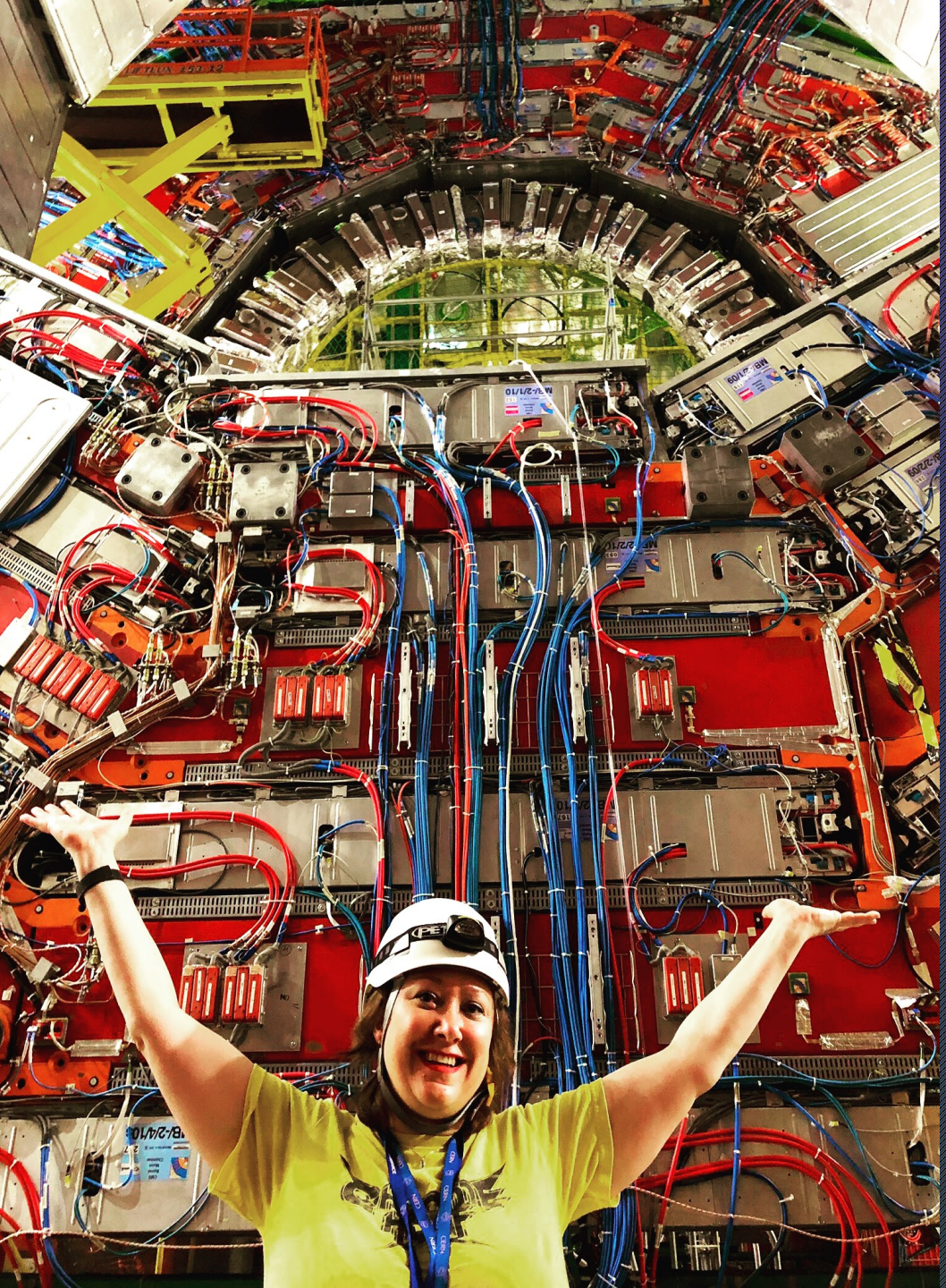
Beamline for Schools 2023

Particle Physics and CERN: more than meets the eye

Prof. Dr. Freya Blekman

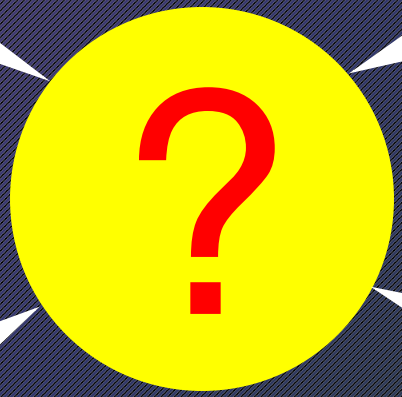
DESY.
UHH Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG



- From Amsterdam, NL
- Ph.D. at Nikhef (NL), the Netherlands' national particle physics institute
  - Largely based at Fermilab in Chicago (USA)
- Postdoc Imperial College London (UK)
- Postdoc Cornell University (USA)
- Up to recently: Professor at Vrije Universiteit Brussel, Brussels (BE)
- Presently: Professor at University of Hamburg & Lead scientist at DESY
  - Distinguished Researcher Fermilab
  - Visiting prof Univ. of Oxford & VUB

As a job:
Travel
Variation
Colleagues
Science

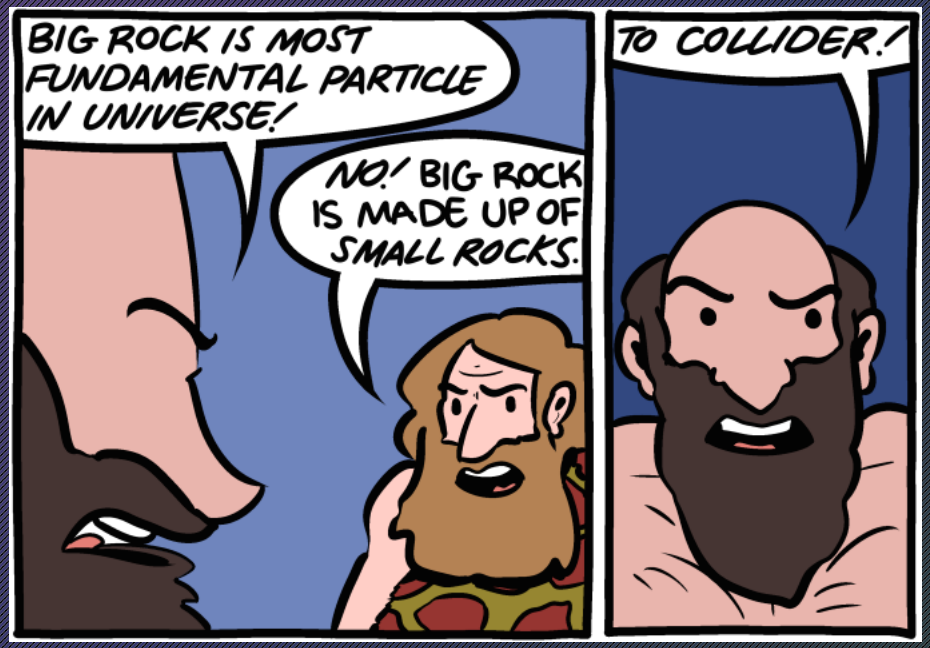
In school:
Liked science,
also art, history



University:
Experimental
Computers
Mathematics

For my PhD:
Exciting
Doing things first
See the world

Curiosity



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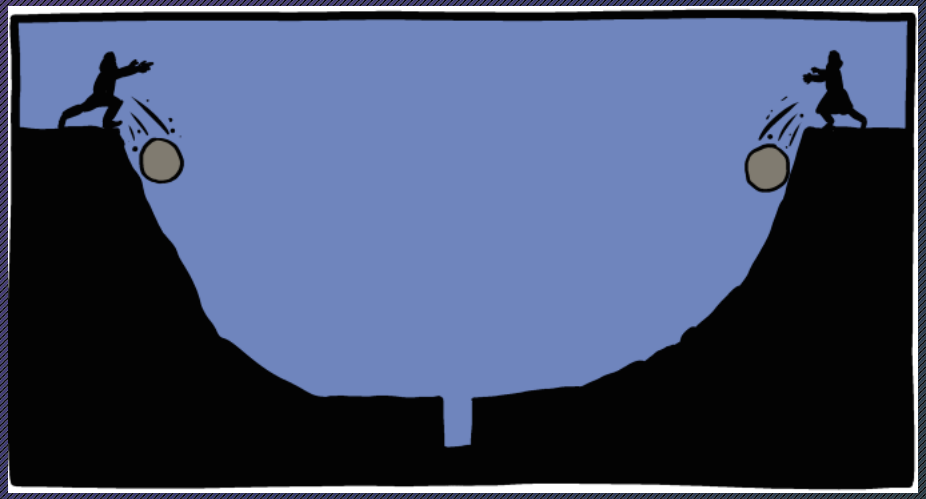
Curiosity



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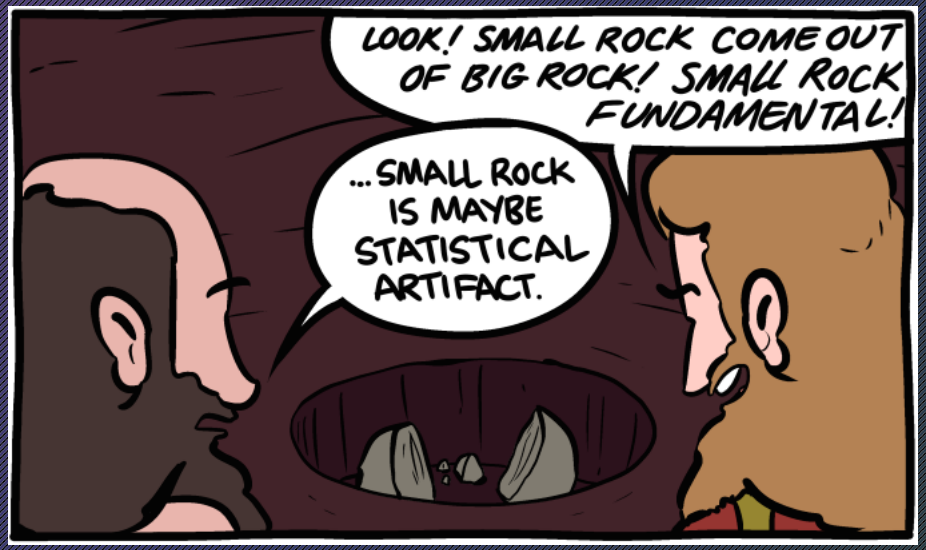

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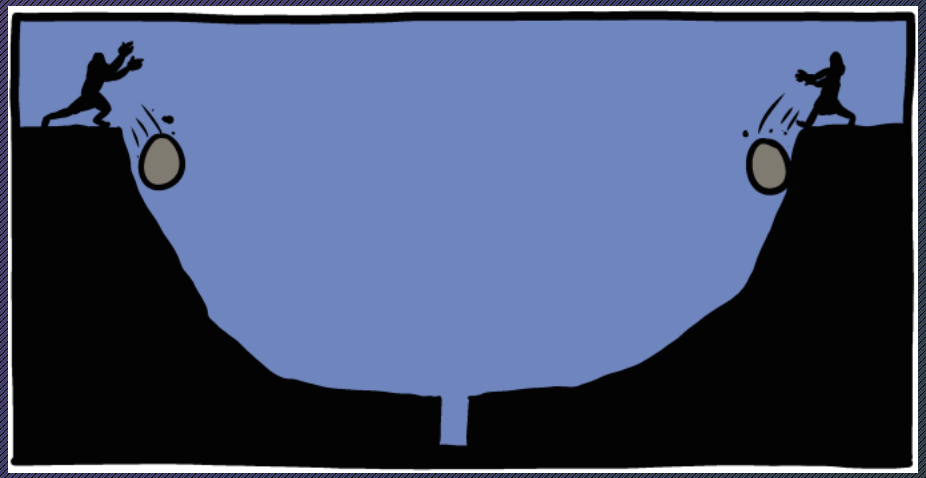

