

# Neutrino's and astronomie

Maarten de Jong  
HOVO, Leiden – 2010

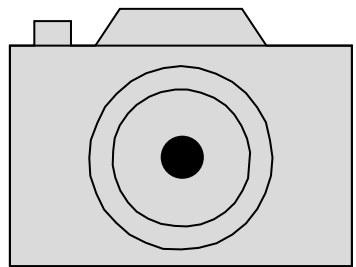
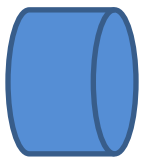
Wat is een neutrino?

# Radioactief verval (~1920)



elektron

magneet



detector

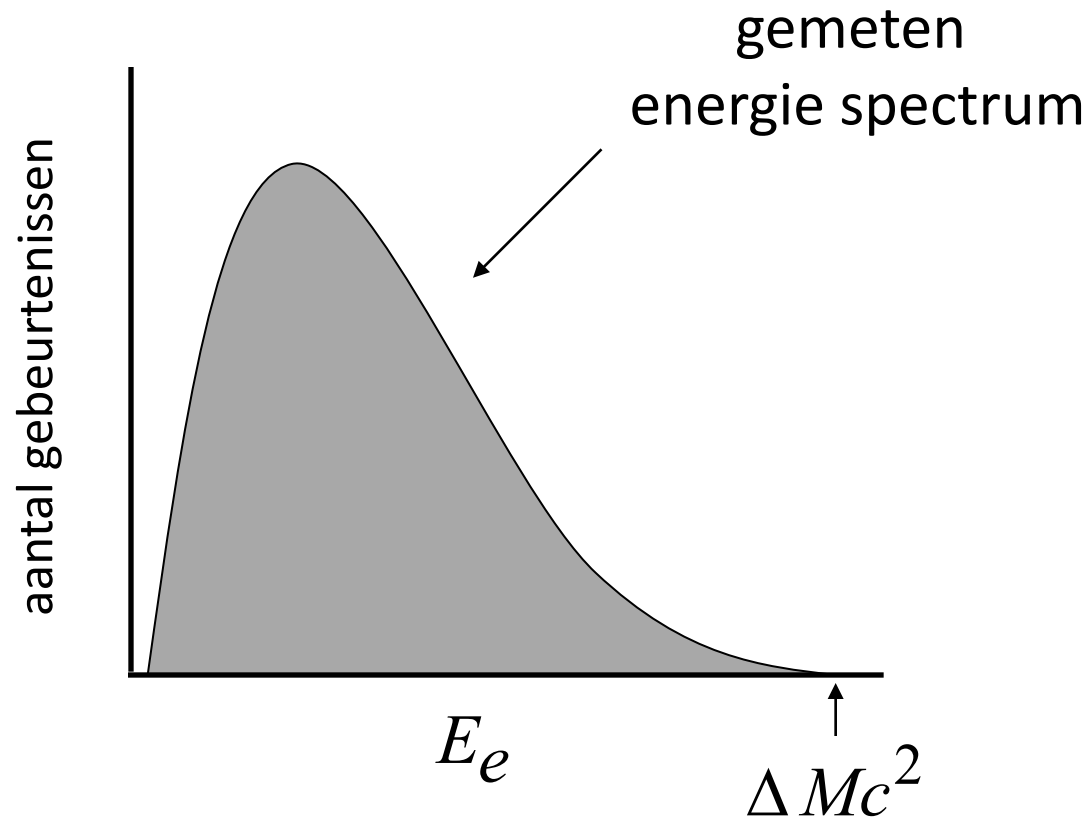
2-deeltjes verval?



Einstein:

$$E_e = \Delta Mc^2$$

# Radioactief verval (II)



Energie niet behouden?

Geachte radioactieve dames en heren,

Ik heb misschien een oplossing gevonden om de wet van energie behoud te redden.

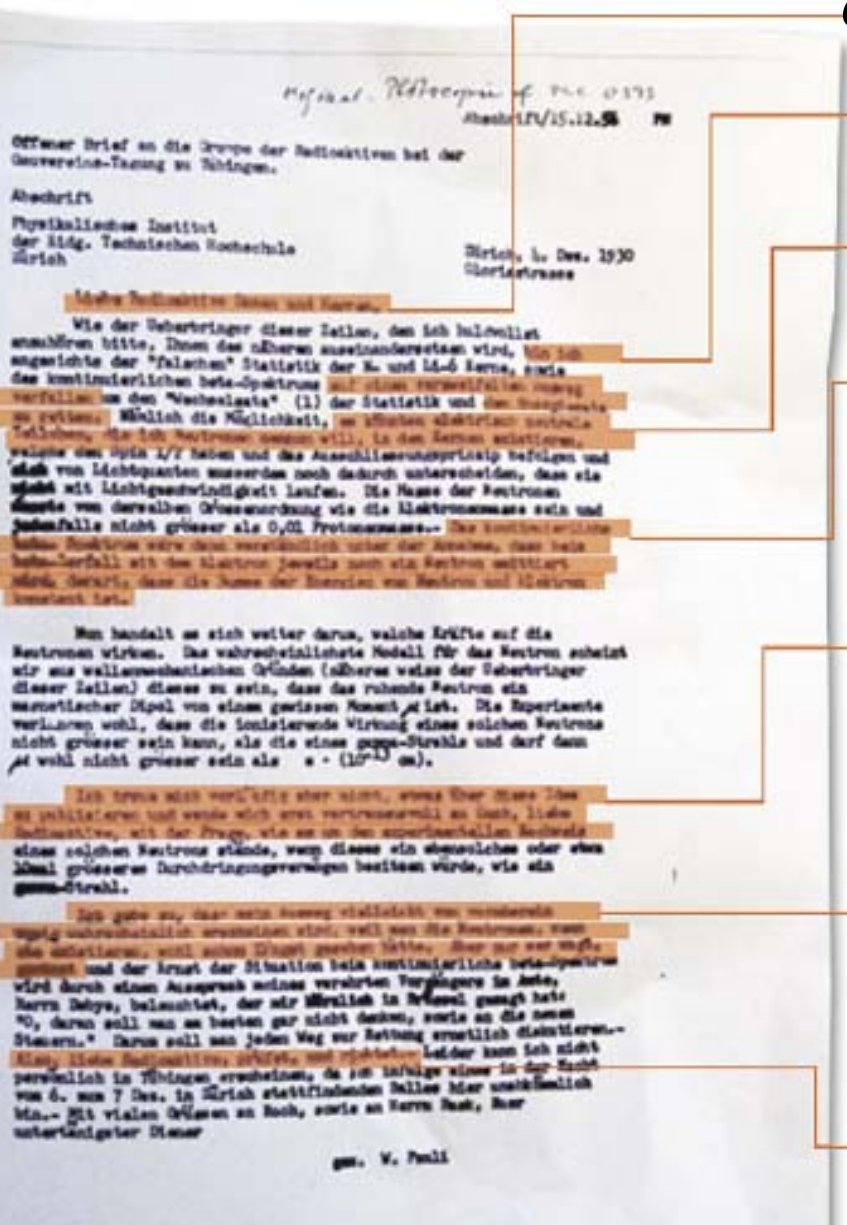
... het bestaan van onzichtbare deeltjes –welke ik aldus neutronen noem– in de atoom kern.

Het gemeten spectrum kan verklaard worden als zo'n onzichtbaar deeltje ontsnapt tegelijkertijd met het elektron zodat de totale energie klopt.

Maar tot nu toe heb ik dit niet durven publiceren en vraag ik u – radioactieve mensen – of het mogelijk is om het bestaan van dit deeltje experimenteel aan te tonen.

Ik geef toe dat dit idee onwaarschijnlijk is omdat de neutronen – als ze bestaan – al veel eerder gezien zouden moeten zijn...

Dus, geliefde radioactieve mensen, denk hierover na en oordeel.

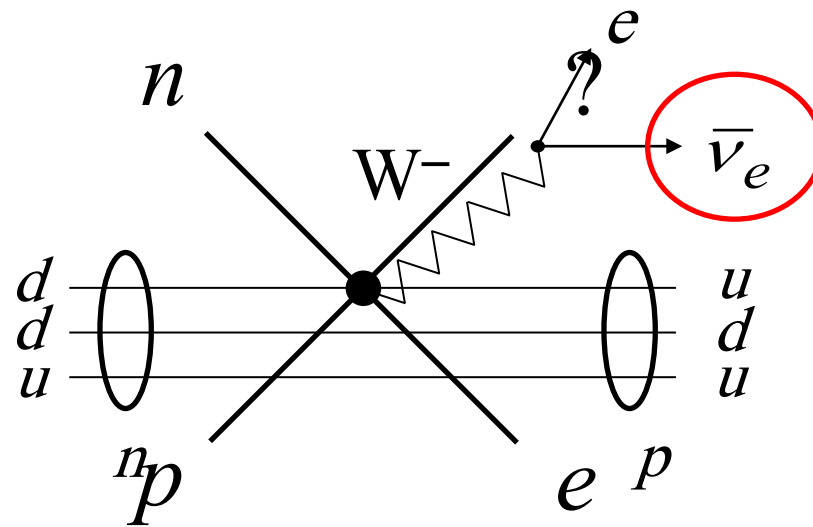


Pauli (1930):  $n \rightarrow p + e + \bar{\nu}_e$

Fermi:

Theorie van de zwakke kracht

neutrino



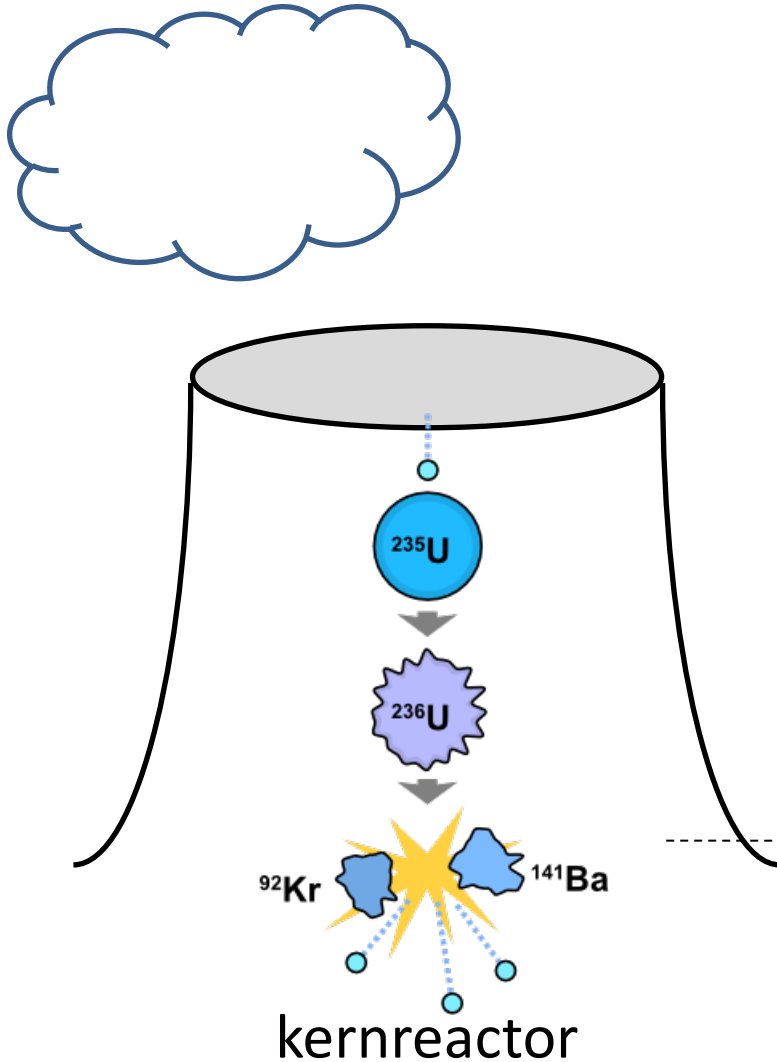
Feynman diagram

# 1950 – Reines & Cowan

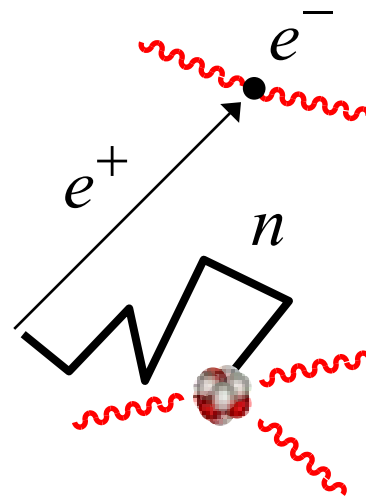
## “Poltergeist”, Savannah River



Het bewijs van het bestaan van neutrino's



$\bar{\nu}_e$



neutrino detectie

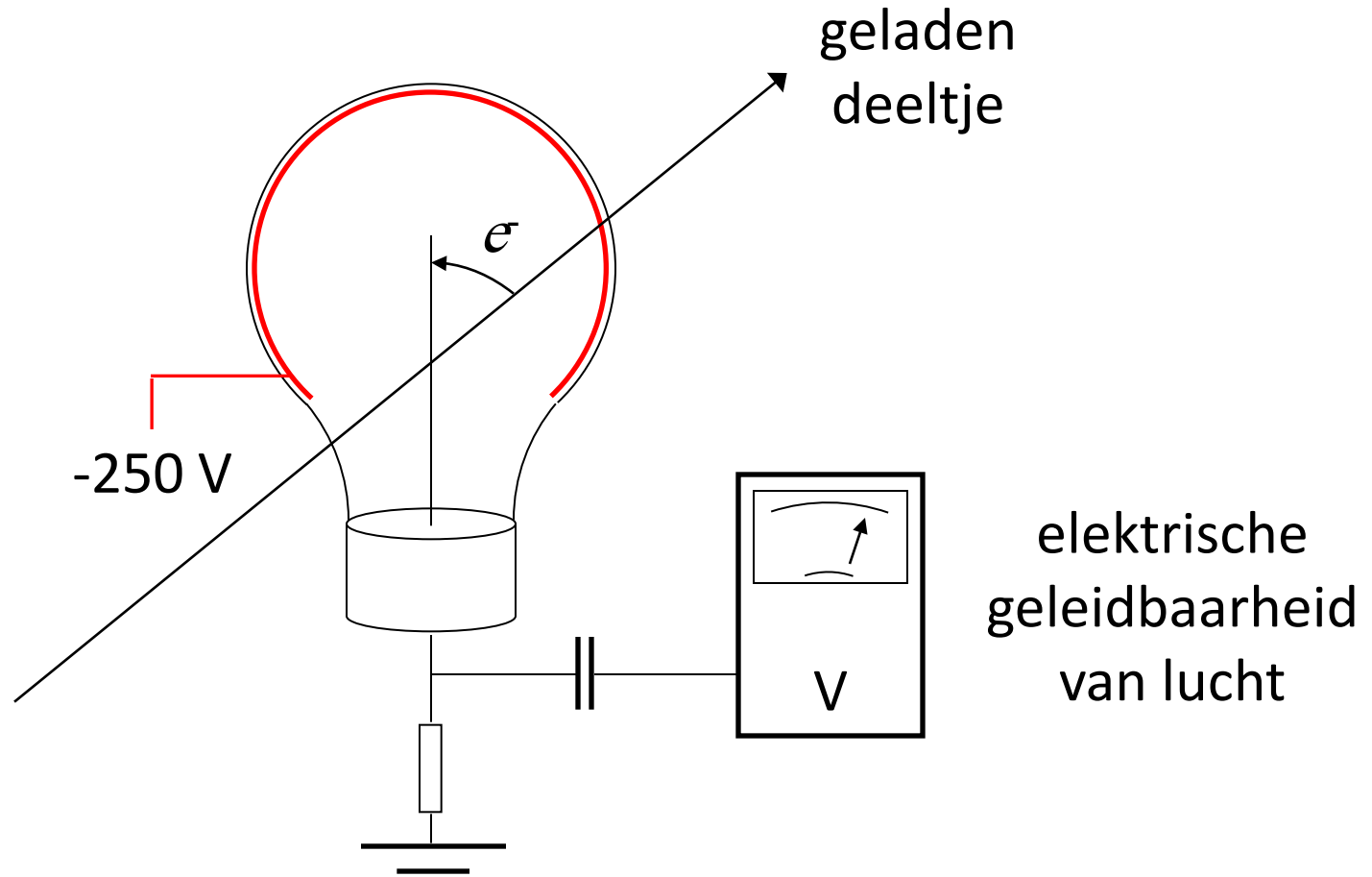


Neutrino  
astronomie



kosmische straling

# Ionisatie kamer (~1910)

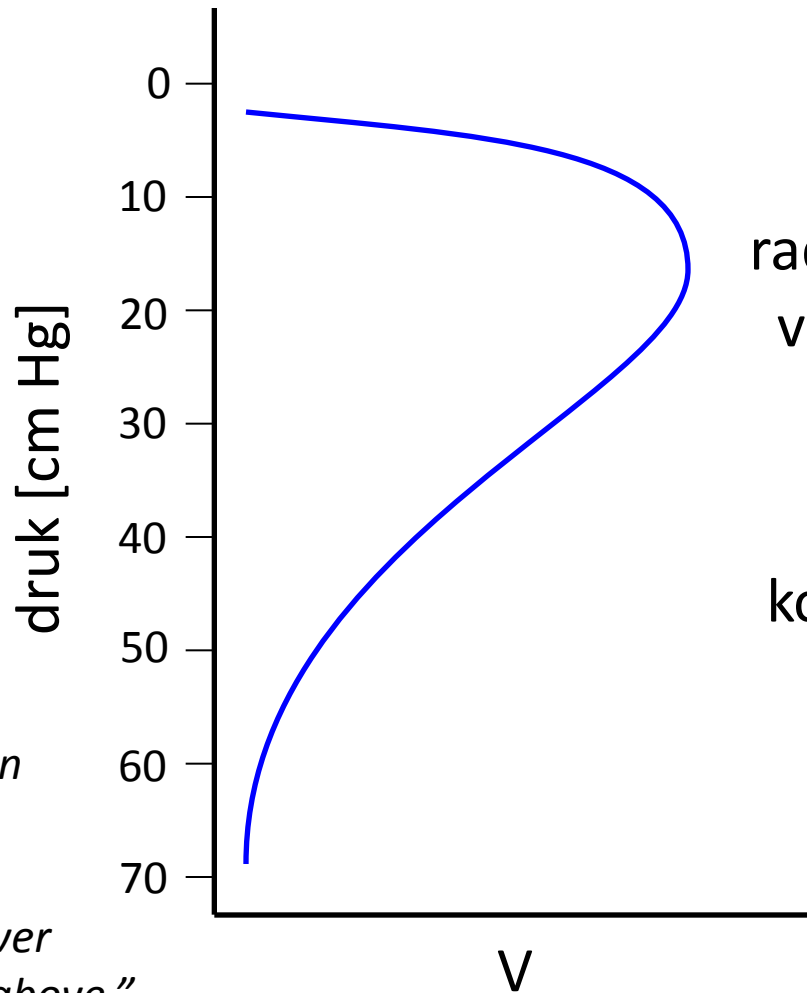


radioactiviteit van de Aarde?

