



# De magische wereld van het allerkleinste

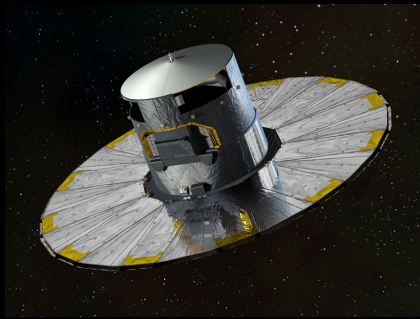
Ivo van Vulpen (UvA/Nikhef)



# De wereld van het allergrootste

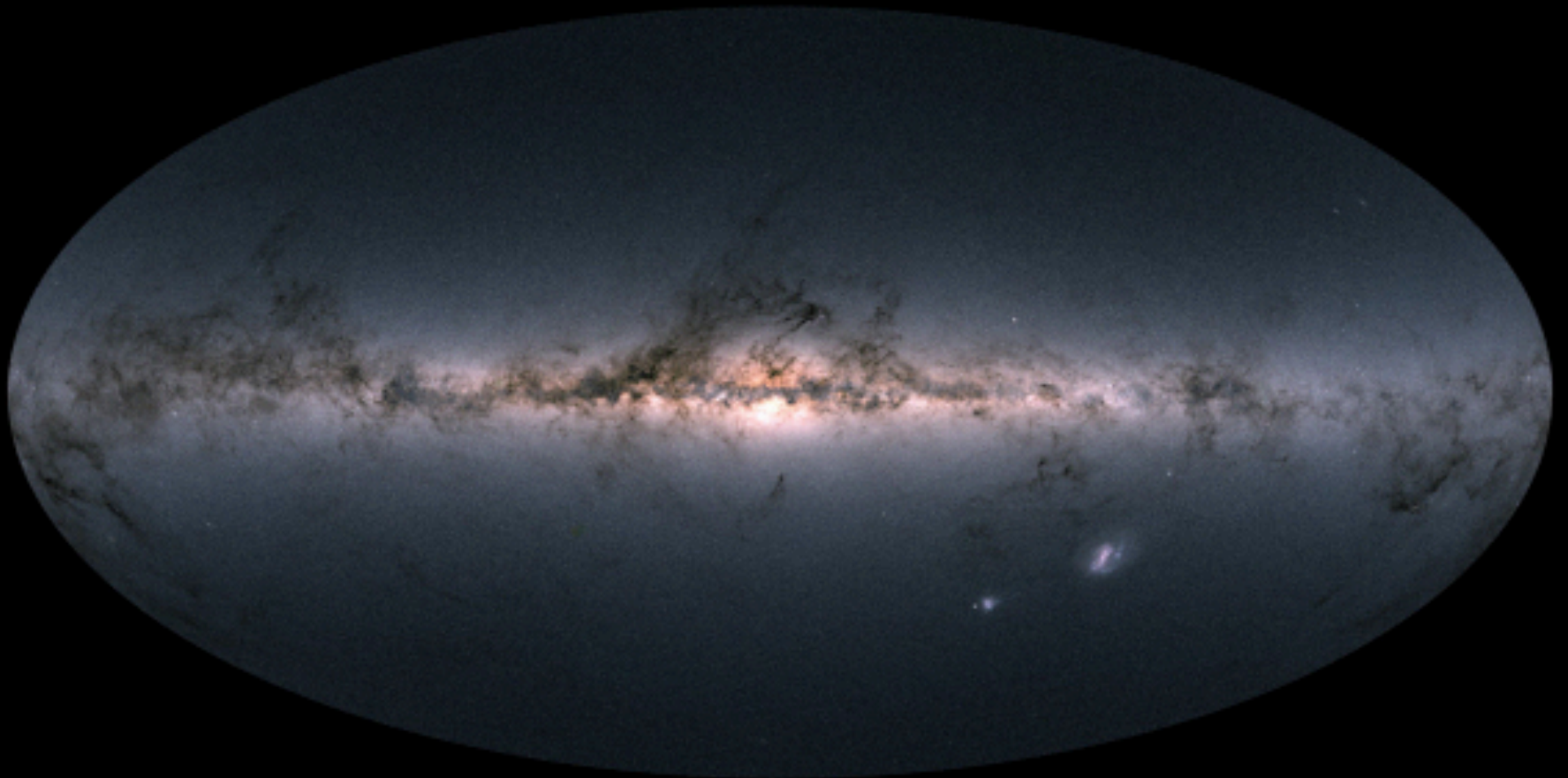







# Gaia experiment

@ESAGaia



*Gedetailleerde meting van 1,7 miljard sterren*



- 
- A night sky with the Milky Way galaxy visible, silhouetted against a dark background. A large tree is visible on the left side of the frame.
- 1) (Hoe) is de ruimte-tijd begonnen
  - 2) Hoe groot is het heelal
  - 3) Microscopische structuur ruimte-tijd
  - 4) Waarom zit er iets in
  - 5) Is er meer dan één heelal
  - 6) Donkere materie en donkere energie

**Waarom is er iets?**





$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

ALBERT EINSTEIN (1879-1955) 

toneel

acteurs

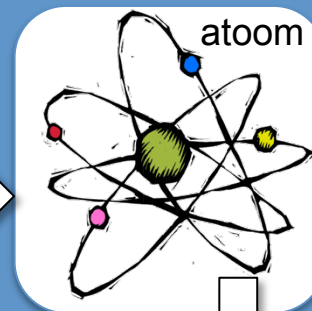
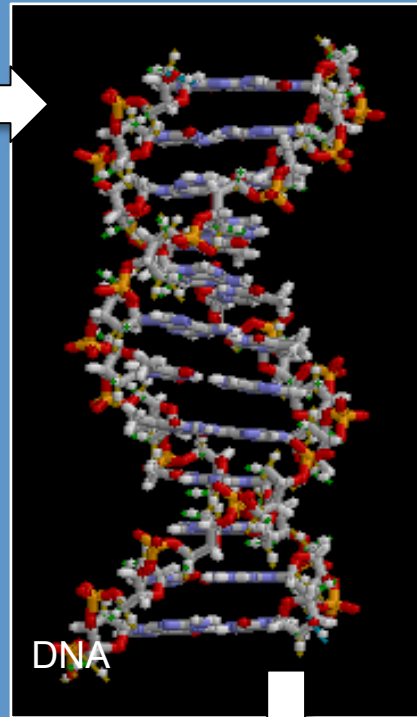
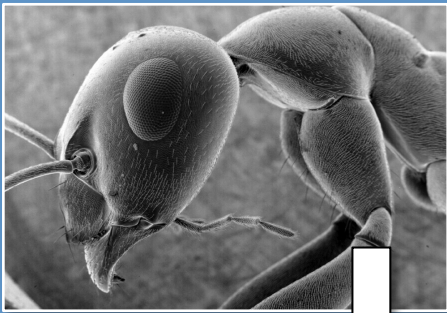


# CERN in Genève, Zwitterland





# Zoektocht naar de elementaire bouwstenen van de natuur



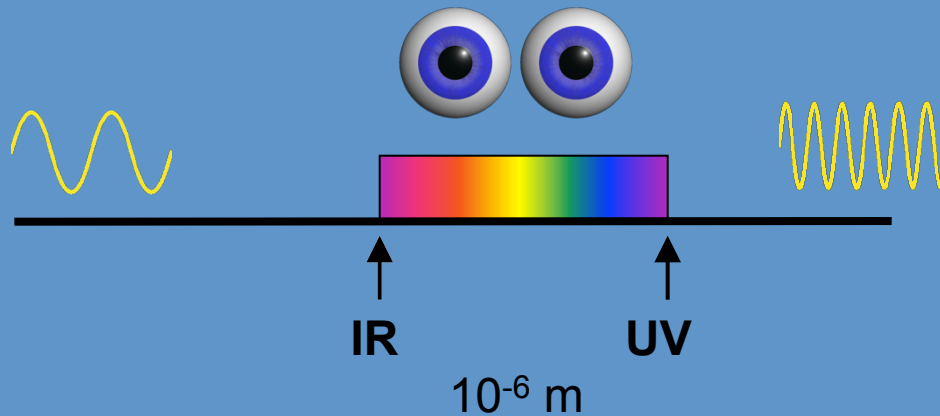
atoomkern



Hoe onderzoek je de wereld  
van het allerkleinste ?

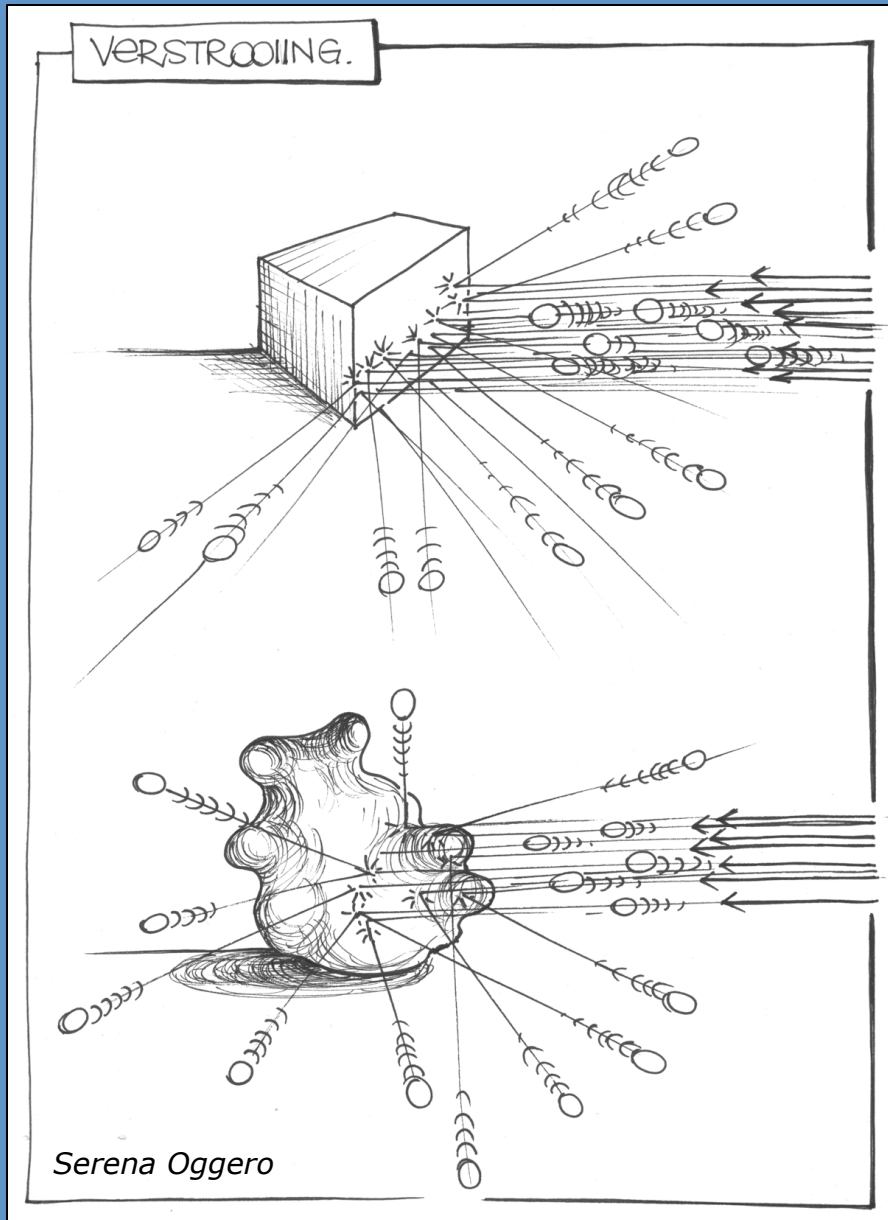


# Kijken naar de wereld om ons heen



Licht ketst alleen af van objecten die groter zijn dan zijn golflengte



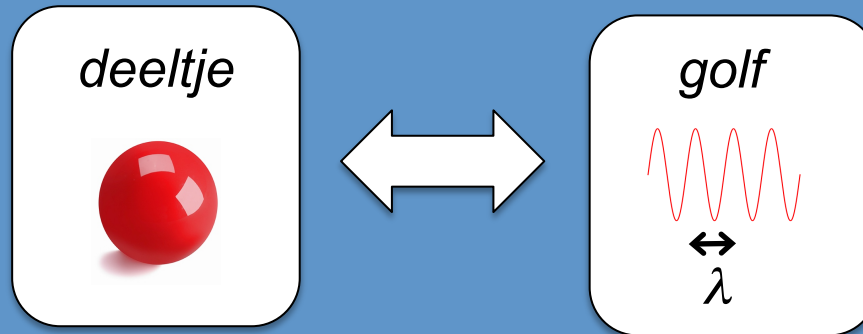


Kijken zonder je ogen  
te gebruiken

kleine projectielen afketsen



# De wereld van de quantummechanica

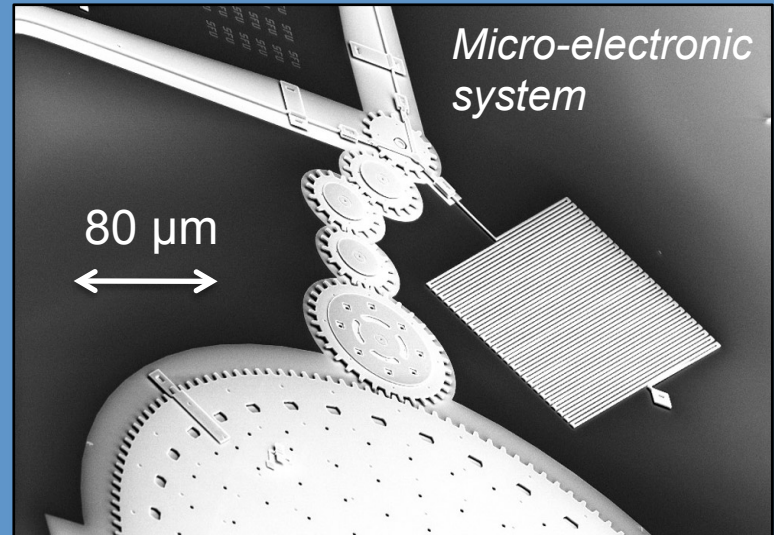
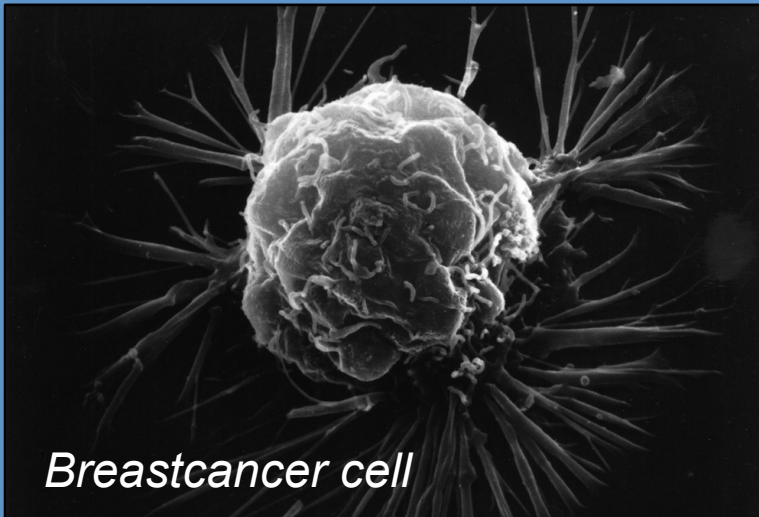
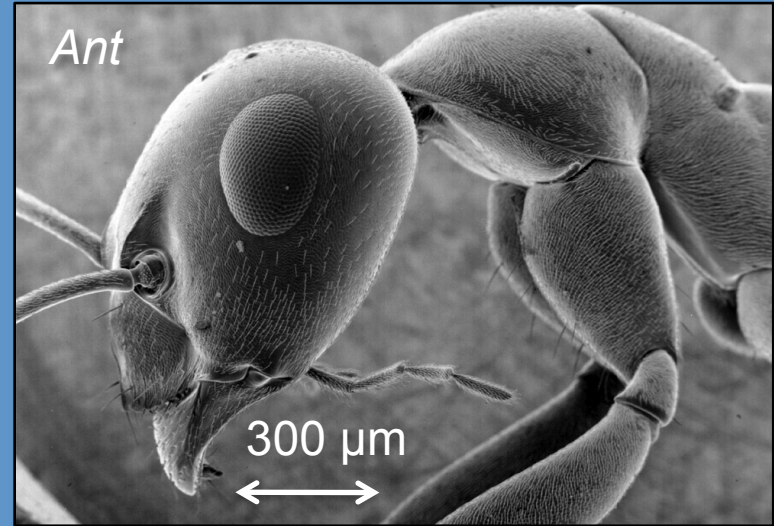
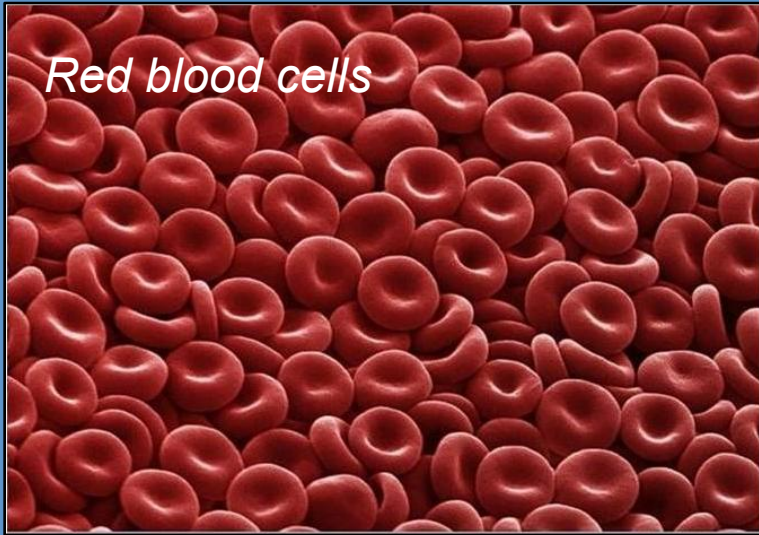


***“Hoe hoger de energie, hoe kleiner het deeltje/golfje”***

zichtbaar licht:  $10^{-7}$  [m]

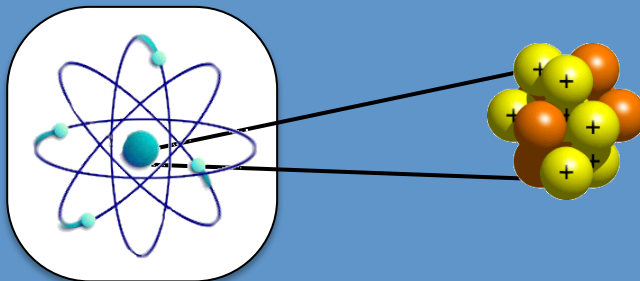
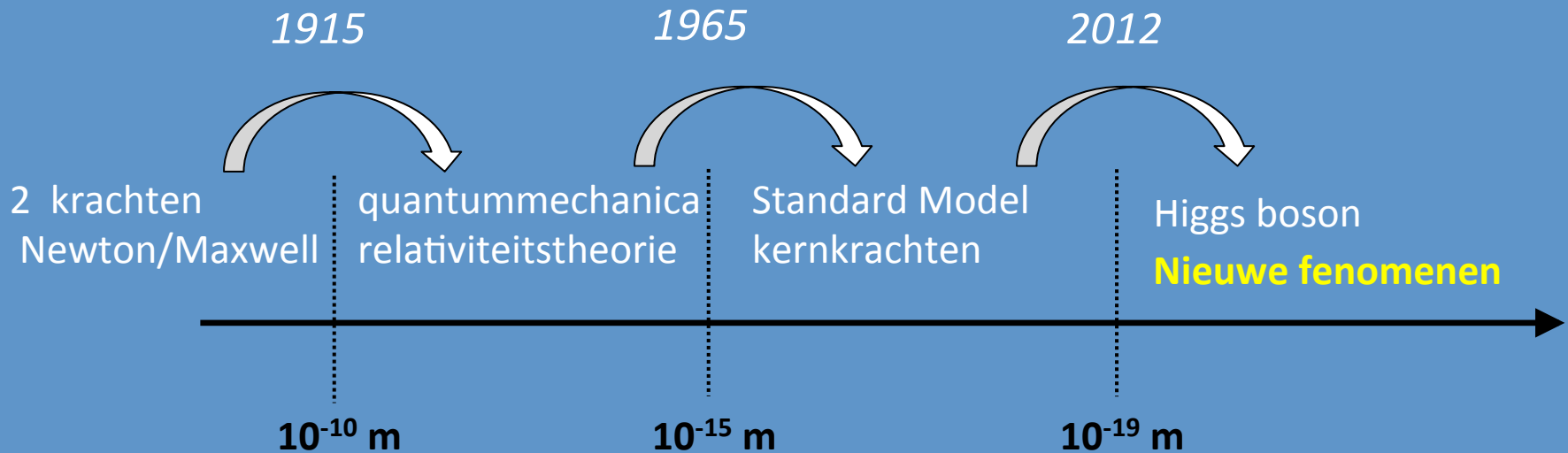
wereldrecord:  $10^{-20}$  [m]





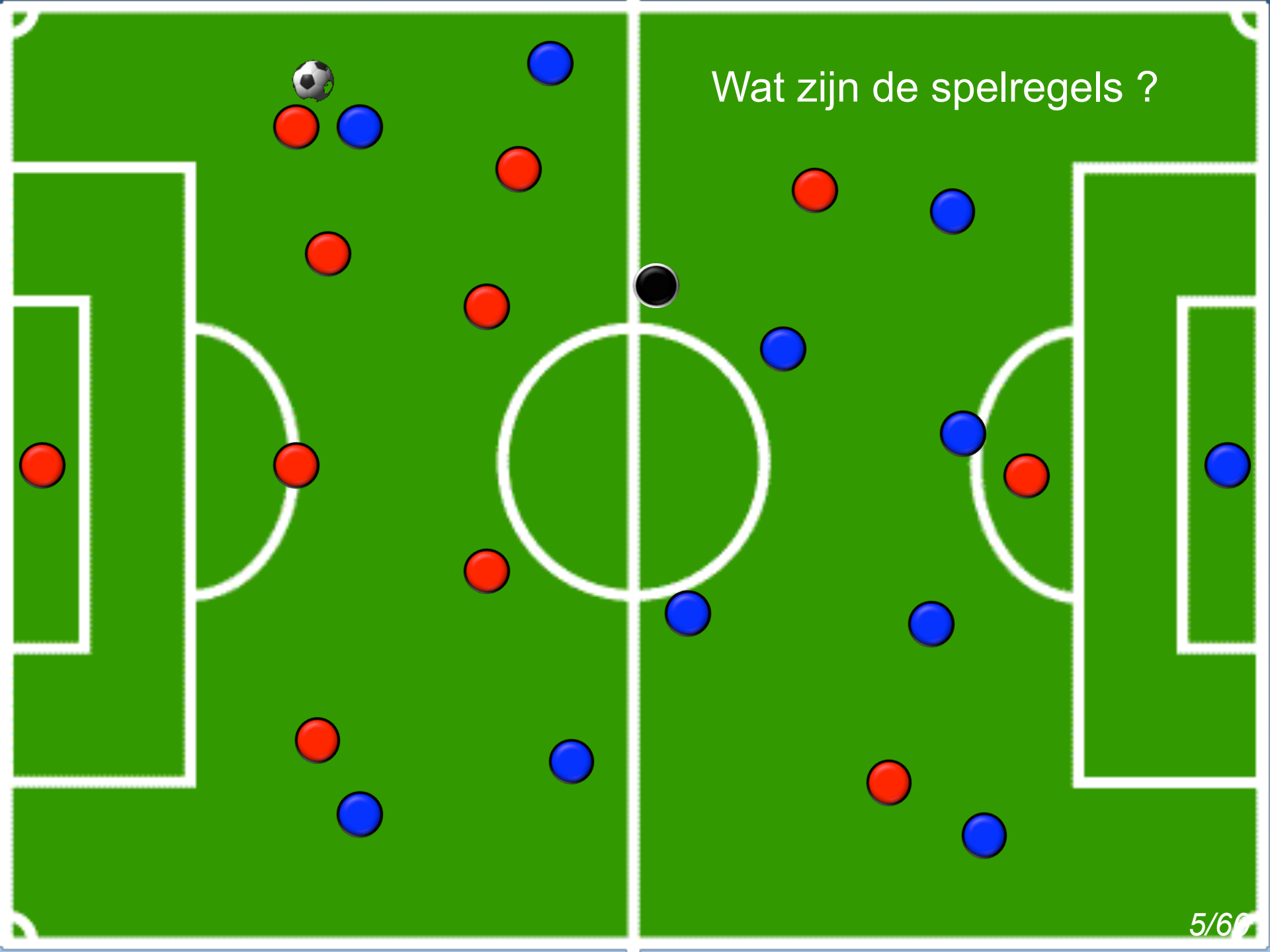


# Honderd jaar fundamentele natuurkunde



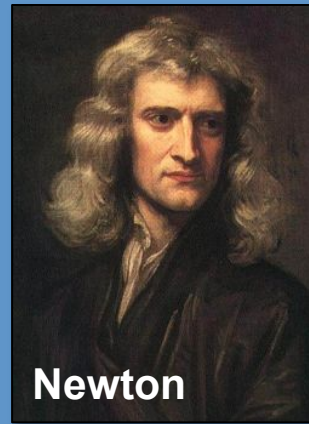
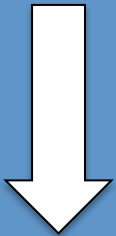


Wat zijn de spelregels ?