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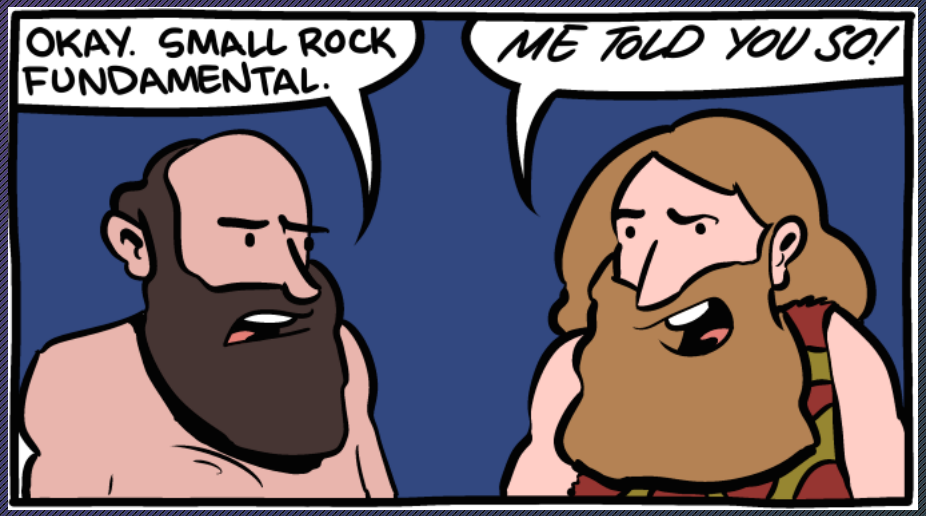
Curiosity



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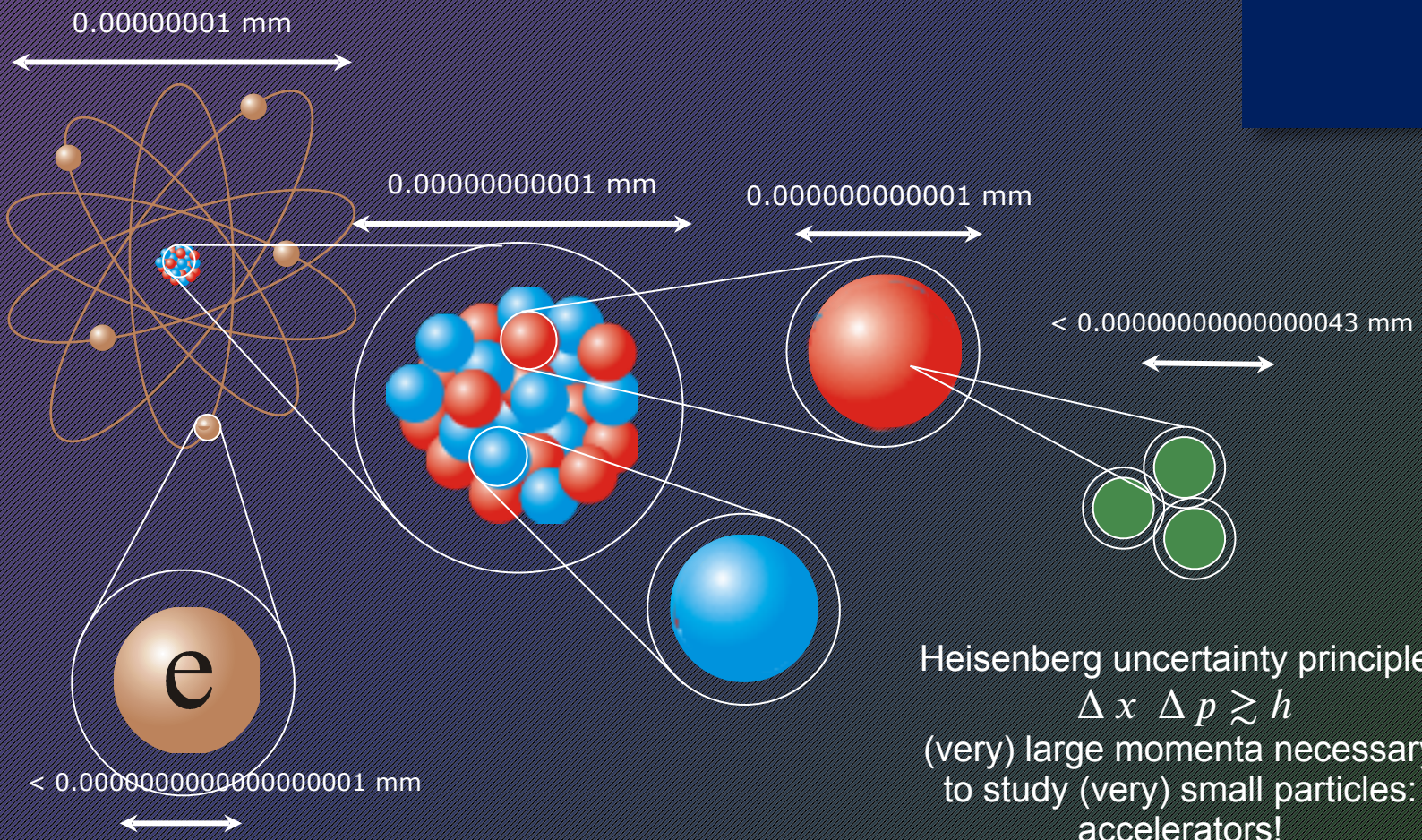
Scales of the subatomic world



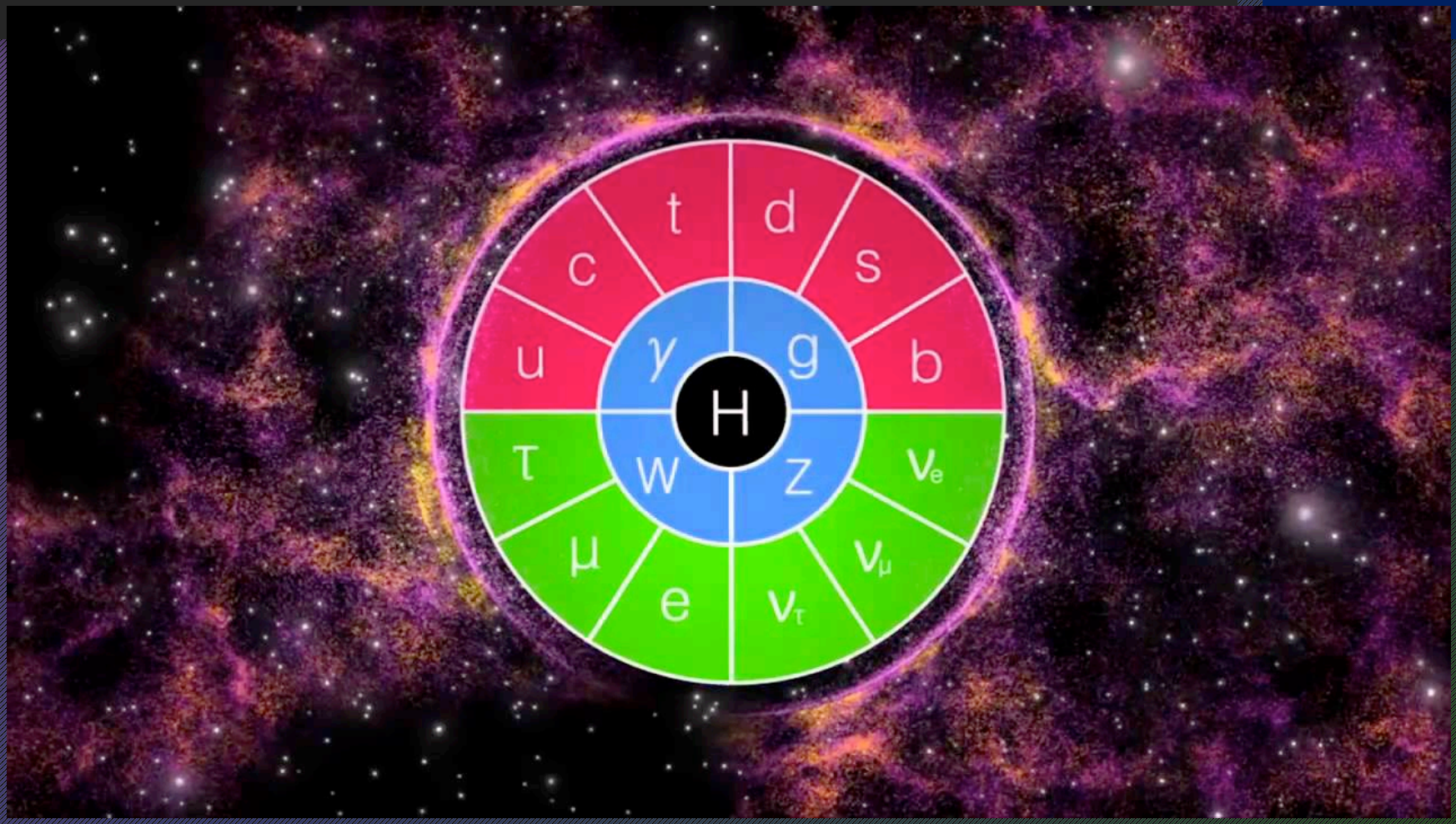
Heisenberg uncertainty principle:

$$\Delta x \ \Delta p \gtrsim h$$

(very) large momenta necessary to study (very) small particles: accelerators!

Colliders!

The Standard Model!




$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \not{D} \psi + h.c$
$+ \psi_i y_{ij} \psi_j \phi + h.c$
$+ |D_\mu \phi|^2 - V(\phi)$

$$
\begin{aligned}
&1 \quad -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
&\tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
&2 \quad M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \\
&\tfrac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2\phi^+\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \\
&\tfrac{2M}{g}H + \tfrac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - \\
&W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - \\
&W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
&\tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
&g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
&\tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - \\
&gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - \\
&W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
&\phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
&igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
&igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
&\tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - \\
&g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j - \\
&3 \quad \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \\
&\tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - \\
&1-\gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + \\
&(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 + \\
&\gamma^5)u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}\tfrac{m^\lambda_e}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \\
&4 \quad \tfrac{g}{2}\tfrac{m^\lambda_e}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + \\
&m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1- \\
&\gamma^5)u^\kappa_j] - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \\
&\tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \\
&5 \quad \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \\
&\partial_\mu\bar{X}^+Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^-Y - \\
&\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+X^+ - \\
&\partial_\mu\bar{X}^-X^-) - \tfrac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \tfrac{1}{c_w^2}\bar{X}^0X^0H] + \\
&\tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \\
&igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]
\end{aligned}
$$

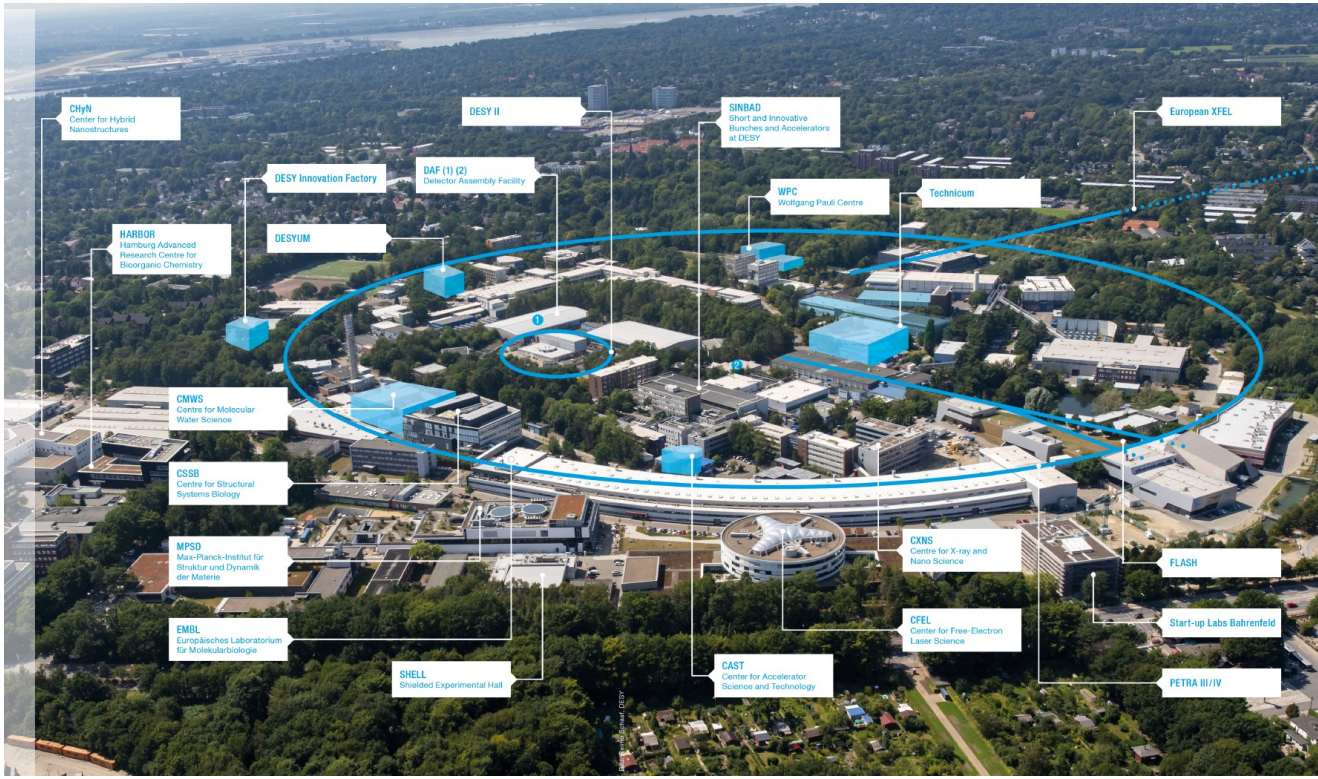
Physicists are world citizens

- Live in many different countries
- Travel to even more places for work
- Working with people from all over the world

