Birth
of
Neutrino Astrophysics

M. Koshiba

November 2002

For more details, see my review article;

"Observational Neutrino Astrophysics"; Physics Report, **220** (1992) Nos.5&6, pp.229-482.

LIGO-G020544-00-R

Conception

There was a very important prenatal event.

That was the radiochemical work of R.Davis using the reaction $\nu_e + Cl^{37}$ to $e^- + Ar^{37}$. The conclusion was that the solar neutrinos are only about 1/3 of what you expect from the Standard Solar Model of J.Bahcall.

This could be considered as the conception of the Neutrino Astrophysics and was the impetus for us to begin seriously working on the solar neutrinos

The experiments

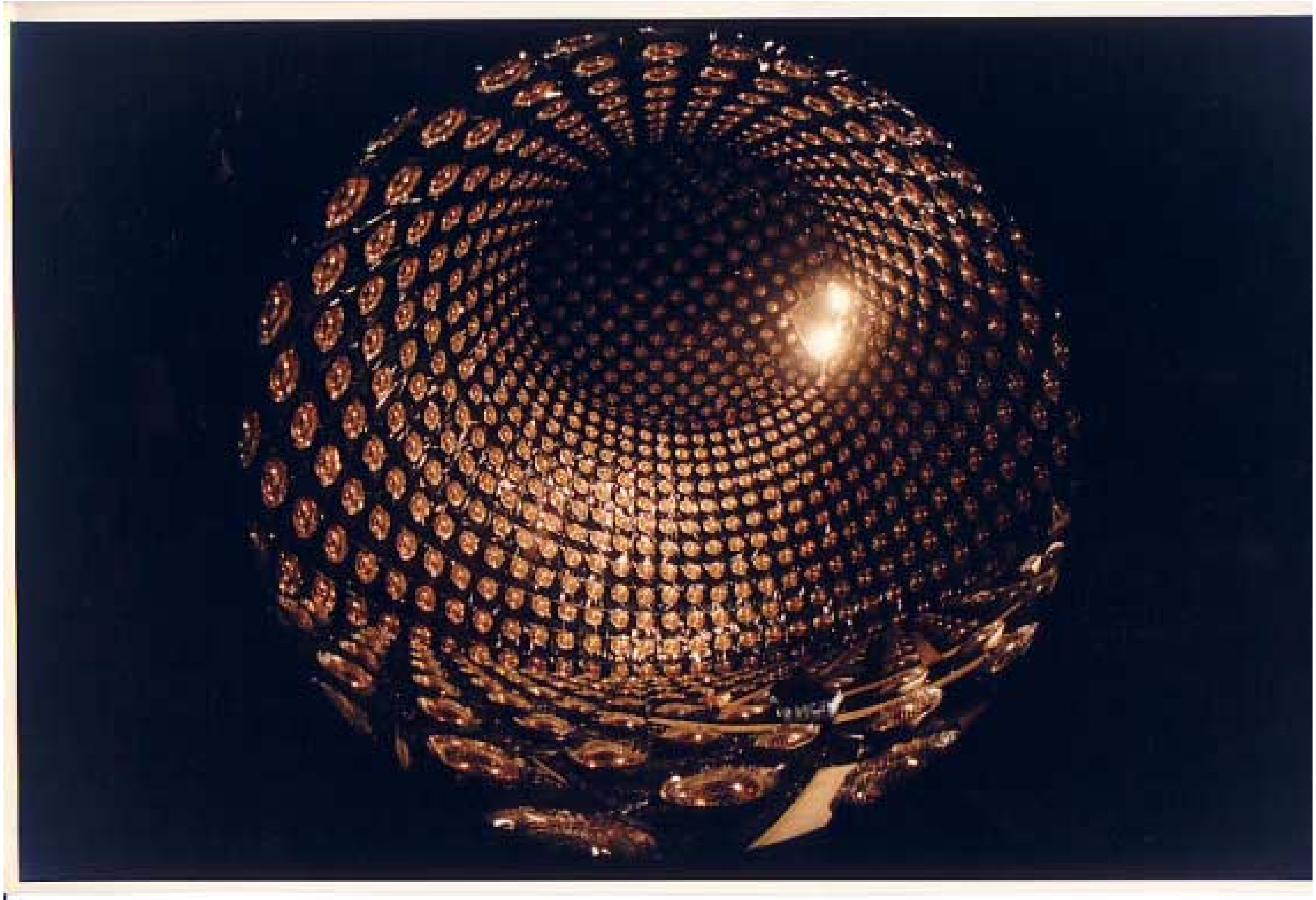
1) KamiokaNDE; Imaging Water Cerenkov,
   20% PMT coverage, 3,000tons,
   ca.3MUS$
   Feasibility experiment.

2) Super-KamiokaNDE; the same as above,
   40% PMT coverage, 50,000tons,
   ca.100MUS$.
   Full scale solar neutrino observatory.

