Neutrino Physics:
Aspects on Neutrino (Mass-) and Mixing

Caren Hagner, Universität Hamburg

- Introduction: neutrino mass and mixing
- Neutrino Oscillation (I): mu – tau mixing
  - atmospheric neutrinos
  - present neutrino beam experiments:
    - MINOS (NuMi beam: Fermilab – Soudan Mine)
    - OPERA (CNGS beam: Cern – LNGS)
- Neutrino Oscillation (II): e – mu mixing
  - solar neutrino experiments
    - short review on past experiments (SNO)
    - neutrino oscillation in matter
    - Borexino
    - reactor experiment: KamLand
- Neutrino Oscillation (III): Future prospects (theta13 and CPV)
  - reactor experiments: Double Chooz and Daya Bay
  - off-axis (super)beams: T2K and NovA
  - (neutrinofactory and beta beams)
- Nature of neutrino mass: Majorana or Dirac?
  - Double beta decay

Neutrino Oscillations (12)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

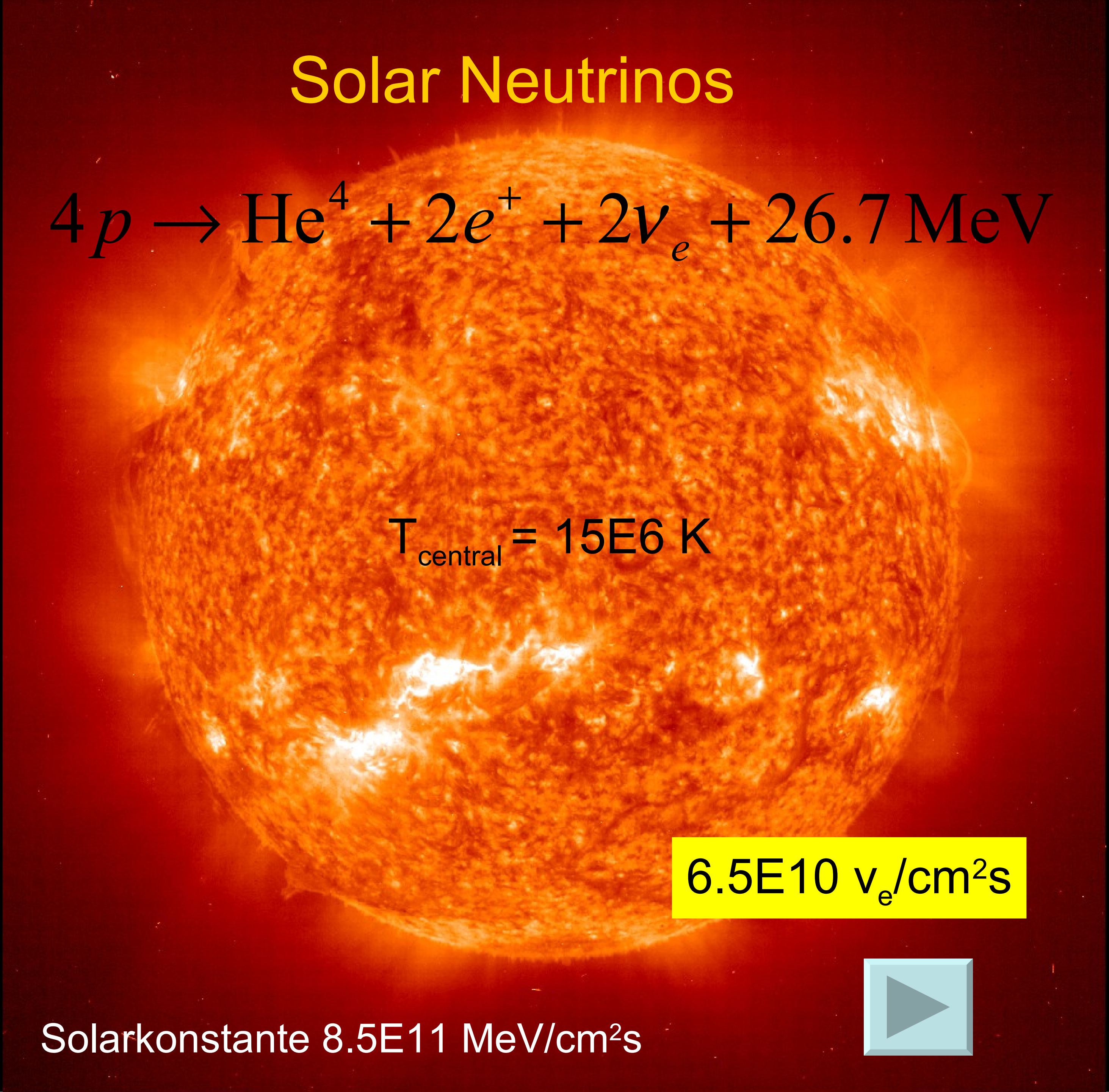
$\nu_e \longrightarrow \nu_{\mu\tau}$ Oscillations

Solar neutrinos & Reactor neutrinos

Solar Neutrinos

$$4p \rightarrow He^4 + 2e^+ + 2\nu_e + 26.7\,\text{MeV}$$

$T_{central} = 15E6$ K

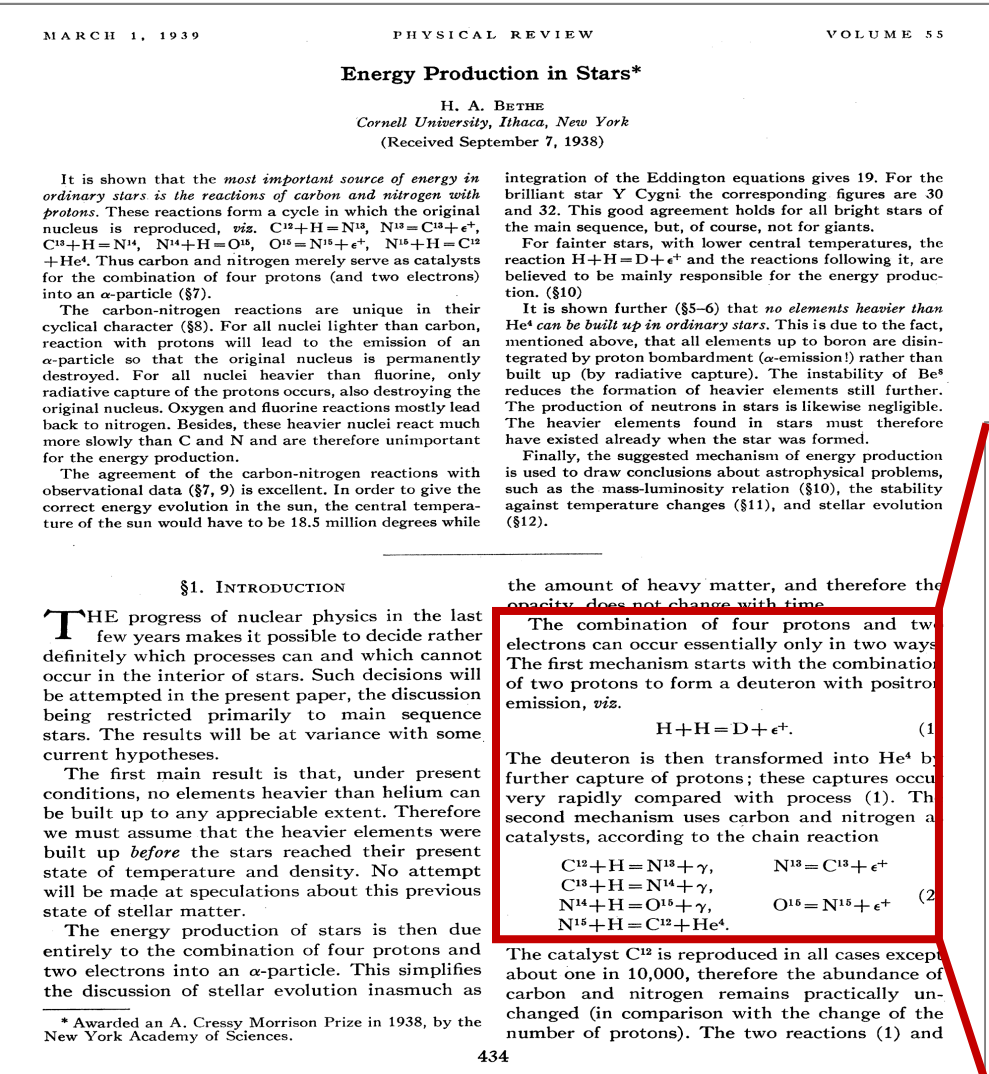


$6.5E10\ \nu_e/cm^2s$

Solarkonstante 8.5E11 MeV/cm^2s

Energy production in stars

Hans Bethe 1939 (Nobel prize 1967)



MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55

Energy Production in Stars*

H. A. Bethe
Cornell University, Ithaca, New York
(Received September 7, 1938)

It is shown that the *most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons.* These reactions form a cycle in which the original nucleus is reproduced, *viz.* $C^{12}+H=N^{13}$, $N^{13}=C^{13}+\epsilon^+$, $C^{13}+H=N^{14}$, $N^{14}+H=O^{15}$, $O^{15}=N^{15}+\epsilon^+$, $N^{15}+H=C^{12}+He^4$. Thus carbon and nitrogen merely serve as catalysts for the combination of four protons (and two electrons) into an α-particle (§7).

The carbon-nitrogen reactions are unique in their cyclical character (§8). For all nuclei lighter than carbon, reaction with protons will lead to the emission of an α-particle so that the original nucleus is permanently destroyed. For all nuclei heavier than fluorine, only radiative capture of the protons occurs, also destroying the original nucleus. Oxygen and fluorine reactions mostly lead back to nitrogen. Besides, these heavier nuclei react much more slowly than C and N and are therefore unimportant for the energy production.

The agreement of the carbon-nitrogen reactions with observational data (§7, 9) is excellent. In order to give the correct energy evolution in the sun, the central temperature of the sun would have to be 18.5 million degrees while integration of the Eddington equations gives 19. For the brilliant star Y Cygni the corresponding figures are 30 and 32. This good agreement holds for all bright stars of the main sequence, but, of course, not for giants.

For fainter stars, with lower central temperatures, the reaction $H+H=D+\epsilon^+$ and the reactions following it, are believed to be mainly responsible for the energy production. (§10)

It is shown further (§5–6) that *no elements heavier than* He^4 *can be built up in ordinary stars.* This is due to the fact, mentioned above, that all elements up to boron are disintegrated by proton bombardment (α-emission!) rather than built up (by radiative capture). The instability of Be^8 reduces the formation of heavier elements still further. The production of neutrons in stars is likewise negligible. The heavier elements found in stars must therefore have existed already when the star was formed.

Finally, the suggested mechanism of energy production is used to draw conclusions about astrophysical problems, such as the mass-luminosity relation (§10), the stability against temperature changes (§11), and stellar evolution (§12).

§1. Introduction

The progress of nuclear physics in the last few years makes it possible to decide rather definitely which processes can and which cannot occur in the interior of stars. Such decisions will be attempted in the present paper, the discussion being restricted primarily to main sequence stars. The results will be at variance with some current hypotheses.

The first main result is that, under present conditions, no elements heavier than helium can be built up to any appreciable extent. Therefore we must assume that the heavier elements were built up *before* the stars reached their present state of temperature and density. No attempt will be made at speculations about this previous state of stellar matter.

The energy production of stars is then due entirely to the combination of four protons and two electrons into an α-particle. This simplifies the discussion of stellar evolution inasmuch as the amount of heavy matter, and therefore the opacity, does not change with time.

The combination of four protons and tw[o] electrons can occur essentially only in two ways[.] The first mechanism starts with the combinatio[n] of two protons to form a deuteron with positro[n] emission, *viz.*

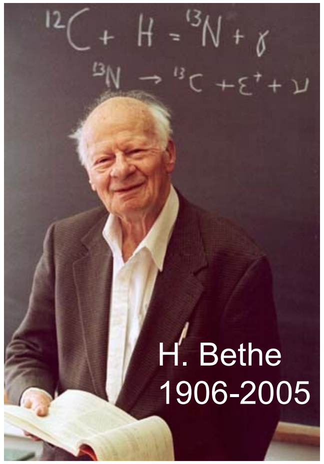
$$H+H=D+\epsilon^+. \quad (1$$

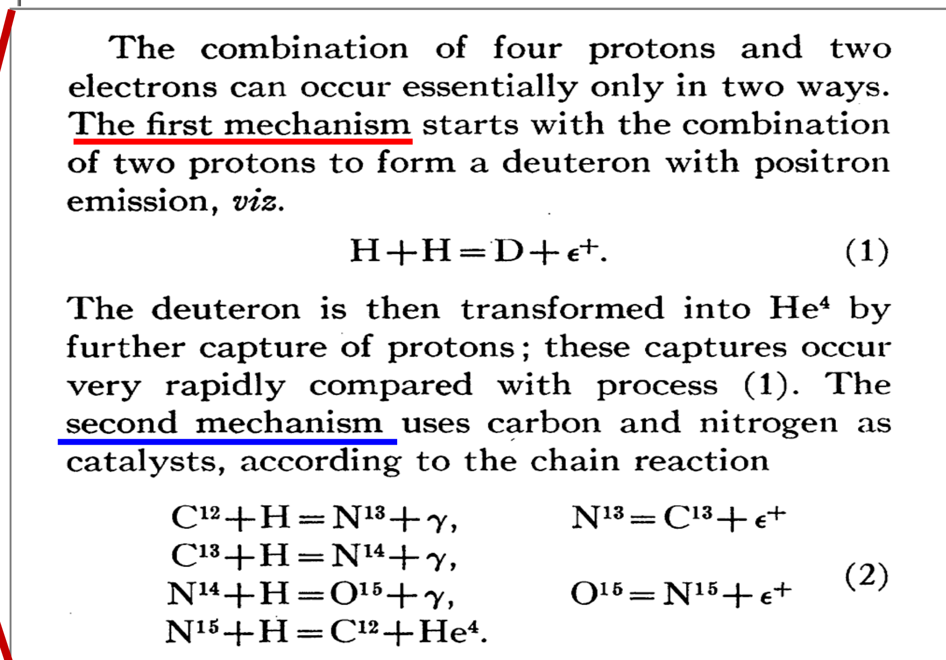
The deuteron is then transformed into He^4 b[y] further capture of protons; these captures occu[r] very rapidly compared with process (1). Th[e] second mechanism uses carbon and nitrogen a[s] catalysts, according to the chain reaction

$$\begin{aligned} &C^{12}+H=N^{13}+\gamma, && N^{13}=C^{13}+\epsilon^+ \\ &C^{13}+H=N^{14}+\gamma, && \\ &N^{14}+H=O^{15}+\gamma, && O^{15}=N^{15}+\epsilon^+ \quad (2 \\ &N^{15}+H=C^{12}+He^4. && \end{aligned}$$

The catalyst C^{12} is reproduced in all cases except about one in 10,000, therefore the abundance of carbon and nitrogen remains practically unchanged (in comparison with the change of the number of protons). The two reactions (1) and

* Awarded an A. Cressy Morrison Prize in 1938, by the New York Academy of Sciences.





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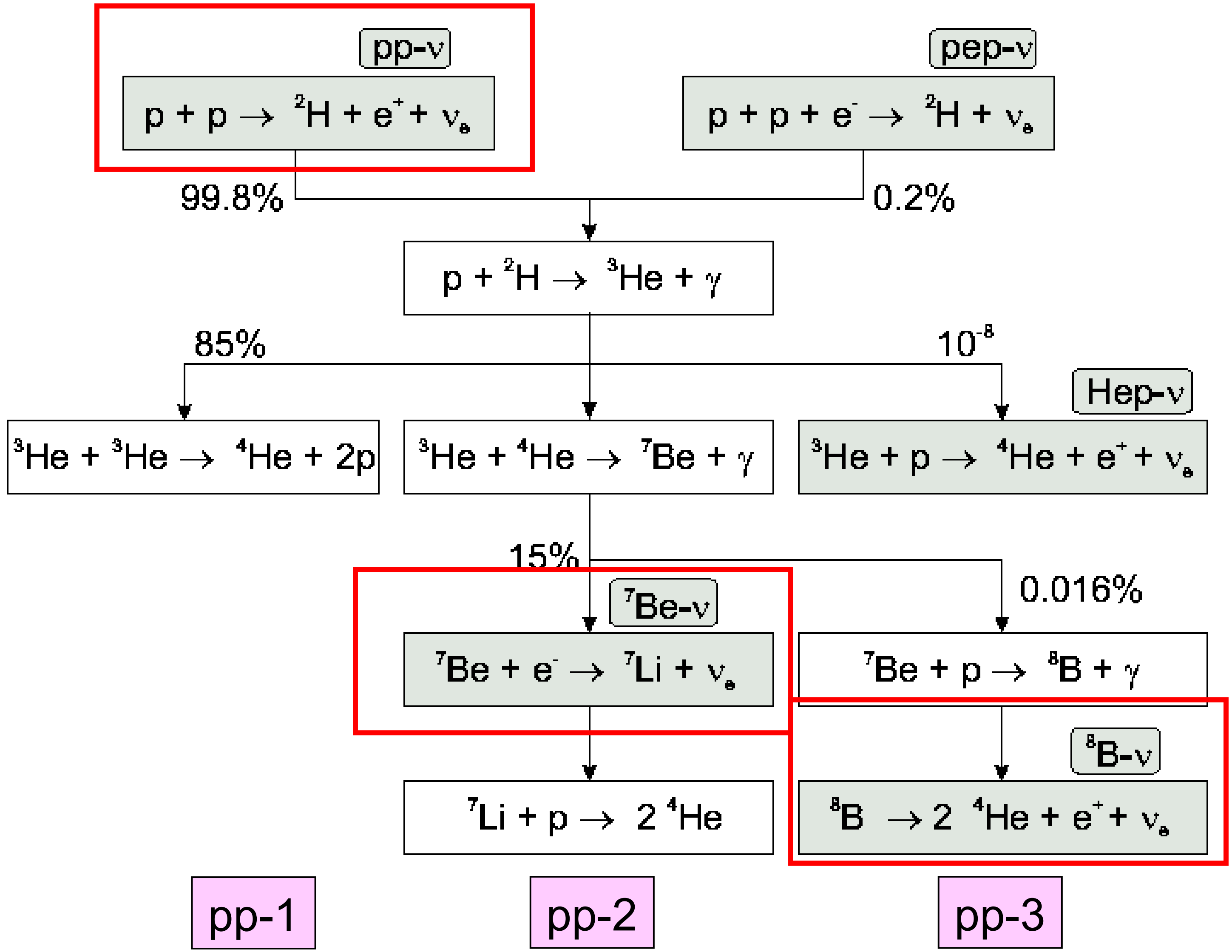
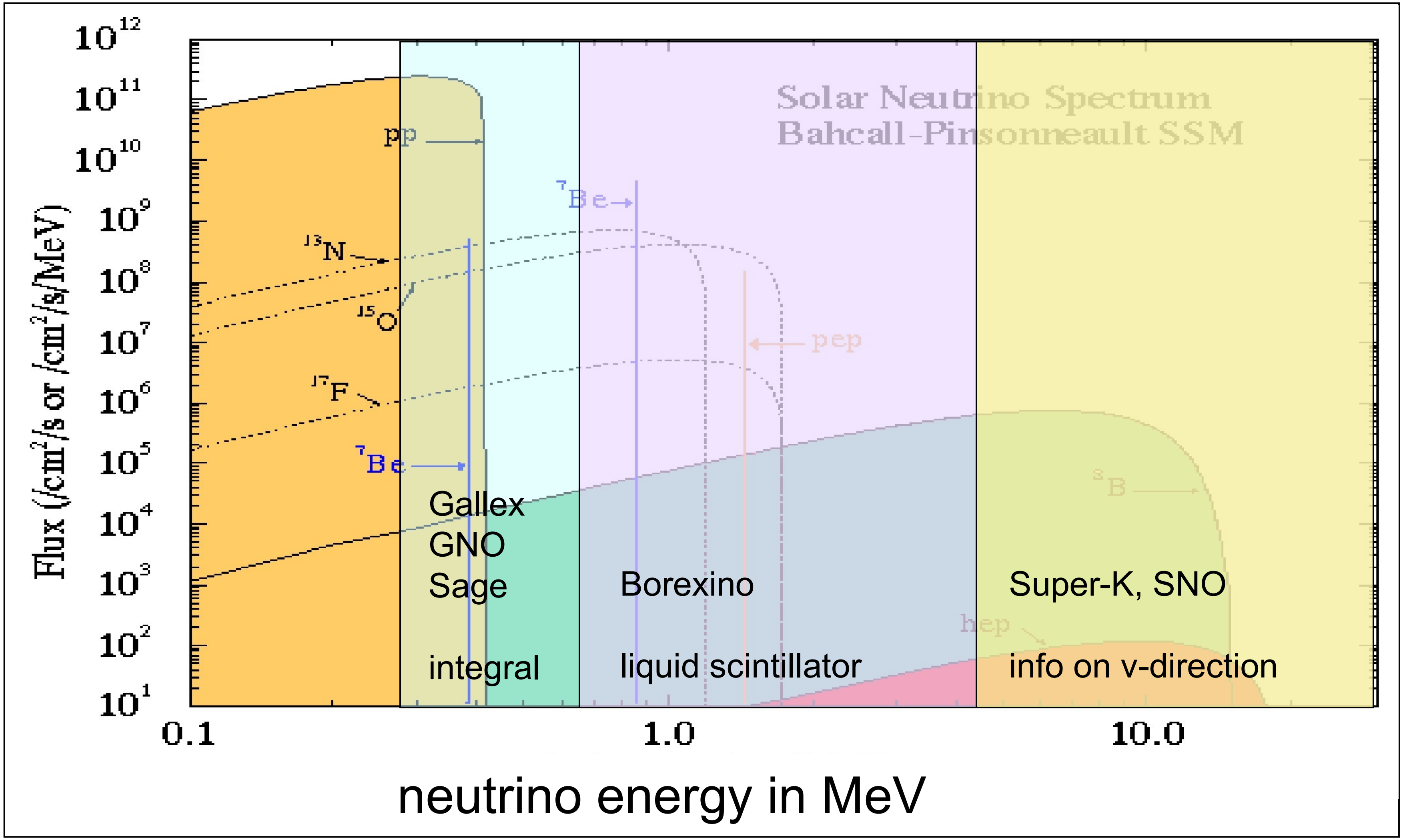
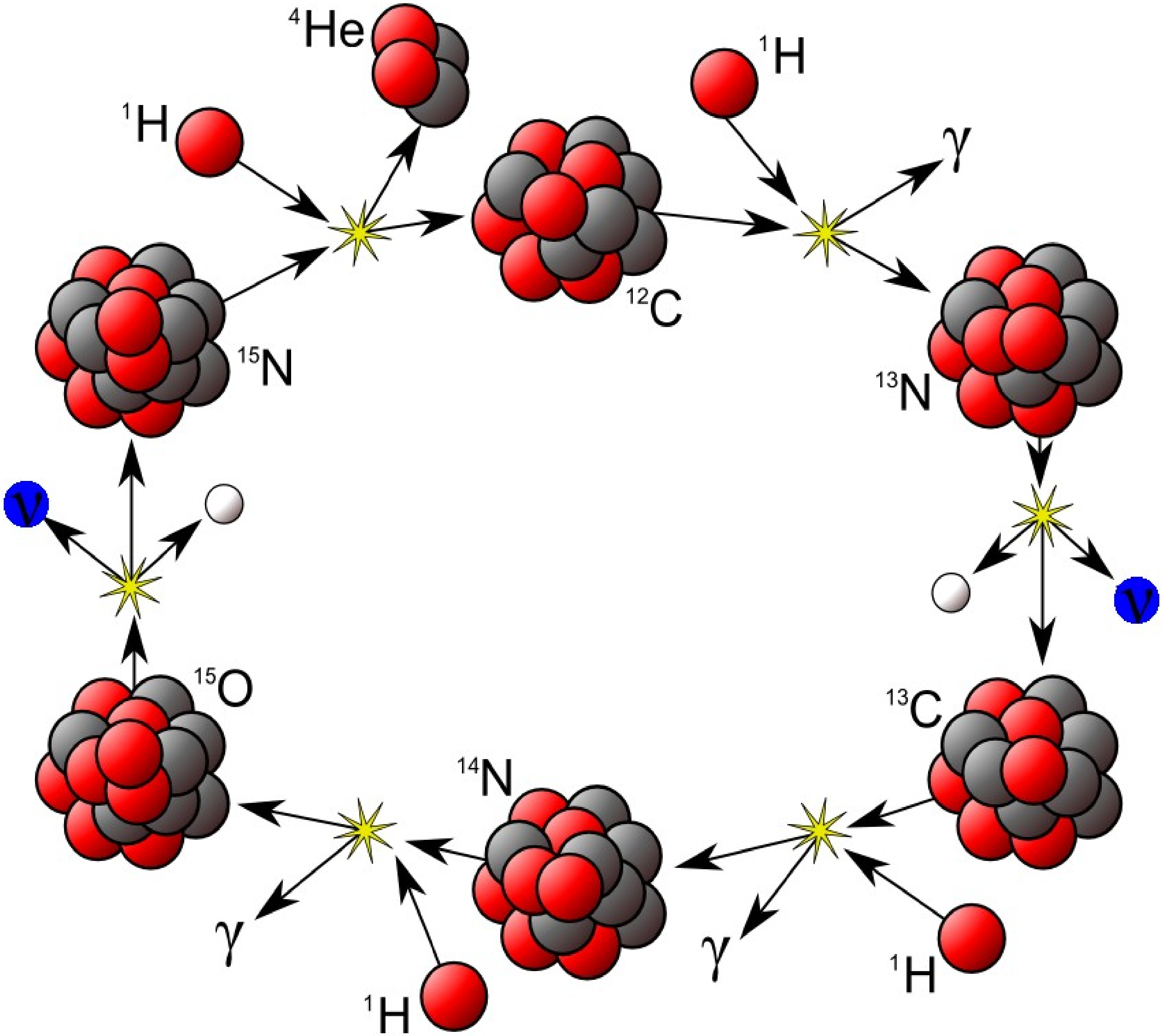
Energy production in the sun: pp cycle