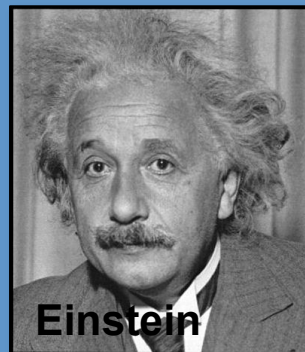
Waarom valt een appel naar beneden ?



massa's trekken elkaar aan

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

*Maar waarom trekken twee massa's elkaar dan aan ?*



ruimte-tijd is gekromd

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G_N}{c^4} T_{\mu\nu}$$



Deeltjes bewegen gewoon 'rechtdoor'

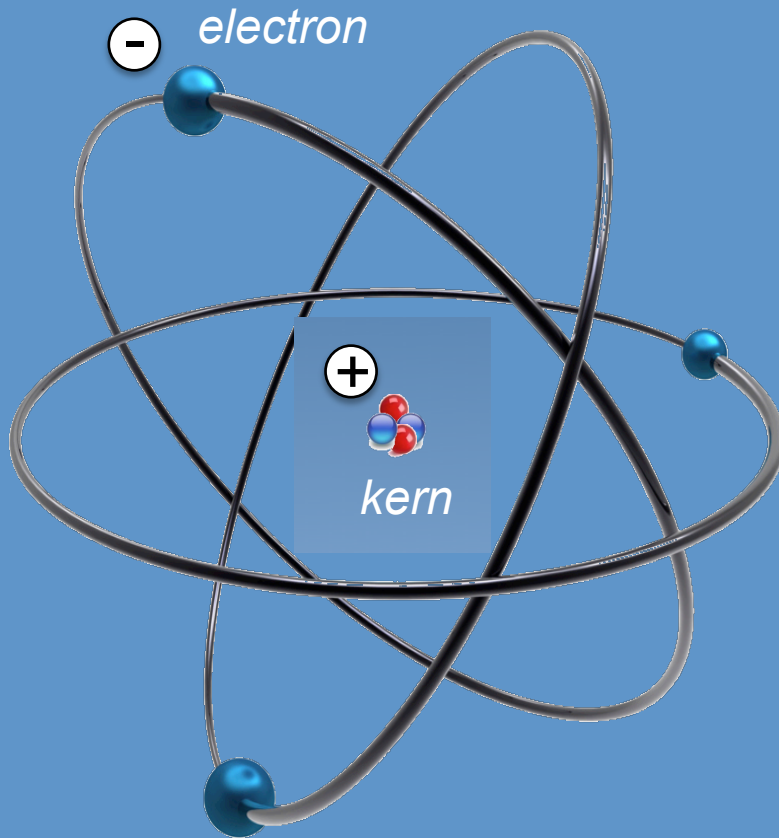


De ruimte zelf is echter niet 'recht'



De wereld van het atoom

# Schatgraven in de atoomwereld



- 1) *elektron vallen niet op de kern!*  
→ **wet: quantummechanica**
- 2) *kerndeeltjes kleven aan elkaar!*  
→ **kracht: kernkrachten**
- 3) *maar 2 elektronen in 1<sup>e</sup> baan!*  
→ **eigenschap: spin**

$$\Psi_{nlm}(r, \theta, \varphi) = R_{nl}(r) Y_l^m(\theta, \varphi) \chi_{s, s_z}$$



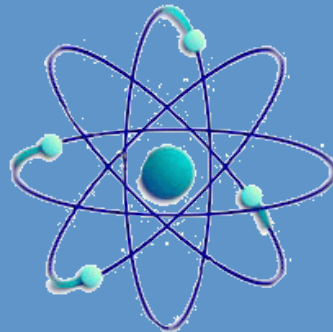
# Quantummechanica

Deeltjes zijn op meerdere plekken tegelijk !

*Quantum-computer*

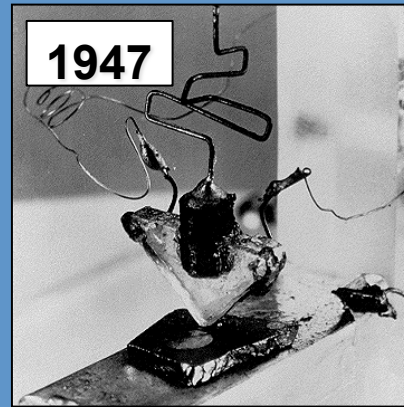


Leo Kouwenhoven



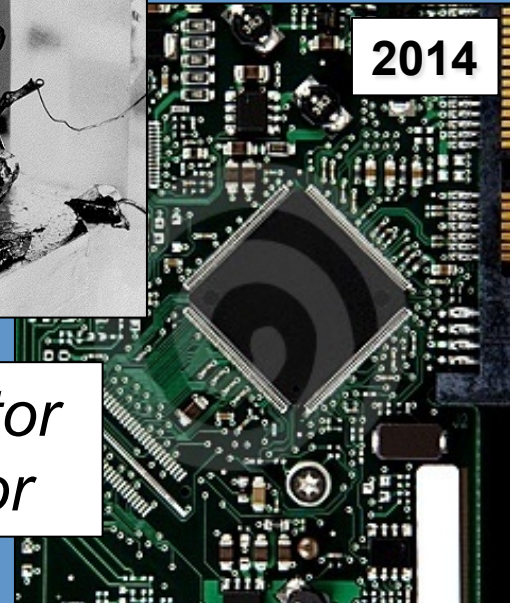
*atoom*

1947



*Transistor  
& sensor*

2014



Maar *waarom* zijn dingen nou gequantiseerd ?



Ivo van Vulpen @IvovanVulpen · Oct 5

Wow!!! Quantum mag weer (en kwantum ook @sensemolen). Ge-wel-dig. Handjes op elkaar voor de @taalunie. @onzetaal @maresep @michelvanbaal

taal:  
unie

Taalunie @taalunie · 3m

@onzetaal @IvovanVulpen @maresep @michelvanbaal Conclusie: in de volgende release van [woordenlijst.org](http://woordenlijst.org) zullen alle vormen >>



taal:  
unie

Taalunie @taalunie · 50s

View translation

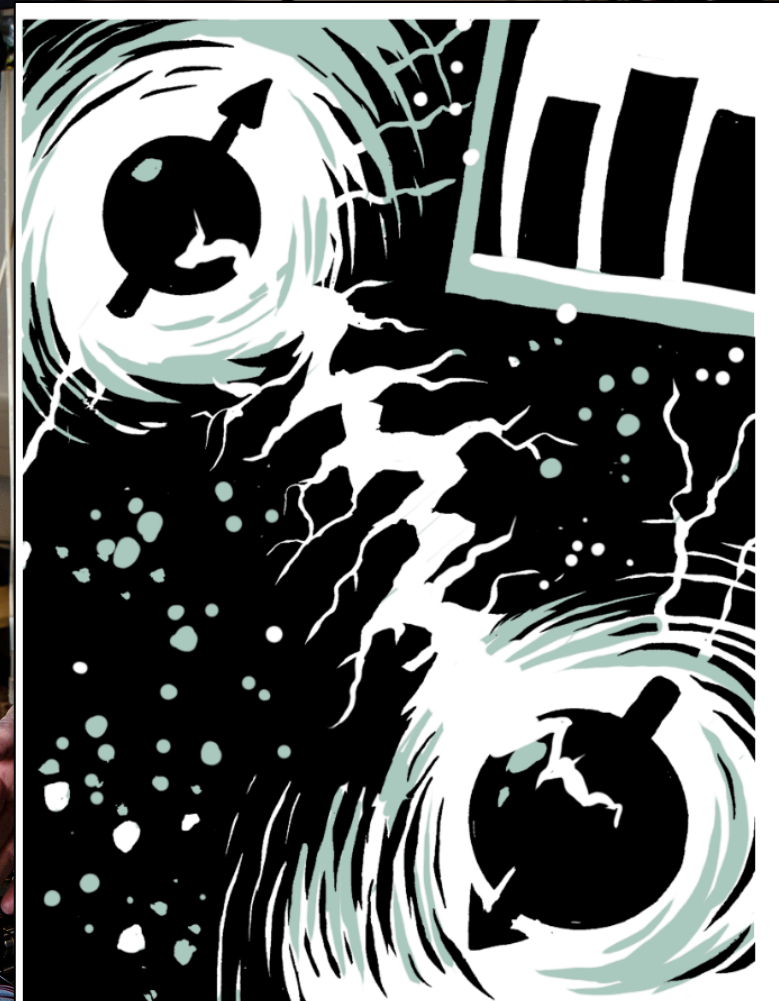
@onzetaal @IvovanVulpen @maresep @michelvanbaal met 'kwantum'/'quantum' dubbel opgenomen zijn. Motivatie: de twee vormen komen in >>



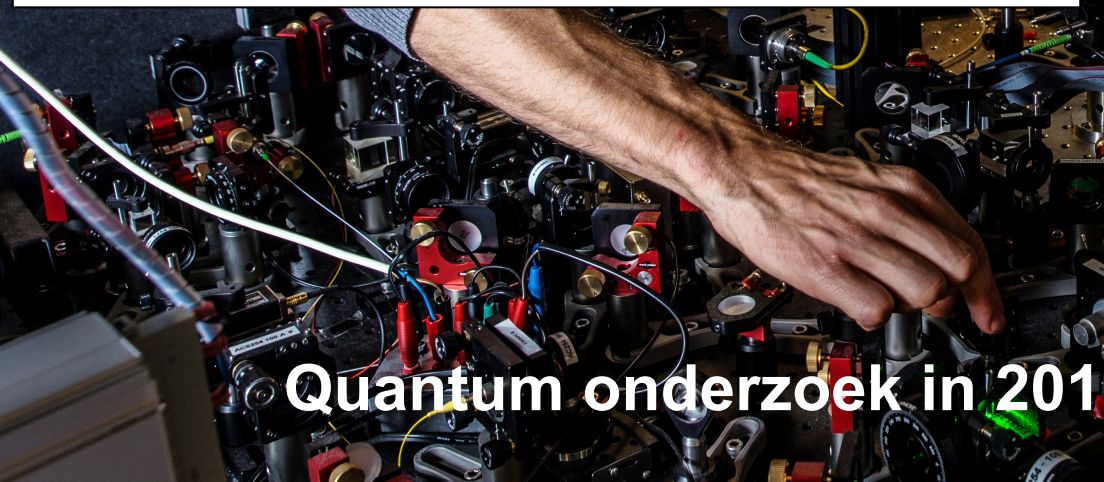
taal:  
unie

Taalunie @taalunie · 18s

@onzetaal @IvovanVulpen @maresep @michelvanbaal de praktijk veel naast elkaar voor.

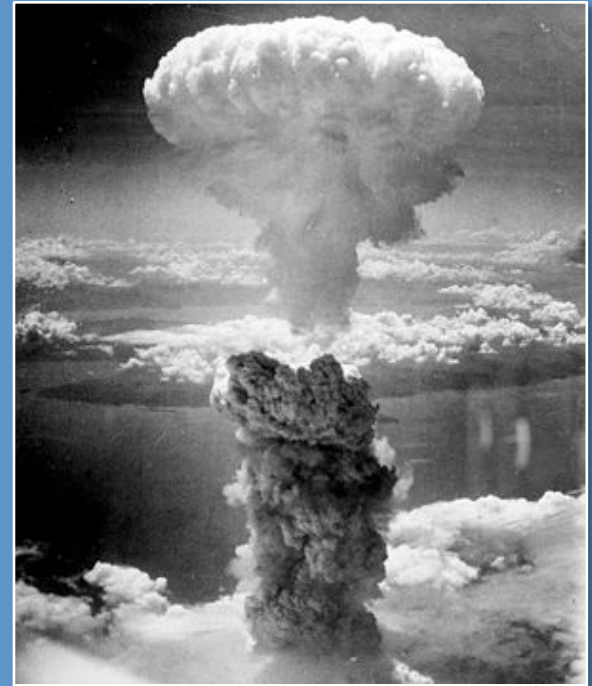


HALF JULI IS HET ZOVER. NA DRIE WEKEN METEN STAAT VAST DAT DE QUANTUMDEELTJES ELKAAR OP KILOMETERS AFSTAND VOELEN, SNELLER DAN HET LICHT.

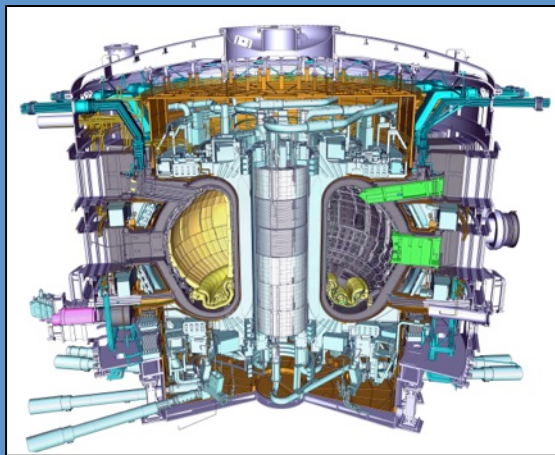


Quantum onderzoek in 2018





Kernkrachten



ITER (fusieractor)



# Het Standaard Model

*Drie families van deeltjes en drie quantum krachten*



# De (drie) elementaire deeltjes



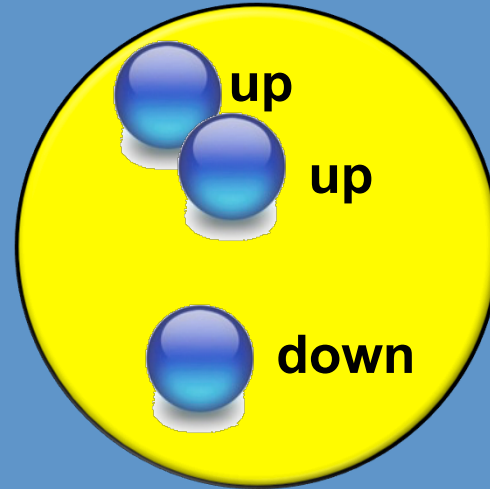
up



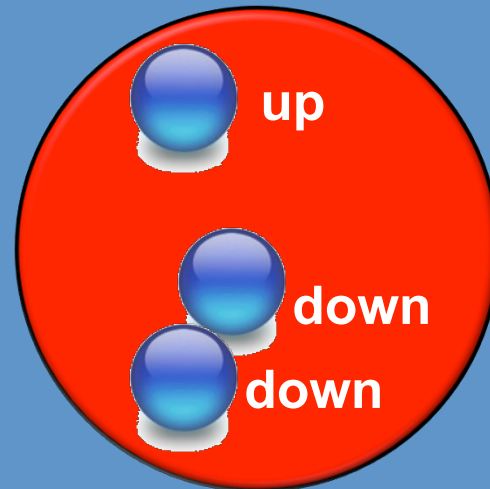
down



elektron















*Proton*



*Neutron*

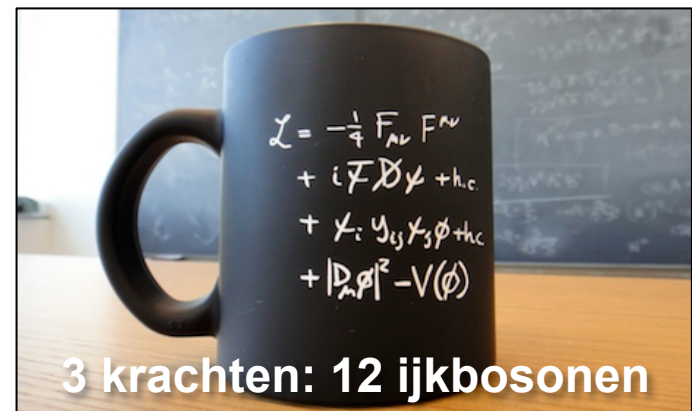
# Het Standaard Model

## Elementaire deeltjes

up-quark			
down-quark			
elektron			
neutrino			

muon

## Interacties





# Er is meer tussen hemel en aarde

antenne

*“Er zweven electromagnetische golven in deze zaal die stemmen en beelden bevatten”*

radio



# Er is meer tussen hemel en aarde



*“Er schieten exotische deeltjes door de Beurs van Berlage die 0.000002 seconde leven”*

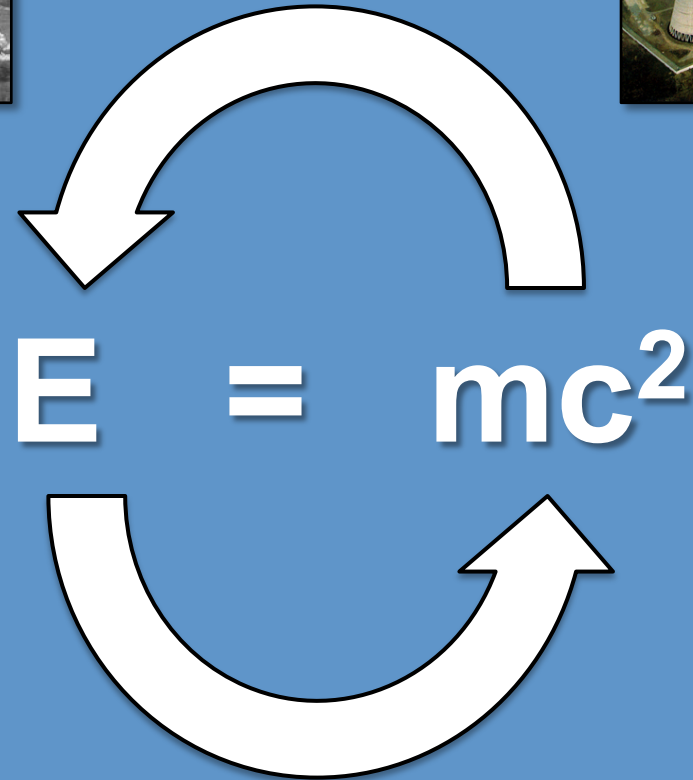
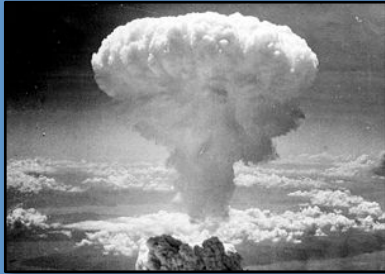
*“Ze worden gemaakt als kosmische stralen op luchtmoleculen botsen in de atmosfeer”*

