

VAN ATOOM TOT KOSMOS

Wie het kleine niet eert ...

Piet Mulders

pjg.mulders@gmail.com

<https://www.nat.vu.nl/~mulders>



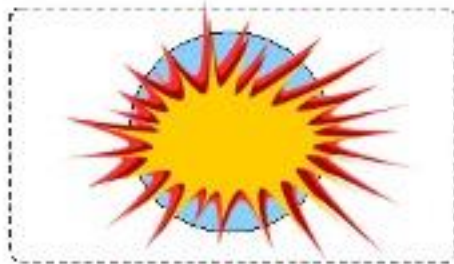
European Research Council



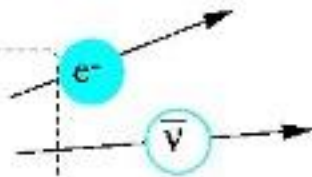
Hoofdstuk 7

Het ongrijpbare neutrino

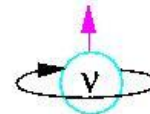
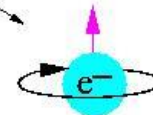
HET ONGRIJPBARE NEUTRINO



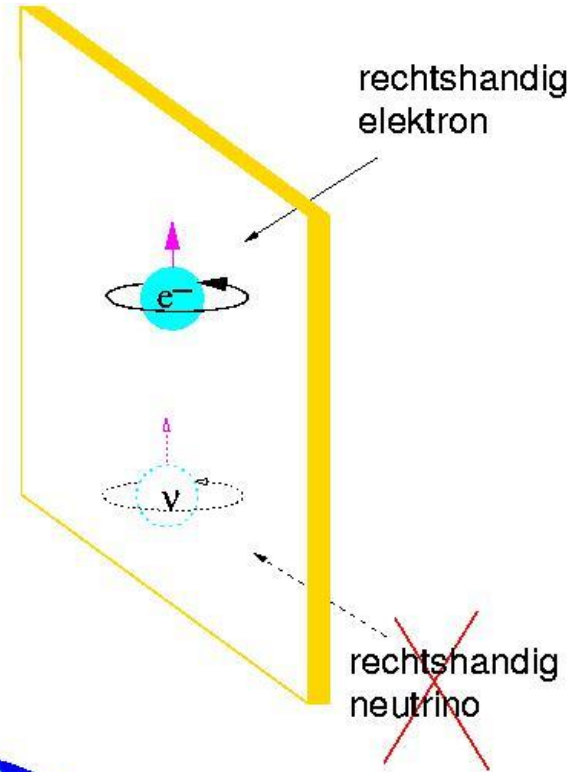
Na 15 min
($\tau_n = 877,8 \text{ s}$)



elektron



linkshandig
neutrino



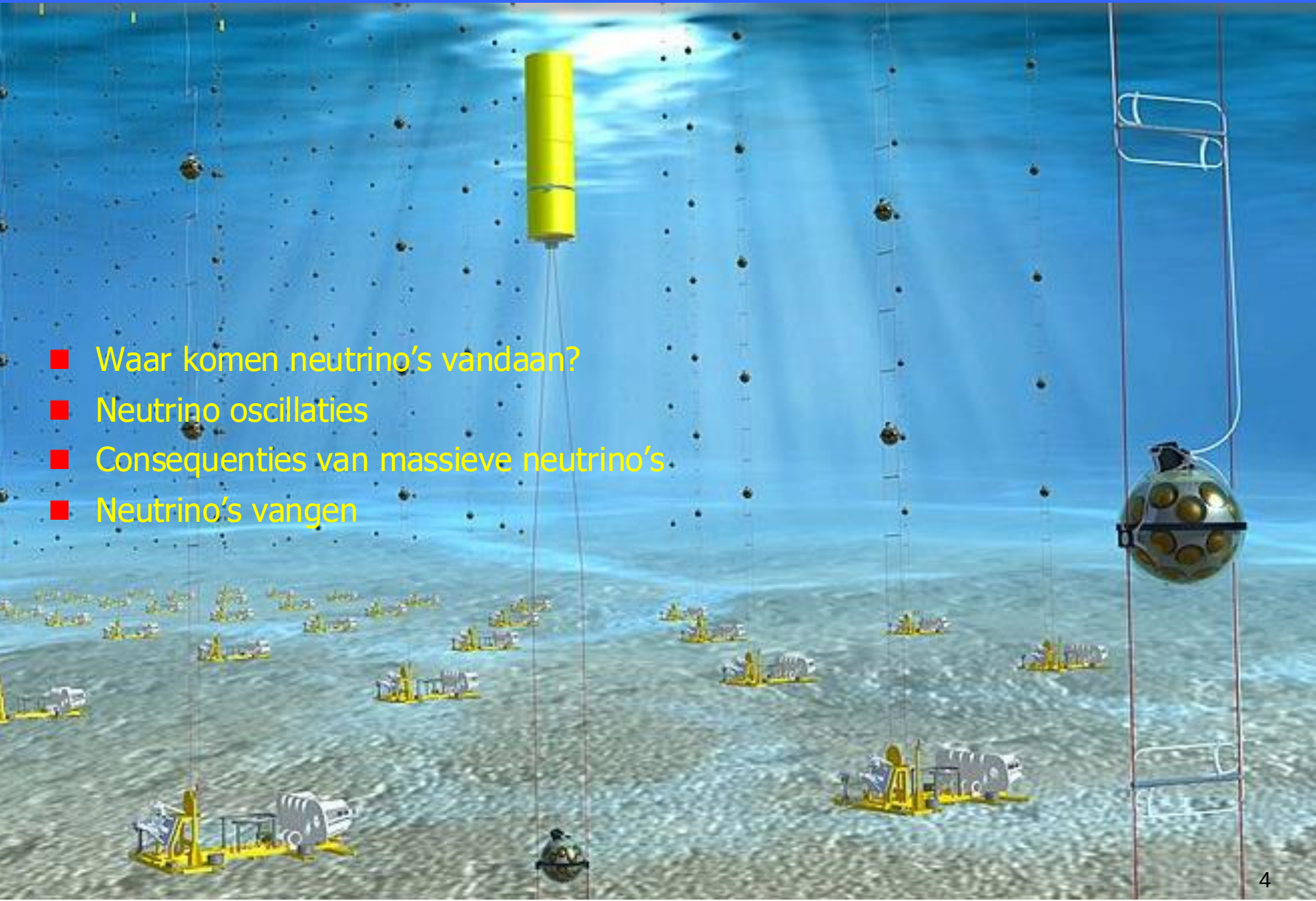
rechtshandig
elektron

~~rechtshandig
neutrino~~



HET ONGRIJPBARE NEUTRINO

- Waar komen neutrino's vandaan?
- Neutrino oscillaties
- Consequenties van massieve neutrino's
- Neutrino's vangen



Het ongrijpbare neutrino

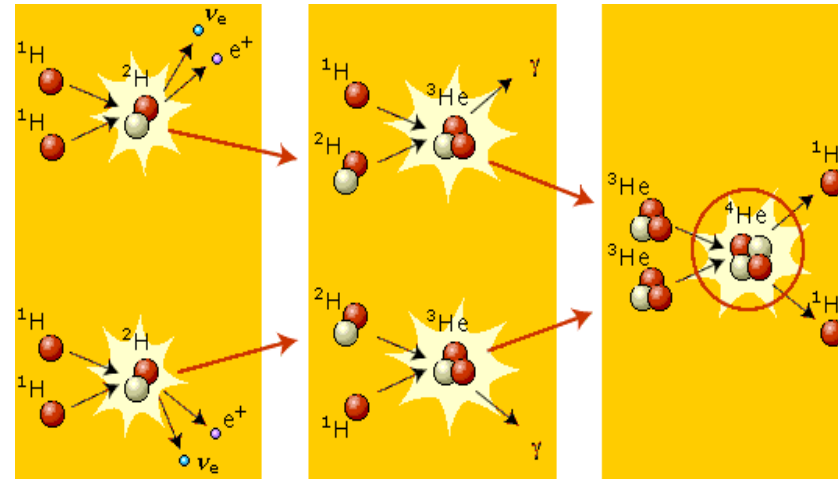
Waar komen neutrino's vandaan?

■ Zwak verval van atoomkernen

(Zon/kernreactoren):

...n... $\rightarrow$...p... + e^- + ν_e (rechtshandig)

...p... $\rightarrow$...n... + e^+ + ν_e (linkshandig)



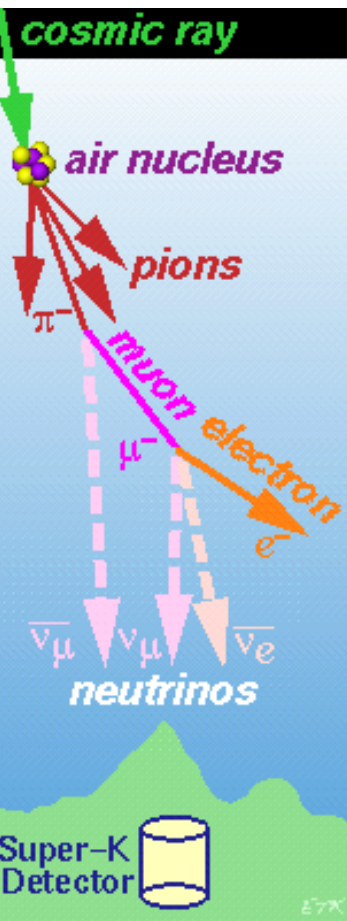
• Kosmische straling (pion verval)

$\pi^- \rightarrow \mu^- + \nu_\mu$ (rechtshandig)

$\pi^+ \rightarrow \mu^+ + \nu_\mu$ (linkshandig)

• Overgebleven na de oerknal

net als fotonen (achtergrondstraling $T = 3 \text{ K}$),
van alle neutrino soorten (ν_e , ν_μ en ν_τ) zo'n
500 per cm^3