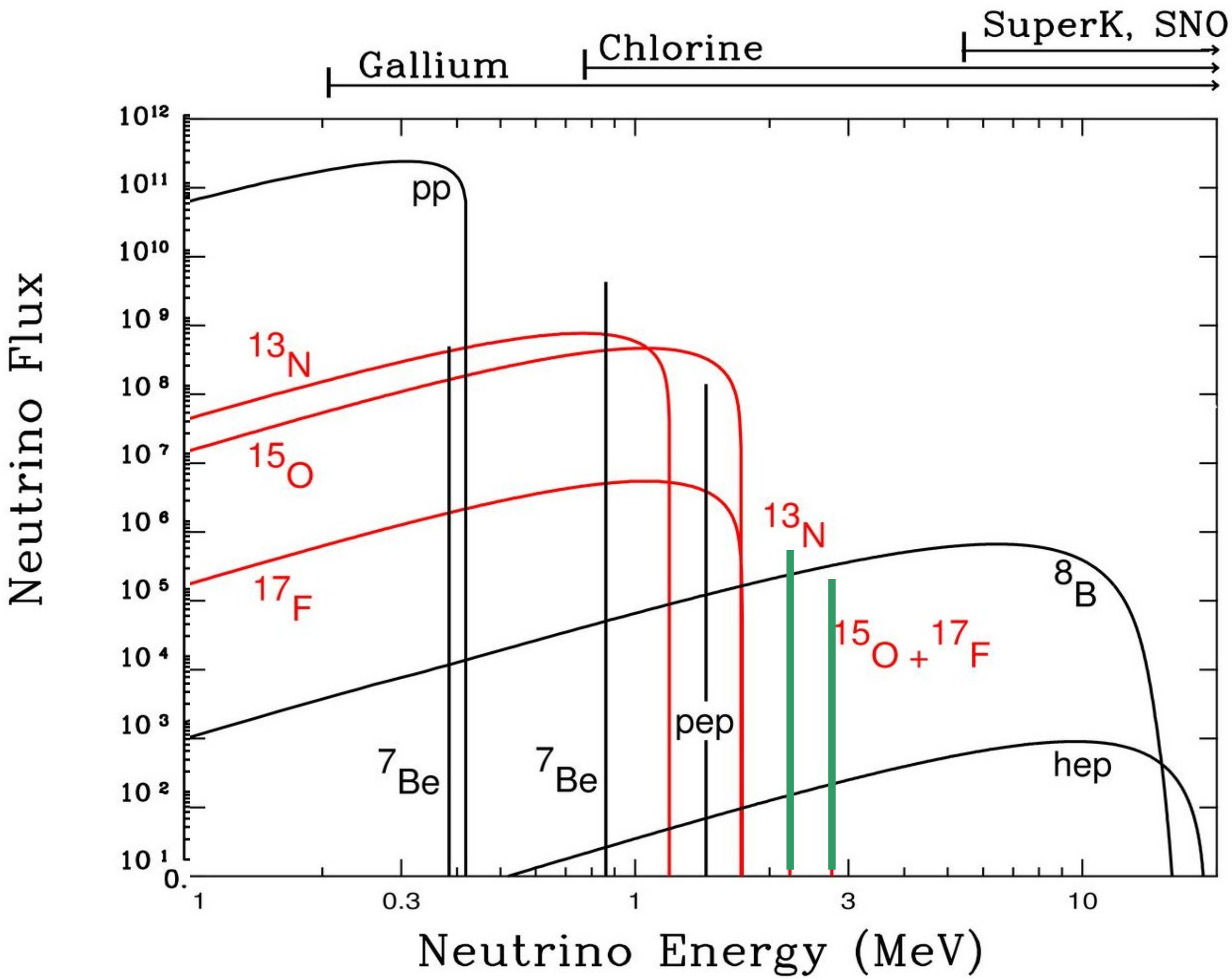
Solar Neutrino Spectrum



Der CNO - Zyklus (subdominant in der Sonne)



Neutrinos from the CNO-cycle



Calculation and Measurement of the flux of solar neutrinos

Bahcall, Davis 1964

VOLUME 12, NUMBER 11 PHYSICAL REVIEW LETTERS 16 MARCH 1964

SOLAR NEUTRINOS. I. THEORETICAL*

John N. Bahcall
California Institute of Technology, Pasadena, California
(Received 6 January 1964)

The principal energy source for main-sequence stars like the sun is believed to be the fusion, in the deep interior of the star, of four protons to form an alpha particle.[1] The fusion reactions are thought to be initiated by the sequence $^1H(p, e^+\nu)^2H(p,\gamma)^3He$ and terminated by the following sequences: (i) $^3He(^3He, 2p)^4He$; (ii) $^3He(\alpha,\gamma)^7Be(e^-\nu)^7Li(p,\alpha)^4He$; and (iii) $^3He(\alpha,\gamma)^7Be(p,\gamma)^8B(e^+\nu)^8Be^*(\alpha)^4He$. No direct evidence for the existence of nuclear reactions in the interiors of stars has yet been obtained because the mean free path for photons emitted in the center of a star is typically less than 10^{-10} of the radius of the star. Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars.

The most promising method[2] for detecting solar neutrinos is based upon the endothermic reaction ($Q = -0.81$ MeV) $^{37}Cl(\nu_{solar}, e^-)^{37}Ar$, which was first discussed as a possible means of detecting neutrinos by Pontecorvo[3] and Alvarez.[4] In this note, we predict the number of absorptions of

SOLAR NEUTRINOS. II. EXPERIMENTAL*

Raymond Davis, Jr.
Chemistry Department, Brookhaven National Laboratory, Upton, New York
(Received 6 January 1964)

The prospect of observing solar neutrinos by means of the inverse beta process $^{37}Cl(\nu, e^-)^{37}Ar$ induced us to place the apparatus previously described[1] in a mine and make a preliminary search. This experiment served to place an upper limit on the flux of extraterrestrial neutrinos. These results will be reported, and a discussion will be given of the possibility of extending the sensitivity of the method to a degree capable of measuring the solar neutrino flux calculated by Bahcall in the preceding paper.[2]

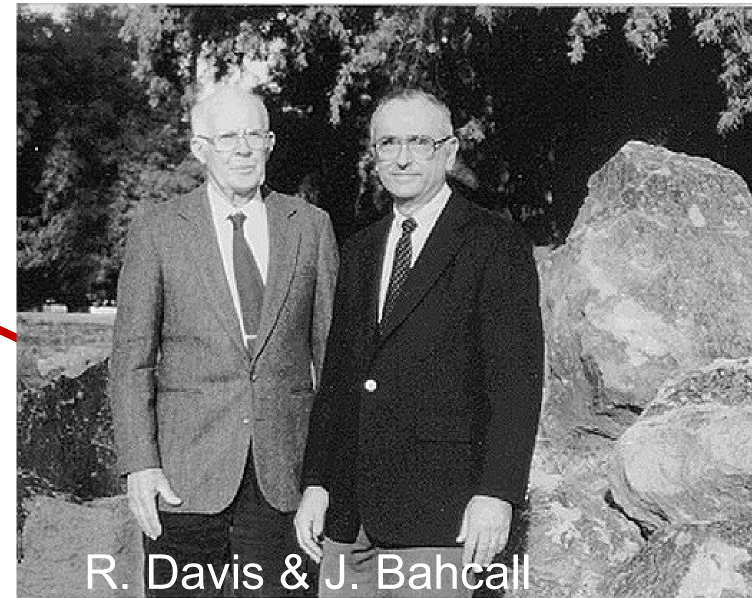
The apparatus consists of two 500-gallon tanks of perchlorethylene, C_2Cl_4, equipped with agitators and an auxiliary system for purging with helium. It is located in a limestone mine 2300 feet below the surface[3] (1800 meters of water equivalent shielding, m.w.e.). Initially the tanks were swept completely free of air argon by purging the tanks with a stream of helium gas. ^{36}Ar carrier (0.10 cm^3) was introduced and the tanks exposed for periods of four months or more to allow the 35-d ^{37}Ar activity to reach nearly the saturation value. Carrier argon along with any ^{37}Ar pro-

3 counts in 18 days is probably entirely due to the background activity. However, if one assumes that this rate corresponds to real events and uses the efficiencies mentioned, the upper limit of the neutrino capture rate in 1000 gallons of C_2Cl_4 is ≤ 0.5 per day or $\varphi\bar{\sigma} \leq 3\times10^{-34}$ sec^{-1} (^{37}Cl atom)$^{-1}$. From this value, Bahcall[2] has set an upper limit on the central temperature of the sun and other relevant information.

On the other hand, if one wants to measure the solar neutrino flux by this method one must use a much larger amount of C_2Cl_4, so that the expected ^{37}Ar production rate is well above the background of the counter, 0.2 count per day. Using Bahcall's expression,

$$\sum \varphi_\nu(\text{solar})\,\sigma_{abs} = (4\pm2)\times10^{-35}\ \text{sec}^{-1}\ (^{37}\text{Cl atom})^{-1},$$

then the expected solar neutrino captures in 100 000 gallons of C_2Cl_4 will be 4 to 11 per day, which is an order of magnitude larger than the counter background. On the basis of experience



the star. Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars.

Untergrundlabore weltweit

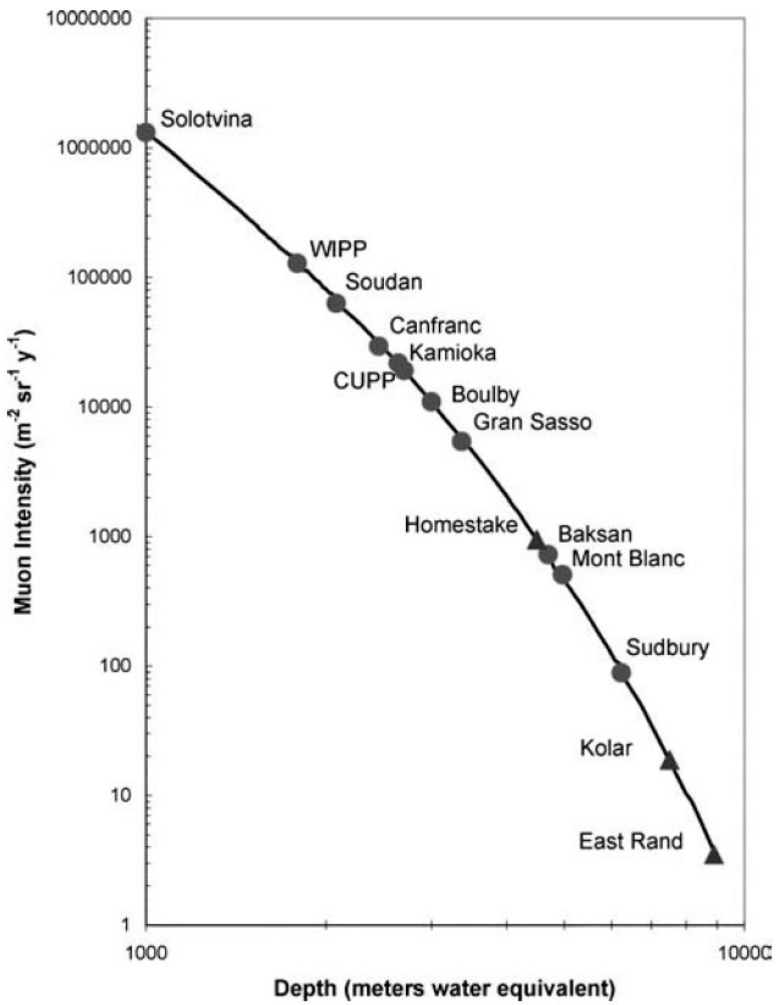
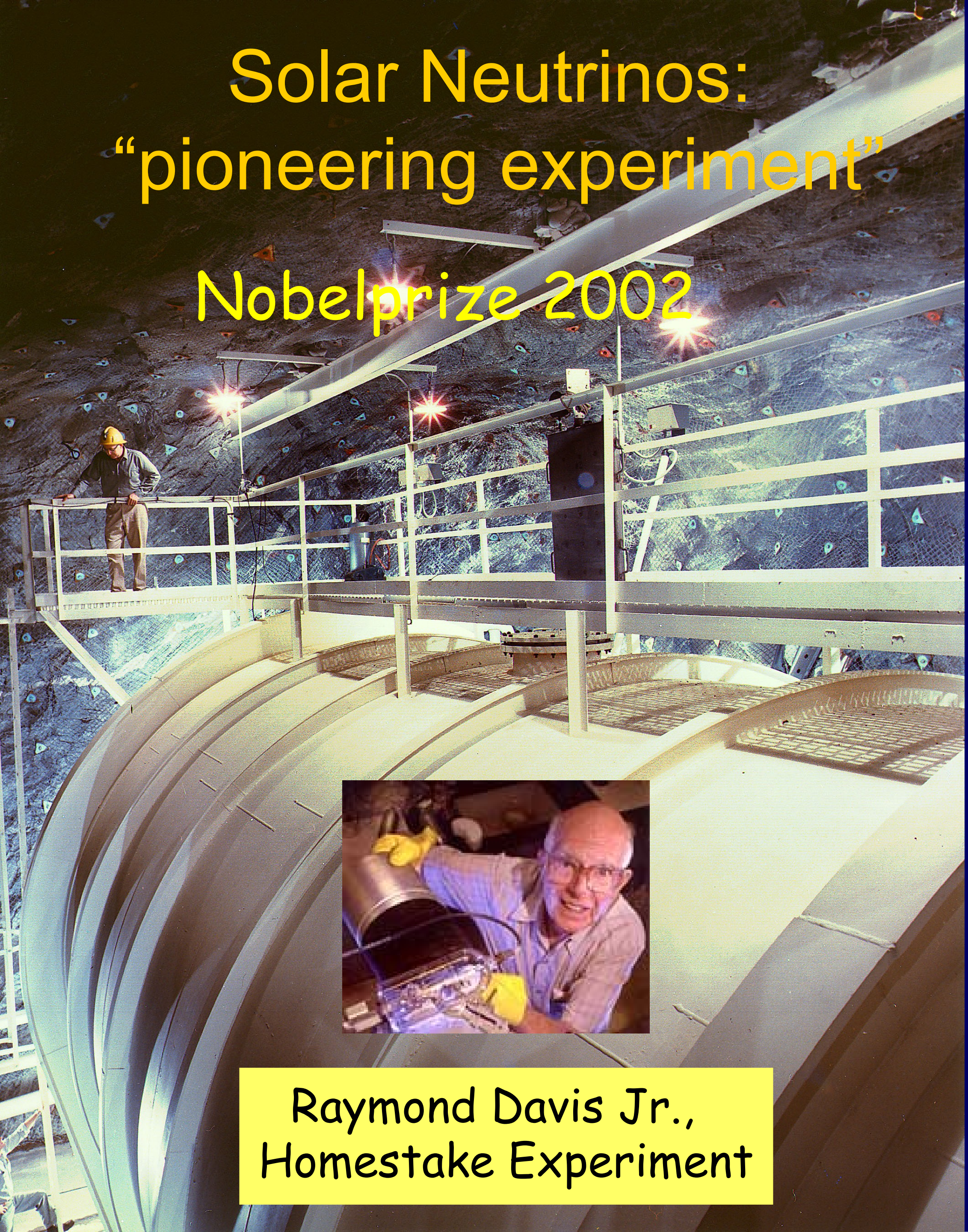


Figure 2 Vertical muon flux as a function of depth, normalized to meter water equivalent (mwe), with current (*circles*) and closed (*triangles*) underground facilities. The CUPP and Kamioka cites are at equal depth.

Solar Neutrinos: “pioneering experiment”

Nobelprize 2002



Raymond Davis Jr., Homestake Experiment

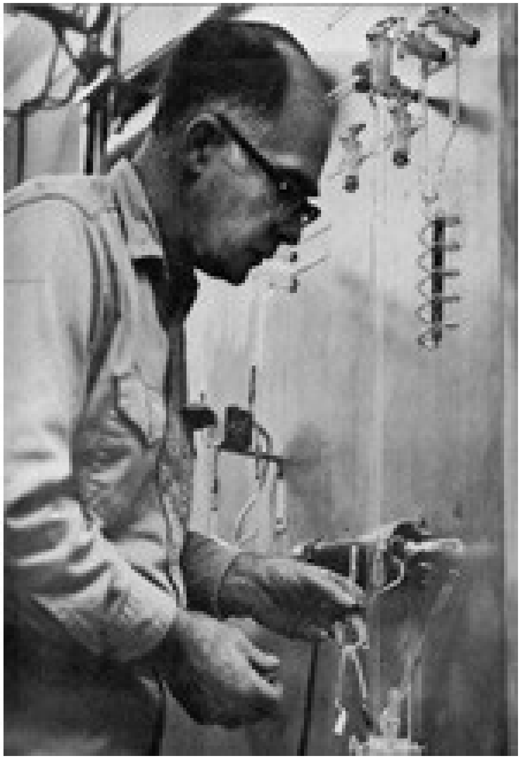
Since≈1970

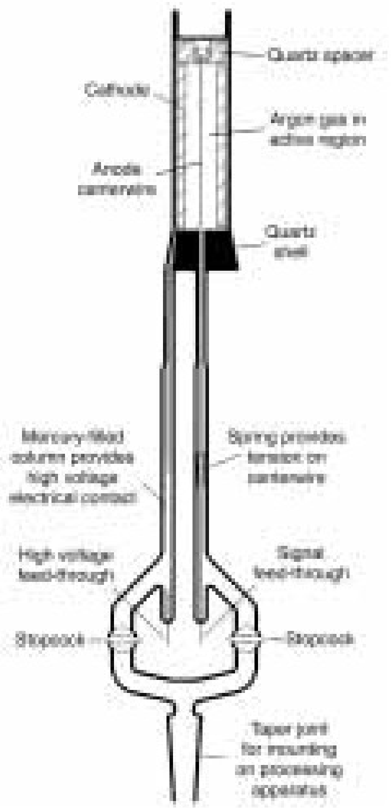
$$\nu_e + Cl^{37} \rightarrow Ar^{37} + e^-$$

E_ν > 814 keV

R_{exp} = 0.34 × SSM

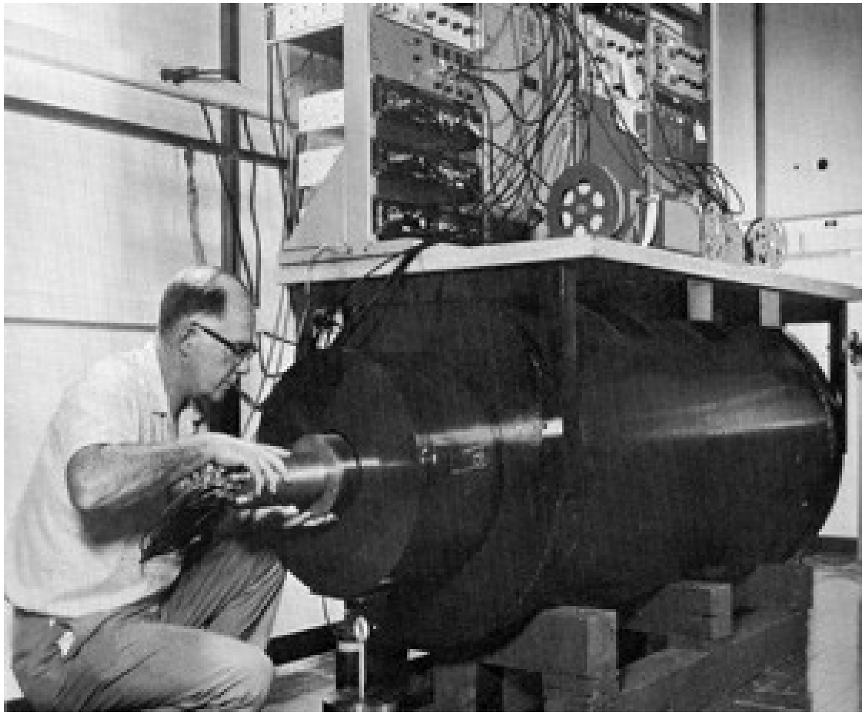
Ar – Counting





$$\mathrm{Ar}^{37} + e^{-} \rightarrow \nu_e + \mathrm{Cl}^{37}$$

$T_{1/2}$ = 35 Tage



Homestake: Ergebnis

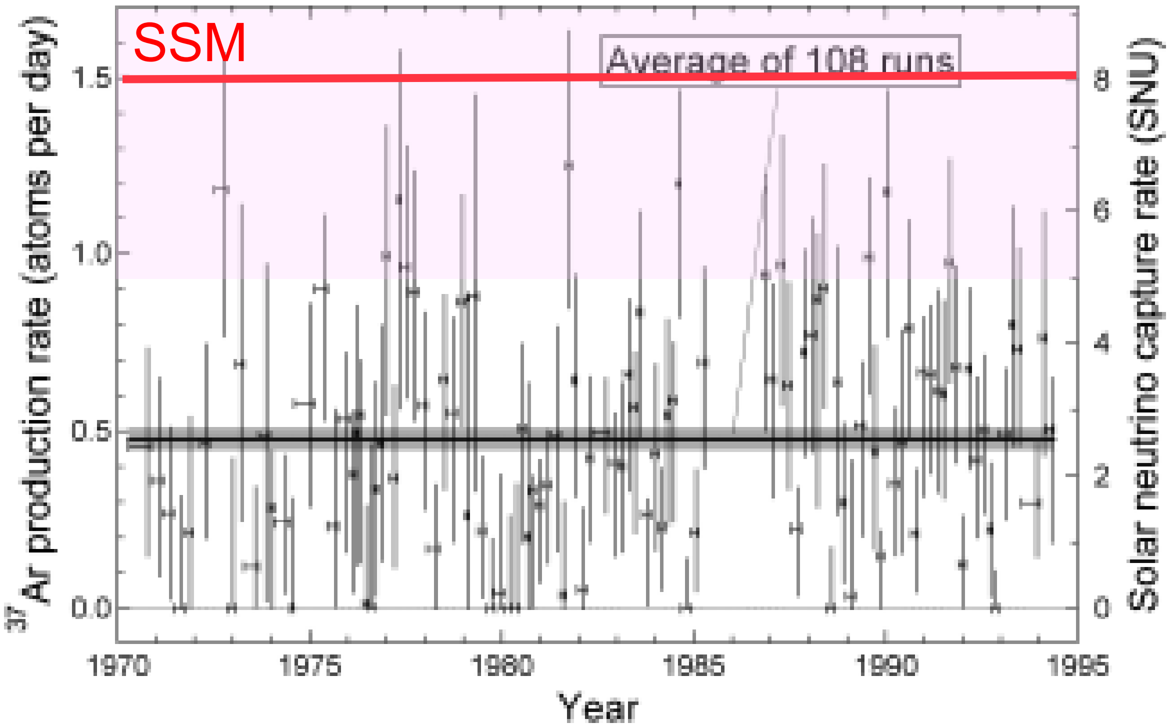


Figure 15. A summary of all of the runs made at Homestake after implementation of rise-time counting. Background has been subtracted. Over a period of 25 years, 2200 atoms of ^{37}Ar were detected, corresponding to an average solar neutrino flux of 2.56 SNU. The gap in 1986 occurred when both perchloroethylene circulation pumps failed. Based on data from Cleveland *et al.* (1998).