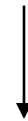
# V. Hess (1912)



*"The results of my observation are best explained by the assumption that a radiation of very great penetrating power enters our atmosphere from above."*



radioactiviteit komt vanuit de ruimte!



kosmische straling

Aarde

# P. Auger (1938)

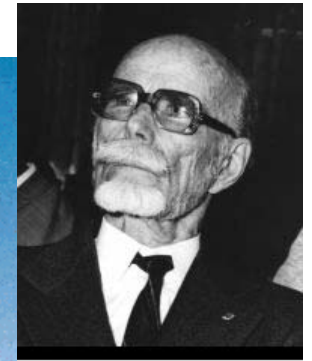
## Extensive Cosmic-Ray Showers

PIERRE AUGER

In collaboration with

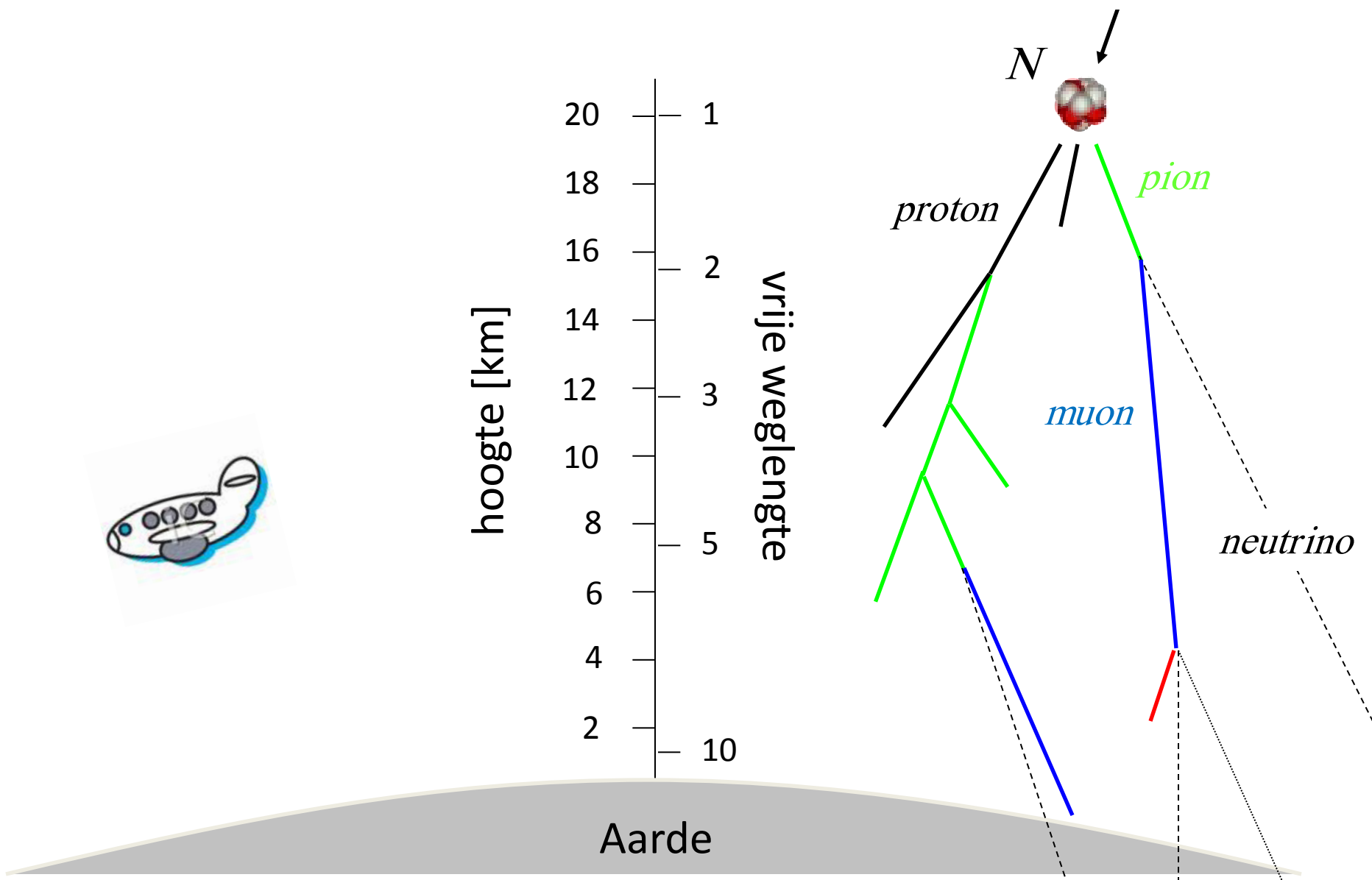
P. EHRENFEST, R. MAZE, J. DAUDIN, ROBLEY, A. FRÉON  
*Paris, France*

One of the consequences of the extension of the energy spectrum of cosmic rays up to  $10^{15}$  eV is that it is actually impossible to imagine a single process able to give to a particle such an energy. It seems much more likely that the charged particles which constitute the primary cosmic radiation acquire their energy along electric fields of a very great extension.



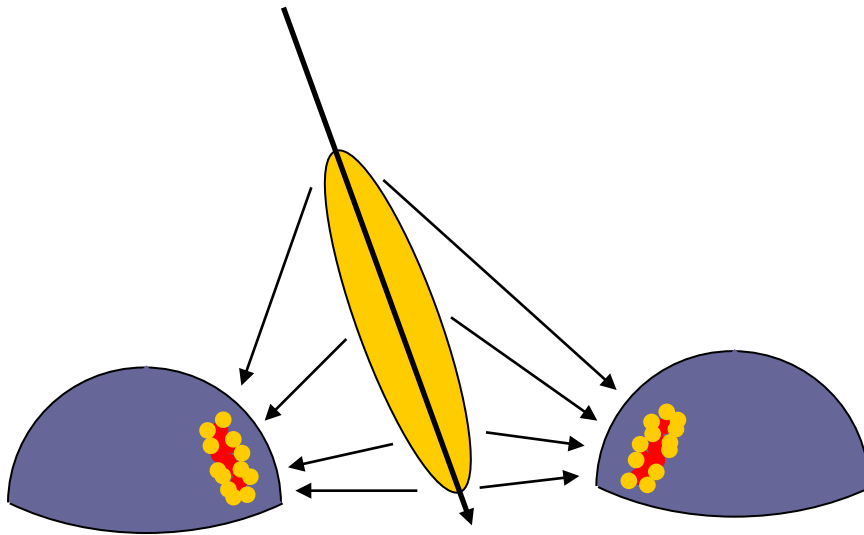
ontdekking van uitgebreide “deeltjes regens”

# Aarde gezien door kosmische straling



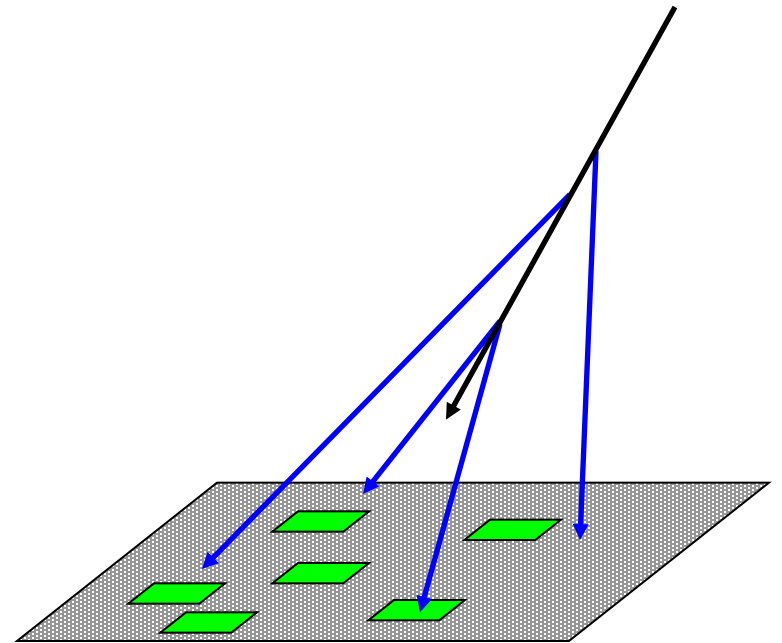
# Detectie van kosmische straling

fluorescentie  
(ultraviolet → 'zichtbaar')



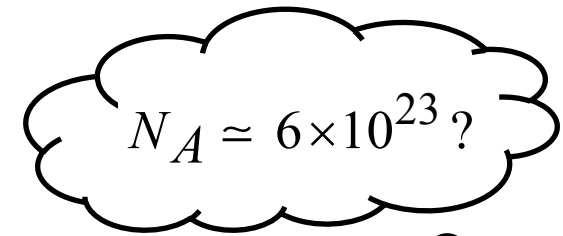
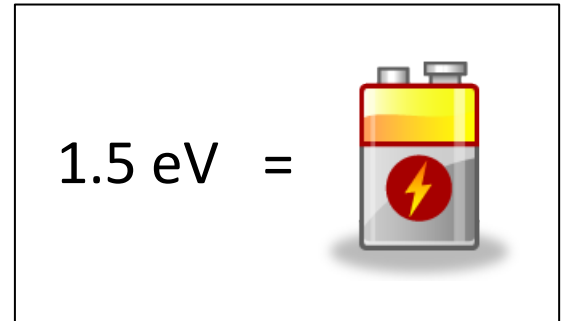
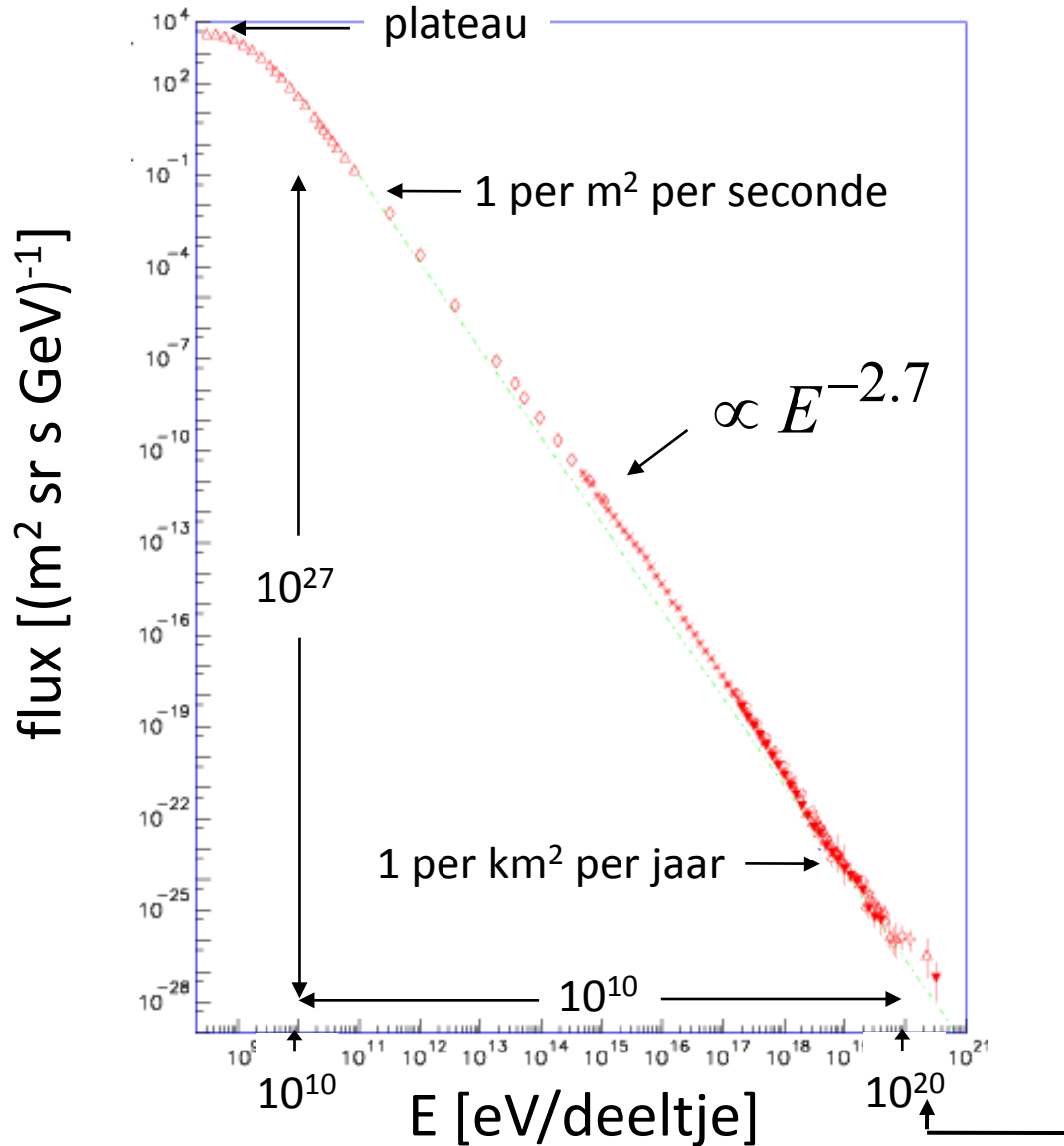
multipixel camera's  
(stereoscopisch zicht)

grond oppervalk



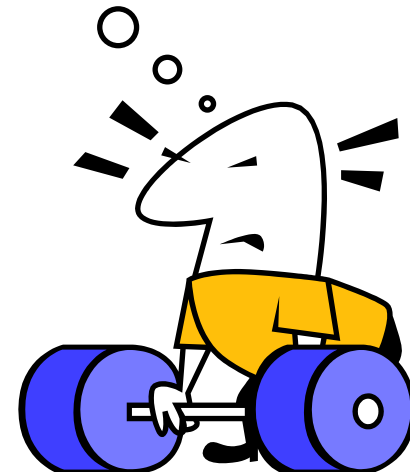
muon detectoren  
(aankomst tijden → richting)

# Energie spectrum



1 m

1 kg



impuls van het deeltje

straal v/e cirkel  $\longrightarrow$

$$R = \frac{p}{ZeB}$$

lading van het deeltje

Magnetisch veld

$$\frac{R}{a.u.} = 0.2 \frac{p}{GeV} \frac{1\mu G}{B}$$

$p \approx 1 GeV$

$\ll 1$

Afstand aarde – zon  
( $\sim 150 \times 10^6 km$ )

Magnetisch veld zon  
( $\sim 10 \mu G$ )

