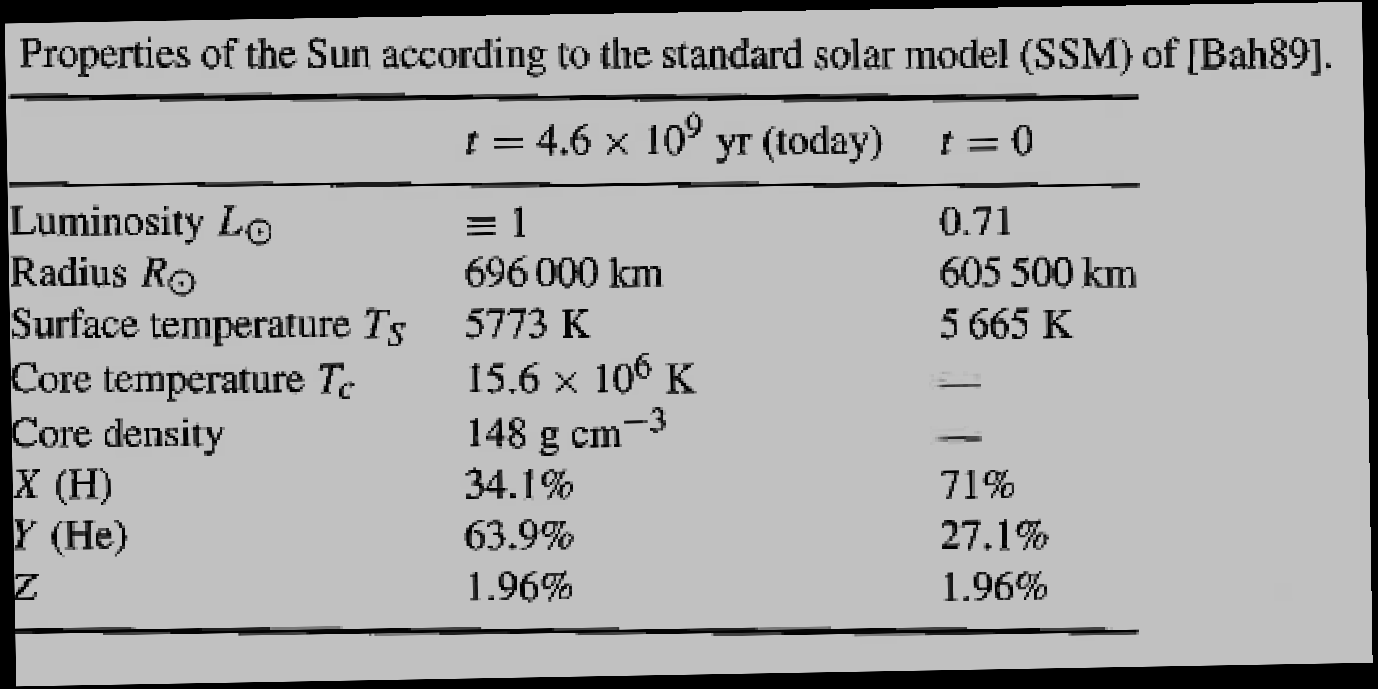
Energy Production in the Sun

„Birth of the Sun“ by Corrado Giaquinto (1762)



Properties of the Sun according to the standard solar model (SSM) of [Bah89].

	$t = 4.6 \times 10^9$ yr (today)	$t = 0$
Luminosity $L_\odot$	$\equiv 1$	0.71
Radius $R_\odot$	696 000 km	605 500 km
Surface temperature T_S	5773 K	5 665 K
Core temperature T_c	15.6×10^6 K	—
Core density	148 g cm^{-3}	—
X (H)	34.1%	71%
Y (He)	63.9%	27.1%
Z	1.96%	1.96%

Big mystery around 1900:
What is the mechanism of energy production of the Sun?

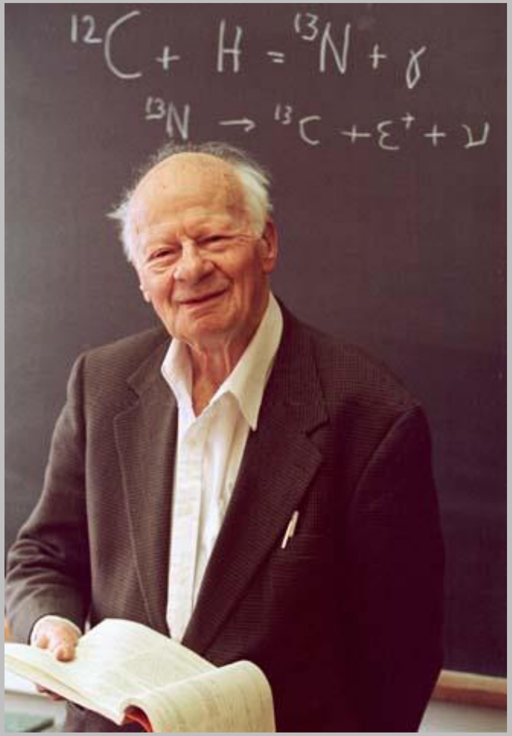
Explanation around 1930:

- radioactivity discovered
- begin of nuclear physics, fusion of protons discussed

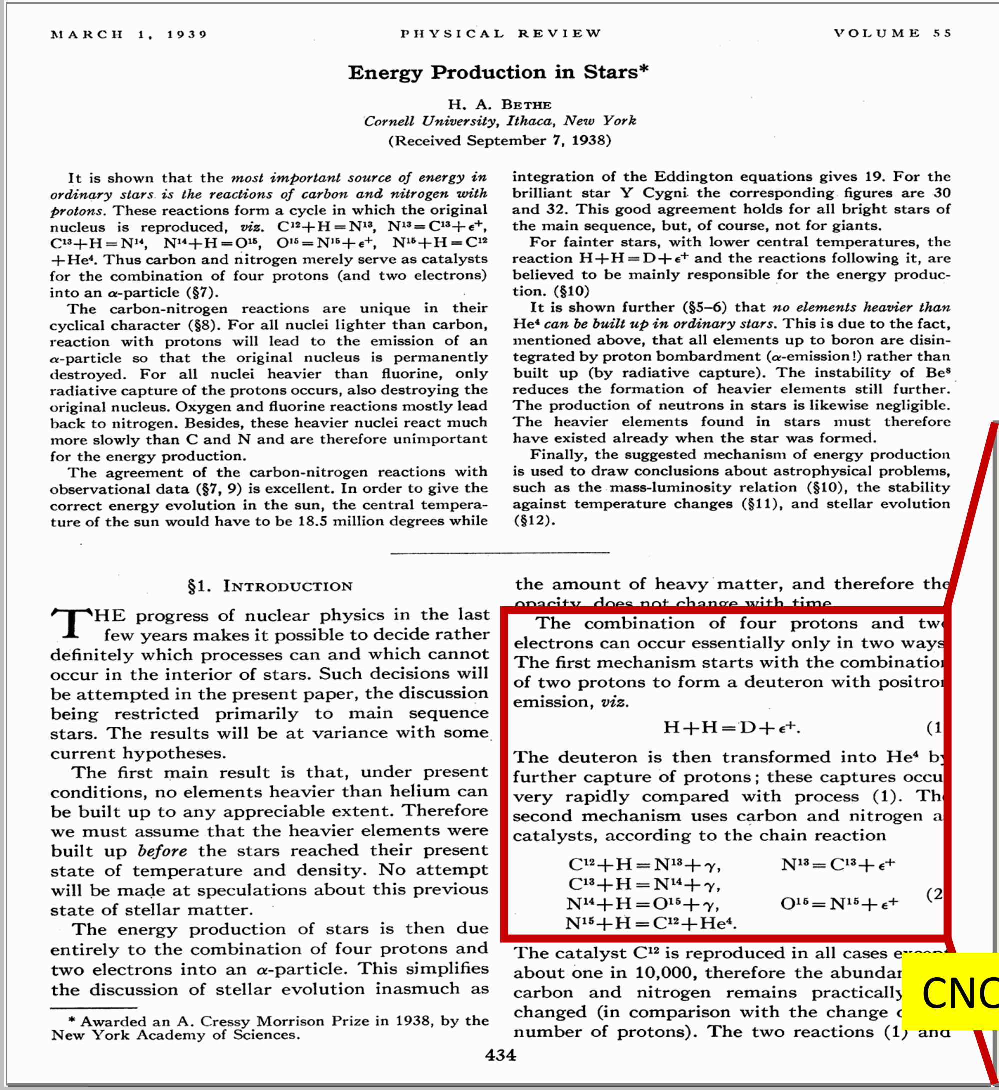
Sum reaction: $4p + 2e^- \rightarrow {}^4\mathrm{He} + 2\nu_e + 26.7\mathrm{MeV}$

Energy Production in Stars

Hans Bethe 1938 (Nobel prize 1967)



H. Bethe
1906-2005



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 electrons can occur essentially only in two ways The first mechanism starts with the combinatio of two protons to form a deuteron with positro emission, *viz.*

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

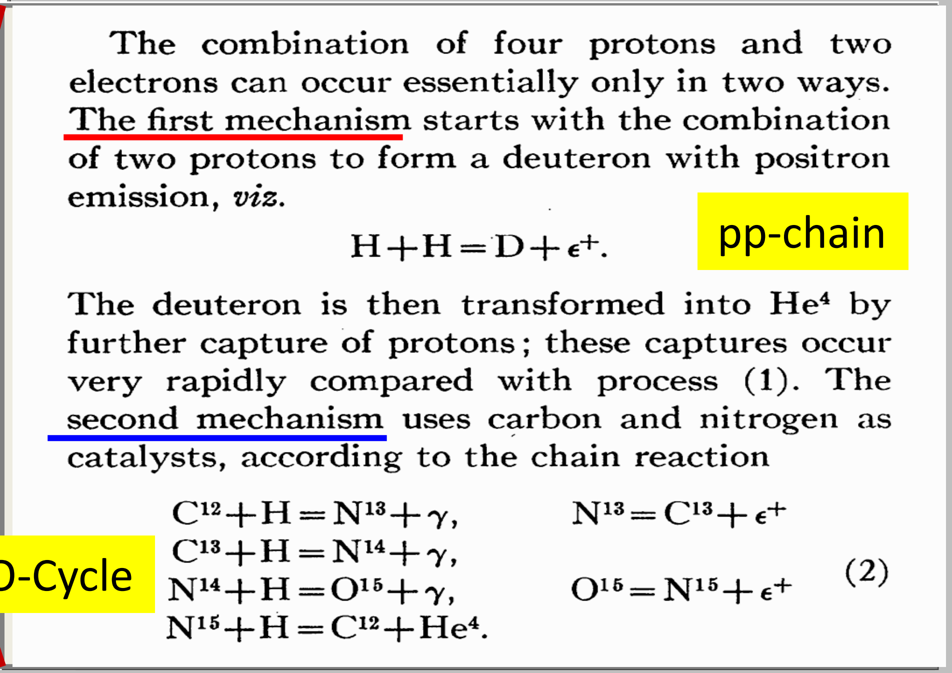
The deuteron is then transformed into He^4 b further capture of protons; these captures occu very rapidly compared with process (1). Th second mechanism uses carbon and nitrogen a catalysts, according to the chain reaction

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

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

---

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



The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*

$$H+H=D+\epsilon^+.$$

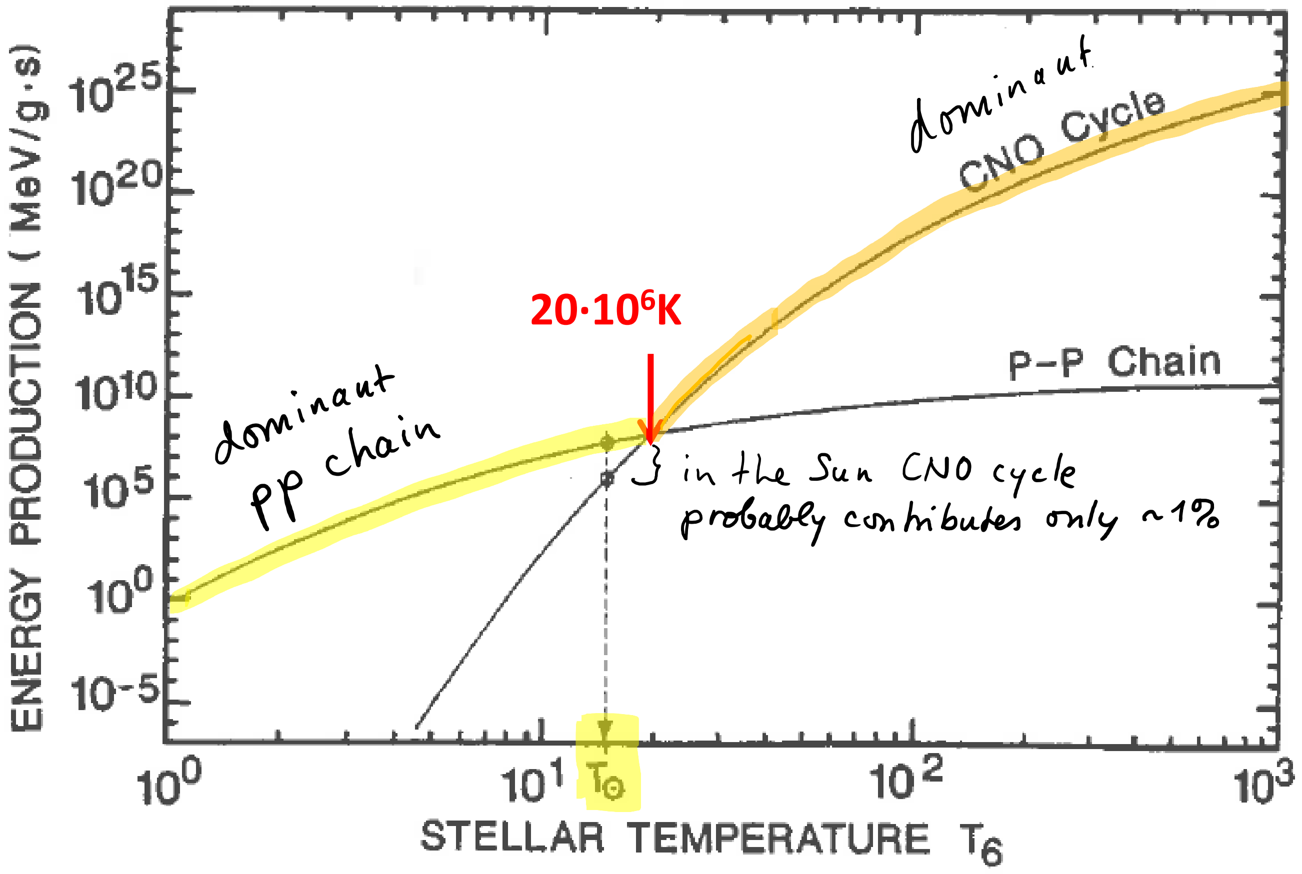
The deuteron is then transformed into He^4 by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction

