



United Nations
Educational, Scientific and
Cultural Organization



International
Year of Light
2015

*Fiat
lux!*

**Pure logical thinking cannot yield us
any knowledge of the empirical world;
all knowledge of reality starts from
experience and ends in it.**

A. Einstein (1933)

Нобелівська премія з фізики 2015



Такаакі Кадзіта

(Takaaki Kajita, University of Tokyo, Kashiwa, Japan)

Артуру Макдоналду

(Arthur B. McDonald, Queen's University, Kingston, Canada)

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



“за відкриття взаємних перетворень нейтрино, яке доводить, що нейтрино мають масу”

Семінар Тернопільського осередку УФТ, 19.11.2015 р.



Photo © Takaaki Kajita

Takaaki Kajita

Born: 1959, Higashimatsuyama,
Japan

**Affiliation at the time of the
award:** University of Tokyo,
Kashiwa, Japan;
Director of the Institute for
Cosmic Ray Research

Prize share: 1/2

"Takaaki Kajita - Facts". *Nobelprize.org*. Nobel
Media AB 2014. Web. 12 Nov 2015.
<[http://www.nobelprize.org/nobel_prizes/physics/lau
reates/2015/kajita-facts.html](http://www.nobelprize.org/nobel_prizes/physics/lau
reates/2015/kajita-facts.html)>



Colleagues of Takaaki Kajita give a banzai cheer Tuesday at their research facility in Hida, Gifu Prefecture, after learning he had won the Nobel Prize.



Born in Higashimatsuyama

Ph.D. from the University of Tokyo in 1986
(Doctoral advisor - Masatoshi Koshiba).

Director of the Institute for Cosmic Ray
Research and a professor at the University of
Tokyo.

Notable awards

Asahi Prize (1988)

Bruno Rossi Prize (1989)

Nishina Memorial Prize(1999)

Panofsky Prize (2002)

Japan Academy Prize(2012)

Nobel Prize in Physics(2015)

Fundamental Physics Prize (2016)



Arthur B. McDonald

Born: 1943, Sydney, Canada

Affiliation at the time of the award: Queen's University,
Kingston, Canada

Professor (Emeritus)

Prize share: 1/2

Photo: K. MacFarlane.
Queen's University
/SNOLAB

"Arthur B. McDonald - Facts". *Nobelprize.org*. Nobel Media AB 2014. Web. 13 Nov 2015.
<http://www.nobelprize.org/nobel_prizes/physics/laureates/2015/mcdonald-facts.html>

Position	Institution	Year
Professor Emeritus	Queen's University	2013 - Present
Director	Sudbury Neutrino Observatory Collaboration	1989 - Present
Gordon and Patricia Gray Chair in Particle Astrophysics	Queen's University	2006 - 2013
University Research Chair	Queen's University	2002 - 2006
Director	SNO Institute	1991-2003, 2006 - 2009
Associate Director	SNOLAB Institute	2009 - 2013
Professor	Queen's University	1989 - 2013
Professor	Princeton	1982 - 1989
Sr. Research Officer	Atomic Energy of Canada (Chalk River, Ontario)	1980 - 1982
Assoc. Research Officer	Chalk River	1975 - 1980
Assist. Research Officer	Chalk River	1970 - 1975
Postdoctoral Fellow	Chalk River	1969 - 1970

Education:

Dalhousie University, Halifax, Nova Scotia - B.Sc. Physics (1964)

Dalhousie University, Halifax, Nova Scotia - M.Sc. Physics (1965)

California Institute of Technology, Pasadena, CA, USA - Ph.D. Physics (1969)

Visiting Positions:

CERN, Geneva (2004), University of Hawaii (2004, 2009), Affiliate Graduate Faculty, University of Hawaii (2010-), Oxford University (2003, 2009), University of Washington, Seattle (1978), Los Alamos National Laboratory (1981), Queen's University (1988)

Awards:

Governor General's Gold Medal, Dalhousie, 1964

Rutherford Memorial Fellowship, (1969-1970)

Fellow of the American Physical Society, 1983

LL.D., *honoris causa*, Dalhousie, 1997

Fellow of Royal Society of Canada, 1997

Honorary Life Membership at Science North, Sudbury, Ontario, 1997

Killam Research Fellowship, 1998

LL.D., *honoris causa*, University College of Cape Breton, 1999

D. Sc., *honoris causa*, Royal Military College, 2001

T.W. Bonner Prize in Nuclear Physics from the American Physical Society, 2003

Canadian Association of Physicists Medal for Lifetime Achievement in Physics, 2003

Natural Sciences and Engineering Research Council of Canada Award of Excellence, 2003

Gerhard Herzberg Canada Gold Medal for Science and Engineering, 2003

UK-Canada Rutherford Lecturer for the Royal Society, 2003

Welsh Lecturer at the University of Toronto, 2004

Basterfield Lecturer at the University of Regina, 2004

Sigma Xi Fund of Canada Award for Scientific Achievement, 2004

Bruno Pontecorvo Prize in Particle Physics, JINR, Dubna, 2005

Manne Siegbahn Lecturer at Stockholm University, 2005
E.W. Guptill Lecturer at Dalhousie University, 2005
Helmut Baer Lecturer at University of Michigan, 2006
D. Sc., *honoris causa*, University of Chicago, 2006
NSERC John C. Polanyi Award to the SNO team, 2006
Officer of the Order of Canada, 2006
Co-recipient, Benjamin Franklin Medal in Physics, 2007
Donald R. Hamilton Lecturer at Princeton University, 2008
Huggins Science Lecturer at Acadia University, 2008
LL.D., *honoris causa*, Saint Francis Xavier University, 2009
Fellow of the Royal Society of the UK and the Commonwealth, 2009
Member of Canadian Science and Engineering Hall of Fame, 2009
Killam Prize in the Natural Sciences, 2010
Member of the Nova Scotia Discovery Centre Hall of Fame, 2010
E. Segre Lecture, Berkeley, 2010
D. Sc., *honoris causa*, University of Alberta, 2011
Guelph Waterloo Physics Institute Distinguished Lecturer, 2011
Henry Marshall Tory Medal, Royal Society of Canada, 2011
D. Sc., *honoris causa*, University of Waterloo, 2012
Order of Ontario, 2012
European Physics Society HEP Division Giuseppe and Vanna Cocconi Prize, 2013
Co-recipient, The Nobel Prize in Physics, 2015

Evidence for Oscillation of Atmospheric Neutrinos

Y. Fukuda,¹ T. Hayakawa,¹ E. Ichihara,¹ K. Inoue,¹ K. Ishihara,¹ H. Ishino,¹ Y. Itow,¹ T. Kajita,¹ J. Kameda,¹
S. Kasuga,¹ K. Kobayashi,¹ Y. Kobayashi,¹ Y. Koshio,¹ M. Miura,¹ M. Nakahata,¹ S. Nakayama,¹ A. Okada,¹
K. Okumura,¹ N. Sakurai,¹ M. Shiozawa,¹ Y. Suzuki,¹ Y. Takeuchi,¹ Y. Totsuka,¹ S. Yamada,¹ M. Earl,² A. Habig,²
E. Kearns,² M. D. Messier,² K. Scholberg,² J. L. Stone,² L. R. Sulak,² C. W. Walter,² M. Goldhaber,³ T. Barszczak,⁴
D. Casper,⁴ W. Gajewski,⁴ P. G. Halverson,^{4,*} J. Hsu,⁴ W. R. Kropp,⁴ L. R. Price,⁴ F. Reines,⁴ M. Smy,⁴ H. W. Sobel,⁴
M. R. Vagins,⁴ K. S. Ganezer,⁵ W. E. Keig,⁵ R. W. Ellsworth,⁶ S. Tasaka,⁷ J. W. Flanagan,^{8,†} A. Kibayashi,⁸
J. G. Learned,⁸ S. Matsuno,⁸ V. J. Stenger,⁸ D. Takemori,⁸ T. Ishii,⁹ J. Kanzaki,⁹ T. Kobayashi,⁹ S. Mine,⁹
K. Nakamura,⁹ K. Nishikawa,⁹ Y. Oyama,⁹ A. Sakai,⁹ M. Sakuda,⁹ O. Sasaki,⁹ S. Echigo,¹⁰ M. Kohama,¹⁰
A. T. Suzuki,¹⁰ T. J. Haines,^{11,4} E. Blaufuss,¹² B. K. Kim,¹² R. Sanford,¹² R. Svoboda,¹² M. L. Chen,¹³ Z. Conner,^{13,‡}
J. A. Goodman,¹³ G. W. Sullivan,¹³ J. Hill,¹⁴ C. K. Jung,¹⁴ K. Martens,¹⁴ C. Mauger,¹⁴ C. McGrew,¹⁴ E. Sharkey,¹⁴
B. Viren,¹⁴ C. Yanagisawa,¹⁴ W. Doki,¹⁵ K. Miyano,¹⁵ H. Okazawa,¹⁵ C. Saji,¹⁵ M. Takahata,¹⁵ Y. Nagashima,¹⁶
M. Takita,¹⁶ T. Yamaguchi,¹⁶ M. Yoshida,¹⁶ S. B. Kim,¹⁷ M. Etoh,¹⁸ K. Fujita,¹⁸ A. Hasegawa,¹⁸ T. Hasegawa,¹⁸
S. Hatakeyama,¹⁸ T. Iwamoto,¹⁸ M. Koga,¹⁸ T. Maruyama,¹⁸ H. Ogawa,¹⁸ J. Shirai,¹⁸ A. Suzuki,¹⁸ F. Tsushima,¹⁸
M. Koshiya,¹⁹ M. Nemoto,²⁰ K. Nishijima,²⁰ T. Futagami,²¹ Y. Hayato,^{21,§} Y. Kanaya,²¹ K. Kaneyuki,²¹
Y. Watanabe,²¹ D. Kielczewska,^{22,4} R. A. Doyle,²³ J. S. George,²³ A. L. Stachyra,²³ L. L. Wai,^{23,||}
R. J. Wilkes,²³ and K. K. Young²³
(Super-Kamiokande Collaboration)



(Super-Kamiokande Collaboration)

¹*Institute for Cosmic Ray Research, University of Tokyo, Tanashi, Tokyo, 188-8502, Japan*

²*Department of Physics, Boston University, Boston, Massachusetts 02215*

³*Physics Department, Brookhaven National Laboratory, Upton, New York 11973*

⁴*Department of Physics and Astronomy, University of California at Irvine, Irvine, California 92697-4575*

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⁹*Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK),
Tsukuba, Ibaraki 305-0801, Japan*

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¹¹*Physics Division, P-23, Los Alamos National Laboratory, Los Alamos, New Mexico 87544*

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¹⁴*Department of Physics and Astronomy, State University of New York, Stony Brook, New York 11794-3800*

¹⁵*Department of Physics, Niigata University, Niigata, Niigata 950-2181, Japan*

¹⁶*Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan*

¹⁷*Department of Physics, Seoul National University, Seoul 151-742, Korea*

¹⁸*Department of Physics, Tohoku University, Sendai, Miyagi 980-8578, Japan*

¹⁹*The University of Tokyo, Tokyo 113-0033, Japan*

²⁰*Department of Physics, Tokai University, Hiratsuka, Kanagawa 259-1292, Japan*

²¹*Department of Physics, Tokyo Institute of Technology, Meguro, Tokyo 152-8551, Japan*

²²*Institute of Experimental Physics, Warsaw University, 00-681 Warsaw, Poland*

²³*Department of Physics, University of Washington, Seattle, Washington 98195-1560*

**Measurement of the Rate of $\nu_e + d \rightarrow p + p + e^-$ Interactions Produced
by ^8B Solar Neutrinos at the Sudbury Neutrino Observatory**

Q. R. Ahmad,¹⁵ R. C. Allen,¹¹ T. C. Andersen,¹² J. D. Anglin,⁷ G. Bühler,¹¹ J. C. Barton,^{13,*} E. W. Beier,¹⁴
M. Bercovitch,⁷ J. Bigu,⁴ S. Biller,¹³ R. A. Black,¹³ I. Blevis,³ R. J. Boardman,¹³ J. Boger,² E. Bonvin,⁹ M. G. Boulay,⁹
M. G. Bowler,¹³ T. J. Bowles,⁶ S. J. Brice,^{6,13} M. C. Browne,¹⁵ T. V. Bullard,¹⁵ T. H. Burritt,^{15,6} K. Cameron,¹²
J. Cameron,¹³ Y. D. Chan,⁵ M. Chen,⁹ H. H. Chen,^{11,†} X. Chen,^{5,13} M. C. Chon,¹² B. T. Cleveland,¹³ E. T. H. Clifford,^{9,1}
J. H. M. Cowan,⁴ D. F. Cowen,¹⁴ G. A. Cox,¹⁵ Y. Dai,⁹ X. Dai,¹³ F. Dalnoki-Veress,³ W. F. Davidson,⁷ P. J. Doe,^{15,11,6}
G. Doucas,¹³ M. R. Dragowsky,^{6,5} C. A. Duba,¹⁵ F. A. Duncan,⁹ J. Dunmore,¹³ E. D. Earle,^{9,1} S. R. Elliott,^{15,6}
H. C. Evans,⁹ G. T. Ewan,⁹ J. Farine,³ H. Fergani,¹³ A. P. Ferraris,¹³ R. J. Ford,⁹ M. M. Fowler,⁶ K. Frame,¹³
E. D. Frank,¹⁴ W. Frati,¹⁴ J. V. Germani,^{15,6} S. Gil,¹⁰ A. Goldschmidt,⁶ D. R. Grant,³ R. L. Hahn,² A. L. Hallin,⁹
E. D. Hallman,⁴ A. Hamer,^{6,9} A. A. Hamian,¹⁵ R. U. Haq,⁴ C. K. Hargrove,³ P. J. Harvey,⁹ R. Hazama,¹⁵ R. Heaton,⁹
K. M. Heeger,¹⁵ W. J. Heintzelman,¹⁴ J. Heise,¹⁰ R. L. Helmer,^{10,‡} J. D. Hepburn,^{9,1} H. Heron,¹³ J. Hewett,⁴
A. Hime,⁶ M. Howe,¹⁵ J. G. Hykawy,⁴ M. C. P. Isaac,⁵ P. Jagam,¹² N. A. Jelley,¹³ C. Jillings,⁹ G. Jonkmans,^{4,1}
J. Karn,¹² P. T. Keener,¹⁴ K. Kirch,⁶ J. R. Klein,¹⁴ A. B. Knox,¹³ R. J. Komar,^{10,9} R. Kouzes,⁸ T. Kutter,¹⁰
C. C. M. Kyba,¹⁴ J. Law,¹² I. T. Lawson,¹² M. Lay,¹³ H. W. Lee,⁹ K. T. Lesko,⁵ J. R. Leslie,⁹ I. Levine,³ W. Locke,¹³
M. M. Lowry,⁸ S. Luoma,⁴ J. Lyon,¹³ S. Majerus,¹³ H. B. Mak,⁹ A. D. Marino,⁵ N. McCauley,¹³ **A. B. McDonald,^{9,8}**
D. S. McDonald,¹⁴ K. McFarlane,³ G. McGregor,¹³ W. McLatchie,⁹ R. Meijer Drees,¹⁵ H. Mes,³ C. Mifflin,³
G. G. Miller,⁶ G. Milton,¹ B. A. Moffat,⁹ M. Moorhead,^{13,5} C. W. Nally,¹⁰ M. S. Neubauer,¹⁴ F. M. Newcomer,¹⁴
H. S. Ng,¹⁰ A. J. Noble,^{3,‡} E. B. Norman,⁵ V. M. Novikov,³ M. O'Neill,³ C. E. Okada,⁵ R. W. Ollerhead,¹²
M. Omori,¹³ J. L. Orrell,¹⁵ S. M. Oser,¹⁴ A. W. P. Poon,^{5,6,10,15} T. J. Radcliffe,⁹ A. Roberge,⁴ B. C. Robertson,⁹
R. G. H. Robertson,^{15,6} J. K. Rowley,² V. L. Rusu,¹⁴ E. Saettler,⁴ K. K. Schaffer,¹⁵ A. Schuelke,⁵ M. H. Schwendener,⁴
H. Seifert,^{4,6,15} M. Shatkay,³ J. J. Simpson,¹² D. Sinclair,³ P. Skensved,⁹ A. R. Smith,⁵ M. W. E. Smith,¹⁵ N. Starinsky,³
T. D. Steiger,¹⁵ R. G. Stokstad,⁵ R. S. Storey,^{7,†} B. Sur,^{1,9} R. Tafirout,⁴ N. Tagg,¹² N. W. Tanner,¹³ R. K. Taplin,¹³
M. Thorman,¹³ P. Thomewell,^{6,13,15} P. T. Trent,^{13,*} Y. I. Tserkovnyak,¹⁰ R. Van Berg,¹⁴ R. G. Van de Water,^{14,6}
C. J. Virtue,⁴ C. E. Waltham,¹⁰ J.-X. Wang,¹² D. L. Wark,^{13,6,§} N. West,¹³ J. B. Wilhelmy,⁶ J. F. Wilkerson,^{15,6}
J. Wilson,¹³ P. Wittich,¹⁴ J. M. Wouters,⁶ and M. Yeh²

(SNO Collaboration)



(SNO Collaboration)

¹Atomic Energy of Canada Limited, Chalk River Laboratories, Chalk River, Ontario K0J 1J0 Canada

²Chemistry Department, Brookhaven National Laboratory, Upton, New York 11973-5000

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⁵Institute for Nuclear and Particle Astrophysics and Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720

⁶Los Alamos National Laboratory, Los Alamos, New Mexico 87545

⁷National Research Council of Canada, Ottawa, Ontario K1A 0R6 Canada

⁸Department of Physics, Princeton University, Princeton, New Jersey 08544

⁹Department of Physics, Queen's University, Kingston, Ontario K7L 3N6 Canada

¹⁰Department of Physics and Astronomy, University of British Columbia, Vancouver, BC V6T 1Z1 Canada

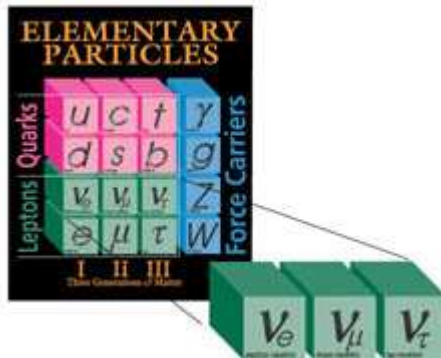
¹¹Department of Physics, University of California, Irvine, California 92717

¹²Physics Department, University of Guelph, Guelph, Ontario N1G 2W1 Canada

¹³Nuclear and Astrophysics Laboratory, University of Oxford, Keble Road, Oxford, OX1 3RH, United Kingdom

¹⁴Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104-6396

¹⁵Center for Experimental Nuclear Physics and Astrophysics, and Department of Physics, University of Washington, Seattle, Washington 98195



Brief History of the Neutrino

1931 – Вольфганг Паулі припустив існування гіпотетичної частинки для пояснення енергетичного балансу радіоактивних розпадів.