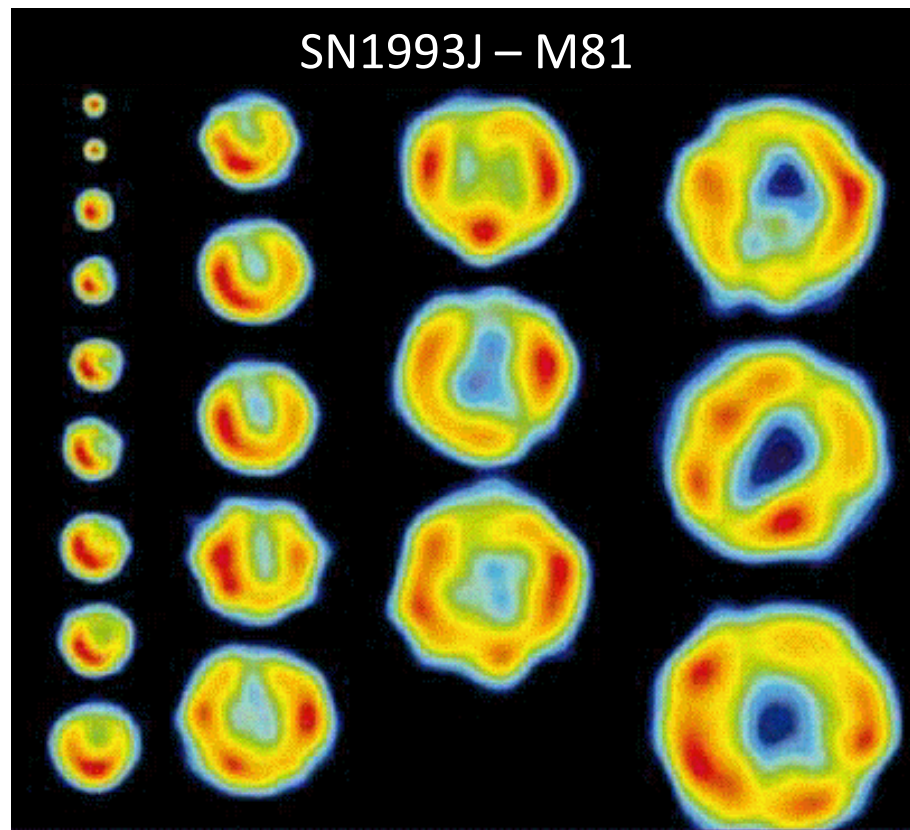


# Kosmische versnellers

*“CERN in the sky”*

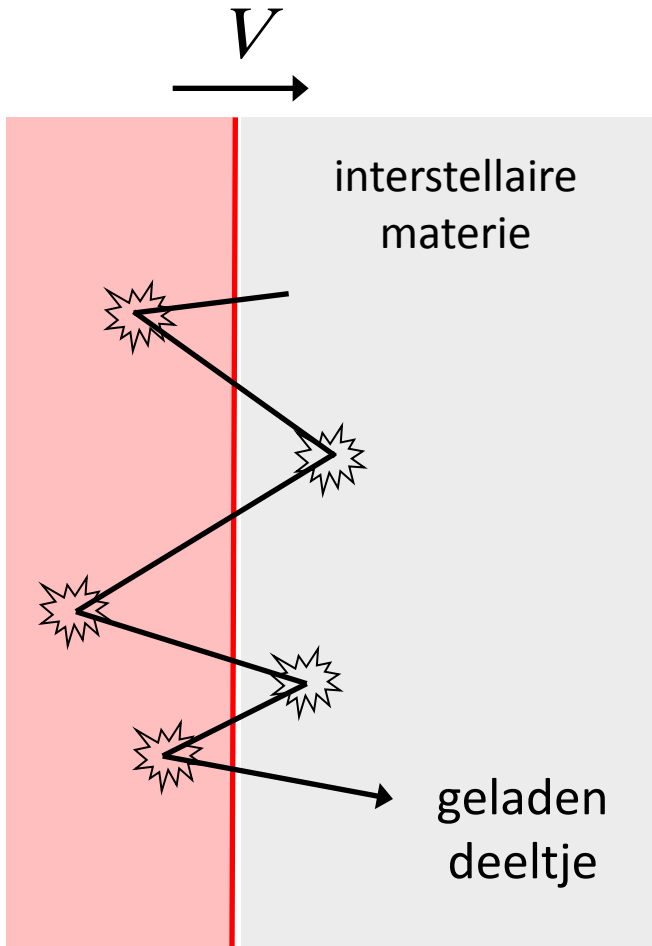
# Fermi schokgolf versneller

snelheid:  $V \approx 20000 \text{ km/s}$



radio beelden April 1993–Juni 1998

# Fermi schokgolf versneller (II)



Simpel model

versnelling

$$\Delta E = \alpha E$$

overlevings kans

$$P = \beta$$



$k$  stappen  $E = E_0 (1 + \alpha)^k$

$$N = N_0 (\beta)^k$$

# Fermi schokgolf versneller (III)

$$\frac{\ln(N/N_0)}{\ln(E/E_0)} = \frac{\ln(\beta)}{\ln(1+\alpha)}$$

$$\frac{N}{N_0} = \left( \frac{E}{E_0} \right)^{\frac{\ln(\beta)}{\ln(1+\alpha)}}$$

$$\frac{dN}{dE} \propto E^{\frac{\ln(\beta)}{\ln(1+\alpha)} - 1} = E^{-2} \approx \text{gemeten spectrum}$$

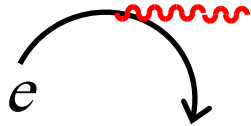
Thermodynamica

Relativiteitsleer

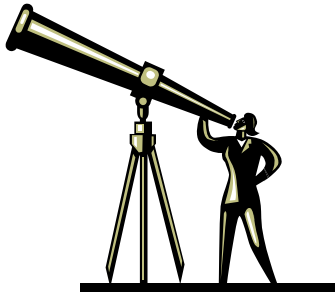
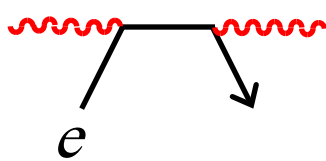
# Welke geladen deeltjes?

elektronen

Synchrotron  
straling

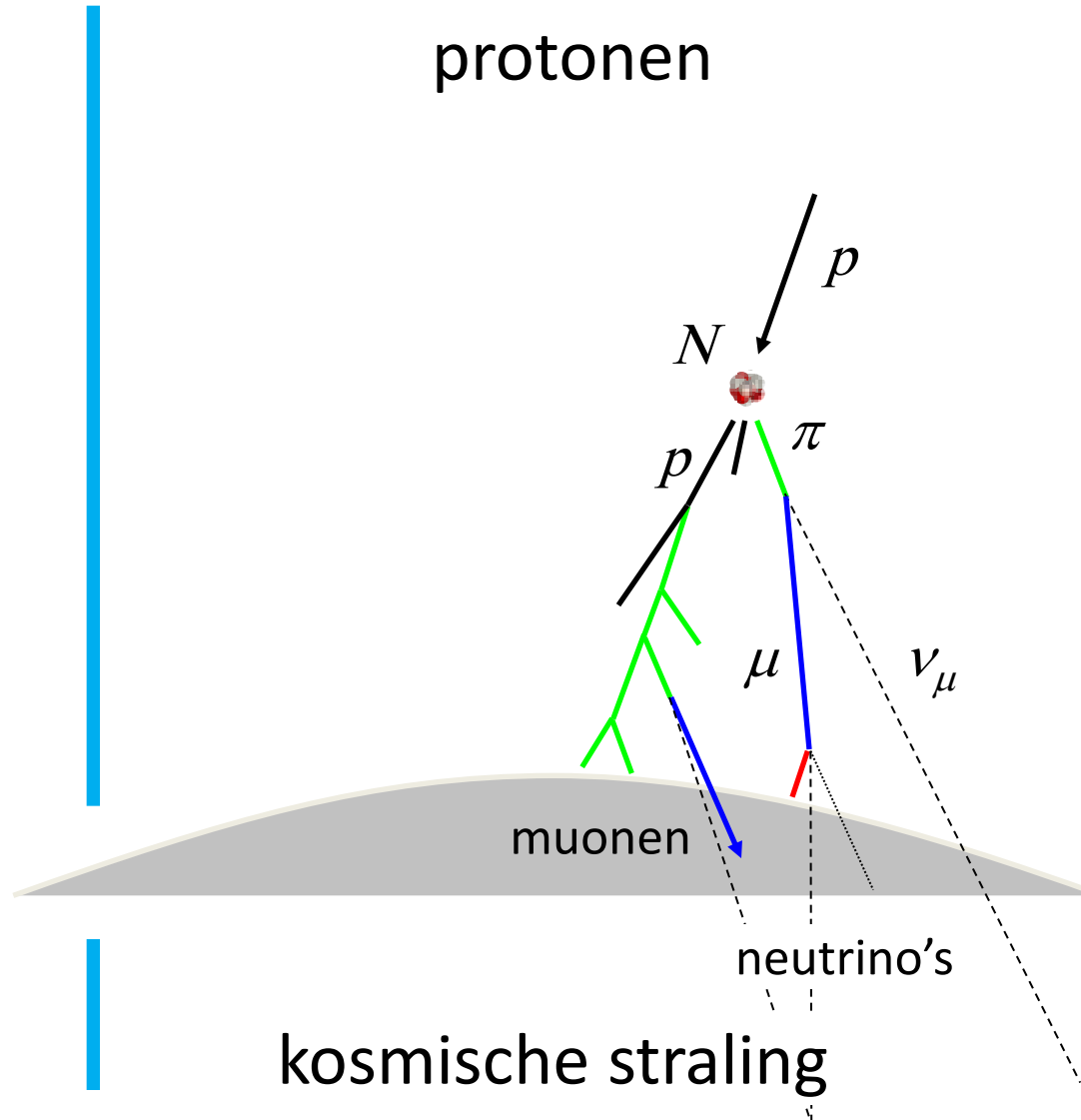


inverse  
Compton  
verstrooiing



astronomie

protonen



# Astronomie

constante van Planck

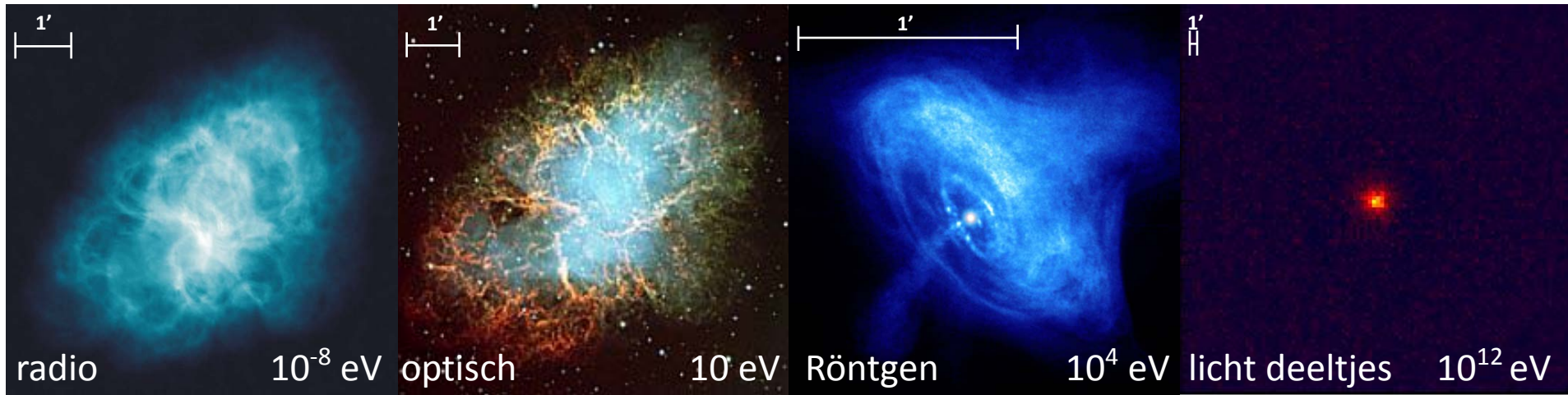
snelheid van het licht

golflengte:

$$\lambda = \frac{hc}{E_\gamma}$$

Energie van 'deeltje'

# Krab nevel

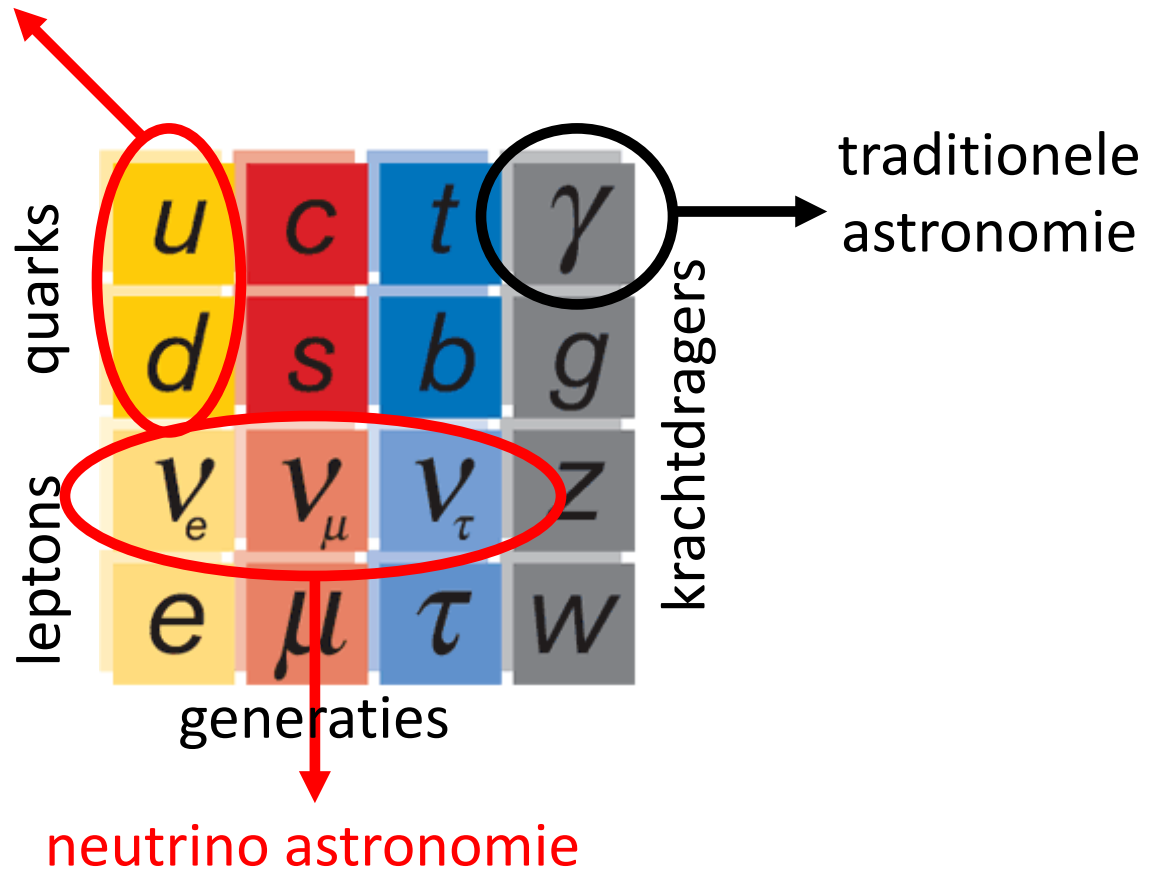


← breedbandig spectrum →

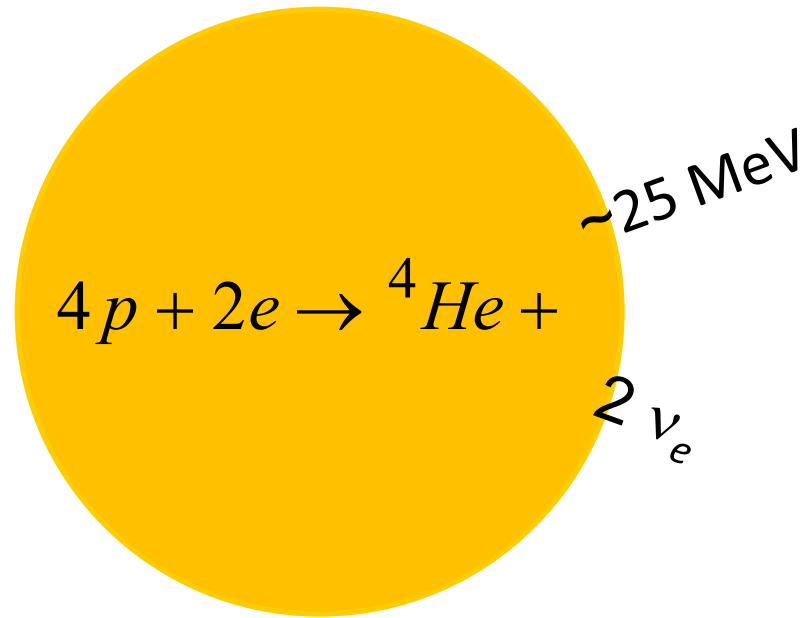


# Astro-deeltjes fysica

kosmische stralen  
(bestaan uit combinaties van  
u en d quarks)



# Zonne energie



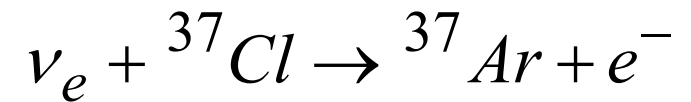
Licht oprbrengst  $L_{\odot} = 3.92 \times 10^{26} \text{ W}$

Neutrinos  $N_{\nu_e} = 2 \frac{L_{\odot}}{1.6 \times 10^{-13} \times 25 \text{ MeV}} \approx 1.8 \times 10^{38} \text{ s}^{-1}$

