particle named after him !!

Only Englert shared the Nobel prize with Higgs in 2013. Englert's colleague Brout died before the prize was announced.

So, to get the Nobel prize:

- **Always state the obvious**
- **And stay healthy**

How are the flashes from the Higgs boson detected ?

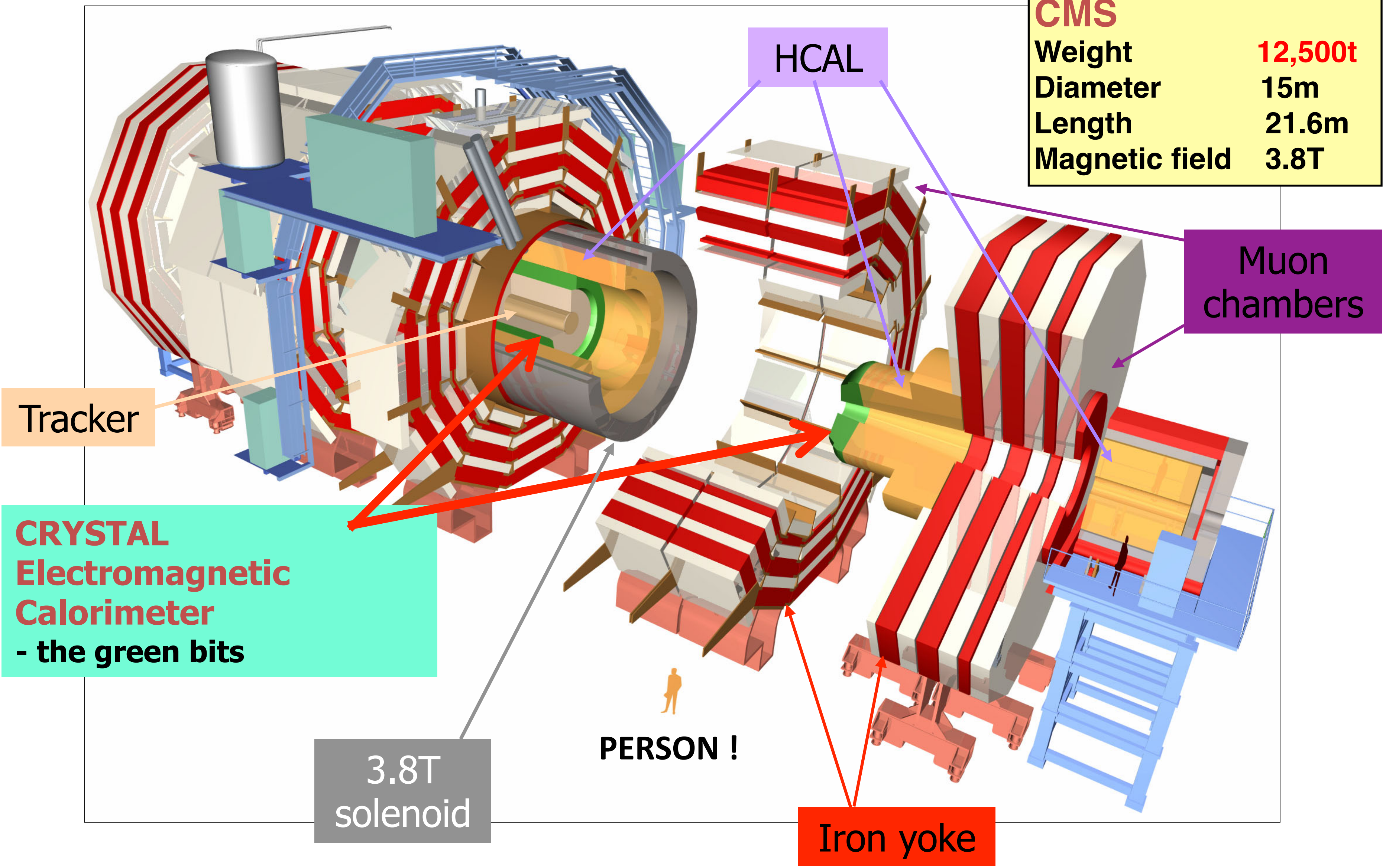


Incoming flash - a gamma ray, with ~100 billion times the energy of a light beam from the sun.

Special crystal, lead tungstate $PbWO_4$ 22 cm long by 3x3 cm^2 absorbs the flash and scintillates. Scintillation light detected by a photo-detector at the back of the crystal

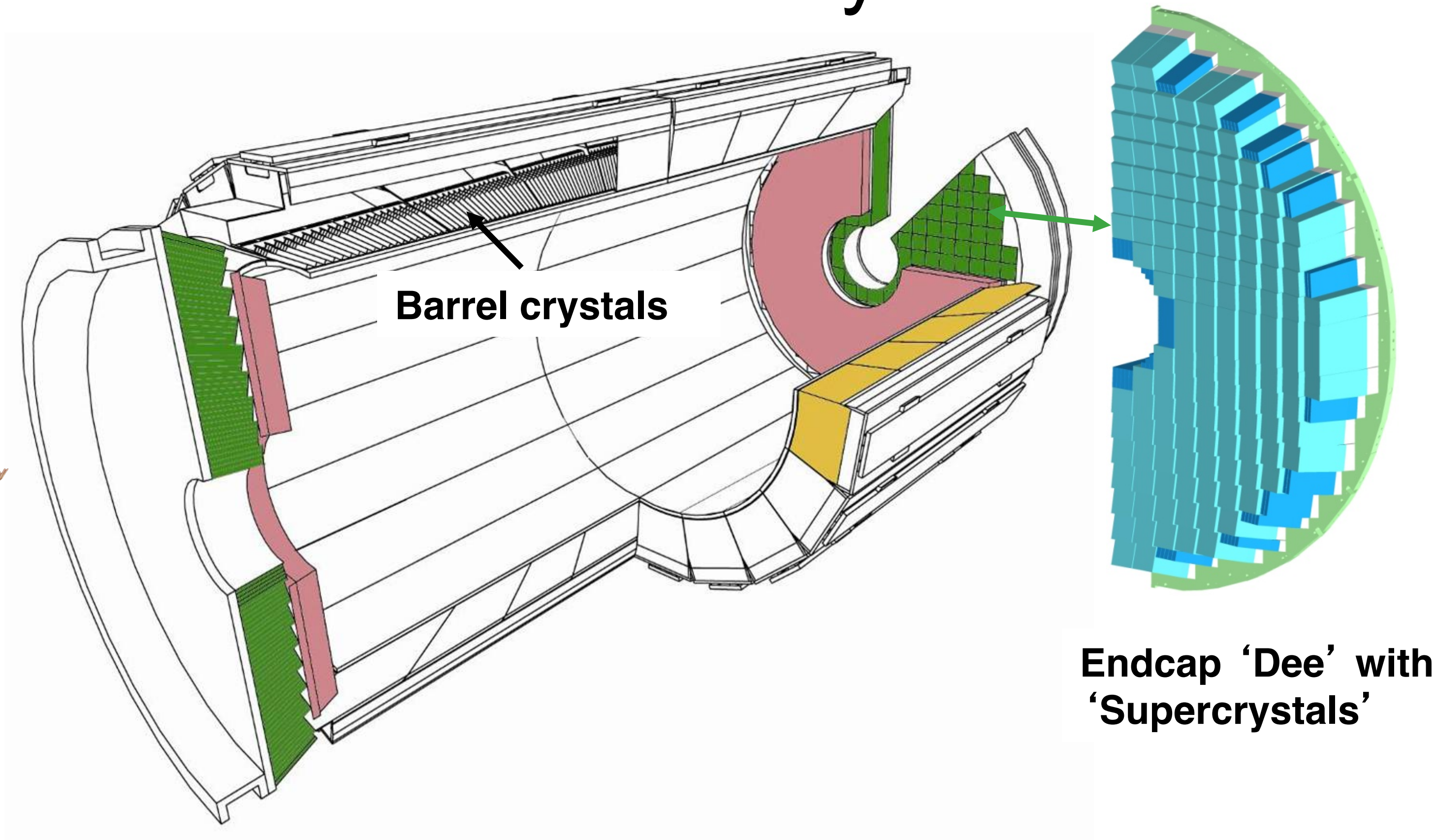
How are the flashes from the Higgs boson detected ?

