Evidence for Neutrino Mass

Leads to

Kamiokande-II

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(KEK, High Energy Accelerator Research Organization)

Neutrino 2006, SantaFe, June 14, 2006

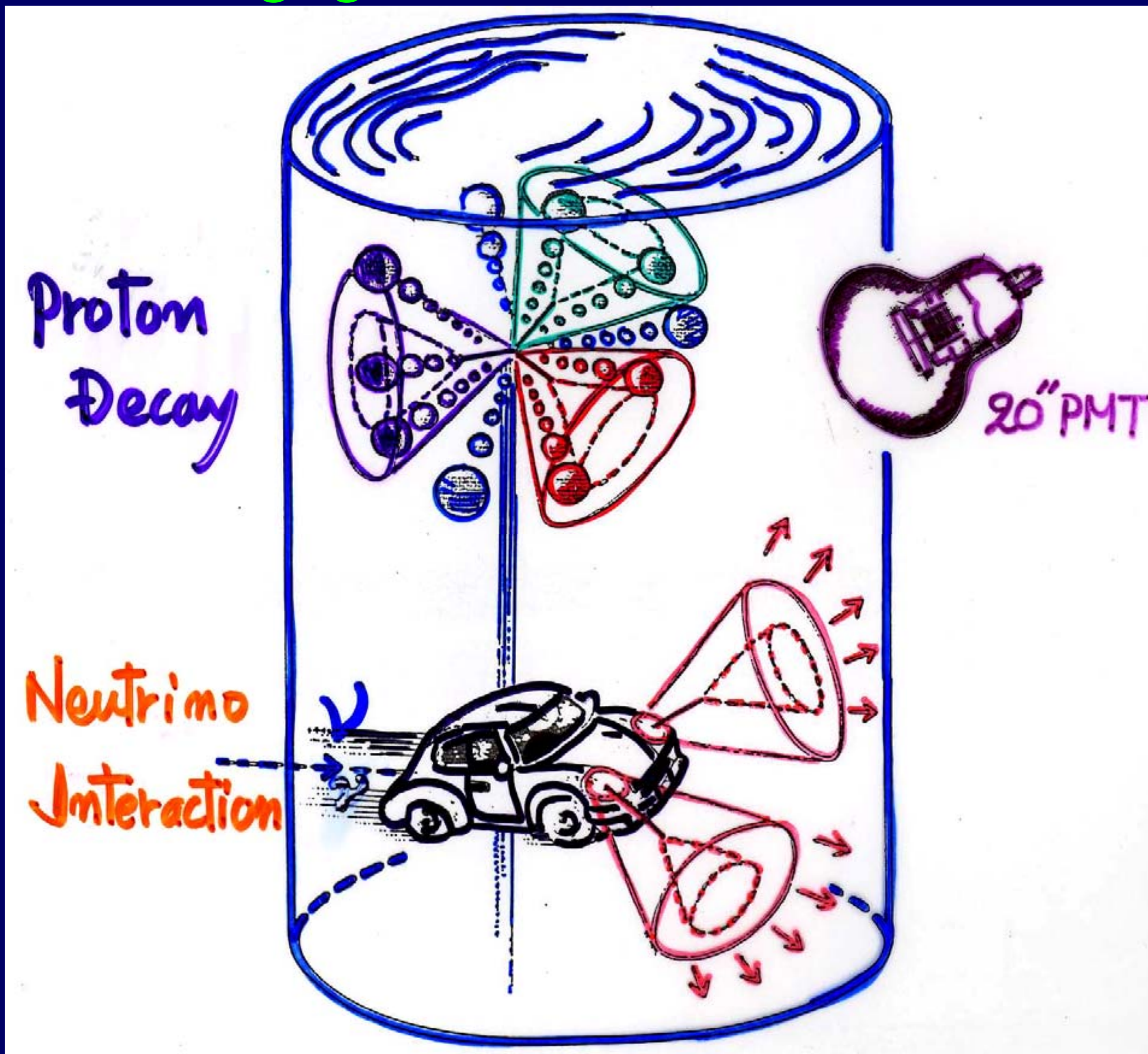
Outline

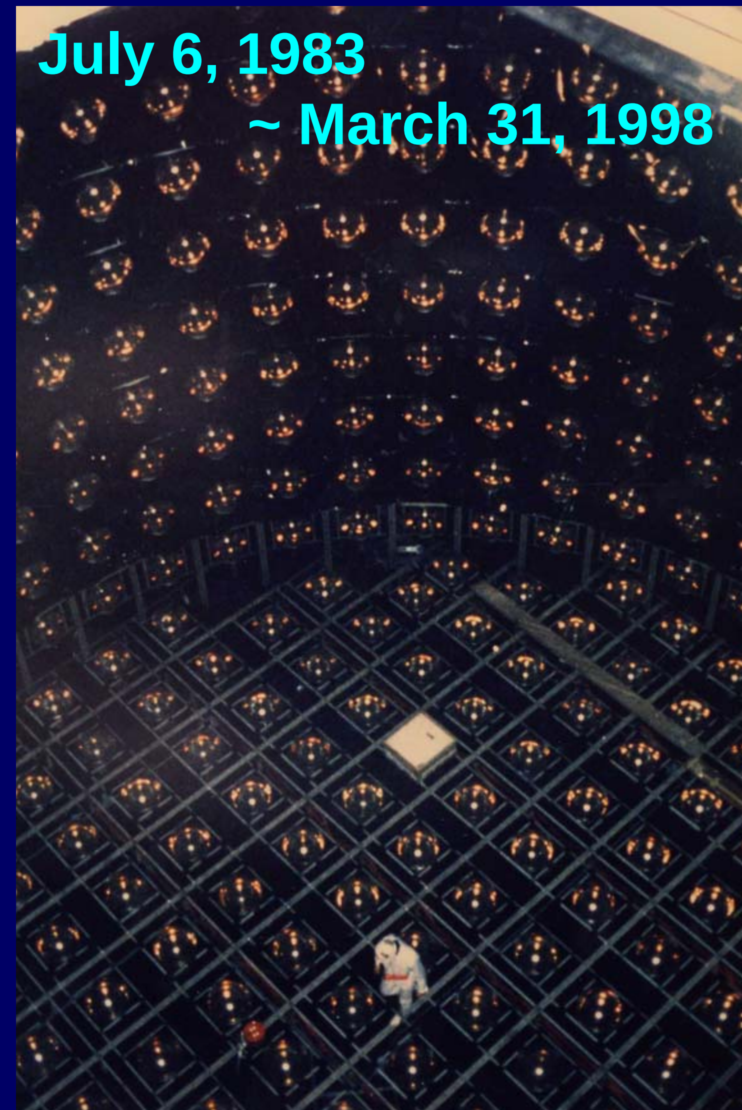
1. Kamiokande-I To Kamiokande-II
2. Solar Neutrino Detection
3. Atmospheric Neutrino Detection
4. Kamiokande to Next Generation Experiments
5. Conclusion

1. Kamiokande-I To Kamiokande-II :

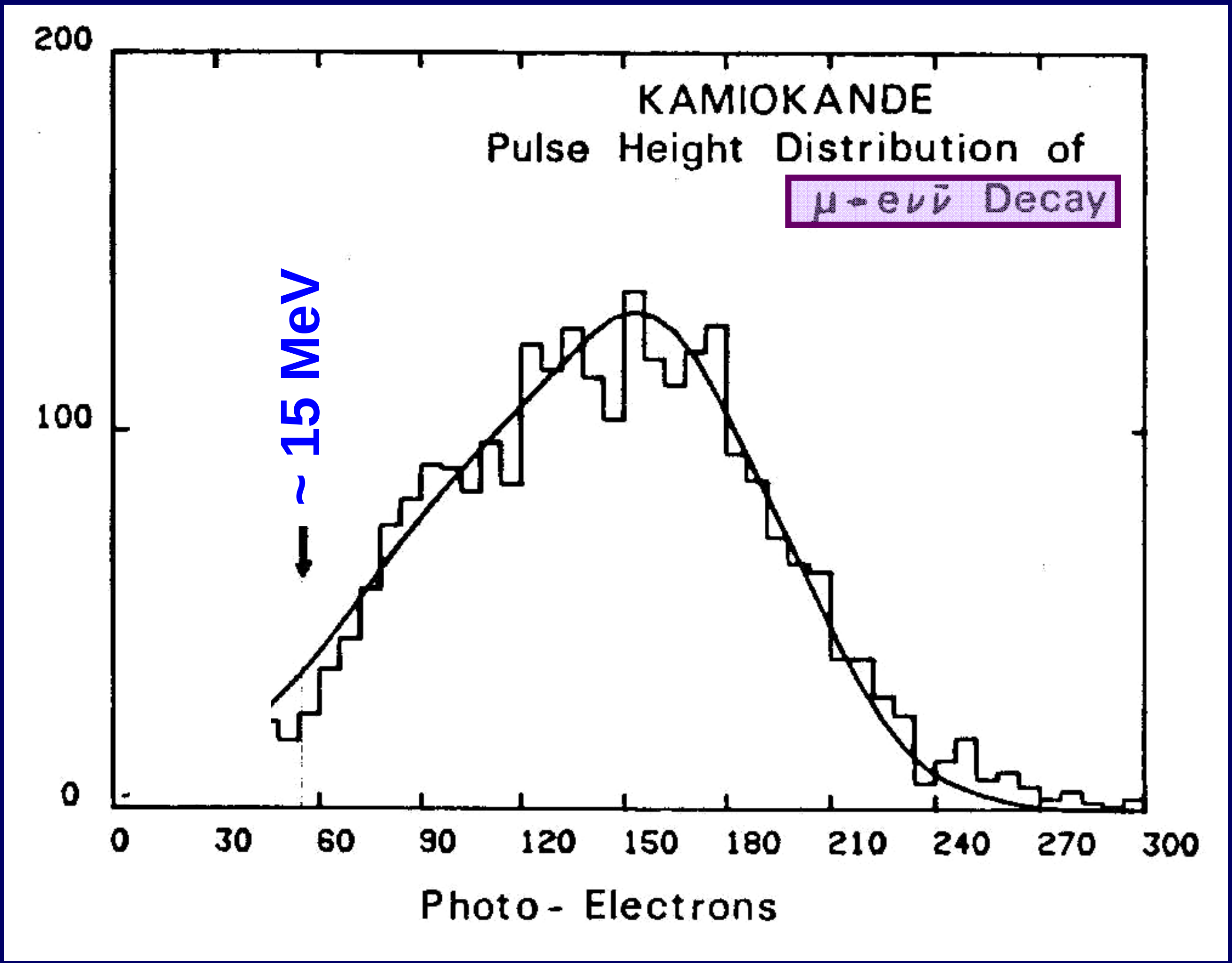
Kamiokande : Kamioka Nucleon Decay Experiment

Imaging Water Cerenkov Detector





What invited Kamiokande-II ?



"Why not lower E_{th} down to 10 MeV to detect ^{8}B Solar ν's!" *(1983)*

Kamiokande-II

Kamiokande-II Collaboration

UNIVERSITY *of* PENNSYLVANIA
PHILADELPHIA 19104

The Faculty of Arts and Sciences
DEPARTMENT OF PHYSICS

February 1, 1984

Professor Masatoshi Koshiba
Director, LICEPP
Faculty of Science
University of Tokyo
7-3-1, Hongo, Bunkyo, Tokyo
Japan

Dear Professor Koshiba,

Enclosed is a draft of the letter that you suggested I write. I prefer to have your comments and suggestions for changes before it is sent. I plan to send it to all members--Japanese and American--of the Committee, if you approve.

Our plans are becoming firm to leave for Japan on March 9 and to return to the U.S. on March 18. At the moment the party will include beside myself, E. W. Beier and R. Van Berg from Penn, B. Cortez from Caltech, and D. H. White from Brookhaven. One or two others may join in the next few days.

ea… …s on the enclosed letter at your
Ma… …latest material on electronics.

