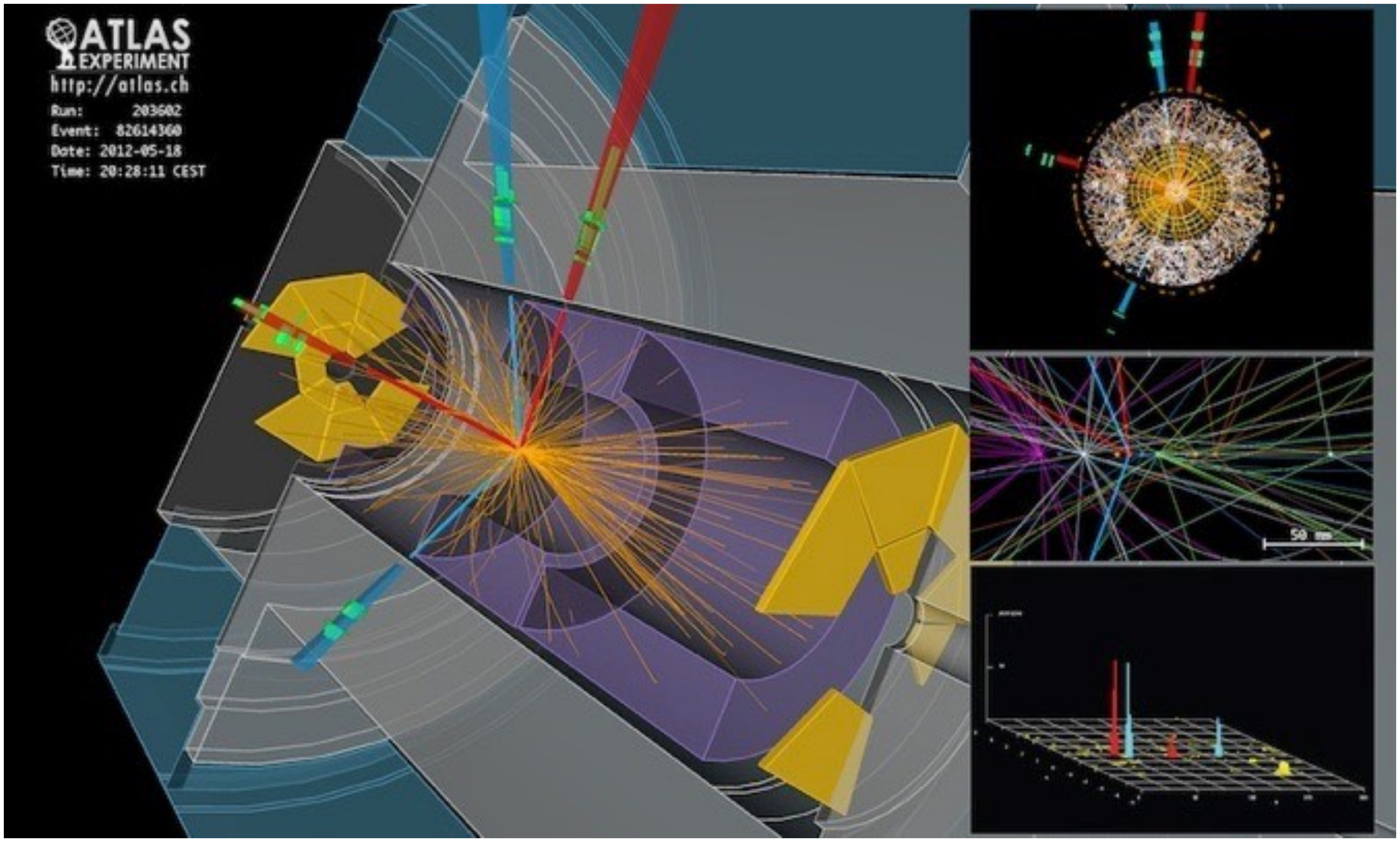
Teilchenphysik mit höchstenergetischen Beschleunigern (Higgs & Co)



1. Einführung / Introduction

16.10.2017

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Prof. Dr. Siegfried Bethke
Dr. Frank Simon

Overview

- Goal of the Course
- Organisation
- Literature recommendations

- Particle physics - Overview and open questions

- Experiments and techniques in particle physics

Goal of the Course

- Overview over
  - highly energetic hadron colliders
  - Particle detectors at the LHC
  - Physics of the Standard Model at high energies
  - Signatures of New Physics beyond the SM
  - Analysis techniques
  - Outlook on planned experiments

- Continuation in the summer:
  - Precision measurements at lepton colliders
  - Astroparticle physics
    - Cosmic radiation
    - Dark Matter, Dark Energy
    - Neutrinos

In general:
Focus on latest results, general overview over the field of High Energy Physics (HEP) from an experimental perspective

Organisation

- Time and place:
  - Mondays, 14:00 - 15:30
  - Physik II, Seminarraum PH 127
- Prerequisites:
  - Introductory lecture to Particle, Nuclear & Astrophysics
- Exercise Classes: None
- Exams: On request
- Slides: Available on-line
  at the moment accessible via our indico system -
  link from main webpage will come soon:
  https://indico.mpp.mpg.de/category/123/

Literature

An up-to-date book (incl. Higgs discovery): Basics and material covered in lecture:
Mark Thomson, ***Modern Particle Physics,*** Cambridge University Press 2013

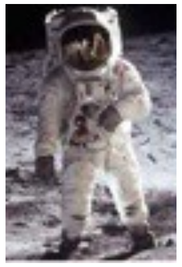
- **In addition - Basics:**
  - D.H. Perkins, “Introduction to High Energy Physics”, Cambridge University Press 2000
  - F.Halzen, D.Martin, “Quarks & Leptons”, Wiley&Sons
  - Ch. Berger, “Teilchenphysik”, Springer
  - R.K.Ellis, W.J.Stirling, B.R. Webber, “QCD and Collider Physics”, Cambridge Univ. Press
- **More detailed / advanced:**
  - M.Peskin, “Beyond the Standard Model”, hep-ph/9705479
  - J.Ellis, “Beyond the Standard Model for Hillwalkers”, hep-ph/9812235
  - M.Herrero, “The Standard Model”, hep-ph/9812242
  - Particle Data Group: `pdg.lbl.gov` (-> “reviews, tables and plots”, -> “exp. Methods”…)
  - SPIRES HEP library: `http://slac.stanford.edu/spires/`
  - `www.cern.ch, www.desy.de, www.fnal.gov, www.slac.stanford.edu, www.kek.jp`

Schedule

1.	Introduction	16.10.
2.	Accelerators	23.10.
3.	Particle Detectors I	30.10.
	----------- no lecture -------------	**06.11.**
4.	Particle Detectors II	13.11.
5.	Monte Carlo Generators and Detector Simulation	20.11.
6.	Trigger, Data Acquisition, Computing	27.11.
7.	QCD, Jets, Proton Structure	04.12.
8.	Top Physics Tests of the Standard Model	11.12
9.	Topic Open - Wishes, Ideas?	18.12.
	----------- Christmas --------------------	
10.	Tests of the Standard Model	08.01.
11.	Higgs Physics II	15.01.
12.	Physics beyond the SM	22.01.
13.	Higgs Physics II	29.01.
14.	LHC Outlook & Future Collider Projects	05.02.

Particle Physics - Overview, Open Questions

Connecting the Smallest and Largest Structures



	Size	Mass
Universe	10^{26} m	10^{52} kg
Galaxy	10^{21} m	10^{41} kg
Solar System	10^{13} m	10^{30} kg
Earth	10^{7} m	10^{24} kg
Man	10^{0} m	10^{2} kg
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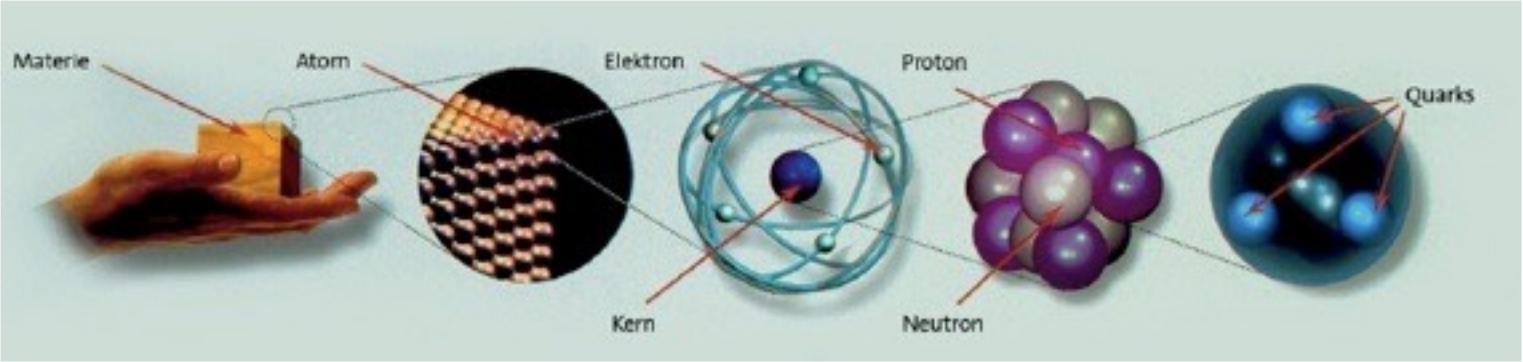

“Astroteilchenphysik in Deutschland”, http://www.astroteilchenphysik.de/, und darin angegebene Referenzen

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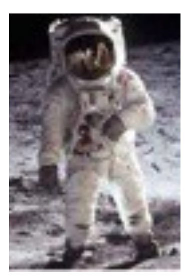

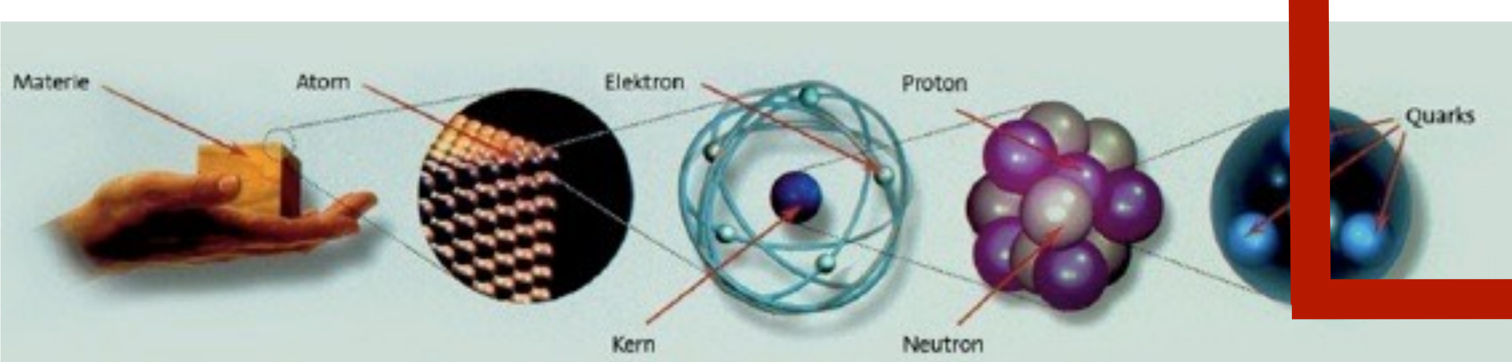

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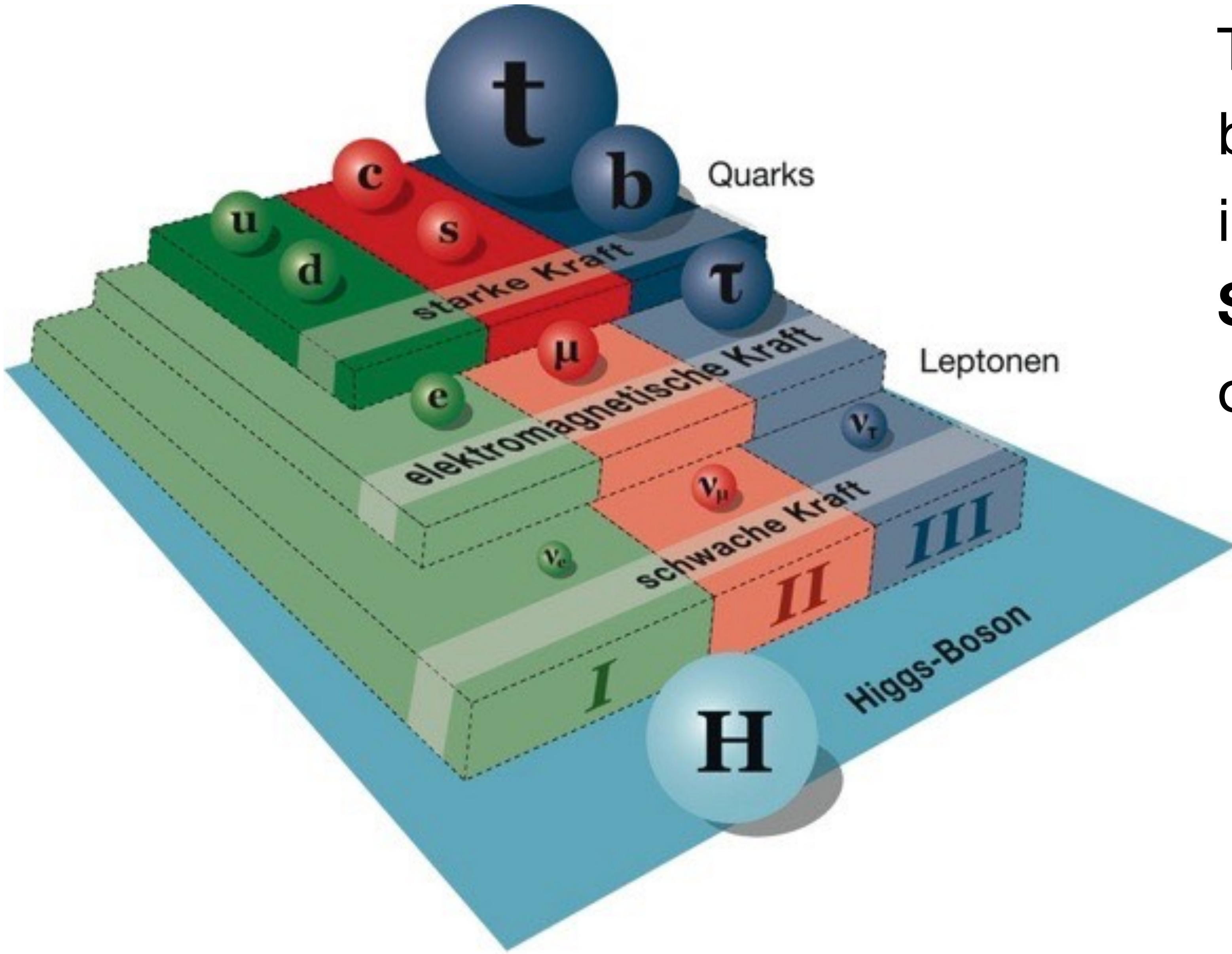
Particle Physics: The Standard Model

- detailed knowledge about the structure of matter based on decades of experimental and theoretical work



The fundamental building blocks of matter and their interactions form the **Standard Model** of particle physics