(Both 1,000m underground in Kamioka Mine)

(NDE for Nucleon Decay Experiment/
Neutrino Detection Experiment))

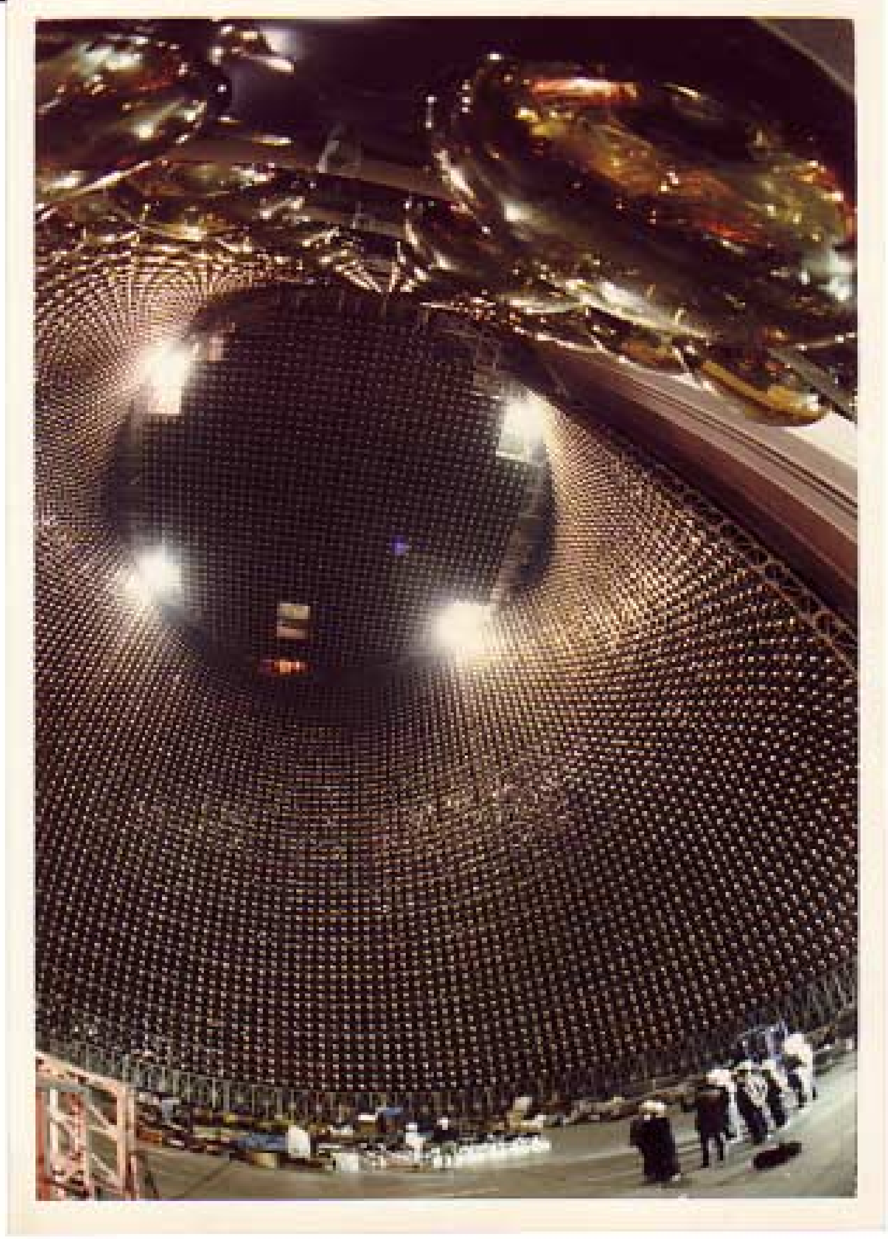
Fish-eye View of KamiokaNDE's Interior



50cmϕ PMT

which made the two detectors precision devices

Fish-Eye View of Super-KamiokaNDE's Interior

