Introduction to Neutrino Physics and JUNO

Yu-Feng Li

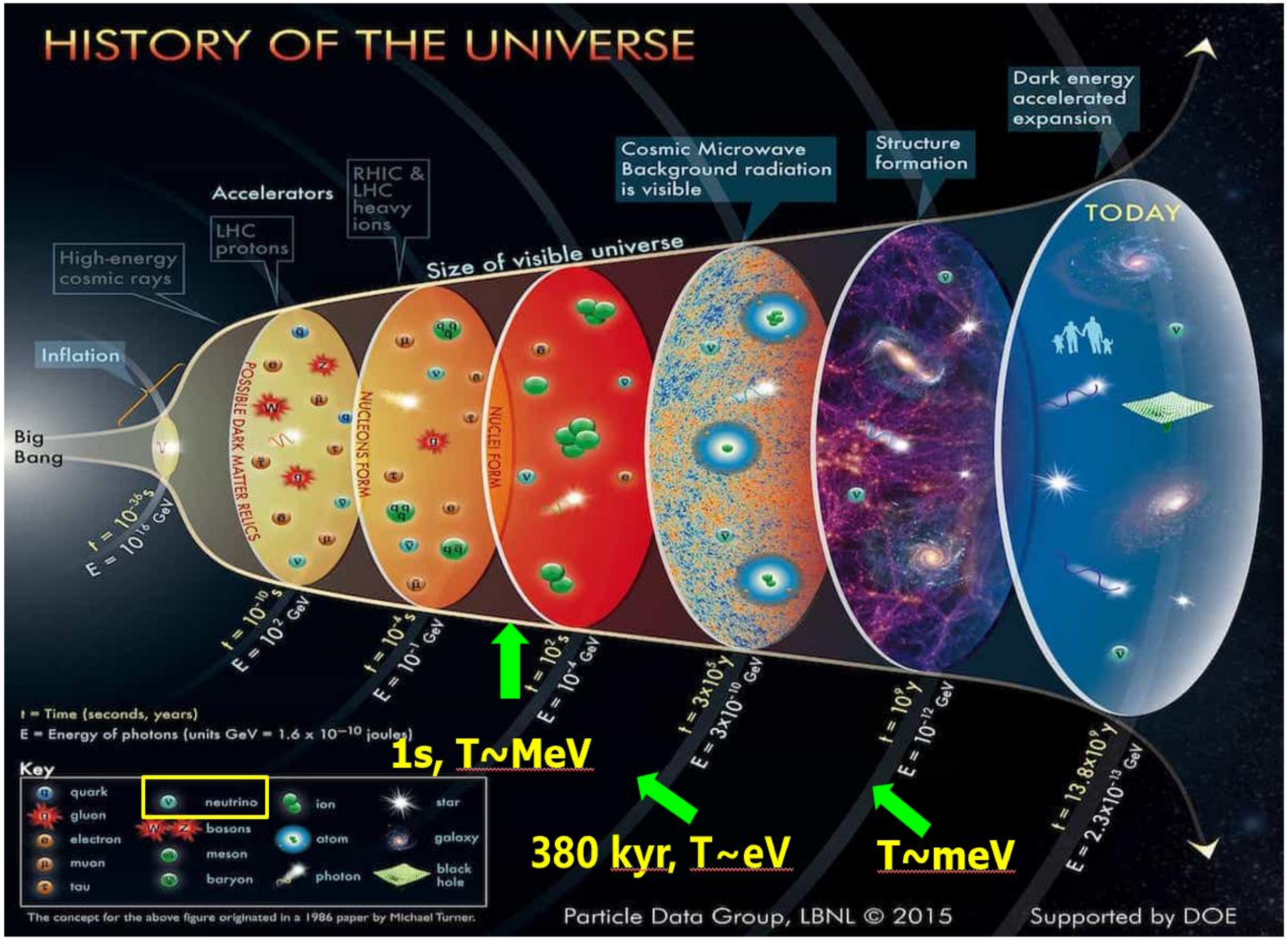
liyufeng@ihep.ac.cn

Institute of High Energy Physics, Beijing

2026 China-Thailand International Summer School on High Energy Physics and Astrophysics

2026-7-14@SYSU Guangzhou

Neutrino from the History of the Universe

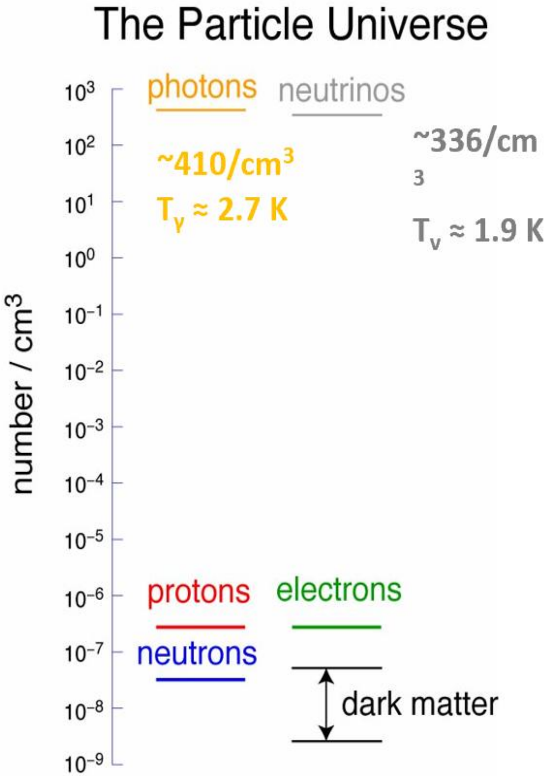


1s, T~MeV

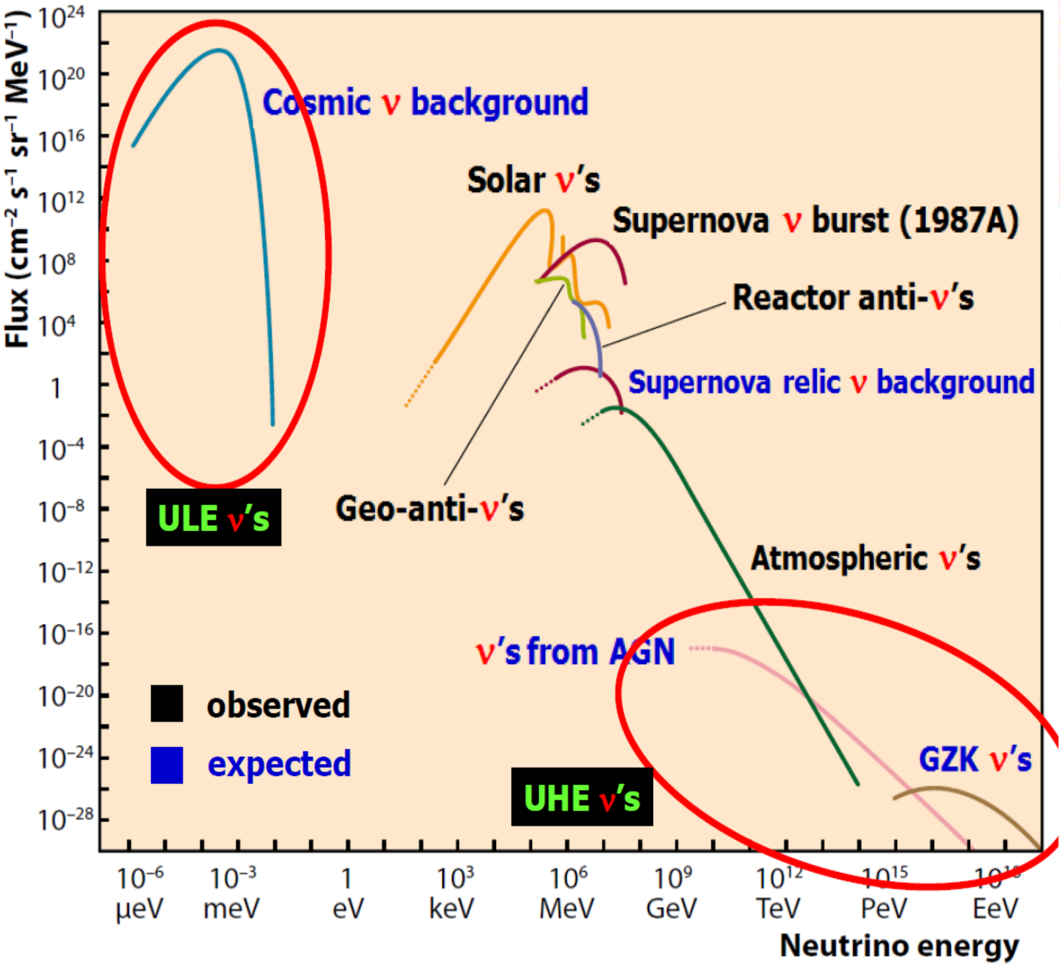
380 kyr, T~eV

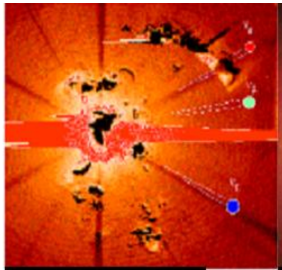
T~meV

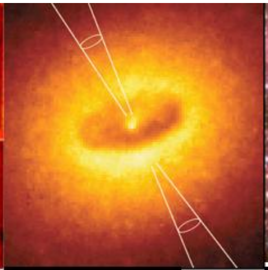
Neutrinos are participants and witnesses to the origin and evolution of the universe



Neutrinos are from everywhere




Big Bang


Galaxy

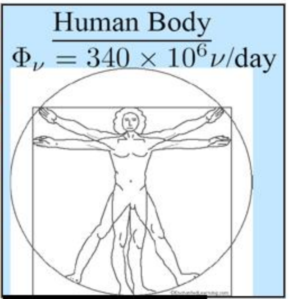

Supernova


Sun


Earth


Reactor

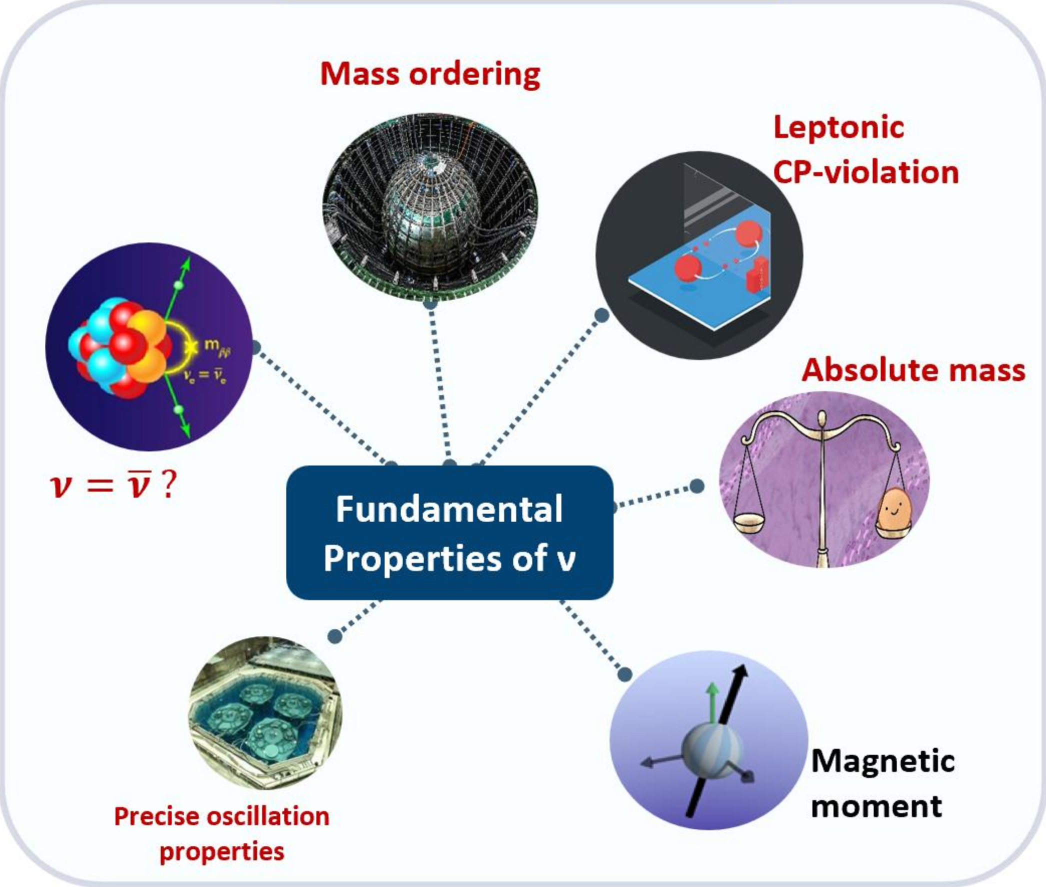

Accelerator



Human

Sciences from detecting neutrinos

Particle Physics relevant



Mass ordering

Leptonic CP-violation

$\nu = \bar{\nu}$?

Fundamental Properties of ν

Absolute mass

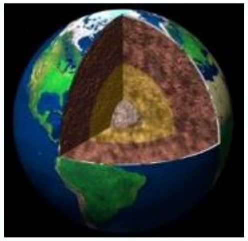
Precise oscillation properties

Magnetic moment

Astro-physics, Cosmology relevant

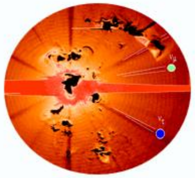
Supernova ν
(mechanism, relic)

Solar ν
(Metallicity)



Geo ν
(geo phys, geo chem)

Big-Bang ν



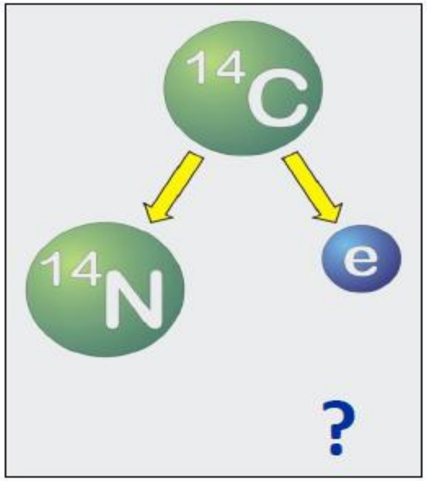
ν from extreme astronomical phenomena?
(NS merger, AGN, γ burst, …)

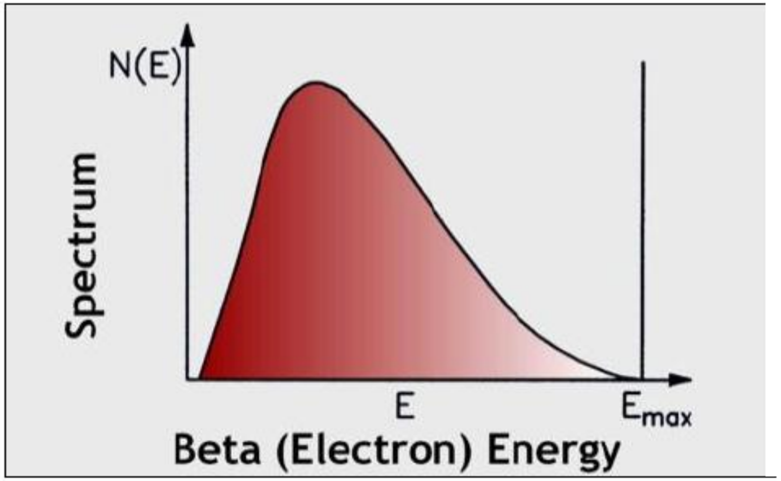
Origin of cosmic rays?

Part I:

Brief history of neutrinos

1930: Neutrino hypothesis





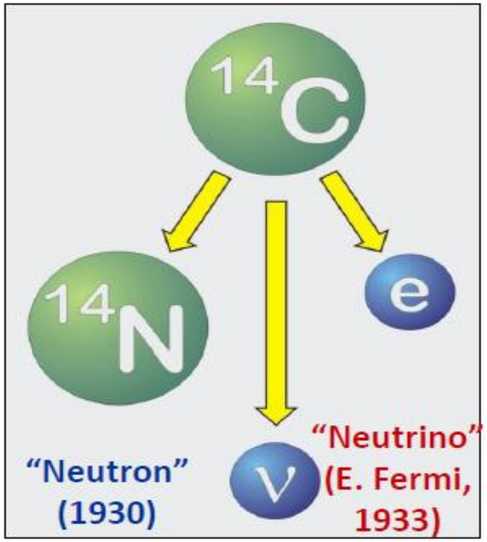
1914: Chadwick observed the **continuous energy spectrum** of **electrons**

James Chadwick
(1891-1974)
Nobel Prize
1935

Niels Bohr
(1885-1962)
Nobel Prize
1922

Wolfgang Pauli
(1900-1958)
Nobel Prize
1945

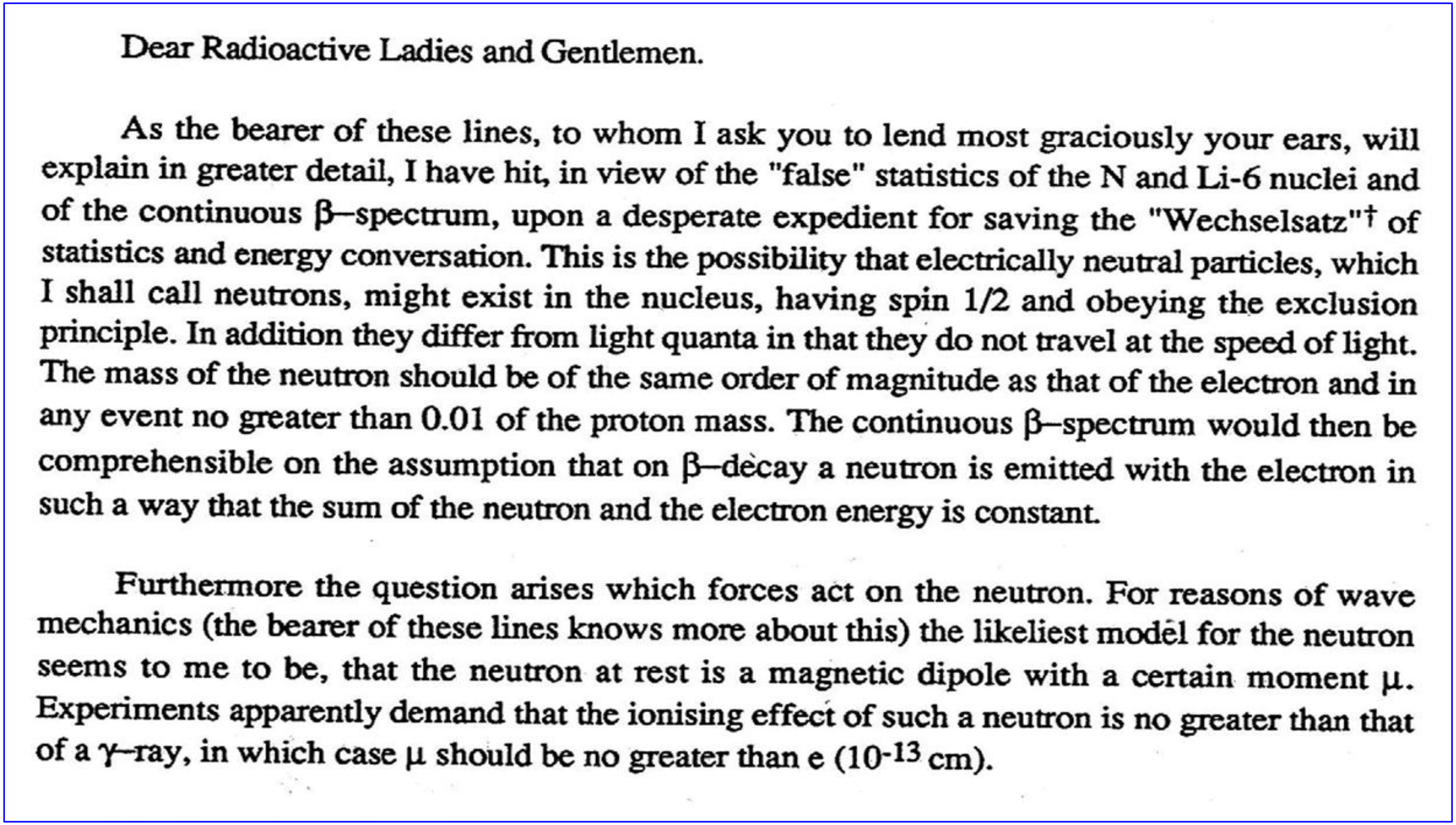
1930: Pauli proposed the **spin ½ neutral particle** to solve the energy and spin crisis



Enrico Fermi
(1901-1954)
Nobel Prize
1938

The famous letter from Pauli：1930/12/04

- **The birth of neutrino and its properties**

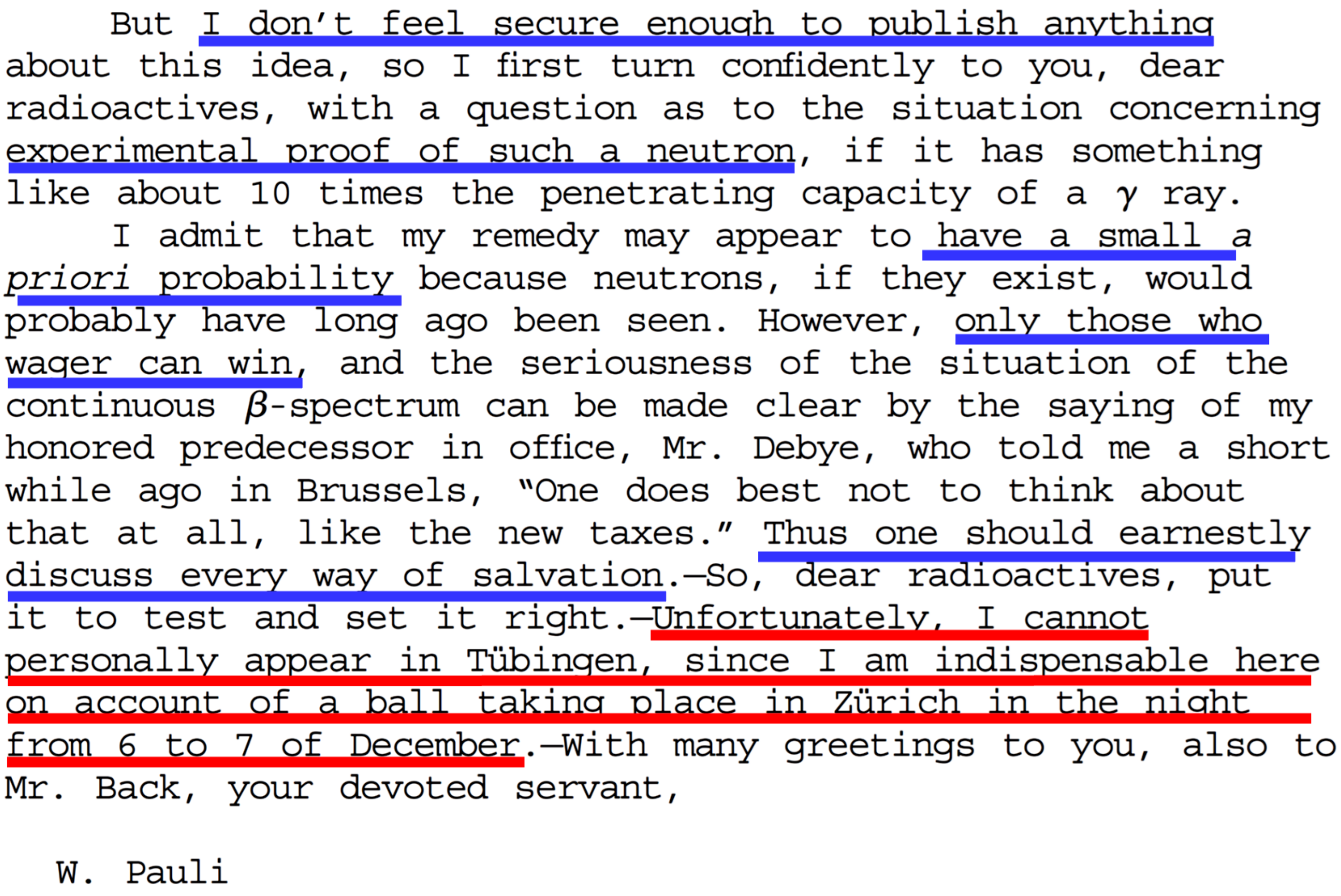


Dear Radioactive Ladies and Gentlemen.

As the bearer of these lines, to whom I ask you to lend most graciously your ears, will explain in greater detail, I have hit, in view of the "false" statistics of the N and Li-6 nuclei and of the continuous β–spectrum, upon a desperate expedient for saving the "Wechselsatz"† of statistics and energy conversation. This is the possibility that electrically neutral particles, which I shall call neutrons, might exist in the nucleus, having spin 1/2 and obeying the exclusion principle. In addition they differ from light quanta in that they do not travel at the speed of light. The mass of the neutron should be of the same order of magnitude as that of the electron and in any event no greater than 0.01 of the proton mass. The continuous β–spectrum would then be comprehensible on the assumption that on β–decay a neutron is emitted with the electron in such a way that the sum of the neutron and the electron energy is constant.

Furthermore the question arises which forces act on the neutron. For reasons of wave mechanics (the bearer of these lines knows more about this) the likeliest model for the neutron seems to me to be, that the neutron at rest is a magnetic dipole with a certain moment μ. Experiments apparently demand that the ionising effect of such a neutron is no greater than that of a γ–ray, in which case μ should be no greater than e $(10^{-13}$ cm).

