Matter Antimatter Symmetry in Nature

FMF symposium “Symmetry and Harmony” University of Groningen

Niels Tuning (Nikhef/CERN) – 19 Apr 2024

Asymmetry

Matter Antimatter ~~Symmetry~~ in Nature

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Outline

- Symmetry
- Particle Physics
- Antimatter

Symmetry

“Everyone likes objects
or patterns
that are in some way symmetrical”

Richard Feynman, https://www.feynmanlectures.caltech.edu/I_52.html

Sphere

People *believe* in symmetry!

Instruction for Abel Tasman, explorer of Australia (1642):

"Since many rich mines and other treasures have been found in countries north of the equator between 15º and 40º latitude,

there is no doubt that countries alike exist south of the equator

People *believe* in symmetry!

Instruction for Abel Tasman, explorer of Australia (1642):

"Since many rich mines and other treasures have been found in countries north of the equator between 15° and 40° latitude,

there is no doubt that countries alike exist south of the equator

(The provinces in Peru and Chili rich of gold and silver, all positioned south of the equator, are revealing proofs hereof.)"

(And off you go to Australia……)

Symmetry in space and time

A *physical law* can also be symmetrical

we cannot test the laws of physics in every point in the universe, can we?!

Emmy Noether (1882 - 1935)

Emmy Noether (1918)

Invariante Variationsprobleme.

(F. Klein zum fünfzigjährigen Doktorjubiläum.)

Von

Emmy Noether in Göttingen.

Vorgelegt von F. Klein in der Sitzung vom 26. Juli 1918[1]).

Es handelt sich um Variationsprobleme, die eine kontinuierliche Gruppe (im Lieschen Sinne) gestatten; die daraus sich ergebenden Folgerungen für die zugehörigen Differentialgleichungen finden ihren allgemeinsten Ausdruck in den in § 1 formulierten, in den folgenden Paragraphen bewiesenen Sätzen. Über diese aus Variationsproblemen entspringenden Differentialgleichungen lassen sich viel präzisere Aussagen machen als über beliebige, eine Gruppe gestattende Differentialgleichungen, die den Gegenstand der Lieschen Untersuchungen bilden. Das folgende beruht also auf einer Verbindung der Methoden der formalen Variationsrechnung mit denen der Lieschen Gruppentheorie. Für spezielle Gruppen und Variationsprobleme ist diese Verbindung der Methoden nicht neu; ich erwähne Hamel und Herglotz für spezielle endliche, Lorentz und seine Schüler (z. B. Fokker), Weyl und Klein für spezielle unendliche Gruppen[2]). Insbesondere sind die zweite Kleinsche Note und die vorliegenden Ausführungen gegenseitig durch einander beein-

Emmy Noether (1918)

“For each symmetry of the Lagrangian, there is a conserved quantity"

Noether Theorem

$$\frac{\partial L}{\partial q} = \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right)$$

Euler-Lagrange equation

If Lagrangian does not depend on q … then time derivative is zero (ie. conserved)

Symmetries

Transformations	Unobservables	Conservation laws and selection rules
Translation in space $\boldsymbol{r} \rightarrow \boldsymbol{r} + \Delta$	Absolute position in space	Momentum

Symmetries

Transformations	Unobservables	Conservation laws and selection rules
Translation in space $\boldsymbol{r} \rightarrow \boldsymbol{r} + \Delta$	Absolute position in space	Momentum
Translation in time $t \rightarrow t + \tau$	Absolute time	Energy
Rotation $\boldsymbol{r} \rightarrow \boldsymbol{r}'$	Absolute direction in space	Angular momentum

It almost feels as if everything is symmetric?!

Scale: not a symmetry!

Scale up?

- Collapse…

Scale: not a symmetry!

Scale up?

- Collapse…

Absolute scale?

- Yes! Atom

A MATCH MADE IN HEAVEN

Single again... man who's spent 6 years building his own Salisbury Cathedral and only needs another 9 to finish!

Sticking to the task: Model statues and, above, the real ones in stone

By **David Wilkes**

ONE day back in 2013, Barry King set himself quite a challenge – to create the world's biggest matchstick model.

Six very fiddly years, 750,000 matches, 40 litres of glue, around £6,000 and one relationship later, his replica of Salisbury Cathedral is really taking shape.

He has finished the west front, including details such as the niches containing statues of priests and worthies connected with the 13th century cathedral.

He has also painstakingly recreated the central gable with its four lancet windows and two quatrefoil windows.

The maintenance man, 49, estimates he will complete his task sometime in 2028, by when he will have used six million matchsticks.

That would make him a Guinness world record holder, taking him past David Reynolds of Southampton, who finished his replica of a North Sea oil rig in 2009 after 15 years and 4.75million matchsticks.

Mr King, from Amesbury, Wiltshire, said: 'I started in earnest six years ago and progress was good to start with.

'But when I got into a relationship I found I wasn't able to devote a lot of time to it. Since the relationship ended, I can now spend my weekends and a few hours every evening on it.'

He uses tweezers and a craft knife to whittle the matchsticks to the right size and shape them as he replicates the cathedral's intricate details.

The actual cathedral took slightly longer to build, its main body being completed in 38 years from 1220 to 1258 – 23 years longer than Mr King hopes his model will take.

The model, which will measure 15ft by 9ft when complete, is on show at the Salisbury Guildhall later this month in a charity fundraiser.

'It's always been something I want to be known for doing,' Mr King said.

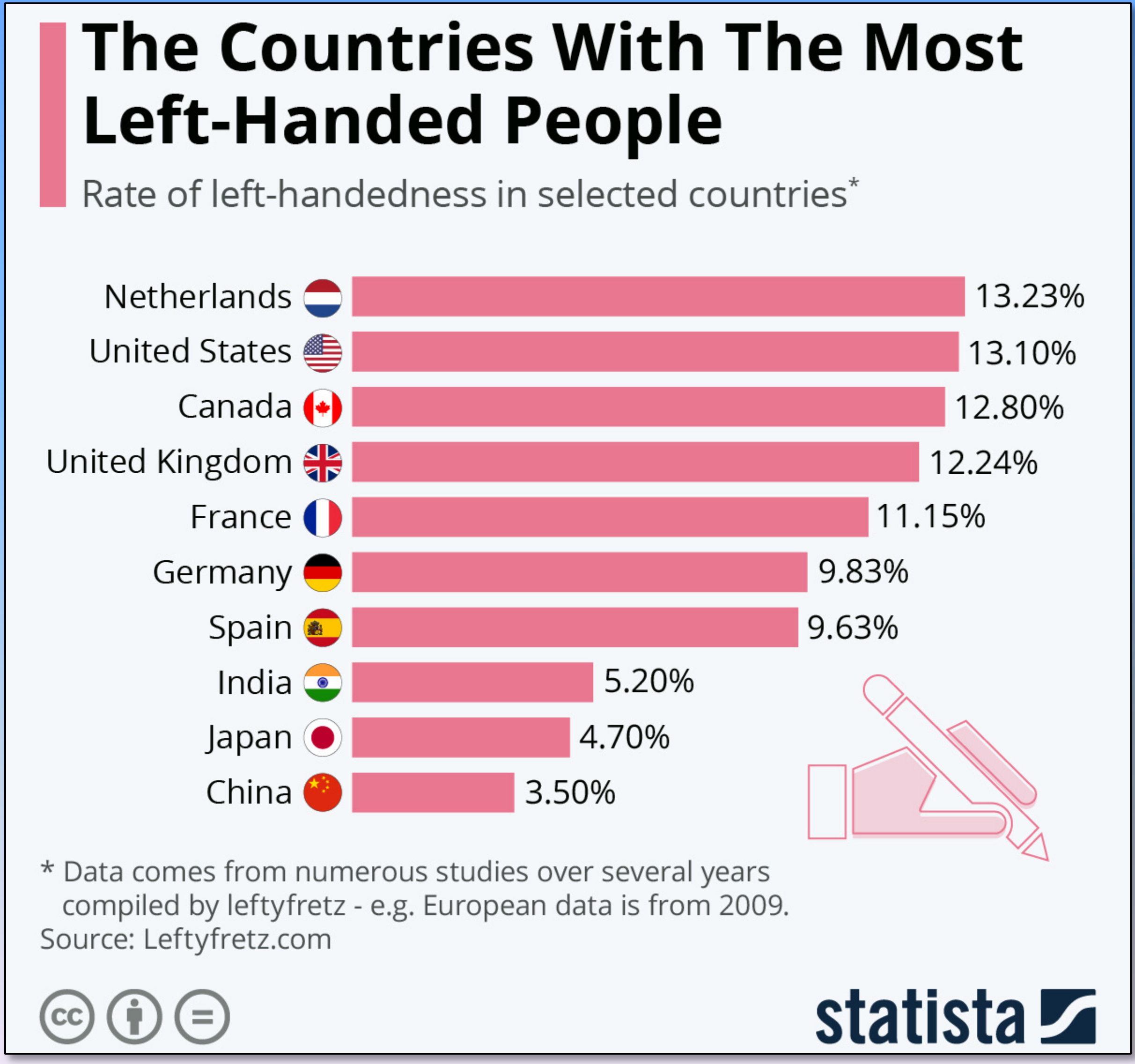
And lo! Barry did a mighty cathedral build: Mr King and his matchstick model of the Salisbury building

Inspiring: The real cathedral

https://www.pressreader.com/uk/scottish-daily-mail/20190801/282222307368402

Left – right

Left – right asymmetry?



- The asymmetry is not even (translation) invariant

What is left?

Phone a friendly Martian.

What is left?

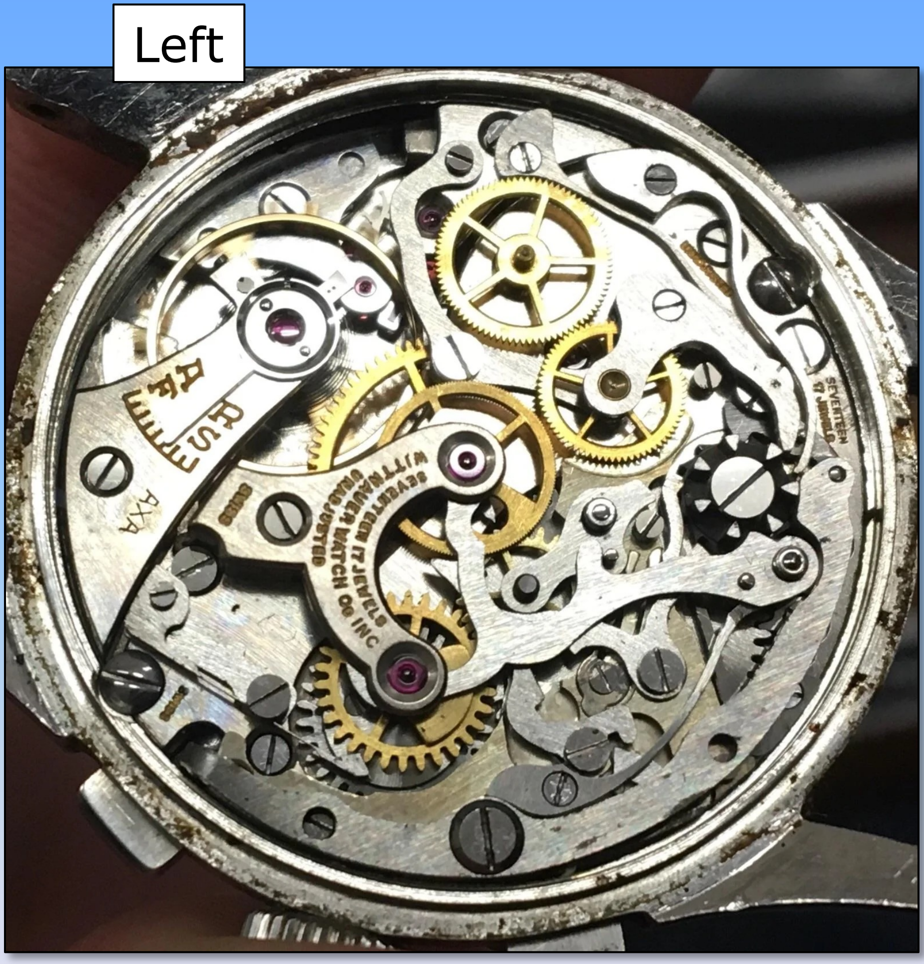
Phone a friendly Martian.

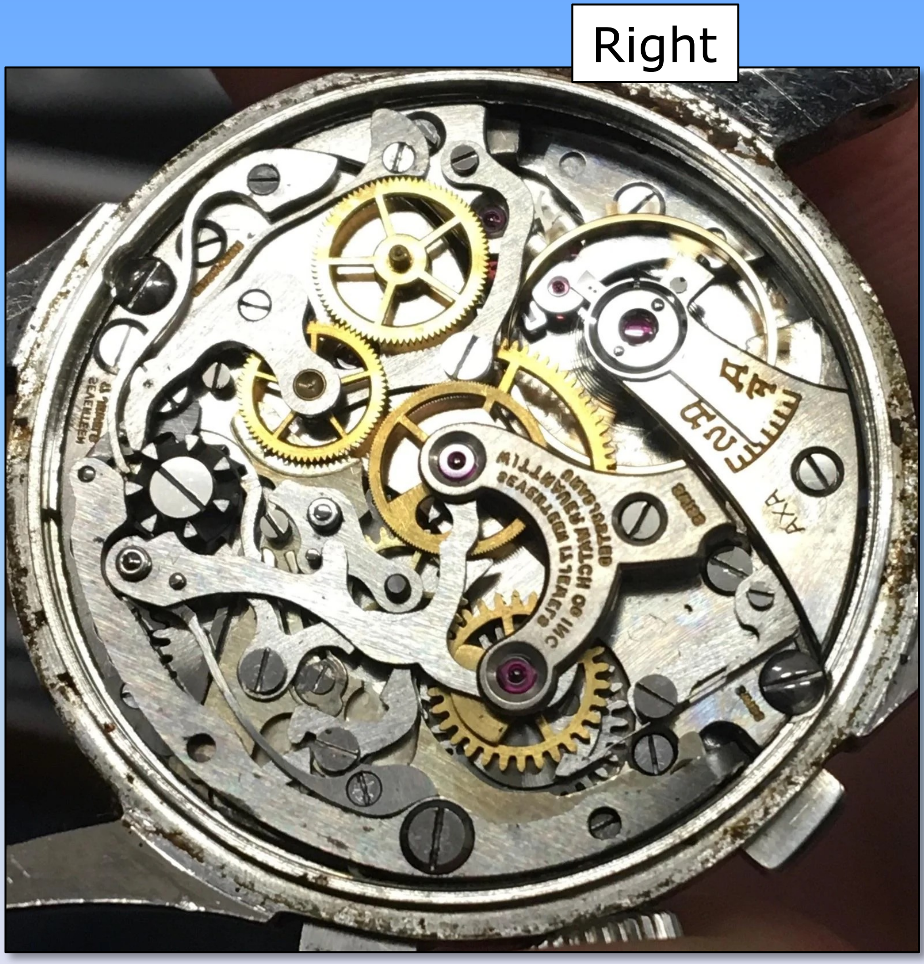
Explain what humans are. Scale is easy to explain.

- me: “*Heart is on the left.*”

- ET: “*Left ?*”

Left – right symmetric?





- Would it work?
- What if it is nuclear powered…?

Left – right symmetric?

Almost everything (ie. every physical law) is...

Left – right symmetric?

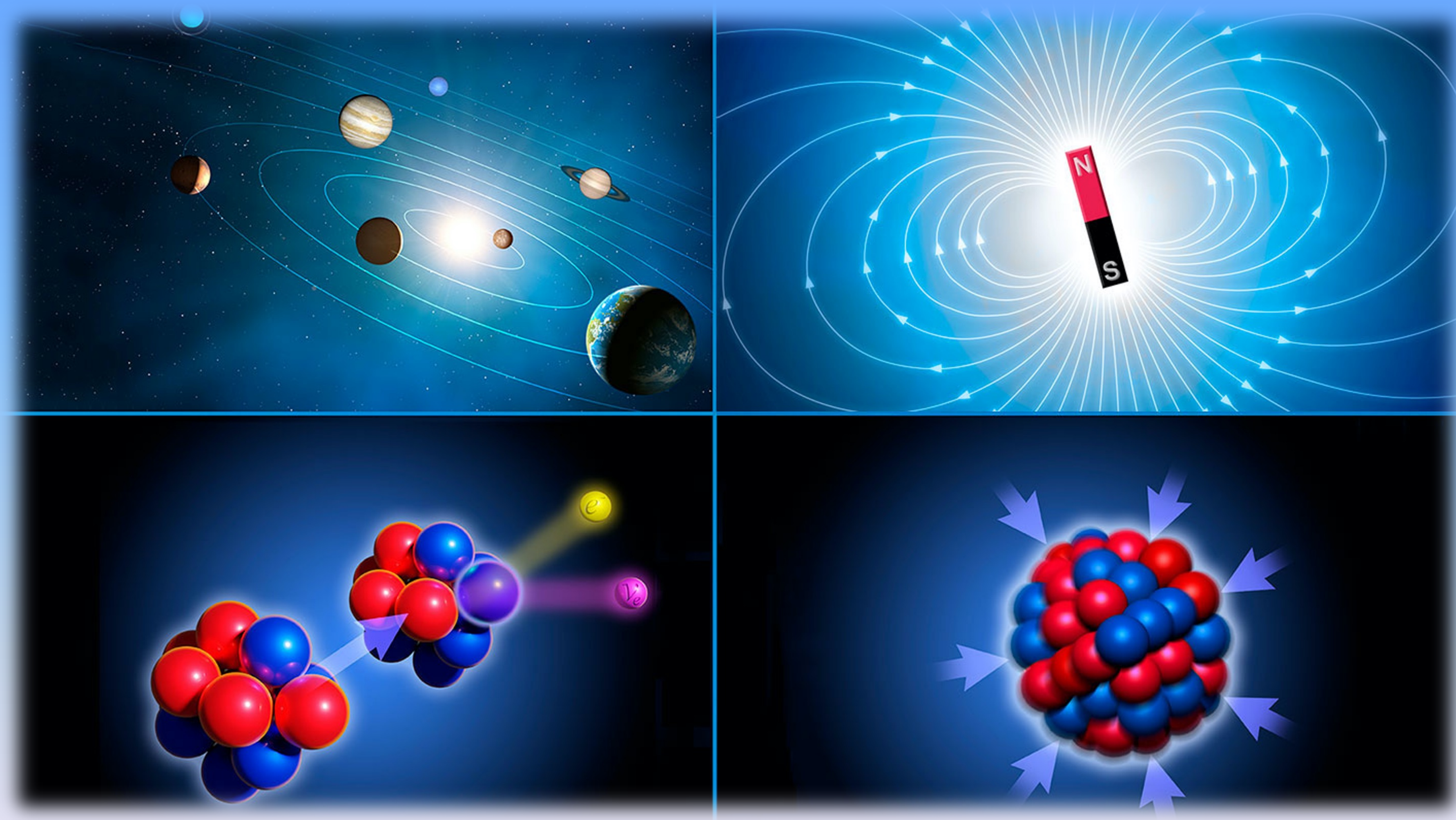
Almost everything (ie. every physical law) is…

- The "weak nuclear force" is not!

Outline

- Symmetry
- Particle Physics
- Antimatter

Intermezzo: Forces of nature

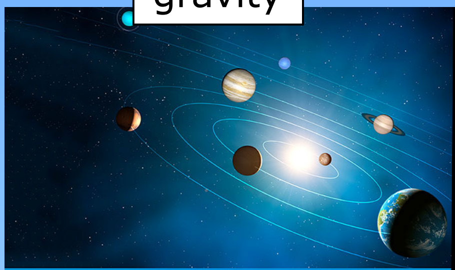


See talk by Nichol Furey

Intermezzo: Forces of nature

Force = interaction = exchange of a particle

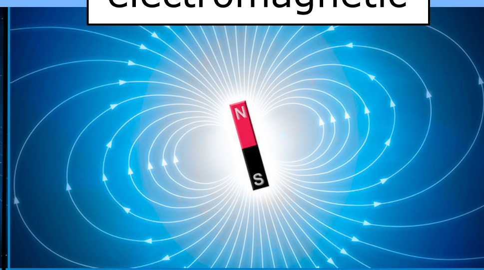
gravity

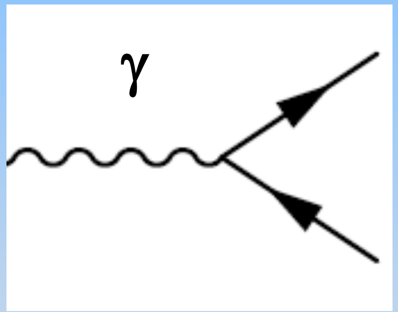


Graviton?

apples
planets
dark matter

electromagnetic

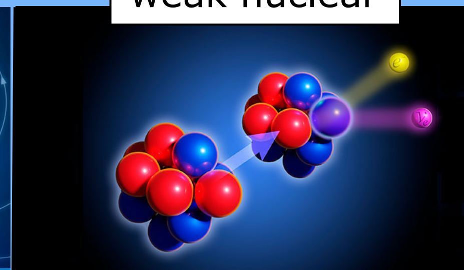


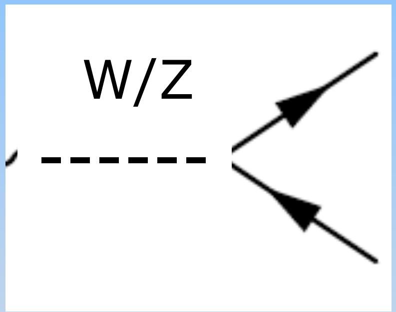


Photon

atoms
+/-
magnetism
van der Waals
springs
muscles
…

weak nuclear

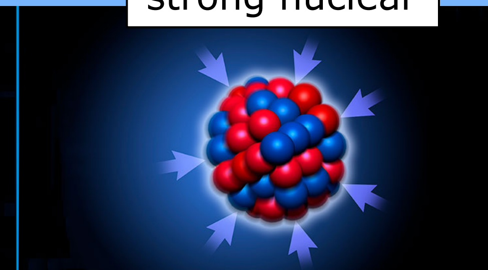


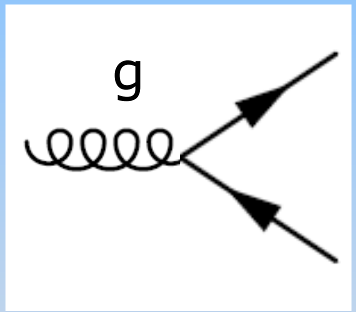


W or Z

radioactive
decay
neutrino's

strong nuclear

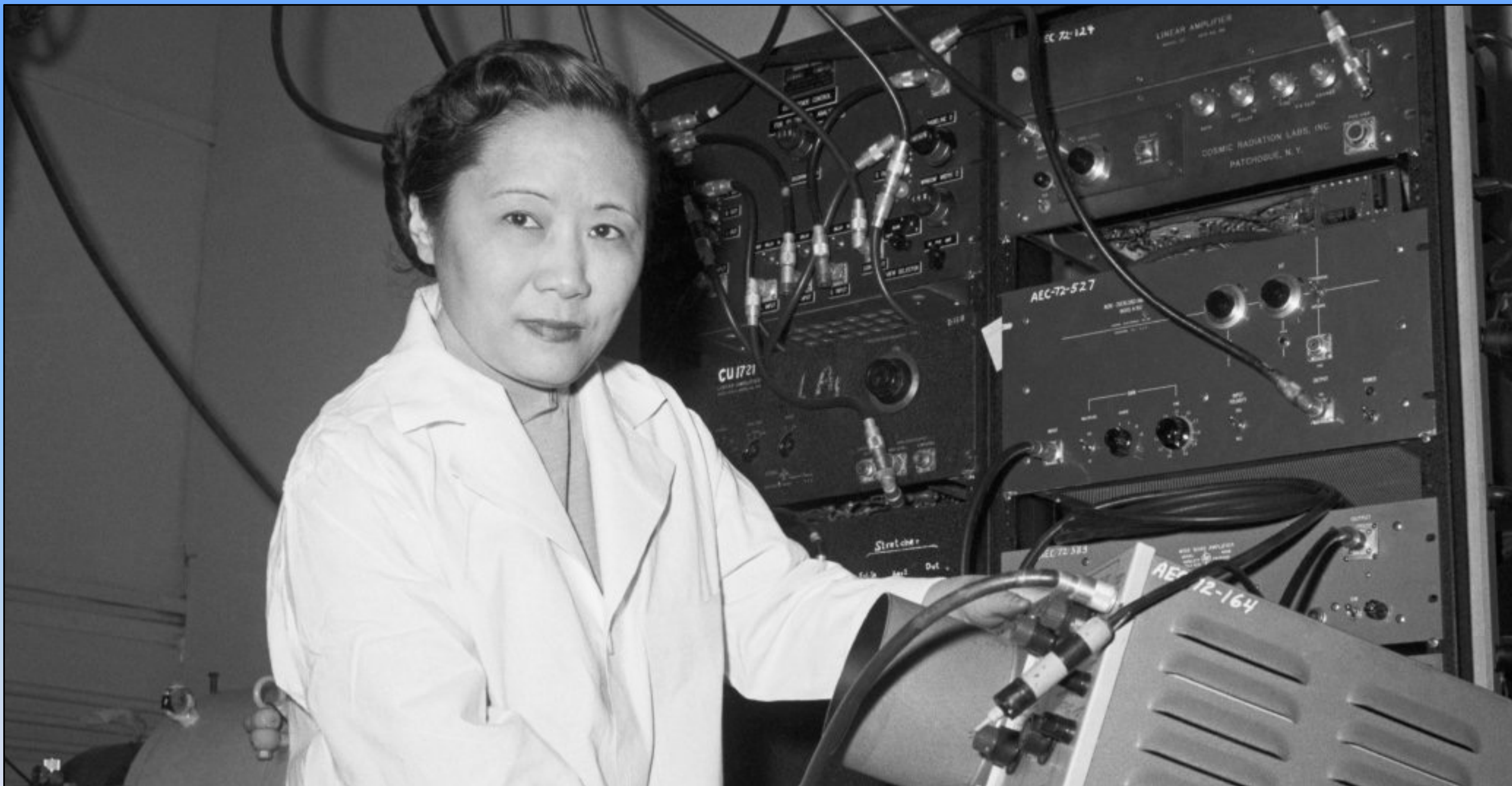




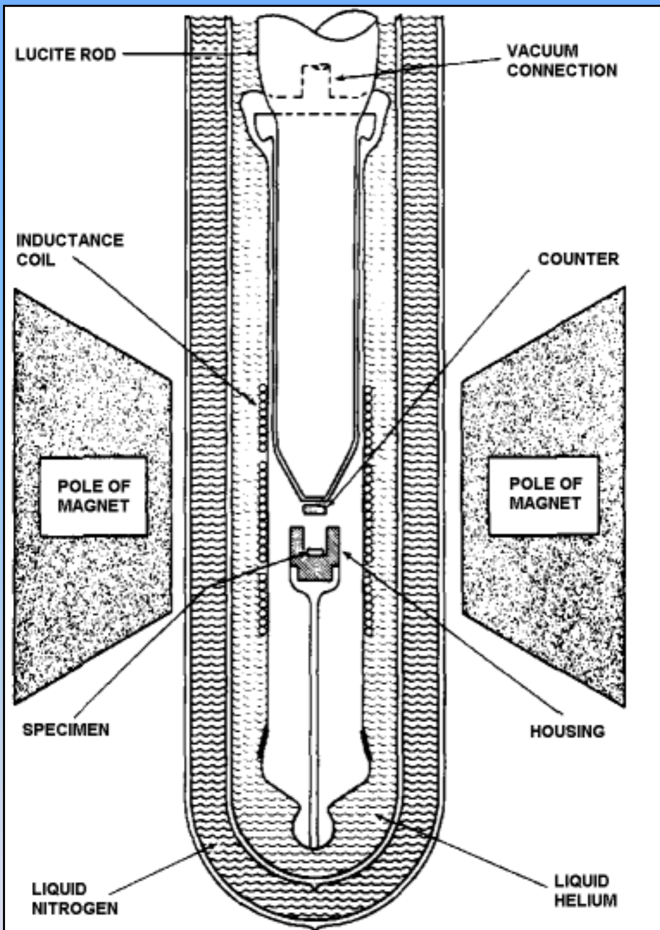
gluon

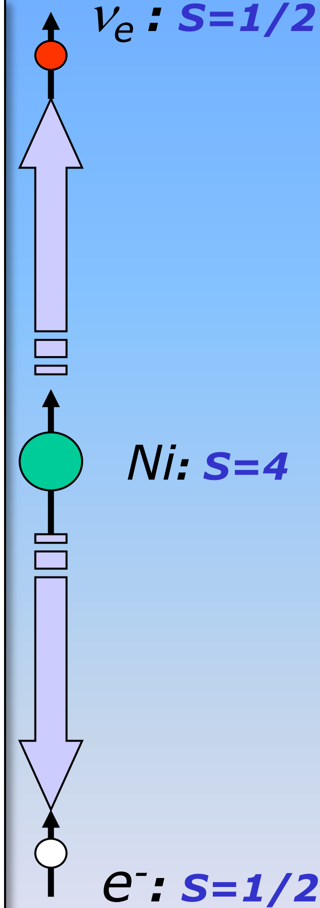
nuclei

Chien-Shiung Wu (1912 - 1997)



Chien-Shiung Wu (1956)





Sample of Polarized ^{60}Co (s=5)

Decay $^{60}Co \rightarrow {}^{60}Ni + e^- + \nu_e$

Electrons predominantly down

Why ?!

- Weak interaction purely couples to left-handed neutrino's
- Right-handed neutrino's do not exist

Symmetries

Transformations	Unobservables	Conservation laws and selection rules
Translation in space $\boldsymbol{r} \rightarrow \boldsymbol{r} + \Delta$	Absolute position in space	Momentum
Translation in time $t \rightarrow t + \tau$	Absolute time	Energy
Rotation $\boldsymbol{r} \rightarrow \boldsymbol{r}'$	Absolute direction in space	Angular momentum
Space inversion $\boldsymbol{r} \rightarrow -\boldsymbol{r}$	Absolute left or right	Parity
Time reversal $t \rightarrow -t$	Absolute sign of time	Kramers degeneracy
Sign reversion of charge $e \rightarrow -e$	Absolute sign of electric charge	Charge conjugation

See talk by Nichol Furey

Transformations	Unobservables	Conservation laws and selection rules
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Sign reversion of charge $e \to -e$	Absolute sign of electric charge	Charge conjugation
Particle substitution	Distinguishability of identical particles	Bose or Fermi statistics
$\psi(x) \to \psi'(x) = e^{i\alpha(x)}\psi(x)$	Absolute phase	Charge (electric)
$\psi \to \psi' = \exp\left(i\frac{\vec{\sigma}\cdot\vec{\alpha}}{2}\right)\psi$	Absolute phase	Charge (weak isospin)
$\psi \to \psi' = \exp\left(\sum_{a=1,8}\frac{i}{2}\theta_a(x)\lambda_a\right)\psi$	Absolute phase	Charge (color)

What is "left" ?

we can tell a Martian where to put the heart: we say,

"Listen, build yourself a magnet, and put the coils in, and put the current on, and then take some cobalt and lower the temperature. Arrange the experiment so the electrons go from the foot to the head, then the direction in which the current goes through the coils is the direction that goes in on what we call the right and comes out on the left."

People *believe* in symmetry!

Chen Ning Yang
Prize share: 1/2

Tsung-Dao (T.D.) Lee
Prize share: 1/2

Award Ceremony Speech Nobel Prize (1957):

- *"it was assumed almost tacitly, that elementary particle reactions are symmetric with respect to right and left"*
- *"In fact, most of us were inclined to regard the symmetry of elementary particles with respect to right and left as a necessary consequence of the general principle of right-left symmetry of Nature"*
- *"… only Lee and Yang … asked themselves what kind of experimental support there was for the assumption that all elementary particle processes are symmetric with respect to right and left"*

Clock

Left

Right

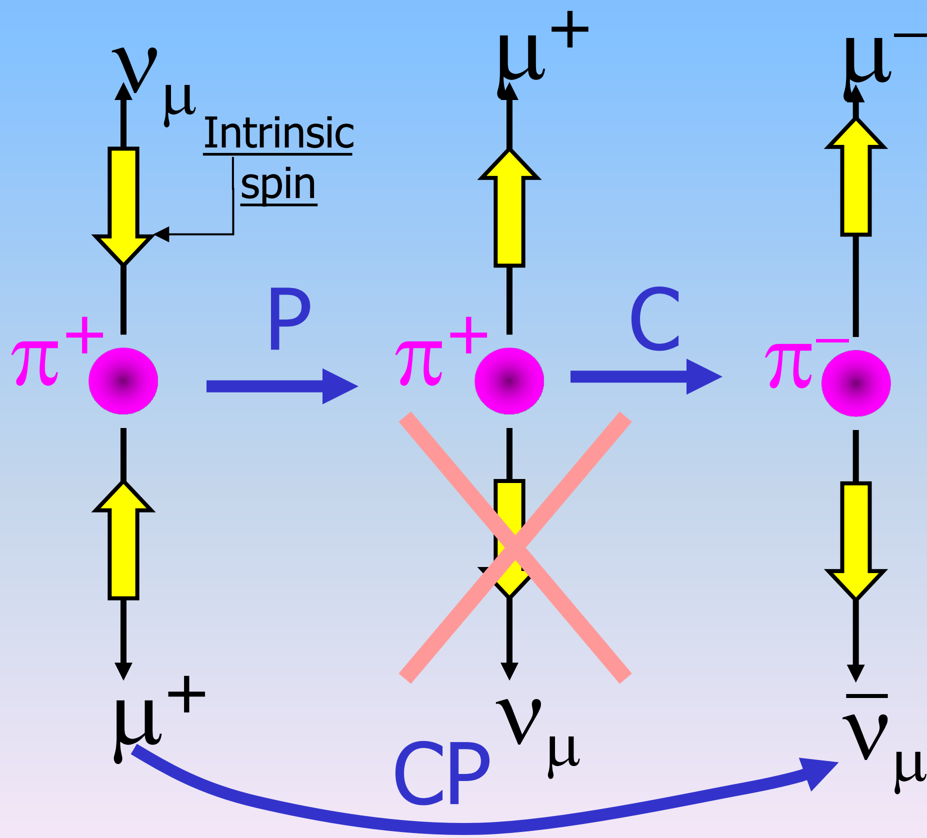
- ➢ But what if it is nuclear powered…? It would not work

CP symmetry?

1) Swap left – right
2) And swap particle – antiparticle?!

CP symmetry?

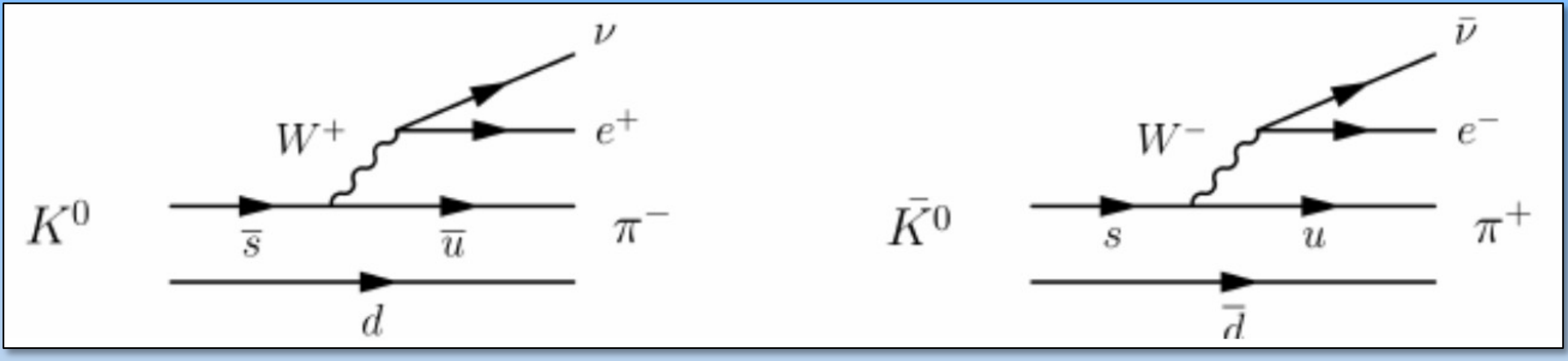
1) Swap left – right
2) And swap particle – antiparticle!