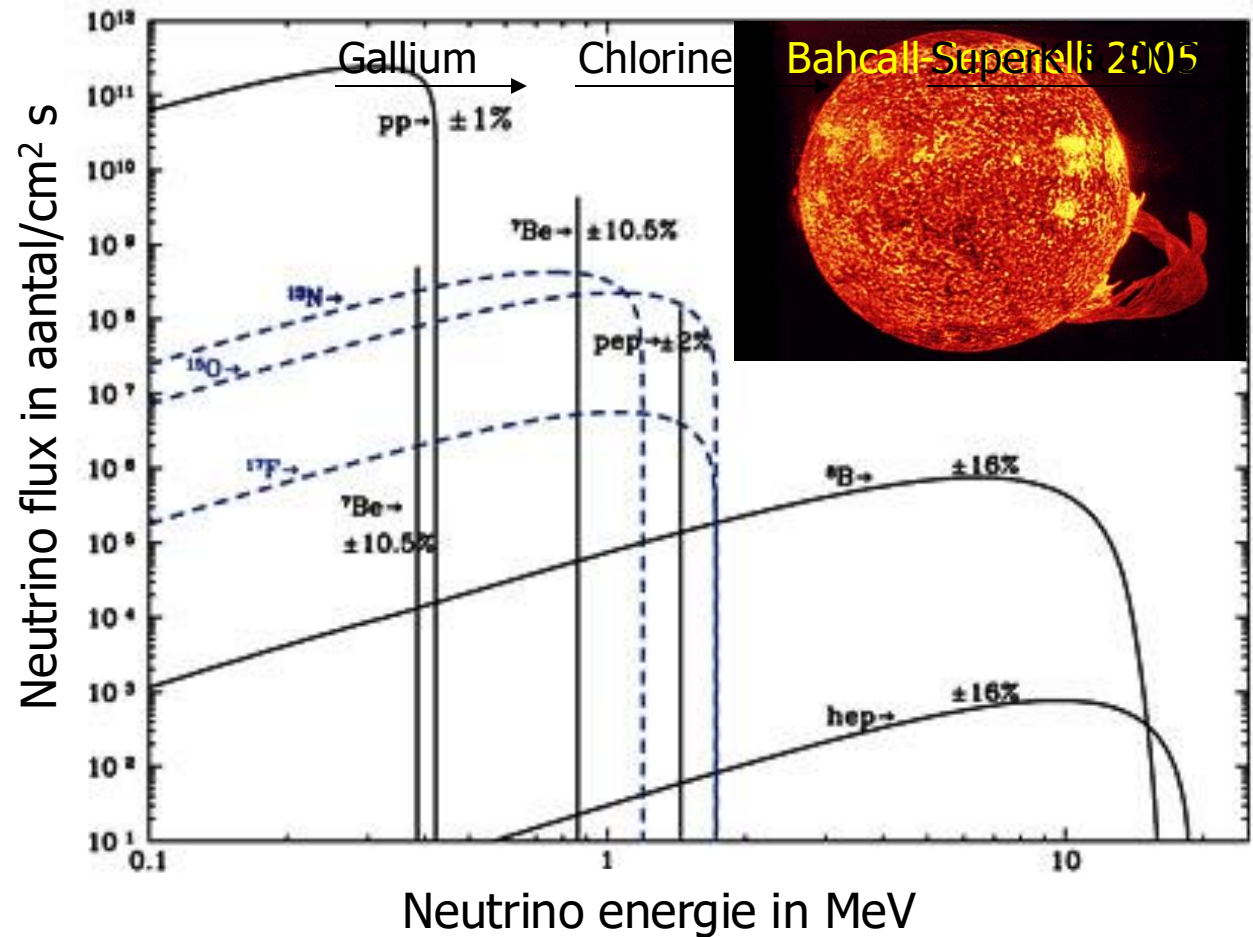


Recentelijk beantwoorde vragen

- Hoe zwaar zijn neutrino's ?
- Waar blijven de neutrino's van de Zon? Helpt was zoek!

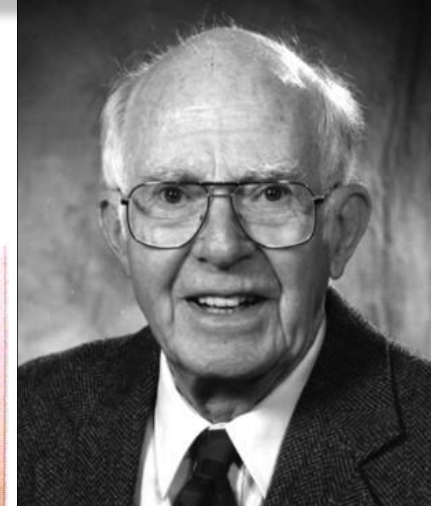
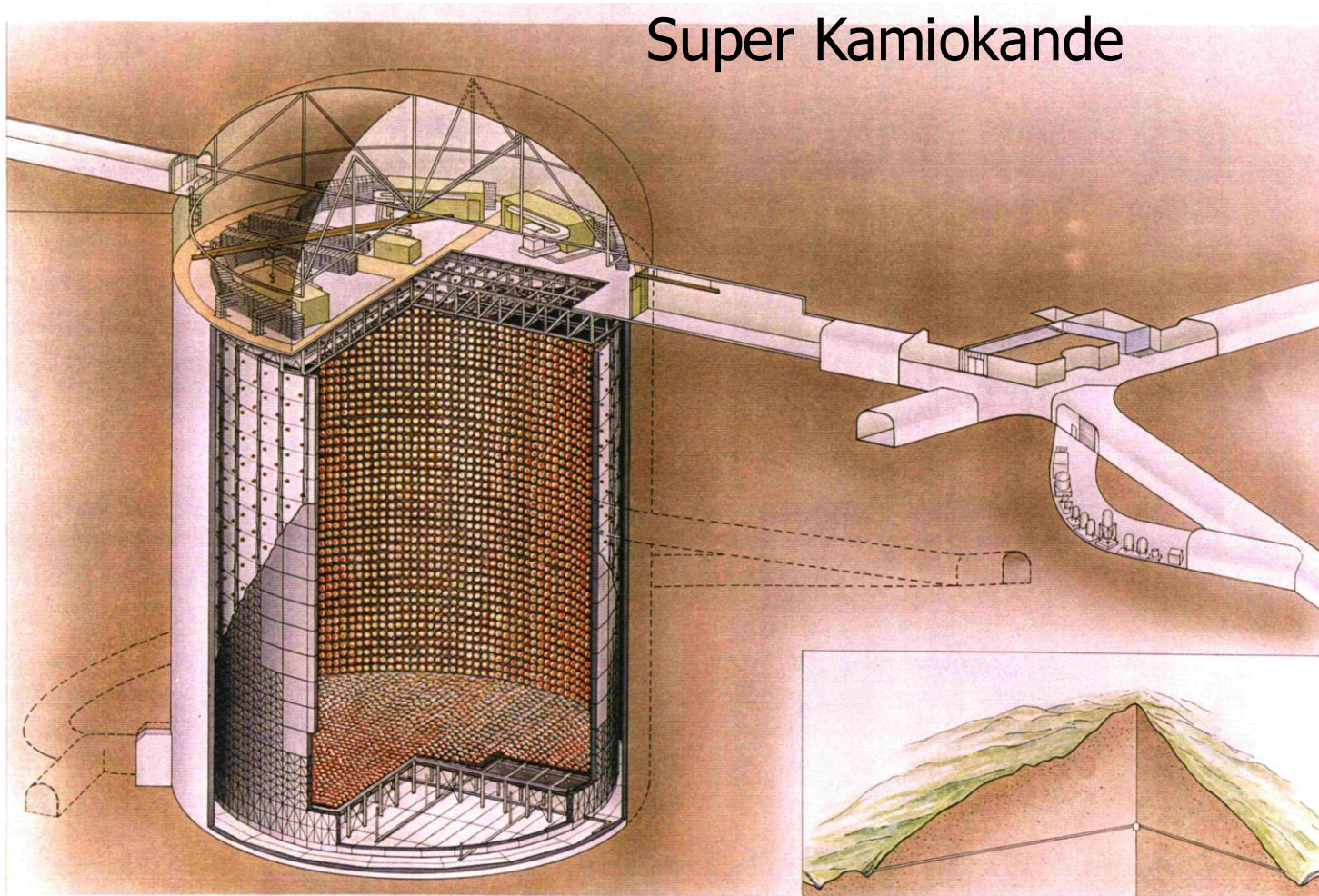


