



1 mei 2018
High-School Students
Internship Programme
Nederland

Sijbrand de Jong
President van de CERN Council

Quantum Mechanics:

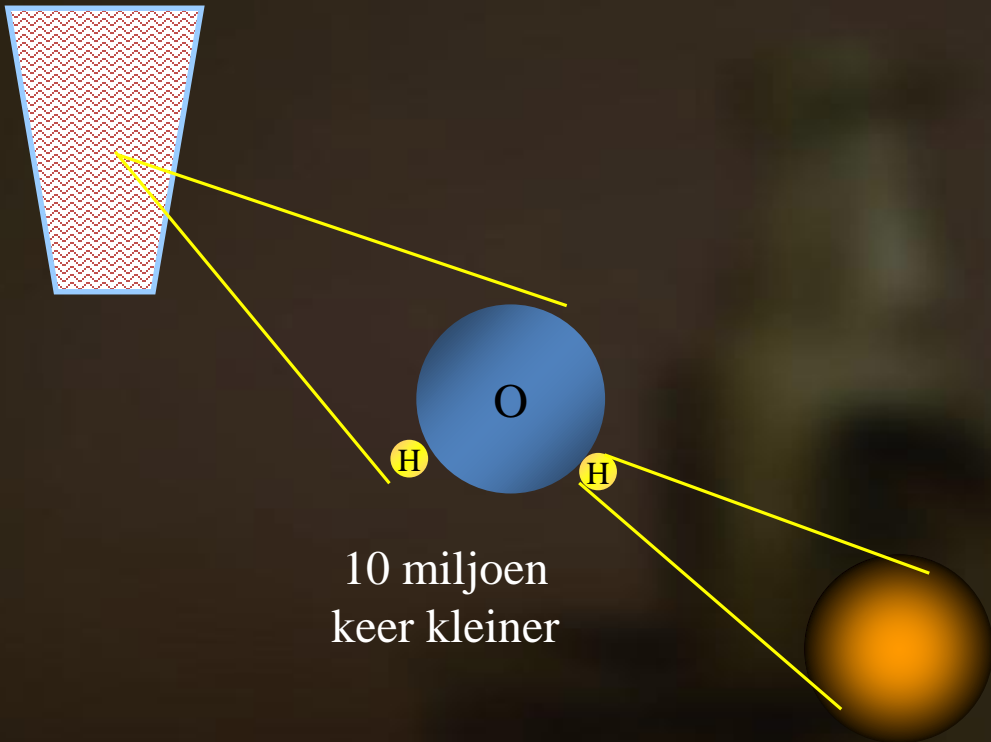
$$\lambda = hc/E$$

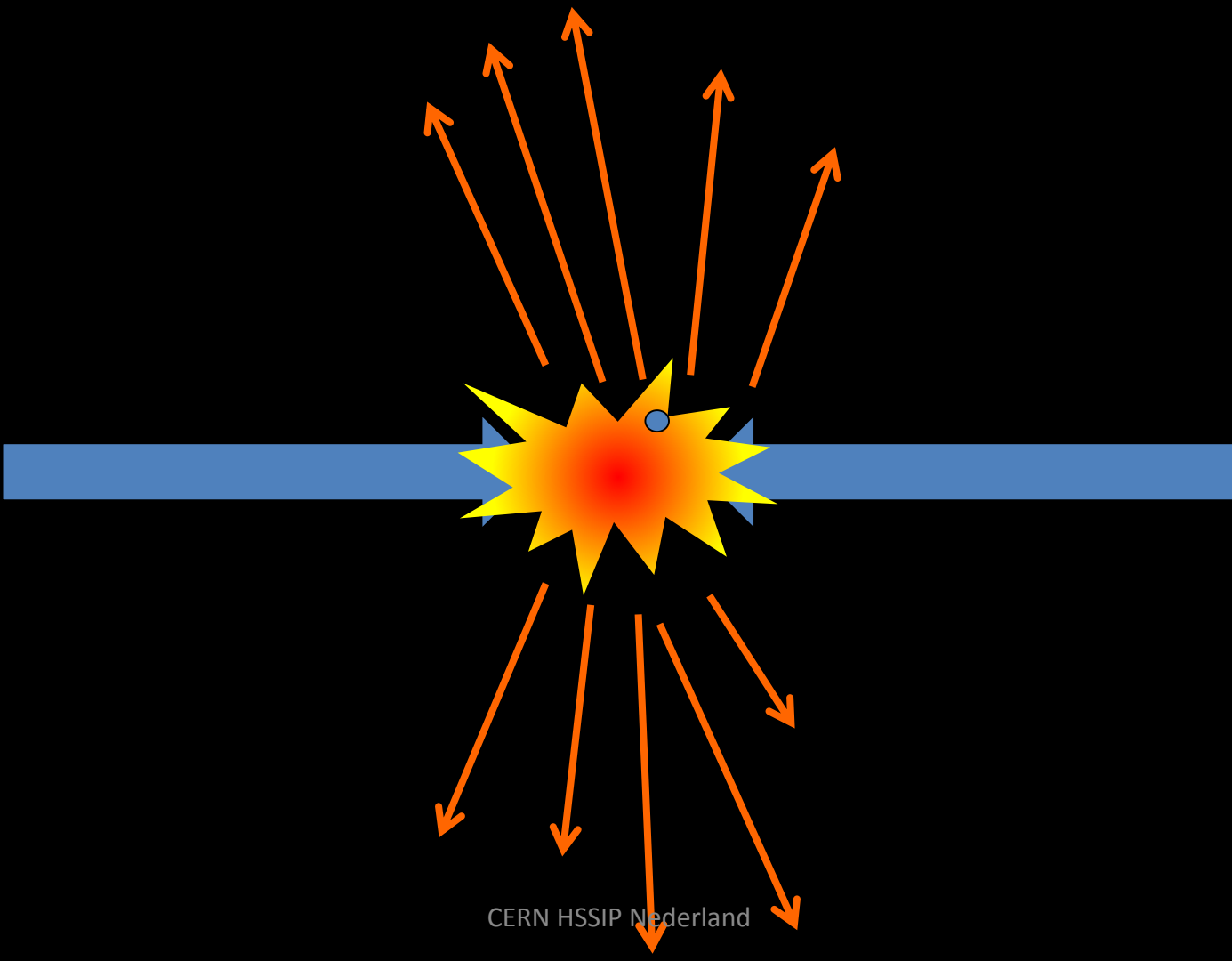
Relativiteit:

$$m = E/c^2$$

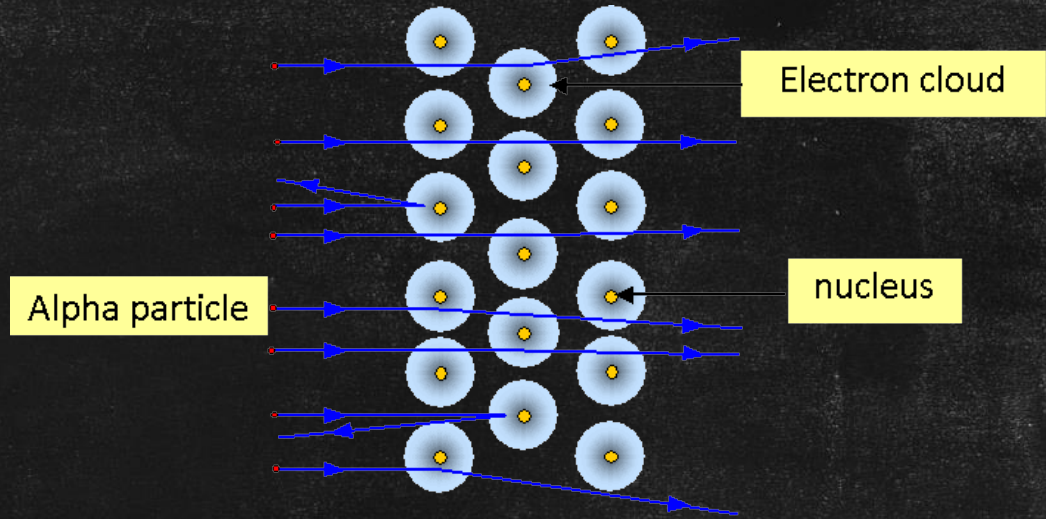
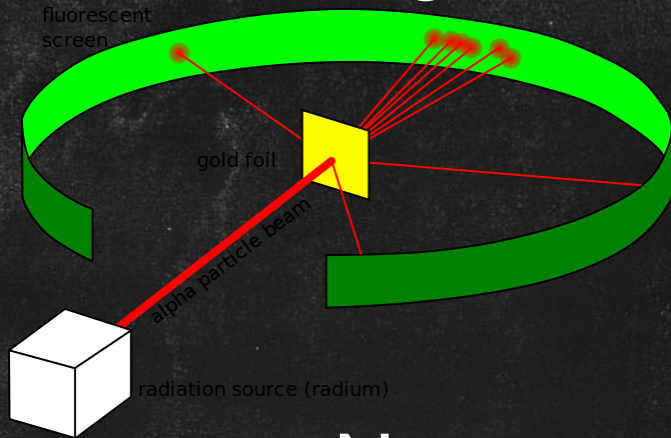
Voor onderzoek van de **kleinste afstanden** en
elementaire deeltjes met de **grootste massa**:

Energy matters !