Sincerely,

Alfred K. Mann

*** At ICOBAN'84, upgrading the Kamiokande detector was opened up by Prof. Koshiba.**

*** The US group led by Prof. A. Mann (U. of Pennsylvania) expressed a desire for collaboration.**

*** First collaboration meeting was held in Tokyo in March, 1984.**

U.S. : new timing electronics for each PMT

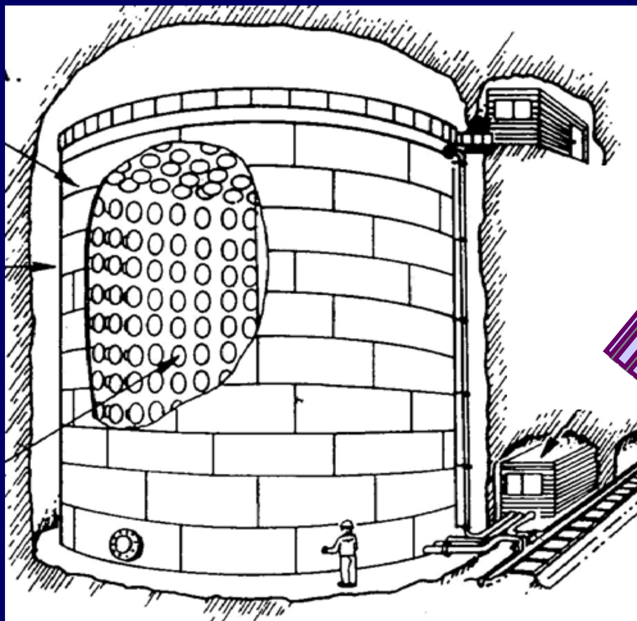
:

(improvement of vertex resolution)

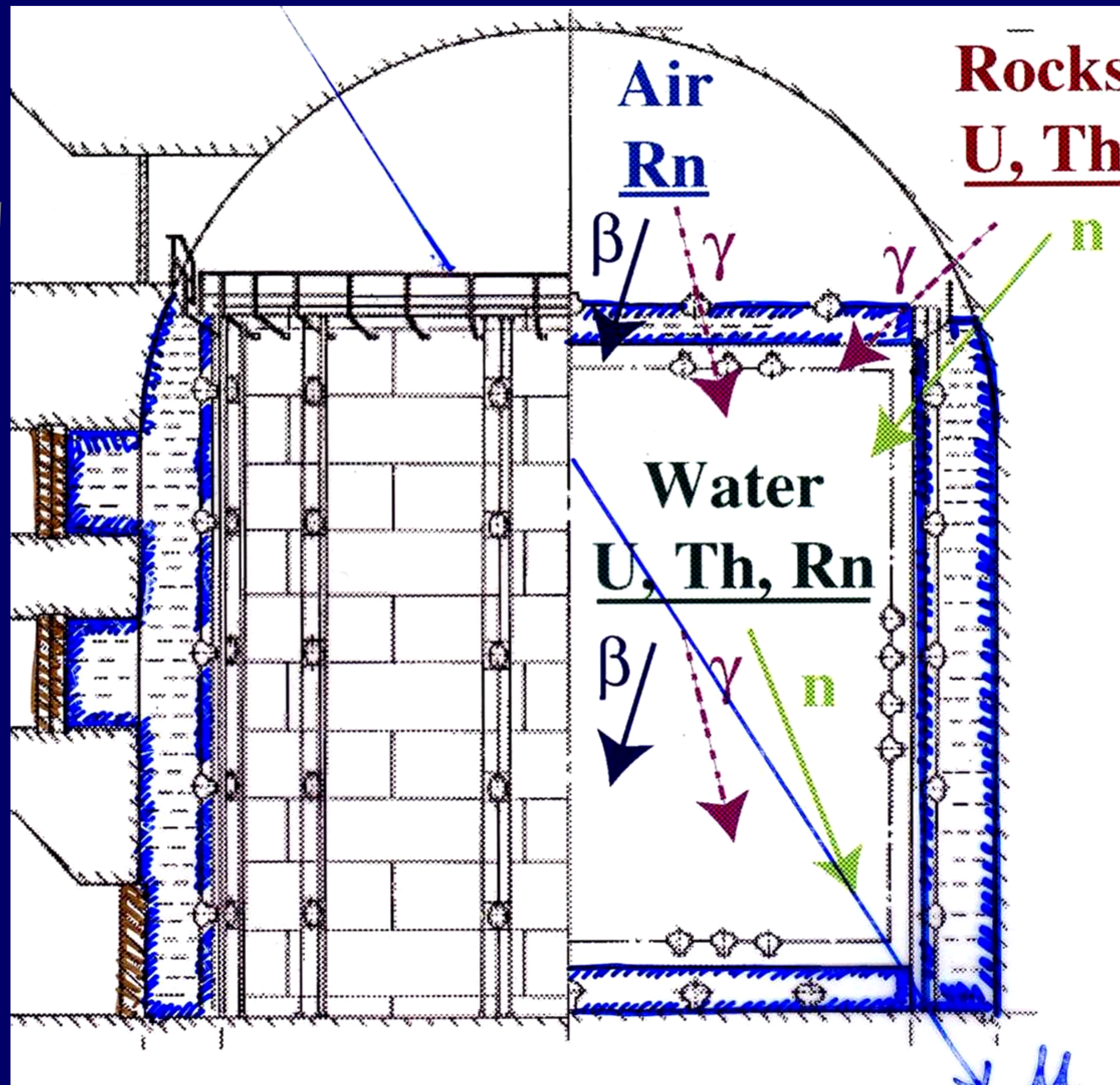
Kamiokande-II Collaborators (1984)

T. Kajita, M. Koshiba, M. Nakahata, Y. Oyama,
A. Suzuki, M. Takita, Y. Totsuka
(U. of Tokyo)
T. Kifune, T. Suda
(ICRR, U. of Tokyo)
K. Takahashi
(KEK)
K. Miyano
(U. of Niigata)
B.G. Cortez
(Caltech.)
E.W. Beier, L. Feldscher, S.B. Kim, A.K. Mann,
F.M. Newcomer, R. Van Berg, W.P. Zhang
(U. of Pennsylvania)

Kamiokande-I



Kamiokande-II Detector

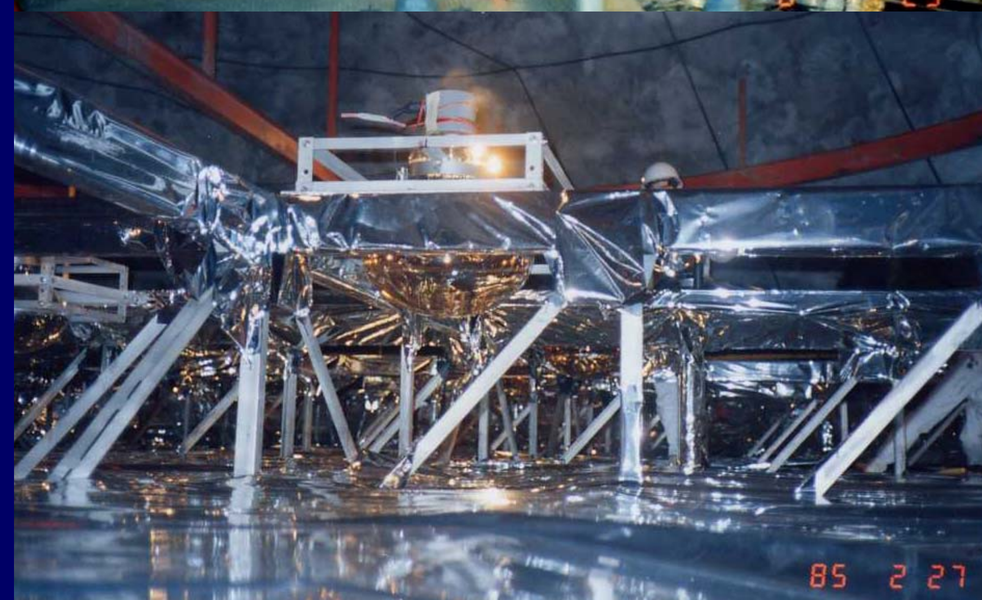


upgrade :

- **hermetic, live anticounter**
- **water purification system**
- **multi-hit time and charge measurements**

Kamiokande-II Construction

(September, 1984 ~)



Water Purification

Kamiokande-II

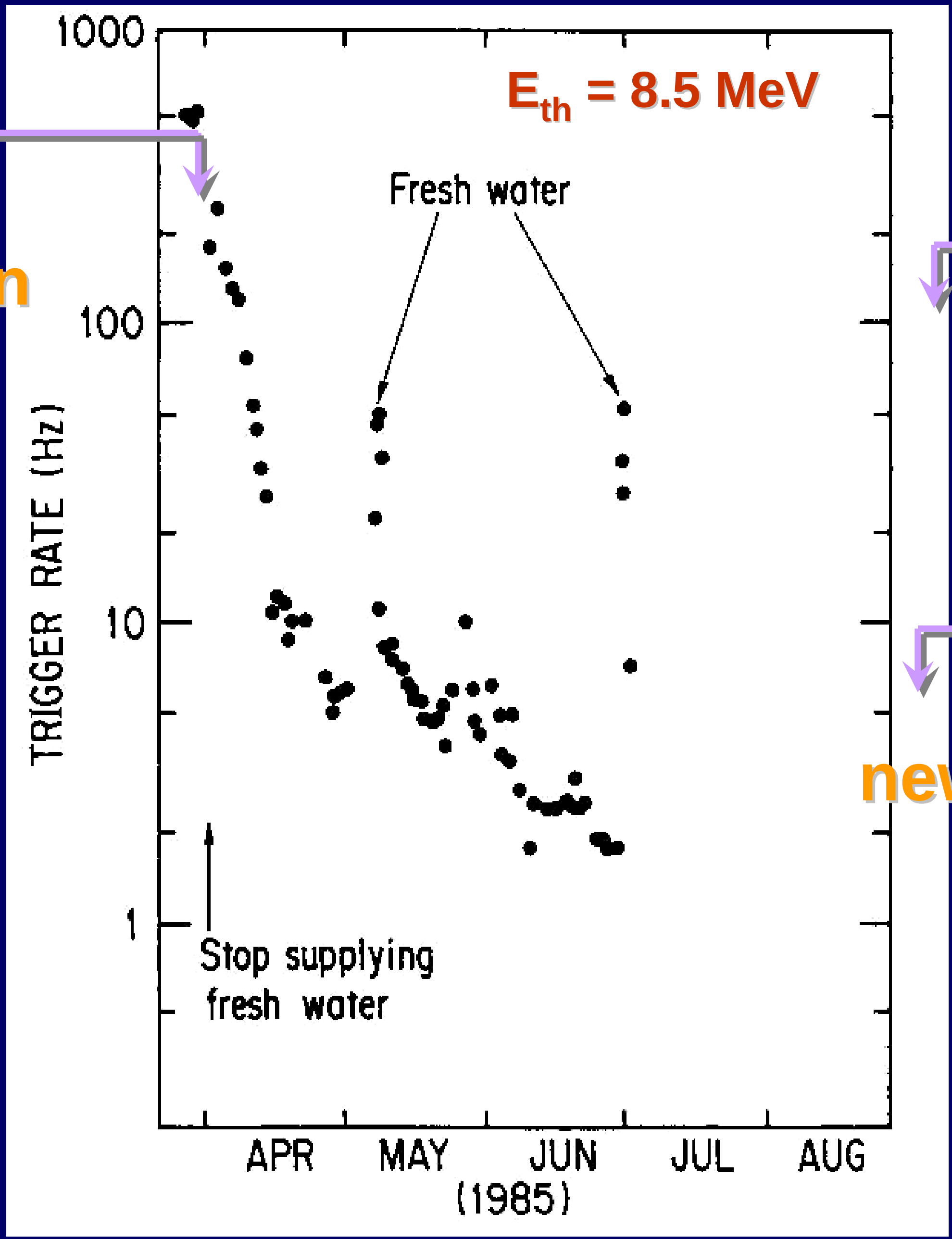
Kamiokande-II Launched

April 1985

water purification

:

start



Dec. 1985

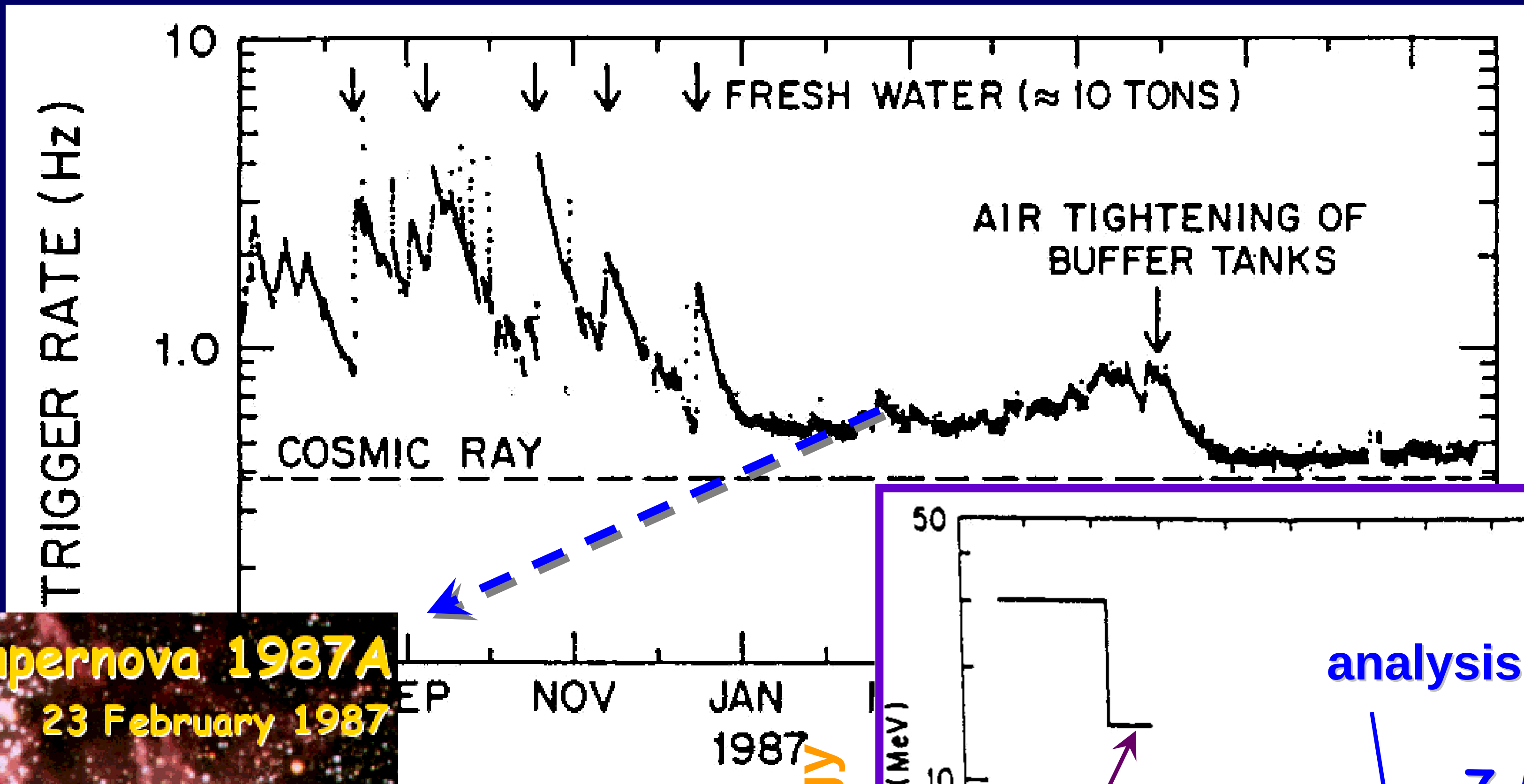
Nov. 1985

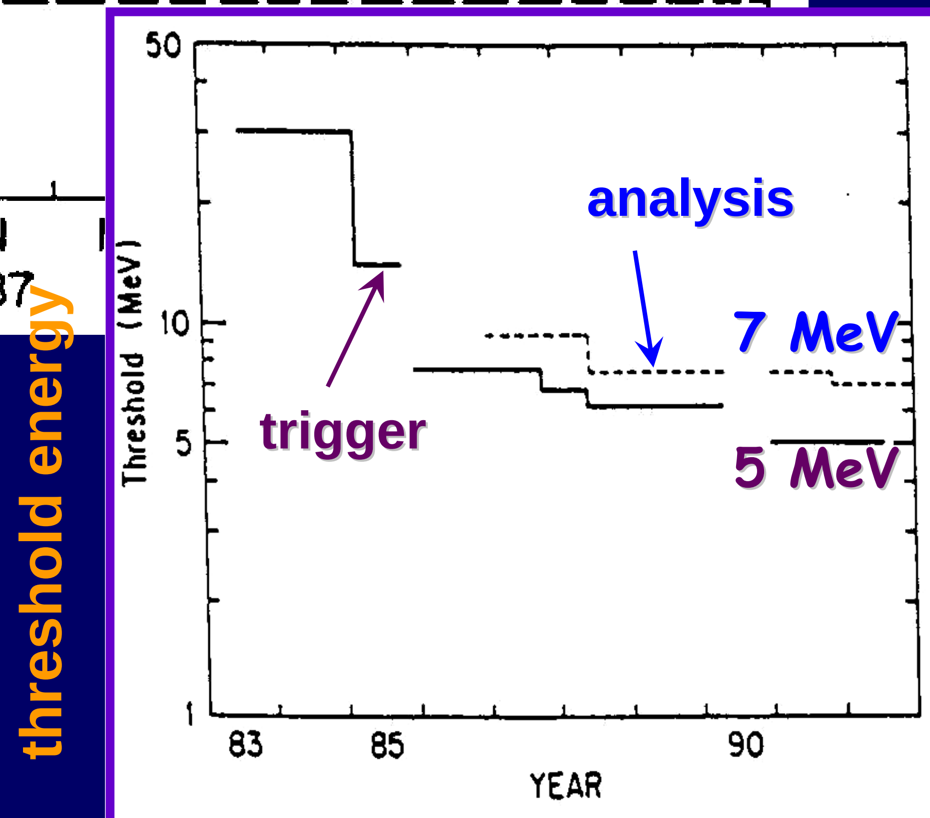
new electronics

:

ready

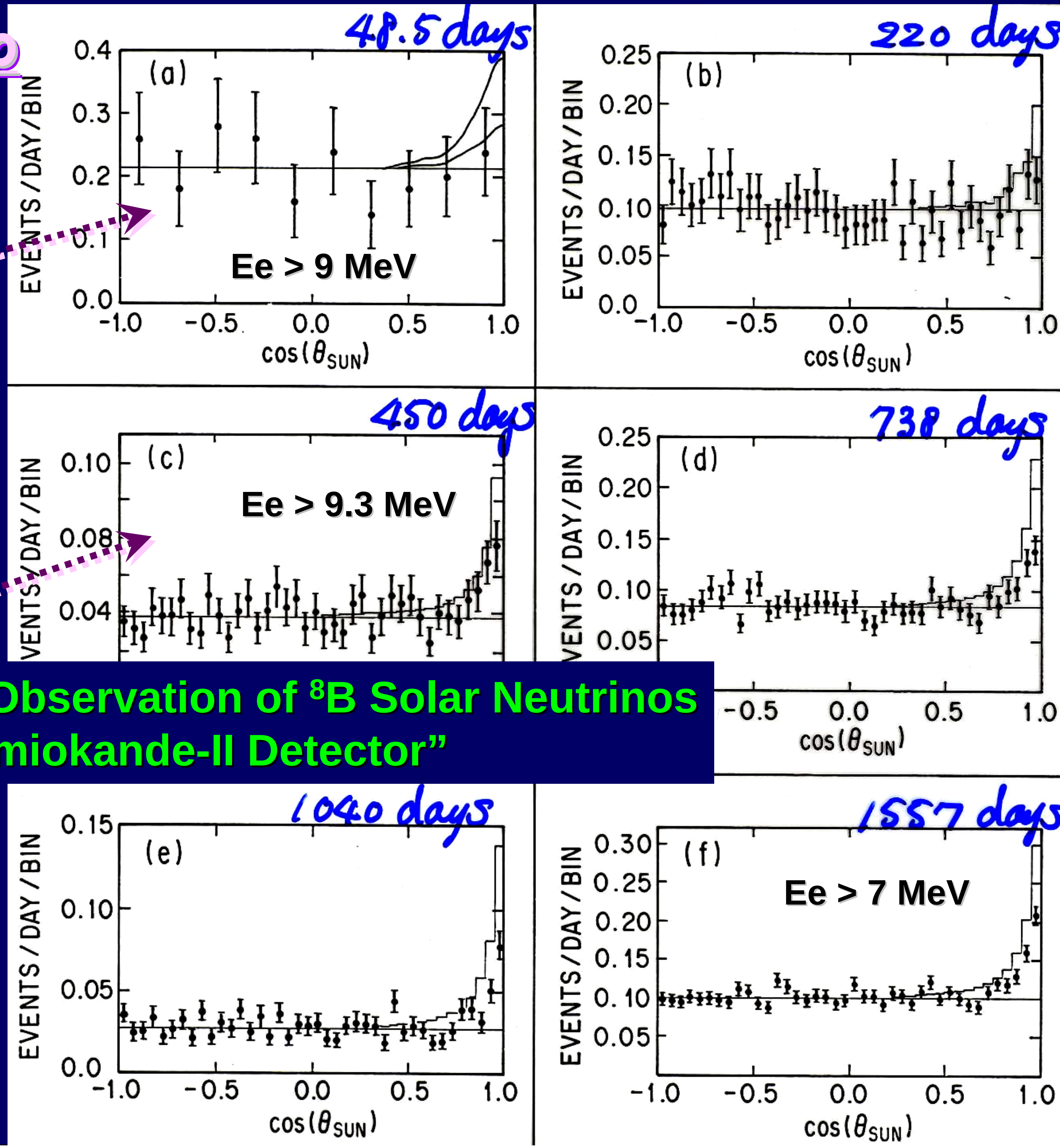
Trigger Rate Change (1986 ~)





2. Solar Neutrino Detection

First presentation in Neutrino '86 (Sendai)



First paper entitled "Observation of ^{8}B Solar Neutrinos in the Kamiokande-II Detector"

in PRL (1989)

:

$0.46 \pm 0.13 \pm 0.08$

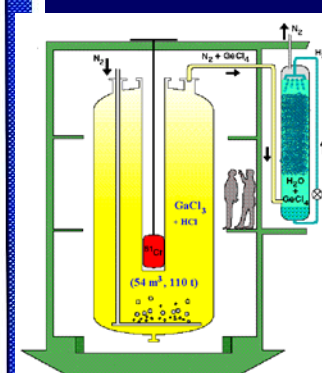
of SSM

Kamiokande-II Reconfirmed "Solar Neutrino Problem"

Solar Neutrino Observations (~ 1995)

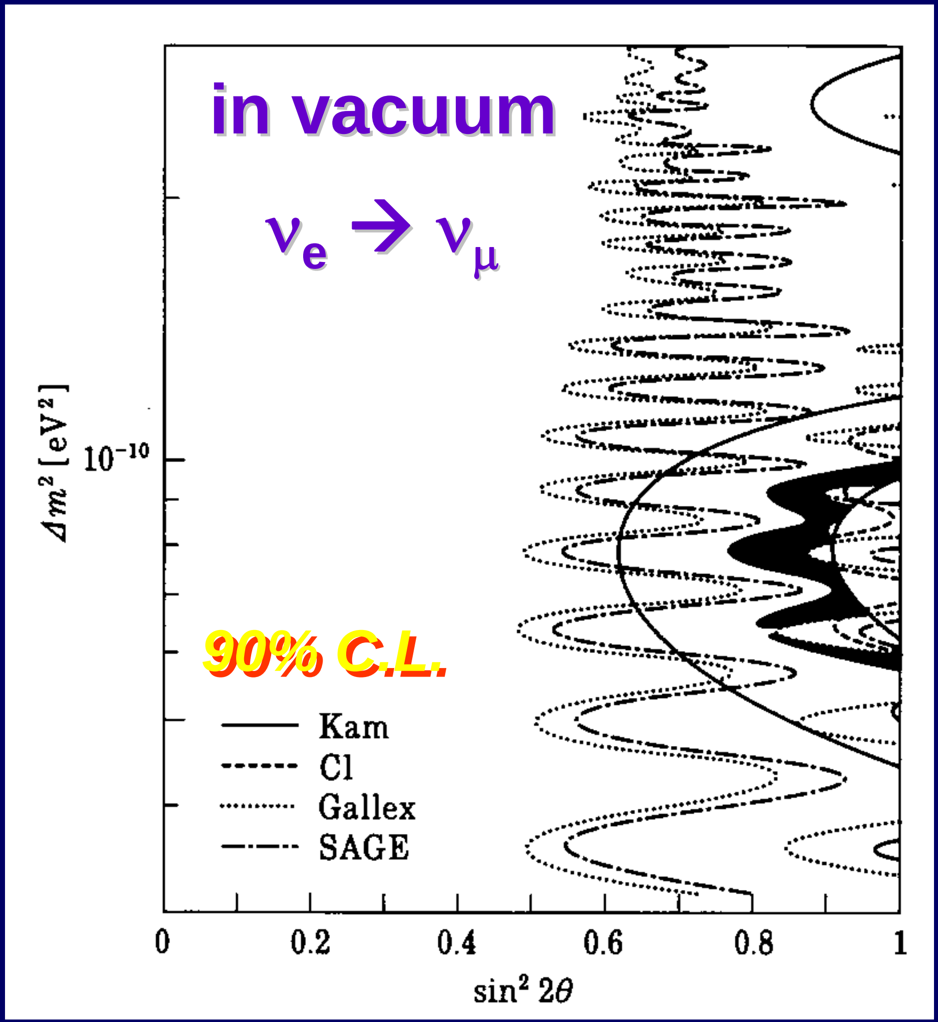
experiment	solar neutrinos	data / theory
Homestake (Cl)	$^{7}Be + {}^{8}B + \cdots$	0.29 ± 0.03
Kamiokande (H_2O)	^{8}B	0.48 ± 0.08
GALLEX (Ga)	$pp + {}^{7}Be + {}^{8}B + \cdots$	0.60 ± 0.09
SAGE (Ga)	$pp + {}^{7}Be + {}^{8}B + \cdots$	0.52 ± 0.09