Бруно Понтекорво

ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

JOINT INSTITUTE FOR NUCLEAR RESEARCH

Москва, Главный почтамт п/я 79. Head Post Office, P.O. Box 79, Moscow, USSR

№ 994/31 April 6/10 1972

Prof. J.N.Bahcall
The Institute for Advanced Study
School of Natural Science
Princeton, New Jersey 08540, USA

Dear Prof. Bahcall,

Thank you very much for your letter and the abstract of the new Davis investigation the numerical results of which I did not know. It starts to be really interesting! It would be nice if all this will end with something unexpected from the point of view of particle physics. Unfortunately, it will not be easy to demonstrate this, even if nature works that way.

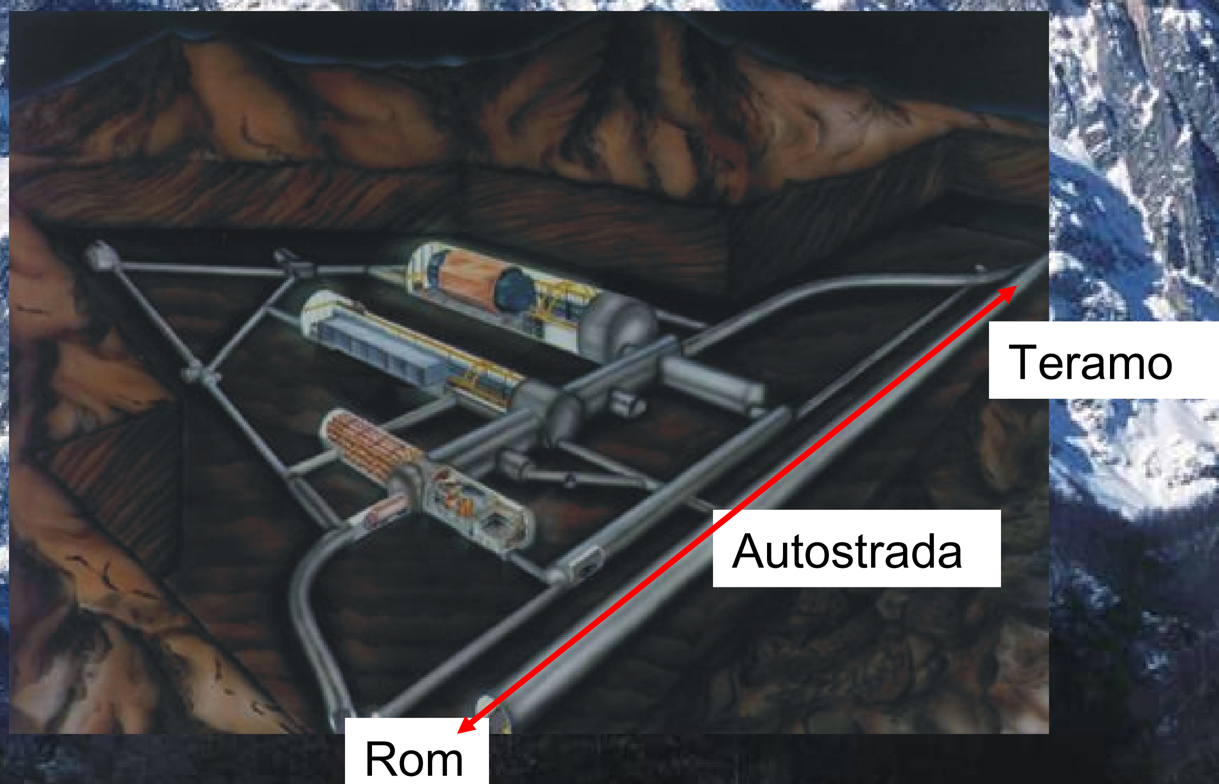
I will attend the Balaton meeting on neutrinos and looking forward to see you there.

Yours sincerely,

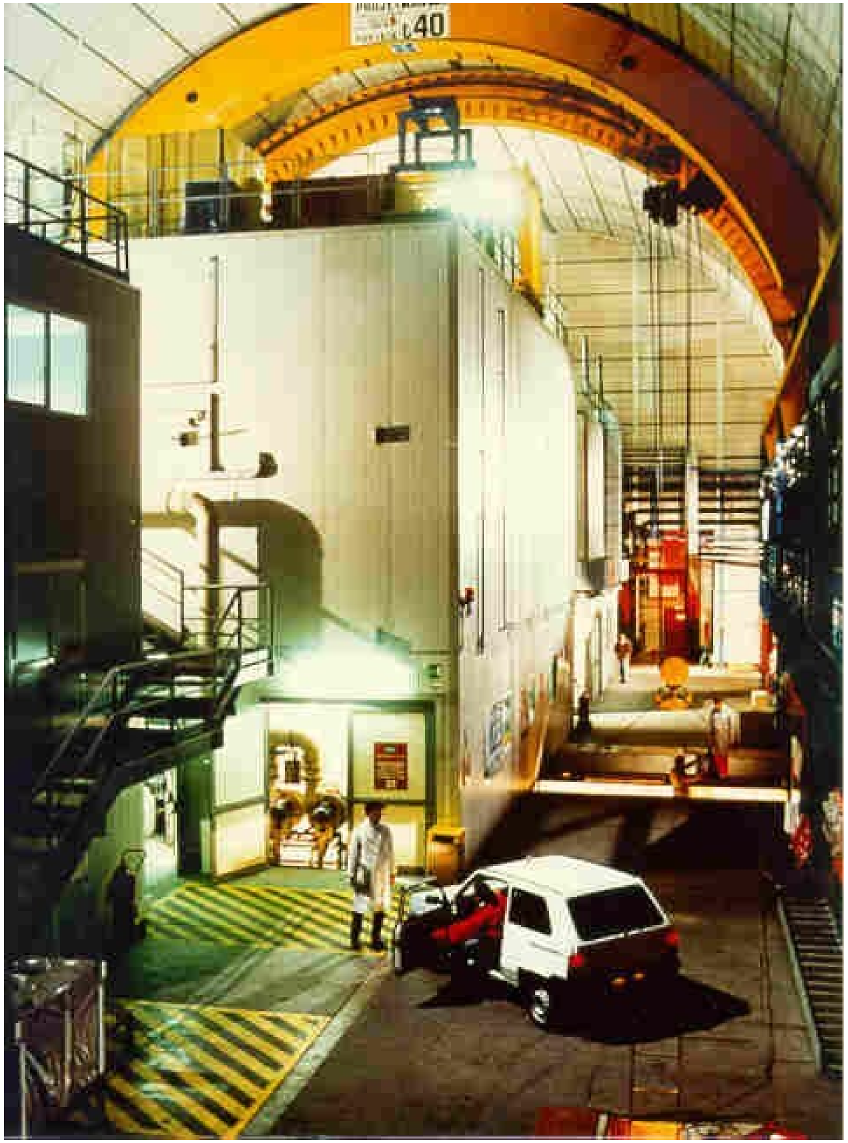
B.Pontecorvo

Gran Sasso Untergrundlabor (Italien)

150 km von Rom

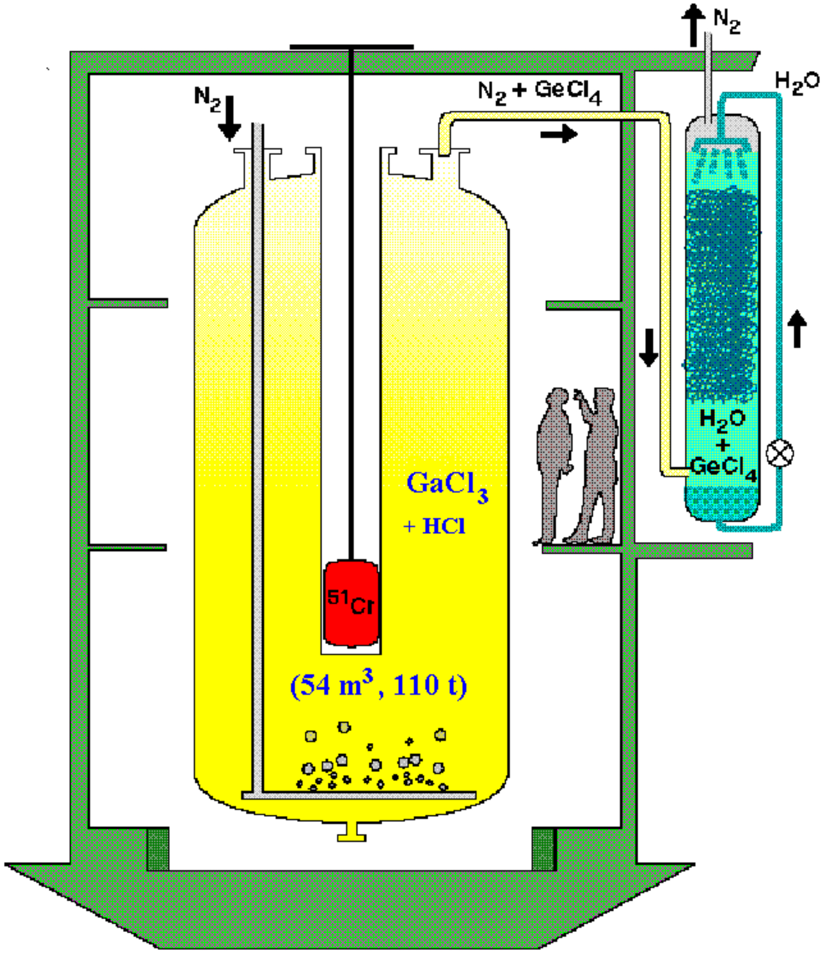


GALLEX (& GNO)



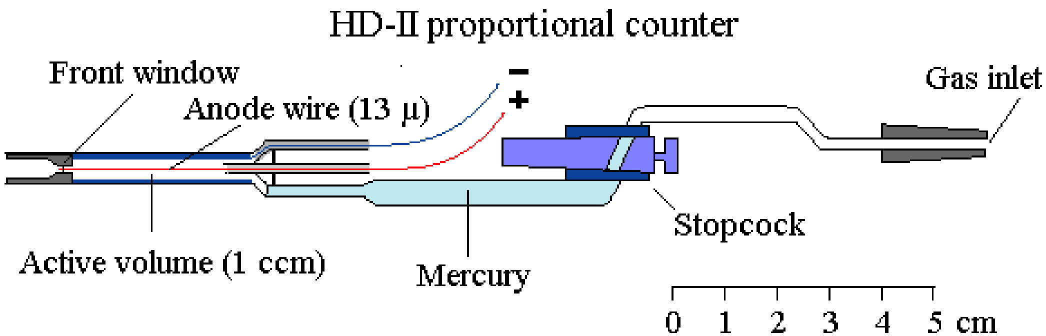
$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$$

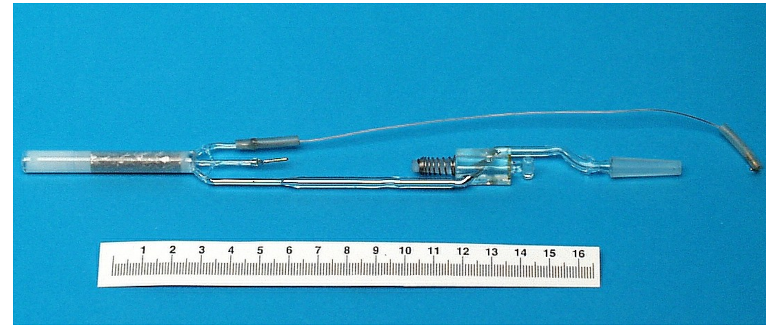
$E_\nu > 233$ keV

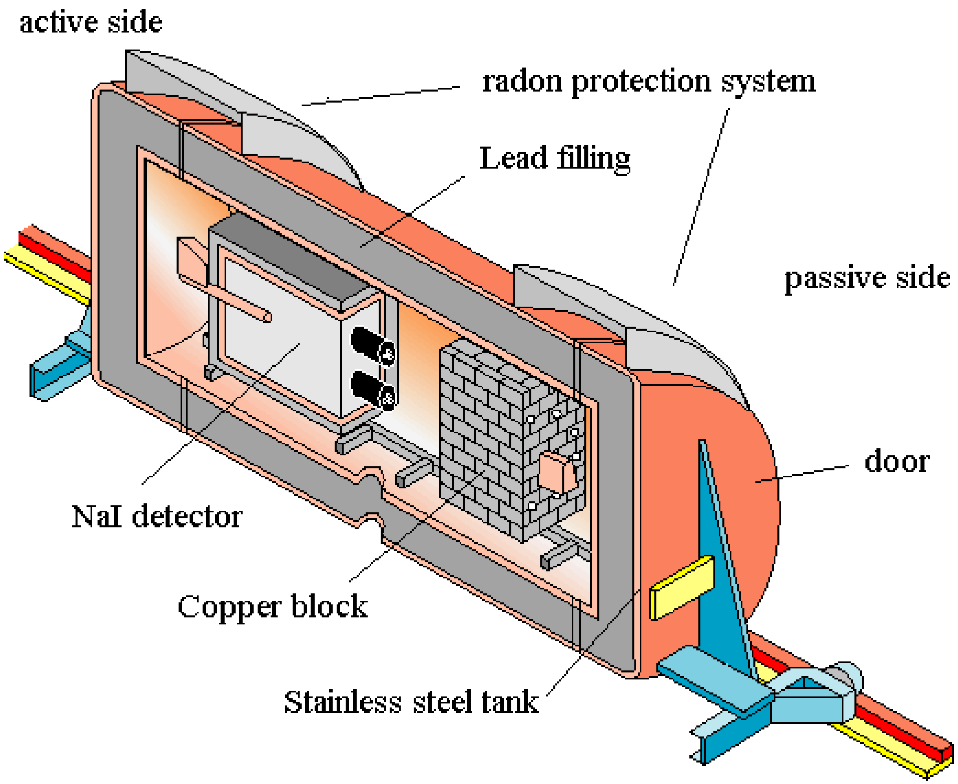


Extraction of ^{71}Ge (as $GeCl_4$) in GALLEX

Ge - Counting



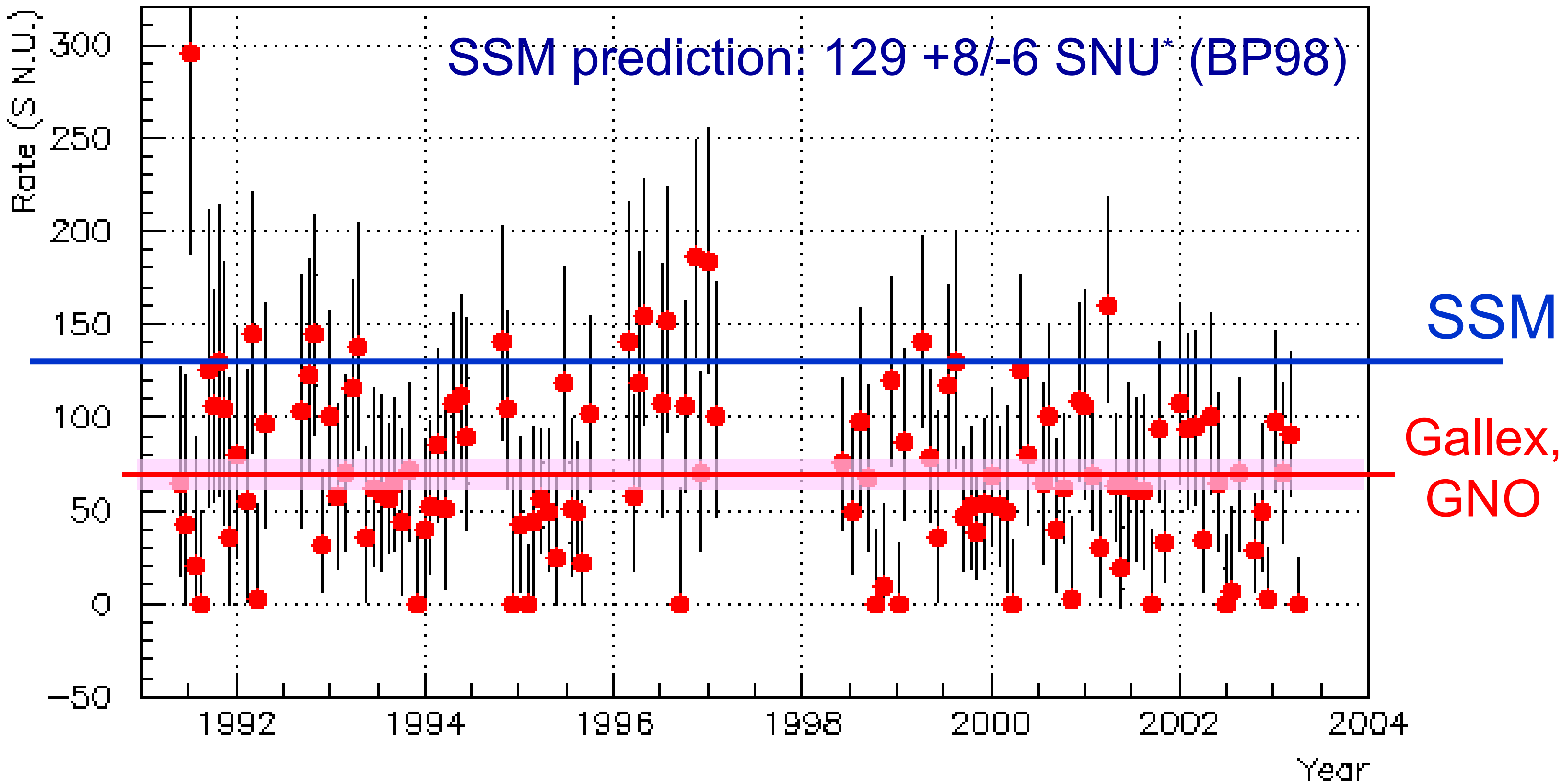




$$e^{-} + {}^{71}\mathrm{Ge} \rightarrow {}^{71}\mathrm{Ga} + \nu_e$$

$T_{1/2} = 11.4$ d

Gallex / GNO results



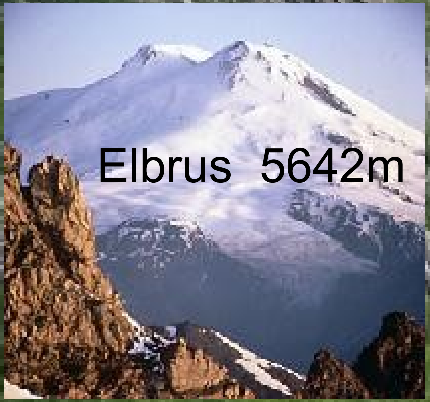
Gallex/GNO: 69.3 ± 4.1 ± 3.6 SNU

*) 1 SNU (solar neutrino unit) = 1 ν-capture / 10^{36} target atoms

SAGE (soviet american gallium experiment)

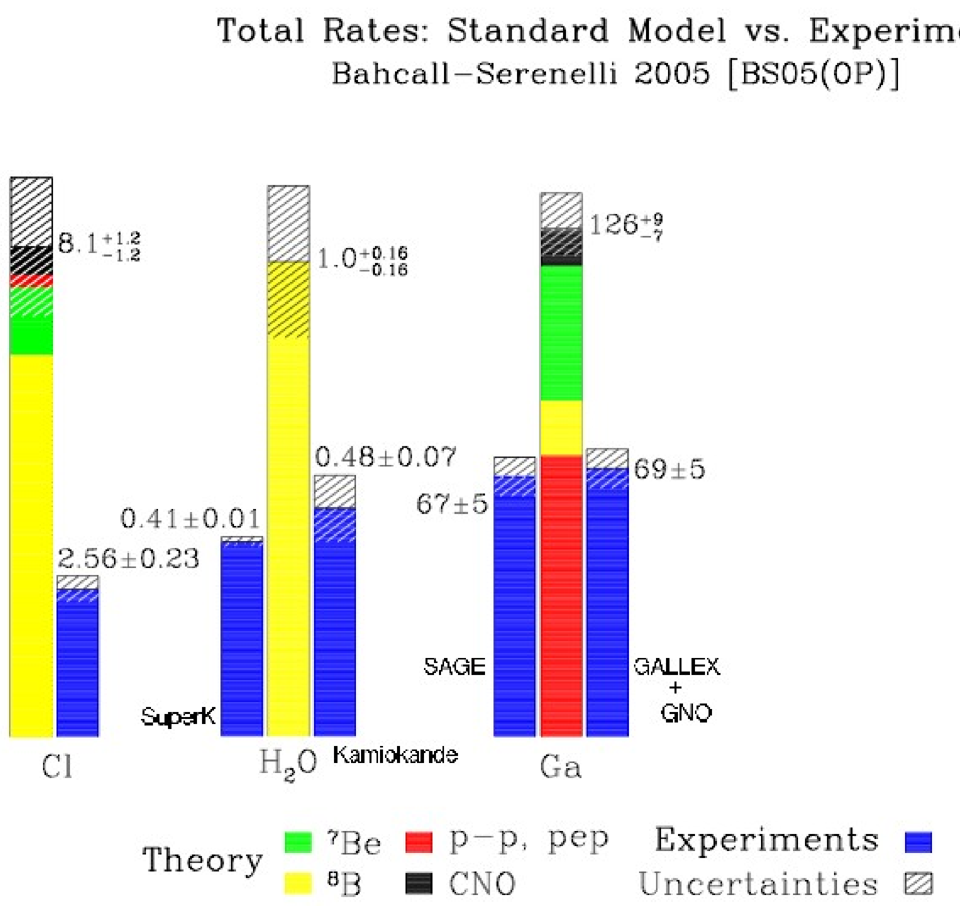
Heute: BNO (Baksan Neutrino Observatory)

