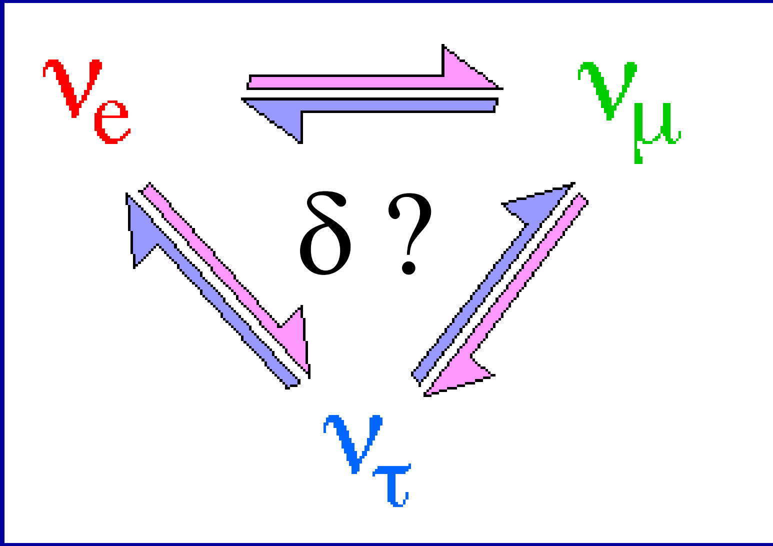
ニュートリノ物理学



金　信弘
(筑波大学物理学系)

2003年9月25日

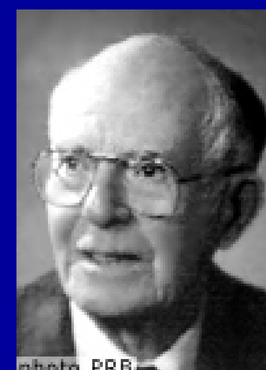
Soo-Bong Kim氏(SNU)講演より引用

❑ 2002年度ノーベル物理学賞

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

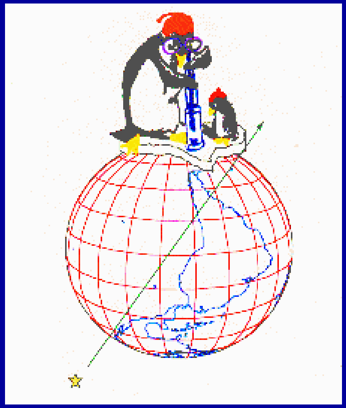
[Raymond Davis Jr.](#) **USA**
(University of Pennsylvania)

[Masatoshi Koshiba](#) **Japan**
(University of Tokyo)

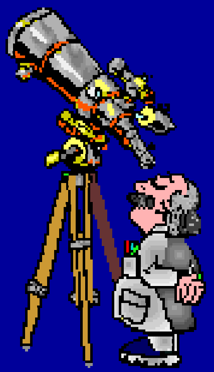


"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources“

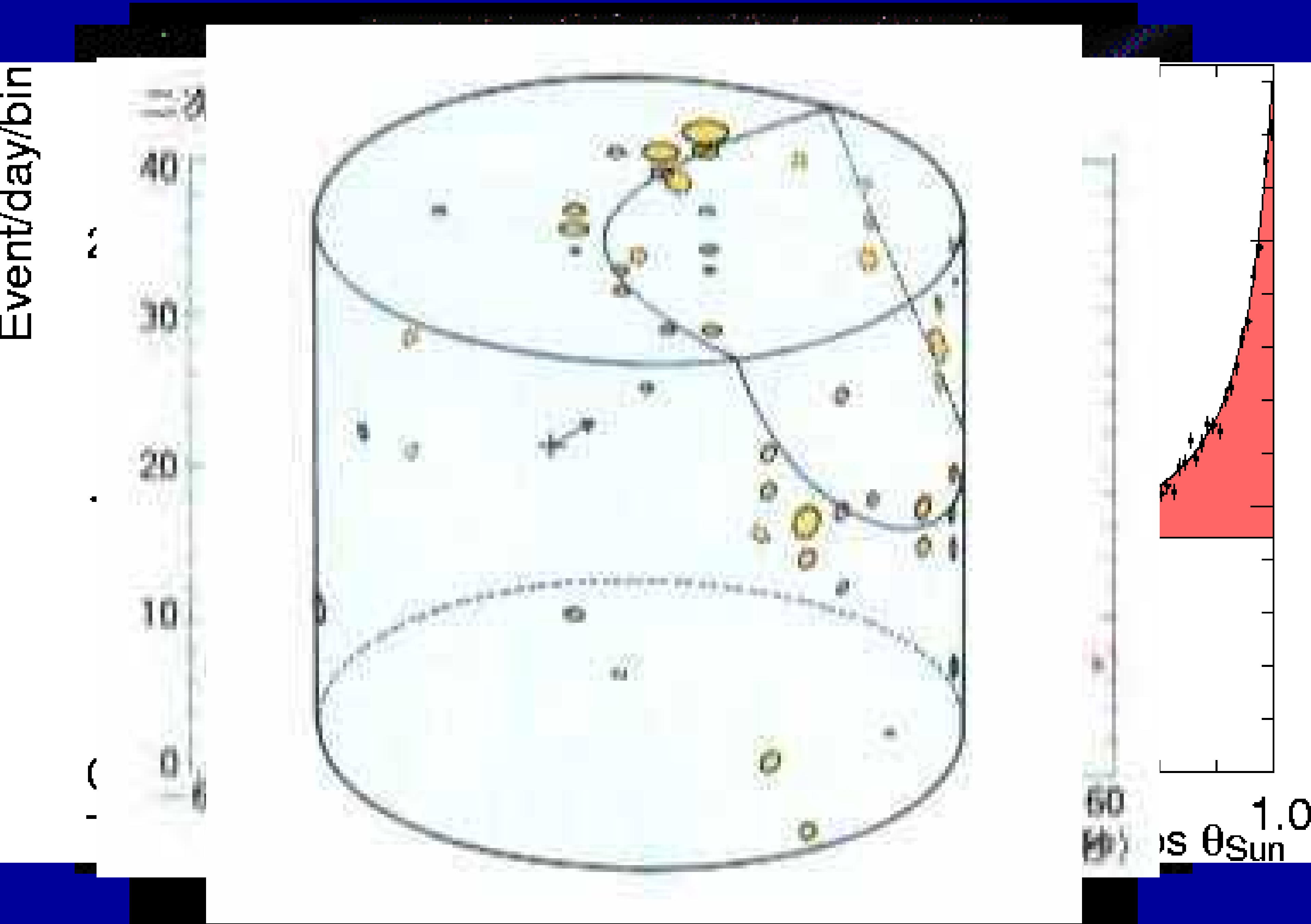
[Riccardo Giacconi](#) **USA**
(Associated Universities Inc.)



ニュートリノ天文学



- Neutrinos can probe the interior of stars (**星の内部**) .
- Neutrinos are transparent to the Milky way (**銀河通過**) .
- Neutrinos are efficient to carry out energies from the star explosion (**星の爆発**) .
- Neutrinos from Sun, Supernova explosion, Galaxy, Dark-Matter Annihilation, etc (**太陽, 超新星爆発, 銀河, 暗黒物質消滅**) .



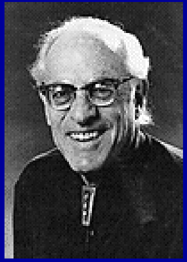
Event/day/bin
40
30
20
10
0
1.0
os θSun

ニュートリノ物理学の歴史

❑ W. Pauli (1931): Undetectable neutral particle

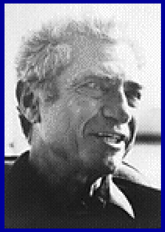
❑ E. Fermi (1934): "Neutrino"

❑ F. Reines (1956): Discovery



Nobel Prize (1995)

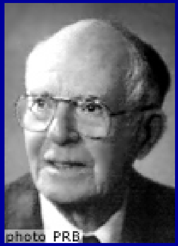
❑ L. Lederman, M. Schwartz, J. Steinberg (1962): Muon Neutrino



Nobel Prize (1988)

❑ R. Davis (1968): First detection of solar neutrinos

Nobel Prize (2002)



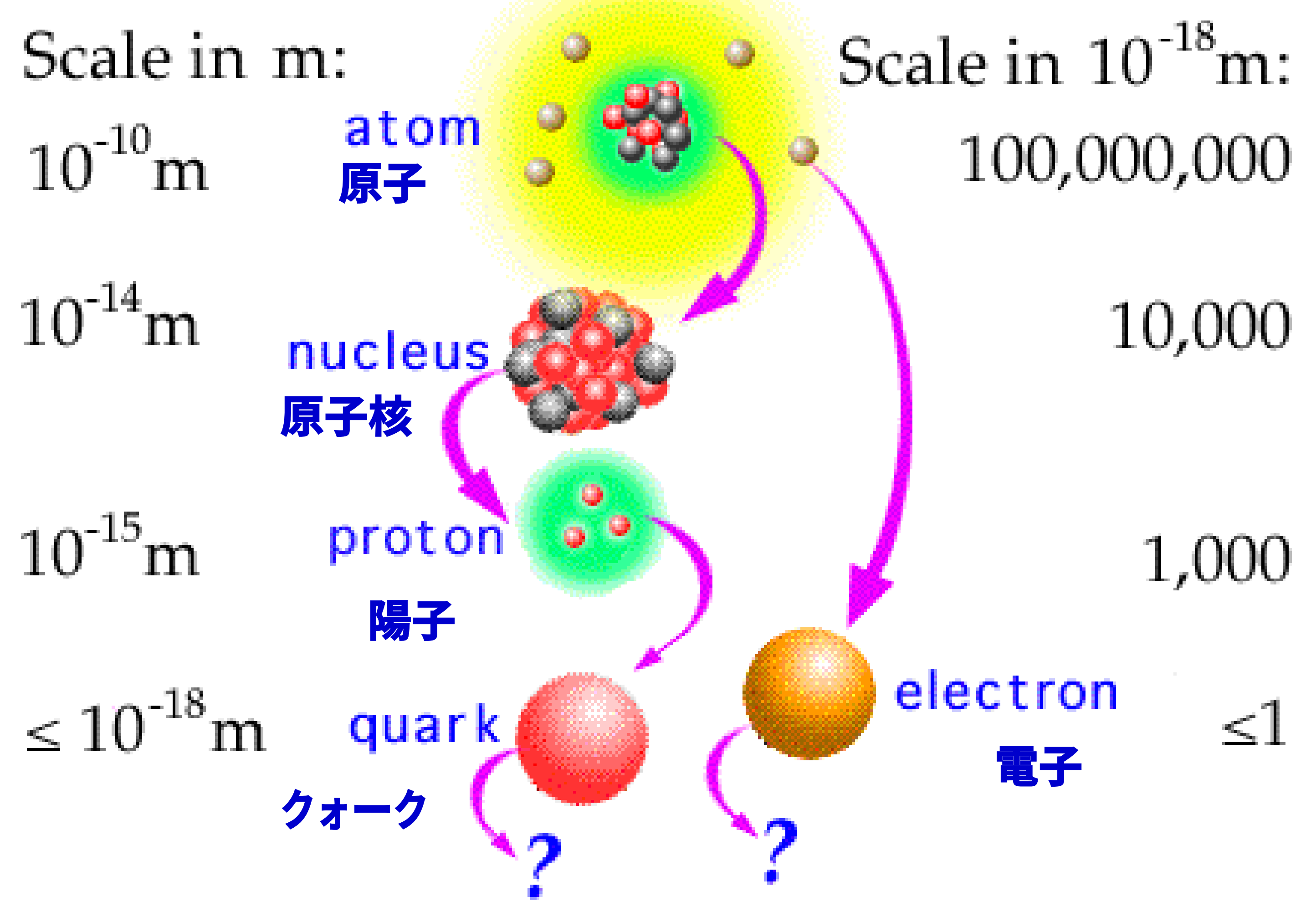
❑ M. Koshiba (1987): Supernova neutrinos by Kamiokande-II and IMB

