

Nobelovská neutrina

Polovina NC za fyziku pro rok 2002 byla udělena

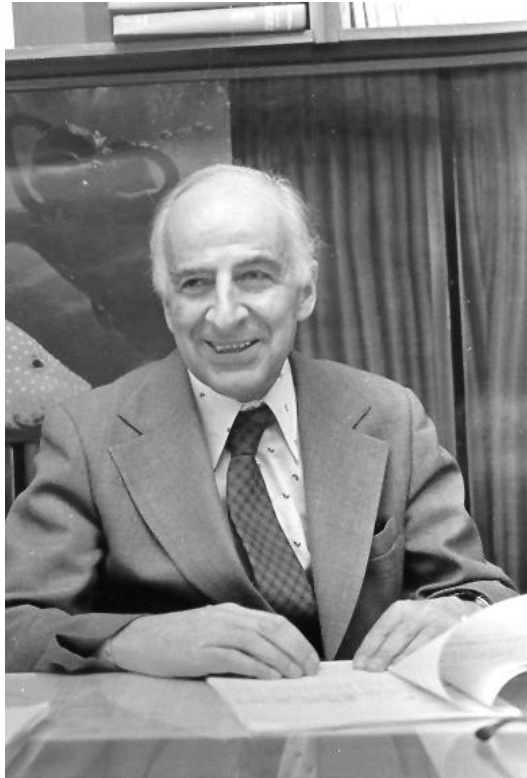
Raymondu Davisovi a Masatoshi Koshibovi

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



Bruno Pontecorvo



Ray Davis a John Bahcall

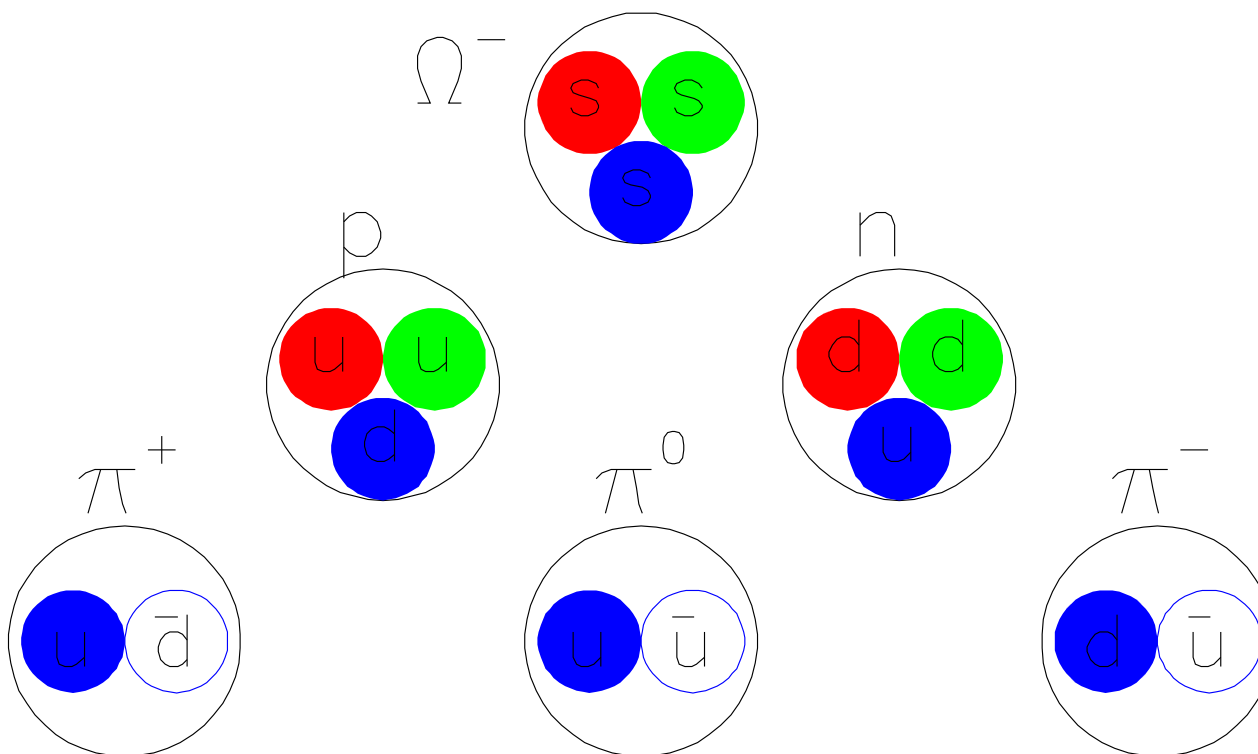
Kvarky a leptony – atomy dneška

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



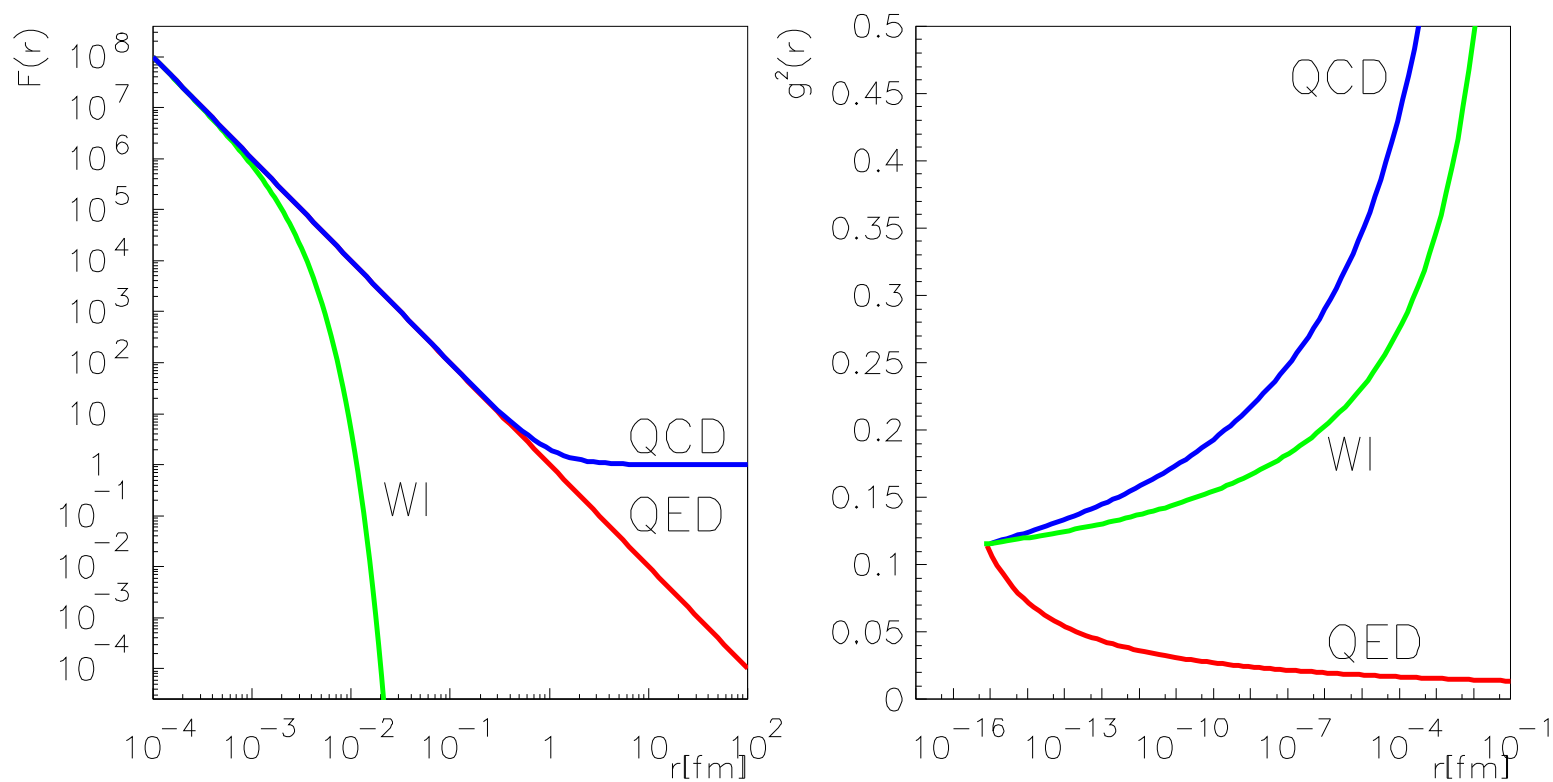
Mezi kvarky a leptony působí **tři typy sil**

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

- které mají všechny **výměnný charakter**
- ale **různý** dosah a velikost
- jejichž **zprostředkující částice**
 - mají **stejný** spin **1** \Rightarrow 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.



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

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

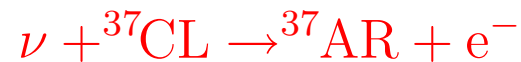
1928: G. Gamow: výpočet **průchodu bariérou**

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

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

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

1946: B. Pontecorvo: návrh detegovat ν pomocí reakce



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

1955: R. Davis: náznak, že $\bar{\nu}_e \neq \nu_e$

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

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

- 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**

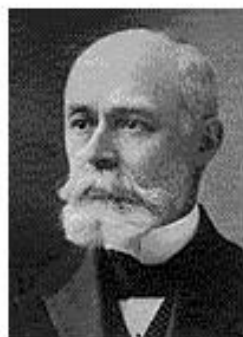
- 1983: M. Koshiba: experiment **Kamiokande**
- 1984: M. Koshiba: navrhl **Kamiokande II** a **Superkamiokande**
- 1986: Michejev, Smirnov: oscilace **neutrin ve Slunci**
- 1987: Kamiokande II: neutrina ze **supernovy**
- 1988: Kamiokande II: první měření **slunečních ν**
- 1995: J. Bahcall, M. Pinsonneault: výpočet toku $\Phi(\nu_e)$
- 1996: **Superkamiokande** v provozu, M. Koshiba \rightarrow 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 1/2 of the prize
France

École Polytechnique
Paris, France



Pierre Curie

① 1/4 of the prize
France

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



Marie Curie, née Skłodowska

① 1/4 of the prize
France

RADIOACTIVITY, NEW PROPERTY OF MATTER

*60 - 1000 90. . Sulfate double d'uranyle et de Potassium
Papier noir - Cour. De la source lumineuse
Exposé au soleil le 27. et à la lampe à gaz le 28
Résultat le 15 mars.*



