

Evidence for Neutrino Mass

Leads to

Kamiokande-II

Atsuto Suzuki

(KEK, High Energy Accelerator Research Organization)

Neutrino 2006, SantaFe, June 14,
2006

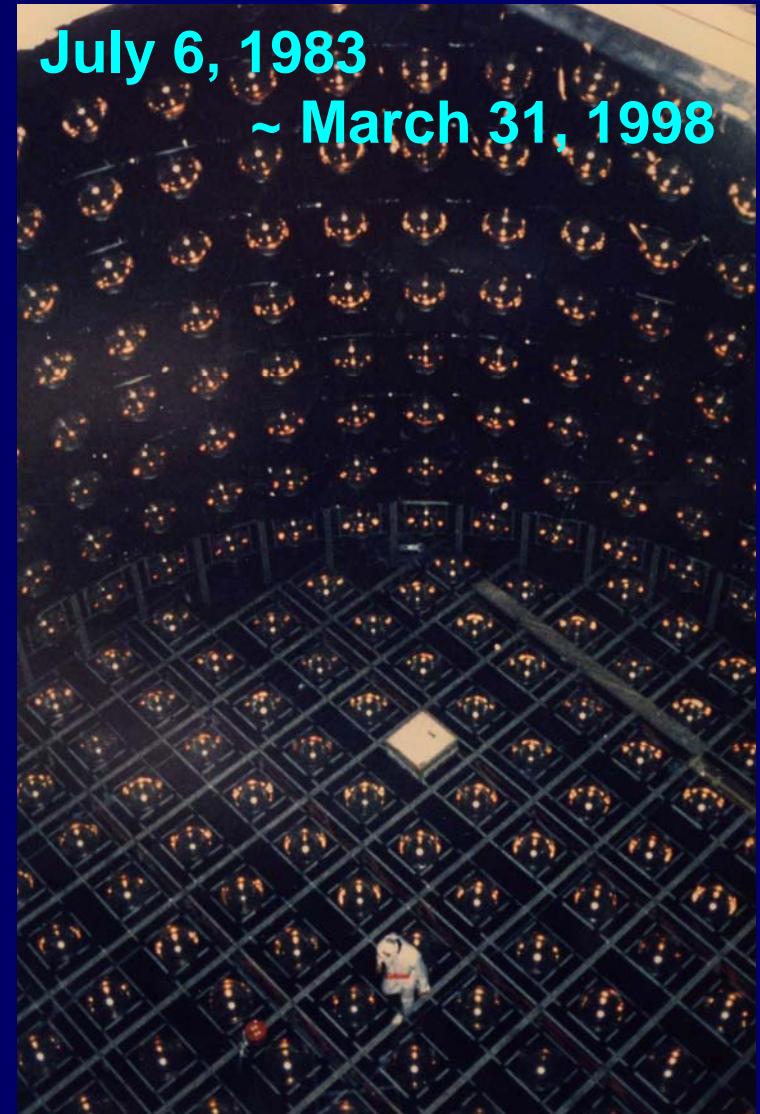
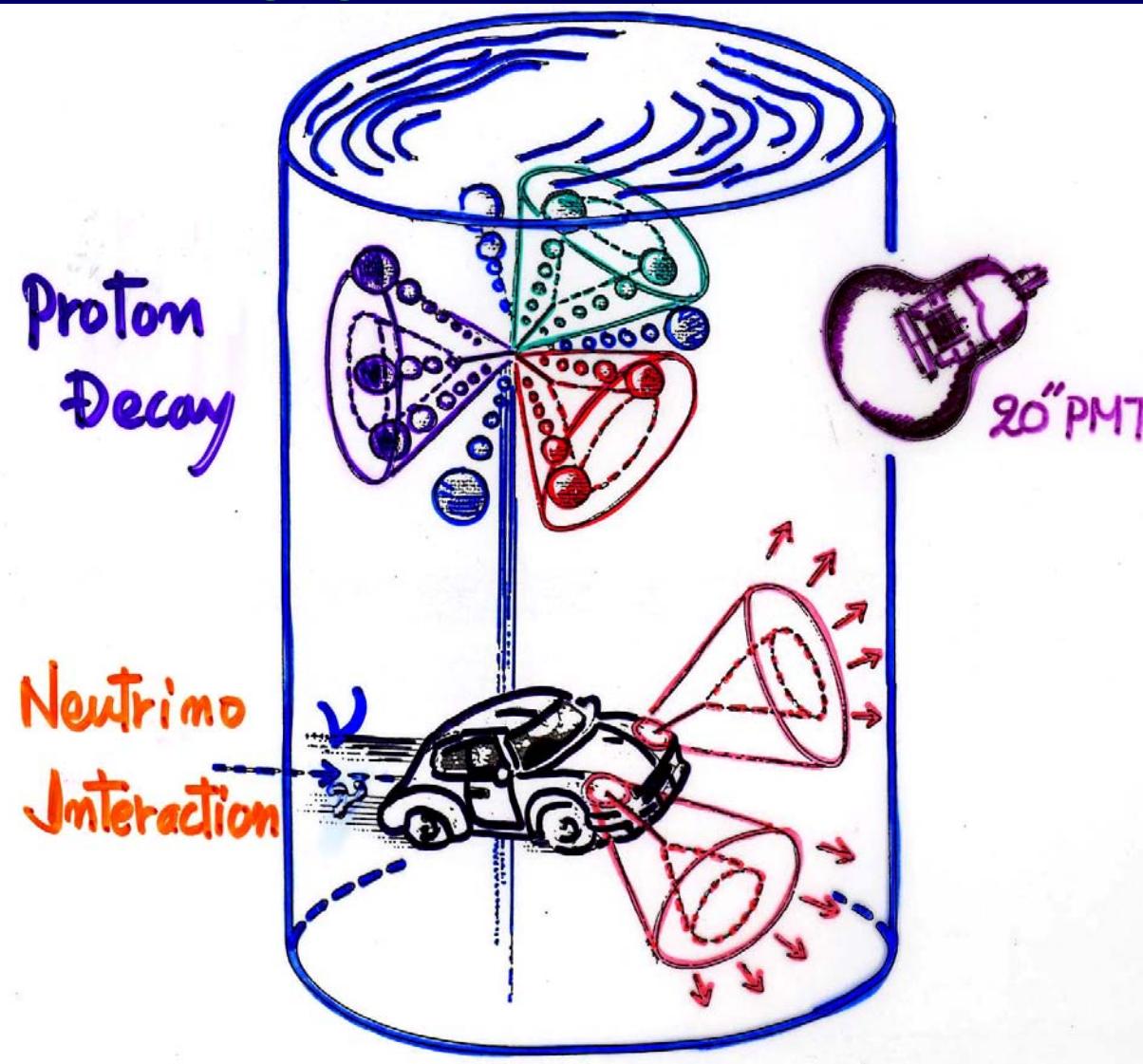
Outline

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

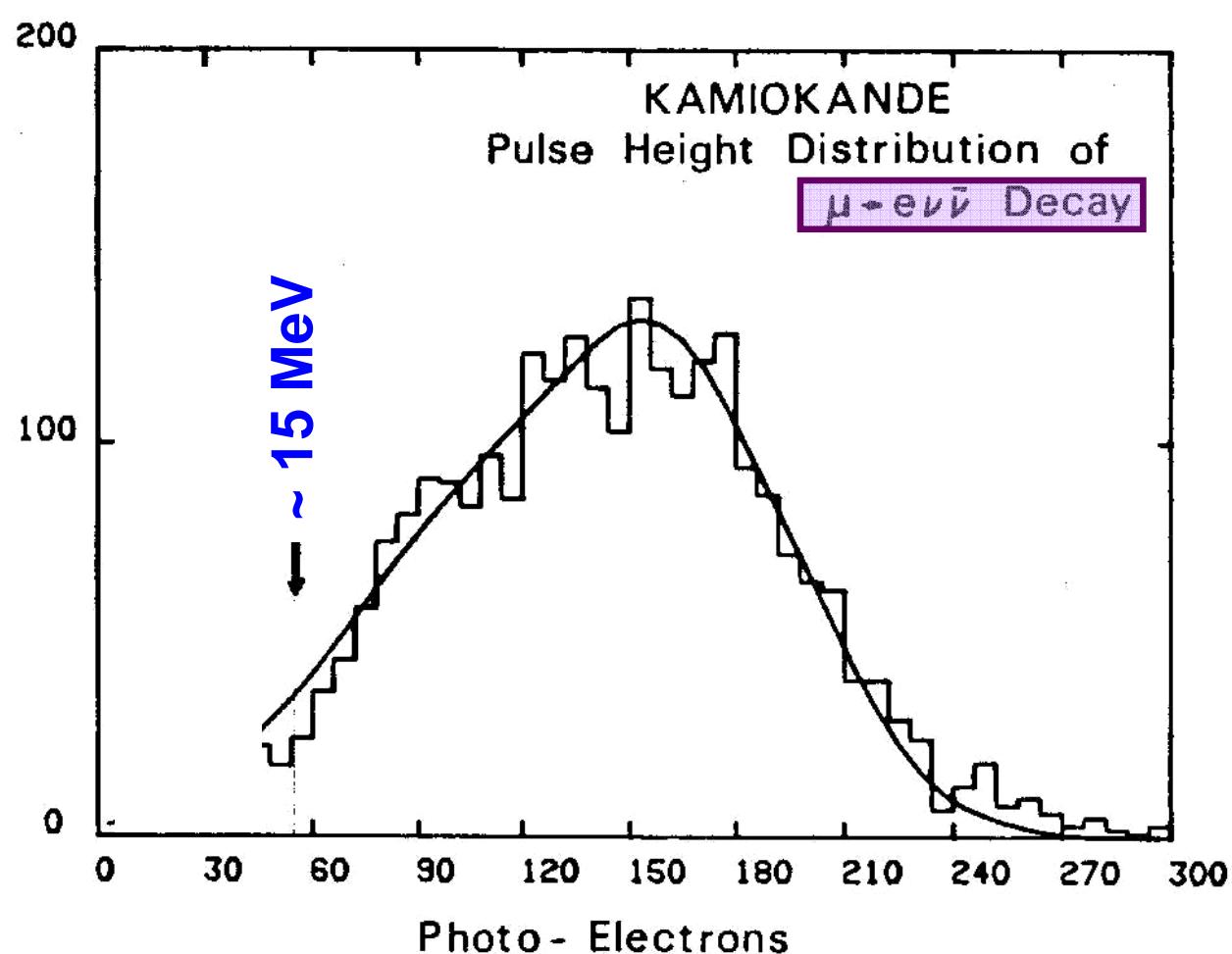
1. Kamiokande-I To Kamiokande-II :

Kamiokande : Kamioka Nucleon Decay Experiment

Imaging Water Cerenkov Detector



What invited Kamiokande-II ?

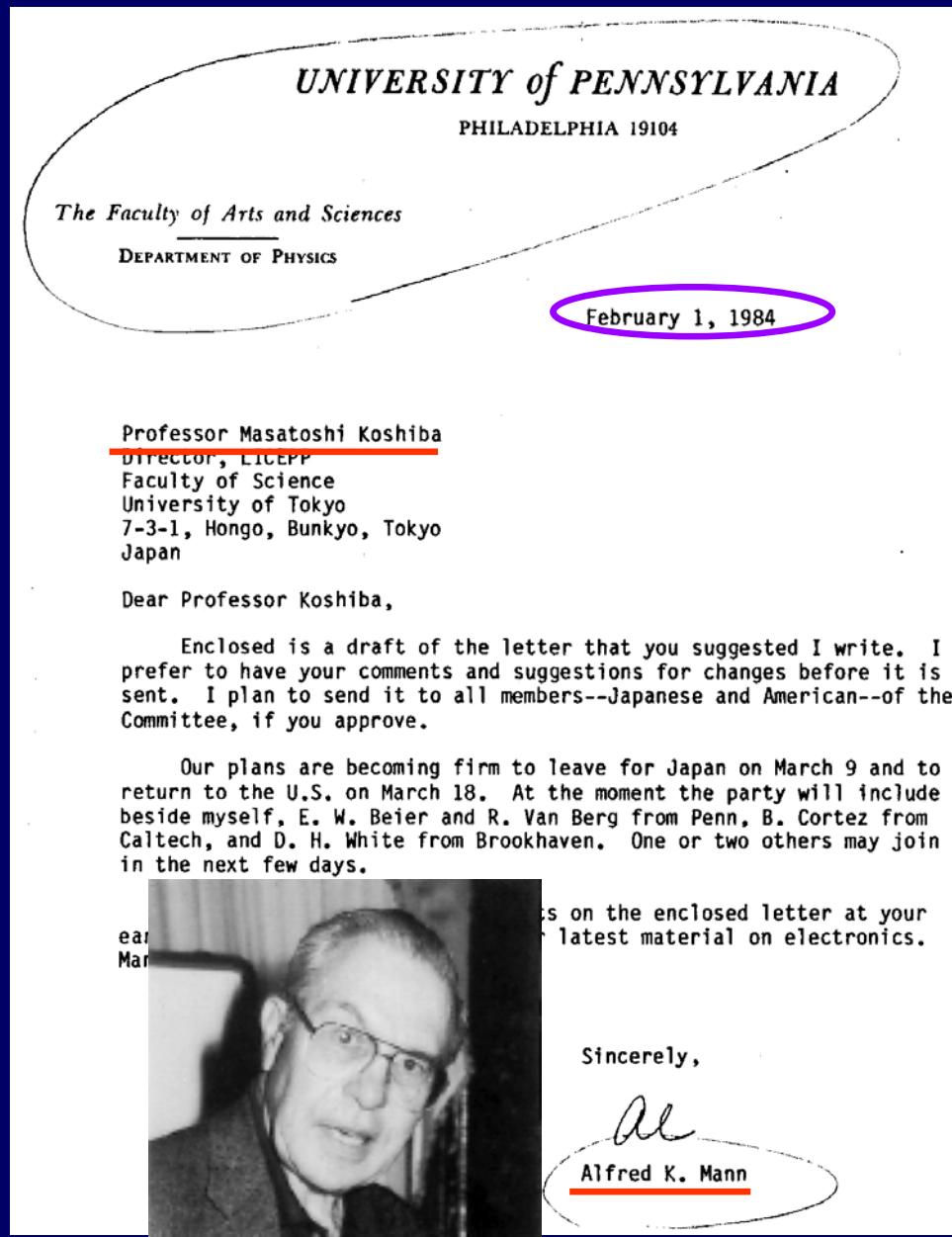


"Why not lower E_{th}
down to 10 MeV
to
detect ${}^8\text{B}$ Solar ν 's!"
(1983)