The famous letter from Pauli：1930/12/04

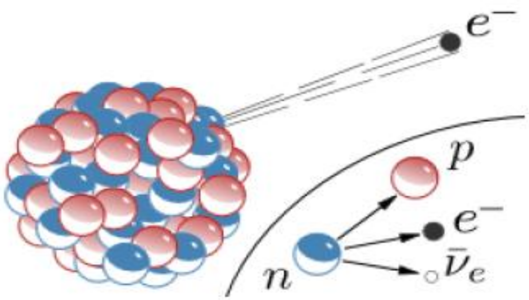


But I don't feel secure enough to publish anything about this idea, so I first turn confidently to you, dear radioactives, with a question as to the situation concerning experimental proof of such a neutron, if it has something like about 10 times the penetrating capacity of a γ ray.

I admit that my remedy may appear to have a small *a priori* probability because neutrons, if they exist, would probably have long ago been seen. However, only those who wager can win, and the seriousness of the situation of the continuous β-spectrum can be made clear by the saying of my honored predecessor in office, Mr. Debye, who told me a short while ago in Brussels, "One does best not to think about that at all, like the new taxes." Thus one should earnestly discuss every way of salvation.—So, dear radioactives, put it to test and set it right.—Unfortunately, I cannot personally appear in Tübingen, since I am indispensable here on account of a ball taking place in Zürich in the night from 6 to 7 of December.—With many greetings to you, also to Mr. Back, your devoted servant,

W. Pauli

1934: undetectable neutirnos?

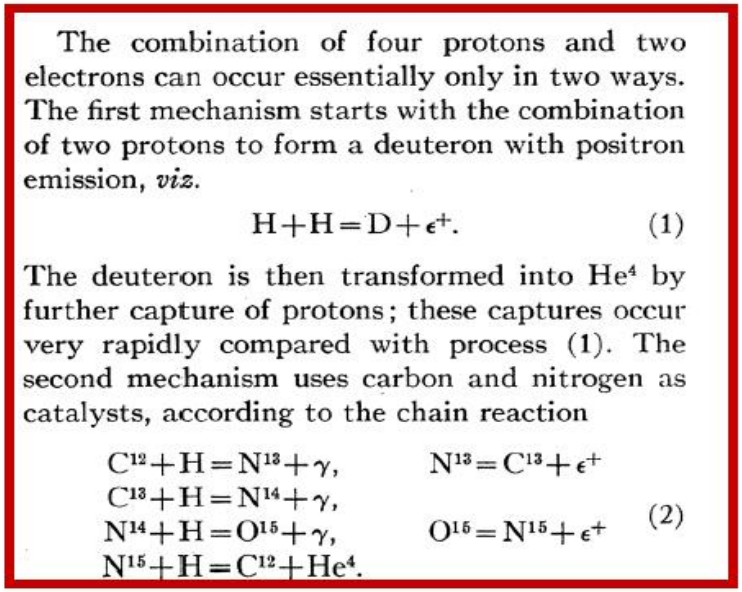


Bethe & Peierls (1934)

$$\bar{\nu}_e + p \rightarrow n + e^+ \quad \text{Cross section } \sigma < 10^{-44}\ \text{cm}^2$$

“It is therefore absolutely impossible to observe the processes of this kind with the neutrinos created in nuclear transformations.”

Hans A. Bethe
(1906–2005)
Nobel Prize 1967



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.*

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

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

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

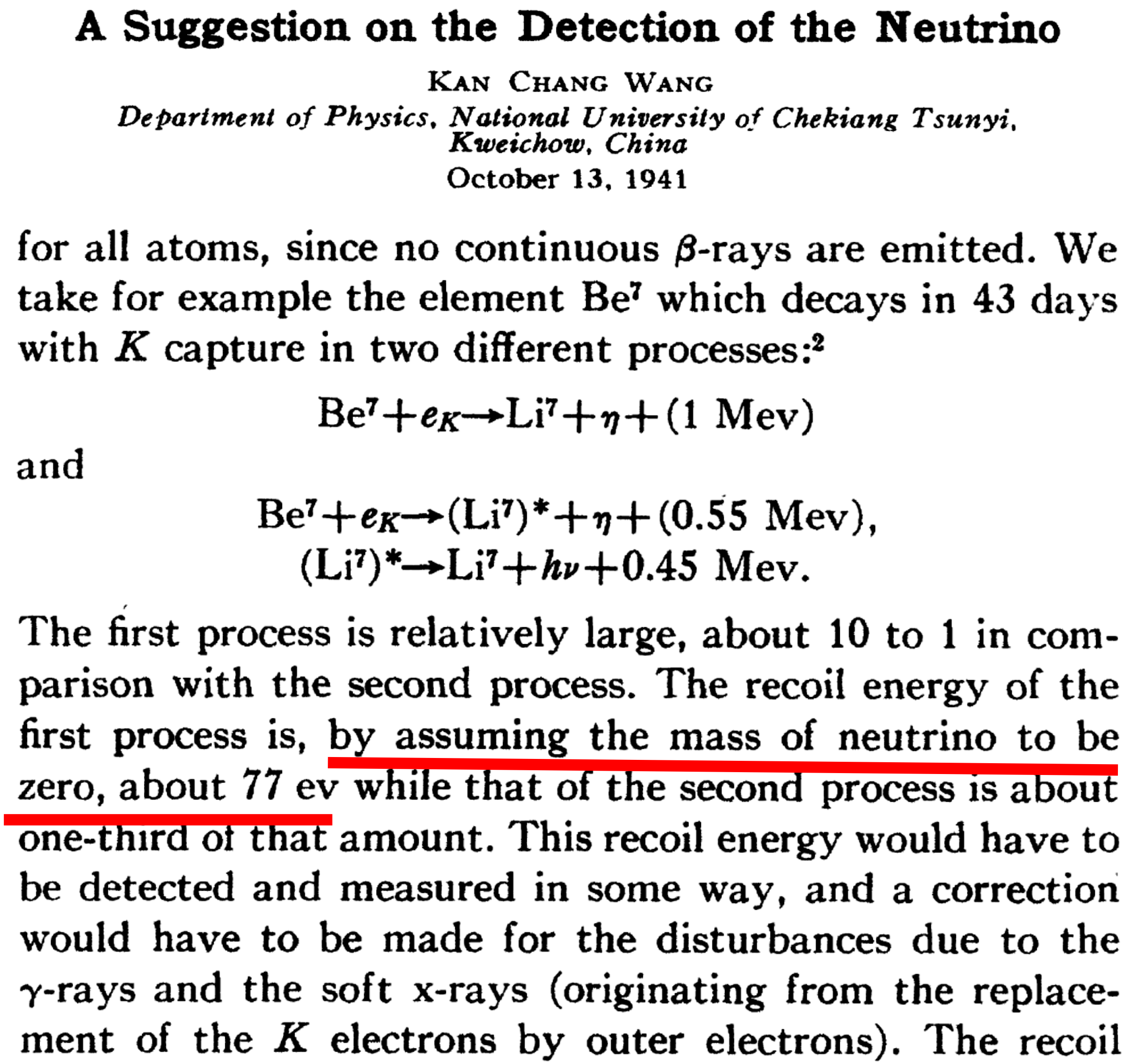
1939: neutrino was neglected in solar evolution

1951: Reines discussed with Fermi the possibility of using bomb

1941: A Suggestion by Kan Chang Wang

王淦昌
(1907-1998)

Phys. Rev. 61 (1941) 97



A Suggestion on the Detection of the Neutrino

Kan Chang Wang
Department of Physics, National University of Chekiang Tsunyi, Kweichow, China
October 13, 1941

for all atoms, since no continuous β-rays are emitted. We take for example the element Be^7 which decays in 43 days with K capture in two different processes:[2]

$$Be^7+e_K\rightarrow Li^7+\eta+(1\ \mathrm{Mev})$$

and

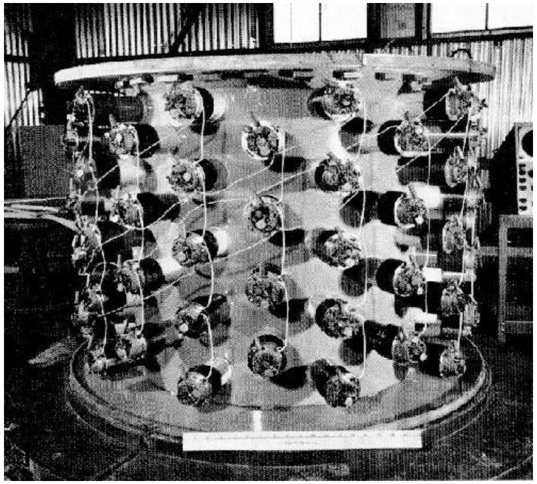
$$Be^7+e_K\rightarrow (Li^7)^*+\eta+(0.55\ \mathrm{Mev}),$$
$$(Li^7)^*\rightarrow Li^7+h\nu+0.45\ \mathrm{Mev}.$$

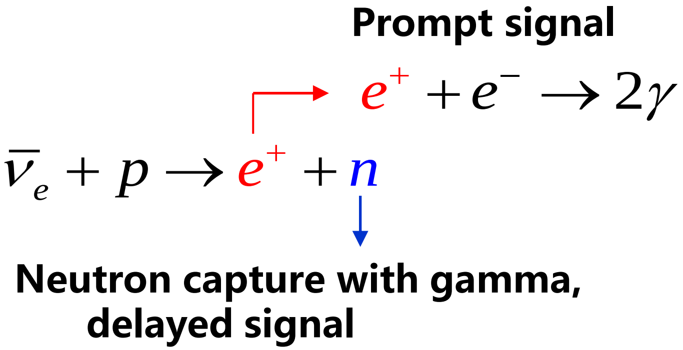
The first process is relatively large, about 10 to 1 in comparison with the second process. The recoil energy of the first process is, by assuming the mass of neutrino to be zero, about 77 ev while that of the second process is about one-third of that amount. This recoil energy would have to be detected and measured in some way, and a correction would have to be made for the disturbances due to the γ-rays and the soft x-rays (originating from the replacement of the K electrons by outer electrons). The recoil

Reactor neutrinos: 1953@Hanford

C. Cowan

F. Reines





Prompt signal

$$e^+ + e^- \to 2\gamma$$

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

Neutron capture with gamma,
delayed signal

Expected: 0.1~0.3 /min
Observed: 5/min (background >> signal)

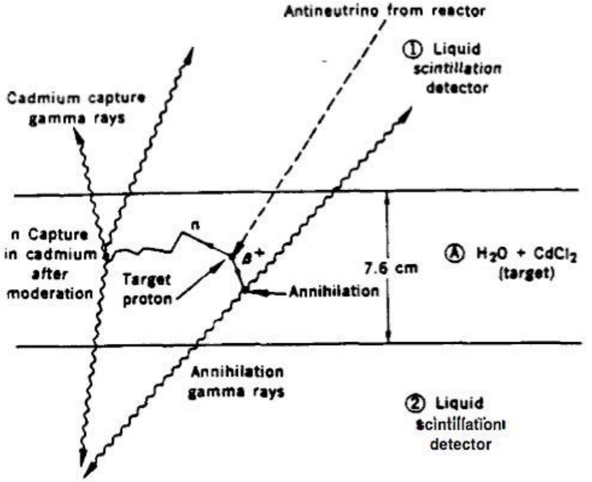
Cowan: The lesson of the work was clear: It is easy to shield out the noise men make, but impossible to shut out the cosmos.

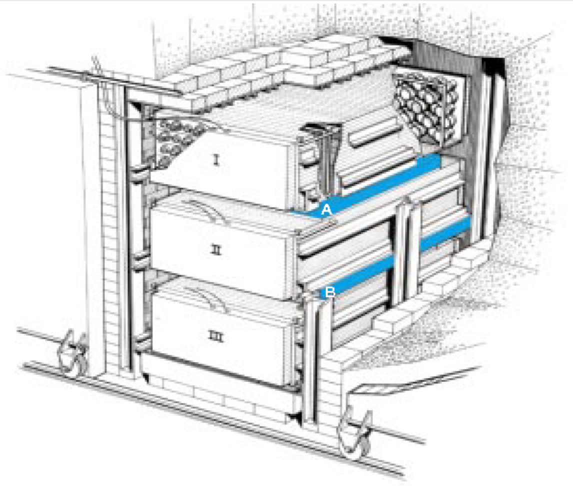
1956: @Savannah River: with 12 m rock overburden + veto

Reactor neutrinos: 1956@ Savannah River

C. Cowan

F. Reines



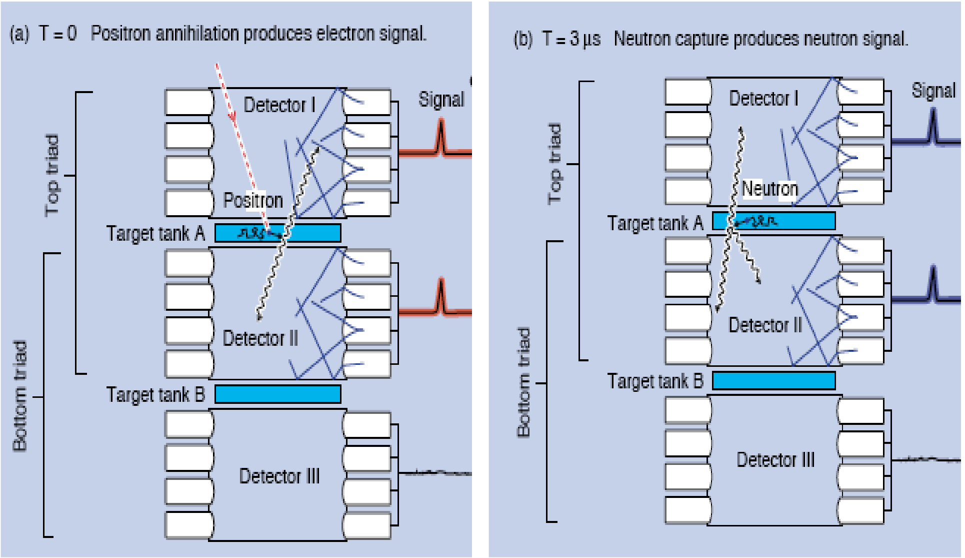


Prompt signal

$$e^{+} + e^{-} \rightarrow 2\gamma$$

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

Neutron capture with gamma, delayed signal

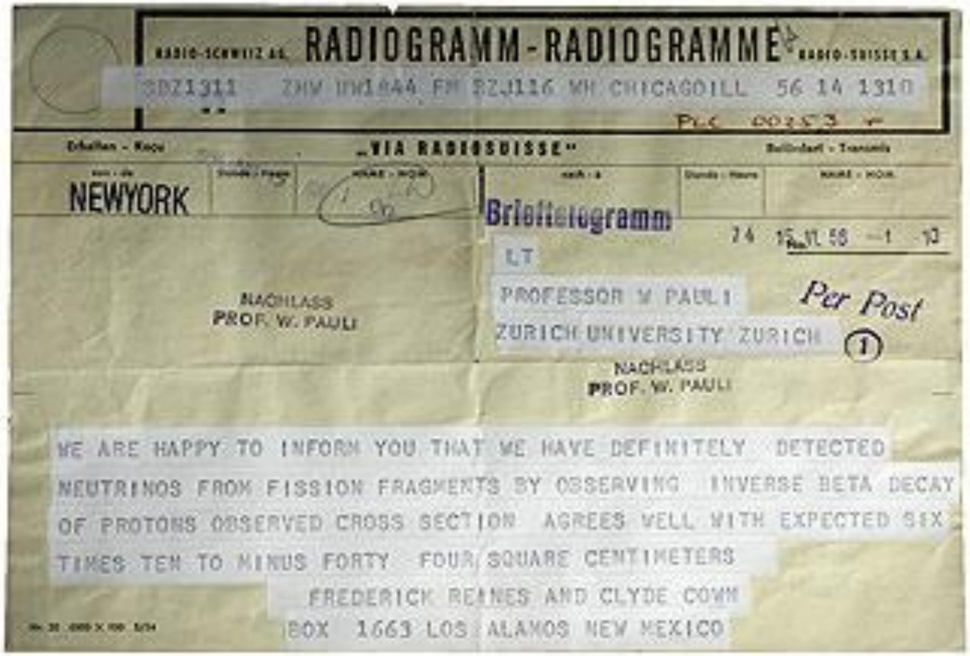


(1) I, II, III LS + 5 inch PMTs

(2) Blue: 200 L water with 40 kg $CdCl_2$

(3) Coincidence, sig. v.s. backg. 3:1

Reactor neutrinos: story behind discovery



RADIO-SCHWEIZ AG. RADIOGRAMM-RADIOGRAMME RADIO-SUISSE S.A.

SDZ1311 ZHW WW1844 FM SZJ116 WH CHICAGOILL 56 14 1310

"VIA RADIOSUISSE"

NEWYORK

Briefletegramm

74 15.VI.56 -1 -13

LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

①

NACHLASS
PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWAN
BOX 1663 LOS ALAMOS NEW MEXICO

Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico

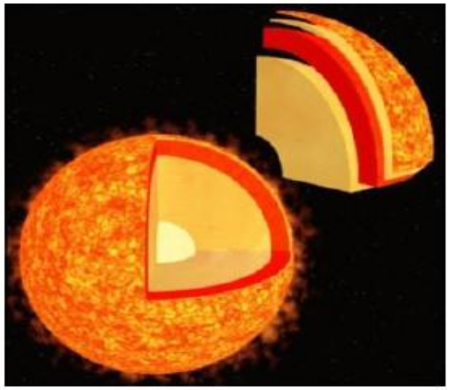
Thanks for message. Everything comes to him who knows how to wait.

Pauli

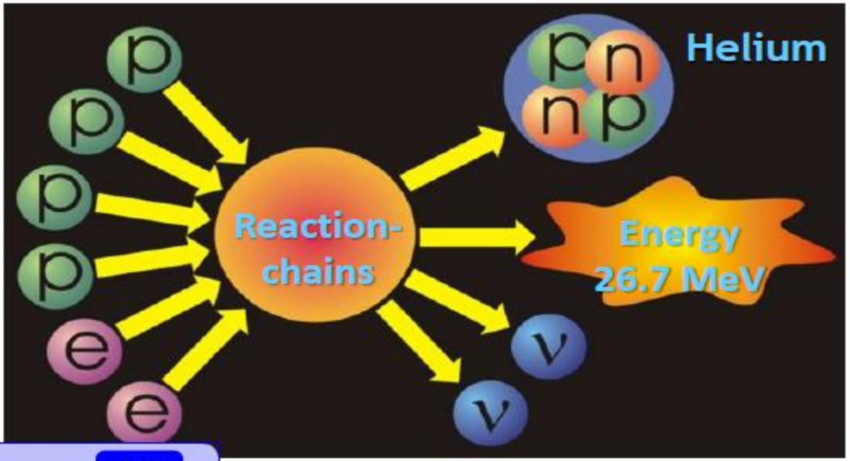
abg. 15.6.56 / 15.35h
als night letter

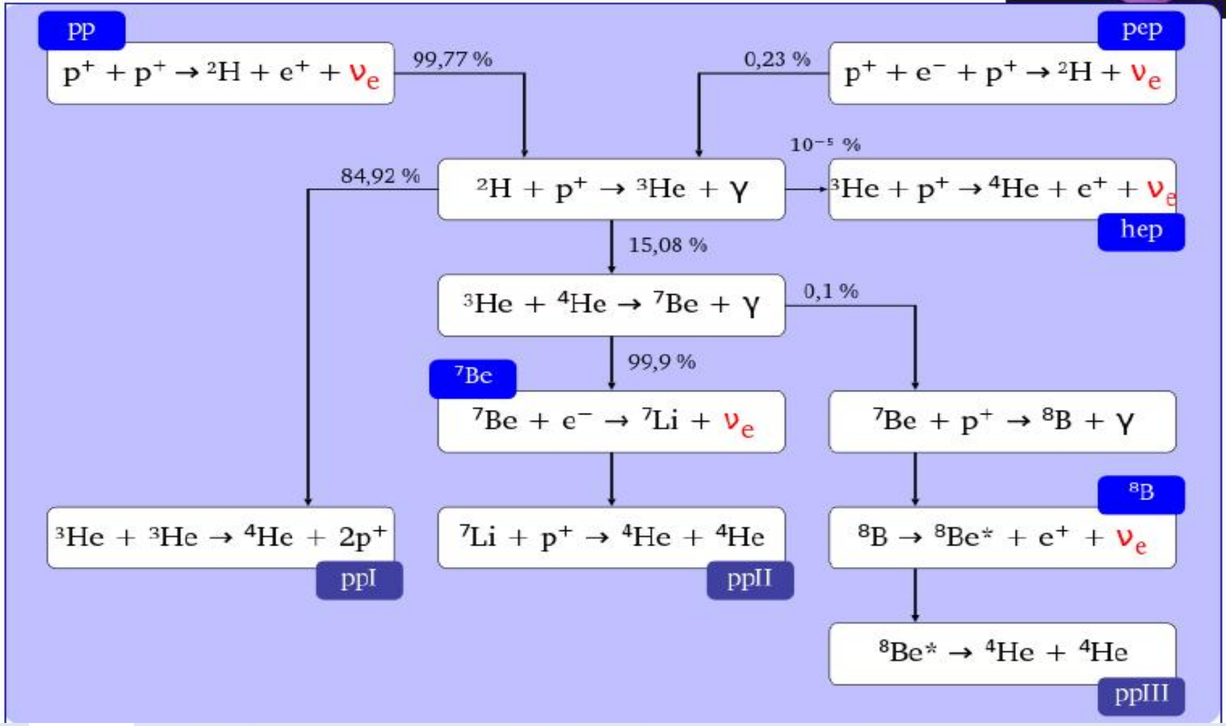
- A Science article reported that the observed cross section was within 5% of the 6.3×10^{-44} cm^2 expected (although the predicted cross section has a 25% uncertainty).
- In 1959, following the discovery of parity violation in 1956, the theoretical cross section was increased by ×2 to $(10\pm1.7)\times10^{-44}$ cm^2
- In 1960, Reines and Cowan reported a reanalysis of the 1956 experiment and quoted $\sigma=(12^{+7}_{-4})\times10^{-44}$ cm^2

1968: Solar neutrinos



Why sun shines?