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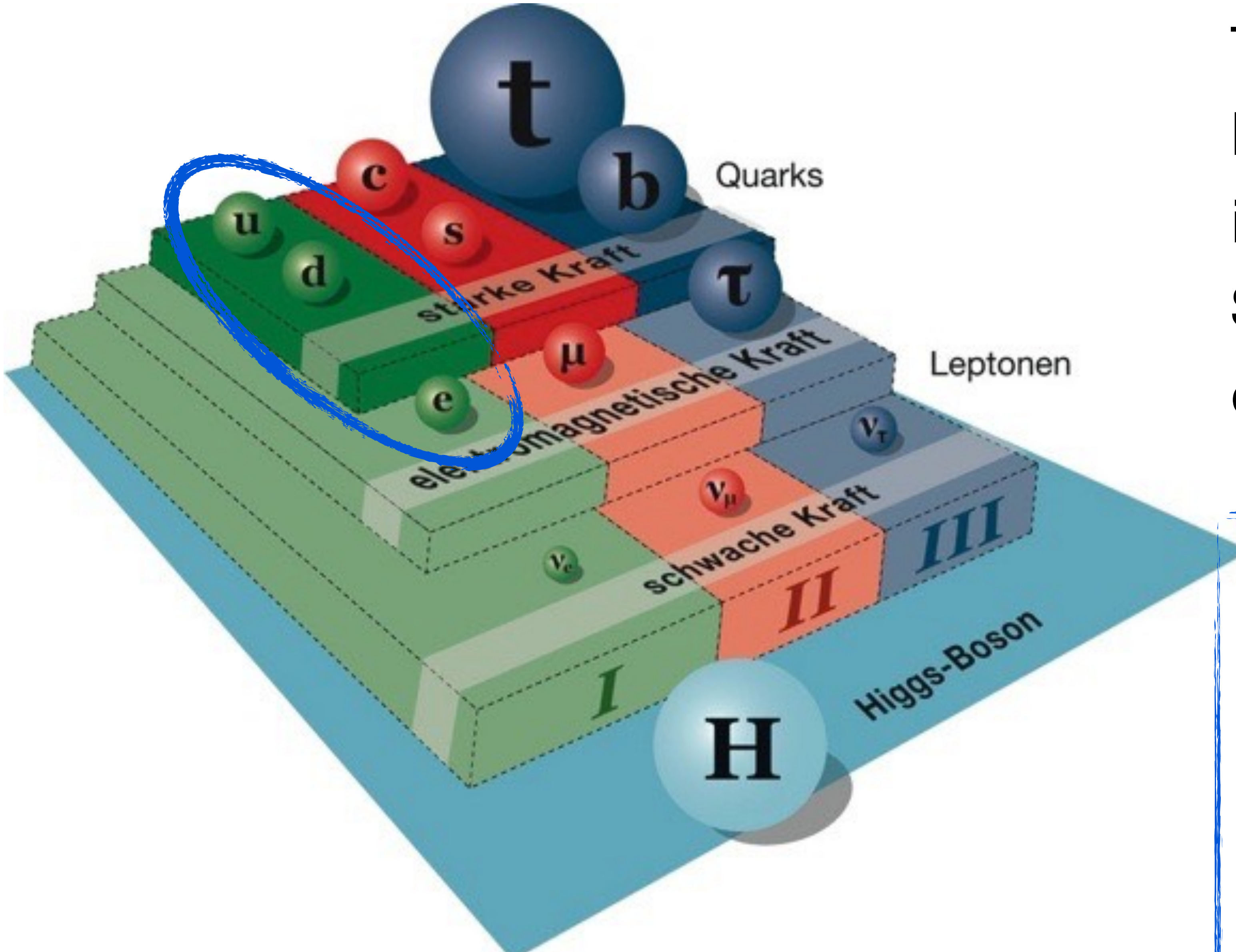

The fundamental building blocks of matter and their interactions form the **Standard Model** of particle physics

The stuff we are made of:

- Protons and Neutrons consist (mainly) of *u* and *d* Quarks
- Atoms have an “electron cloud”

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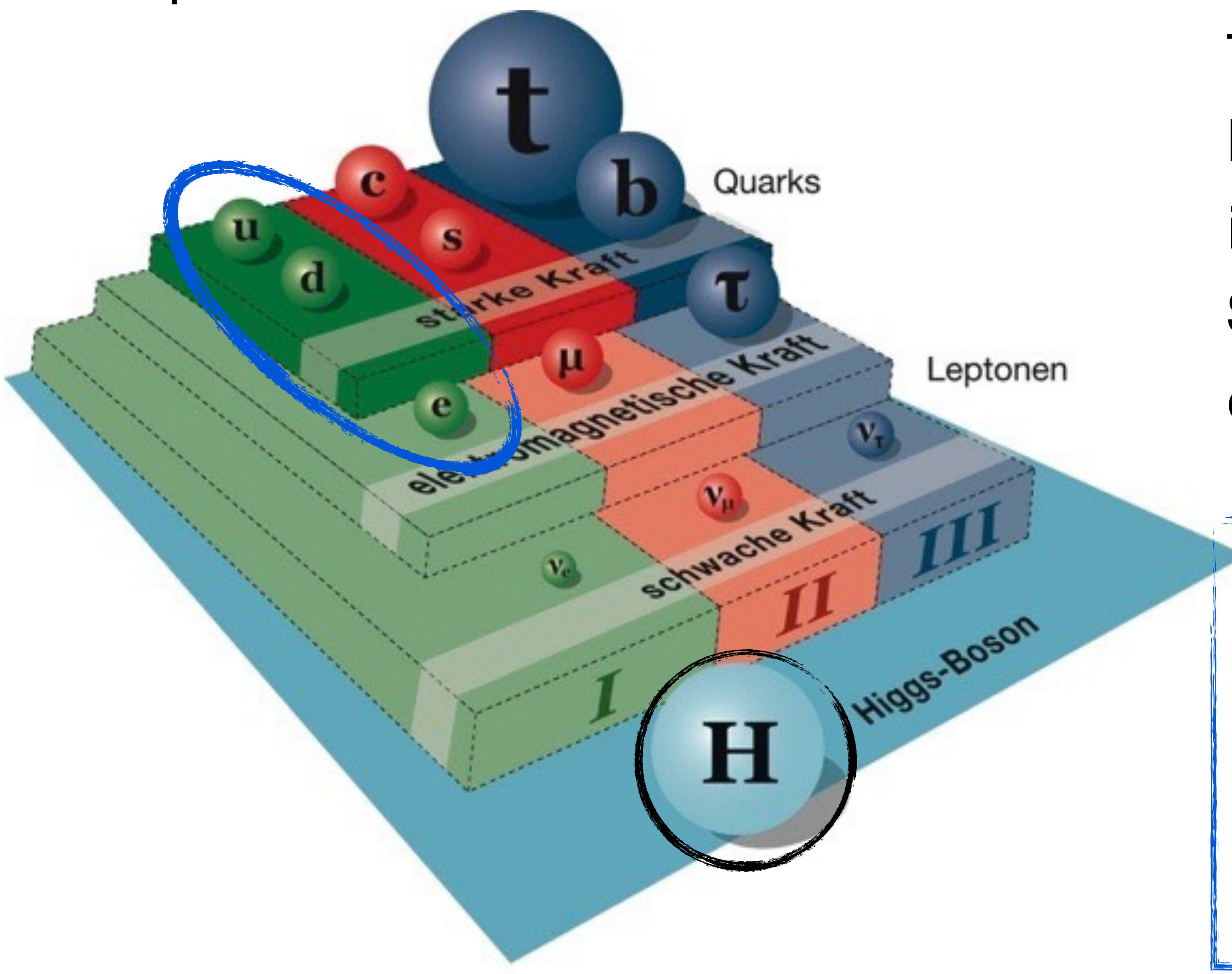

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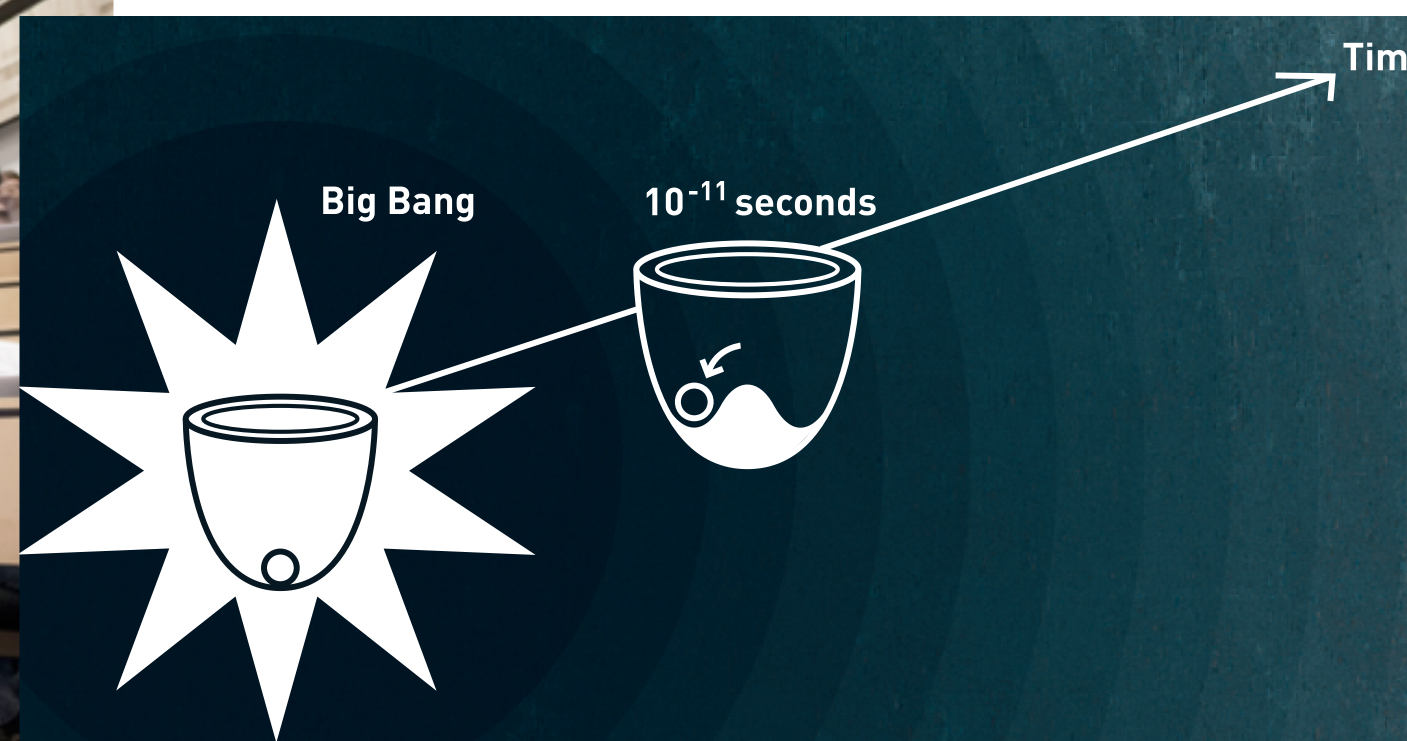
Discovered 2012: Generation of mass via the Higgs field

Generation of Mass - Nobel Prize 2013

The Nobel Prize in Physics 2013 - François Englert, Peter Higgs

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

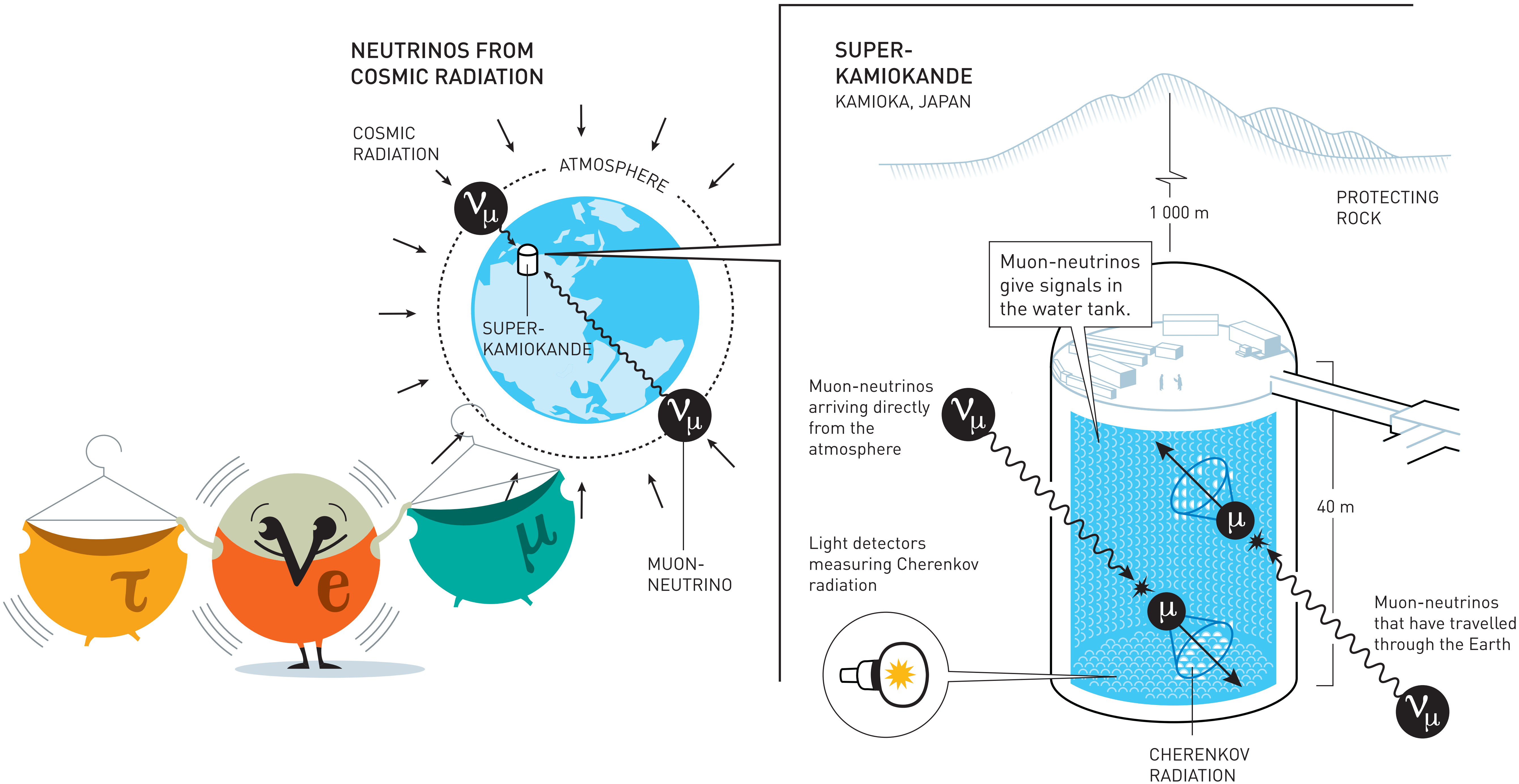


CERN, July 4, 2012

Neutrino Masses - Nobel Prize 2015

The Nobel Prize in Physics 2015 - Takaaki Kajita, Arthur McDonald

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"



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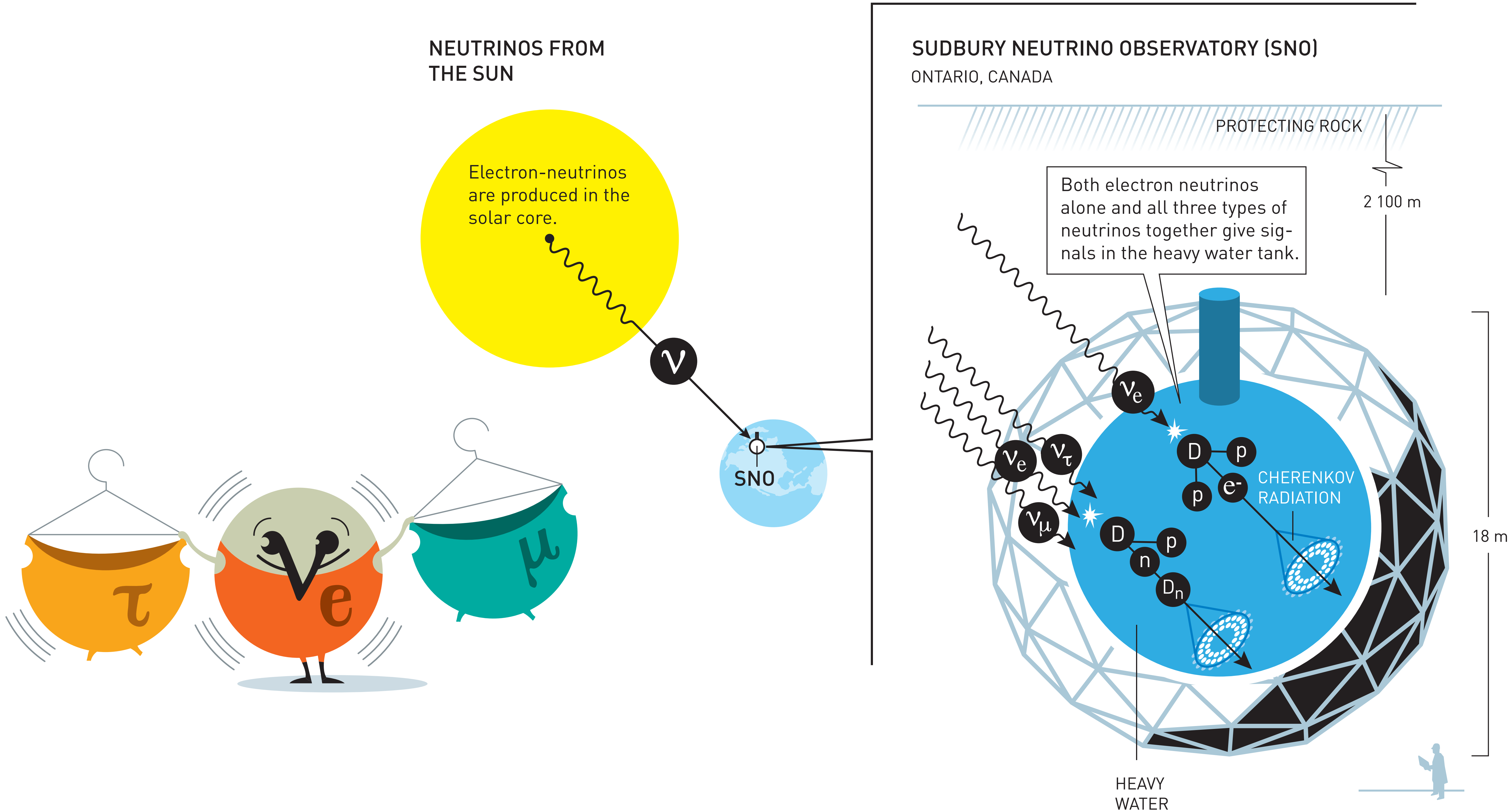