1934 - Енріко Фермі розвинув теорію радіоактивних розпадів, в якій ввів термін “нейтрино”

1959 – Нейтрино було експериментально зафіксовано Кованом та Райнсом (1995 Nobel Prize in physics)

1962 – Експериментально відкрито інший вид нейтрино – мюонне нейтрино (Brookhaven National Laboratory та CERN).

1968 - Перші експерименти з вивчення сонячних нейтрино показали можливість їх перетворення

1978 – Відкриті тау-нейтрино (Stanford Linear Accelerator Center)

1985 – Зроблено припущення про ненульову масу нейтрино

1987 - Початок експериментальних досліджень з нейтрино в Kamiokande (burst of neutrinos from Supernova 1987A).

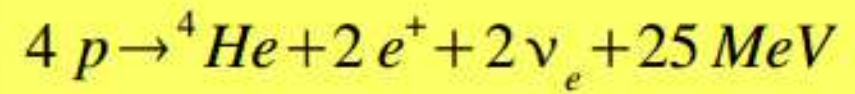
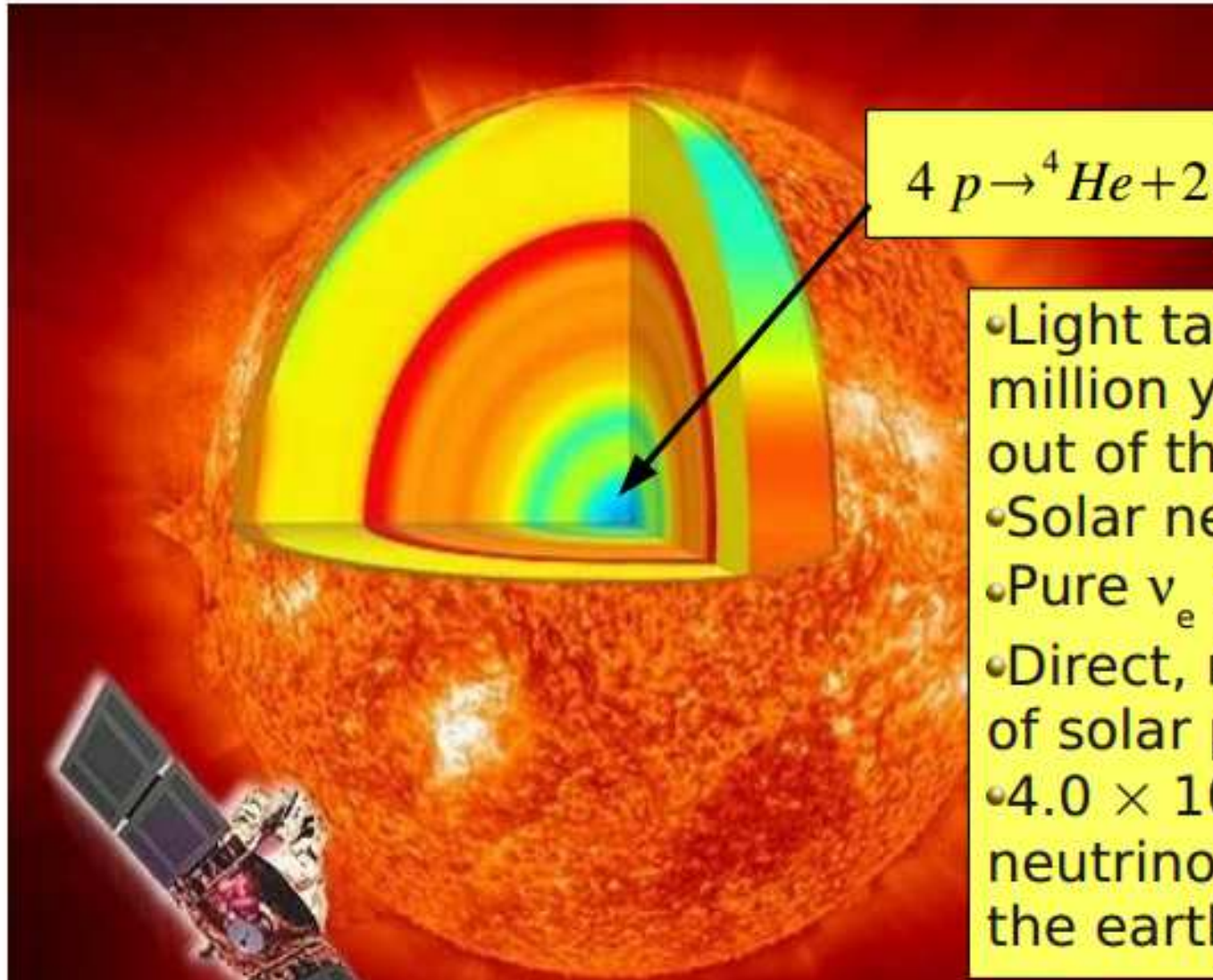
1989 – Експерименти в CERN (Large Electron-Positron) показали, що є лише три види нейтрино

1989 - Kamiokande вперше досліджує сонячні нейтрино

1996 – Початок експериментів на Super-Kamiokande.

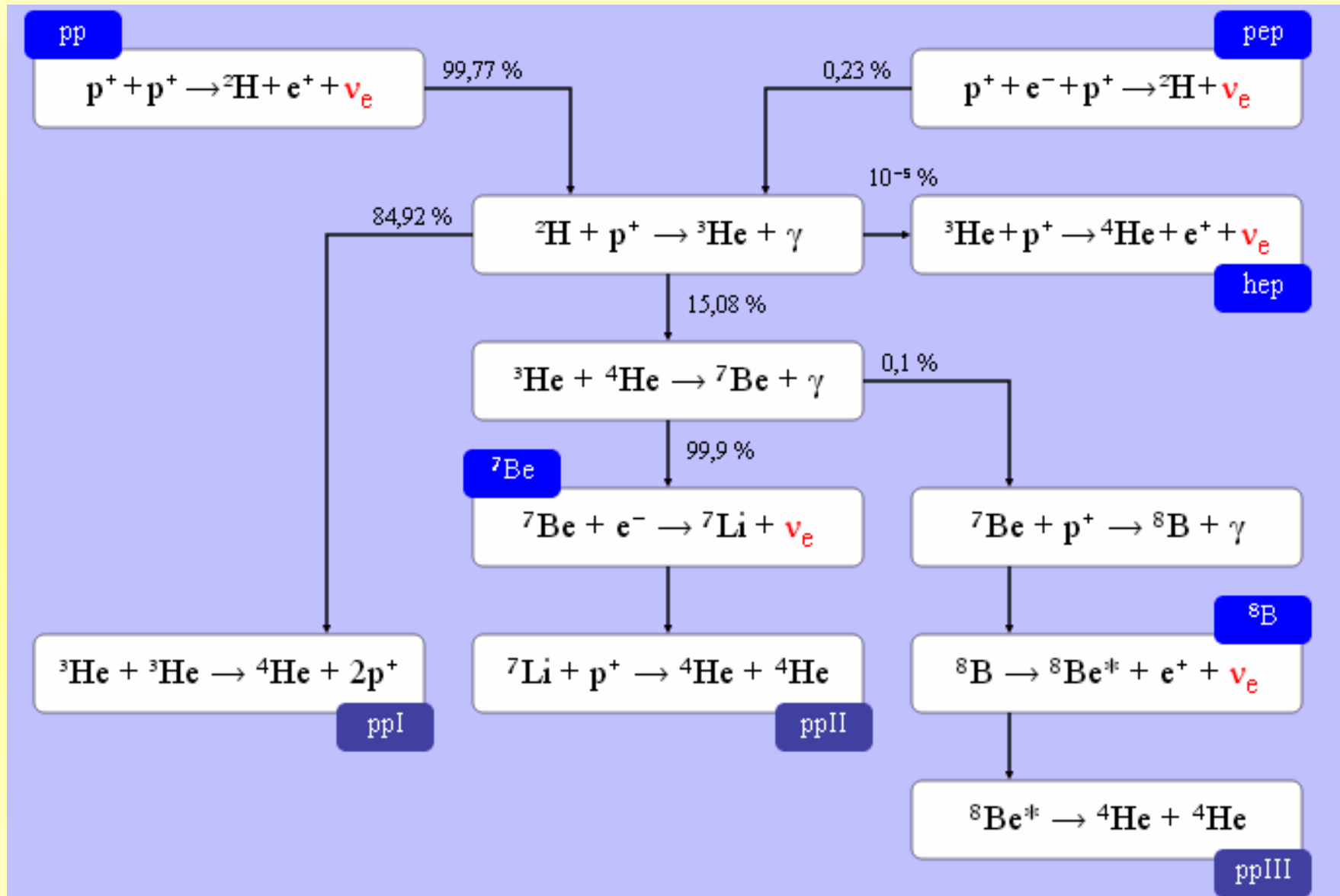
1997 - Super-Kamiokande reports a deficit of cosmic-ray muon neutrinos and solar electron neutrinos

How the Sun burns



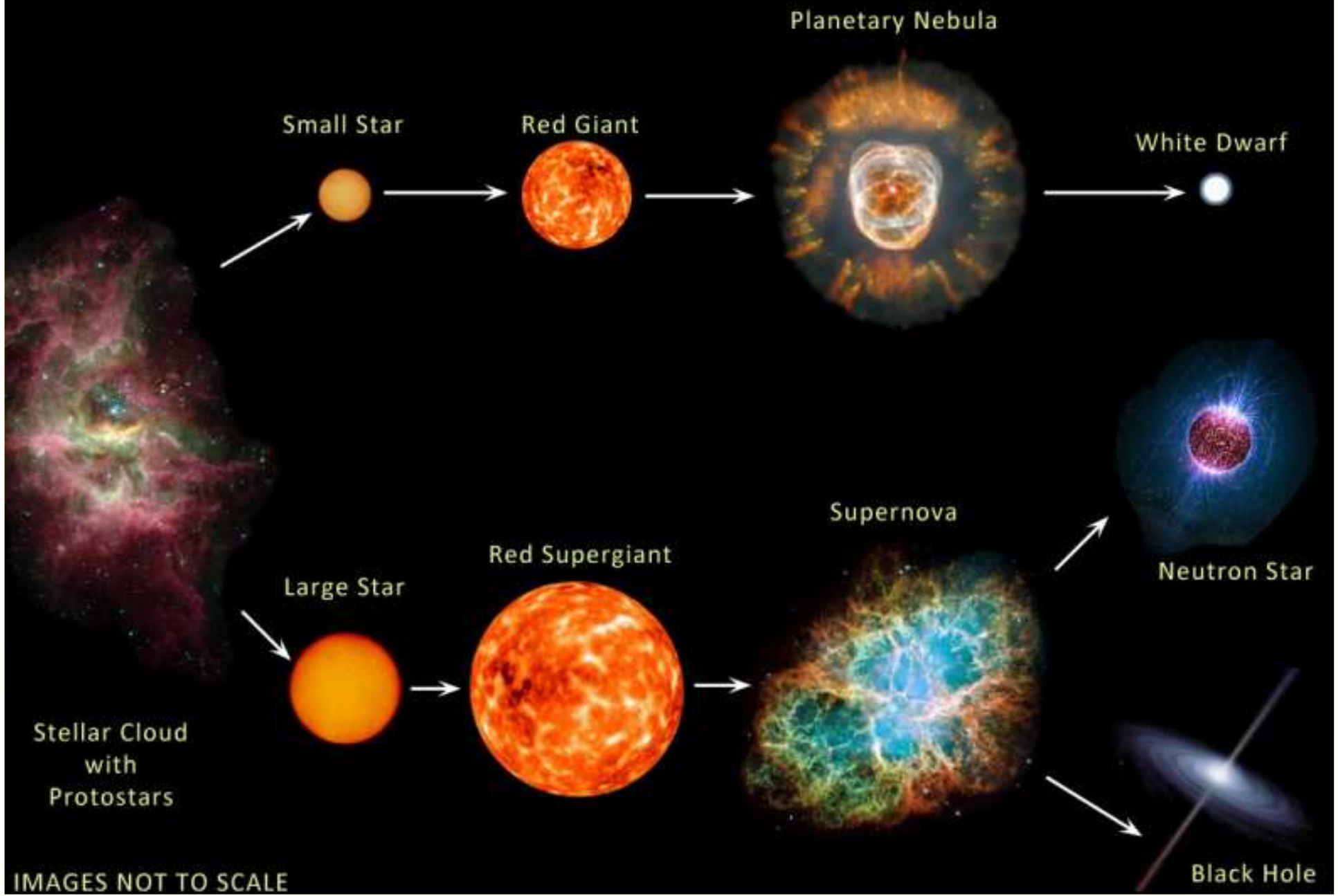
- Light takes about a million years to get out of the solar core
- Solar neutrinos take 2 s
- Pure ν_e source
- Direct, real-time probe of solar processes
- 4.0×10^{10} solar neutrinos / cm^2 / sec at the earth

Standard solar model



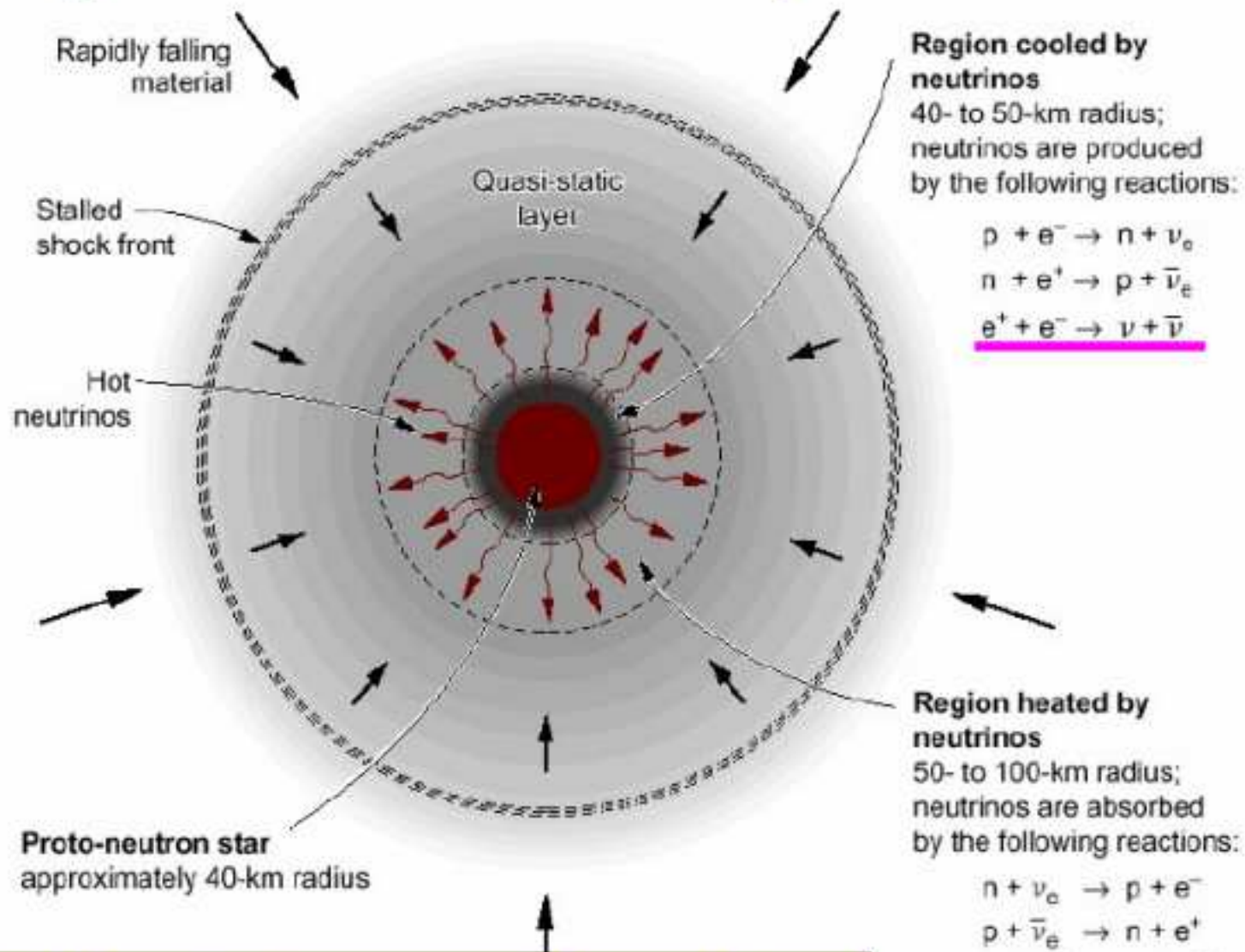
"Proton proton cycle" by Dorottya Szam - file:Proton proton cycle.png. Licensed under CC BY 2.5 via Commons - https://commons.wikimedia.org/wiki/File:Proton_proton_cycle.svg#/media/File:Proton_proton_cycle.svg

