Nobelovská neutrina

Polovina NC za fyziku pro rok 2002 byla udělena

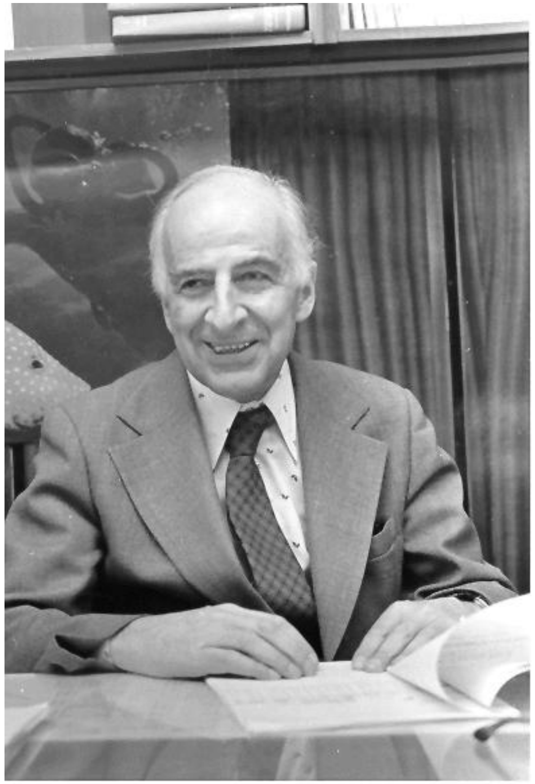
Raymondu Davisovi a Masatoshi Koshibovi

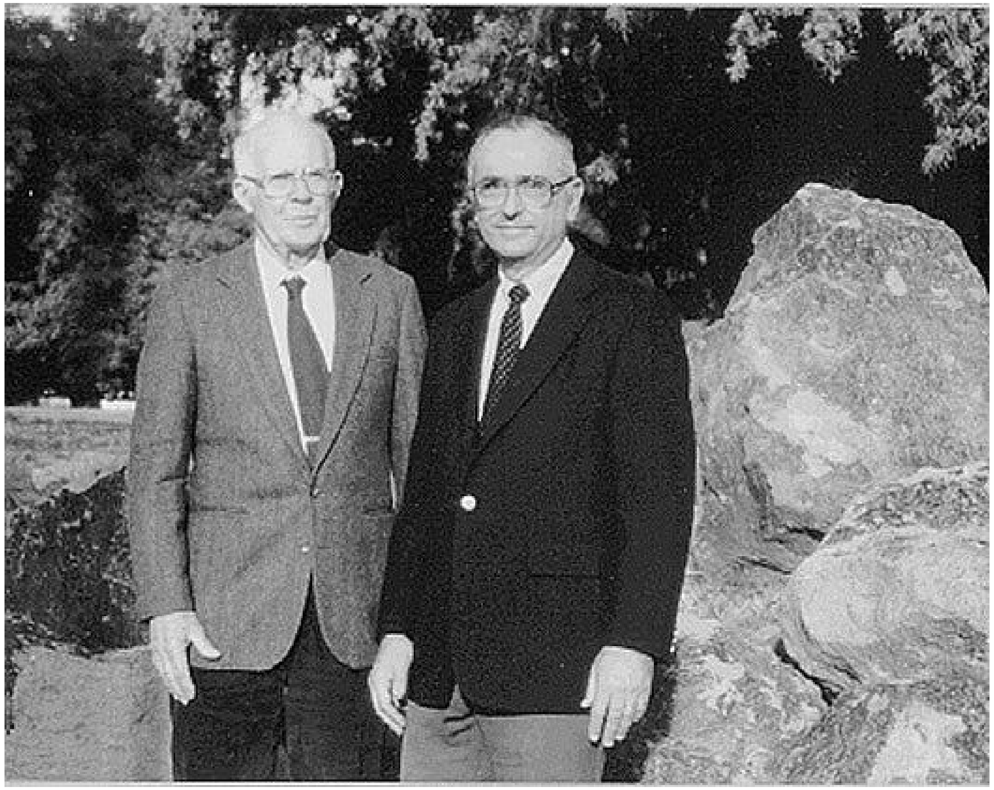
za

průkopnické příspěvky k astrofyzice, zejména za detekci kosmických neutrin

Motivy, okolnosti a důsledky jejich objevů ilustrují skutečnost, že k zásadnímu pokroku ve vědě obvykle dochází

- za součinosti **různých** oborů
- v úzké spolupráci **experimentu a teorie** a
- za přispění štěstí, které **přeje připraveným**.





Bruno Pontecorvo **Ray Davis a John Bahcall**

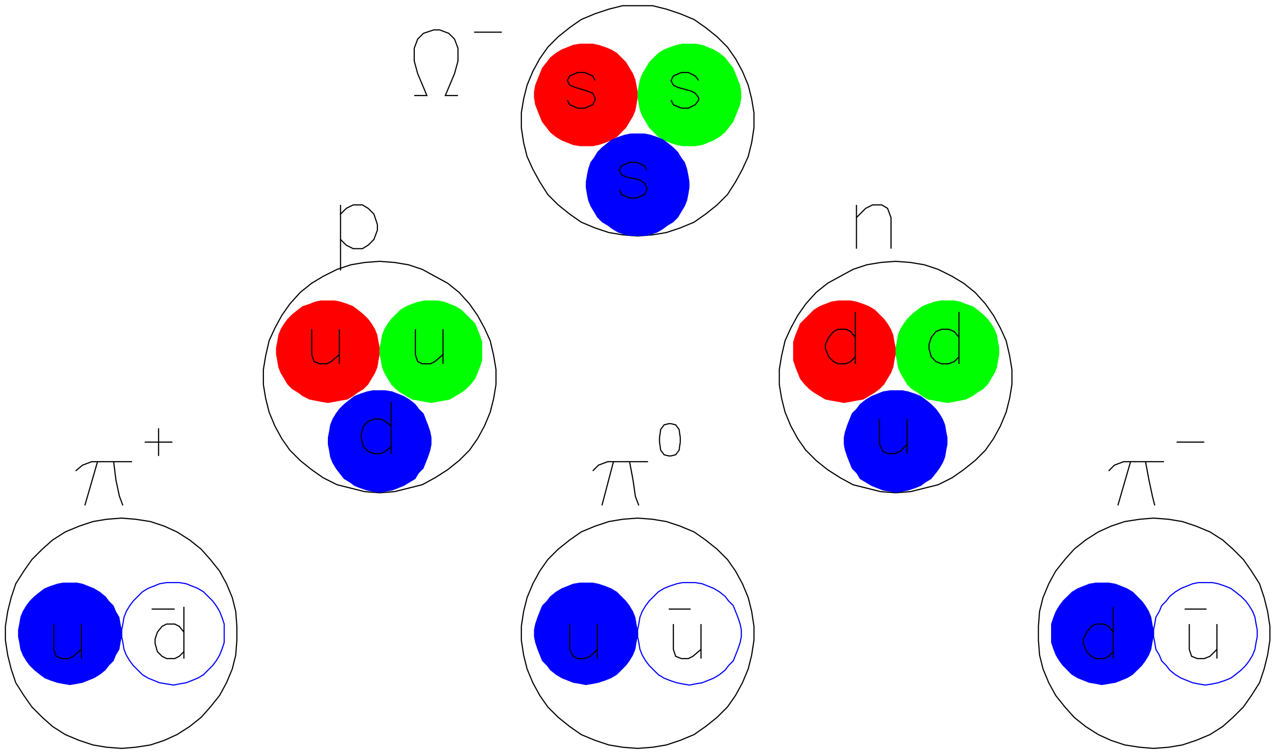
Kvarky a leptony – atomy dneška

jsou základními objekty **Standardního** modelu

Q= 2/3	u	u	u	c	c	c	t	t	t
Q= -1/3	d	d	d	s	s	s	b	b	b
Q= 0	ν_e			ν_μ			ν_τ		
Q= -1	e^-			μ^-			τ^-		

- mají **stejný spin** 1/2
- nesou kvantová čísla **leptonová a kvarková**
- kvarky existují různých **barvách**

Kvarková struktura hadronů



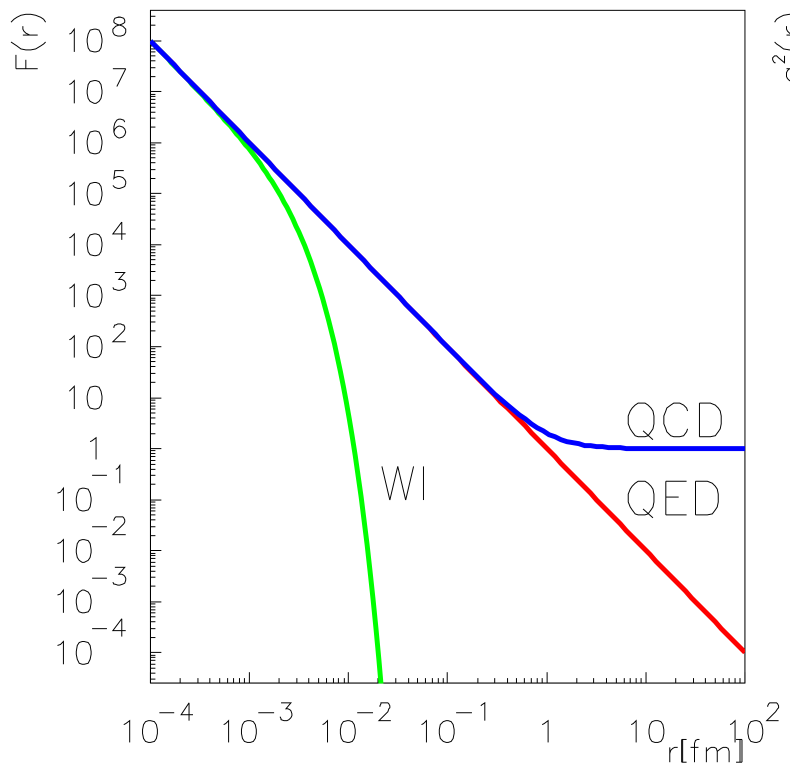
Mezi kvarky a leptony působí **tři typy sil**

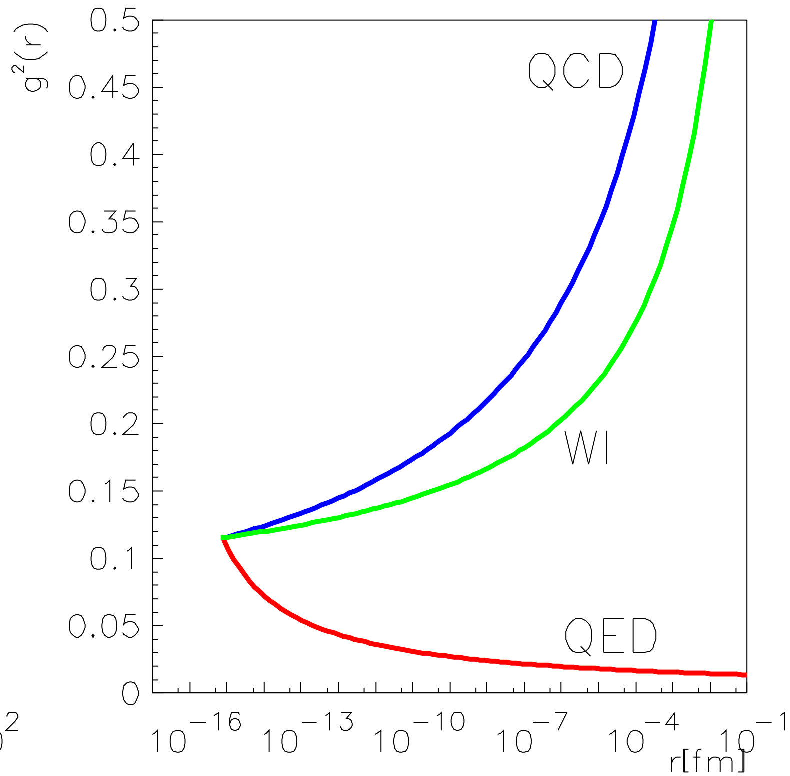
	zprostředkující částice
gravitační	graviton
elektroslabé, (GSW)	W^+, W^-, Z
silné, (QCD)	gluony

- které maji všechny **výměnný charakter**
- ale **různý** dosah a velikost
- jejichž **zprostředkující částice**
  - mají **stejný** spin **1**⇒ výchozí bod pro **sjednocení**
  - ale **různé** hmotnosti
  - a působí jen mezi **určitými** kvarky a leptony

Sjednocení sil

Kalibračních teorie: přirozený rámec pro **sjednocení elektromagnetických, slabých a silných sil**.





