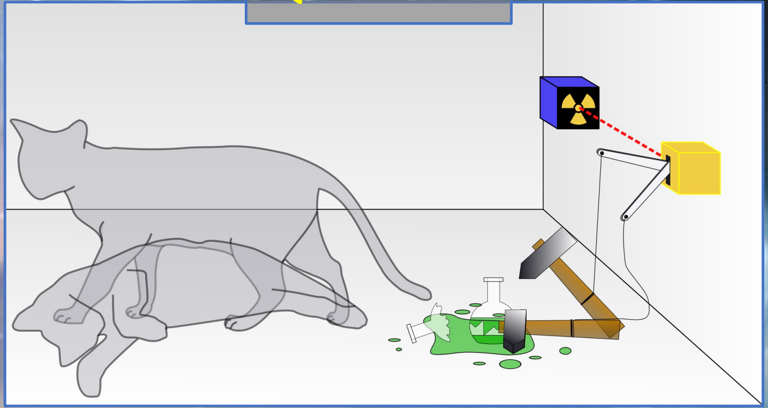
The Relativistic Quantum World

A lecture series on
Relativity Theory and Quantum Mechanics

Relativity

Quantum



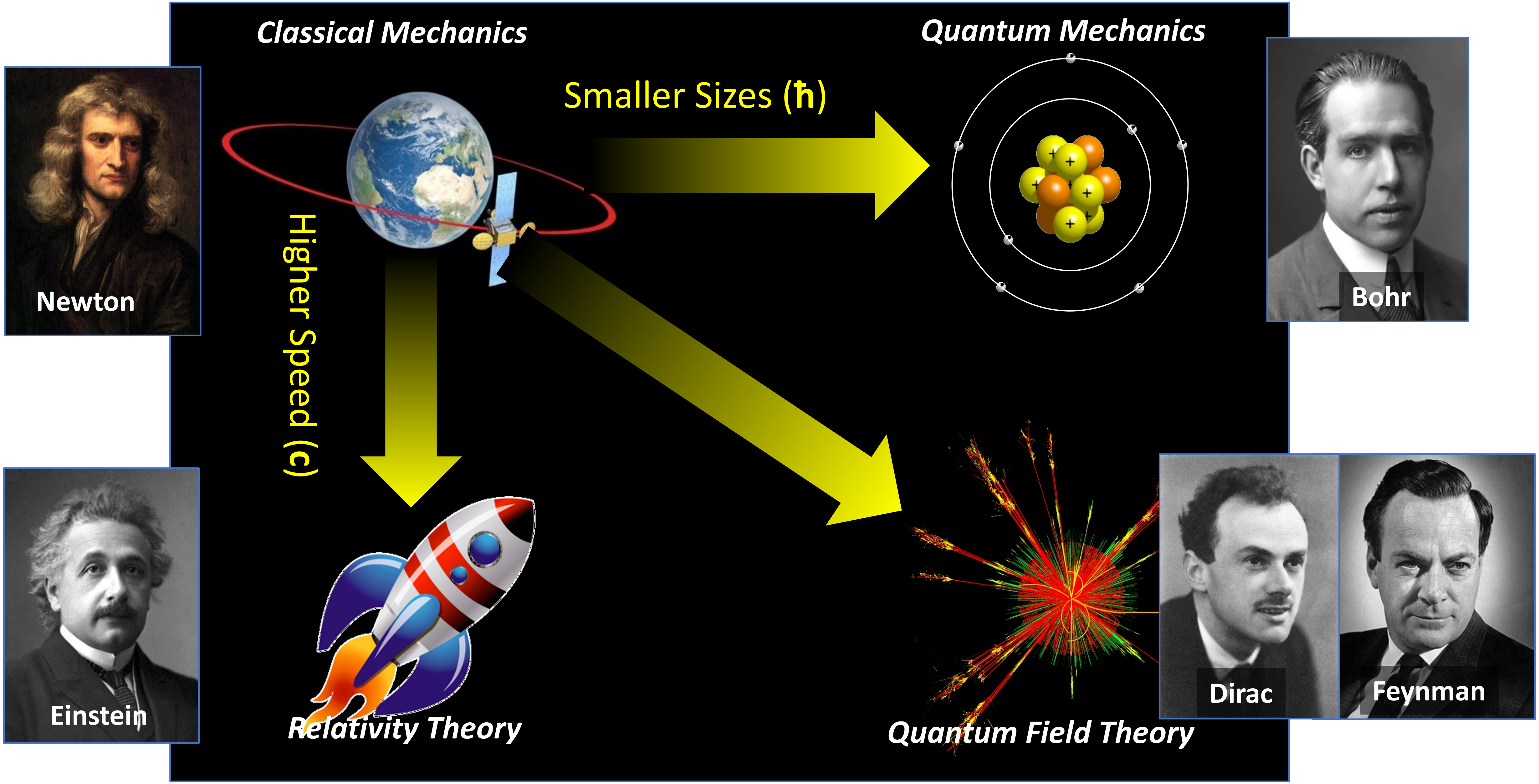
Marcel Merk
Studium Generale Maastricht
Nov 1 – Nov 29, 2023

The Relativistic Quantum World

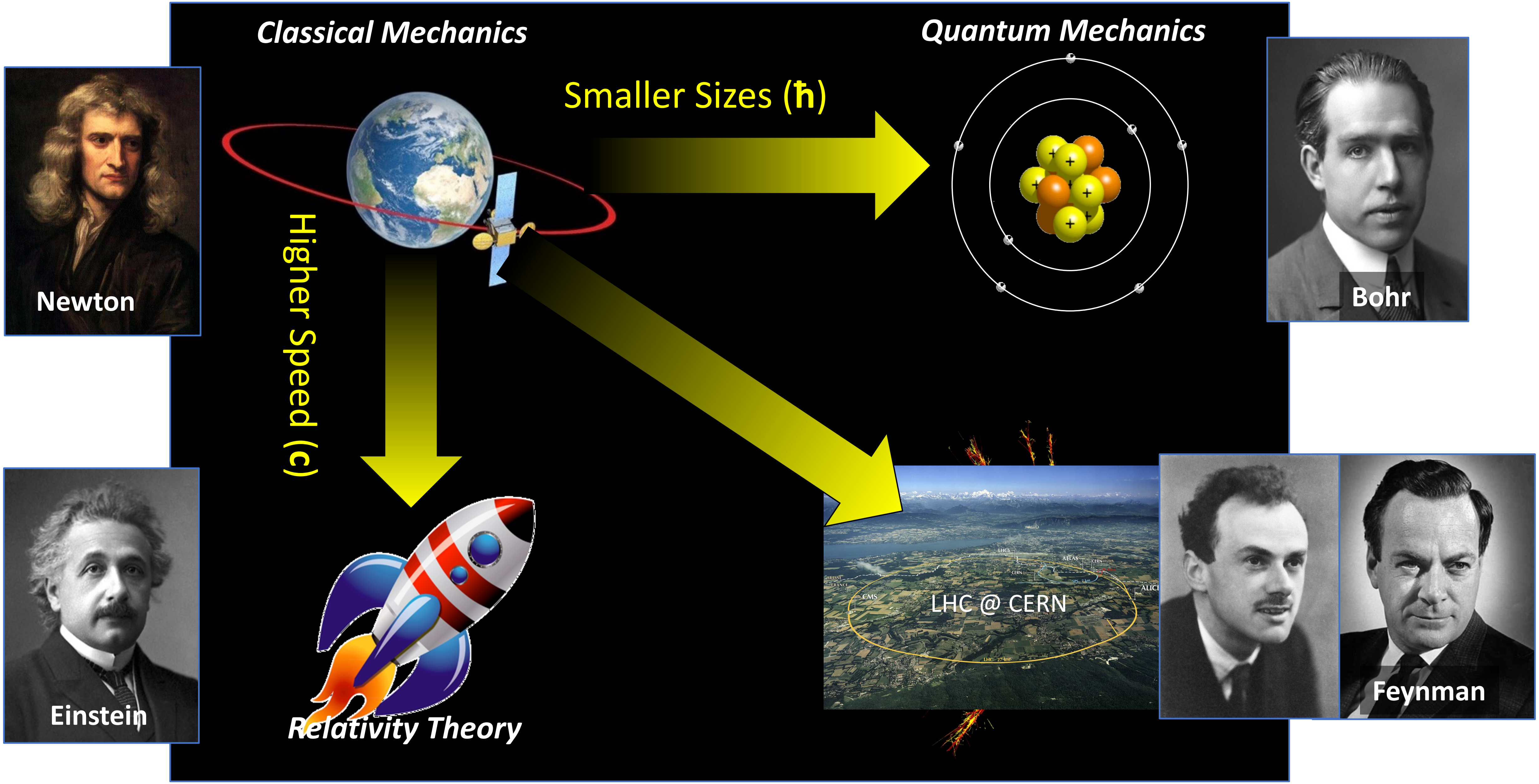
Relativity	Nov. 1:	Lecture 1: The Principle of Relativity and the Speed of Light Lecture 2: Time Dilation and Lorentz Contraction
	Nov. 8:	Lecture 3: The Lorentz Transformation and Paradoxes Lecture 4: General Relativity and Gravitational Waves
Quantum Mechanics	Nov. 15:	Lecture 5: The Early Quantum Theory Lecture 6: Feynman's Double Slit Experiment
	Nov 22:	Lecture 7: Wheeler's Delayed Choice and Schrodinger's Cat Lecture 8: Quantum Reality and the EPR Paradox
Standard Model	Nov. 29:	Lecture 9: The Standard Model and Antimatter Lecture 10: Why is there something rather than nothing?

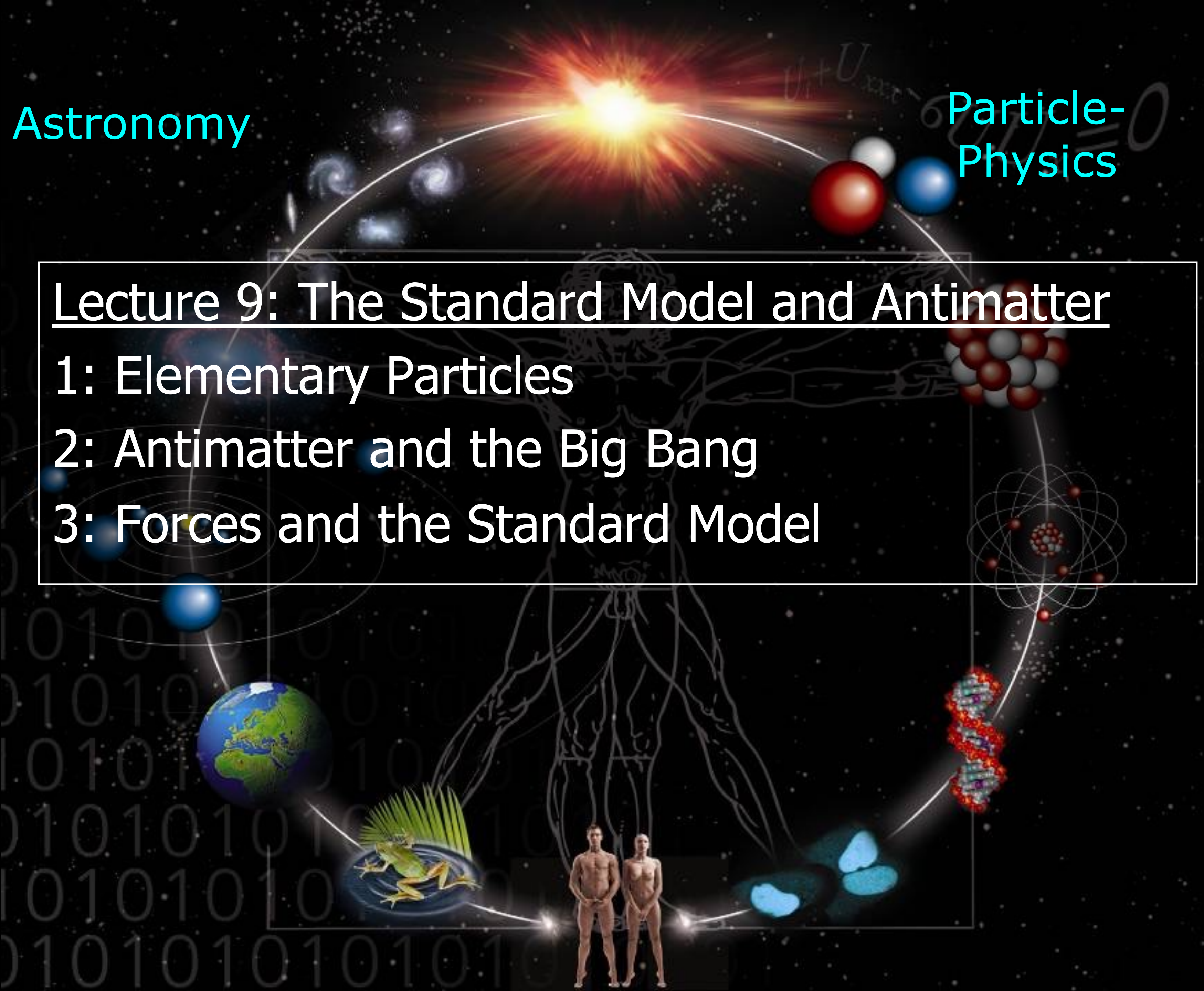
Lecture notes, written for this course, are available: www.nikhef.nl/~i93/Teaching/
Prerequisite for the course: High school level physics & mathematics.

Relativity and Quantum Mechanics



Relativity and Quantum Mechanics



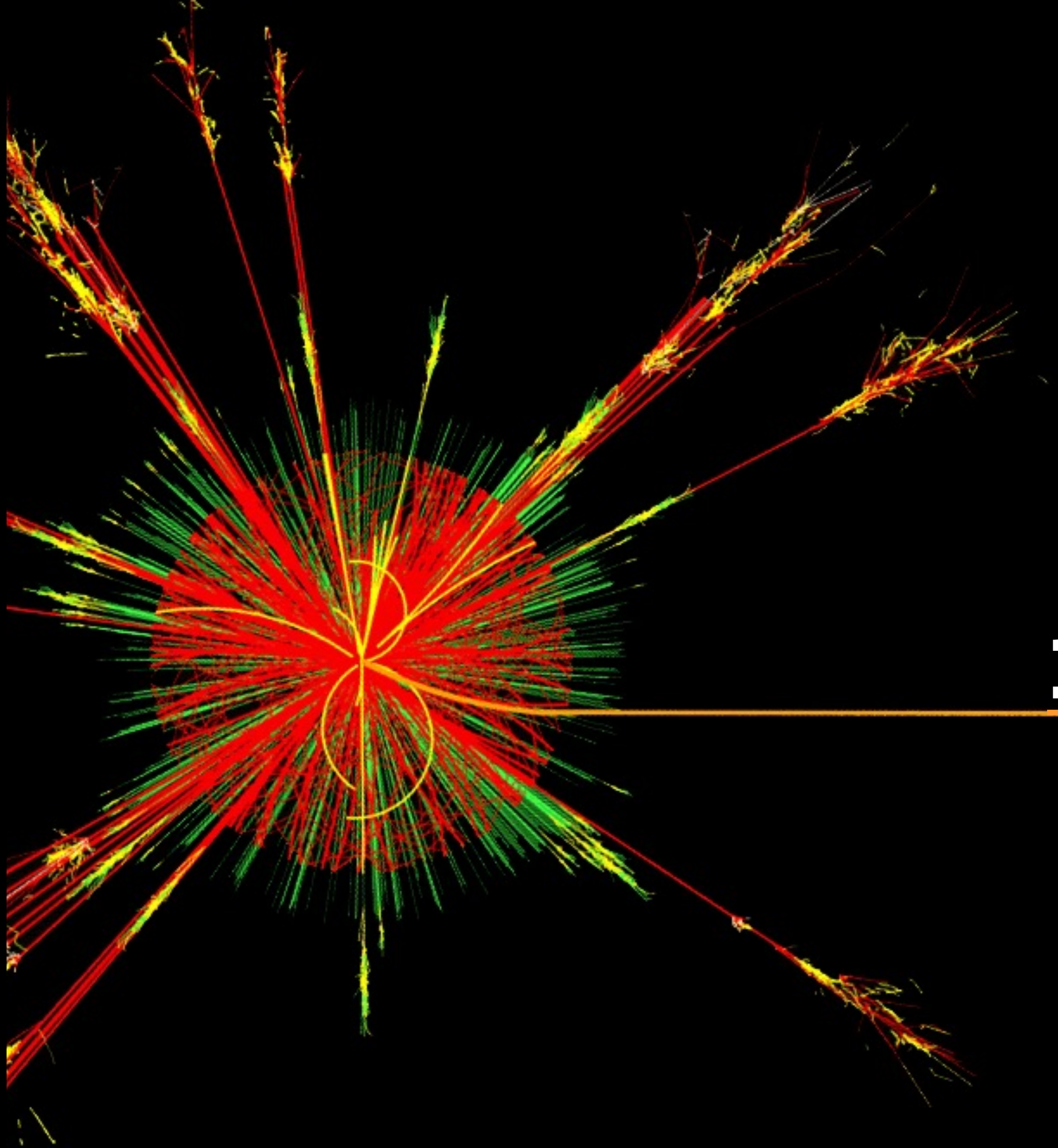


Lecture 9: The Standard Model and Antimatter

1: Elementary Particles

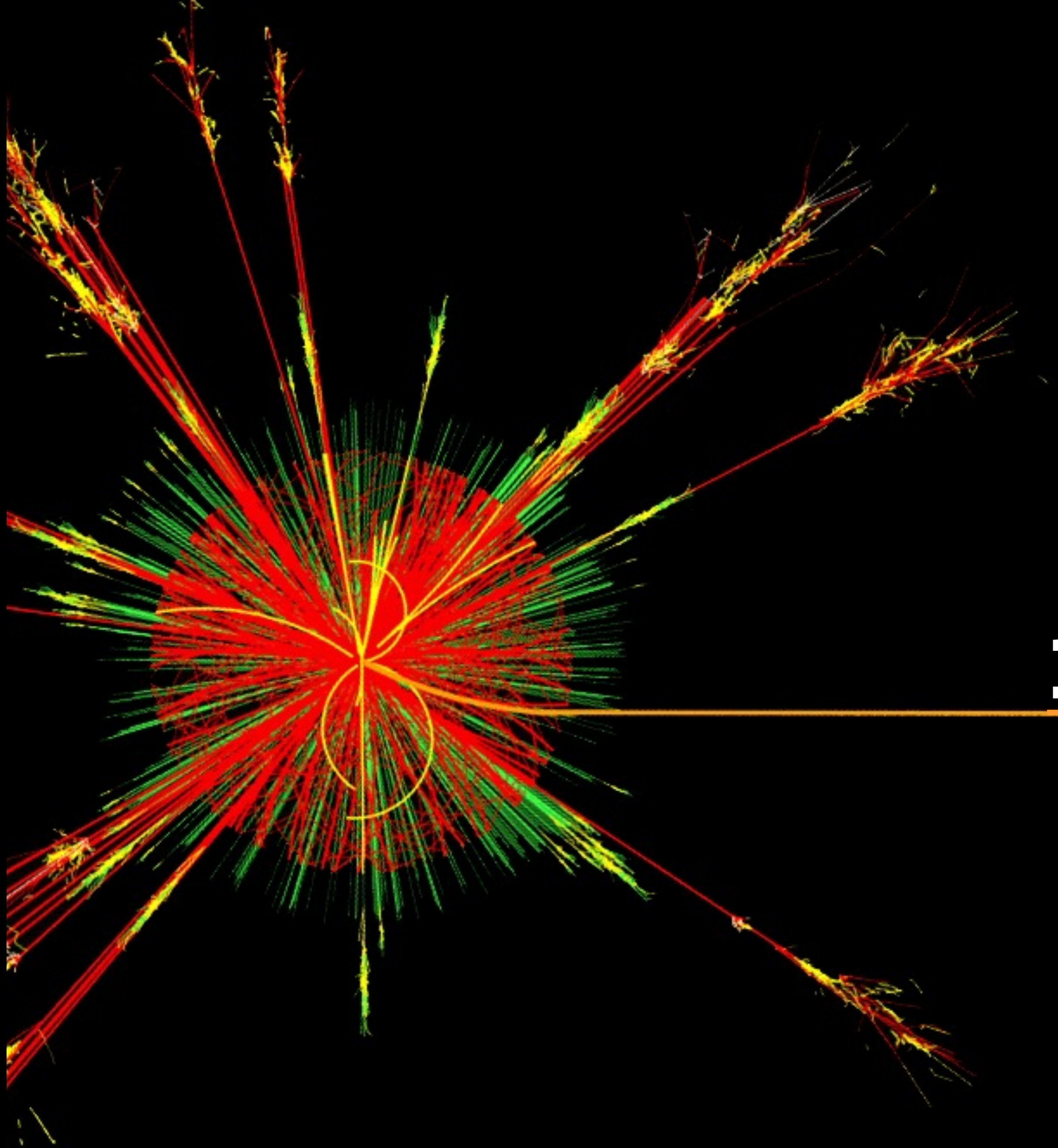
2: Antimatter and the Big Bang

3: Forces and the Standard Model



1: Elementary Particles

"All things come in three"



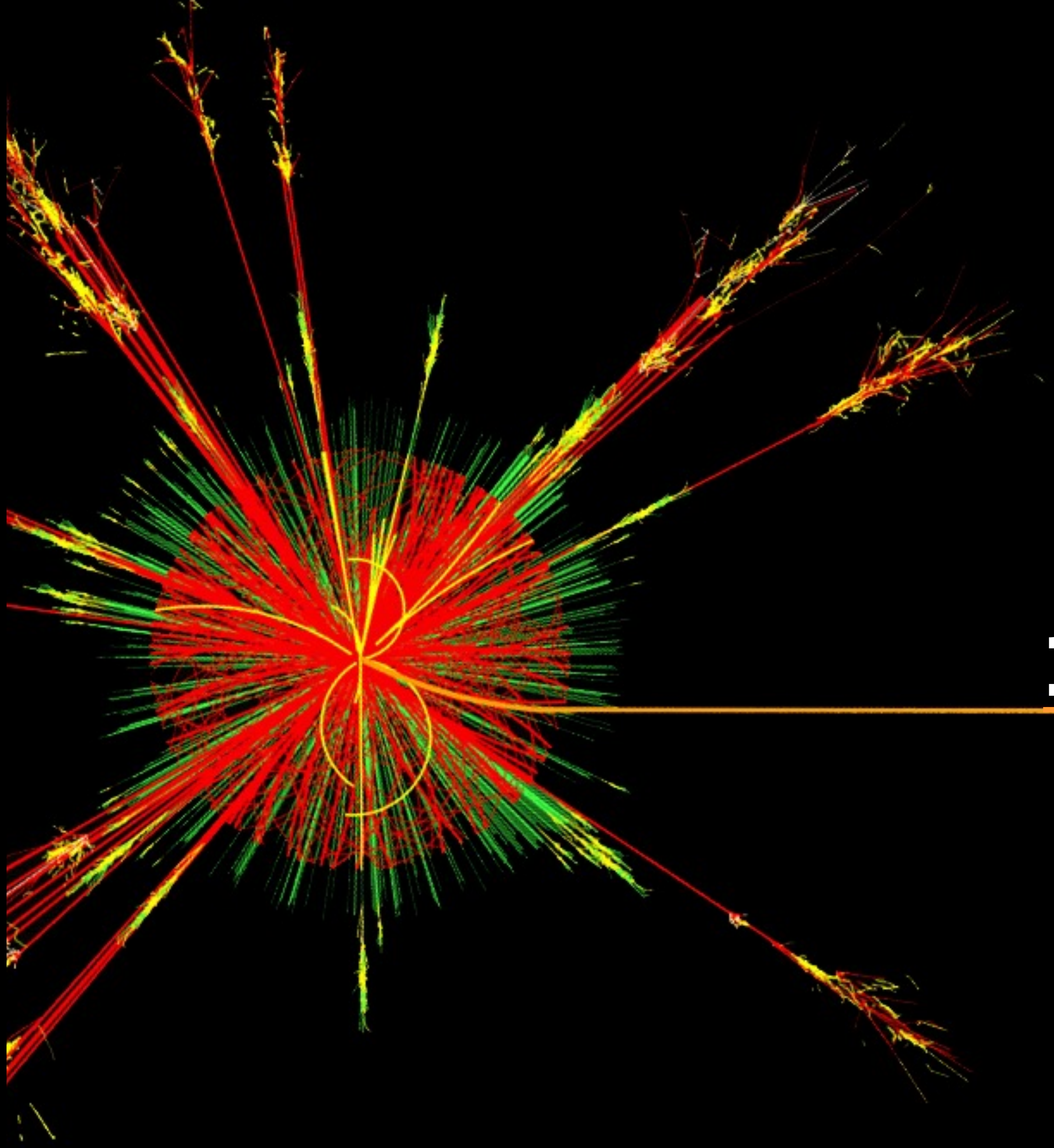
Pie de Bökkum,

Ensinck de Kletskop

Flup de Koojstart

1: Elementary Particles

"All things come in three"