Ray Davis & John Bahcall



Neutrino detectors

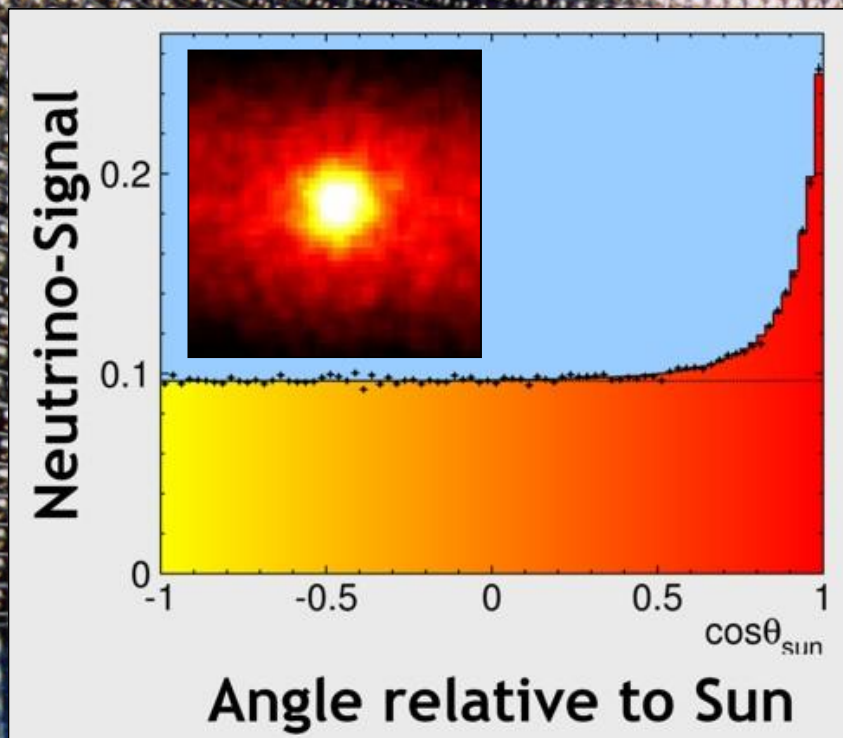
Super Kamiokande



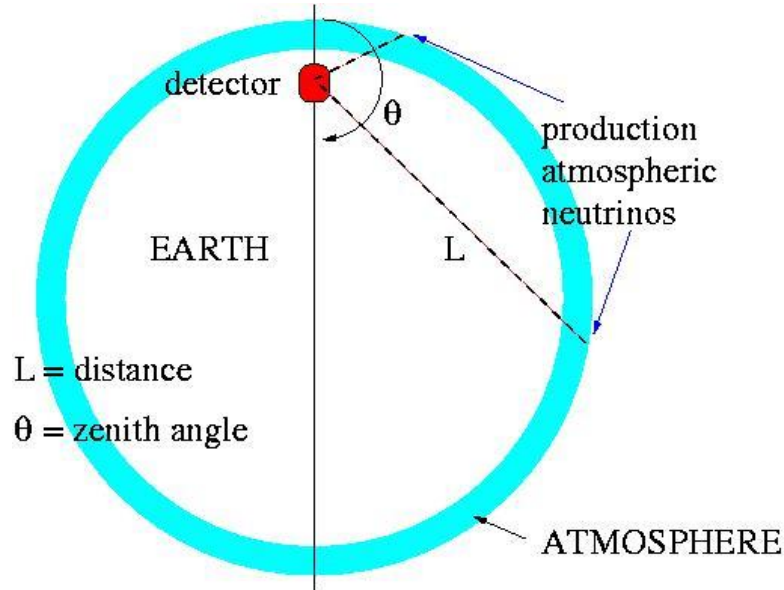
Ray Davis Jr



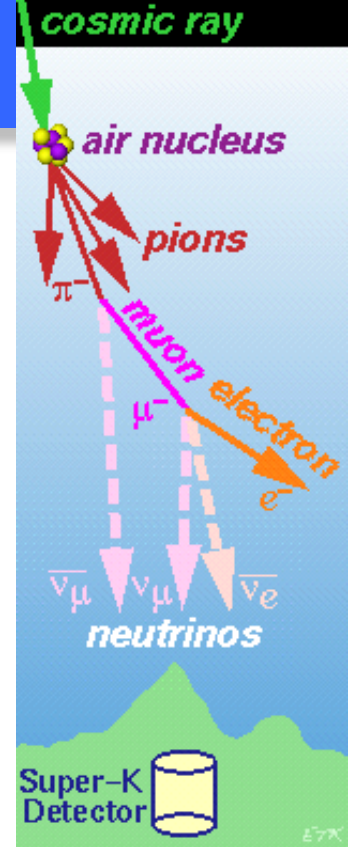
Masatoshi Koshiba



Neutrino oscillaties in atmosfeer

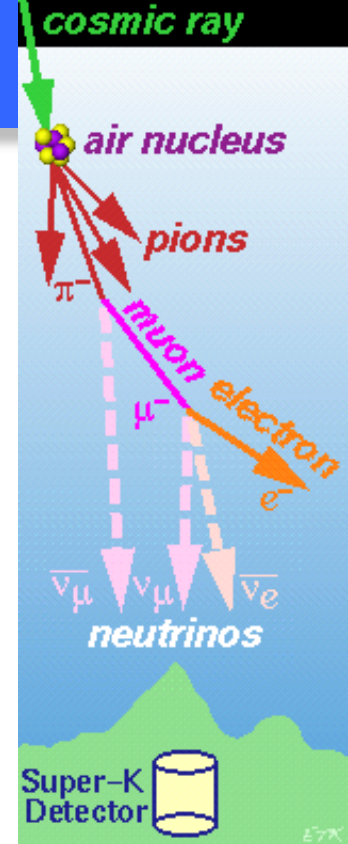
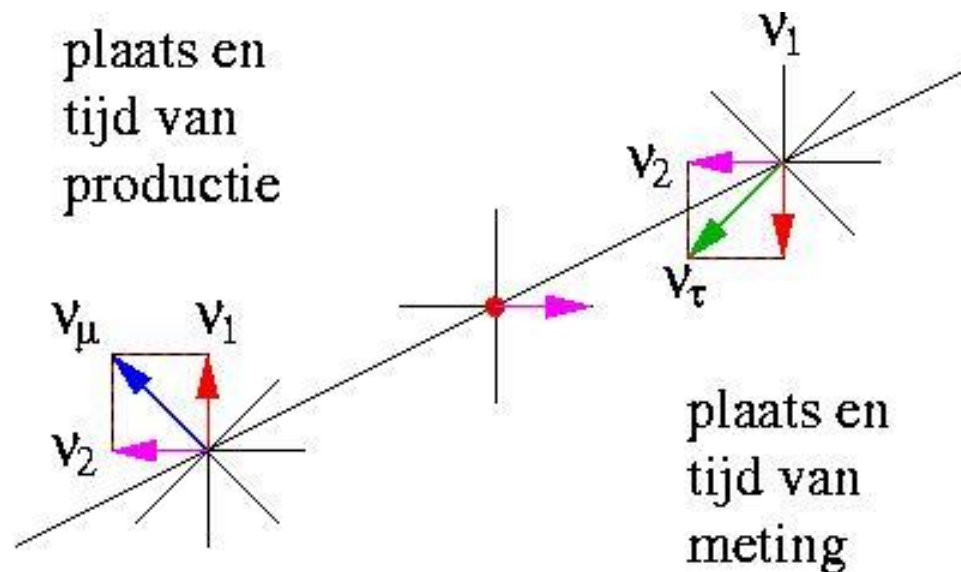


- Superkamiokande heeft aangetoond dat neutrinos van de ene in een andere soort veranderen (oscillaties)
- Oscillatie-golflengte is duizenden kilometers $\leftrightarrow$ massa's kleiner dan 0.000 000 01 van die van het electron
- Het blijkt hier te gaan om overgangen $\nu_{\mu} \rightarrow \nu_{\tau}$



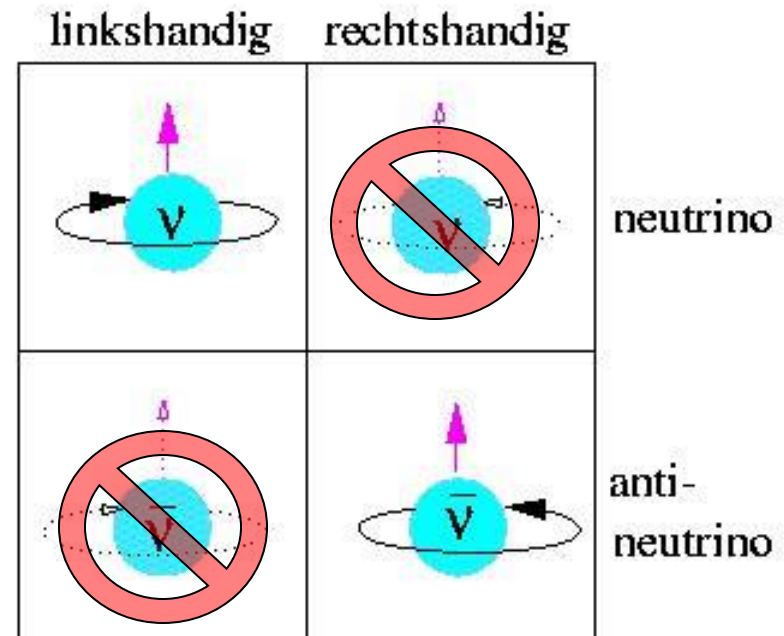
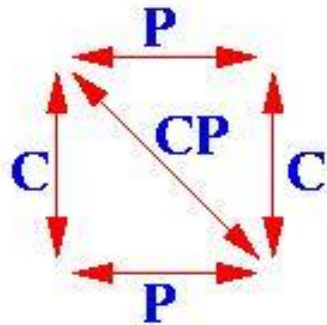
Neutrino oscillaties in atmosfeer

- Neutrino's worden in atmosfeer gecreeerd in verval van pionen. Dit zijn ν_μ neutrino's
- Als het ν_μ neutrino een quantummechanische superpositie is van neutrino's ν_1 en ν_2 leidt dit tot oscillaties
- Maar alleen als neutrinos massa hebben ($m_1 \neq m_2$)
- Consequenties?



Wat zijn consequenties

- Deeltjes met massa komen in rechtshandige **én** linkshandige variant!
- Dat kan alleen als een neutrino zijn eigen antideeltje is, net als foton, maar anders dan elektron (**Majorana deeltje!**)