Klíčové okamžiky

1897: H. Becquerel, P. a M. Currie: objev α, β-radioaktivity

1914: J. Chadwick: **spojité spektrum** β-rozpadu

1928: G. Gamow: výpočet **průchodu bariérou**

1930: W. Pauli: hypotéza **neutrina** ν

1934: E. Fermi: **teorie slabých interakcí** zahrnující ν

1939: H. Bethe: **produkce energie** ve hvězdách

1946: B. Pontecorvo: návrh detegovat ν pomocí reakce

$$\nu + ^{37}\mathrm{CL} \rightarrow ^{37}\mathrm{AR} + \mathrm{e}^-$$

1953-1956: F. Reines, W. Cowan: důkaz existence ν_e

1955: R. Davis: náznak, že $\overline{\nu_e} \neq \nu_e$

1955: Gell-Mann, Pais: oscilace $\overline{K}_0 \leftrightarrow K_0$

1957: B. Pontecorvo: hypotéza oscilace $\nu_e \leftrightarrow \overline{\nu}_e$

1962: L. Lederman, M. Schwartz, J. Steinberger: $\nu_\mu \neq \nu_e$

1964: J. Bahcall a R. Davis: **první analýza** slunečních ν_e

1967-9: B. Pontecorvo, V. Gribov: **nezachování leptonového čísla** a oscilace $\nu_e \leftrightarrow \nu_\mu$

1968: R. Davis a J. Bahcall: **deficit slunečních neutrin**

1968-94: Davis & Bahcall: pozvolný **růst věrohodnosti** jevu

1967-1972: S. Glashow, A. Salam, S. Weinberg: formulace **jednotné teorie elektroslabých interakcí**

1973: D. Gross, D. Politzer, F. Wilczek: formulace **kvantové chromodynamika**

1974: H. Georgi, S. Glashow: GUT $\Rightarrow$ **proton nestabilní!**

1975: M. Perl: objeven **třetí nabitý lepton** τ

1978: Wolfenstein: oscilace neutrin v **hmotě**

1983: M. Koshiba: experiment **Kamiokande**

1984: M. Koshiba: navrhl **Kamiokande II** a **Superkamiokande**

1986: Michejev, Smirnov: oscilace **neutrin ve Slunci**

1987: Kamiokande II: neutrina ze **supernovy**

1988: Kamiokande II: první měření **slunečních** ν

1995: J. Bahcall, M. Pinsonneault: výpočet toku $\Phi(\nu_e)$

1996: **Superkamiokande** v provozu, M. Koshiba→Y. Totsuka

1998-2001: Superkamiokande: změřilo

- oscilace **atmosférických** ν_μ
- tok **slunečních** ν_e

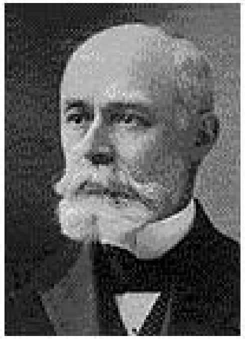
2000: Fermilab: pozorovány interakce ν_τ

2001-2002: Sudbury Neutrino Observatory: změřila součet toků
$\Phi(\nu_e) + \Phi(\nu_\mu) + \Phi(\nu_\tau) \Rightarrow$ Slunci dobře rozumíme! Opravdu?

The Nobel Prize in Physics 1903

"in recognition of the extraordinary services he has rendered by his discovery of spontaneous radioactivity"

"in recognition of the extraordinary services they have rendered by their joint researches on the radiation phenomena discovered by Professor Henri Becquerel"



Antoine Henri Becquerel

1/2 of the prize

France

École Polytechnique

Paris, France

Pierre Curie

1/4 of the prize

France

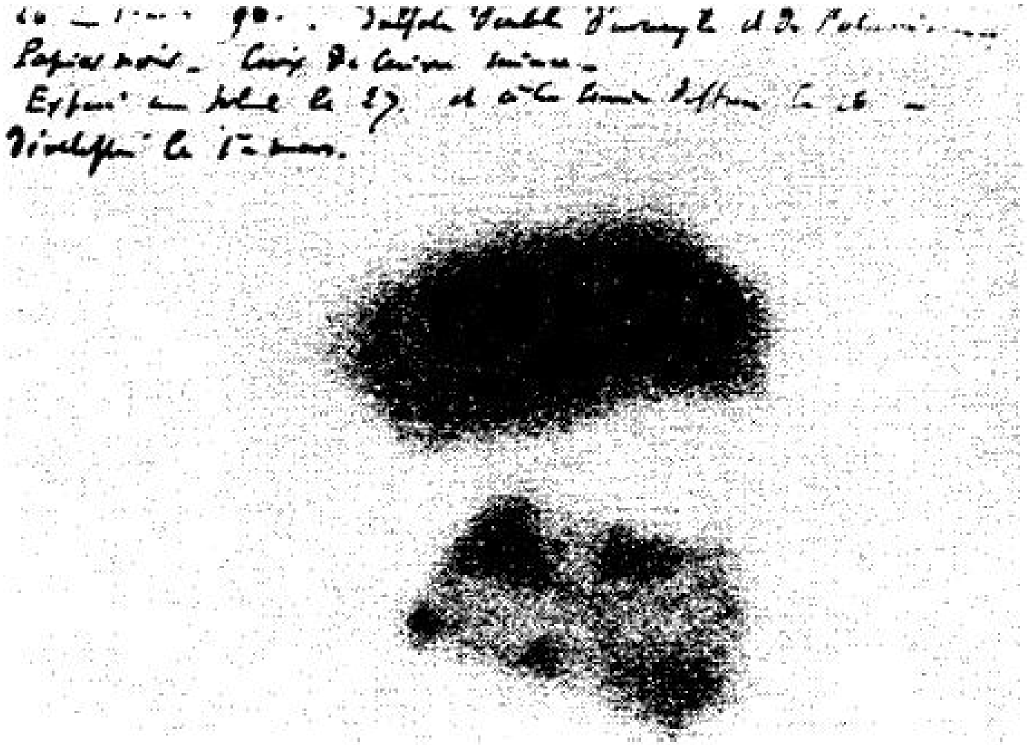
École municipale de physique et de chimie industrielles (Municipal School of Industrial Physics

Marie Curie, née Sklodowska

1/4 of the prize

France

RADIOACTIVITY, NEW PROPERTY OF MATTER



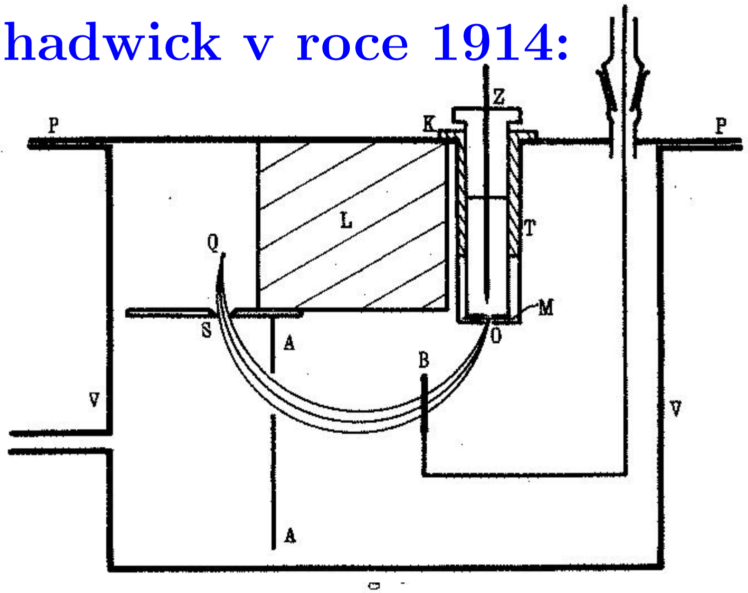
Thus I placed sheets of double sulphate of uranium and potassium on photographic plates enveloped in black paper or protected by a sheet of aluminium and exposed them to light for several hours. On developing the plates, I found that the uranium salt had emitted rays which reproduced the silhouettes of the crystalline sheets through the black paper and various screens of metal or thin glass laid on the plates.

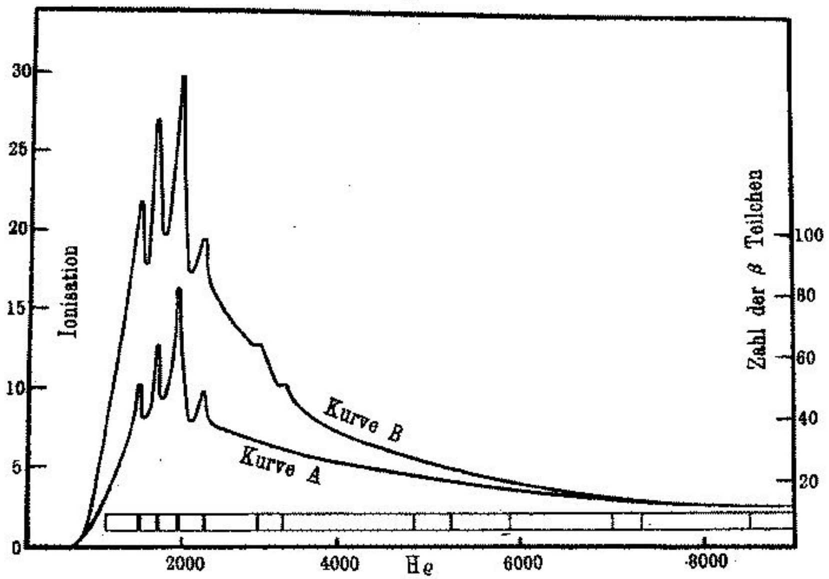
Under these conditions the phenomenon could be ascribed to a transformation of solar energy, like phosphorescence, but I soon recognized that the emission was independent of any familiar source of excitation, such as light, electricity or heat.

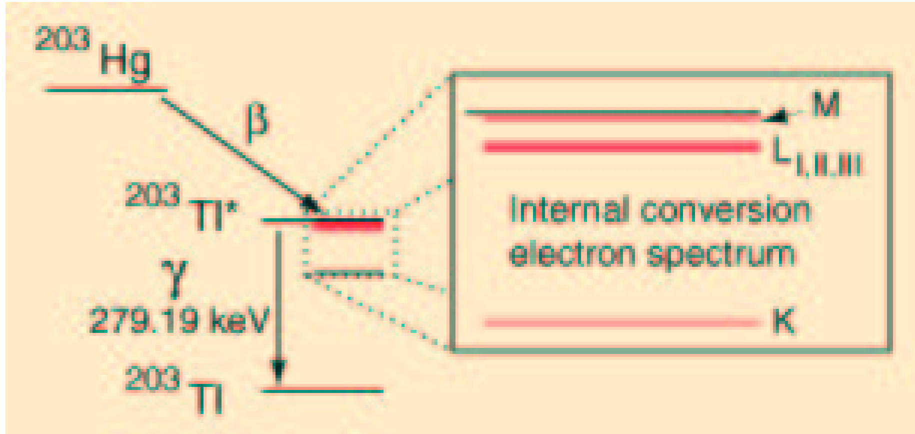
We were thus faced with a spontaneous phenomenon of a new order.

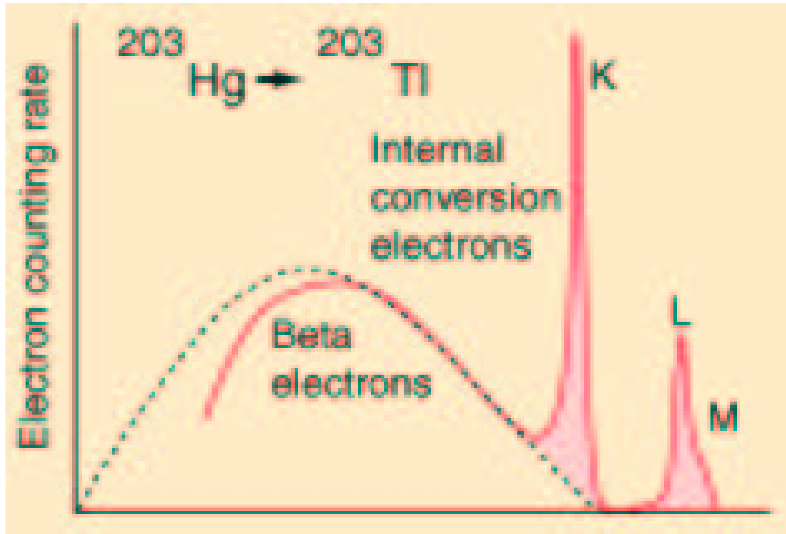
Objev spojitého spektra v β-rozpadu Radia B+C

Chadwick v roce 1914:









Záření β má spojité spektrum
přes něž je přeloženo čárové spektrum

Pauli: hypotéza neutrina

4.12.1930: Pauliho dopis účastníkům konference v Tübingen:

I have come upon a desperate way out regarding the „wrong" statistics of the nitrogen and lithium nuclei, as well as the continuous β-spectrum ... to wit, the possibility that there could exist in the nuclei electrically neutral particles ... The mass of the „neutrons" should be ... not larger than 0.01 times the proton mass ... For the time being I dare not publish anything about this idea.

17. 6. 1931: zpráva o Pauliho hypotéze v **New York Times:**

A new inhabitant at the heart of the atom was introduced to the world of physics today when Dr. W. Pauli of the Institute of Technology in Zurich, Switzerland, postulated the existence of particles or entities which he christened „neutrons".

Oficiální požehnání Pauliho hypotéze fyzikální obcí přislo až během Solvayské konference v říjnu 1933, kde Pauli se svou myšlenkou poprvé veřejně vystoupil a kde Perrin vyslovil předpoklad $m_\nu = 0$.