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

pp-chain

CNO-Cycle

Contribution of the pp and CNO cycles as a function of the central temperature



$20\cdot10^{6}$K

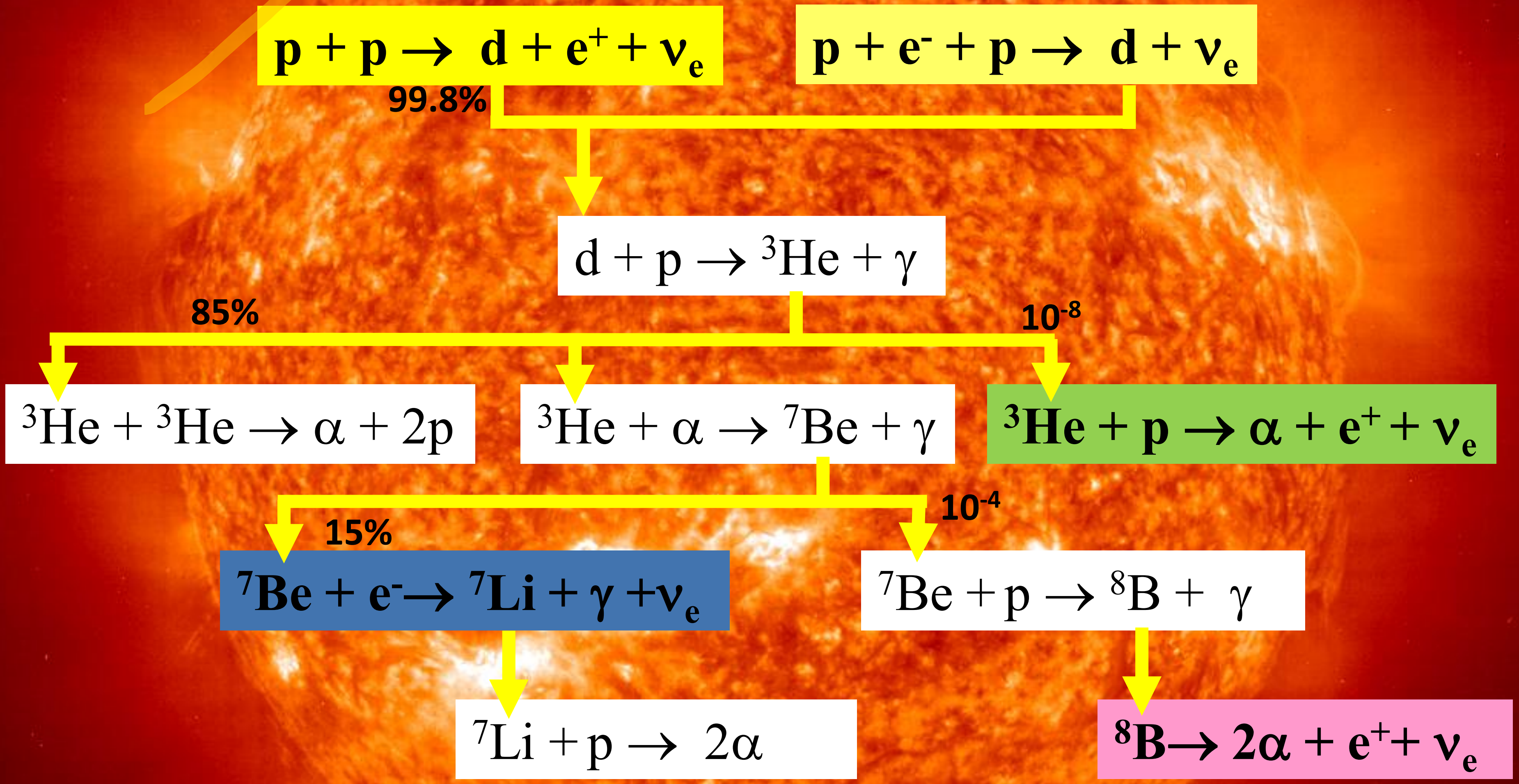
dominant pp chain

dominant CNO cycle

} in the Sun CNO cycle probably contributes only ~1%

From: C.E. Rolfs and W. S. Rodney, „Cauldrons in the Cosmos“, 1988, University of Chicago Press

The pp-chain



$p + p \rightarrow d + e^+ + \nu_e$

$p + e^- + p \rightarrow d + \nu_e$

99.8%

$d + p \rightarrow {}^3He + \gamma$

85%

10^{-8}

${}^3He + {}^3He \rightarrow \alpha + 2p$

${}^3He + \alpha \rightarrow {}^7Be + \gamma$

${}^3He + p \rightarrow \alpha + e^+ + \nu_e$

15%

10^{-4}

${}^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e$

${}^7Be + p \rightarrow {}^8B + \gamma$

${}^7Li + p \rightarrow 2\alpha$

${}^8B \rightarrow 2\alpha + e^+ + \nu_e$

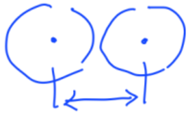
The pp chain

- Start reaction : $p + p \to d + e^+ + \nu_e$

  $(p \to n + e^+ + \nu_e)$

  Weak interaction → very slow

- p has to overcome Coulomb wall



Protons touch

$d = 2fm$ $\Rightarrow E = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{d^2} \approx 800 keV$

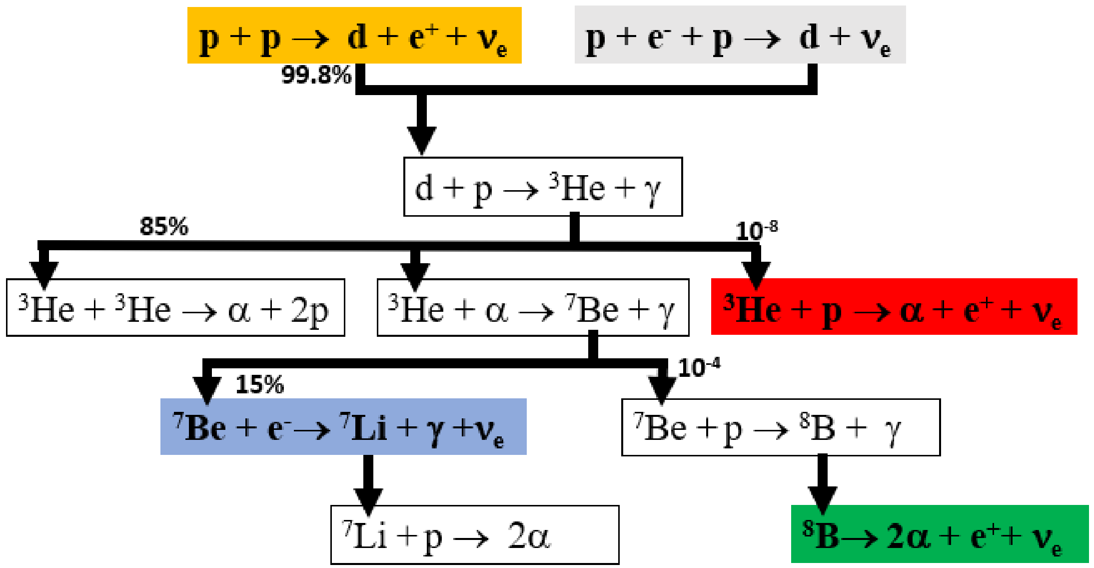
- energy of p inside the Sun

  $T_c = 15.6 \cdot 10^6 K \to E_{th} = k_B T \approx 1{,}3 keV$

  too small to overcome Coulomb wall

  ↳ Tunneleffect necessary

⇒ extremely slow process
Sun shines very stable
over billions of years



$p + p \to d + e^+ + \nu_e$

$p + e^- + p \to d + \nu_e$

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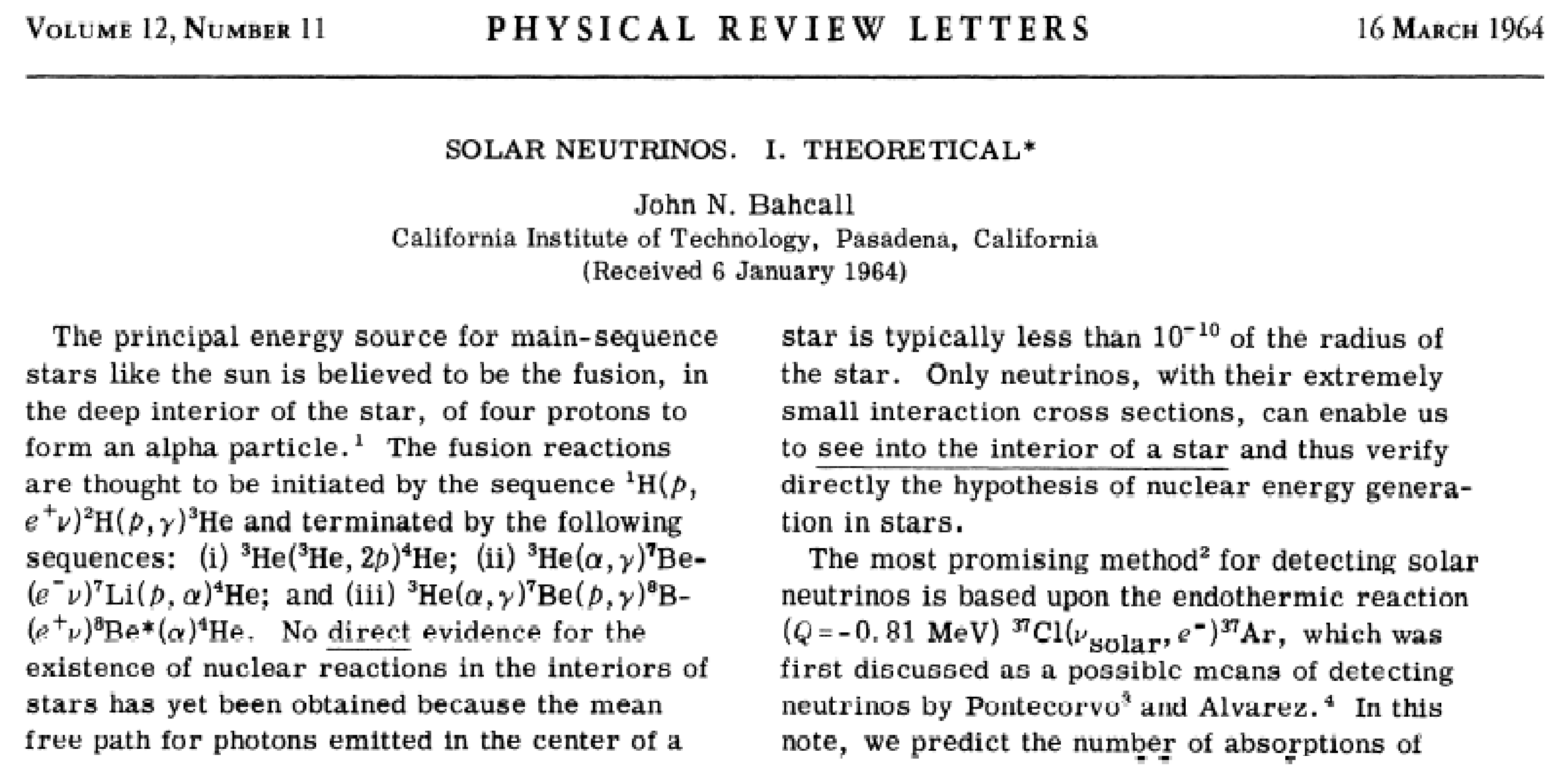
${}^8B \to 2\alpha + e^+ + \nu_e$

calculation of solar neutrino flux



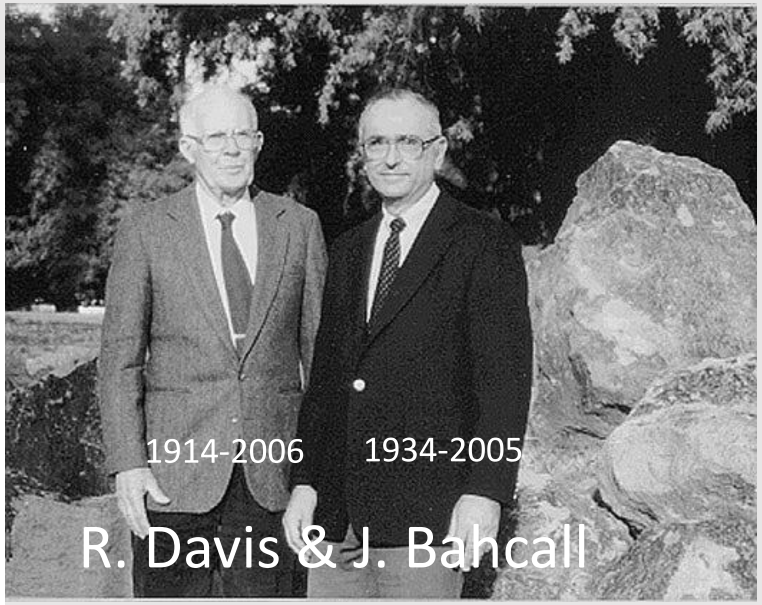
Volume 12, Number 11 PHYSICAL REVIEW LETTERS 16 March 1964

SOLAR NEUTRINOS. I. THEORETICAL*

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

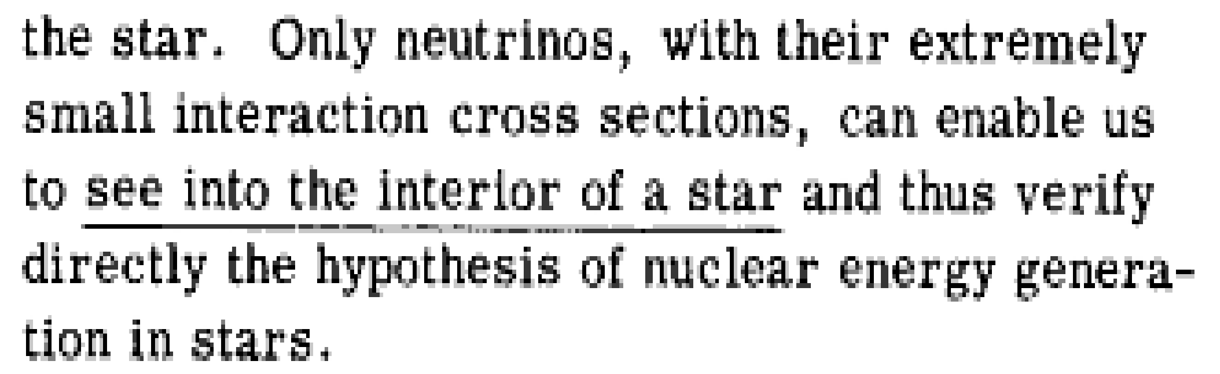
The principal energy source for main-sequence stars like the sun is believed to be the fusion, in the deep interior of the star, of four protons to form an alpha particle.[1] The fusion reactions are thought to be initiated by the sequence ${}^1\mathrm{H}(p, e^+\nu){}^2\mathrm{H}(p,\gamma){}^3\mathrm{He}$ and terminated by the following sequences: (i) ${}^3\mathrm{He}({}^3\mathrm{He}, 2p){}^4\mathrm{He}$; (ii) ${}^3\mathrm{He}(\alpha,\gamma){}^7\mathrm{Be}(e^-\nu){}^7\mathrm{Li}(p,\alpha){}^4\mathrm{He}$; and (iii) ${}^3\mathrm{He}(\alpha,\gamma){}^7\mathrm{Be}(p,\gamma){}^8\mathrm{B}(e^+\nu){}^8\mathrm{Be}^*(\alpha){}^4\mathrm{He}$. 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 method[2] for detecting solar neutrinos is based upon the endothermic reaction ($Q = -0.81$ MeV) ${}^{37}\mathrm{Cl}(\nu_{\mathrm{solar}}, e^-){}^{37}\mathrm{Ar}$, 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



1914-2006 1934-2005

R. Davis & J. Bahcall



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.