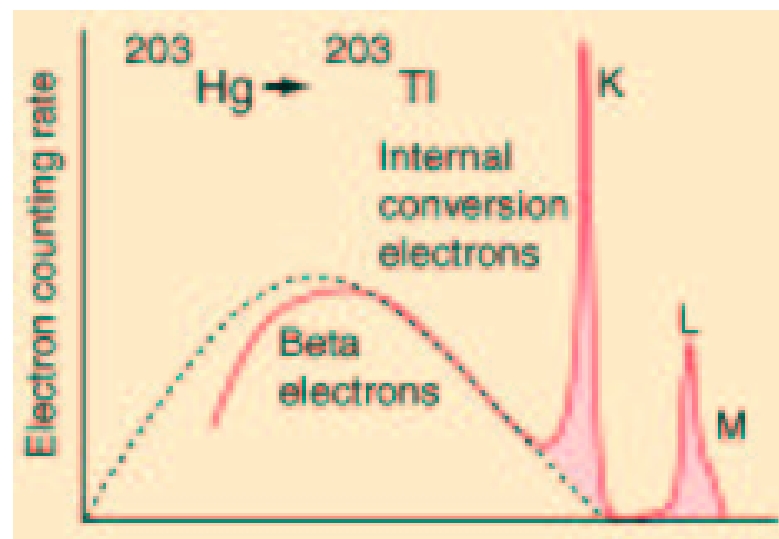
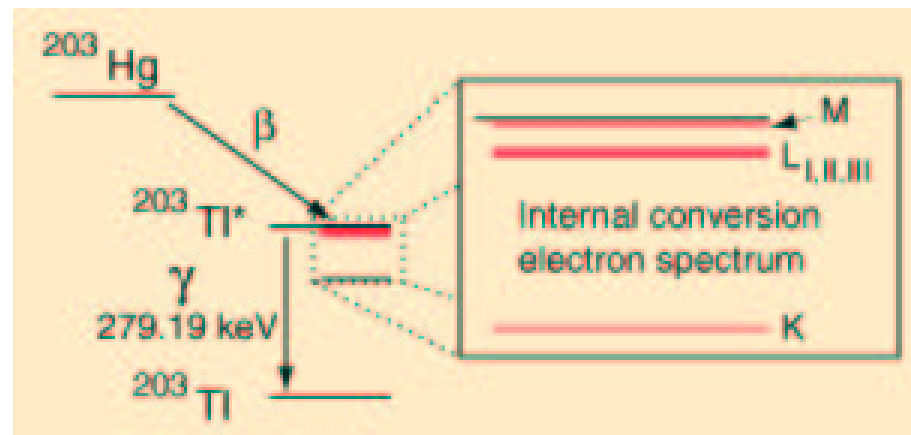
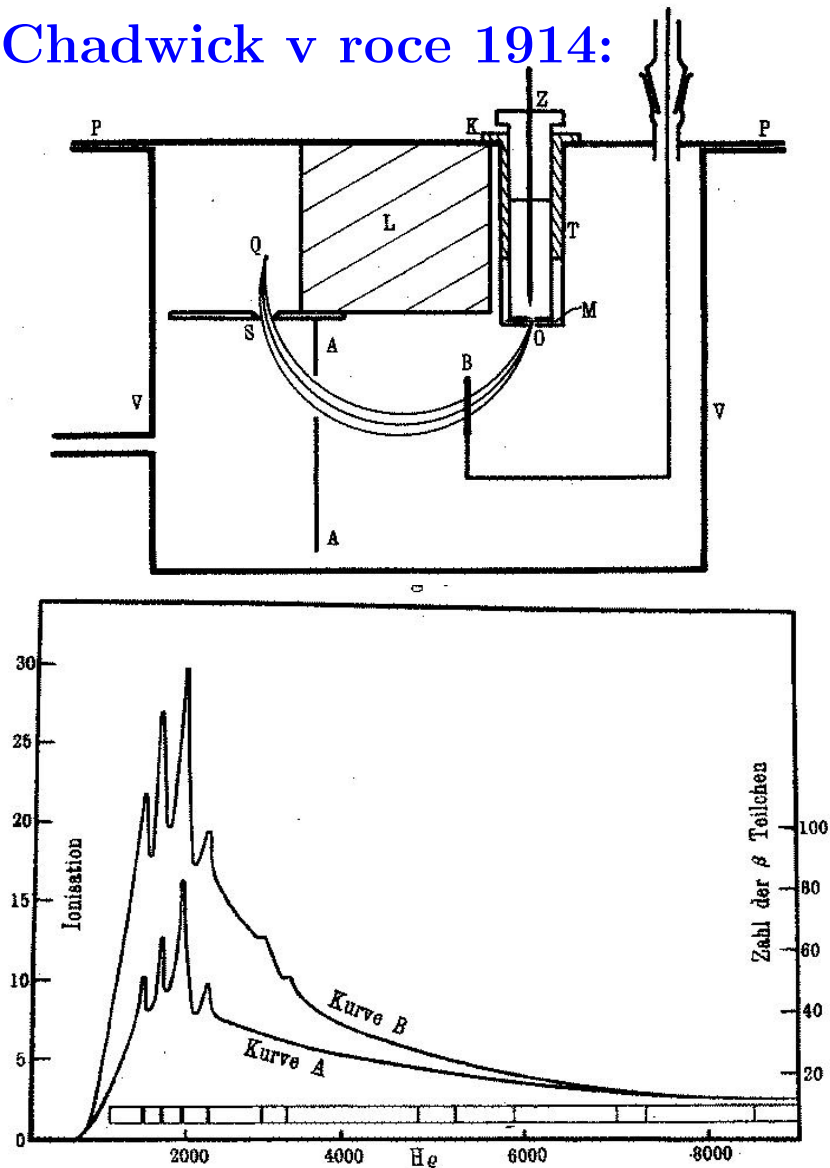
Thus I placed sheets of double sulphate of uranium and potassium on photographic plates enveloped in black paper or protected by a sheet of aluminium and exposed them to light for several hours. On developing the plates, I found that the uranium salt had emitted rays which reproduced the silhouettes 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 něj 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 přišlo 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 součástí jádra**

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

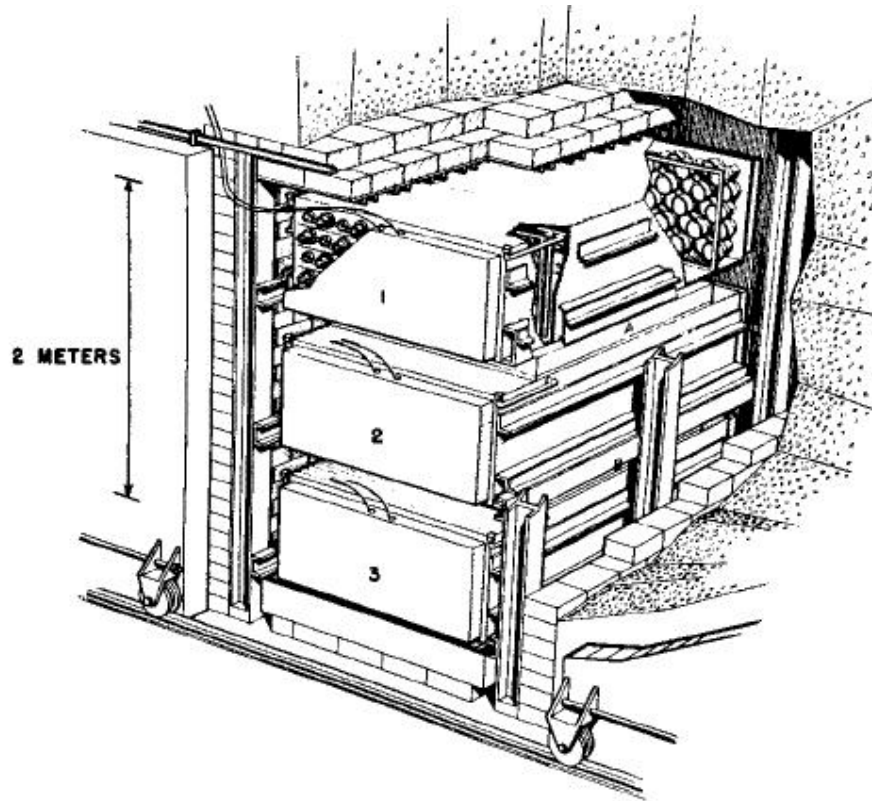
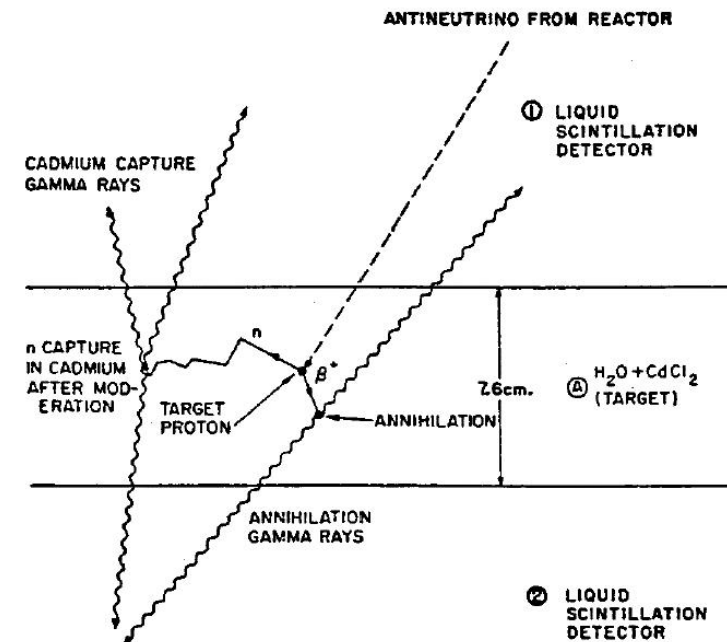


FIG. 5. A sketch of the equipment used at Savannah River. The tanks marked 1, 2, and 3 contained 1400 liters of liquid scintillator solution and were viewed on each end by 55 photomultiplier tubes. The thin tanks marked A and B were polystyrene and contained 200 liters of water, which provided the target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

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



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

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

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).

