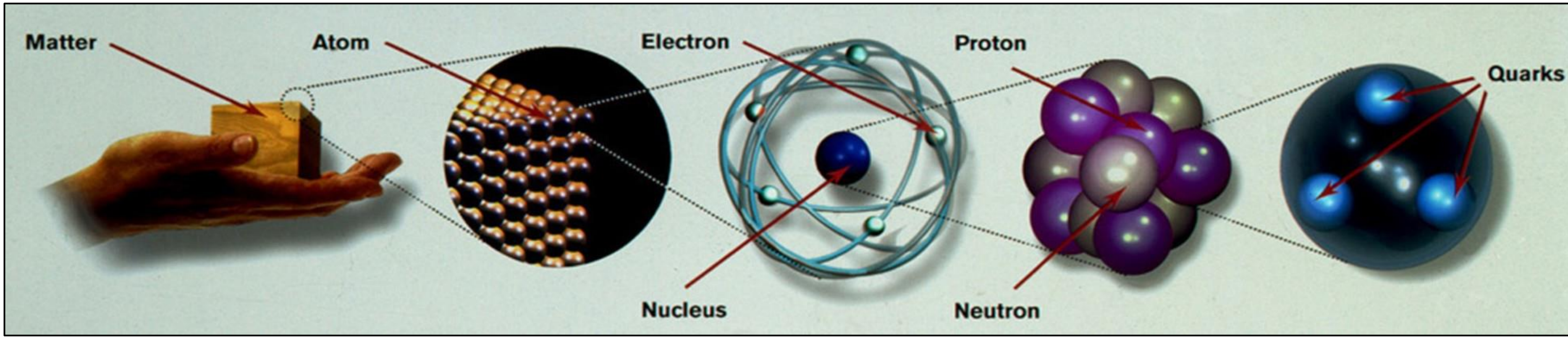
Neutrinos
in Astrophysics and Cosmology

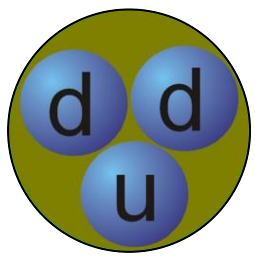
Introductory Remarks

Georg G. Raffelt
Max-Planck-Institut für Physik, München, Germany

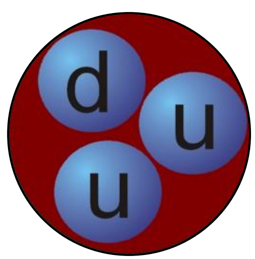
Periodic System of Elementary Particles



Quarks		Leptons	
Charge −1/3	Charge +2/3	Charge −1	Charge 0
Down d	Up u	Electron e	e-Neutrino ν_e

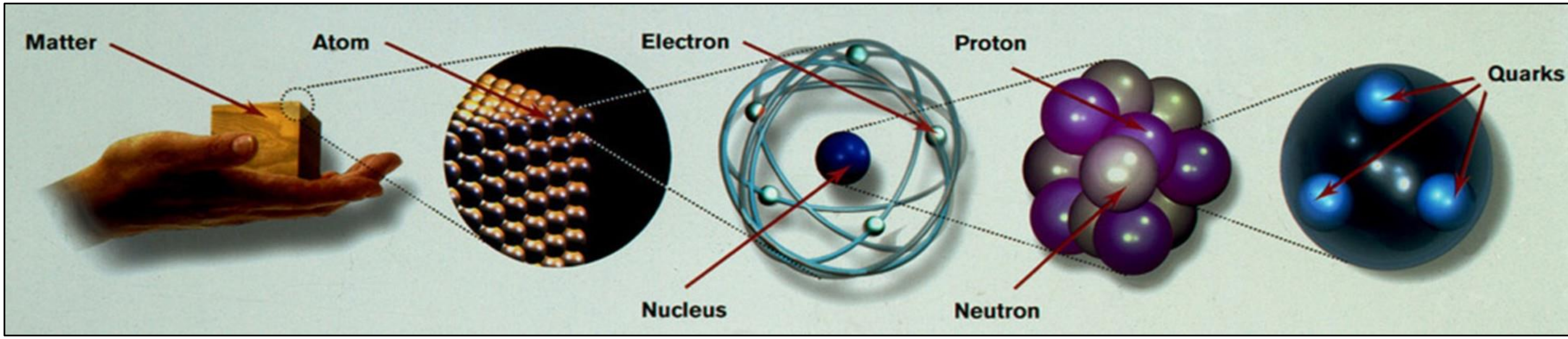


Neutron



Proton

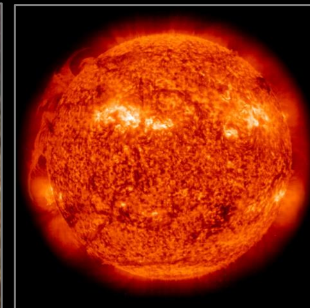
Periodic System of Elementary Particles



	Quarks		Leptons	
	Charge −1/3	Charge +2/3	Charge −1	Charge 0
1st Family	Down d	Up u	Electron e	e-Neutrino ν_e
2nd Family	Strange s	Charm c	Muon μ	μ-Neutrino ν_μ
3rd Family	Bottom b	Top t	Tau τ	τ-Neutrino ν_τ
Higgs	Strong Interaction (8 Gluons)			
	Electromagnetic Interaction (Photon)			
	Weak Interaction (W and Z Bosons)			
	Gravitation (Gravitons?)			

Where do Neutrinos Appear in Nature?

✓ Nuclear Reactors

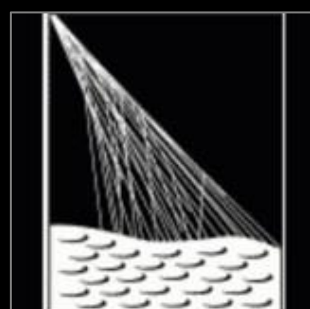


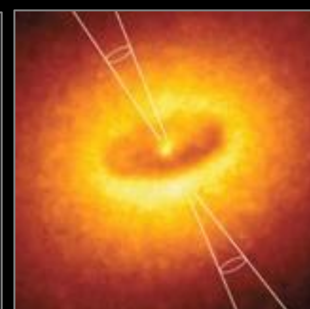
Sun ✓

✓ Particle Accelerators

Supernovae
(Stellar Collapse)
SN 1987A ✓

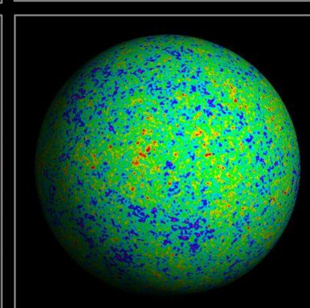
✓ Earth Atmosphere
(Cosmic Rays)





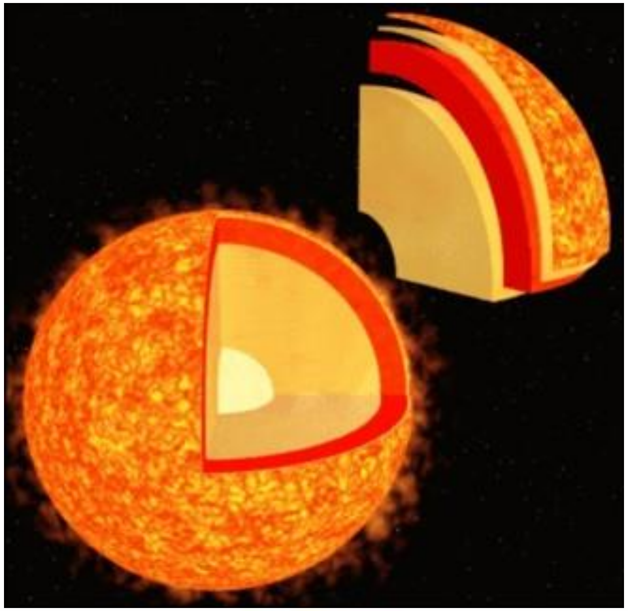
Astrophysical
Accelerators ✓

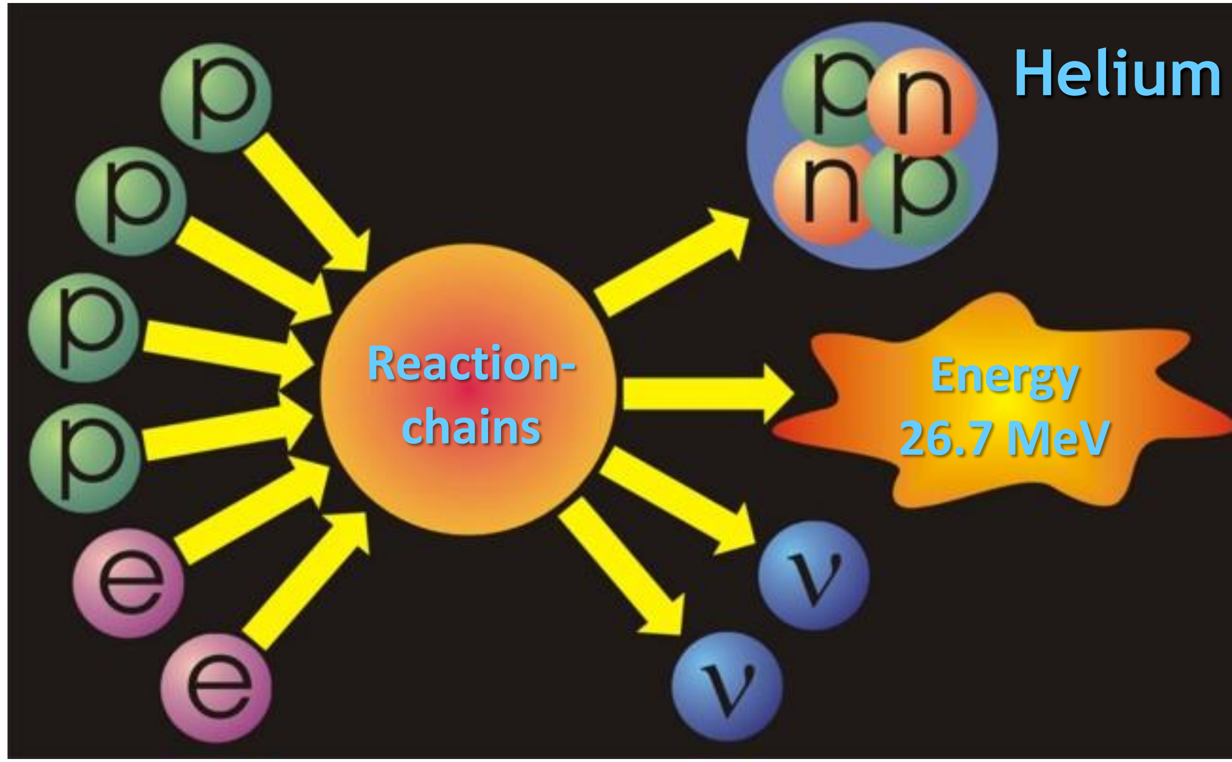
✓ Earth Crust
(Natural Radioactivity)



Cosmic Big Bang
(Today 336 ν/cm^3)
Indirect Evidence

Neutrinos from the Sun





Solar radiation: 98 % light (photons)
2 % neutrinos
At Earth 66 billion neutrinos/cm^2 sec

Hans Bethe (1906–2005, Nobel prize 1967)
Thermonuclear reaction chains (1938)

Bethe's Classic Paper on Nuclear Reactions in Stars

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 He⁴ 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 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.*

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

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

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

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.

No neutrinos from nuclear reactions in 1938 …

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.*

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

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

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

Predicting Neutrinos from Stars

The Possible Role of Neutrinos in Stellar Evolution

It can be considered at present as definitely established that the energy production in stars is caused by various types of thermonuclear reactions taking place in their interior. Since these reaction chains usually contain the processes of β-disintegration accompanied by the emission of high speed neutrinos, and since the neutrinos can pass almost without difficulty through the body of the star, we must assume that a certain part of the total energy produced escapes into interstellar space without being noticed as the actual thermal radiation of the star. Thus, for example, in the case of the carbon-nitrogen cycle in the sun, about 7 percent of the energy produced is lost in the form of neutrino radiation. However, since, in such reaction chains, the energy taken away by neutrinos represents a definite fraction of the total energy liberation, these losses are of but secondary importance for the problem of stellar equilibrium and evolution.

More detailed calculations on this collapse process are now in progress.

G. Gamow

The George Washington University,
Washington, D. C.,

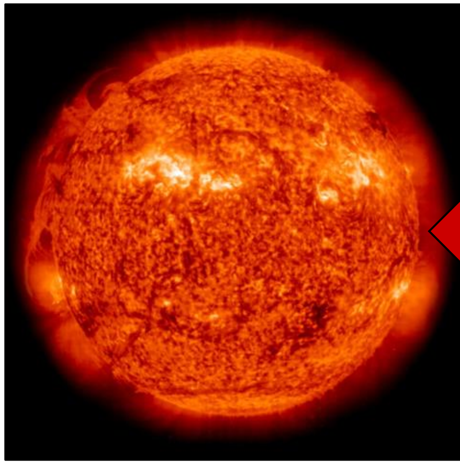
M. Schoenberg*

University of São Paulo,
São Paulo, Brazil,
November 23, 1940.