EVOLUTION OF STARS

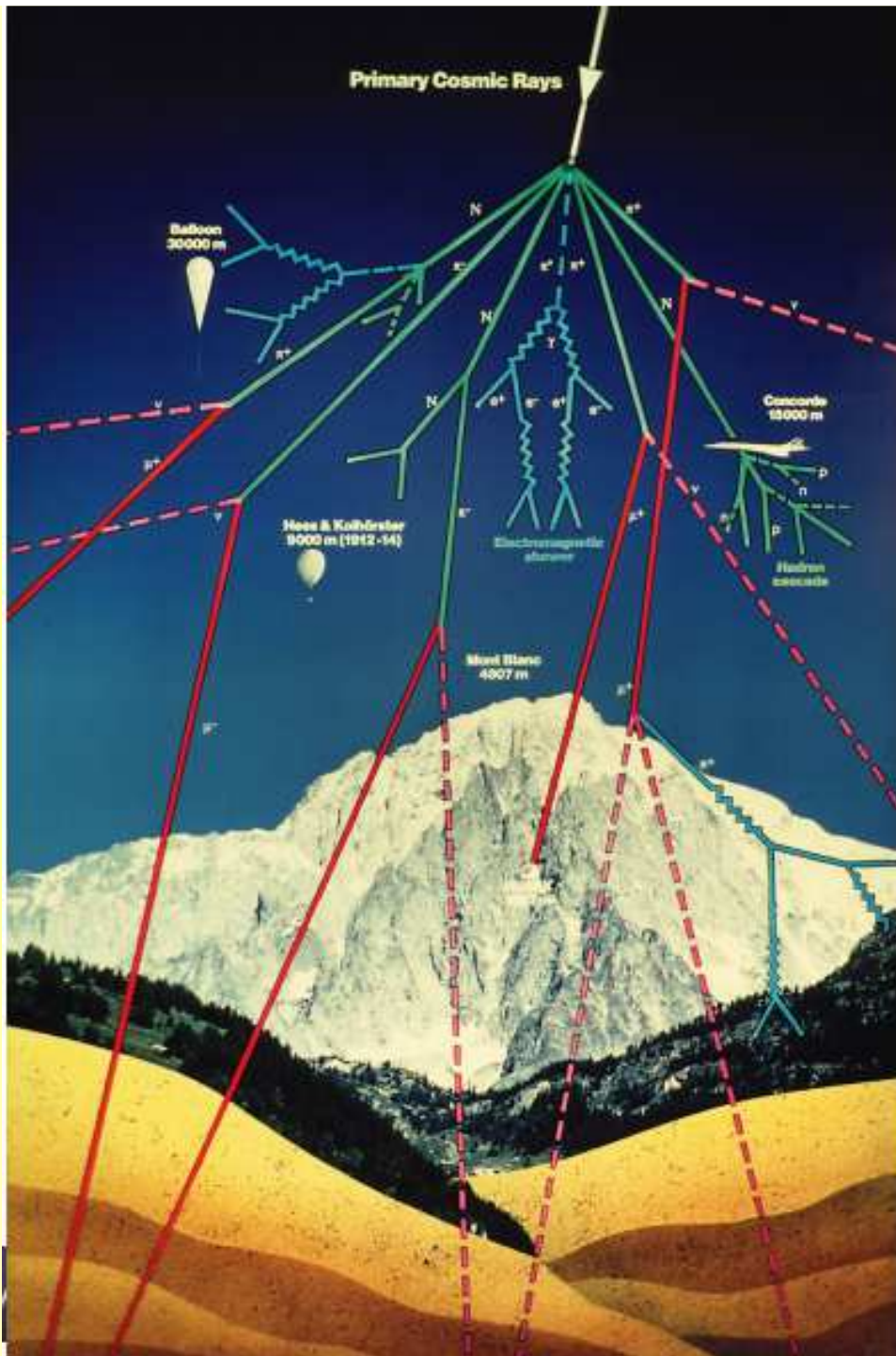


IMAGES NOT TO SCALE

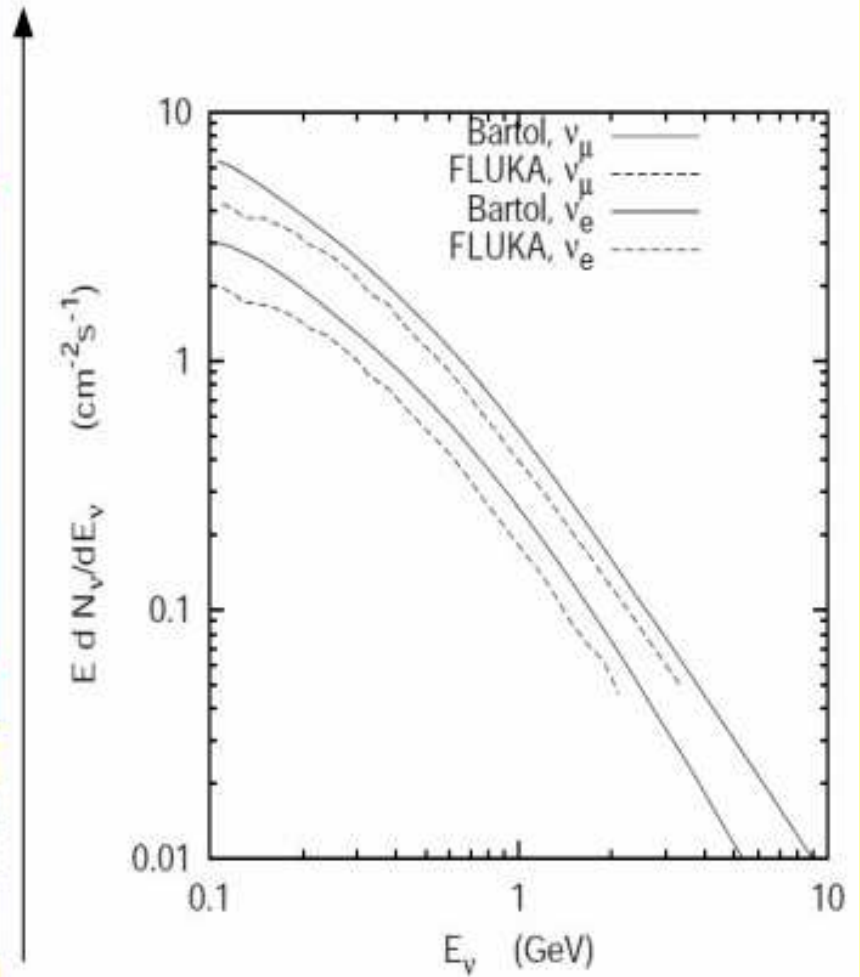
SuperNova Collapse



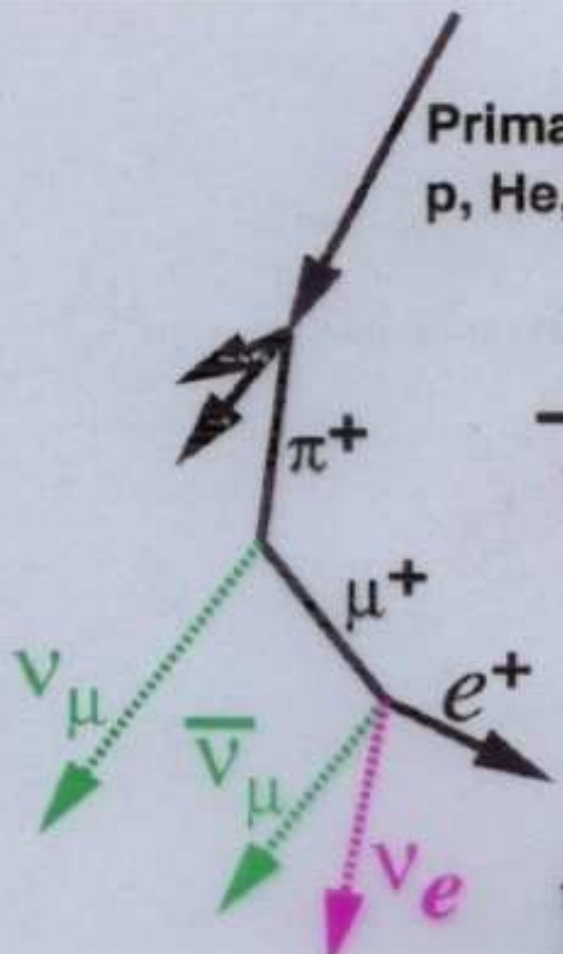
SN is "a gravity powered neutrino explosion"



30 km



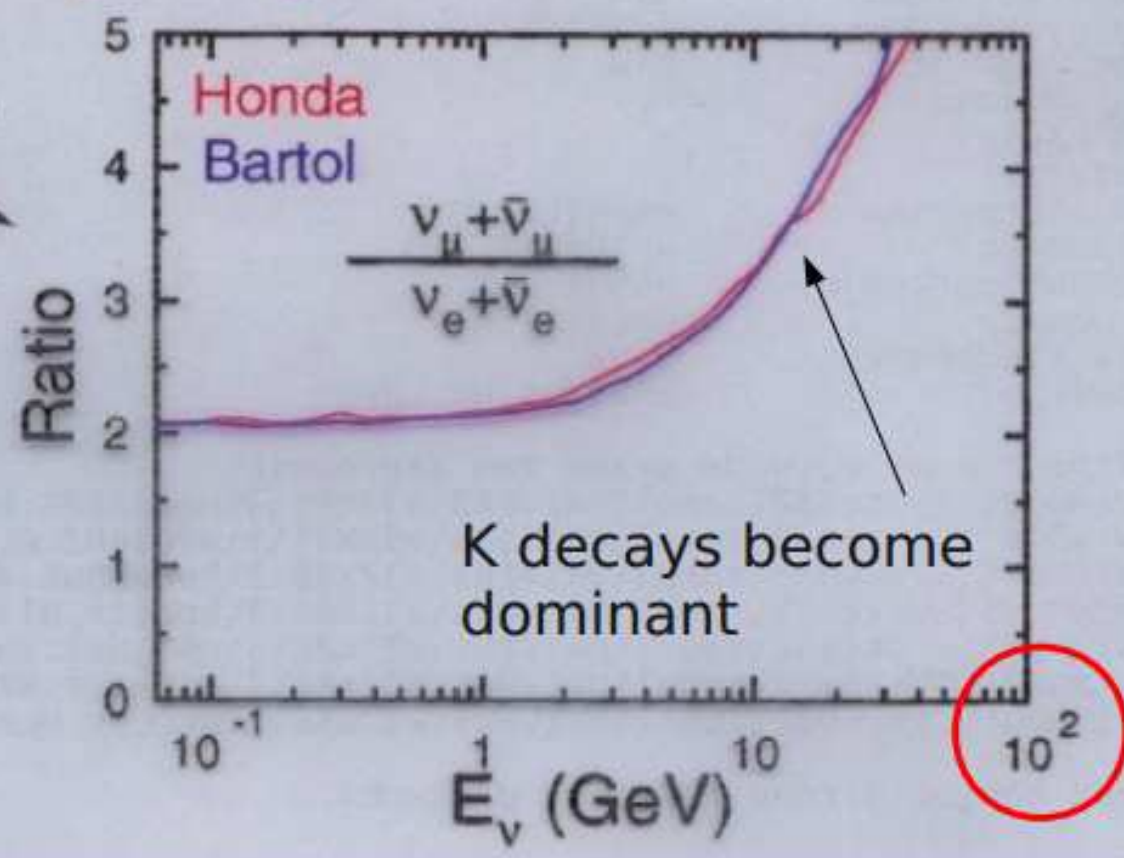
PX435 – ν Physics



Primary cosmic ray
p, He, ...

ν Flux ~20% uncertain

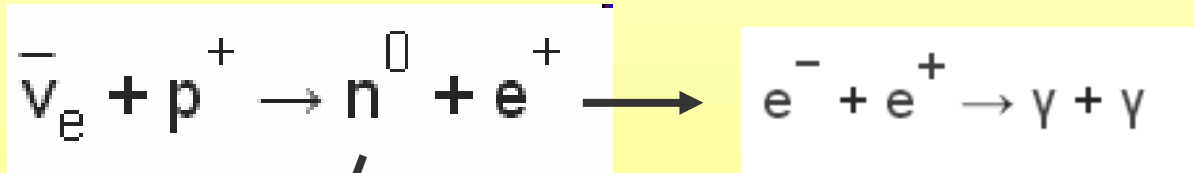
$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \cong 2 \quad 5\% \text{ uncertain}$$



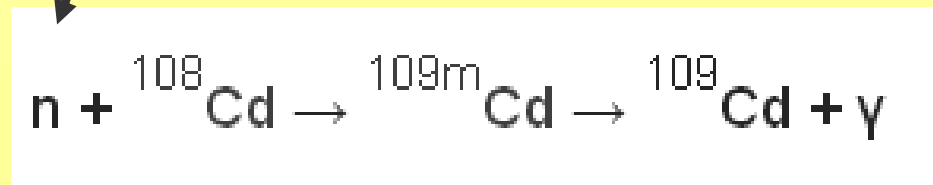
K decays become dominant

Детектування нейтрино

Бета-захоплення (Кан-Чанг Ванг, 1942)



Wang Ganchang
(1907-1998)



Клайд Ковен



Фредерік Райнс

1956 (Los Alamos, Hanford, Savannah)

Нобелівська премія 1995

"for the detection of the neutrino and pioneering experimental contributions to lepton physics"



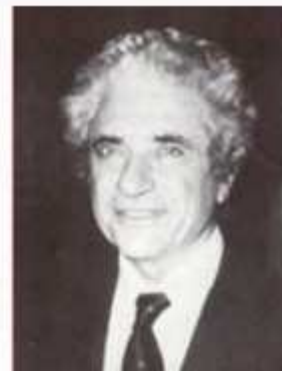
1962



Leon M. Lederman
Fermi National
Accelerator
Laboratory,
Batavia, Illinois, USA



Melvin Schwartz
Digital Pathways Inc.,
Mountain View,
California, USA



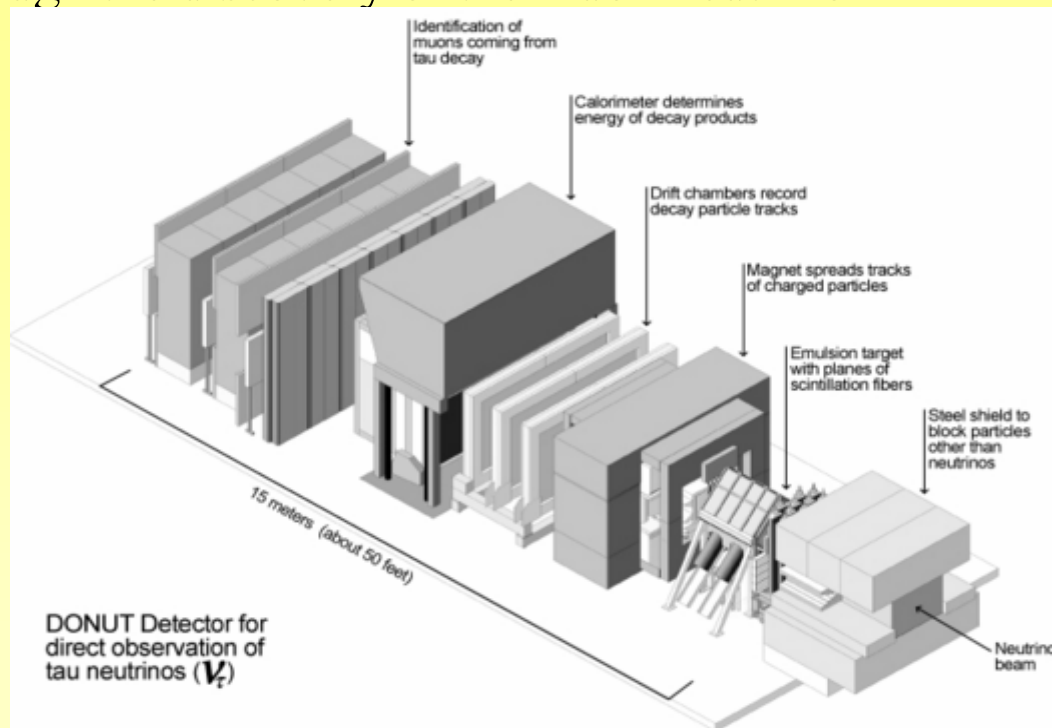
Jack Steinberger
CERN,
Geneva, Switzerland

1988 Nobel Prize in Physics "for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino"

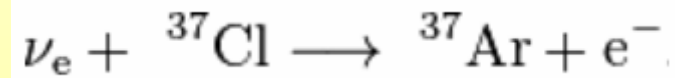


1997-2000

Direct Observation of the NU Tau (DONUT) collaboration



Homestake experiment та *Solar neutrino problem*



Raymond Davis, Jr.
(1914-2006)



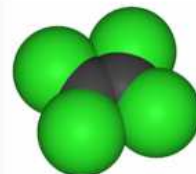
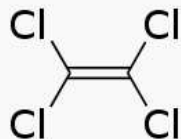
John N. Bahcall
(1934-2005)



Нобелівська премія 2002
"for pioneering contributions
to astrophysics, in particular for the
detection of cosmic neutrinos"

Разом з Masatoshi Koshiba
(Kamiokande II)

Tetrachloroethylene



Гіпотеза про перетворення нейтрино

MESONIUM AND ANTIMESONIUM

B. PONTECORVO

Joint Institute for Nuclear Research

Submitted to JETP editor May 23, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) 33, 549-551 (August, 1957)



Bruno Pontecorvo
(1913-1993)

It was assumed above that there exists a conservation law for the neutrino charge, according to which a neutrino cannot change into an antineutrino in any approximation. This law has not yet been established; evidently it has been merely shown that the neutrino and the antineutrino are not identical particles.⁹ If the two-component neutrino theory¹⁰ should turn out to be incorrect (which at present seems to be rather improbable) and if the conservation law of neutrino charge would not apply, then in principle neutrino \rightarrow antineutrino transitions could take place in vacuo. Even in this case, as well as in the case where one assumes that to every world there exists an antiworld, the number of neutrinos and antineutrinos in the universe would have to be the same.

⁹R. Davis, Bull. Am. Phys. Soc. II 1, 219 (1956); M. Awschalom, Phys. Rev. 101, 1041 (1956).

¹⁰L. Landau, J. Exptl. Theoret. Phys. (U.S.S.R.) 32, 407 (1957); Soviet Phys. JETP 5, 337 (1957); T. D. Lee and C. N. Yang, Phys. Rev. 105, 1671 (1957).

