

*Deeltjesversnellers
en detectoren*



*Ontdekking van het
Higgs deeltje*



Anti-materie

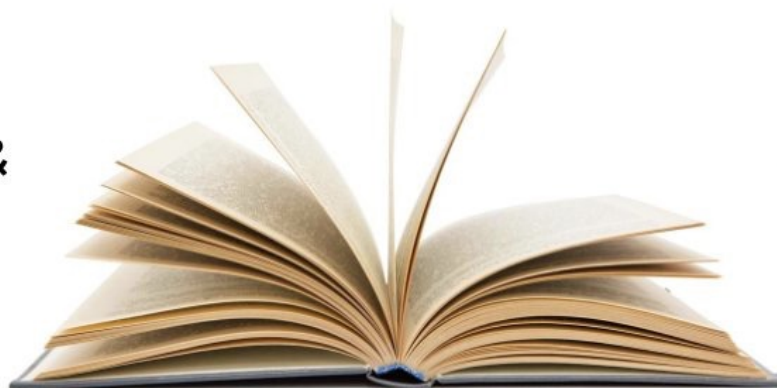


*Elementaire deeltjes
in de kosmos*

Neutrino's



*Deeltjes &
krachten*



*Donkere
materie*



Expeditie deeltjesfysica

90^{ste} verjaardag!



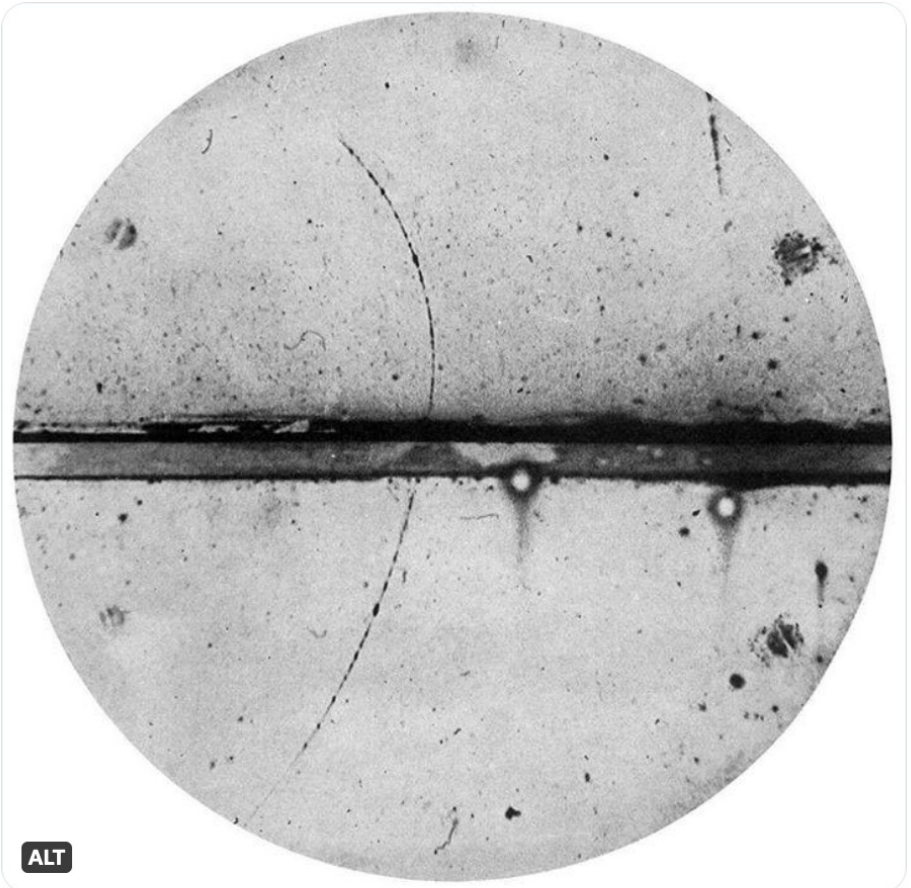
The Nobel Prize 
@NobelPrize



The Positive Electron: Carl Anderson's discovery of the positron was published [#OTD](#) 90 years ago.

Image: Cloud chamber photograph by Anderson, the first positron ever observed. The deflection and direction of the particle's ion trail indicate it is a positron.

[#NobelPrize](#)



ALT

8:01 AM · Mar 15, 2023 · 25.4K Views

Antimaterie

Studium Generale, Leiden



Niels Tuning – 15 maart 2023

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

Slechts materie om ons heen?

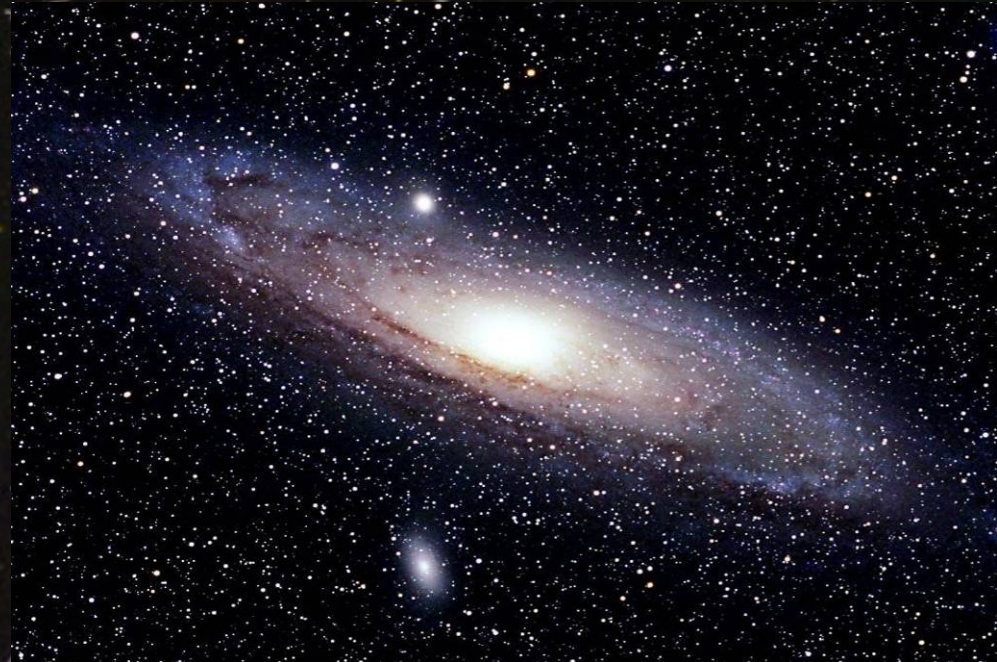


Is dit alles?

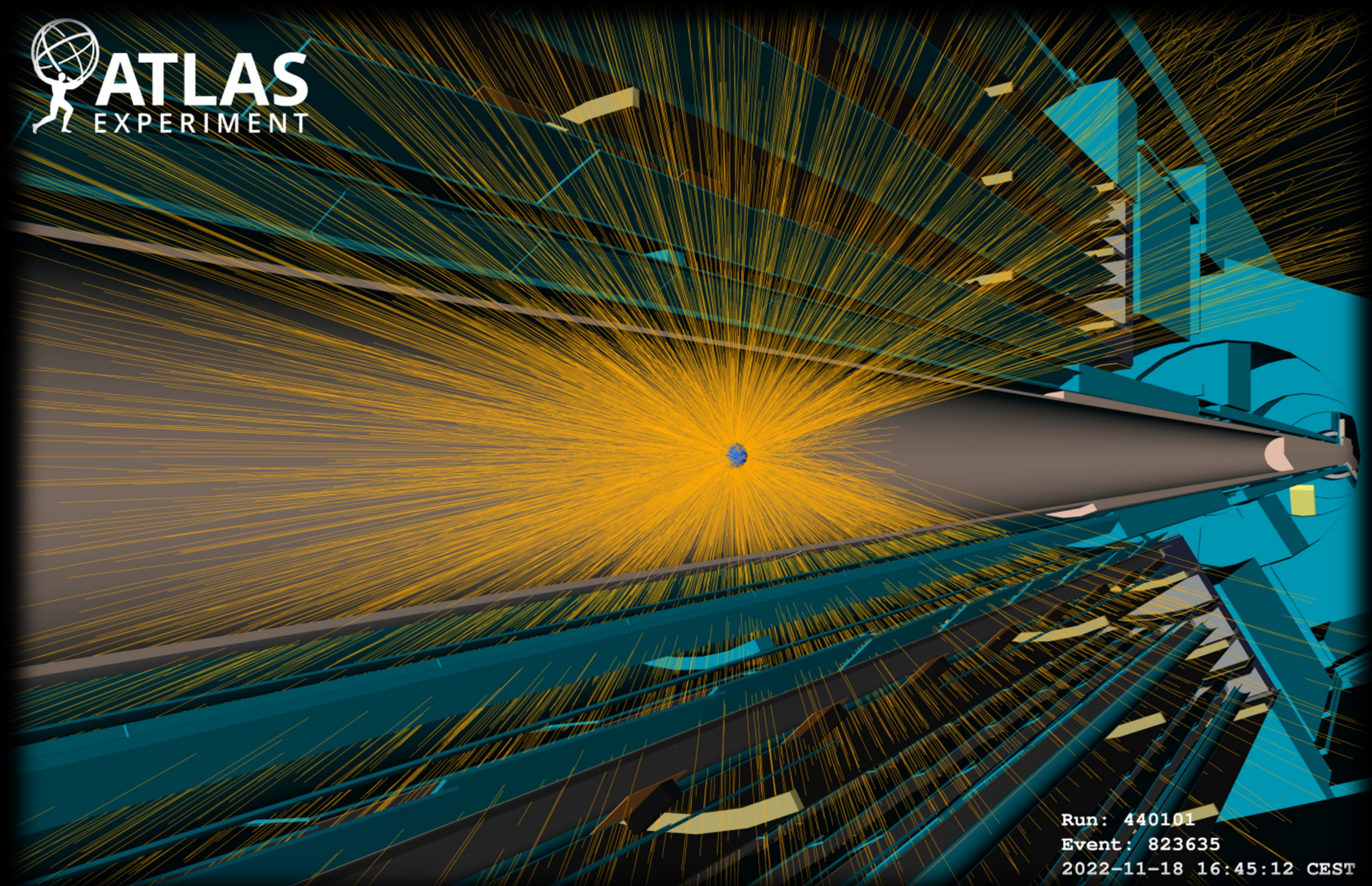
Generatie:

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

Materie

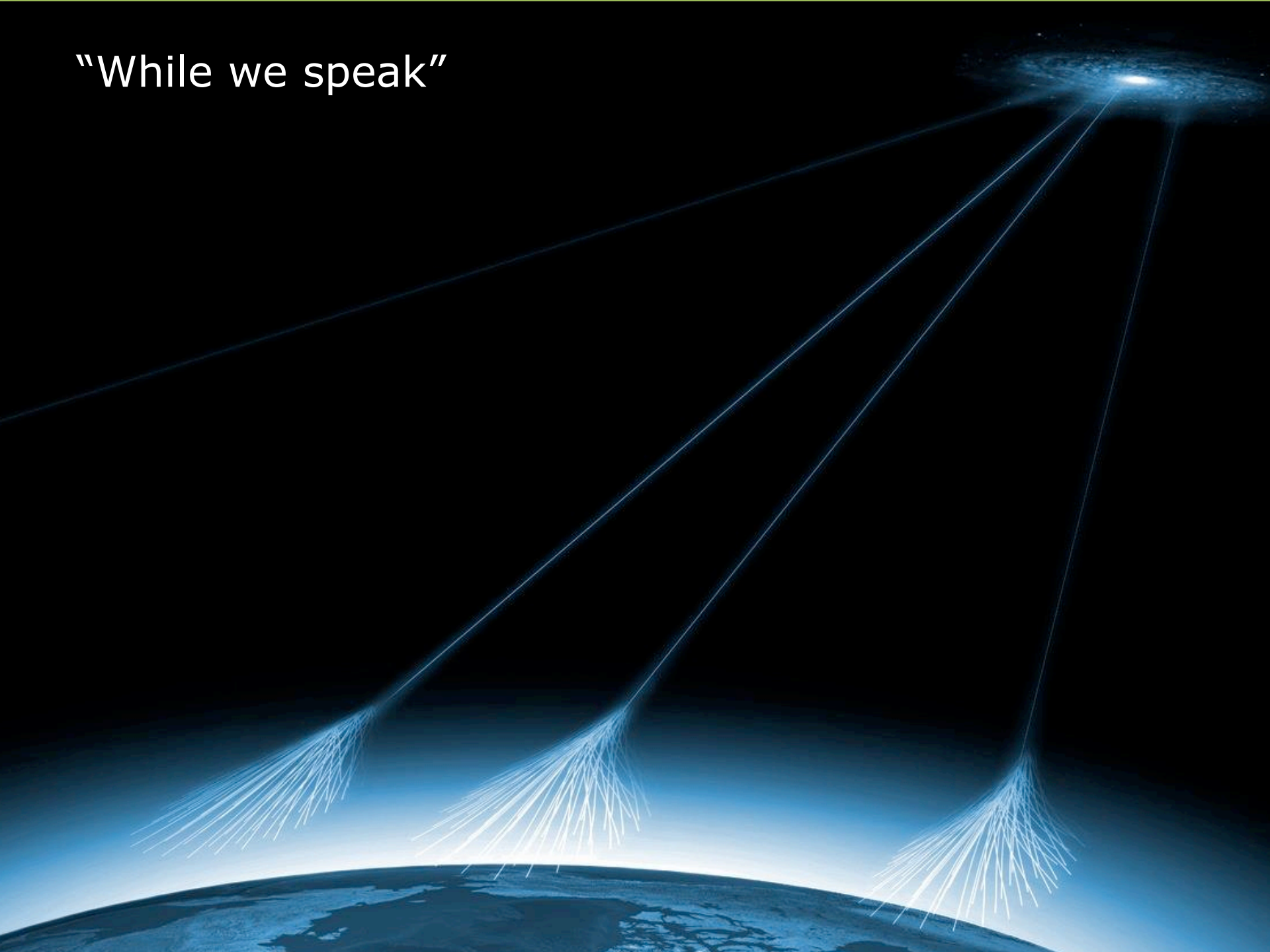


“Gesneden koek” bij de deeltjesversneller



Run: 440101
Event: 823635
2022-11-18 16:45:12 CEST

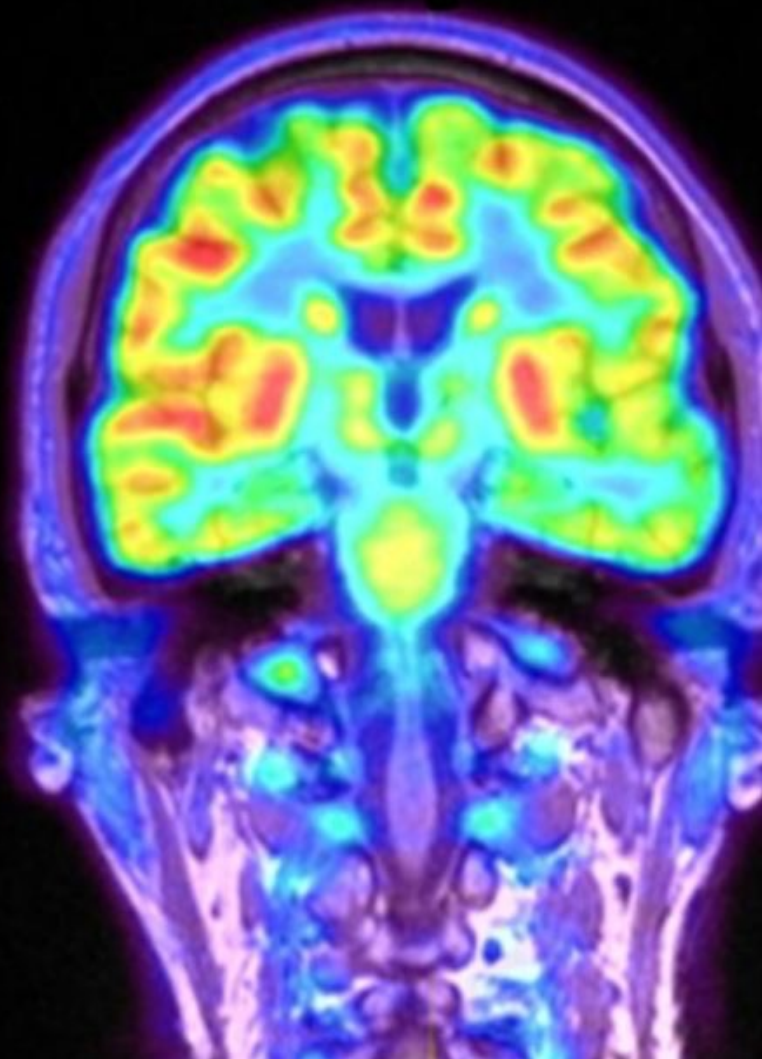
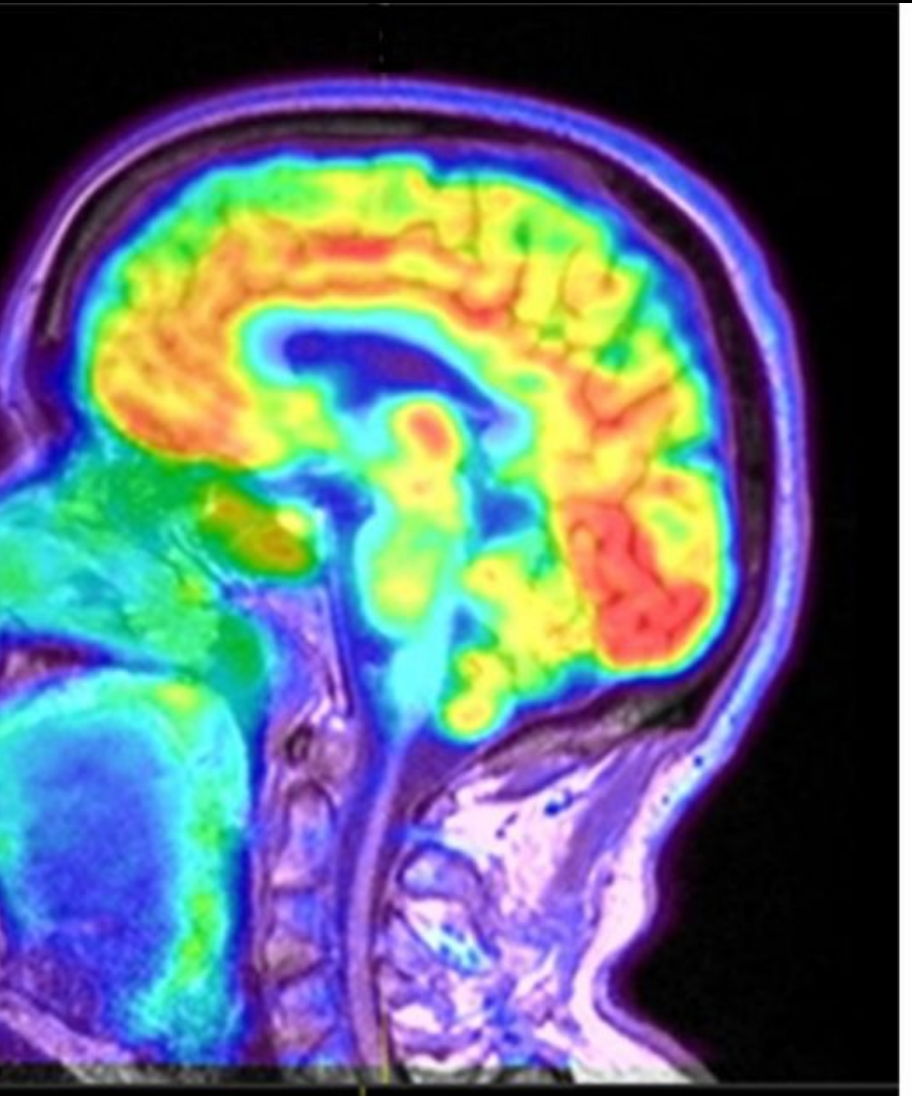
“While we speak”



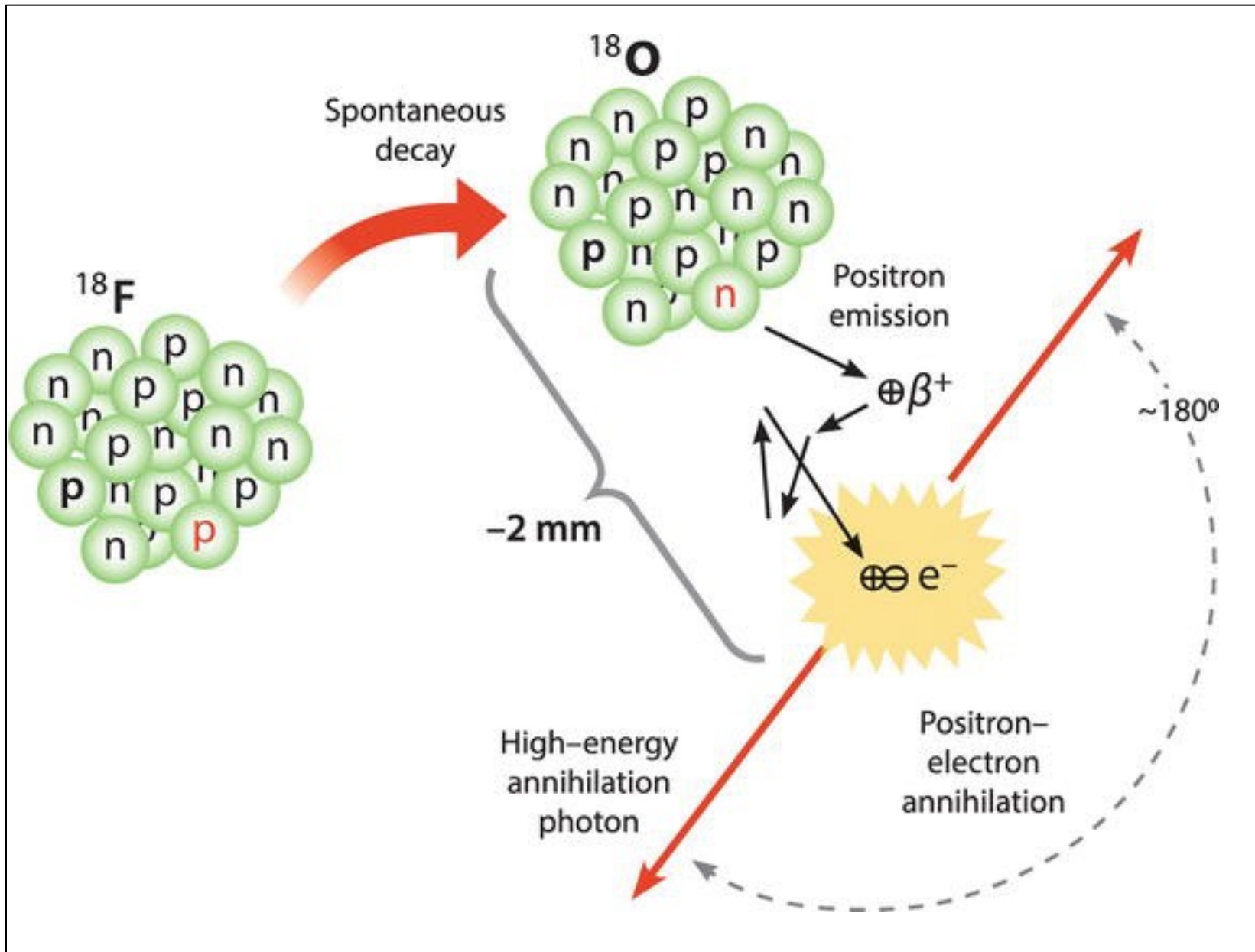
(een handvol anti-muonen per seconde)