Compact Muon Solenoid



CMS	
Weight	12,500t
Diameter	15m
Length	21.6m
Magnetic field	3.8T

CMS ECAL Layout



Barrel: 61200 crystals

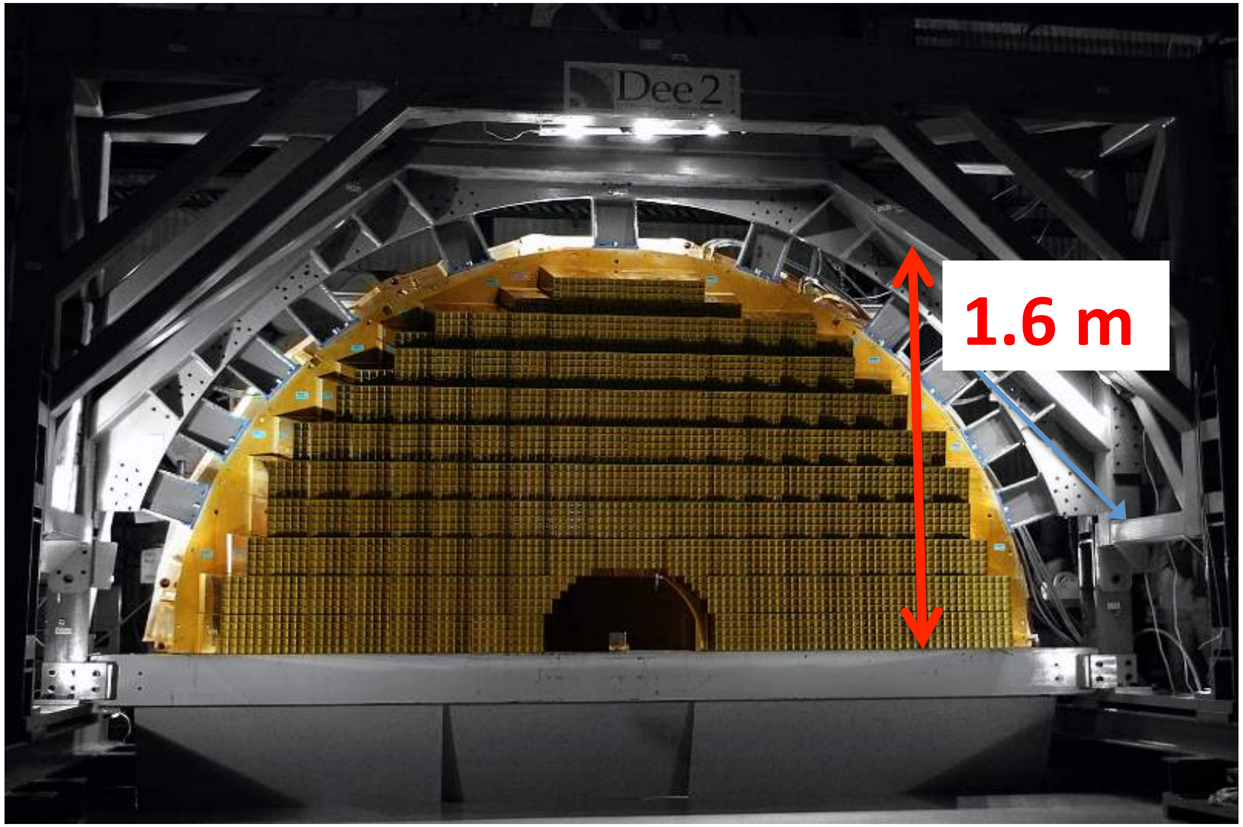
Endcaps: 14648 crystals

Total: 75,848 crystals at ~$1000 each

The CMS Endcap ECAL

A module of
25 crystals

Mounting the modules
on a backplate support

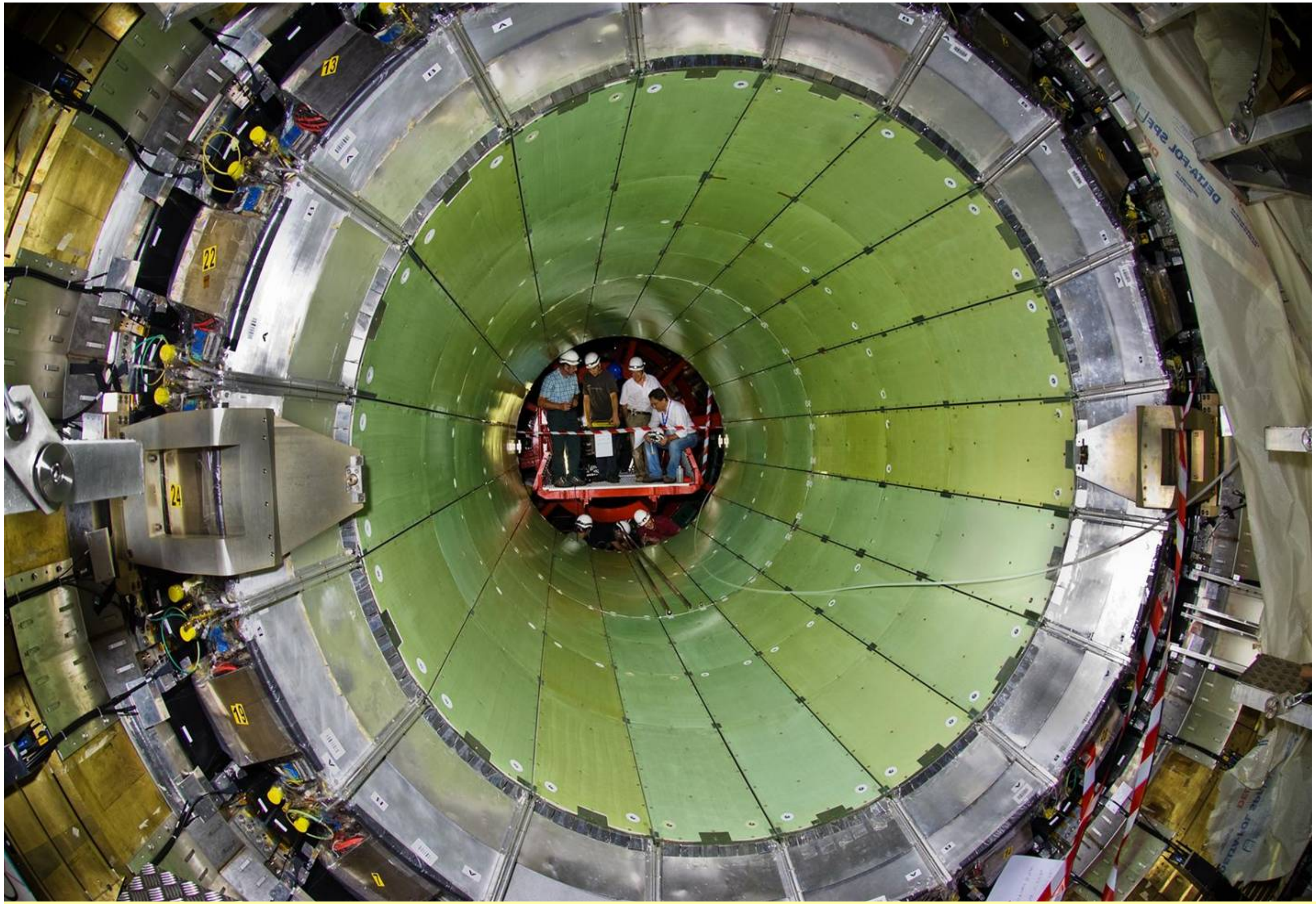


One of 4 completed
“Dees” with 3662
crystals

The CMS Endcap ECAL
The final stages of installation of one of the “Dees”

John Hill, now UKAEA, with red jacket

The CMS Barrel ECAL



Barrel installation in CMS complete
61200 crytals, 27 July 2007

Why is the Higgs Field YOUR ultimate Personal Manager ?

The discovery of the Higgs boson gives credence to the models of Peter Higgs and others, that there is a Higgs field pervading the whole universe, and that this Higgs field gives fundamental particles their mass

The Higgs field interacts with fundamental particles through the exchange of the Higgs bosons.

However, the Higgs field puts us in a very dependent position – our very lives depend on its characteristics.

Why is the Higgs Field YOUR ultimate Personal Manager ?

Suppose the Higgs field were weaker or stronger.
What consequences for ourselves, the sun and the solar system ??

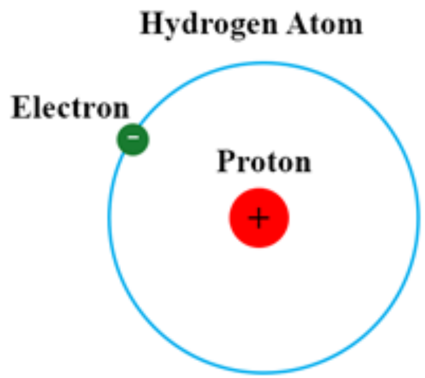
The mass of the electron, the most important sub-atomic particle in our bodies, would immediately be different.

The electron mass is determined by the strength of the Higgs field:

A weaker Higgs field – a lighter electron
A stronger Higgs field – a heavier electron

The size of our bodies, and associated chemistry, depends on the size of atoms like hydrogen, carbon, oxygen etc.

Consider the simplest atom – Hydrogen:

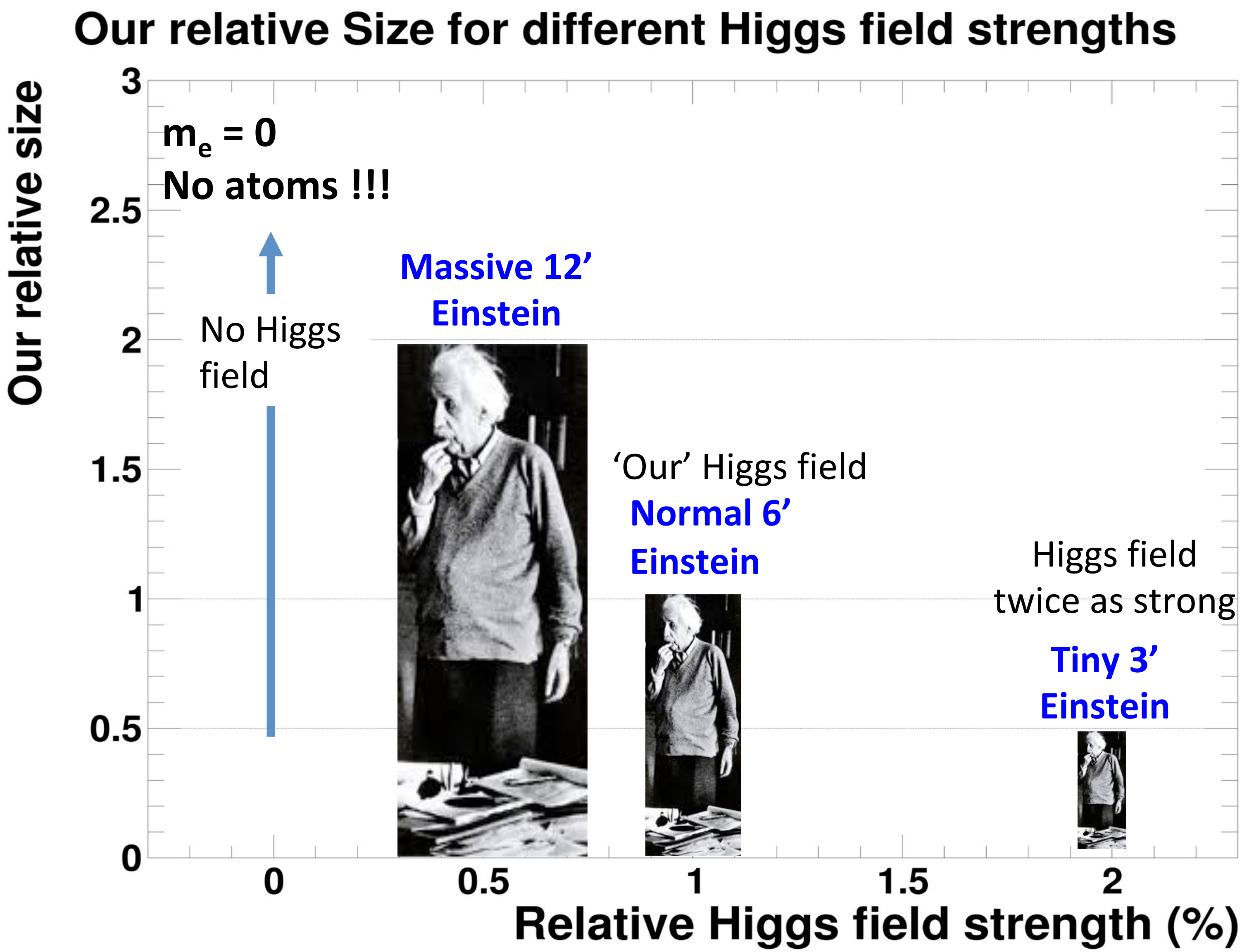


The electron's mass determines the distance of the electron from the proton

A more massive electron would be nearer the nucleus – a smaller atom

A less massive electron would be further from the nucleus – a larger atom

The strength of the Higgs field directly determines the mass of the electron and, thereby, the size of our bodies

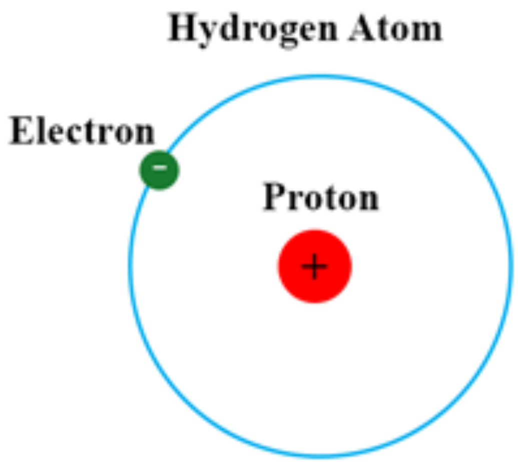


The magnitude of the interaction of the electron to the Higgs field determines the size of atoms and the very structure of our universe

What about the chemistry in our bodies ??

For example:

The energy needed to remove an electron from hydrogen goes as m_e



$$\text{Energy needed} \sim m_e$$

A higher electron mass

– more energy needed to remove the electron

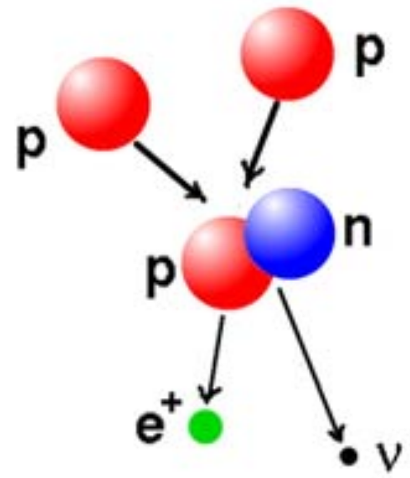
A lighter mass

– less energy needed to remove the electron

If the strength of the Higgs field was different, our body chemistry would be very different

How the Sun makes energy:

At the start of the process, protons in the Sun’s core fuse with other protons to form deuterons



$$p + p \longrightarrow d + W^+$$

$$W^+ \longrightarrow e^+ + \nu$$

The overlapping protons enable one proton to change to a neutron, through the emission of a **“W”** particle that changes an up quark to a down quark

The **“W”** then decays, liberating its energy to a positron and a neutrino

The positron annihilates with an electron, the net process being the source of most of the sun’s energy.

The **rate** of making deuterons, and therefore the energy emitted by the sun, depends on the mass of the "W", m_W

The rate goes as: $1 / m_W^4$

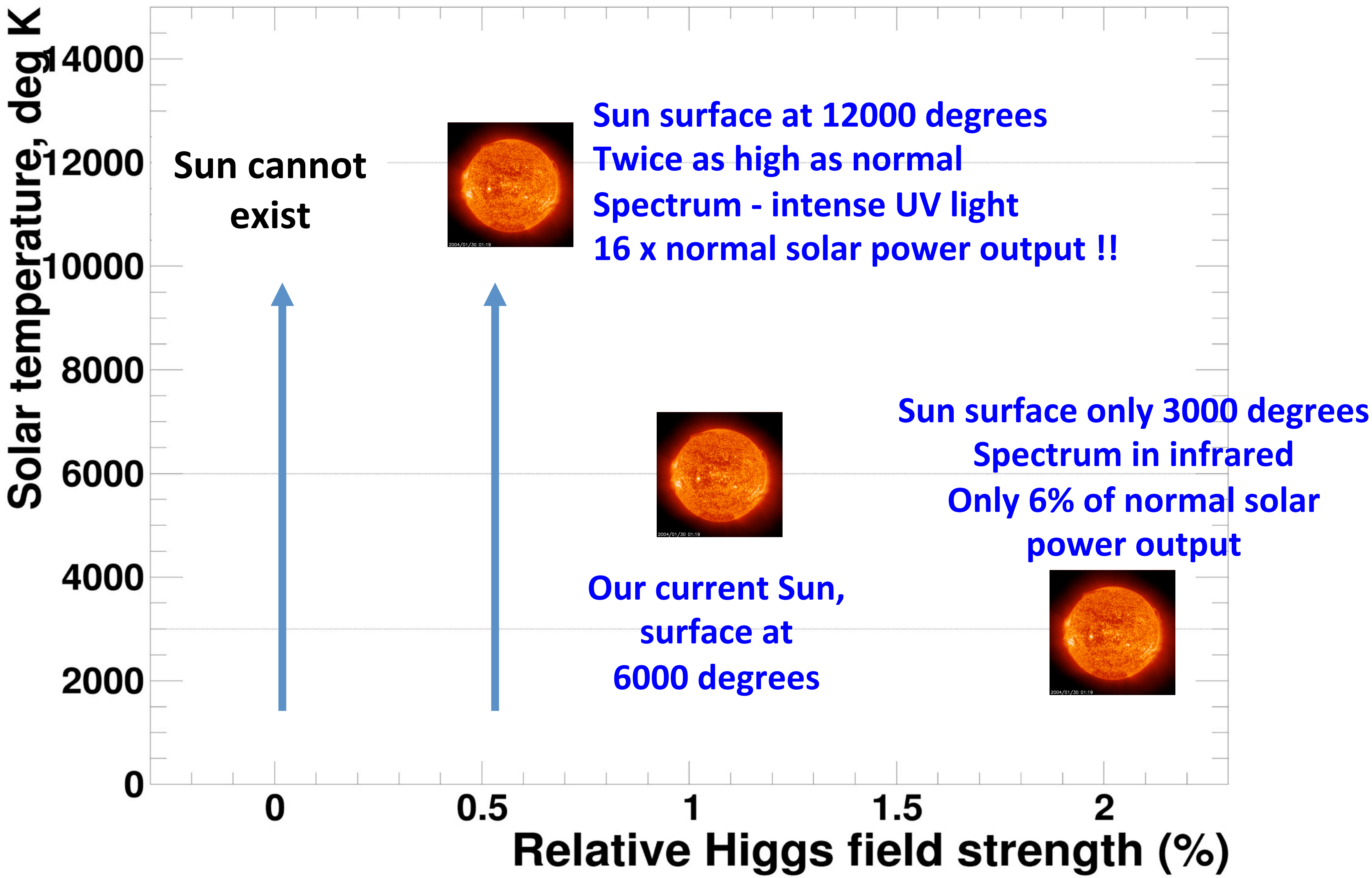
The Sun's temperature is thus VERY sensitive to the value of m_W