Nobel Prize (2002)

❑ Y. Totsuka (1998): Oscillation of atmospheric neutrinos at Super-Kamiokande

❑ SNO (2002): Oscillation of solar neutrinos

素粒子とは？


Scale in m:
Scale in 10^{-18}m:
10^{-10}m
atom
原子
100,000,000
10^{-14}m
nucleus
原子核
10,000
10^{-15}m
proton
陽子
1,000
$\leq 10^{-18}$m
quark
クォーク
?
electron
電子
?
≤1

素粒子と素粒子間の力 (素粒子物理標準理論)

物質を構成する粒子 (フェルミオン)

クォーク

			電荷
アップ(0.002)	チャーム(1.3)	トップ(175)	2/3
ダウン(0.005)	ストレンジ(0.14)	ボトム(4.2)	- 1/3

レプトン

電子(0.0005)	ミュー粒子(0.106)	タウレプトン(1.8)	- 1
電子ニュートリノ ν_e	ミューニュートリノ ν_μ	タウニュートリノ ν_τ	0

力を伝える粒子 (ゲージボソン)

強い力	電磁気力	弱い力
グルオン(0)	光子(0)	W粒子(80) Z粒子(91)

( ) 内の数字はGeVの単位で書かれた質量

ニュートリノを用いた
素粒子物理学と宇宙物理学

- ❑ GUT (大統一理論) 規模の物理の検証
  (ニュートリノの質量･振動)
- ❑ 宇宙膨張
  (暗黒物質)
- ❑ レプトンセクターの混合
  (MNS 行列)
- ❑ ニュートリノ天文学
  (超高エネルギーニュートリノ, 超新星ニュートリノ, …)

ニュートリノ振動

ニュートリノが2種類の場合

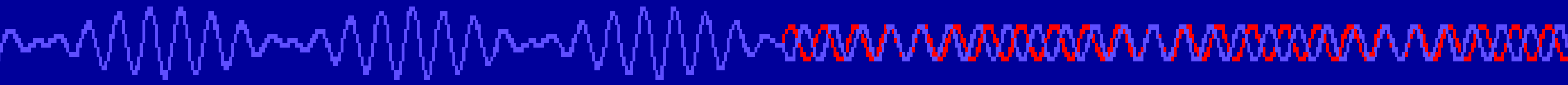
$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

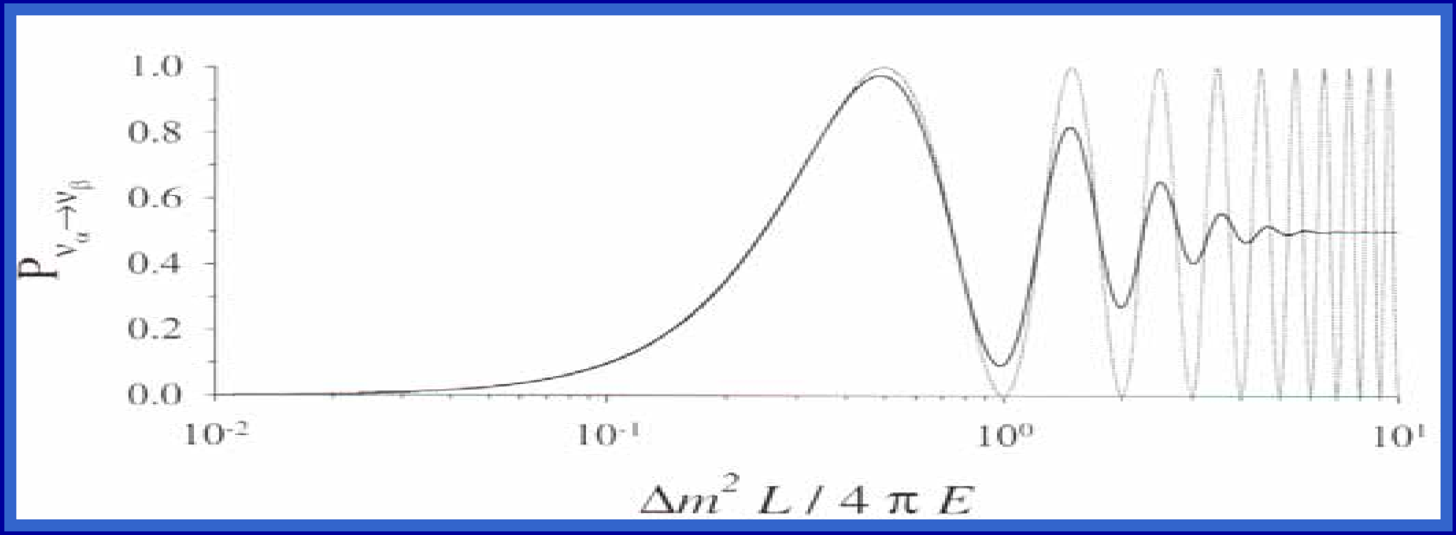
$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \, \sin^2(1.27 \Delta m^2 L/E)$$

$\Delta m^2 = m_2^2 - m_1^2$ (eV^2)

L (km): Distance from source to detector

E (GeV): Neutrino energy

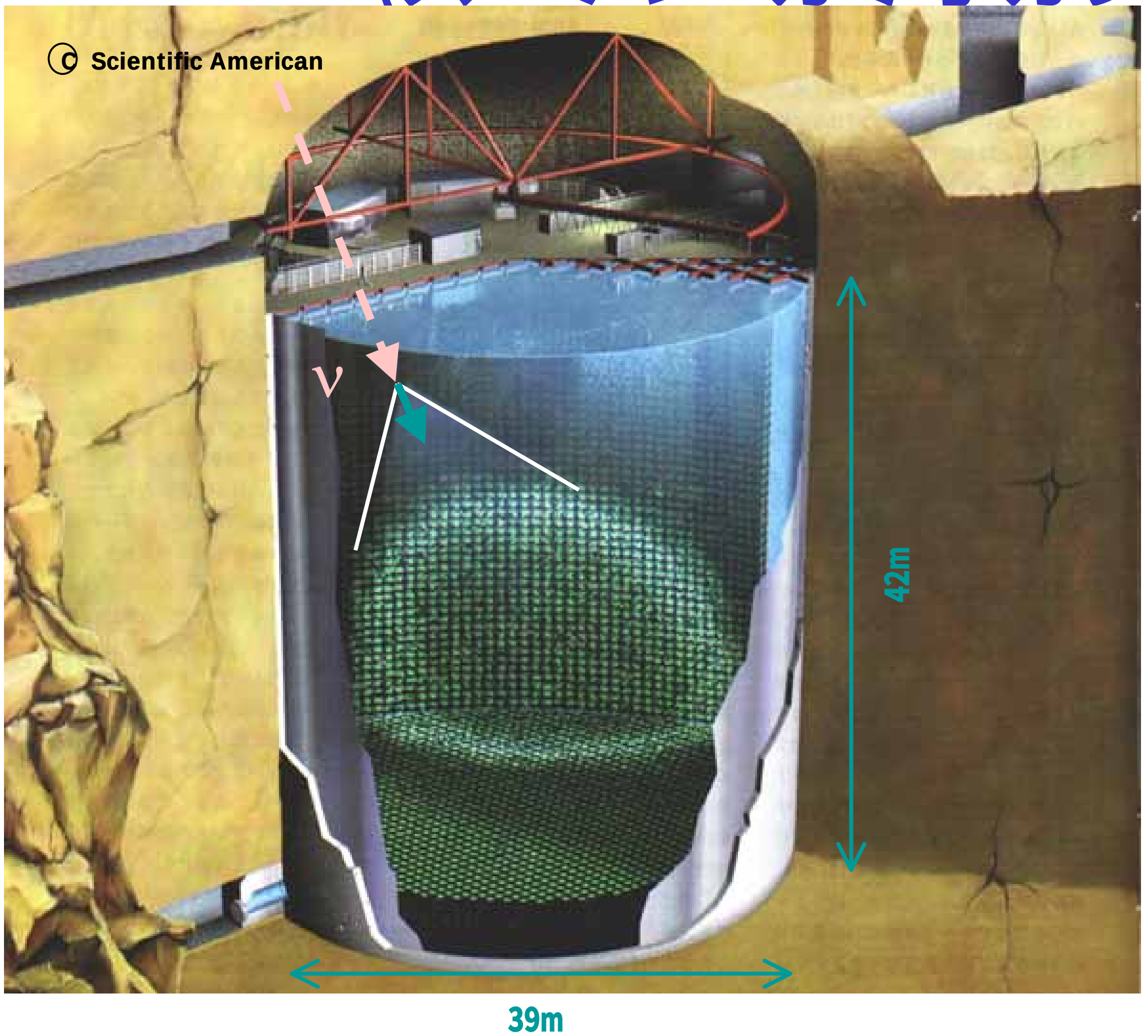




ニュートリノ振動の実験結果

- ❑ Solar neutrino data　太陽ニュートリノ
  (Super-Kamiokande, SNO)
- ❑ Atmospheric neutrino data　大気ニュートリノ
  (Super-Kamiokande)
- ❑ Neutrino beam data (K2K)　ニュートリノ·ビーム

Super- Kamiokande
(スーパーカミオカンデ)