Total: GALLEX/GNO & SAGE: 68.1 ± 3.75 SNU

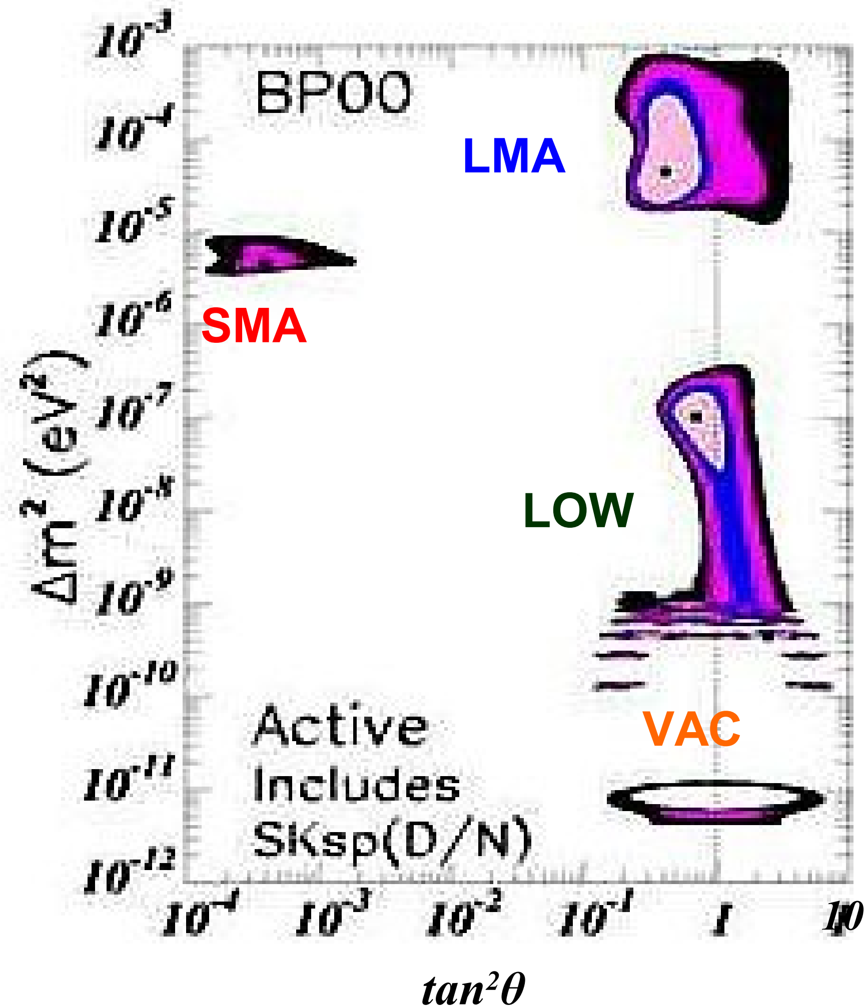


Baksan Valley,
Kabardino-Balkaria, Russia

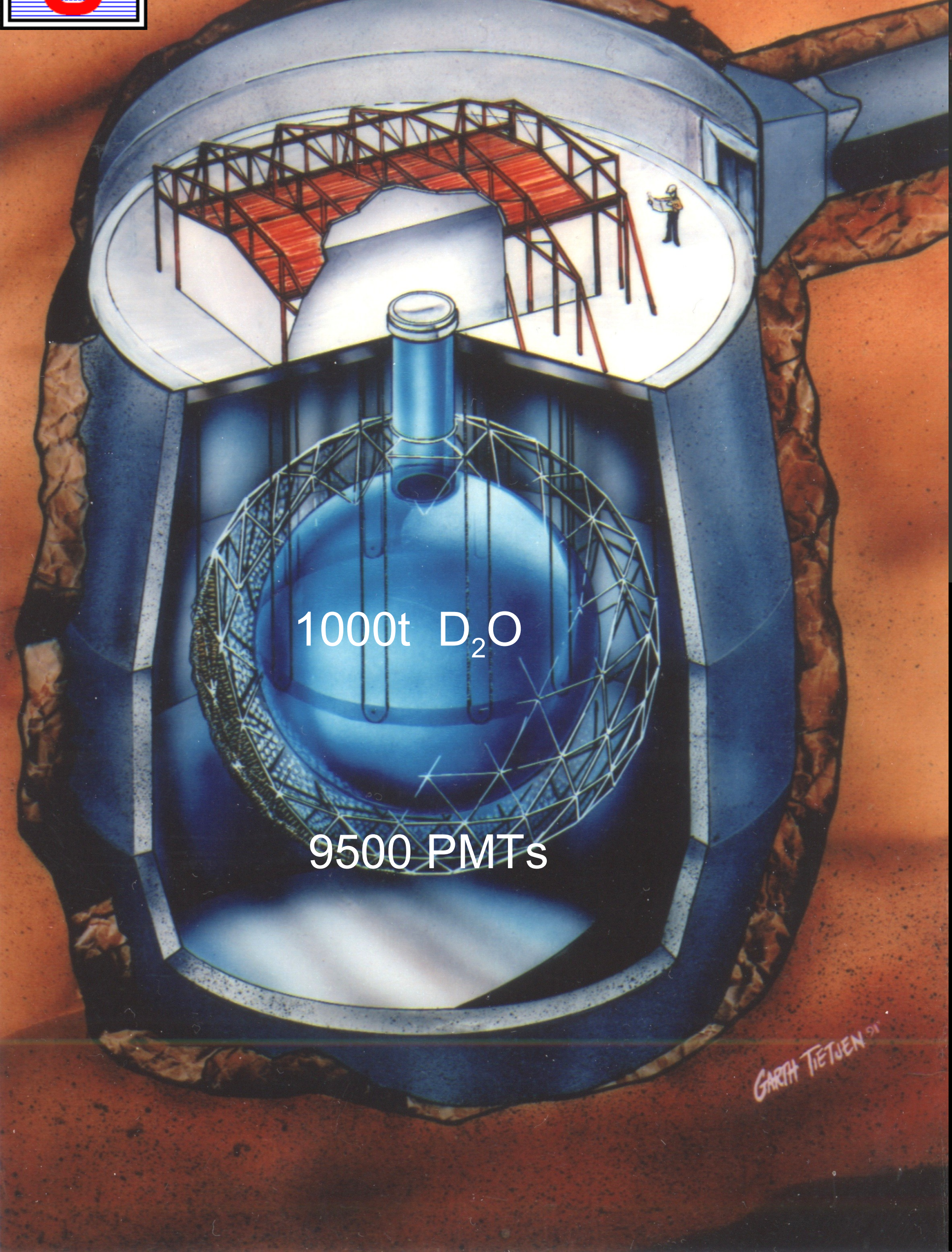
The solar neutrino puzzle



Status of solar neutrino oscillation spring 2000

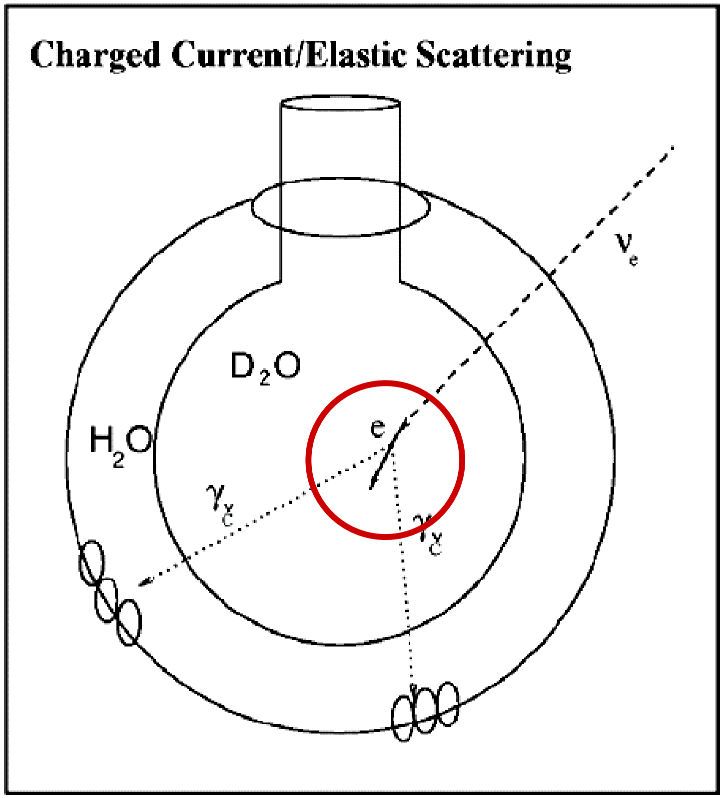


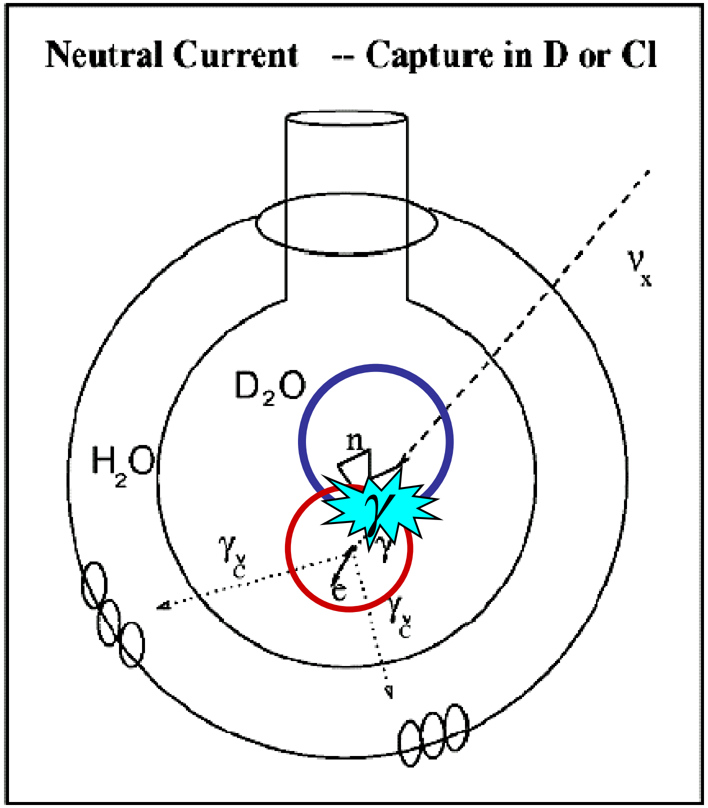
SNO: Sudbury Neutrino Observatory



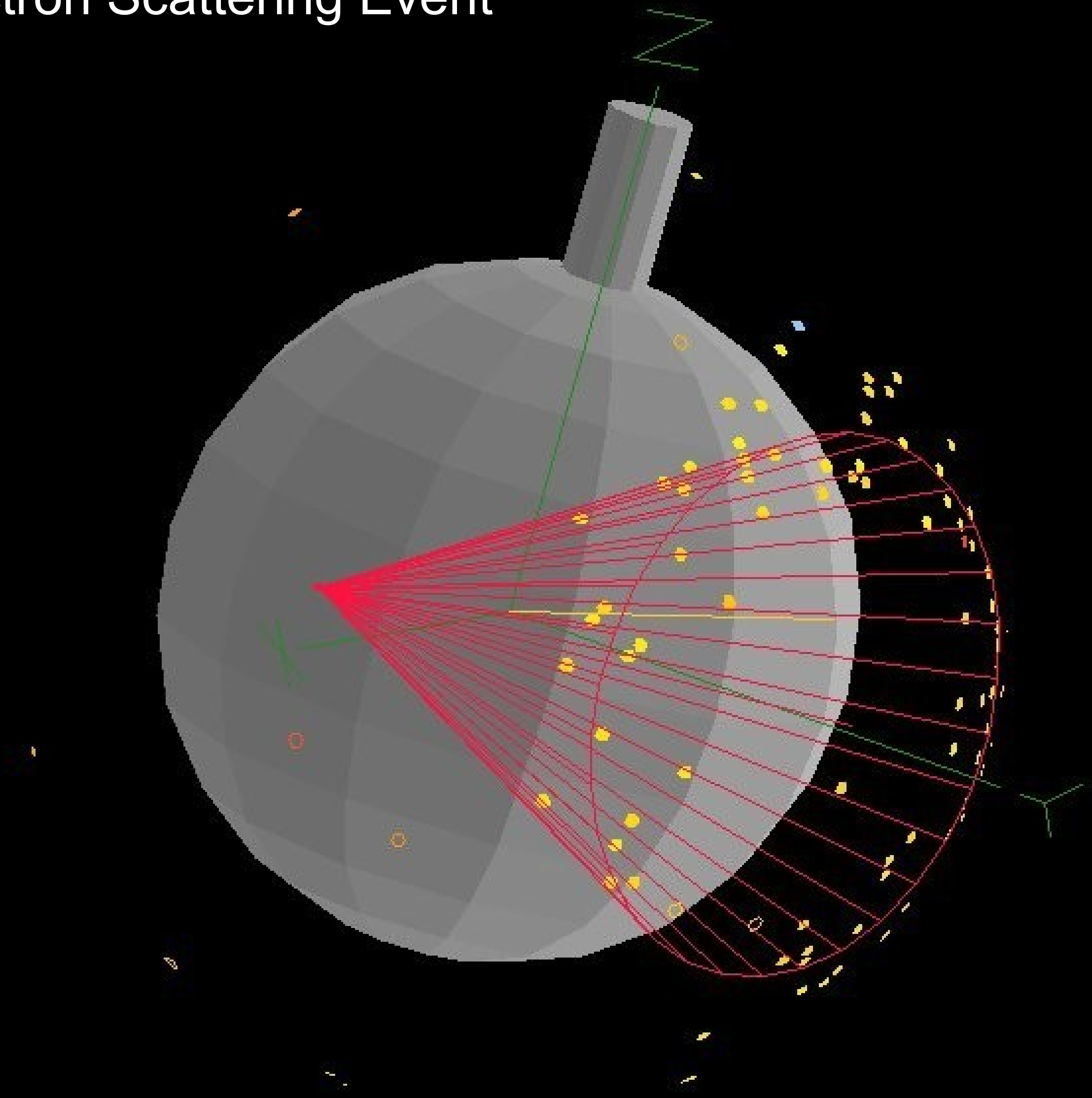
Neutrino detection in SNO

CC	$\nu_e + d \longrightarrow p + p + e^-$
ES	$\nu_e + e^- \longrightarrow \nu_e + e^-$
NC	$\nu_x + d \longrightarrow p + n + \nu_x$



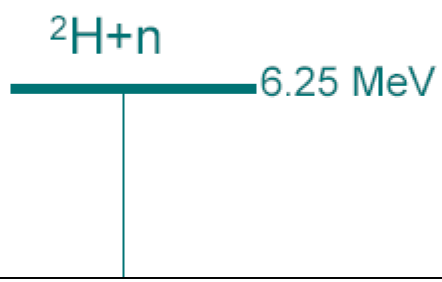


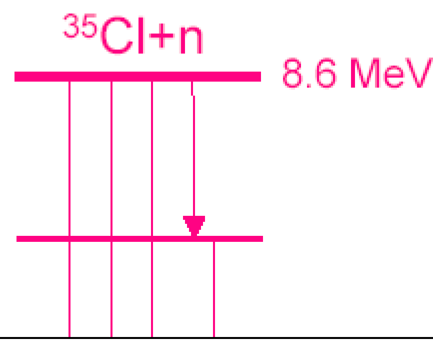
Neutrino - Electron Scattering Event

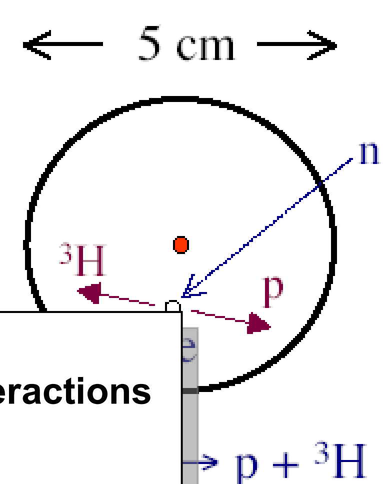


Neutron detction in SNO

Phase I (D_2O)	Phase II (salt)	Phase III (^3He)
Nov. 99 - May 01	July 01 - Sep. 03	Summer 04 - Dec. 06
n captures on $^2H(n, \gamma)^3H$	2 t NaCl. n captures on $^{35}Cl(n, \gamma)^{36}Cl$	40 proportional counters $^3He(n, p)^3H$
$\sigma = 0.0005$ b	$\sigma = 44$ b	$\sigma = 5330$ b
Observe 6.25 MeV γ	Observe multiple γ's	Observe p and ^3H
PMT array readout	PMT array readout	PC independent readout
Good CC	Enhanced NC	Event by Event Det.







Ergebnis der ersten Phase:
"Direct Evidence for Neutrino Flavor Transformation from Neutral-Current Interactions in the Sudbury Neutrino Observatory",
The SNO Collaboration Phys. Rev. Lett. volume 89, No. 1, 011301 (2002).

SNO results

„Independent Measurement of the Total Active 8B Solar Neutrino Flux Using an Array of 3He Proportional Counters at the Sudbury Neutrino Observatory“, SNO Collaboration, PRL 101, 111301 (2008):

CC	$\nu_e + d \longrightarrow p + p + e^-$
ES	$\nu_e + e^- \longrightarrow \nu_e + e^-$
NC	$\nu_x + d \longrightarrow p + n + \nu_x$

$$\phi_{CC}^{SNO} = 1.67^{+0.05}_{-0.04}(\text{stat})^{+0.07}_{-0.08}(\text{syst})$$

$$\phi_{ES}^{SNO} = 1.77^{+0.24}_{-0.21}(\text{stat})^{+0.09}_{-0.10}(\text{syst})$$

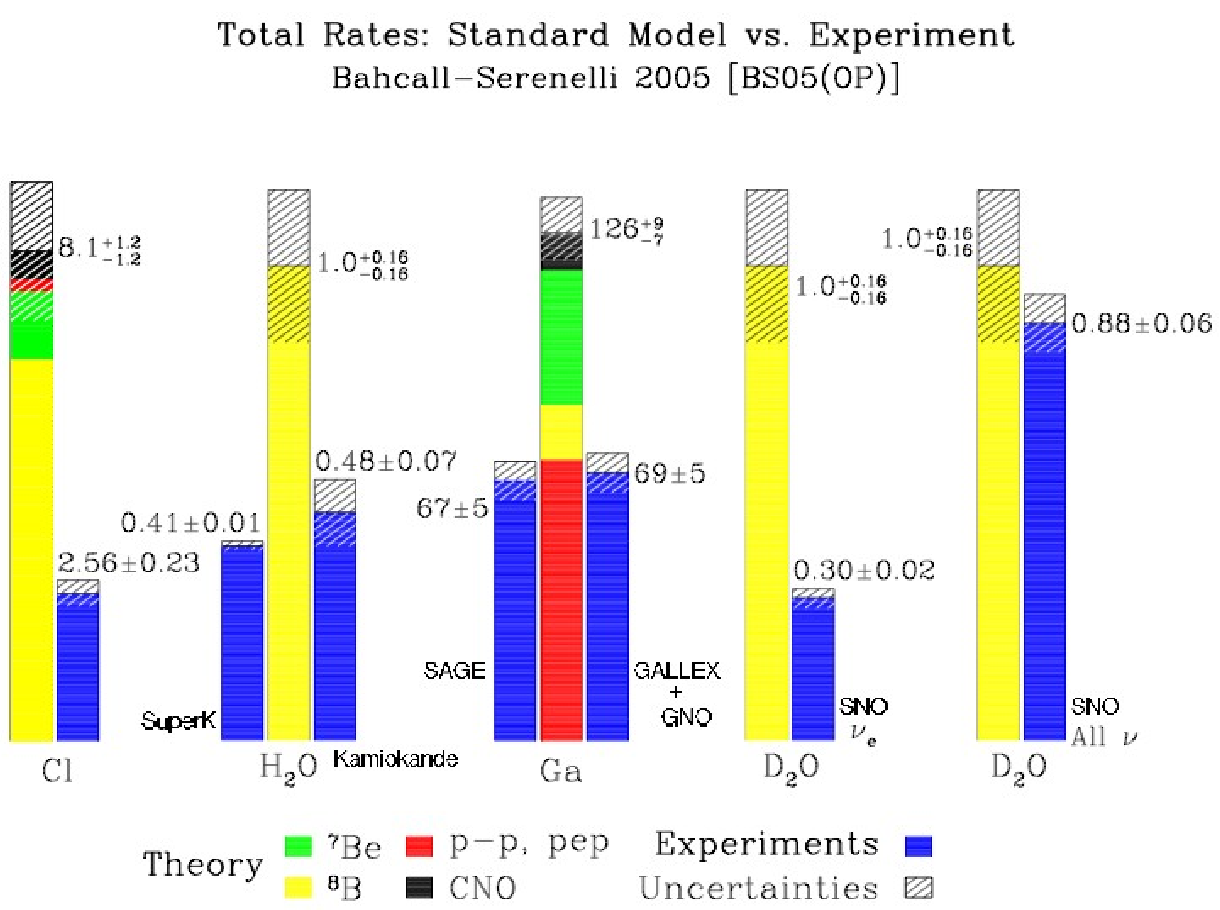
$$\phi_{NC}^{SNO} = 5.54^{+0.33}_{-0.31}(\text{stat})^{+0.36}_{-0.34}(\text{syst}),$$

(in units of $10^6\ \text{cm}^{-2}\,\text{s}^{-1}$)

$$\frac{\phi_{CC}^{SNO}}{\phi_{NC}^{SNO}} = 0.301 \pm 0.033(\text{total})$$

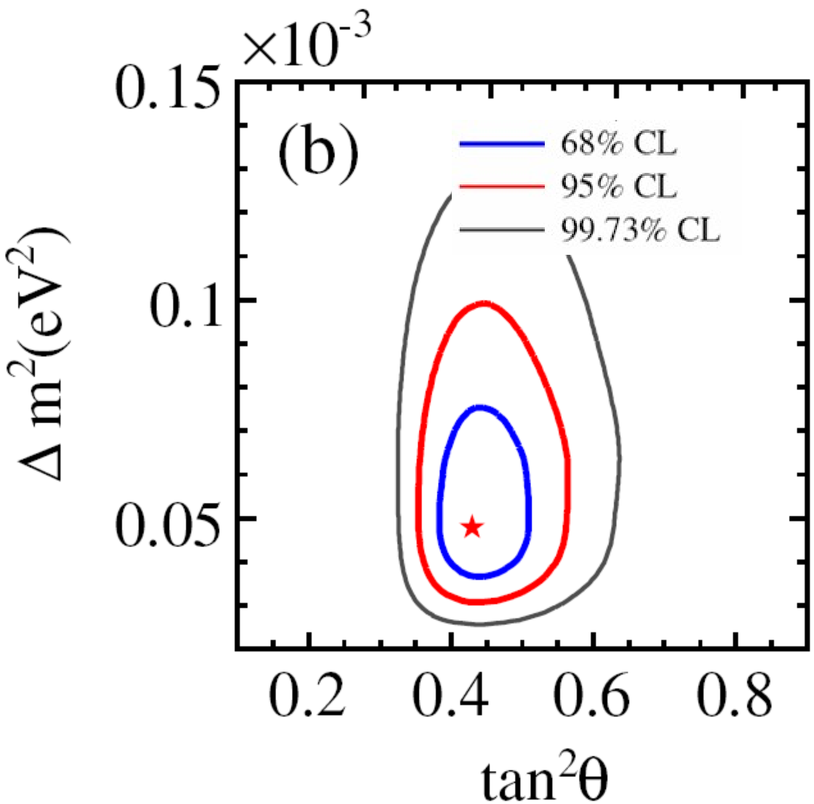
- 1/3 of solar neutrinos are detected as ν_e in SNO.
- 2/3 of solar neutrinos are detected as ν_μ or ν_τ in SNO.
- measured total neutrino flux = SSM predicted flux

Lösung des solaren Neutrinorätsels: Es liegt an den Neutrinos



Neutrino Oscillation Analysis (after SNO)

Global Analysis using data from
SNO, SK, Cl, Ga, Borexino



SNO coll., PRL 101, 111301 (2008)

Solution of the solar neutrino puzzle

Results are compatible with:

≈ 60% of pp, ^{7}Be neutrinos,

but

≈ 33% of ^{8}B neutrinos arrive on earth as ν_e

Explanation of results of solar neutrino experiments:

(≈60% of pp-neutrinos and ≈33% of ^8B neutrinos arrive on earth as ν_e)

- We assume:
  $\Delta m_{12}^2 = 8\cdot 10^{-5} eV^2$, $\theta_{12} \approx 33°$

- The probability of vacuum oscillations is then given by:

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta_{12} \sin^2 \underbrace{\left(1.27 \frac{\Delta m_{12}^2 / \mathrm{eV}^2 \cdot L/\mathrm{m}}{E/\mathrm{MeV}} \right)}_{\text{Phase } \delta}$$

$$\delta = 1.27 \frac{8 \cdot 10^{-5} \cdot 1.5 \cdot 10^{11}}{\text{values of } 0.1 - 10} = 10^{7\pm1}$$

The phase varies over a large range!