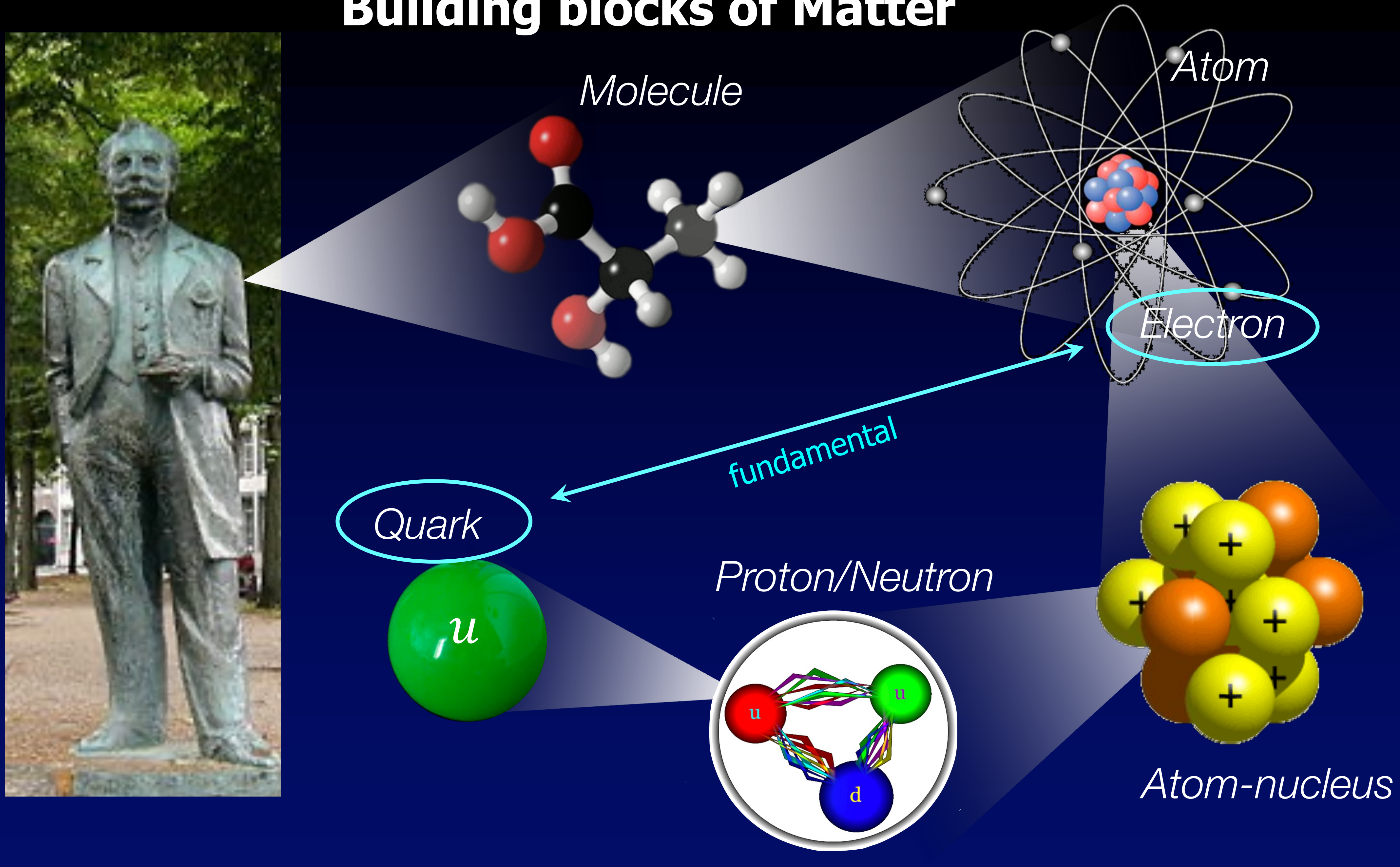


Fons Olterdissen (1865-1923)

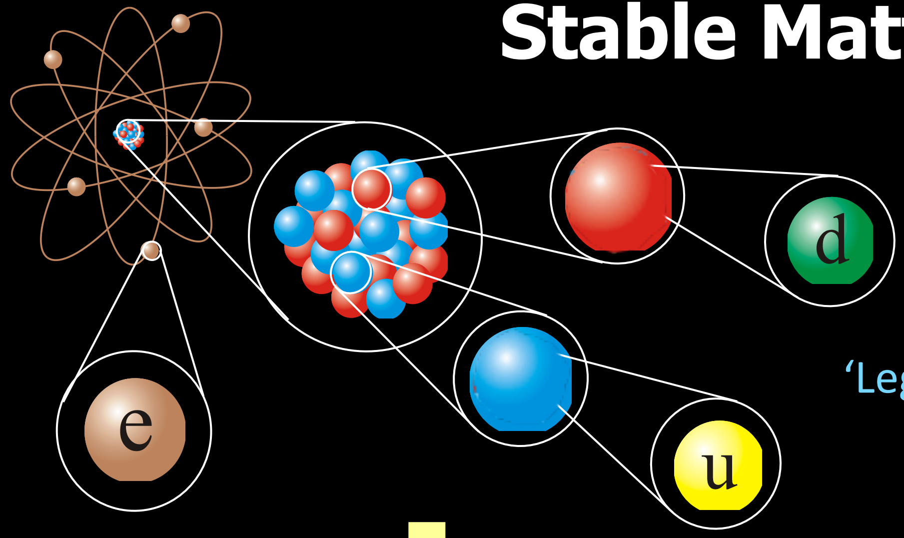
1: Elementary Particles

"All things come in three"