Gamow and Teller.⁴ The total number of processes per gram per second is⁴

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

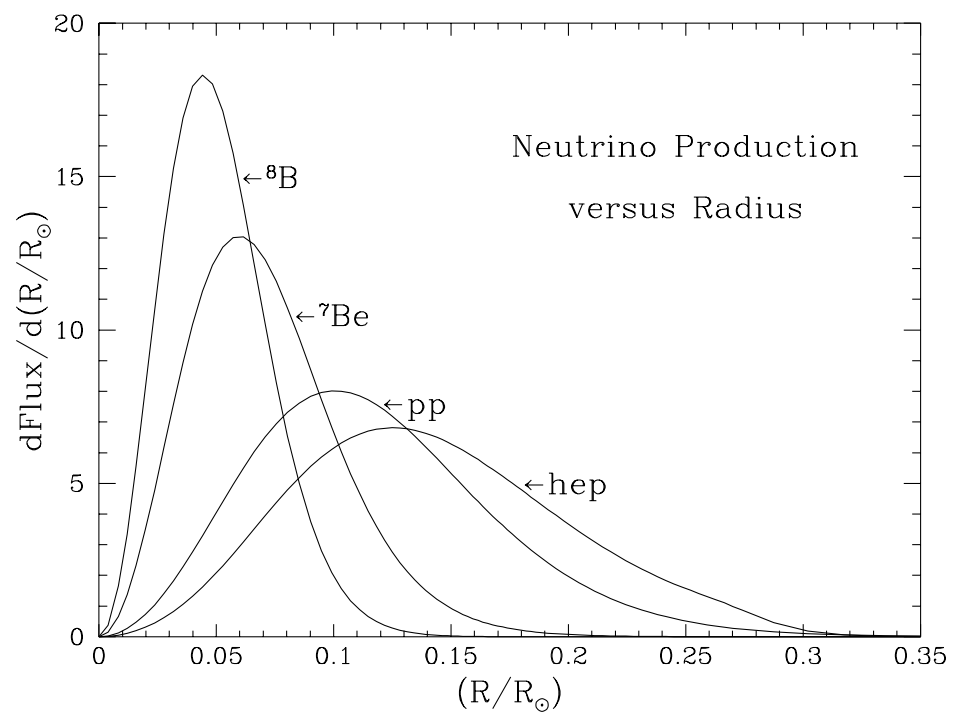
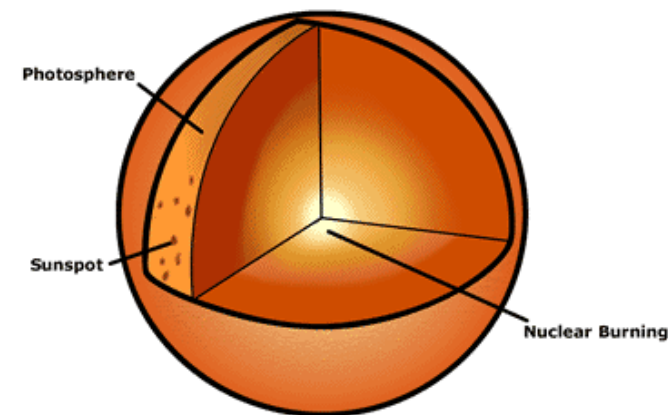
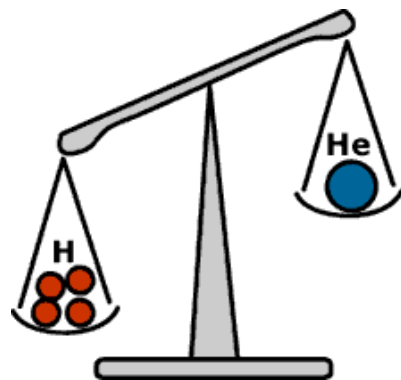
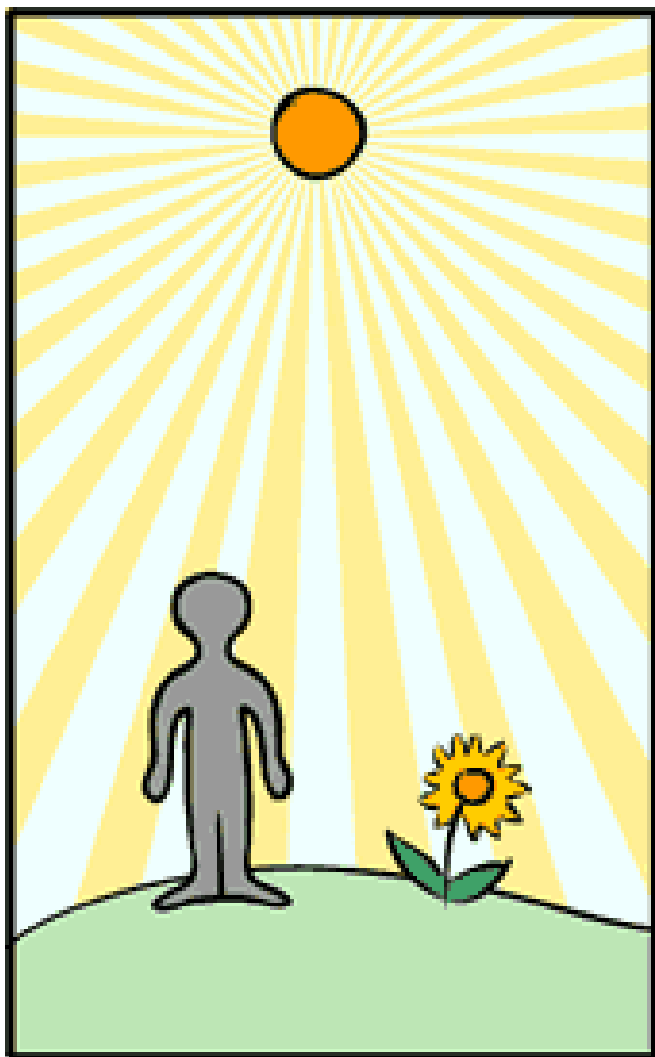
integration of the Eddington equations gives 19. For the brilliant star Y Cygni the corresponding figures are 30 and 32. This good agreement holds for all bright stars of the main sequence, but, of course, not for giants.

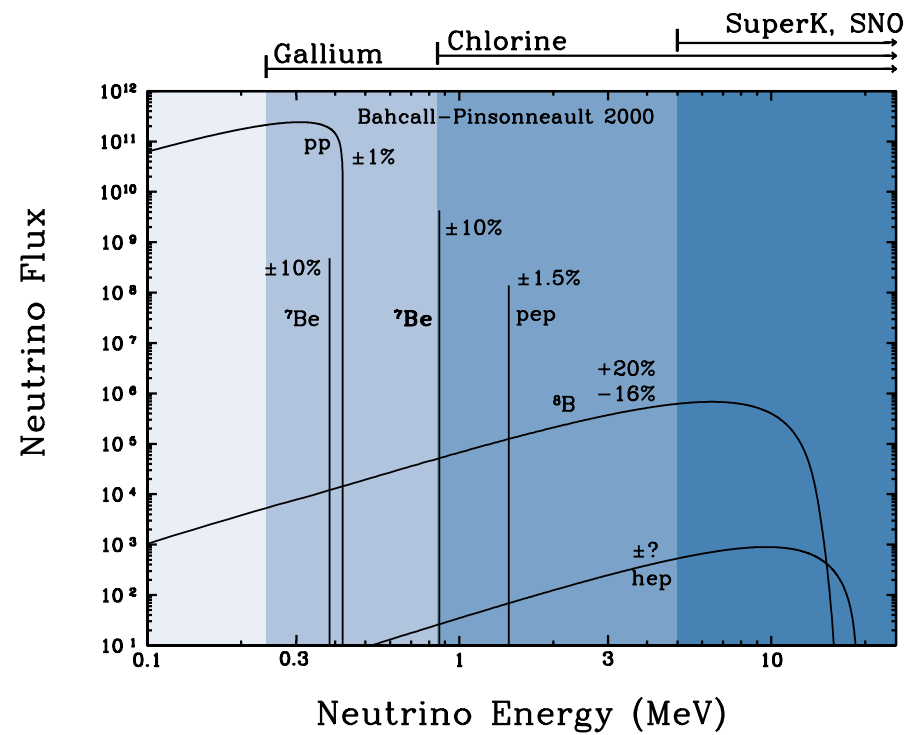
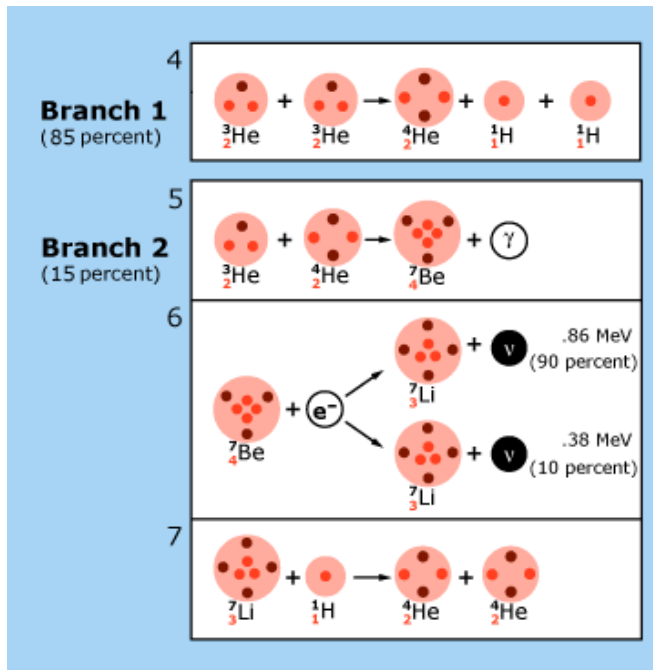
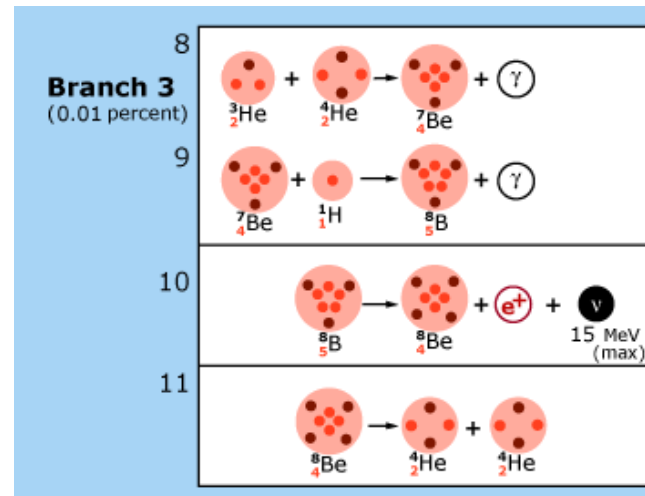
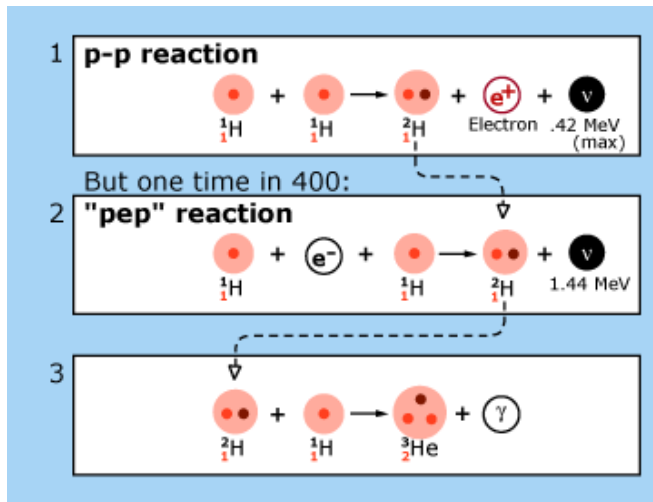
For fainter stars, with lower central temperatures, the reaction $H + H = D + \epsilon^+$ and the reactions following it, are believed to be mainly responsible for the energy production. (§10)