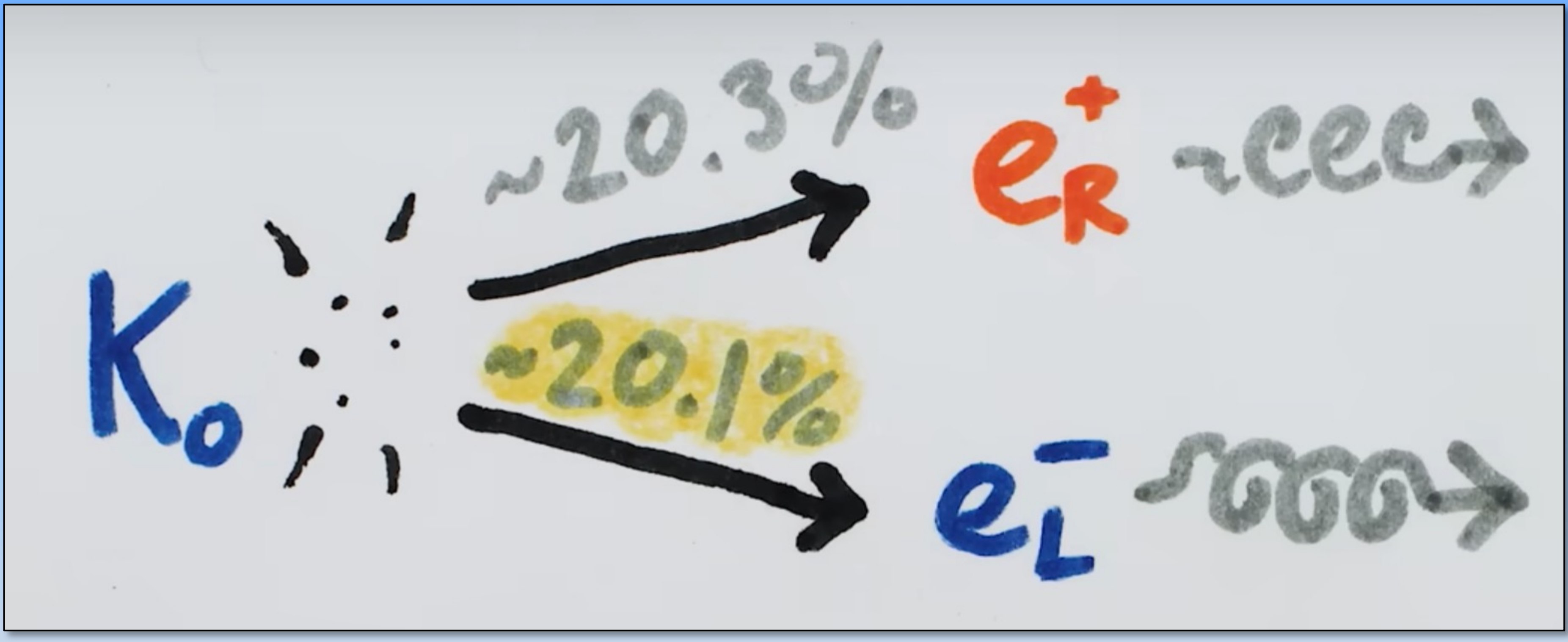
CP appears to be preserved in weak interaction!

CP symmetry 😞

- Only ‘slightly’ broken symmetry (Cronin & Fitch, 1964)
- But still…

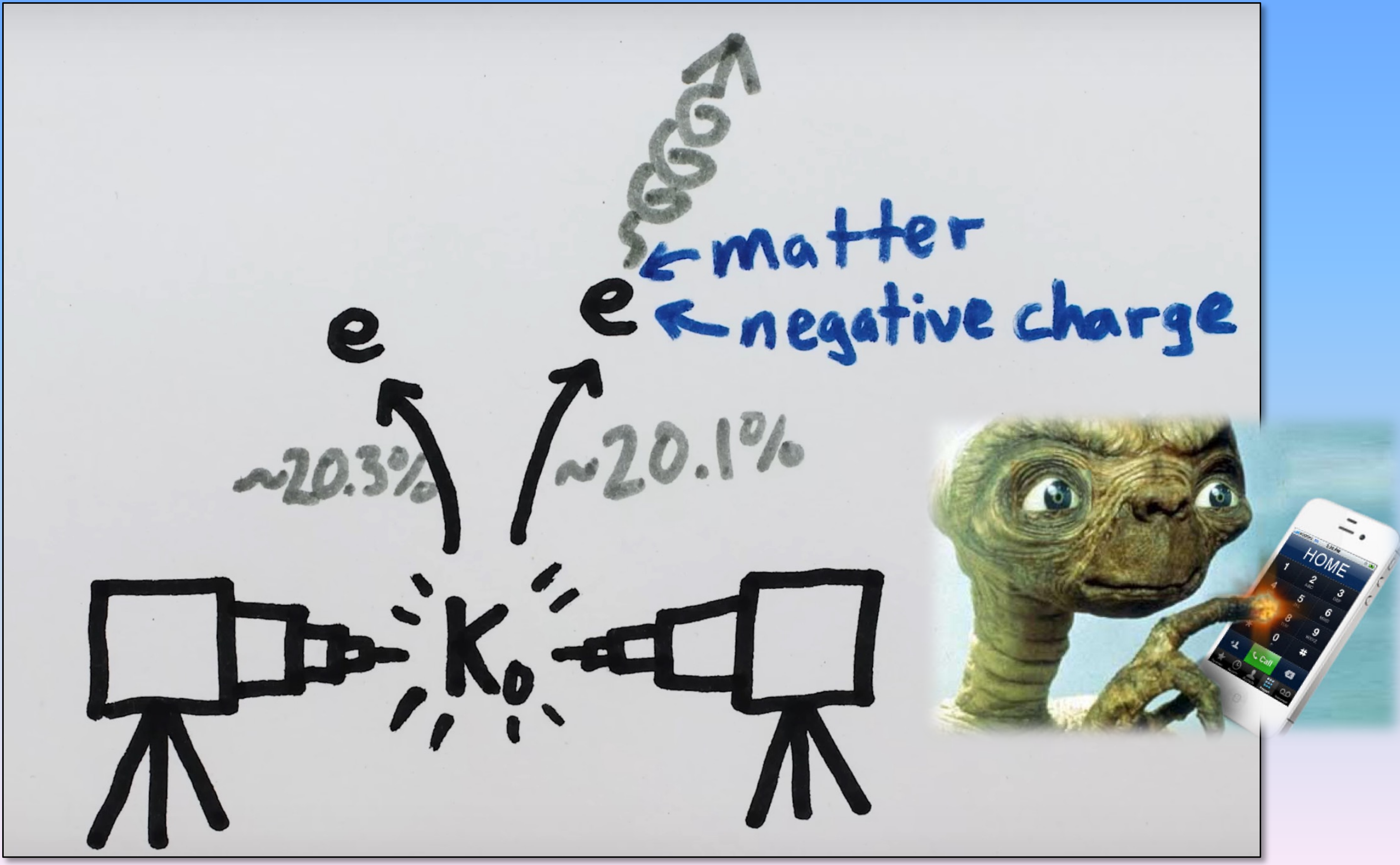


CP symmetry



From: https://youtu.be/Elt0Gt9Cb6Q?feature=shared

CP symmetry



From: https://youtu.be/Elt0Gt9Cb6Q?feature=shared

Outline

- Symmetry
- Particle Physics
- Antimatter

Antimatter?

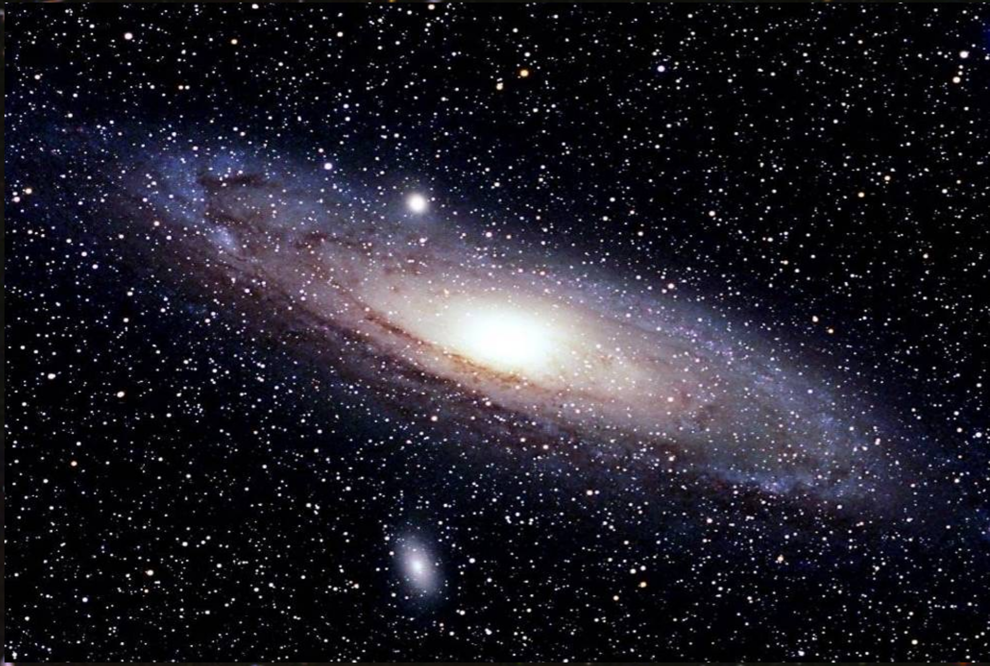

Only matter around us?

Is this all?

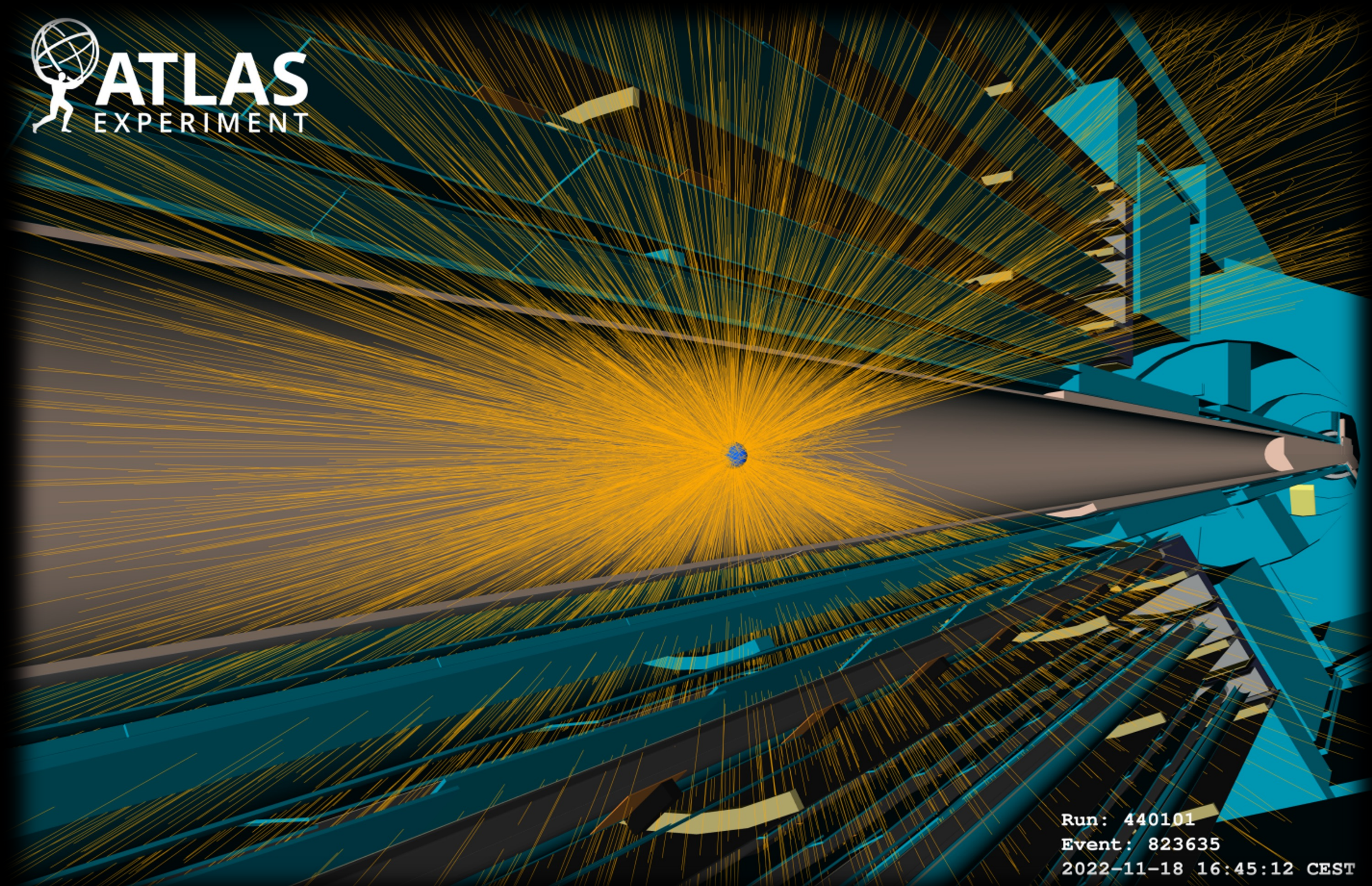
Generation:

	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

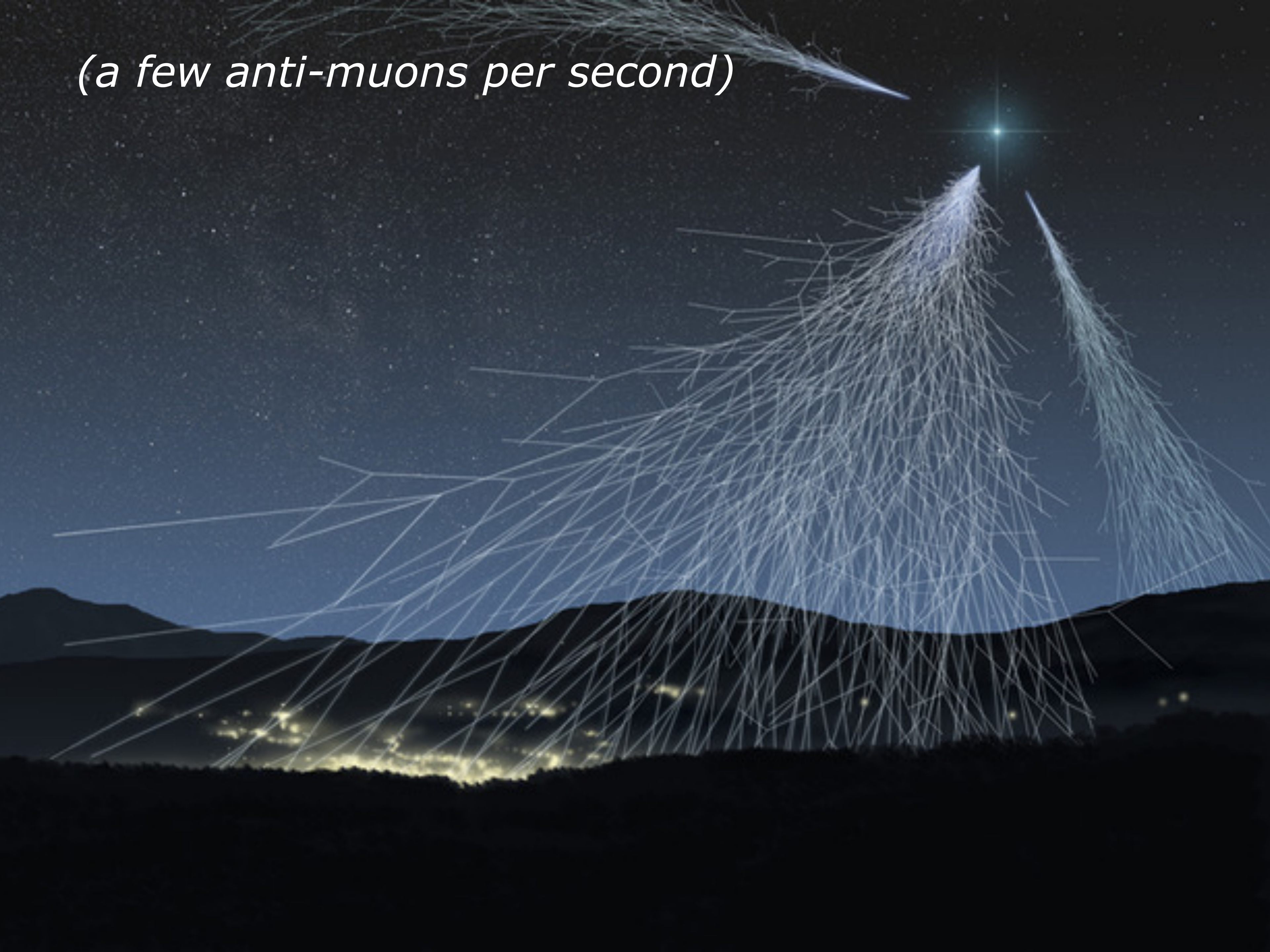
Matter



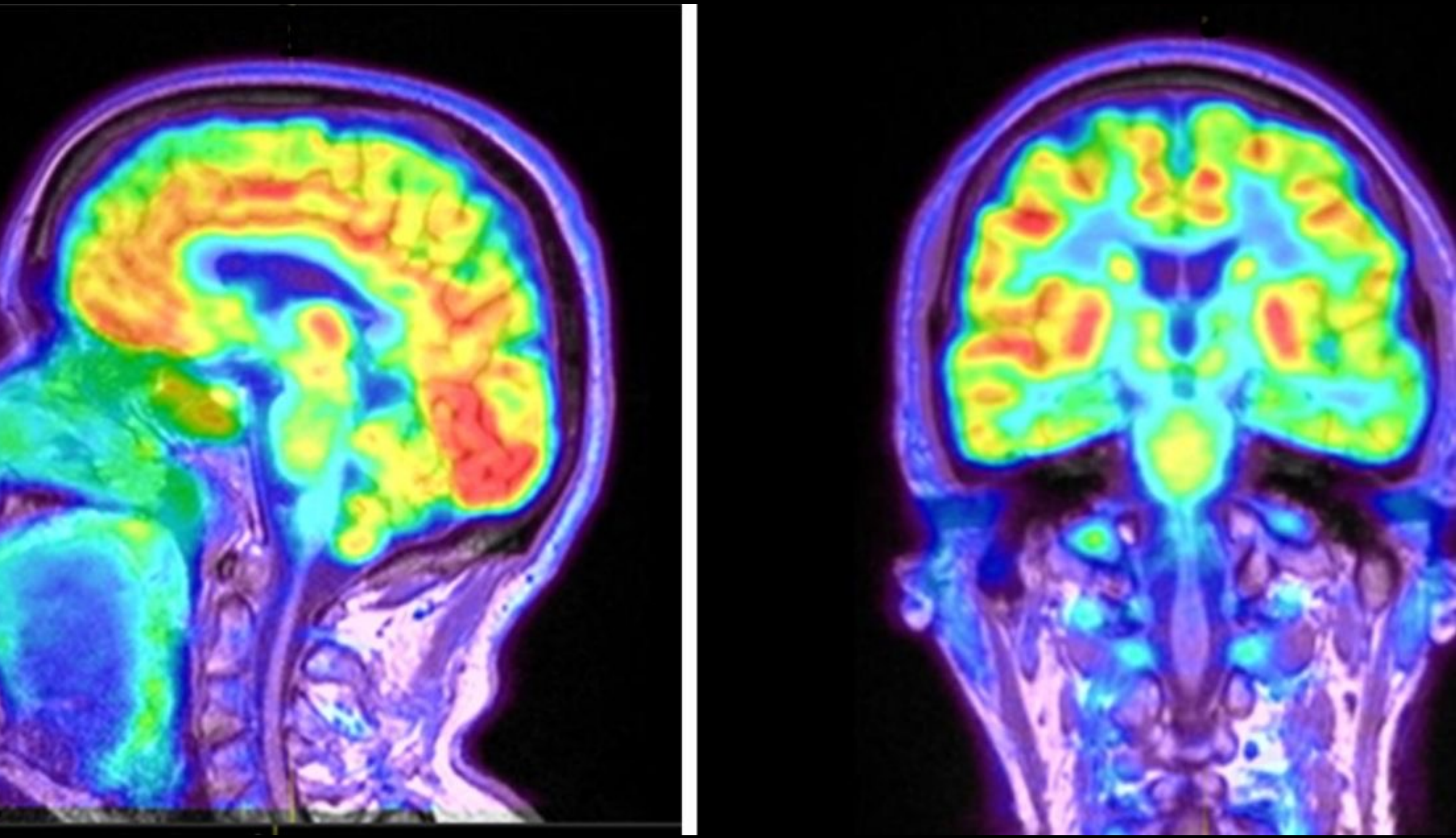
Daily business at accelerators



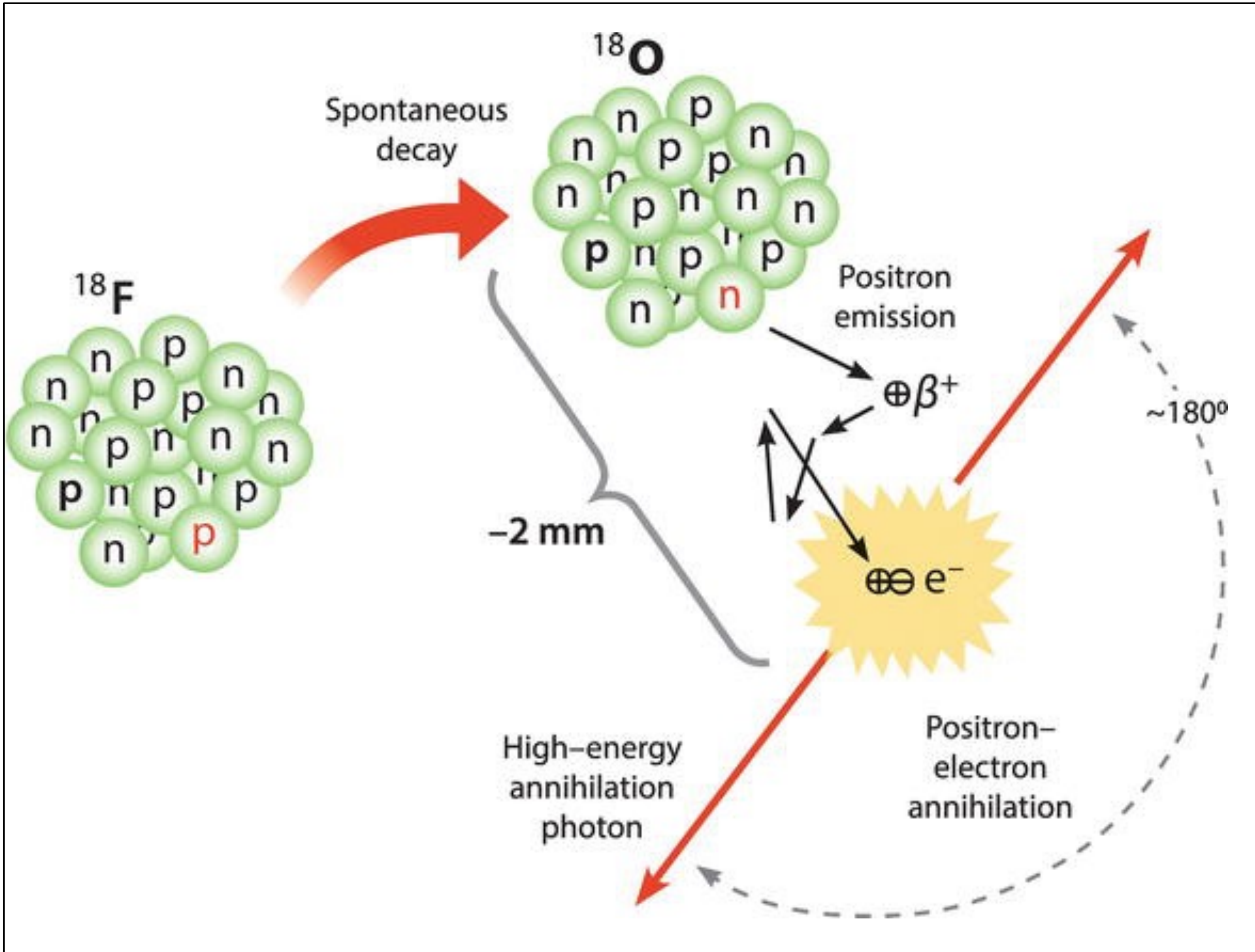
"While we speak"


(a few anti-muons per second)

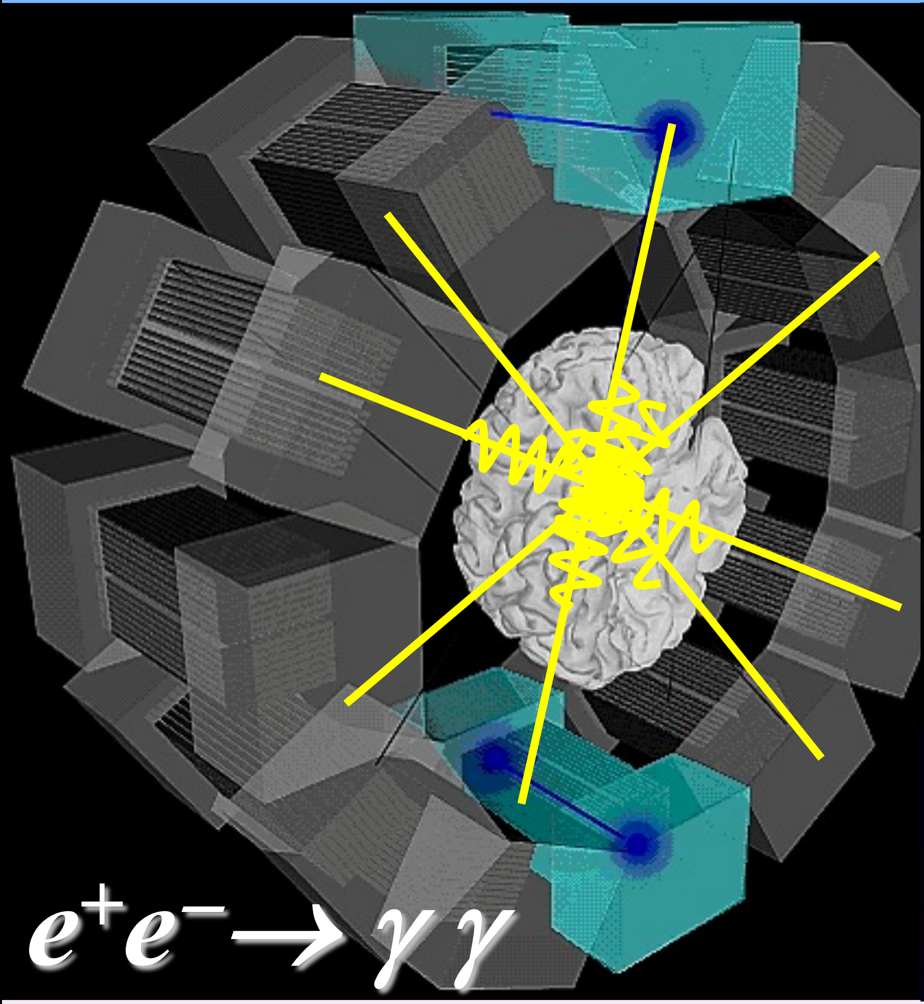
In your neighbourhood



Antimatter in hospitals



Antimatter in hospitals: PET scan



The elementary particles

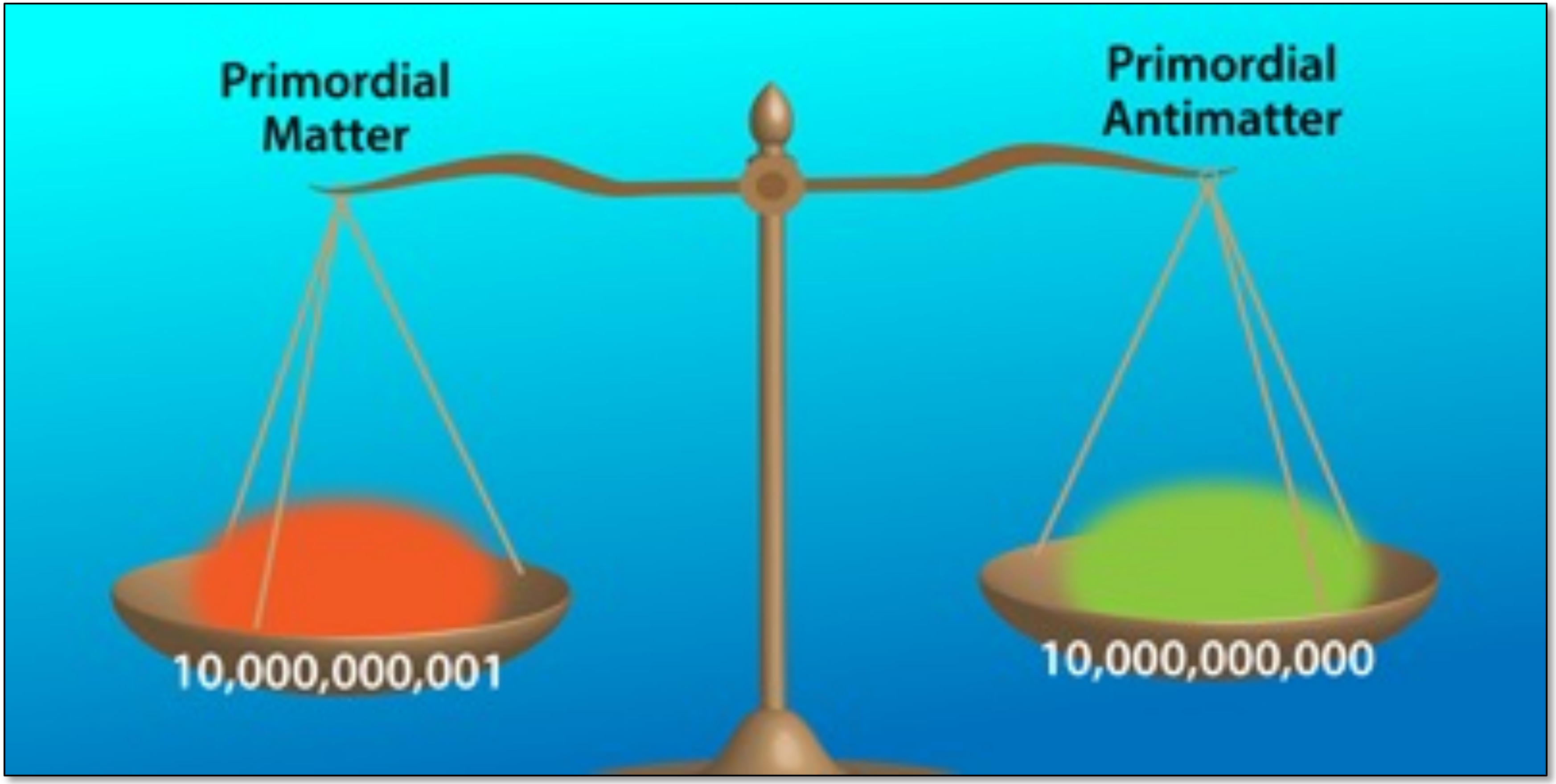
Matter

	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

Antimatter

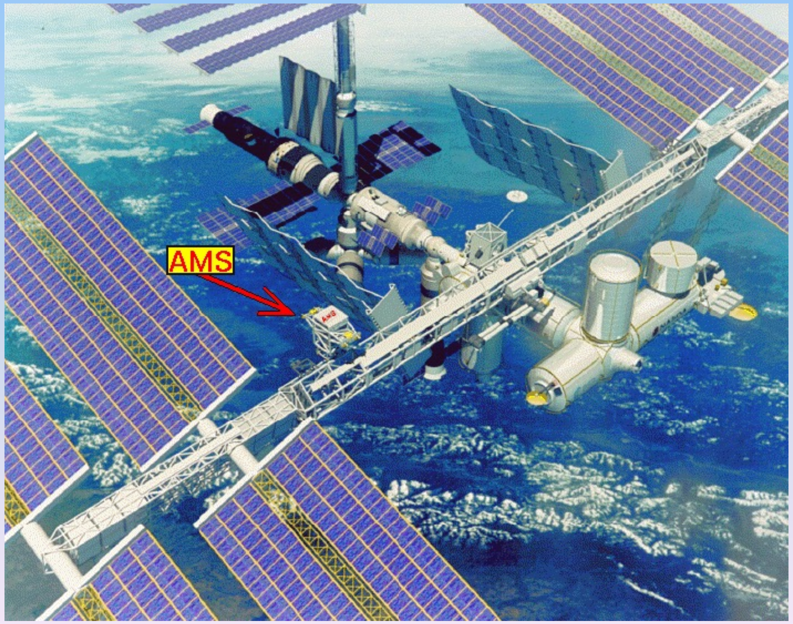
Charge	I	II	III
-2/3 e	$\bar{u}$	$\bar{c}$	$\bar{t}$
+1/3 e	$\bar{d}$	$\bar{s}$	$\bar{b}$
+1 e	$\bar{e}$	$\bar{\mu}$	$\bar{\tau}$
0 e	$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$

Where did the antimatter go?