BUT m_W is determined by the strength of the Higgs field

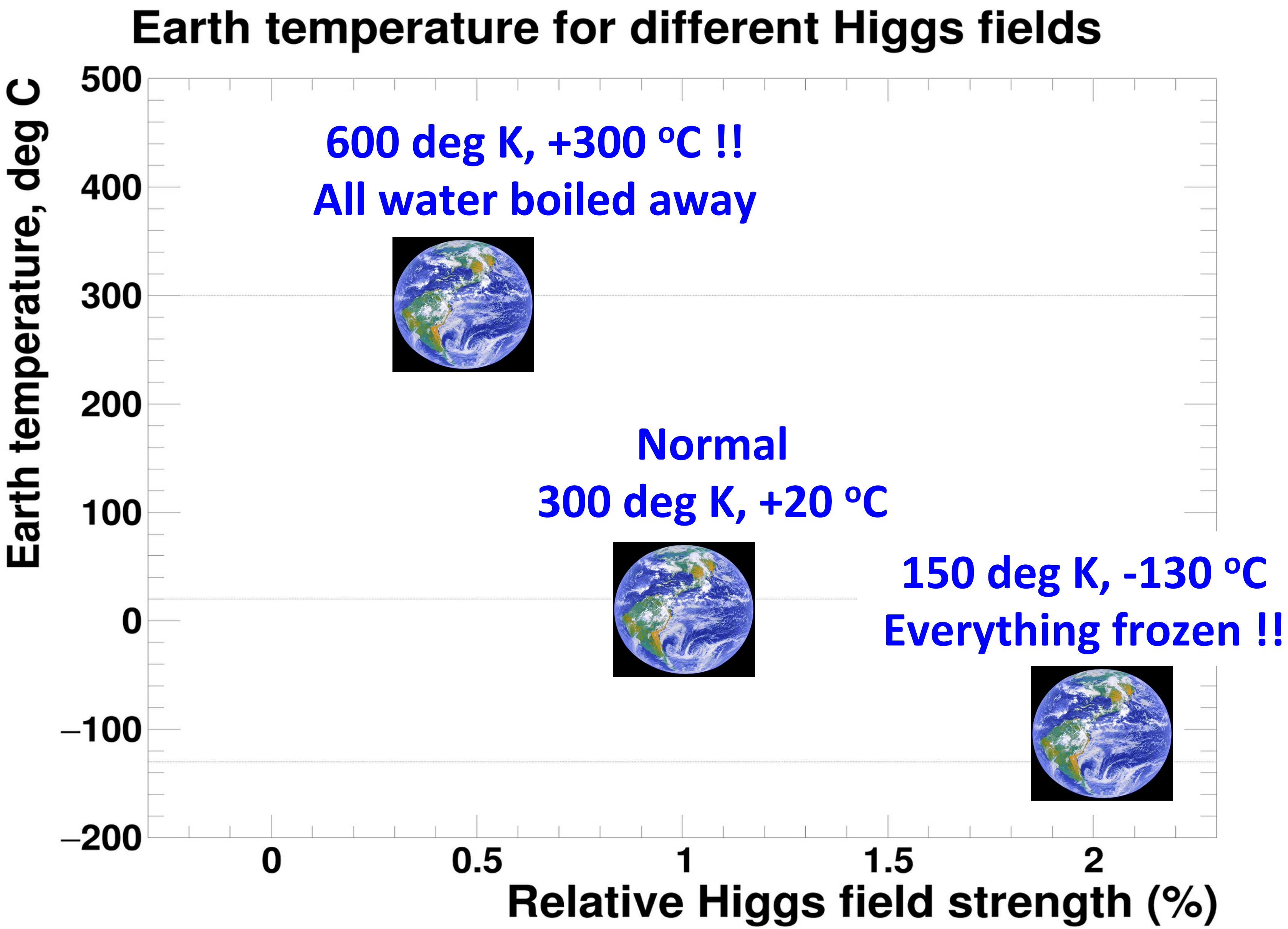
If the Higgs field were stronger or weaker, this would lead to a heavier or lighter m_W

What would happen to the Sun, and therefore to us ??

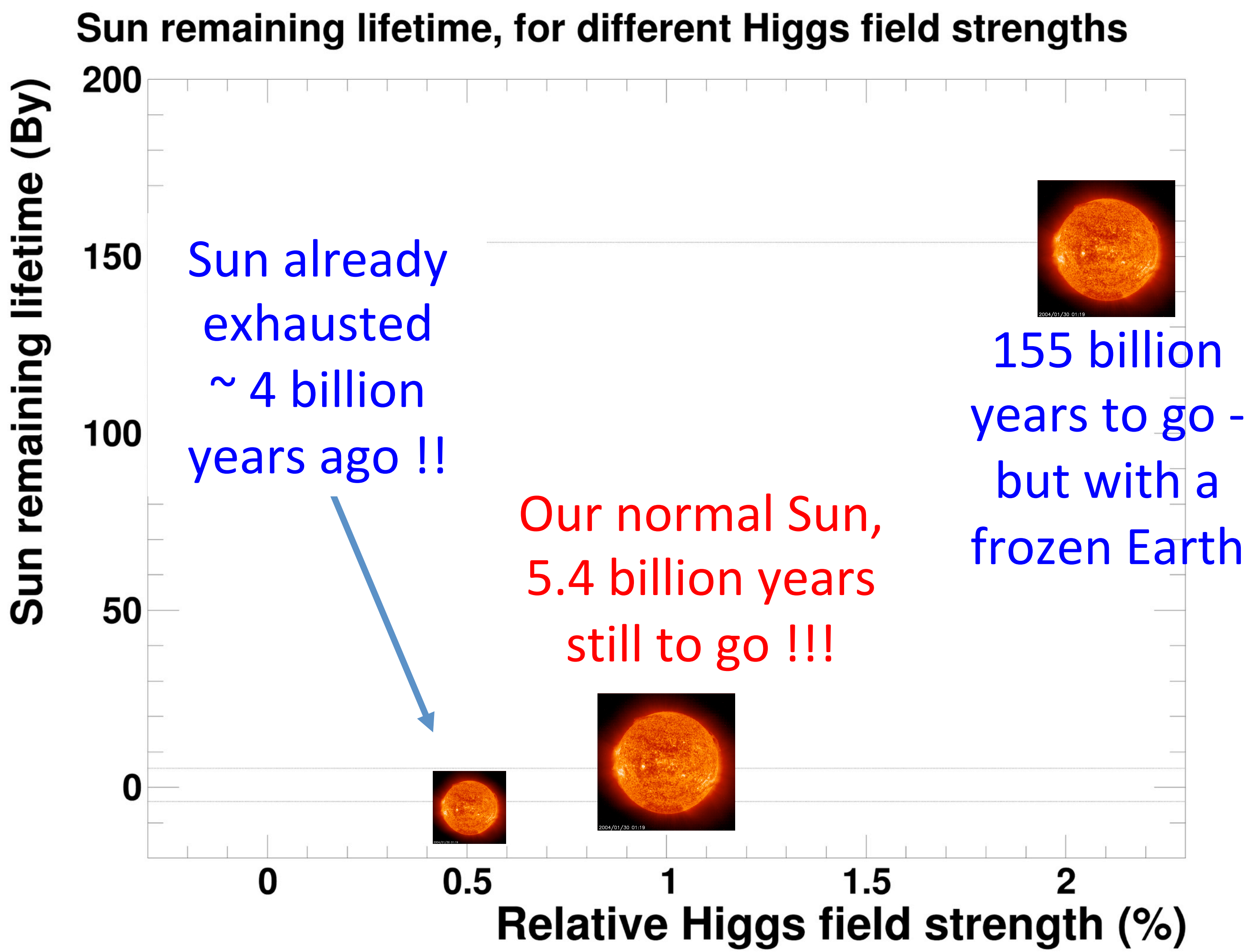
Solar surface temperatures for different Higgs fields



A different Higgs field strength would have had a dramatic effect on the Sun's temperature



We are immersed in just the right Higgs field strength
for a "comfortable" life – thank goodness !!!!!!