muon detector op Nikhef



# Deeltjesversnellers

*zelf deeltjes maken*

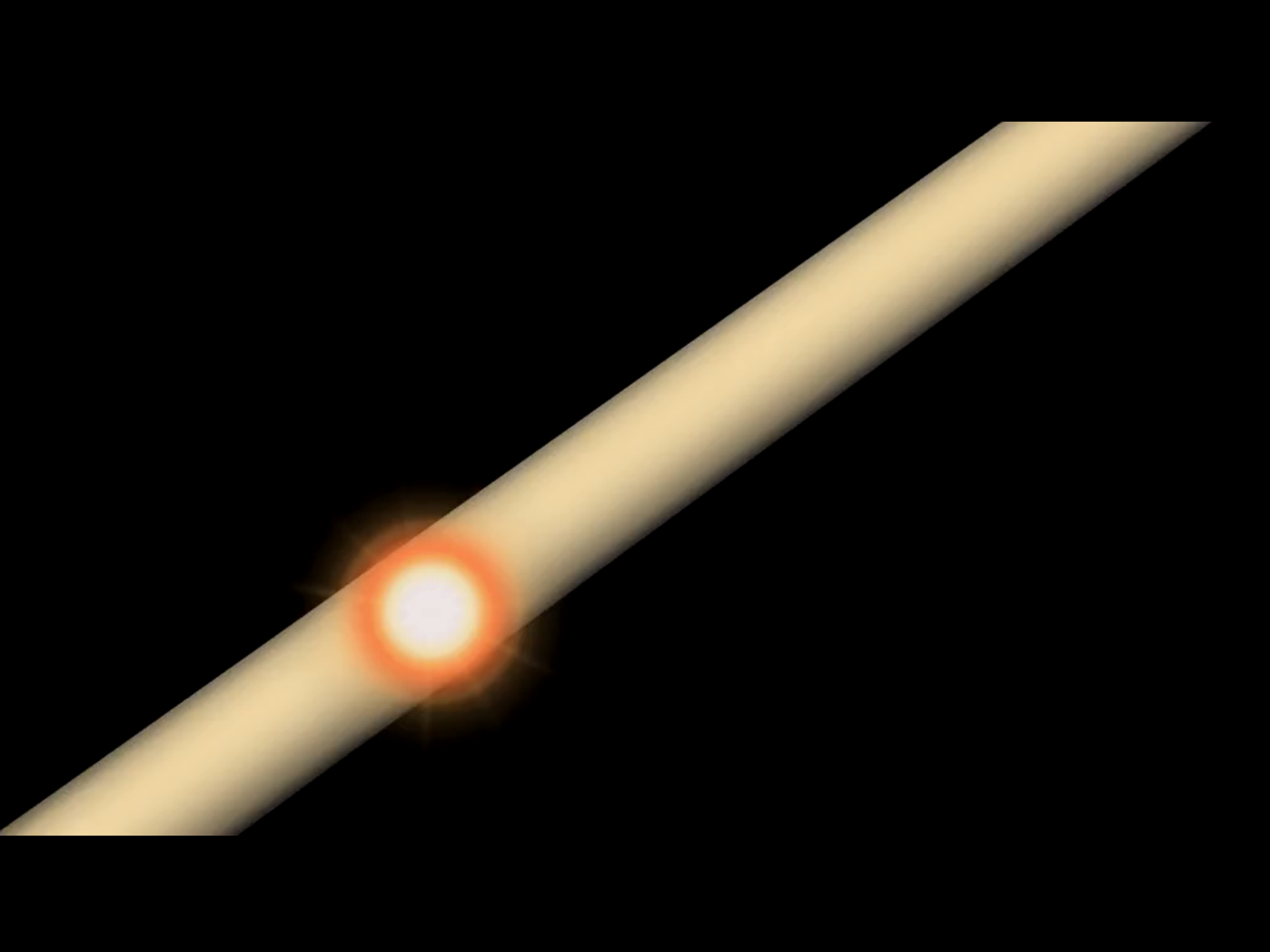




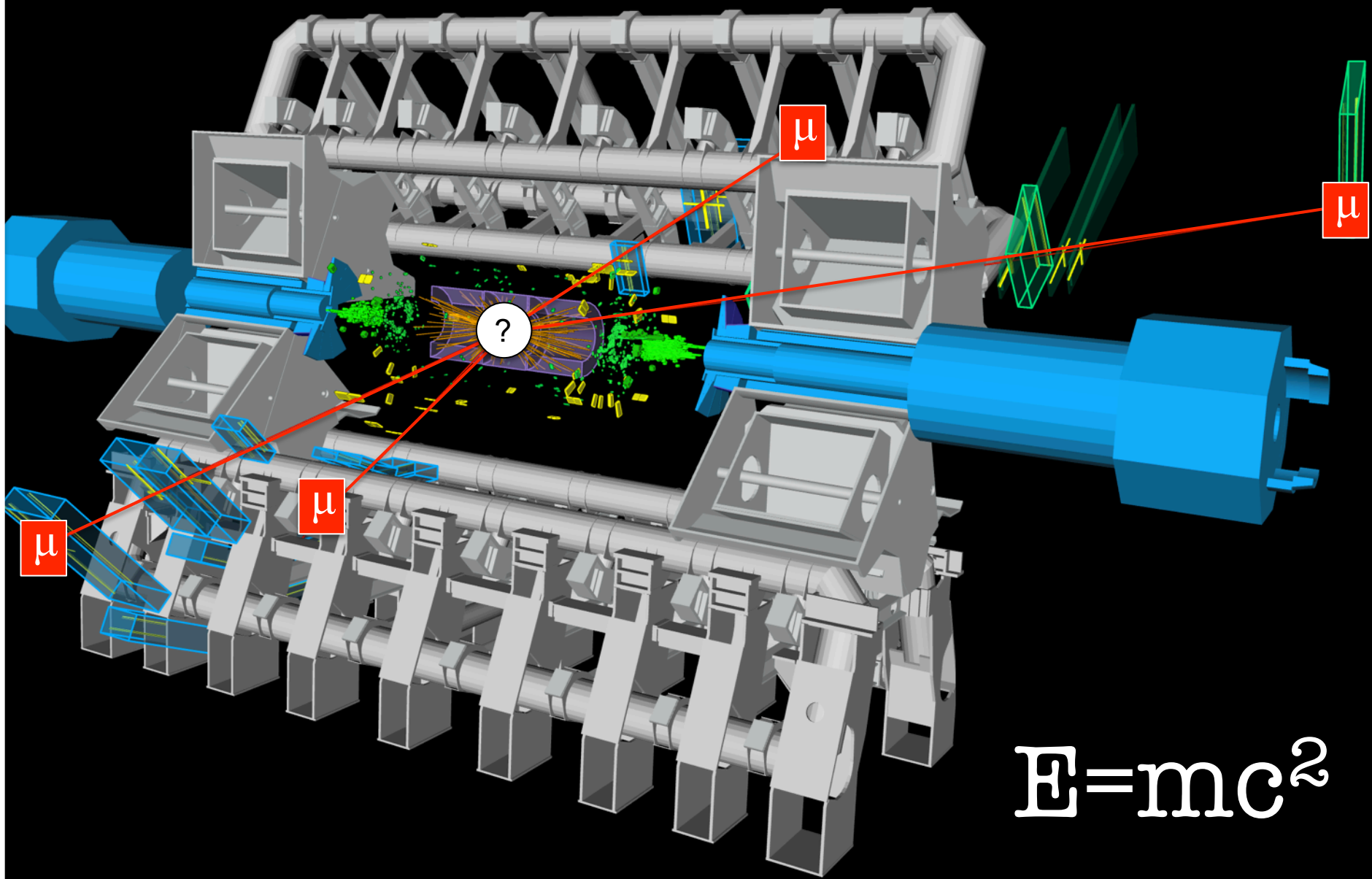
An aerial photograph of the Geneva region in Switzerland. In the background, there are snow-capped mountains and a large lake. The foreground shows a patchwork of green fields and some buildings. A red oval is drawn around the central part of the image, highlighting the location of the Large Hadron Collider (LHC) tunnel. The text 'Nieuwe deeltjes maken' is overlaid in white on this oval.

# Nieuwe deeltjes maken

De Large Hadron Collider (LHC)  
op CERN bij Genève





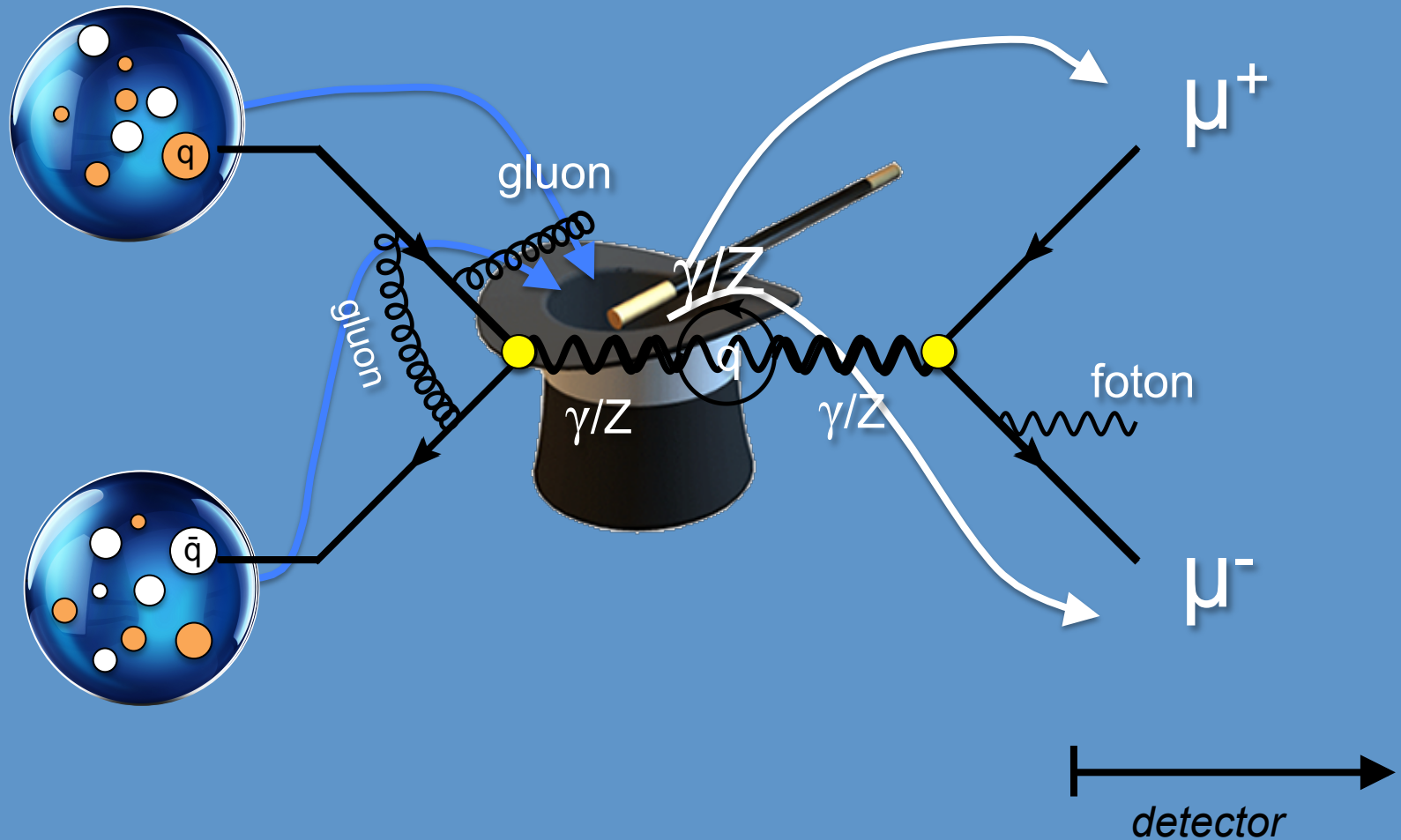


$$E=mc^2$$

# Iets reconstrueren uit overblijfselen

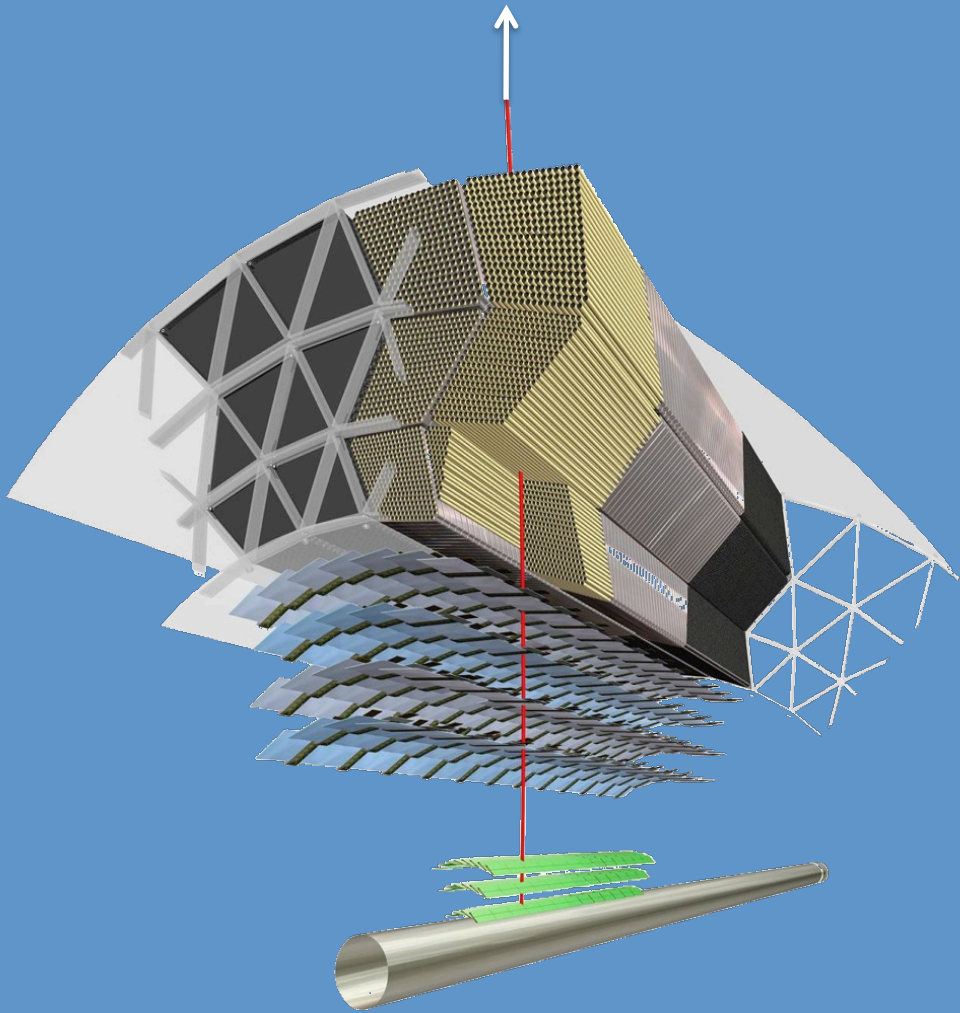


# Overgangen in het Standaard Model





*muon of electron ?*



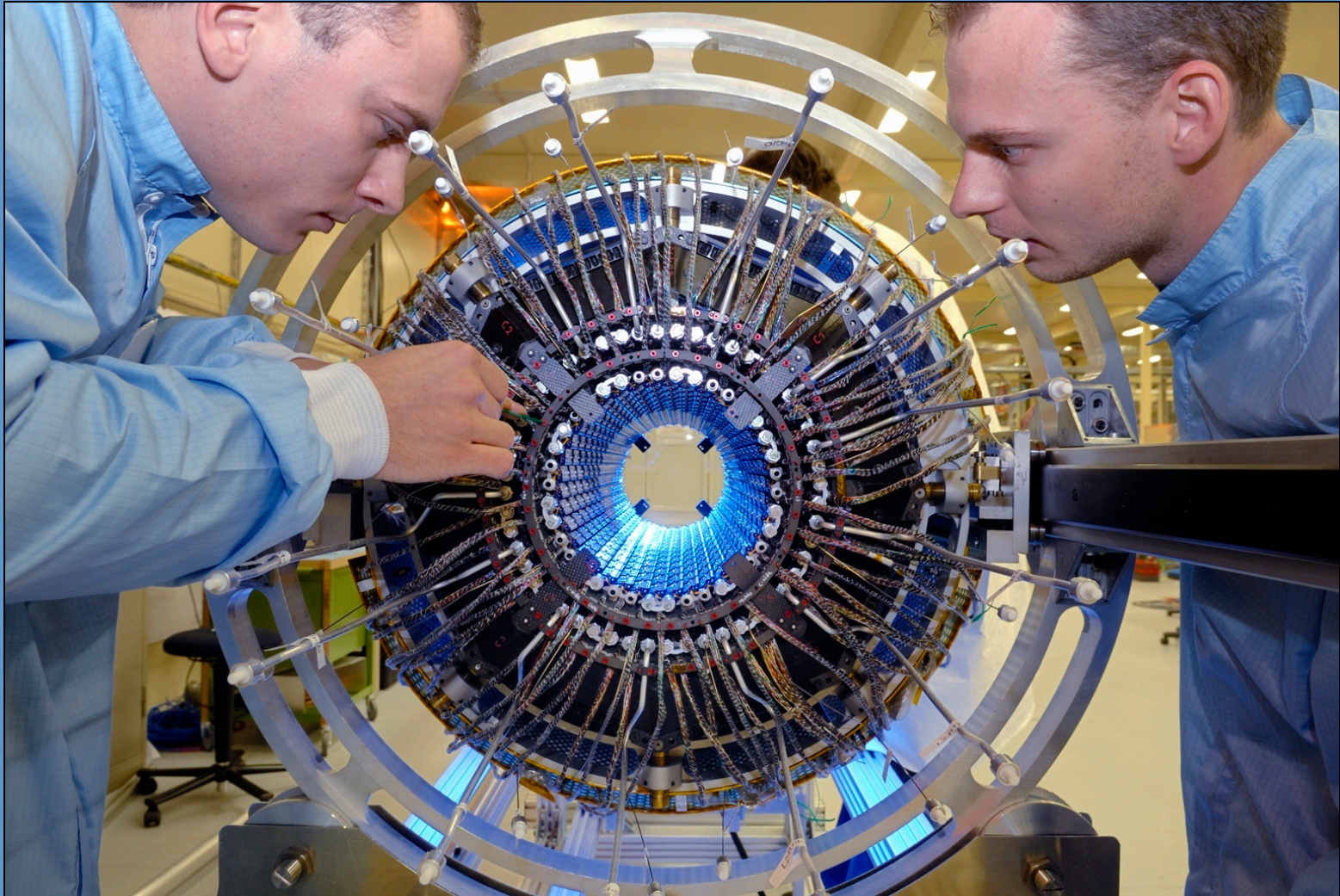
**Identificatie**

*konijn of mens ?*





# The Atlas pixel detector



80 MegaPixel camera

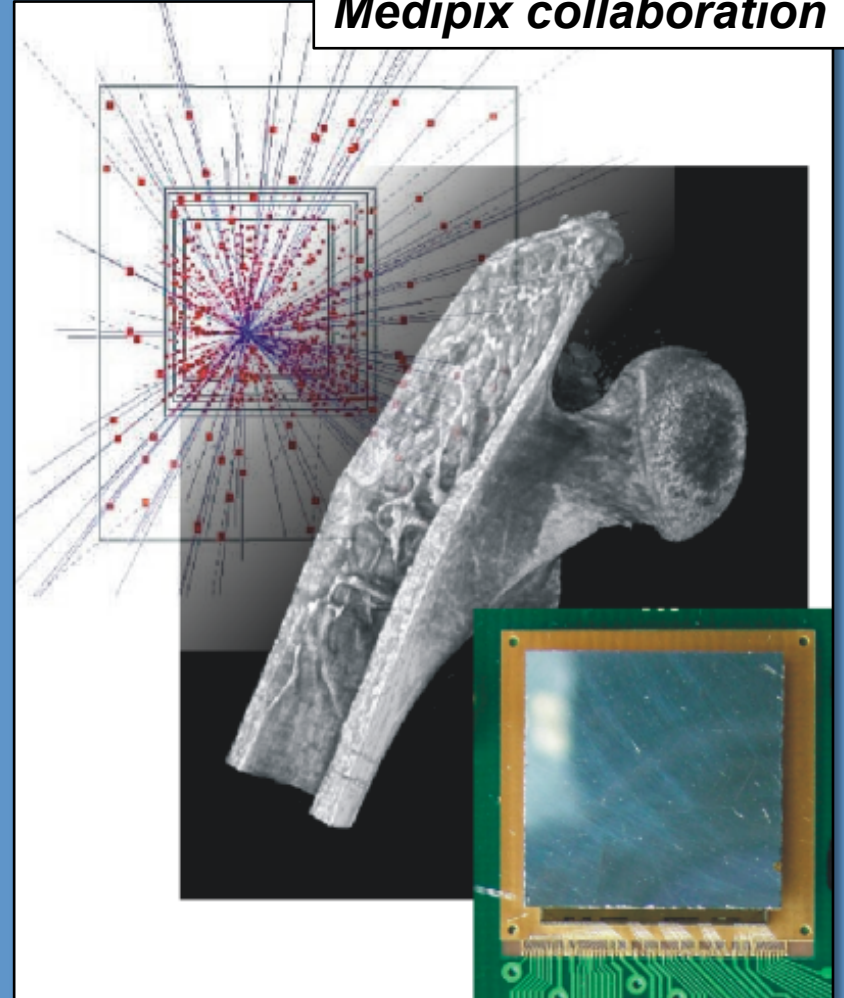
1.000.000.000 pictures per second

# Deeltjes(versnellers) in het ziekenhuis

**Röntgen**

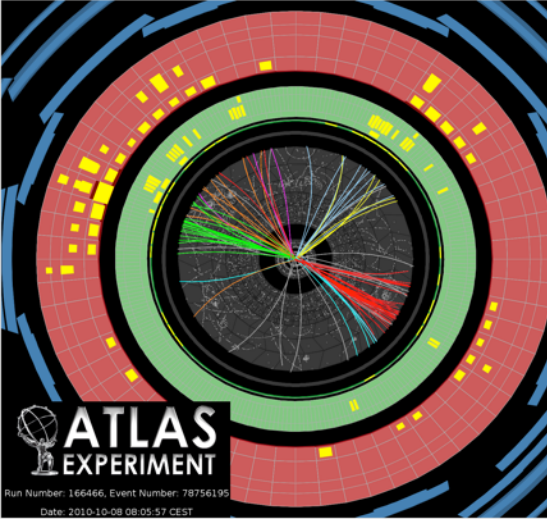


**Medipix collaboration**

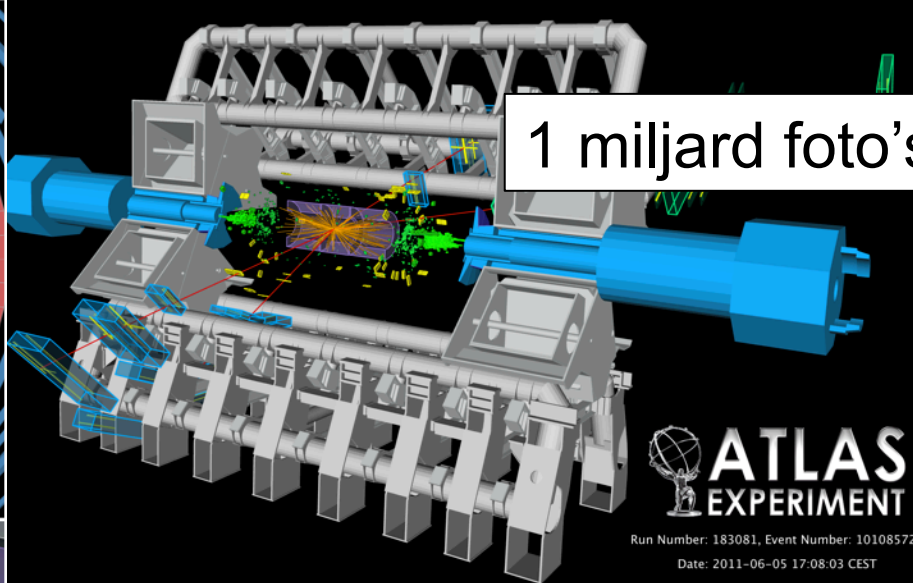




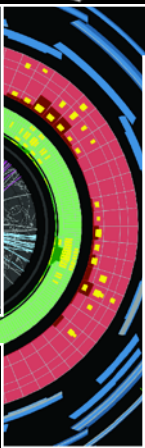
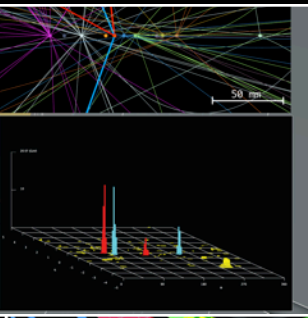
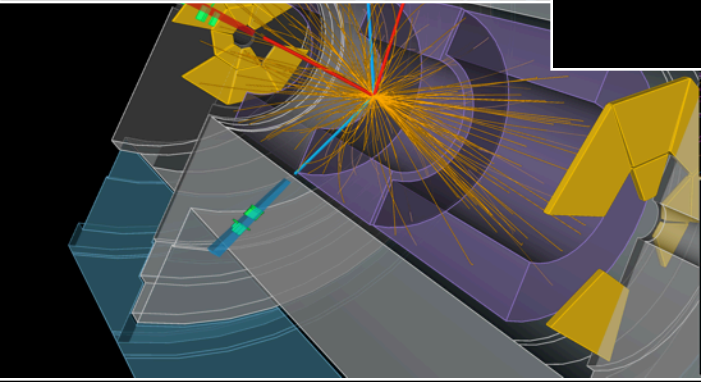
1 miljard foto's per seconde



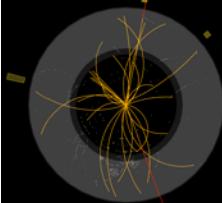
**ATLAS EXPERIMENT**  
Run Number: 166466, Event Number: 78756195  
Date: 2010-10-08 08:05:57 CEST



**ATLAS EXPERIMENT**  
Run Number: 183081, Event Number: 10108572  
Date: 2011-06-05 17:08:03 CEST

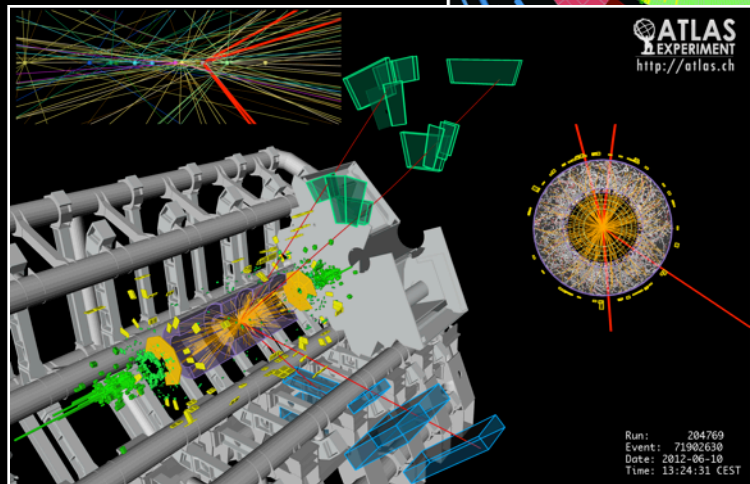
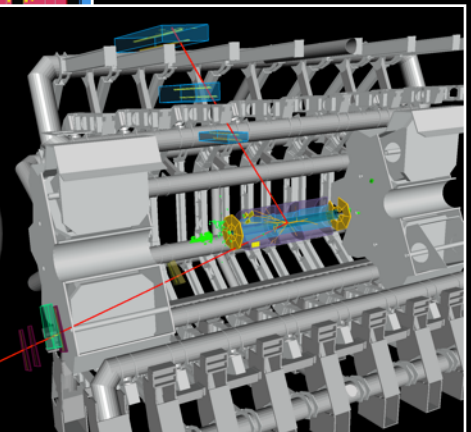


