

Neutrinos

Neues von den Geisterteilchen

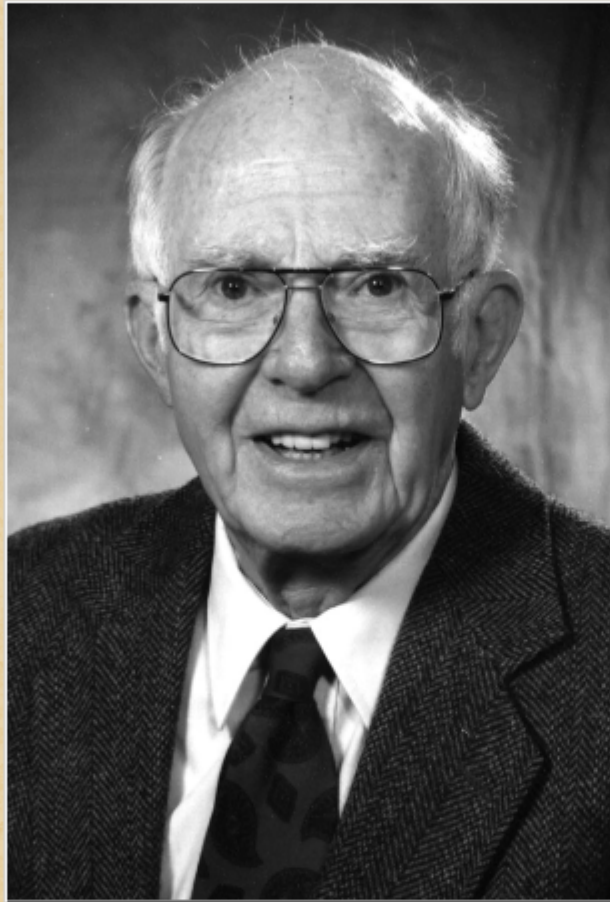
LMU (Seniorenstudium), 2. Dezember 2002



Georg Raffelt

Max-Planck-Institut für Physik, München

Physik Nobel-Preis 2002 für Neutrino-Astronomie



Ray Davis Jr.
(*1914)



Masatoshi Koshihara
(*1926)

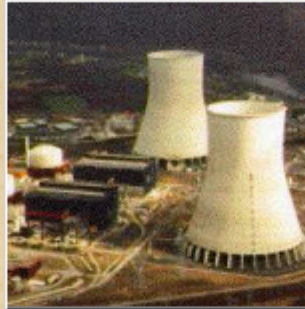


„für Pionierbeiträge zur Astrophysik, insbesondere für den Nachweis kosmischer Neutrinos“

Wo treten Neutrinos in der Natur auf?



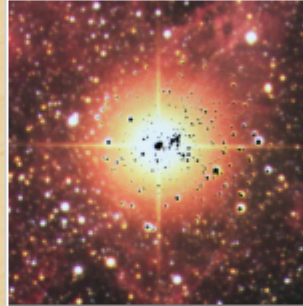
Kernreaktoren



Sonne



Teilchen-
beschleuniger

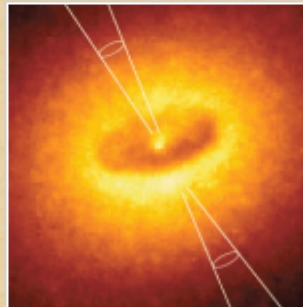


Supernovae
(Kollabierende Sterne)

SN 1987A ✓



Erdatmosphäre
(Kosmische Strahlen)

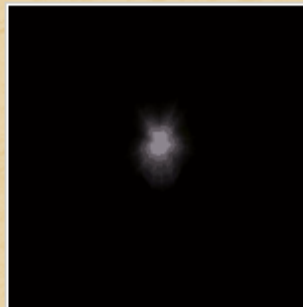


Astrophysikalische
Beschleuniger

Bald ?

2003 ?

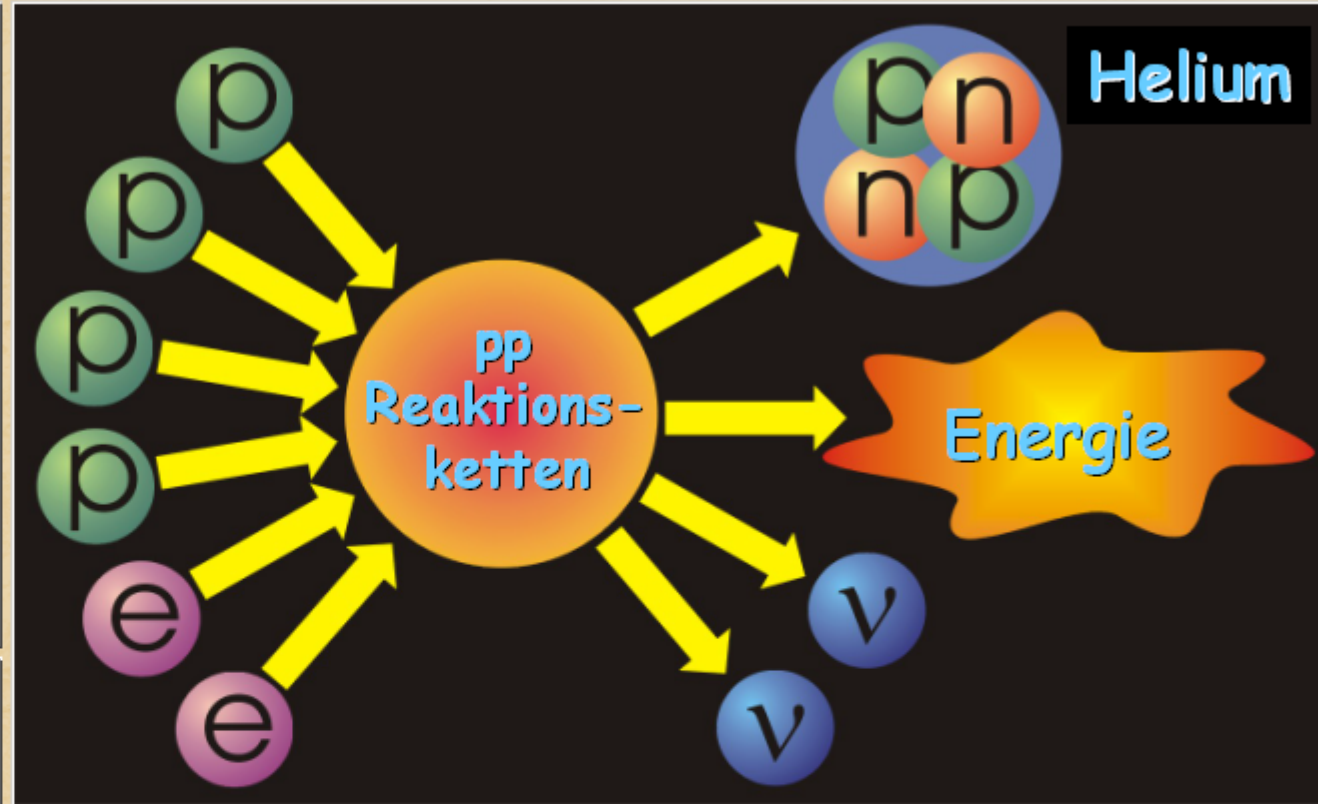
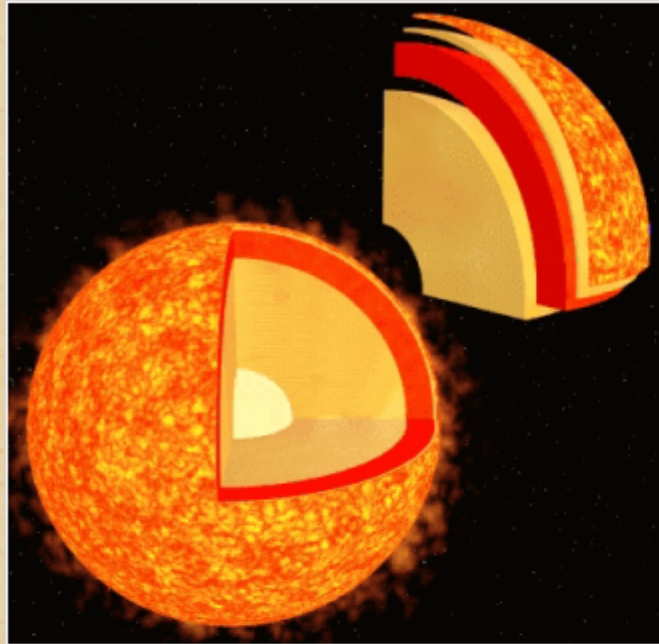
Erdkruste
(Natürliche
Radioaktivität)



Urknall des Universums
(Heute $330 \nu/\text{cm}^3$)

Indirekte Evidenz

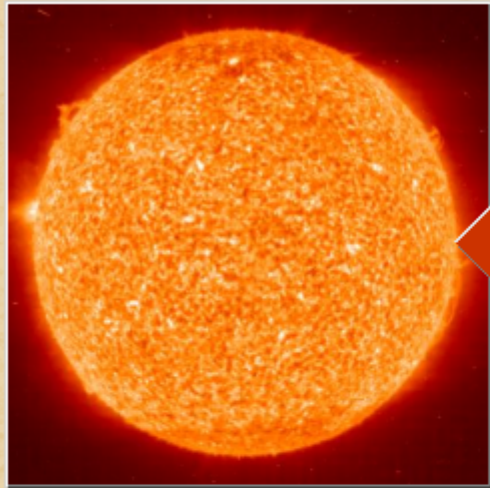
Neutrinos aus der Sonne



**Sonnenabstrahlung: 98 % Licht
2 % Neutrinos
(Hier 66 Milliarden Neutrinos/cm² sec)**

Hans Bethe (geb. 1906, Nobelpreis 1938)
pp Reaktionsketten (1938)

Sonnenbrille für Neutrinos?



8,3 Lichtminuten



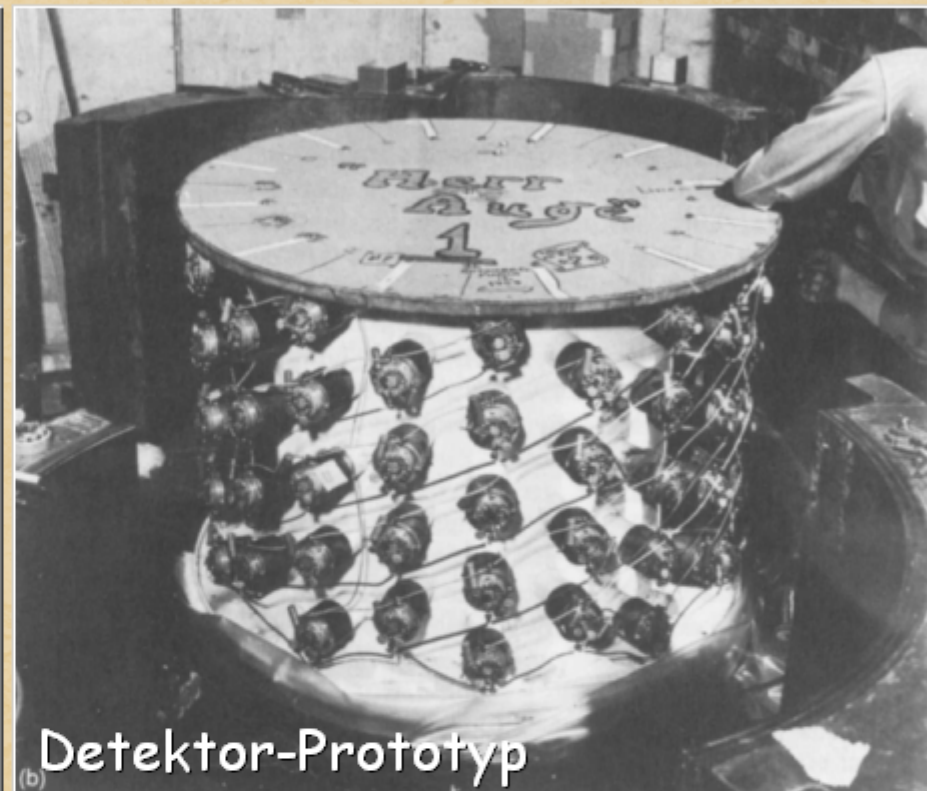
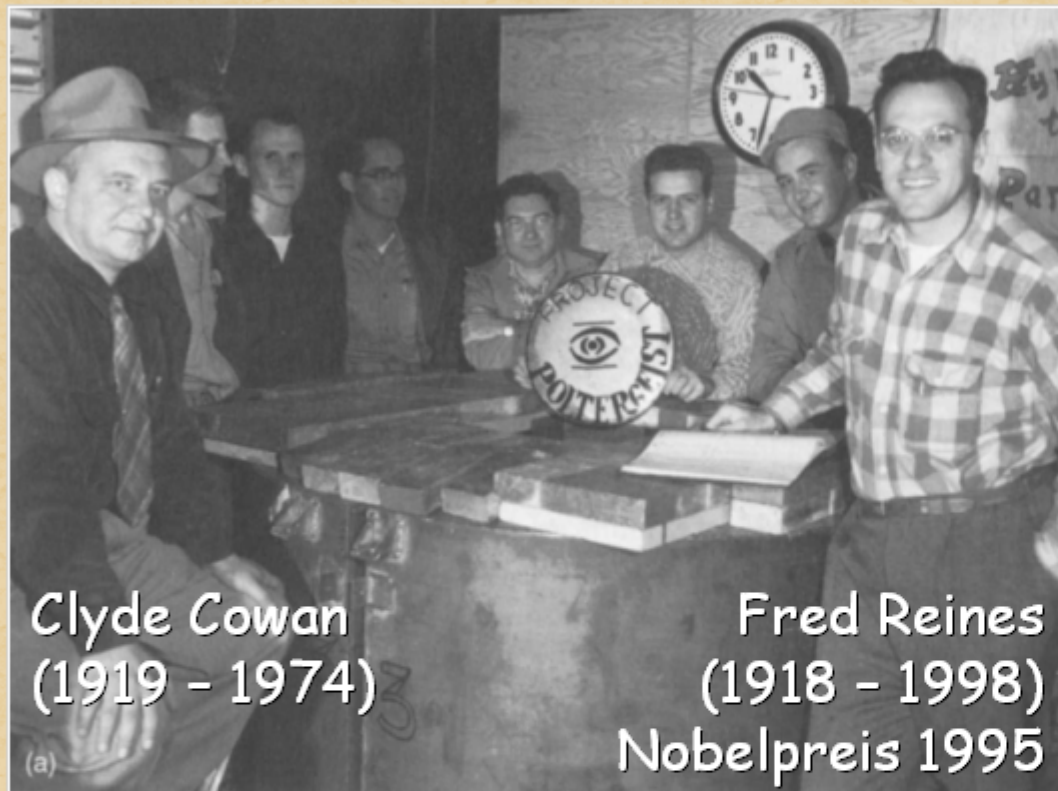
Eine Bleischicht der Dicke von etwa 1000 Lichtjahren nötig

Bethe & Peierls 1934:

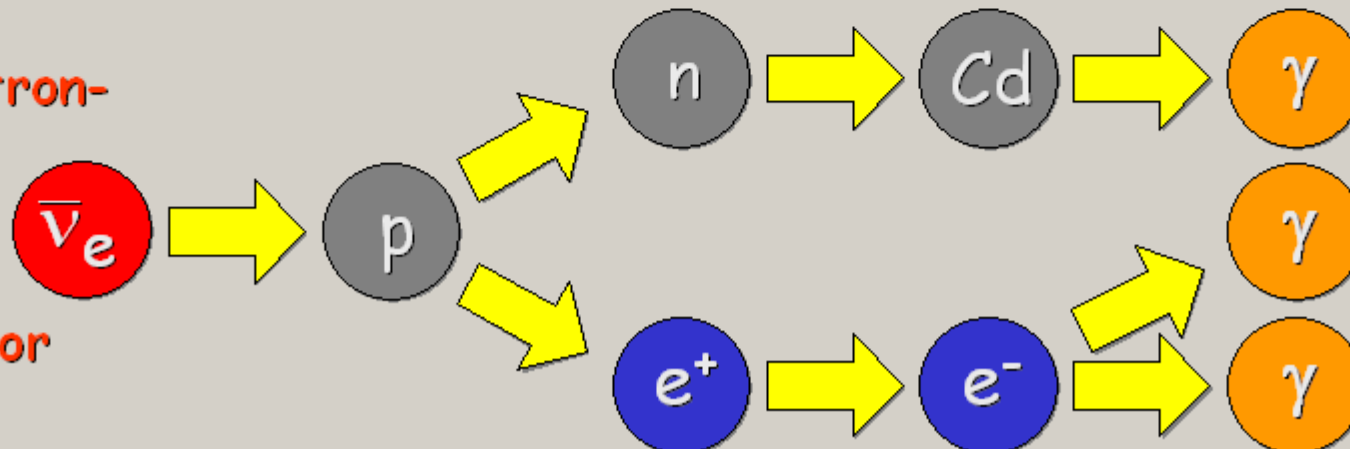
„... dies bedeutet, dass man offensichtlich niemals in der Lage sein wird, ein Neutrino zu beobachten.“



Erster Nachweis (1954 - 1956)



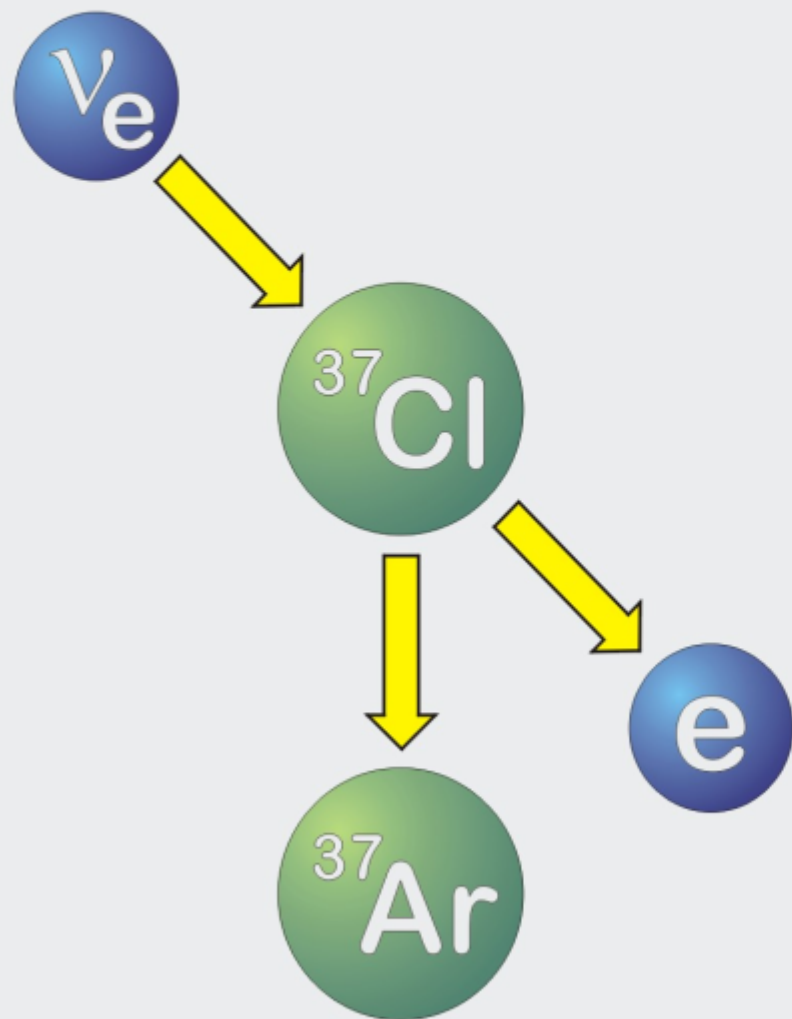
Anti-Elektron-
Neutrinos
von
Hanford
Kernreaktor



3 Gammas
in
Koinzidenz

Erste Messung der Sonnenneutrinos

Inverser Beta-Zerfall („Neutrino-Einfang“)



Homestake Sonnenneutrino-
observatorium (1967-2002)

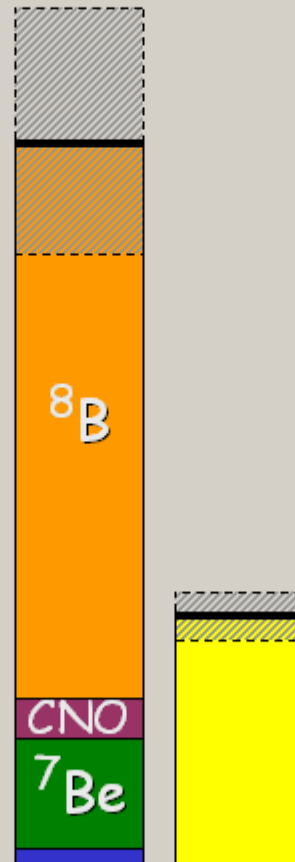
Das Problem der fehlenden Sonnenneutrinos