- Therefore the survival probability for solar neutrinos (in vacuum) is:

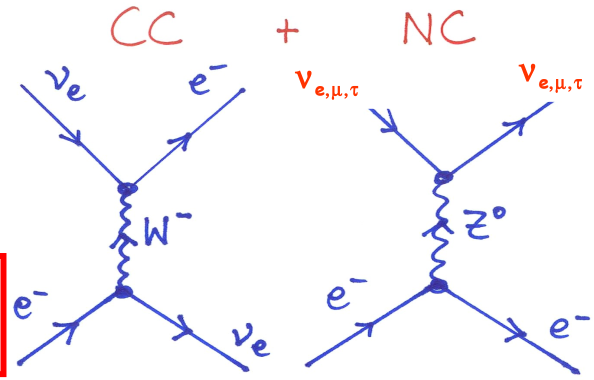
$$\langle P(\nu_e \to \nu_e) \rangle_{\text{averaging over phases}} = 1 - \tfrac{1}{2} \sin^2 2\theta_{12} \approx 0.6$$

This explains quite well the experimental results for pp-neutrinos

But this is independent of energy!
→ Therefore we need another effect to explain why only 33% of ^8B neutrinos arrive…

Neutrino propagation in matter – MSW (Mikheyev, Smirnov, Wolfenstein) Effect

Origin: ν_e and $\nu_{\mu,\tau}$ have different interaction with matter
(ν_e can undergo CC and NC reaction, $\nu_{\mu,\tau}$ only NC!)



Only elastic forward scattering of neutrinos is relevant

In matter: $+4E\sqrt{2}G_F N_e$

Vacuum:
$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}=\frac{1}{4E}\begin{pmatrix}-\Delta m^2\cos 2\theta & \Delta m^2\sin 2\theta\\ \Delta m^2\sin 2\theta & \Delta m^2\cos 2\theta\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

In matter there is an additional potential in the equation of motion for ve → ve scattering (Flavor base)

Matter:
$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}=\frac{1}{4E}\begin{pmatrix}-\Delta m^2\cos 2\theta+2\sqrt{2}G_F N_e E & \Delta m^2\sin 2\theta\\ \Delta m^2\sin 2\theta & \Delta m^2\cos 2\theta-2\sqrt{2}G_F N_e E\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

with
$$2\sqrt{2}G_F \underbrace{N_e}_{\frac{Y_e\rho}{m}} E = 1.53\cdot 10^{-7}\,\mathrm{eV}^2\left(\frac{Y_e\rho}{\mathrm{g/cm}^3}\cdot\frac{E}{\mathrm{MeV}}\right)$$

center of Sun: $\frac{Y_e\rho}{\mathrm{g/cm}^3}\cong 100$

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}=\frac{1}{4E}\begin{pmatrix}-\Delta m^2\cos 2\theta+2\sqrt{2}G_F N_e E & \Delta m^2\sin 2\theta\\ \Delta m^2\sin 2\theta & \Delta m^2\cos 2\theta-2\sqrt{2}G_F N_e E\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

can be written as:

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}=\frac{1}{4E}\begin{pmatrix}-\Delta m_m^2\cos 2\theta_m & \Delta m_m^2\sin 2\theta_m\\ \Delta m_m^2\sin 2\theta_m & \Delta m_m^2\cos 2\theta_m\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

where $\Delta m_m^2 = m_2^2 - m_1^2$ and θ_m, denote the “effective” masses and mixing angles in matter and:

$$\Delta m_m^2\cos 2\theta_m = \Delta m^2\cos 2\theta - 2\sqrt{2}G_F N_e E$$
$$\Delta m_m^2\sin 2\theta_m = \Delta m^2\sin 2\theta$$

Solving these equations gives:

$$\Delta m_m^2 = \sqrt{\left(\Delta m^2\cos 2\theta - 2\sqrt{2}G_F N_e E\right)^2 + \left(\Delta m^2\sin 2\theta\right)^2}$$
$$\sin 2\theta_m = \frac{\sin 2\theta}{\sqrt{\left(\frac{2\sqrt{2}G_F N_e E}{\Delta m^2} - \cos 2\theta\right)^2 + \left(\sin 2\theta\right)^2}}$$

Neutrino propagation in matter: 3 regimes

1. Quasi – vacuum: $2\sqrt{2}G_F N_e E \ll \Delta m^2 \cos 2\theta$ pp, ^{7}Be Neutrinos

$$\Delta m_m^2 \cong \Delta m^2, \qquad \theta_m \cong \theta$$

2. Resonance: $2\sqrt{2}G_F N_e E = \Delta m^2 \cos 2\theta$

(Mikheyev, Smirnov 1985)

$$\Delta m_m^2 = \Delta m^2 \sin^2 2\theta$$

$$\theta_m = \tfrac{\pi}{4} \quad \left(45^\circ\right)$$

3. Matter dominated: $2\sqrt{2}G_F N_e E \gg \Delta m^2 \cos 2\theta$ ^{8}B Neutrinos

$$\Delta m_m^2 \to 2\sqrt{2}G_F N_e E$$

$$\theta_m \to \tfrac{\pi}{2} \quad \left(90^\circ\right)$$

Neutrino mixing in matter:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_m & \sin\theta_m \\ -\sin\theta_m & \cos\theta_m \end{pmatrix} \begin{pmatrix} \nu_{1m} \\ \nu_{2m} \end{pmatrix}$$

and

$$\begin{pmatrix} \nu_{1m} \\ \nu_{2m} \end{pmatrix} = \begin{pmatrix} \cos\theta_m & -\sin\theta_m \\ \sin\theta_m & \cos\theta_m \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

^{8}B neutrinos at center of Sun:
θ_m = 73°,
with:
$\Delta m_{12}^2 = 8\cdot10^{-5}$eV^2,
$\theta_{12} \approx 33°$,
$Y\rho \approx 90$g/cm^3.

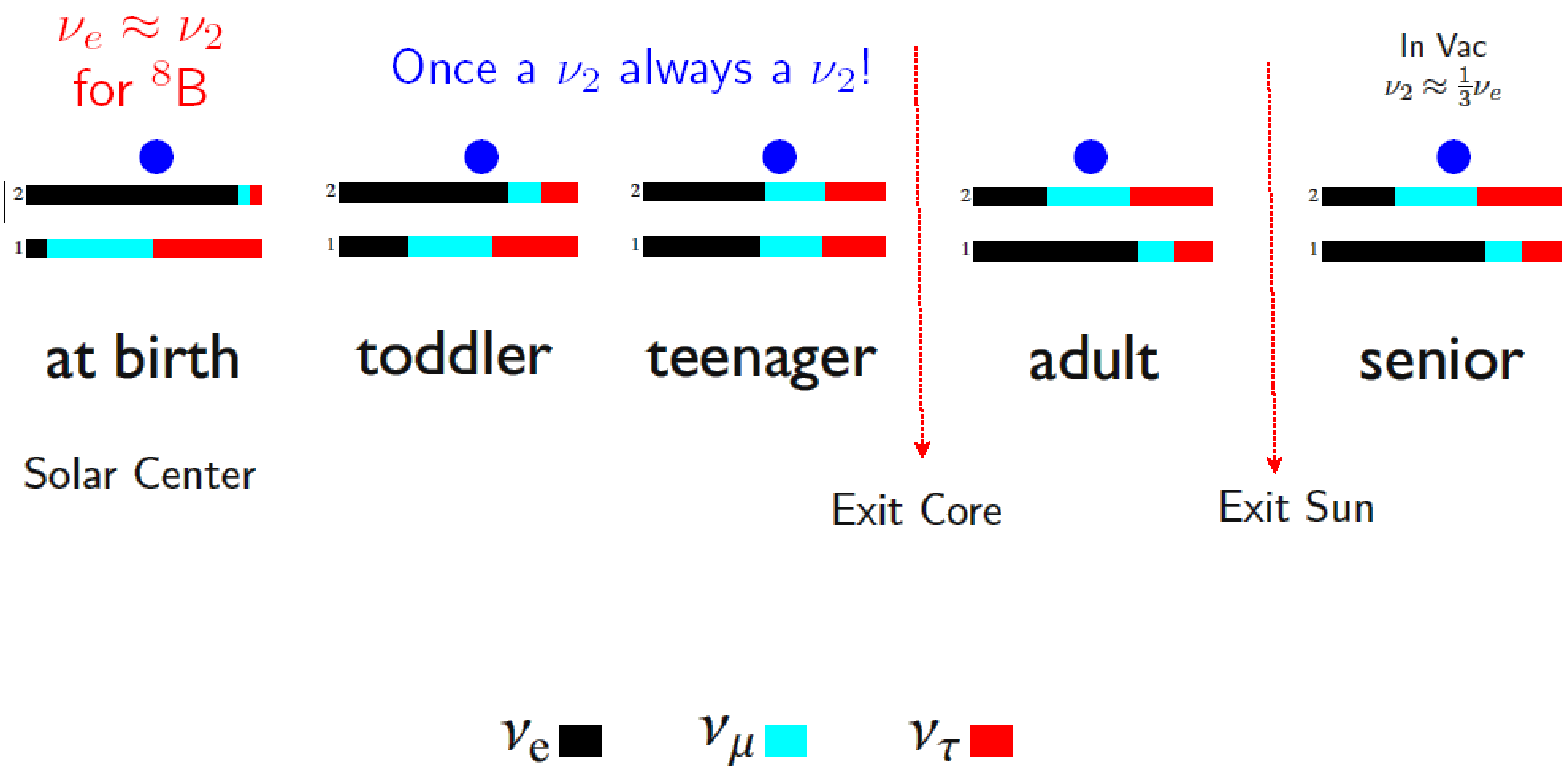
For ^{8}B neutrinos at the center of Sun:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos 73^\circ & \sin 73^\circ \\ -\sin 73^\circ & \cos 73^\circ \end{pmatrix} \begin{pmatrix} \nu_{1m} \\ \nu_{2m} \end{pmatrix}$$

The probability that the created ν_e is in the state ν_{2m} is then given by $\sin^2(73°)$ = 91%!

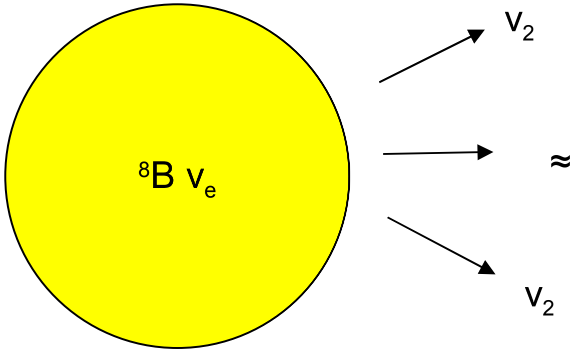
On its way through the Sun, the neutrino is with a constant probability of 91% in the state ν_{2m}.
But the composition of ν_{2m} from ν_e and ν_μ changes with the varying density.

Life of a Boron-8 Solar Neutrino:

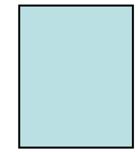


From Stephen Parke http://boudin.fnal.gov/AcLec/AcLecParke.html (part1)

Explanation of ^8B solar neutrino results with matter effect



≈ only ν_2 leave the Sun (91%)



the detector observes the amount of ν_e in ν_2

The probabilty that a ^8B neutrino is detected as ν_e is then given by:

$$\langle P(\nu_e \rightarrow \nu_e) \rangle_{\text{incoherent}} = f_1 \cos^2\theta + f_2 \sin^2\theta$$

where:

f_1 = probability that a neutrino leaving the Sun is in the state ν_1 = $\cos^2(73^o)$ = 0.09.

f_2 = probability that a neutrino leaving the Sun is in the state ν_2 = $\sin^2(73^o)$ = 0.91.

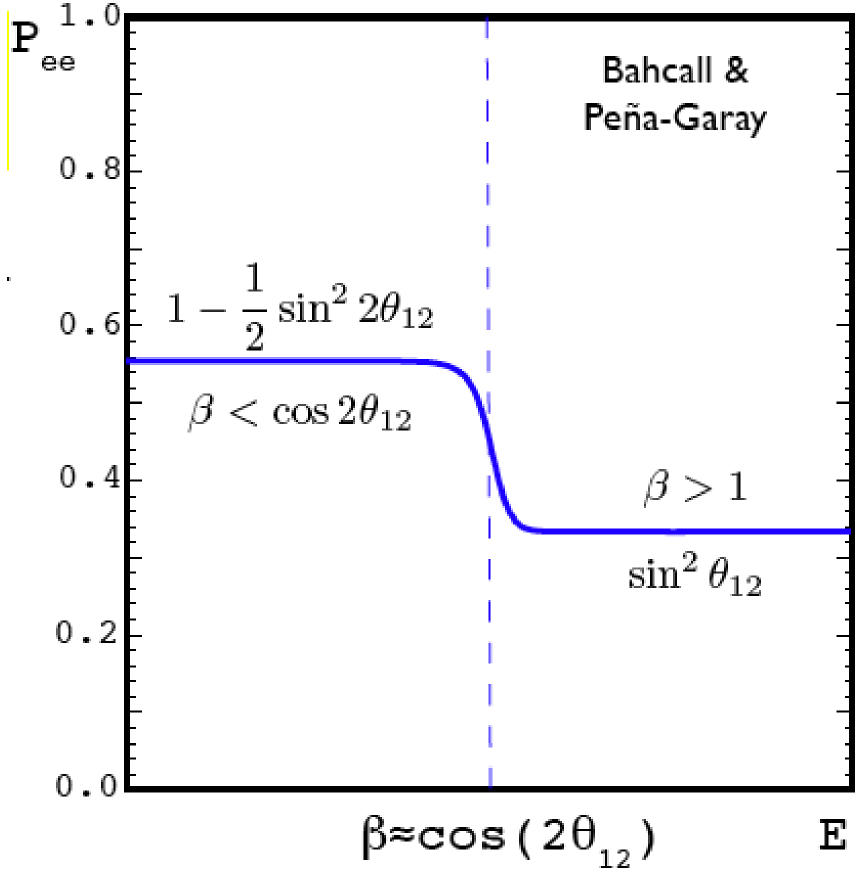
$\cos^2\theta$ = probability that ν_1 contains the state ν_e = $\cos^2(33^o)$ = 0.70.

$\sin^2\theta$ = probability that ν_2 contains the state ν_e = $\sin^2(33^o)$ = 0.30.

$$\langle P(\nu_e \rightarrow \nu_e) \rangle_{\text{incoherent}} = 0.09 \cdot 0.70 + 0.91 \cdot 0.30 = 0.336$$

This is exactly what we observe in SNO and Super-K for ^8B neutrinos!

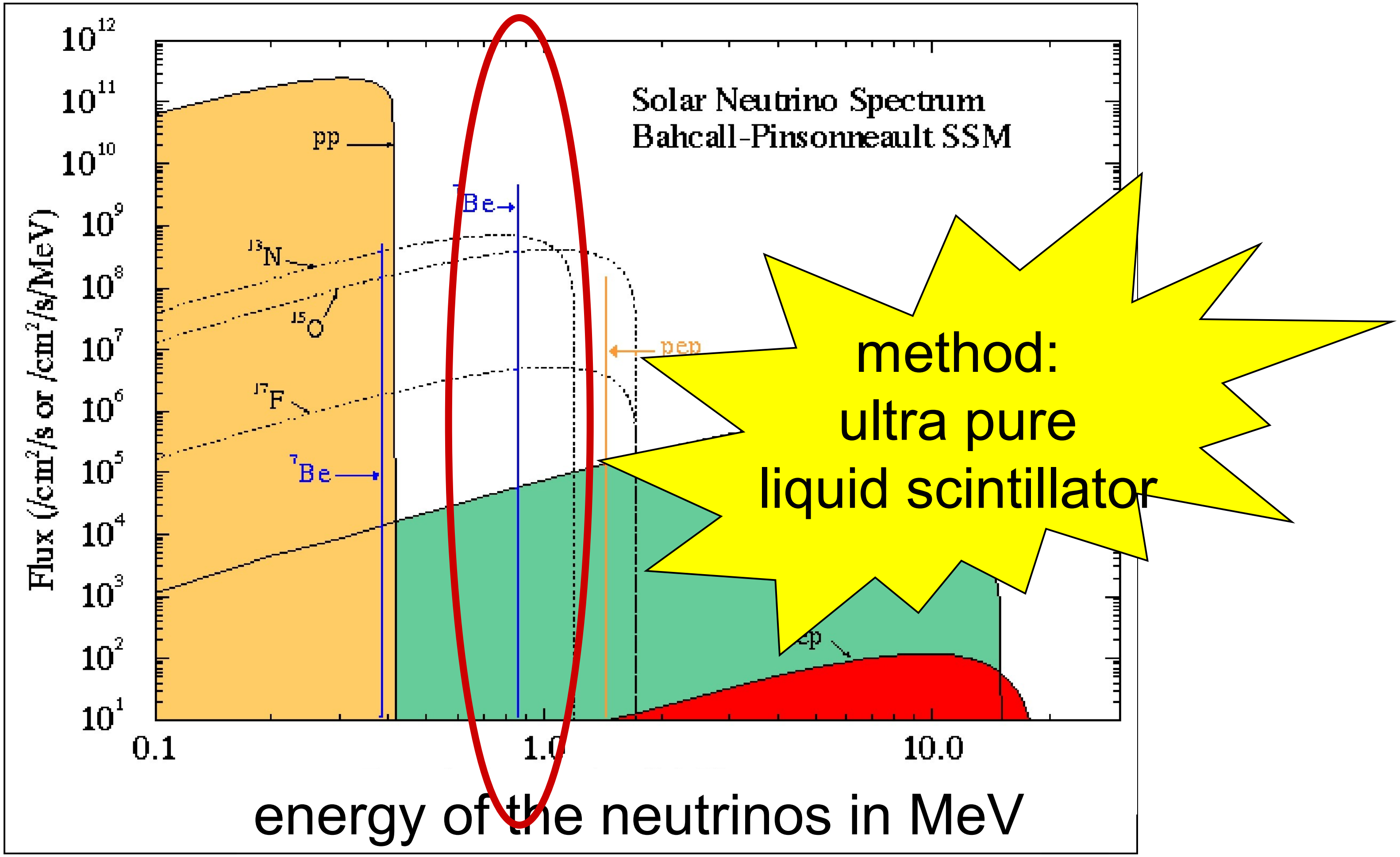
„Survival probability“ of a solar neutrino



$$\beta = \frac{2^{3/2} G_F N_e E}{\Delta m^2} = 0.22 \left[\frac{E}{1\ \mathrm{MeV}}\right] \left[\frac{\rho \cdot Z/A}{100\ \mathrm{g\ cm^{-3}}}\right] \left[\frac{7 \times 10^{-5}\ \mathrm{ev}^2}{\Delta m^2}\right]$$

$$E[\mathrm{MeV}] = 6.8 \times 10^6 \frac{\cos(2\theta_{12}) \Delta \mathrm{m}^2_{12}[\mathrm{eV}^2]}{\rho[\mathrm{g/cm}^3]\mathrm{Z/A}} \simeq 1\text{–}2\ \mathrm{MeV}$$

The new generation of solar neutrino experiments

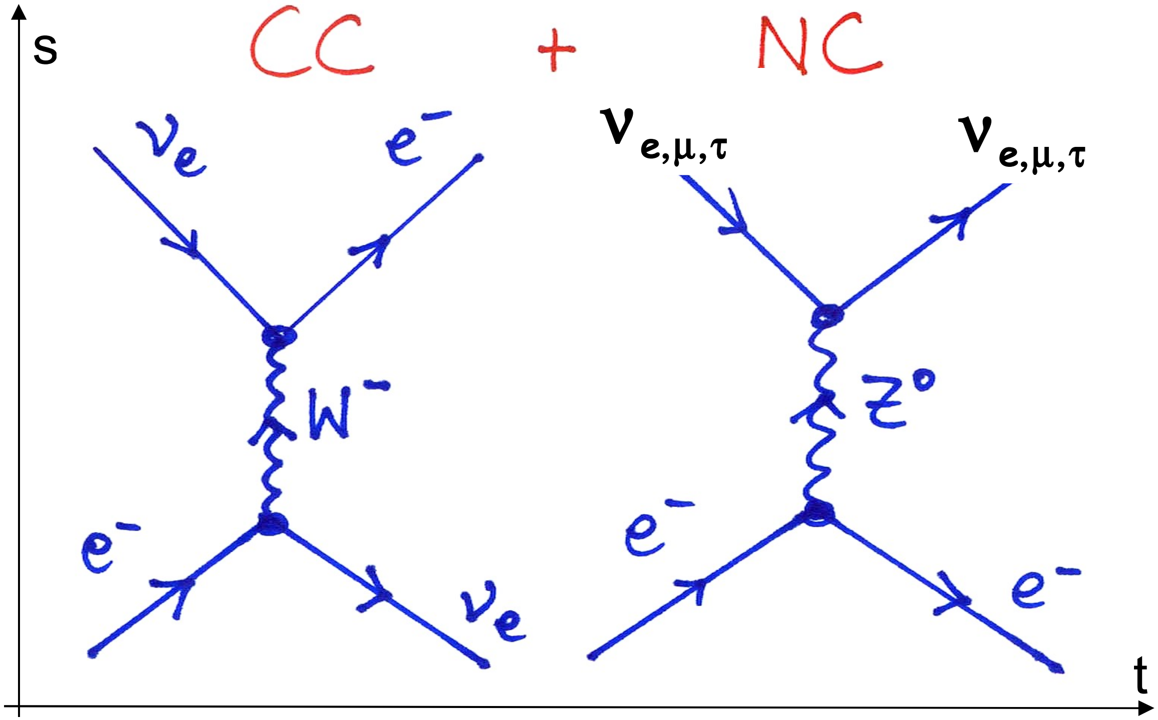


^{7}Be: E_ν = 860 keV, monoenergetic line

Detection of solar neutrinos in BOREXINO: Elastic neutrino – electron scattering

$$\nu_x + e^- \rightarrow \nu_x + e^-$$ (dominated by ν_e)

(Kinematics like Compton effect)

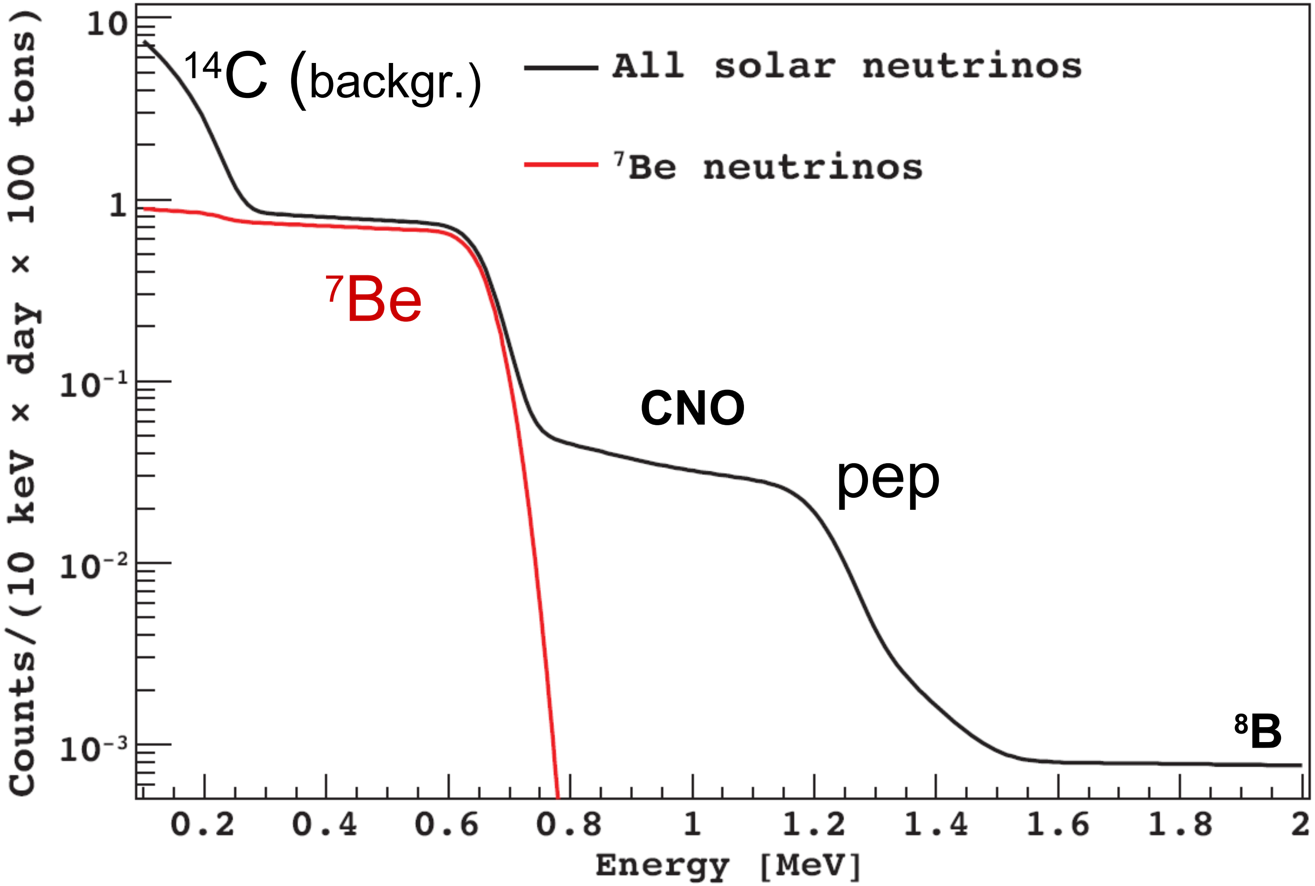


ν_e can interact via CC + NC

ν_μ and ν_τ can only interact via NC!