* Fellow of the Guggenheim Memorial Foundation. Now in Washington, D. C.

Phys. Rev. 58:1117 (1940)

Sun Glasses for Neutrinos?



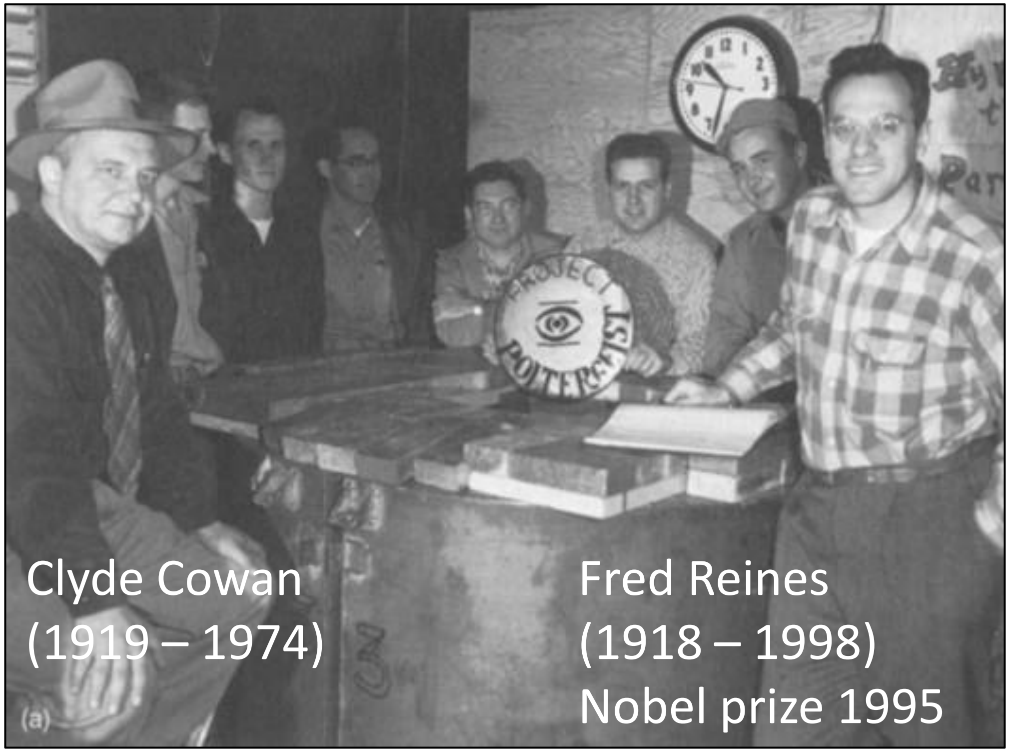
8.3 light minutes

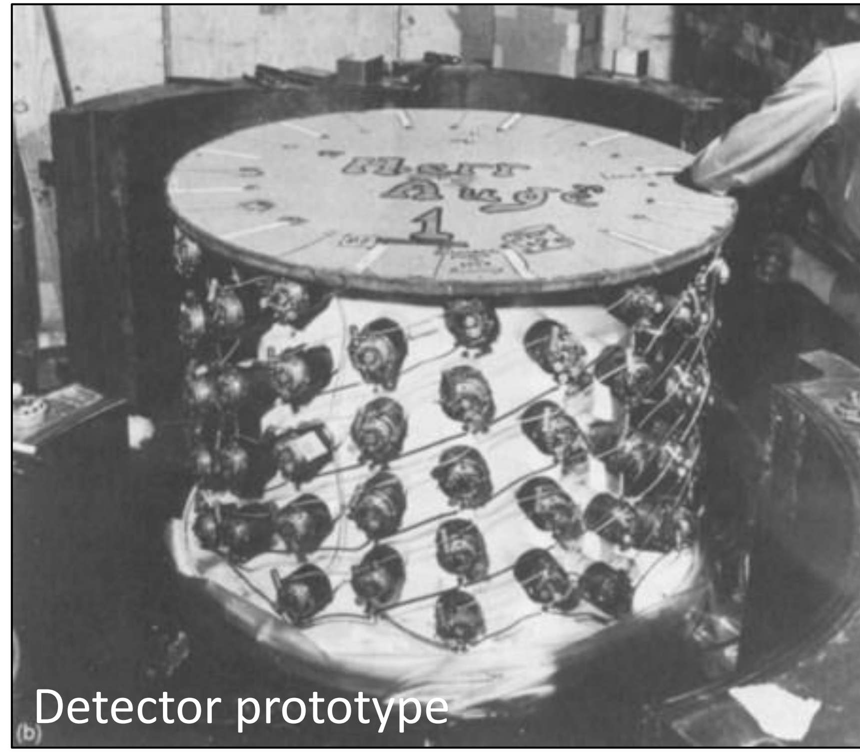
Several light years of lead needed to shield solar neutrinos

Bethe & Peierls 1934:

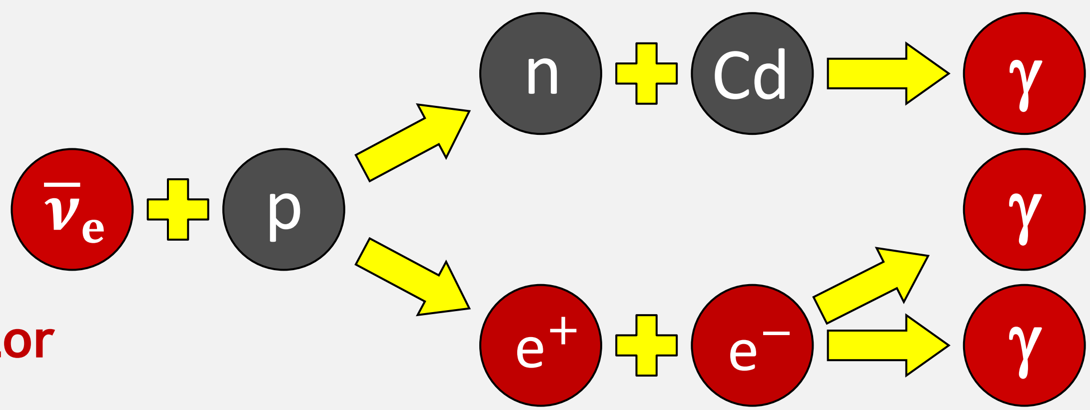
… this evidently means that one will never be able to observe a neutrino.

First Detection (1954 – 1956)



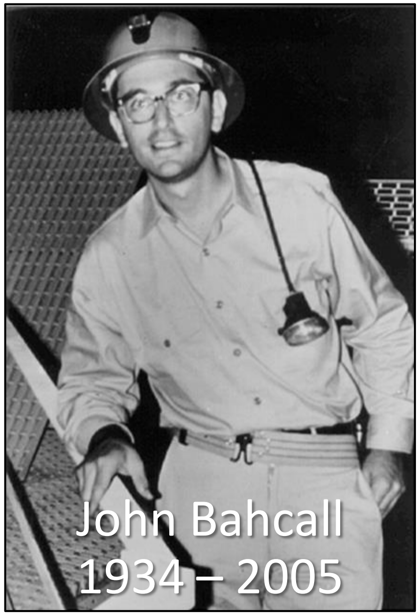


Anti-Electron Neutrinos from Hanford Nuclear Reactor



3 Gammas in coincidence

Proposing the First Solar Neutrino Experiment



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

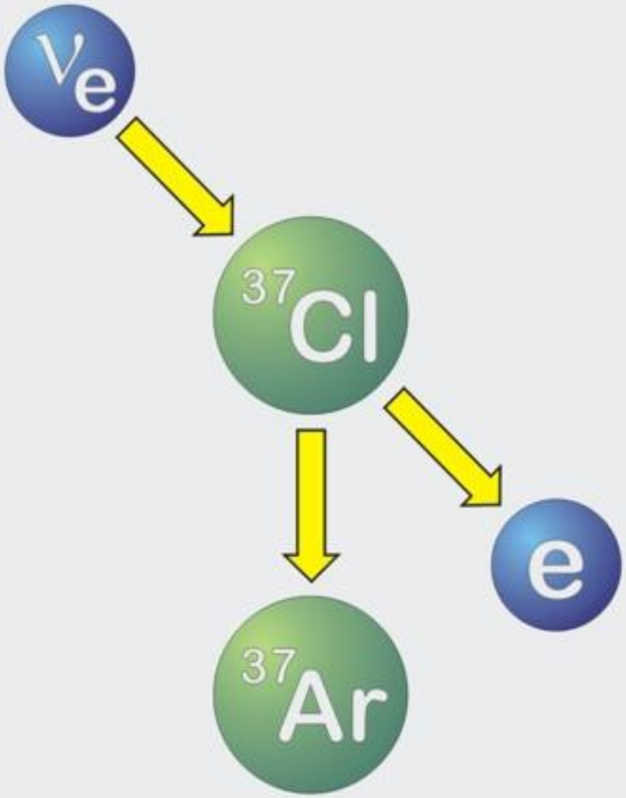
SOLAR NEUTRINOS. II. EXPERIMENTAL*

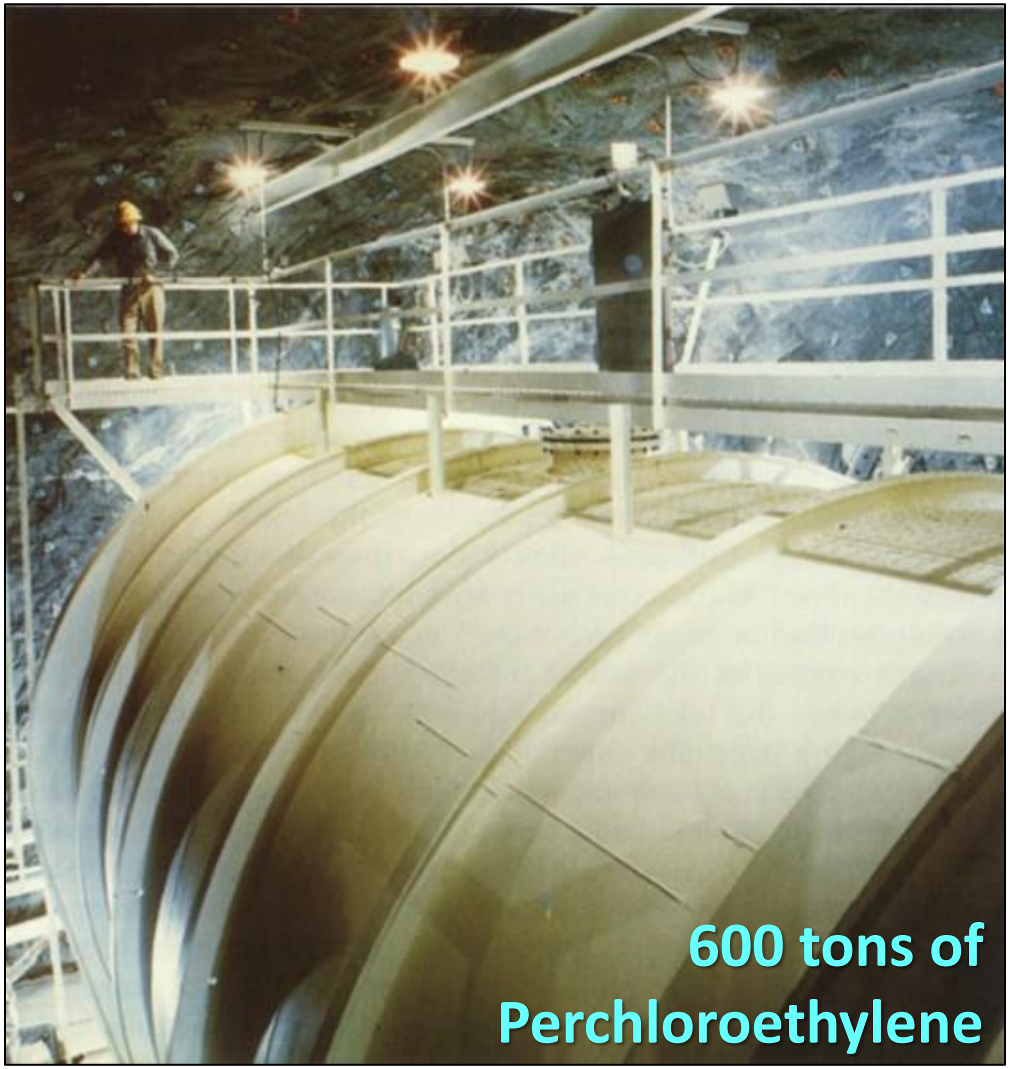
Raymond Davis, Jr.
Chemistry Department, Brookhaven National Laboratory, Upton, New York
(Received 6 January 1964)

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 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)$^{-1}$.

