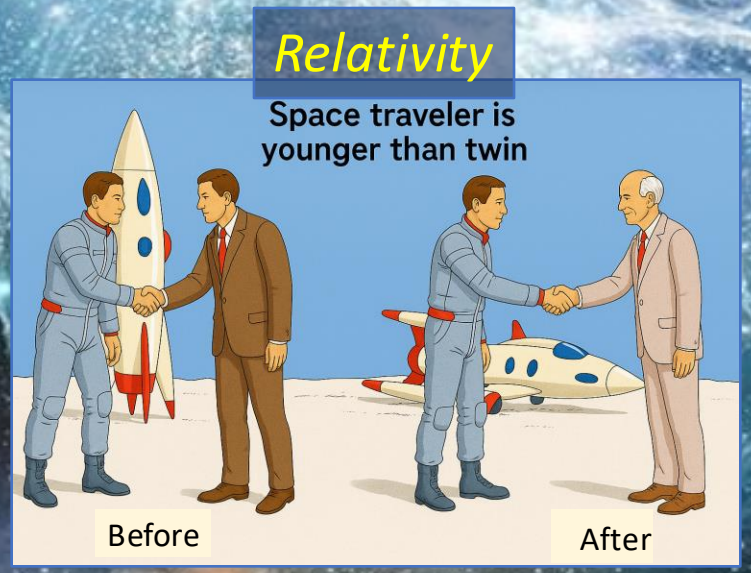
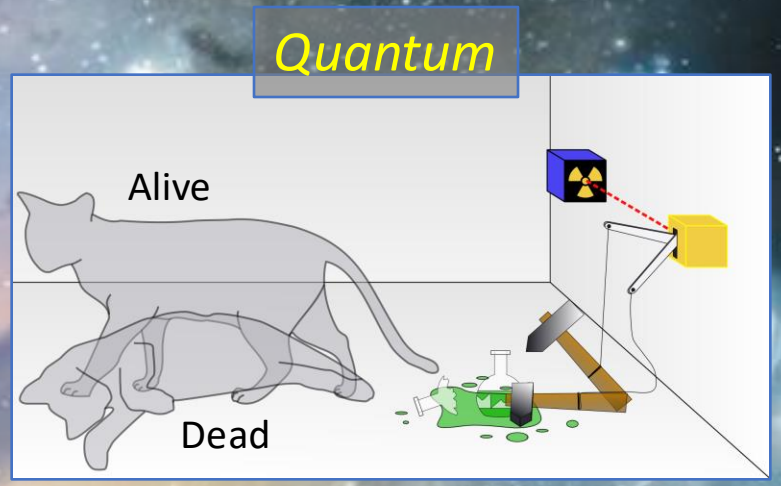
The Relativistic Quantum World

A lecture series on
Relativity Theory and Quantum Mechanics





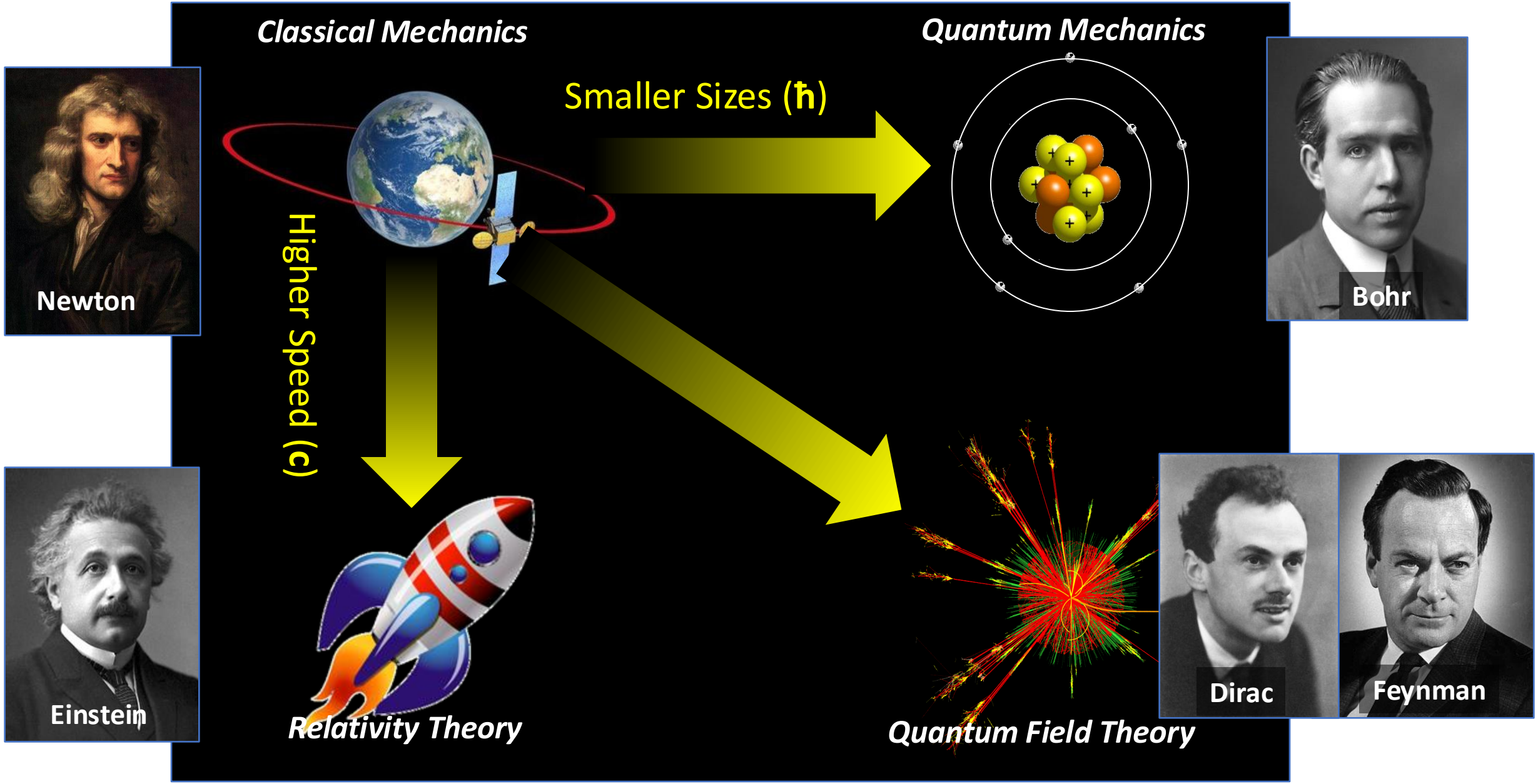
Marcel Merk
Studium Generale Maastricht
Sep 10 – Oct 8, 2025

The Relativistic Quantum World

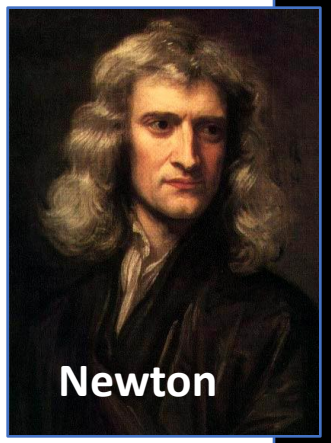
Relativity	Sep. 10:	Lecture 1: The Principle of Relativity and the Speed of Light Lecture 2: Time Dilation and Lorentz Contraction
	Sep. 17:	Lecture 3: The Lorentz Transformation and Paradoxes Lecture 4: General Relativity and Gravitational Waves
Quantum Mechanics	Sep. 24:	Lecture 5: The Early Quantum Theory Lecture 6: Feynman's Double Slit Experiment
	Oct. 1 :	Lecture 7: Wheeler's Delayed Choice and Schrodinger's Cat Lecture 8: Quantum Reality and the EPR Paradox
Standard Model	Oct. 8:	Lecture 9: The Standard Model and Antimatter Lecture 10: Why is there something rather than nothing?

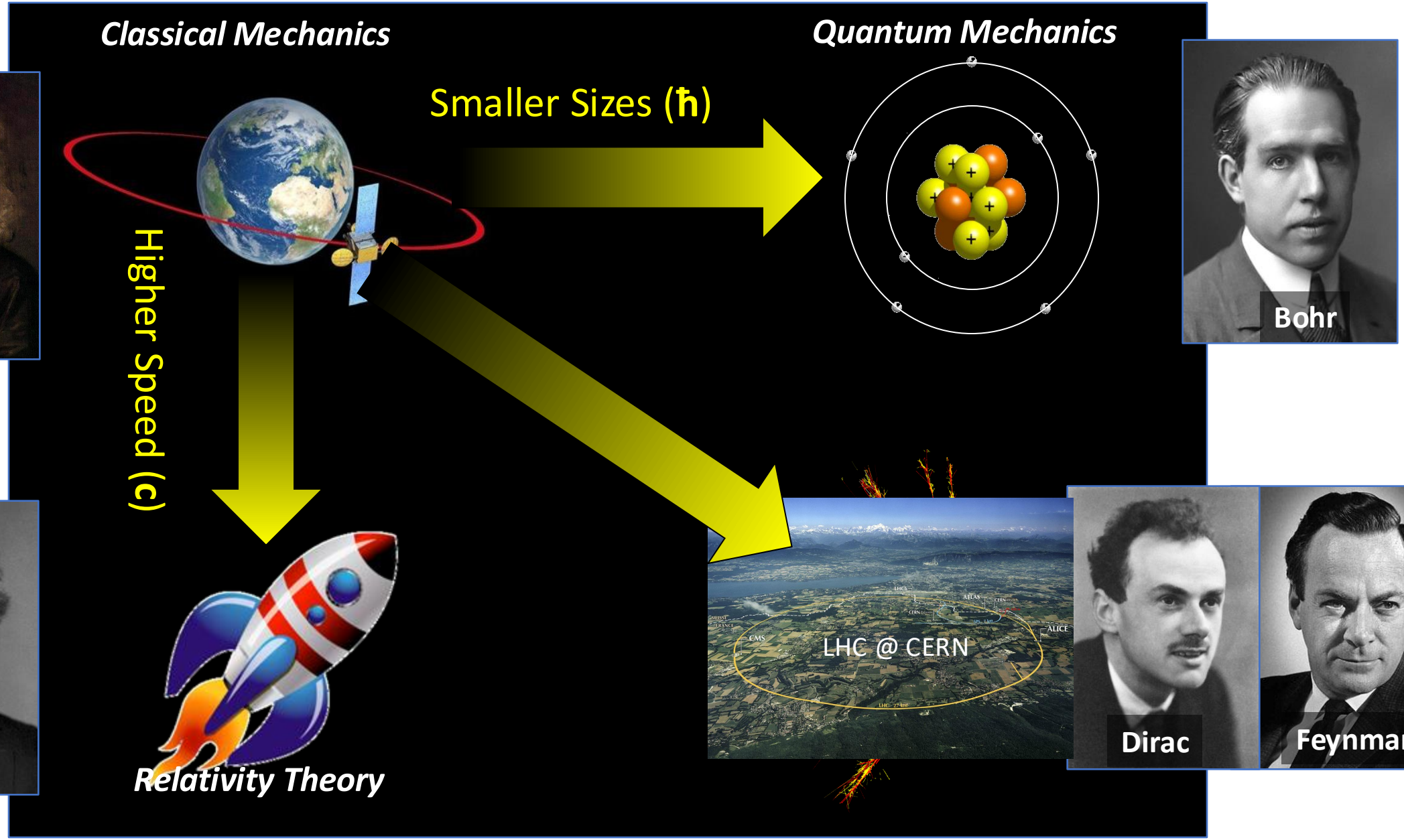
Lecture notes, written for this course, are available: www.nikhef.nl/~i93/Teaching/
Prerequisite for the course: High school level physics & mathematics.

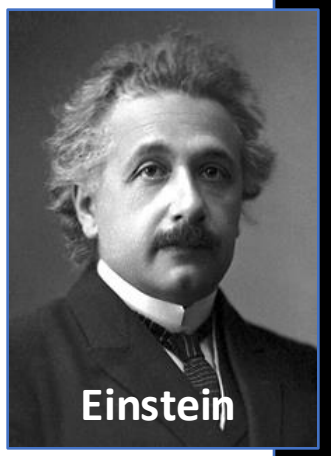
Relativity and Quantum Mechanics

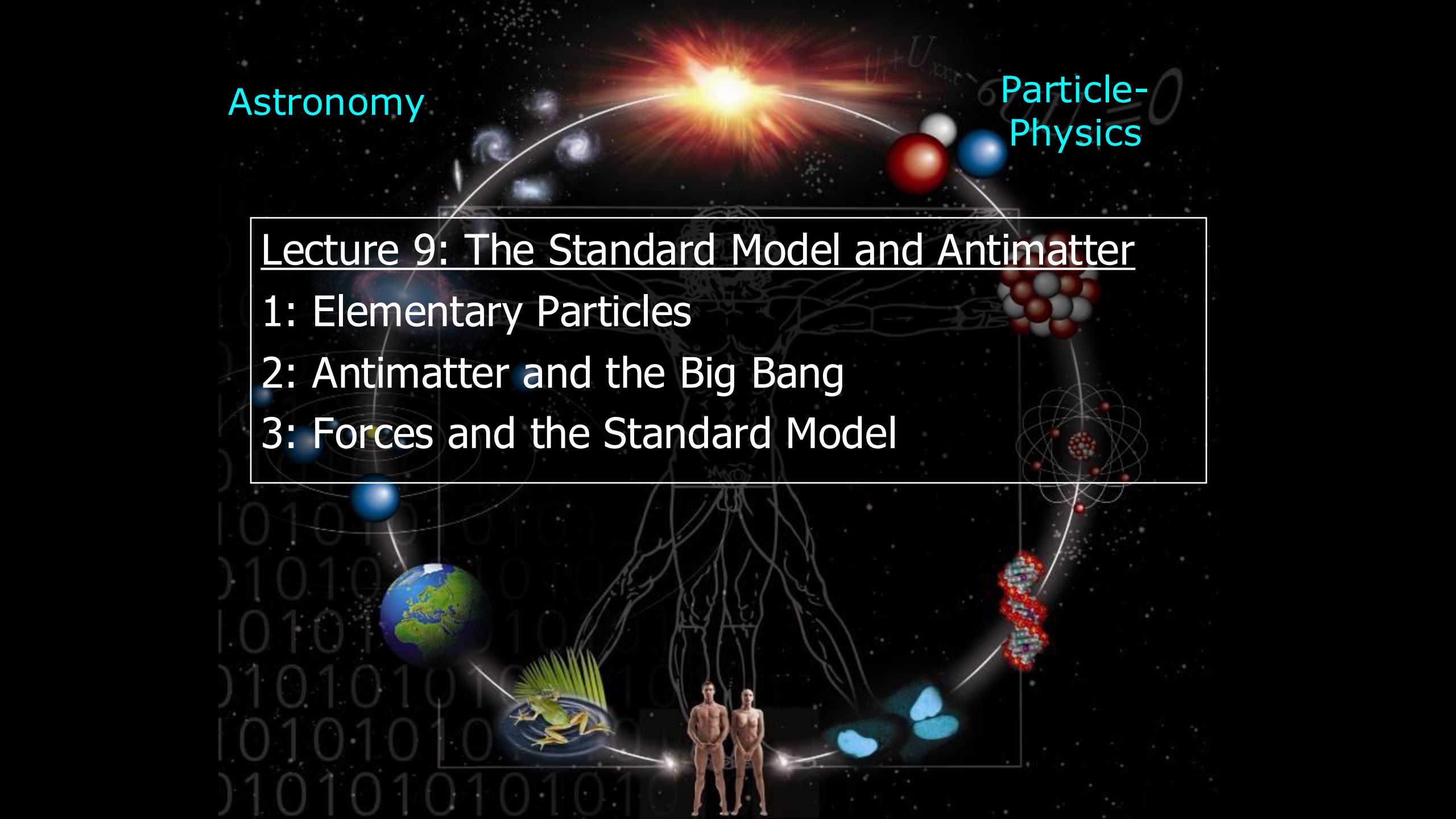


Relativity and Quantum Mechanics







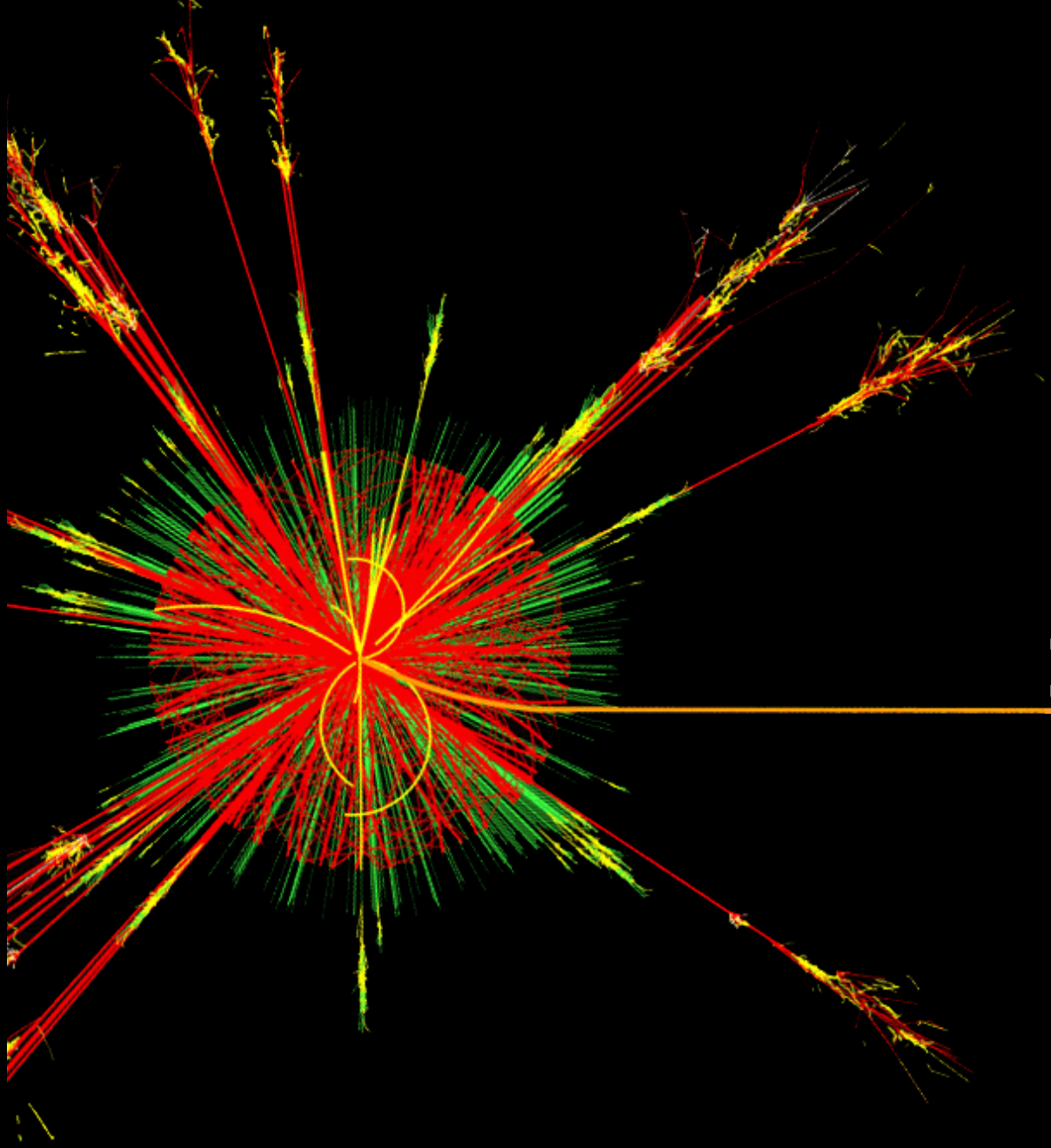


Lecture 9: The Standard Model and Antimatter

1: Elementary Particles

2: Antimatter and the Big Bang

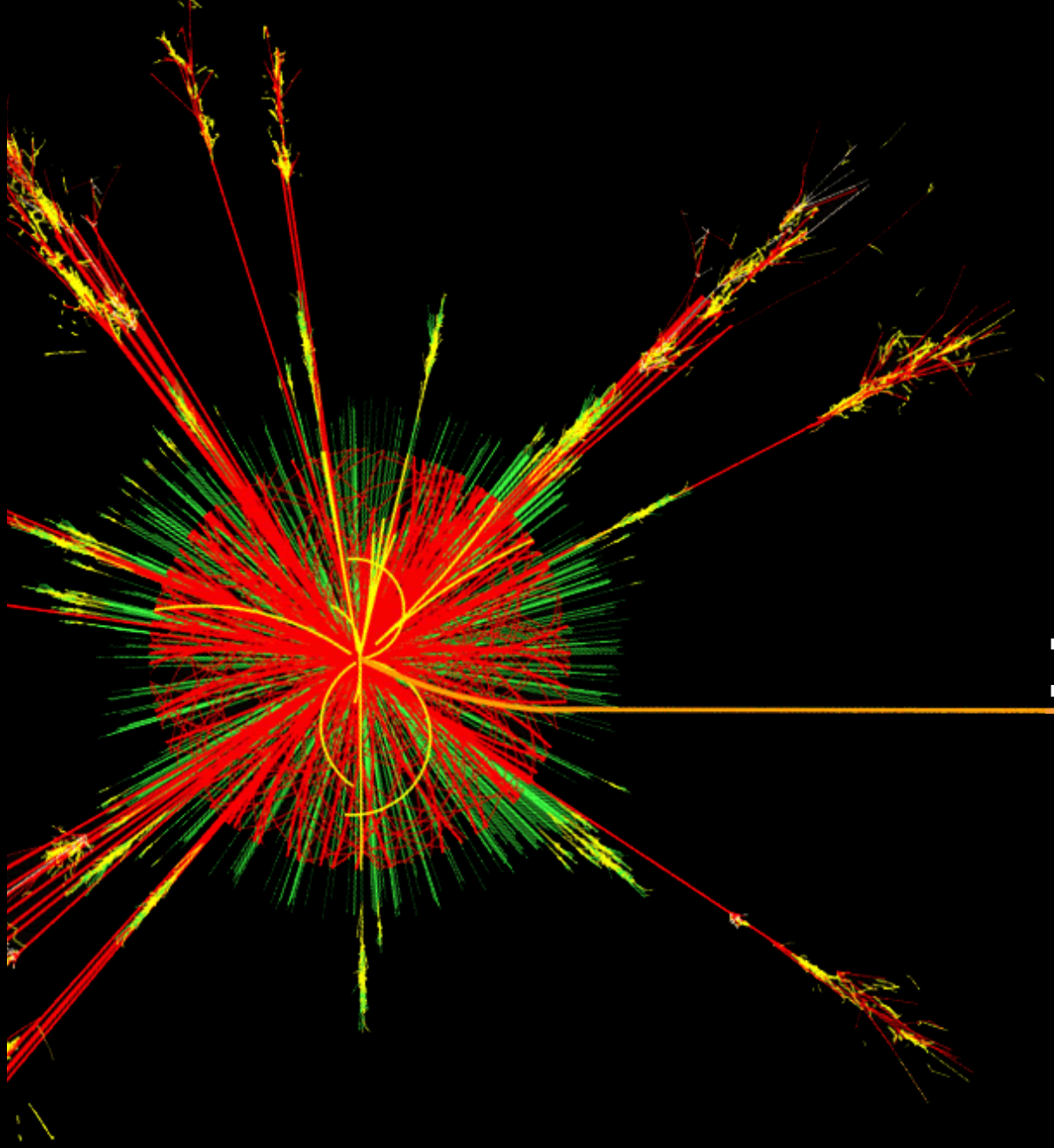
3: Forces and the Standard Model



?