Kamiokande-II



Kamiokande-II Collaboration



- * 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)

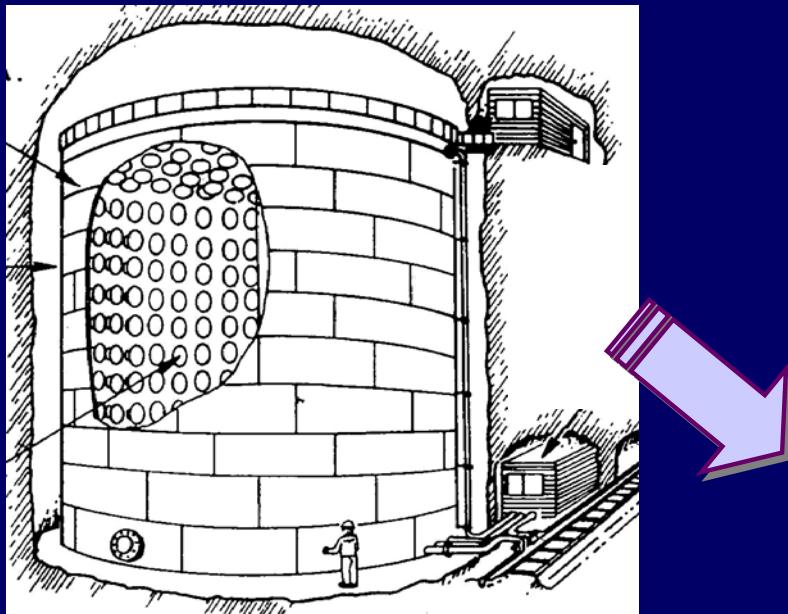
K. Takahashi
(KEK)

K. Miyano
(U. of Niigata)

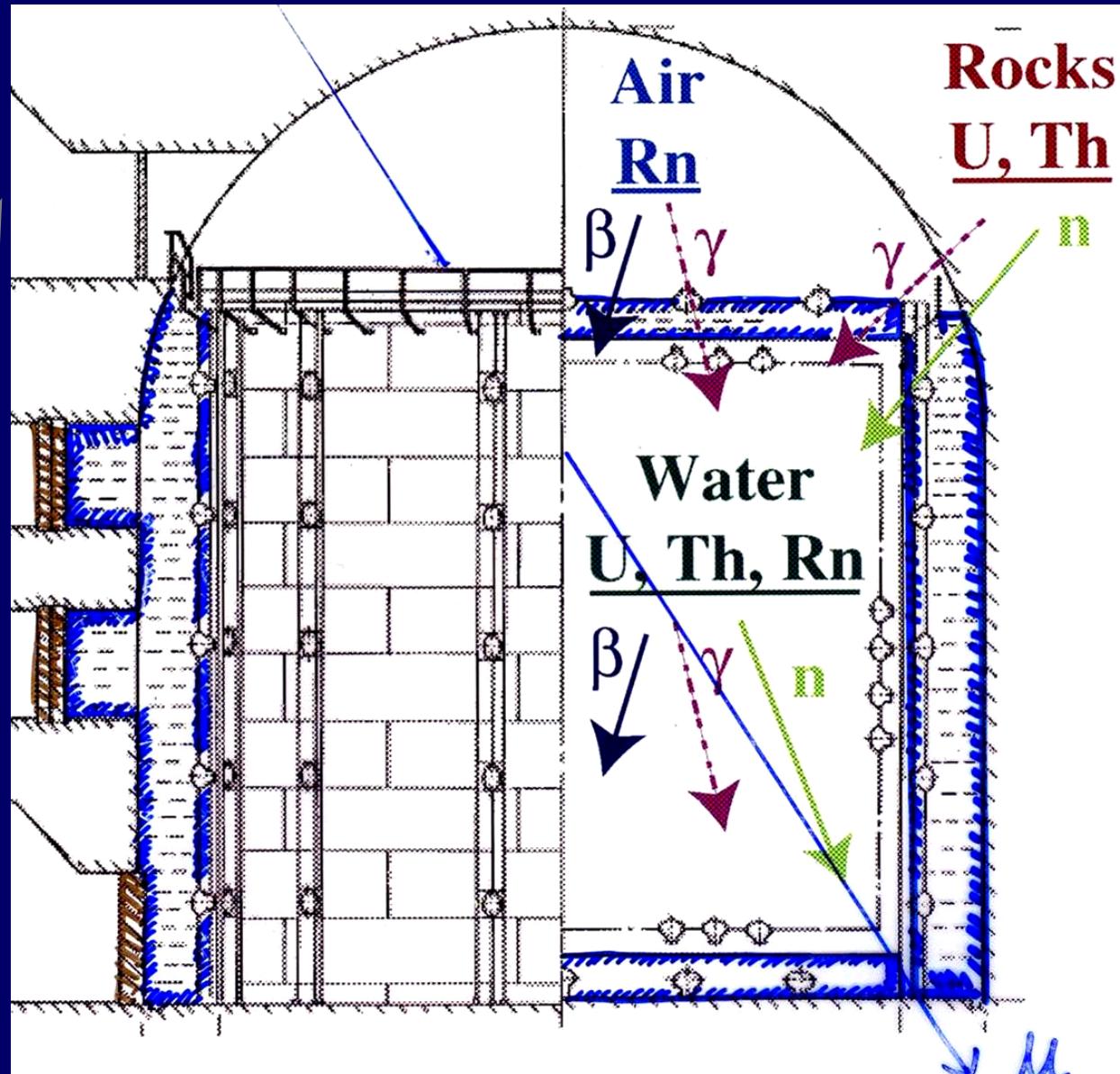
B.G. Cortez
(Caltech.)

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

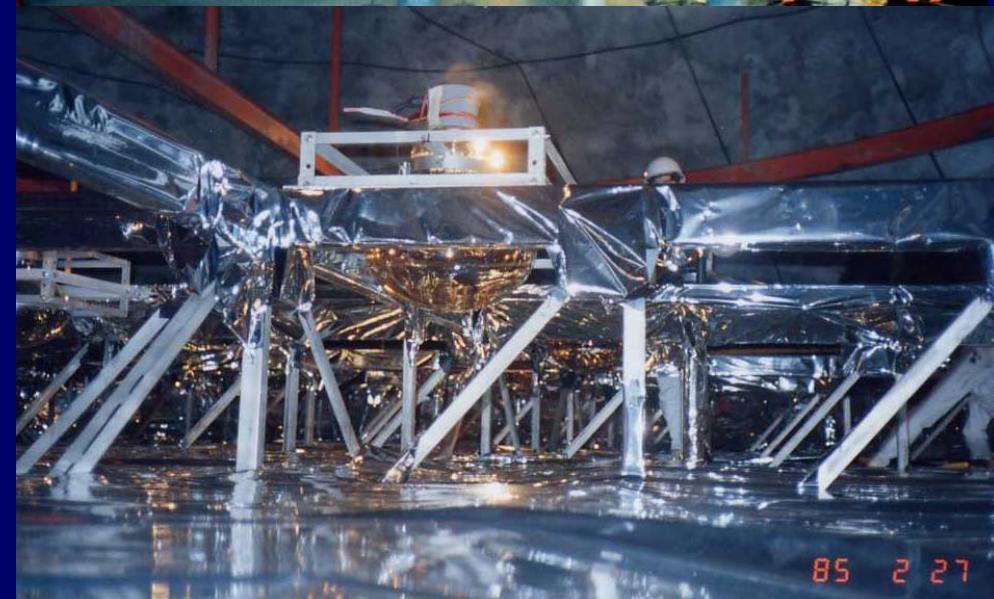
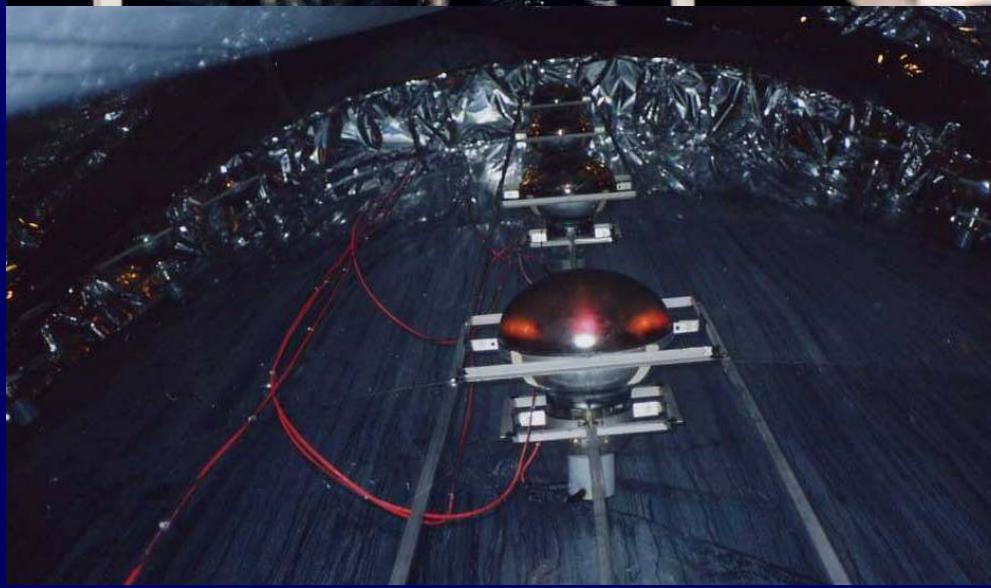


upgrade :

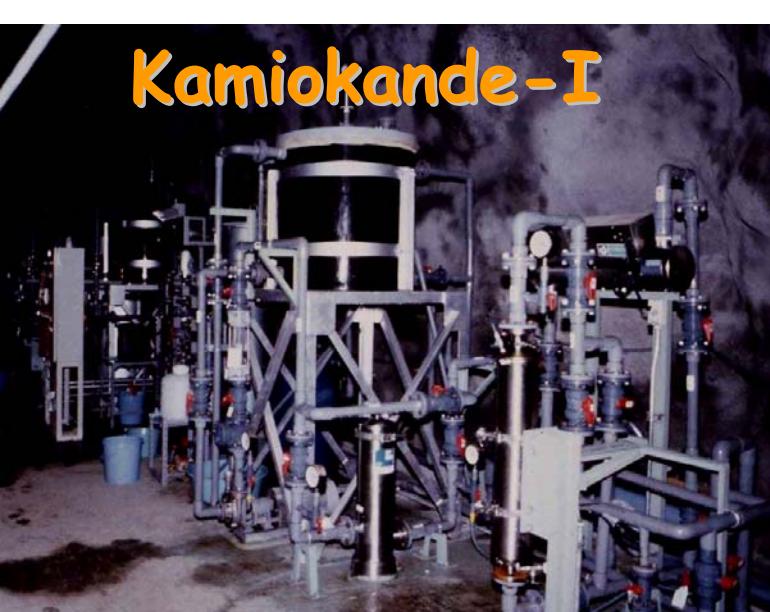
- hermetic, live anticounter
- water purification system
- multi-hit time and charge measurements

Kamiokande-II Construction

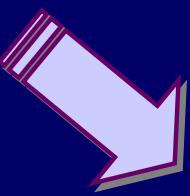
(September, 1984 ~)