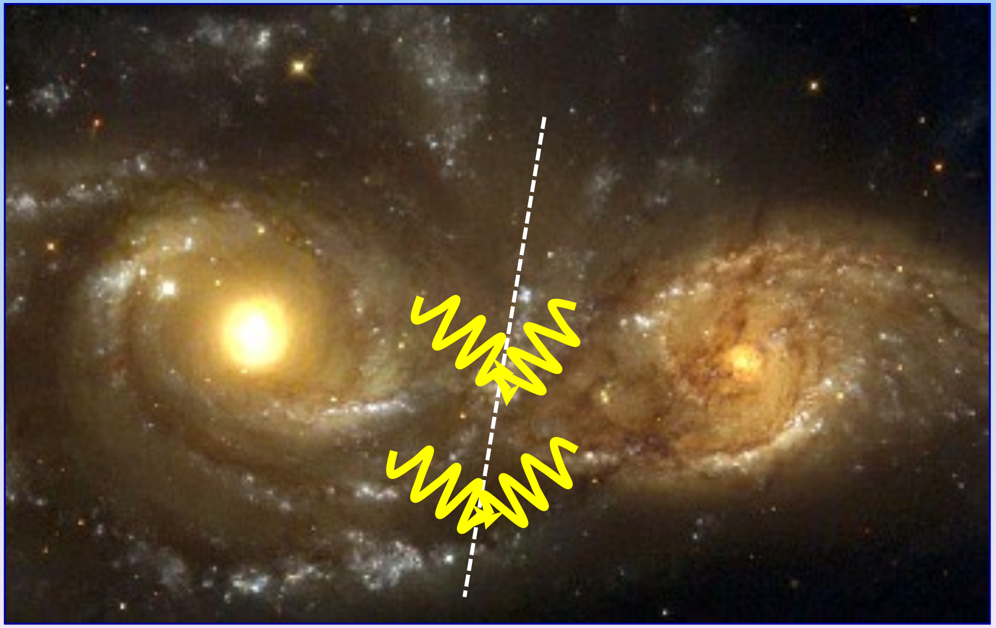


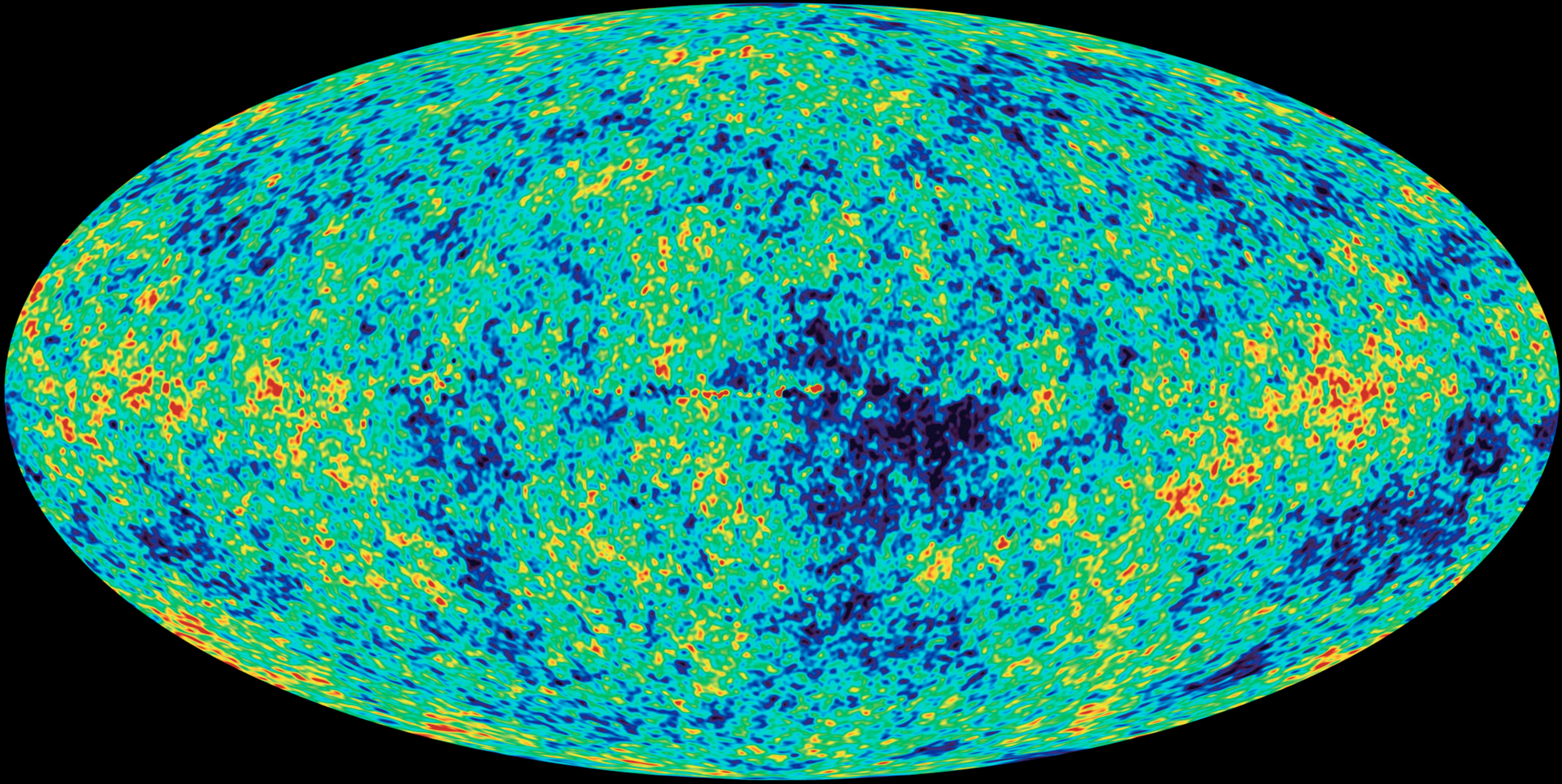
Where did the matter go?

No antimatter seen with satellites



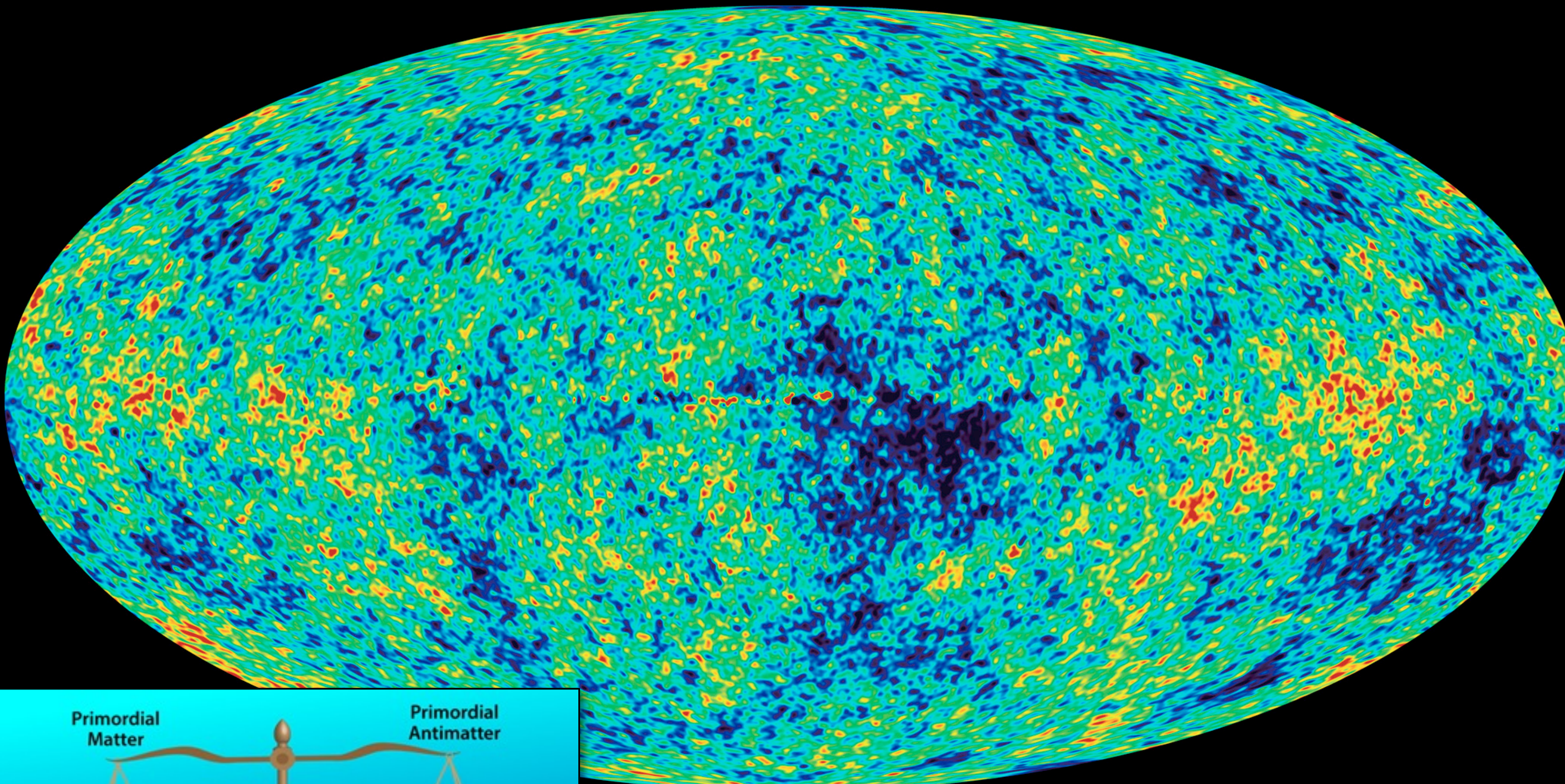
No antimatter galaxies

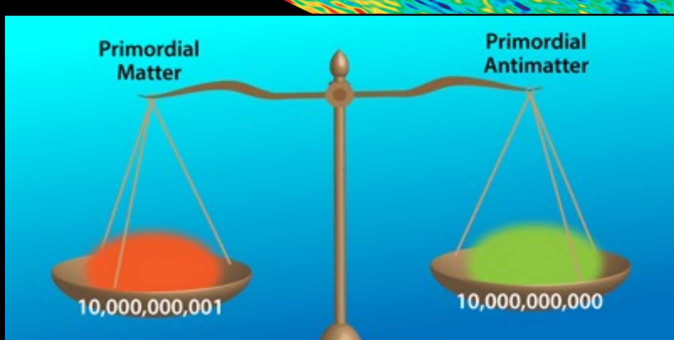




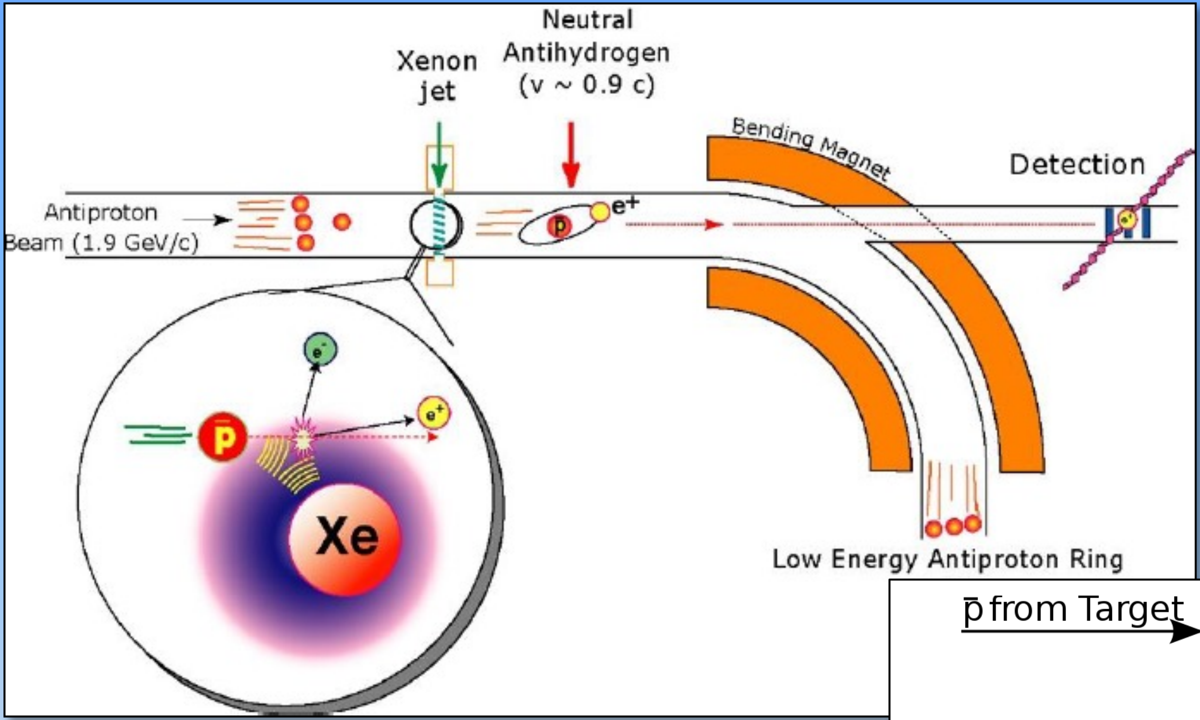
300,000 year after the BigBang,
the Universe became transparent

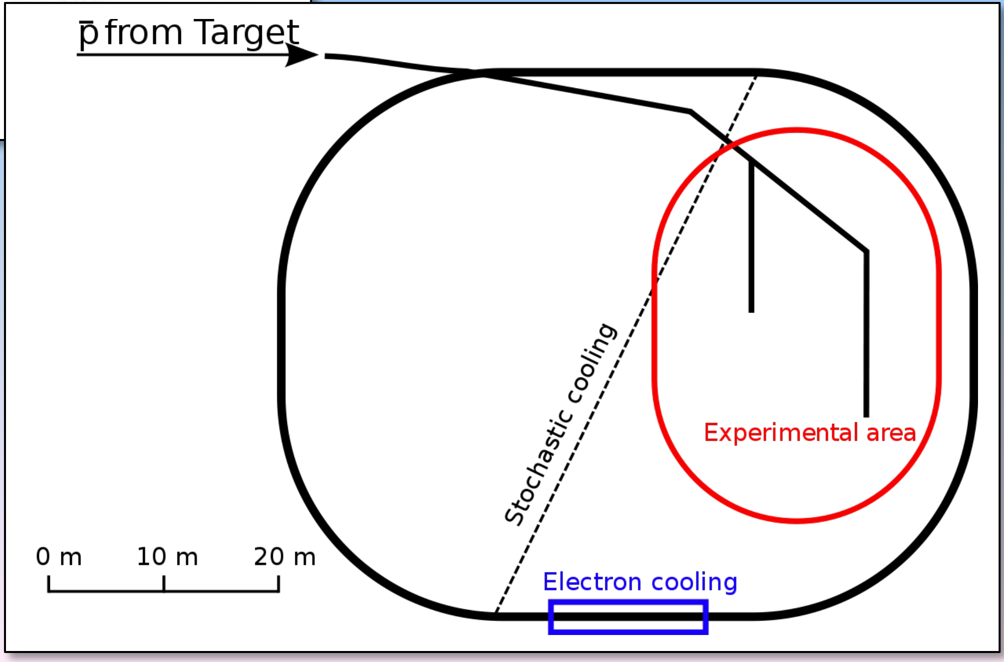
After annihilation: 10,000,000 photons & 1 matter particle



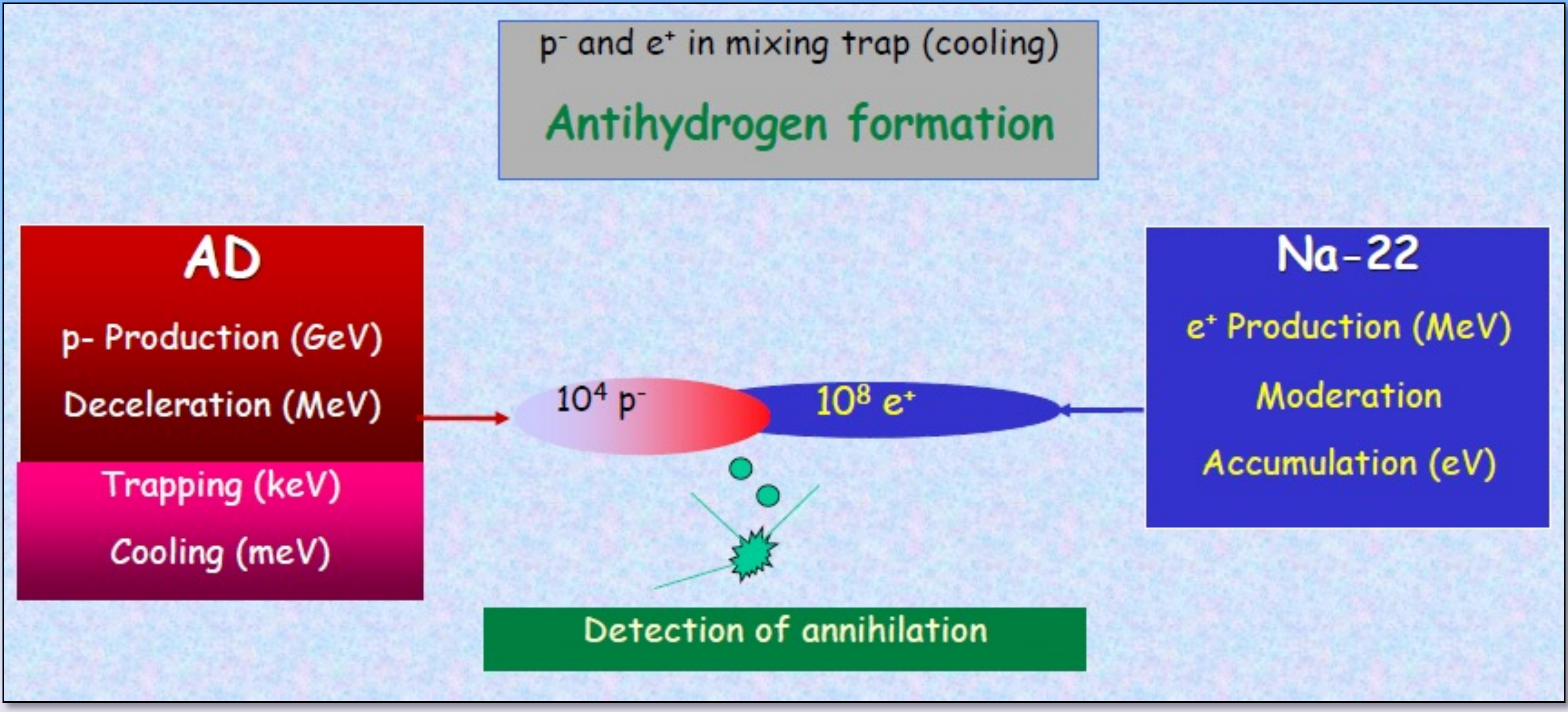


Current Research at the Antimatter Factory

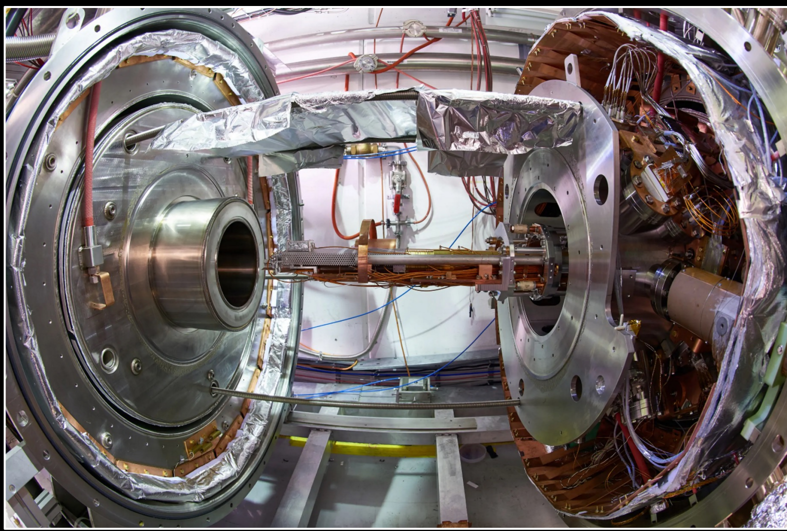


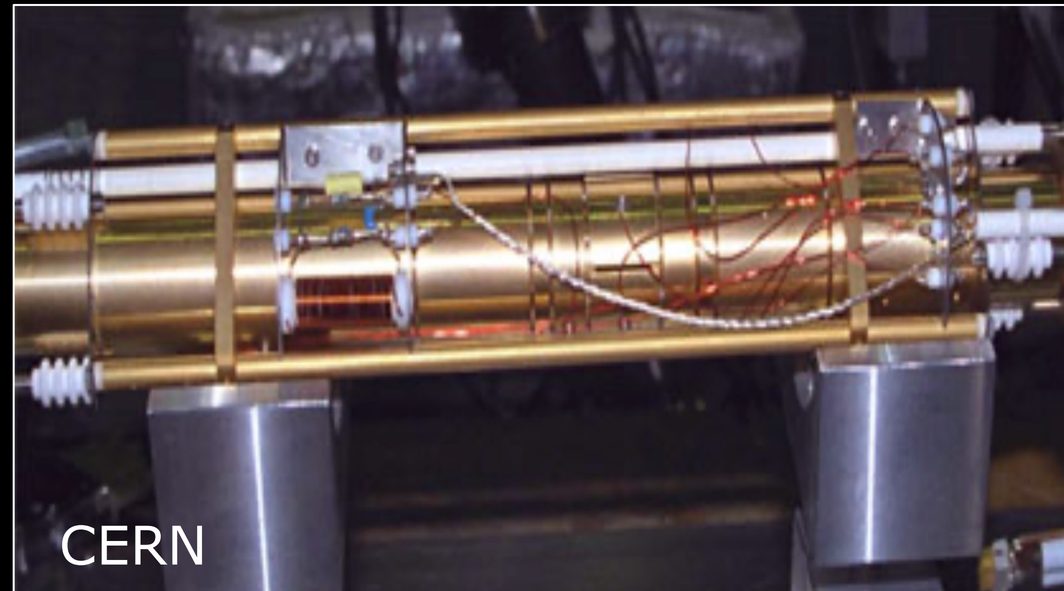


Anti-hydrogen production



Antimatter cannister
(“Penning trap”)

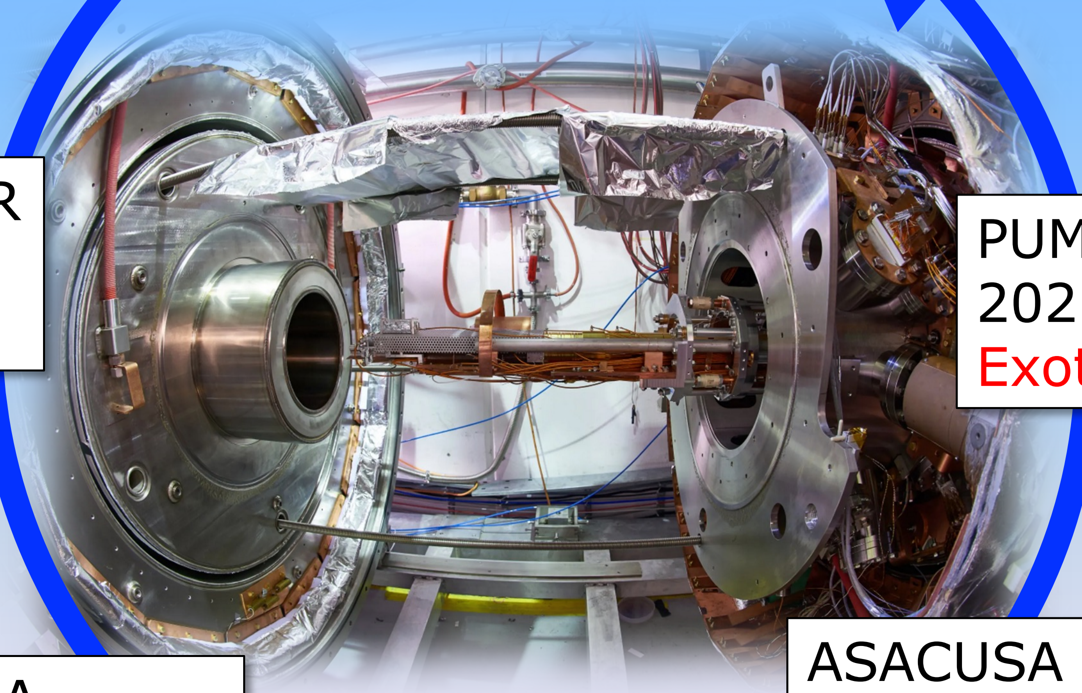




Anti-hydrogen experiments

ATRAP, ATHENA
2002:
Production

BASE-STEP (transport)
2023+:
Magnetic moment



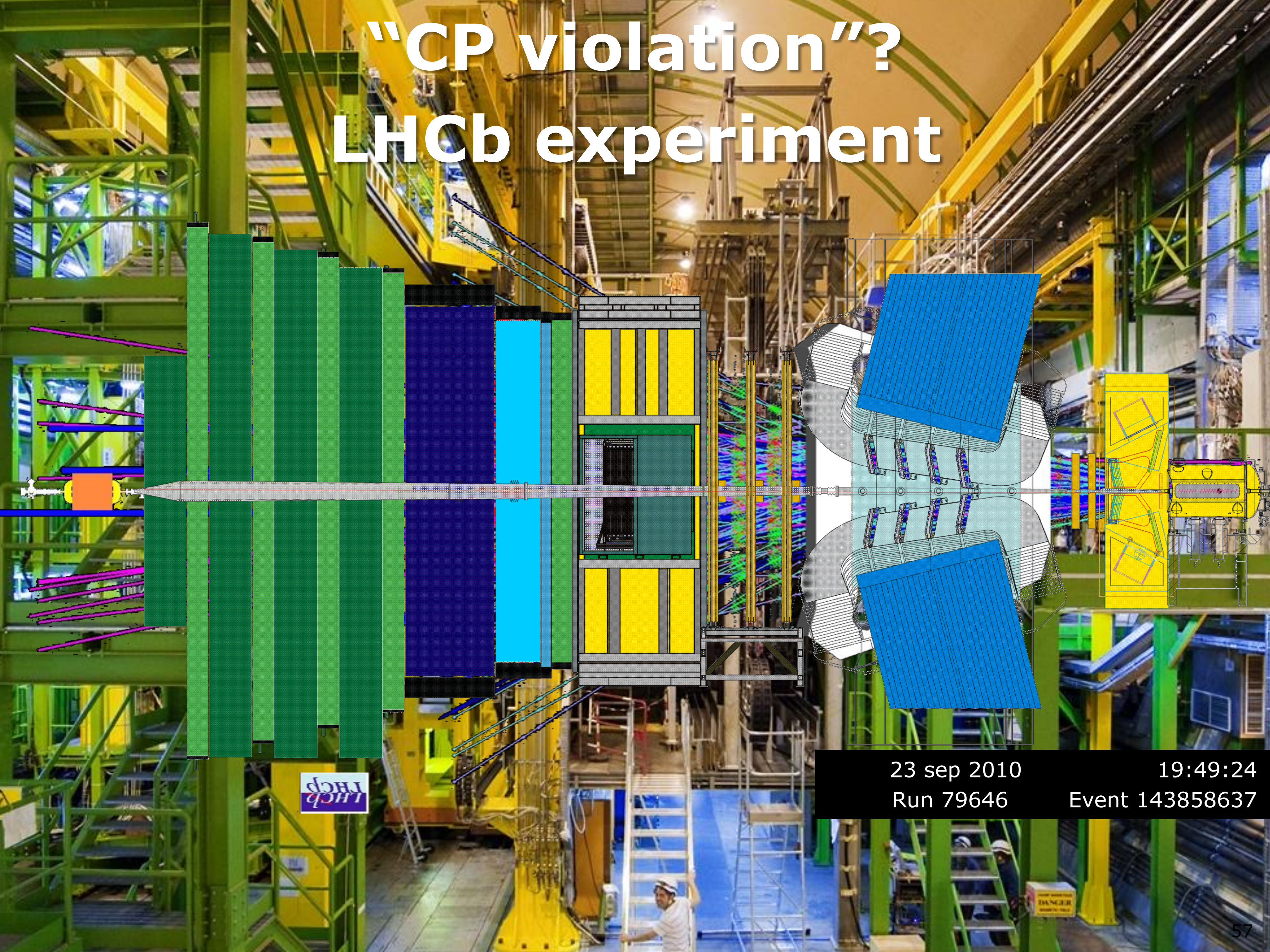
AEgIS, GBAR
2013:
Gravity

PUMA (transport)
2023+:
Exotic nuclei

ALPHA
2011:
Spectroscopy

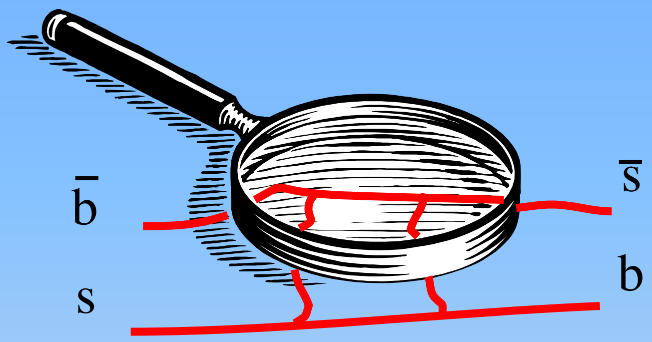
ASACUSA
2011:
Anti-protonic He
Mass

"CP violation"?
LHCb experiment

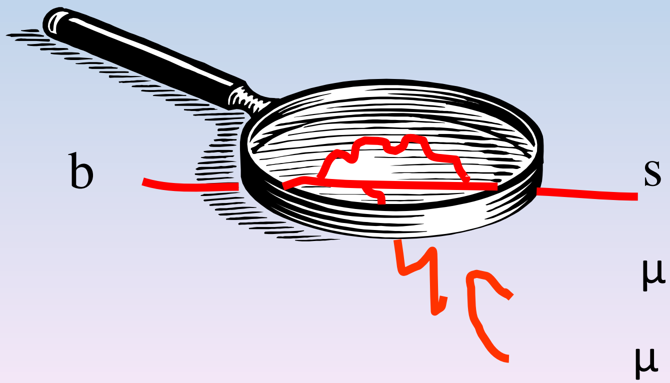


Current Research at LHCb experiment

1) Quantify differences between matter and antimatter

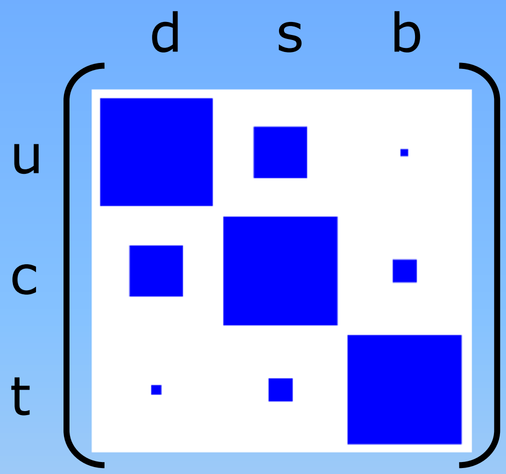


2) Find new particles, that could be responsible for the mystery



Current Research at LHCb experiment

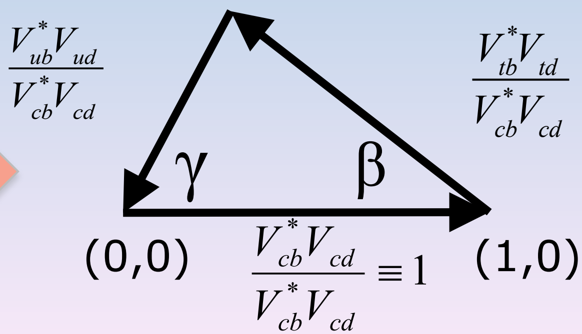
Quark koppelingen:



Matrix is unitary:

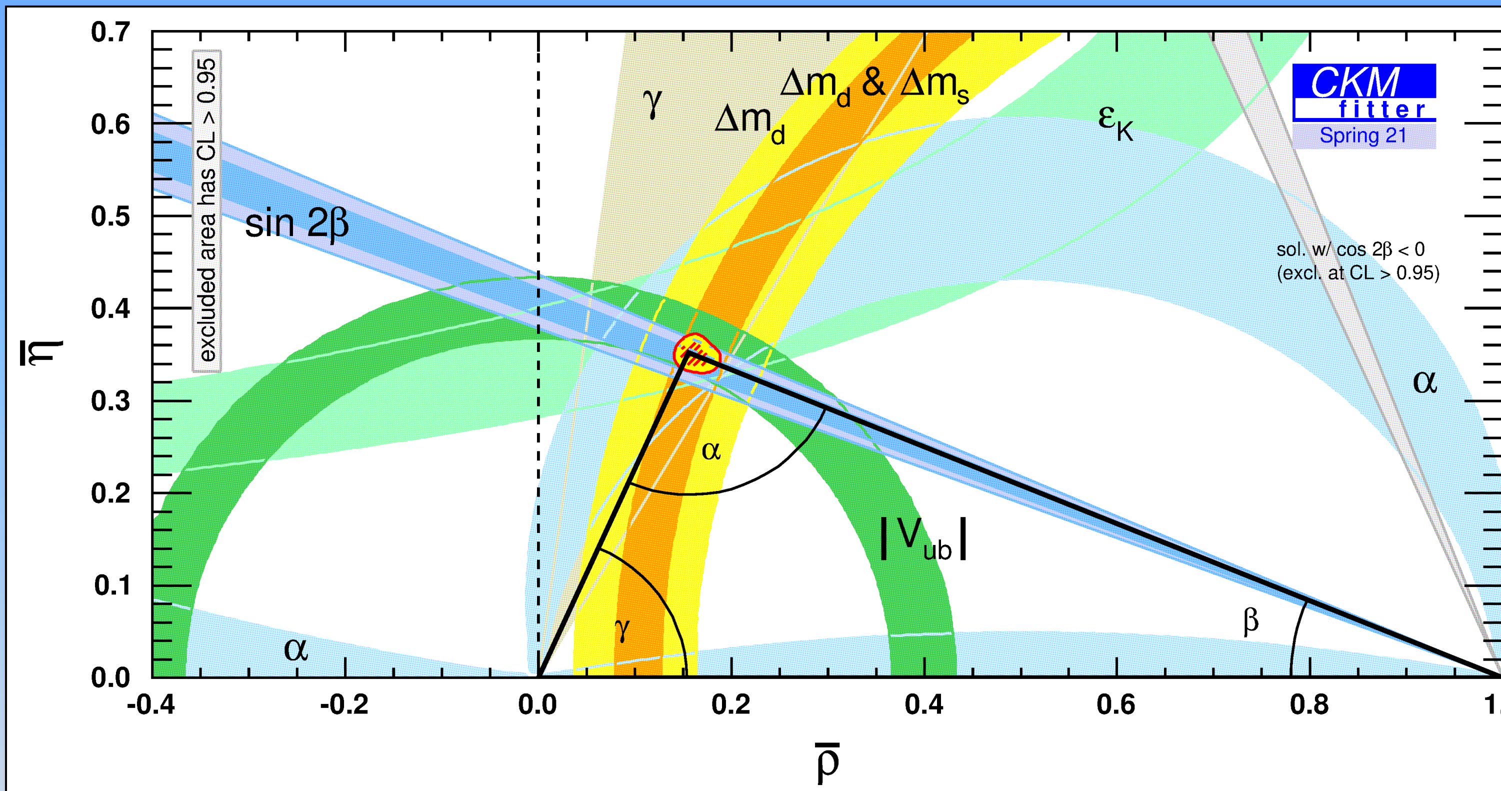
$$V^{+}V=\begin{pmatrix} V^{*}_{ud} & V^{*}_{cd} & V^{*}_{td} \\ V^{*}_{us} & V^{*}_{cs} & V^{*}_{ts} \\ V^{*}_{ub} & V^{*}_{cb} & V^{*}_{tb} \end{pmatrix}\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}=\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$V^{*}_{ub}V_{ud}+V^{*}_{cb}V_{cd}+V^{*}_{tb}V_{td}=0$$



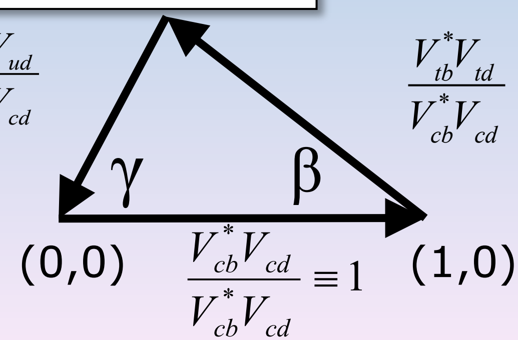
Current Research at LHCb experiment

Multiple precision measurements to probe consistency



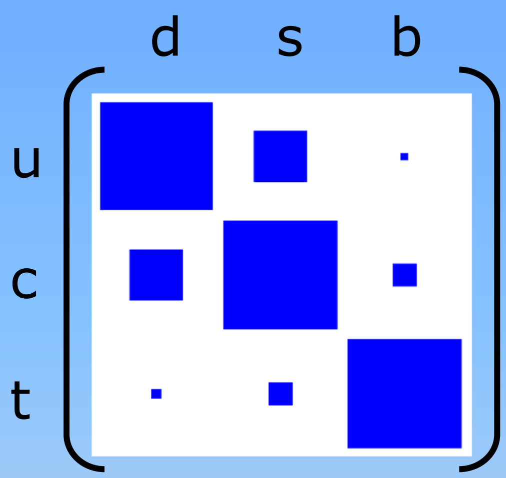
$$V^+V = \begin{pmatrix} V^*_{ud} & V^*_{cd} & V^*_{td} \\ V^*_{us} & V^*_{cs} & V^*_{ts} \\ V^*_{ub} & V^*_{cb} & V^*_{tb} \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$V^*_{ub}V_{ud} + V^*_{cb}V_{cd} + V^*_{tb}V_{td} = 0$$



Intermezzo: Higgs & quark interactions?