Example: DESY where you are now

Many particle accelerators and research projects at DESY

- Globally unique research possibilities
- Interdisciplinary research
- Close cooperation between DESY and UHH
- International cooperation
- Approx. 3500 people on campus
- Second campus in Zeuthen



An ambitious research programme

Scientific challenges that DESY addresses

How can we **control the function of materials** on the level of individual electrons and spins?

How can we **film chemical reactions** in real time?

How can we **understand infections** on the molecular level?

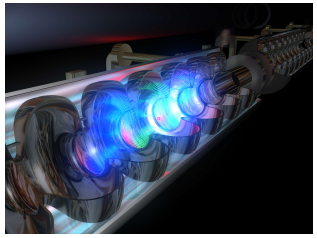
What does **physics beyond the Standard Model** look like?

What can astroparticles tell us about **the early universe**?

What do the **accelerators of the future** look like?

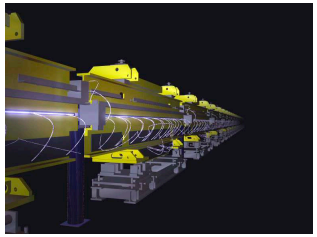
What do we do at DESY?

Create a knowledge base that is needed to solve challenges in society, science, and the economy.



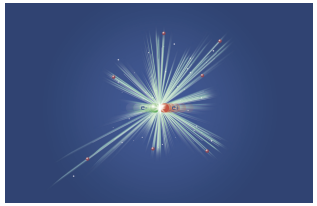
Accelerators

We develop and operate high-tech and large-scale particle accelerators



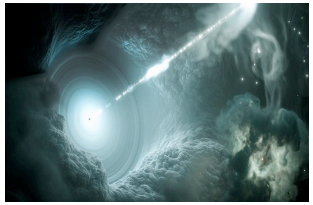
Photon Science

X-ray radiation from accelerators allows us investigate the atomic structures



Particle Physics

With particle accelerators, we explore the smallest particles of the universe and their interactions



Astroparticle Physics

We investigate high-energy processes in the universe using telescopes and detectors

The Helmholtz Association

DESY is a member of the largest scientific organisation in Germany

18 research centres

More than 43 000 employees

4.5 billion euro budget

Six research areas

Aerospace and transport

Earth and environment

Energy

Health

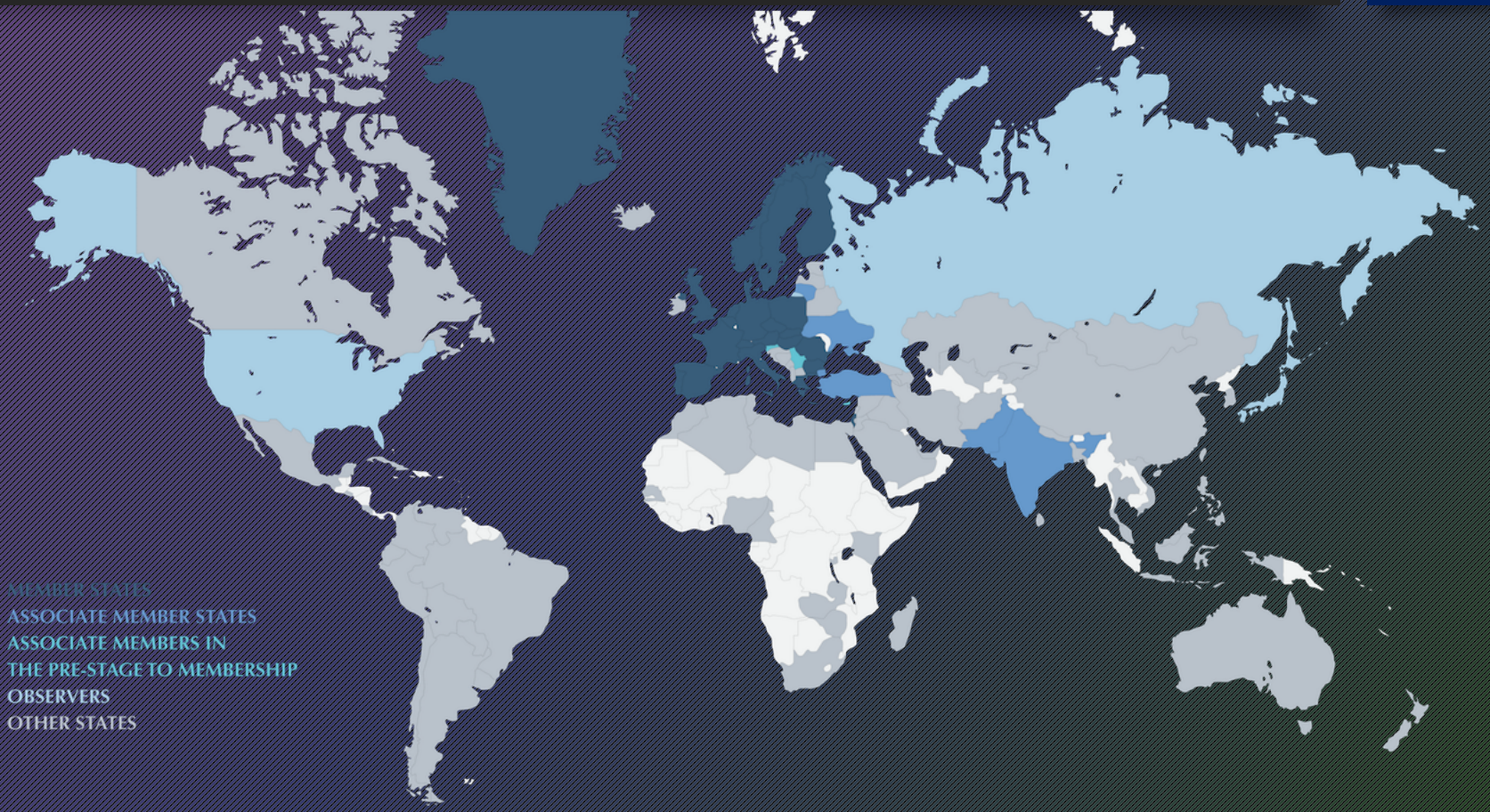
Key technologies

Structure of matter

Other example: CERN

- 3000 people employed by CERN
  - Physicists, engineers, computer scientists, mathematicians, firemen, cooks, builders, technicians, secretaries, security, etc
- >7500 physicists associated with CERN
  - Including yours truly

Who works at CERN?



Who visits CERN

- CERN is an open laboratory
- Anyone is welcome to visit, ask questions, take photographs, etc

- In 2019, 75,000 people visit CERN
  - Anyone is welcome http://www.cern.ch/visits
  - CERN is TripAdvisor top Geneva destination :)
  - New visitor centre just opened, increasing capacity (now 300,000 people can visit)

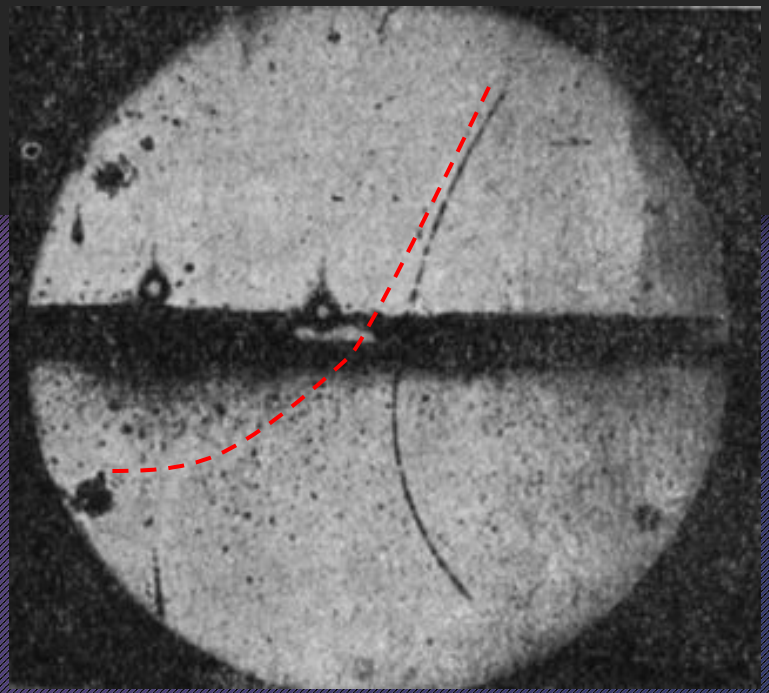
Problems with the Standard Model – experimentalist perspective

- Matter vs antimatter asymmetry
  - Standard Model cannot provide enough CP violation to explain dominance of matter
- Dark Matter
  - if it exists, it is very likely not described by the Standard Model
  - Neither is dark energy
- Standard Model neutrinos are massless
  - The 2015 Nobel Prize (Kajita and McDonald) was for neutrino oscillations, directly proving that neutrinos have mass
- Structure is not really explained

Basic Questions

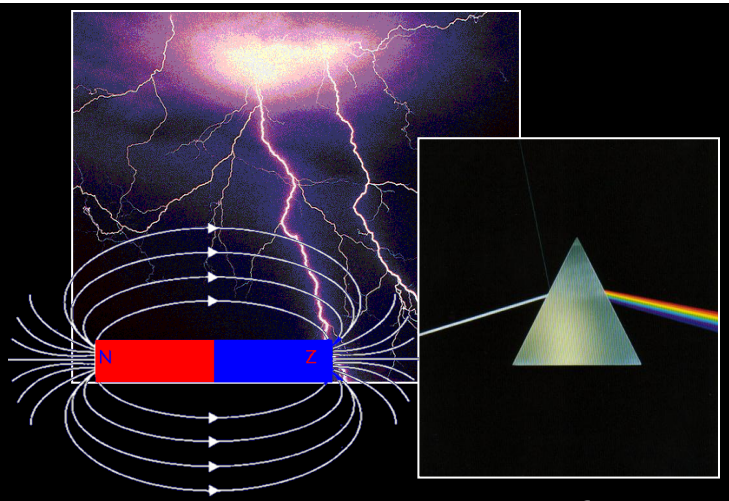
- What is everything around us made of?
- How does matter stick together?
- What, really, is mass?
  - Now that we have a particle that could possibly create mass, what is it and what does it do?
- Are there really only 3 spatial dimensions?
- Are the smallest particles we know fundamental?
- Where did the anti-matter go?
- Where's the rest of the matter anyway?