Na této konferenci také definitivně odmítnuta Bohrova hypotéza nezachování energie v mikrosvětě

1934: E. Fermi:

- poprvé použil název **neutrino**
- ukázal, že neutrino **není součást jádra**

Reines a Cowan: detekce neutrin v reakci $\overline{\nu}_e + p \rightarrow e^+ n$

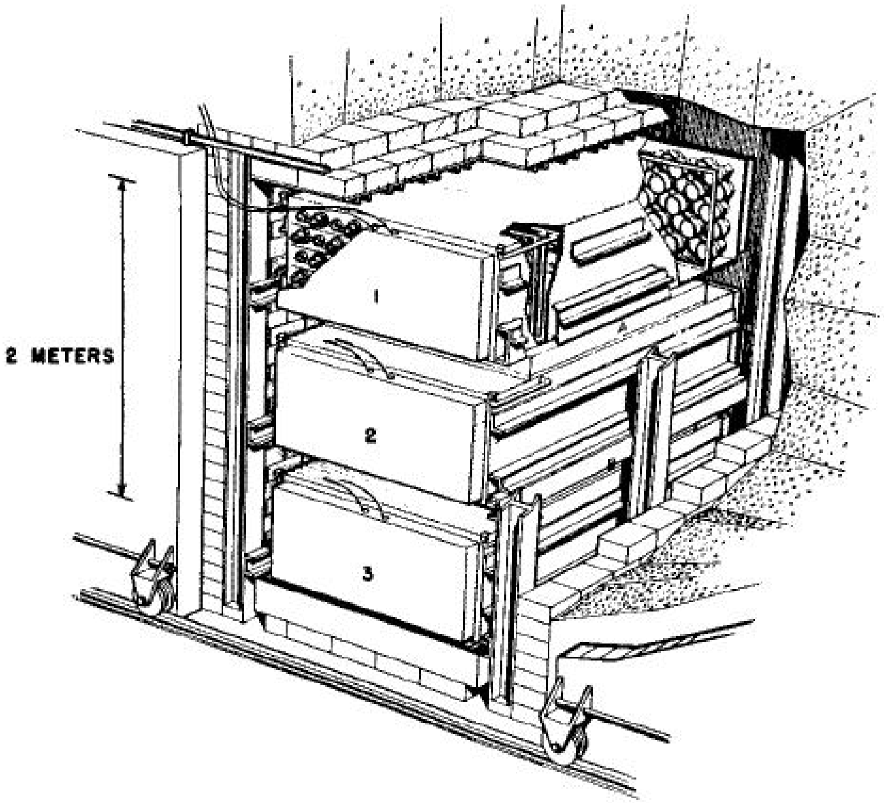
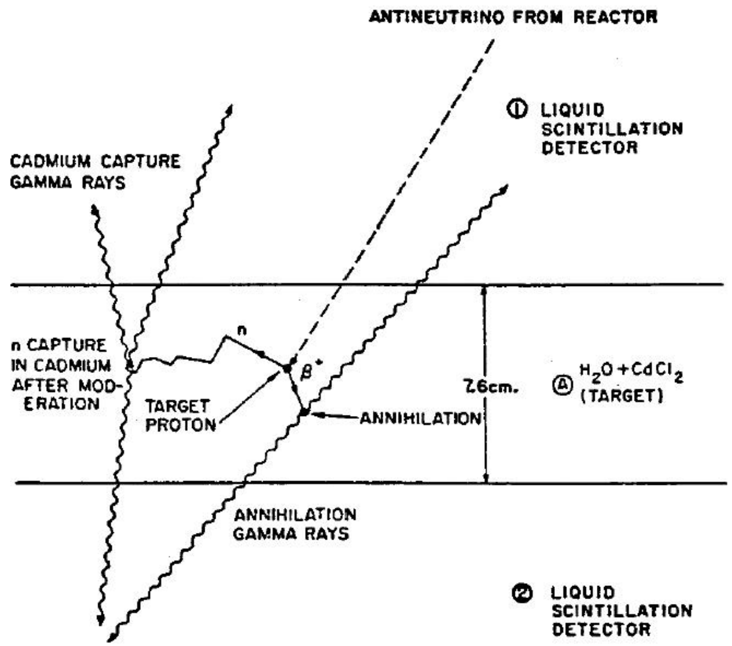


FIG. 5. A sketch of the equipment used at Savannah River. The tanks marked 1, 2, and 3 contained 1400 liters of liquid scintillator solution and were viewed on each end by 55 photomultiplier tubes. The thin tanks marked *A* and *B* were polystyrene and contained 200 liters of water, which provided the target protons and contained as much as 40 kilograms of dissolved $CdCl_2$ to capture the product neutrons.

$\overline{\nu}_e$ z reaktoru v Savannah River



$$\sigma_{\rm exp} = \left(12^{+7}_{-4}\right) \times 10^{-44}\ {\rm cm}^2$$

$$\sigma_{\rm teor} = (5 \pm 1) \times 10^{-44}\ {\rm cm}^2$$

Jak svítí hvězdy

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).

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)

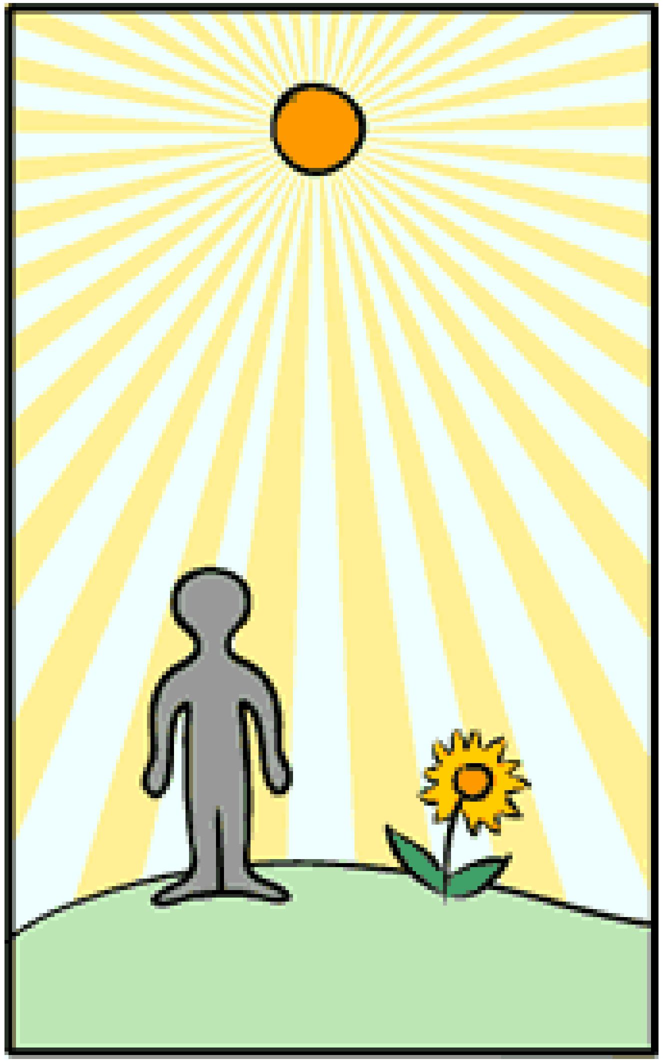
Gamow and Teller.[4] The total number of processes per gram per second is[4]

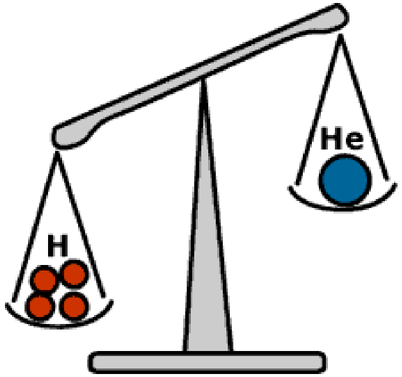
$$p=\frac{4}{3^{5/2}}\frac{\rho x_1 x_2}{m_1 m_2}\frac{\Gamma}{\hbar}aR^2 e^{4(2R/a)^{\frac{1}{2}}}\tau^2 e^{-\tau}. \tag{4}$$

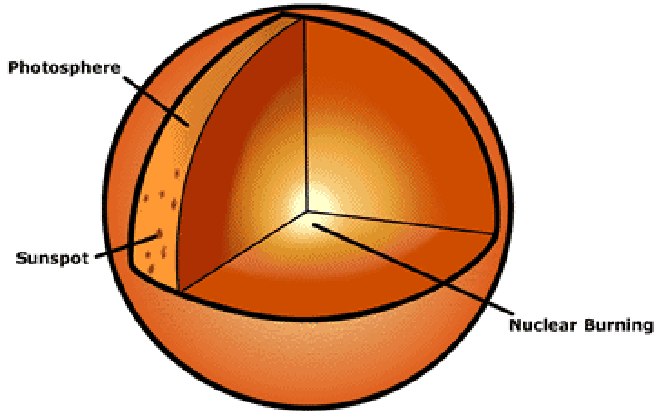
$$a=\hbar^2/me^2Z_1Z_2 \tag{5}$$

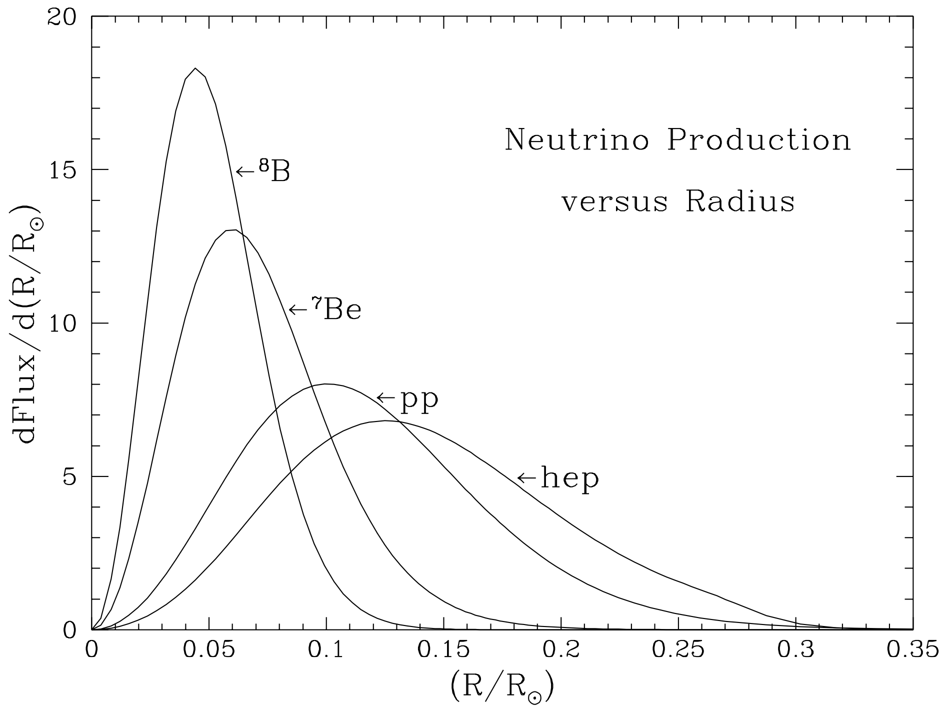
the "Bohr radius" for the system, $\Gamma/\hbar$ the probability of the nuclear reaction, in sec.$^{-1}$, after penetration, and

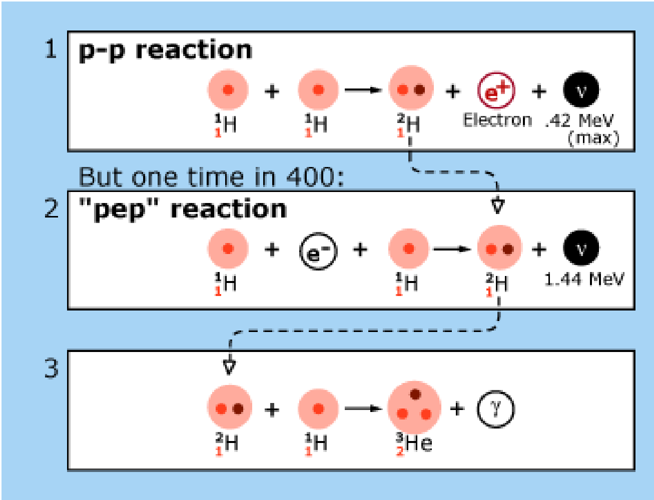
$$\tau=3\left(\frac{\pi^2 me^4 Z_1^2 Z_2^2}{2\hbar^2 kT}\right)^{\frac{1}{3}}. \tag{6}$$