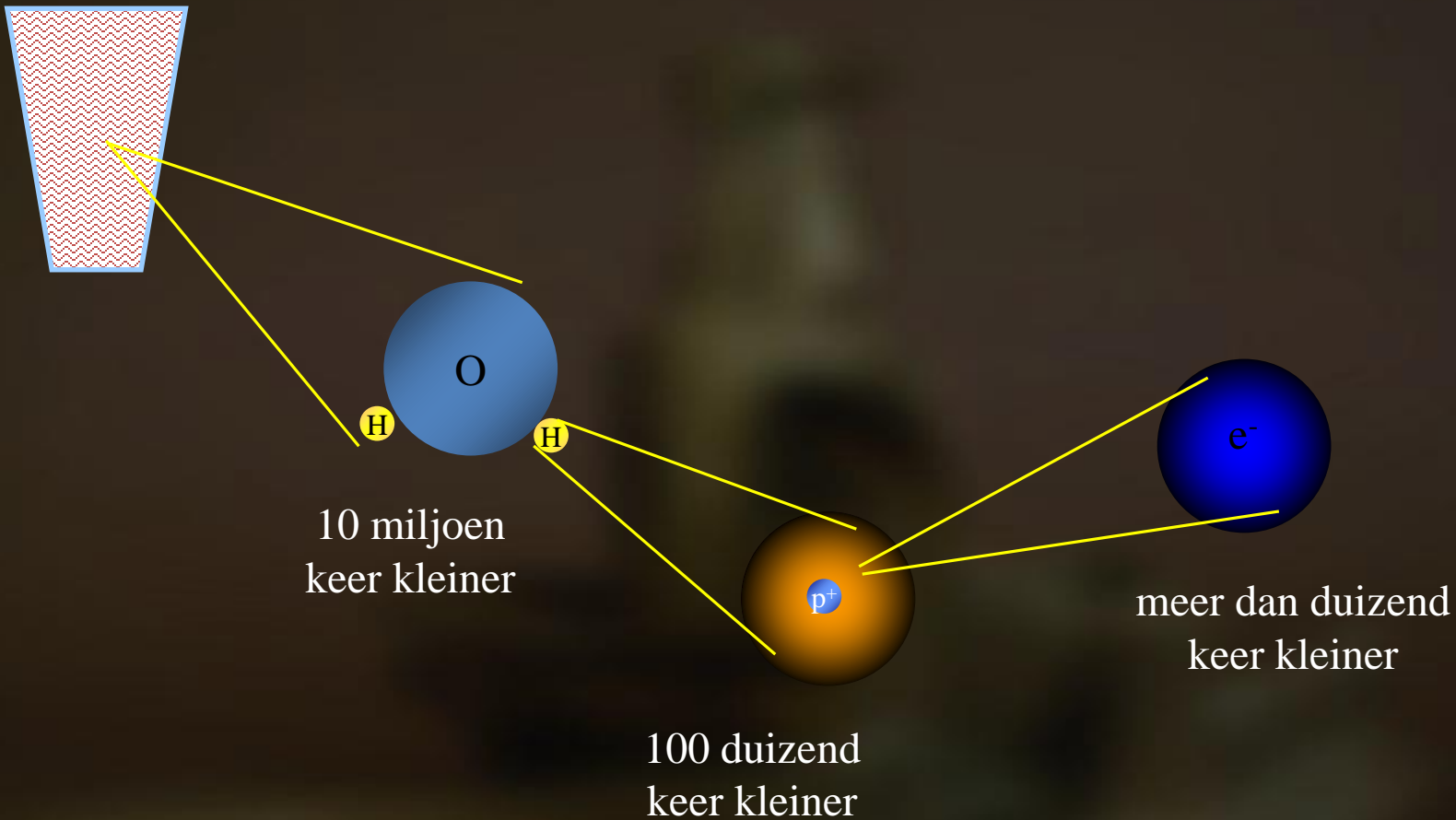


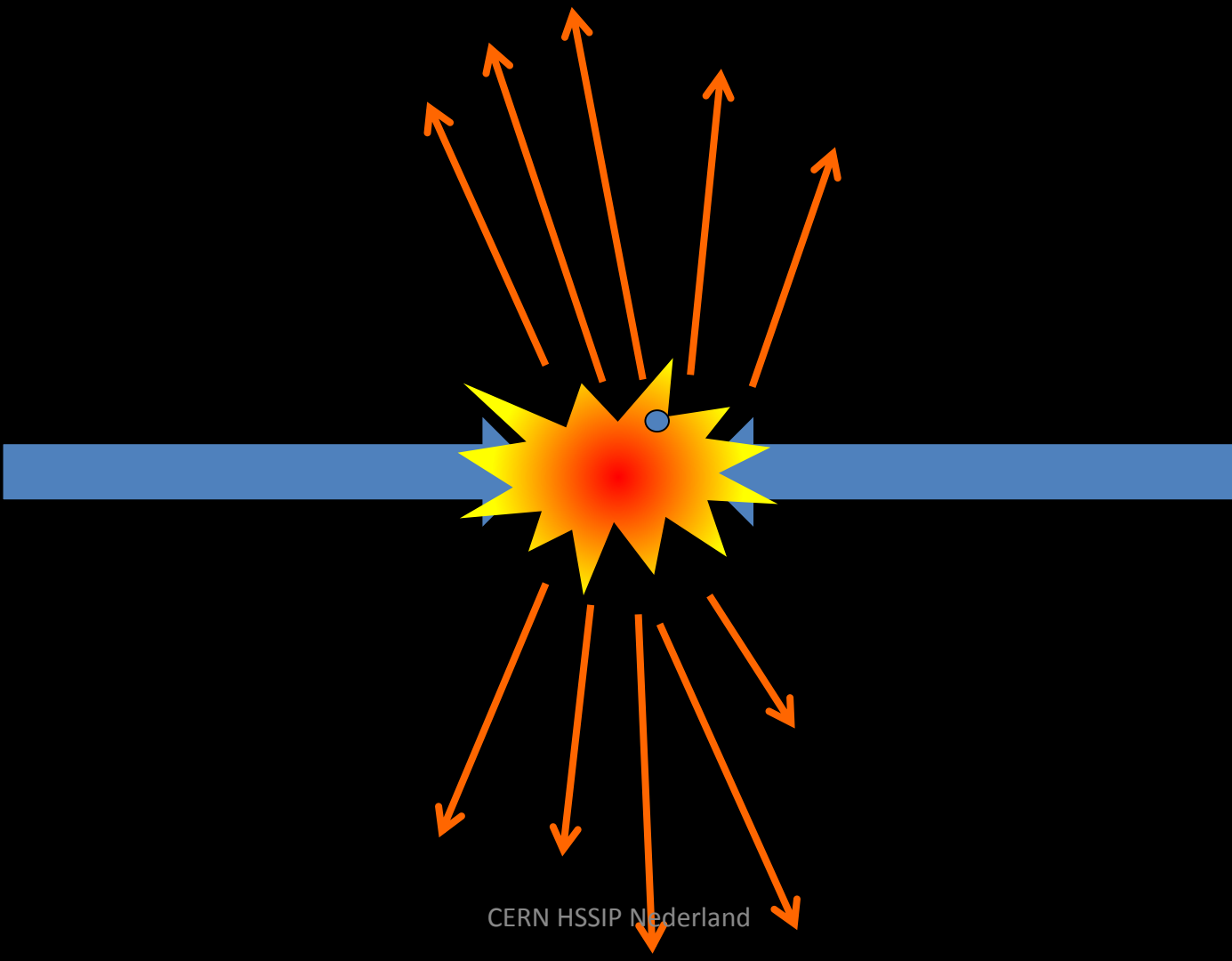


Verstrooiing

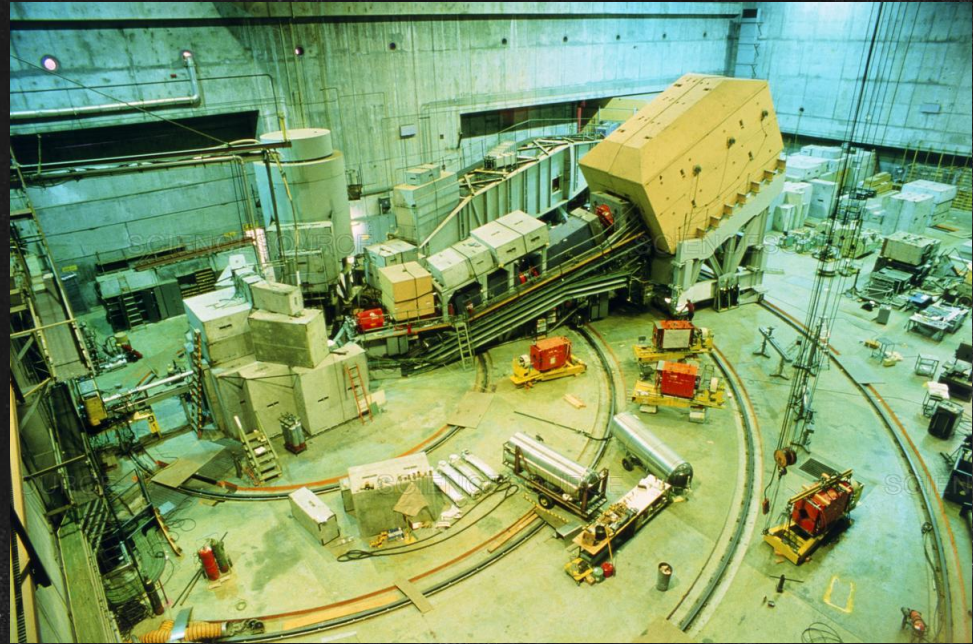
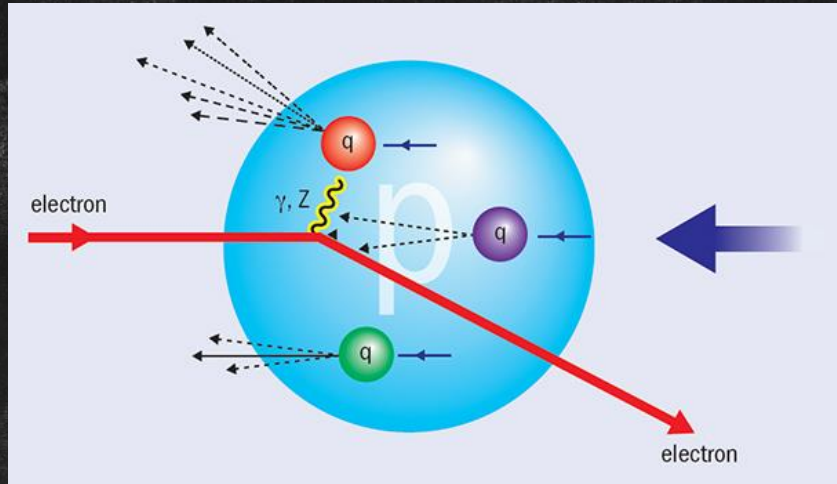


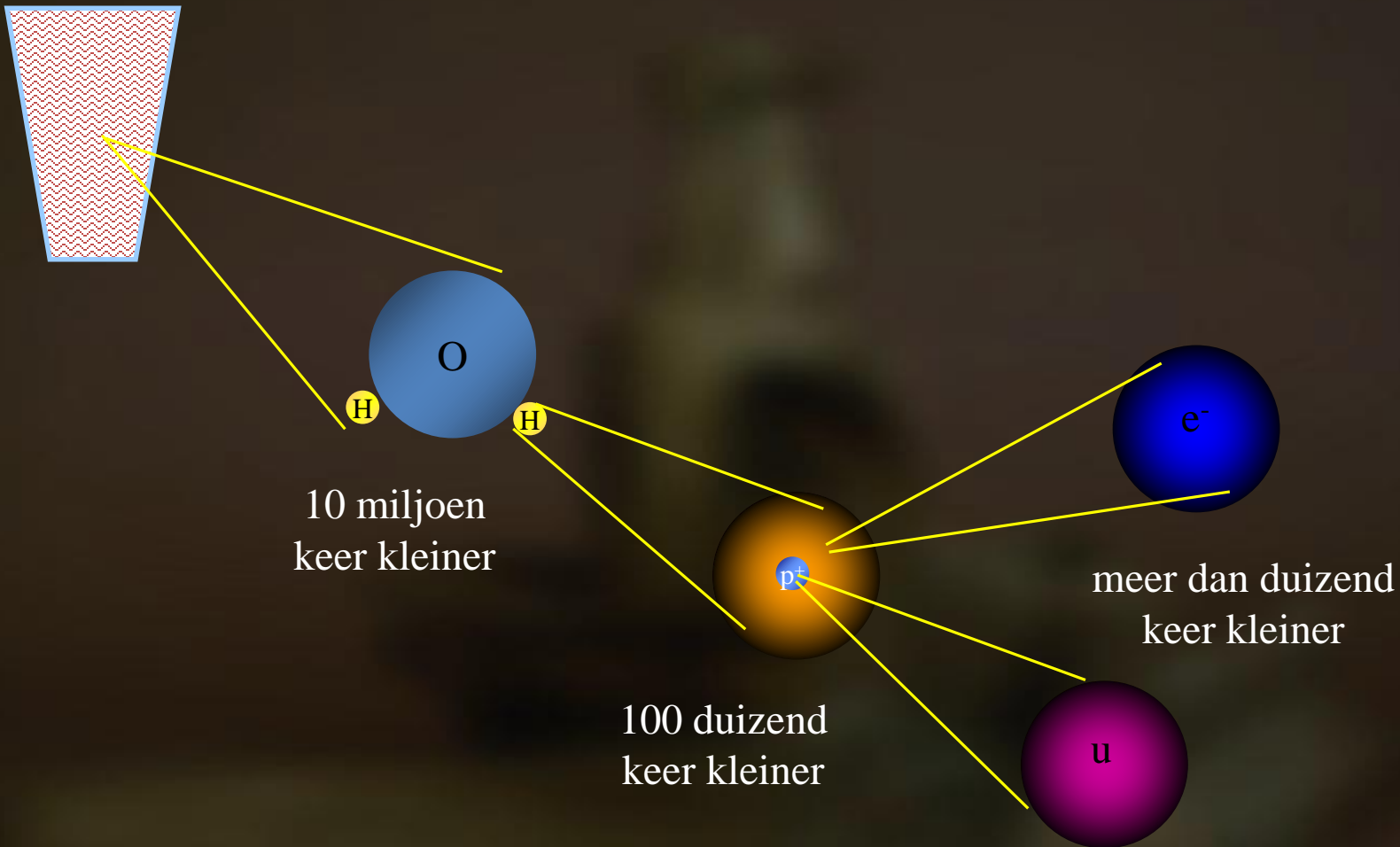
$$\begin{array}{c} N \\ \updownarrow \\ \text{Experiment} \end{array} = \begin{array}{c} L \\ \updownarrow \\ \text{Versneller} \end{array} \quad \begin{array}{c} \sigma \\ \updownarrow \\ \text{Theorie} \end{array}$$



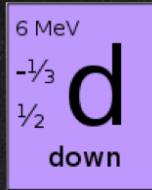
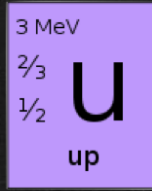


Diep Inelastische Verstrooiing

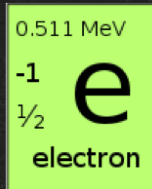




Gewone
materie:
 $p^+ = uud$
 $n^0 = udd$



e^-



Gewone
materie:

$p^+ = uud$

$n^0 = udd$

3 MeV
 $\frac{2}{3}$
 $\frac{1}{2}$ **u**
up

6 MeV
 $-\frac{1}{3}$
 $\frac{1}{2}$ **d**
down

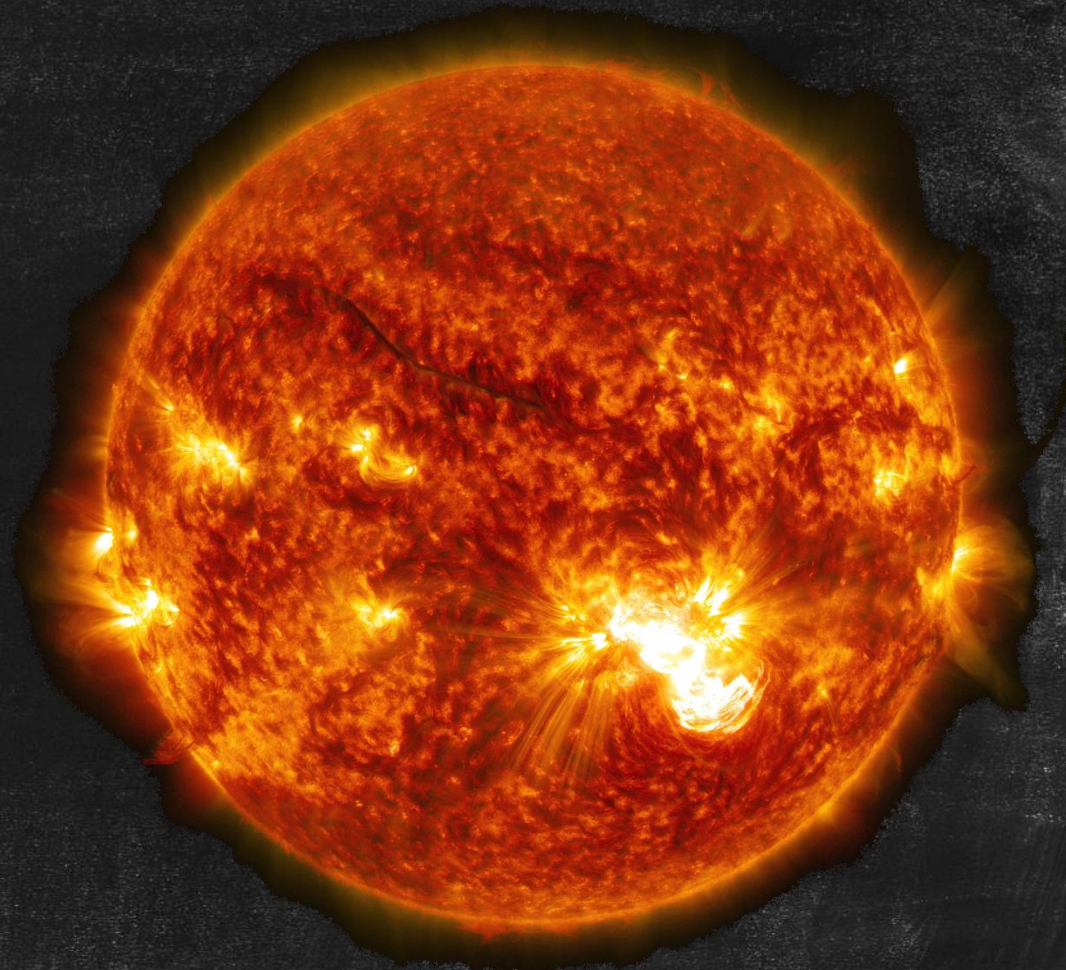
<2 eV
0 **ν_e**
 $\frac{1}{2}$
electron
neutrino

0.511 MeV
-1
 $\frac{1}{2}$ **e**
electron

ν

e^-

$n^0 \rightarrow p^+ e^- \bar{\nu}_e$

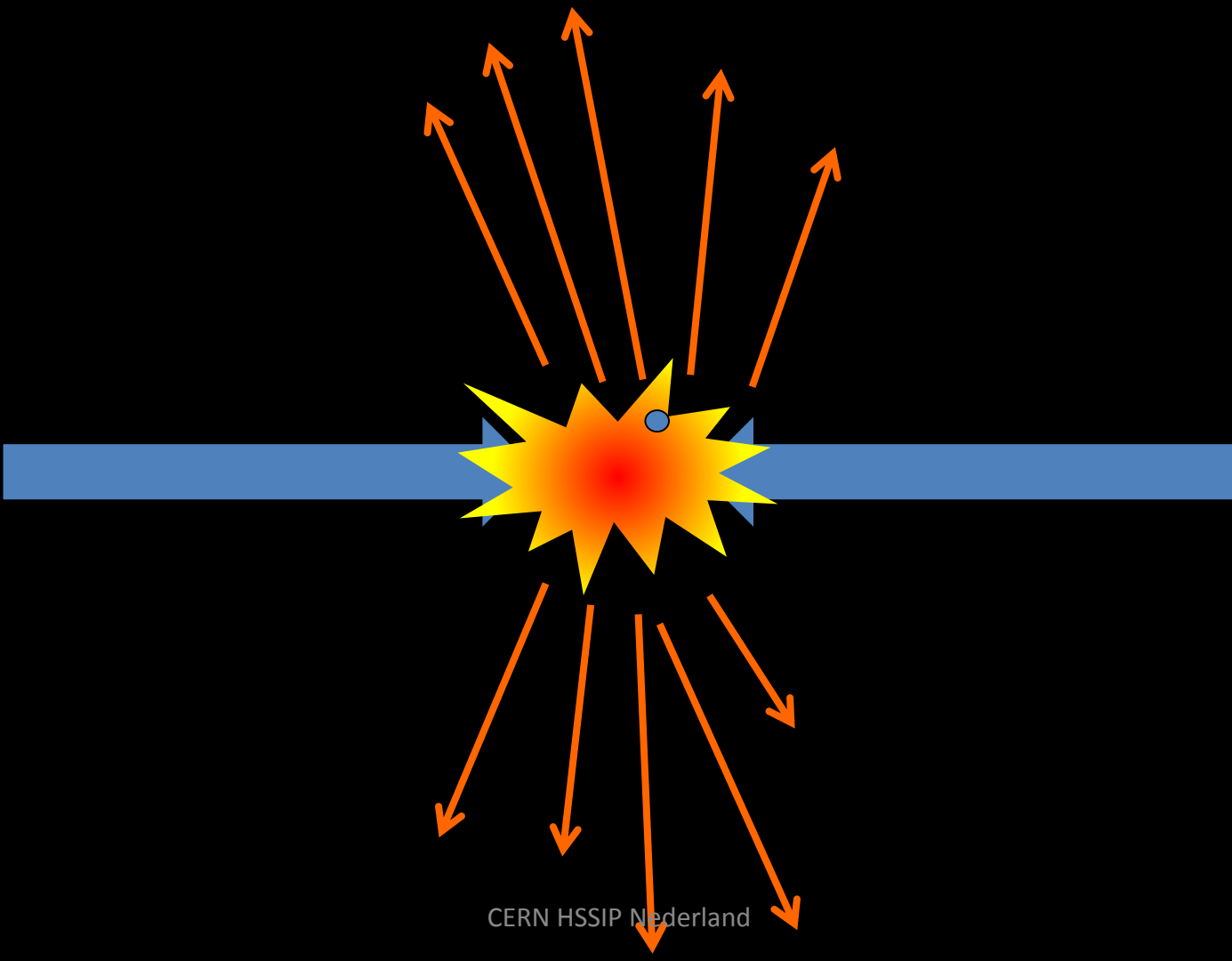


Quantum Mechanics: $\lambda=hc/E$

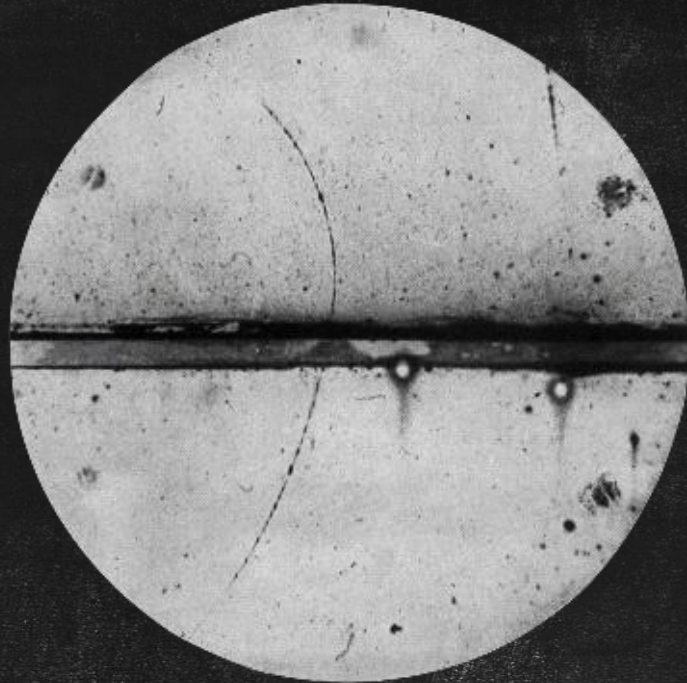
Relativiteit: $m=E/c^2$

Voor onderzoek van de **kleinste afstanden** en
elementaire deeltjes met de **grootste massa**:

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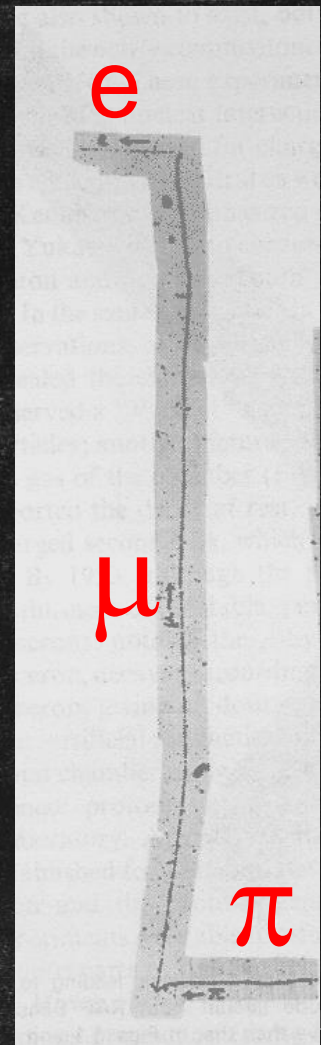