Kamiokande-I



Water Purification



Kamiokande-II

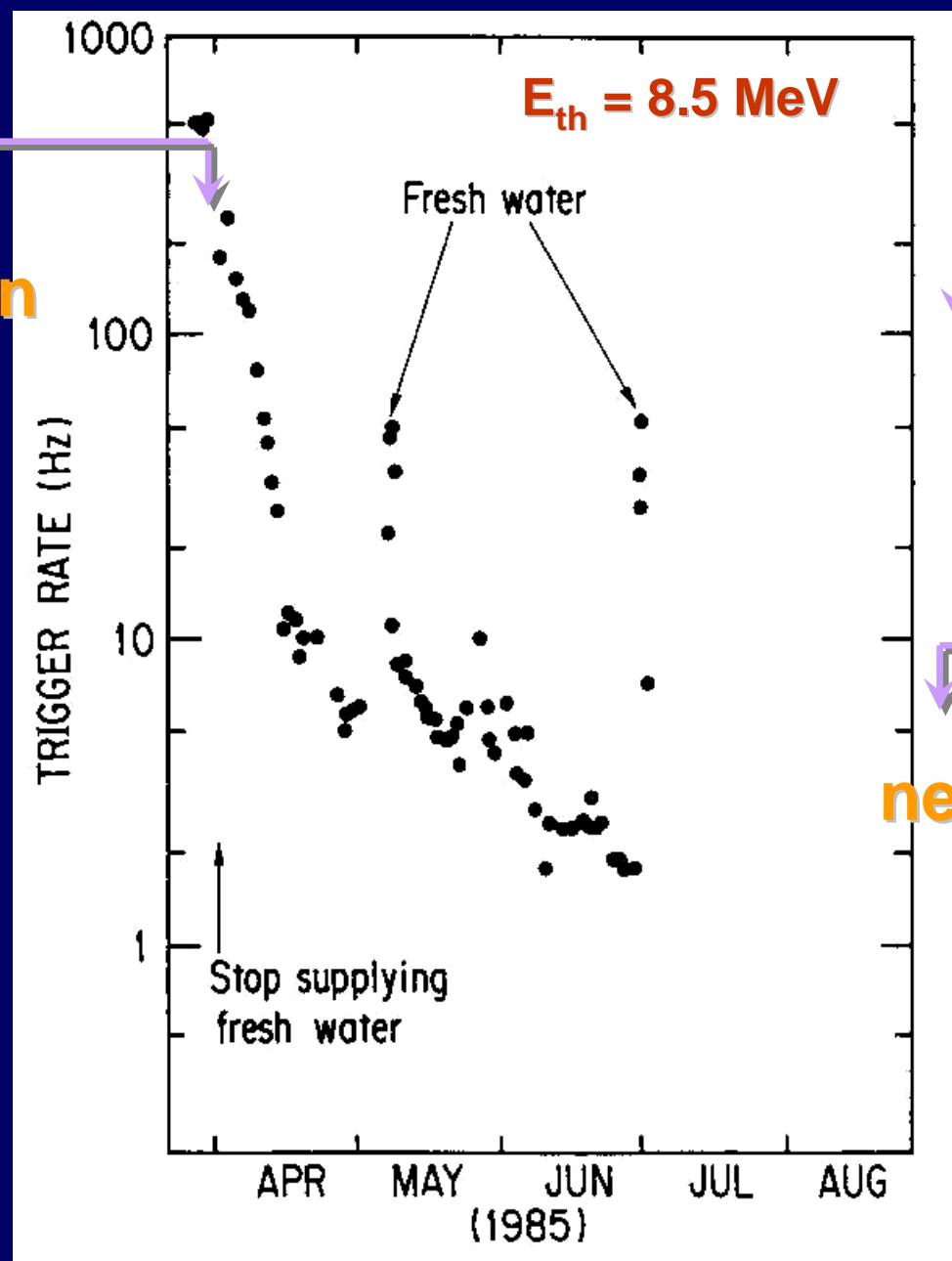


Kamiokande-II Launched

April 1985

water purification

:
start



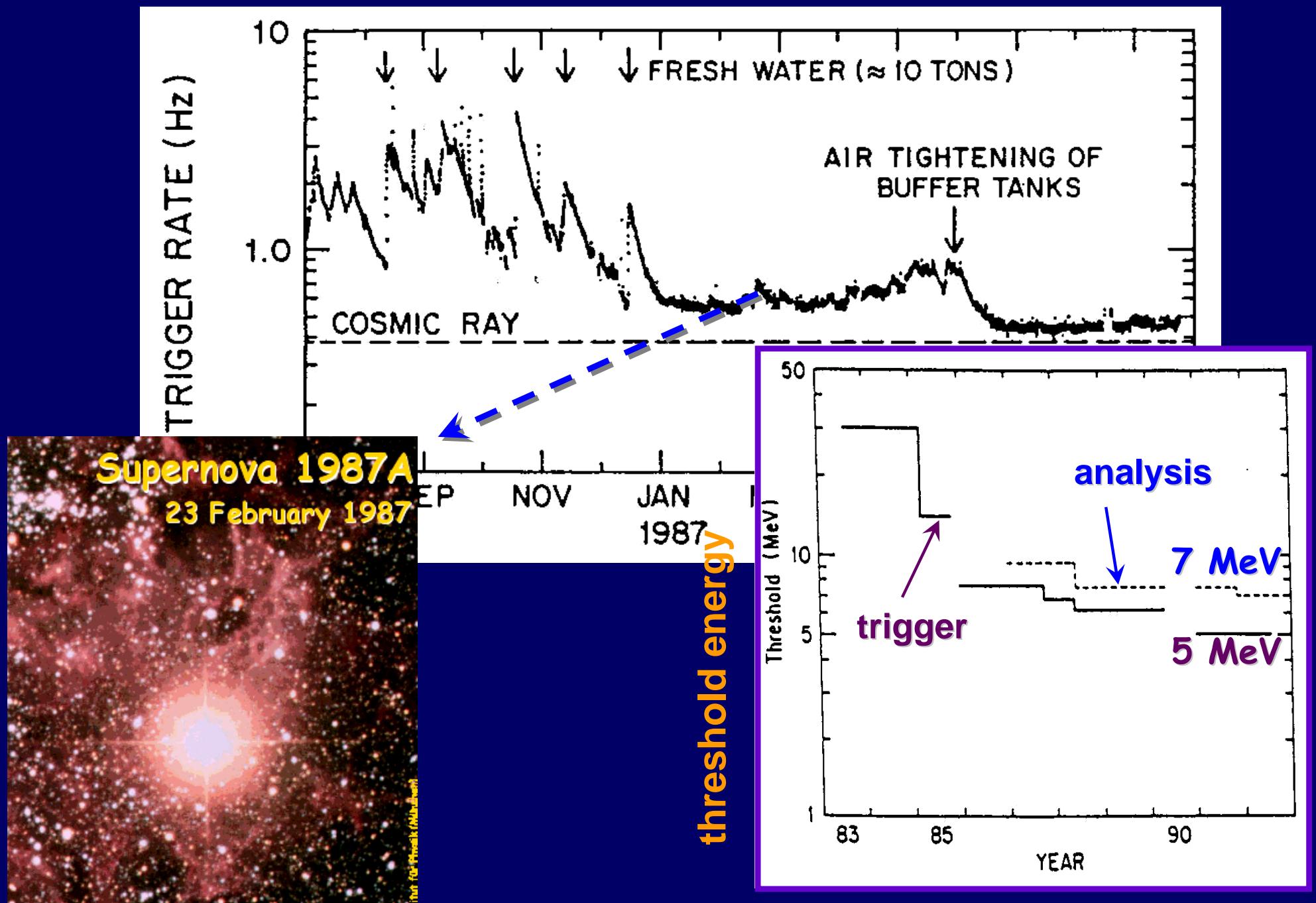
Dec. 1985

Nov. 1985

new electronics

:
ready

Trigger Rate Change (1986 ~)

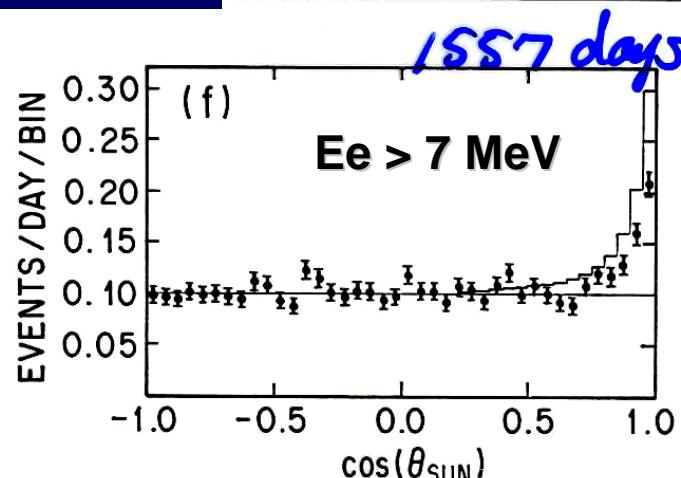
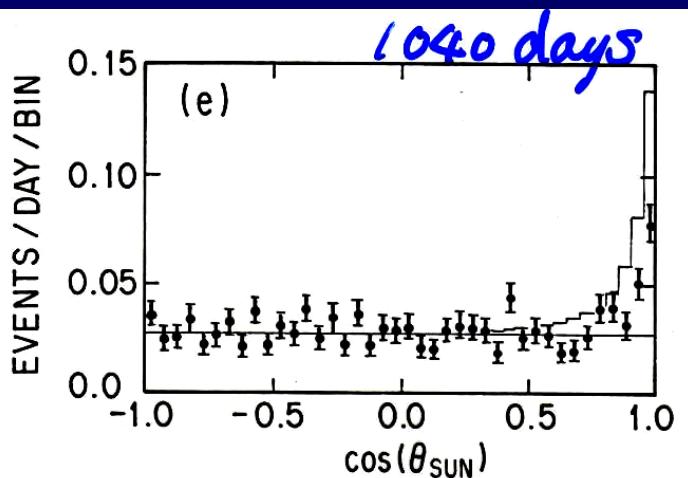
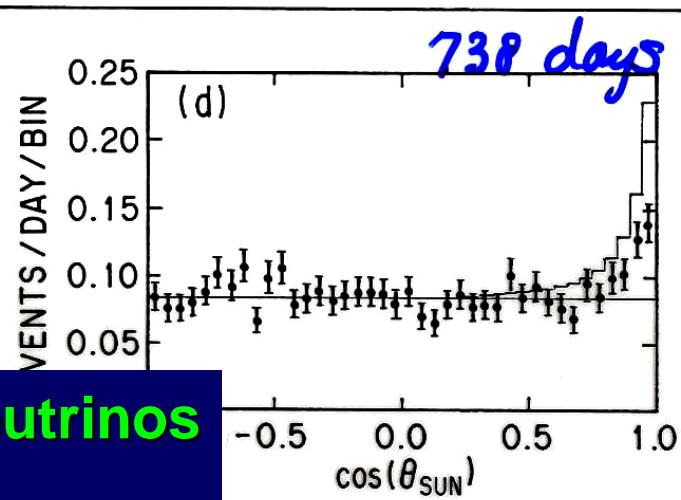
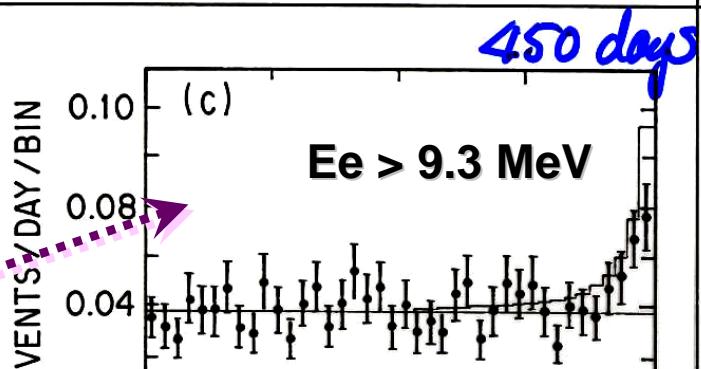
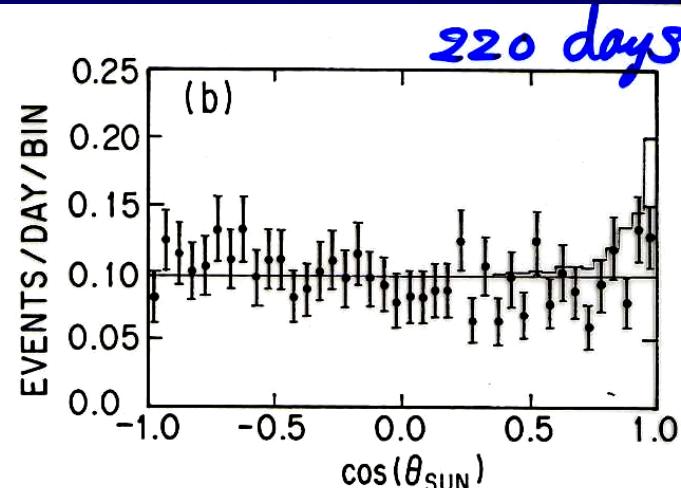
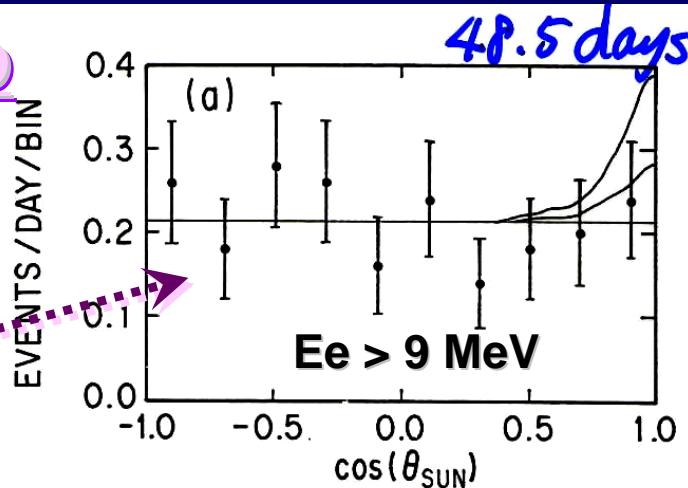


2. Solar Neutrino Detection

First presentation
in Neutrino '86
(Sendai)

First paper entitled “Observation of ${}^8\text{B}$ Solar Neutrinos
in the Kamiokande-II Detector”

in PRL (1989)
:
 $0.46 \pm 0.13 \pm 0.08$
of SSM

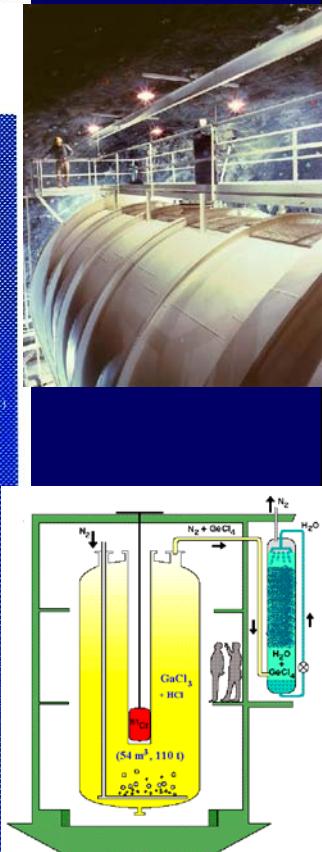


Kamiokande-II Reconfirmed "Solar Neutrino Problem"



