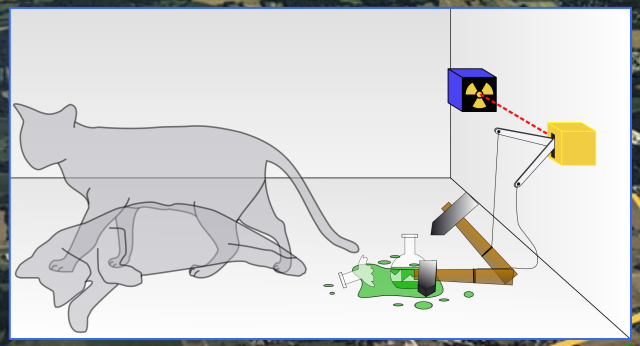
The Relativistic Quantum World

A lecture series on Relativity Theory and Quantum Mechanics

Marcel Merk



University of Maastricht, Sept 16 – Oct 14, 2020

The Relativistic Quantum World

Relativity

Sept 16:

Lecture 1: The Principle of Relativity and the Speed of Light

Lecture 2: Time Dilation and Lorentz Contraction

Sept 23:

Lecture 3: The Lorentz Transformation and Paradoxes

Lecture 4: General Relativity and Gravitational Waves

Quantum Mechanics

Sept 30:

Lecture 5: The Early Quantum Theory

Lecture 6: Feynman's Double Slit Experiment

Oct 7:

Lecture 7: The Delayed Choice and Schrodinger's Cat

Lecture 8: Quantum Reality and the EPR Paradox

Standard Model

Oct 14:

Lecture 9: The Standard Model and Antimatter

Lecture 10: The Large Hadron Collider

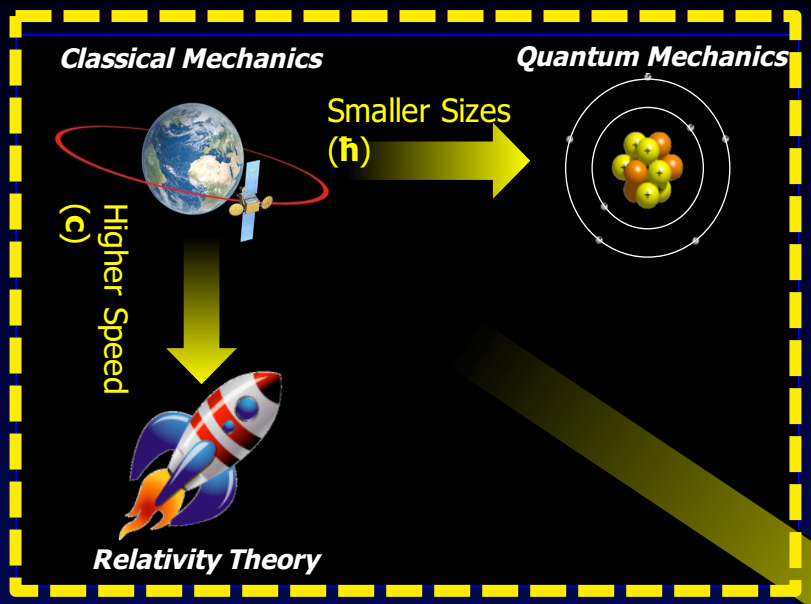
Lecture notes, written for this course, are available: www.nikhef.nl/~i93/Teaching/

Prerequisite for the course: High school level mathematics.

Lecture 9

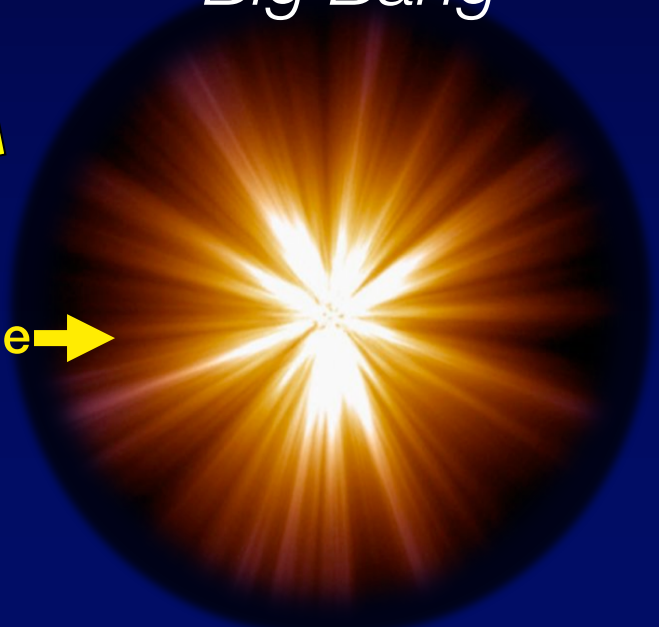
The Standard Model and Antimatter

How does nature behave in extreme conditions?



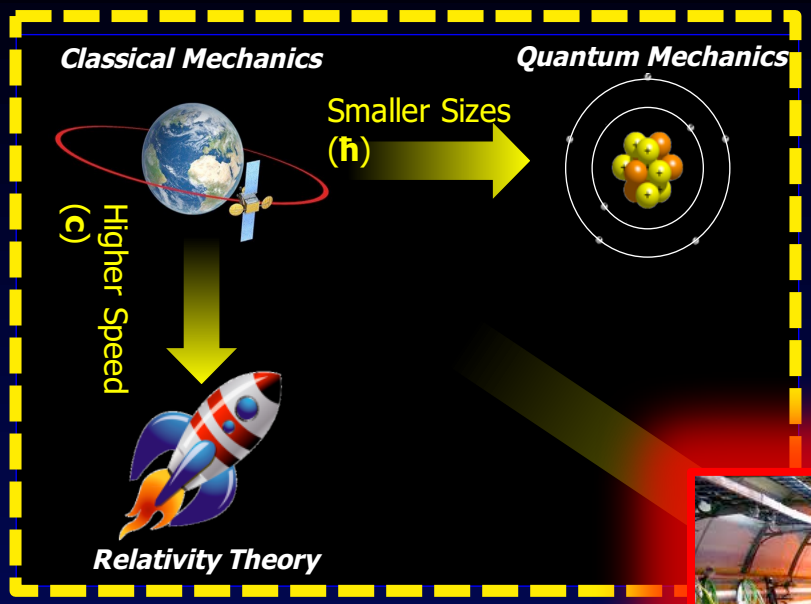
Experimentally tested
domain of the Standard Model

Big Bang



Do we understand the physics also here?

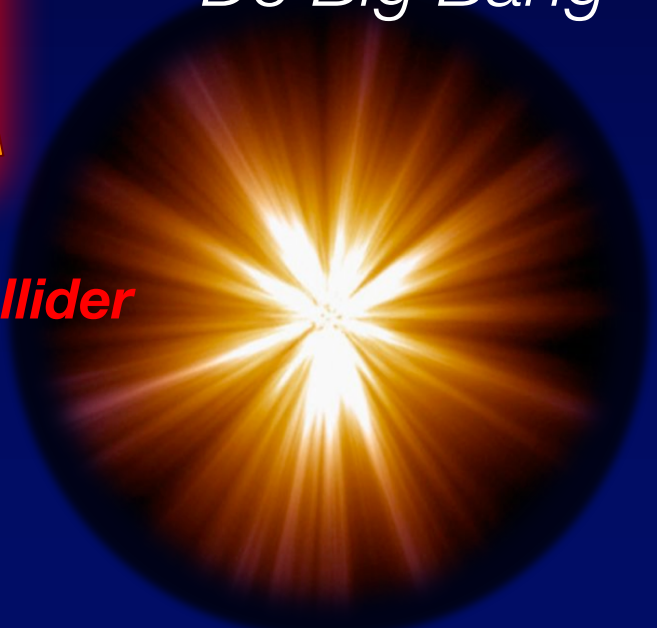
How does nature behave in extreme conditions?



Experimentally tested
domain of the Standard Model

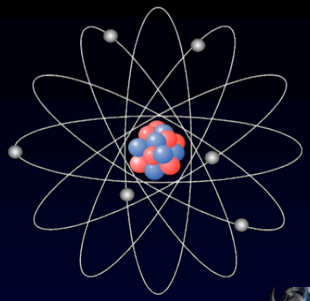
The Large Hadron Collider

De Big Bang



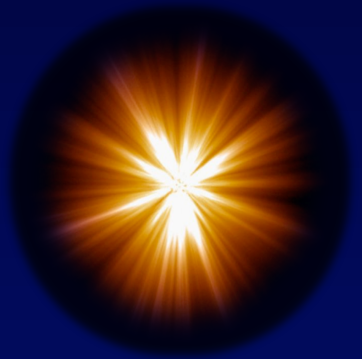
The 'big open questions'?

1. Which are the elementary building blocks of matter?

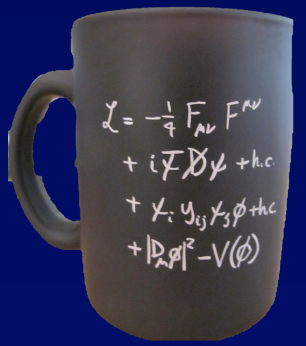


2. Which forces exist in nature and what are their essential differences?

3. Is empty space ('the vacuum') truly empty?



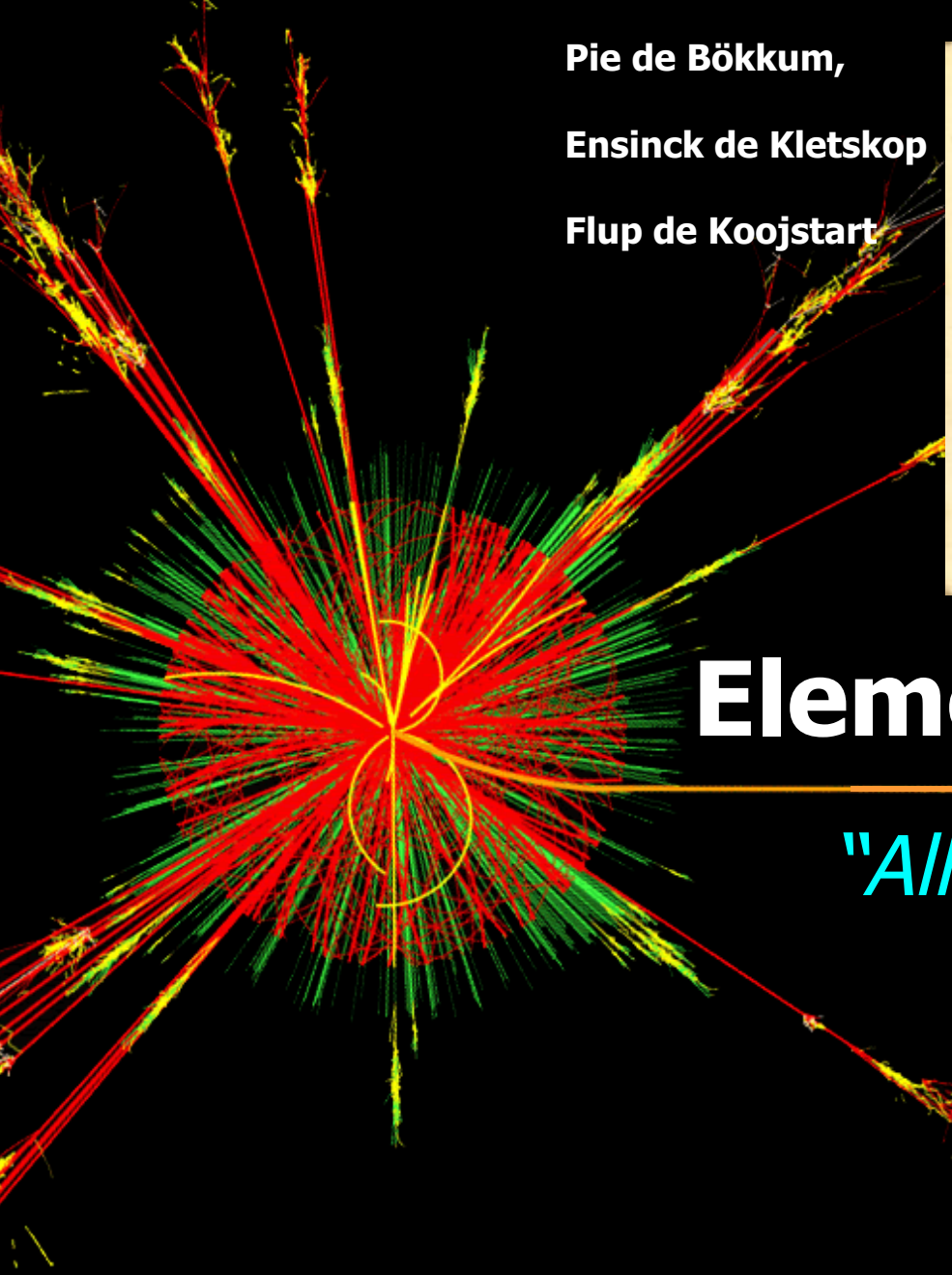
4. Can we explain the existance of our universe from the *big bang* using the known laws of nature?



- *Wanted: a consistent theory that can answer these questions*

Elementary Particles

"All things come in three"



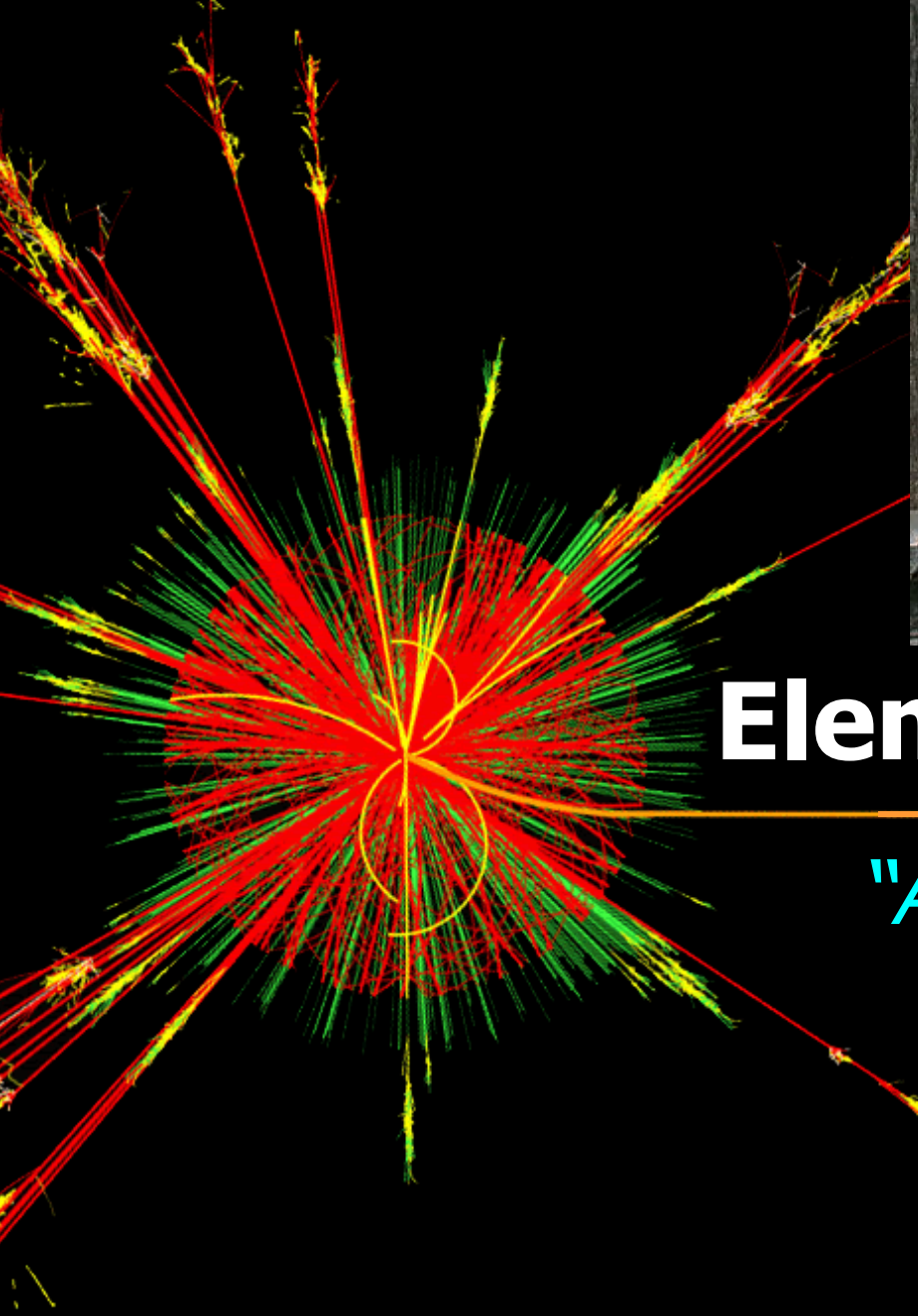
Pie de Bökkum,

Ensinck de Kletskop

Flup de Koojstart

Elementary Particles

"All things come in three"

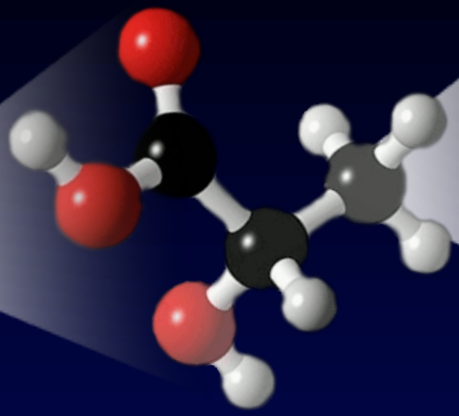


Elementary Particles

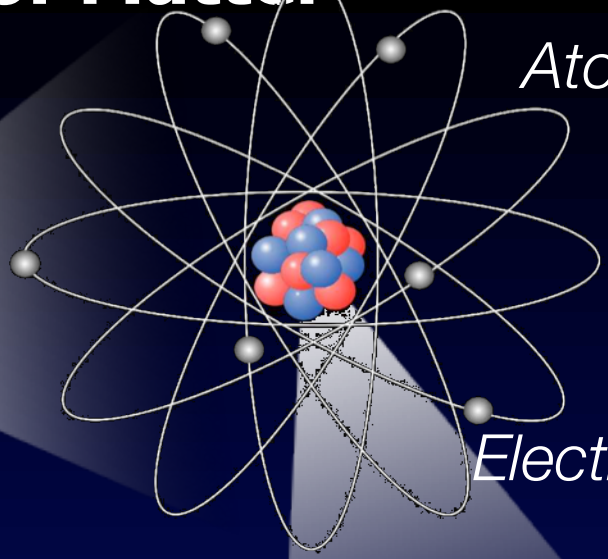
"All things come in three"

Building blocks of Matter

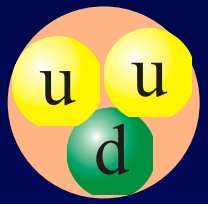
Molecule



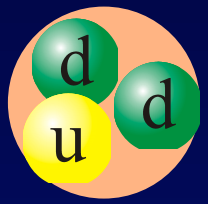
Atom



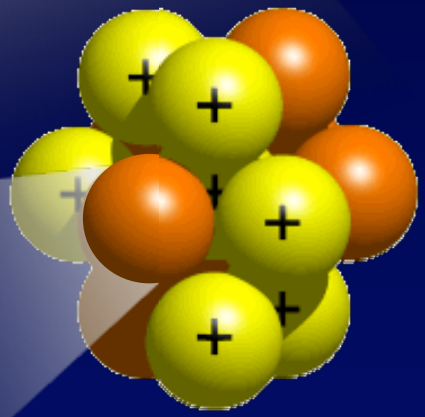
Electron



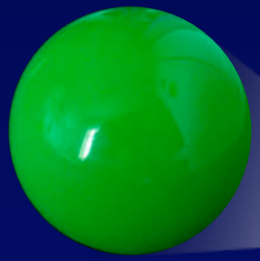
Proton



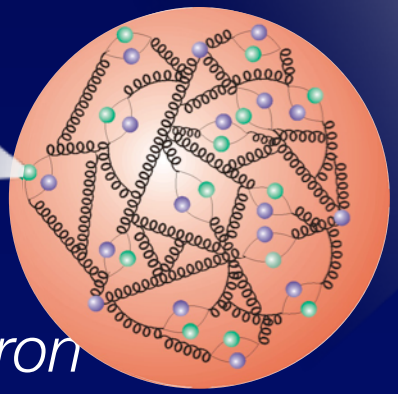
Neutron



Atom-nucleus

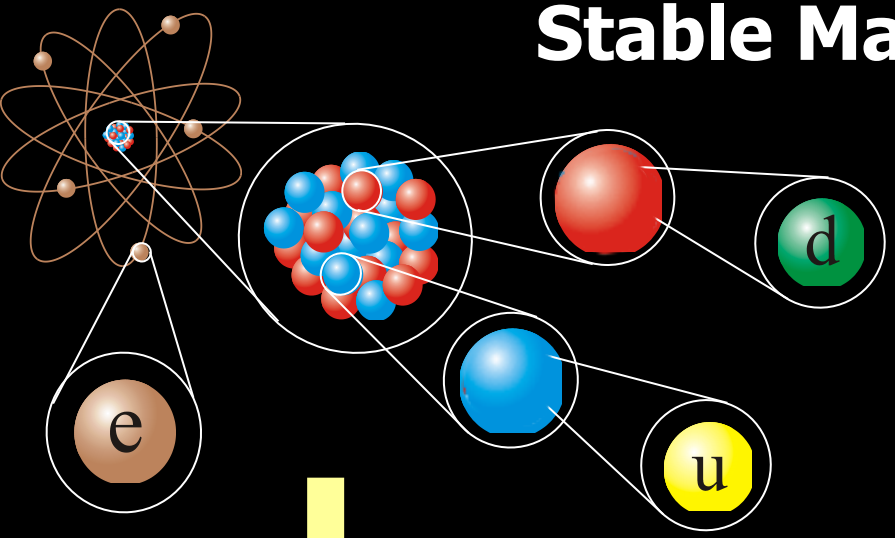


'Quark'



Proton/Neutron

Stable Matter on Earth

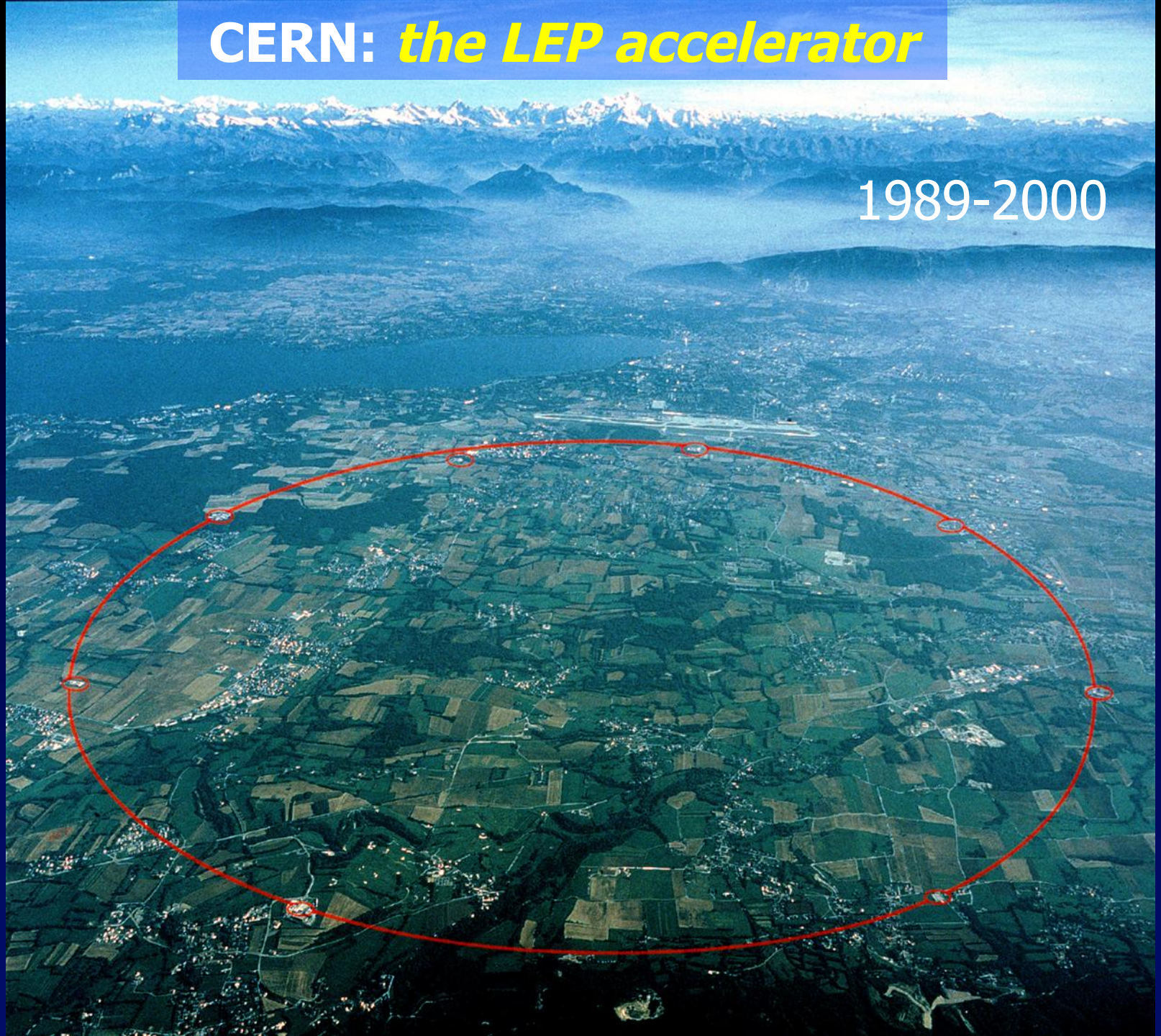


	1 Ia												13 IIIa	14 IVa	15 Va	16 VIa	17 VIIa	18 0
1	1 H	2 IIa																2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg	3 IIIb	4 IVb	5 Vb	6 VIb	7 VIIb	8 VIIIb	9 VIIIb	10 VIIIb	11 Ib	12 IIb	13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	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
6	55 Cs	56 Ba	*	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
7	87 Fr	88 Ra	**	(104) Rf	(105) Db	(106) Sg	(107) Bh	(108) Hs	(109) Mt	(110) Ds	(111) Rg	(112) Cn	(113) Uut	(114) Fl	(115) Uup	(116) Lv	(117) Uus	(118) Uuo