BOREXINO

Expected (electron) energy distribution:

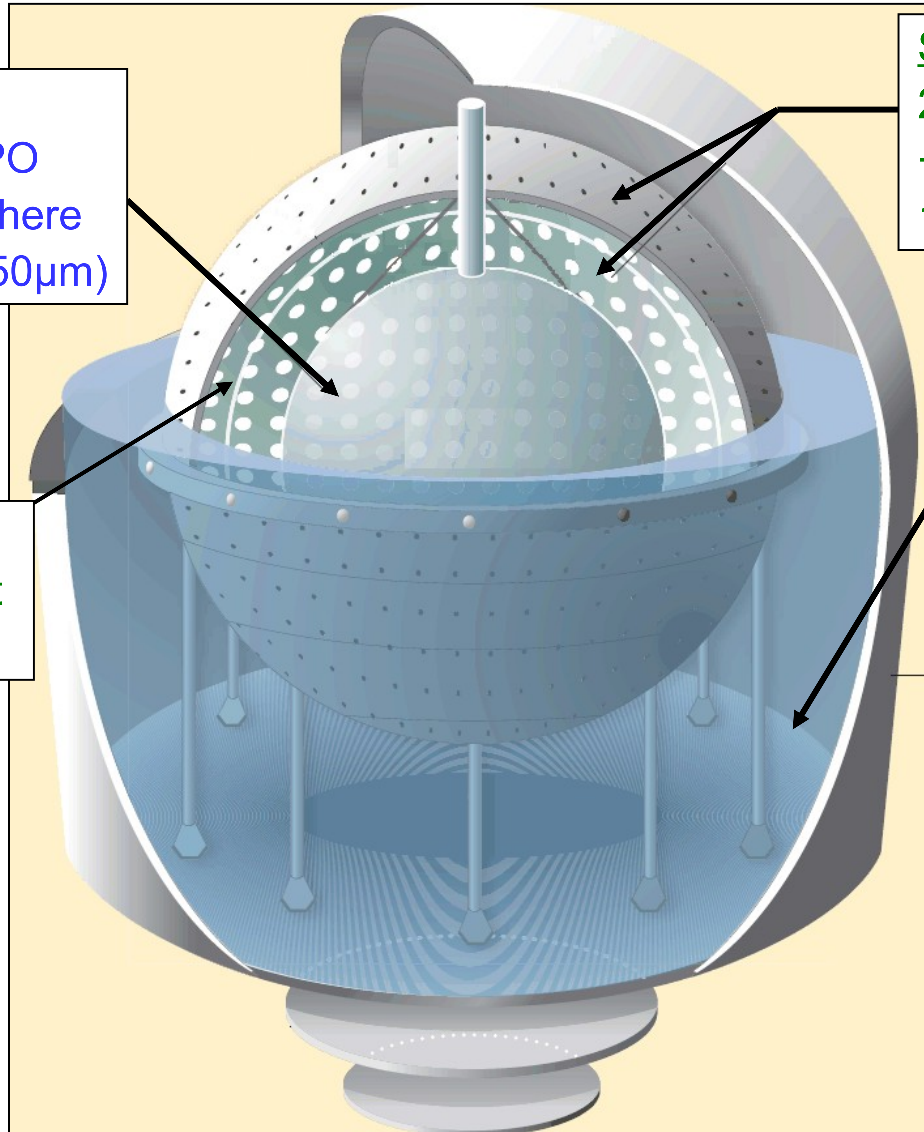


Edge at 665 keV

BOREXINO Detector

Scintillator:
300 t PC+PPO
in a nylon sphere
(thickness 150µm)

Stainless steel sphere:
2212 PMTs
+light concentrators
1350 m³



Radon barrier:
Nylon membrane at
5.50 m

Water:
γ and n shielding,
water Č detector
208 PMTs
2100 m³

Excellent shielding against external background

Increasing purity of materials from outside to center

Untergrund in Borexino

Erwartetes Signal (mit Neutrinomischung): ca. 50 cpd/100t

- **^{14}C Gehalt des Flüssigszintillators:**
  $^{14}C/^{12}C < 10^{-18}$

- **Radioaktive Nuklide aus den natürlichen Zerfallsketten**:
  Gehalt an U238 (< 10^{-16}g/g) , Th232 (< 10^{-16}g/g), K40 (< 10^{-14}g/g)
  muss extrem gering sein, dann Beitrag jeweils nur 1cpd/100t.
  Besonders wichtig: Rn muss vermieden werden!

- **Untergrund durch Kr85**:
  Spaltprodukt (Kernreaktoren), Edelgas, $T_{1/2}$=10.756y, $Q(\beta^-)$=687 keV
  (Beitrag ca. 22 cpd/100t)

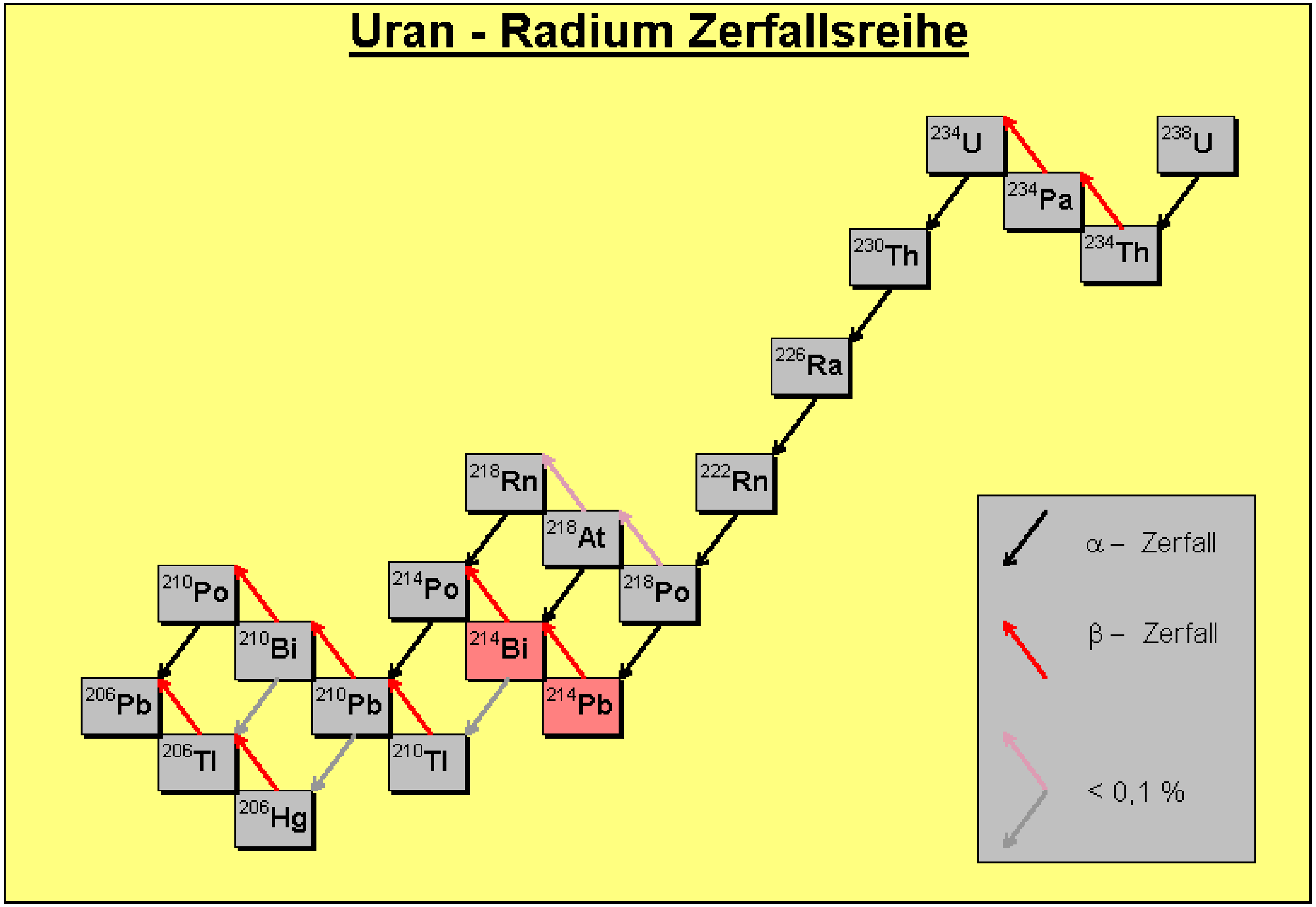
- **Kosmogener Untergrund**:
  Durch kosmische Myonen und sekundäre Schauerteilchen können aus ^{12}C instabile Radionuklide gebildet werden.
  Deren Zerfall kann ein Neutrinoereignis simulieren.

  Besonders wichtig:
  ^{7}Be (EC, $T_{1/2}$=53d, in 10% E_γ =478keV) (Beitrag ca. 0.3 cpd/100t)
  ^{11}C (β^+, $T_{1/2}$=20min, E=960keV) (Beitrag ca. 7 cpd/100t)

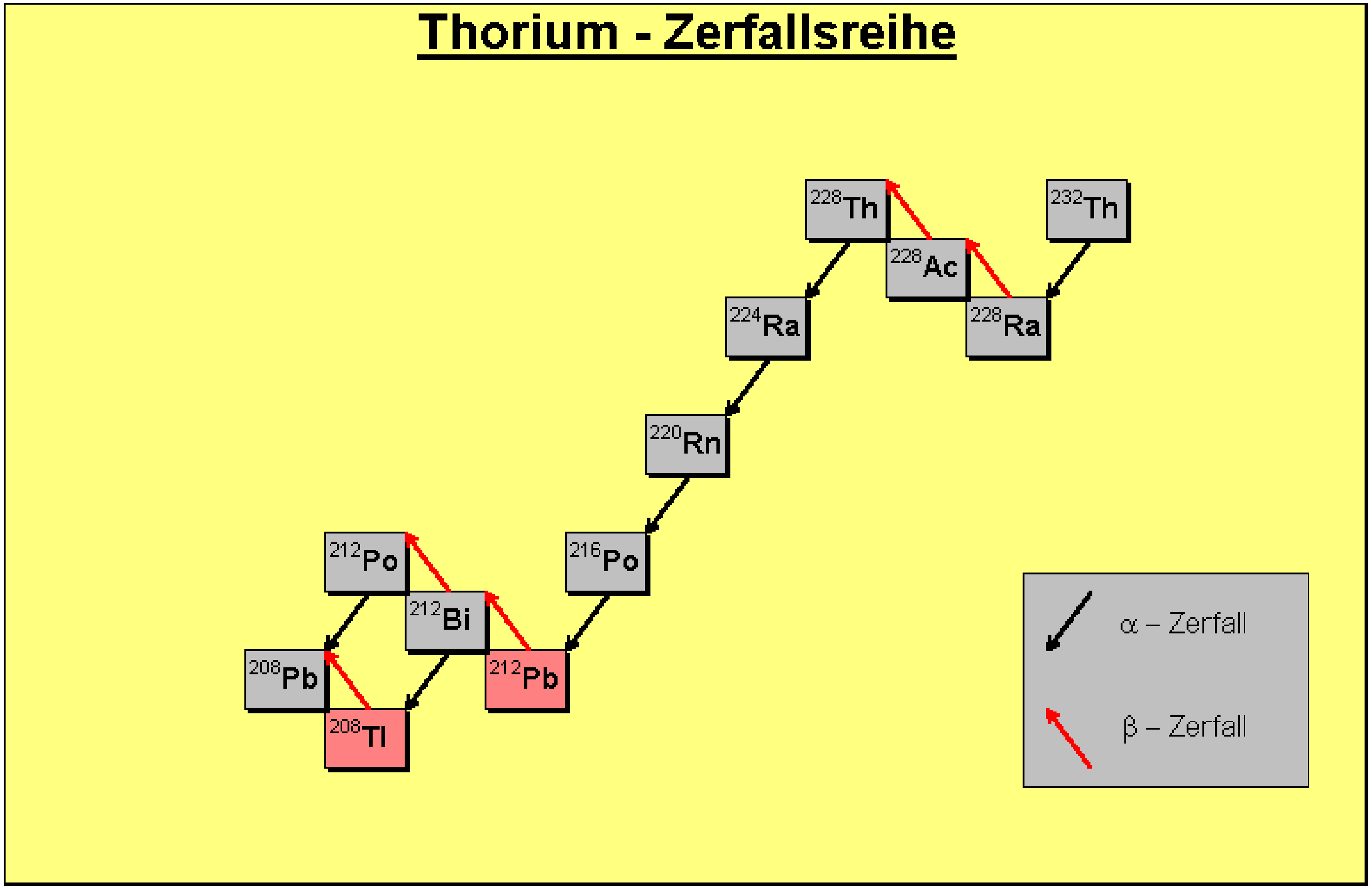
Natürliche Zerfallsketten

Name	Typ	Endkern	Startkern (langlebigster Kern)	$T_{1/2}$ (Startk.) in Jahren
Thorium	4n	^{208}Pb	^{232}Th	1.41×10^{10}
~~Neptunium~~	~~4n+1~~ **ausgestorben**	~~^{209}Bi~~	~~^{237}Np~~	~~2.14×10^{6}~~
Uran	4n+2	^{206}Pb	^{238}U	4.47×10^{9}
Actinium	4n+3	^{207}Pb	^{235}U	7.04×10^{8}

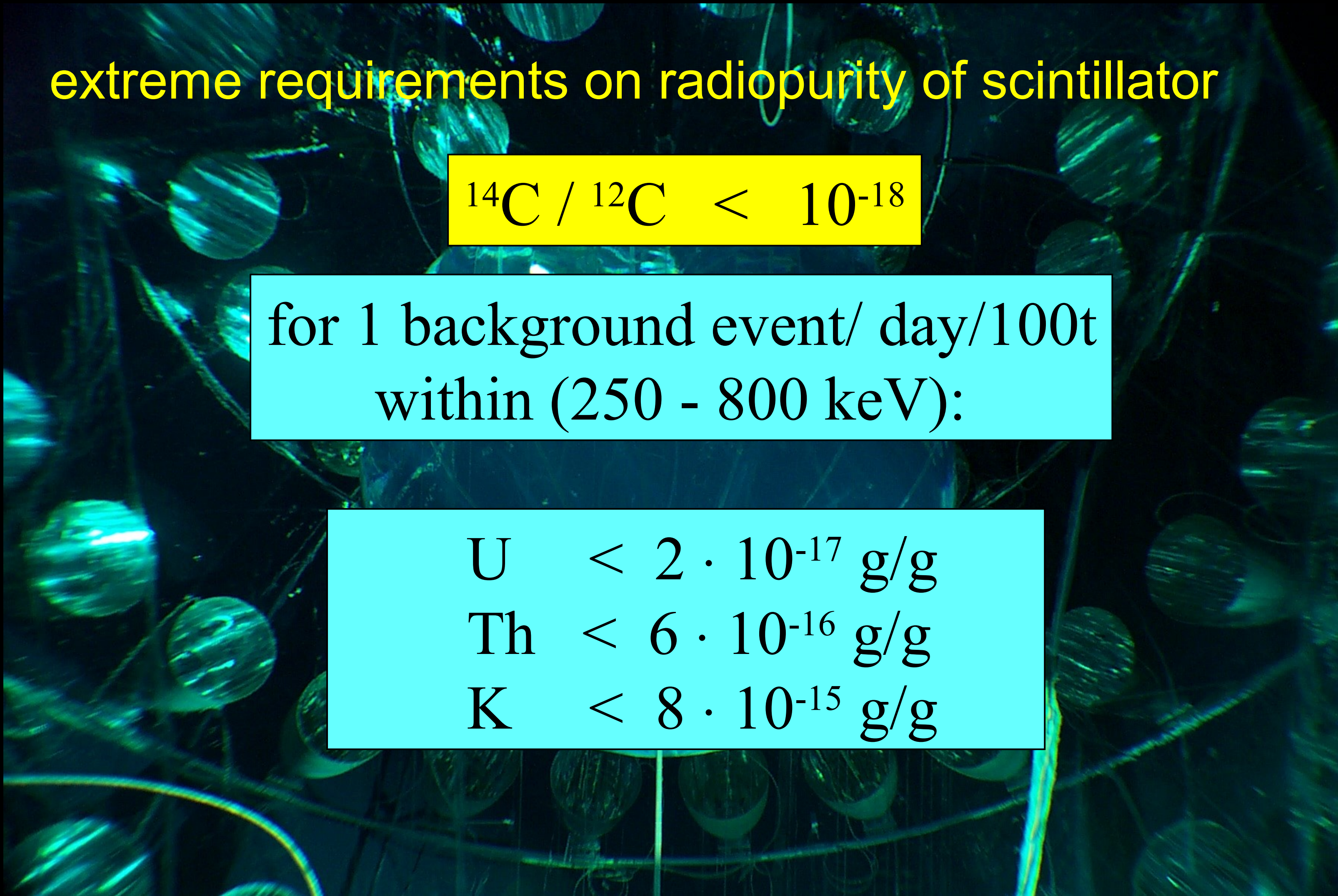
Uran Zerfallsreihe



Thorium Zerfallskette



Technical challenge for Borexino & KamLAND



extreme requirements on radiopurity of scintillator

$^{14}C\ /\ ^{12}C\ <\ 10^{-18}$

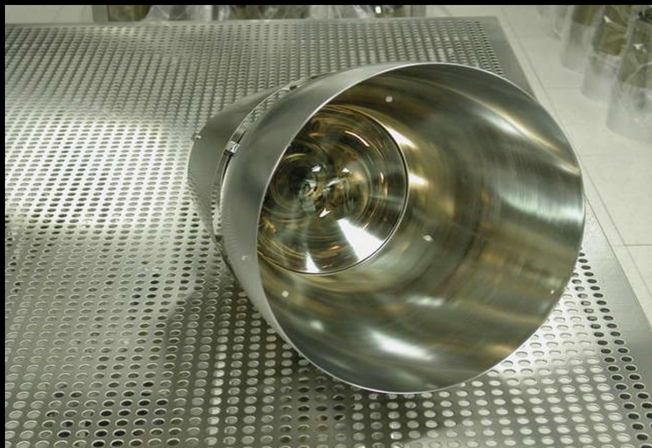
for 1 background event/ day/100t
within (250 - 800 keV):