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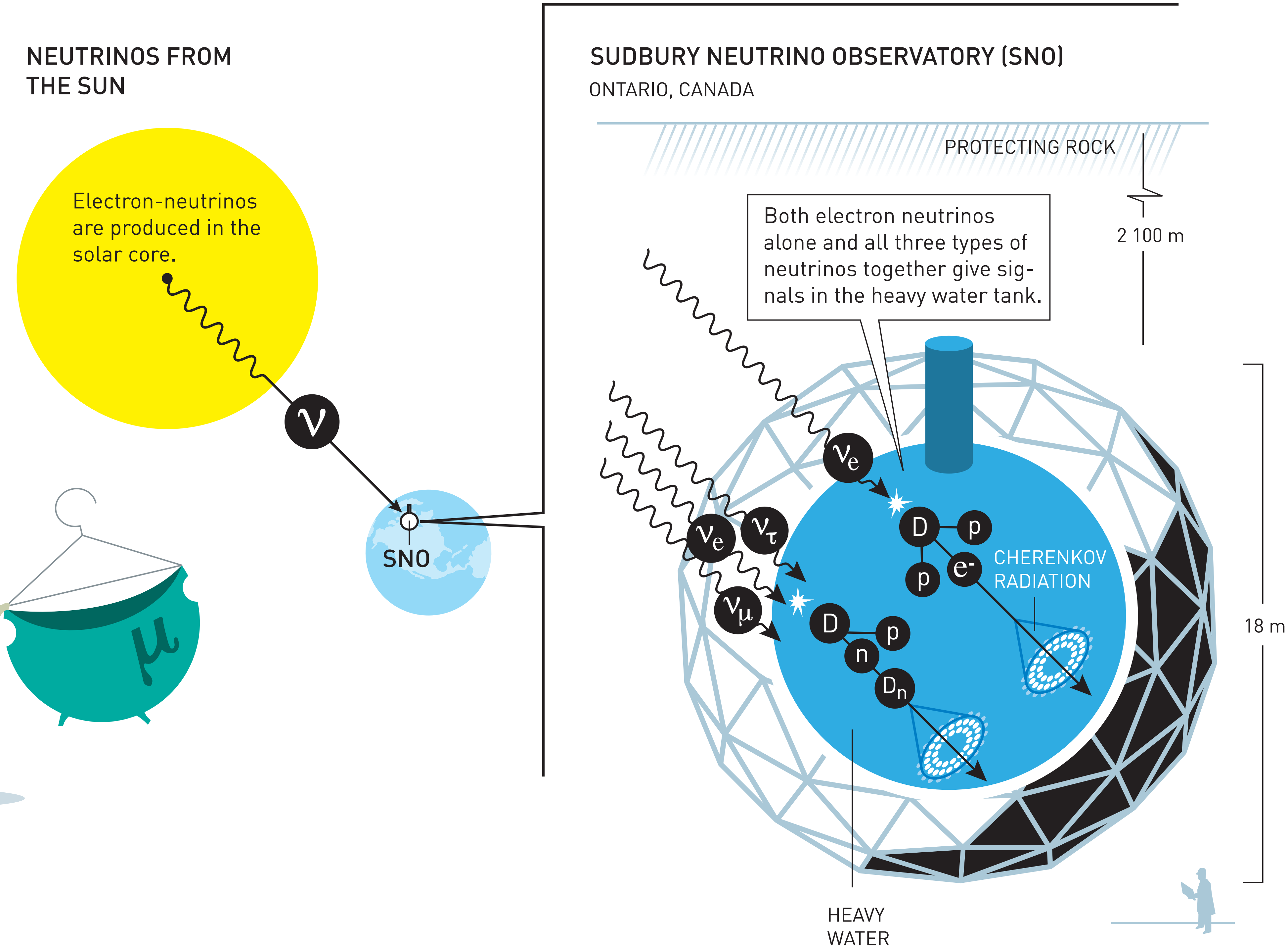


More in the Summer Semester

Fundamental Forces

- Four known Forces
  - Gravitation governs our every-day life, evolution of the Universe
  - ‣ It is irrelevant on the scales of particle physics

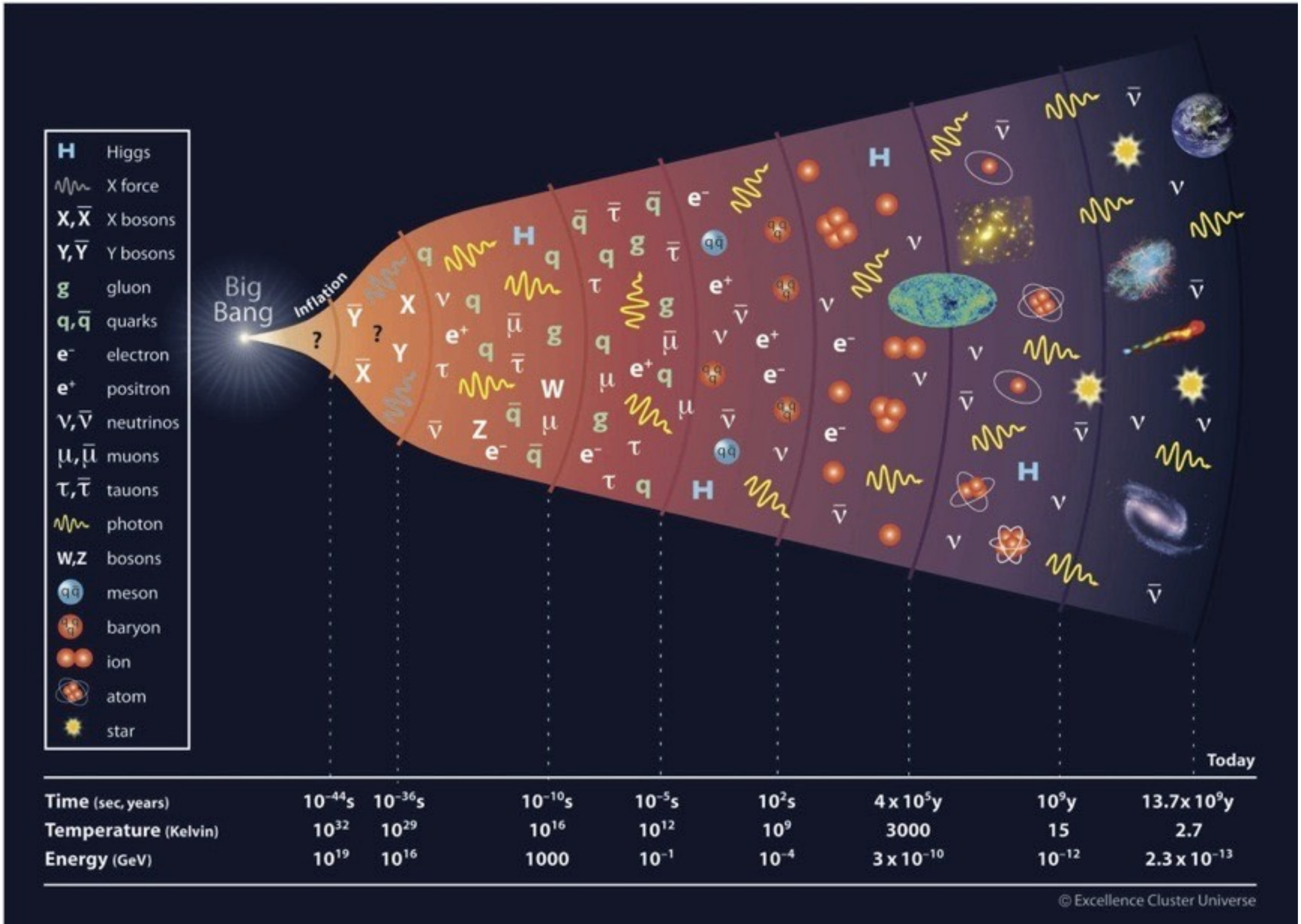
couples to mass	couples to charge	couples to weak isospin	couples to color

Relative strength at low energies

$\sim 10^{-40}$	1/137	10^{-13}	~1

due to the high mass of W, Z:
W: ~ 80 GeV , Z: ~ 91 GeV

Understanding the Universe



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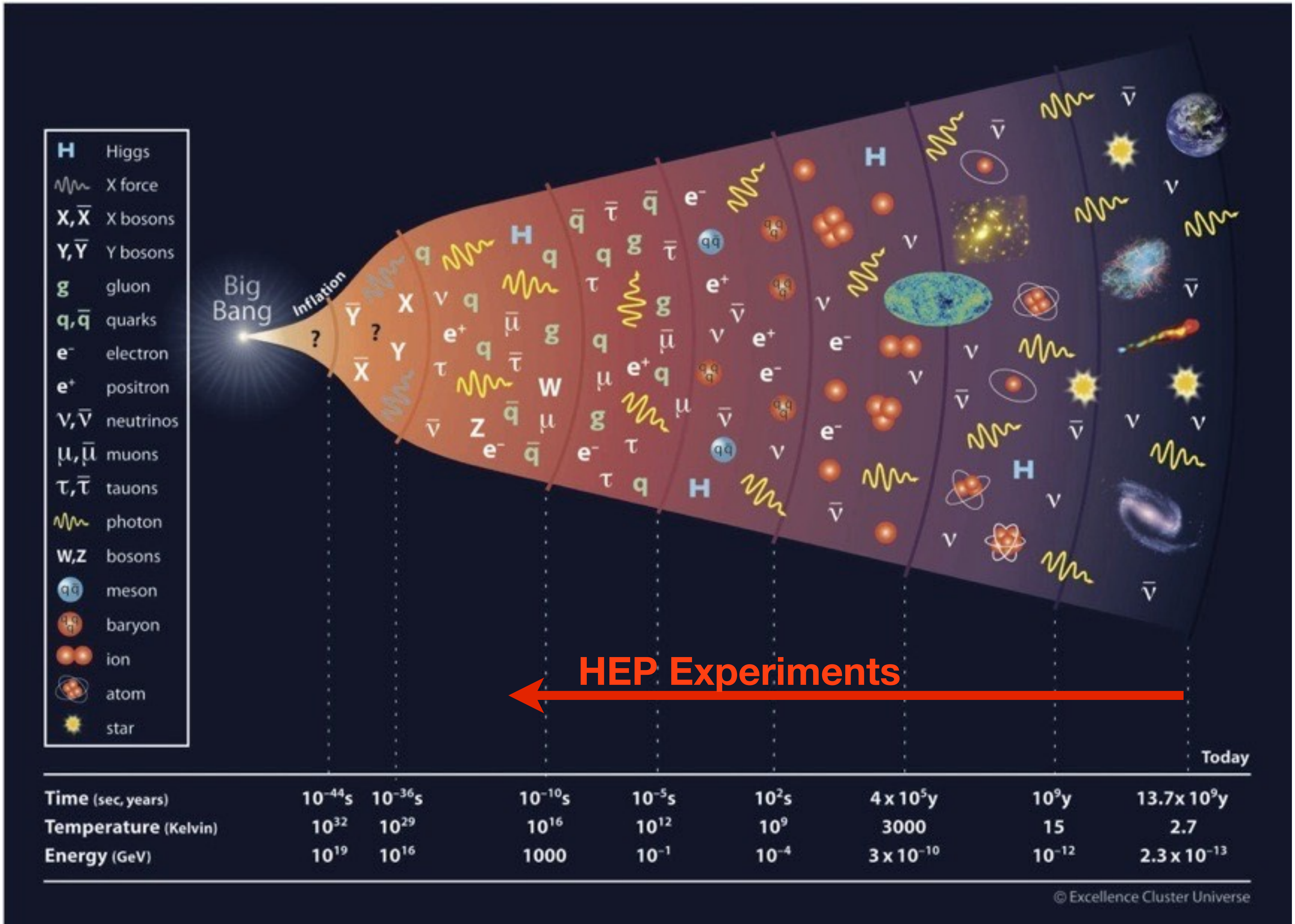

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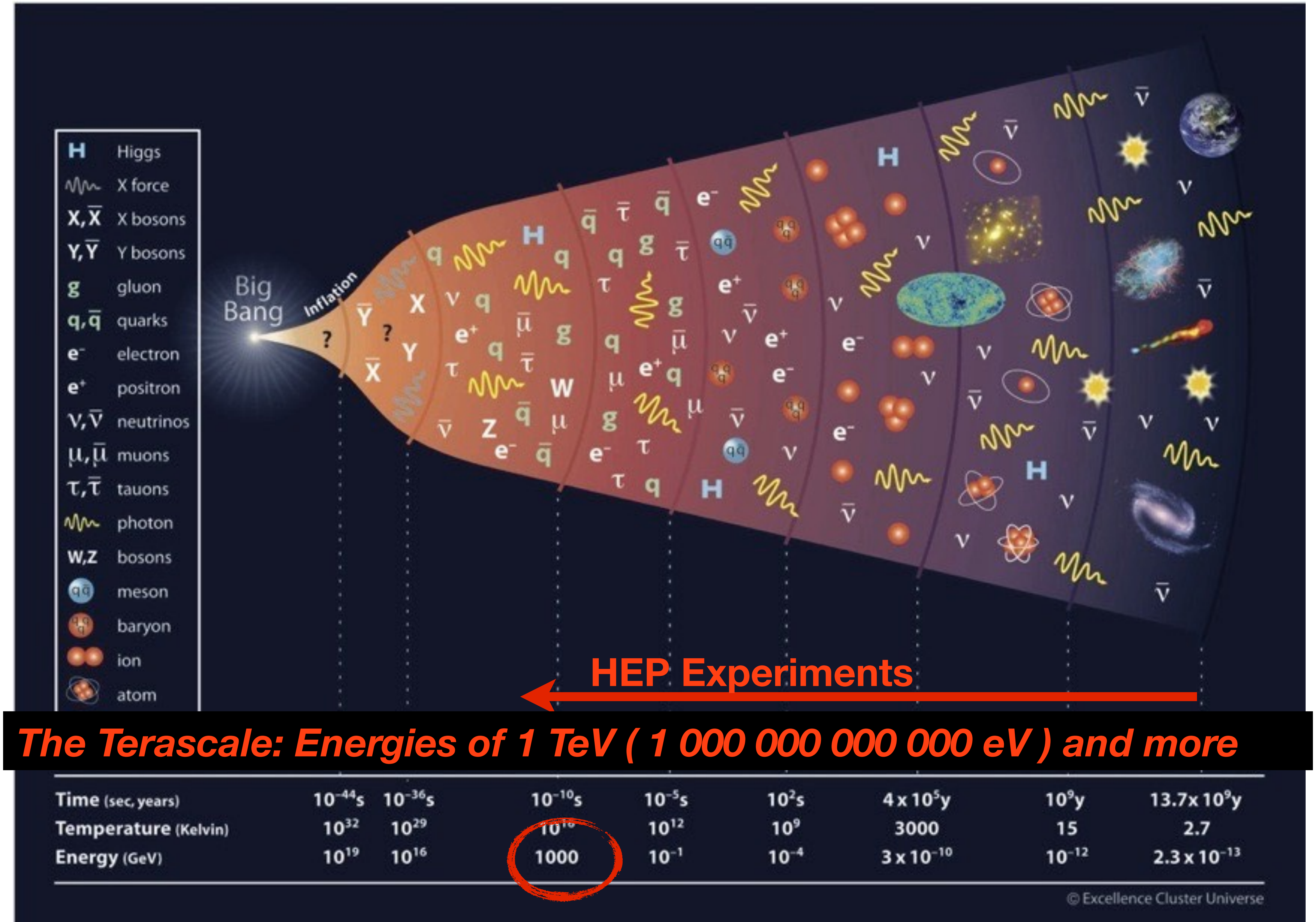
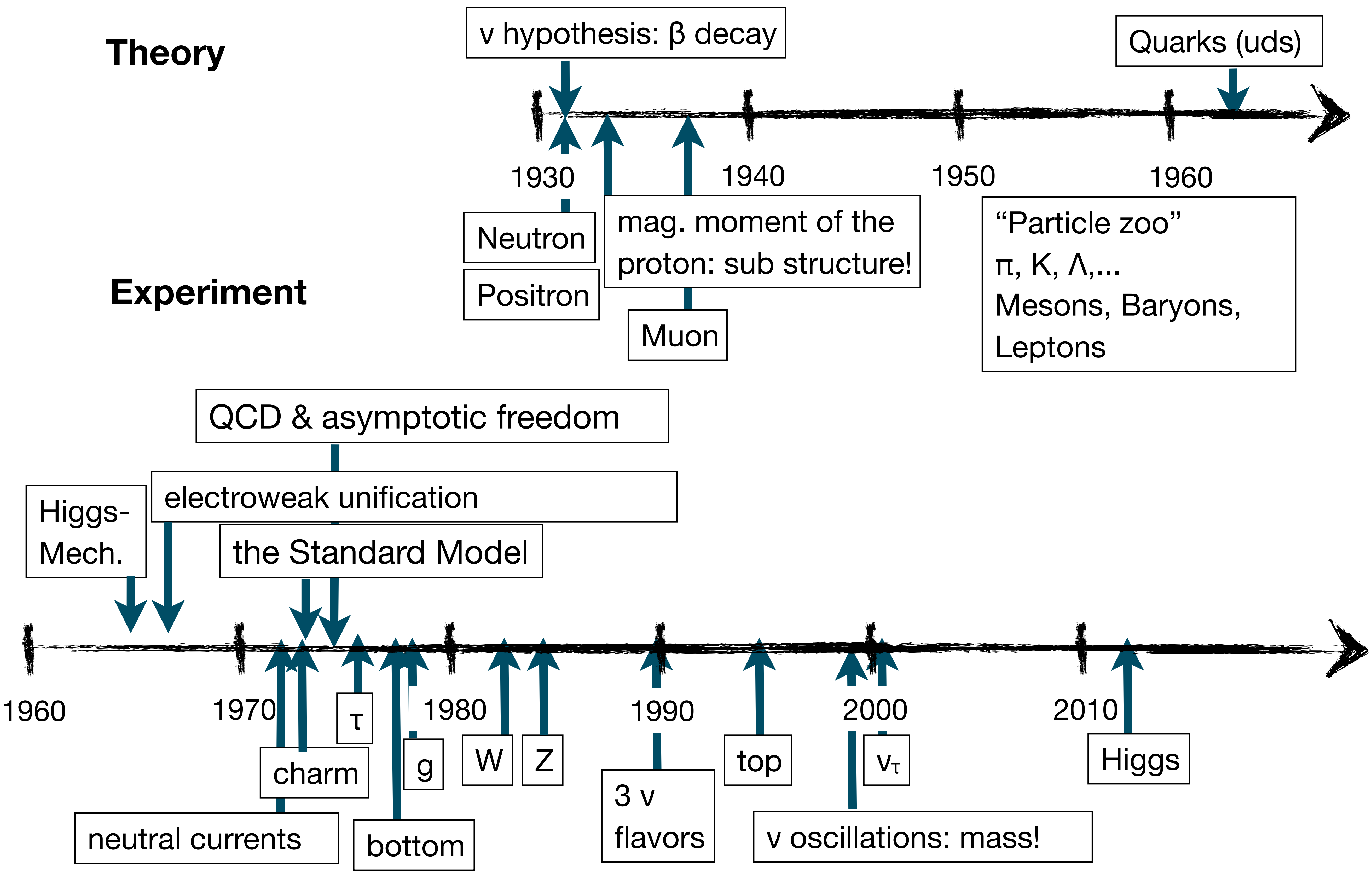