# Homestake goud mijn (USA)



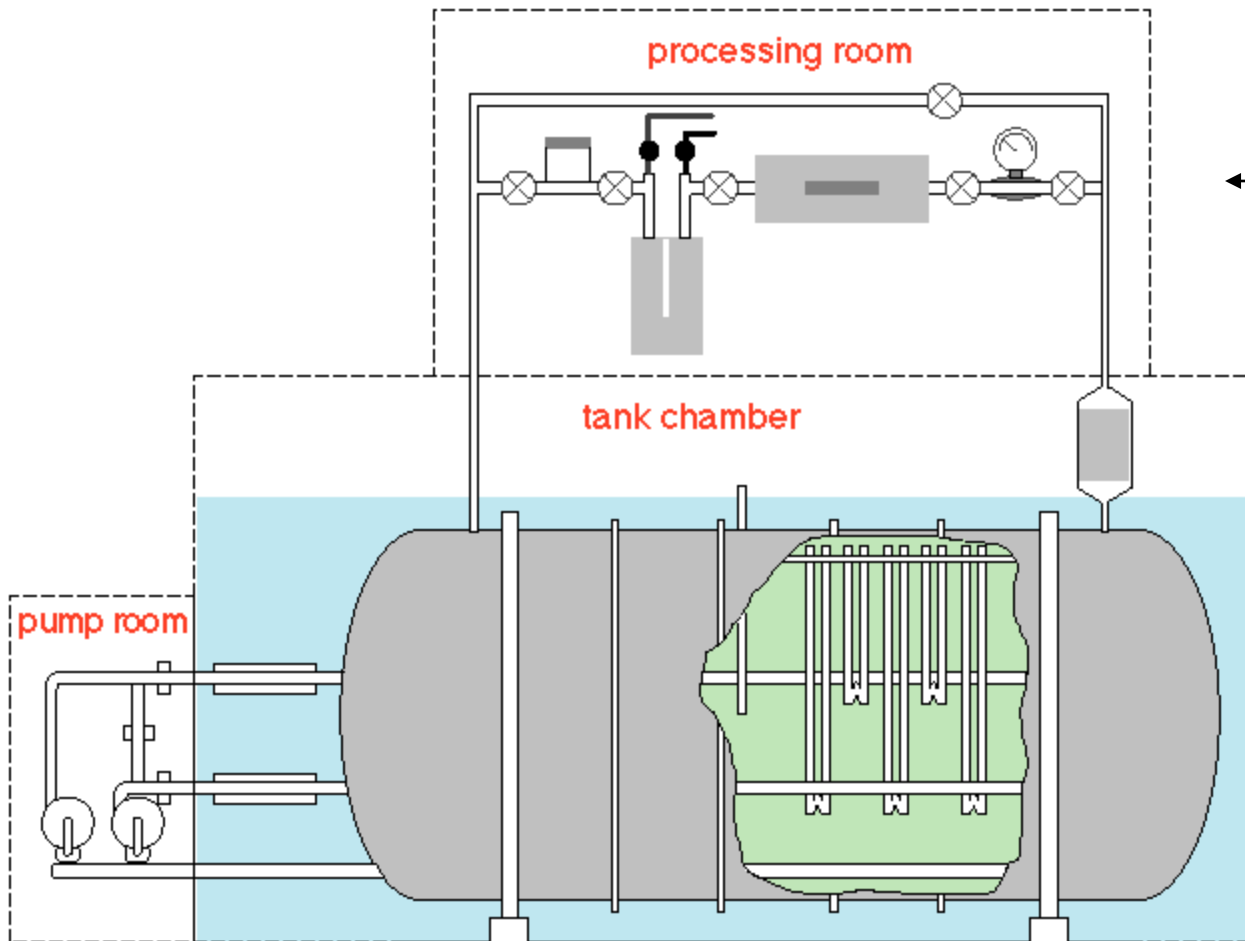
‘omgekeerd verval’



130 ton Chloor

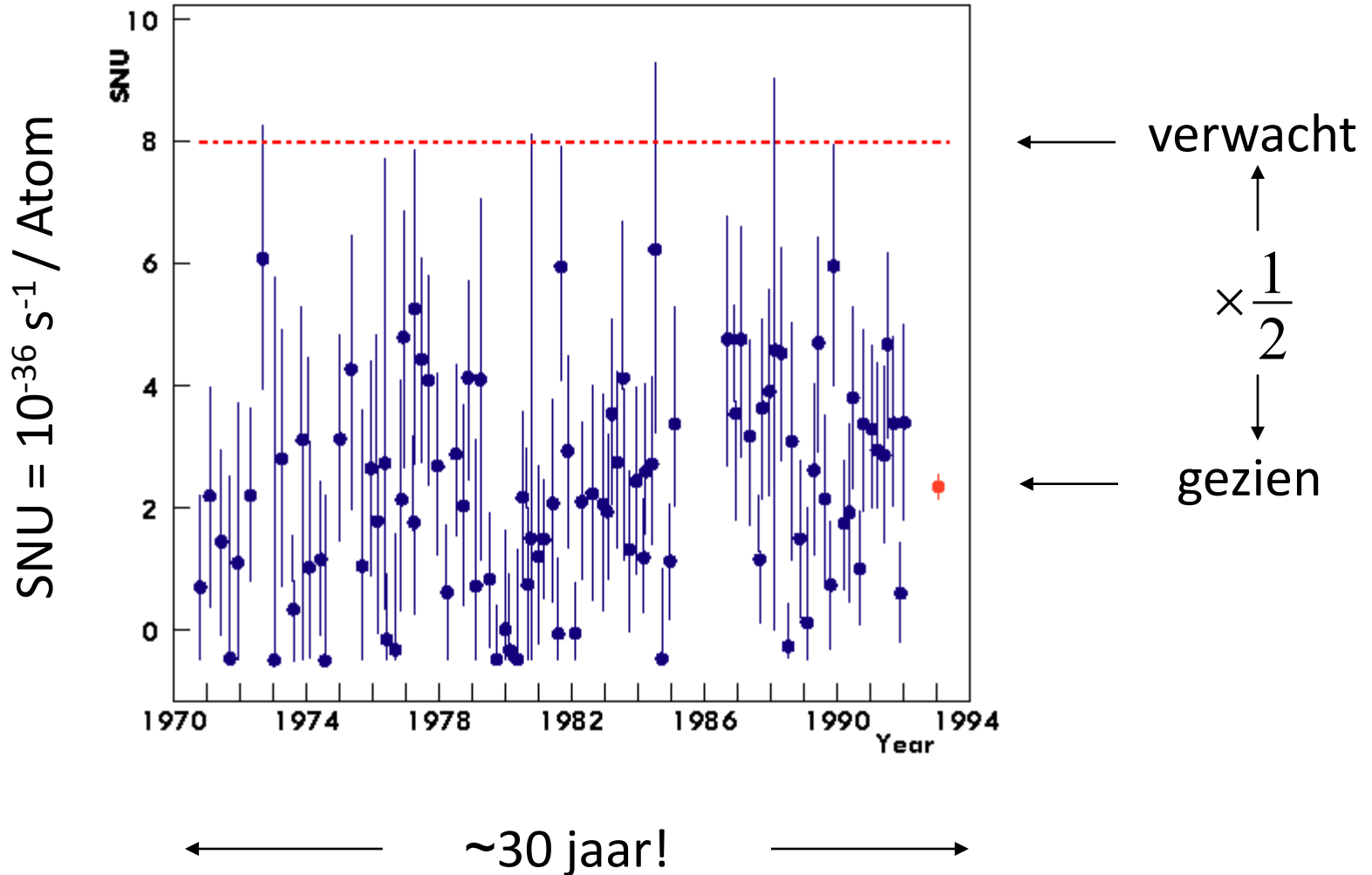
$$E_{\nu_e} \geq 0.814 \text{ MeV}$$

# detectie principe



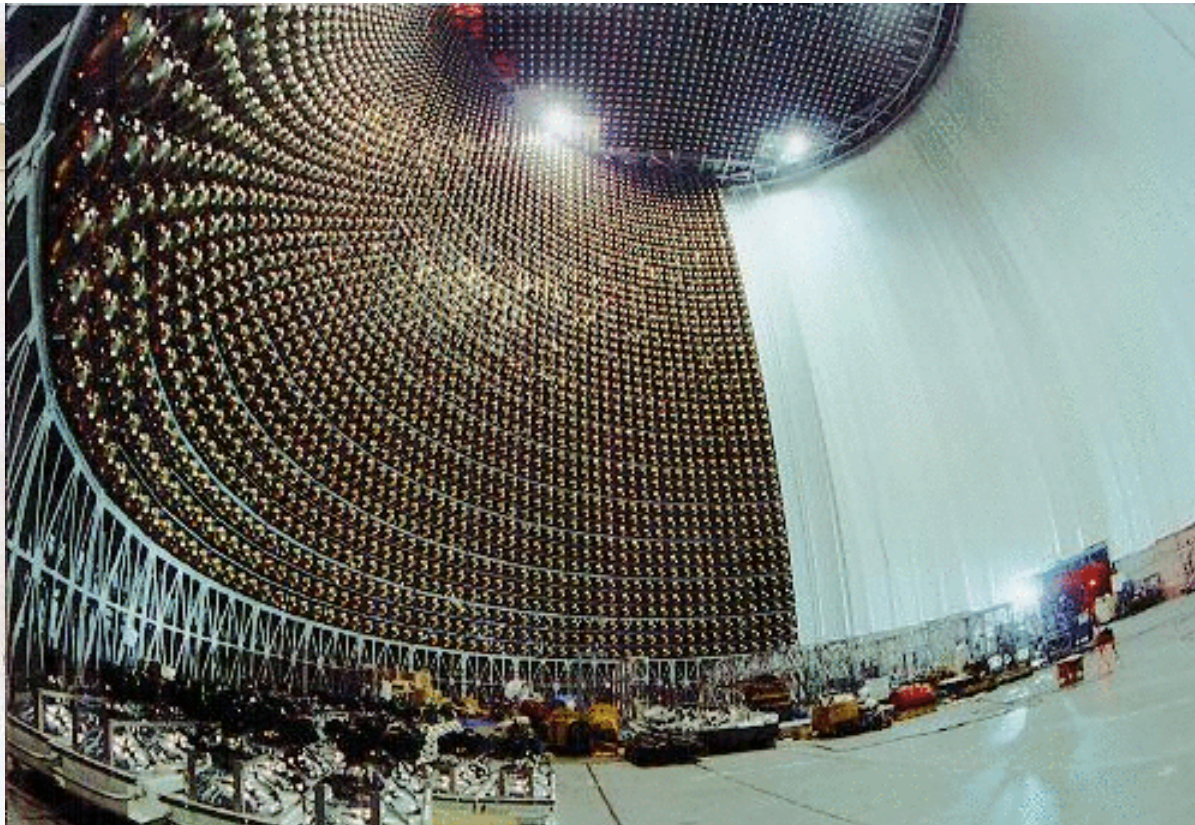
← extractie van enkele *Ar* atomen (~15 / maand)

# Neutrino's van de zon



# Super Kamiokande (Japan)

nucleon  
decay  
experiment

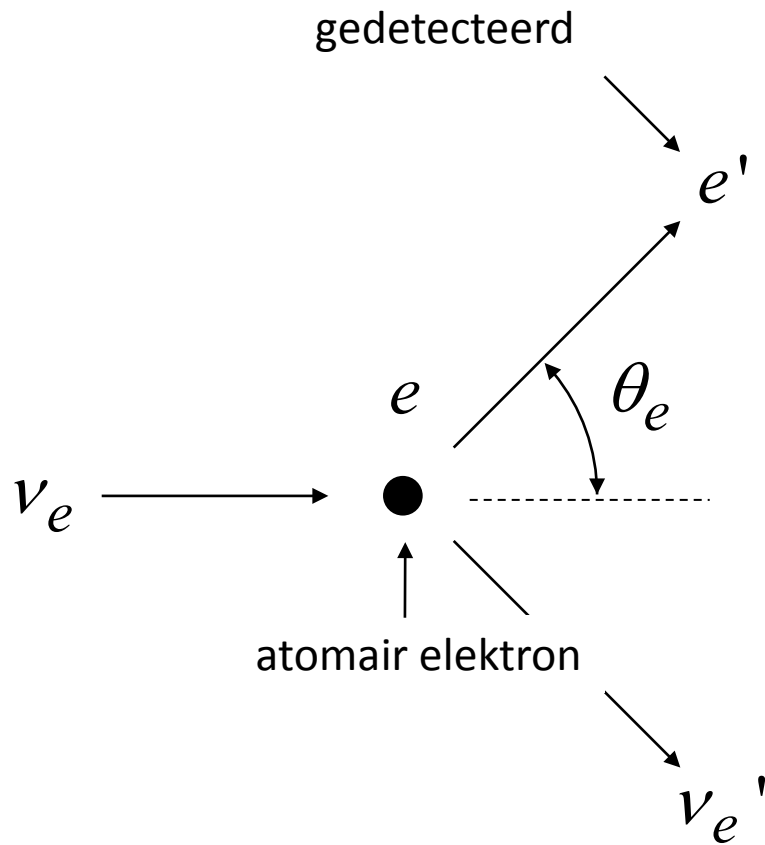


- ~50 kton puur water
- 12000 PMTs

Geen proton verval gezien

Maar Kamiokande is ook een  
neutrino detector...

# detectie principe



Energie en impuls behoud:

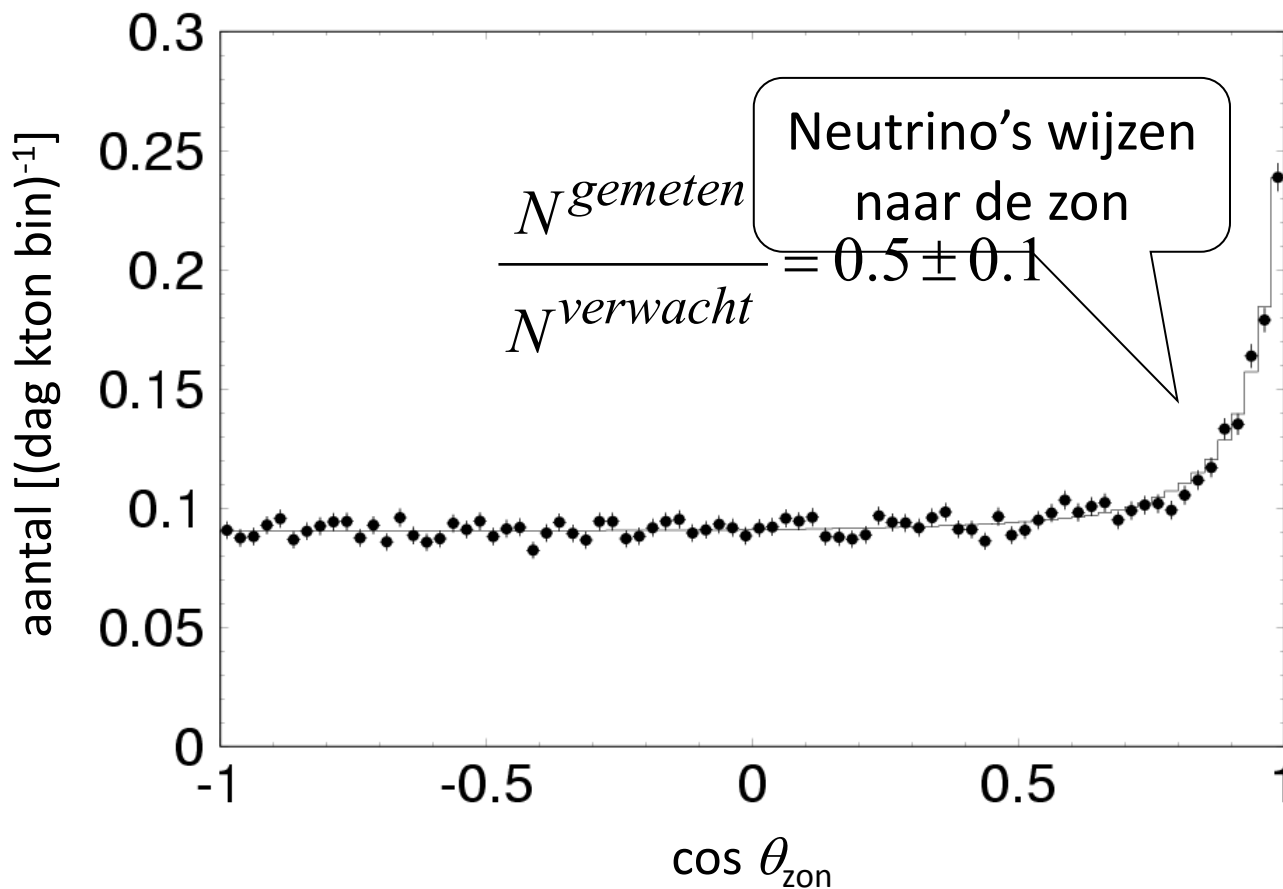
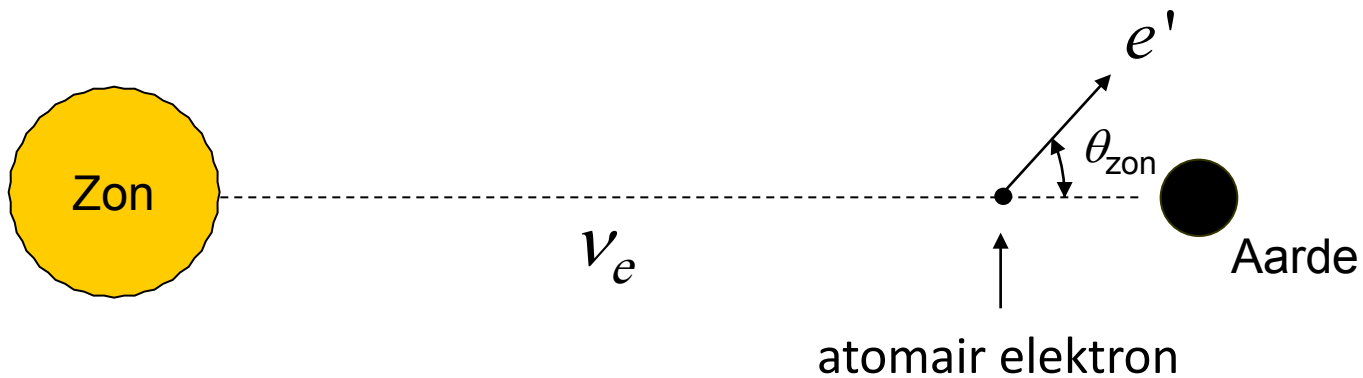
$$2 \sin^2 \frac{\theta_e}{2} = \frac{m_e c^2}{E_{e'}} \left(1 - \frac{E_{e'}}{E_{\nu_e}}\right)$$