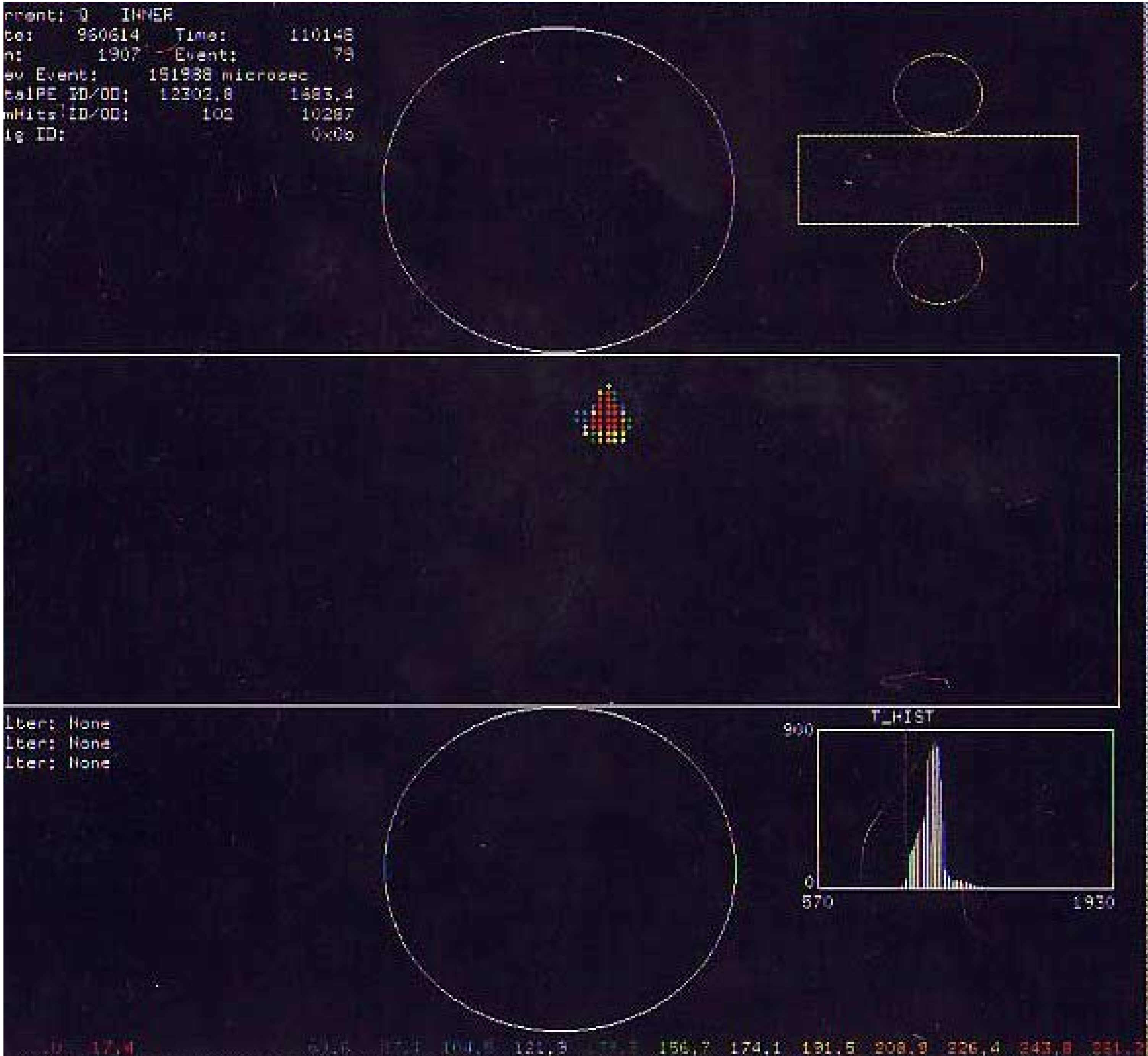


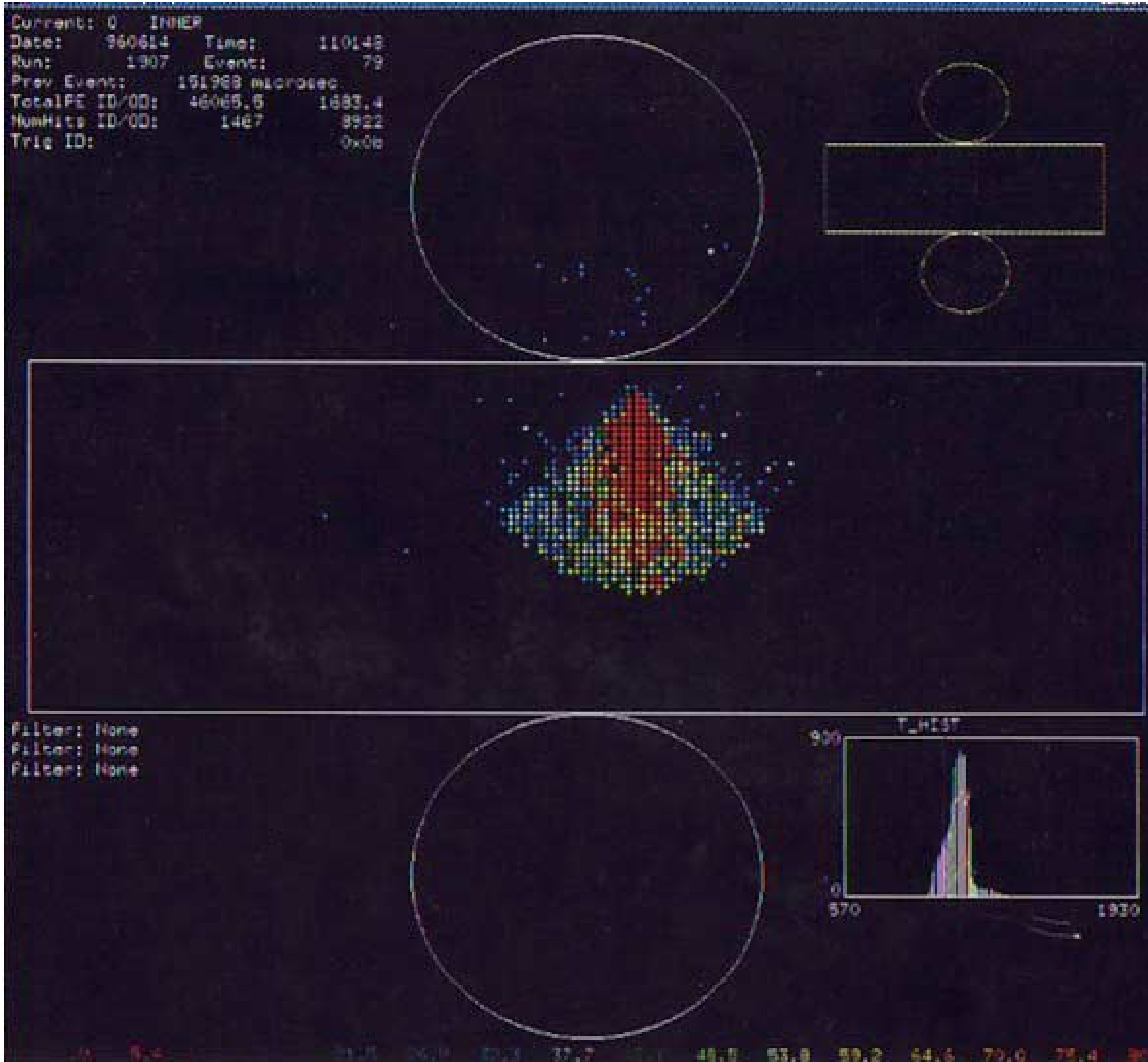
Detector Performances

1) Through μ in S-KamiokaNDE
   Shots at 50 nanosecond intervals

2) Discrimination between electron and muon

The μ has just entered the detector.