History of Particle Physics



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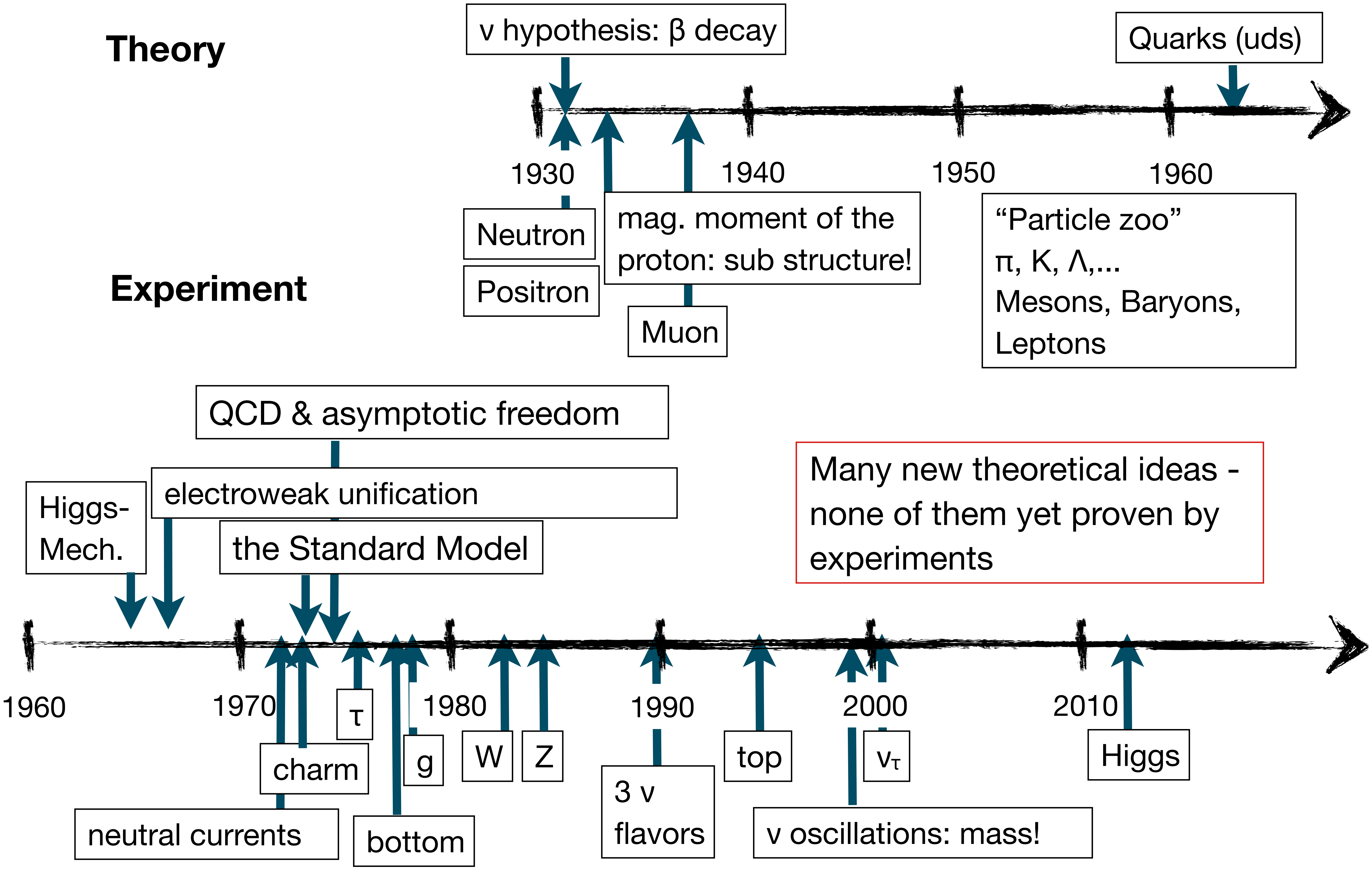
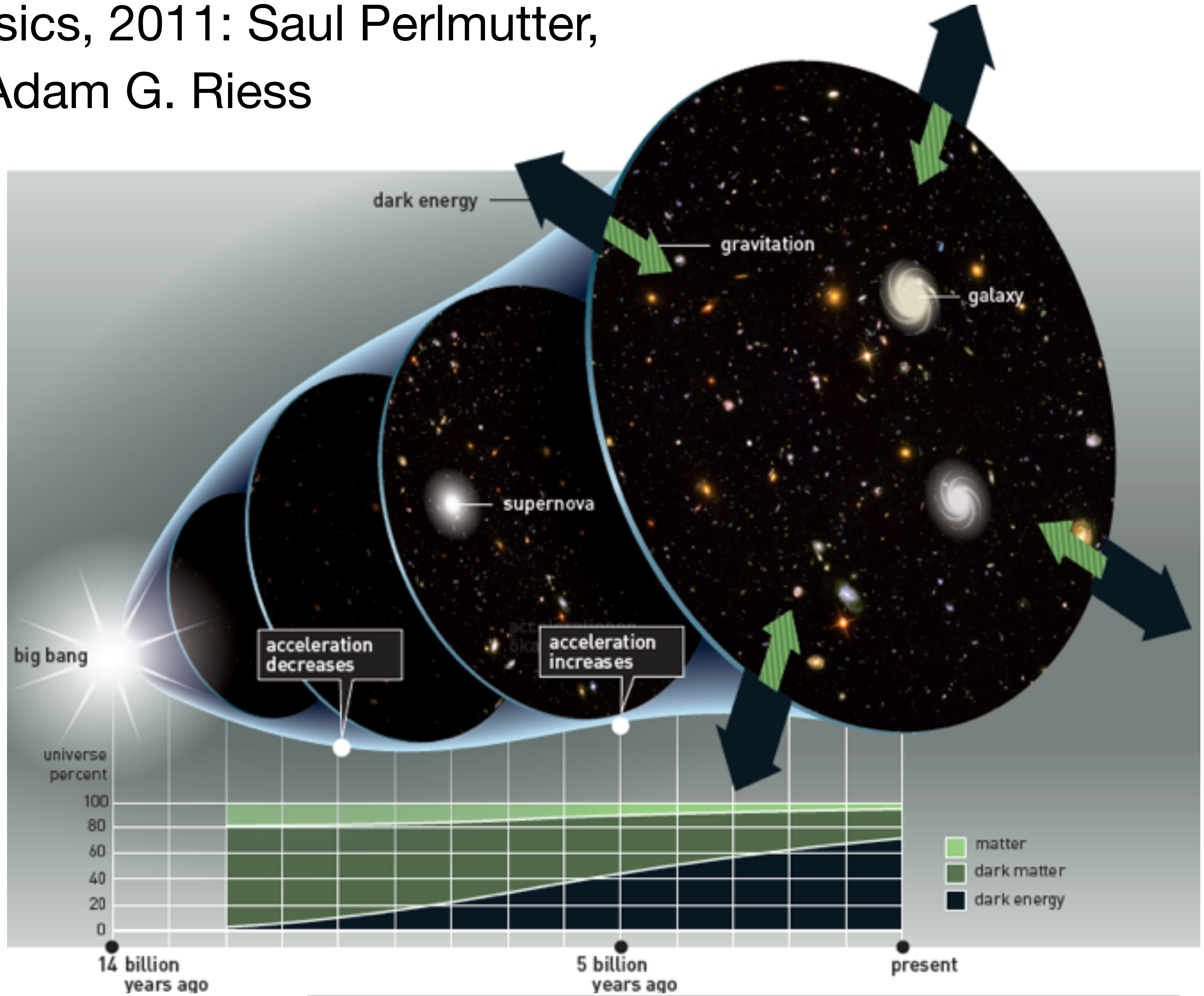


Accelerated Expansion of the Universe: Dark Energy

Nobel Prize in Physics, 2011: Saul Perlmutter, Brian P. Schmidt, Adam G. Riess

- Discovery of the accelerated expansion of the Universe, discovery of Dark Energy:

  Observation of special distant supernova-explosions



"The Nobel Prize in Physics 2011 - Popular Information". Nobelprize.org. 12 Oct 2011

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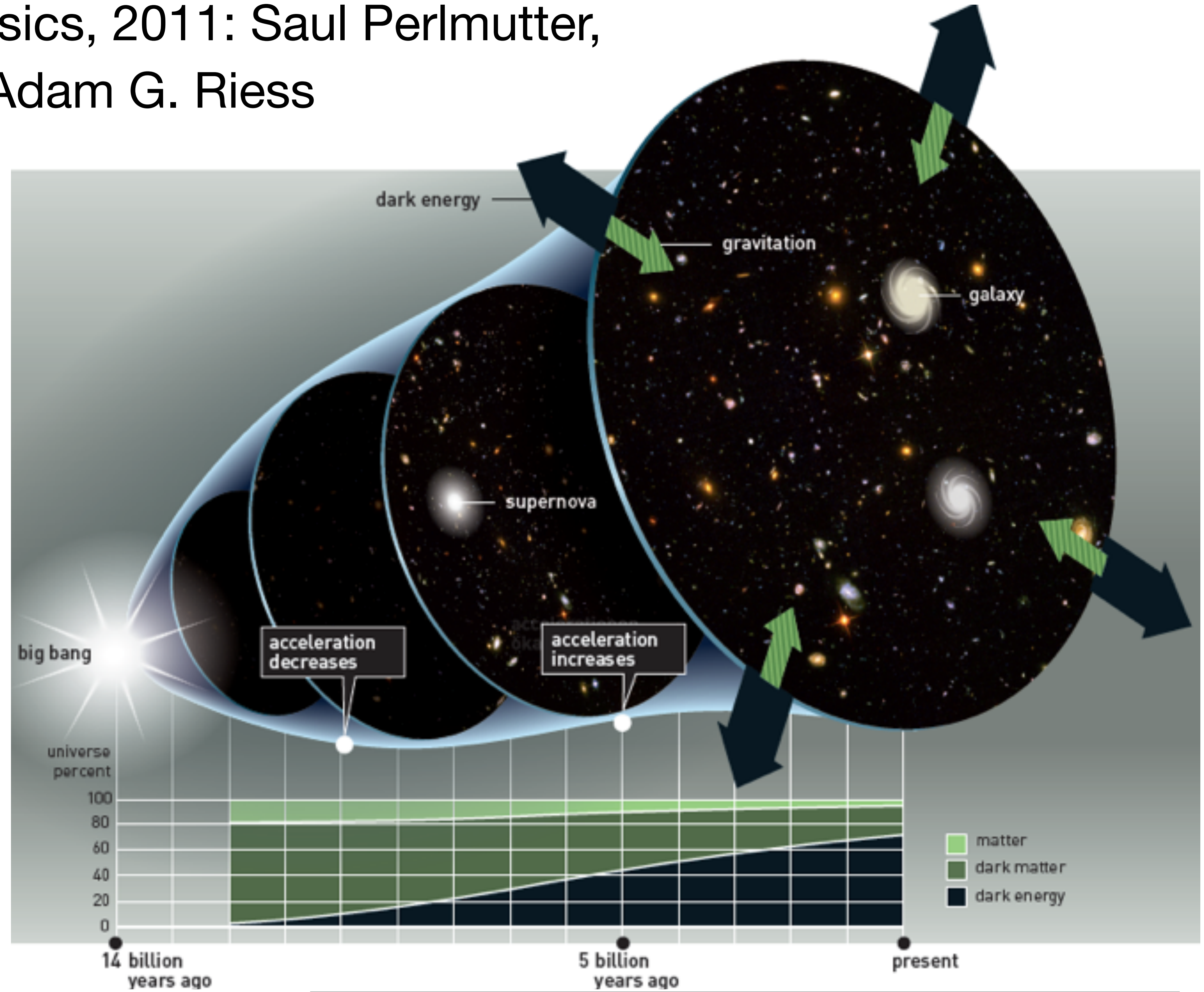