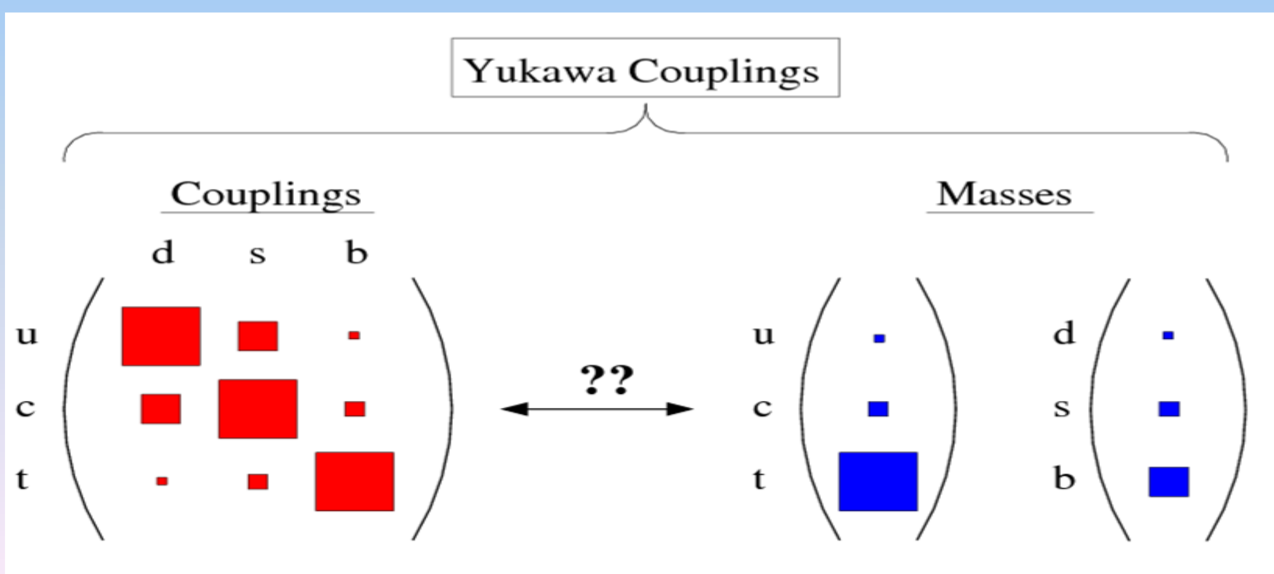
Quark koppelingen:



What is origin of coupling pattern?

What is origin of mass pattern?

→ **Is there a connection?**



Intermezzo: How about the leptons?

the equivalent of the CKM matrix

- *Pontecorvo-Maki-Nakagawa-Sakata matrix*

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

vs

$$\begin{bmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{bmatrix}.$$

a completely different hierarchy!

$$U_{MNSP} \approx \begin{pmatrix} 0.85 & 0.53 & 0 \\ -0.37 & 0.60 & 0.71 \\ -0.37 & 0.60 & -0.71 \end{pmatrix}$$

$$V_{CKM} = \begin{pmatrix} 0.97428 & 0.2253 & 0.00347 \\ 0.2252 & 0.97345 & 0.0410 \\ 0.00862 & 0.0403 & 0.999152 \end{pmatrix}$$

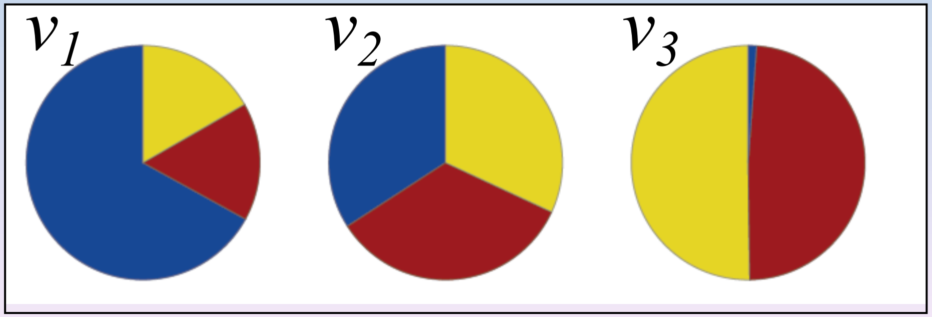
Intermezzo: How about the leptons?

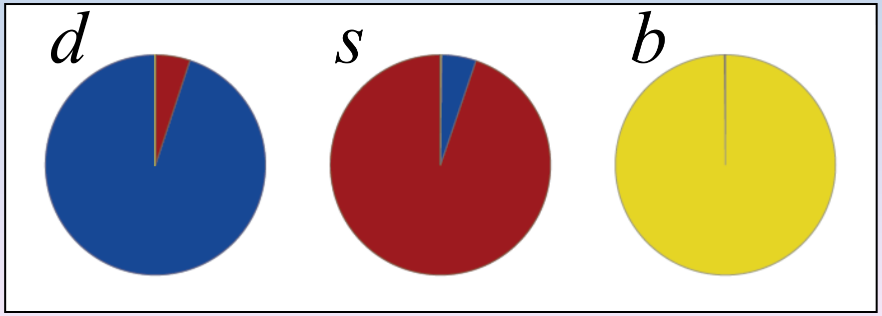
the equivalent of the CKM matrix

- *Pontecorvo-Maki-Nakagawa-Sakata matrix*

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} \quad \textbf{vs} \quad \begin{bmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{bmatrix}.$$

a completely different hierarchy!





See eg. PhD thesis R. de Adelhart Toorop

LHCb: hot topic

deVolkskrant

Moeder aller deeltjes: de zoektocht naar de leptoquark

Is het fundamenteelste deeltje in het universum altijd over het hoofd gezien? Komende week kan de wereld opgeschud worden, als natuurkundigen in Seoul hun resultaten bekendmaken. Leptoquark, onthoud dat woord.

Martijn van Calmthout 29 juni 2018, 11:25

Maar de LHCb-metingen geven al jaren kleine hints dat er iets mis is met deze keurige lepton-universaliteit. En dat elektronen en muonen ergens diep van binnen toch net iets anders met quarks omgaan.

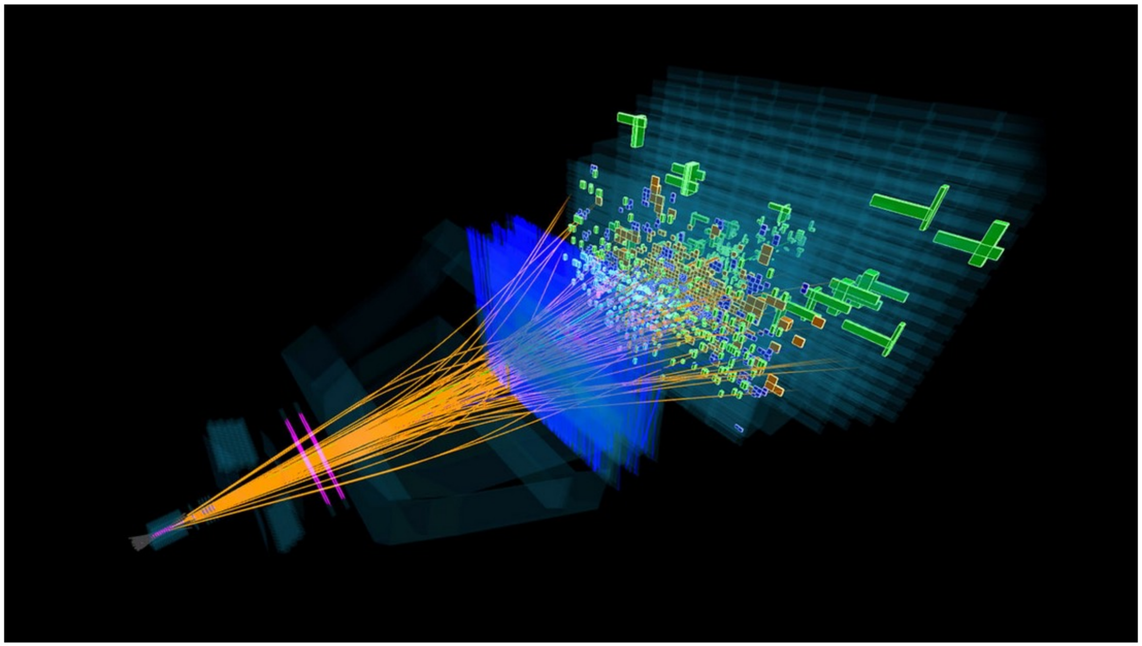
Beeld Rein Janssen

29 Jun 2018

Muon gedraagt zich toch best normaal – of is er meer aan de hand?

29 Dec 2022

Nieuws Jean-Paul Keulen 29-12-2022 15:00:00 Deel dit artikel:



Vervallend B-deeltje in LHCb. Beeld: LHCb/CERN

Een verrassend resultaat uit de deeltjesfysica lijkt te zijn afgeserveerd. Toch zijn er nog openstaande vragen.

Het gold als een van de interessantste resultaten binnen de deeltjesfysica sinds de ontdekking van het higgsdeeltje: het feit dat er bij het verval van bepaalde deeltjes **minder vaak muonen ontstaan dan je zou verwachten**. Zou die afwijking van onze huidige deeltjestheorie, blootgelegd met het deeltjesexperiment **LHCb**, wijzen op het bestaan van nieuwe deeltjes of nieuwe natuurkrachten?

“Toch zijn er nog openstaande vragen”

KIJK magazine, https://www.kijkmagazine.nl/nieuws/muon-gedraagt-zich-toch-best-normaal-of-is-er-meer-aan-de-han

Take home message

- Symmetry
  - Not *just* beautiful…
- Particle Physics
  - Is symmetry more than a tool?
- Antimatter
  - The absence is a big existential question…

+ why are right-handed couplings absent in the weak interaction?
+ why does only the weak interaction violate P and CP ?
+ why are there precisely 3 generations ?
+ why is electric charge of a down quark precisely 1/3 of the electron charge ?
+ …

Thank you!

Symmetry and Harmony!

式外，他们还需要提出力载体的概念。力载体以十分特定的方式连接自由移

标准模型公式

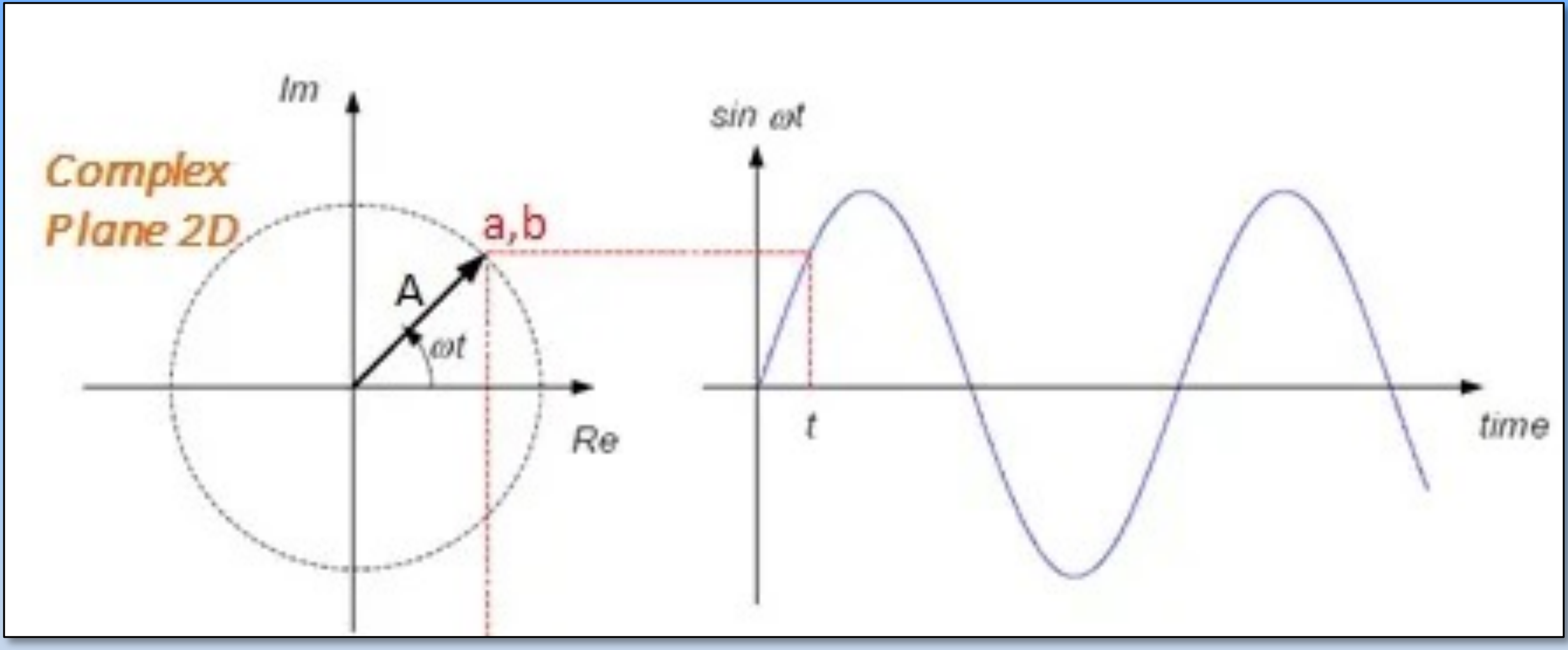
乐谱

Ivo van Vulpen, *De melodie van de natuur*, Uitgeverij Olympus

Backup slides…

Symmetry and particle physics

Symmetric to a change of "*phase*"?



Symmetry and particle physics

Symmetric to a change of "*phase*"?

Yes!

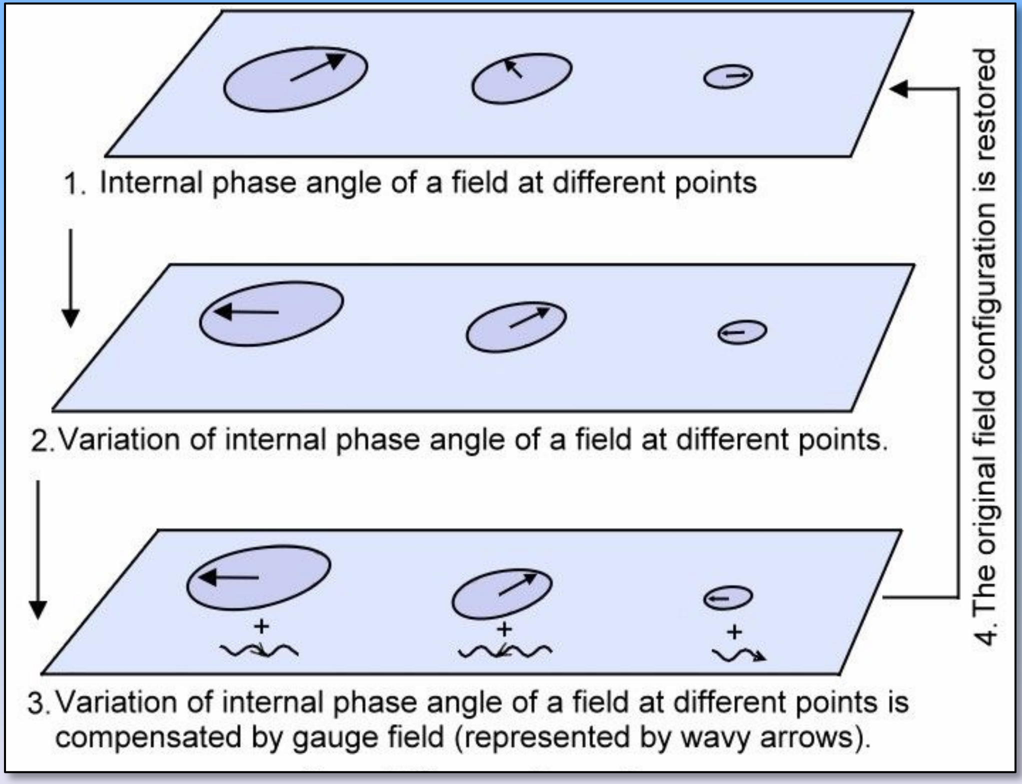
Remember quantum mechanics:

- Wave function: $\psi(x,t) = e^{ikx - i\omega t}$
- Expectation value: $\langle Q \rangle = \int_{-\infty}^{+\infty} \psi^*(x,t)\hat{Q}\psi(x,t)dx$

Symmetry and particle physics

Symmetric to a change of "*phase*"?

What if we require that the phase is *everywhere* different?



https://web2.ph.utexas.edu/~coker2/index.files/gaugef.htm

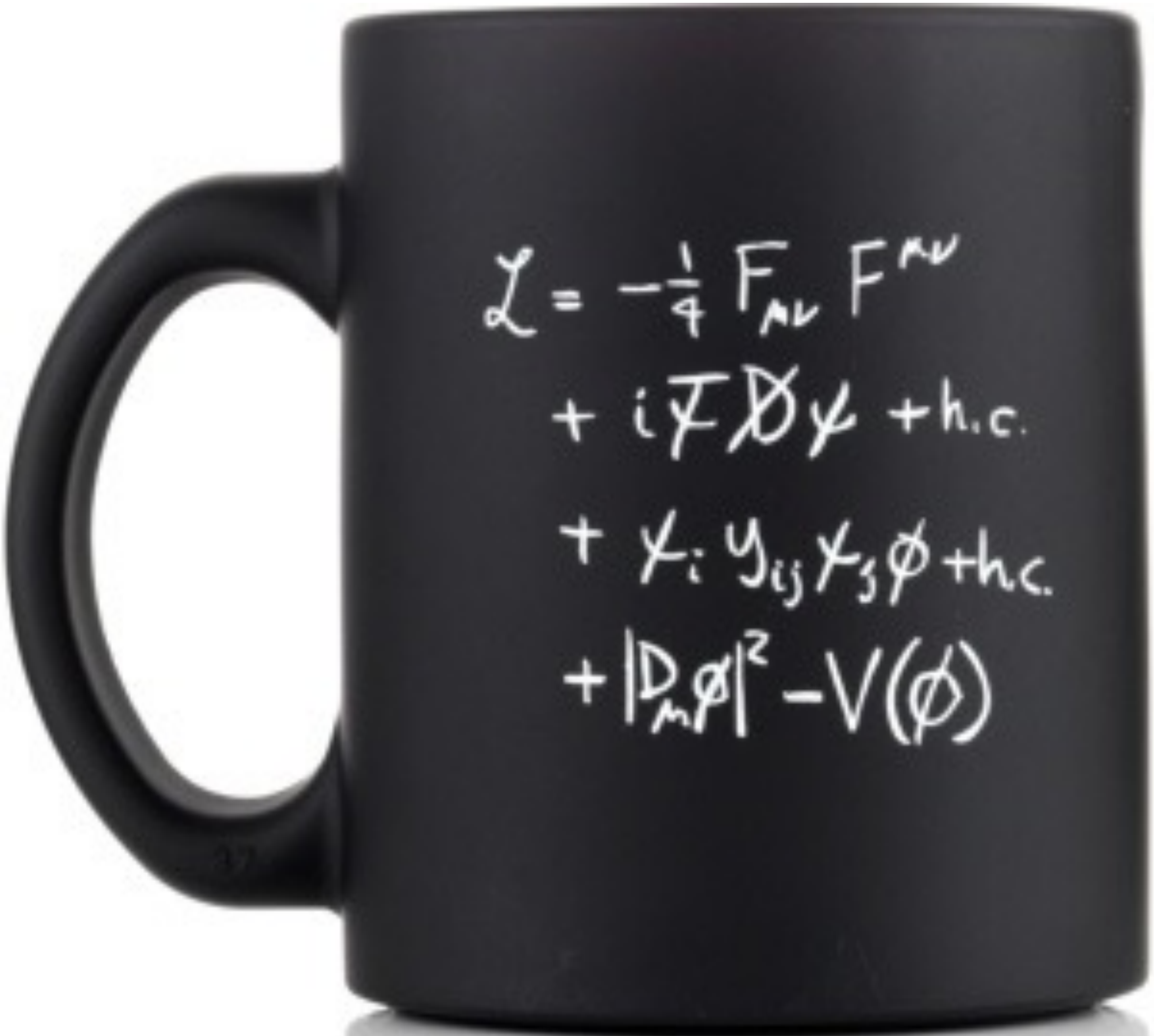
Local Gauge Invariance

Symmetry = Magic!

Imposing Local Gauge Invariance gives the Forces

Symmetries

Transformations	Unobservables	Conservation laws and selection rules
Translation in space $\boldsymbol{r} \rightarrow \boldsymbol{r} + \Delta$	Absolute position in space	Momentum
Translation in time $t \rightarrow t + \tau$	Absolute time	Energy
Rotation $\boldsymbol{r} \rightarrow \boldsymbol{r}'$	Absolute direction in space	Angular momentum
Space inversion $\boldsymbol{r} \rightarrow -\boldsymbol{r}$	Absolute left or right	Parity
Time reversal $t \rightarrow -t$	Absolute sign of time	Kramers degeneracy
Sign reversion of charge $e \rightarrow -e$	Absolute sign of electric charge	Charge conjugation
Particle substitution	Distinguishability of identical particles	Bose or Fermi statistics
$\psi(x) \rightarrow \psi'(x) = e^{i\alpha(x)}\psi(x)$	Absolute phase	Charge (electric)
$\psi \rightarrow \psi' = \exp\left(i\frac{\vec{\sigma}\cdot\vec{\alpha}}{2}\right)\psi$	Absolute phase	Charge (weak isospin)
$\psi \rightarrow \psi' = \exp\left(\sum_{a=1,8}\frac{i}{2}\theta_a(x)\lambda_a\right)\psi$	Absolute phase	Charge (color)



- Describes the behaviour of particles

Photons $F_{\mu\nu}$

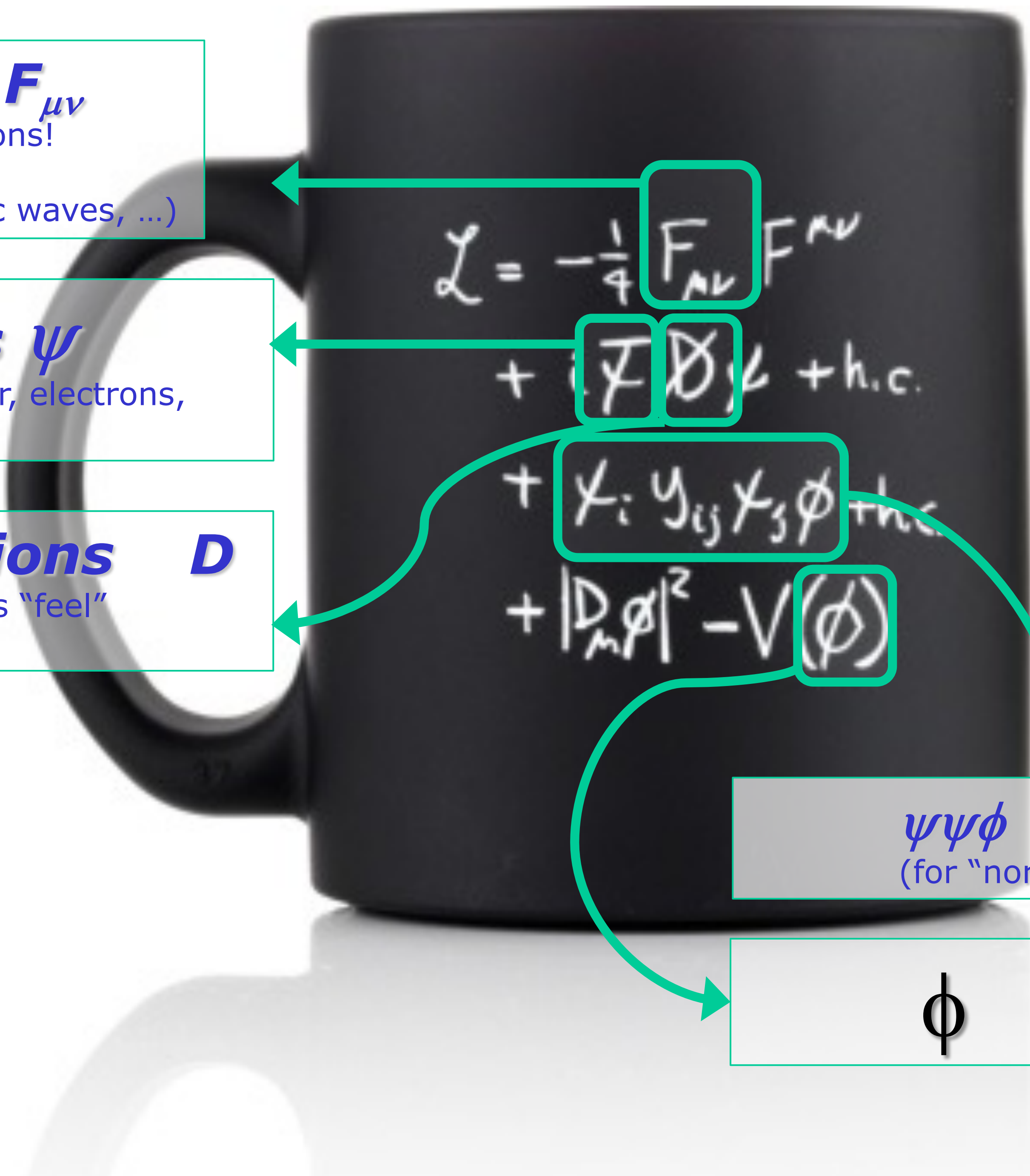
(Maxwell equations!
E-field, B-field,
electro-magnetic waves, …)

Particles ψ

(“normal” matter, electrons,
quarks, …)

Interactions D

(how the partiles “feel”
eachother)



$\psi\psi\phi$ ***Mass***

(for “normal” particles)

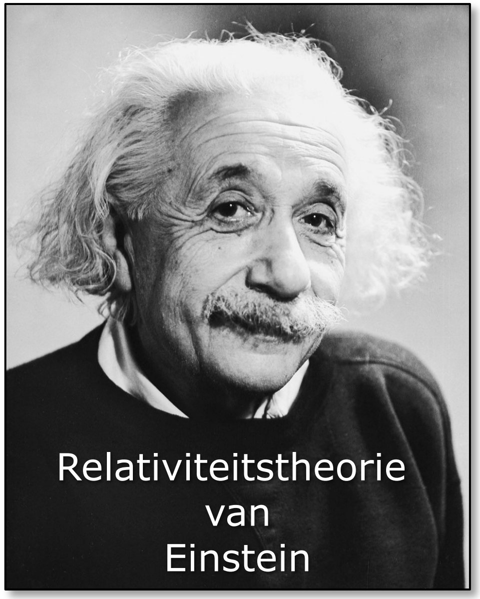
ϕ Higgs

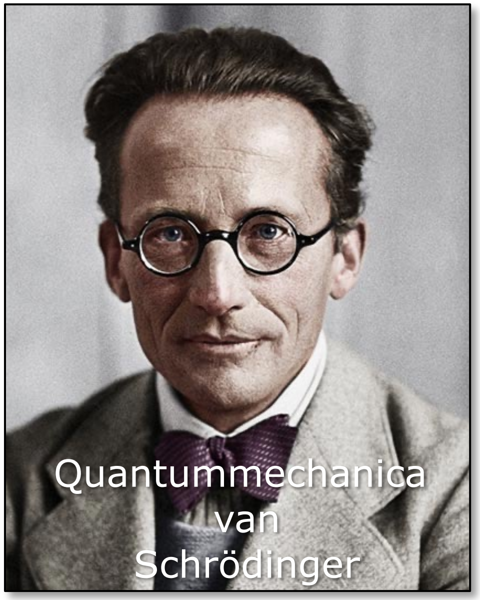
Antimaterie

- <u>Deel 1: Hoezo?</u>
  - Wat is het
  - Hoe is het bedacht
  - Wat is het probleem
- <u>Deel 2: Wat nu?</u>
  - Uit de ruimte
  - Antiwaterstof
  - Antimaterie verschillen

77

~ 1920





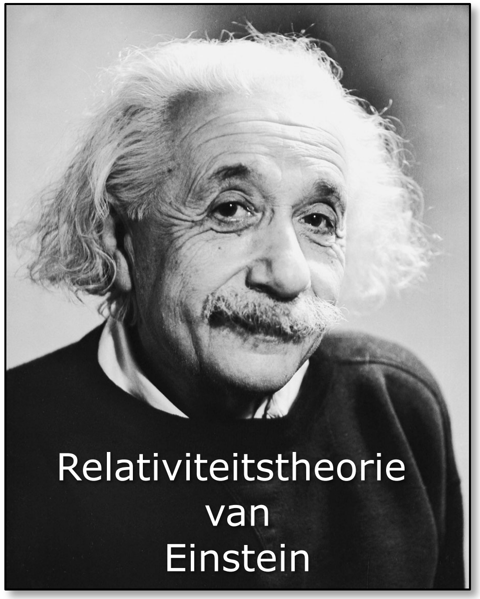
"Relativistisch"

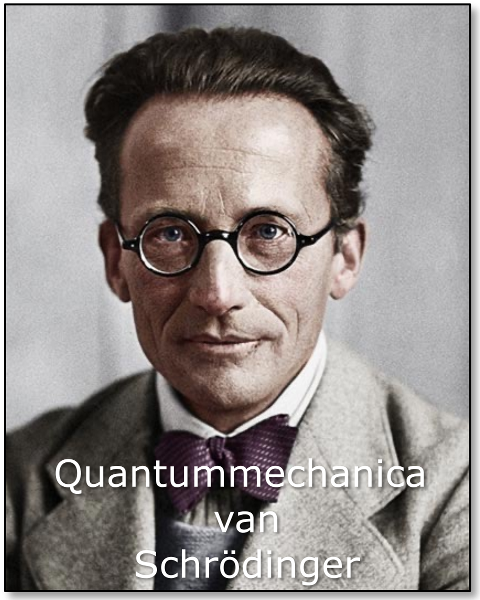
$$E = mc^2$$

"Gewoon"

$$i\frac{\partial}{\partial t}\psi = -\frac{\nabla^2}{2m}\psi$$

~ 1920





"Relativistisch"

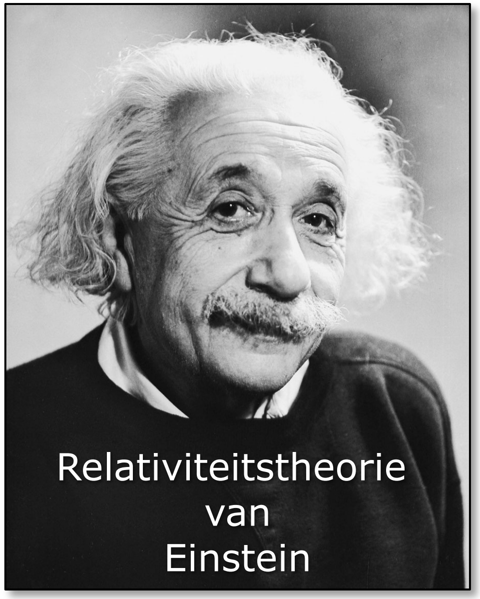
$$E = mc^2$$

"Gewoon"

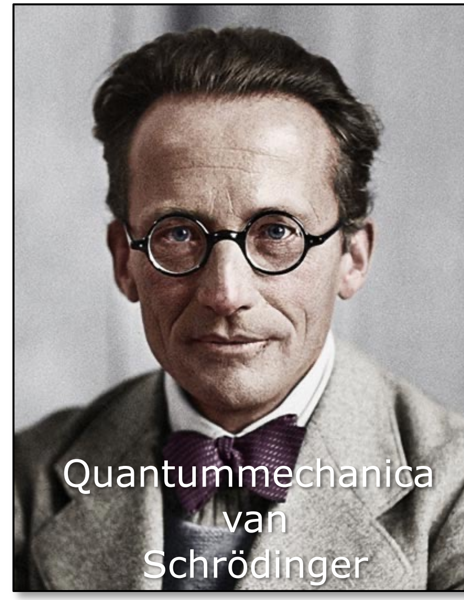
$$E = \frac{1}{2}mv^2$$

$$(p = mv)$$

$$E = \frac{p^2}{2m}$$



~ 1920



"Relativistisch"

$$E = mc^2 \quad (p = 0)$$

$$E^2 = p^2 + m^2$$

⇦ Anders! ⇨

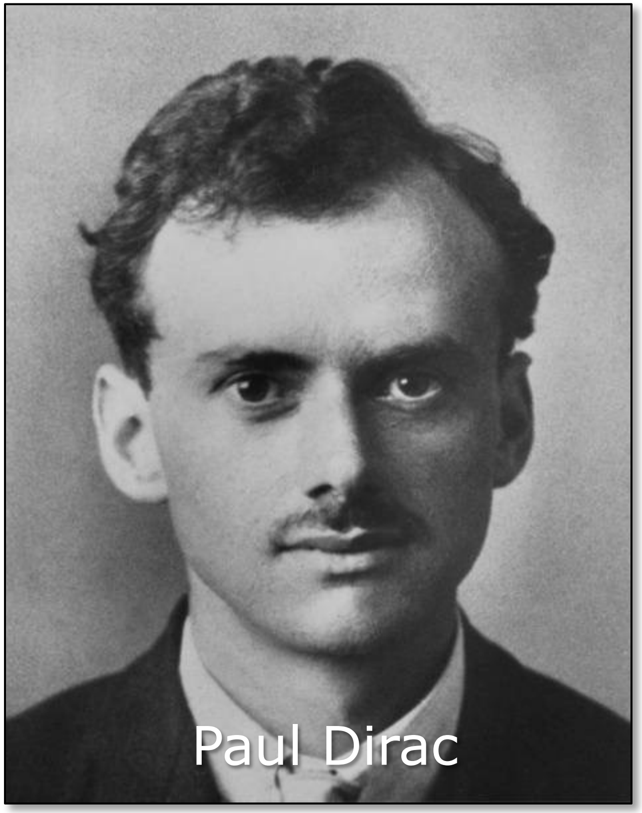
"Gewoon"

$$E = \frac{1}{2}mv^2$$

$$i\frac{\partial}{\partial t}\psi = -\frac{\nabla^2}{2m}\psi$$

$$E = \frac{p^2}{2m}$$

1928 !