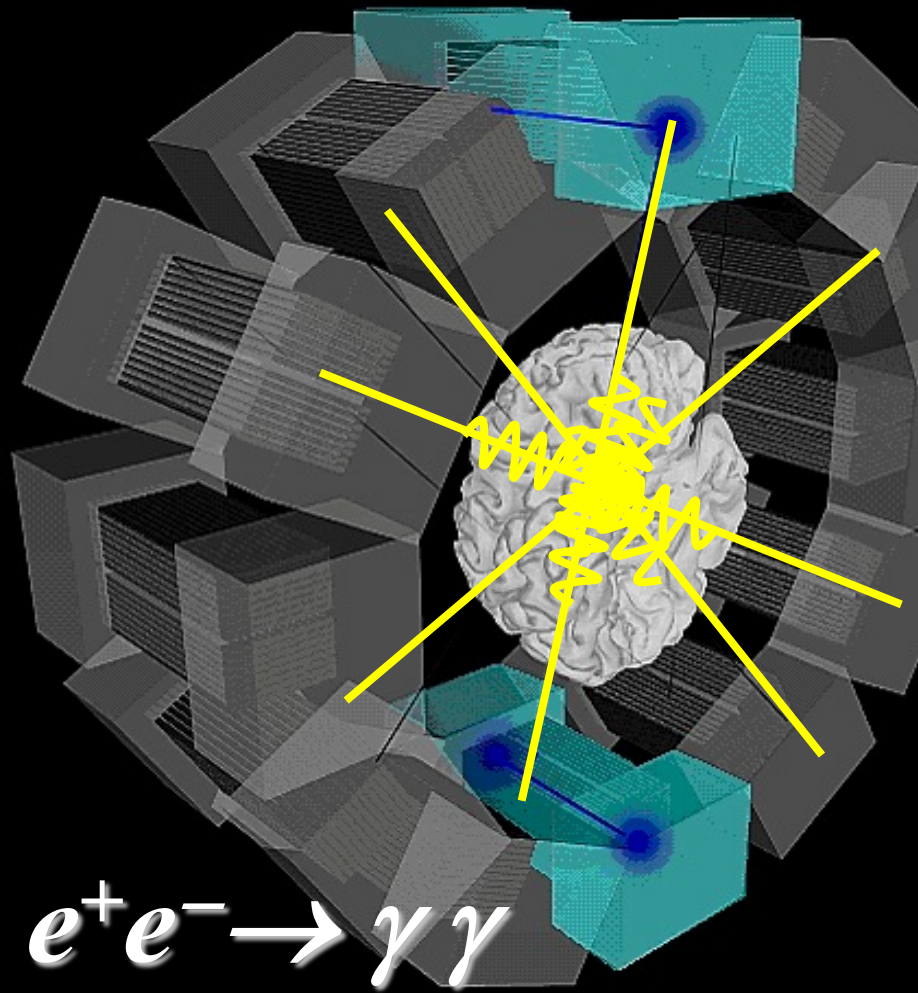
Bij u in de buurt



Antimaterie in het ziekenhuis



Anti-materie in ziekenhuizen: de PET-scan



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

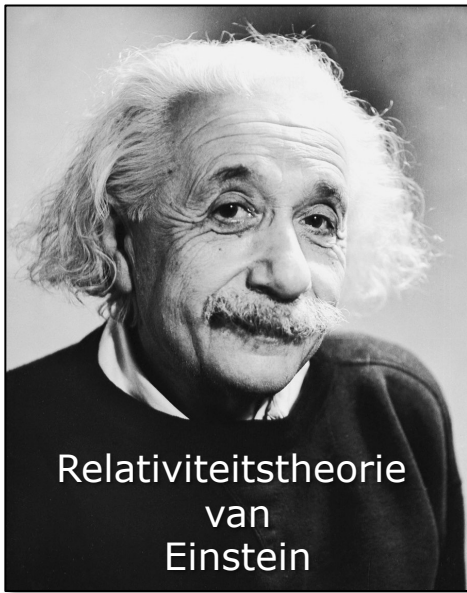
“Nooit formules gebruiken”

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

$$\begin{aligned}
 & -\frac{1}{2}\partial_\mu g_\nu^\mu \partial_\nu g_\mu^\nu - g_\mu f^{abc} \partial_\mu g_\nu^a g_\nu^b g_\nu^c - \frac{1}{4}g_\mu^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\nu^d g_\nu^e + \\
 & \frac{1}{2}ig_\mu^2 (\bar{q}^i \gamma^\mu q_i^j) g_\mu^0 + G^a \partial^2 G^a + g_s f^{abc} \partial_\mu G^a G^b g_\mu^c - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
 & M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{24}M^2 Z_\mu^0 Z_\mu^0 - \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} M \phi^0 \phi^0 - \beta_h [\frac{2M^2}{g^2} + \\
 & \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \frac{2M^2}{g^2} \alpha_h - ig c_w [\partial_\nu (W_\mu^+ W_\nu^- - \\
 & W_\mu^- W_\nu^+) - Z_\mu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\mu^+ \partial_\nu W_\mu^- - \\
 & W_\mu^- \partial_\nu W_\mu^+)] - ig s_w [\partial_\nu (A_\mu (W_\mu^+ W_\nu^- - W_\mu^- W_\nu^+) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - \\
 & W_\mu^- \partial_\nu W_\mu^+)) + A_\mu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \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_\mu^0 W_\nu^+ Z_\mu^0 W_\nu^- - Z_\mu^0 W_\nu^+ W_\nu^-) + \\
 & g^2 s_w^2 (A_\mu W_\nu^+ A_\nu W_\mu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^2 + 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)^2 H^2] - \\
 & g M W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w} Z_\mu^0 Z_\mu^0 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}ig [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_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{2c_w}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \\
 & ig s_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
 & ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4}g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\
 & \frac{1}{4}g^2 \frac{c_w}{c_w} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{2c_w}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{2c_w}{c_w} Z_\mu^0 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{2c_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
 & g^4 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m_e^0) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}_j^2 (\gamma \partial + m_u^0) u_j^2 - \\
 & \bar{d}_j^2 (\gamma \partial + m_d^0) d_j^2 + ig s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^2 \gamma^\mu u_j^2) - \frac{1}{3}(\bar{d}_j^2 \gamma^\mu d_j^2)] + \\
 & \frac{ig}{4c_w} Z_\mu^0 [(\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}_j^2 \gamma^\mu (\frac{4}{3}s_w^2 - \\
 & 1 - \gamma^5) u_j^2) + (\bar{d}_j^2 \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^2)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + \\
 & (\bar{u}_j^2 \gamma^\mu (1 + \gamma^5) C_{\lambda k} d_j^k)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^2 C_{\lambda k}^1 \gamma^\mu (1 + \\
 & \gamma^5) u_j^2)] + \frac{ig}{2\sqrt{2}} M [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \\
 & \frac{g}{2} \frac{m_c^2}{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^0 (\bar{u}_j^2 C_{\lambda k} (1 - \gamma^5) d_j^k) + \\
 & m_u^0 (\bar{u}_j^2 C_{\lambda k} (1 + \gamma^5) d_j^k)] + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^0 (\bar{d}_j^2 C_{\lambda k}^1 (1 + \gamma^5) u_j^2) - m_u^0 (\bar{d}_j^2 C_{\lambda k}^1 (1 - \\
 & \gamma^5) u_j^2) - \frac{g}{2} \frac{m_h^2}{M} H (\bar{u}_j^2 u_j^2) - \frac{g}{2} \frac{m_h^2}{M} H (\bar{d}_j^2 d_j^2) + \frac{ig}{2} m_\phi^0 (\bar{u}_j^2 \gamma^5 u_j^2) - \\
 & \frac{ig}{2} \frac{m_\phi^0}{M} (\bar{d}_j^2 \gamma^5 d_j^2) + \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 + ig c_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + ig s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \\
 & \partial_\mu \bar{X}^+ Y) + ig c_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + ig s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \\
 & \partial_\mu \bar{Y} X^+) + ig c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + ig s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
 & \partial_\mu \bar{X}^- X^-) - \frac{1}{2}g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w} \bar{X}^0 X^0 H] + \\
 & \frac{1-2c_w^2}{2c_w} ig M [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} ig M [\bar{X}^0 X^- \phi^+ - \bar{X}^+ X^+ \phi^-] + \\
 & \frac{1}{2} ig M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^+ X^+ \phi^-] + \frac{1}{2} ig M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$

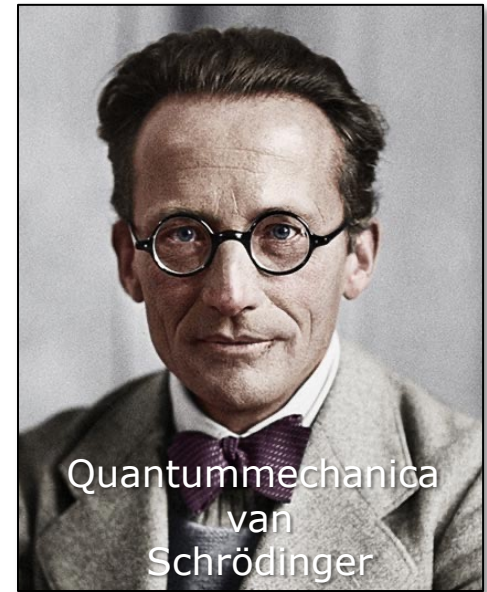
标准模型公式

乐谱



Relativiteitstheorie
van
Einstein

~ 1920



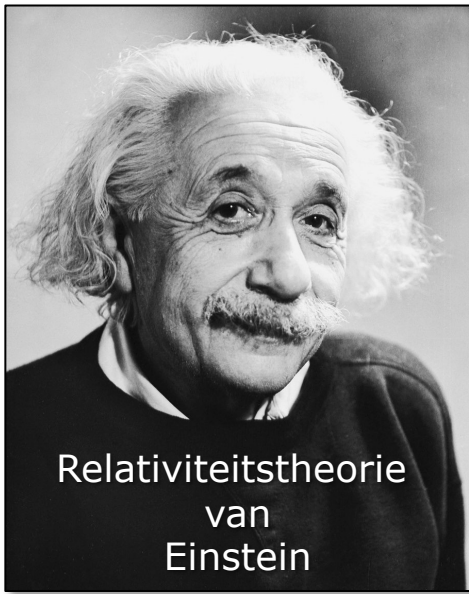
Quantummechanica
van
Schrödinger

“Relativistisch”

$$E = mc^2$$

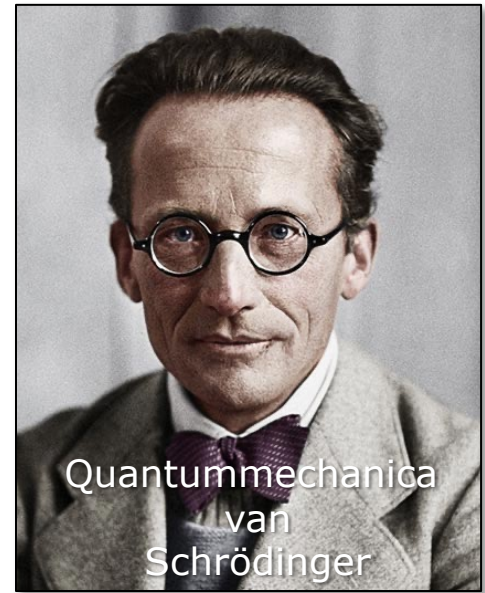
“Gewoon”

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



Relativiteitstheorie
van
Einstein

~ 1920



Quantummechanica
van
Schrödinger

“Relativistisch”

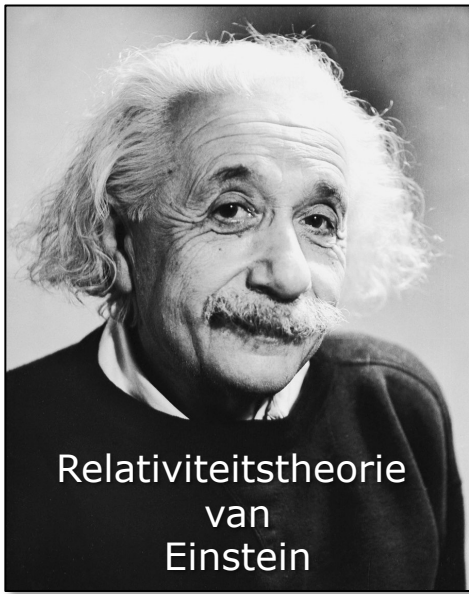
$$E = mc^2$$

“Gewoon”

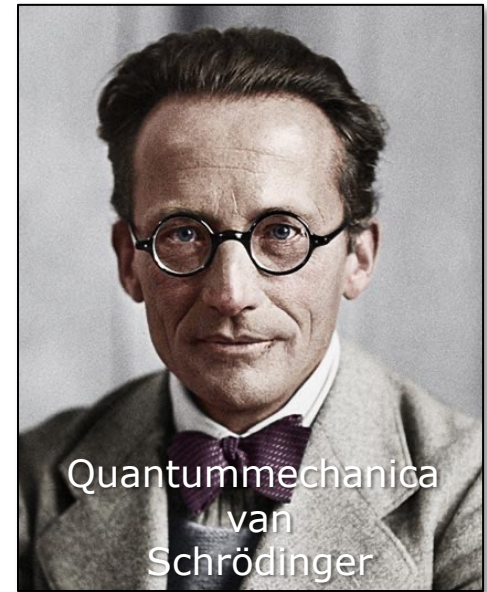
$$E = \frac{1}{2}mv^2$$

$$(p = mv)$$

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



~ 1920



“Relativistisch”

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

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

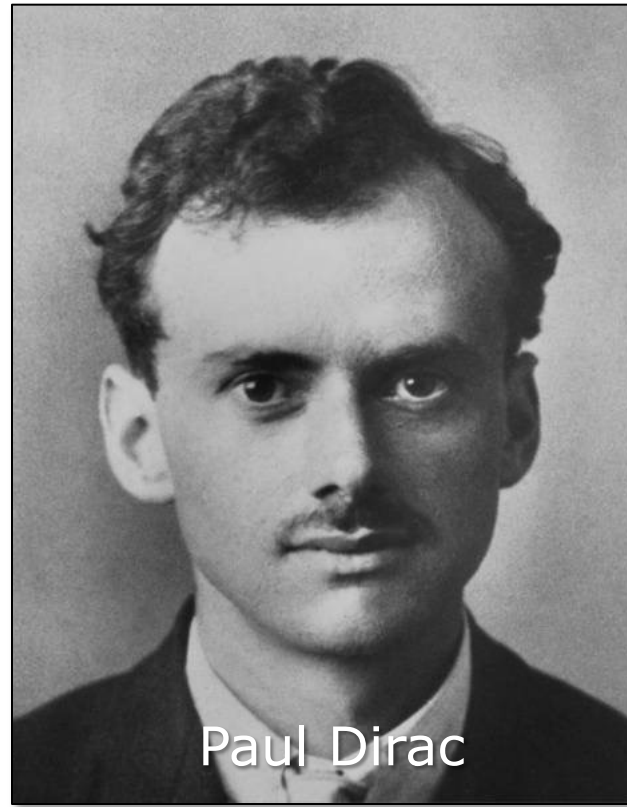
← Anders! →

“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!

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





Einstein:

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



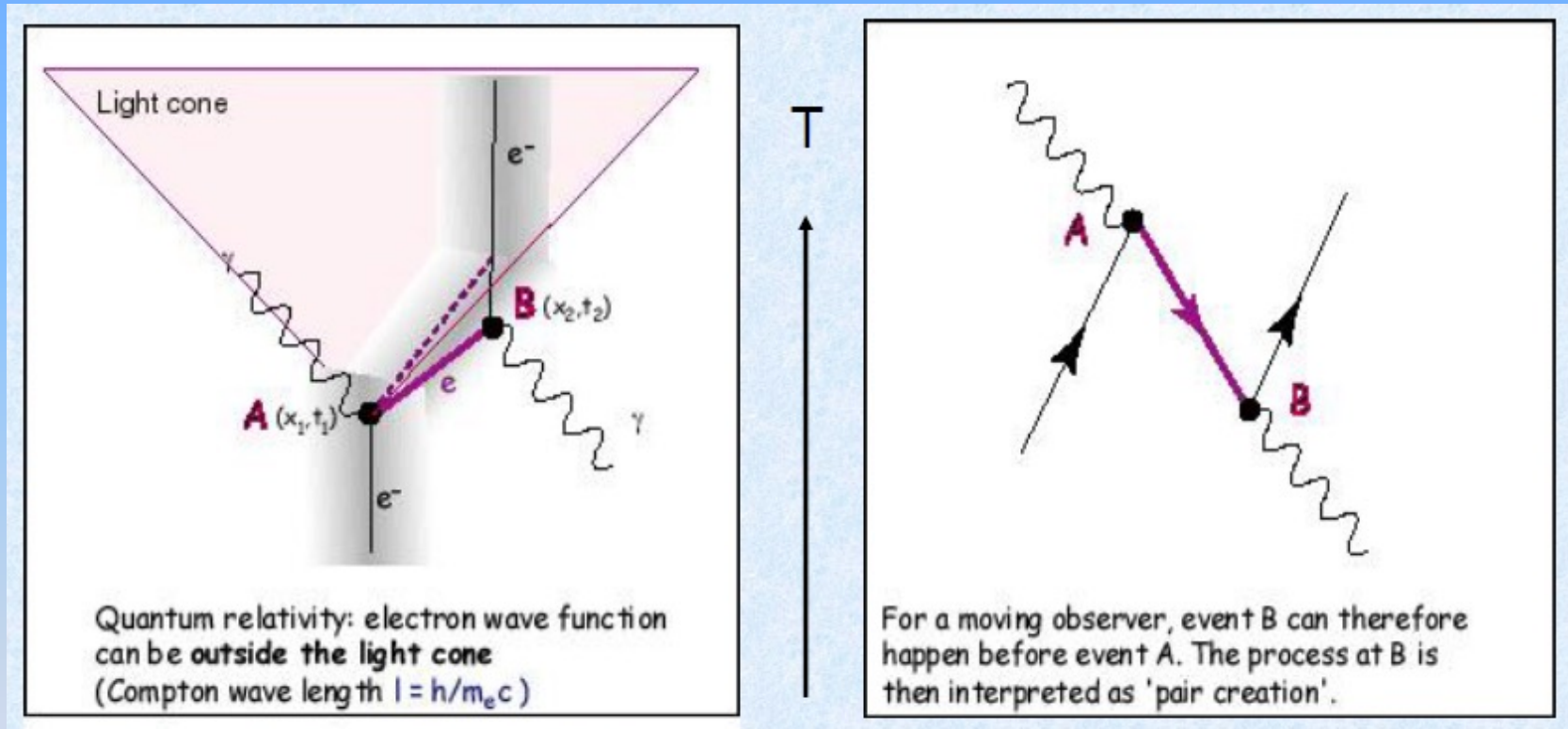
Dirac:

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


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


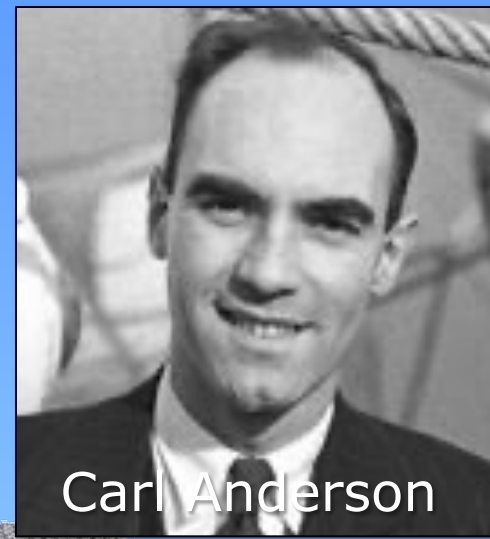
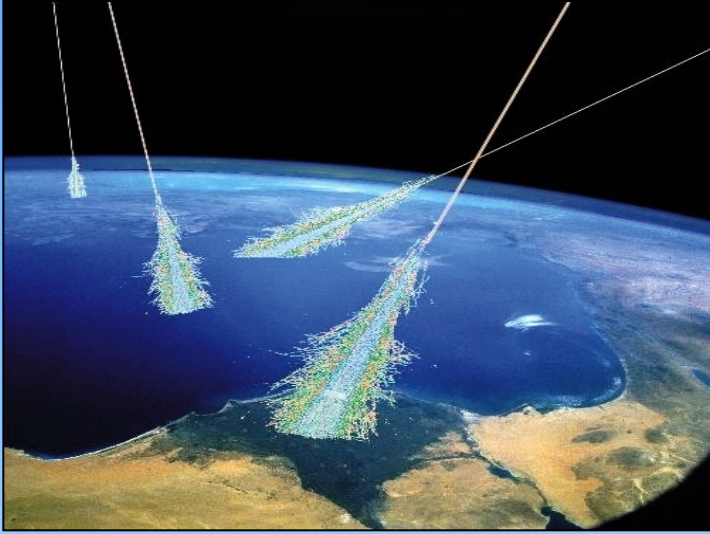
Why anti-matter must exist!

“Feynman-Stueckelberg interpretation”

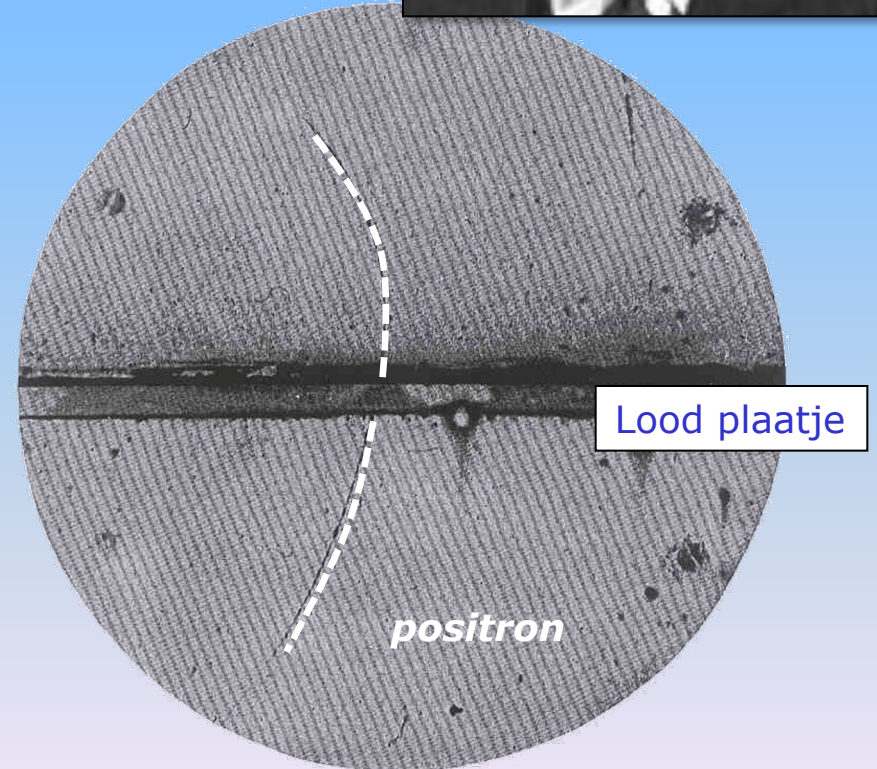
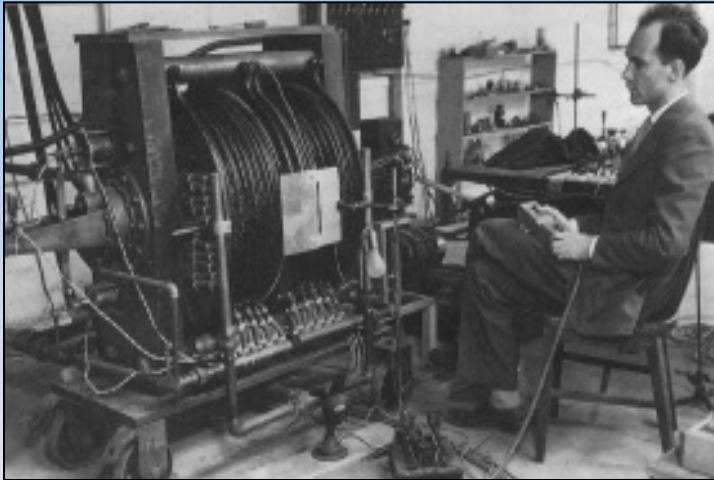


“One observer’s electron is the other observer’s positron”

1932: Ontdekking van antimaterie!