Матриця Понтекорво - Макі - Накагави - Сакати (1962)

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

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$c_{ij} = \cos \theta_{ij} \text{ и } s_{ij} = \sin \theta_{ij}$$

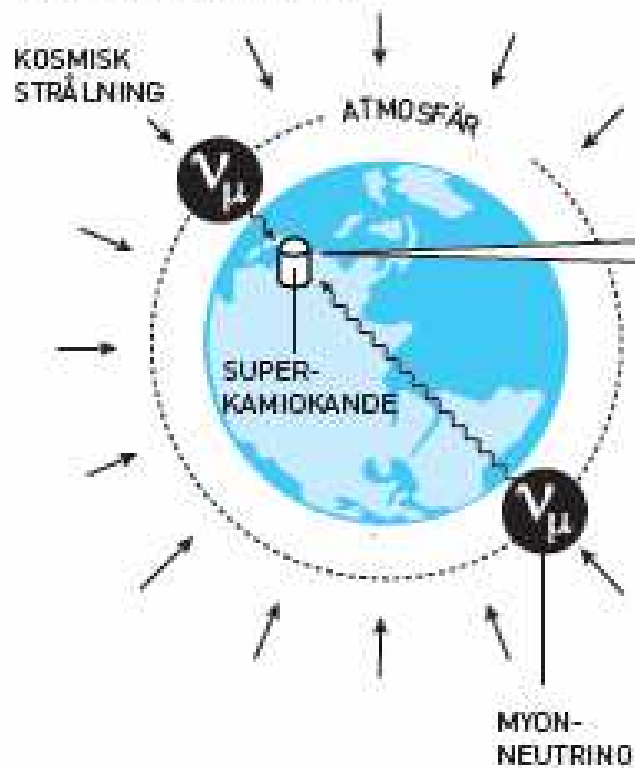
As of July 2014, the current best directly measured values are:

$$\sin^2 2\theta_{12} = 0.857 \pm 0.024$$

$$\sin^2 2\theta_{23} > 0.95$$

$$\sin^2 2\theta_{13} = 0.095 \pm 0.010$$

NEUTRINER FRÅN KOSMISK STRÅLNING



SUPER-KAMIOKANDE KAMIOKA, JAPAN

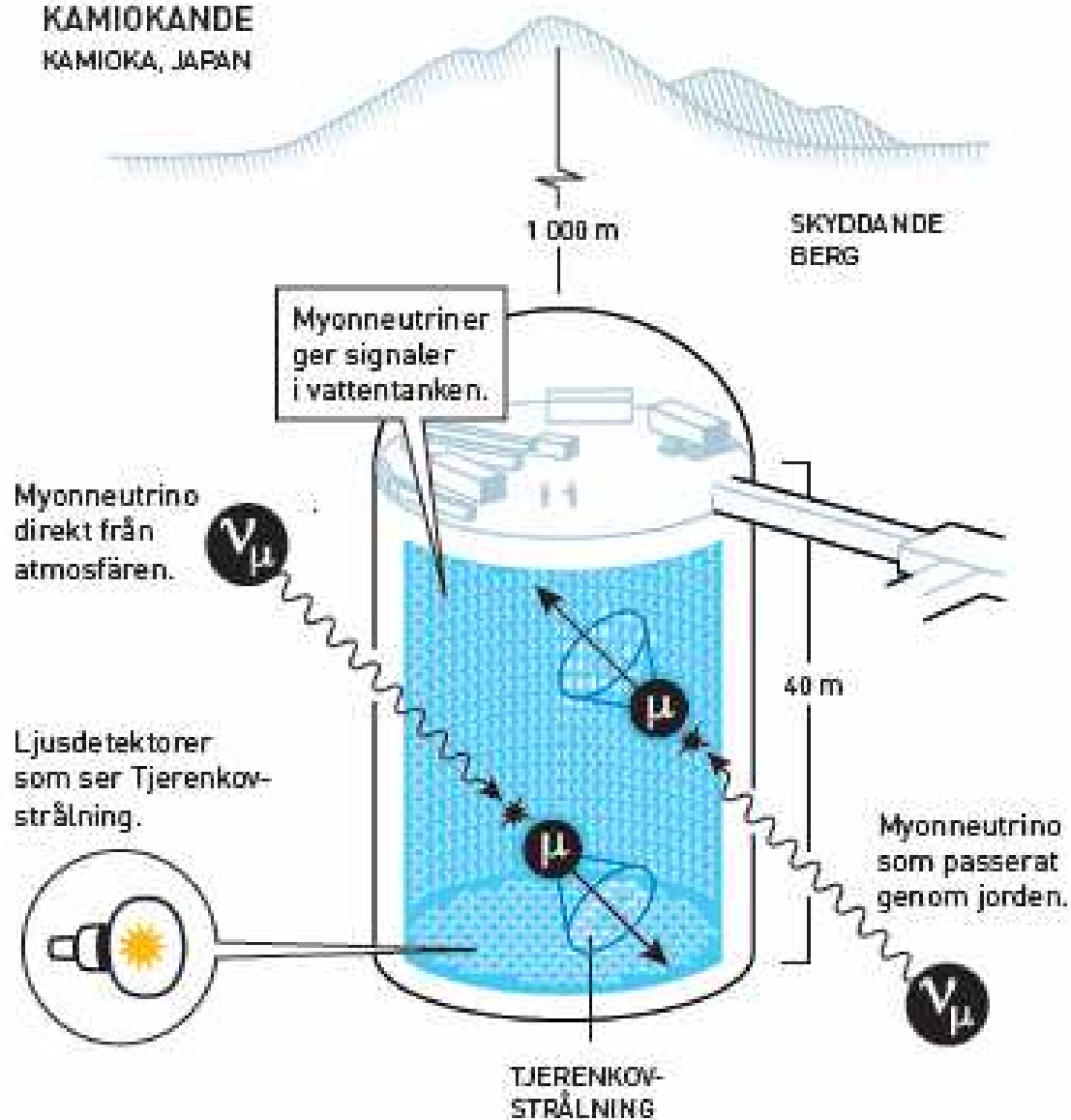
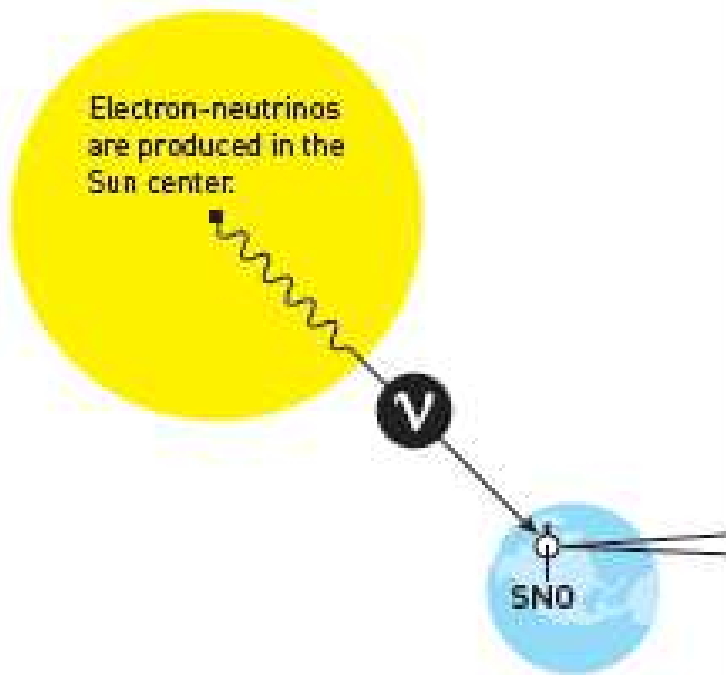


Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

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NEUTRINOS FROM THE SUN



SUDBURY NEUTRINO OBSERVATORY (SNO) ONTARIO, CANADA

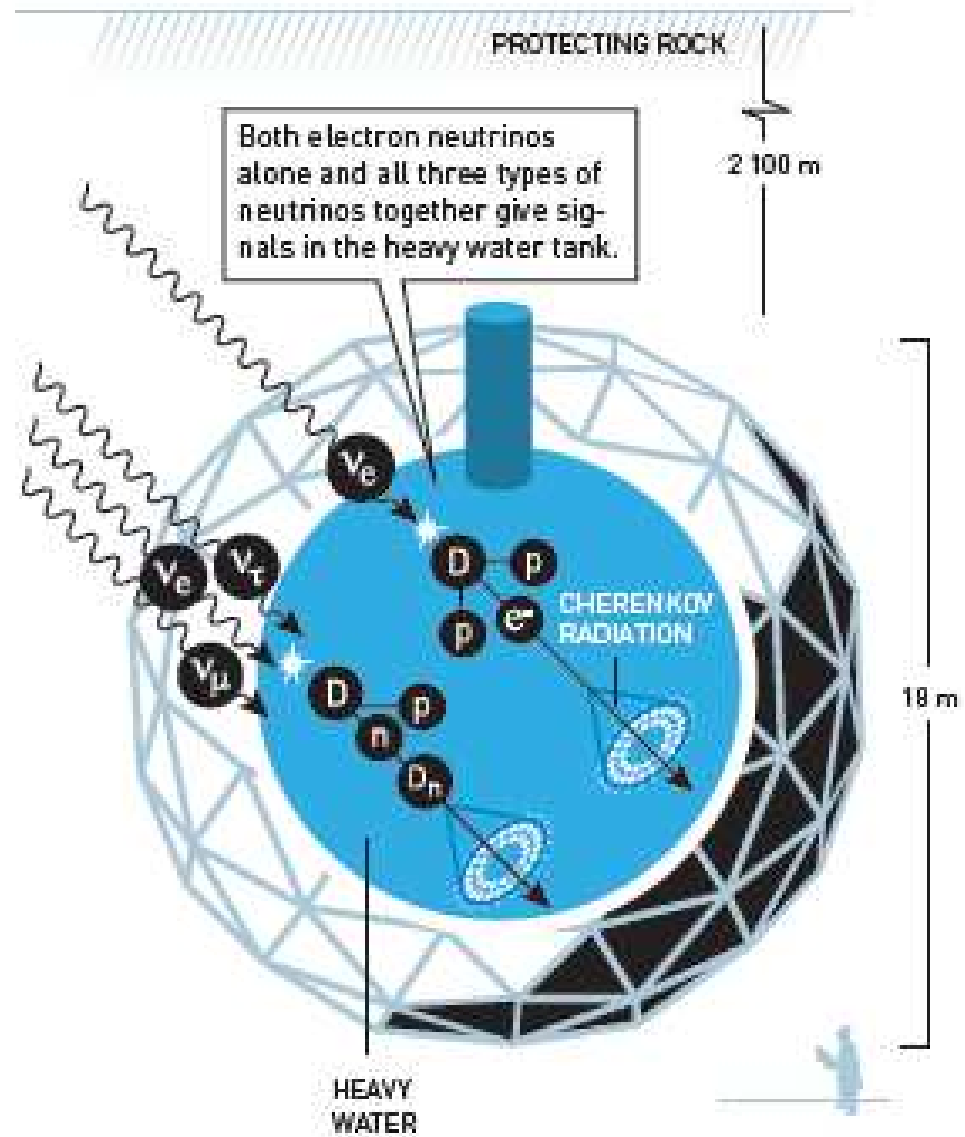
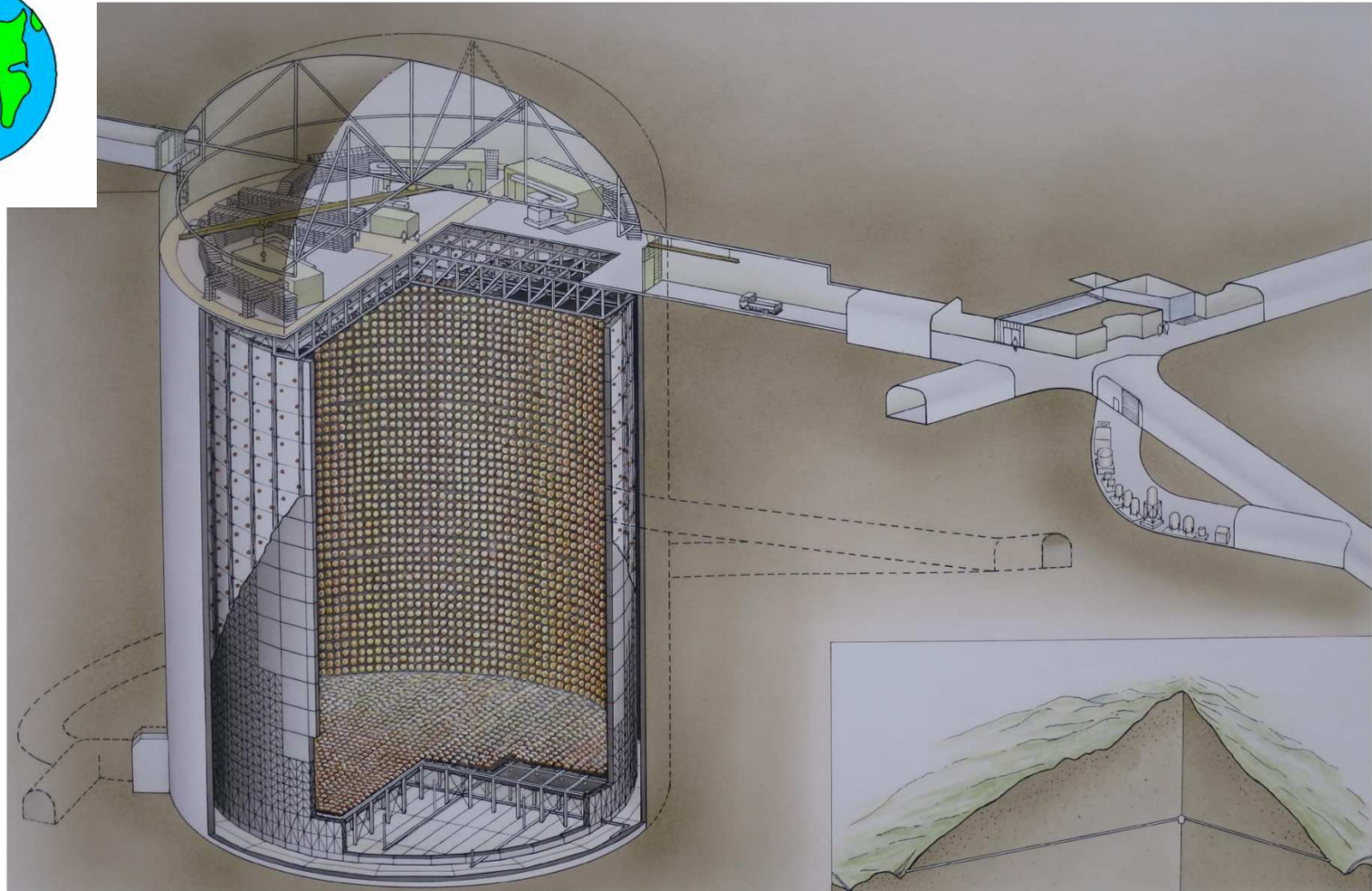
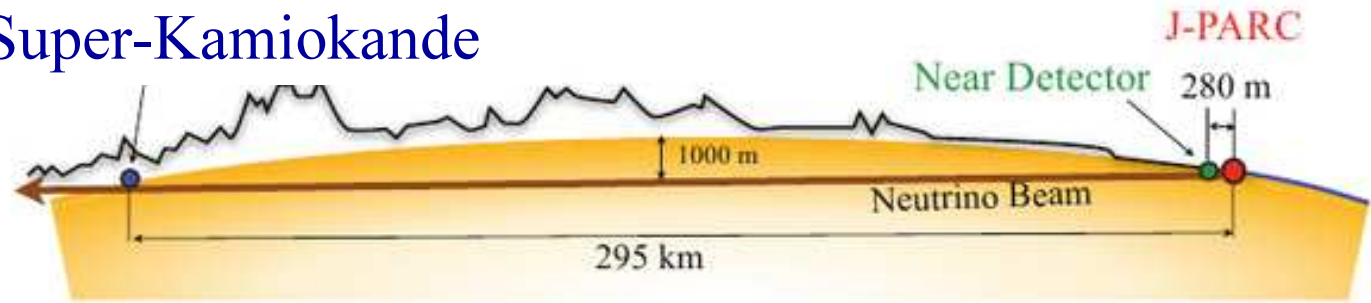
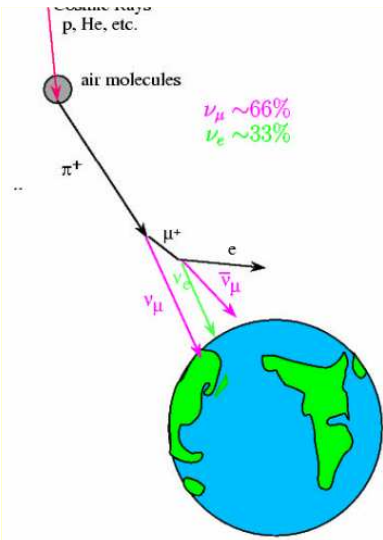


Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

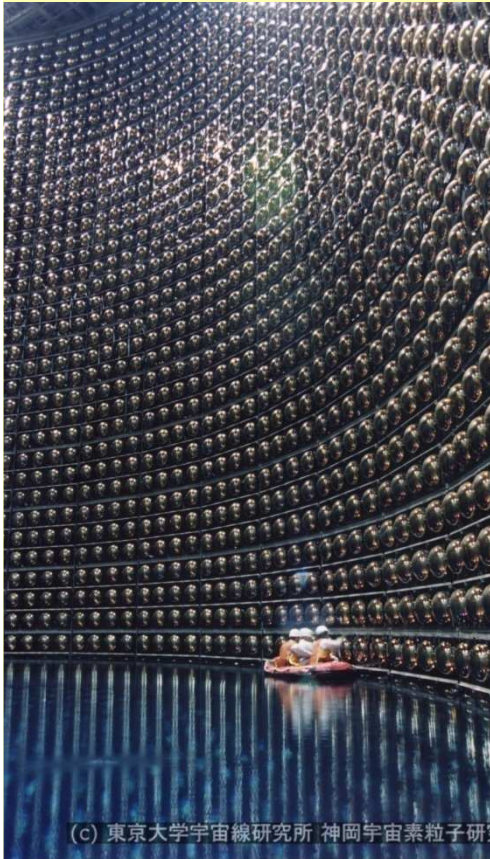
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Super-Kamiokande