Antimaterie!

$$\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix}$$

$$H\psi = (\vec{\alpha} \cdot \vec{p} + \beta m)\ \psi$$

Einstein:

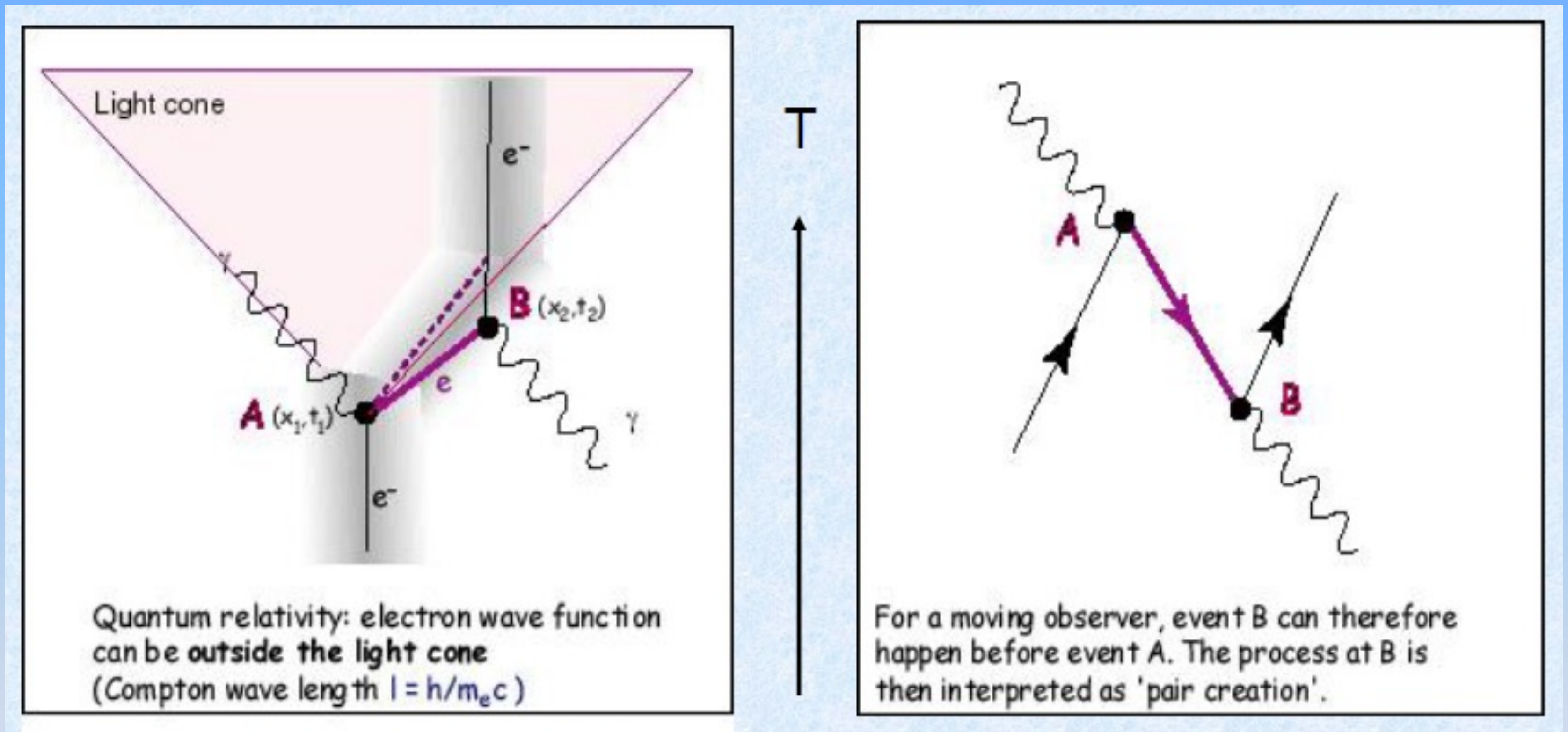
$$H^2\psi = \left(\vec{p}^2 + m^2\right)\ \psi$$

Dirac:

$$\begin{aligned} H^2\psi &= (\alpha_i p_i + \beta m)^2\ \psi \qquad \text{with: } i = 1,2,3 \\ &= \Big(\underbrace{\alpha_i^2}_{=1}\ p_i^2 + \underbrace{(\alpha_i\alpha_j + \alpha_j\alpha_i)}_{=0 \quad i>j}\ p_i p_j + \underbrace{(\alpha_i\beta + \beta\alpha_i)}_{=0} p_i m + \underbrace{\beta^2}_{=1}\ m^2\Big)\ \psi \end{aligned}$$

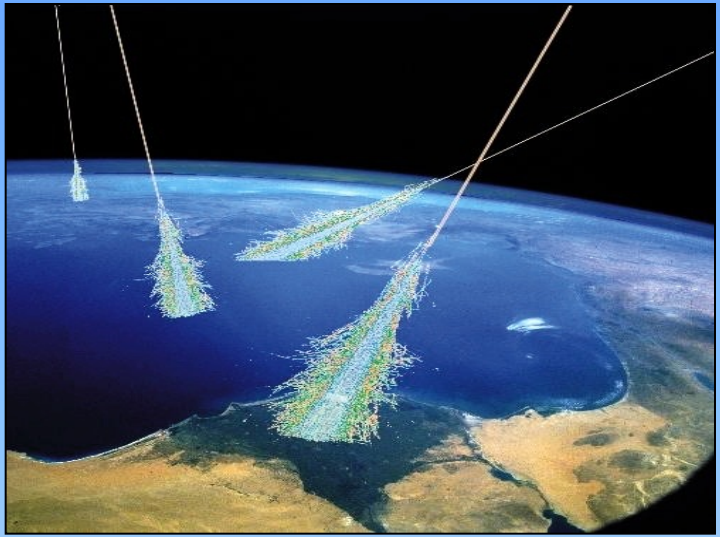
Why anti-matter must exist!

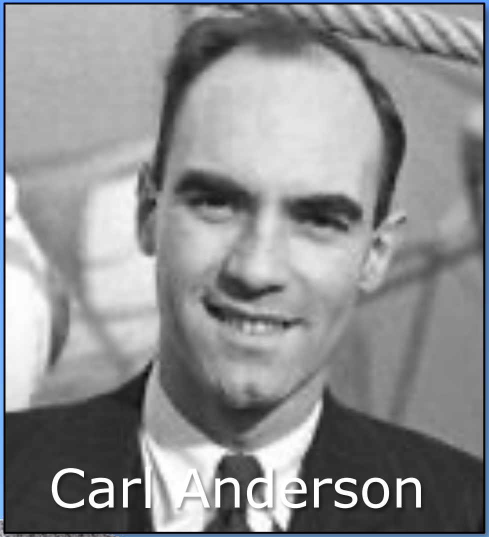
"Feynman-Stueckelberg interpretation"

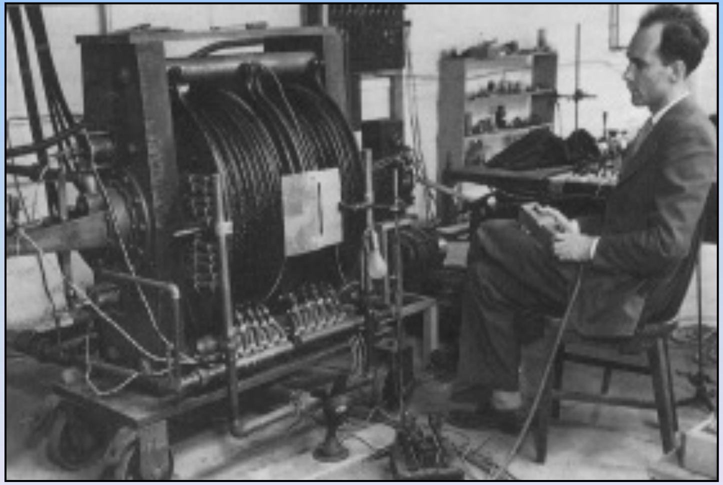


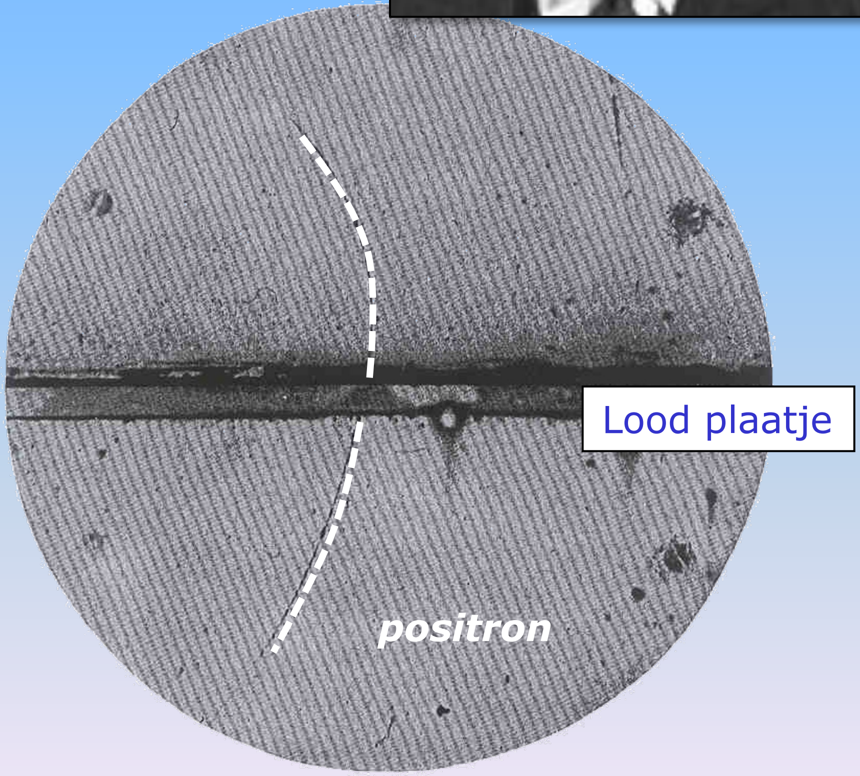
"One observer's electron is the other observer's positron"

1932: Ontdekking van antimaterie!









Nobelprijs 1936

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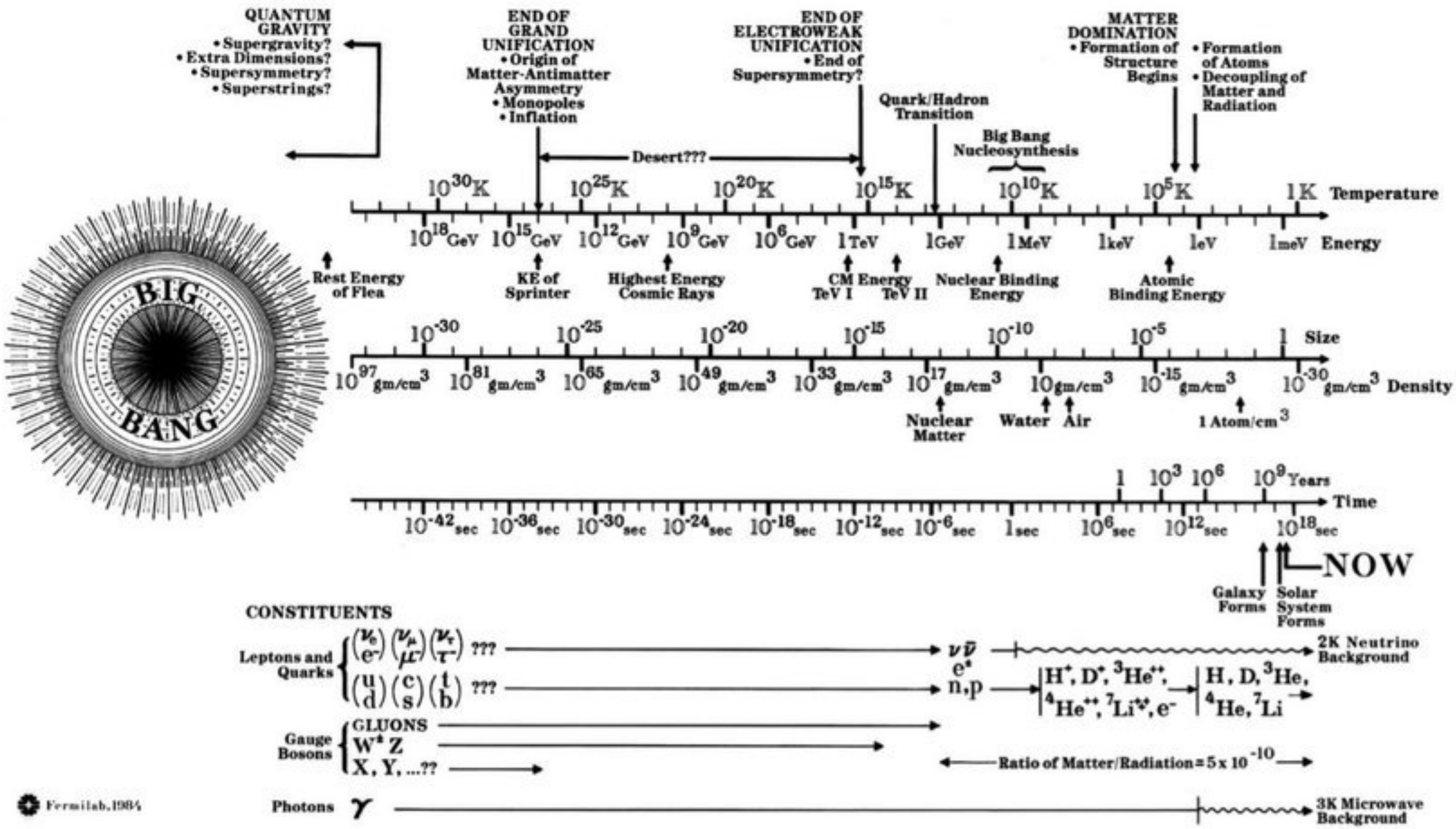
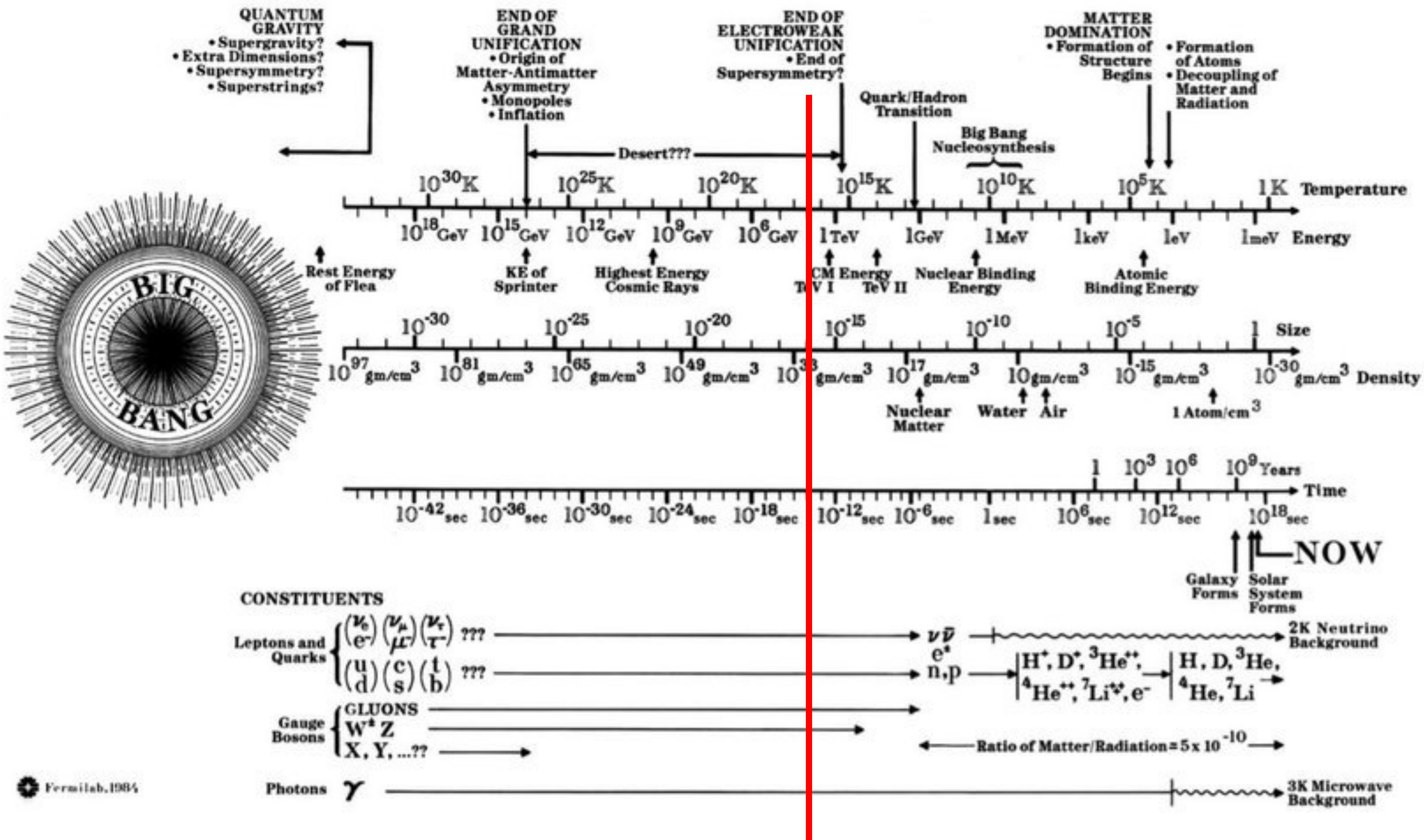
  - Antiwaterstof
  - Antimaterie verschillen

Geschiedenisles



https://www.researchgate.net/publication/357823952/figure/fig1/AS:1111988524589069@1642130132503/Complete-history-of-the-Universe-a-collaboration-of-Angela-Gonzalez-of-Fermilab-and-the.jpg

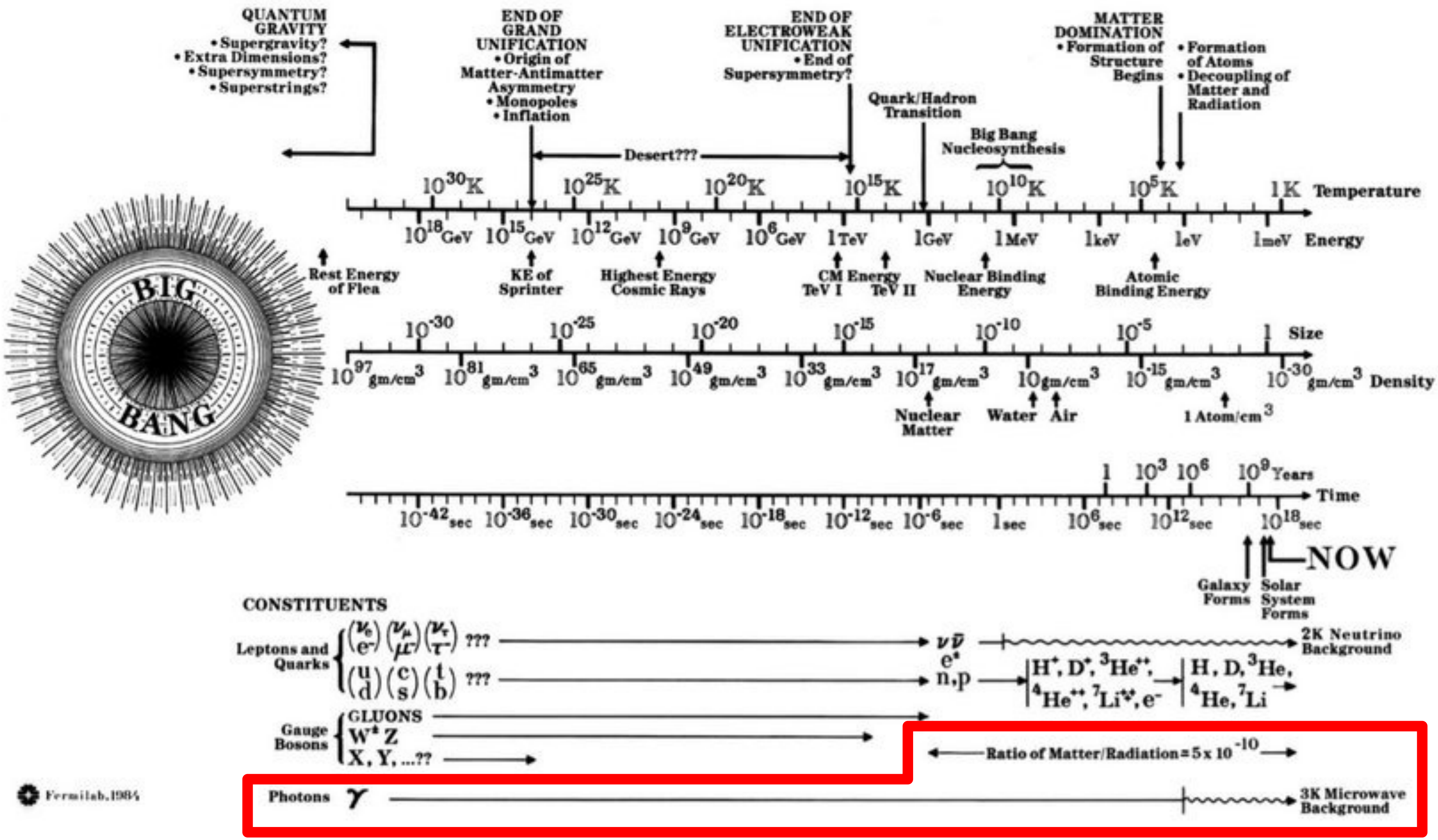
Geschiedenisles



U bent hier: ◆ 10^{-16} m, 10^{-14} s, 10^{16} K

https://www.researchgate.net/publication/357823952/figure/fig1/AS:1111988524589069@1642130132503/Complete-history-of-the-Universe-a-collaboration-of-Angela-Gonzalez-of-Fermilab-and-the.jpg

Geschiedenisles



Fotonen van materie – antimaterie annihilatie

https://www.researchgate.net/publication/357823952/figure/fig1/AS:1111988524589069@1642130132503/Complete-history-of-the-Universe-a-collaboration-of-Angela-Gonzalez-of-Fermilab-and-the.jpg

De stand van zaken in 2023

http:// pdg.lbl.gov

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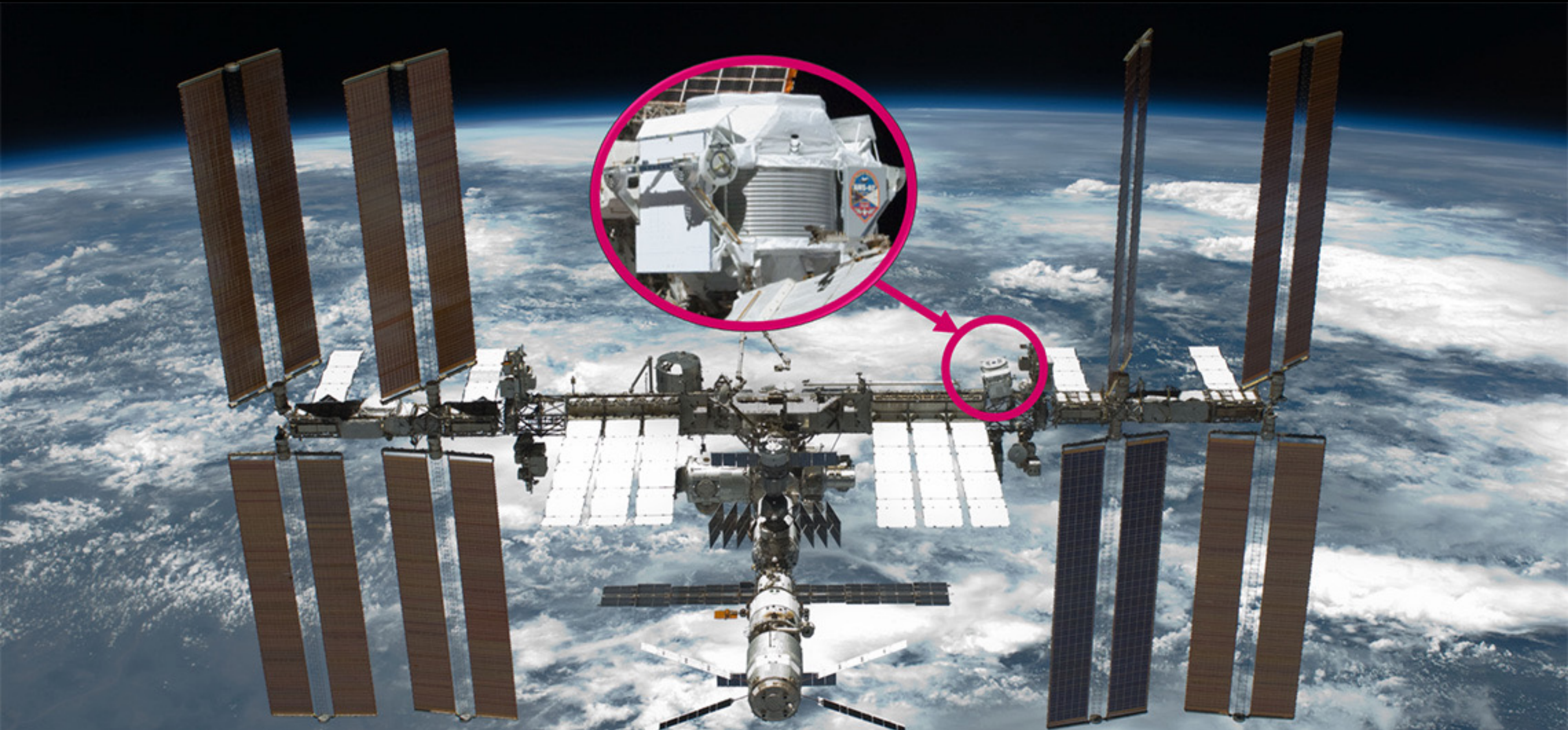
89

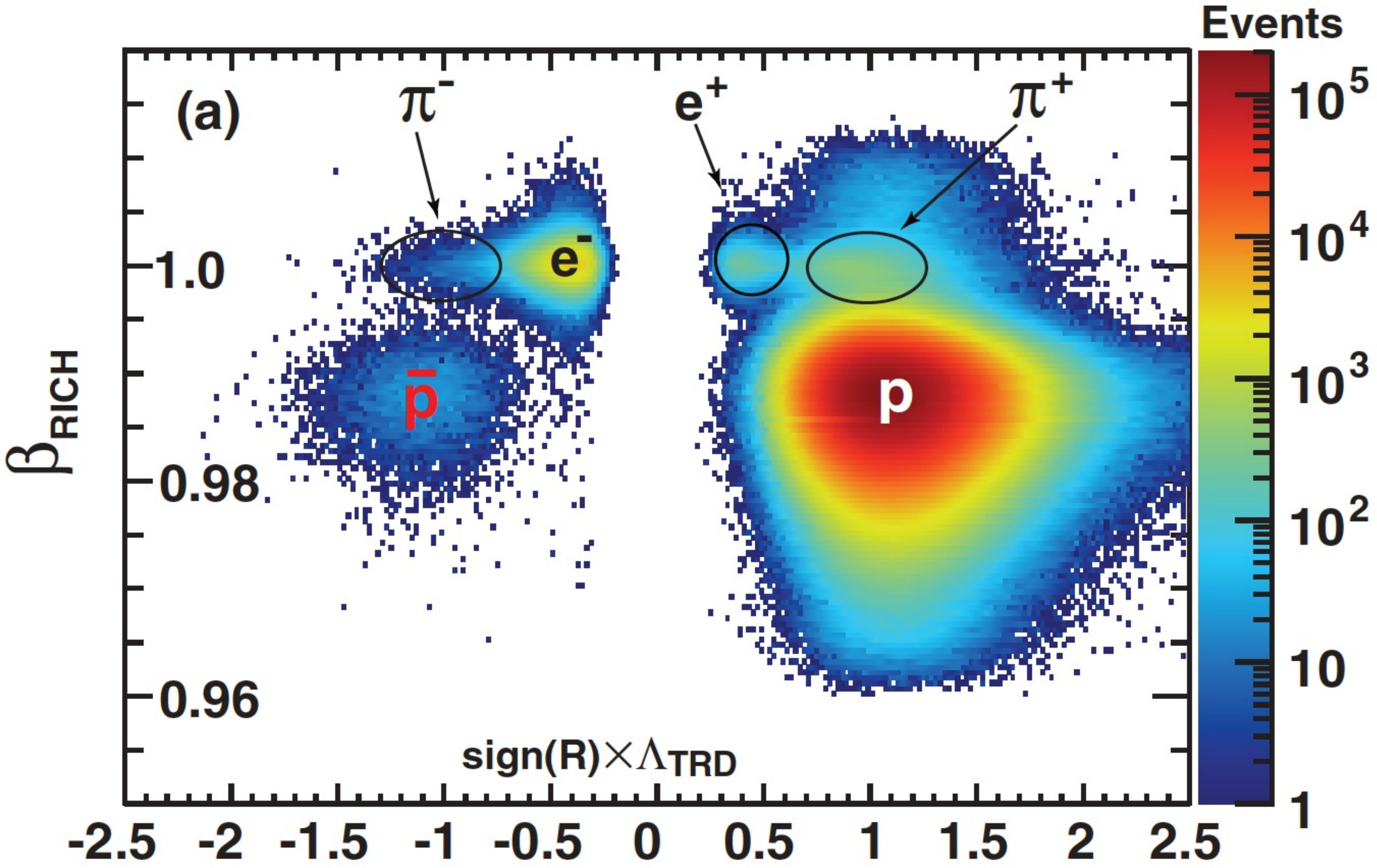
Uit de ruimte?

Het AMS experiment



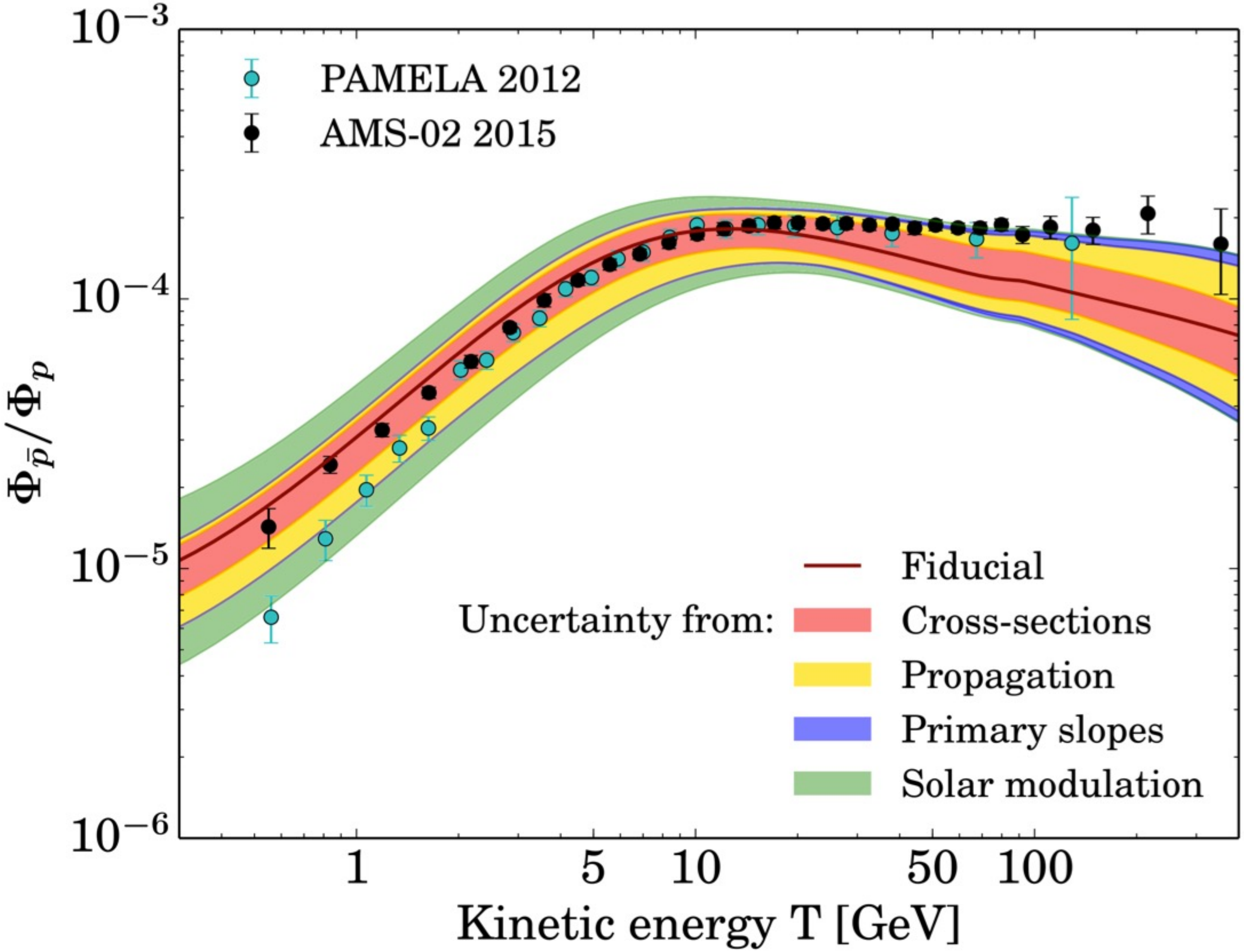
Anti-protonen?

- Men verwacht anti-protonen uit ster-processen…



Anti-protonen?

… maar niet te veel! (ongeveer 1 op de 10,000)



Giessen et al, *JCAP* 09 (2015) 023 ; arXiv:1504.04276

Anti-helium ?? Geruchten…

- AMS-02 schijnt 8 anti-He atomen te hebben gezien…
  - 1 anti-He op 100 miljoen He *(AMS days La Palma 18 Apr 2018, not published)*
  - *"Should these events be confirmed, their detection would be a breakthrough discovery, with immediate and considerable implications onto our current understanding of cosmology"* *(https://inspirehep.net/literature/1830770)*

- Mysterie:
  - ^{3}He bevat 3 nucleonen (2 protonen + 1 neutron)
  - voor elk extra nucleon, verwacht je 1000x lagere productie
  - **Maar er zijn geen anti-deuteronen gezien! (1 proton + 1 neutron)**

“We then entertain the possibility that these events originate from anti-matter-dominated regions in the form of anti-clouds or anti-stars.”