$$\leq \frac{m_e c^2}{E_{e'}}$$

$$\theta_e \leq 30^\circ$$

neutrino telescoop





we zien  $\frac{1}{2}$  neutrino's uit de zon

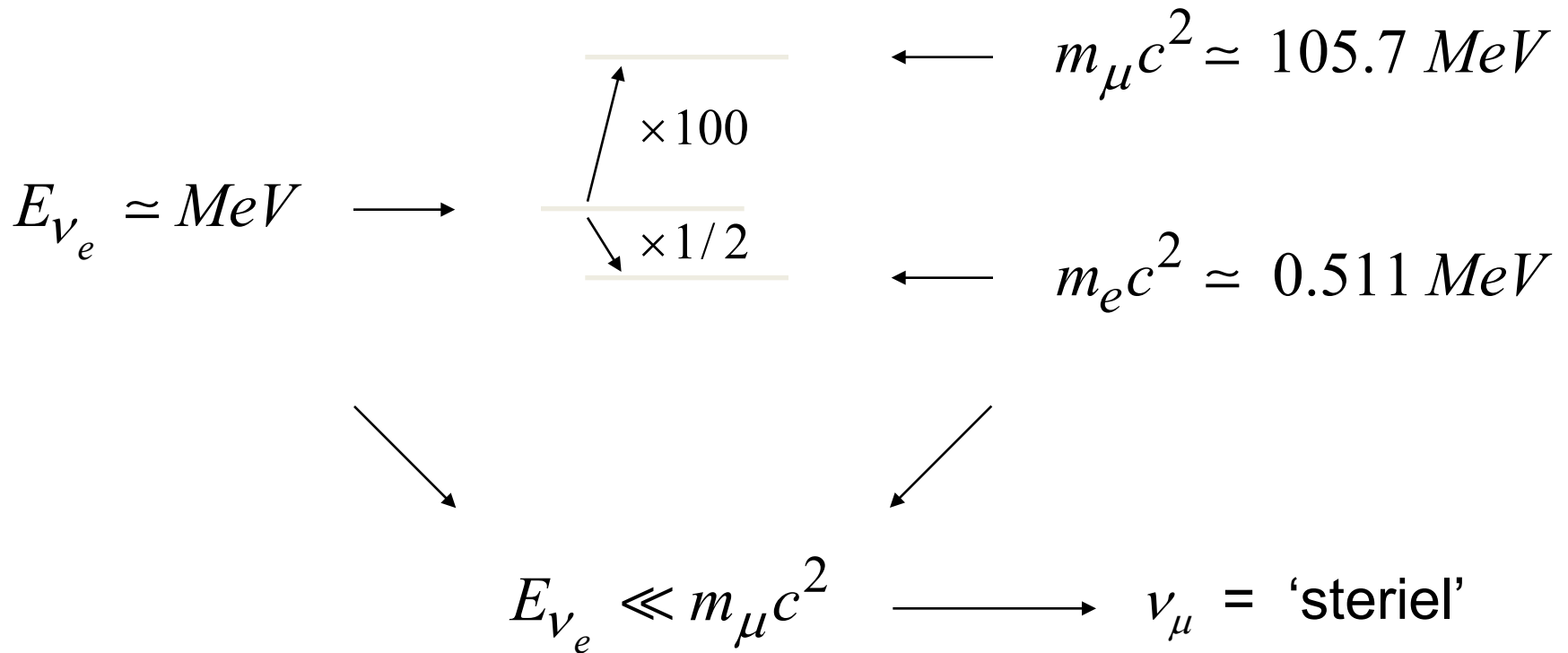
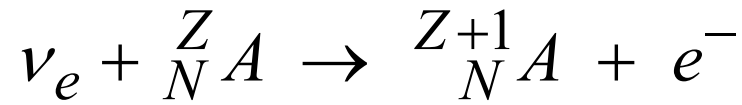


neutrino oscillaties<sup>¶</sup>

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<sup>¶</sup> B. Pontecorvo, 1957

# Energie drempe



# Mengen van neutrino toestanden

zwakke  
toestanden

massa  
toestanden

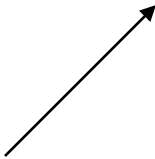
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

3x3 matrix  
(unitair)

# Mengen van 2 toestanden

$$\begin{pmatrix} v_1 \\ v_2 \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \times \begin{pmatrix} v_e \\ v_\mu \end{pmatrix}$$

reizen  
door de ruimte



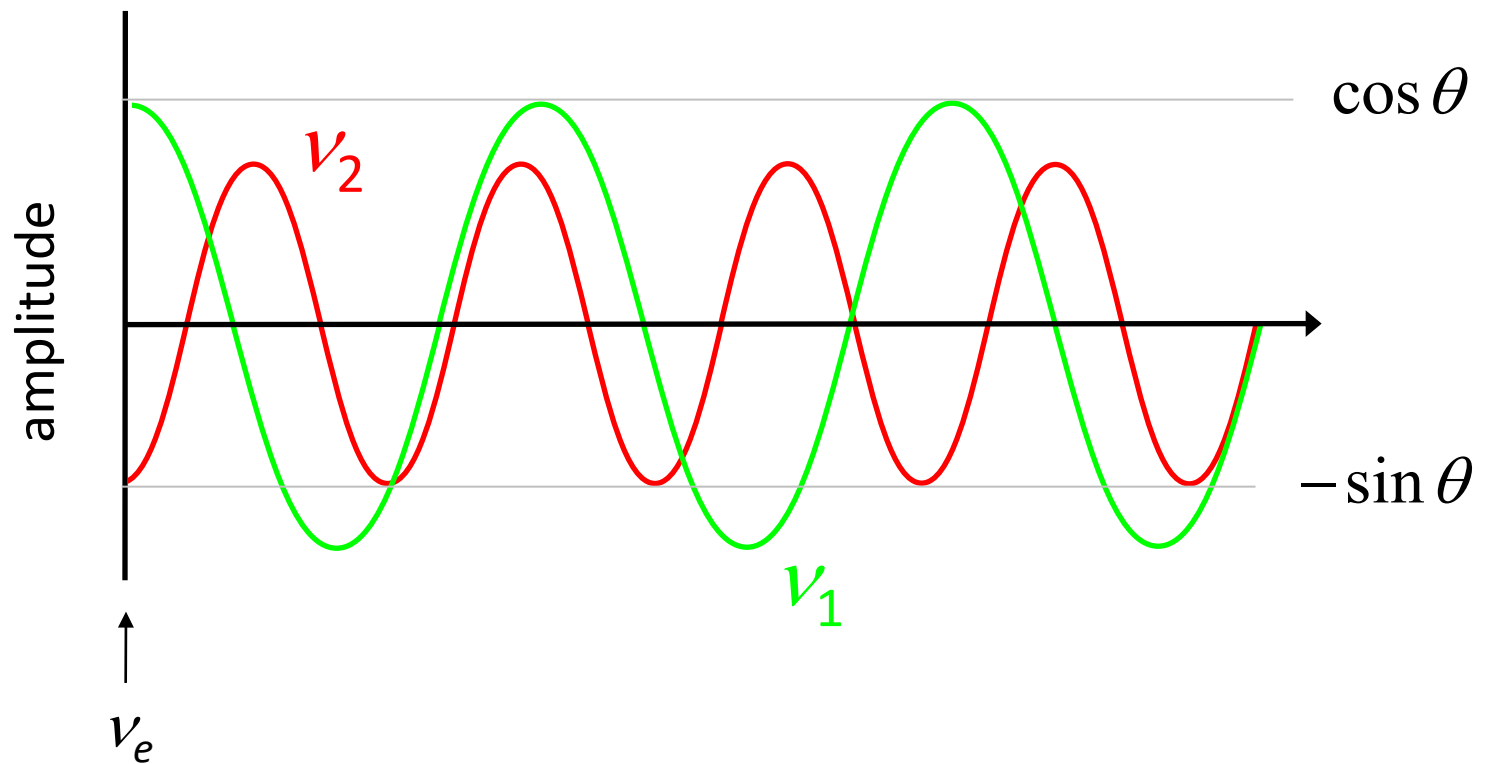
'rotatie'



creatie



# Reizen van neutrino's door de ruimte

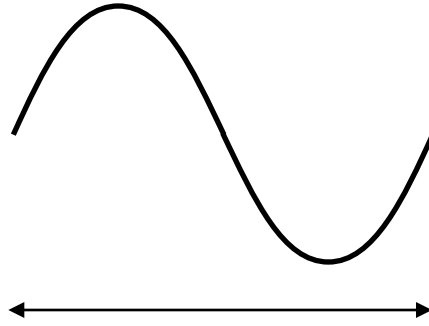


relatieve amplitudes veranderen met tijd of afstand

# Neutrino oscillations (II)

$$P(\nu_e \rightarrow \nu_e) = \left| \langle \nu_e(x) | \nu_e(x) \rangle \right|^2$$
$$\simeq 1 - \underbrace{\sin^2 2\theta}_{\text{amplitude}^2} \sin^2 \left( \underbrace{\frac{(m_2^2 - m_1^2)c^4}{4E\hbar c}}_{\equiv \frac{\pi}{\lambda}} x \right)$$

golflengte:



Heisenberg:

$$\lambda \sim \frac{hc}{|m_2 - m_1|c^2}$$

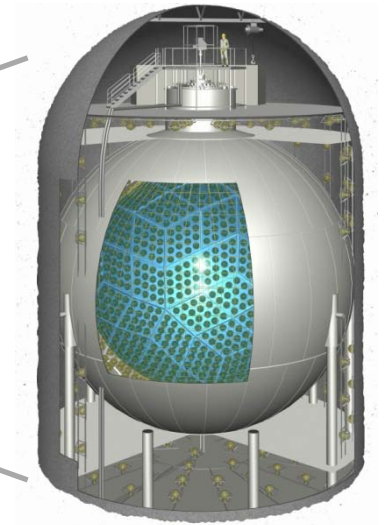
Lorentz boost:

$$\lambda' = \frac{E}{m} \times \lambda$$

$$\sim \frac{E}{\frac{m_2 + m_1}{2}c^2} \frac{hc}{|m_2 - m_1|c^2} \sim \frac{4\pi E \hbar c}{(m_2^2 - m_1^2)c^4}$$

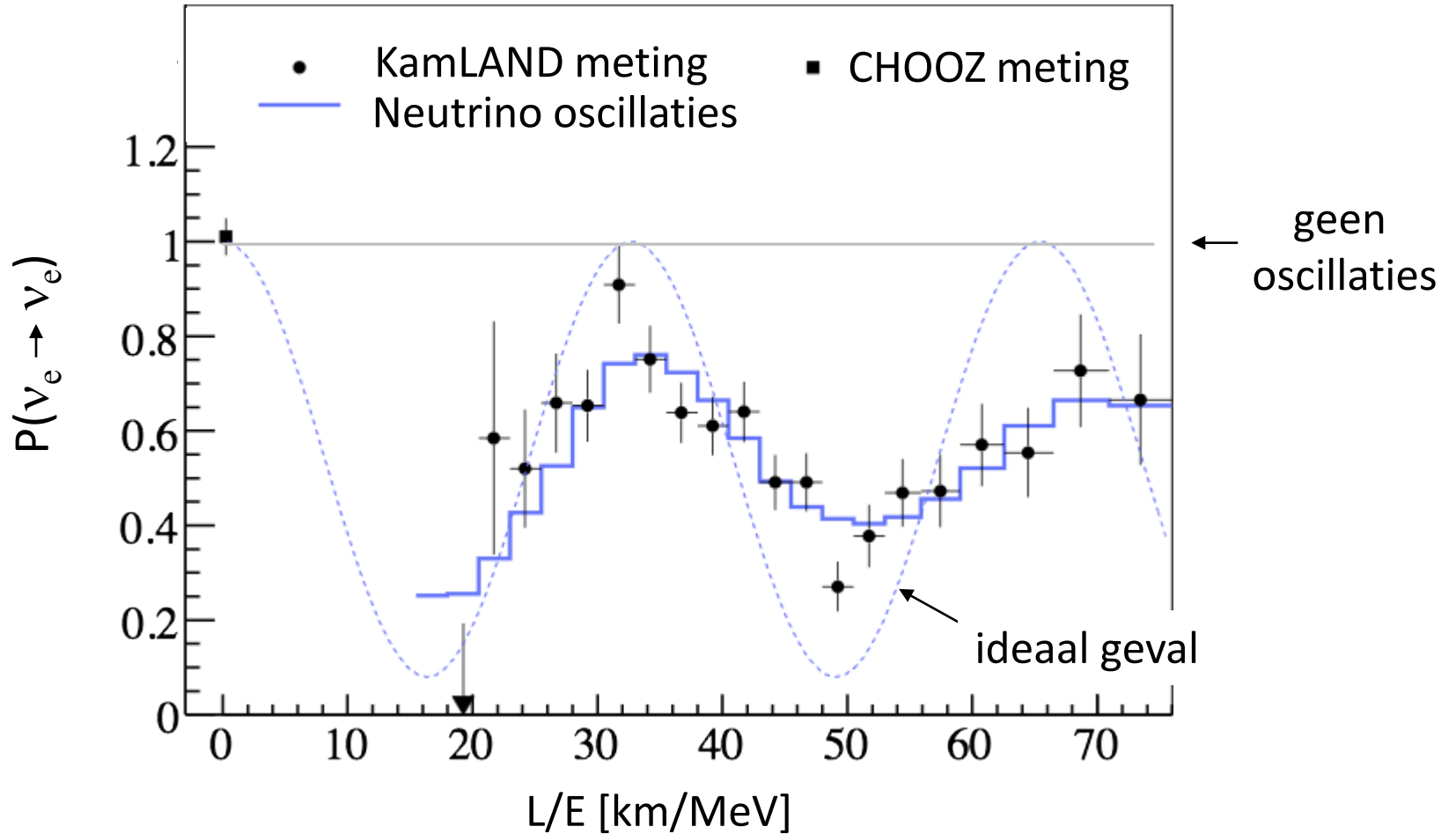


# KamLAND



55 kernreactoren met totaal vermogen 70 GW (~7% v/d wereldproductie)  
Neutrino's worden geproduceerd op 130–220 km afstand van de detector

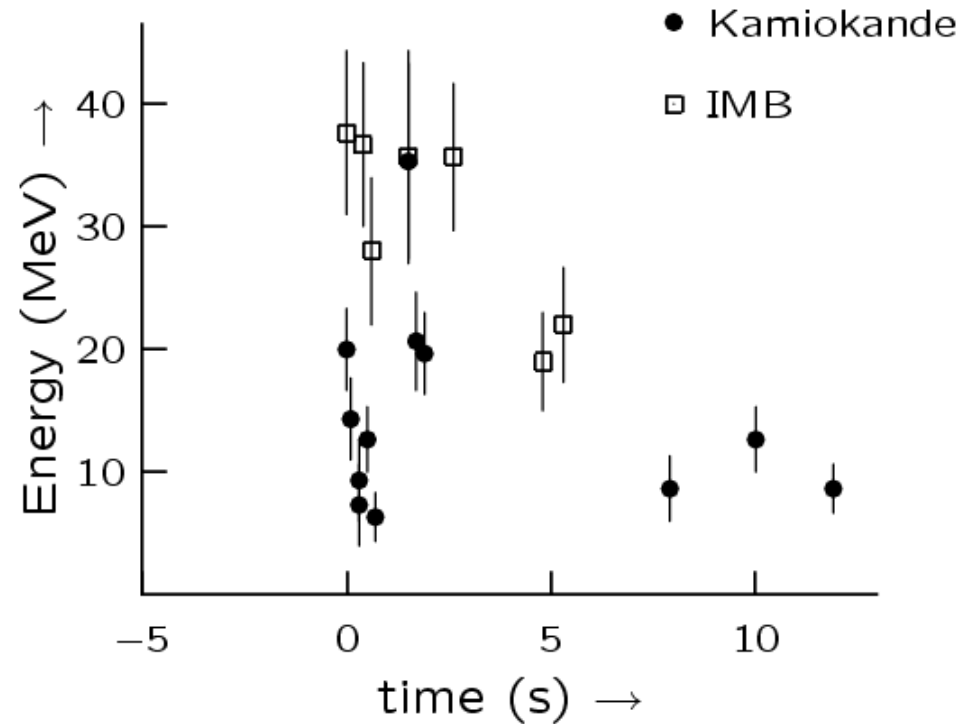
# KamLAND (II)