*Lanthaniden	57 La	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
**Actiniden	89 Ac	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: *the laboratory*

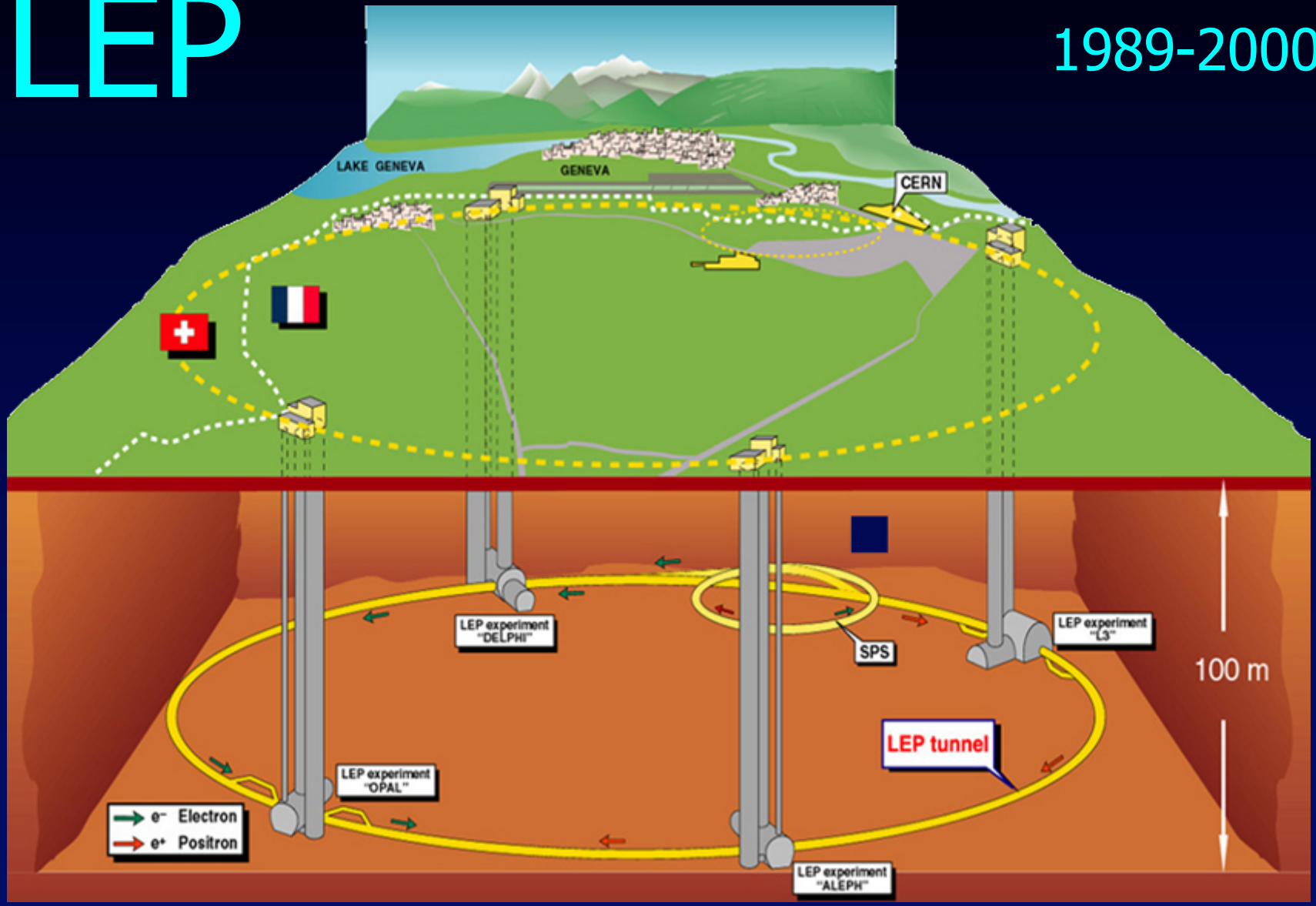
CERN: *the LEP accelerator*



Large Electron Positron collider

LEP

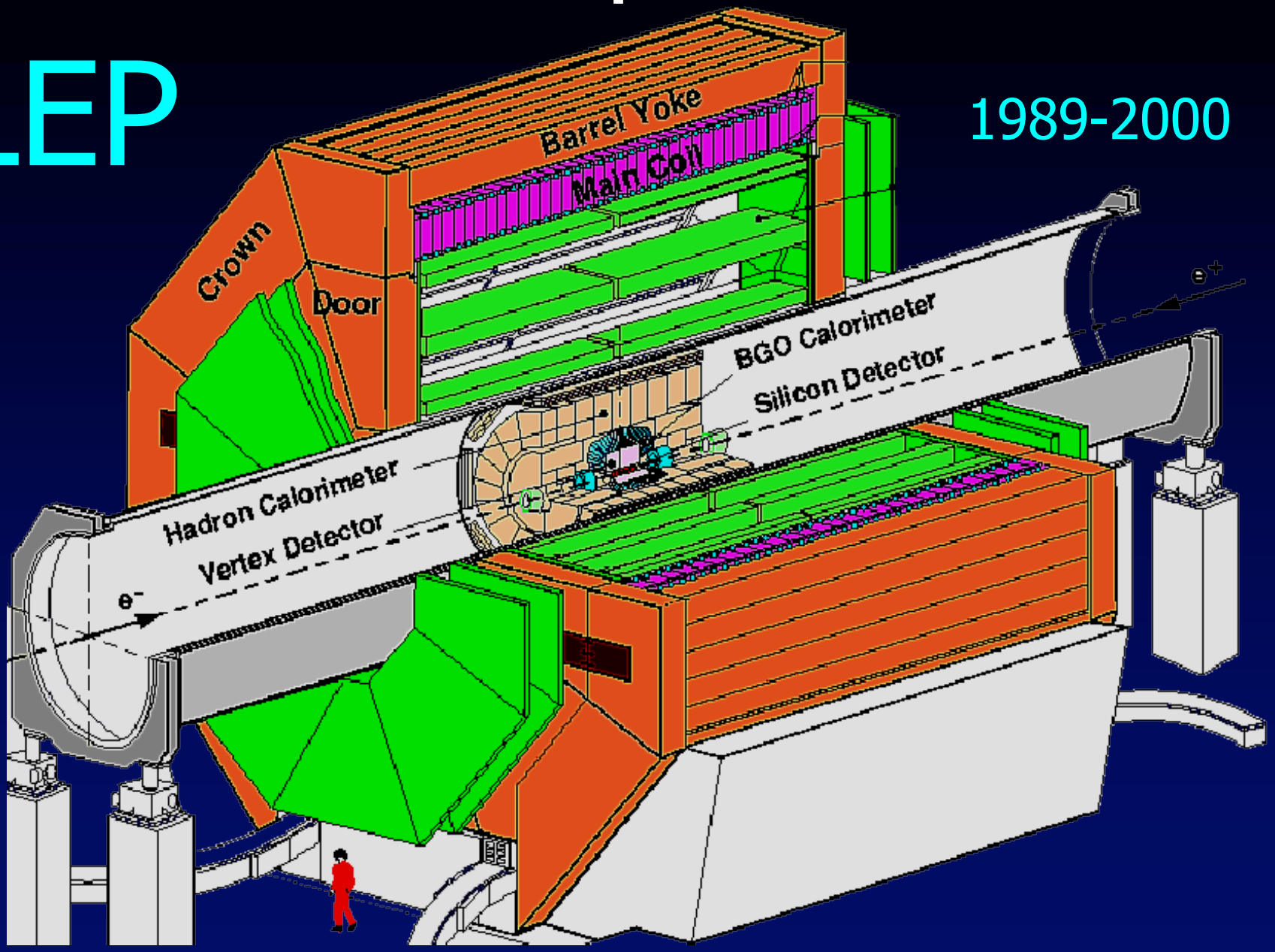
1989-2000



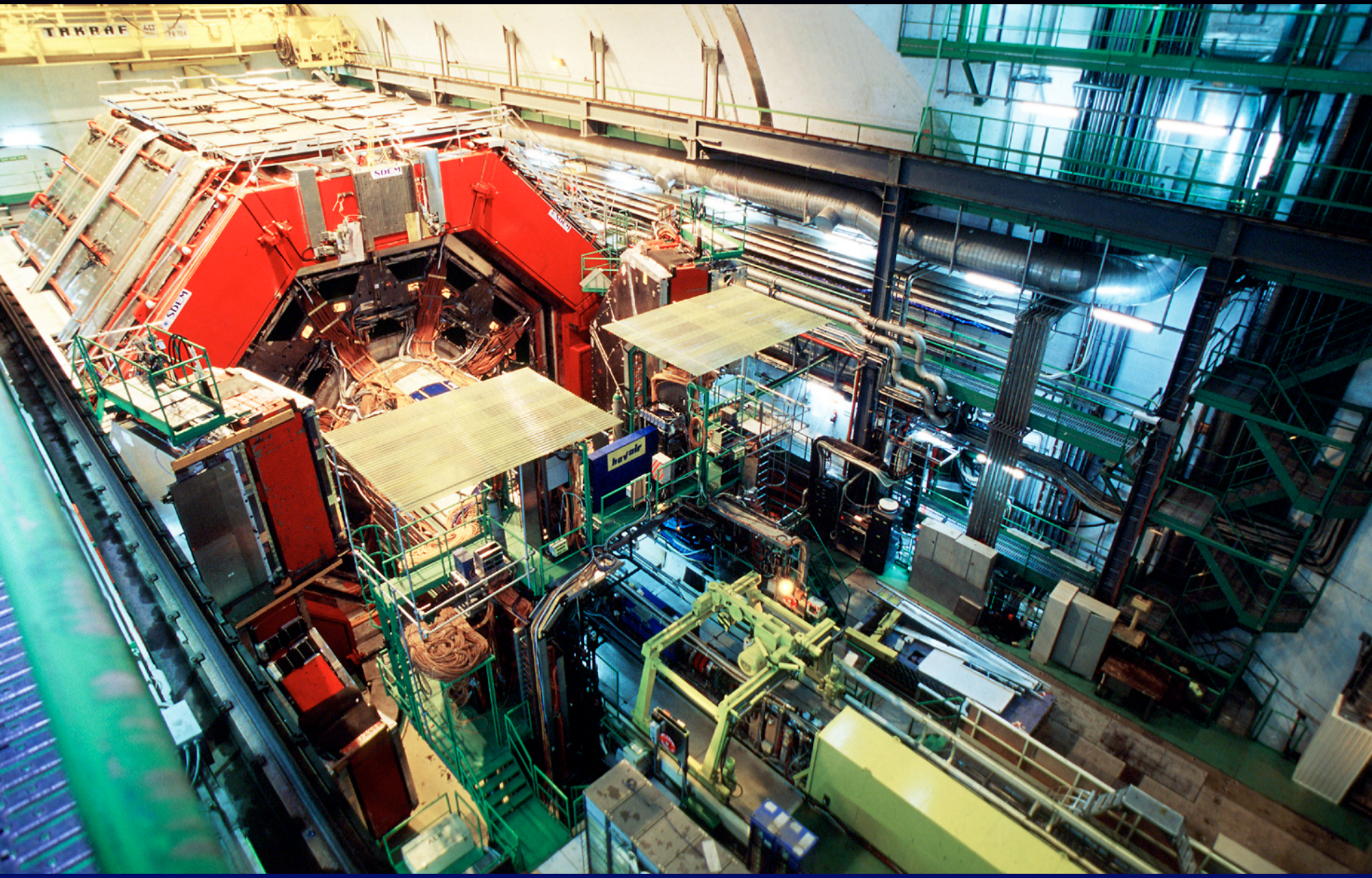
The L3 Experiment

LEP

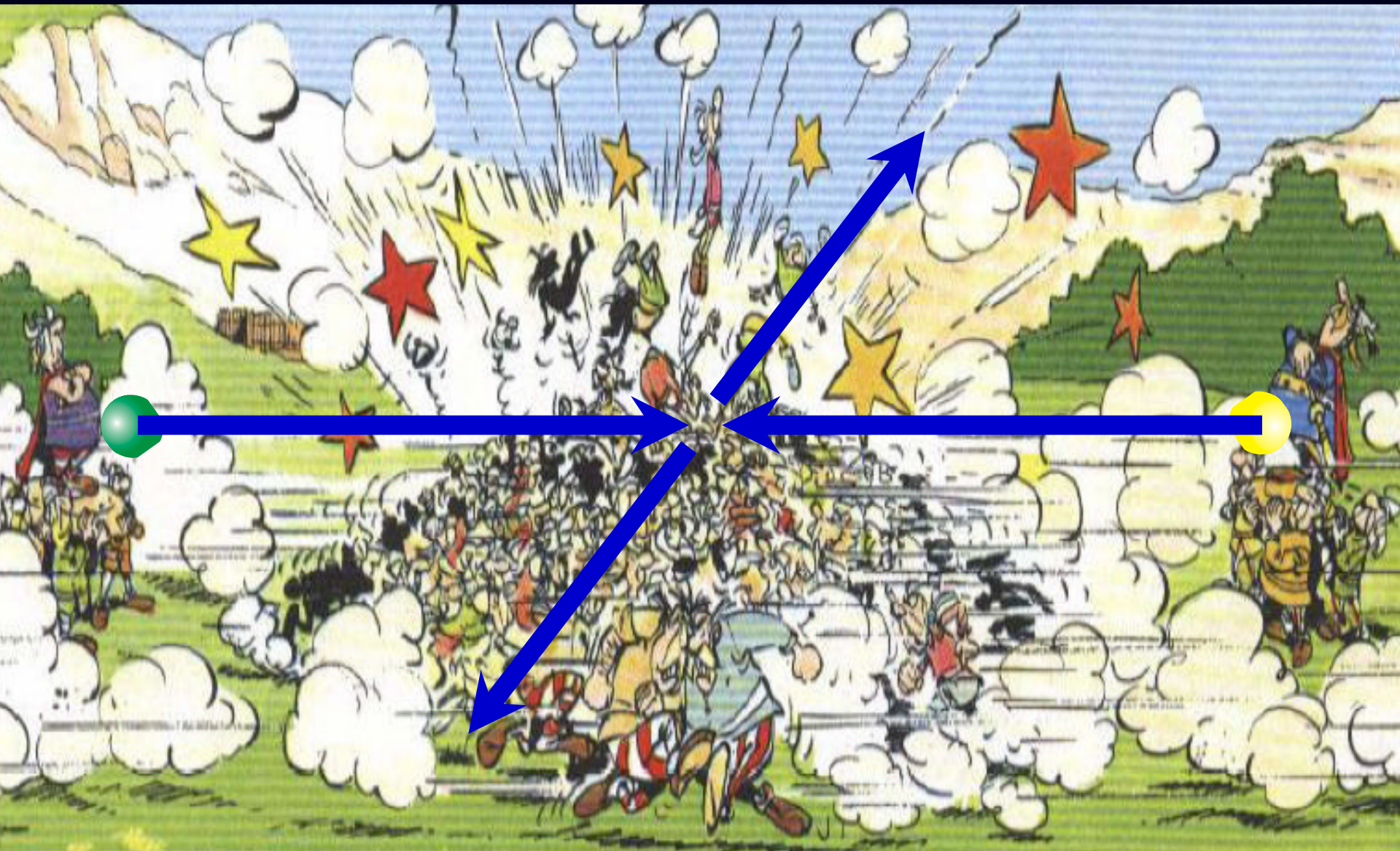
1989-2000



The L3 Experiment



Anything possible is produced



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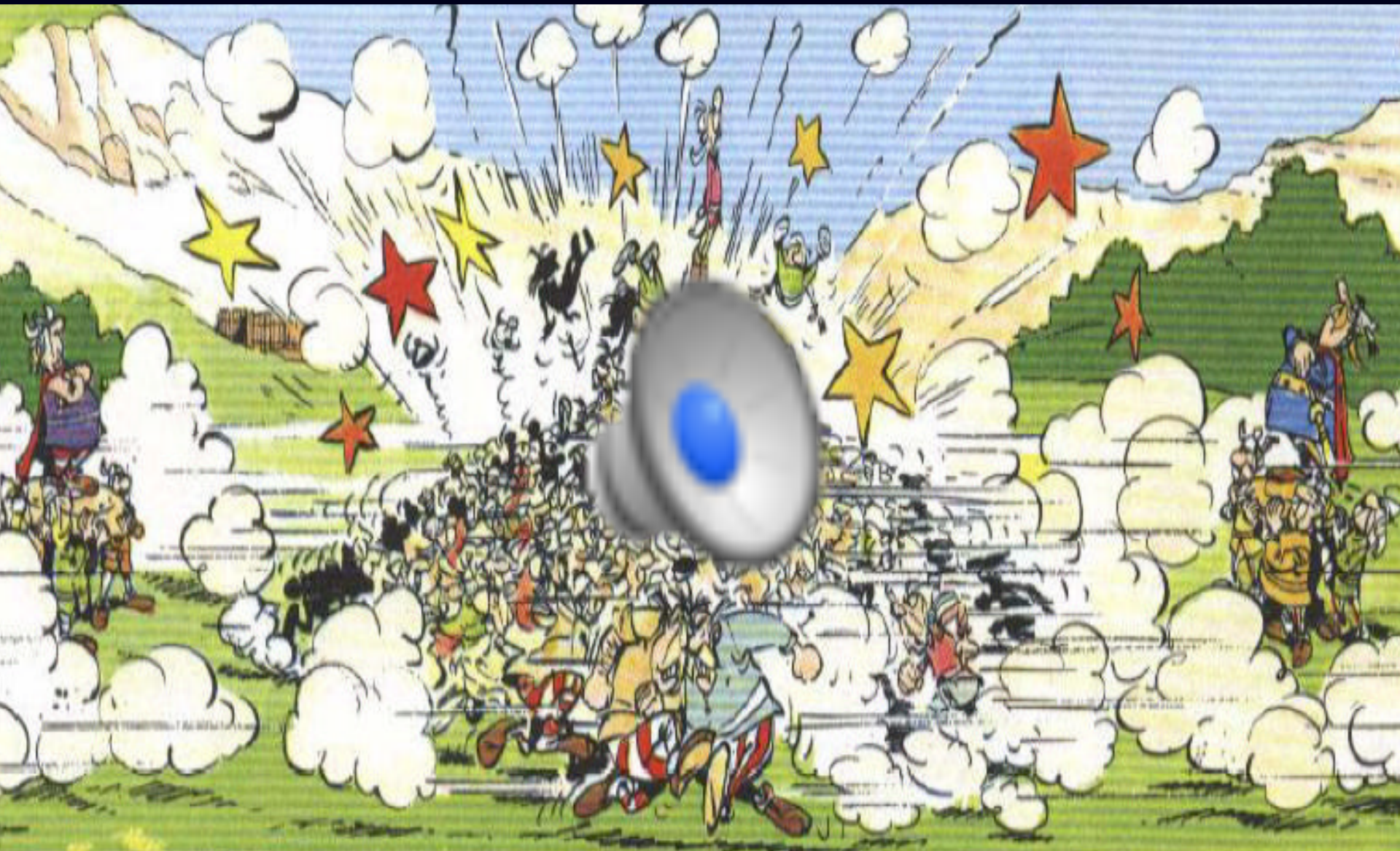
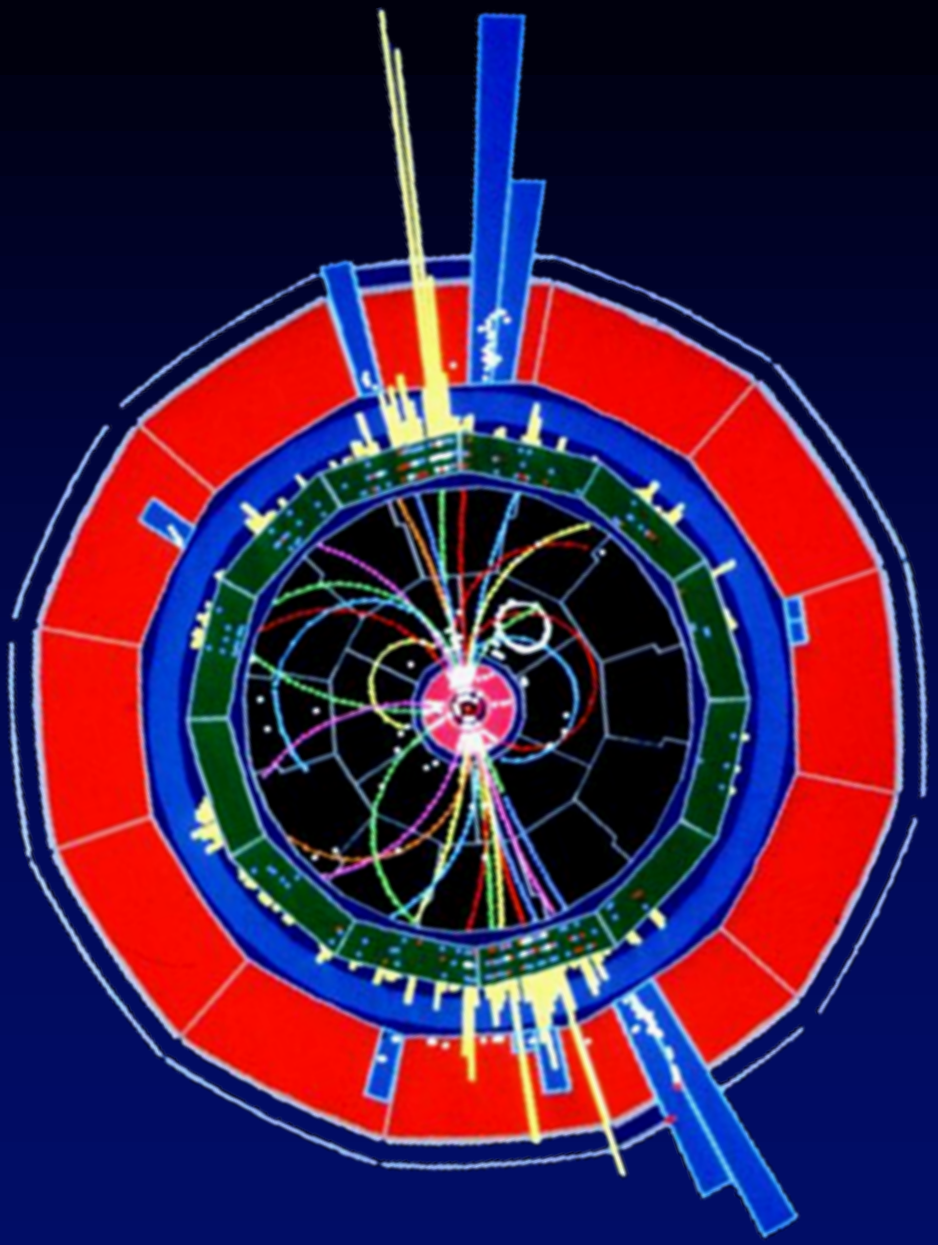


The Elementary Particles

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

Matter



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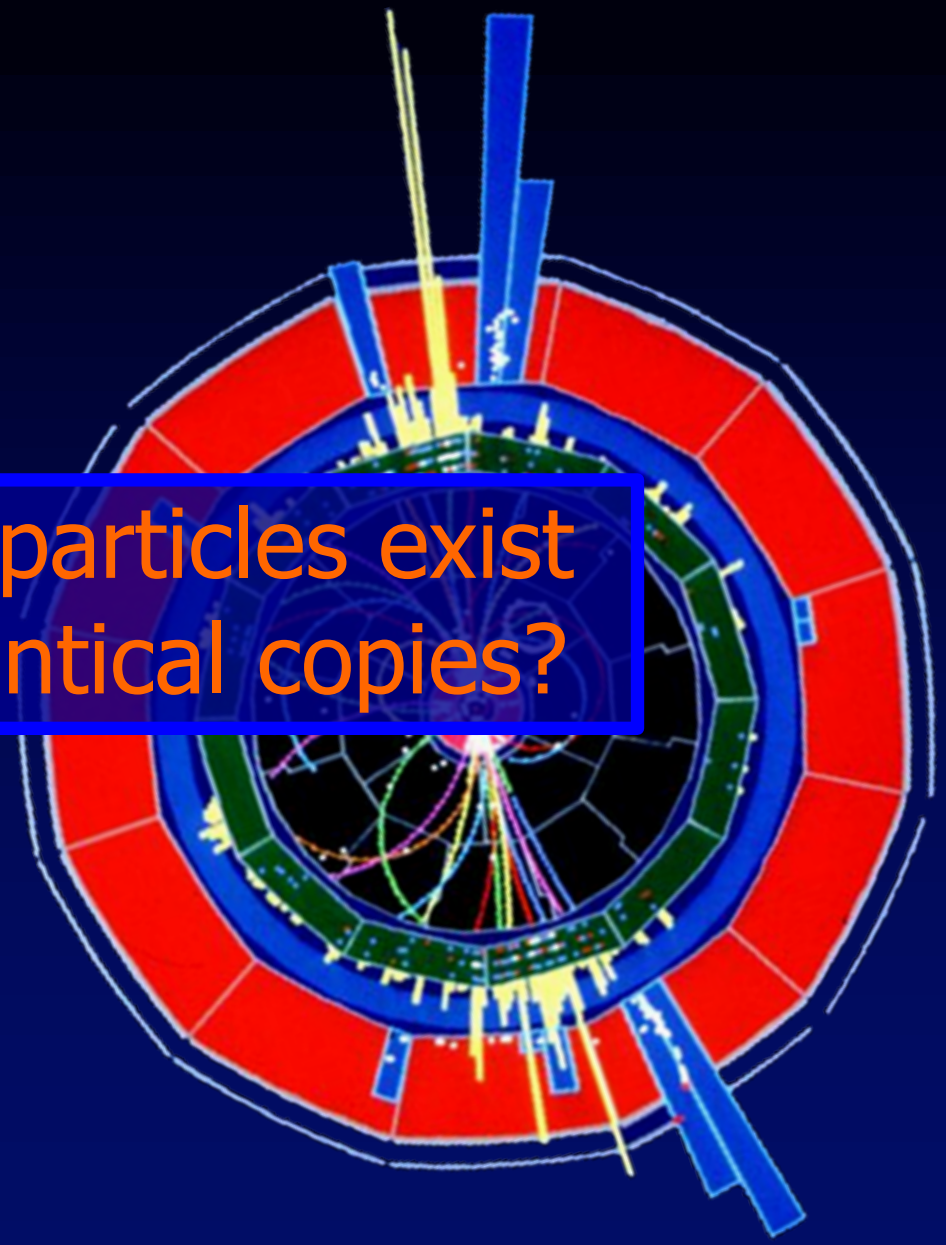
	ν_e (1956)	ν_μ (1963)	ν_τ (2000)	0 e

Matter

Why do all particles exist in three identical copies?