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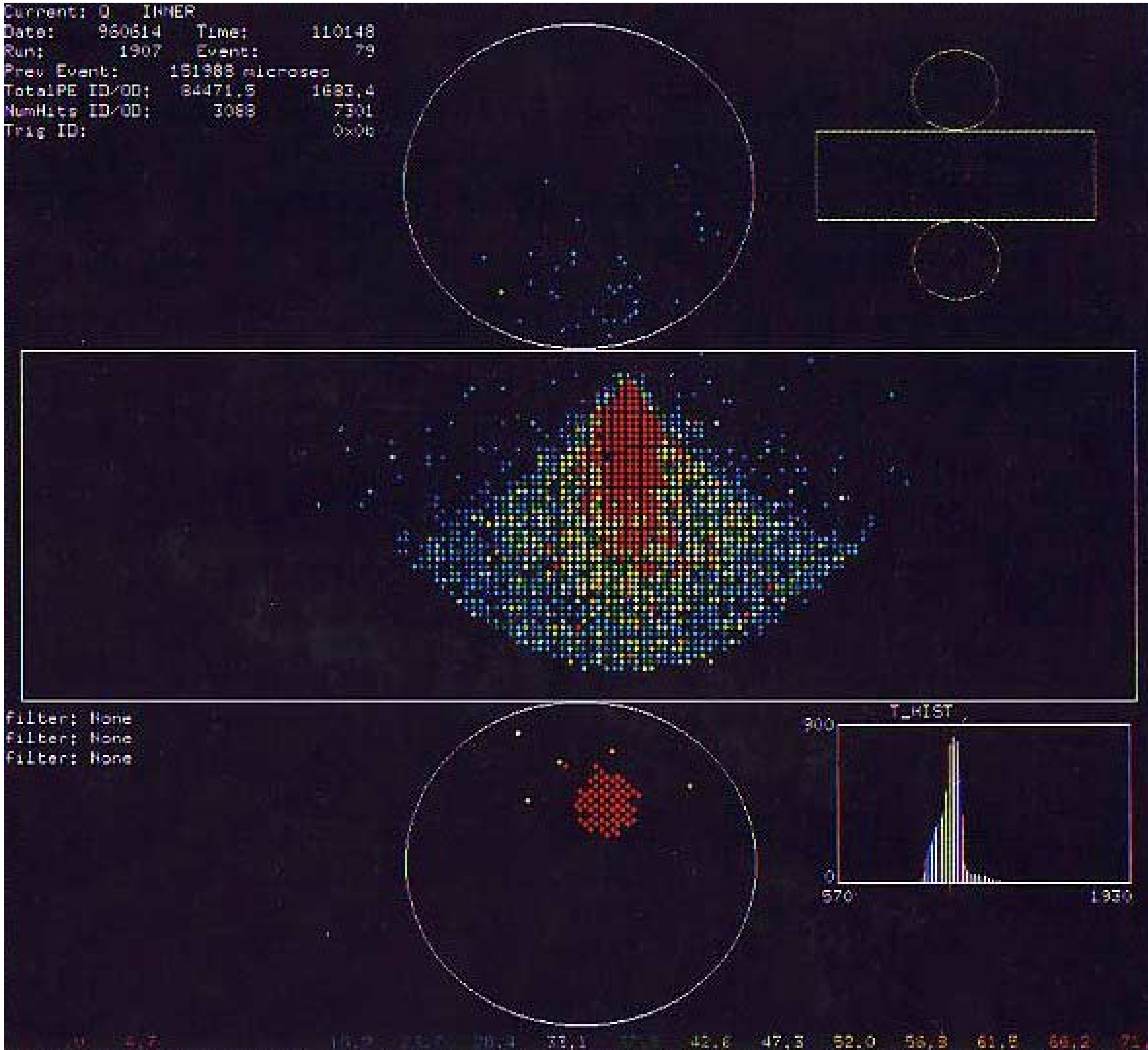
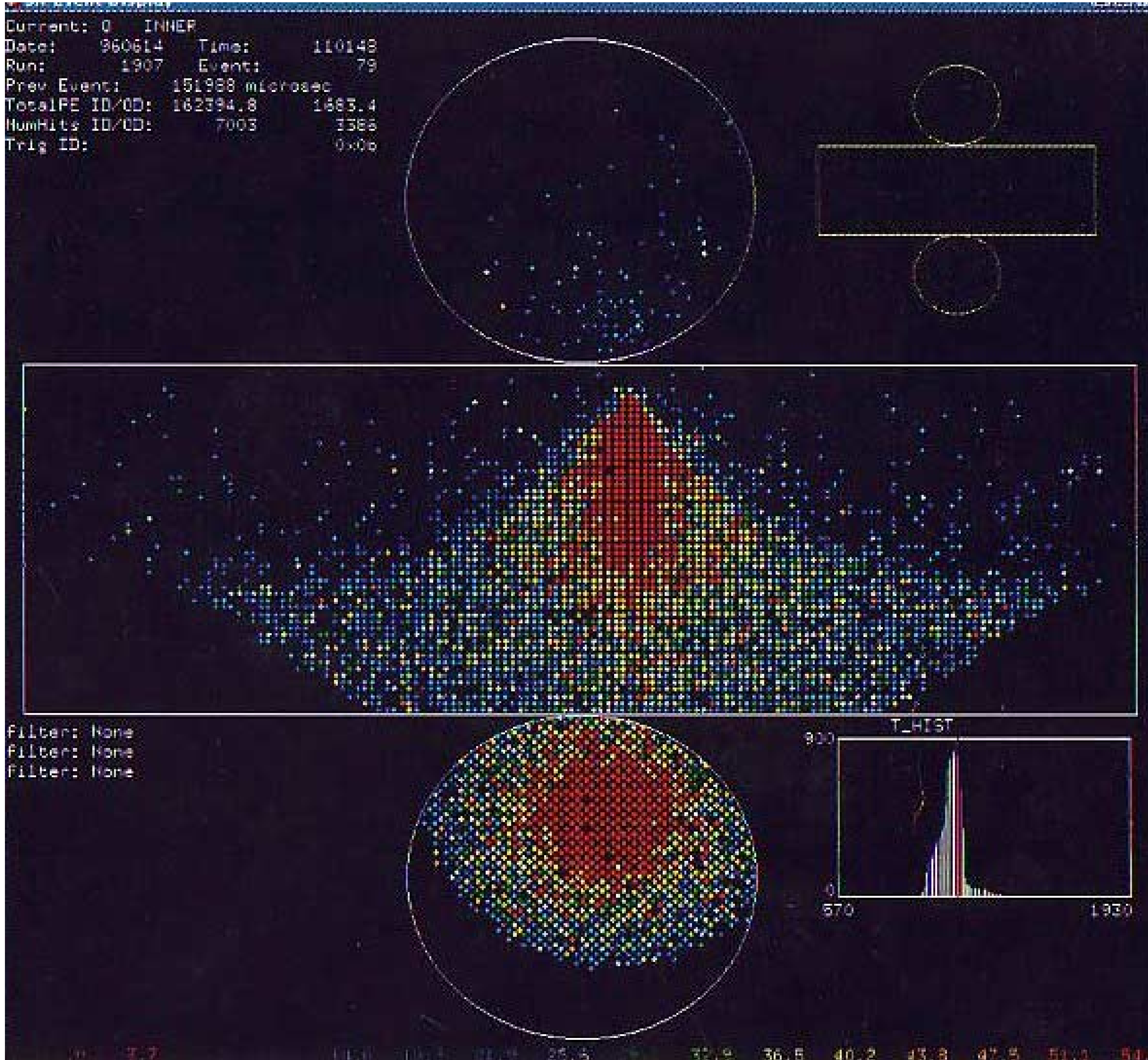
Run: 1907 Event: 79
Prev Event: 151968 microsec
TotalPE ID/OD: 46065.5 1683.4
NumHits ID/OD: 1467 8922
Trig ID: 0x0b
Filter: None
Filter: None
Filter: None
T_HIST
900
0
870
1930
37.7
48.5
53.8
59.2
64.6
70.0
75.4

The μ has reached to the bottom of the detector, while the Cerenkov light in water is still on its way.