First Measurements of Solar Neutrinos

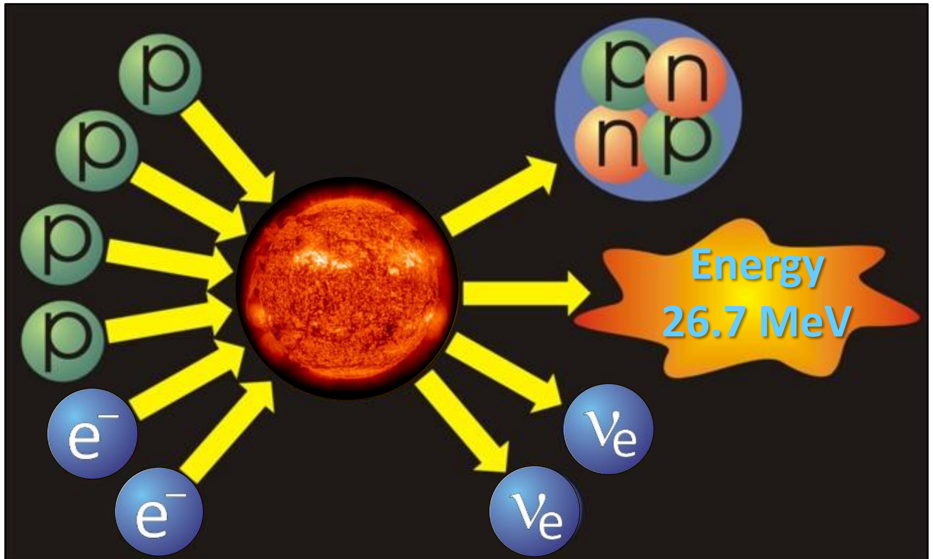
Inverse beta decay of chlorine





Homestake solar neutrino observatory (1967–2002)

Solar Neutrinos vs. Reactor Antineutrinos



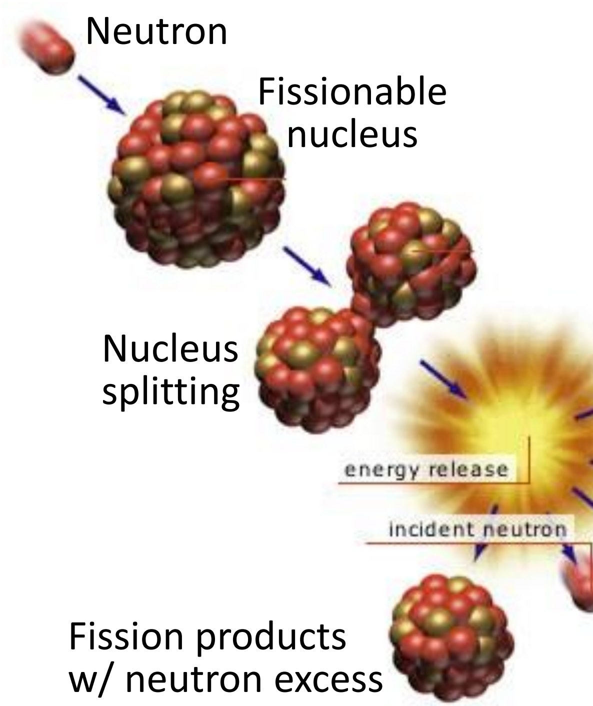
Ray Davis radiochemical detector (1967–1992)

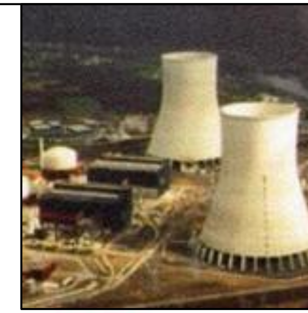
$\nu_e + {}^{37}\mathrm{Cl} \to {}^{37}\mathrm{Ar} + e^-$

Amounts to neutino capture by neutron

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

Does not work for reactor $\overline{\nu}_e$ flux!





β unstable nuclei effectively decay by

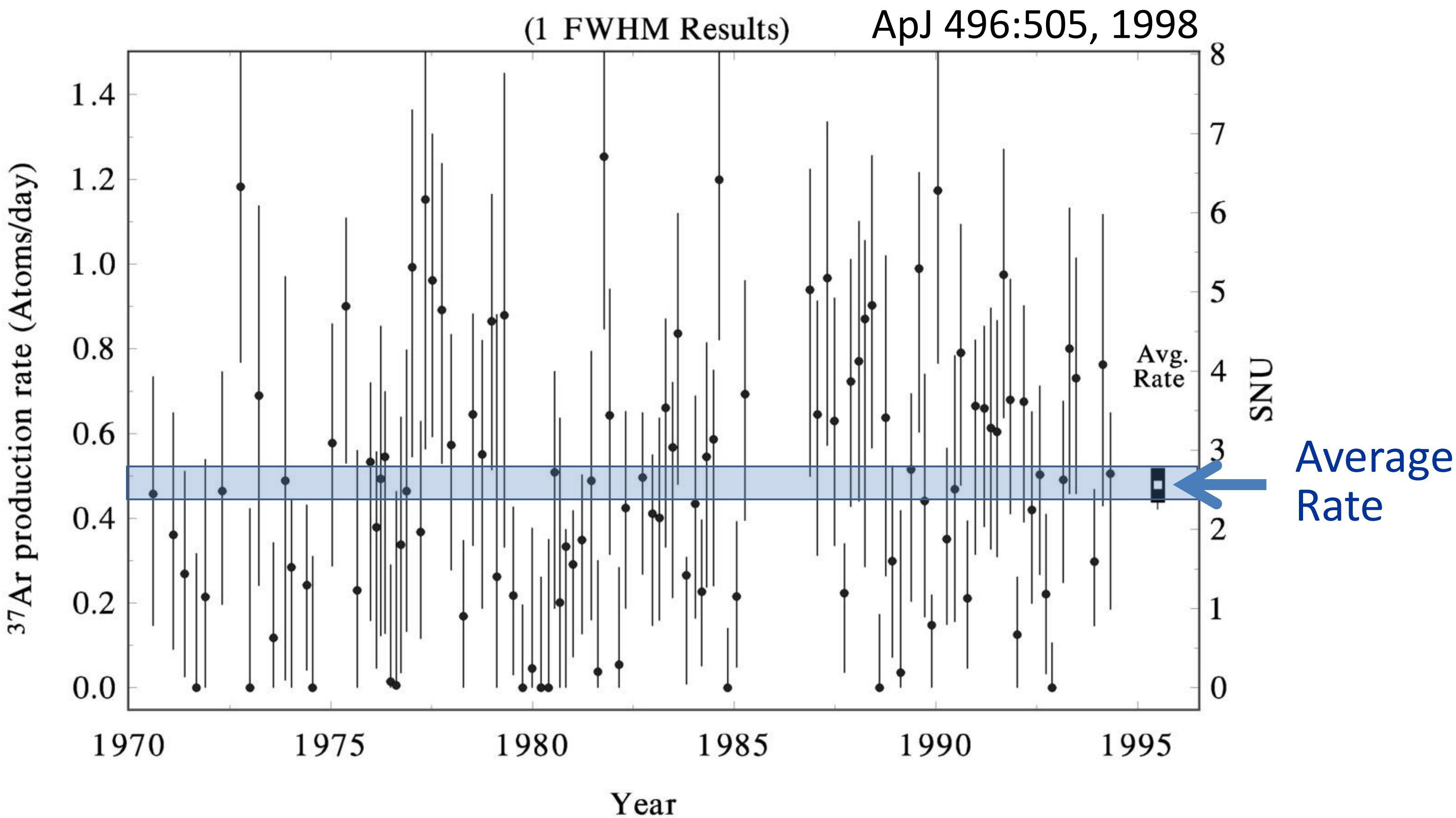
$n \to p + e + \overline{\nu}_e$

Detection by inverse β decay

$\overline{\nu}_e + p \to n + e^+$

Reines and Cowan 1954–1956

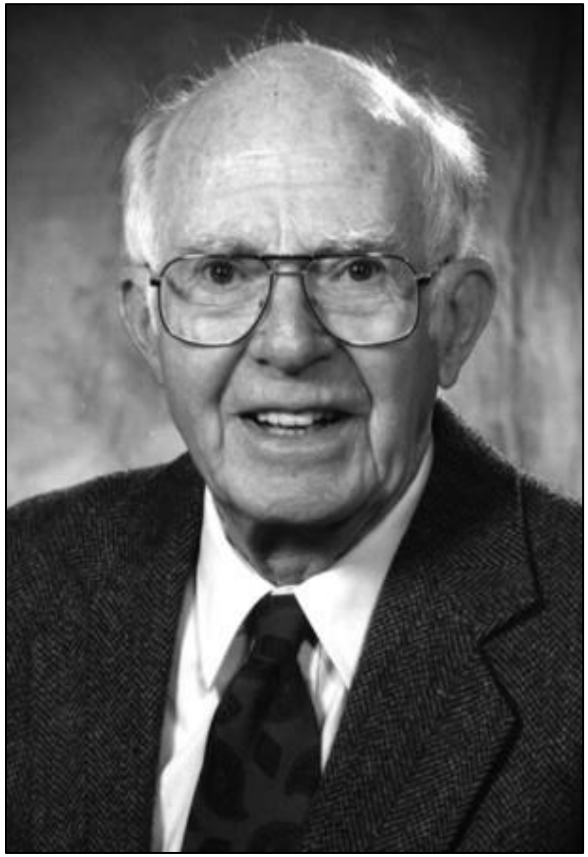
Results of Chlorine Experiment (Homestake)



Average (1970–1994) $\mathbf{2.56 \pm 0.16_{stat} \pm 0.16_{sys}}$ **SNU**

(SNU = Solar Neutrino Unit = 1 Absorption / sec / 10^{36} Atoms)

2002 Physics Nobel Prize for Neutrino Astronomy

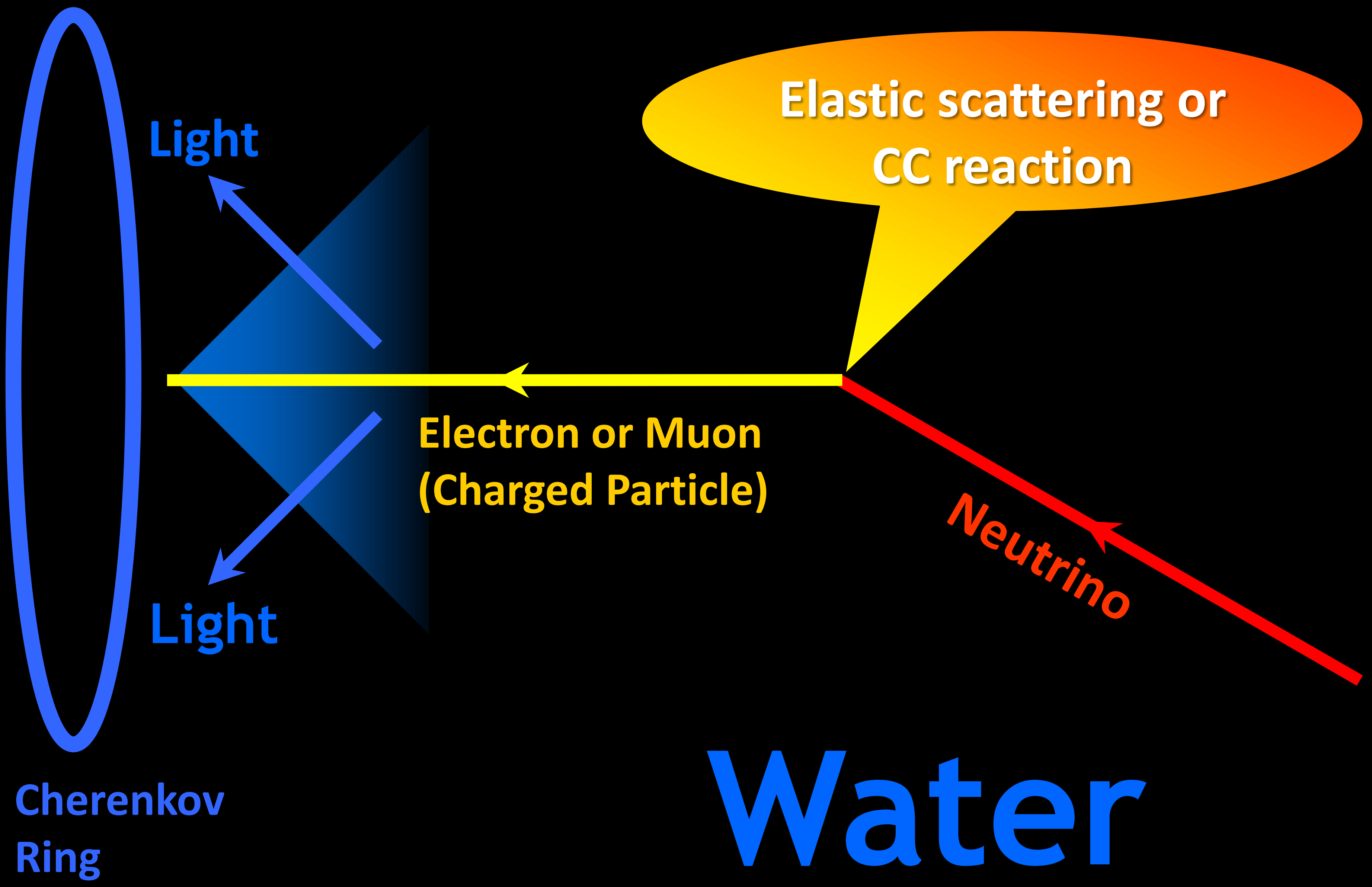


Ray Davis Jr.
(1914–2006)