**ATLAS EXPERIMENT**  
Run: 154822, Event: 14321500  
Date: 2010-05-10 02:07:22 CEST



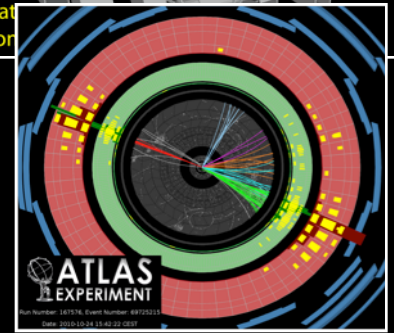
$p_{T}(\mu^+) = 27 \text{ GeV}$   $\eta(\mu^+) = 0.7$   
 $p_{T}(\mu^-) = 45 \text{ GeV}$   $\eta(\mu^-) = 2.2$   
 $M_{\mu\mu} = 87 \text{ GeV}$

Z → μμ candidate  
in 7 TeV collision



**ATLAS EXPERIMENT**  
<http://atlas.ch>

Run: 204769  
Event: 71902630  
Date: 2012-06-10  
Time: 13:24:31 CEST



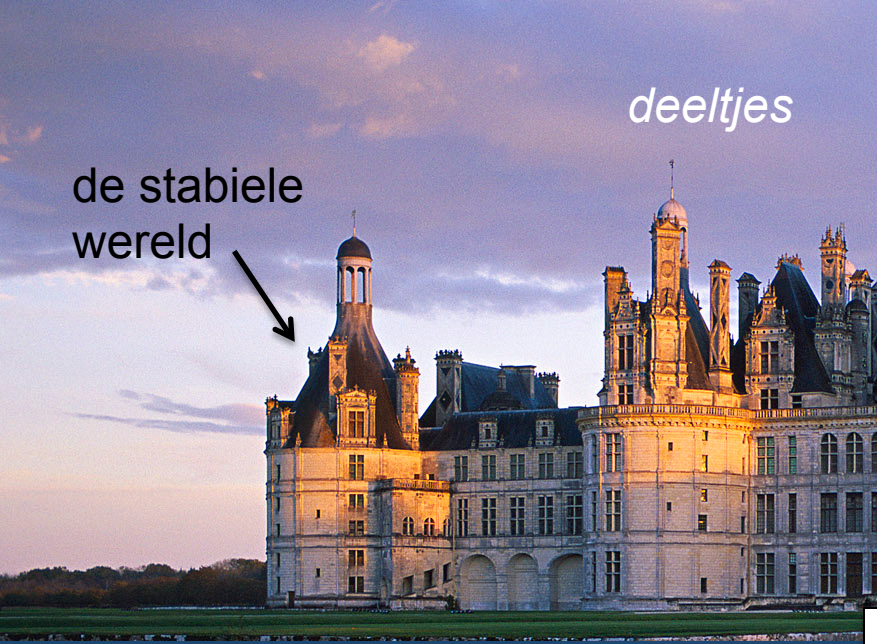
**ATLAS EXPERIMENT**  
Run Number: 181736, Event Number: 69720113  
Date: 2010-10-24 15:42:21 CEST

Higgs boson



*deeltjes*

de stabiele  
wereld

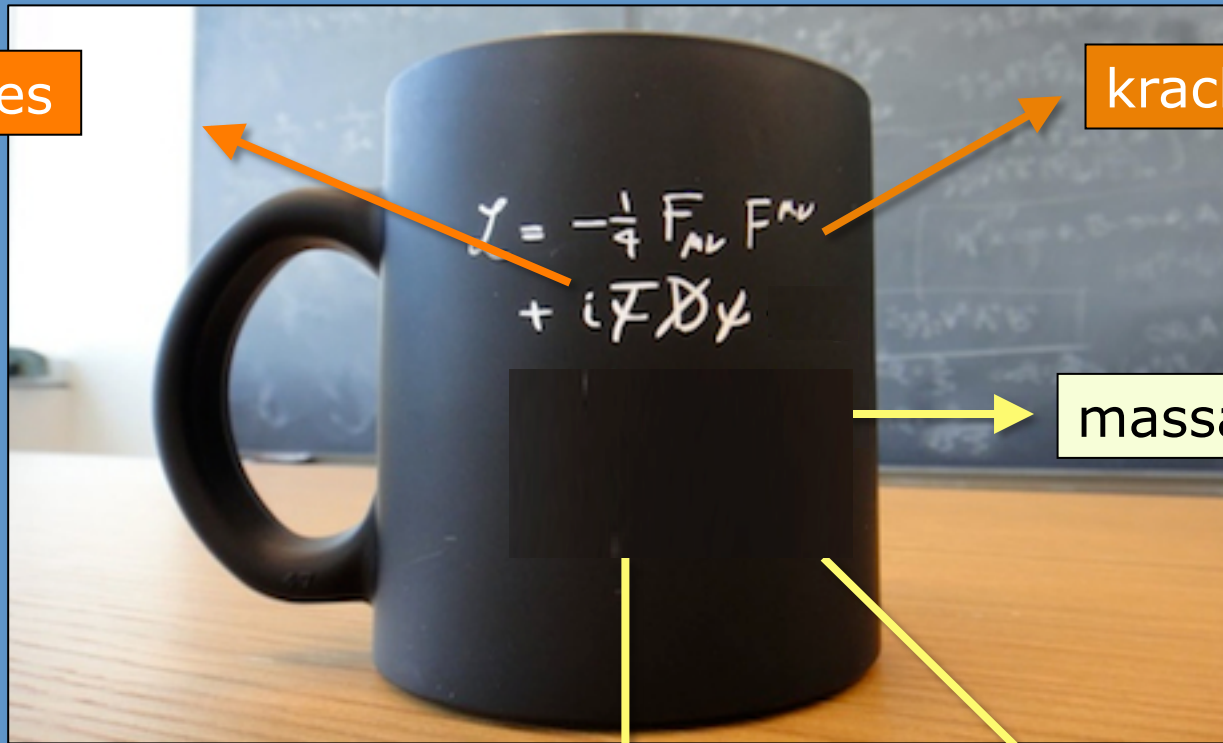


*Het Standaard Mod*





# Structuur Standaard Model



interacties

krachtdeeltjes

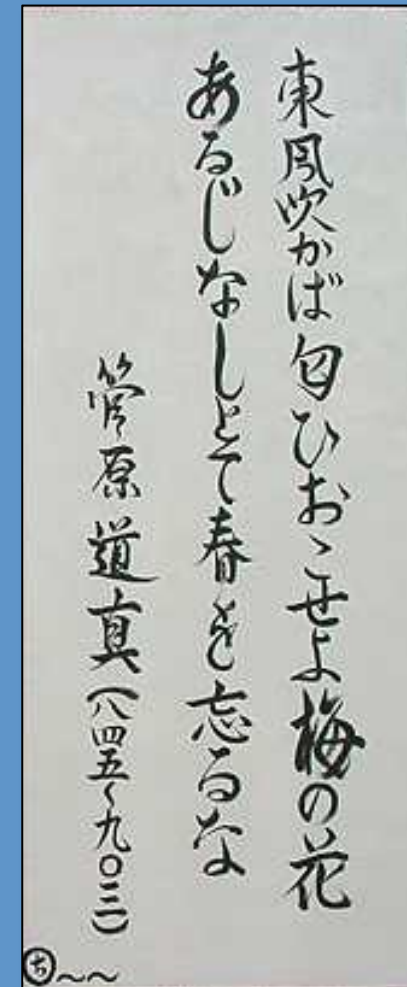
massa fermionen

massa krachtdeeltjes

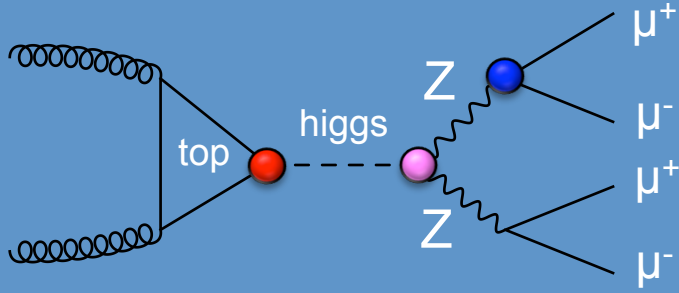
Higgs boson



# Nieuwe taal ... nieuwe inzichten ?



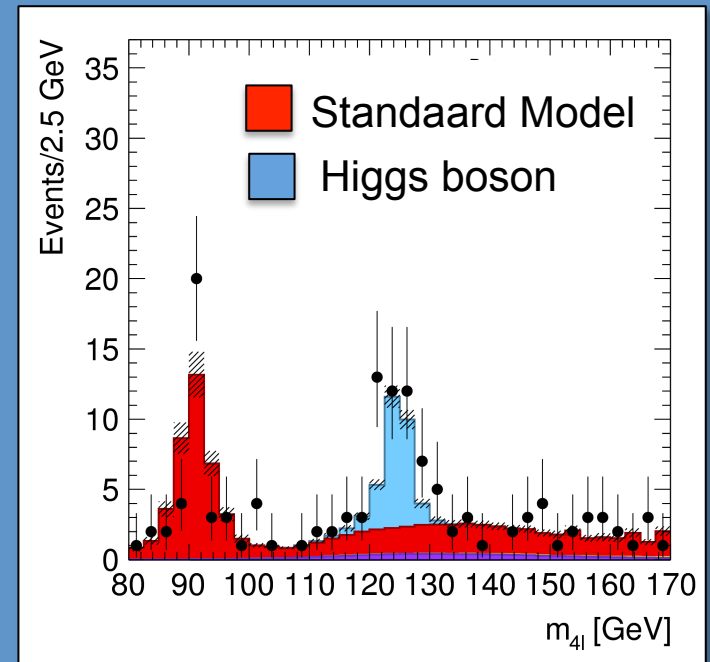
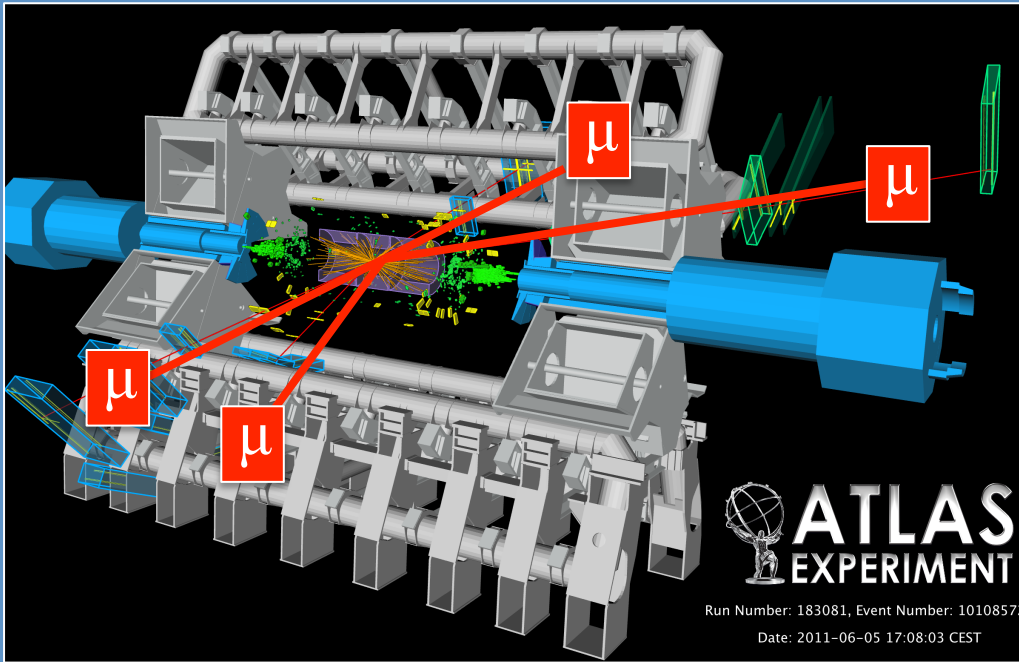
# Higgs boson



## Standard Model Lagrangiaan

$$\begin{aligned}
 \mathcal{L}_{\text{SM}} = & -\frac{1}{2}(\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+)(\partial^\mu W^{-\nu} - \partial^\nu W^{\mu-}) - \frac{1}{4}(\partial_\mu Z_\nu - \partial_\nu Z_\mu)^2 - \frac{1}{4}(\partial_\mu A_\nu - \partial_\nu A_\mu)^2 \\
 & - \frac{1}{4}(\partial_\mu G_\nu^a - \partial_\nu G_\mu^a)^2 + i\frac{g^2}{\sqrt{g^2 + g'^2}}(g^{\alpha\gamma}g^{\beta\delta} - g^{\alpha\delta}g^{\beta\gamma})(W_\gamma^- Z_\delta \partial_\alpha W_\beta^+ + Z_\gamma W_\delta^+ \partial_\alpha W_\beta^- \\
 & + W_\gamma^+ W_\delta^- \partial_\alpha Z_\beta) + i\frac{gg'}{\sqrt{g^2 + g'^2}}(g^{\alpha\gamma}g^{\beta\delta} - g^{\alpha\delta}g^{\beta\gamma})(W_\gamma^- A_\delta \partial_\alpha W_\beta^+ + A_\gamma W_\delta^+ \partial_\alpha W_\beta^- \\
 & + W_\gamma^+ W_\delta^- \partial_\alpha A_\beta) - g_s f^{abc} G_\mu^a G_\nu^b \partial^\mu G^{c\nu} + \frac{g^2 g'^2}{g^2 + g'^2}(g^{\alpha\gamma}g^{\beta\delta} - g^{\alpha\beta}g^{\gamma\delta})W_\alpha^+ W_\beta^- A_\gamma A_\delta \\
 & + \frac{g^4}{g^2 + g'^2}(g^{\alpha\gamma}g^{\beta\delta} - g^{\alpha\beta}g^{\gamma\delta})W_\alpha^+ W_\beta^- Z_\gamma Z_\delta + g^2(g^{\alpha\beta}g^{\gamma\delta} - g^{\alpha\gamma}g^{\beta\delta})W_\alpha^+ W_\beta^+ W_\gamma^- W_\delta^- \\
 & + \frac{g^3 g'}{g^2 + g'^2}(g^{\alpha\delta}g^{\beta\gamma} + g^{\alpha\gamma}g^{\beta\delta} - 2g^{\alpha\beta}g^{\gamma\delta})W_\alpha^+ W_\beta^- A_\gamma Z_\delta - \frac{1}{4}g_s^2 f^{rab} f^{rcd} G_\mu^a G_\nu^b G^{c\mu} G^{d\nu} \\
 & + i\bar{\psi}_e \gamma_\mu \partial^\mu \psi_e + i\bar{\psi}_{\nu_L} \gamma_\mu \partial^\mu \psi_{\nu_L} + i\sum_n \bar{\psi}_{q_n} \gamma_\mu \partial^\mu \psi_{q_n} - \frac{gg'}{\sqrt{g^2 + g'^2}}\bar{\psi}_e \gamma_\mu A^\mu \psi_e \\
 & + \frac{g}{\sqrt{2}}(\bar{\psi}_{\nu_L} \gamma_\mu W^{+\mu} \psi_{e_L} + \bar{\psi}_{e_L} \gamma_\mu W^{-\mu} \psi_{\nu_L}) + \frac{1}{2}\sqrt{g^2 + g'^2}\bar{\psi}_{\nu_L} \gamma_\mu Z^\mu \psi_{\nu_L} \\
 & + \frac{1}{2}\sqrt{g^2 + g'^2}\left(\bar{\psi}_e \gamma_\mu Z^\mu \left[\frac{2g'^2}{g^2 + g'^2} - \frac{1}{2}(1 - \gamma_5)\right] \psi_e\right) + g_s \sum_n \bar{\psi}_{q_n} G_\mu^a \gamma^\mu t^a \psi_{q_n} \\
 & + g \sum_{I,i} (\bar{\psi}_{q_i} \gamma_\mu W^{+\mu} \psi_{q_{iL}} V_{Ii}^+ + \bar{\psi}_{q_i} \gamma_\mu W^{-\mu} \psi_{q_{iL}} V_{iI}) + \frac{gg'}{\sqrt{g^2 + g'^2}} \sum_n Q_n \bar{\psi}_{q_n} \gamma_\mu A^\mu \psi_{q_n} \\
 & + \frac{1}{2}\sqrt{g^2 + g'^2} \sum_I \left(\bar{\psi}_{q_i} \gamma_\mu Z^\mu \left[\frac{1}{2}(1 - \gamma_5) - \frac{2Q_I g'^2}{g^2 + g'^2}\right] \psi_{q_i}\right) \\
 & + \frac{1}{2}\sqrt{g^2 + g'^2} \sum_i \left(\bar{\psi}_{q_i} \gamma_\mu Z^\mu \left[-\frac{1}{2}(1 - \gamma_5) - \frac{2Q_i g'^2}{g^2 + g'^2}\right] \psi_{q_i}\right) \\
 & + \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}m_h^2 \phi^2 + \frac{1}{4}v^2 g^2 W_\mu^+ W^{-\mu} + \frac{1}{8}v^2 (g^2 + g'^2) Z_\mu^2 + \frac{1}{2}v g^2 \phi W_\mu^+ W^{-\mu} \\
 & - \frac{1}{4}v(g^2 + g'^2)\phi Z_\mu^2 + \frac{1}{4}g^2 \phi^2 (W_\mu^+ W^{-\mu} + 2Z_\mu^2) - \frac{m_h^2}{2v}\phi^3 - \frac{m_h^2}{8v^2}\phi^4 \\
 & - m_e \bar{\psi}_e \psi_e - \sum_n m_n \bar{\psi}_{q_n} \psi_{q_n} - \frac{m_e}{v}\phi \bar{\psi}_e \psi_e - \frac{1}{v} \sum_n m_n \phi \bar{\psi}_{q_n} \psi_{q_n}
 \end{aligned}$$

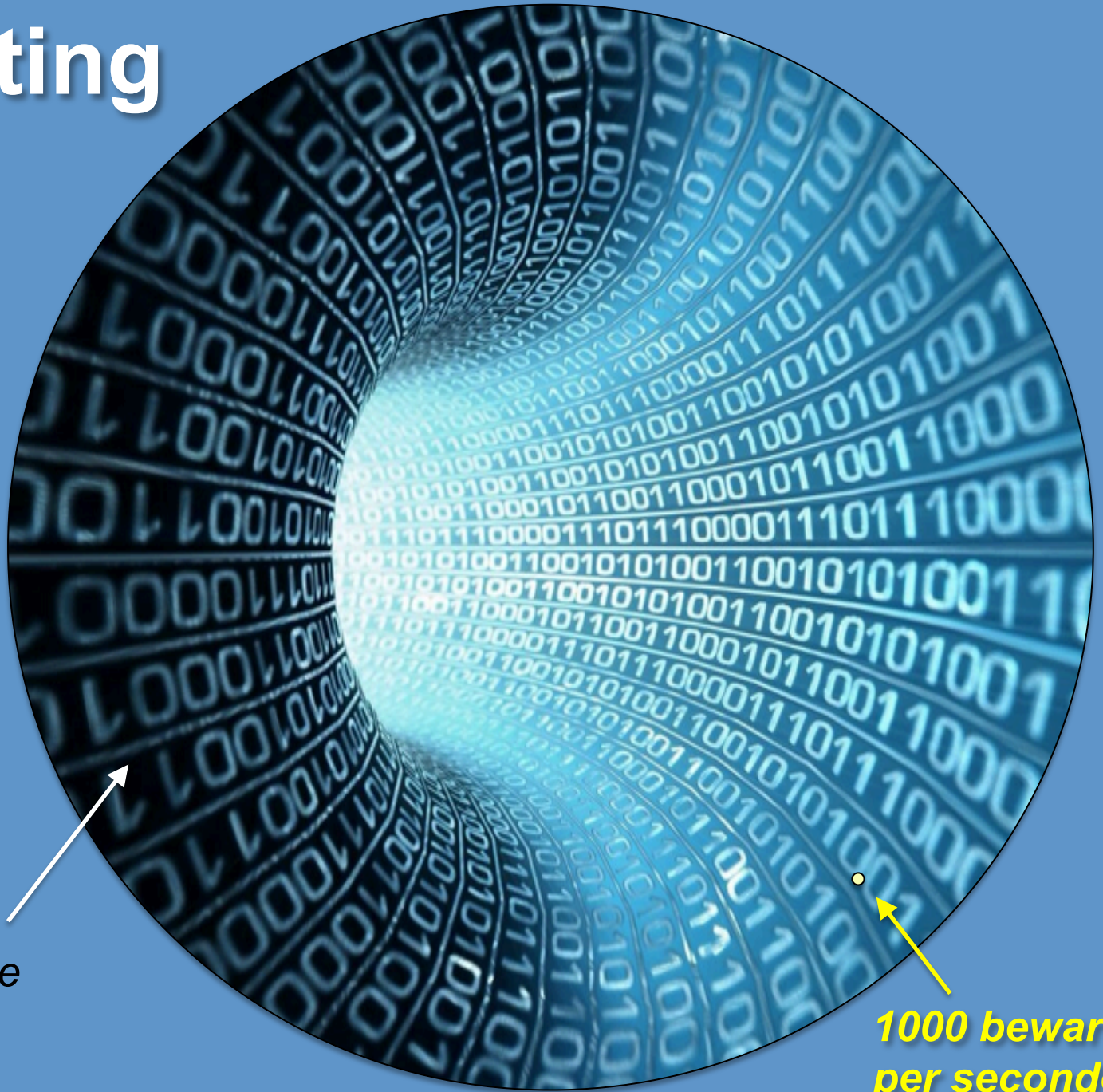
# Higgs boson verval: 4 muonen



Yes, ... gevonden!