Carl Anderson



Nobelprijs 1936

De elementaire deeltjes

quarks

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

leptons

	e <i>(1895)</i>	μ <i>(1936)</i>	τ <i>(1973)</i>	-1 e
	ν_e <i>(1956)</i>	ν_μ <i>(1963)</i>	ν_τ <i>(2000)</i>	0 e

Materie

<u>Lading</u>	I	II	III
-2/3 e	ū	c̄	t̄
+1/3 e	d̄	s̄	b̄
+1 e	ē	μ̄	τ̄
0 e	ν̄_e	ν̄_μ	ν̄_τ

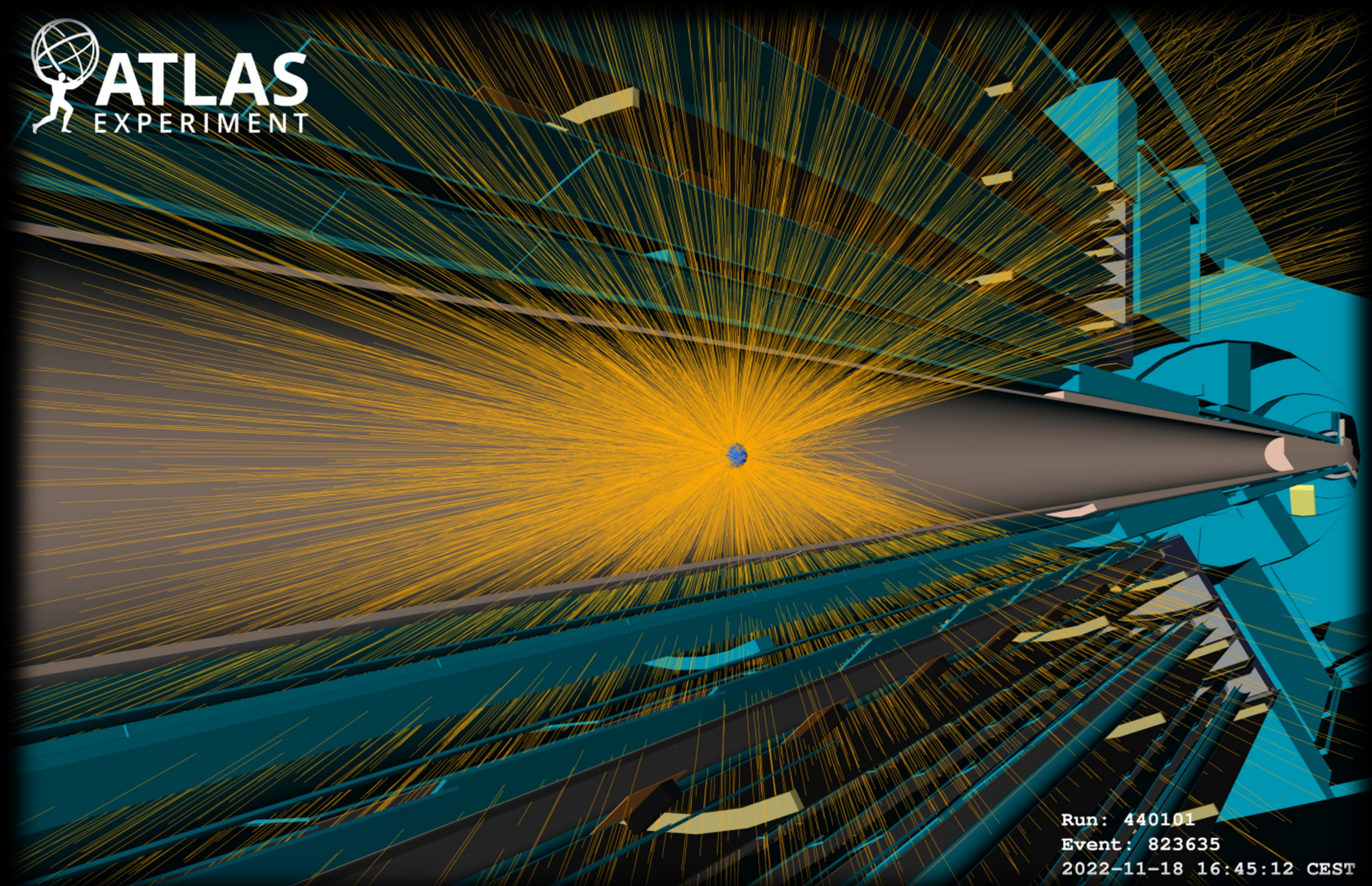
Anti-materie

Antimaterie

- Deel 1: Hoezo?
 - Wat is het
 - Hoe is het bedacht
 - Wat is het probleem

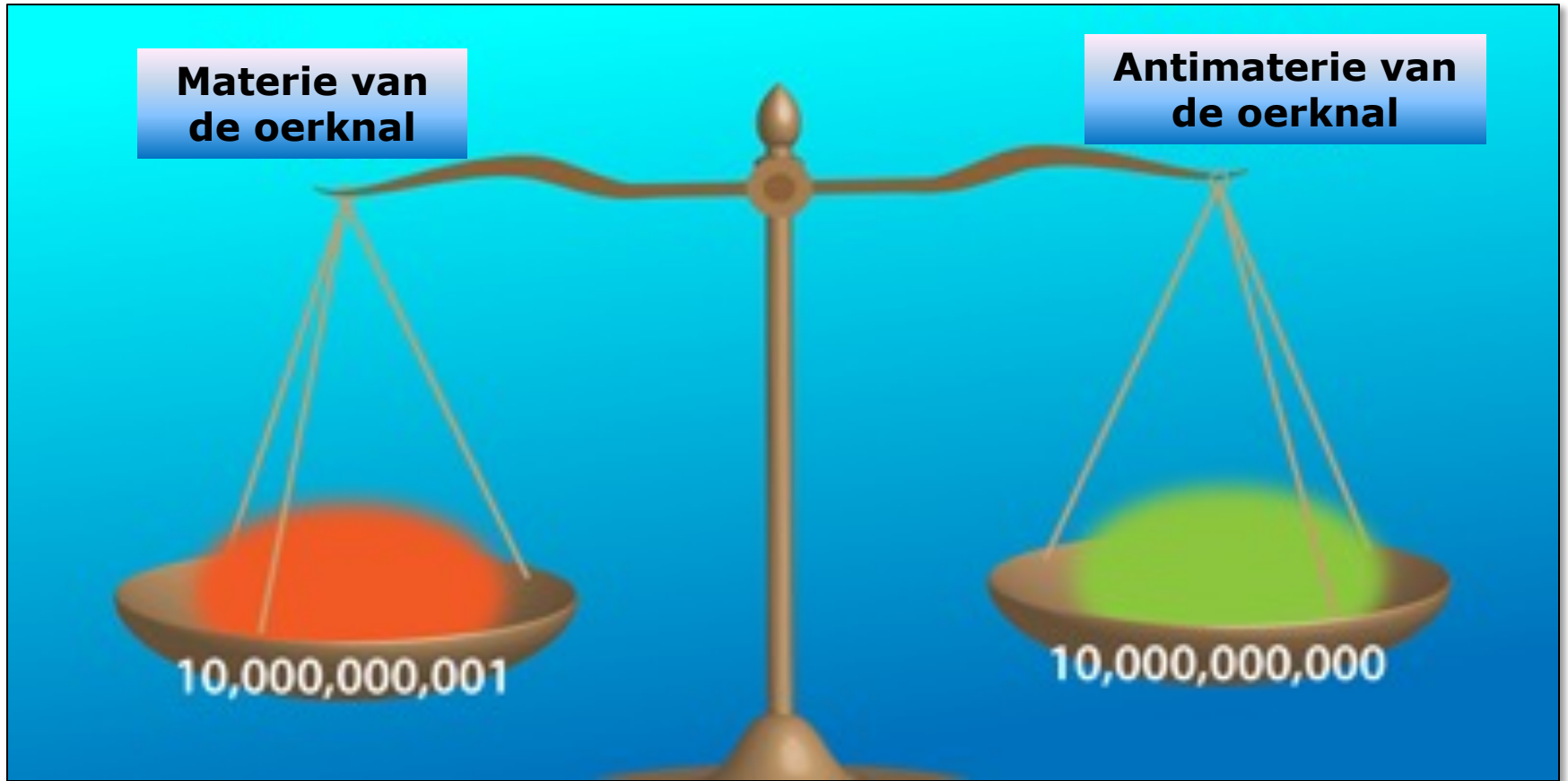
- Deel 2: Wat nu?
 - Uit de ruimte
 - Antiwaterstof
 - Antimaterie verschillen

“Gesneden koek” bij de deeltjesversneller



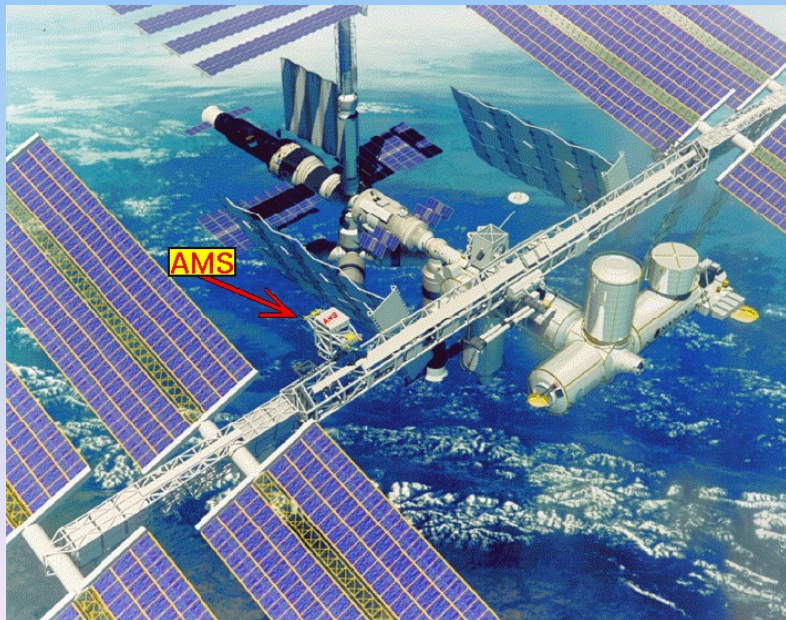
Run: 440101
Event: 823635
2022-11-18 16:45:12 CEST

Waar is de antimaterie gebleven?

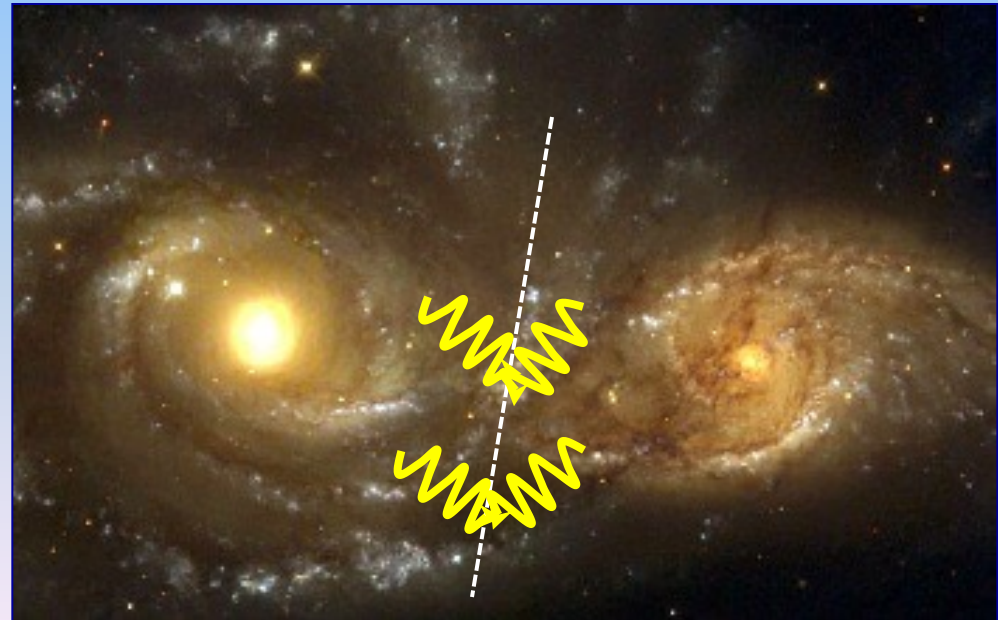


Waar is de anti-materie gebleven?

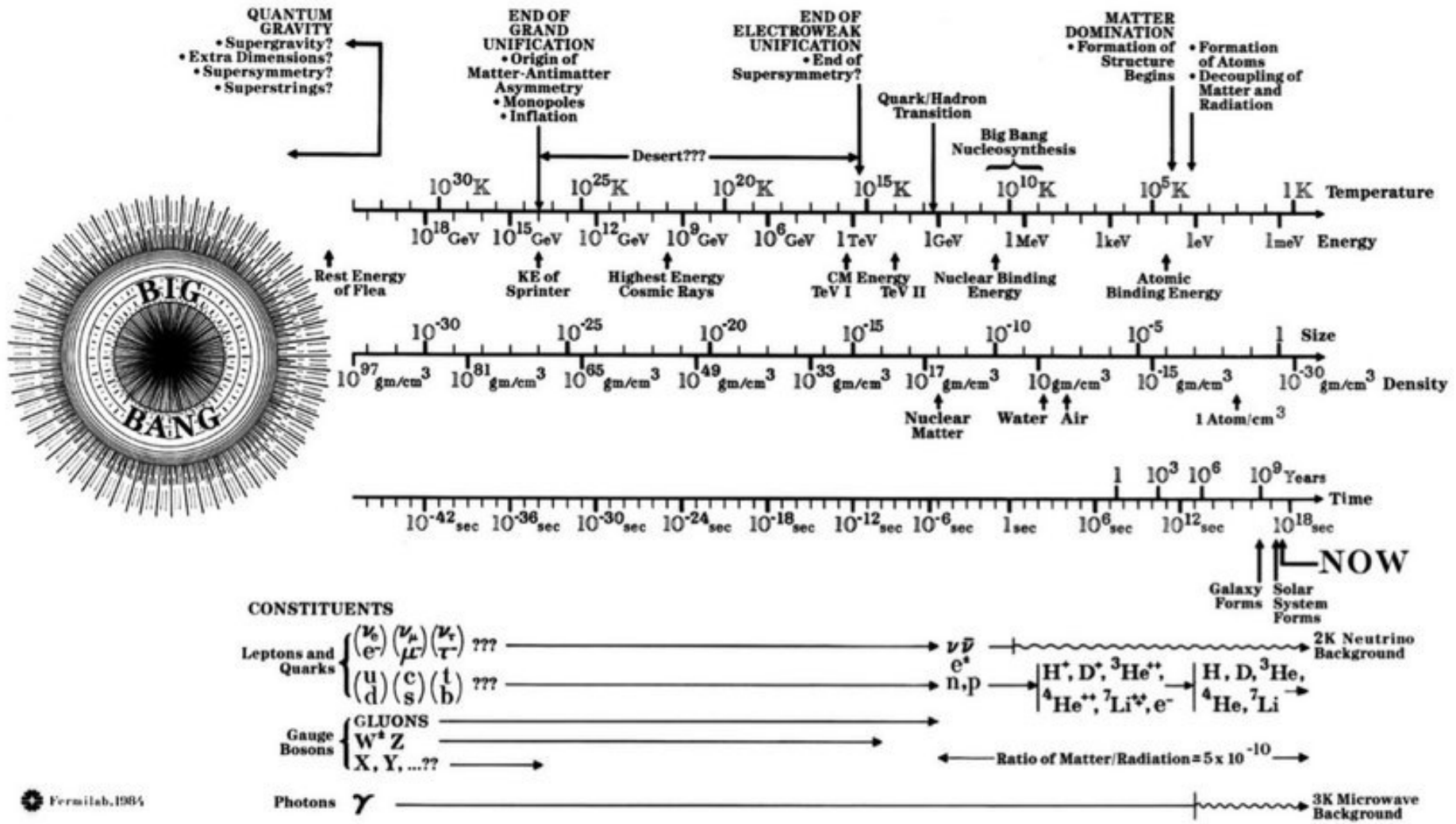
*Geen anti-materie
met satellieten*



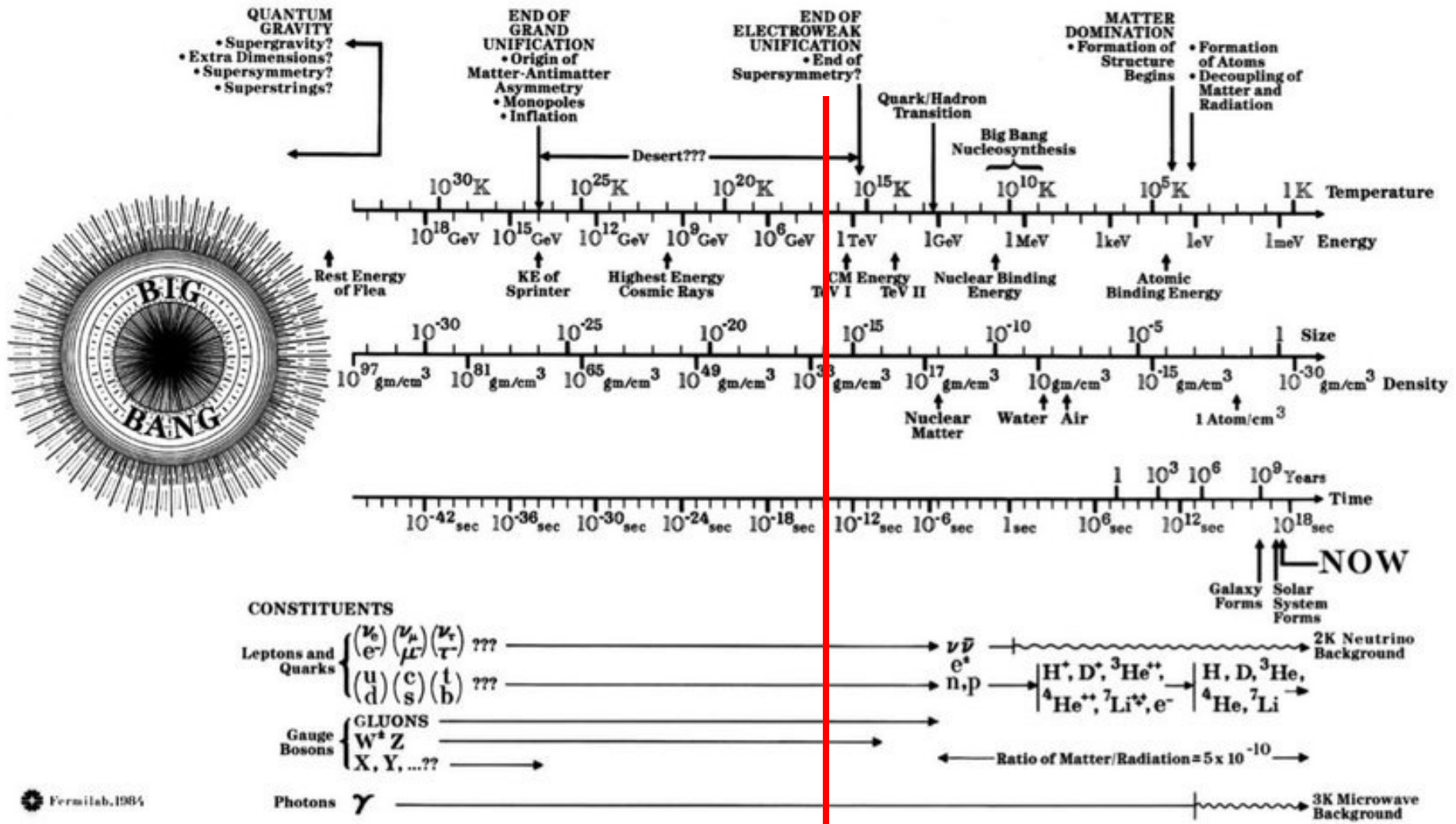
*Geen anti-materie
sterrenstelsels*



Geschiedenisses

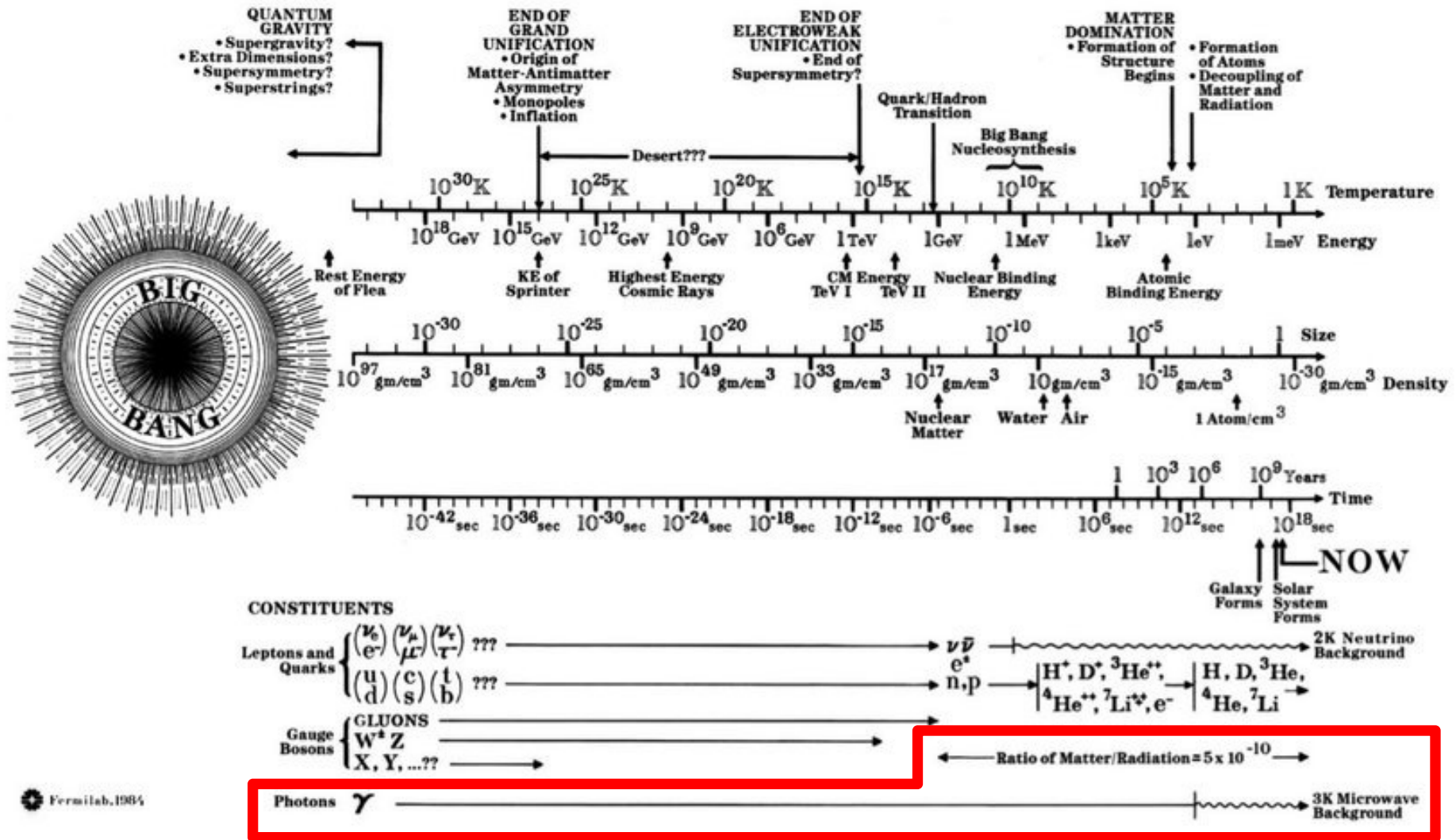


Geschiedenises



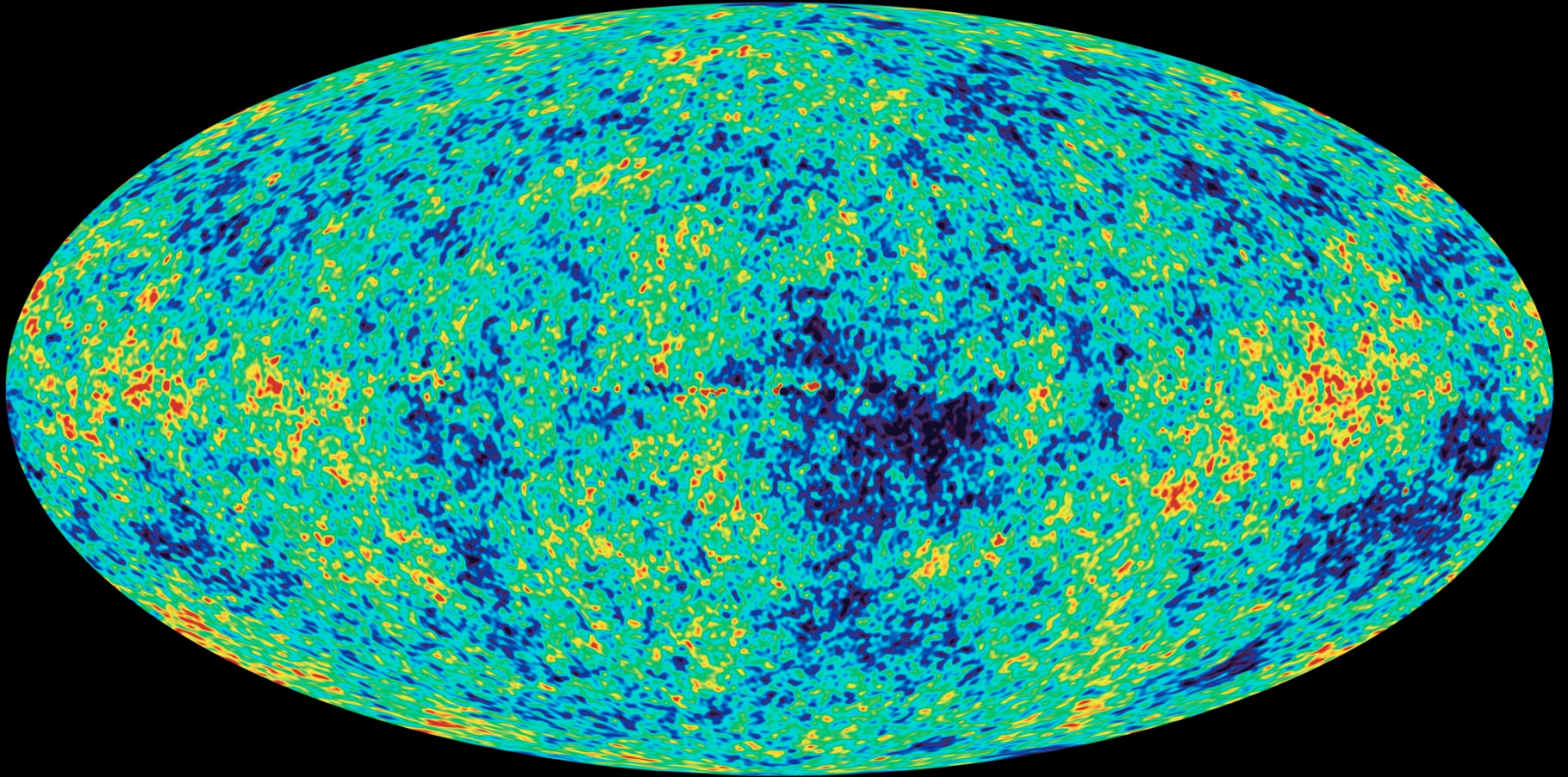
U bent hier: \blacktriangledown $10^{-16} \text{ m}, 10^{-14} \text{ s}, 10^{16} \text{ K}$

Geschiedenisles

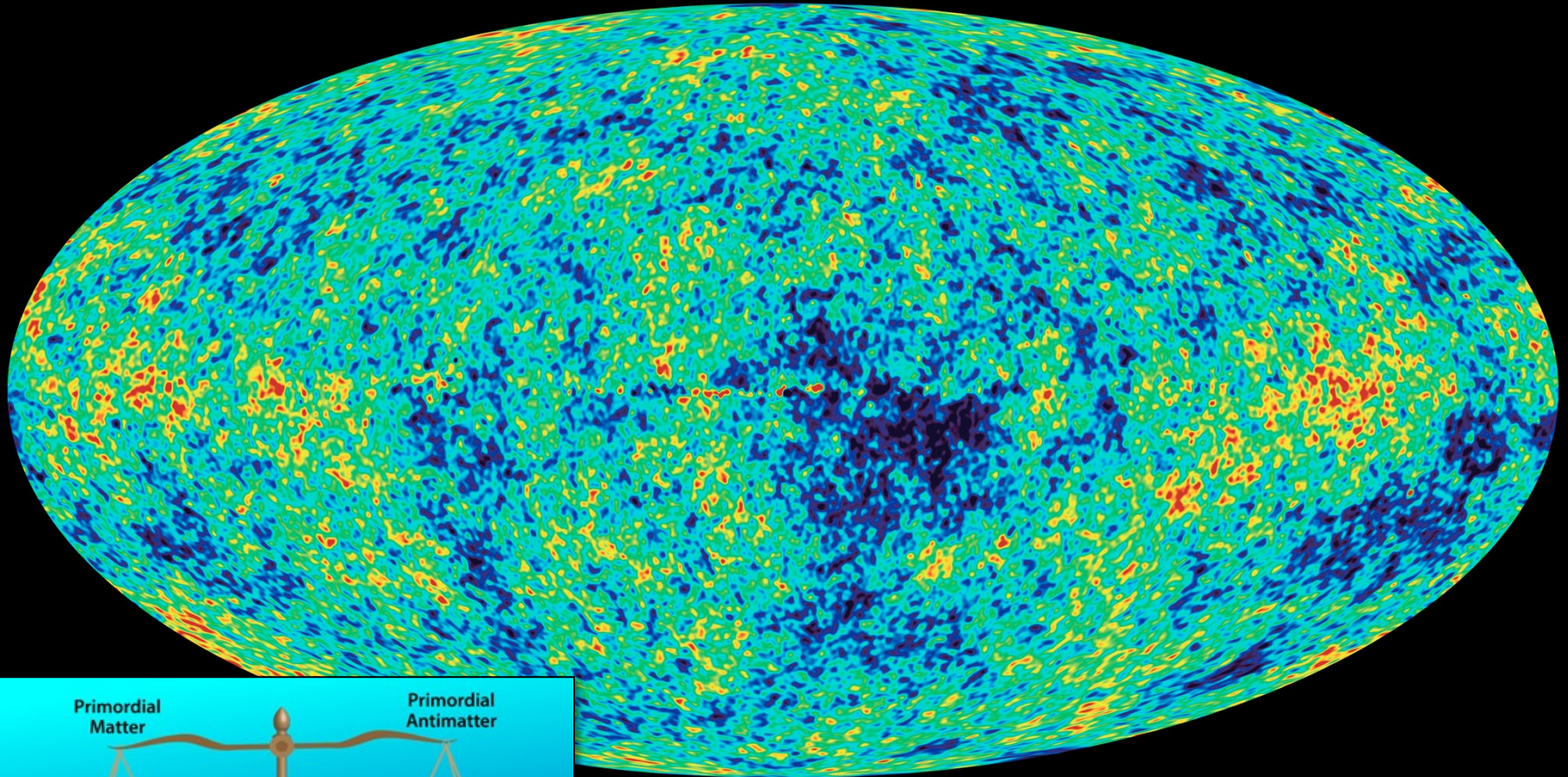


Fotonen van materie – antimaterie annihilatie

300,000 jaar na de oerknal werd het heelal doorzichtig



Na annihilatie: 10,000,000 fotonen en 1 materie deeltje



Pauze?