Het positron: de eerste anti-materie

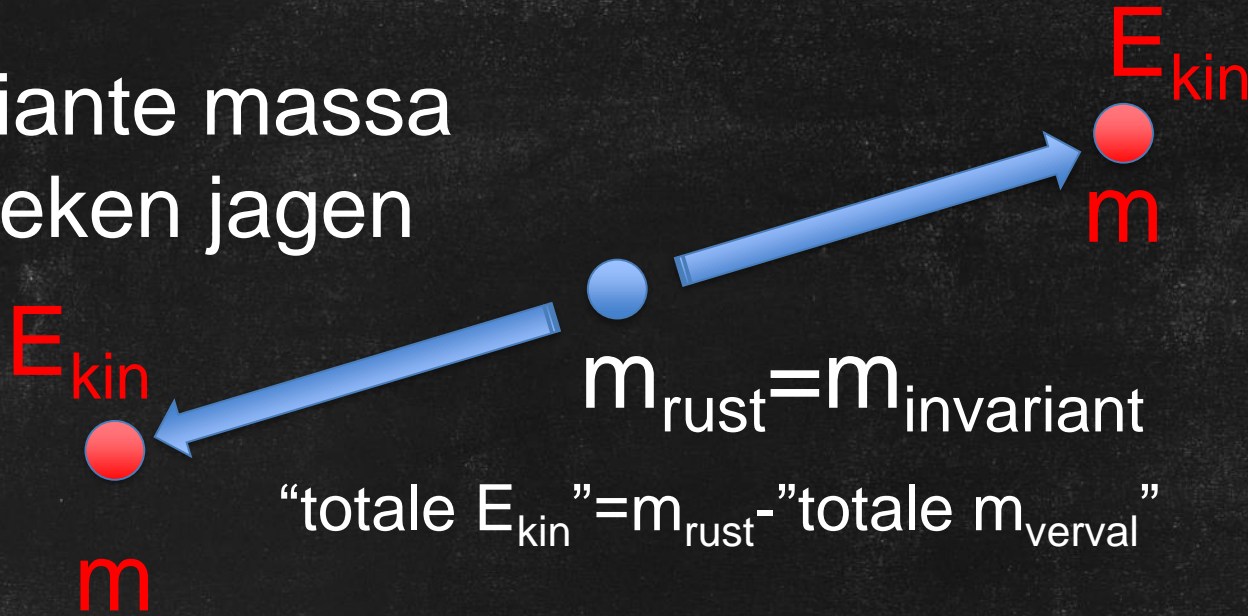


Muon: zwaar elektron
heeft geen kerninteracties

Pion: lijkt op muon
heeft **wel** kerninteracties



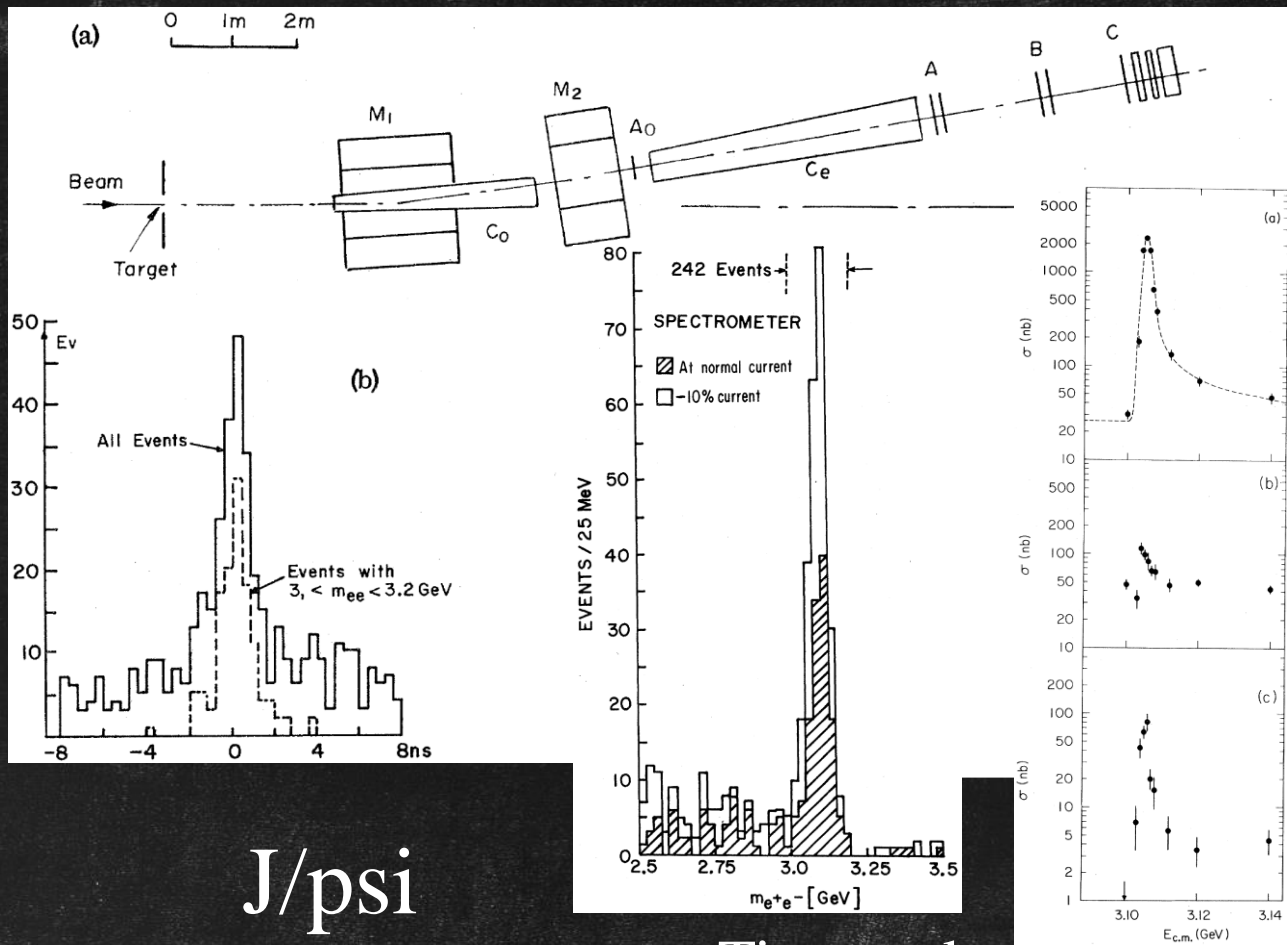
Invariante massa en Pieken jagen



$$m_{minvariant} = \sum_i \sqrt{m_i^2 + (p_i/c)^2}$$

Pieken jagen

c-quark

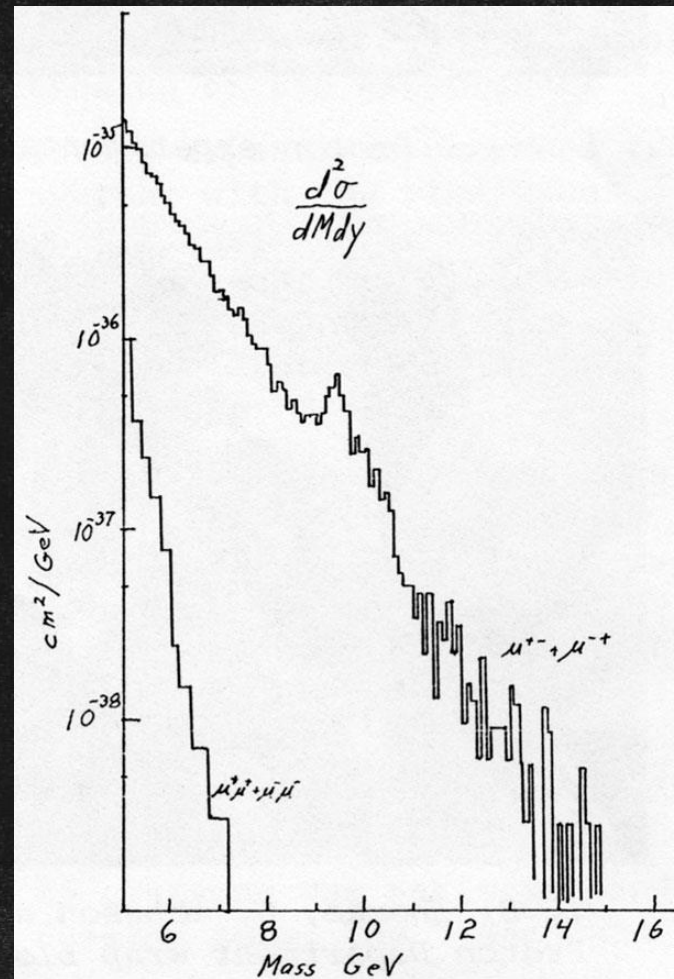
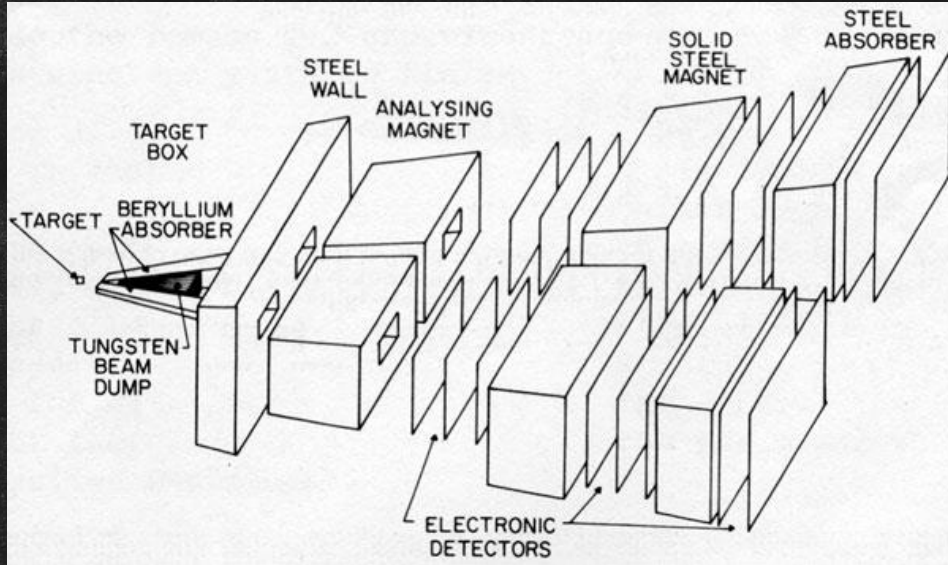


J/ψ

Ting et al.

Richter et al.

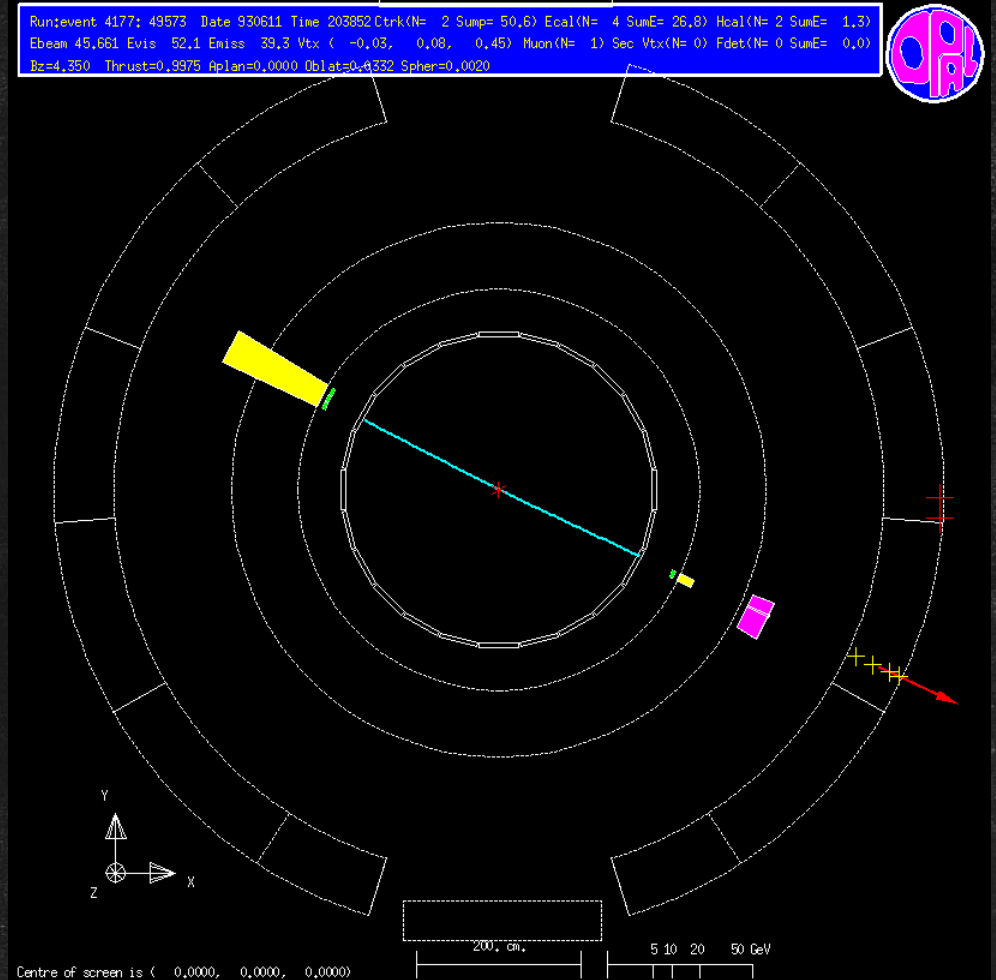
Pieken jagen b-quark



Run: event 4177: 49573 Date 930611 Time 203852 Ctrk(N= 2 Sump= 50,6) Ecsl(N= 4 SumE= 26,8) Hcal(N= 2 SumE= 1,3)
Ebeam 45,661 Evis 52,1 Emiss 39,3 Vtx (-0,03, 0,08, 0,45) Muon(N= 1) Sec Vtx(N= 0) Fdet(N= 0 SumE= 0,0)
Bz=4,350 Thrust=0,9975 Aplan=0,0000 Oblat=0,4332 Spher=0,0020



Gecompliceerder: tau lepton



Quarks

Gewone materie:
 $p^+ = uud$
 $n^0 = udd$

3 MeV $\frac{2}{3}$ $\frac{1}{2}$ u up	1.24 GeV $\frac{2}{3}$ $\frac{1}{2}$ c charm	172.5 GeV $\frac{2}{3}$ $\frac{1}{2}$ t top
6 MeV $-\frac{1}{3}$ $\frac{1}{2}$ d down	95 MeV $-\frac{1}{3}$ $\frac{1}{2}$ s strange	4.2 GeV $-\frac{1}{3}$ $\frac{1}{2}$ b bottom
<2 eV 0 ν_e $\frac{1}{2}$ electron neutrino	<0.19 MeV 0 ν_μ $\frac{1}{2}$ muon neutrino	<18.2 MeV 0 ν_τ $\frac{1}{2}$ tau neutrino
0.511 MeV -1 $\frac{1}{2}$ e electron	106 MeV -1 $\frac{1}{2}$ μ muon	1.78 GeV -1 $\frac{1}{2}$ τ tau

Nog twee Families !?!?