John Bahcall

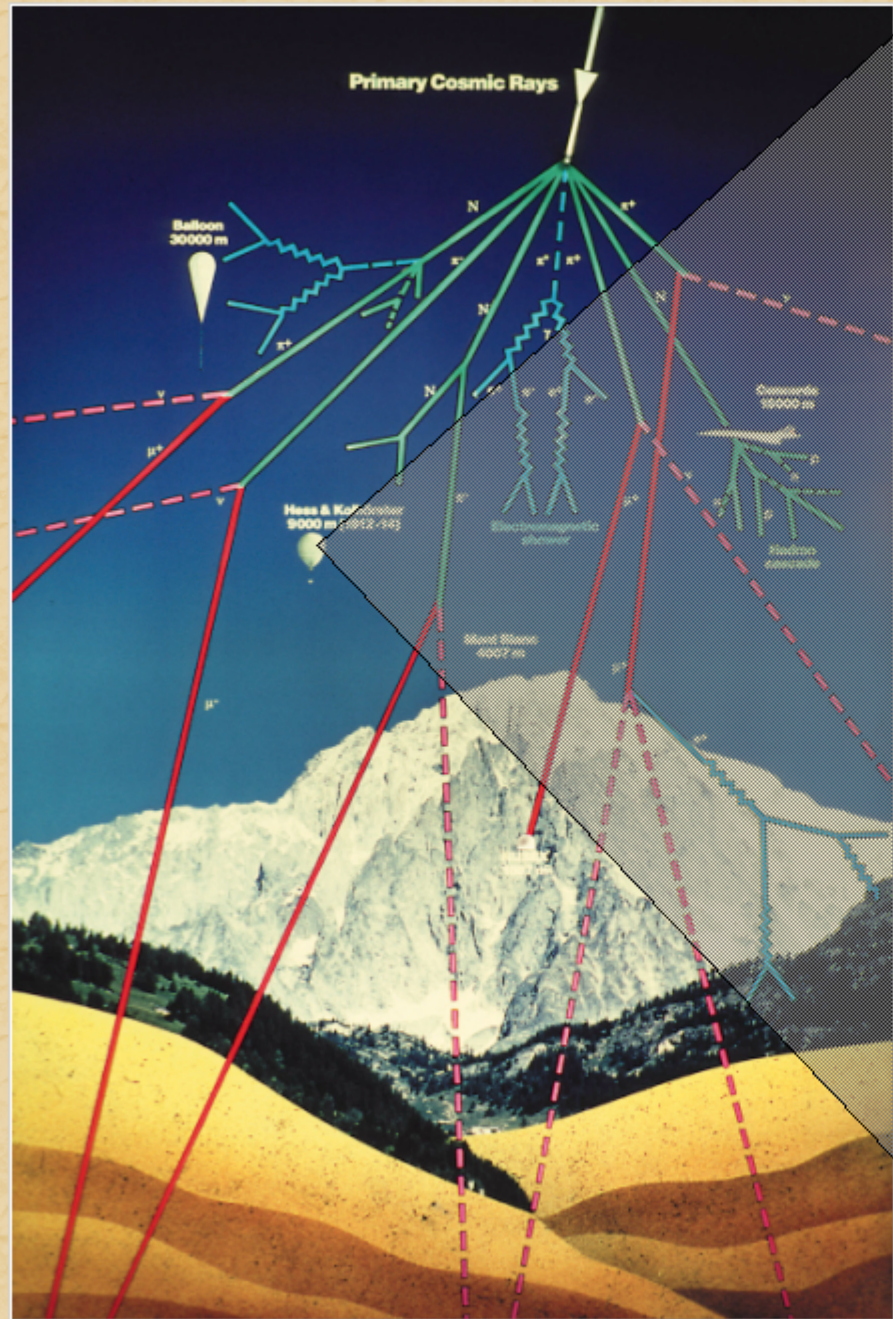
Homestake

Chlor



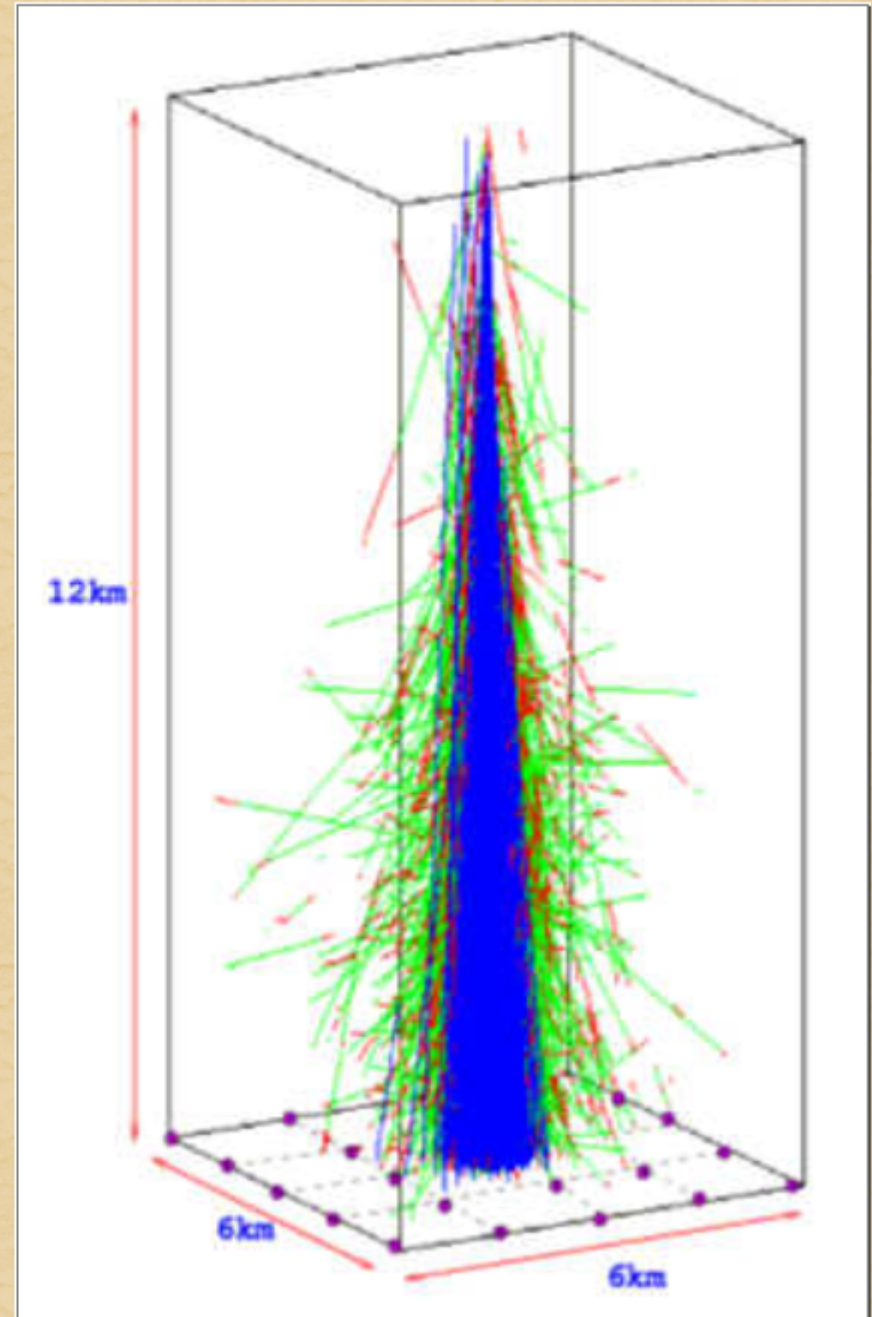
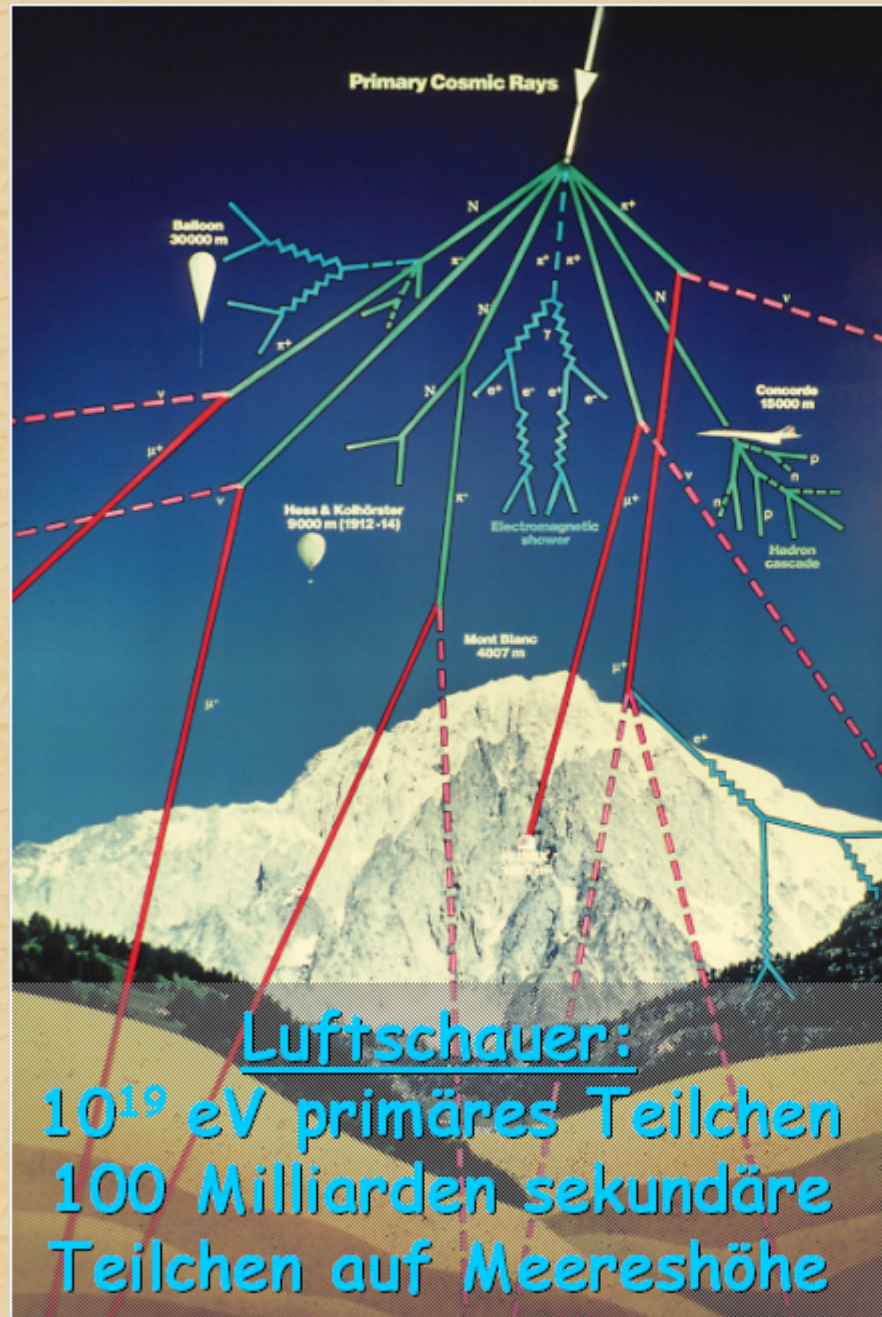
Raymond Davis Jr.

Kosmische Strahlung („Höhenstrahlung“)

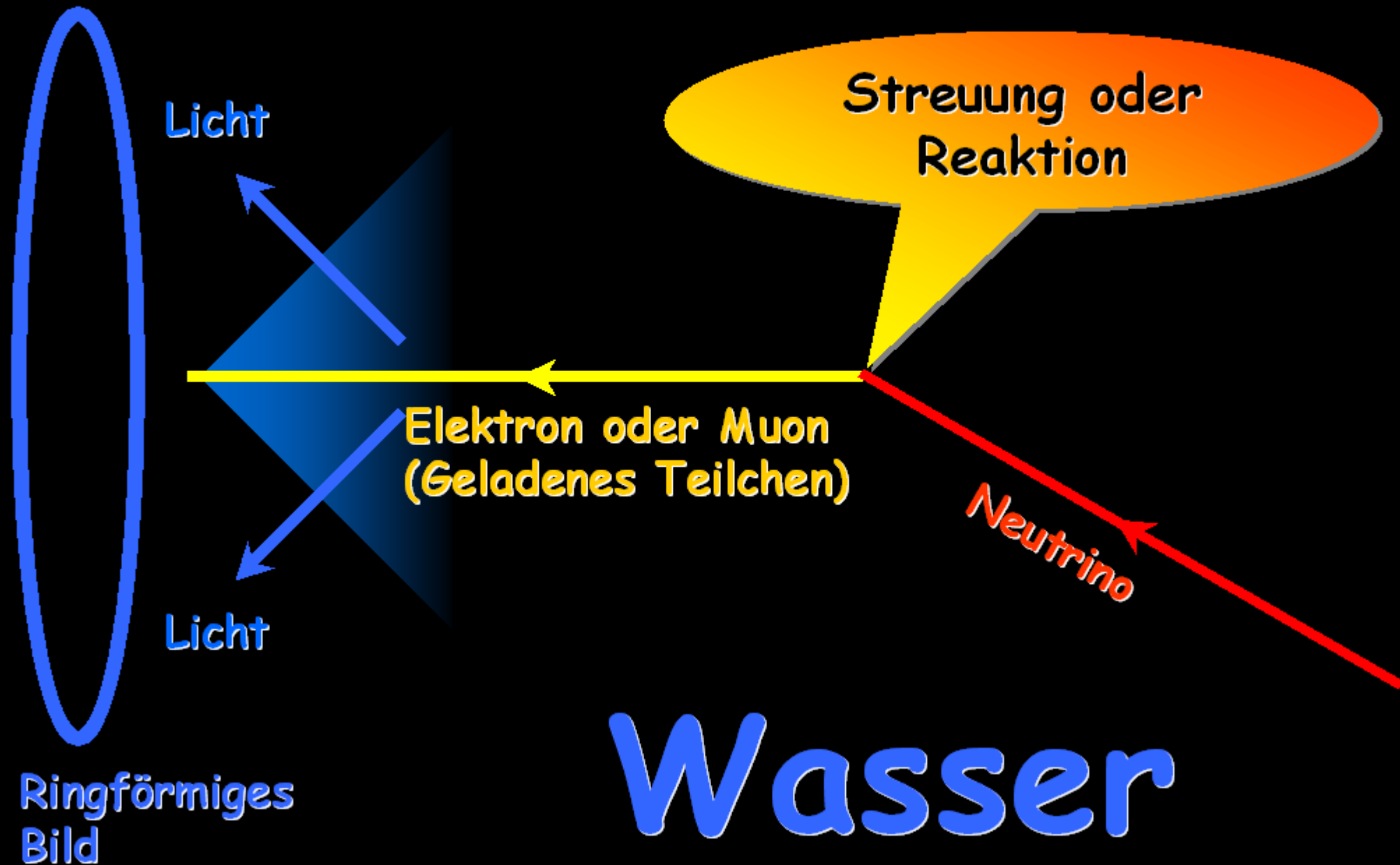


Victor Hess (1911)

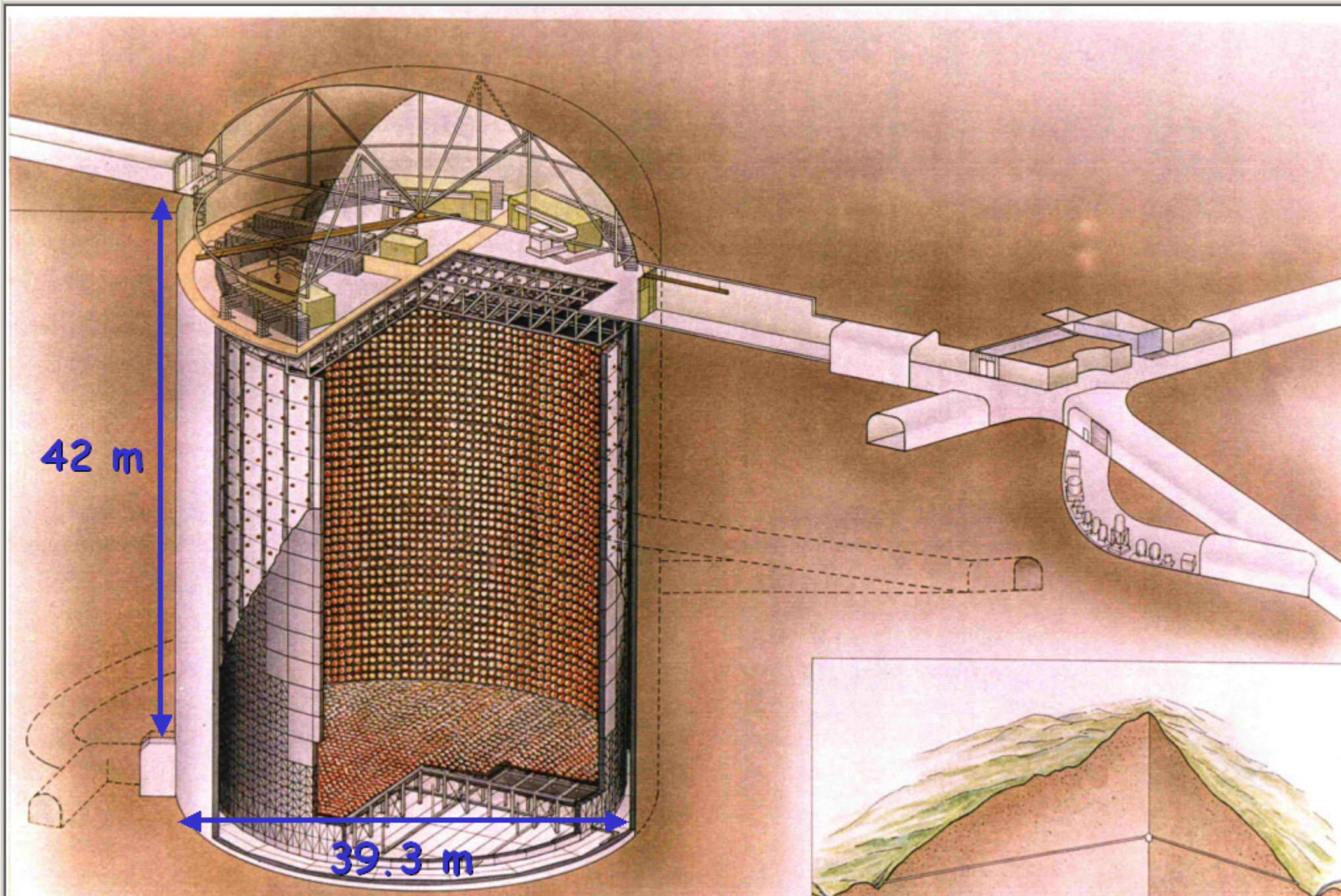
Kosmische Strahlung („Höhenstrahlung“)



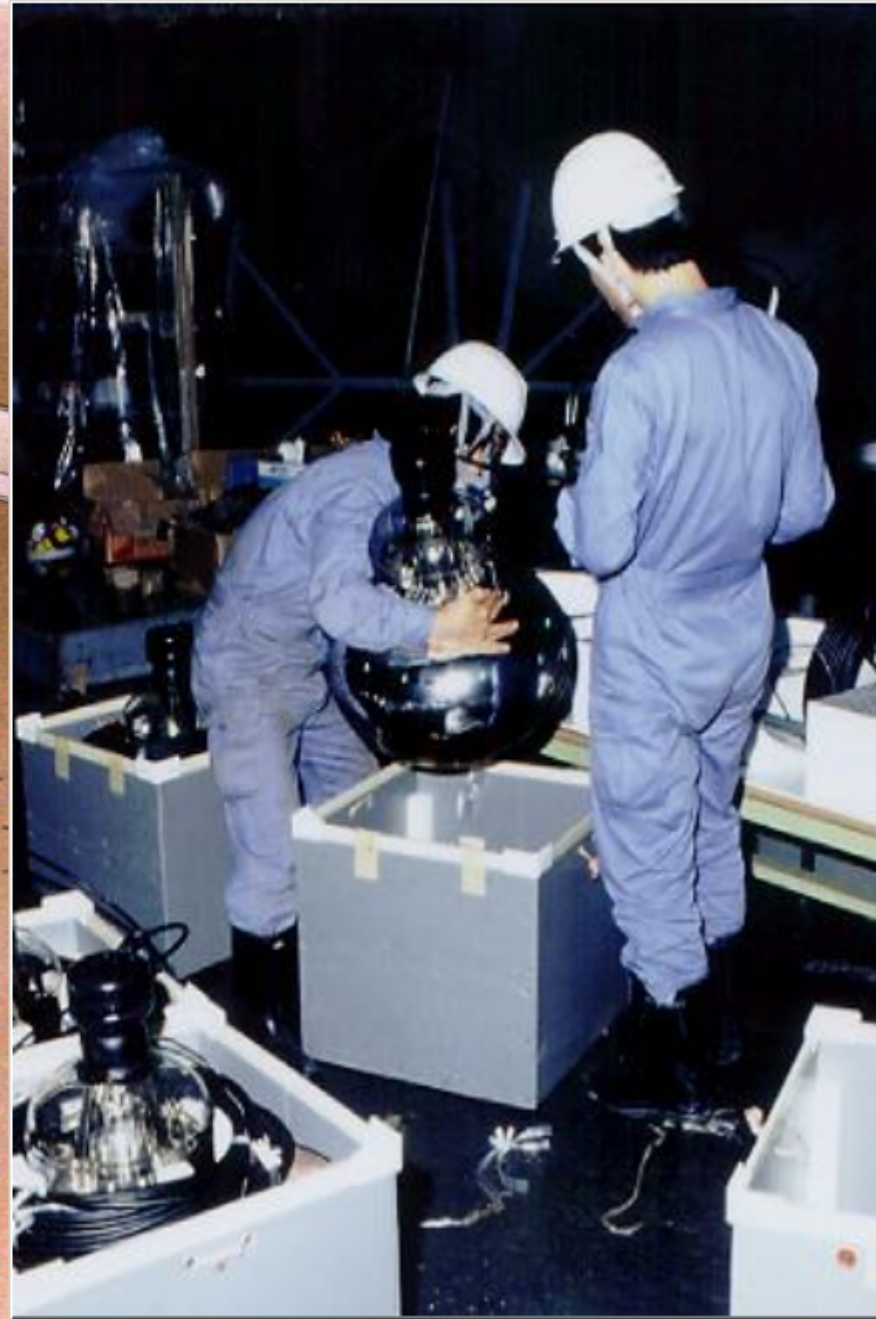
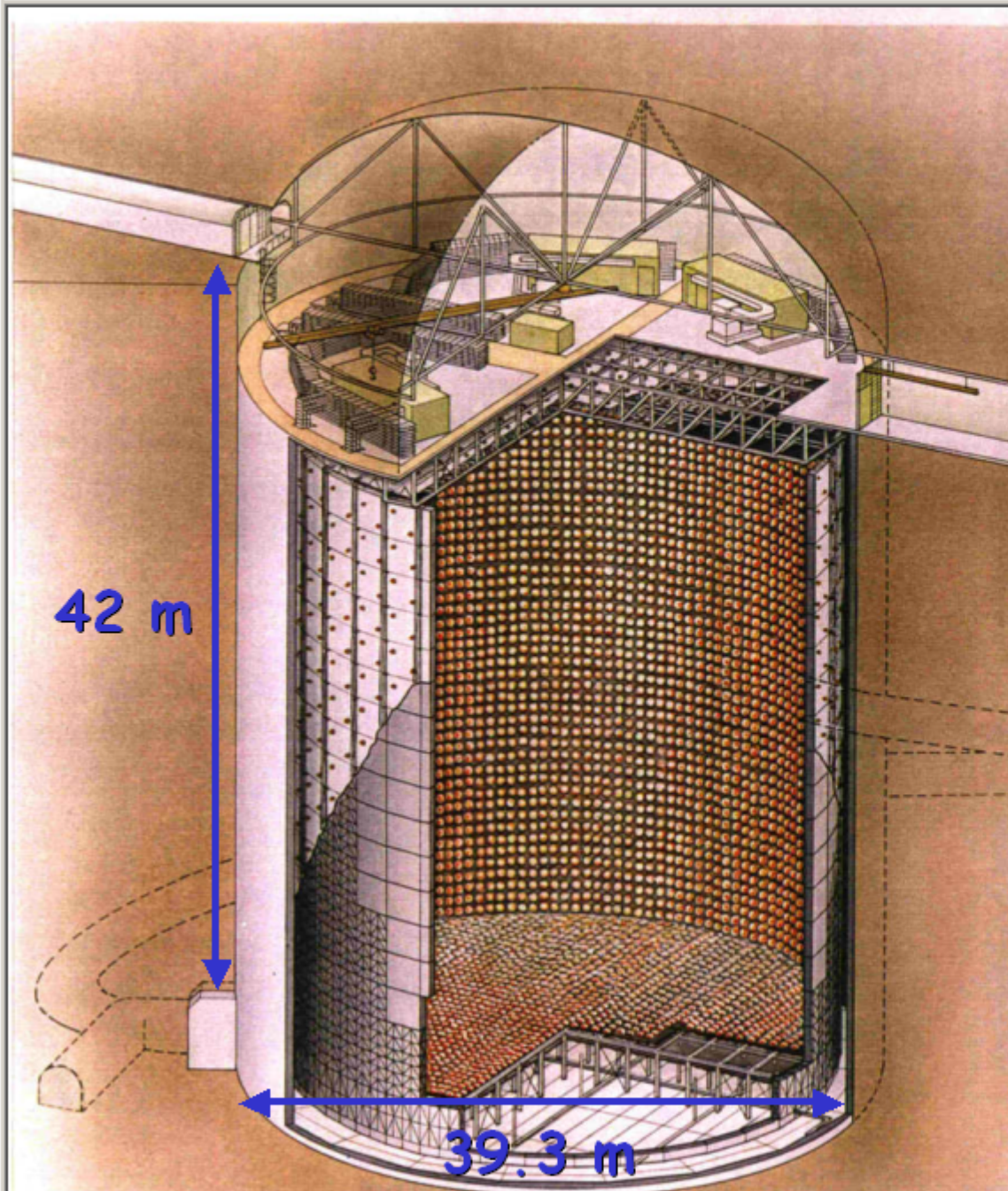
Tscherenkow-Effekt