De stand van zaken in 2023



[http:// pdg.lbl.gov](http://pdg.lbl.gov)

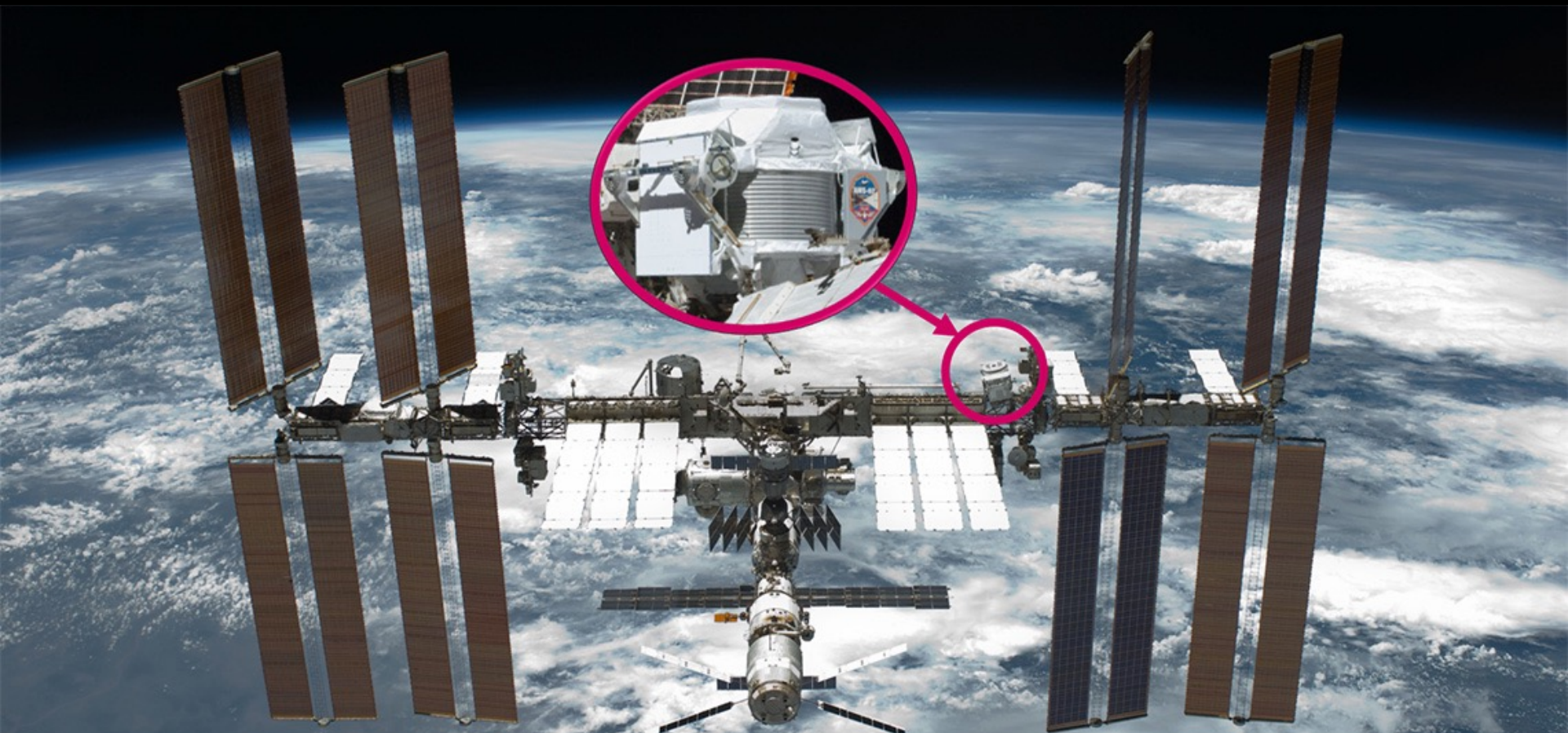
Antimaterie

- Deel 1: Hoezo?
 - Wat is het
 - Hoe is het bedacht
 - Wat is het probleem

- Deel 2: Wat nu?
 - Uit de ruimte
 - Antiwaterstof
 - Antimaterie verschillen

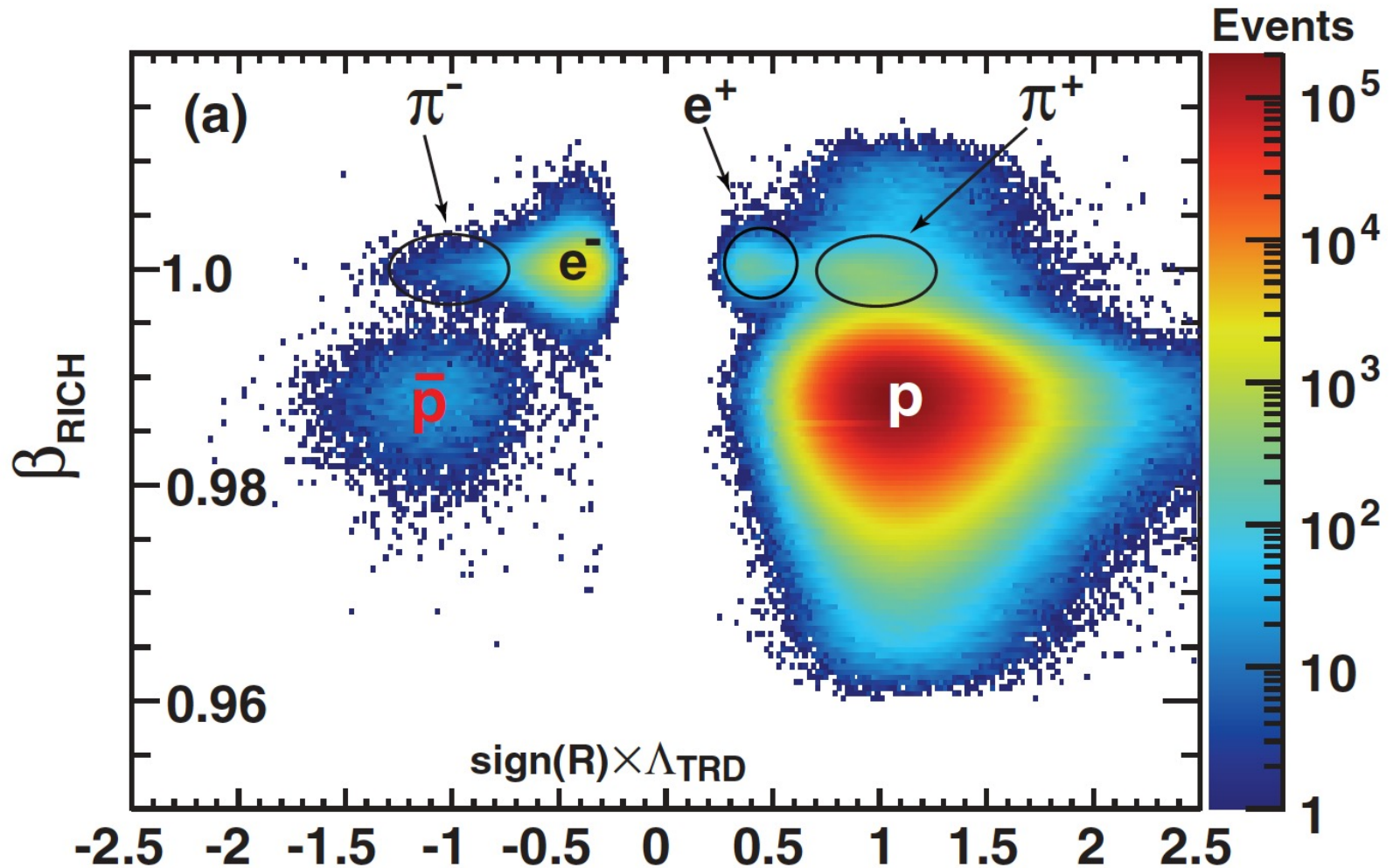
Uit de ruimte?

Het AMS experiment



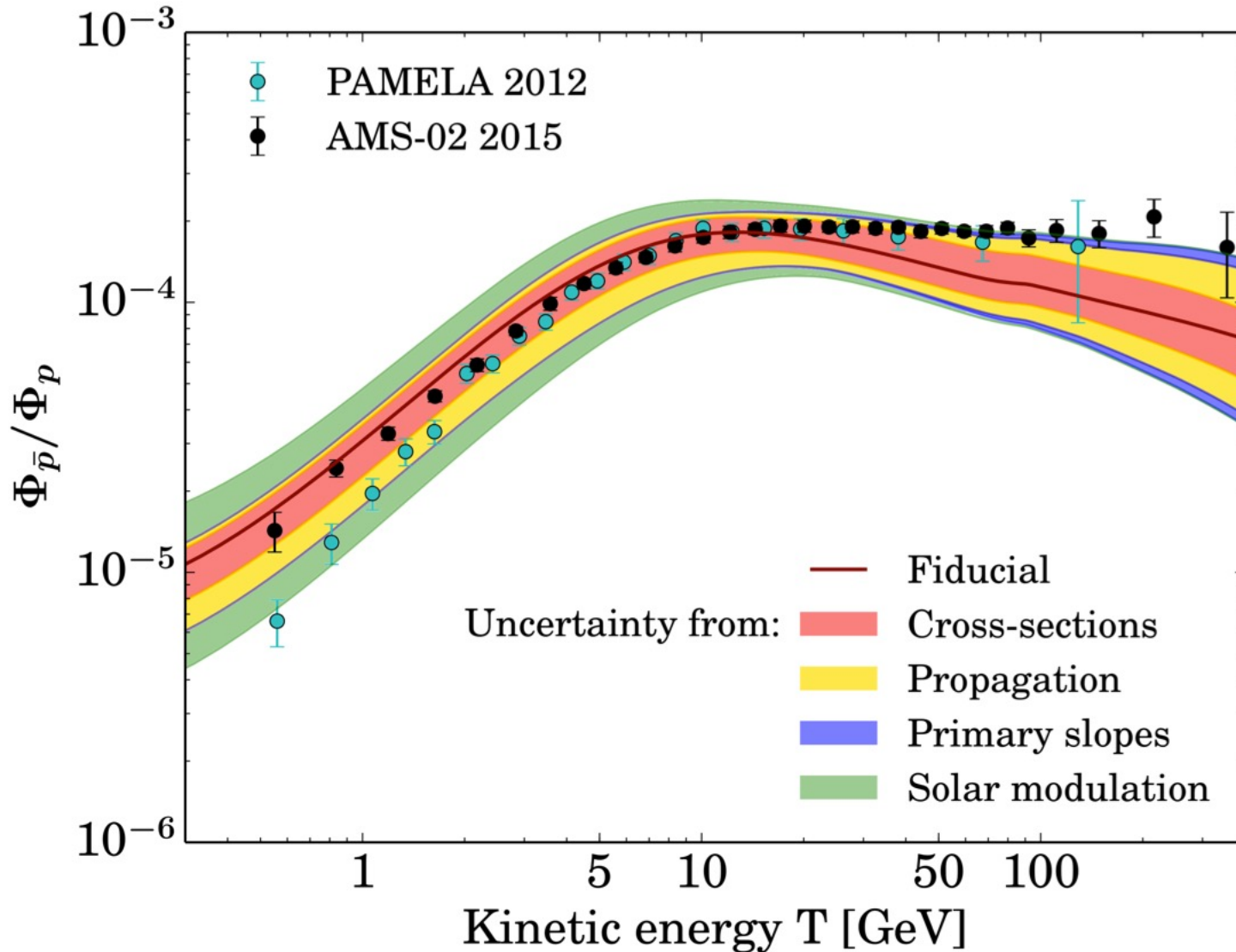
Anti-protonen?

- Men verwacht anti-protonen uit ster-processen...



Anti-protonen?

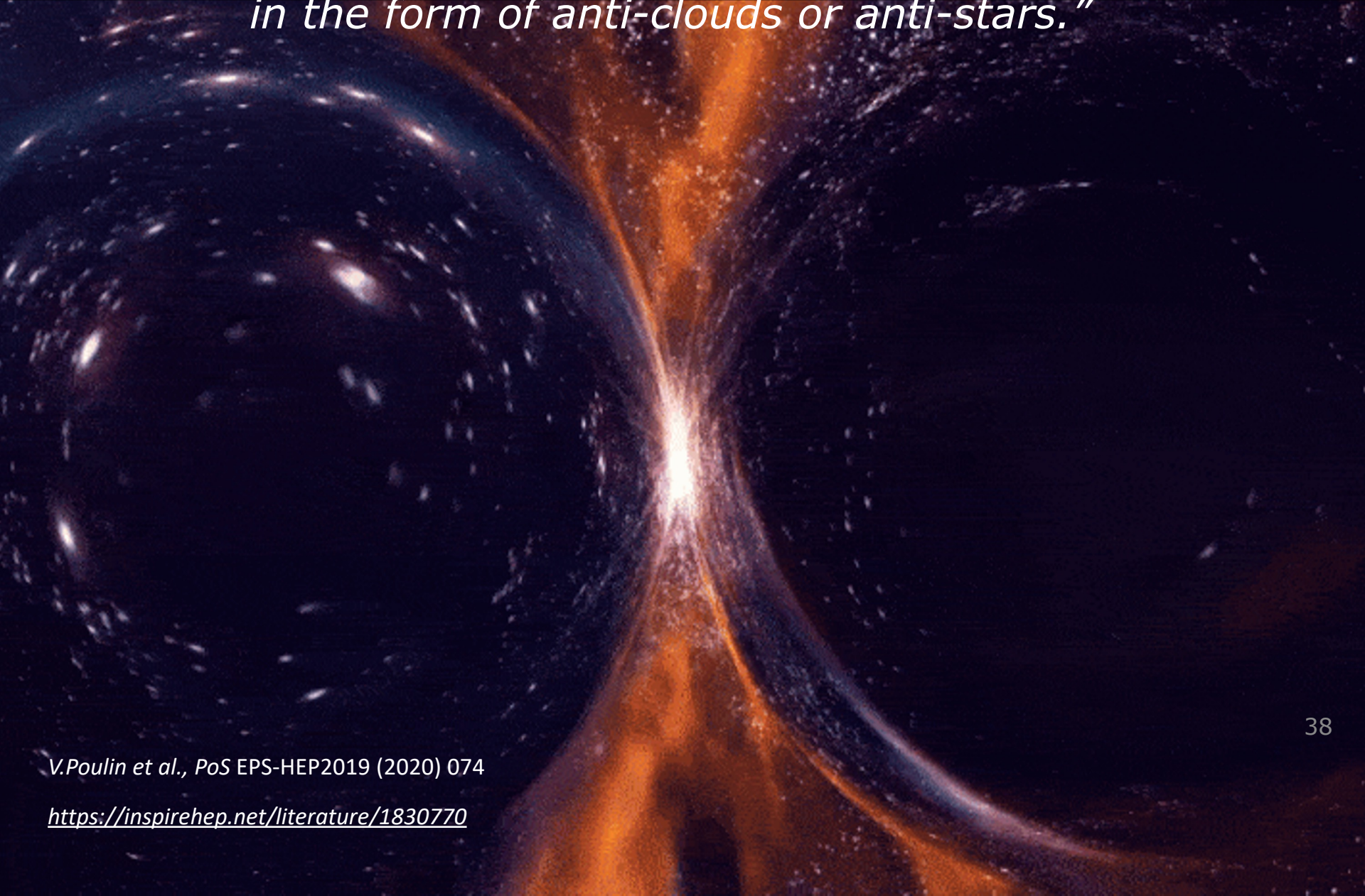
... maar niet te veel! (ongeveer 1 op de 10,000)



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:**
 - ^3He 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."



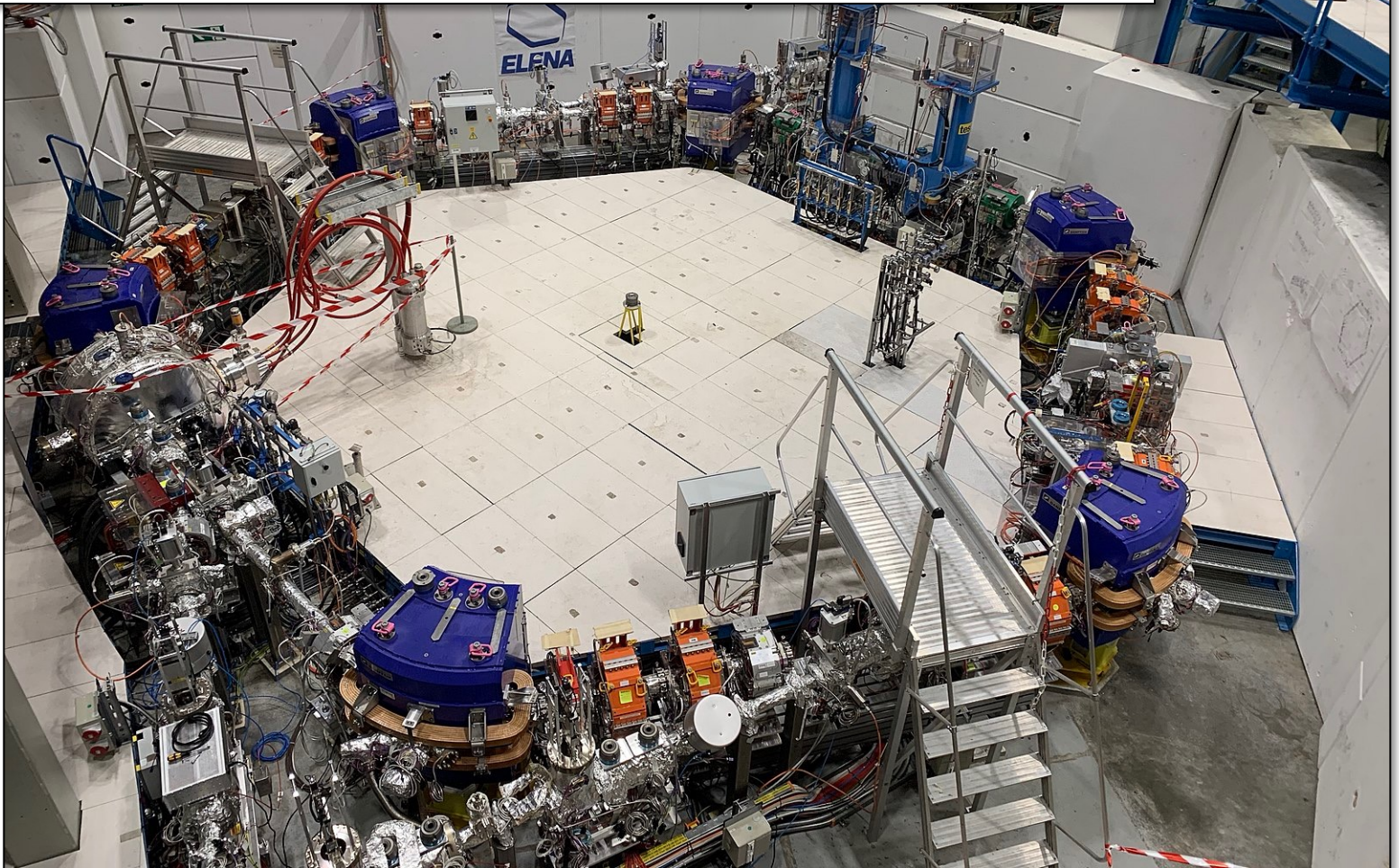
Antimaterie

- Deel 1: Hoezo?
 - Wat is het
 - Hoe is het bedacht
 - Wat is het probleem

- Deel 2: Wat nu?
 - Uit de ruimte
 - Antiwaterstof
 - Antimaterie verschillen

Reportage

De antimateriefabriek



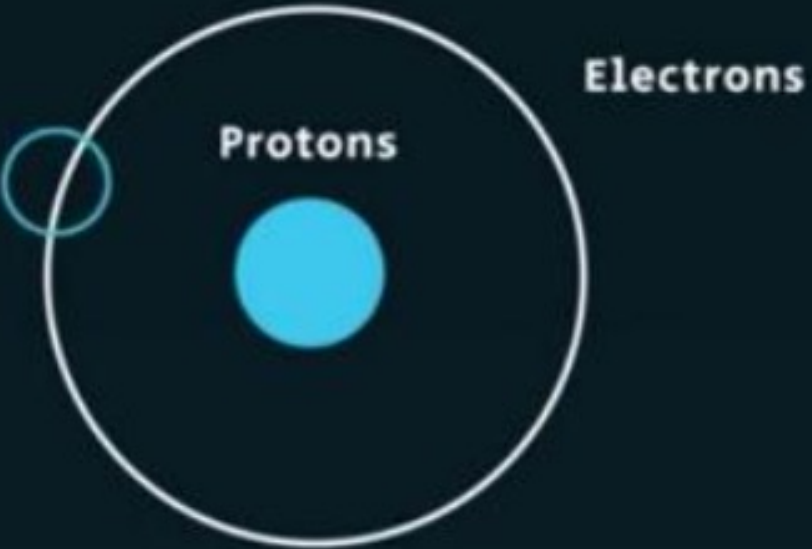


Het Bernini mysterie ("Angels & Demons", 2009)