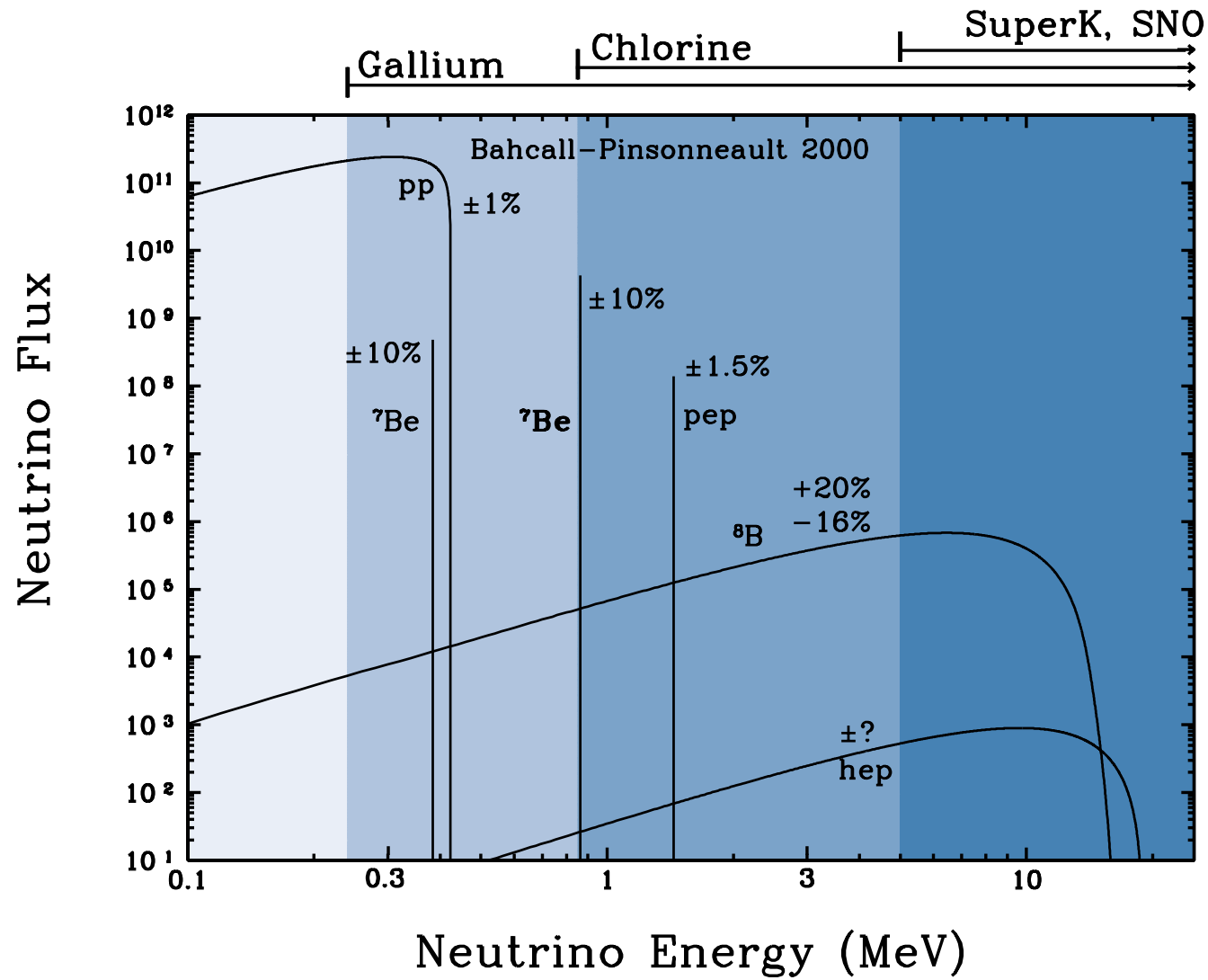
$$a = \hbar^2 / m e^2 Z_1 Z_2 \quad (5)$$

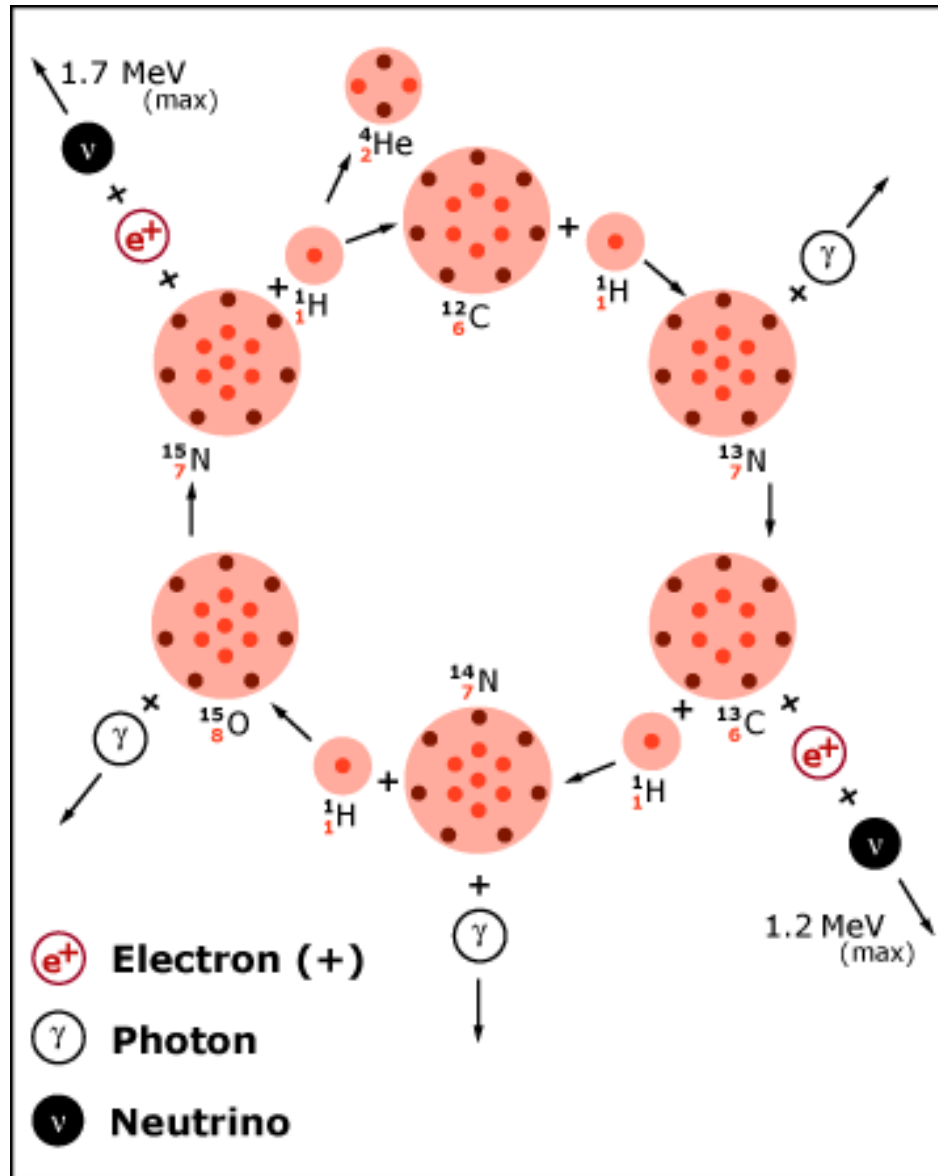
the "Bohr radius" for the system, Γ/\hbar the probability of the nuclear reaction, in sec.^{-1} , after penetration, and

$$\tau = 3 \left(\frac{\pi^2 m e^4 Z_1^2 Z_2^2}{2 \hbar^2 k T} \right)^{1/2}. \quad (6)$$









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 $\text{Cl}^{37}(\bar{\nu}, e^-)\text{A}^{37}$ 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 $\text{Cl}^{37}(\bar{\nu}, e^-)\text{A}^{37}$ 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 Pontecorvo³ suggested a radiochemical method of detecting the neutrino by employing the reaction $\text{Cl}^{37}(\bar{\nu}, e^-)\text{A}^{37}$. 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 $\text{Cl}^{37}(\bar{\nu}, e^-)\text{A}^{37}$. A positive experiment of this type would. These studies have indicated that neutrinos and antineutrinos do differ in their interactions with nucleons.⁵

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 ${}^1\text{H}(p, e^+\nu){}^2\text{H}(p, \gamma){}^3\text{He}$ and terminated by the following sequences: (i) ${}^3\text{He}({}^3\text{He}, 2p){}^4\text{He}$; (ii) ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}(e^-\nu){}^7\text{Li}(p, \alpha){}^4\text{He}$; and (iii) ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}(p, \gamma){}^8\text{B}(e^+\nu){}^8\text{Be}^*(\alpha){}^4\text{He}$. 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 method² for detecting solar neutrinos is based upon the endothermic reaction ($Q = -0.81$ MeV) ${}^{37}\text{Cl}(\nu_{\text{solar}}, e^-){}^{37}\text{Ar}$, which was first discussed as a possible means of detecting neutrinos by Pontecorvo³ 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 ${}^{37}\text{Cl}(\nu, e^-){}^{37}\text{Ar}$ induced us to place the apparatus previously described¹ 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 ${}^{37}\text{Ar}$ production rate at least a factor of ten below the expected rate from solar neutrinos. It should be noted that if a positive result

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 $\text{Cl}^{37}(\nu, e^-)\text{Ar}^{37}$. The upper limit of the product of the neutrino flux and the cross sections for all sources of neutrinos was $3 \times 10^{-36} \text{ sec}^{-1}$ 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 $2 \times 10^6 \text{ cm}^{-2} \text{ sec}^{-1}$ 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 $\text{Cl}^{37}(\nu, e^-)\text{Ar}^{37}$.