Solar Neutrino Observations (~ 1995)

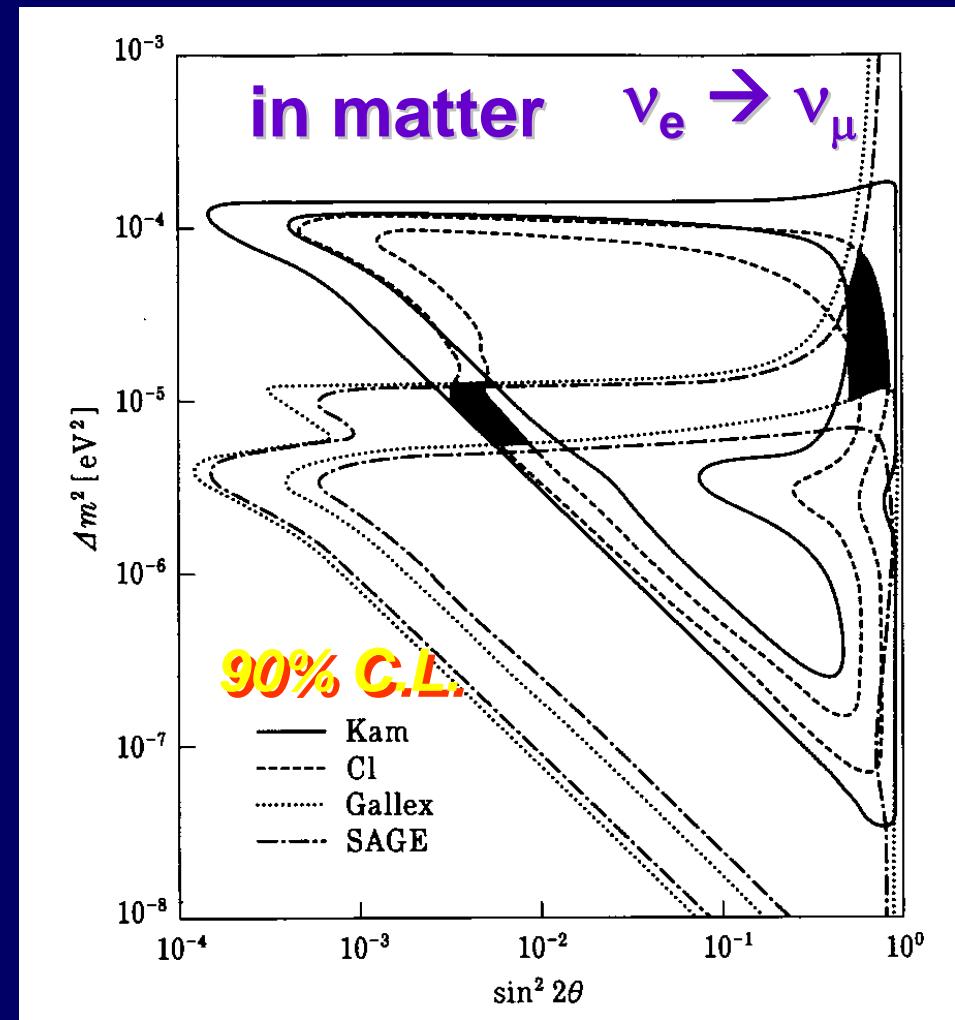
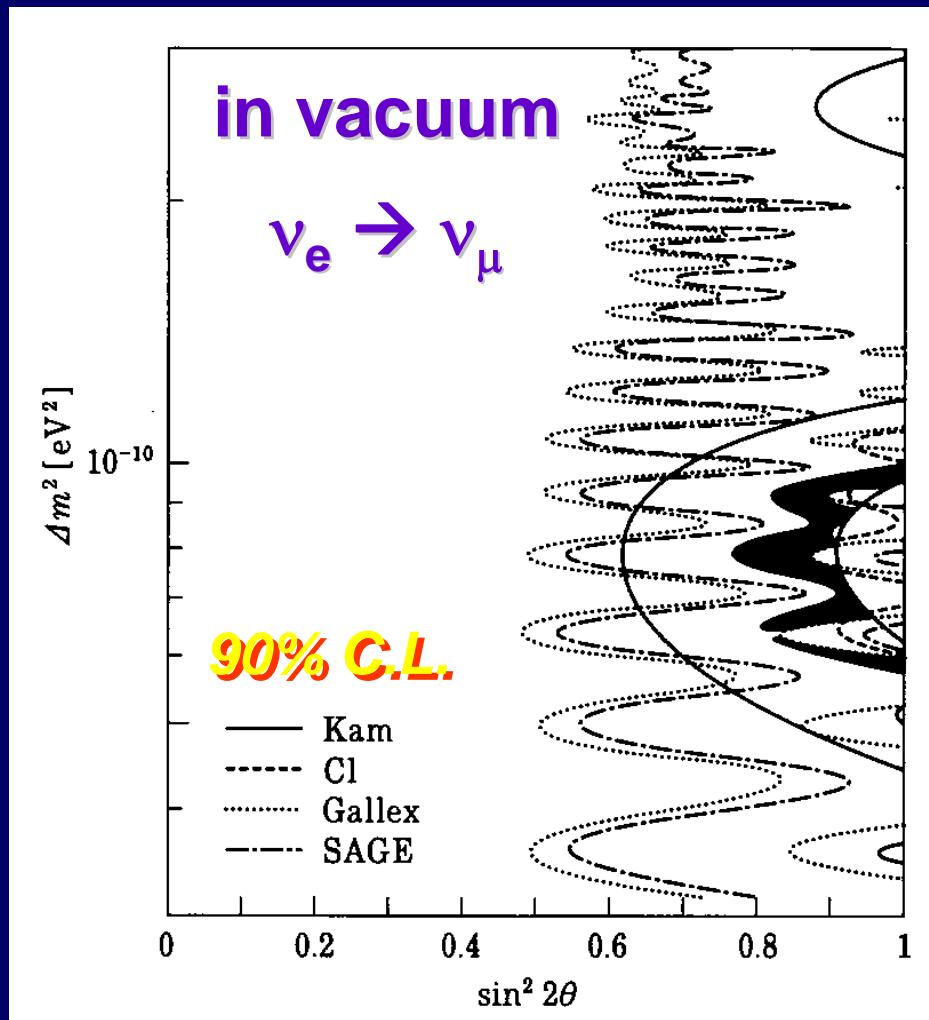
experiment	solar neutrinos	data / theory
Homestake (Cl)	${}^7\text{Be} + {}^8\text{B} + \dots$	0.29 ± 0.03
Kamiokande (H ₂ O)	${}^8\text{B}$	0.48 ± 0.08
GALLEX (Ga)	$\text{pp} + {}^7\text{Be} + {}^8\text{B} + \dots$	0.60 ± 0.09
SAGE (Ga)	$\text{pp} + {}^7\text{Be} + {}^8\text{B} + \dots$	0.52 ± 0.09



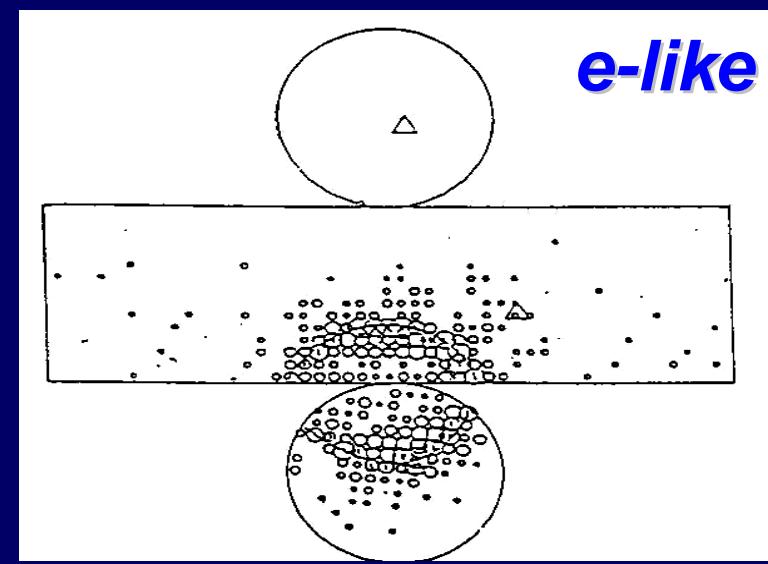
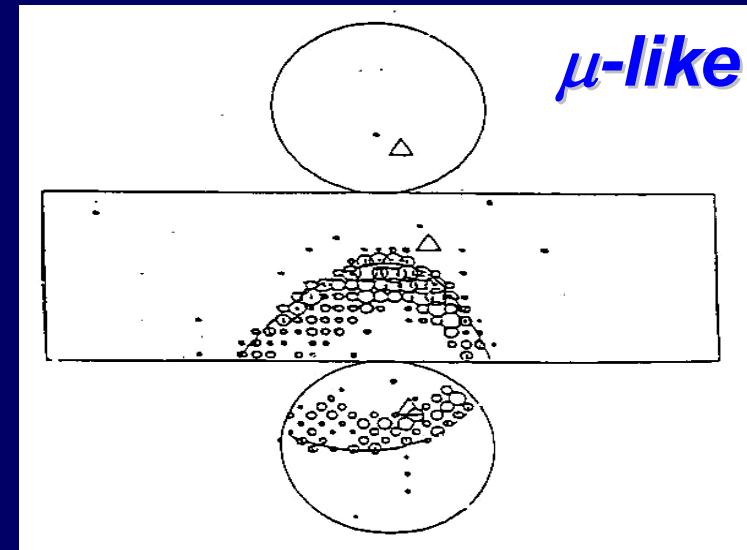
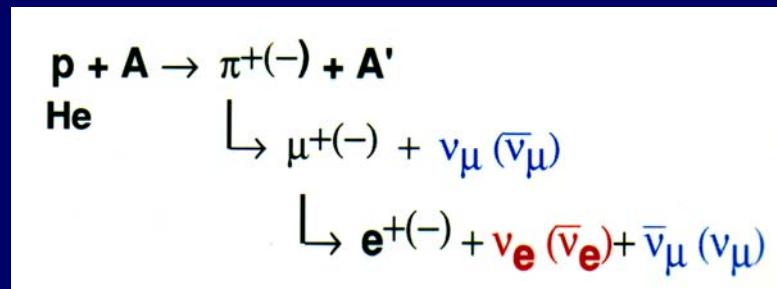
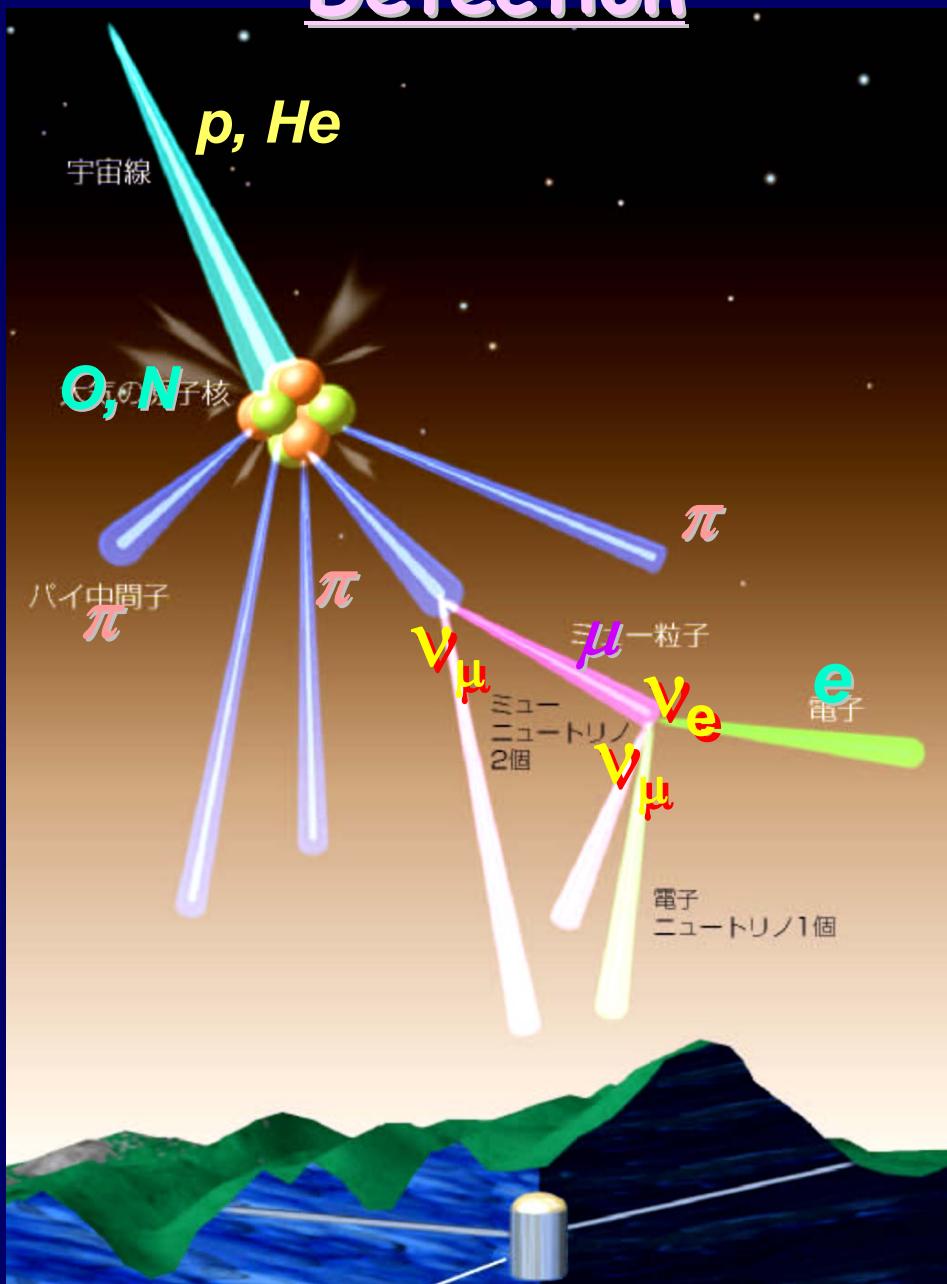
Where have Solar Neutrinos gone ?