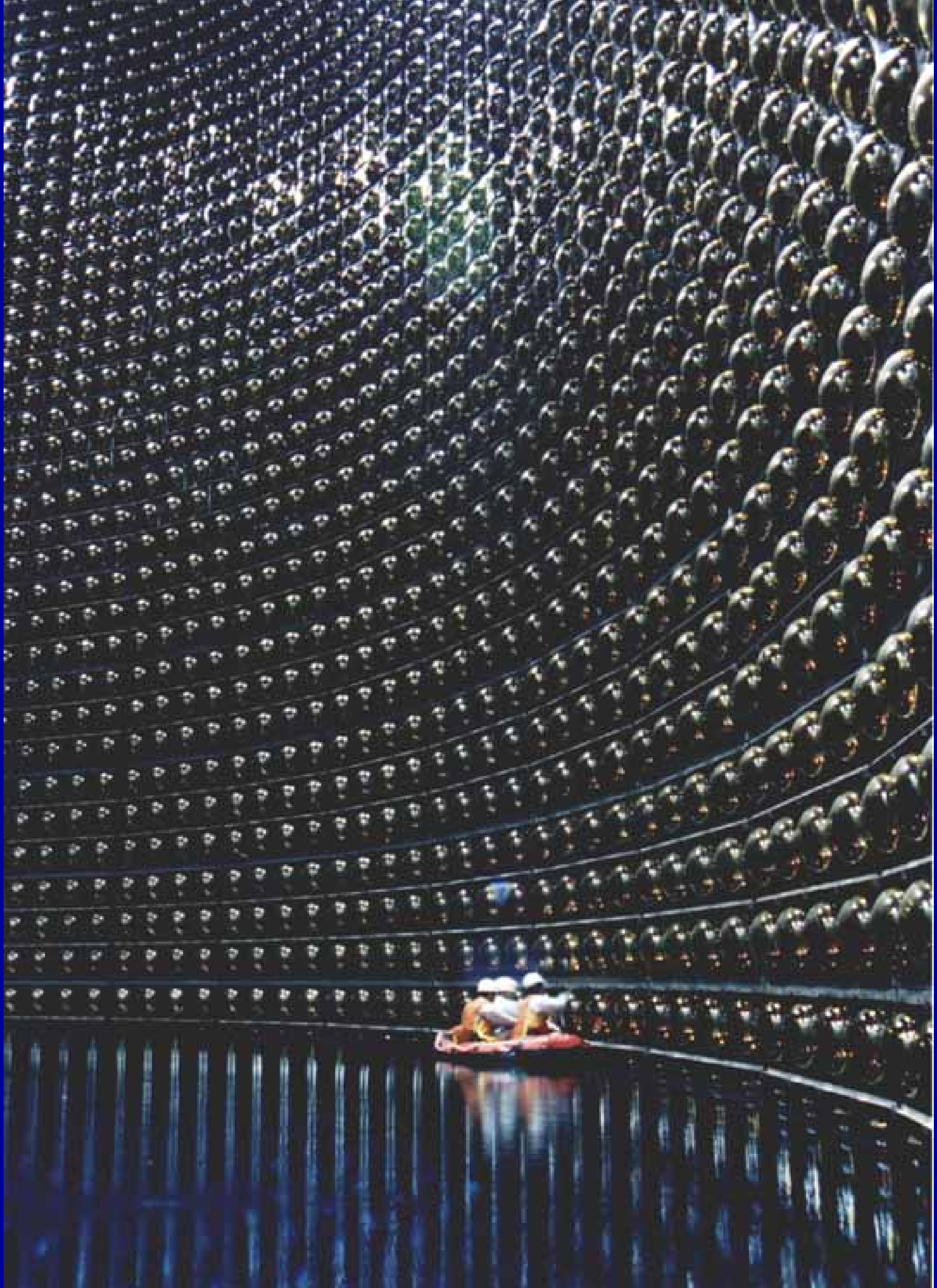
Water Cherenkov detector

- 1000 m underground
- 50,000 ton
  (22,500 ton fid.)
- 11,146 20 inch PMTs
- 1,885 anti-counter PMTs

SK-I: Apr 1996 – Jul 2001
SK-II: Dec 2002 –

SK-1

(Jan. 1996)



2001年11月12日の事故

6777 ID + 1100 OD PMTs destroyed


011227 1335 001 0047918

事故を繰り返さない為に

- Encase all the existing PMTs (5246) in acrylic + frp cases to prevent shock wave generation

修理完了
(Sep. 17, 2002)

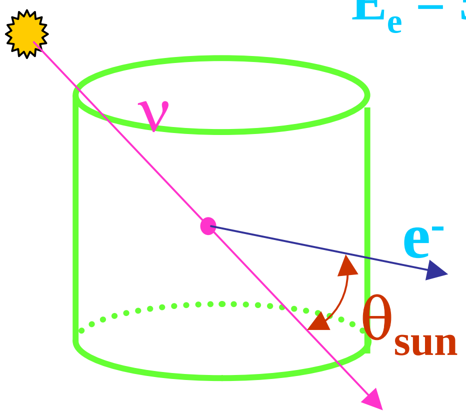
SK-II

Resumed data-taking in Dec, 2002!

Solar Neutrino Data of Super-Kamiokande

$\nu_e\, e \rightarrow \nu_e e$ scattering
(contains 15% of NC)

E_e = 5.0 - 20 MeV

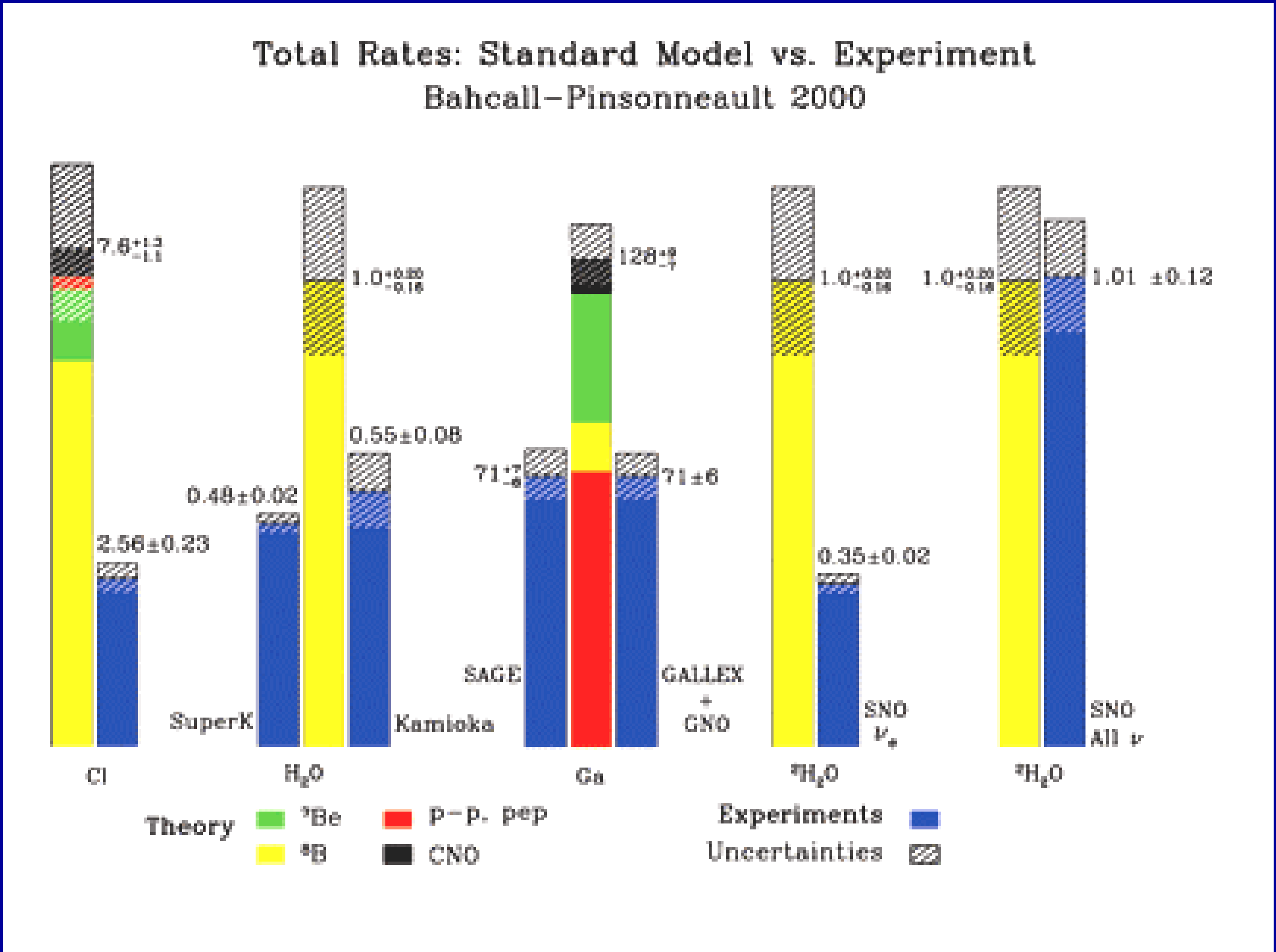


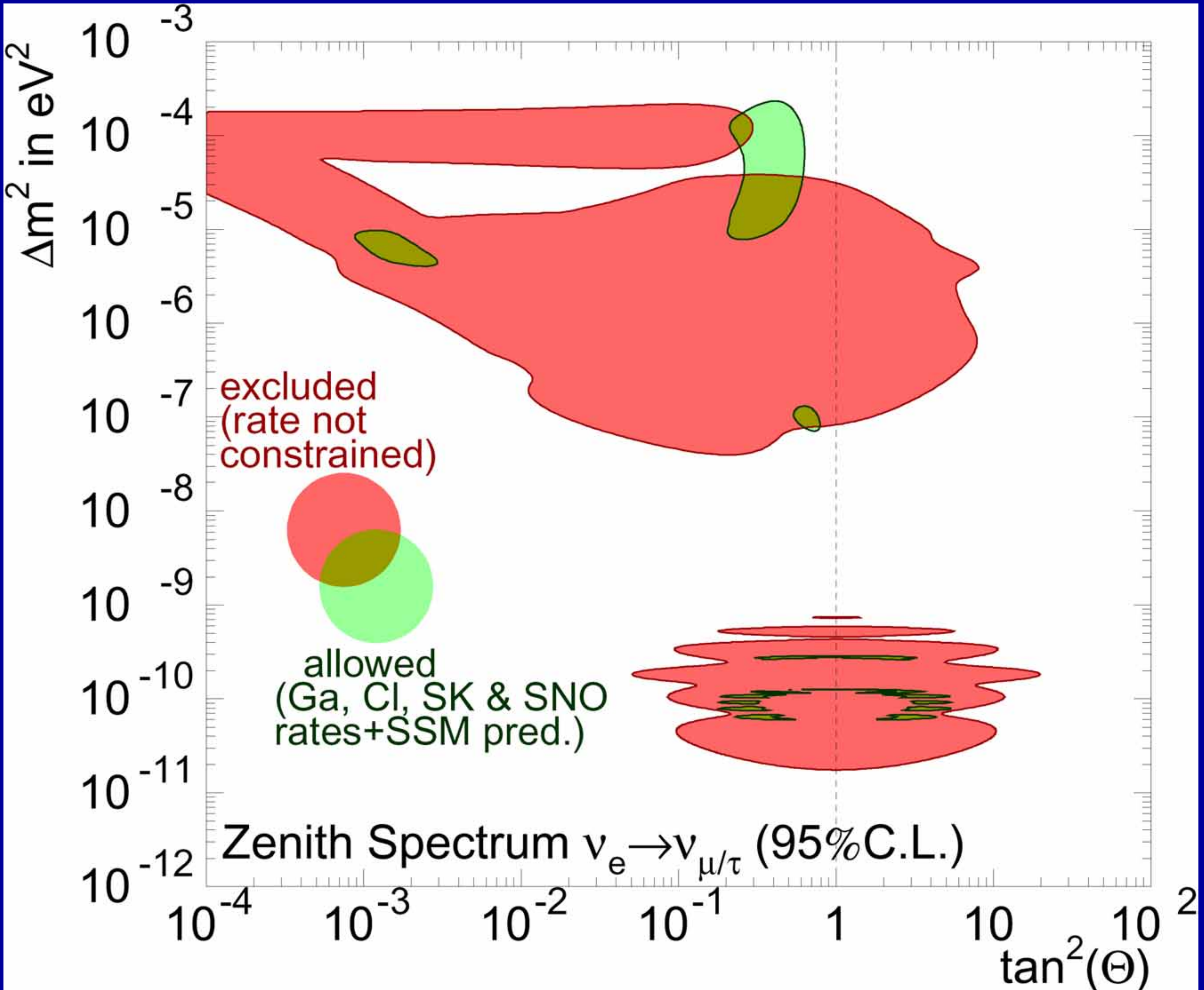
^{8}B flux : 2.35 ± 0.02 ± 0.08
[x 10^6 /cm^2/sec]