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

$$\sum \varphi \sigma \leq 0.3 \times 10^{-35} \text{ sec}^{-1} \text{ per } \text{Cl}^{37} \text{ atom,}$$

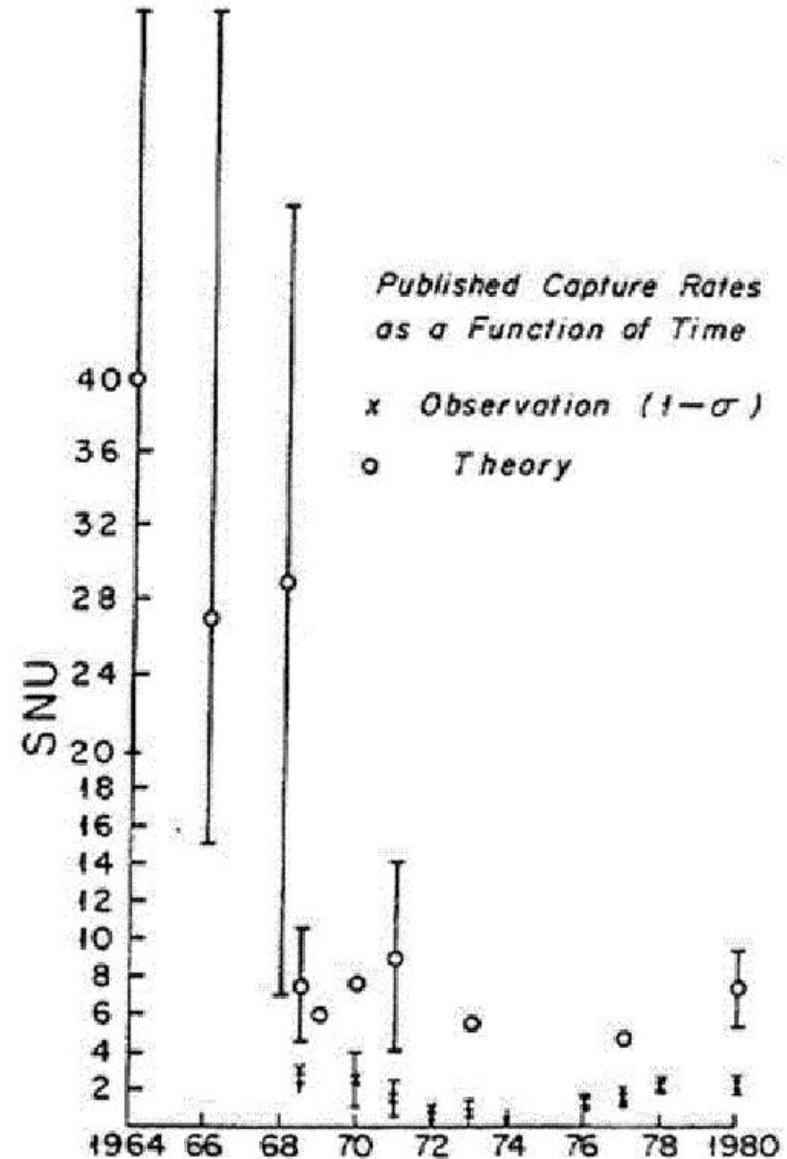
can be compared with the predicted value of $(2.0 \pm 1.2) \times 10^{-35} \text{ sec}^{-1}$ per Cl^{37} atom (Table I). It may be seen that this limit is approximately a factor of 7 below that expected from these solar-model calculations. From this limit and the

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”**.

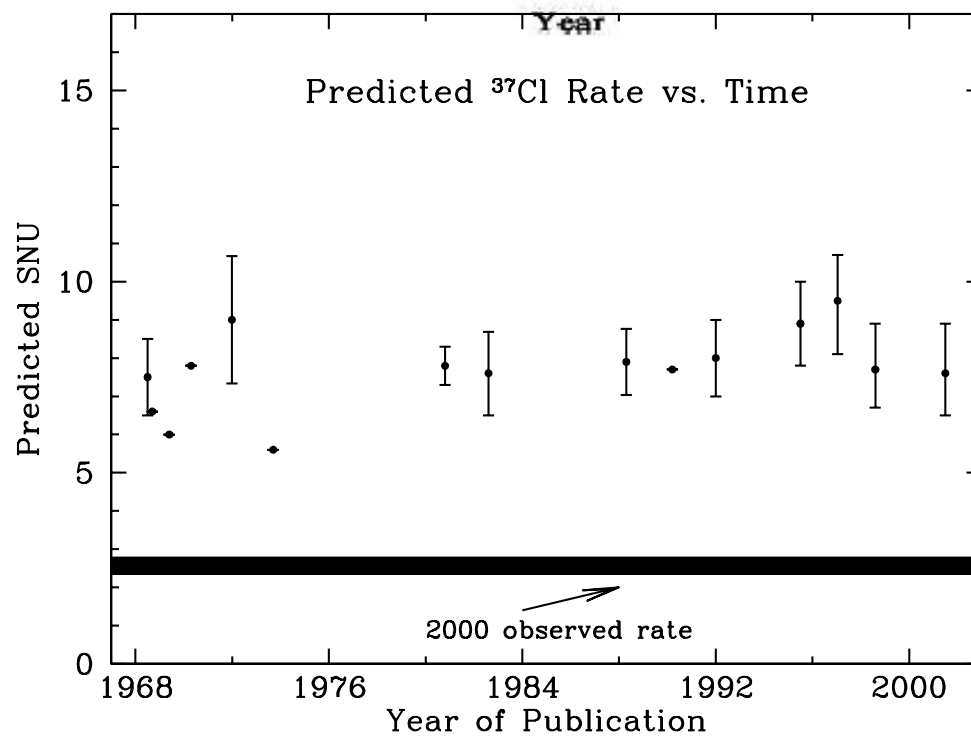
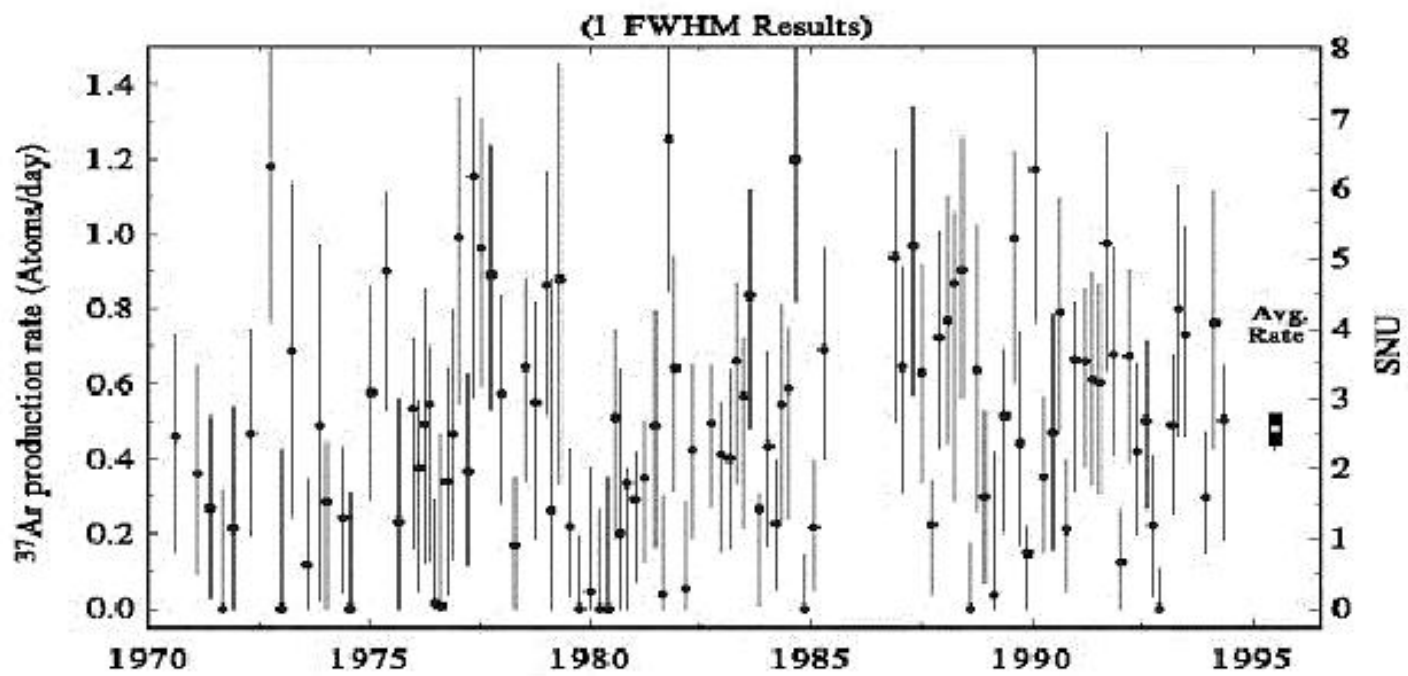
1982: konec prvního dějství

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, astrofyziků, geofyziků a fyziků elementárních částic) během uplynulých dvou desetiletí nakonec přinese větší porozumění dějů probíhajících v nitru Slunce i hranic našich dnešních znalostí.... Budoucí experimenty se slunečními netriny musí jasněji vymezit chybějící články našich znalostí a ukázat, zda je primárně ve fyzice nebo astrofyzice.