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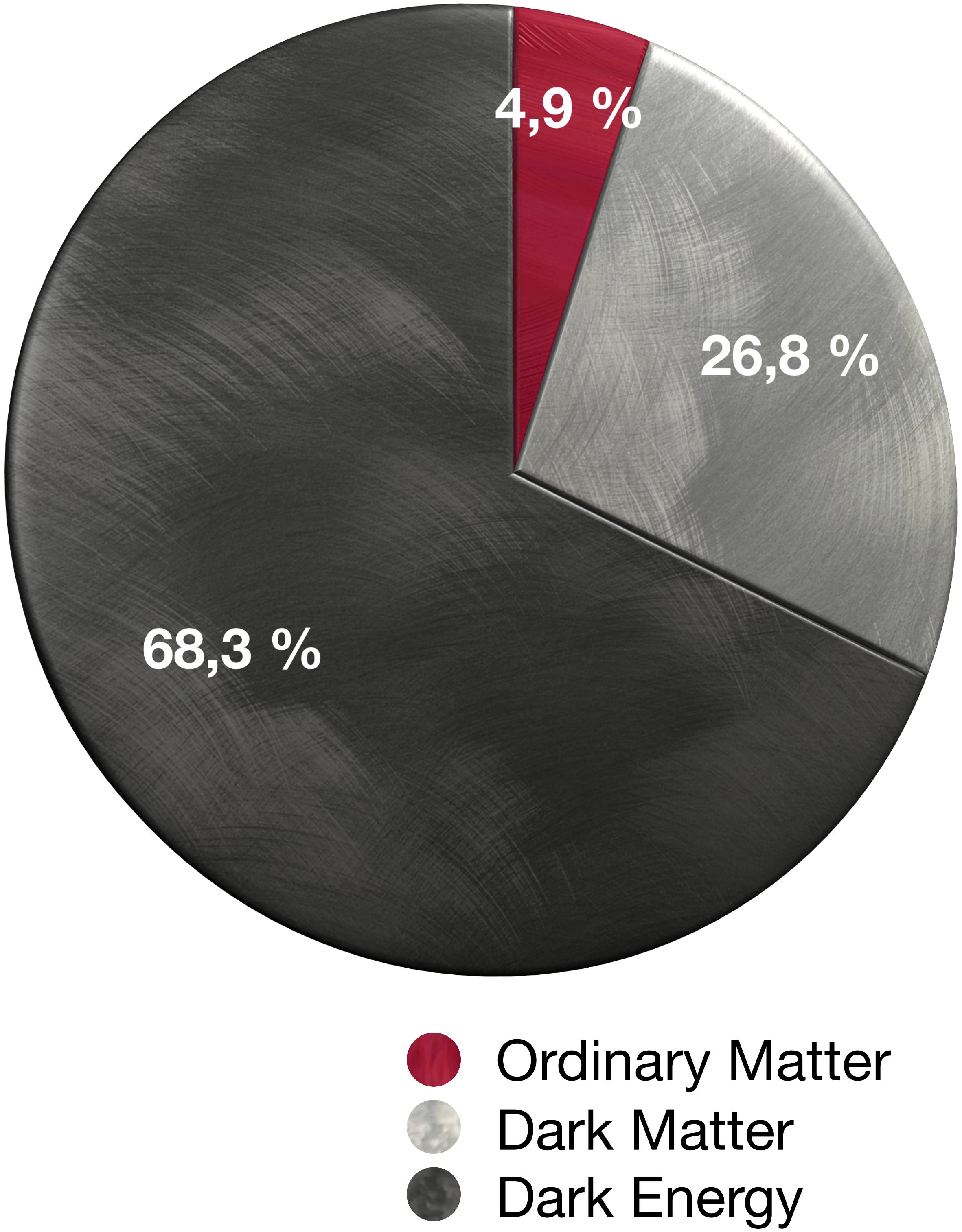
More in the Summer Semester

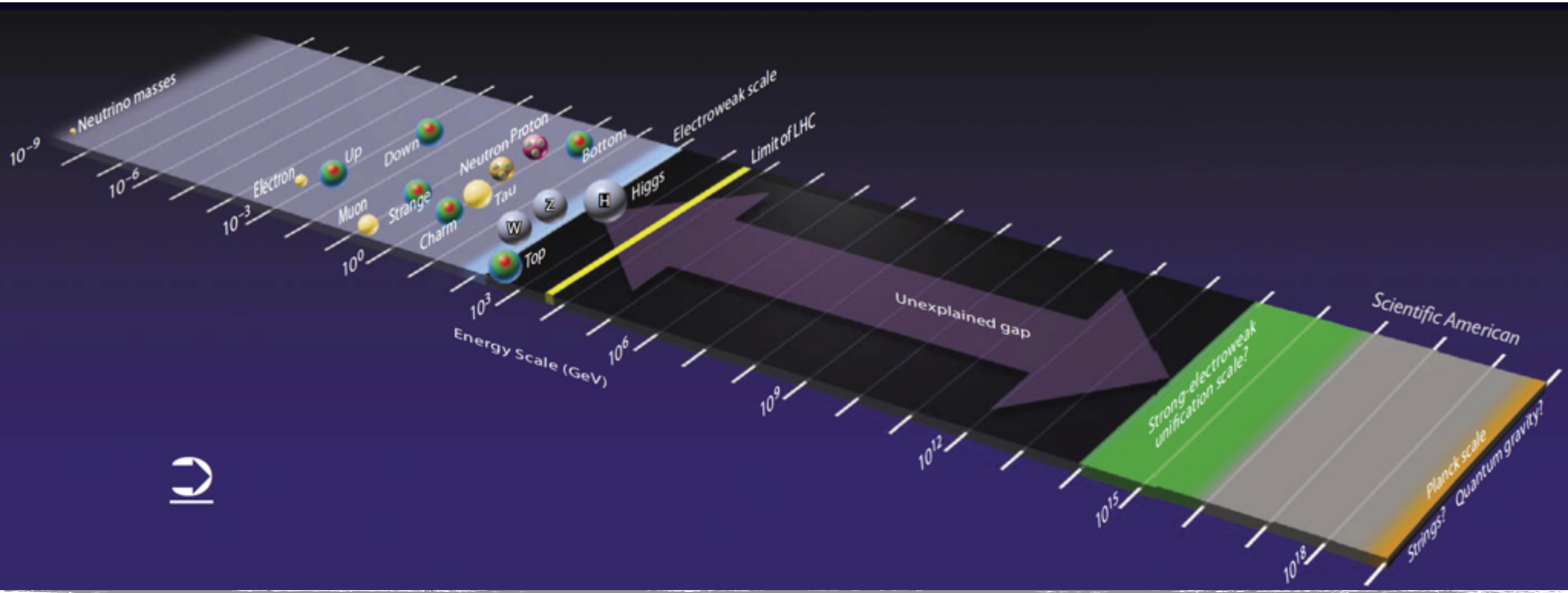
Open Questions: Energy Content of the Universe

- Long known from the observed rotation curves of galaxies: galaxies contain much more mass than would be expected by the number of their stars
- Substantially improved understanding in the last ~ 15 years: Today we know that only 5% of the energy content of the universe is in Standard Model particles
  - 1/4: Dark Matter - A new particle? Could be produced at accelerators!
  - 3/4: Dark Energy - Up to now no good explanation!



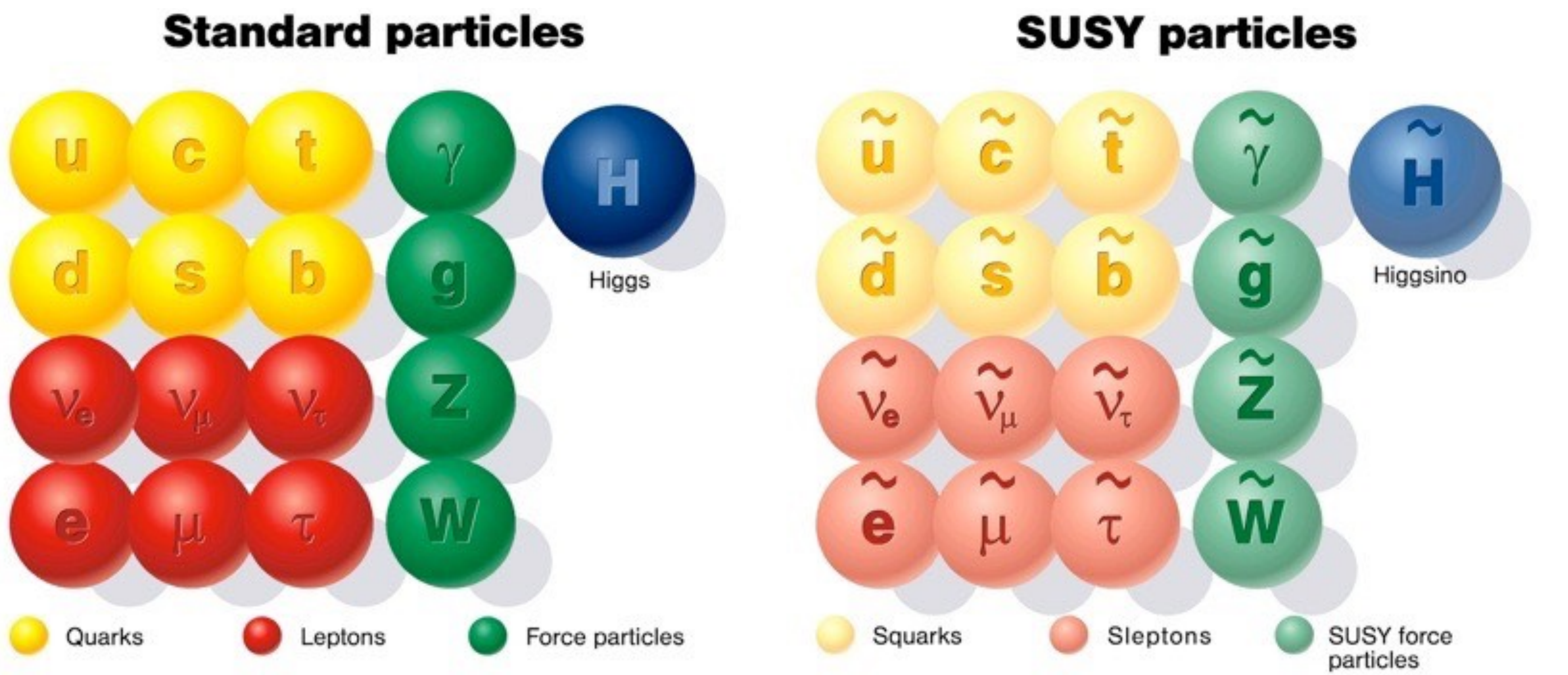
Fundamental Questions: Particle Masses

- How are the particle masses generated?
  In the Standard Model: The Higgs mechanism
  - But: Why are particle masses so different, and why are particles so light?
  - Two very different energy scales: The electroweak scale, and the scale of gravity: “Hierarchy Problem”



Ideas for Solutions

- New symmetries and new particles at higher energies:
  Protection for the SM particles by cancelations in higher order loop contributions

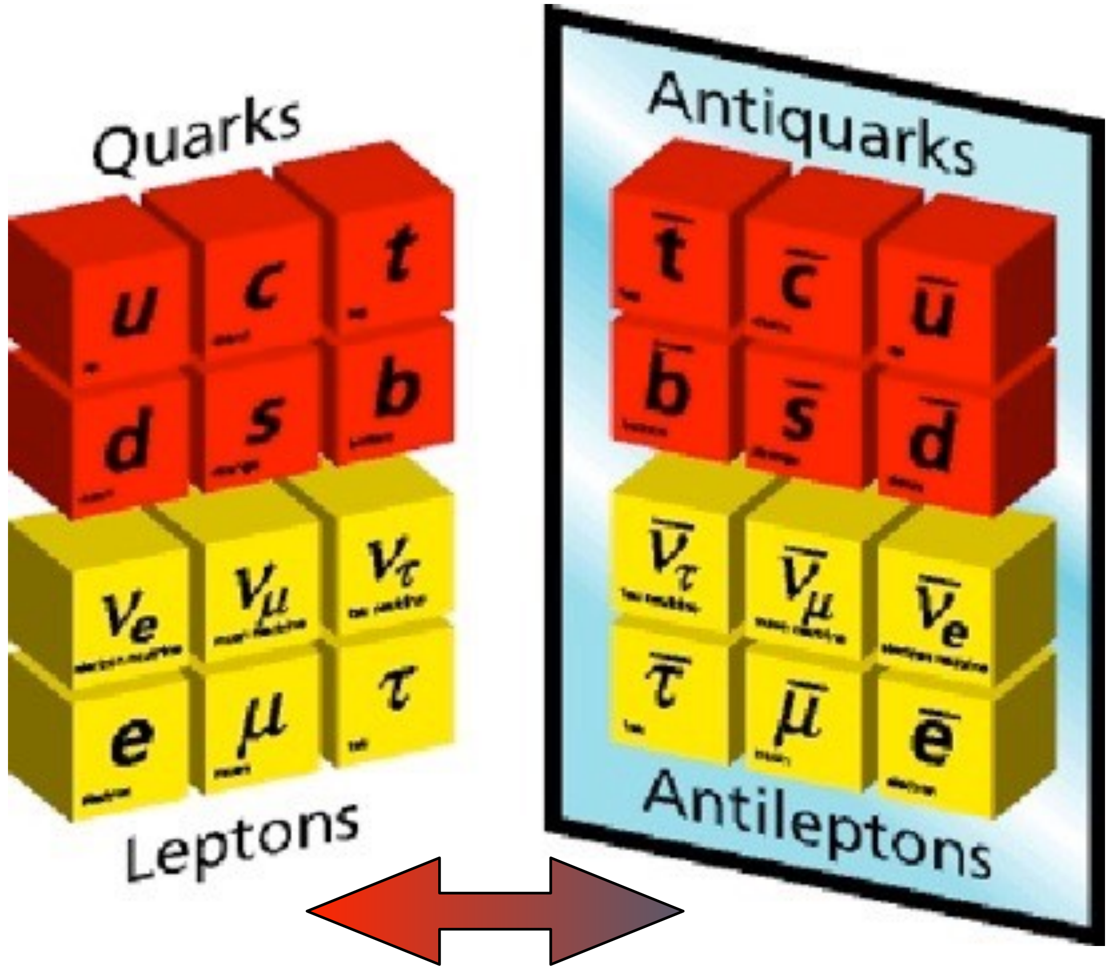


- The most popular scenario: Supersymmetry - A rich phenomenology to discover - and provides dark matter candidate!
- Many other possibilities: Large extra dimensions particularly attractive

Fundamental Questions: Matter Dominance

- Today, the whole Universe consists of Matter:
  What happened to the anti-matter that was created in the Big Bang?

- A slight preference (on the 10^{-9} level) for matter over anti-matter is needed to explain cosmological observations
  - CP violation can provide such an asymmetry...



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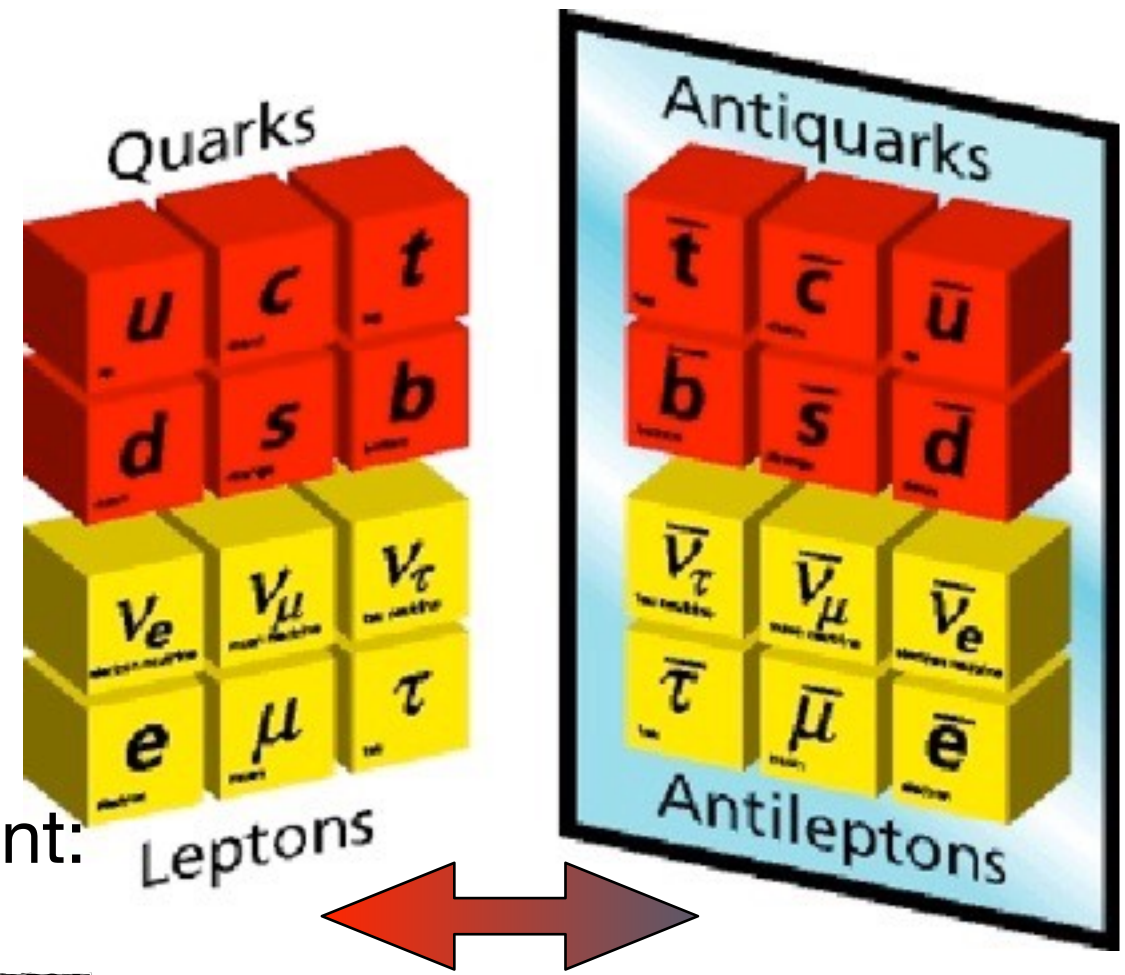
... but the SM effect is by far not sufficient:



an imperfect symmetry!

New CP violating processes are required at higher energy scales!

Open Questions

- Short Summary:

  We expect New Physics beyond the Standard Model to get answers for at least some of these questions

  High expectations for LHC Experiments!

... with the discovery in 2012 we have not been disappointed!