Building blocks of Matter

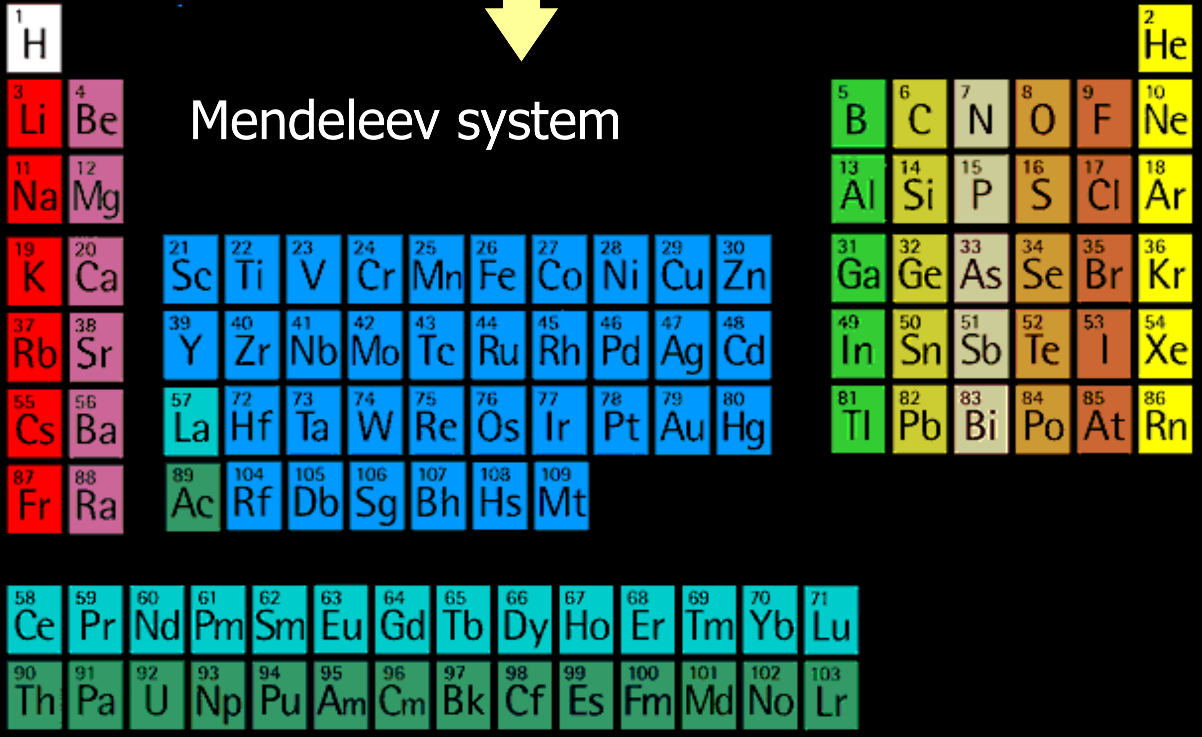


Stable Matter on Earth

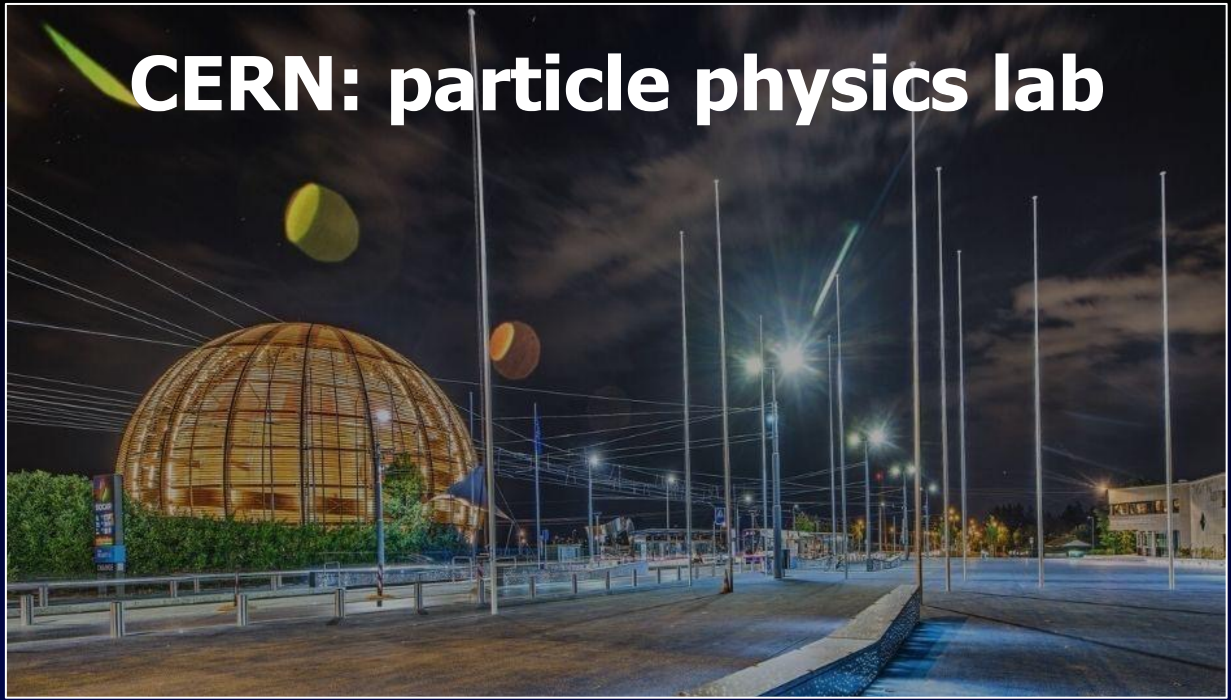


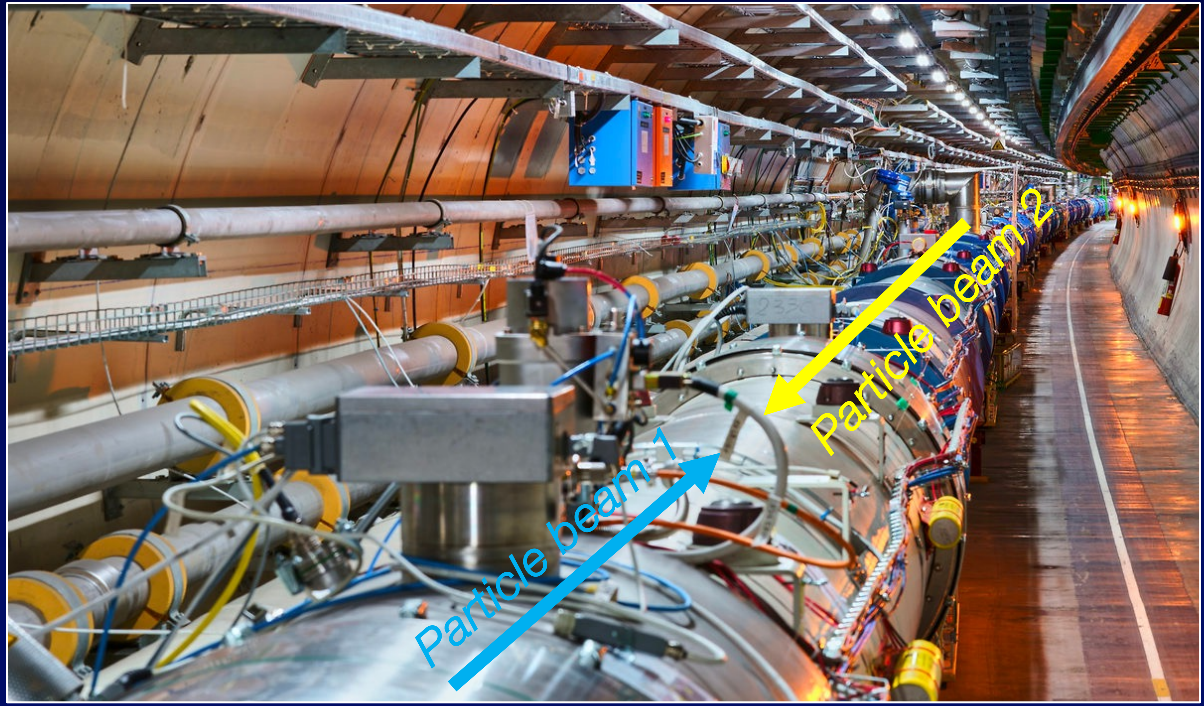
‘Lego blocks’ of nature

Mendeleev system

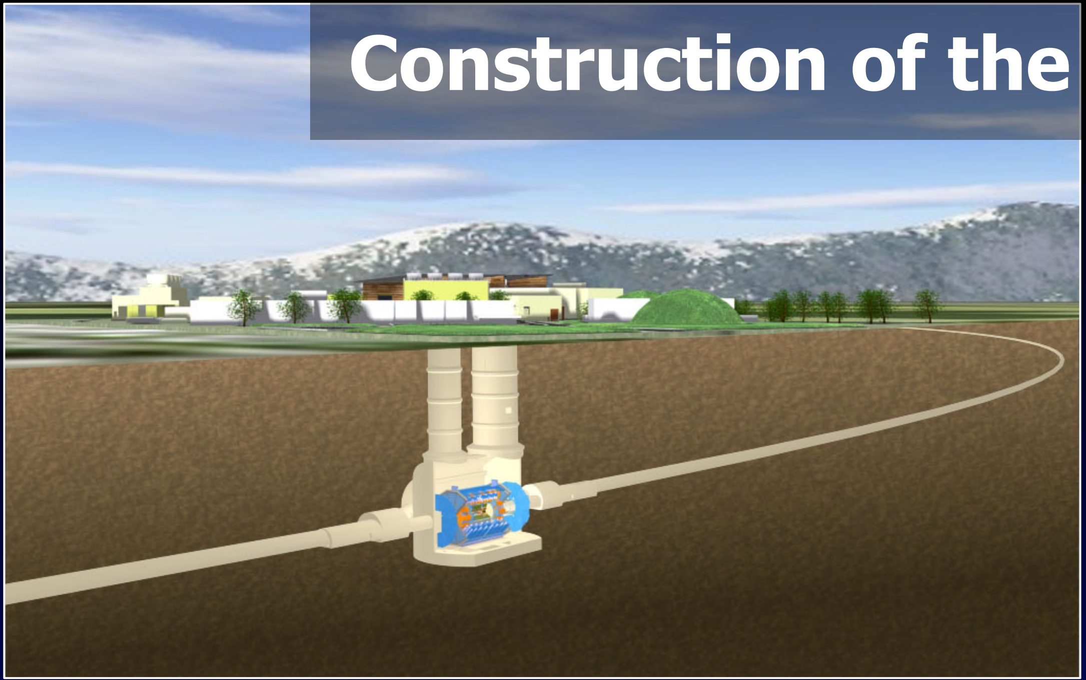


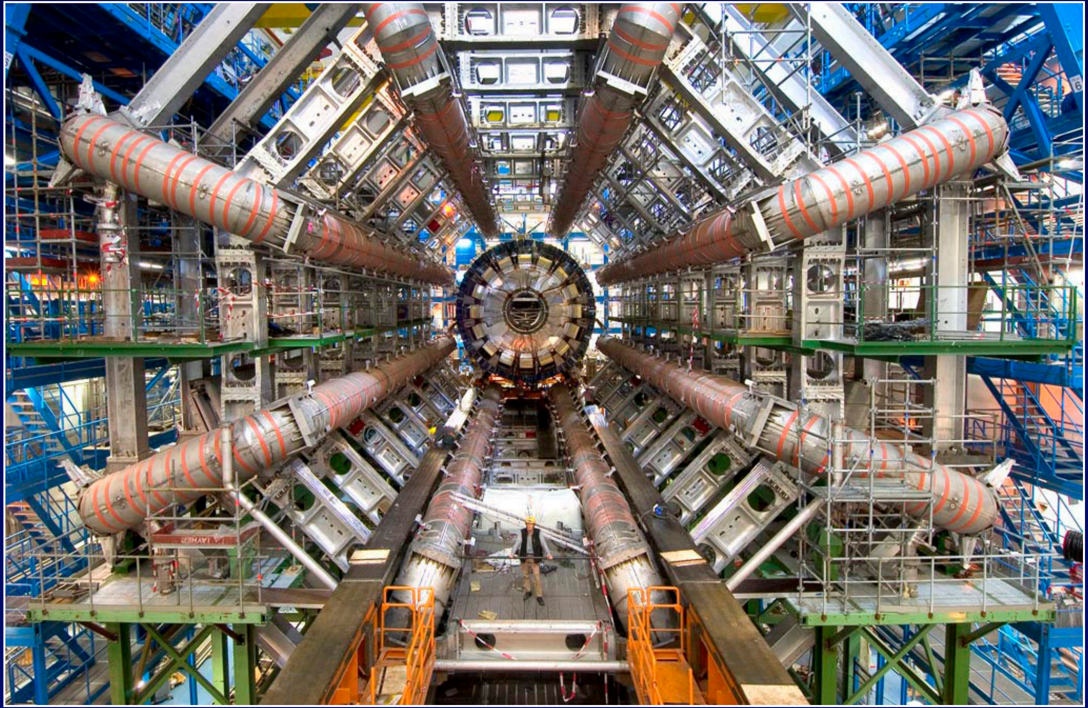
CERN: particle physics lab

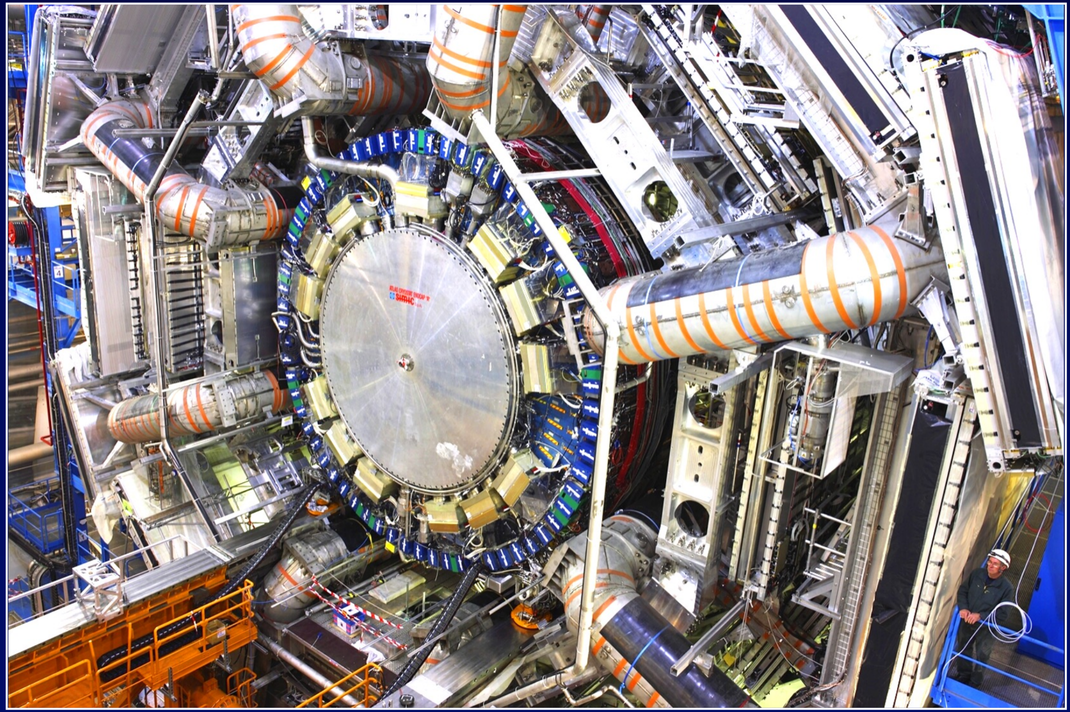




Construction of the Atlas detector at LHC



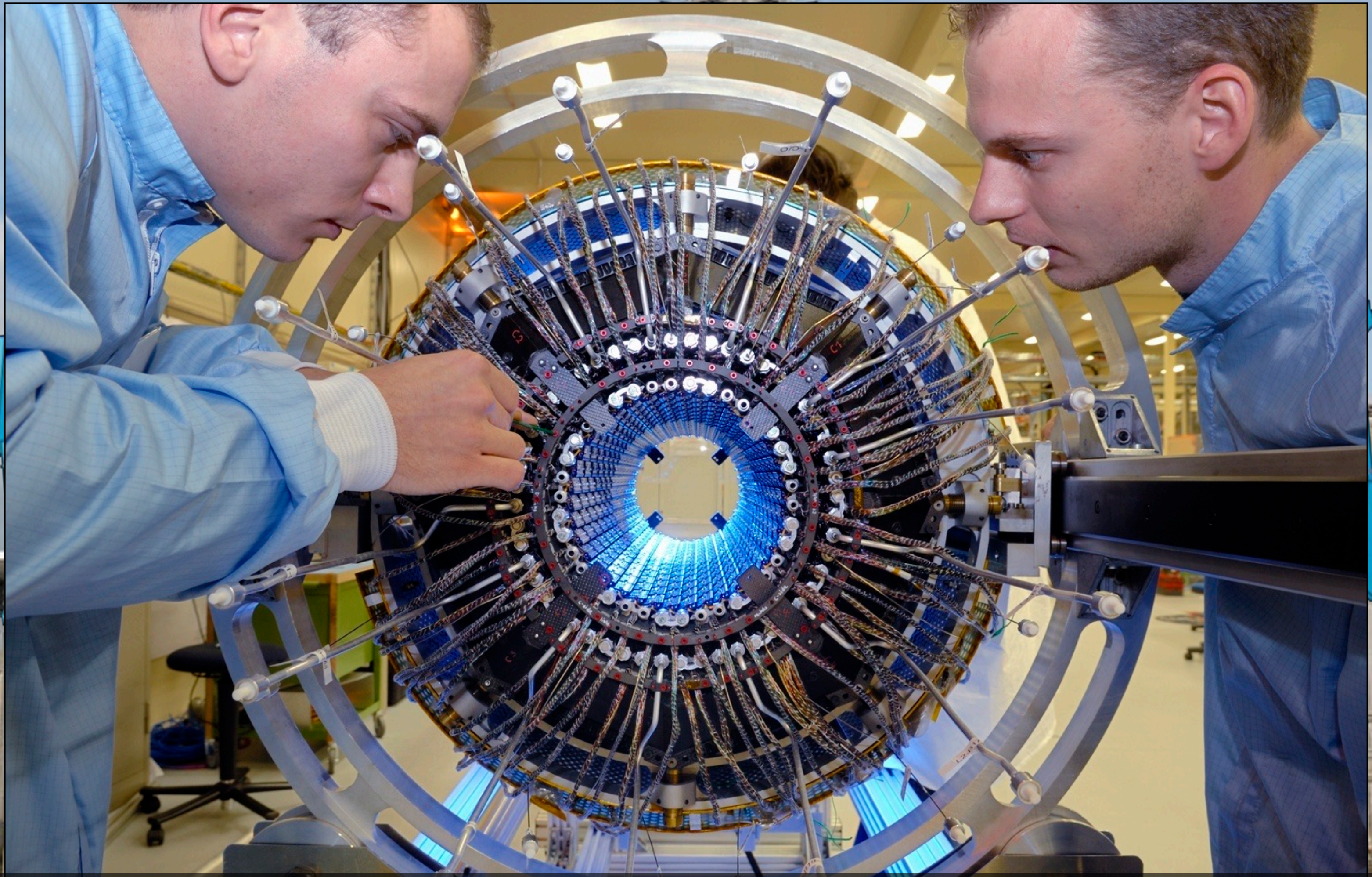




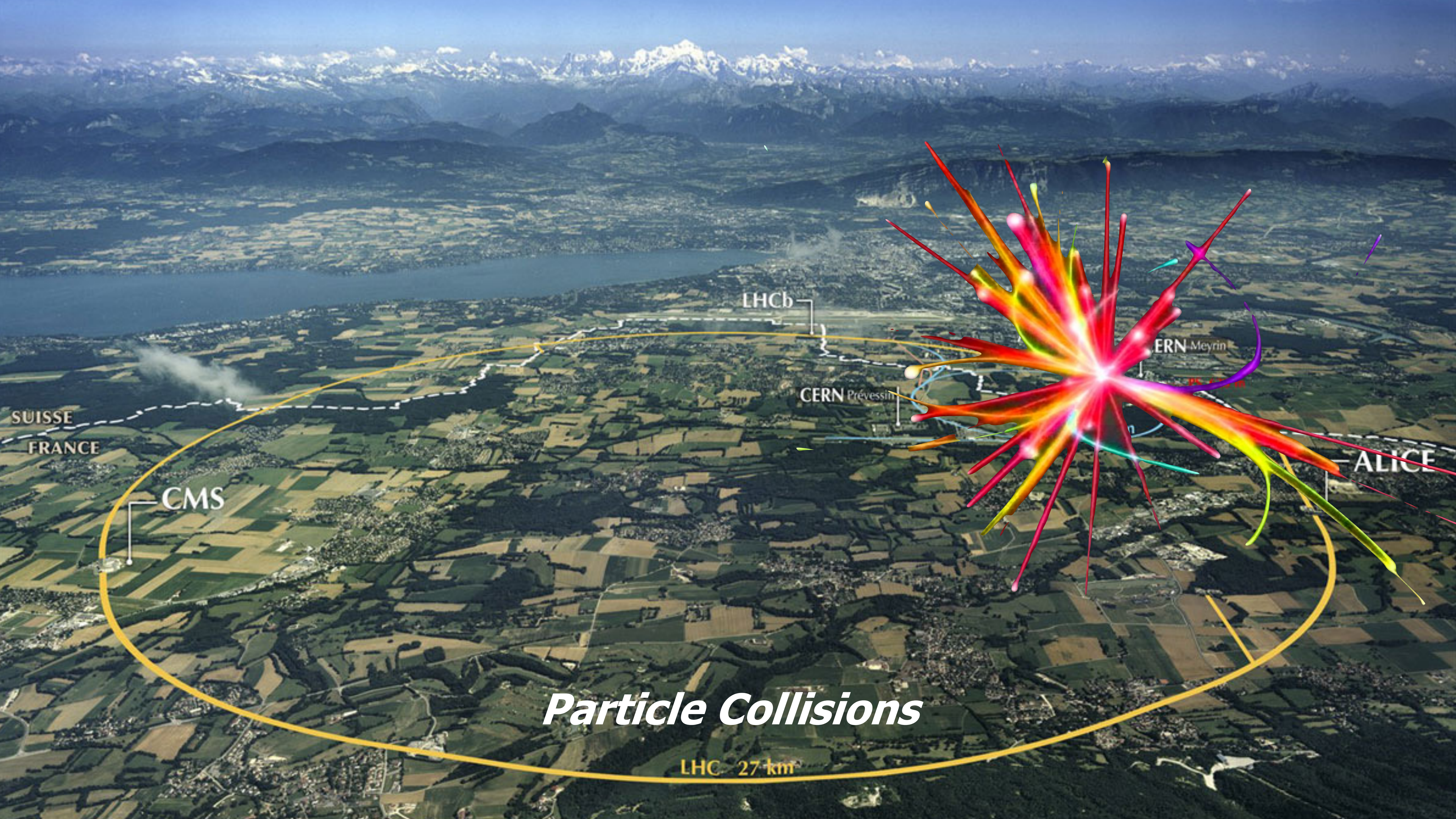
The Atlas Experiment

Largest "photocamera" on earth

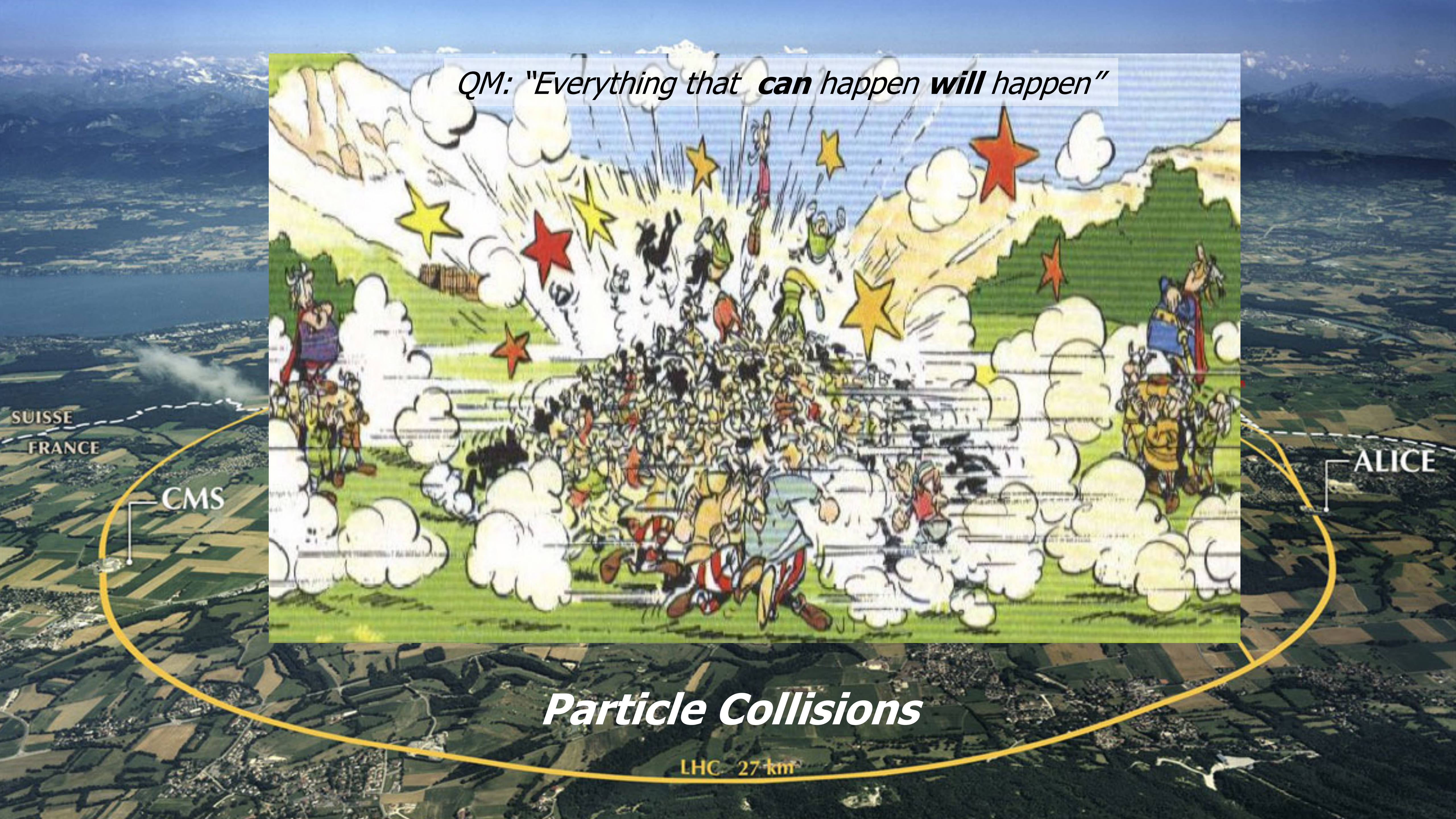
- *45 m x 25 m*
- *3000 physicists*



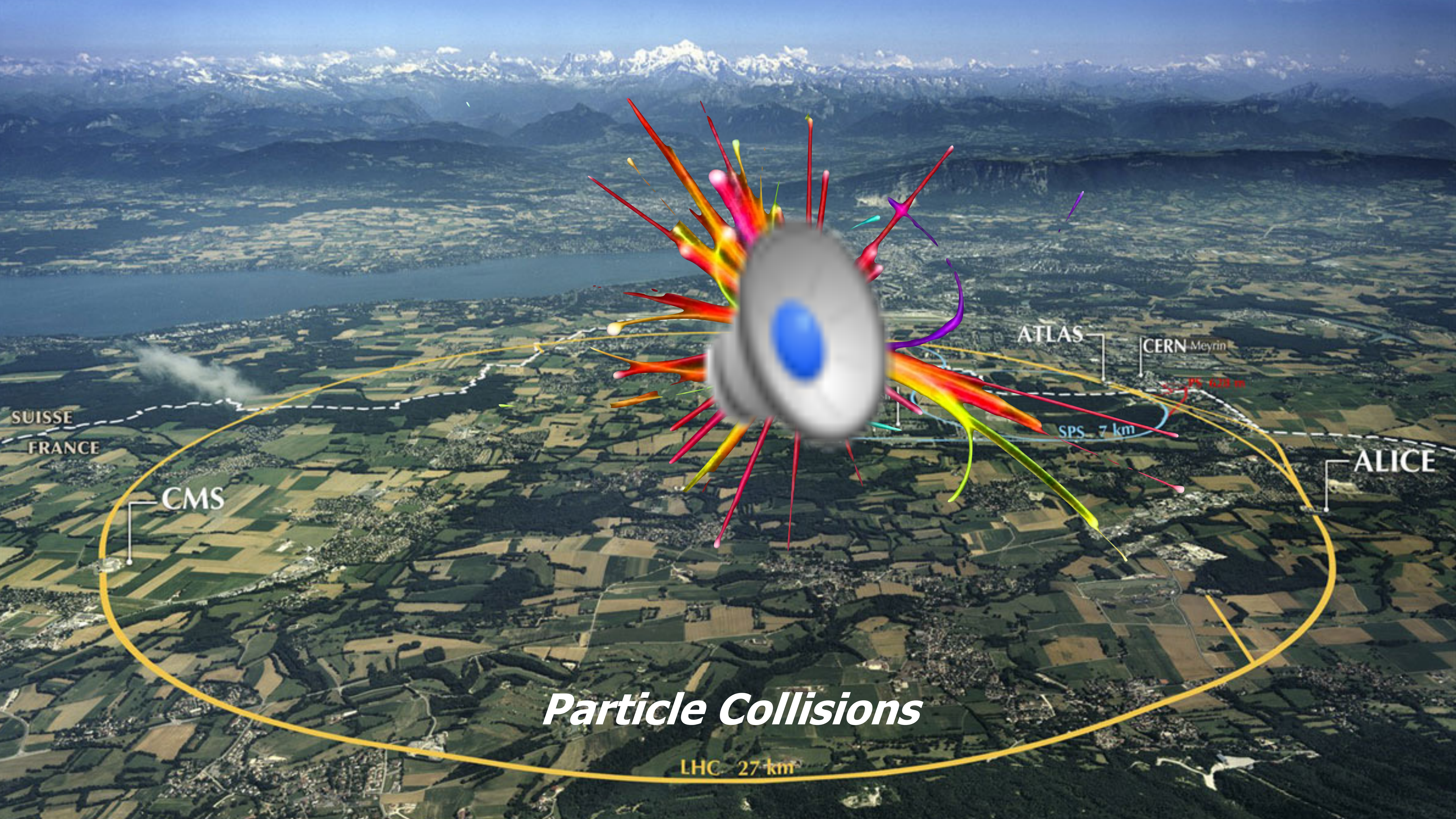
80 MegaPixel "camera": 40.000.000 pictures per second


LHCb
CERN Meyrin
CERN Prévessin
SUISSE
FRANCE
CMS
ALICE
Particle Collisions
LHC 27 km

QM: "Everything that ***can*** *happen* ***will*** *happen"*



Particle Collisions


ATLAS
CERN Meyrin
PS 628 m
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
Particle Collisions
LHC 27 km

Elementary Particles

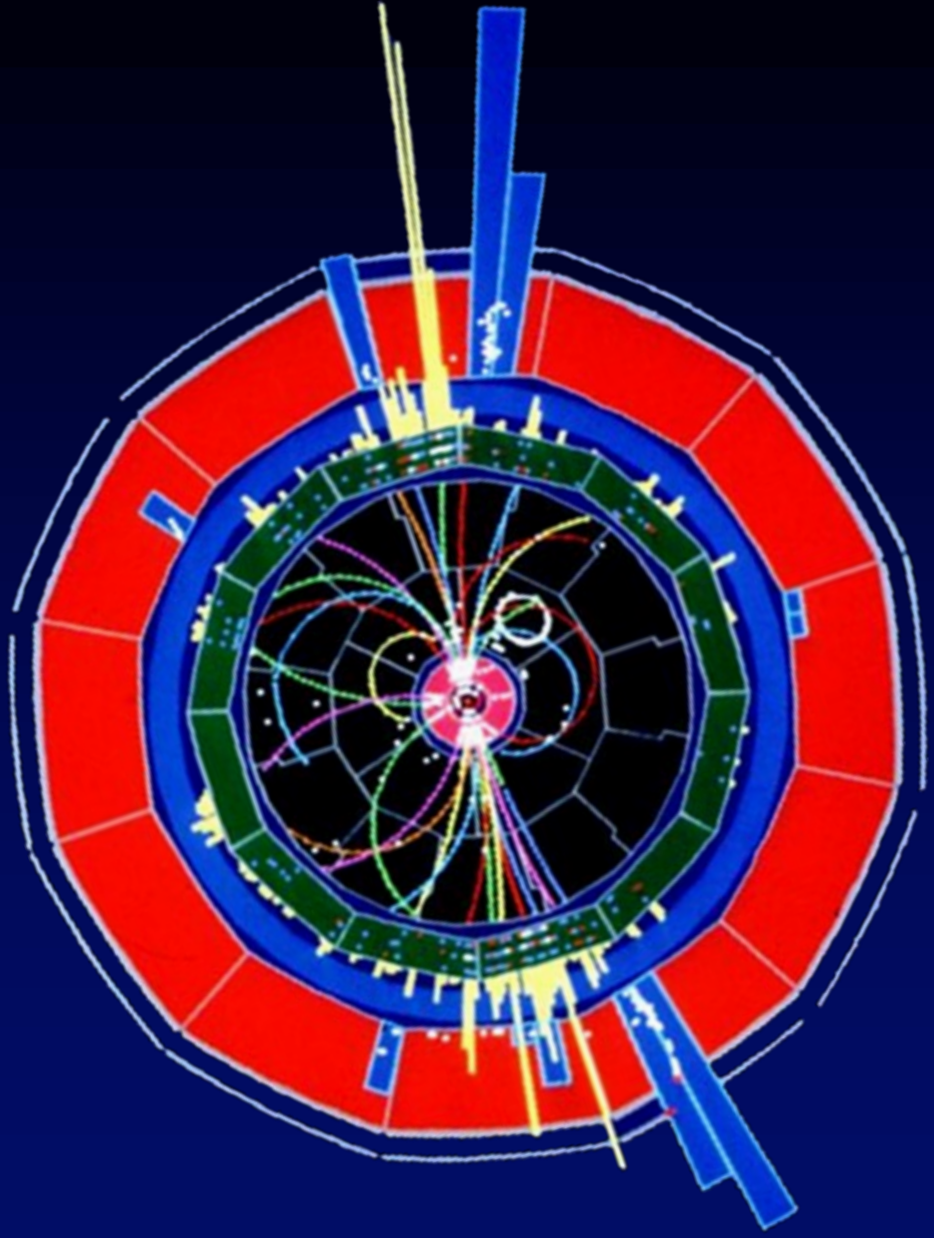
Generation:

	I	II	III	Charge
quarks	u	c (1976)	t (1995)	+2/3 e
	d	s (1947)	b (1978)	-1/3 e

3 “generations” of particles?!

leptons	e (1895)	μ (1936)	τ (1973)	-1 e
	ν_e (1956)	ν_μ (1963)	ν_τ (2000)	0 e

Matter



Elementary Particles

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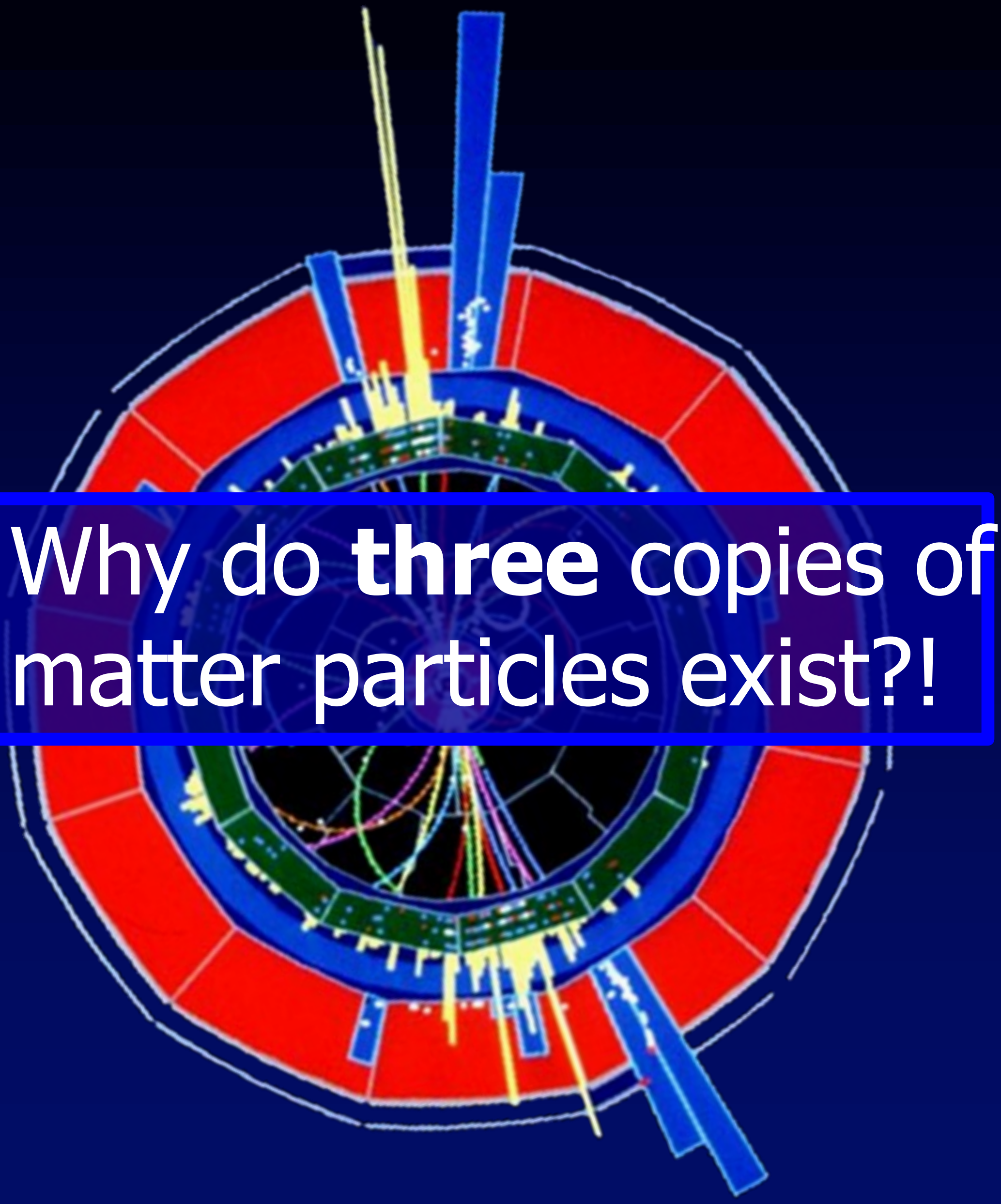
Matter



Why do **three** copies of matter particles exist?!

Elementary Particles

Generation:

	I	II	III	Charge
quarks	u	c (1976)	t (1995)	+2/3 e
	d	s (1947)	b (1978)	-1/3 e

3 “generations” of particles?!