# computing

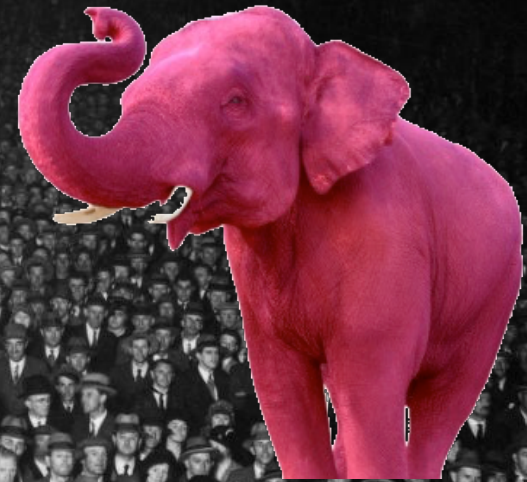


1.000.000.000  
foto's per seconde

1000 bewaren  
per seconde



4 muonen



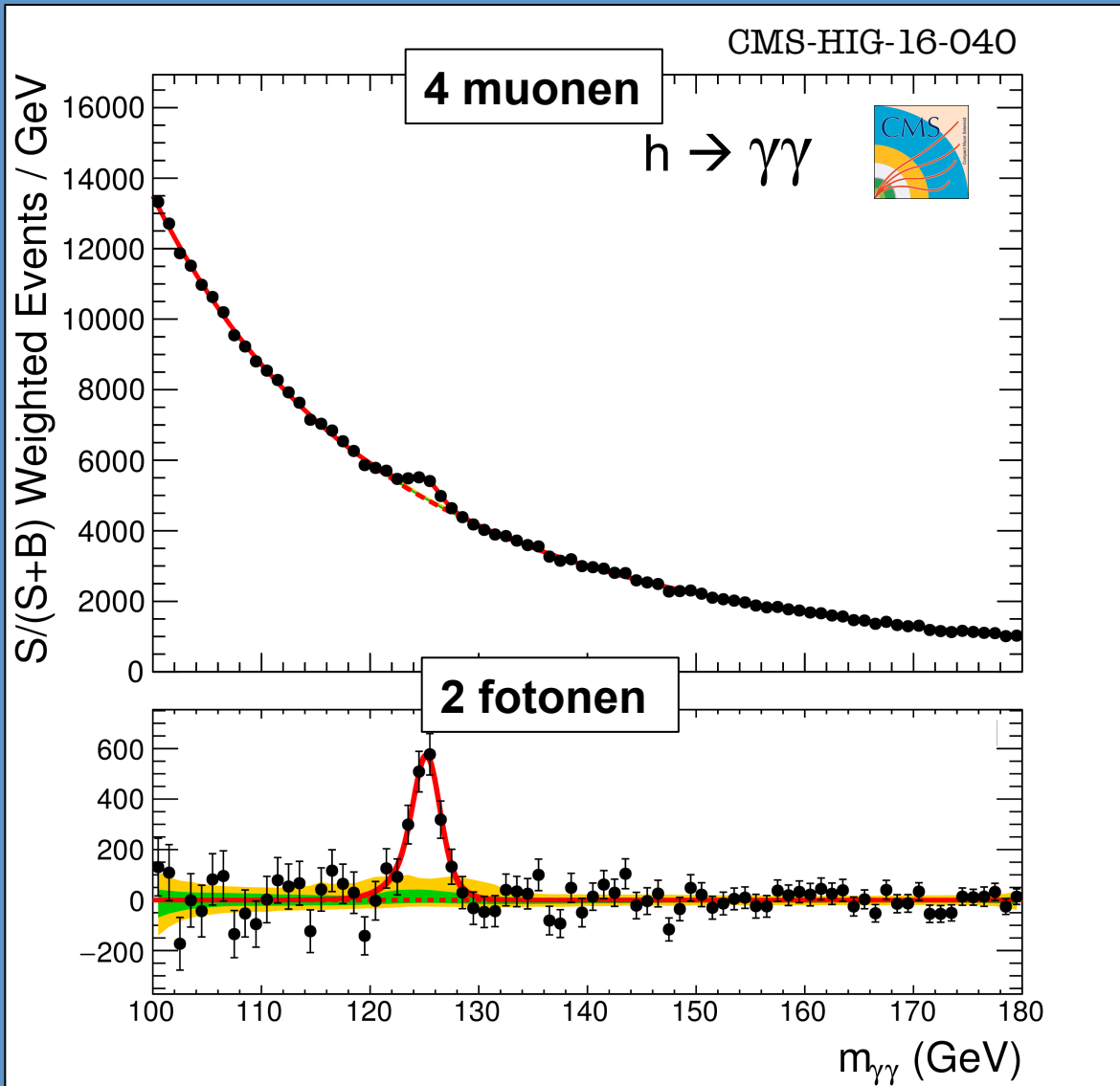


Liu Bolin

Of is het verstopt in de achtergrond ?



# CMS resultaat: even genieten



@freyablekman

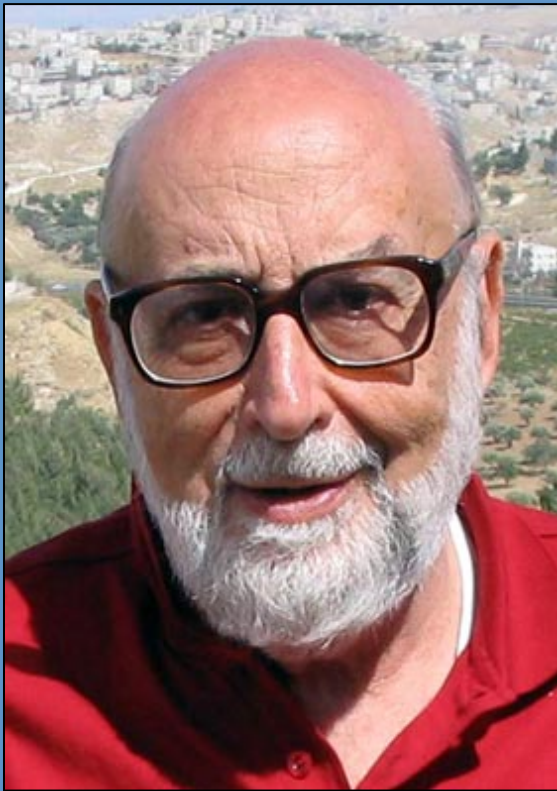
An underwater photograph looking up towards the surface of the ocean. Sunlight filters through the water, creating a shimmering, dappled pattern of light and shadow on the surface. The water is a deep, clear blue, and the overall atmosphere is serene and ethereal.

Elke  $\text{m}^3$  ruimte zit vol met Higgs veld

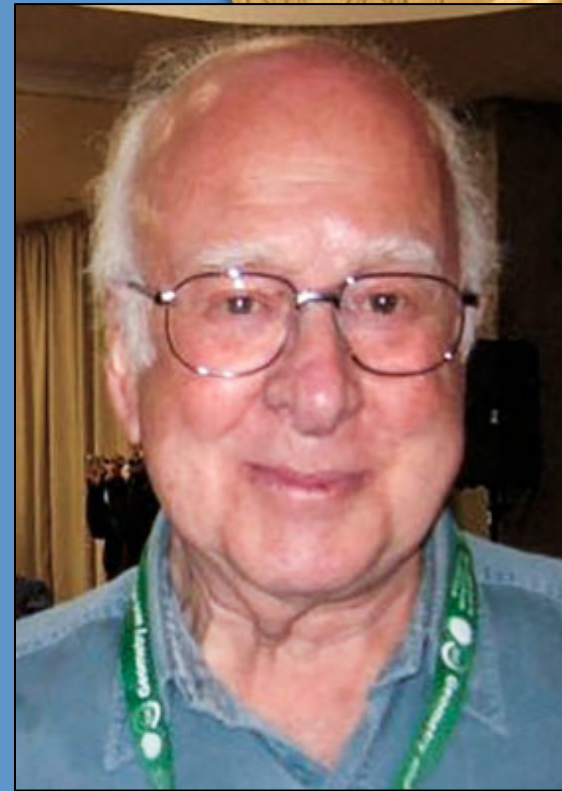


# Nobelprijs natuurkunde 2013

*“Er is een Higgs-veld in het vacuüm”*



*François Englert*



*Peter Higgs*

















de problemen



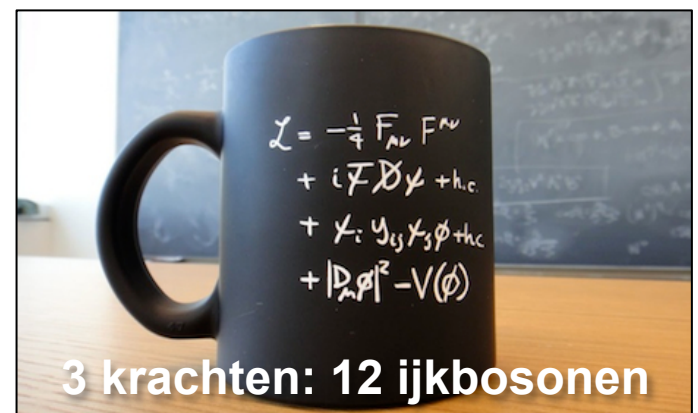


# Het Standaard Model

## Elementaire deeltjes

up-quark			
down-quark			
elektron			
neutrino			

## Interacties







# Paar 'kleine' dingetjes:

1

80% van alle massa in het heelal is onbekend

2

Waar is alle anti-materie gebleven?

3

**Problemen met het Higgs boson**

4

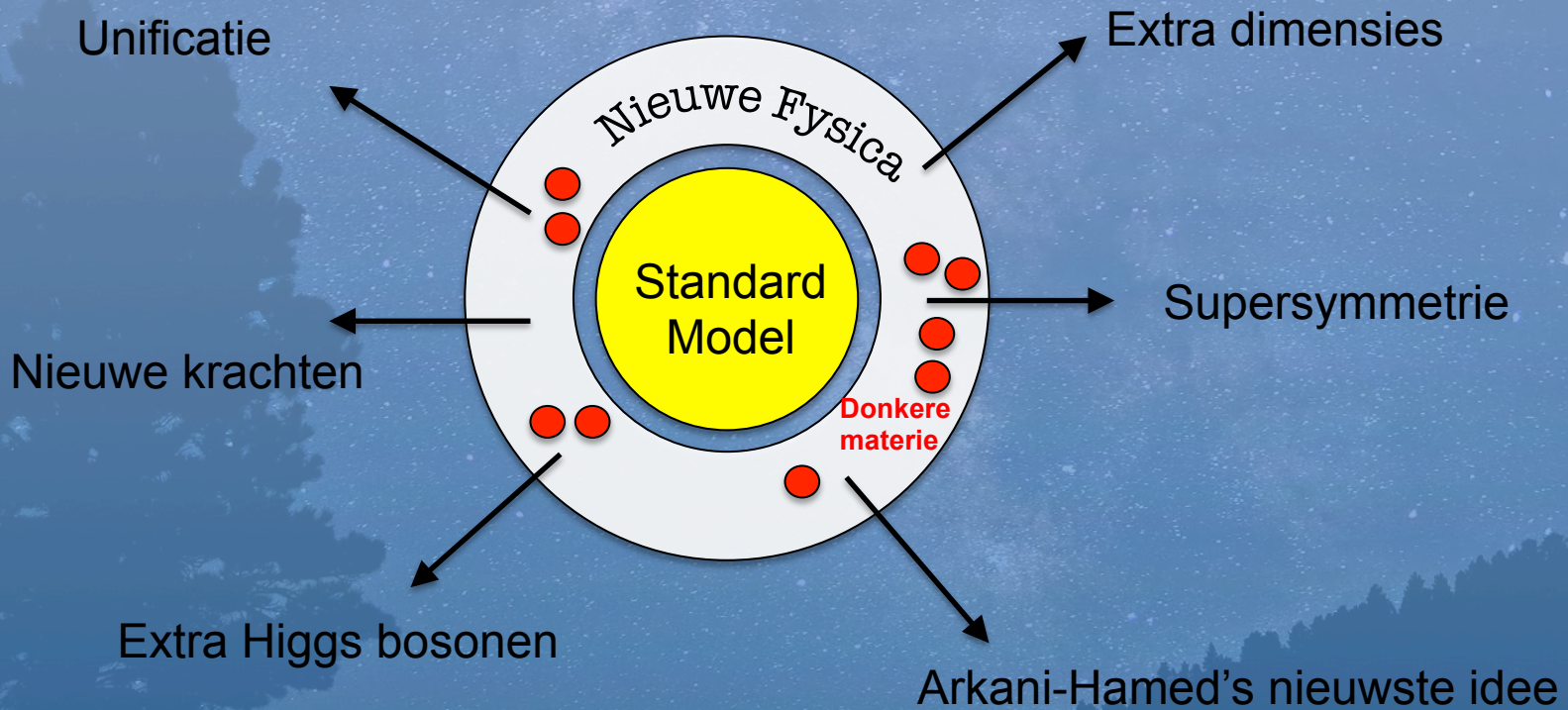
Waarom is de zwaartekracht zo zwak?

5

drie families, kracht-unificatie, patronen, ...



# Standaard Model is niet de ultieme theorie



Nieuwe deeltjes, nieuwe krachten, nieuwe fenomenen



avontuur



# de 'Nederlandse' avonturiers



*Sascha Caron*

Supersymmetrie



*Freya Blekman*

top quarks



*Tristan du Pree*

Higgs-boson



# de 'Groningse' avonturiers



*Jordy de Vries*

theorie (Nikhef)



*Gerco Onderwater*

anti-materie (RUG)



*Steven Hoekstra*

EDM (RUG)

# De mysteries

*raadsels en echte problemen*

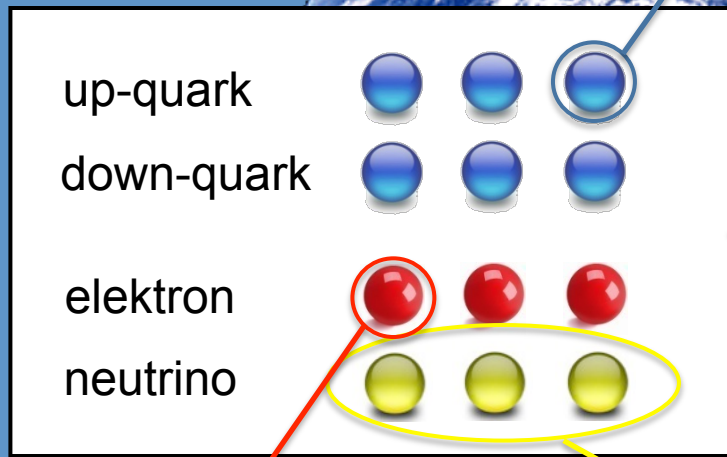


# STANDAARD MODEL

Top quark:  
- weegt: 175.000 MeV  
- leeft:  $10^{-24}$  sec



## Deeltjes



Algemeen:  
- Waarom 3 families?  
- Aantal quarks vs leptonen?

Electron  
- weegt: 0.5 MeV  
- Leeft: forever

neutrino's  
- Wegen:  $< 0.0000000001$  MeV  
- Leeft: onduidelijke vraag

3

# Het massa-mysterie: Higgs boson



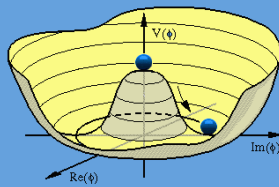
*“Het Higgs veld is overal in de lege ruimte”*





# Uitbreiding Higgs sector

## Standaard Model



SM-doublet &  
 $V(\phi) = \mu^2\phi^2 + \lambda\phi^4$



(1) compositeness

(2) extra EW singlet



(3) Two Higgs doublet models



*h*      *A*      *H*      *H<sup>+</sup>*      *H<sup>-</sup>*

Standaard Model:

1 doublet, CP-even neutral scalar

(4) Dark Matter portal

*Invisible Higgs decays*

Coupling scale factor	Type I	Type II	Type III	Type IV
$\kappa_V$	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$
$\kappa_u$	$\cos(\alpha) / \sin(\beta)$	$\cos(\alpha) / \sin(\beta)$	$\cos(\alpha) / \sin(\beta)$	$\cos(\alpha) / \sin(\beta)$
$\kappa_d$	$\cos(\alpha) / \sin(\beta)$	$-\sin(\alpha) / \cos(\beta)$	$\cos(\alpha) / \sin(\beta)$	$-\sin(\alpha) / \cos(\beta)$
$\kappa_l$	$\cos(\alpha) / \sin(\beta)$	$-\sin(\alpha) / \cos(\beta)$	$-\sin(\alpha) / \cos(\beta)$	$\cos(\alpha) / \sin(\beta)$

*specific couplings to fermions/bosons*



# Wereldkampioenen rekenen



Jos Vermaseren

$$\gamma_{L,1}^{(3)}(N) = 16 \left( -353/48 + 119917/864 D_1^2 + 15689/324 D_1^3 + 433/72 D_1^4 + 19/3 D_1^5 + 5/3 D_1^6 \right. \\ - 112979/2592 \eta + 13405/648 \eta^2 - 8045/1296 \eta^3 - 61/18 \eta^4 - 1/2 \eta^5 - 5/6 \eta^6 - 5 \zeta_5 \\ - 15 \zeta_5 \eta + 10 \zeta_5 \eta^2 - 33/8 \zeta_4 - 11/4 \zeta_4 \eta + 235/16 \zeta_3 + 8/3 \zeta_3 D_1^2 + 2 \zeta_3 D_1^3 + 83/8 \zeta_3 \eta \\ + 3/2 \zeta_3 \eta^2 + 2/3 \zeta_3 \eta^3 - 39883/1296 S_1 + 19009/324 S_1 D_1^2 + 77/9 S_1 D_1^3 + 79/6 S_1 D_1^4 \\ + 20/3 S_1 D_1^5 - 19927/324 S_1 \eta + 1453/81 S_1 \eta^2 - 7/24 S_1 \eta^3 + 38/9 S_1 \eta^4 + 3 S_1 \eta^5 \\ + 10 S_1 \zeta_5 + 11/2 S_1 \zeta_4 - 317/12 S_1 \zeta_3 + 4 S_1 \zeta_3 D_1^2 + 8/3 S_1 \zeta_3 \eta - 8/3 S_1 \zeta_3 \eta^2 - 4 S_1 \zeta_3 \eta^3 \\ + 85175/2592 S_2 - 1873/54 S_2 D_1^2 - 20/3 S_2 D_1^3 - 4 S_2 D_1^4 + 4943/648 S_2 \eta + 95/216 S_2 \eta^2 \\ + 229/36 S_2 \eta^3 + 25/6 S_2 \eta^4 + 2/3 S_2 \zeta_3 + 2 S_2 \zeta_3 \eta - 4 S_2 \zeta_3 \eta^2 - 22247/648 S_3 + 241/18 S_3 D_1^2 \\ + 2/3 S_3 D_1^3 - 113/54 S_3 \eta + 37/18 S_3 \eta^2 + 19/6 S_3 \eta^3 - 8/3 S_3 \zeta_3 + 725/24 S_4 - 16/3 S_4 D_1^2 \\ - 73/36 S_4 \eta + 5/3 S_4 \eta^2 - 46/3 S_5 + 8/3 S_5 \eta + 20/3 S_6 + 8/3 S_{1,1} D_1^2 + 8/3 S_{1,1} D_1^3 + 8 S_{1,1} D_1^4 \\ + 4/3 S_{1,1} \eta + 9/4 S_{1,1} \eta^2 - 12 S_{1,1} \eta^3 - 14/3 S_{1,1} \eta^4 - 8 S_{1,1} \zeta_3 \eta + 8 S_{1,1} \zeta_3 \eta^2 + 6673/324 S_{1,2} \\ - 28/3 S_{1,2} D_1^2 + 28/3 S_{1,2} \eta - 8/3 S_{1,2} \eta^2 - 8/3 S_{1,2} \eta^3 + 4 S_{1,2} \zeta_3 - 605/54 S_{1,3} + 4/3 S_{1,3} D_1^2 \\ - 14/3 S_{1,3} \eta - 1/3 S_{1,3} \eta^2 + 2 S_{1,3} \eta^3 + 181/18 S_{1,4} + 10/3 S_{1,4} \eta - 16/3 S_{1,5} + 6673/324 S_{2,1} \\ - 28/3 S_{2,1} D_1^2 + 28/3 S_{2,1} \eta - 8/3 S_{2,1} \eta^2 - 8/3 S_{2,1} \eta^3 + 4 S_{2,1} \zeta_3 - 1021/54 S_{2,2} + 4 S_{2,2} D_1^2 \\ + 2/3 S_{2,2} \eta - 2 S_{2,2} \eta^2 + 181/18 S_{2,3} - 8/3 S_{2,3} \eta + 2 S_{2,3} \eta^2 - 2 S_{2,4} - 479/18 S_{3,1} \\ + 16/3 S_{3,1} D_1^2 + 59/9 S_{3,1} \eta - 2 S_{3,1} \eta^2 - 2 S_{3,1} \eta^3 + 275/18 S_{3,2} - 10/3 S_{3,2} \eta - 22/3 S_{3,3} \\ + 343/18 S_{4,1} - 4/3 S_{4,1} \eta - 2 S_{4,1} \eta^2 - 12 S_{4,2} - 12 S_{5,1} + 4 S_{1,1,3} \eta - 4 S_{1,1,3} \eta^2 - 20/3 S_{1,1,4} \\ - 20/3 S_{1,2,2} + 4/3 S_{1,2,3} - 94/9 S_{1,3,1} - 20/3 S_{1,3,1} \eta + 4 S_{1,3,1} \eta^2 + 20/3 S_{1,3,2} + 20/3 S_{1,4,1} \\ - 20/3 S_{2,1,2} + 4/3 S_{2,1,3} - 20/3 S_{2,2,1} + 4 S_{2,2,2} + 8/3 S_{2,3,1} - 20/3 S_{3,1,1} + 4/3 S_{3,1,1} \eta \\ + 16/3 S_{3,1,2} + 16/3 S_{3,2,1} + 28/3 S_{4,1,1} + 16/3 S_{1,1,3,1} - 8/3 S_{1,3,1,1} \Big) . \quad (3.7)$$

$$\begin{aligned} & \left[ 10317600287587322672417525639 \zeta_5 - 22176170947759 \zeta_6 \right] \\ & + C_1^2 C_2^2 \left[ -44014119696332728422480000 \zeta_5 - 33508344870 \zeta_6 \right] \\ & + C_1^2 C_2^2 \left[ -13762838063490015696346356725691463249848729 \zeta_5 \right. \\ & \quad \left. - 68309157221399309554067272529185240000000 \zeta_6 \right] \\ & + 15923437134502520764317446141 \zeta_5 - 59290512768143 \zeta_6 + 40278295293893 \zeta_7 \\ & + 234741971713774551586560000 \zeta_5 - 284313229200 \zeta_6 + 42646984380 \zeta_7 \\ & + C_1^2 C_2^2 \left[ 258914251298466366542816679113637834371 \zeta_5 \right. \\ & \quad \left. - 92035679216332067581789246208000000 \zeta_6 \right] \\ & + 220146403042236864687668923 \zeta_5 - 59290512768143 \zeta_6 - 1804393628665651 \zeta_7 \\ & + 16767283693841039399040000 \zeta_5 - 189542152800 \zeta_6 - 625489104240 \zeta_7 \\ & + C_1^2 C_2^2 \left[ 14183627547279601657840082208324742517 \zeta_5 \right. \\ & \quad \left. - 12843000517166864476020965376000000 \zeta_6 \right] \\ & + 2649527312649305104376683 \zeta_5 - 59290512768143 \zeta_6 - 101176031536771 \zeta_7 \\ & + 3862475881756882790400 \zeta_5 - 56826458400 \zeta_6 + 63970476570 \zeta_7 \\ & + n_1 C_1^2 C_2^2 \left[ 94403012063925170595517180859037562017787057 \zeta_5 \right. \\ & \quad \left. - 317149658527925365792959784081711104000000 \zeta_6 \right] \\ & + 2575252164686212840197 \zeta_5 - 59290512768143 \zeta_6 - 128839202 \zeta_7 \\ & + 86215979503501848000 \zeta_5 - 1563722760600 \zeta_6 - 153153 \zeta_7 \\ & + n_1 n_2 C_1^2 C_2^2 \left[ 2893023190248781306760837247560962327027 \zeta_5 \right. \\ & \quad \left. - 724780973828615032206903013888000000 \zeta_6 \right] \\ & + 6301056648029446207079 \zeta_5 - 54163986863623 \zeta_6 - 64419601 \zeta_7 \\ & + 5747731969001232000 \zeta_5 - 104281840400 \zeta_6 - 459459 \zeta_7 \\ & + n_1 C_1^2 C_2^2 C_3^2 \left[ 674736712195880468279822790324541 \zeta_5 \right. \\ & \quad \left. - 99303611447435941596860416000000 \zeta_6 - 766564262253497600 \zeta_7 \right] \\ & + 1506311935054583 \zeta_5 - 4569981743 \zeta_6 \\ & + 312744521200 \zeta_5 + 7209972 \zeta_6 \\ & + n_1^2 C_1^2 C_2^2 \left[ 1499767303942721479649857809345185131 \zeta_5 \right. \\ & \quad \left. - 28885034779593394007378225049600000 \zeta_6 - 14073304845400 \zeta_7 \right] \\ & + 64419601 \zeta_5 \\ & + 765765 \zeta_6 \\ & + 952171998190084348273938825232327 \zeta_5 - 2491999394100703 \zeta_6 - 64419601 \zeta_7 \\ & + n_1^2 C_1 C_2 C_3^2 \left[ 354928612312271219988787200000 \zeta_5 - 14073504845400 \zeta_6 - 765765 \zeta_7 \right] \\ & + n_1^2 C_2^2 C_3^2 \left[ 54369616195548207942967542719 \zeta_5 - 128839202 \zeta_6 \right] \\ & + 3802819941763147735702720000 \zeta_5 + 20675655 \zeta_6 \\ & + \frac{d^{3\text{loop}}}{d^{3\text{loop}}} \left[ 13544672049501491403276515417 \zeta_5 - 3791955378871486958507 \zeta_6 \right. \\ & \quad \left. - 5744913623184647 \zeta_7 - 5301437484764348928000000 \zeta_8 + 483002686294128000 \zeta_9 \right] \\ & + 5744913623184647 \zeta_5 \\ & + 469116828180 \zeta_6 \\ & + n_1^2 \frac{d^{3\text{loop}}}{d^{3\text{loop}}} \left[ 63048309341247319711503473 \zeta_5 + 1361755723179569 \zeta_6 \right. \\ & \quad \left. + 108438494006543500800000 \zeta_7 + 2020810952160 \zeta_8 \right] \end{aligned}$$