pp

$p^+ + p^+ \to {}^2H + e^+ + \nu_e$

99,77 %

0,23 %

pep

$p^+ + e^- + p^+ \to {}^2H + \nu_e$

10^{-5} %

84,92 %

${}^2H + p^+ \to {}^3He + \gamma$

${}^3He + p^+ \to {}^4He + e^+ + \nu_e$

hep

15,08 %

${}^3He + {}^4He \to {}^7Be + \gamma$

0,1 %

99,9 %

${}^7Be$

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

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

${}^8B$

${}^3He + {}^3He \to {}^4He + 2p^+$

ppI

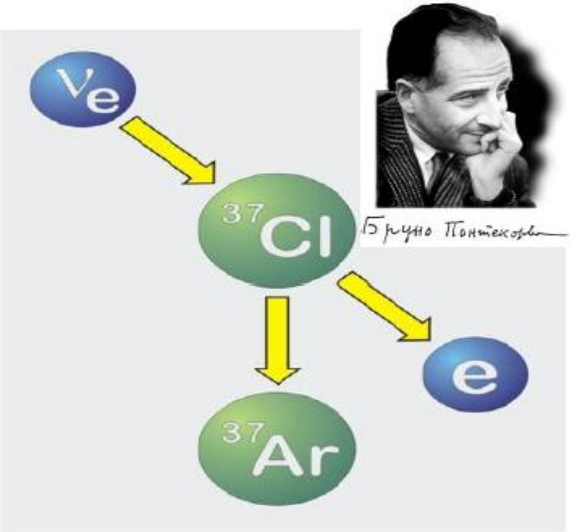
${}^7Li + p^+ \to {}^4He + {}^4He$

ppII

${}^8B \to {}^8Be^* + e^+ + \nu_e$

${}^8Be^* \to {}^4He + {}^4He$

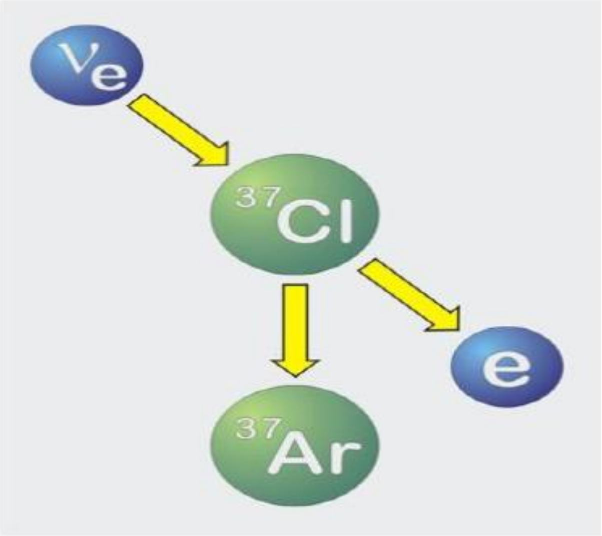
ppIII



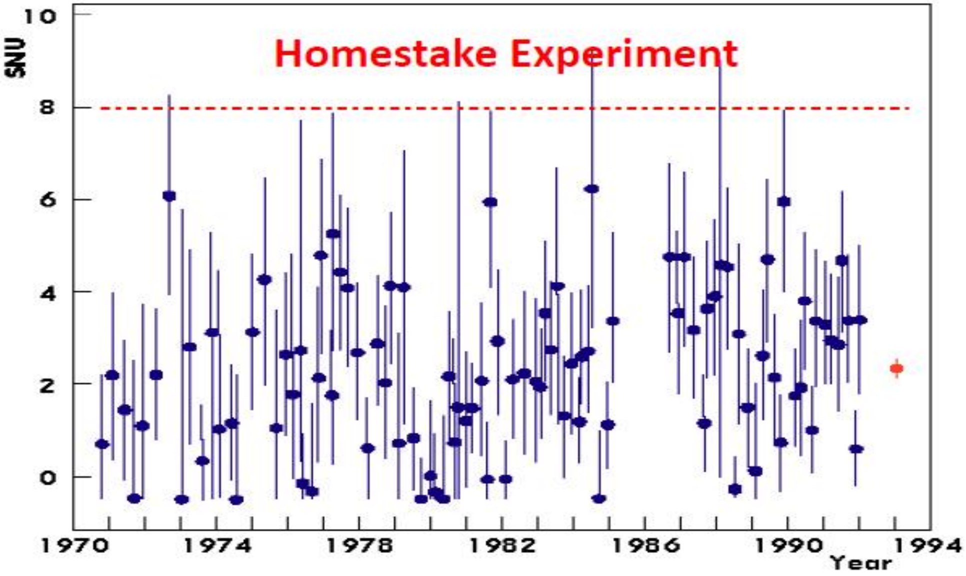
Бруно Понтекорво

Davis noticed this method and started experiments

1968: discovery of solar neutrinos

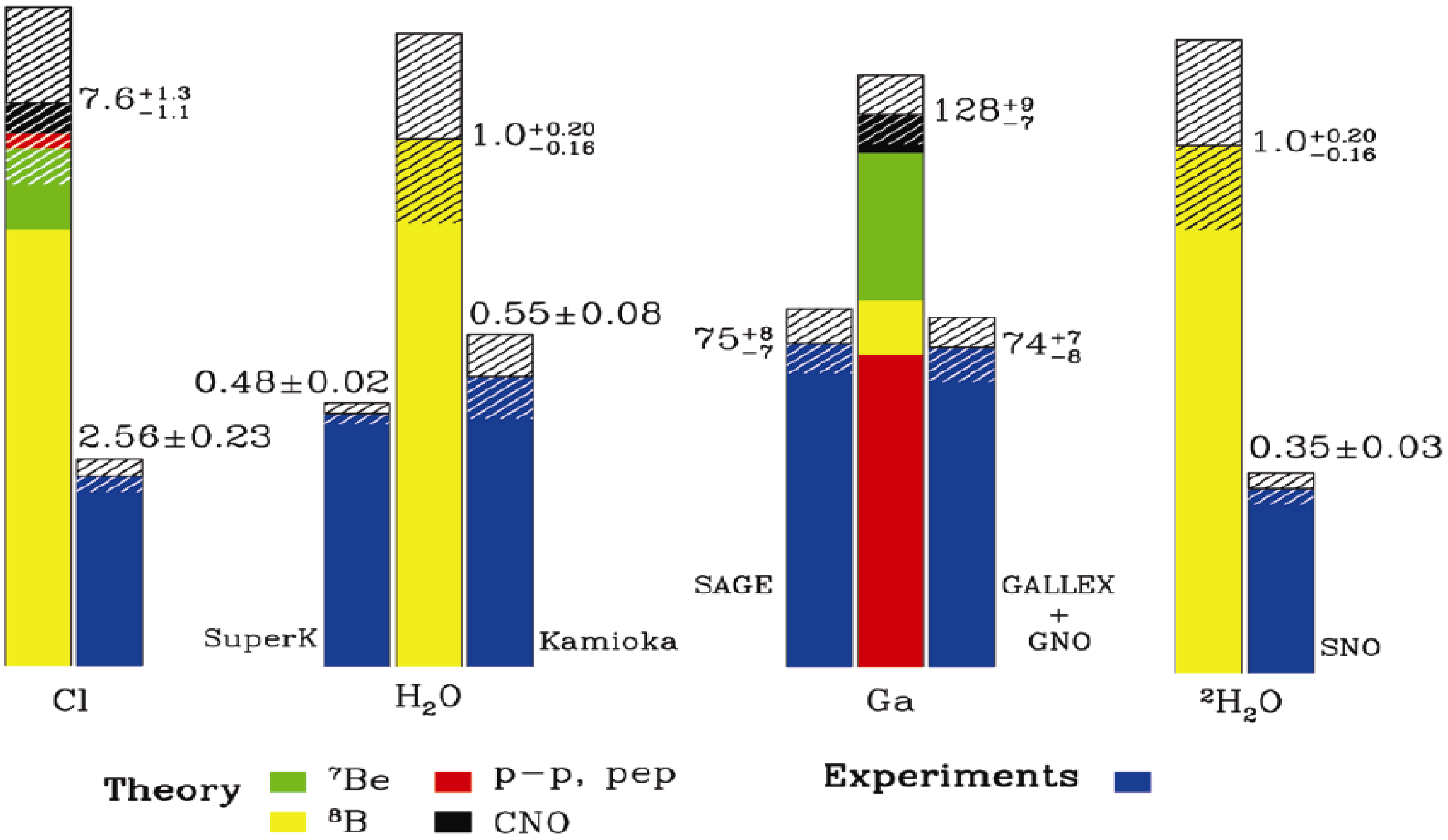


- Located in the Homestake Gold Mine, USA, at a depth of about 1500 meters, using 600 tons of perchloroethylene
- Argon atoms were extracted via chemical methods to measure the neutrino flux; the expected rate was 1.5 events per day
- The theorist John Bahcall developed the Standard Solar Model (SSM)

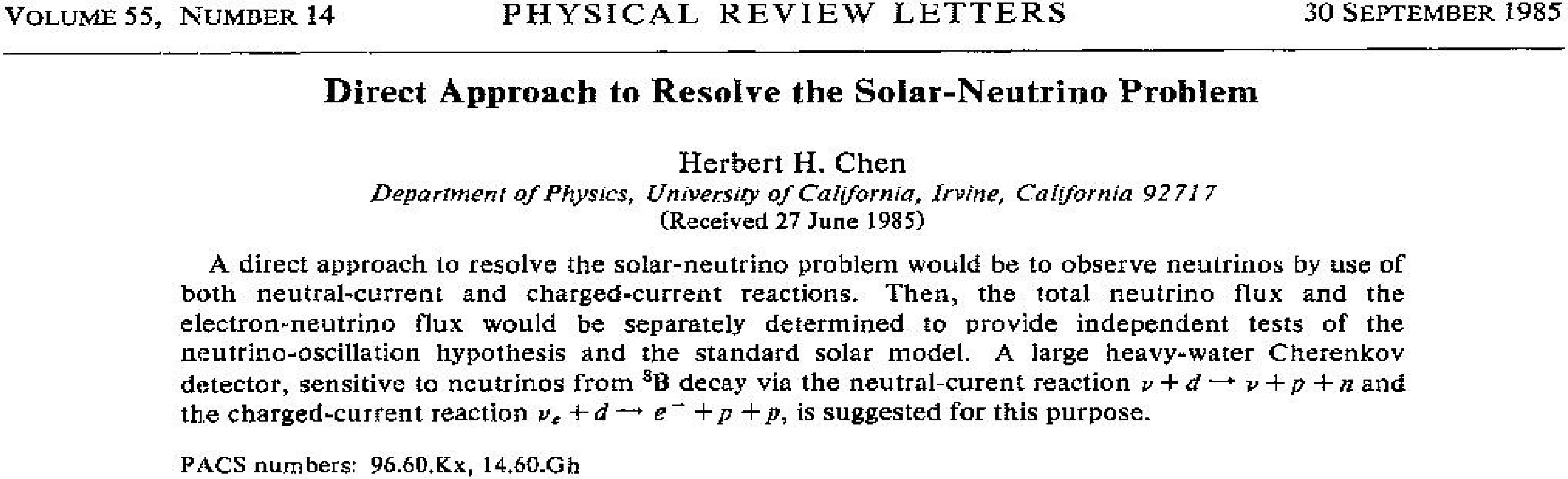


Solar neutrino experiments

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



SNO: Another approach → heavy water



VOLUME 55, NUMBER 14 PHYSICAL REVIEW LETTERS 30 SEPTEMBER 1985

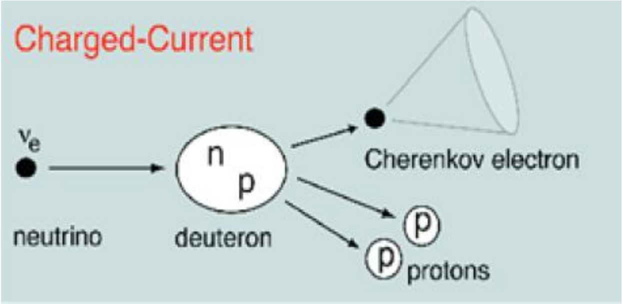
Direct Approach to Resolve the Solar-Neutrino Problem

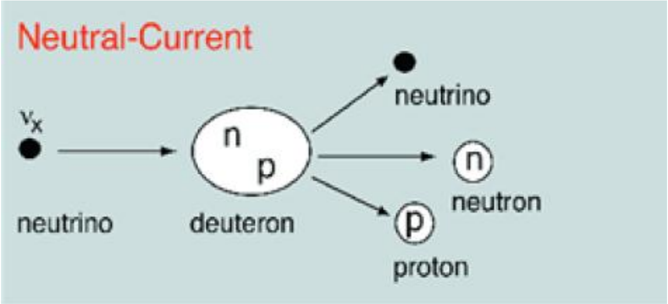
Herbert H. Chen
Department of Physics, University of California, Irvine, California 92717

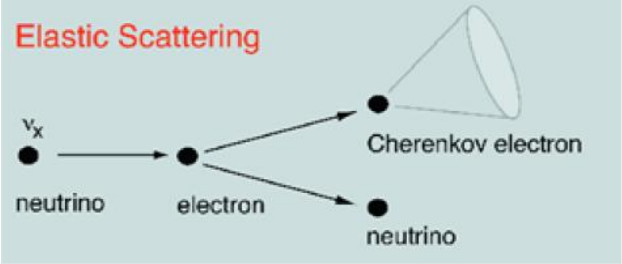
(Received 27 June 1985)

A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions. Then, the total neutrino flux and the electron-neutrino flux would be separately determined to provide independent tests of the neutrino-oscillation hypothesis and the standard solar model. A large heavy-water Cherenkov detector, sensitive to neutrinos from ^{8}B decay via the neutral-curent reaction $\nu + d \to \nu + p + n$ and the charged-current reaction $\nu_e + d \to e^- + p + p$, is suggested for this purpose.

PACS numbers: 96.60.Kx, 14.60.Gh



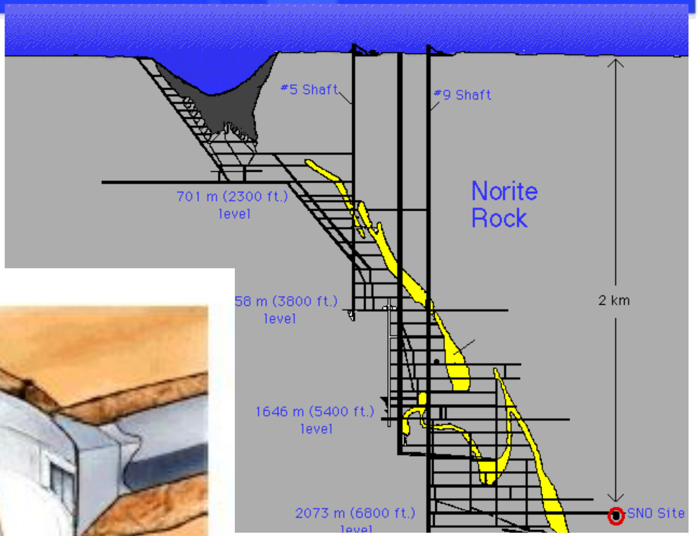




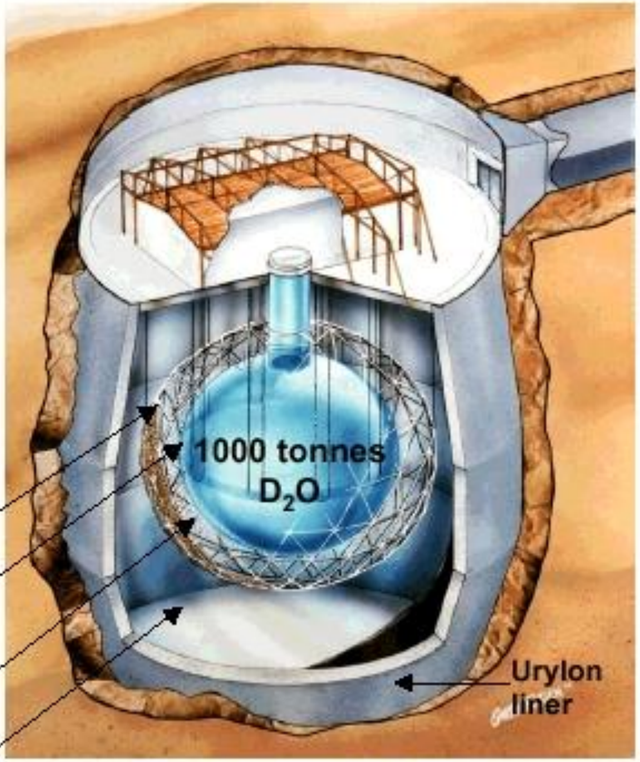
Heavy Water → Kill three birds with one stone

Independent of the SSM

SNO: Another approach → heavy water



Canada: Sudbury Neutrino Observatory



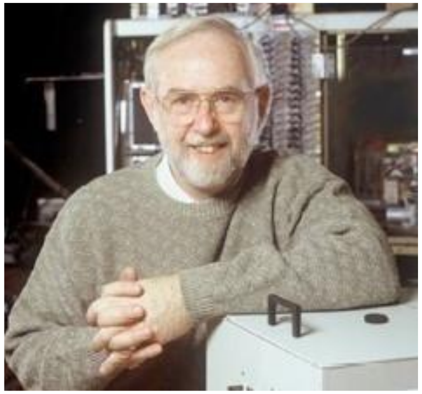
17.8m dia. PMT Support Structure
9456 PMTs, 56% coverage

12.01m dia. acrylic vessel

1700 tonnes of inner shielding H_2O

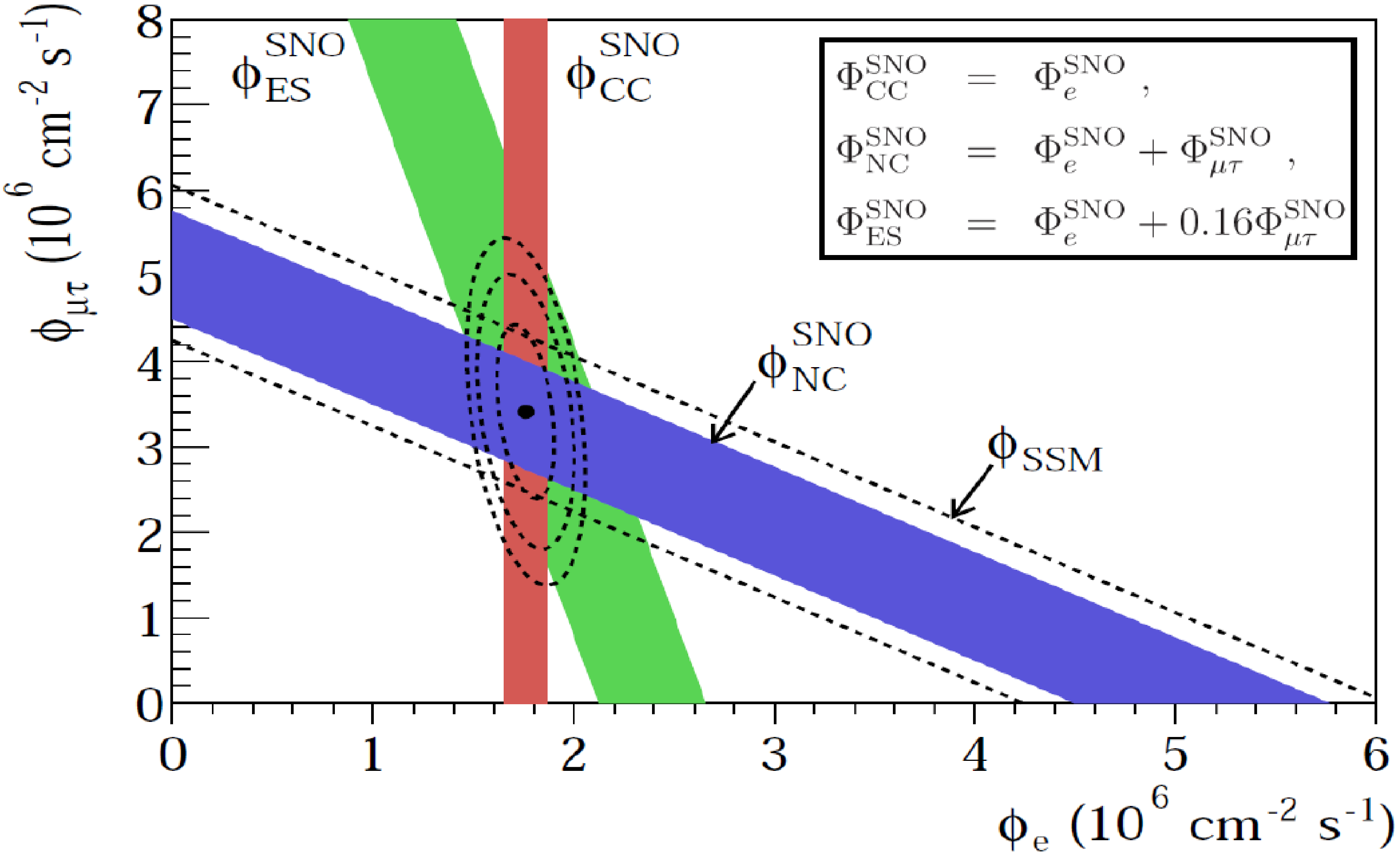
5300 tonnes of outer shielding H_2O

Host: INCO Ltd., Creighton #9 mine
Coordinates: 46°28'30"N 81°12'04"W
Depth: 2092 m (~6010 m.w.e., ~70 μ day^{-1})



Arthur B. McDonald

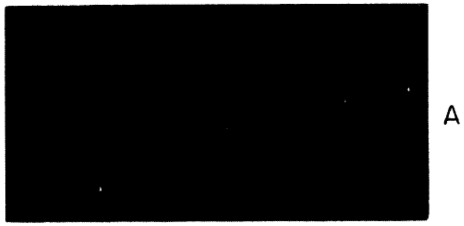
Evidence of solar neutrino flavor conversion !



1962: Discovery of the second type of neutrinos

Famous "two neutrino experiment"
muon neutrino proved (1962),
Nobel prize in 1988.

$\neq$



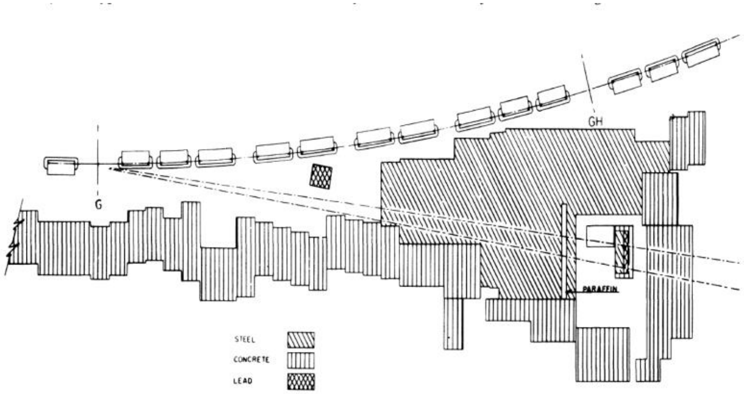
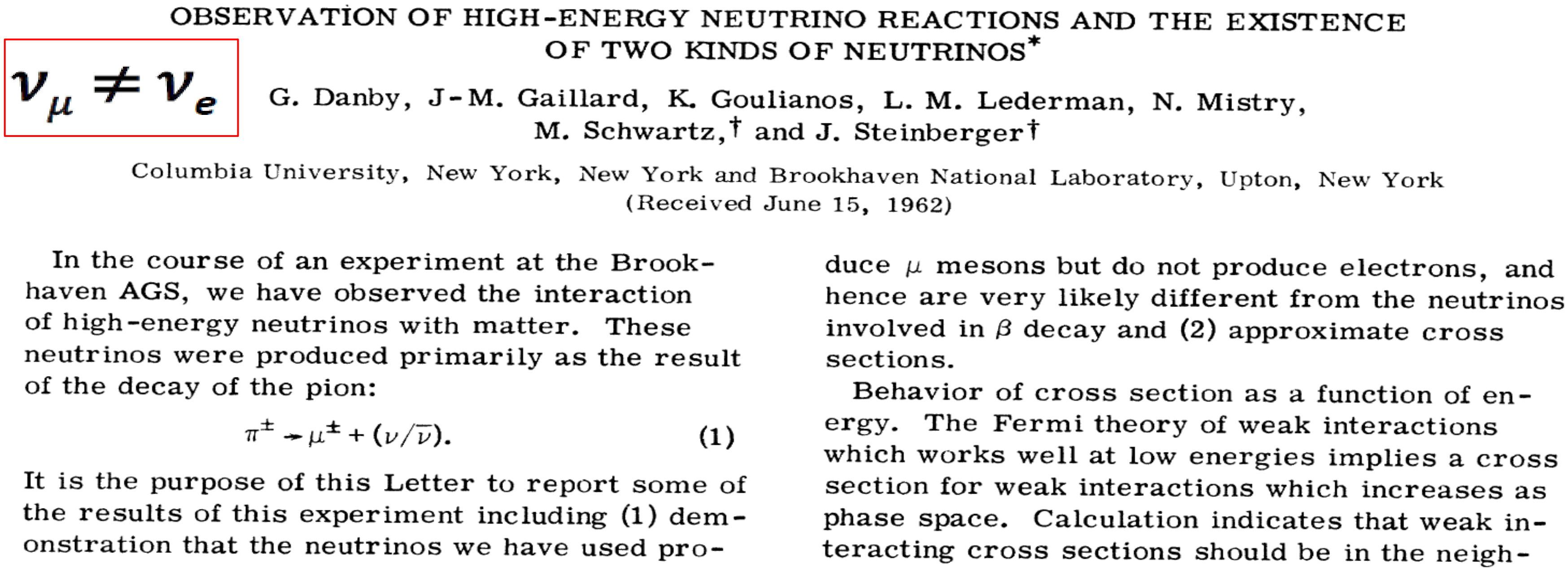


FIG. 1. Plan view of AGS neutrino experiment.

$\nu_\mu \neq \nu_e$



OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz,† and J. Steinberger†

Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York

(Received June 15, 1962)

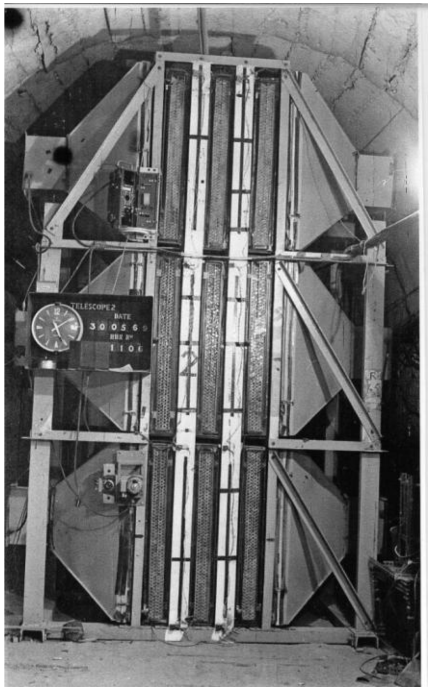
In the course of an experiment at the Brookhaven AGS, we have observed the interaction of high-energy neutrinos with matter. These neutrinos were produced primarily as the result of the decay of the pion:

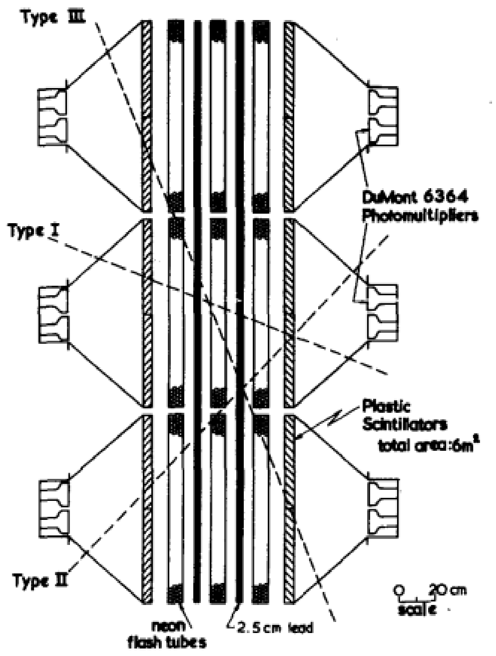
$$\pi^\pm \to \mu^\pm + (\nu/\bar{\nu}). \qquad (1)$$

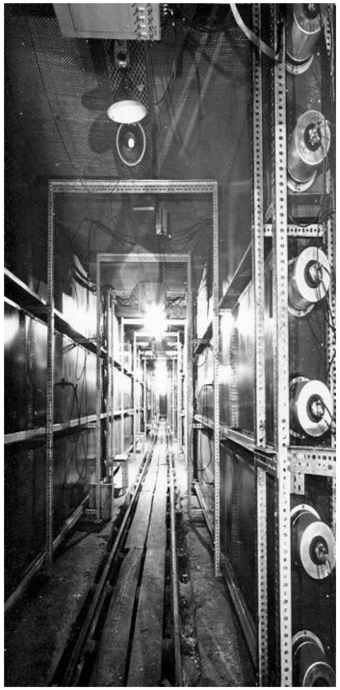
It is the purpose of this Letter to report some of the results of this experiment including (1) demonstration that the neutrinos we have used produce μ mesons but do not produce electrons, and hence are very likely different from the neutrinos involved in β decay and (2) approximate cross sections.