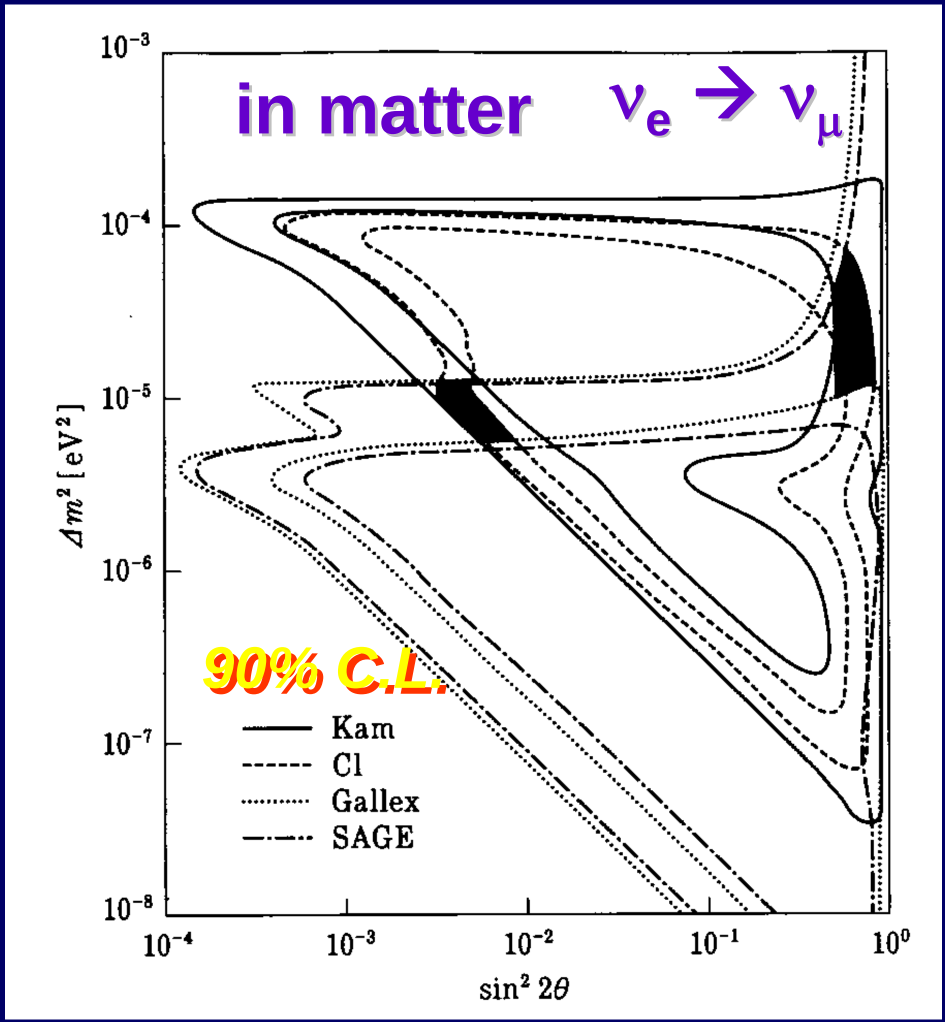
Where have Solar Neutrinos gone ?



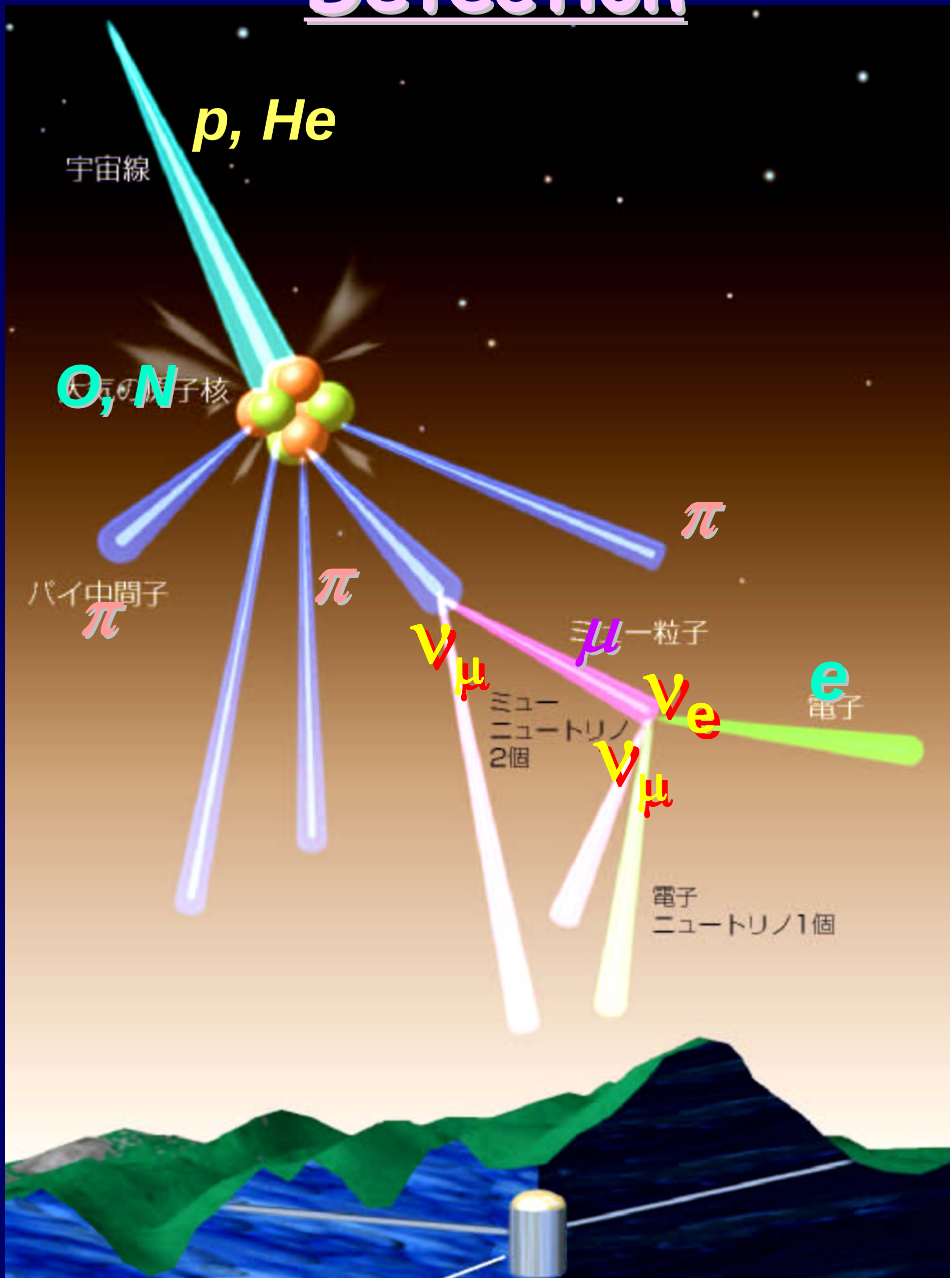
The Most Plausible Solution to "Solar Neutrino Problem"

neutrino oscillations





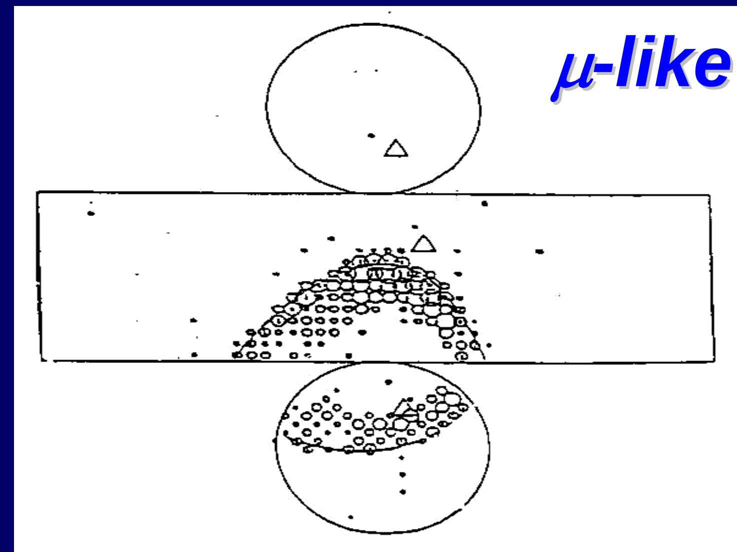
3. Atmospheric Neutrino Detection

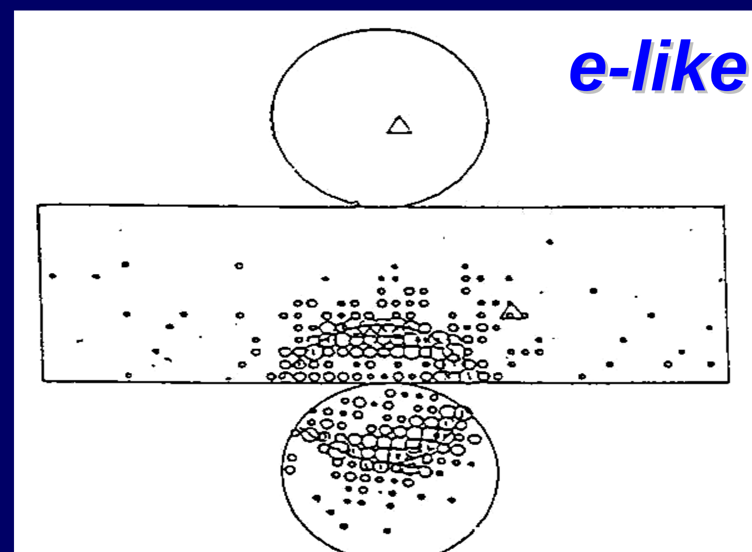


$$p + A \rightarrow \pi^{+(-)} + A'$$
He

$$\hookrightarrow \mu^{+(-)} + \nu_\mu\ (\bar{\nu}_\mu)$$

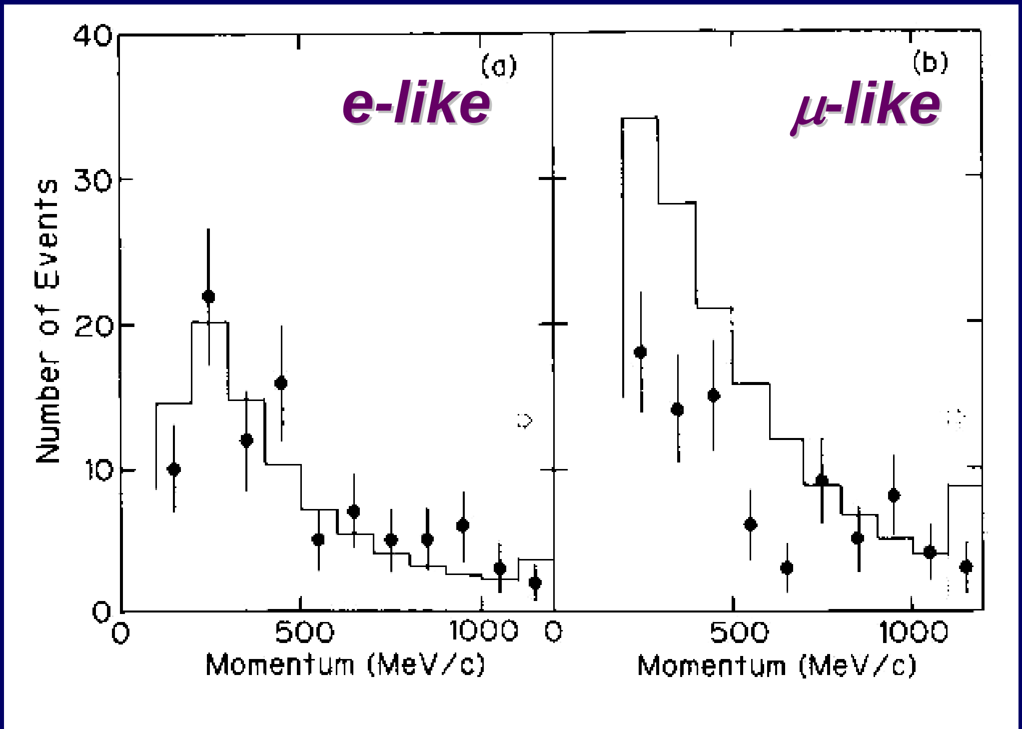
$$\hookrightarrow e^{+(-)} + \nu_e\ (\bar{\nu}_e) + \bar{\nu}_\mu\ (\nu_\mu)$$