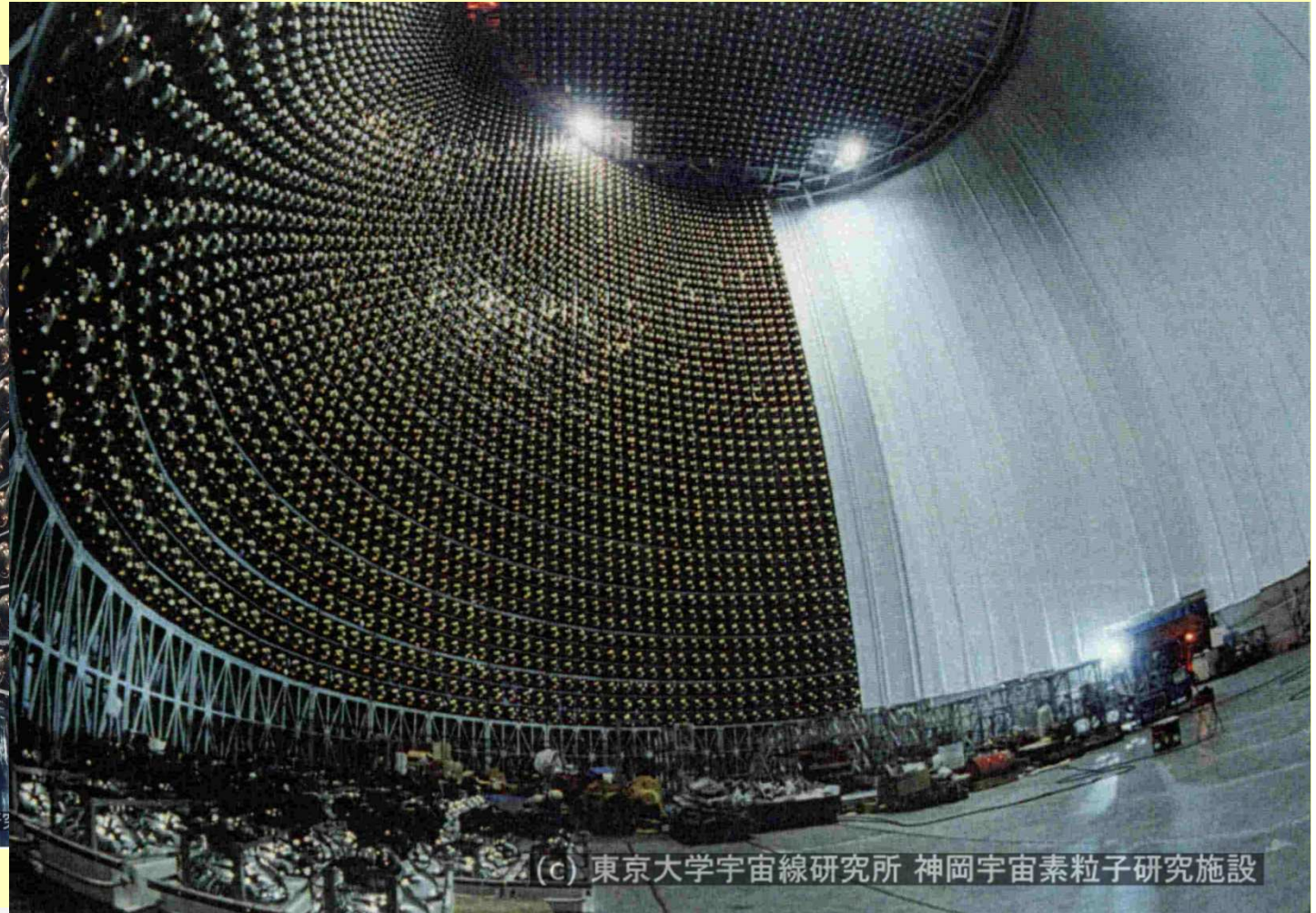




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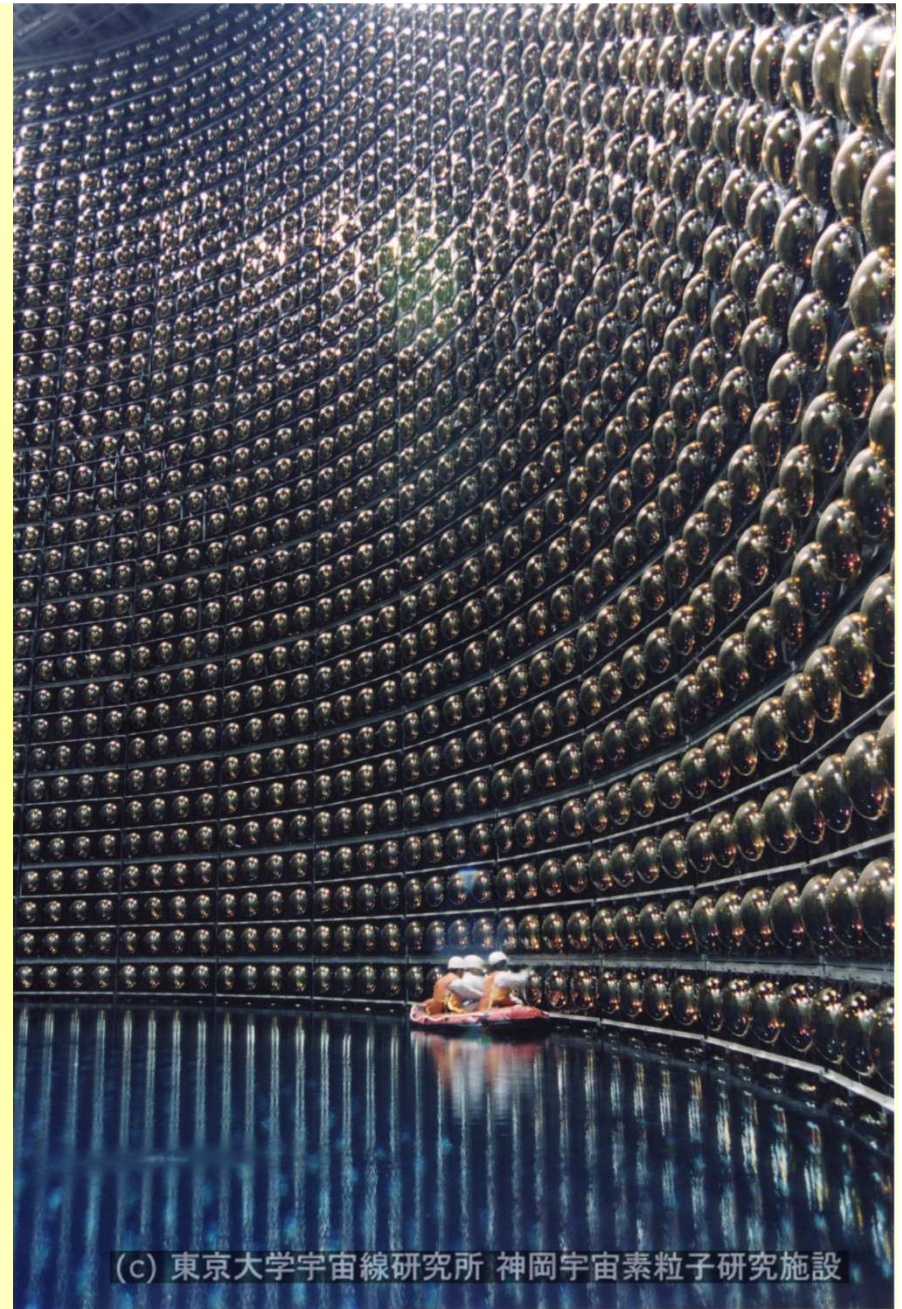


(c) 東京大学宇宙線研究所 神岡宇宙素粒子研究施設



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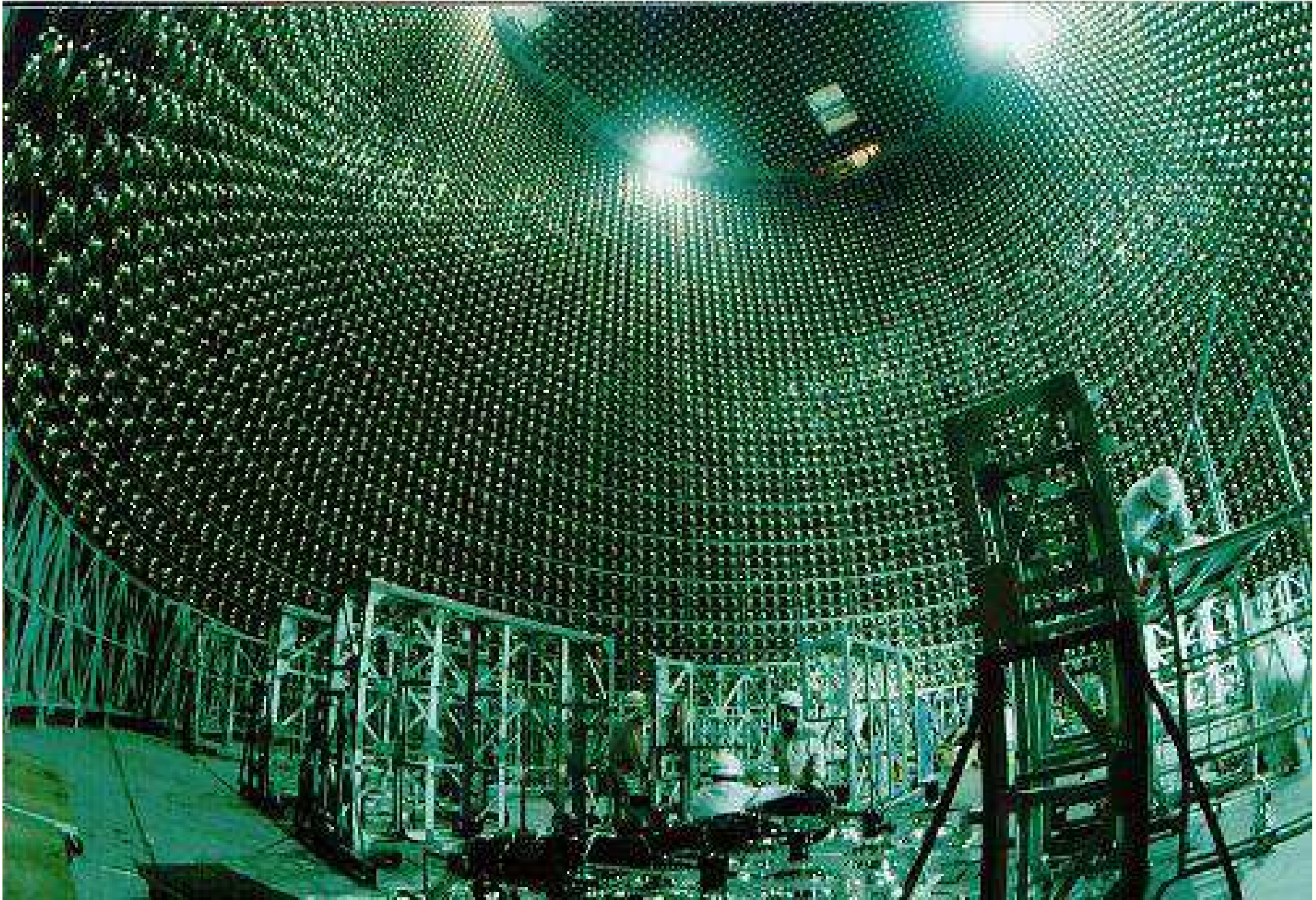


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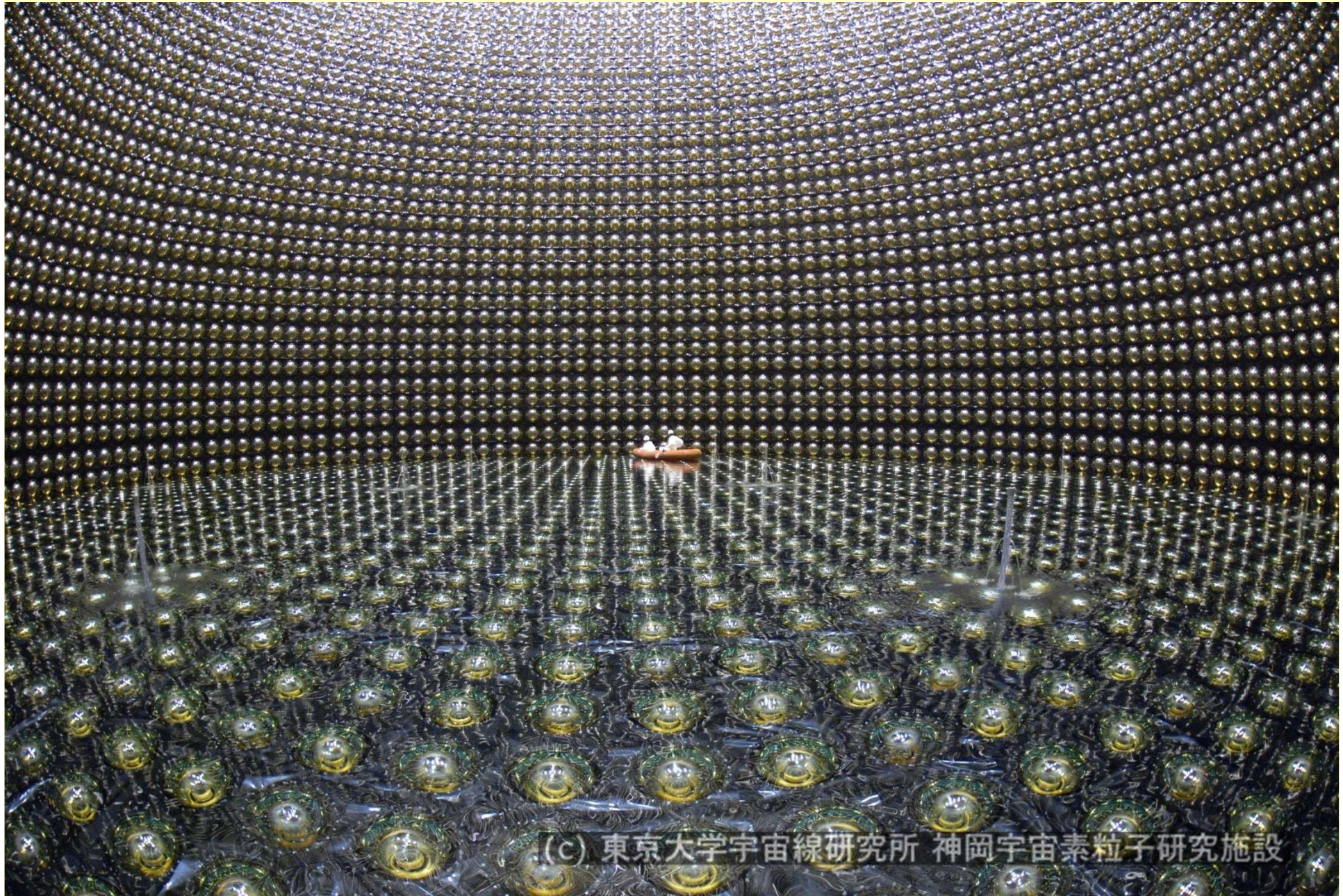
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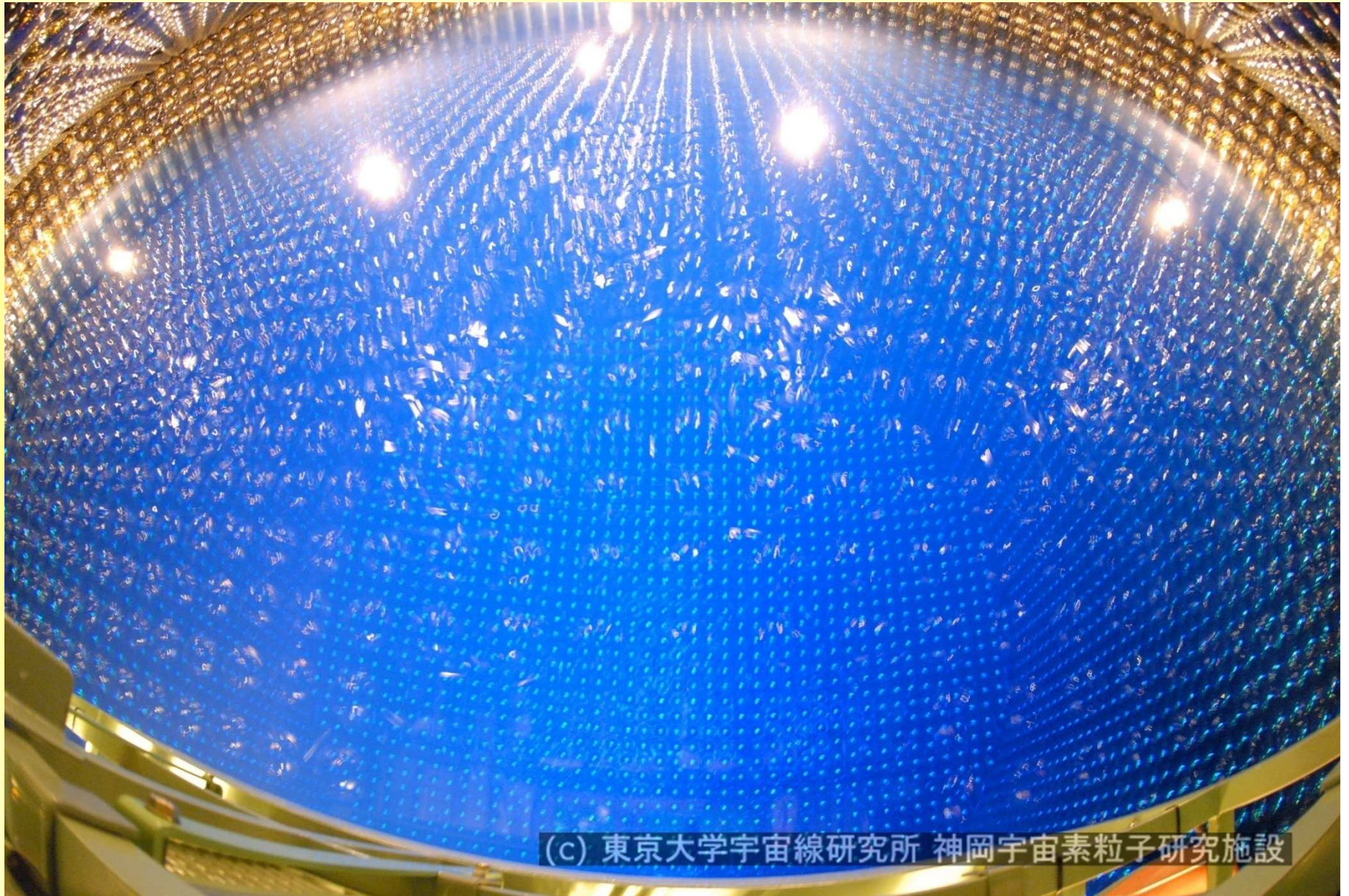
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TABLE I. Data reduction steps.