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



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

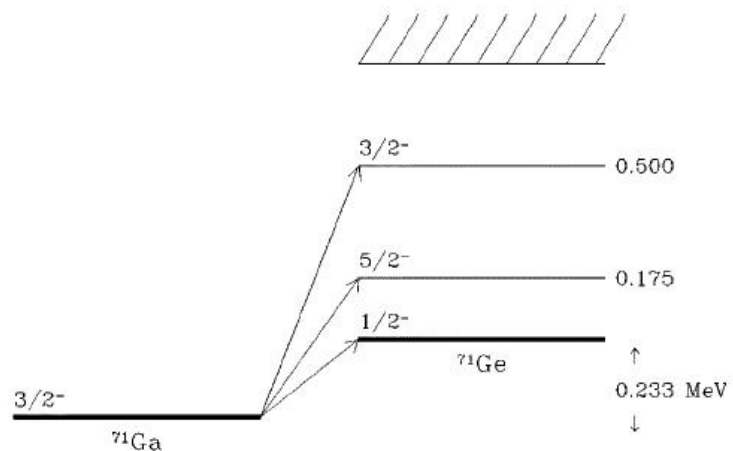
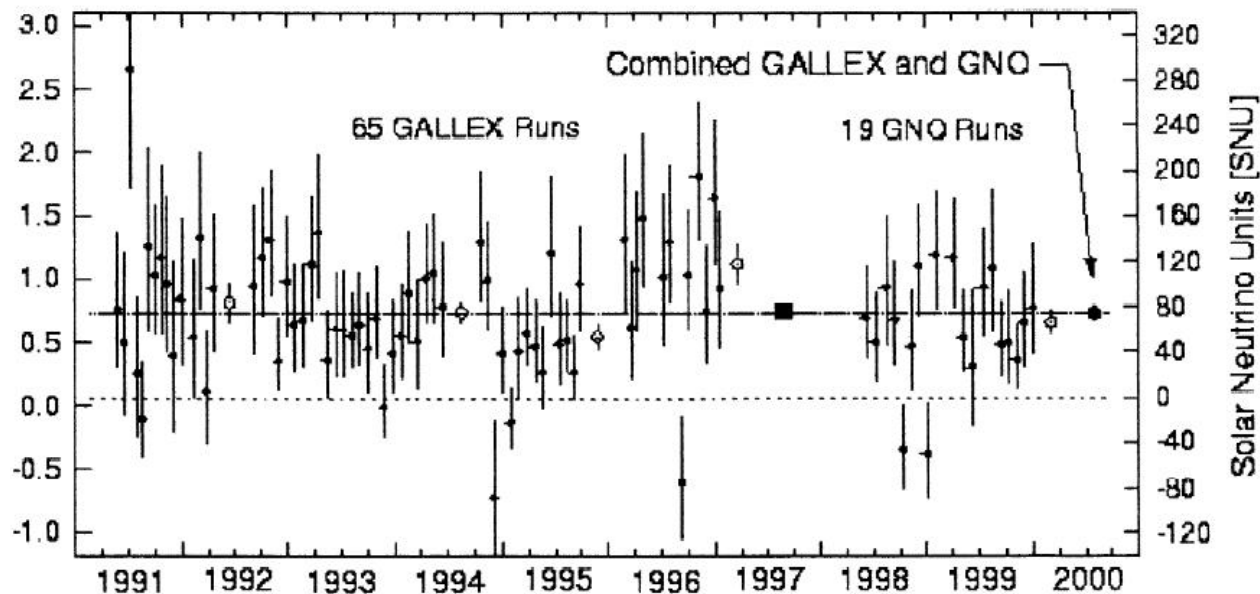
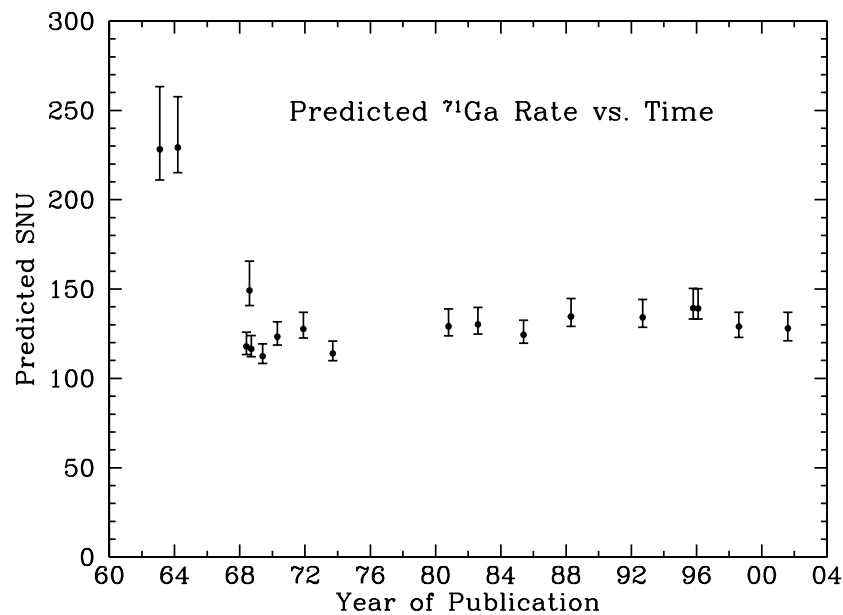


FIG. 1. The ${}^{71}\text{Ga}$ - ${}^{71}\text{Ge}$ transitions for low energy neutrinos. Only the ground state and the first two allowed excited state transitions contribute to the absorption of pp , ${}^7\text{Be}$, and ${}^5\text{Cr}$ neutrinos.



- 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

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

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

PHYSICAL REVIEW D

VOLUME 17, NUMBER 9

1 MAY 1978

Neutrino oscillations in matter

L. Wolfenstein

Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213

(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 $\bar{K}_0 \leftrightarrow K_0$

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 path¹⁶ ignoring the passage through matter. Thus, in the detailed solar neutrino calculations¹⁰ 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)**:

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

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

to vede například k rozpadu **proton**(uud) $\rightarrow \pi^0(d\bar{d}) + e^+$ teoretický odhad doby života $\tau_p \geq 10^{31 \pm 1}$ let

Kamioka nucleon decay experiment

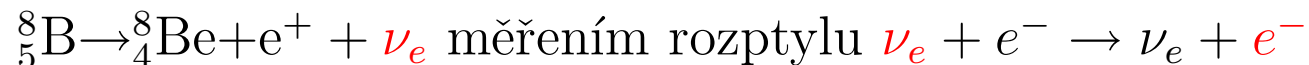
Hlavní motivace: hledání **rozpadu protonu**

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, $m_p \doteq 1.7 \cdot 10^{-27} \text{kg} \rightarrow$ v 100 kg je $0.6 \cdot 10^{29}$ protonů
- 1000 fotonásobičů o průměru 50 cm
- čerenkovské záření částic pro něž $(v/c)n > 1$, $n_{\text{voda}} = 1.33$
- rozlišení elektronů od mionů a pionů
- možnost detekce **slunečních neutrin** z rozpadu