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NumHits ID/OD: 7003 3386
Trig ID: 0x0b
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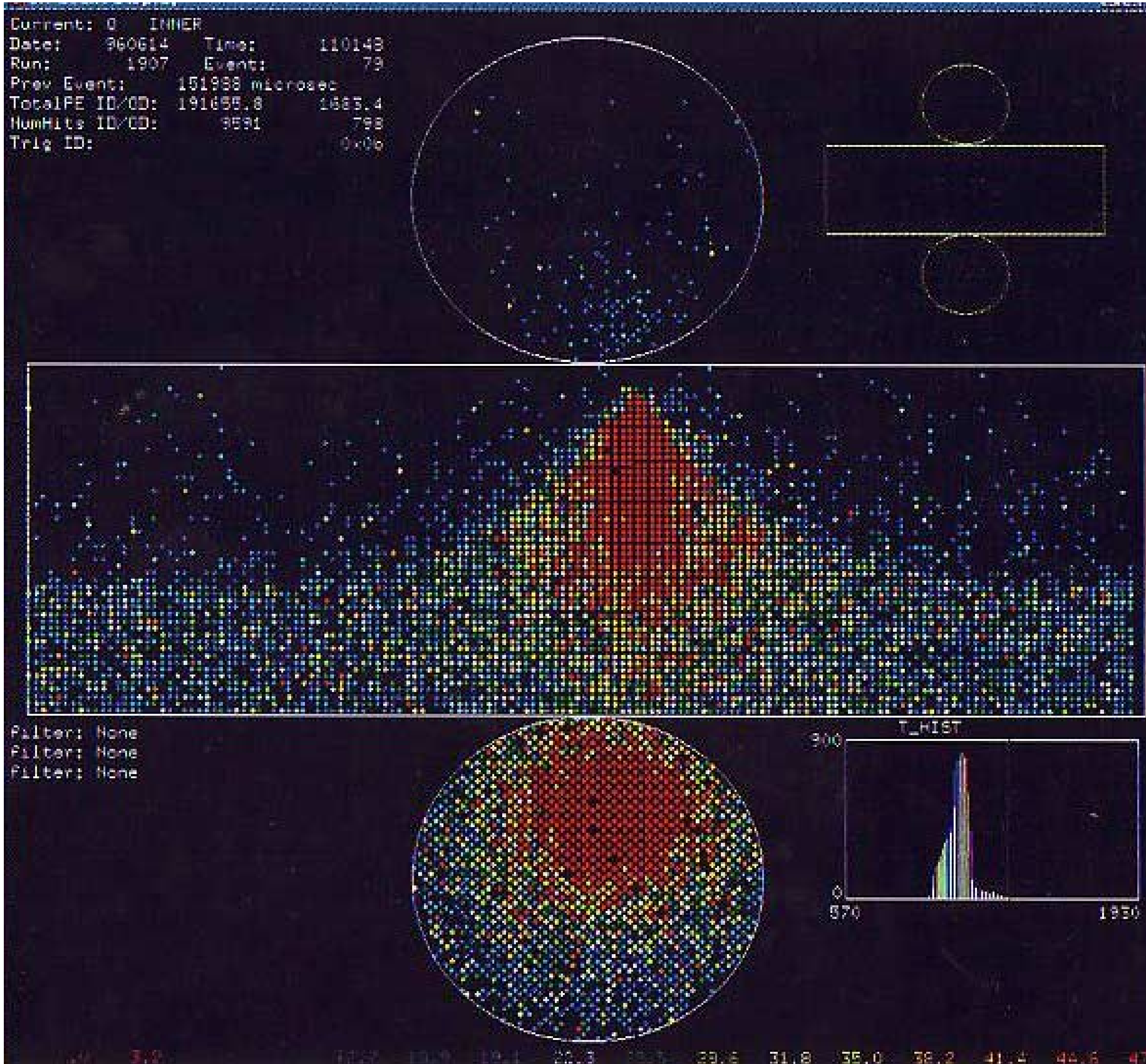
filter: None
filter: None
T_HIST
900
0
570
1930
36.5
40.2
43.8