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

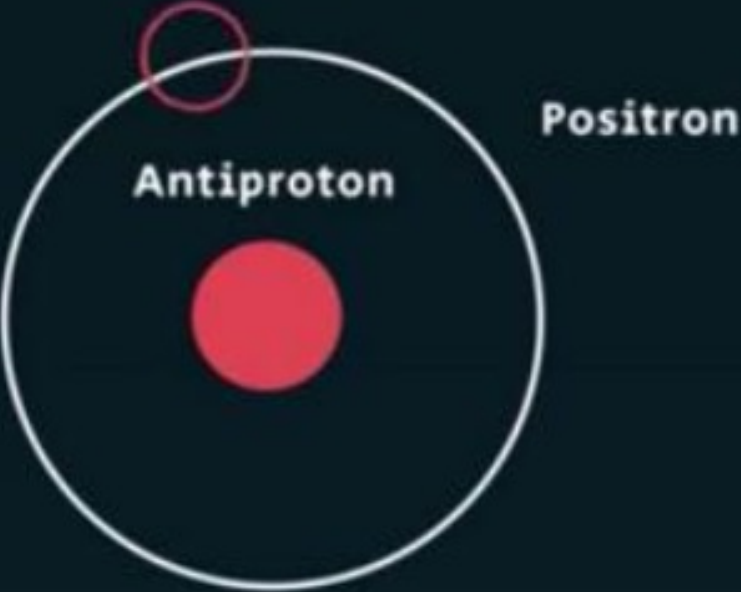


Materie



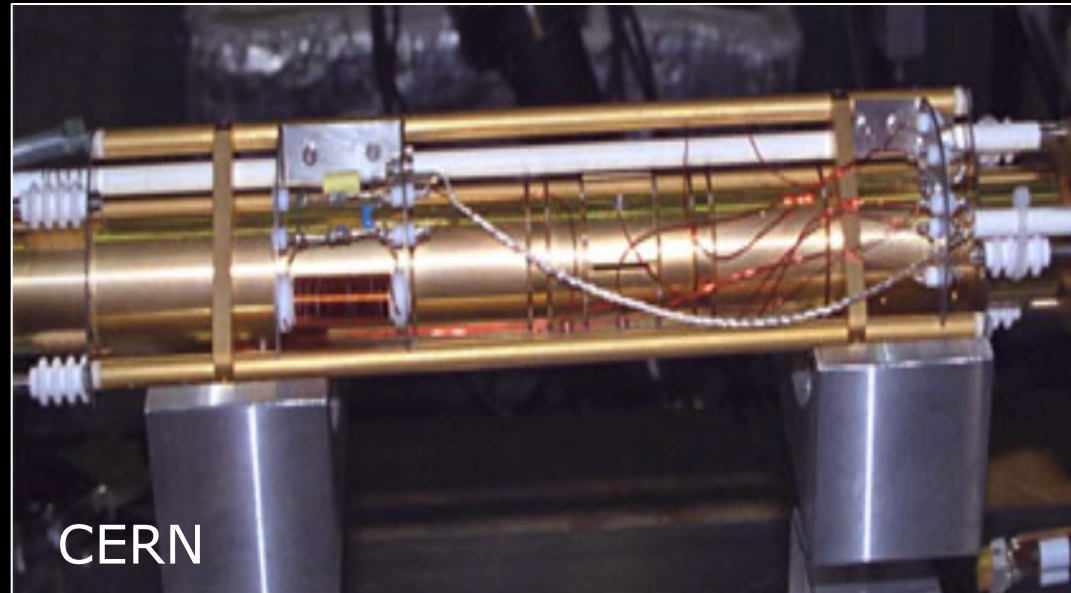
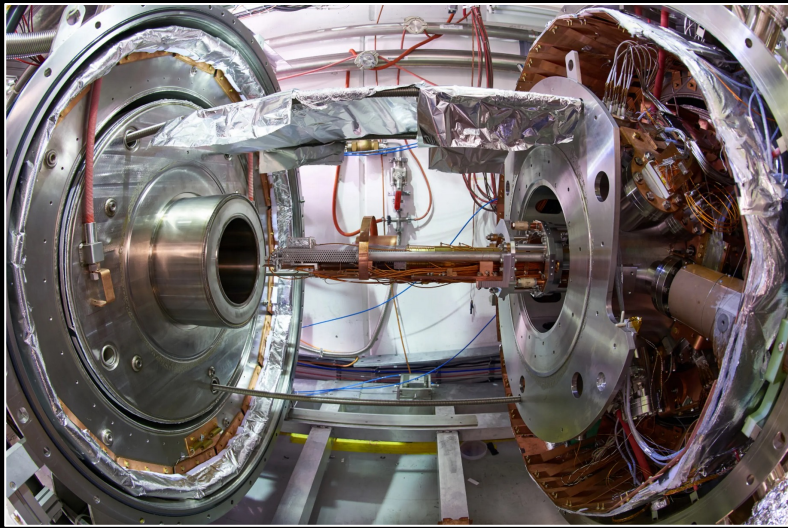
waterstof

Antimaterie

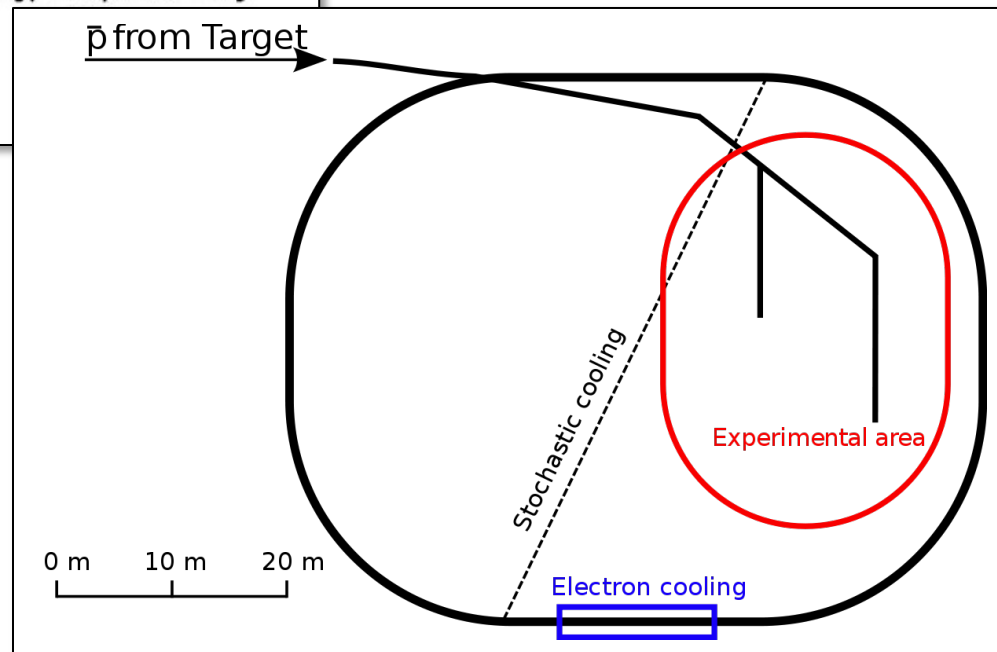
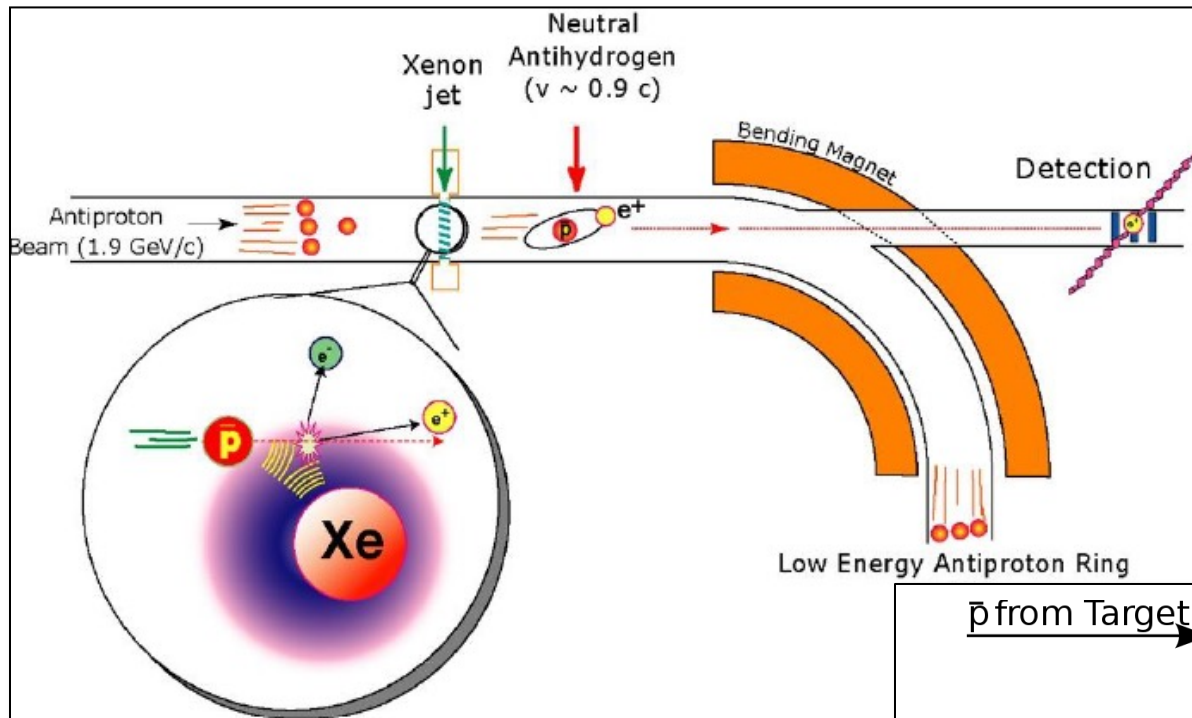


Anti-waterstof

Antimatter cannister ("Penning trap")



Anti-proton productie



Anti-hydrogen productie

p^- and e^+ in mixing trap (cooling)

Antihydrogen formation

AD

p^- Production (GeV)

Deceleration (MeV)

Trapping (keV)

Cooling (meV)

$10^4 p^-$

$10^8 e^+$

Na-22

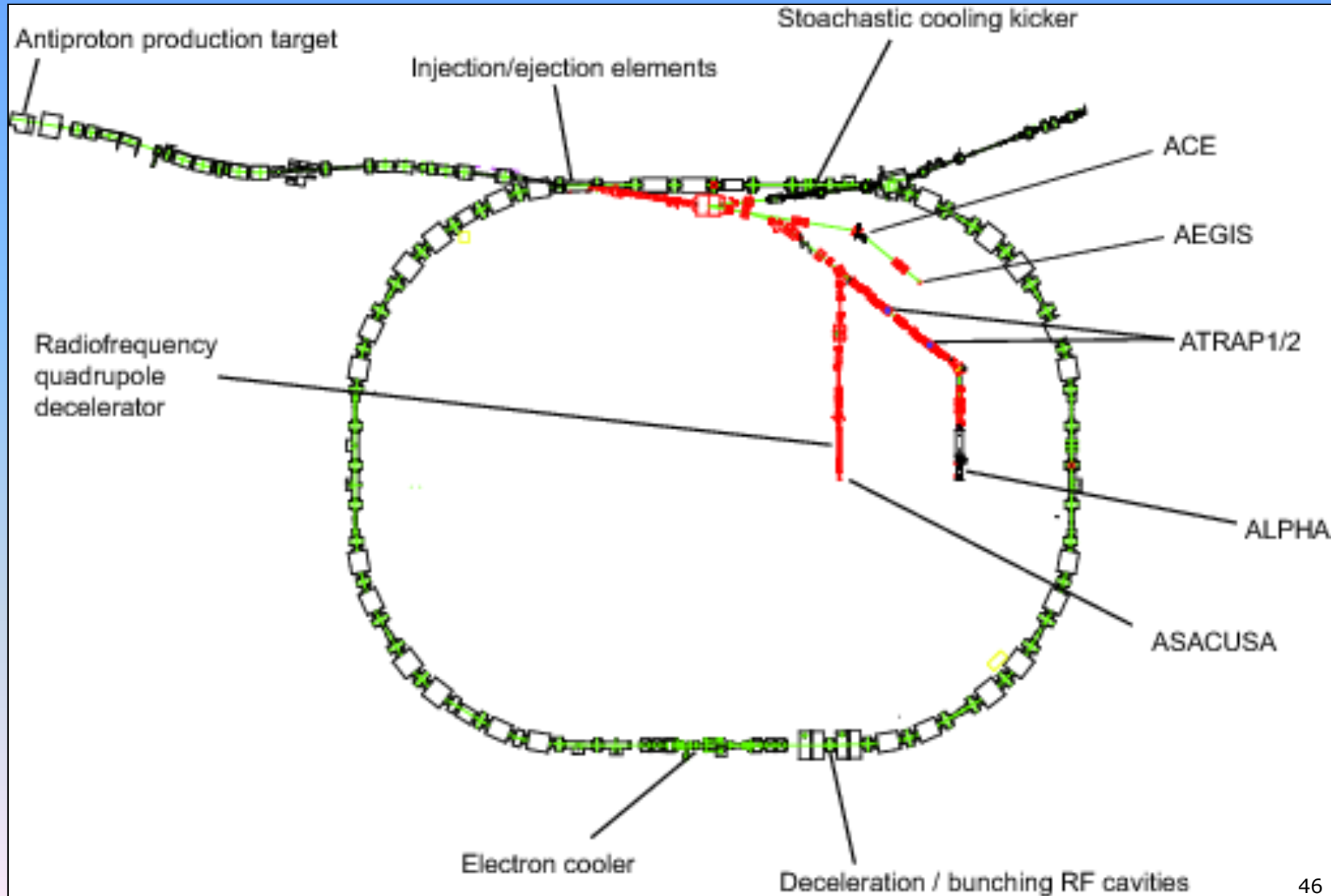
e^+ Production (MeV)

Moderation

Accumulation (eV)

Detection of annihilation

Anti-waterstof experimenten



Anti-waterstof experimenten

ATRAP, ATHENA
2002:
Productie

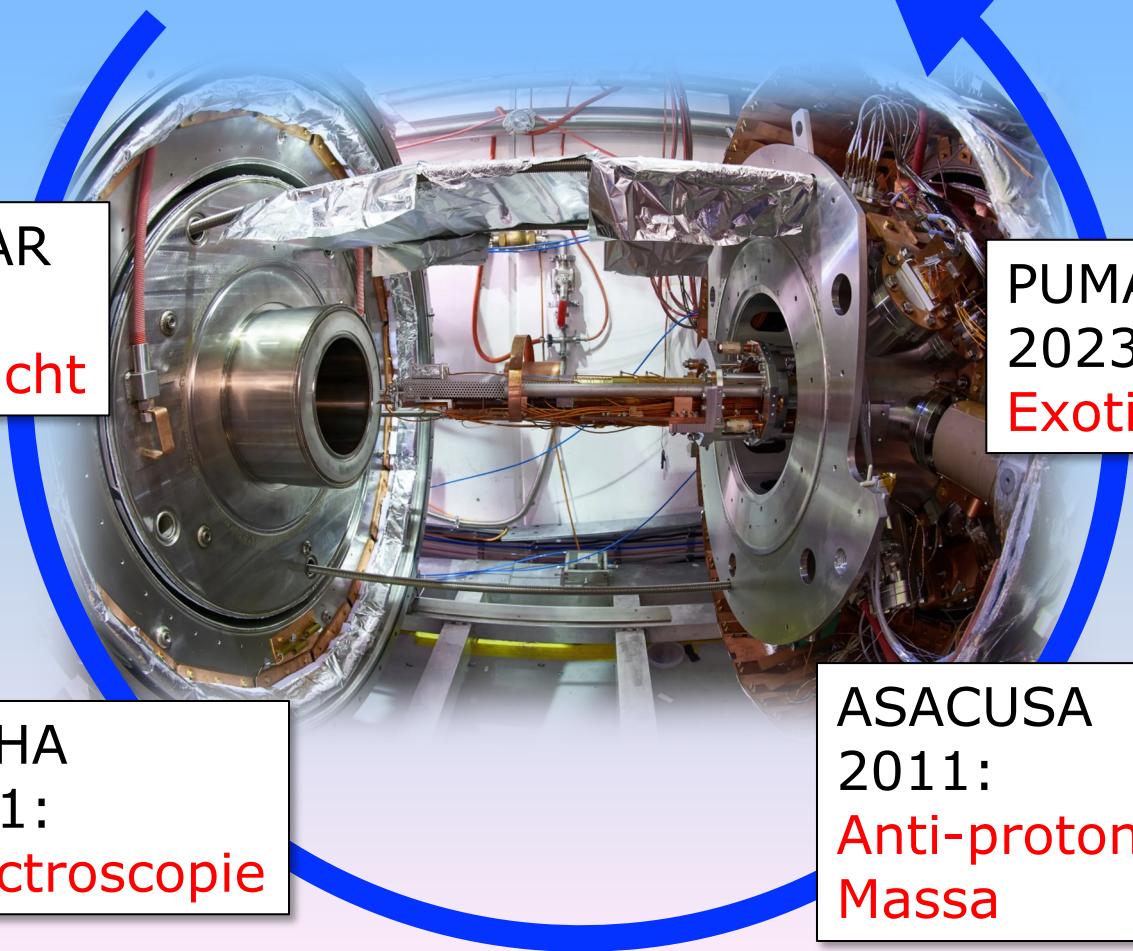
BASE-STEP (transport)
2023+:
Magnetisch moment

AEGIS, GBAR
2013:
Zwaartekracht

PUMA (transport)
2023+:
Exotische kernfysica

ALPHA
2011:
Spectroscopie

ASACUSA
2011:
Anti-protonisch He
Massa



Valt antimaterie omhoog?

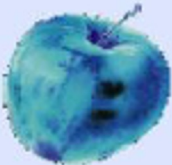
CPT-Symmetric Situation

Apple



Earth

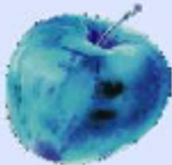
Anti-Apple



Anti-Earth

Not

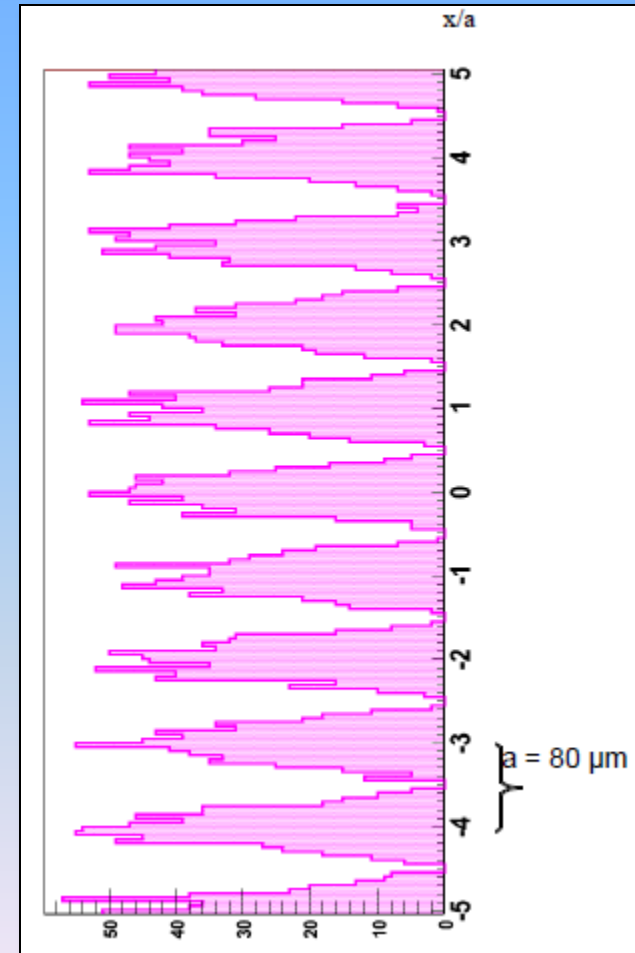
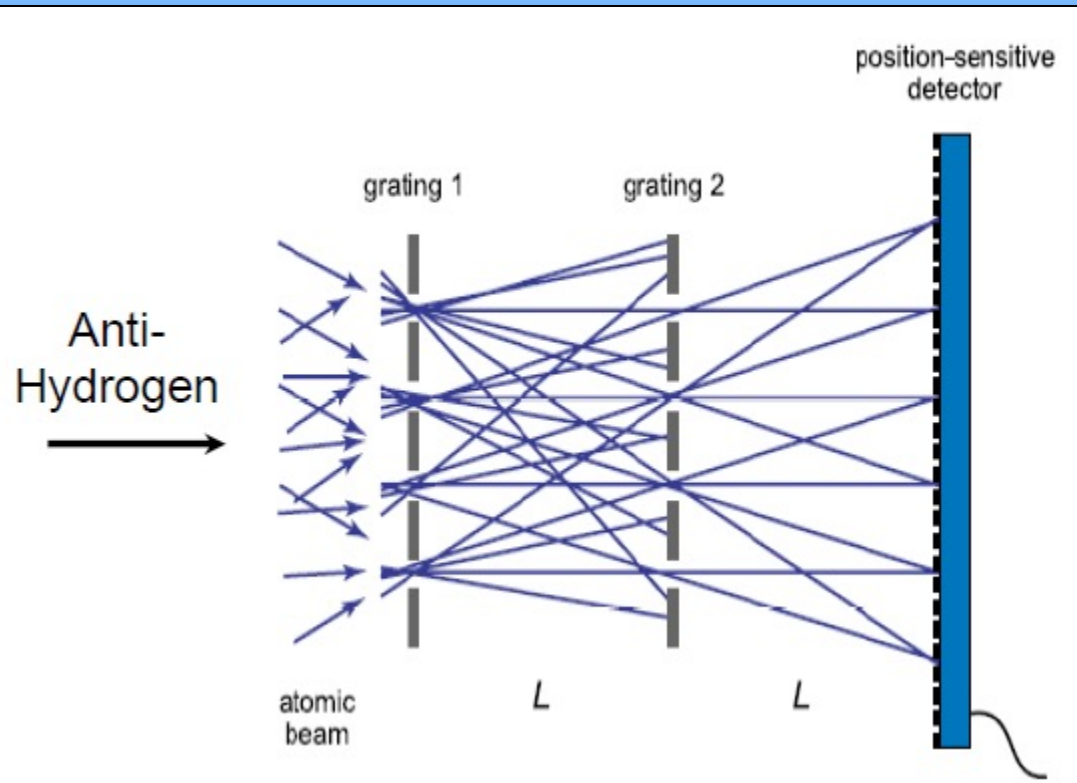
Anti-Apple



Earth

Anti-H detective (AEgIS)

Valt anti-waterstof omhoog...?