1: Elementary Particles

"All things come in three"



Pie de Bökkum

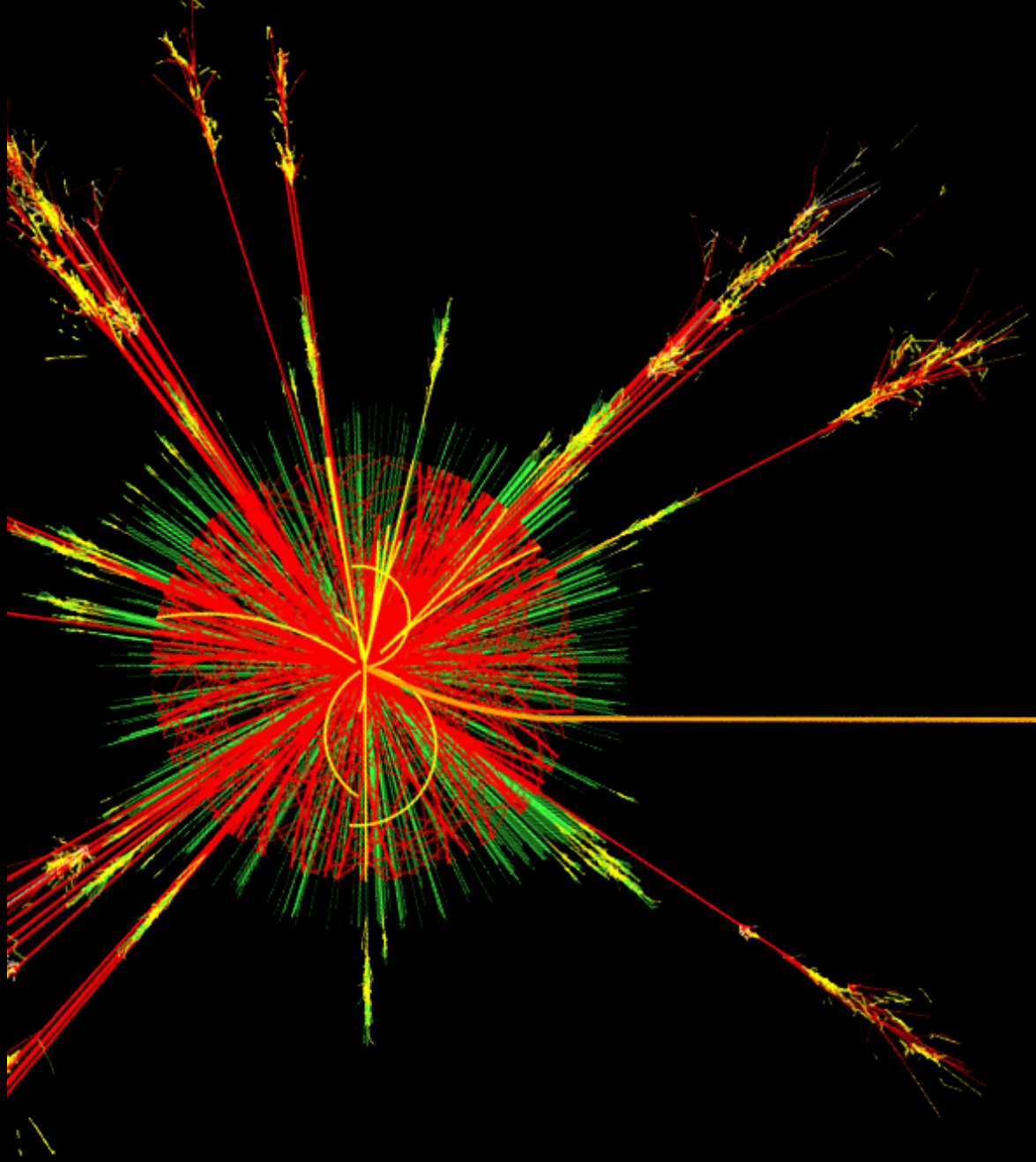
Ensinck de Kletskop

Flup de Koojstart

Operetta by Jacques Pirson, executed by Fons Olterdissen (1928)

1: Elementary Particles

"All things come in three"



Fons Olterdissen (1865-1923)
Author Maastricht anthem

1: Elementary Particles

"All things come in three"

Building blocks of Matter

Molecule

Atom

Electron

fundamental

Quark

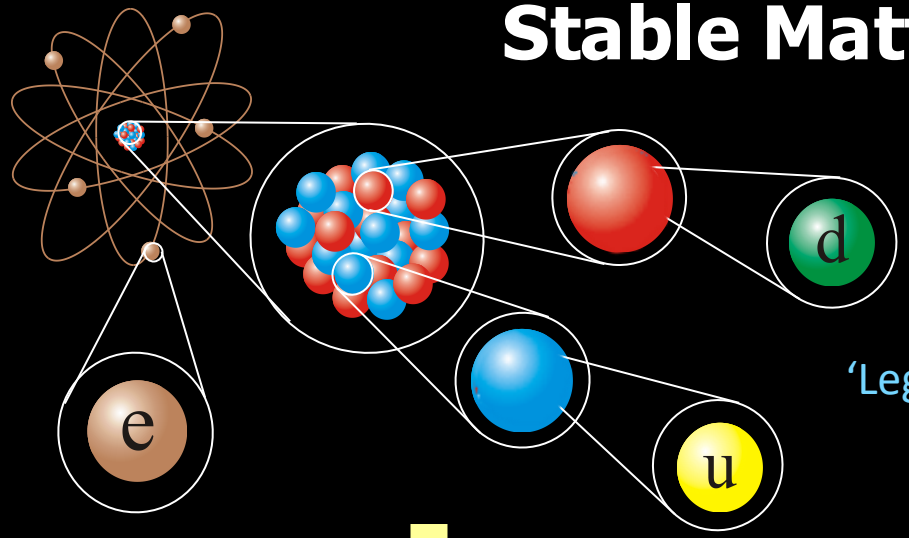
u

Proton/Neutron

u
u
d

Atom-nucleus

Stable Matter on Earth



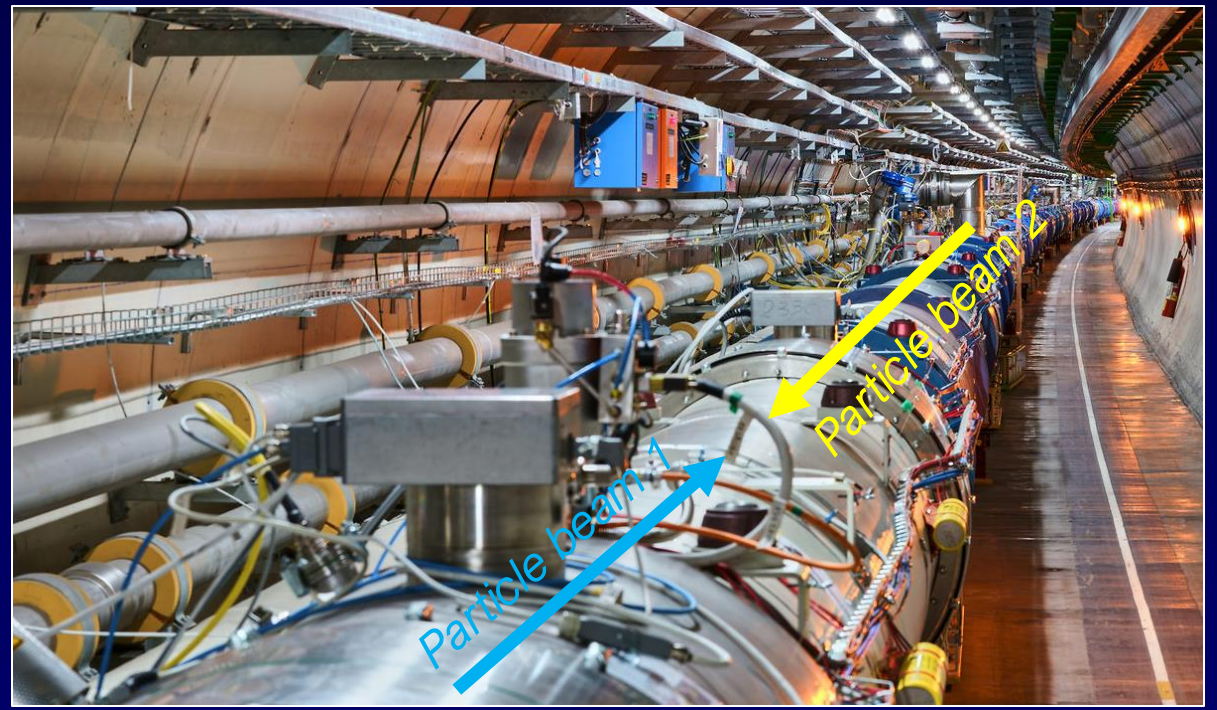
'Lego blocks' of nature

Mendeleev system

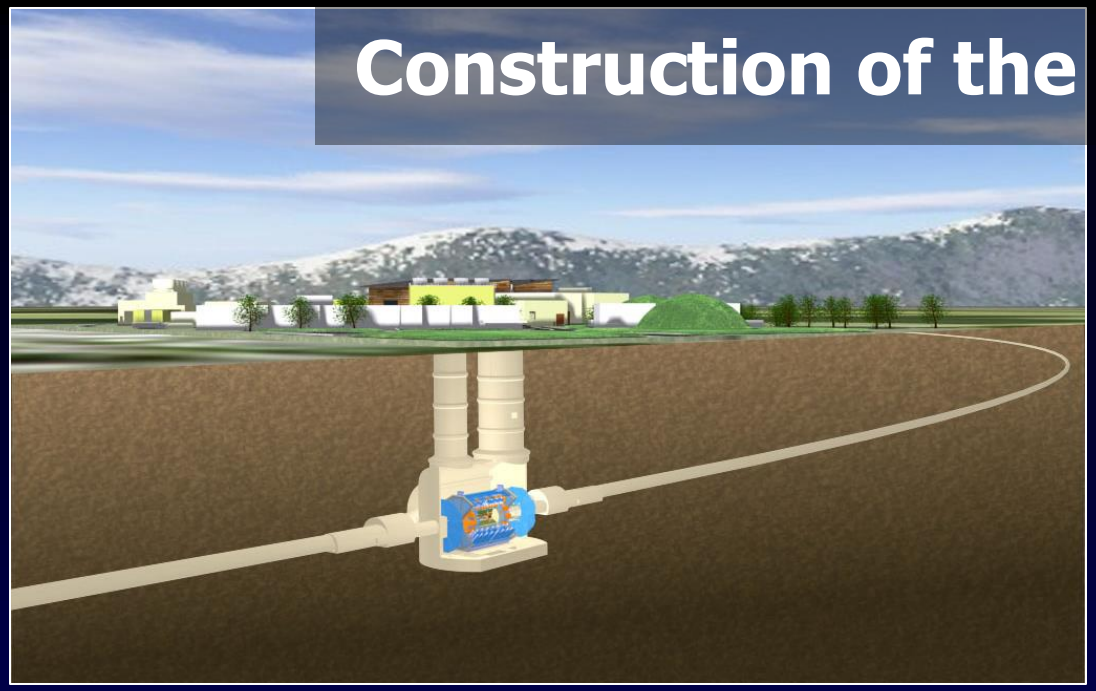
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 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									

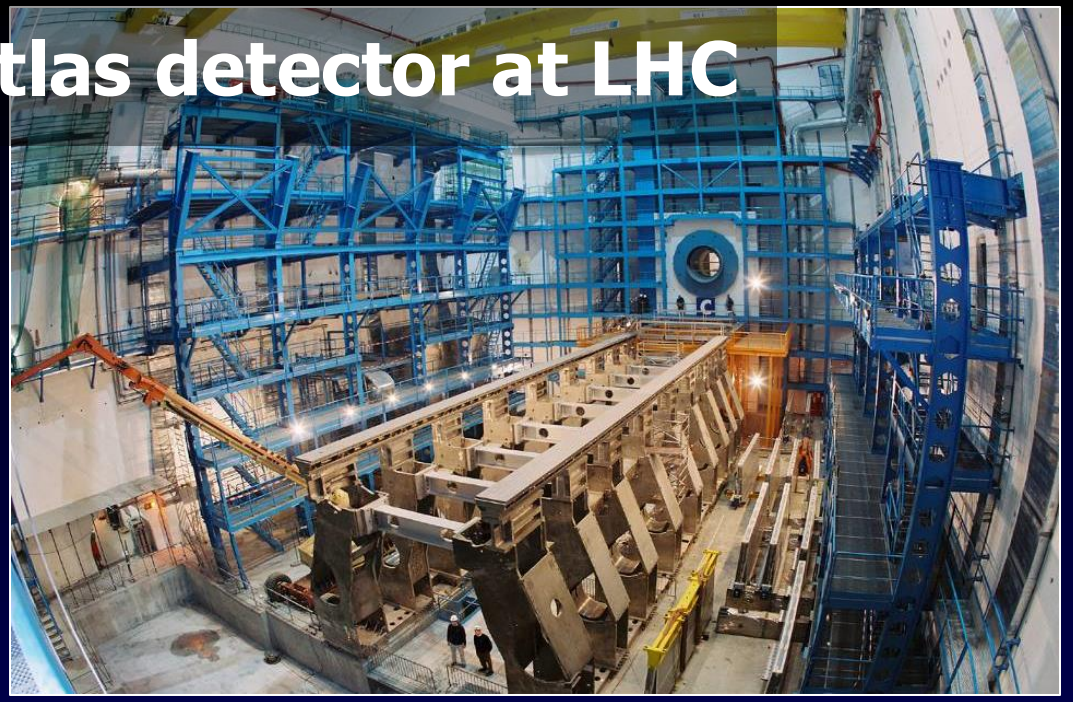
58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