Estimation of neutrino flux from the Sun from energy consideration

$1\,W = \frac{1}{1.6\cdot10^{-19}}\,eV/s$

Sum reaction: $4p + 2e^- \rightarrow {}^4\mathrm{He} + 2\nu_e + 26.7\,\mathrm{MeV}$

Energy that we see on Earth: Solar constant $1361\,\frac{W}{m^2} = S_\odot$

"Only" process of energy loss (cooling) are neutrinos, average energy of ≈ 200keV = 0.2MeV

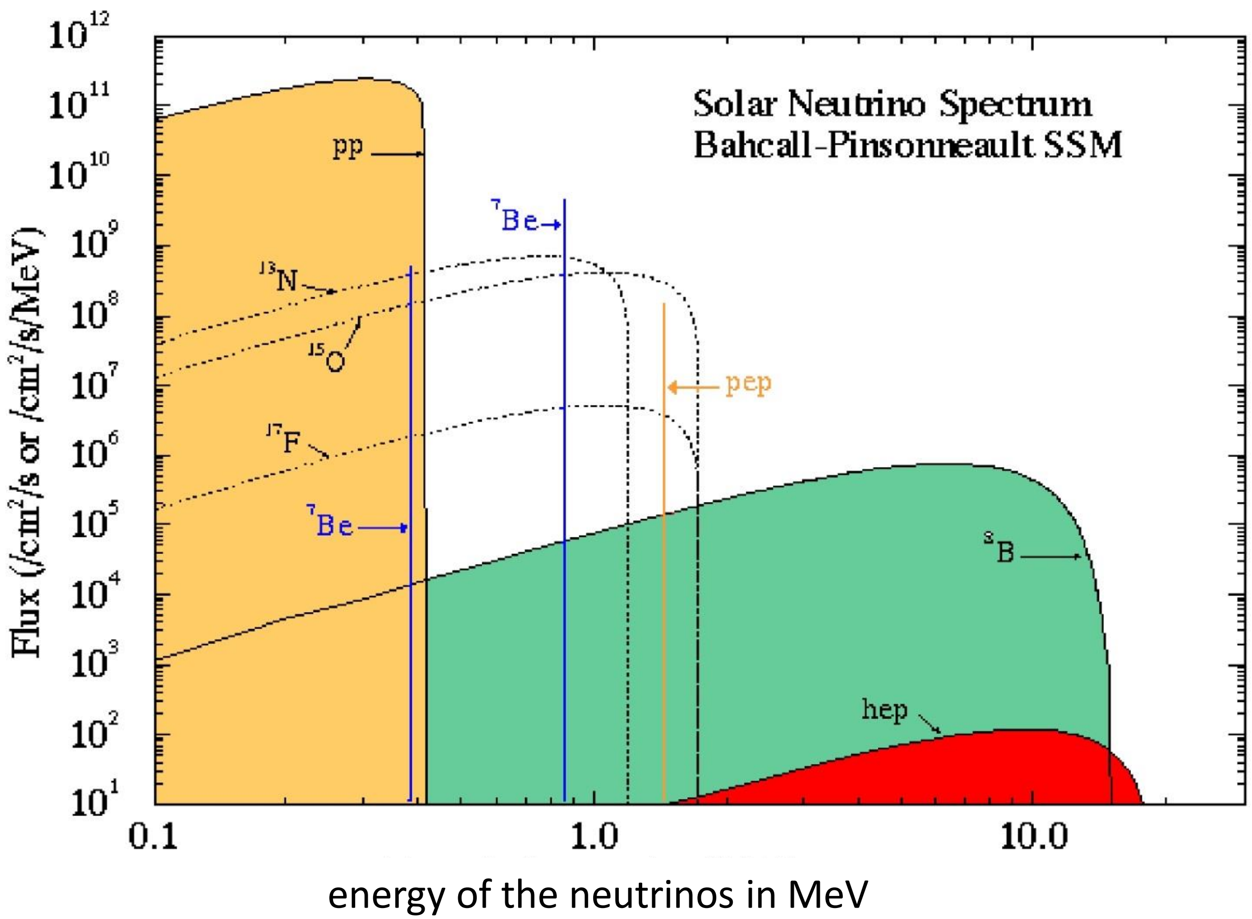
↳ so roughly 27MeV thermal energy per fusion reaction is a good estimate

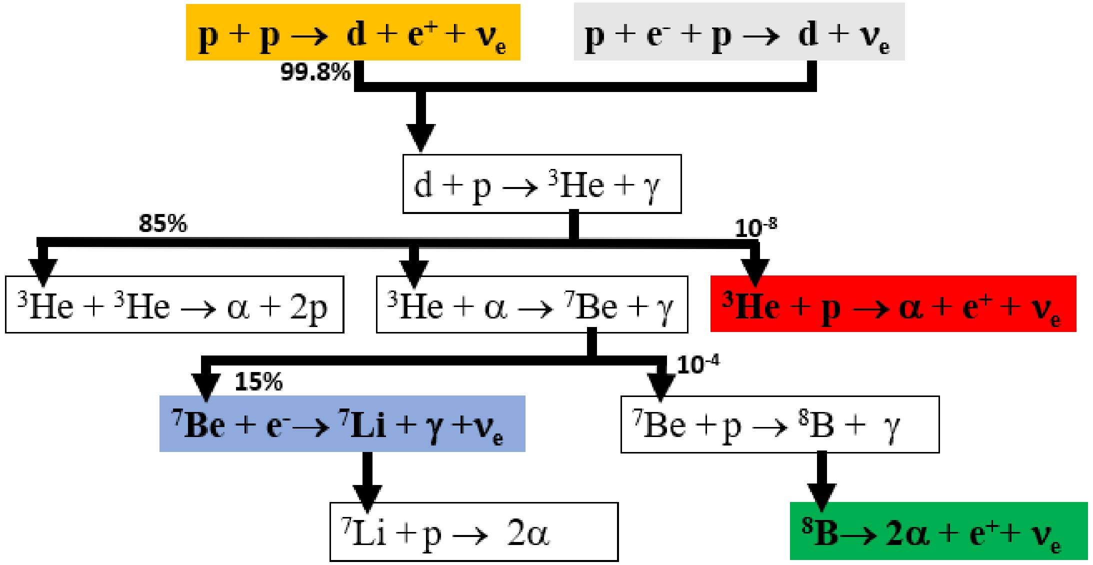
$$\phi_\nu \approx 2\cdot\frac{S_\odot}{27\,MeV} = 2\cdot\frac{8.5\cdot10^{21}\,eV/m^2s}{27\cdot10^{6}\,eV} \underset{\substack{\uparrow \\ m^2=10^4cm^2}}{=} 0.6\cdot10^{11}\,\frac{1}{cm^2s}$$