# 23 Februari 1987

## Tijd correlatie

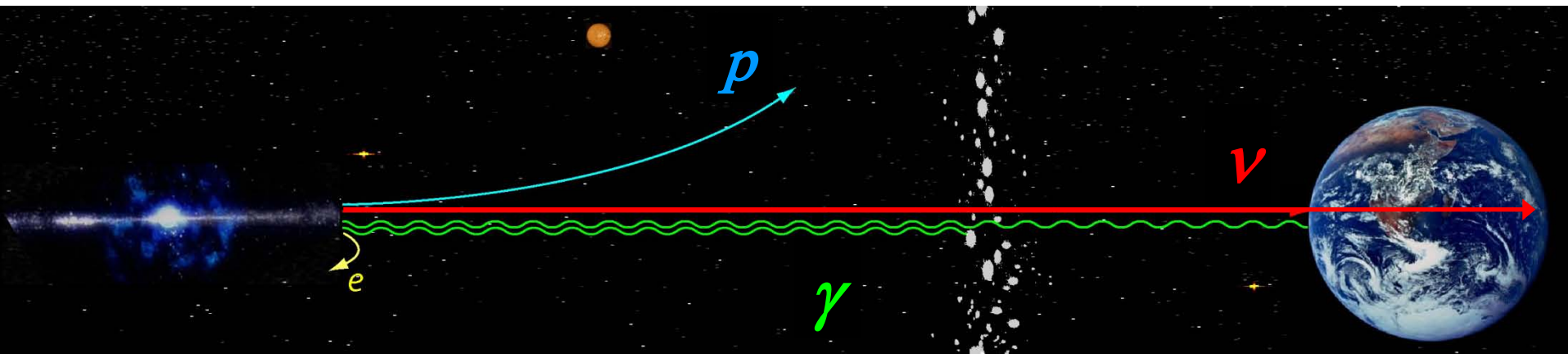
- 99% energie is neutrino's
- 1% energie is licht



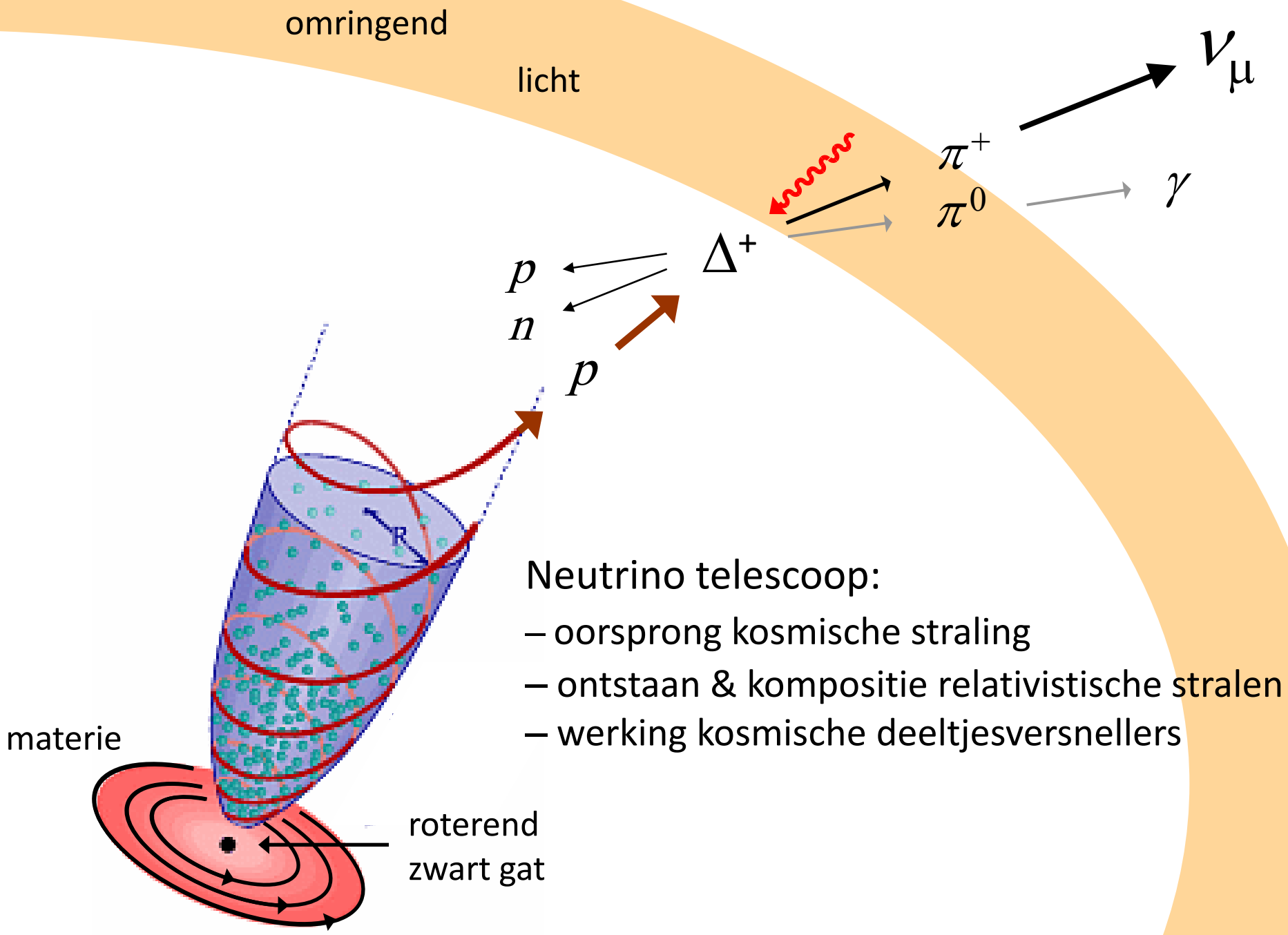
Supernova → 160,000 jaar → Aarde

# Neutrino astronomie

# Waarom?



- kosmische stralen buigen af door magneet velden
- licht kan worden geabsorbeerd



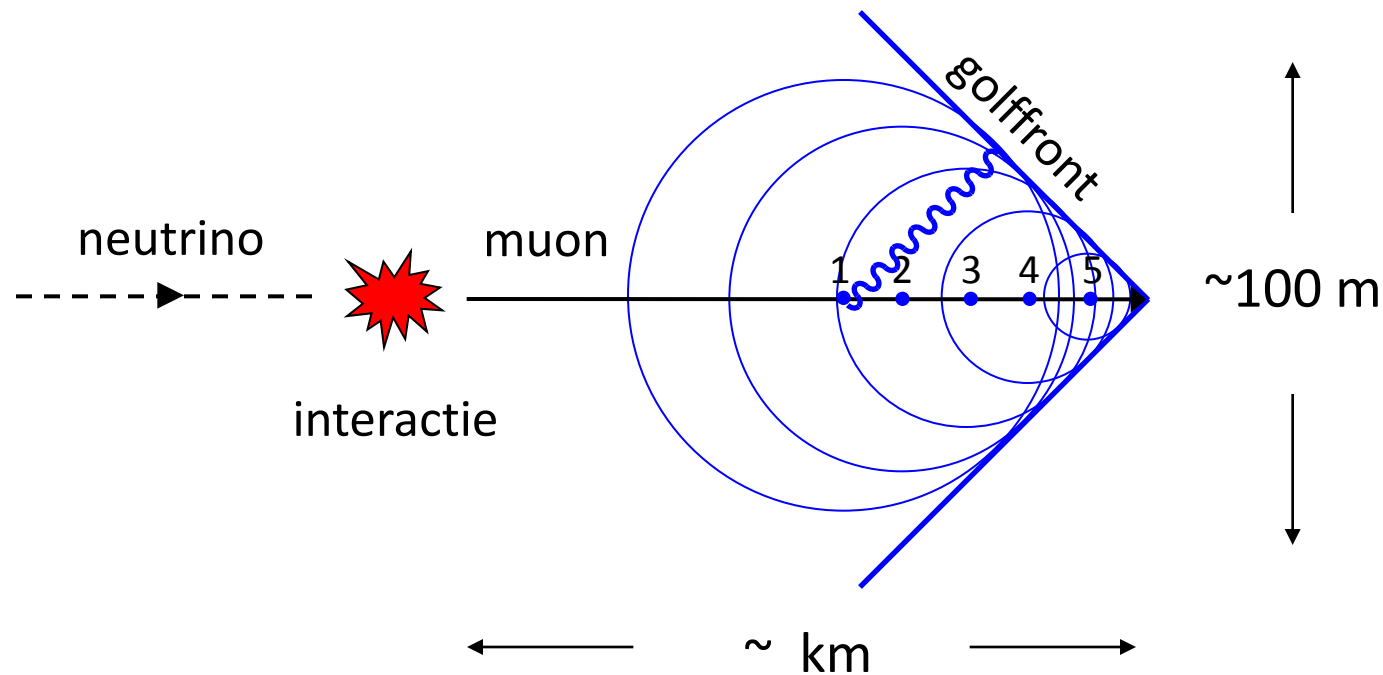
# Hoe?

1960 Markov's idee:

Zeewater als interactie en detectie medium

- Lengte muon spoor
- Detectie Cherenkov licht
- Water is transparant

# neutrino detectie



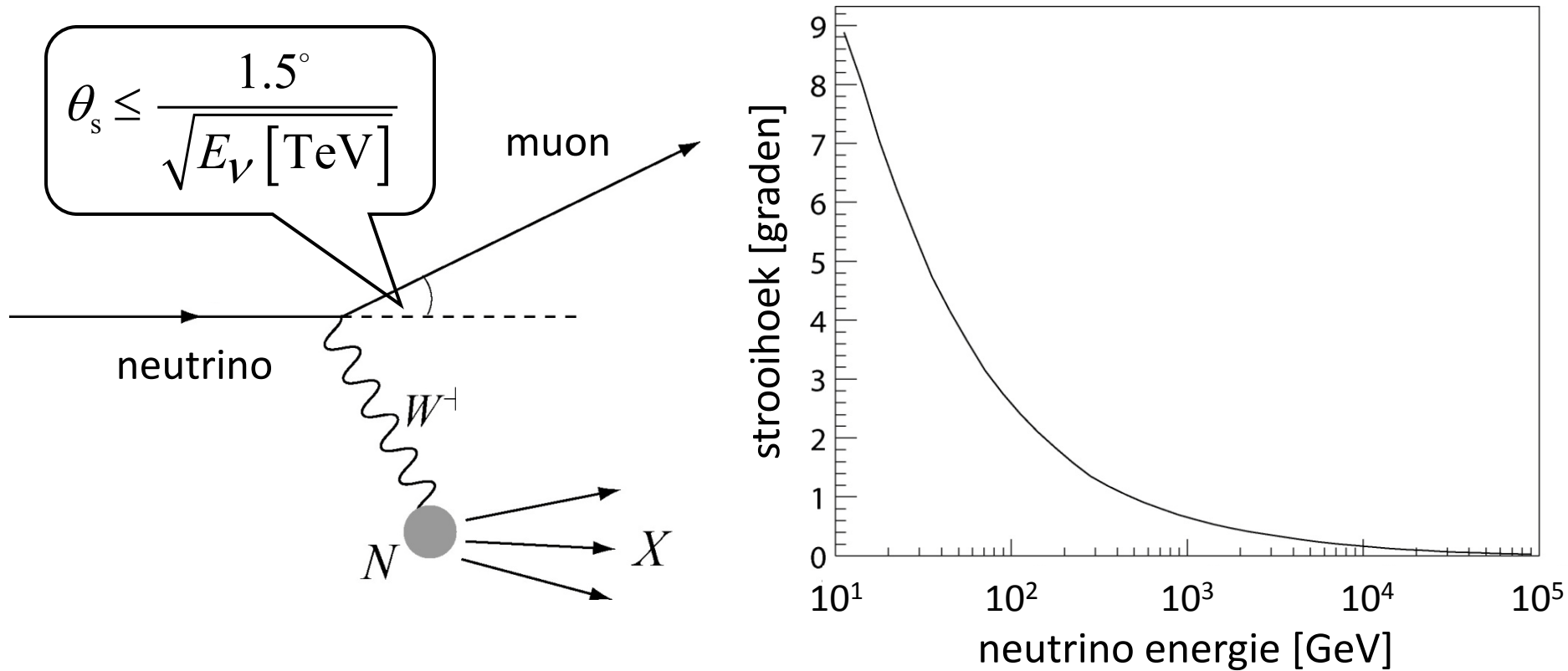
muon reist met de lichtsnelheid (300,000 km/s)



detectie Cherenkov licht *ns – km*

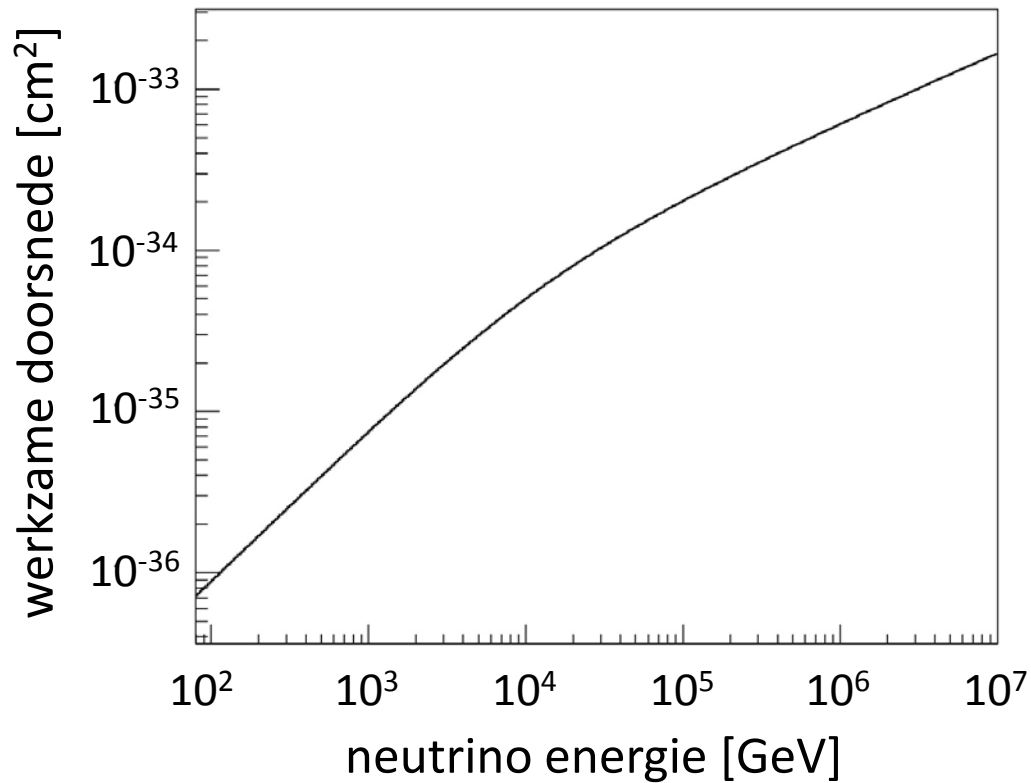


# Neutrino richting



Neutrino telescoop!