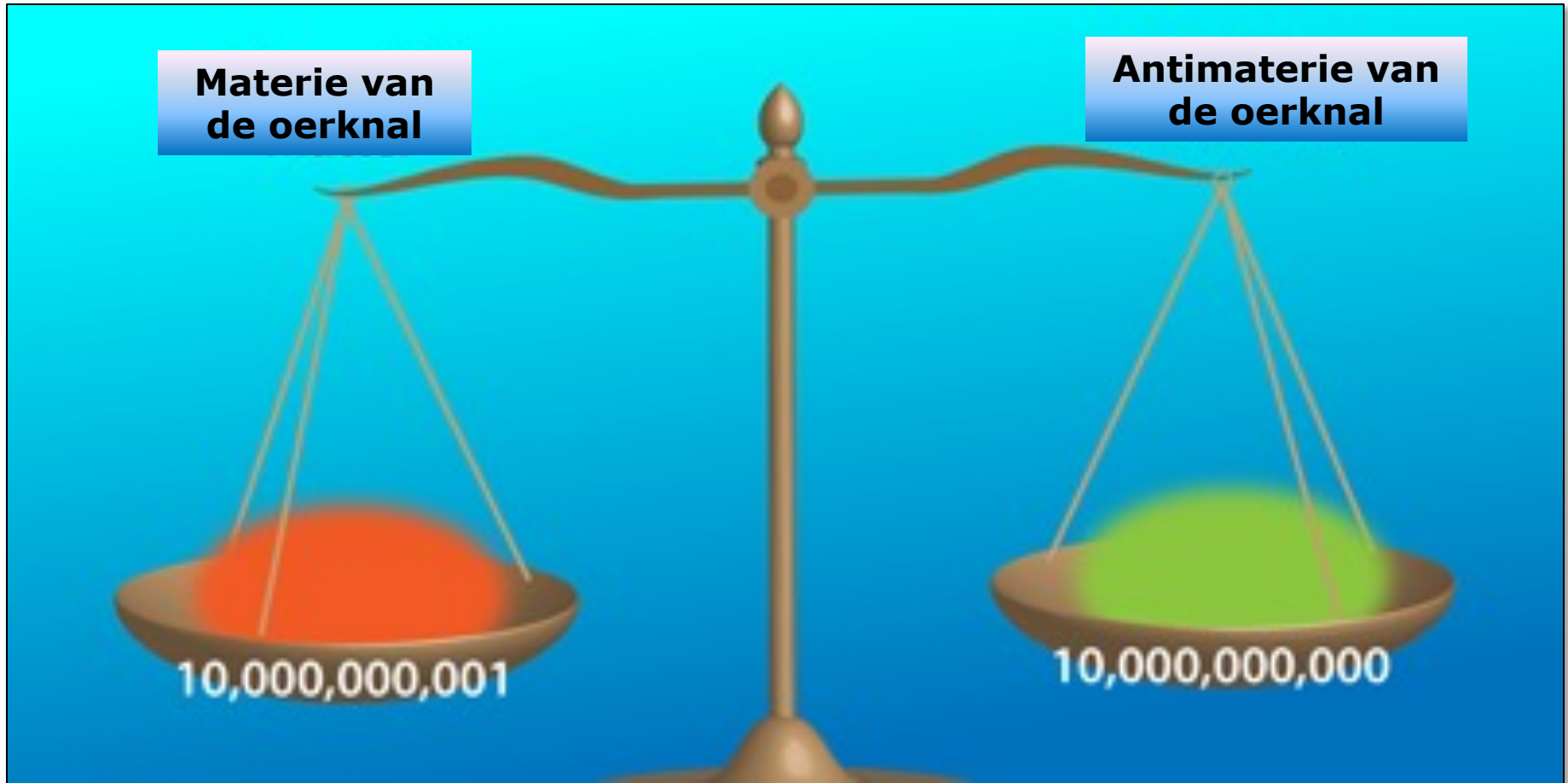


Antimaterie

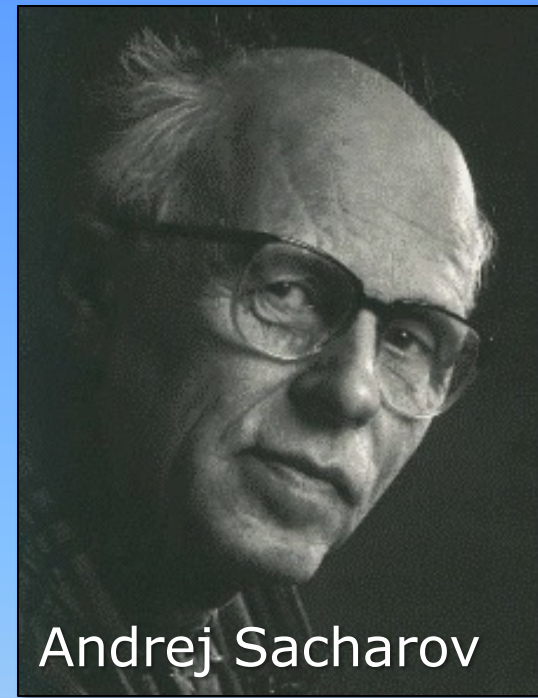
- Deel 1: Hoezo?
 - Wat is het
 - Hoe is het bedacht
 - Wat is het probleem

- 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)

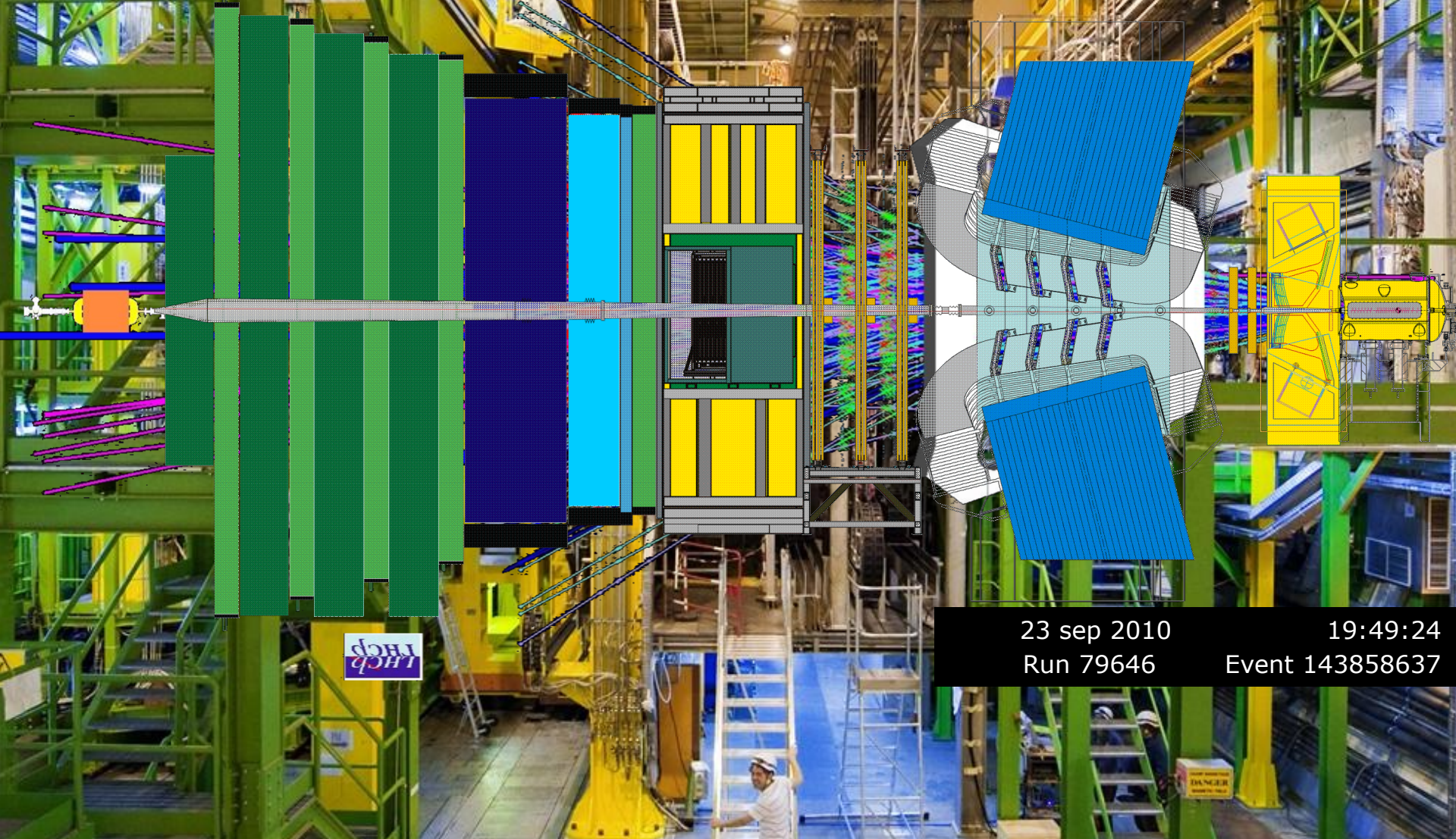
20 jaar gekeken naar 50000 kg ultra-puur water

- $1.5 \cdot 10^{30}$ moleculen H_2O
- 0 proton vervalLEN gezien...

Levensduur: $> 10^{34}$ jaar...

Vraag Jorinde van der Vis naar
Baryogenese !

“CP schendinging”? Het LHCb experiment

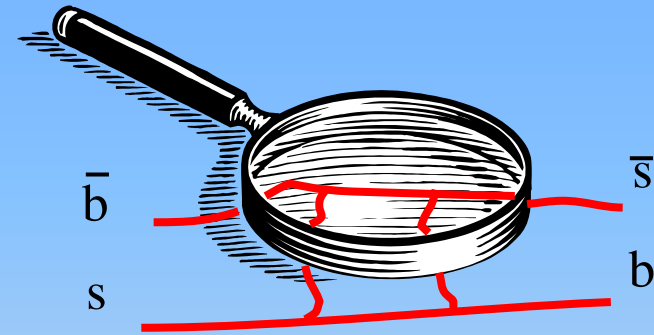


LHCb

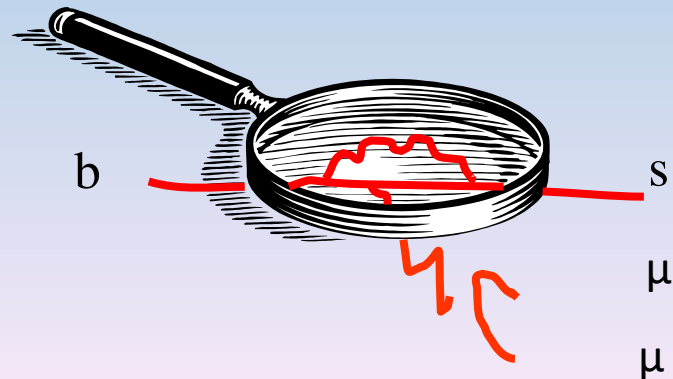
⚠ DANGER

LHCb: bestuderen van B deeltje

1) Vind verschillen tussen materie en anti-materie

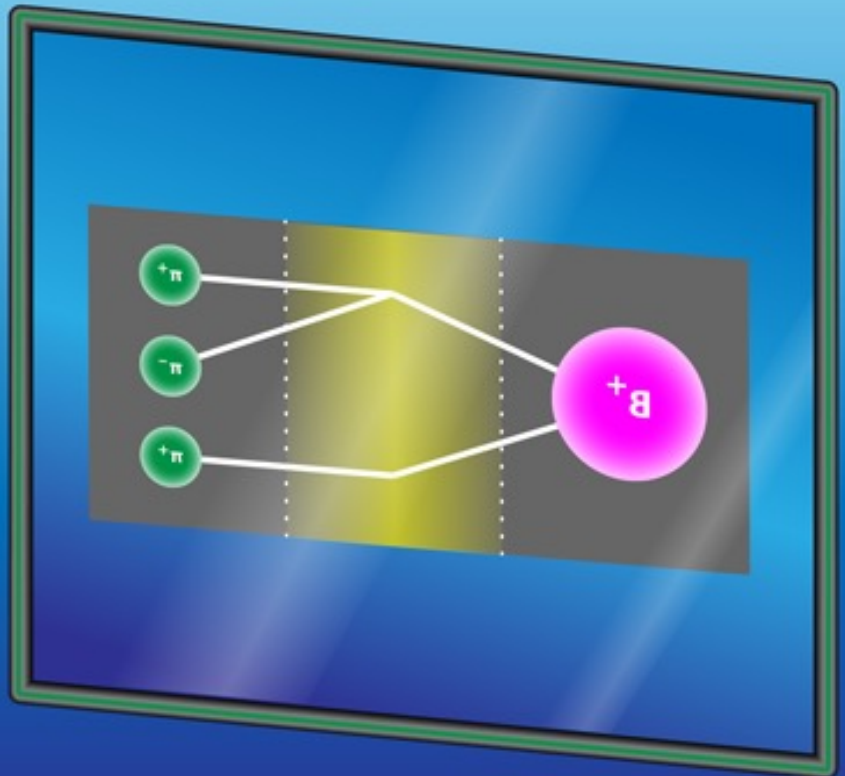
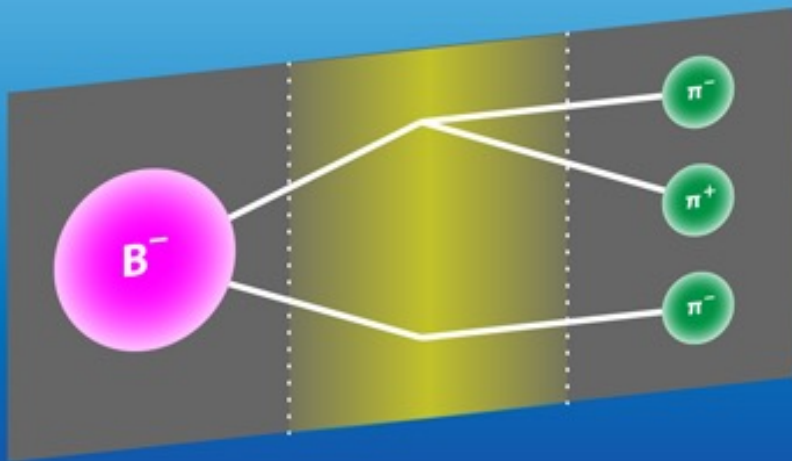


2) Vind nieuwe deeltjes



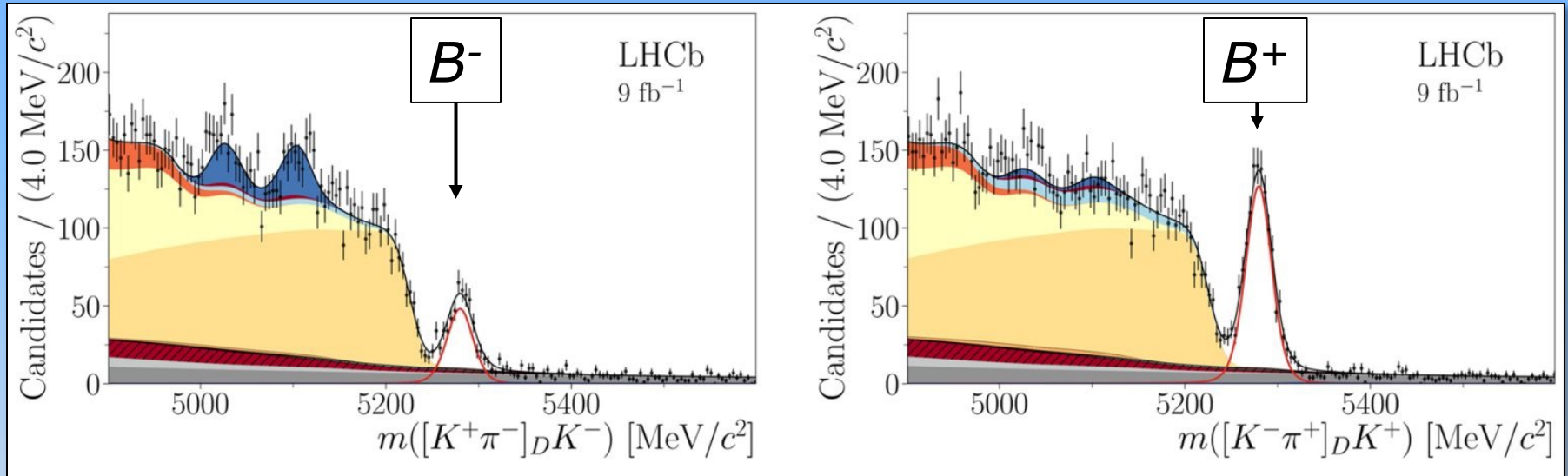
LHCb: bestuderen van B deeltje

1) Vind verschillen tussen materie en anti-materie



LHCb: bestuderen van B deeltje

1) Vind verschillen tussen materie en anti-materie



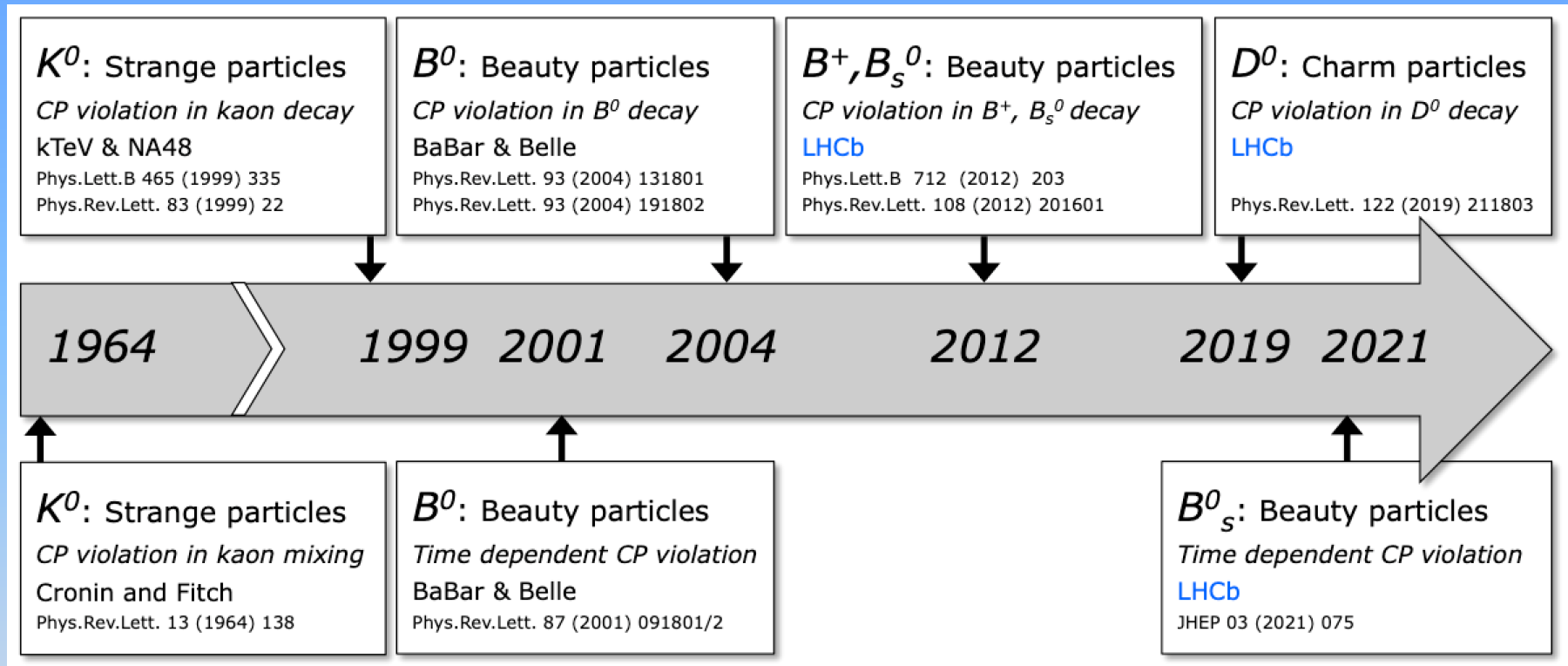
✓ Check!



☒ Maar niet genoeg...



LHCb: antimaterie verschillen

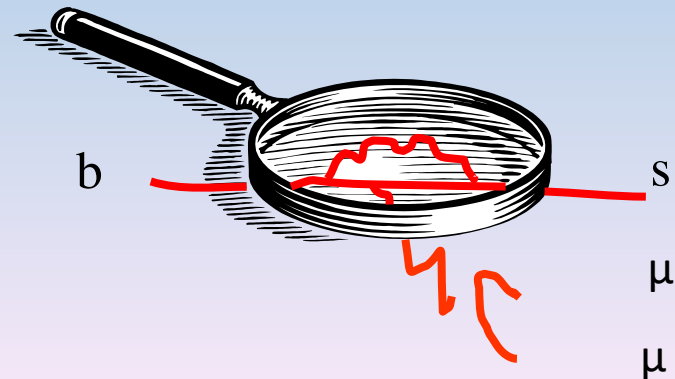


- | | | |
|------|---------------------------------------|-------------------|
| (ds) | 1964: CP schending met K^0 | (Nobelprijs 1980) |
| (bd) | 2000: CP schending met B^0 | (Nobelprijs 2008) |
| (bs) | 2012: CP schending met B_s^0 | (LHCb) |
| (cu) | 2019: CP schending met D^0 | (LHCb) |

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 standaardmodel. Beeld: Cern.

de Volkskrant

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



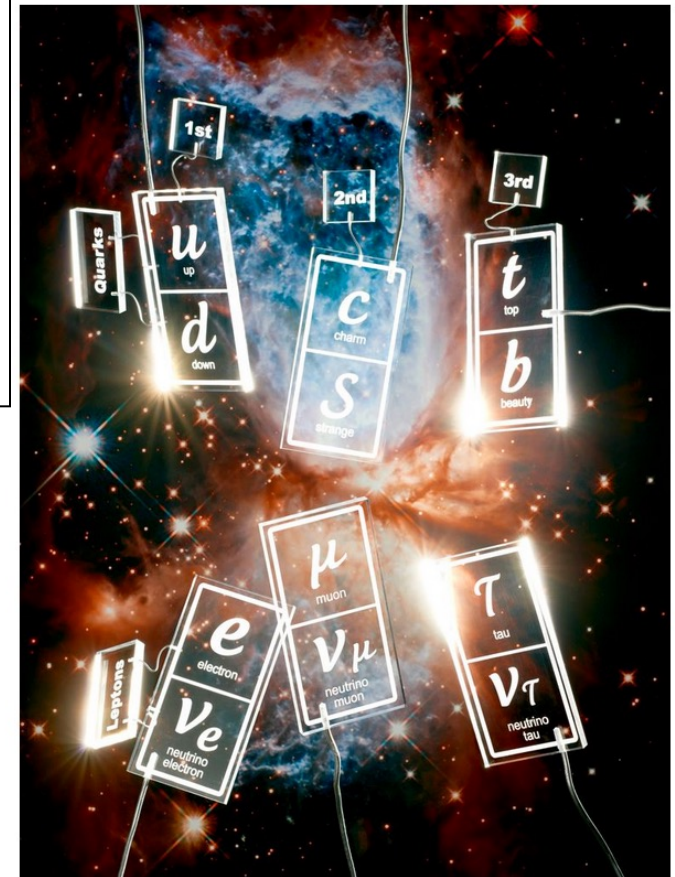
Wellicht is de deeltjeswereld niet zo democratisch als vooraf gedacht werd. Beeld: epa

de Volkskrant

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

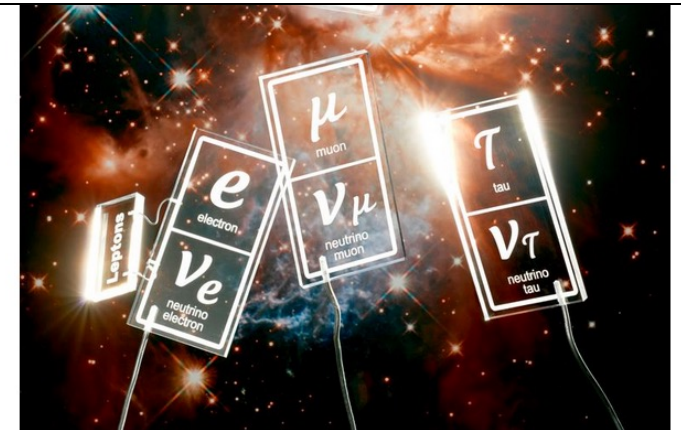
de Volkskrant

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

$t \rightarrow W^+ b$

$$BR(t \rightarrow Wb) = \frac{\Gamma(t \rightarrow Wb)}{\Gamma(t \rightarrow Wb) + \Gamma(t \rightarrow Wc) + \Gamma(t \rightarrow Ws)}$$

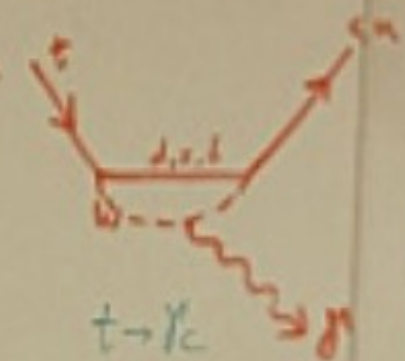


$$= \frac{|V_{cb}|^2}{|V_{cb}|^2 + |V_{cb}|^2 + |V_{cb}|^2}$$
$$\approx \frac{(0.9945)^2}{(0.9945)^2 + (0.0079)^2 + (0.004)^2}$$
$$= 99.82\%$$

but F.C.N.C...