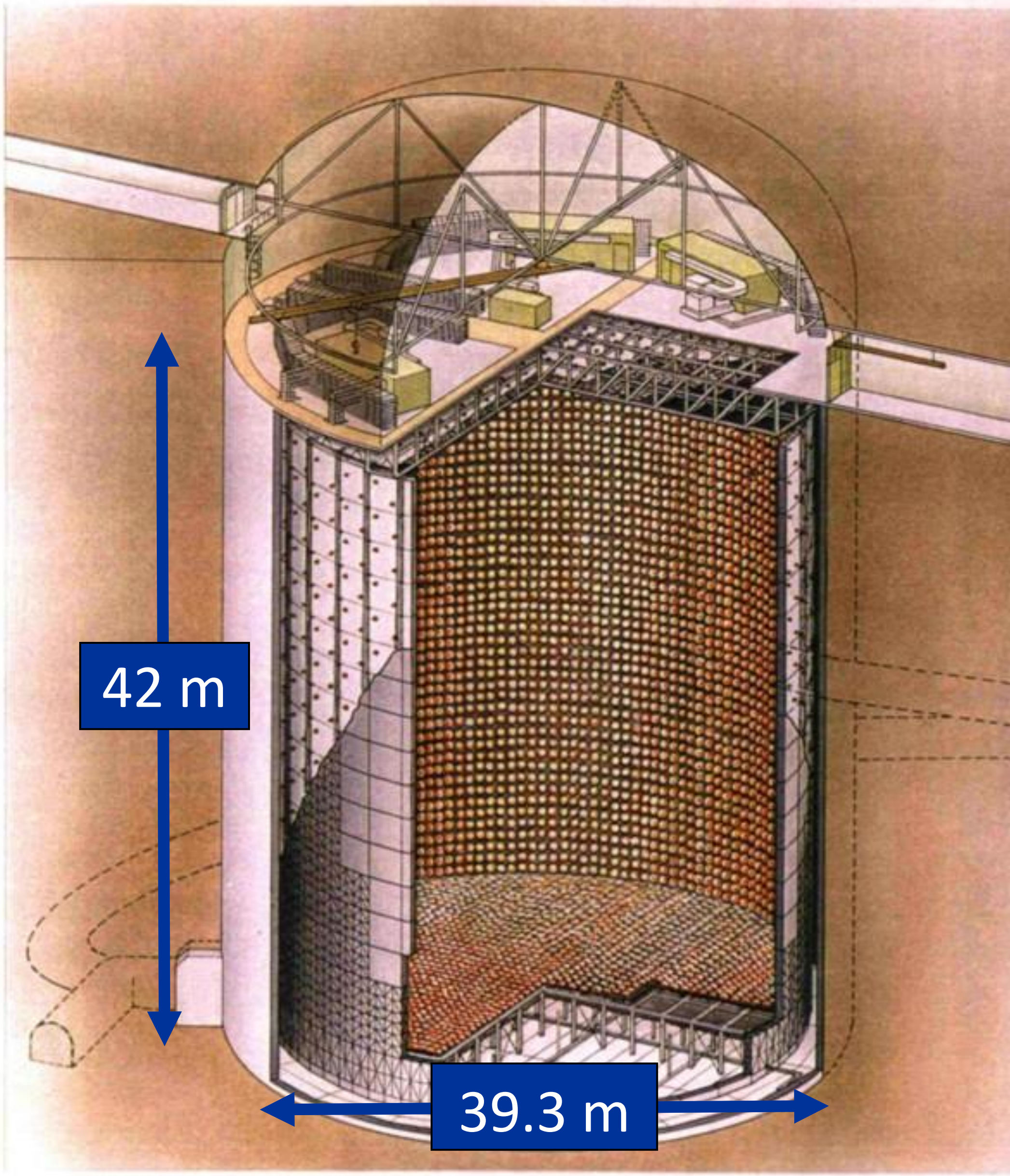
Masatoshi Koshiba
(*1926)

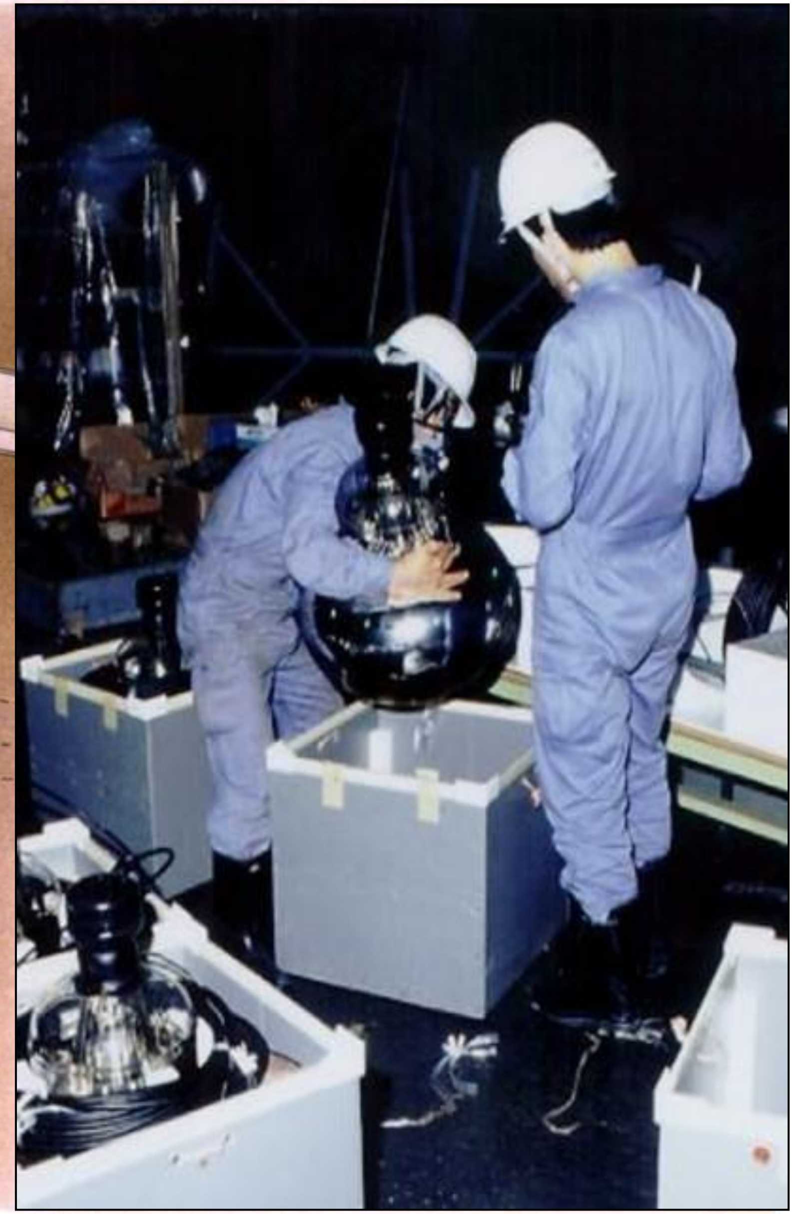
"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

Cherenkov Effect

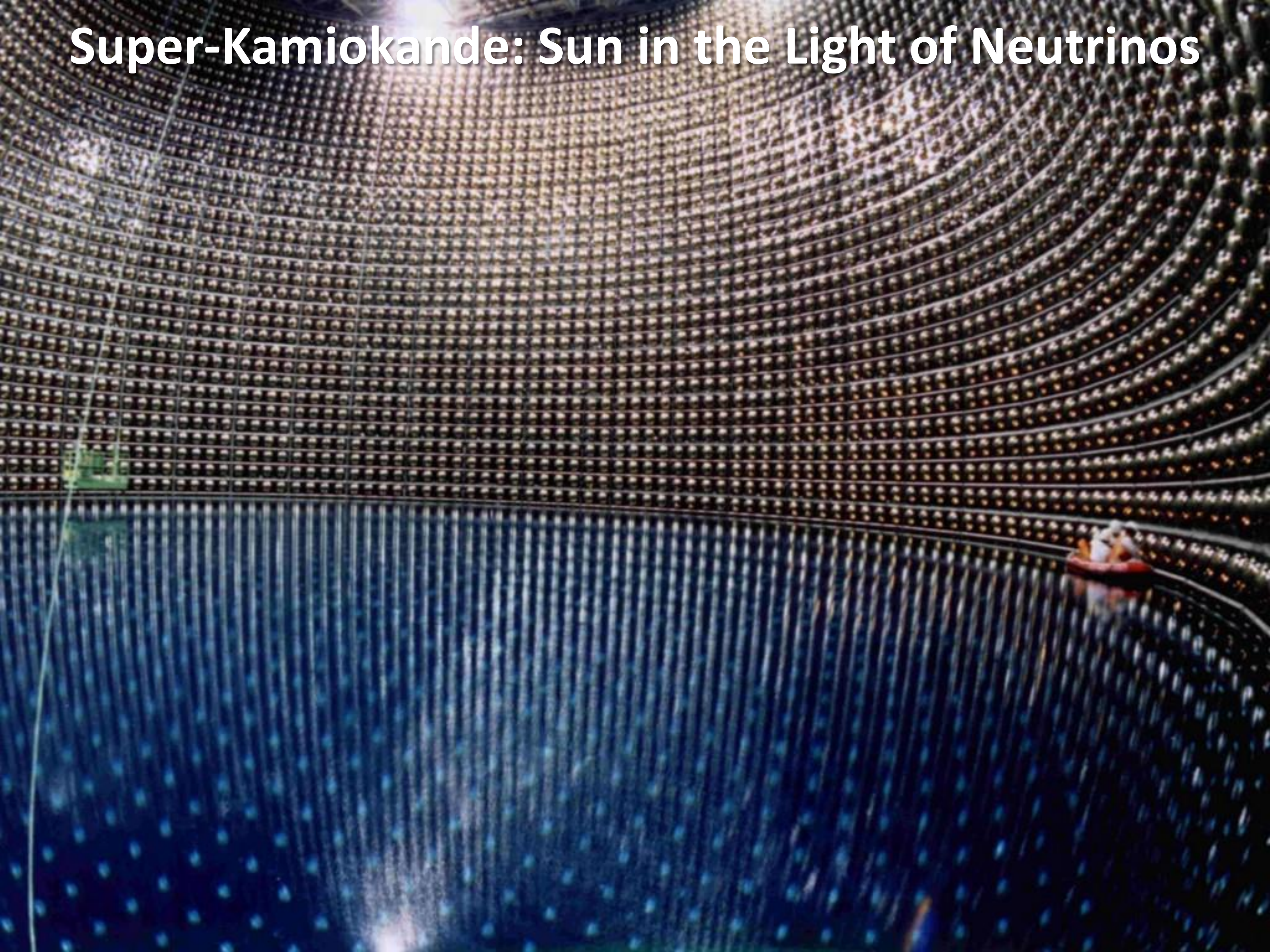


Super-Kamiokande Neutrino Detector (Since 1996)