V.Poulin et al., PoS EPS-HEP2019 (2020) 074

https://inspirehep.net/literature/1830770

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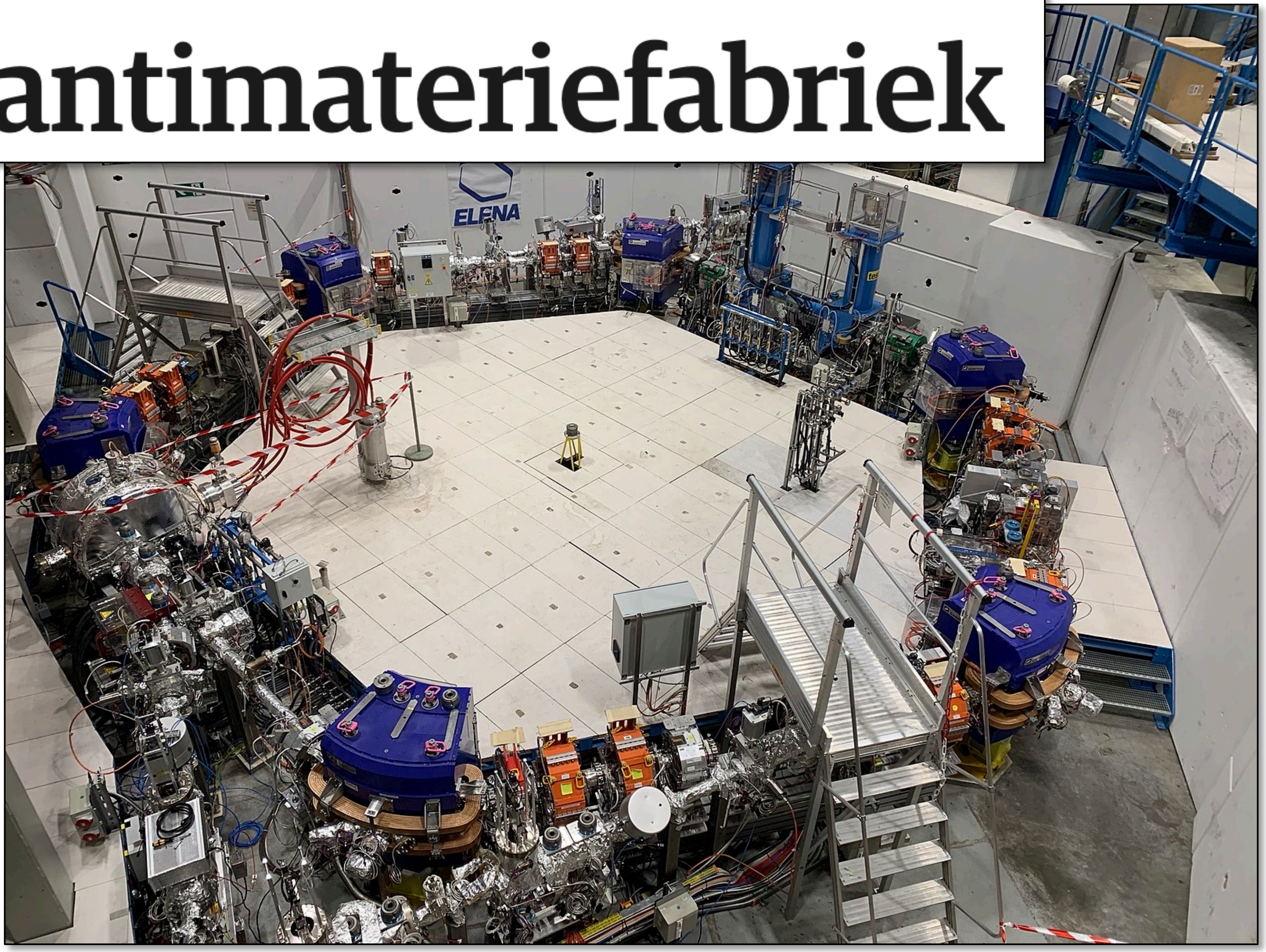
≡ Menu **nrc›**

Reportage

De antimateriefabriek



https://www.nrc.nl/nieuws/2019/11/29/de-antimateriefabriek-a3982140

Het Bernini mysterie

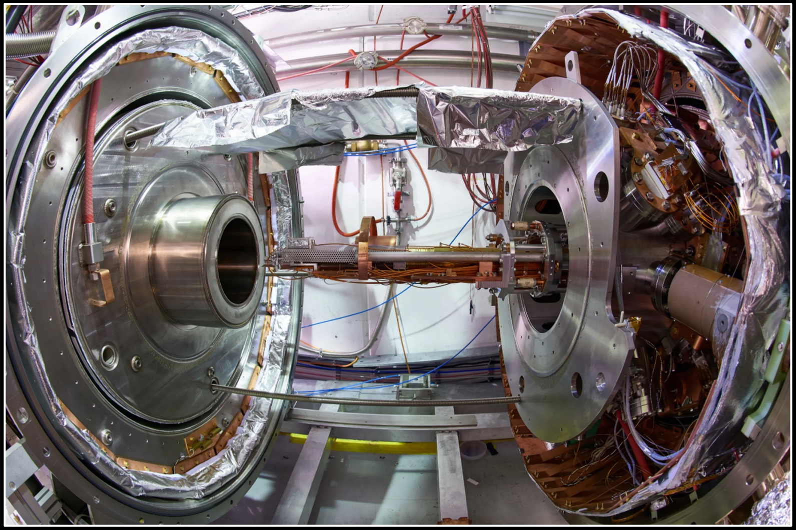
("Angels & Demons", 2009)

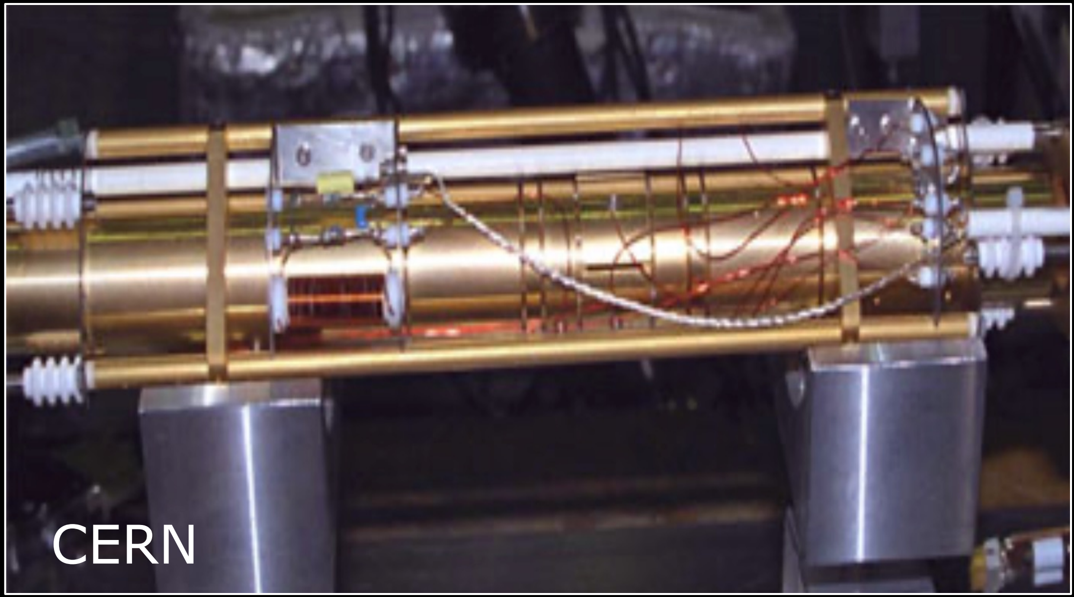
https://www.imdb.com/title/tt0808151/

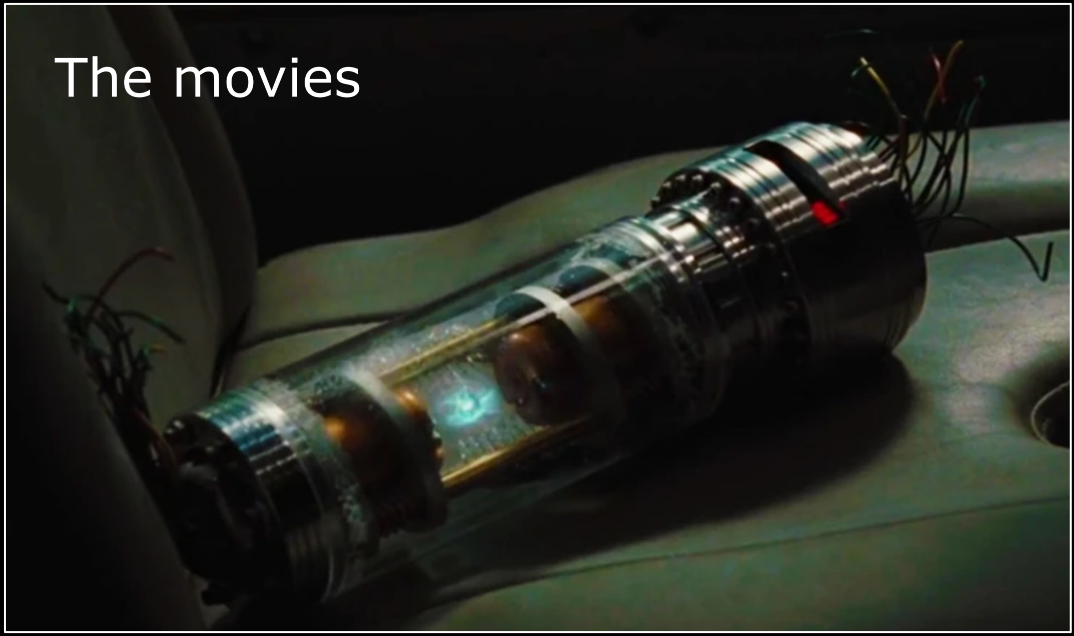
Materie | Antimaterie

waterstof | Anti-waterstof

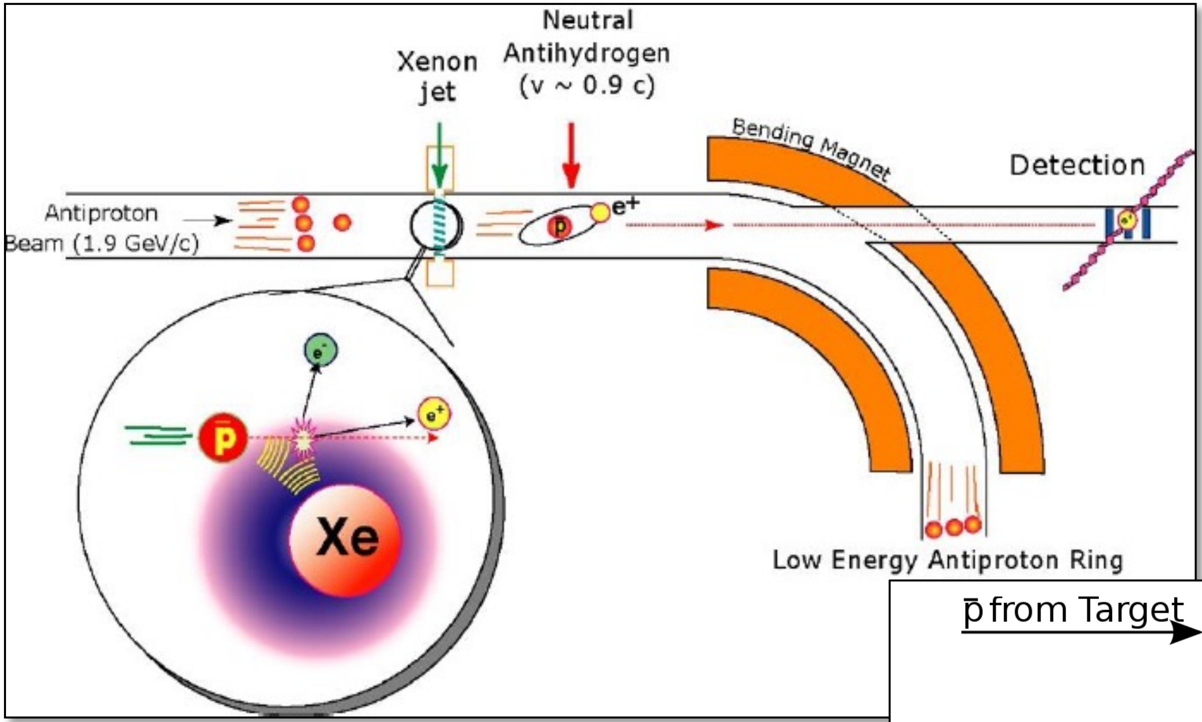
Antimatter cannister ("Penning trap")

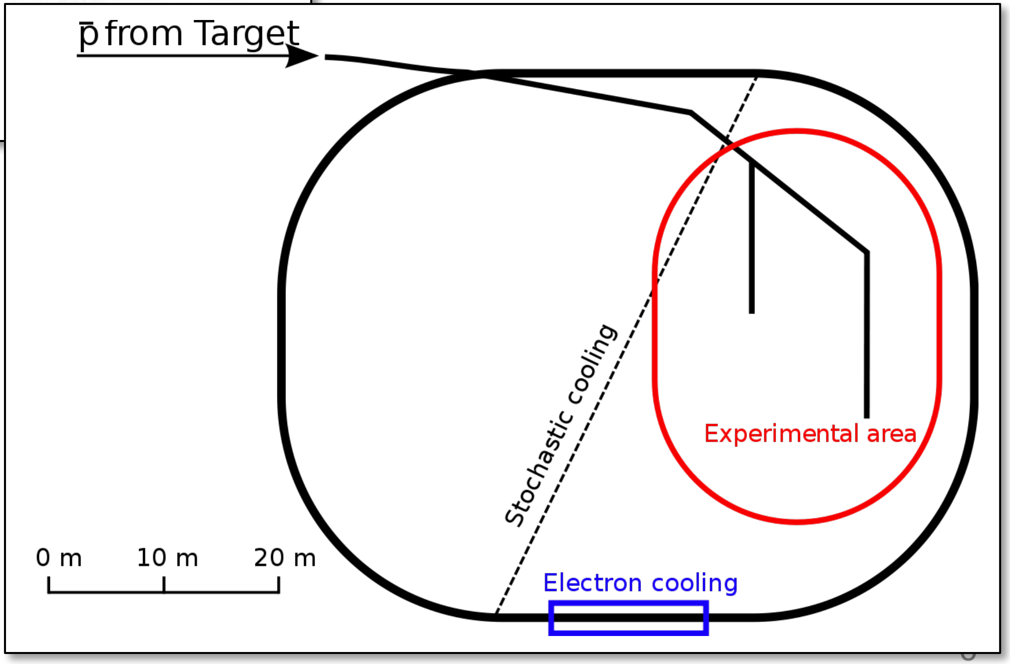




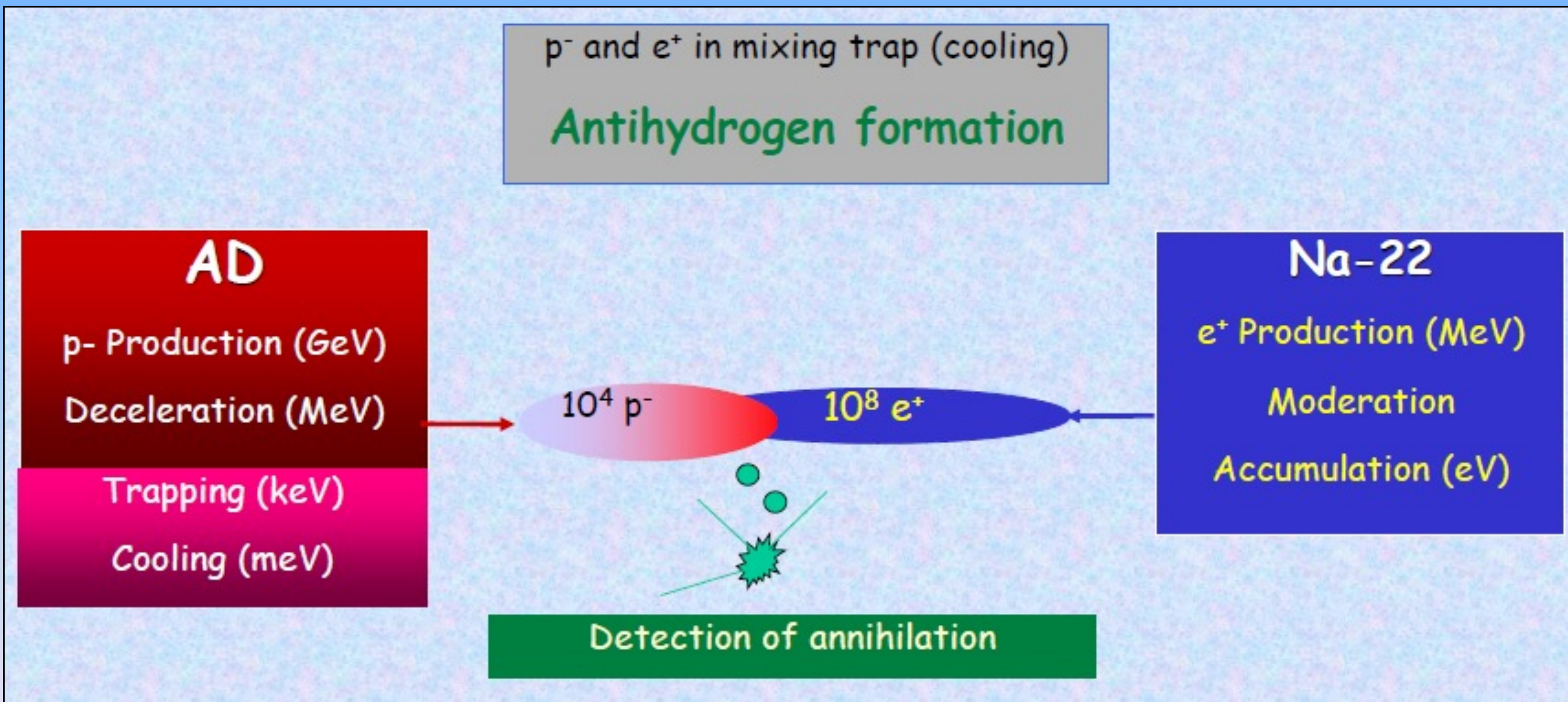


Anti-proton productie

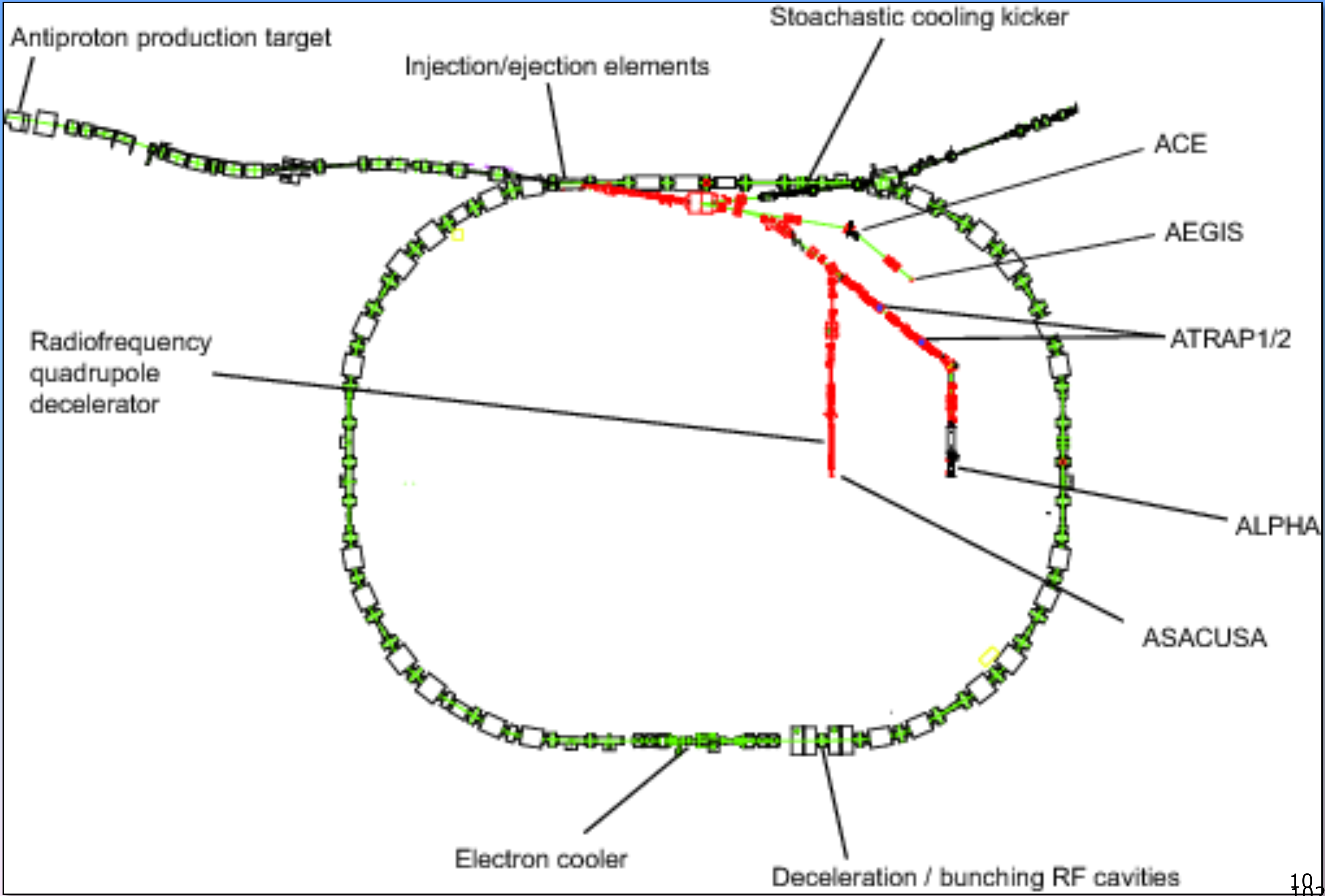




Anti-hydrogen productie



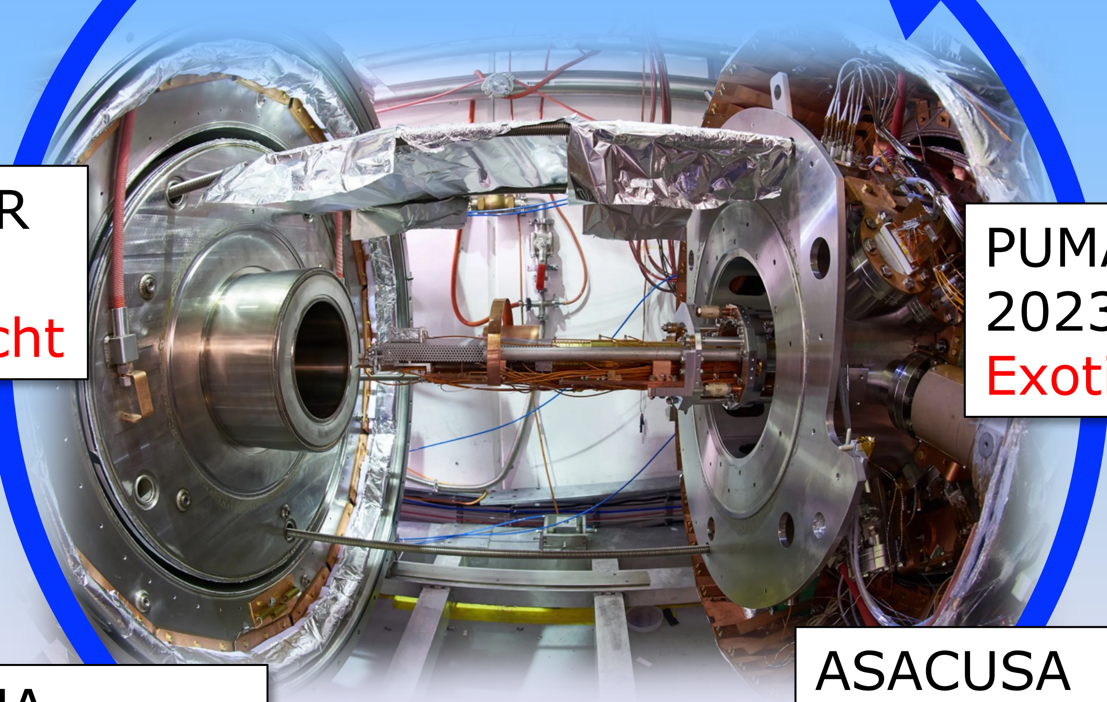
Anti-waterstof experimenten



Anti-waterstof experimenten

ATRAP, ATHENA
2002:
Productie

BASE-STEP (transport)
2023+:
Magnetisch moment



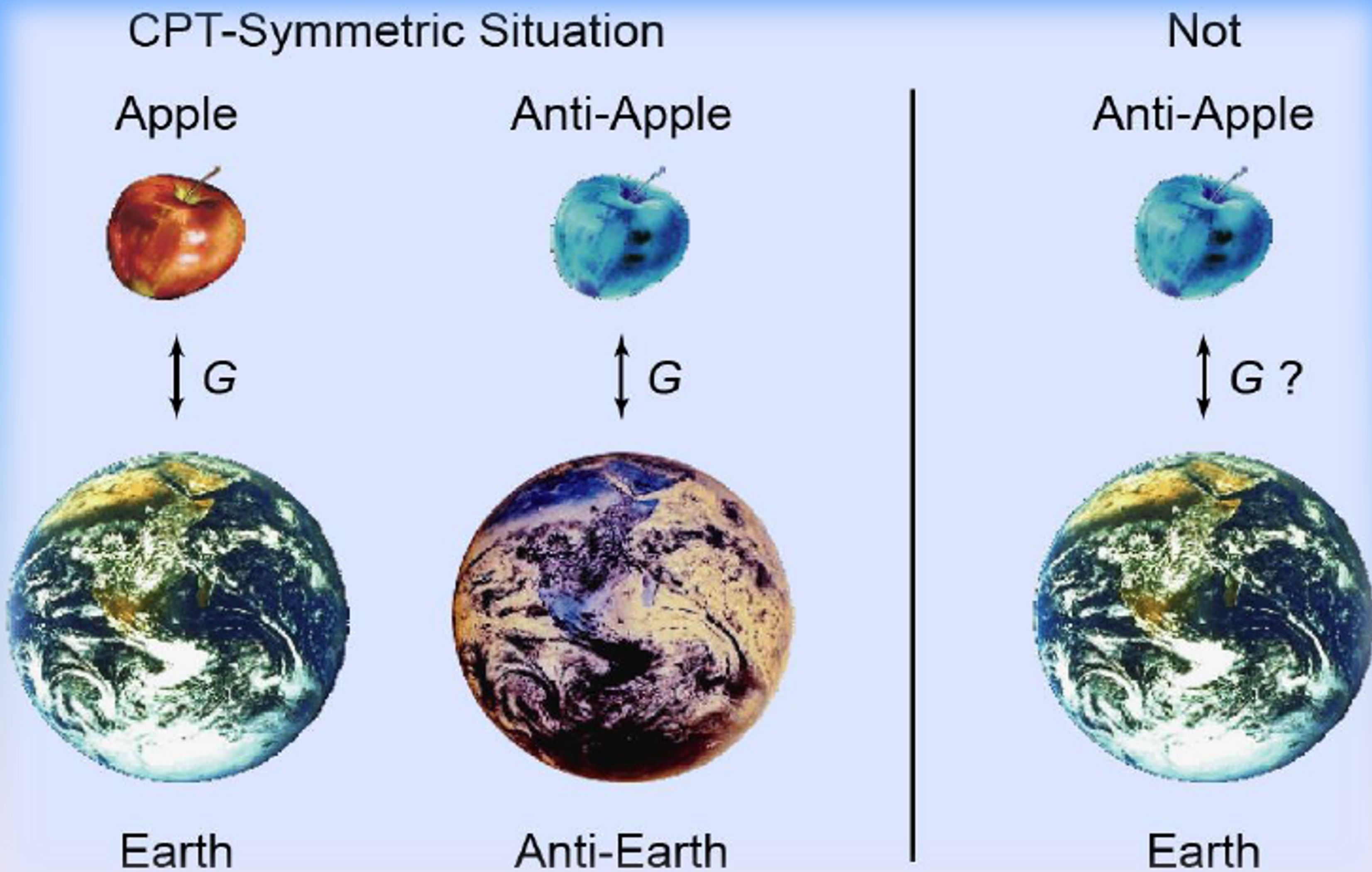
AEgIS, GBAR
2013:
Zwaartekracht

PUMA (transport)
2023+:
Exotische kernfysica

ALPHA
2011:
Spectroscopie

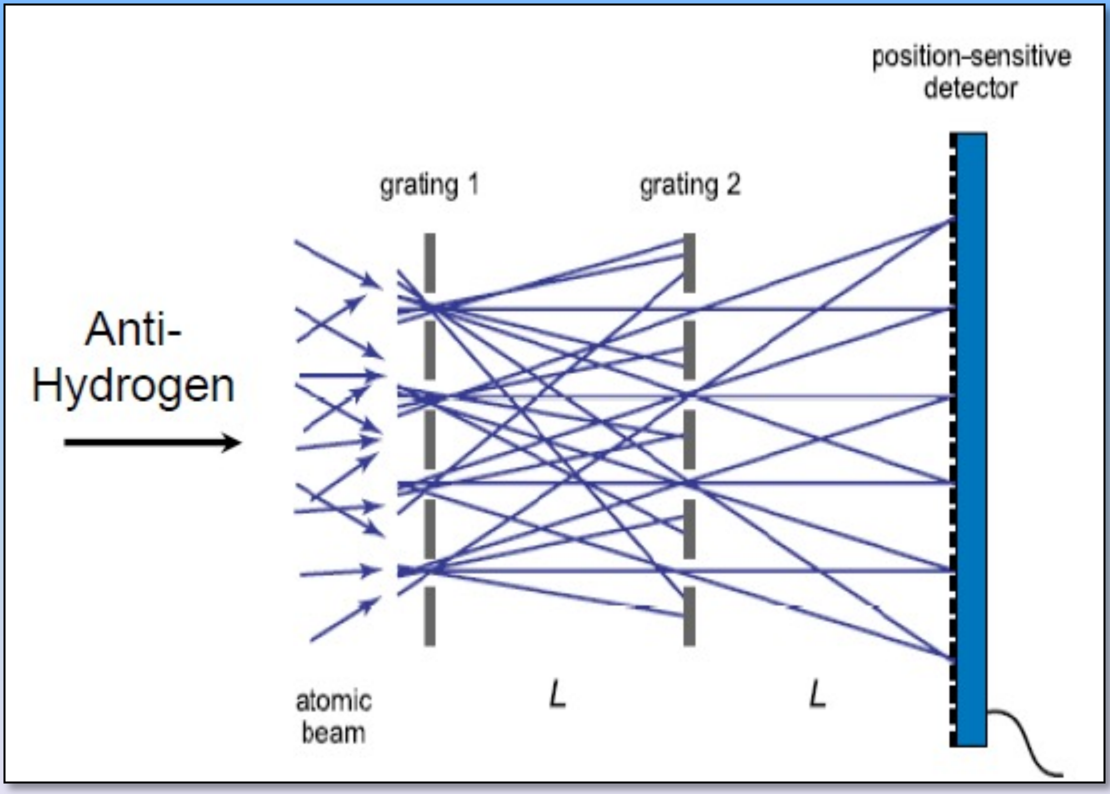
ASACUSA
2011:
Anti-protonisch He
Massa

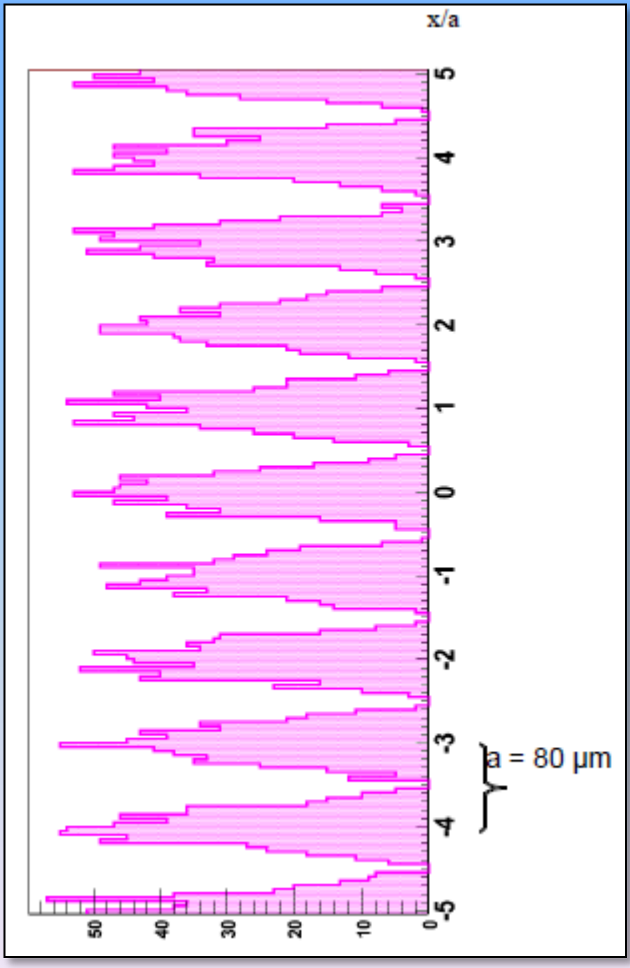
Valt antimaterie omhoog?



Anti-H detective (AEgIS)

Valt anti-waterstof omhoog…?

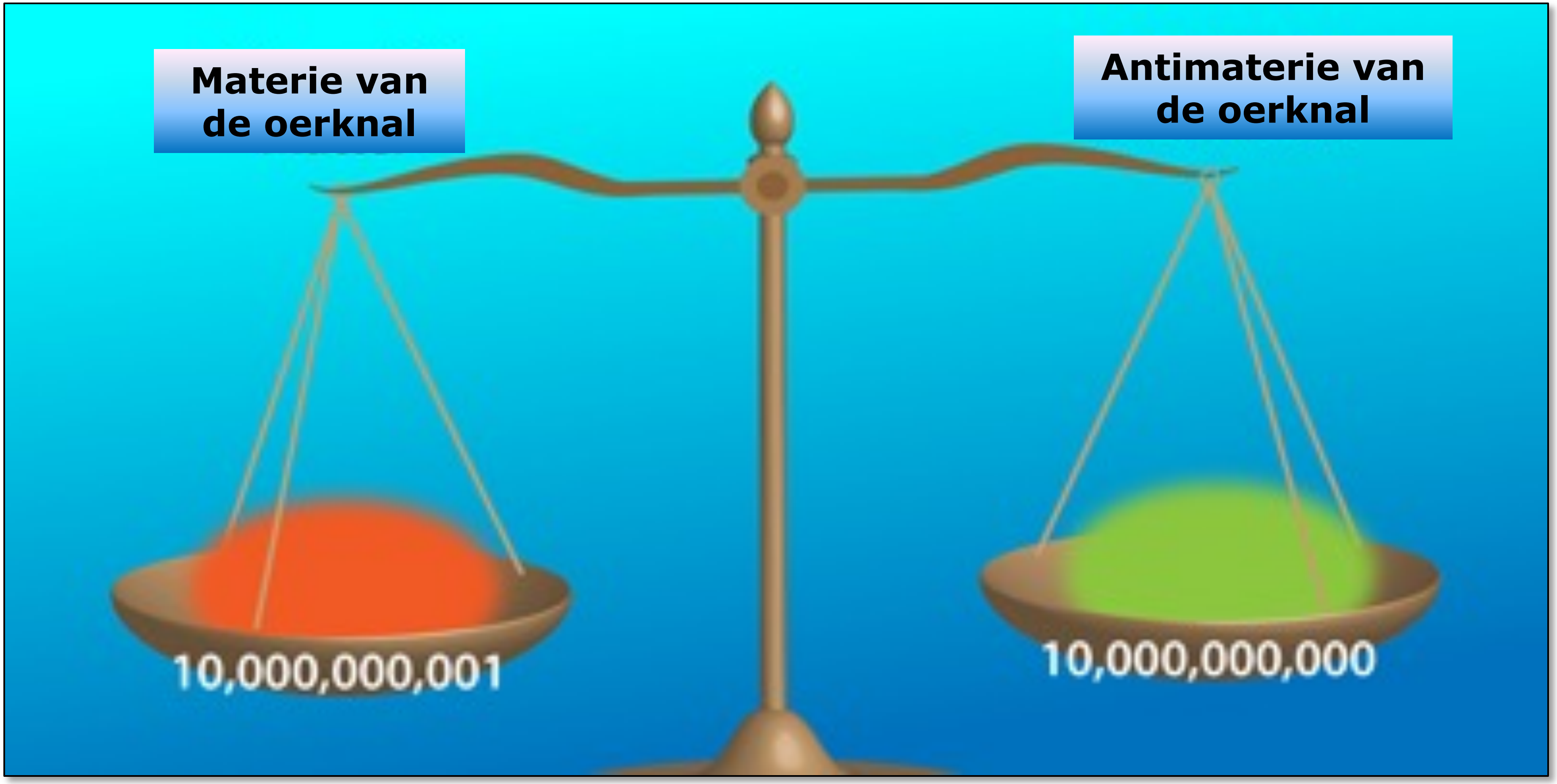




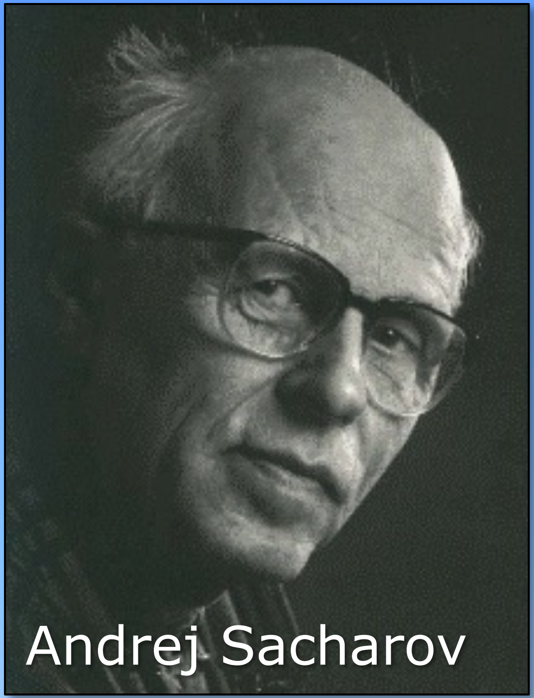
Antimaterie

- Deel 1: Hoezo?
  - Wat is het
  - Hoe is het bedacht
  - Wat is het probleem
- Deel 2: Wat nu?
  - Uit de ruimte
  - Antiwaterstof
  - Antimaterie verschillen

Waar is de antimaterie gebleven?



Wat is er nodig voor deze asymmetry?