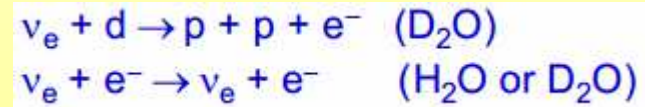
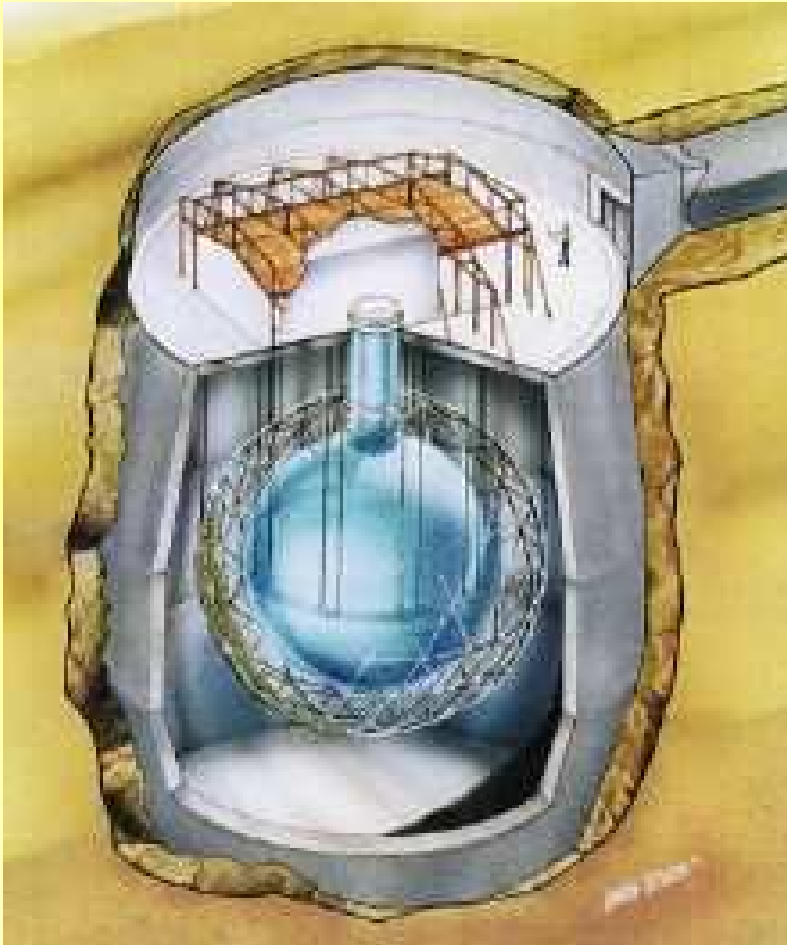
Analysis step	Number of events
Total event triggers	355 320 964
Neutrino data triggers	143 756 178
$N_{\text{hit}} \geq 30$	6 372 899
Instrumental background cuts	1 842 491
Muon followers	1 809 979
High level cuts ^a	923 717
Fiducial volume cut	17 884
Threshold cut	1169
Total events	1169



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The Sudbury Neutrino Observatory



1000 tonnes of heavy water loaned from Atomic Energy of Canada Limited (AECL), and contained by a 12 meter diameter acrylic vessel. Neutrinos reacted with the heavy water (D_2O)