$$\Phi_\nu \approx 6\cdot10^{10}\,\frac{1}{cm^2s}$$

60 billion ν_e/cm^2s

Standard Solar Model (SSM) predicted solar neutrino fluxes





$p + p \rightarrow d + e^{+} + \nu_e$ 99.8%

$p + e^{-} + p \rightarrow d + \nu_e$

$d + p \rightarrow {}^{3}He + \gamma$

85%

$^{3}He + {}^{3}He \rightarrow \alpha + 2p$

$^{3}He + \alpha \rightarrow {}^{7}Be + \gamma$

10^{-8}

$^{3}He + p \rightarrow \alpha + e^{+} + \nu_e$

15%

$^{7}Be + e^{-} \rightarrow {}^{7}Li + \gamma + \nu_e$

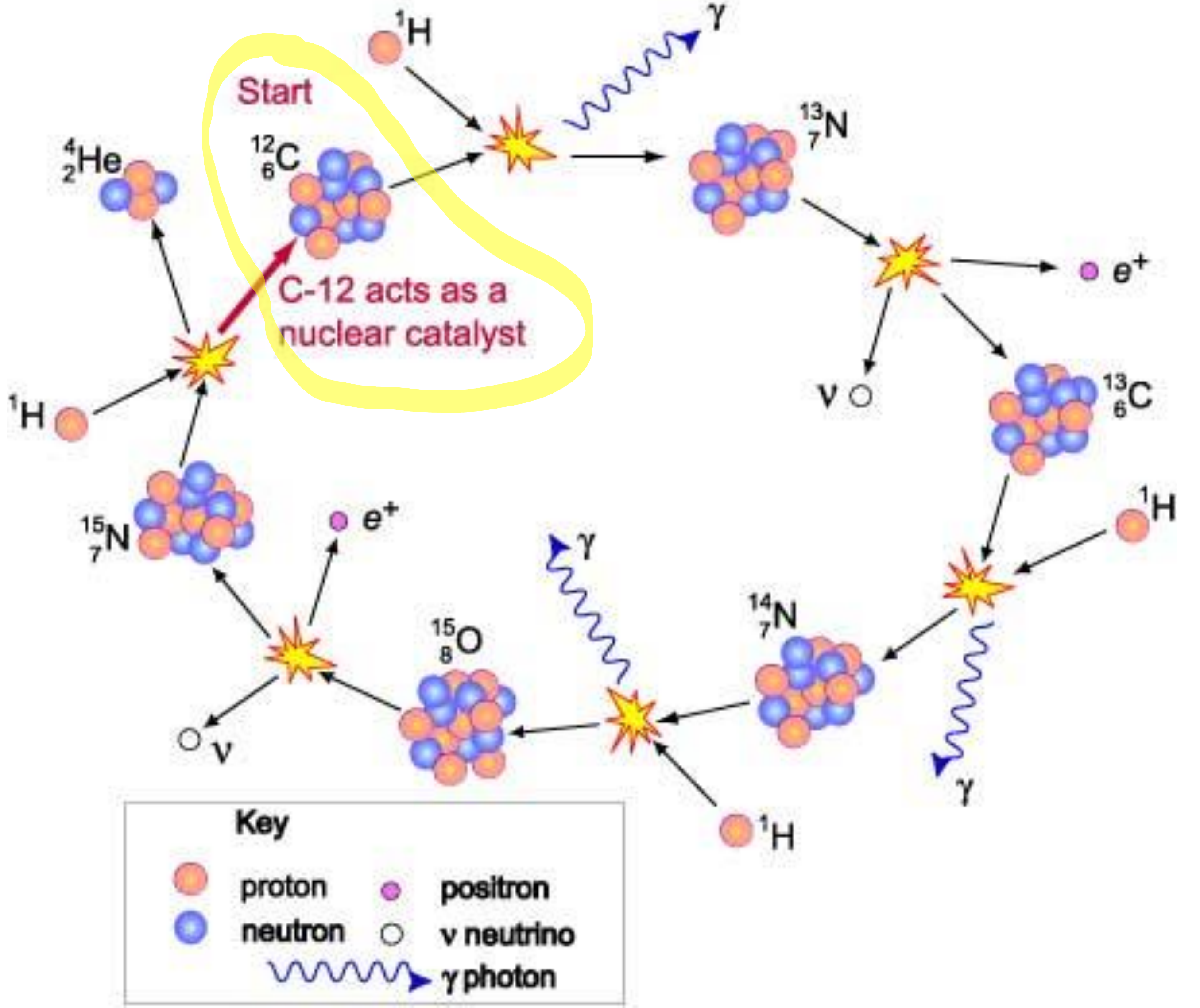
10^{-4}

$^{7}Be + p \rightarrow {}^{8}B + \gamma$

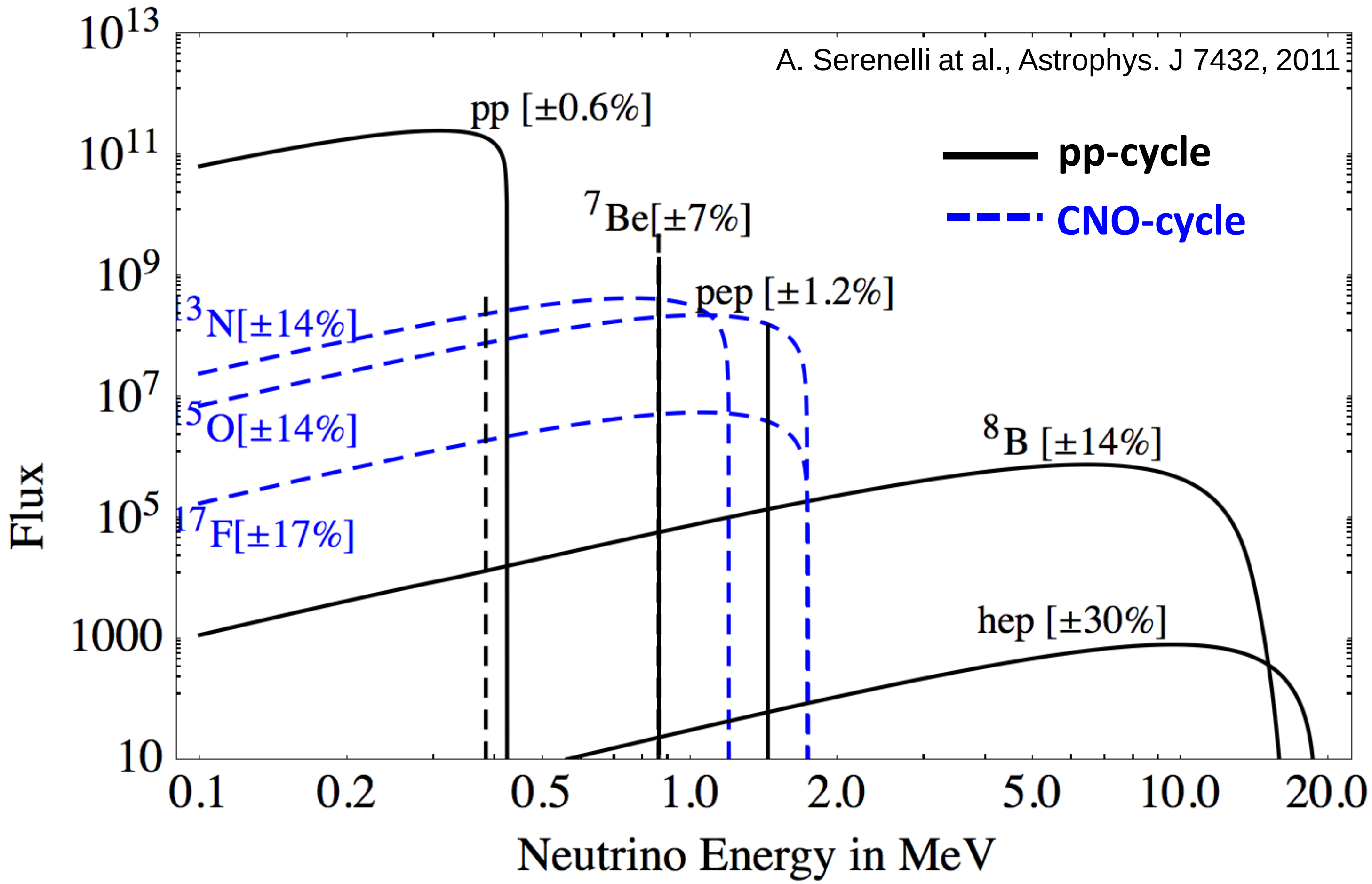
$^{7}Li + p \rightarrow 2\alpha$

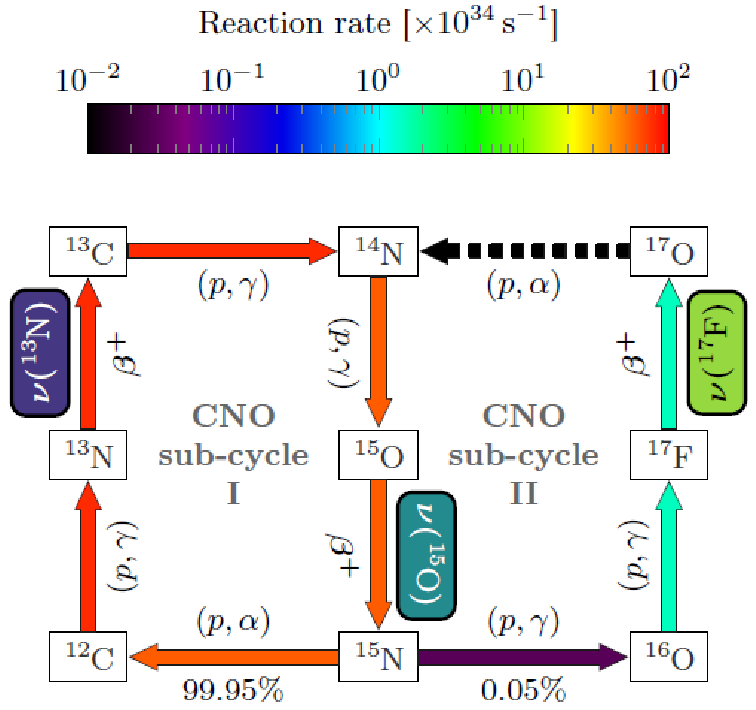
$^{8}B \rightarrow 2\alpha + e^{+} + \nu_e$

The CNO Cycle

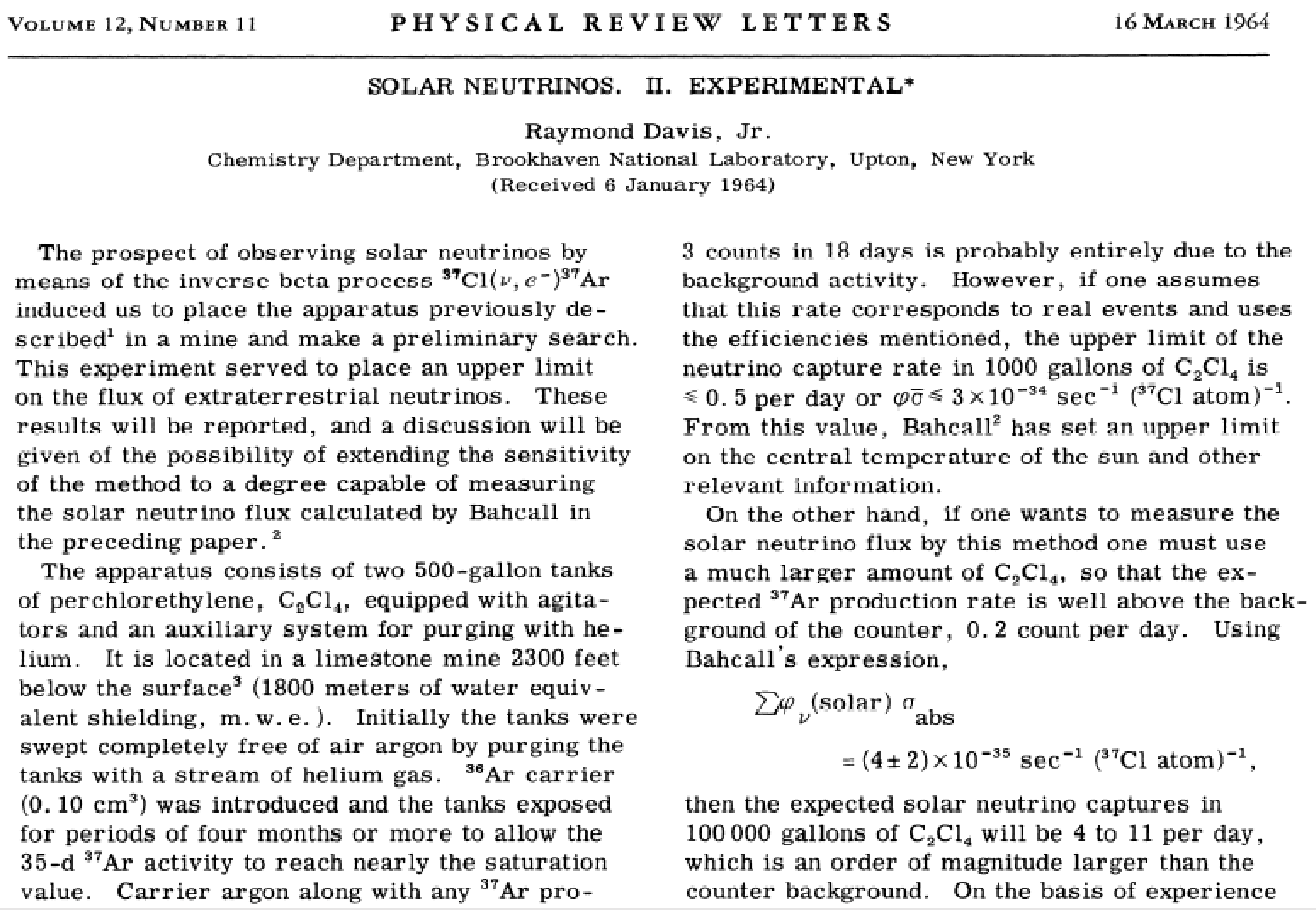


Standard Solar Model (SSM)





measurement of solar neutrino flux



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 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]

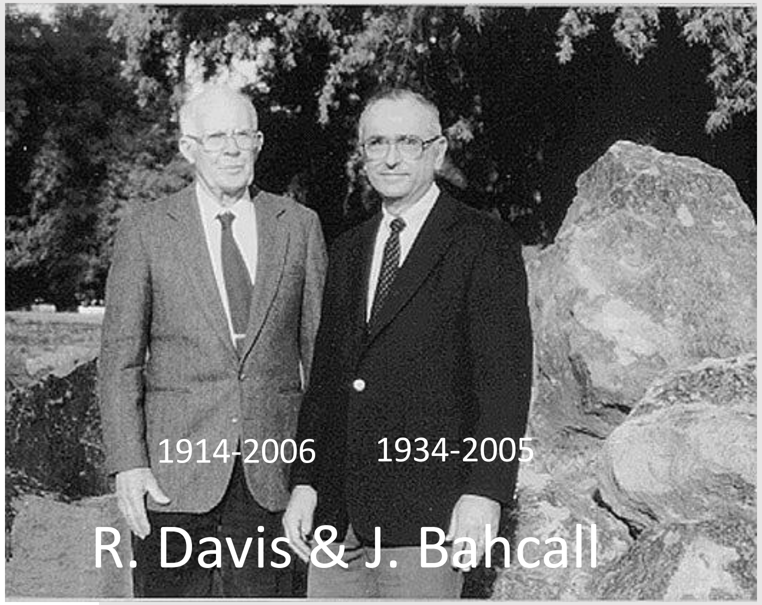
The apparatus consists of two 500-gallon tanks of perchlorethylene, C_2Cl_4, equipped with agitators and an auxiliary system for purging with helium. It is located in a limestone mine 2300 feet below the surface[3] (1800 meters of water equivalent shielding, m.w.e.). Initially the tanks were swept completely 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 $\varphi\bar{\sigma} \leq 3\times10^{-34}\ \text{sec}^{-1}\ (^{37}\text{Cl atom})^{-1}$. 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,

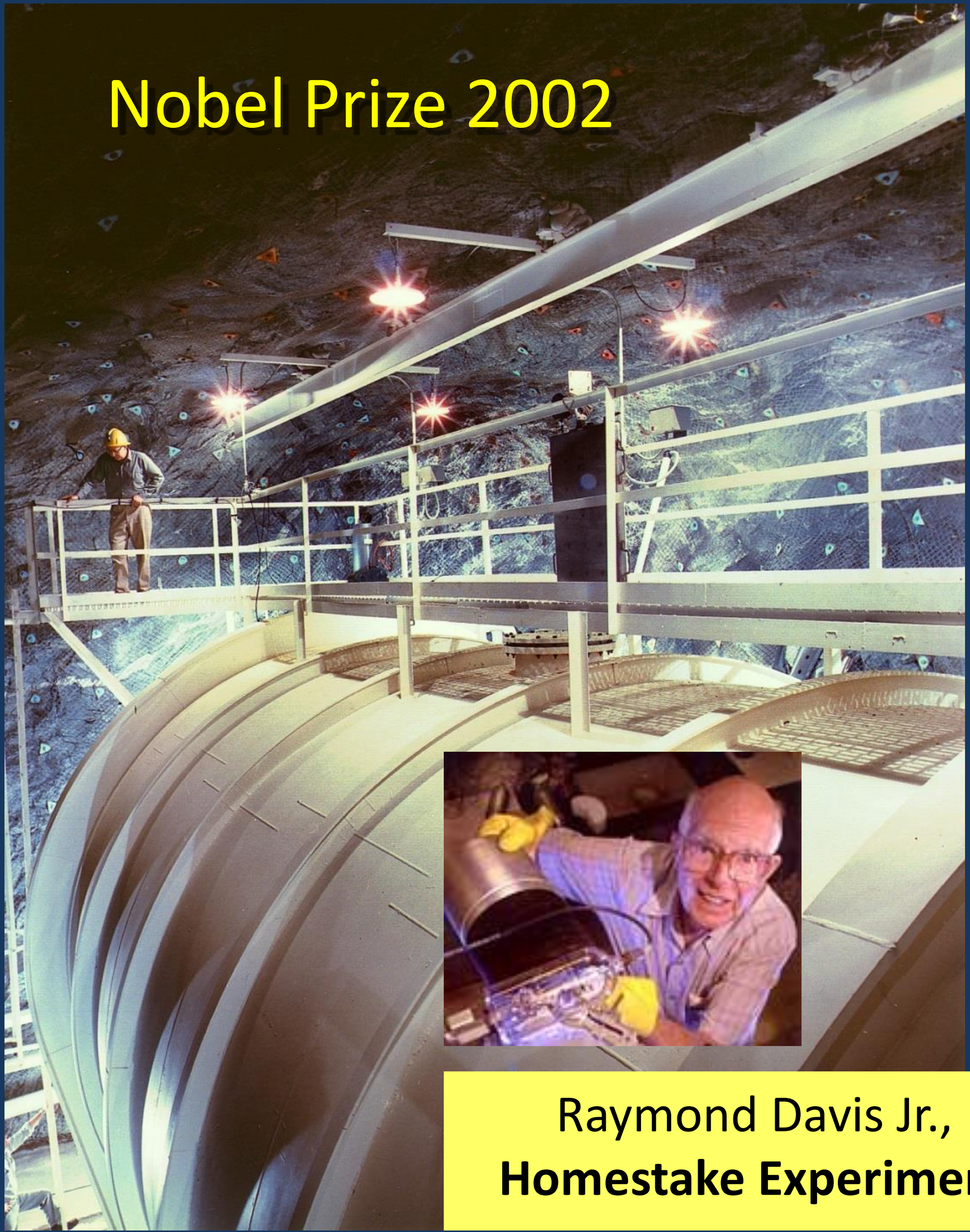
$$\sum\varphi_\nu(\text{solar})\,\sigma_{\text{abs}} = (4\pm2)\times10^{-35}\ \text{sec}^{-1}\ (^{37}\text{Cl atom})^{-1},$$

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



R. Davis & J. Bahcall

Solar Neutrinos: First Detection



Raymond Davis Jr.,
Homestake Experiment

1970 - 1994

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

$E_\nu > 814$ keV (^{8}B Neutrinos)

^{7}Be Neutrinos

radiochemical experiments

$$R = N_{Target} \cdot \int \phi_\nu(E) \cdot \sigma(E)\, dE$$

To produce 1 Atom per day (here ^{37}Ar)

$$\left.\begin{array}{l} \phi \sim 10^{10} \frac{1}{cm^2 s} \\ \sigma \sim 10^{-45} cm^2 \end{array}\right\} \text{ need } 10^{30} \text{ target Atoms}$$