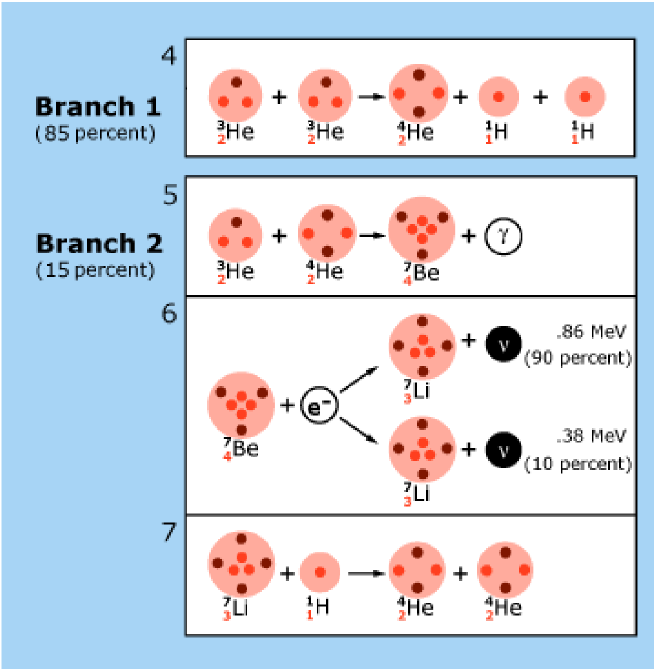


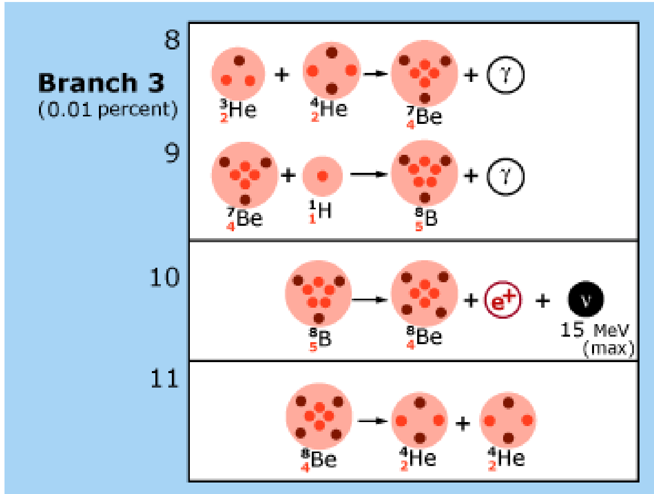

H
He

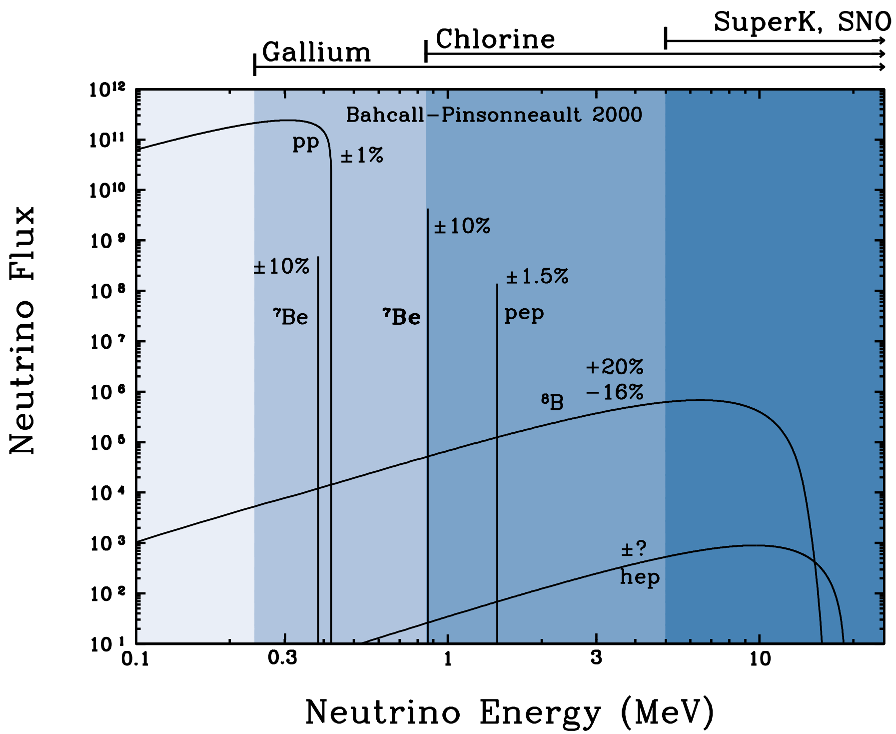

Photosphere
Sunspot
Nuclear Burning

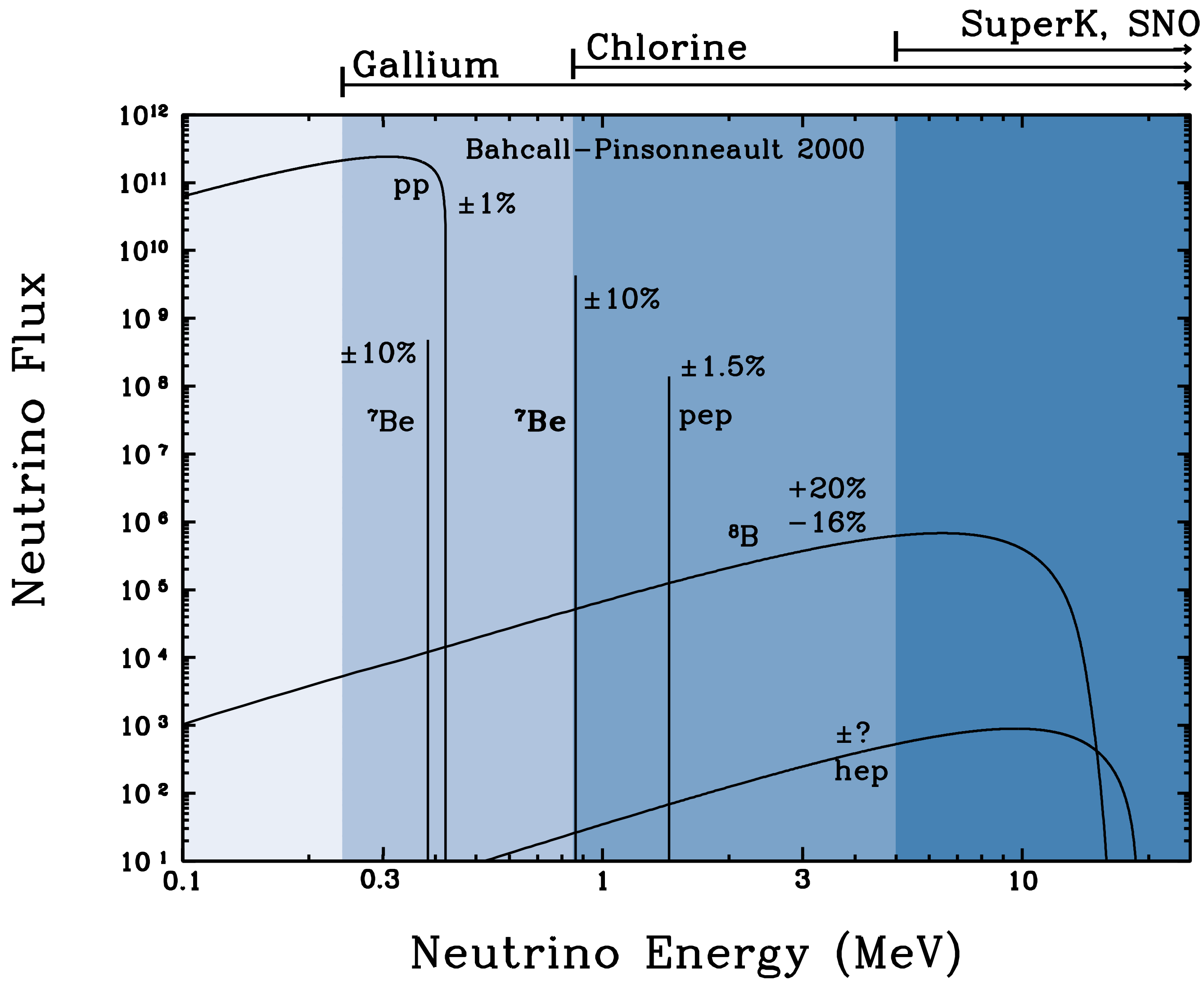

Neutrino Production
versus Radius
←⁸B
←⁷Be
←pp
←hep
dFlux/d(R/R⊙)
(R/R⊙)
0
5
10
15
20
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35

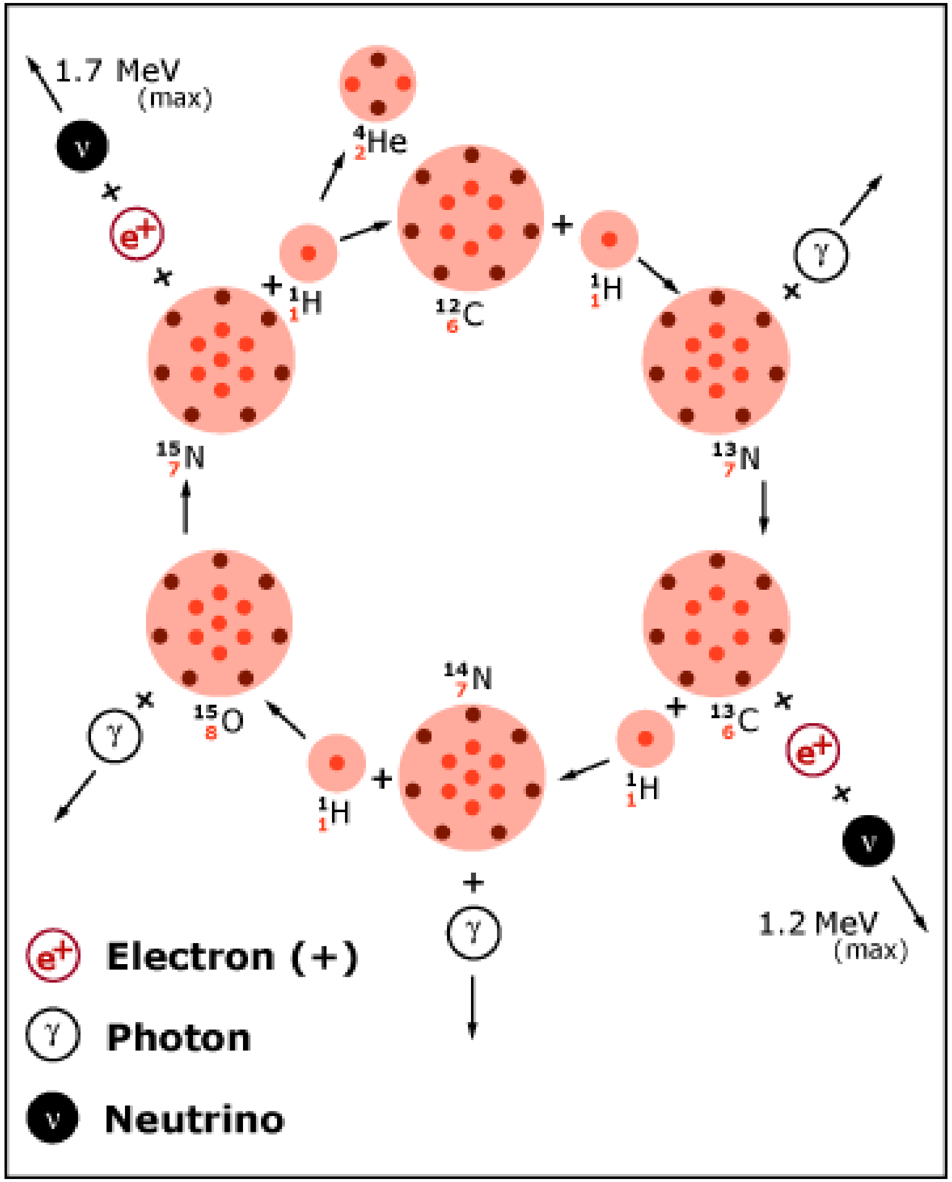

1
p-p reaction
Electron
.42 MeV (max)
But one time in 400:
2
"pep" reaction
1.44 MeV
3


4
Branch 1
(85 percent)
5
Branch 2
(15 percent)
6
.86 MeV
(90 percent)
.38 MeV
(10 percent)
7


8
Branch 3
(0.01 percent)
9
10
15 MeV (max)
11


Gallium
Chlorine
SuperK, SNO
Bahcall−Pinsonneault 2000
pp
±1%
±10%
±10%
±1.5%
⁷Be
⁷Be
pep
+20%
−16%
⁸B
±?
hep
Neutrino Flux
Neutrino Energy (MeV)


Gallium
Chlorine
SuperK, SNO
Bahcall−Pinsonneault 2000
pp
±1%
±10%
±10%
⁷Be
⁷Be
±1.5%
pep
+20%
−16%
⁸B
±?
hep
Neutrino Flux
Neutrino Energy (MeV)
0.1
0.3
1
3
10


1.7 MeV
(max)
4 2 He
12 6 C
1 1 H
15 7 N
13 7 N
14 7 N
15 8 O
13 6 C
1.2 MeV
(max)
Electron (+)
Photon
Neutrino

Ray Davis a sluneční neutrina

PHYSICAL REVIEW VOLUME 97, NUMBER 3 FEBRUARY 1, 1955

Attempt to Detect the Antineutrinos from a Nuclear Reactor by the $Cl^{37}(\bar{\nu},e^-)A^{37}$ Reaction*

RAYMOND DAVIS, JR.
Department of Chemistry, Brookhaven National Laboratory, Upton, Long Island, New York
(Received September 21, 1954)

Tanks containing 200 and 3900 liters of carbon tetrachloride were irradiated outside of the shield of the Brookhaven reactor in an attempt to induce the reaction $Cl^{37}(\bar{\nu},e^-)A^{37}$ with fission product antineutrinos. The experiments serve to place an upper limit on the antineutrino capture cross section for the reaction of 2×10^{-42} cm² per atom. Cosmic-ray-induced A^{37} was observed and the production rate measured at 14 100 feet altitude and sea level. Measurements with the 3900-liter container shielded from cosmic rays with 19 feet of earth permit placing an upper limit on the neutrino flux from the sun.

