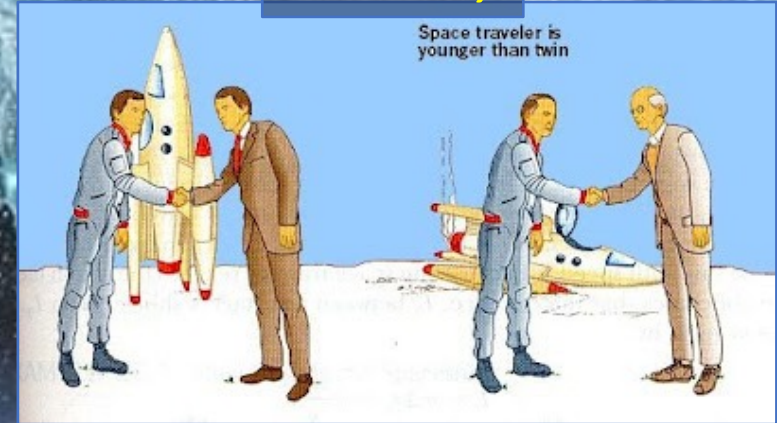


The Relativistic Quantum World

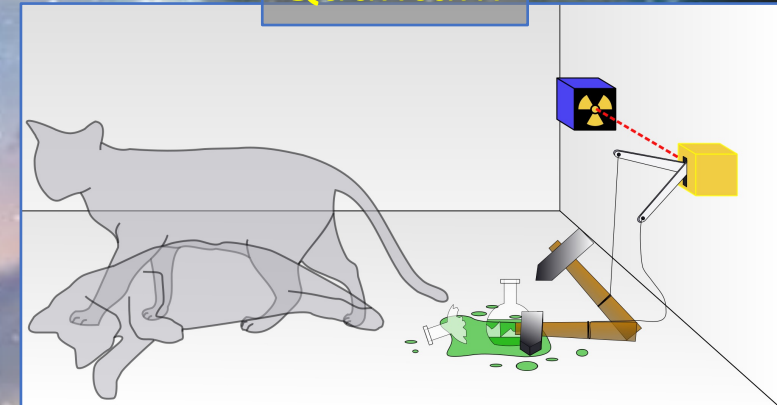
A lecture series on
Relativity Theory and Quantum Mechanics

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

Relativity



Quantum



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

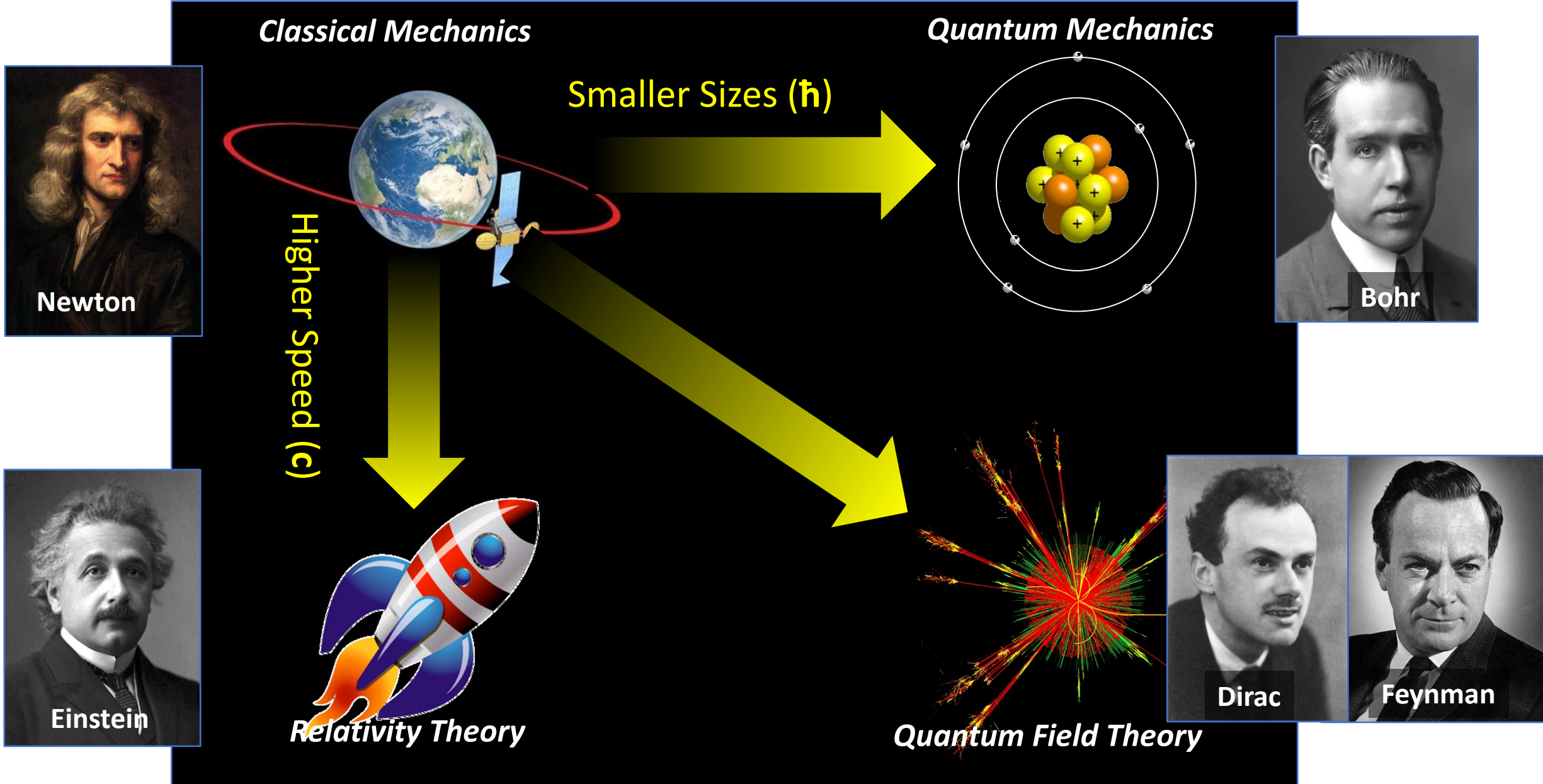
Standard Model

Nov. 29:

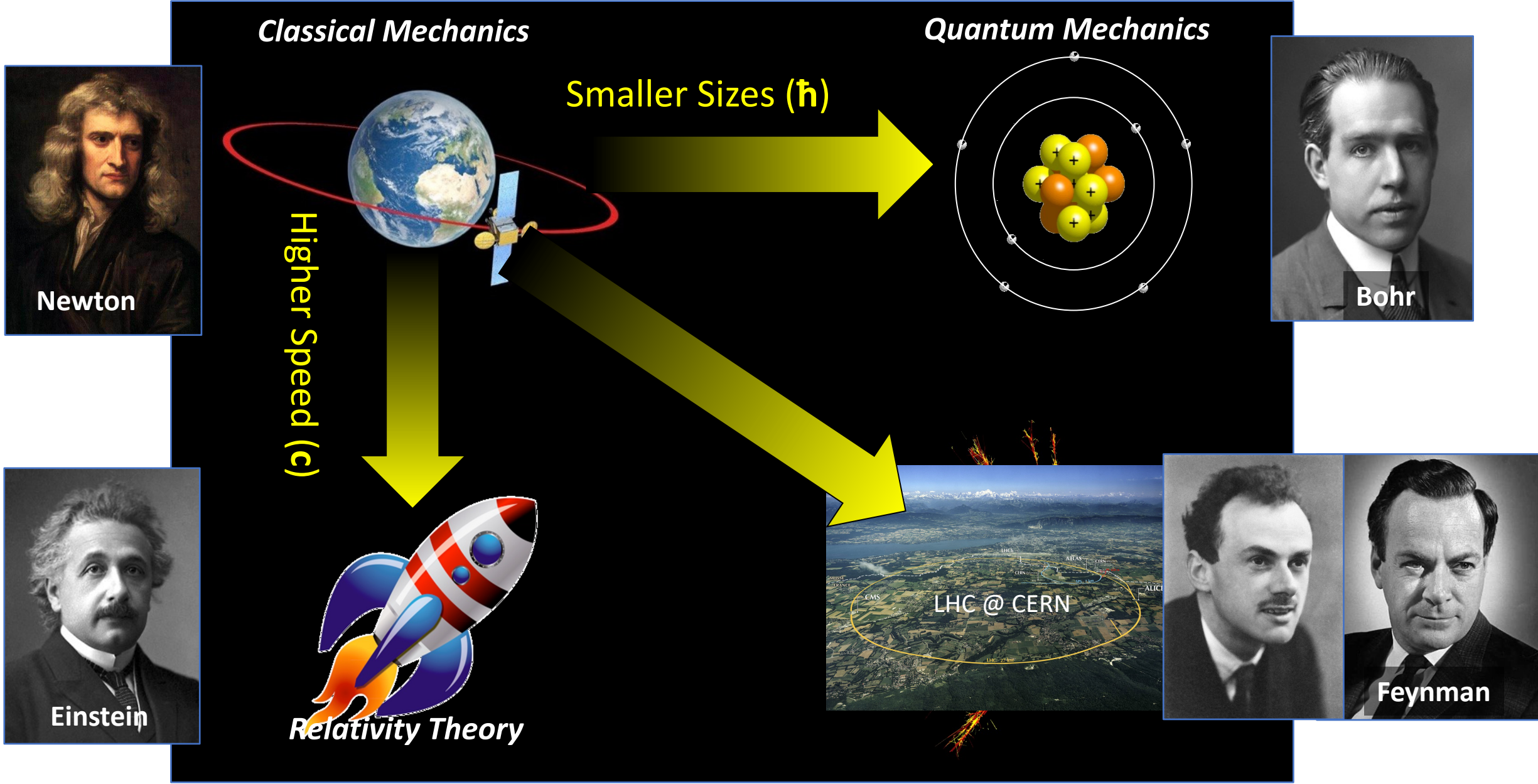
Lecture 9: The Standard Model and Antimatter
Lecture 10: Why is there something rather than nothing?

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



Astronomy

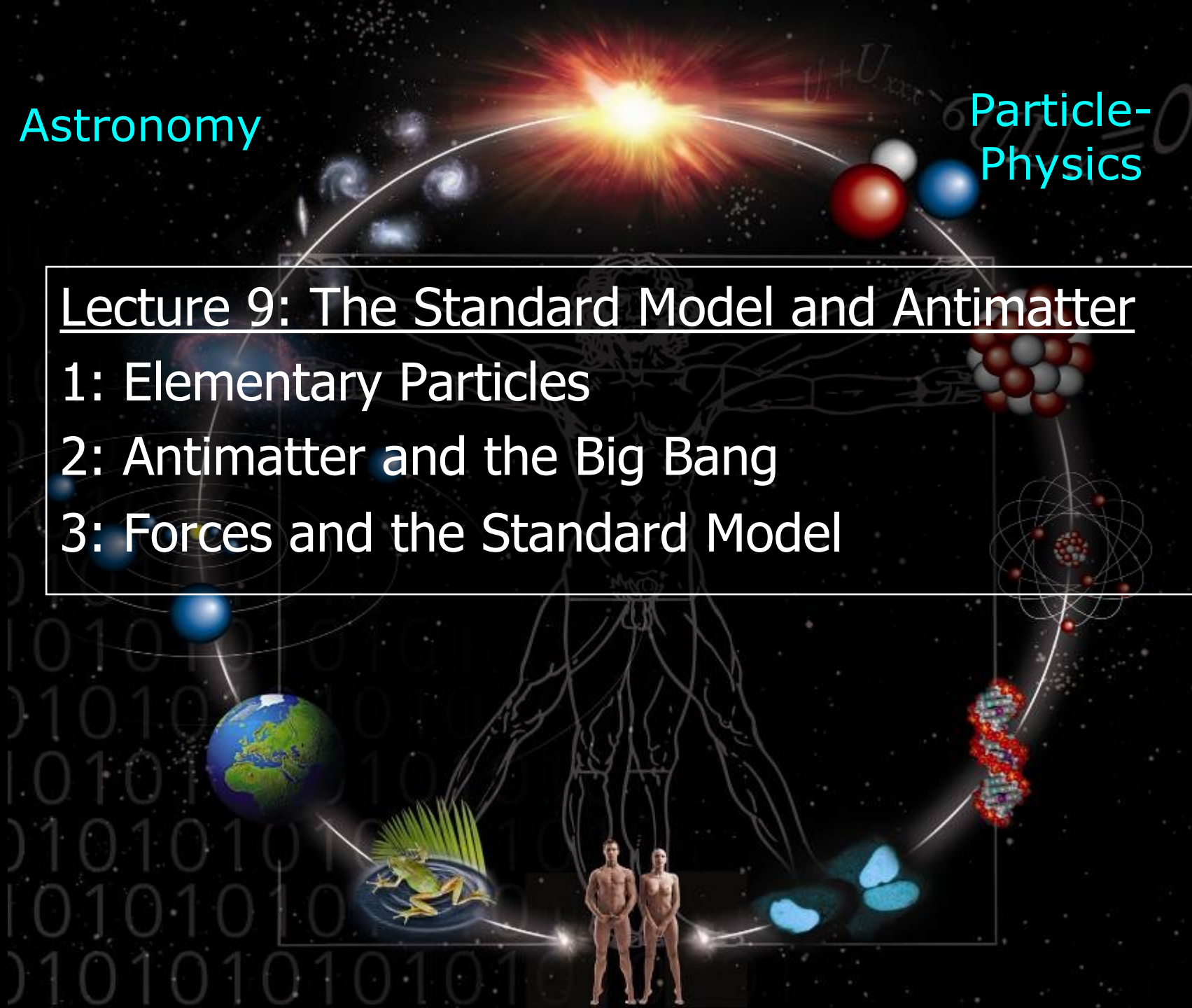
Particle-
Physics

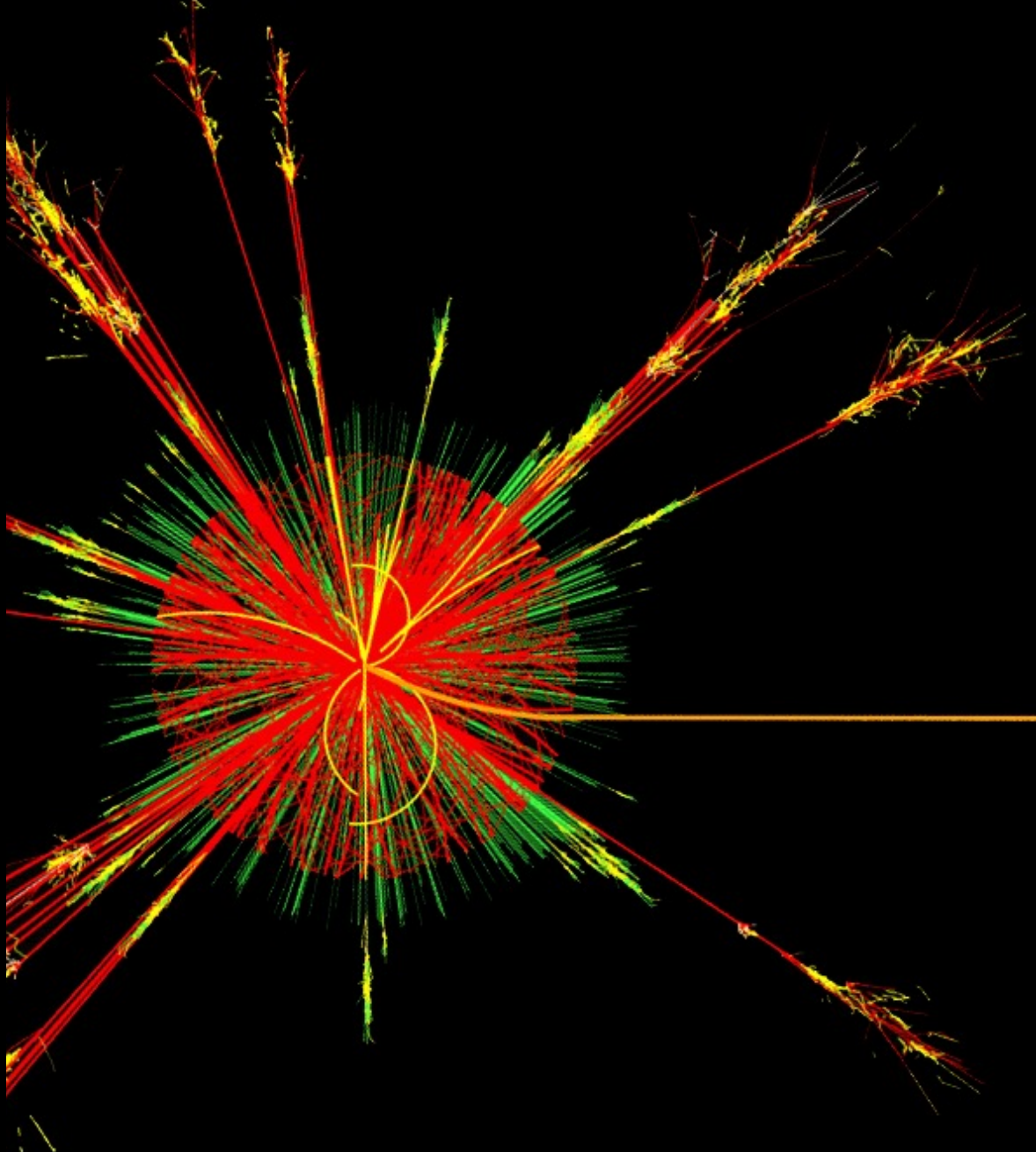
Lecture 9: The Standard Model and Antimatter

1: Elementary Particles

2: Antimatter and the Big Bang

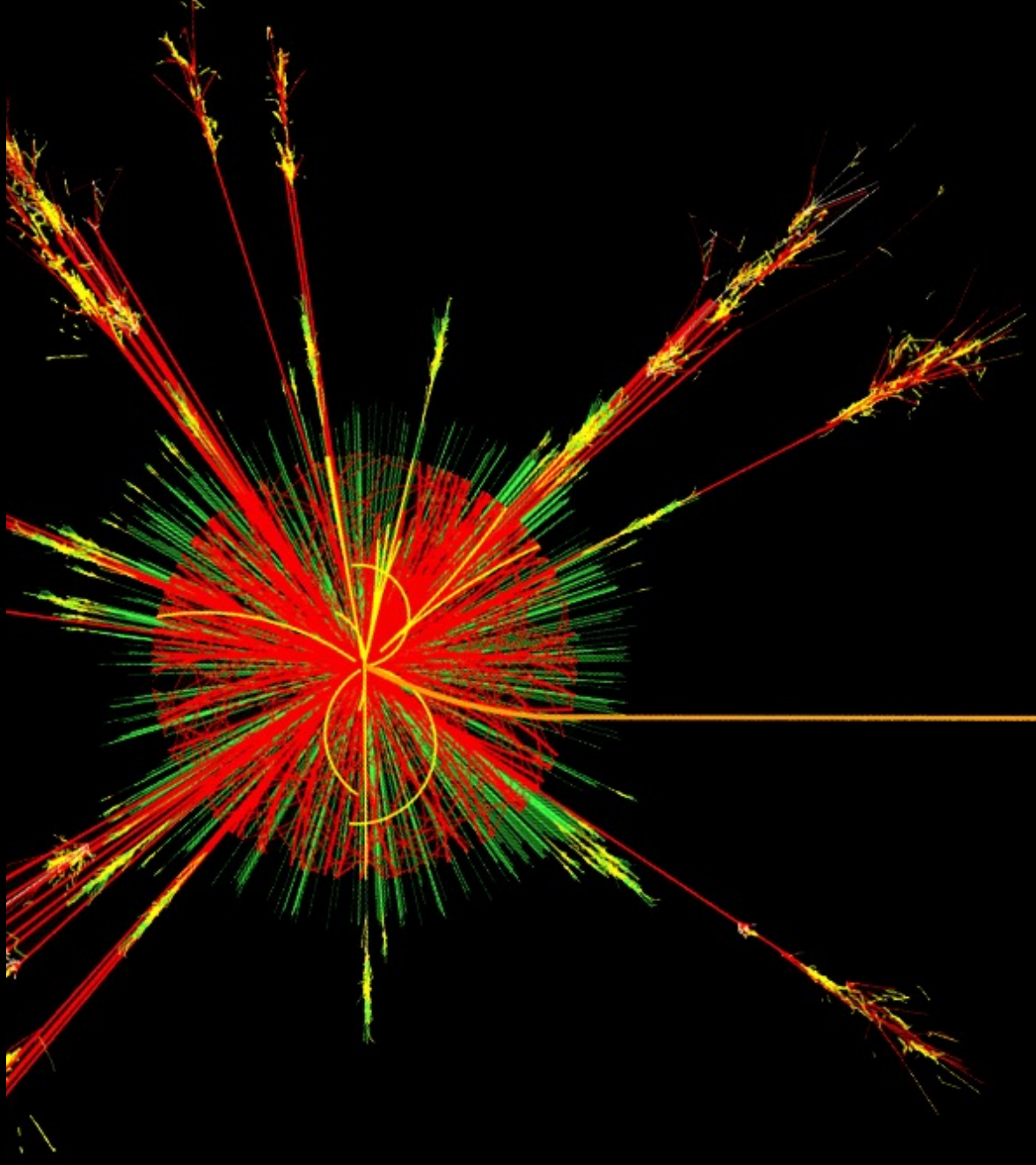
3: Forces and the Standard Model





1: Elementary Particles

"All things come in three"