Behavior of cross section as a function of energy. The Fermi theory of weak interactions which works well at low energies implies a cross section for weak interactions which increases as phase space. Calculation indicates that weak interacting cross sections should be in the neigh-

1965: Discovery of atmospheric neutrinos







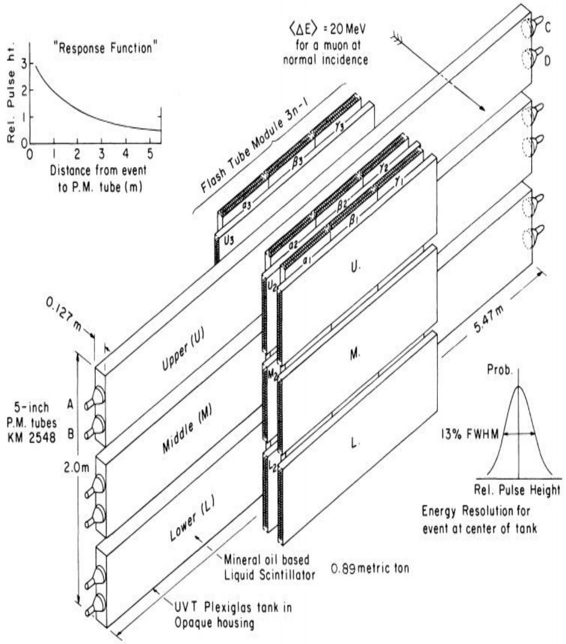


FIG. 2. Details of the nth scintillator bay and the $(3n-1)$st flash-tube module.

DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINO DEEP UNDERGROUND

C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM, P. V. RAMANA MURTHY and B. V. SREEKANTAN,
Tata Institute of Fundamental Research, Colaba, Bombay

K. HINOTANI and S. MIYAKE,
Osaka City University, Osaka, Japan

D. R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLFENDALE
University of Durham, Durham, U.K.

Received 12 July 1965

EVIDENCE FOR HIGH-ENERGY COSMIC-RAY NEUTRINO INTERACTIONS*

F. Reines, M. F. Crouch, T. L. Jenkins, W. R. Kropp, H. S. Gurr, and G. R. Smith

Case Institute of Technology, Cleveland, Ohio

and

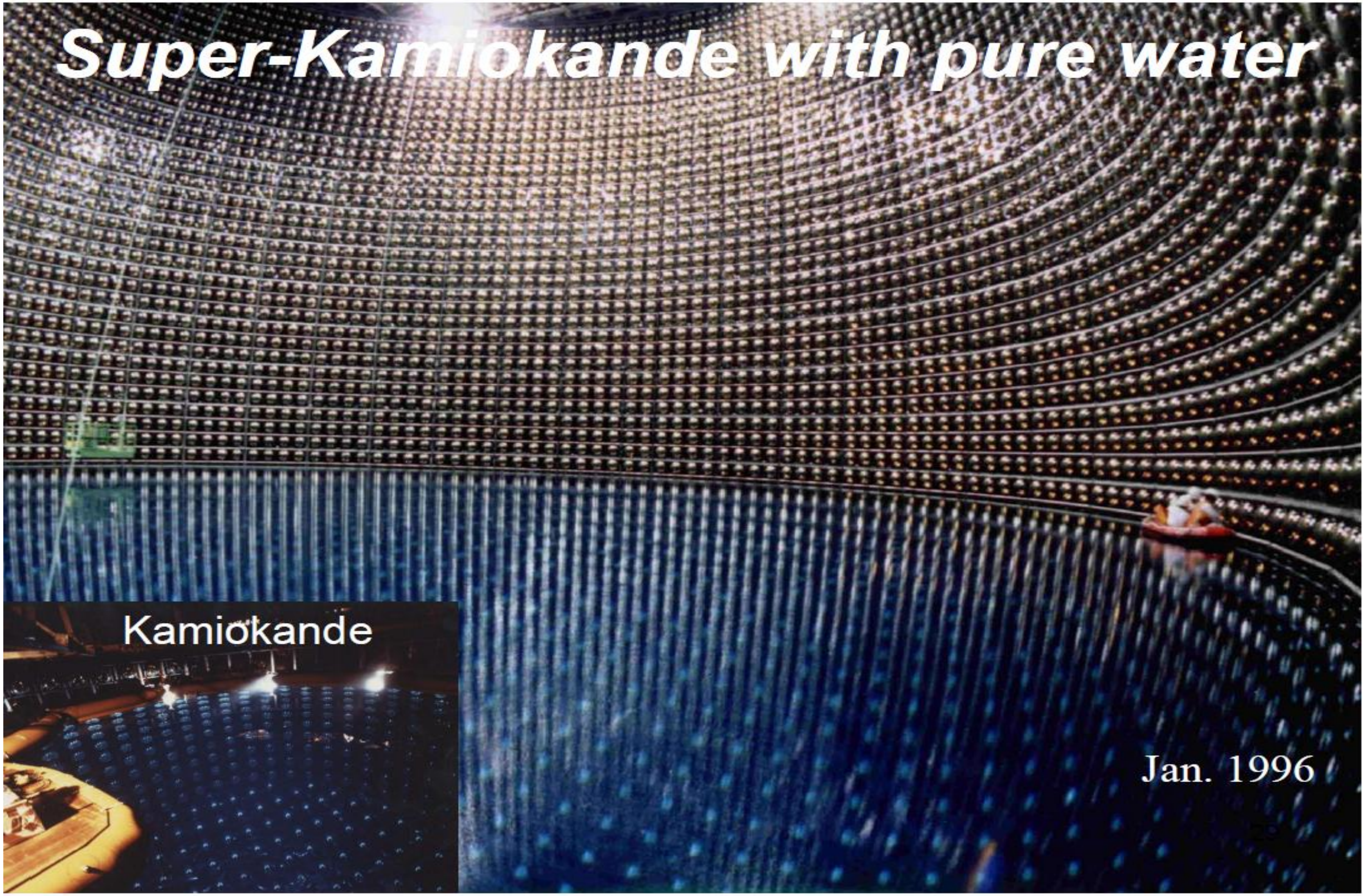
J. P. F. Sellschop and B. Meyer

University of the Witwatersrand, Johannesburg, Republic of South Africa
(Received 26 July 1965)

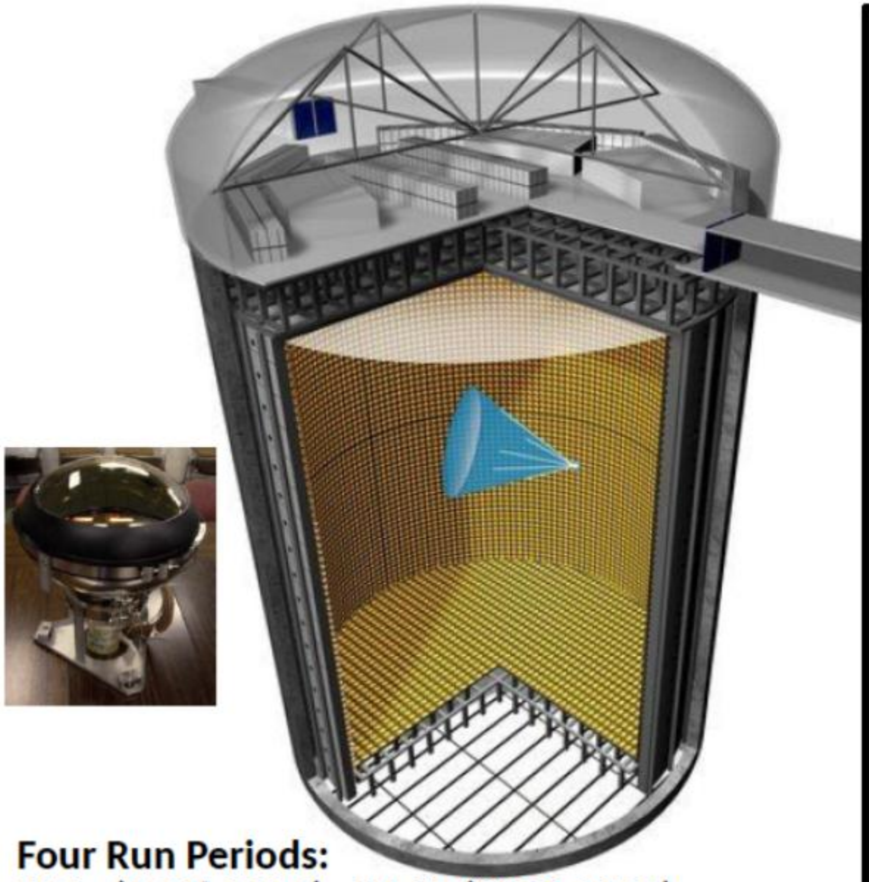
Neutrino telescope at Kolar Gold Fields, India 1965 @ 2400m (rock)

Neutrino telescope at East Rand Proprietary Mine, South Africa 1965 @ 3200m (rock)

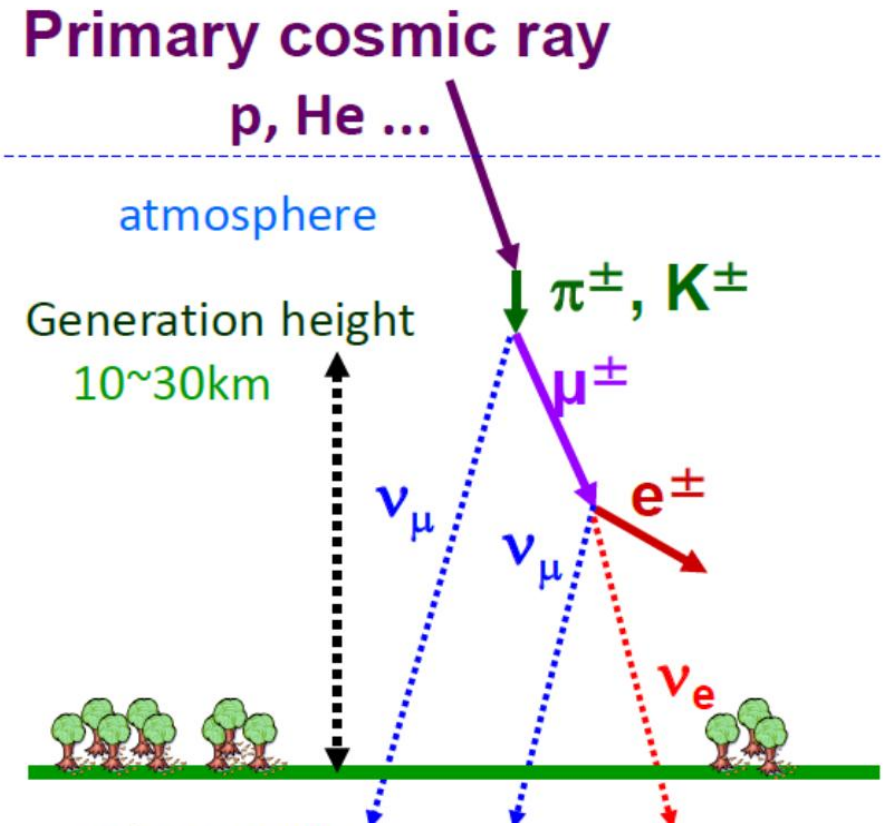
Super-Kamiokande: thirty years of running



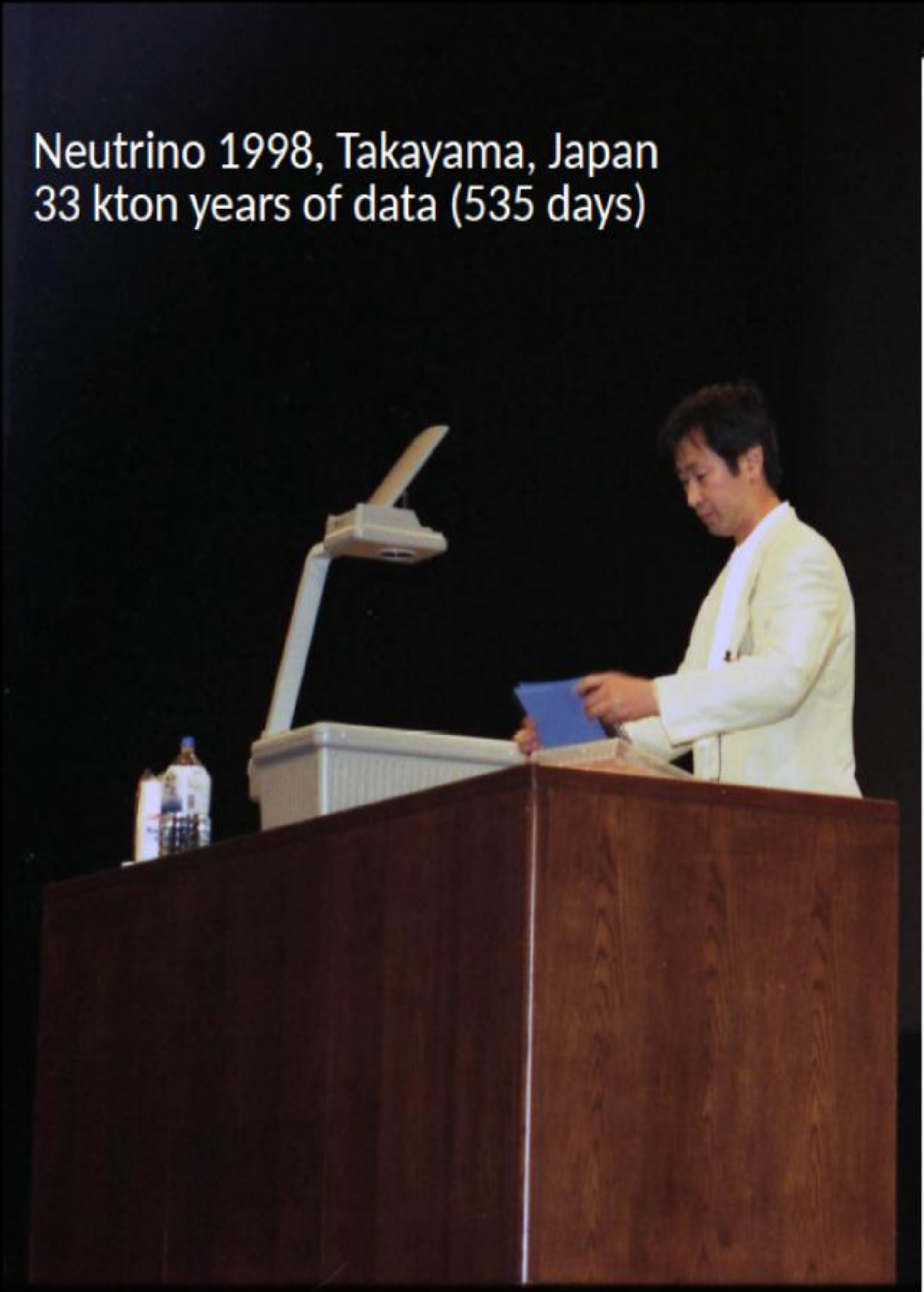
Super-Kamiokande: thirty years of running



Four Run Periods:
SK-I (1996-2001) SK-II (2003-2005)
SK-III (2005-2008) SK-IV (2008-Present)

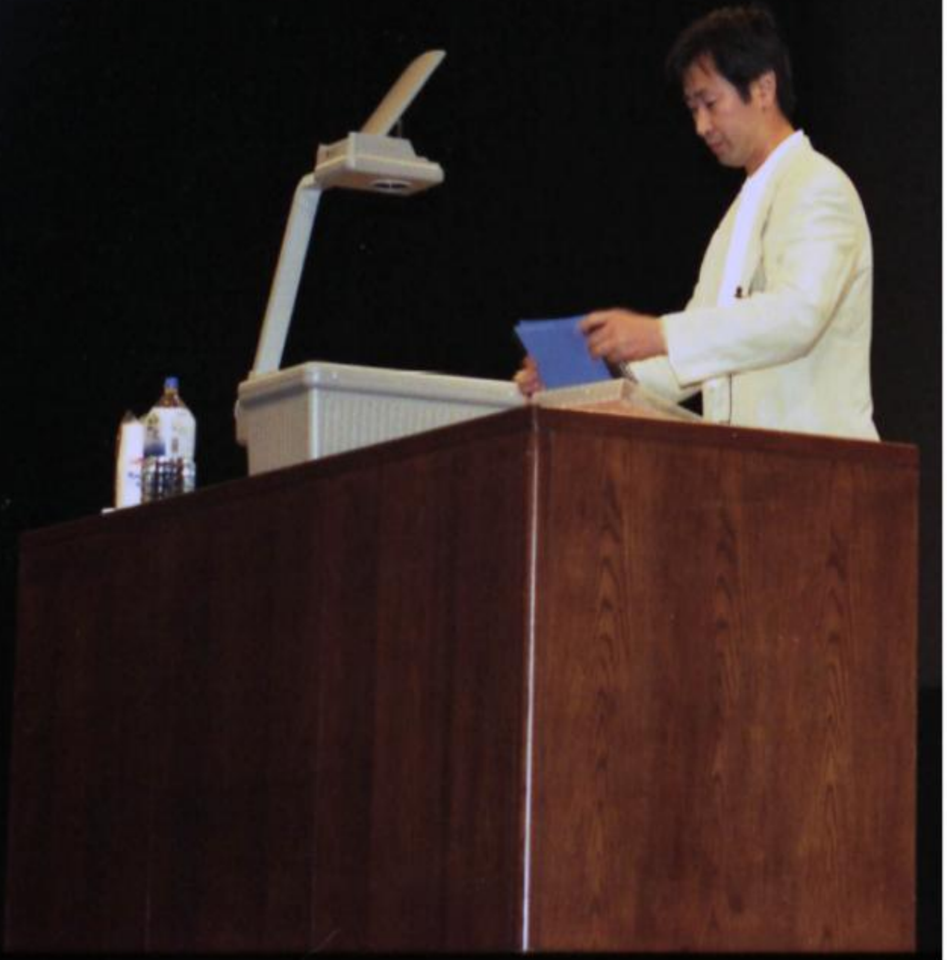


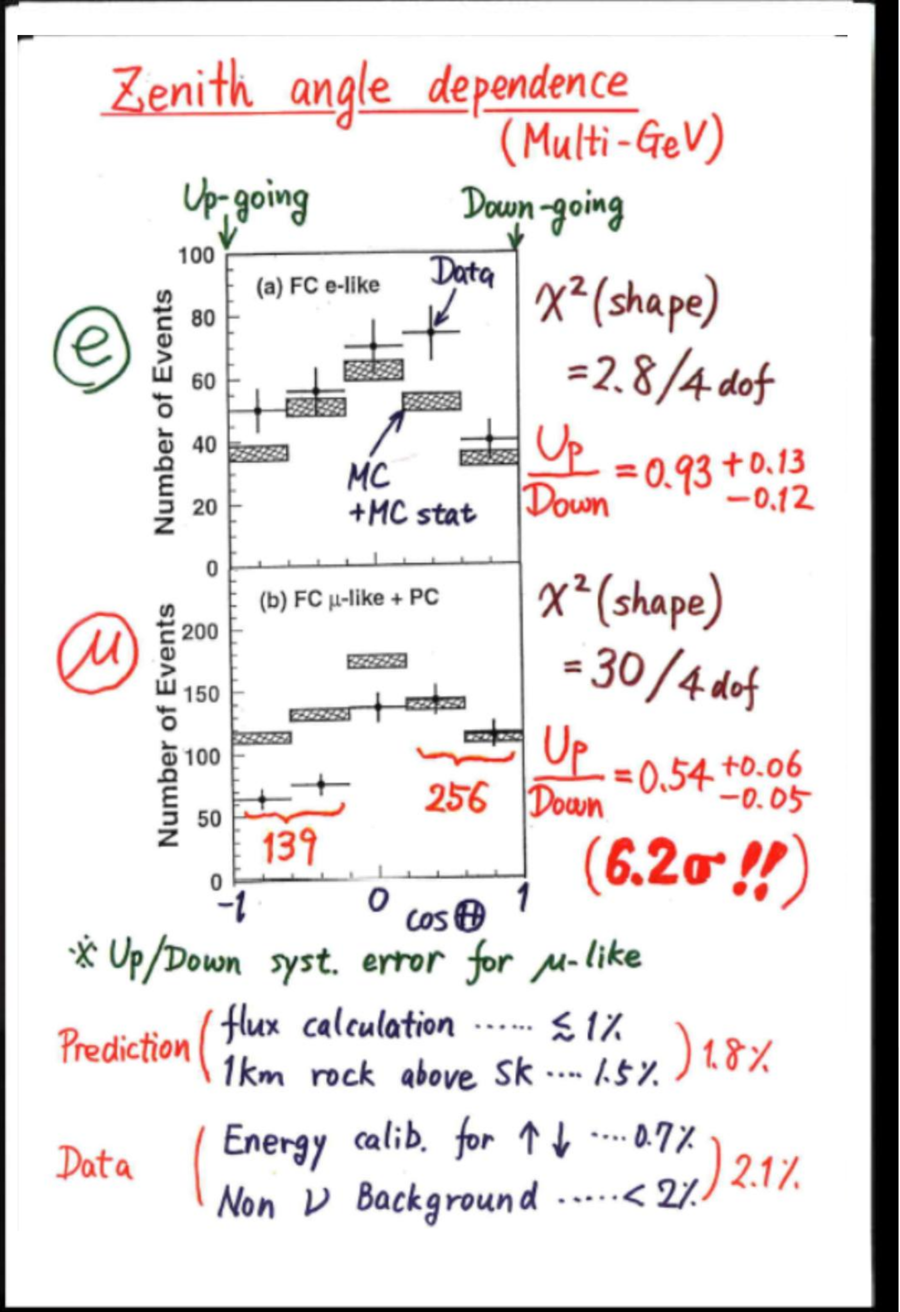
- Multipurpose machine
  - Solar and Supernova Neutrinos
  - Atmospheric Neutrinos (this talk)
  - Nucleon Decay
  - Far detector for T2K



Neutrino 1998, Takayama, Japan
33 kton years of data (535 days)

Neutrino 1998, Takayama, Japan
33 kton years of data (535 days)





Zenith angle dependence
(Multi-GeV)

χ^2(shape) $= 2.8/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.93 {}^{+0.13}_{-0.12}$

χ^2(shape) $= 30/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.54 {}^{+0.06}_{-0.05}$

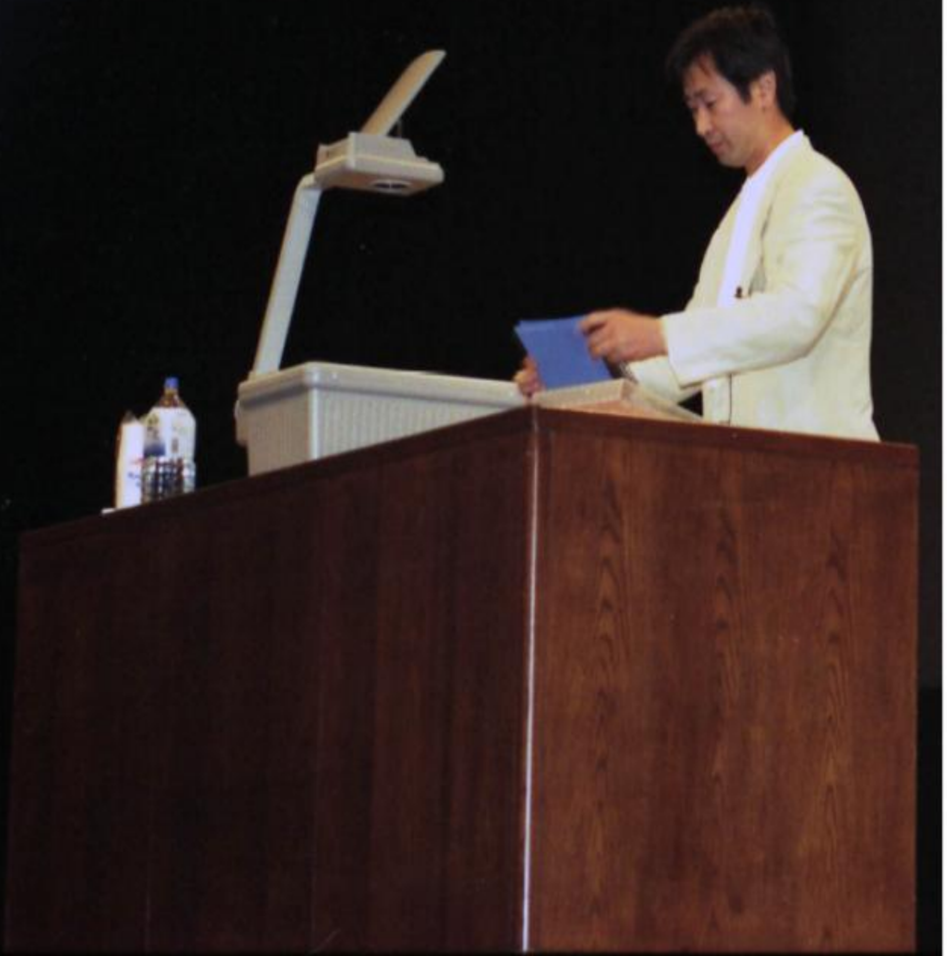
(6.2σ !!)