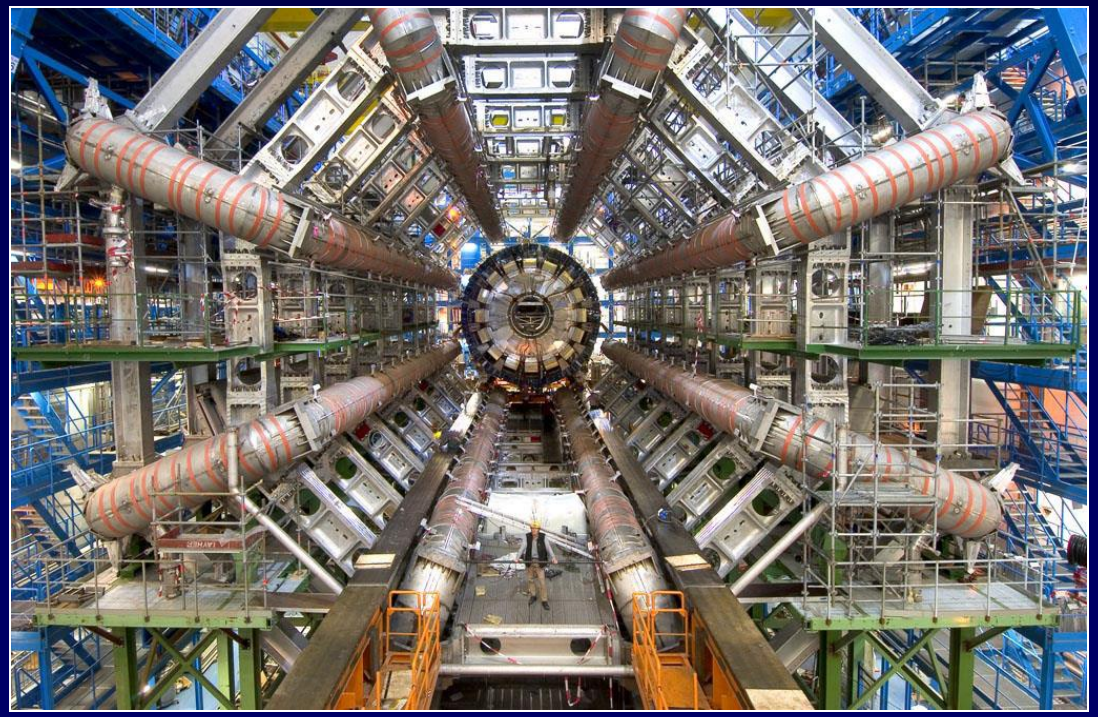
CERN: particle physics lab

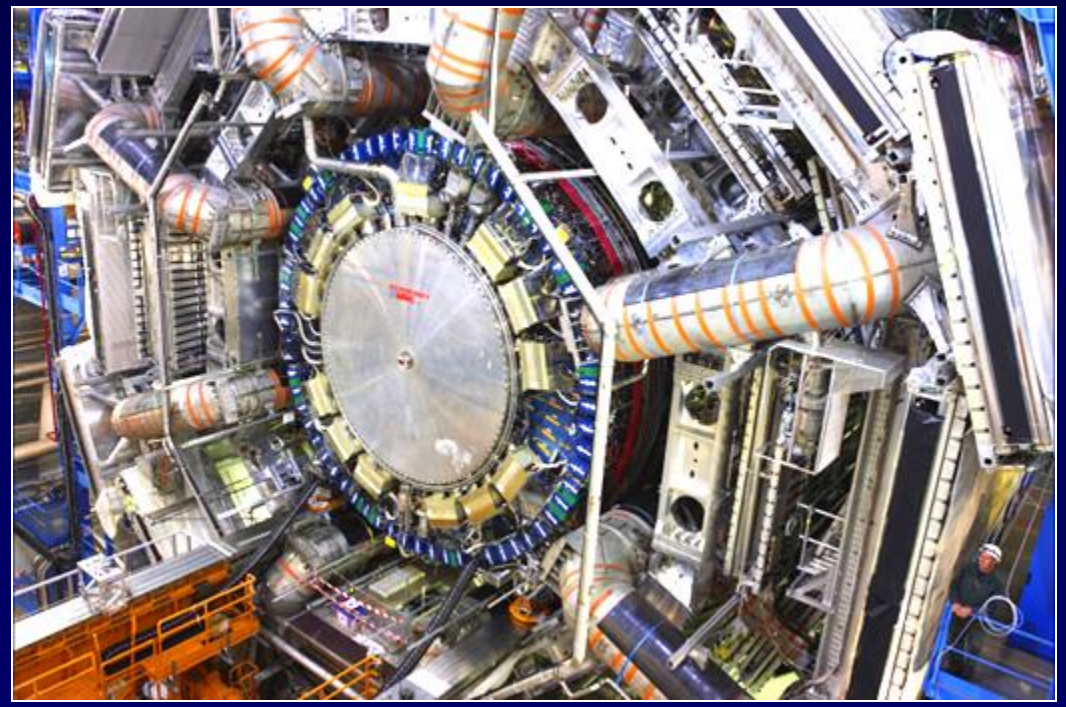


Construction of the Atlas detector at LHC





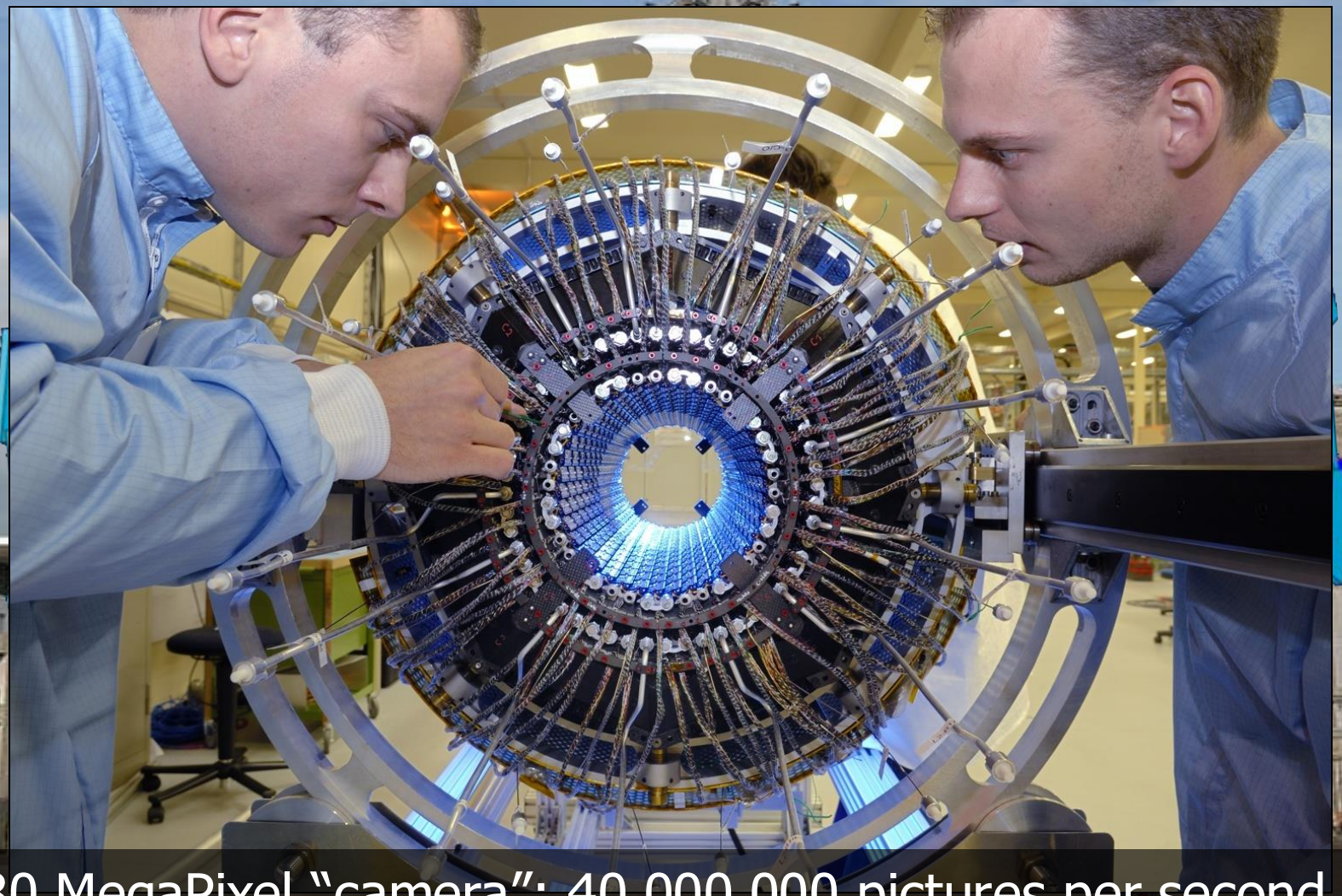




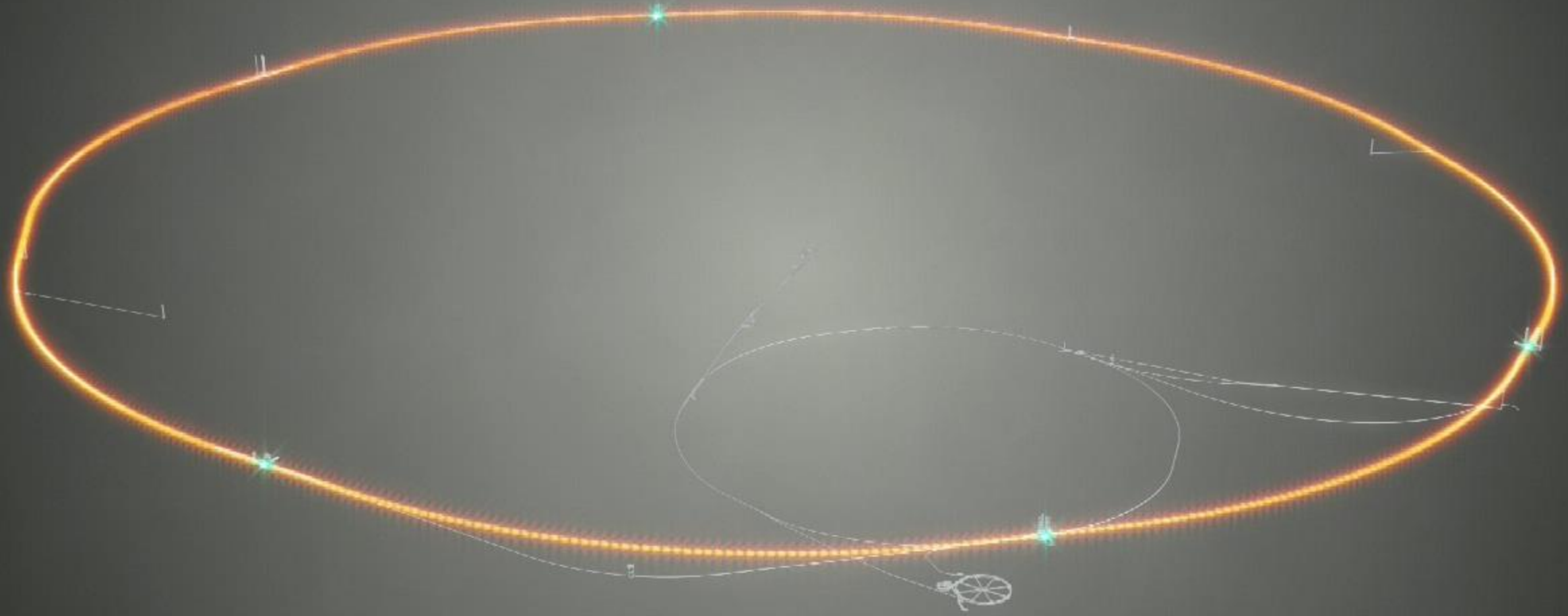
The Atlas Experiment

Largest "photocamera" on earth

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

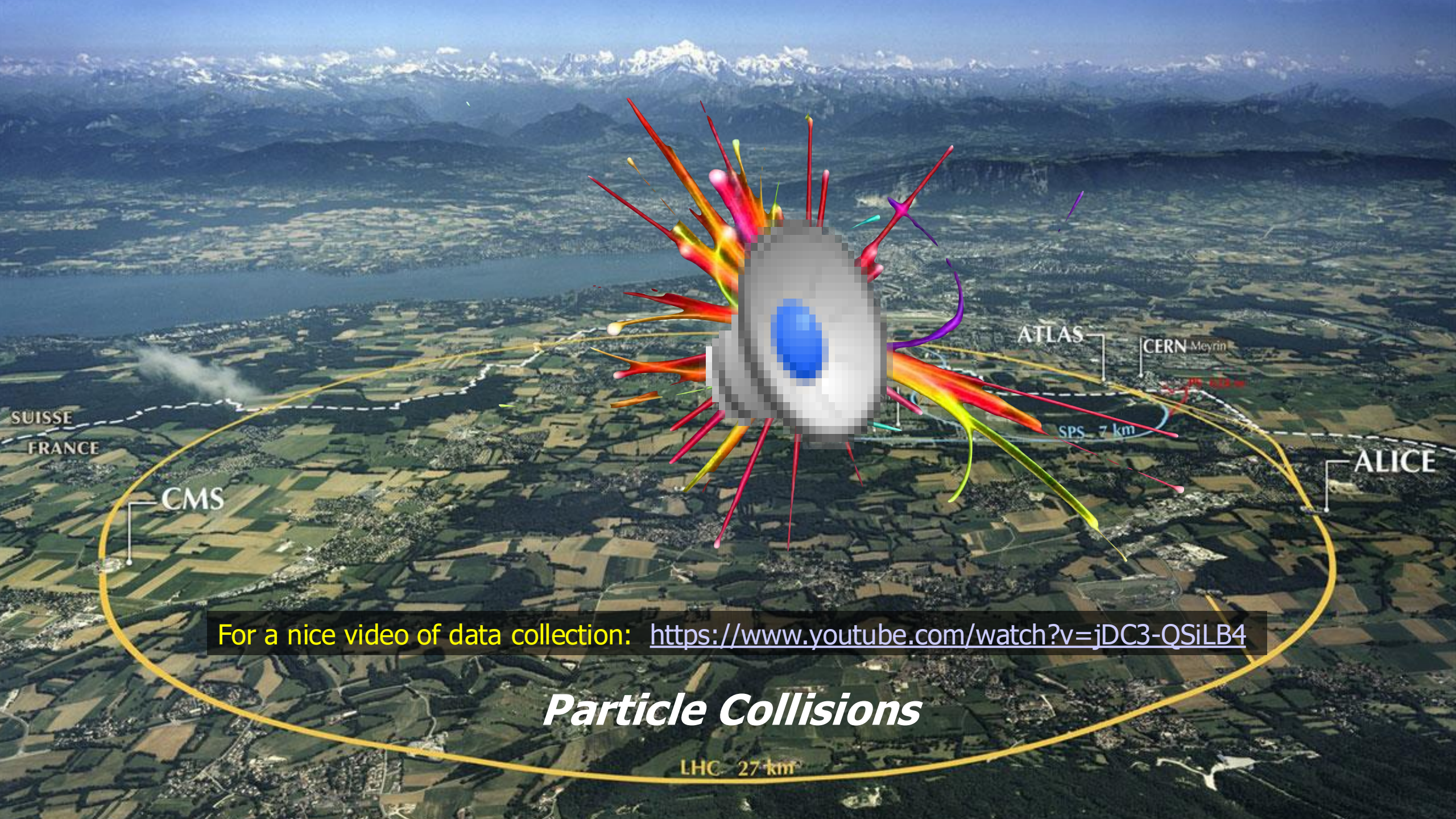


80 MegaPixel "camera": 40.000.000 pictures per second



SUISSE
FRANCE
CMS
ALICE
LHC 27 km

Particle Collisions



For a nice video of data collection: https://www.youtube.com/watch?v=jDC3-QSiLB4

Particle Collisions

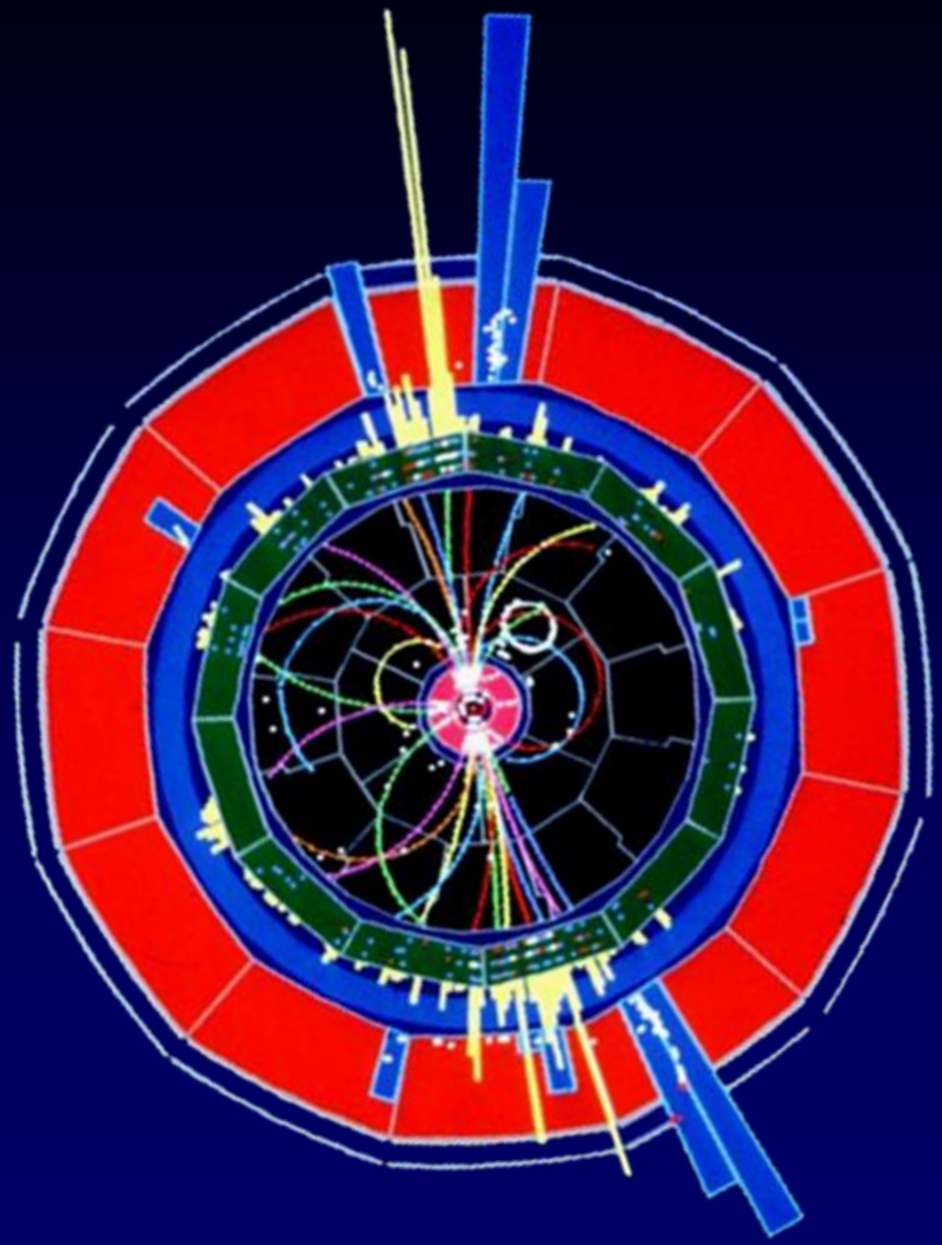
Elementary Particles

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

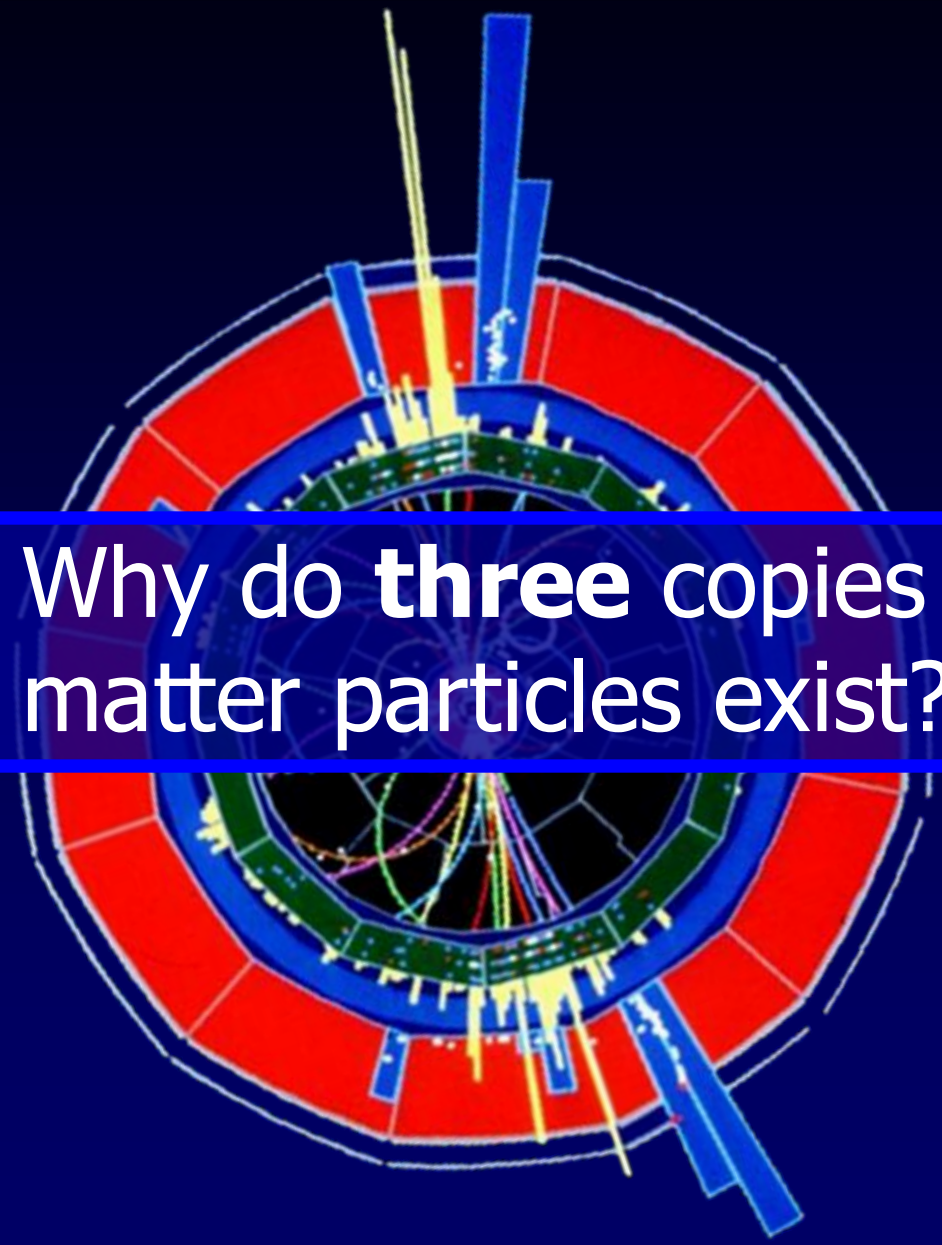


Elementary Particles

Generation:	I	II	III	Charge
quarks	u	c (1976)	t (1995)	+2/3 e
	d	s (1947)	b (1978)	-1/3 e
leptons	e (1895)	μ (1936)	τ (1973)	-1 e
	ν_e (1956)	ν_μ (1963)	ν_τ (2000)	0 e

3 "generations" of particles?!

Matter



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

Elementary Particles

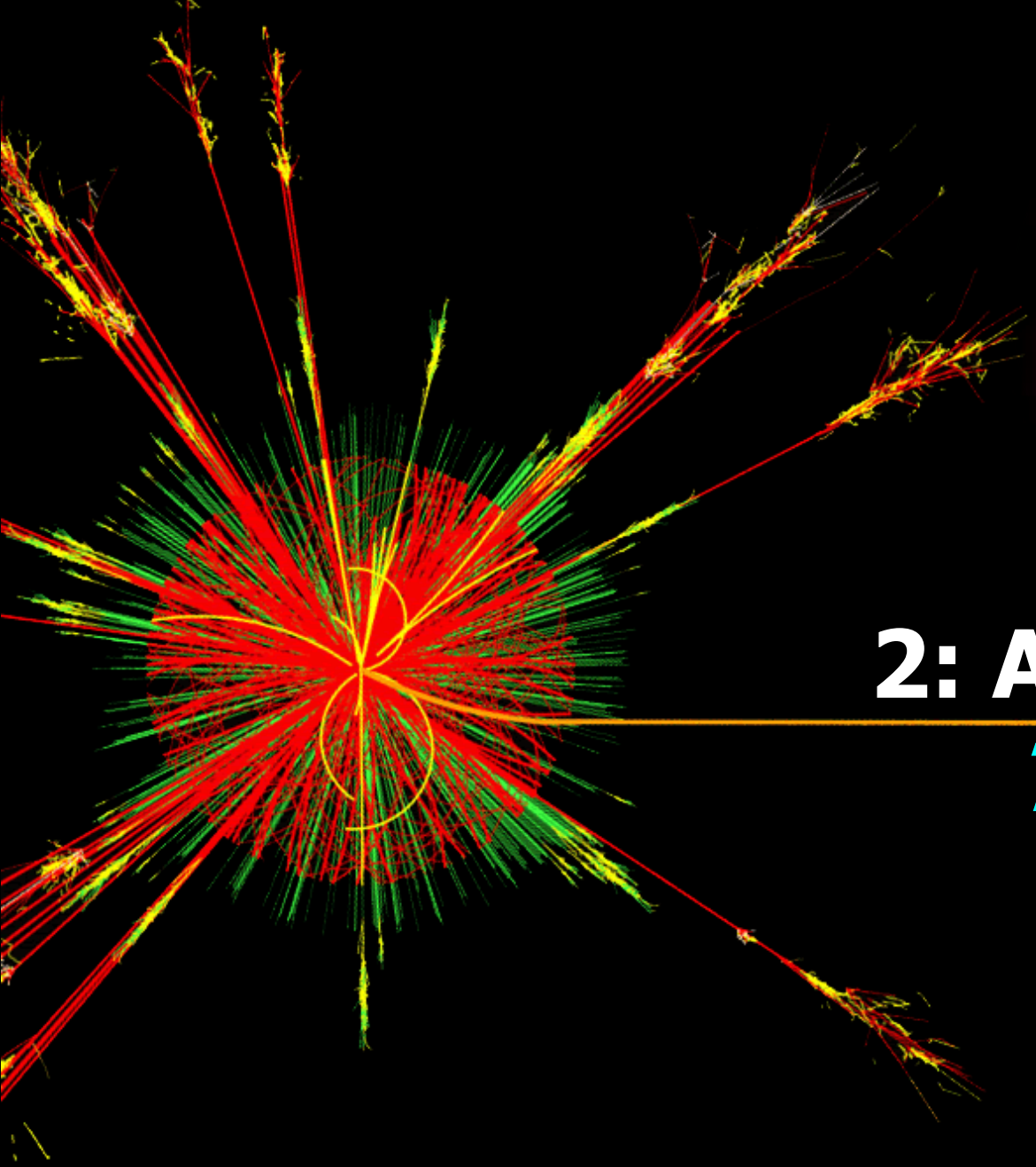
Generation:	I	II	III	Charge
quarks	u	c (1976)	t (1995)	+2/3 e
	d	s (1947)	b (1978)	-1/3 e

3 "generations" of particles?!

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

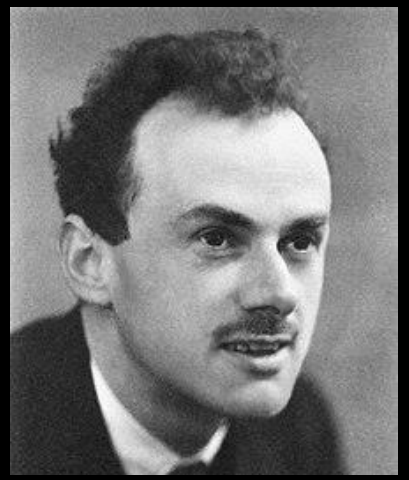
Matter

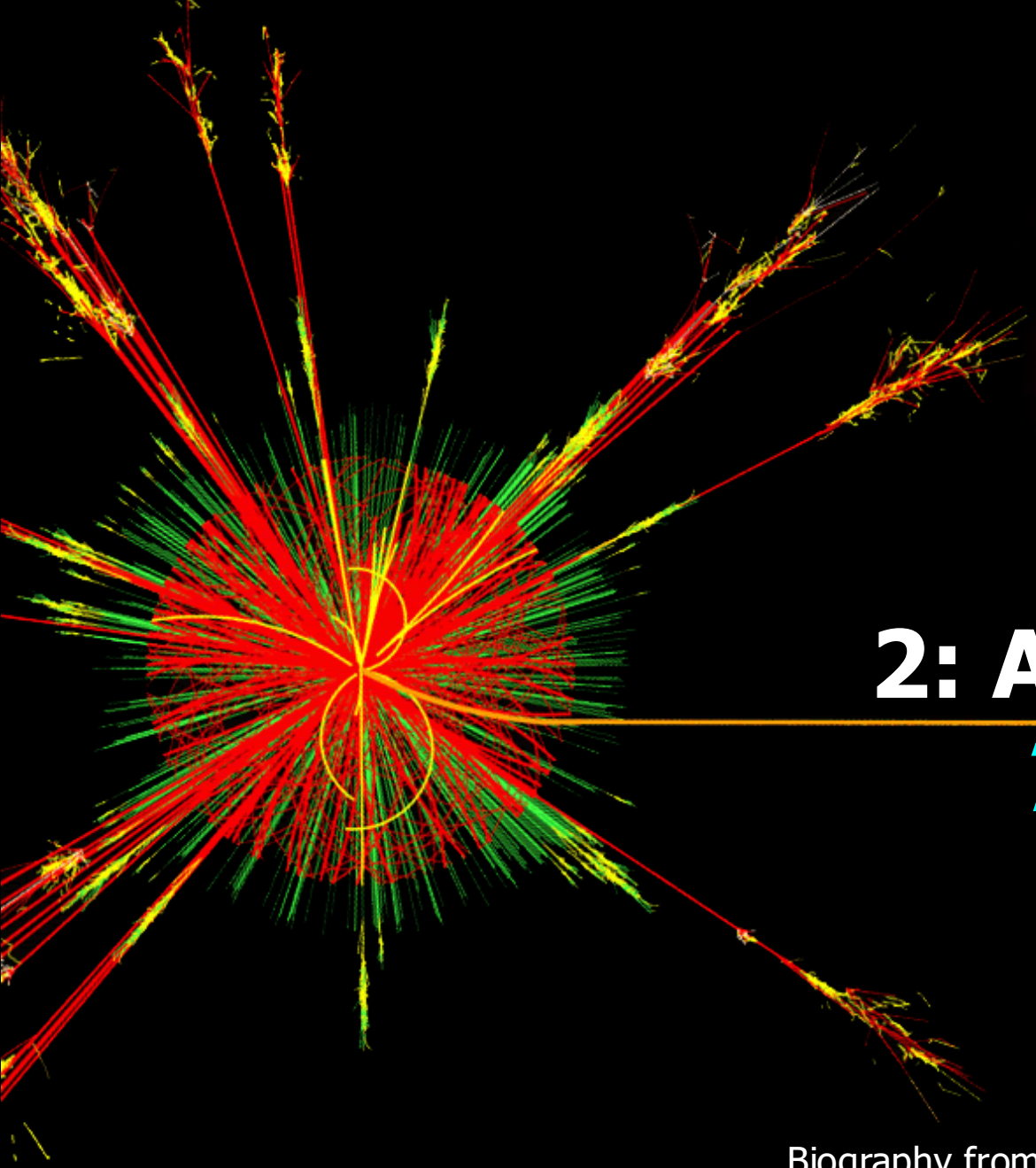
How about…



2: Antimatter and Big Bang

The genius of Paul Dirac



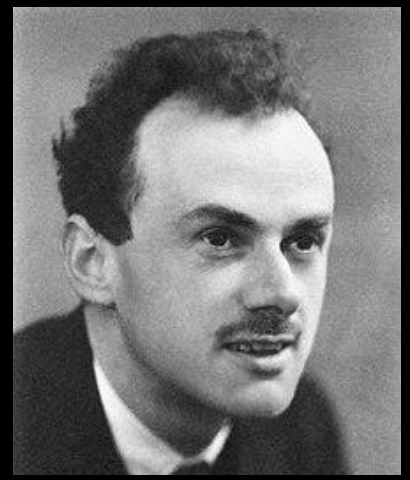


Rika (genius of frites?)