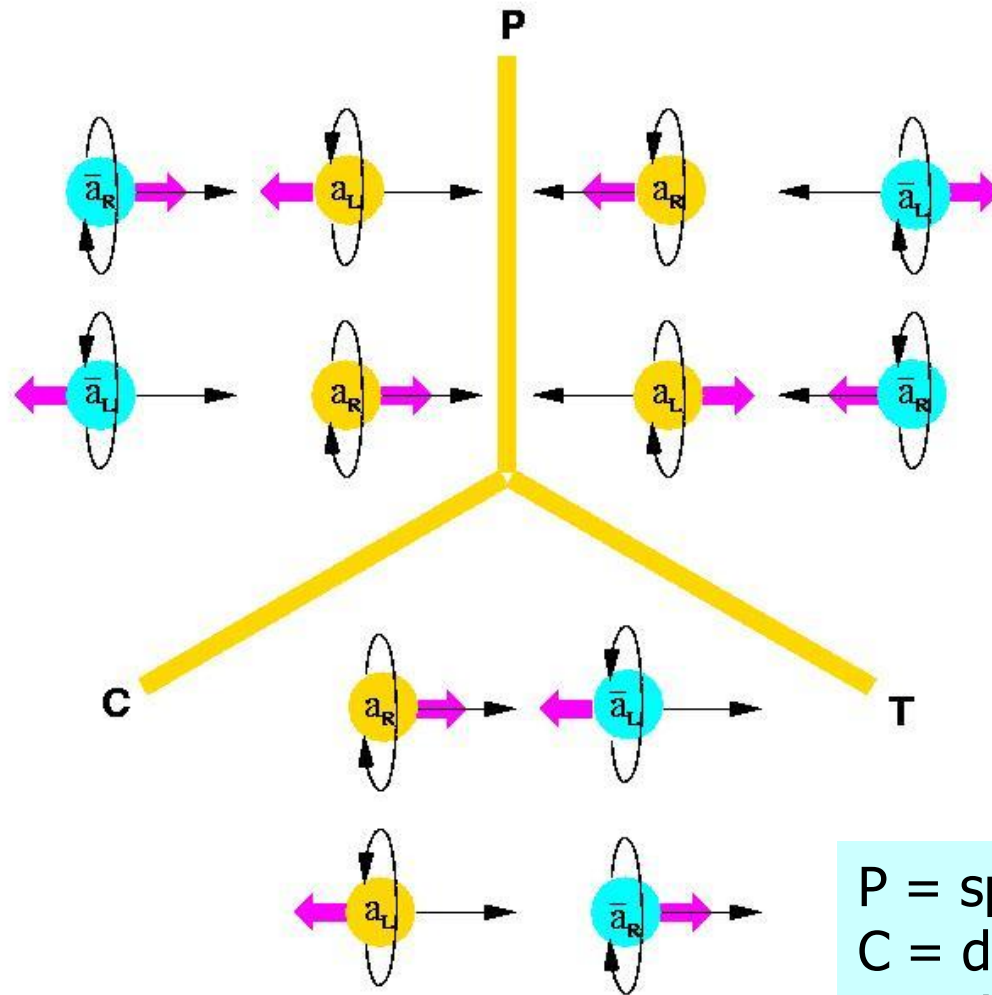


Dirac and Majorana neutrinos

Dirac neutrino



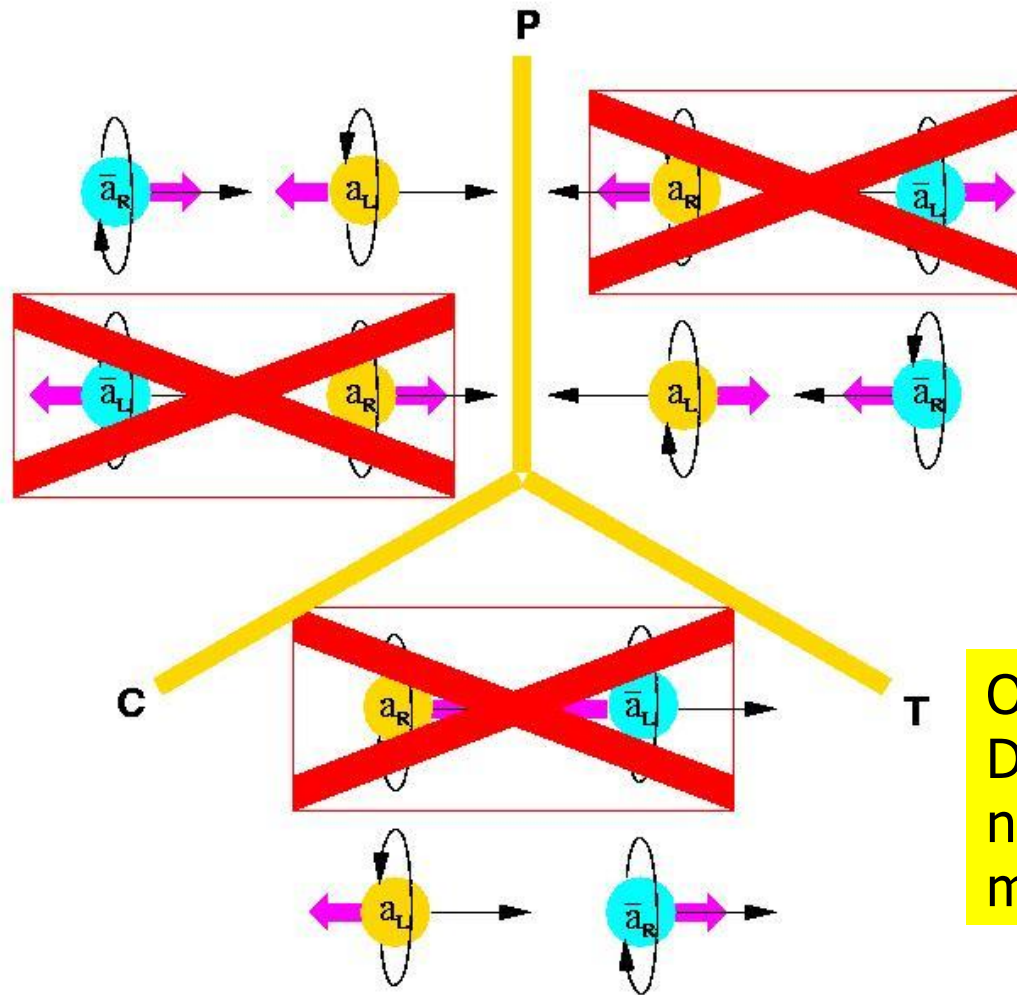
Paul Dirac



P = spiegelen
C = deeltje-antideeltje
T = tijdomkeer

Dirac and Majorana neutrinos

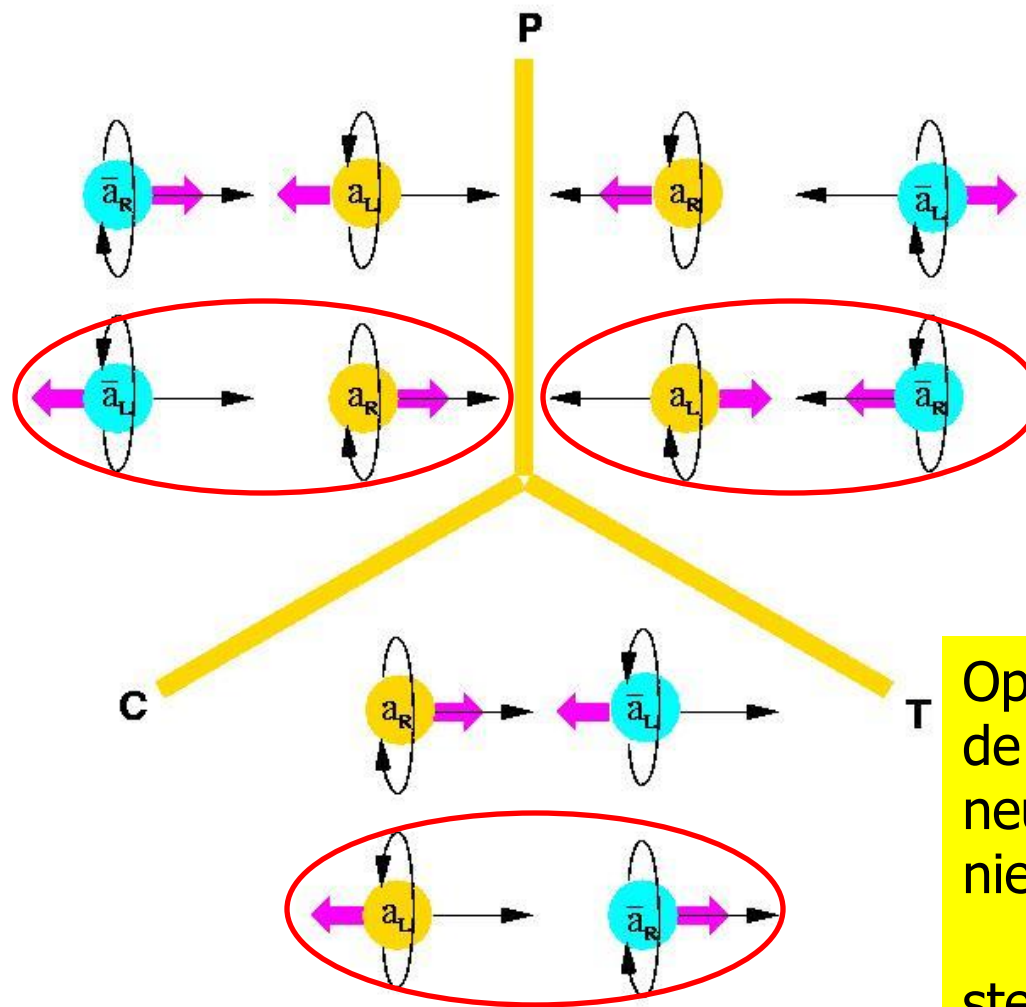
**Dirac
neutrino**



Oplossing 1:
Dit kan alleen als
neutrinos geen
massa hebben!

Dirac and Majorana neutrinos

**Dirac
neutrino**



Oplossing 2:
de omcirkelde
neutrinos voelen
niets

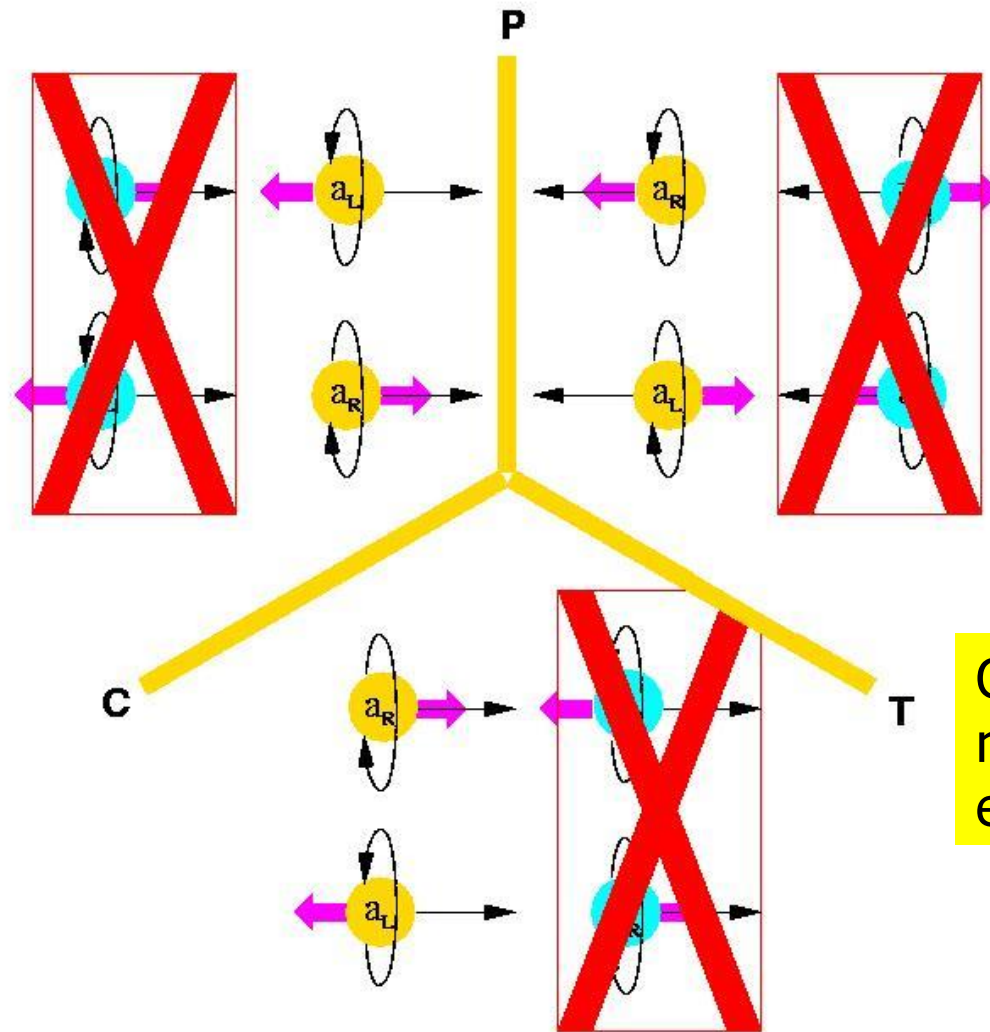
steriele neutrinos!

Dirac and Majorana neutrinos

Majorana neutrino



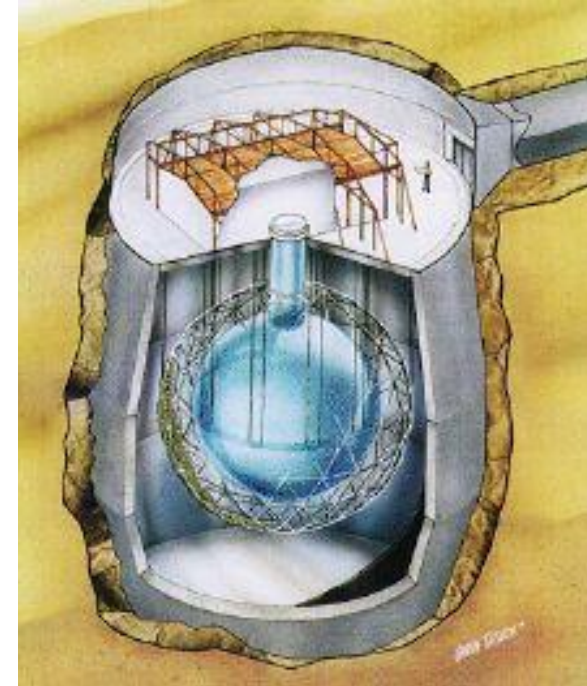
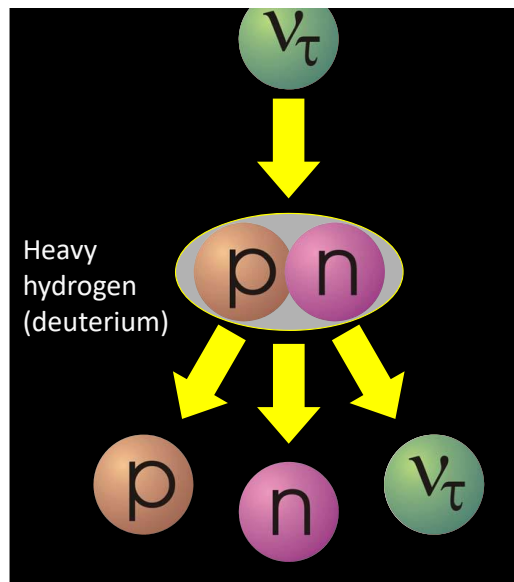
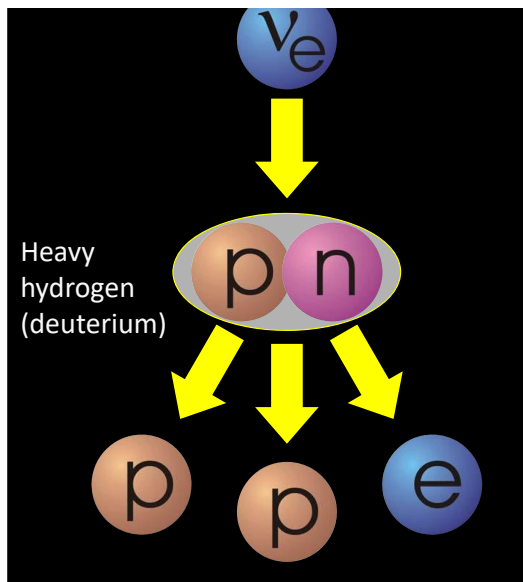
Ettore Majorana



Oplossing 3:
neutrino is zijn
eigen antideeltje!