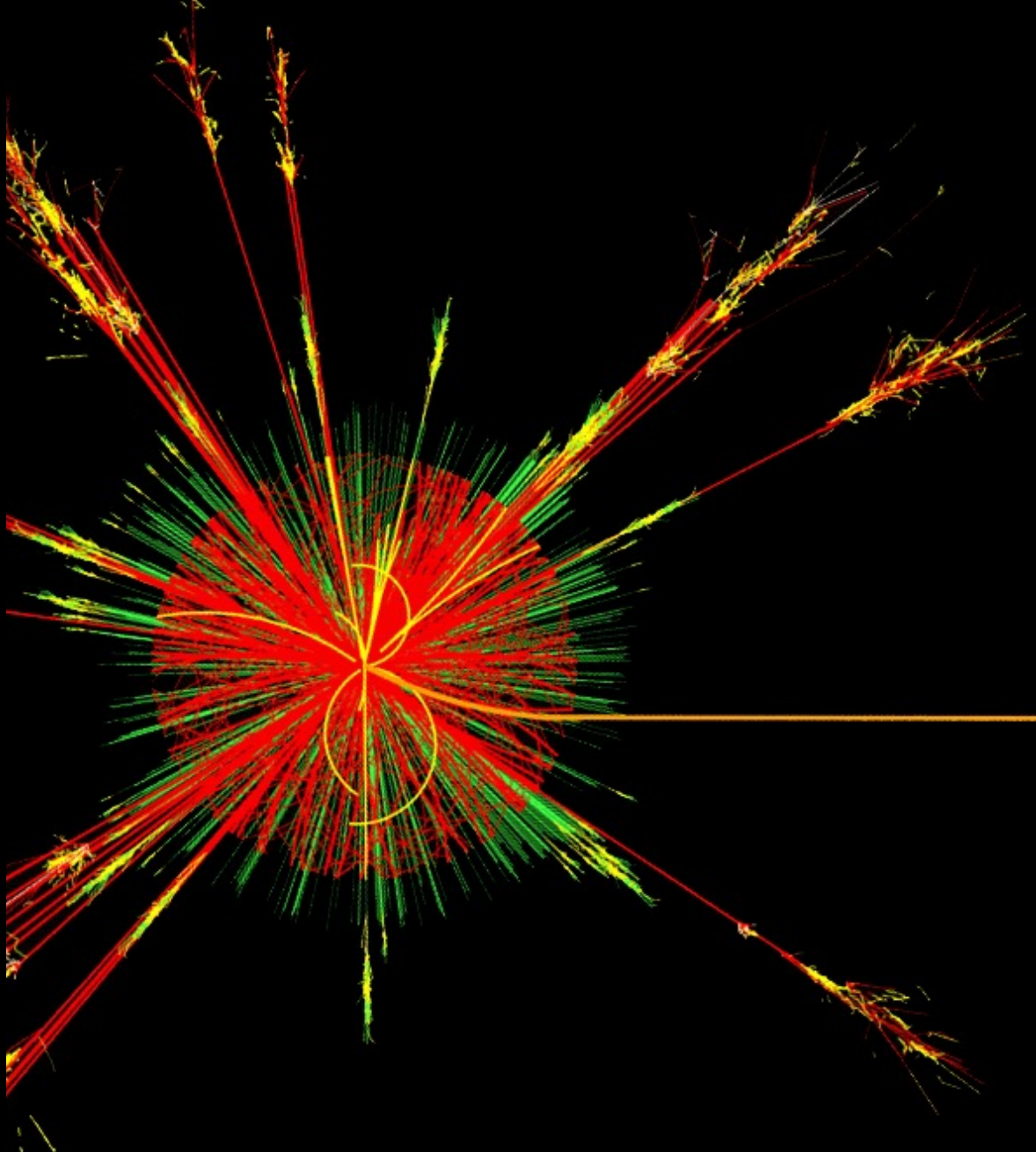


Pie de Bökkum,
Ensinck de Kletskop
Flup de Koojstart



1: Elementary Particles

"All things come in three"

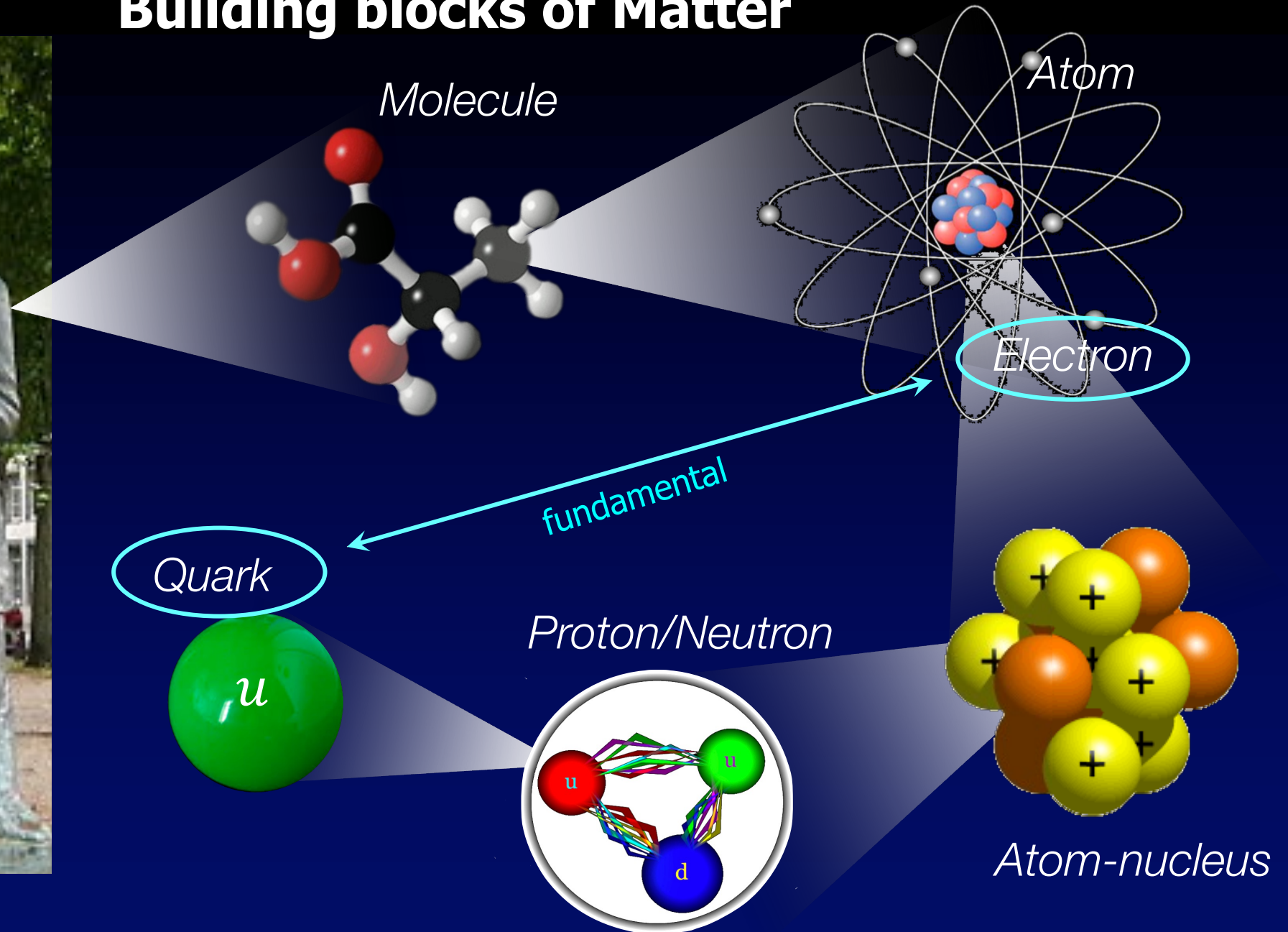


Fons Olterdissen (1865-1923)

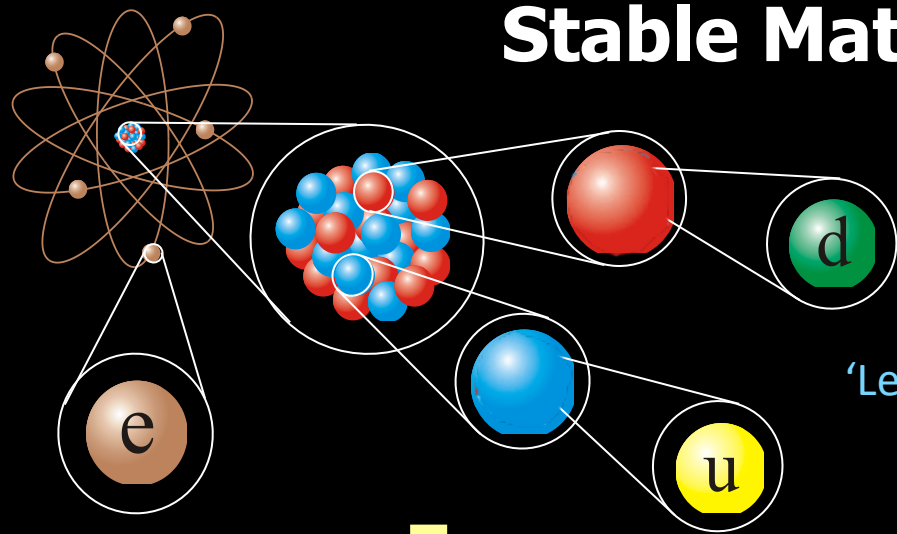
1: Elementary Particles

"All things come in three"

Building blocks of Matter



Stable Matter on Earth

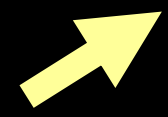


'Lego blocks' of nature

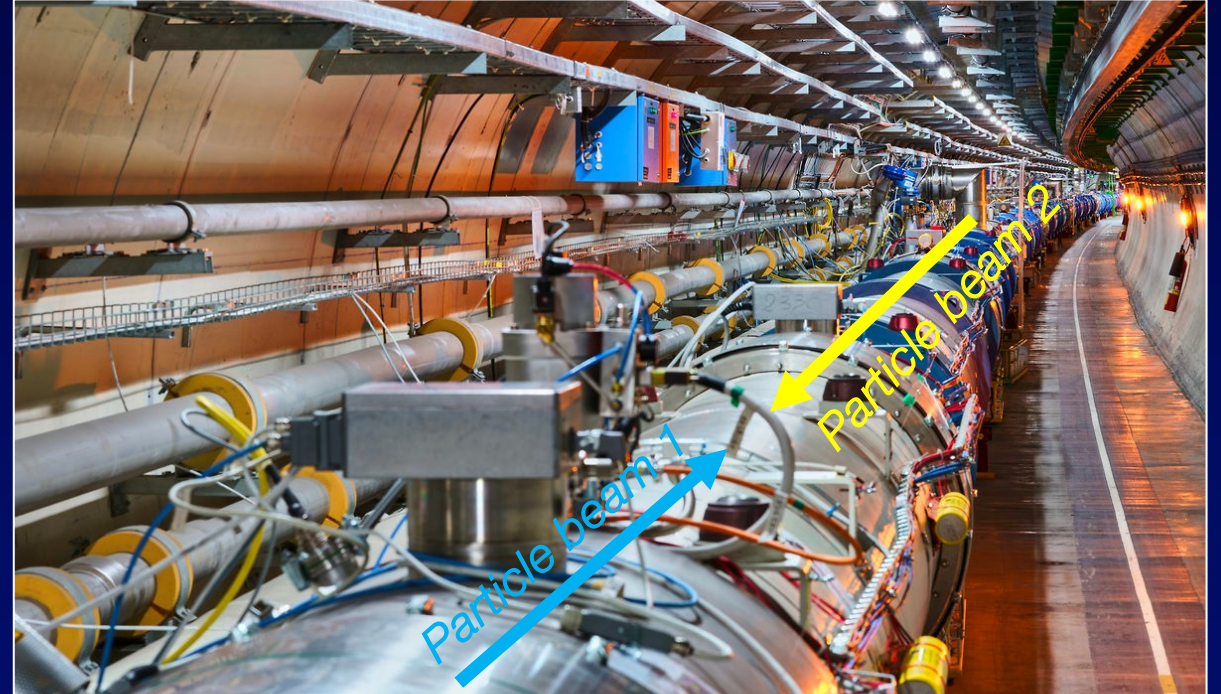
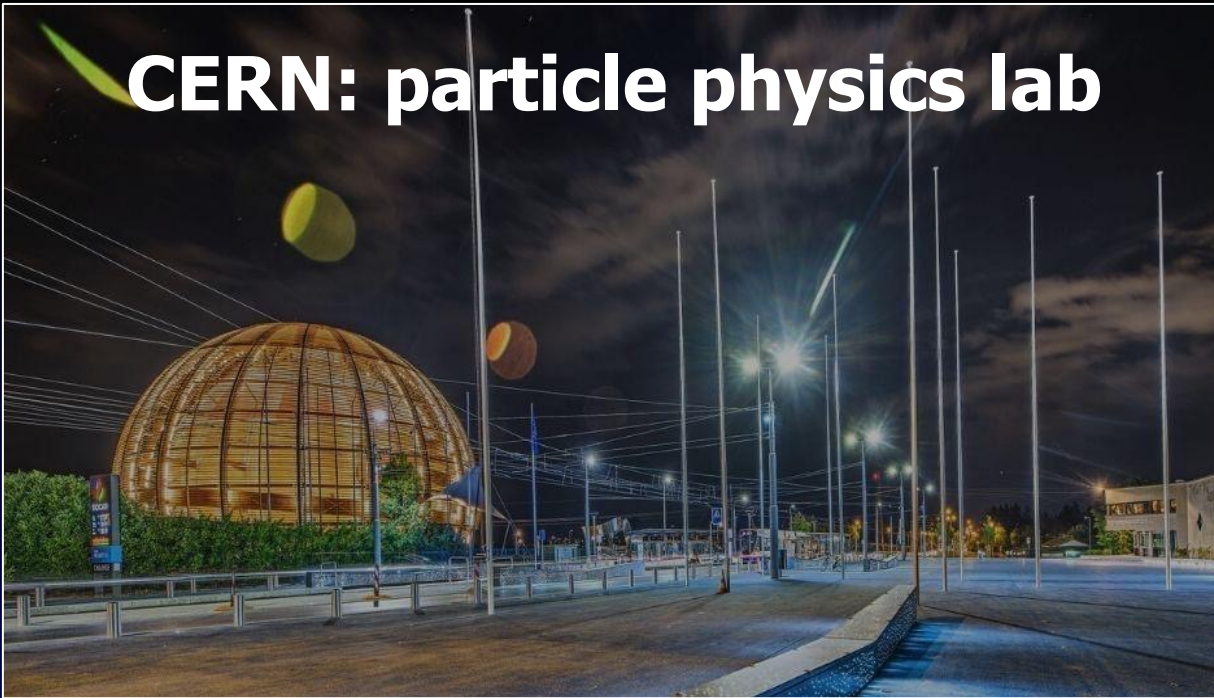


Mendeleev system

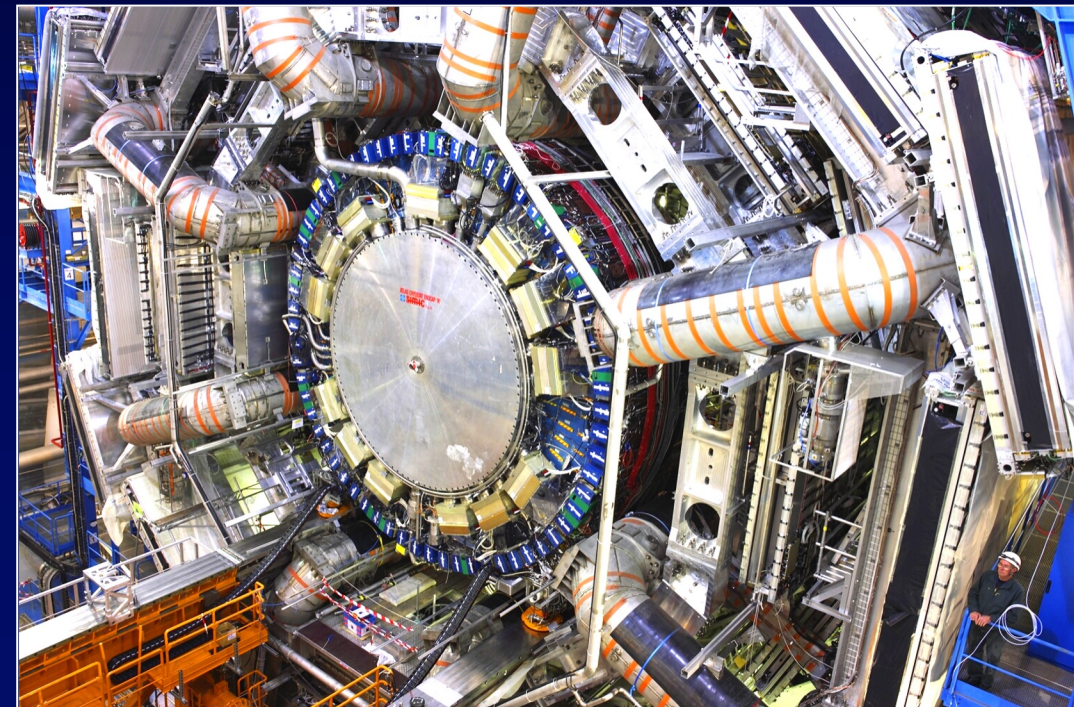
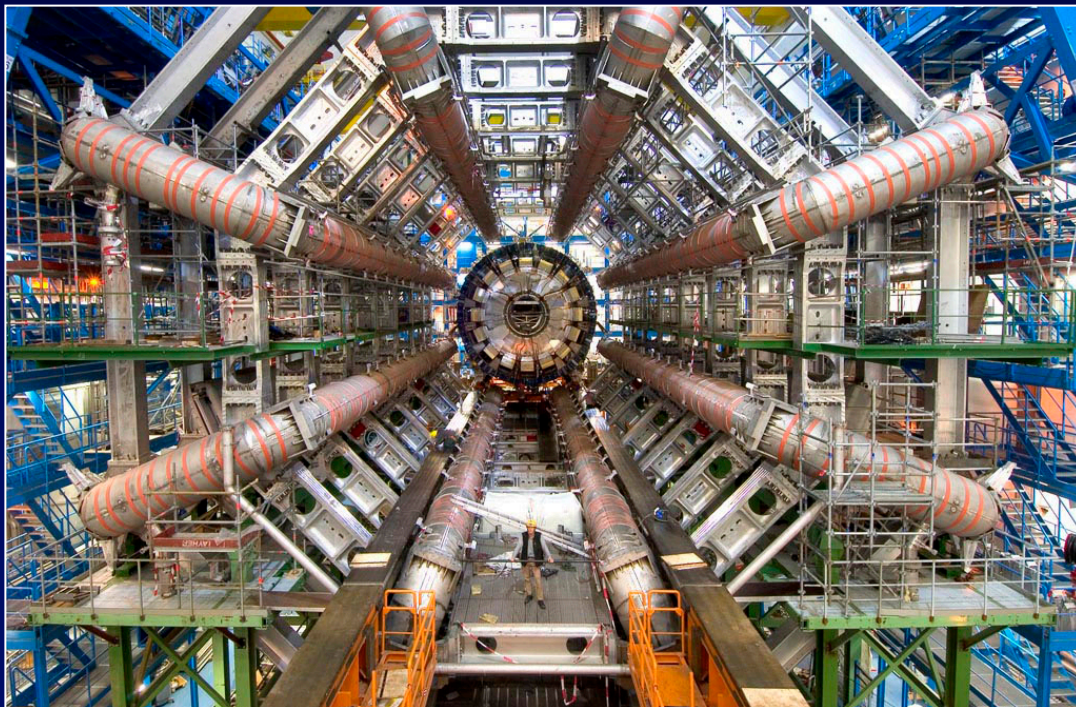
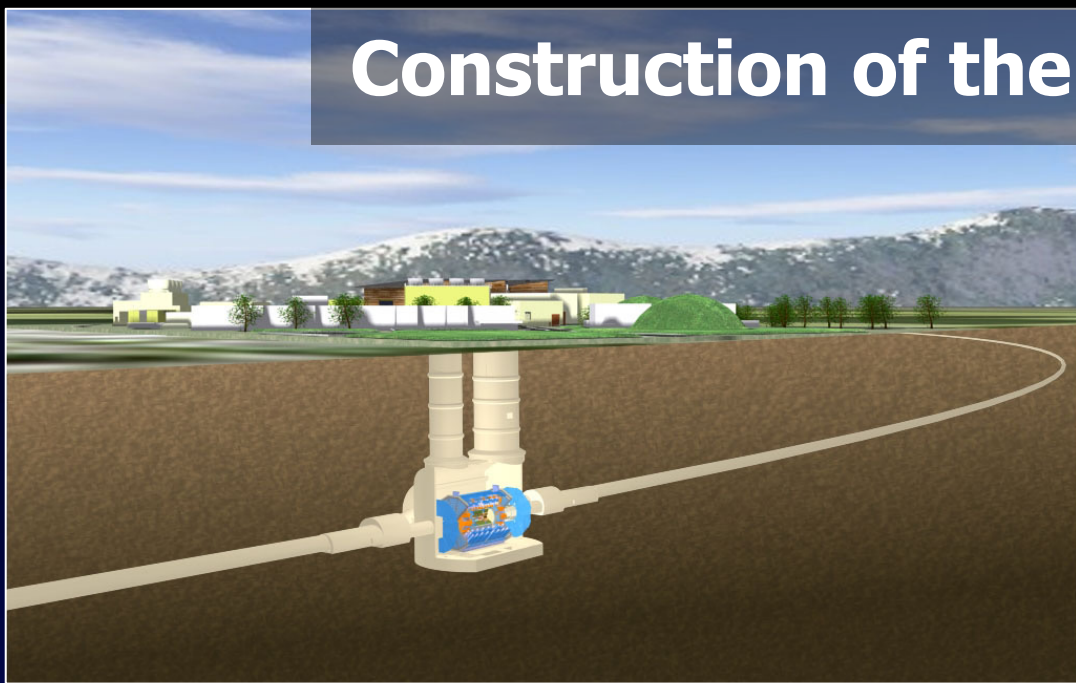
1 H																	2 He														
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne														
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar														
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr														
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe														
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn														
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt																							
																		58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
																		90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr



CERN: particle physics lab



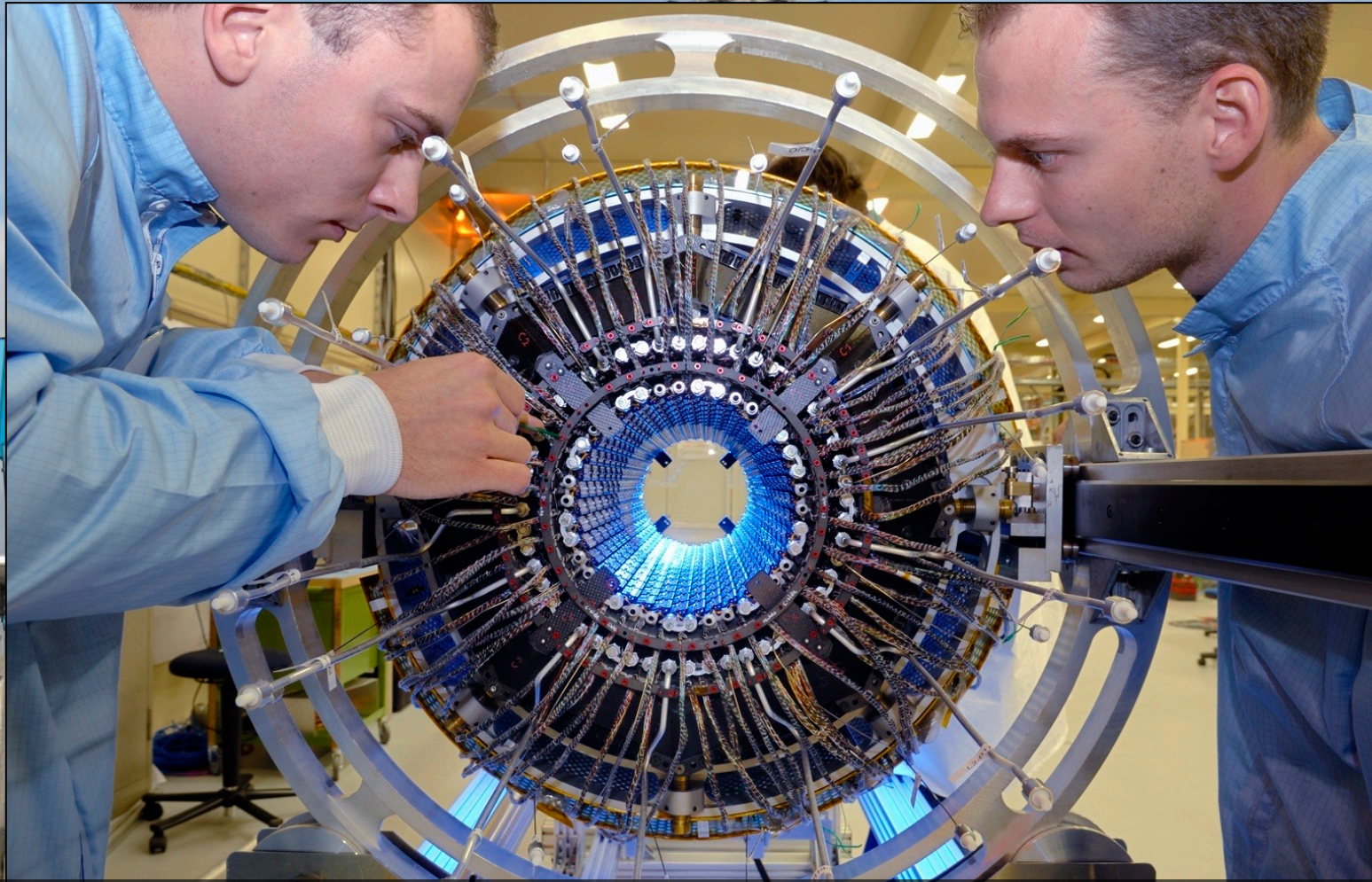
Construction of the Atlas detector at LHC



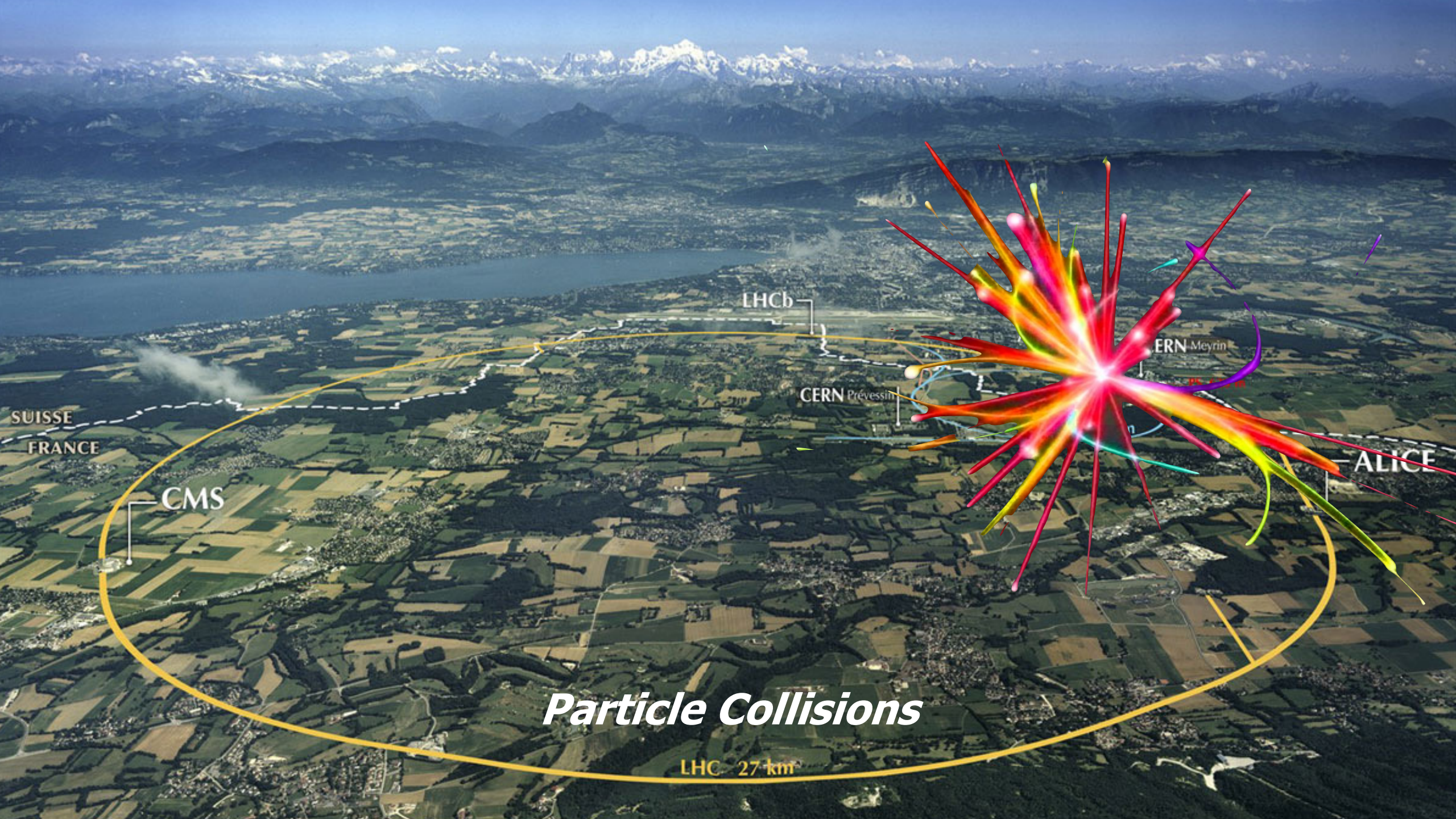
The Atlas Experiment

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

ALICE

CMS

SUISSE
FRANCE

Particle Collisions

LHC 27 km

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



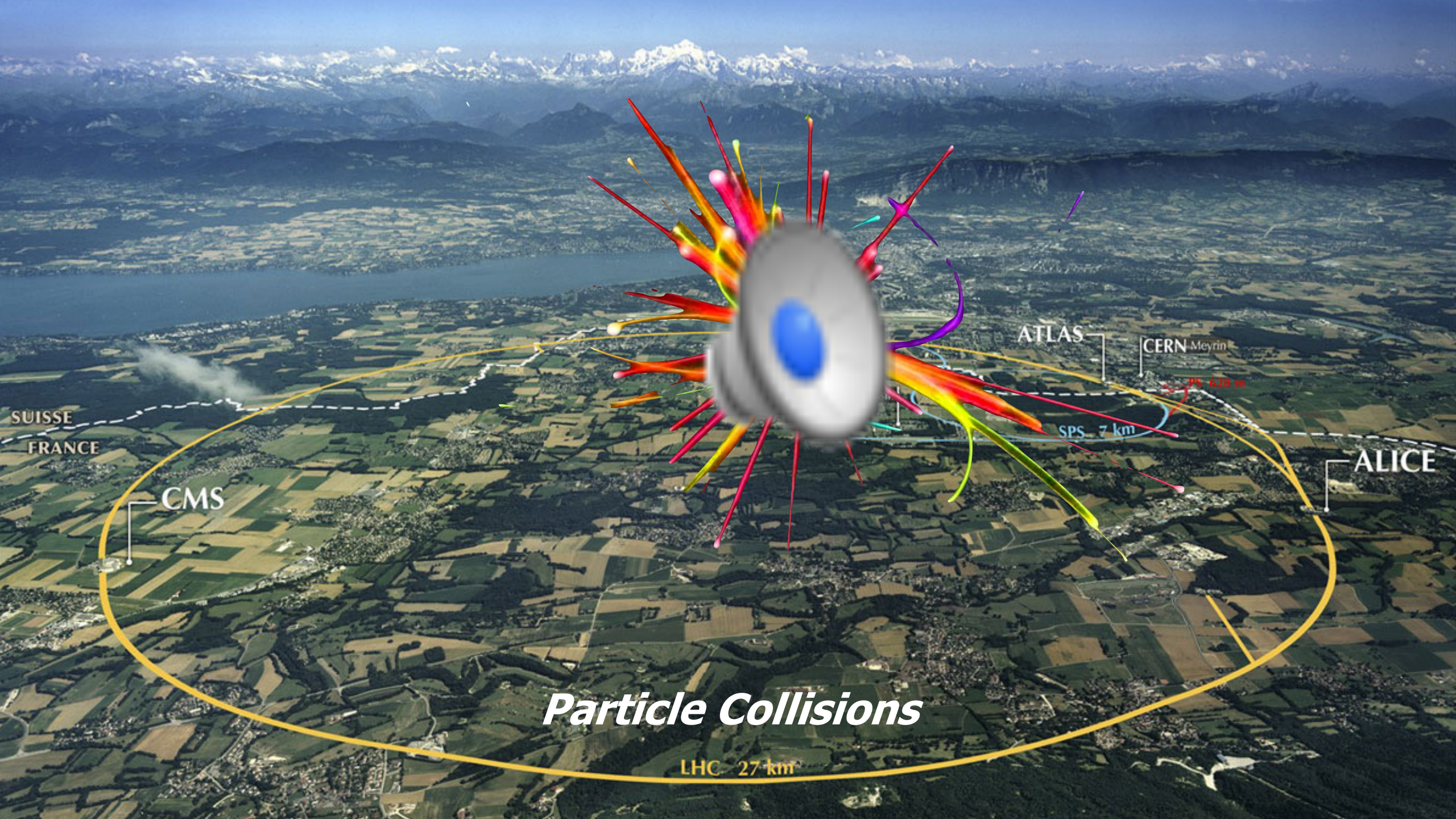
SUISSE
FRANCE

CMS

ALICE

Particle Collisions

LHC 27 km



SUISSE
FRANCE

CMS

ATLAS

CERN Meyrin

SPS 7 km

PS 6.28 km

ALICE

Particle Collisions

LHC 27 km

Elementary Particles

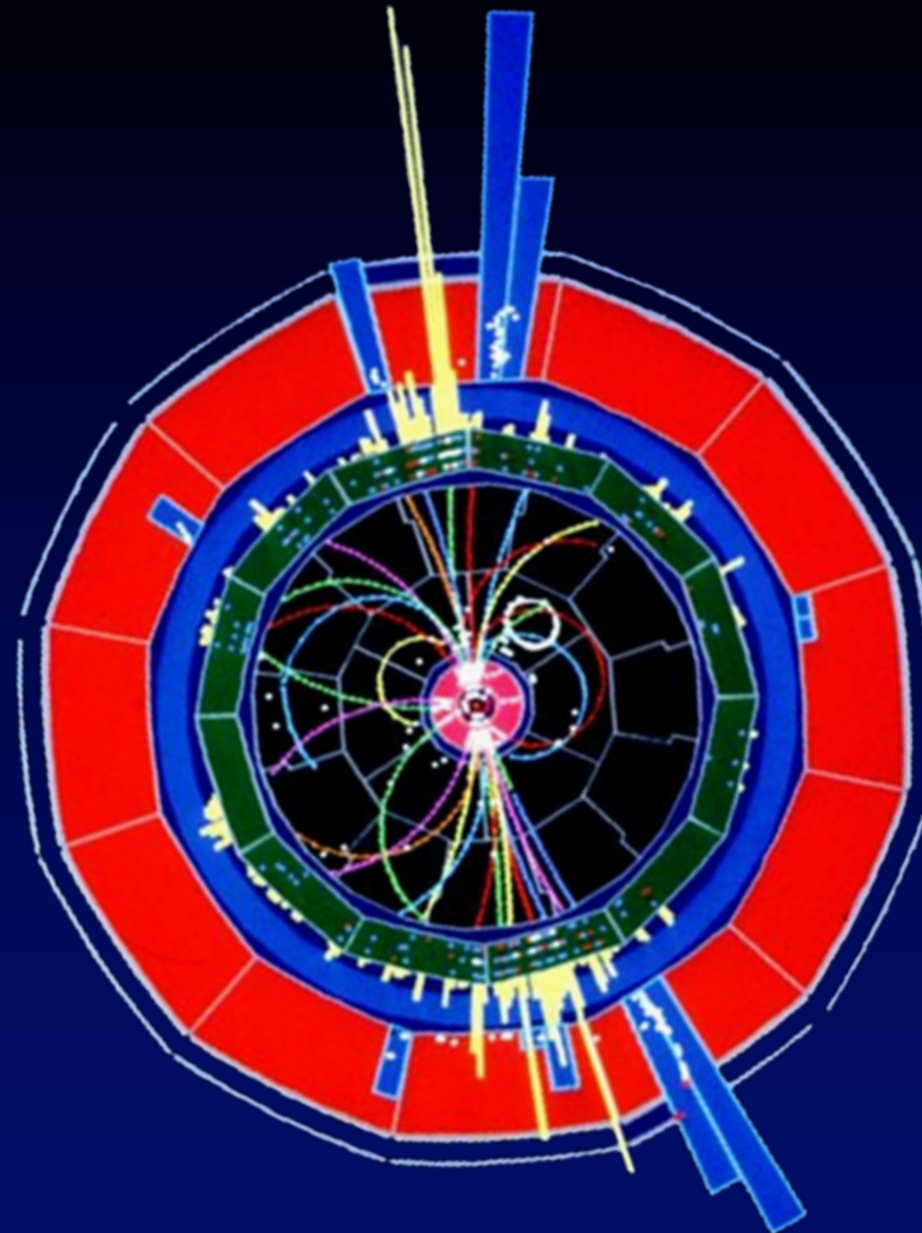
Generation:

	I	II	III	<u>Charge</u>
quarks	u (1976)	c (1976)	t (1995)	+2/3 e
	d (1947)	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

Generation:

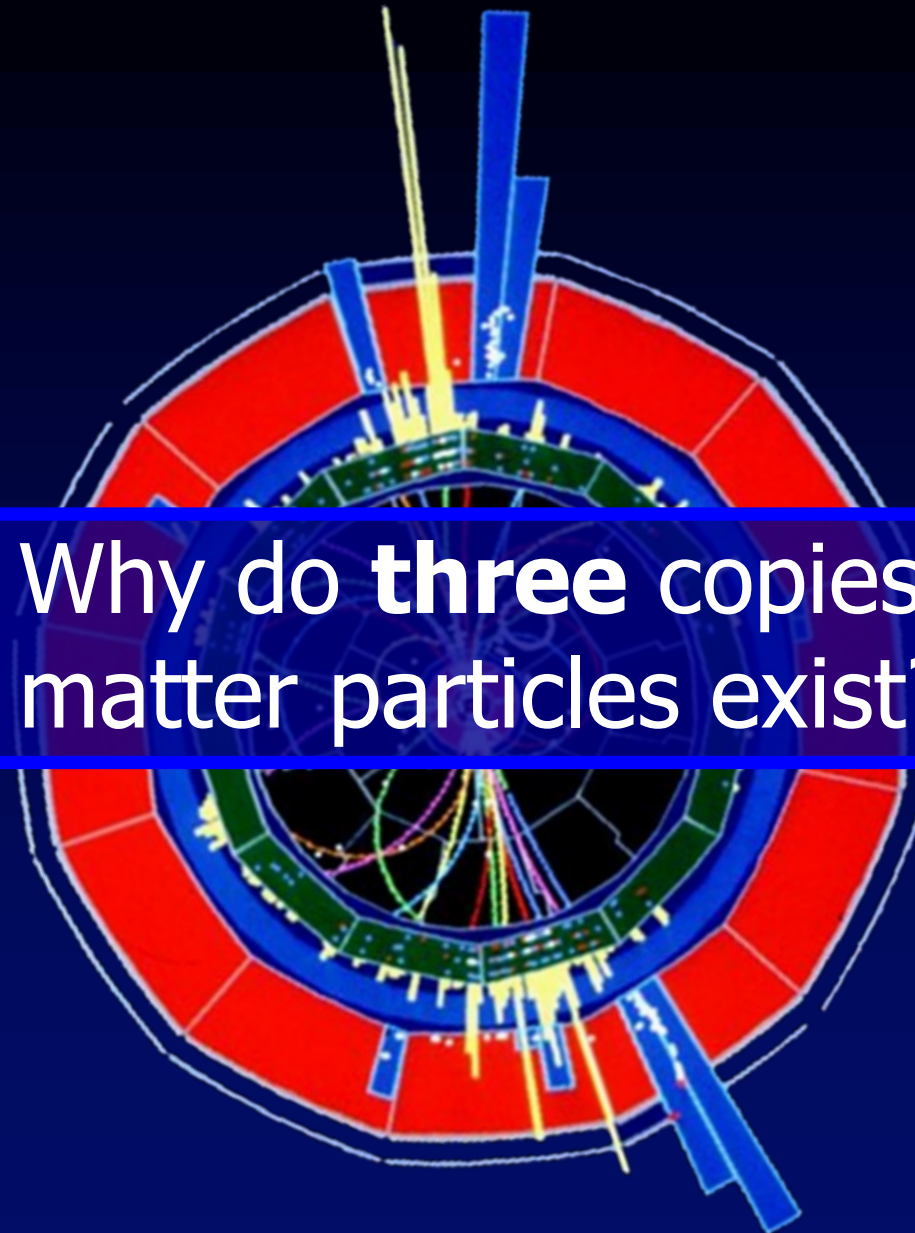
	I	II	III	<u>Charge</u>
quarks	u (1947)	c (1976)	t (1995)	+2/3 e
	d (1947)	s (1976)	b (1978)	-1/3 e

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

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



Elementary Particles

Generation:

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

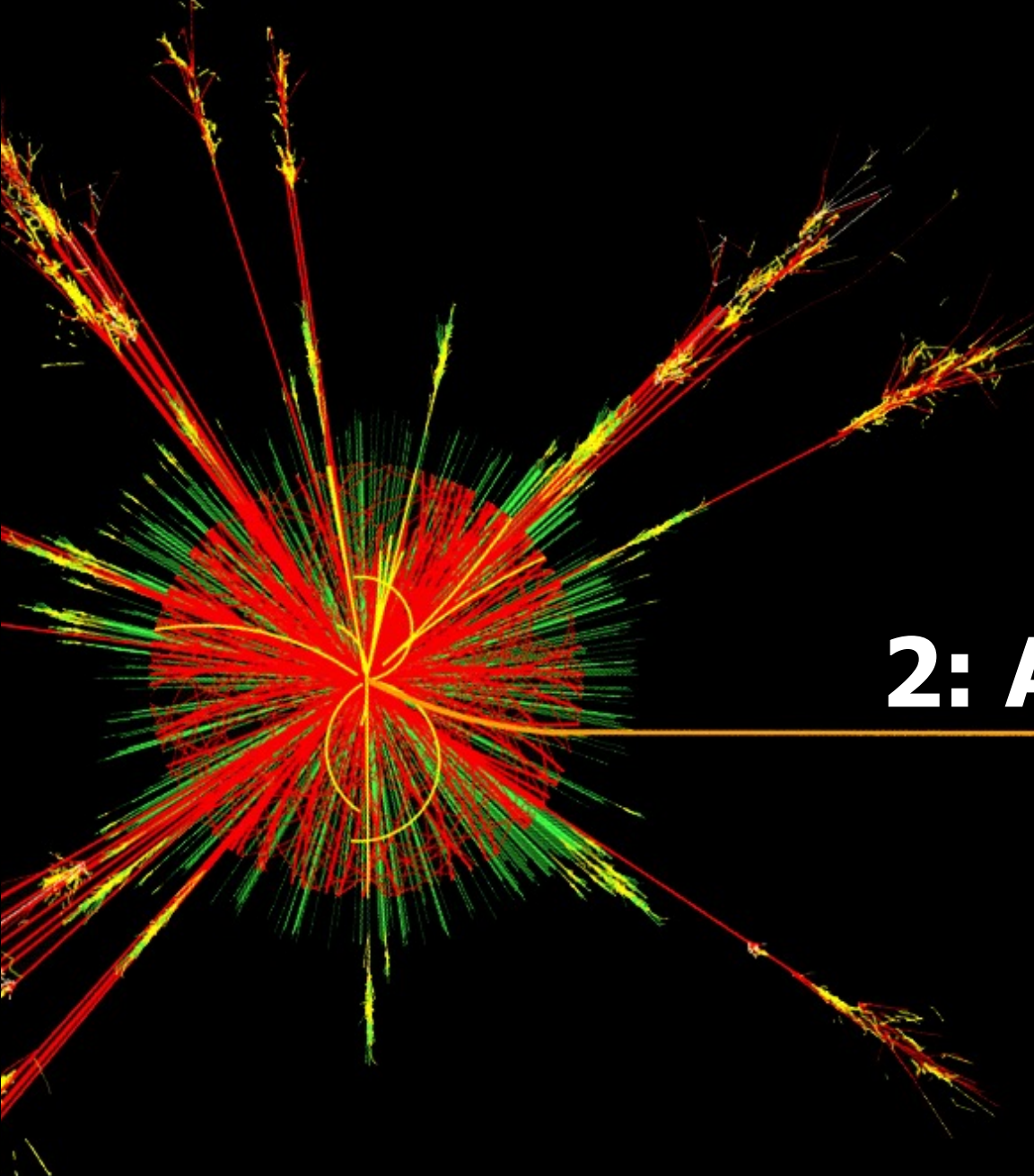
3 "generations" of particles?!