2: Antimatter and Big Bang

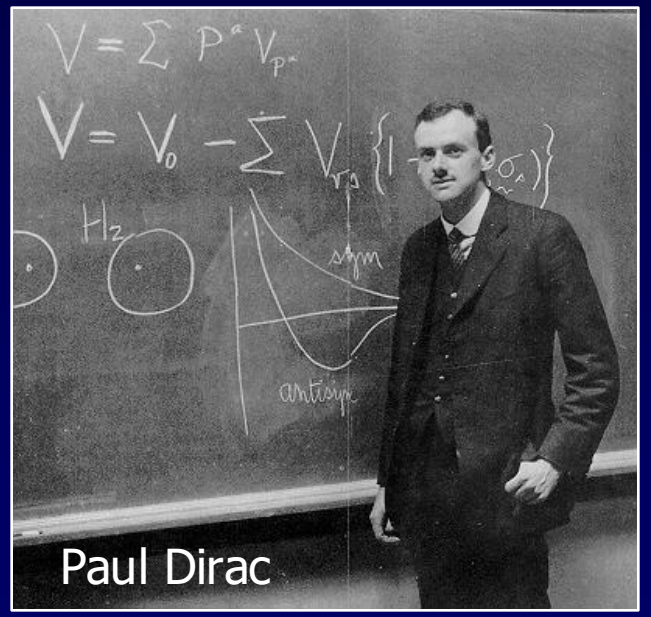
The genius of Paul Dirac

Biography from Graham Farmelo:"The Strangest Man"
(The hidden life of Paul Dirac, quantum genius)



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

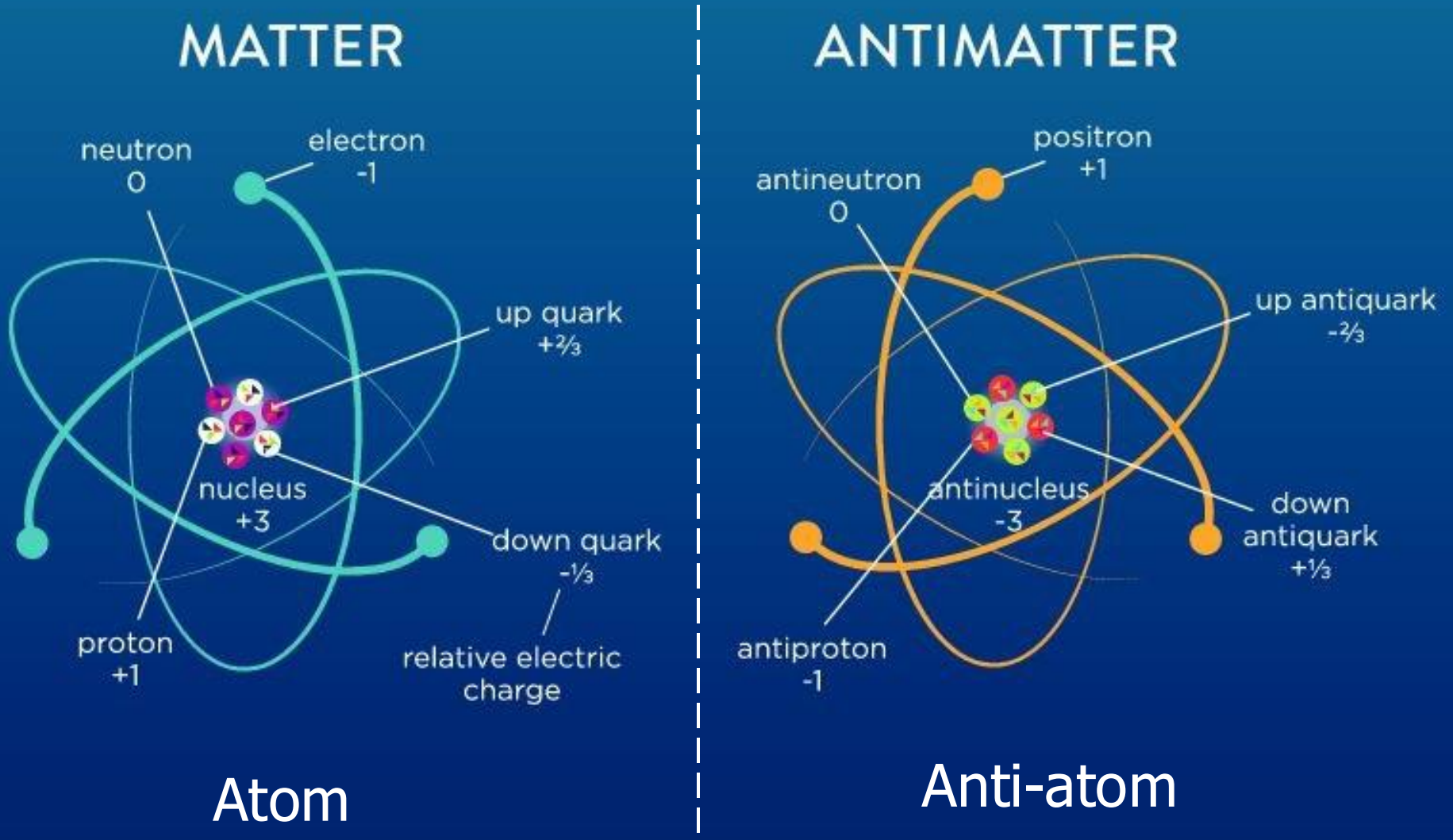

Paul Dirac


Carl Anderson


Dirac

AntiDirac

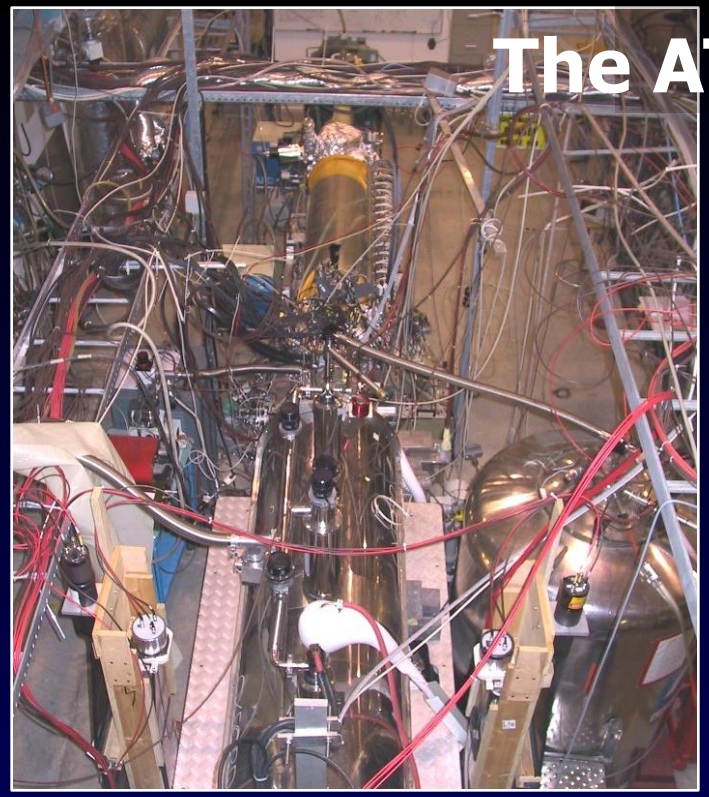
Matter and Antimatter

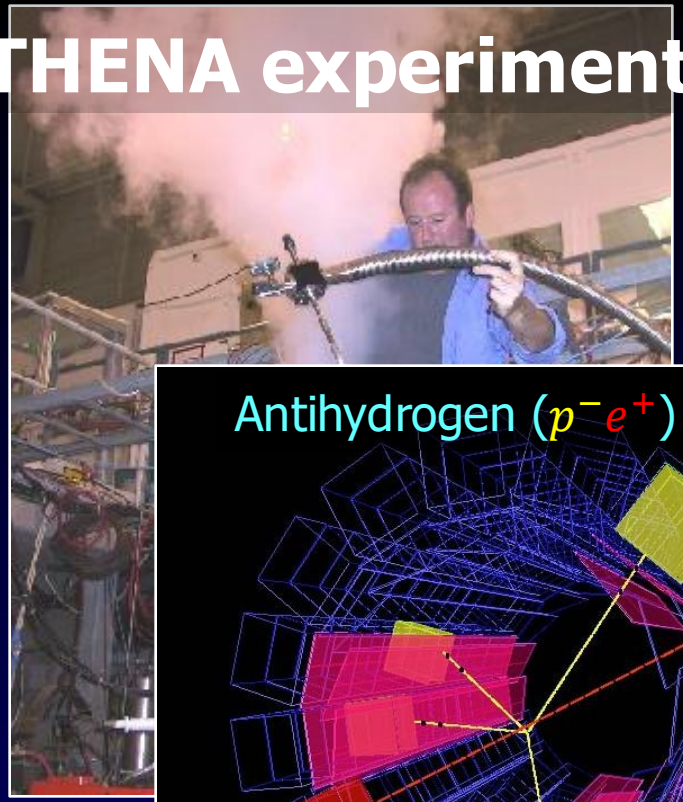


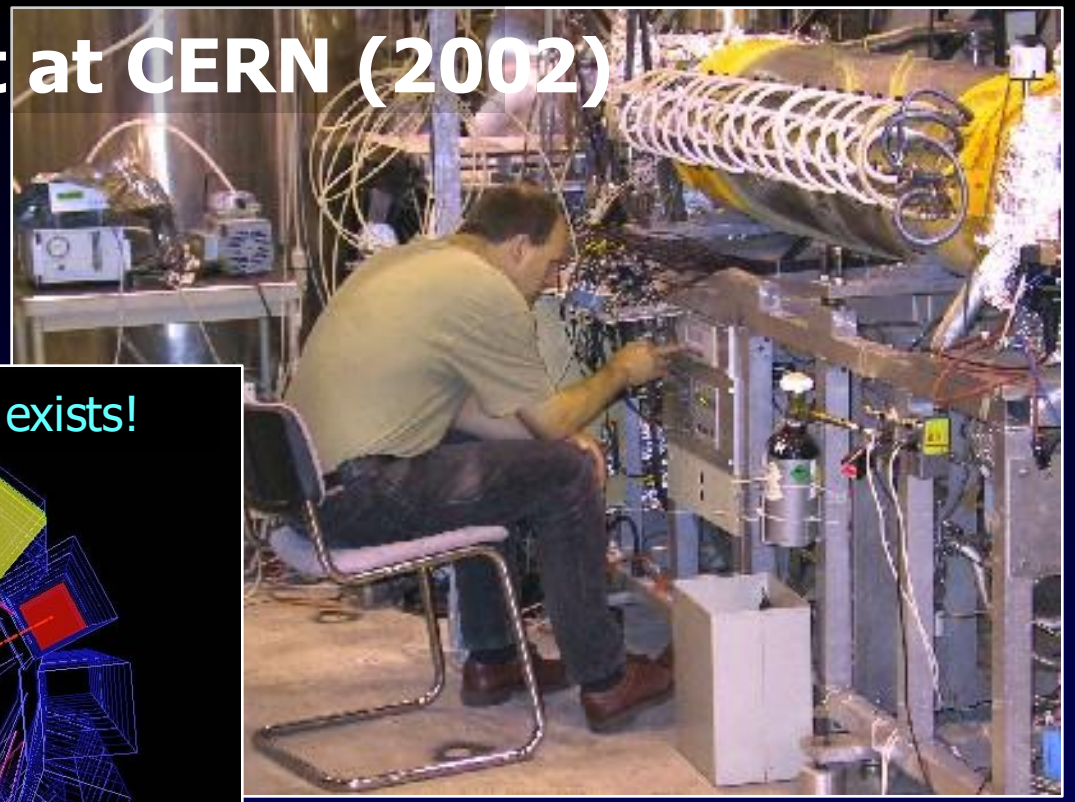
Atom

Anti-atom

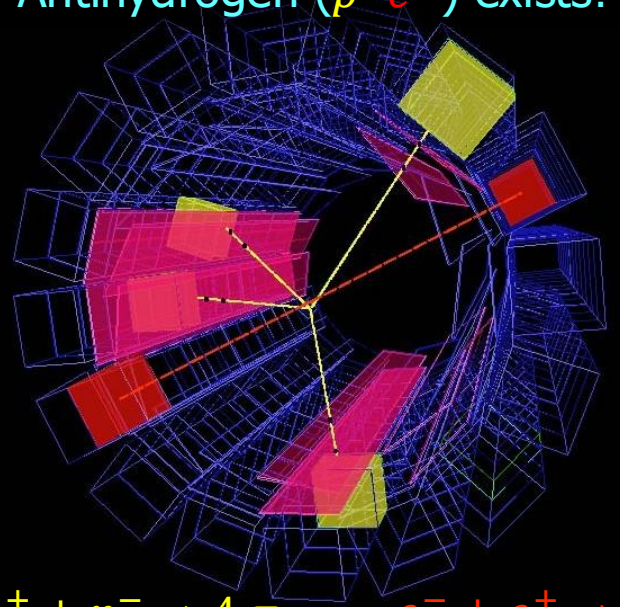
The ATHENA experiment at CERN (2002)



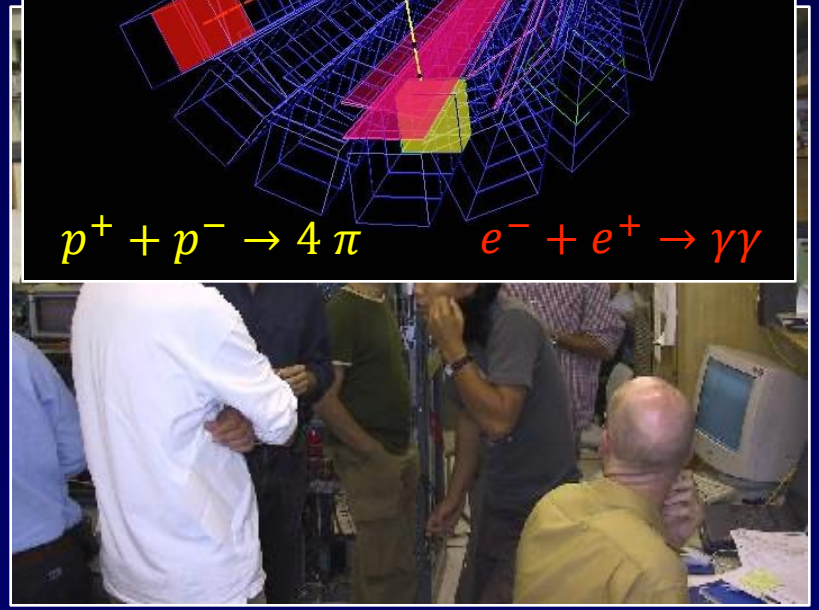




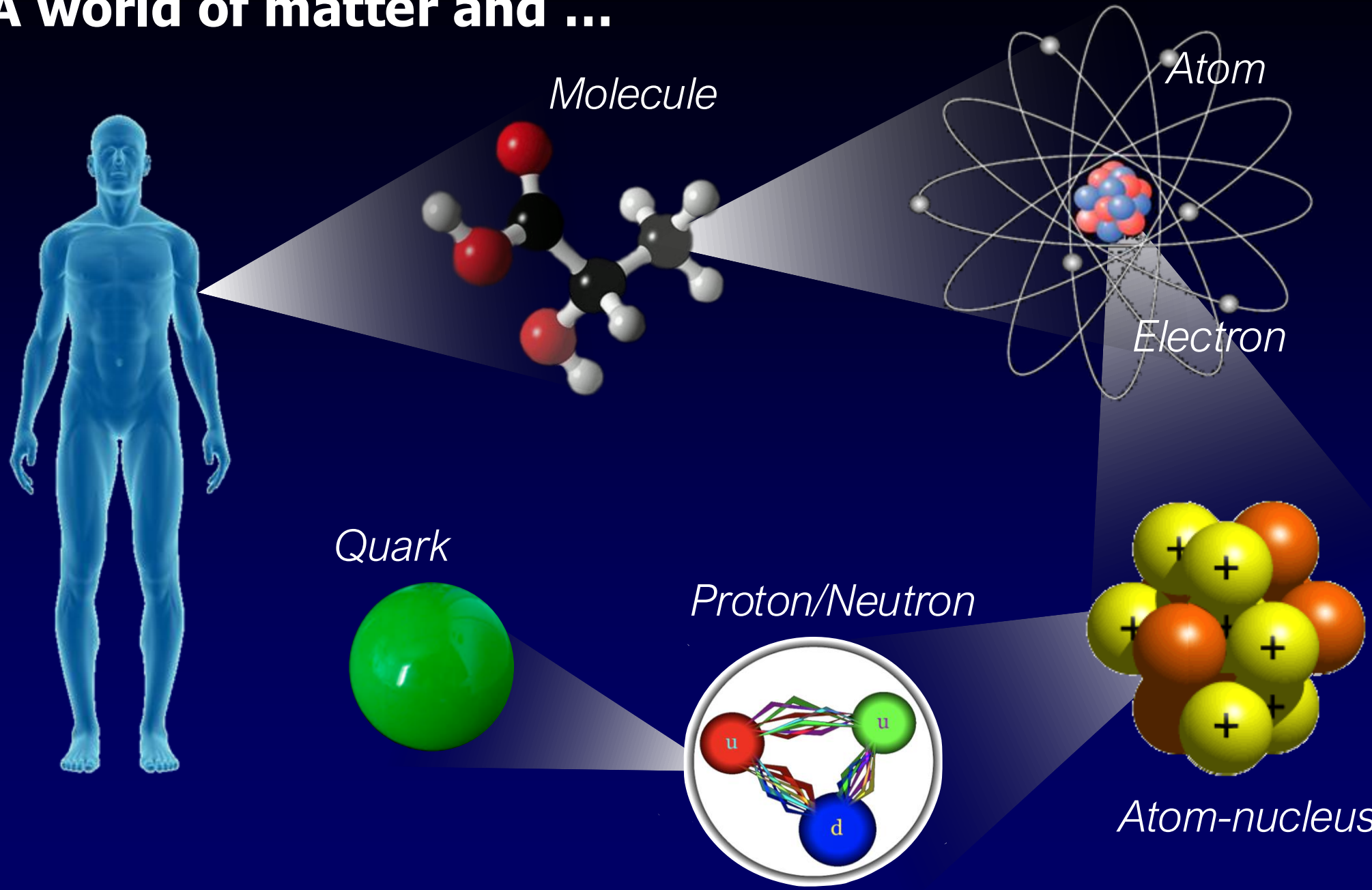
Antihydrogen ($p^- e^+$) exists!



$p^+ + p^- \rightarrow 4\,\pi$ $\quad e^- + e^+ \rightarrow \gamma\gamma$



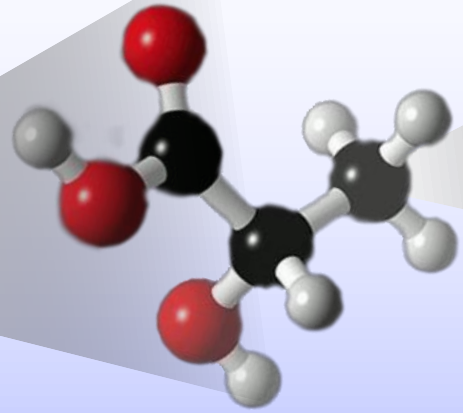
A world of matter and …



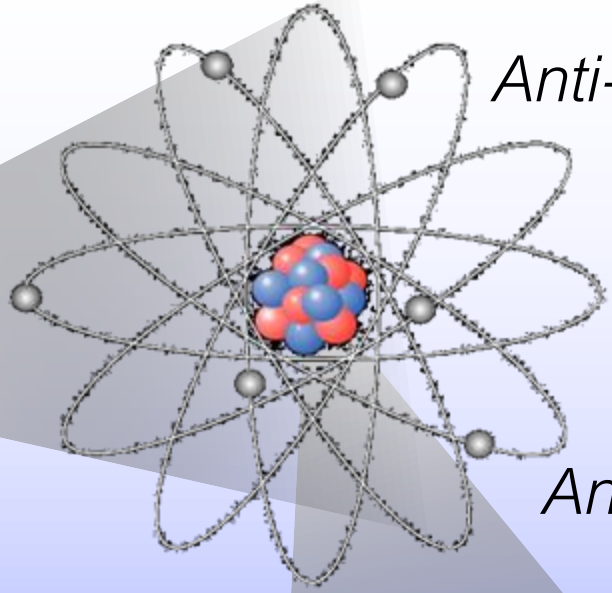
… a world of antimatter?