1707.08315

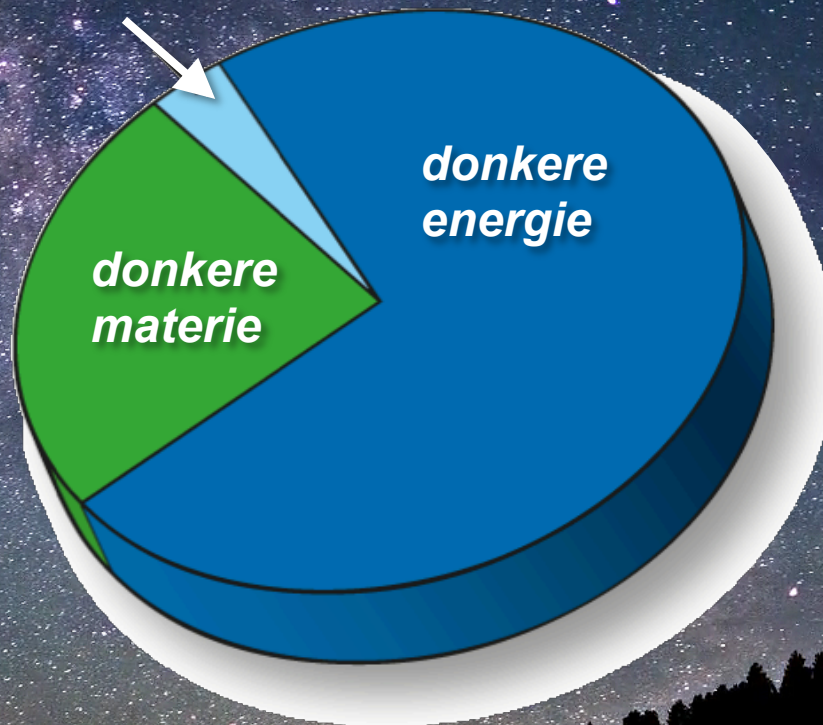
2 maanden rekenen op 25000 computers tegelijk  
 En dat is alleen om de formule te krijgen  
 (samen met Franz Herzog en anderen)



# Donkere materie

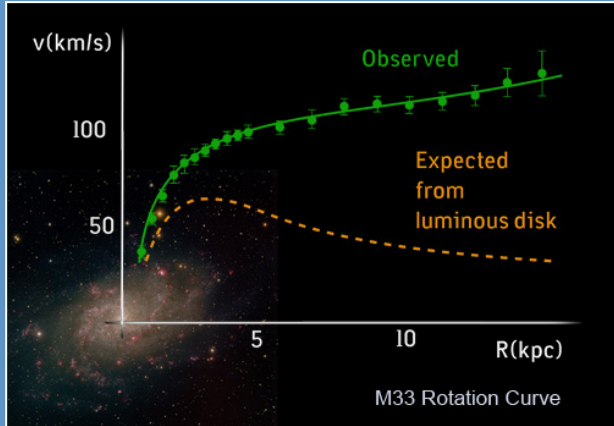
*Nieuwe deeltjes*

*sterren, planeten, gas, pulsars, ...*

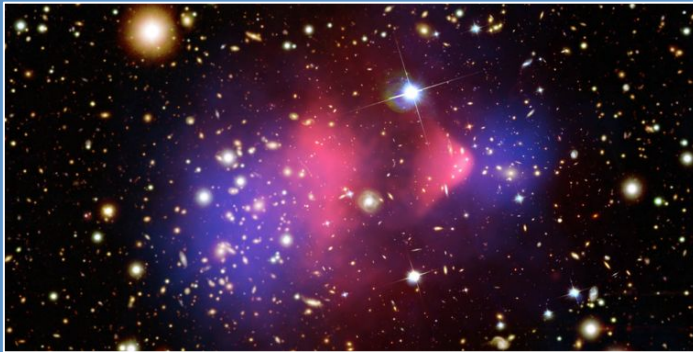
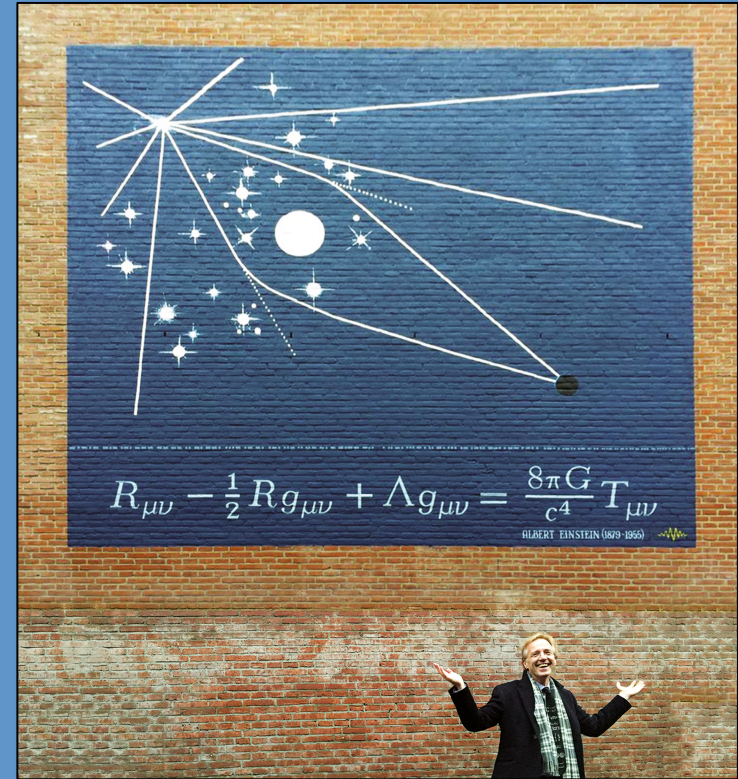




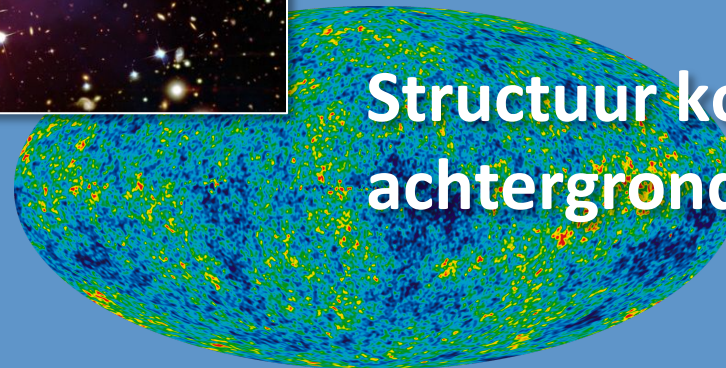
# rotatiesnelheden in sterrenstelsels



# Gravitationele lensing



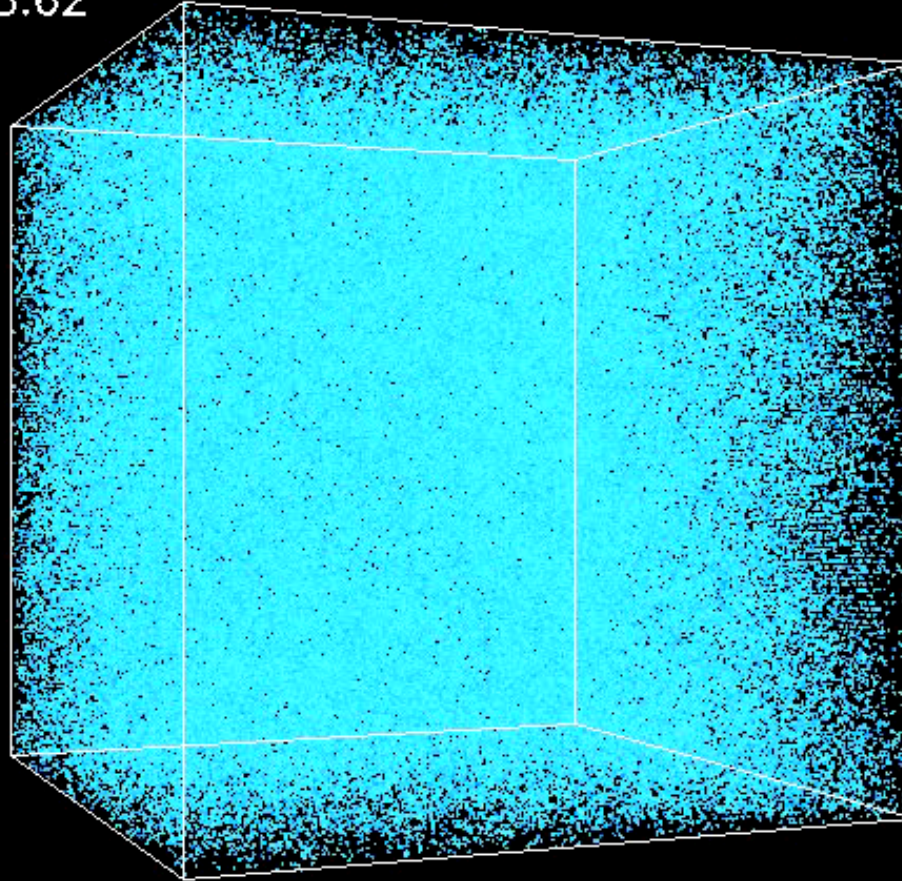
# Botsende stelsels



# Structuur kosmische achtergrondstraling

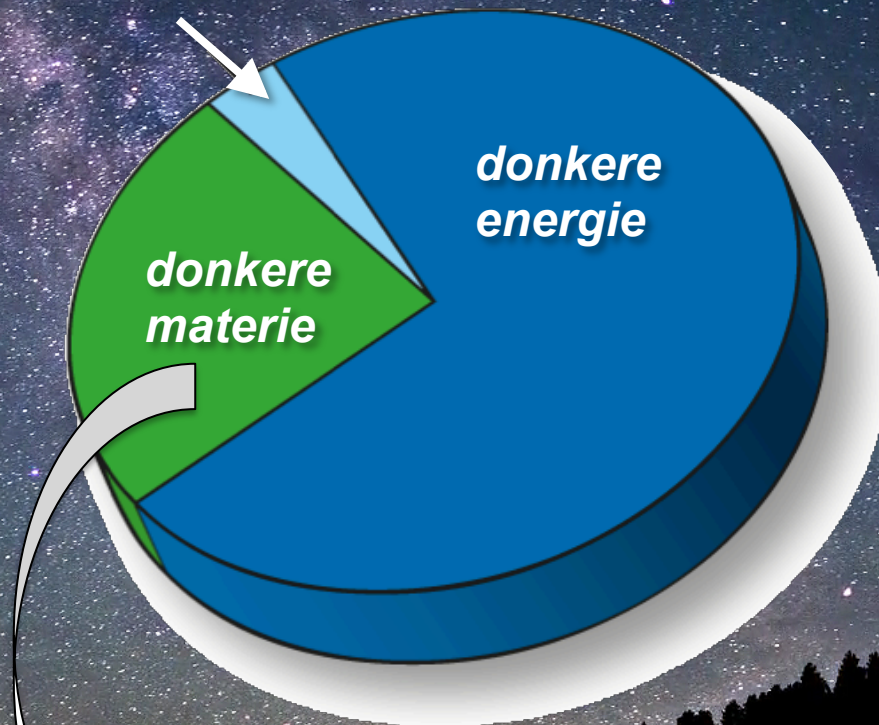
# Large scale structure formation = (klonteren)

Z=28.62





*sterren, planeten, gas, pulsars, ...*



deeltje uit een spiegelwereld ?



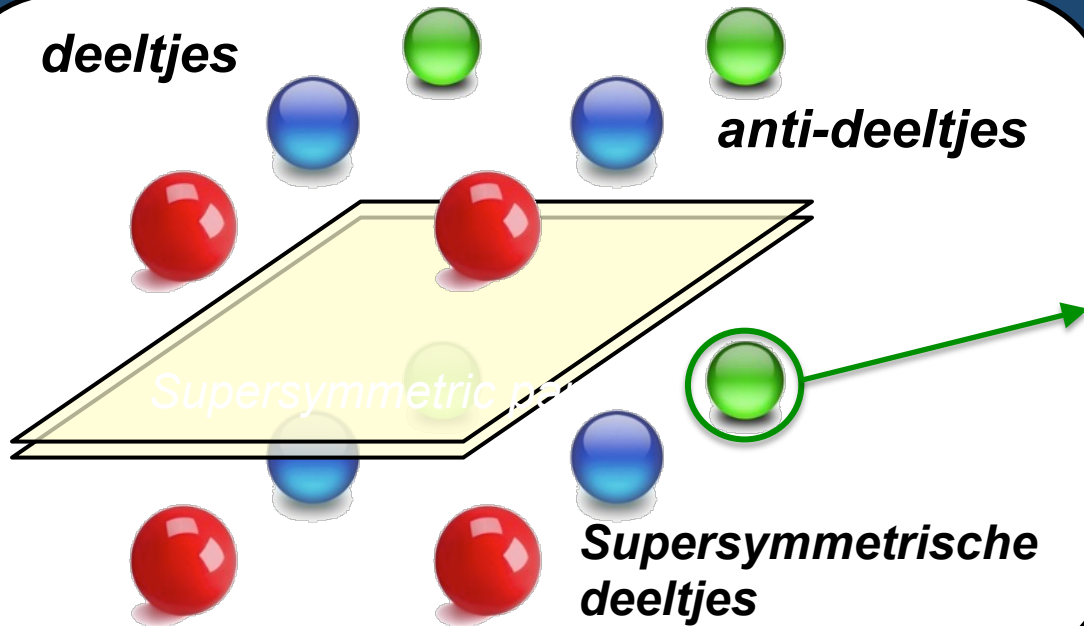
*deeltjes*

*anti-deeltjes*



***deeltjes***

***anti-deeltjes***



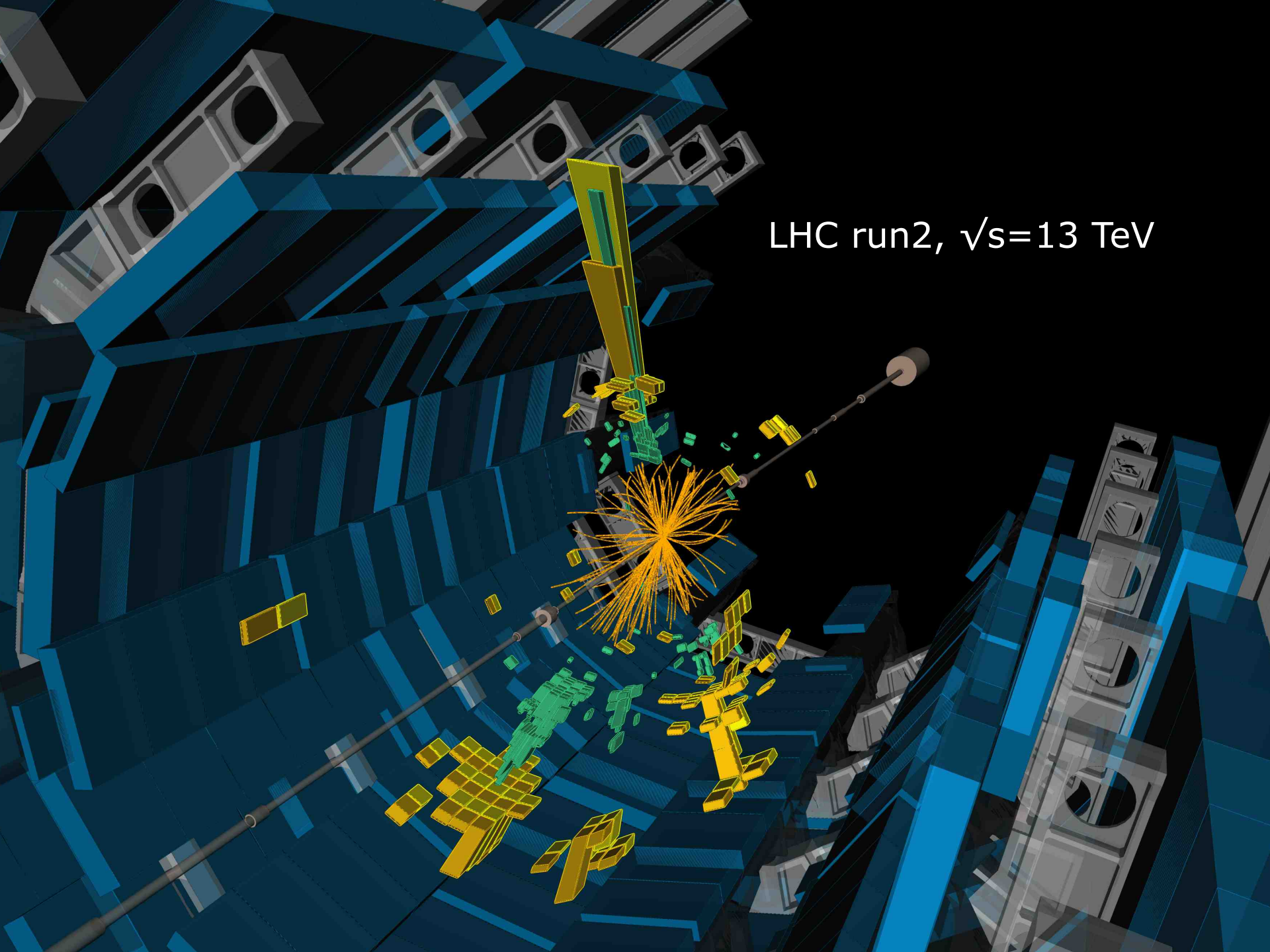
*Supersymmetrische partner*

***Supersymmetrische deeltjes***

*lichtste deeltje is stabiel*

*→ donkere materie?*

LHC run2,  $\sqrt{s}=13$  TeV







1 miljard foto's per seconde  
storage rate = 750 Hz



# ATLAS experiment



We hebben nog maar een paar % van de data verzameld



# Pieken zoeken

*Nieuwe krachten*

# Nieuwe krachtdeeltjes:

## Elementaire deeltjes

up-quark



down-quark



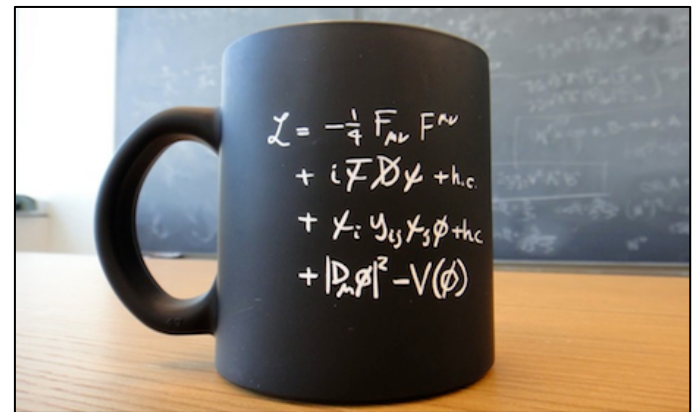
elektron



neutrino



## Interacties



$U(1)_B \times$

$U(1)_Y \times SU(2)_L \times SU(3)_C$

$\beta$

$g'$

$g$

$\alpha_s$

$Z'$

$\gamma, W^+, W^-, Z, 8 \text{ gluons}$

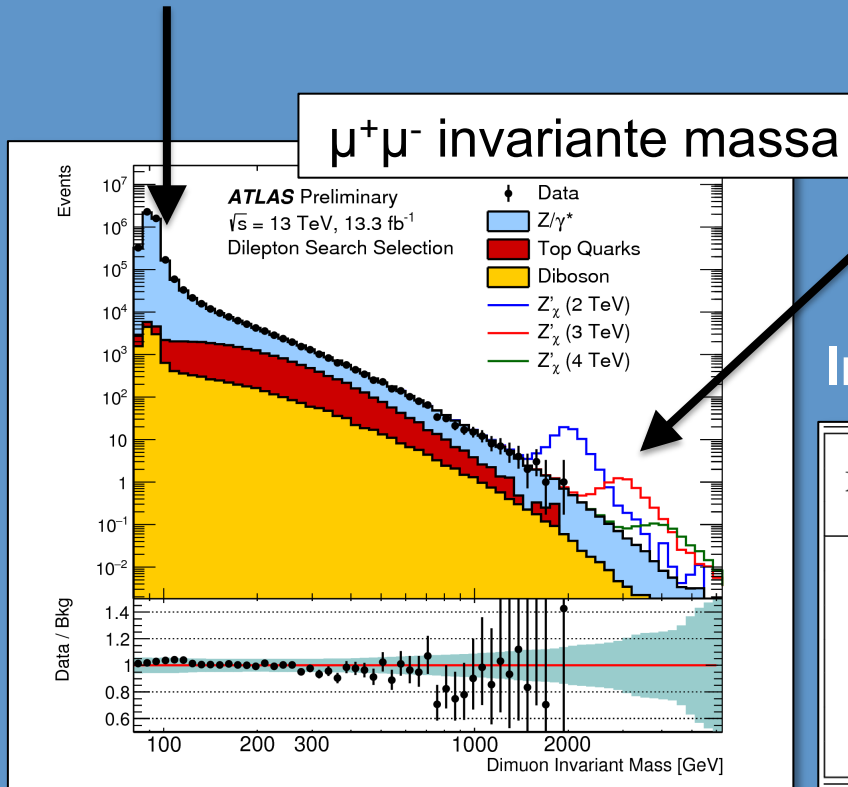
enkele spinor (1 grote familie)

kracht-unificatie:  $SO(10)$



# Zoeken naar nieuwe krachtdeeltjes met muonen

oude resonantie Z-boson (91 GeV)



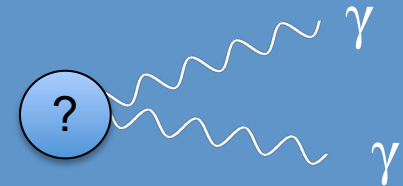
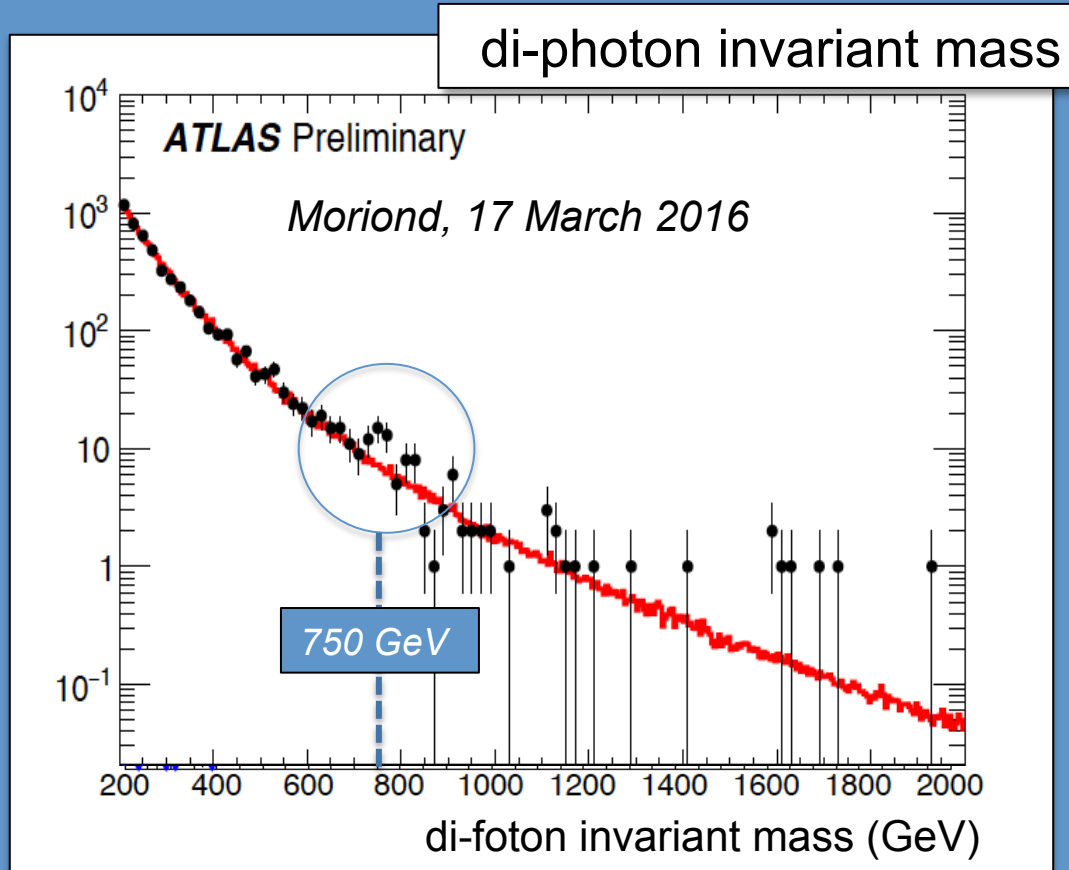
nieuwe resonantie (simulatie)