$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \not{D} \psi + h.c$
$+ \psi_i y_{ij} \psi_j \phi + h.c$
$+ |D_\mu \phi|^2 - V(\phi)$

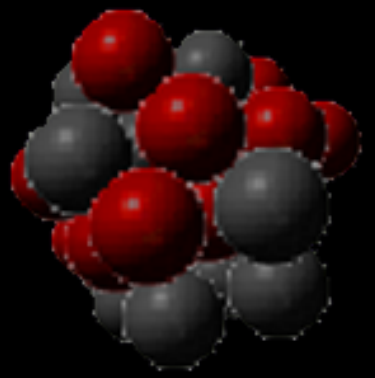


- Anti-matter: discovered in 1923
  - Predicted by theory
- Almost same as matter… But oppositely charged
- Problem: at big bang there was just as much matter as anti-matter… Where did it go?

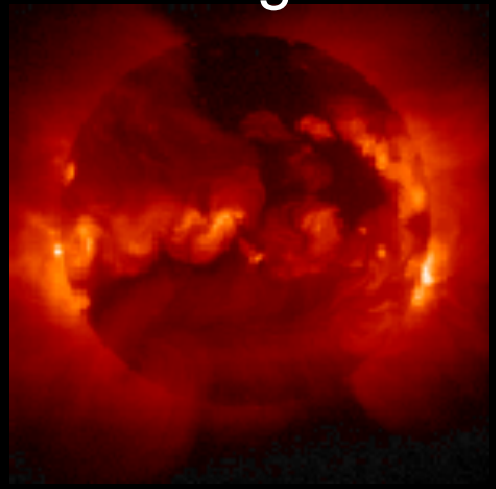
The four fundamental forces



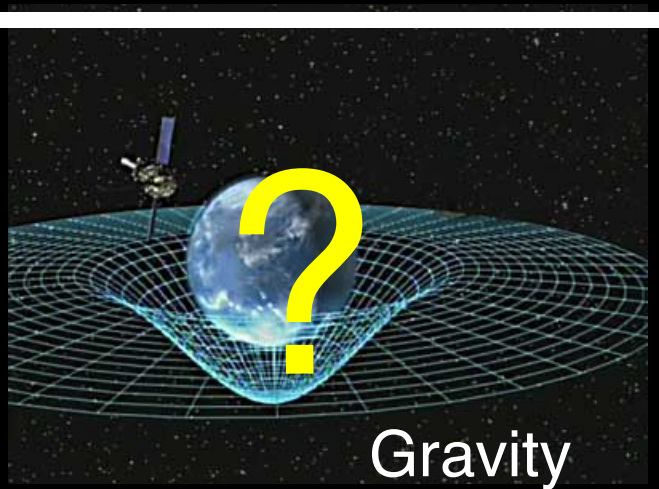
Electro-magnetic force



Strong force



Weak force



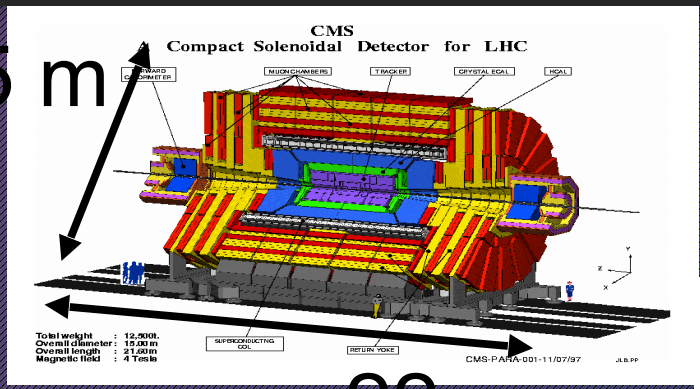
Gravity

The Dark Matter Puzzle

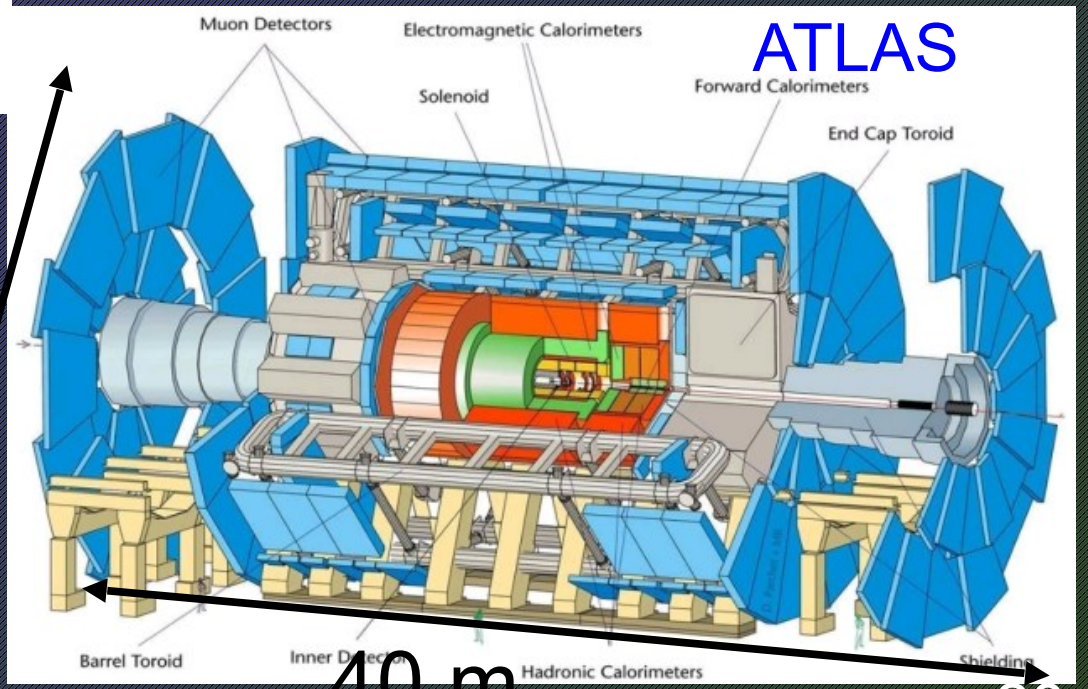
src: G. Watts ↑

←src: JWST

Detecting collisions

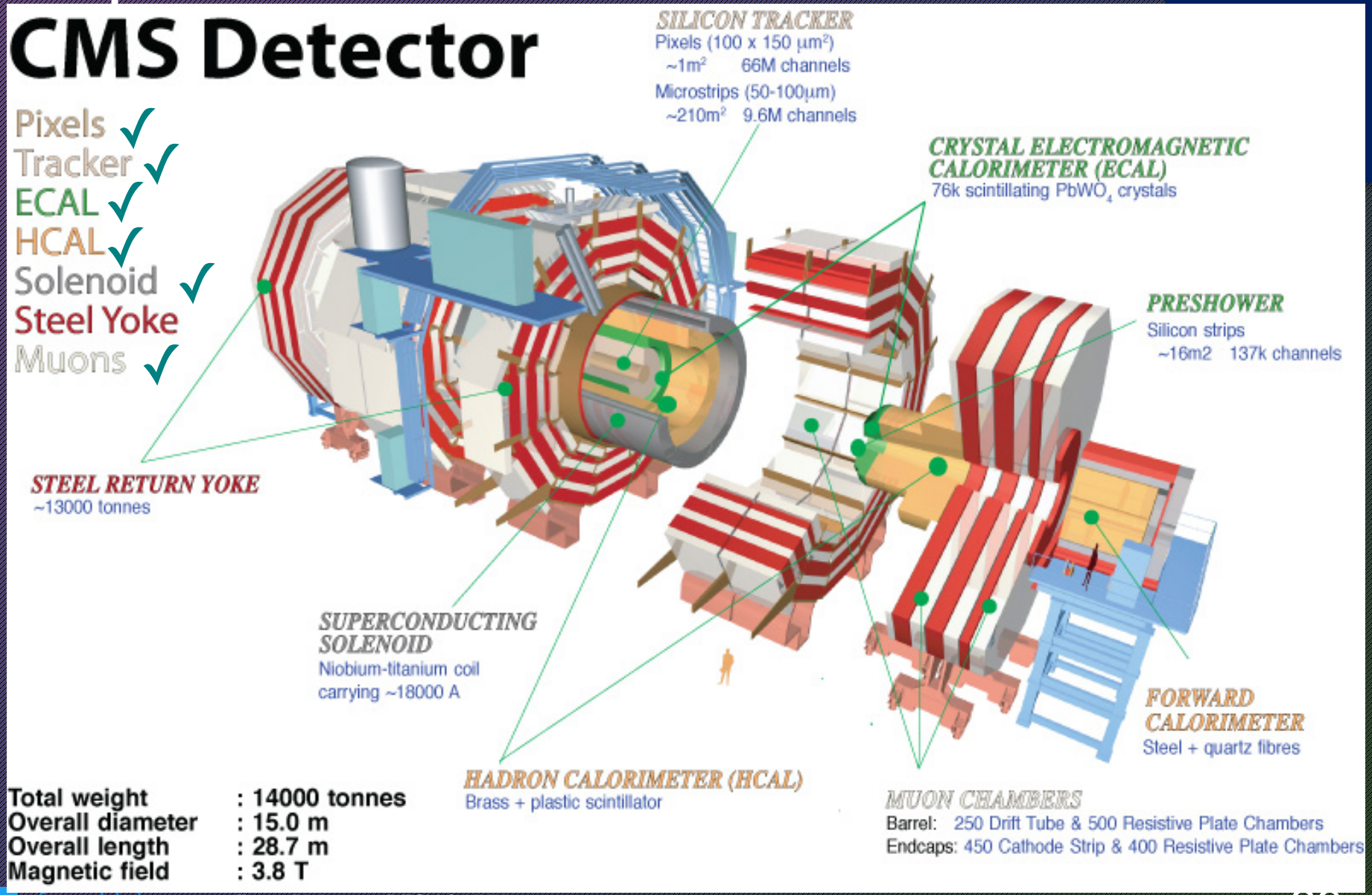


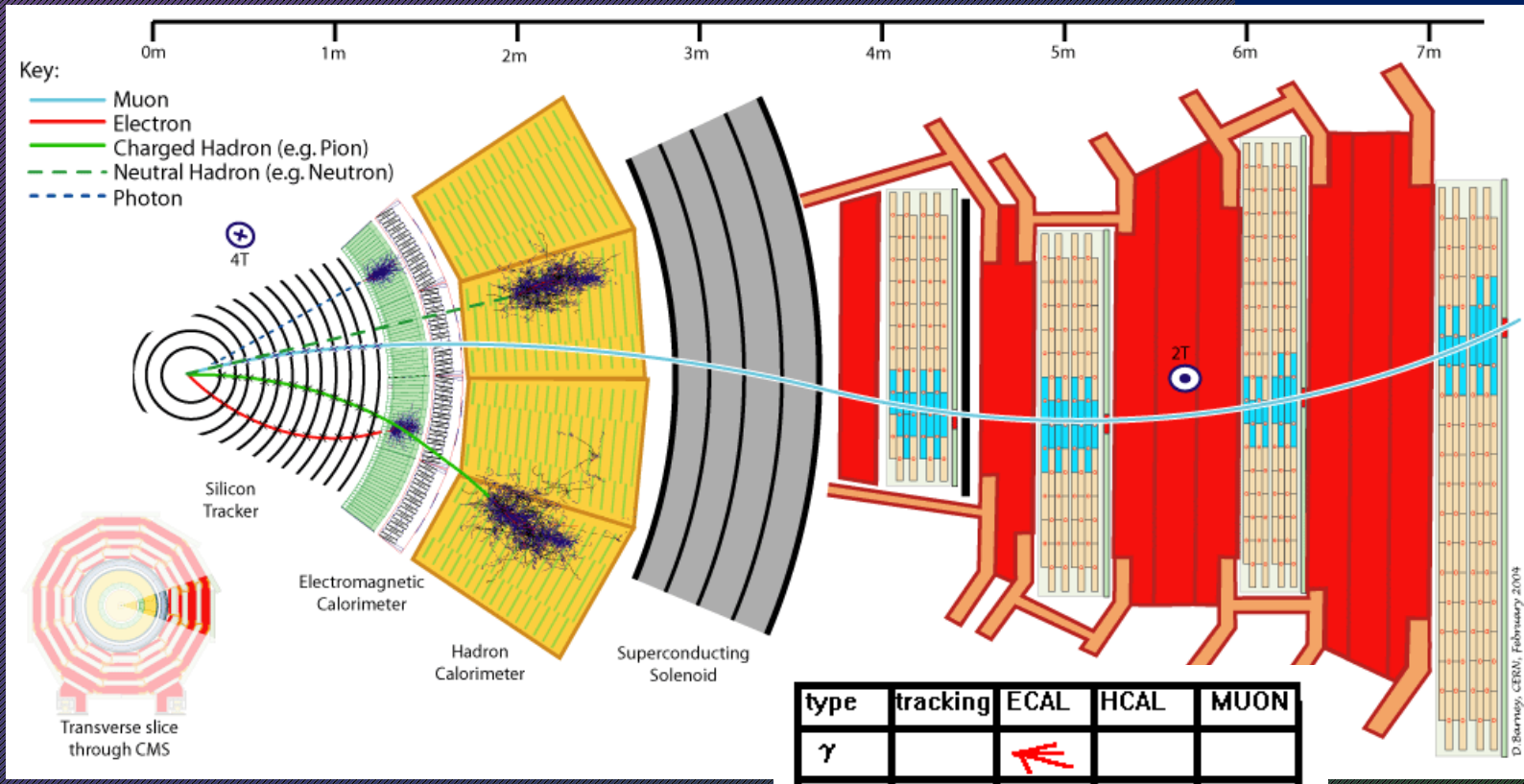
- Compared to the ATLAS experiment CMS is much smaller
- CMS weighs 12,000 tons *vs.* 7,500 tons for ATLAS