The Most Plausible Solution to “Solar Neutrino Problem”

neutrino oscillations

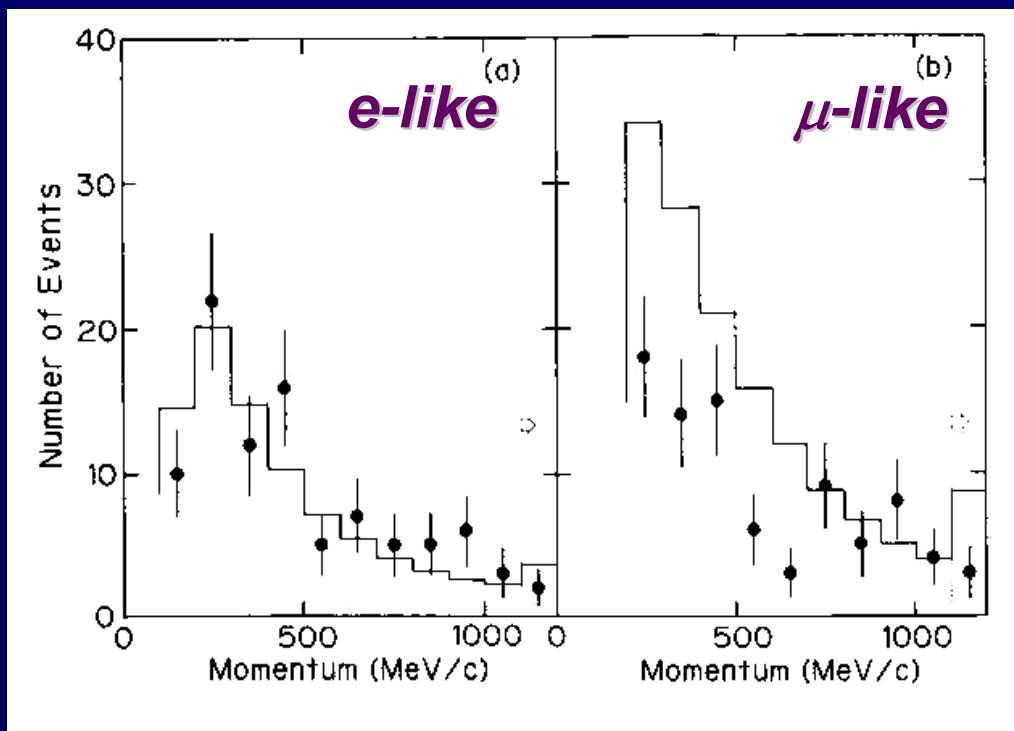


3. Atmospheric Neutrino Detection



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

"Experimental study of the atmospheric neutrino flux"



of single rings

	Data	MC
μ -like	85	144
$\mu \rightarrow e$	(52)	(104)
e-like	105	106

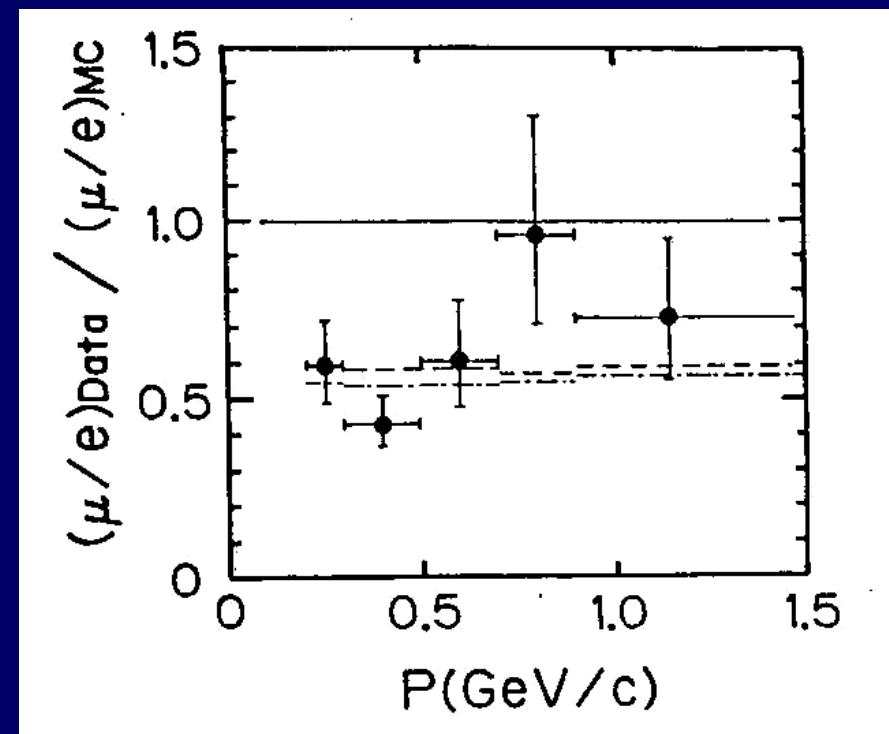
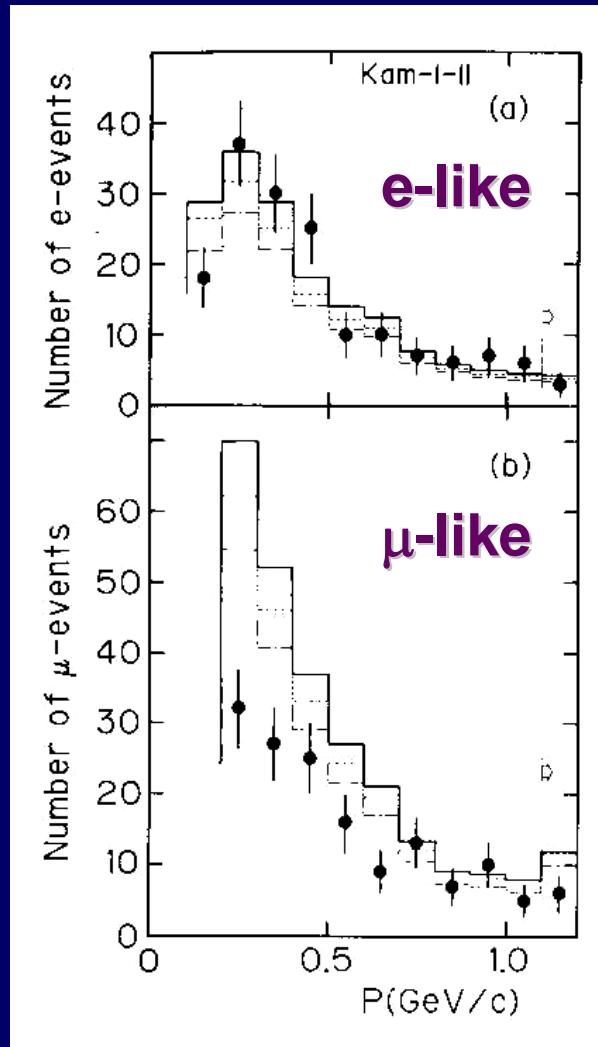
$(110 < P_e < 4500)$

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

Atmospheric Neutrino Anomaly :

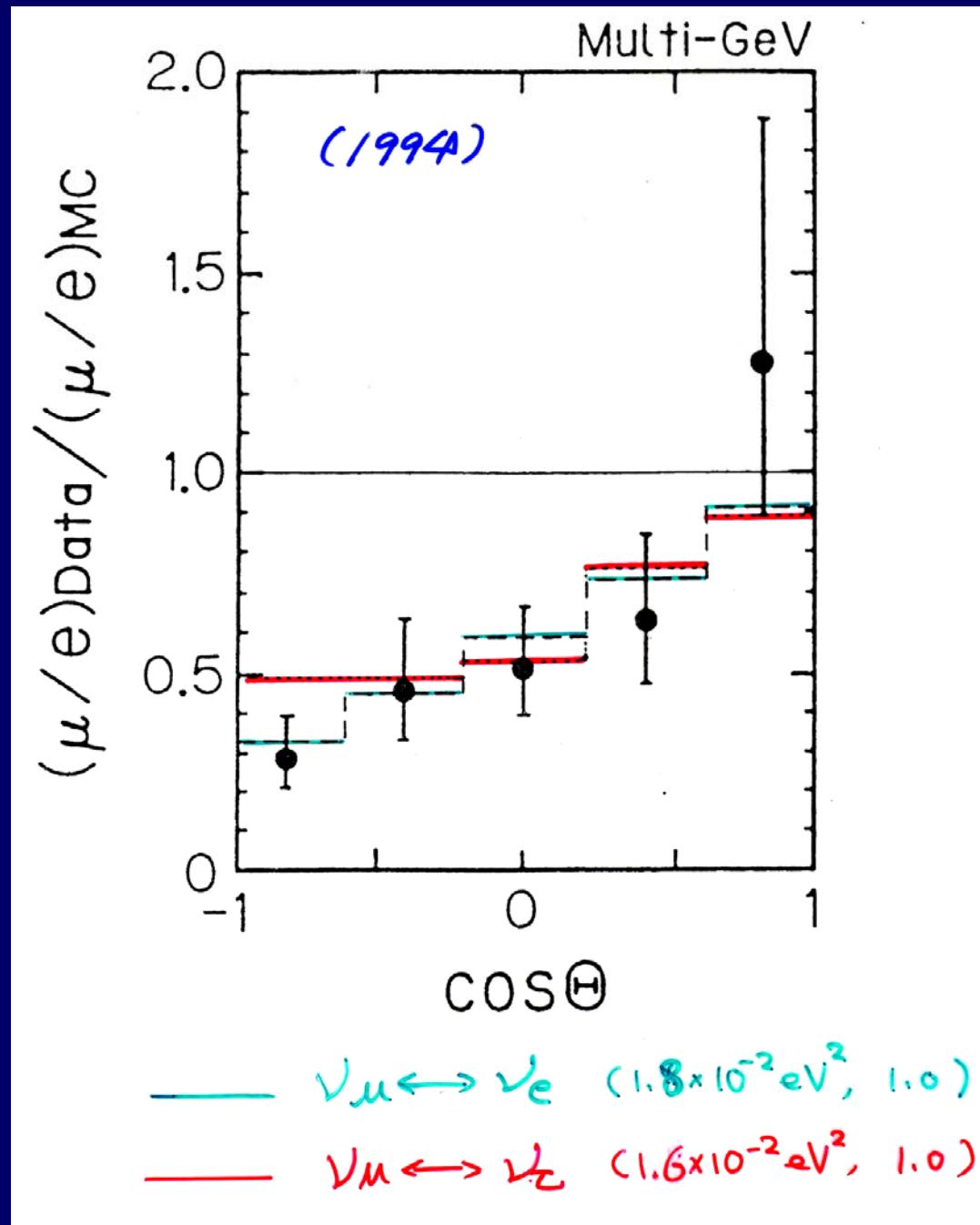
Phys. Lett. B280 (1992) 146

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



$$R(\mu/e) = 0.60^{+0.07}_{-0.06} \text{ (stat.)} \pm 0.05 \text{ (syst.)}$$

Zenith Angle Dependence of $R(\mu/e)$



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
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Atmospheric Neutrino Anomaly

:

Water Cerenkov Effect

 :

 ν_e

 (μ/e discrimination ?)