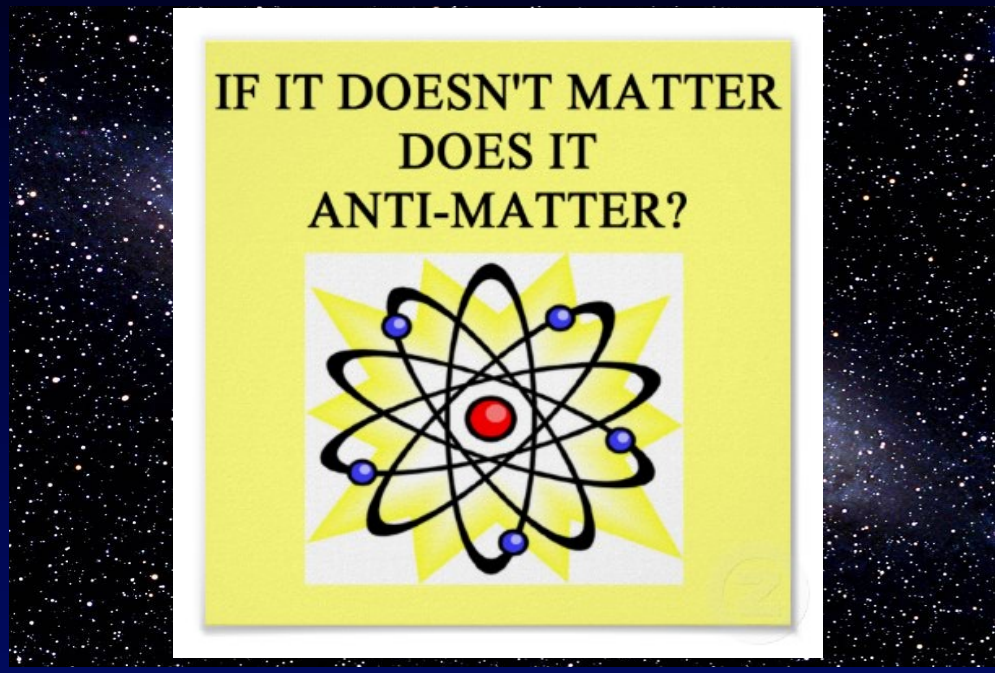


Is that all there is?

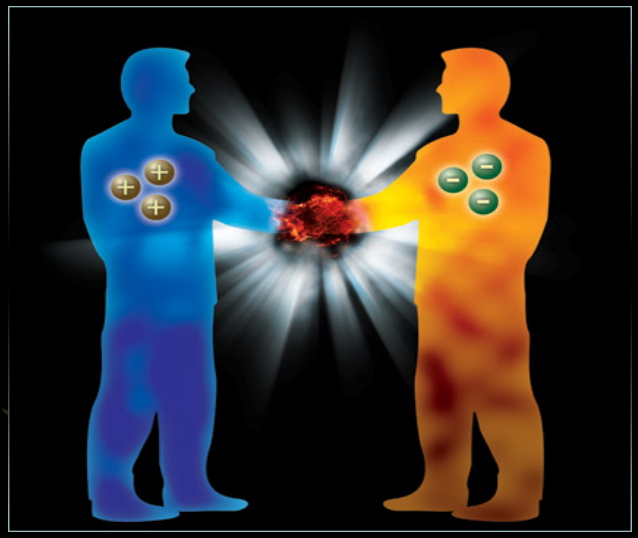
Generation:

	I	II	III	Charge
quarks	u ~3	c 1200	t 176300	+2/3 e
	d ~7	s 120	b 4300	-1/3 e
leptons	e 0.511	μ 106	τ 1777	-1 e
	ν_e ~0	ν_μ ~0	ν_τ ~0	0 e

Matter



1 MeV = 1.8 x 10^{-30} kg



Antimatter and Big Bang

Paul Dirac and

Albert Einstein

Rika (antimatter?)

Antimatter and Big Bang

Paul Dirac and

Albert Einstein

Paul Adrian Maurice Dirac

- Einstein, Bohr et.al. ~1925:
  - Relativity theory
  - Quantum Mechanics
- Paul Dirac (1928):
  - Relativistic Quantum Mechanics

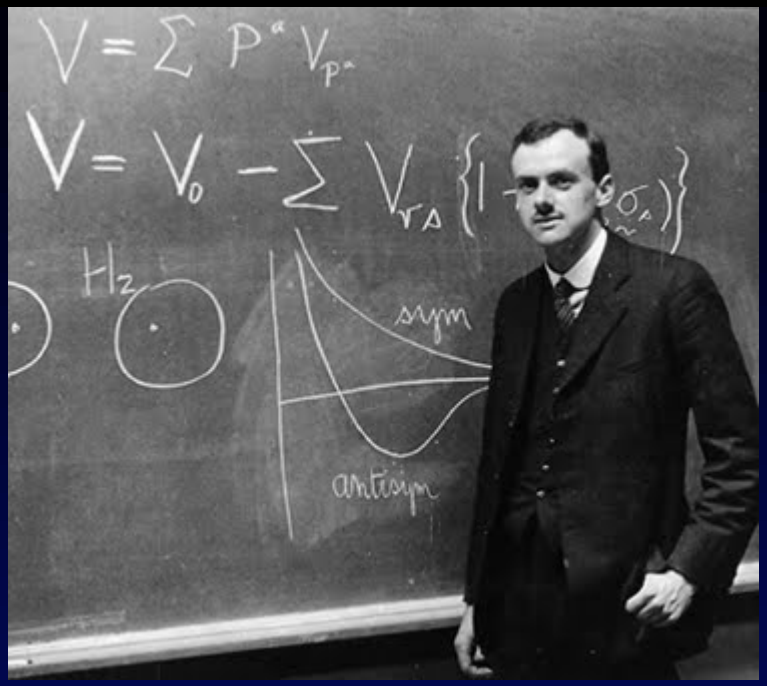
(Westminster abbey)

Dirac

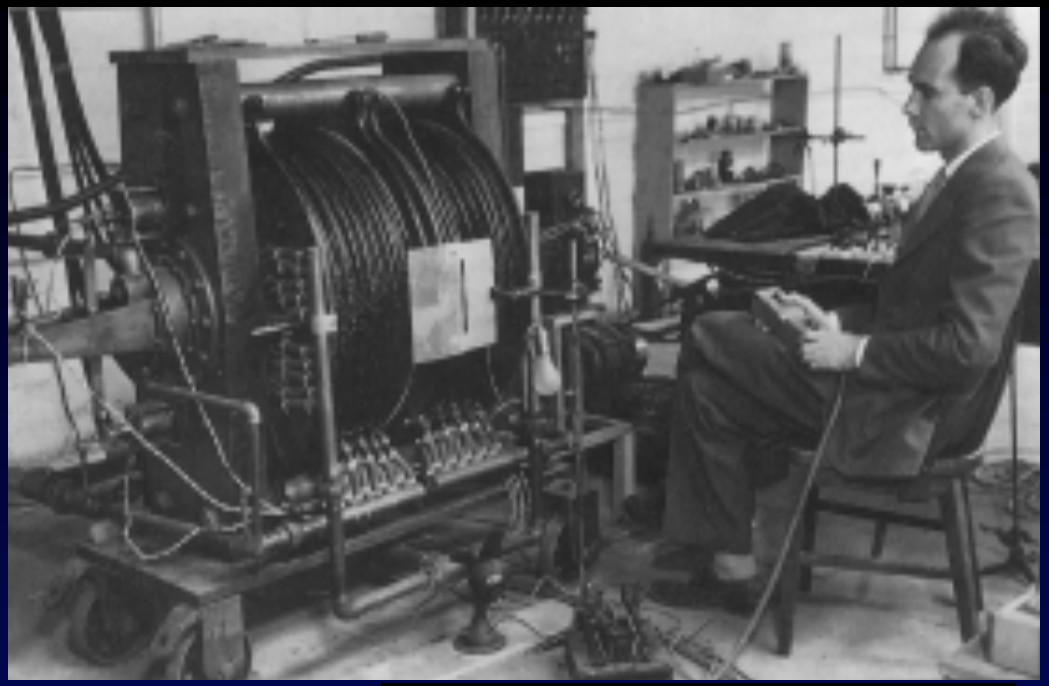
AntiDirac

Prediction Dirac 1928:
For each matter particle an antiparticle exists!

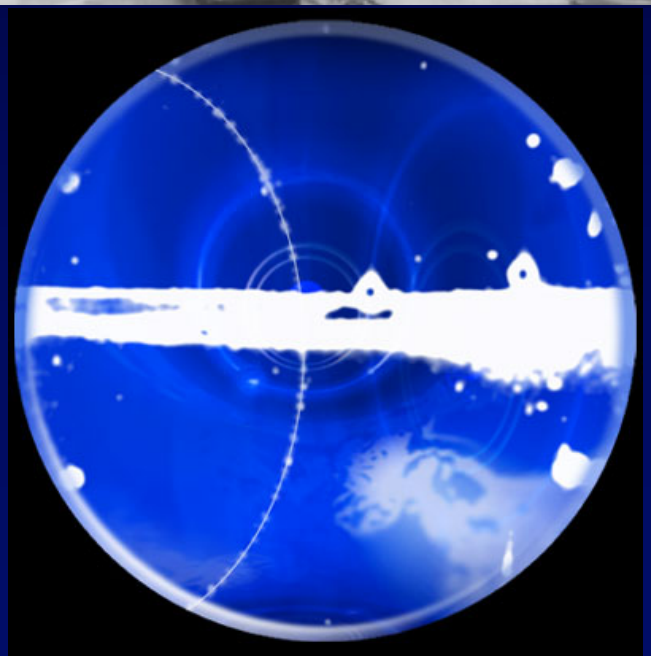
1928: Dirac predicts anti-particles



1932: Anderson discovers anti-electron



- Anderson saw an electron with "wrong" charge: e^+
- Observed with bubble chamber



Elementary Particles

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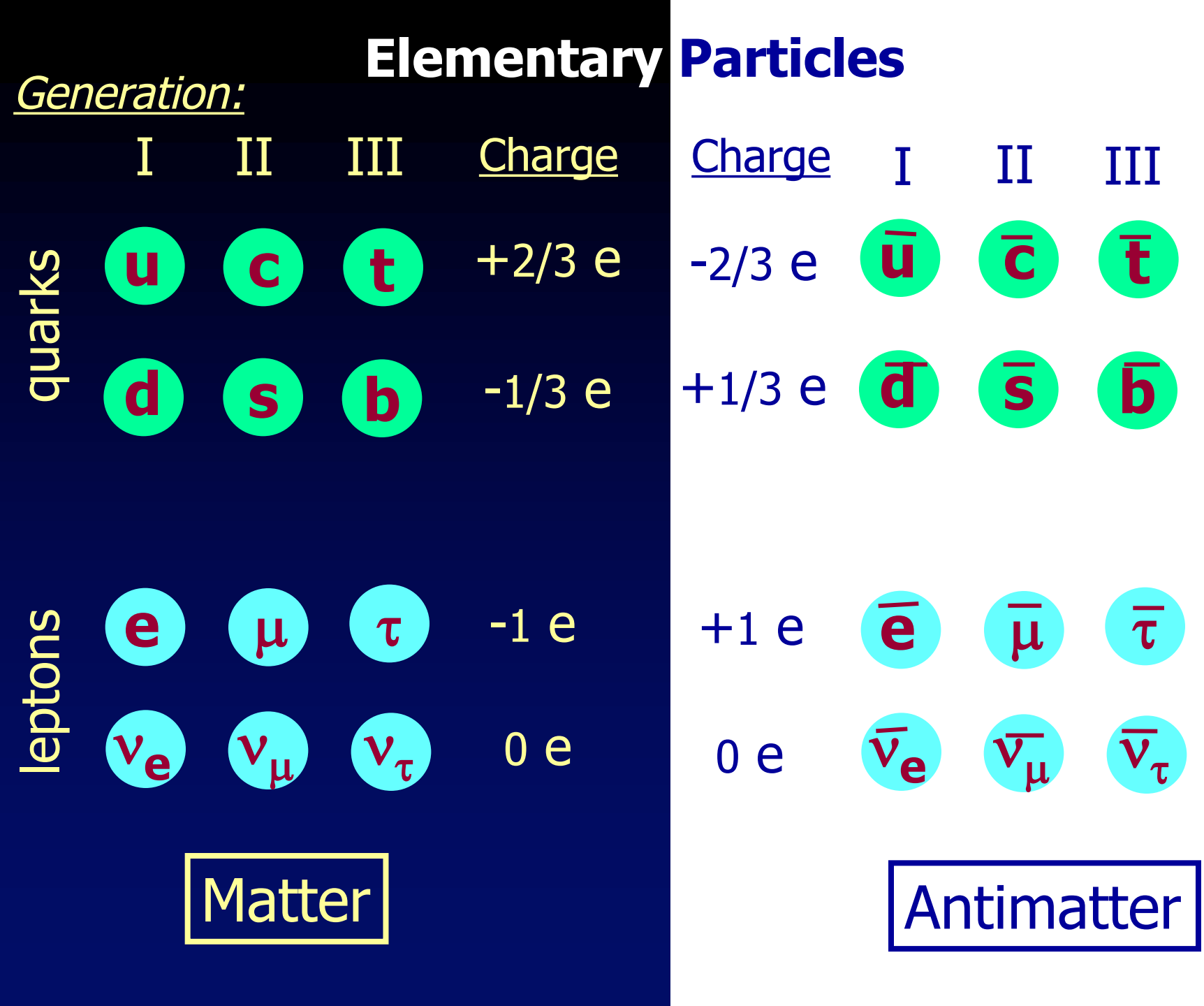
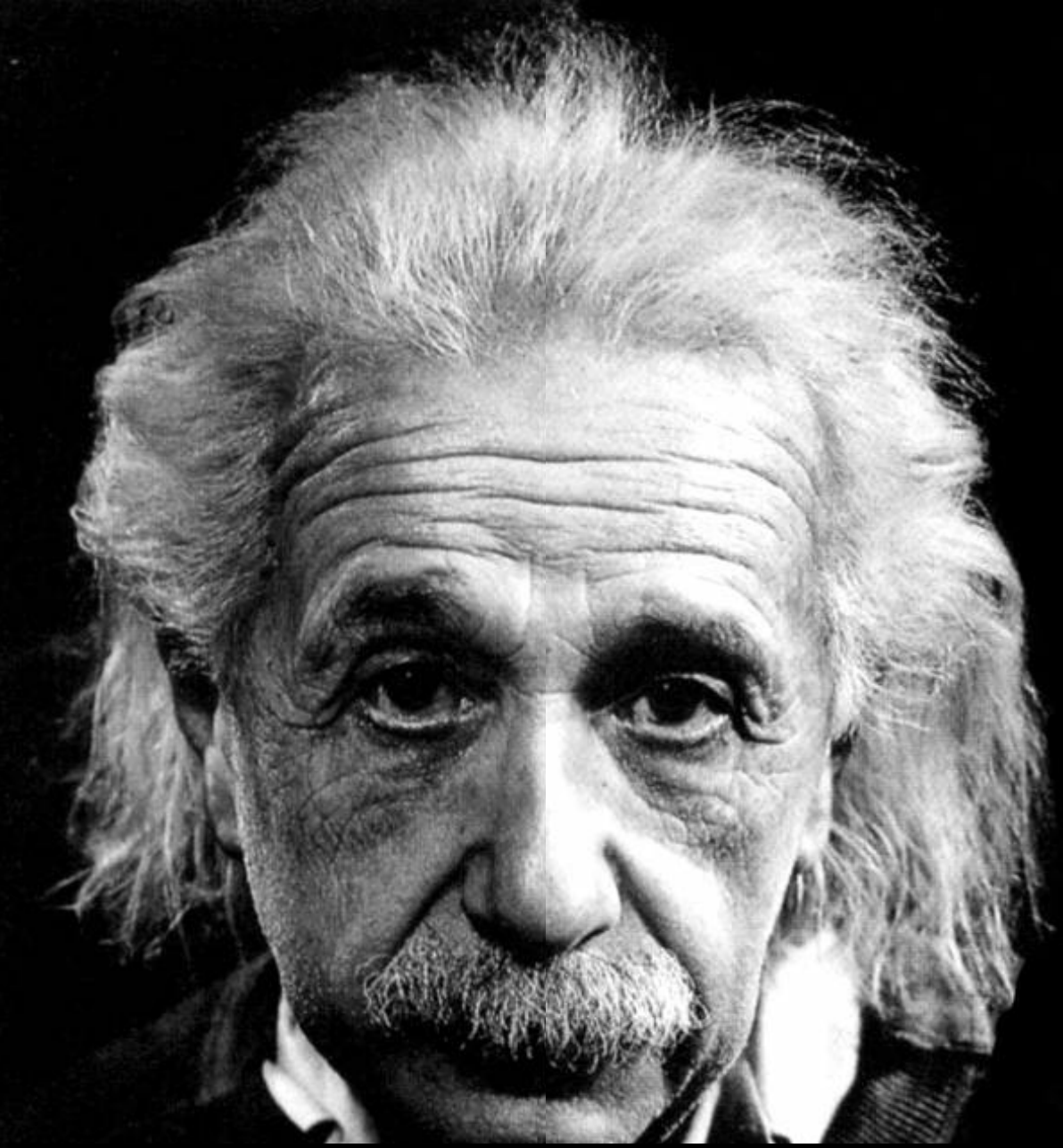
Matter

Elementary Particles





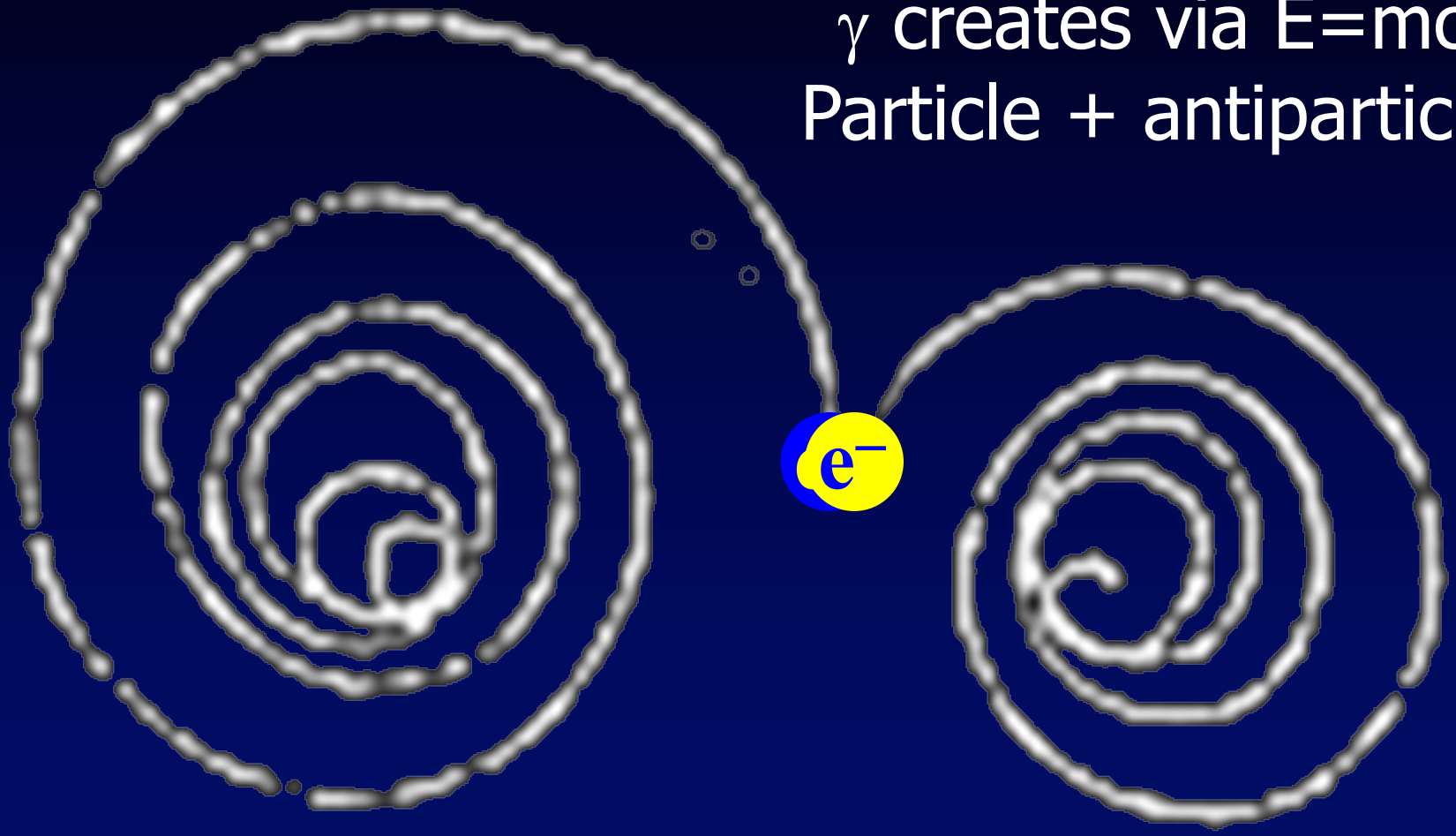
Energy= Matter + Antimatter

$$E=mc^2$$

Matter and antimatter particles go hand-in-hand

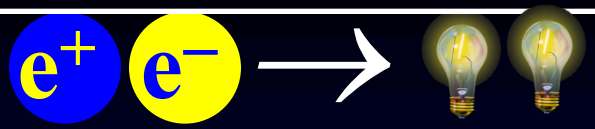
Creation: $\gamma \rightarrow e^+e^-$

γ creates via $E=mc^2$
Particle + antiparticle

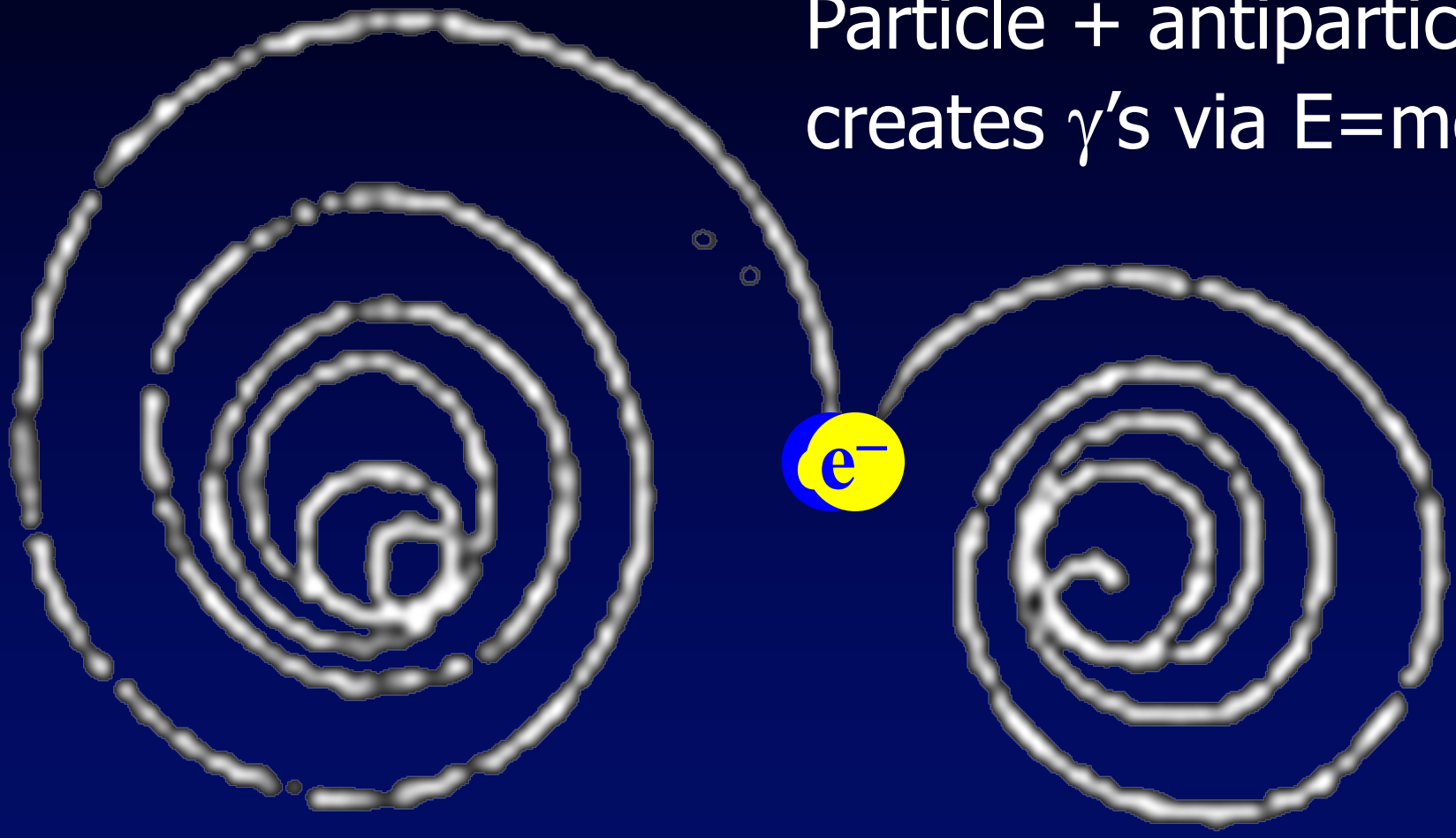


pure energy i.e. light (γ)