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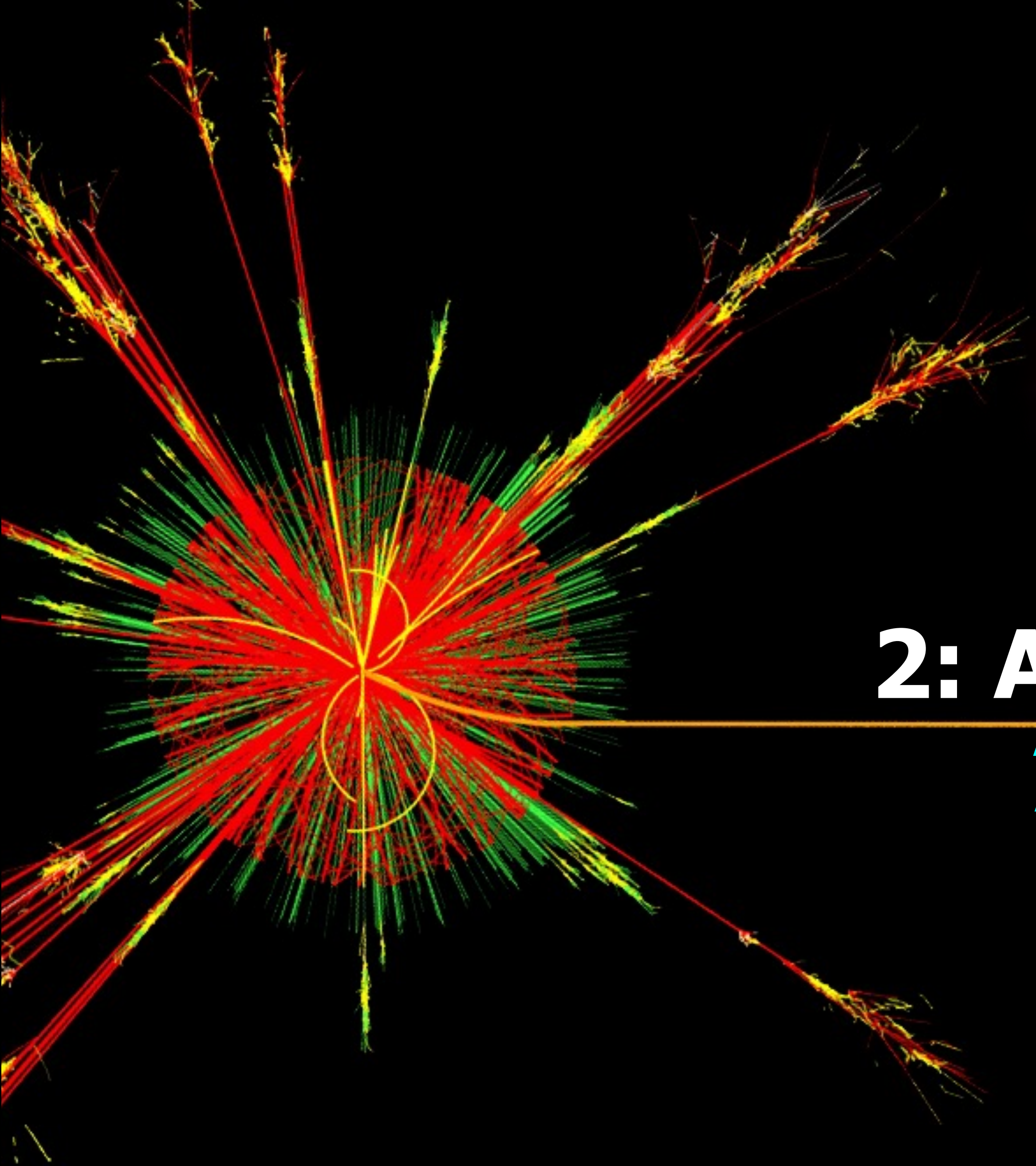
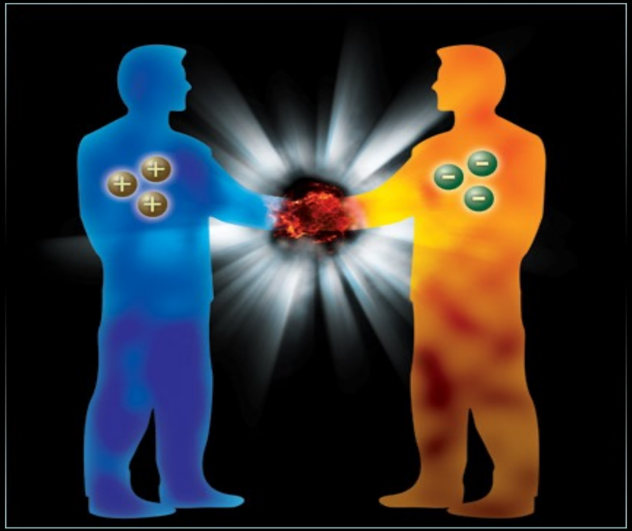
Matter

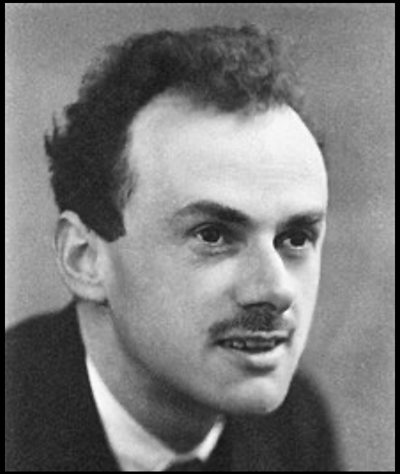
How about…

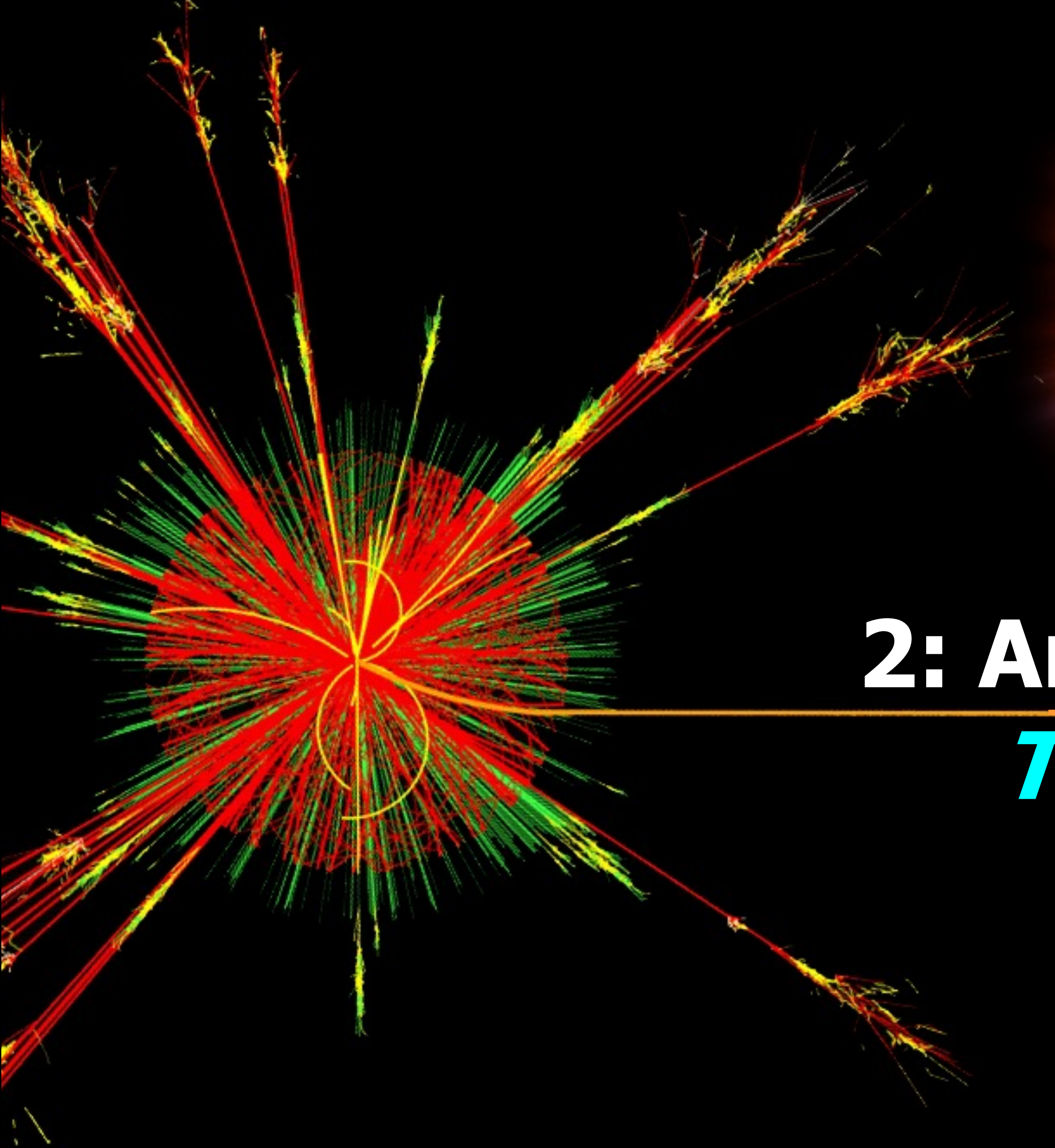




2: Antimatter and Big Bang

The genius of Paul Dirac

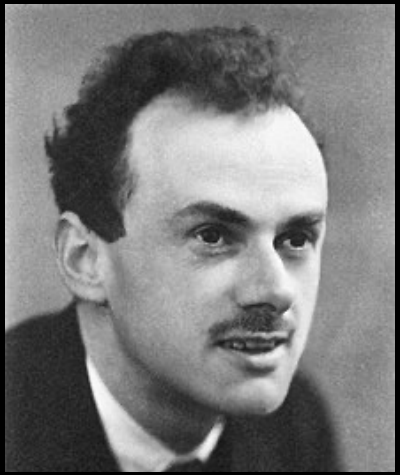




Rika (antimatter frites?)

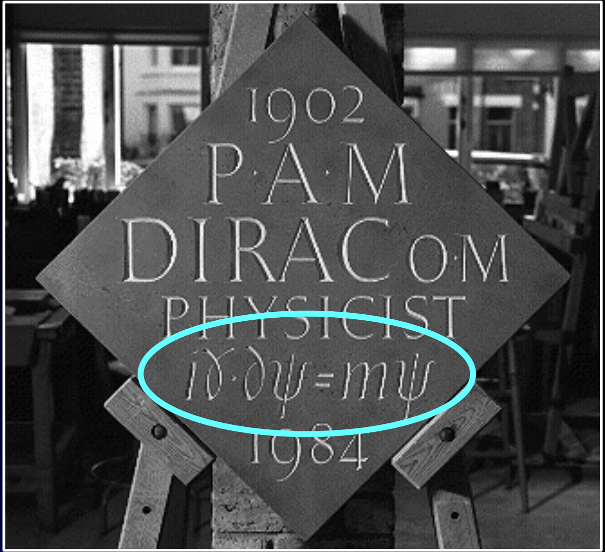
2: Antimatter and Big Bang

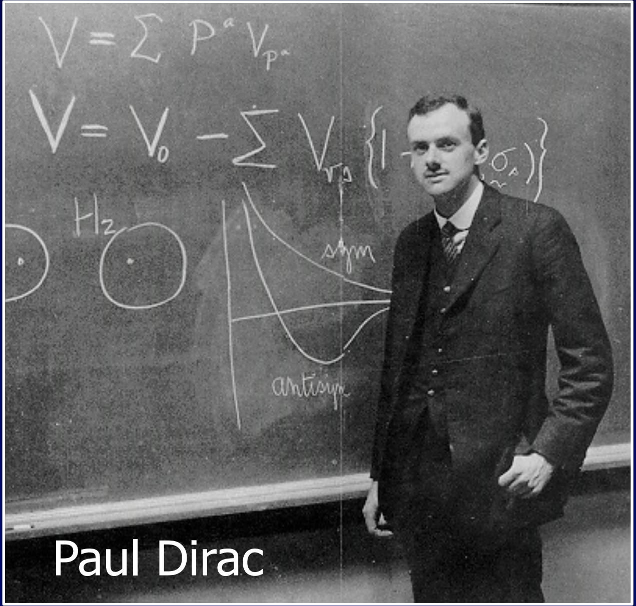
The genius of Paul Dirac



Paul Dirac and antimatter

- 1928:
  - Dirac's relativistic quantum theory
  - Prediction: *for each matter particle there exists an identical antimatter particle!*
- 1932:
  - Anderson discovers the anti-electron



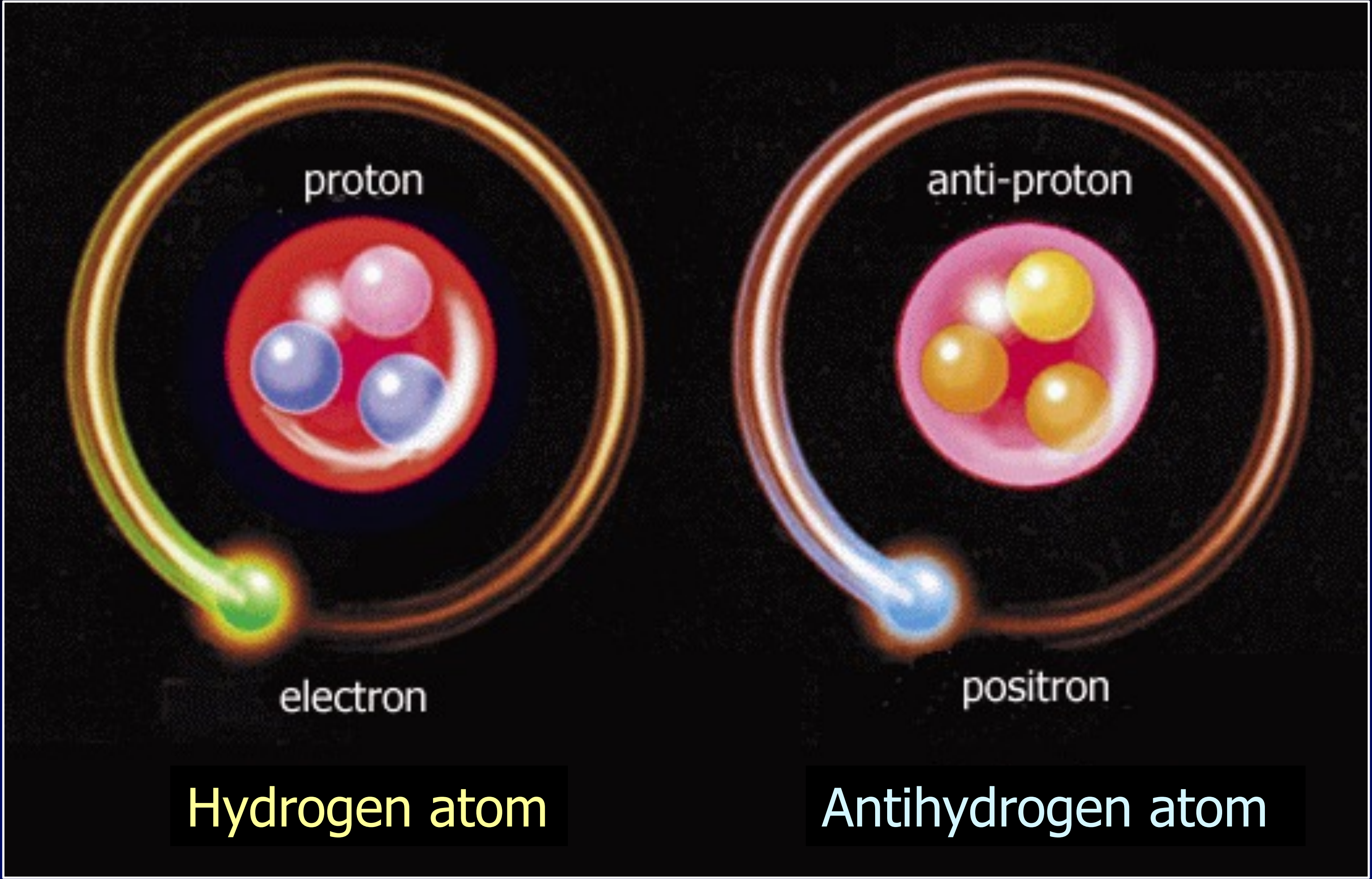

Paul Dirac


Carl Anderson

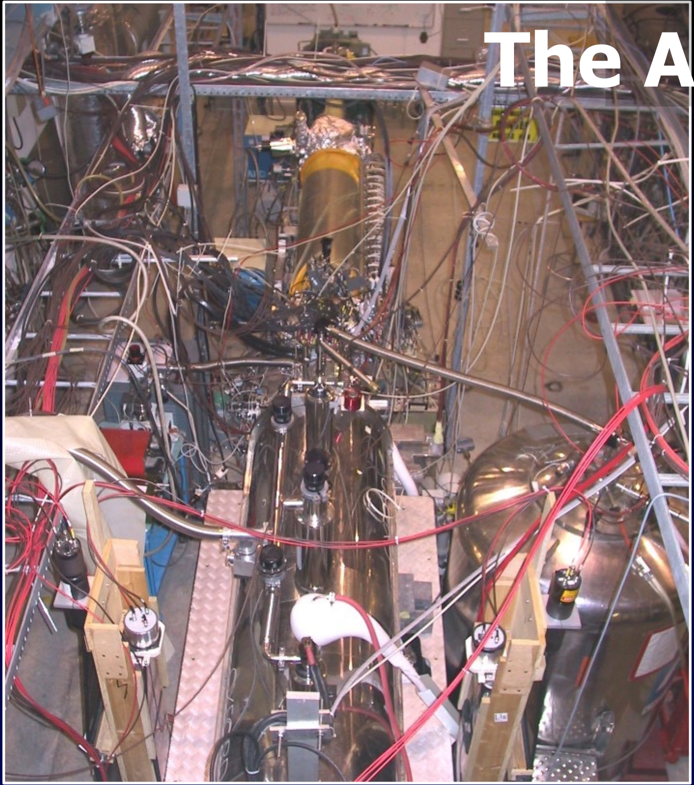

Dirac

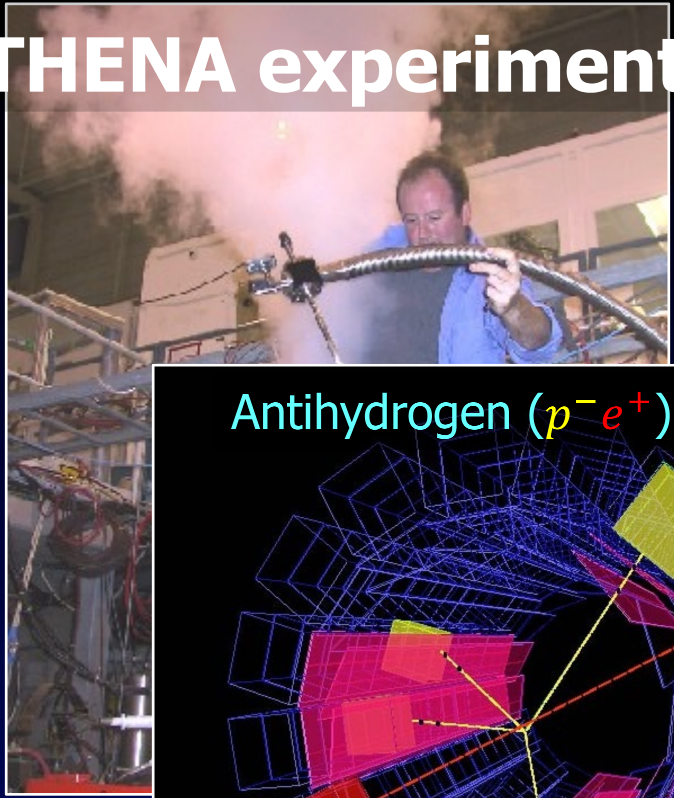
AntiDirac

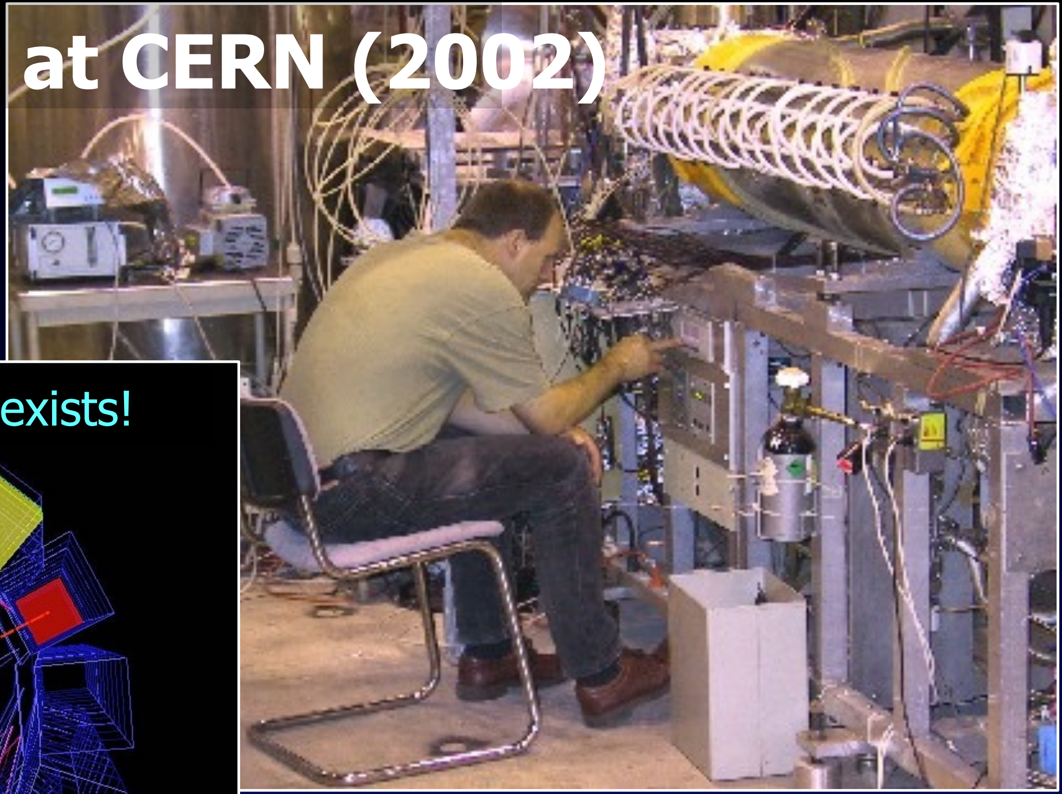
Antimatter

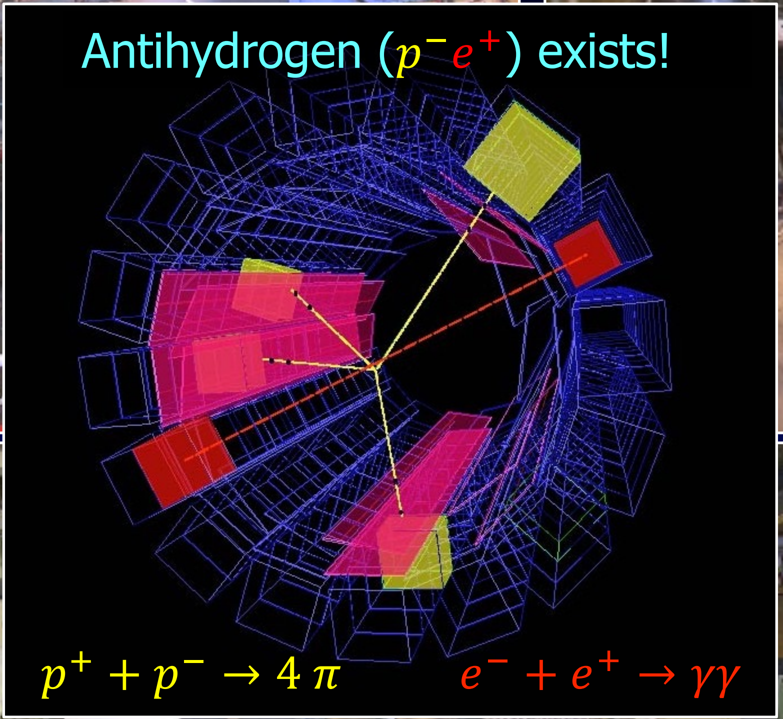

proton
electron
anti-proton
positron
Hydrogen atom
Antihydrogen atom

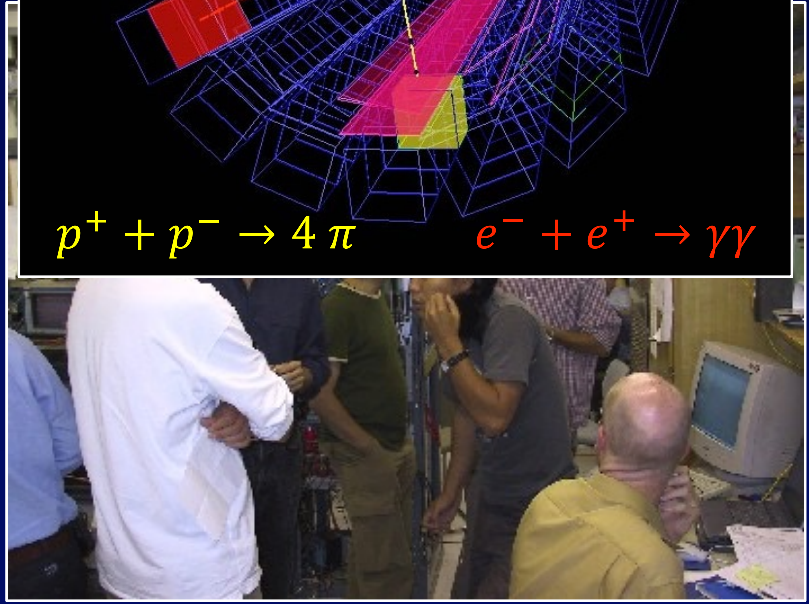
The ATHENA experiment at CERN (2002)