Identical anti-world

Anti-Molecule

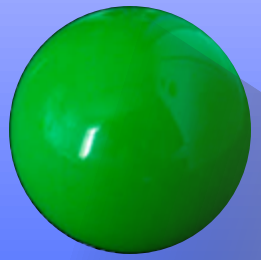


Anti-Atom

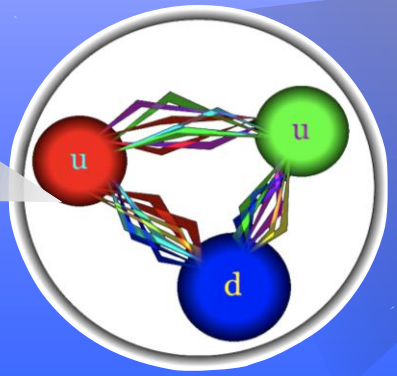


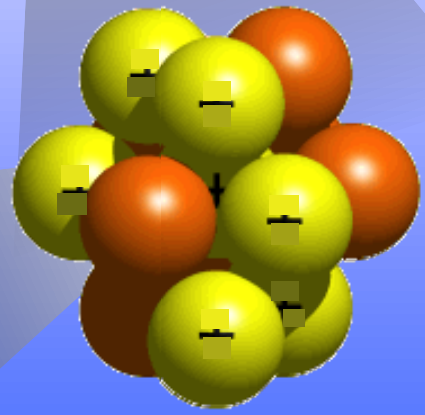
Anti-electron

Anti-Quark



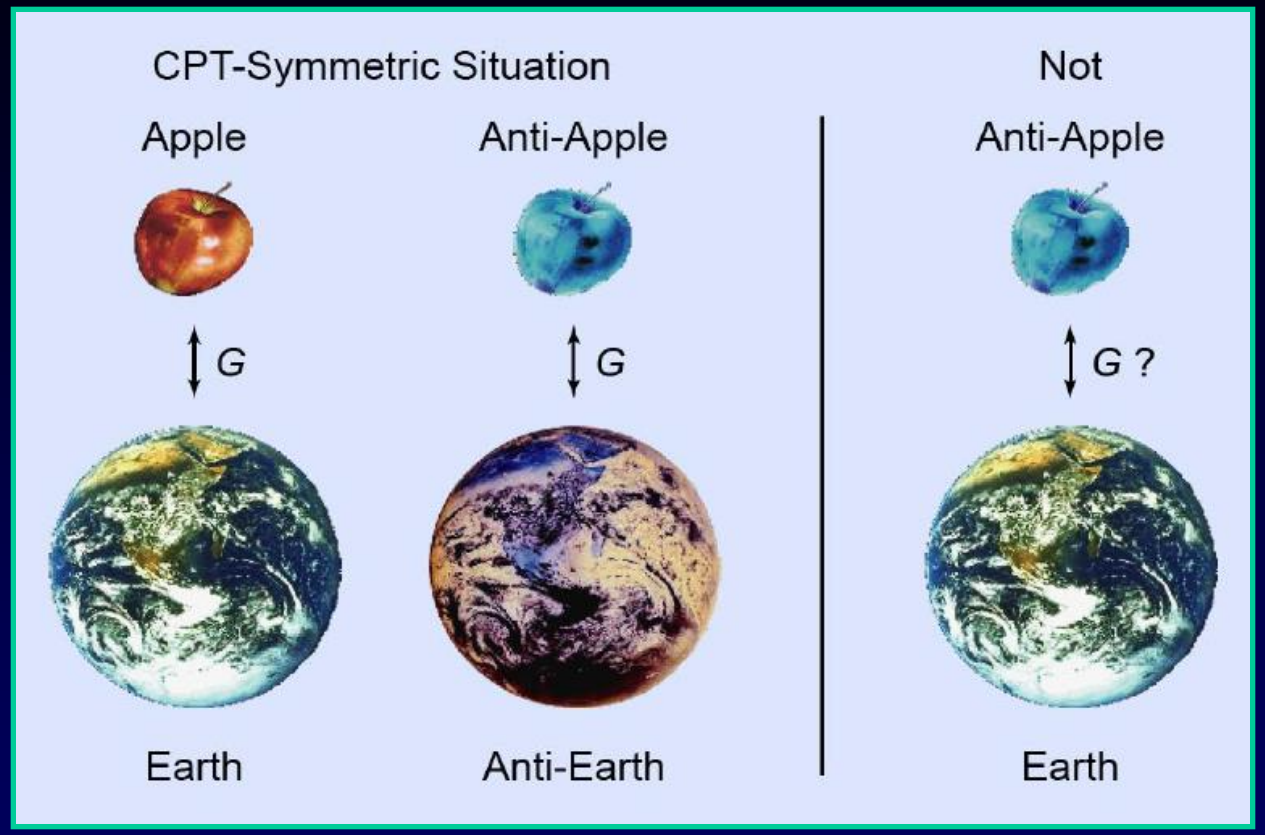
Anti-Proton / anti-Neutron

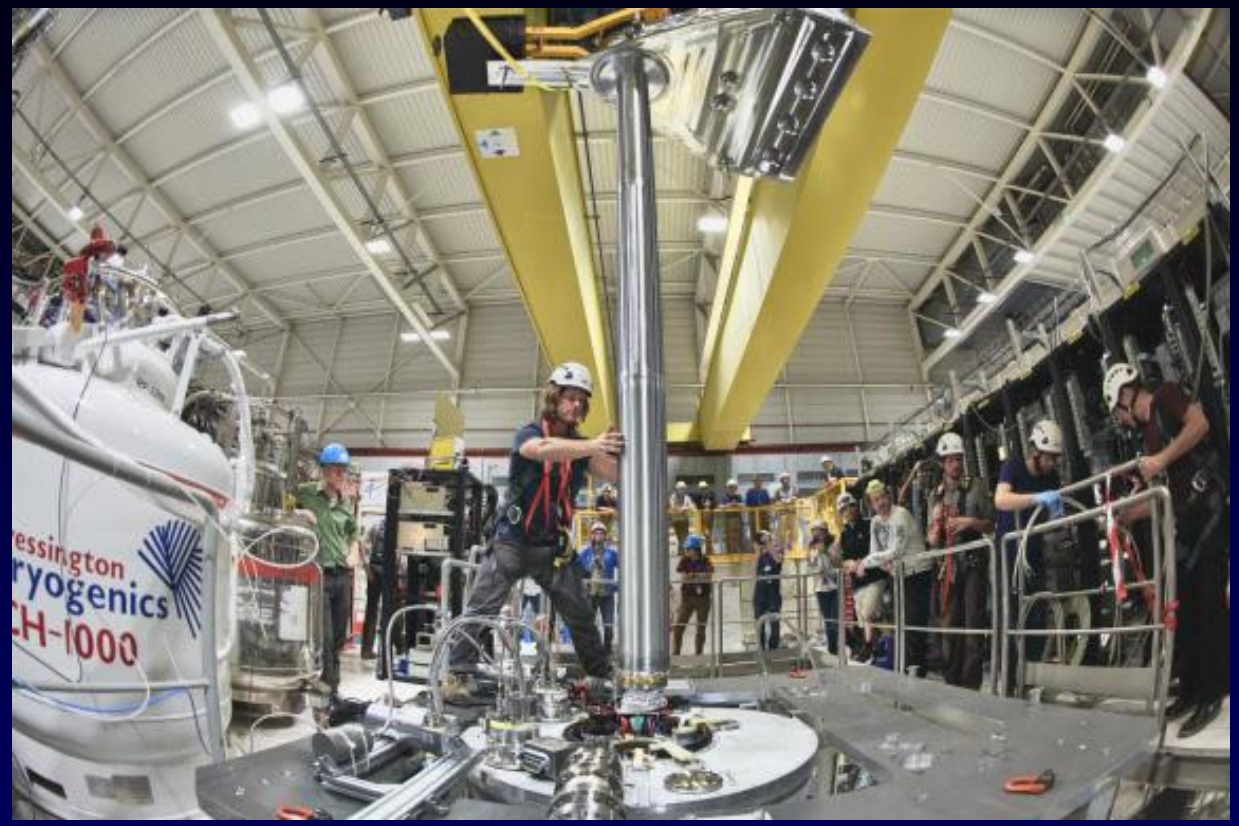




Anti atom-nucleus

Alpha experiment: successor of Athena



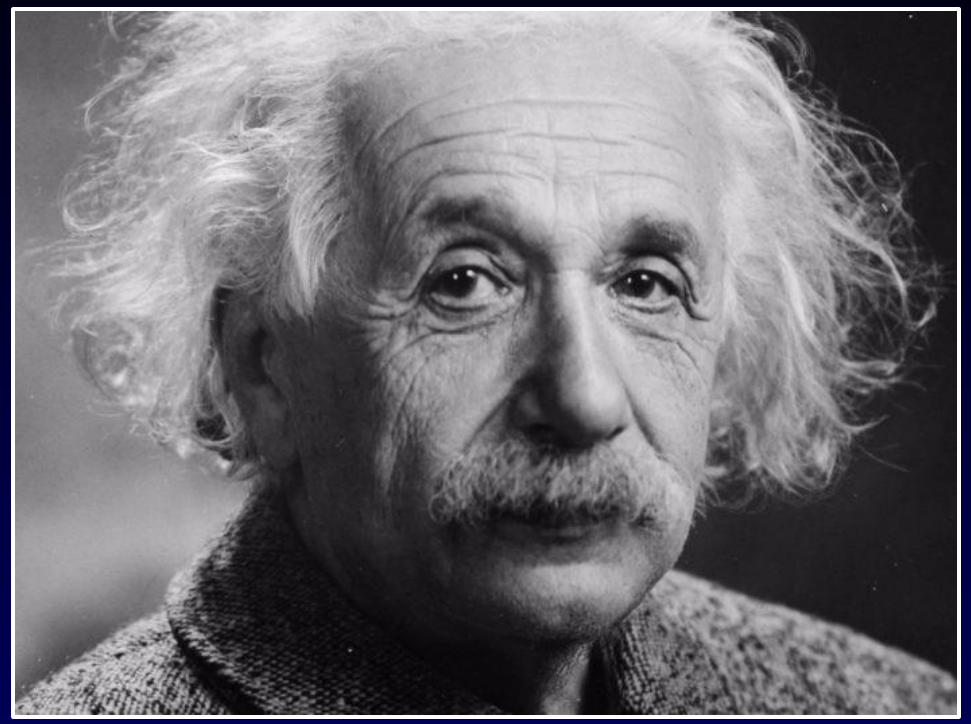


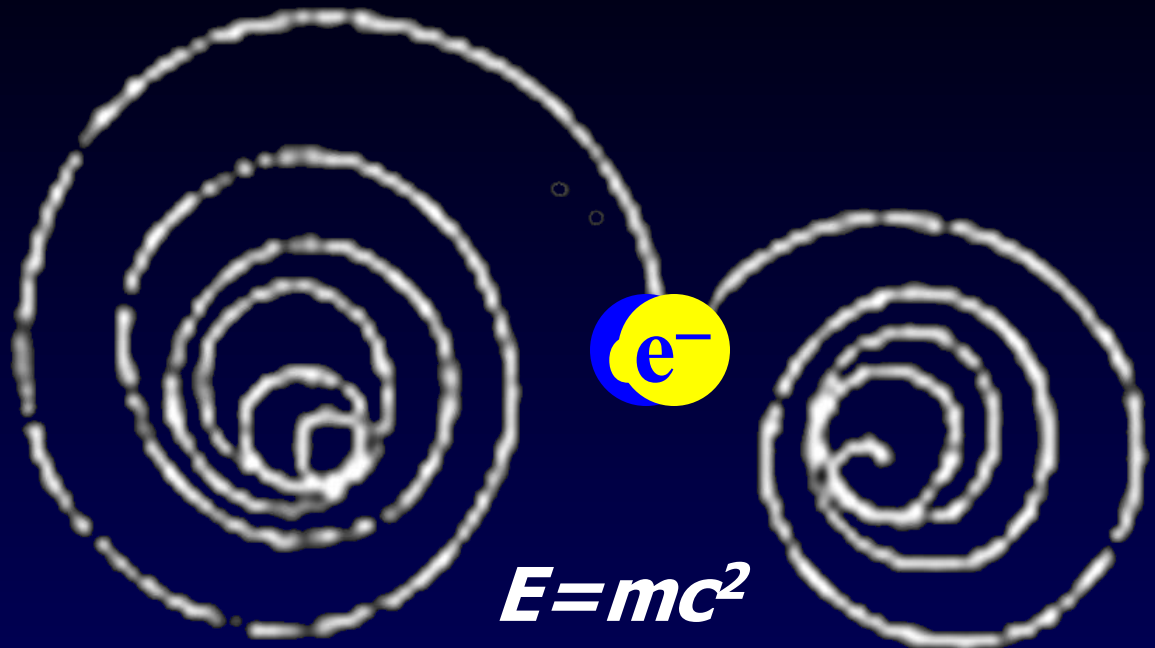
- News on 27 Sept 2023:

See: CERN news

  - 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

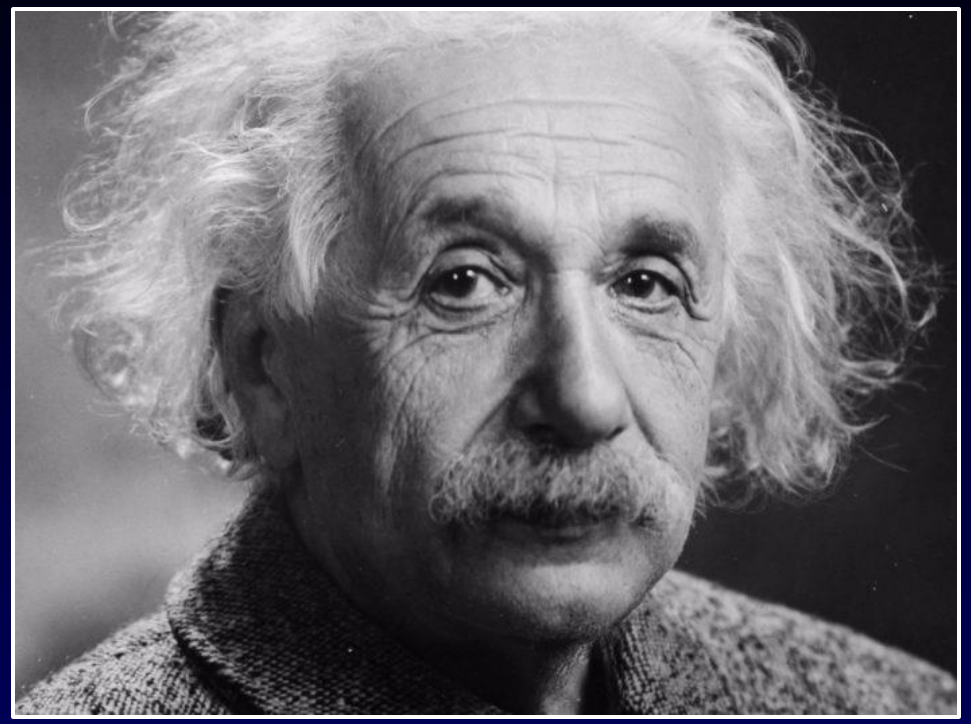




<u>Creation:</u>
Energy → matter + antimatter : e^+ e^-

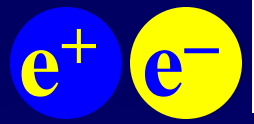
<u>Annihilation:</u>
matter + antimatter → energy : e^+ e^-

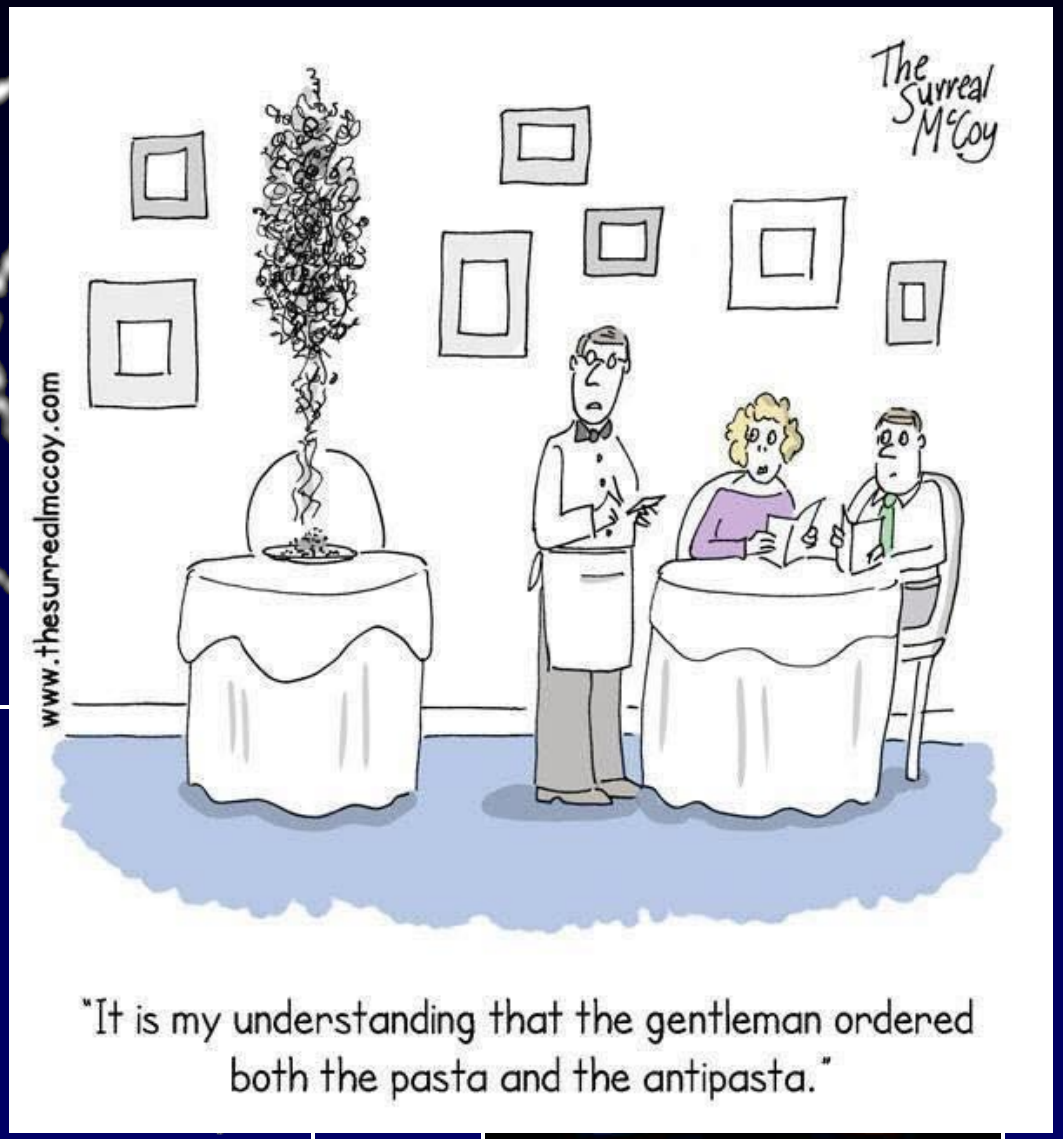
Albert Einstein: Energy = matter + antimatter



<u>Creation:</u>
Energy → matter + antimatter :

<u>Annihilation:</u>
matter + antimatter → energy :



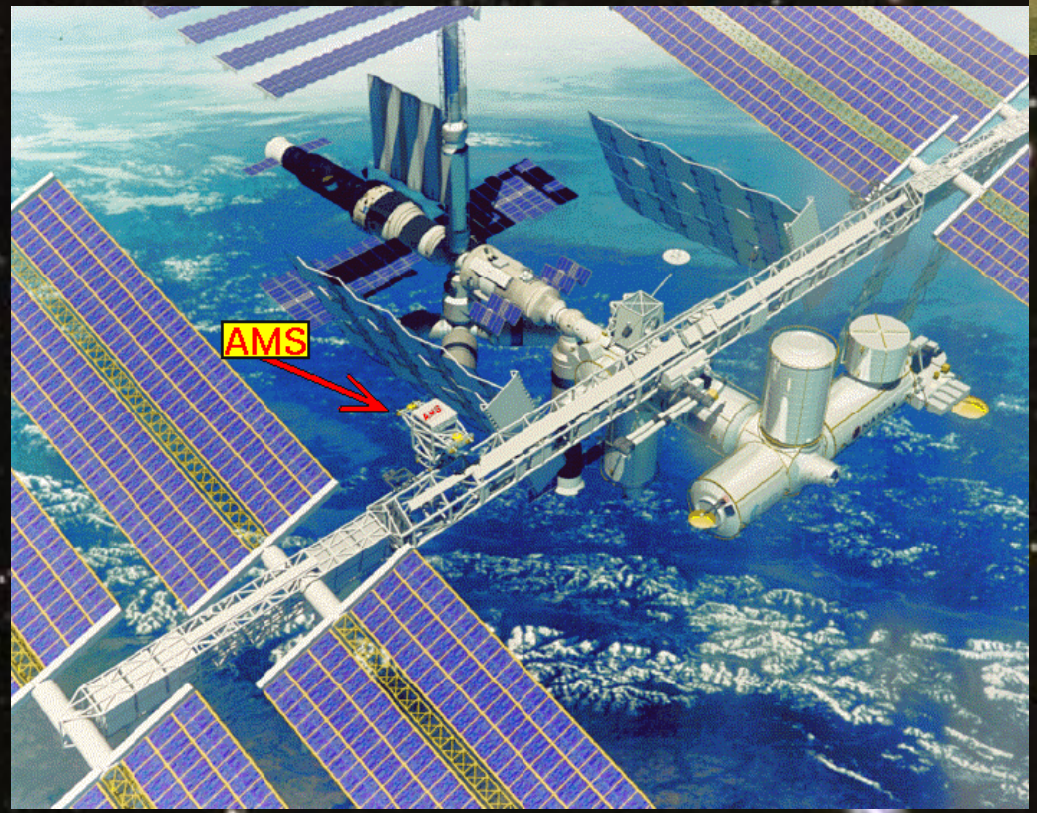


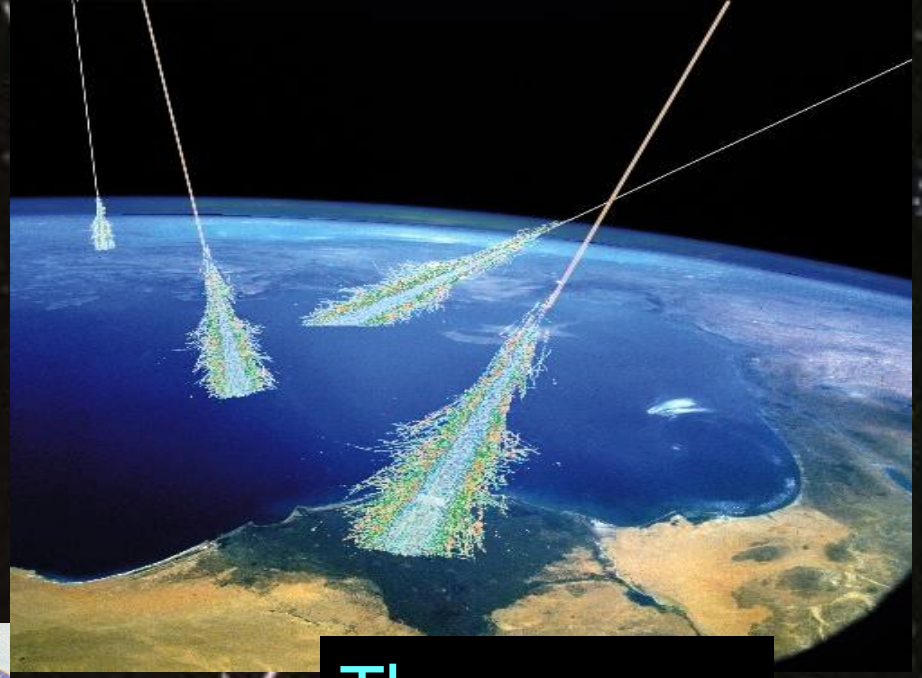
Is there antimatter in nature?

- Does it occur on earth?

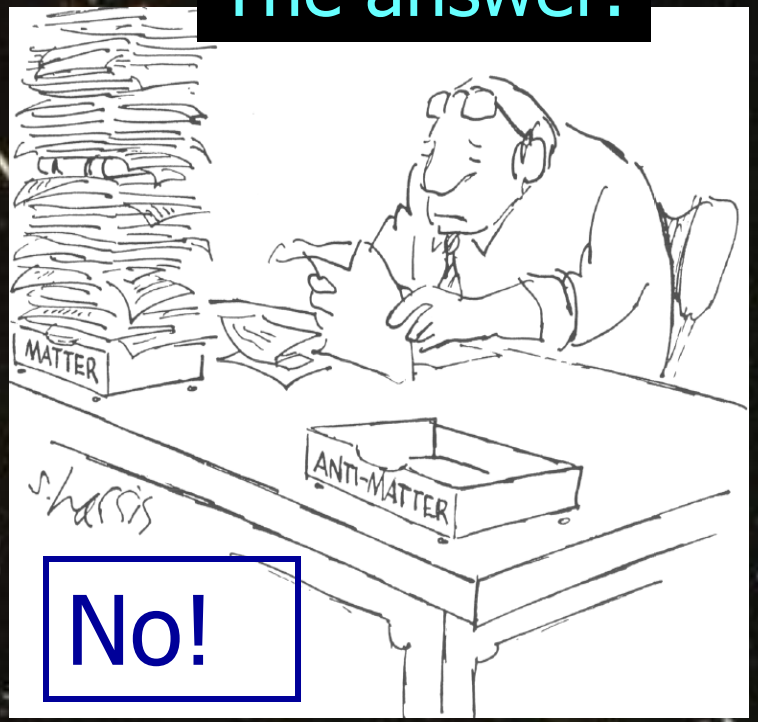
- No, we would immediately see it:
  - "Annihilation"

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





The answer:



No!

Are there antimatter galaxies?

No!

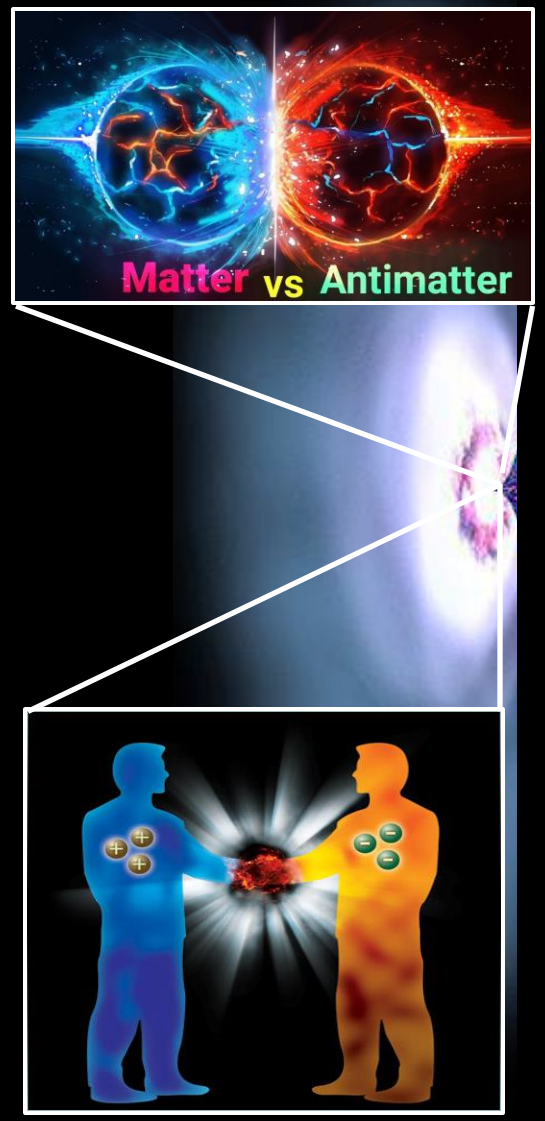
(matter + anti-matter =
Intense gamma radiation)

Early Universe: where did the antimatter go?

Only matter

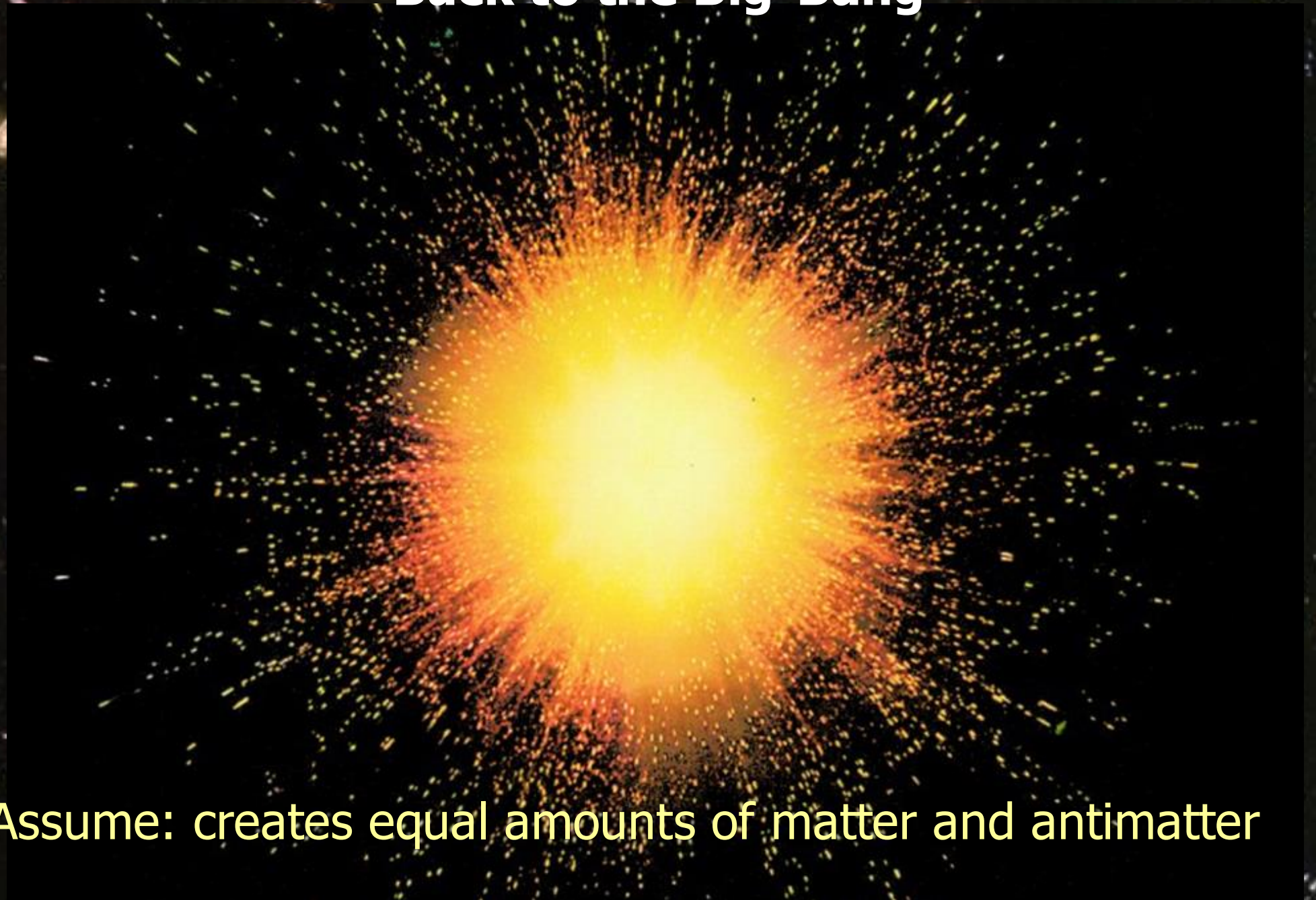
Why is there something rather than nothing?