Experiments and Techniques in Particle Physics

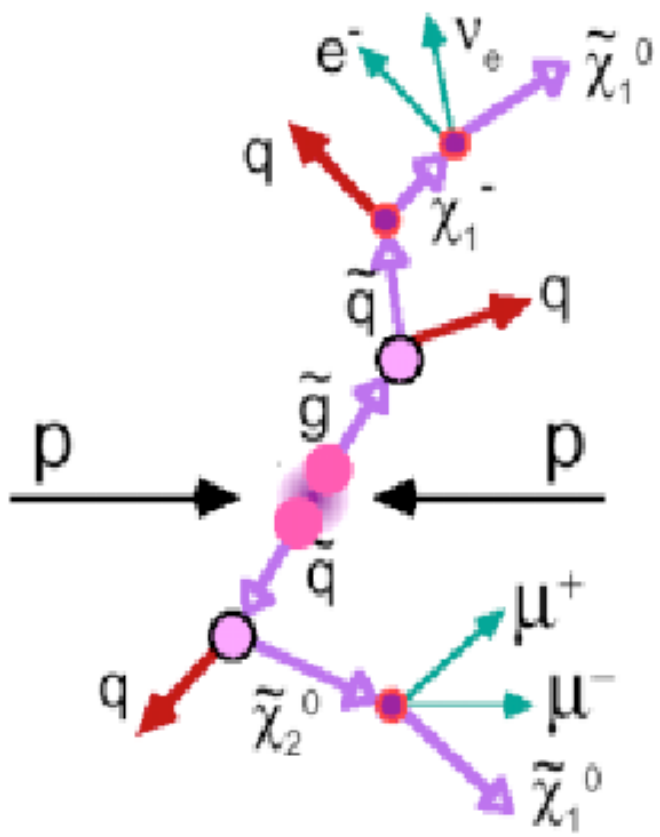
Strategies for Discovery in Particle Physics

- Two complementary approaches:

Direct searches at highest energies:

Production and detection of new particles

The Emphasis of this Lecture Series



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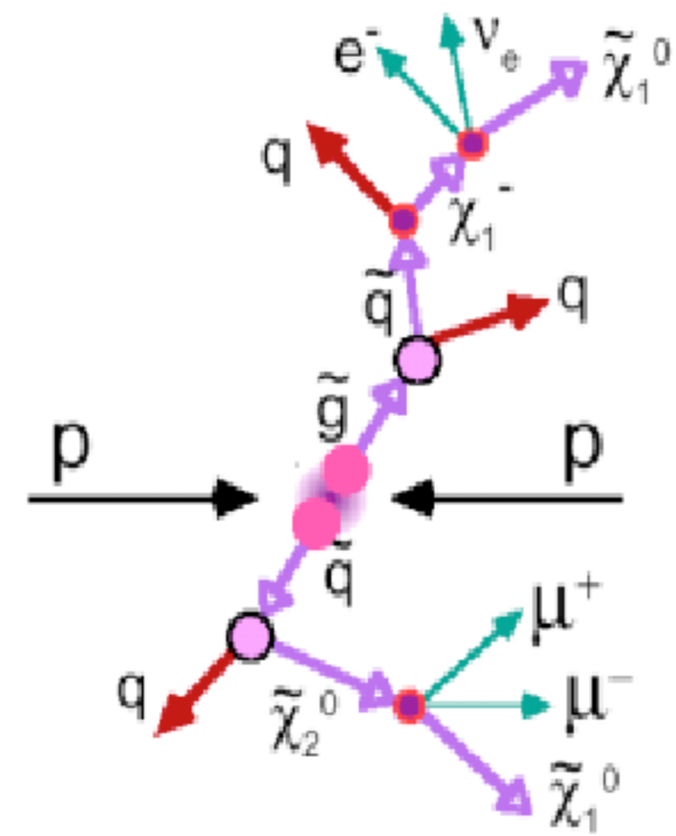

Direct searches at highest energies:

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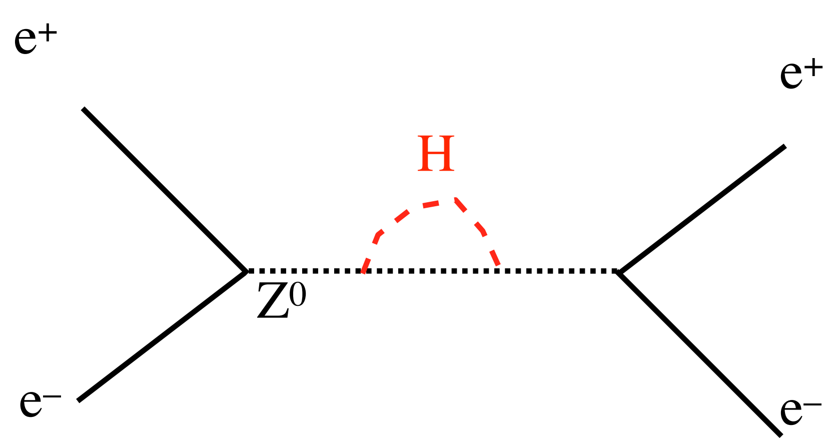
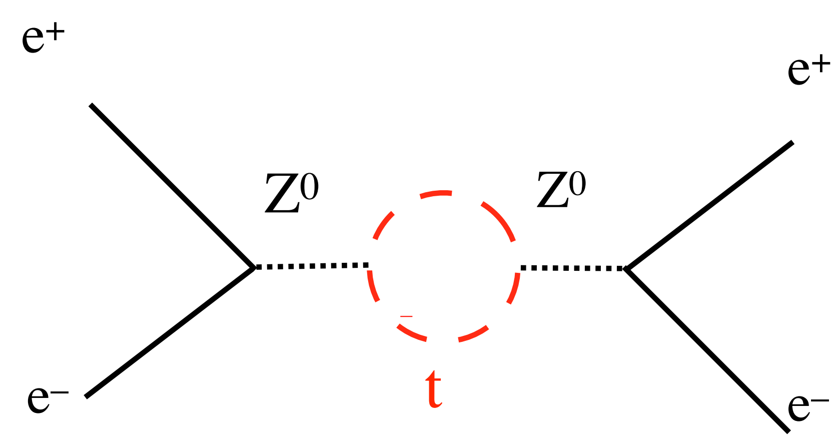
The Emphasis of this Lecture Series

Precision measurements:

Indirect evidence for new particles in virtual quantum loops





The Tools: Accelerators & Detectors

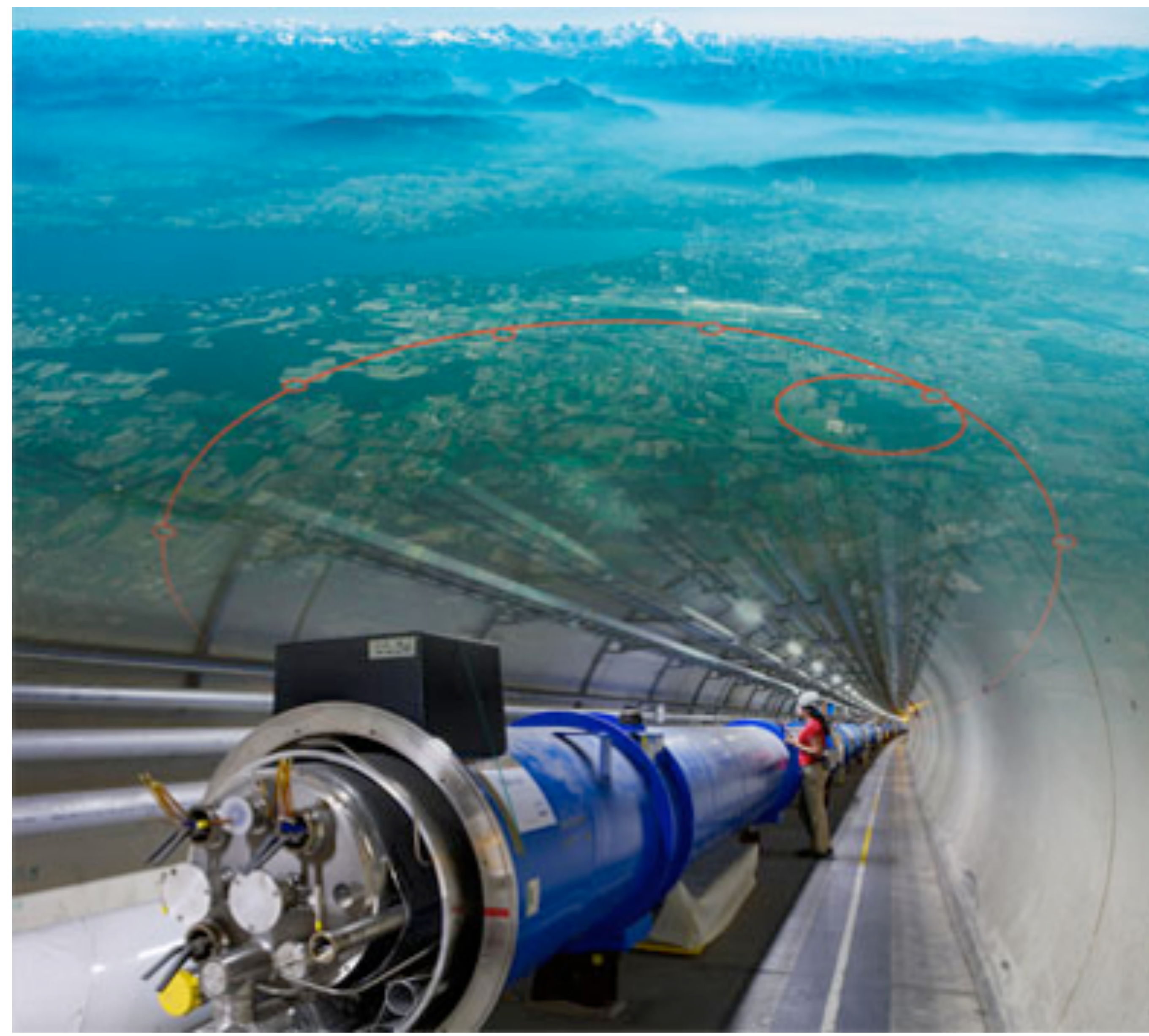
- To study the smallest structures very high energies are necessary:
  Energy ⇔ distance (de Broglie - wavelength)
  - Resolution d[fm] ~ 0.197/E [GeV]

Accelerators for highest energies, collisions in the lab frame: Colliders!

The biggest collider:
Large Hadron Collider (LHC),

The “Weltmaschine”:
10 000 scientists and engineers
from more than 100 countries

Currently: On-going “Run 2”:
Second phase of LHC running,
energies of 13 TeV (6.5 TeV + 6.5 TeV)



The most important Accelerators

Collider	start – end date	beam type	max. beam energy (GeV)	circumference *or length* (km)
PETRA (DESY)	1978 - 1986	$e^+ e^-$	23.4	2.304
SLC (SLAC)	1989 – 1999	$e^+ e^-$	50	*1.45 + 1.47*
LEP (CERN)	1989 – 2000	$e^+ e^-$	104	26.7
ILC / CLIC (?)	?? (> 2025)	$e^+ e^-$	250 / 1500	15+15 / 25+25
CEPC / FCC-ee	?? (> 2025 / > 2035)	$e^+ e^-$	120 / 175	50 - 70 / 100
KEKB (KEK)	1999 - 2010	$e^+ e^-$	8 x 3.5	3.0
PEP-II (SLAC)	1999 - 2008	$e^+ e^-$	9 x 3.1	2.2
SuperKEKB (KEK)	2016 - ?	$e^+ e^-$	7 x 4	3.0
HERA (DESY)	1991 - 2007	e p	30 x 920	6.3
$Sp\bar{p}S$ (CERN)	1981 – 1990	$p\bar{p}$	315	6.9
TEVATRON (Fermilab)	1987 - 2011	$p\bar{p}$	1000	6.28
LHC (CERN)	2009 -	pp	7000	26.7
FCC-hh	?? (> 2035)	pp	50 000	100

Detectors / HEP Experiments

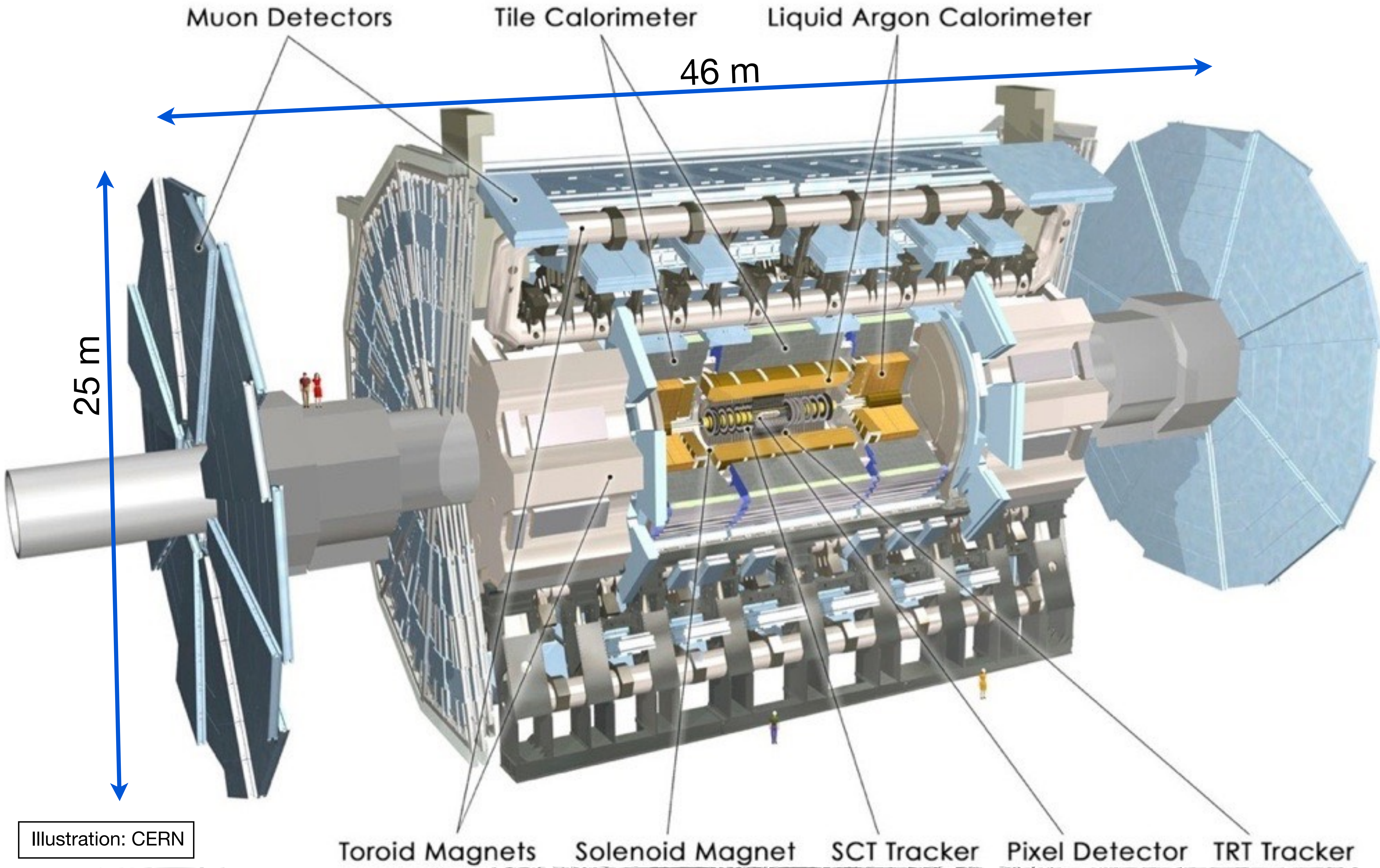
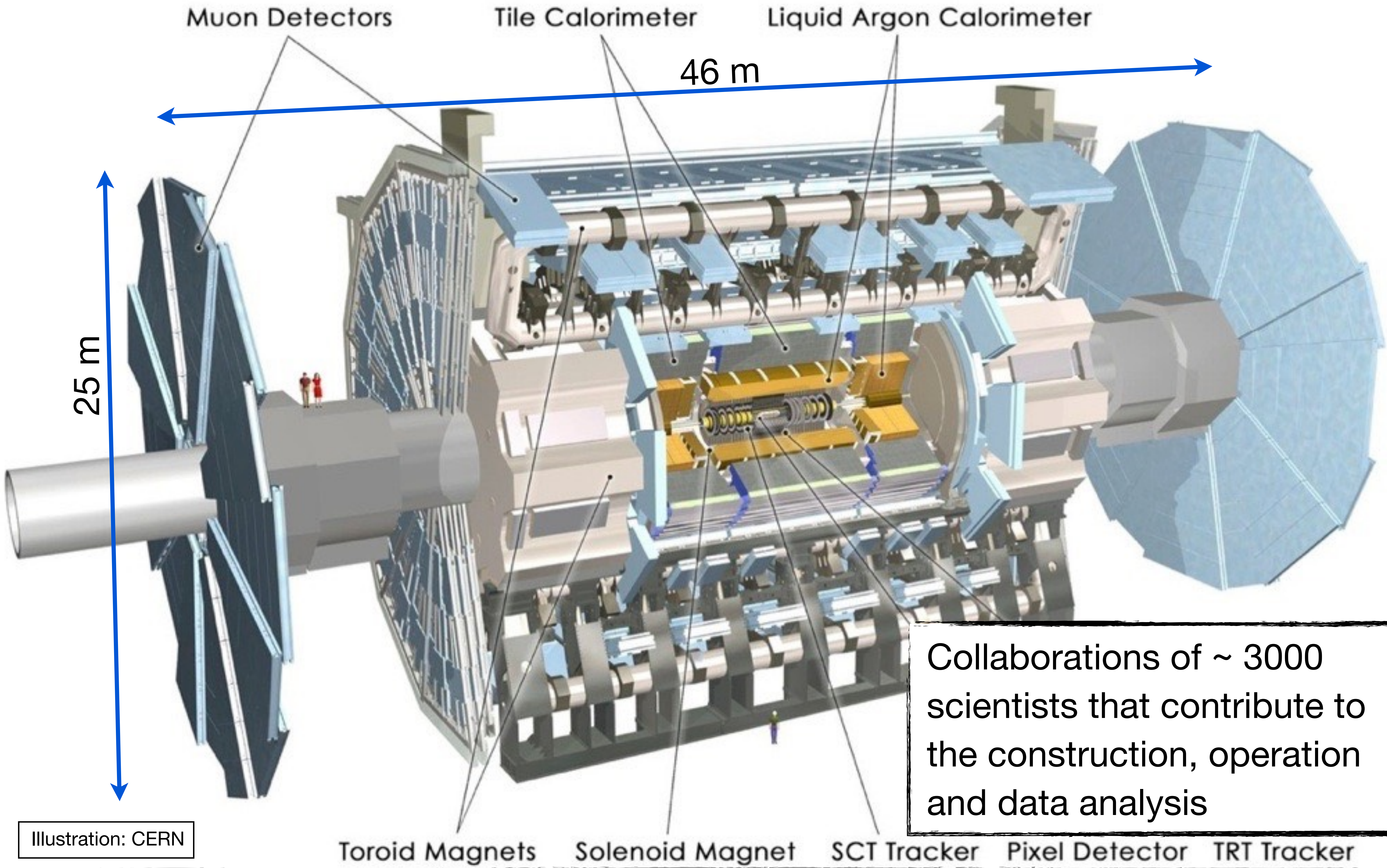