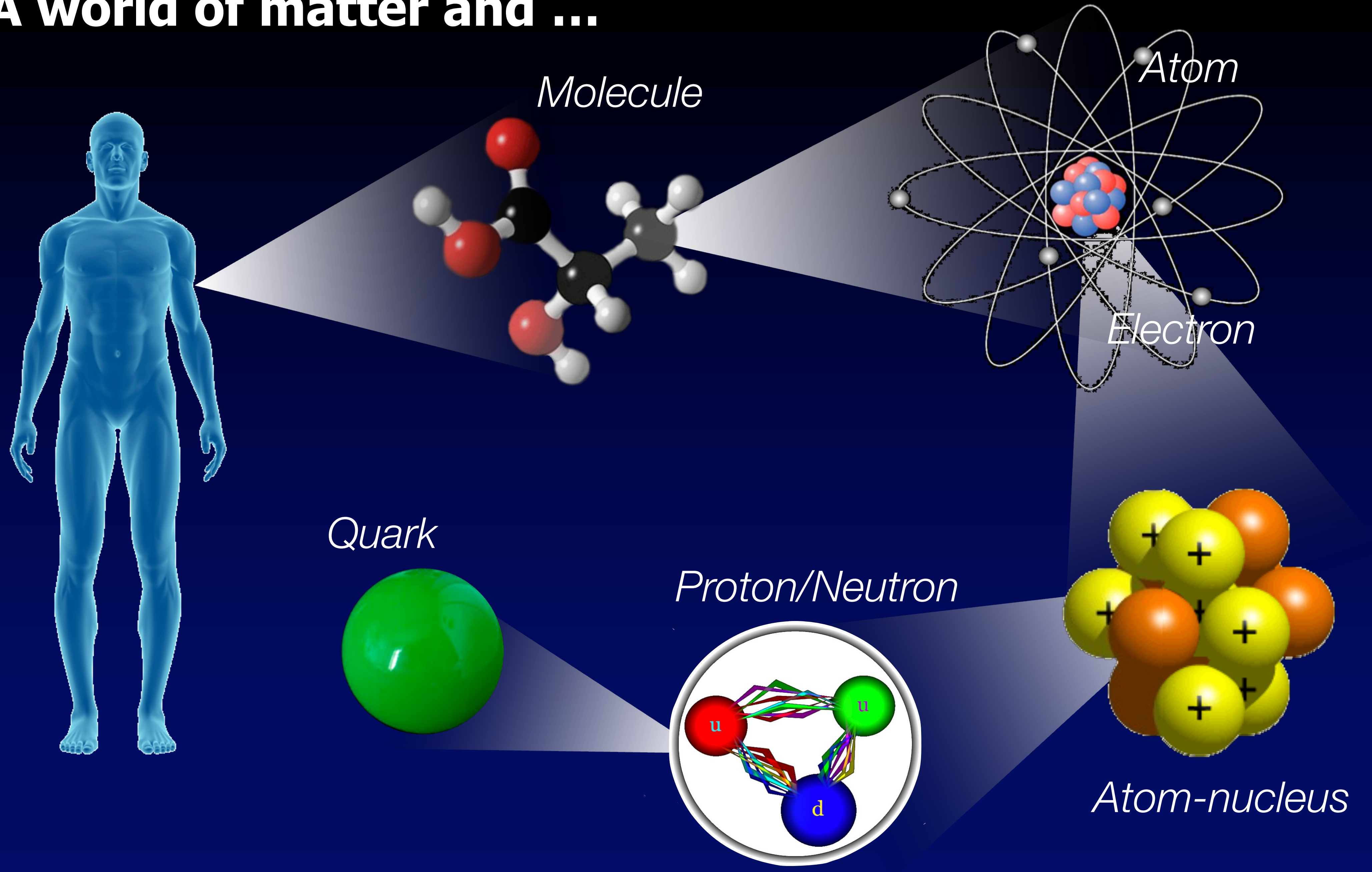




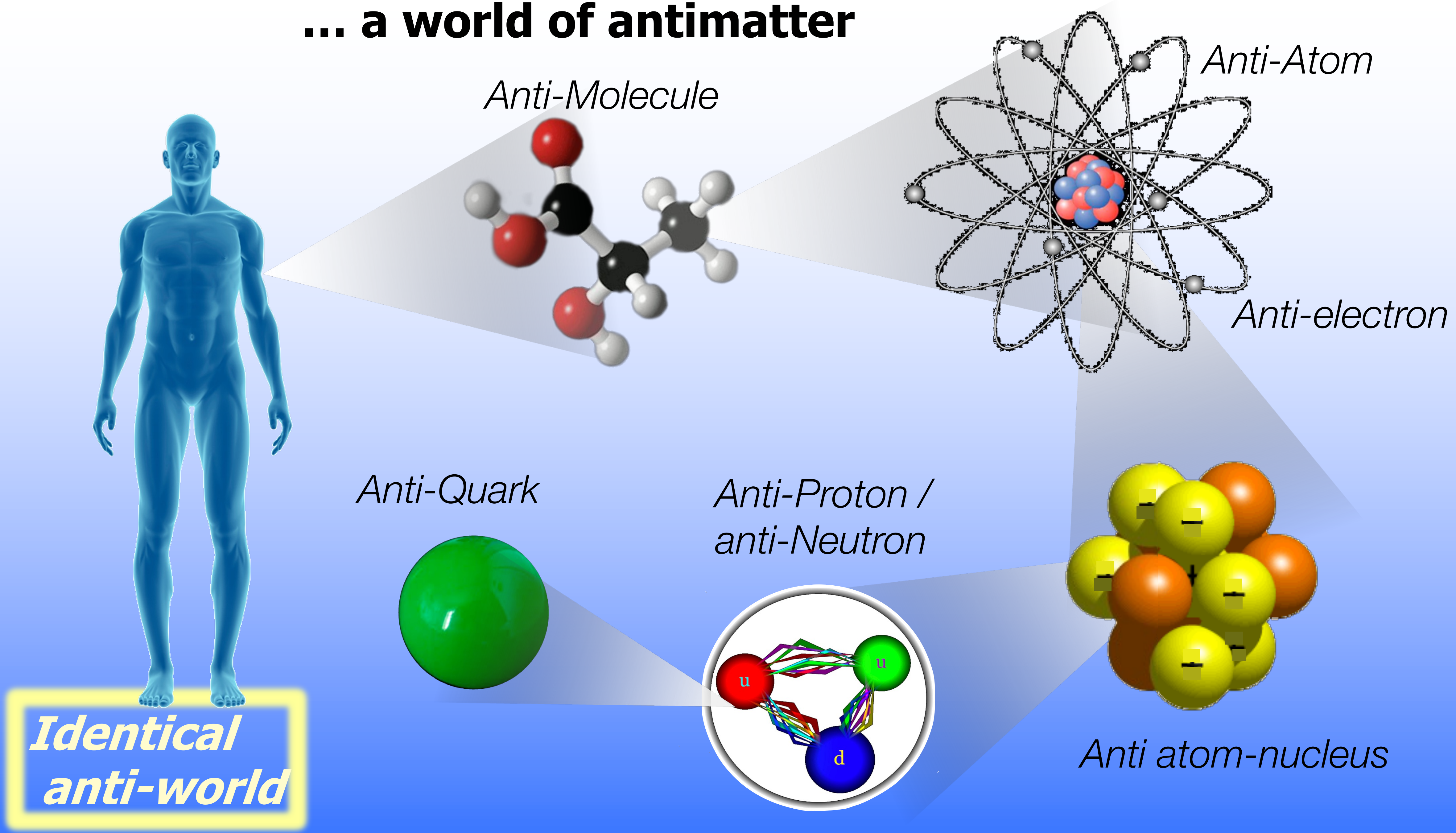




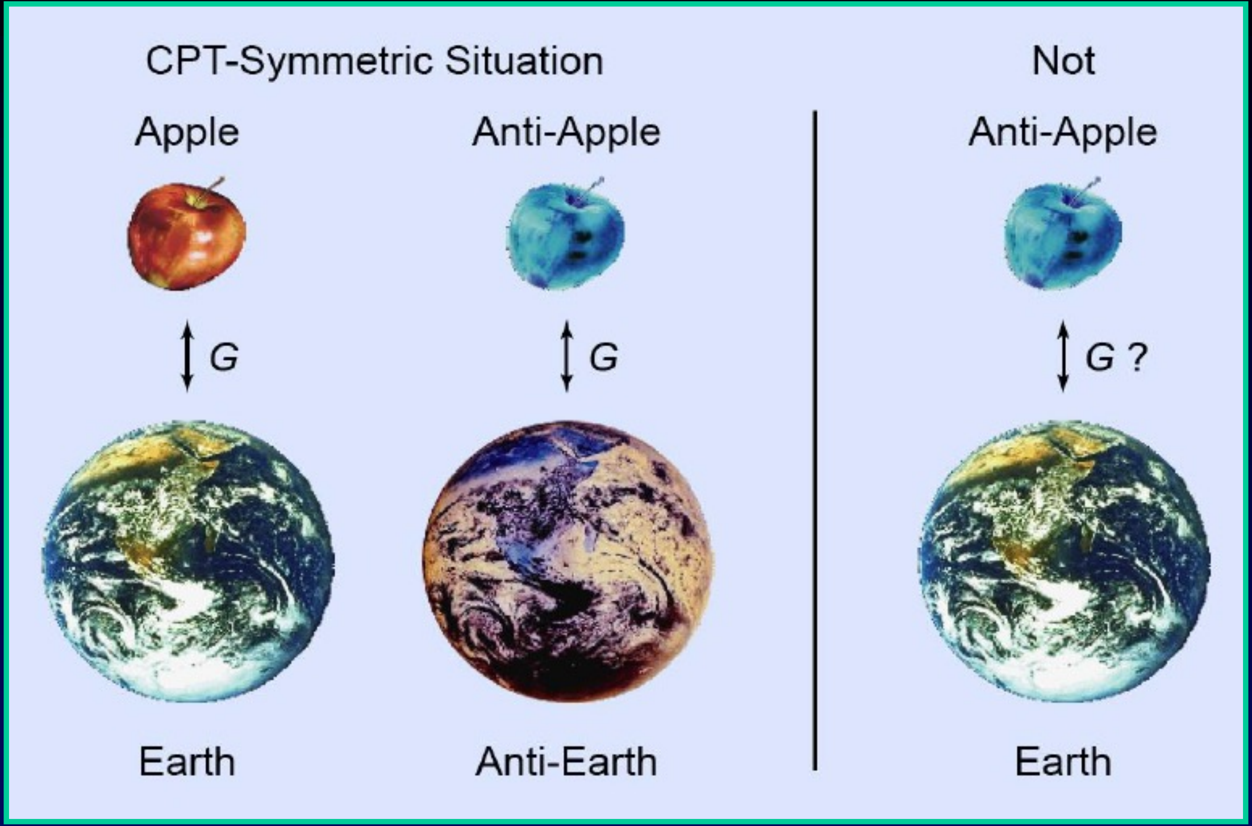
A world of matter and ...

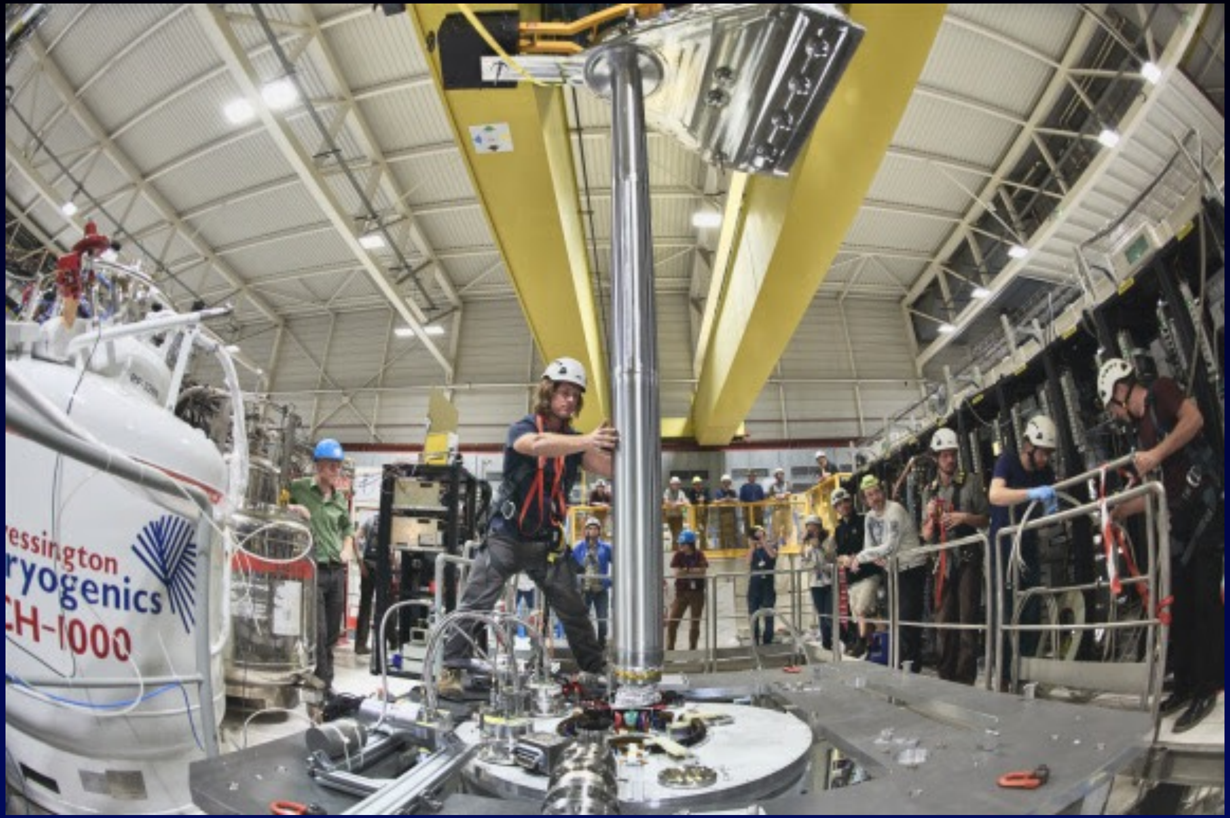


… a world of antimatter



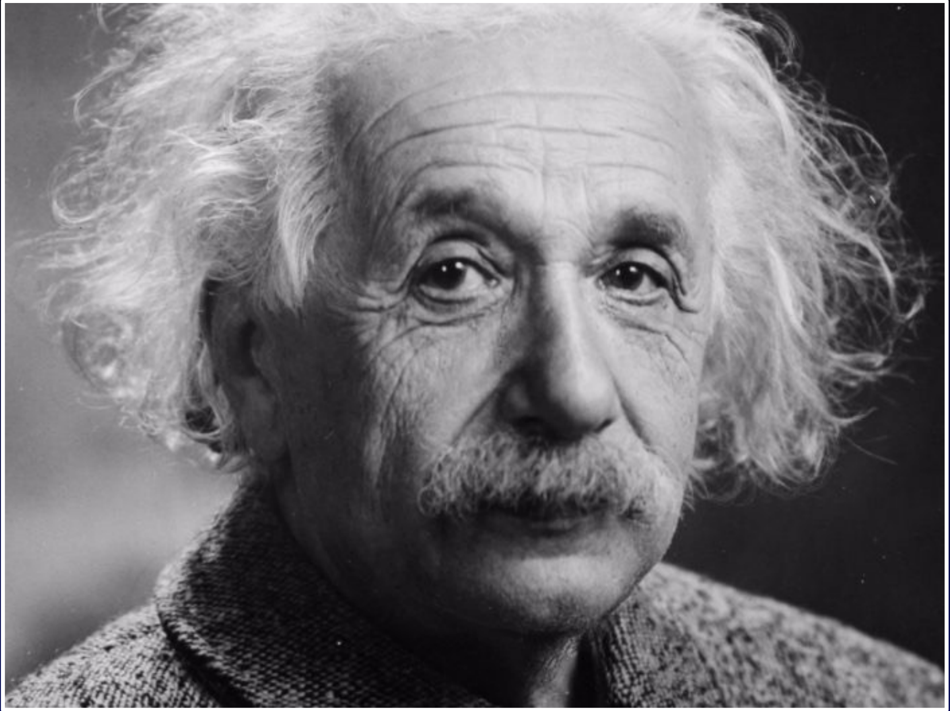
Alpha experiment: successor of Athena

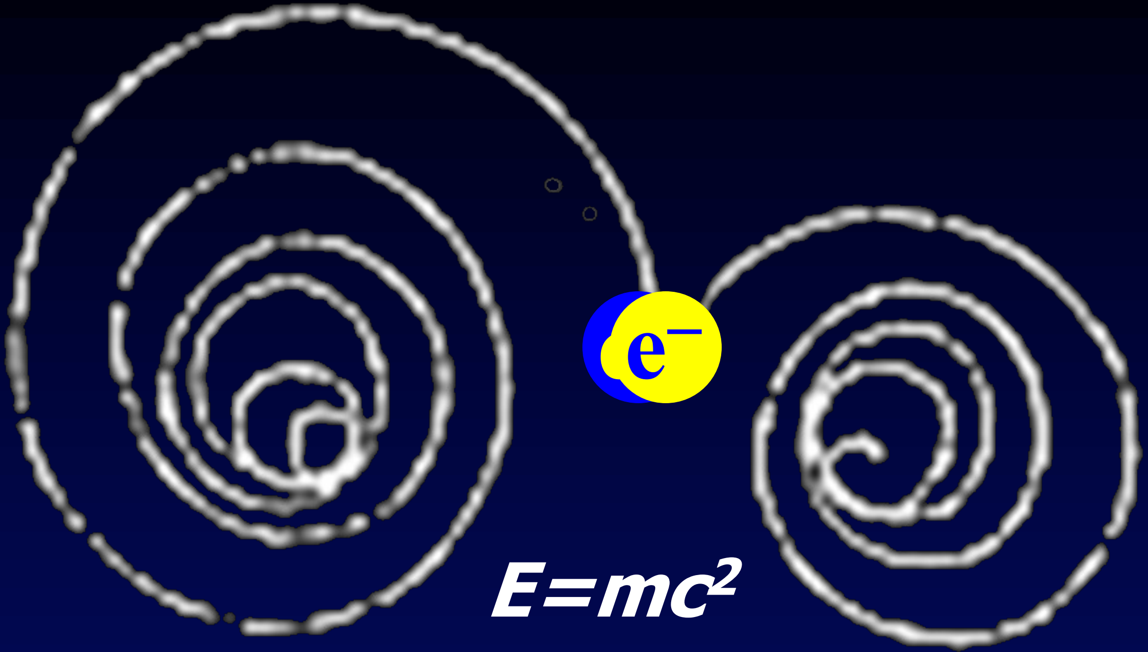




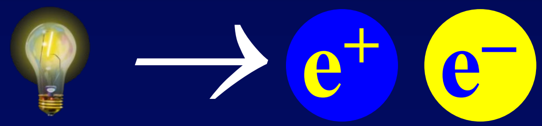
- News on 27 Sept 2023:
  - Several thousands of antimatter hydrogen atoms were dropped in the gravitational field
  - Antimatter falls “down” to earth in the same way as matter does

Albert Einstein: Energy = matter + antimatter

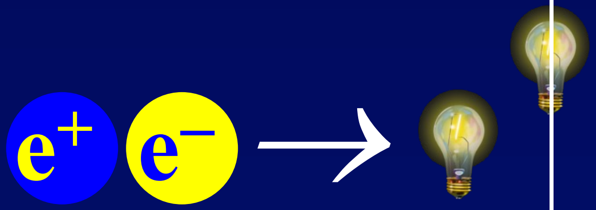


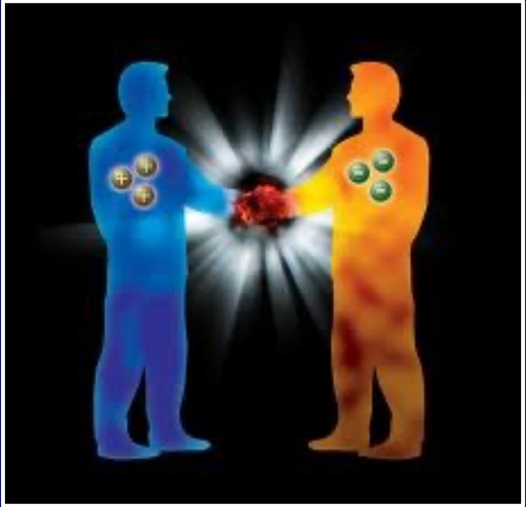


Creation:
Energy → matter + antimatter :

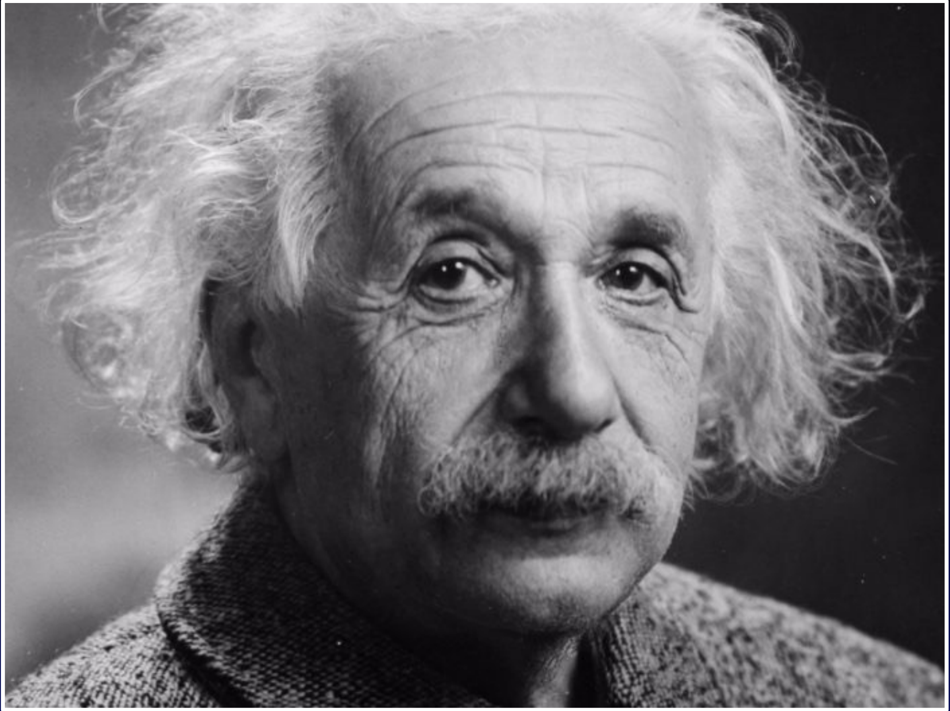


Annihilation:
matter + antimatter → energy :





Albert Einstein: Energy = matter + antimatter

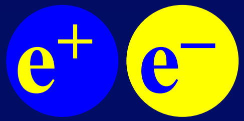


<u>Creation:</u>

Energy → matter + antimatter :

<u>Annihilation:</u>

matter + antimatter → energy :

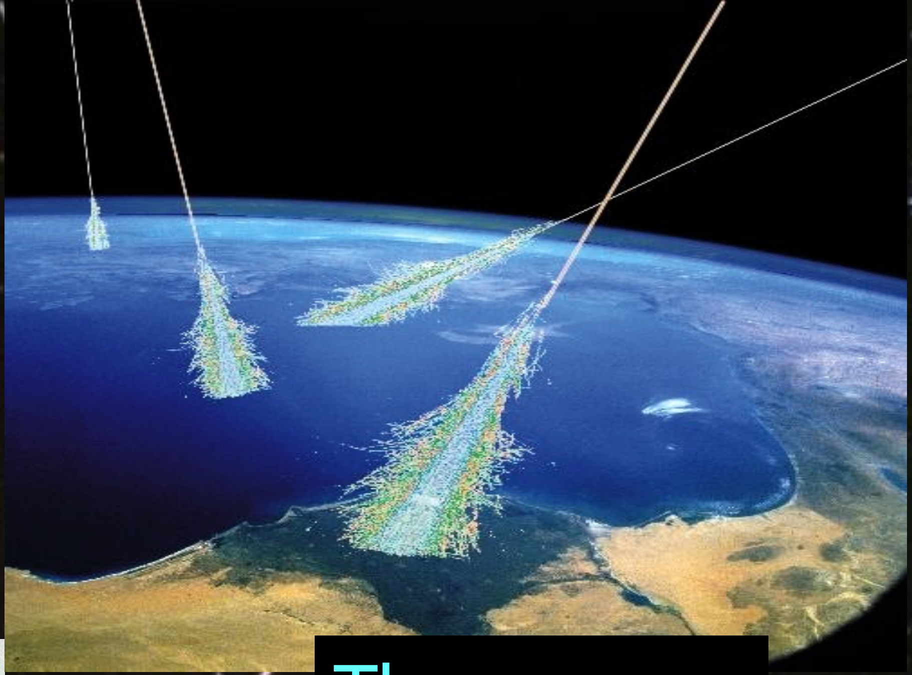


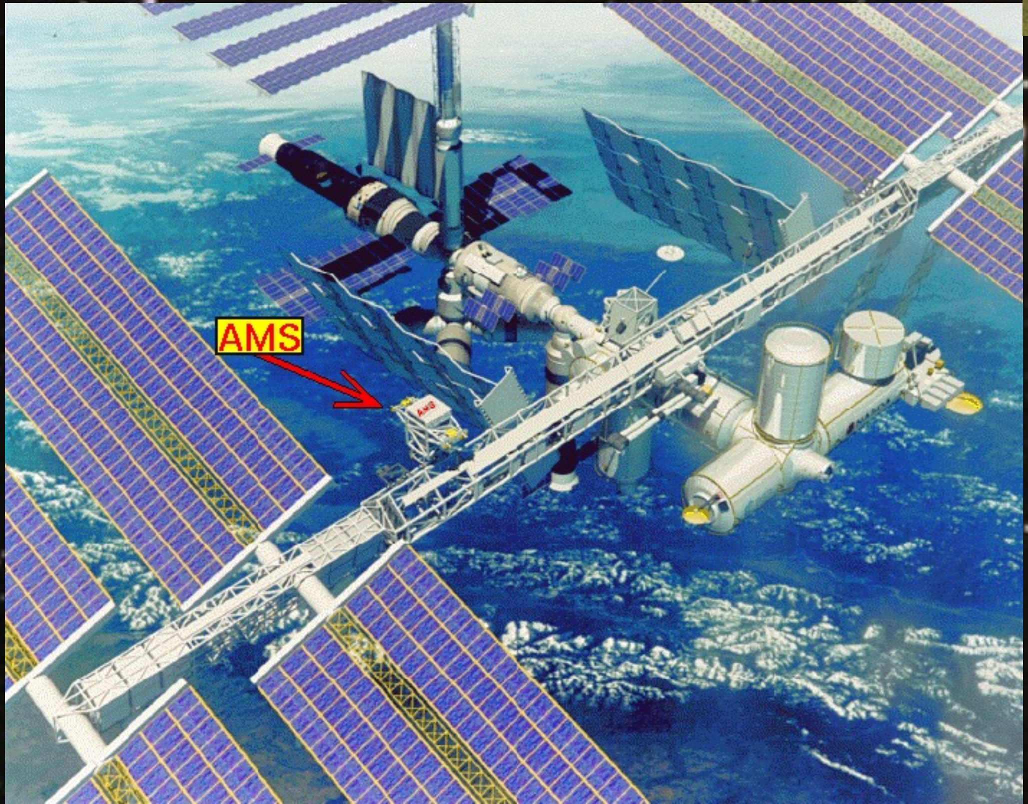
Is there antimatter in nature?