Creighton mine shaft head

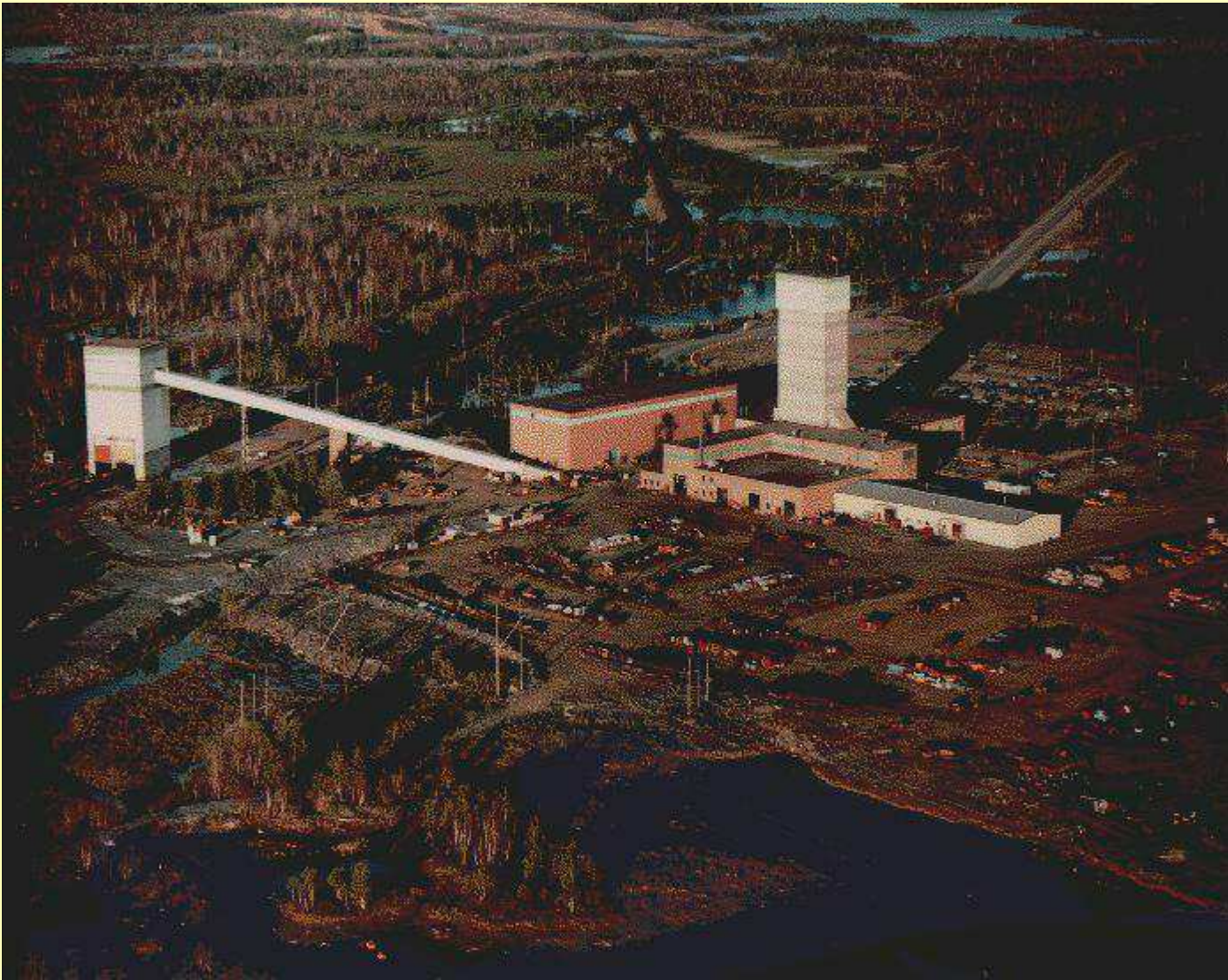


Photo courtesy of SNO

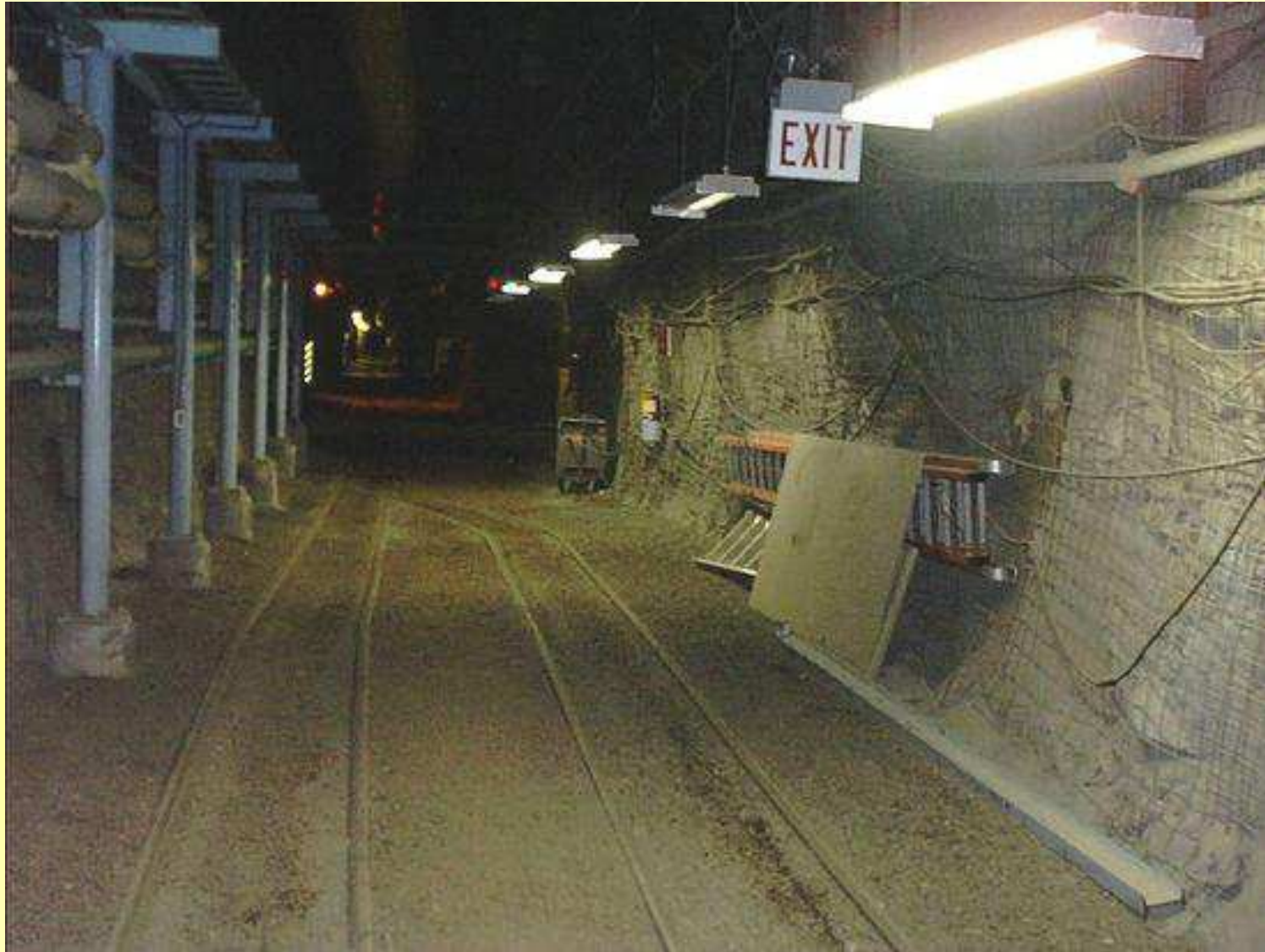


Photo courtesy of SNO



Photo courtesy of SNO

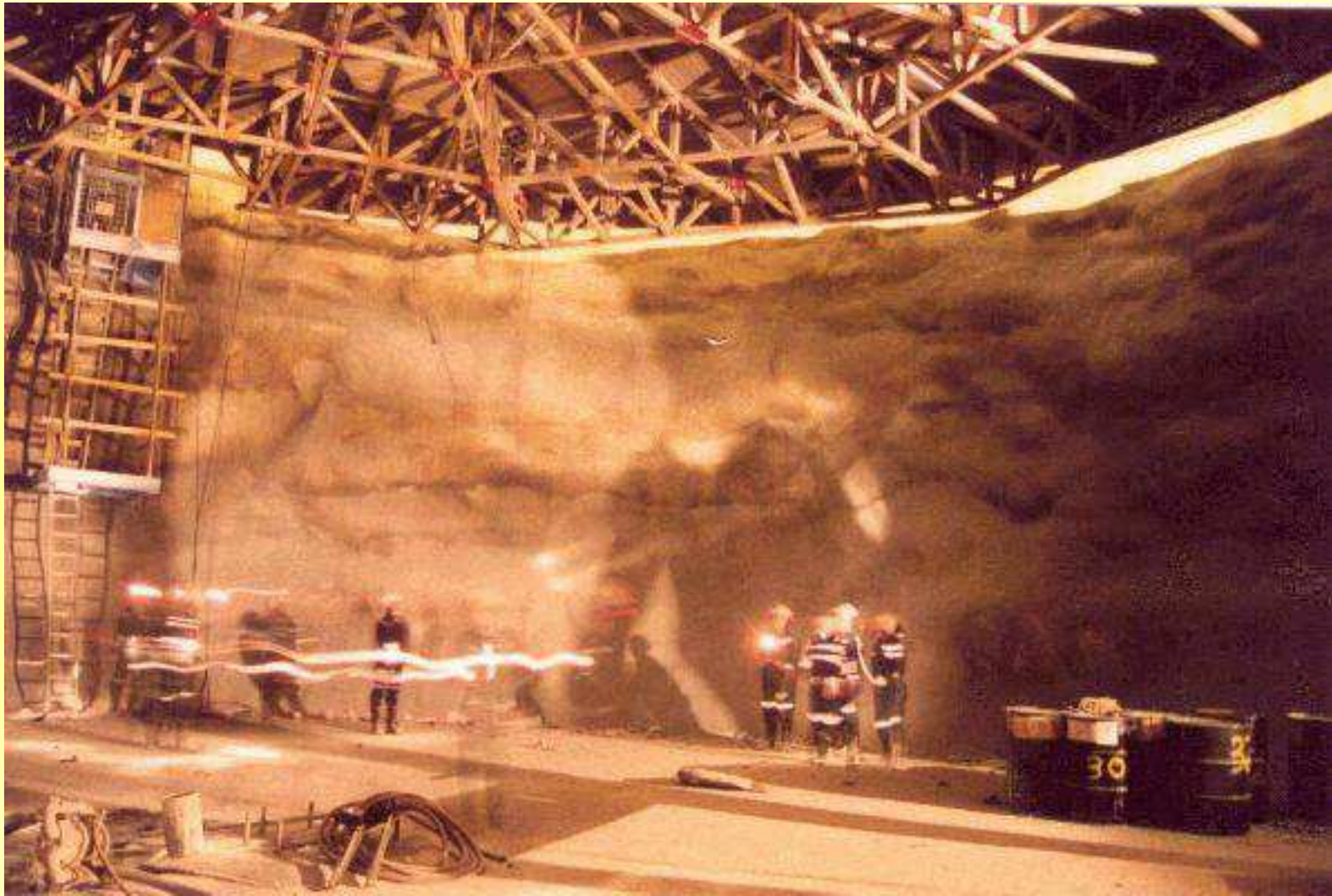


Photo courtesy of SNO

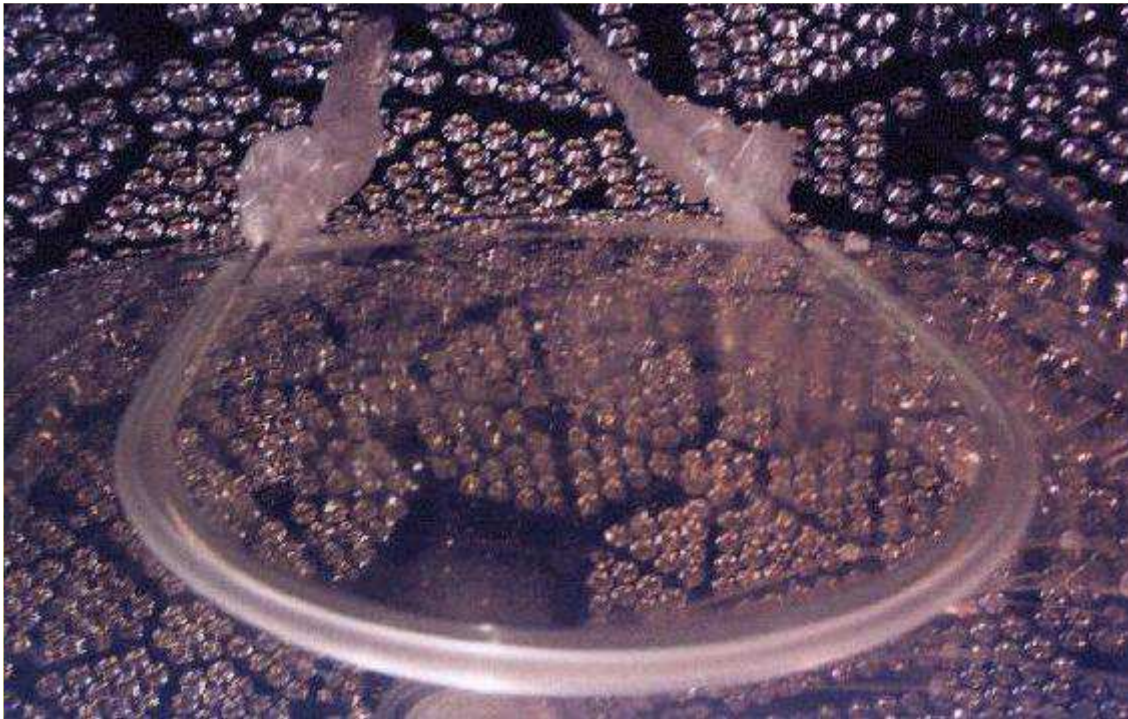


Photo courtesy of SNO



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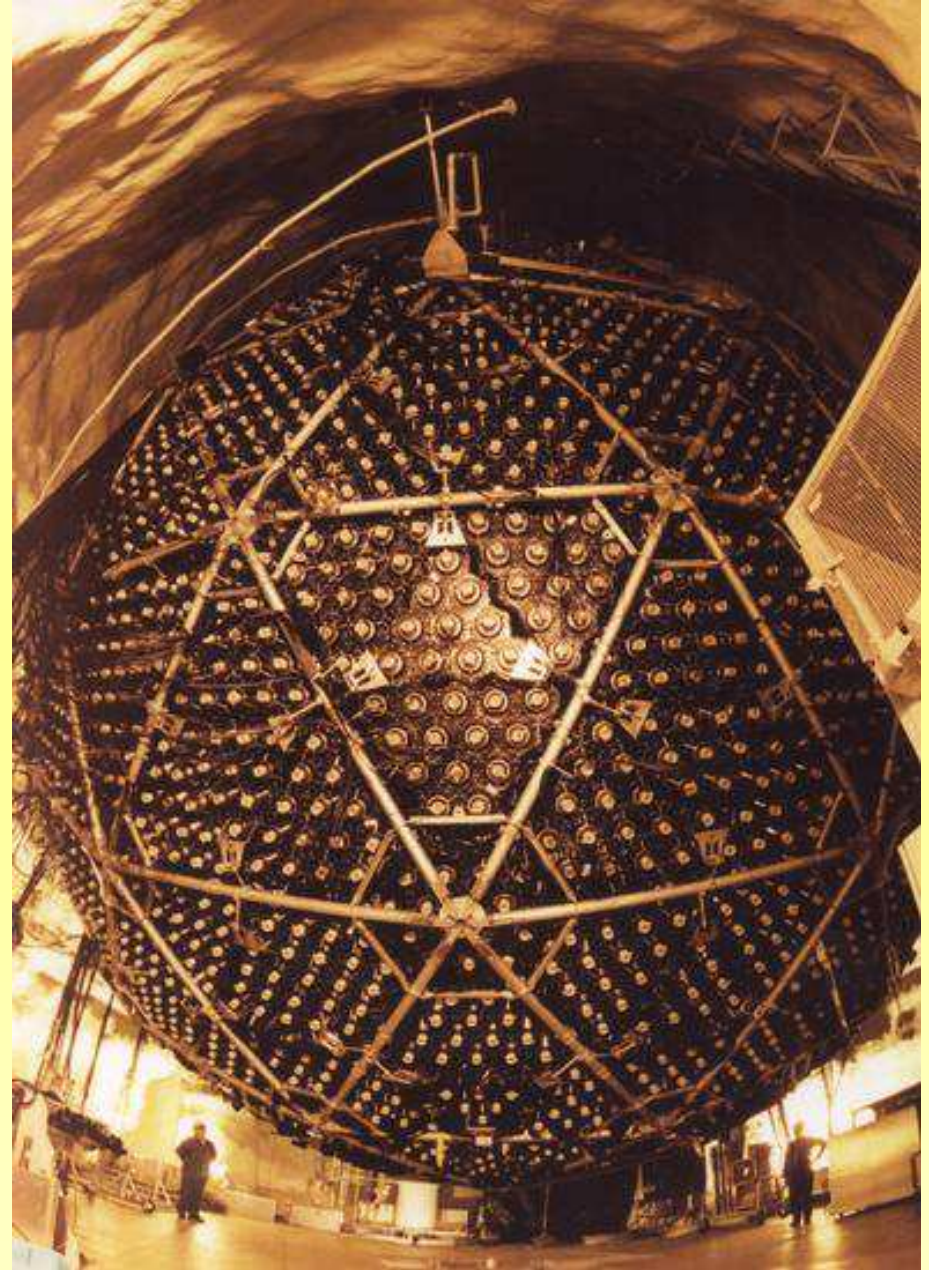
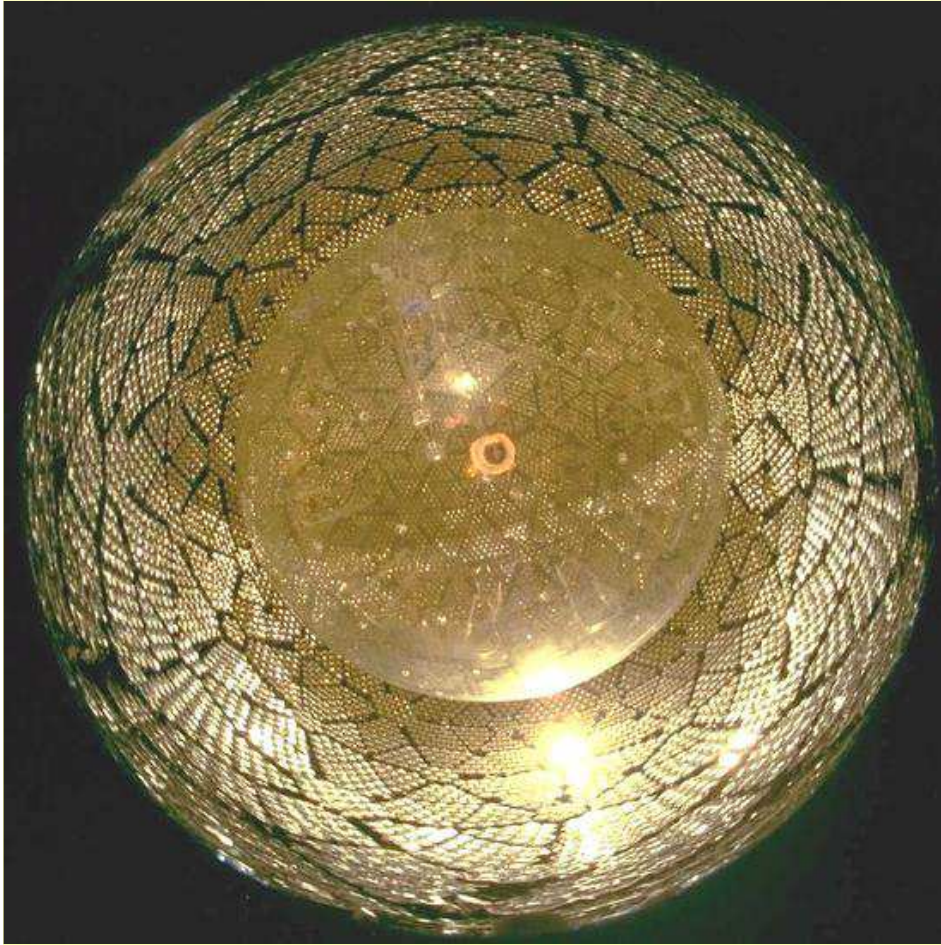


Photo courtesy of SNO

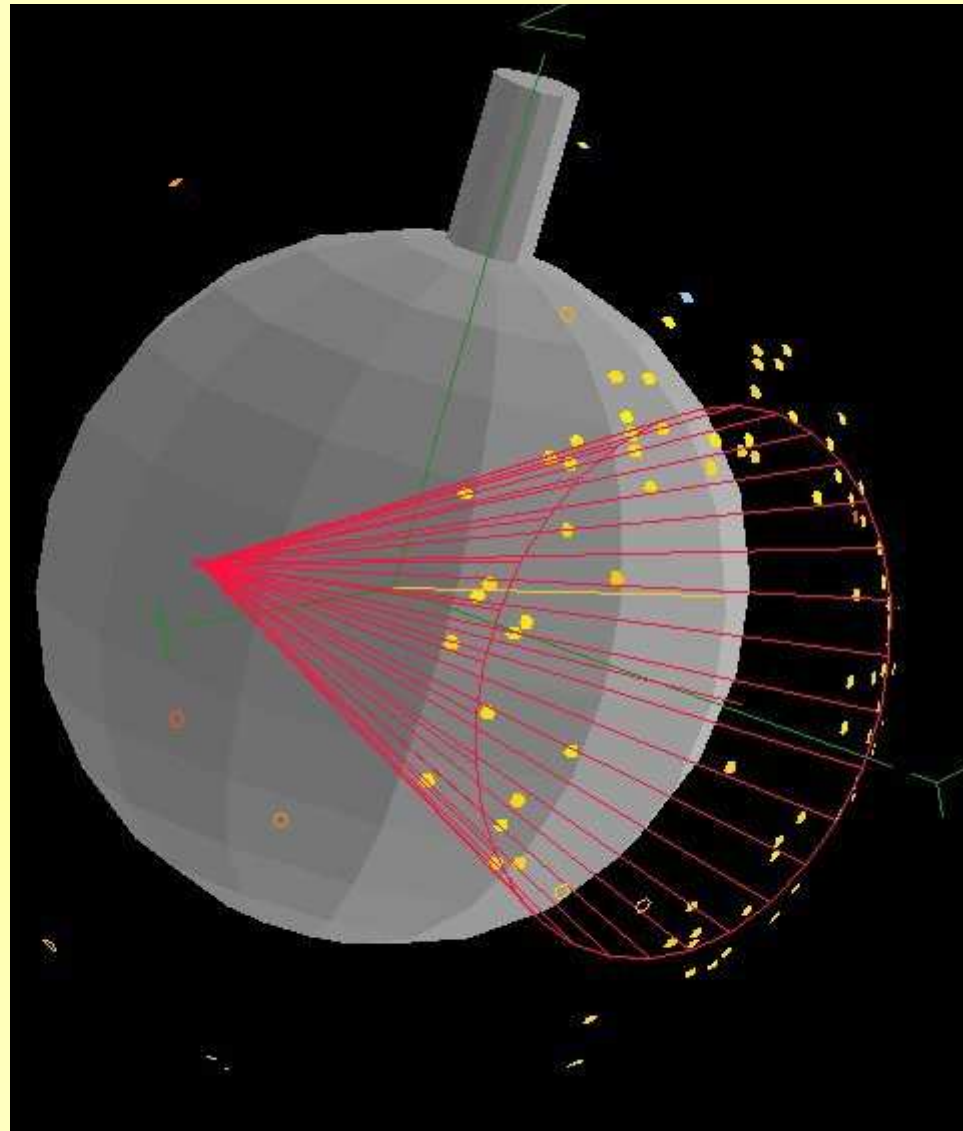
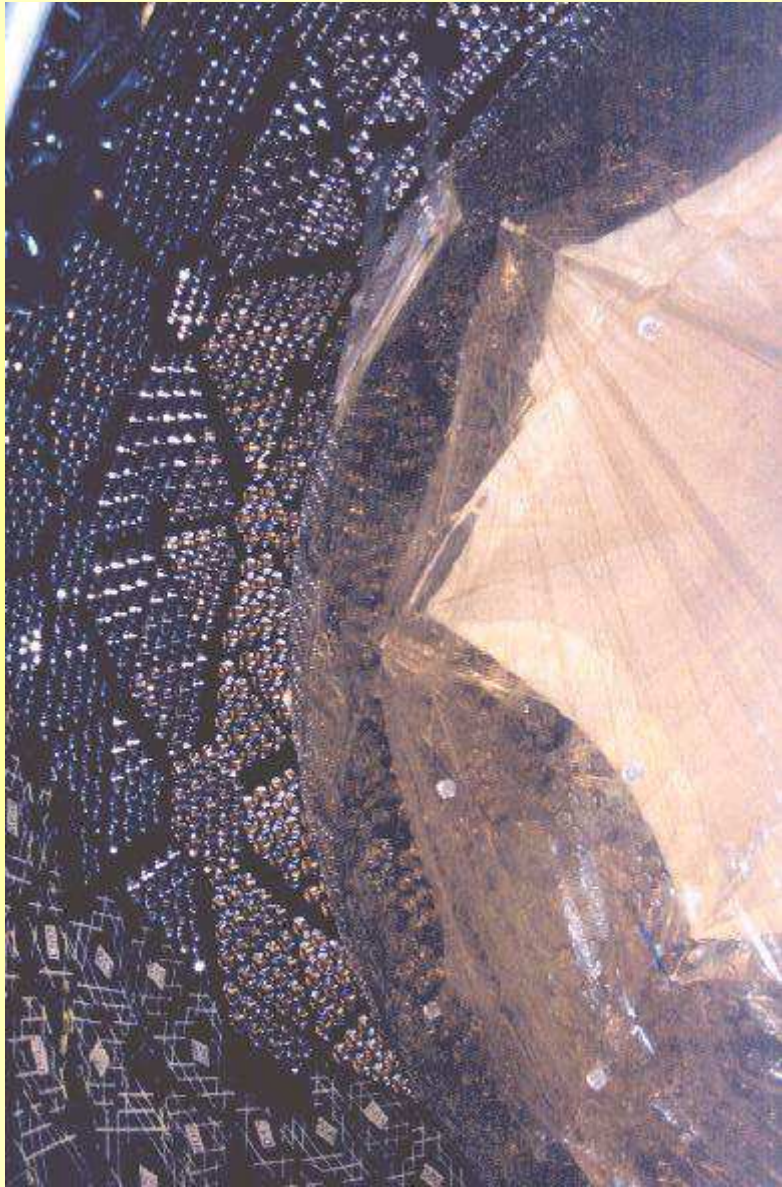


Photo courtesy of SNO

The control room for the SNO detector.



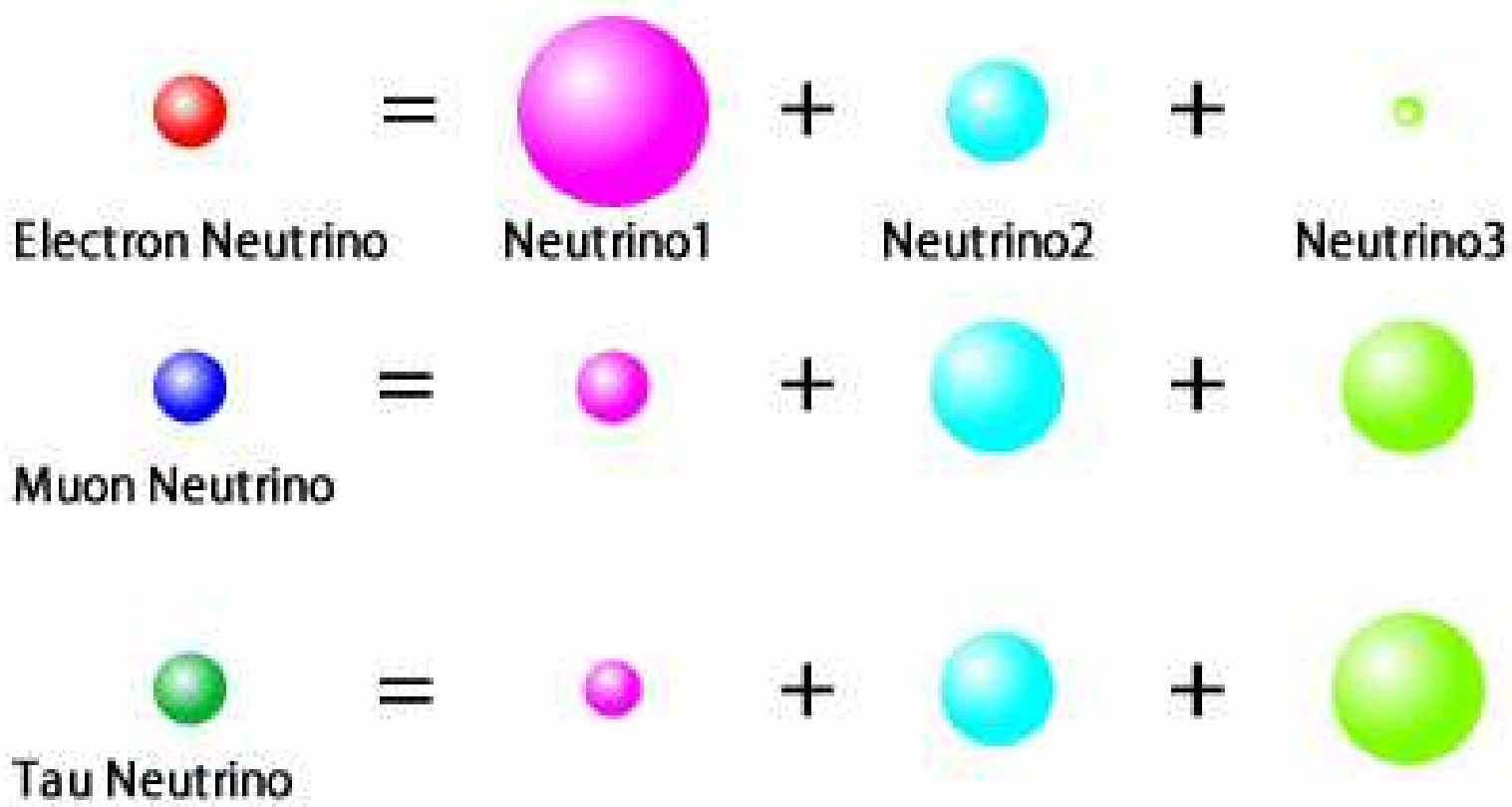
Photo courtesy of SNO

SNO surface control room in new SNOLab building. Photo by P. Harvey, Feb. 2006.



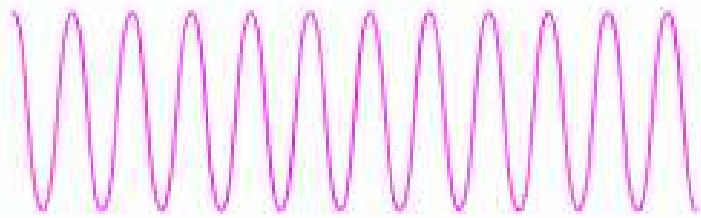


Photo courtesy of SNO

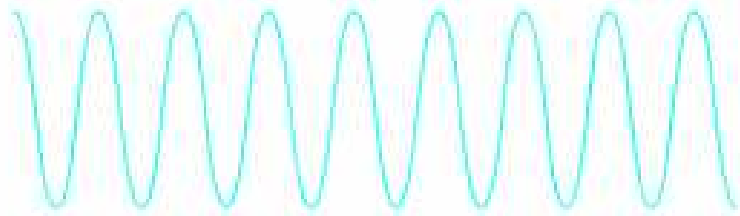


Neutrinos are mixing between flavor classification and mass classification.

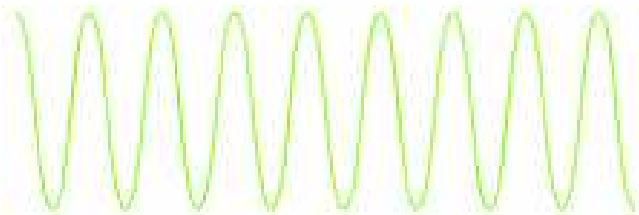
Neutrino1



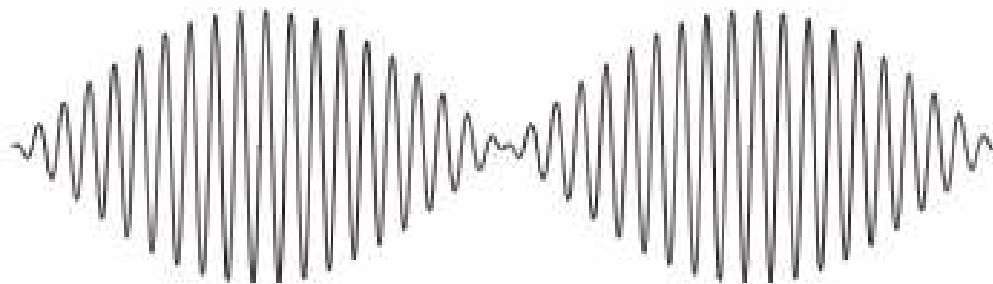
Neutrino2



Neutrino3



Superposed waves



Electron Neutrino

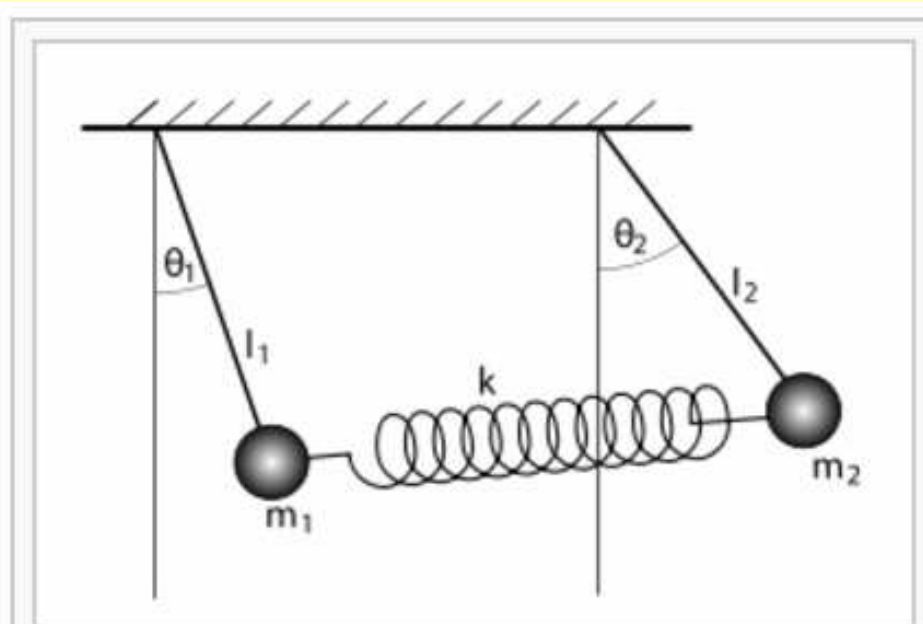
Muon Neutrino

Electron Neutrino

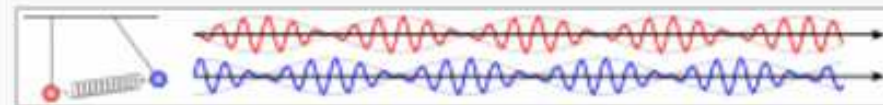


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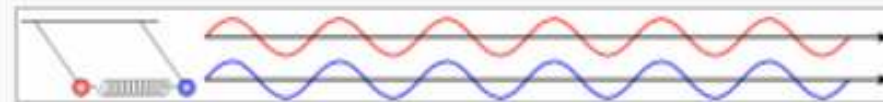
Класичний аналог осциляцій нейтрино