Illustration: CERN

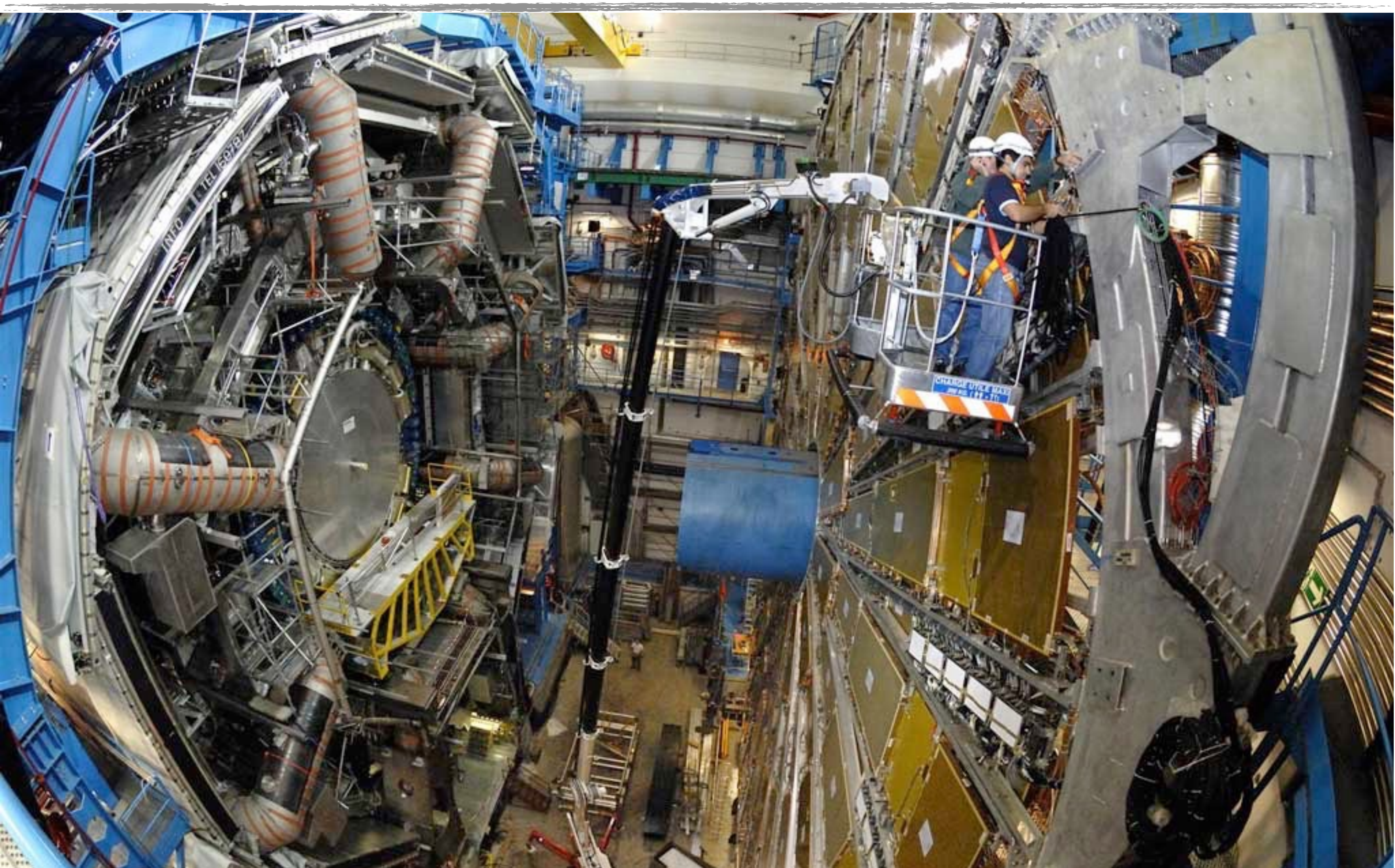
Detectors / HEP Experiments



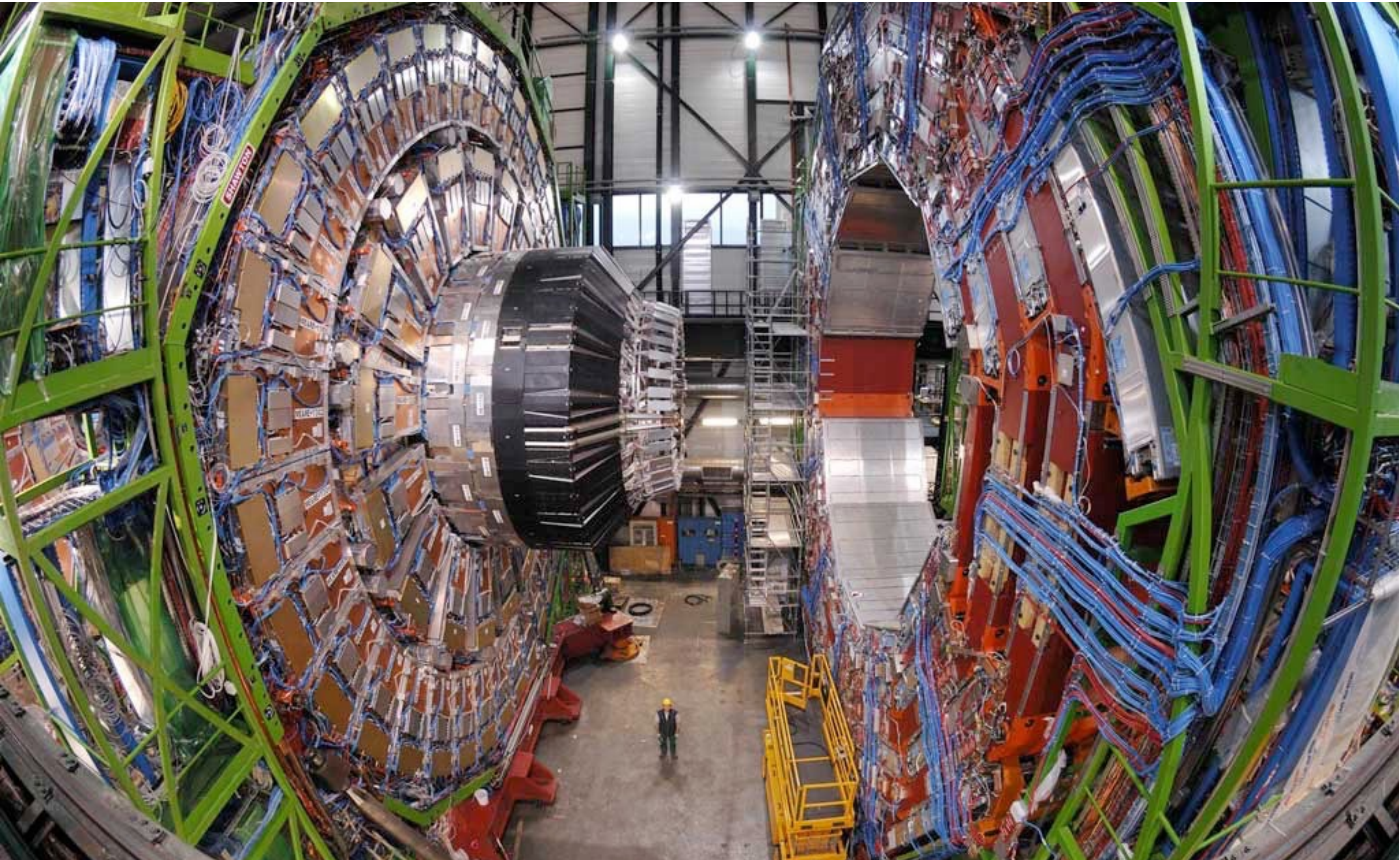
Collaborations of ~ 3000 scientists that contribute to the construction, operation and data analysis