Andrej Sacharov

Andrej Sacharov kwam in 1967 met dit eisenpakket:

1) Er moet een proces zijn dat "*Baryon getal*" verandert
2) C en CP symmetrie moet geschonden zijn
3) De eisen 1) en 2) gebeuren in de fase zonder "*thermisch evenwicht*"

Baryon getal? (= ontstaan of verdwijnen van protonen)

20 jaar gekeken naar 50000 kg ultra-puur water

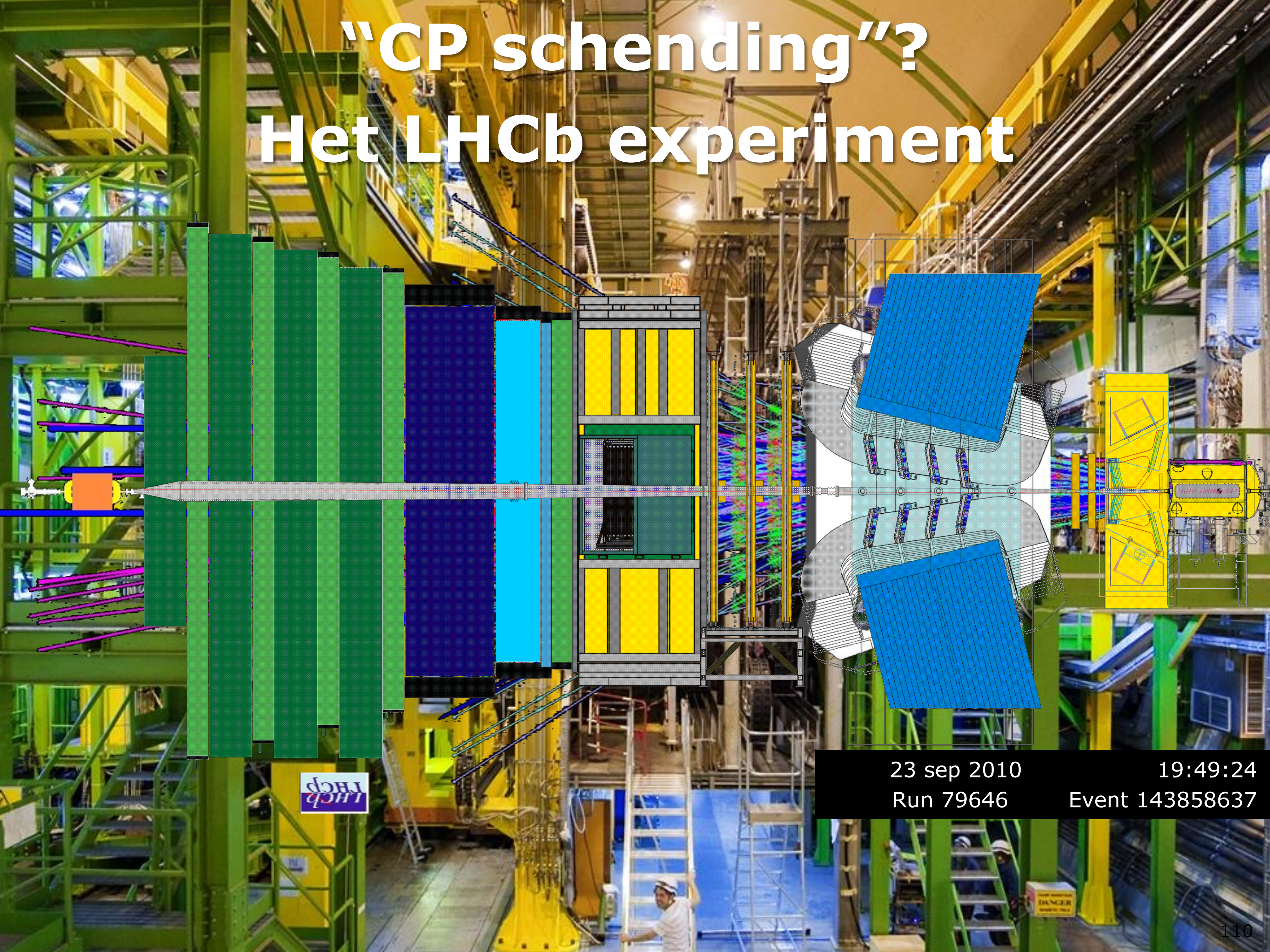
- 1.5 10^{30} moleculen $H_2 0$
- 0 proton vervallen gezien…

Levensduur: > 10^{34} jaar…

Vraag Jorinde van der Vis naar Baryogenese !

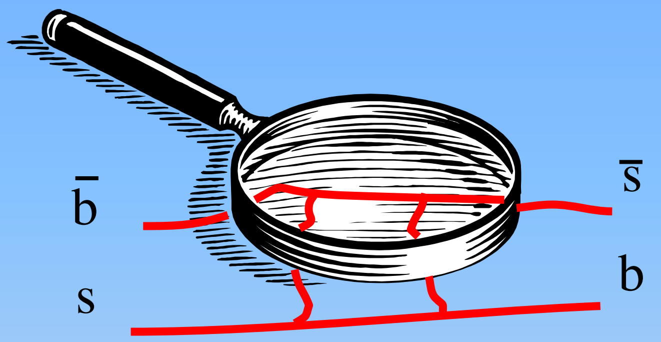
Super-Kamiokande Collaboration, arxiv:1610.03597

"CP schending"?
Het LHCb experiment

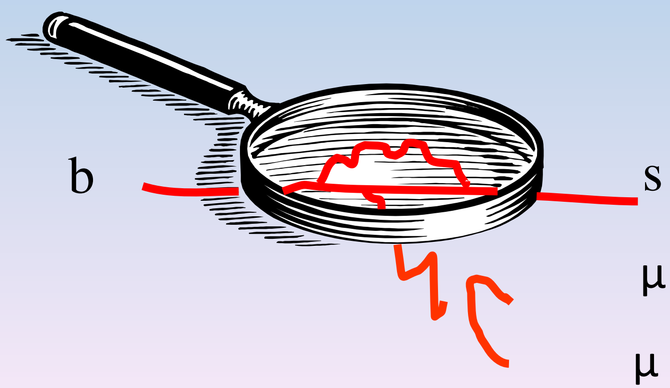


LHCb: bestuderen van *B* deeltje

1) Vind verschillen tussen materie en anti-materie

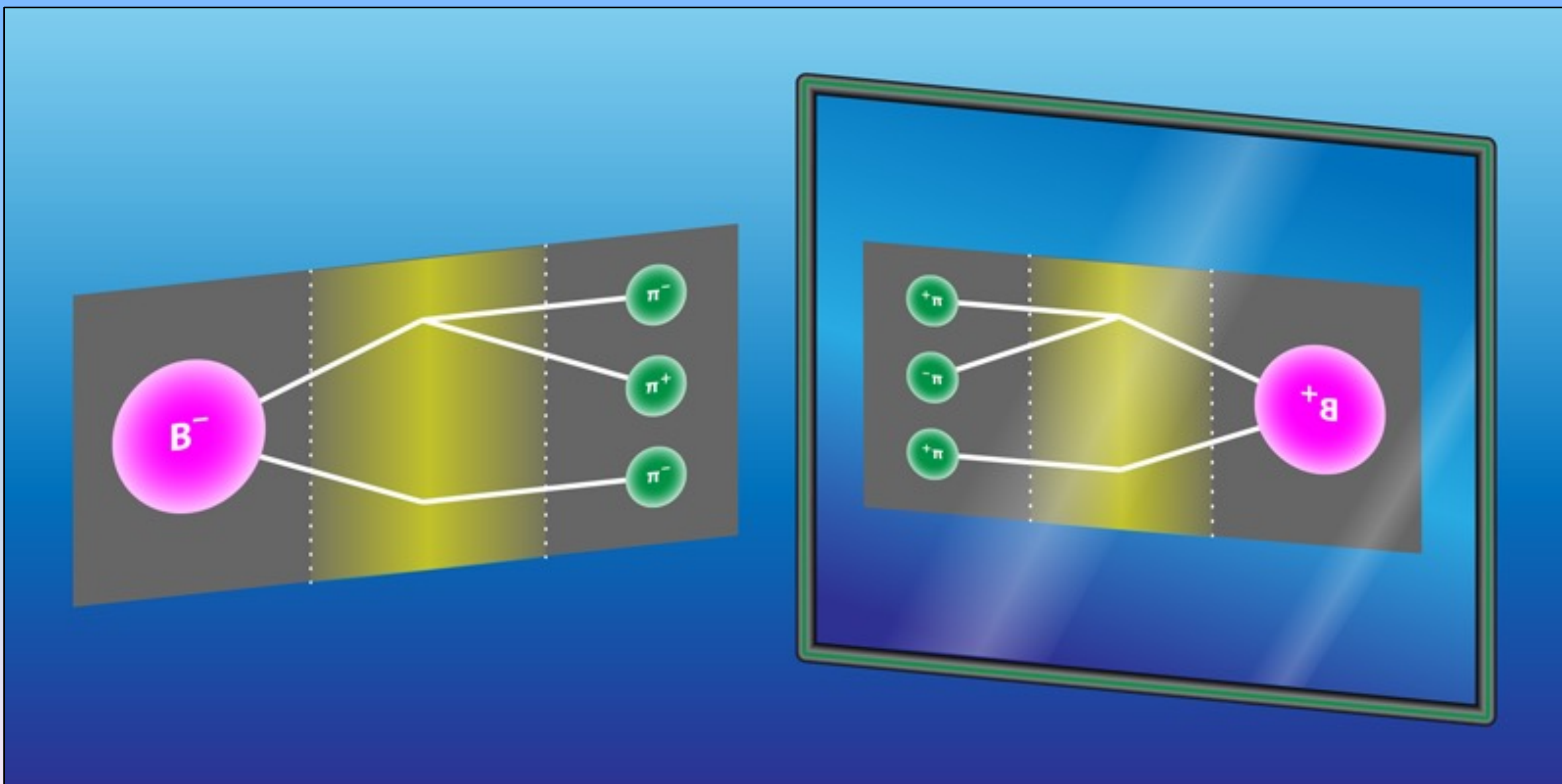


2) Vind nieuwe deeltjes



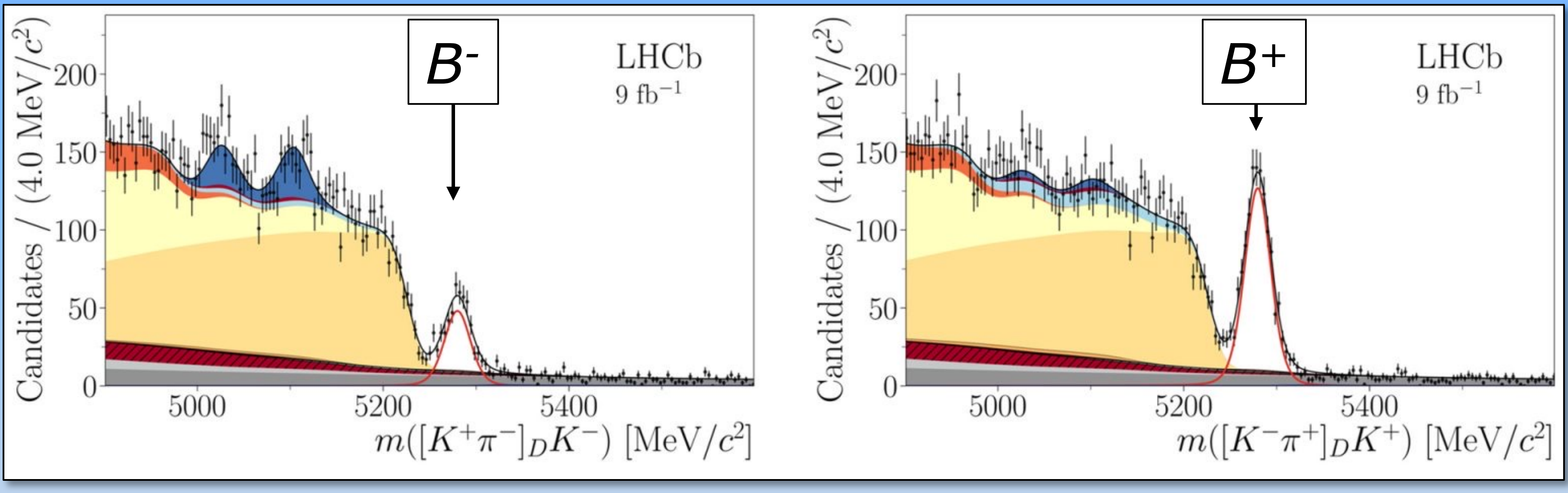
LHCb: bestuderen van *B* deeltje

1) Vind verschillen tussen materie en anti-materie



LHCb: bestuderen van *B* deeltje

1) Vind verschillen tussen materie en anti-materie

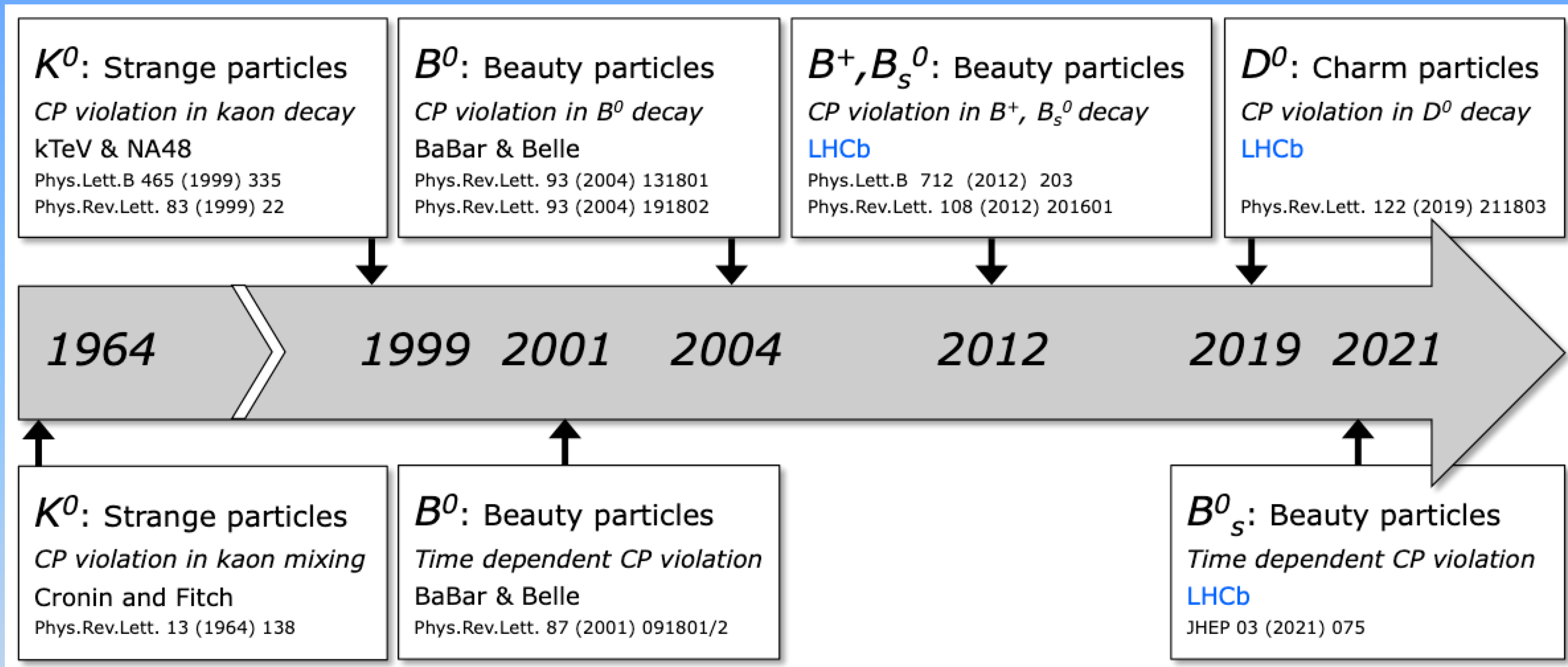


✓ Check! ☺

☒ Maar niet genoeg… ☹

LHCb Collaboratie, *Measurement of CP observables in $B^{\pm}\to D^{(*)}K^{\pm}$ and $B^{\pm}\to D^{(*)}\pi^{\pm}$ decays using two-body D final states*, arXiv:2012.09903

LHCb: antimaterie verschillen

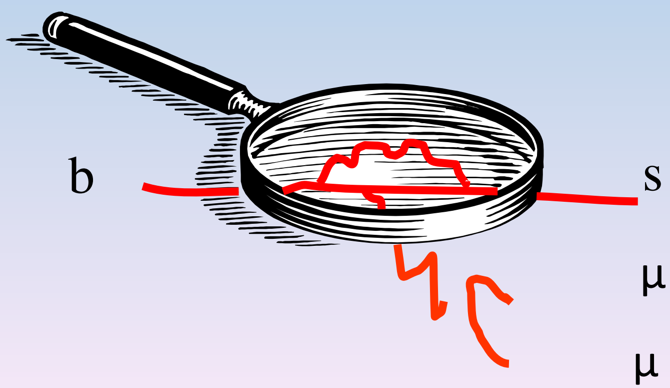


(ds)	**1964**: CP schending met K^0	(Nobelprijs 1980)
(bd)	**2000**: CP schending met B^0	(Nobelprijs 2008)
(bs)	**2012**: CP schending met B^0_s	(LHCb)
(cu)	**2019**: CP schending met D^0	(LHCb)

LHCb: bestuderen van *B* deeltje

Nieuwe deeltjes of processen kunnen leiden tot antwoorden!

1) Vind nieuwe deeltjes



LHCb: hot topic

NewScientist
IDEEËN DIE DE WERELD VERANDEREN

Cern vindt nieuwe hint voor scheurtjes in standaardmodel

19 april 2017

George van Hal

mogelijke hint dat er meer is dan alleen het
rdmodel. Beeld: Cern.

deVolkskrant

CERN is 'voorzichtig opgewonden' over subtiele verschillen in deeltjeswereld

Een gevoel van 'voorzichtige opwinding' heeft zich meester gemaakt van deeltjesfysici van CERN in Genève. Dinsdag maakte de LHCb-detector daar bekend subtiele verschillen te zien tussen bepaalde deeltjes. De gangbare deeltjestheorie neemt aan dat deeltjes in essentie identiek zijn.

Martijn van Calmthout 19 april 2017, 21:29

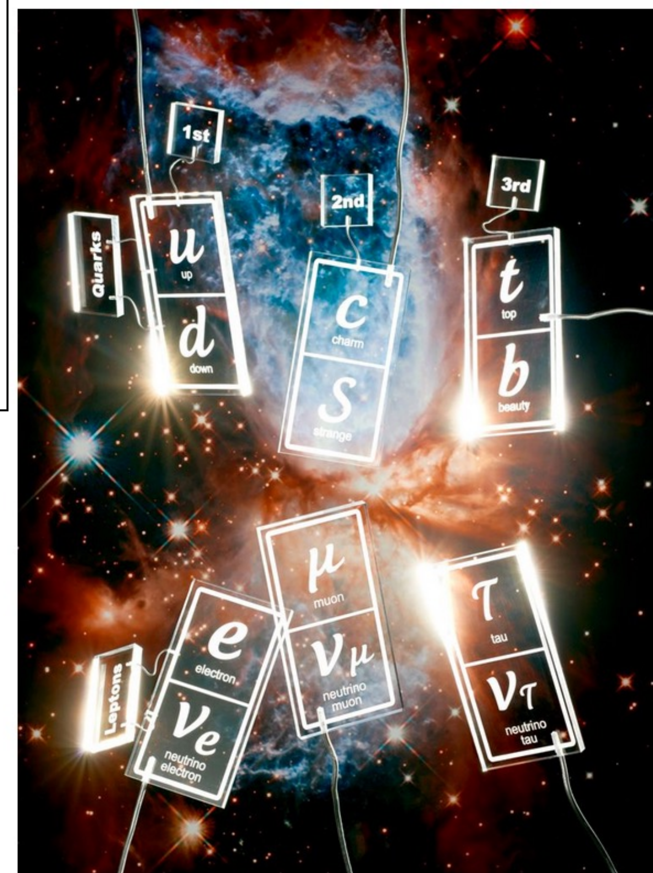
Wellicht is de deeltjeswereld niet zo democratisch als vooraf gedacht werd. Beeld epa

deVolkskrant

Moeder aller deeltjes: de zoektocht naar de leptoquark

Is het fundamenteelste deeltje in het universum altijd over het hoofd gezien? Komende week kan de wereld opgeschud worden, als natuurkundigen in Seoul hun resultaten bekendmaken. Leptoquark, onthoud dat woord.

Martijn van Calmthout 29 juni 2018, 11:25



Beeld Rein Janssen

LHCb: hot topic

deVolkskrant

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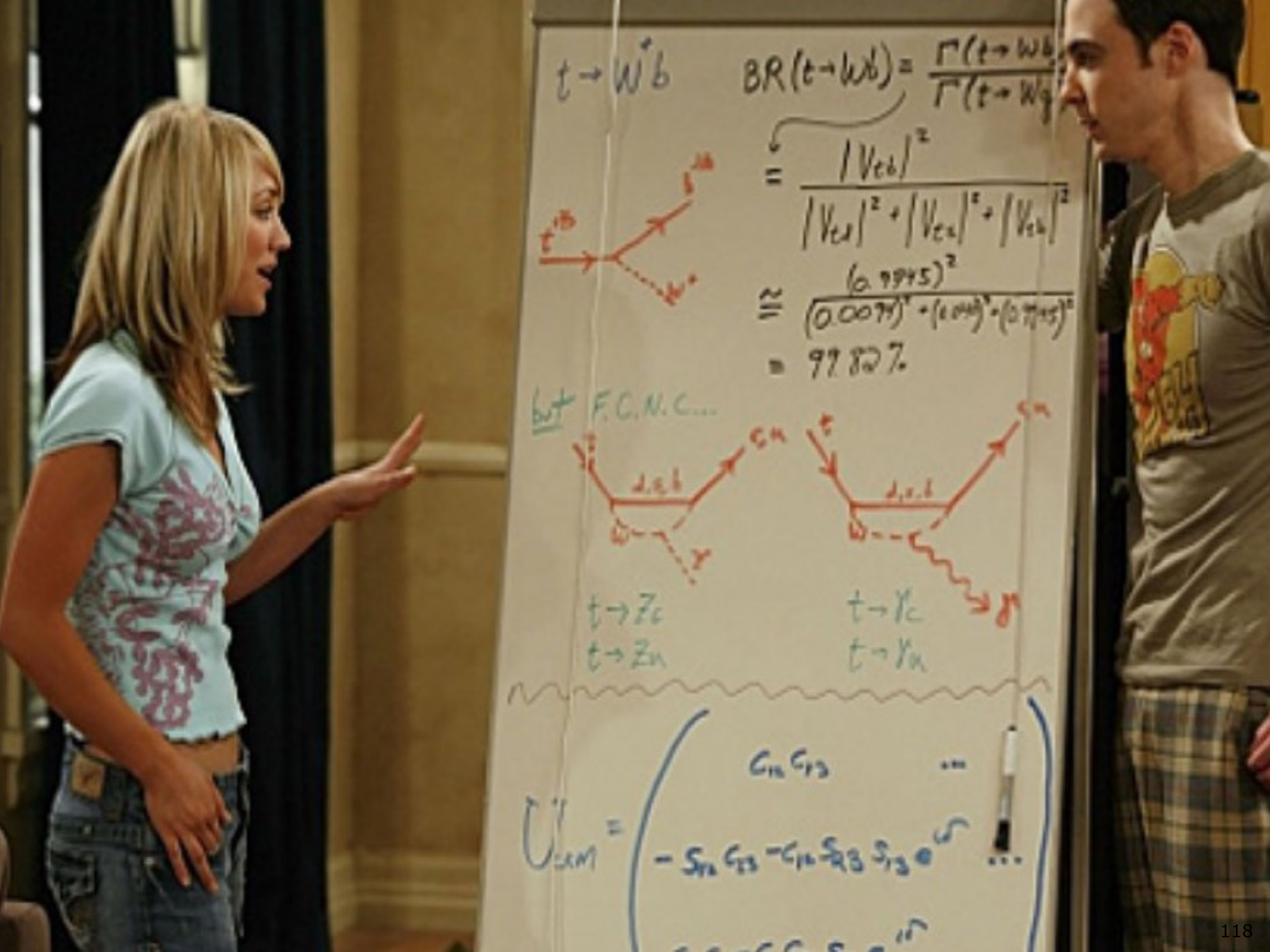
Martijn van Calmthout 29 juni 2018, 11:25

Maar de LHCb-metingen geven al jaren kleine hints dat er iets mis is met deze keurige lepton-universaliteit. En dat elektronen en muonen ergens diep van binnen toch net iets anders met quarks omgaan.

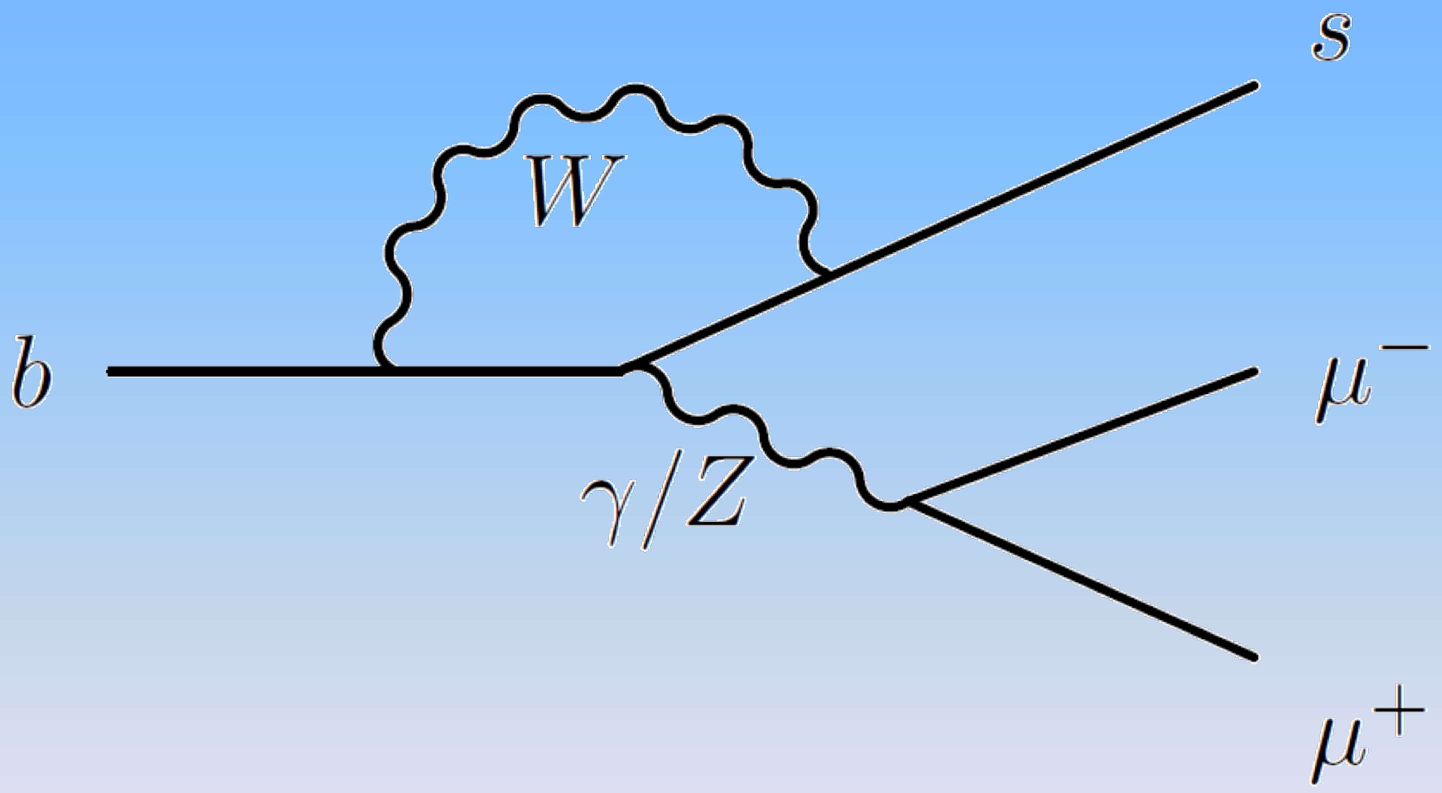
Beeld Rein Janssen



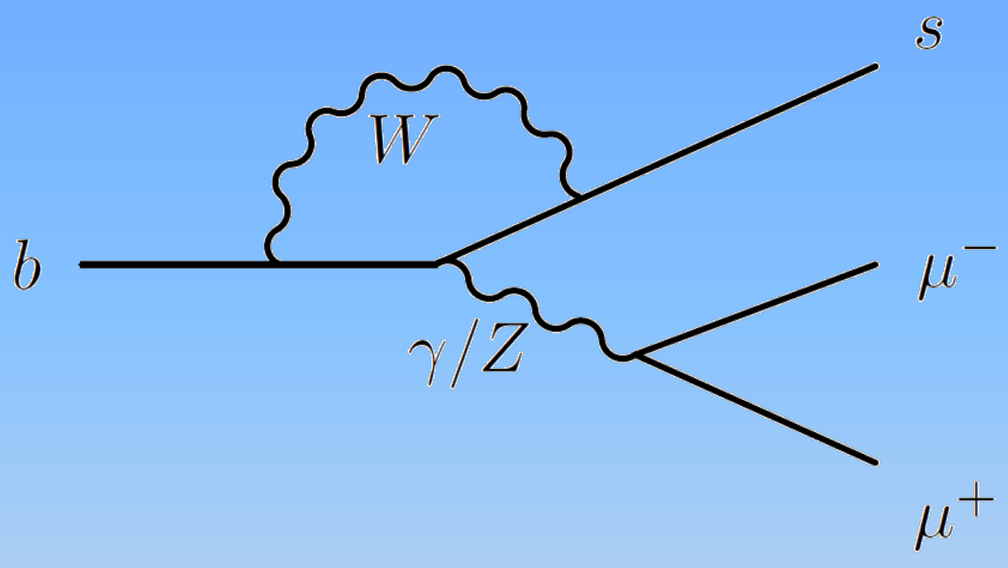
t → W⁺b
BR(t→Wb) =
≅ 99.82%
but F.C.N.C...
t → Zc
t → Zu
t → γc
t → γu


INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS
CERNCOURIER
VOLUME 55 NUMBER 9 NOVEMBER 2015
Tensions in the Standard Model

LHCb: hot topic



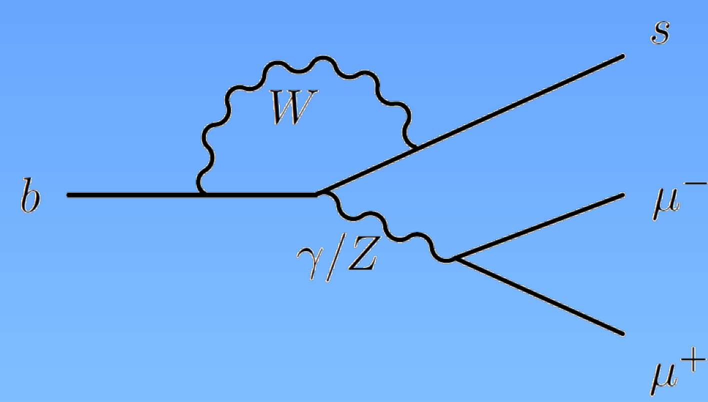
LHCb: hot topic



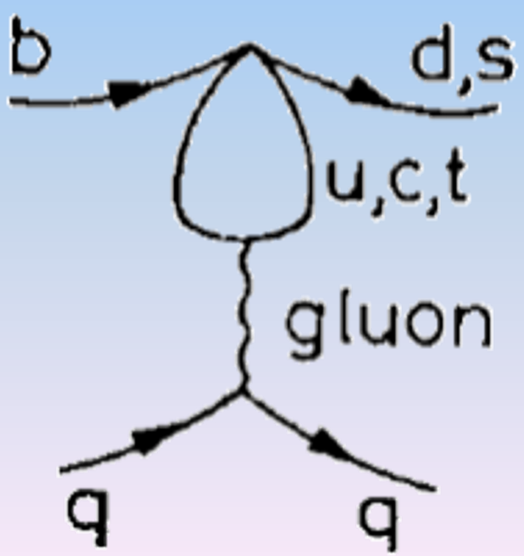
Flavour changing neutral current electroweak penguin

FCNC EWP

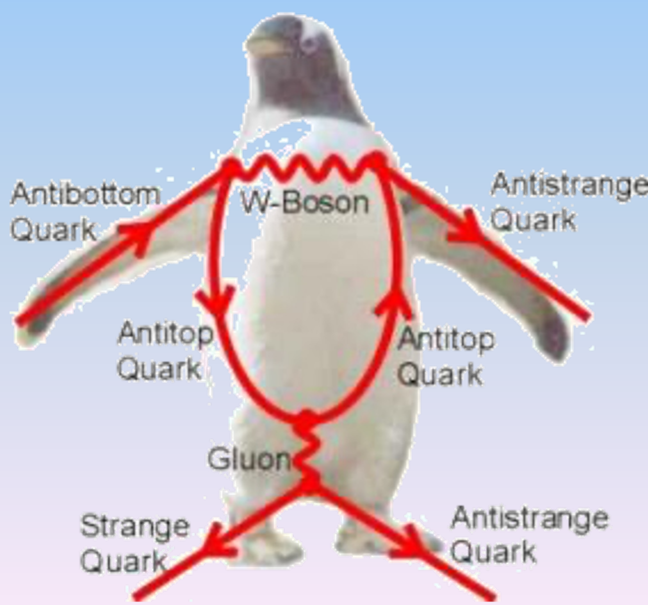
LHCb: hot topic



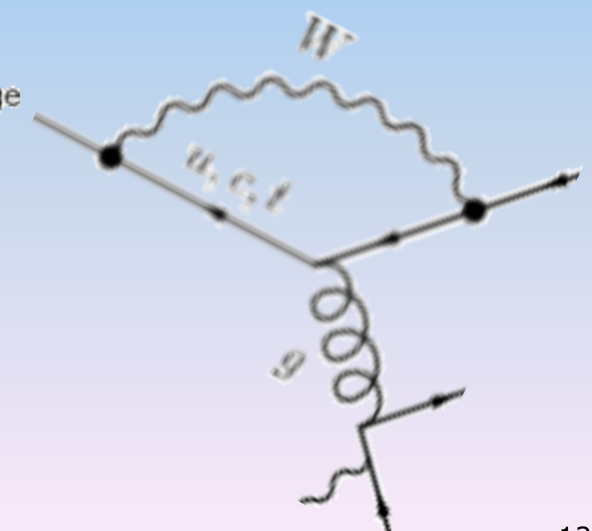
The original penguin:



A real penguin:

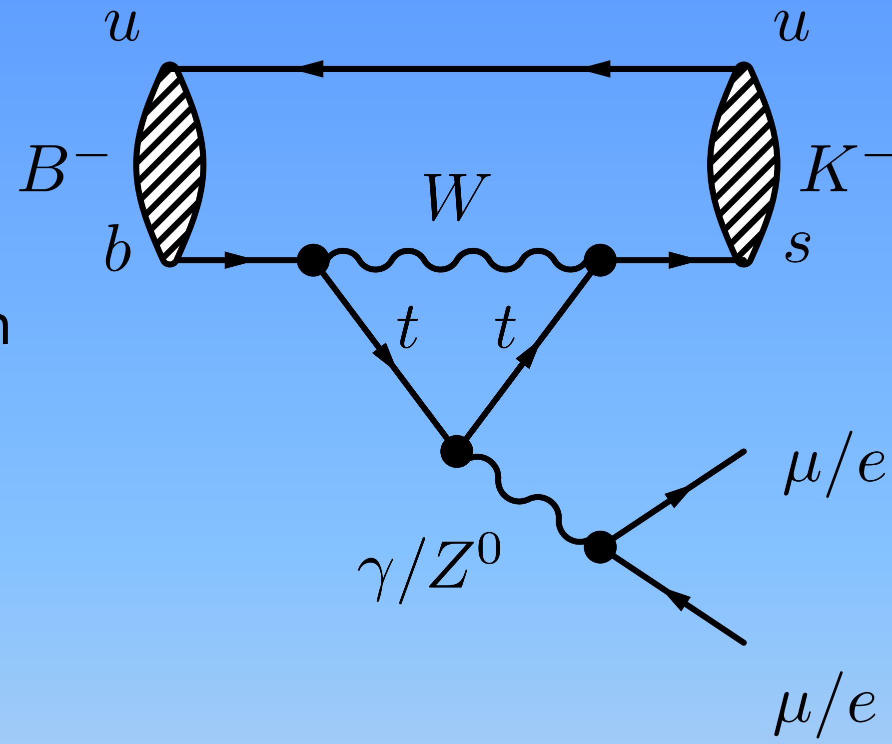


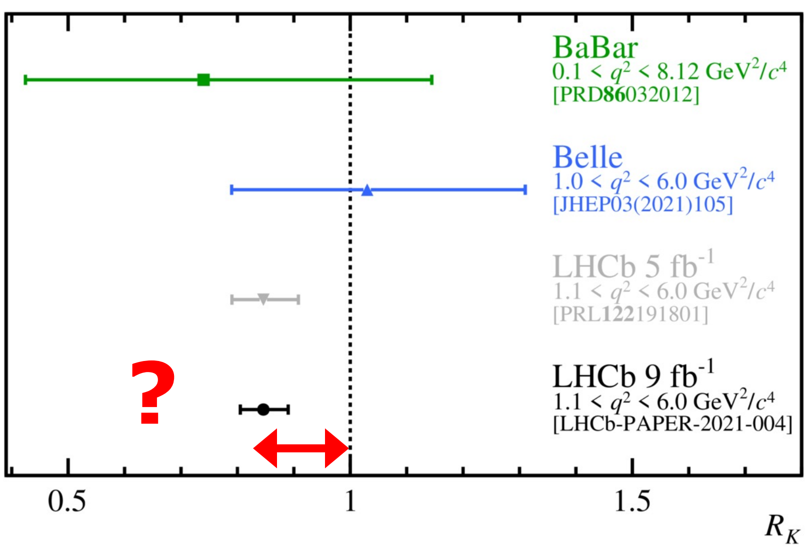
Our penguin:

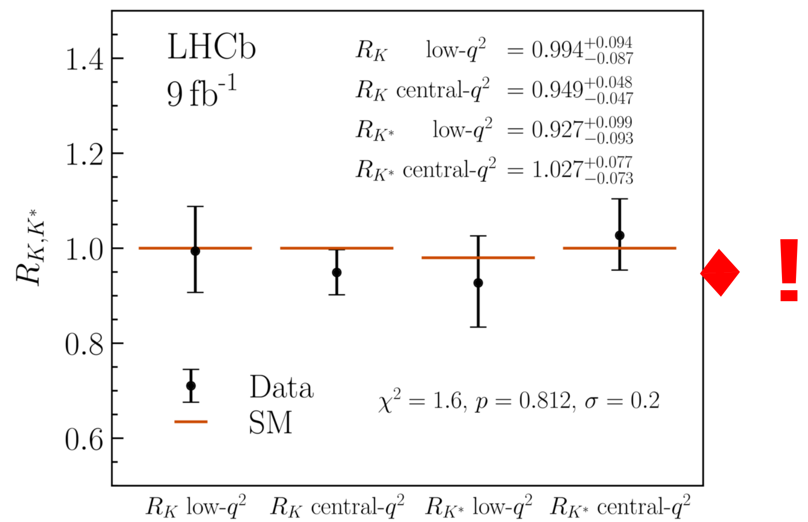


LHCb: hot topic

Electronen en muonen gedragen zich anders?