- ATLAS has a toroidal magnetic field for their muon system

Compact Muon Solenoid





type	tracking	ECAL	HCAL	MUON
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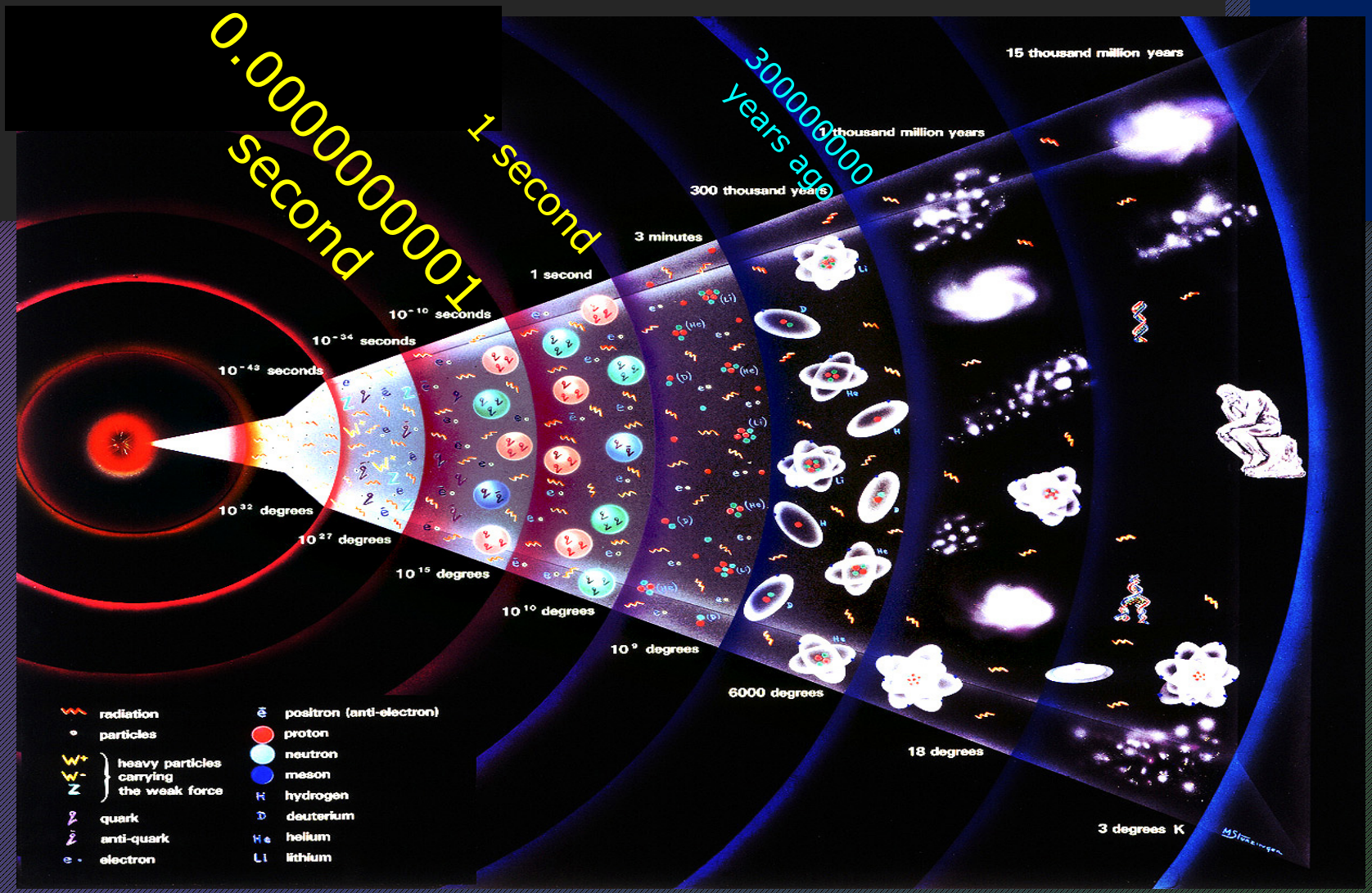
e				
μ				
Jet				
Et miss				


0.000000001 second
1 second
300000000 years ago
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
1 second
10^{-10} seconds
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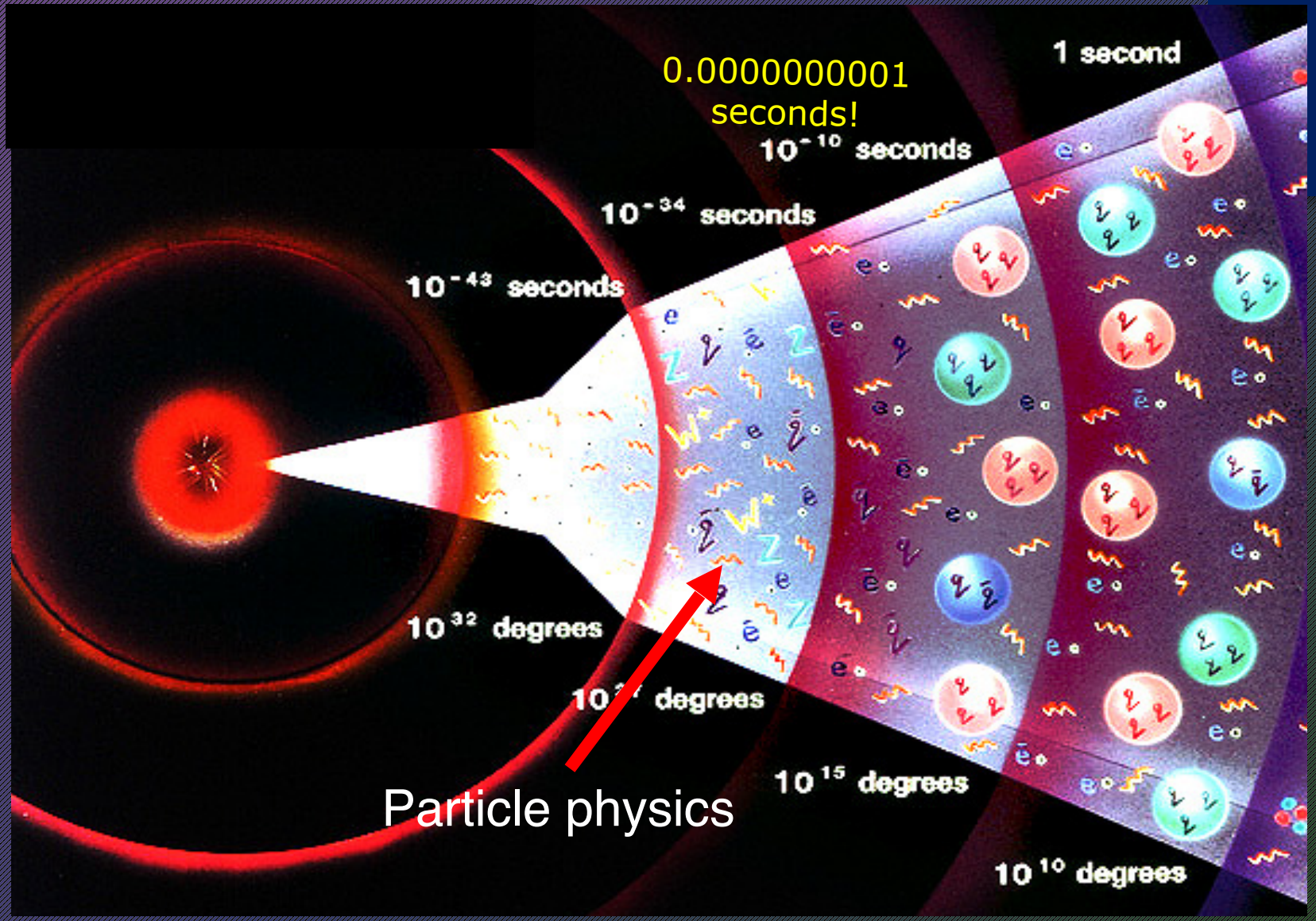
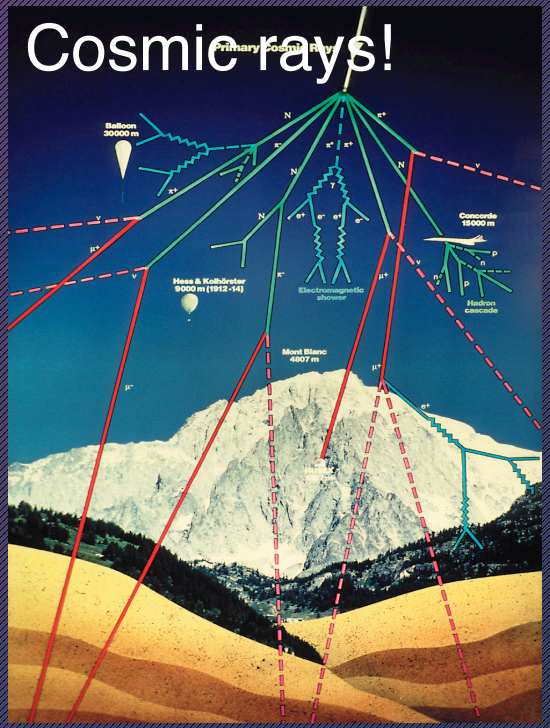
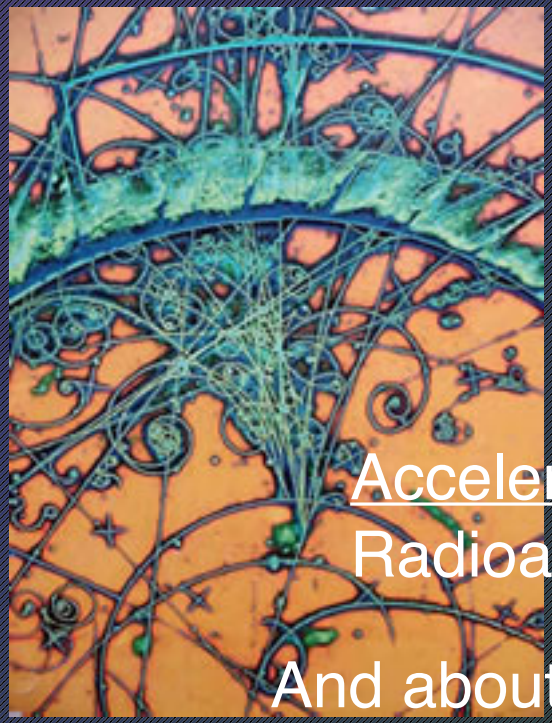
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium