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

Matter

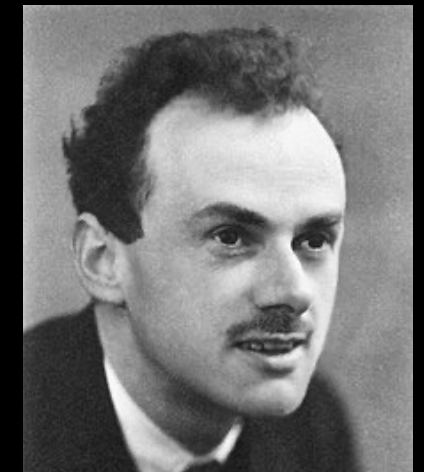


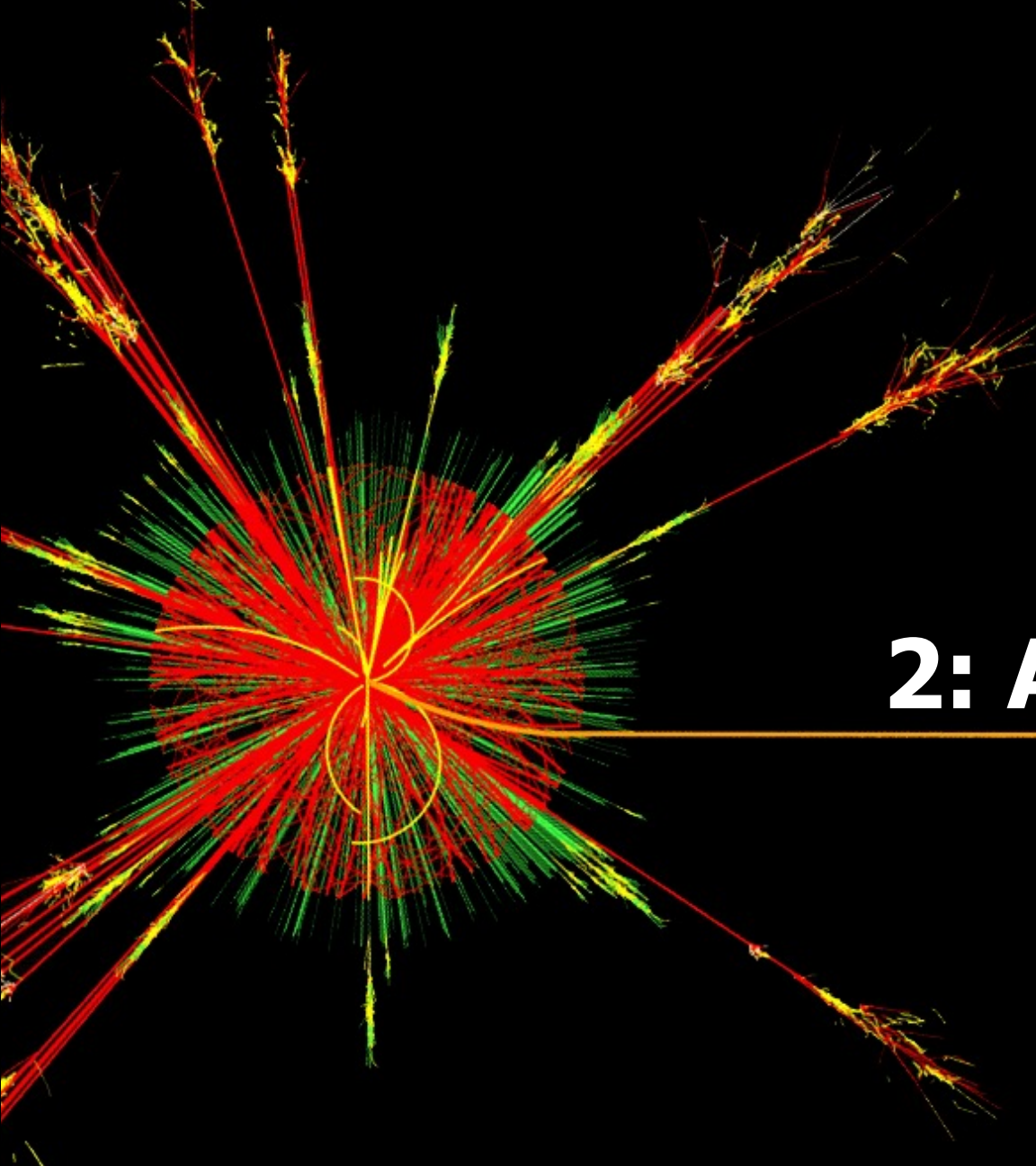
How about...



2: Antimatter and Big Bang

The genius of Paul Dirac





Rika (antimatter frites?)



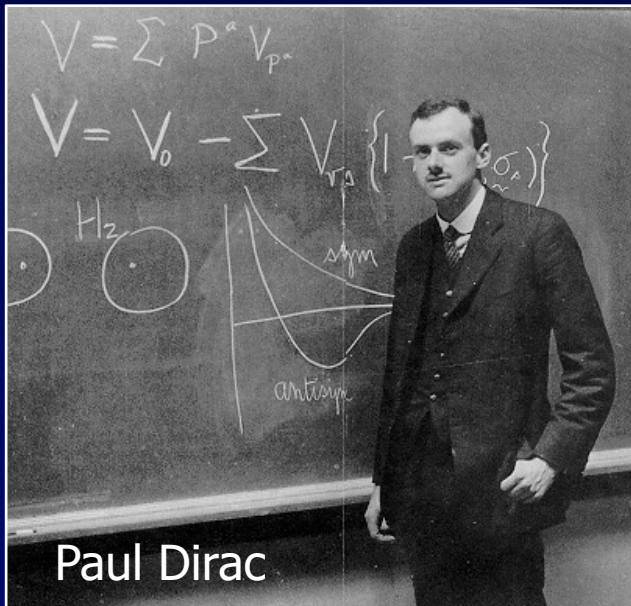
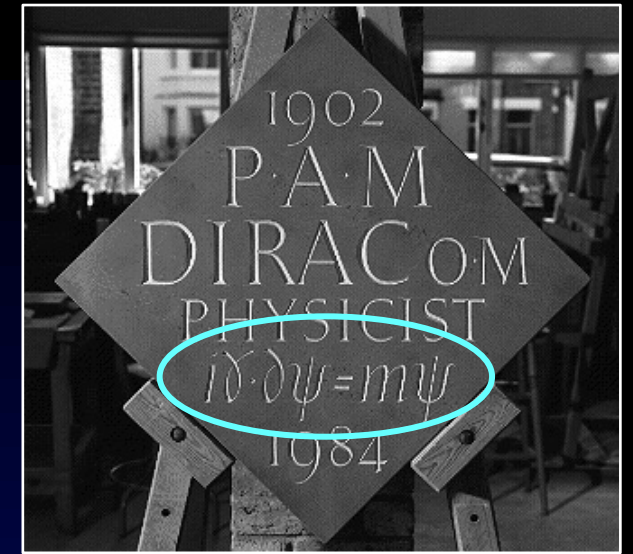
2: Antimatter and Big Bang

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



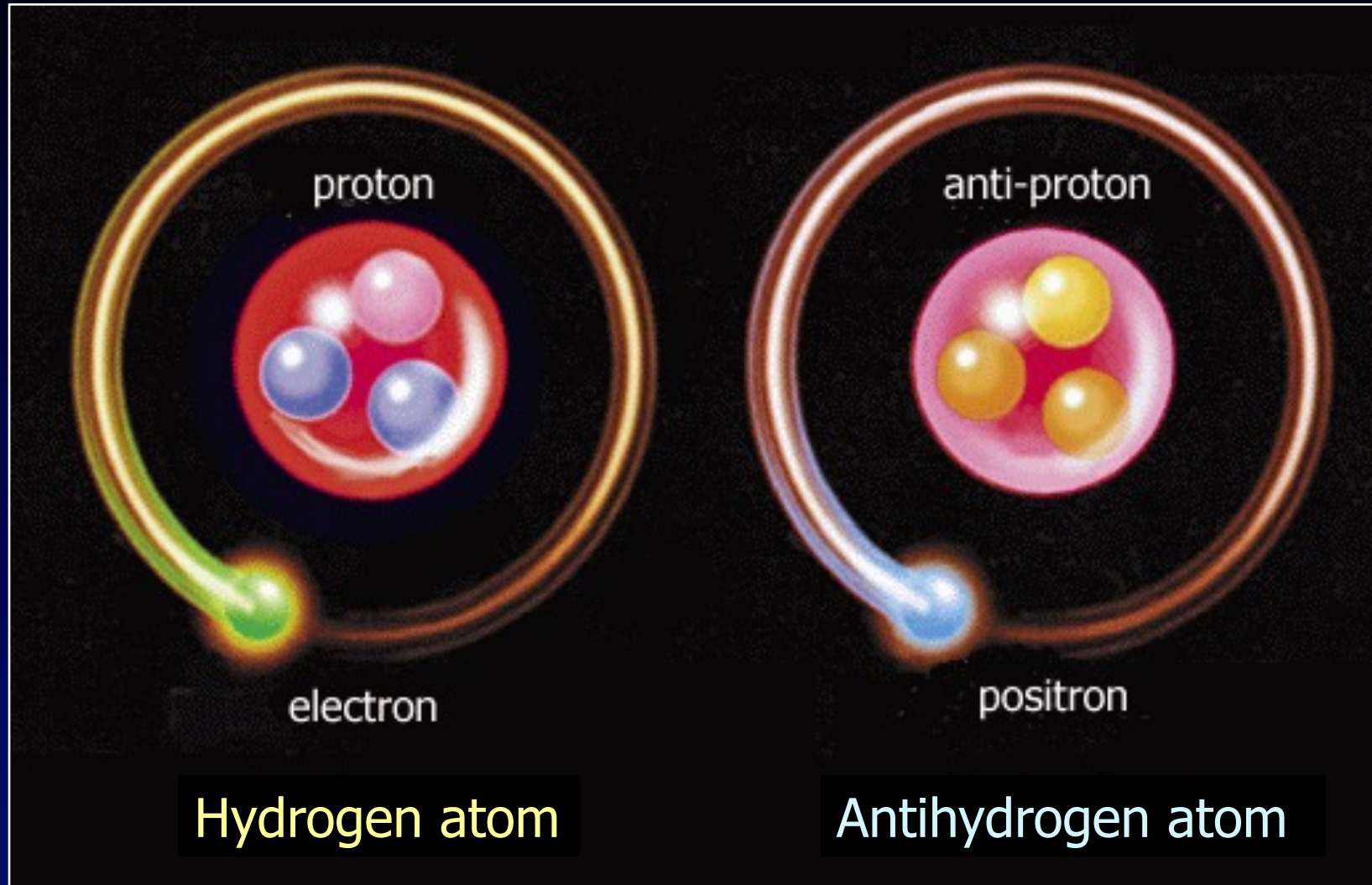
Carl Anderson



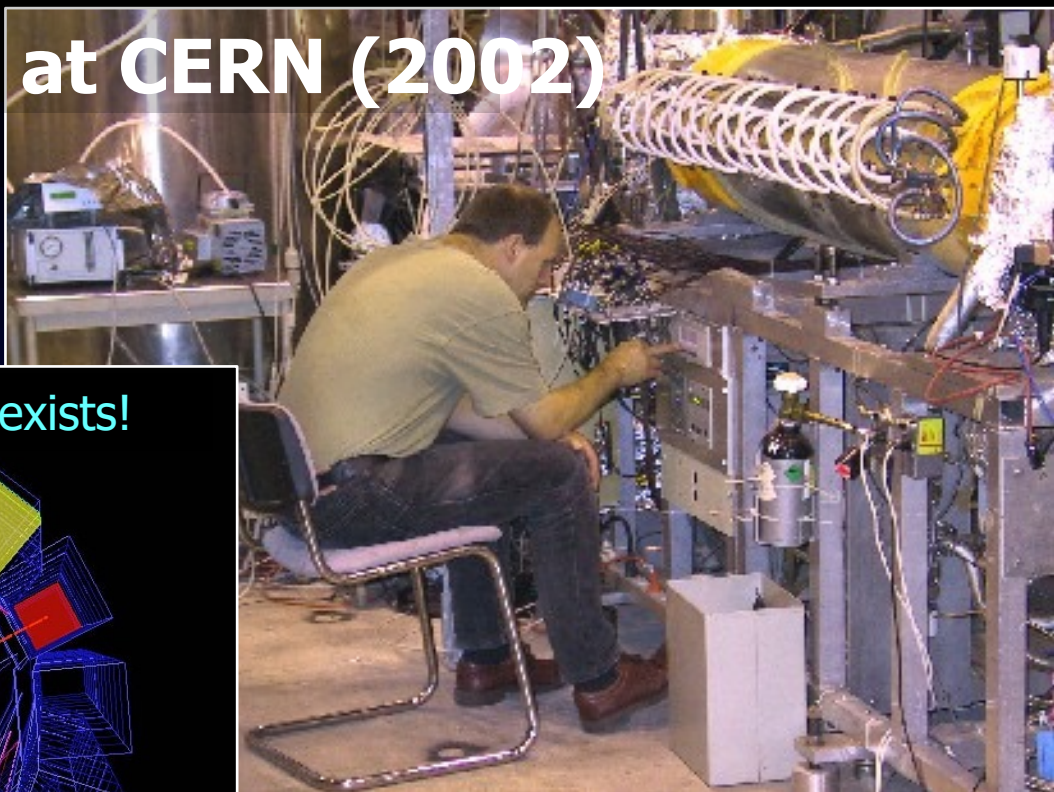
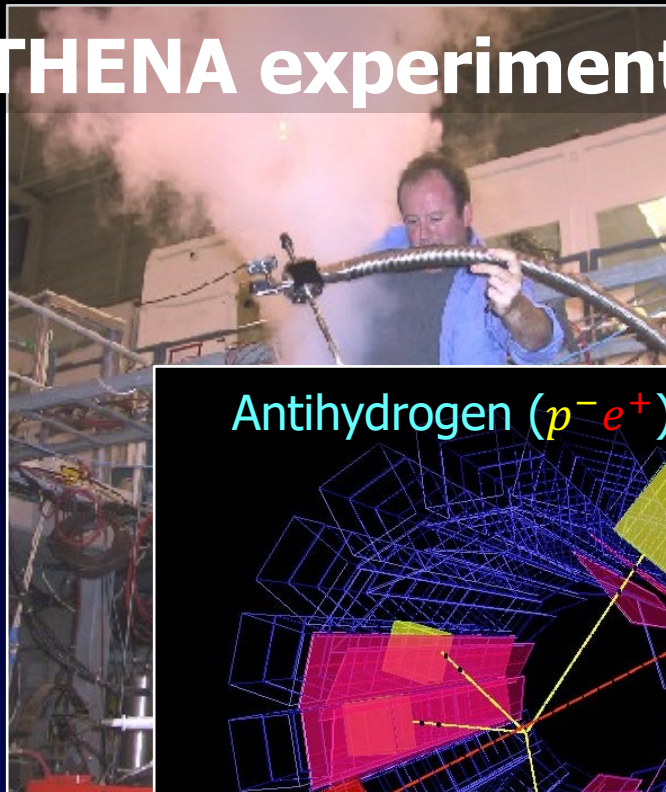
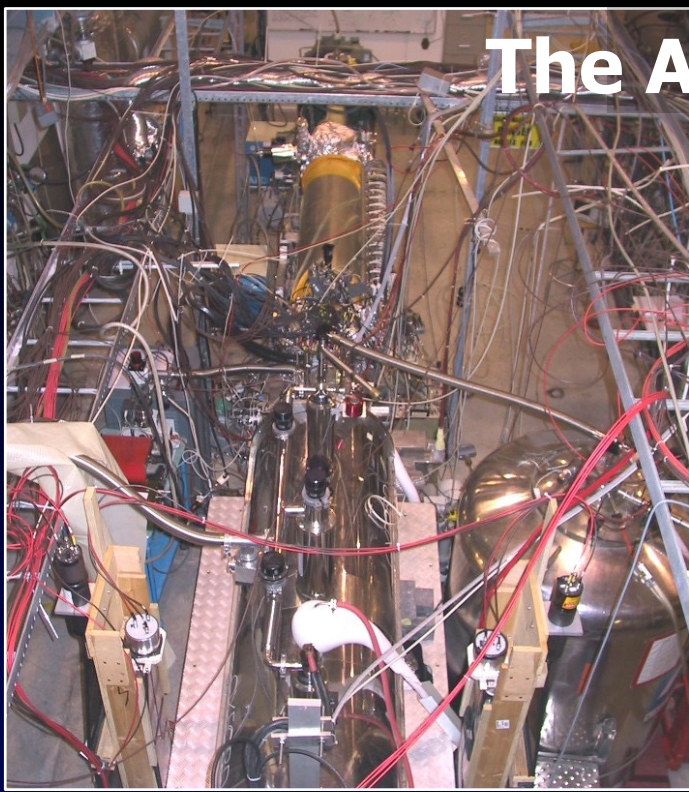
Dirac

AntiDirac

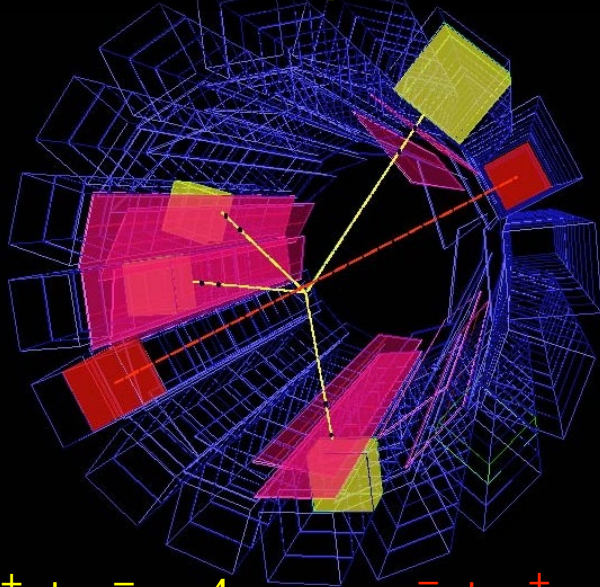
Antimatter



The ATHENA experiment at CERN (2002)



Antihydrogen ($p^- e^+$) exists!



$$p^+ + p^- \rightarrow 4\pi$$

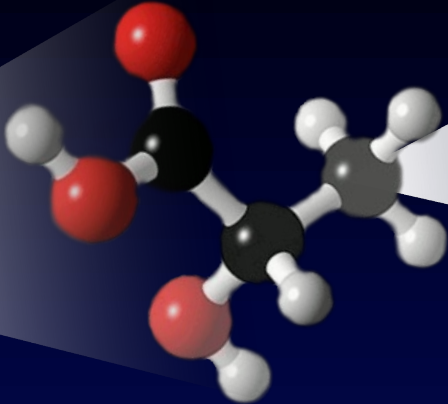
$$e^- + e^+ \rightarrow \gamma\gamma$$



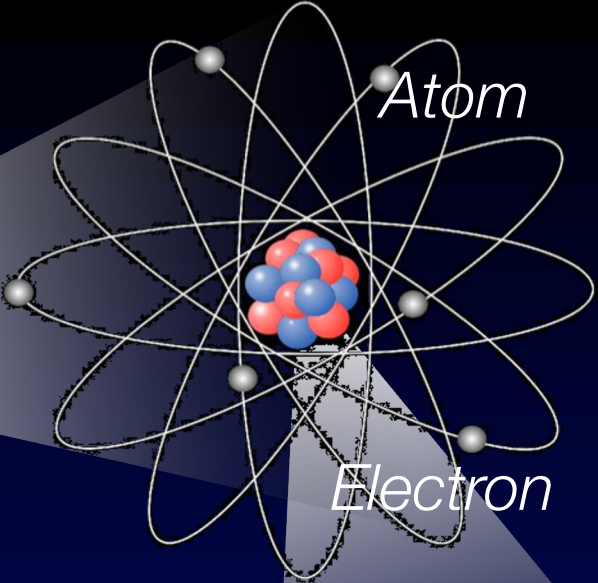
A world of matter and ...