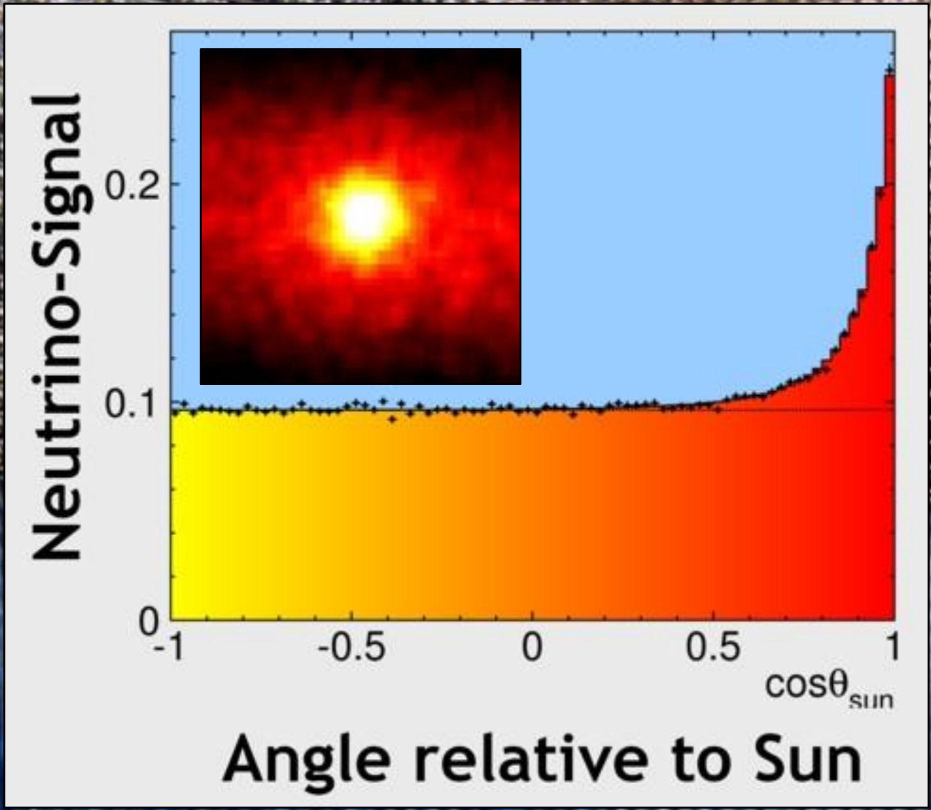


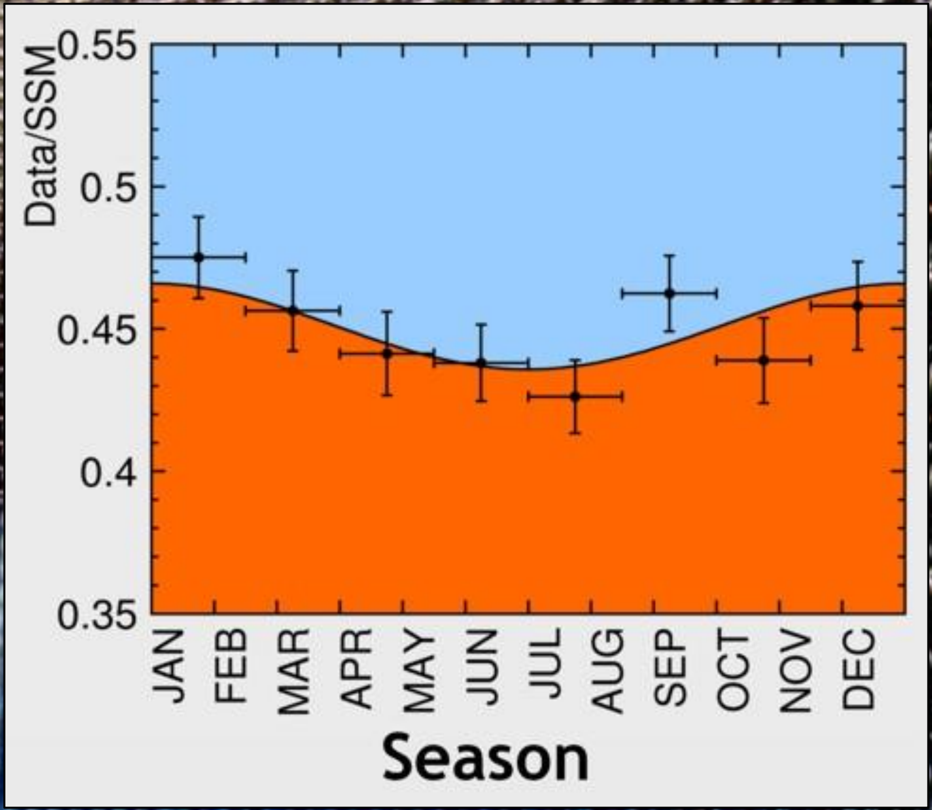


Super-Kamiokande: Sun in the Light of Neutrinos



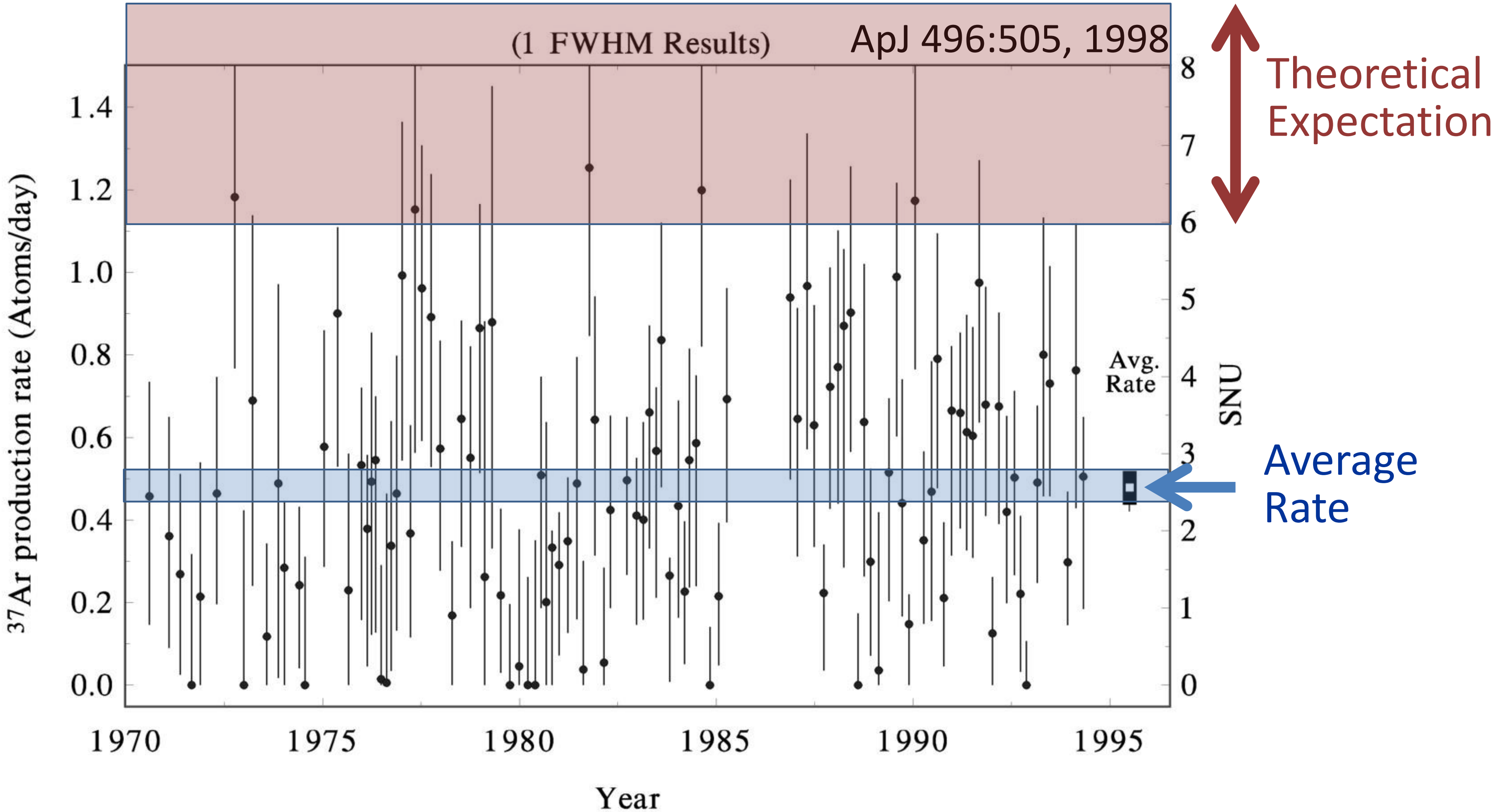
Super-Kamiokande: Sun in the Light of Neutrinos





ca. 70,000 solar neutrinos measured in Super-K (1996–2014)

Results of Chlorine Experiment (Homestake)



Average (1970–1994) **$2.56 \pm 0.16_{stat} \pm 0.16_{sys}$ SNU**

(SNU = Solar Neutrino Unit = 1 Absorption / sec / 10^{36} Atoms)

Theoretical Prediction 6–9 SNU

"Solar Neutrino Problem" since 1968

Volume 28B, number 7 PHYSICS LETTERS 20 January 1969

NEUTRINO ASTRONOMY AND LEPTON CHARGE

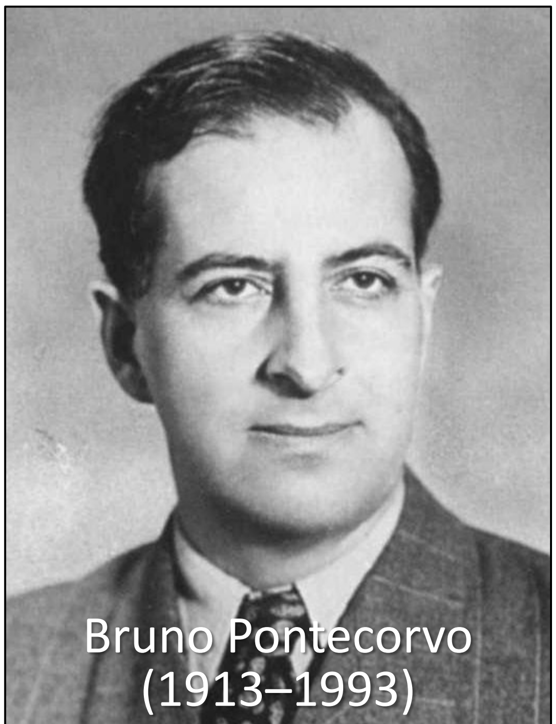
Learning about astrophysical sources with neutrinos

Learning about neutrinos from astrophysics and cosmology

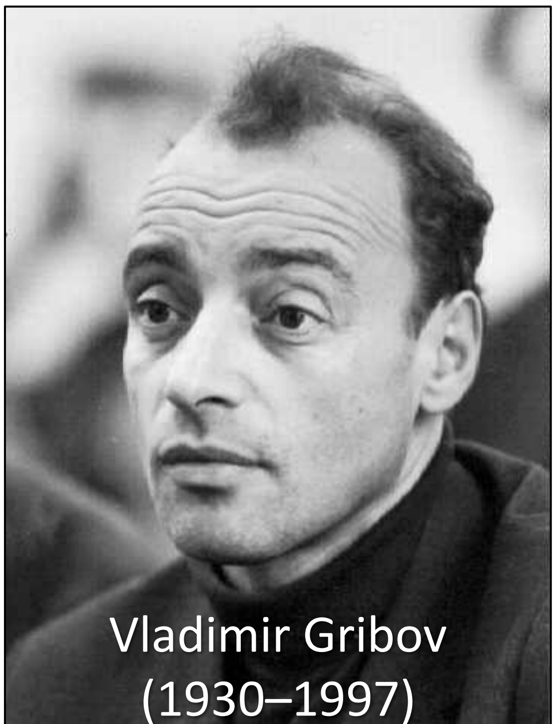
V. GRIBOV* and B. PONTECORVO
Joint Institute for Nuclear Research, Dubna, USSR

Received 20 December 1968

It is shown that lepton nonconservation might lead to a decrease in the number of detectable solar neutrinos at the earth surface, because of $\nu_e \rightleftarrows \nu_\mu$ oscillations, similar to $K^0 \rightleftarrows \tilde{K}^0$ oscillations. Equations are presented describing such oscillations for the case when there exist only four neutrino states.