47.5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Trig ID: 0x0b
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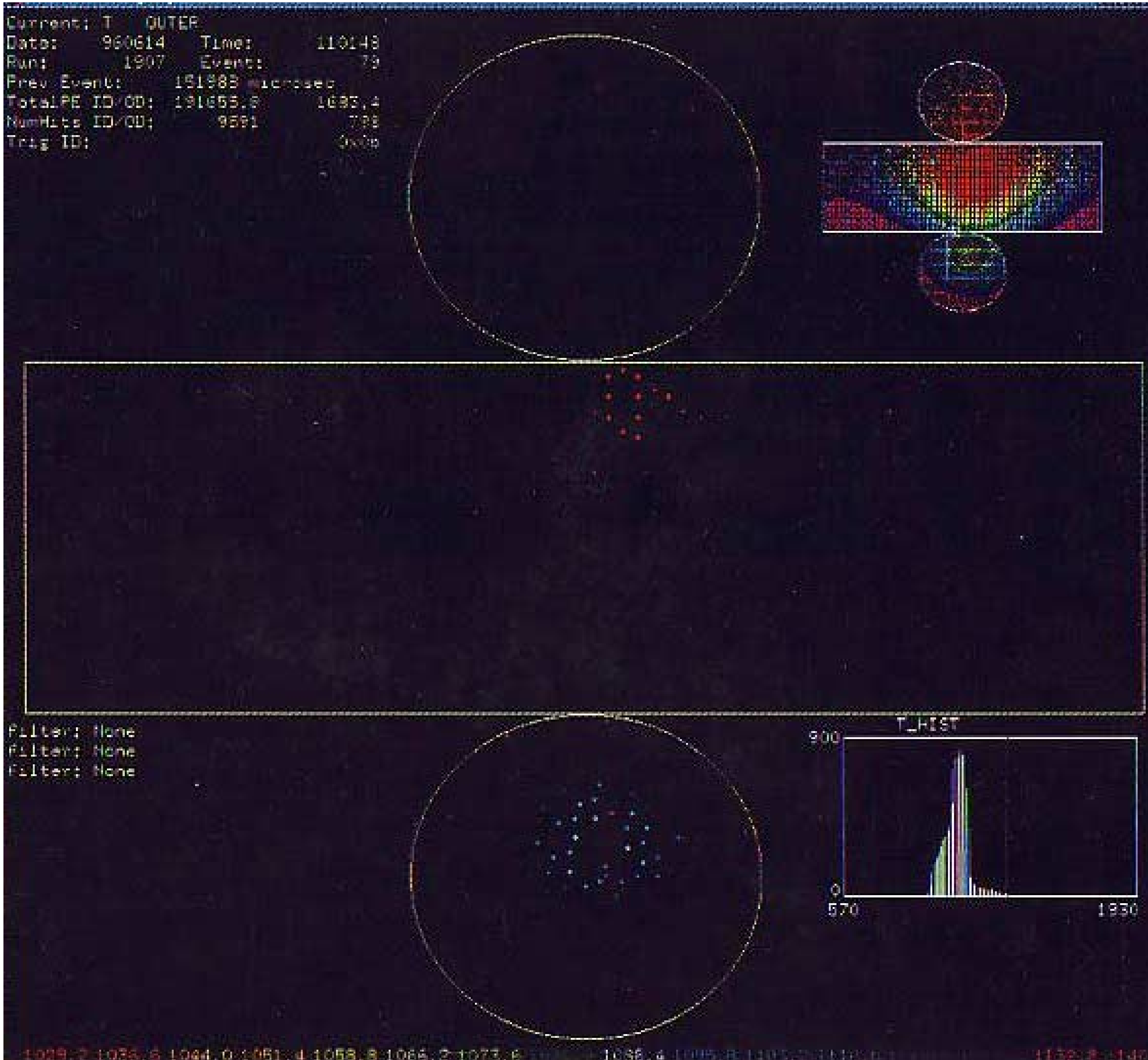
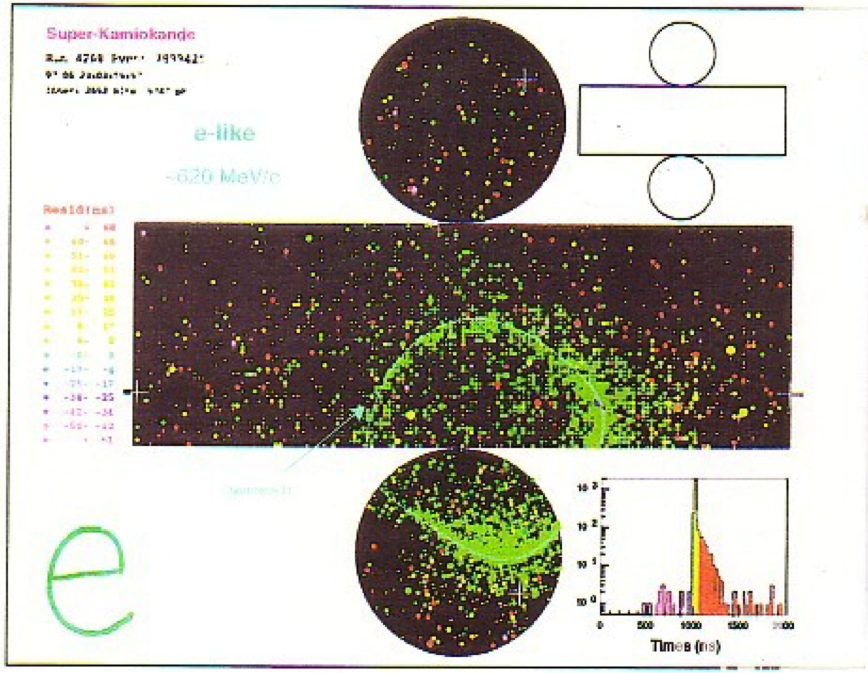
Filter: None
Filter: None
T_HIST
900
0
570
1950