22385 solar ν events
(14.5 events/day)

$$\frac{\text{Data}}{\text{SSM}} = 0.465 \pm 0.005 \,{}^{+0.016}_{-0.015}$$

COSθ_{sun}


Total Rates: Standard Model vs. Experiment
Bahcall-Pinsonneault 2000
7.6 +1.3 −1.1
2.56±0.23
0.48±0.02
1.0 +0.20 −0.16
0.55±0.08
SuperK
Kamioka
128 +9 −7
71 +7 −6
71±6
SAGE
GALLEX + GNO
1.0 +0.20 −0.16
0.35±0.02
SNO ν_e
1.0 +0.20 −0.16
1.01 ±0.12
SNO All ν
Cl
H_2O
Ga
^2H_2O
^2H_2O
Theory
^{7}Be
^{8}B
p-p, pep
CNO
Experiments
Uncertainties

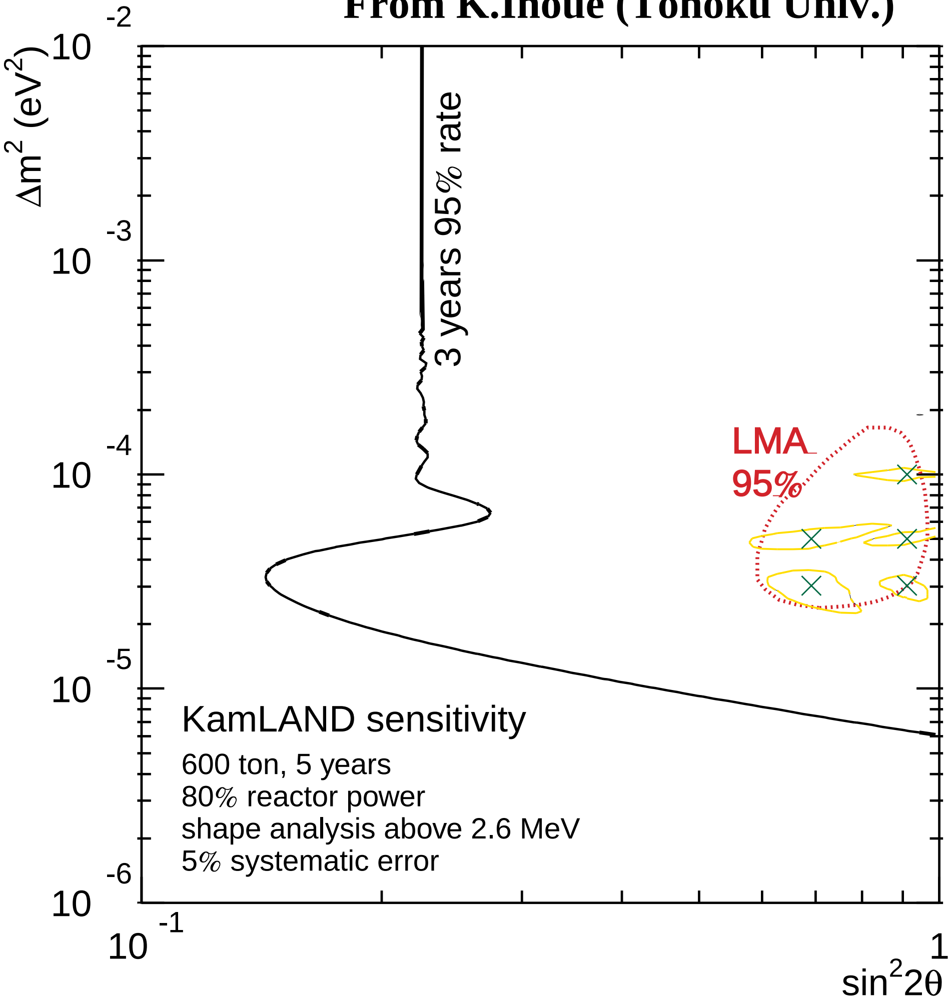


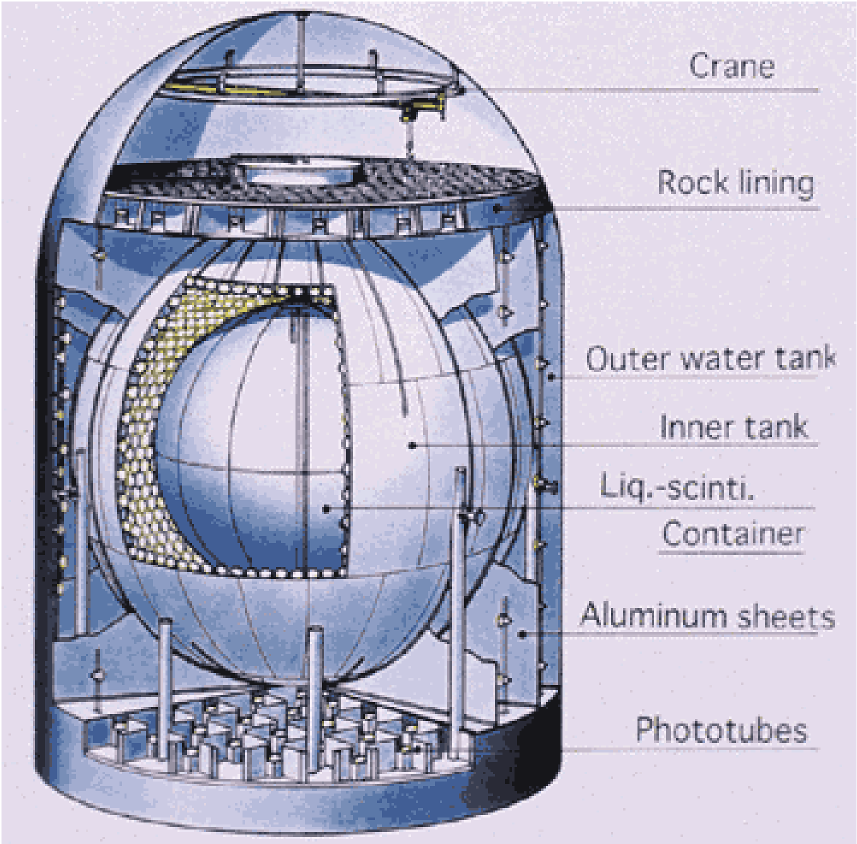
Δm^2 in eV^2
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
excluded
(rate not
constrained)
allowed
(Ga, Cl, SK & SNO
rates+SSM pred.)
Zenith Spectrum $\nu_e \rightarrow \nu_{\mu/\tau}$ (95%C.L.)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\Theta)$

KamLAND (カムランド)

(Confirmation of solar neutrino oscillations)

From K.Inoue (Tohoku Univ.)





太陽ニュートリノデータのまとめ

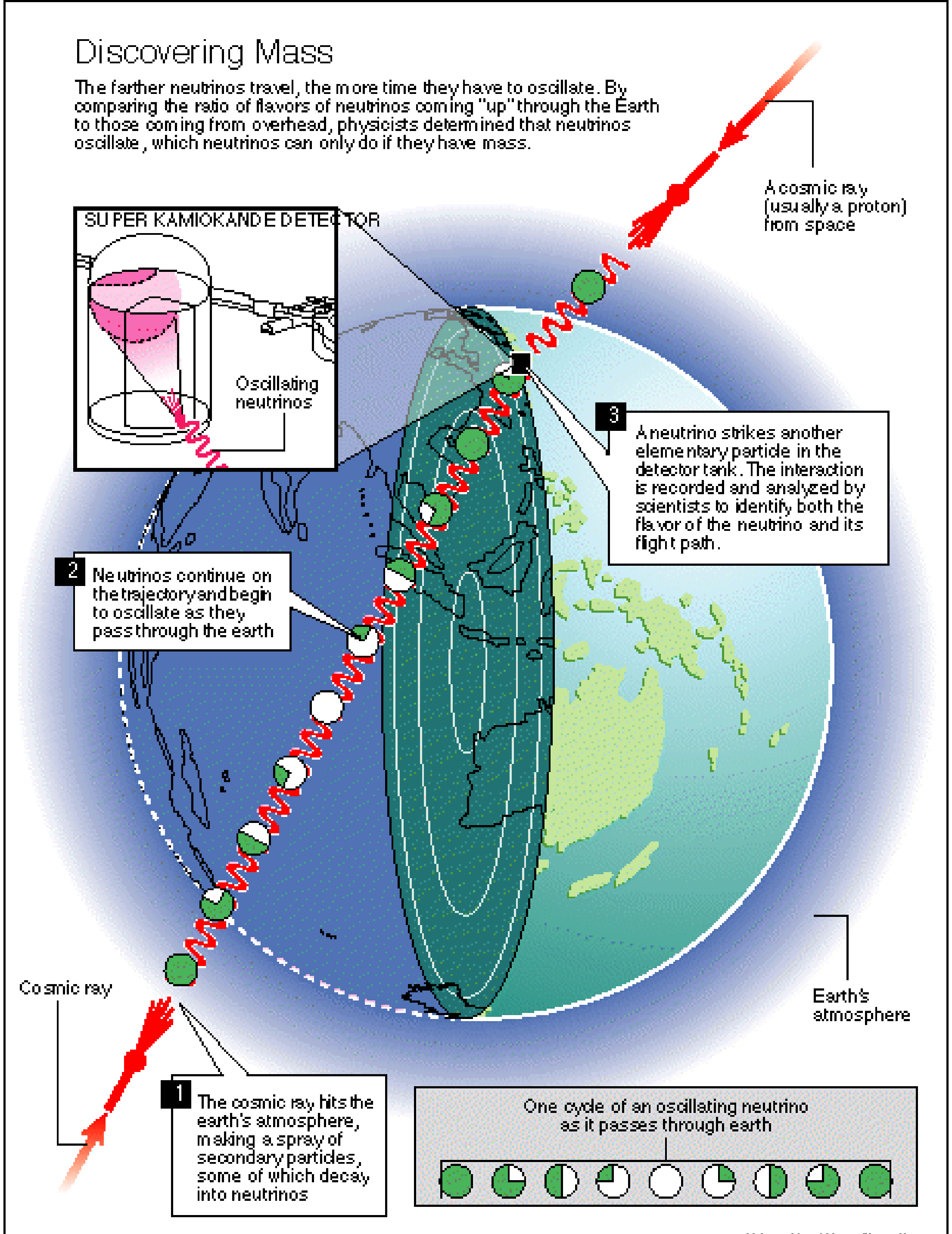
- Solar neutrino oscillations ($\nu_e \rightarrow \nu_\mu/\nu_\tau$) are established by Super-Kamiokande and SNO data. ($\Delta m_{12}^2 \sim 10^{-4} eV^2$)
- LMA solutions are favored by no spectrum distortion and no day/night effect.
- Large Mixing Angle(LMA) by a global fit:

  $2.5 \times 10^{-5} eV^2 < \Delta m^2$ (Δm_{12}^2) $< 3.3 \times 10^{-4} eV^2$

  $0.25 < \tan^2\theta < 0.9$ (3σ C.L.)
- KamLAND confirmed the LMA at 4.6σ C.L.