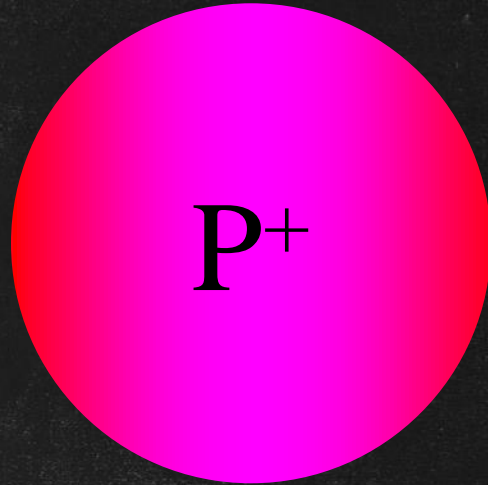
ν

e^-

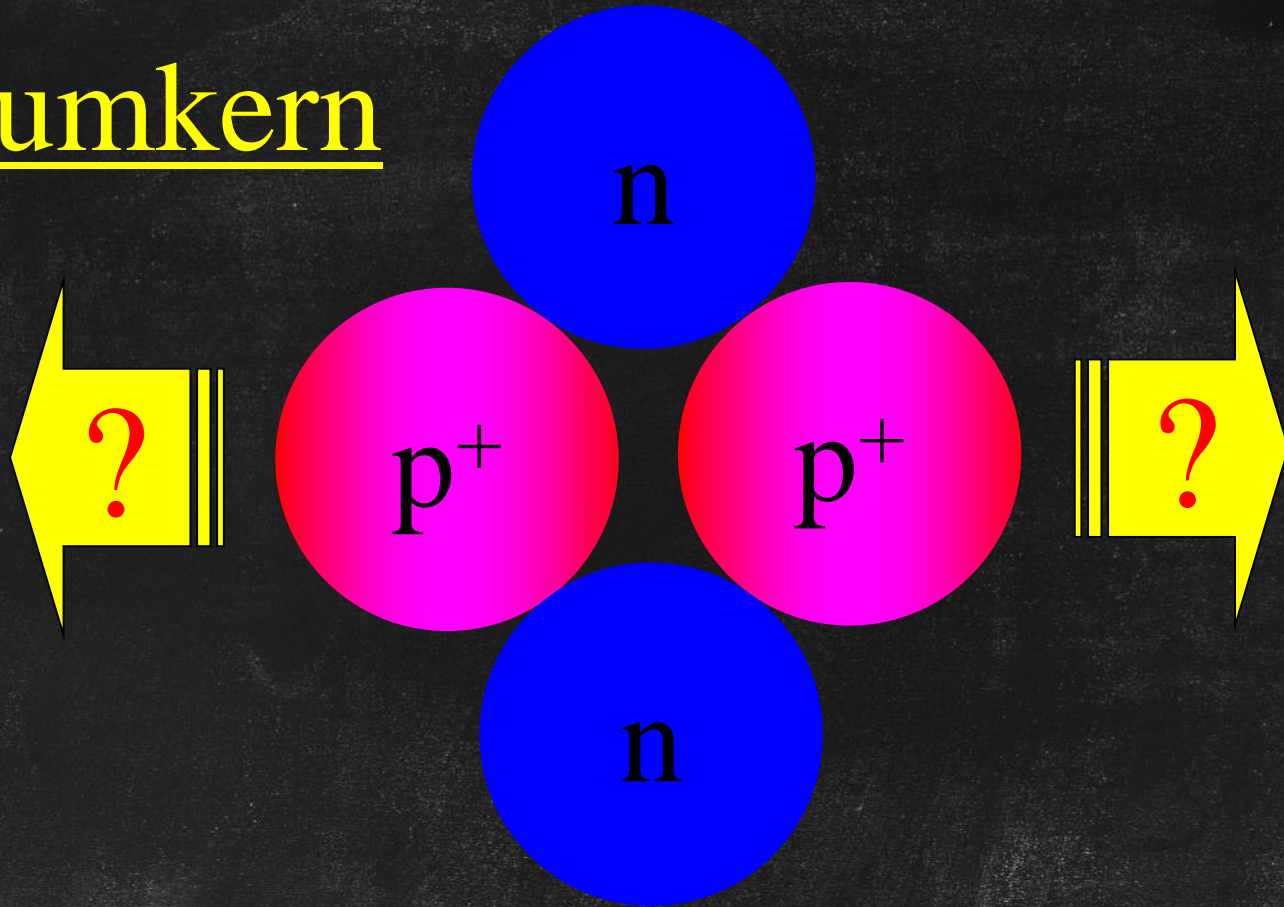
$n^0 \rightarrow p^+ e^- \bar{\nu}_e$ **Leptonen**

Interacties

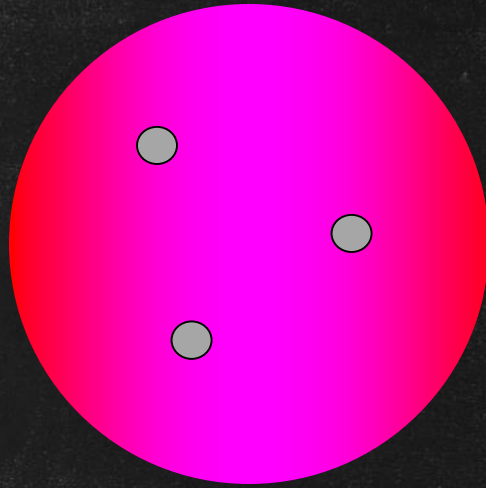
waterstofkern



heliumkern



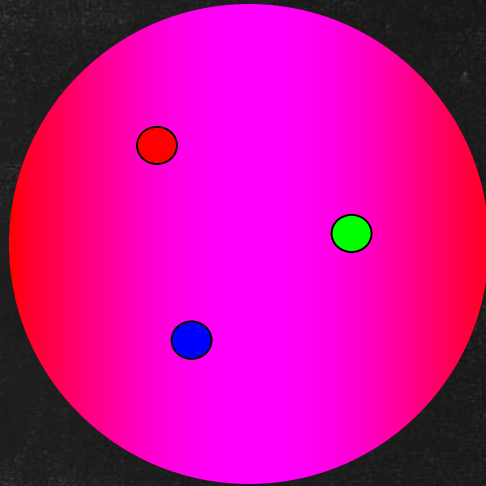
proton



quarks

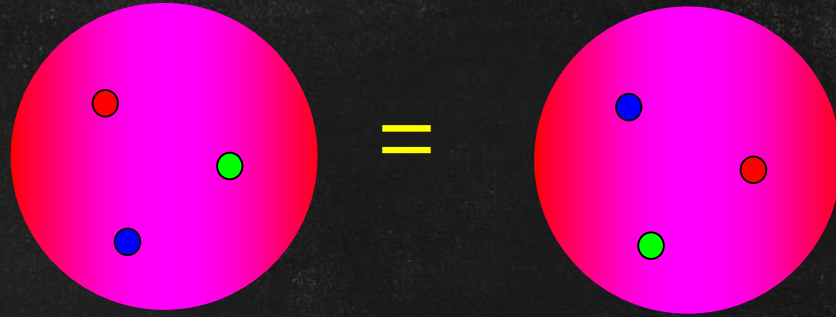
Pauli principe

Dezelfde quarks
kunnen **niet**
in zelfde
toestand zitten



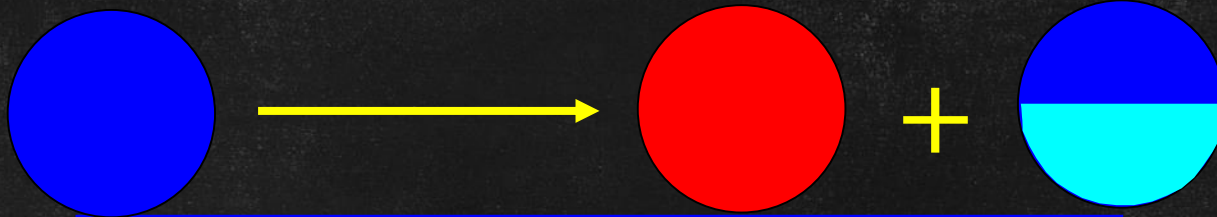
Nieuw
quantumgetal:
KLEUR
KLEUR
KLEUR

quarks bestaan in drie kleuren



cyclisch verwisselen
van kleuren \Rightarrow geen effect

Wat als 1 quark wil
wisselen van kleur ?



Kleur veranderen



Boodschapper sturen

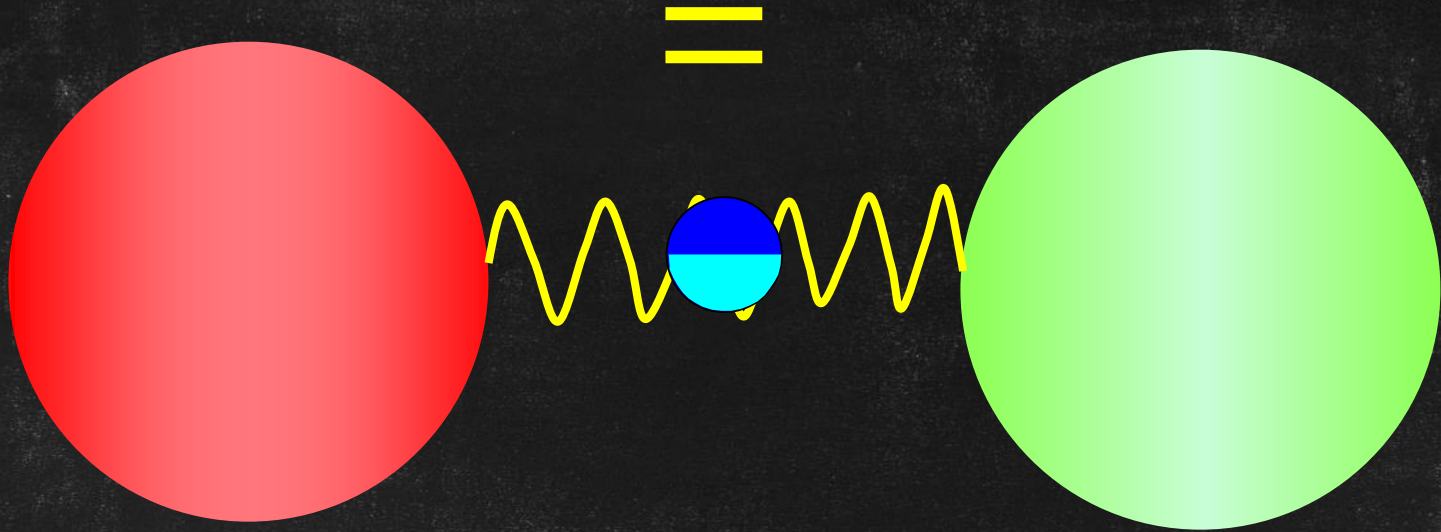
kracht

=



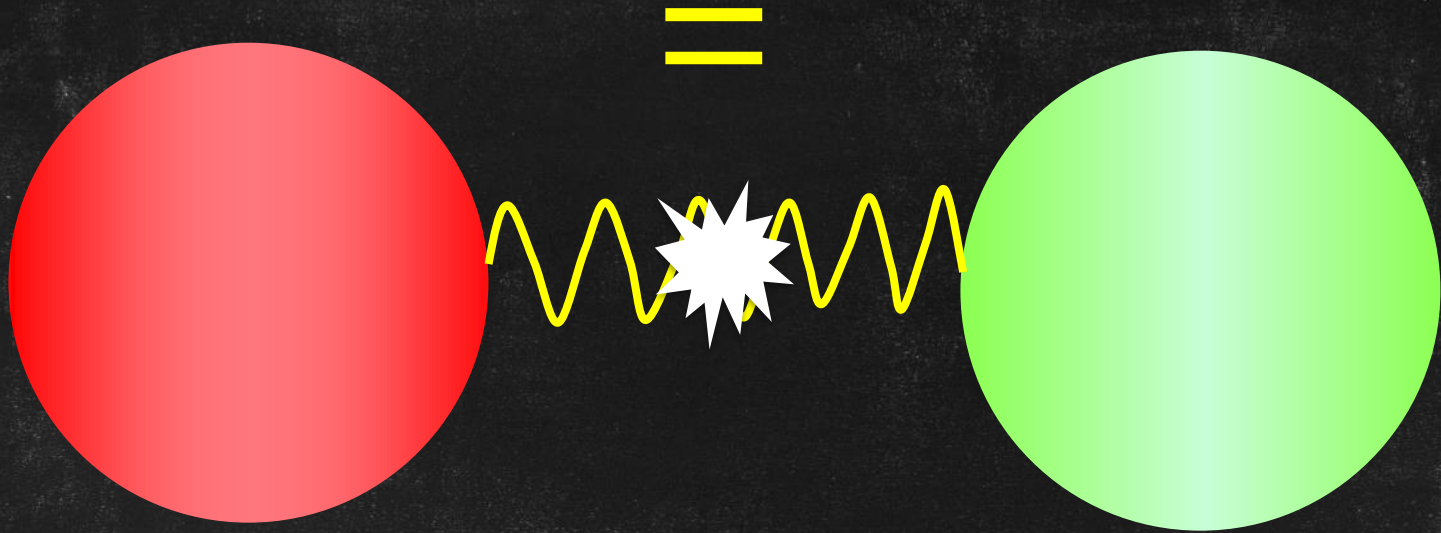
uitwisseling van deeltjes

Sterke Kracht



uitwisseling van gluon

Electromagnetische Kracht



uitwisseling van foton

Gewone
materie:
 $p^+ = uud$
 $n^0 = udd$

Quarks

3 MeV $\frac{2}{3}$ $\frac{1}{2}$ u up	1.24 GeV $\frac{2}{3}$ $\frac{1}{2}$ c charm	172.5 GeV $\frac{2}{3}$ $\frac{1}{2}$ t top
---	---	--