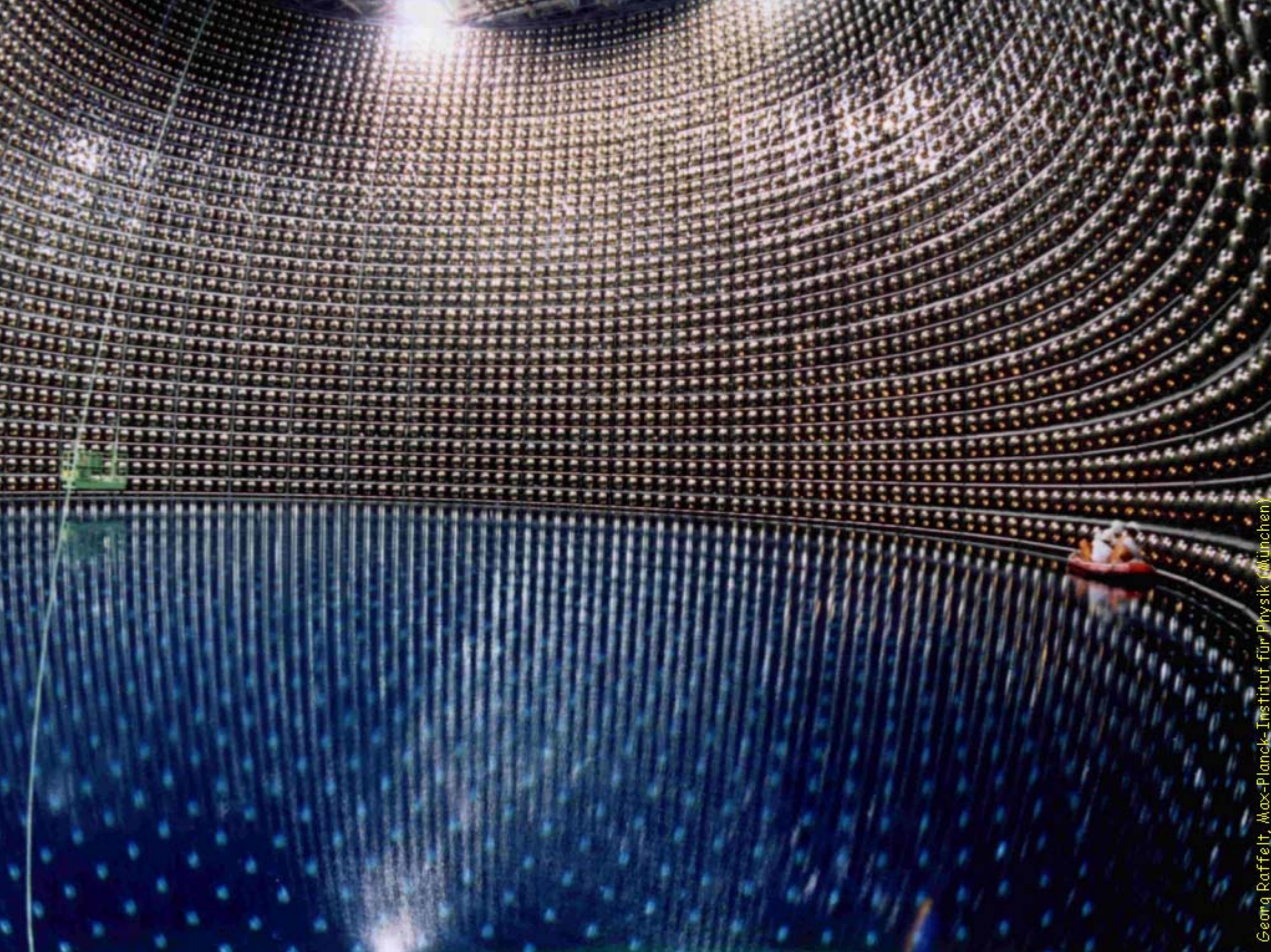


Super-Kamiokande Neutrino-Detektor



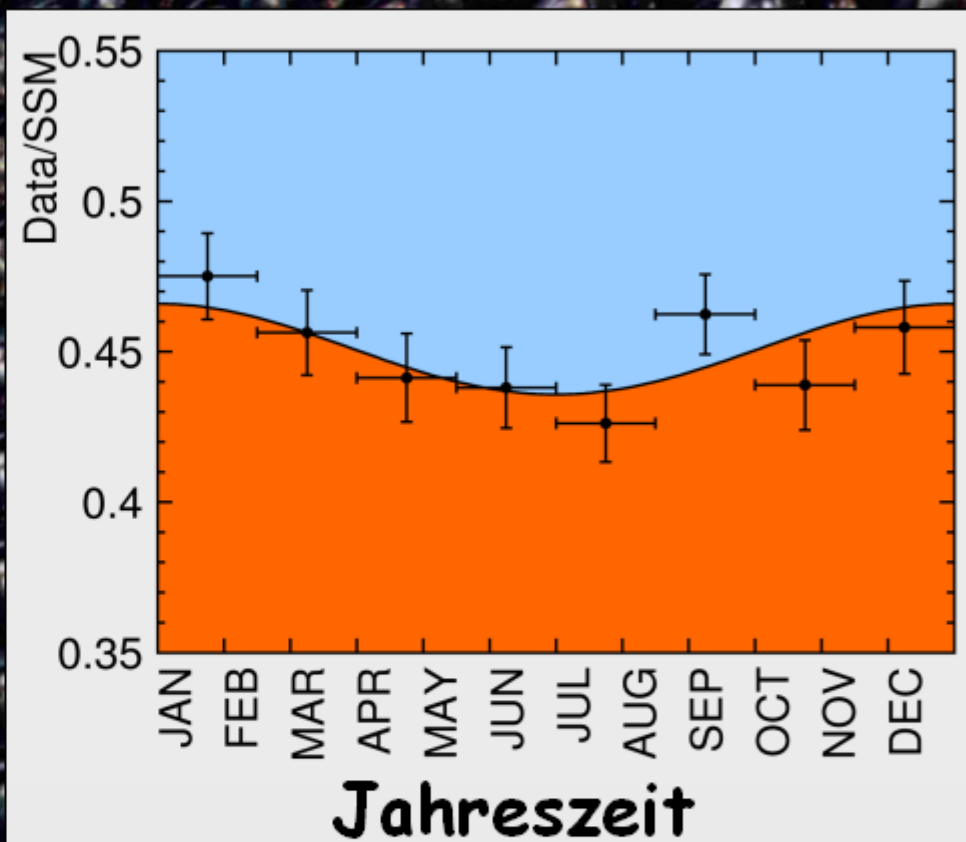
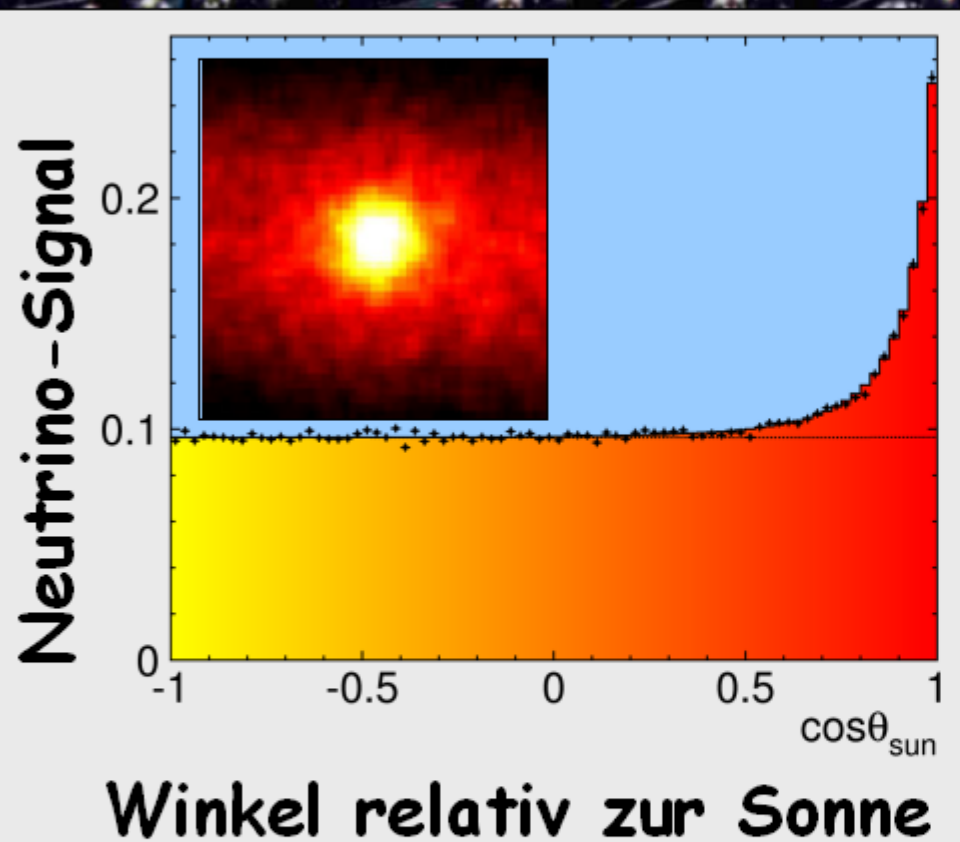
Super-Kamiokande Neutrino-Detektor



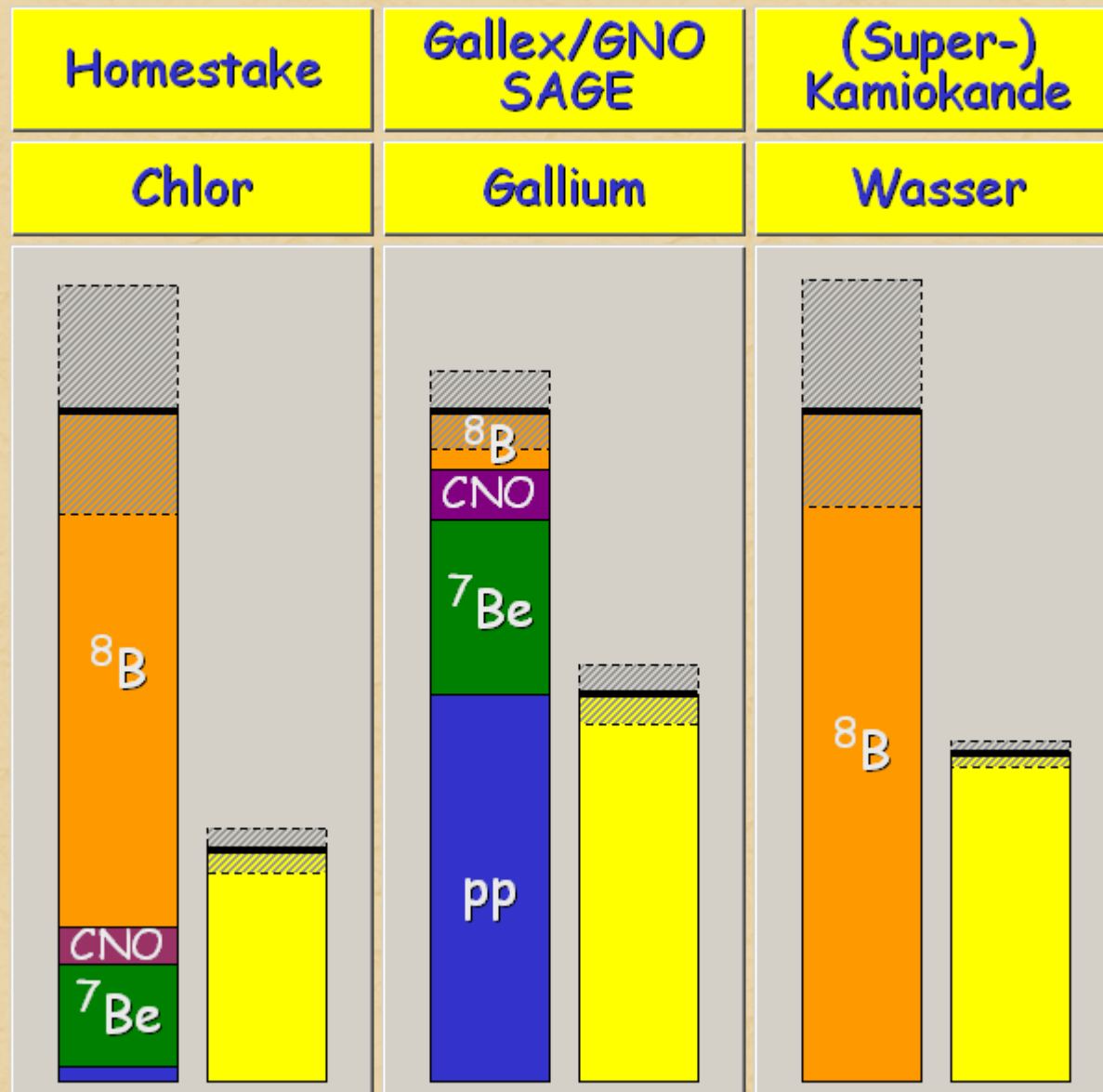




Sonne im „Neutrinolicht“

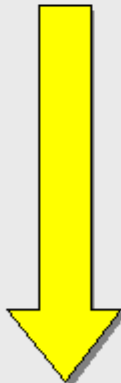
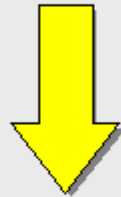


Das Problem der fehlenden Sonnenneutrinos



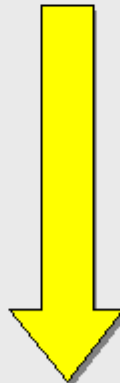
Drei Elektron- und Neutrinosorten

Elektron
0.511 MeV



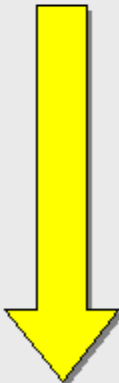
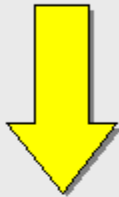
Elektron-
Neutrino

Müon
106 MeV



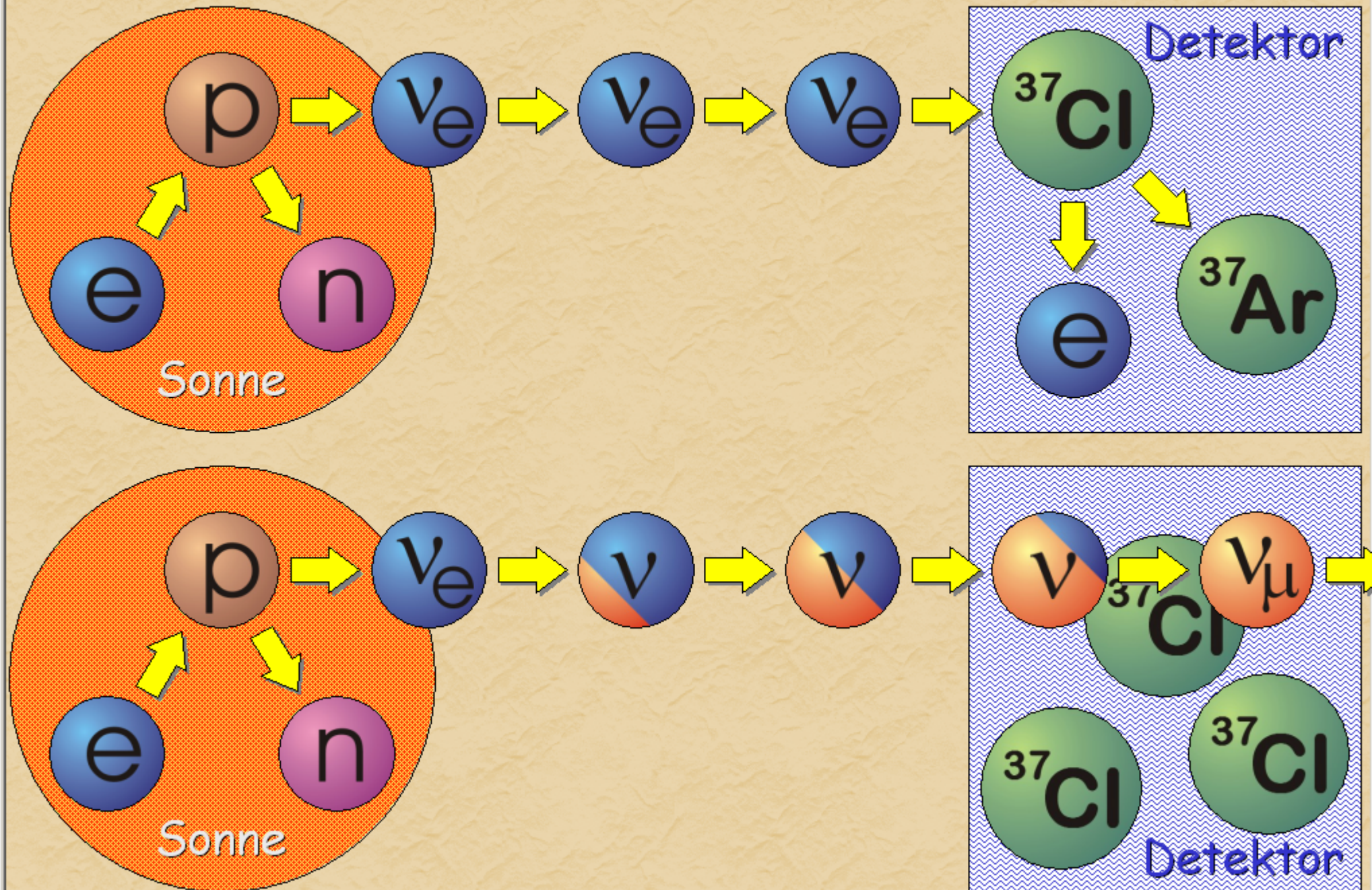
Müon-
Neutrino

Tauon
1777 MeV



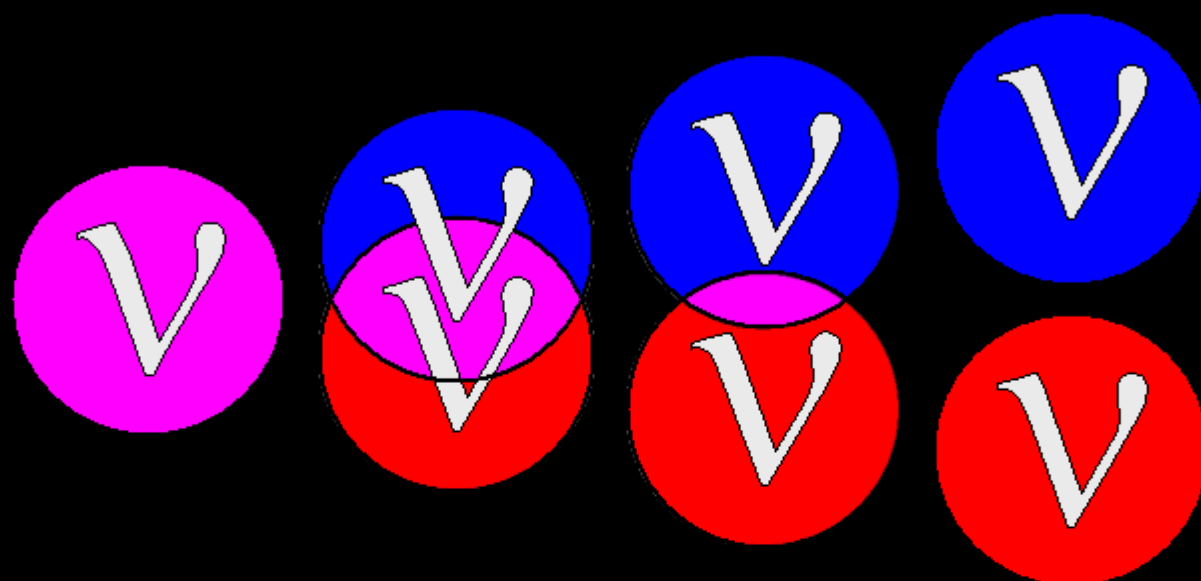
Tau-
Neutrino

„Neutrino-Verwandlung“ des Rätsels Lösung?