See also: Phys. Lett. B539 179-187, 2002

大気ニュートリノ振動



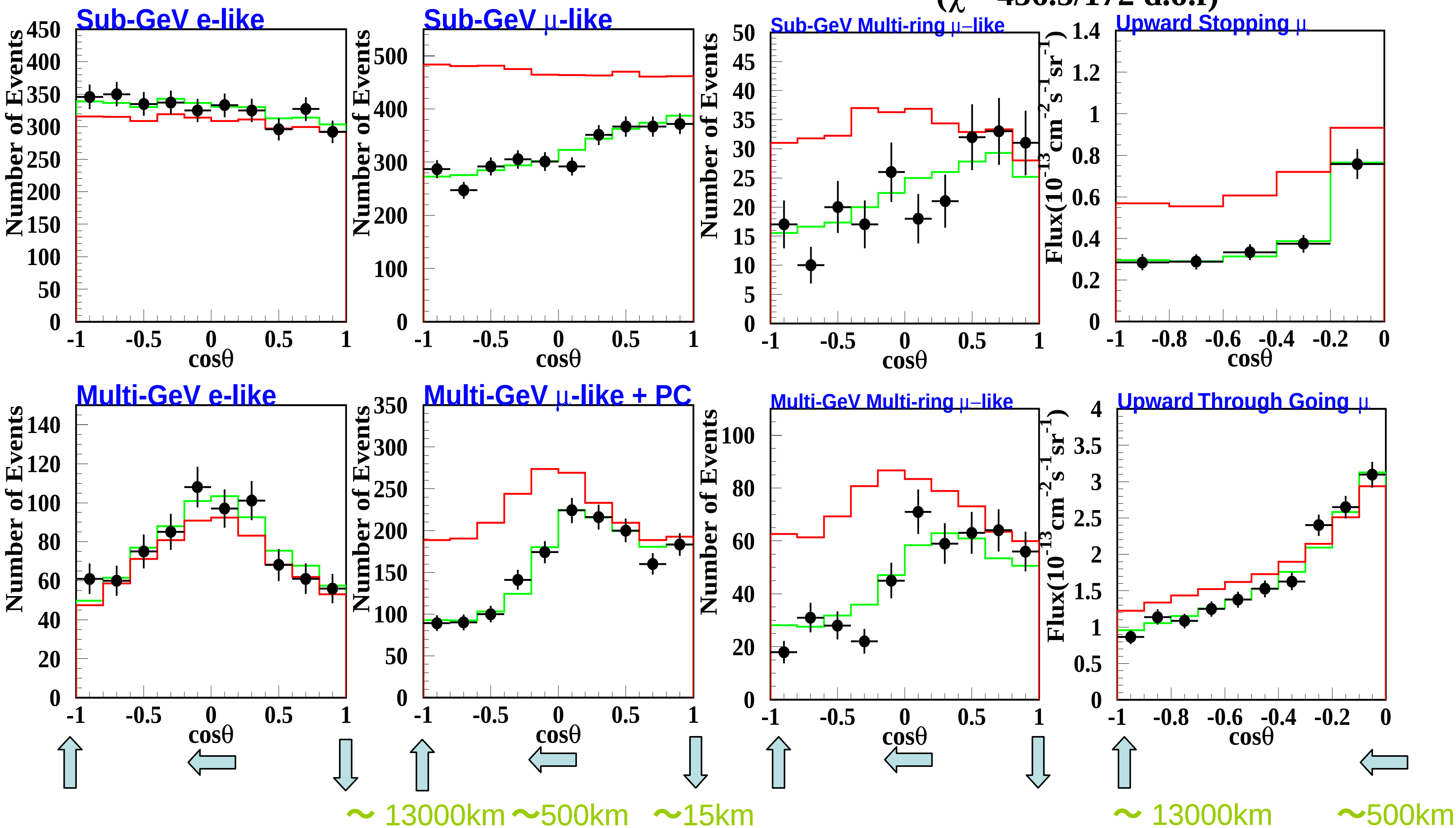
Discovering Mass
The farther neutrinos travel, the more time they have to oscillate. By comparing the ratio of flavors of neutrinos coming "up" through the Earth to those coming from overhead, physicists determined that neutrinos oscillate, which neutrinos can only do if they have mass.
SUPER KAMIOKANDE DETECTOR
Oscillating neutrinos
A cosmic ray (usually a proton) from space
3
A neutrino strikes another elementary particle in the detector tank. The interaction is recorded and analyzed by scientists to identify both the flavor of the neutrino and its flight path.
2
Neutrinos continue on the trajectory and begin to oscillate as they pass through the earth
Cosmic ray
Earth's atmosphere
1
The cosmic ray hits the earth's atmosphere, making a spray of secondary particles, some of which decay into neutrinos
One cycle of an oscillating neutrino as it passes through earth

Zenith Angle Distributions 天頂角分布

$\nu_\mu \leftrightarrow \nu_\tau$
2-flavor oscillations

Best fit ($\Delta m^2=2.5\times10^{-3}eV^2$, $\sin^2 2\theta=1.0$
$\chi^2_{min}=163.2/170$ d.o.f)

Null oscillation
($\chi^2=456.5/172$ d.o.f)



Evidence for neutrino oscillations and masses

The most cited paper in the experimental particle physics (more than 1,600)

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. Koshiba,[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. Young[23]

(Super-Kamiokande Collaboration)

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[22] *Institute of Experimental Physics, Warsaw University, 00-681 Warsaw, Poland*
[23] *Department of Physics, University of Washington, Seattle, Washington 98195-1560*

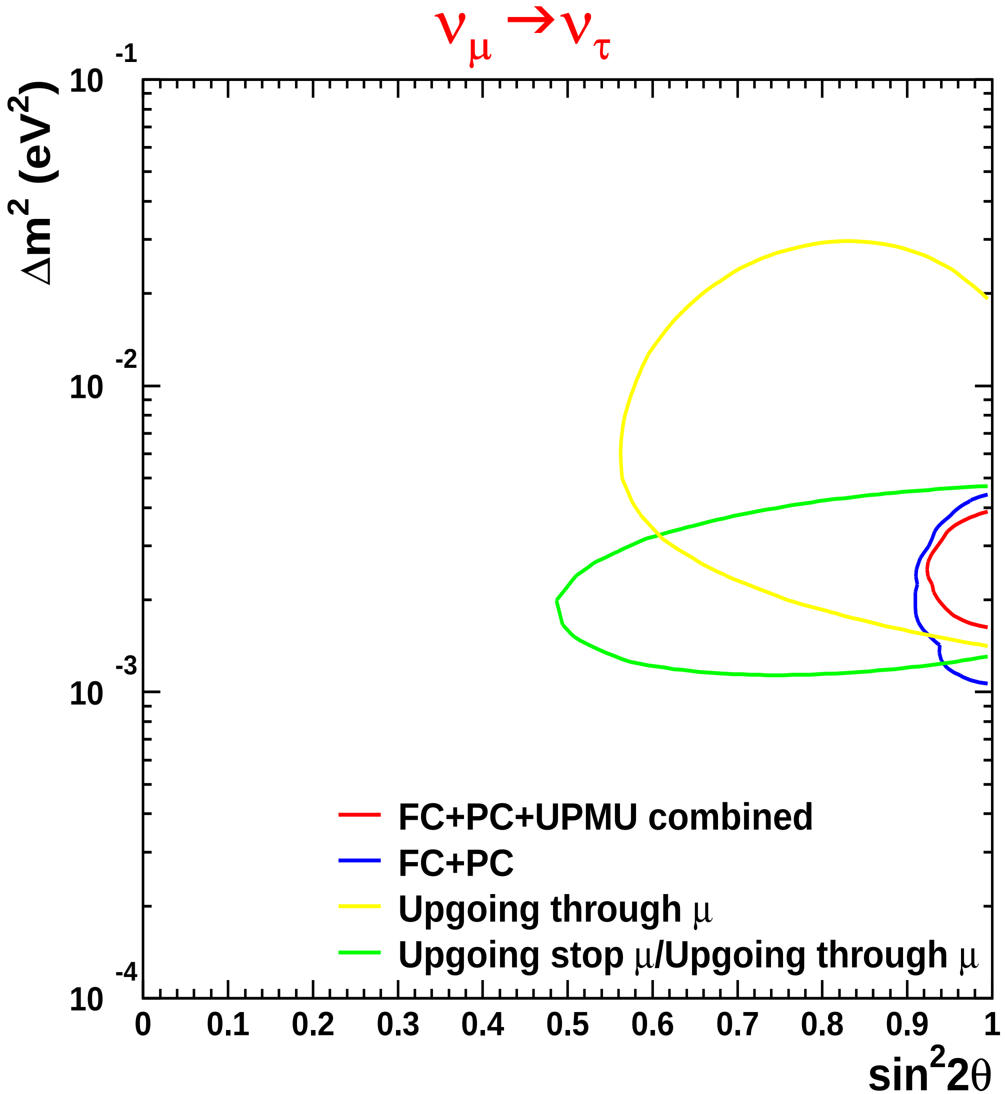
(Received 6 July 1998)

We present an analysis of atmospheric neutrino data from a 33.0 kton yr (535-day) exposure of the Super-Kamiokande detector. The data exhibit a zenith angle dependent deficit of muon neutrinos which is inconsistent with expectations based on calculations of the atmospheric neutrino flux. Experimental biases and uncertainties in the prediction of neutrino fluxes and cross sections are unable to explain our observation. The data are consistent, however, with two-flavor $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with $\sin^2 2\theta > 0.82$ and $5 \times 10^{-4} < \Delta m^2 < 6 \times 10^{-3}$ eV^2 at 90% confidence level. [S0031-9007(98)06975-0]

PACS numbers: 14.60.Pq, 96.40.Tv

Atmospheric neutrinos are produced as decay products in hadronic showers resulting from collisions of cosmic rays with nuclei in the upper atmosphere. Production of electron and muon neutrinos is dominated by the processes $\pi^+ \to \mu^+ + \nu_\mu$ followed by $\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$ (and their charge conjugates) giving an expected ratio

$\nu_\mu \Leftrightarrow \nu_\tau$ 振動 (Δm_{23}^2)



Best fit(Δm^2=2.5x10^{-3},$\sin^2 2\theta$=1.0

χ^2_{min}=163.2/170 d.o.f)

$\Delta m_{23}^2 = (1.6\sim3.9)\times10^{-3}\,\mathrm{eV}^2$

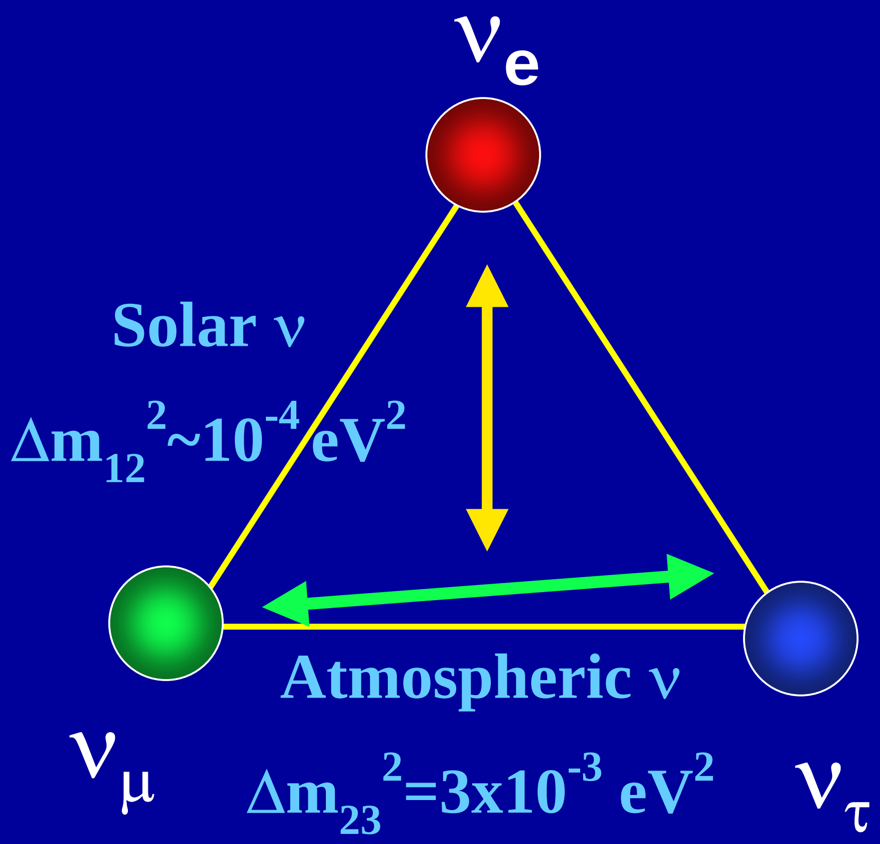
$\sin^2 2\theta_{23} > 0.92$ (90%CL)

3-flavor mixing

3つのフレーバー間の混合

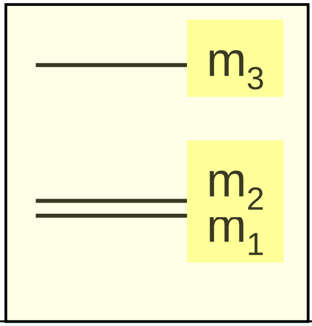
θ_{13}?