$U < 2 \cdot 10^{-17}$ g/g

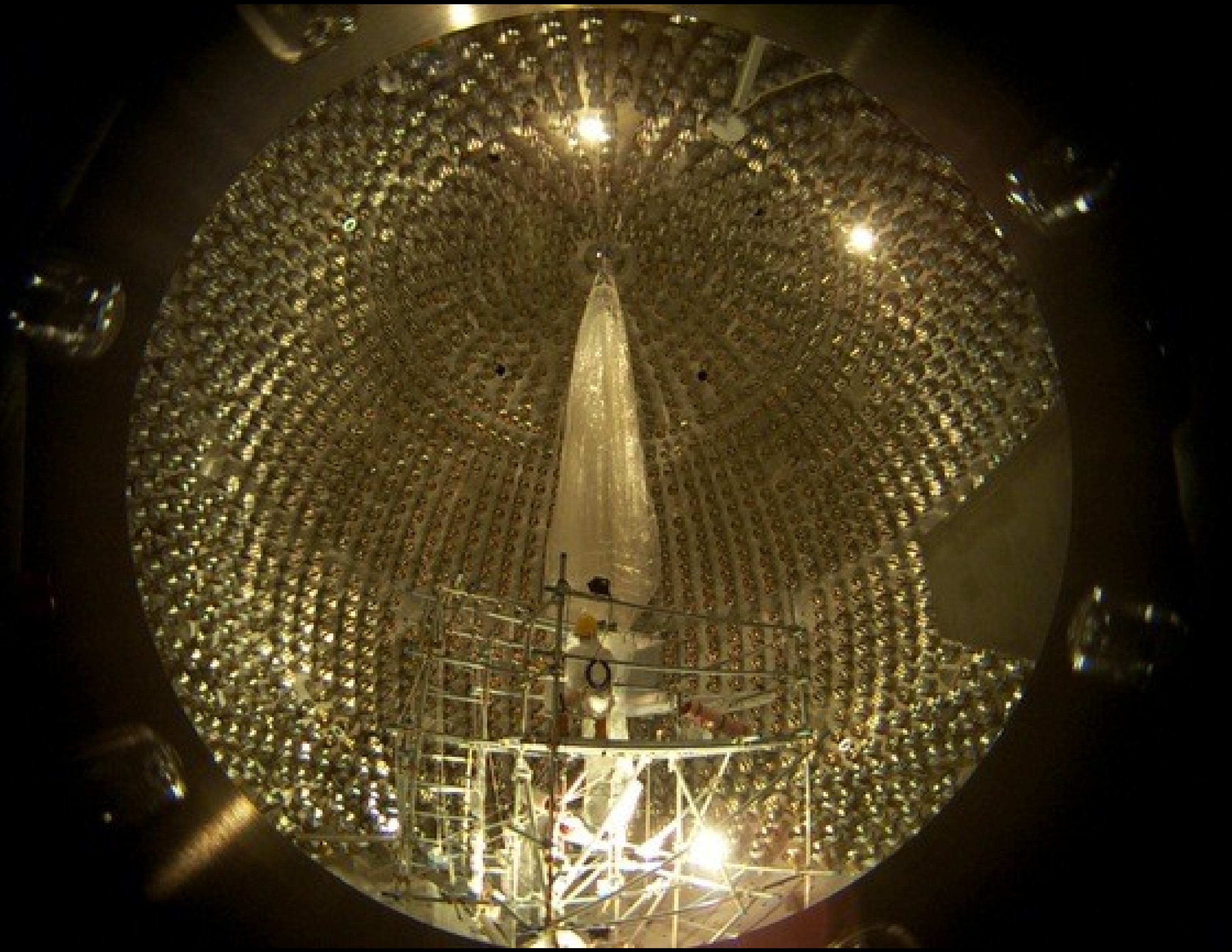
$Th < 6 \cdot 10^{-16}$ g/g

$K < 8 \cdot 10^{-15}$ g/g

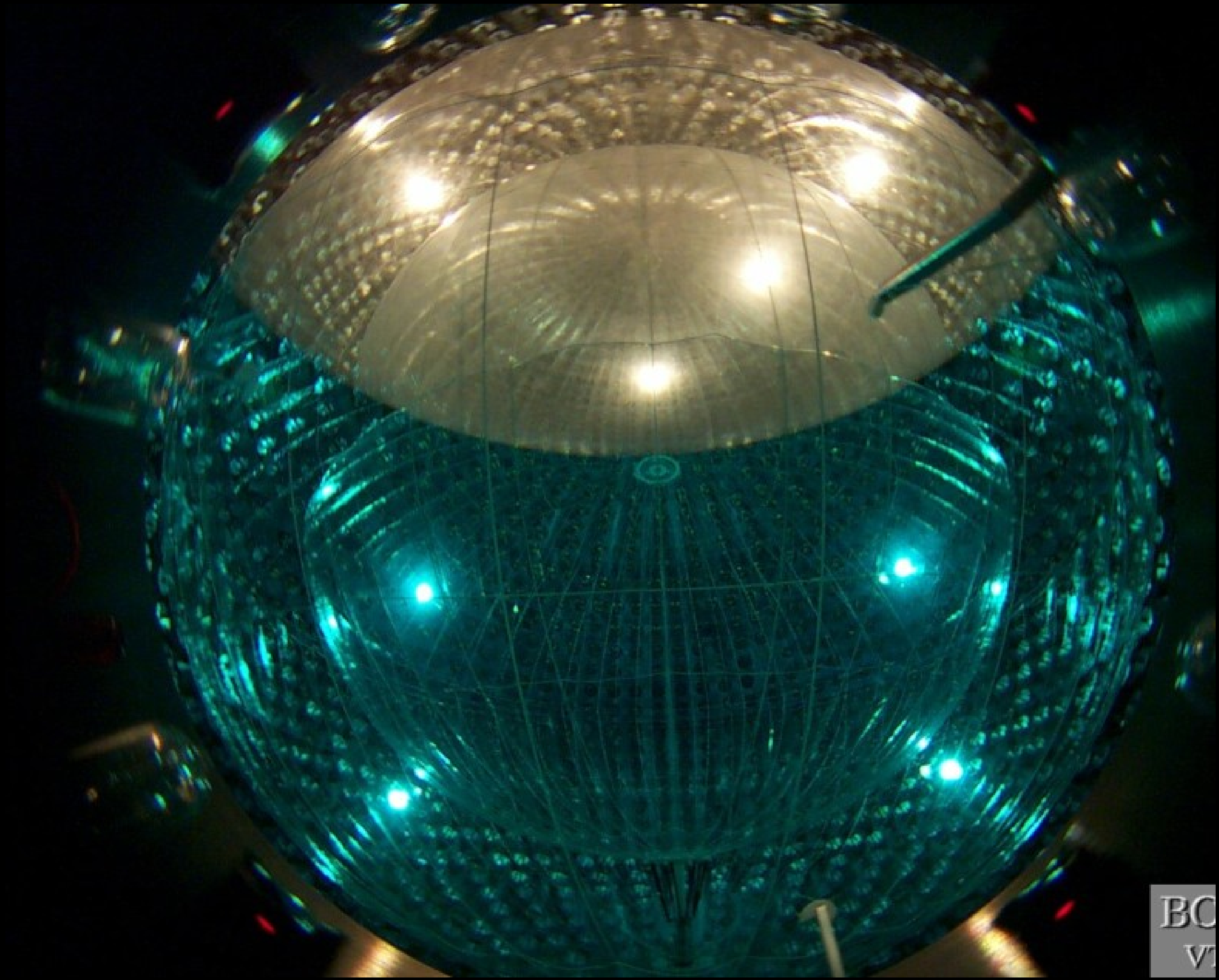
Mounting of Borexino photomultipliers with light concentrators



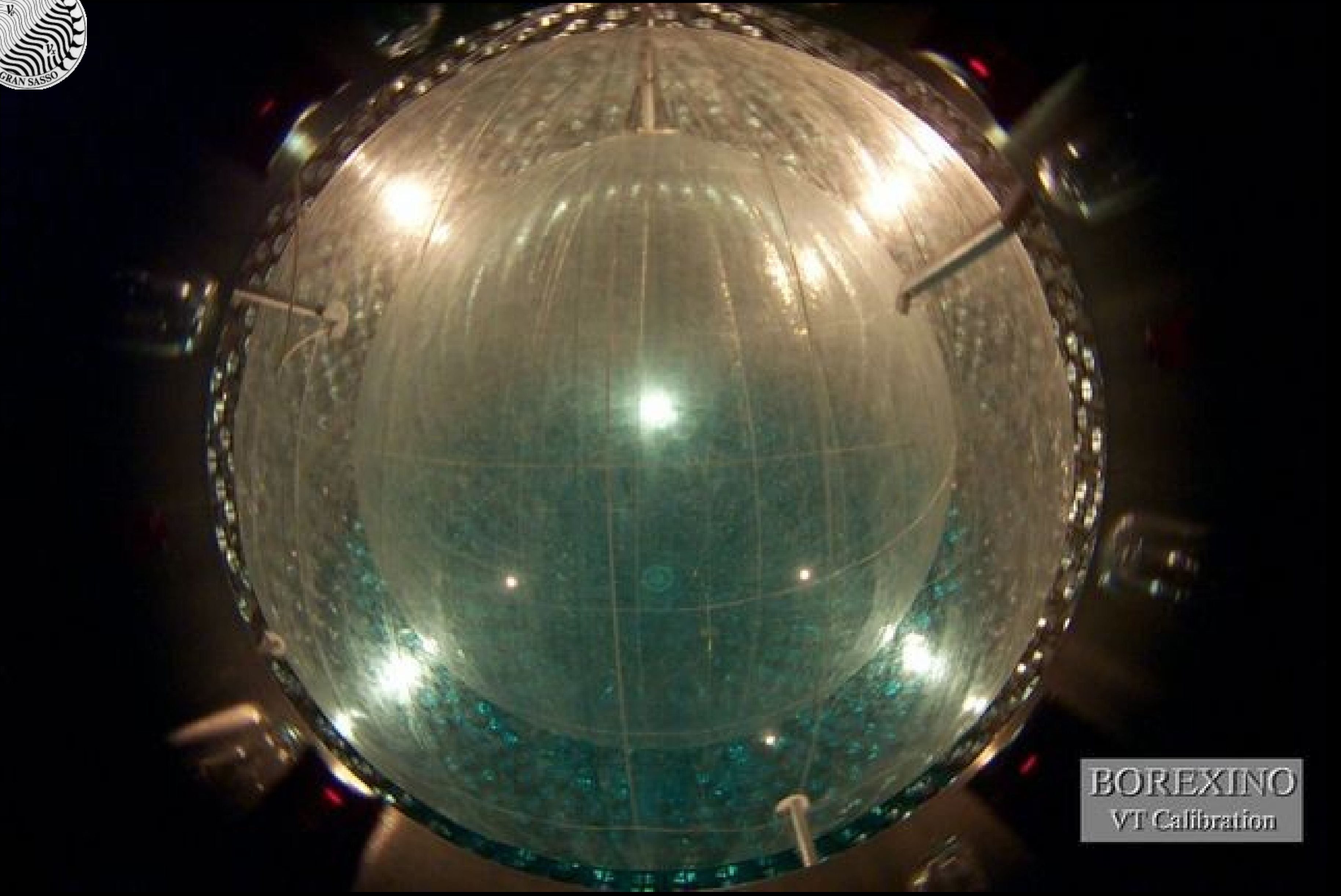
BOREXINO GRAN SASSO



Installation of the 2 inner nylon spheres

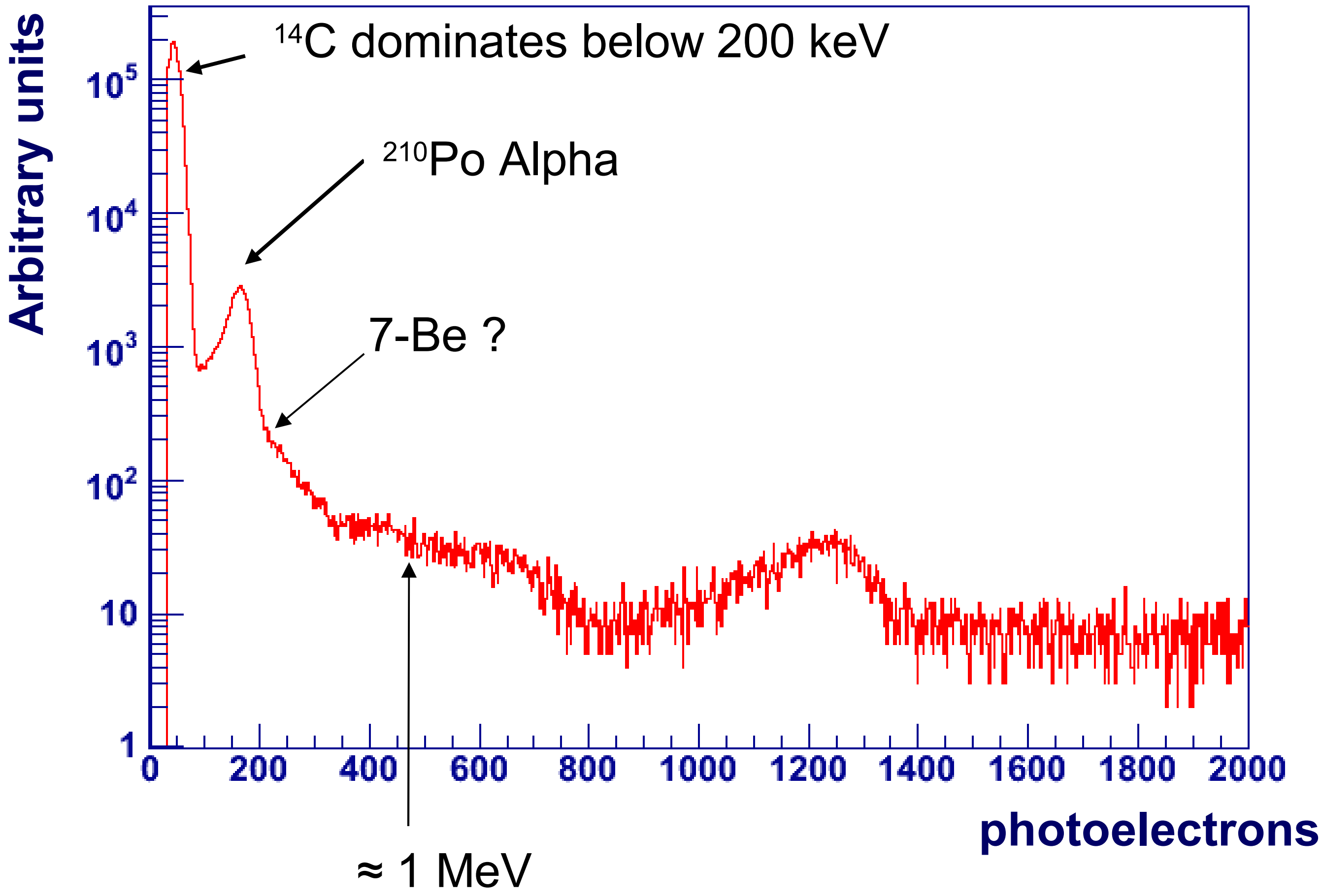


Borexino during filling phase (scintillator in upper part, ultra pure water in lower part)

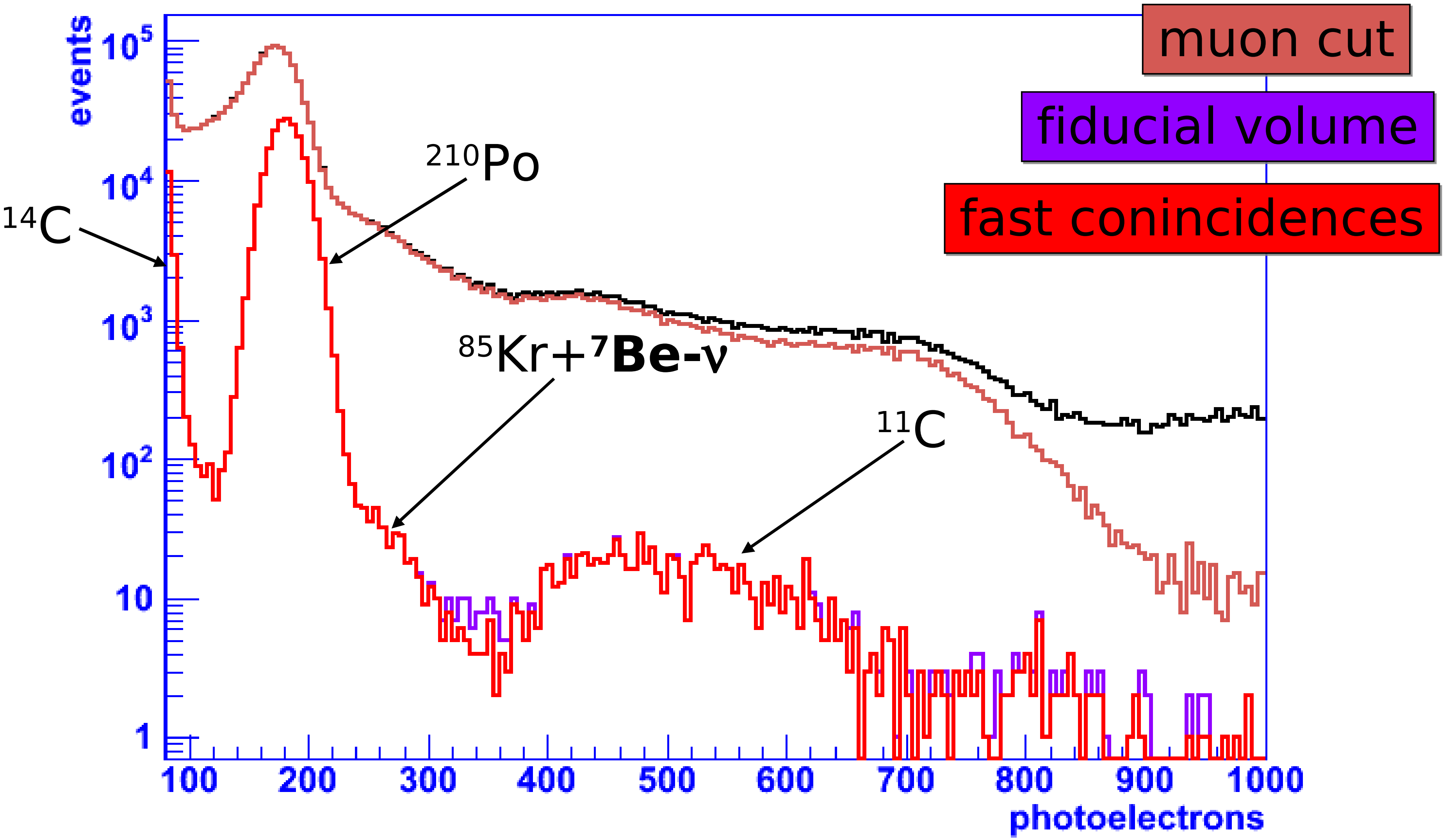


Scintillator filling completed May 15, 2007

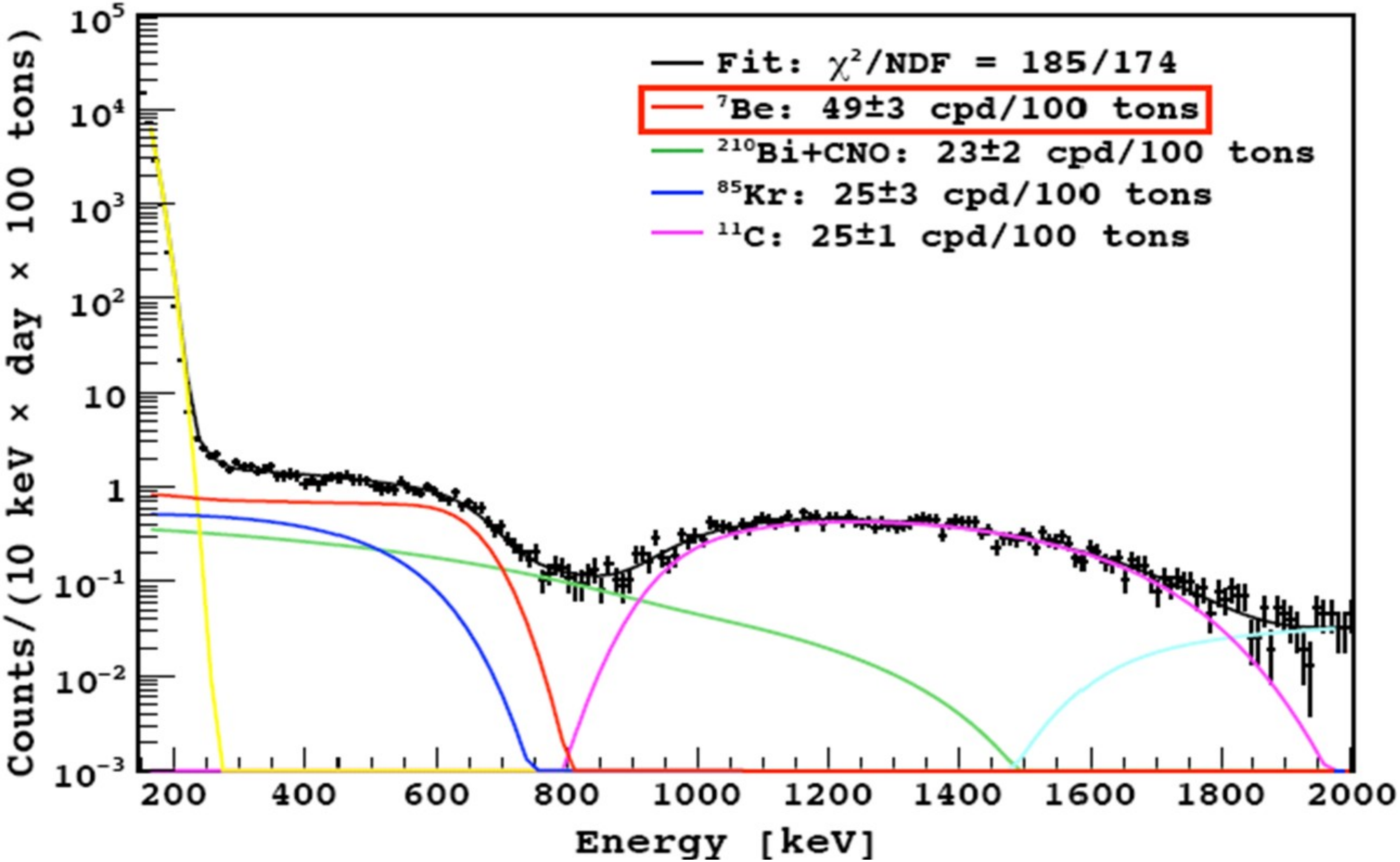
Borexino: raw data, without cuts



Borexino: Spectrum after cuts



Borexino: result



PRL 101:091302 (2008).
arXiv:0805.3843

Borexino result: what does it mean?

49 ± 3stat ± 4sys cpd/100 t

Prediction of standard solar model:

No oscillation	75 ± 5 cpd/100 t
Oscillation (LMA):	
„high metalicity“	48 ± 4 cpd/100 t
„low metalicity“	44 ± 4 cpd/100 t

„No-Oscillation“ is excluded from BOREXINO alone with 4 sigma.

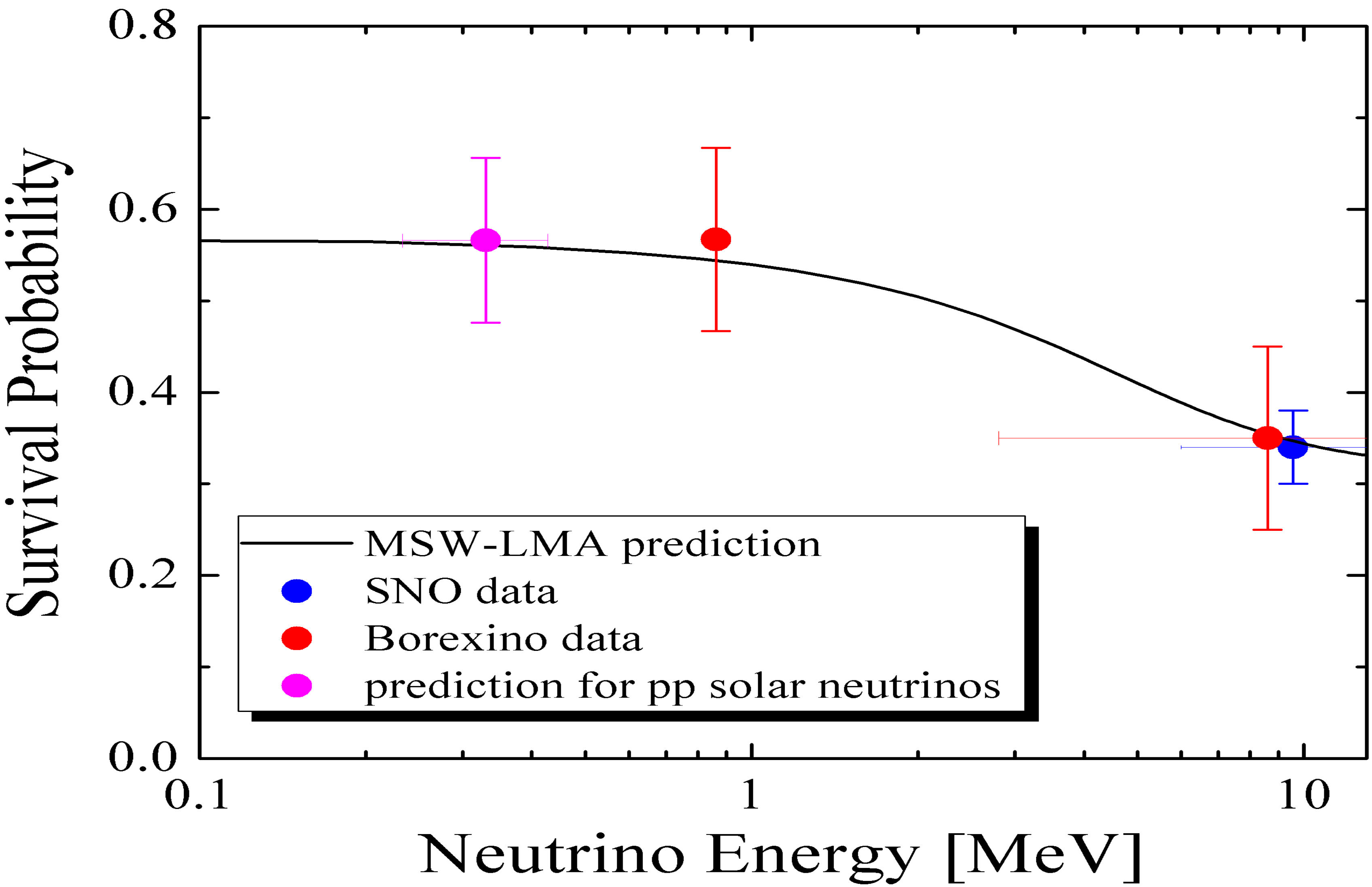
$$\phi(^7\mathrm{Be}) = (5.18 \pm 0.51) \times 10^9\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