First Paper : Phys. Lett. B205 (1988) 416

"Experimental study of the atmospheric neutrino flux"



# of single rings

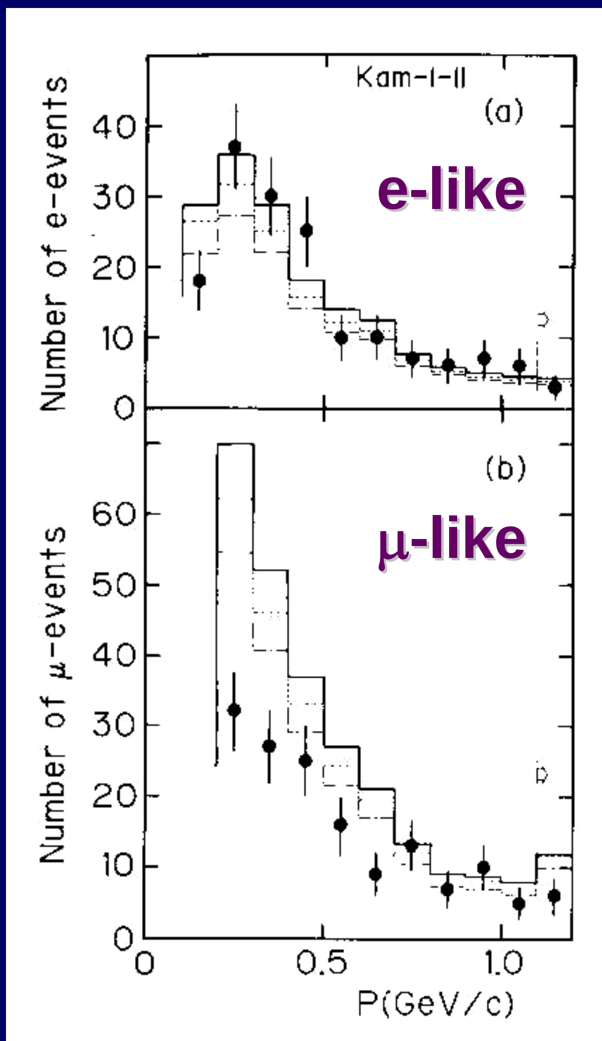
	Data	MC
μ-like	85	144
μ → e	(52)	(104)
e-like	105	106

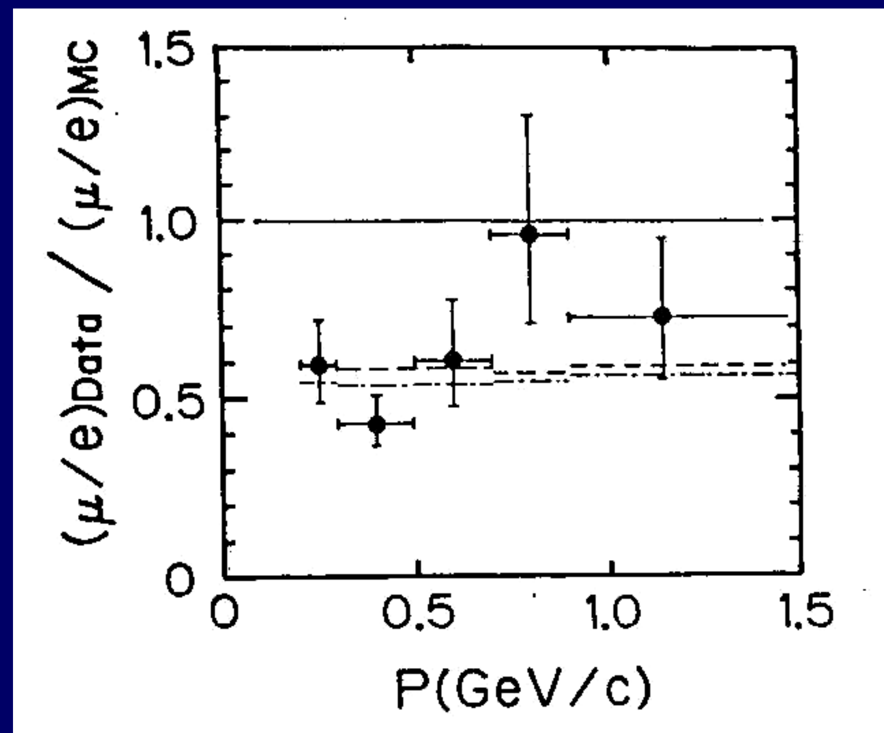
($110 < P_e < 4500$)

We are unable to explain the data as the result of systematic detector effects or uncertainties in the atmospheric neutrino fluxes.

Atmospheric Neutrino Anomaly : Phys. Lett. B280 (1992) 146

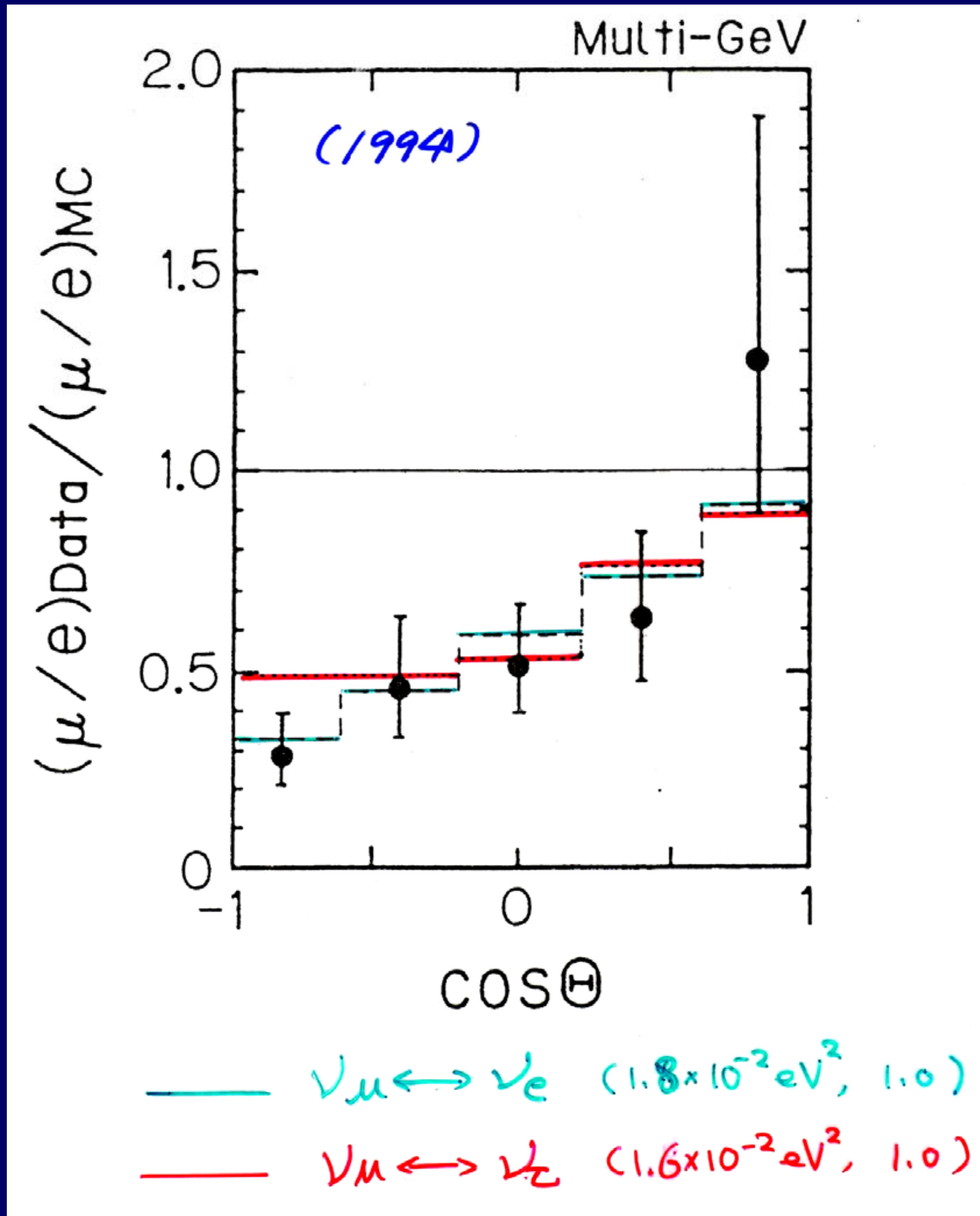
"Observation of a small atmospheric ν_μ/ν_e ratio in Kamiokande"





R (μ / e)
$= 0.60 \; ^{+0.07}_{-0.06}$ (stat.) ± 0.05 (syst.)

Zenith Angle Dependence of R(μ/e)



Comparison of R(μ/e) with Other Experiments

1992	NUSEX	Frejus	Soudan 2	IMB 3	Kamiokande
Exposure (kton·yr)	0.74	1.56	1.01	7.7	7.7
R(μ/e) → $\frac{(\mu/e)_{DATA}}{(\mu/e)_{MC}}$	**0.99**	**1.06**	1.9σ **0.64**	3.5σ **0.54**	5.1σ **0.60**
(stat.)	$^{+0.35}_{-0.25}$	$^{+0.19}_{-0.16}$	±0.17	±0.05	$^{+0.06}_{-0.05}$
(sys.)	± small	±0.15	±0.09	±0.12	±0.05
$\frac{(e)_{DATA}}{(e)_{MC}}$	**0.88**	**0.80**	**1.23**	**1.26**	**1.09**
(error)#	±0.21	±0.11	±0.21	±0.07	±0.07
$\frac{(\mu)_{DATA}}{(\mu)_{MC}}$	**0.87**	**0.86**	**0.80**	**0.68**	**0.66**
(error)#	±0.15	±0.08	±0.14	±0.05	±0.04