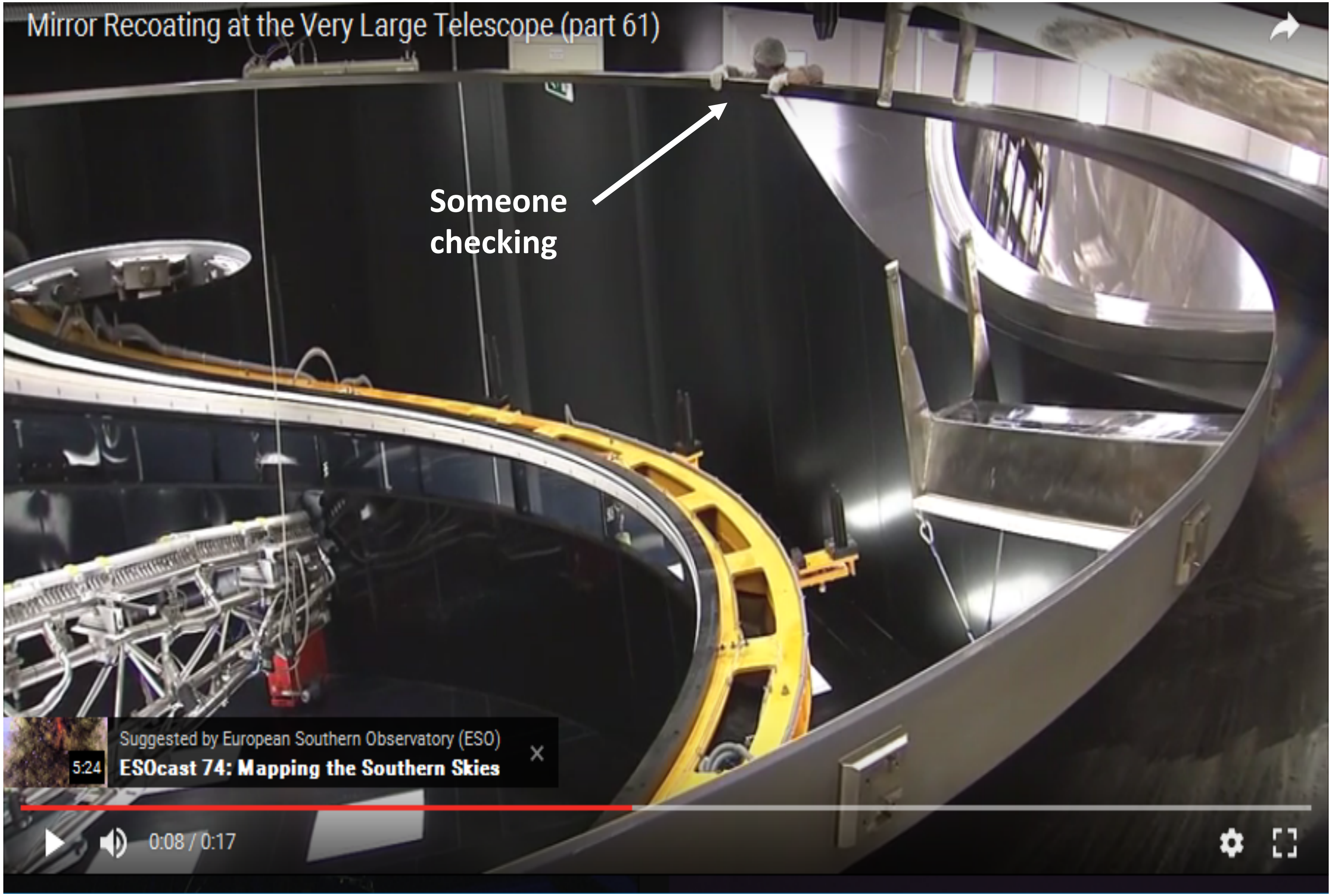


Our current Higgs field strength has given us enough time to get away (possibly) before the Sun becomes an enveloping Red Giant !!

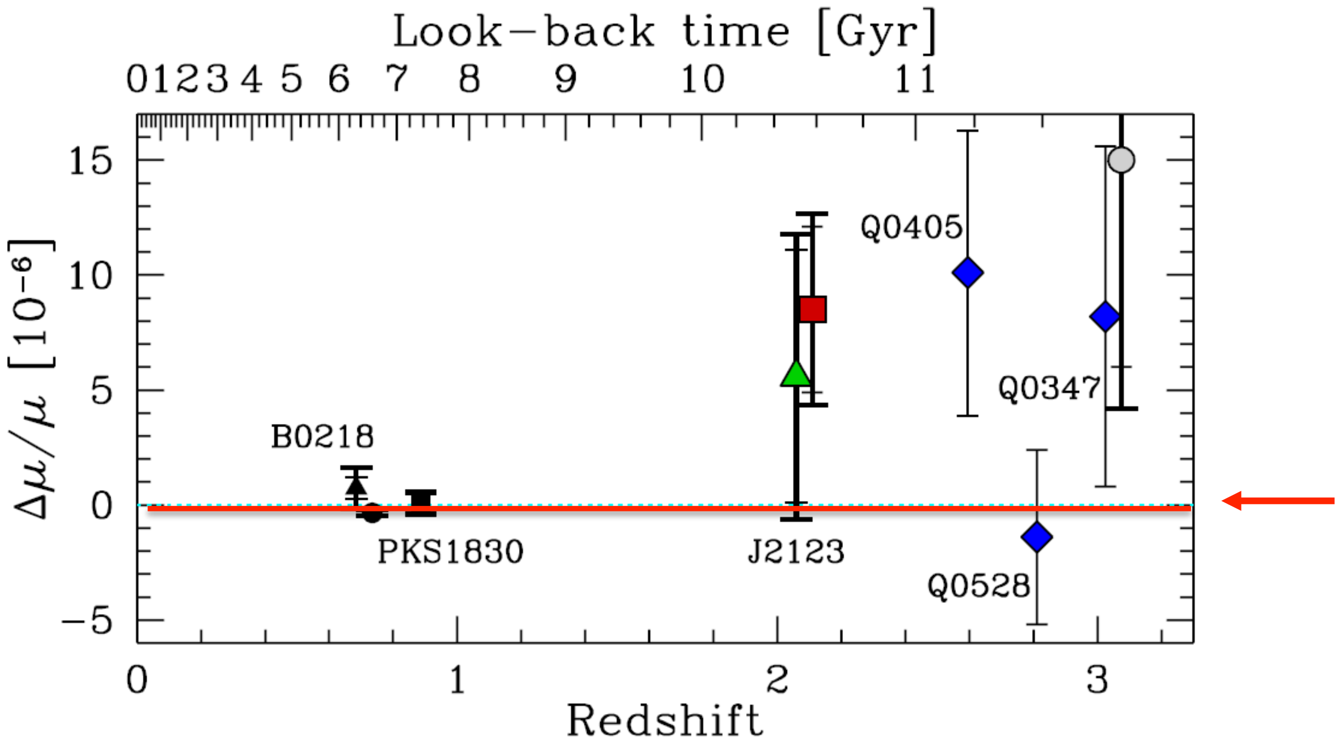
What about the Higgs field strength elsewhere in the Universe ?

Results from the European Southern Observatory Very Large Telescope
Site: Chile, Atacama desert

One of the four VLT mirrors, 8.2 m across (27 feet !)



The Very Large Telescope: results from quasars, looking at H_2 and HD spectral lines



Zero difference to on Earth

Conclusion:

The H_2 and HD spectral lines in outer space the same as on earth.

So, within errors, the Higgs field strength in outer space the same as on earth for the Universe from 6 billion to more than 11 billion years ago

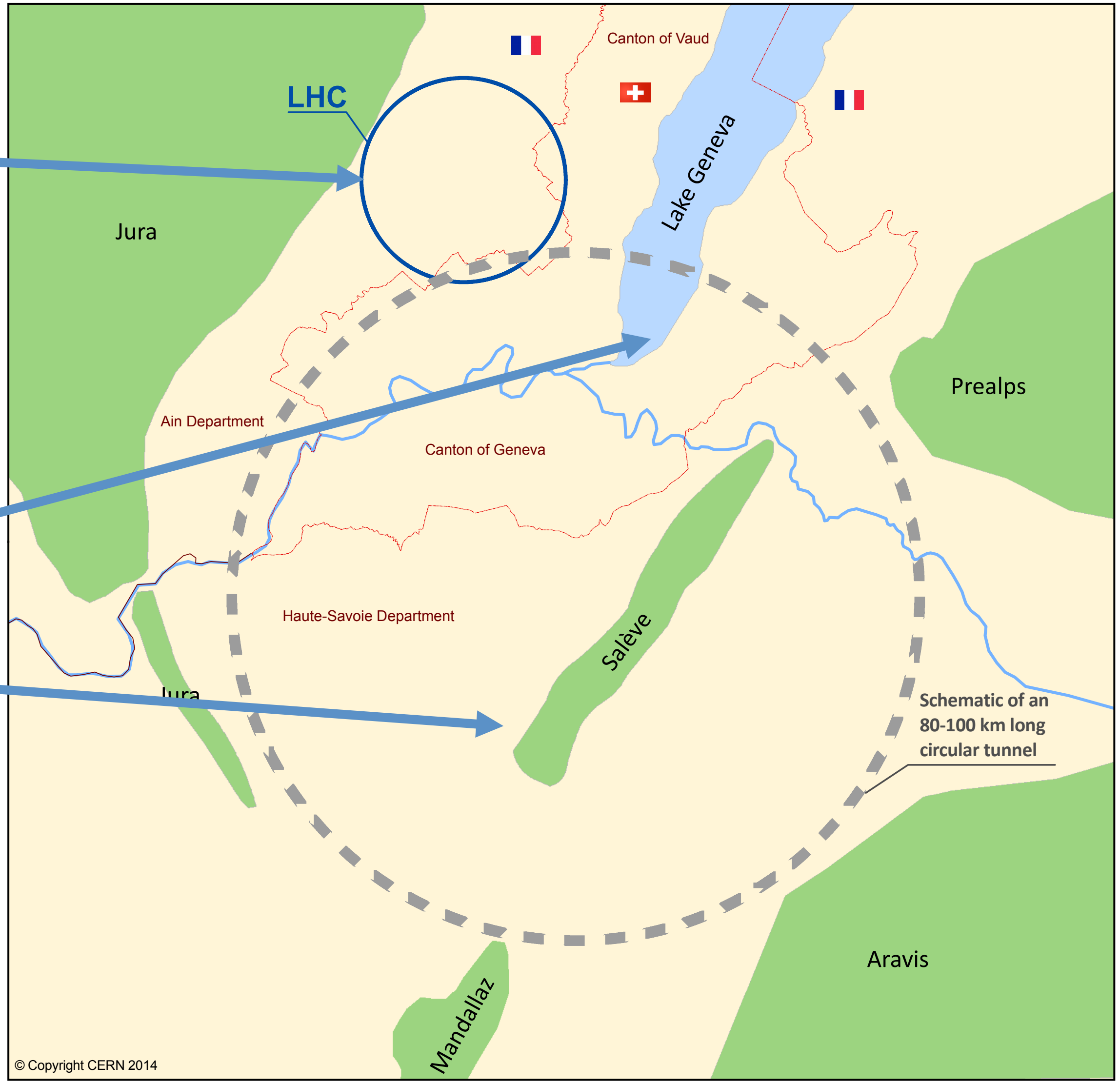
What next at CERN?
The new Future Circular Collider (FCC) ??
Collision energy : Seven times the LHC