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

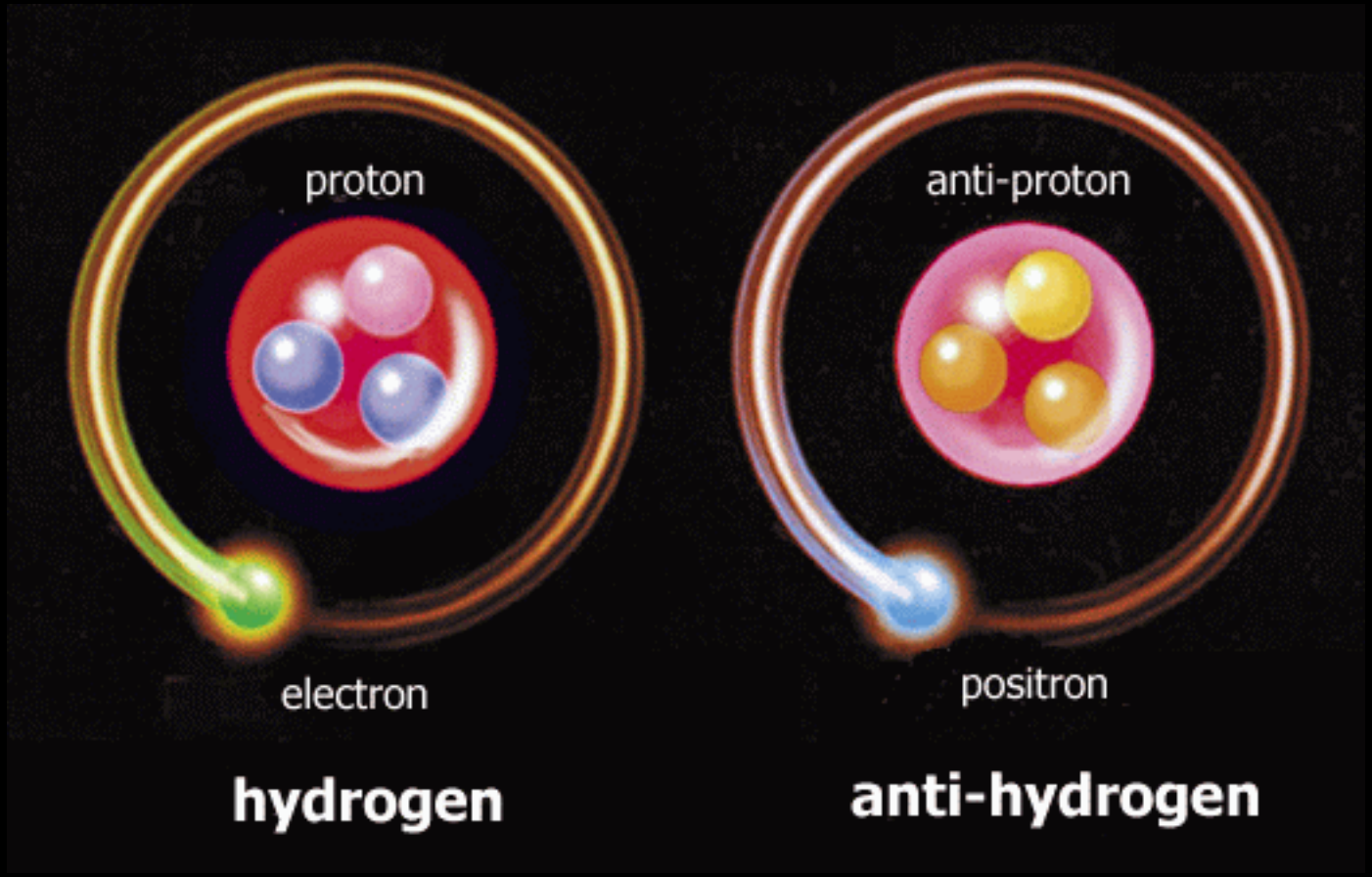


Particle + antiparticle creates γ's via $E=mc^2$

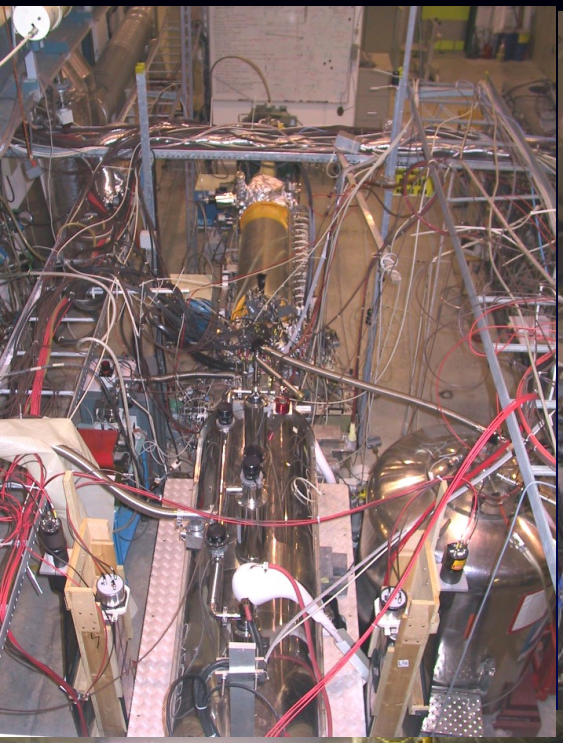


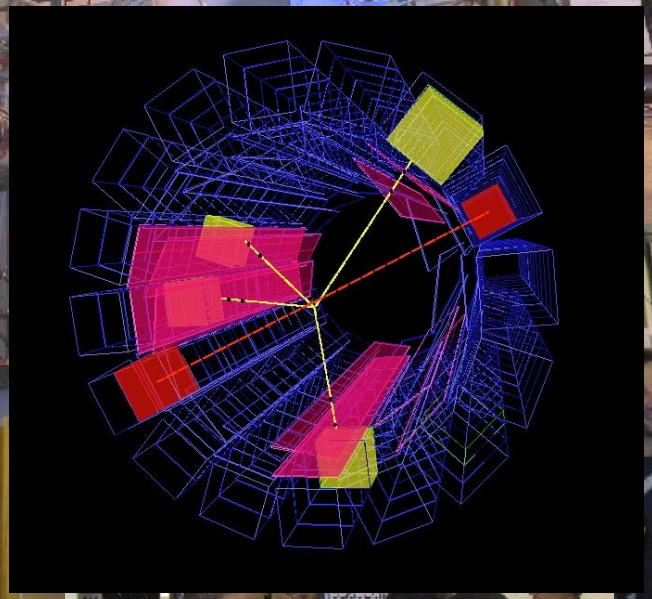
pure energy i.e. light (γ)

Anti-matter


proton
electron
hydrogen
anti-proton
positron
anti-hydrogen

The ATHENA experiment at CERN

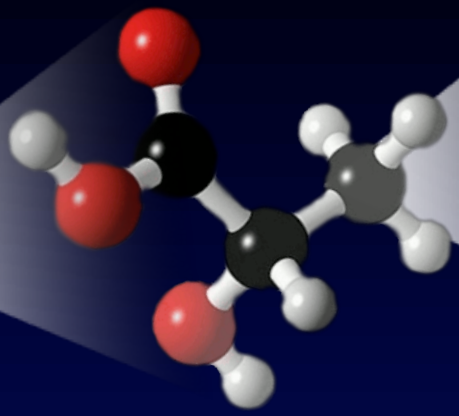




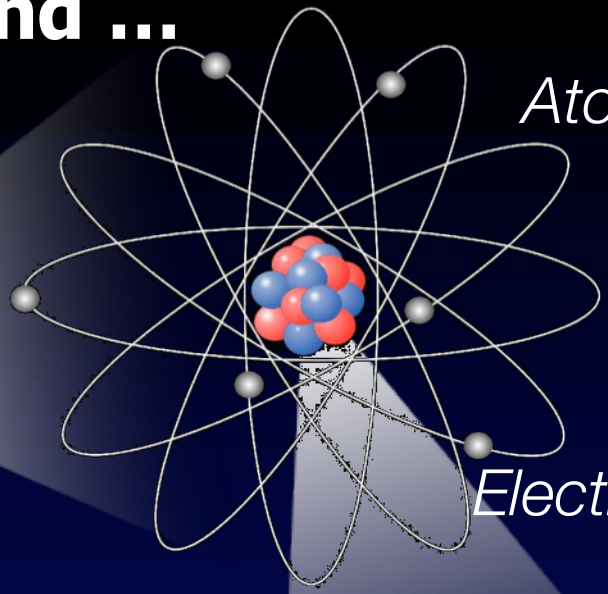
Antimatter does exist!

A world of matter and …

Molecule

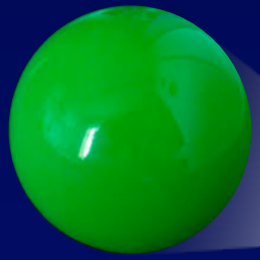


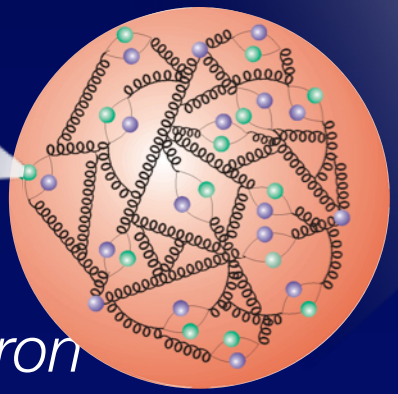
Atom



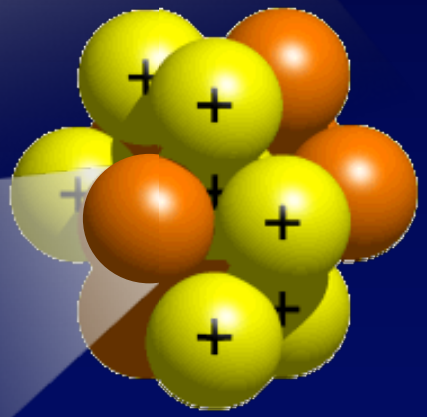
Electron

‘Quark’





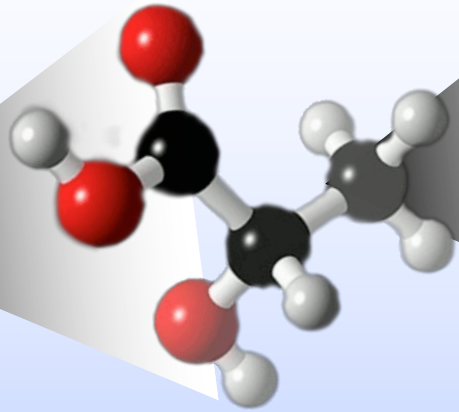
Proton/Neutron



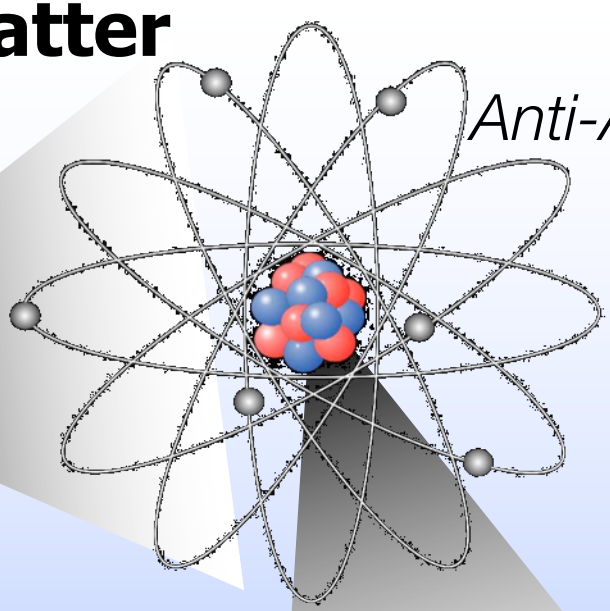
Atom-nucleus

… a world of antimatter

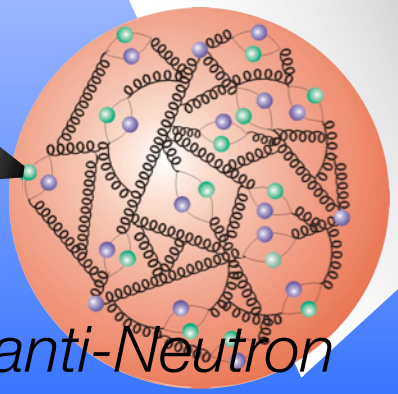
Anti-Molecule



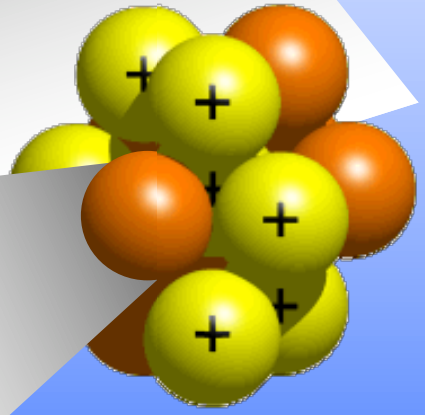
Anti-Atom



Anti-Quark



Anti-Proton/anti-Neutron



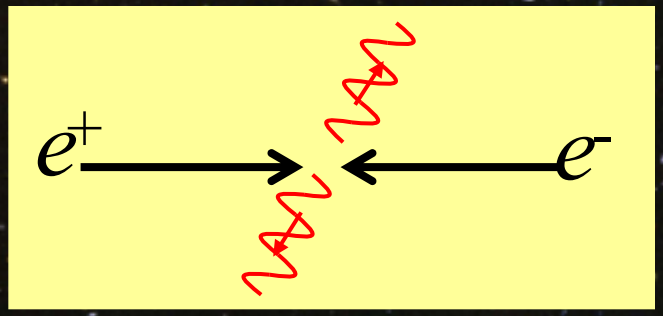
Anti-Atom-nucleus

Identical anti-world!

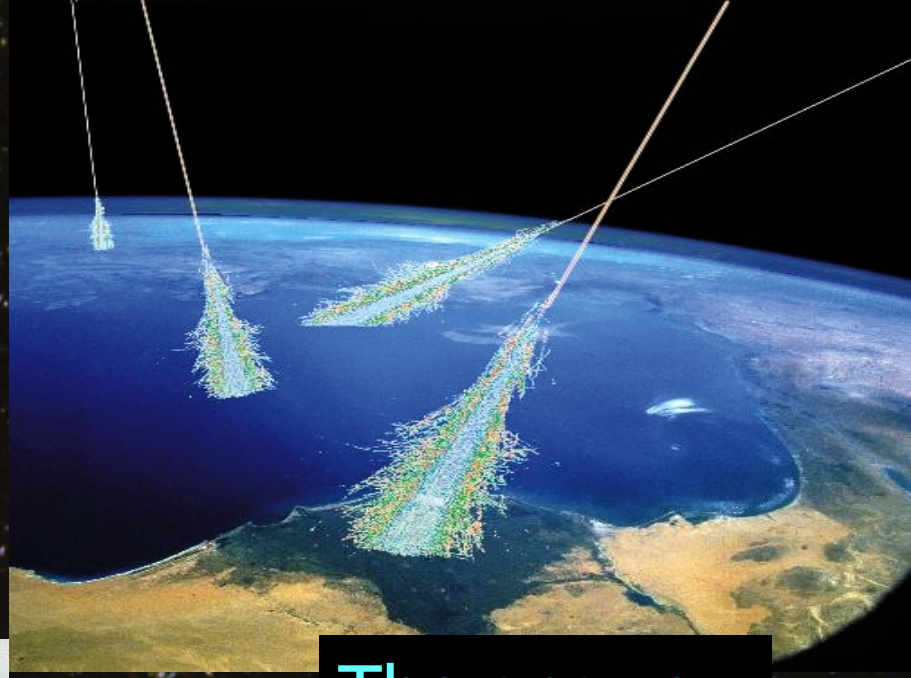
Is there antimatter in nature?

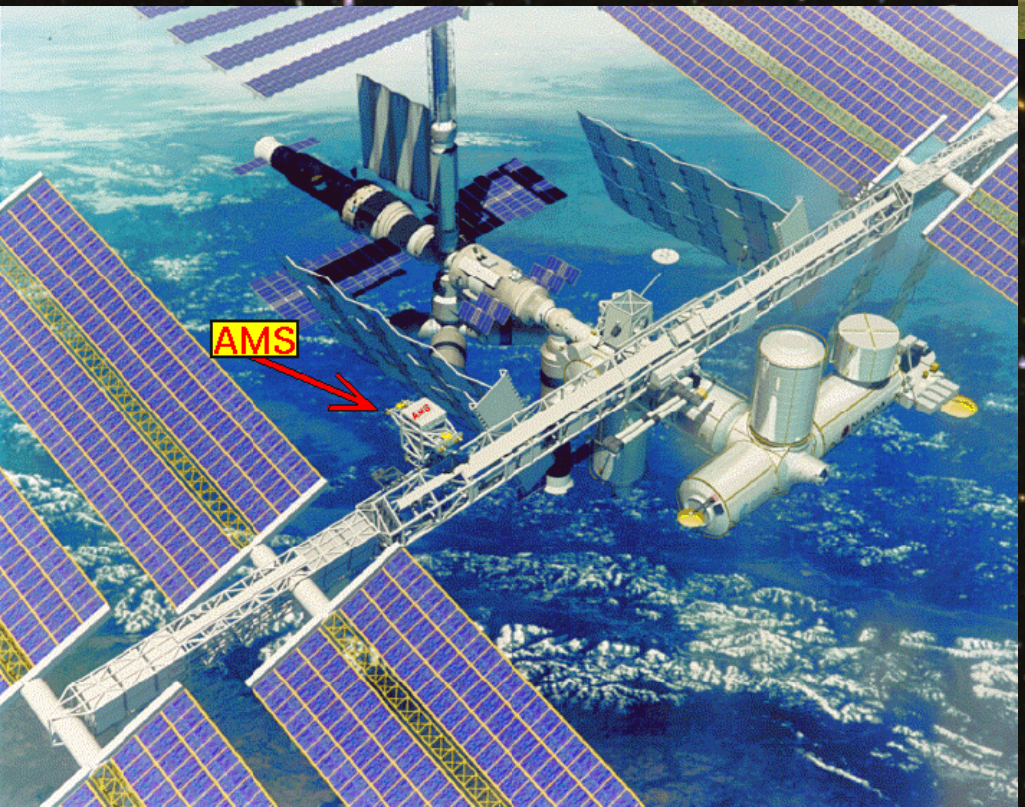
- Does it occur on earth?

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

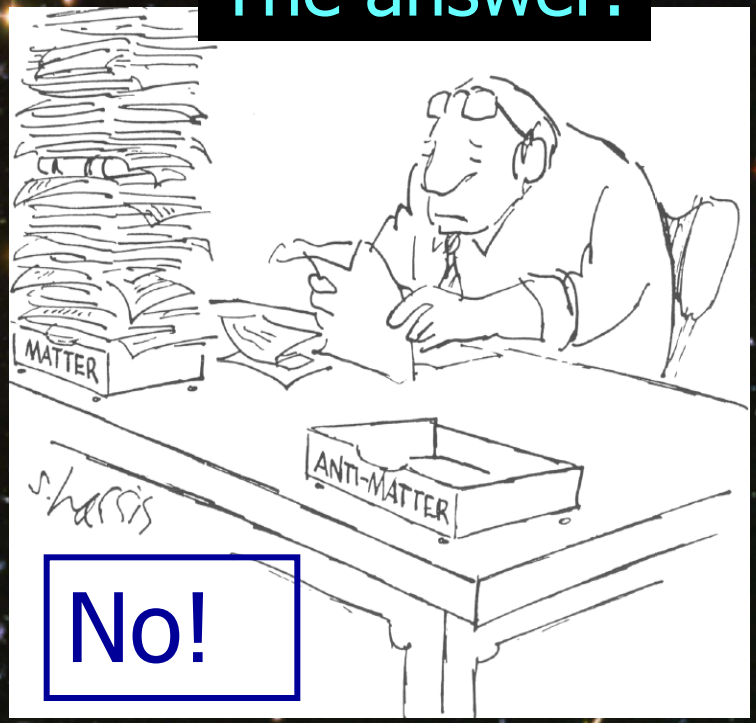


- Is there antimatter in cosmic radiation?
  - The AMS experiment





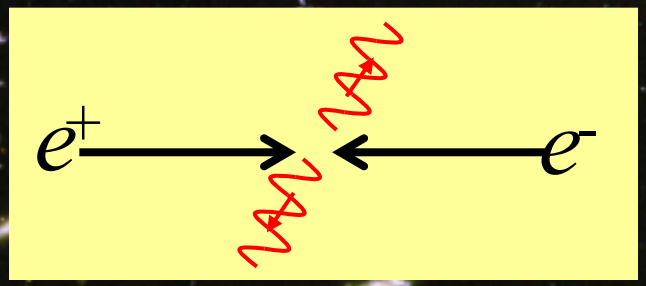
The answer:



No!

Are there antimatter galaxies?

No!