Bruno Pontecorvo (1913–1993)



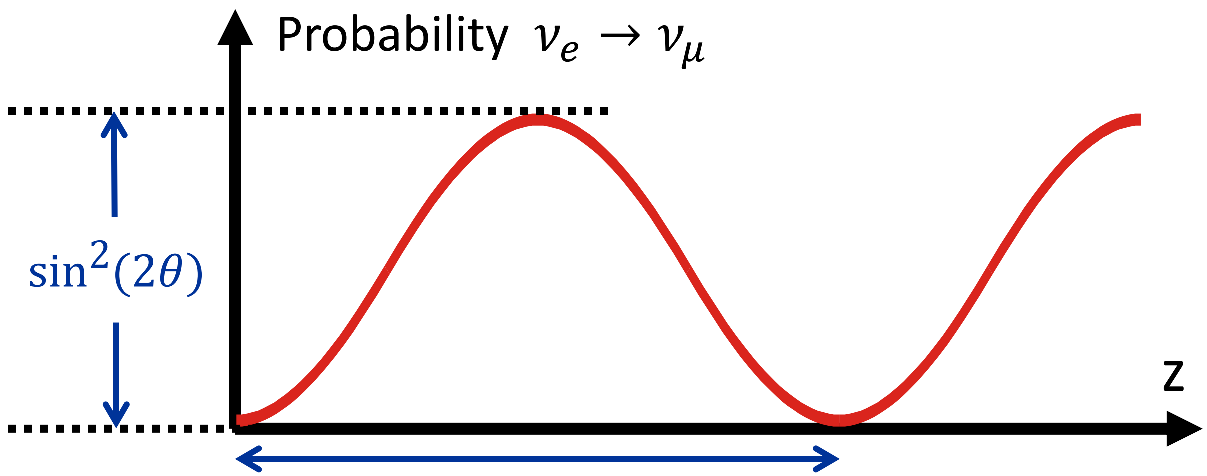
Vladimir Gribov (1930–1997)

Neutrino Flavor Oscillations

Two-flavor mixing $\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$

Each mass eigenstate propagates as $e^{\mathrm{i}p_{1,2}z}$ with $p_{1,2} = \sqrt{E^2 - m_{1,2}^2} \approx E - \frac{m_{1,2}^2}{2E}$

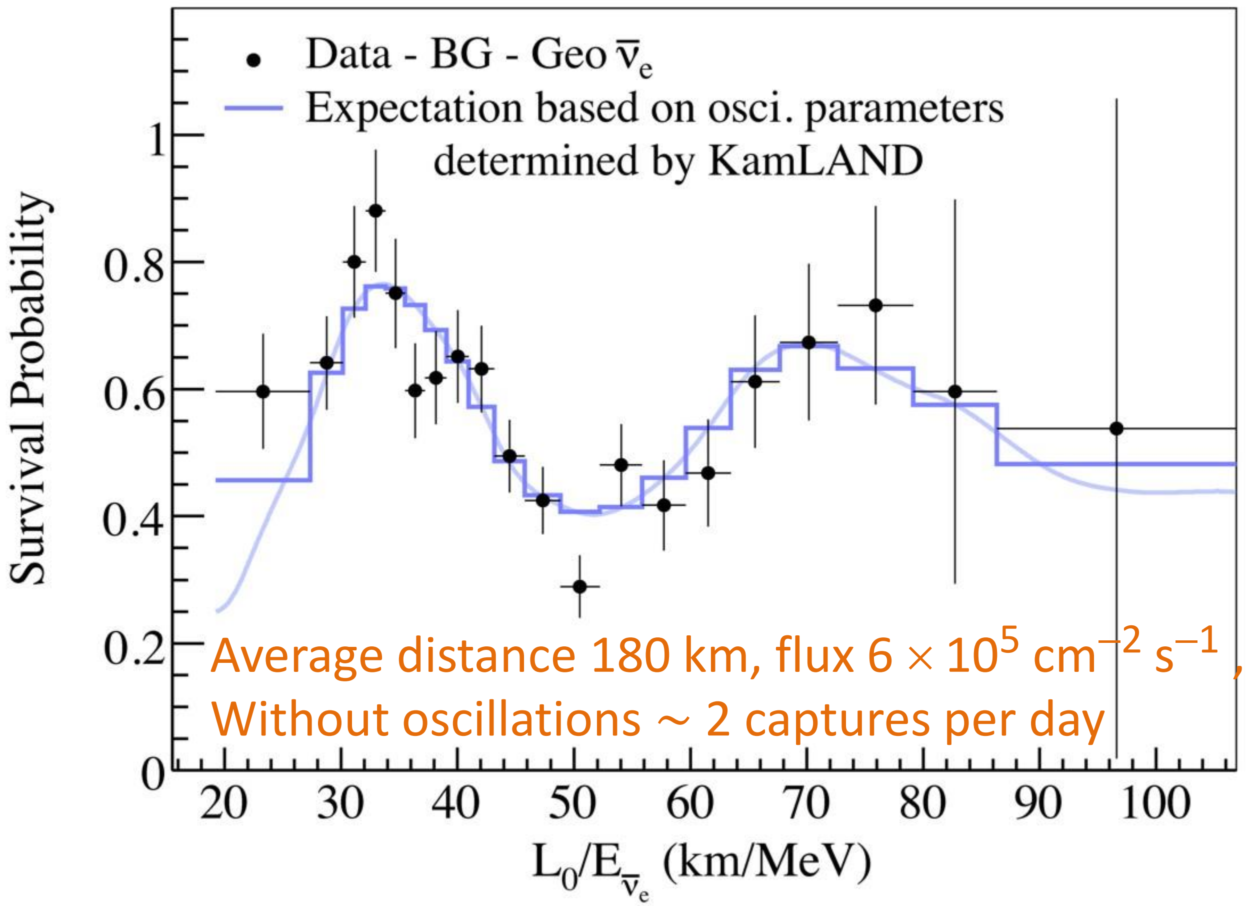
Phase difference $\frac{\delta m^2}{2E} z$ implies flavor oscillations



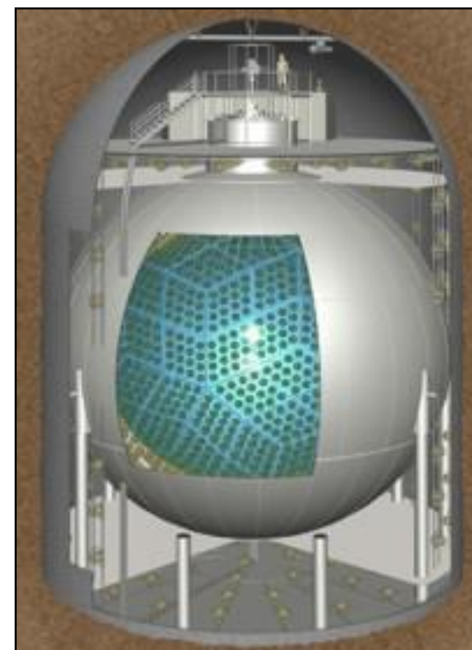
Oscillation Length $\frac{4\pi E}{\delta m^2} = 2.5\ \mathrm{m}\ \frac{E}{\mathrm{MeV}} \left(\frac{\mathrm{eV}}{\delta m}\right)^2$

Oscillation of Reactor Neutrinos at KamLAND (Japan)

Oscillation pattern for anti-electron neutrinos from Japanese power reactors as a function of L/E



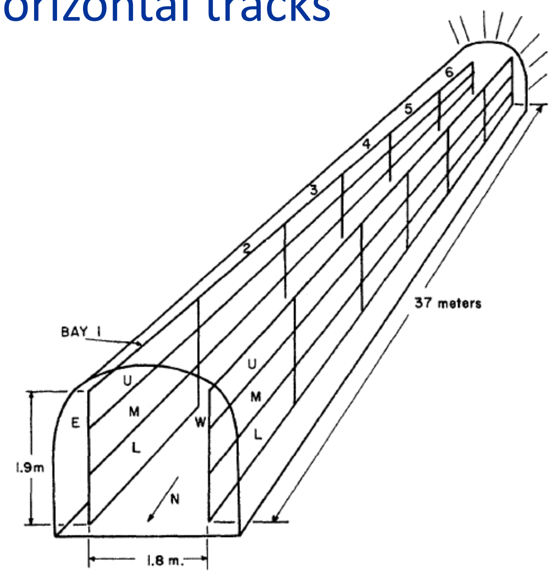
Average distance 180 km, flux $6 \times 10^5\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$,
Without oscillations ~ 2 captures per day

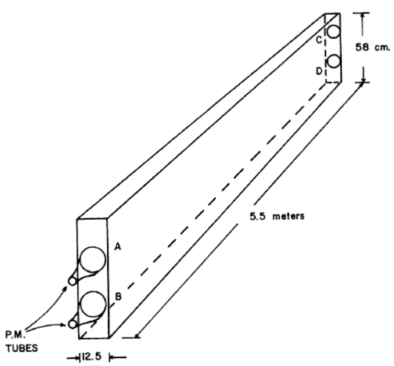


KamLAND Scintillator detector (1000 t)

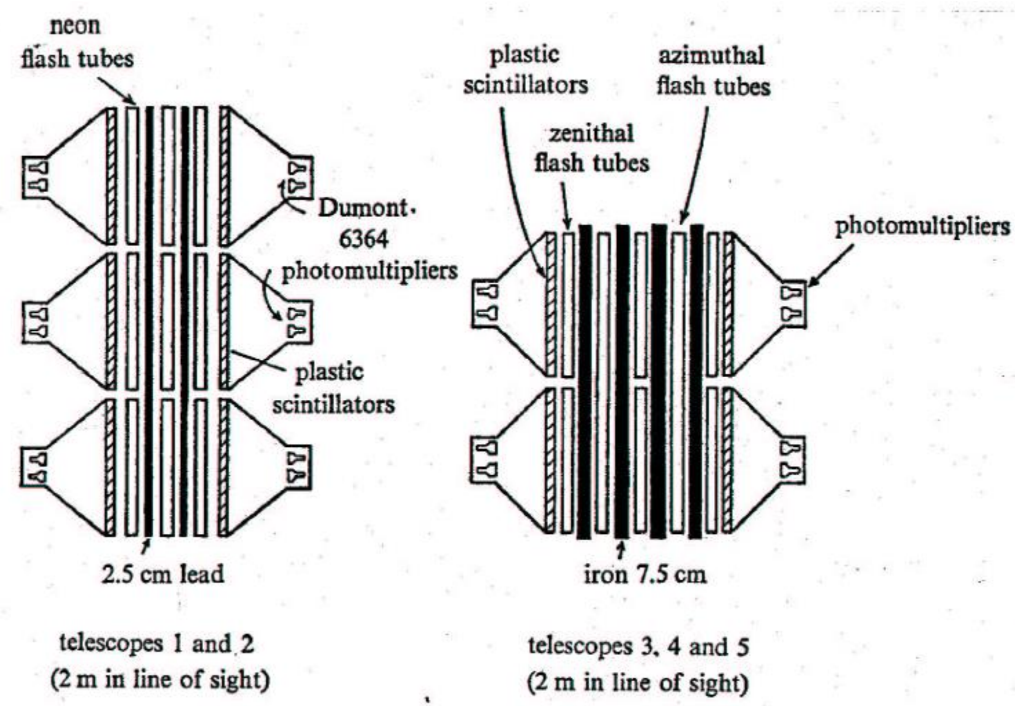
Detection of First Atmospheric Neutrinos

Chase-Witwatersrand-Irvine (CWI) Coll.
Mine in South Africa, 8800 mwe
- Liquid scintillator
- Horizontal tracks





Kolar Gold Field (KGF) Collaboration
(Japan-India-UK group), 7500 mwe
- Plastic scintillator
- Flash tubes



The Race

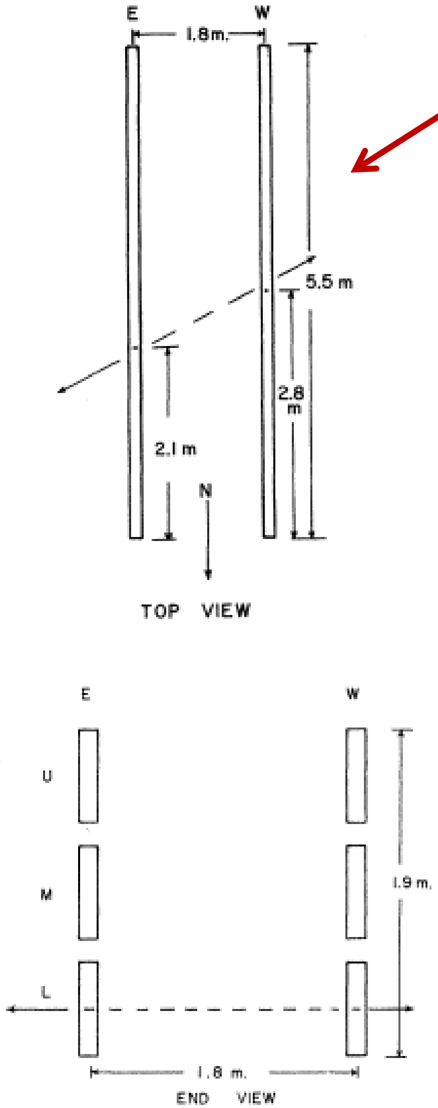


FIG. 3. Reconstruction of event of 23 February 1965.