0.0000000001 seconds!
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{15} degrees
10^{10} degrees
Particle physics

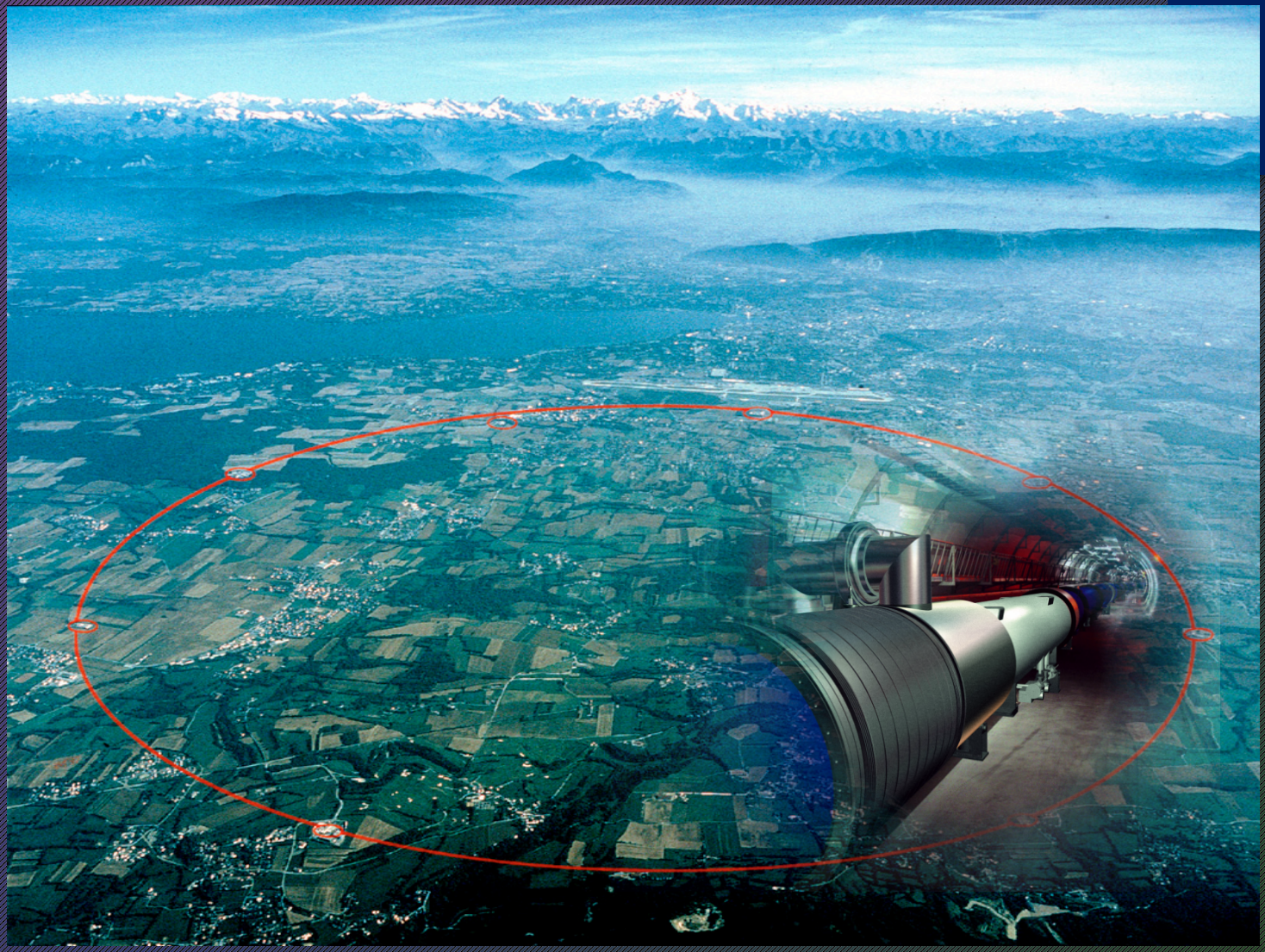
How do we know all this?

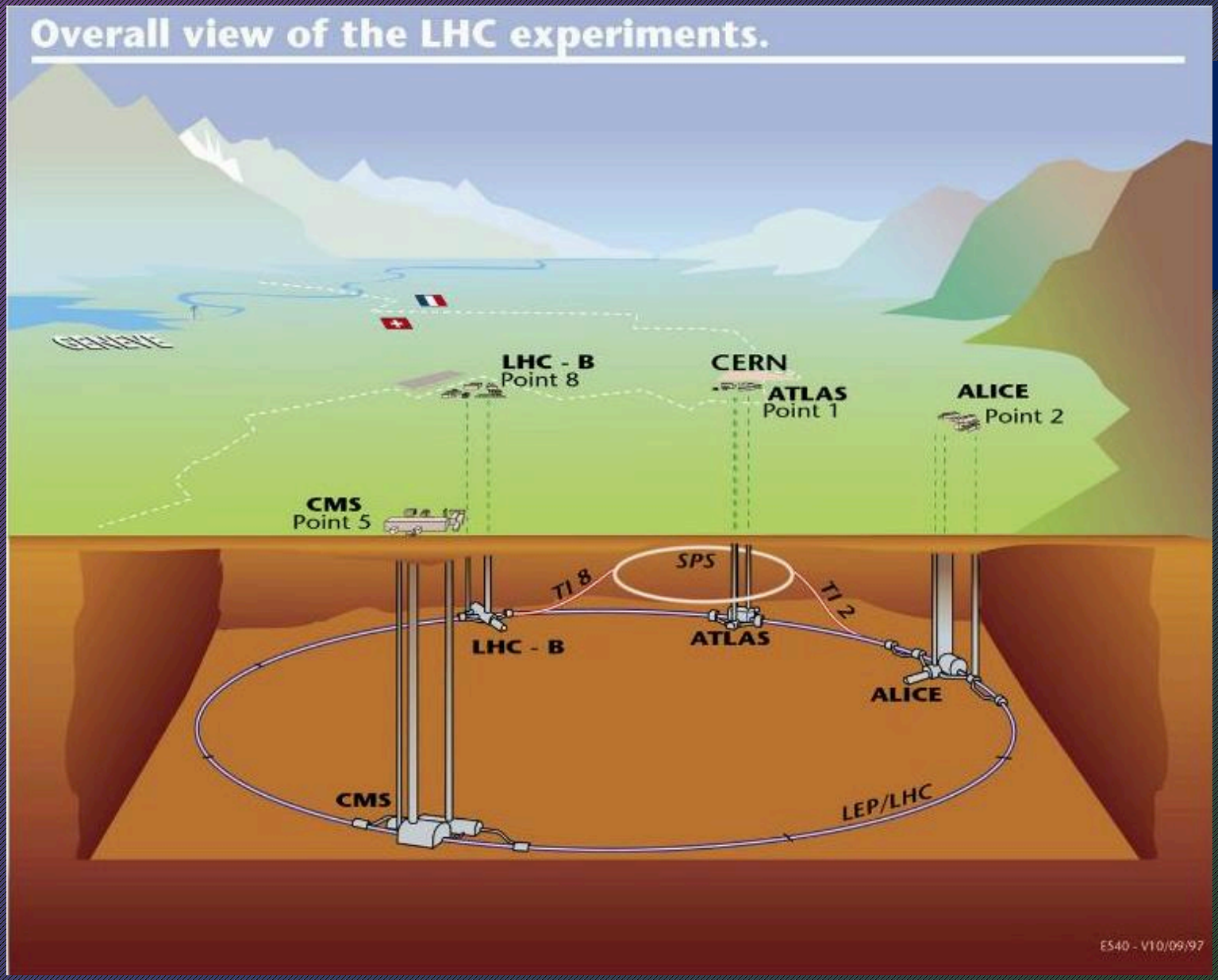


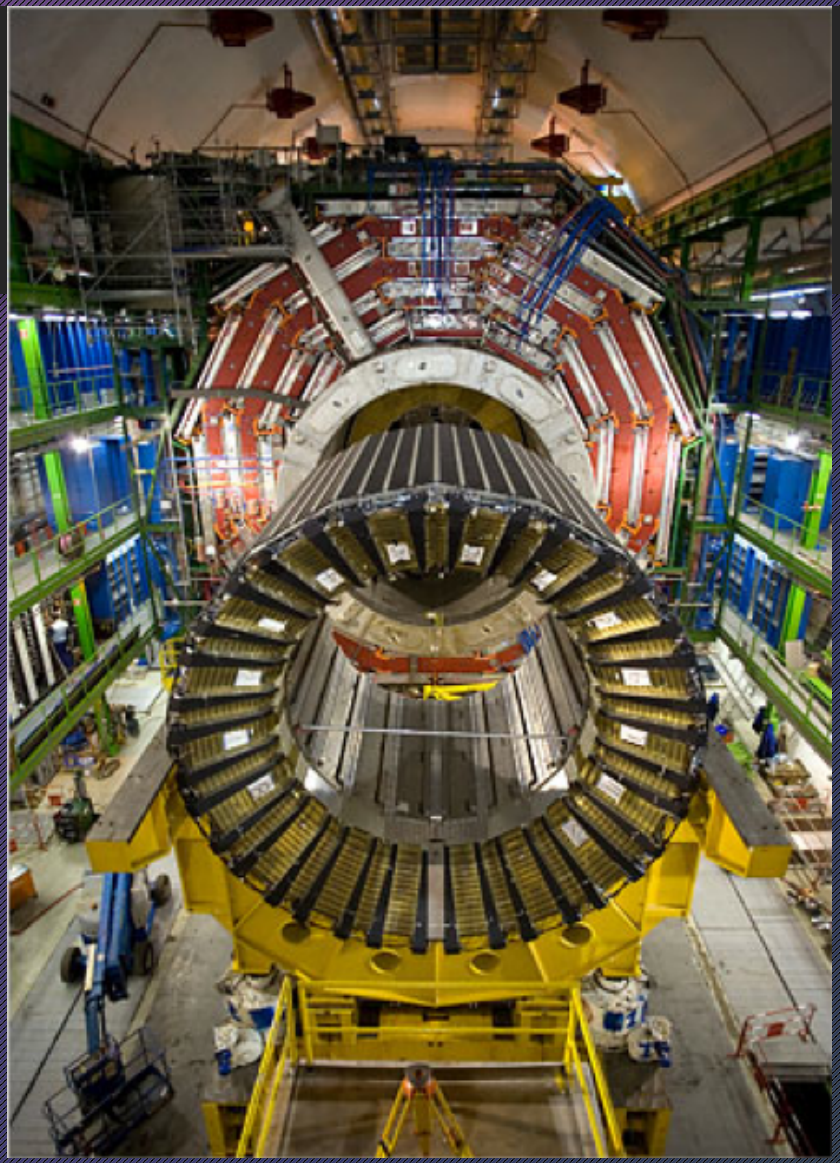


Accelerator experiments
Radioactivity experiments

And about 100 years of
hard work by many people...