太陽ニュートリノと大気ニュートリノにおける3つのフレーバー間の混合



3つのフレーバー間の振動

Oscillation Probabilities when $\Delta m_{12}^2 << \Delta m_{23}^2 \approx \Delta m_{13}^2$



Atmospheric ν

- θ_{23} :ν_μ disappearance

$$P_{\mu \to x} \approx 1 - \cos^4\theta_{13} \cdot \sin^2 2\theta_{23} \cdot \sin^2\left(1.27\,\Delta m_{23}^2 L / E_\nu\right)$$

- θ_{13}:ν_e appearance

$$P_{\mu \to e} \approx \sin^2\theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(1.27\,\Delta m_{23}^2 L / E_\nu\right)$$

common

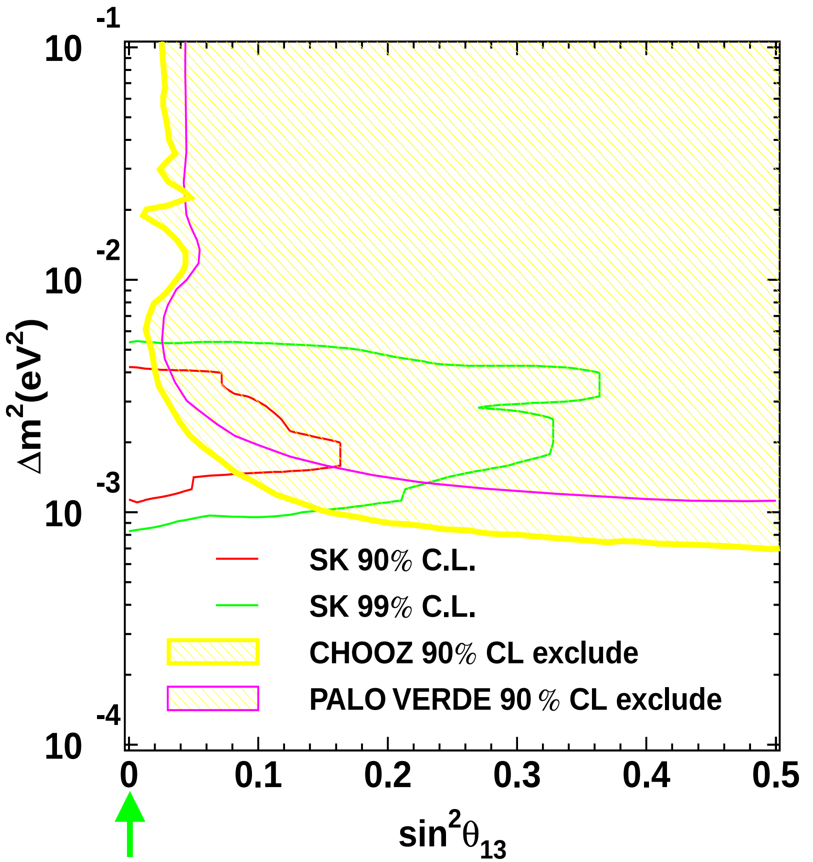
Solar ν

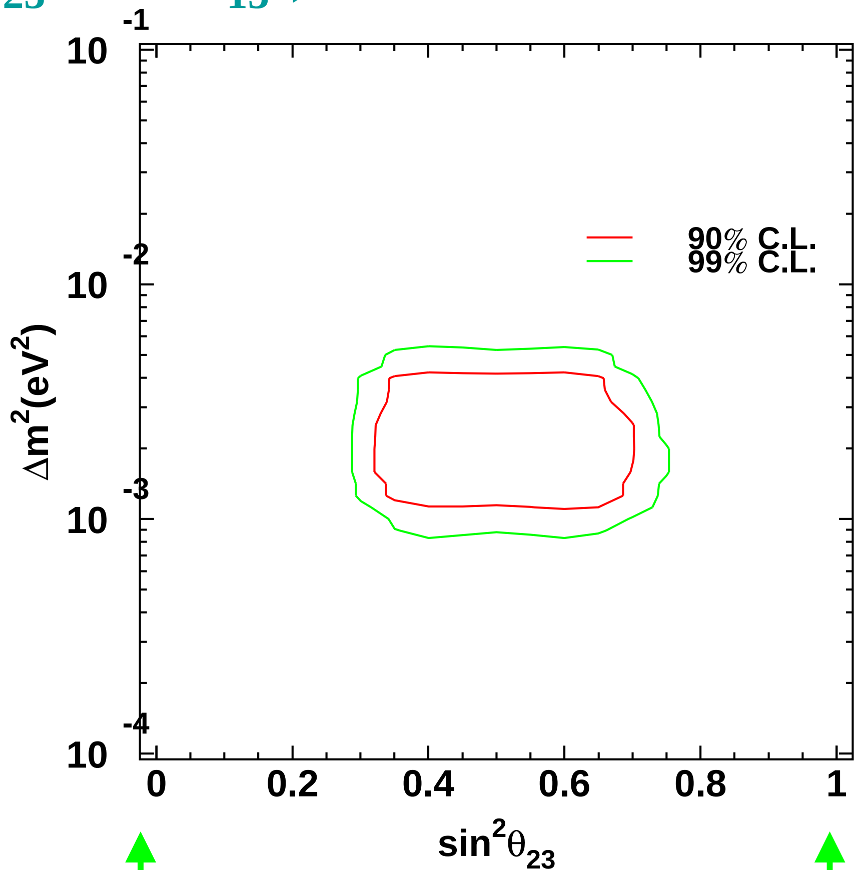
- θ_{12}:ν_e disappearance

$$P_{e \to x} \approx \cos^4\theta_{13} \cdot \sin^2 2\theta_{12} \cdot \sin^2\left(1.27\,\Delta m_{12}^2 L / E_\nu\right)$$
$$+ \tfrac{1}{2}\sin^2 2\theta_{13}$$

3つのフレーバー間の振動の実験結果から許された領域

$(\Delta m^2 = \Delta m_{23}^2 \sim \Delta m_{13}^2)$





Pure $\nu_\mu \leftrightarrow \nu_\tau$

getting close to CHOOZ's limit on θ_{13}

Pure $\nu_e \leftrightarrow \nu_\tau$

Pure $\nu_e \leftrightarrow \nu_\mu$

consistent with CHOOZ's excluded region

大気ニュートリノデータのまとめ

- ❑ $\nu_\mu \leftrightarrow \nu_\tau$ 2 flavor oscillations are established.

  $(\Delta m^2 = \Delta m_{23}^2 \sim \Delta m_{13}^2 >> \Delta m_{12}^2)$

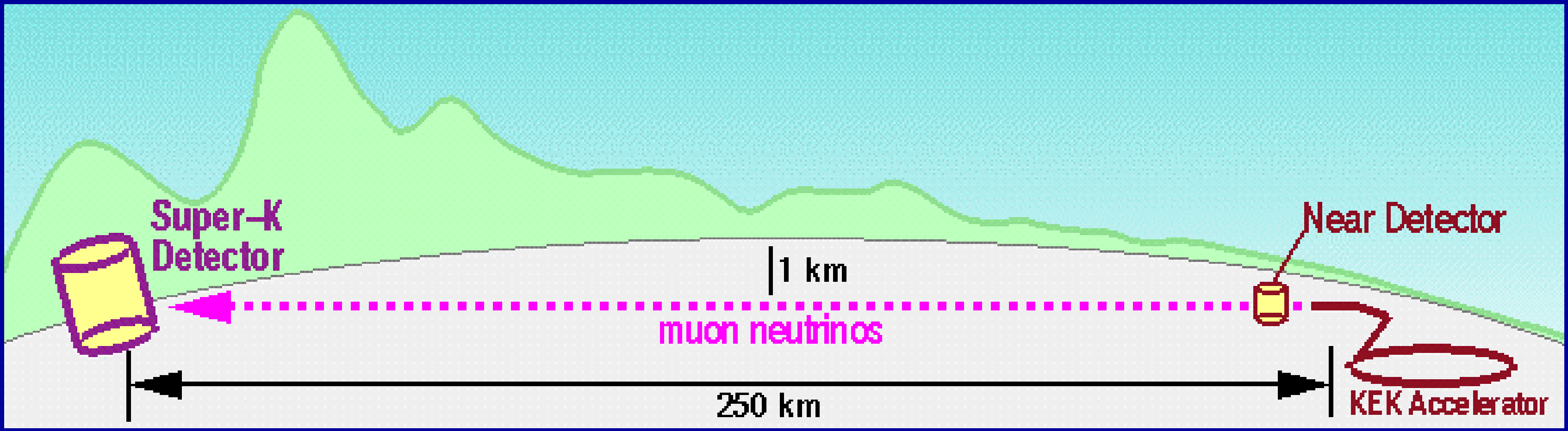
  $\Delta m^2 = (1.6\sim3.9)\text{x}10^{-3}\text{eV}^2$

  $\sin^2 2\theta_{23} > 0.92$ (90% C.L.)

- ❑ ν_s admixture is disfavored ($\sin^2 \xi$<0.19 @90%CL).
- ❑ 3 flavor oscillations are tested and give an allowed region of θ_{13}, consistent with CHOOZ:

  $\sin^2\theta_{13} < 0.1$ (90% C.L.)