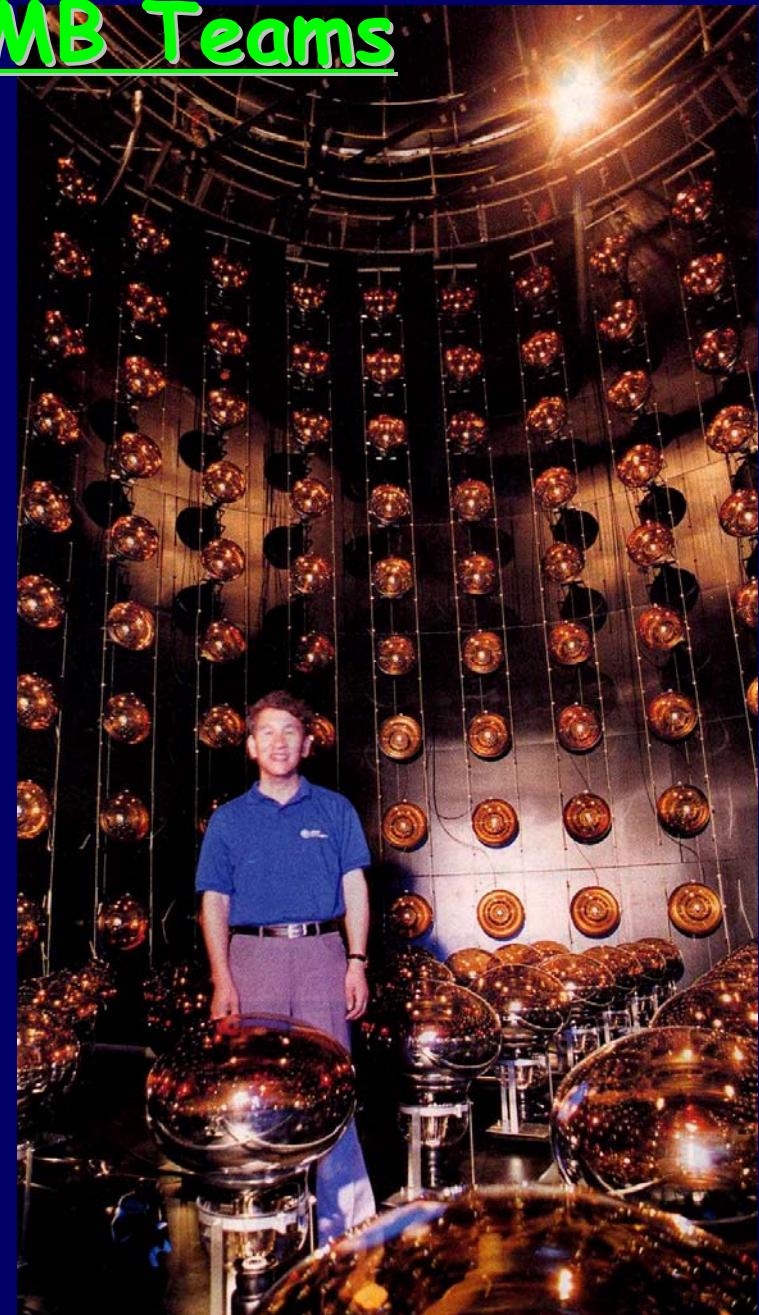
	μ-like	50.8	125.8	42.1	208.0	350.8
$\frac{(\mu/e)_{DATA}}{(\mu/e)_{MC}}$		<u>0.99</u>	<u>1.06</u>	<u>1.90</u>	<u>3.50</u>	<u>5.10</u>
(stat.)		± 0.35	± 0.19	± 0.17	± 0.05	± 0.06
(sys.)		± small	± 0.15	± 0.09	± 0.12	± 0.05
$\frac{(e)_{DATA}}{(e)_{MC}}$		0.88	0.80	1.23	1.26	1.09
(error) [#]		± 0.21	± 0.11	± 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

R(μ/e)



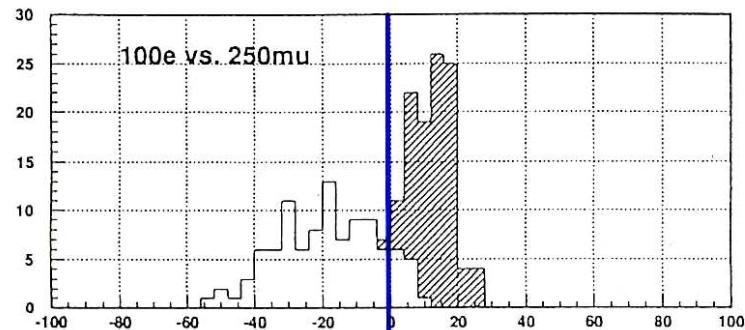
Beam (μ , e, π) Test at KEK by Kamiokande & IMB Teams

(1994)

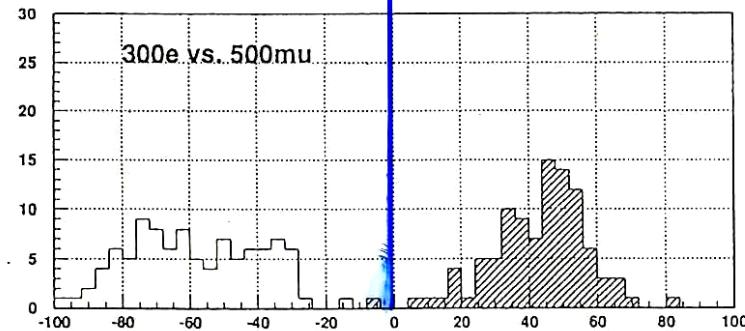
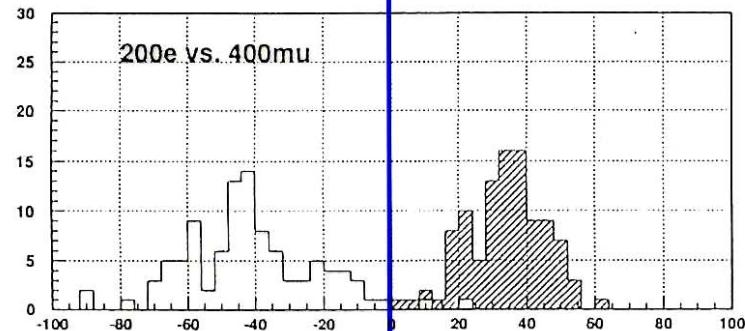


Beam Test Results

MC

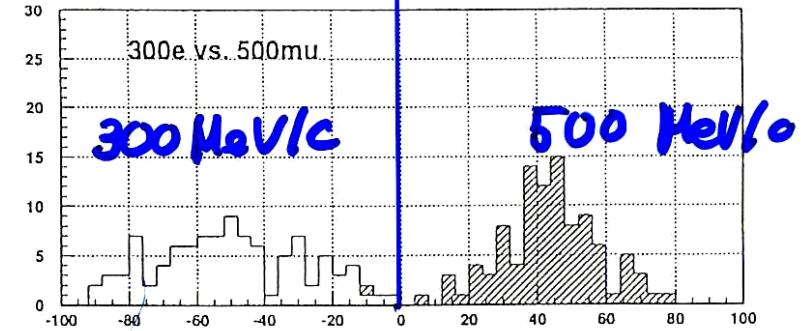
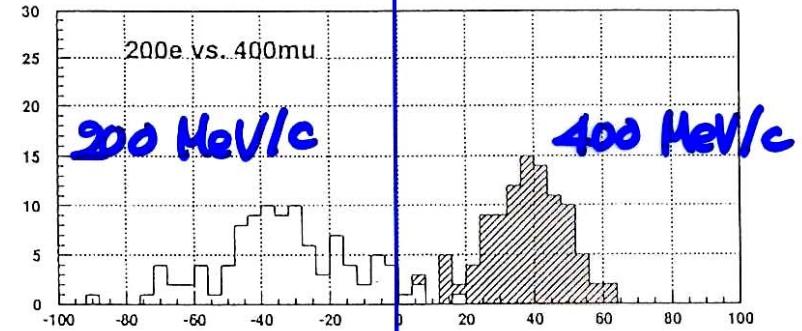
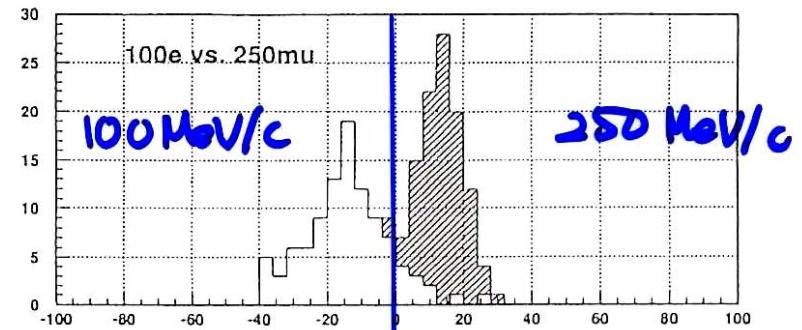


μ
 e



e-like \leftarrow \rightarrow μ -like

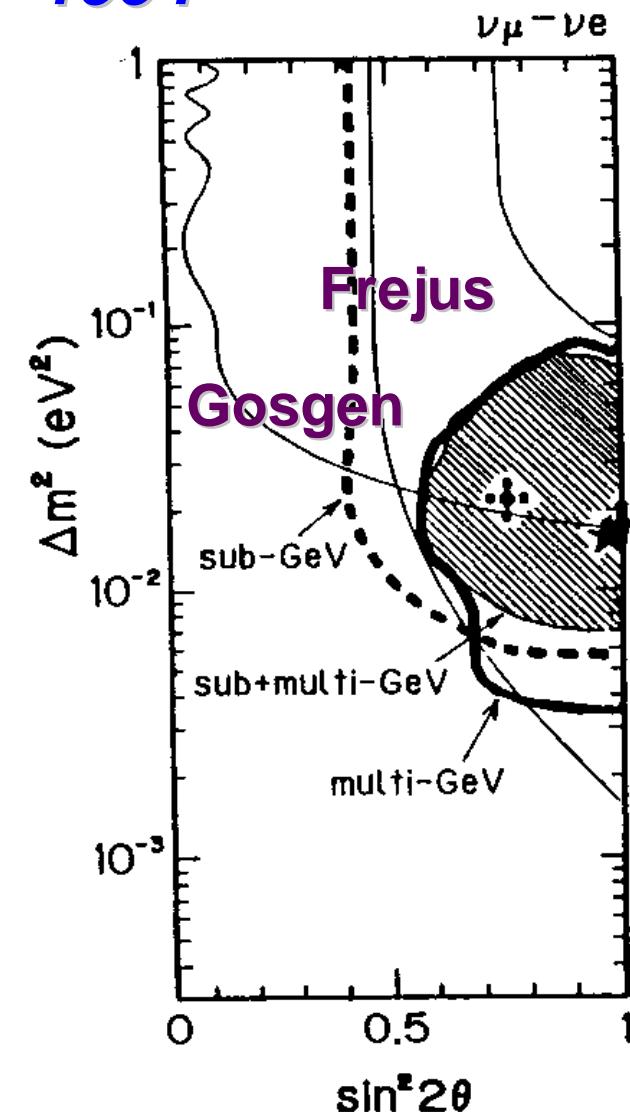
Data



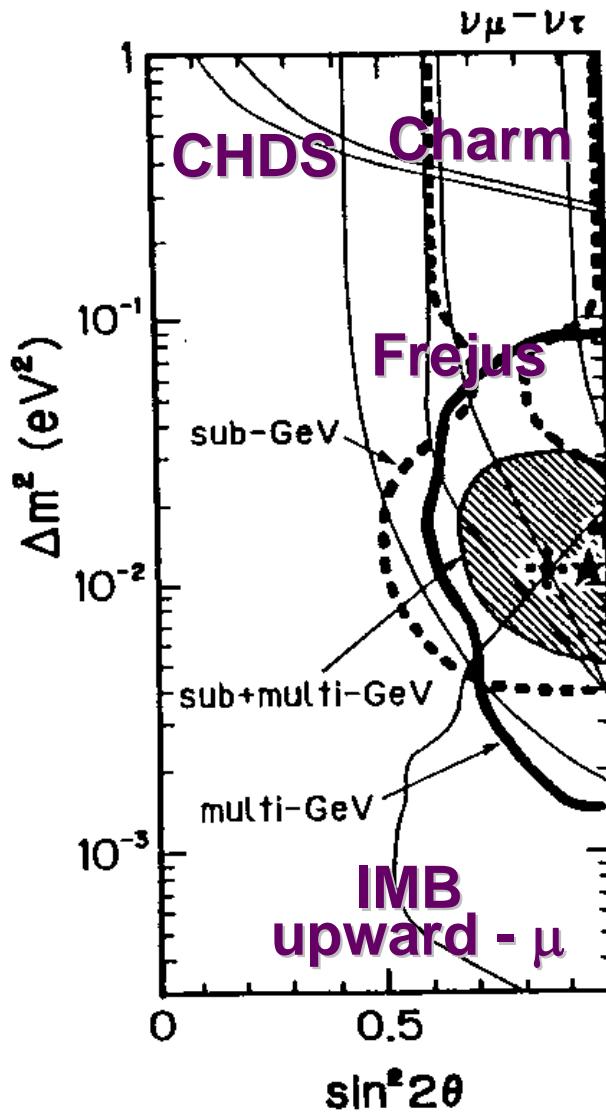
e-like \leftarrow \rightarrow μ -like

Neutrino Oscillation Studies for Atmospheric Neutrino Events

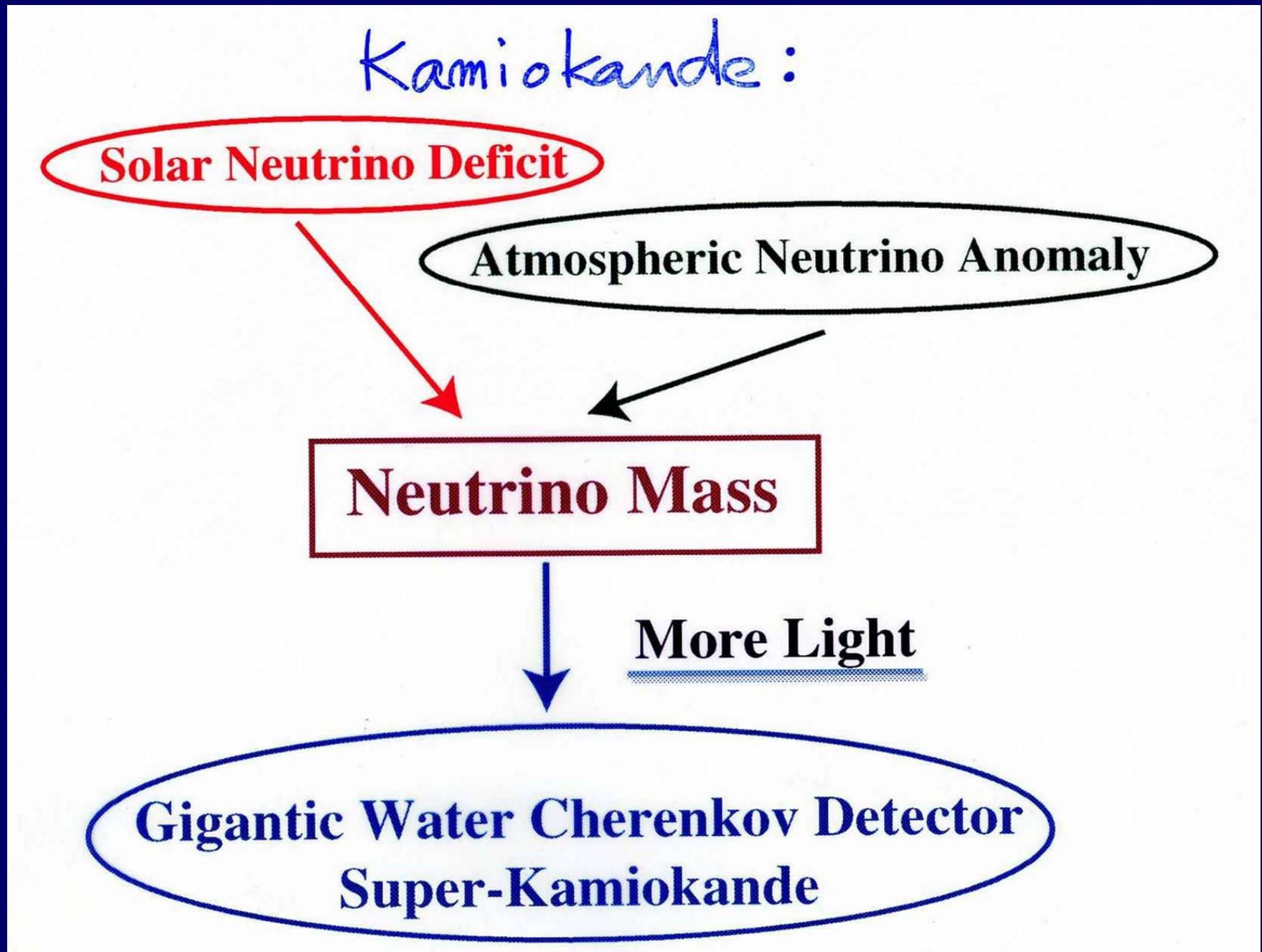
1994



90% C.L.