Molecule

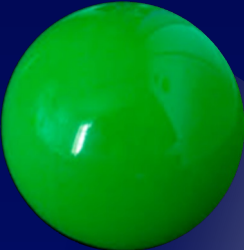


Atom

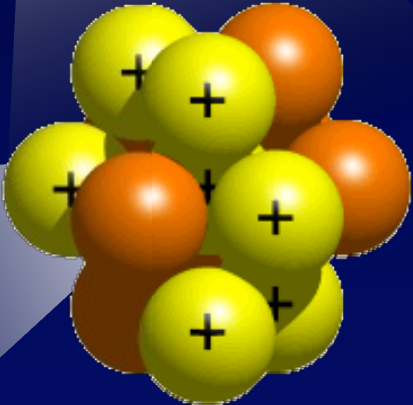
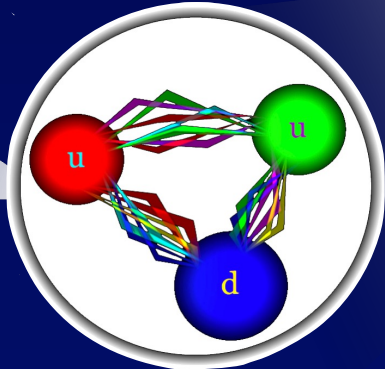


Electron

Quark



Proton/Neutron



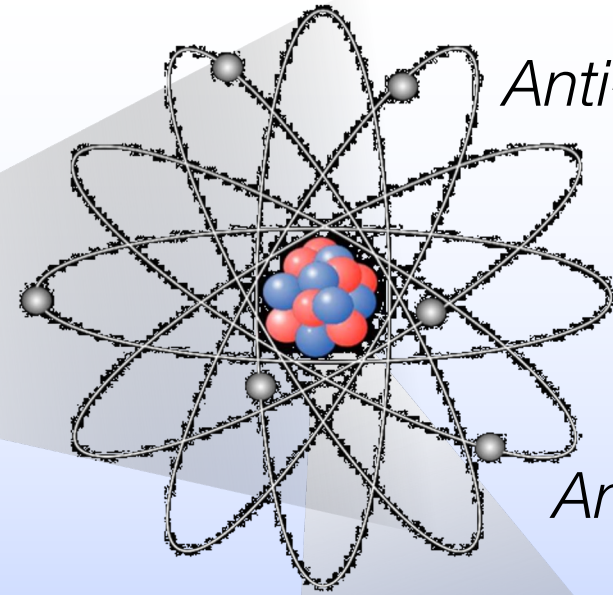
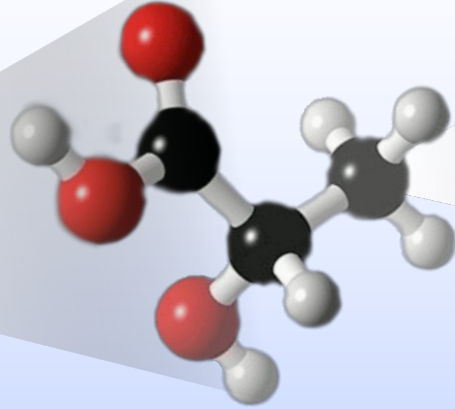
Atom-nucleus

... a world of antimatter



**Identical
anti-world**

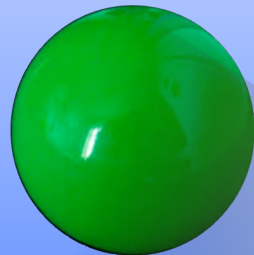
Anti-Molecule



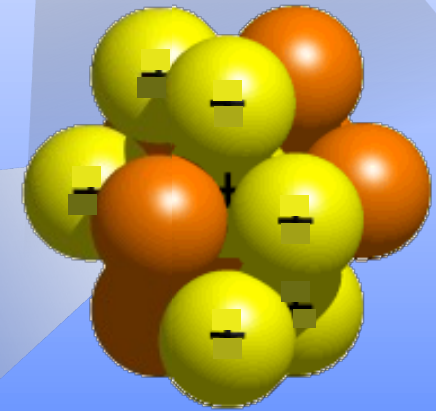
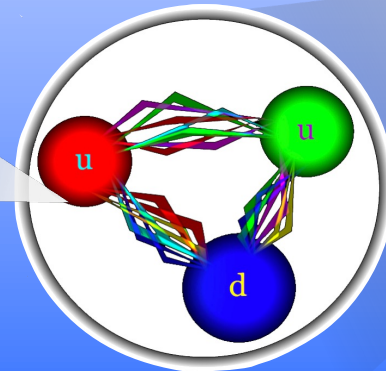
Anti-Atom

Anti-electron

Anti-Quark

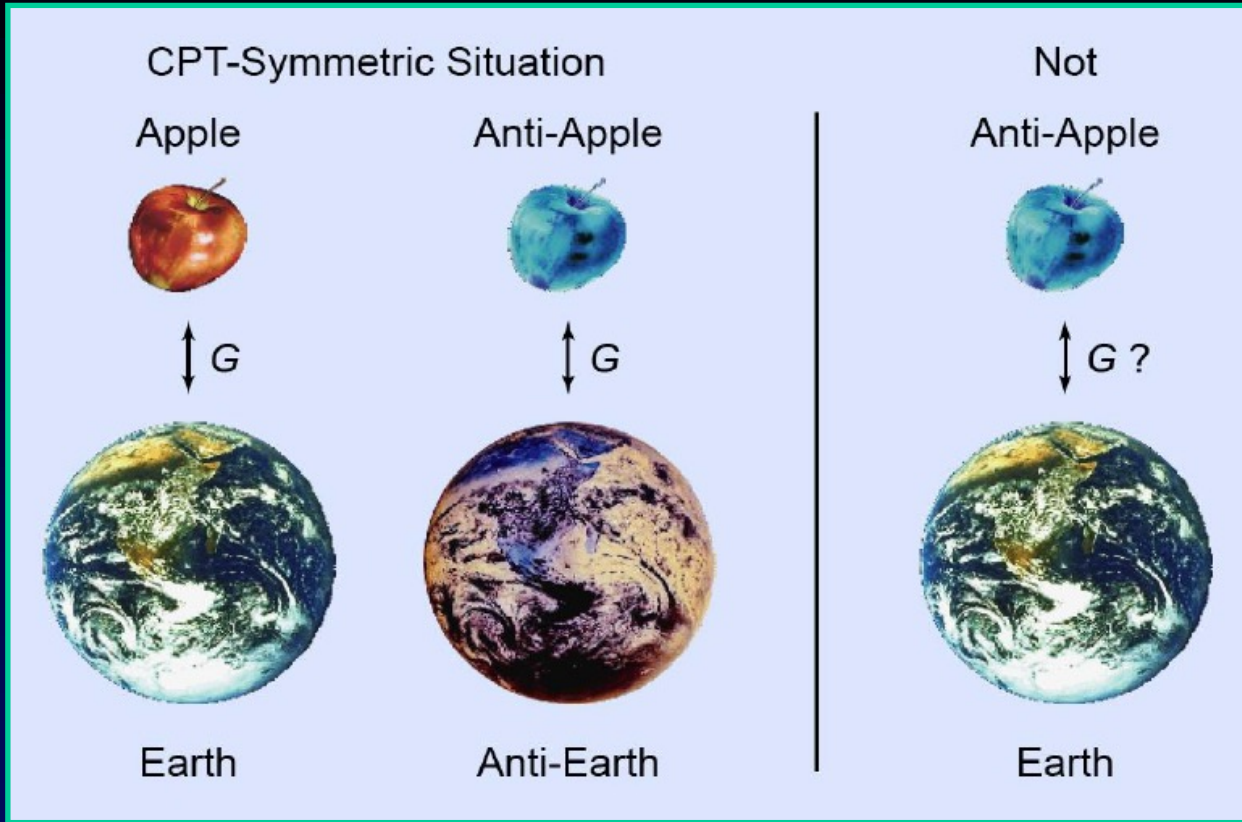


*Anti-Proton /
anti-Neutron*



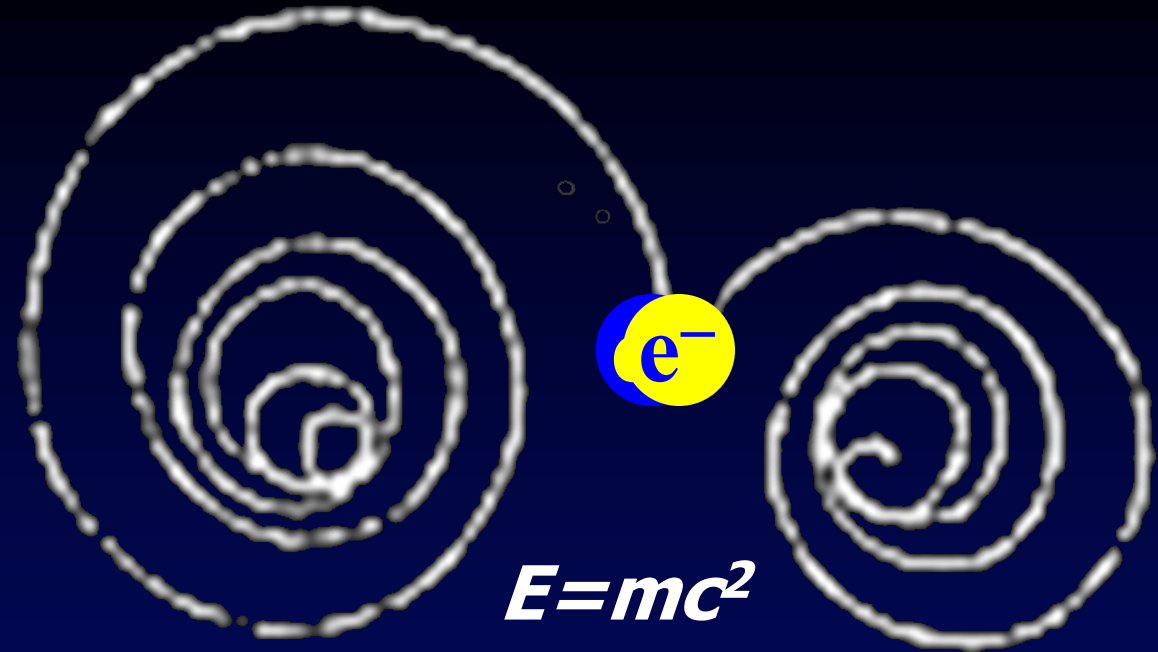
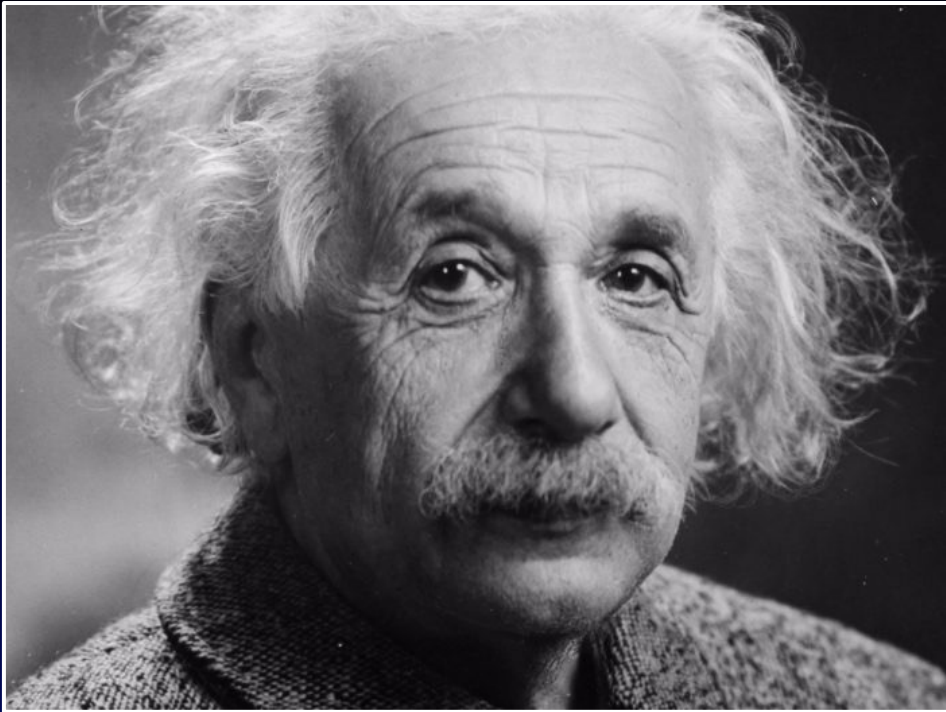
Anti atom-nucleus

Alpha experiment: successor of Athena



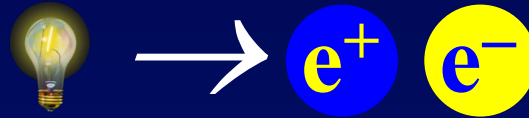
- News on 27 Sept 2023:
 - Several thousands of antimatter hydrogen atoms were dropped in the gravitational field
 - Antimatter falls “down” to earth in the same way as matter does

Albert Einstein: Energy = matter + antimatter



Creation:

Energy \rightarrow matter + antimatter :

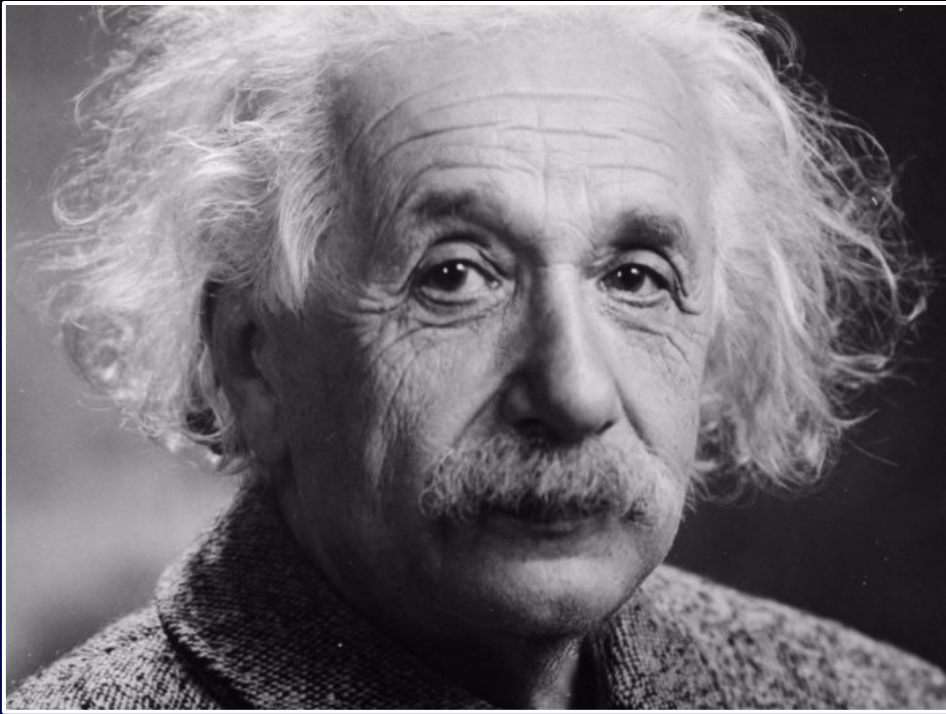


Annihilation:

matter + antimatter \rightarrow energy :



Albert Einstein: Energy = matter + antimatter



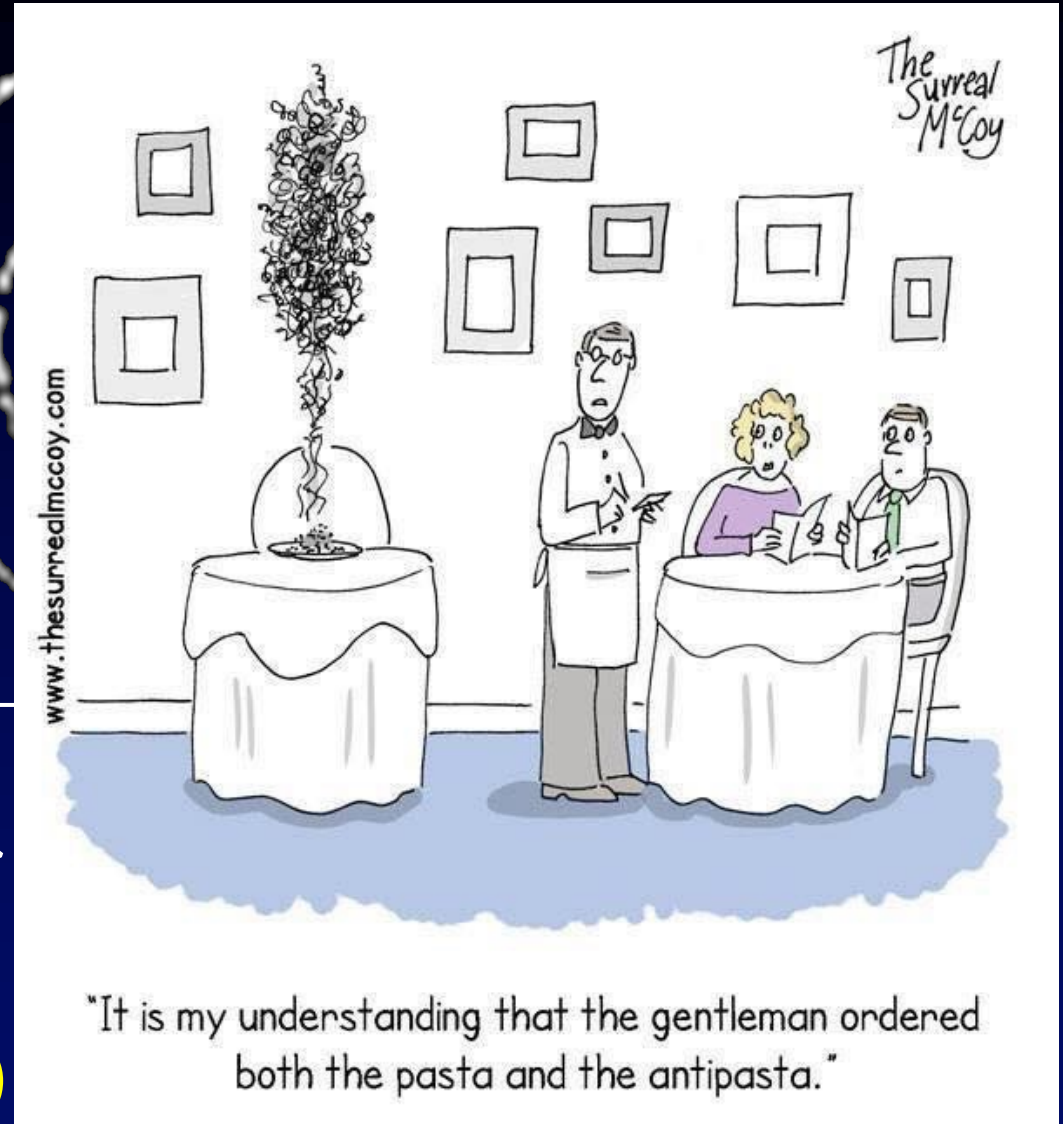
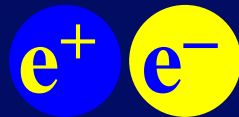
Creation:

Energy \rightarrow matter + antimatter :



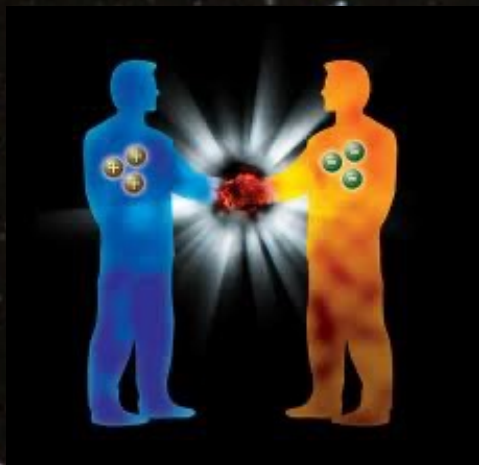
Annihilation:

matter + antimatter \rightarrow energy :



Is there antimatter in nature?

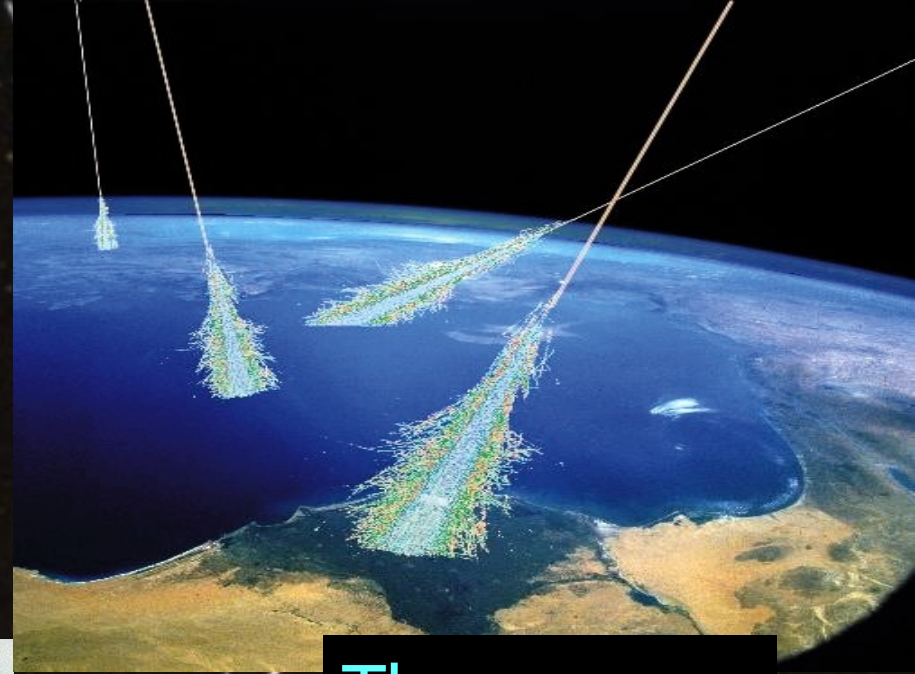
- Does it occur on earth?



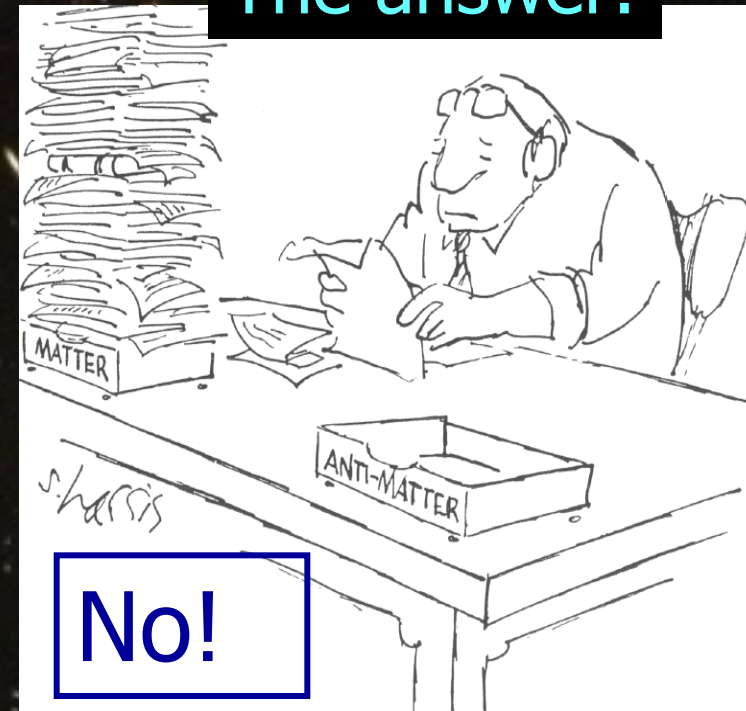
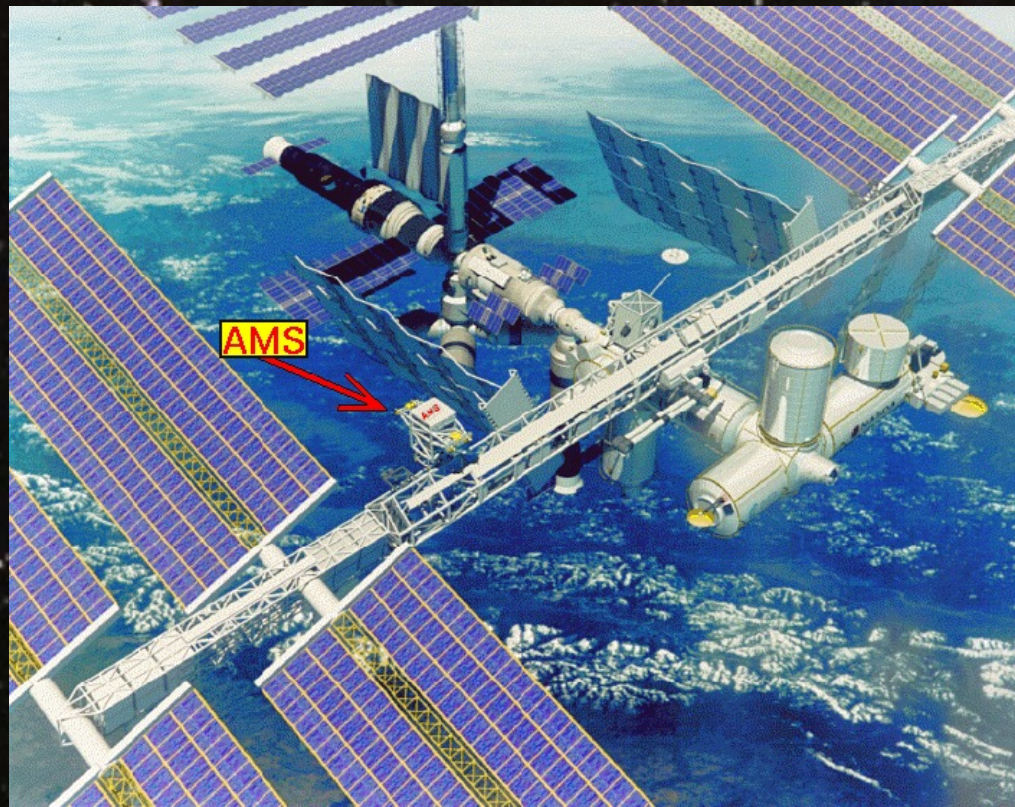
- No, we would immediately see it:
 - "Annihilation"



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



The answer:

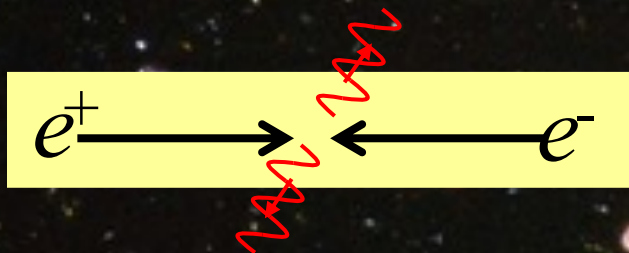


No!