Early Universe: where did the antimatter go?



Why is there something rather than nothing?

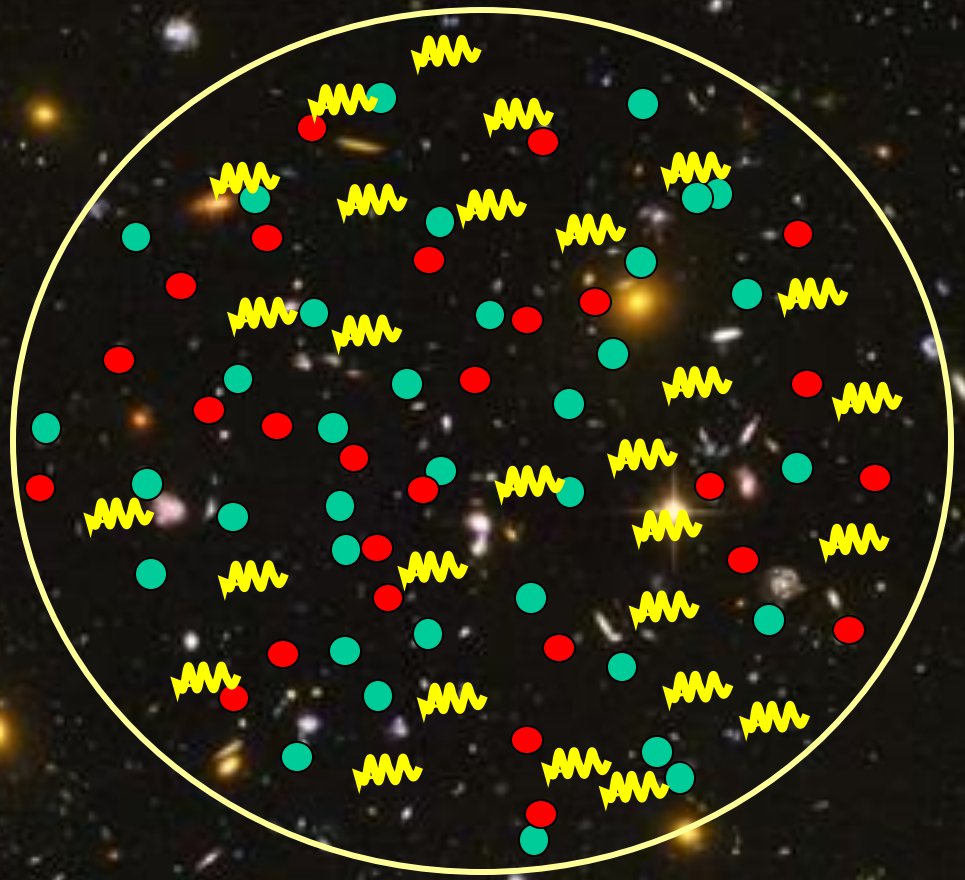
Back to the Big-Bang



Assume: creates equal amounts of matter and antimatter

The early hot universe

Time=0.00000000001 second



($E=mc^2$)

Imagine:

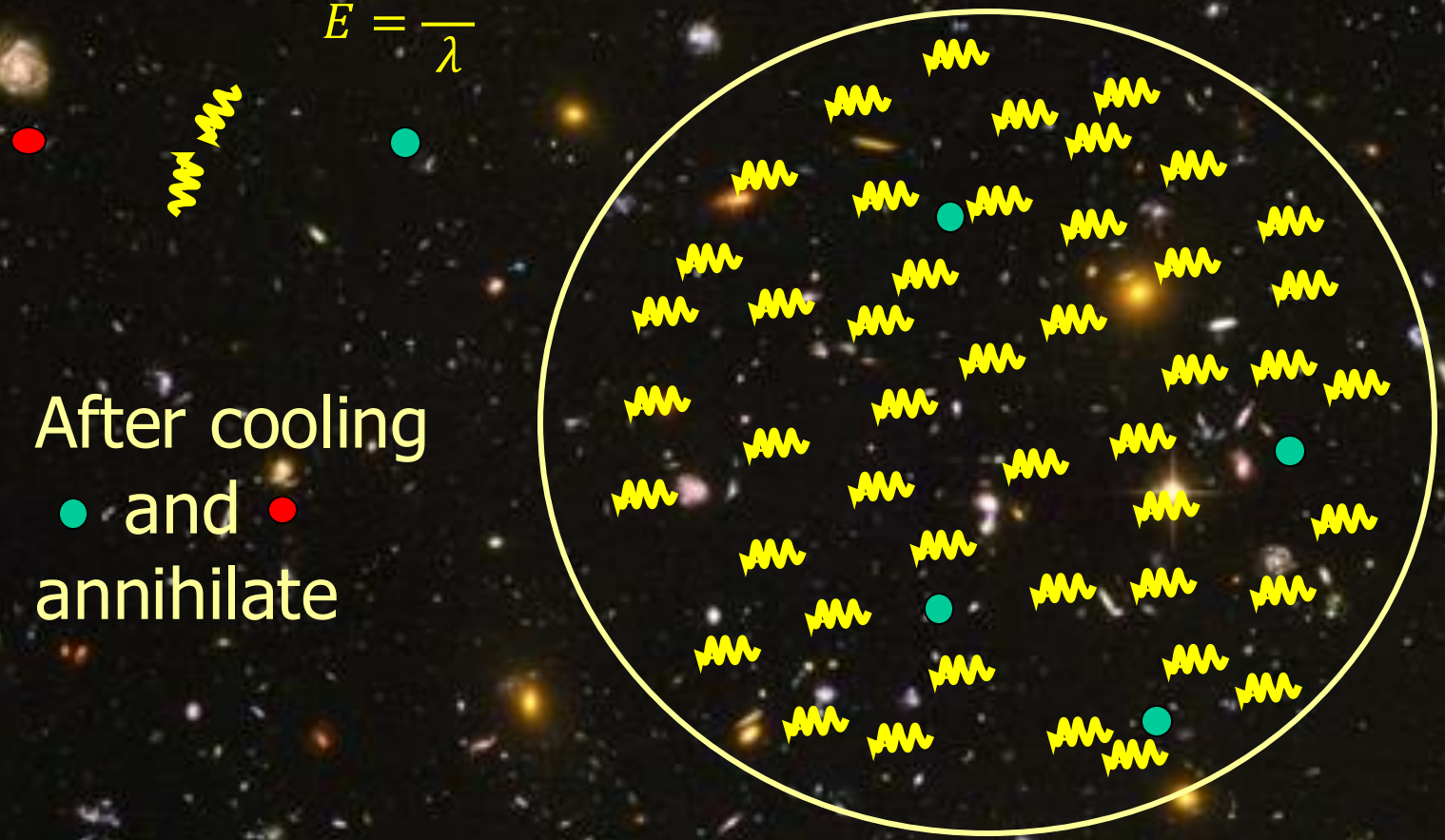
- *matter:* 1000000001
- *antimatter:* 1000000000
- light

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

The expanding and cooling universe

Time ~1 second

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



matter

antimatter

light

After cooling and annihilate

What remains: lots of light and a bit of matter

Ratio : 1000000000 1

Cosmic Microwave Background Radiation

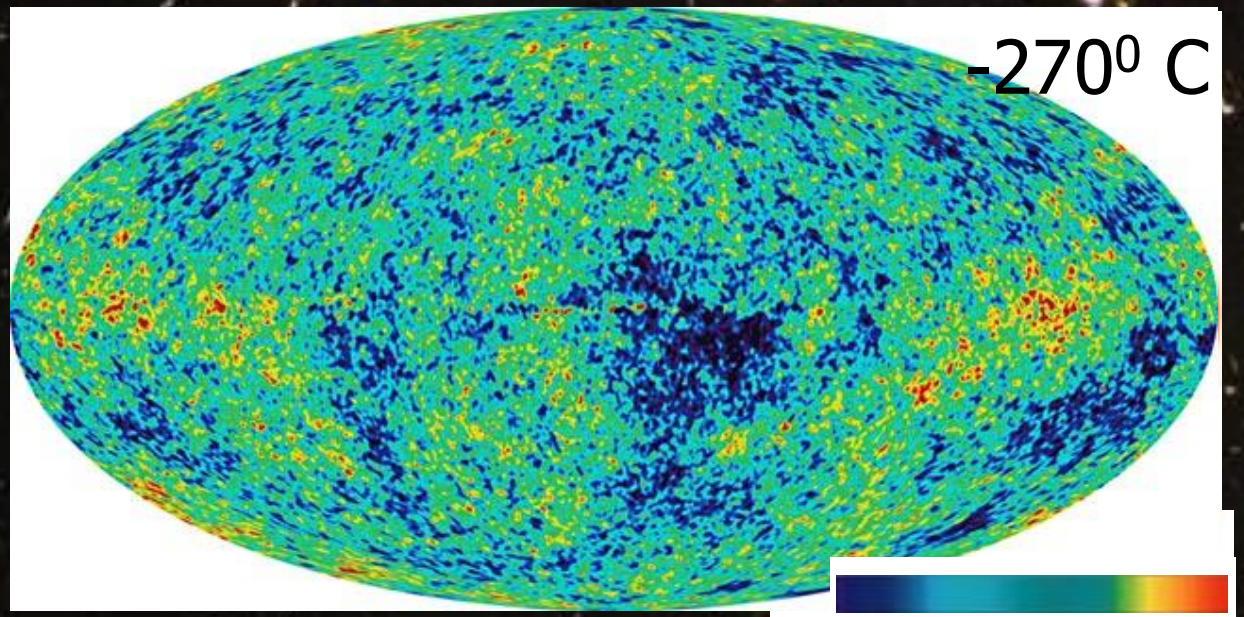
1964: Penzias and Wilson discover: "background light" (photons)

Remnant of the Big Bang

A temperature map…

Of the univesre

-270^0 C



Nobelprize 1978

For each matter particle there are a billion photons…

The universe as we see it today

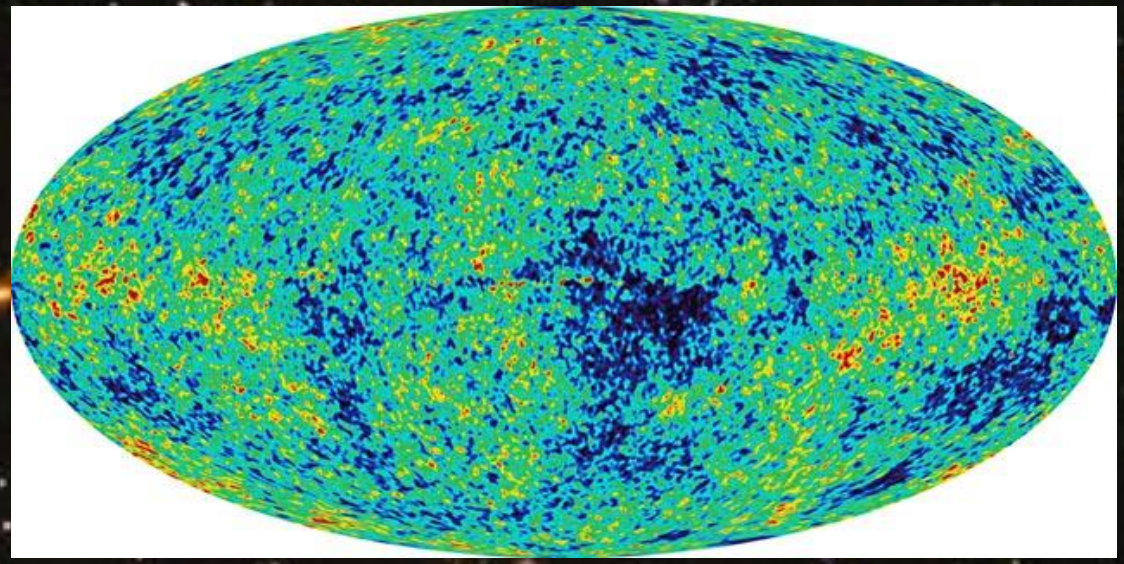
- Observed Background light:

  "many"
  (1000000000)

  +

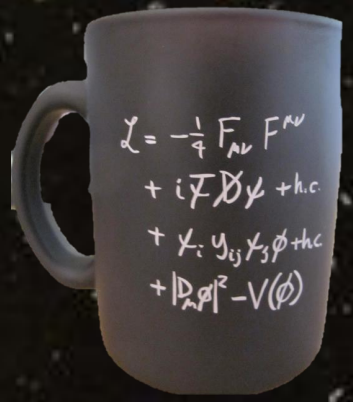
- Remaining Matter particles:

  "few"
  (1)



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

Laws of Nature



?

Big Bang

Small surplus

49.999999% anti-matter

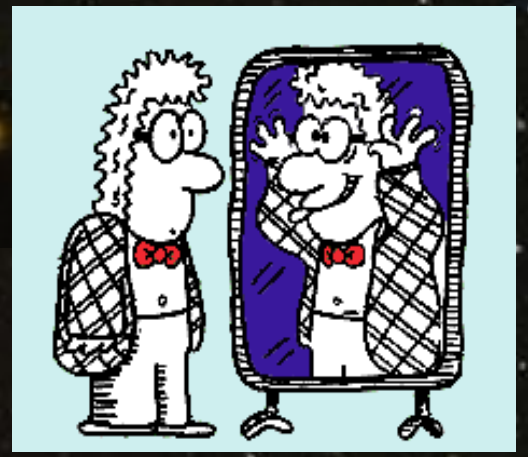
50.000001% matter

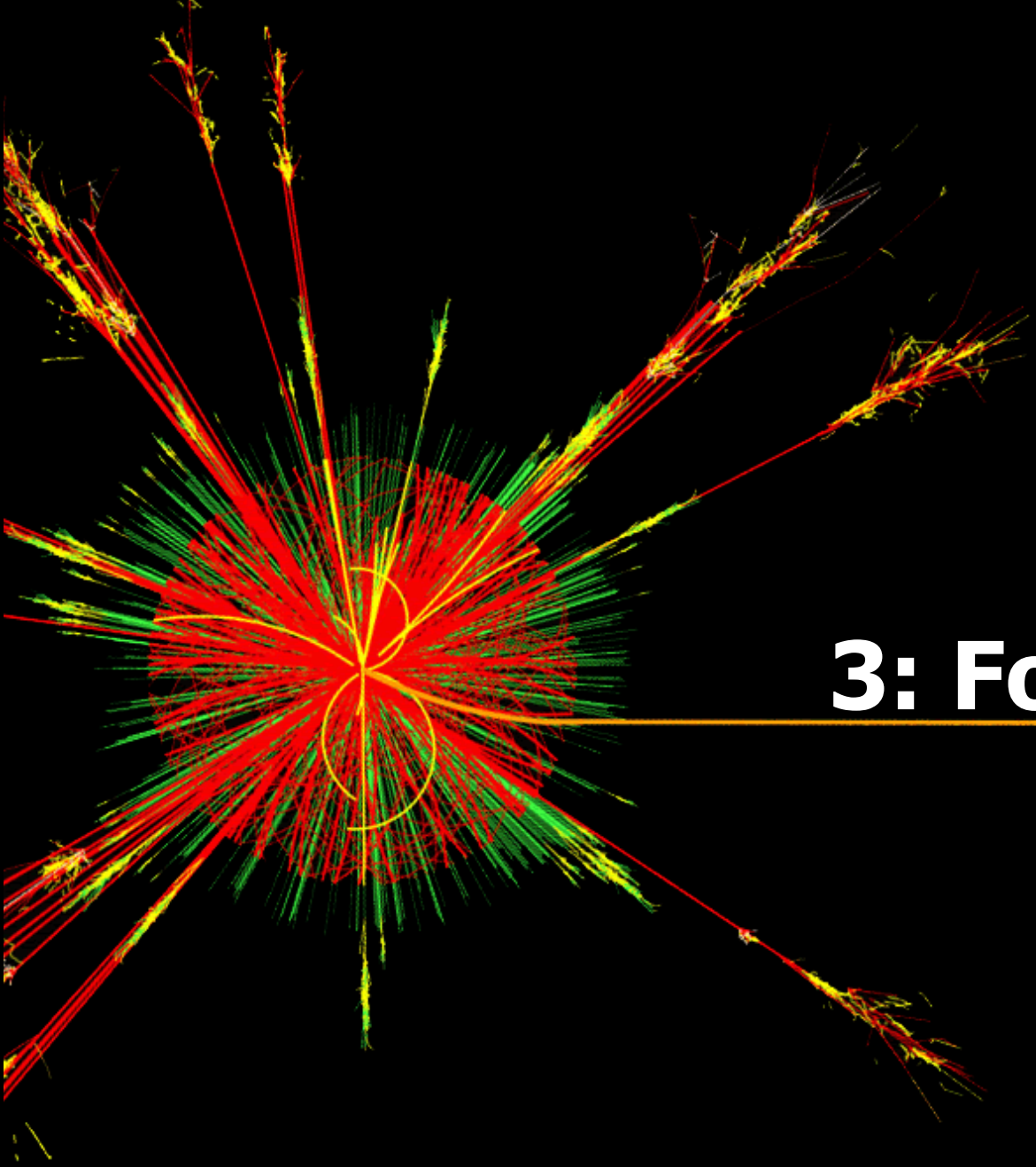
Matter Dominates

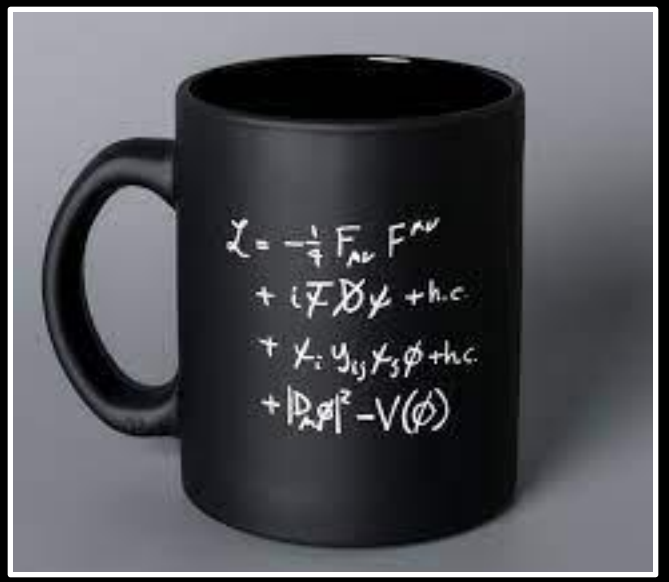
0.000001% matter

(+99.999999% radiation)

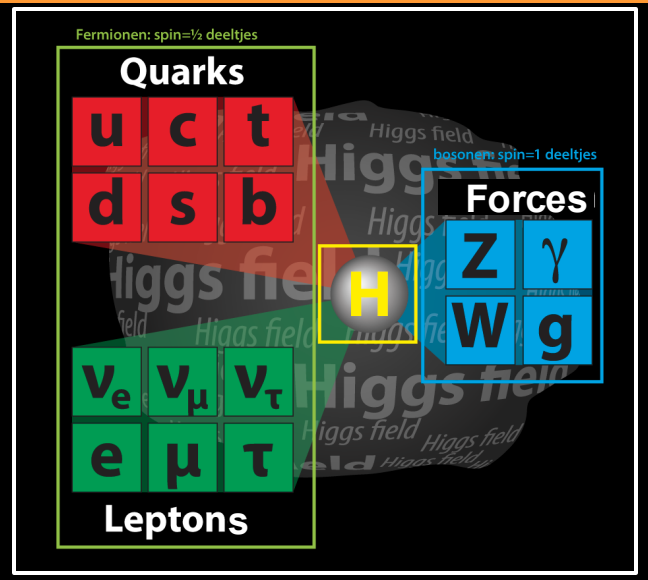
Apparently anti-matter is not the exact mirror image of matter!

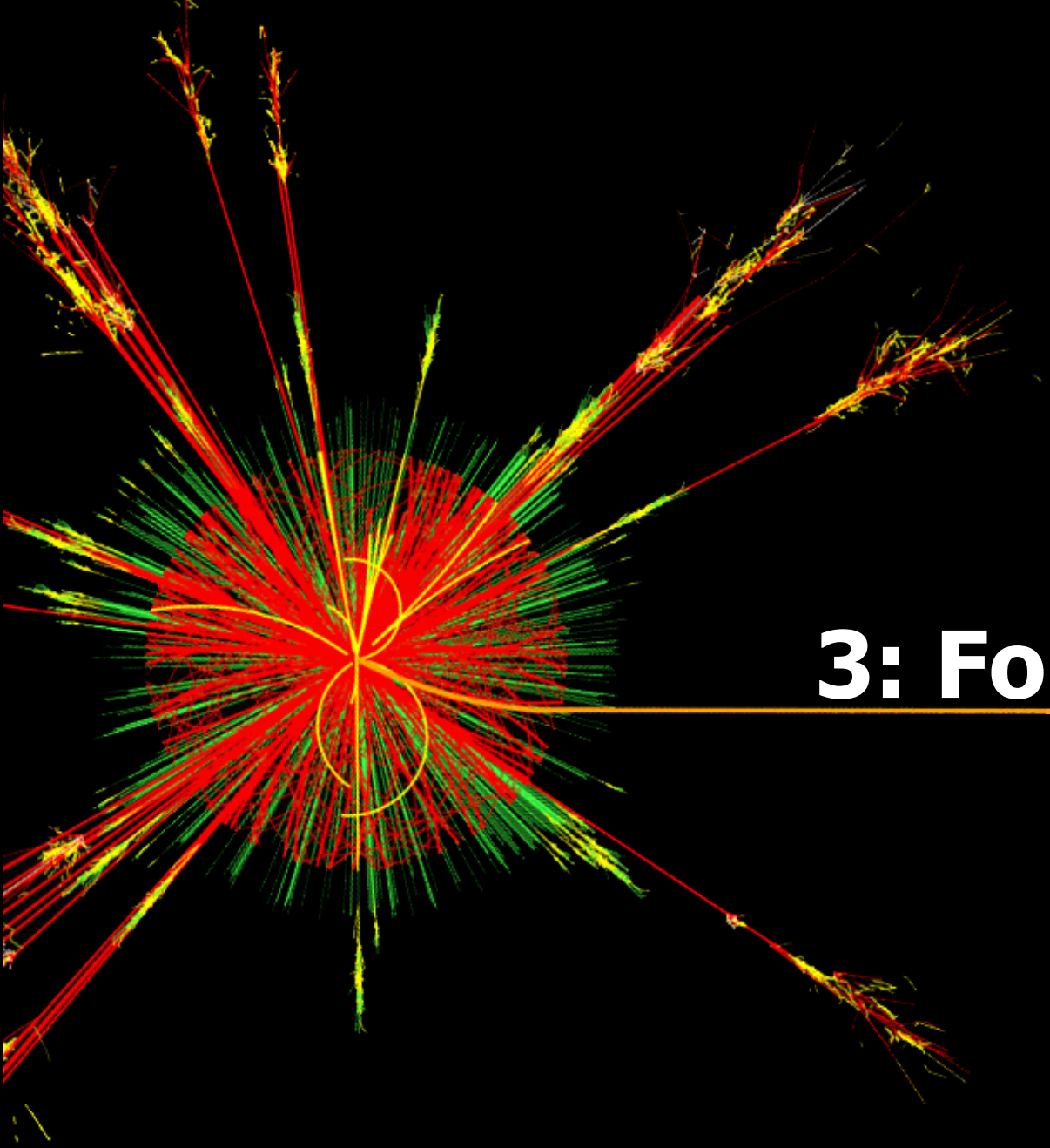






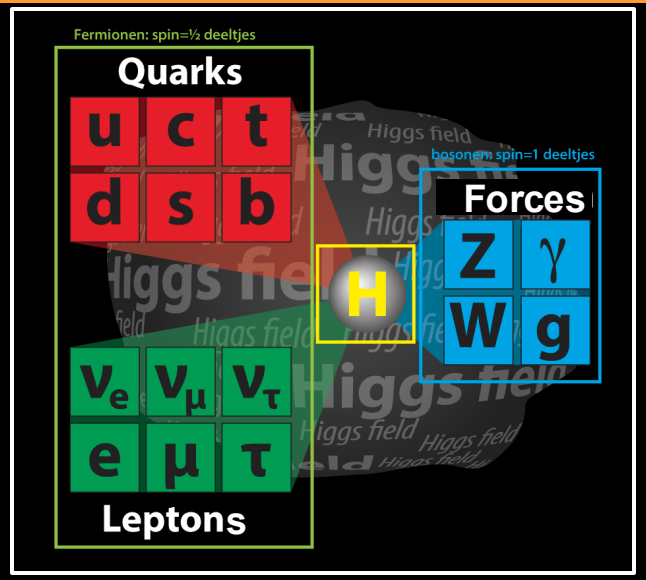
3: Forces: “Standard Model”





Giel ("de Piele") Hameleers: also standard model?