Current LHC
Length ~London's circle line

The new machine will go under Lake Geneva and circle this mountain range

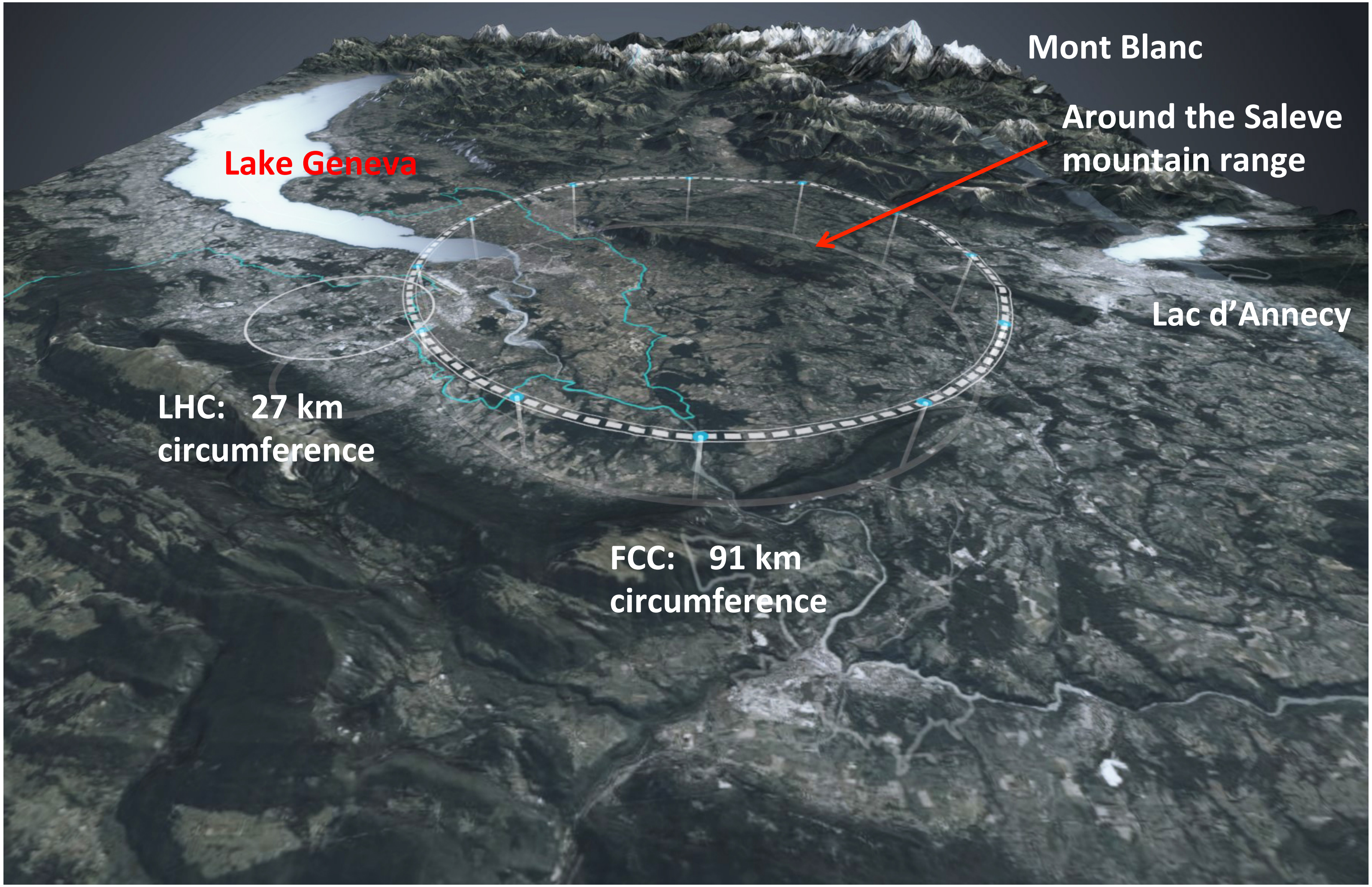
Length ~ M25 / 2

Date: 2070-2090++ ??