- Does it occur on earth?

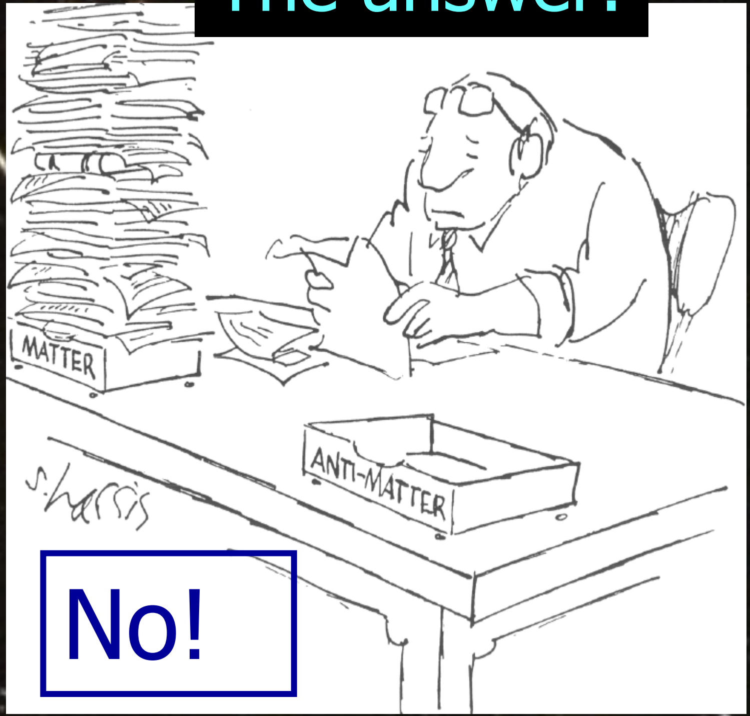
- No, we would immediately see it:
  - "Annihilation"

- Is there antimatter in cosmic radiation?
  - The AMS experiment





The answer:



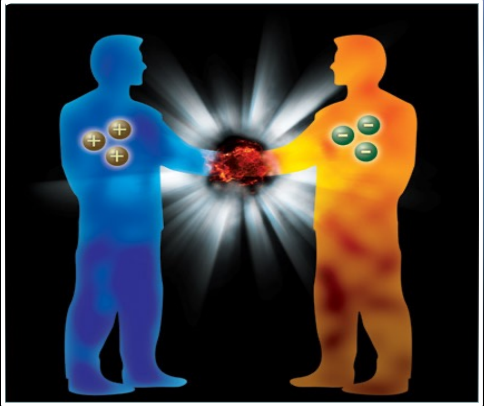
No!

Are there antimatter galaxies?

No!

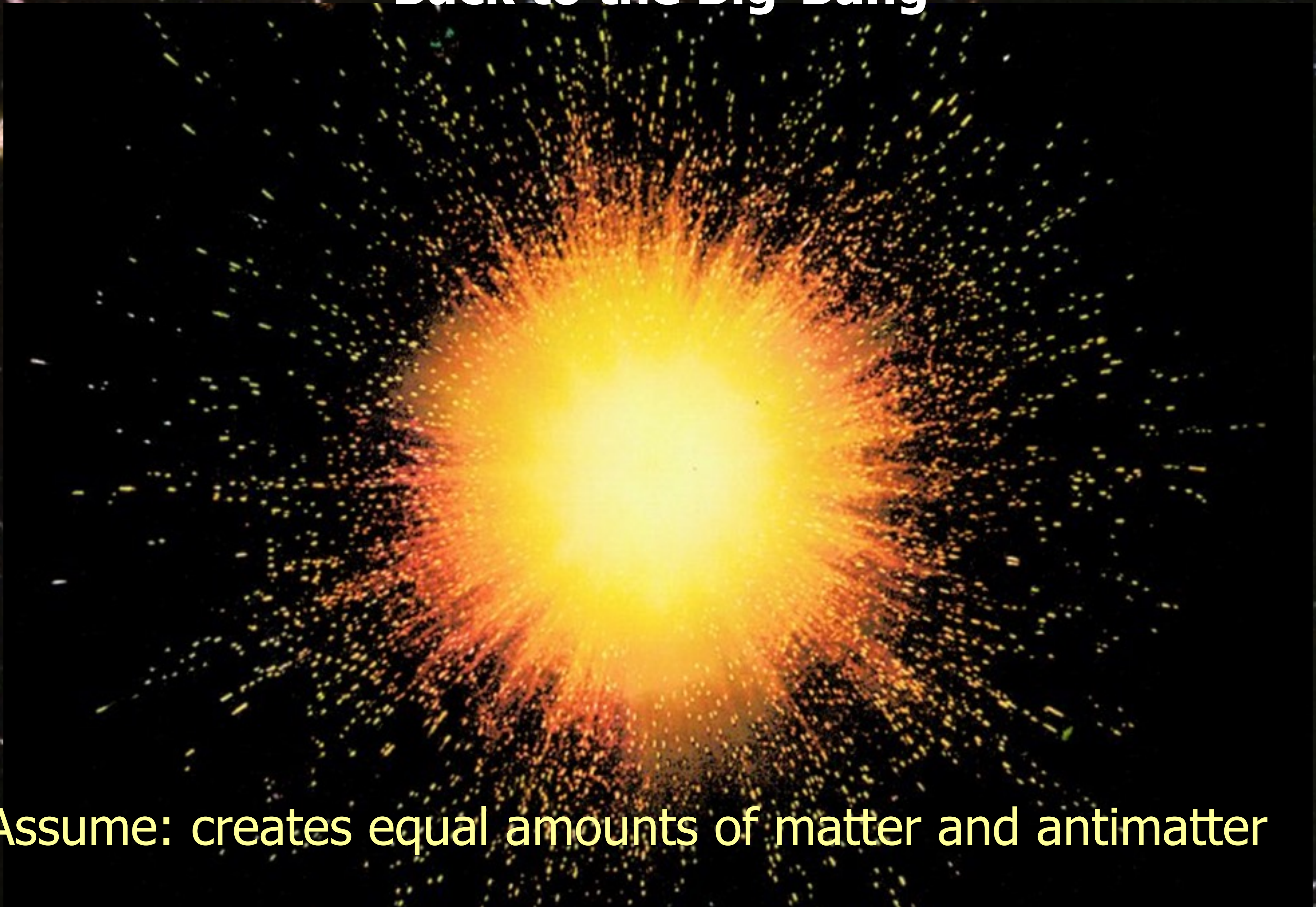
(matter + anti-matter = Intense gamma radiation)

Early Universe: where did the antimatter go?



***Indeed*: Why is there something rather than nothing?**

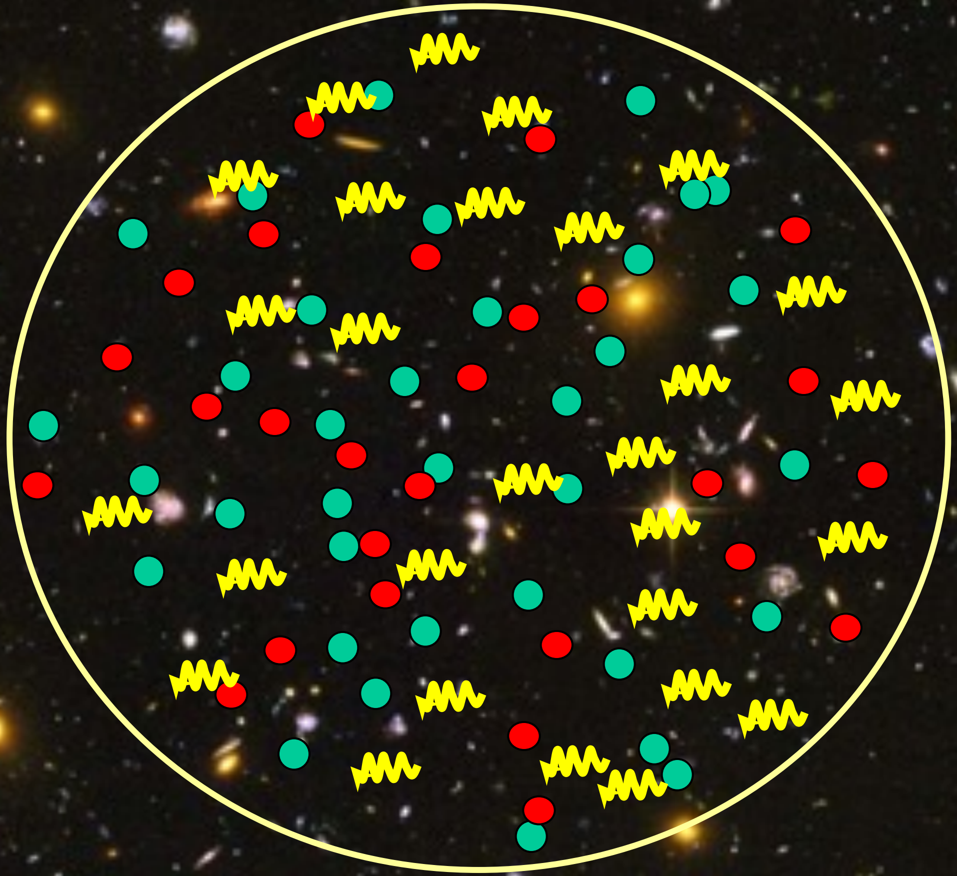
Back to the Big-Bang



Assume: creates equal amounts of matter and antimatter

The early hot universe

Time=0.00000000001 second



($E=mc^2$)

Imagine:

- *matter:* 1000000001
- *antimatter:* 1000000000
- light

So: "teeny weeny" more matter particles than antimatter particles

The expanding and cooling universe

Time ~1 second

$$E = \frac{hc}{\lambda}$$

After cooling and annihilate

matter

antimatter

light

What remains: lots of light and a bit of matter

Ratio : 1000000000 1

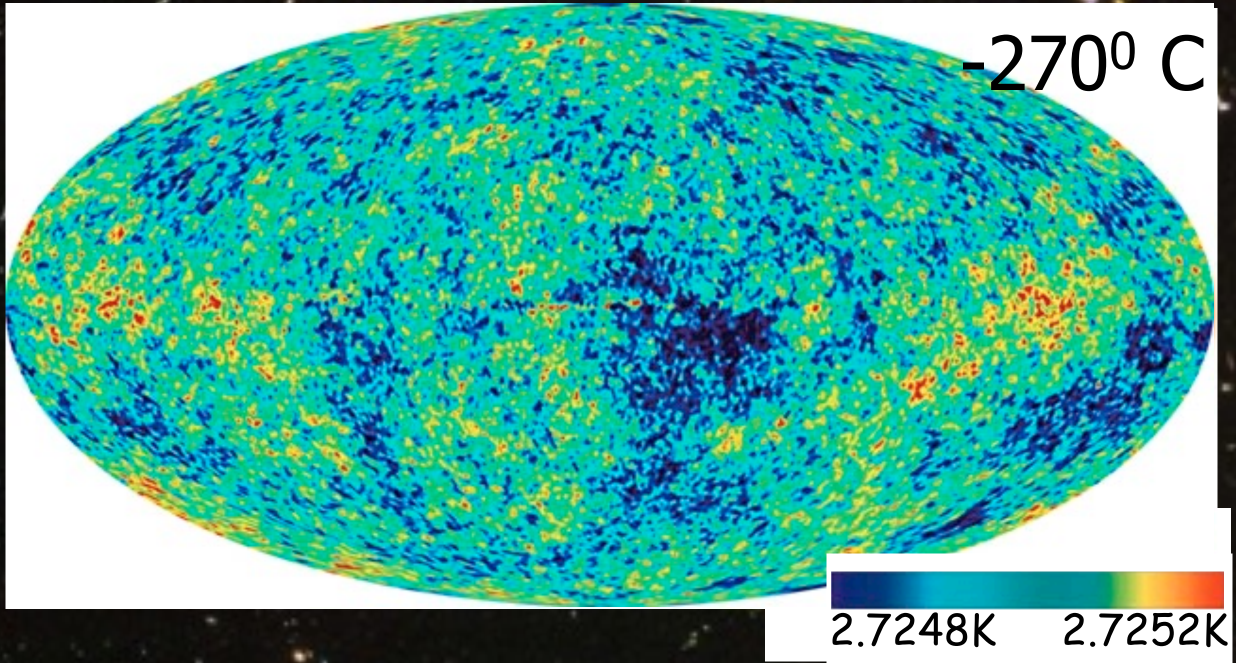
Cosmic Microwave Background Radiation

1964: Penzias and Wilson discover: “background light” (photons)

Remnant of the Big Bang

A temperature map…

Of the univesre

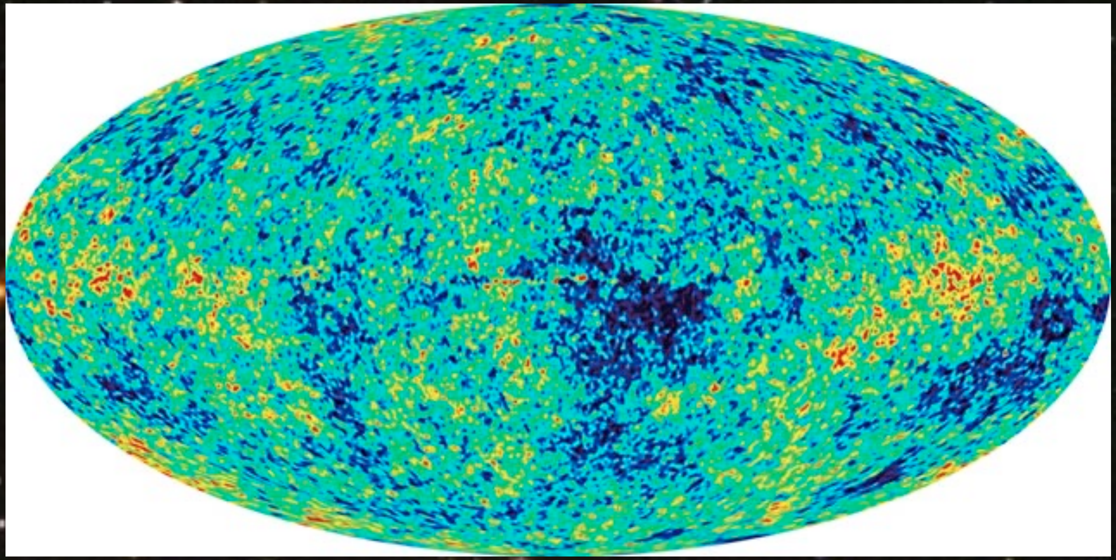


For each matter particle there are a billion photons…

The universe as we see it today

- Observed Background light:

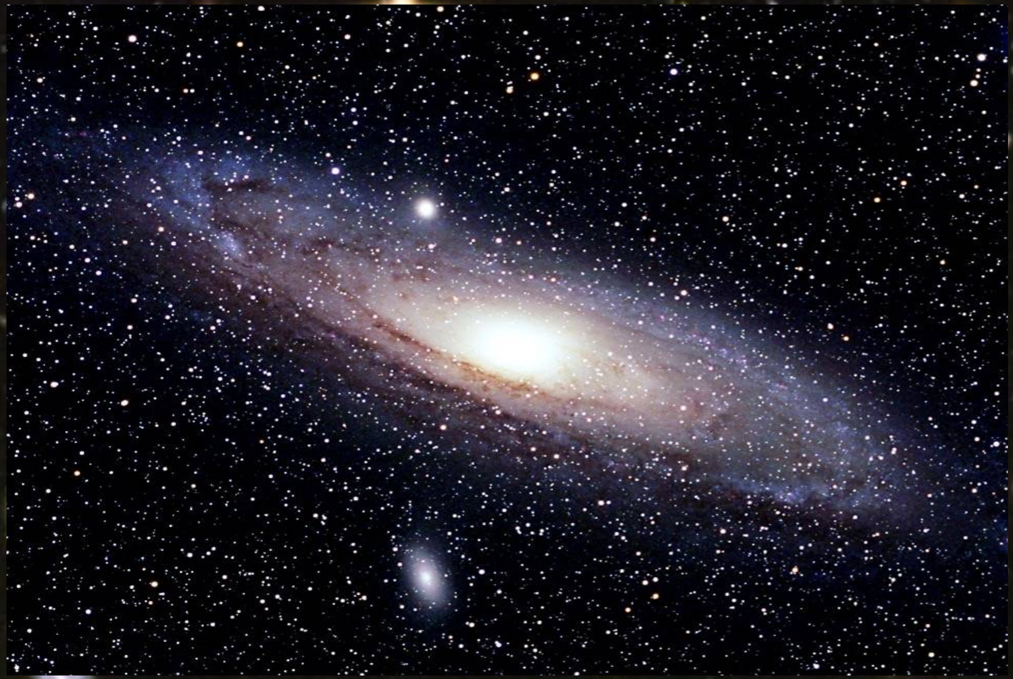
  "many"
  (1000000000)



+

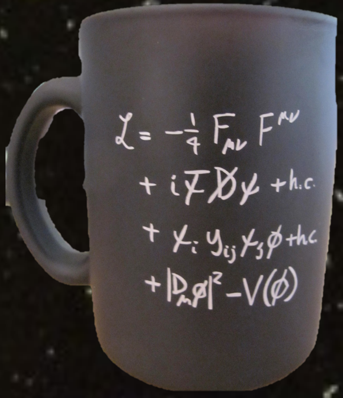
- Remaining Matter particles:

  "few"
  (1)



How did we get a small asymmetry in the Big Bang?

Laws of Nature



?

Big Bang

Small surplus

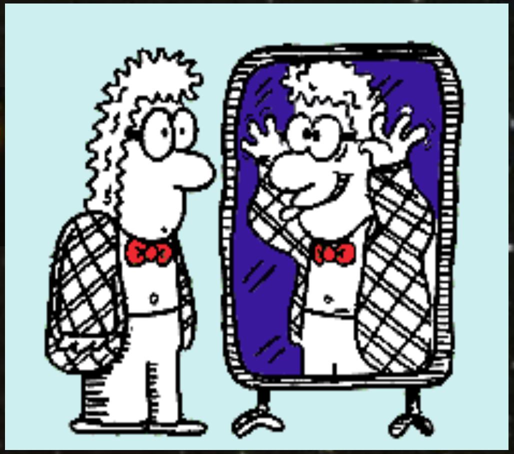
49.999999% anti-matter
50.000001% matter

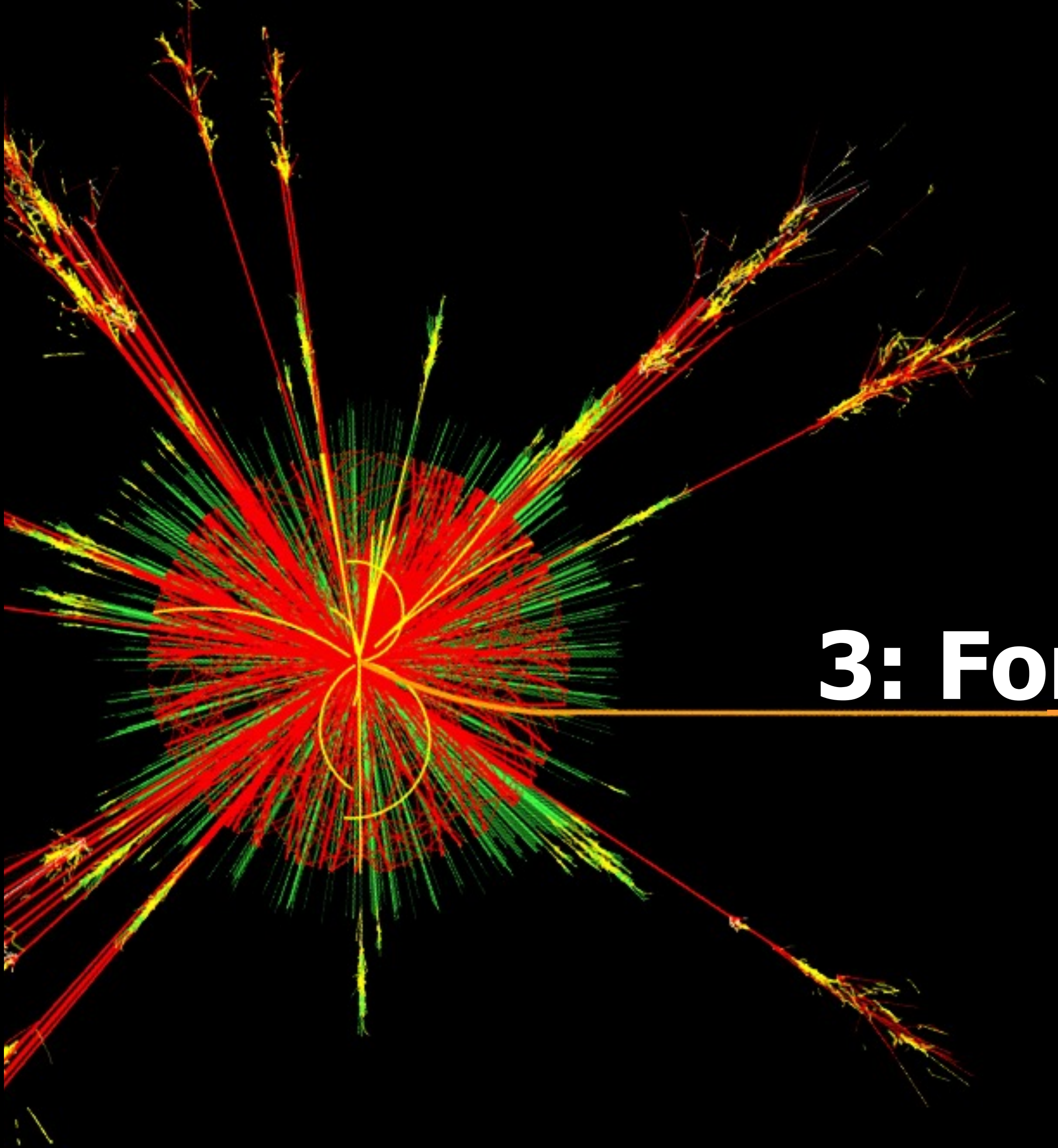
Matter Dominates

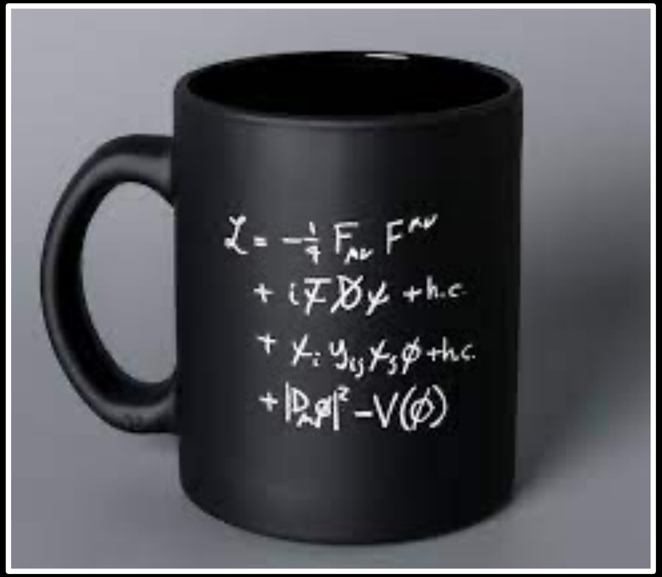
0.000001% matter

(+99.999999% radiation)

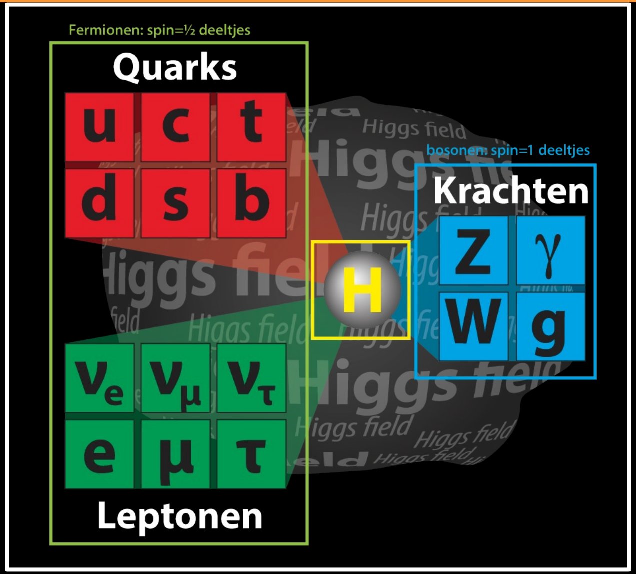
Apparently anti-matter is not the exact mirror image of matter!