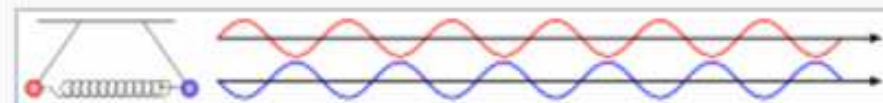
Spring-coupled pendulums



Time evolution of the pendulums

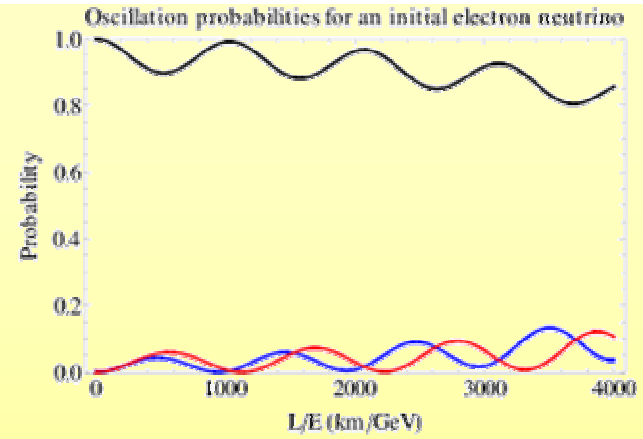
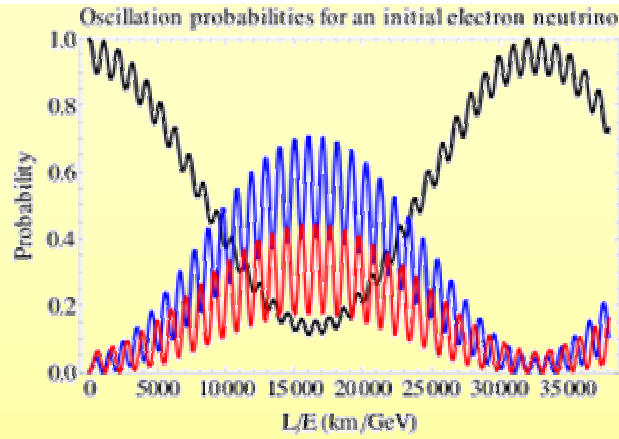


Lower frequency normal mode

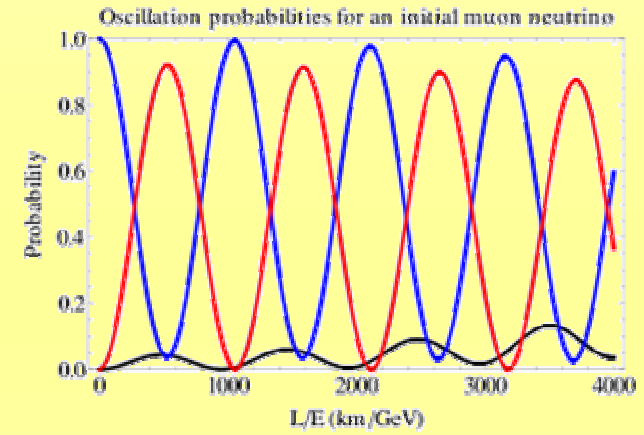
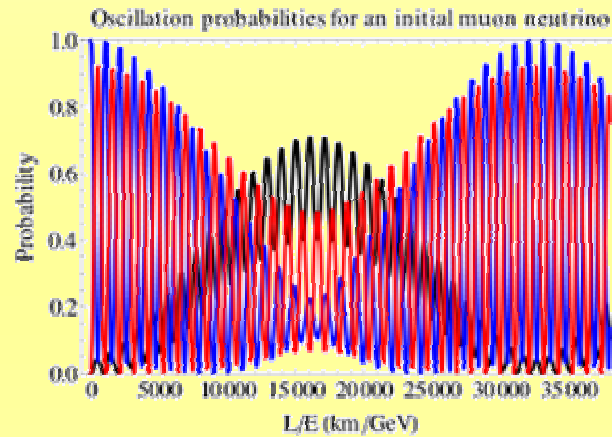


Higher frequency normal mode

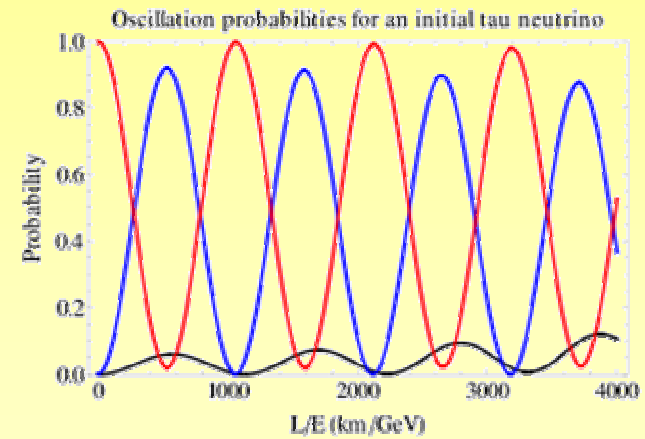
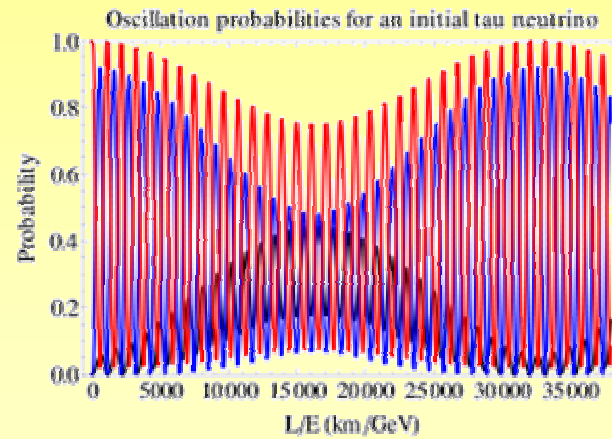
Electron
neutrino



Muon
neutrino

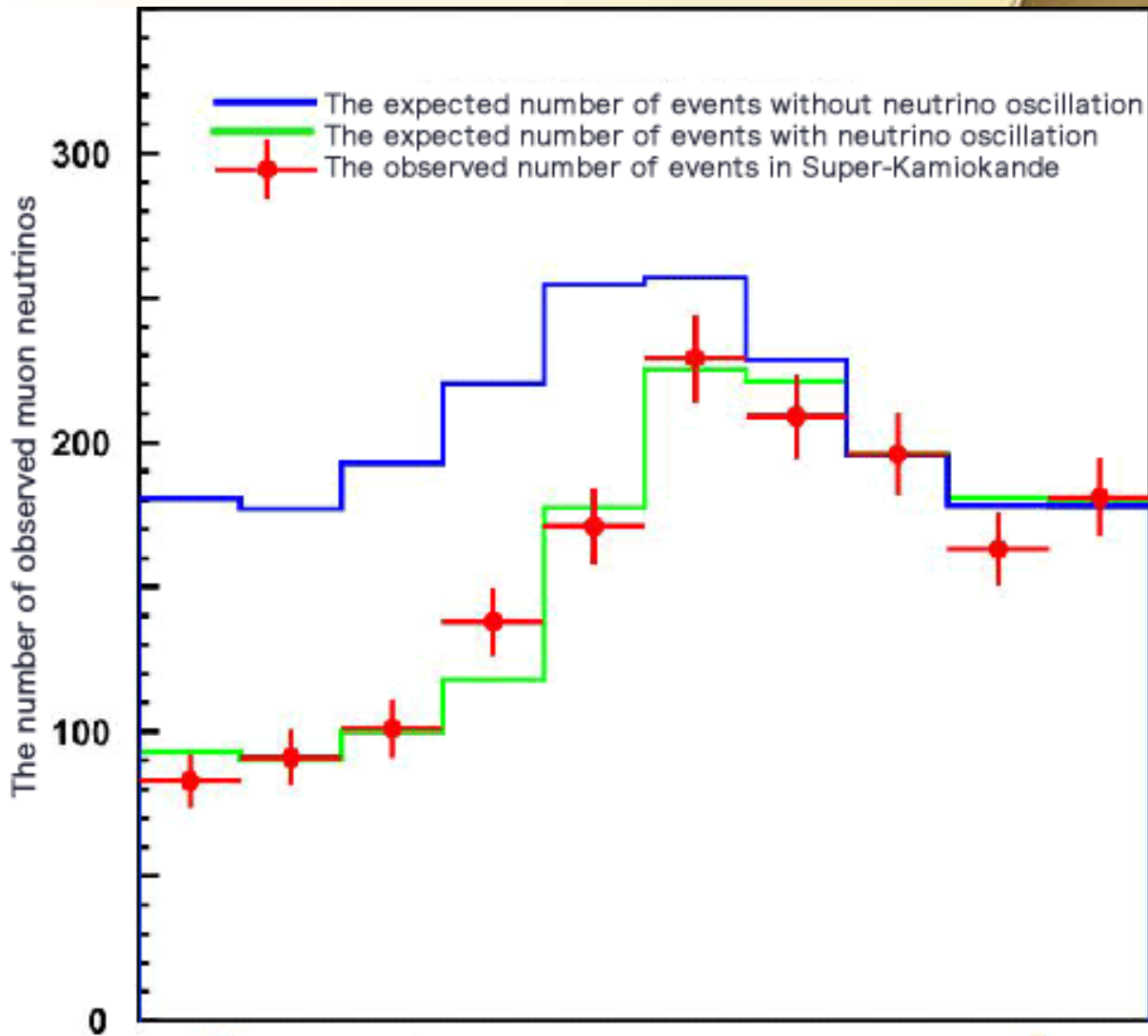



Tau
neutrino




long range

short range






 Upward going Neutrinos
 Flight length: 12800km
 Only a half of the expected
 number (blue line) was observed.



 Horizontal going Neutrinos
 Flight length: 500km
 Only 80% of the expected
 number was observed.



 Downward going Neutrinos
 Flight length: 15km
 Consistent with the
 expected number.



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 фізики 2015**

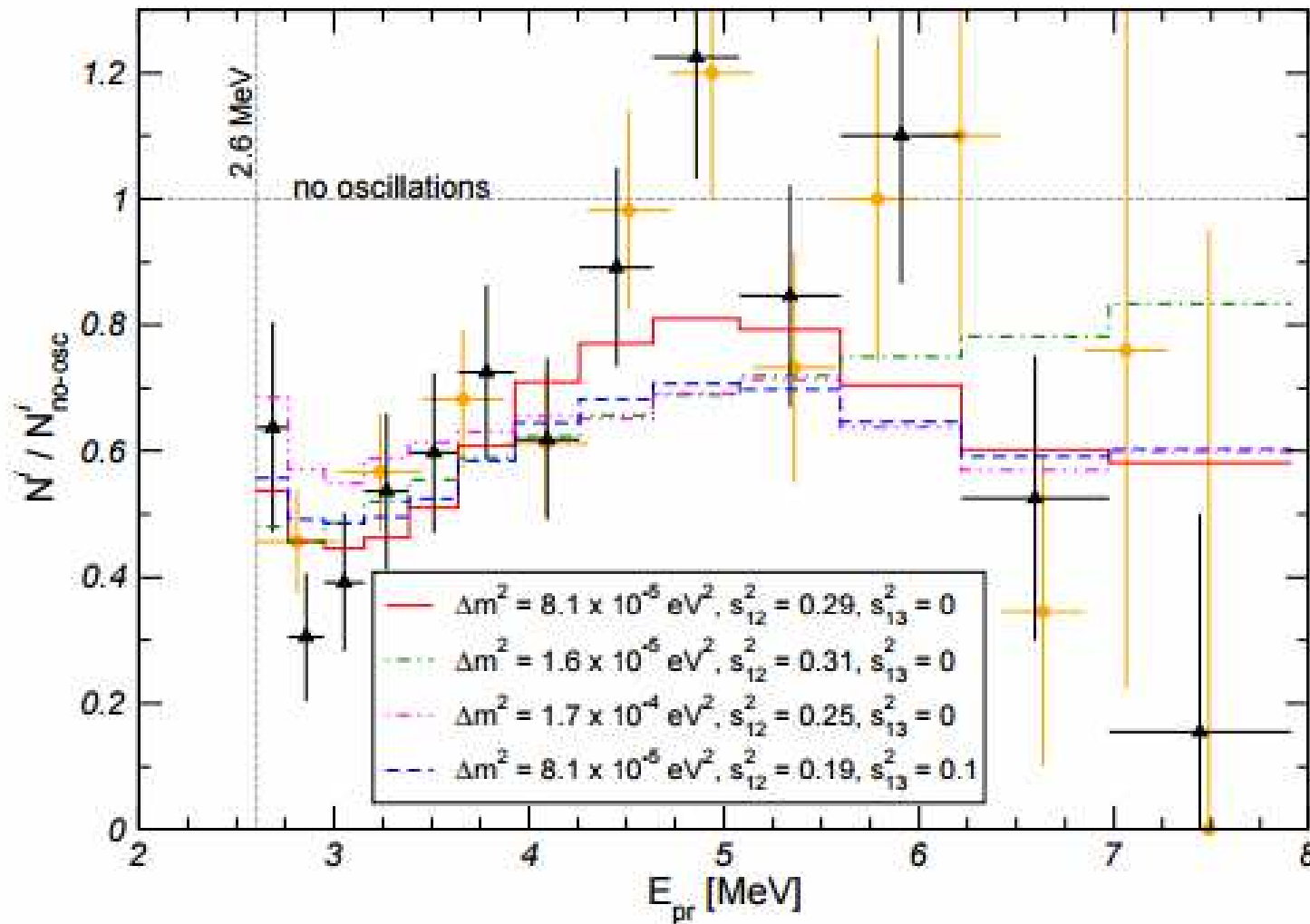
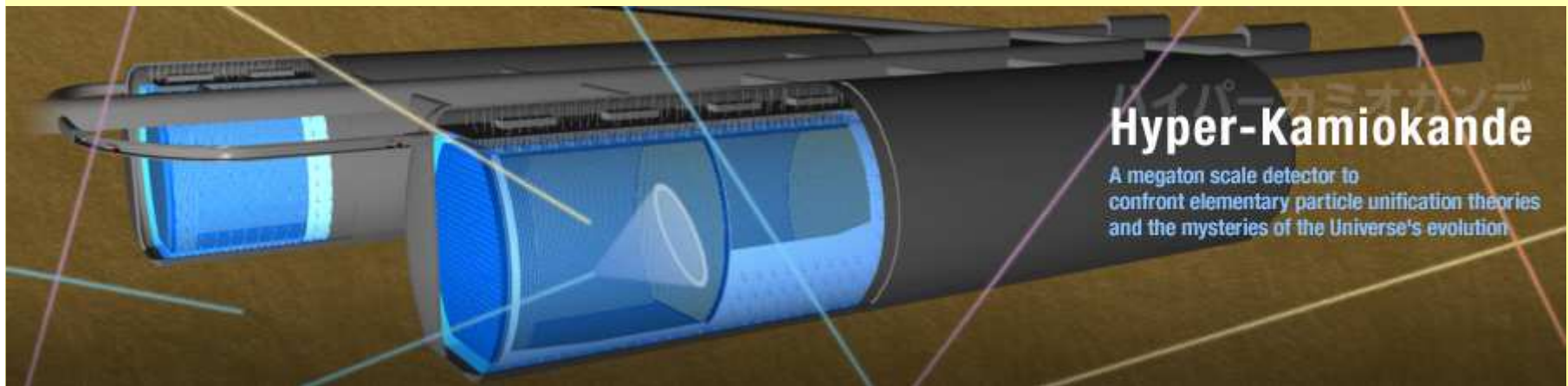


Figure A1. Data divided by the expectation for no oscillations for equal bins in $1/E_{\text{pr}}$ (triangles) and in E_{pr} (dots). Also shown is the spectrum for the best fit point (solid), the local best fit points in the low Δm^2 (dash-dotted) and high Δm^2 (dash-dot-dotted) regions, and for a large value of $\sin^2 \theta_{13}$ (dashed).

<http://www.hyper-k.org/en/>



- 25, May 2015 [Hyper-Kamiokande paper is published in Progress of Theoretical and Experimental Physics.](#)
.....
- 18, May 2015 [\[Topics\] A strength test of new photosensors has been commenced.](#)
.....
- 19, Apr. 2015 [The third Hyper-Kamiokande EU meeting will be held on 27, 28 April at CERN.](#)
.....
- 25, Feb. 2015 [The article "Physics Potential of a Long Baseline Neutrino Oscillation Experiment Using J-PARC Neutrino Beam and Hyper-Kamiokande" is submitted.](#)
.....



www.nobelprize.org/nobel_prizes/physics/laureates/2015/

physics.aps.org/articles/v8/97



Phys. Rev. Focus 2, 10



Super-Kamiokande Official Homepage:
www-sk.icrr.u-tokyo.ac.jp/sk/index-e.html



Sudbury Neutrino Observatory Homepage:
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cds.cern.ch



www.bnl.gov



www.fnal.gov



www.nu.to.infn.it/Neutrino_Lectures/



arXiv.org > hep-ph >

www.ps.uci.edu/~superk



www.youtube.com/watch?v=RGv-pcKRf6Q

Neutrinos, Einstein, Time and Paradox: Tom Weiler at TEDxNashville

www.youtube.com/watch?v=BFcKxL0z41M