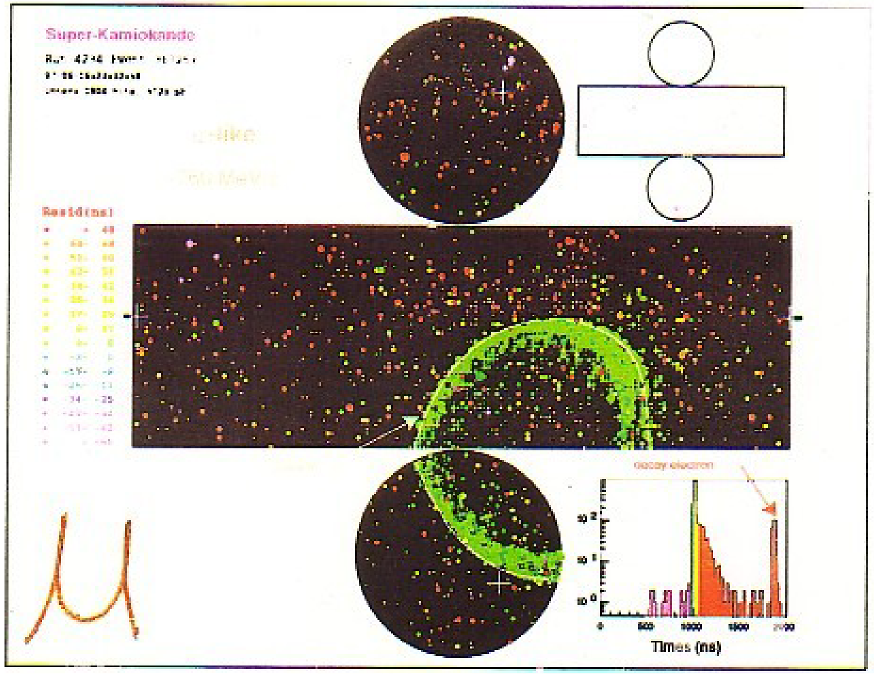
The data of the outer anti-counter are shown, while the inner data are moved to the top right.