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?

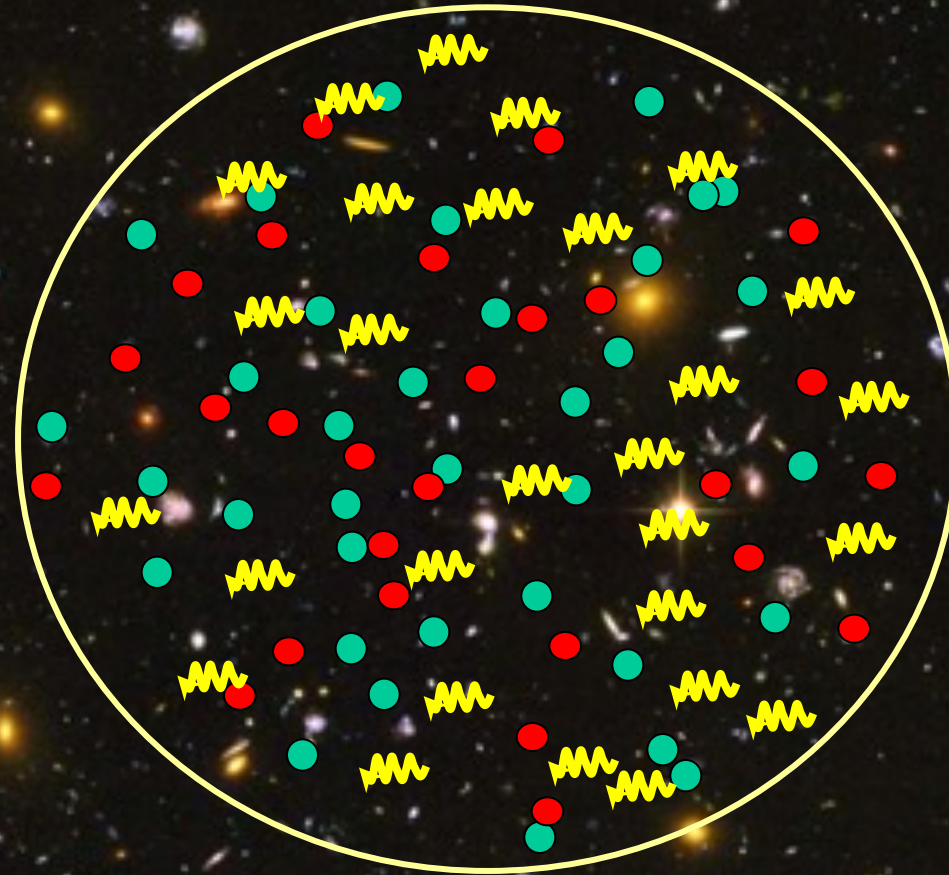
Back to the Big-Bang

Assume: creates equal amounts of matter and antimatter

The early hot universe

Time=0.000000000001 second

$$(E=mc^2)$$



Imagine:

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

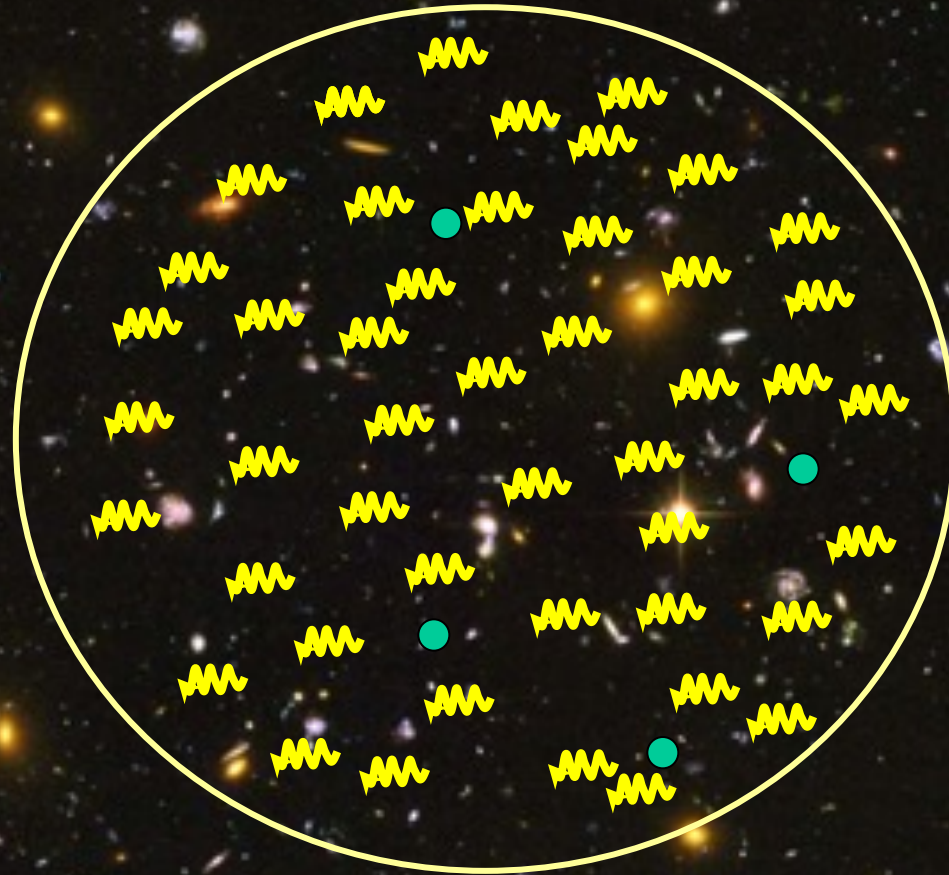
So: "teeny weeny" more **matter** particles
than **antimatter** particles

The expanding and cooling universe

Time ~ 1 second

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

After cooling
● and ●
annihilate



- *matter*
- *antimatter*
- ⤴ *light*

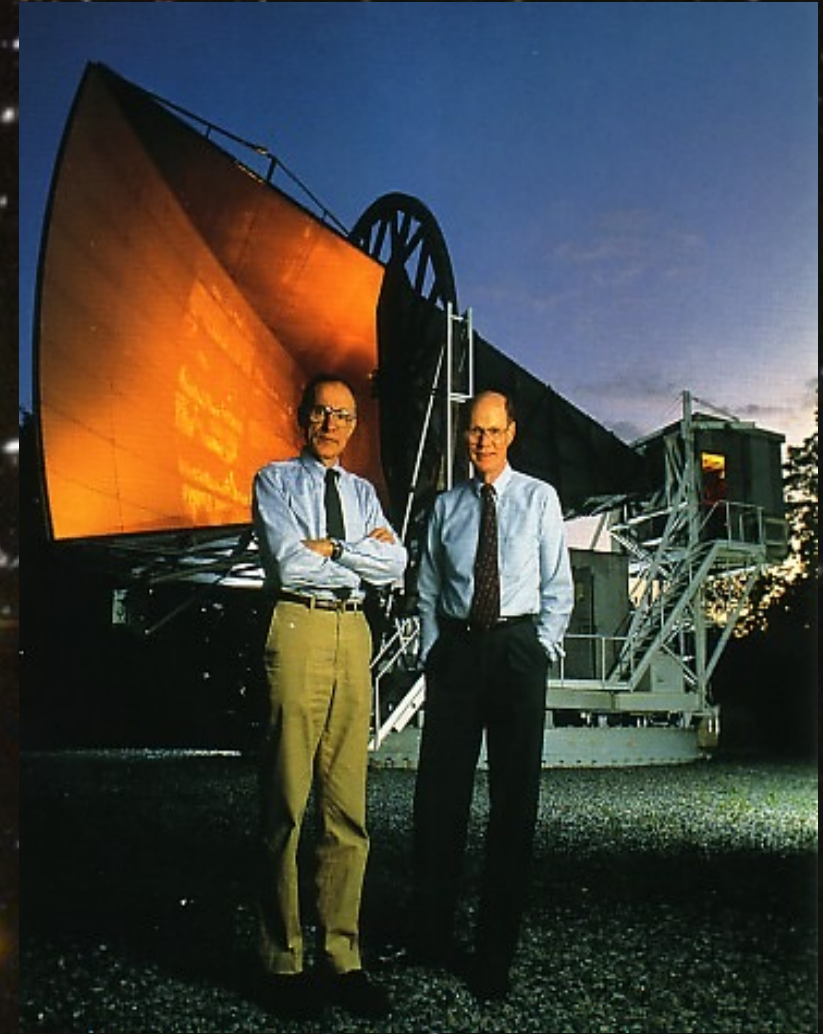
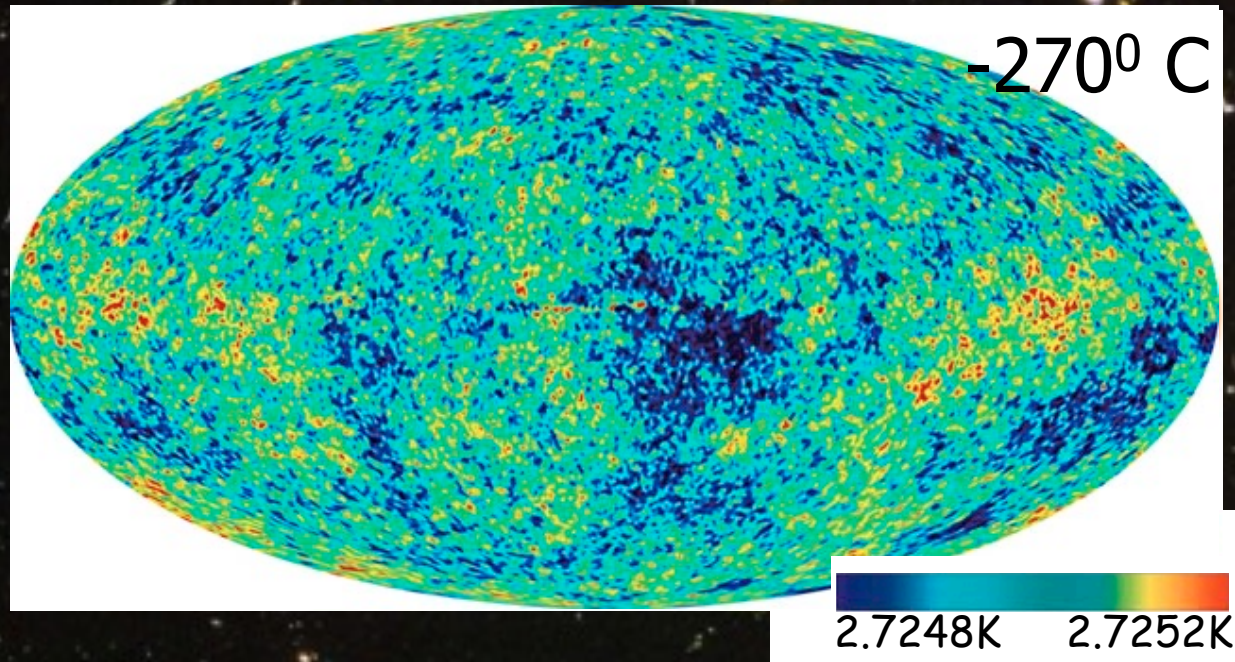
What remains: lots of light and a bit of matter
Ratio : 10000000000 : 1

Cosmic Microwave Background Radiation

1964: Penzias and Wilson
discover: "background light"
(photons)
Remnant of the Big Bang

A temperature map...

Of the universe



For each matter particle
there are a billion photons...

The universe as we see it today



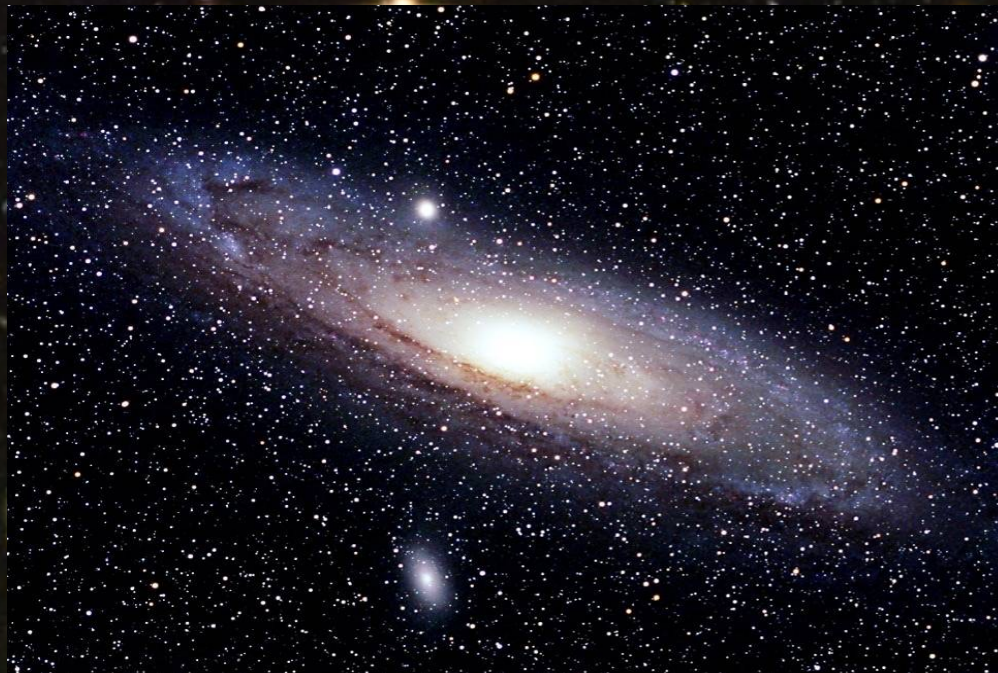
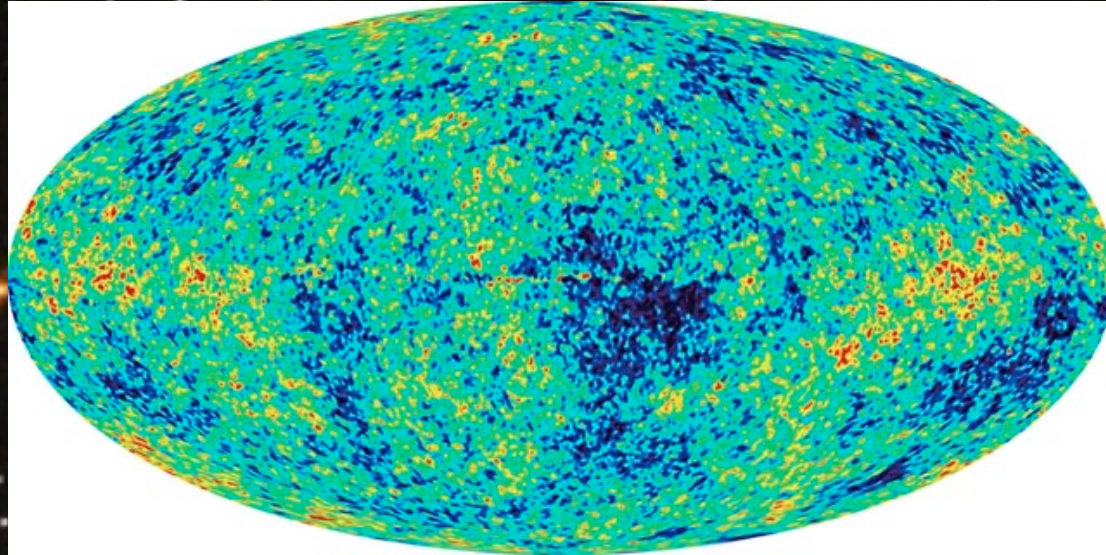
Observed
Background light:

"many"
(1000000000)

+

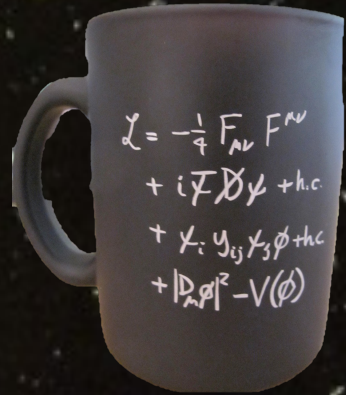
● Remaining
Matter particles:

"few"
(1)



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

Laws of Nature



Big Bang



Small surplus

49.9999999%
anti-matter
50.0000001%
matter



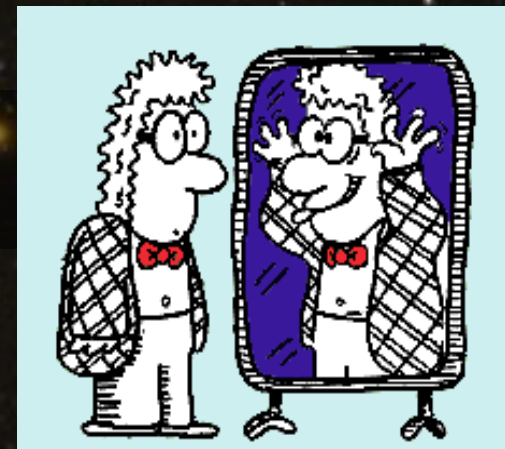
Matter Dominates

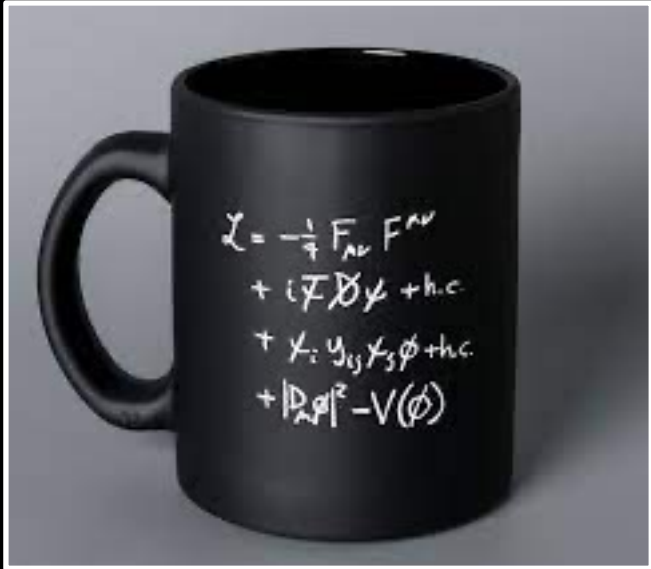
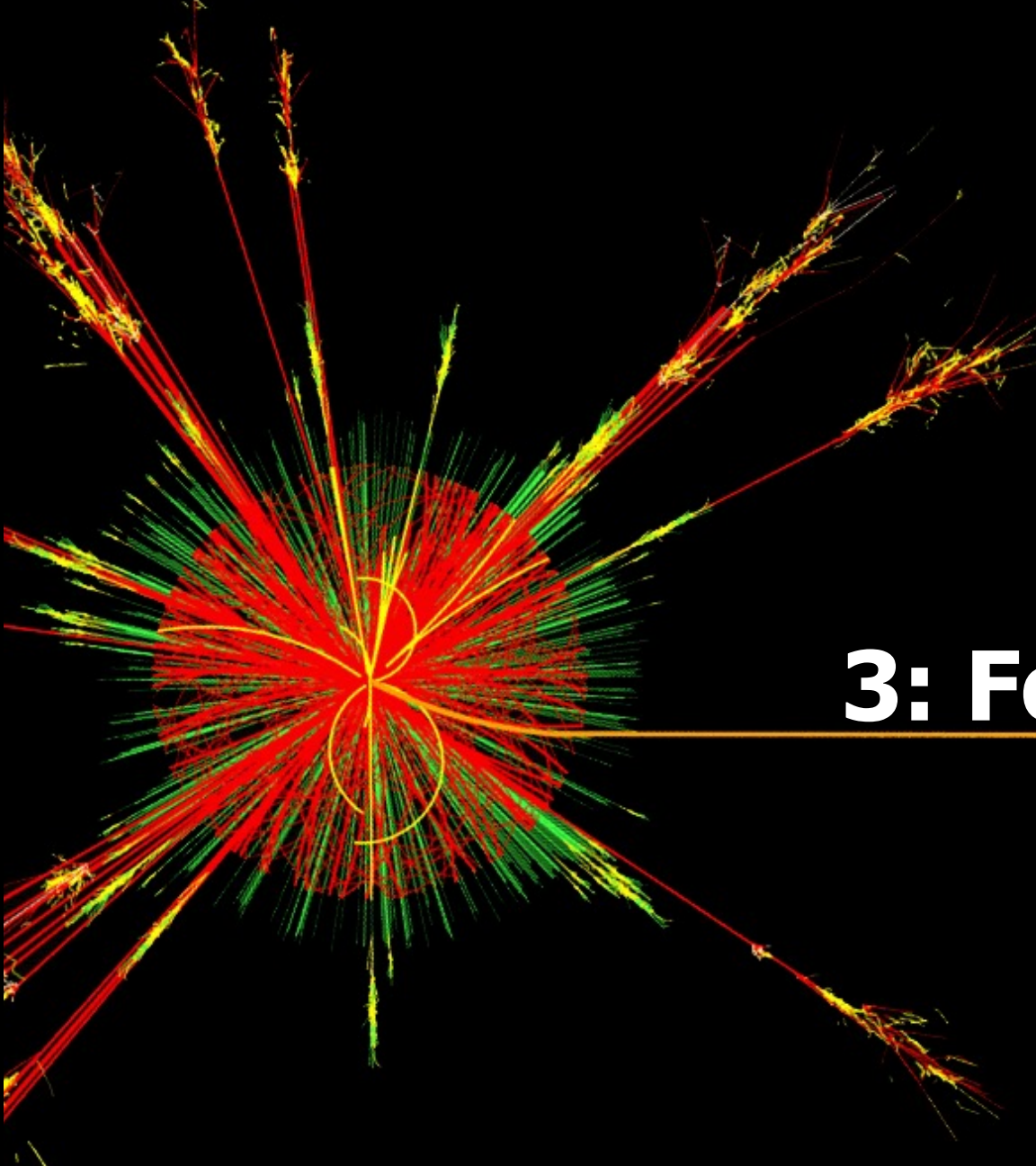
0.000001%
matter