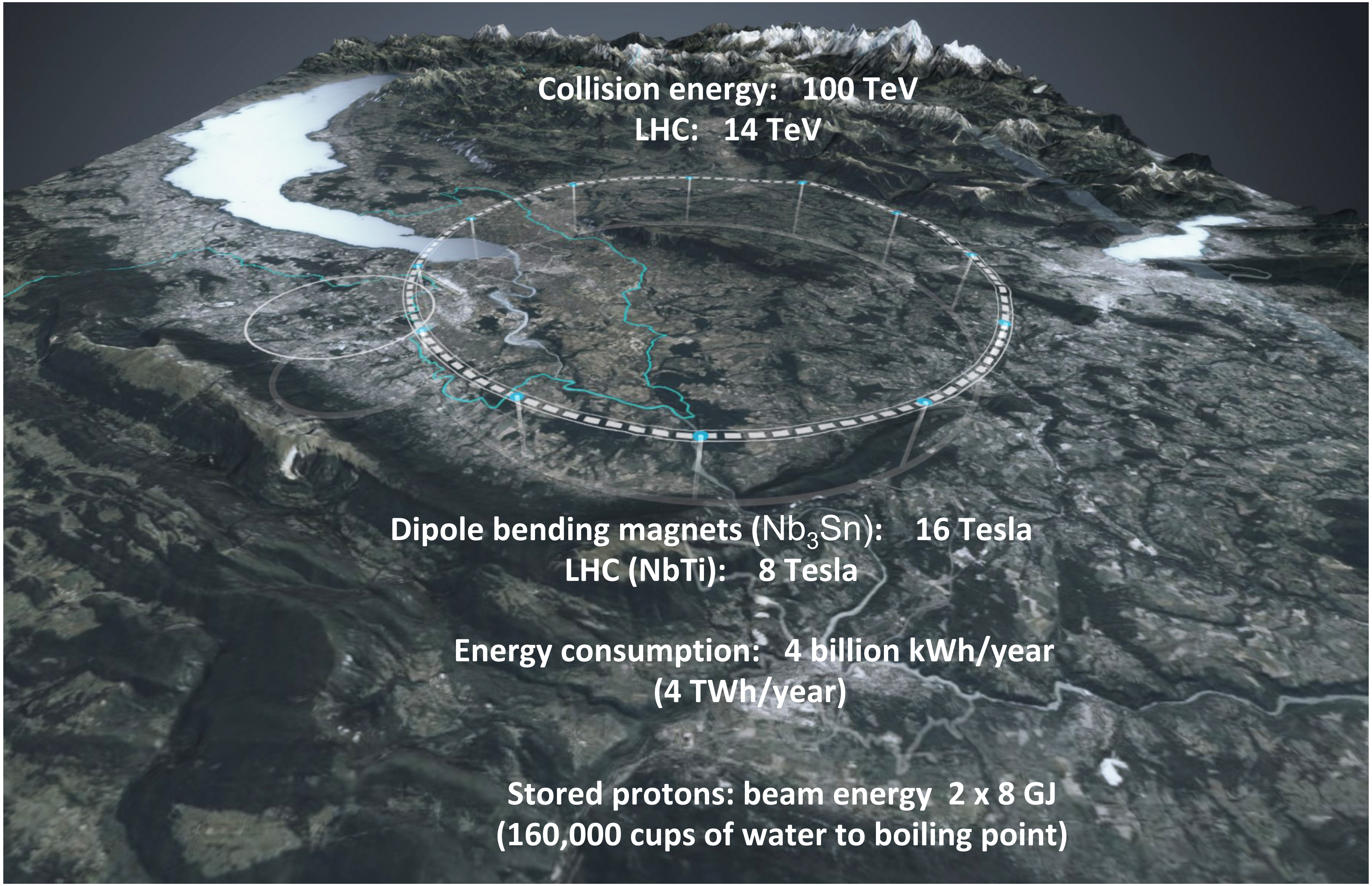


The Future Circular Collider (FCC) at CERN

A new 91 km long tunnel 3.4 times larger than the LHC



The FCC: some of the challenges



In summary

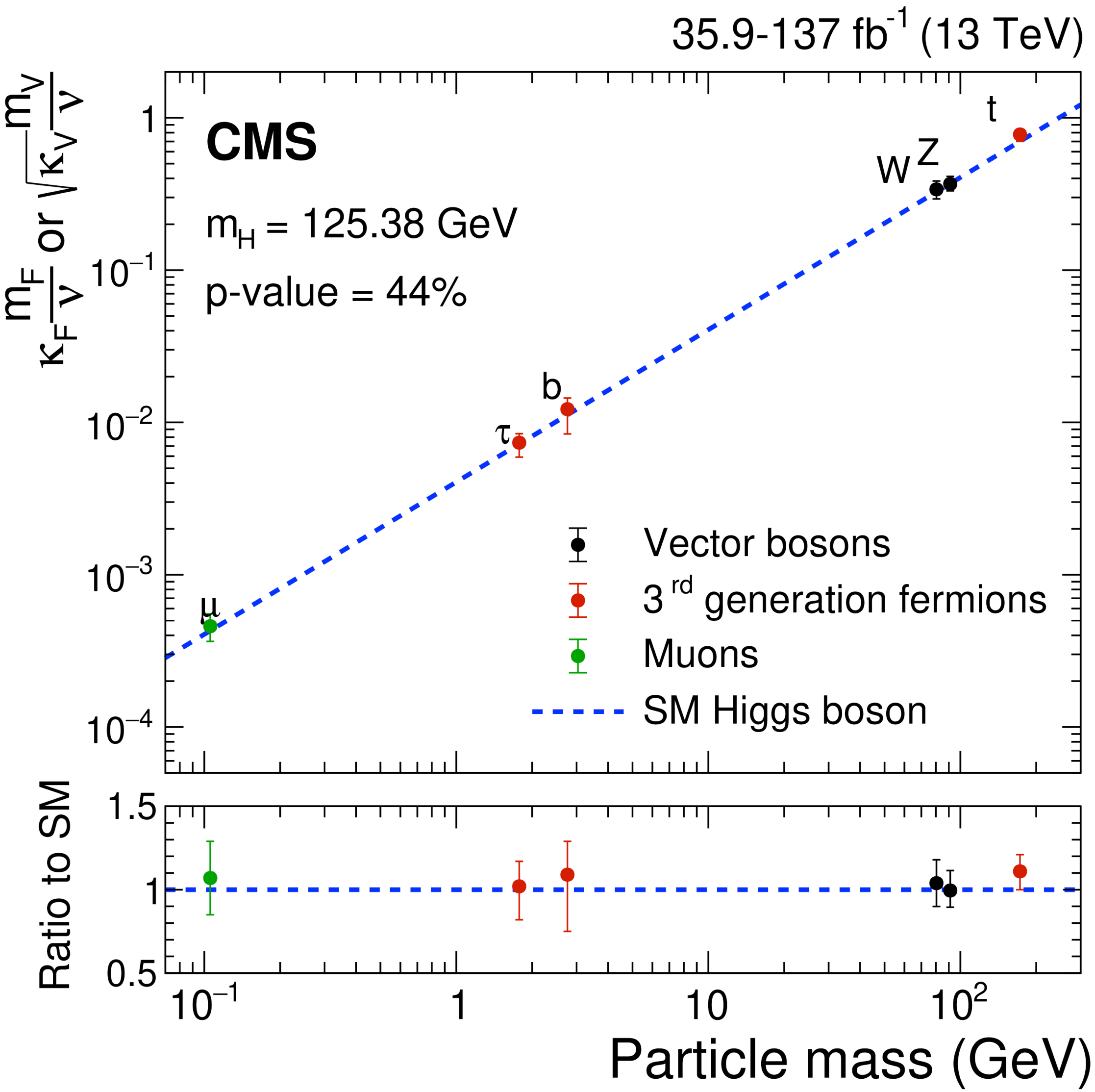
- The Higgs field is responsible for the structure of our Universe
- The Higgs field determines the size of all atoms and molecules
- The Higgs field determines our chemistry, and our climate and environment on Earth

- The Higgs field determined why we inhabit the Earth – it provided the perfect conditions for life as we know it

And this is why

the Higgs Is YOUR ultimate Personal Manager !!!

Measured Higgs couplings at the LHC by CMS



All in order so far. Need to run LHC for longer, to seek out any deviations.

https://arxiv.org/pdf/2009.04363.pdf

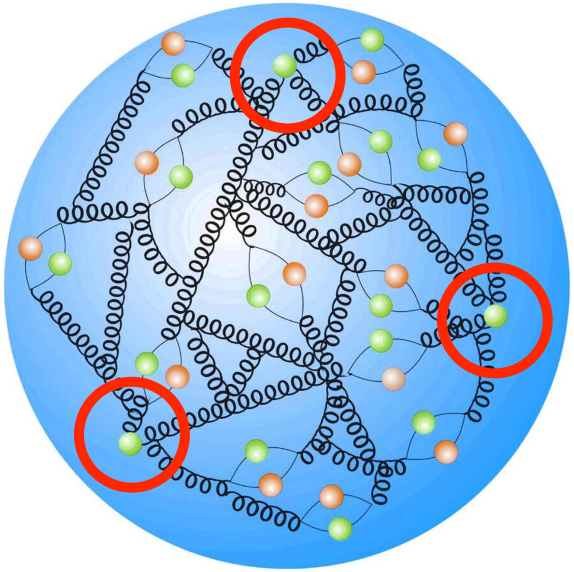
Main machine parameters for FCC-hh

parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	**100**		14	14
dipole field [T]	**~16**		8.33	8.33
circumference [km]	**~ 91**		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2400		7.3	3.6
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [mm]	2.2		2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	**5**	**30**	5 (lev.)	2
events/bunch crossing	**170**	**1000**	140	27
integrated luminosity [ab^{-1}]	**20-30**		**3-4**	**> 0.3**
stored energy/beam [GJ]	8.4		0.7	0.36
energy consumption [TWh/year]	4		1.4	1.2

Formidable challenges:

- ❑ high-field superconducting magnets: ≥ 16 T
- ❑ power load in arcs from synchrotron radiation: 5 MW → cryogenics, vacuum
- ❑ stored beam energy: 8 GJ → machine protection
- ❑ pile-up in the detectors: ~1000 events/xing
- ❑ energy consumption: 4 TWh/year → R&D on cryo, operate > 1.9 K, HTS, beam current, …?

The Proton



The proton permanently has 2 up quarks and one down quark

…. BUT the proton also has many other quarks and gluons that come and go !

M_P = 938 MeV/c^2
M_u only ~2.3 MeV/c^2
M_d only ~4.8 MeV/c^2

Most of the protons mass, 929 MeV/c^2 (99%) , is in the form of stored energy with $E = M * c^2$, where M is 929 MeV/c^2

http://www.forbes.com/sites/startswithabang/2016/08/03/where-does-the-mass-of-a-proton-come-from/#27a3f27447ad

Which is why it's such a puzzling fact that when you take a look at the particles that make up the proton -- the three different quarks at the heart of them -- their combined masses are only **0.2%** of the mass of the proton as a whole.

The way quarks bind into protons is fundamentally different from all the other forces and interactions we know of. Instead of the force getting stronger when objects get closer -- like the gravitational, electric or magnetic forces -- the attractive force goes down to zero when quarks get arbitrarily close.

And instead of the force getting weaker when objects get farther away, the force pulling quarks back together gets stronger the farther away they get.

This property of the strong nuclear force is known as asymptotic freedom, and the particles that mediate this force are known as gluons. Somehow, the energy binding the proton together, the other **99.8% of the proton's mass**, comes from these gluons.

Constants which are NOT (unfortunately) predicted by the Standard model of particle physics

The complete standard model **requires 25 fundamental dimensionless constants** (Baez, 2011). At present, their numerical values are not understood !!!!!!!!!

This includes the masses of particles
The strengths of the electroweak and strong forces.

The 25 constants are:
the fine structure constant;
the strong coupling constant;
The fifteen masses of the fundamental particles** namely:

- six quarks
- six leptons
- the Higgs boson
- the W boson
- the Z boson

four parameters of the CKM matrix, describing how quarks oscillate between different forms;
four parameters of the Pontecorvo–Maki–Nakagawa–Sakata matrix, which does the same thing for neutrinos.

Plus, outside the standard model: the gravitational coupling constant,
proton-to-electron mass ratio, the electron charge + lots of others – oooops !!!!!!!!!

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

$$\{\partial^2 - 4\varphi_0{}^2 V''(\varphi_0{}^2)\}(\Delta\varphi_2) = 0, \tag{2b}$$

$$\partial_\nu F^{\mu\nu} = e\varphi_0\{\partial^\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\}. \tag{2c}$$

Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0{}^2)\}^{1/2}$; Eqs. (2a) and (2c)

The prediction of a new particle – explicitly mentioned only by Peter Higgs

Size of hydrogen atom (most probable value)

In SI units the Bohr radius is:[2]

$$a_0 = \frac{4\pi\varepsilon_0\hbar^2}{m_e e^2} = \frac{\hbar}{m_e\, c\, \alpha}$$

= 0.53 10^{-10} m radius
= 0.053 nm radius

Hydrogen ground state energy of the electron

$$E_0 = -\frac{m_e\, e^4}{2\,(4\pi\,\epsilon_0)^2\,\hbar^2} = -\frac{e^2}{8\pi\,\epsilon_0\,a_0} = -13.6\,\mathrm{eV},$$

Atom	Radius
Hydrogen	0.12 nm = 2 x 0.053 nm (approx.)
Oxygen	0.14 nm
Nitrogen	0.15 nm
Carbon	0.16 nm
Sulphur	0.185 nm
Phosphorus	0.19 nm

The magical "Bosons", the particles that drive the forces of Nature

Spinning top value

Higgs boson	- gives mass to particles	0
The photon	- generates the electromagnetic force	1
The gluon	- generates the strong force	1
The Zs and Ws	- generate the weak force/radio-active decay	1
The Graviton	- generates the gravitational force	2

Higgs relations

$M_W = g f / 2$ f is the vacuum expectation value of the Higgs field,
$f \sim 246$ GeV
g is the coupling strength of the weak interaction

$g \sin(\theta_W) = e$ e is the coupling strength of electromagnetic interactions

$M_Z = f (g'^2 + g^2)^{1/2} / 2 = M_W / \cos(\theta_W)$

$M_e = g_e f / \mathrm{sqrt}(2)$ for the mass of the electron

The amount of energy radiated by the Sun or the Earth:

Proportional to the temperature of the object raised to the fourth power!