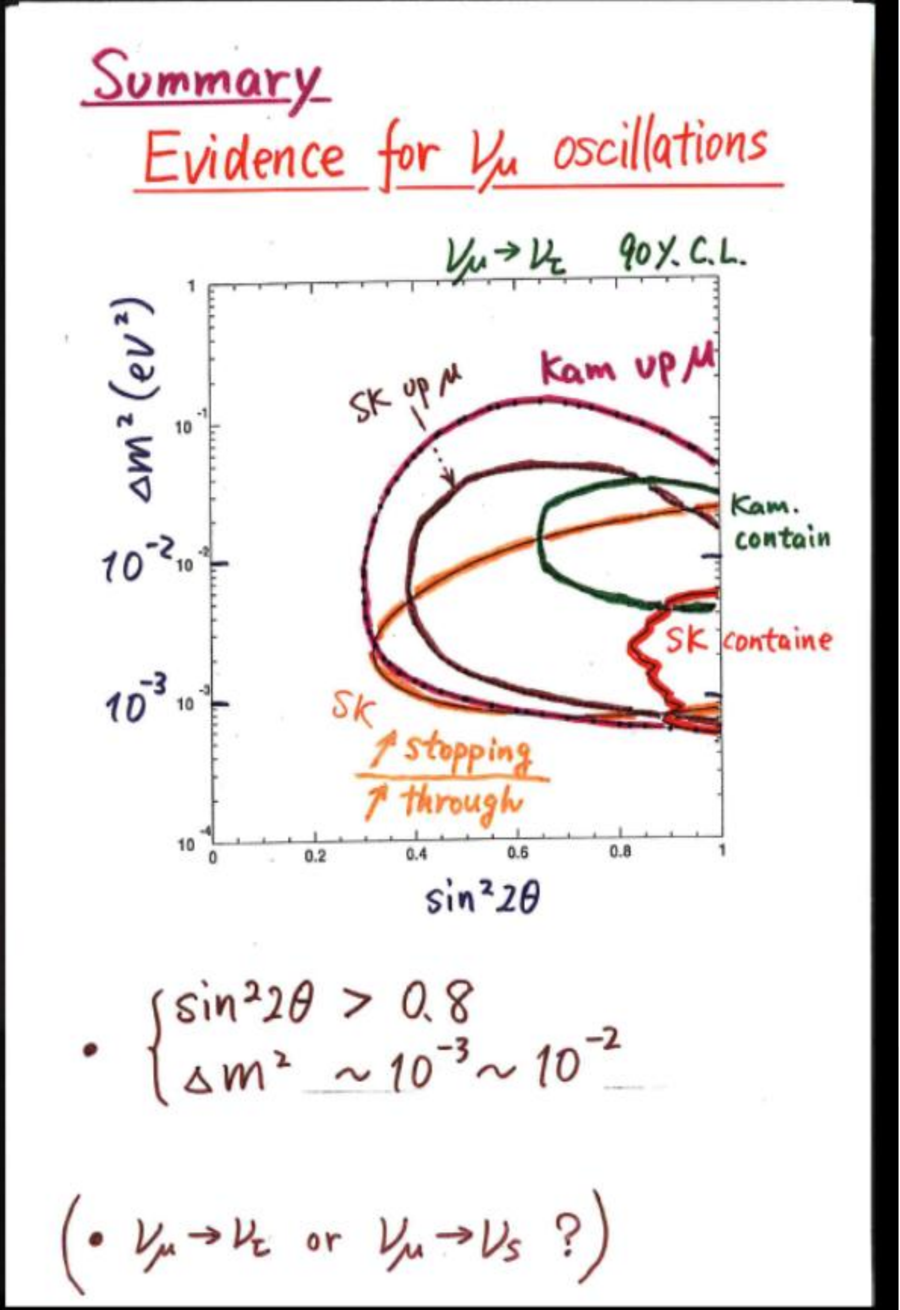
※ Up/Down syst. error for μ-like

Prediction (flux calculation …… ≲ 1%
1km rock above SK …. 1.5%) 1.8%

Data (Energy calib. for ↑↓ …. 0.7%
Non ν Background …..< 2%) 2.1%

Neutrino 1998, Takayama, Japan
33 kton years of data (535 days)





Summary

Evidence for ν_μ oscillations

- $\begin{cases} \sin^2 2\theta > 0.8 \\ \Delta m^2 \sim 10^{-3} \sim 10^{-2} \end{cases}$

(• $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$?)

On October 6, 2015, 2015 Nobel Prize in Physics was awarded to Professor Takaaki Kajita from the University of Tokyo, Japan, and Professor Arthur B. McDonald from Queen's University, Canada, in recognition of the discovery of neutrino oscillation, which demonstrates that neutrinos have mass.

Nobelpriset i fysik 2015 The Nobel Prize in Physics 2015

Nobelpriset i fysik 2015

KUNGL.
VETENSKAP
AKADEMIE
THE ROYAL SWEDISH ACADEMY OF SCIEN

Takaaki Kajita
Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan

Arthur B. McDonald
Sudbury Neutrino Observatory Collaboration
Queen's University, Kingston, Canada

”för upptäckten av neutrinooscillationer, som visar att neutriner har massa”

the discovery of neutrino oscillations, which shows that neutrinos have mass

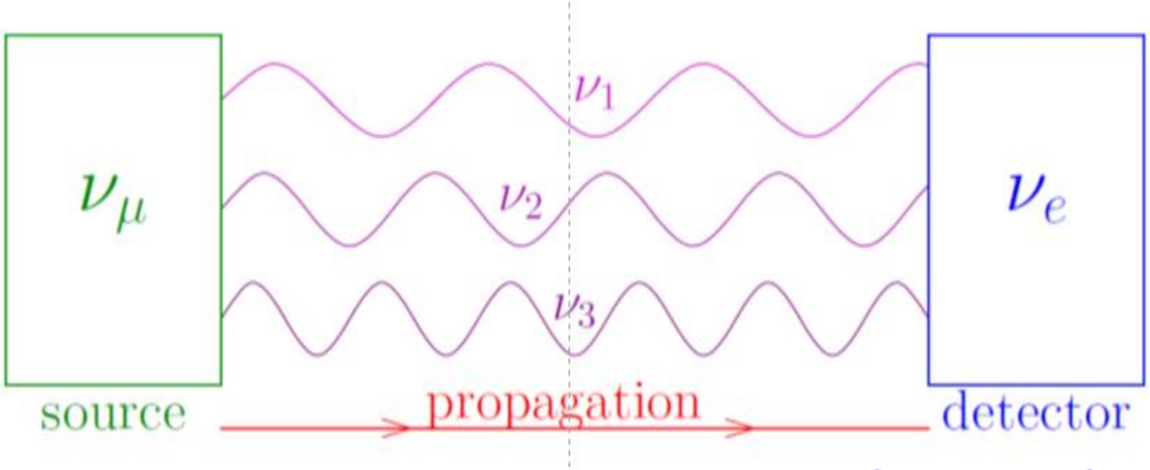
Part II:
Theory of neutrino oscillations

Neutrino oscillation: the theory framework

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

Pontecorvo, 1957; Maki, Nakagawa, Sakata, 1962

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



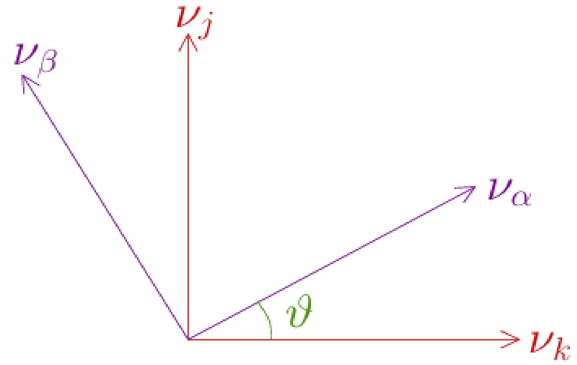
$$\sum_{k>j} \mathrm{Re}\left[U_{ek}\,U^*_{\mu k}\,U^*_{ej}\,U_{\mu j}\right] \sin^2\left(\frac{\Delta m^2_{kj} L}{4E}\right)$$

Bruno Pontecorvo
(1913–1993)
Invented ν oscillations

Neutrino Oscillations:
quantum phenomena of massive neutrinos at the macroscopic distances

ν Oscillations: 2-flavor approximation

$$|\nu_\alpha\rangle = \cos\vartheta\,|\nu_k\rangle + \sin\vartheta\,|\nu_j\rangle$$
$$|\nu_\beta\rangle = -\sin\vartheta\,|\nu_k\rangle + \cos\vartheta\,|\nu_j\rangle$$



$$U = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix}$$

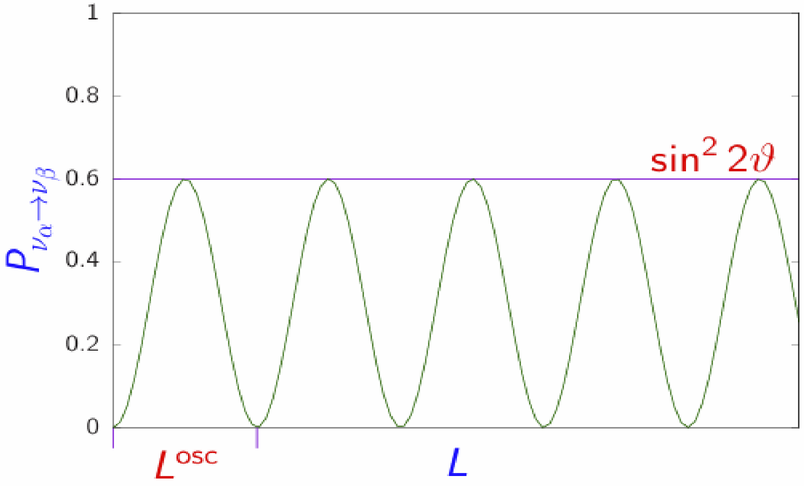
$$\Delta m^2 \equiv \Delta m^2_{kj} \equiv m_k^2 - m_j^2$$

Transition Probability: $P_{\nu_\alpha\to\nu_\beta} = P_{\nu_\beta\to\nu_\alpha} = \sin^2 2\vartheta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$

Survival Probabilities: $P_{\nu_\alpha\to\nu_\alpha} = P_{\nu_\beta\to\nu_\beta} = 1 - P_{\nu_\alpha\to\nu_\beta}$

ν Oscillations: 2-flavor approximation

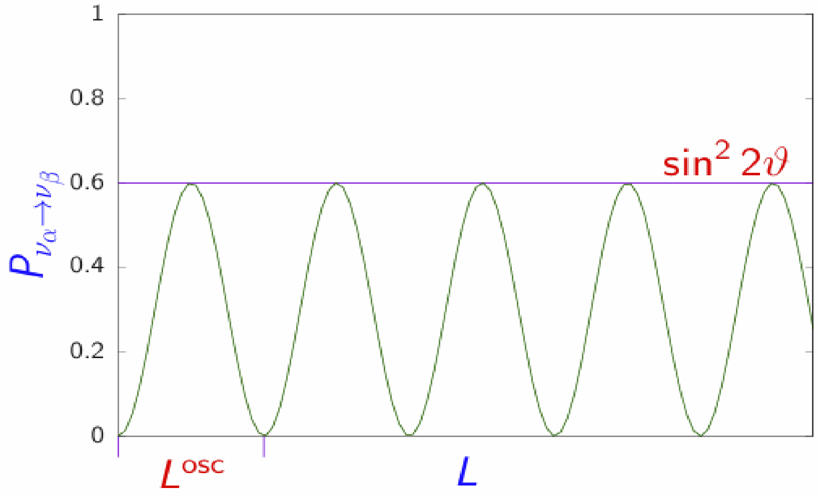
2ν-mixing: $$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\vartheta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \quad \Longrightarrow \quad L^{\text{osc}} = \frac{4\pi E}{\Delta m^2}$$



- The effect of a tiny Δm^2 can be amplified by a large distance L.
- A tiny Δm^2 generates oscillations observable at macroscopic distances!
- Neutrino oscillations are the optimal tool to reveal tiny neutrino masses!

ν Oscillations: 2-flavor approximation

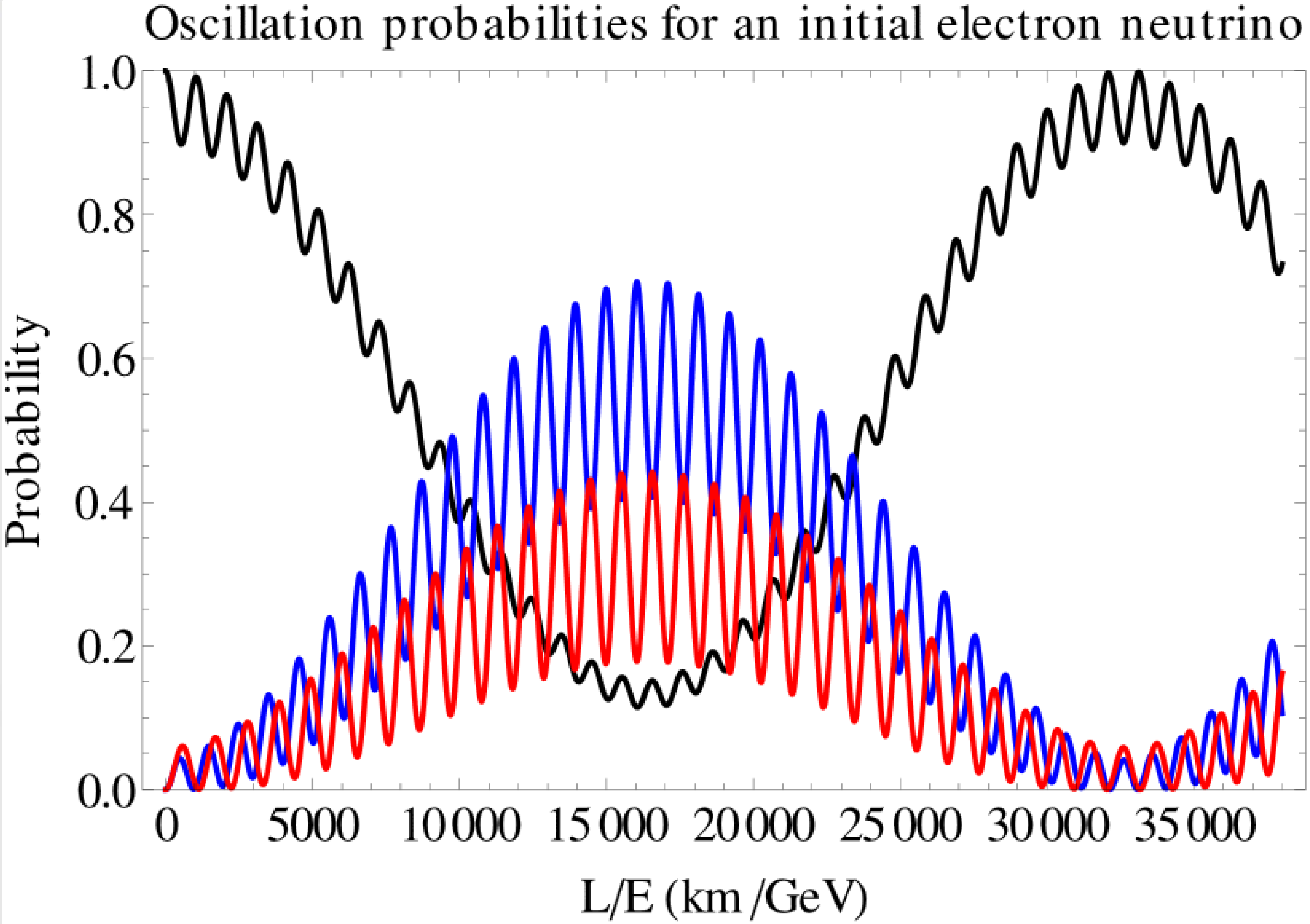
2ν-mixing: $$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\vartheta \, \sin^2\left(1.27 \, \frac{\Delta m^2[\mathrm{eV}^2] \, L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)$$



$$\frac{L}{E} \gtrsim \begin{cases} 10 \, \frac{\mathrm{m}}{\mathrm{MeV}} \; \left(\frac{\mathrm{km}}{\mathrm{GeV}}\right) \\ 10^3 \, \frac{\mathrm{m}}{\mathrm{MeV}} \; \left(\frac{\mathrm{km}}{\mathrm{GeV}}\right) \\ 10^4 \, \frac{\mathrm{km}}{\mathrm{GeV}} \\ 10^{11} \, \frac{\mathrm{m}}{\mathrm{MeV}} \end{cases}$$

$10 \, \frac{\mathrm{m}}{\mathrm{MeV}} \left(\frac{\mathrm{km}}{\mathrm{GeV}}\right)$	short-baseline experiments	$\Delta m^2 \gtrsim 10^{-1} \, \mathrm{eV}^2$
$10^3 \, \frac{\mathrm{m}}{\mathrm{MeV}} \left(\frac{\mathrm{km}}{\mathrm{GeV}}\right)$	long-baseline experiments	$\Delta m^2 \gtrsim 10^{-3} \, \mathrm{eV}^2$
$10^4 \, \frac{\mathrm{km}}{\mathrm{GeV}}$	atmospheric neutrino experiments	$\Delta m^2 \gtrsim 10^{-4} \, \mathrm{eV}^2$
$10^{11} \, \frac{\mathrm{m}}{\mathrm{MeV}}$	solar neutrino experiments	$\Delta m^2 \gtrsim 10^{-11} \, \mathrm{eV}^2$

ν Oscillation: A QM phenomenon



ν_e

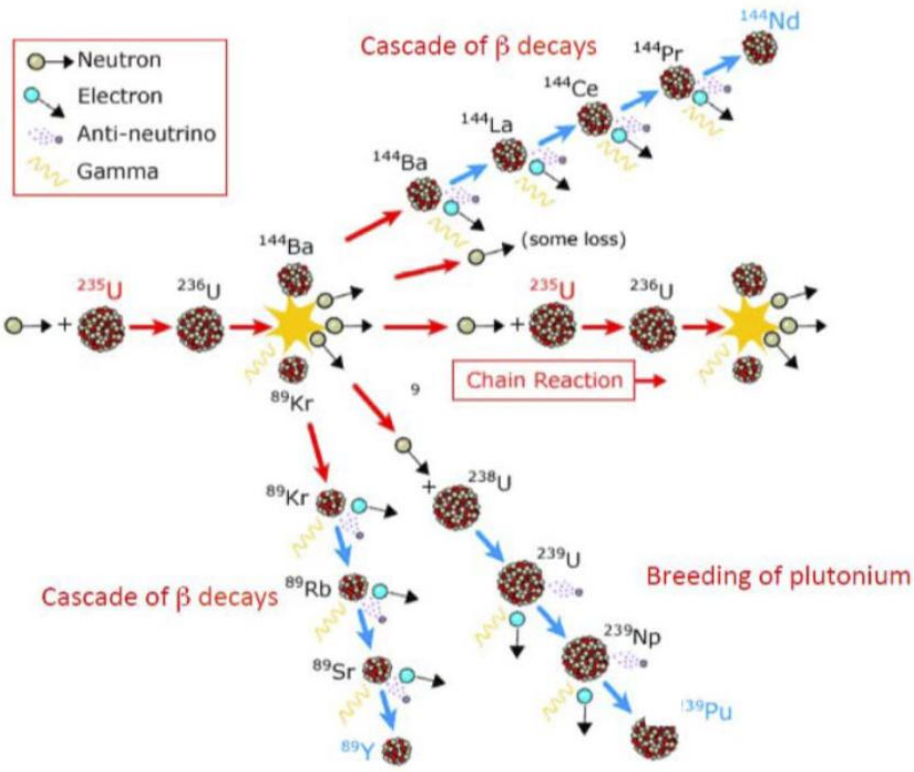
ν_μ

ν_τ

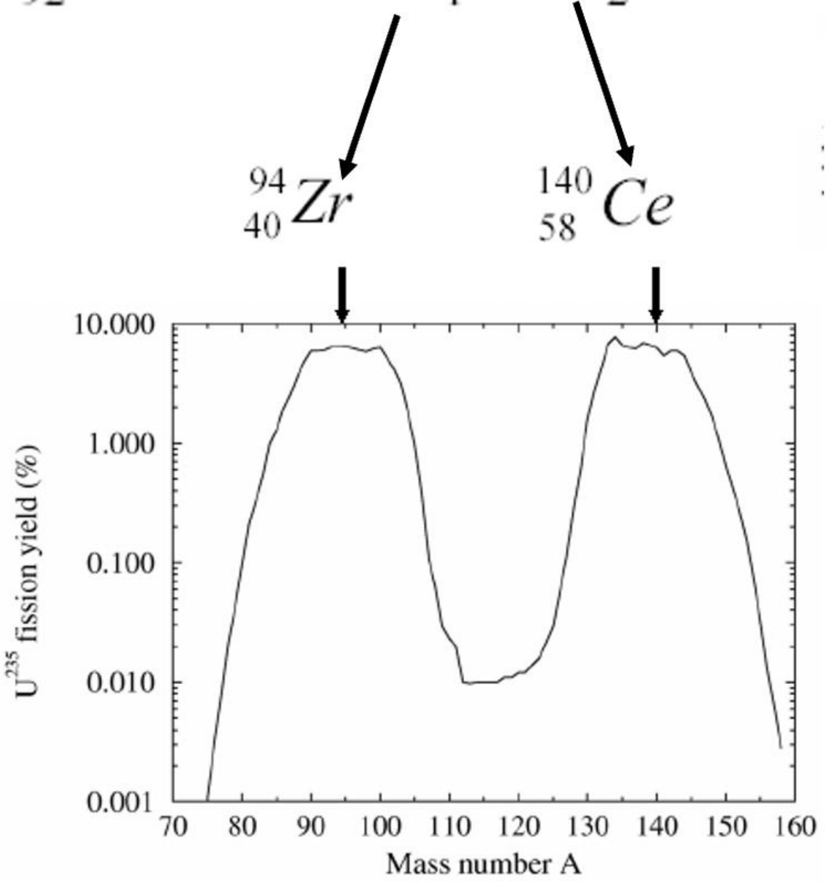
Part III:

Reactor neutrino experiments

How to produce reactor neutrinos?



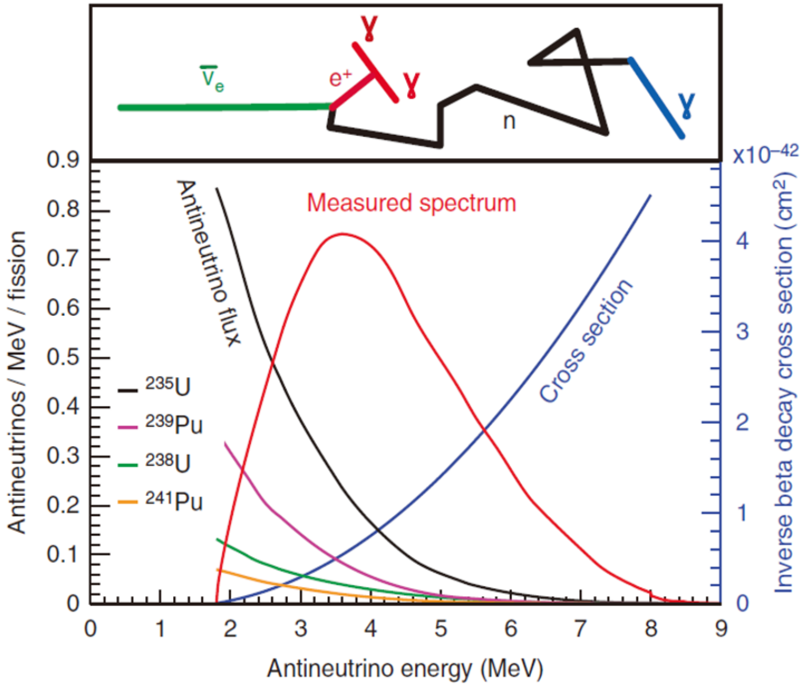
$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$



Neutrino flux of a commercial reactor with 3 $GW_{thermal}$: 6×10^{20} /s

How to detect reactor neutrinos?