Illustration: CERN

Detectors: ATLAS

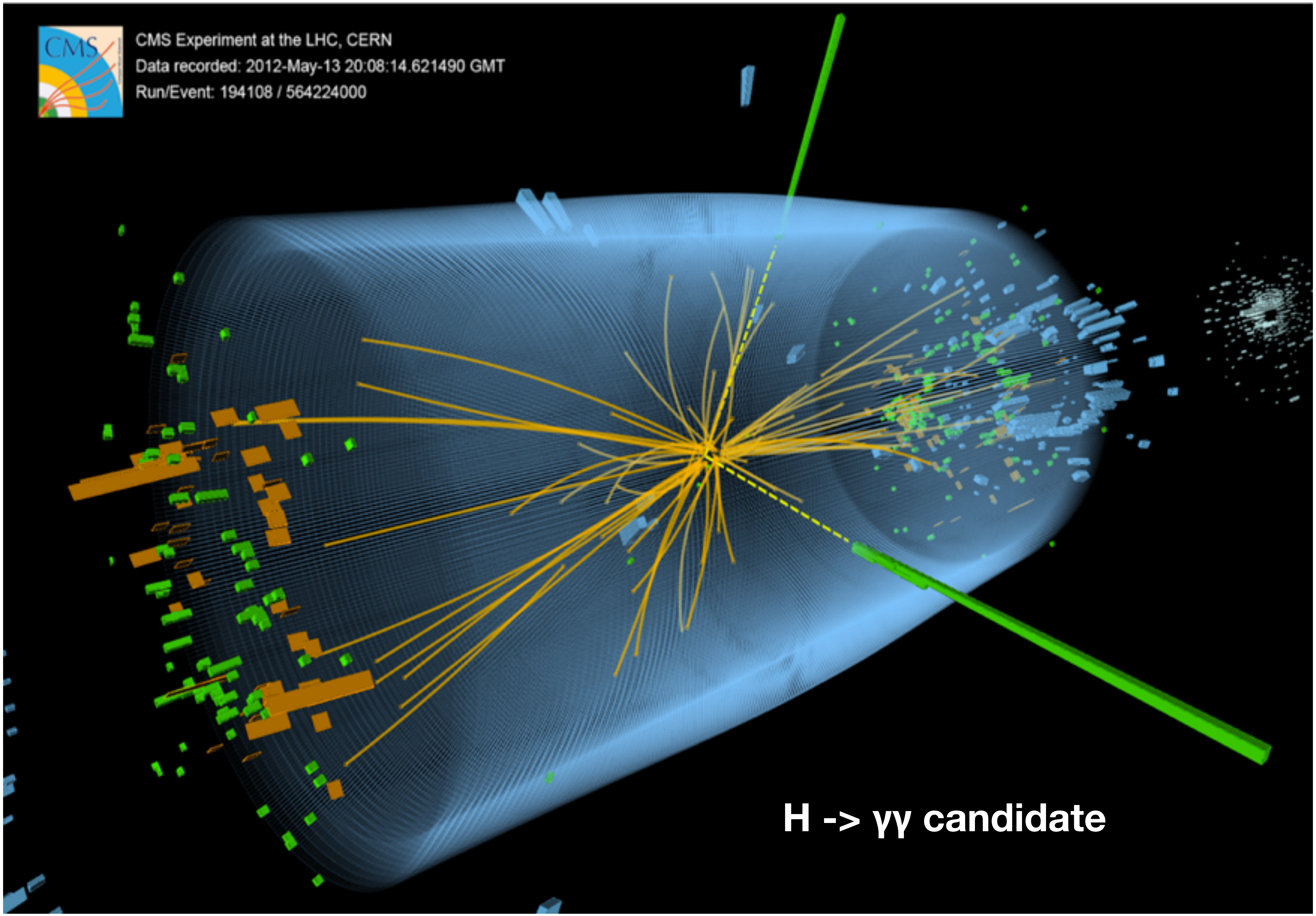


Detectors: CMS



4. Juli 2012: Long awaited...

A possible Higgs Event



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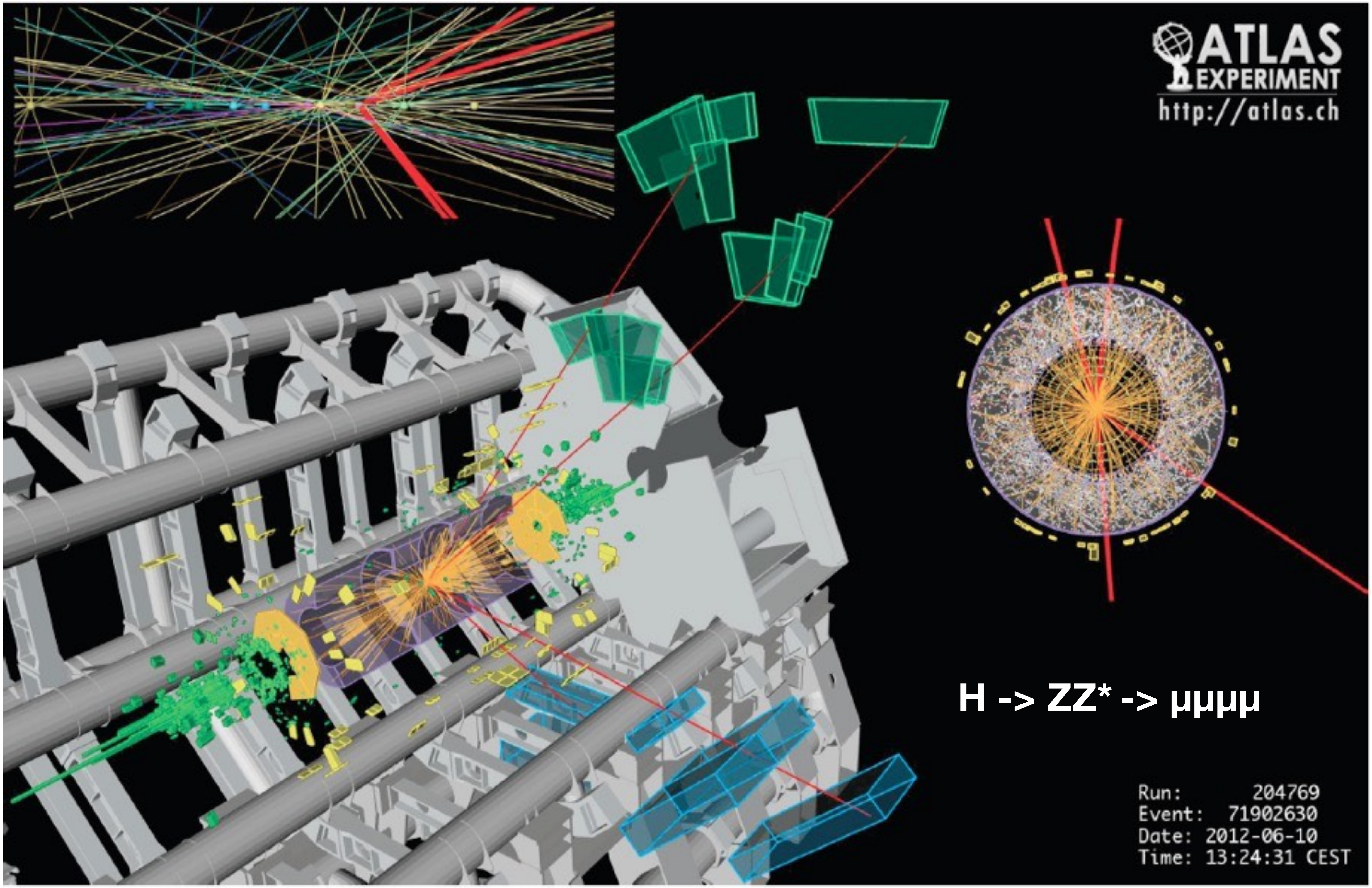
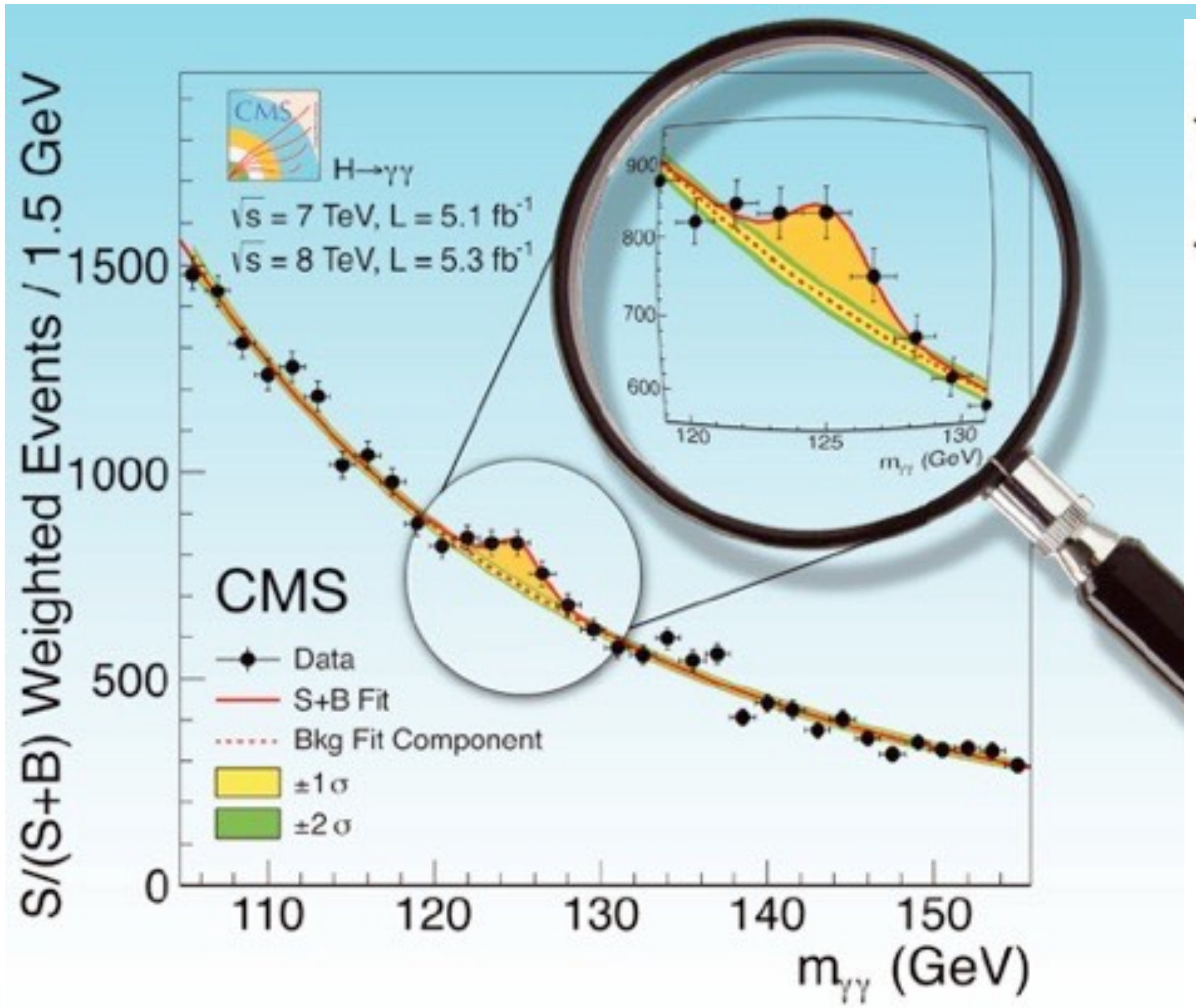
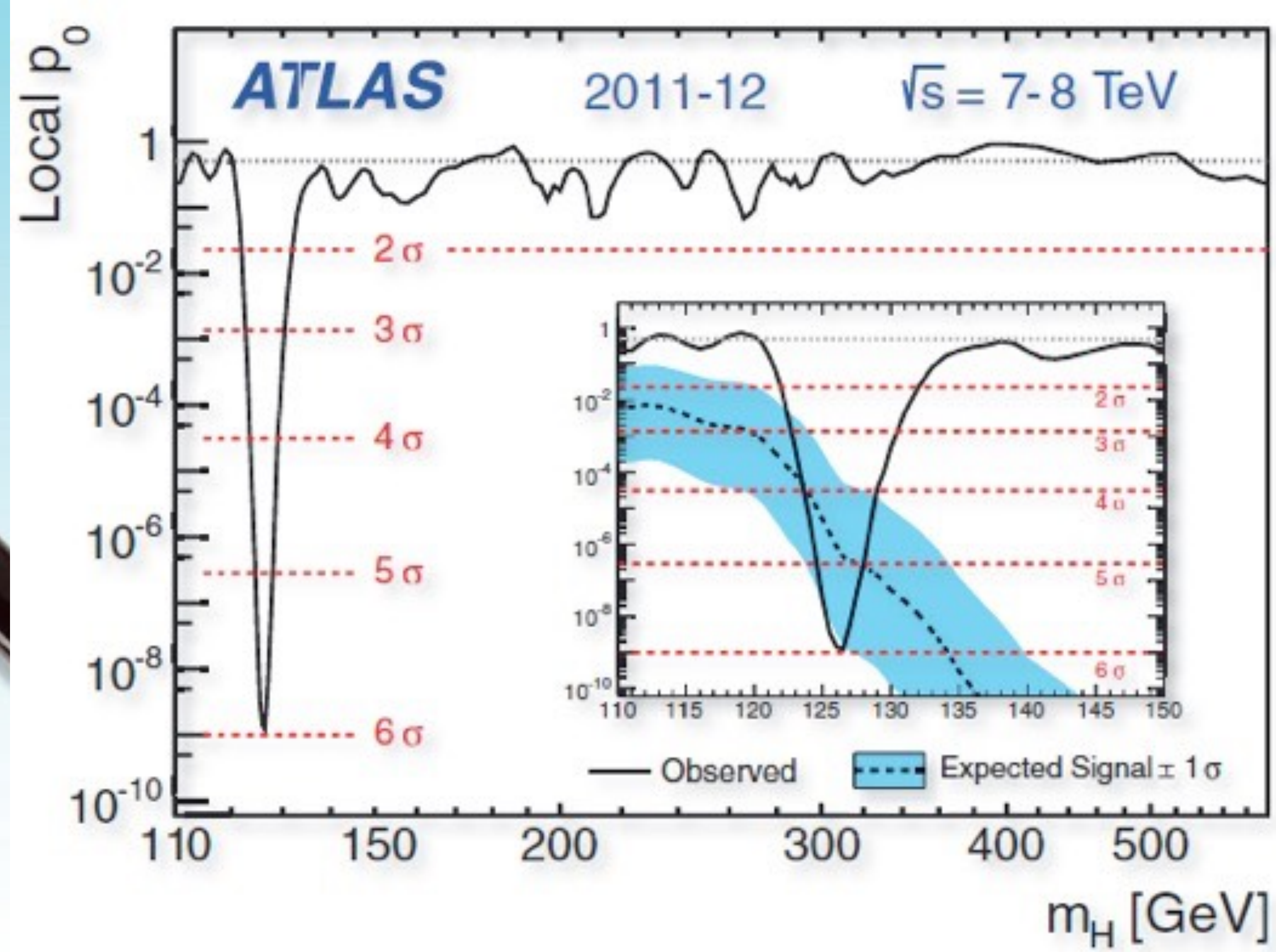


Successful Higgs Search





- Fully confirmed signal, at a mass of 125.1 GeV - up to now perfectly consistent with the expectations for the SM Higgs

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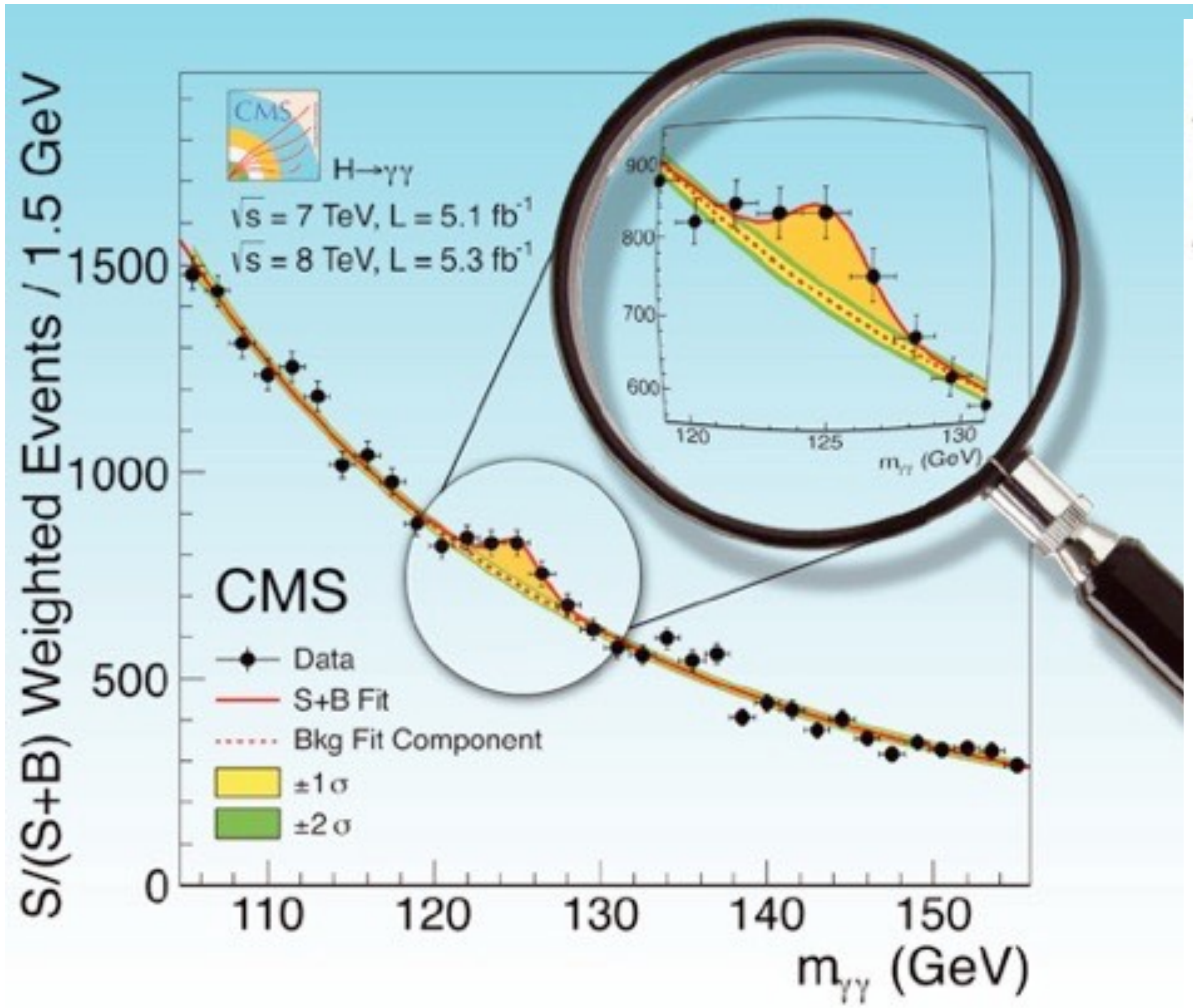

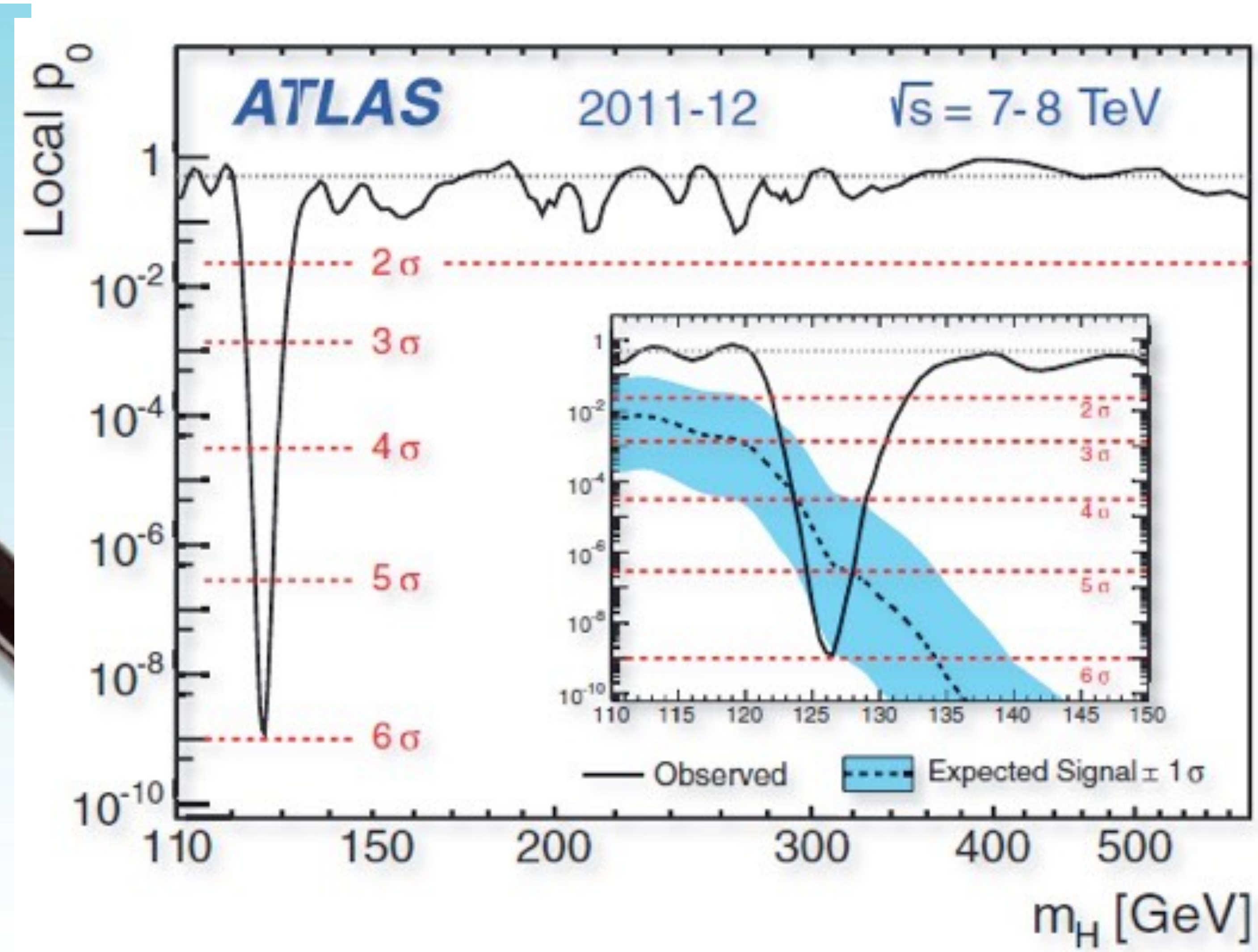

- Fully confirmed signal, at a mass of 125.1 GeV - up to now perfectly consistent with the expectations for the SM Higgs

... but despite the striking shortcomings of the Standard Model, no signs of "New Physics" in collider experiments (yet)!

Outlook

Next Lecture: October 23

Accelerators, F. Simon