(+99.999999% radiation)



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





3: Forces: "Standard Model"

Fermionen: spin=1/2 deeltjes

Quarks		
u	c	t
d	s	b

Higgs field

bosonen spin=1 deeltjes

Krachten	
Z	γ
W	g

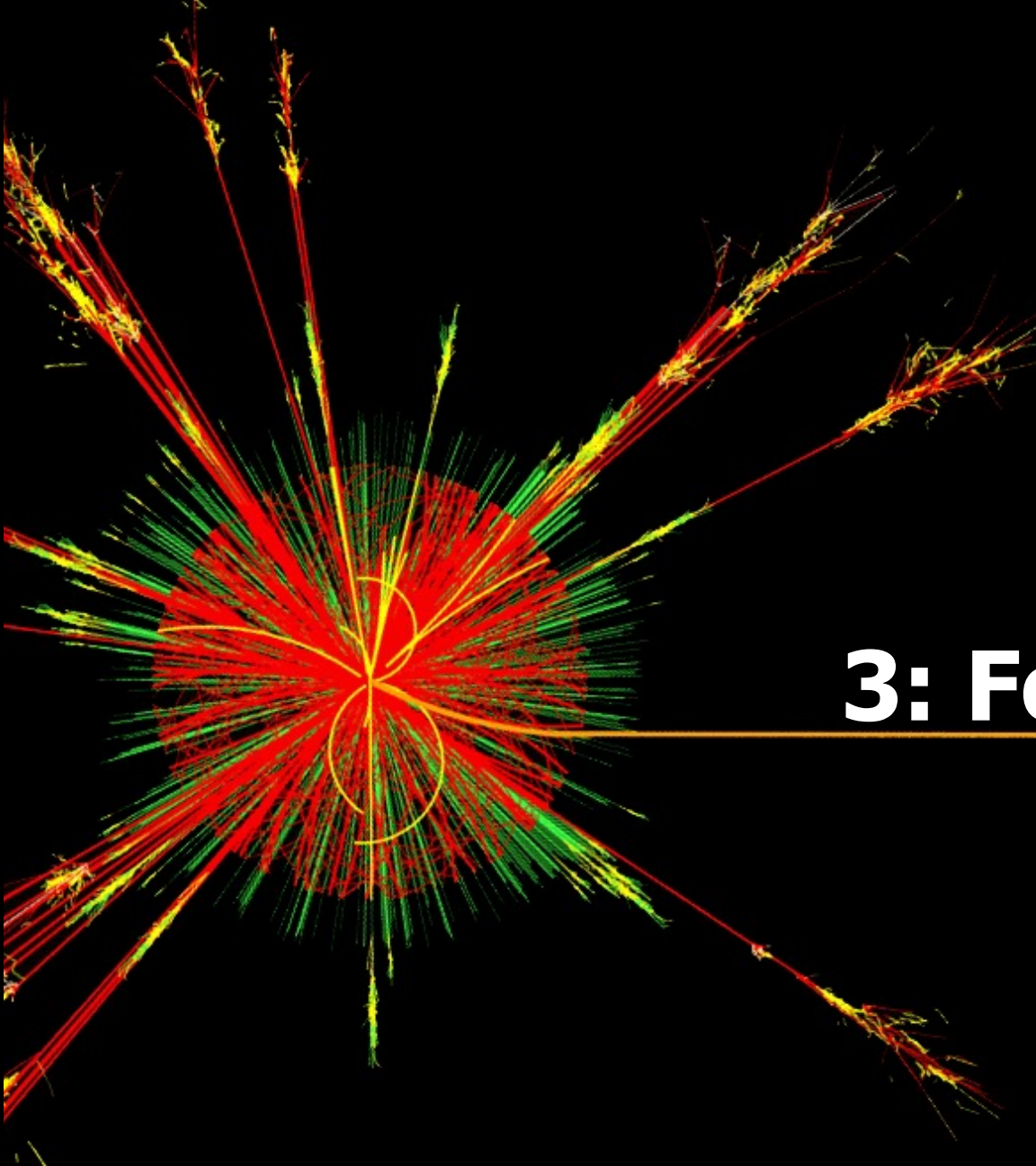
H

Leptonen		
ν_e	ν_μ	ν_τ
e	μ	τ

Piele (Giel) Hameleers: also standard model?



3: Forces: "Standard Model"



Fermionen: spin=1/2 deeltjes

Quarks		
u	c	t
d	s	b

Higgs field

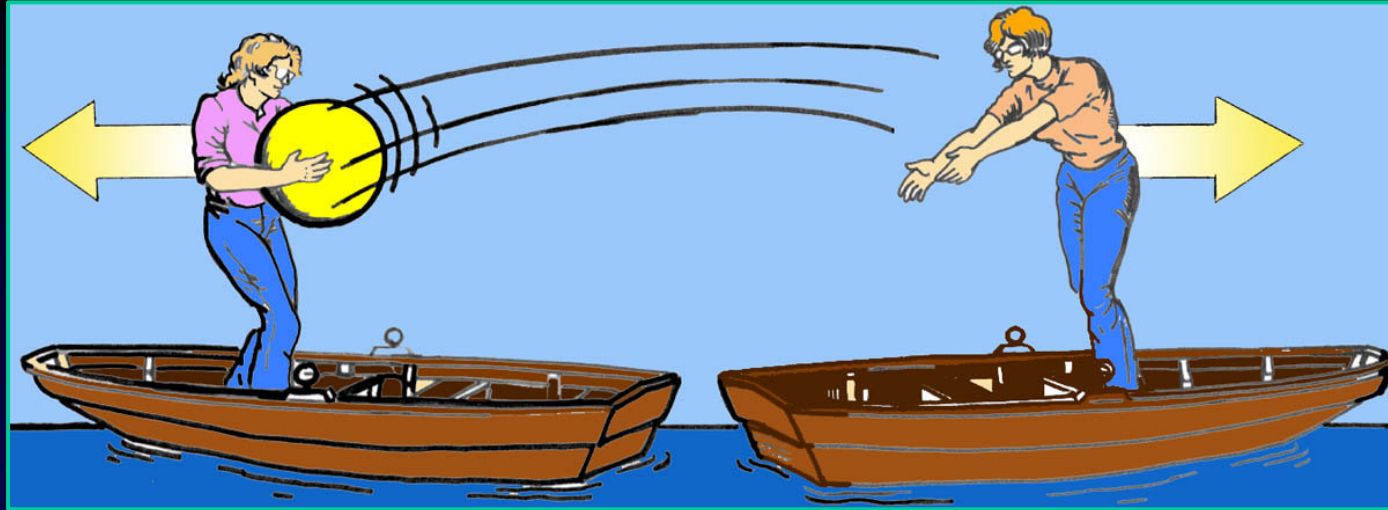
bosonen: spin=1 deeltjes

Krachten	
Z	γ
W	g

H

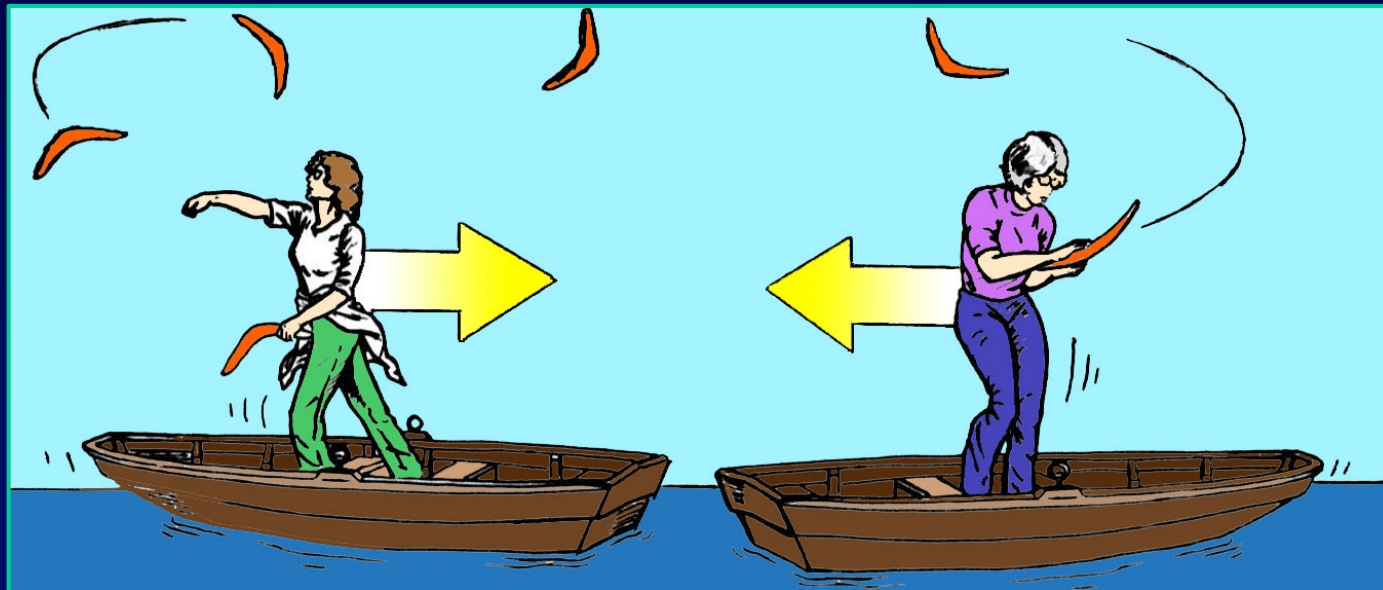
Leptonen		
ν_e	ν_μ	ν_τ
e	μ	τ

Forces in Quantum Mechanics: exchange of quanta



“Repulsive force”

There is no
“action at a distance”



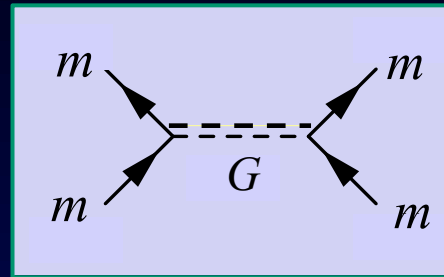
“Atractive force”

Four fundamental forces of nature

Gravity:



Quantum
Graviton exchange?



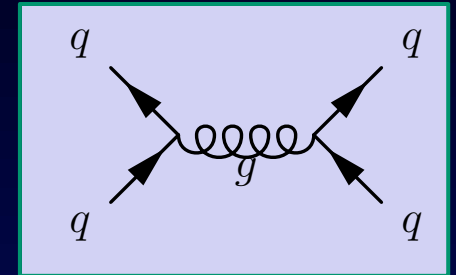
Acts on particles with mass

Strong nuclear force:



Acts on quarks

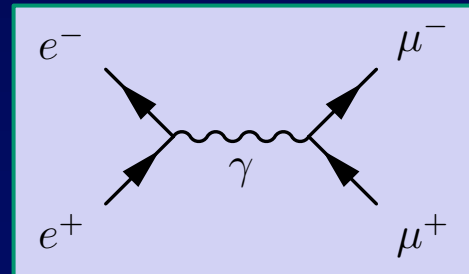
Quantum
gluon exchange:



Electromagnetism:



Quantum
photon exchange:



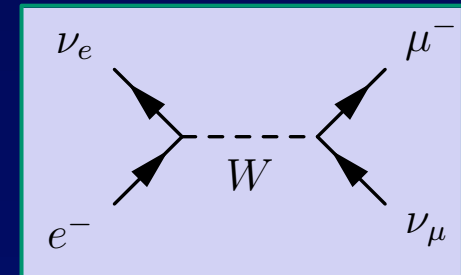
Acts on all charged particles

Weak nuclear force:



Acts on all particles

Quantum
W, Z exchange:

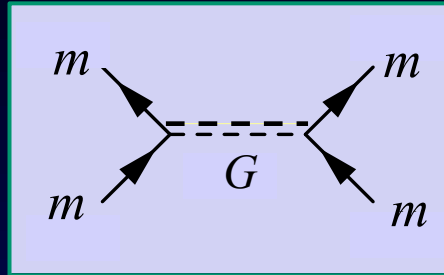


Four fundamental forces of nature

Gravity:

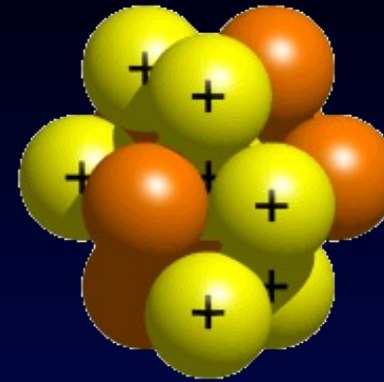


Quantum
Graviton exchange?



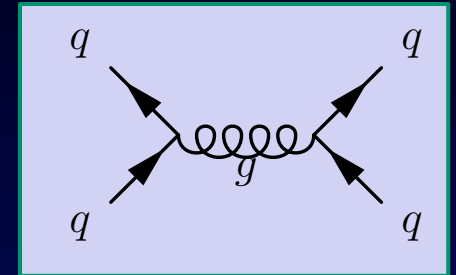
Acts on particles with mass

Strong nuclear force:



Acts on quarks

Quantum
gluon exchange:

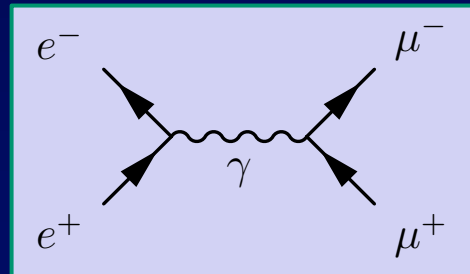


Electromagnetic



Richard Feynman and particles

Quantum
photon exchange:

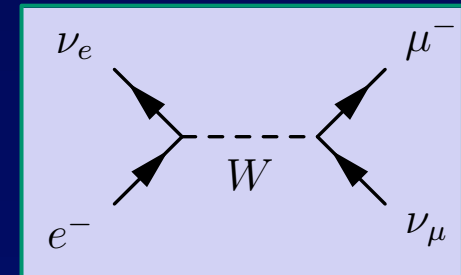


Weak nuclear force:



Acts on all particles

Quantum
W, Z exchange:

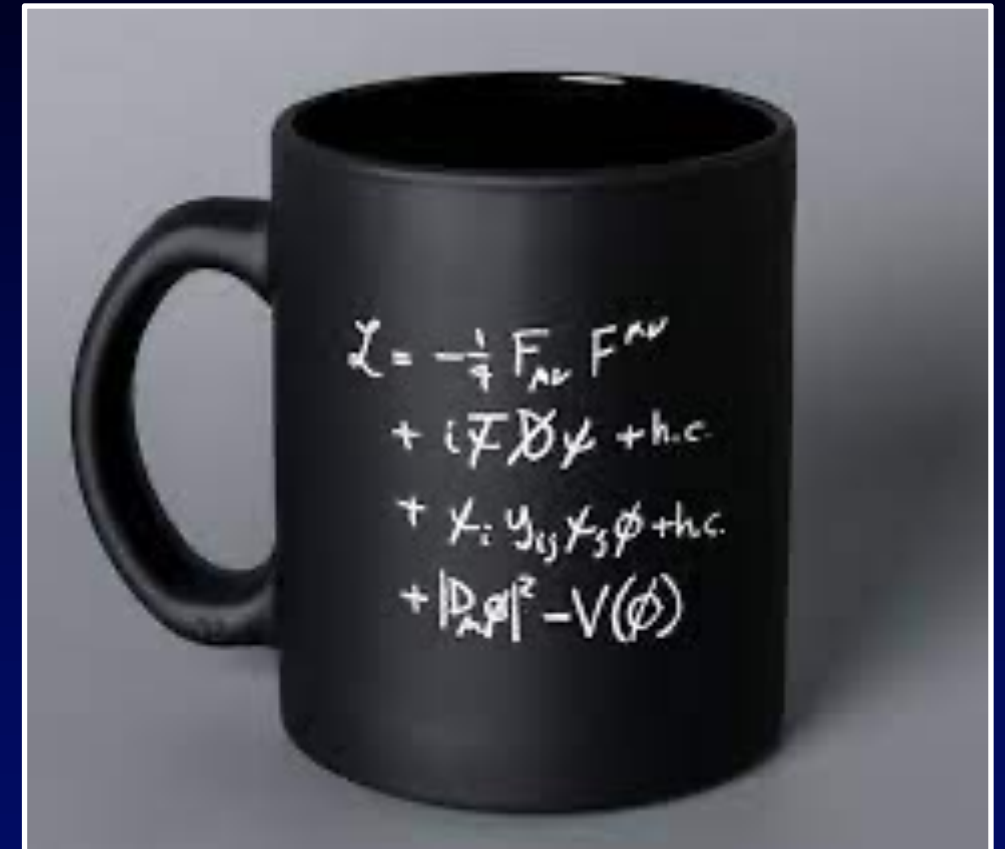
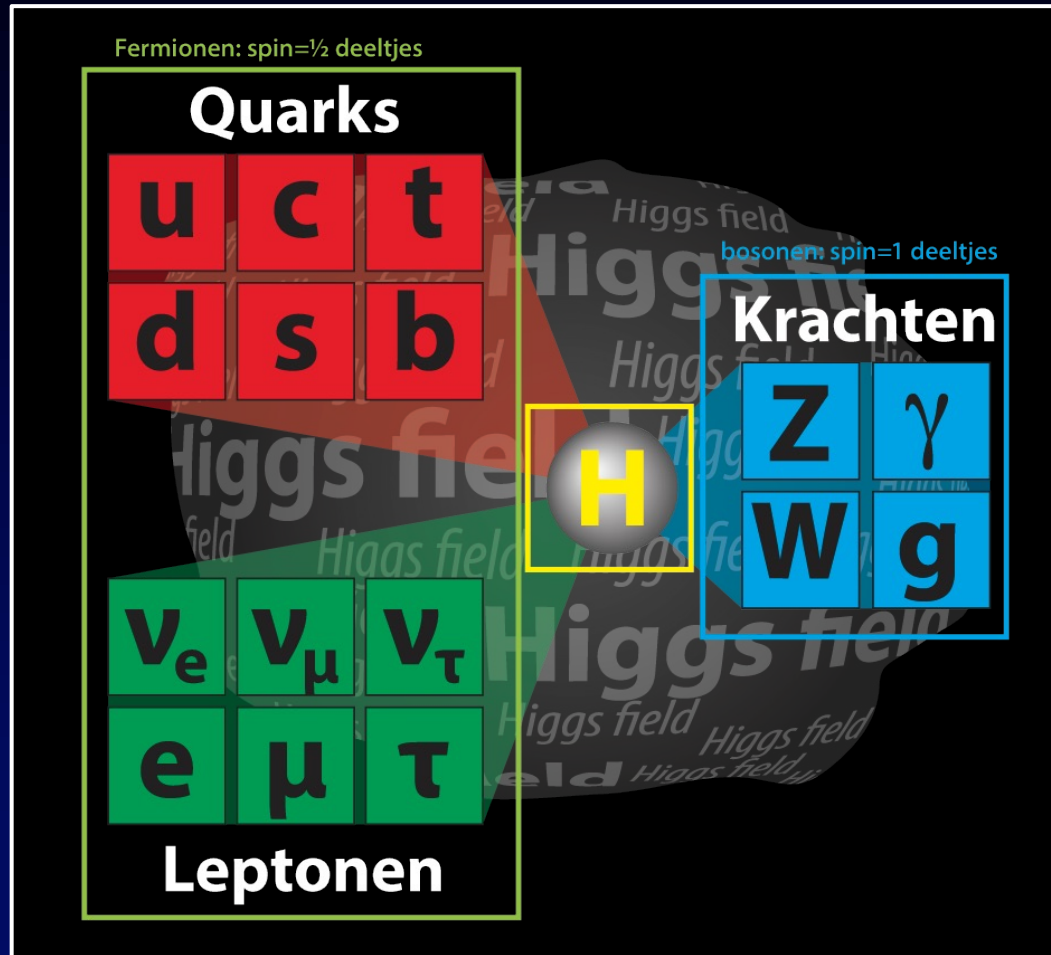


How strong are the forces?