Mischung von Neutrinos verschiedener Masse

Elektron-
Neutrino



Neutrino
Masse m_1

Neutrino
Masse m_2

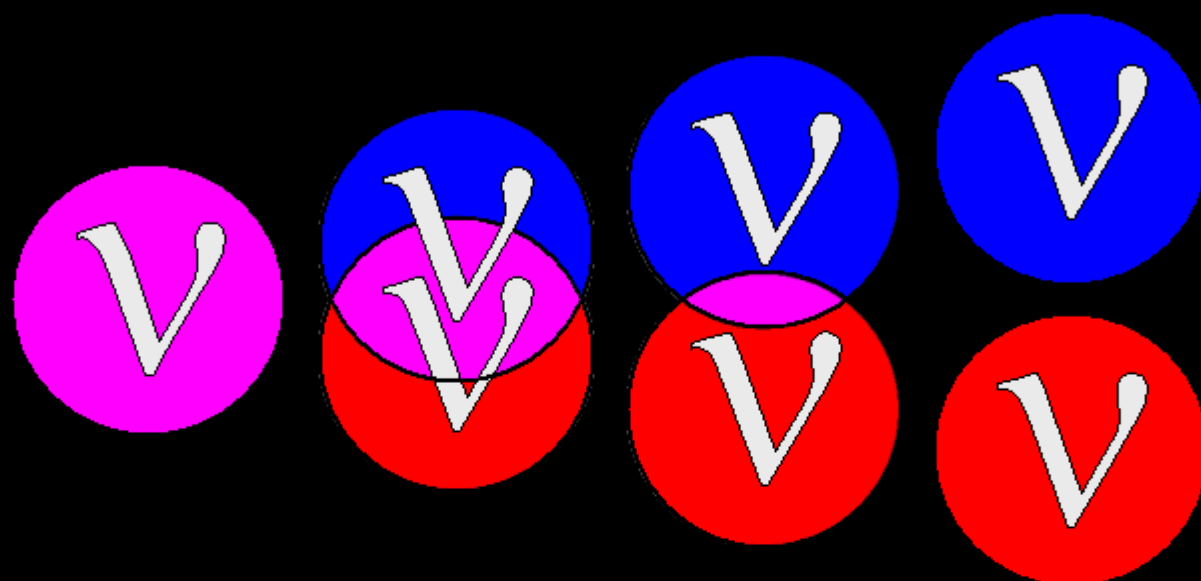
Masse m_1

Masse $m_2 = m_1$

Neutrino-Ausbreitung als Wellenphänomen
(Welle-Teilchen-Dualismus)

Mischung von Neutrinos verschiedener Masse

Elektron-
Neutrino



Neutrino
Masse m_1

Neutrino
Masse m_2

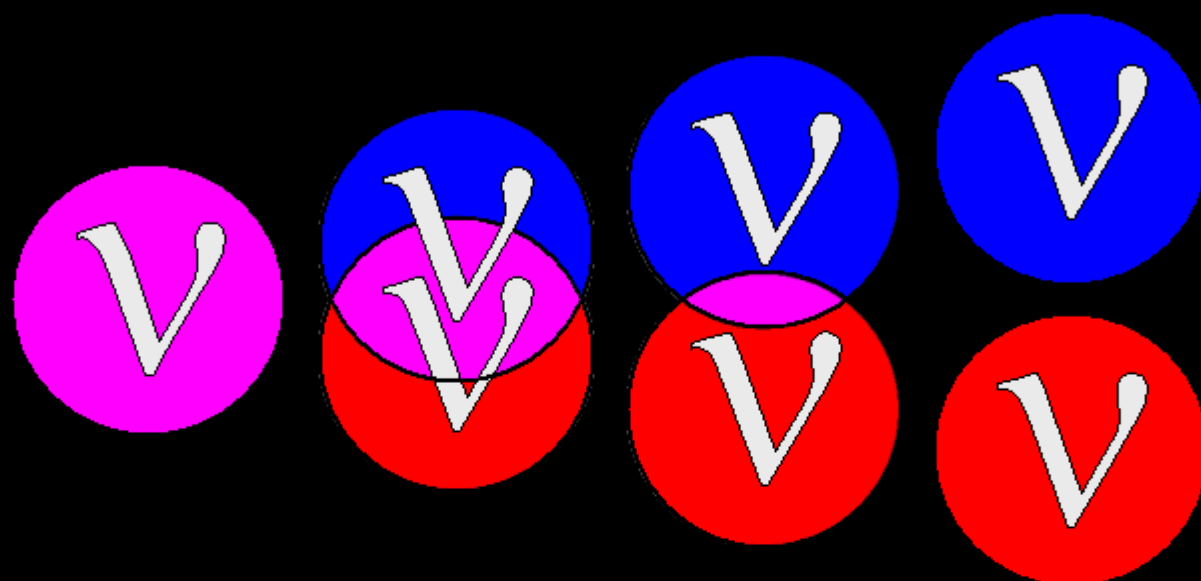
Masse m_1

Masse $m_2 > m_1$

Neutrino-Ausbreitung als Wellenphänomen
(Welle-Teilchen-Dualismus)

Mischung von Neutrinos verschiedener Masse

Elektron-
Neutrino



Neutrino
Masse m_1

Neutrino
Masse m_2

Masse m_1

Masse $m_2 > m_1$

Neutrino-Ausbreitung als Wellenphänomen
(Welle-Teilchen-Dualismus)

Neutrino-Oszillationen



Masse m_1

Masse $m_2 > m_1$

Oszillationslänge
$$\frac{4\pi E}{m_2^2 - m_1^2}$$

Neutrino-Oszillationen



Masse m_1

Masse $m_2 > m_1$

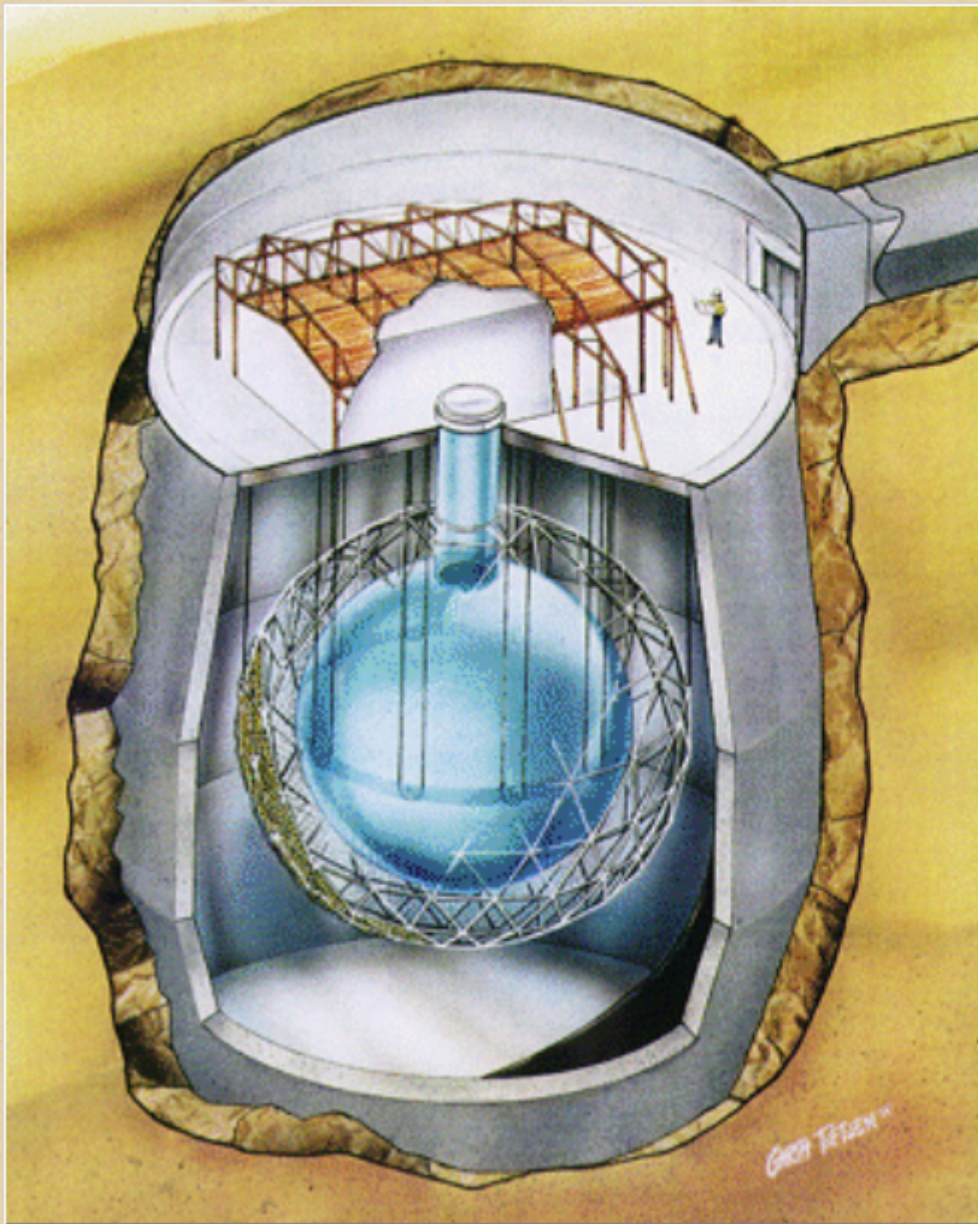
Oszillationslänge
$$\frac{4\pi E}{m_2^2 - m_1^2}$$



Bruno Pontecorvo
(1913 - 1993)
„Erfinder“ der Neutrinooszillationen

Sudbury Neutrino Observatory (SNO)

1000 Tonnen schweren Wassers



Normales (leichtes) Wasser:



Schweres Wasser:



Kern des Wasserstoffs (Proton)

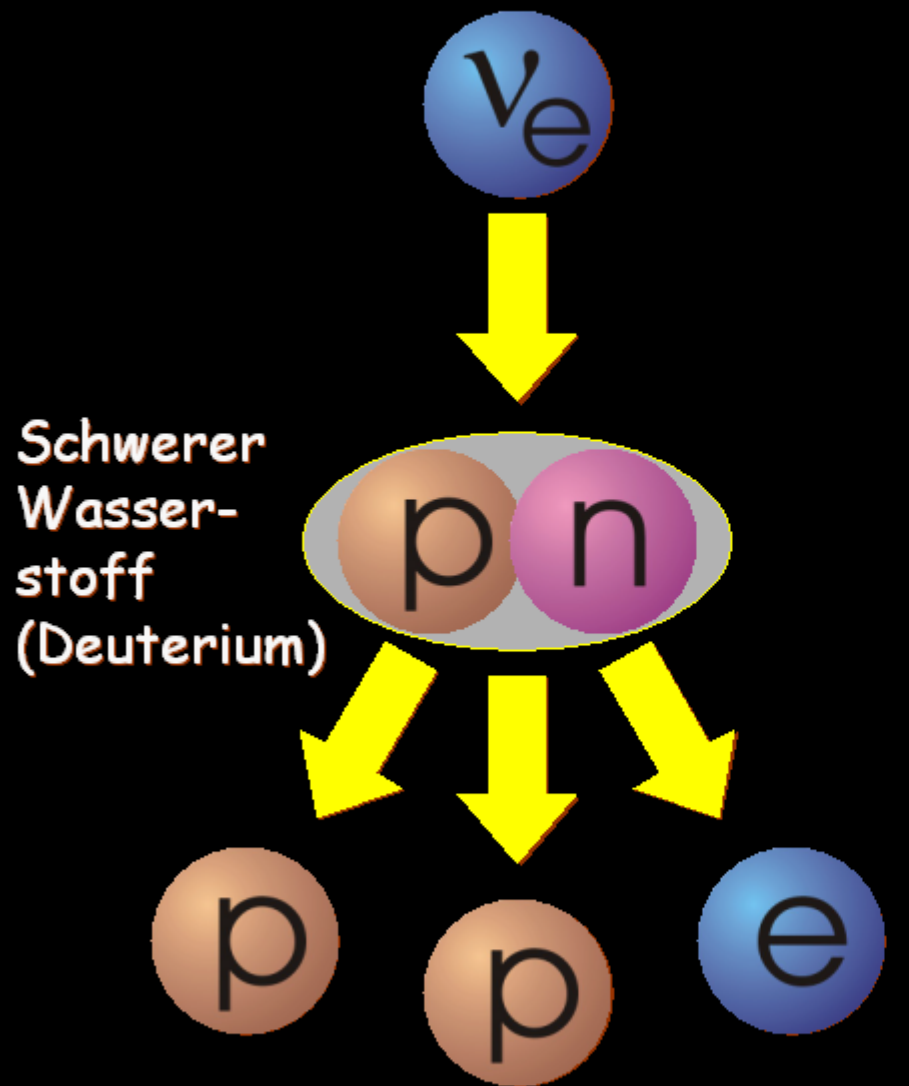


Kern des schweren Wasserstoffs
(Deuterium)

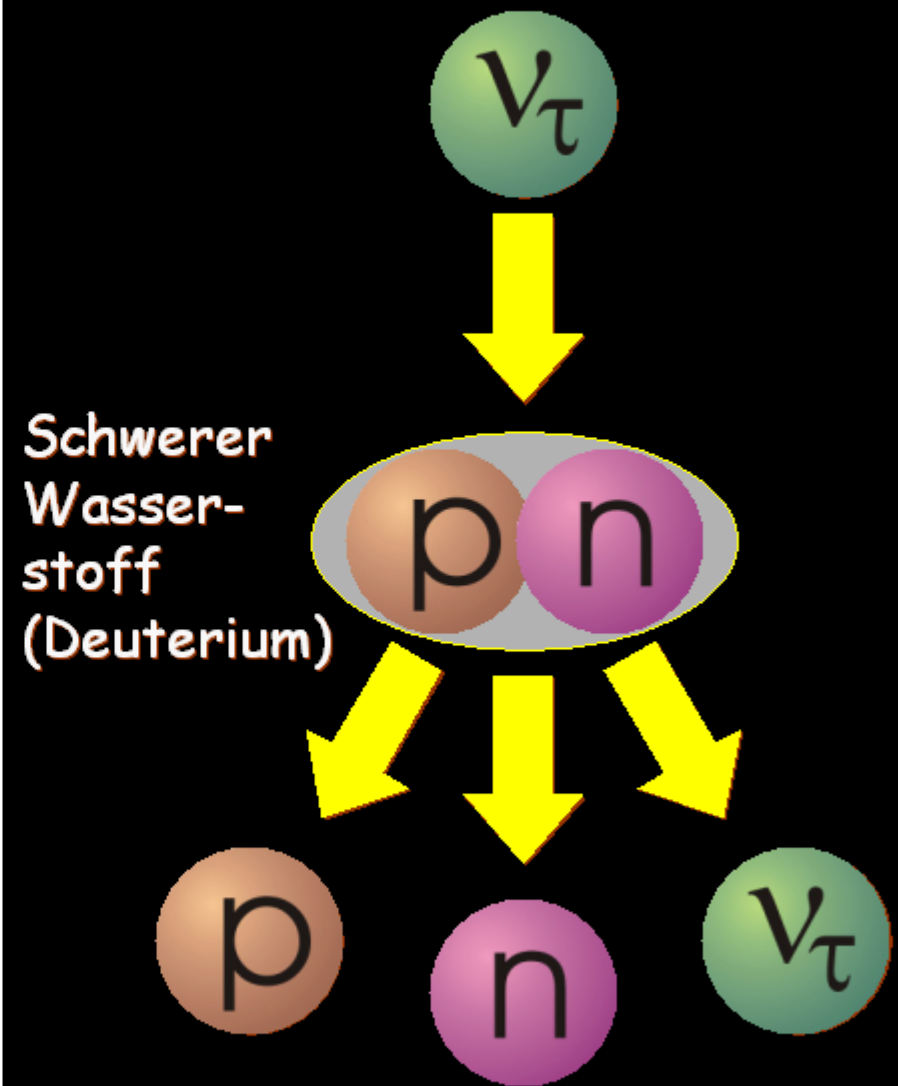


Sudbury Neutrino Observatory (SNO)

1000 Tonnen schweren Wassers

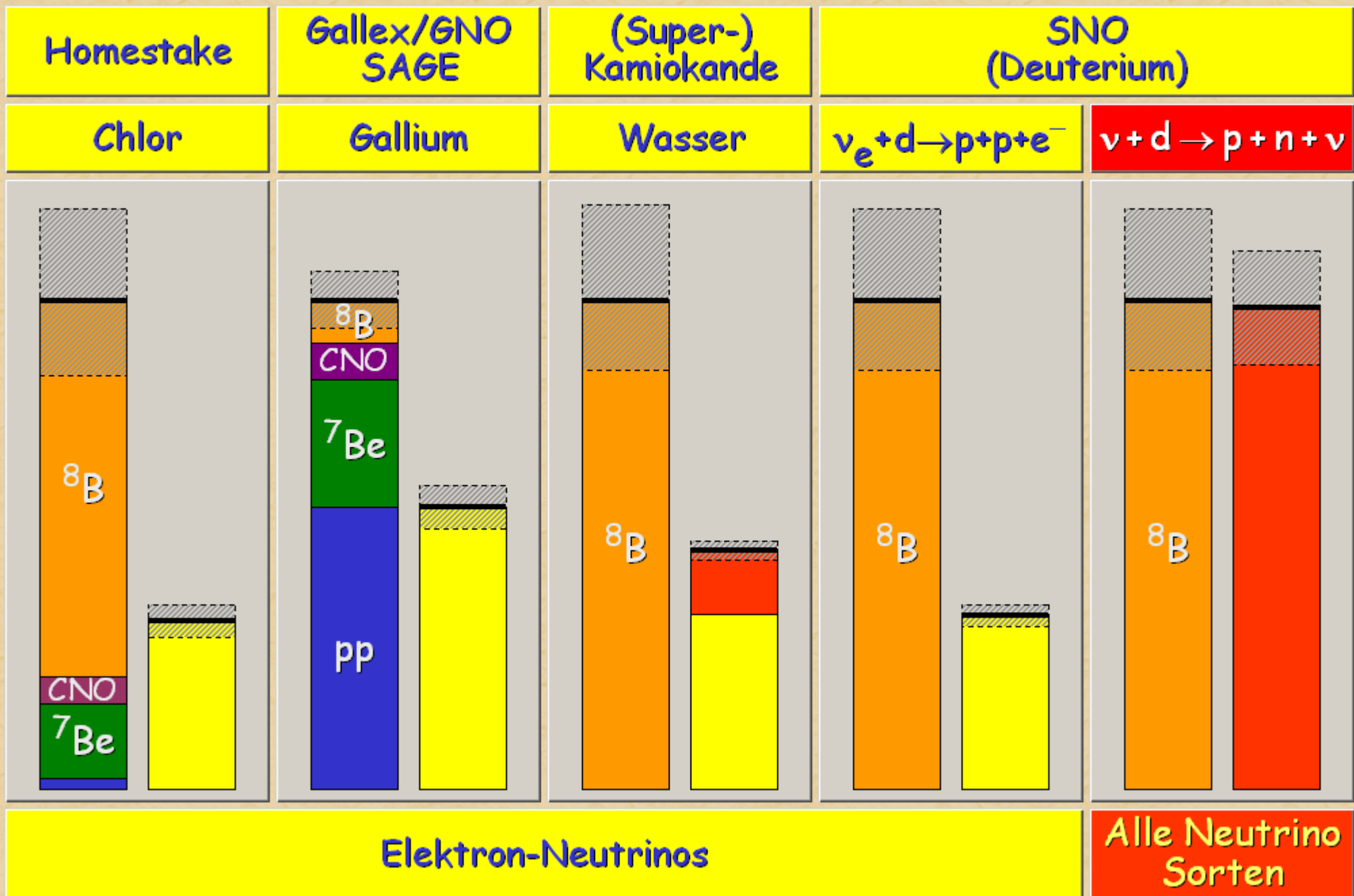


Nur Elektron-Neutrinos



Alle Neutrino-Sorten

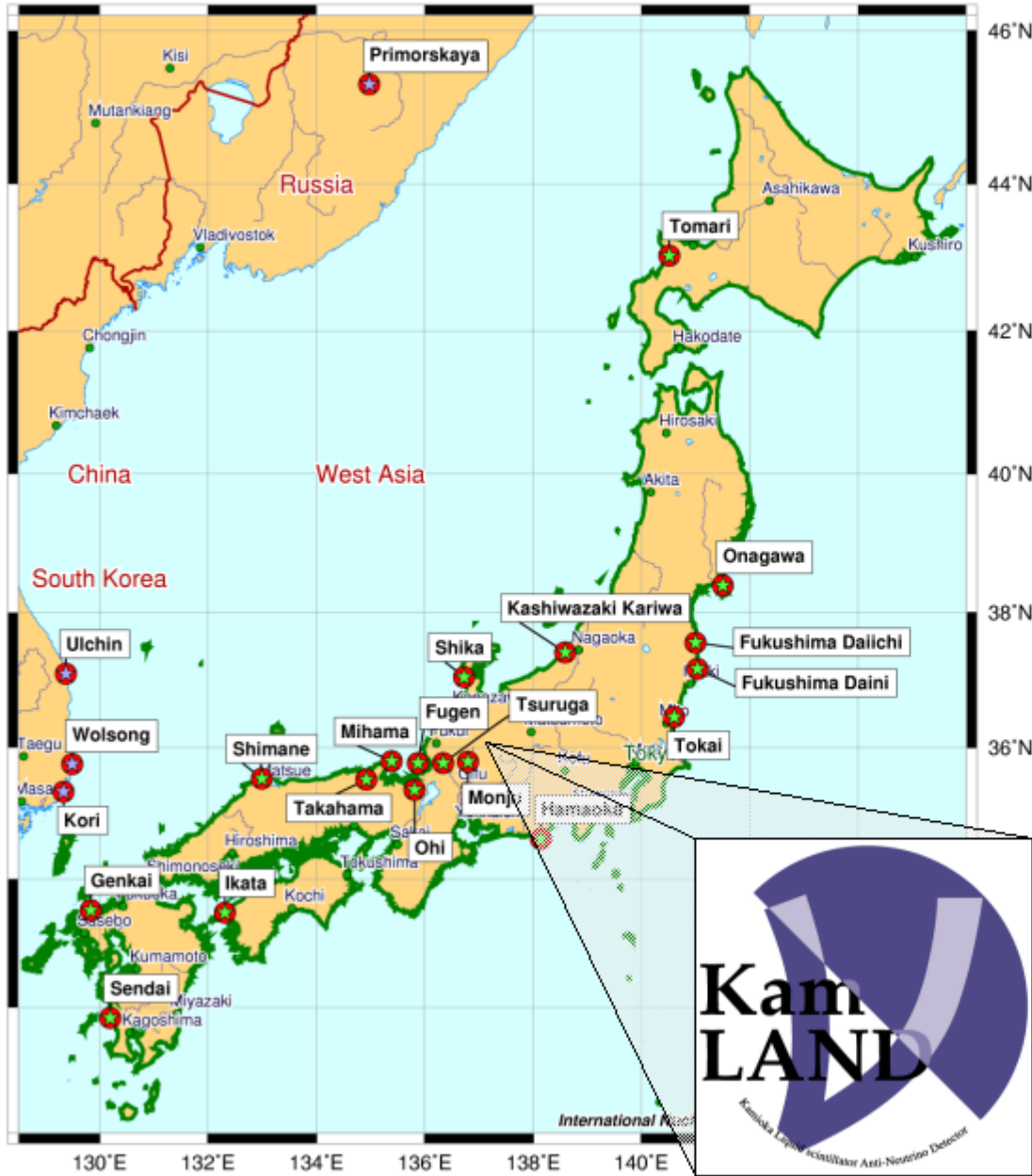
Das Problem der fehlenden Sonnenneutrinos