(matter + antimatter =
Intense gamma radiation)

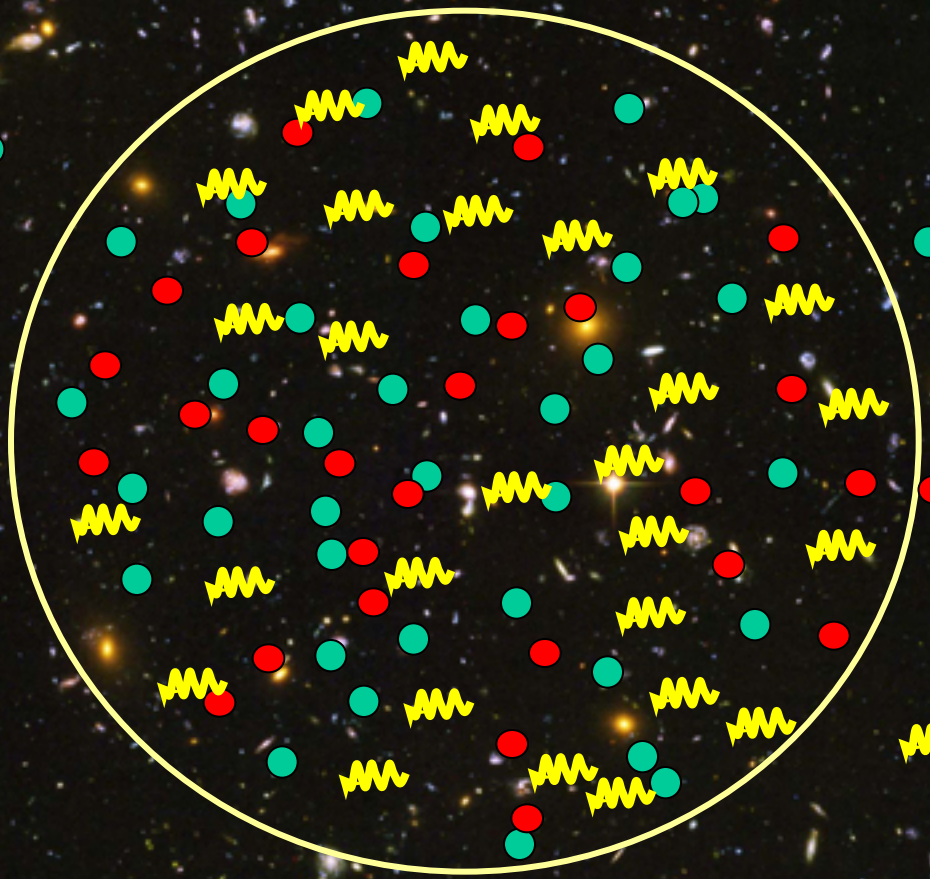

ANTIMATTER'S GONE MISSING...
WHEN DID THIS HAPPEN, SIR?
ABOUT 15 BILLION YEARS AGO...
LOST-PROPERTY OFFICE
CERN

Back to the Big-Bang

Assume: creates equal amount of matter and antimatter

The early hot universe

Time=0.00000000001 second



Imagine:

matter:

1000000001

antimatter:

1000000000

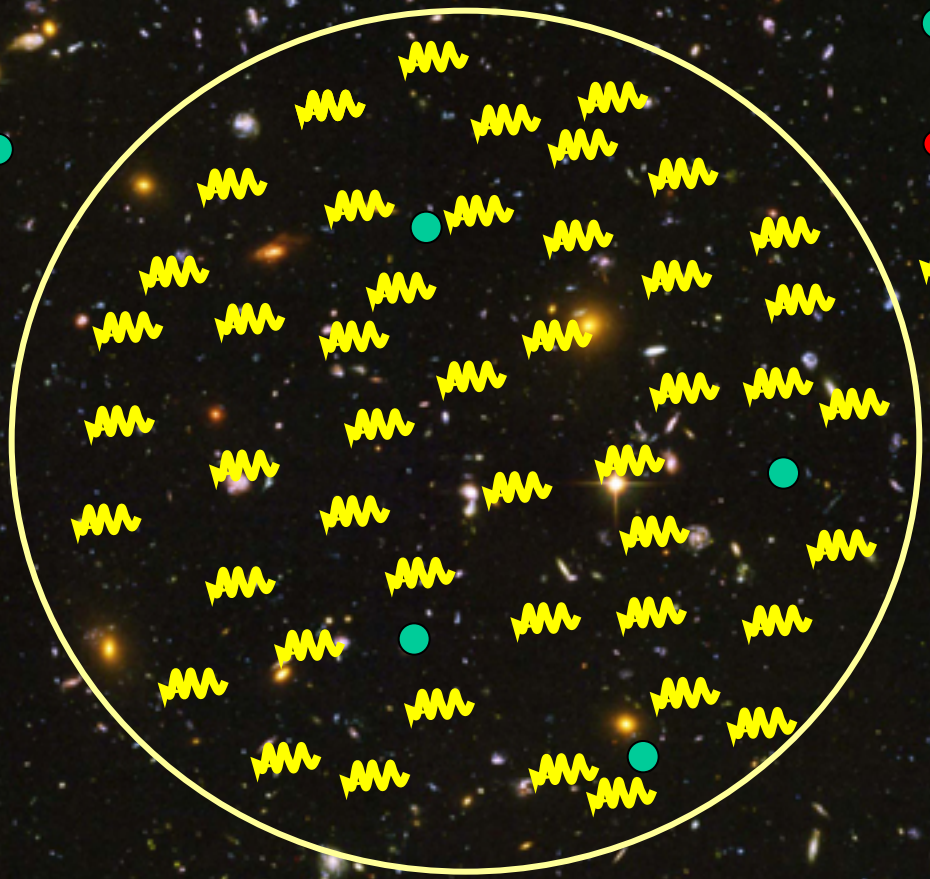
light

$(E=mc^2)$

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

The expanding & cooling universe

Time ~1 second



matter

antimatter

light

After cooling
and
annihilate

What remains: lots of light and a bit of matter

Ratio : 1000000000 1

The expanding & cooling universe

Time ~1 second

matter

antimatter

light

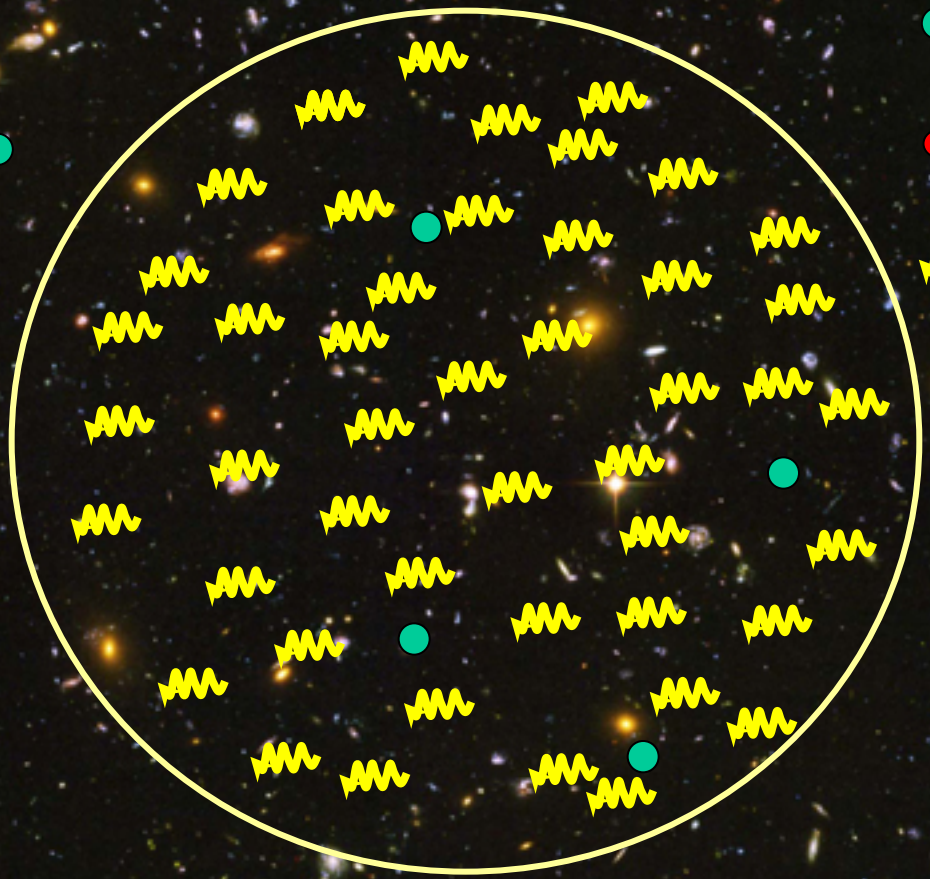
After cooling and annihilate

What remains: lots of light and a bit of matter

Ratio : 1000000000 1

The expanding & cooling universe

Time ~1 second



matter

antimatter

light

After cooling

and

annihilate

What remains: lots of light and a bit of matter

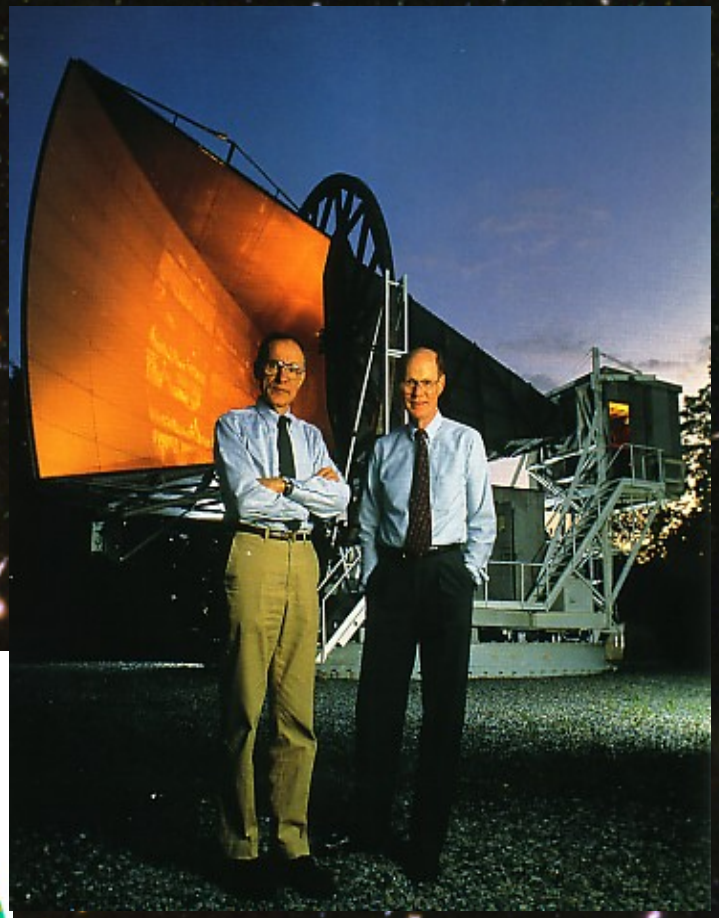
Ratio : 1000000000 1

→ Our current universe….

Cosmic Microwave Background Radiation

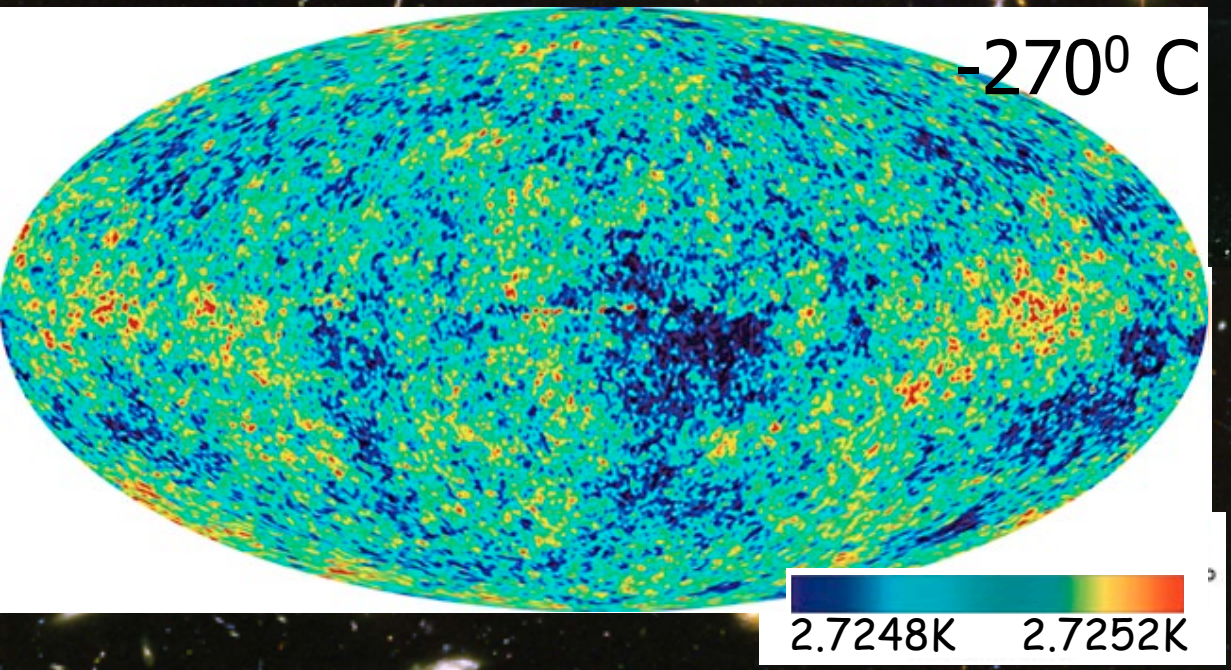
1964: Penzias en Wilson discover: "background light" (photons)

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

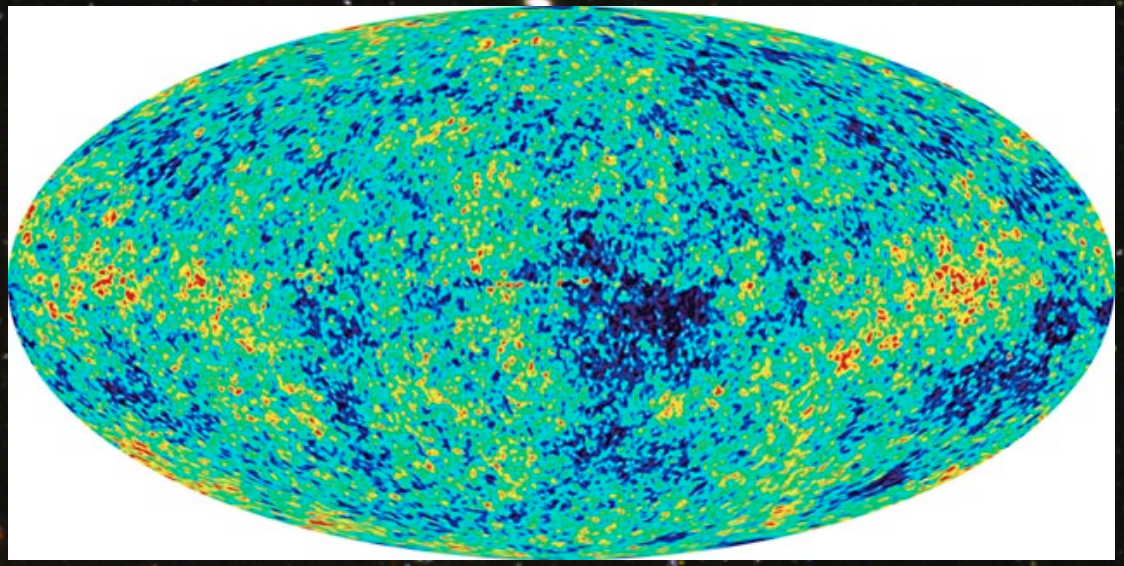
- Observed Background light:

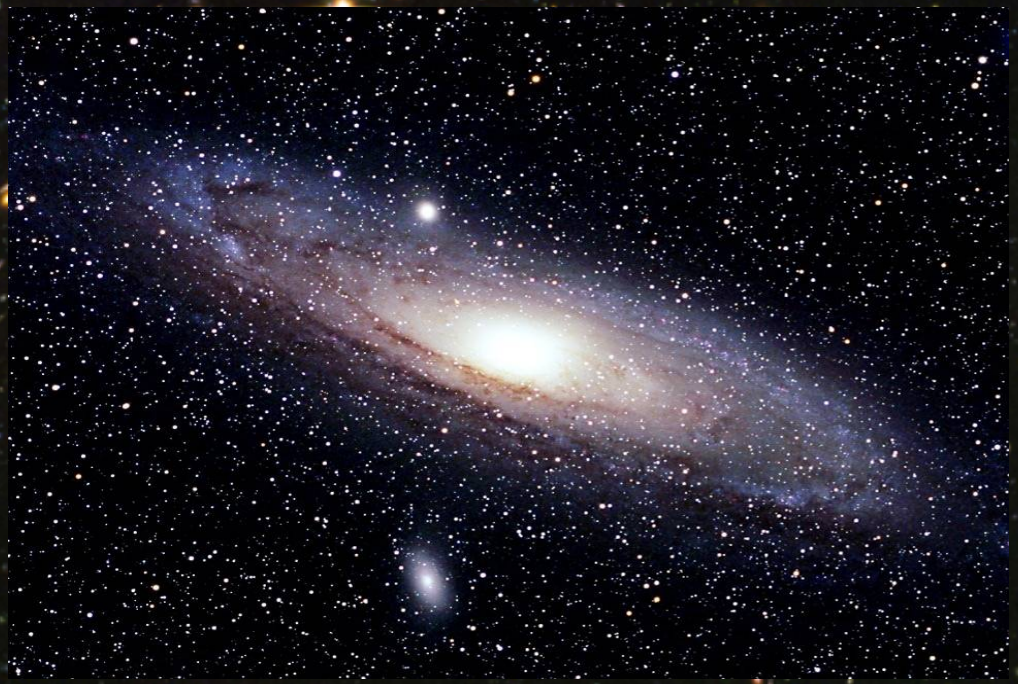
  "many"
  (1000000000)

  +

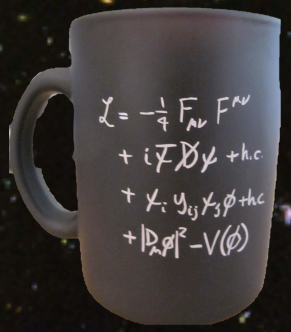
- Remaining Matter particles:

  "little"
  (1)





How to get an asymmetry in Big Bang?



Big Bang

Small surplus

Dominates

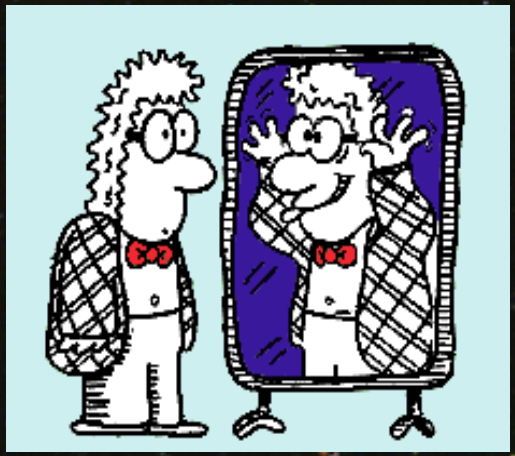
49.999999% anti-materie

50.000001% materie

0.000001% materie

(+99.999999% radiation)

Apparenty anti-matter is **not** the exact mirror image of matter!



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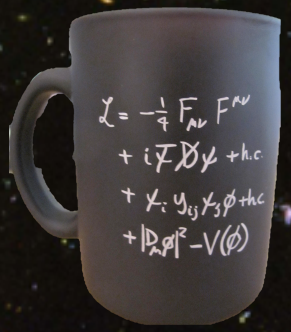
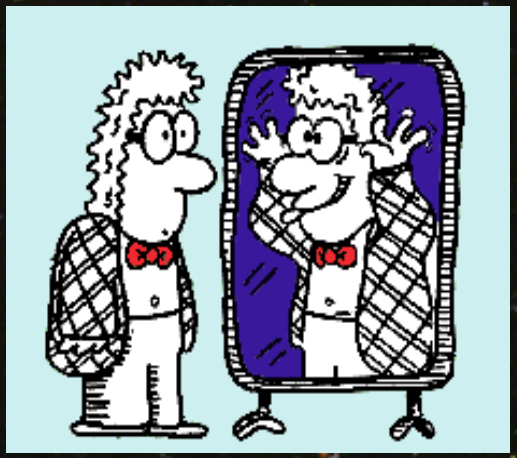


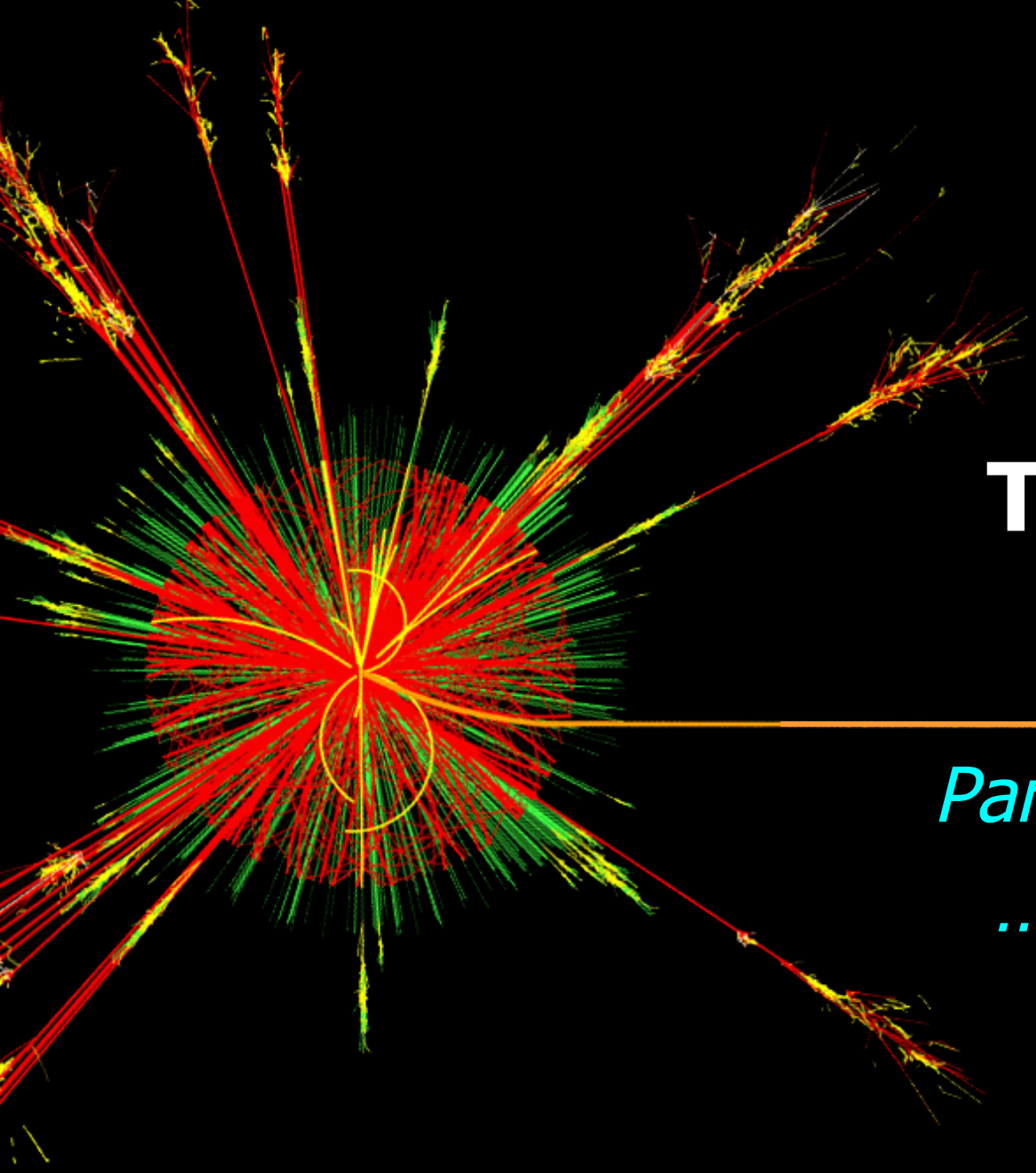
Dominates

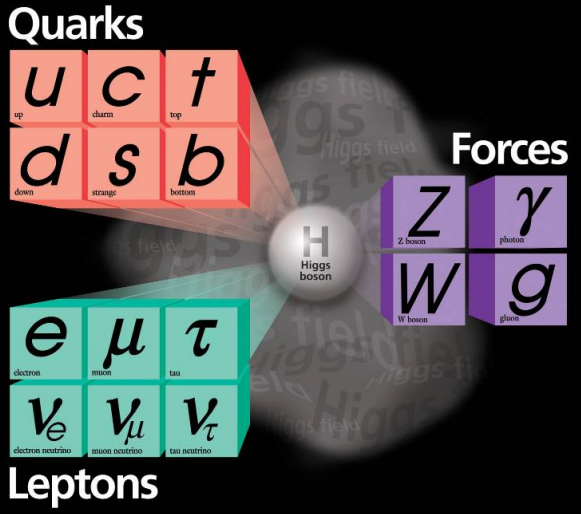
0.000001% materie

(+99.999999% radiation)

Apparenty anti-matter is **not** the exact mirror image of matter!