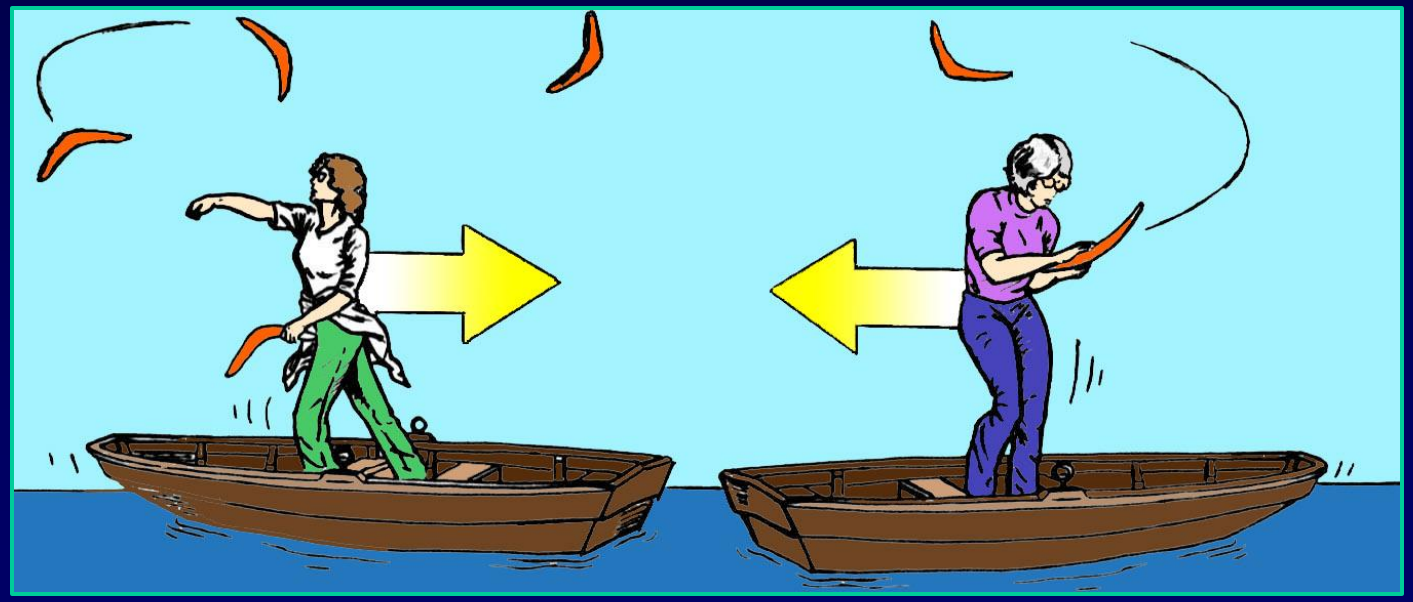
3: Forces: "Standard Model"



Forces in Quantum Mechanics: exchange of quanta

"Repulsive force"

There is no
"action at a distance"

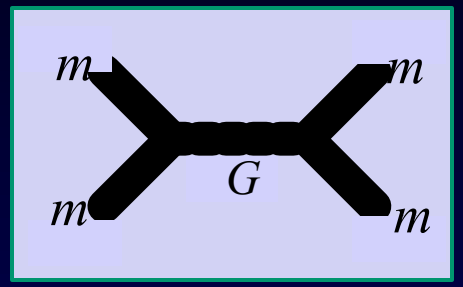


"Atractive force"

Four fundamental forces of nature

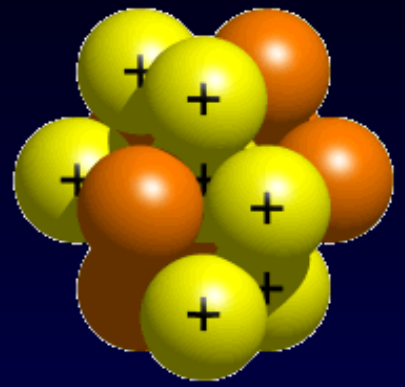
Gravity:

Quantum
Graviton exchange?



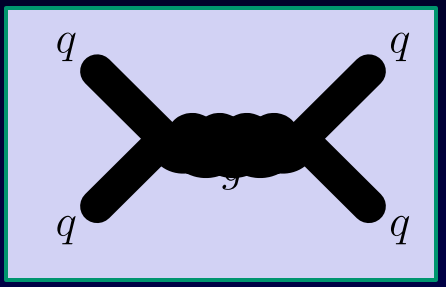
Acts on particles with mass

Strong nuclear force:

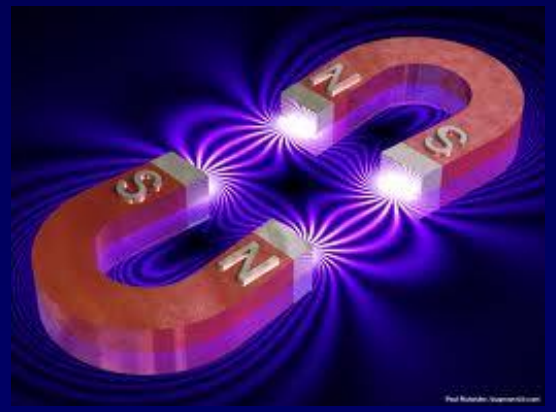


Acts on quarks

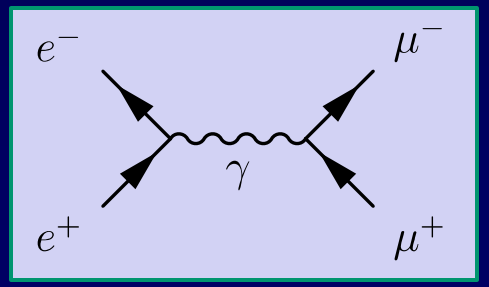
Quantum
gluon exchange:



Electromagnetism:



Quantum
photon exchange:

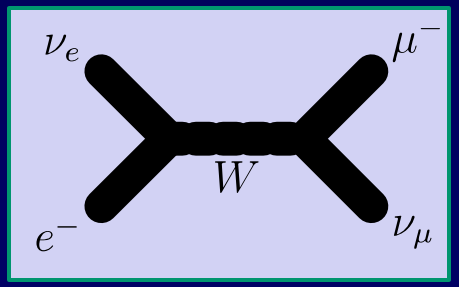


Acts on all charged particles

Weak nuclear force:

Acts on all particles

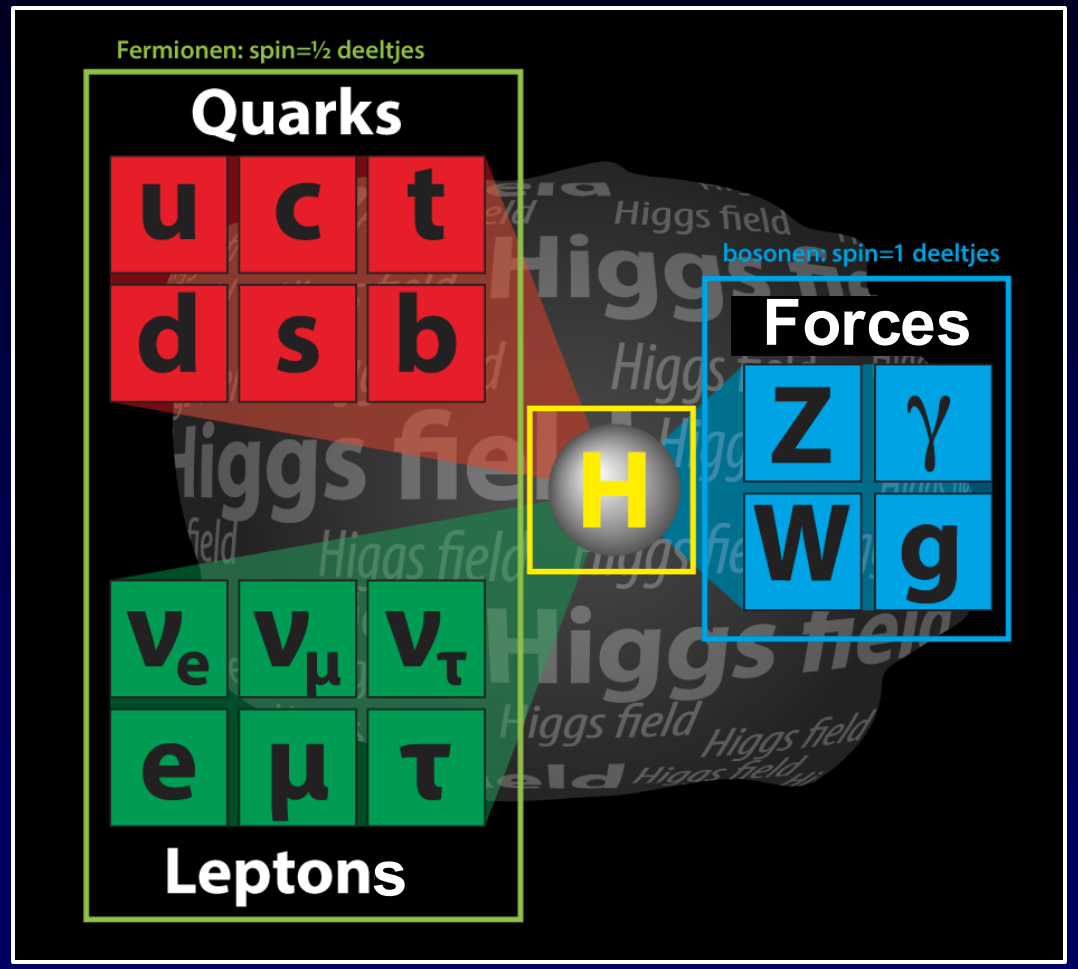
Quantum
W, Z exchange:

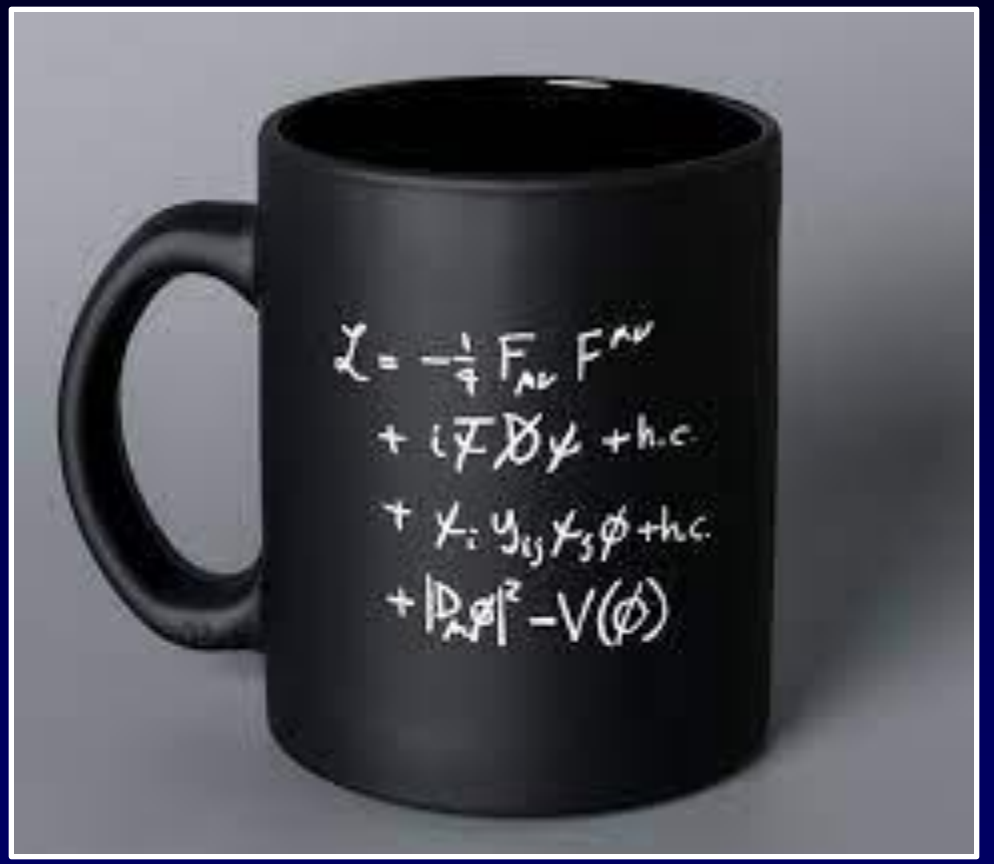


How strong are the forces?

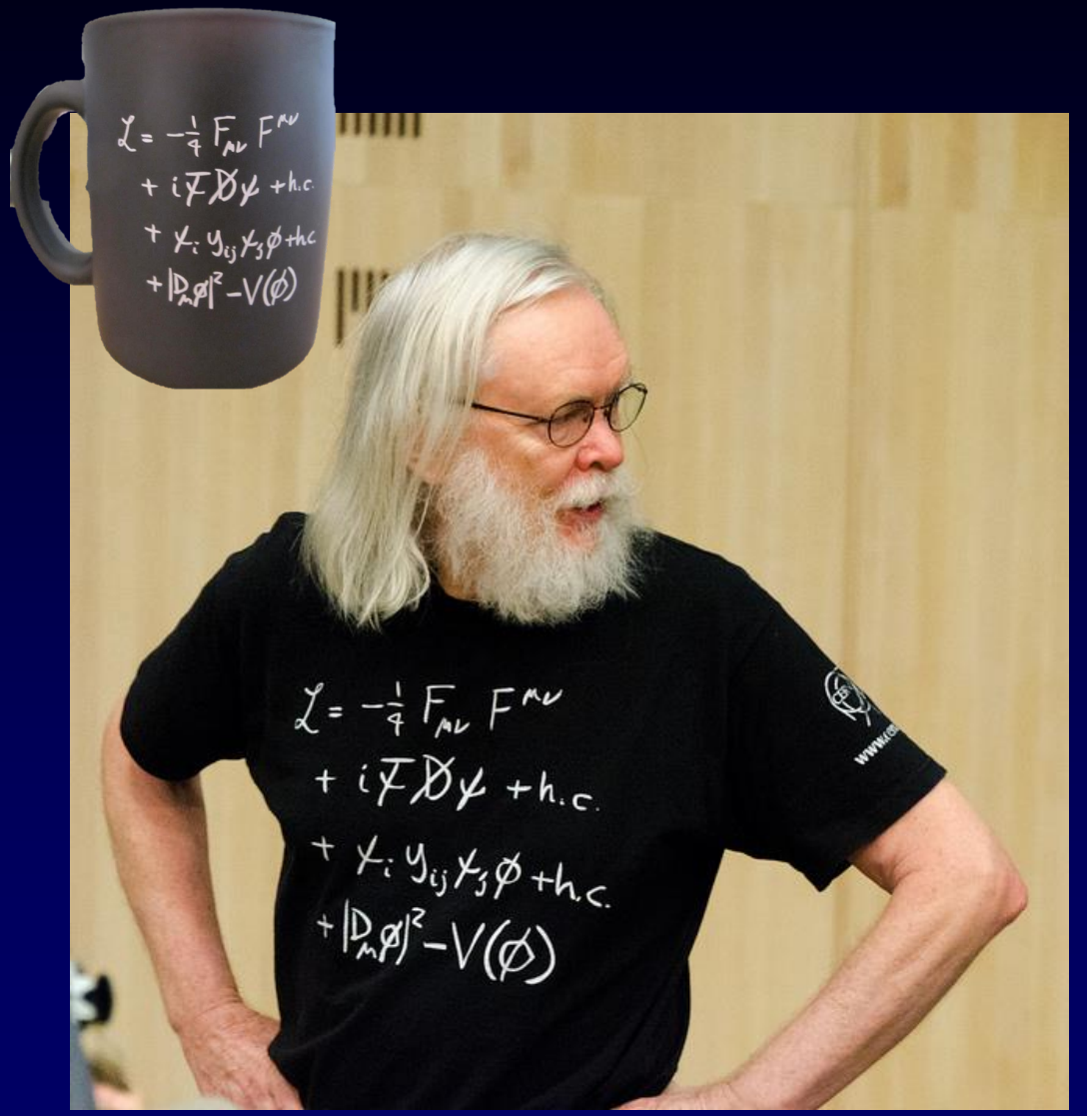
	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons
Strength	0.00000000000000000000000000000001	0.0001	1	60

Standard Model: Particles and Forces





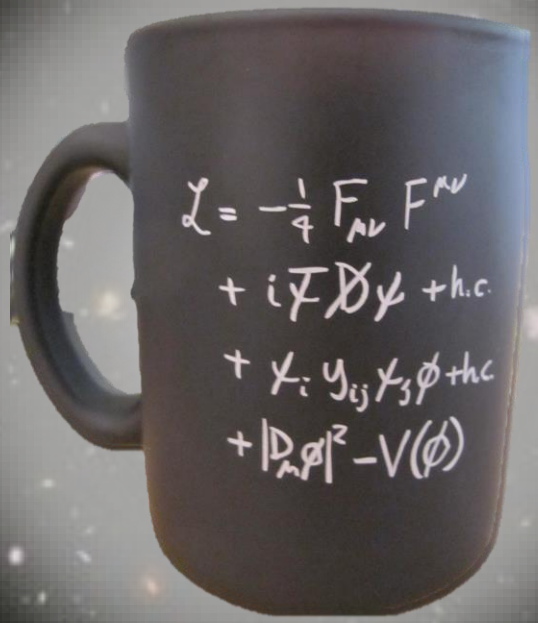
Standard Model: Theory



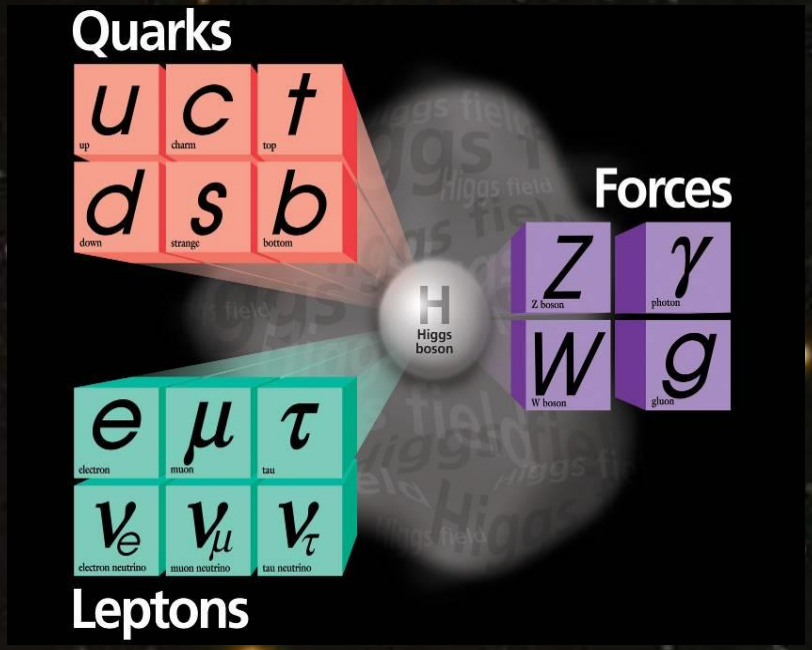
$$-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4} g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$
$$\tfrac{1}{2} i g_s^2 (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$
$$M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu$$
$$\tfrac{1}{2} m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \tfrac{1}{2c_w^2} M \phi$$
$$\tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu$$
$$W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W$$
$$W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu($$
$$W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2} g^2 W^+_\mu$$
$$\tfrac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu$$
$$g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2$$
$$\tfrac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi$$
$$gMW^+_\mu W^-_\mu H - \tfrac{1}{2} g \tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \tfrac{1}{2} ig[W^+_\mu (\phi^0 \partial_\mu \phi^- -$$
$$W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \tfrac{1}{2} g[W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) -$$
$$\phi^+ \partial_\mu H)] + \tfrac{1}{2} g \tfrac{1}{c_w} (Z^0_\mu (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \tfrac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu$$
$$igs_w M A_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) - ig \tfrac{1-2c_w^2}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- -$$
$$igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \tfrac{1}{4} g^2 W^+_\mu W^-_\mu [H^2 + (\phi^0$$
$$\tfrac{1}{4} g^2 \tfrac{1}{c_w^2} Z^0_\mu Z^0_\mu [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+\phi^-] - \tfrac{1}{2} g^2 \tfrac{s_w^2}{c_w}$$
$$W^-_\mu \phi^|) - \tfrac{1}{2} ig^2 \tfrac{s_w^2}{c_w} Z^0_\mu H (W^|_\mu \phi^- - W^-_\mu \phi^|) + \tfrac{1}{2} g^2 s_w A_\mu$$
$$W^-_\mu \phi^+) + \tfrac{1}{2} ig^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \tfrac{s_w}{c_w} (2c_w^2 -$$
$$g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma\partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}^\lambda_j (\gamma\partial + m$$
$$m_d^\lambda) d_j^\lambda + igs_w A_\mu [-(\bar{e}^\lambda \gamma e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j \gamma u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j \gamma d^\lambda_j)] + \tfrac{i}{4}$$
$$\gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (\tfrac{4}{3} s_w^2 - 1$$
$$(\bar{d}^\lambda_j \gamma^\mu (1 - \tfrac{8}{3} s_w^2 - \gamma^5) d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} W^+_\mu [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda)$$
$$\gamma^5) C_{\lambda\kappa} d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}} W^-_\mu [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}^\kappa_j C^|_{\lambda\kappa} \gamma^\mu ($$
$$\tfrac{ig}{2\sqrt{2}} \tfrac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \tfrac{g}{2}$$
$$i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}^\lambda_j C_{\lambda\kappa} (1 - \gamma^5) d^\kappa_j) + m$$
$$\gamma^5) d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 + \gamma^5) u^\kappa_j) - m_u^\kappa (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}$$
$$\tfrac{g}{2} \tfrac{m_u^\lambda}{M} H (\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2} \tfrac{m_d^\lambda}{M} H (\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2} \tfrac{m_u^\lambda}{M} \phi^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \tfrac{ig}{2}$$
$$\bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \tfrac{M^2}{c_w^2}$$
$$igc_w W^+_\mu (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + igs_w W^+_\mu (\partial_\mu \bar{Y} X^-$$
$$igc_w W^-_\mu (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + igs_w W^-_\mu (\partial_\mu \bar{X}^- Y$$
$$igc_w Z^0_\mu (\partial_\mu \bar{X}^| X^| - \partial_\mu \bar{X}^- X^-) + igs_w A_\mu (\partial_\mu \bar{X}^| X^| -$$
$$\tfrac{1}{2} gM [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2} \bar{X}^0 X^0 H] + \tfrac{1-2c_w^2}{2c_w} igM$$
$$\bar{X}^- X^0 \phi^-] + \tfrac{1}{2c_w} igM [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + igMs_w [\bar{X}^0 X^- \phi^+ -$$
$$\bar{X}^0 X^+ \phi^-] + \tfrac{1}{2} igM [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]$$