4. Kamiokande to Next Generation Experiments



Discovery of Atmospheric Neutrino Oscillations

1998

"All the News
That's Fit to Print"

The New York Times

**Mass Found in Elusive Particle;
Universe May Never Be the Same**

**Discovery on Neutrino
Rattles Basic Theory
About All Matter**

By MALCOLM W. BROWNE

TAKAYAMA, Japan, June 5 — In what colleagues hailed as a historic landmark, 120 physicists from 23 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

The neutrino, a particle that carries no electric charge, is so light that it was assumed for many years to have no mass at all. After today's announcement, cosmologists will have to confront the possibility that a significant part of the mass of the universe might be in the form of neutrinos. The discovery will also compel scientists to revise a highly successful theory of the composition of matter known as the Standard Model.

Word of the discovery had drawn some 300 physicists here to discuss neutrino research. Among other things, the finding of neutrino mass might affect theories about the formation and evolution of galaxies and the ultimate fate of the universe. If neutrinos have sufficient mass, their presence throughout the universe would increase the overall mass of the universe, possibly slowing its present expansion.

Others said the newly detected but as yet unmeasured mass of the neutrino must be too small to cause cosmological effects. But whatever the case, there was general agreement here that the discovery will have far-reaching consequences for the investigation of the nature of matter.

Speaking for the collaboration of scientists who discovered the existence of neutrino mass using a huge underground detector called Super-Kamiokande, Dr. Takaaki Kajita of the Institute for Cosmic Ray Research of Tokyo University and that organization's spokesman, for the data collected by the detector, a neutrino collision with the detector's metal walls re-



And Detecting Their Mass

By analyzing the cones of light, physicists determine that some neutrinos have changed form on their journey. If they can change form, they must have mass.

Source: University of Hawaii

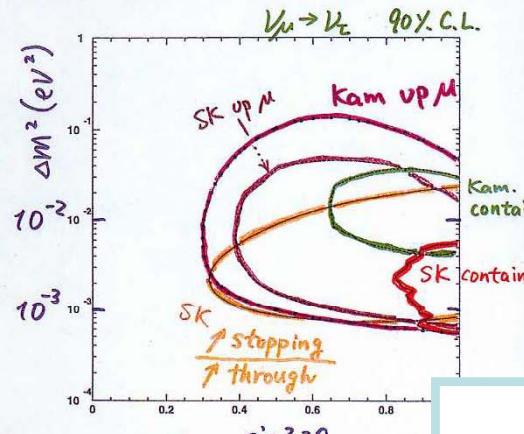
**Yankee Owner
Warns Vallone
On Referendum**

By NORIMITSU ONISHI

Opening a new front in the political battle over the future of Yankee Stadium, George M. Steinbrenner ad, the team's chairman, declared yesterday that he would not sell the team if voters do not approve his plan to relocate it to a new site in Bronx Park.

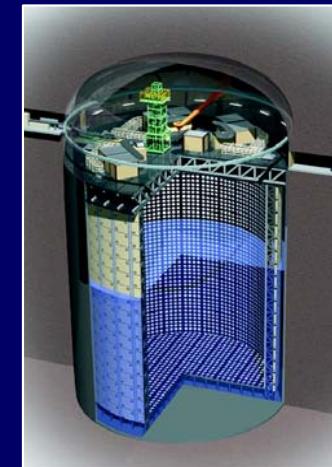
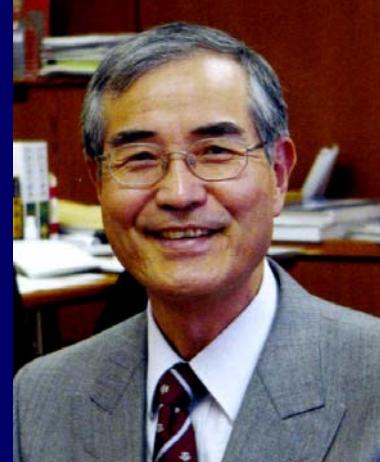
Summary

Evidence for ν_μ oscillations



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

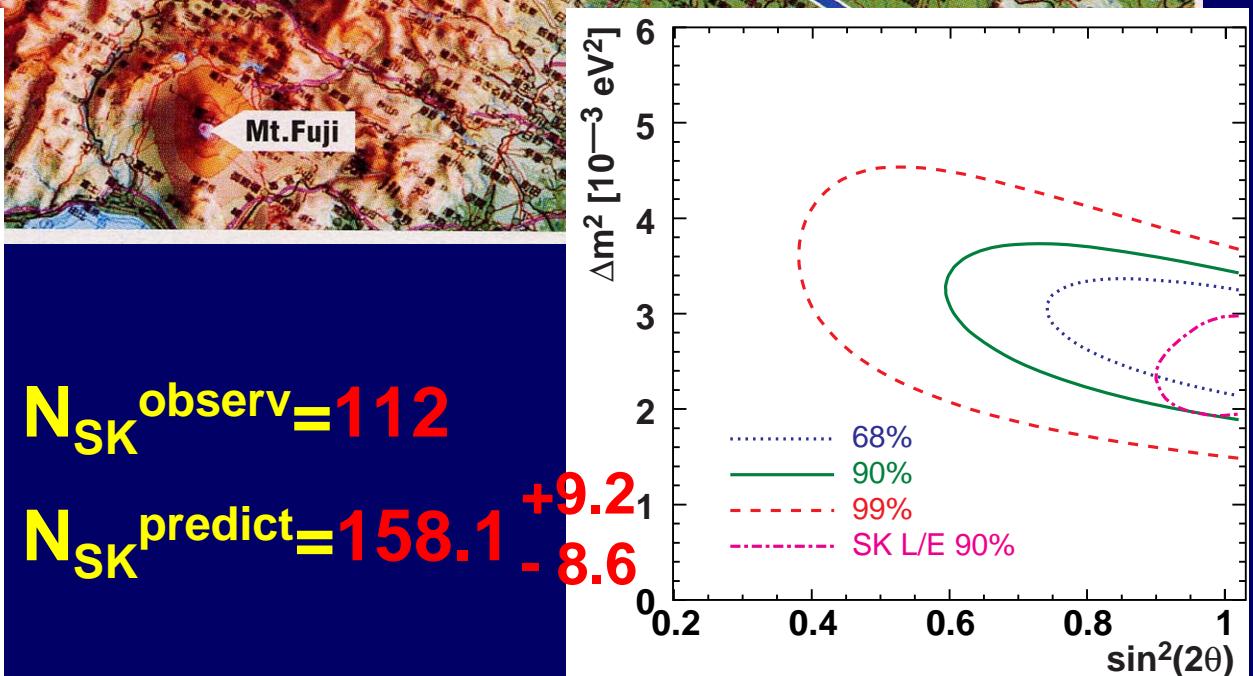
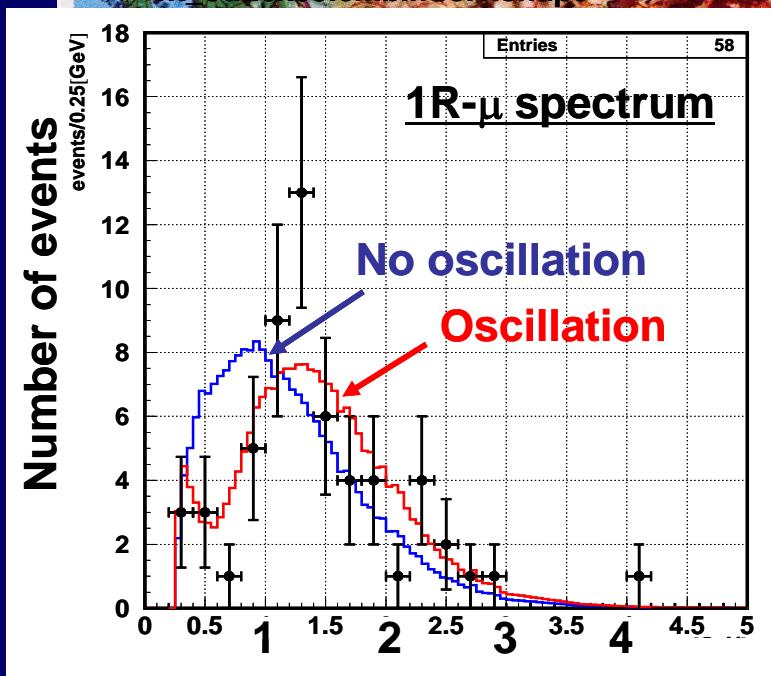
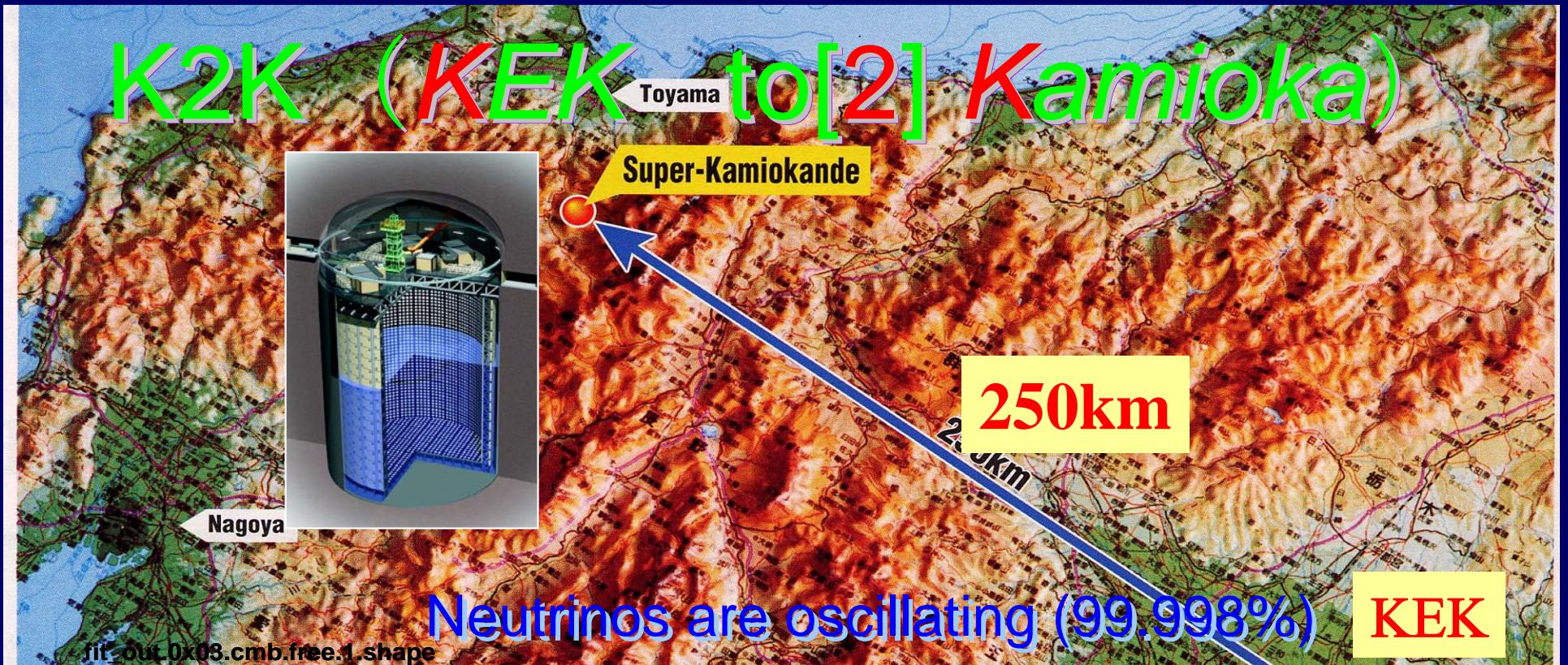
(• $\nu_\mu \rightarrow \nu_\tau$ or $\nu_\mu \rightarrow \nu_s$?)