$6 \cdot 10^{23}$ Atom in 1 mol $\Rightarrow$ few 1000 tons

Here: 4 500 m^3 of Perchlorethylene

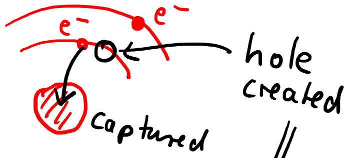
Ar – Counting:

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

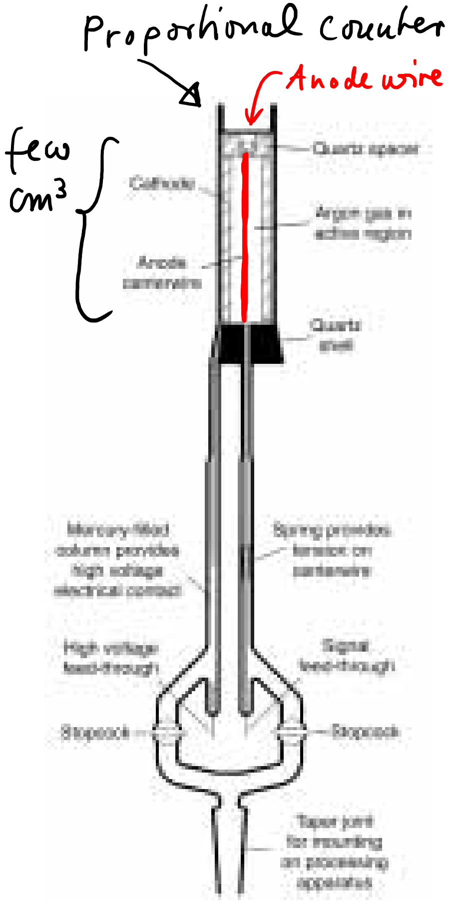
+ X-rays

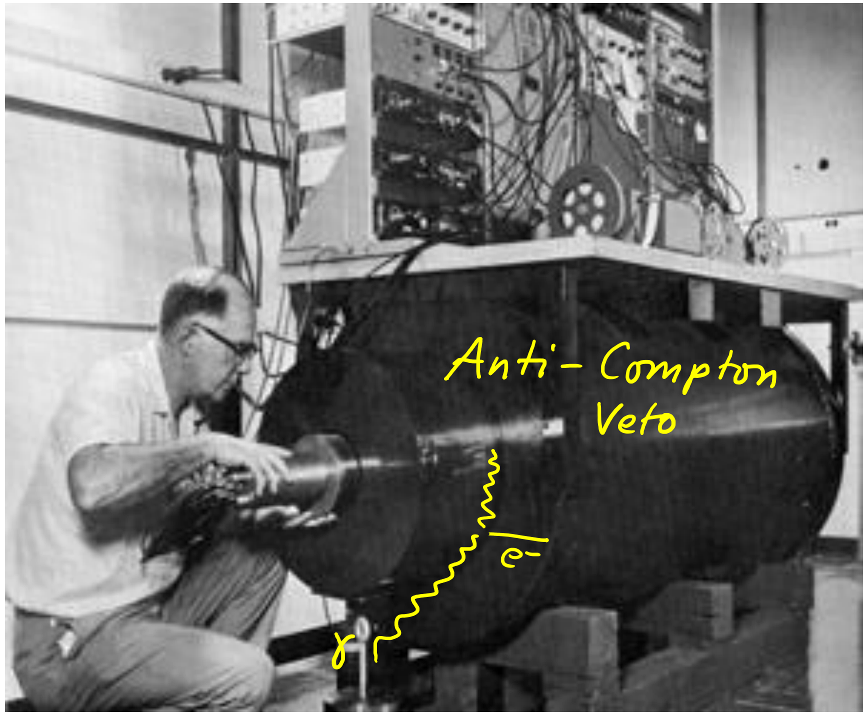
$T_{1/2}$ = 35 d

^{37}A is radioactive!
Electron capture decay



⇓ hole is filled by outer e⁻
⇒ emission of X-rays





Result of the Homestake experiment: Where are the neutrinos?

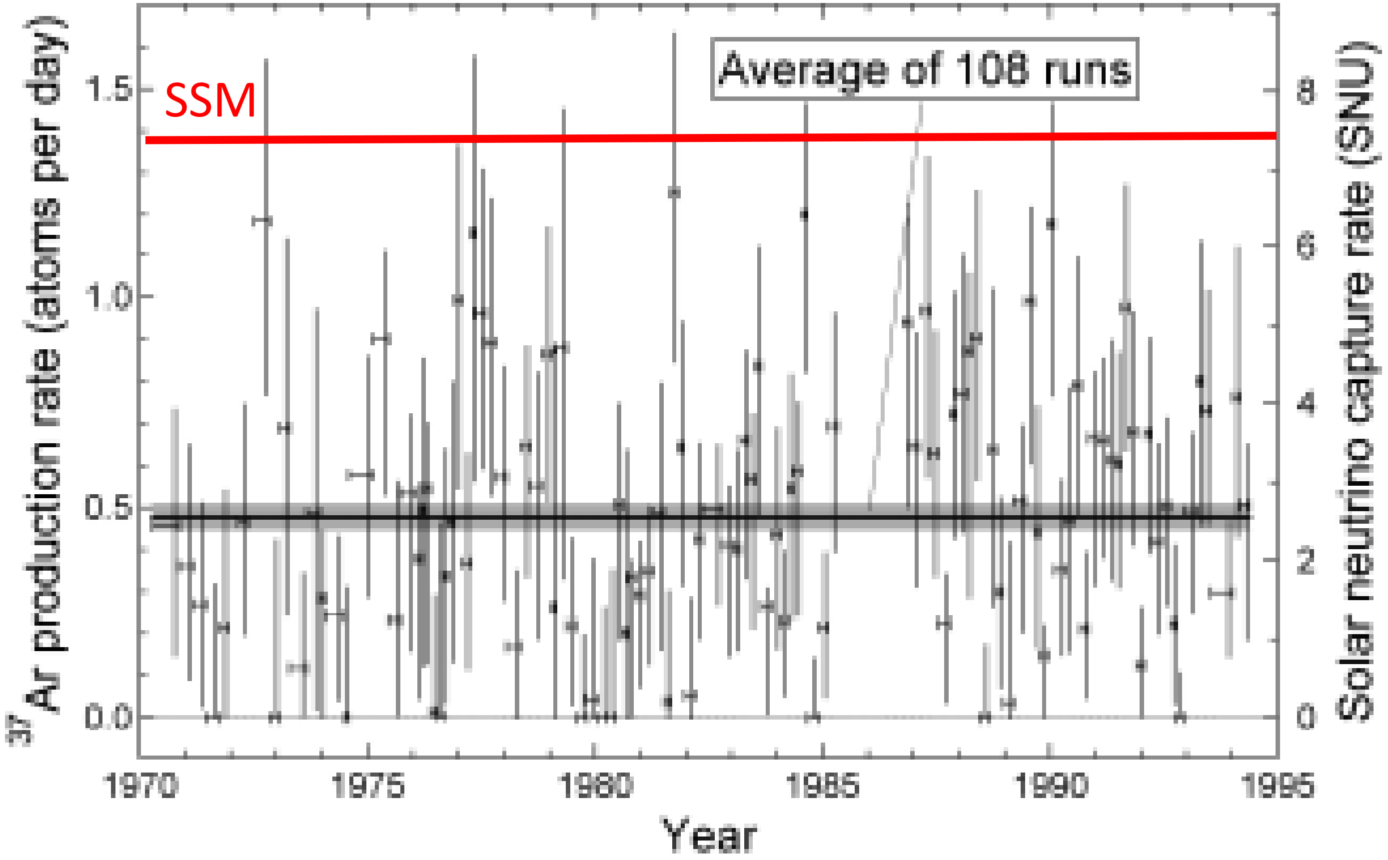
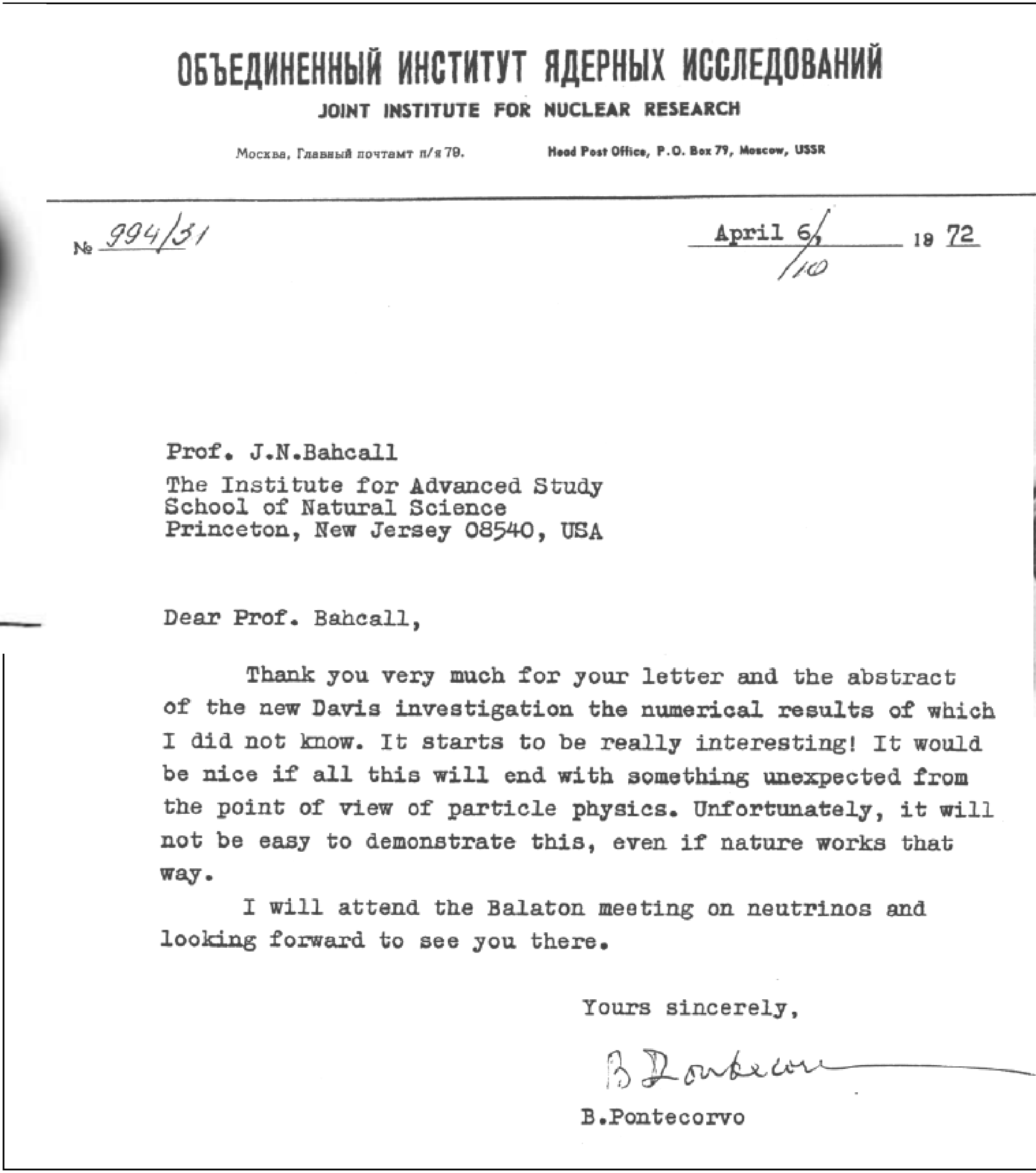


Figure 15. A summary of all of the runs made at Homestake after implementation of rise-time counting. Background has been subtracted. Over a period of 25 years, 2200 atoms of ^{37}Ar were detected, corresponding to an average solar neutrino flux of 2.56 SNU. The gap in 1986 occurred when both perchloroethylene 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/ 1972
/10

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

Davis & Bahcall (1964)