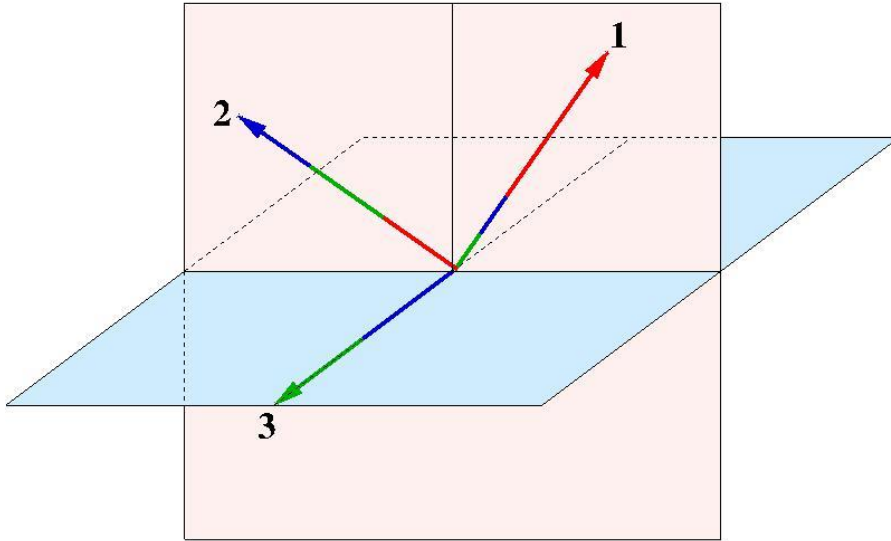
Neutrino oscillaties in de zon

- Oscillaties veroorzaakt doordat ν_e anders wisselwerkt met **materie** dan ν_μ en ν_τ
- ν_e 'voelt' elektronen en neutronen anders
- SNO heeft laten zien dat wat er tekort is aan ν_e verschijnt als een andere soort
- Oscillaties van het type $\nu_e \rightarrow$ combinatie van ν_μ en ν_τ

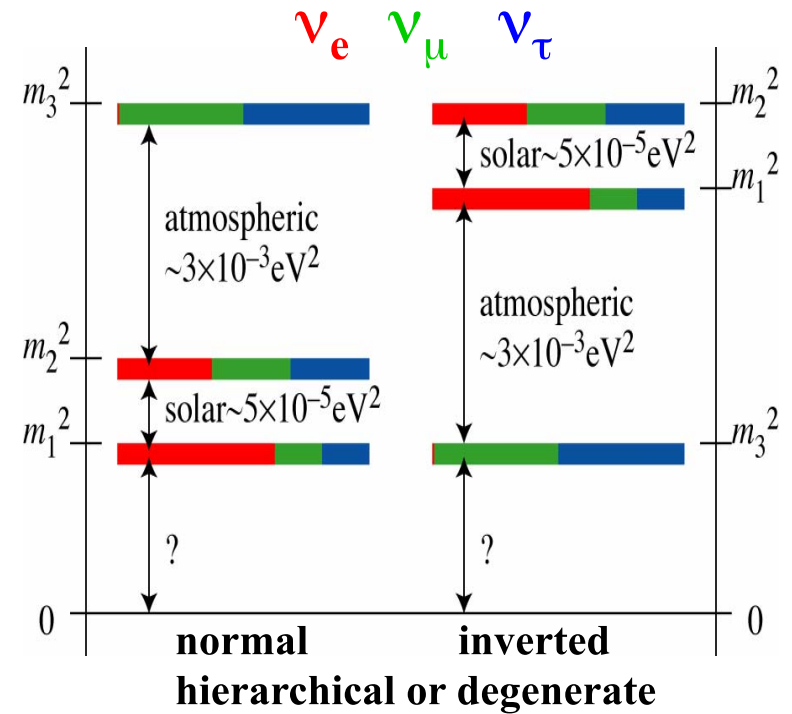


Sudbury
Neutrino
Observatory
(SNO)

Menging van 3 neutrino's



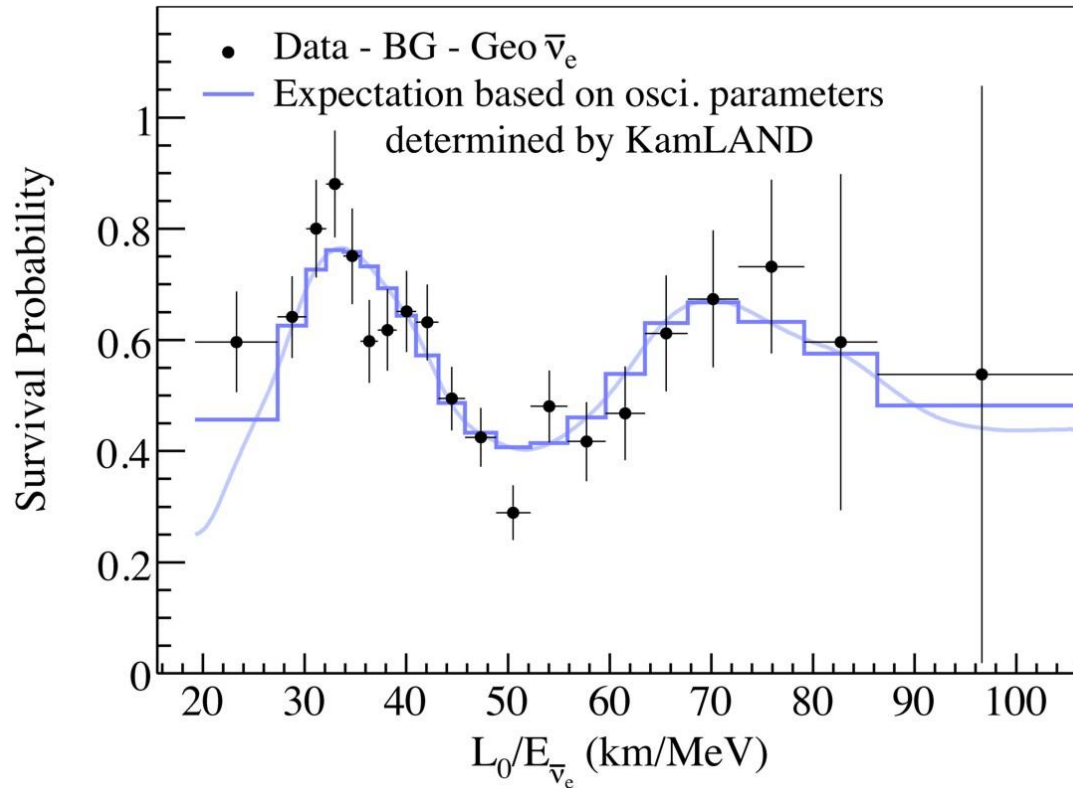
Massa's:



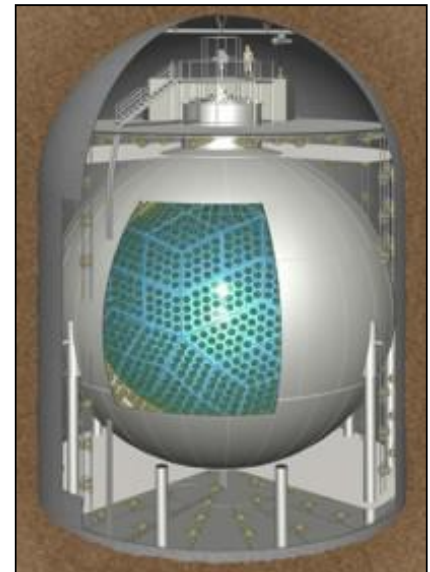
(lichte voorkeur)

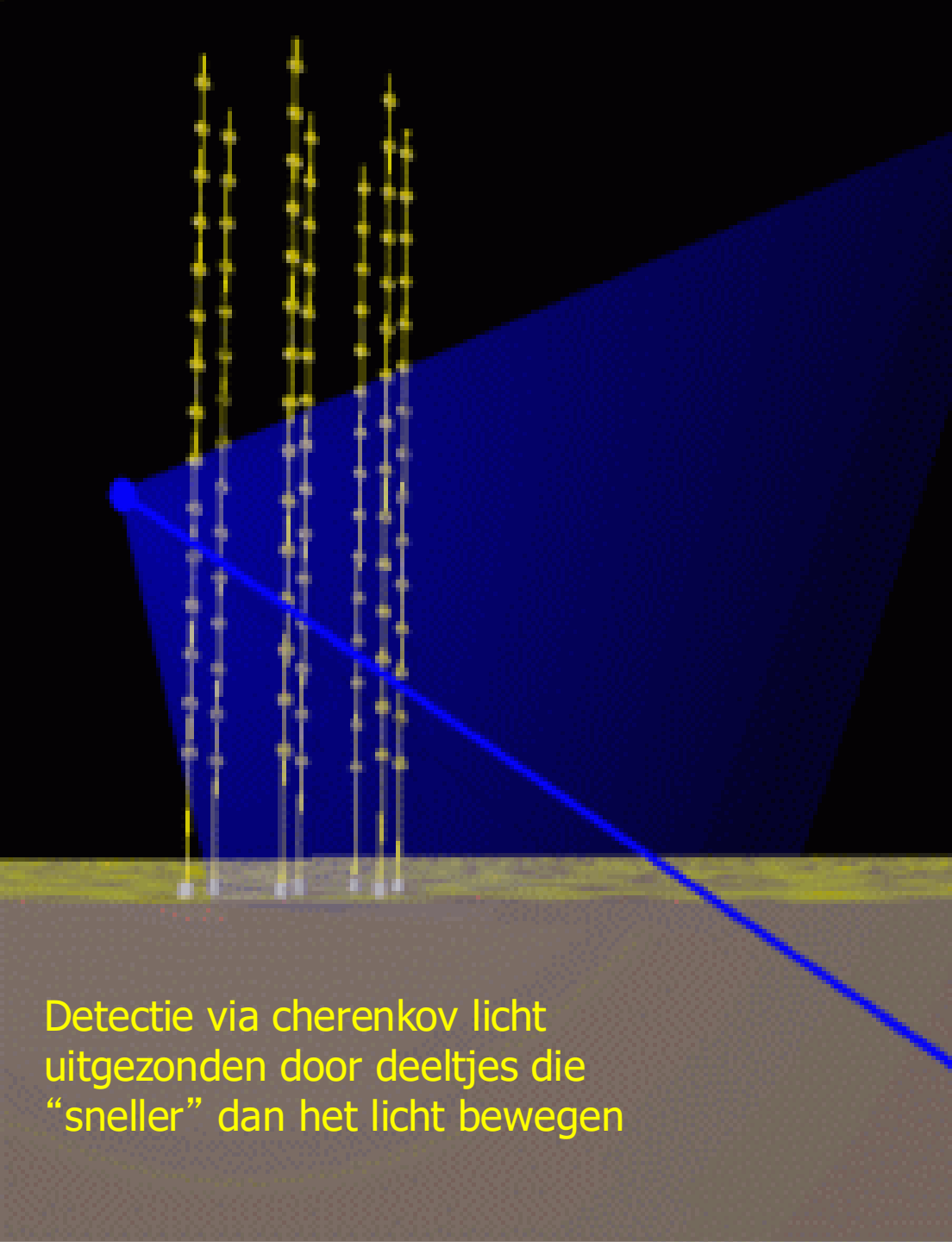
Neutrinos afkomstig van Aarde

Oscillation pattern for anti-electron neutrinos from Japanese power reactors as a function of L/E