- The first neutrino underground (CWI, 23/2/1965) out of 7 recorded February – July 1965
- KGF group started data taking some months later
- Sees first of 3 neutrino candidates 20/4/1965, two months later than Reines group
- KGF publishes two weeks earlier than the CWI
  - KGF at August 15, 1965 (submitted 12/7/1965)
  - CW at August 30, 1965 (submitted 26/7/1965)
- **Reines recorded the first cosmic neutrino ever, but the formal priority is with the KGF group.**

East Rand Proprietary Mine/South Africa

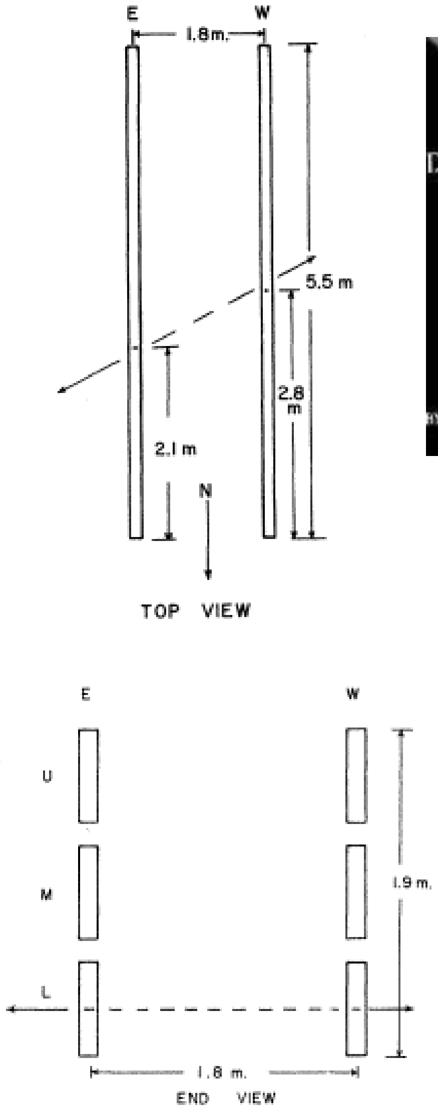
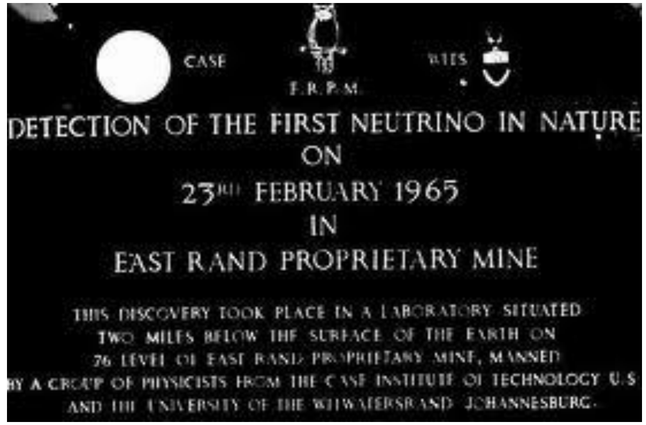


FIG. 3. Reconstruction of event of 23 February 1965.

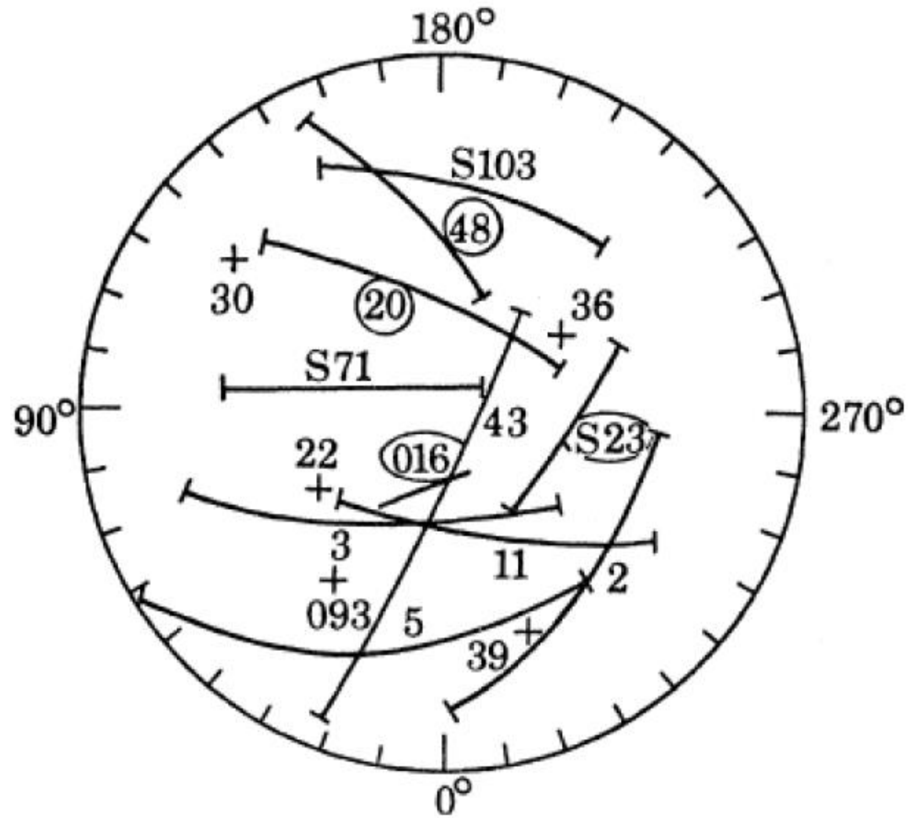


- First “natural” neutrino 23 February 1965
- 23 February 1987: Neutrino burst of SN 1987A

First Neutrino Sky Map

The first neutrino sky map with the celestial coordinates of 18 Kolar Gold Field neutrino events

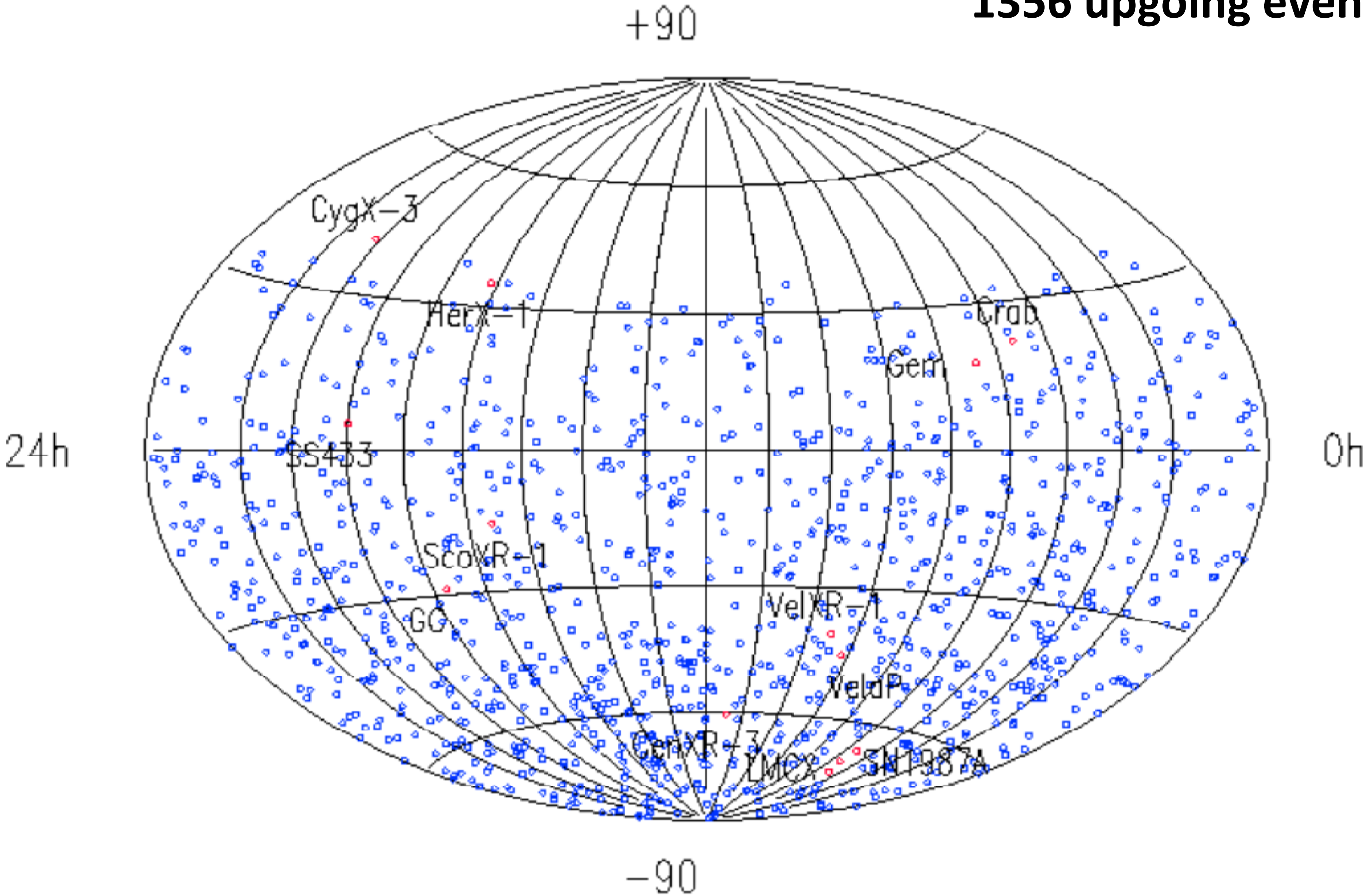
(Krishnaswamy et al. 1971)



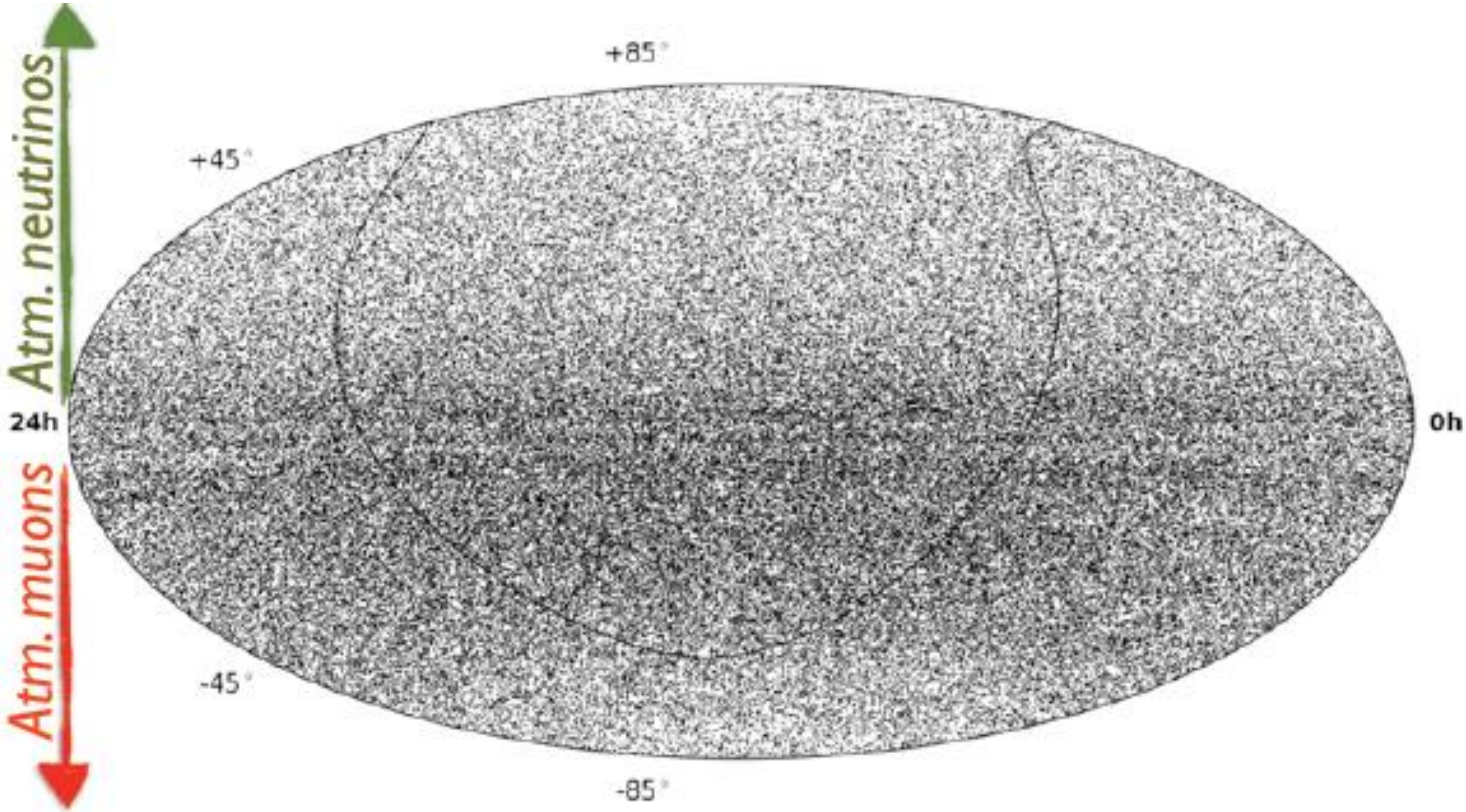
Due to uncertainties in the azimuth, the coordinates for some events are arcs rather than points. The labels reflect the numbers and registration mode of the events (e.g. S for spectrograph). Only for the ringed events the sense of the direction of the registered muon is known.