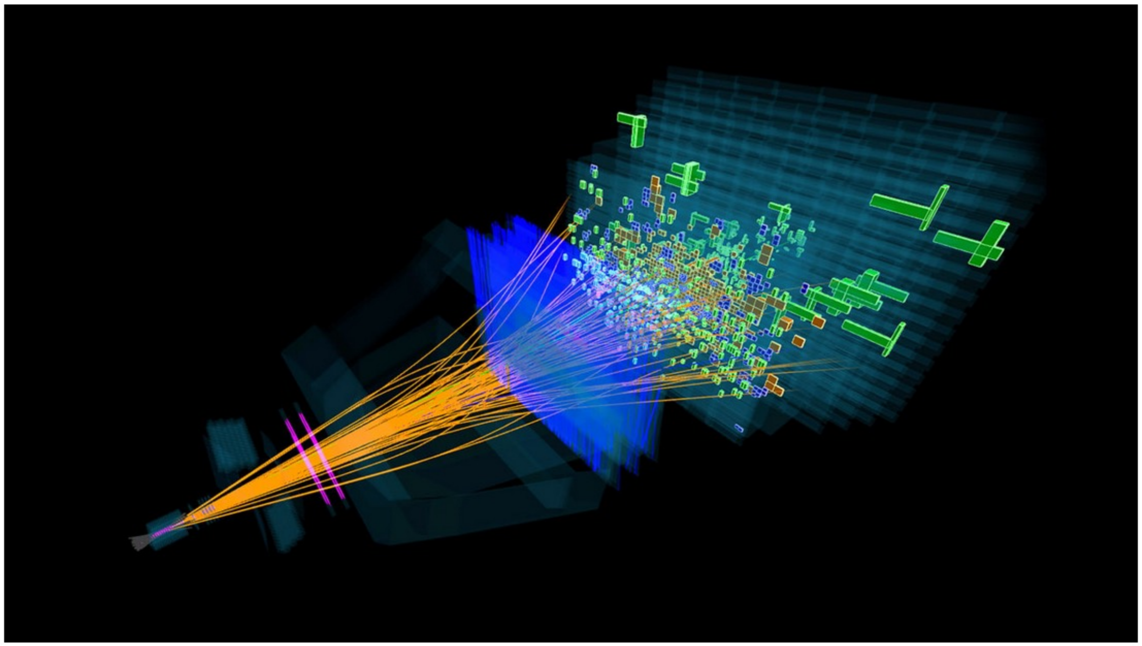




Muon gedraagt zich toch best normaal – of is er meer aan de hand?

29 Dec 2022

Nieuws Jean-Paul Keulen 29-12-2022 15:00:00 Deel dit artikel:



Vervallend B-deeltje in LHCb. Beeld: LHCb/CERN

Een verrassend resultaat uit de deeltjesfysica lijkt te zijn afgeserveerd. Toch zijn er nog openstaande vragen.

"Toch zijn er nog openstaande vragen"

Het gold als een van de interessantste resultaten binnen de deeltjesfysica sinds de ontdekking van het higgsdeeltje: het feit dat er bij het verval van bepaalde deeltjes **minder vaak muonen ontstaan dan je zou verwachten**. Zou die afwijking van onze huidige deeltjestheorie, blootgelegd met het deeltjesexperiment **LHCb**, wijzen op het bestaan van nieuwe deeltjes of nieuwe natuurkrachten?

KIJK magazine, https://www.kijkmagazine.nl/nieuws/muon-gedraagt-zich-toch-best-normaal-of-is-er-meer-aan-de-han

Antimaterie

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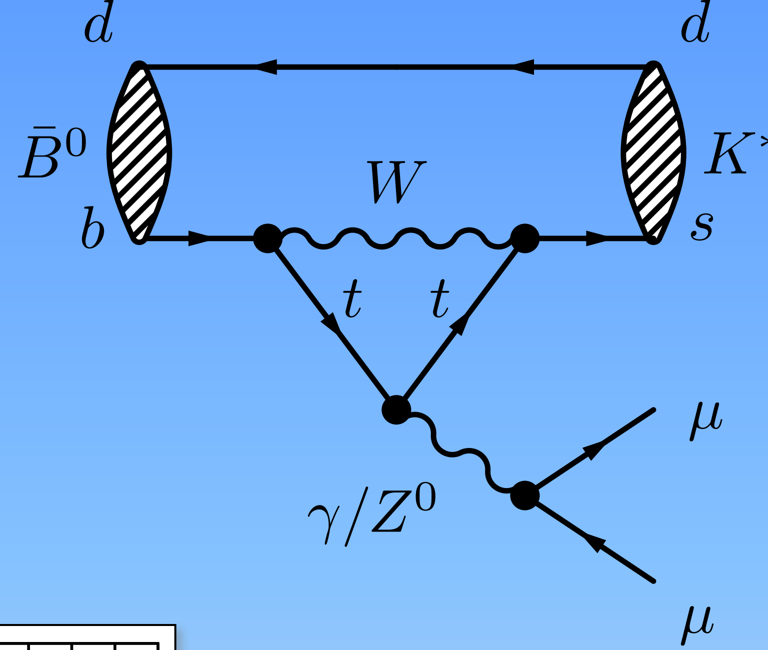
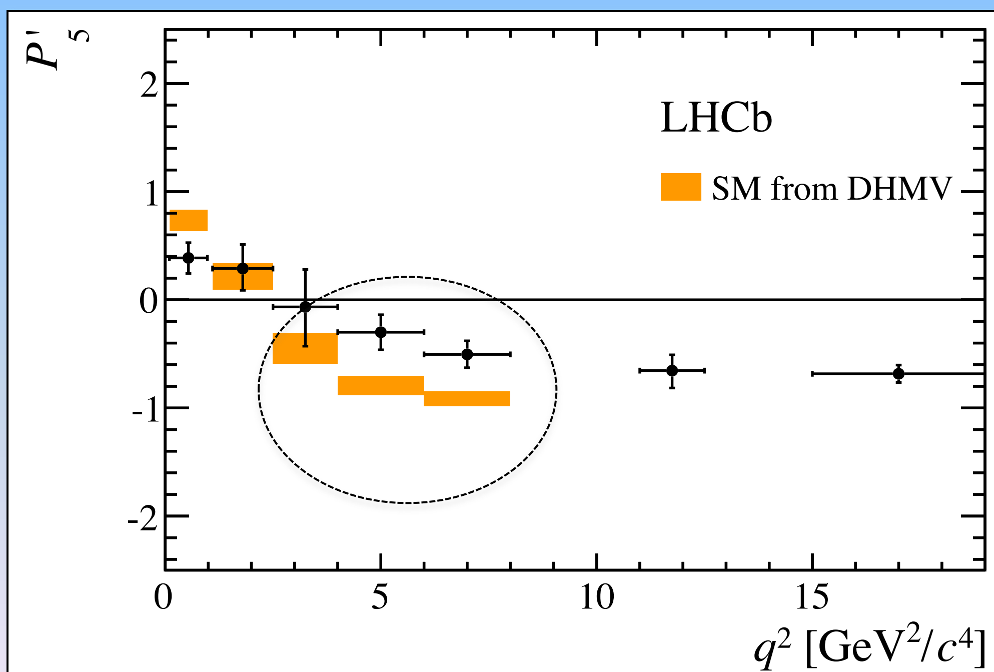
  - Antimaterie verschillen

LHCb: hot topic

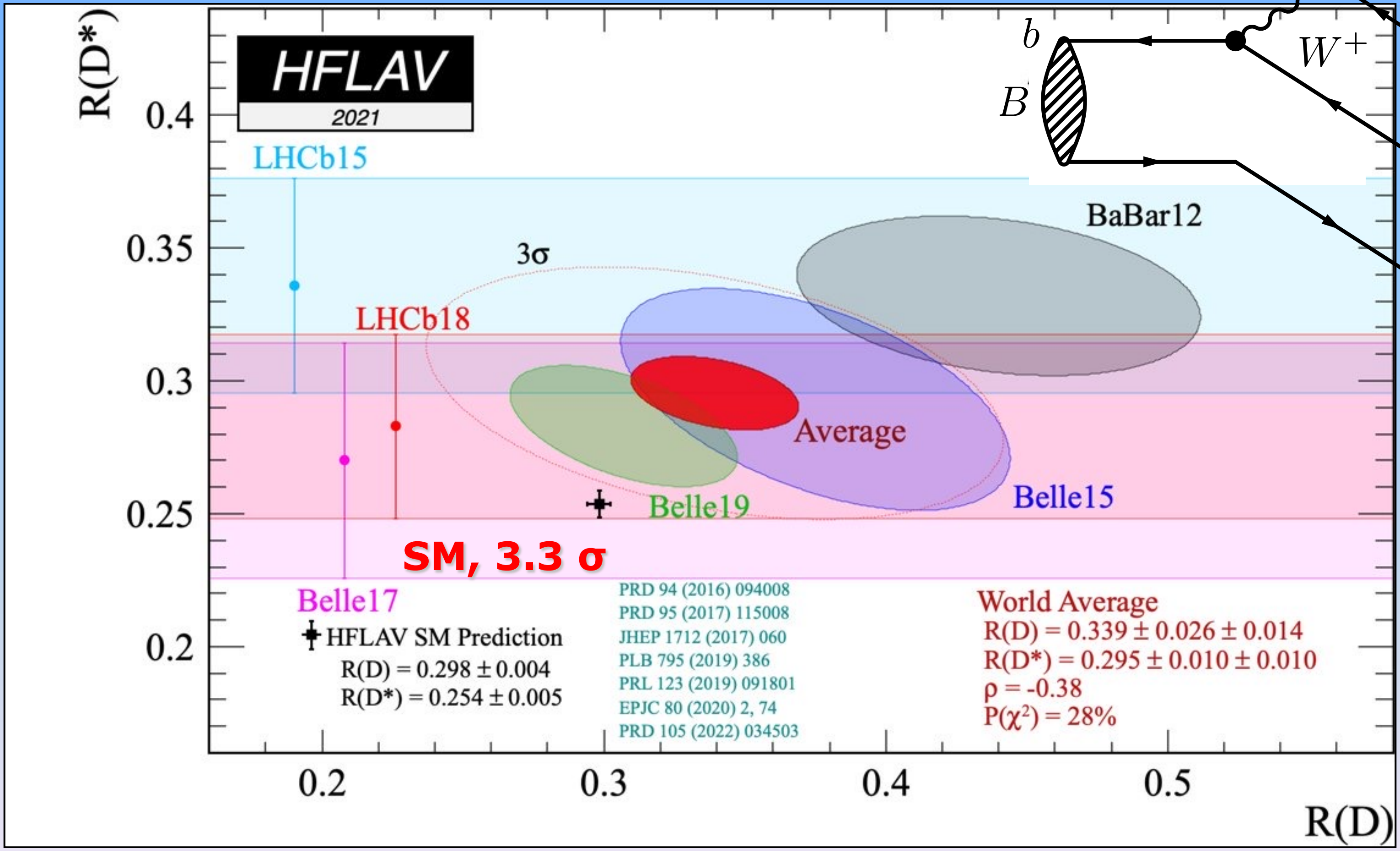
Ook hoekverdeling is anders…

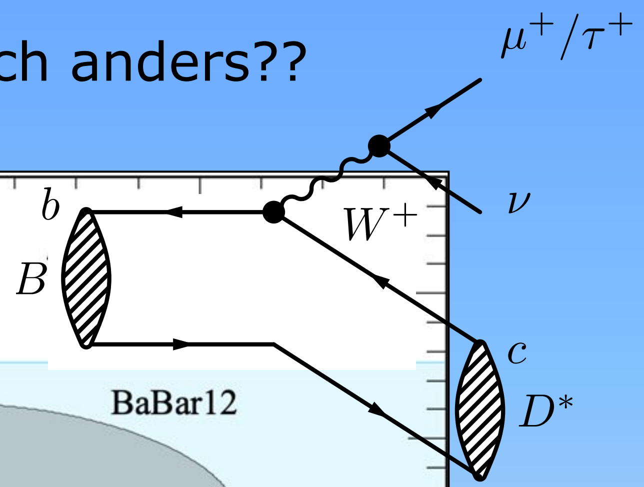




LHCb: hot topic

En muonen en tau-deeltjes gedragen zich anders??

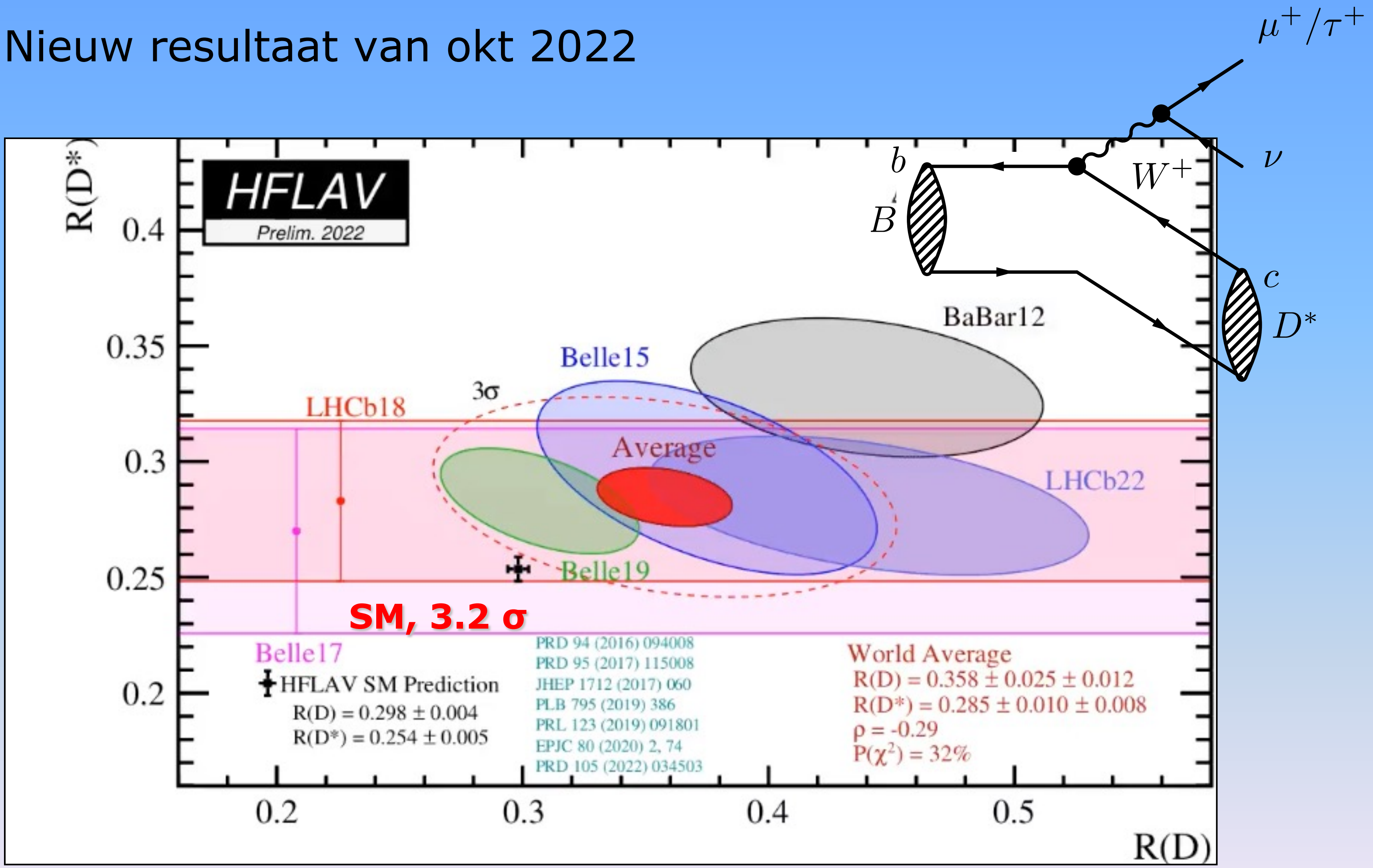




NB: contours contain less than 68% CL…

LHCb: hot topic

Nieuw resultaat van okt 2022



https://hflav-eos.web.cern.ch/hflav-eos/semi/fall22/html/RDsDsstar/RDRDs.html

LHCb: wat kan het zijn?


deVolkskrant

Moeder aller deeltjes: de zoektocht naar de leptoquark

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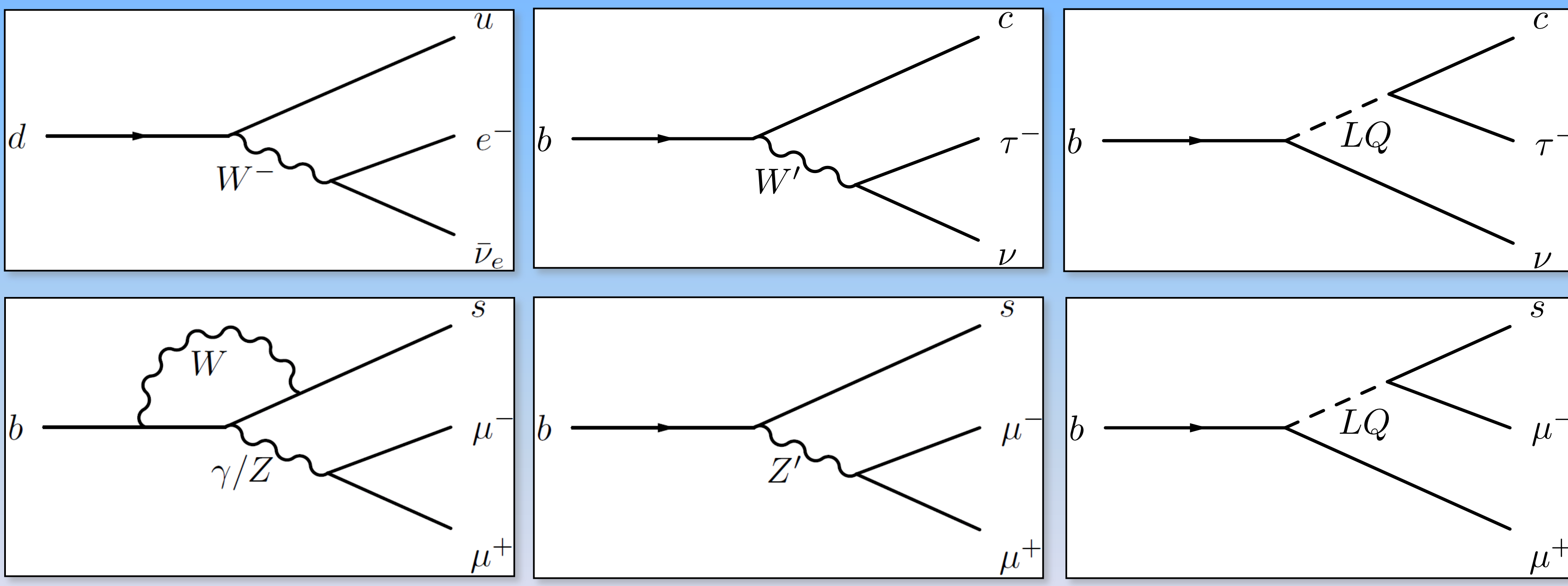
Martijn van Calmthout 29 juni 2018, 11:25

SM | SU(2)′ | Leptoquark



Leptoquark, onthoud dat woord.

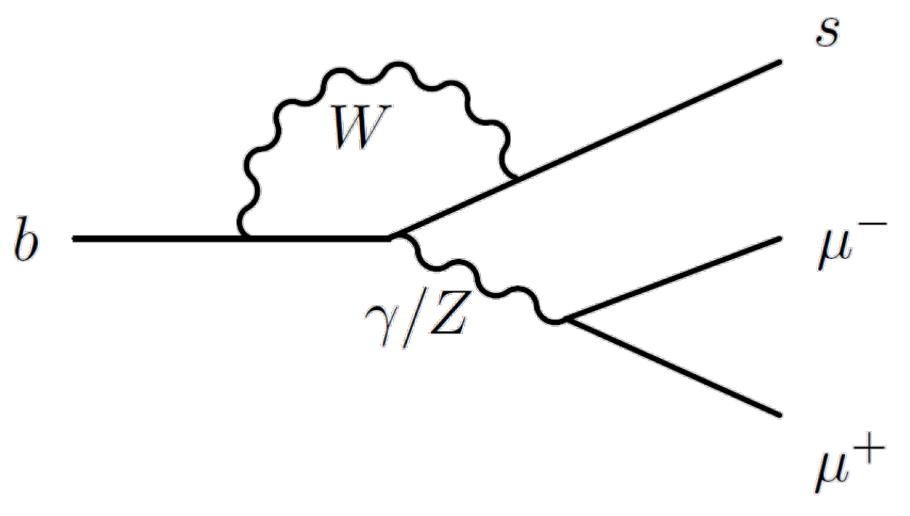
M. Van Calmthout

Take home message

1) LHCb zoekt verschillen tussen materie en antimaterie

2) LHCb kan zeer zware deeltjes vinden (maar alleen *virtueel*)

3) Nieuwe deeltjes helpen om grote vragen te beantwoorden



Modelleren van interactie

Standaard Model Lagrangiaan

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

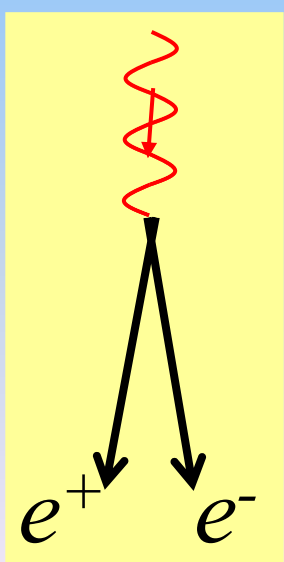
Bladmuziek (J.S. Bach)

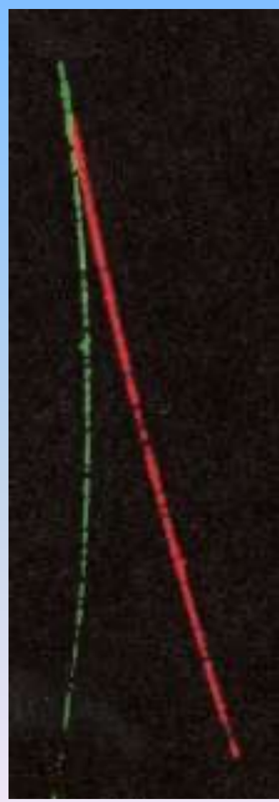
bladmuziek

Higgs: Deeltje? Veld?

Deeltje

Foton (lichtdeeltje)

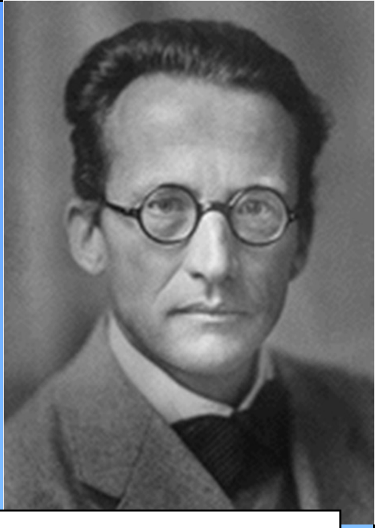




Veld

Elektrisch veld

Schrödinger



Klassiek verband tussen E and p:

$$E = \frac{\vec{p}^2}{2m}$$

Quantum mechanische substitutie:

(*operator acting on wave function* ψ)

$$E \rightarrow i\frac{\partial}{\partial t} \quad \text{and} \quad \vec{p} \rightarrow -i\vec{\nabla}$$

Schrodinger vergelijking:

$$i\frac{\partial}{\partial t}\psi = \frac{-1}{2m}\nabla^2\psi$$

Oplossing:

$$\psi = N\, e^{i(\vec{p}\vec{x} - Et)}$$

- (show it is a solution)

Klein-Gordon

Relativistisch verband tussen E and p: $E^2 = \vec{p}^2 + m^2$

Quantum mechanische substitutie: $E \rightarrow i\frac{\partial}{\partial t}$ and $\vec{p} \rightarrow -i\vec{\nabla}$

(*operator acting on wave function* ψ)

Klein Gordon vergelijking: $$-\frac{\partial^2}{\partial t^2}\phi = -\nabla^2\phi + m^2\,\phi$$

or : $$\left(\Box + m^2\right)\,\phi(x) = 0$$

or : $$\left(\partial_\mu\partial^\mu + m^2\right)\,\phi(x) = 0$$

Oplossing: $\phi(x) = N\,e^{-ip_\mu x^\mu}$ $\quad E^2 = \vec{p}^2 + m^2$

Maar: negatieve energie oplossing? $$E = \pm\sqrt{\vec{p}^2 + m^2}$$

Dirac

Paul Dirac zocht een vergelijking, die

- relativistisch correct is,
- Maar *<u>lineair</u>* in d/dt om negatieve energie te vermijden
- (en lineair in d/dx (or ∇) vanwege Lorentz covariantie)

Hij vond een vergelijking, die

- spin-1/2 deeltjes bleek te beschrijven en
- het bestaan van anti-deeltjes voorspelde

Dirac

- How to find that relativistic, linear equation ??

Write Hamiltonian in general form, $H\psi = (\vec{\alpha}\cdot\vec{p} + \beta m)\ \psi$

but when squared, it must satisfy: $H^2\psi = \left(\vec{p}^2 + m^2\right)\ \psi$

Let's find α_i and β !

$$\begin{aligned} H^2\psi &= (\alpha_i p_i + \beta m)^2\ \psi \qquad \text{with}:\ i = 1,2,3 \\ &= \left(\underbrace{\alpha_i^2}_{=1}\ p_i^2 + \underbrace{(\alpha_i\alpha_j + \alpha_j\alpha_i)}_{=0\quad i>j}\ p_i p_j + \underbrace{(\alpha_i\beta + \beta\alpha_i)}_{=0} p_i m + \underbrace{\beta^2}_{=1}\ m^2\right)\ \psi \end{aligned}$$

So, α_i and β must satisfy:

- $\alpha_1{}^2 = \alpha_2{}^2 = \alpha_3{}^2 = \beta^2$
- $\alpha_1, \alpha_2, \alpha_3, \beta$ anti-commute with each other
- (not a unique choice!)

Dirac

$$H\psi = (\vec{\alpha}\cdot\vec{p} + \beta m)\,\psi$$

- What are α and β ??

- The lowest dimensional matrix that has the desired behaviour is 4x4 !?
- Often used
- Pauli-Dirac representation:

$$\vec{\alpha} = \begin{pmatrix} 0 & \vec{\sigma} \\ \vec{\sigma} & 0 \end{pmatrix} \quad ; \quad \beta = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}$$

- with:

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad ; \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad ; \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

So, α_i and β must satisfy:

- $\alpha_1{}^2 = \alpha_2{}^2 = \alpha_3{}^2 = \beta^2$
- $\alpha_1, \alpha_2, \alpha_3, \beta$ anti-commute with each other
- (not a unique choice!)

Dirac

$$H\psi = (\vec{\alpha}\cdot\vec{p} + \beta m)\ \psi$$

Usual substitution: $H \rightarrow i\frac{\partial}{\partial t},\ \vec{p} \rightarrow -i\vec{\nabla}$

Leads to: $$i\frac{\partial}{\partial t}\psi = \left(-i\vec{\alpha}\cdot\vec{\nabla} + \beta m\right)\ \psi$$

Multiply by β: $$\left(i\beta\frac{\partial}{\partial t}\psi \quad + \quad i\beta\alpha_1\frac{\partial}{\partial x} + i\beta\alpha_2\frac{\partial}{\partial y} + i\beta\alpha_3\frac{\partial}{\partial z}\right)\ \psi - m\psi = 0$$

•($\beta^2 = \mathbf{1}$)

Gives the famous Dirac equation:

$$\begin{aligned} (i\gamma^\mu\partial_\mu - m)\ \psi \quad &= \quad 0 \\ \text{with}:\ \gamma^\mu = (\beta, \beta\vec{\alpha}) \quad &\equiv \quad \text{Dirac } \gamma\text{−matrices} \end{aligned}$$

for each j=1,2,3,4 : $$\sum_{k=1}^{4}\left[\sum_{\mu=0}^{3} i\,(\gamma^\mu)_{jk}\ \partial_\mu - m\delta_{jk}\right](\psi_k) = 0$$

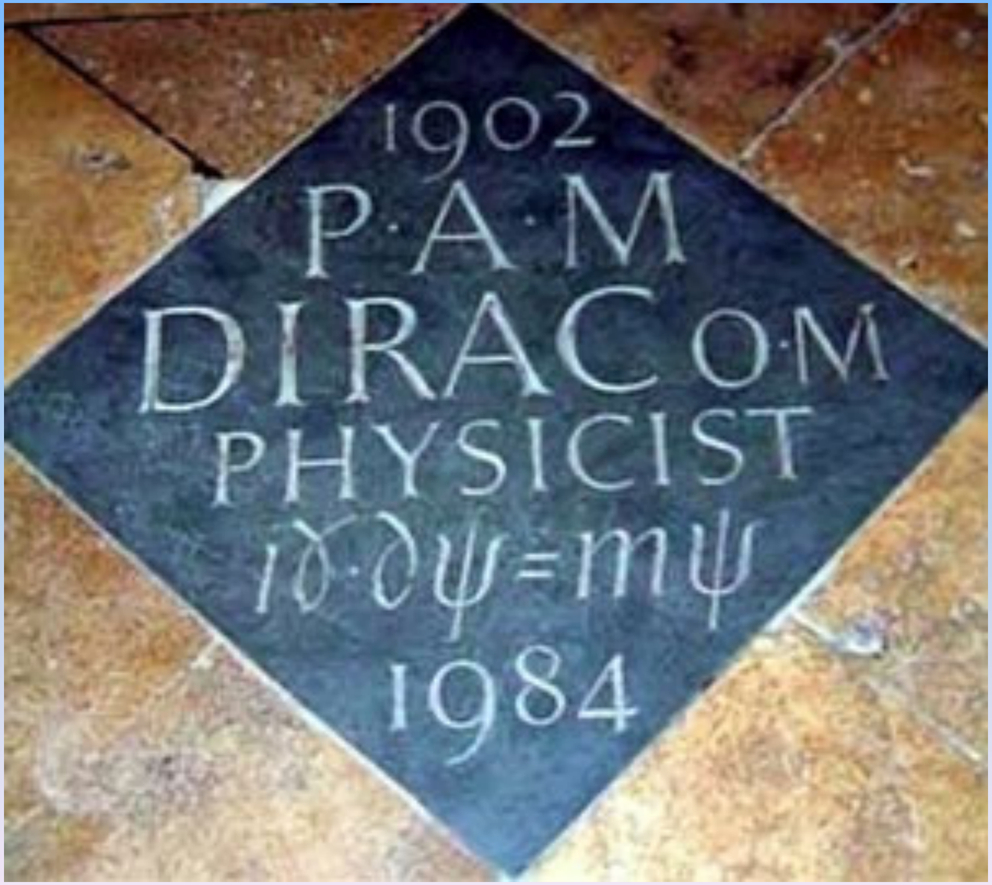
Dirac

$$H\psi = (\vec{\alpha} \cdot \vec{p} + \beta m)\ \psi$$

The famous Dirac equation:

$$\begin{aligned} (i\gamma^\mu \partial_\mu - m)\ \psi &= 0 \\ \text{with}:\ \ \gamma^\mu = (\beta, \beta\vec{\alpha}) &\equiv \text{Dirac } \gamma\text{−matrices} \end{aligned}$$

R.I.P. :



Dirac vergelijking

Schrödinger equation

- Time-dependence of wave function

$$E = \frac{\vec{p}^2}{2m}$$

$$i \frac{\partial}{\partial t} \psi = \frac{-1}{2m} \nabla^2 \psi$$

Klein-Gordon equation

- Relativistic equation of motion of scalar particles

$$E^2 = \vec{p}^2 + m^2$$

$$-\frac{\partial^2}{\partial t^2} \phi = -\nabla^2 \phi + m^2 \phi$$

Dirac equation

- Relativistically correct, and linear
- Equation of motion for spin-1/2 particles
- Prediction of anti-matter

$$(i\gamma^\mu \partial_\mu - m) \psi = 0$$

$$\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix}$$