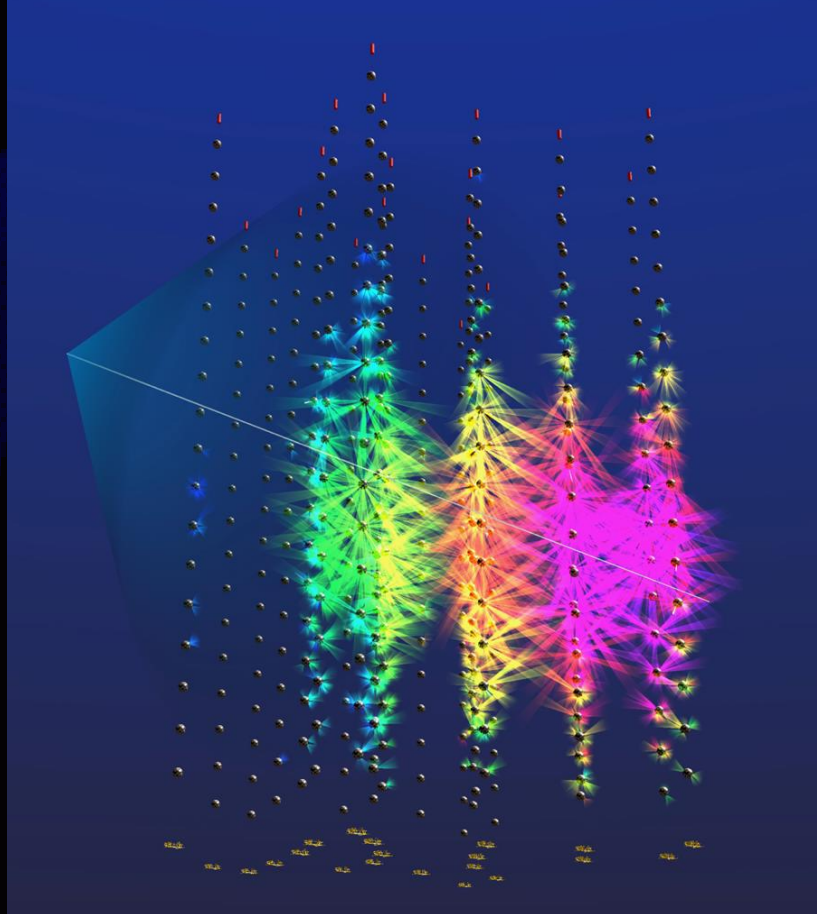


KamLAND Scintillator detector (1000 t)





Detectie via cherenkov licht
uitgezonden door deeltjes die
“sneller” dan het licht bewegen



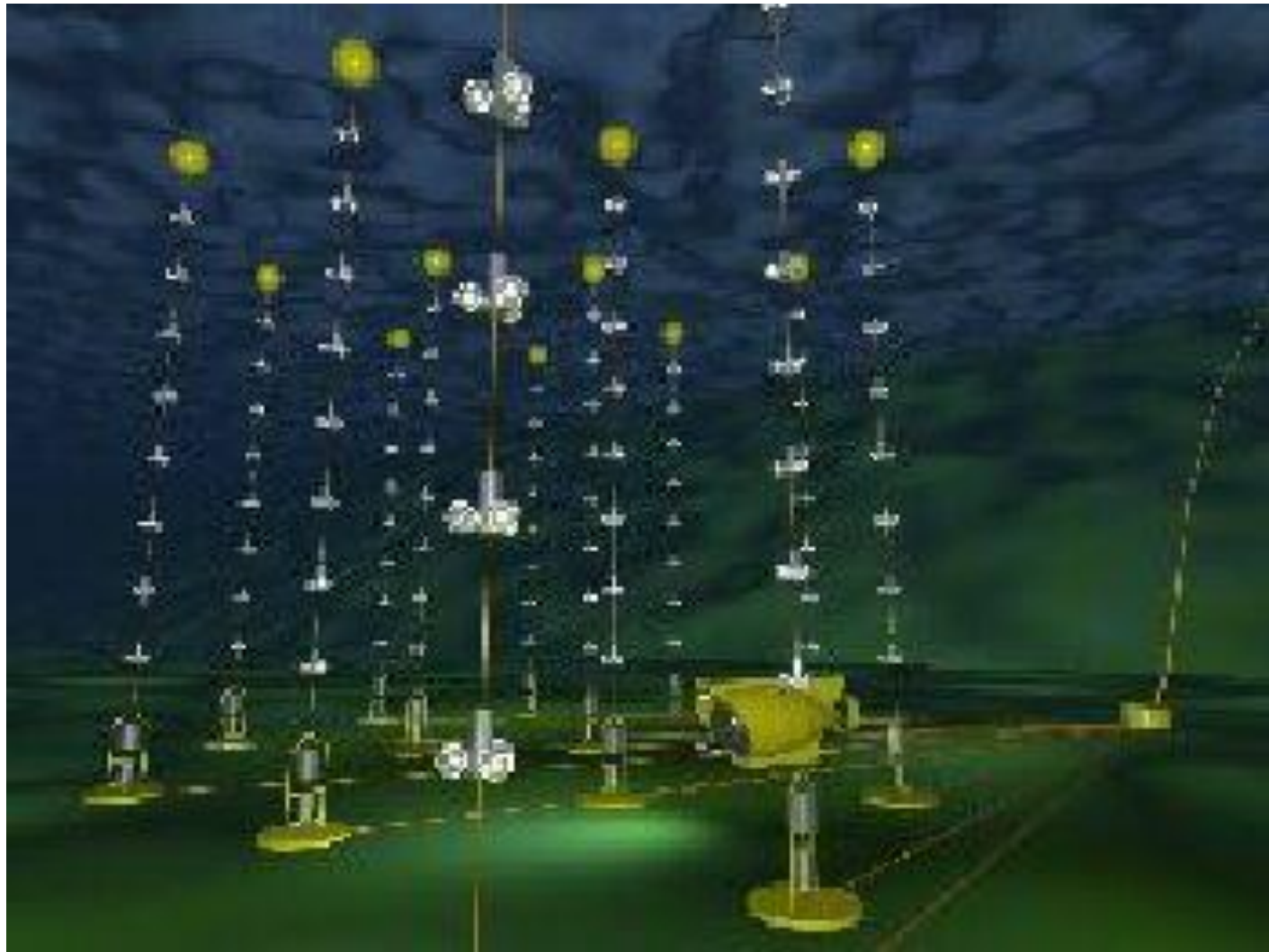
The track of the unusually energetic muon detected on 13 February 2023 by the KM3NeT array was reconstructed by the arrival times of light at various sensors. Unlike many of the particles spotted by the detectors, the muon was traveling horizontally (right to left along the line). (Image from KM3NeT/CC BY-NC 4.0.)

ANTARES

(middellandse
zee)