Gallium Experiment at Gran Sasso

GALLEX

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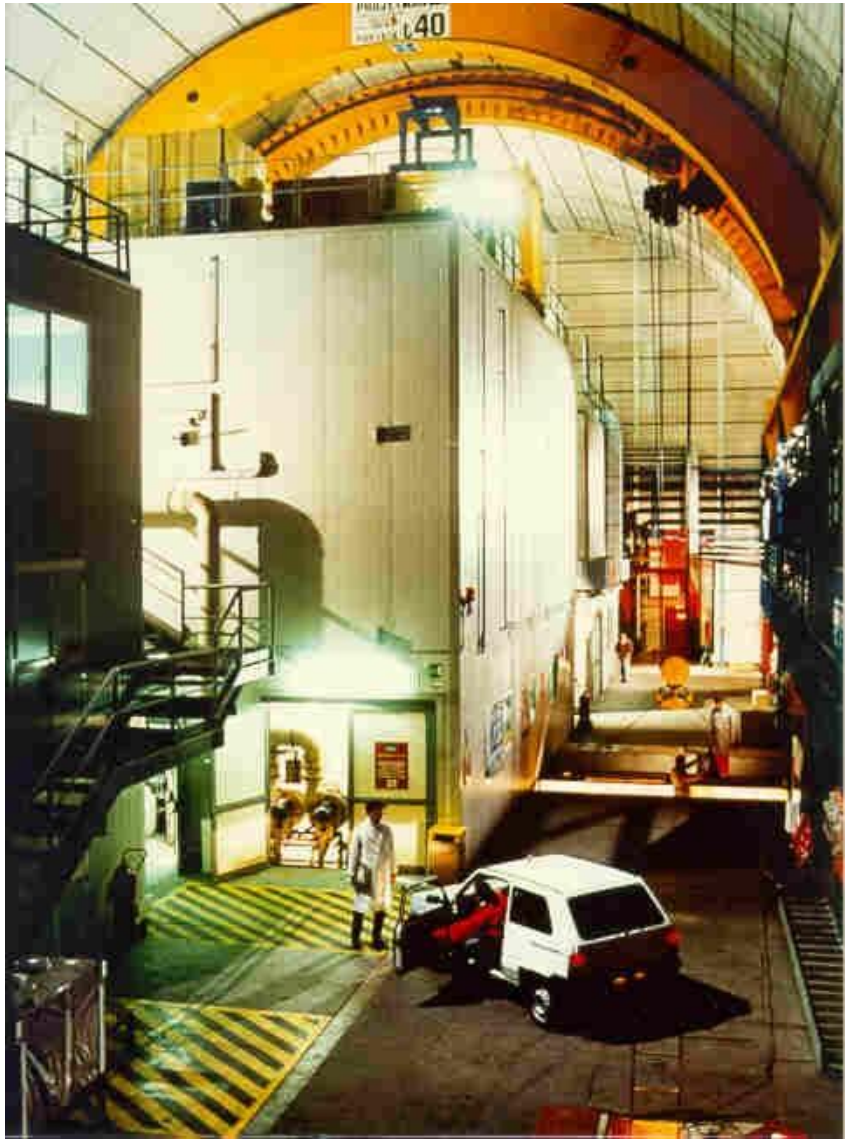
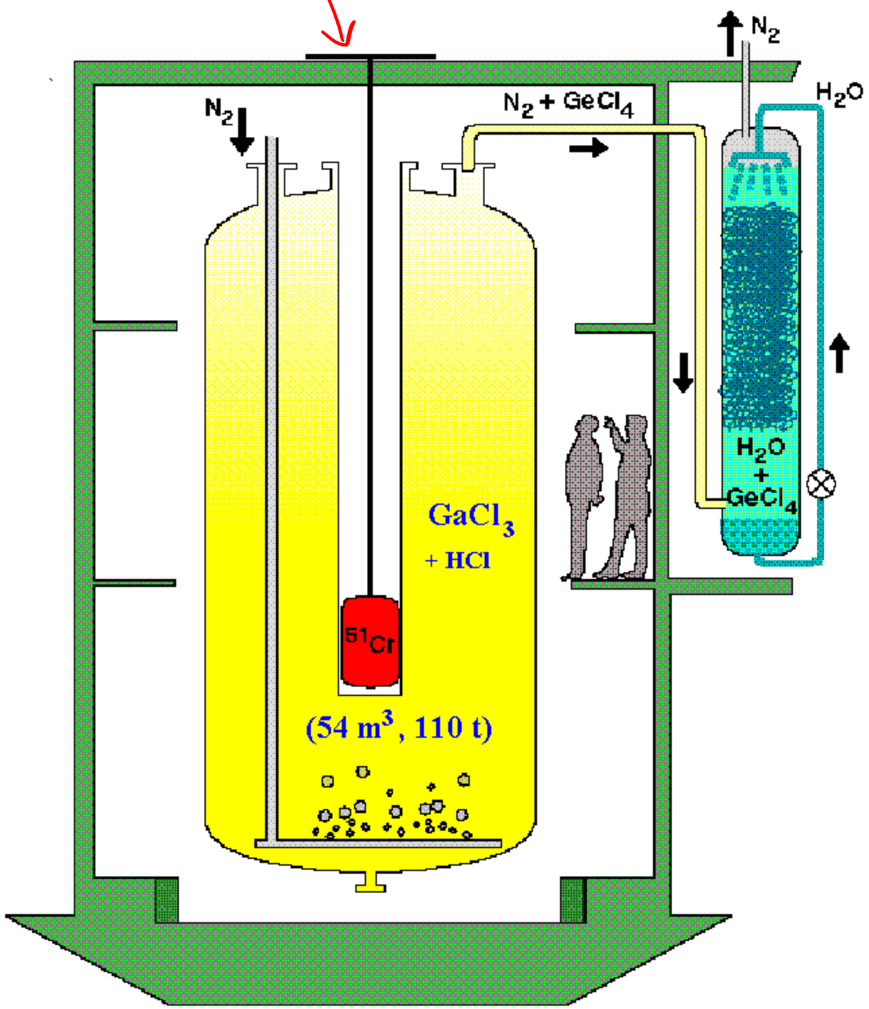
COLLABORATION

$$\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^- \qquad E_\nu > 233\ \text{keV}$$



Possibility to calibrate with ν_e source



Gallium Experiment at Gran Sasso

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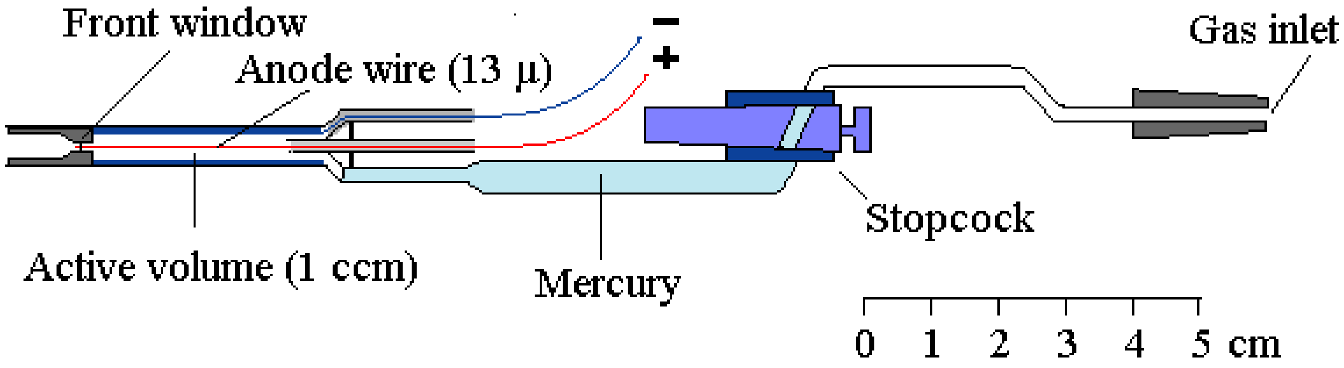
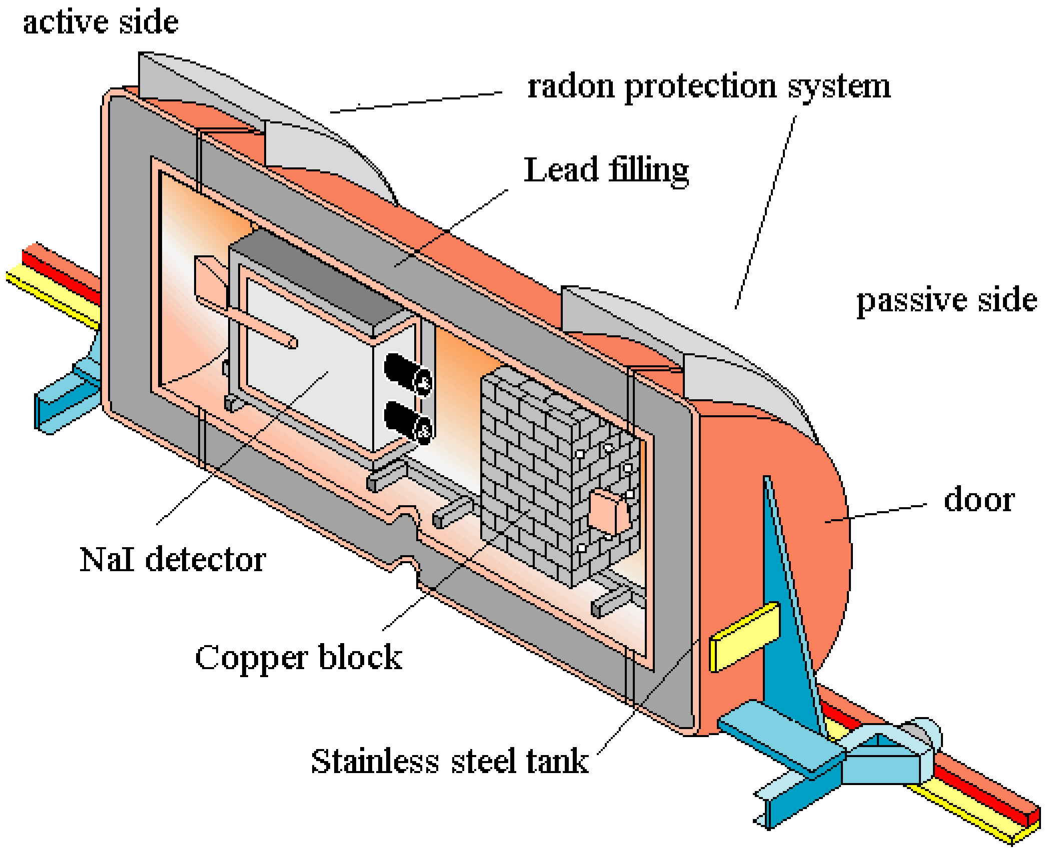
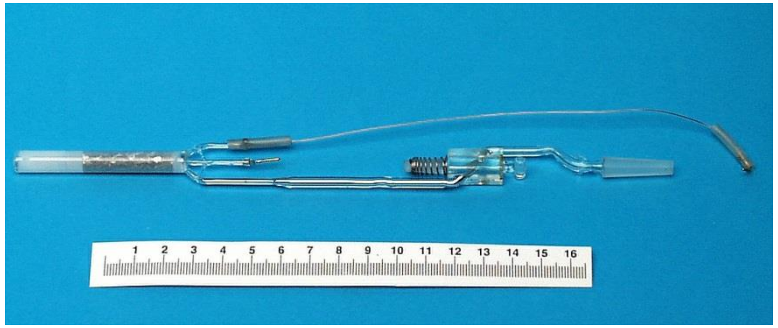
HD-II proportional counter





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

$T_{1/2} = 11.4$ d



Gallium Experiment at Gran Sasso
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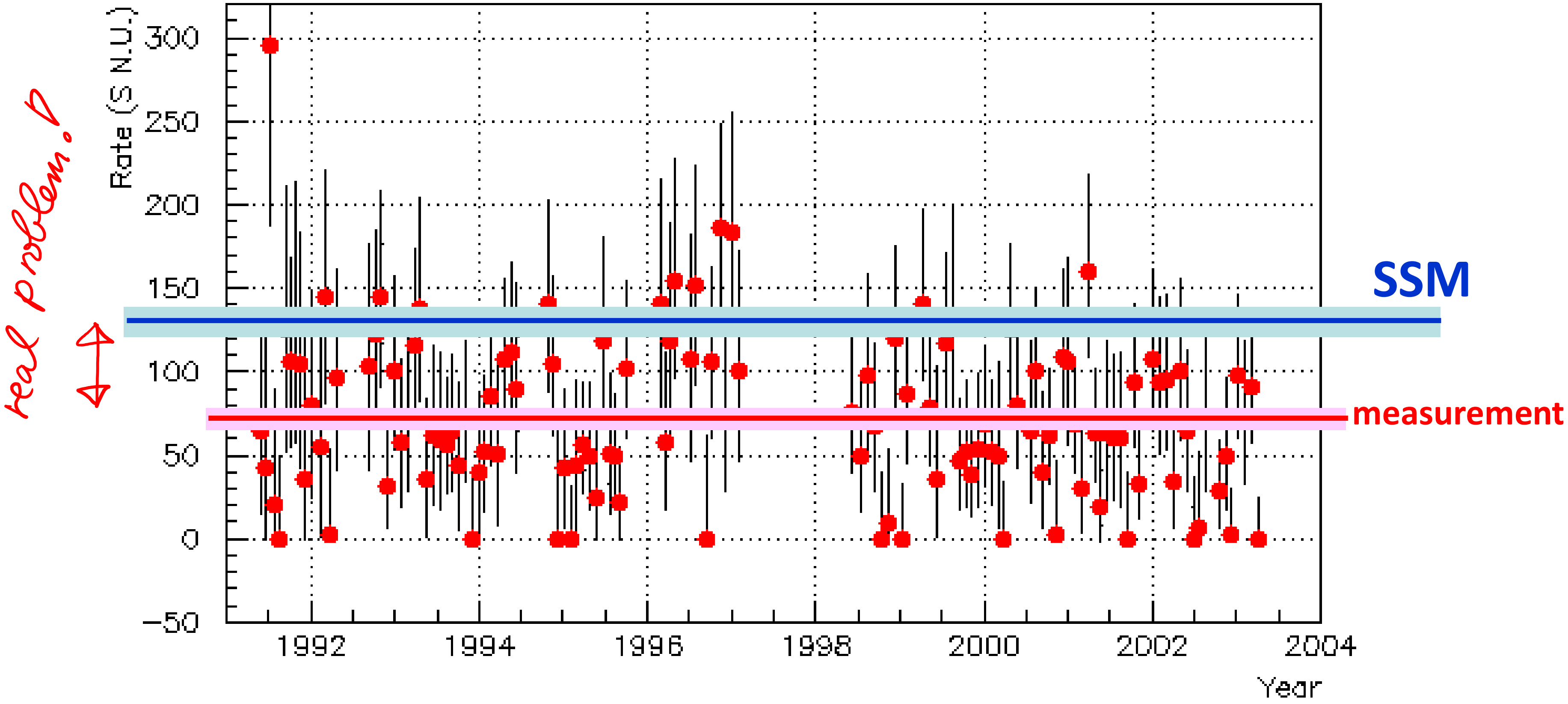
Gallex / GNO data

SNU (solar neutrino unit): neutrino flux that produces 10^{-36} ν_e captures per target atom per second



real problem?