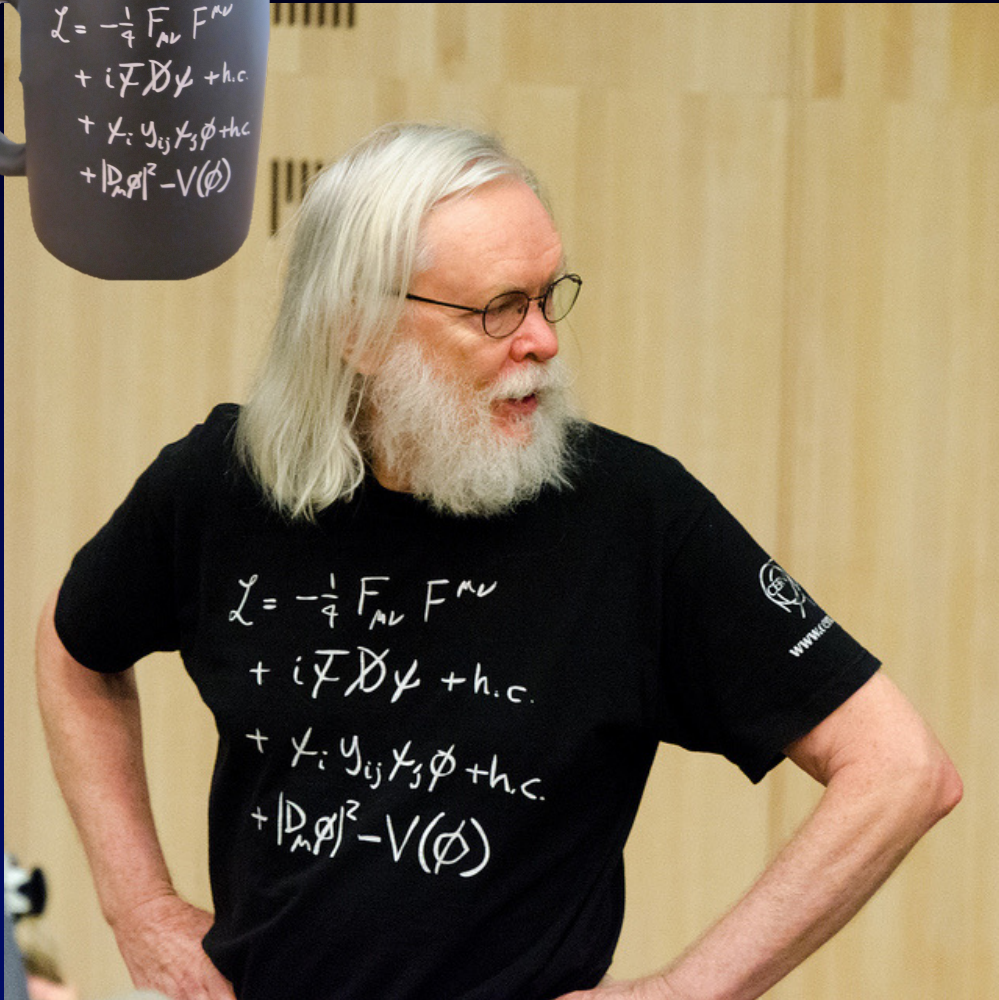
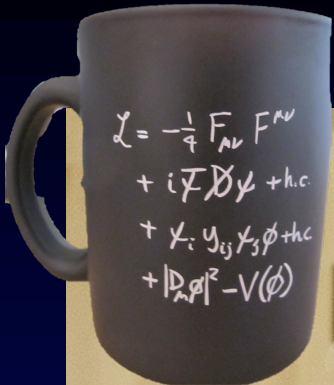


	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried By	Graviton <small>(not yet observed)</small>	$W^+ W^- Z^0$	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and $W^+ W^-$	Quarks and Gluons
Strength	0 00000000000000 0000000000000000 00000000000001	0.0001	1	60

Standard Model: Particles and Forces



Standard Model: Theory

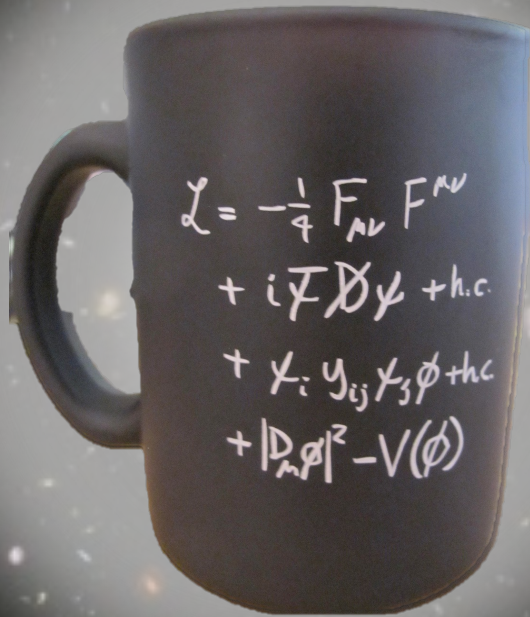


$$-\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^b \partial_\mu g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \frac{1}{2}ig_s^2 (\bar{q}_i^\mu \gamma^\mu q_j^\nu) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu + \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M q \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) + \frac{2M^4}{g^2} \alpha_h - igc_w [\partial_\nu W_\nu^+ W_\mu^- - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\nu^0 (W_\nu^- \partial_\mu W_\mu^+) - ig s_w [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)] - \frac{1}{2}g^2 W_\mu^+ \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\nu^0 g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 W_\nu^+ W_\mu^- - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^3 + H\phi^0 \phi^0 + \frac{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^-] + gM W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w} Z_\mu^0 Z_\nu^0 H - \frac{1}{2}ig [W_\mu^+ (\phi^0 \partial_\mu \phi^- - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0))] + \frac{1}{2}g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - \phi^+ \partial_\mu H] + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w}{c_w} M Z_\mu^0 (W_\mu^+ ig s_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4}g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0 \frac{1}{2}g^2 \frac{1}{c_w} Z_\mu^0 Z_\nu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_w^2}{c_w} W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + n m_\lambda^j) d_j^\lambda + ig s_w A_\mu [-(\bar{e}^\lambda \gamma e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma d_j^\lambda)] + \frac{1}{4} \gamma^5 \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - 1) (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda \gamma^5) C_{\lambda c} d_j^\lambda] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\lambda C_{\lambda c}^\dagger \gamma^\mu (\frac{ig}{2\sqrt{2}} \frac{m_c^2}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2} i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_\lambda^2 (\bar{u}_j^\lambda C_{\lambda c} (1 - \gamma^5) d_j^\lambda) + n \gamma^5) d_j^\lambda] + \frac{ig}{2M\sqrt{2}} \phi^- [m_\lambda^2 (\bar{d}_j^\lambda C_{\lambda c}^\dagger (1 + \gamma^5) u_j^\lambda) - m_\lambda^2 (\bar{d}_j^\lambda C_{\lambda c}^\dagger \frac{g m_\lambda^2}{2M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g m_\lambda^2}{2M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig m_\lambda^2}{2M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig n}{2M} \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2} igc_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + ig s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - igc_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + ig s_w W_\mu^- (\partial_\mu \bar{X}^- Y - igc_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^1 - \partial_\mu \bar{X}^- X^-) + ig s_w A_\mu (\partial_\mu \bar{X}^+ X^1 - \frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} ig[\bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} igM[\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2}igM[\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]$$

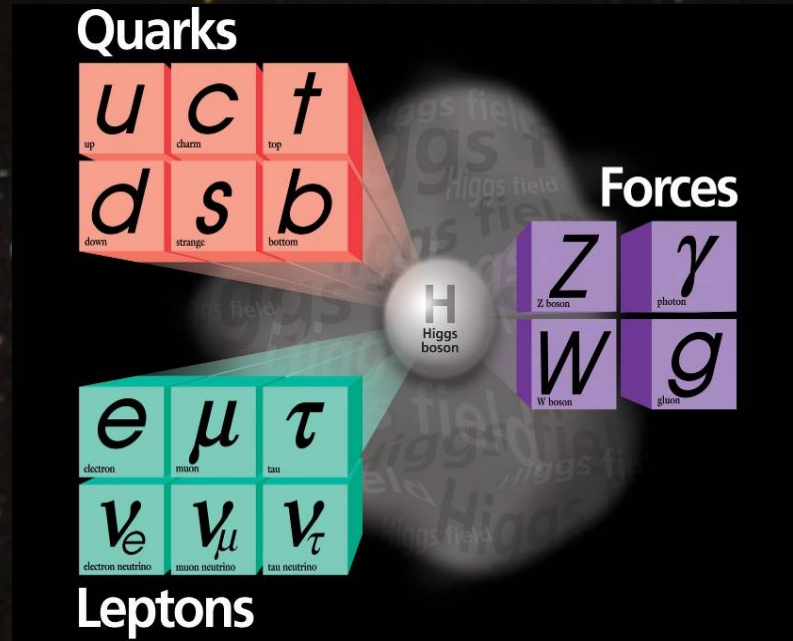


Standard Model

"The formula"



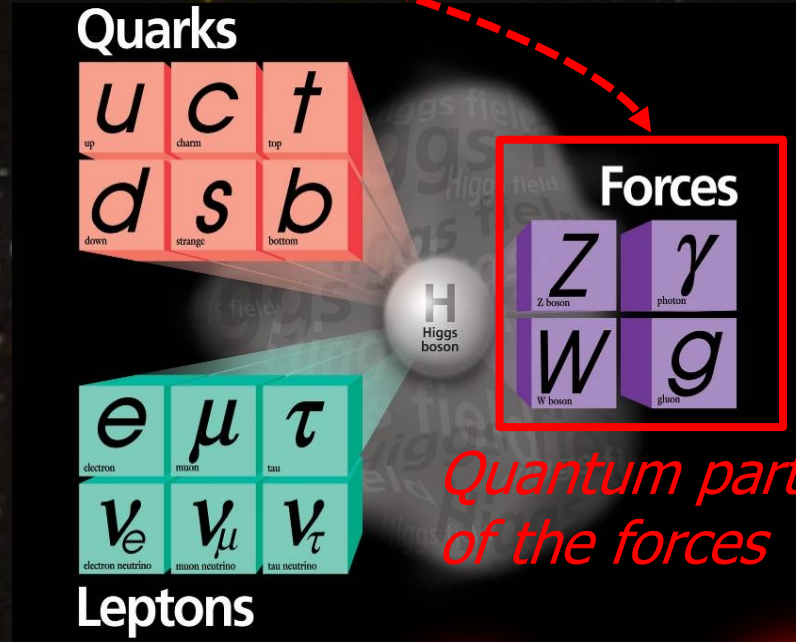
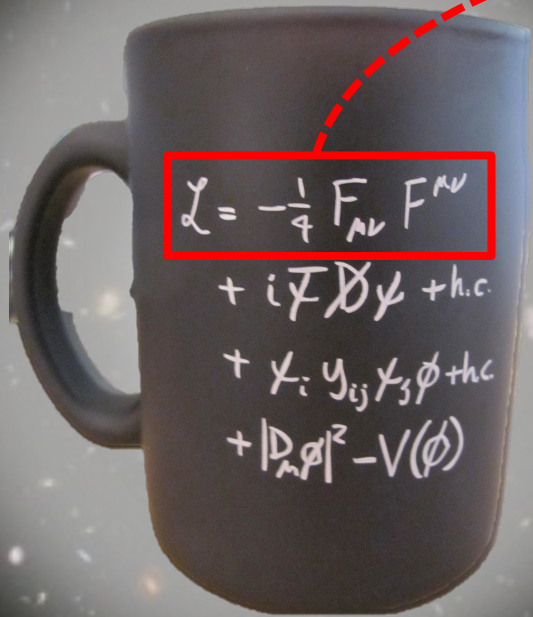
"The building blocks"



Standard Model

"The formula"

"The building blocks"



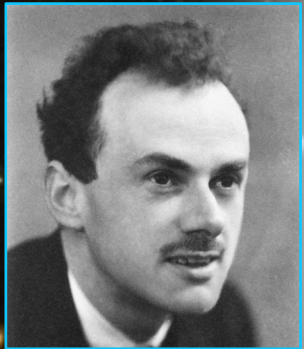
Quantum particles of the forces



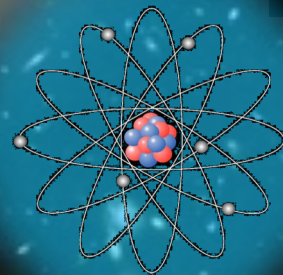
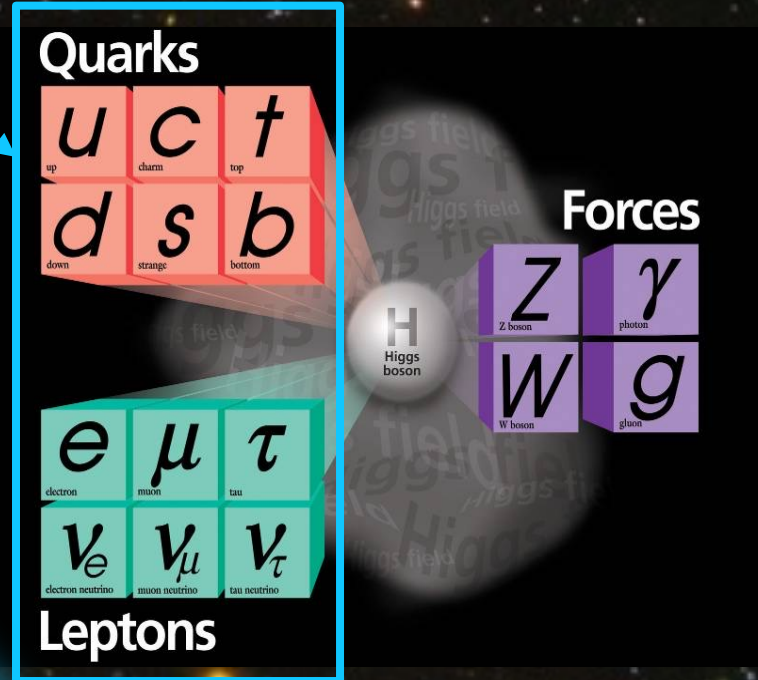
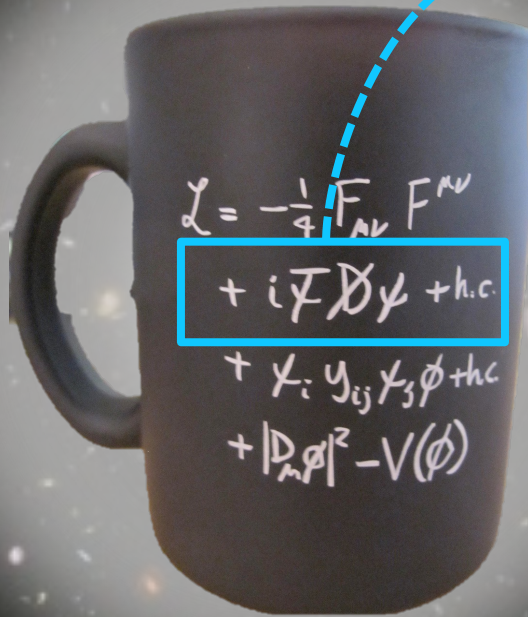
Standard Model

"The formula"

"The building blocks"



1928: Dirac equation

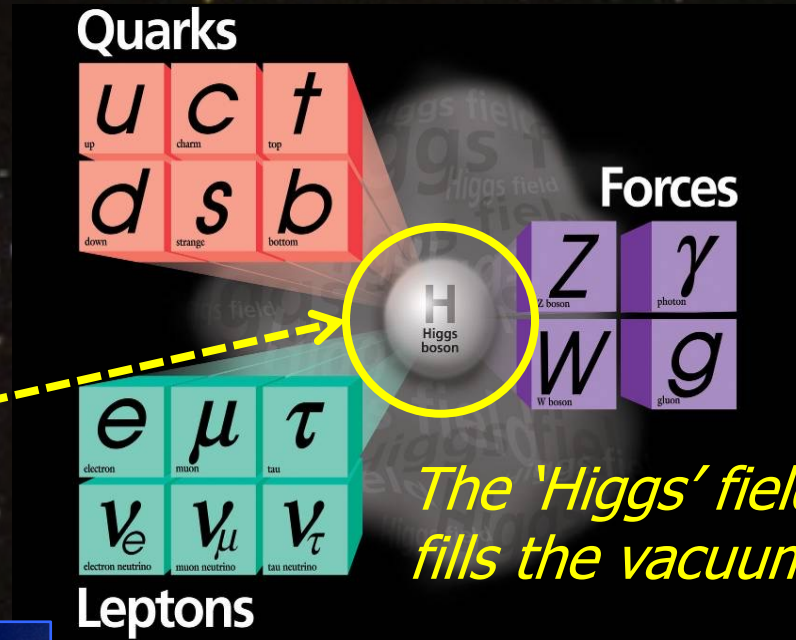
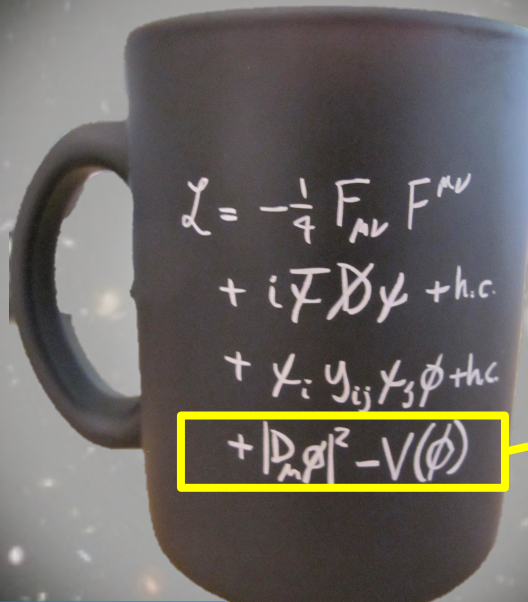


Matter particles

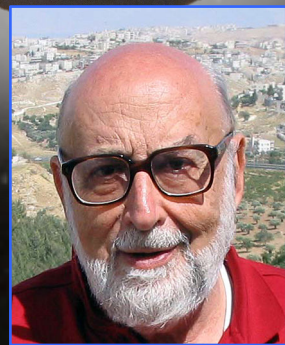
Standard Model

"The formula"

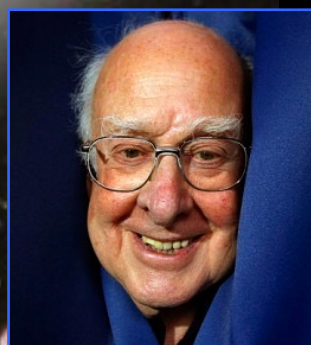
"The building blocks"



Brout



Englert



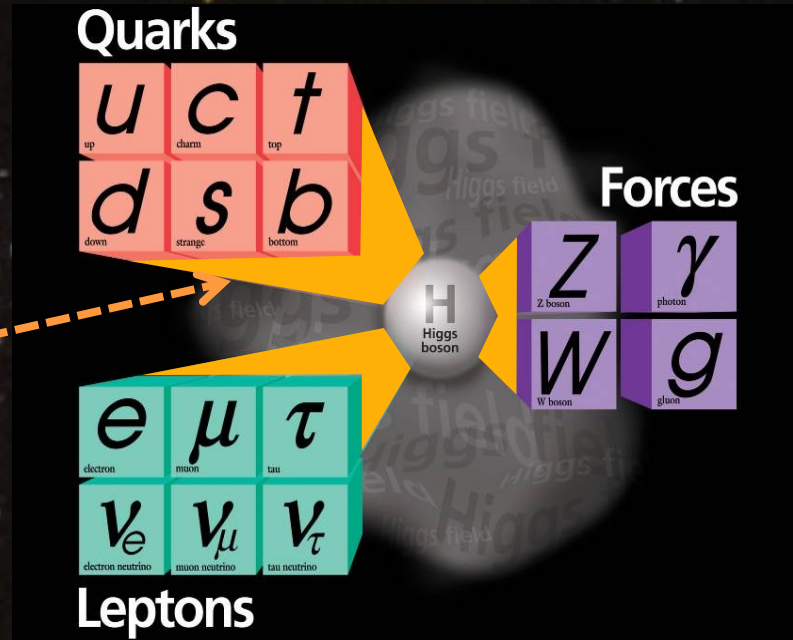
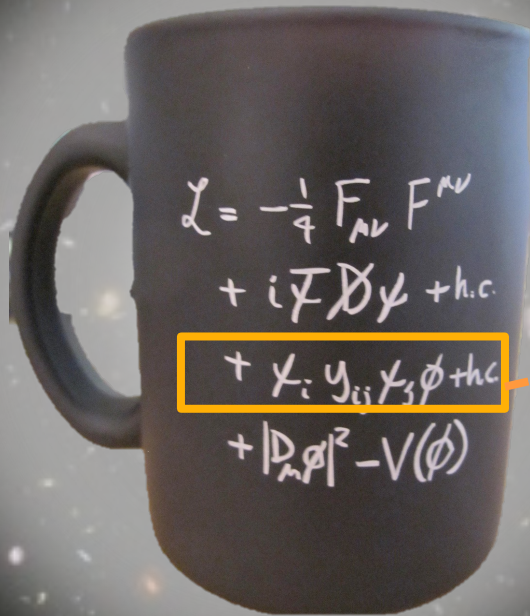
Higgs

1964:
Standard Model prediction:
empty space is not empty!

Standard Model

"The formula"

"The building blocks"



Kobayashi



Maskawa

Mass is generated by the Higgs field!

1972:

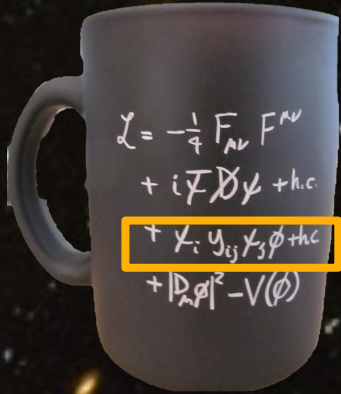
With 3 copies of particles an asymmetry between matter and antimatter is possible!

How did antimatter disappear in the Big bang?

Big Bang

Small Surplus

Dominates



49.9999999%
anti-matter
50.0000001%
matter



0.000001%
matter

(+99.999999% radiation)



Antimaterie not the exact mirror image of matter?!

Theoretically this requires three copies of all particles!

Fermionen: spin=1/2 deeltjes

Quarks			H	Krachten	
u	c	t		Z	γ
d	s	b	W	g	
1	2	3			
Leptonen					
ν_e	ν_μ	ν_τ			
e	μ	τ			

bosonen: spin=1 deeltjes





"LIEVERD, JE HEBT JE BEST GEDAAN,
MAAR ZO SMERIG HEB IK NOG NOOIT GEGETEN."

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



"KOFFIE!"

60