Atmospheric Neutrino Anomaly

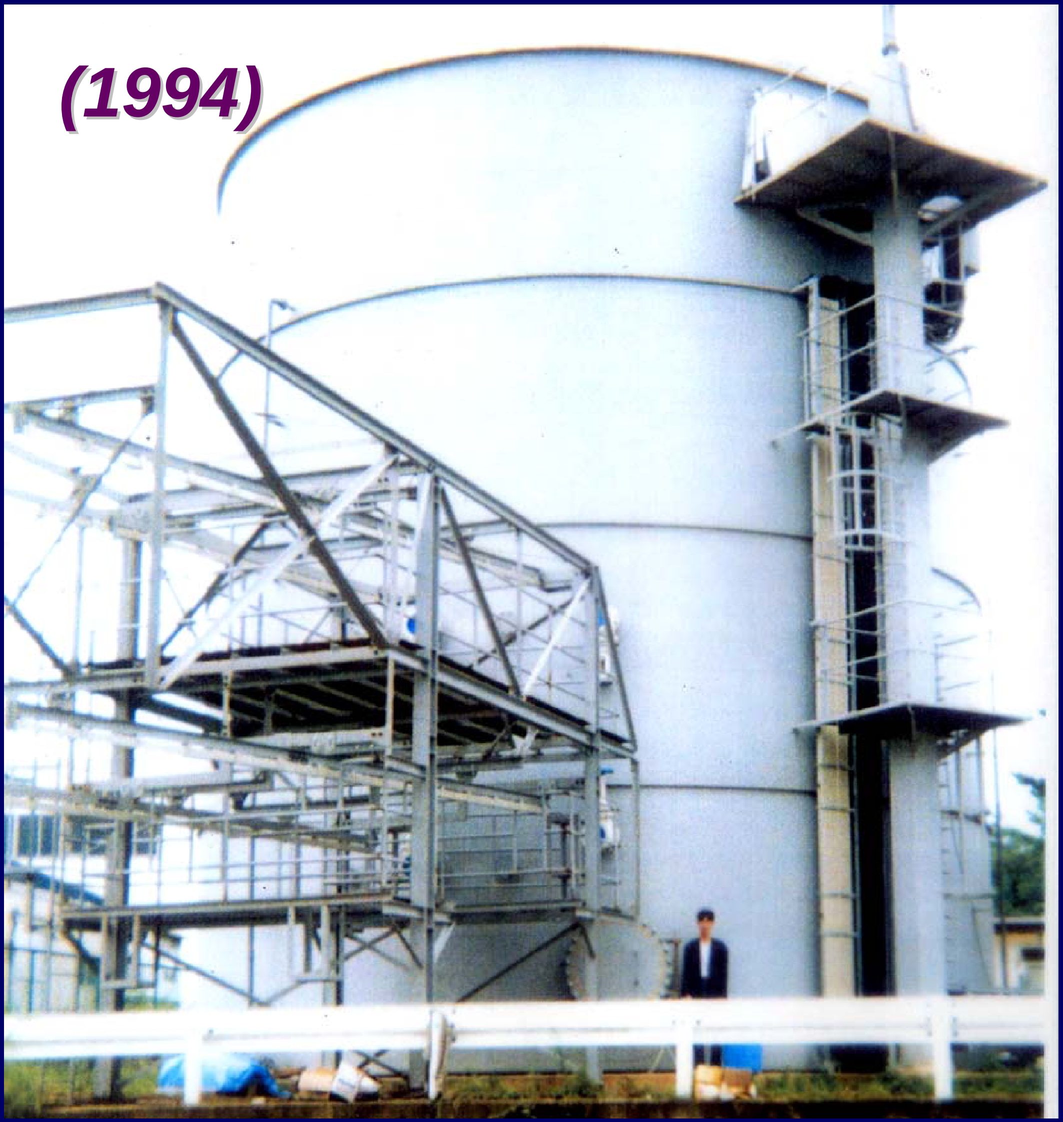
:

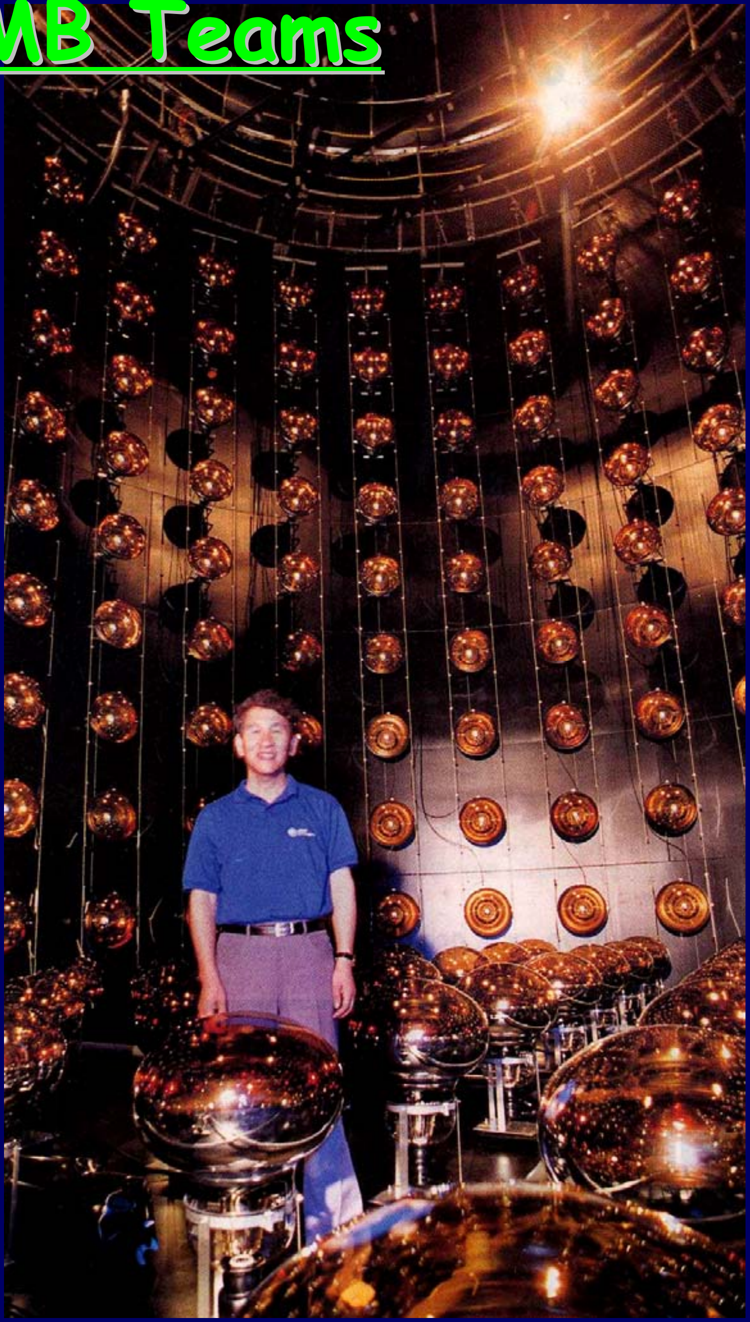
Water Cerenkov Effect

:

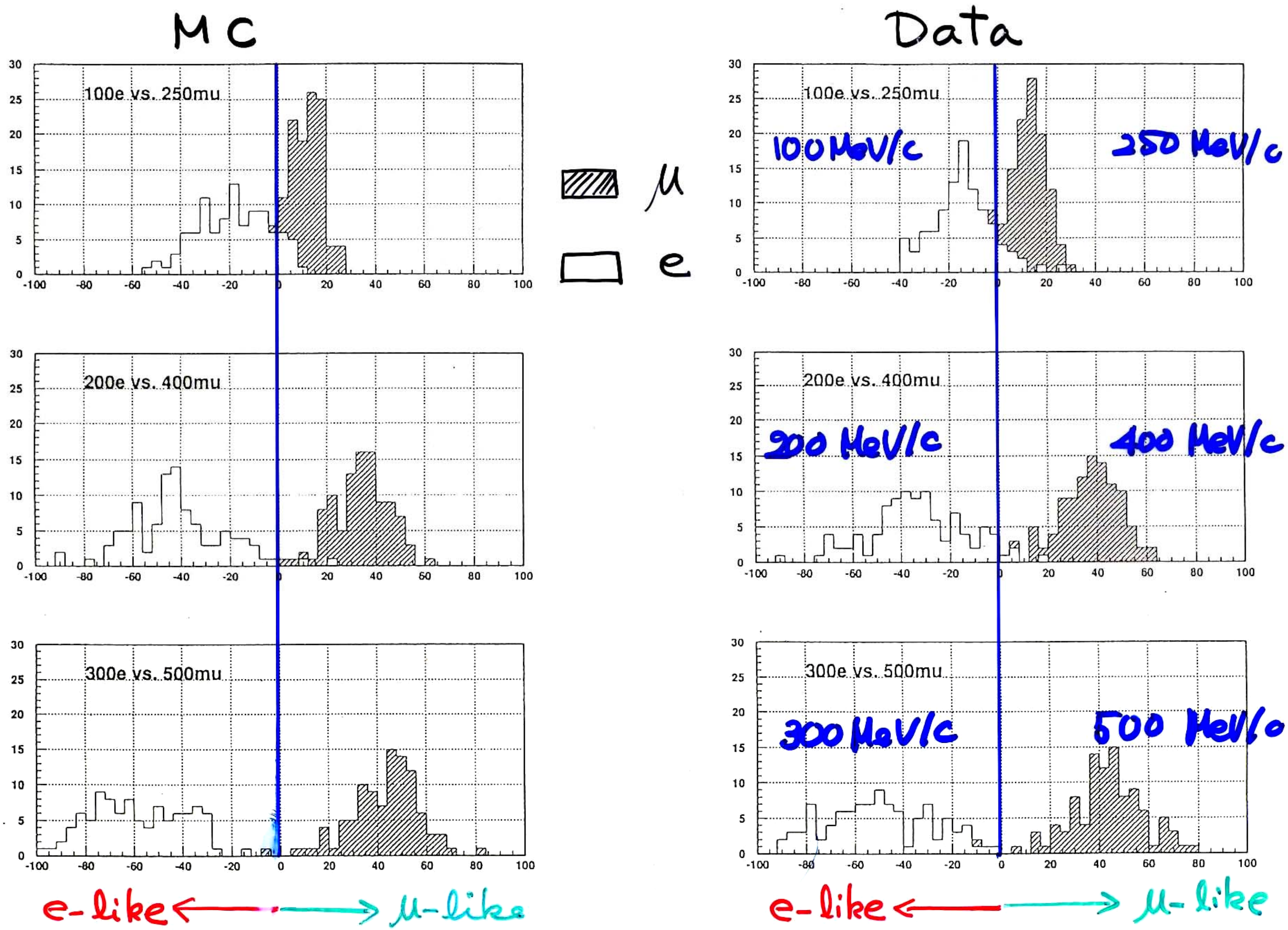
(μ/e discrimination ?)