K2K (KEK to Kamioka)実験



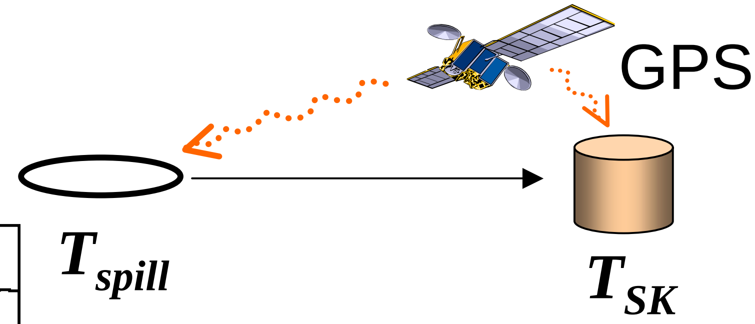
KEKで検出されたニュートリノ

(June 1999 – July 2001)

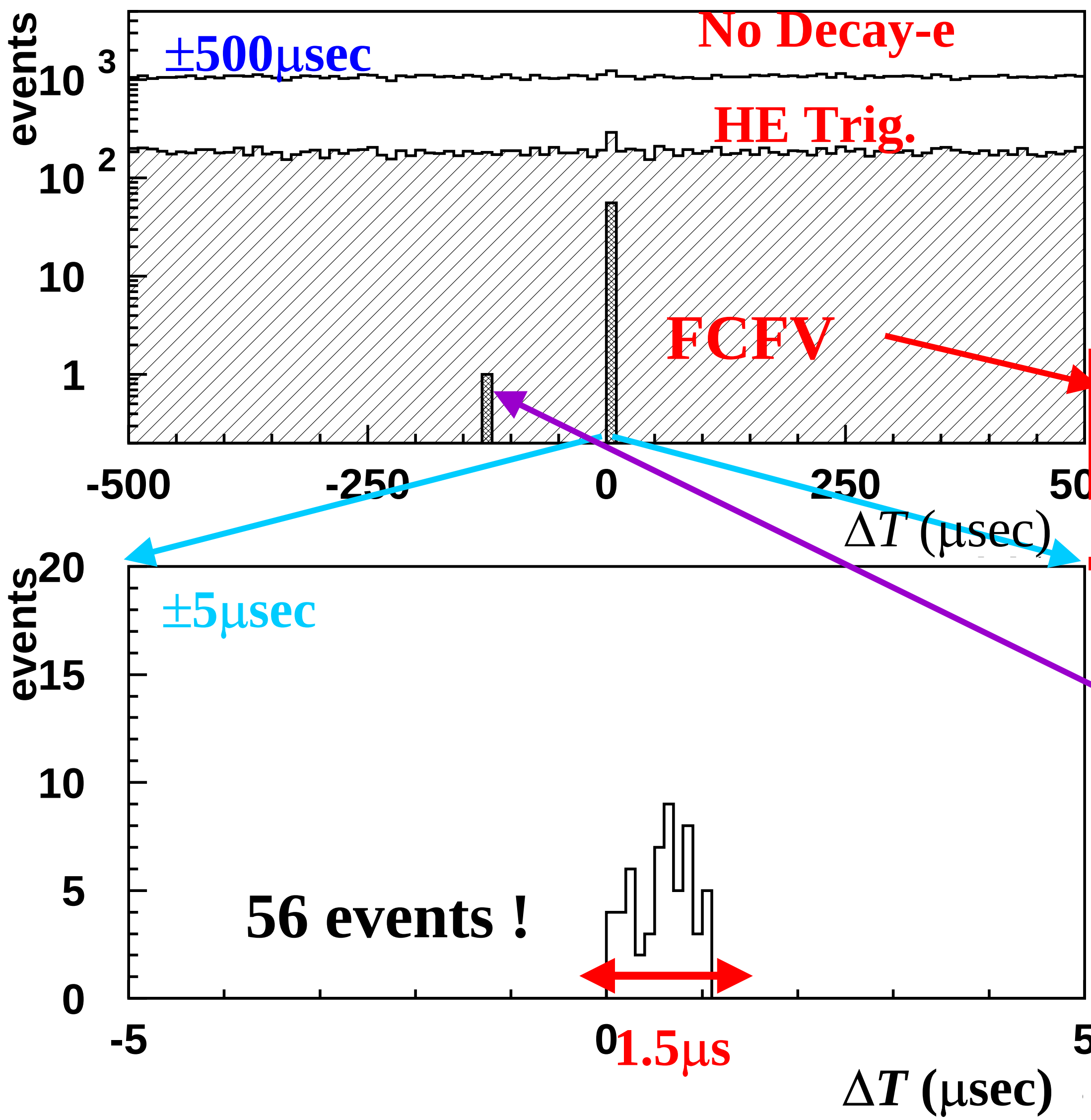
Detector	Neutrino Events	Expectation at SK
1kt (25t, H_2O)	~80,000	80.6 $\pm 0.3(stat)^{+7.3}_{-8.0}(sys)$
SciFi (5.9t, H_2O+Al)	7,240	87.6 $\pm 1.03(stat)^{+10.6}_{-11.9}(sys)$
MRD (73t, Fe)	~125,000	87.4 $\pm 0.24(stat)^{+12.7}_{-13.9}(sys)$

Super-K での事象検出

$$-0.2 \le \Delta T \equiv T_{SK} - T_{Spill} - \mathrm{TOF} \le 1.3\mu\mathrm{sec}$$



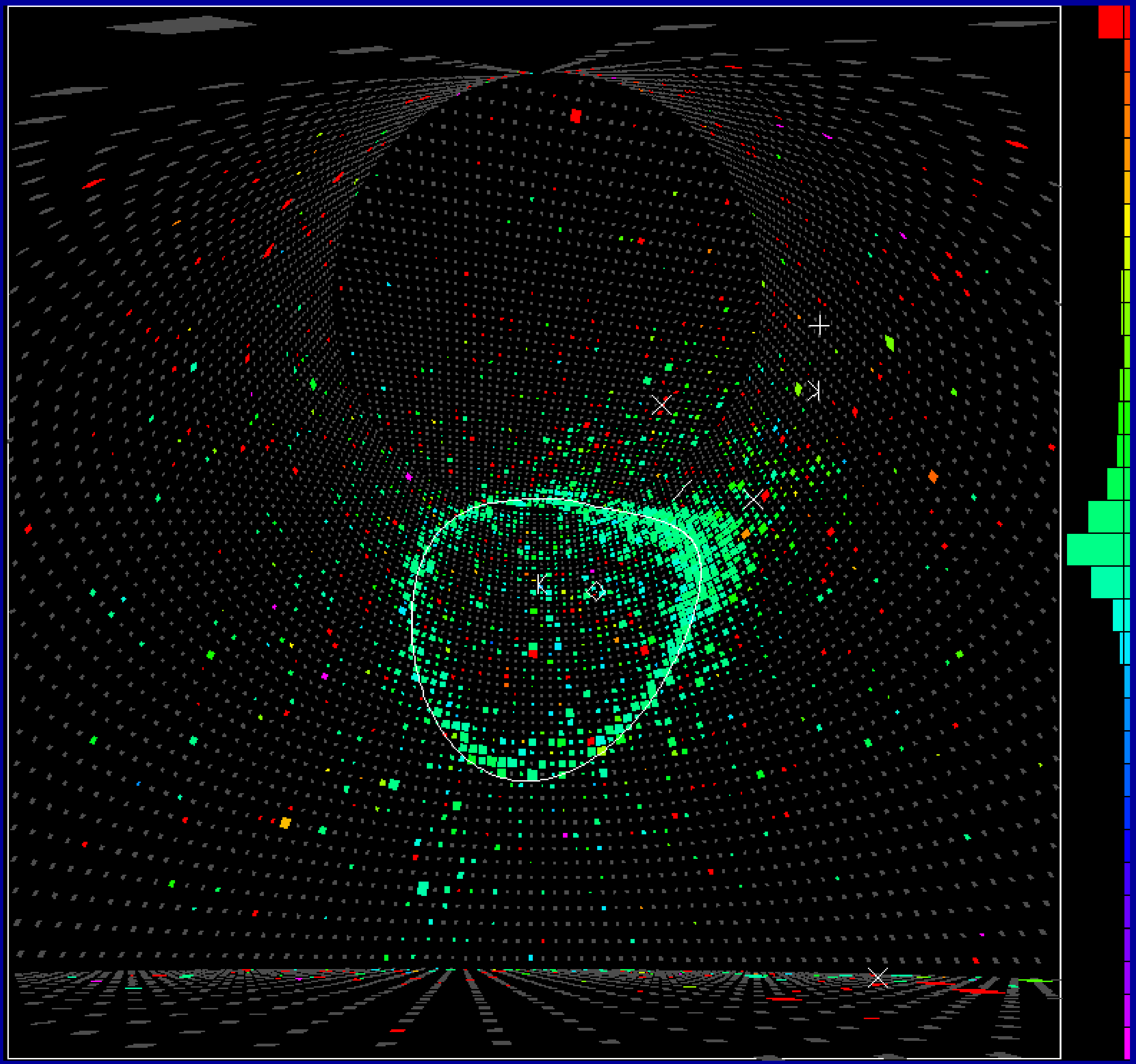
T_{Spill}: Abs. time of spill start
T_{SK}: Abs. time of SK event
TOF: 0.83ms (KEK to Kamioka)



FC: fully contained
(No activity in Outer Detector)
FV: 22.5kt Fiducial Volume

Expected Atm. ν BG
$<10^{-3}$ within 1.5μs.

Super-Kamiokandeでのニュートリノ反応

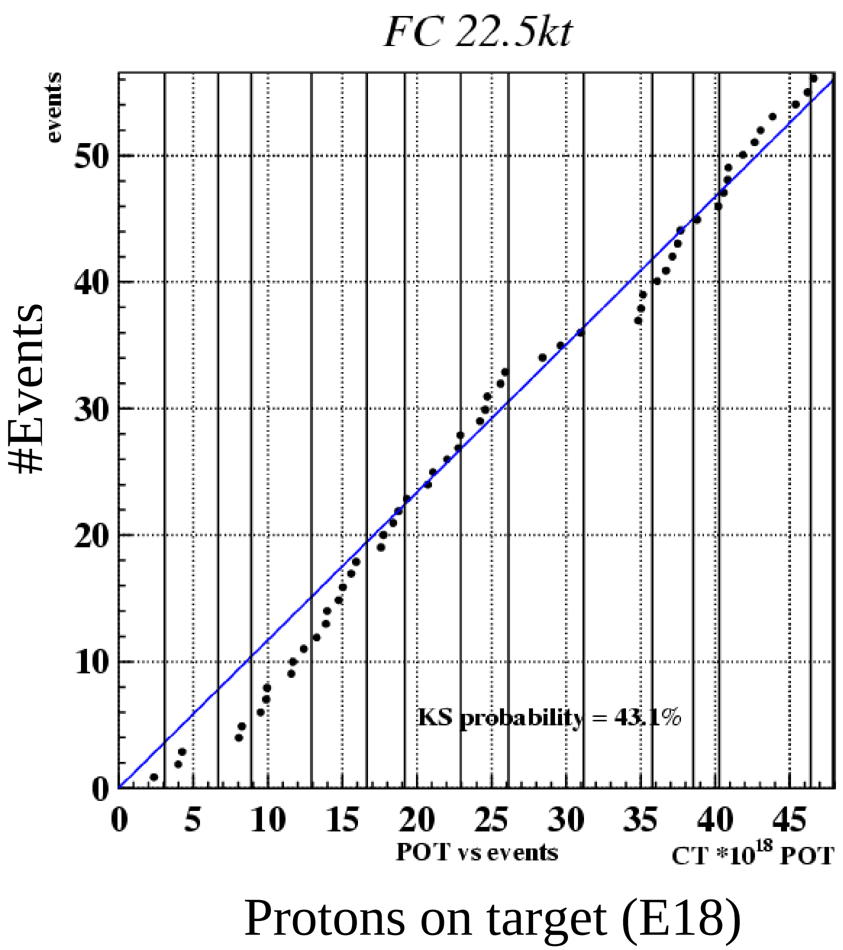


K2K実験でのニュートリノ振動の結果

●Number of total interactions
(Jun99-Jul01)