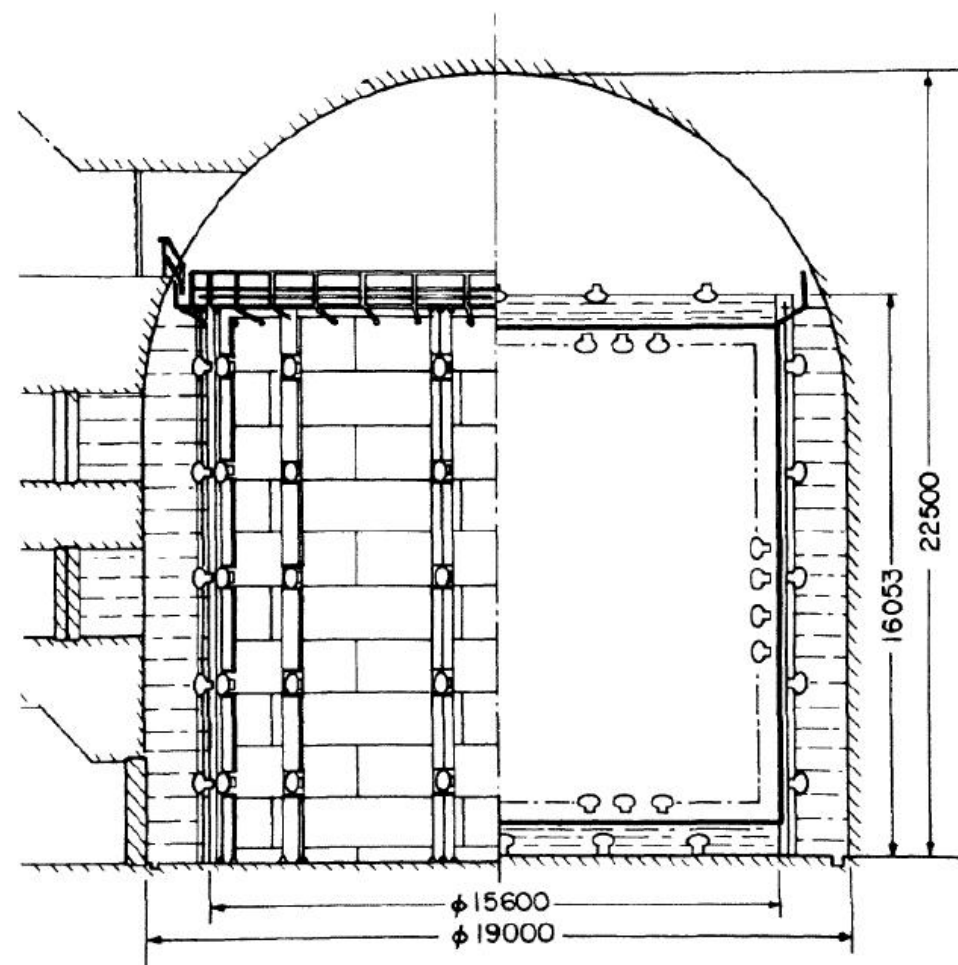
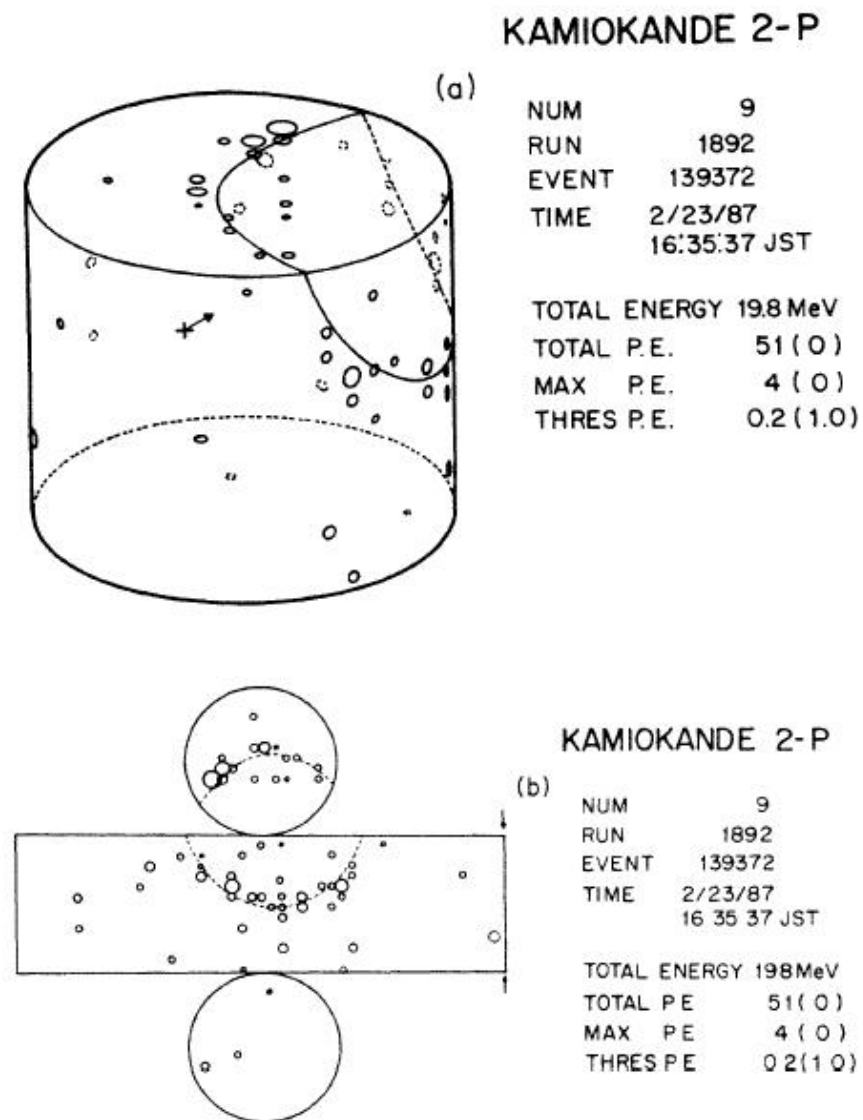
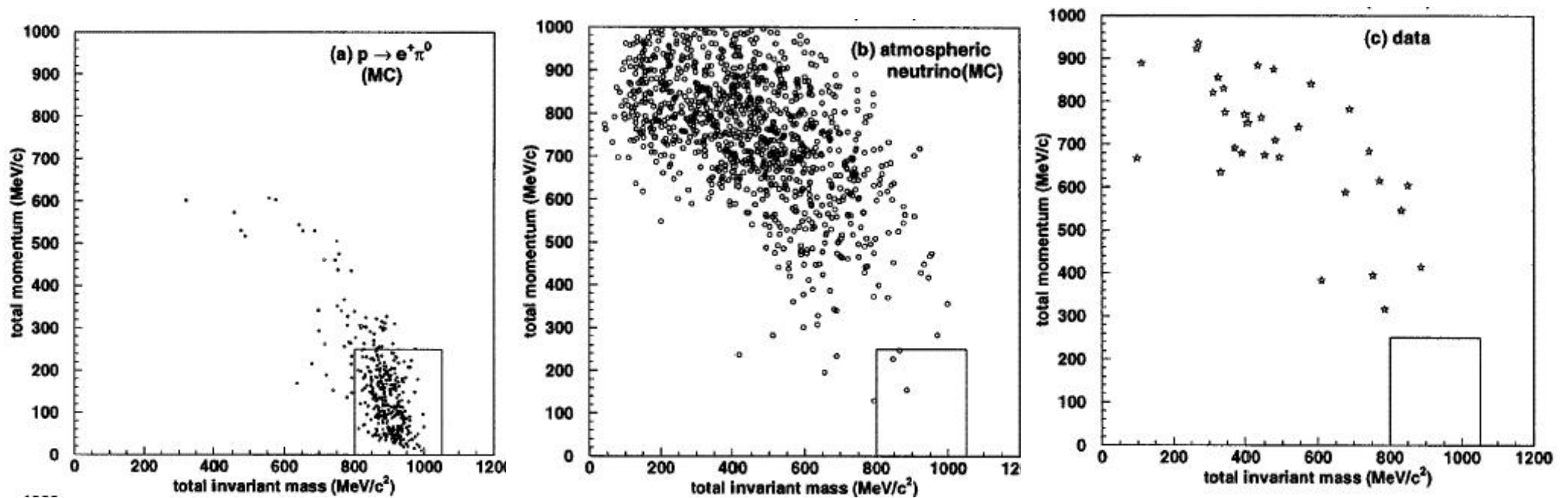


FIG. 1. Schematic outline of the detector, Kamiokande-II. The anticounter is shown by the dashed area. Dimensions are in mm.

Rozpad protonu v Kamiokande a Superkamiokande

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



Kamiokande: $\tau_p(e^+ \pi^0) \geq 2.6 \cdot 10^{32}$ let, $\tau_p(\bar{\nu}_e K^0) \geq 0.9 \cdot 10^{32}$ let

Superkamiokande: $\tau_p(e^+ \pi^0) \geq 1.6 \cdot 10^{33}$ let, $\tau_p(\bar{\nu}_e K^0) \geq 0.7 \cdot 10^{33}$ let

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

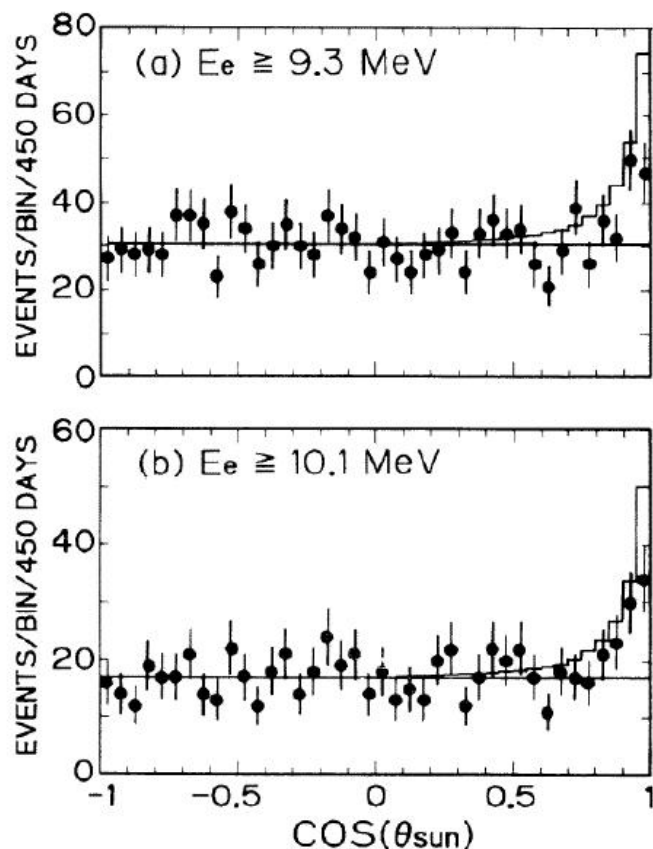


FIG. 2. Distributions in $\cos\theta_{\text{Sun}}$, the cosine of the angle between the trajectory of an electron and the direction of the Sun at a given time. The data are in the 680-ton fiducial region (a) with $E_e \geq 9.3$ MeV and (b) with $E_e \geq 10.1$ MeV, respectively. Events identified as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

The measured value of the ${}^8\text{B}$ 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 model² and subject to the same event criteria and experimental

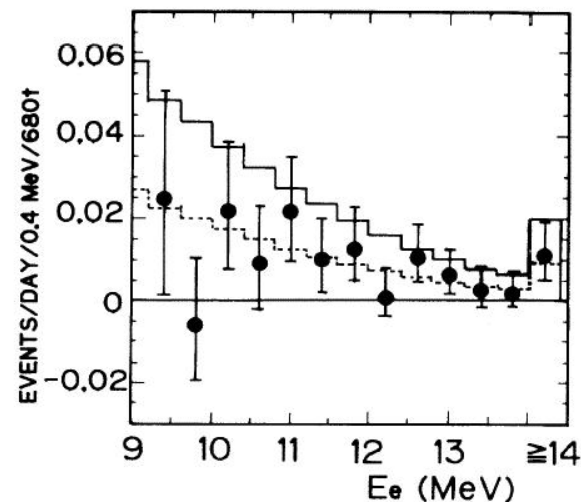
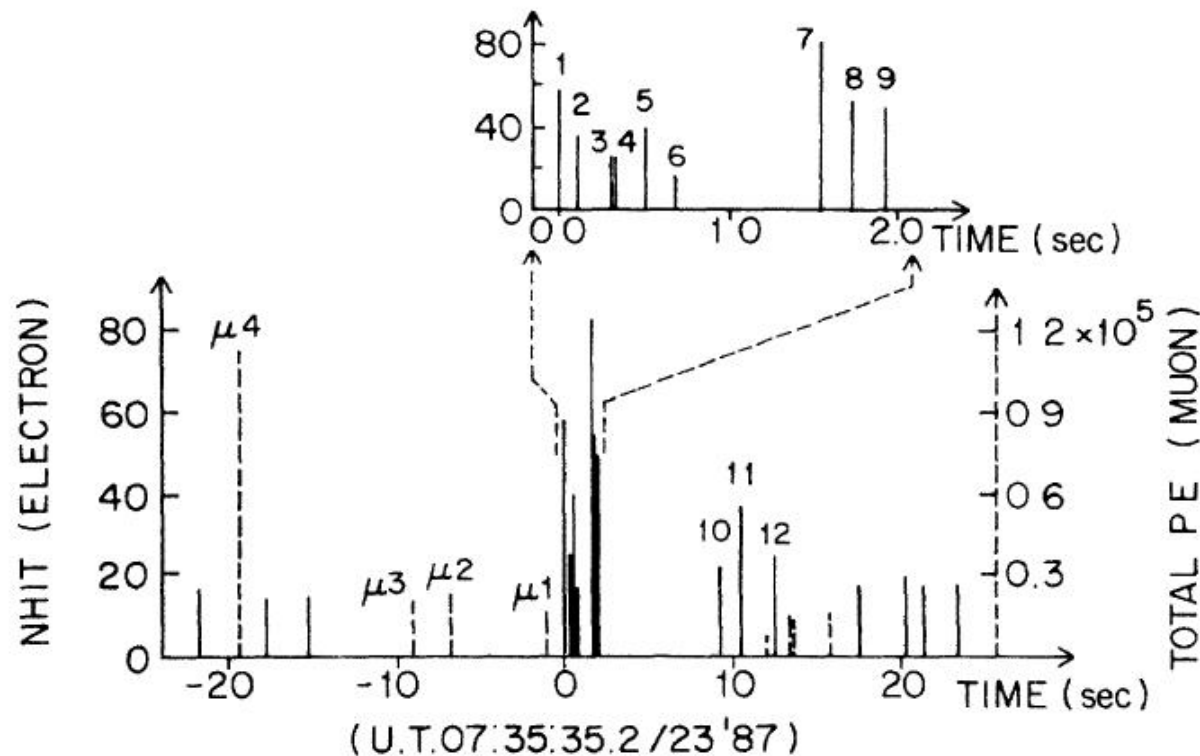