Impact op toegestane  $Z'$  massa's [TeV]

Model	Width [%]	$\theta_{E_6}$ [Rad]	Lower limits on $m_{Z'}$ [TeV]					
			$ee$		$\mu\mu$		$ll$	
			Obs	Exp	Obs	Exp	Obs	Exp
$Z'_{SSM}$	3.0	-	3.85	3.86	3.49	3.53	4.05	4.06
$Z'_X$	1.2	0.50	3.48	3.49	3.18	3.19	3.66	3.67
$Z'_S$	1.2	$0.63 \pi$	3.43	3.44	3.14	3.14	3.62	3.61
$Z'_I$	1.1	$0.71 \pi$	3.37	3.37	3.08	3.08	3.55	3.55
$Z'_\eta$	0.6	$0.21 \pi$	3.25	3.25	2.96	2.94	3.43	3.42
$Z'_N$	0.6	$-0.08 \pi$	3.23	3.23	2.95	2.94	3.41	3.41
$Z'_\psi$	0.5	$0 \pi$	3.18	3.18	2.90	2.88	3.36	3.35

Modellen met extra (ruimte) dimensies voorspellen ook pieken (Kaluza-Klein)

# Di-photon resonance: 2015 data



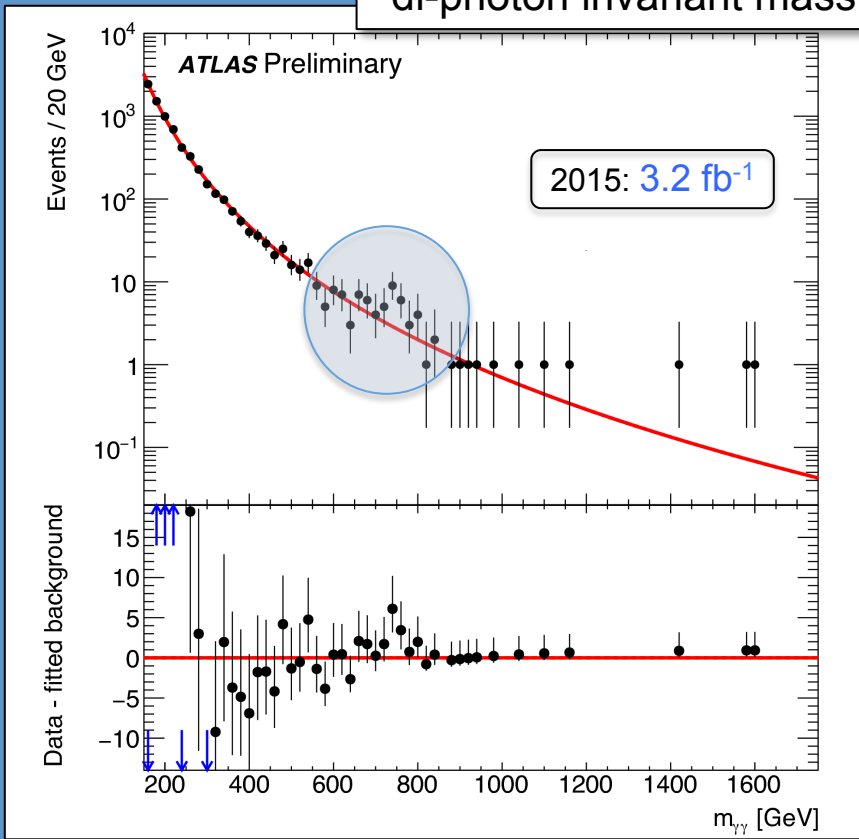
Significance: 3.9/1.8 sigma (local/global)





# 2015

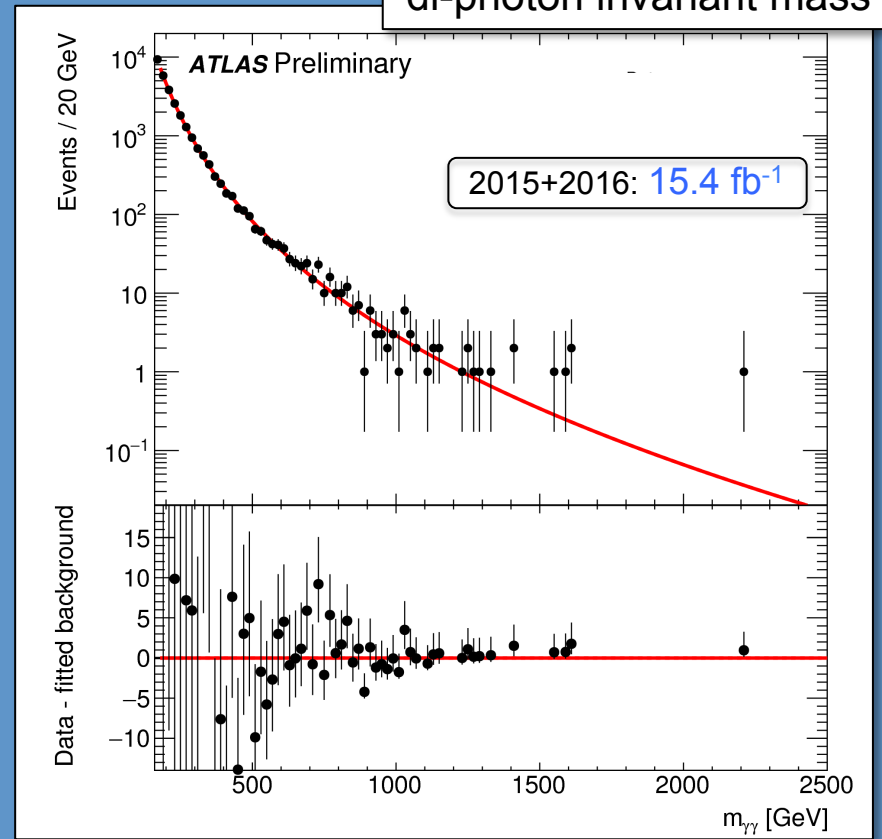
## di-photon invariant mass



Significance: 3.9/1.8 sigma (local/global)

# 2015 + 2016

## di-photon invariant mass

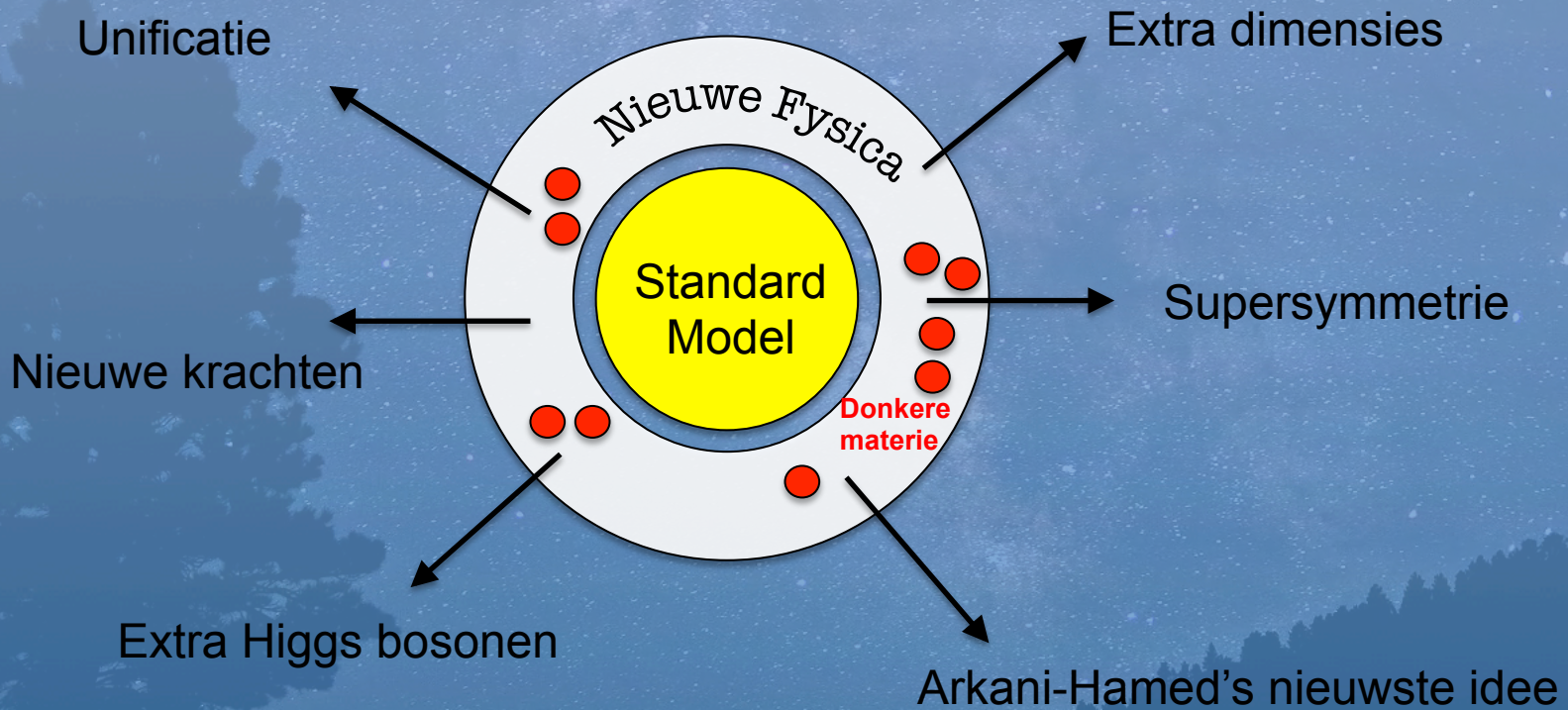


Significance: 2.3/<1 sigma (local/global)



# Schatgraven

# Standaard Model is niet de ultieme theorie





# De wereld van de elementaire deeltjes



Standaard Model werkt prima

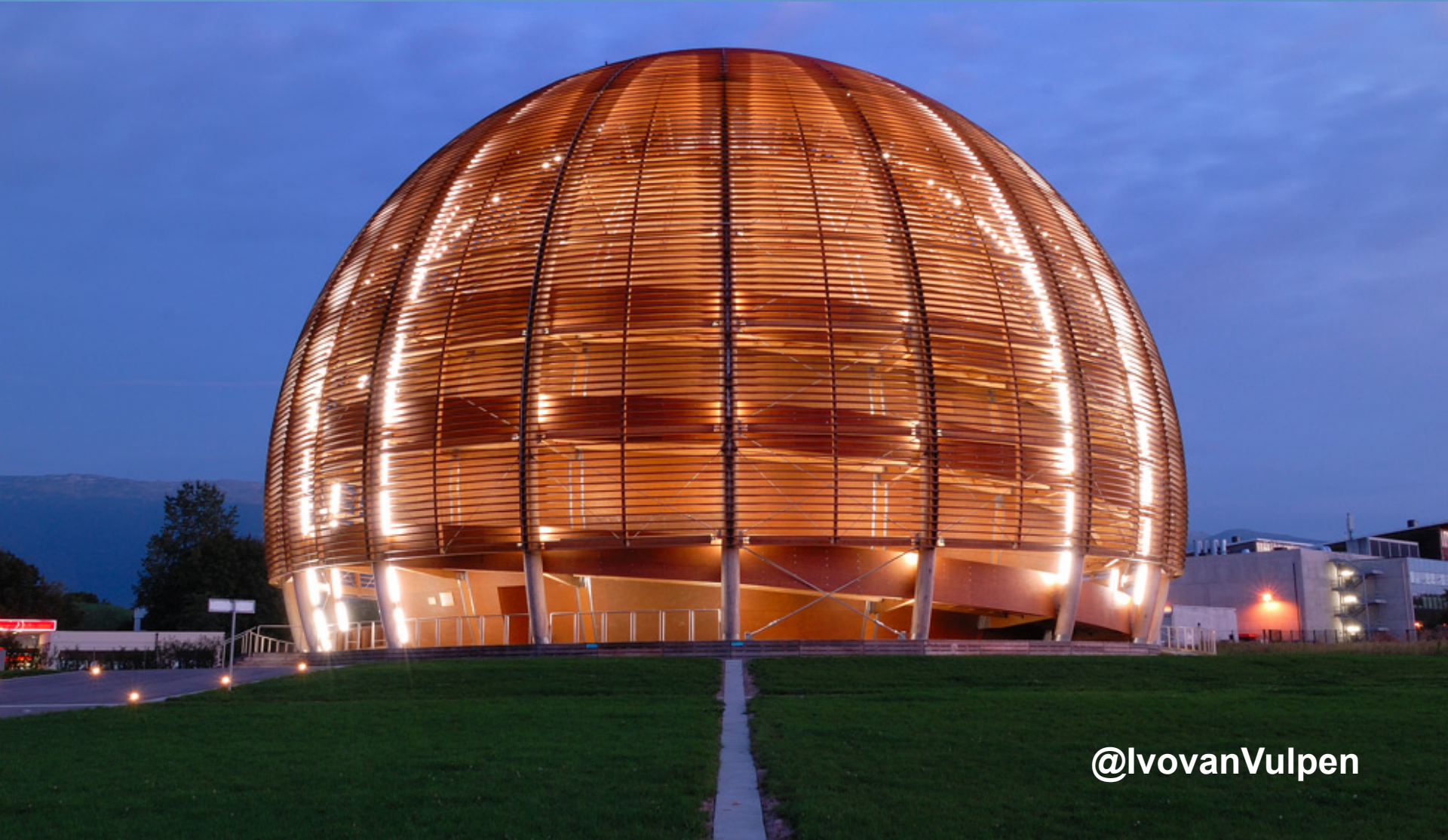
Higgs boson is ontdekt

LHC 'ontdekkingsmachine'

Grote mysteries



Schitterend avontuur de komende jaren!



@lvovanVulpen



Volg het avontuur

**@IvovanVulpen**



BACKUP

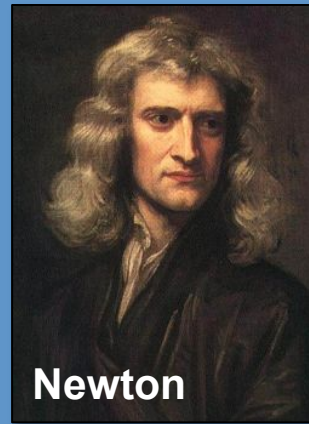
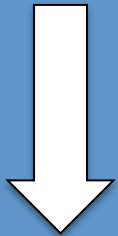
# zwaartekracht

*De big picture klopt niet:*

*Waarom is het heelal groter dan een voetbal ?*



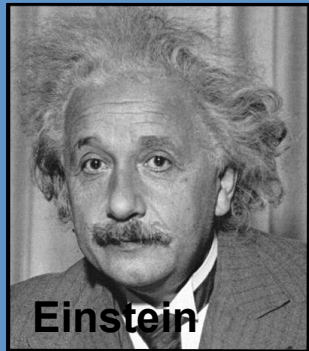
Waarom valt een  
appel naar beneden ?



Newton

massa's trekken elkaar aan

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



Einstein

ruimte-tijd is gekromd

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G_N}{c^4} T_{\mu\nu}$$

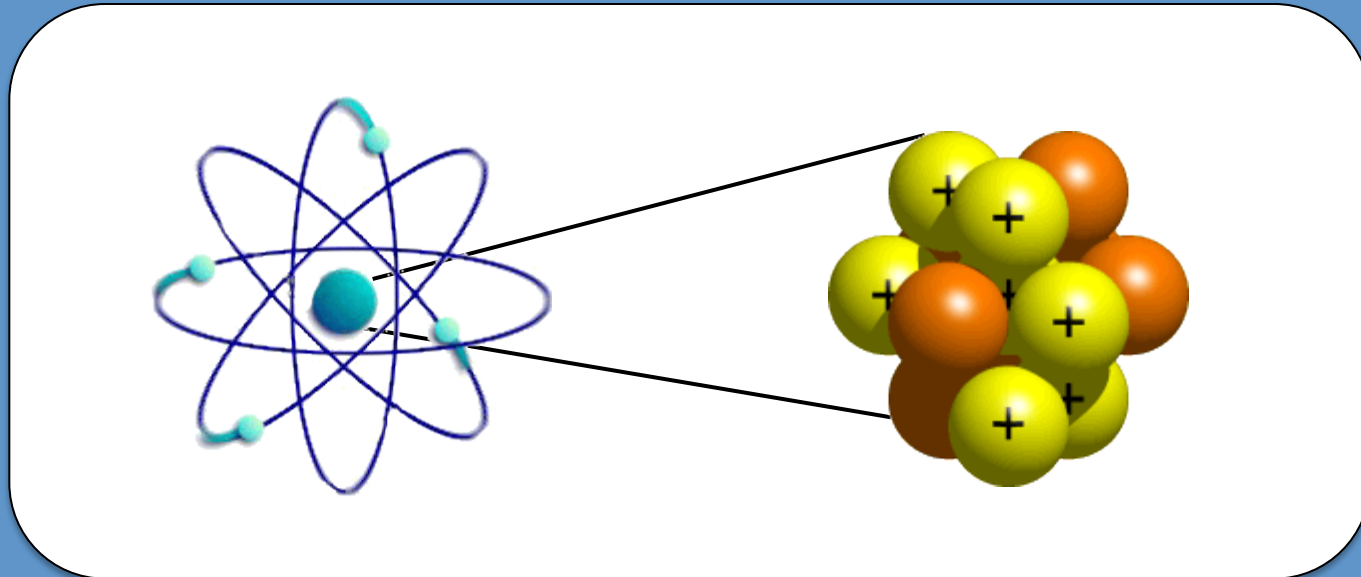


Verlinde

Entropie (informatie) ?



# Waarom is de zwaartekracht zo raar en zo zwak ?



Standaard Model: drie quantum krachten, ongeveer even sterk

Zwaartekracht: klassieke kracht,  $10^{-40}$  keer zo zwak

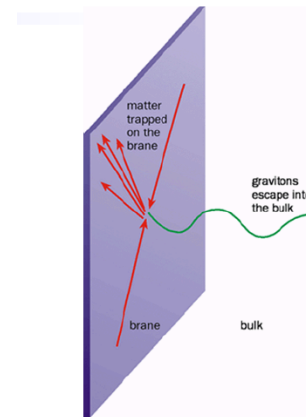
# Extra ruimte dimensies

Mier op een vlak (schuin) tafelblad



Ziet niet de 'echte' reden (3e dimensie)

Wij (SM) vastgeplakt op 3-dim vlak



Gravitatie komt in de 'volle' ruimte en wij zien maar een schijfje

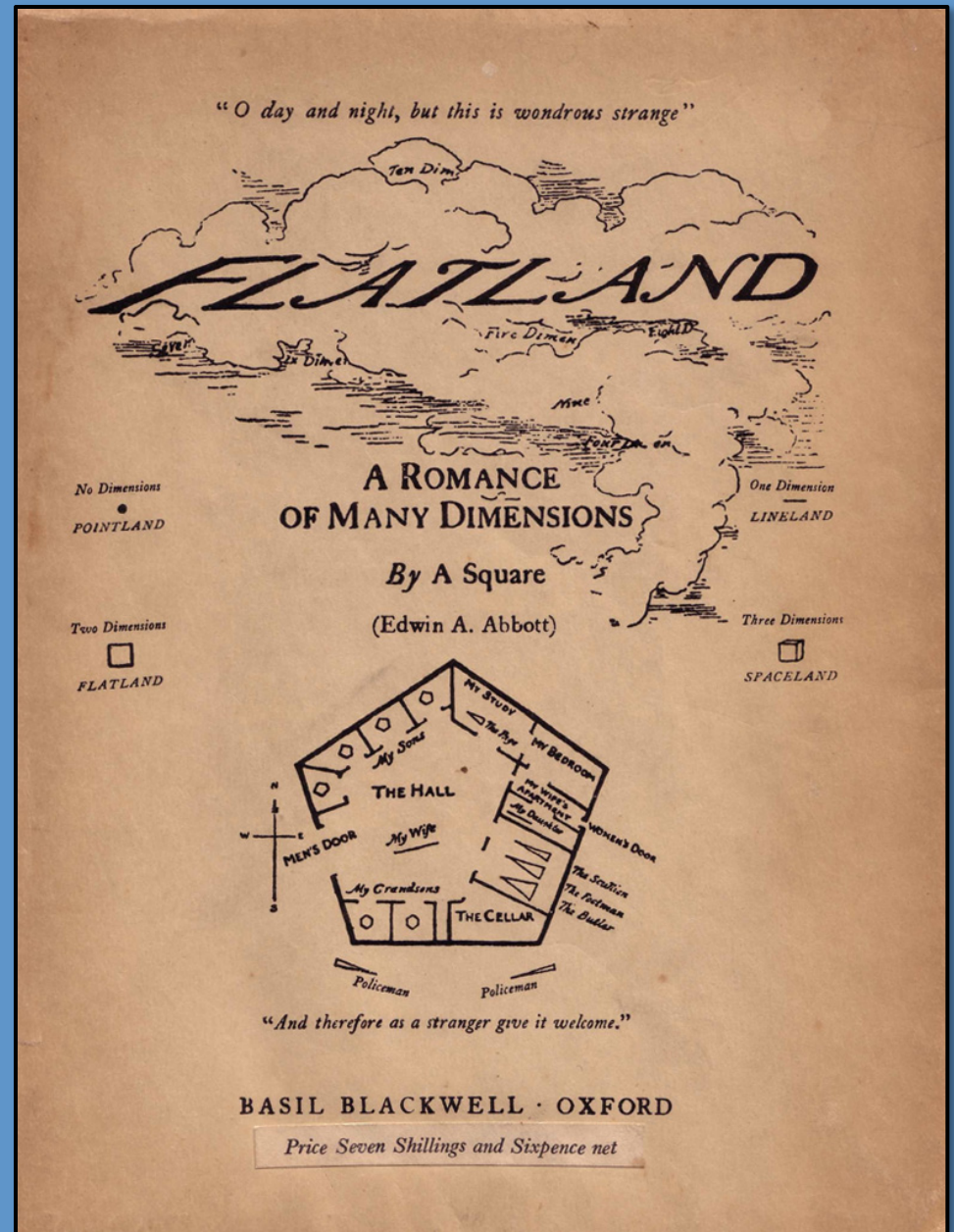
Ziet niet de 'echte' reden (4e dimensie)

Bij de LHC is er misschien genoeg energie (en deeltjes klein genoeg) om de dimensie te 'voelen'