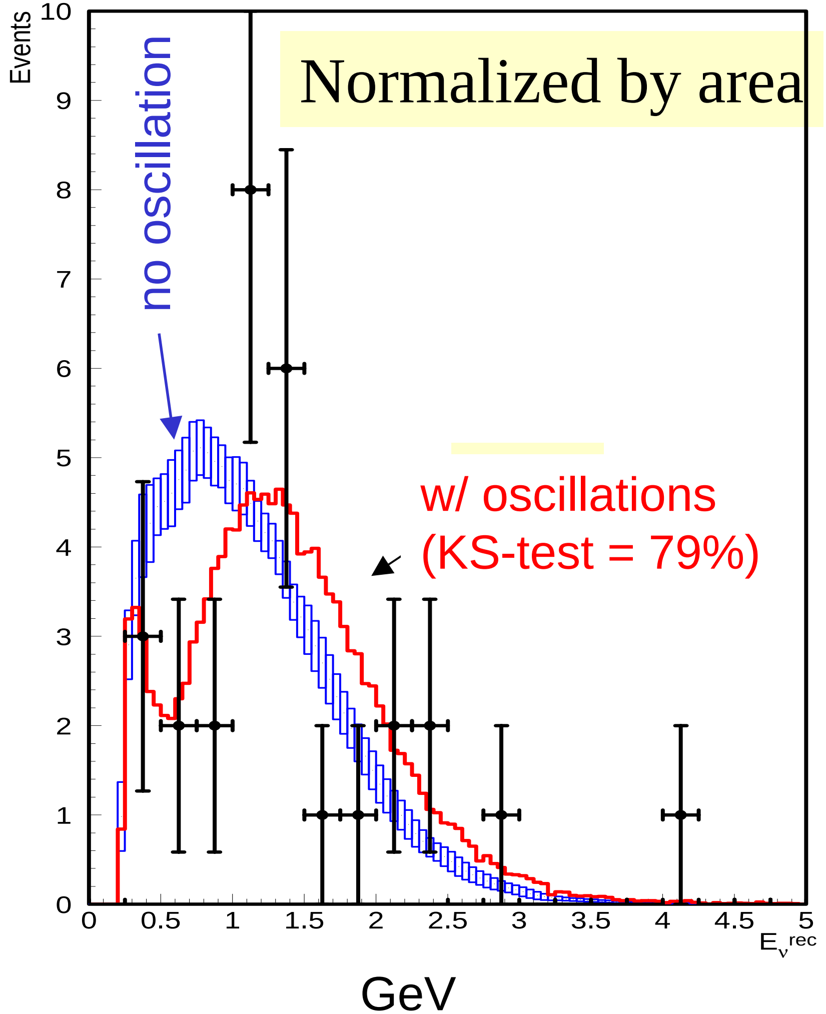
N_{obs}=56

N_{exp}=80.1 $^{+6.2}_{-5.4}$

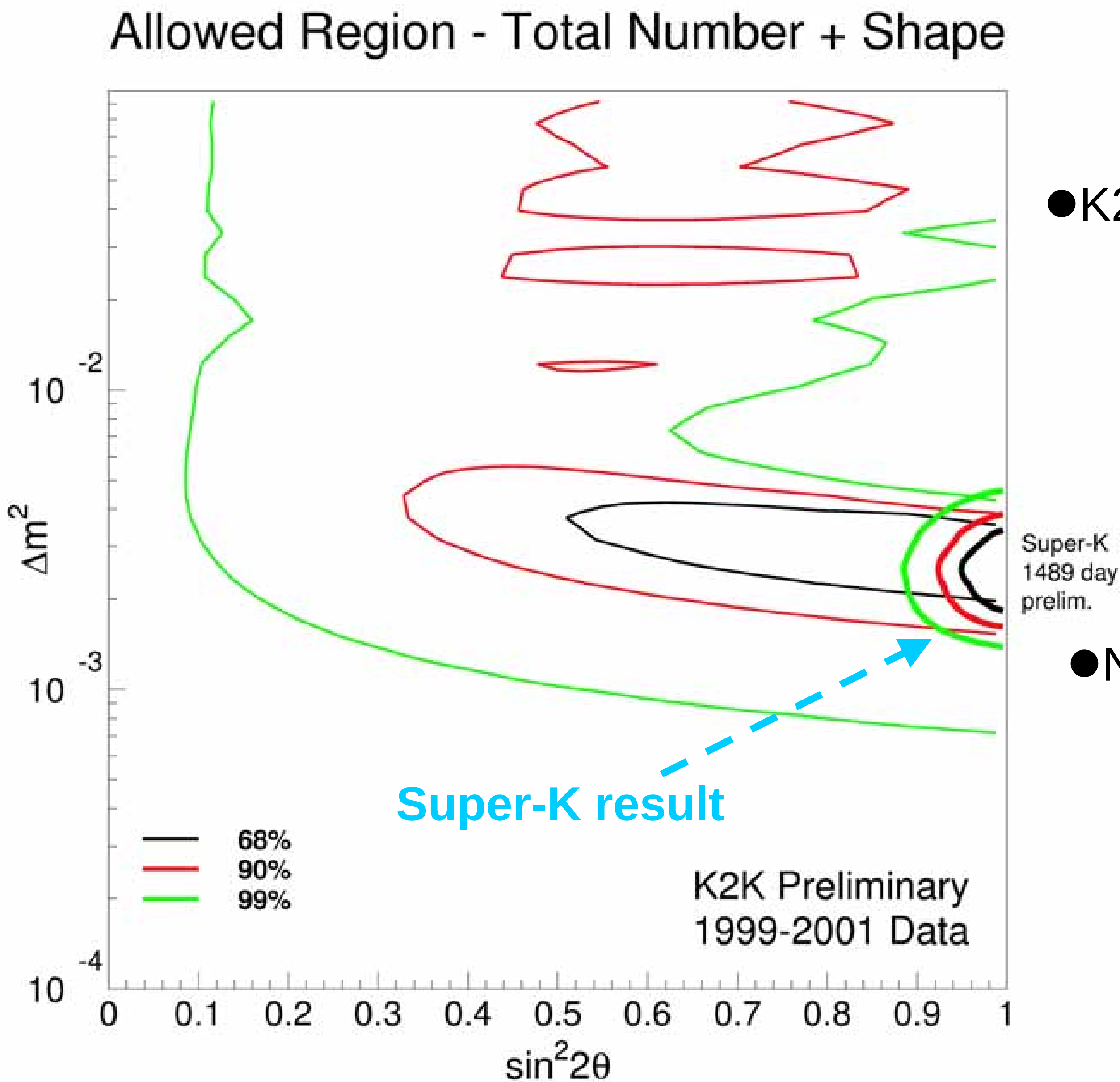


+

●Reconstructed Eν shape of 1-RFCμ
(29 1-R events in Nov99-Jul01)



K2K実験結果



- K2K Best fit point =

  (1.0, 2.8x10^{-3}eV^2)

  - Method1 2.8x10^{-3}
  - Method2 2.7x10^{-3}

- Null oscillation probability

  ⇨ < 1%

  - Method1 0.7%
  - Method2 0.4%

Two independent methods agree with each other

レプトンセクターでのフレーバー混合
(素粒子物理の新分野が始まった!)

- MNS(Maki-Nakagawa-Sakata) 混合行列

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} & & \\ & U_{\alpha i} & \\ & & \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \qquad (\Delta \mathrm{m}^2_{12} + \Delta \mathrm{m}^2_{23} + \Delta \mathrm{m}^2_{31} = 0)$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

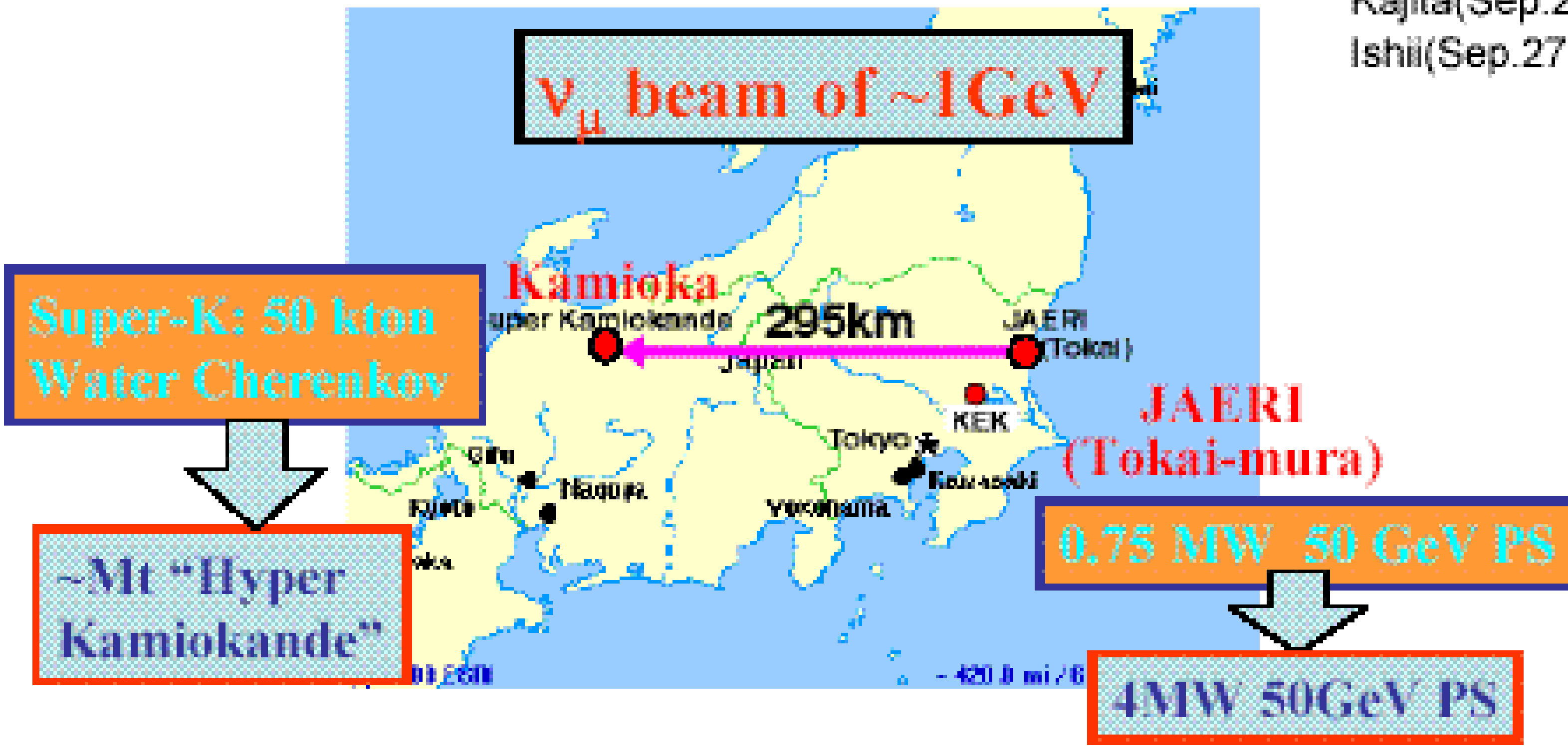
$$\mathrm{P}(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2 \Phi_{ij}$$
$$\pm 2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2 \Phi_{ij}$$

$$\Phi_{ij} \equiv \Delta \mathrm{m}^2_{ij} L / 4E_\nu = 1.27 \Delta \mathrm{m}^2_{ij} [\mathrm{eV}^2] L[\mathrm{km}] / E_\nu [\mathrm{GeV}]$$

JHF-神岡ニュートリノ実験(2007)

Overview of experiment

Kajita(Sep.26)
Ishii(Sep.27)



1st Phase

- $\nu_\mu \rightarrow \nu_x$ disappearance
- $\nu_\mu \rightarrow \nu_e$ appearance
- NC measurement

2nd Phase

- CPV
- proton decay