$$f(^7\mathrm{Be}) = \phi(^7\mathrm{Be}) / \phi_{\mathrm{SSM}} = 1.02 \pm 0.10$$

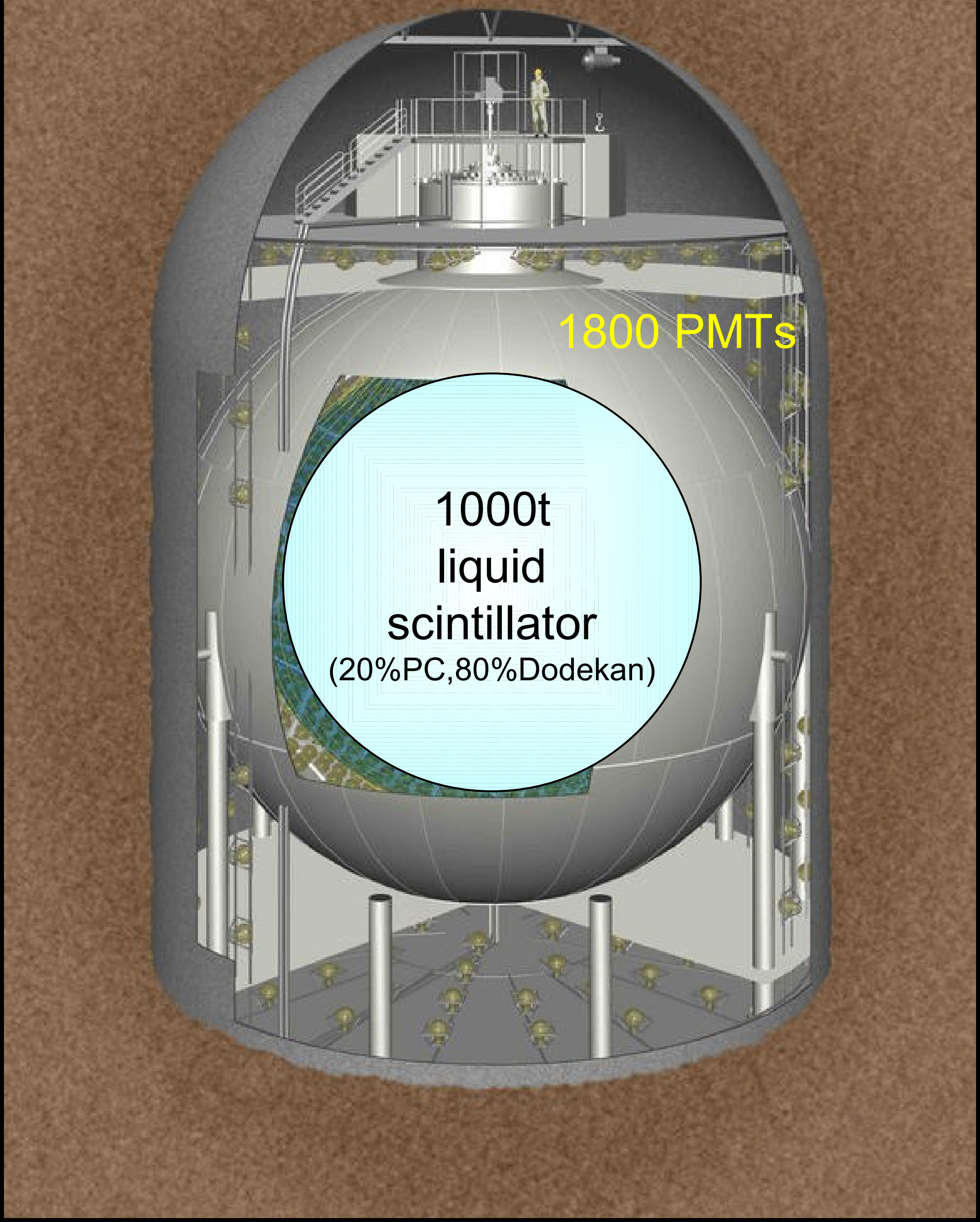
$$f(\mathrm{pp}) = 1.005^{+0.008}_{-0.020}$$

$$f_{\mathrm{CNO}} < 3.8\%$$

Testing the MSW hypothesis:

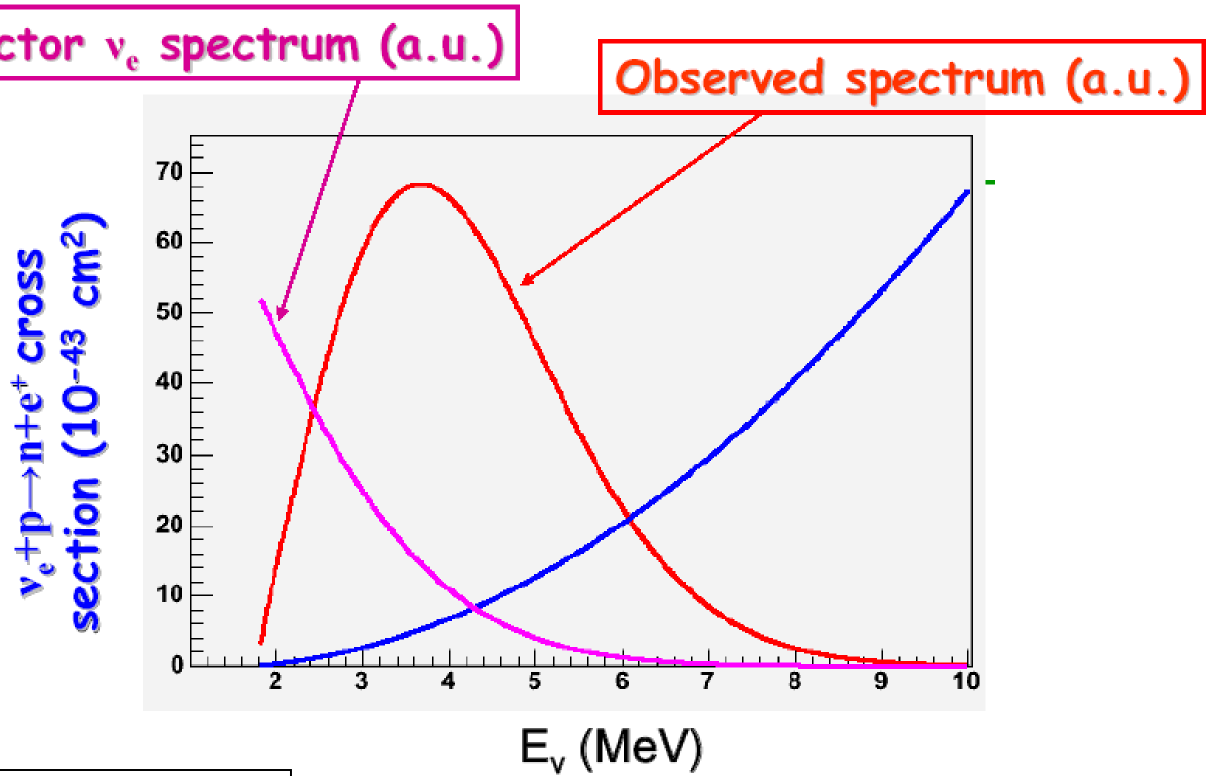


KAMLAND



Kamioka Liquid Scintillator Anti-Neutrino Detector

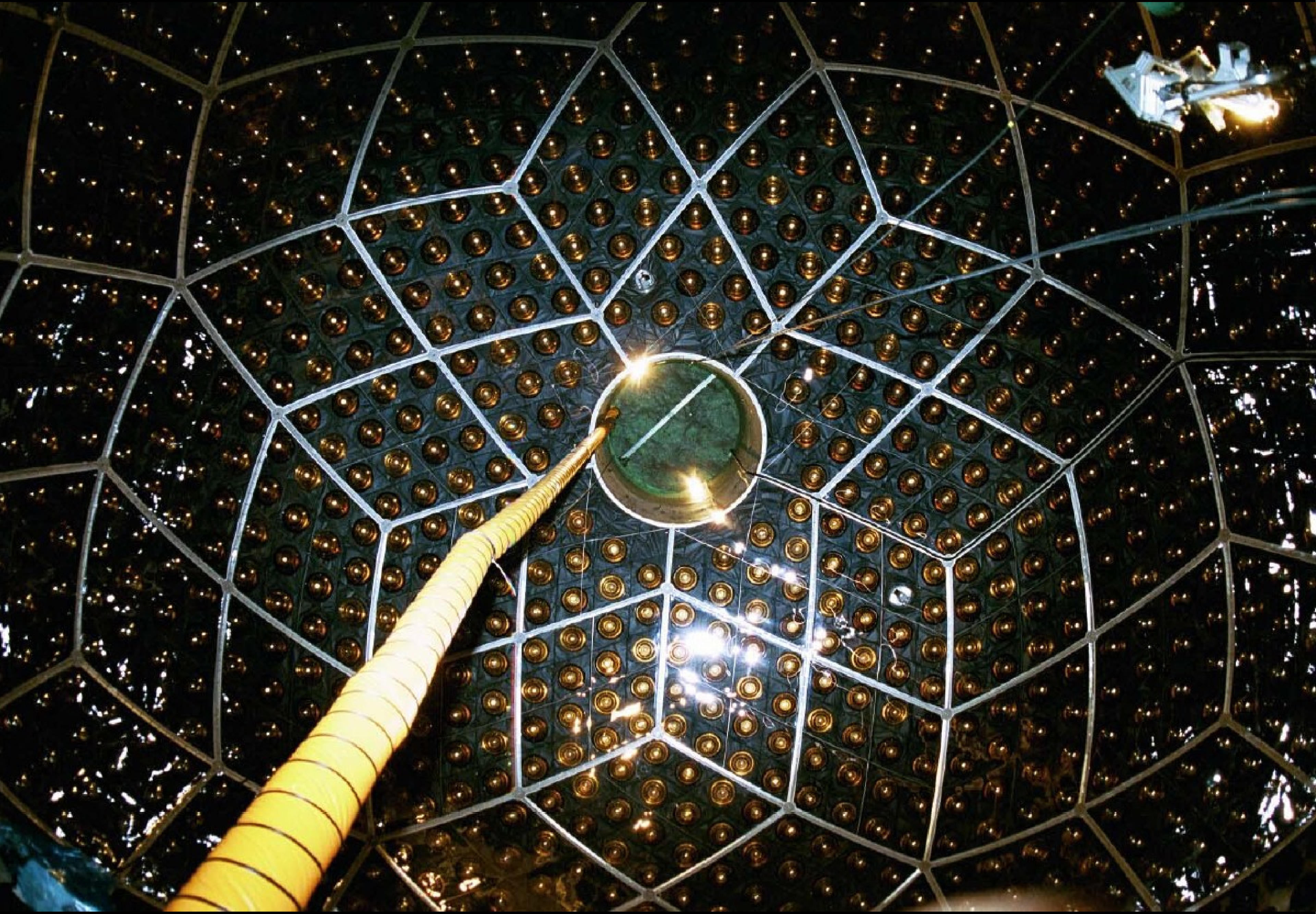
How to detect reactor neutrinos



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

prompt signal
E_ν – 0.8 MeV

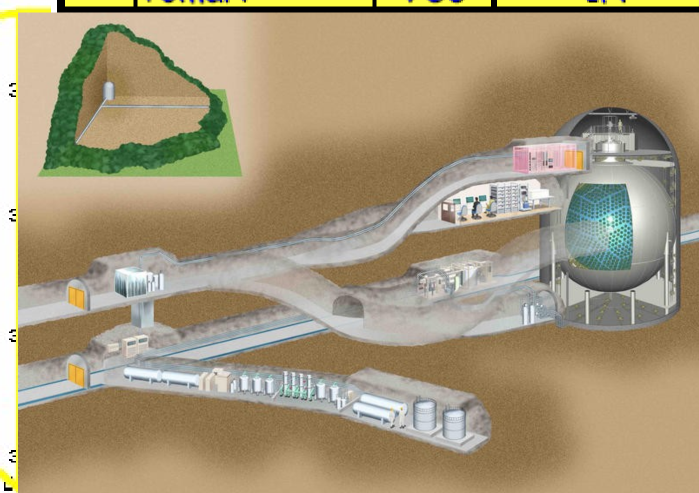
delayed signal
$n + p \rightarrow d + \gamma(2.2\text{MeV})$



Reactor distances & event rates

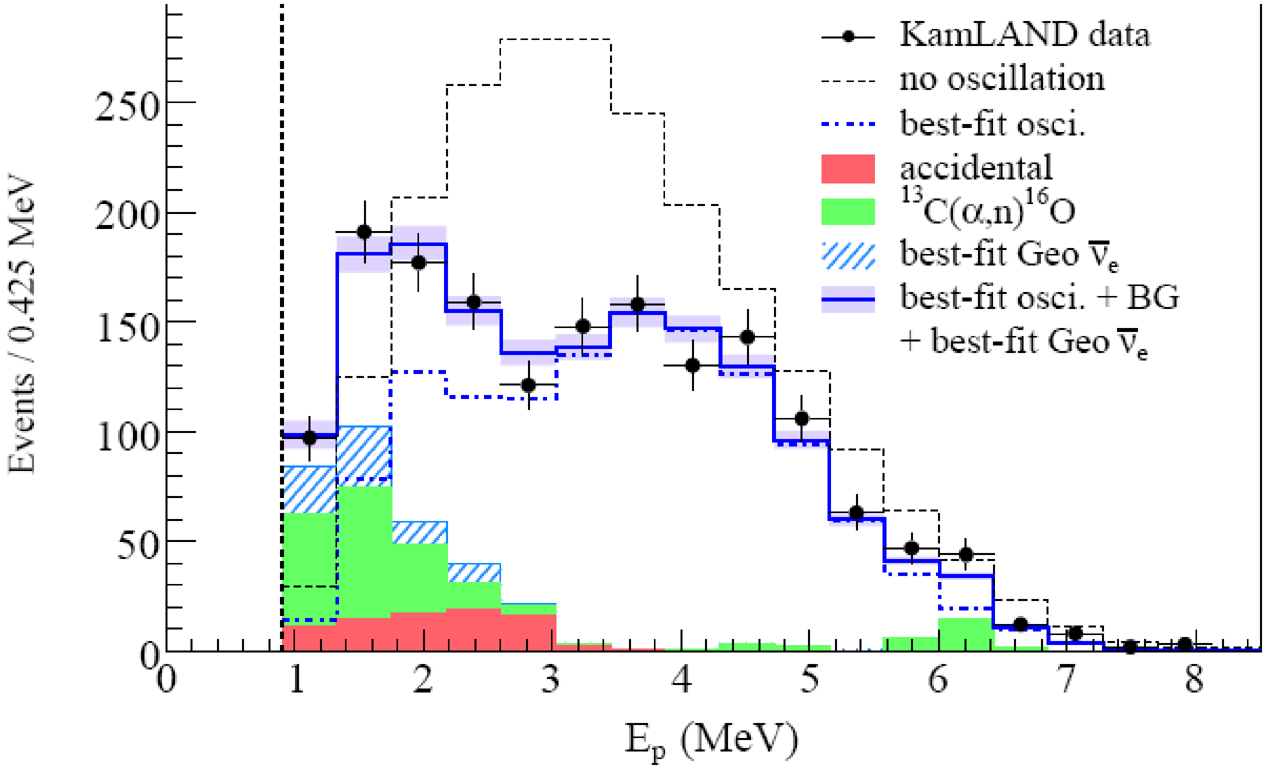
Average distance of reactors from Kamland: 180km

	Site	Dist (km)	Rate noosc* (yr^{-1} kt^{-1})
Japan	Kashiwazaki	160	254.0
	Ohi	179	114.3
	Takahama	191	74.3
	Tsuruga	138	62.5
	Hamaoka	214	62.0
	Mihama	146	62.0
	Sika	88	55.2
	Fukushima1	349	31.1
	Fukushima2	345	29.5
	Tokai2	295	10.1
	Onagawa	431	9.3
	Simane	401	6.3
	Ikata	561	5.1
	Genkai	755	4.8
	Sendai	830	2.1
	Tomari	783	1.4



KamLAND result (2008)

prompt event energy spectrum of anti-ν_e candidates



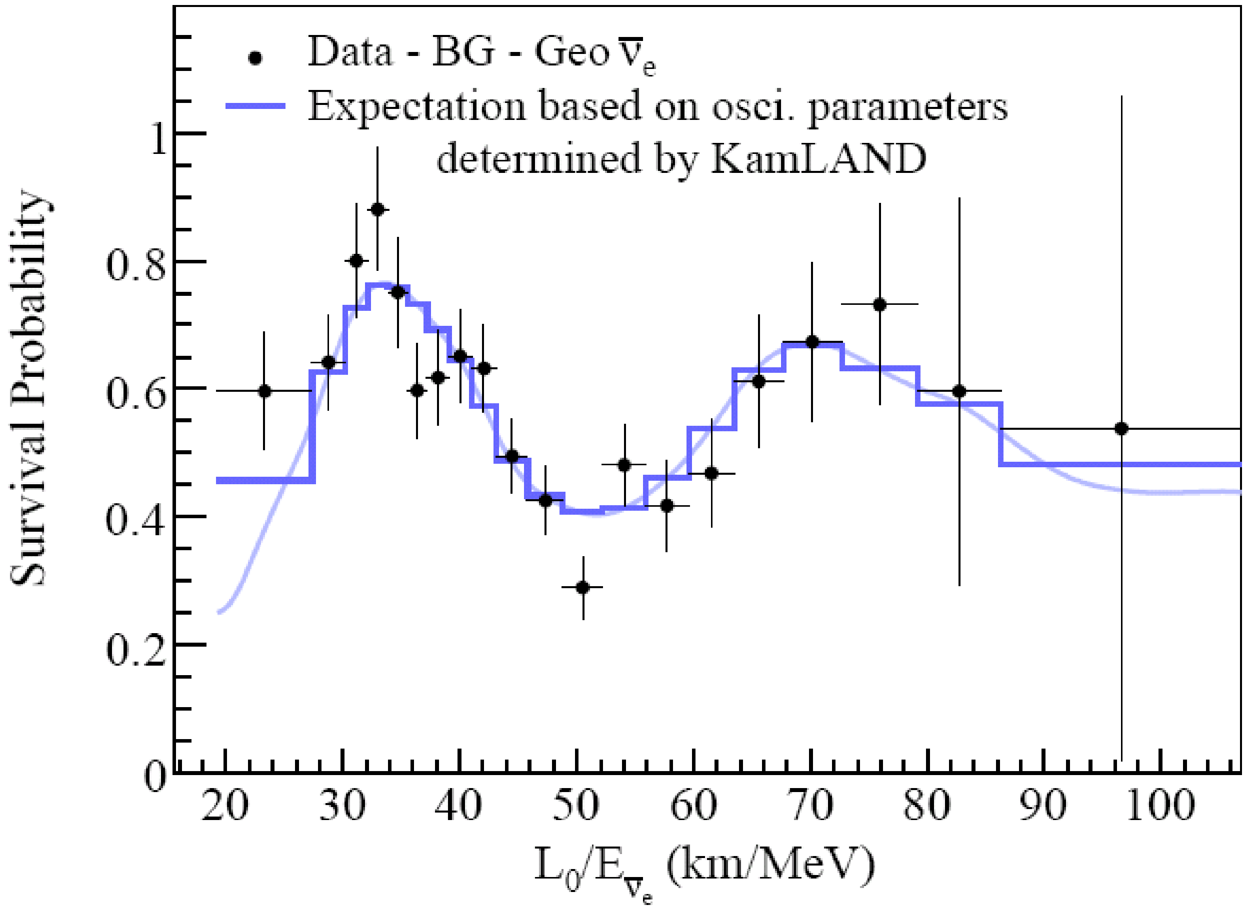
best fit: $\Delta m^2_{21} = 7.58^{+0.14}_{-0.13}(\text{stat})^{+0.15}_{-0.15}(\text{syst}) \times 10^{-5}\ \text{eV}^2$

$\tan^2\theta_{12} = 0.56^{+0.10}_{-0.07}(\text{stat})^{+0.10}_{-0.06}(\text{syst})$

„Precision Measurement of Neutrino Oscillation Parameters with KamLAND“, Phys.Rev.Lett.100:221803,2008

KamLAND result (2008)

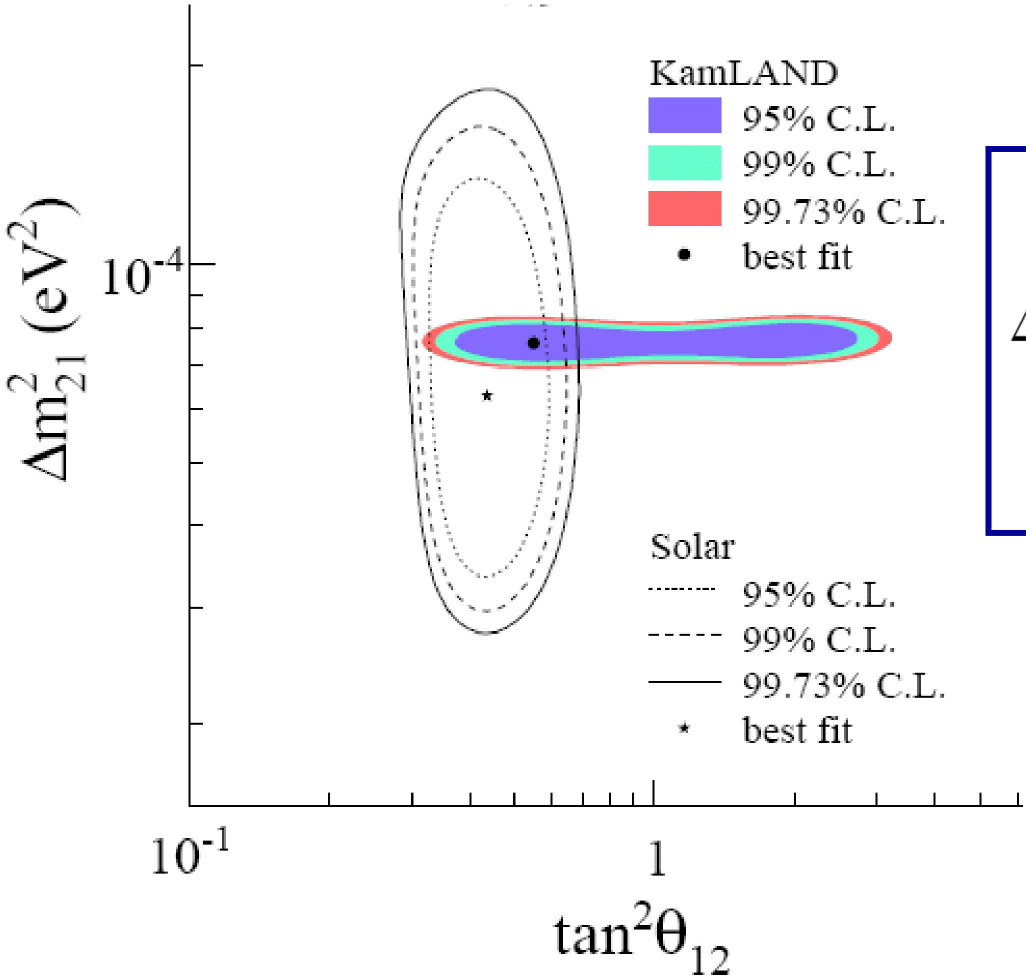
„Precision Measurement of Neutrino Oscillation Parameters with KamLAND“, Phys.Rev.Lett.100:221803,2008



L_0 is the „effective“ baseline = flux-weighted average of distance = 180km

KamLAND result (2008)

„Precision Measurement of Neutrino Oscillation Parameters with KamLAND“, Phys.Rev.Lett.100:221803,2008



KamLAND + solar:

$$\Delta m^2_{21} = 7.59^{+0.21}_{-0.21} \times 10^{-5}\, \mathrm{eV}^2$$

$$\tan^2\theta_{12} = 0.47^{+0.06}_{-0.05}$$

Design Study for a future detector for Low Energy Neutrino Astronomy (LENA)

- proton decay (p → K^+ anti-v)
- SN neutrinos
- diffuse SN neutrino background
- solar neutrinos
- geo neutrinos
- depending on site: reactor neutrinos
- possibility to use as detector for neutrino beam is studied