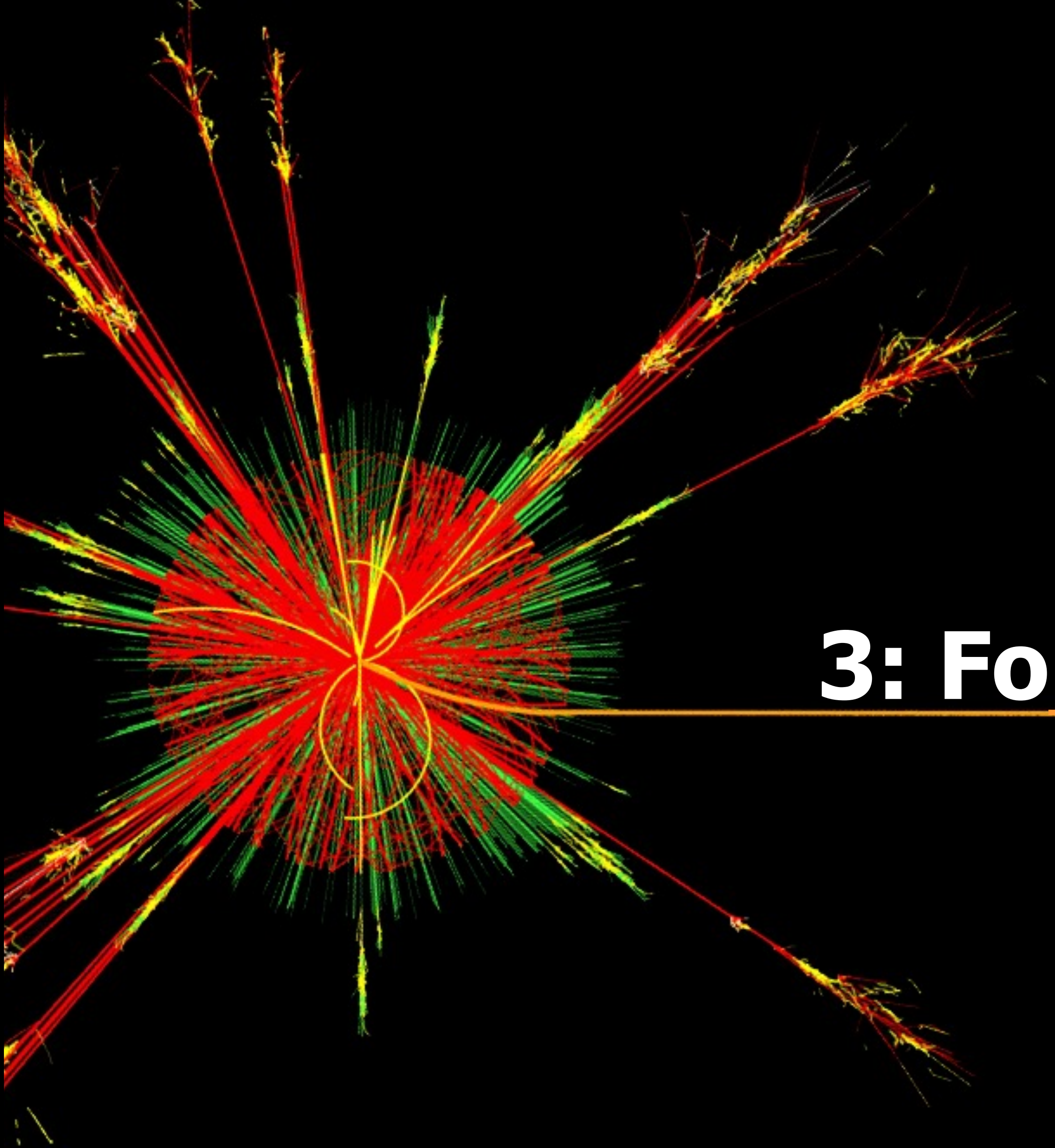






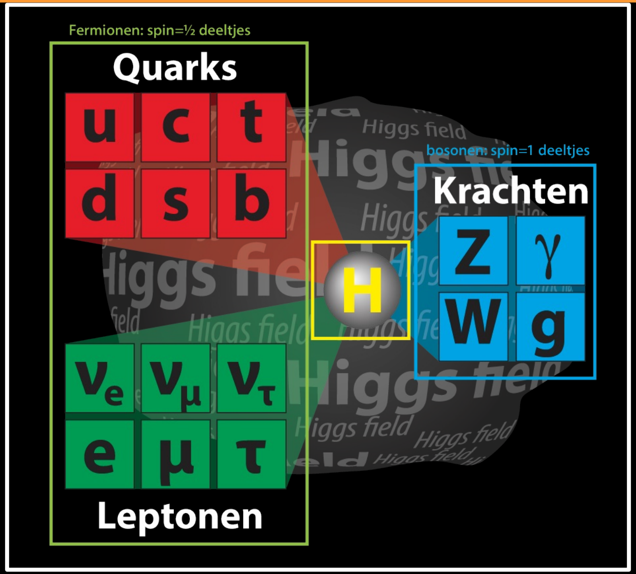
3: Forces: “Standard Model”



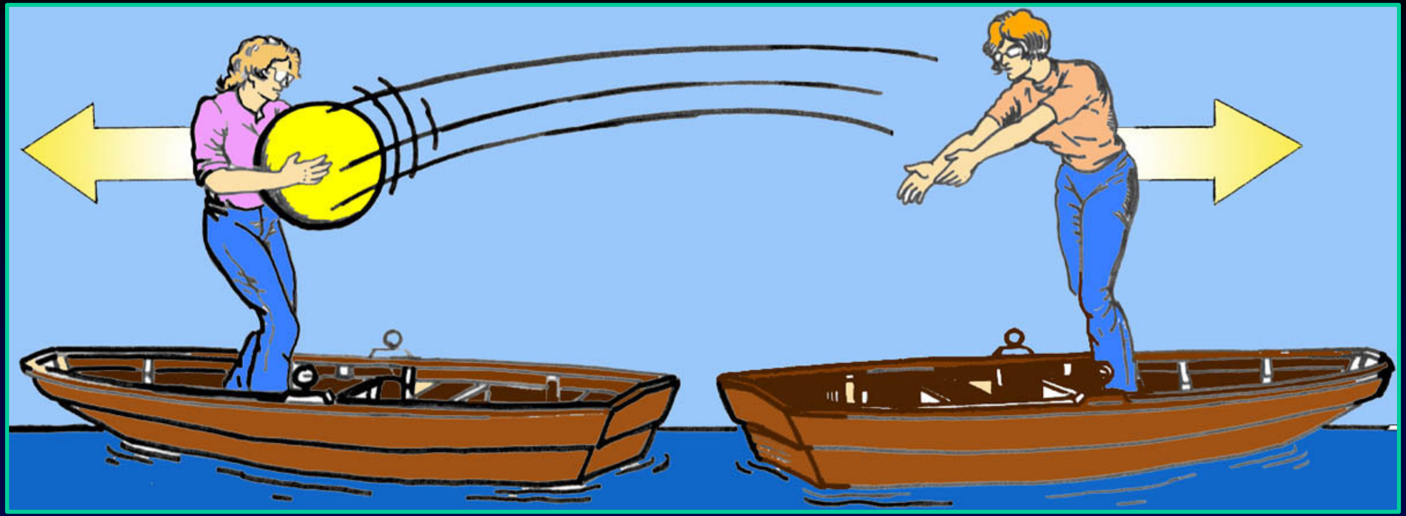


Piele (Giel) Hameleers: also standard model?

3: Forces: “Standard Model”

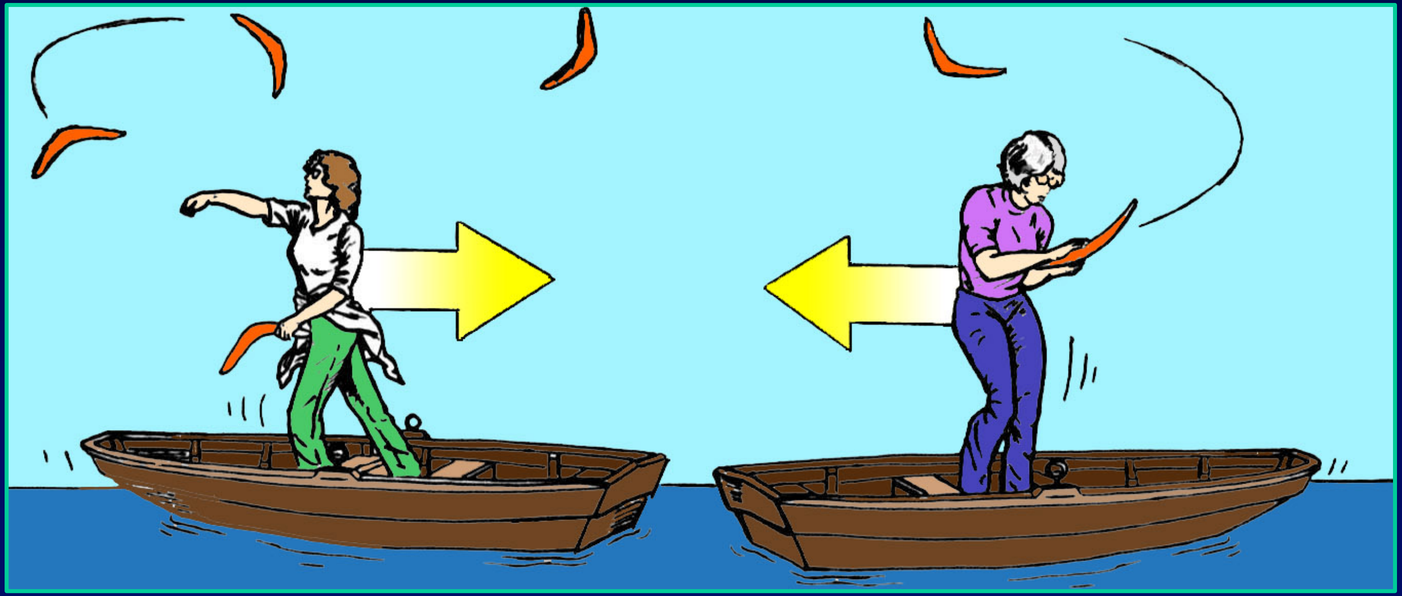


Forces in Quantum Mechanics: exchange of quanta



"Repulsive force"

There is no
"action at a distance"

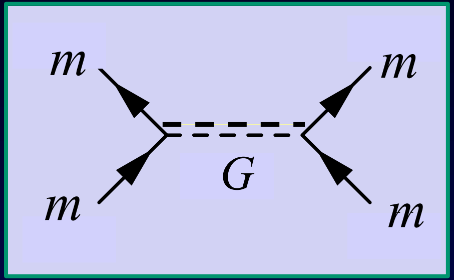


"Atractive force"

Four fundamental forces of nature

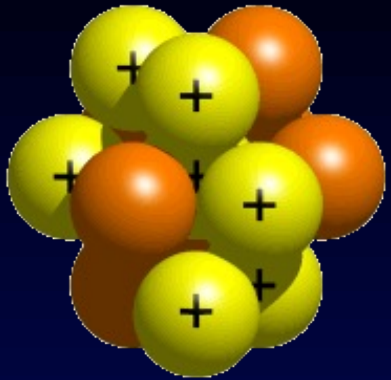
Gravity:

Quantum
Graviton exchange?



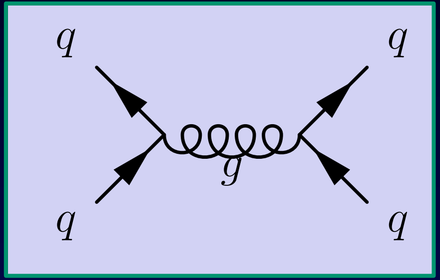
Acts on particles with mass

Strong nuclear force:



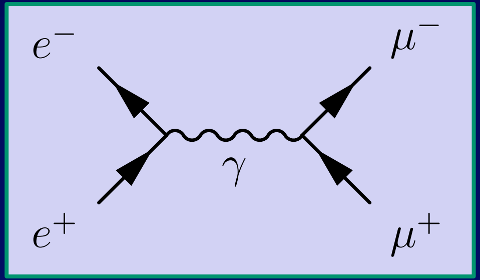
Acts on quarks

Quantum
gluon exchange:



Electromagnetism:

Quantum
photon exchange:

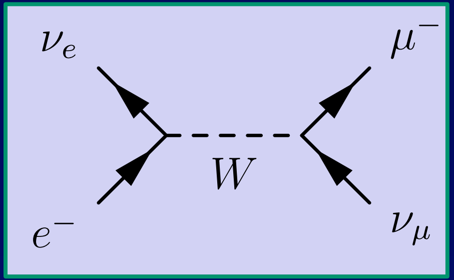


Acts on all charged particles

Weak nuclear force:

Acts on all particles

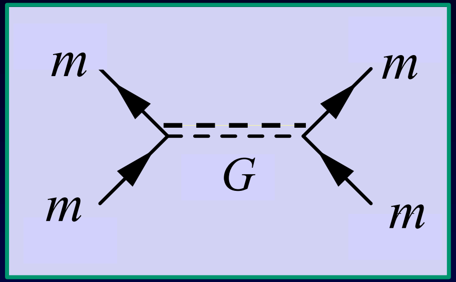
Quantum
W, Z exchange:



Four fundamental forces of nature

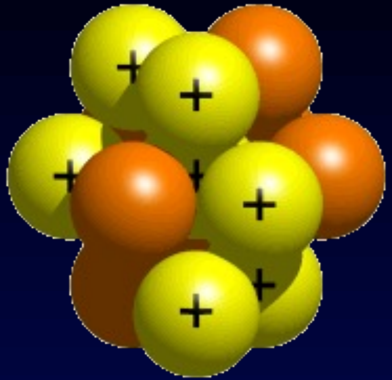
Graivity:

Quantum
Graviton exchange?



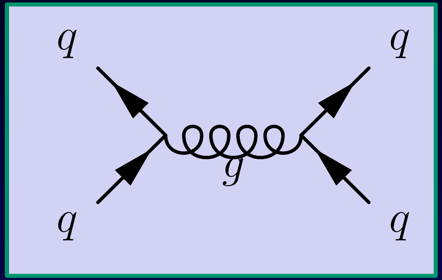
Acts on particles with mass

Strong nuclear force:



Acts on quarks

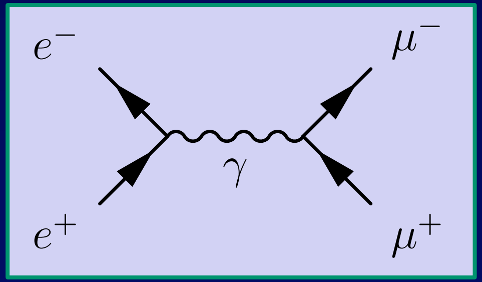
Quantum
gluon exchange:



Ele

ed particles

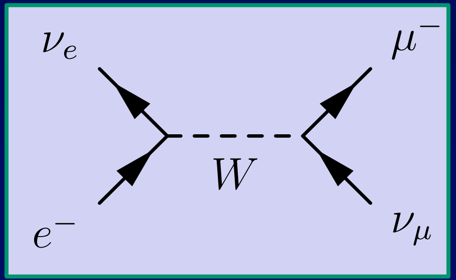
Quantum
photon exchange:



Weak nuclear force:

Acts on all particles

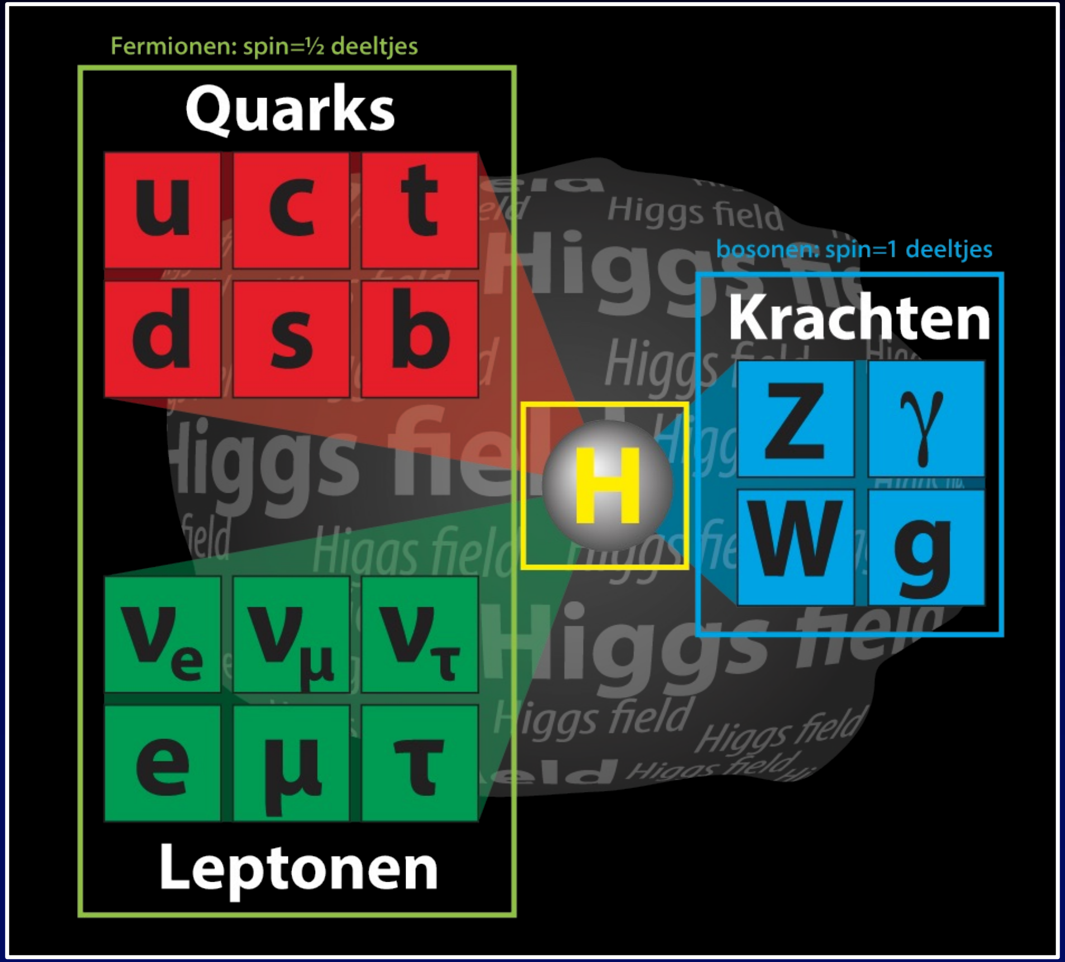
Quantum
W, Z exchange:

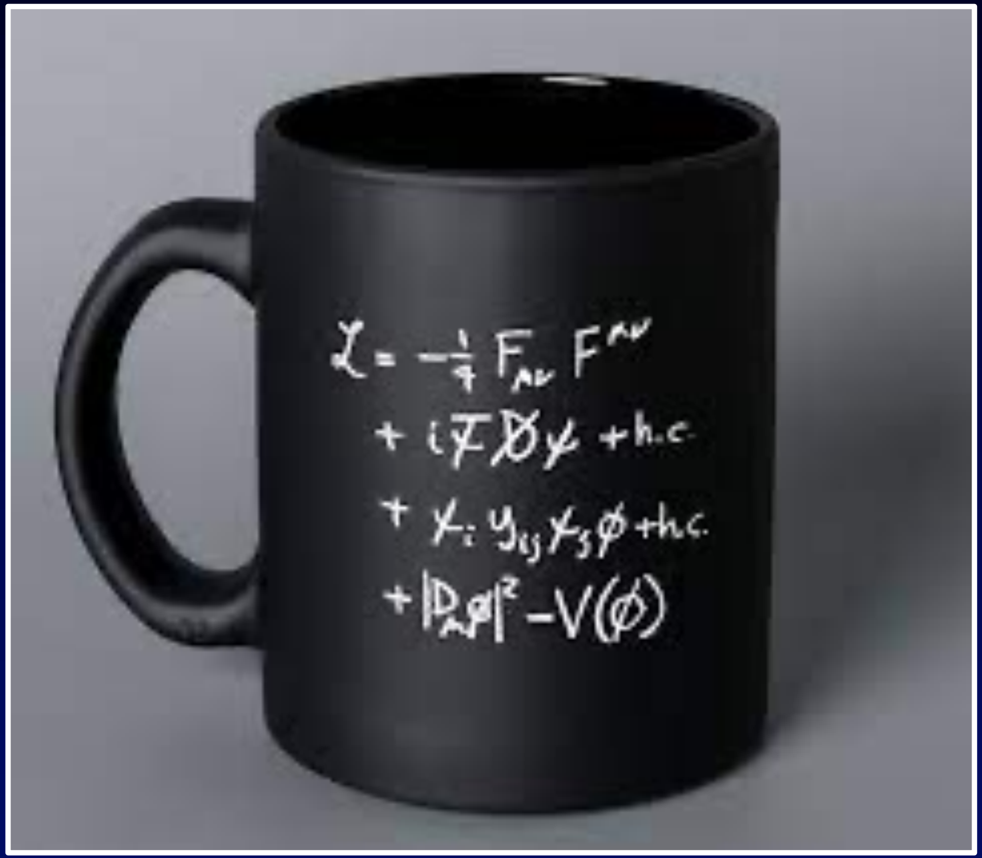


How strong are the forces?