This is the Stefan-Boltzmann Law: $F = \sigma T^4$

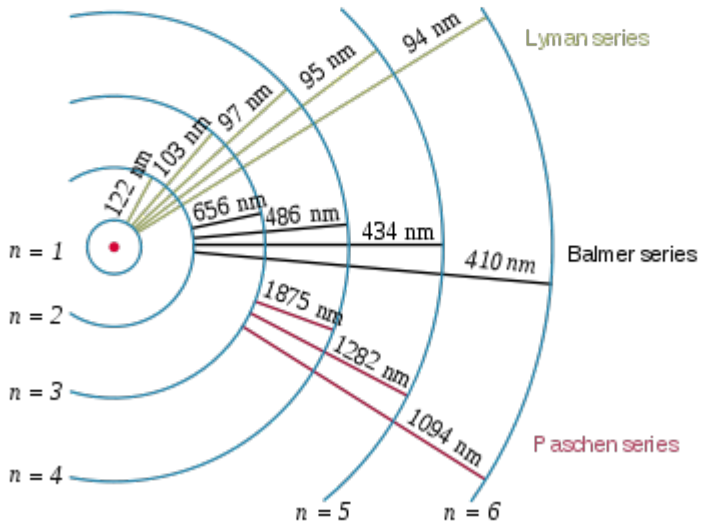
F = the flux of energy (W/m2)

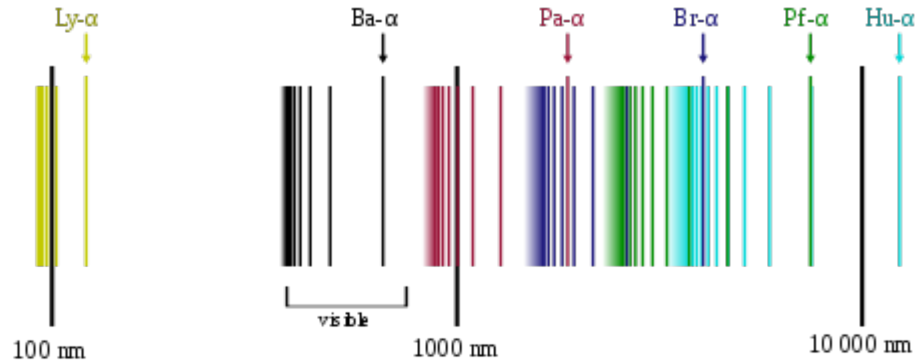
σ is the Stefan-Boltzmann constant

Wavelength of the light radiated by the Sun:

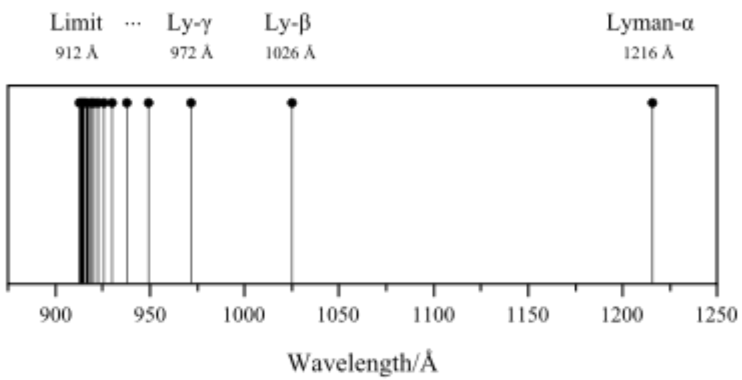
Wien's law: spectrum peaks at $\lambda_{max} = b / T$

T is the temperature, b is Wien's constant





The spectral series of hydrogen, on a logarithmic scale.



Lyman series of hydrogen atom spectral lines in the ultraviolet

The four visible hydrogen emission spectrum lines in the Balmer series. H-alpha is the red line at the right

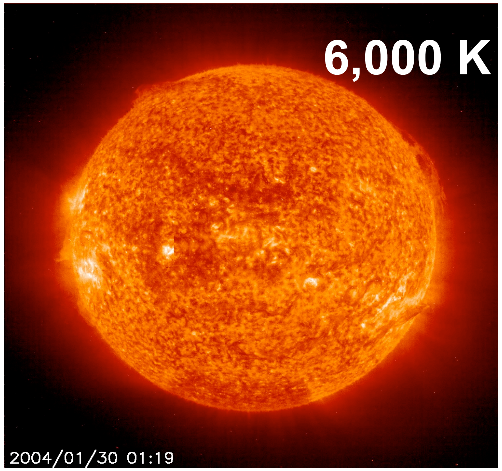
The Brout-Englert-Higgs mechanism

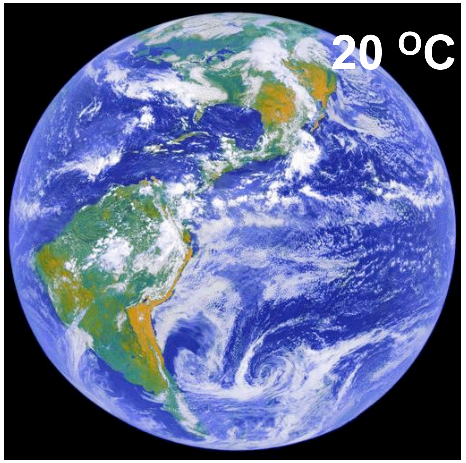
In the 1970s, physicists realised that there are very close ties between two of the four fundamental forces – the weak force and the electromagnetic force. The two forces can be described within the same theory, which forms the basis of the Standard Model. This “unification” implies that electricity, magnetism, light and some types of radioactivity are all manifestations of a single underlying force known as the electroweak force.

The basic equations of the unified theory correctly describe the electroweak force and its associated force-carrying particles, namely the photon, and the W and Z bosons, except for a major glitch. All of these particles emerge without a mass. While this is true for the photon, we know that the W and Z have mass, nearly 100 times that of a proton. Fortunately, theorists Robert Brout, François Englert and Peter Higgs made a proposal that was to solve this problem. What we now call the Brout-Englert-Higgs mechanism gives a mass to the W and Z when they interact with an invisible field, now called the “Higgs field”, which pervades the universe.

Just after the big bang, the Higgs field was zero, but as the universe cooled and the temperature fell below a critical value, the field grew spontaneously so that any particle interacting with it acquired a mass. The more a particle interacts with this field, the heavier it is. Particles like the photon that do not interact with it are left with no mass at all. Like all fundamental fields, the Higgs field has an associated particle – the Higgs boson. The Higgs boson is the visible manifestation of the Higgs field, rather like a wave at the surface of the sea.

The Sun and the Earth



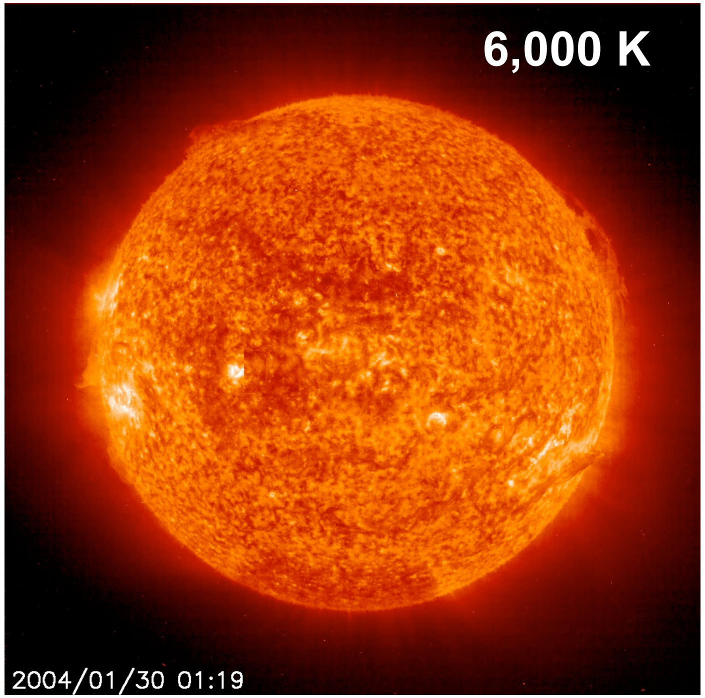


At equilibrium, the earth re-radiates all the solar energy it receives. This corresponds to earth having an expected temperature of ~7 ^{O}C

Greenhouse effects and the reflection of sun light off clouds, means the earth ends up with a temperature of ~20 ^{O}C

What would be the effect of the temperature on Earth if the strength of the Higgs field were different ??

Lets look inside the Sun:

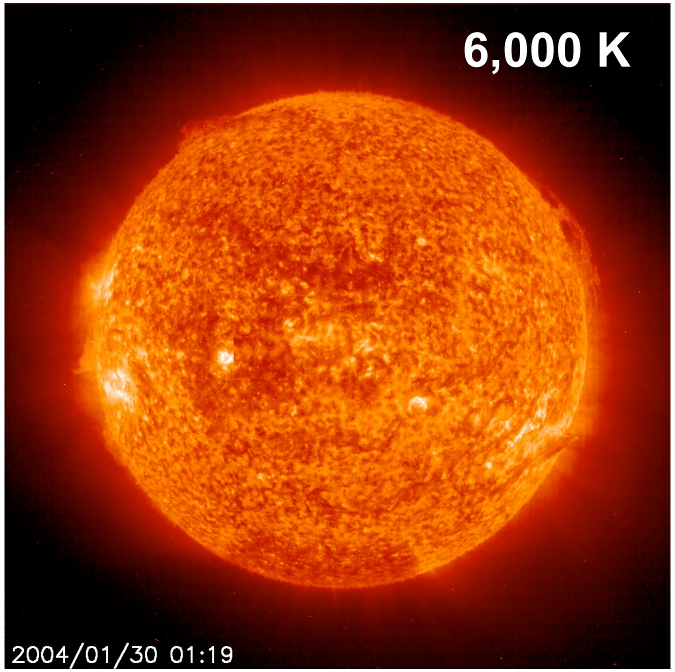


Despite its intense temperature, the peak power production density of the sun's core is similar to a compost heap !!

Power about 276.5 watts/m^3 = ¼ of an electric fire per m^3

The Sun is much hotter than a compost heap due to the Sun's enormous volume!

Solar power density is lower than that for human metabolism!



Compost heap density ~ 1 g / cc One spade full: 1 Kg
Core Solar density ~ 150 g / cc One spade full: 150 Kg

Core solar temperature ~ 15 million degrees Celsius

The core contains a high energy plasma of protons, electrons and other particles, all smashing in to one another