Standard Model

"The formula"



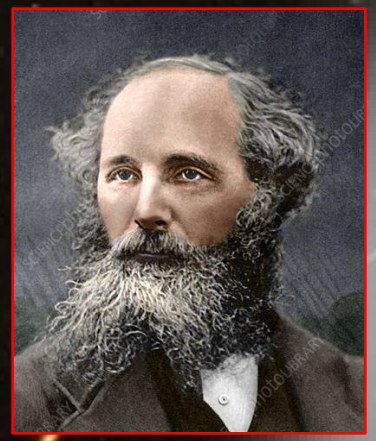
"The building blocks"



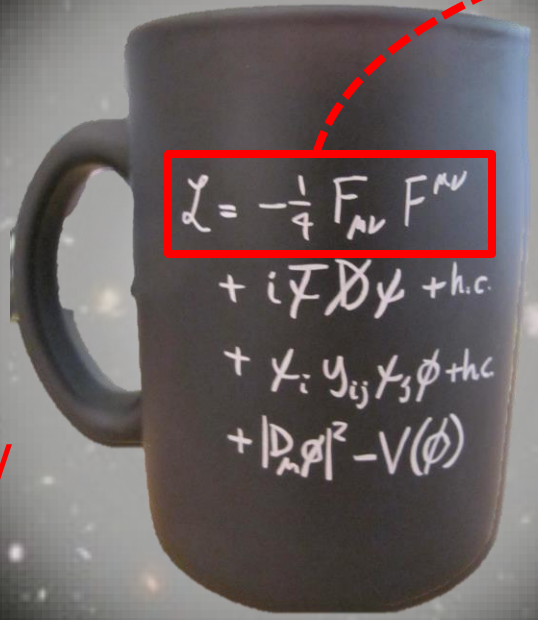
Standard Model

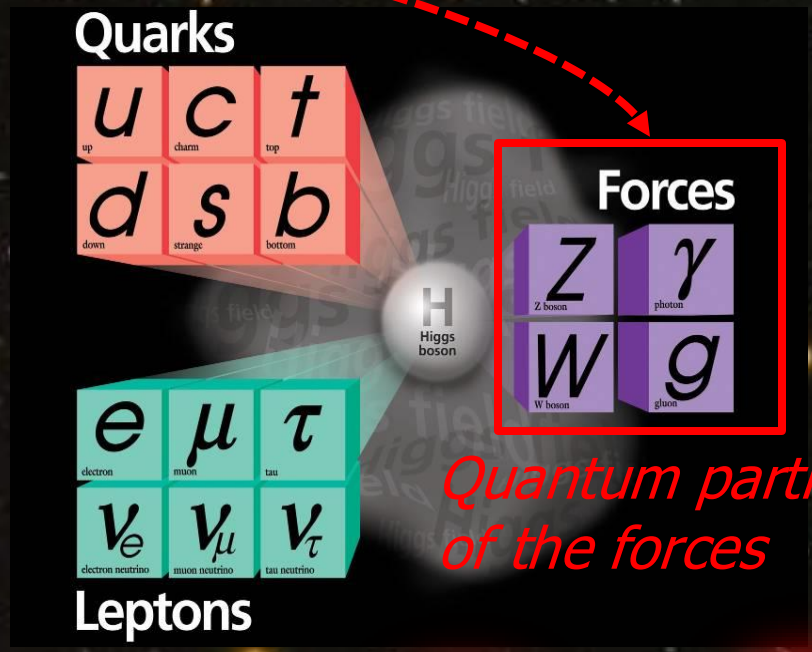
"The formula"

"The building blocks"

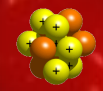


1865: Maxwell equations





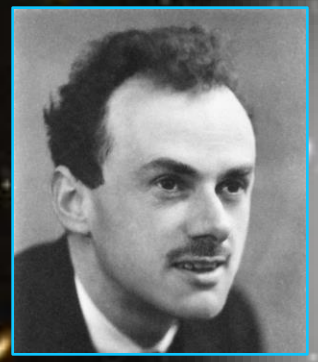
Quantum particles of the forces



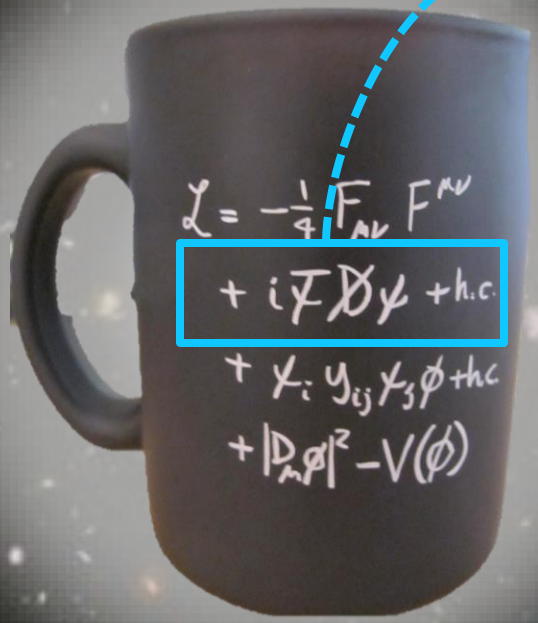
Standard Model

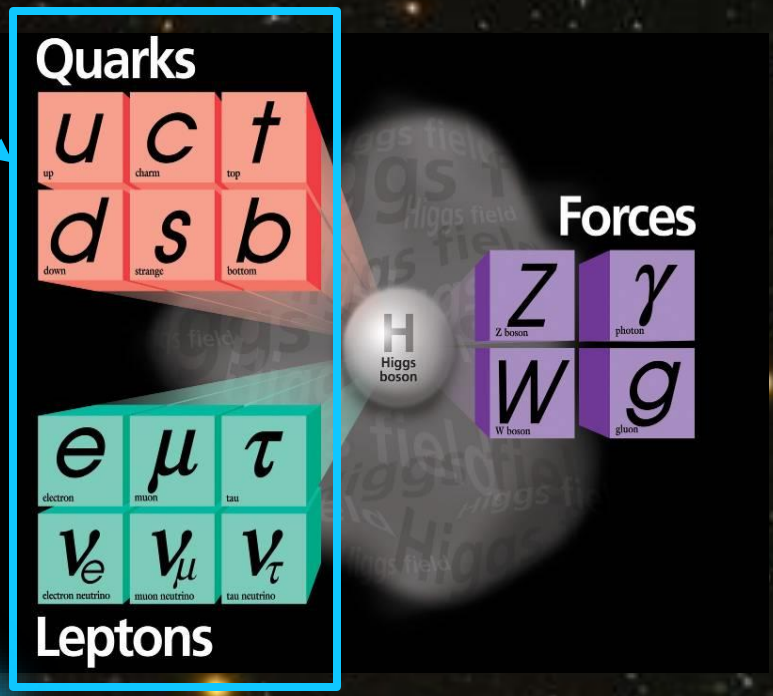
"The formula"

"The building blocks"



1928: Dirac equation

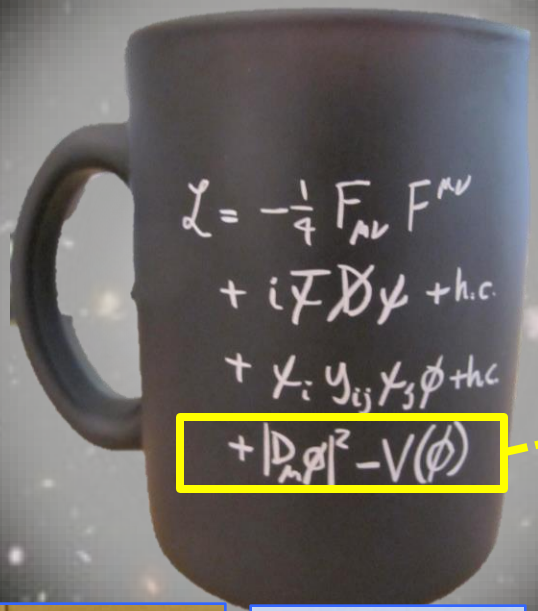




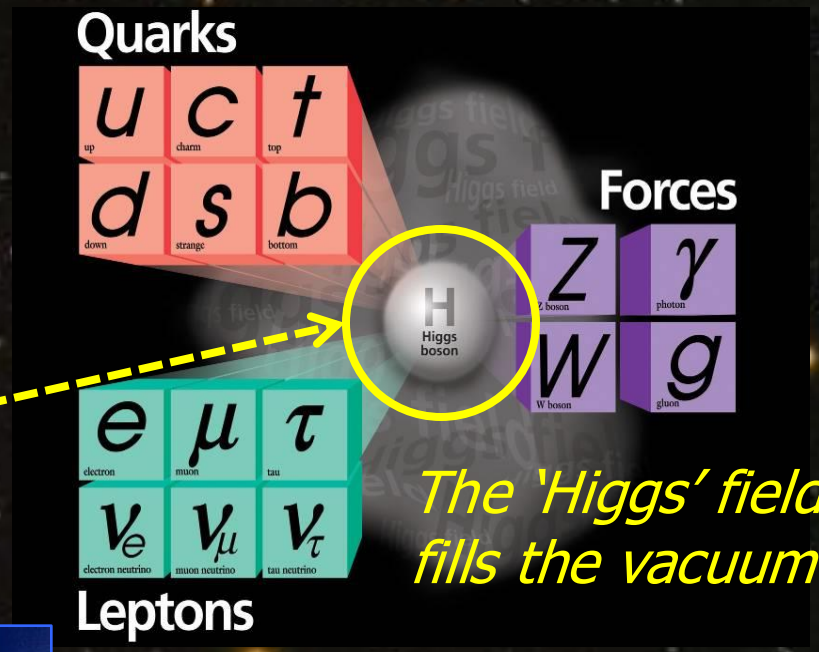
Matter particles

Standard Model

"The formula"

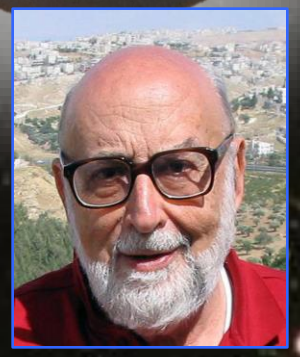


"The building blocks"



The 'Higgs' field fills the vacuum

Brout



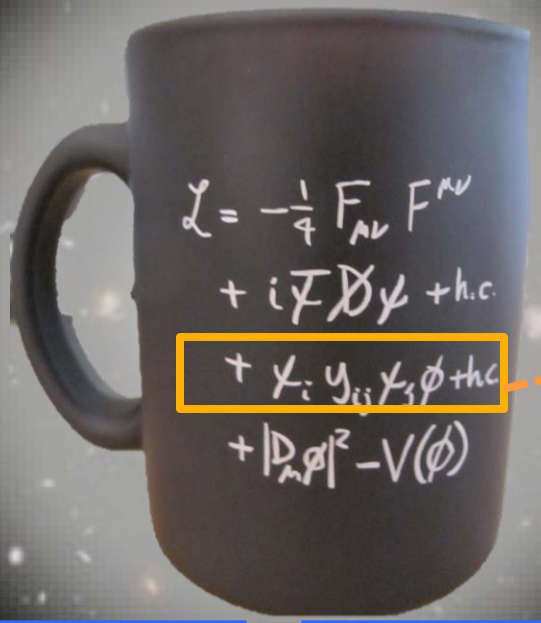
Englert

Higgs

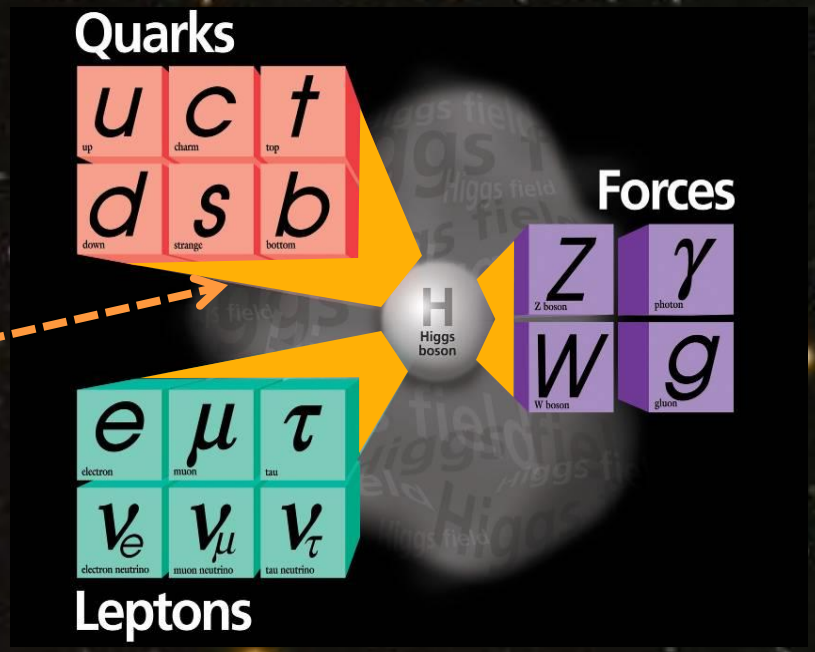
1964:
Standard Model prediction:
empty space is not empty!

Standard Model

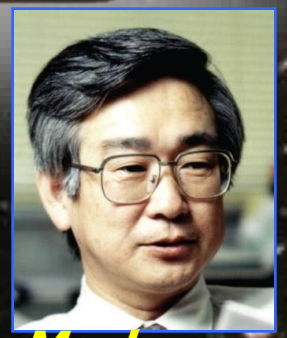
"The formula"



"The building blocks"



Kobayashi

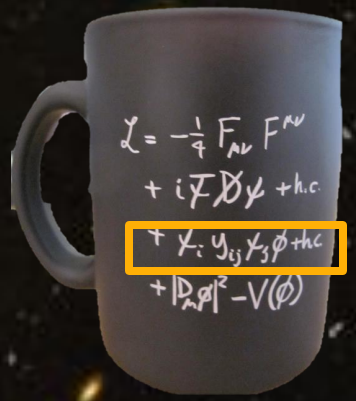


Maskawa

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

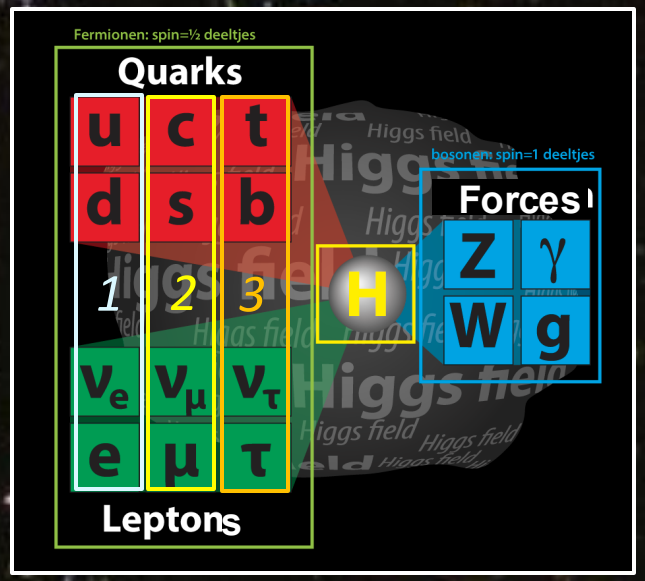
49.999999% anti-matter

50.000001% matter

Dominates

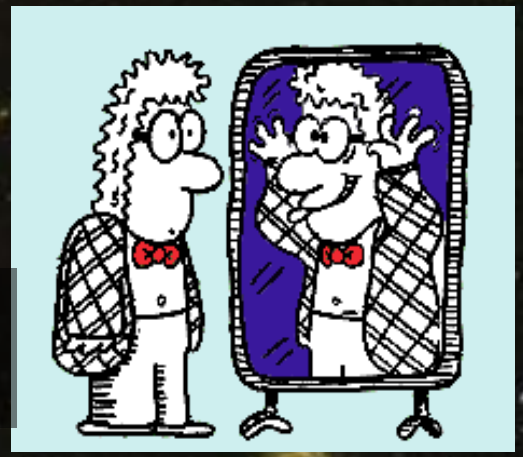
0.000001% matter

(+99.999999% radiation)

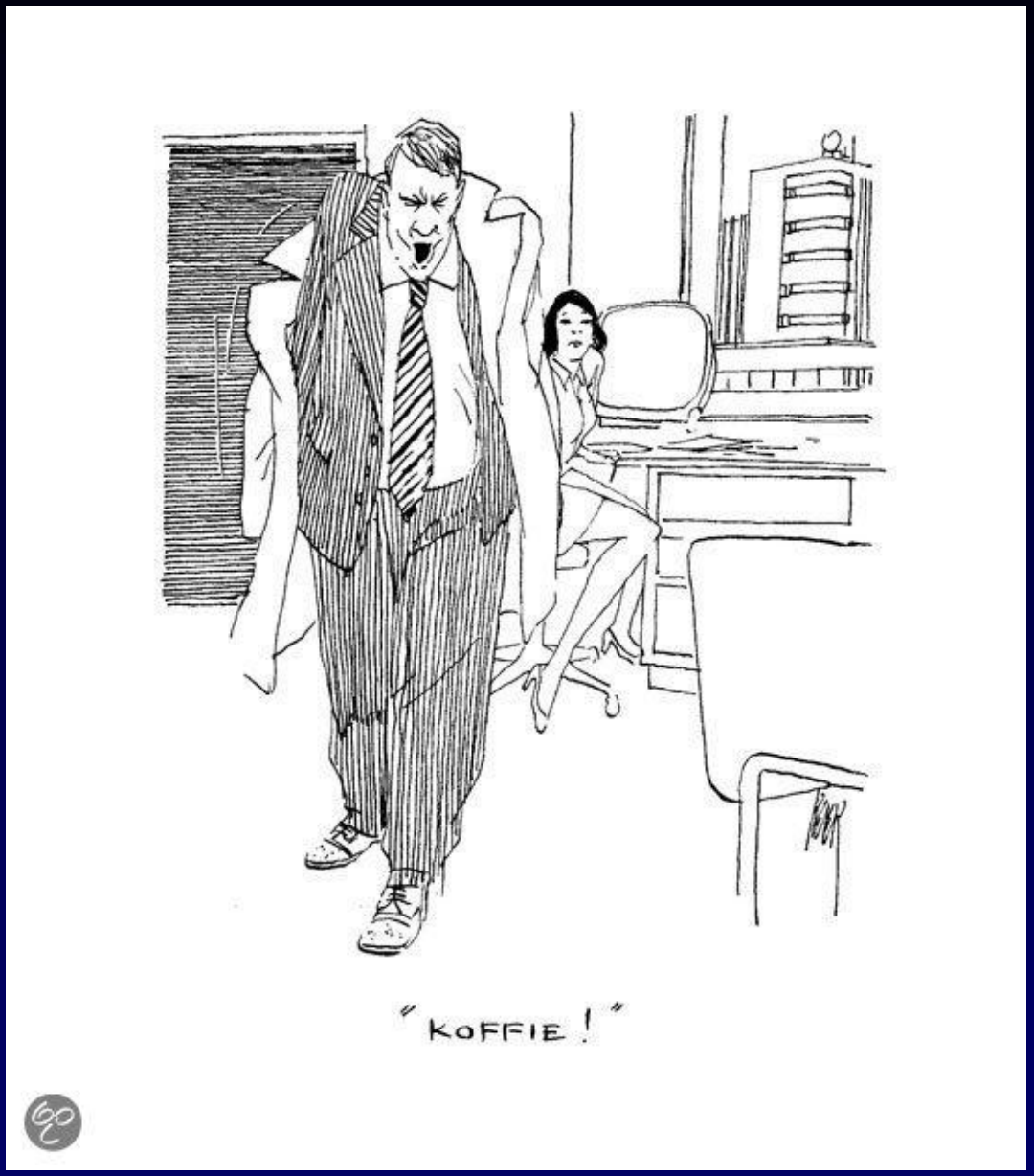


Antimaterie not the exact mirror image of matter?!

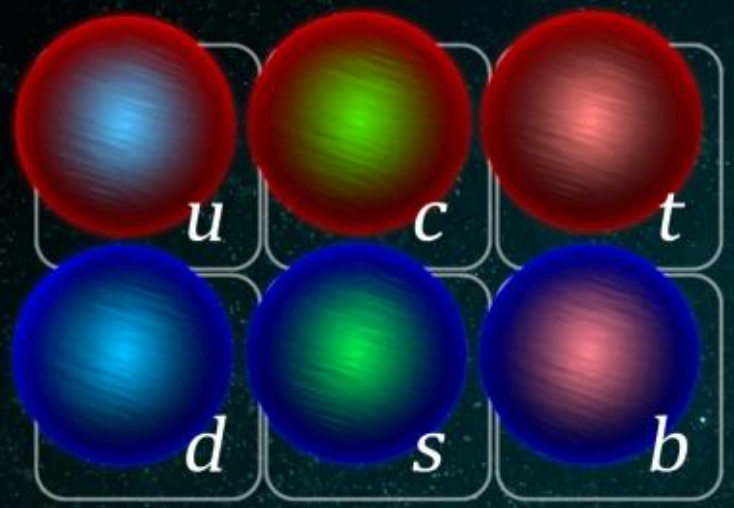
Theoretically this requires three copies of all particles!



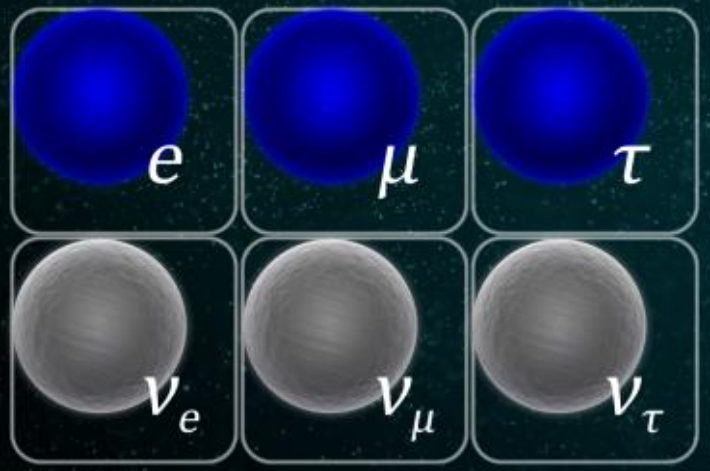
Honey, you did your best, but that was really disgusting!



Standard Model

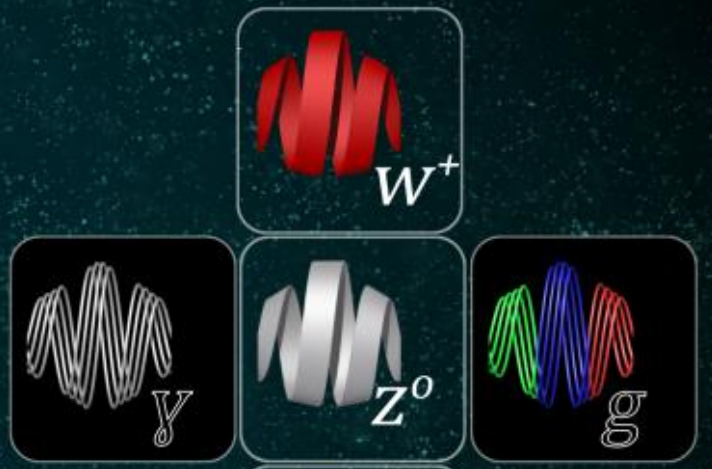


Quarks



Leptons

Higgs boson



Forces