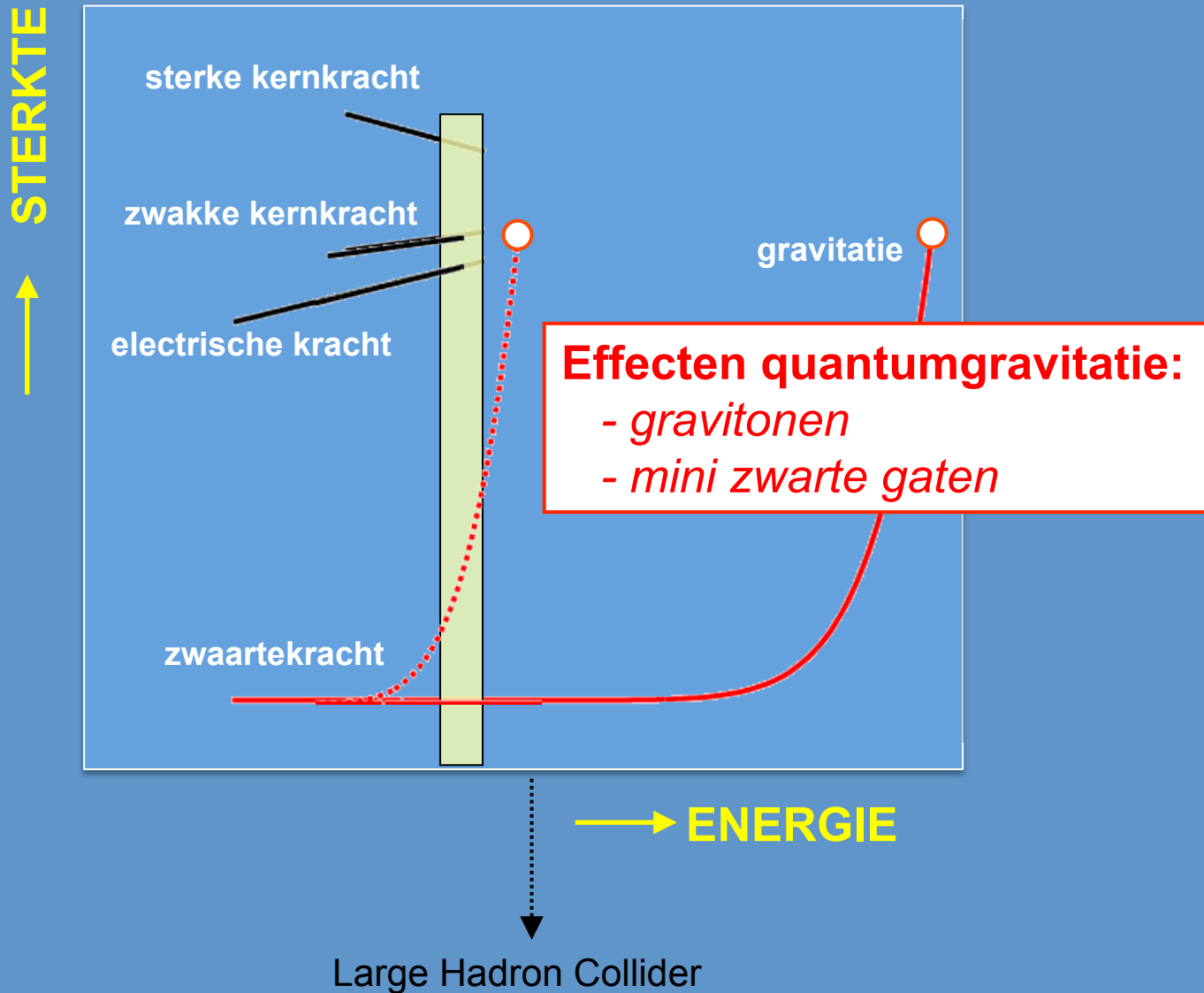
Flatland (1884)

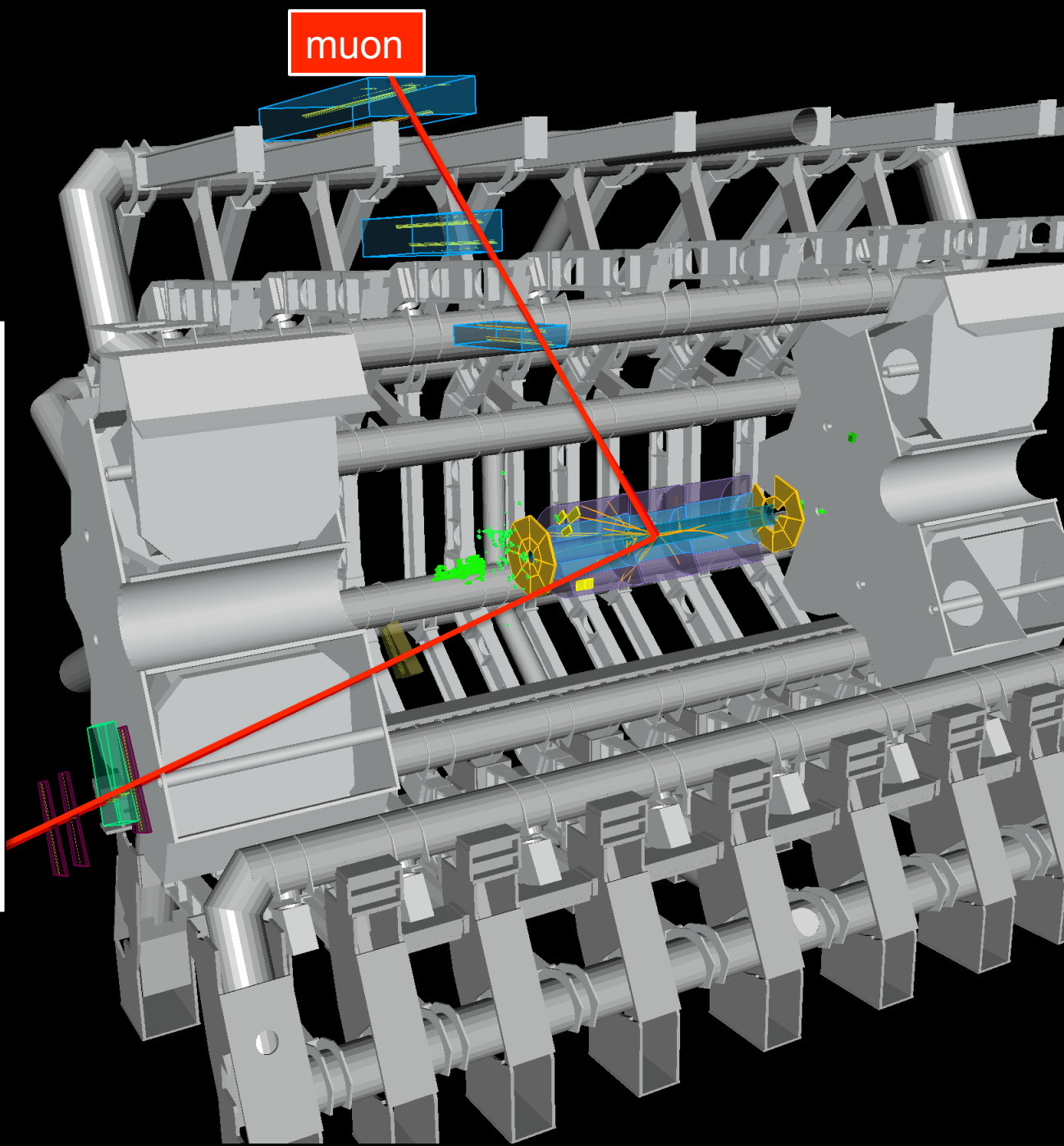
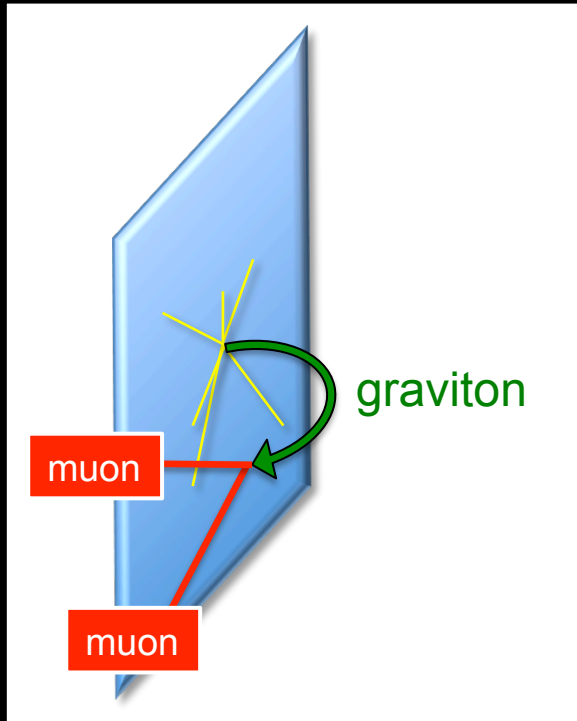
Edwin A. Abbott



€3,99 bij bol.com

# De 4 natuurkrachten





muon

muon

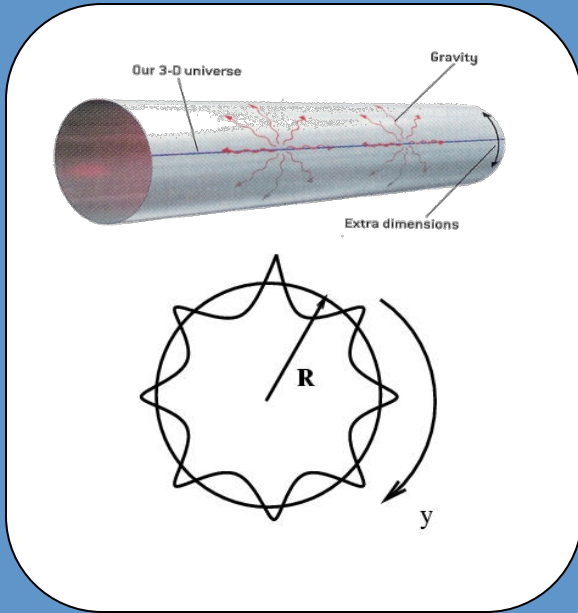
muon

graviton

muon



# Hoe 'zie' je de extra dimensies ?

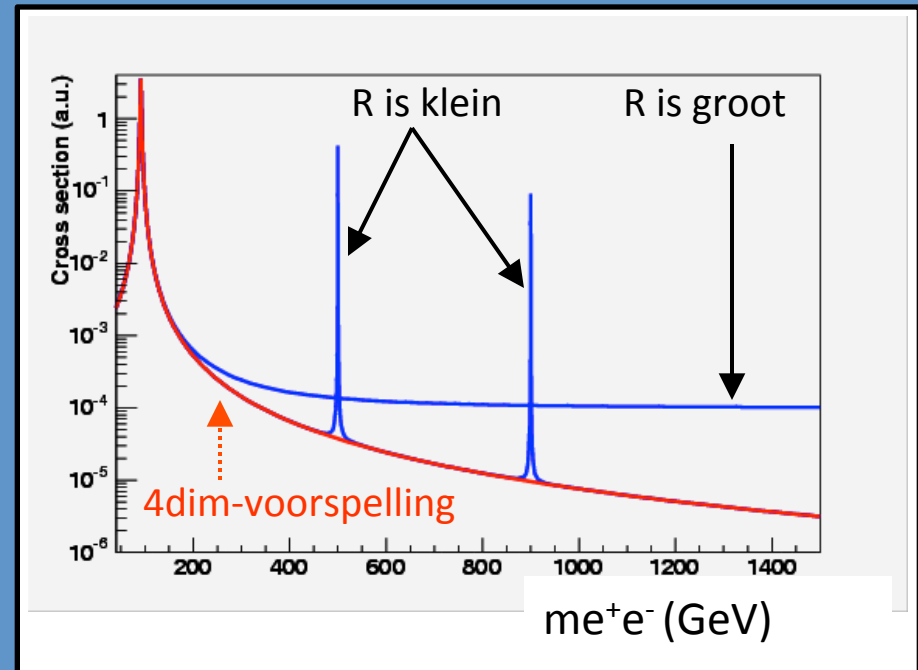
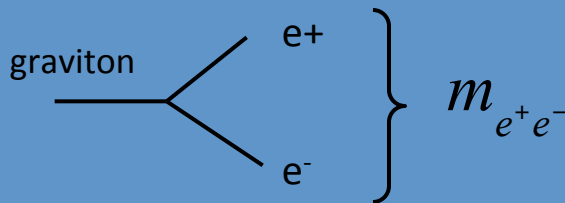


**4+n dimensies:** massaloos graviton met impuls  $p_i$   
(gequantiseerd) in extra dimensie

**4 dimensies:** massief graviton met massa  $m_i$

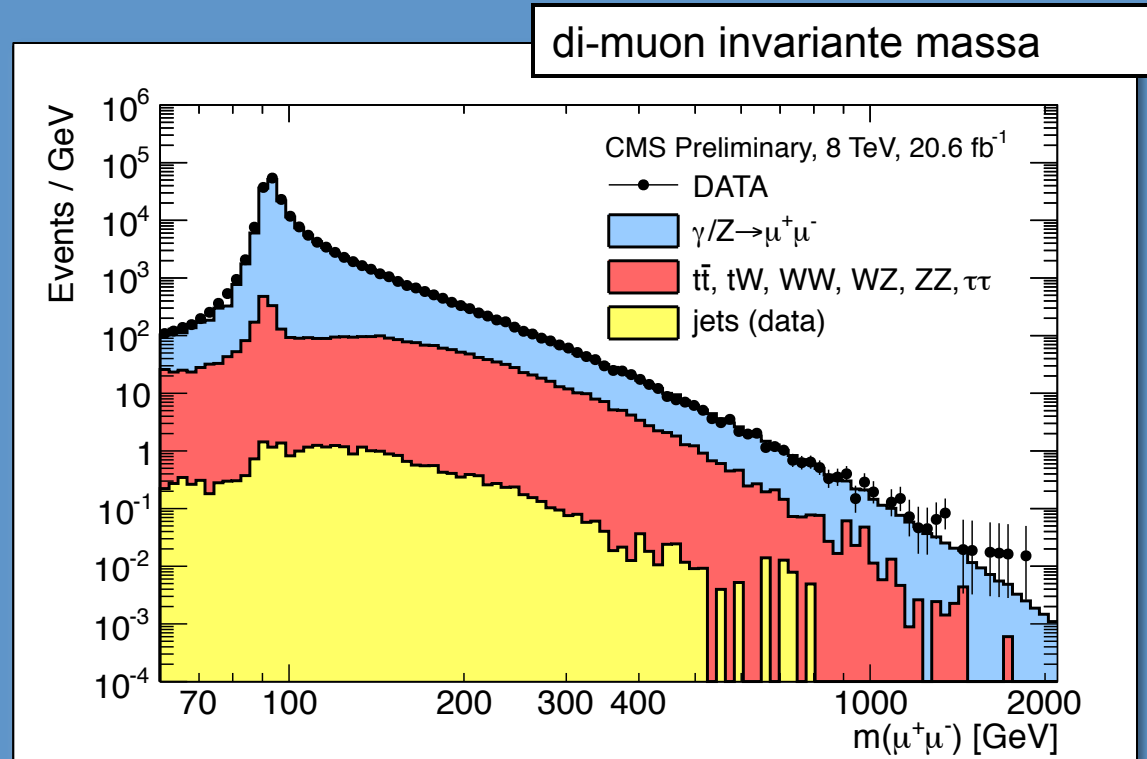
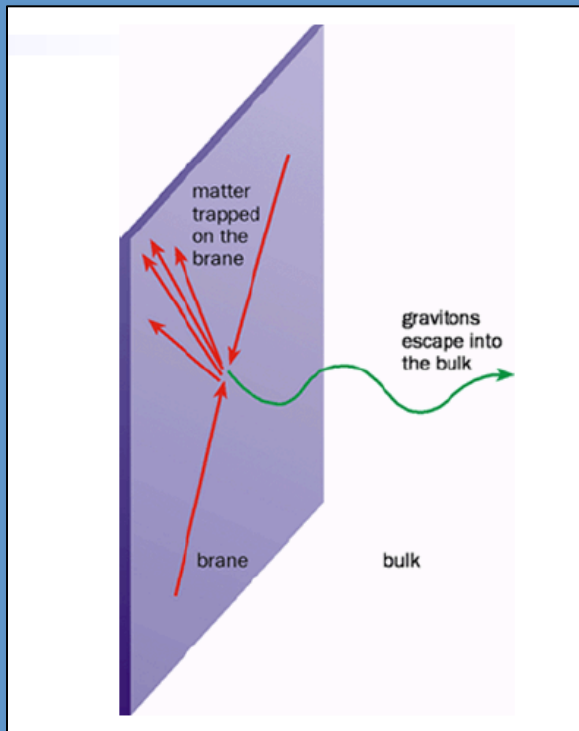
## De experimentele signatuur:

- Gravitonen vervallen in **alle** deeltjesparen
- Experimenteel schoonste verval is  $G \rightarrow e^+e^-$

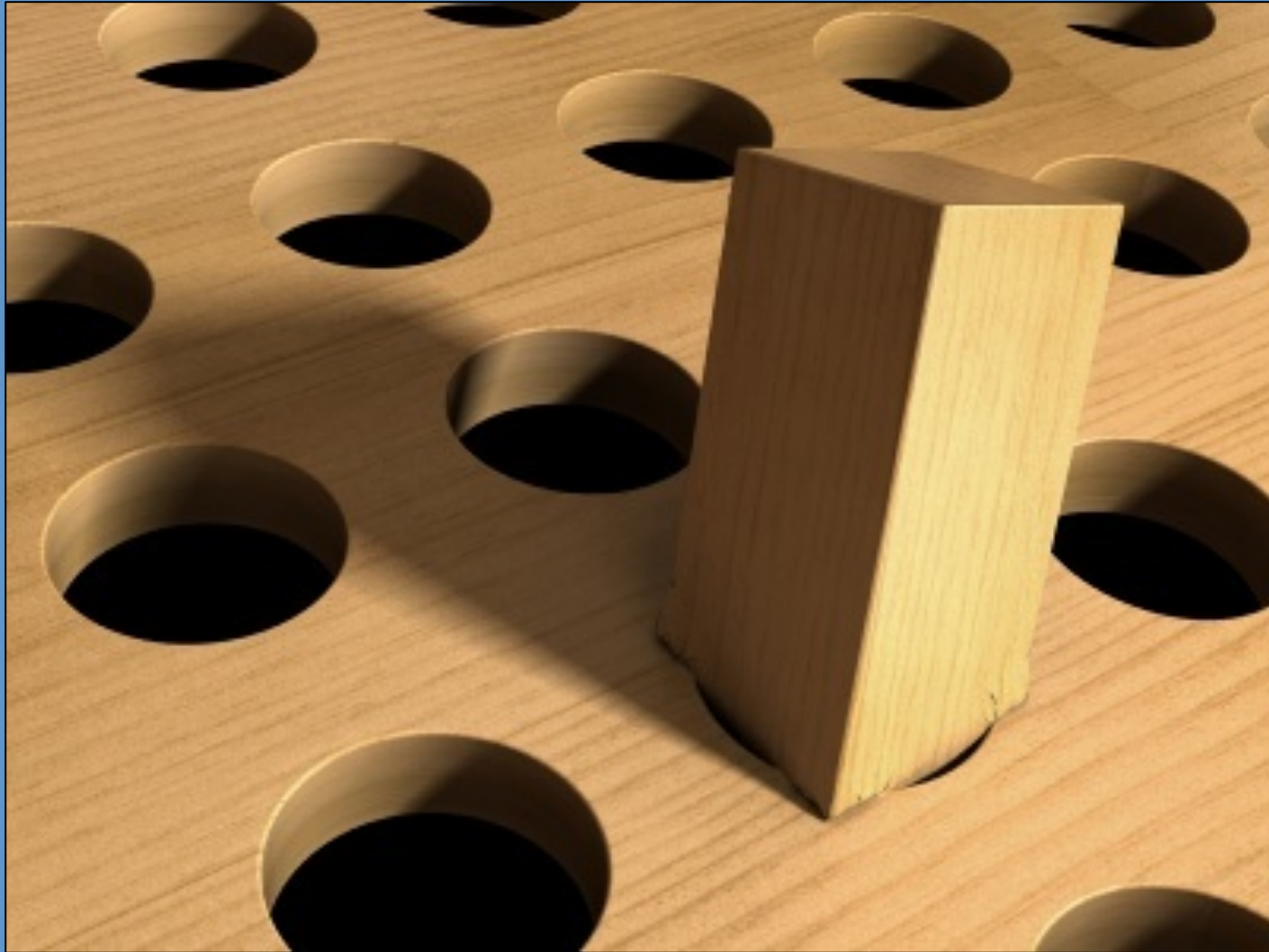


# Extra dimensies: (1) Kaluza-Klein excitaties

Excitatie van gravitonen zichtbaar als piekjes in massaspectrum

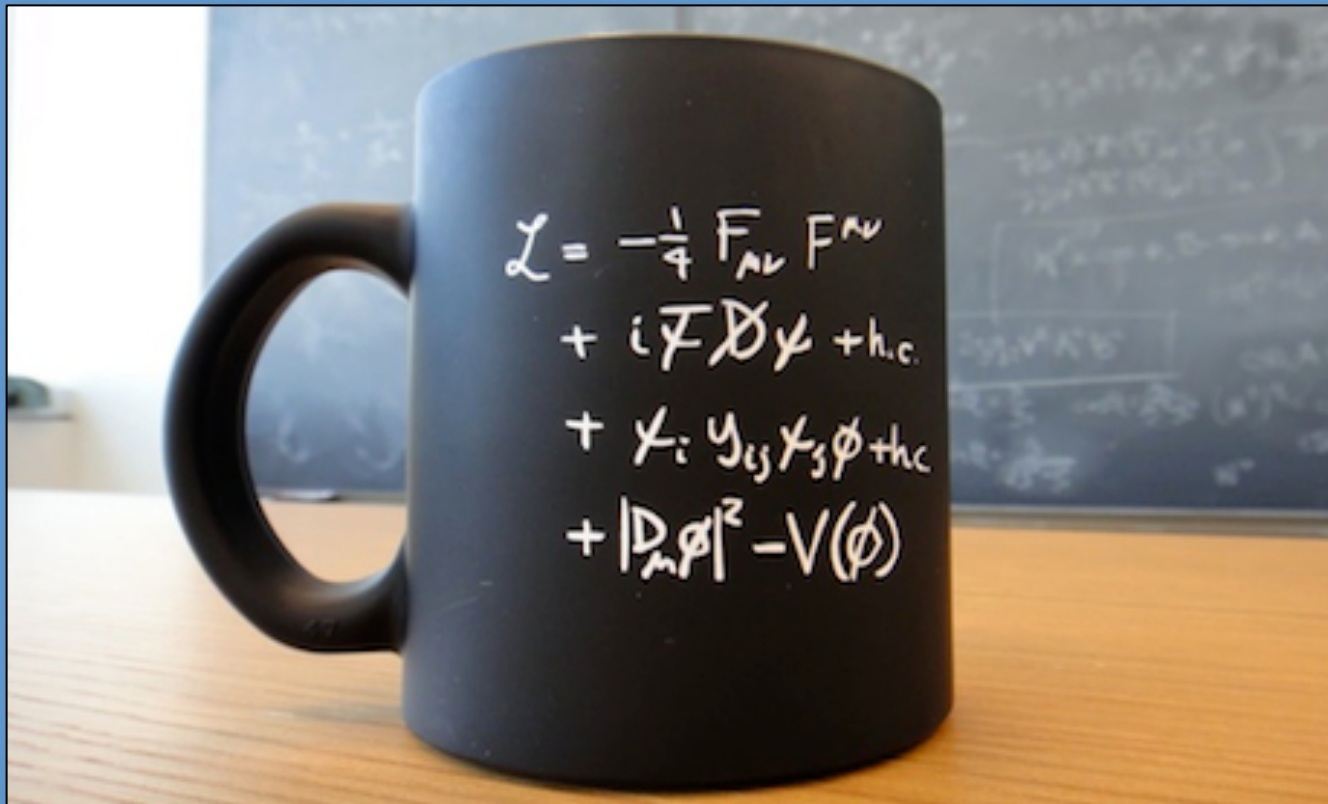


Nu wel doordringen in de extra dimensie ?





# De wereld van het allerkleinste



# De wereld van elementaire deeltjes

Standaard Model werkt prima

Higgs boson is ontdekt

Grote open vragen?