In 1946 Pontecorvo[3] suggested a radiochemical method of detecting the neutrino by employing the reaction $Cl^{37}(\bar{\nu},e^-)A^{37}$. The experiment involved irradiating a large volume of carbon tetrachloride near a nuclear reactor, removing the A^{37} by physical methods,

první zmínka o možnosti měření slunečních neutrin

If neutrinos and antineutrinos are identical in their interactions with nucleons one should be able to observe the process upon carrying the experiment to the required sensitivity. However, if neutrinos and antineutrinos differ in their interactions with nucleons one would not expect to induce the reaction $Cl^{37}(\bar{\nu},e^-)A^{37}$. A positive experiment of this type would

These studies have indicated that neutrinos and antineutrinos do differ in their interactions with nucleons.[5]

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

VOLUME 12, NUMBER 11 PHYSICAL REVIEW LETTERS 16 MARCH 1964

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]

We may conclude from the above considerations that an experiment using 100 000 gallons of pure perchlorethylene in a mine 4500 feet deep, properly shielded from fast neutrons, would have a background ^{37}Ar production rate at least a factor of ten below the expected rate from solar neutrinos. It should be noted that if a positive result

VOLUME 20, NUMBER 21 PHYSICAL REVIEW LETTERS 20 MAY 1968

SEARCH FOR NEUTRINOS FROM THE SUN*

Raymond Davis, Jr., Don S. Harmer,† and Kenneth C. Hoffman
Brookhaven National Laboratory, Upton, New York 11973
(Received 16 April 1968)

A search was made for solar neutrinos with a detector based upon the reaction $Cl^{37}(\nu, e^-)Ar^{37}$. The upper limit of the product of the neutrino flux and the cross sections for all sources of neutrinos was 3×10^{-36} sec^{-1} per Cl^{37} atom. It was concluded specifically that the flux of neutrinos from B^8 decay in the sun was equal to or less than 2×10^6 cm^{-2} sec^{-1} at the earth, and that less than 9% of the sun's energy is produced by the carbon-nitrogen cycle.

Recent solar-model calculations have indicated that the sun is emitting a measurable flux of neutrinos from decay of B^8 in the interior.[1-8] The possibility of observing these energetic neutrinos has stimulated the construction of four separate neutrino detectors.[9] This paper will present the results of initial measurements with a detection system based upon the neutrino capture reaction $Cl^{37}(\nu, e^-)Ar^{37}$.

The detector design.—A detection system that contains 390 000 liters (520 tons chlorine) of liquid tetrachloroethylene, C_2Cl_4, in a horizontal cylindrical tank was built along the lines proposed earlier.[11] The system is located 4850 ft underground [4400 m (w.e.)] in the Homestake gold mine at Lead, South Dakota. It is essential to place the detector underground to reduce the production of Ar^{37} from (p, n) reactions by pro-

This limit, expressed as

$$\sum\varphi\sigma \leq 0.3\times10^{-35}\ sec^{-1}\ \text{per}\ Cl^{37}\ \text{atom},$$

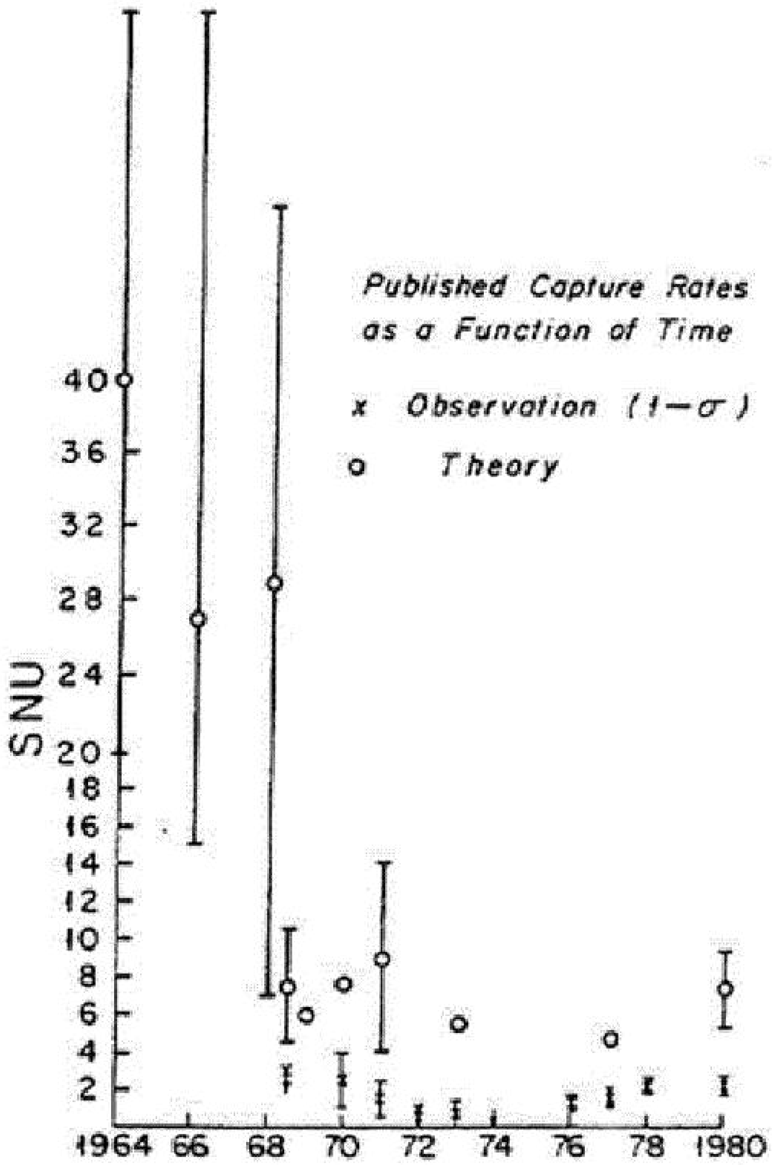
can be compared with the predicted value of $(2.0 \pm 1.2)\times10^{-35}$ sec^{-1} per Cl^{37} atom (Table I). It may be seen that this limit is approximately a factor of 7 below that expected from these solar-model calculations. From this limit and the

J. Bahcall, N. Bahcall, G. Shaviv (PRL 21 (1968), 1209): data jsou **"faktorem asi 2 nad horní hranicí stanovenou Davisem, Harmerem a Hoffmanem"**, ale při započtení všech teoretických nejistot tento rozdíl **"není nepřekonatelný"**.

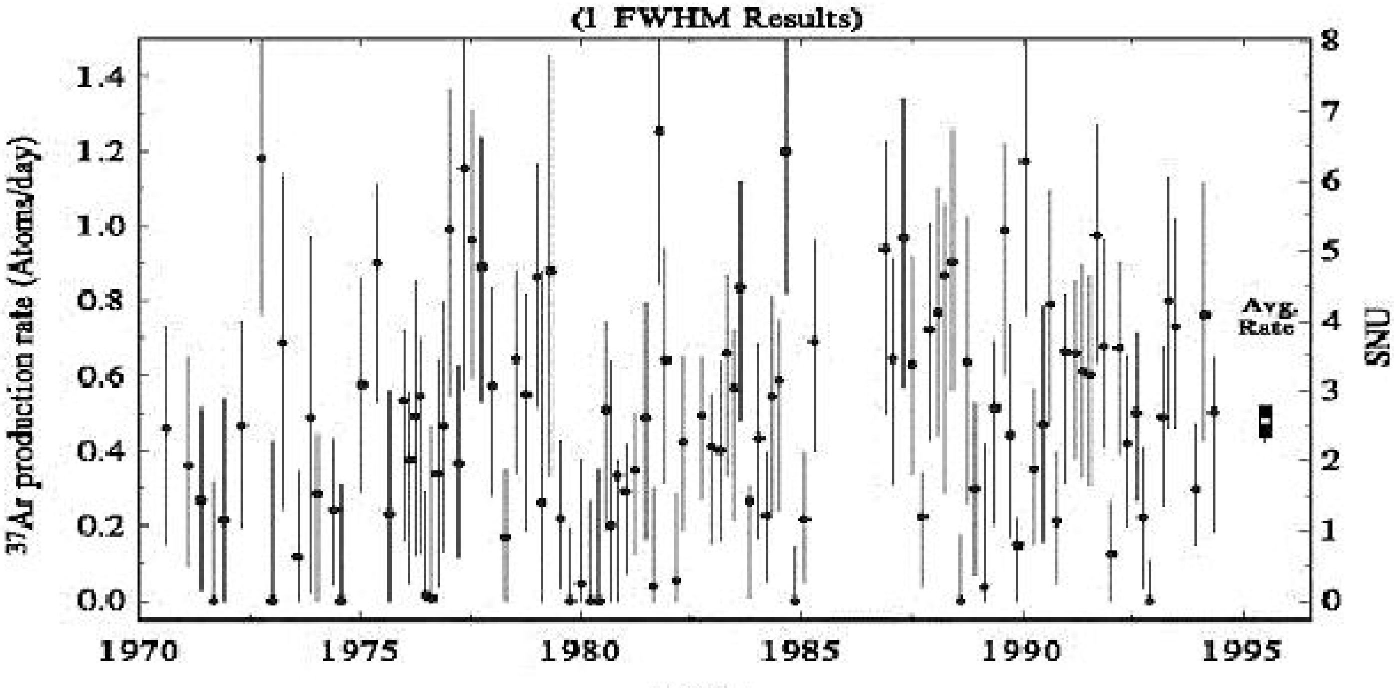
1982: konec prvního dějství

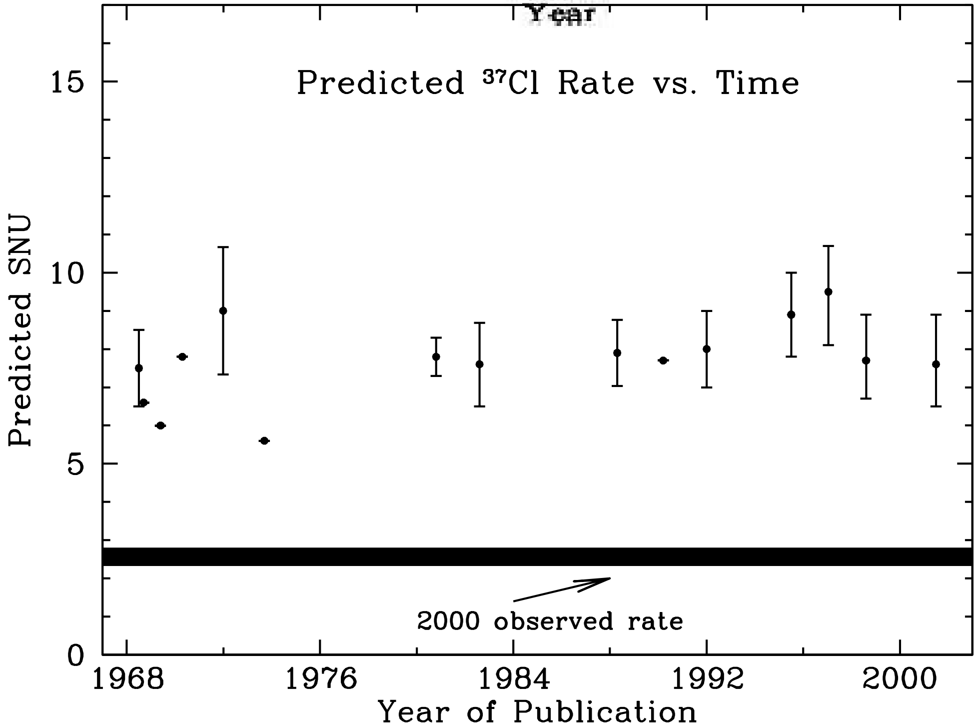
J. Bahcall, R. Davis, v *Nuclear Astrophysics*, CUP, 1982, st. 243:

Závěrem bychom chtěli říci, že věříme, že ať bude řešení problému slunečních neutrin jakékoliv, spojené úsilí mnoha lidí (chemiků, jaderných fyziků, atrofyziků, geofyziků a fyziků elementárních částic) během uplnynulých dvou destiletí nakonec přinese větší porozumění dějů probíhajících v nitru Slunce i hranic našich dnešních znalostí.... Budoucí experimenty se slunečními netriny musí jasněji vymezit chybějíci článek našich znalostí u ukázat, zda je primárně ve **fyzice** nebo **astrofyzice**.