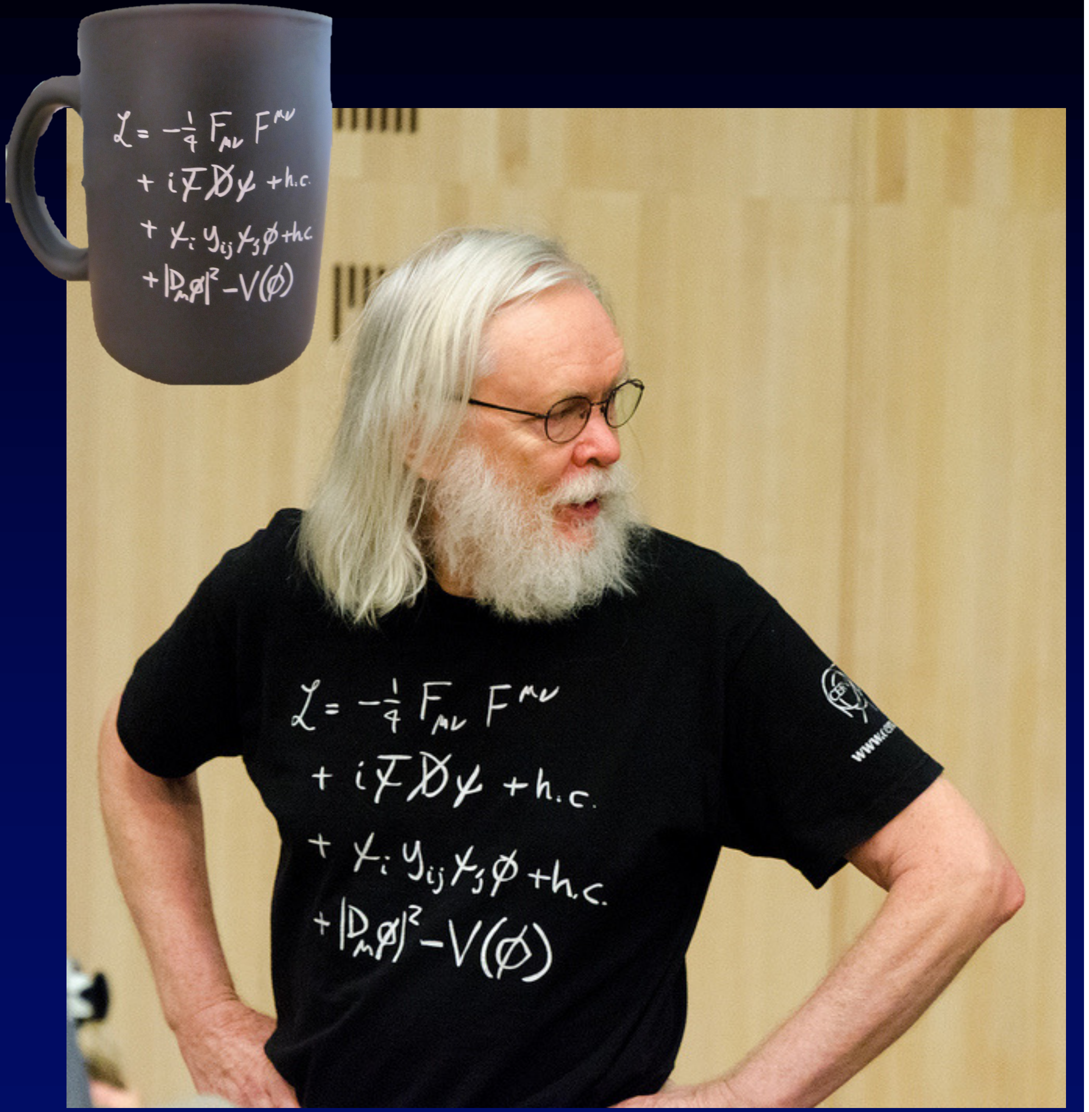
	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons
Strength	0.0000000000000 000000000000000 0000000000001	0.0001	1	60

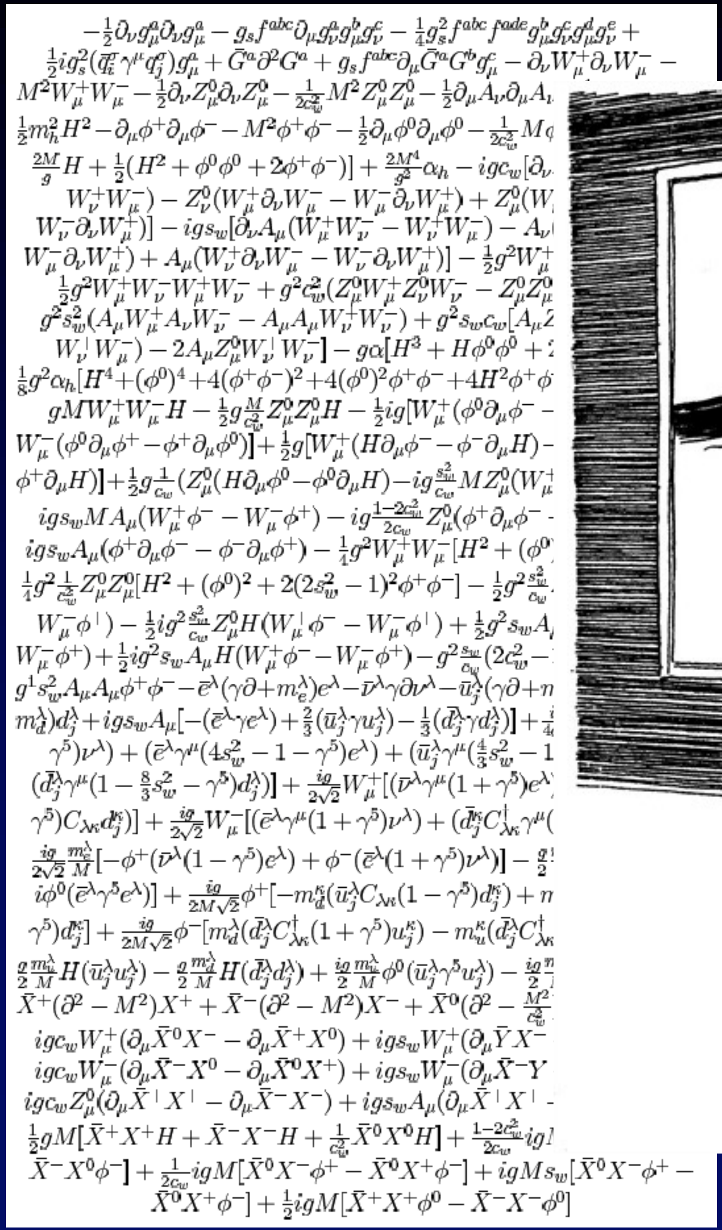
Standard Model: Particles and Forces





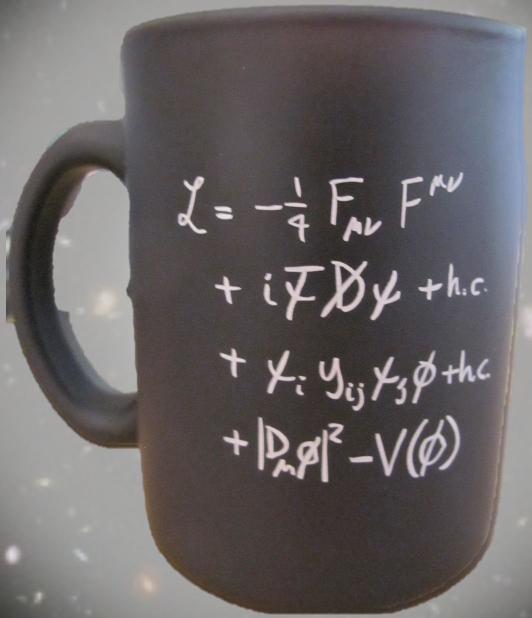
Standard Model: Theory



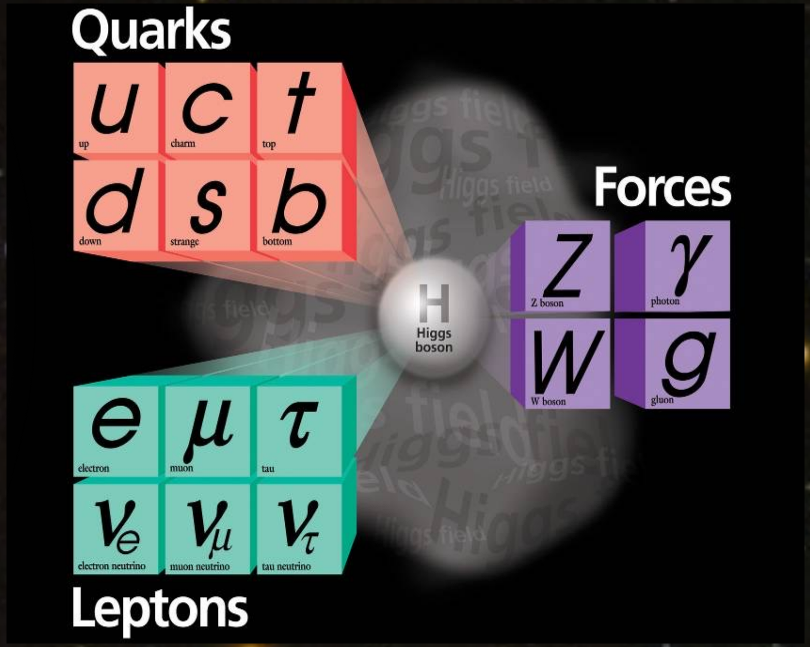


Standard Model

"The formula"



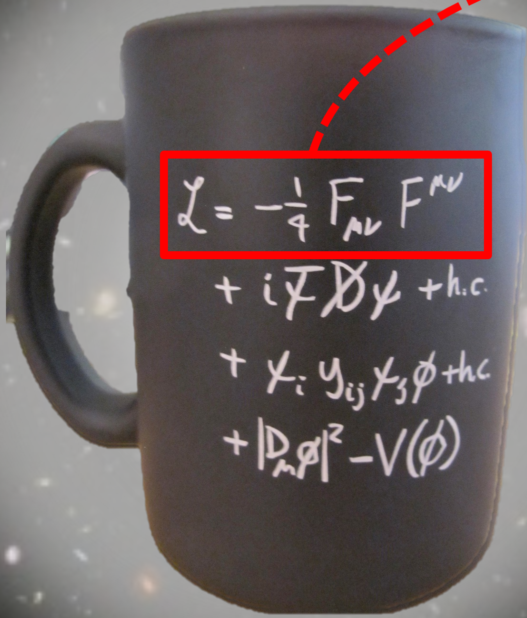
"The building blocks"

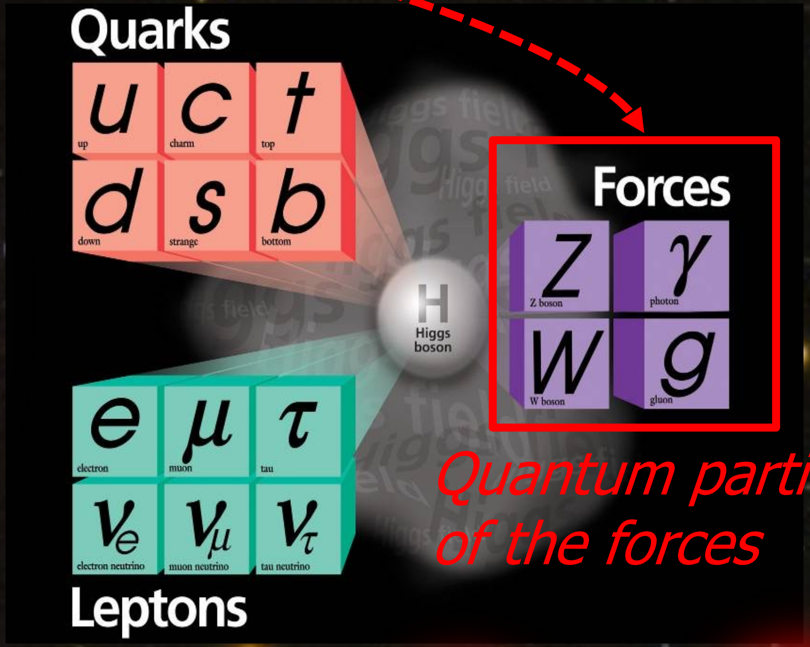


Standard Model

"The formula"

"The building blocks"



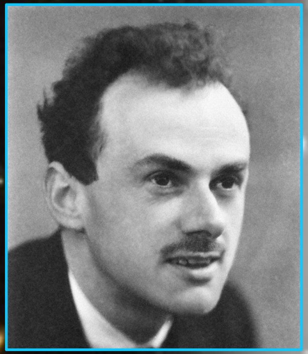


Quantum particles of the forces

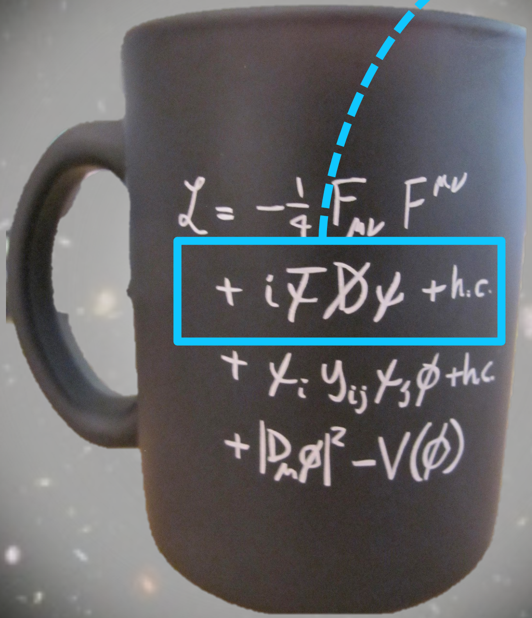
Standard Model

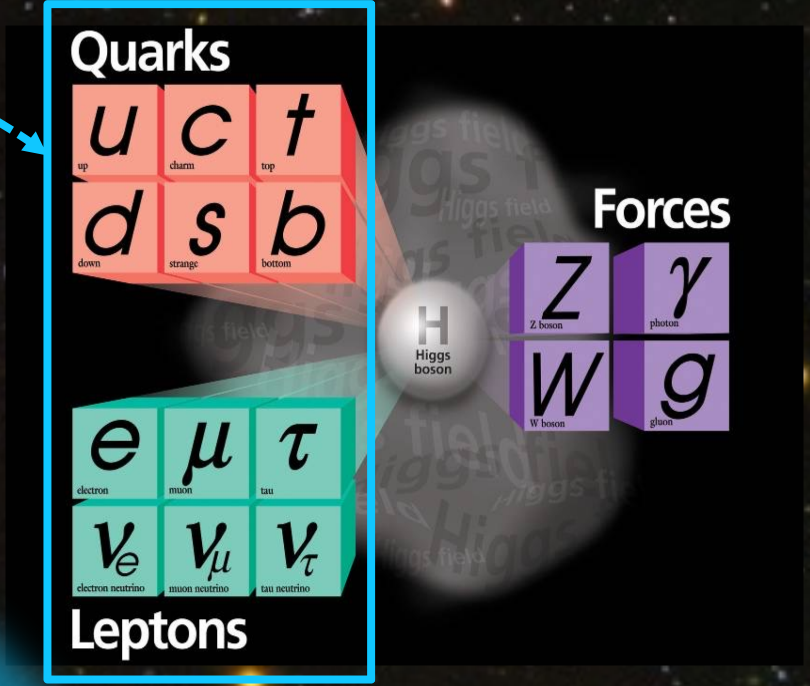
"The formula"

"The building blocks"

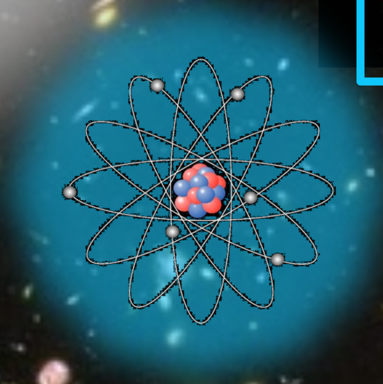


1928: Dirac equation



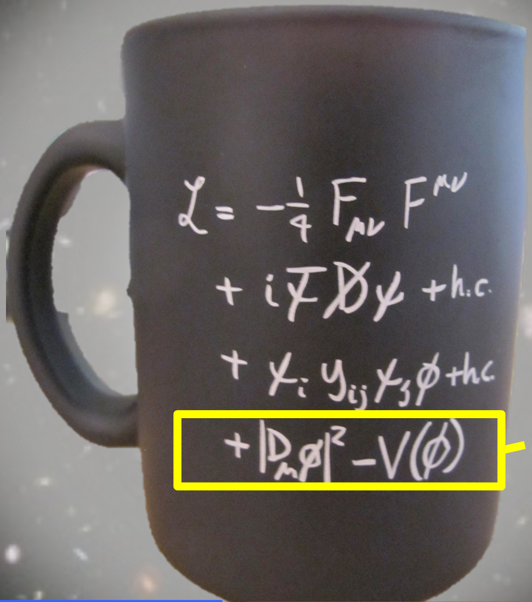


Matter particles

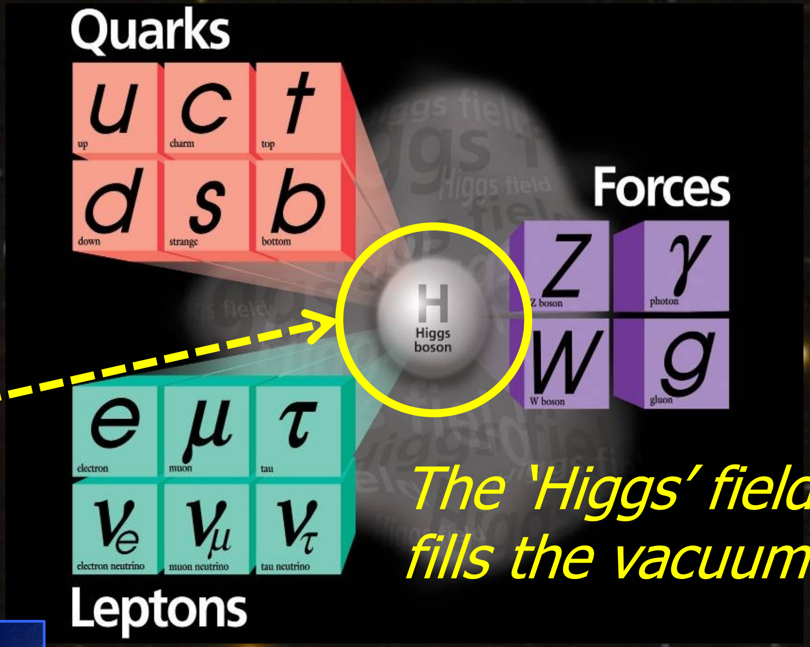


Standard Model

"The formula"

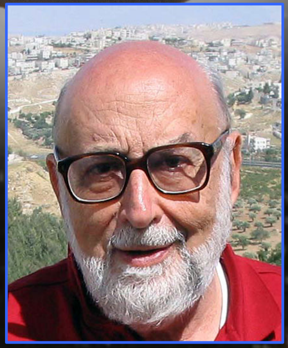


"The building blocks"



The 'Higgs' field fills the vacuum

Brout



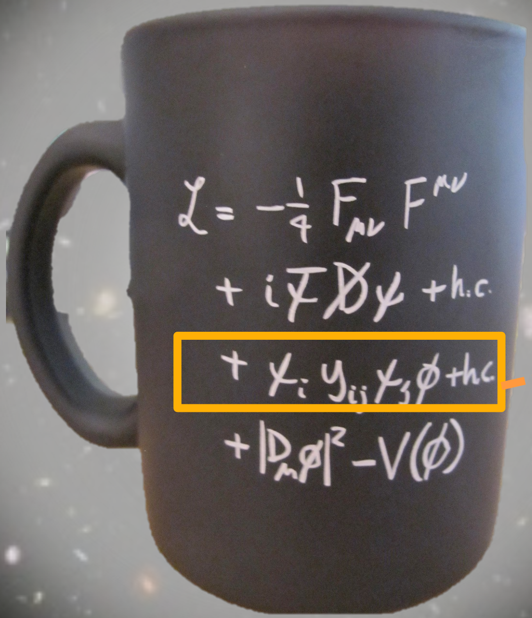
Englert

Higgs

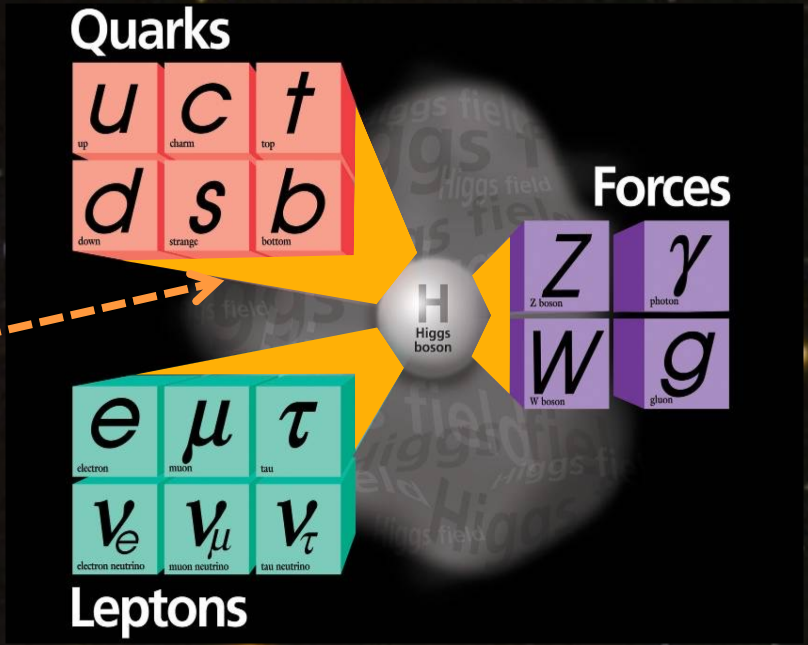
1964:
Standard Model <u>prediction:</u>
empty space is not empty!

Standard Model

"The formula"



"The building blocks"



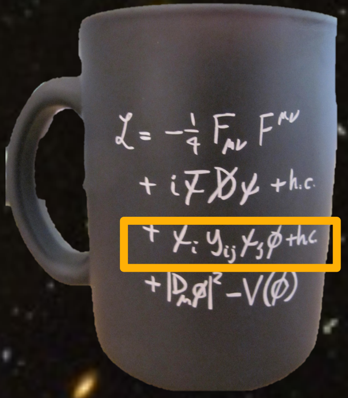
Mass is generated by the Higgs field!

Kobayashi

Maskawa

1972:
With 3 ***copies of particles*** *an asymmetry between matter and antimatter is possible!*

How did antimatter disappear in the Big bang?



Big Bang

Small Surplus

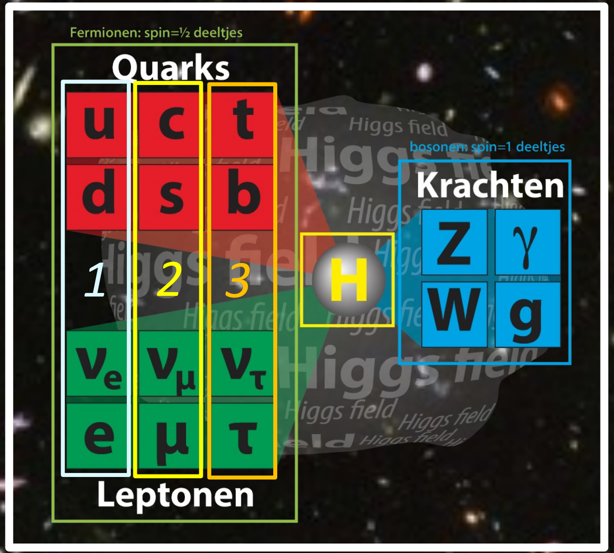
49.999999% anti-matter

50.000001% matter

Dominates

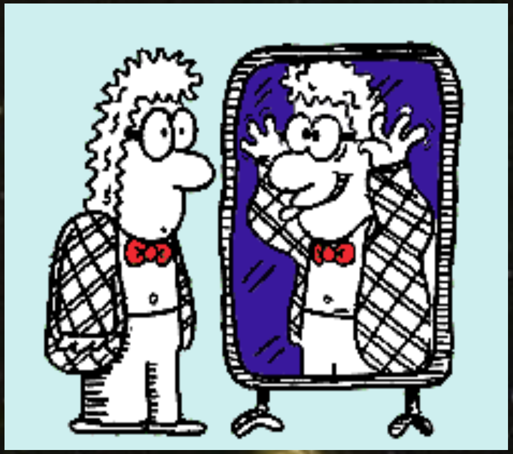
0.000001% matter

(+99.999999% radiation)



Antimaterie not the exact mirror image of matter?!

Theoretically his requires three copies of all particles!



Honey, you did your best, but that was really disgusting!