Das Problem der fehlenden Sonnenneutrinos

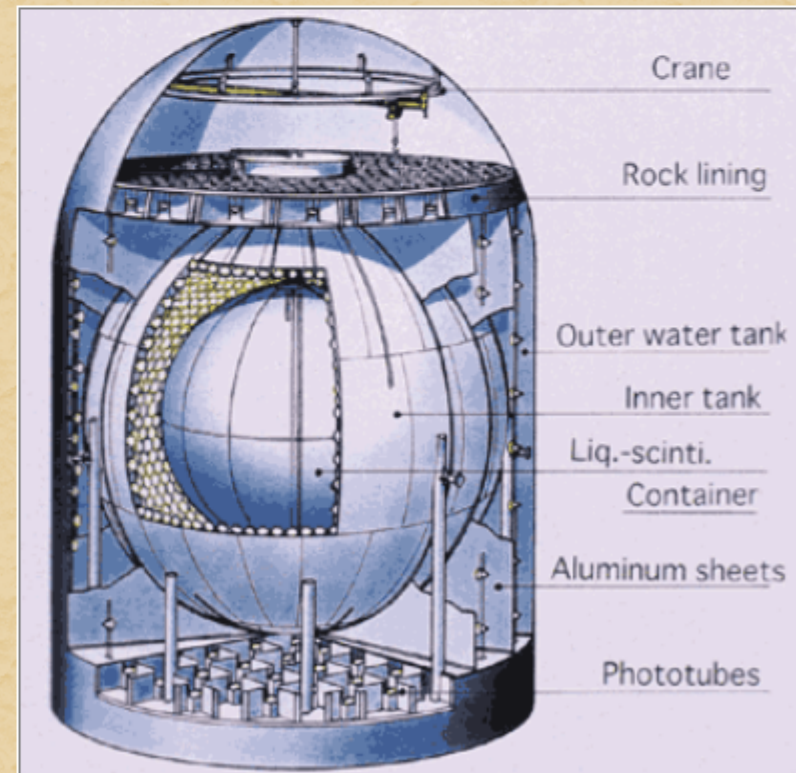


Kamland Reaktor Neutrino Experiment (Japan)

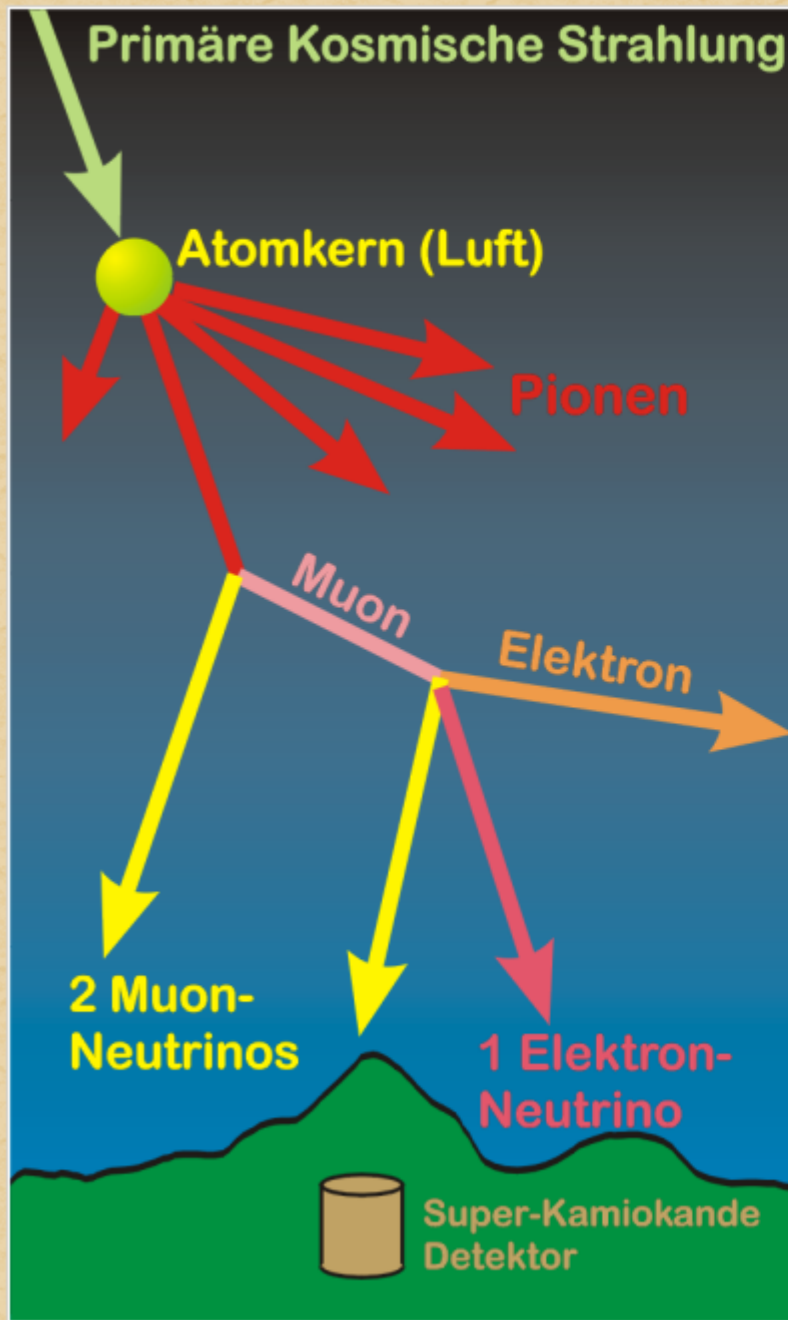


Japanische Kernreaktoren
60 GW (20% Weltkapazität)

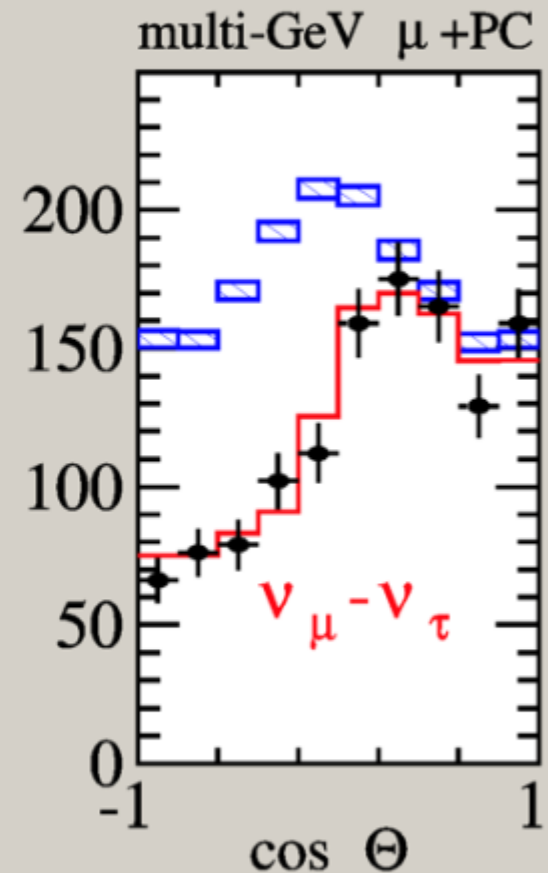
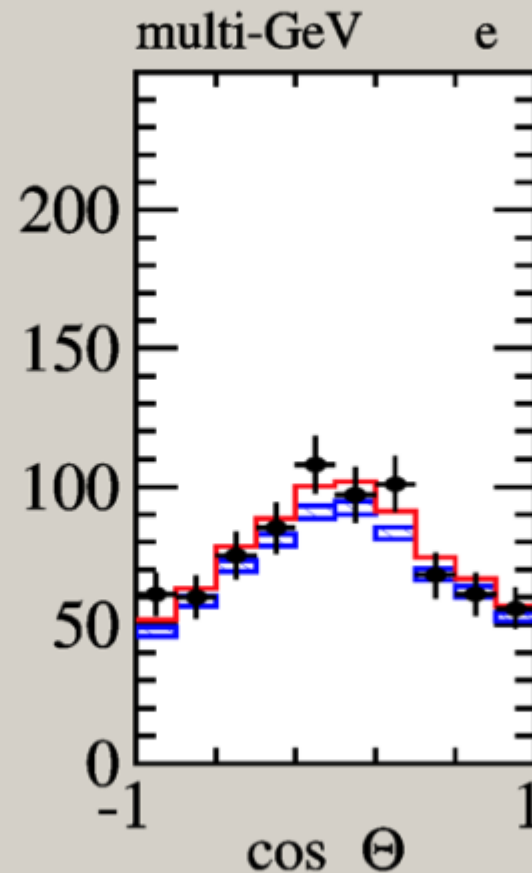
- Ohne Oszillationen
2 Neutrinoeinfänge pro Tag
- Datennahme seit
22 Januar 2002



Atmosphärische Neutrino-Anomalie

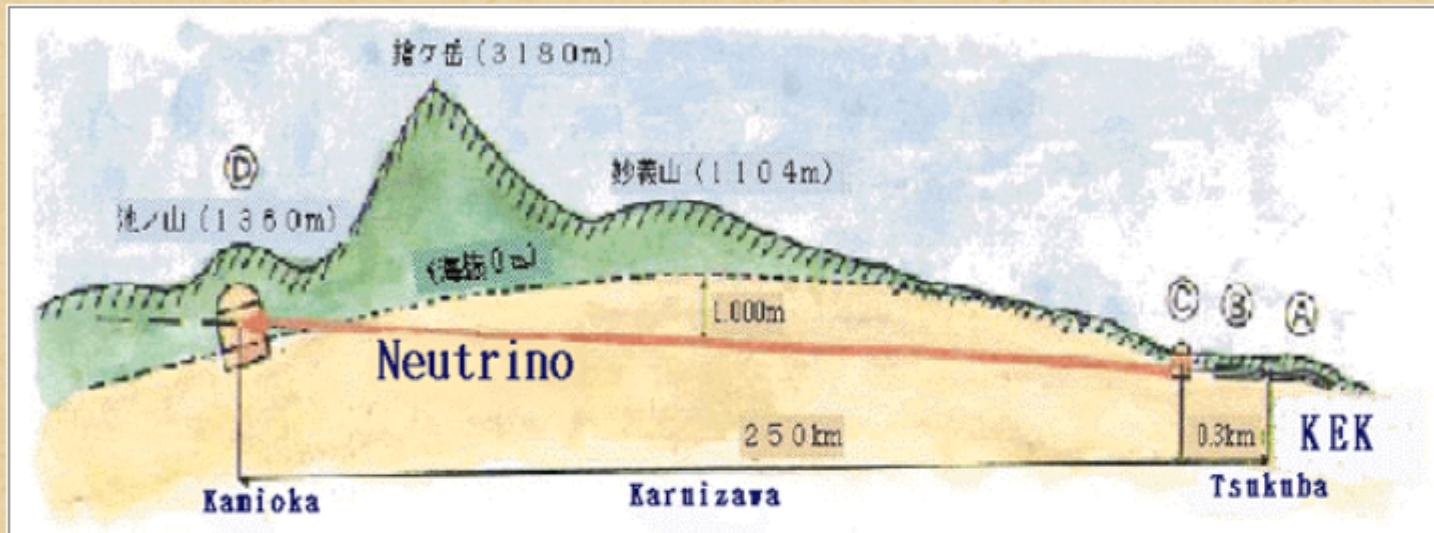


Zenitwinkelverteilung der atmosphärischen Neutrinos in Super-Kamiokande



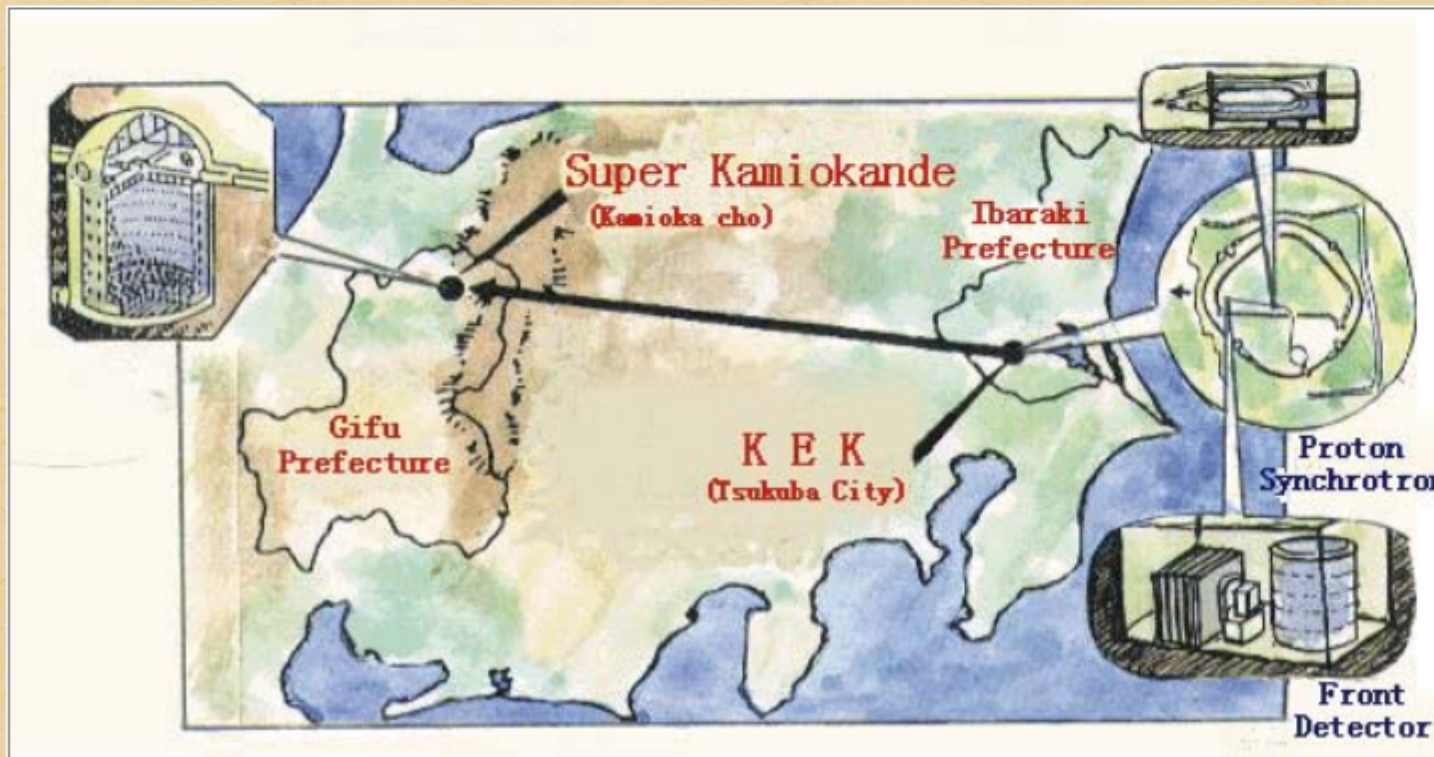
Die Hälfte der Muon-Neutrinos von unten fehlen

Japanisches „Long-Baseline“ Experiment K2K



K2K
Experiment

KEK to
Kamiokande



- Erste Daten bestätigen Neutrino-Oszillationen
- Derzeit keine Messungen wegen Unfall in Super-Kamiokande

„Long-Baseline“ Experimente in Vorbereitung

FermiLab-Soudan (MINOS)



CERN – Gran Sasso



Sanduleak -69 202



Tarantel-Nebel

Große Magellan'sche Wolke
Abstand 50 kpc
(160.000 Lichtjahre)



Sanduleak -69 202



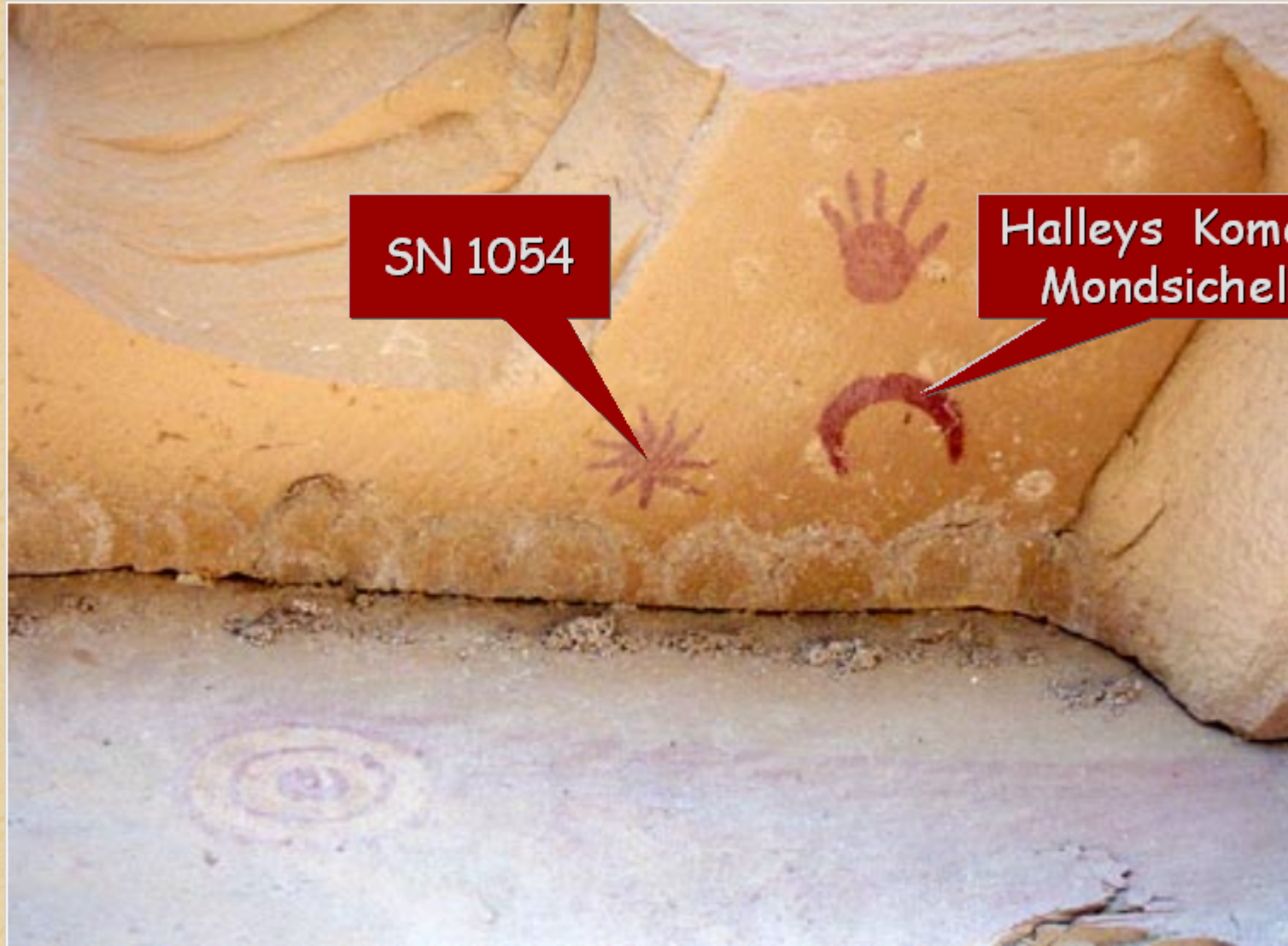
Supernova 1987A

23. Februar 1987



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速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囷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