# Werkzame doorsnede



Vrije weglengte:

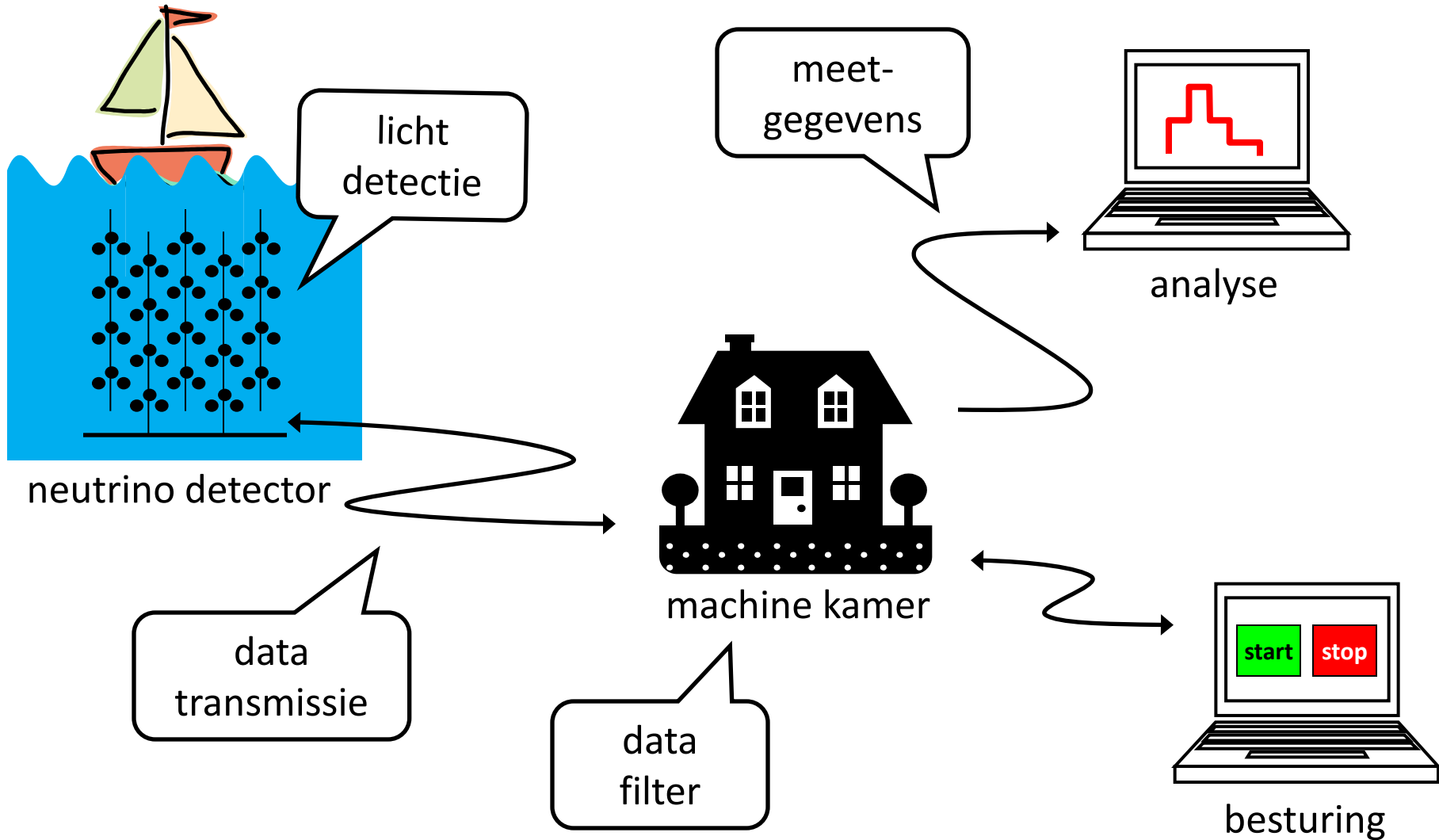
$$\lambda(E) \equiv \frac{1}{\sigma N_A \rho}$$
$$\simeq 10^8 \text{ km}$$

↑

$$E = 10^3 \text{ GeV}$$

“Size matters”

# Architectuur



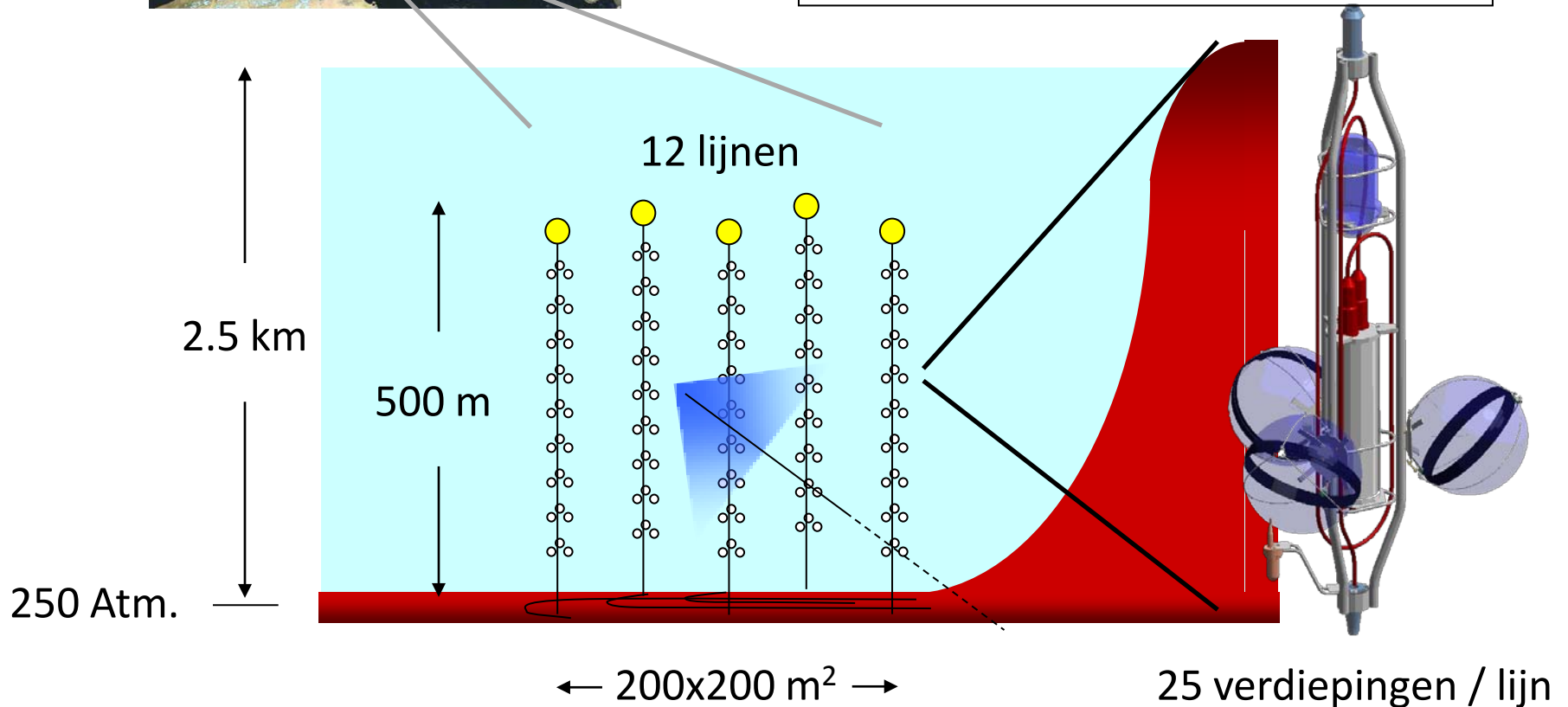
# Antares

prototype neutrino telescope

# Antares



- 200 personen
- 6 landen
- 40 km uit de kust bij Toulon
- gereed 2008



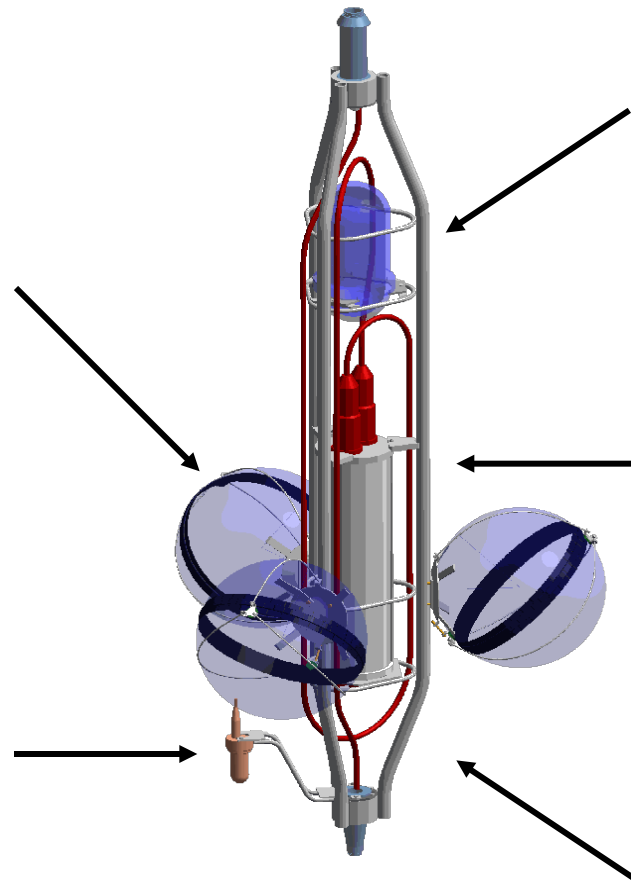
12 x 25 = 300 detectie eenheden



10" PMT  
*licht detectie*



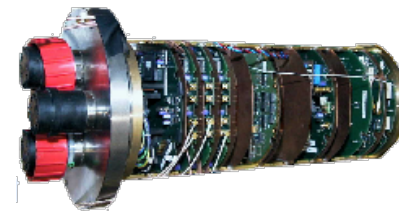
Hydrofoon  
*acoustische positie meting*



← ~1 m →



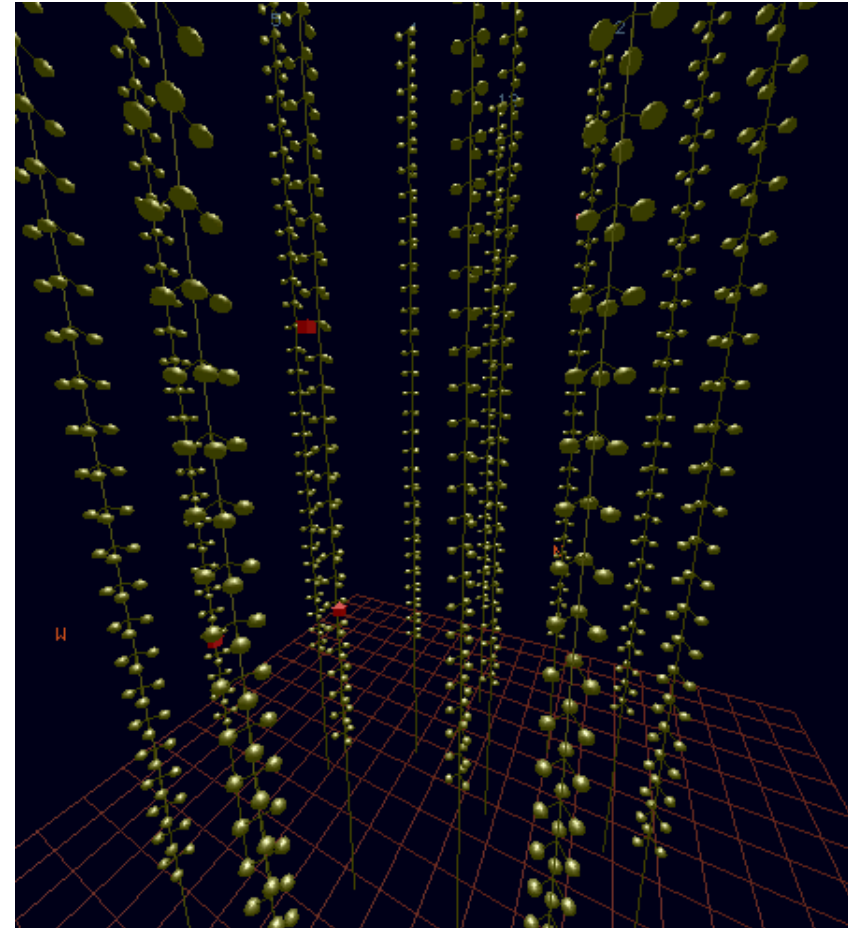
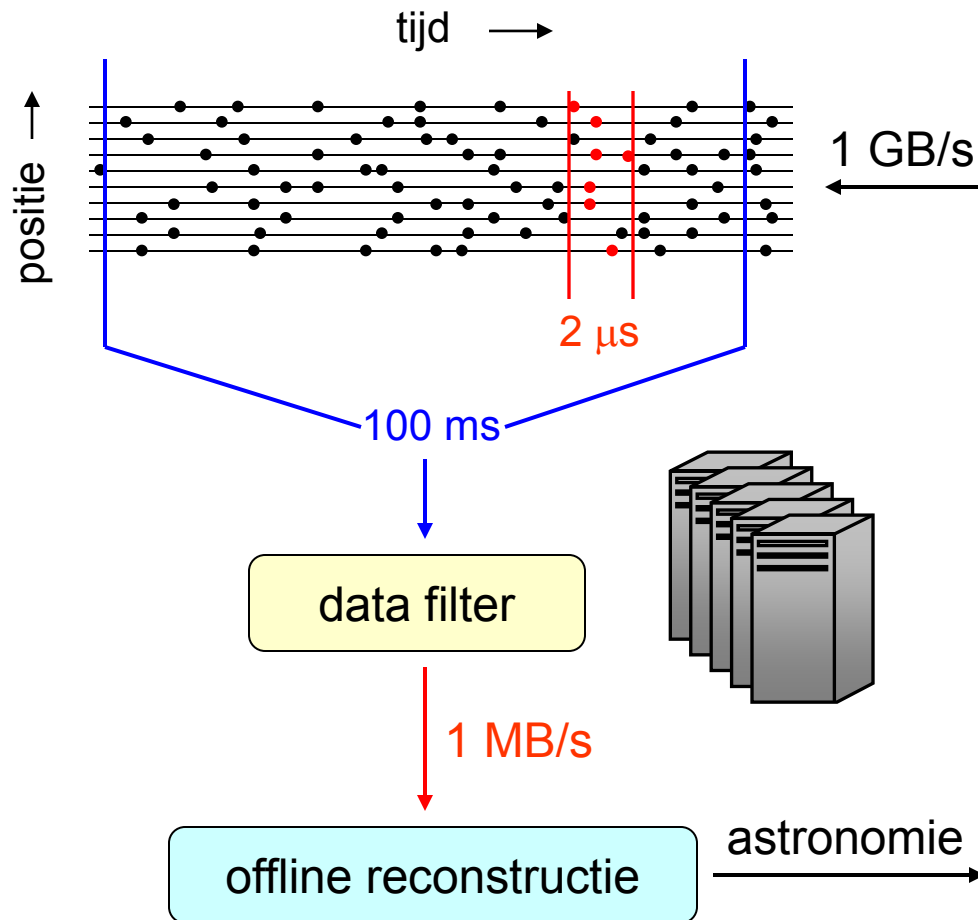
Optisch bakken  
*tijd calibratie*



Electronica  
*uitlezing*

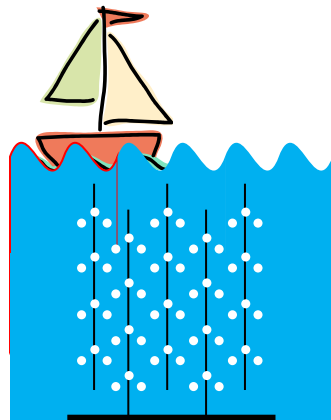
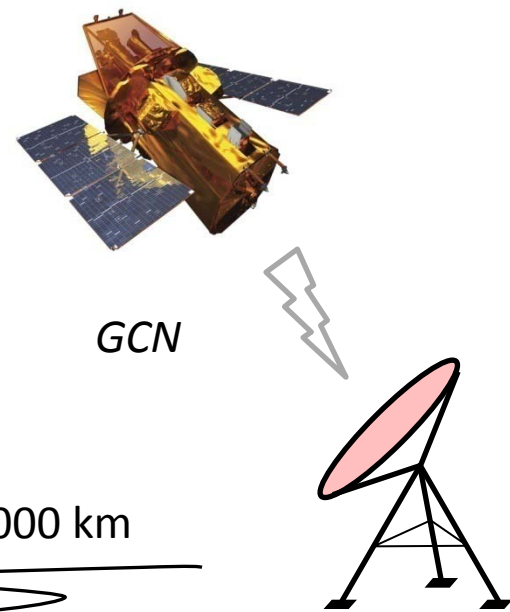
titanium frame  
*mechanisch drager*