$\Phi_{teorie} = 7.5 \pm 1.5$ SUN, $\Phi_{exp} = 2.2 \pm 0.4$ SUN


(1 FWHM Results)
^{37}Ar production rate (Atoms/day)
SNU
Avg. Rate
Year
1970
1975
1980
1985
1990
1995


Predicted ^{37}Cl Rate vs. Time
Predicted SNU
2000 observed rate
Year of Publication
1968
1976
1984
1992
2000

GALLEX a SAGE: $\nu_e + {}^{71}_{31}\mathrm{Ga} \rightarrow {}^{71}_{32}\mathrm{Ge}$

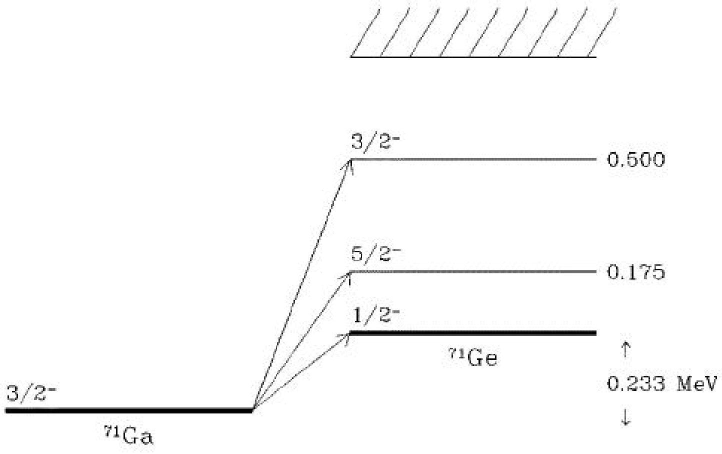
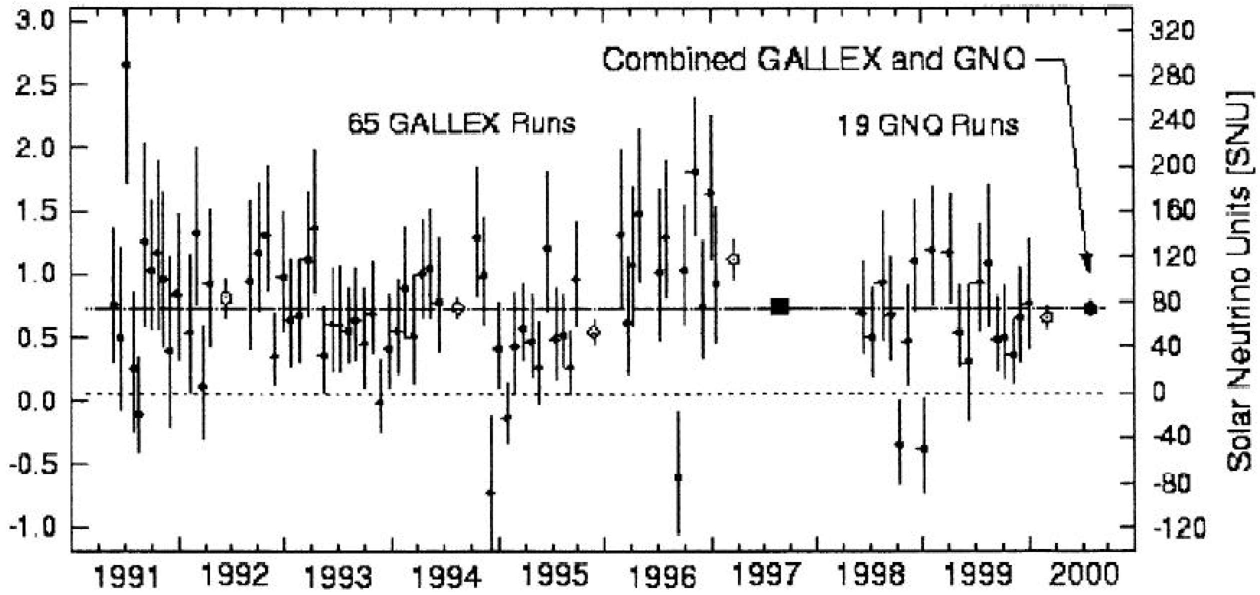


FIG. 1. The ^{71}Ga-^{71}Ge transitions for low energy neutrinos. Only the ground state and the first two allowed excited state transitions contribute to the absorption of pp, ^{7}Be, and ^{51}Cr neutrinos.

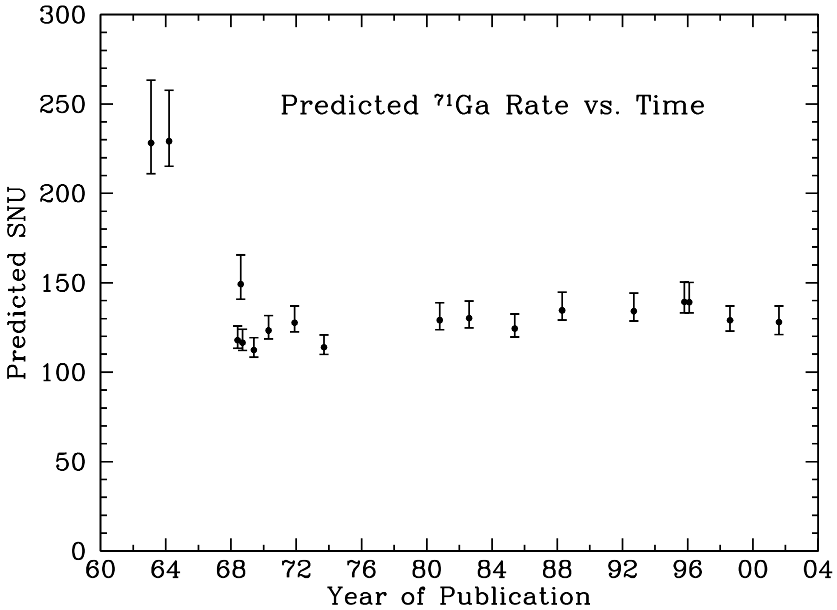


GALLEX: 78 ± 6.5 SUN

SAGE: 67 ± 8 SUN

GA+SA: 73.4 ± 5.7 SUN

BP98: 129 ± 6 SUN



Co to jsou oscilace neutrin?

Zákon **zachování leptonových čísel neplyne** ze žádných hlubších principů, ale byl odvozen z experimentu. V případě dvou typů neutrin, např. ν_e a ν_μ, Pontecorvo předpokládal, že v okamžiku jejich vzniku lze stavy ν_e, ν_μ vyjádřit jako lineární kombinace

$$\begin{aligned} \pi^+ \rightarrow \mathrm{e}^+ + \nu_e, \qquad \nu_e &\equiv \nu_1 \cos\theta + \nu_2 \sin\theta \\ \pi^+ \rightarrow \mu^+ + \nu_\mu, \qquad \nu_\mu &\equiv -\nu_1 \sin\theta + \nu_2 \cos\theta \end{aligned}$$

ν_1, ν_2 mají dobře definované hmotnosti. Pokud $\Delta m^2 = m_1^2 - m_2^2 \neq 0$, nejsou ν_e, ν_μ stacionární stavy, což vede ke **oscilace**

$$\begin{aligned} P(\nu_e \rightarrow \nu_e) &= 1 - \sin^2(2\theta) \sin^2 \frac{\Delta m^2 L}{4E} \\ P(\nu_e \rightarrow \nu_\mu) &= \sin^2(2\theta) \sin^2 \frac{\Delta m^2 L}{4E} \end{aligned}$$

kde E jejich energie a L vzdálenost detektoru od zdroje.

Oscilace neutrin v hmotě

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Neutrino oscillations in matter

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(Received 6 October 1977; revised manuscript received 5 December 1977)

The effect of coherent forward scattering must be taken into account when considering the oscillations of neutrinos traveling through matter. In particular, for the case of massless neutrinos for which vacuum oscillations cannot occur, oscillations can occur in matter if the neutral current has an off-diagonal piece connecting different neutrino types. Applications discussed are solar neutrinos and a proposed experiment involving transmission of neutrinos through 1000 km of rock.

1978: Lincoln Wolfenstein:

systém $\nu_e \leftrightarrow \nu_\mu$
jako analogie
systému $\overline{K}_0 \leftrightarrow K_0$
oscilace ve hmotě analog
regenerace K_0^S

In general, if one is considering the possibility of large vacuum oscillation lengths, as in the discussion of solar neutrinos, the oscillations should be calculated for the actual vacuum path[16] ignoring the passage through matter. Thus, in the detailed solar neutrino calculations[10] the effective distance over which neutrino oscillations take place is from the solar surface to the earth's surface; there are no significant oscillations inside the sun or in traversals through the earth.

Jednotné teorie a stabilita protonu

Stabilita protonu není důsledkem fyzikálního principu, ale je to (zatím) čistě experimentální fakt. Výchozím bodem jednotných teorií je předpoklad, že kvarky a leptony jsou součástí stejného multipletu jisté grupy vnitřní symetrie. To vede na předpověď **nestability všech hadronů, včetně nukleonů!**

1974: Georgi, Glashow navrhli grupu SU(5):

$$\mathbf{5} = (\overline{d}, \overline{d}, \overline{d}, \nu_e, e^-)$$

$$\mathbf{10} = (\overline{u}, \overline{u}, \overline{u}, u, u, u, d, d, d, e^+) \Rightarrow uu \rightarrow X \rightarrow \overline{d}e^+$$

to vede například k rozpadu proton$(uud) \rightarrow \pi^0(d\overline{d})$+e$^+$ teoretický odhad doby života $\tau_p \geq 10^{31\pm1}$ let

Kamioka nucleon decay experiment

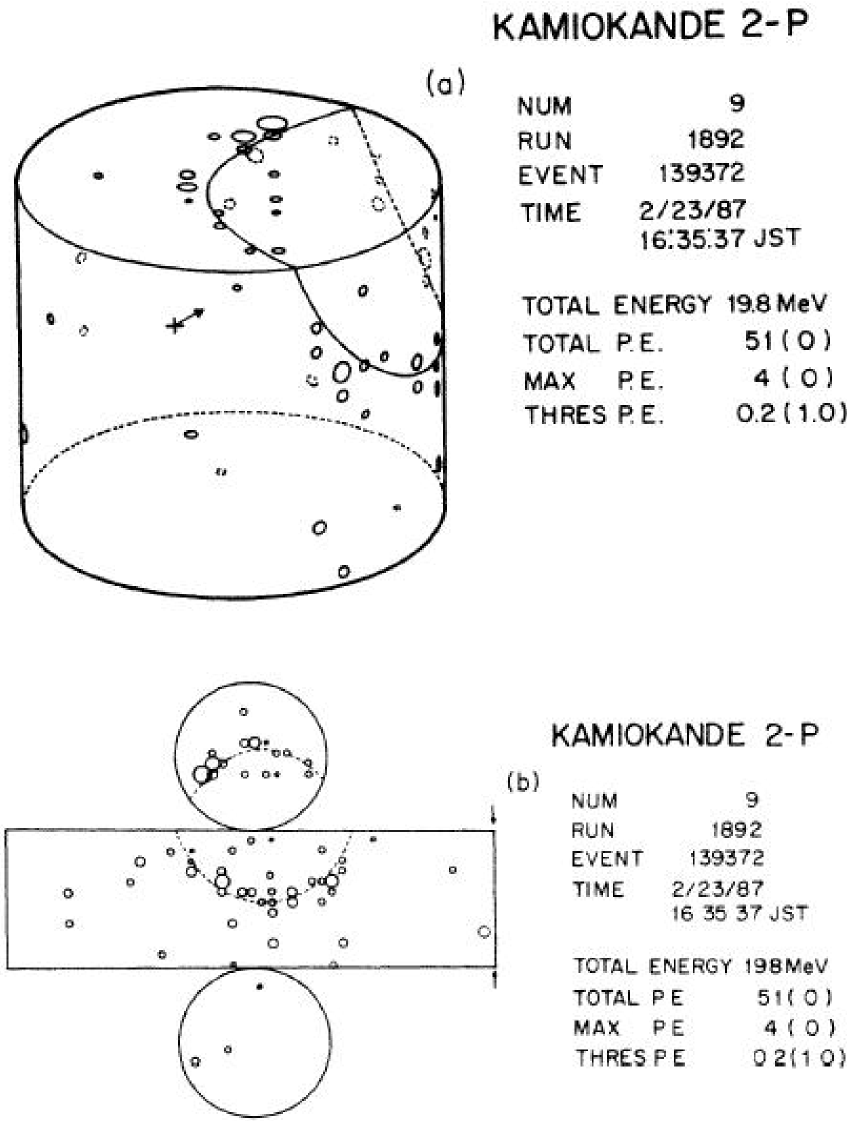
Hlavní motivace: hledání **rozpadu protonu**

První Koshibovy úvahy v roce 1978

Dokončení v roce 1983, zhruba ve stejné době i další experimenty

Čerenkovský vodní detektor:

- 1000 metrů pod zemí v dole na zinek Kamioka
- 3000 tun vody, $m_{\mathrm{p}} \doteq 1.7\ 10^{-27}kg\rightarrow$ v 100 kg je 0.6 10^{29} protonů
- 1000 fotonásobičů o průměru 50 cm
- čerenkovské záření částic pro než $(v/c)n > 1$, $n_{voda} = 1.33$
- rozlišení elektronů od mionů a pionů
- možnost detekce **slunečních neutrin** z rozpadu
  ${}^8_5\mathrm{B}\rightarrow{}^8_4\mathrm{Be}+\mathrm{e}^+ + \nu_e$ měřením rozptylu $\nu_e + e^- \rightarrow \nu_e + e^-$



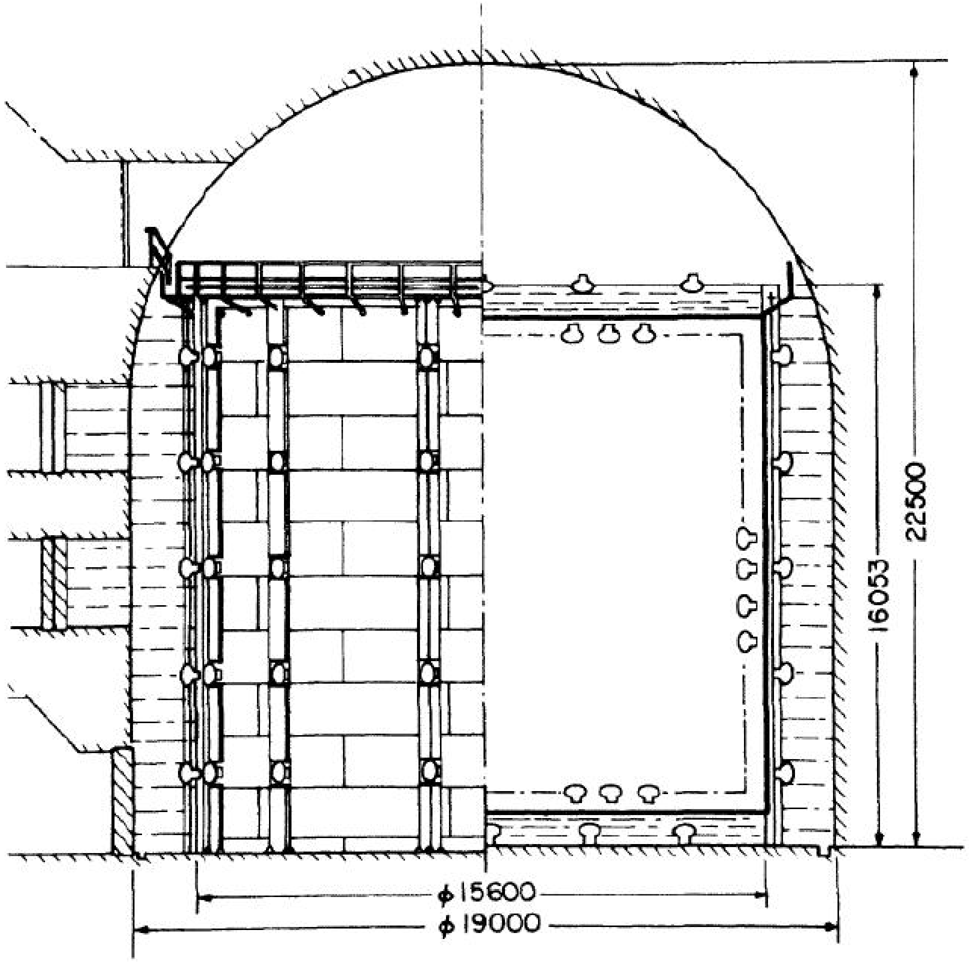
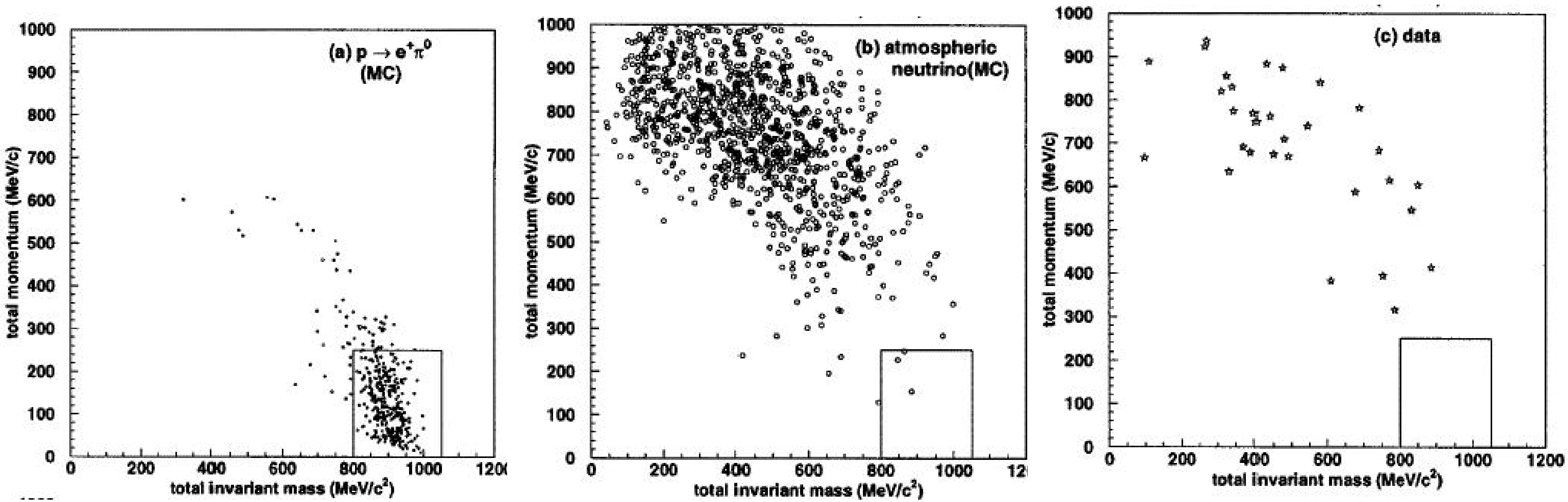


FIG. 1. Schematic outline of the detector, Kamiokande-II. The anticounter is shown by the dashed area. Dimensions are in mm.

Rozpad protonu v Kamiokande a Superkamiokande

celková hybnost P_{tot} vs invariantní hmota $M_{tot} \equiv \sqrt{E_{tot}^2 - P_{tot}^2}$



Kamiokande: $\tau_{\rm p}(e^+\pi^0) \geq 2.6\ 10^{32}$ let, $\tau_{\rm p}(\overline{\nu}_e K^0) \geq 0.9\ 10^{32}$ let

Superkamiokande: $\tau_{\rm p}(e^+\pi^0) \geq 1.6\ 10^{33}$ let, $\tau_{\rm p}(\overline{\nu}_e K^0) \geq 0.7\ 10^{33}$ let

Sluneční neutrina v Kamiokande: $\nu_e + e^- \to \nu_e + e^-$

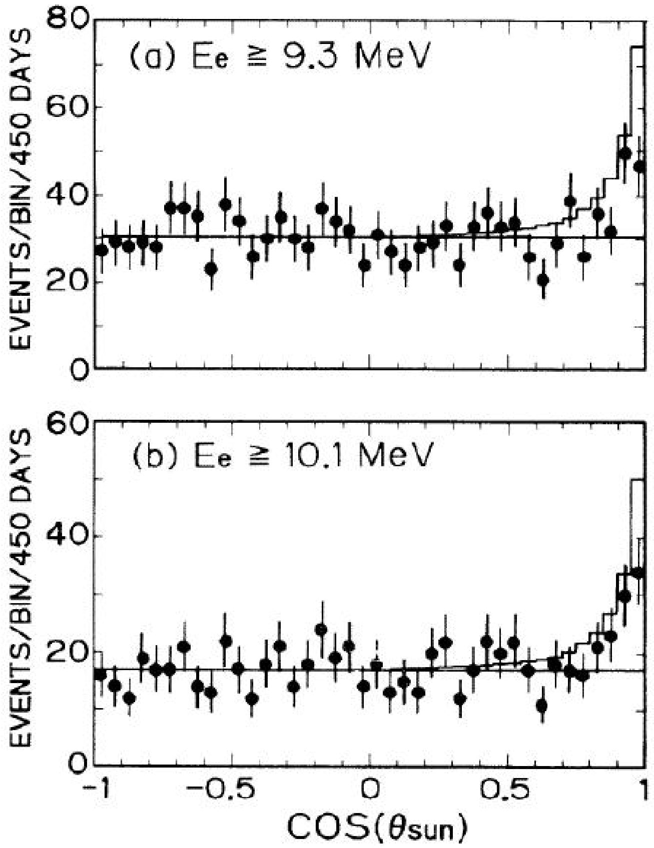


FIG. 2. Distributions in $\cos\theta_{\rm Sun}$, the cosine of the angle between the trajectory of an electron and the direction of the Sun at a given time. The data are in the 680-ton fiducial region (a) with $E_e \geq 9.3$ MeV and (b) with $E_e \geq 10.1$ MeV, respectively. Events identified as spallation products or remaining γ rays have been excluded.

The measured value of the ^{8}B solar neutrino flux for $E_e \geq 9.3$ MeV from the Kamiokande-II detector in the time period January 1987 through May 1988 (450 live detector days) is given by

$$\frac{\text{Kam-II data}}{\text{SSM}} = 0.46 \pm 0.13(\text{stat.}) \pm 0.08(\text{syst.}), \quad (1)$$

where SSM is the central value predicted by a Monte Carlo calculation based on the standard solar model[2] and subject to the same event criteria and experimental

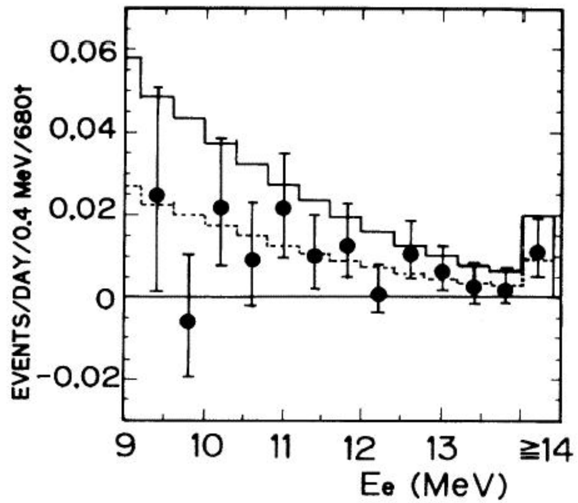
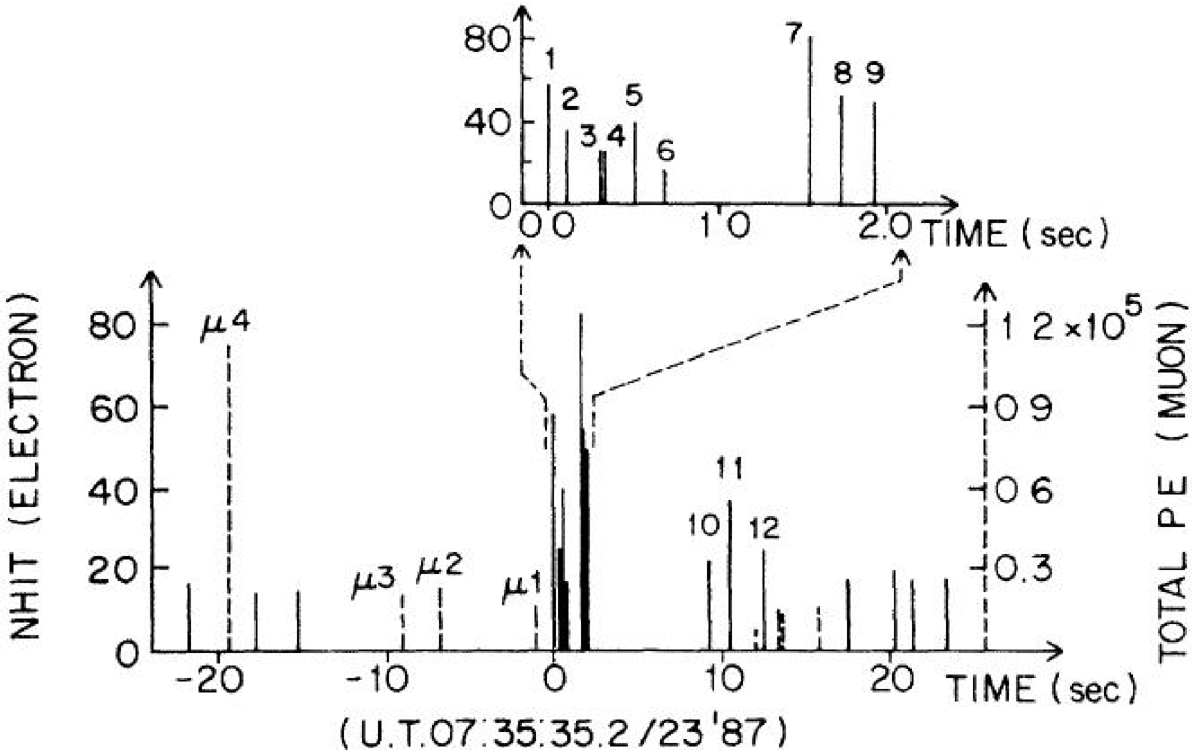


FIG. 3. Energy distribution of the solar neutrino signal (see text). The histogram is the distribution predicted by the SSM. The highest bin corresponds to $E_e \geq 14$ MeV. The dotted line shows the best fit to the data (0.46 SSM).