FIG. 3. Energy distribution of the solar neutrino signal (see text). The histogram is the distribution predicted by the SSM. The highest bin corresponds to $E_e \geq 14$ MeV. The dotted line shows the best fit to the data (0.46 SSM).

Neutrino 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: neutrino doprovázející vznik **neutronové hvězdy** u supernov typu II v procesu: $e^- + p \rightarrow \nu_e + n$

Experiment Superkamiokande

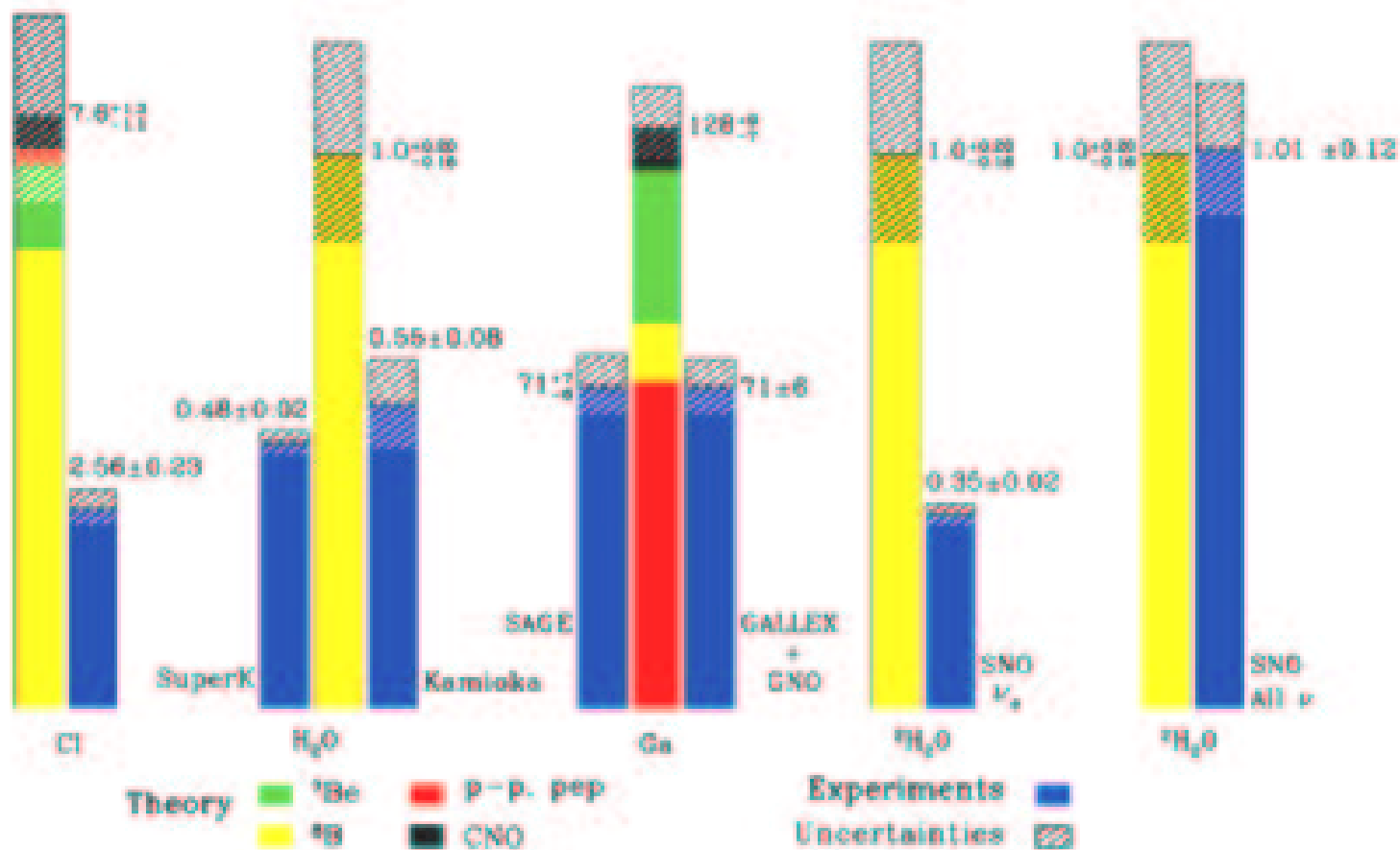
55 000 tun vody, 11 000 fotonásobičů a 135 autorů \Rightarrow SK > 10×K

Program:

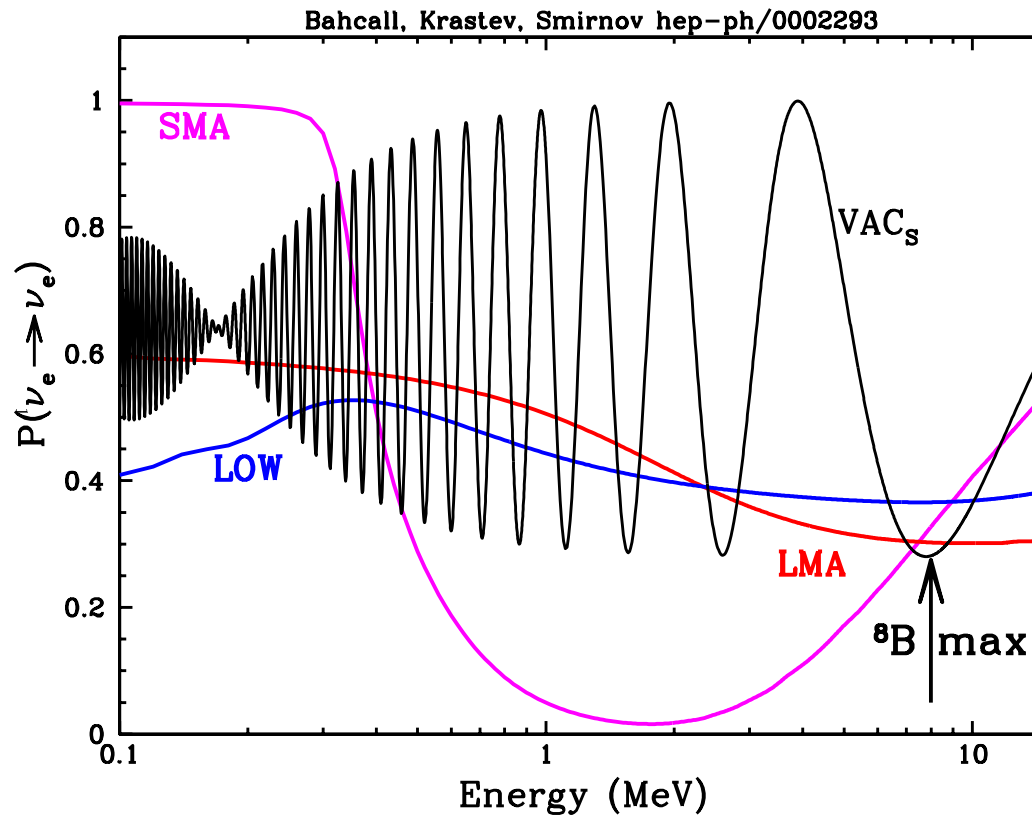
- pokračování hledání **rozpadu nukleonů**
- zpřesnění měření **slunečních neutrin**
- novum: měření **atmosférických neutrin**

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

Total Rates: Standard Model vs. Experiment Bahcall-Pinsonneault 2000



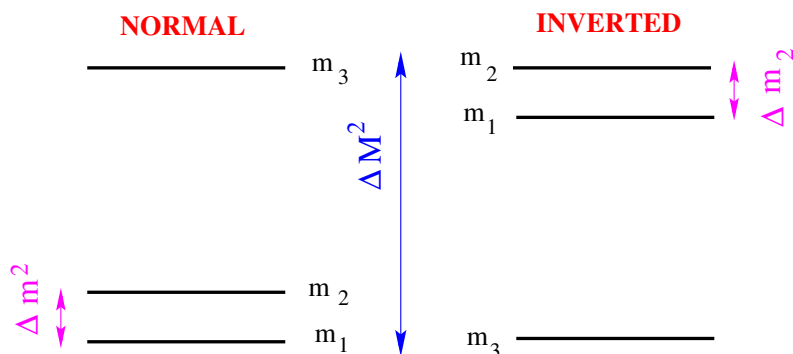
Oscilace slunečních neutrin



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



$$\Delta m^2 \equiv \Delta m_{\text{sol}}^2 \ll \Delta M^2 \equiv \Delta m_{\text{atm}}^2$$

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

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