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<2 eV 0 $\frac{1}{2}$ ν_e electron neutrino	<0.19 MeV 0 $\frac{1}{2}$ ν_μ muon neutrino	<18.2 MeV 0 $\frac{1}{2}$ ν_τ tau neutrino
--	--	--

0.511 MeV -1 $\frac{1}{2}$ e electron	106 MeV -1 $\frac{1}{2}$ μ muon	1.78 GeV -1 $\frac{1}{2}$ τ tau
--	---	--

0 0 1 γ photon

0 0 1 g gluon

90.2 GeV 0 1 Z⁰ weak force

80.4 GeV ± 1 1 W[±] weak force

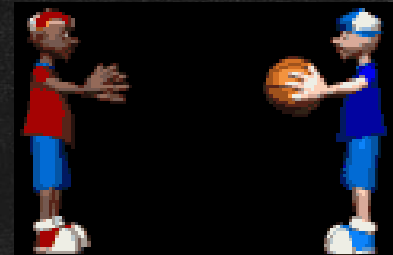
ν

e^-

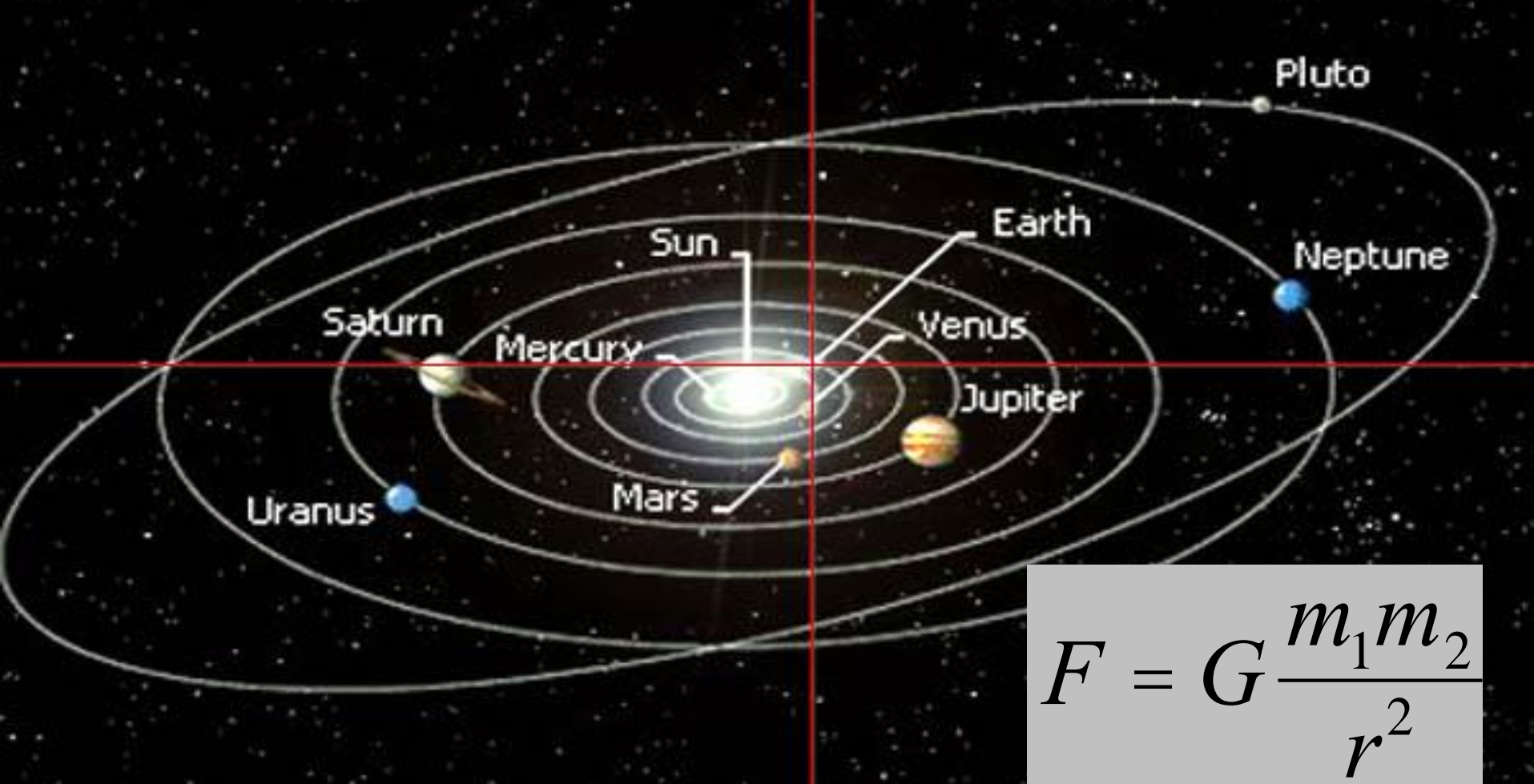
$n^0 \rightarrow p^+ e^- \bar{\nu}_e$

Leptonen

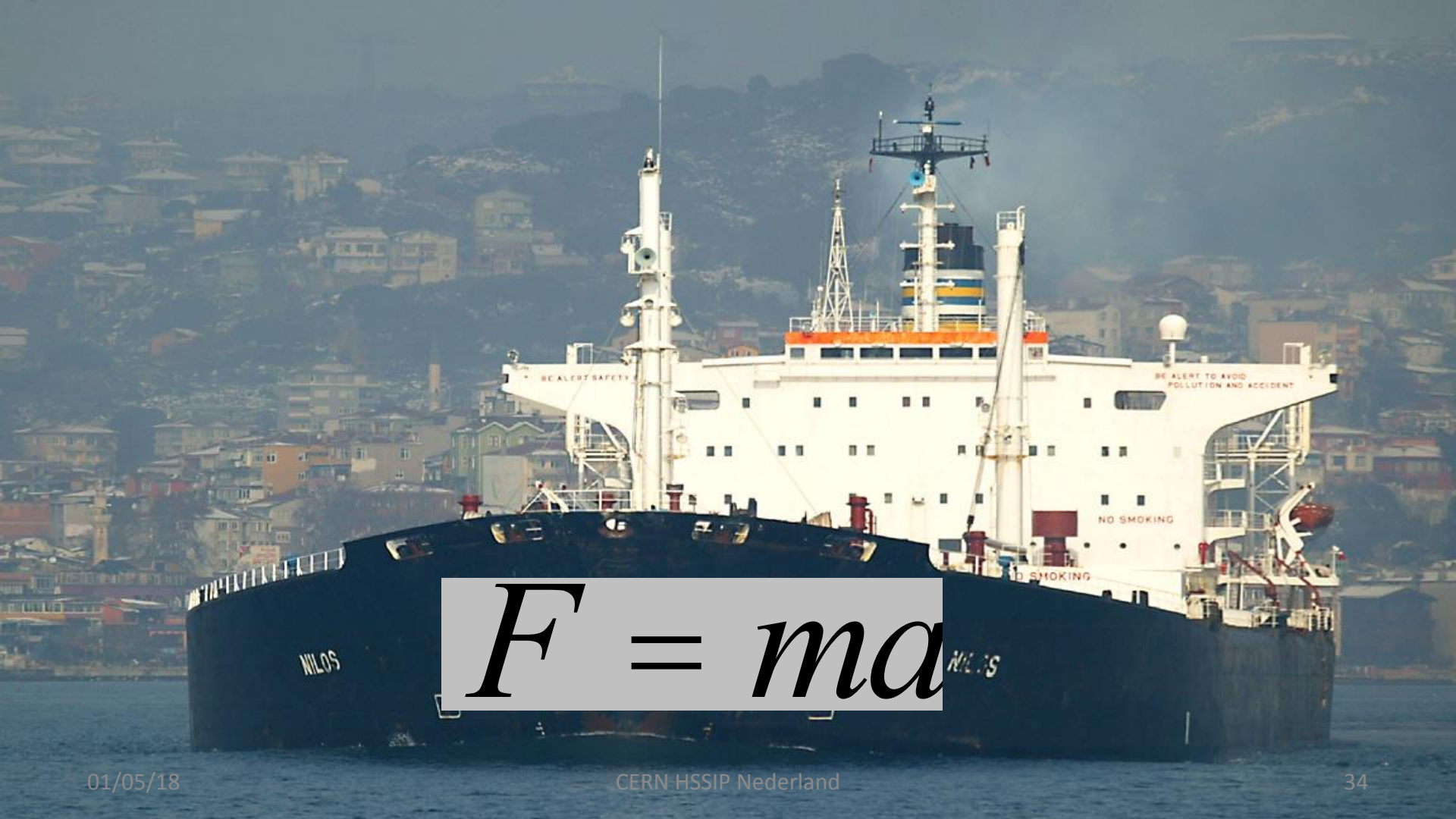
IJK
bosonen



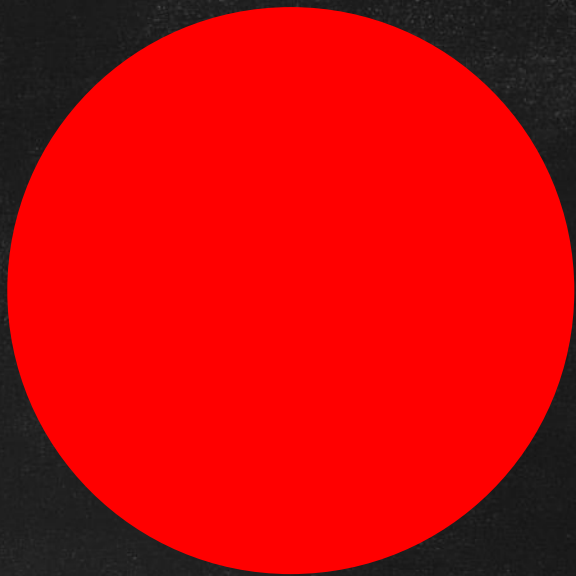


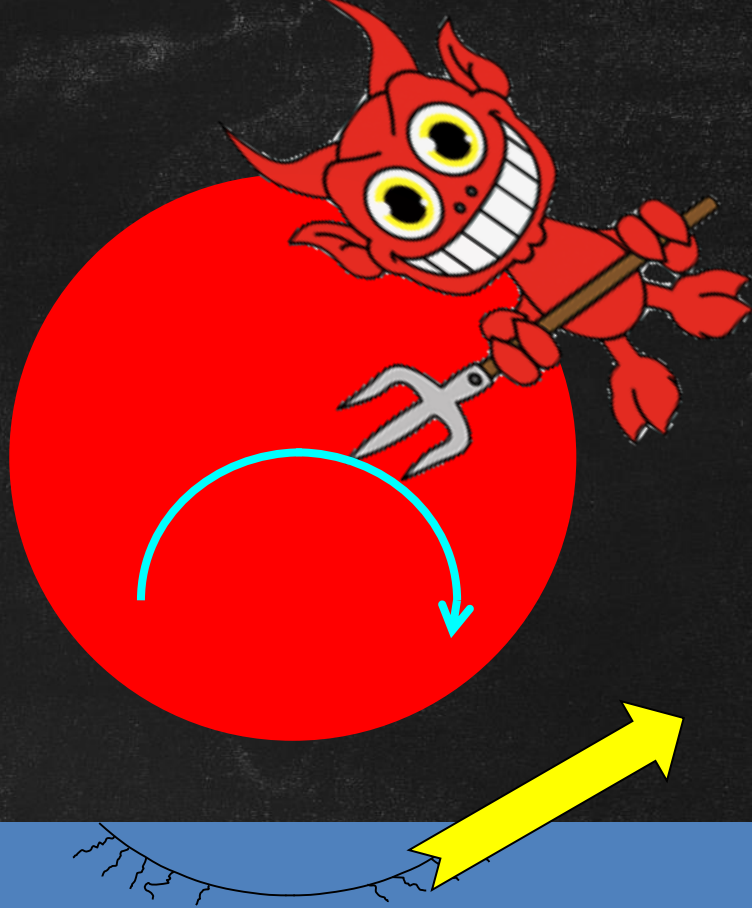


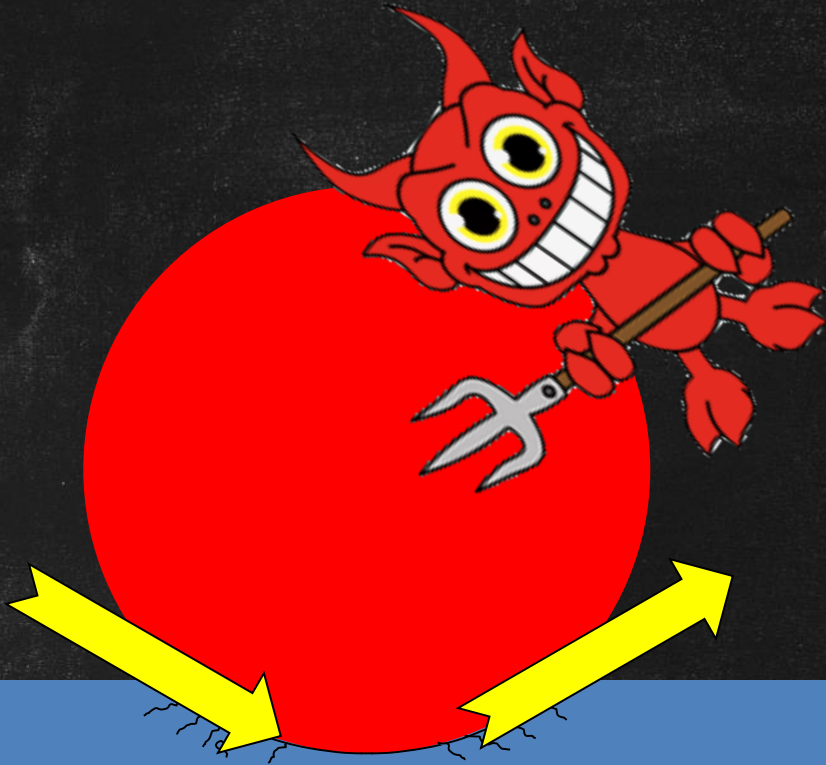
$$F = G \frac{m_1 m_2}{r^2}$$

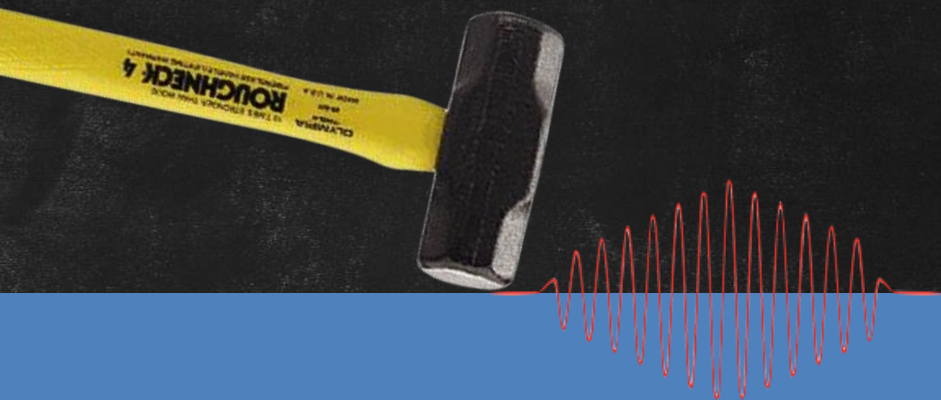


$$F = ma$$











Gewone
materie:
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Leptonen

ν

e^-

$n^0 \rightarrow p^+ e^- \bar{\nu}_e$

0 0 1 γ photon

0 0 1 g gluon

90.2 GeV 0 1 Z⁰ weak force

80.4 GeV ± 1 1 W[±] weak force

125.7 GeV 0 0 H Higgs
--

Higgs

IJK
bosonen

Vreemde
eend in
de bijt

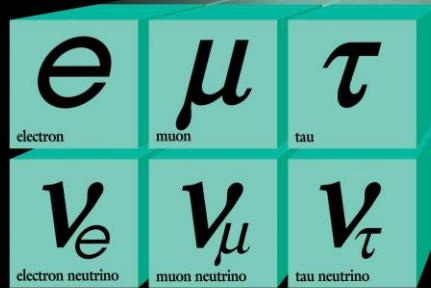
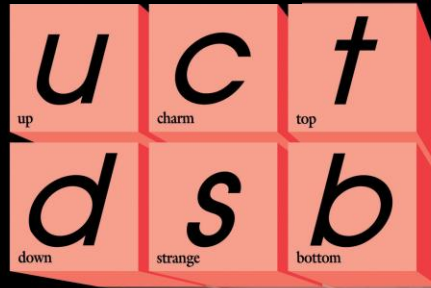
$$\begin{aligned}\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i\bar{\psi} \not{D} \psi + \text{h.c.} \\ & + \chi_i y_{ij} \chi_j \phi + \text{h.c.} \\ & + |D_m \phi|^2 - V(\phi)\end{aligned}$$

Wat
precies
van

$$\begin{aligned} & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^b g_\mu^c g_\nu^a - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \frac{1}{2}ig_s^2 (\bar{q}^T \gamma^\mu q^T) g_\mu \\ & \bar{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}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \\ & \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\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}{g^2} \alpha_h - ig_{c_w} [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\ & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)] - ig_{s_w} \partial_\nu A_\mu (W_\mu^+ W_\nu^- - \\ & W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - 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_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - \\ & A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - W_\nu^- W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^- - 9\alpha [H^3 + \\ & H \phi^0 \phi^0 + 2H \phi^+ \phi^-] - \frac{1}{2}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}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_\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_{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}{2}g^2 W_\mu^+ W_\mu^- H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\ & \frac{1}{2}g^2 \frac{1}{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{2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \\ & \frac{1}{2}ig^2 \frac{s_w}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \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^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - e^\lambda (\gamma \theta + m_\lambda^2) e^\lambda - \\ & \bar{\nu}^\lambda \gamma \theta \nu^\lambda - \bar{u}_3^\lambda (\gamma \theta + m_\lambda^2) u_3^\lambda - d_3^\lambda (\gamma \theta + m_\lambda^2) d_3^\lambda + ig_{s_w} A_\mu [-(e^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_3^\lambda \gamma^\mu u_3^\lambda) - \\ & \frac{1}{3}(d_3^\lambda \gamma^\mu d_3^\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}_3^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - \\ & 1 - \gamma^5) u_3^\lambda) + (d_3^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_3^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) - (u_3^\lambda \gamma^\mu (1 + \\ & \gamma^5) C_{\lambda\lambda} d_3^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(e^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (d_3^\lambda C_{\lambda\lambda} \gamma^\mu (1 + \gamma^5) u_3^\lambda)] + \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_\lambda^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_\lambda^2 (\bar{u}_3^\lambda C_{\lambda\lambda} (1 - \\ & \gamma^5) d_3^\lambda) + m_\lambda^2 (\bar{u}_3^\lambda C_{\lambda\lambda} (1 + \gamma^5) d_3^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^- [m_\lambda^2 (\bar{d}_3^\lambda C_{\lambda\lambda}^1 (1 + \gamma^5) u_3^\lambda) - m_\lambda^2 (\bar{d}_3^\lambda C_{\lambda\lambda}^1 (1 - \\ & \gamma^5) u_3^\lambda)] - \frac{g}{2} \frac{m_\lambda^2}{M} H (u_3^\lambda u_3^\lambda) - \frac{g}{2} \frac{m_\lambda^2}{M} H (d_3^\lambda d_3^\lambda) + \frac{ig}{2} \frac{m_\lambda^2}{M} \phi^0 (u_3^\lambda \gamma^5 u_3^\lambda) - \frac{ig}{2} \frac{m_\lambda^2}{M} \phi^0 (d_3^\lambda \gamma^5 d_3^\lambda) + \\ & X^+ (\partial^2 - M^2) X^+ + X^- (\partial^2 - M^2) X^- + X^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + Y \partial^2 Y + ig_{c_w} W_\mu^+ (\partial_\mu X^0 X^- - \\ & \partial_\nu X^+ X^0) + ig_{s_w} W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu X^+ \bar{Y}) + ig_{c_w} W_\mu^- (\partial_\mu X^- X^0 - \partial_\mu \bar{X}^0 X^+) + \\ & ig_{s_w} W_\mu^- (\partial_\mu X^- Y - \partial_\mu Y X^+) + ig_{c_w} Z_\mu^0 (\partial_\mu X^+ X^+ - \partial_\mu X^- X^-) + ig_{s_w} A_\mu (\partial_\mu 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^+ - \\ & X^- X^0 \phi^-] + \frac{1}{2c_w} ig M [X^0 X^- \phi^+ - X^0 X^+ \phi^-] + ig M s_w [X^0 X^- \phi^+ - X^0 X^+ \phi^-] + \\ & \frac{1}{2}ig M \bar{X}^+ X^+ \phi^0 - X^- X^- \phi^0 \end{aligned}$$

Begrijp
je
niet
?

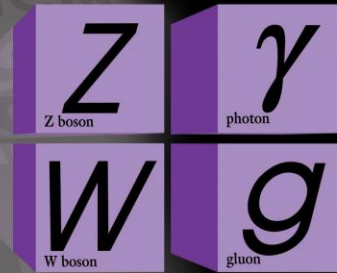
Quarks



Leptonen



Krachten



+ antimaterie

Generaties

Quarks

u up	c charm	t top
d down	s strange	b bottom

Potentiaalzelfkoppeling
Koppeling aan BSM deeltjes

Krachten



Z Z boson	γ photon
W W boson	g gluon

Sterke CP?