Beam (μ, e, π) Test at KEK by Kamiokande & IMB Teams

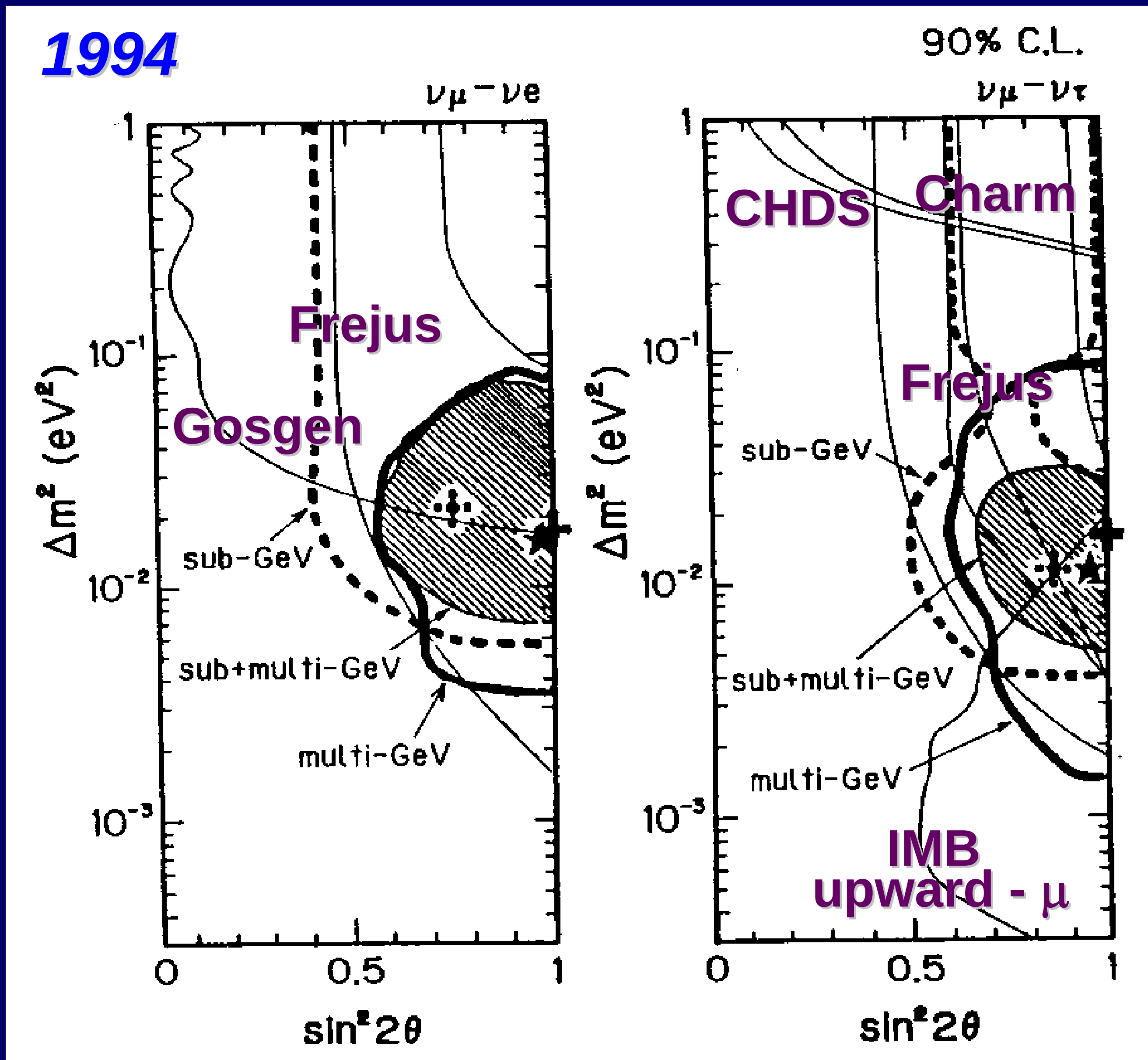




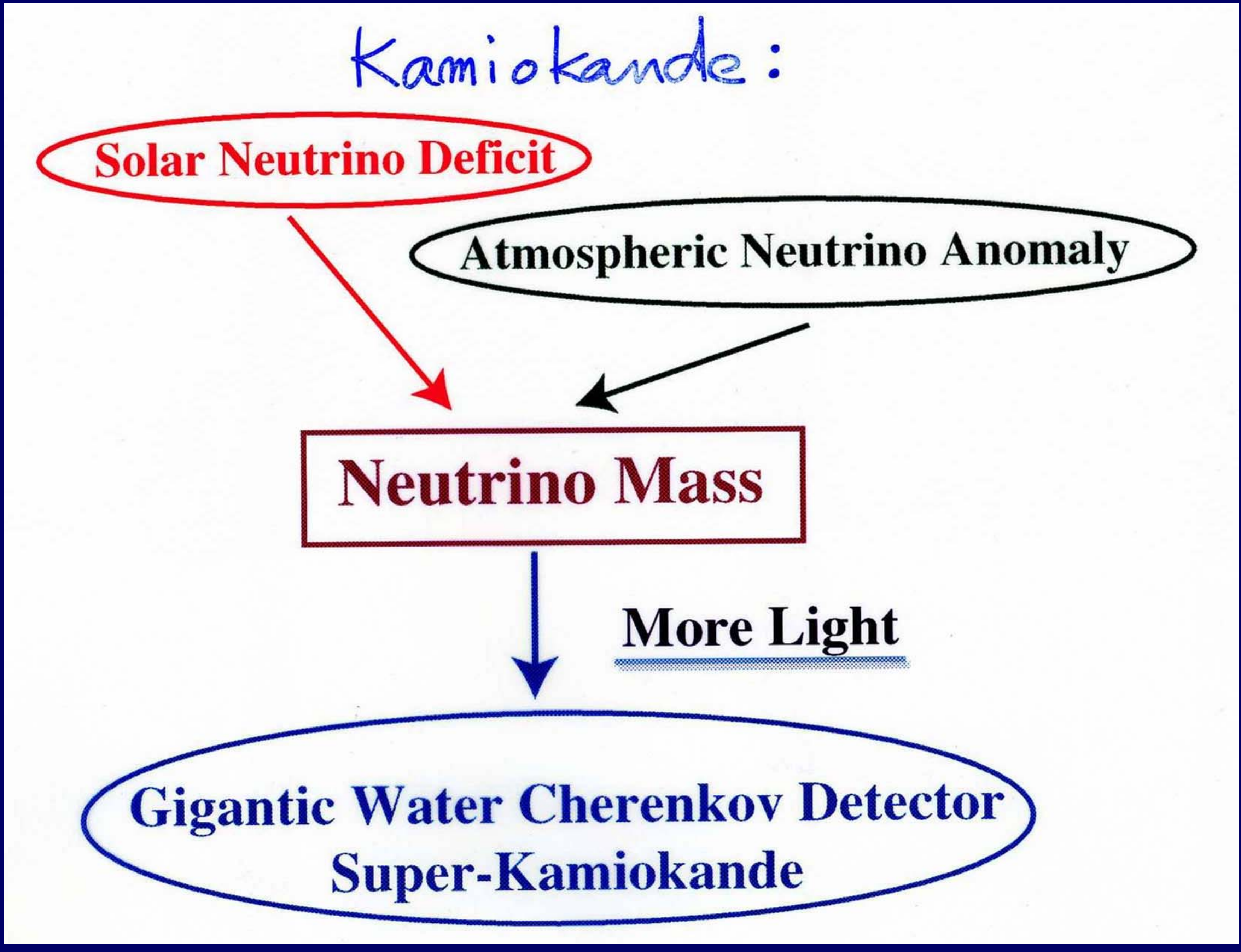
Beam Test Results



Neutrino Oscillation Studies for Atmospheric Neutrino Events

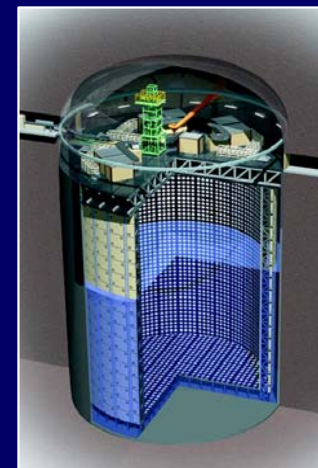


4. Kamiokande to Next Generation Experiments



Discovery of Atmospheric Neutrino Oscillations

1998



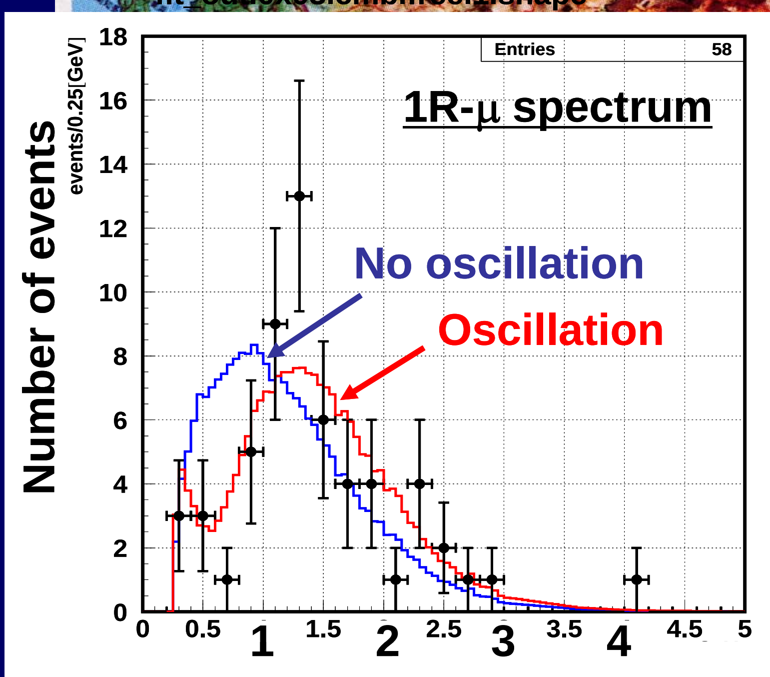
Evidence for oscillation of atmospheric neutrinos

The Super-Kamiokande Collaboration

Y.Fukuda[a], T.Hayakawa[a], E.Ichihara[a], K.Inoue[a], K.Ishihara[a], H.Ishino[a], Y.Itow[a], T.Kajita[a], J.Kameda[a], S.Kasuga[a], K.Kobayashi[a], Y.Kobayashi[a], Y.Koshio[a], M.Miura[a], M.Nakahata[a], S.Nakayama[a], A.Okada[a], K.Okumura[a], N.Sakurai[a], M.Shiozawa[a], Y.Suzuki[a], Y.Takeuchi[a], Y.Totsuka[a], S.Yamada[a], M.Earl[b], A.Habig[b], E.Kearns[b], M.D.Messier[b], K.Scholberg[b], J.L.Stone[b], L.R.Sulak[b], C.W.Walter[b], M.Goldhaber[c], T.Barszczak[d], D.Casper[d], W.Gajewski[d], P.G.Halverson[d,*], J.Hsu[d], W.R.Kropp[d], L.R. Price[d], F.Reines[d], M.Smy[d], H.W.Sobel[d], M.R.Vagins[d], K.S.Ganezer[e], W.E.Keig[e], R.W.Ellsworth[f], S.Tasaka[g], J.W.Flanagan[h,†] A.Kibayashi[h], J.G.Learned[h], S.Matsuno[h], V.J.Stenger[h], D.Takemori[h], T.Ishii[i], J.Kanzaki[i], T.Kobayashi[i], S.Mine[i], K.Nakamura[i], K.Nishikawa[i], Y.Oyama[i], A.Sakai[i], M.Sakuda[i], O.Sasaki[i], S.Echigo[j], M.Kohama[j], A.T.Suzuki[j], T.J.Haines[k,d] E.Blaufuss[l], B.K.Kim[l], R.Sanford[l], R.Svoboda[l], M.L.Chen[m], Z.Conner[m,‡] J.A.Goodman[m], G.W.Sullivan[m], J.Hill[n], C.K.Jung[n], K.Martens[n], C.Mauger[n], C.McGrew[n], E.Sharkey[n], B.Viren[n], C.Yanagisawa[n], W.Doki[o], K.Miyano[o], H.Okazawa[o], C.Saji[o], M.Takahata[o], Y.Nagashima[p], M.Takita[p], T.Yamaguchi[p], M.Yoshida[p], S.B.Kim[q], M.Etoh[r], K.Fujita[r], A.Hasegawa[r], T.Hasegawa[r], S.Hatakeyama[r], T.Iwamoto[r], M.Koga[r], T.Maruyama[r], H.Ogawa[r], J.Shirai[r], A.Suzuki[r], F.Tsushima[r], M.Koshiba[s], M.Nemoto[t], K.Nishijima[t], T.Futagami[u], Y.Hayato[u,§], Y.Kanaya[u], K.Kaneyuki[u], Y.Watanabe[u], D.Kielczewska[v,d], R.A.Doyle[w], J.S.George[w], A.L.Stachyra[w], L.L.Wai[w,**], R.J.Wilkes[w], K.K.Young[w]

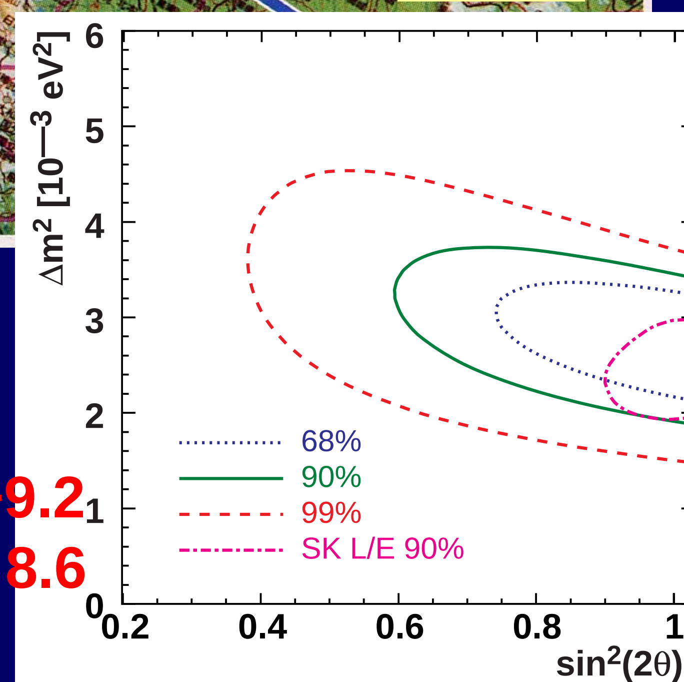
K2K (*KEK* to[2] *Kamioka*)

Neutrinos are oscillating (99.998%)