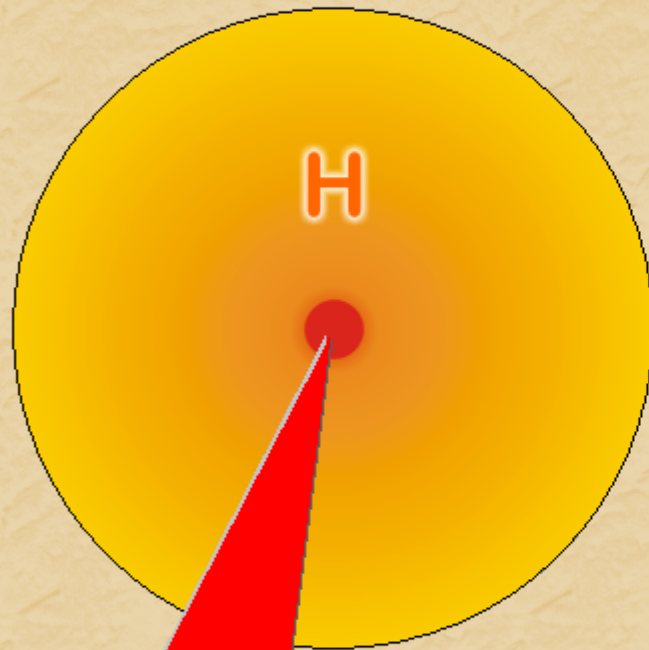
Supernova 1054 Petrograph



**Angeblicher SN 1054 Petrograph des Anasazi-Volkes
(Chaco Canyon, Südwestliche USA)**

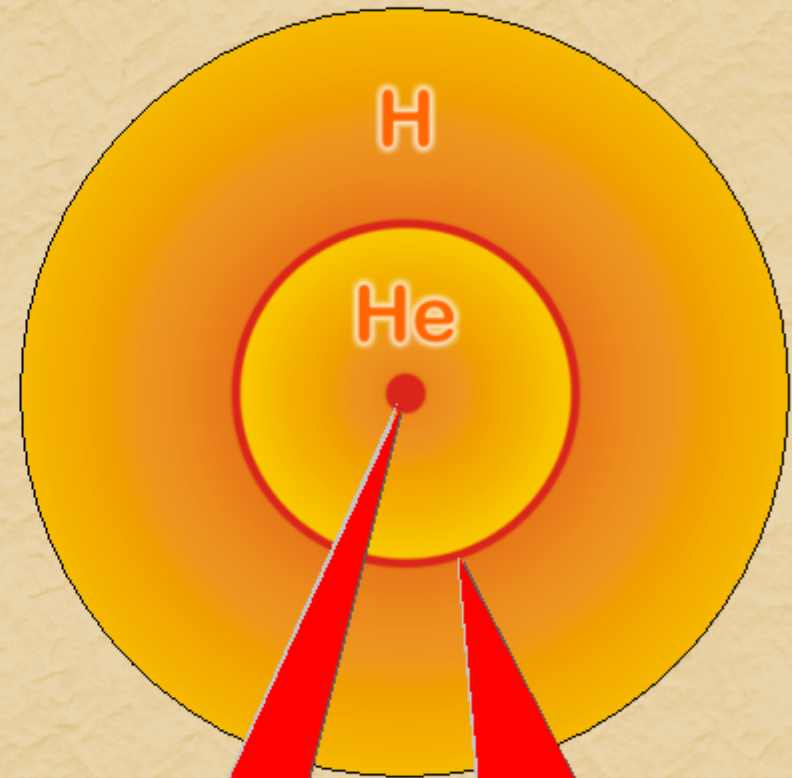
Sternkollaps und Supernovaexplosion

Hauptreihenstern



Wasserstoffbrennen

Roter Riese



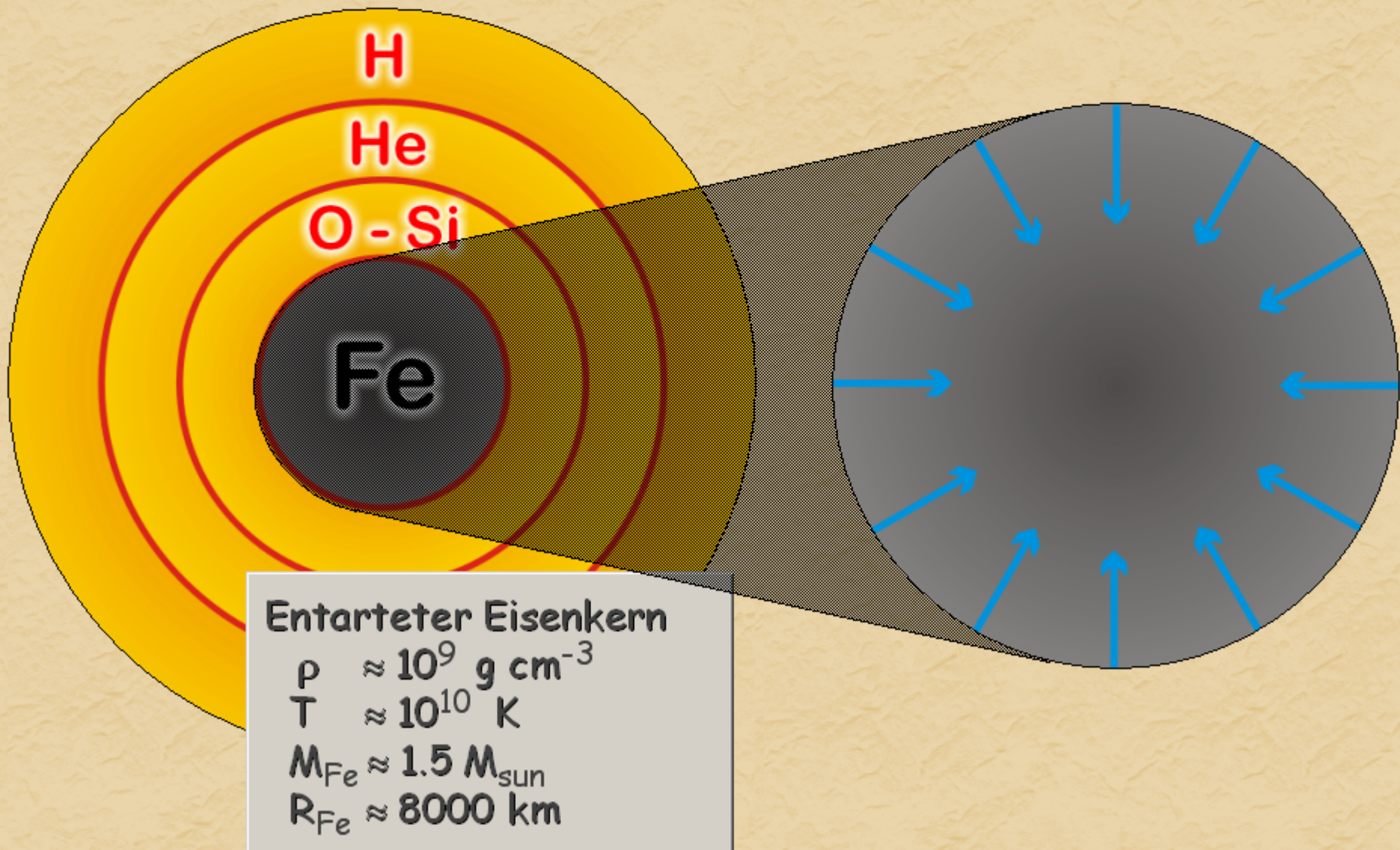
Helium-
brennen

Wasserstoff-
brennen

Sternkollaps und Supernovaexplosion

Zwiebelschalenstruktur

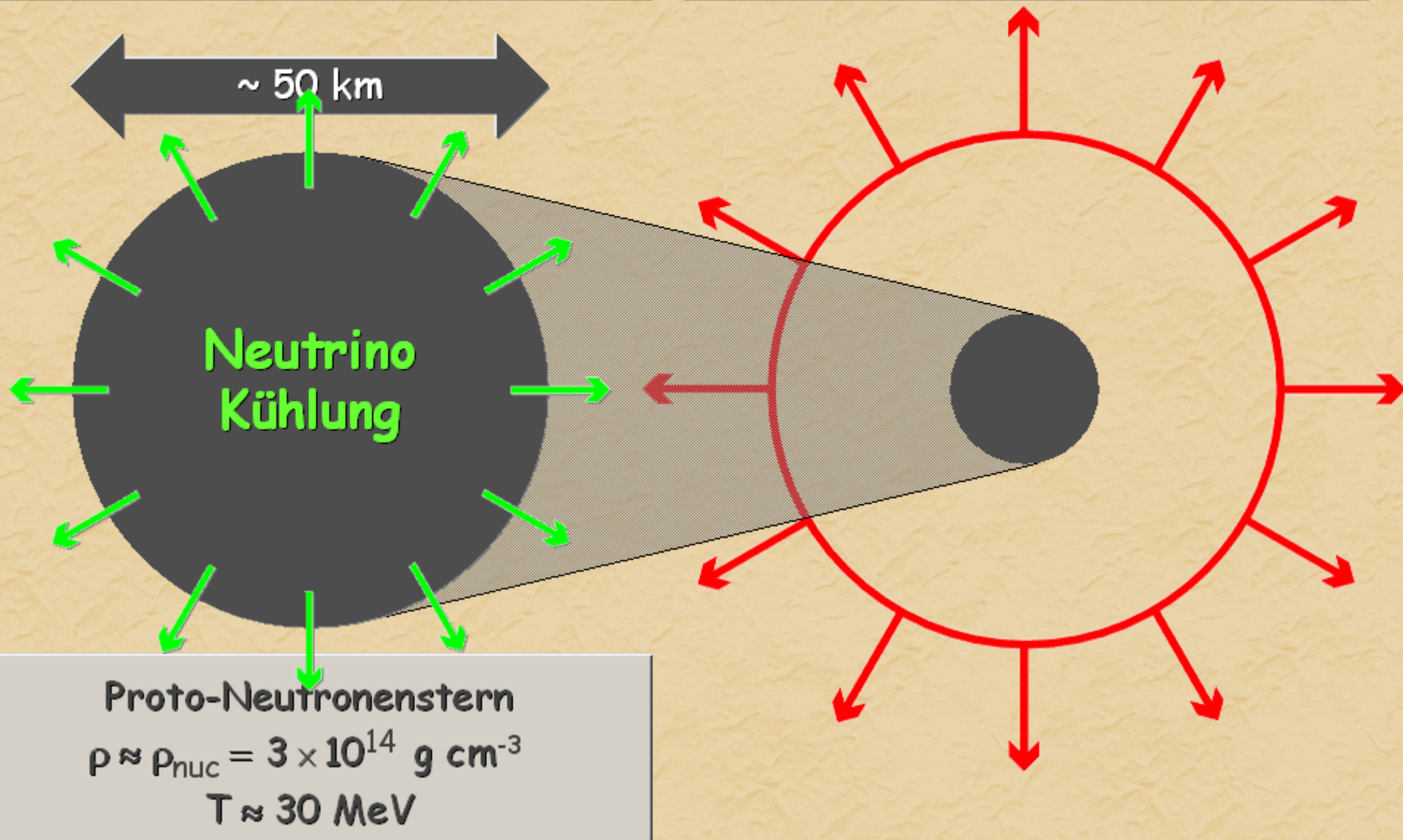
Kollaps (Implosion)



Sternkollaps und Supernovaexplosion

Neugeborener Neutronenstern

Explosion



Sternkollaps und Supernovaexplosion

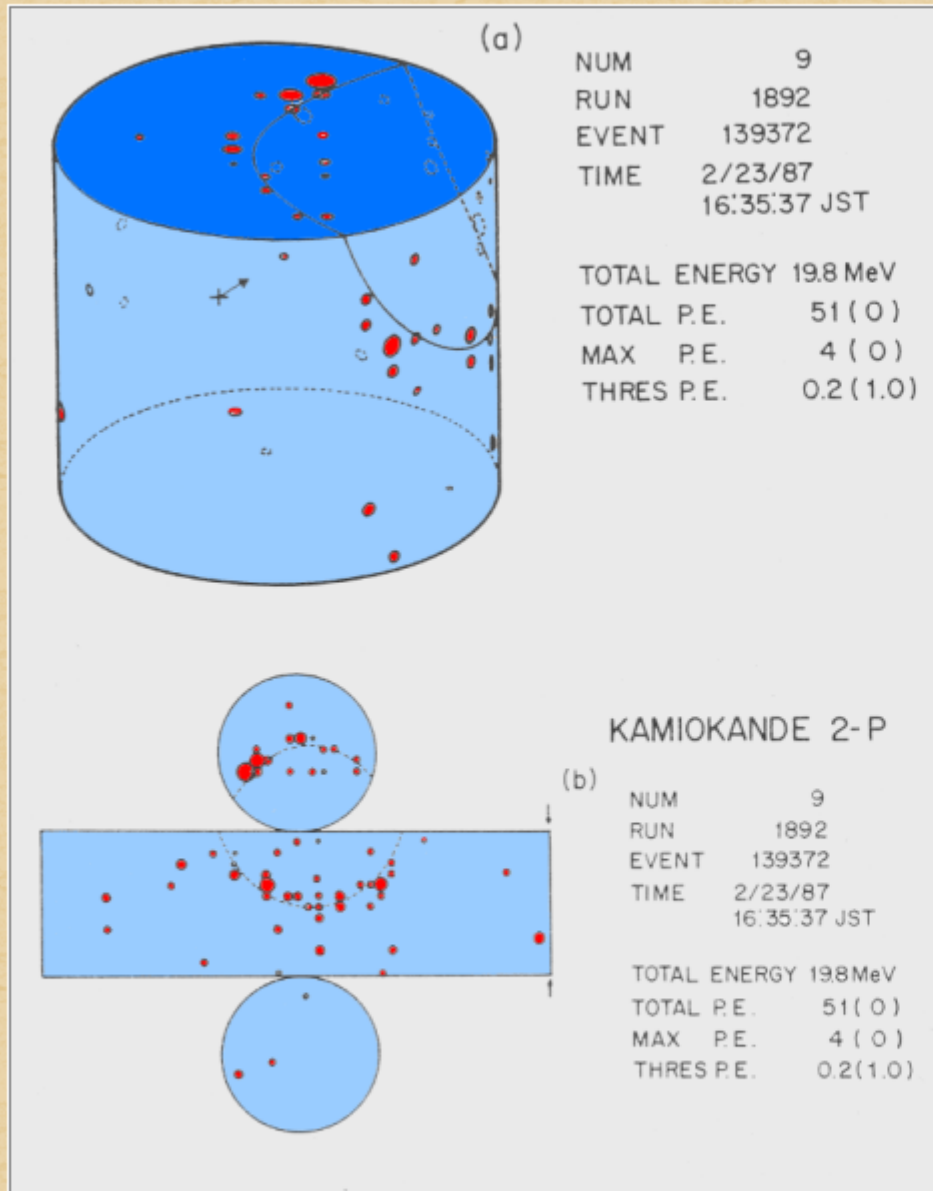
Neugeborener Neutronenstern



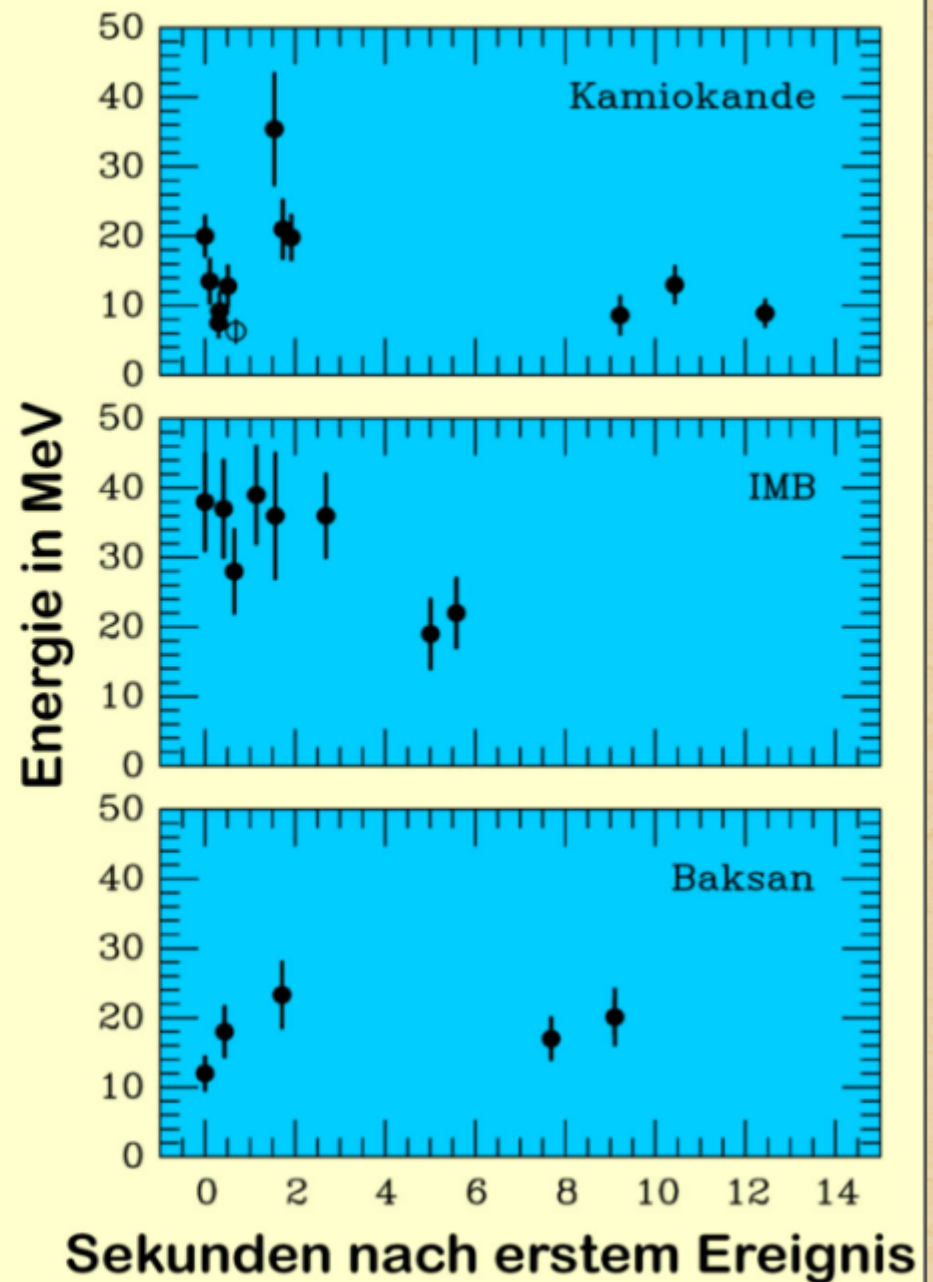
Proto-Neutronenstern
 $\rho \approx \rho_{\text{nuc}} = 3 \times 10^{14} \text{ g cm}^{-3}$
 $T \approx 30 \text{ MeV}$

- Dichte ungefähr 300 Millionen Tonnen /cm³
- Neutrinos sind „gefangen“
- Kühlung durch Neutrinos in ca. 10 Sekunden
- Energiemenge entspricht ca. dem 100-fachen dessen, was die Sonne während ihrer ganzen Lebensdauer umsetzt

Neutrino-Signal der Supernova 1987A



Neutrino No. 9 in Kamiokande

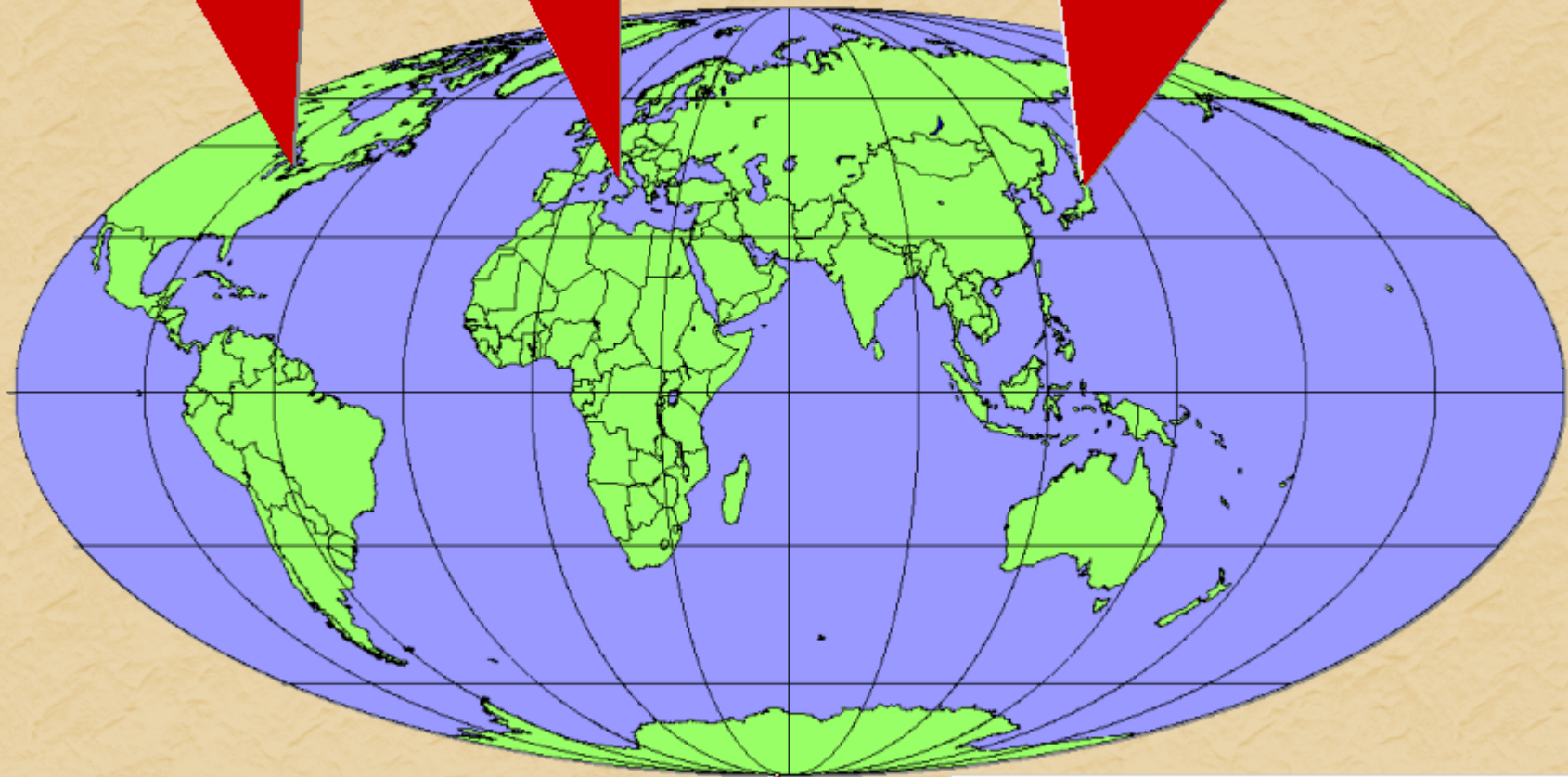


Große Detektoren für Supernova-Neutrinos

SNO (800)
MiniBooNE (190)

LVD (400)
Borexino (80)

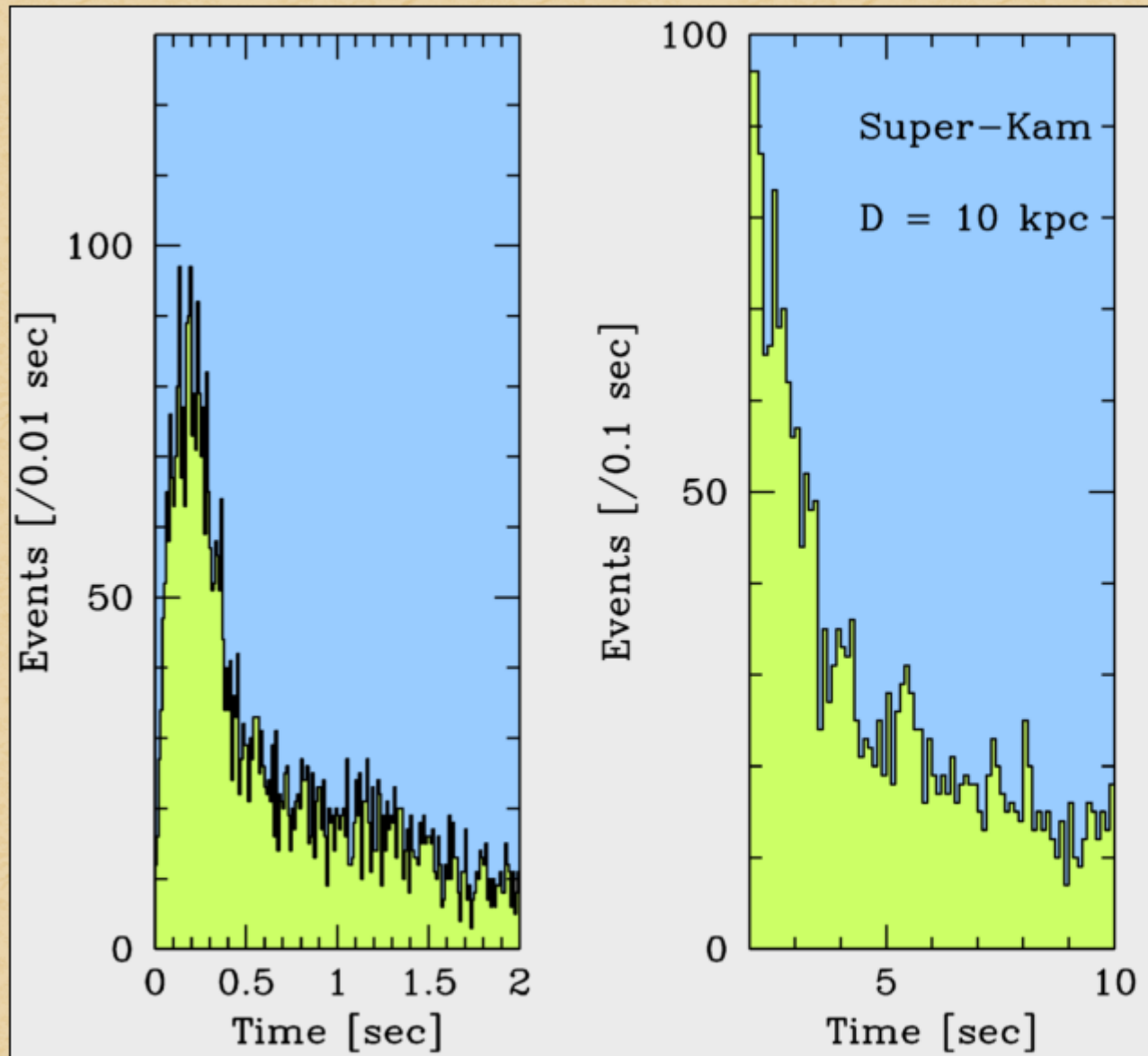
Super-Kamiokande (8500)
Kamland (330)



Amanda
IceCube

In Klammern Zahl der erwarteten Neutrinoeinfänge von einer galaktischen Supernova