$t \rightarrow Zc$
 $t \rightarrow Zs$



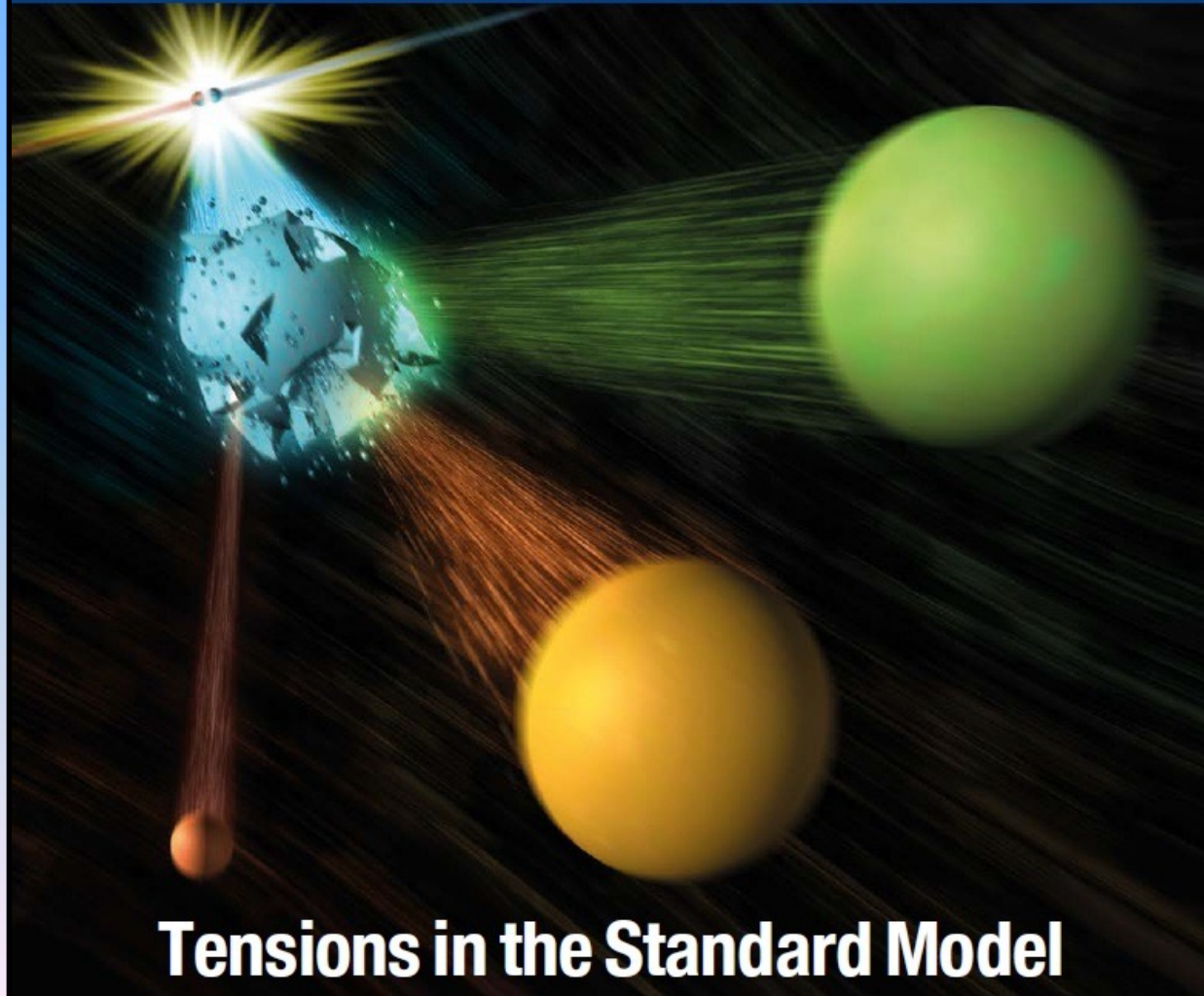
$t \rightarrow \gamma c$
 $t \rightarrow \gamma s$

$$U_{CKM} = \begin{pmatrix} c_{12}c_{13} & & \\ -s_{12}c_{13} & -c_{12}s_{13} & s_{13} \\ s_{12}c_{13} & c_{12}s_{13} & c_{13} \end{pmatrix}$$

INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

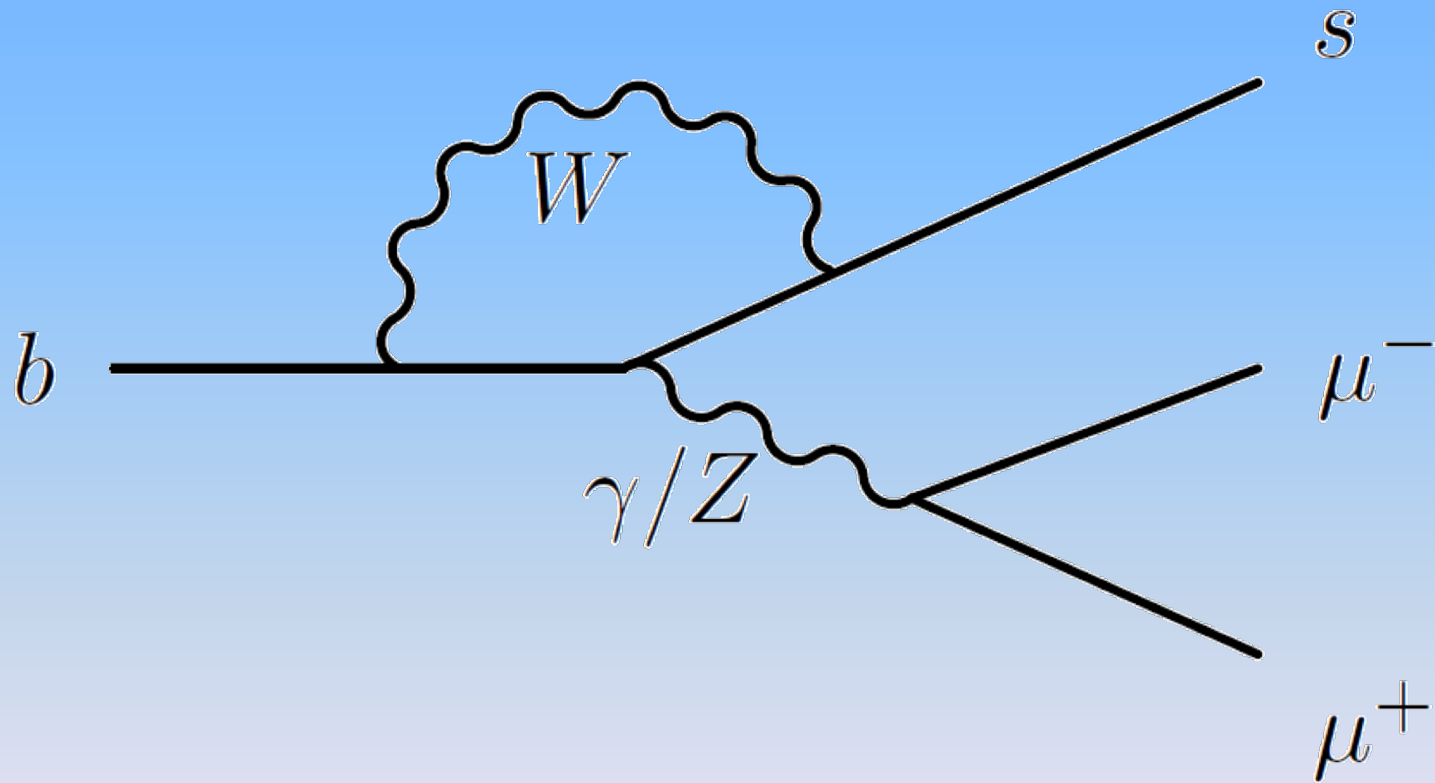
CERN COURIER

VOLUME 55 NUMBER 9 NOVEMBER 2015

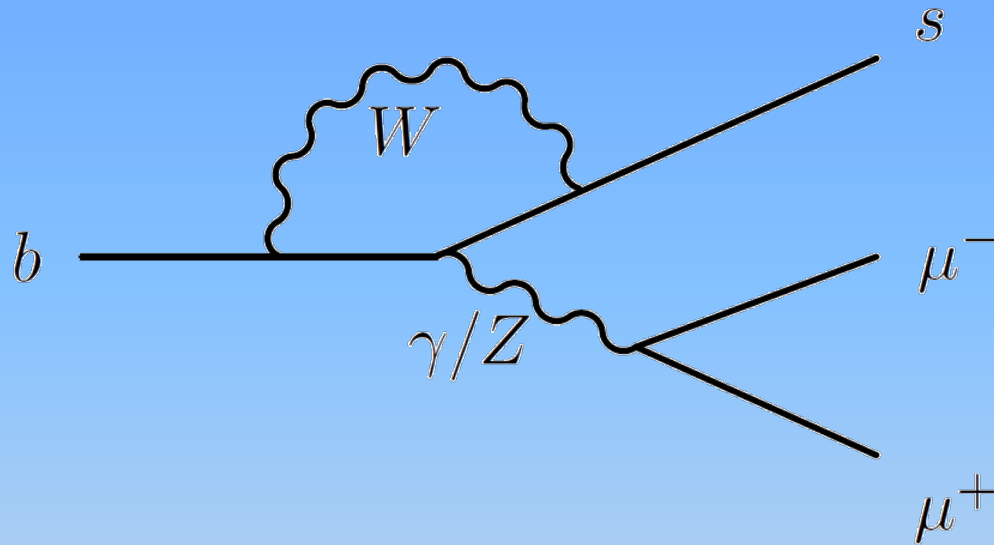


Tensions in the Standard Model

LHCb: hot topic



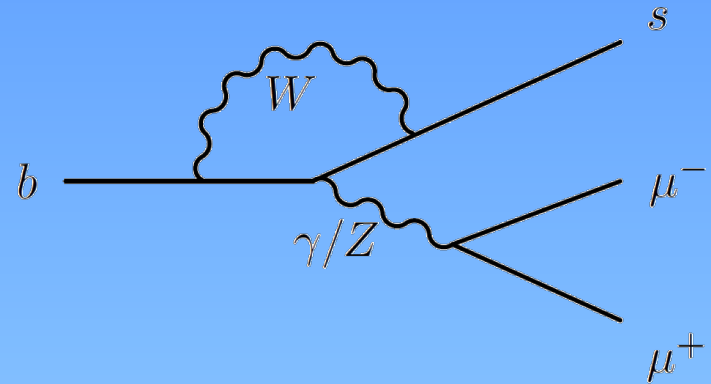
LHCb: hot topic



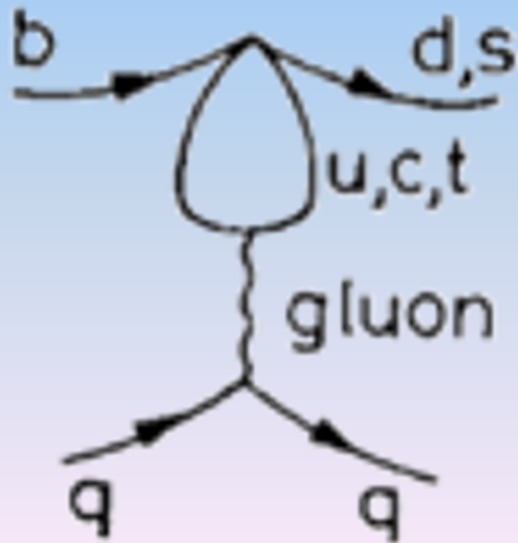
Flavour changing neutral current electroweak penguin

FCNC EWP

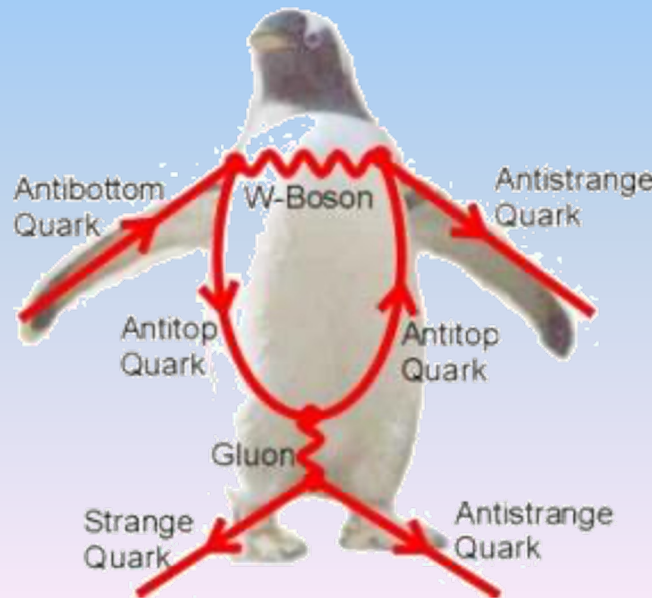
LHCb: hot topic



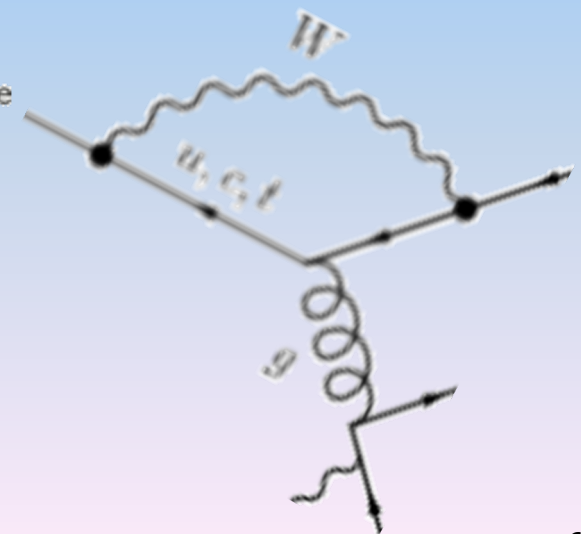
The original penguin:



A real penguin:

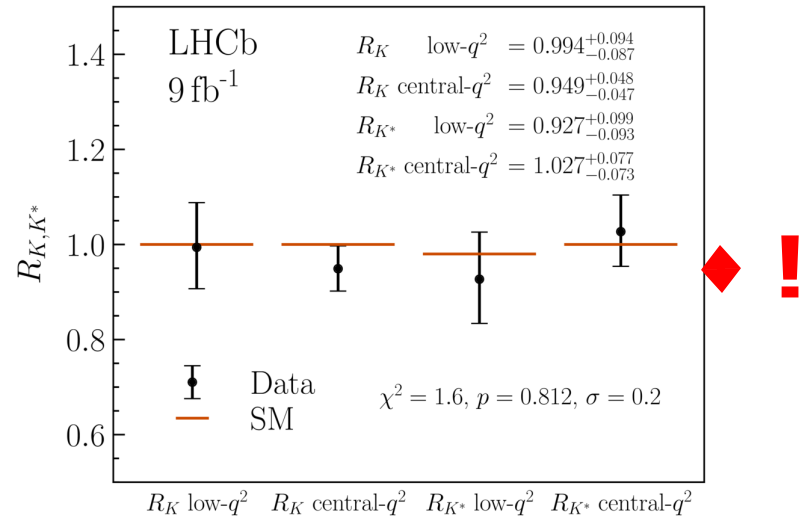
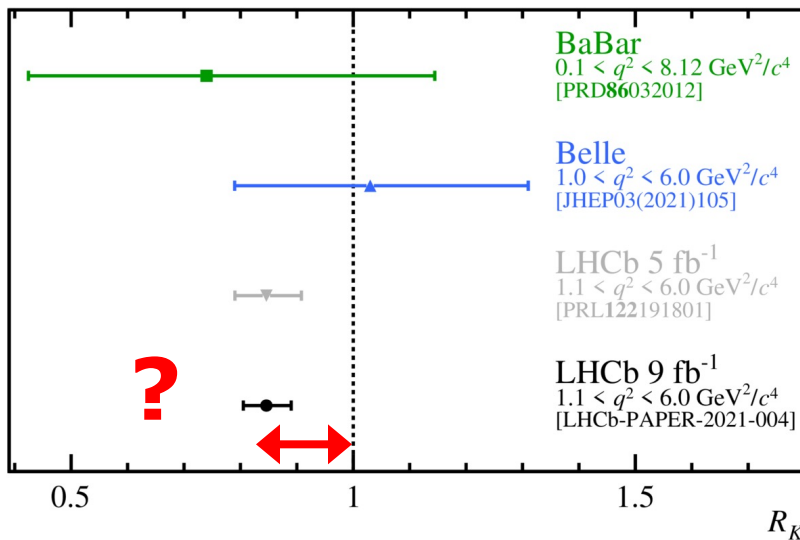
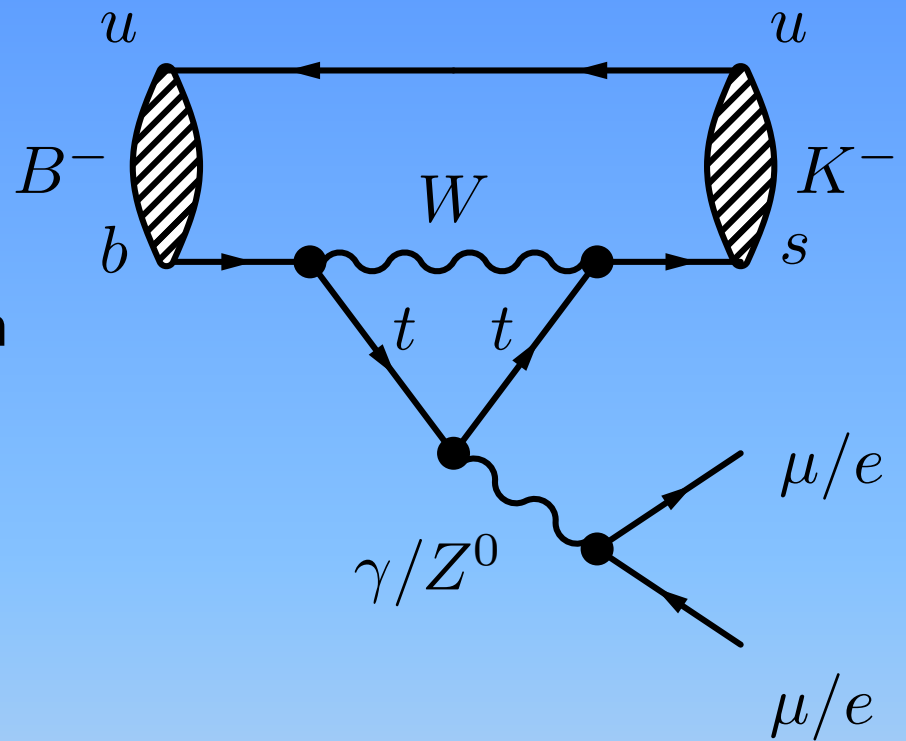


Our penguin:



LHCb: hot topic

Electronen en muonen gedragen zich anders?



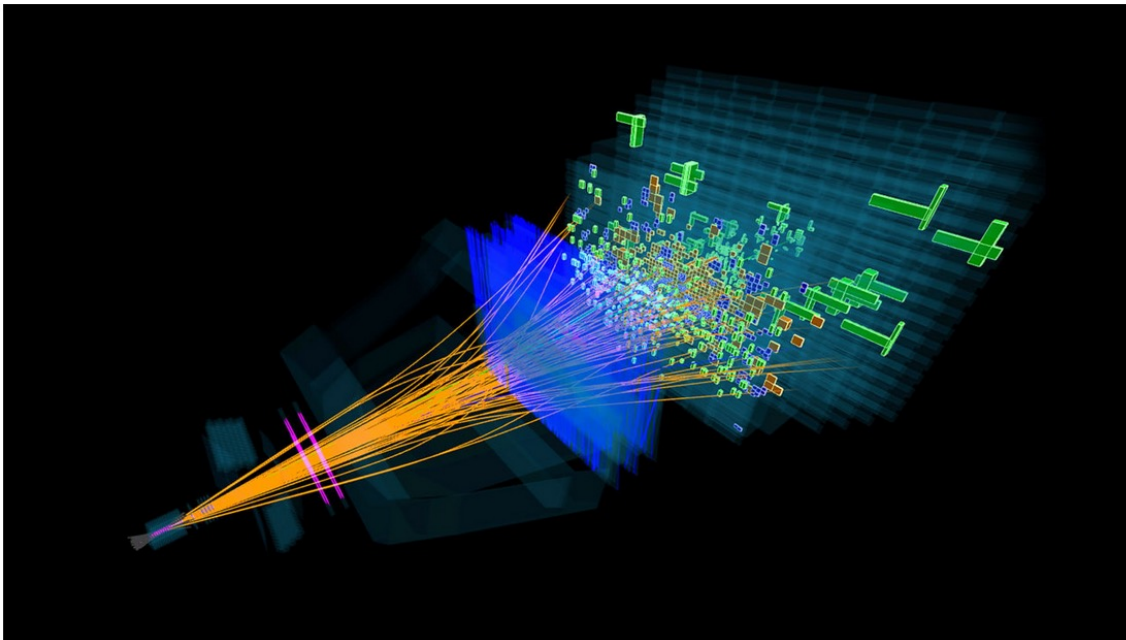
Muon gedraagt zich toch best normaal – of is er meer aan de hand?

29 Dec 2022

Nieuws

Jean-Paul Keulen 29-12-2022 15:00:00

Deel dit artikel: [f](#) [t](#) [p](#) [e](#)



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”

Antimaterie

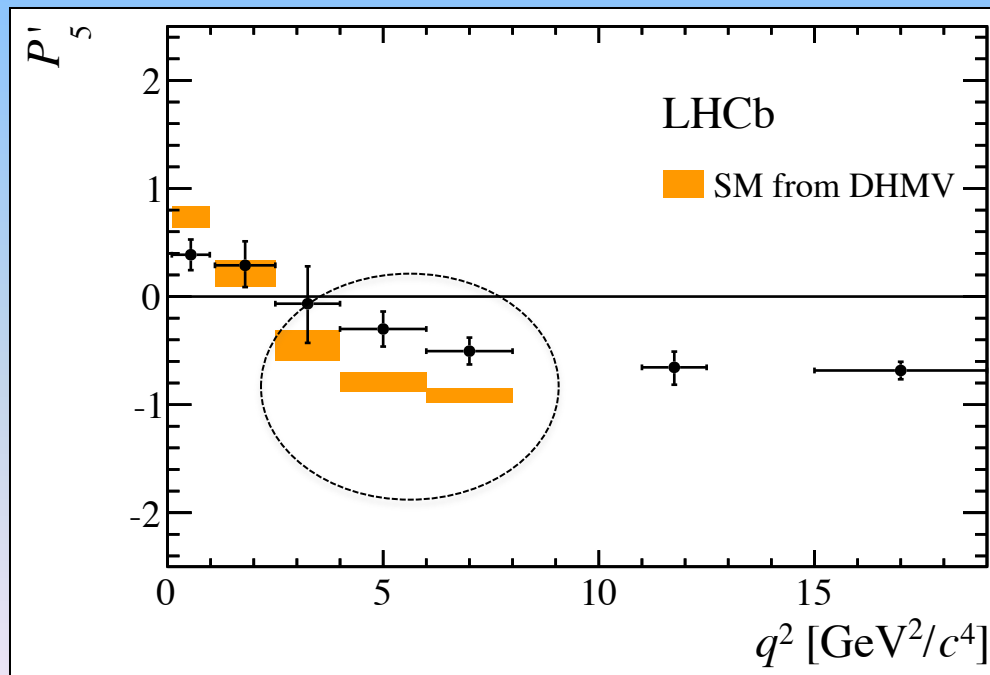
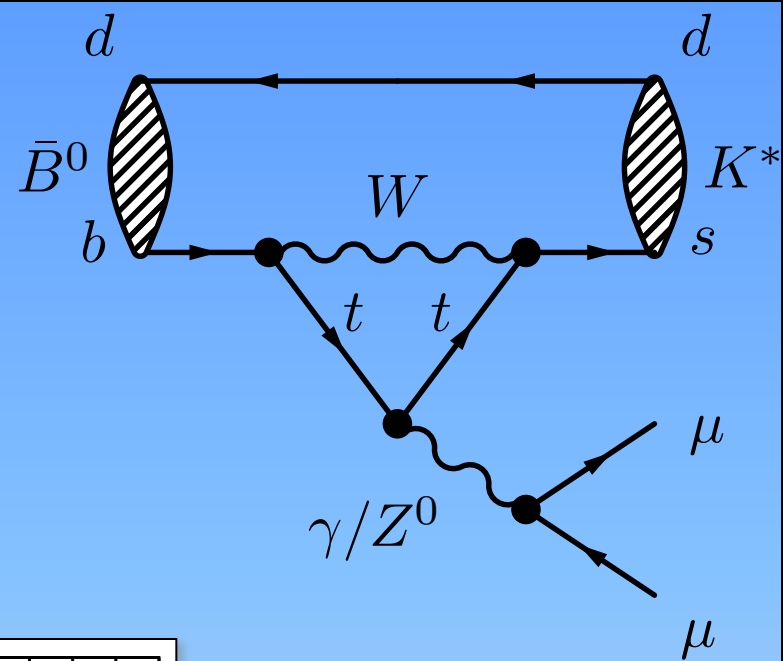
- Deel 1: Hoezo?
 - Wat is het
 - Hoe is het bedacht
 - Wat is het probleem

- Deel 2: Wat nu?
 - Uit de ruimte
 - Antiwaterstof
 - Antimaterie verschillen

Dank!

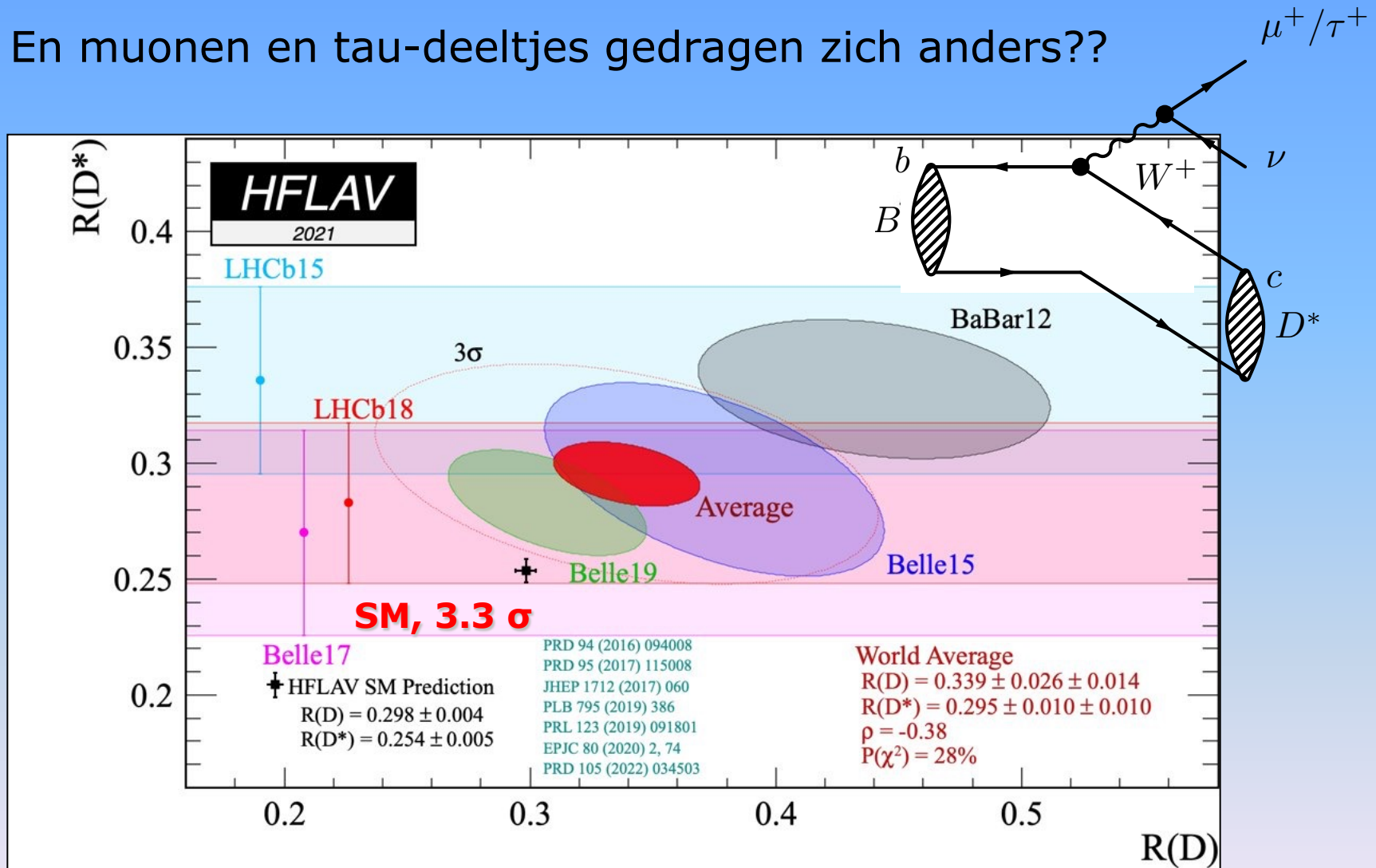
LHCb: hot topic

Ook hoekverdeling is anders...