CPT
zwaartekracht

Nucleon
structuur

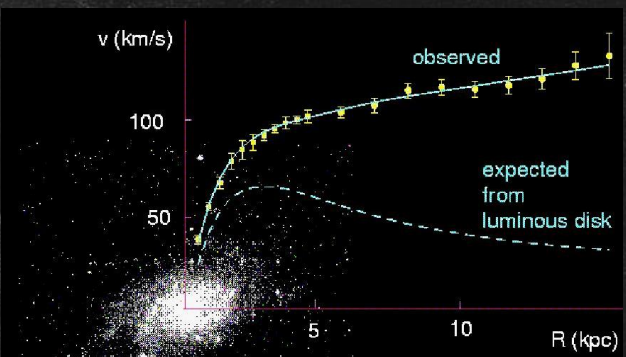
e electron	μ muon	τ tau
ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino

Leptonen

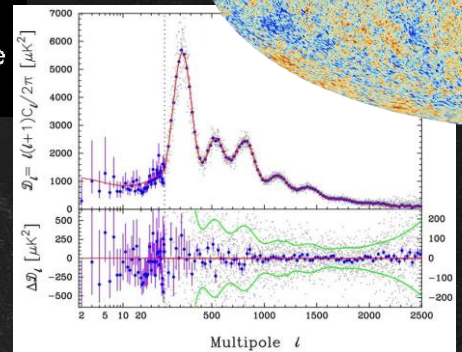
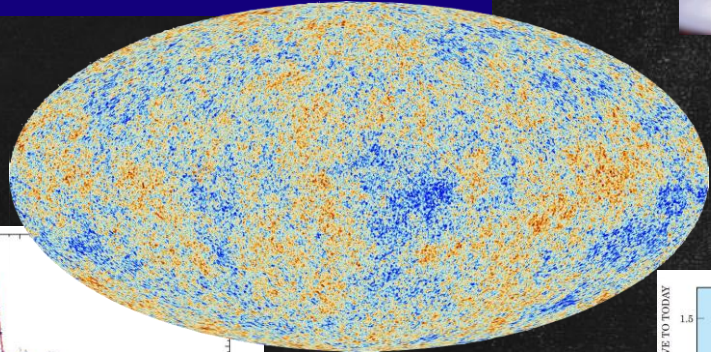
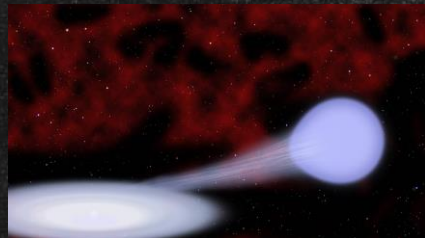
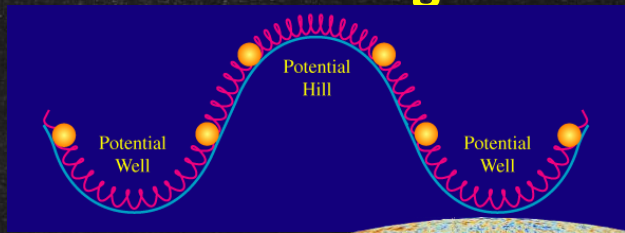
Massa's
Dirac/Majorana
Complexe mengfase

+ antimaterie

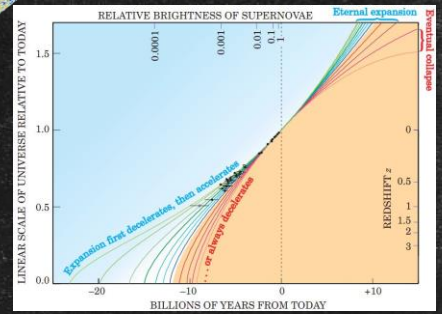
De curieuze samenstelling van ons heelal



M33 rotation curve



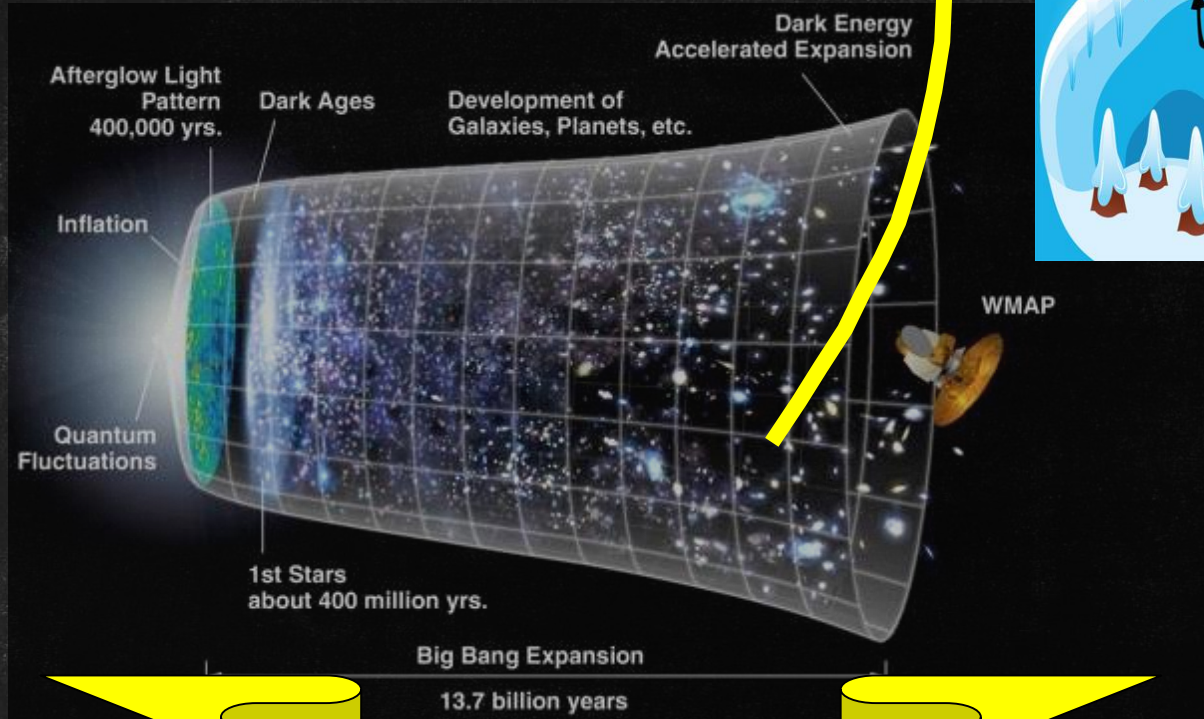
Cosmic microwave background



Versnelde uitdijing heelal

Melkwegstelsels rotatie curves

Een hele korte geschiedenis van ons heelal...

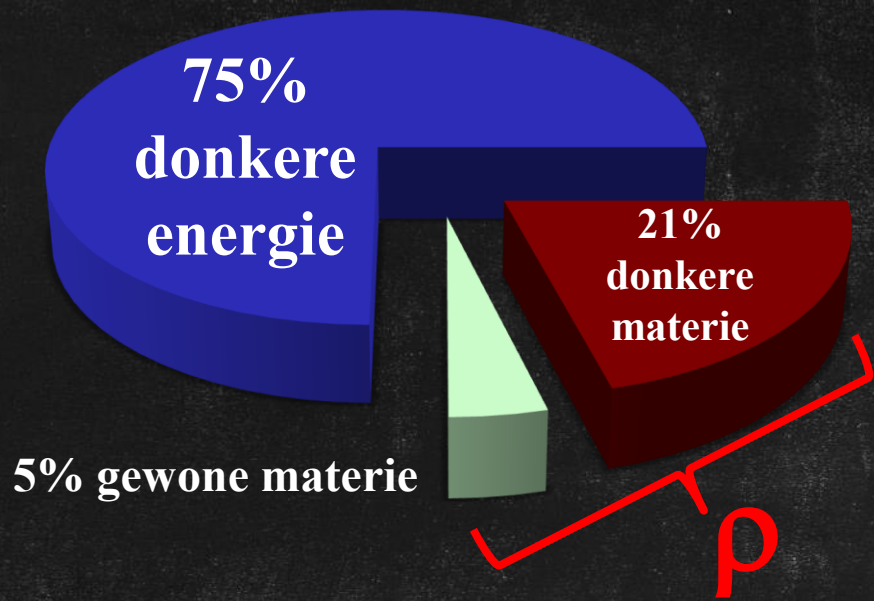


**Uitdijing door het Higgs veld
 $10^{118}x$ te snel**

De curieuze samenstelling van ons heelal



Λ ?



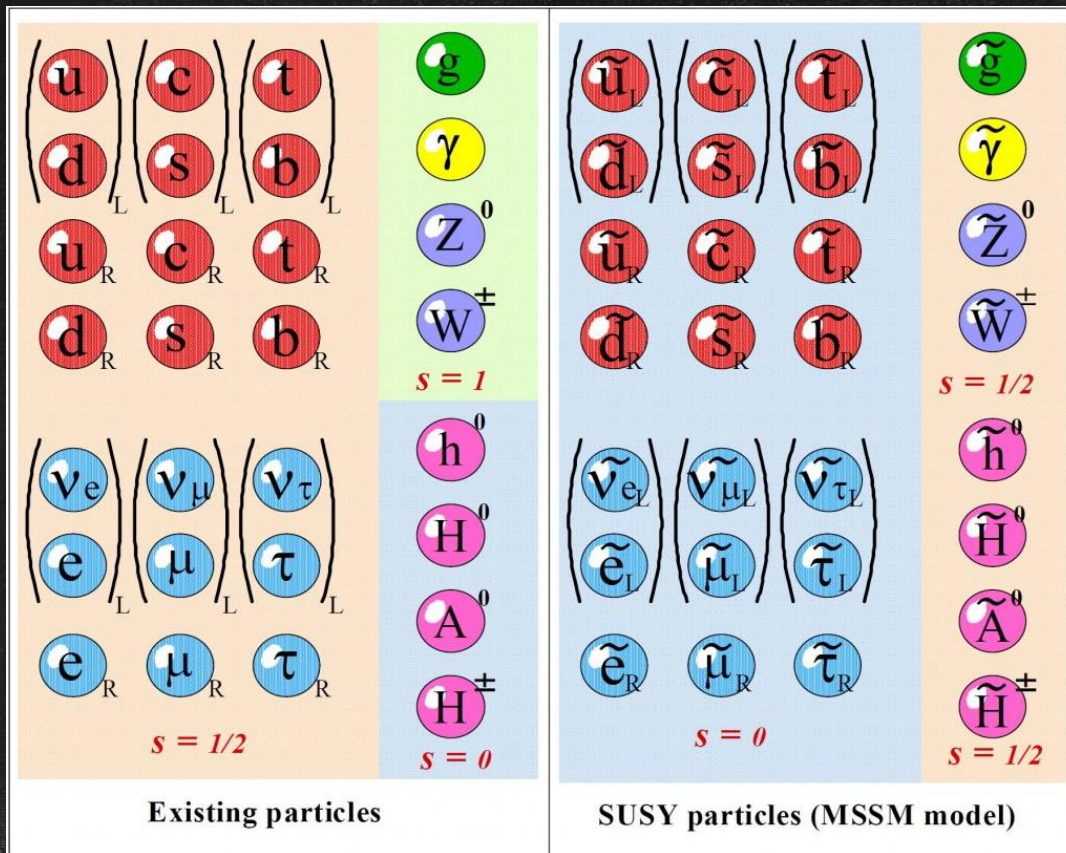
Standaard Model



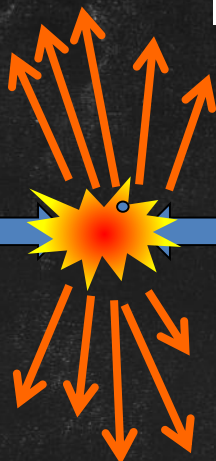
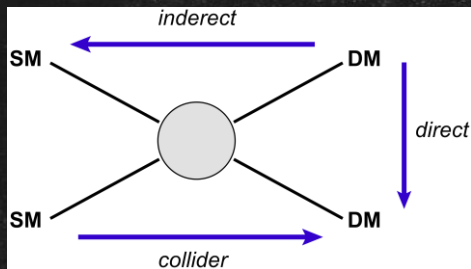
Super Model



Theorie: SuperSymmetrie

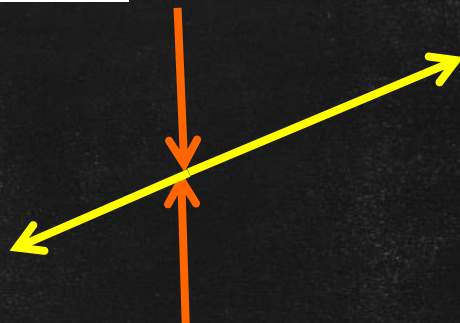


Experiment: 3 manieren om naar donkere materie te zoeken

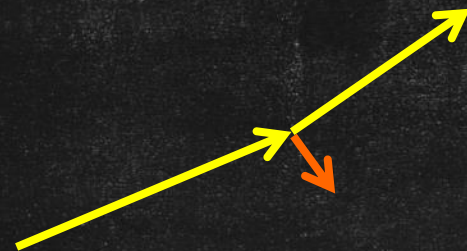


Zelf maken

LHC/FCC/...



annihilatie waarnemen



botsing met materie waarnemen

Astrodeeltjesfysica

Experiment: 3 manieren om naar donkere materie te zoeken



Zelf maken

annihilatie waarnemen

botsing met materie waarnemen

LHC/FCC/...

Astrodeeltjesfysica

Experiment: 3 manieren om naar donkere materie te zoeken



Zelf maken

annihilatie waarnemen

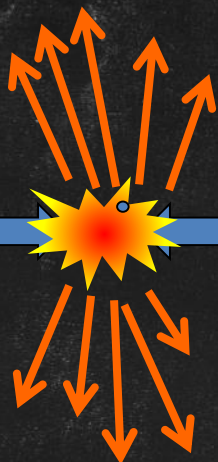
botsing met materie waarnemen

LHC/ILC/FCC/...

Astrodeeltjesfysica

Zelf maken: 2 strategieën

1. Precisiemeting, bijvoorbeeld van Higgs boson eigenschappen
2. Brute kracht: naar hoger energetische versnellers



Zelf maken

LHC/ILC/FCC/...

In beide gevallen ingewikkelde en dure versneller en experimenten nodig

Wereldsamenwerking

Vragen ?