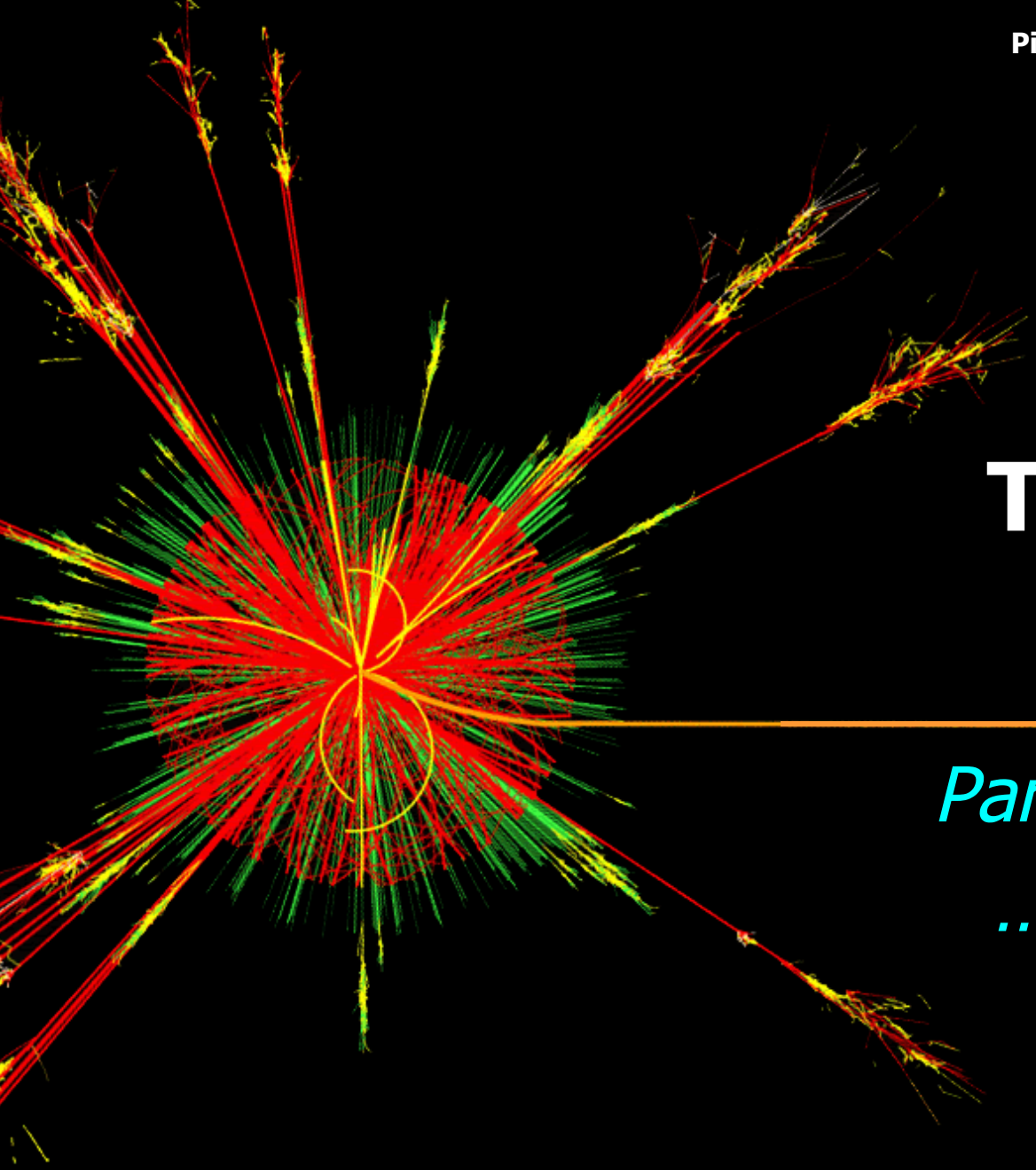






The Standard Model

Particles, Forces and … the Higgs Boson



Piele (Giel) Hameleers: also standard model?

The Standard Model

Particles, Forces and … the Higgs Boson

Elementary Particles

Generation:	I	II	III	Charge	Charge	I	II	III
quarks	u	c	t	+2/3 e	-2/3 e	$\bar{u}$	$\bar{c}$	$\bar{t}$
	d	s	b	-1/3 e	+1/3 e	$\bar{d}$	$\bar{s}$	$\bar{b}$
leptons	e	μ	τ	-1 e	+1 e	$\bar{e}$	$\bar{\mu}$	$\bar{\tau}$
	ν_e	ν_μ	ν_τ	0 e	0 e	$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$

Matter

3 Generations!

Antimatter

Four fundamental forces of Nature

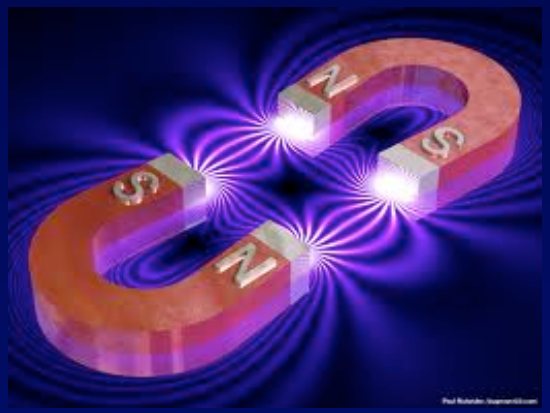
Gravitation

Acts on particles with mass

Strong Nuclear force

Acts on nuclear particles

Electromagnetism

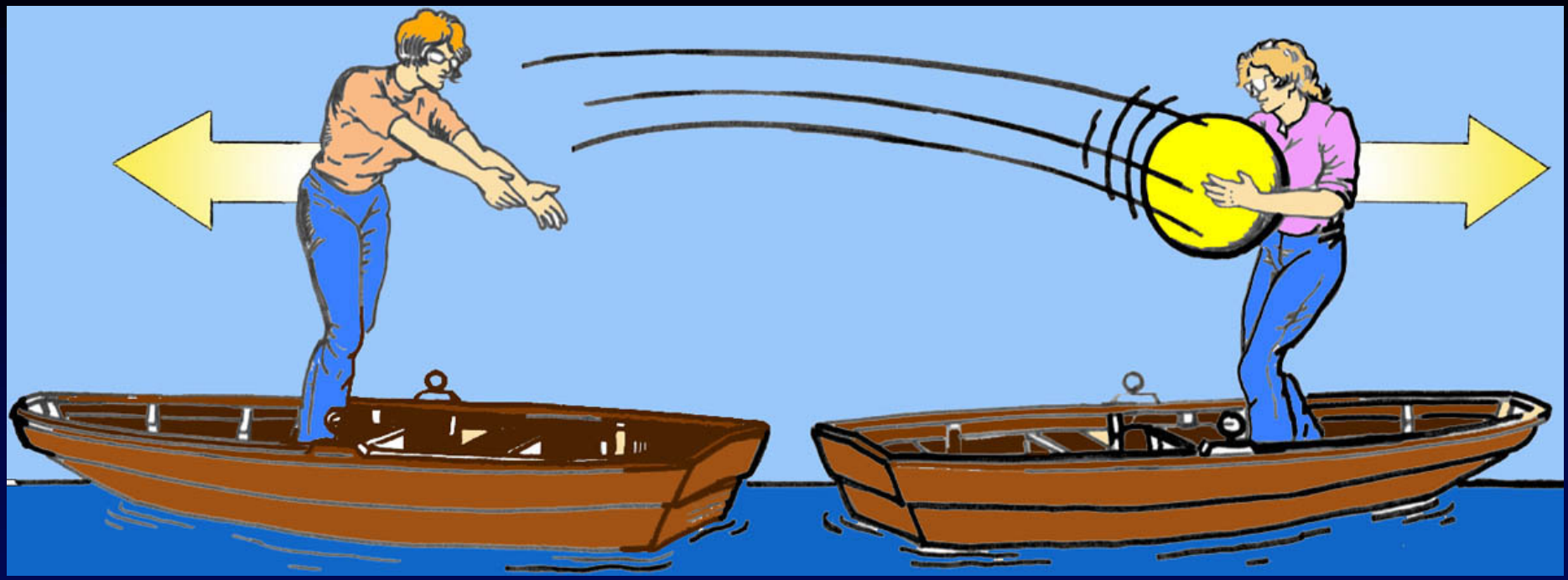


Acts on all charged particles

Weak Nuclear force

Acts on all particles

Force = quantum exchange!

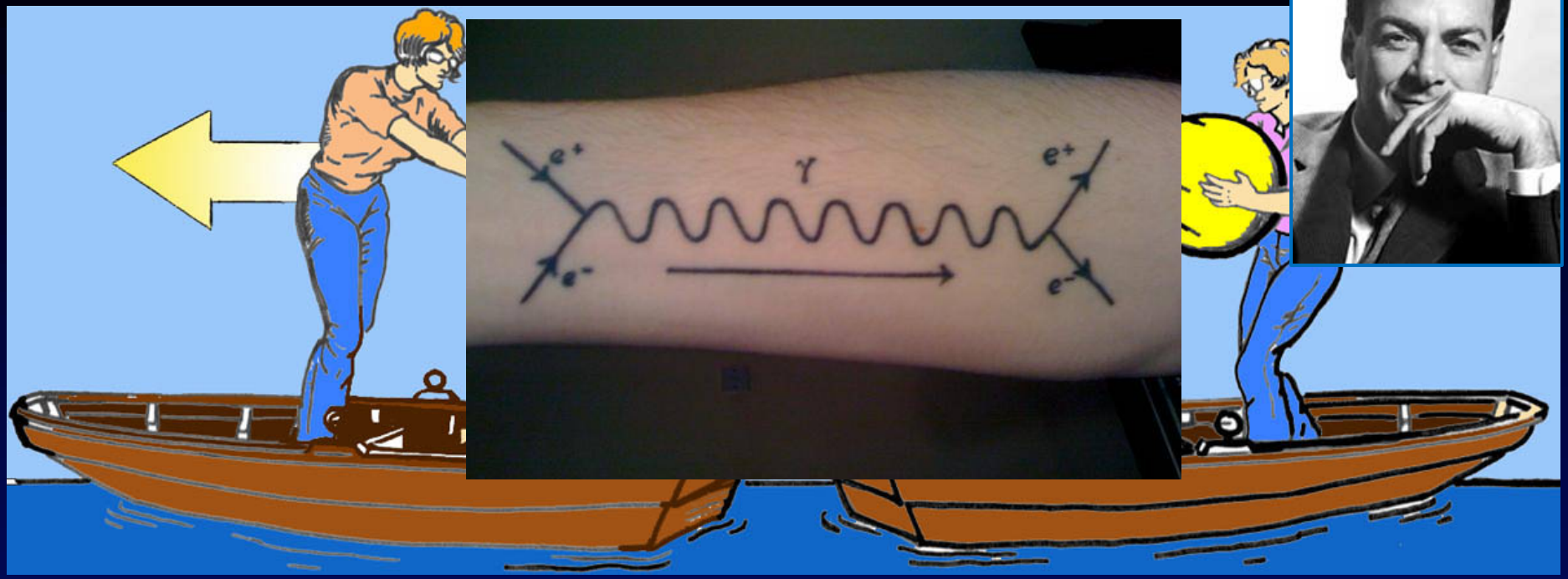


What is exchanged is a "quantum" ➔ Quantum Mechanics

1) Electromagnetism: Photon **γ**
2) Strong nuclear force: gluon
3) Weak nuclear force: W^+, W^-, Z^0
4) Gravitation: graviton ??

The quantum of gravitation is hypothetical.

Force = quantum exchange!



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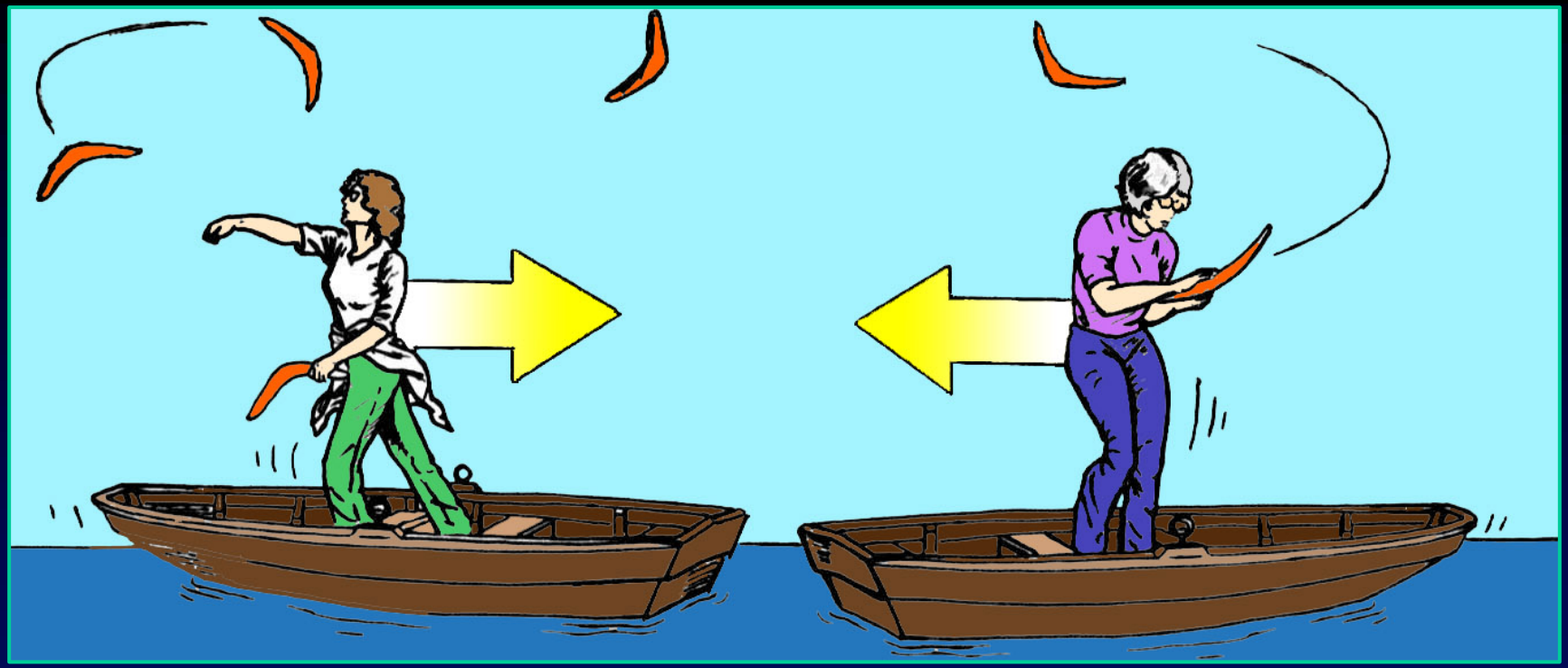

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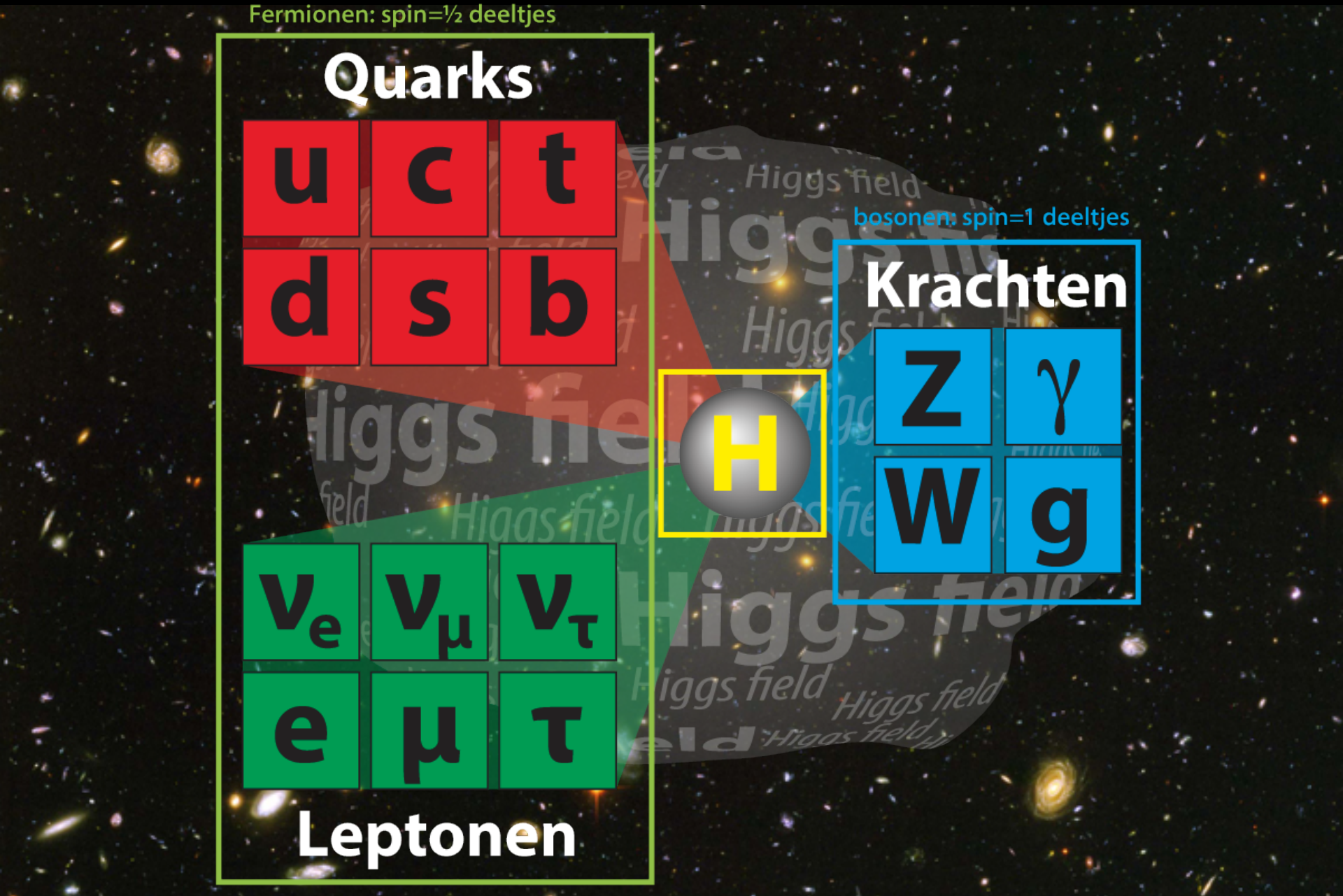
The quantum of gravitation is hypothetical.

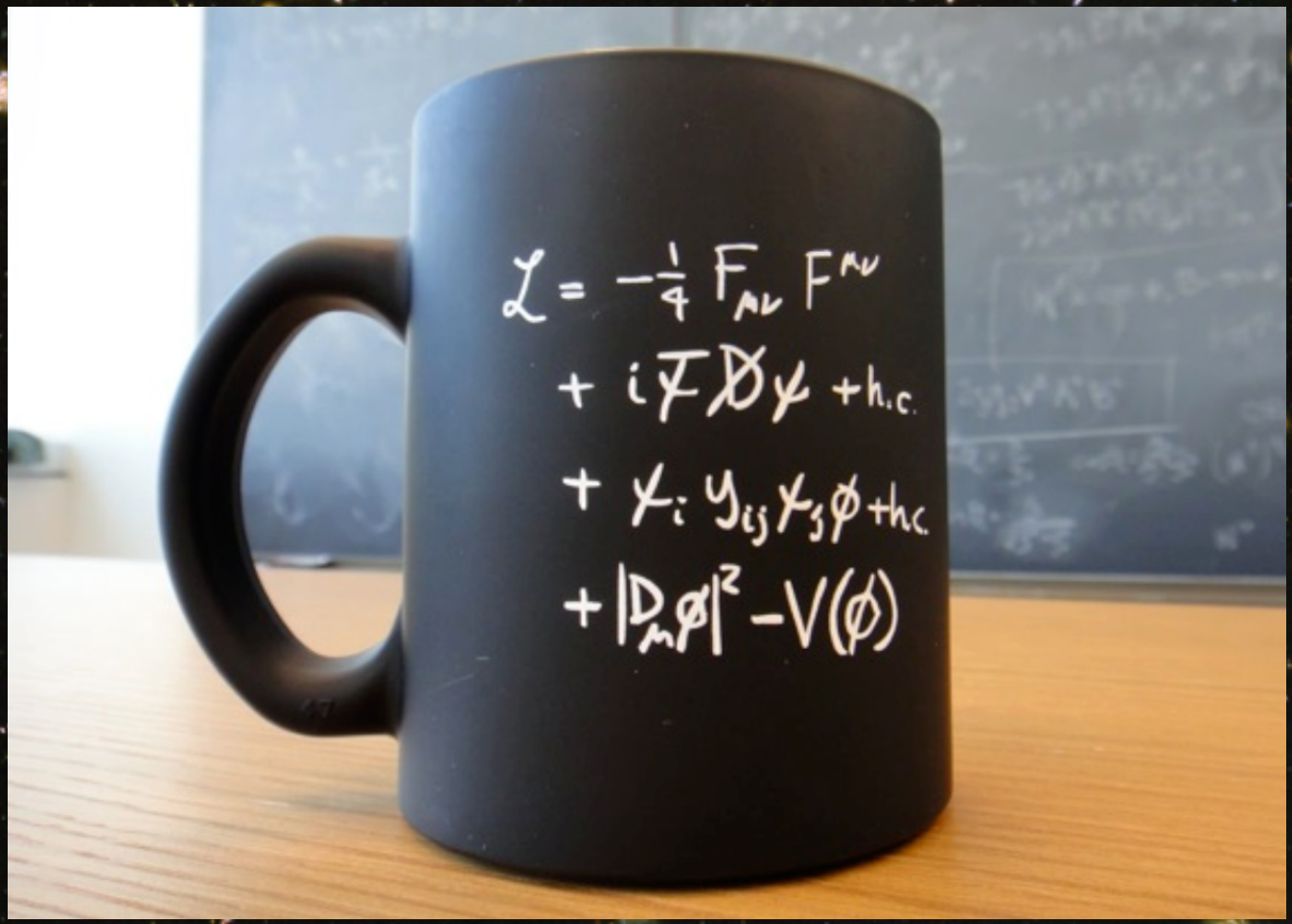
How strong are the forces?

	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

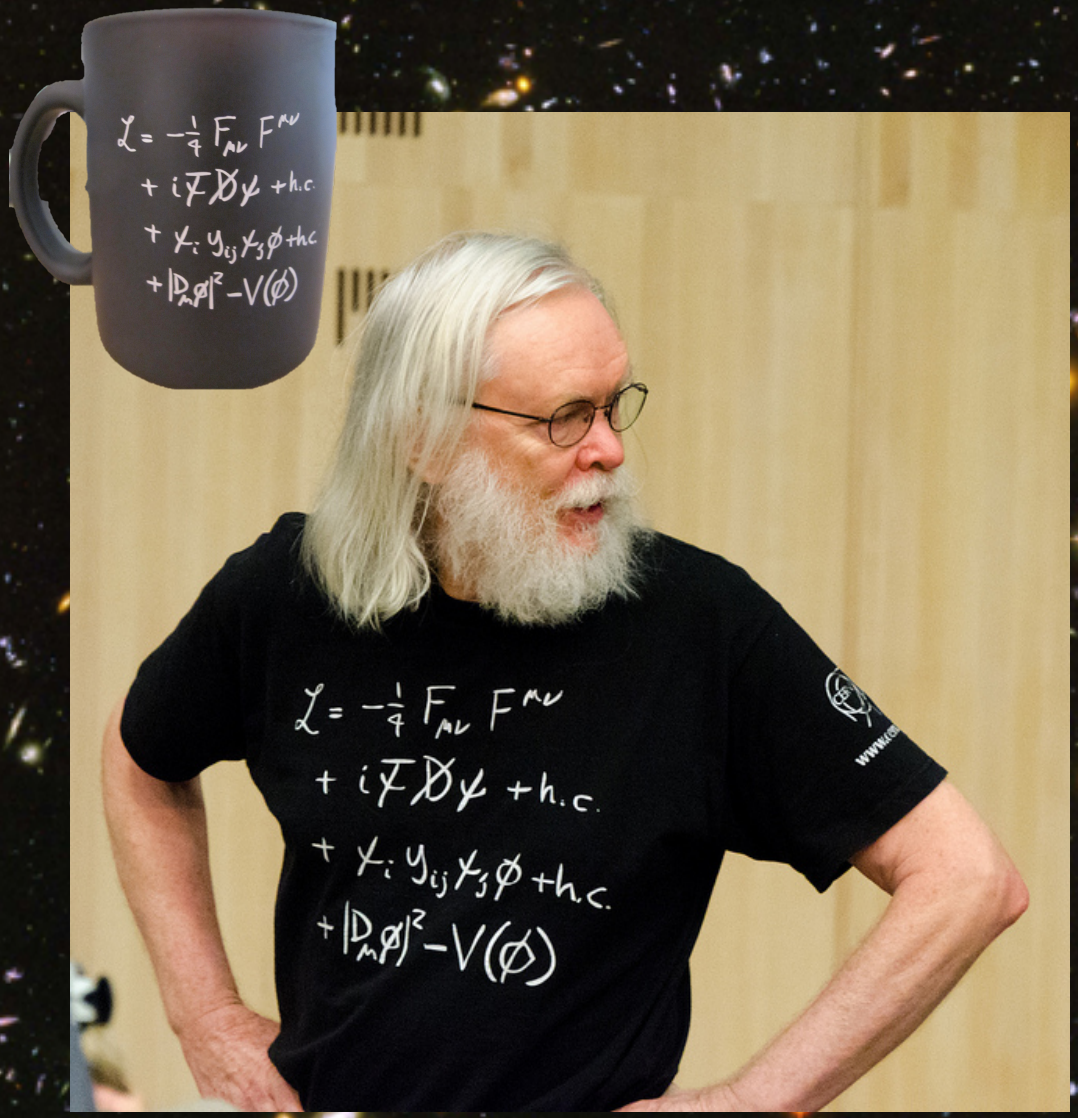
Particles, Forces and Higgs



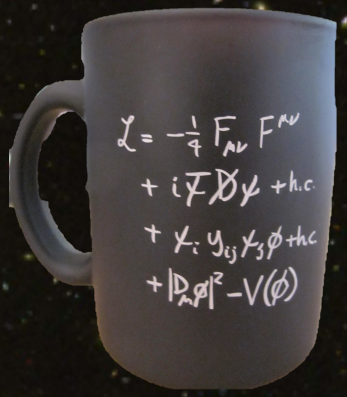
Theory: the Standard Model



The Standard Model



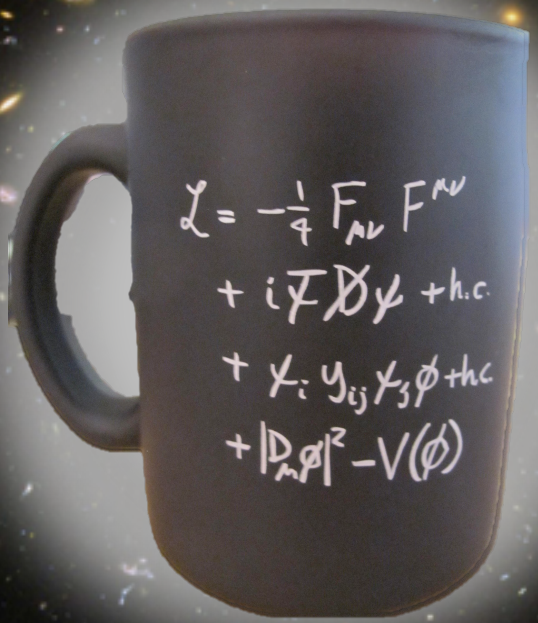
$$
\begin{aligned}
&-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^b_\nu g^b_\mu g^c_\nu - \tfrac{1}{4} g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
&\tfrac{1}{2} i g_s^2 (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s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


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

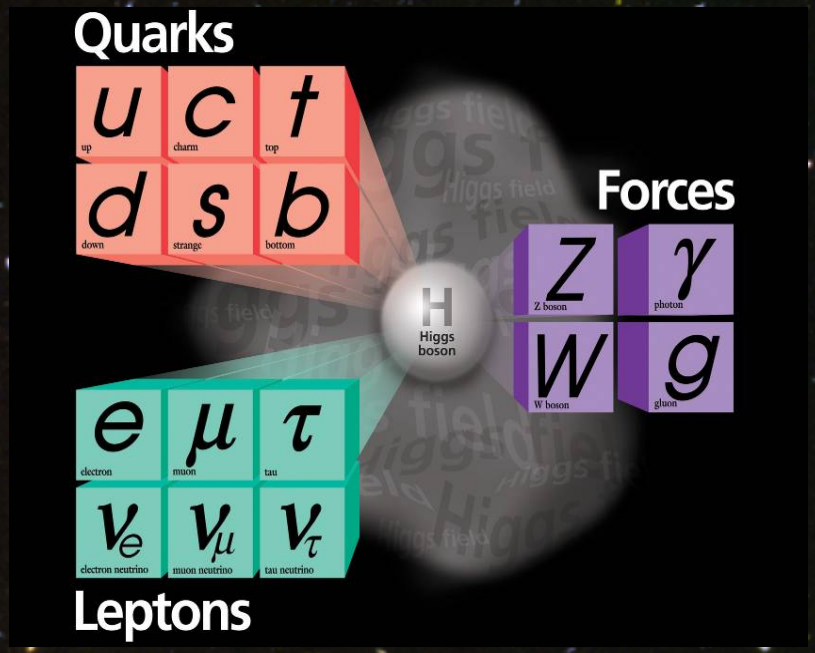
"WOW."