Simuliertes Supernova Signal für Super-Kamiokande



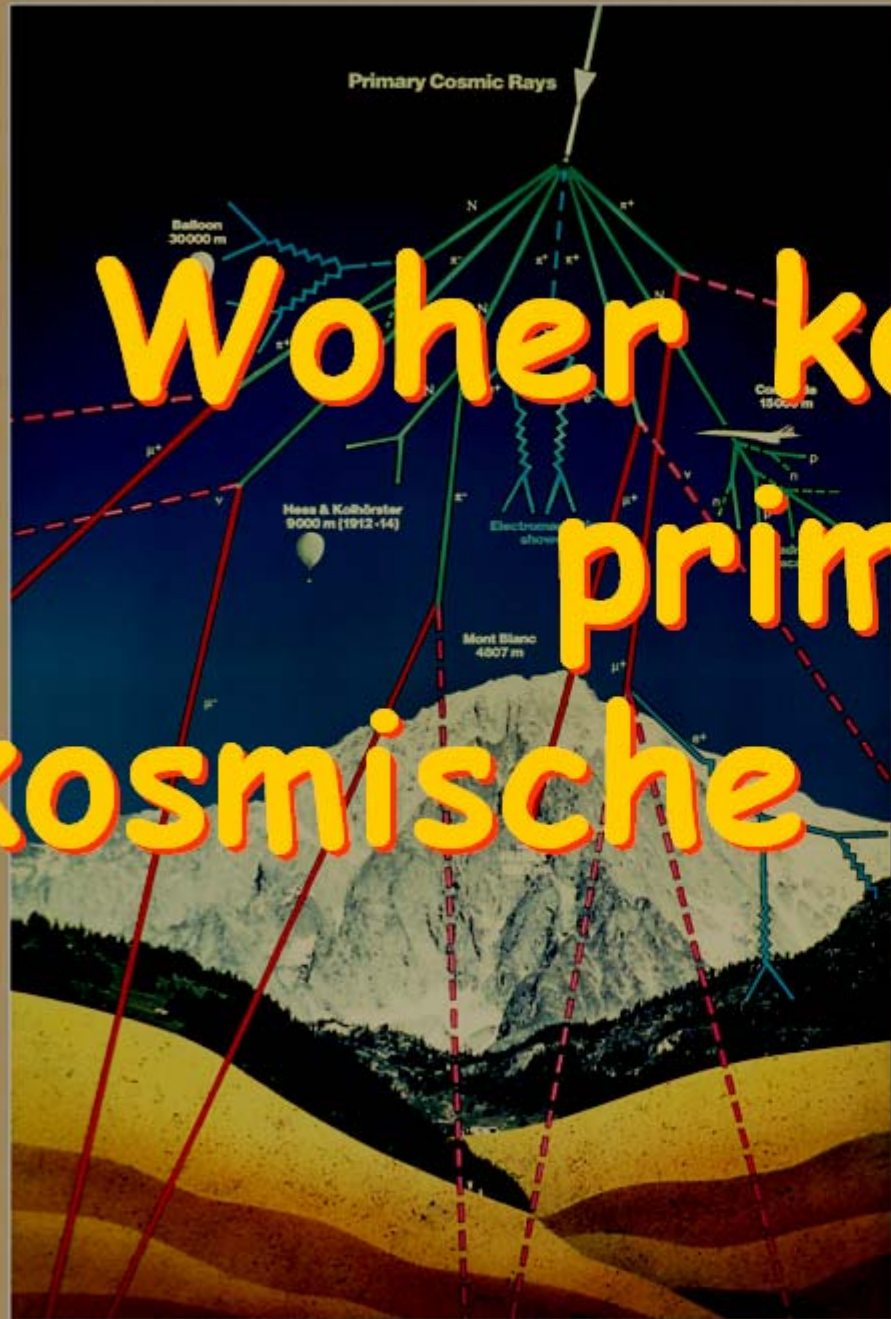
Insgesamt ca. 8300
Ereignisse mit $t < 18$ s

Monte-Carlo Simulation
für Super-Kamiokande
einer SN bei 10 kpc

Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216

Kosmische Strahlung („Höhenstrahlung“)

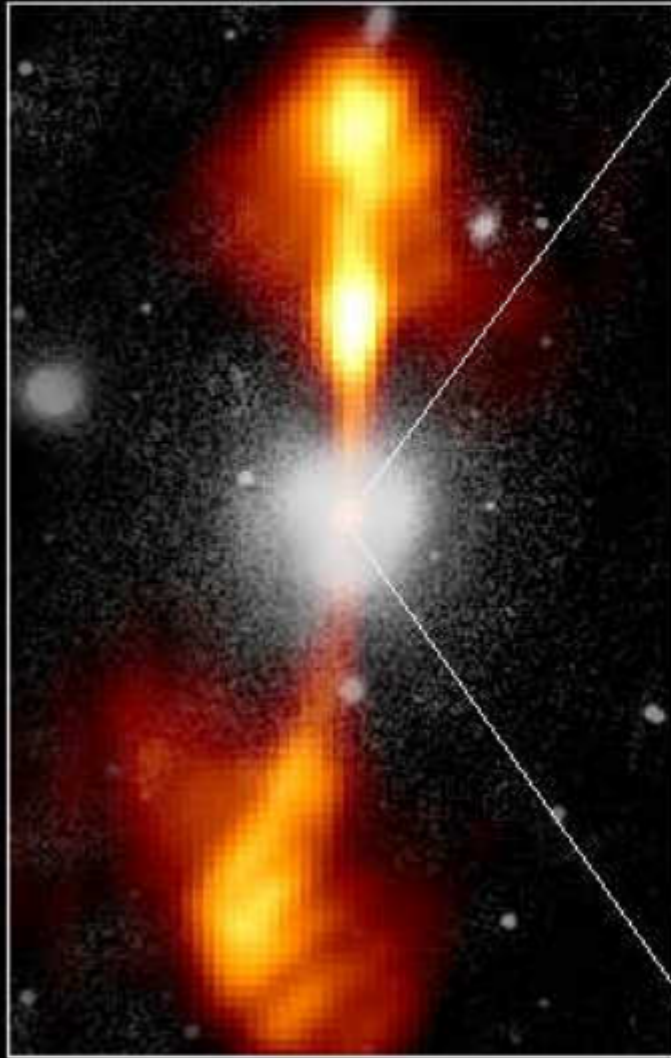
Woher kommt die primäre kosmische Strahlung?



Victor Hess (1911)

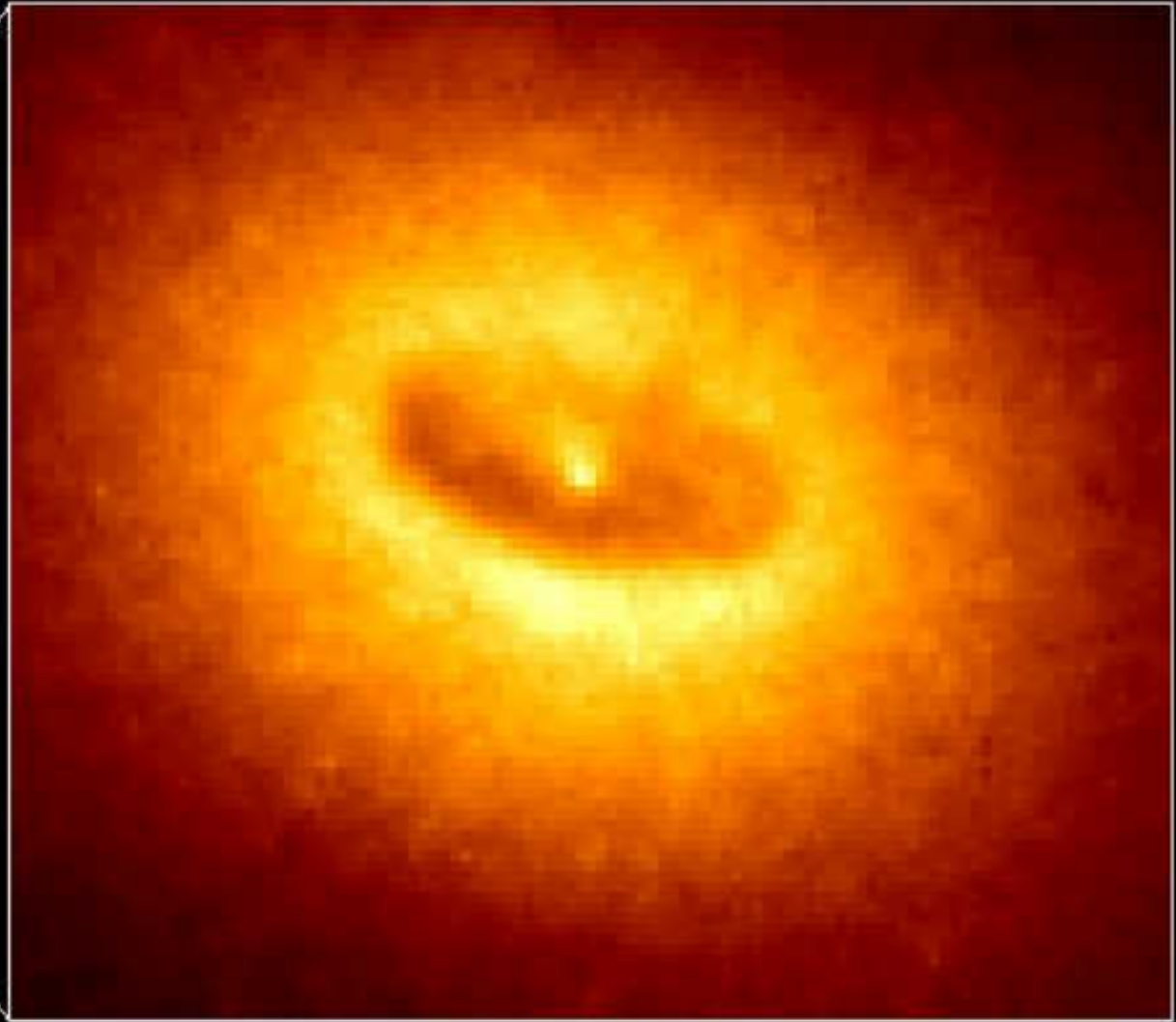
Kern der Galaxie NGC 4261

Ground-Based Optical/Radio Image



380 Arc Seconds
88,000 LIGHT-YEARS

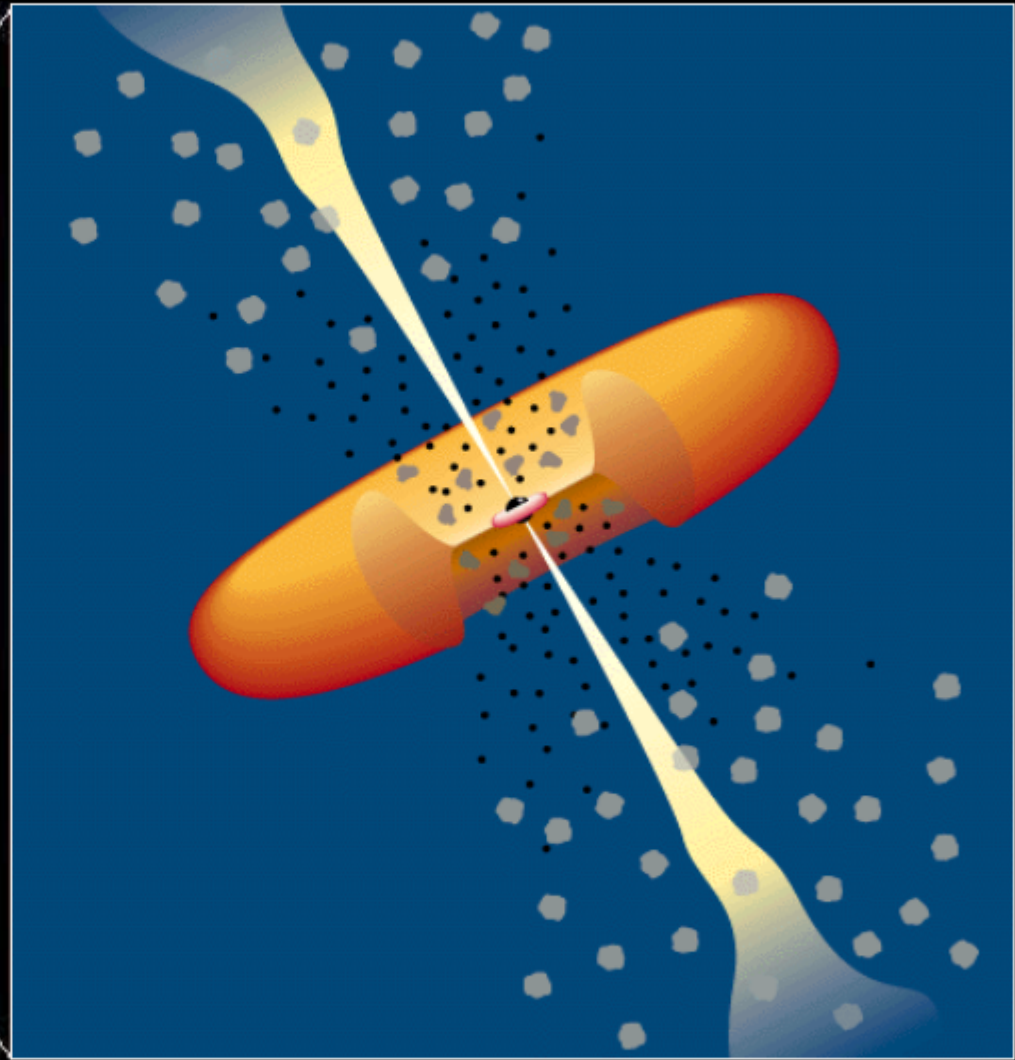
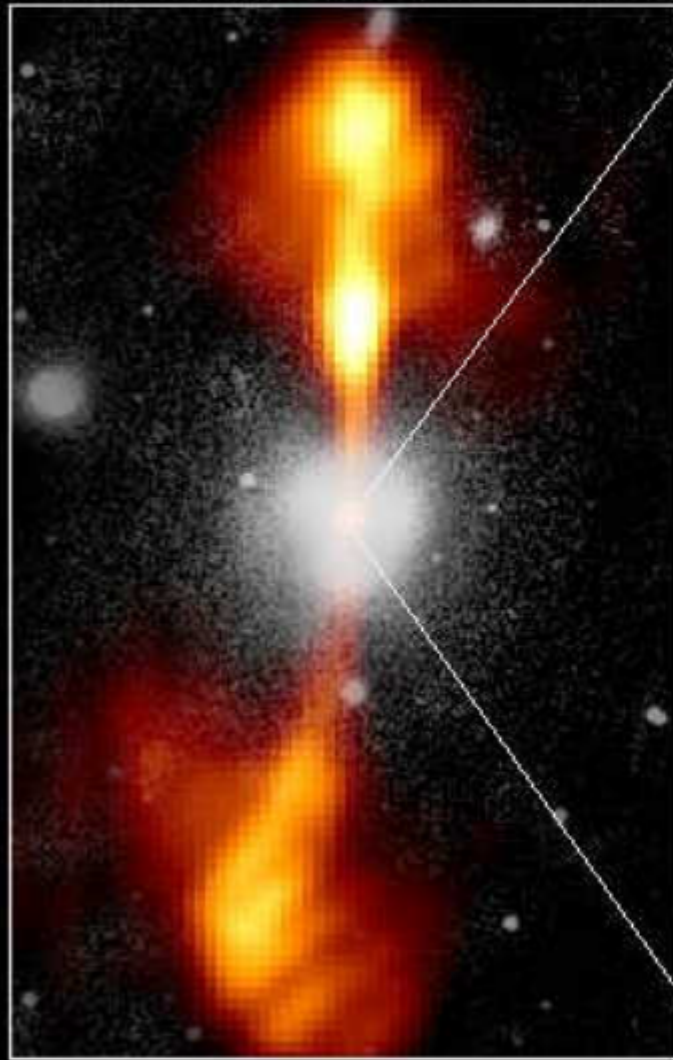
HST Image of a Gas and Dust Disk



1.7 Arc Seconds
400 LIGHT-YEARS

Kern der Galaxie NGC 4261

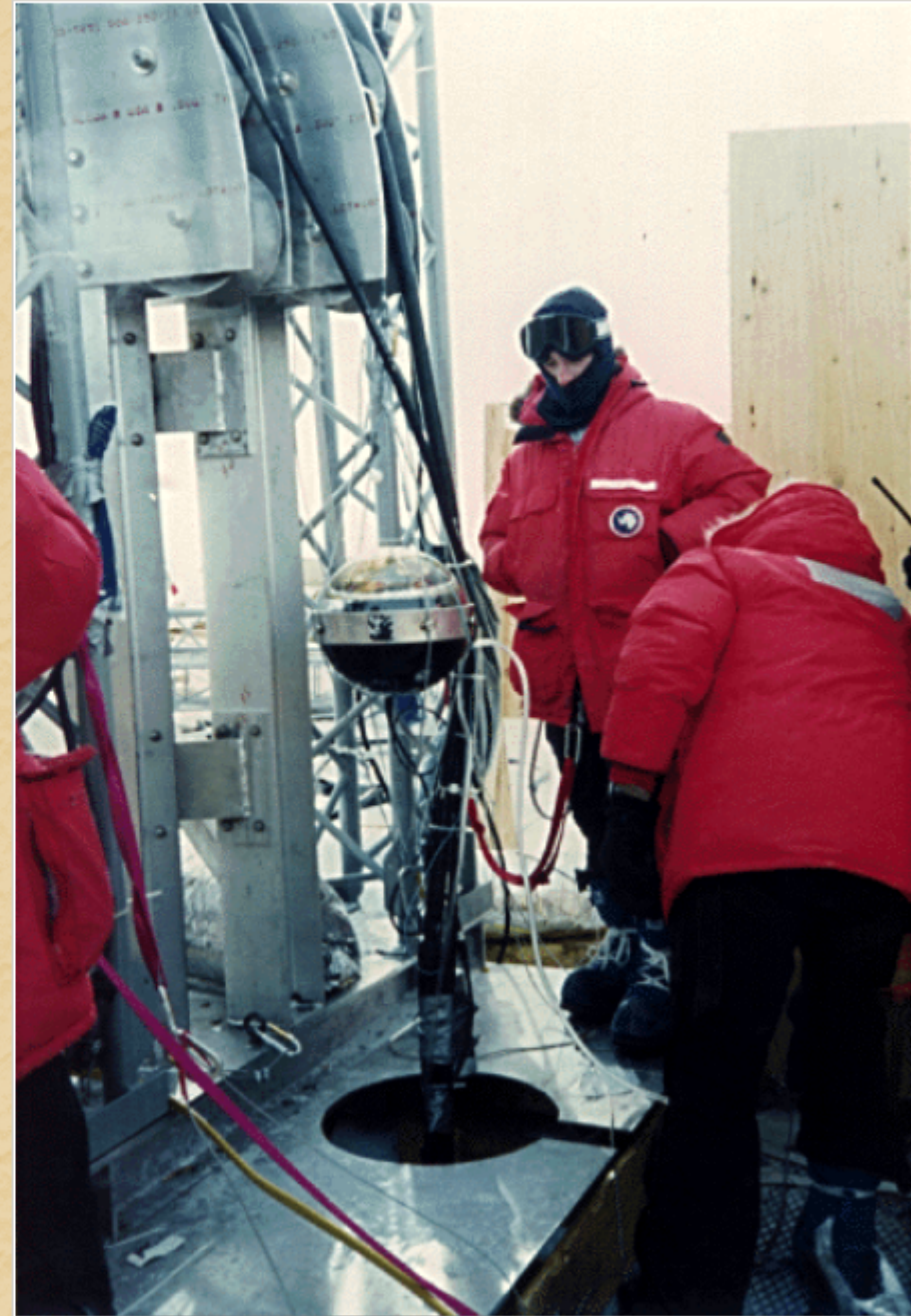
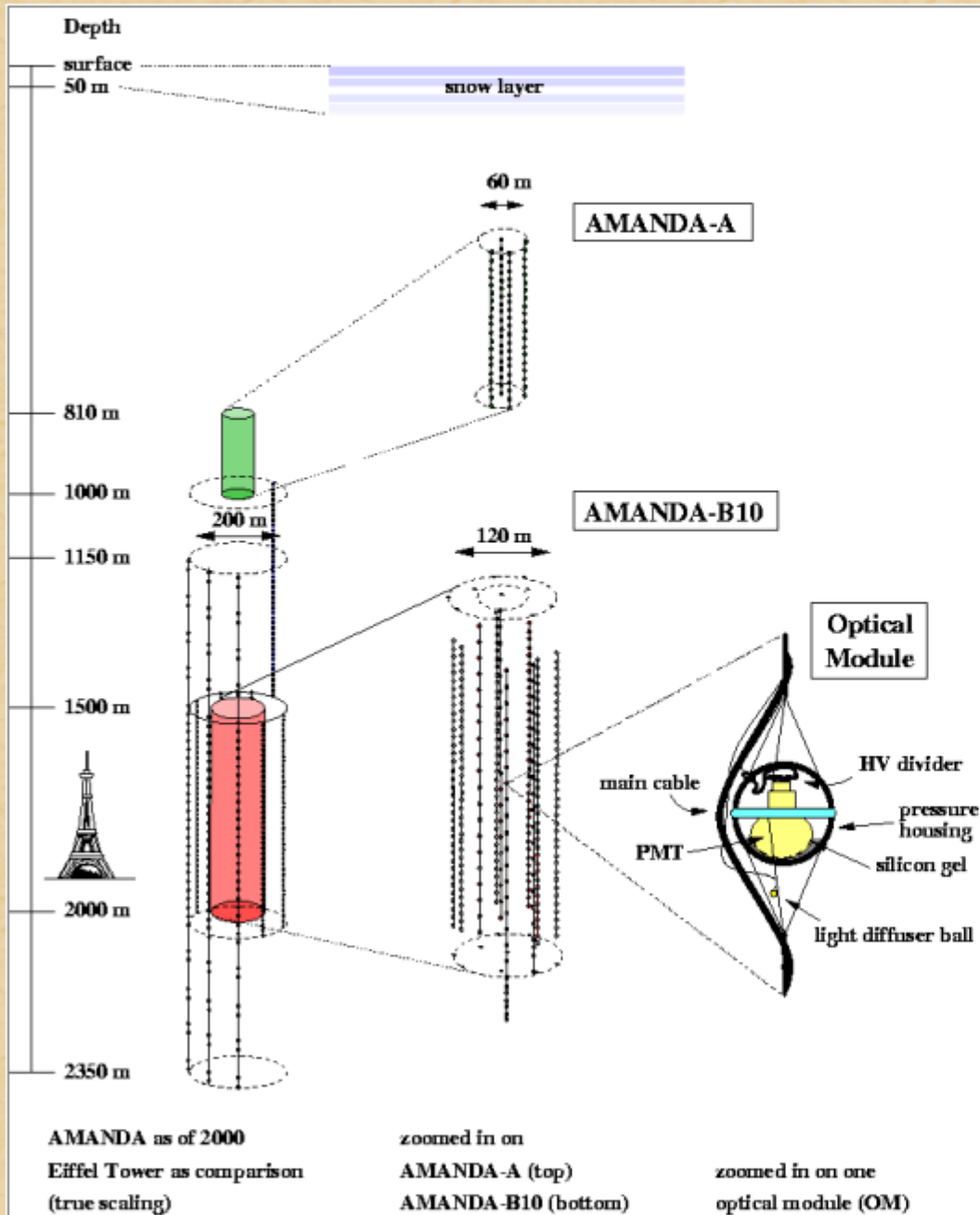
Ground-Based Optical/Radio Image