Doel is een
volume ter
grootte van
een km^3

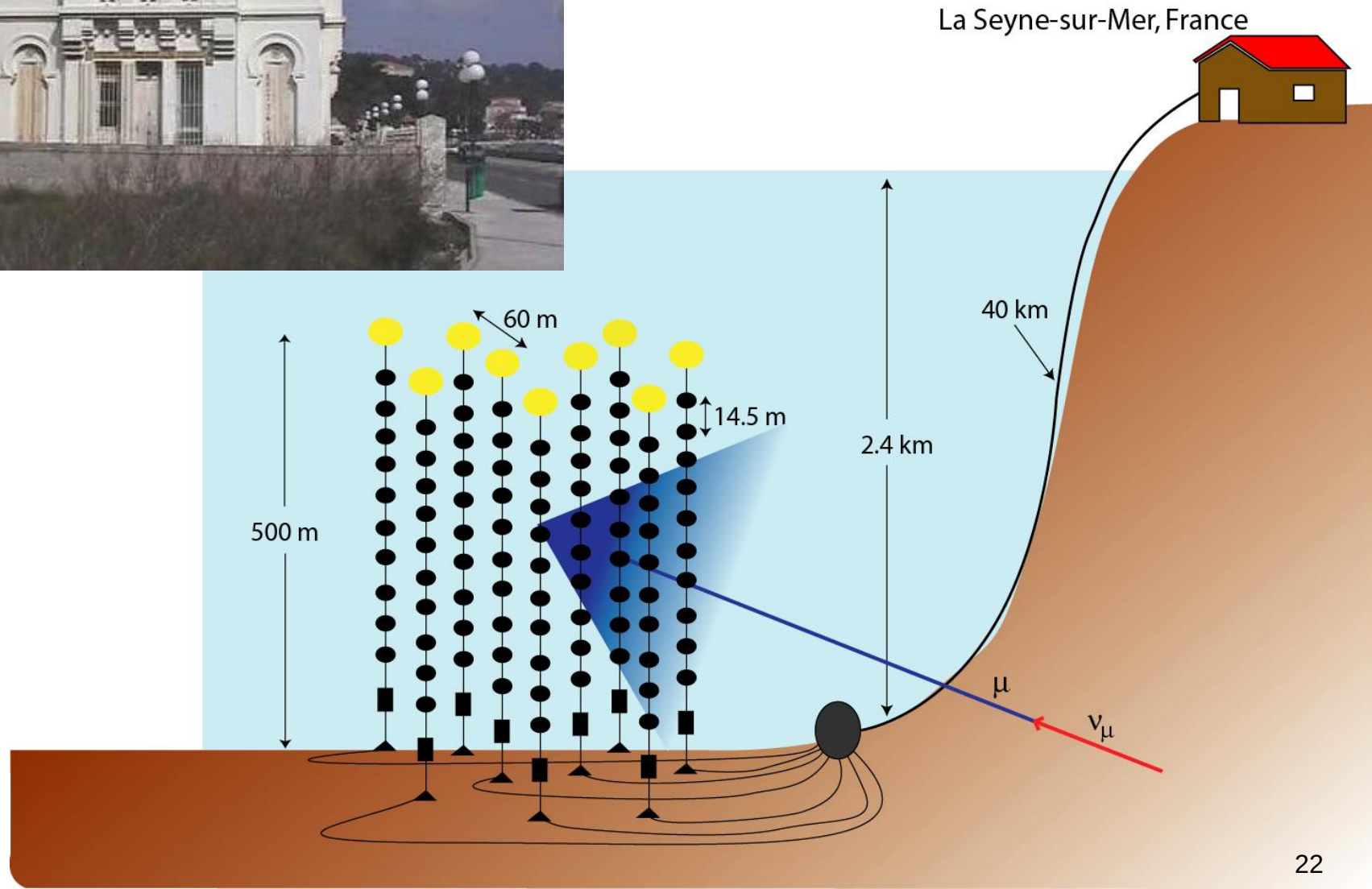
KM3NET



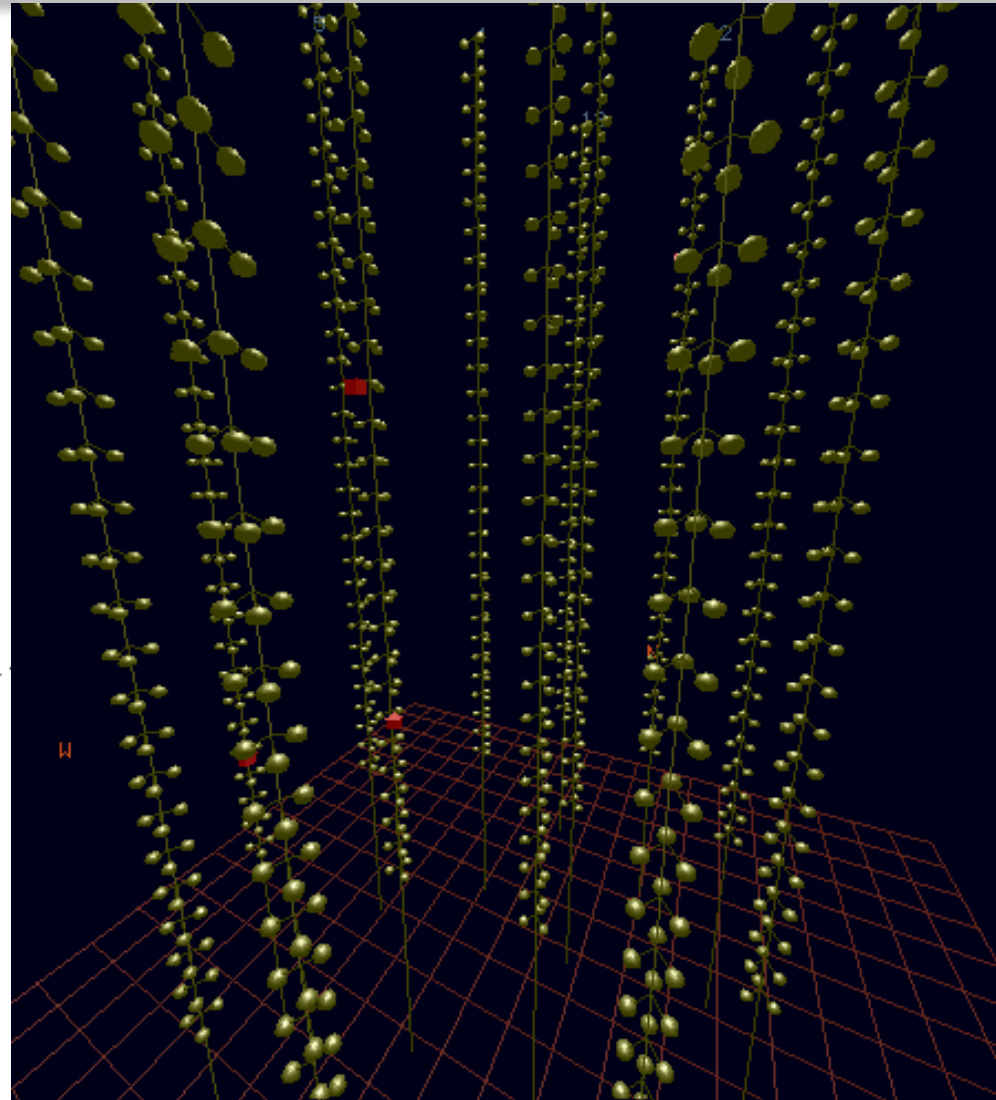
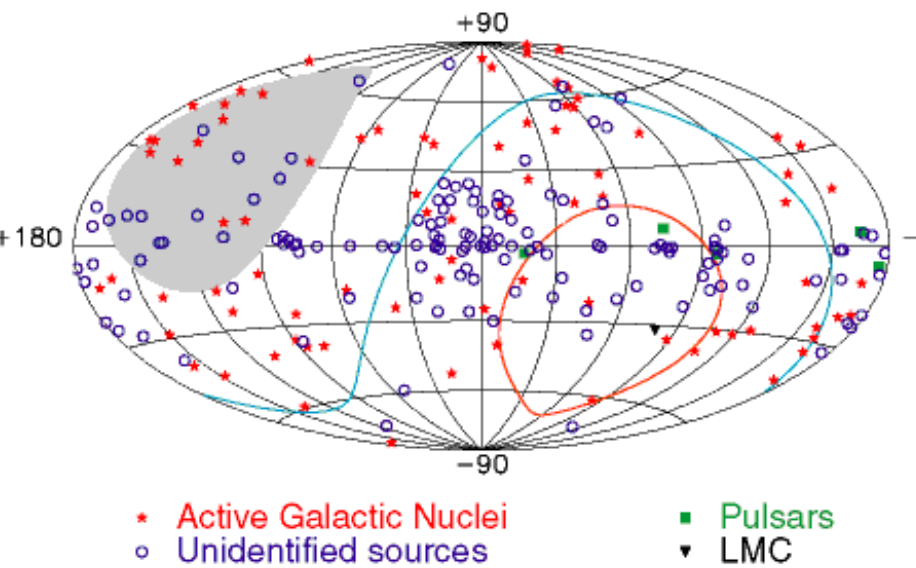
Controlekamer



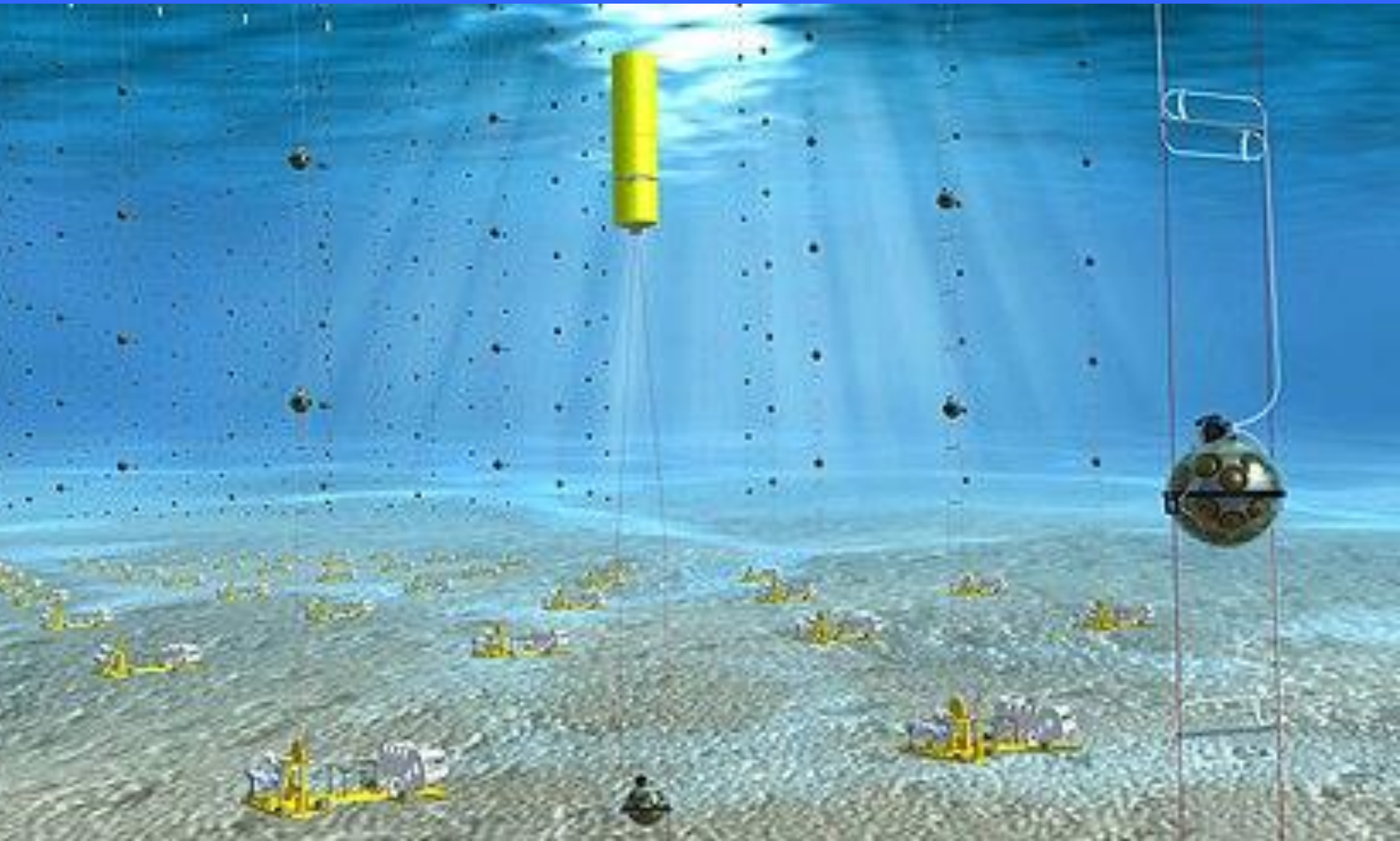
Principe



ANTARES



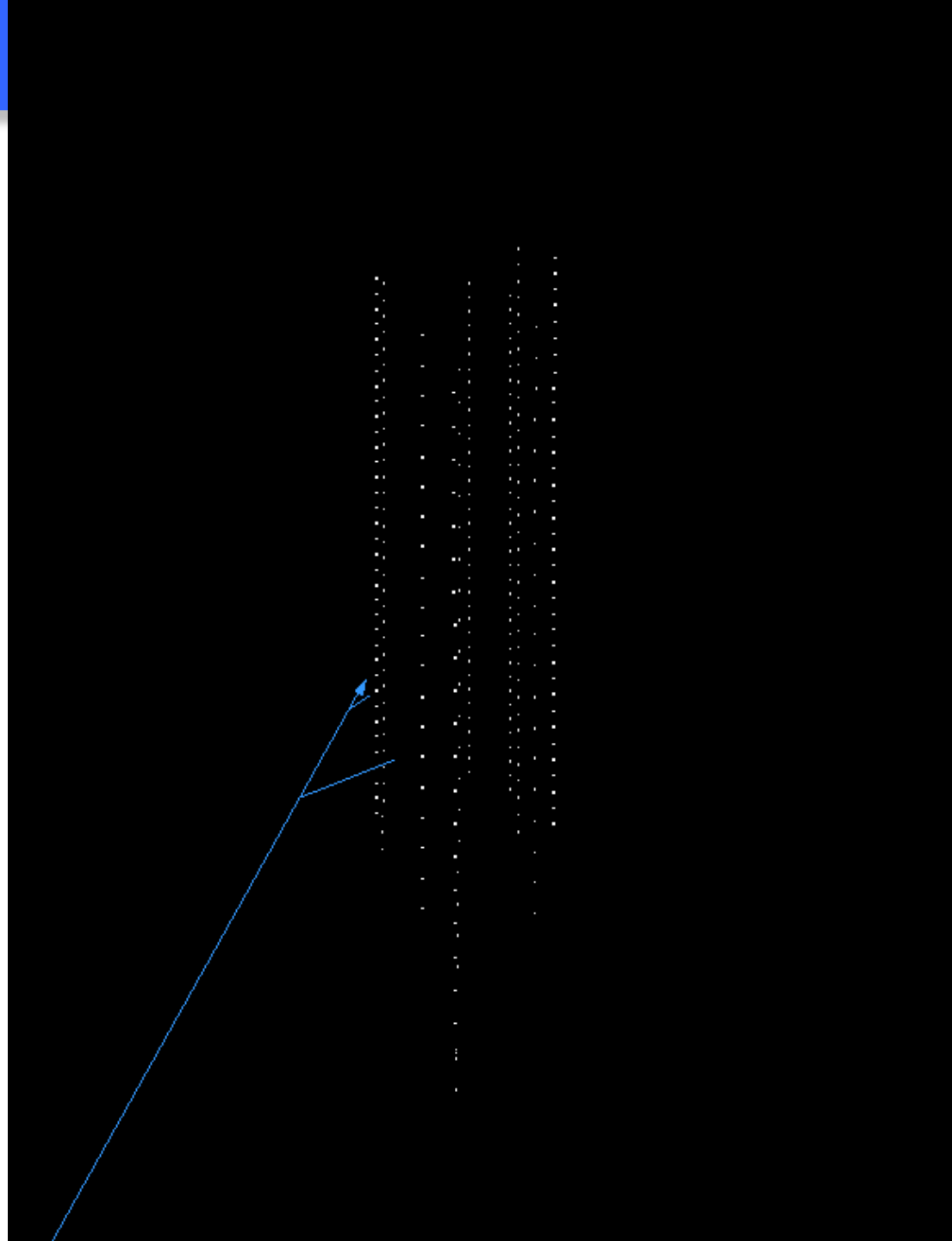
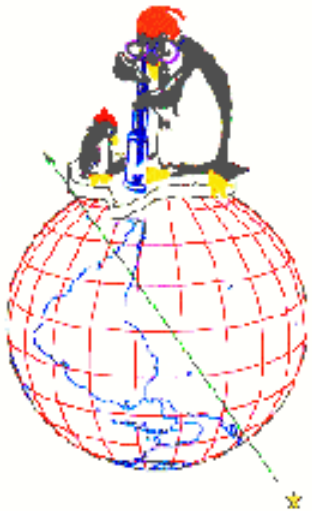
KM3NET