The Standard Model

"The Formula"



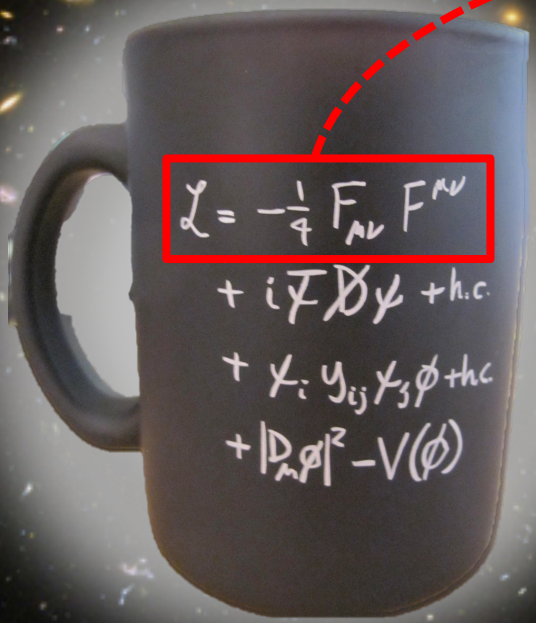
"Elementary quanta of Nature"

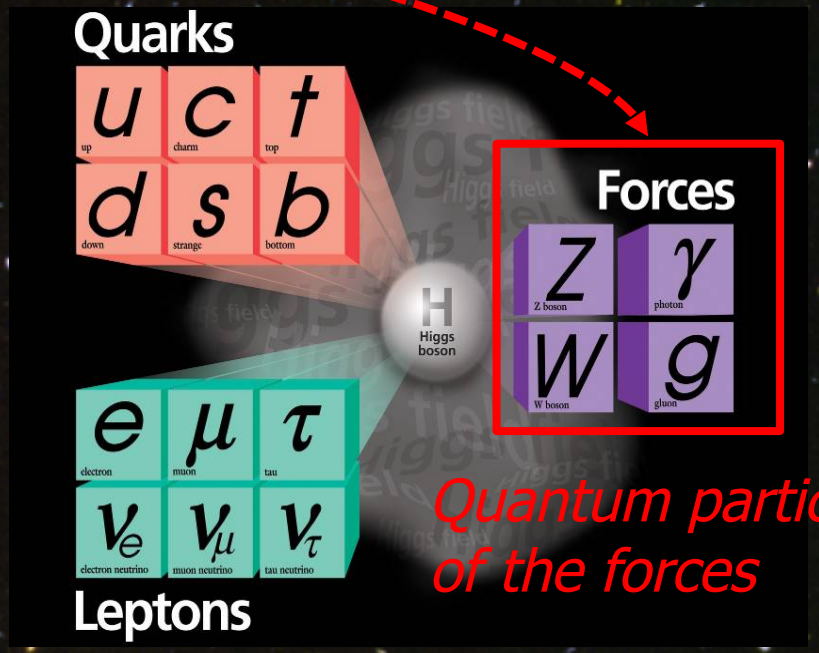


The Standard Model

"The Formula"

"Elementary quanta of Nature"

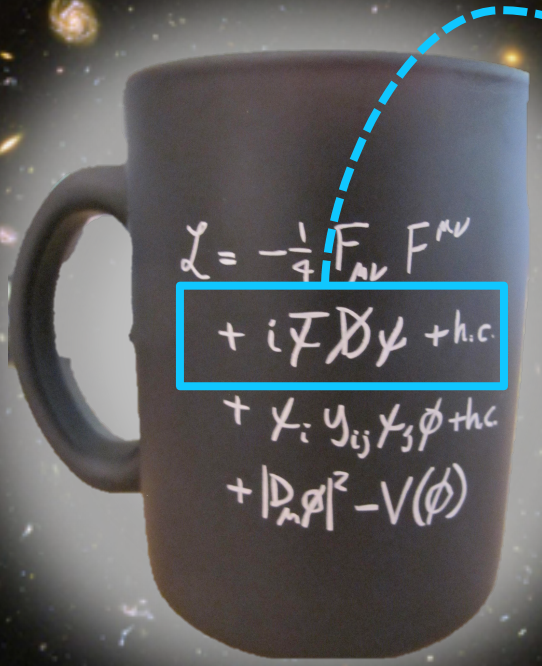


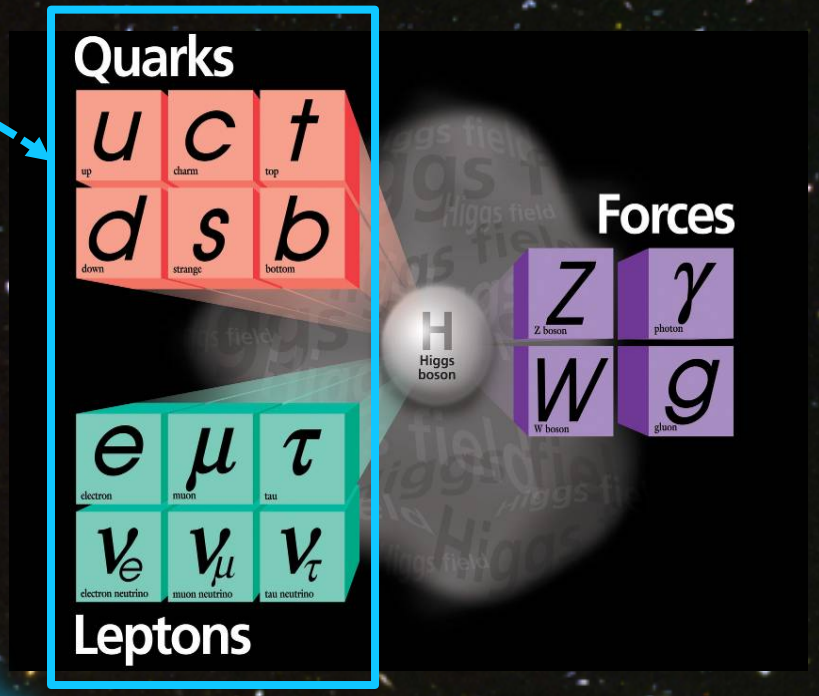


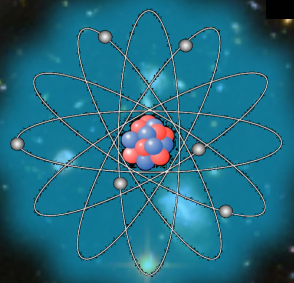
The Standard Model

"The Formula"

"Elementary quanta of Nature"





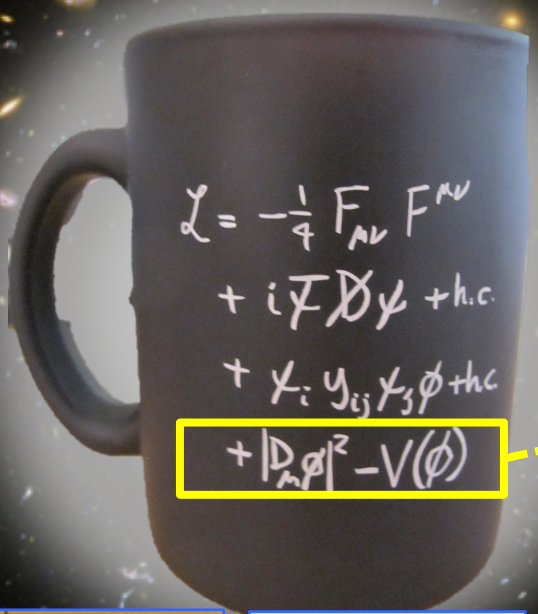


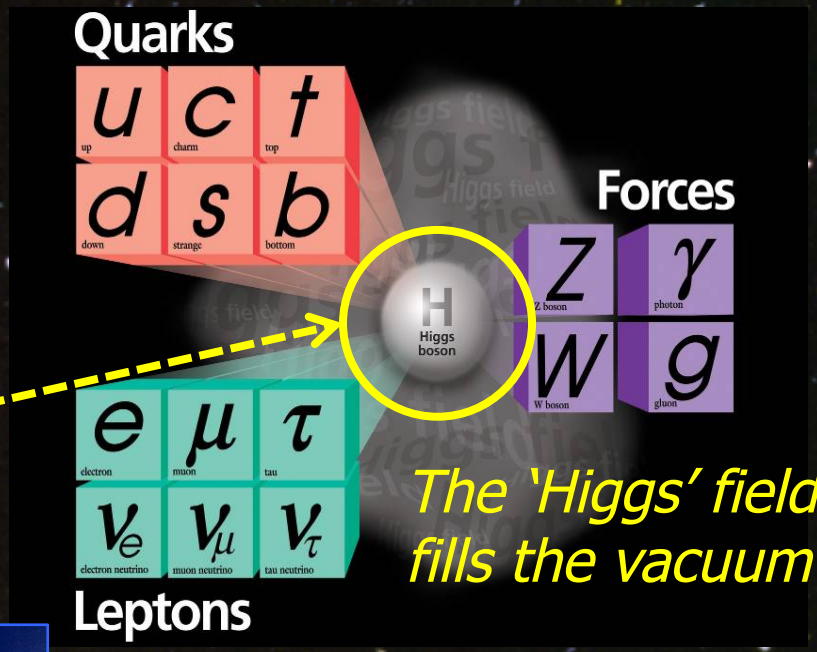
Building blocks of matter

The Standard Model

"The Formula"

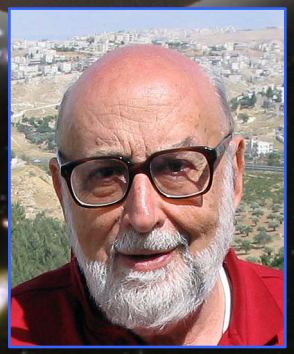
"Elementary quanta of Nature"





The 'Higgs' field fills the vacuum

Brout



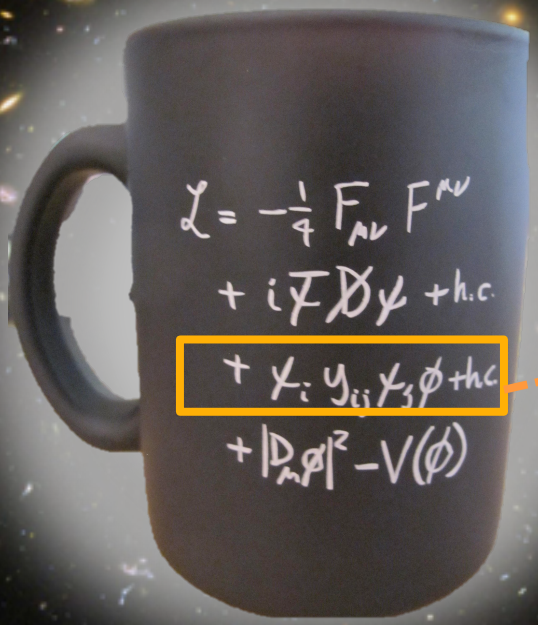
Englert

Higgs

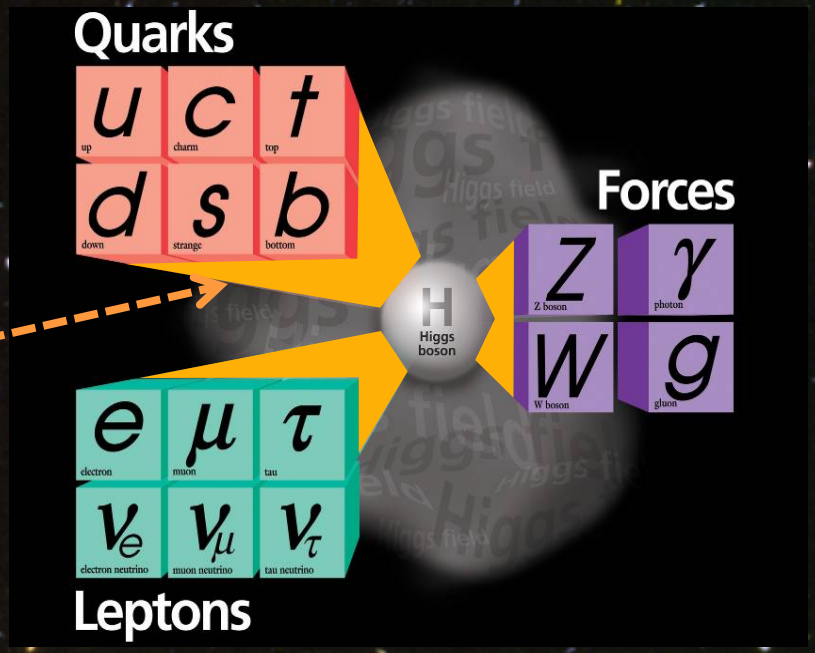
1964:
Standard Model prediction:
empty space is not empty!

The Standard Model

"The Formula"



"Elementary quanta of Nature"

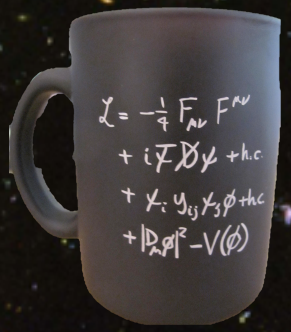


Mass is generated by the Higgs Field!

Kobayashi ***Maskawa***

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

How did antimatter disappear in the Big Bang?



Small Surplus

49.999999% anti-matter

50.000001% matter

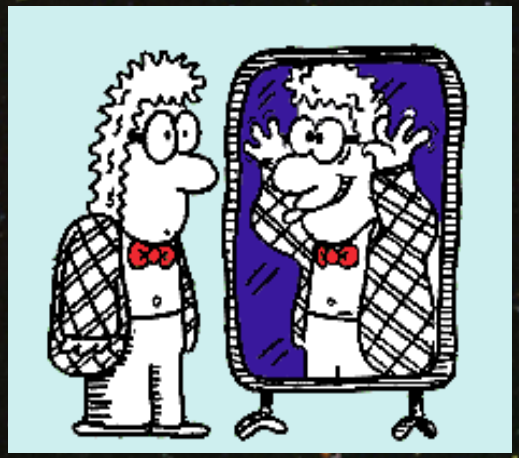
Dominates

0.000001% matter

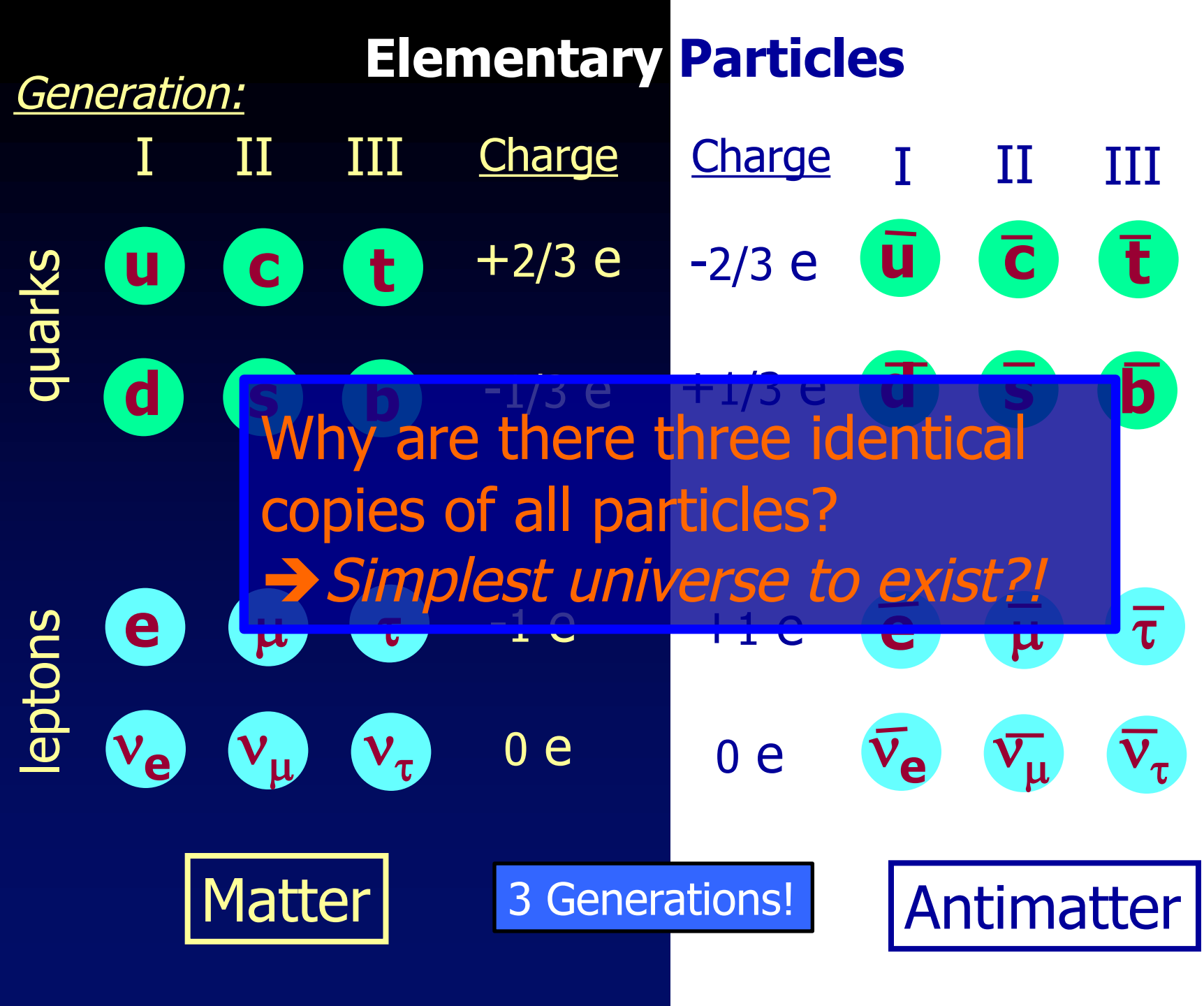
(+99.999999% radiation)

Antimatter no the exact mirror image of matter!

Theoretically this requires three copies of all particles!



Elementary Particles




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

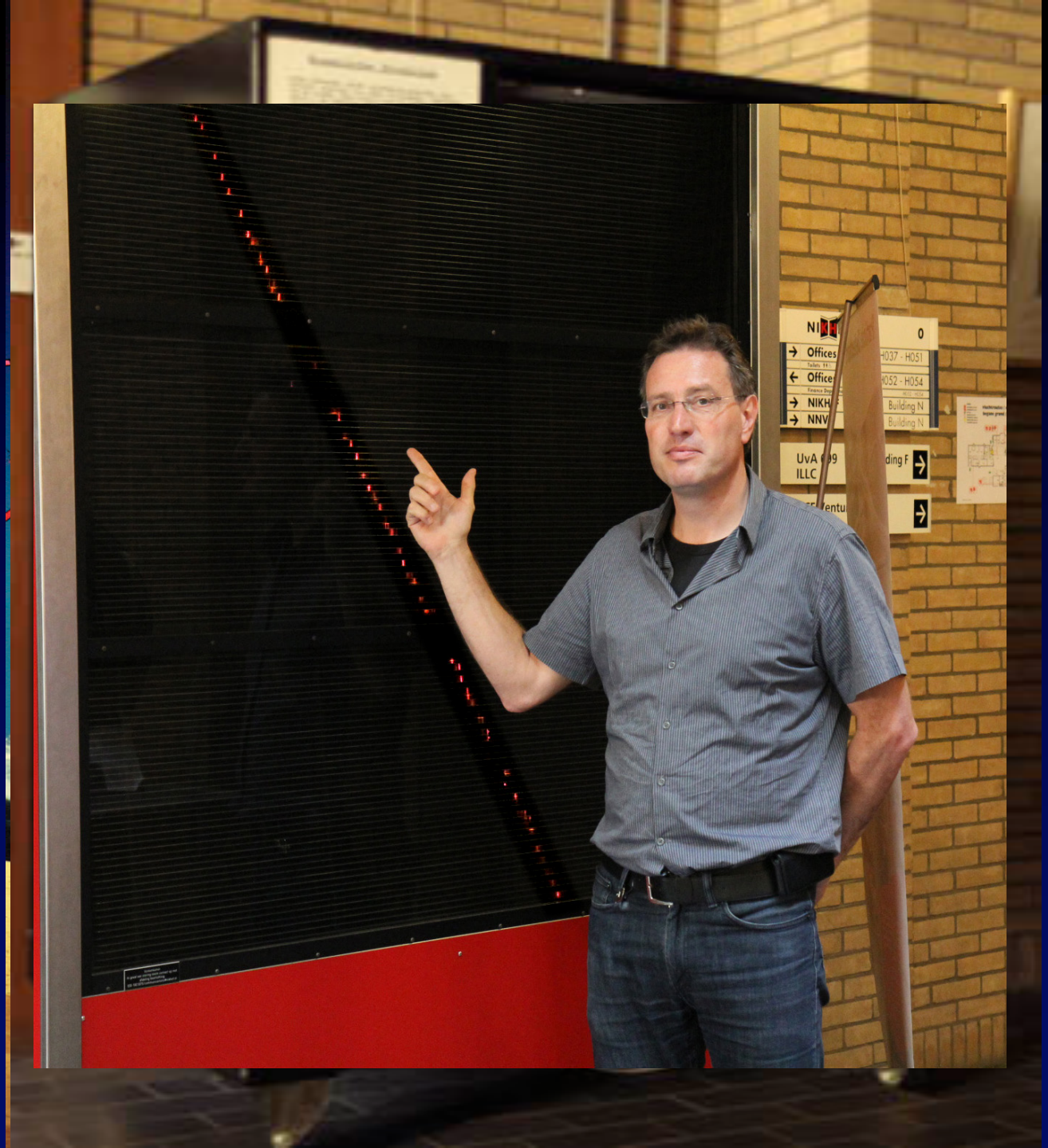

"KOFFIE!"