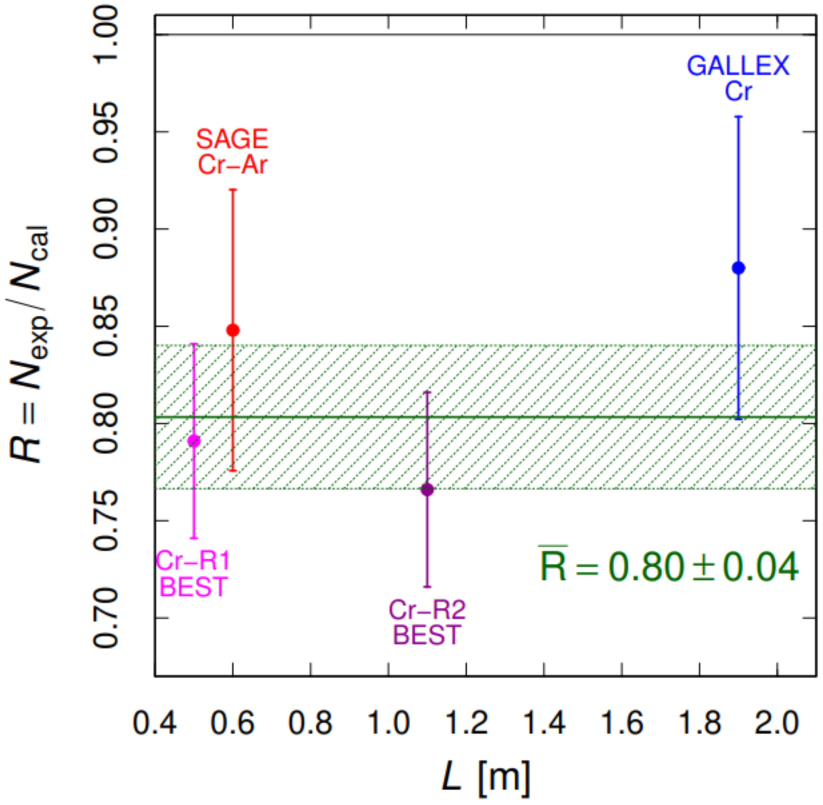
Final result: 69.3 ± 4.1 ± 3.6 SNU

SSM prediction: 129 +8/-6 SNU (BP98)

Combined Gallium: GALLEX/GNO & SAGE: 68.1 ± 3.75 SNU

The Gallium Anomaly:

There seem to be only 80% of neutrinos from ^{51}Cr-neutrino source detected in Ga.
In historic experiments Gallex and Sage and in recent BEST experiment



From arXiv:2209.00916v3 , Giunti et al.,
„Gallium Anomaly: Critical View …“

BEST experiment

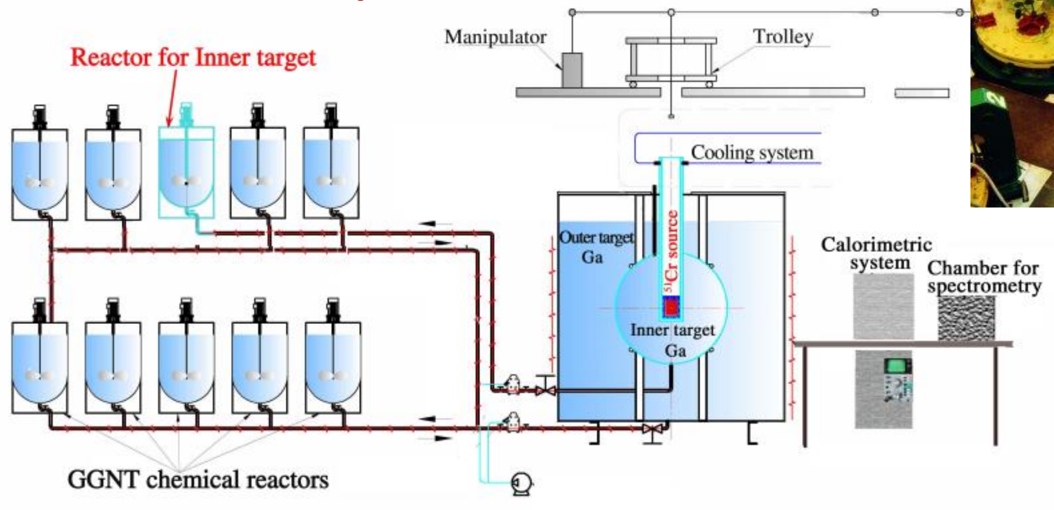


FIG. 1. The Ga target and extraction piping diagram also indicating the source handling apparatus.

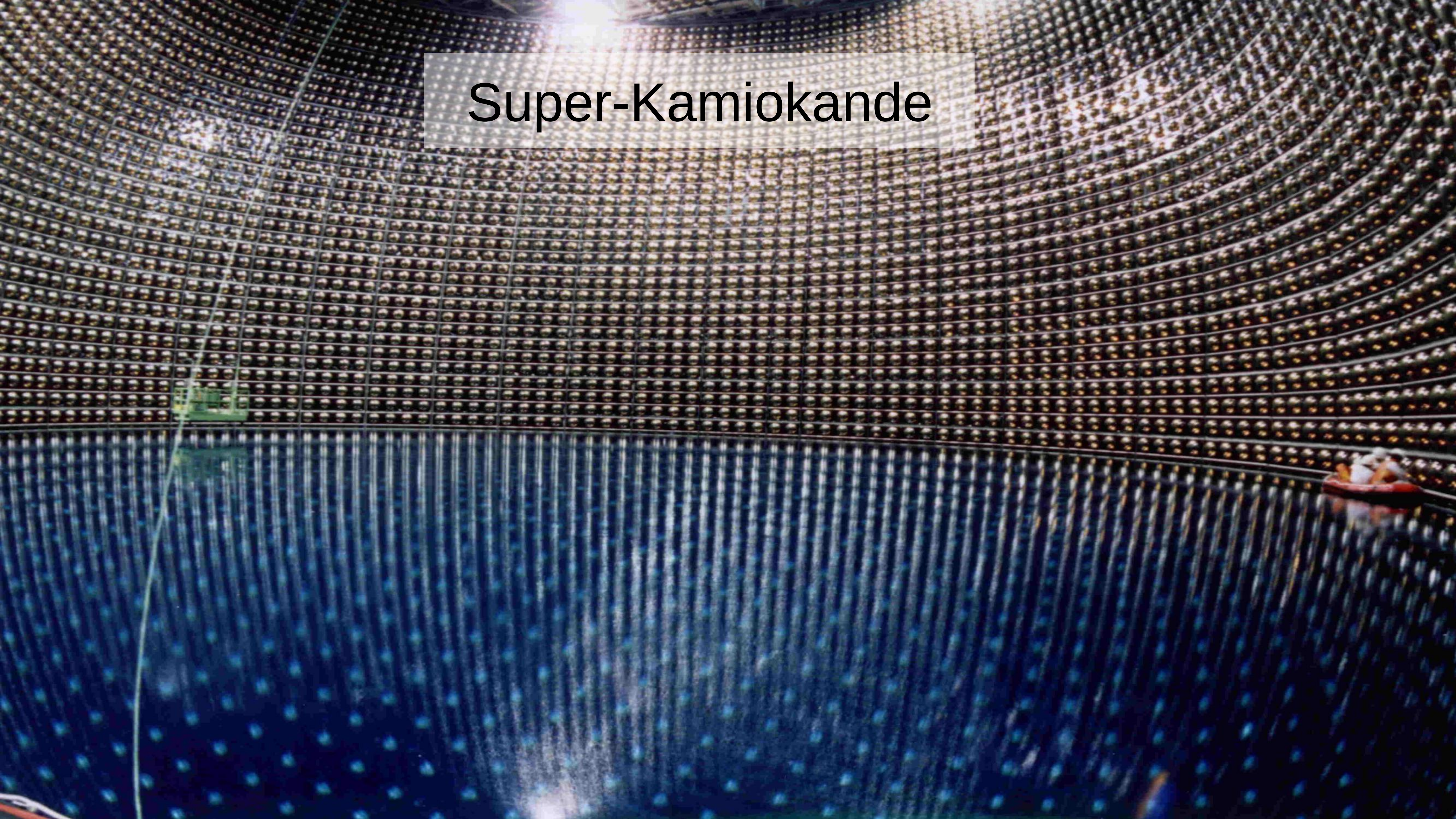
consistent with a short baseline oscillation:

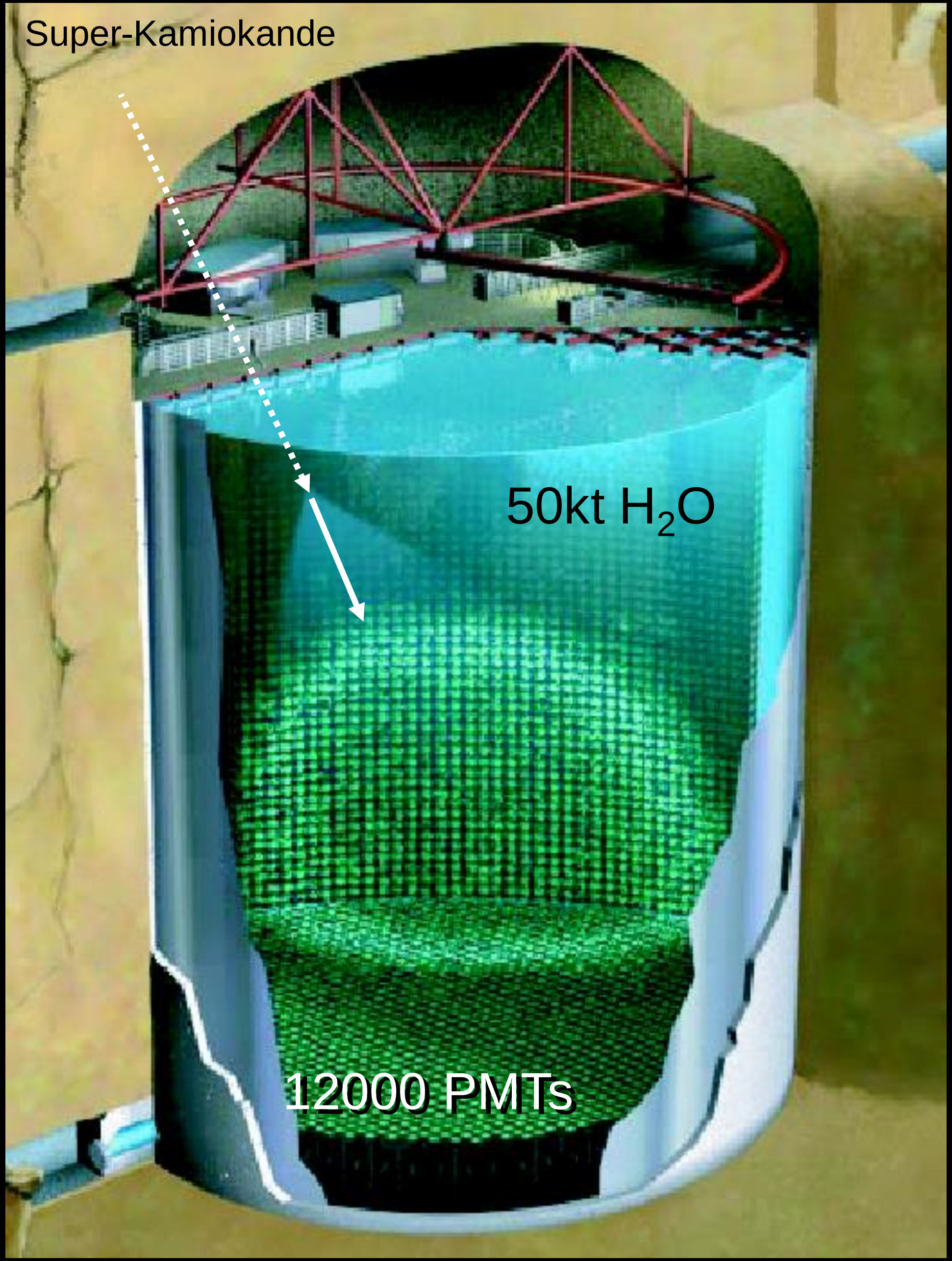
$$\Delta m^2 = 3.3^{+\infty}_{-2.3}\ \mathrm{eV}^2 \text{ and } \sin^2 2\theta = 0.42^{+0.15}_{-0.17}$$

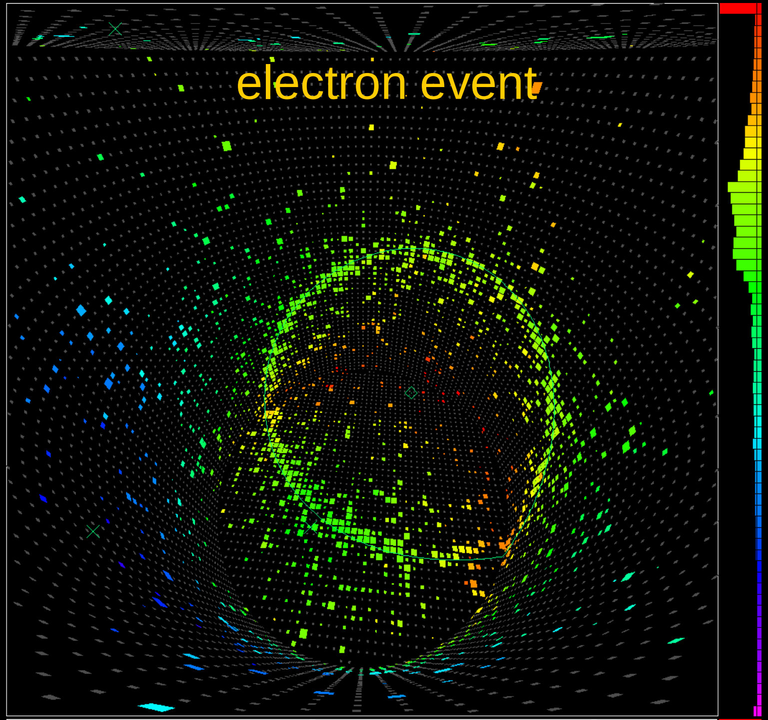
?

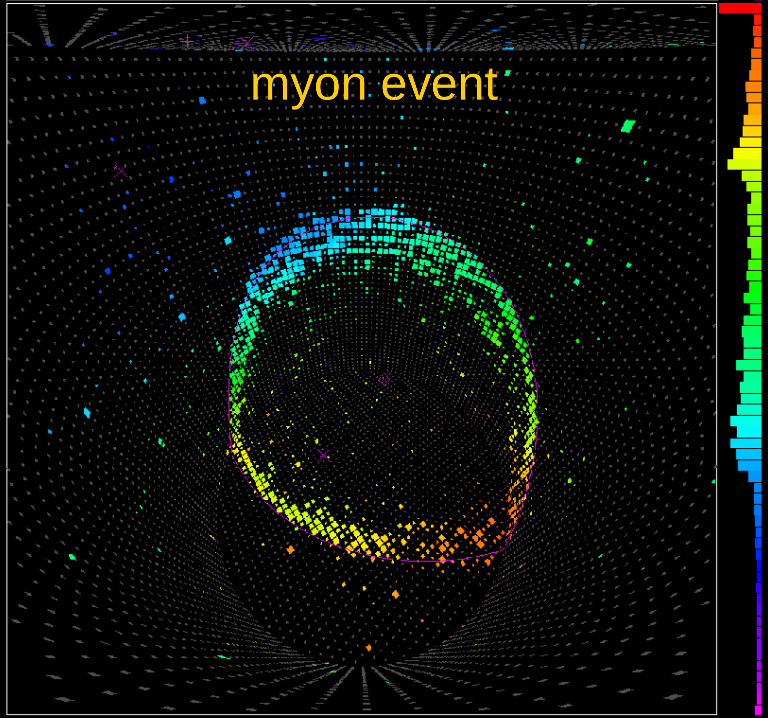
arXiv:2201.07364v3, Barinov et al.,
„A Search for Electron Neutrino Transitions to Sterile States in the BEST Experiment"

Super-Kamiokande




Super-Kamiokande
50kt H_2O
12000 PMTs

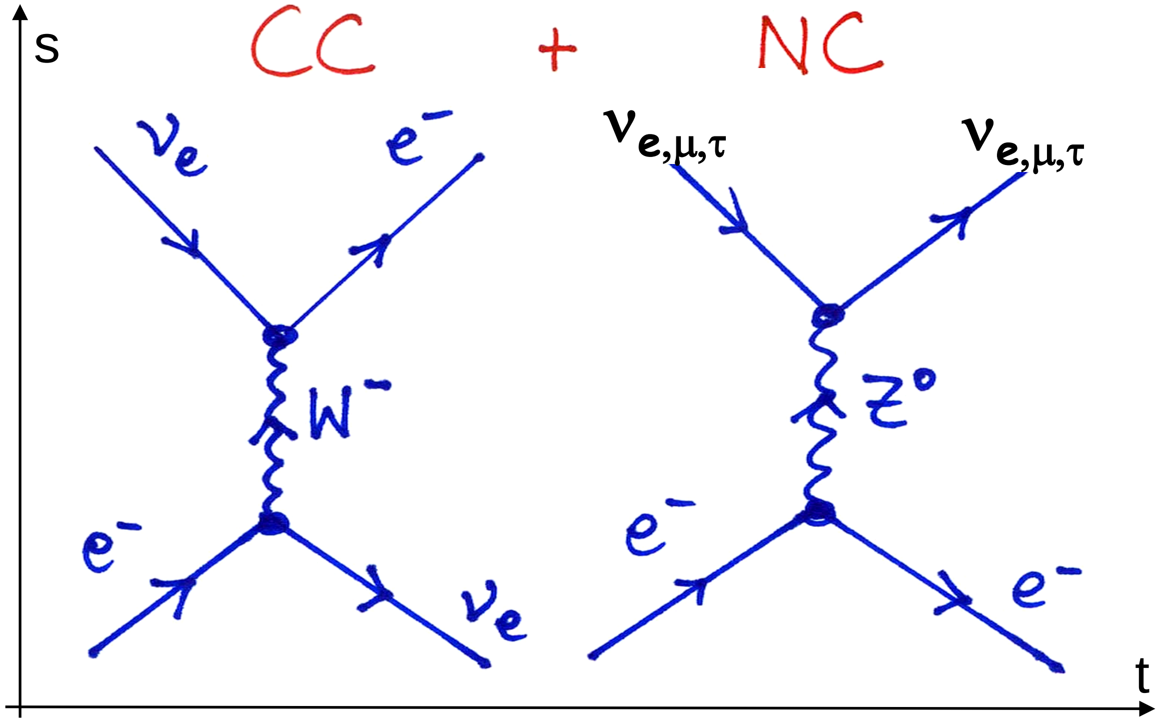

electron event


myon event

Detection of solar neutrinos in Super-Kamiokande: 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!