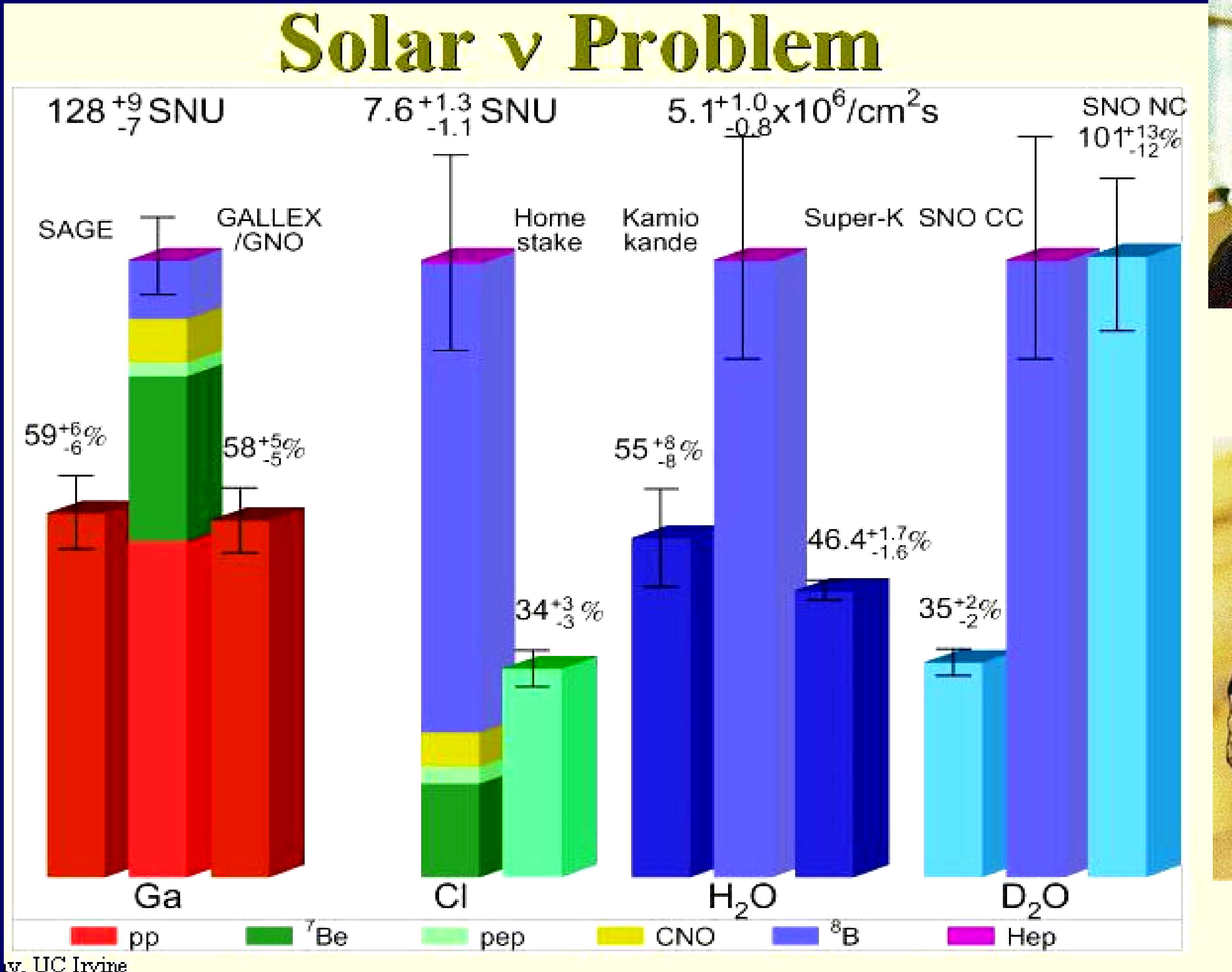


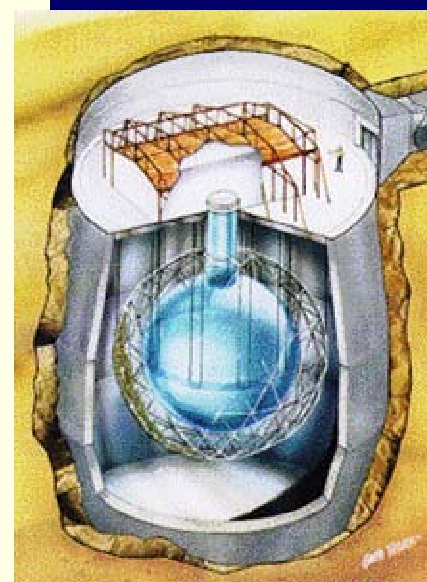
$N_{SK}^{observ} = 112$

$N_{SK}^{predict} = 158.1^{+9.2}_{-8.6}$



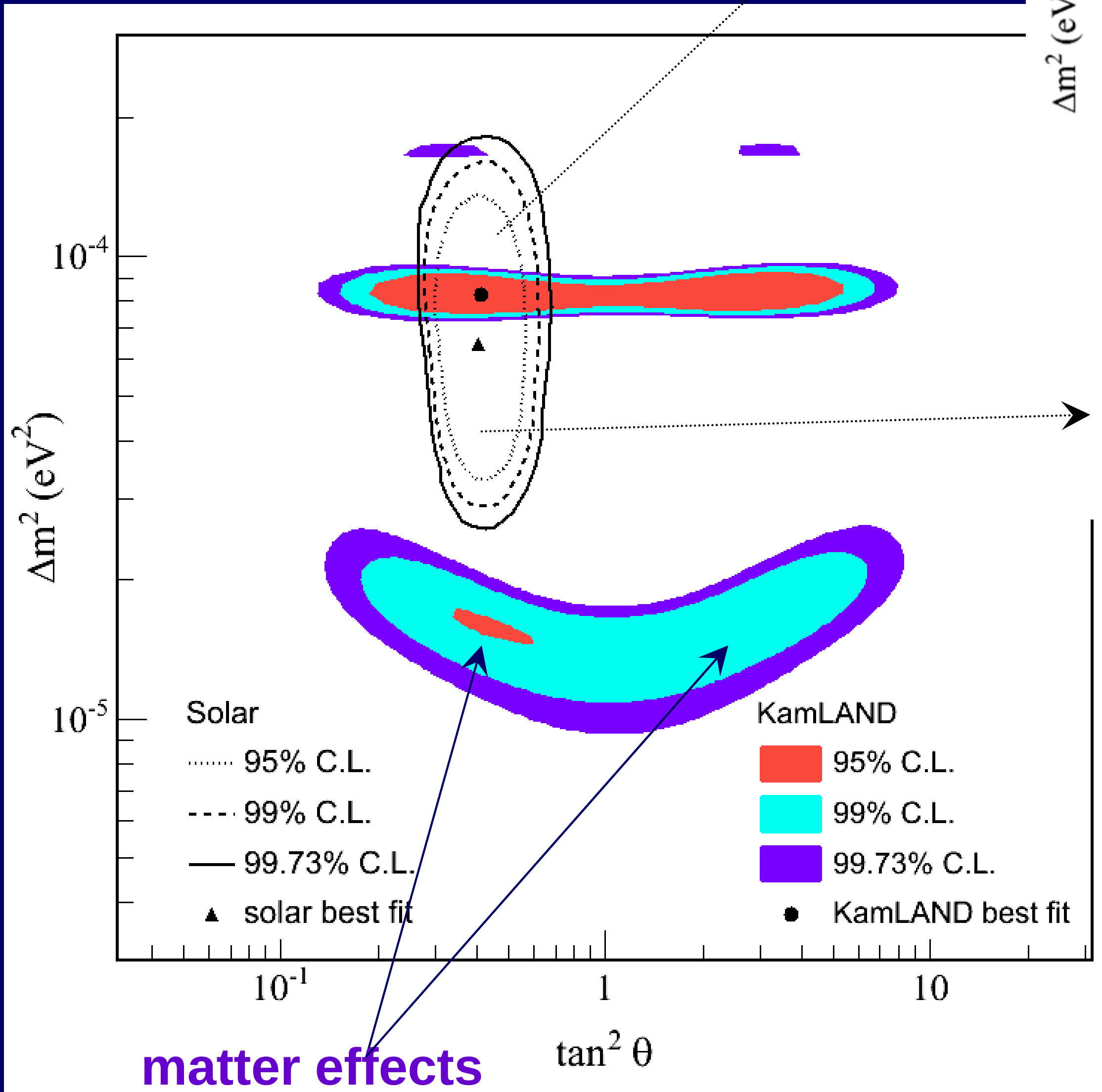
M. Smy, ν 2002

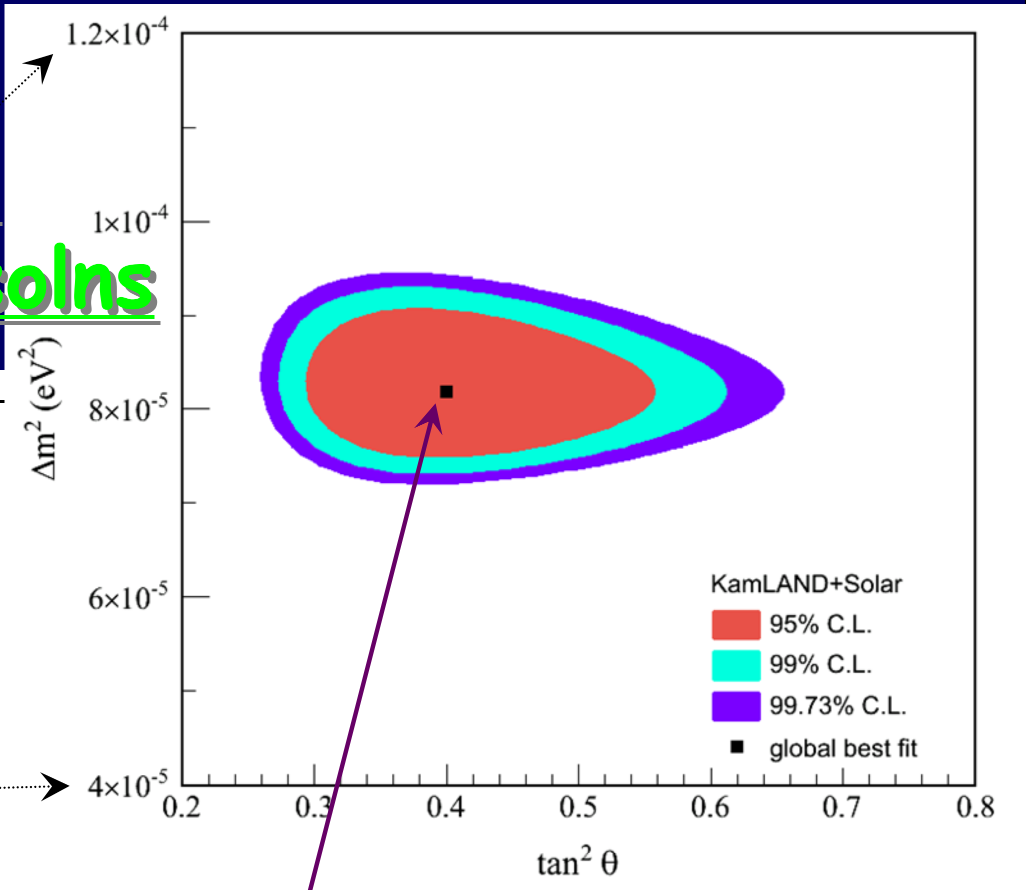

Solar ν Problem
128 +9 -7 SNU
7.6 +1.3 -1.1 SNU
5.1 +1.0 -0.8 x10^6/cm^2s
SNO NC
101 +13 -12 %
SAGE
GALLEX /GNO
Home stake
Kamio kande
Super-K
SNO CC
59 +6 -6 %
58 +5 -5 %
34 +3 -3 %
55 +8 -8 %
46.4 +1.7 -1.6 %
35 +2 -2 %
Ga
Cl
H2O
D2O
pp
7Be
pep
CNO
8B
Hep
y, UC Irvine



KamLAND :

swept out non-standard mechanisms as leading solns





$\Delta m^2 = 8.2^{+0.6}_{-0.5} \times 10^{-5}\ eV^2$

$\tan^2\theta = 0.40^{+0.09}_{-0.07}$

assuming CPT invariance

Conclusion

Evidence for Neutrino Mass

Kamiokande-II