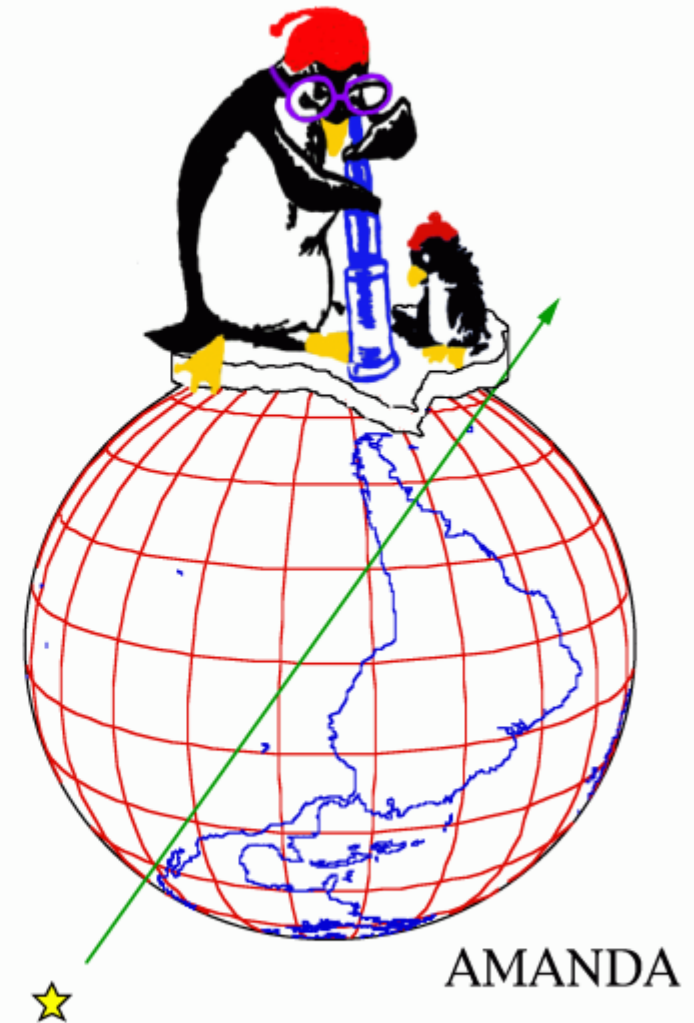
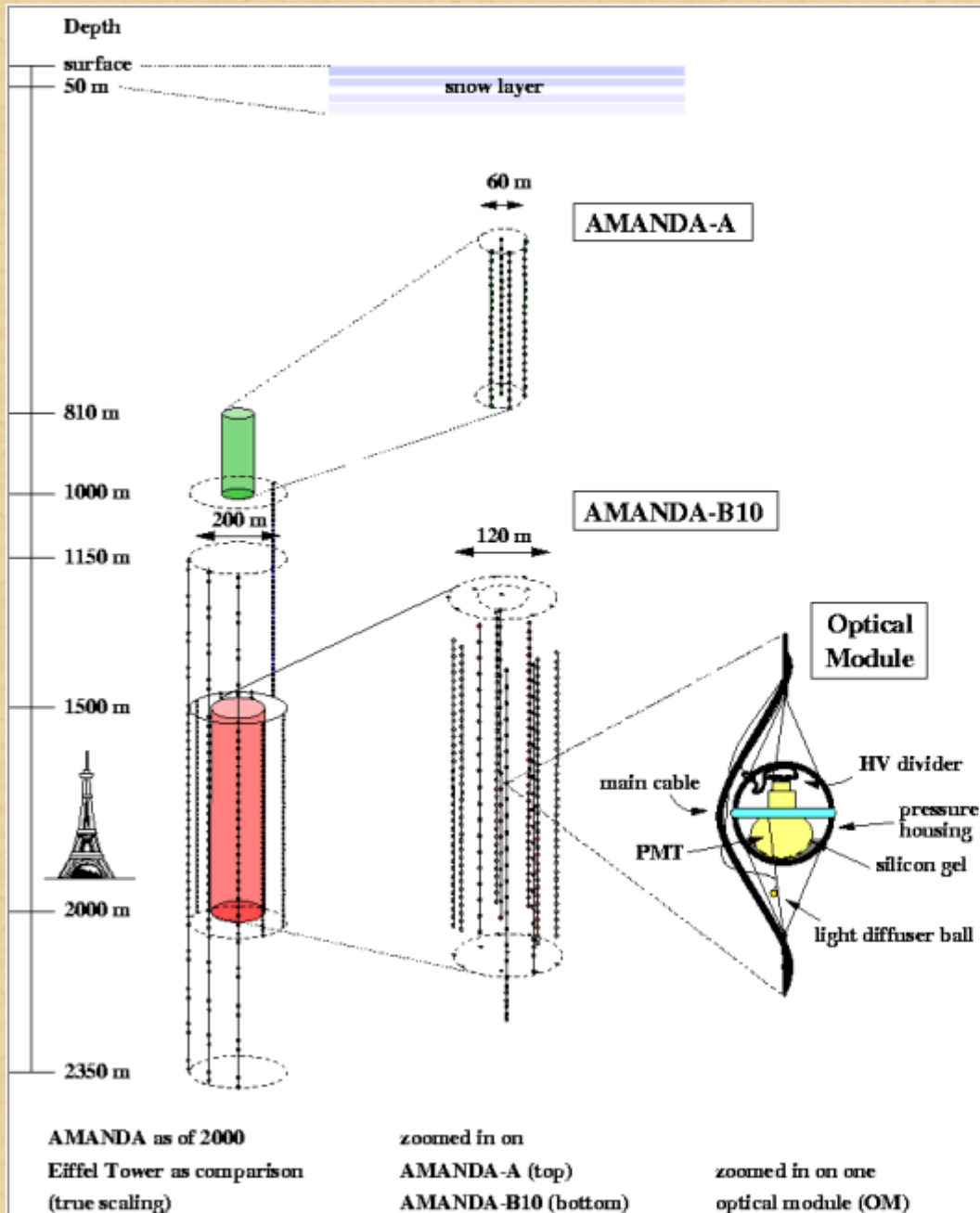
380 Arc Seconds
88,000 LIGHT-YEARS



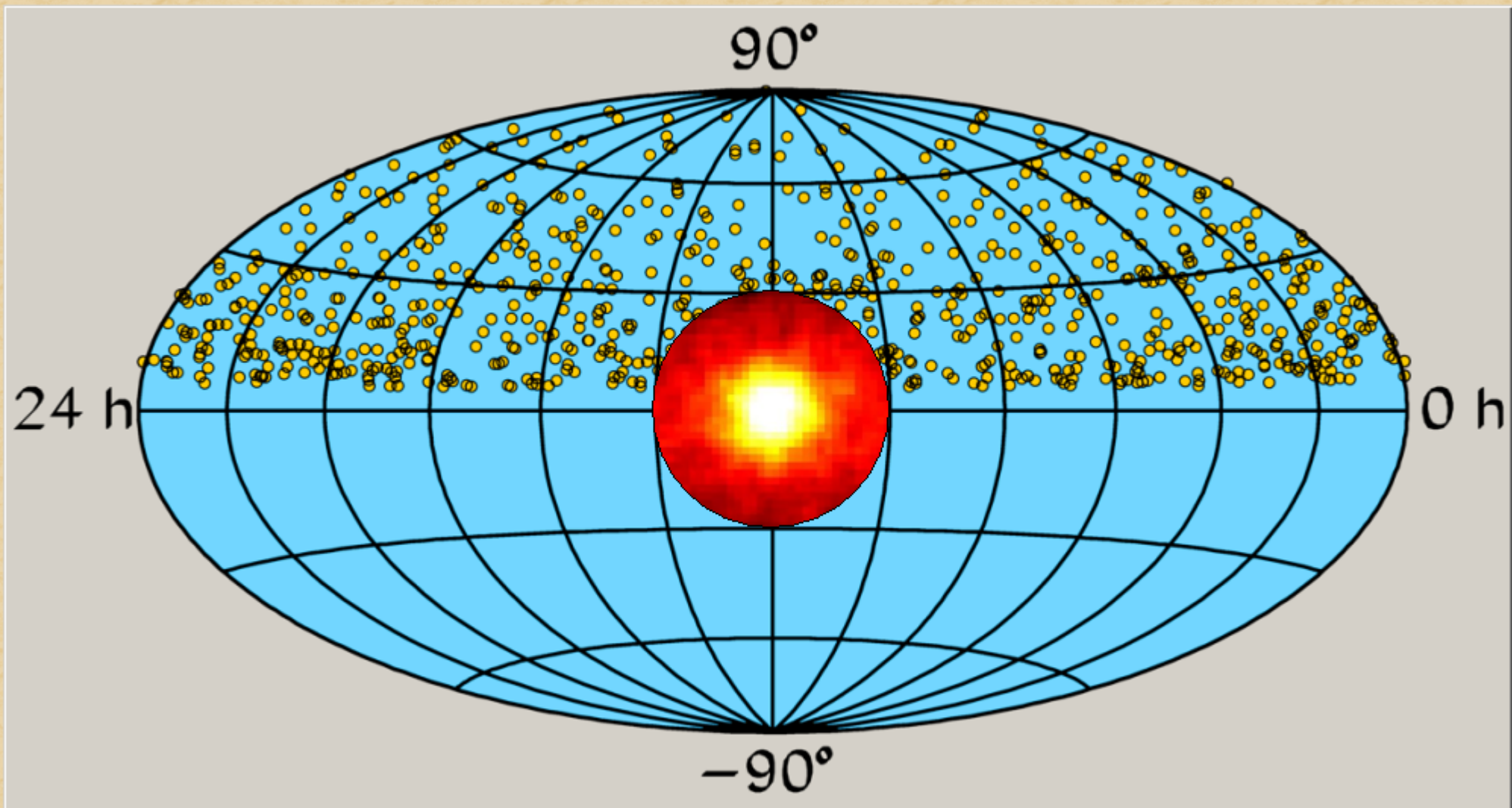
AMANDA - Neutrino teleskop am Südpol



AMANDA - Neutrino teleskop am Südpol



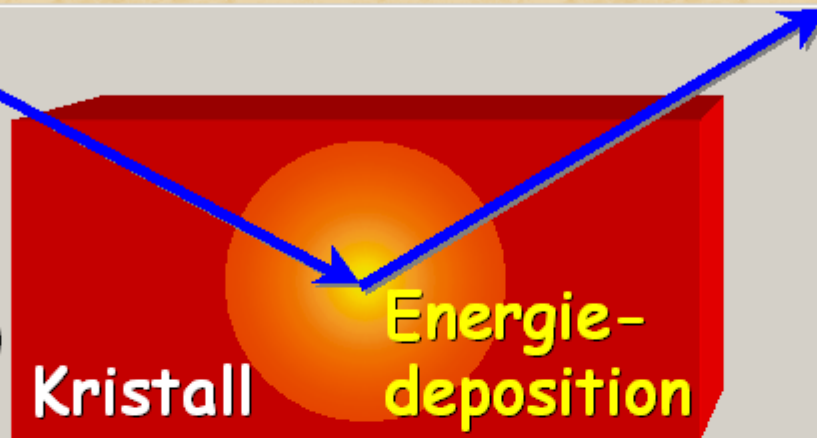
Der Himmel im „Neutrino-Licht“



Suche nach Neutralinos als Dunkler Materie

Direkte Methode (Laboratoriumsexperimente)

Galaktisches
Dunkle Materie
Teilchen
(z.B. Neutralino)

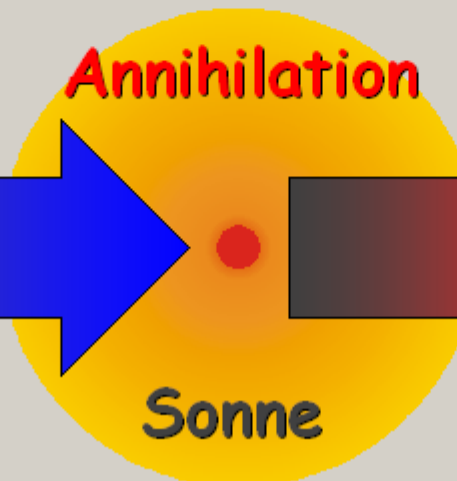


Gemessen wird
Rückstoßenergie
(einige keV) durch

- Ionisation
- Szintillation
- Kryogenisch

Indirekte Methode (Neutrino-Teleskope)

Galaktische Dunkle
Materie
Teilchen
werden akkretiert

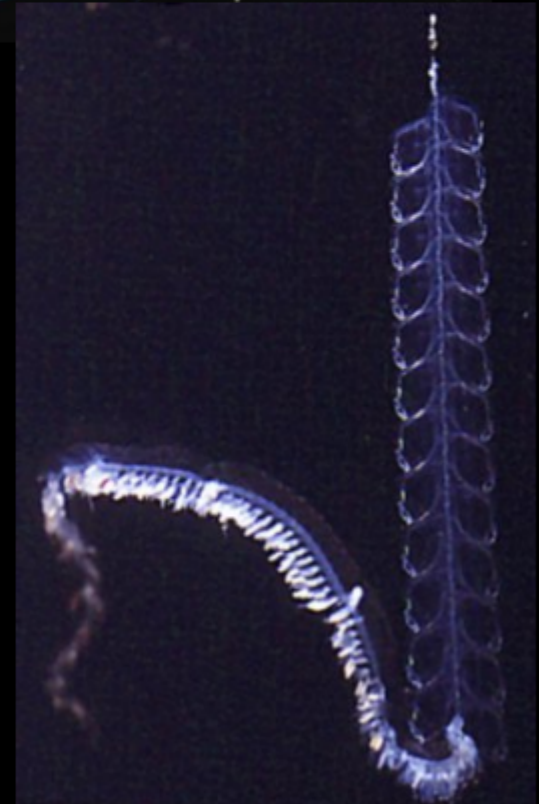
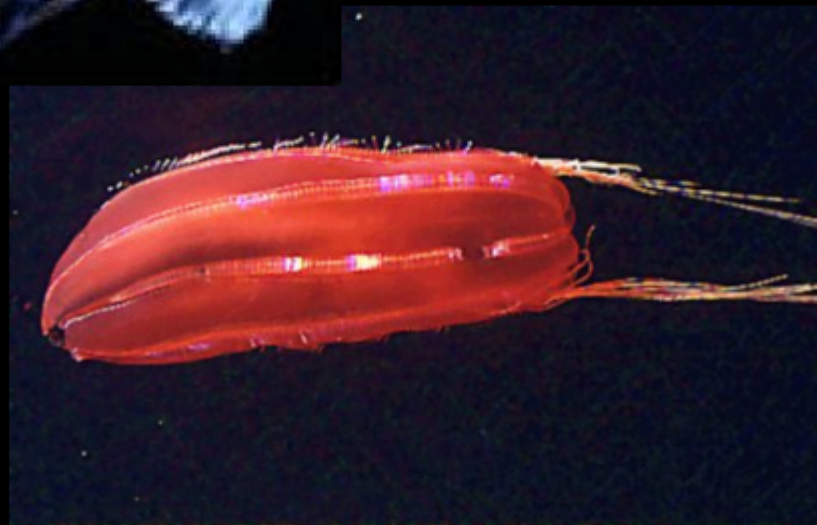
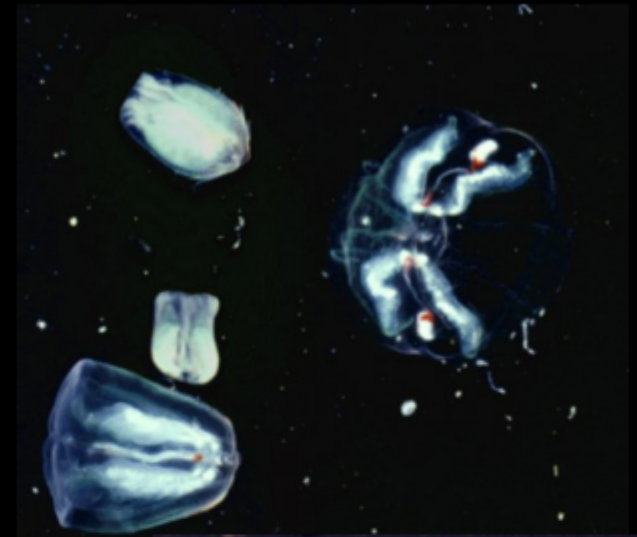
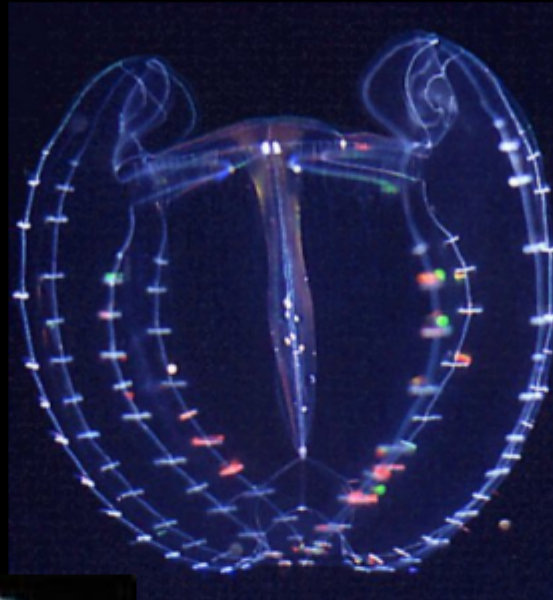
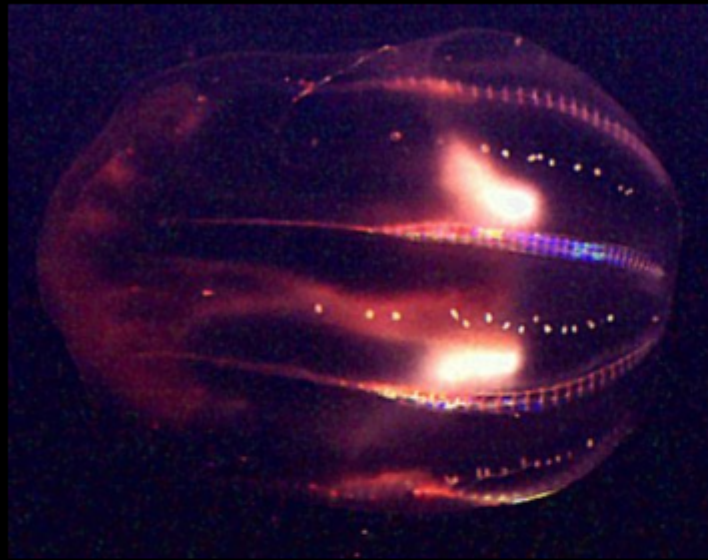


Neutrinos
hoher Energie
(GeV-TeV)
können gemessen
werden

ANTARES - Neutrino-Teleskop im Mittelmeer



Leuchtende Lebewesen der Tiefsee

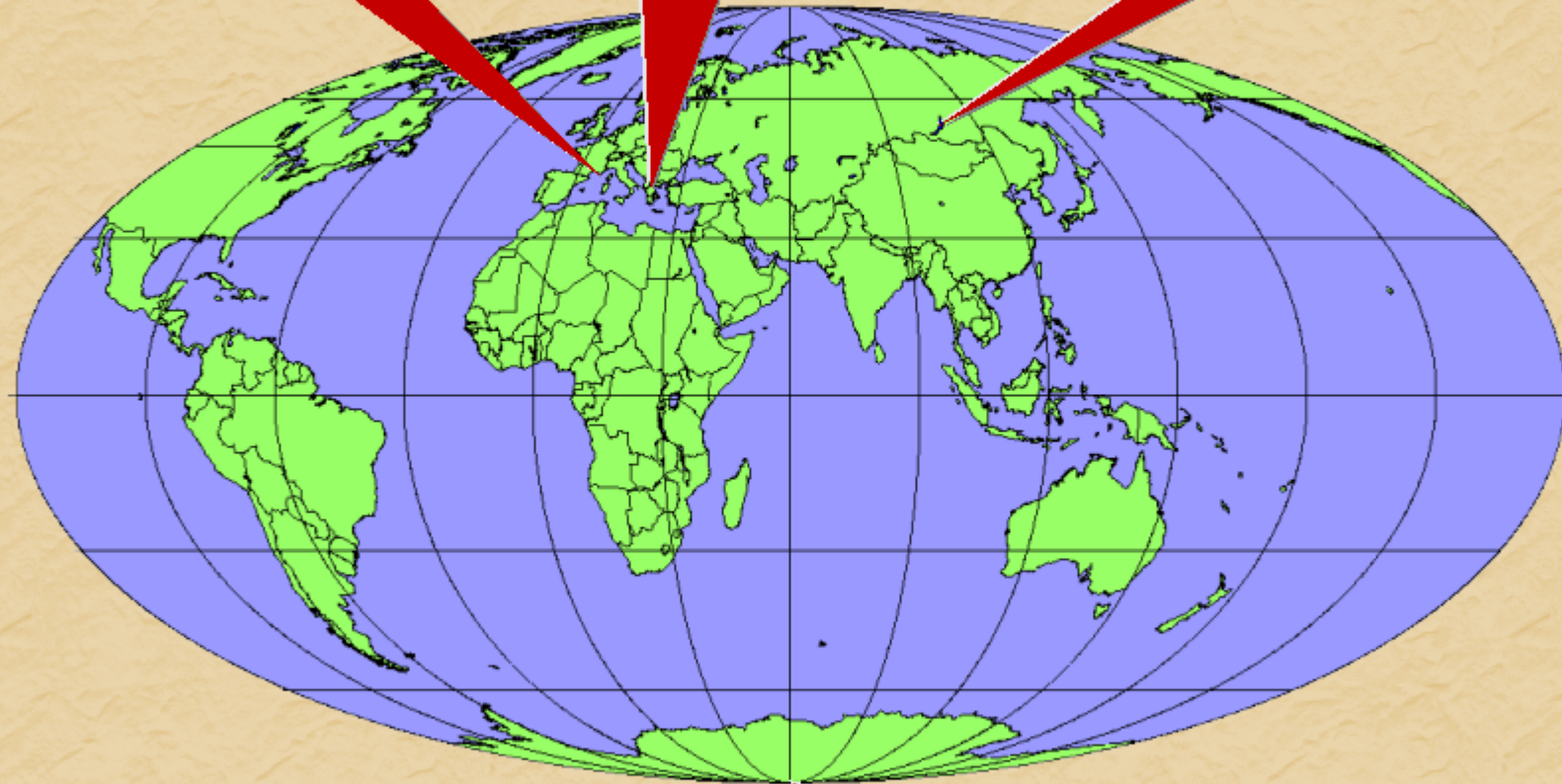


Hochenergie-Neutrino-Teleskope

**Antares
Projekt**

**Nestor
Projekt**

**Baikal
200 PMTs**



**Amanda II, 800 PMTs
(Antarktisches Eis)**

Neutrinos

~~Unsichtbare~~ Botschafter
aus dem Mikrokosmos
und dem fernen Universum