- Inverse-β Decays: $\bar{\nu}_e + p \rightarrow e^+ + n$



τ ≈ 180 μs (H) or 28 μs (0.1% Gd)

$n + p \rightarrow d + \gamma\ (2.2\ \mathrm{MeV})$

$n + Gd \rightarrow Gd^* + \gamma\ (8\ \mathrm{MeV})$

Neutrino Event: coincidence in time, space & energy

Why LS:

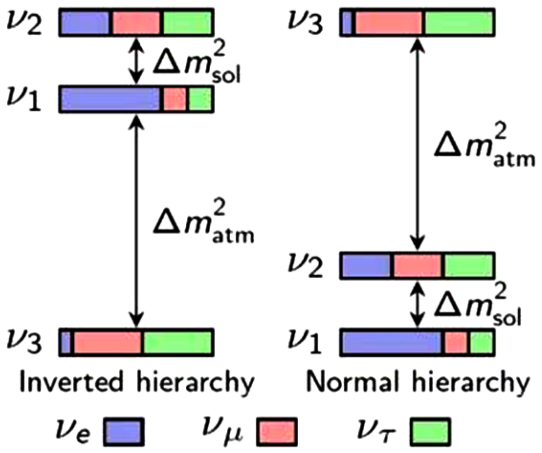
Being both the target and detector
Proton rich material
Good energy resolution
Easy handling for large volume
Cheap

Neutrino energy:

$$E_{\bar{\nu}} \cong T_{e^+} + \underbrace{T_n}_{\text{10-40 keV}} + \underbrace{(M_n - M_p) + m_{e^+}}_{\text{1.8 MeV: Threshold}}$$

Fundamental parameters of neutrinos

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



$2.4 \times 10^{-3} \mathrm{eV}^2$

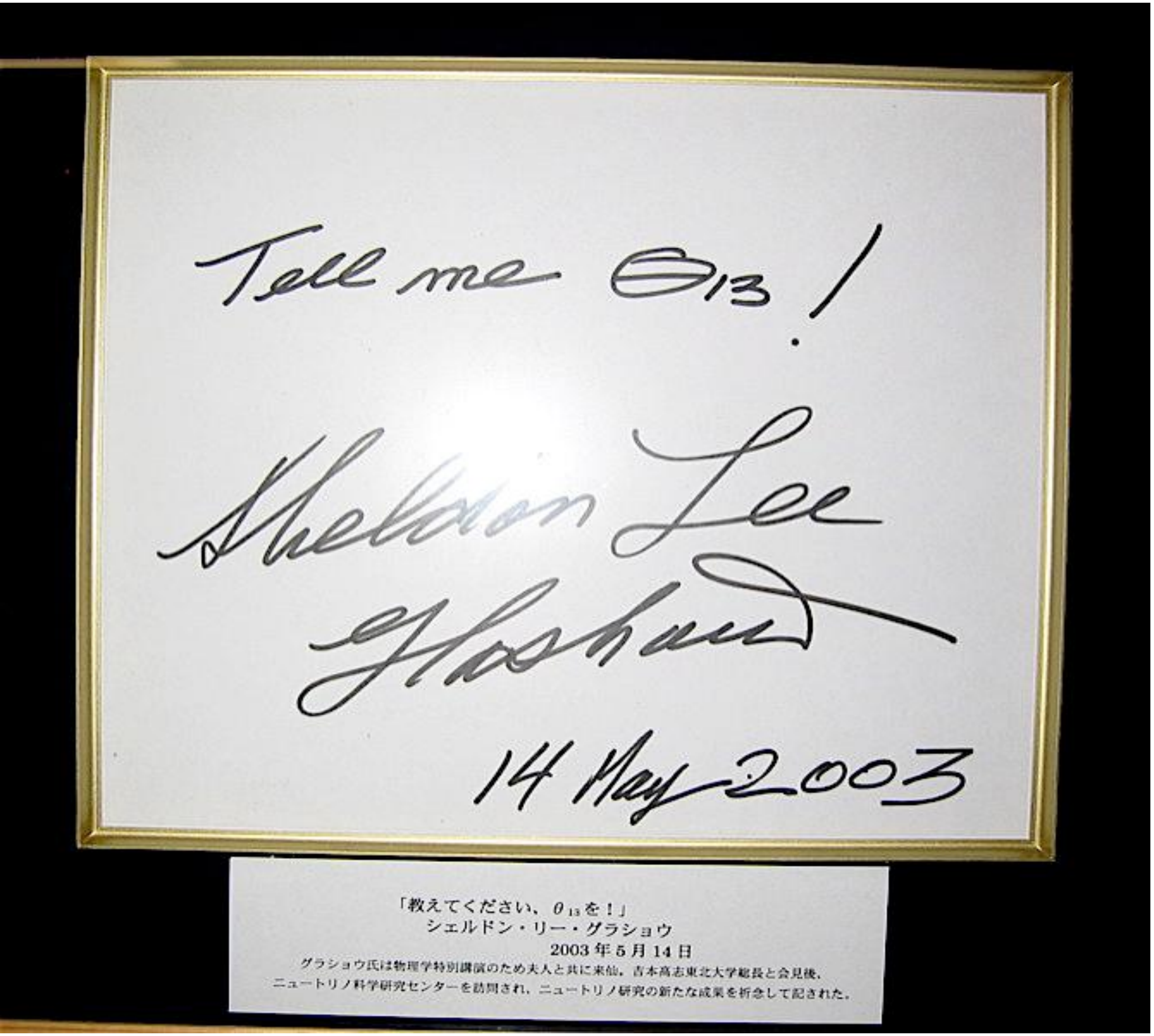
$7.5 \times 10^{-5} \mathrm{eV}^2$

- **3 mixing angle**
- **1 or 3 CP phase**
- **2 mass squared differences**

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23} \sim 45°$	**θ_{13} = ?**	**$\theta_{12} \sim 34°$**	
Atmospheric	**Reactor**	**Solar**	**0νββ**
Accelerator (K2K)	**Accelerator**	**Reactor (Kamland)**	

Reflections of the Nobel Prize Laureates



Tell me θ_{13} !

Sheldon Lee Glashow

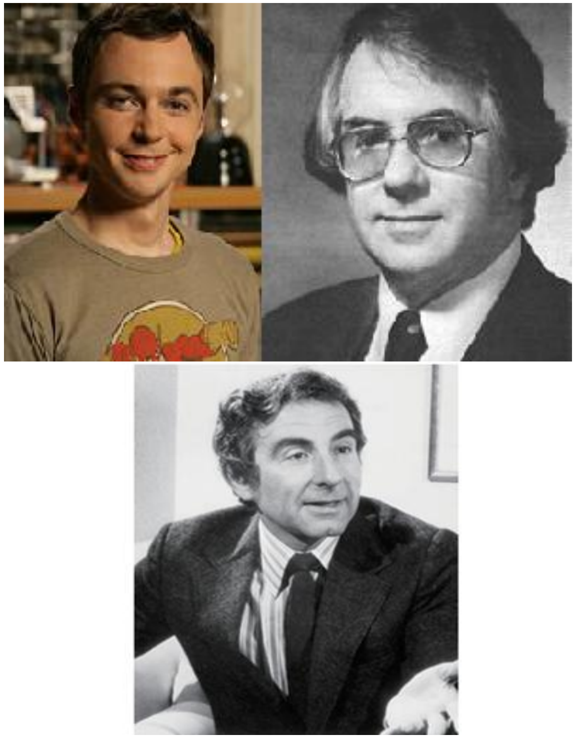
14 May 2003

「教えてください、θ_{13}を！」

シェルドン・リー・グラショウ

2003年5月14日

グラショウ氏は物理学特別講演のため夫人と共に来仙。吉本高志東北大学総長と会見後、ニュートリノ科学研究センターを訪問され、ニュートリノ研究の新たな成果を祈念して記された。



- **Reflections from Sheldon Lee Glashow at Tohoku University**

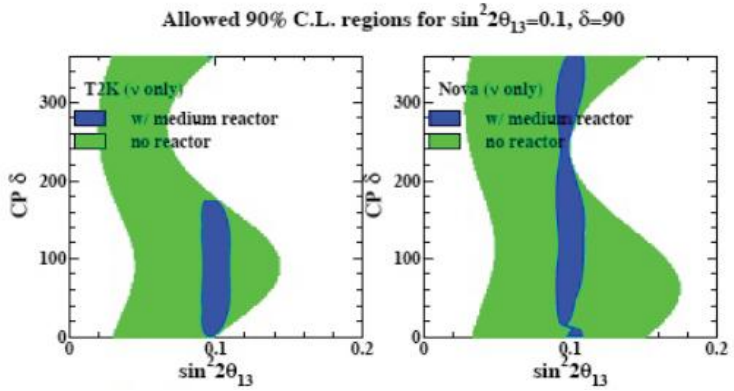
How to detect theta13?

Accelerator neutrinos [(nu(mu)→nu(e)]，affected by CP & matter effects

$$P_{\nu_\mu\to\nu_e} = \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2\left(\Delta m^2_{31}L/4E\right)$$

$$+\ (\text{CPV term}) + (\text{matter term})$$

$$+\ \text{high order terms}$$



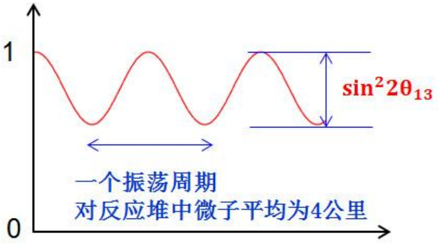
Reactor neutrinos [nu(e)→nu(e)]，independence of CP & matter effect

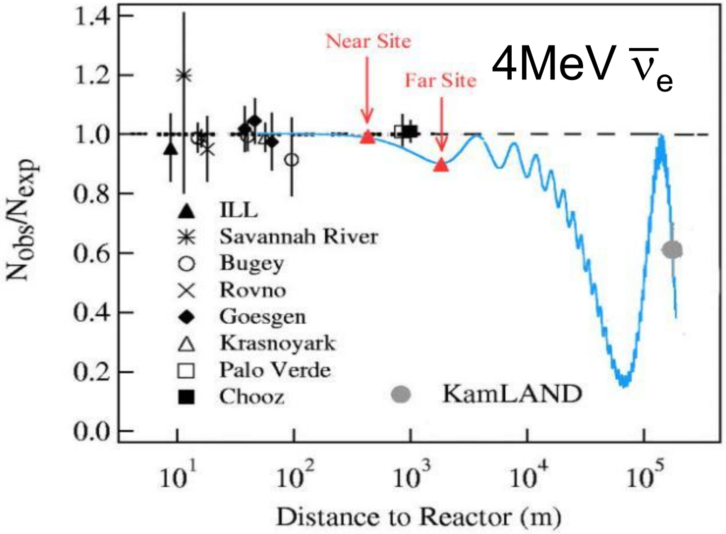
$$P_{\bar\nu_e\to\bar\nu_e} \approx 1-\sin^2 2\theta_{13}\sin^2\left(\Delta m^2_{31}L/4E\right)$$

$$-\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\Delta m^2_{21}L/4E\right)$$

飞行距离/中微子能量

$$P_{sur} \approx 1 - \underbrace{\sin^2 2\theta_{13}}_{\text{振幅大小}} \cdot \underbrace{\sin^2\left(1.27\cdot\Delta m^2_{31}\cdot\frac{L}{E}\right)}_{\text{振荡频率}}$$





How to detect theta(13) from reactors?

Source of systematics

- Reactor related ~2%
- Detector related ~2%
- Background 1~3%

Lesson from previous experiments

- CHOOZ: Good Gd-LS
- Palo Verde: Better shielding
- KamLAND: No fiducial cut

Near-Far detector relative measurment
Mikaelyan and Sinev, hep-ex/9908047

Parameter	Error	Near-far
Reaction cross section	1.9 %	0
Energy released per fission	0.6 %	0
Reactor power	0.7 %	~0.1%
Number of protons	0.8 %	< 0.3%
Detection efficiency	1.5 %	0.2~0.6%
CHOOZ Combined	2.7 %	< 0.6%

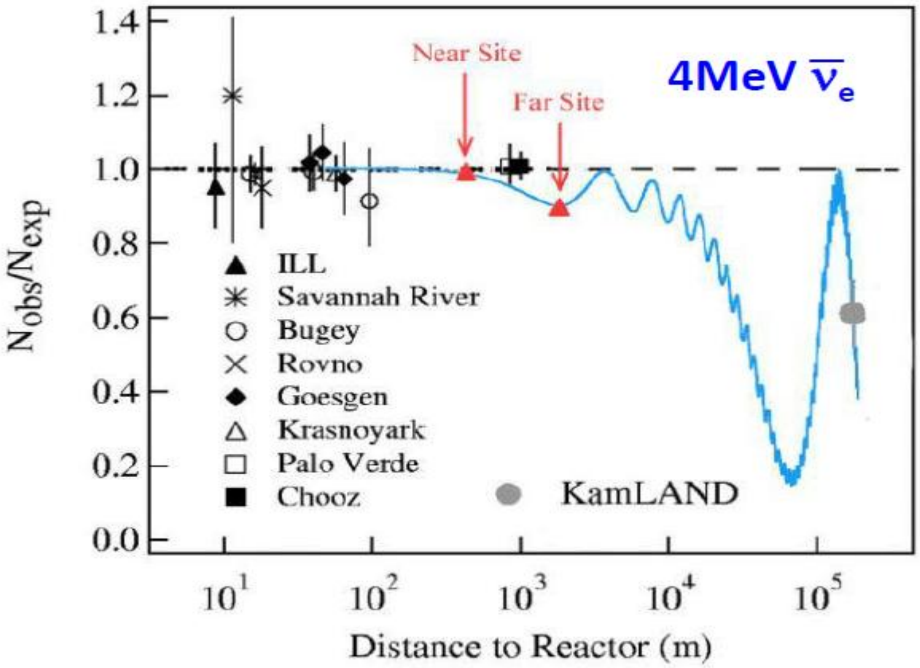
8→3：real experiments

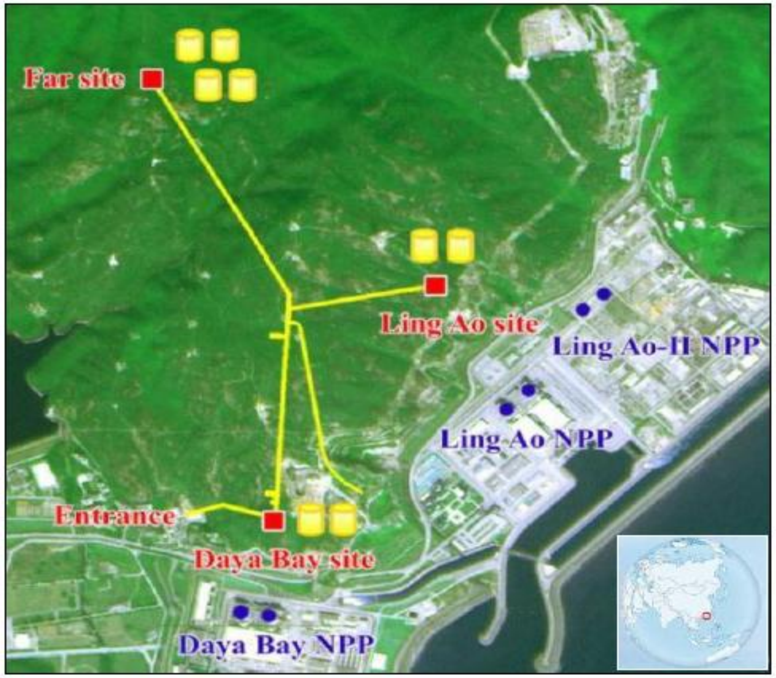
8 proposals, most in 2003 (3 on-going)

- Fundamental parameter
- Gateway to ν-CPV and Mass Hierarchy measurements
- Less expensive

Daya Bay Reactor Neutrino Experiments

2003 idea → 2007 started civil construction，2011 started operation





Dec. 2011	**Double Chooz (far detector):**	$\sin^2\theta_{13} = 0.022 \pm 0.013$	**1.7σ**
Mar. 2012	**Daya Bay (near + far detectors):**	$\sin^2\theta_{13} = 0.024 \pm 0.004$	**5.2σ**
Apr. 2012	**RENO (near + far detectors):**	$\sin^2\theta_{13} = 0.029 \pm 0.006$	**4.9σ**

Decommission in 2020

大亚湾实验于2020年光荣退役！

大亚湾反应堆中微子实验装置
DAYA BAY REACTOR NEUTRINO EXPERIMENT

开始运行：2011/12/24 22:53:52
Start Time: 12/24/2011 22:53:52

结束运行：2020/12/12 10:36:52
Stop Time: 12/12/2020 10:36:52

运行时间：3275天11小时43分0秒
Duration: 3275d, 11h, 43m, 0s

θ_{13}的精度20% → 3%

未来二十年保持国际最高精度。
自然界基本参数，几乎所有中微子研究和部分粒子物理研究与之相关。

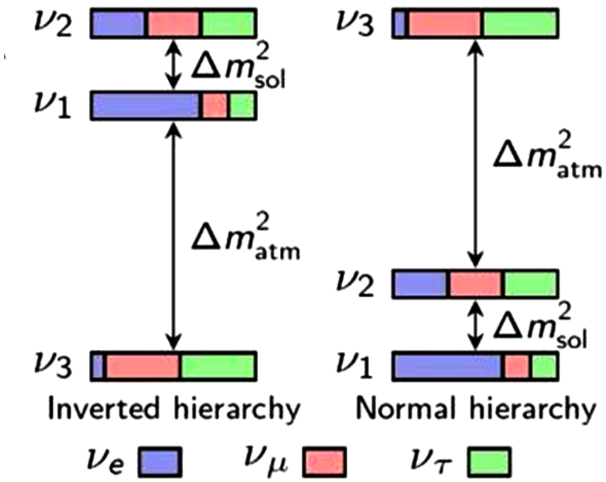
Part IV:

Jiangmen Underground Neutrino Observatory (JUNO)

Global Picture of 3 flavor mixing

Three flavor mixing framework

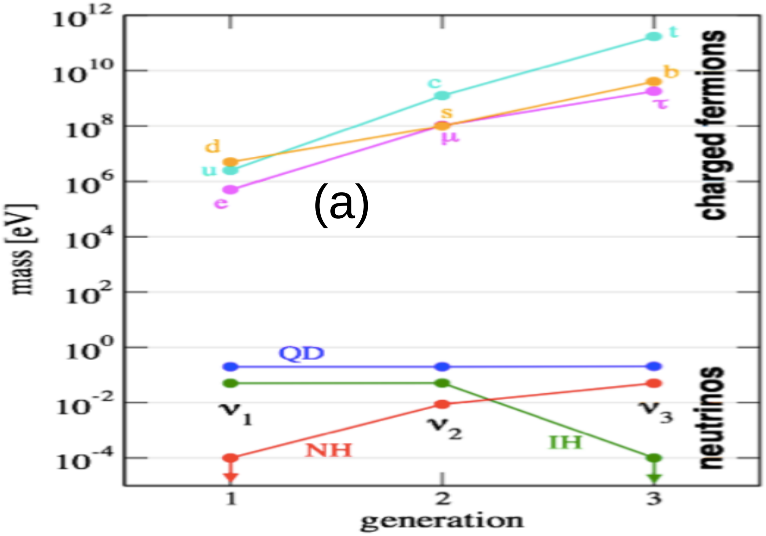
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



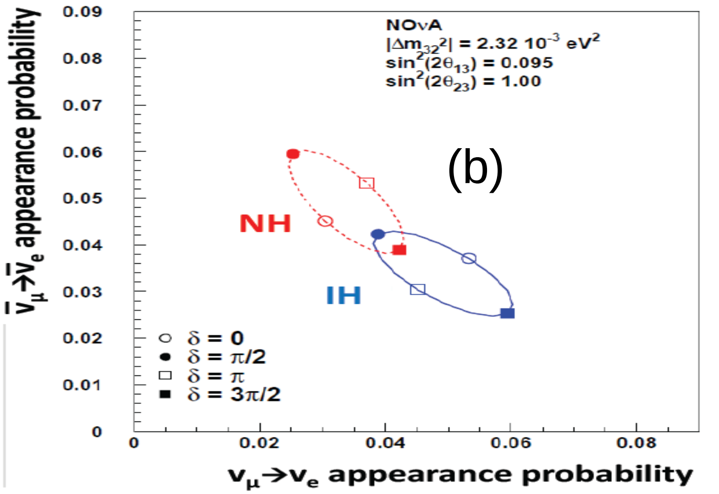
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

θ_{23} ~ 45°	**θ_{13} = 9°**	**θ_{12} ~ 34°**	
Atmospheric	**Reactor**	**Solar**	**0νββ**
Accelerator	**Accelerator**	**Reactor**	

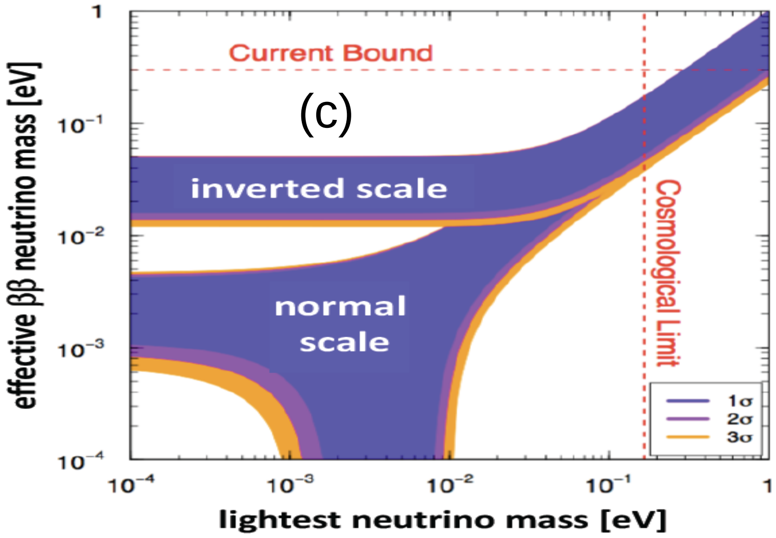
Importance of neutrino mass ordering



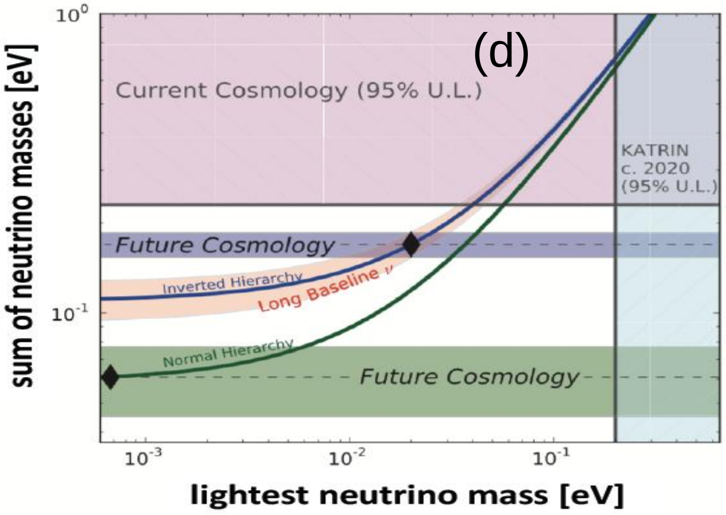
NOvA: degeneracy of MH and δ_{CP}



Lightest vs. effective ββ neutrino mass



Cosmological neutrino mass vs. MH

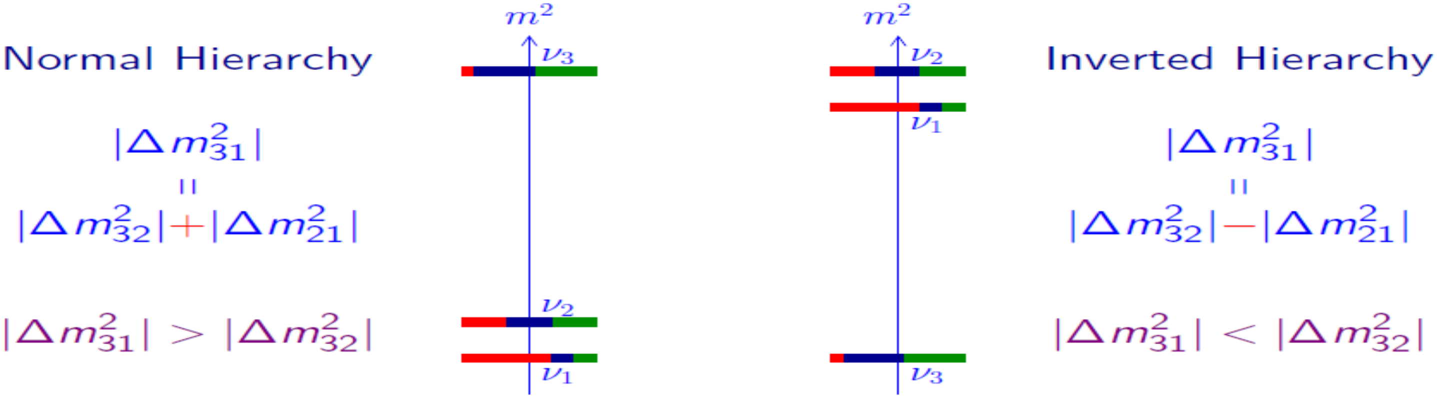


Method to determine mass ordering

Matter effects: **Accelerator, atmospheric, supernova neutrinos**

- $\nu_e \leftrightarrows \nu_\mu$ MSW resonance: $V = \dfrac{\Delta m^2_{13} \cos 2\vartheta_{13}}{2E} \Leftrightarrow \Delta m^2_{13} > 0$ NH
- $\bar\nu_e \leftrightarrows \bar\nu_\mu$ MSW resonance: $V = -\dfrac{\Delta m^2_{13} \cos 2\vartheta_{13}}{2E} \Leftrightarrow \Delta m^2_{13} < 0$ IH

Vacuum Interference: **Reactor neutrinos S. T. Petcov et al., PLB 533, 94 (2002)**