Evidence for oscillation of atmospheric neutrinos

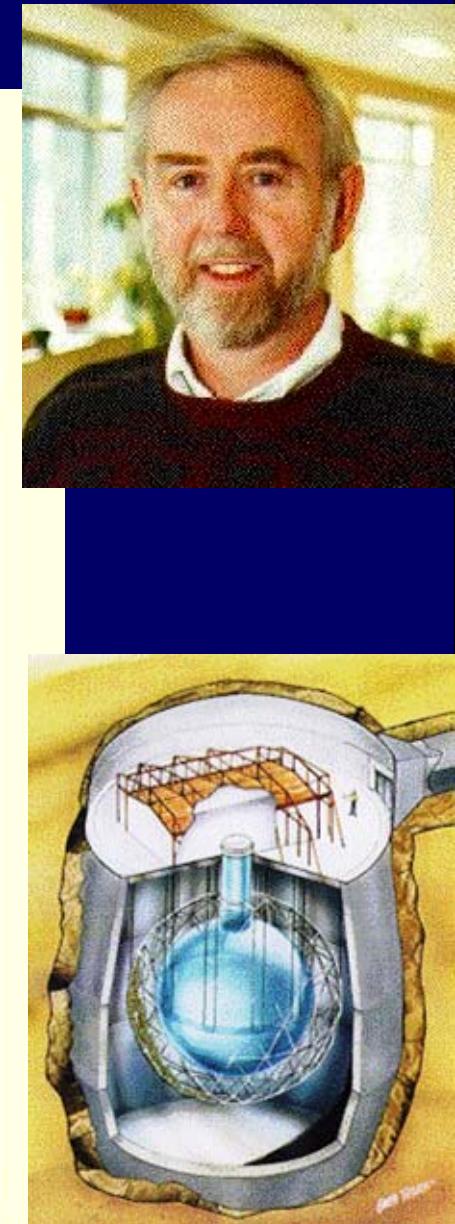
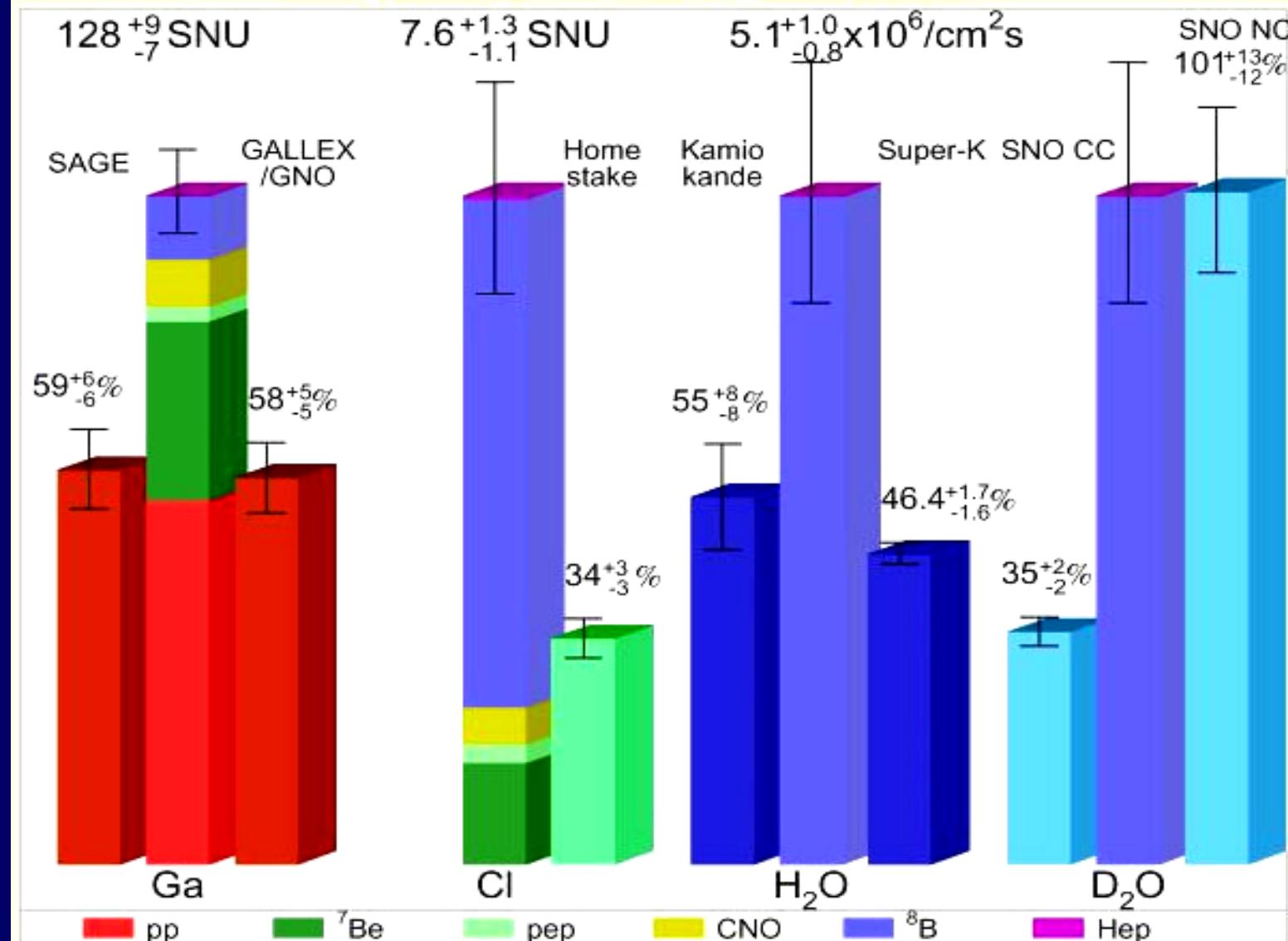
The Super-Kamiokande Collaboration

Y.Fukuda^a, T.Hayakawa^a, E.Ichihara^a, K.Inoue^a, K.Ishihara^a, H.Ishino^a, Y.Ito^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.Tasaki^g, J.W.Flanagan^{h,t}, A.Kibayashi^h, J.G.Learned^h, S.Matsuno^h, V.J.Stenger^h, D.Takemori^h, T.Ishiiⁱ, J.Kanzakiⁱ, T.Kobayashiⁱ, S.Mineⁱ, K.Nakamuraⁱ, K.Nishikawaiⁱ, Y.Oyamaⁱ, A.Sakaiⁱ, M.Sakudaⁱ, O.Sasakiⁱ, S.Echigoⁱ, M.Kohamaⁱ, 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,t}, J.A.Goodman^m, G.W.Sullivan^m, J.Hillⁿ, C.K.Jungⁿ, K.Martensⁿ, C.Maugerⁿ, C.McGrewⁿ, E.Sharkeyⁿ, B.Virenⁿ, C.Yanagisawaⁿ, W.Doki^t, K.Miyano^t, H.Okazawa^t, C.Saji^t, M.Takahata^t, Y.Nagashima^t, M.Takita^t, T.Yamaguchi^t, M.Yoshida^t, 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,s}, 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



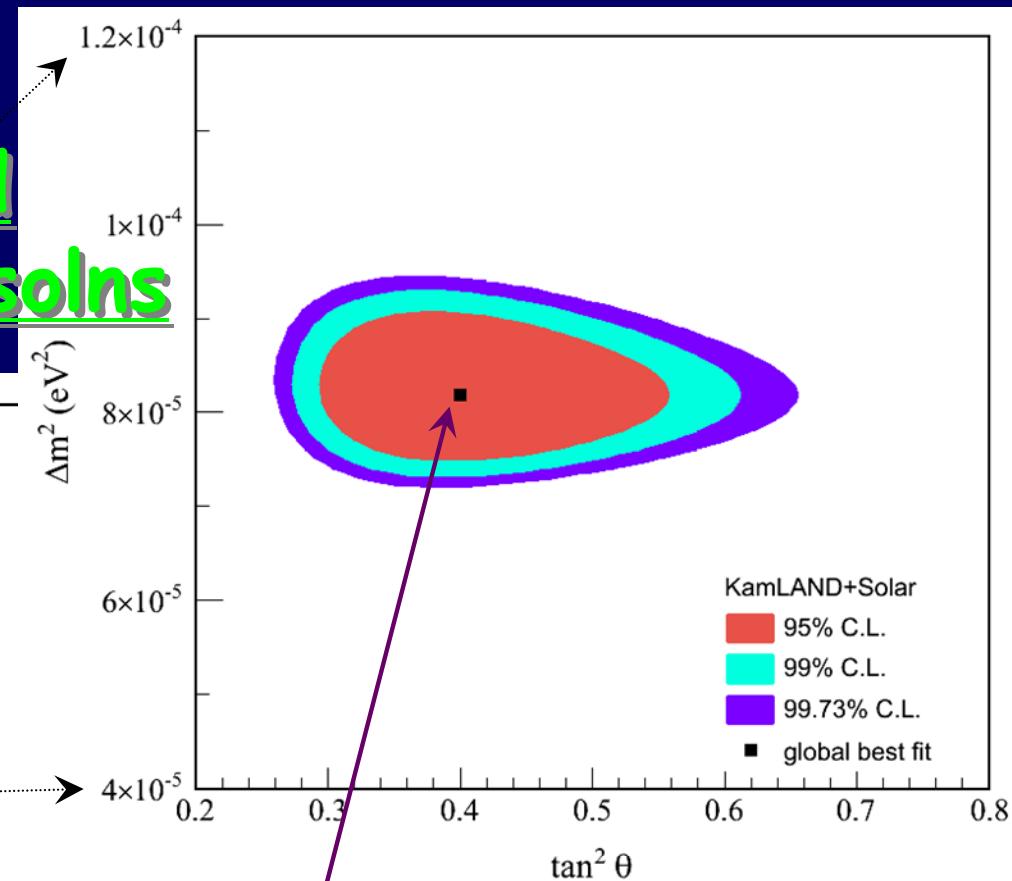
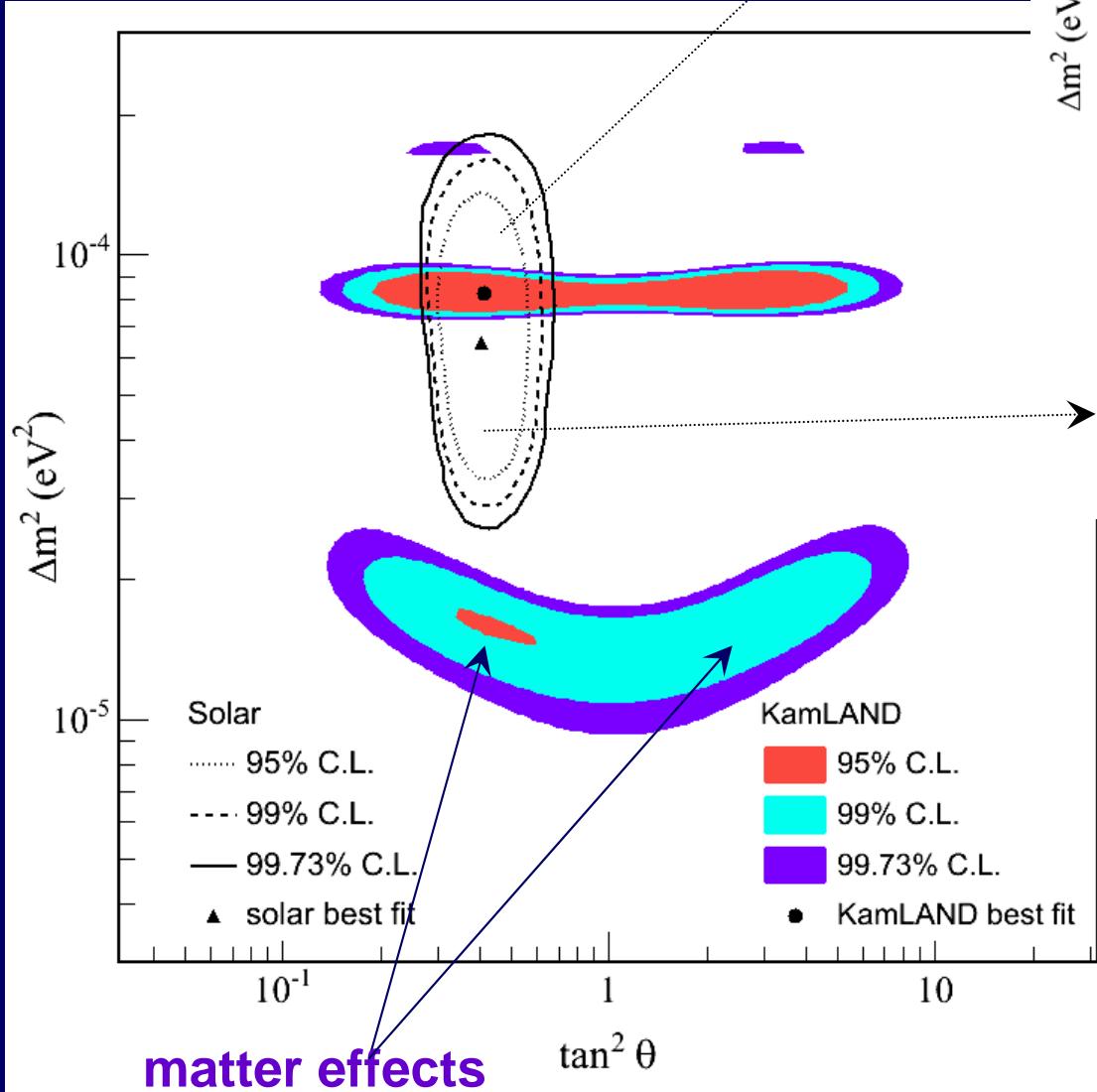
M. Smy, v 2002

Solar ν Problem



KamLAND :

swept out non-standard
mechanisms as leading solns



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

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

assuming CPT invariance

Conclusion

Evidence for Neutrino Mass

Kamiokande-II