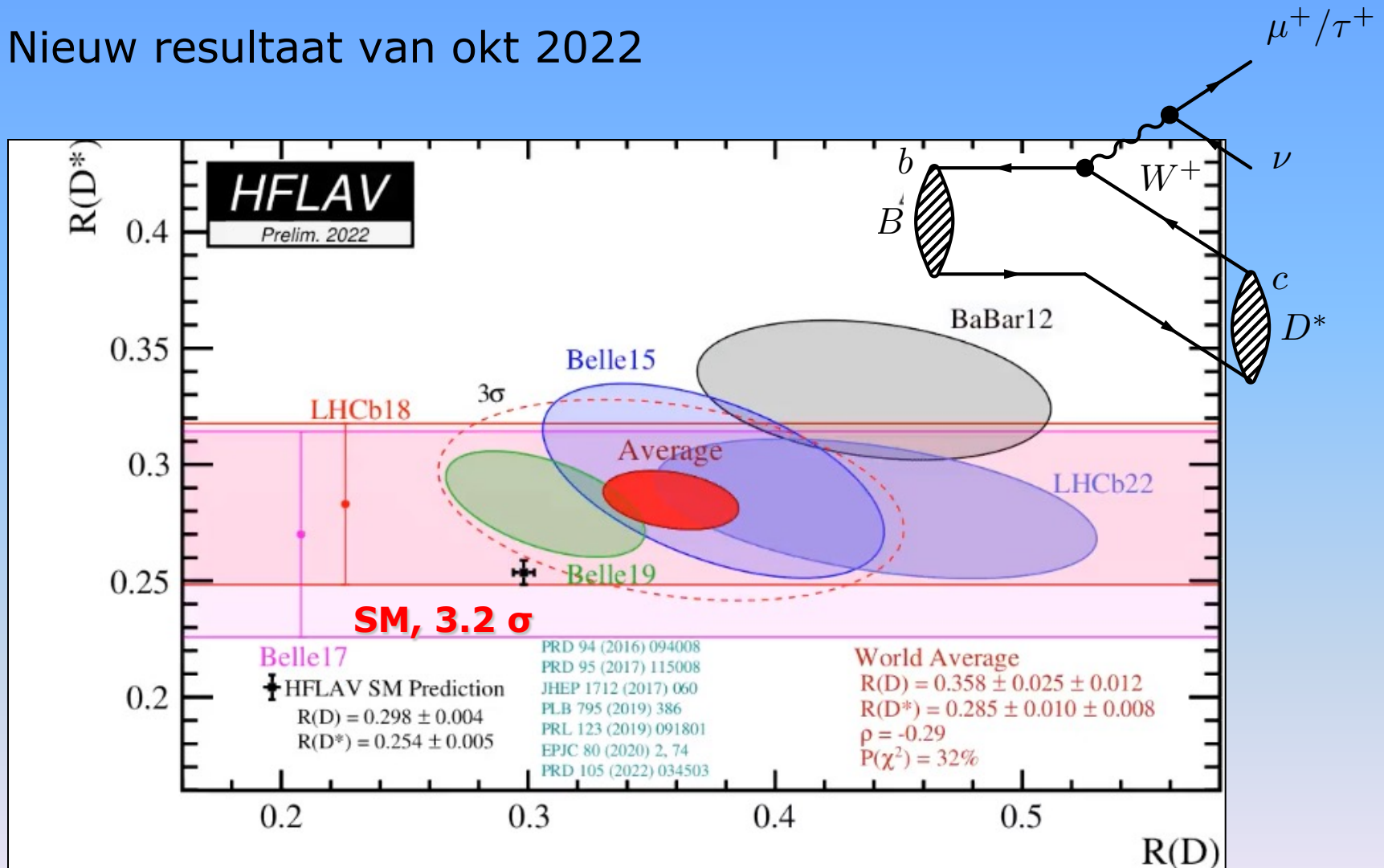
LHCb: hot topic

En muonen en tau-deeltjes gedragen zich anders??



LHCb: hot topic

Nieuw resultaat van okt 2022



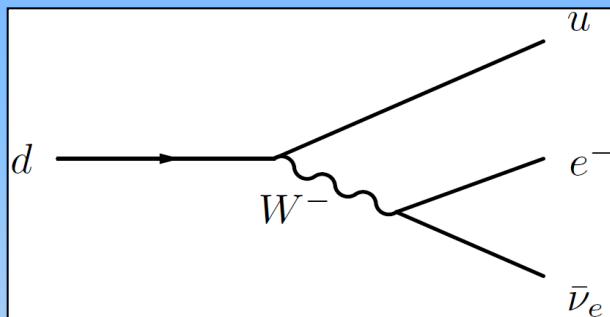
LHCb: wat kan het zijn?

Moeder aller deeltjes: de zoektocht naar de leptoquark

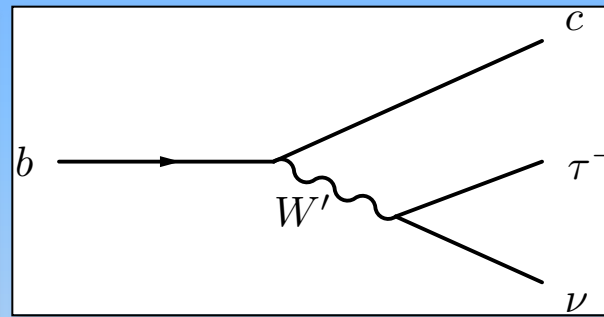
Is het fundamenteelste deeltje in het universum altijd over het hoofd gezien? Komende week kan de wereld opgeschud worden, als natuurkundigen in Seoul hun resultaten bekendmaken. Leptoquark, onthoud dat woord.

Martijn van Calmthout 29 juni 2018, 11:25

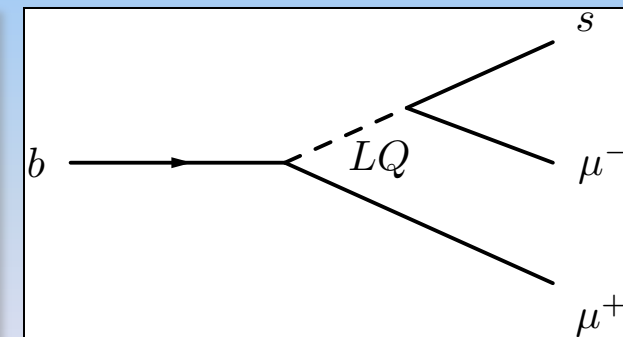
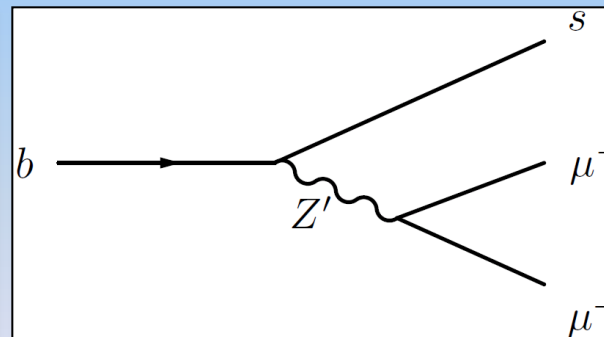
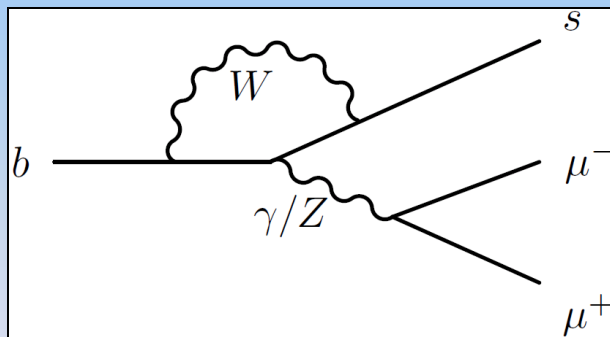
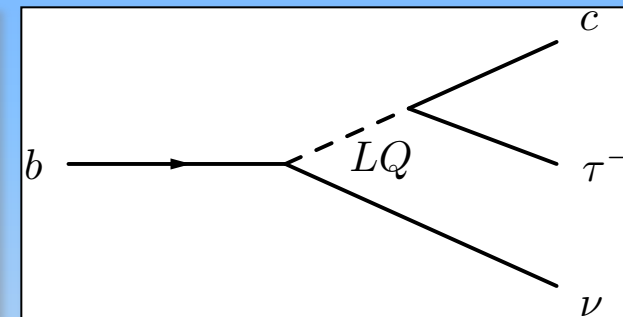
SM



SU(2)'



Leptoquark

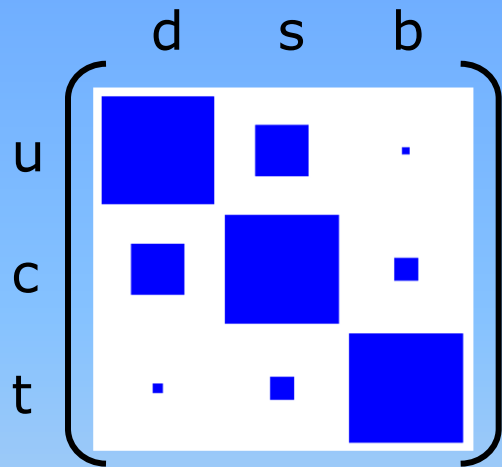


Leptoquark, onthoud dat woord.

M. Van Calmthout

Higgs en LHCb?

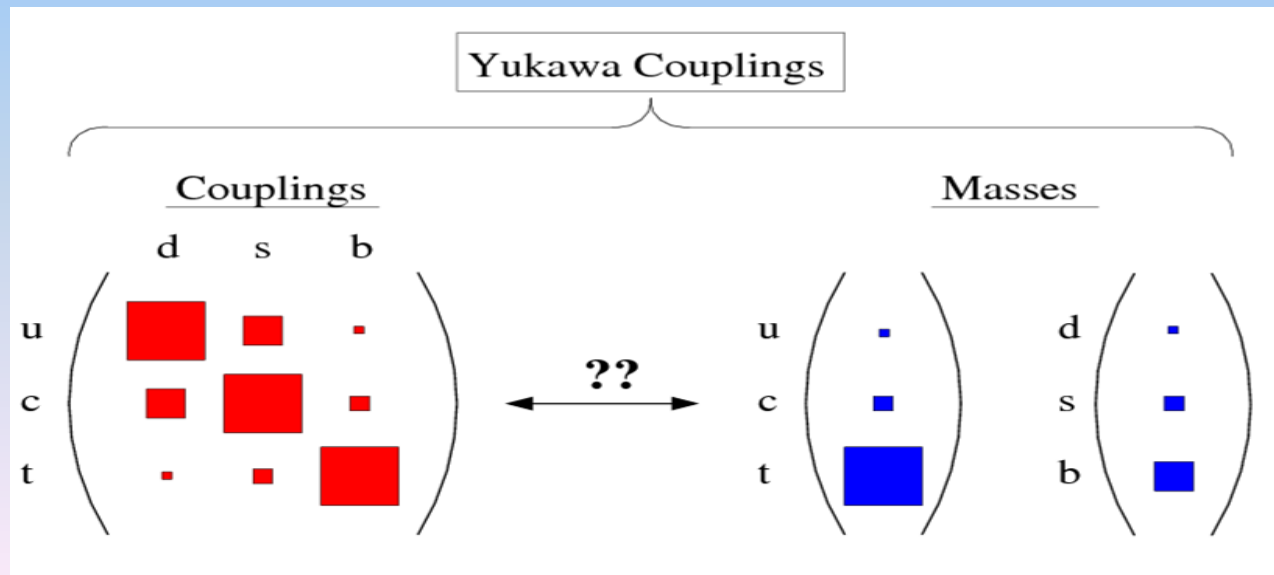
Quark koppelingen:



Waarom dit patroon in quark koppelingen?

Waarom dit patroon in quark massa's?

→ **Is er een verband?**



Intermezzo: How about the leptons?

the equivalent of the CKM matrix

– Pontecorvo-Maki-Nakagawa-Sakata matrix

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} \quad \bullet \text{vs} \quad \begin{bmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{bmatrix}.$$

a completely different hierarchy!

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

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

Intermezzo: How about the leptons?

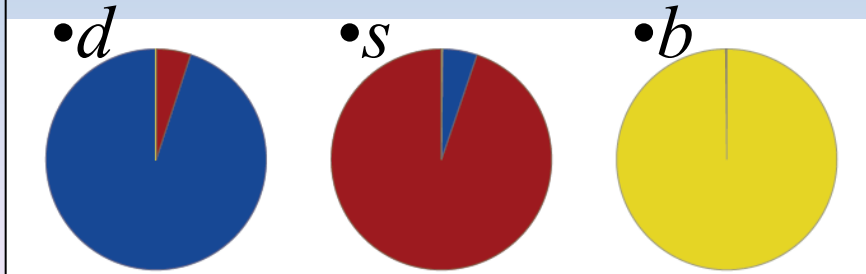
the equivalent of the CKM matrix

– Pontecorvo-Maki-Nakagawa-Sakata matrix

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} \quad \bullet\text{vs} \quad \begin{bmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{bmatrix}.$$

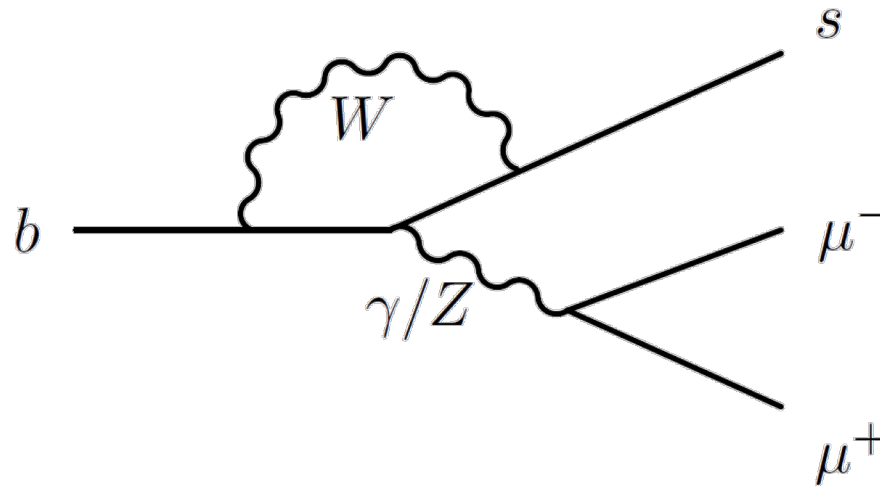
a completely different hi

$$\begin{pmatrix} |U_{e1}|^2 & |U_{e2}|^2 & |U_{e3}|^2 \\ |U_{\mu1}|^2 & |U_{\mu2}|^2 & |U_{\mu3}|^2 \\ |U_{\tau1}|^2 & |U_{\tau2}|^2 & |U_{\tau3}|^2 \end{pmatrix} \approx \begin{pmatrix} \frac{2}{3} & \frac{1}{3} & 0 \\ \frac{1}{6} & \frac{1}{3} & \frac{1}{2} \\ \frac{1}{6} & \frac{1}{3} & \frac{1}{2} \end{pmatrix}$$



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

$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^a g_\nu^b g_\mu^c g_\nu^d - \frac{1}{2}ig_\tau^2 (g_\mu^a \gamma^\mu g_\nu^a) g_\mu^a g_\nu^a + \\
 & \bar{C}^a \partial^2 C^a + g_s f^{abc} \partial_\mu \bar{C}^a G^b g_\mu^c - \partial_\mu W_\nu^+ \partial_\nu W_\mu^- - M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\mu Z_\nu^0 \partial_\nu Z_\mu^0 - \frac{1}{2}g_{2c}^2 M^2 Z_\mu^0 Z_\mu^0 - \\
 & \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^2}{g^2} \alpha_h - ig_{cw} [\partial_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\mu^- W_\nu^+) - Z_\nu^0 (W_\mu^+ \partial_\mu W_\nu^- - W_\mu^- \partial_\mu W_\nu^+) + Z_\nu^0 (W_\nu^+ \partial_\mu W_\mu^- - W_\nu^- \partial_\mu W_\mu^+)] - ig_{sw} [\partial_\mu A_\nu (W_\mu^+ W_\nu^- - \\
 & W_\mu^- W_\nu^+) - A_\nu (W_\mu^+ \partial_\mu W_\nu^- - W_\mu^- \partial_\mu W_\nu^+) + A_\nu (W_\nu^+ \partial_\mu W_\mu^- - W_\nu^- \partial_\mu W_\mu^+)] - \frac{1}{2}g^2 s_w^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_\mu^0 W_\nu^+ Z_\nu^0 W_\mu^- - Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\nu^+ A_\nu W_\mu^- - \\
 & A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - W_\mu^- W_\nu^+) - 2A_\nu Z_\mu^0 W_\mu^+ 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)^2 H^2] - g M W_\mu^+ W_\nu^- H - \frac{1}{2}g \frac{M}{c_w} Z_\mu^0 Z_\nu^0 H - \frac{1}{2}ig [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \\
 & \phi^+ \partial_\mu \phi^0)] + \frac{1}{2}ig [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_\mu^0 (H \partial_\mu \phi^0 - \\
 & \phi^0 \partial_\mu H) - ig \frac{s_w}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + ig_{sw} M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \\
 & \phi^- \partial_\mu \phi^+) + ig_{sw} 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_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \\
 & \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 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_\mu^0 A_\mu \phi^+ \phi^- - g^2 s_w^2 A_\mu A_\mu \phi^+ \phi^- - e^\lambda (\gamma \partial + m_\Delta^2) e^\lambda - \\
 & \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}_2^\lambda (\gamma \partial + m_\Delta^2) u_2^\lambda - \bar{d}_2^\lambda (\gamma \partial + m_\Delta^2) d_2^\lambda + ig_{sw} A_\mu [-(e^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_2^\lambda \gamma^\mu u_2^\lambda) - \\
 & \frac{1}{3}(\bar{d}_2^\lambda \gamma^\mu d_2^\lambda)] + \frac{ig}{4c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (e^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_2^\lambda \gamma^\mu (\frac{2}{3}s_w^2 - \\
 & 1 - \gamma^5) u_2^\lambda) + (\bar{d}_2^\lambda \gamma^\mu (1 - \frac{2}{3}s_w^2 - \gamma^5) d_2^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_2^\lambda \gamma^\mu (1 + \\
 & \gamma^5) C_{\lambda\kappa} d_2^\kappa) + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_2^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_2^\kappa)] + \frac{ig}{2\sqrt{2}} \frac{m_\Delta^2}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \\
 & \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2} \frac{m_\Delta^2}{M} [H (\bar{e}^\lambda e^\lambda) + i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_\Delta^2 (\bar{u}_2^\lambda C_{\lambda\kappa} (1 - \\
 & \gamma^5) d_2^\kappa) + m_\Delta^2 (\bar{u}_2^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_2^\kappa)] + \frac{ig}{2M\sqrt{2}} \phi^- [m_\Delta^2 (\bar{d}_2^\kappa C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_2^\kappa) - m_\Delta^2 (\bar{d}_2^\kappa C_{\lambda\kappa}^\dagger (1 - \\
 & \gamma^5) u_2^\kappa)] - \frac{g}{2} \frac{m_\Delta^2}{M} H (\bar{u}_2^\lambda u_2^\lambda) - \frac{g}{2} \frac{m_\Delta^2}{M} H (\bar{d}_2^\lambda d_2^\lambda) + \frac{ig}{2} \frac{m_\Delta^2}{M} \phi^0 (\bar{u}_2^\lambda \gamma^5 u_2^\lambda) - \frac{ig}{2} \frac{m_\Delta^2}{M} \phi^0 (\bar{d}_2^\lambda \gamma^5 d_2^\lambda) + \\
 & \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 + Y \partial Y + ig_{cw} W_\mu^+ (\partial_\mu \bar{X}^0 X - \\
 & \partial_\mu \bar{X}^+ X^0) + ig_{sw} W_\mu^+ (\partial_\nu \bar{Y} X^- - \partial_\nu \bar{X}^+ Y) + ig_{cw} W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + \\
 & ig_{sw} W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + ig_{cw} Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + ig_{sw} A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
 & \partial_\mu \bar{X}^- X^-) - \frac{1}{2}g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} ig M [\bar{X}^+ X^0 \phi^+ - \\
 & \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} ig M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + ig M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \\
 & \frac{1}{2}ig M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$

Bladmuziek (J.S. Bach)

bladmuziek

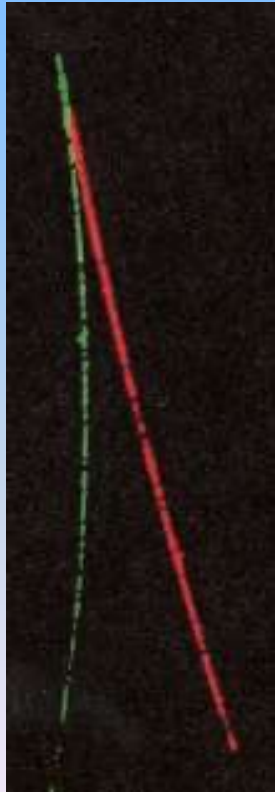
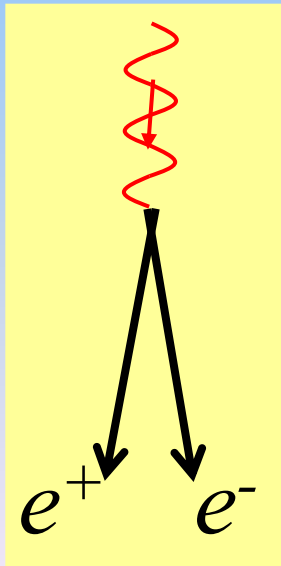
Allegro moderato. (♩ = 96)

The image shows a page of musical notation for J.S. Bach's 'Allegro moderato' in G major, BWV 1006. The score is written for piano and includes a variety of musical notations such as treble and bass clefs, notes, rests, and dynamic markings like 'cresc.', 'dimin.', and 'poco cresc.'.

Higgs: Deeltje? Veld?

Deeltje

Foton (lichtdeeltje)

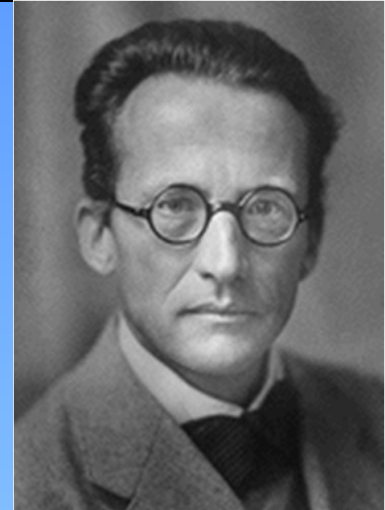


Veld

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:
(operator acting on wave function ψ)

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

Klein Gordon vergelijking:

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

or :

$$(\square + m^2) \phi(x) = 0$$

or :

$$(\partial_\mu \partial^\mu + m^2) \phi(x) = 0$$

Oplossing:

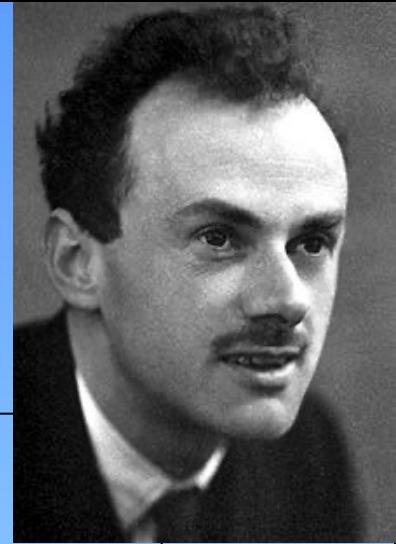
$$\phi(x) = N e^{-ip_\mu x^\mu}$$

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

Maar: negatieve energie oplossing?

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

Dirac



Paul Dirac zocht een vergelijking, die

- relativistisch correct is,
- Maar lineair 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:

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

Let's find α_i and β !

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

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 !?

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

- Often used
- Pauli-Dirac representation:

- 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:

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

Multiply by β :

$$\left(i\beta\frac{\partial}{\partial t}\psi + i\beta\alpha_1\frac{\partial}{\partial x} + i\beta\alpha_2\frac{\partial}{\partial y} + i\beta\alpha_3\frac{\partial}{\partial z} \right) \psi - m\psi = 0 \quad \cdot(\beta^2=1)$$

Gives the famous Dirac equation:

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

with : $\gamma^\mu = (\beta, \beta\vec{\alpha}) \equiv$ Dirac γ -matrices

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

Dirac

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

The famous Dirac equation:

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

with : $\gamma^\mu = (\beta, \beta\vec{\alpha}) \equiv$ Dirac γ -matrices

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

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



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