Normal Hierarchy

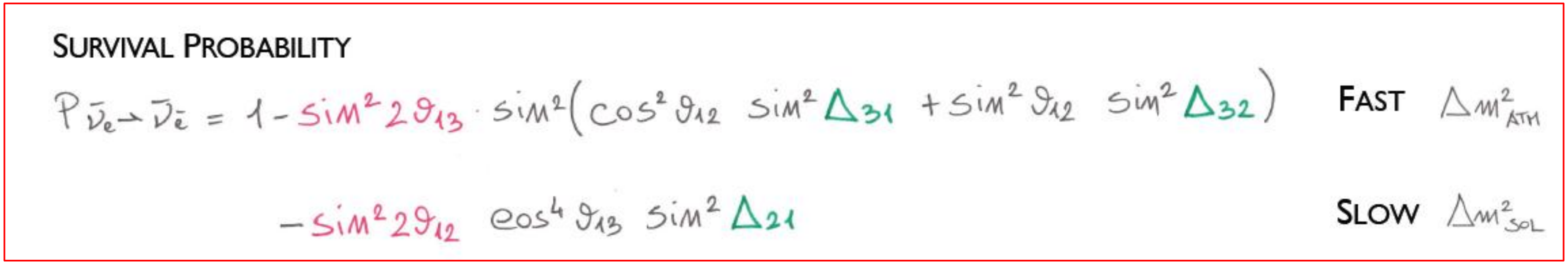
$|\Delta m^2_{31}|$ = $|\Delta m^2_{32}| + |\Delta m^2_{21}|$

$|\Delta m^2_{31}| > |\Delta m^2_{32}|$

Inverted Hierarchy

$|\Delta m^2_{31}|$ = $|\Delta m^2_{32}| - |\Delta m^2_{21}|$

$|\Delta m^2_{31}| < |\Delta m^2_{32}|$

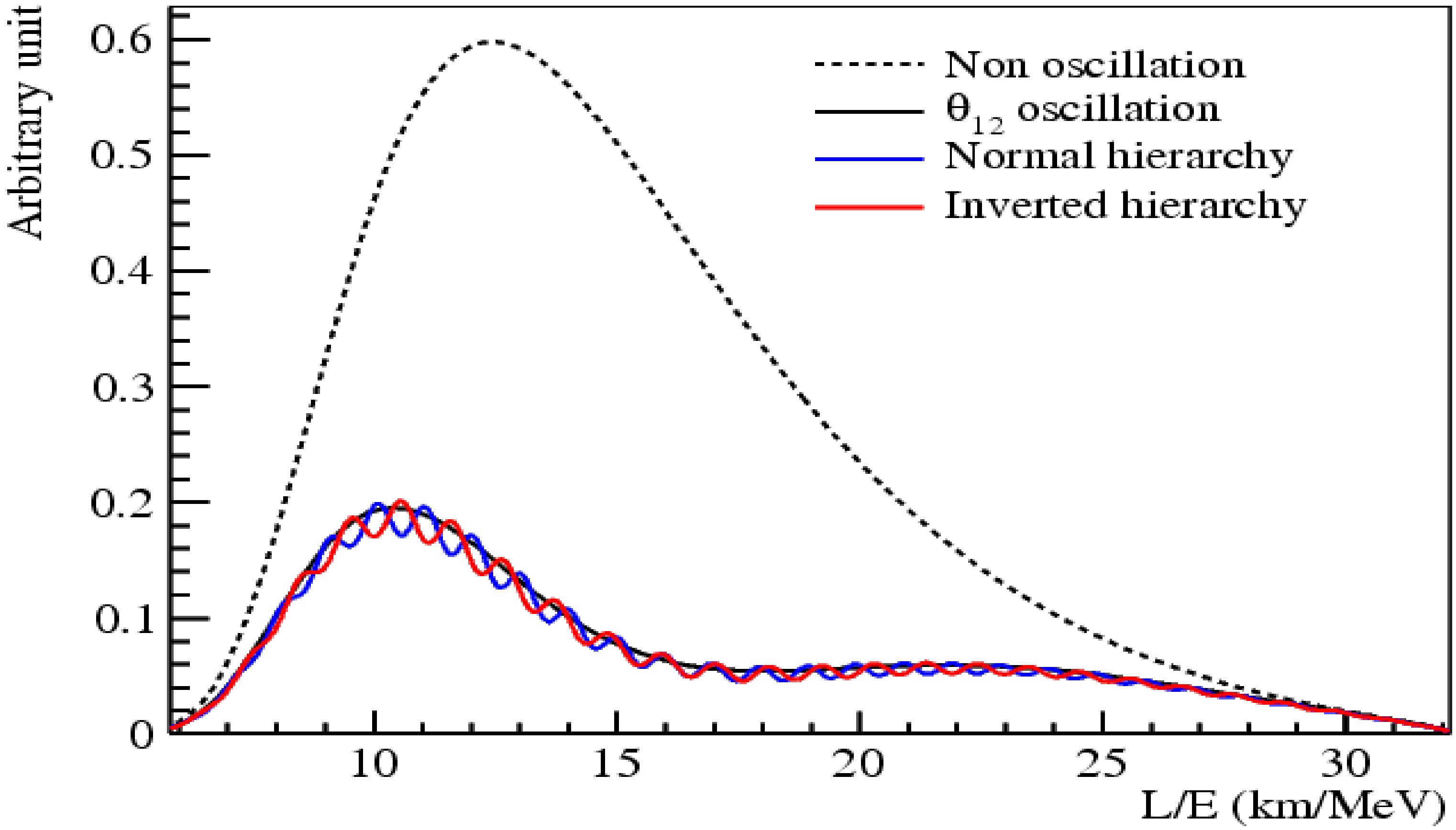


SURVIVAL PROBABILITY

$$P_{\bar\nu_e\to\bar\nu_e} = 1 - \sin^2 2\vartheta_{13} \cdot \sin^2\left(\cos^2\vartheta_{12}\,\sin^2\Delta_{31} + \sin^2\vartheta_{12}\,\sin^2\Delta_{32}\right)$$ FAST Δm^2_{ATM}

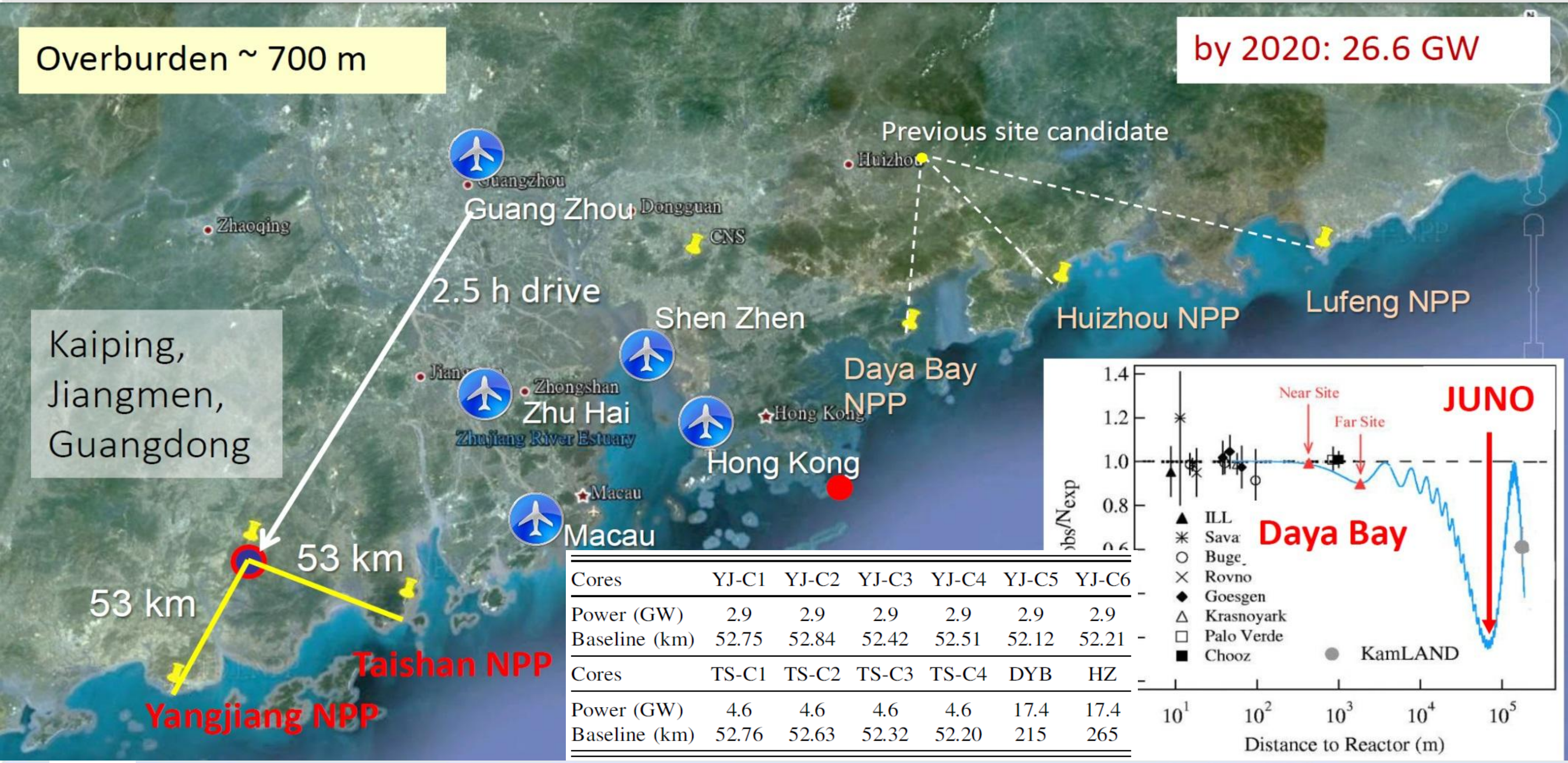
$$-\sin^2 2\vartheta_{12}\,\cos^4\vartheta_{13}\,\sin^2\Delta_{21}$$ SLOW Δm^2_{SOL}

Method of reactor neutrino oscillations



Experimental Site

NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



Overburden ~ 700 m

by 2020: 26.6 GW

Kaiping, Jiangmen, Guangdong

Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.20	215	265

Detector design

- Target mass of 20 kt liquid scintillator ➔ × 20 KamLAND, × 70 Borexino
- Energy resolution < 3%@ 1MeV ➔ > 1200 PE/MeV

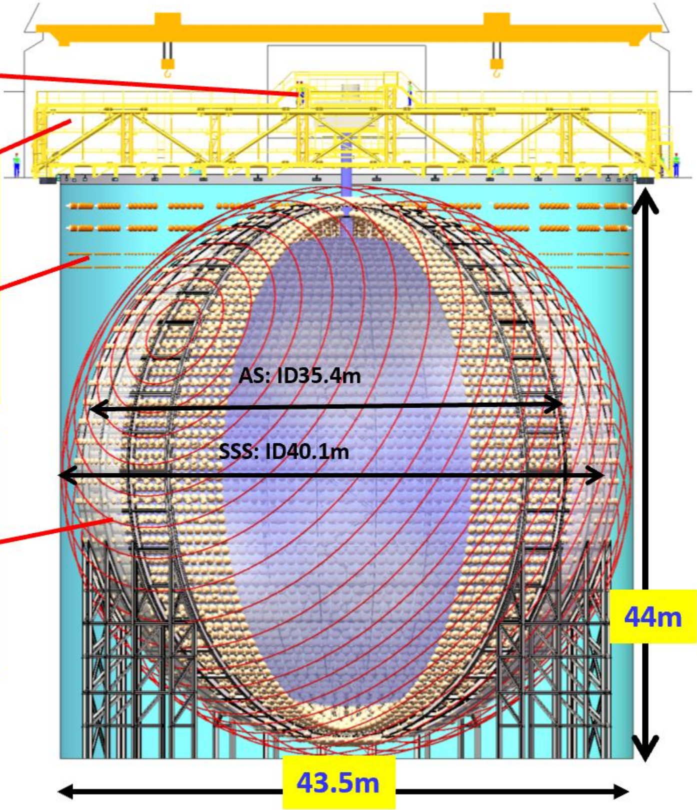
Calibration house

VETO system

- Top Tracker: plastic scintillator
- Water + 2400 20" PMT + 348 20" spare PMTs + 600 8" PMTs from Daya Bay
- Earth Magnetic Field shielding coils

Central detector

- Steel structure
- Acrylic sphere + 20kt Liquid scintillator
- 17612 20" PMT + 25600 3" PMT



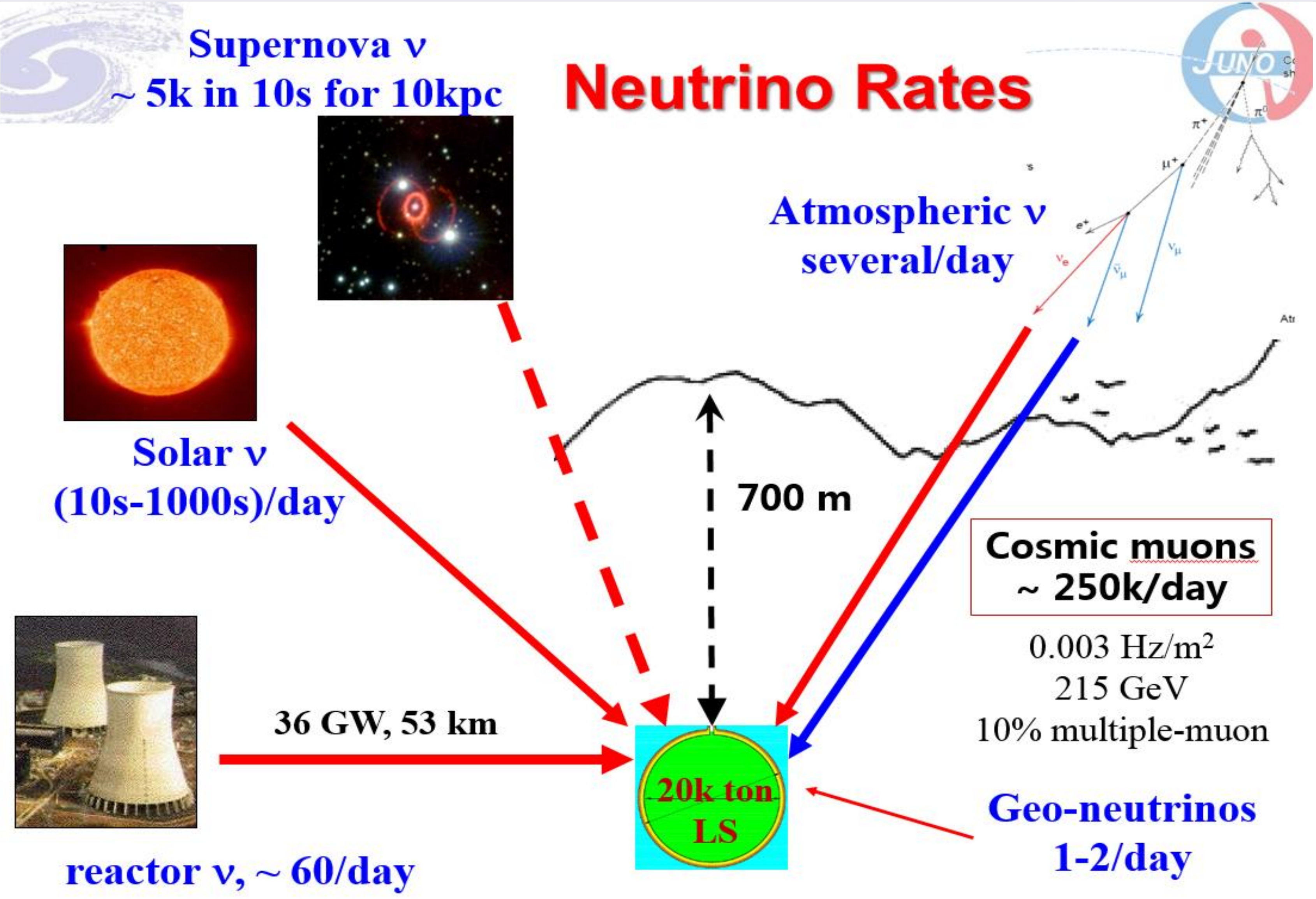
	KamLAND	JUNO	Ratio
Photon Statistics	250 p.e./MeV	1200 p.e./MeV	5
PMT coverage	34%	75%	2.2
LS transparency	~12 m	> 20 m	~0.9
Light yield (anthracene)	30%	45%	~1.5
Detection Eff.(QE×CE)	~15%	30%	~ 2

Main technical challenges

- ➢ Precise mechanical structure for small clearance between PMTs
- ➢ Very transparent LS
- ➢ High photon eff. PMTs

arXiv:1508.07166
Prog. Part. Nucl. Phys. 123(2022), 103927

Multi-purpose neutrino observatory



Neutrino Rates

Supernova ν
~ 5k in 10s for 10kpc

Atmospheric ν
several/day

Solar ν
(10s-1000s)/day

700 m

Cosmic muons
~ 250k/day

0.003 Hz/m²
215 GeV
10% multiple-muon

36 GW, 53 km

20k ton
LS

Geo-neutrinos
1-2/day

reactor ν, ~ 60/day

History of JUNO construction

Project Approved and Funded!

2013

Civil Started

2015

2017

NNVT PMTs Delivered

Civil completed

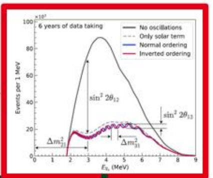
2021

Detector Const. Started

2022

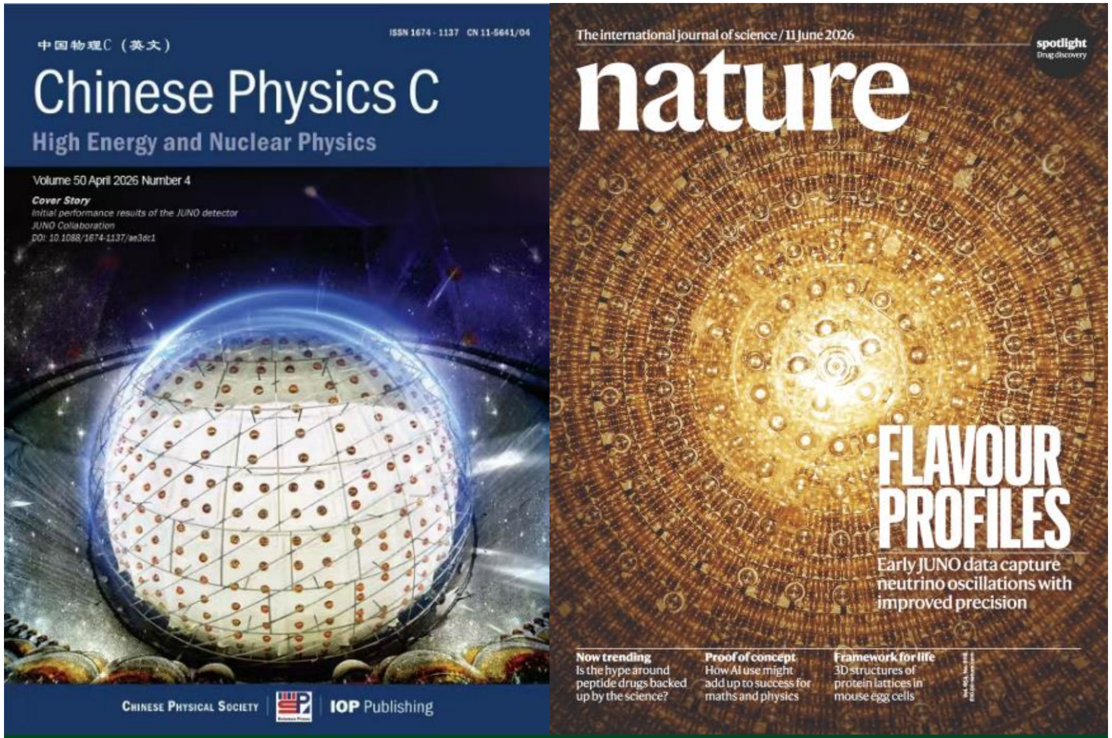
2023-2024-2025

Detector completing, Filling starting



Summer 2025: Data Taking!

Highlight of JUNO achievements



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High Energy and Nuclear Physics

Volume 50 April 2026 Number 4

Cover Story

Initial performance results of the JUNO detector

JUNO Collaboration

DOI: 10.1088/1674-1137/ae3dc1

Chinese Physical Society | IOP Publishing

The international journal of science / 11 June 2026

nature

spotlight
Drug discovery

FLAVOUR PROFILES

Early JUNO data capture neutrino oscillations with improved precision

Now trending
Is the hype around peptide drugs backed up by the science?

Proof of concept
How AI use might add up to success for maths and physics

Framework for life
3D structures of protein lattices in mouse egg cells

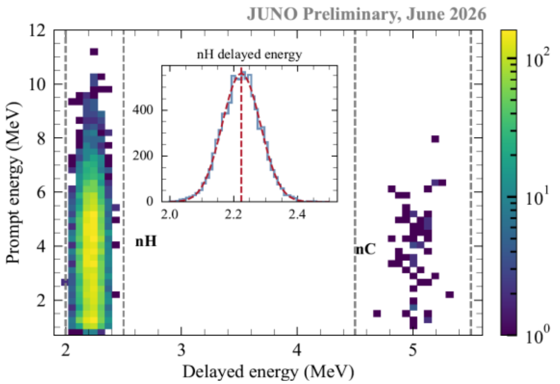
First results using 59 days of data already published, Nov 2025 – Jun 2026

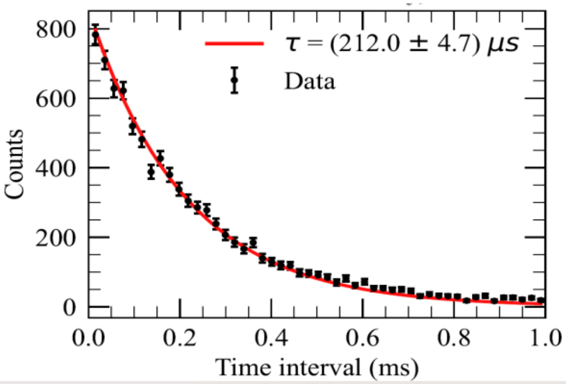
First Neutrino Mass Ordering
207 days of data @ ν'26

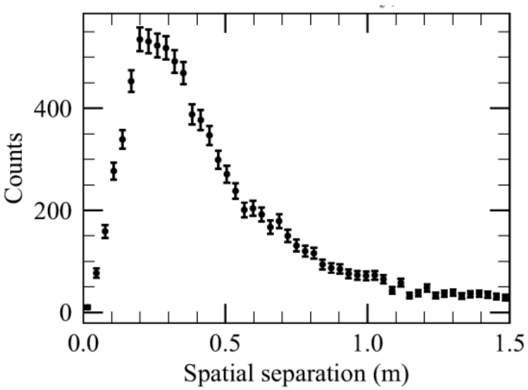
Reactor neutrino event selection

- Prompt and delayed coincidence in time, space with energy features

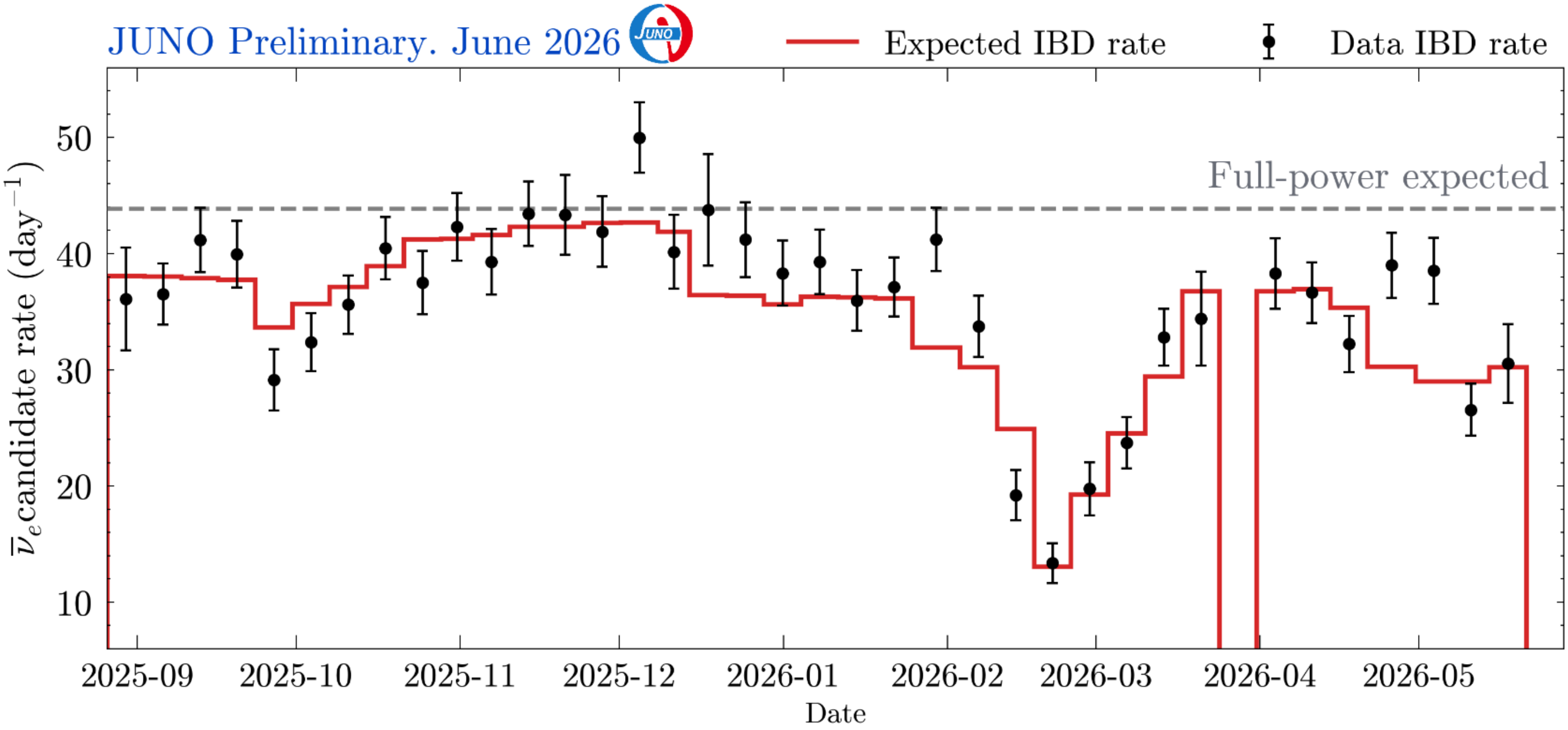
Criterion	Selection
PMT flasher	Applied
Fiducial volume	$r_p < 17.2$ m, $\|z_p\|$<15.5m
Prompt energy	(0.7, 12) MeV
Delayed energy	(2.0, 2.5) $\cup$ (4.5, 5.5) MeV
Coincidence time	(5, 1000) μs
Relative distance	$<$ 1.5 m
Multiplicity cut	No other events $>$ 0.7 MeV in the FV or (2.0, 6.0) MeV outside the FV within 2 ms before and 1 ms after the delayed event
Water pool muon veto	Veto if the delayed is within (0, 2) ms after NPE $>$ 700 in WP
CD muon veto	Veto if the delayed is within (0, 5) ms after NPE $> 3 \times 10^4$ in CD
Spallation neutron veto	Veto if the delayed satisfies Δr $<$ 4 m and Δt $<$ 1.2 s after spallation neutrons with $\mathrm{NPE_{spn}} \in$ (3000, 30000) and $T_{\mathrm{spn2}\mu} \in$ (20, 2000) μs
Muon track veto	Veto if the delayed event: $\frac{\Delta r_{\mu d}}{2.5\mathrm{m}} + \frac{\Delta t_{\mu d}}{0.5\mathrm{s}} < 1$
Correlated discriminator	log(L.R.) > -1.26