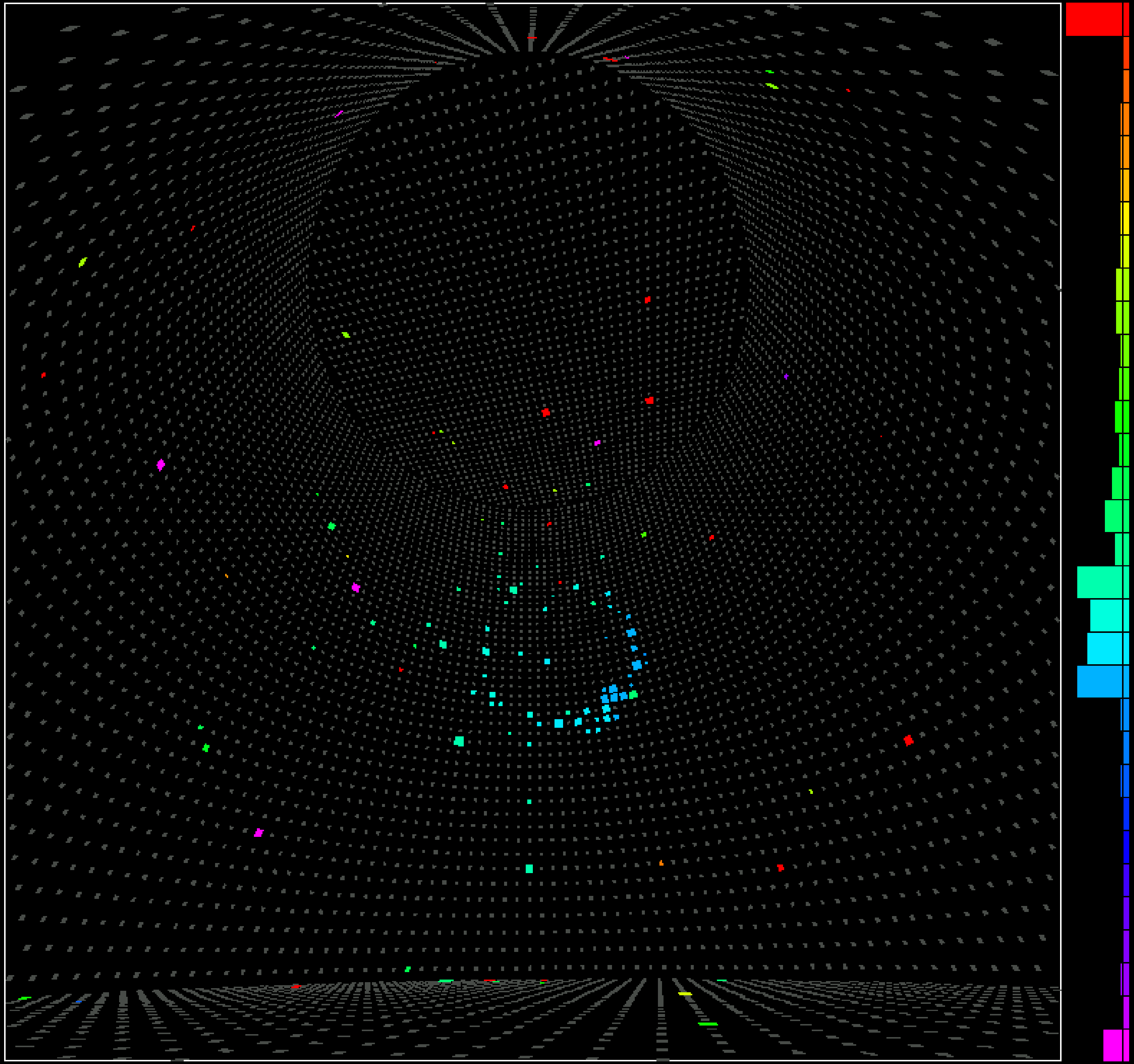
Superkamiokande:

Solar neutrino

This is a real event (not Monte Carlo), recorded on 1998-03-12 14:08:40.

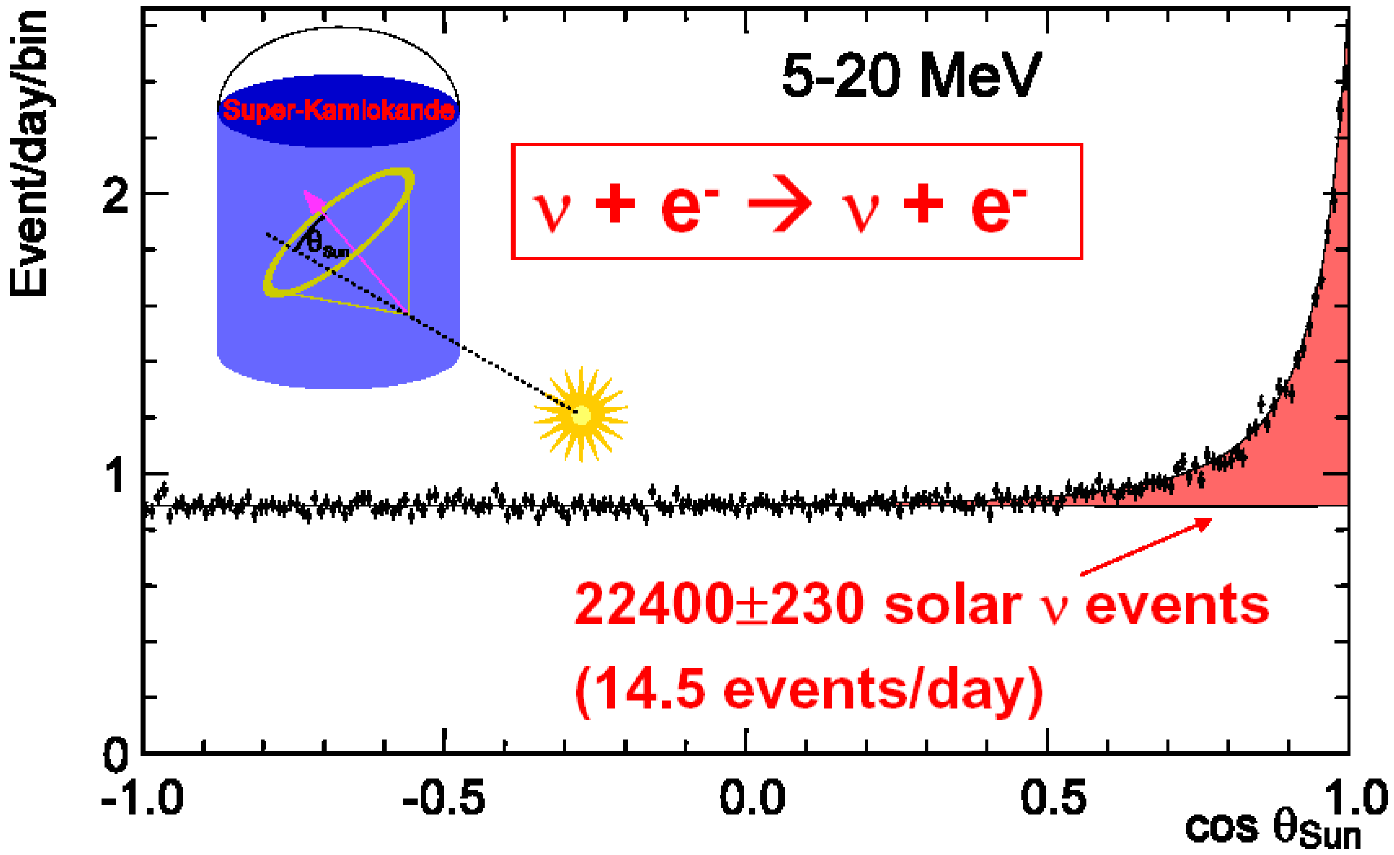
It is about 12.5 MeV and has an unusually nice, well-defined ring.

The color scale is time.



Super-Kamiokande-I solar neutrino data

May 31, 1996 – July 13, 2001 (1496 days)



5-20 MeV

$\nu + e^- \rightarrow \nu + e^-$

22400±230 solar ν events

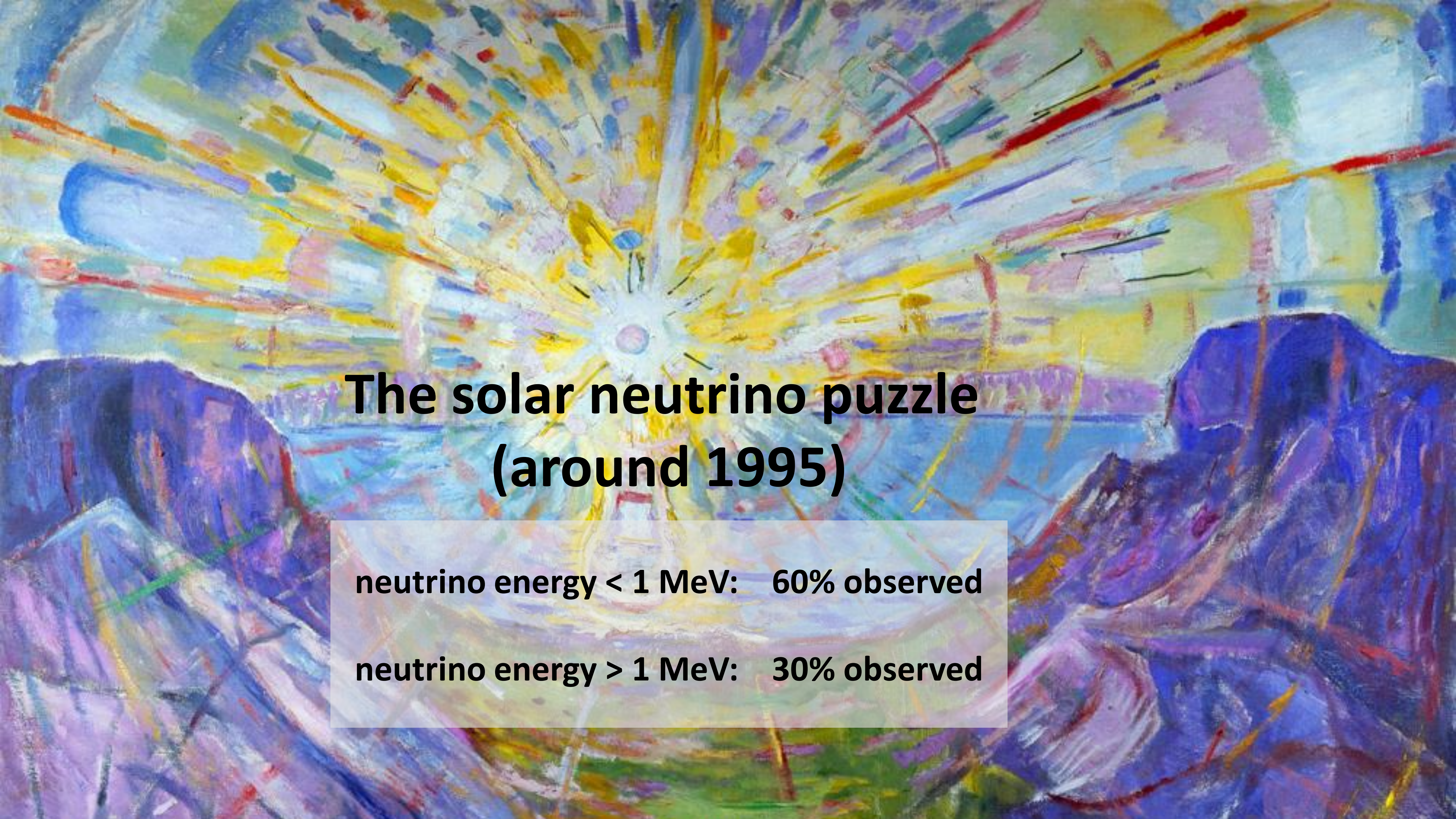
(14.5 events/day)

^{8}B flux : $2.35 \pm 0.02 \pm 0.08$ [x 10^6 /cm^2/sec]

$$\frac{\text{Data}}{\text{SSM(BP2004)}} = 0.406 \pm 0.004 \begin{array}{l} +0.014 \\ -0.013 \end{array}$$

(Data/SSM(BP2000) = 0.465 ±0.005 +0.016/-0.015)

The Sun shines in neutrino light as seen by Super-Kamiokande



The solar neutrino puzzle (around 1995)

neutrino energy < 1 MeV: 60% observed

neutrino energy > 1 MeV: 30% observed