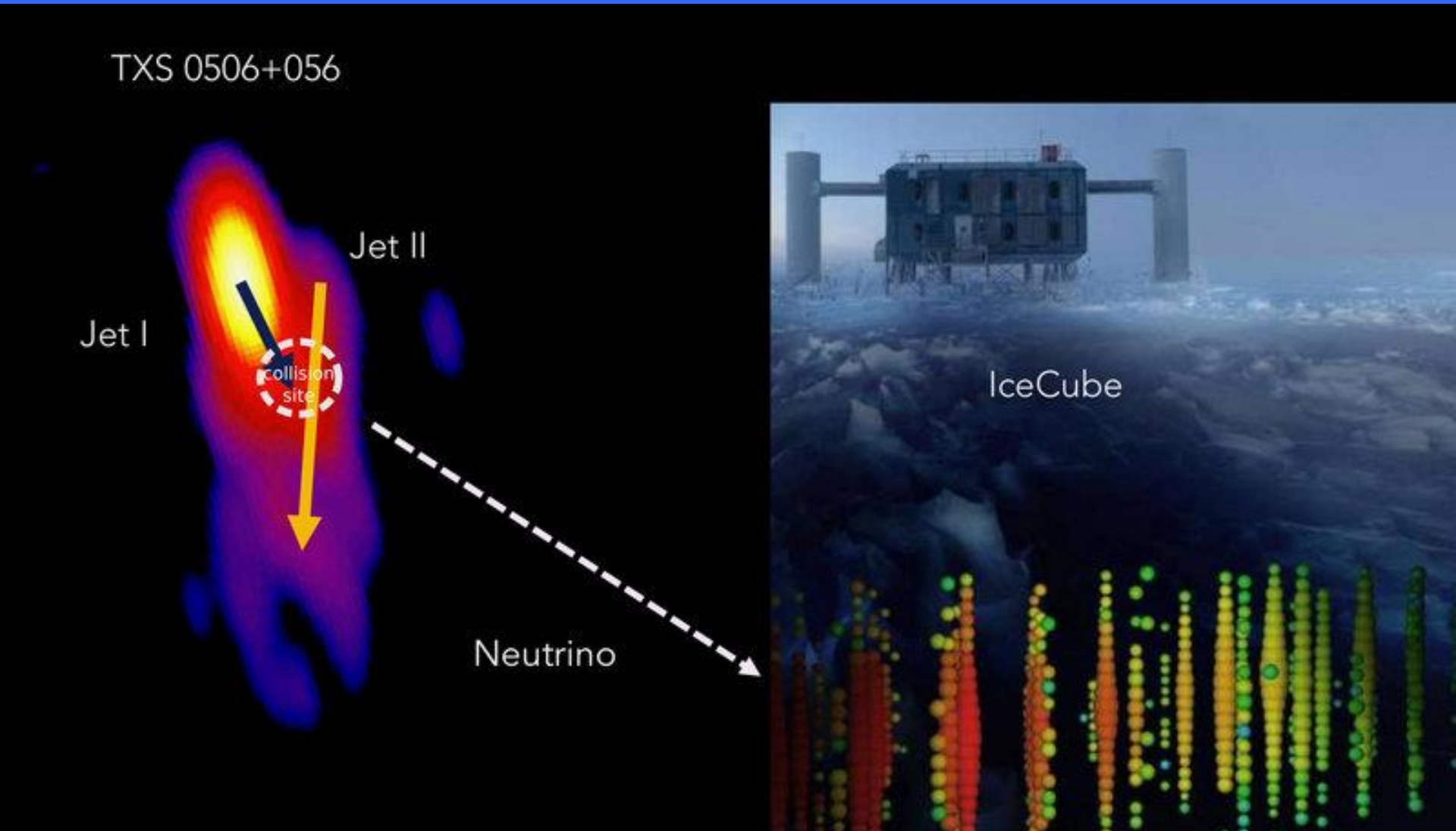
AMANDA

ICE CUBE

(South Pole)



Resultaten van IceCube



IceCube
(Zuidpool)

TeV neutrino's

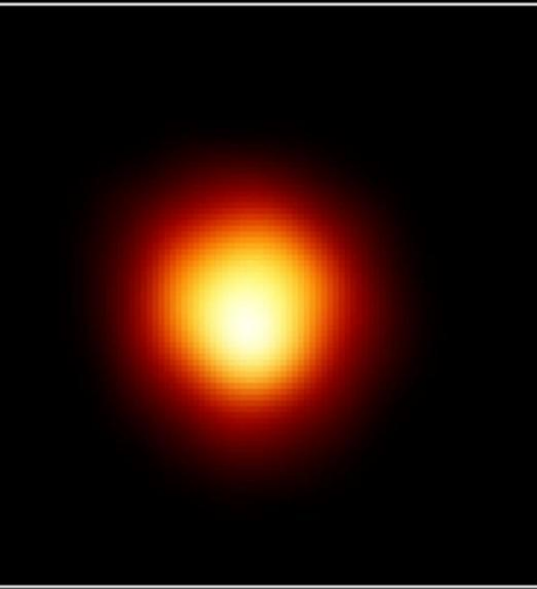
Neutrinos uit de kosmos

凡十一日没三年三月乙巳出東南方大中祥符四年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅前星西北大如桃連行經軒轅太星入太微垣掩右執法犯次將歷屏星西北凡七十五日入濁没明道元年六月乙巳出東北方近濁有芒彗至丁巳凡十三日没至和元年五月己丑出天關東南可數寸歲餘稍没熙寧二年六月丙辰出箕度中至七月丁卯犯箕乃散三年十一月丁未出天因元祐六年十一月辛亥出參度中犯掩側星壬子犯九游星十二月癸酉入奎至七年三月辛亥乃散紹興八年五月守婁

宋史志卷九
三十二



The Red Supergiant Betelgeuse (Alpha Orionis)



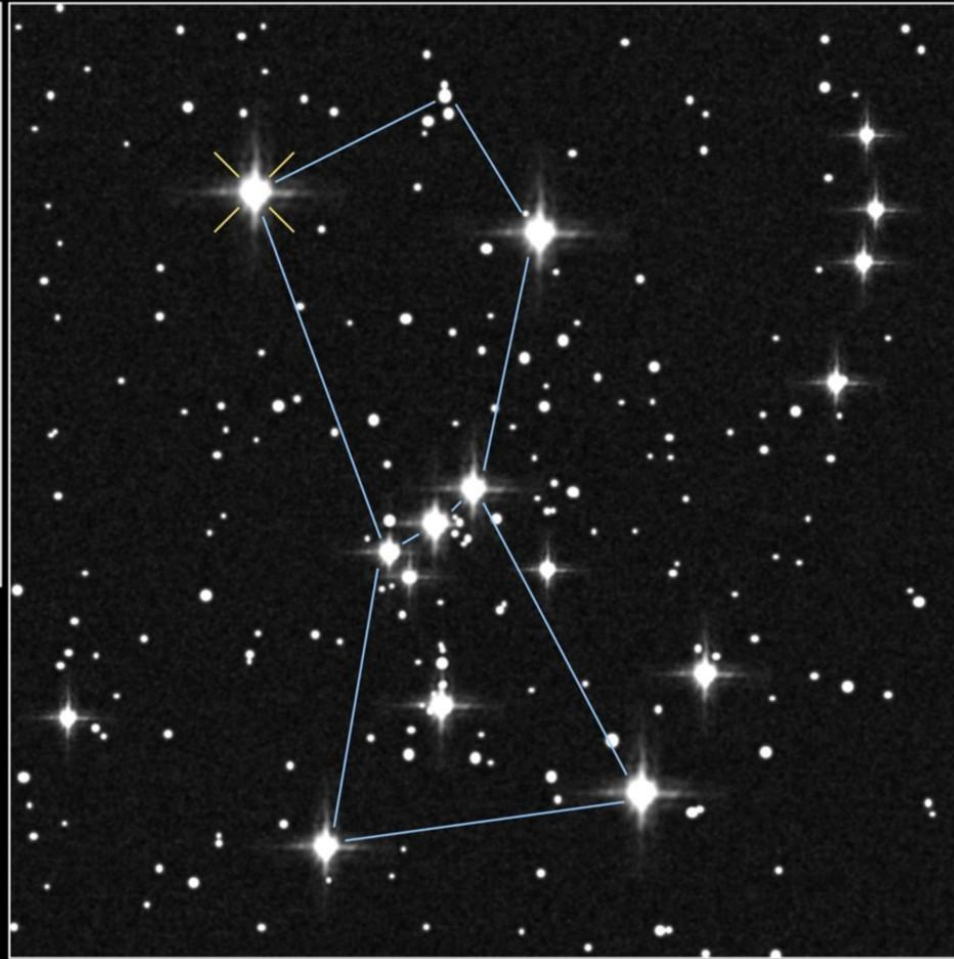
Size of Star



Size of Earth's Orbit



Size of Jupiter's Orbit



First resolved
image of a star
other than Sun

Distance
(Hipparcos)
130 pc (425 lyr)

If Betelgeuse goes Supernova:

- 6×10^7 neutrino events in Super-Kamiokande
- 2.4×10^3 neutrons /day from Si burning phase (few days warning!), need neutron tagging