Overall view of the LHC experiments.
GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
E540 - V10/09/97



CMS

- Compact
- Muon
- Solenoid

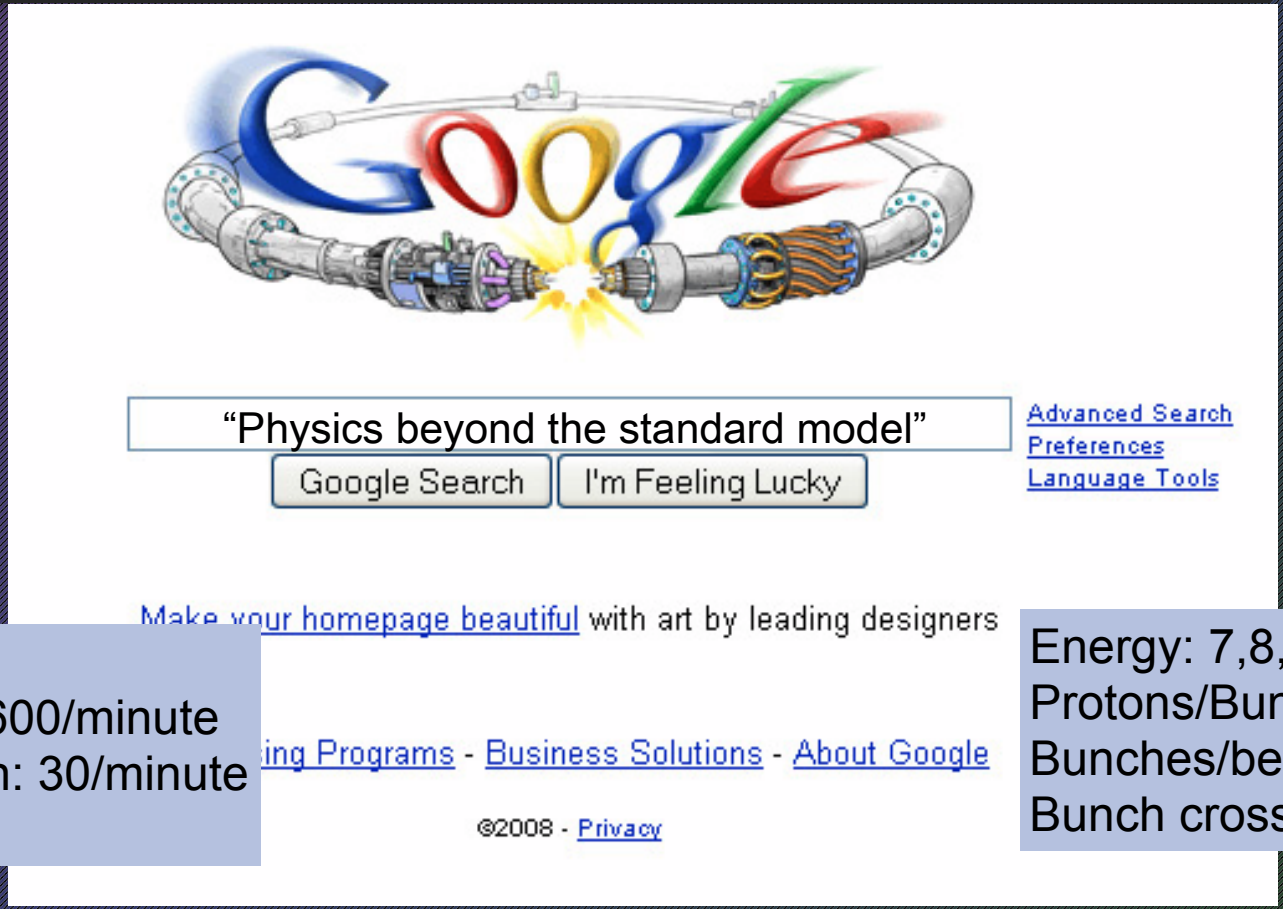
- “Compact” is relative...

More open questions

- Are the quarks and leptons elementary particles?
- Are there other particles we have not seen yet?
- Why are the masses of particles different?
  - And is that connected to the Higgs Boson/field?
- Matter/Antimatter asymmetry in universe?
- What about gravity? Or superstrings? Or extra dimensions?
- Properties of the neutrino?

Answering any one of these questions will get you a Nobel Prize!

LHC: search engine



Rates:
Top quark: 600/minute
Higgs boson: 30/minute
BSM: ?

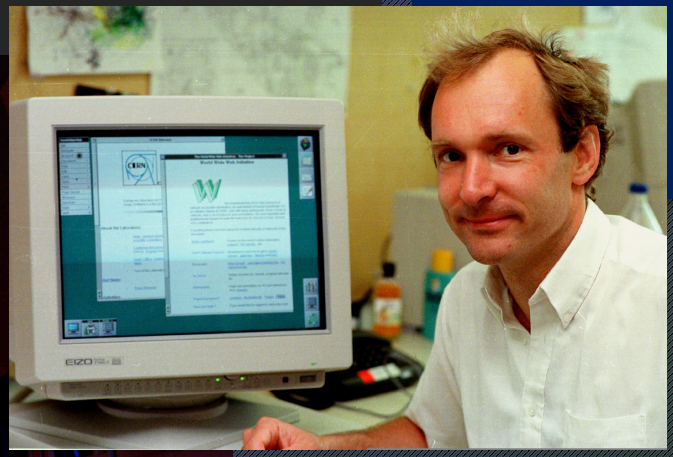
Energy: 7,8,13,14 TeV
Protons/Bunch: 1.5 10^{11}
Bunches/beam: ~3500
Bunch crossing: 40 MHz

Basic vs applied research

- Two types of science research
  - Basic research (how do things work)
  - Applied research (how do I make...)

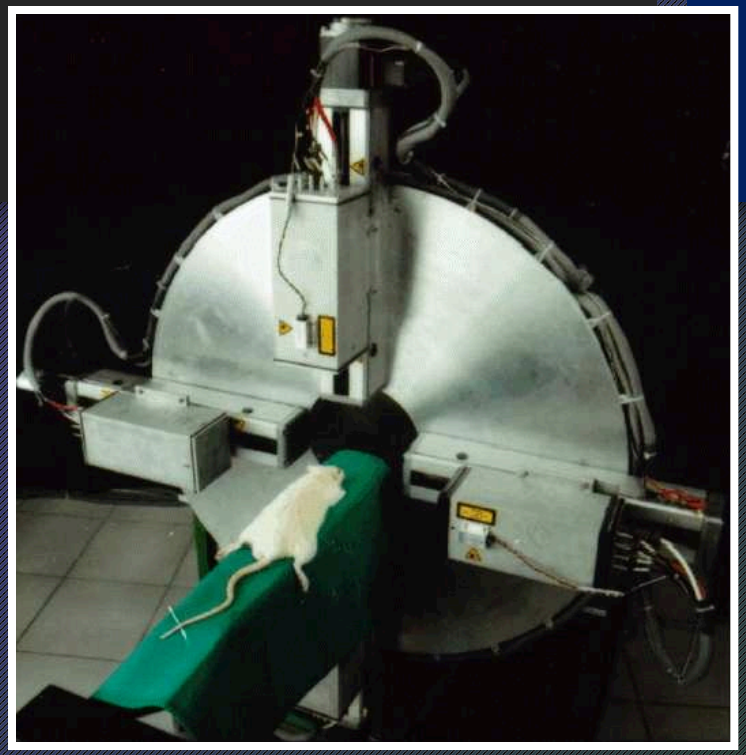
- CERN only does basic research
  - But usually we need to build things that do not exist yet...
- Applied research needs basic research

CERN - where the web was born



Tim Berners-Lee

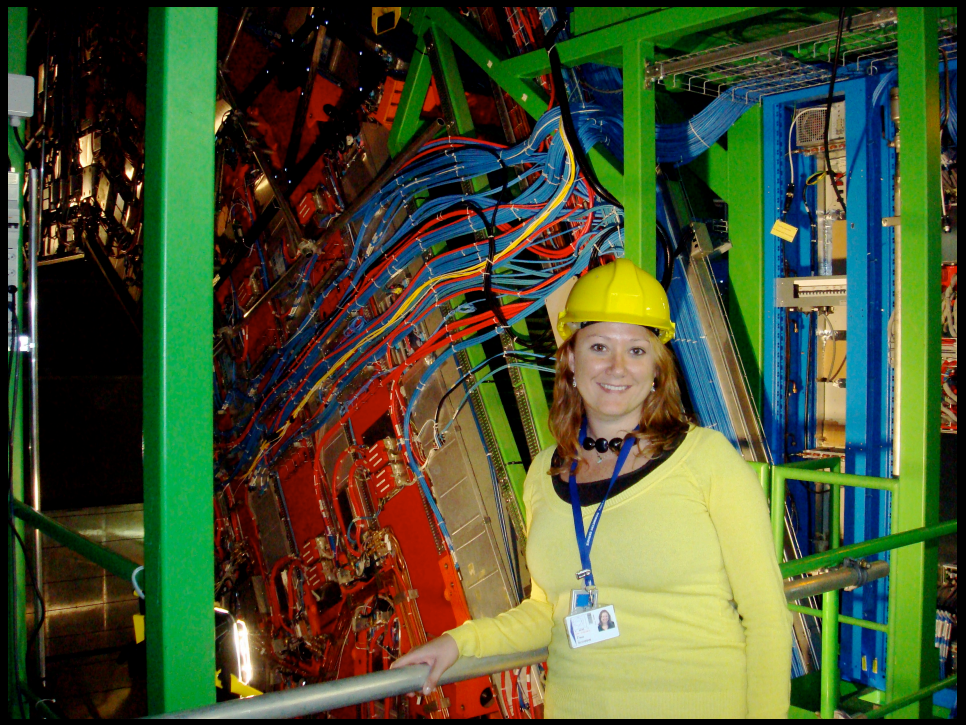
But also...

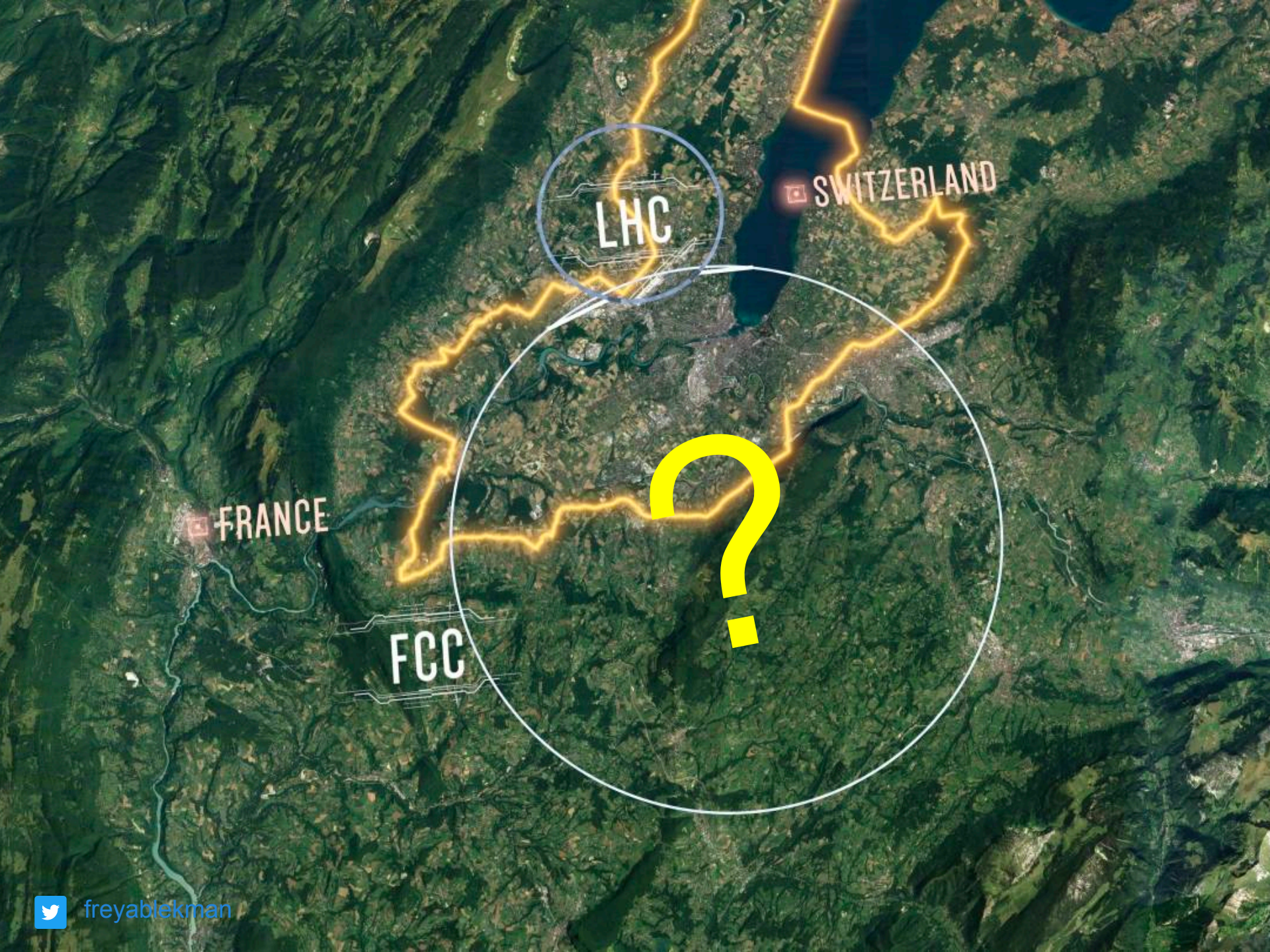


- PET scans
- Touch screen
- Radiation therapy
- Loads of computing/ internet development
  - GRID

Normaal werk?