MACRO Skymap (2002)

1356 upgoing events

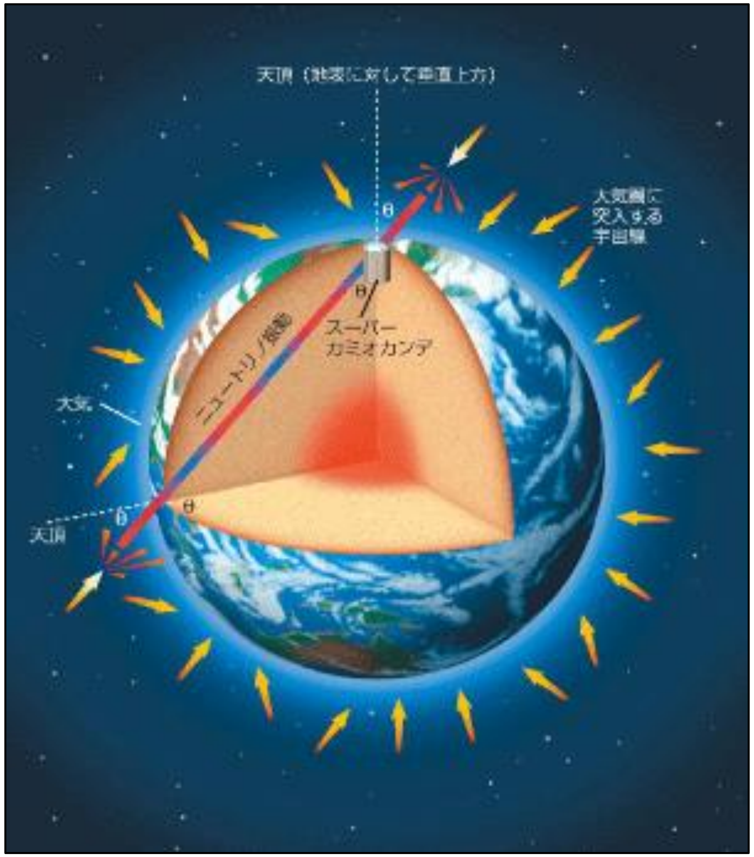


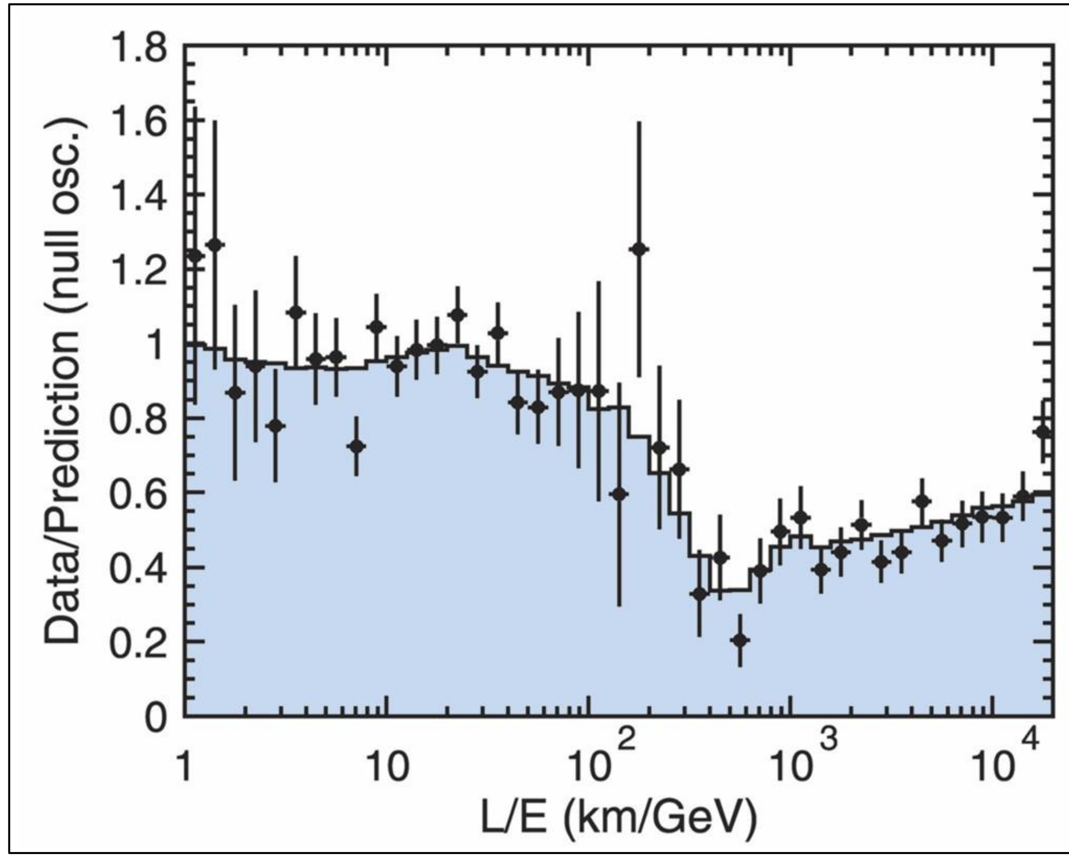
IceCube (40 & 59 strings) Skymap



Total events: 43339 (upgoing) and 64230 (downgoing)
Livetime: 348 days (IC59) and 375 days (IC40)

Atmospheric Neutrino Oscillations (1998)



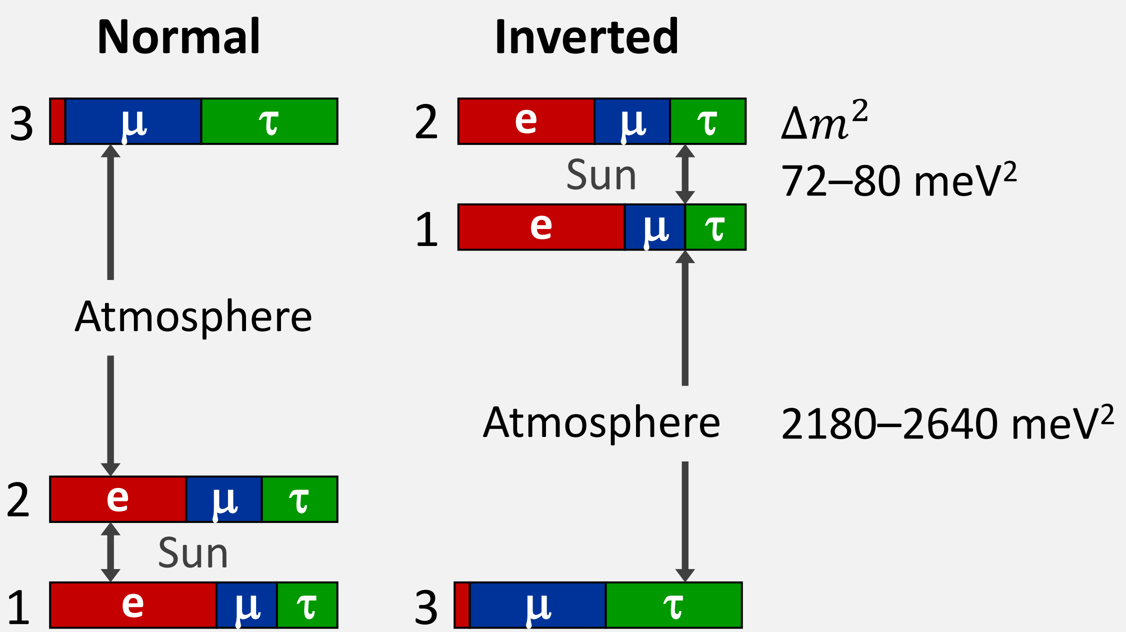


Atmospheric neutrino oscillations show characteristic L/E variation

Three-Flavor Neutrino Parameters

Three mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$ (Euler angles for 3D rotation), $c_{ij} = \cos\theta_{ij}$,
a CP-violating "Dirac phase" δ, and two "Majorana phases" α_2 and α_3

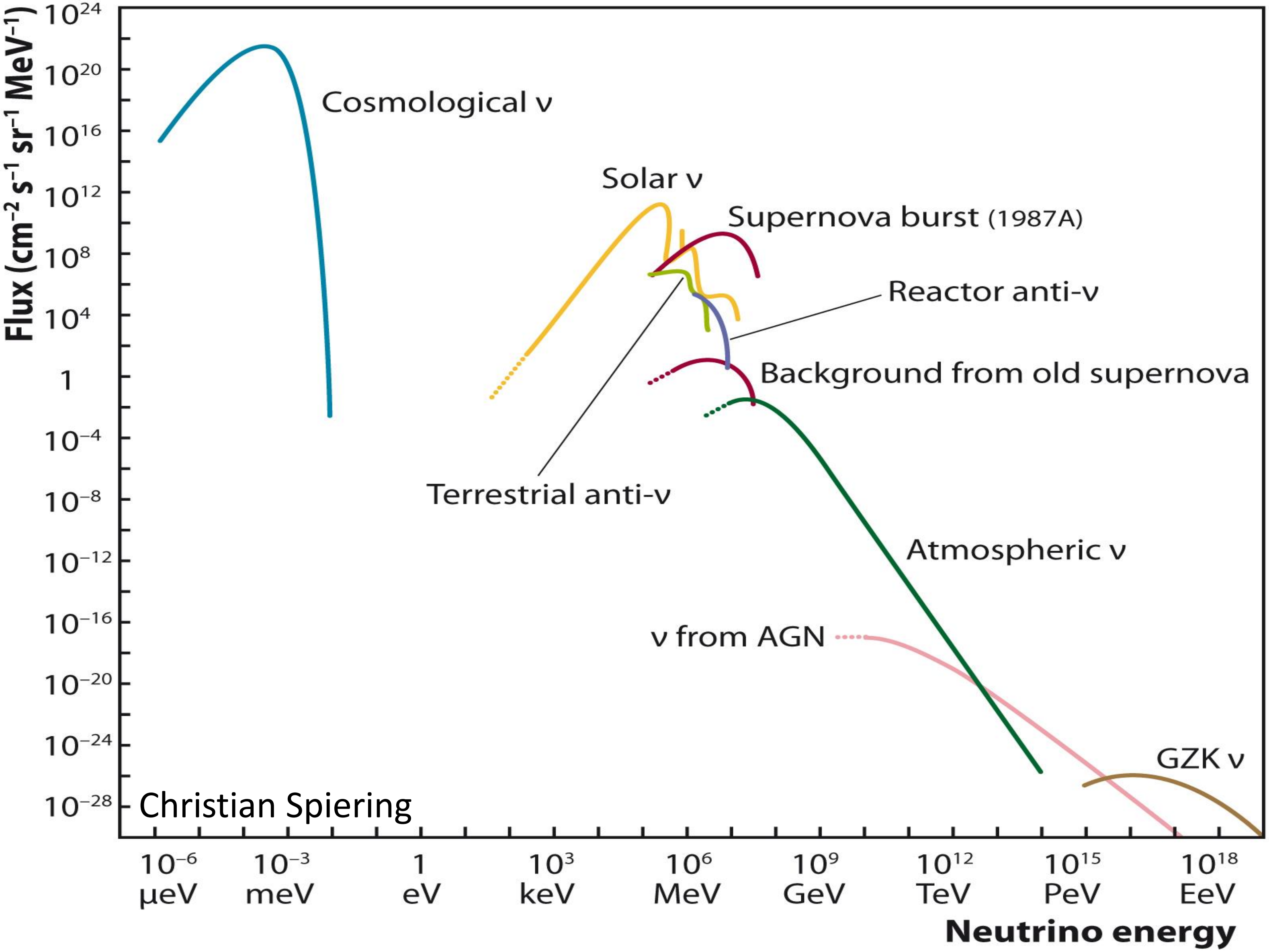
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\substack{39^\circ < \theta_{23} < 53^\circ \\ \text{Atmospheric/LBL-Beams}}} \underbrace{\begin{pmatrix}c_{13} & 0 & e^{-i\delta}s_{13}\\ 0 & 1 & 0\\ -e^{i\delta}s_{13} & 0 & c_{13}\end{pmatrix}}_{\substack{7^\circ < \theta_{13} < 11^\circ \\ \text{Reactor}}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\substack{33^\circ < \theta_{12} < 37^\circ \\ \text{Solar/KamLAND}}} \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & e^{i\frac{\alpha_2}{2}} & 0\\ 0 & 0 & e^{i\frac{\alpha_3}{2}}\end{pmatrix}}_{\substack{\text{Relevant for} \\ 0\nu2\beta\text{ decay}}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



Tasks and Open Questions

- Precision for all angles
- CP-violating phase δ?
- Mass ordering? (normal vs inverted)
- Absolute masses? (hierarchical vs degenerate)
- Dirac or Majorana?

Grand Unified Neutrino Spectrum



Grand Unified Neutrino Spectrum