Neutrina se supernovy SN1987A

23. února 1987 byl ve Velkém Magellanově mraku pozorován výbuch supernovy **SN1987A**. Kamiokande zaznamenal **3 hodiny** před optickým signálem shluk 11 případů během 13 vteřin.



Interpretace: neutrina doprovázející vznik **neutronové hvězdy** u supernov typu II v procesu: $e^- + \mathrm{p} \to \nu_e + \mathrm{n}$

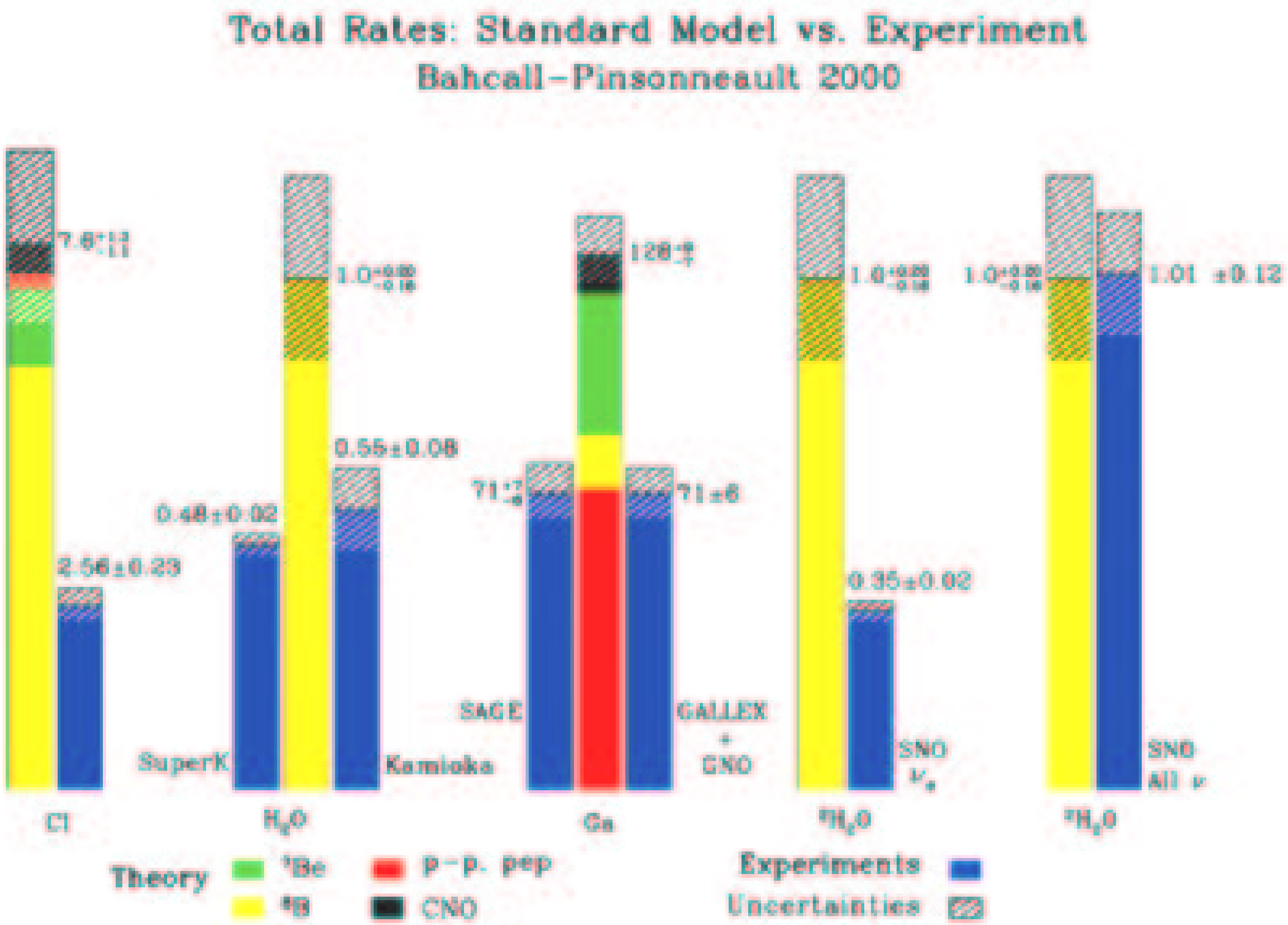
Experiment Superkamiokande

55 000 tun vody, **11 000** fotonásobičů a **135** autorů ⇒ **SK**$>$ 10×**K**

Program:

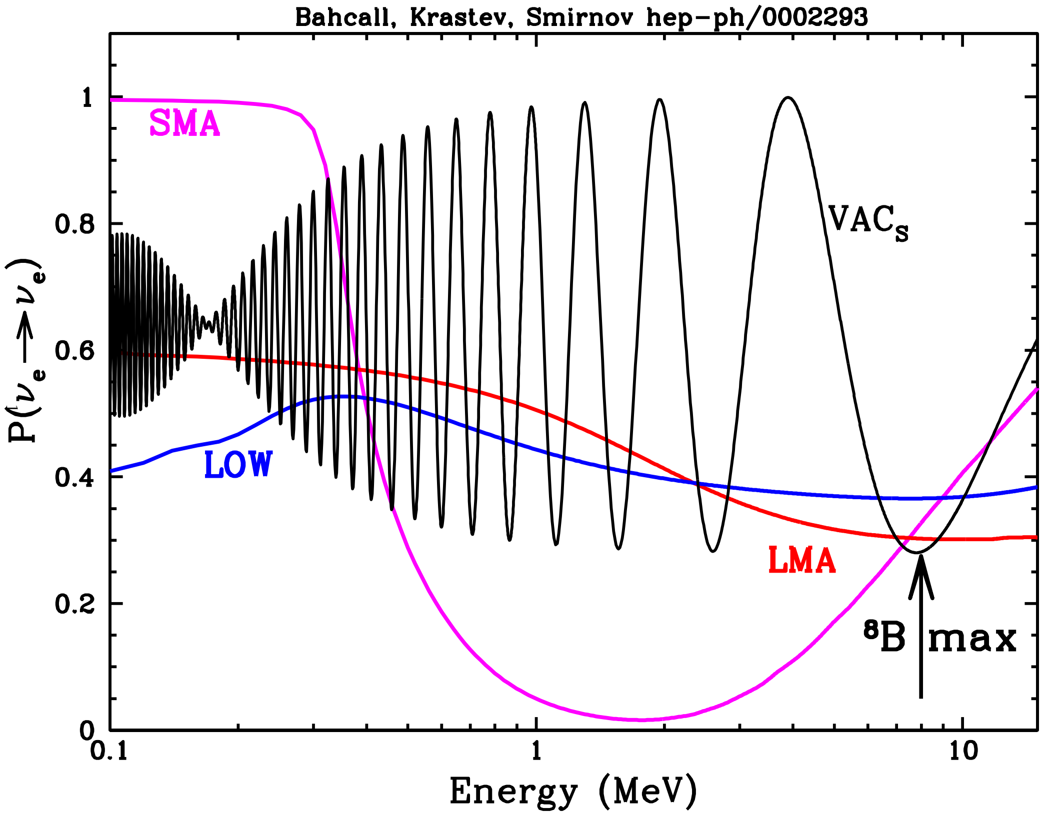
- pokračování hledání **rozpadu nukleonů**
- zpřesnění měření **slunečních neutrin**
- novum: měření **atmosférických neutrin**

V únoru 2001 došlo k **vážné havárie detektoru**



Total Rates: Standard Model vs. Experiment
Bahcall-Pinsonneault 2000
2.56±0.23
0.48±0.02
0.55±0.08
71±6
0.35±0.02
1.01 ±0.12
SuperK
Kamioka
SAGE
GALLEX
+
GNO
SNO
SNO
Cl
Ga
Theory
p-p, pep
CNO
Experiments
Uncertainties

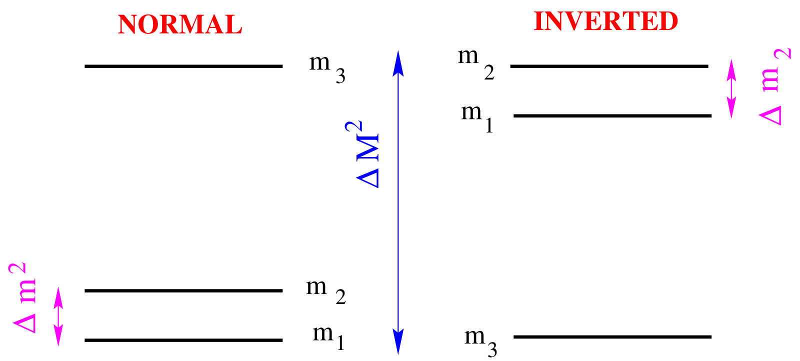
Oscilace slunečních neutrin

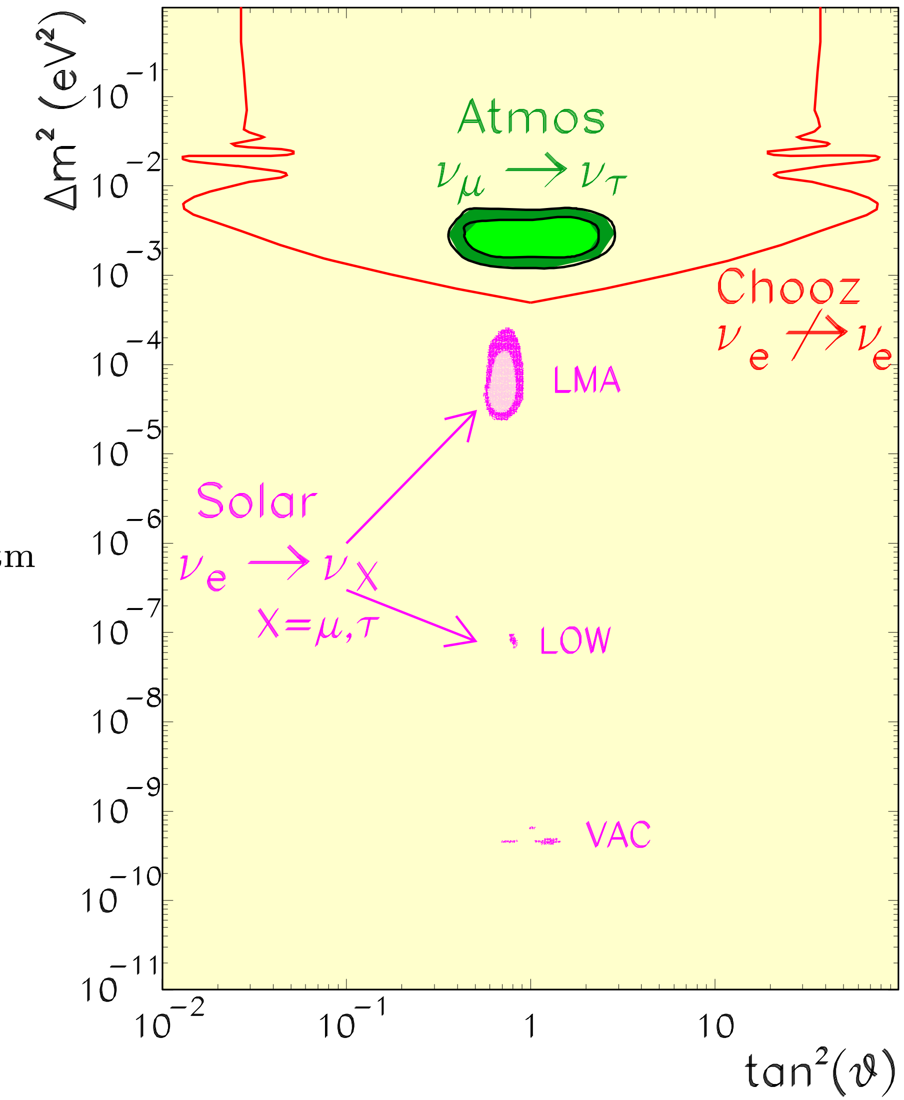


Oscilace slunečních ν jsou rezonančně zesíleny při průchodu Sluncem

$$\sin 2\theta = \frac{\Delta m^2 \sin 2\theta}{\sqrt{(\Delta m^2 \cos 2\theta - A)^2 + (\Delta m^2 \sin 2\theta)^2}}$$

Současný stav našich znalostí o neutrinech





$$\Delta m^2 \equiv \Delta m^2_{\rm sol} \ll \Delta M^2 \equiv \Delta m^2_{\rm atm}$$

$$\theta_{\rm sol} \simeq \theta_{\rm atm} \simeq \pi/4 \Rightarrow$$

- **maximální mixing**
- **kolik je ovšem m_i?**