X-tra slides

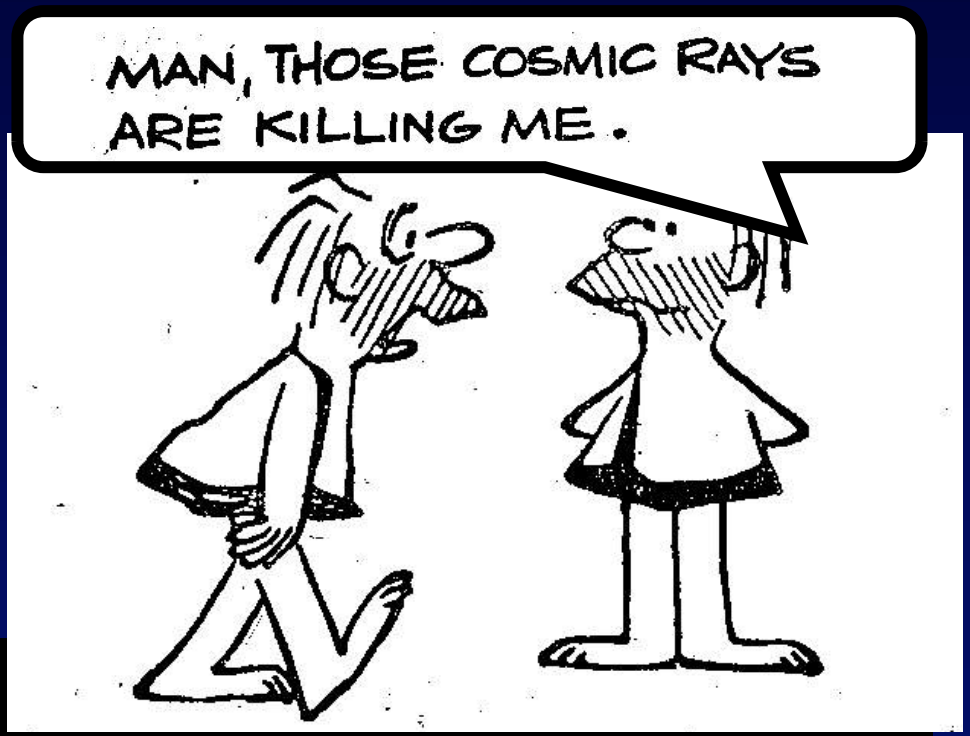
Cosmic Radiation (1909)

1912 Victor Hess

Copy electron: Muon (1936)



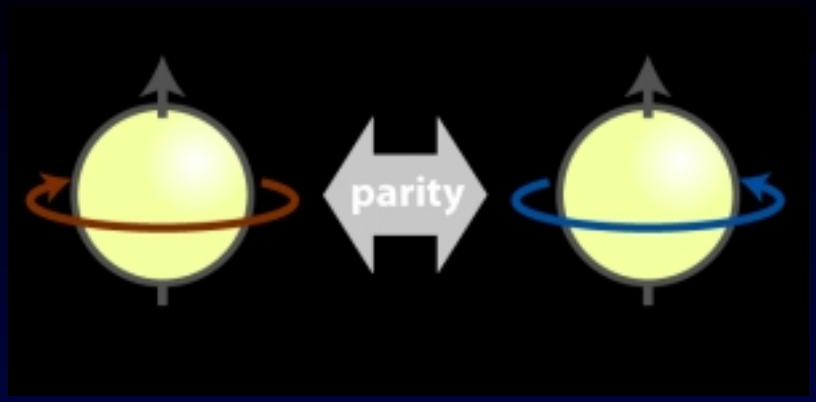
Cosmic muons
Made visible in
The Nikhef hall



Slept well?

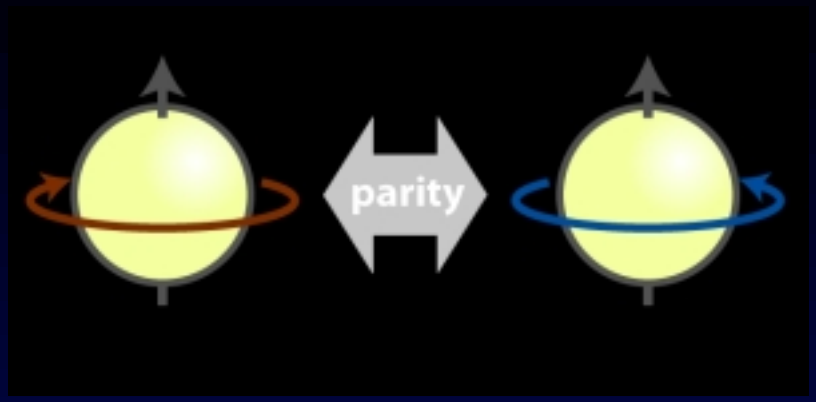
Each night a million muons through your body!

The weak interaction is left-handed



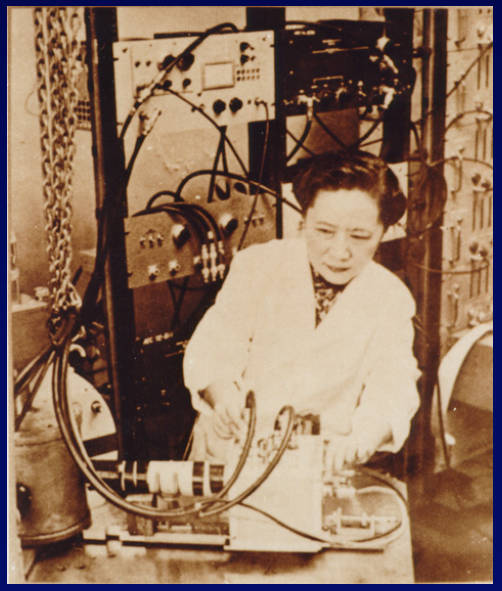
- Parity: Right-handed vs Left-handed

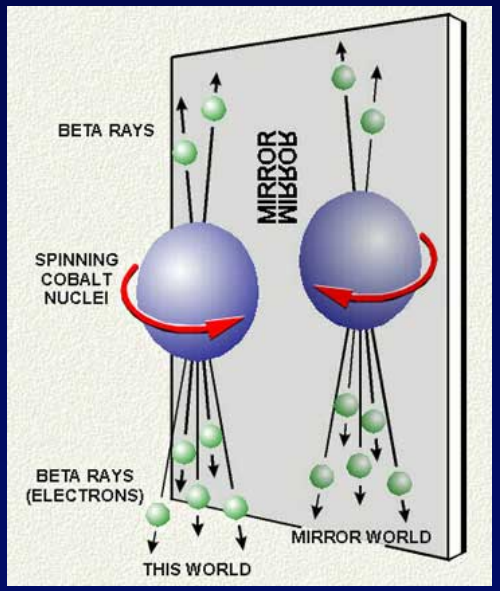
The weak interaction is left-handed

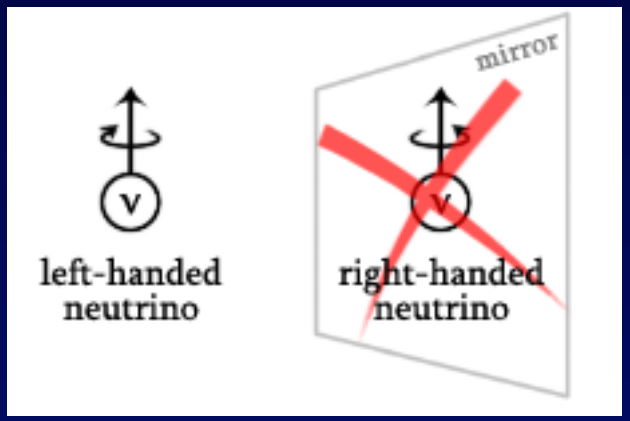


- Parity: Right-handed vs Left-handed

- The Experiment of Mme Wu
  - Radioactive decay: n→p e ν is purely left-handed





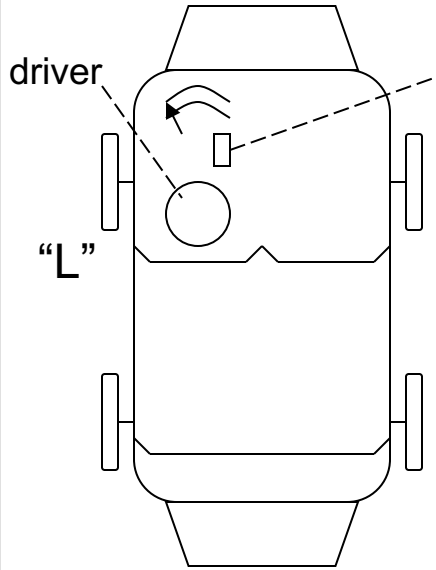


- W. Pauli: "The Lord is a weak left hander"

Violation of Parity Symmetry

Before 1956 physicists were c***onvinced*** that the laws of nature should be left-right symmetric. Strange?

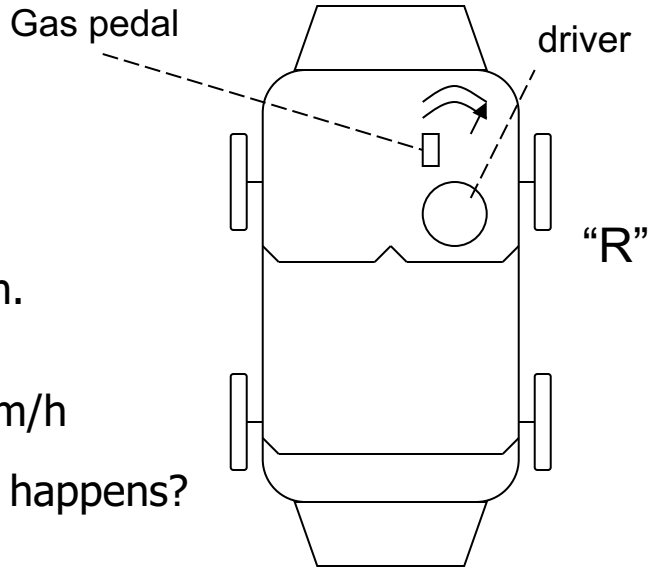
A "gedanken" experiment: two perfectly mirror-symmetric cars:



"L" en "R" are fully symmetric,
Each nut, bolt, molecule, etc. etc.
The engine mechanism is unknown.

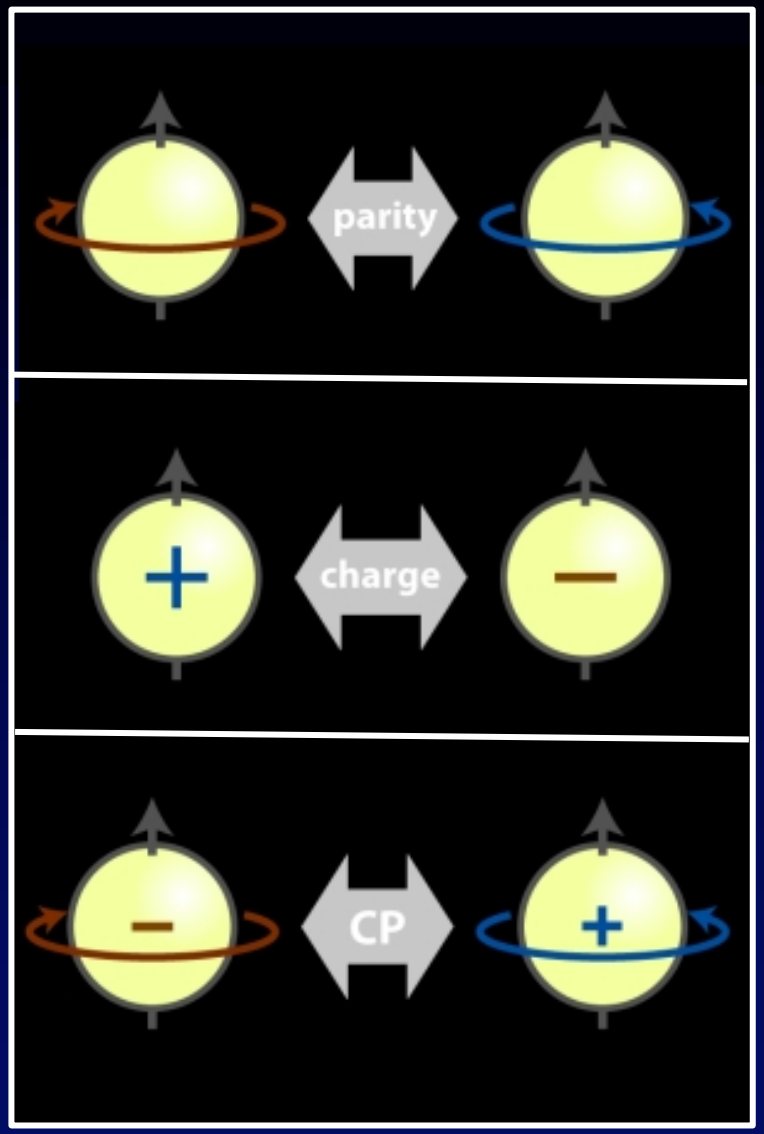
Person "L" gets in, starts, ….. 60 km/h

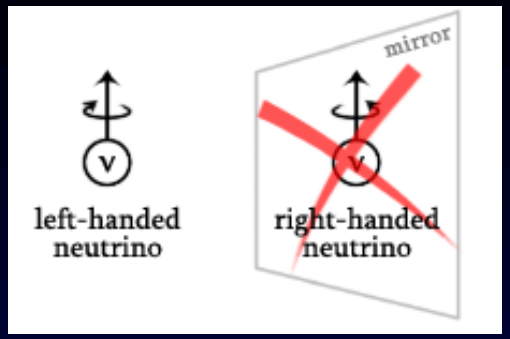
Person "R" gets in, start, ….. What happens?

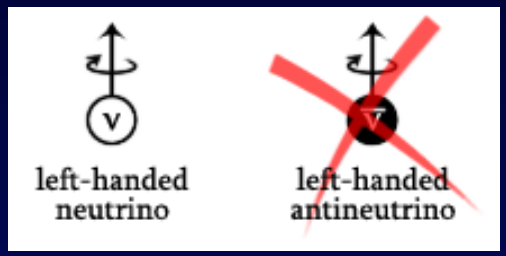


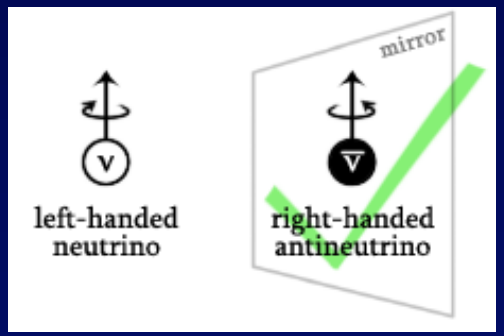
What happens if the ignition makes use of a radio-active decay?

Antimatter: maintaining the symmetry?









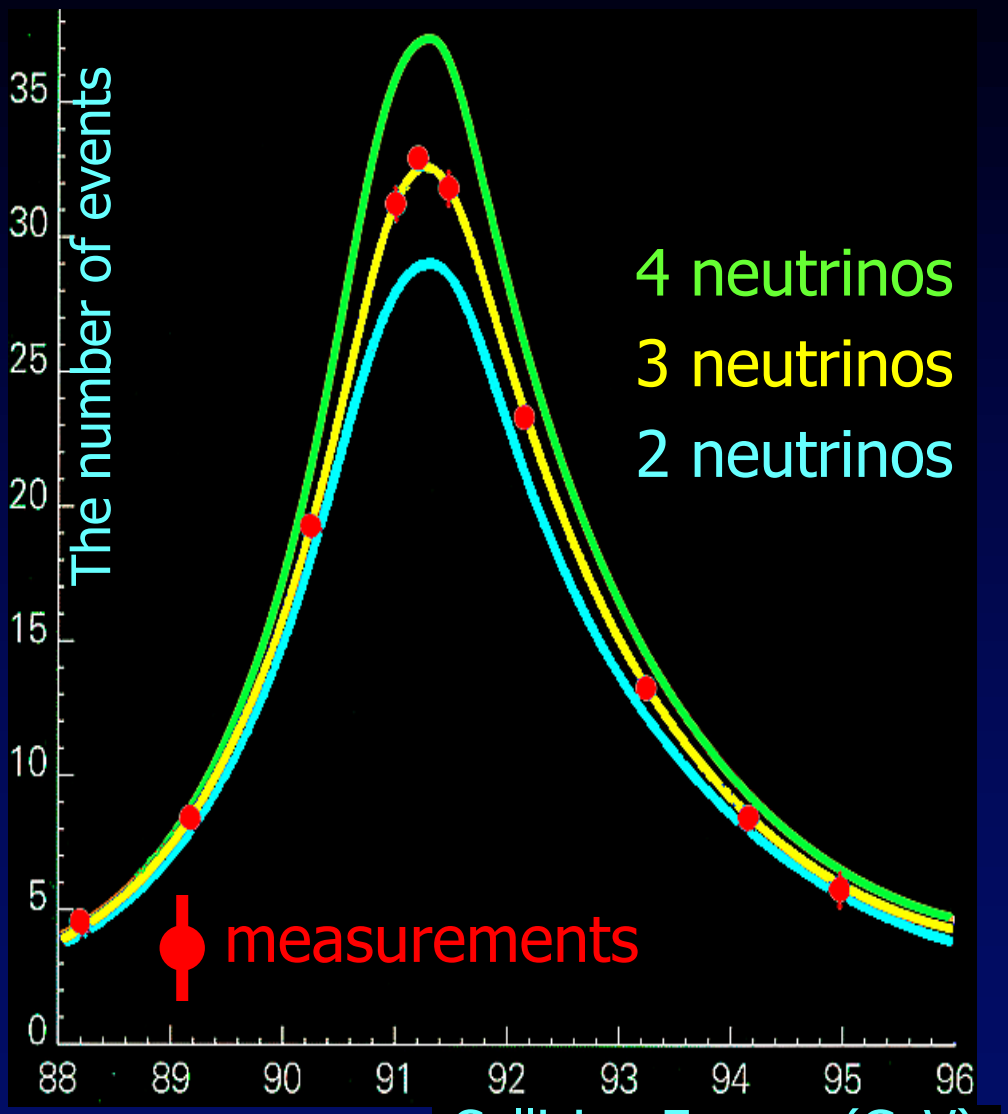
Charge-Parity Symmetry = Matter vs Antimatter symmetry

CERN 1993: There are 3 particle generations!

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

Matter



CERN 1993: There are 3 particle generations!

Generation:

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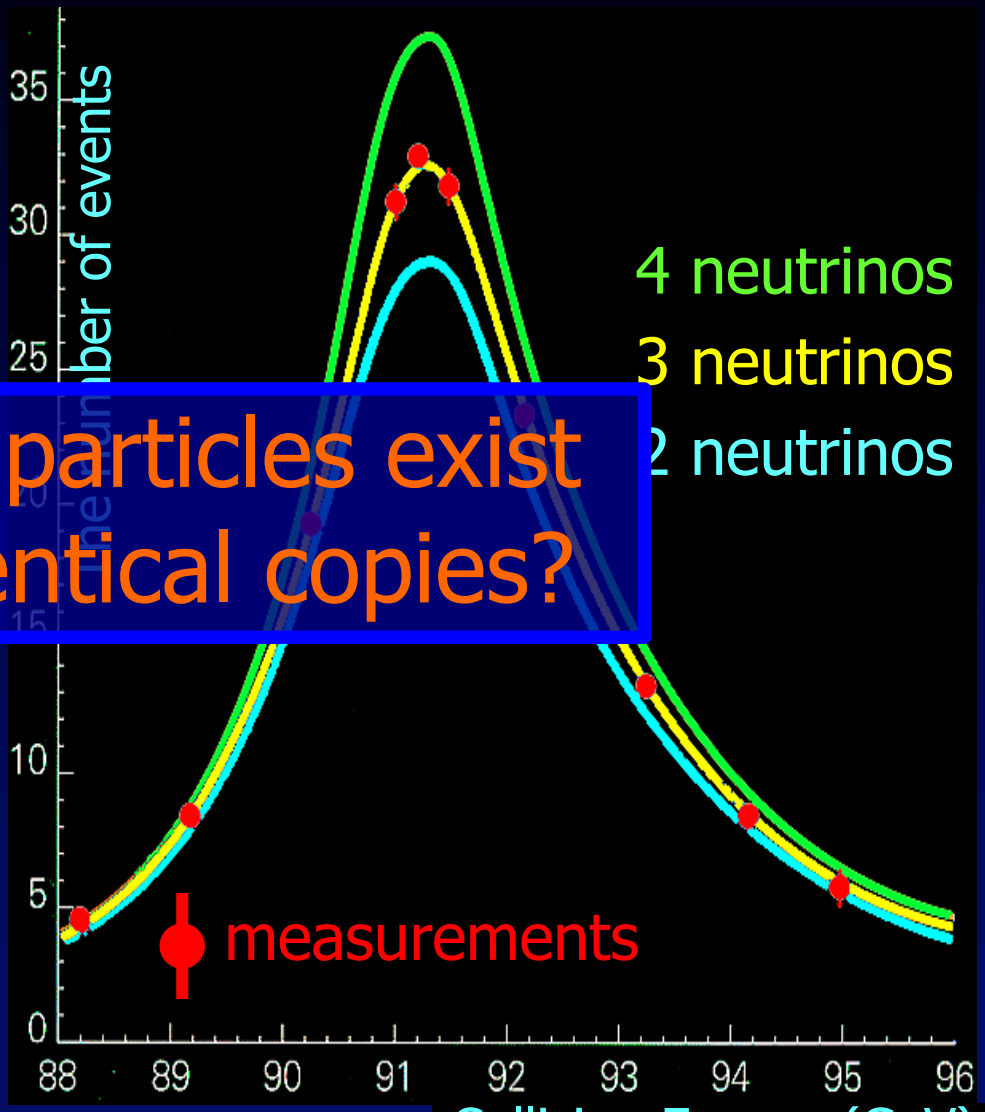
quarks	u	c (1976)	t (1995)	+2/3 e
	d	s	b	-1/3 e
leptons	e (1895)	μ (1936)	τ (1973)	-1 e
	ν_e (1956)	ν_μ (1963)	ν_τ (2000)	0 e

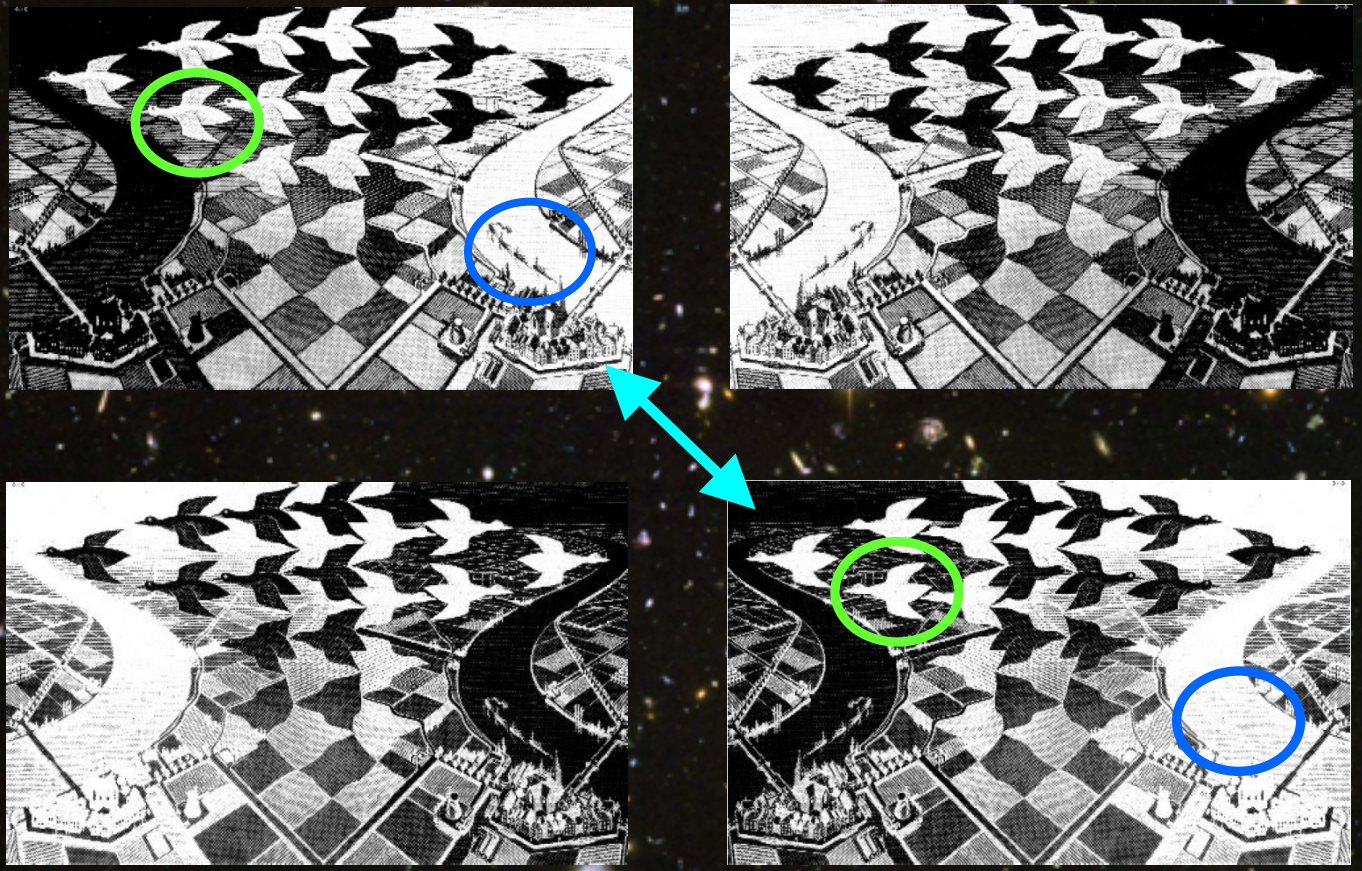
Matter



Why do all particles exist in three identical copies?

Escher's impression on the matter - antimatter difference

matter



colour ⟷ anti-colour

anti-matter

left ⟷ right