- Samenwerken met team
  - samen analyseren
- Programmeren
- Wiskunde/ natuurkunde
- Nieuwe dingen bouwen
- Dingen opschrijven
- Reizen
- Lesgeven




LHC
SWITZERLAND
FRANCE
FCC
?
freyablekman

Vragen?

the ‘periodic table’ of modern physics

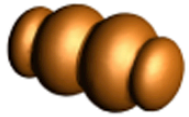
Leptons

Electric Charge

Tau	-1	0	Tau Neutrino
Muon	-1	0	Muon Neutrino
Electron	-1	0	Electron Neutrino

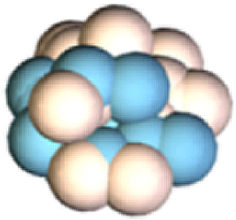
Strong

Gluons (8)



Quarks

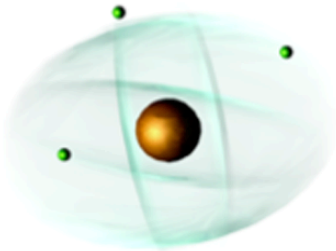
Mesons
Baryons



Nuclei

Electromagnetic

Photon



Atoms
Light
Chemistry
Electronics

Quarks

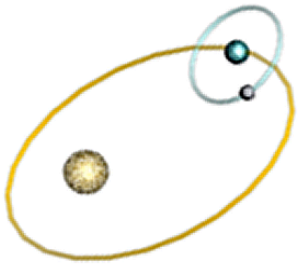
Electric Charge

Bottom	-1/3	2/3	Top
Strange	-1/3	2/3	Charm
Down	-1/3	2/3	Up

each quark: *R,* *B,* *G* *3 colours*

Gravitational

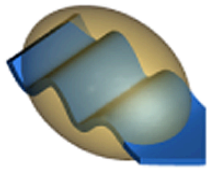
Graviton ?

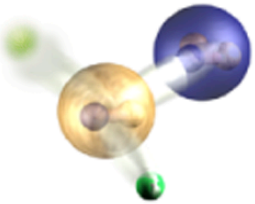


Solar system
Galaxies
Black holes

Weak

Bosons (W,Z)

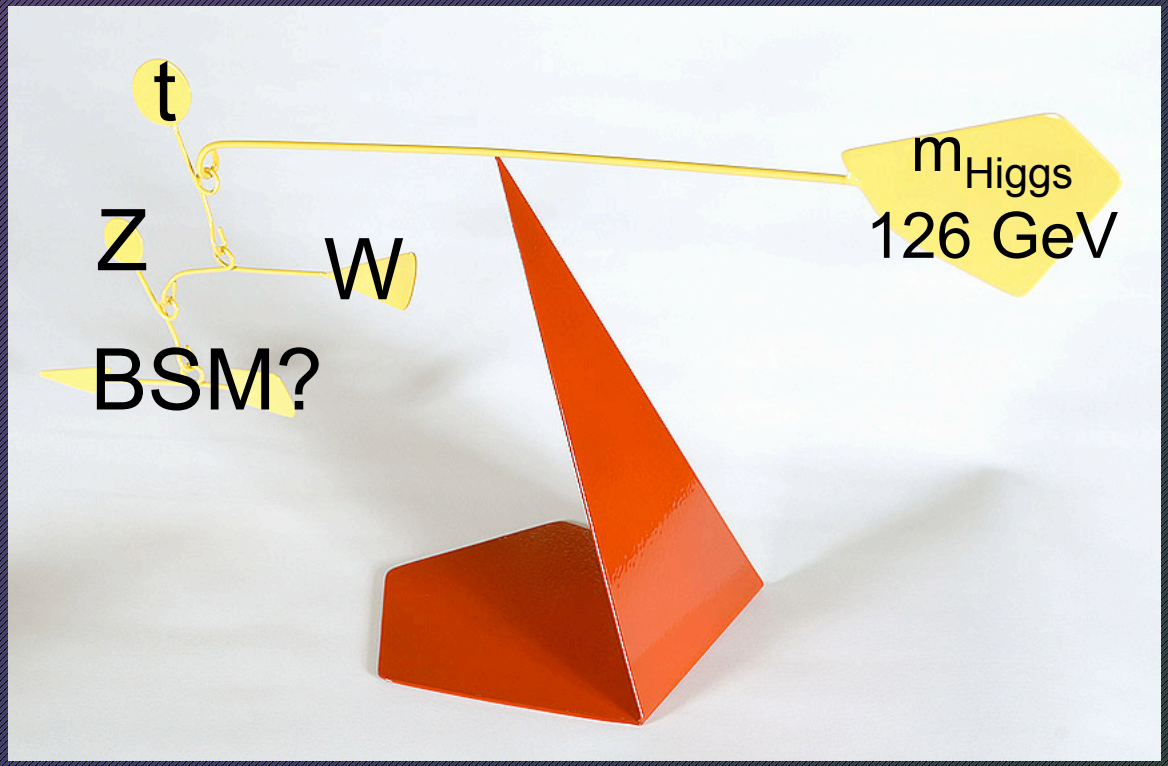




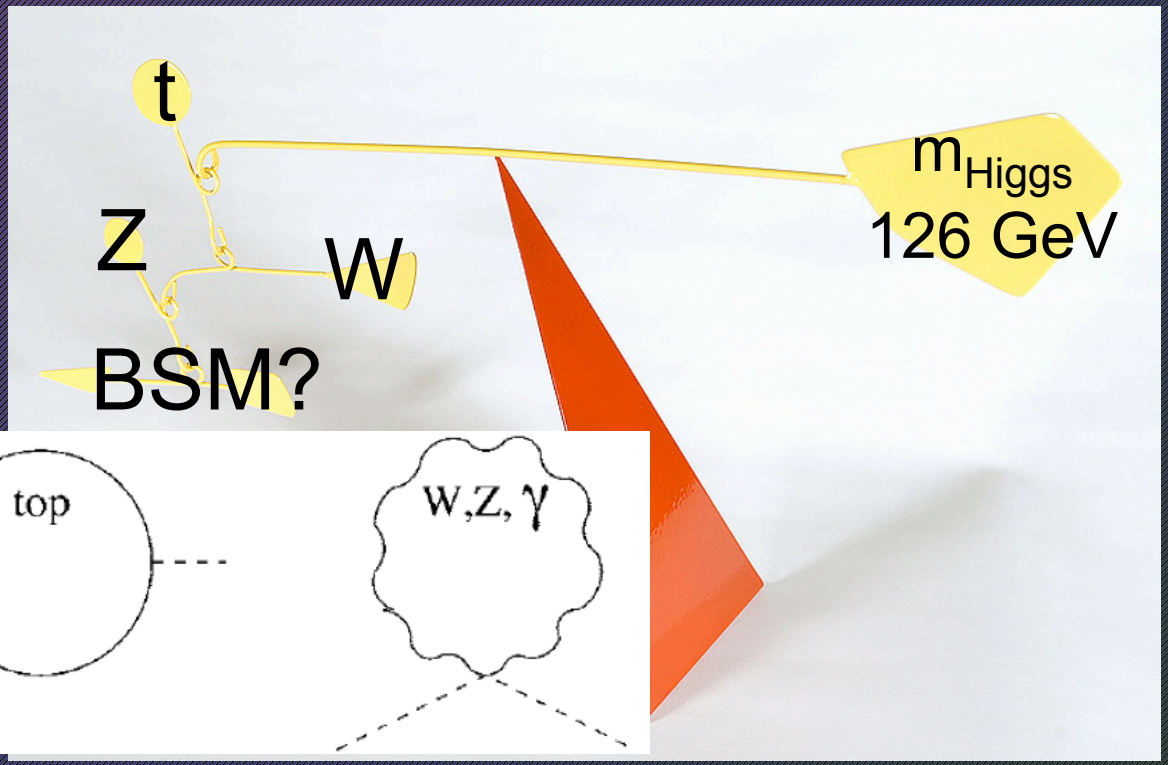
Neutron decay
Beta radioactivity
Neutrino interactions
Burning of the sun

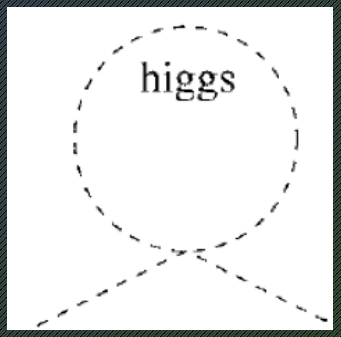
The particle drawings are simple artistic representations

Little Hierarchy problem, Naturalness

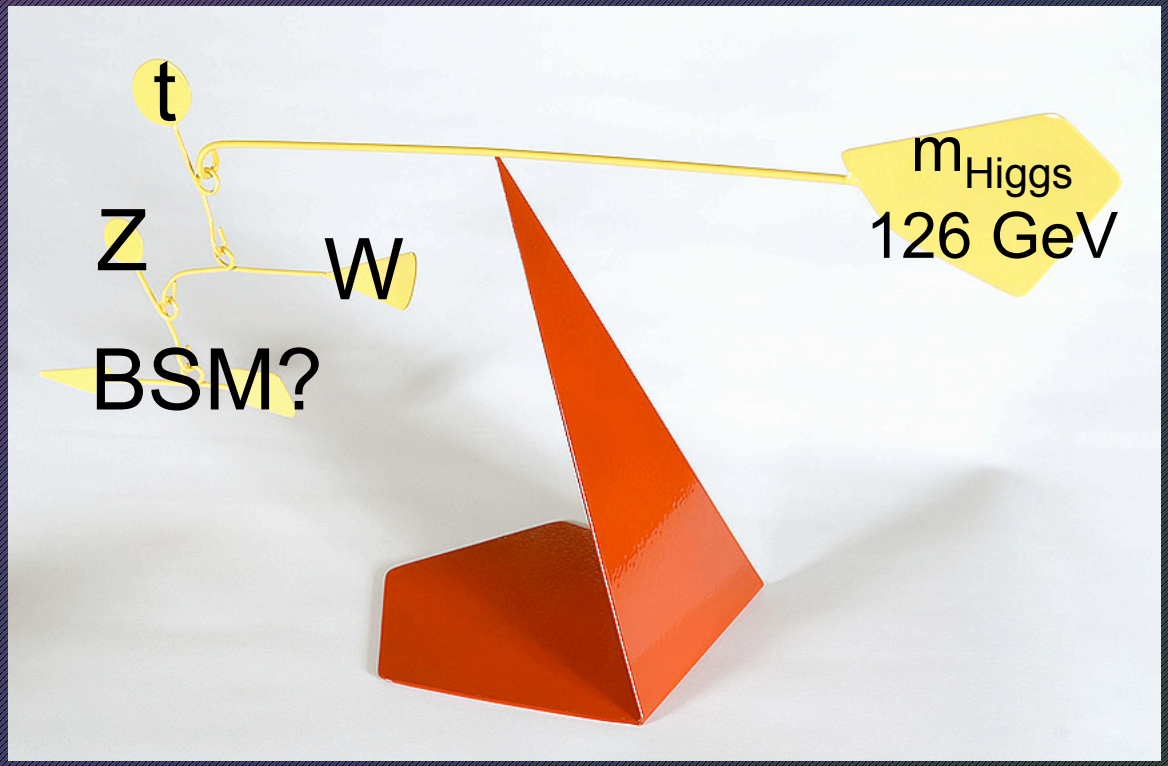


Little Hierarchy problem, Naturalness





Little Hierarchy problem, Naturalness



If fine tuning <=10%:
Restrictions:
Λ_{quarks} ~< 2 TeV
Λ_{gauge} ~< 5 TeV

Strings, Supersymmetry/SUSY and the LHC