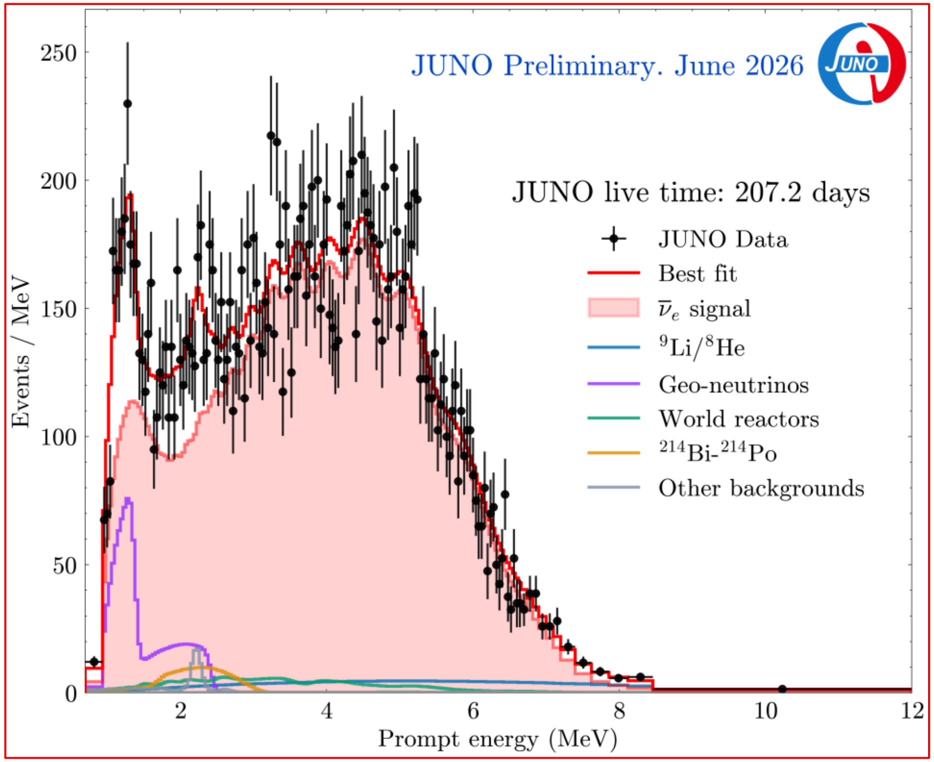


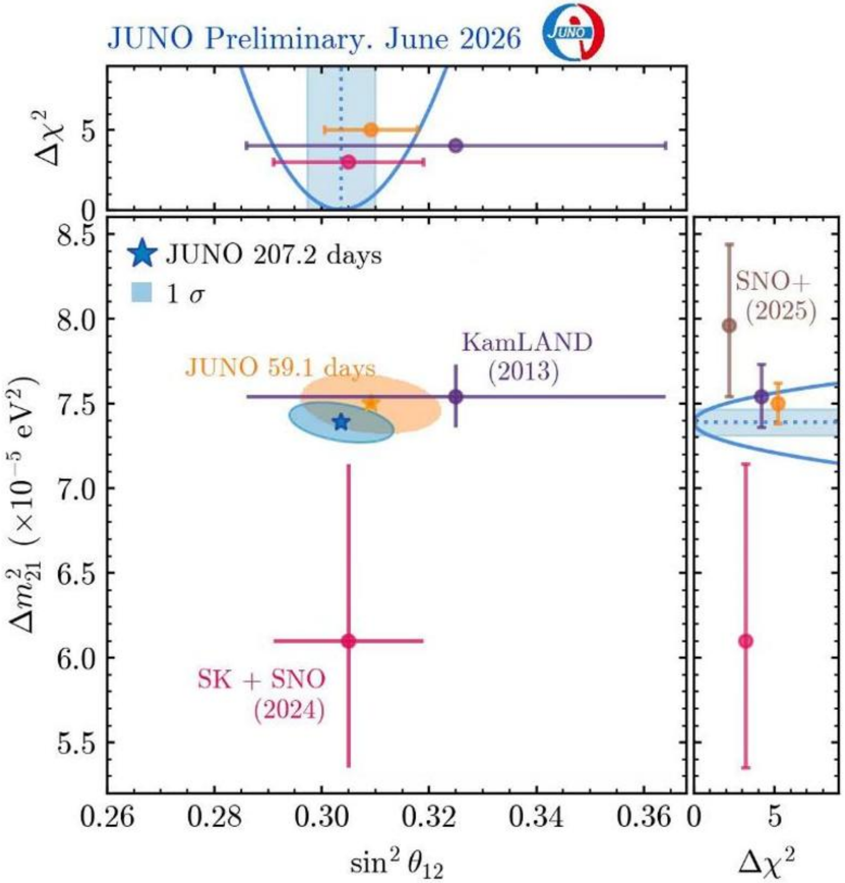


Reactor neutrino rate v.s. time



Solar parameters from reactors

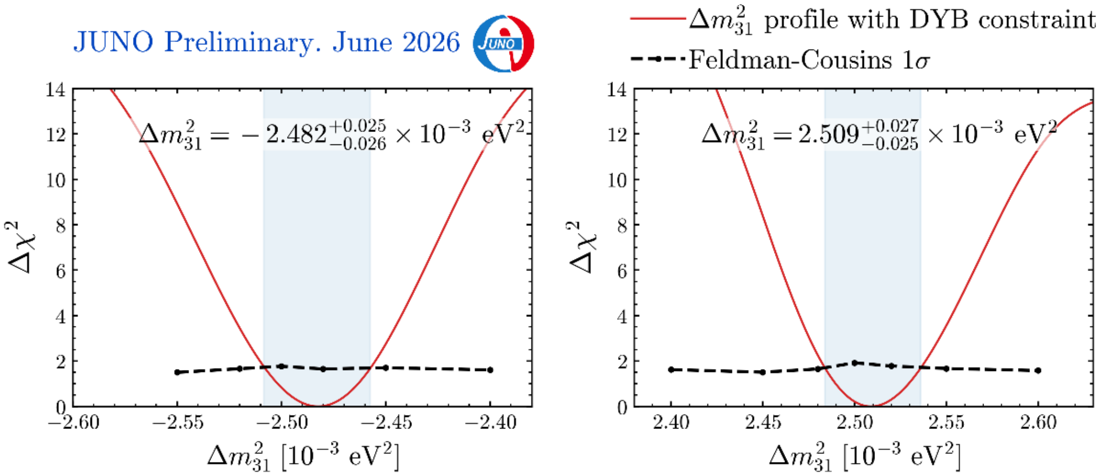




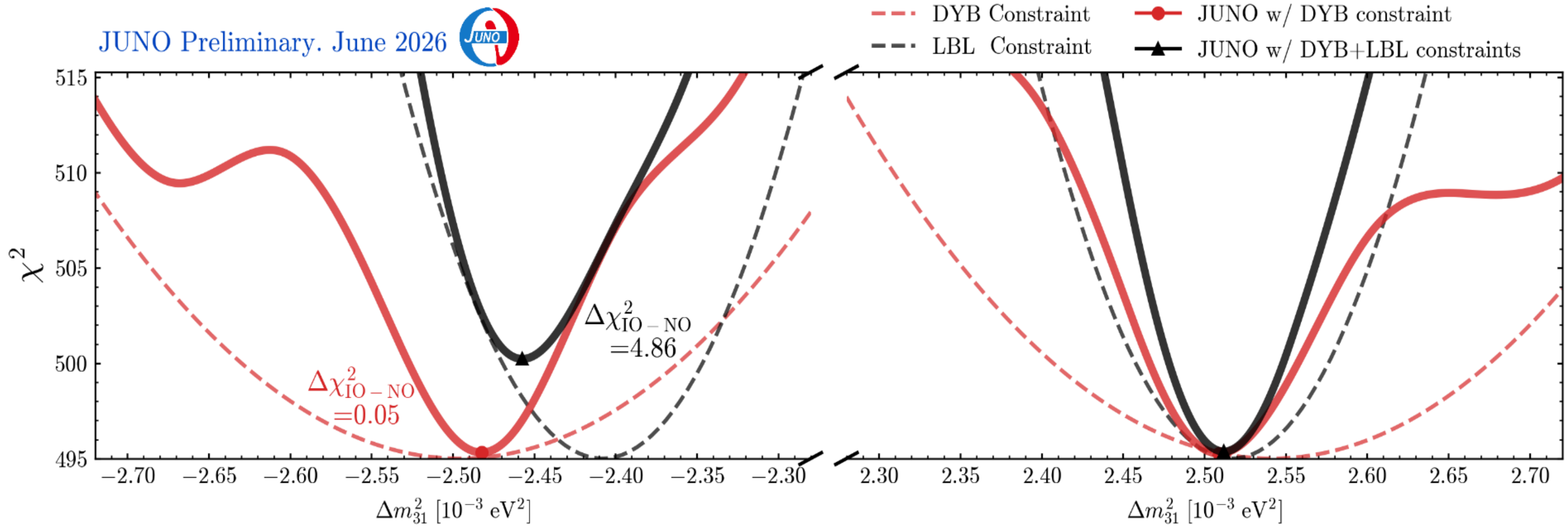
- **Enter precision era with JUNO!**
- **First observe geoneutrino at JUNO**

Δm^2_{21}	7.388±0.078 (1.60% → 1.06%)
$\sin^2\theta_{12}$	0.3036±0.0064 (2.8%→2.1%)

First indication of neutrino mass ordering

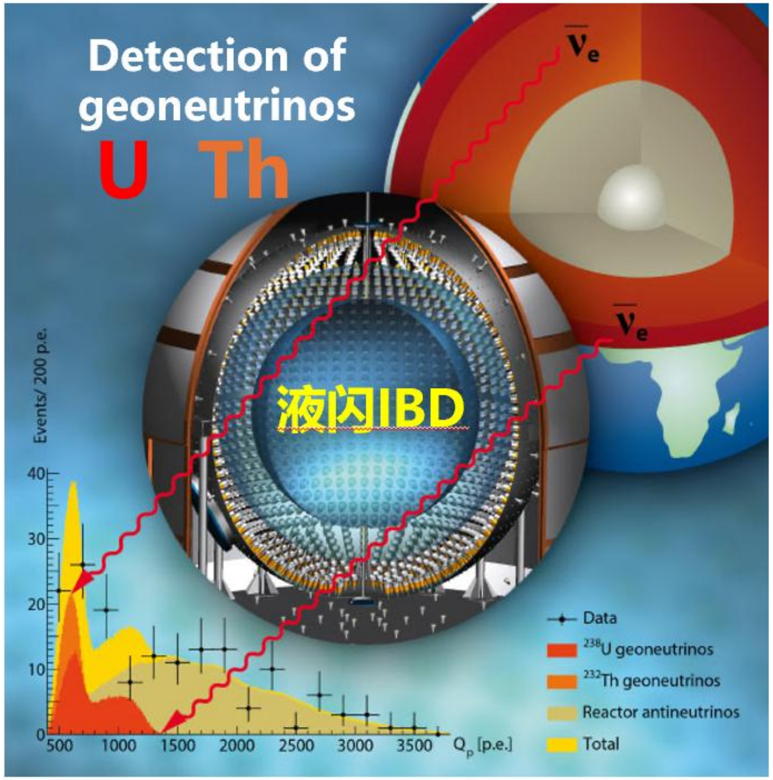


- **Adopt Δm^2_{31} from the NuFit-LBL results: normal mass ordering is favored at $\Delta\chi^2 = 4.86$ (2.3σ)**



Introduction of geoneutrinos

Geoneutrino is the electron antineutrino produced from beta decay of radioactive isotopes.



$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\alpha + 6e^- + 6\bar{\nu}_e + 51.7\ \mathrm{MeV}$$

$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.7\ \mathrm{MeV}$$

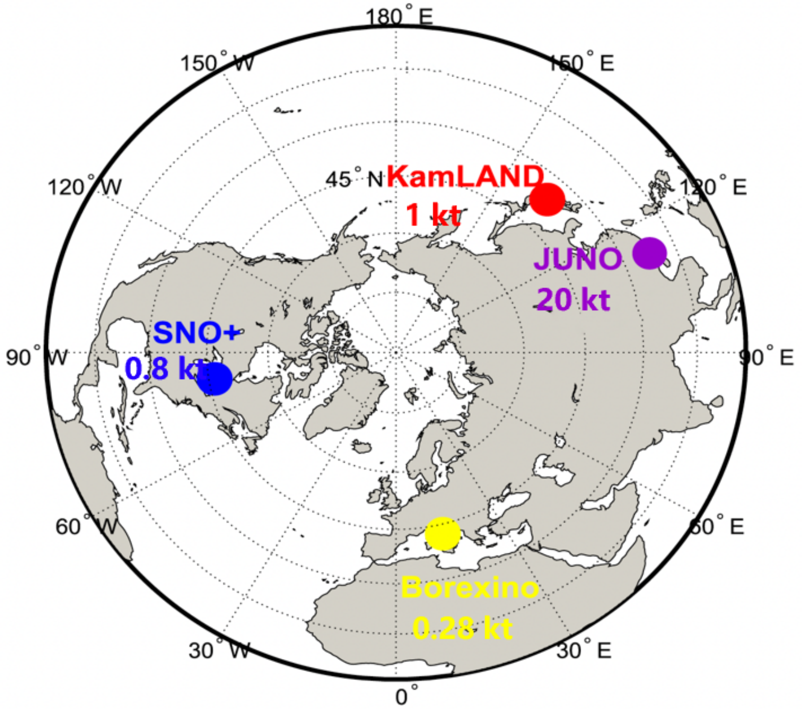
$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e^- + \bar{\nu}_e \qquad + 1.31\ \mathrm{MeV}$$

- **Measurements of the flux of geoneutrinos can constrain the distribution of heat-producing elements inside the Earth, and verify the geoscience models.**

Cover of Nature (28 July 2005)

Introduction of geoneutrinos

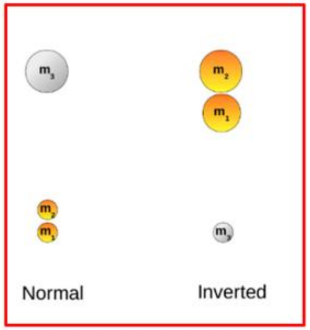
- ❑ There are four geoneutrino observatories in the world and those from Japan and Italy have been running for 20 years.
- ❑ **Limited by statistics and precision**, unable to distinguish geo models



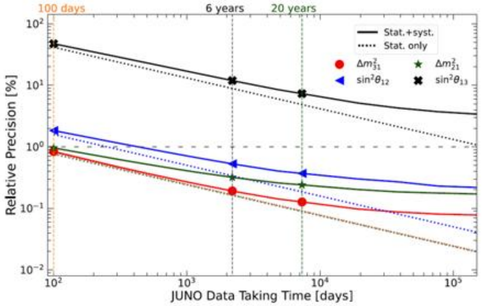
Exps.	Events
JUNO (2025)	~400/year
KamLAND (2002)	20/year
SNO+ (2022)	16/year
Borexino (2007)	4/year

More breakthroughs await your participation!

Mass ordering

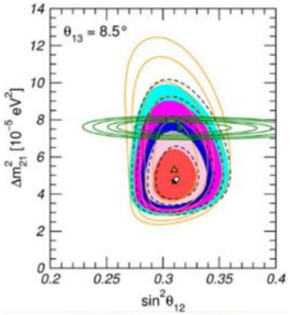


Precision measurement



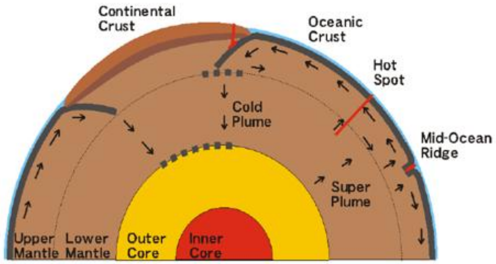
测量振荡参数到1%精度
3年

Solar neutrinos

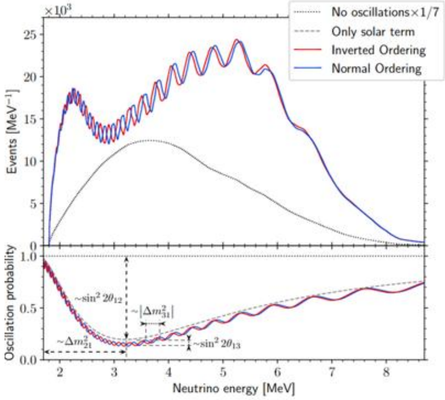


太阳中微子
3-5年

Geoneutrinos



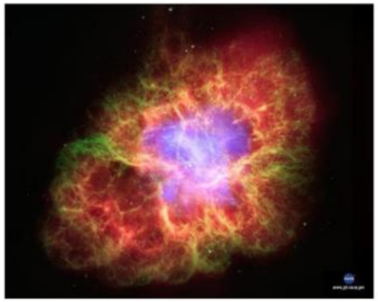
确定地球物理模型
6-10年



中微子质量顺序
~6年

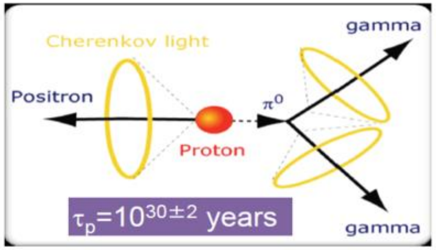
超新星背景中微子
3-5年

Diffuse Supernova Neutrino Background



等待超新星爆发
任何时间

Supernova neutrinos



探索核子衰变
5-10年

Proton decays

Thanks!

谢谢!

参考书

参考资料

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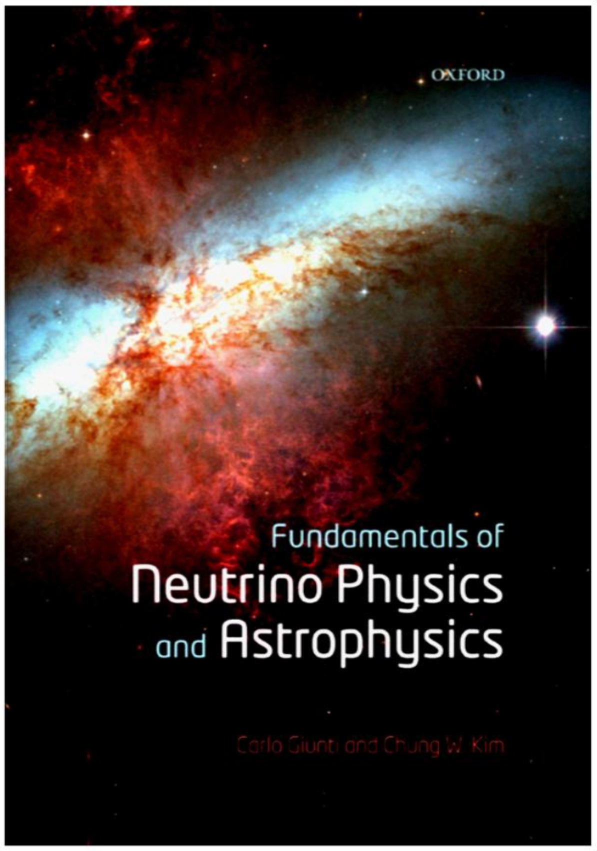
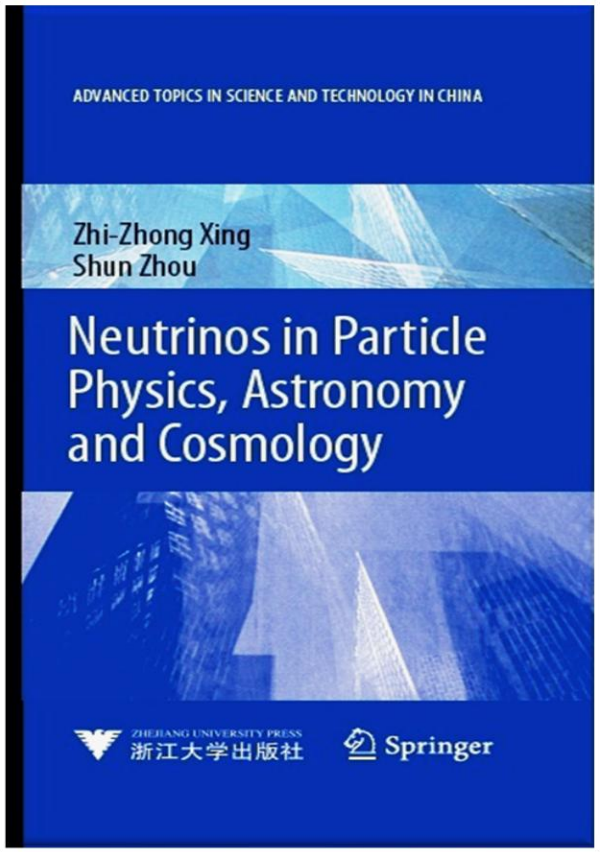
Z.Z. Xing & S. Zhou

A. Strumia & F. Vissani

hep-ph/0606054





- **文献搜索**
- http://inspirehep.net/
- https://arxiv.org/
- https://ui.adsabs.harvard.edu/

	Natural units	**Realistic units**
Phase factors	$\exp\left(-iE_{1,2}t\right)$	$\exp\left(-i\frac{E_{1,2}}{\hbar}t\right)$
Energies and momentum	$E_{1,2} = \sqrt{p^2 + m_{1,2}^2}$	$E_{1,2} = \sqrt{p^2c^2 + m_{1,2}^2c^4}$
Energy difference	$\Delta E = \frac{\Delta m^2}{2E}$	$\Delta E = \frac{\Delta m^2 c^3}{2p} = \frac{\Delta m^2 c^4}{2E}$
Time and distance	$t = L$	$t = \frac{L}{c}$
Oscillation argument	$\frac{1}{2}\Delta E t = \frac{\Delta m^2 L}{4E}$	$\frac{1}{2}\frac{\Delta E}{\hbar}t = \frac{c^3}{\hbar}\cdot\frac{\Delta m^2 L}{4E}$

In ν Oscillations Dirac = Majorana

Evolution of Amplitudes: $$i\,\frac{\mathrm{d}\psi_\alpha}{\mathrm{d}x} = \frac{1}{2E} \sum_\beta \left(U M^2 U^\dagger + 2EV \right)_{\alpha\beta} \psi_\beta$$

difference: $\begin{cases} \text{Dirac:} & U^{(\mathrm{D})} \\ \text{Majorana:} & U^{(\mathrm{M})} = U^{(\mathrm{D})} D(\lambda) \end{cases}$

$$D(\lambda) = \begin{pmatrix} 1 & 0 & \cdots & 0 \\ 0 & e^{i\lambda_{21}} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & e^{i\lambda_{N1}} \end{pmatrix} \quad \Rightarrow \quad D^\dagger = D^{-1}$$

$$M^2 = \begin{pmatrix} m_1^2 & 0 & \cdots & 0 \\ 0 & m_2^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & m_N^2 \end{pmatrix} \quad \Longrightarrow \quad DM^2 = M^2 D \quad \Longrightarrow \quad DM^2 D^\dagger = M^2$$

$$U^{(\mathrm{M})} M^2 (U^{(\mathrm{M})})^\dagger = U^{(\mathrm{D})} D M^2 D^\dagger (U^{(\mathrm{D})})^\dagger = U^{(\mathrm{D})} M^2 (U^{(\mathrm{D})})^\dagger$$

Common Question: Do Charged Leptons Oscillate?

- Mass is the only property which distinguishes e, μ, τ.
- The flavor of a charged lepton is defined by its mass!
- By definition, the flavor of a charged lepton cannot change.

THE FLAVOR OF CHARGED LEPTONS DOES NOT OSCILLATE

[CG, Kim, FPL 14 (2001) 213] [CG, hep-ph/0409230] [Akhmedov, JHEP 09 (2007) 116]