# “All-data-to-shore” concept



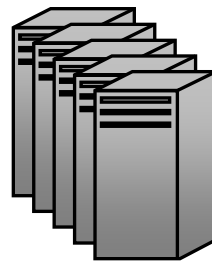
bepaling van het muon spoor

# Gamma Ray Burst

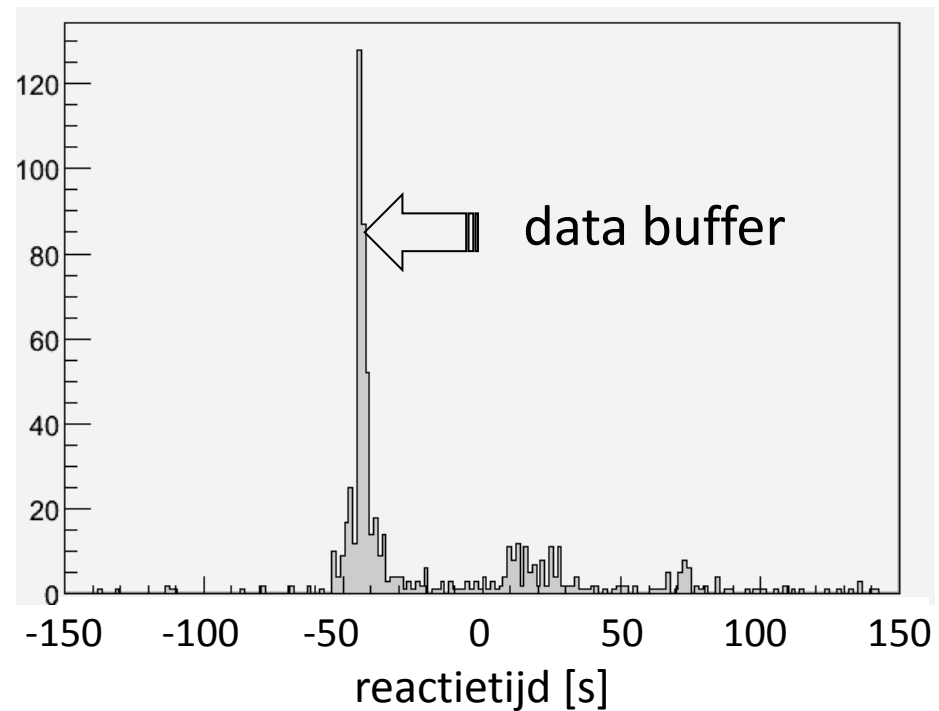
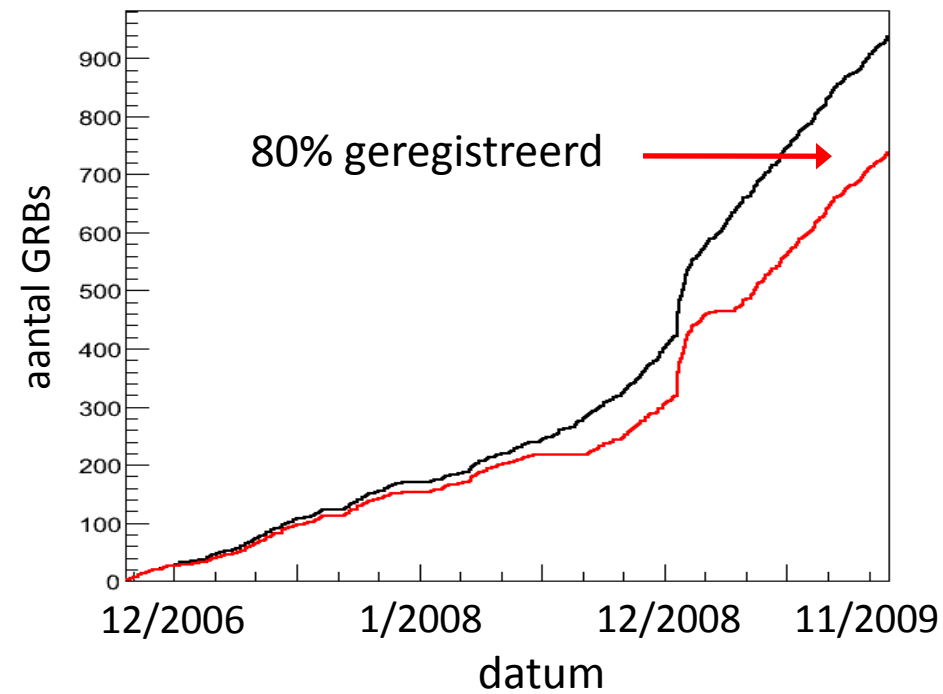
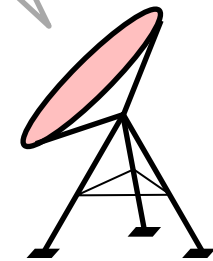


*"All-data-to-shore"*

40 km

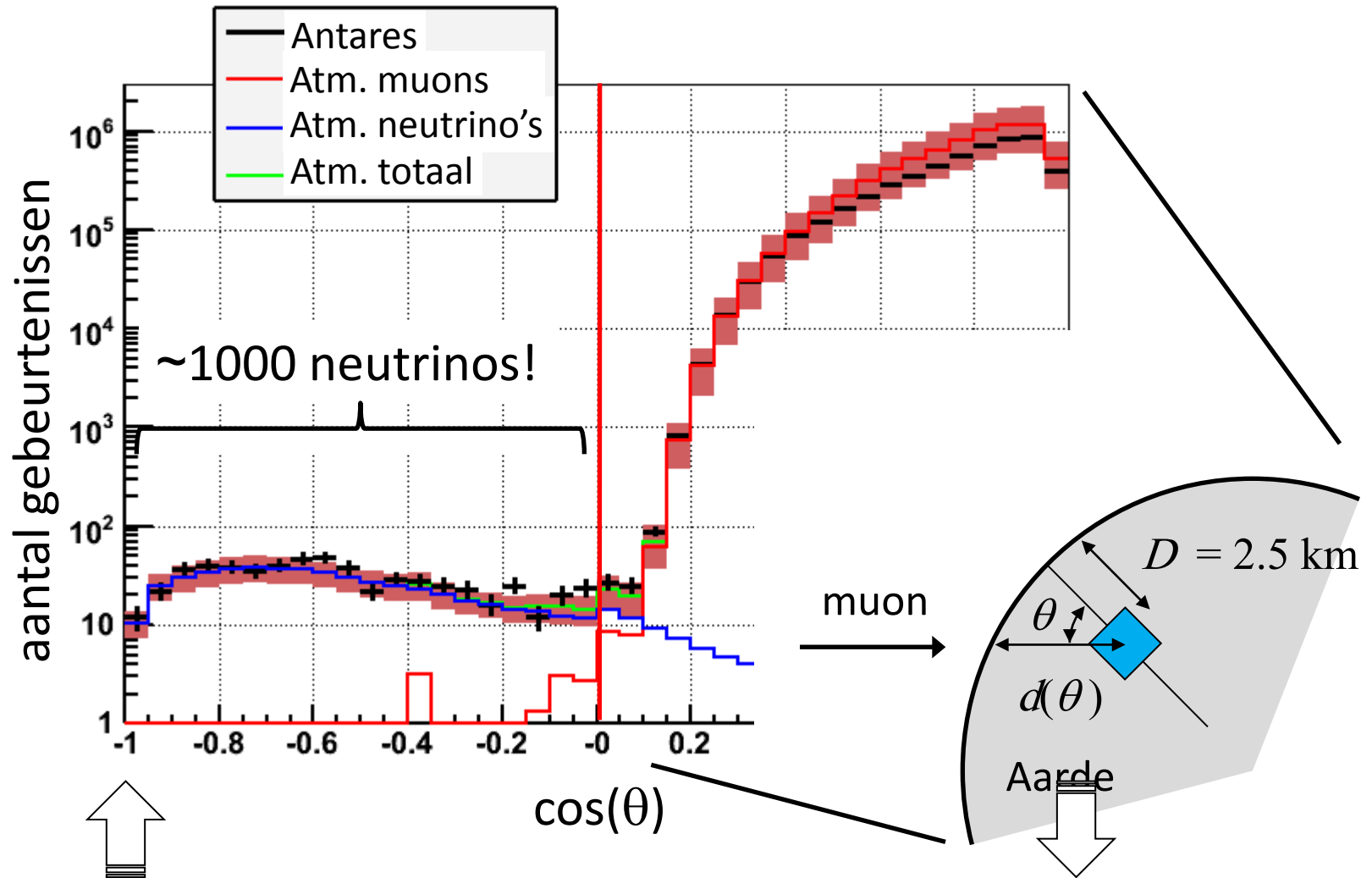


10,000 km

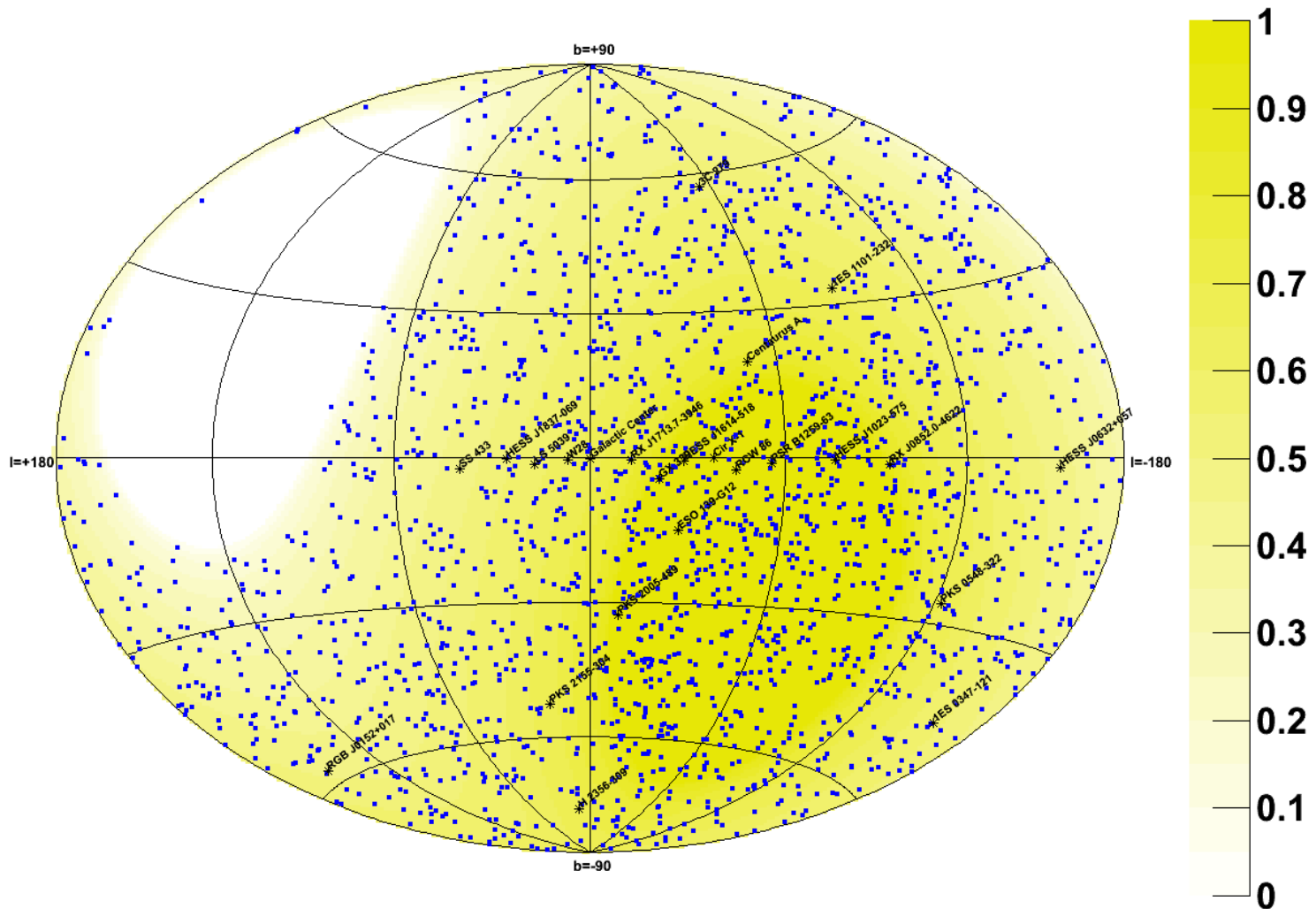




# Neutrino detectie

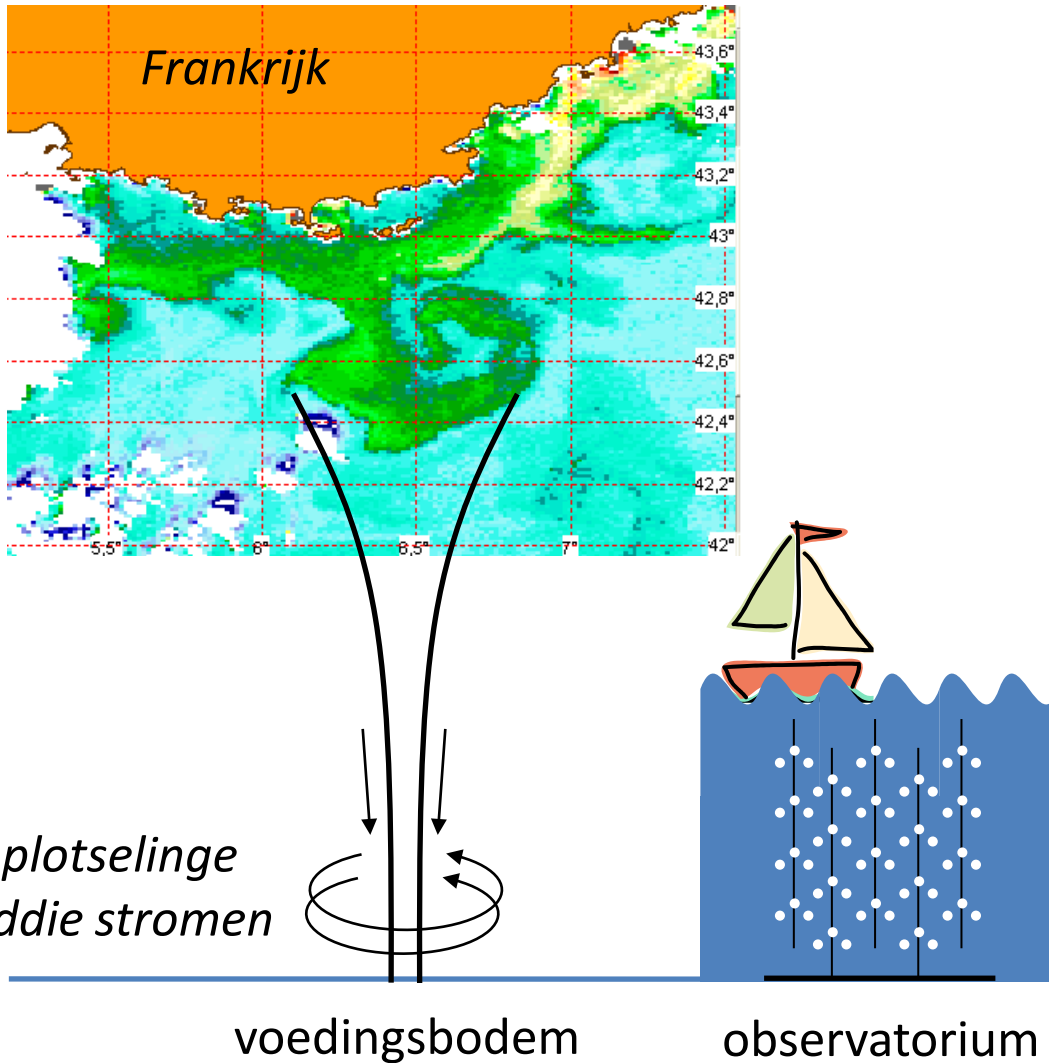


# Neutrino “sky map”

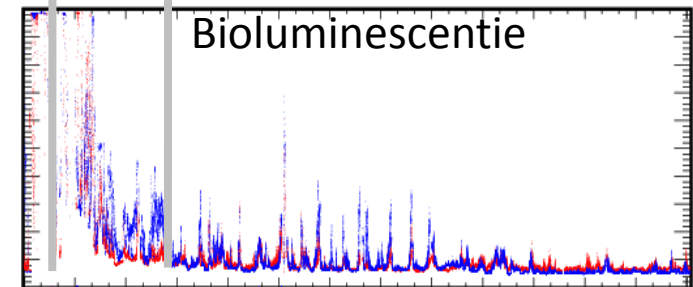
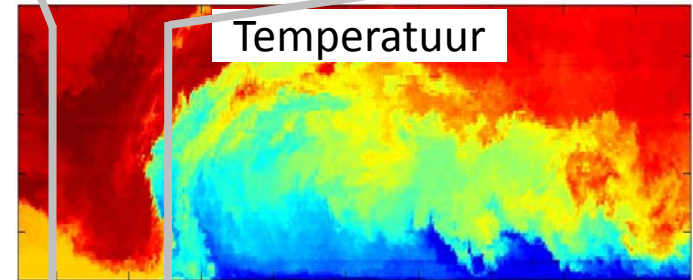


Nog geen puntbronnen gevonden...

# Aard & Zee onderzoek



kortstondige gebeurtenissen  
domineren leven in diepzee  
↓  
permanent observatorium



# Toekomst plannen

KM3NeT: A KM<sup>3</sup> Neutrino Telescope

# Evolutie

*1<sup>e</sup> generatie – pre-prototypes*

*2<sup>e</sup> generatie*

*3<sup>e</sup> generatie*

Dumand Baikal Nestor Nemo Amanda Antares IceCube KM3NeT



1976-1995

1993

1996

1998

2000

2008

2011

2015

*heden*

*toekomst*

# Samenvatting

- Neutrino's bestaan, wisselwerken zwak met materie, en hebben een zeer kleine massa
- Zonneneutrino's zijn gemeten, neutrino's oscilleren spontaan
- Neutrino's uit de SN1987A zijn gezien, neutrino flits
- Neutrino's uit andere astrofysische bronnen?

*Met het in gebruik nemen van de Antares detector als prototype en met KM3NeT als de toekomstige kubieke kilometer detector is neutrino-astronomie thans binnen handbereik...*

*Neutrinos, they are very small.  
They have no charge and have no mass  
And do not interact at all.  
The earth is just a silly ball  
To them, through which they simply pass,  
Like dustmaids through a drafty hall  
Or photons through a sheet of glass.  
They snub the most exquisite gas,  
Ignore the most substantial wall,  
Cold-shoulder steel and sounding brass,  
Insult the stallion in his stall,  
And scorning barriers of class,  
Infiltrate you and me! Like tall  
And painless guillotines, they fall  
Down through our heads into the grass.  
At night, they enter at Nepal  
And pierce the lover and his lass  
From underneath the bed - you call  
It wonderful; I call it crass.*

John Updike