The top e-event has a blurred radial distribution of Cerenkov photons, while the bottom μ-event has a crisp ring image. The discrimination between e and μ is accomplished with an error probability of less than 1%.

The μ–event has the decay electron later.



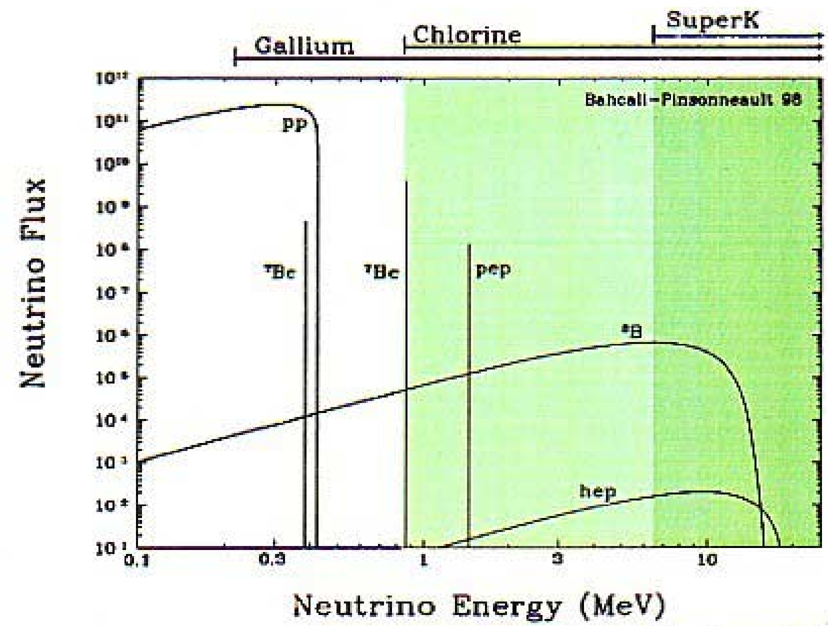


4 Accomplishments of KamiokaNDE

1) The astrophysical,i.e., with D,T and E, observation of solar neutrinos by means of ν_e-e scattering.
2) The observation of the neutrino burst from Supernova 1987A by means of anti-ν_e on p producing e^+ plus neutron.
3) The discovery at more than 4σ of the anomaly in the atmospheric ν_μ/ν_e ratio. Neutrino oscillation. Non-zero masses of ν's.
4) Killed SU(5) by proton decay lifetime and SUSYSU(5) also by non-zero masses of ν's.

Solar Neutrinos

Standard Solar Model (SSM)



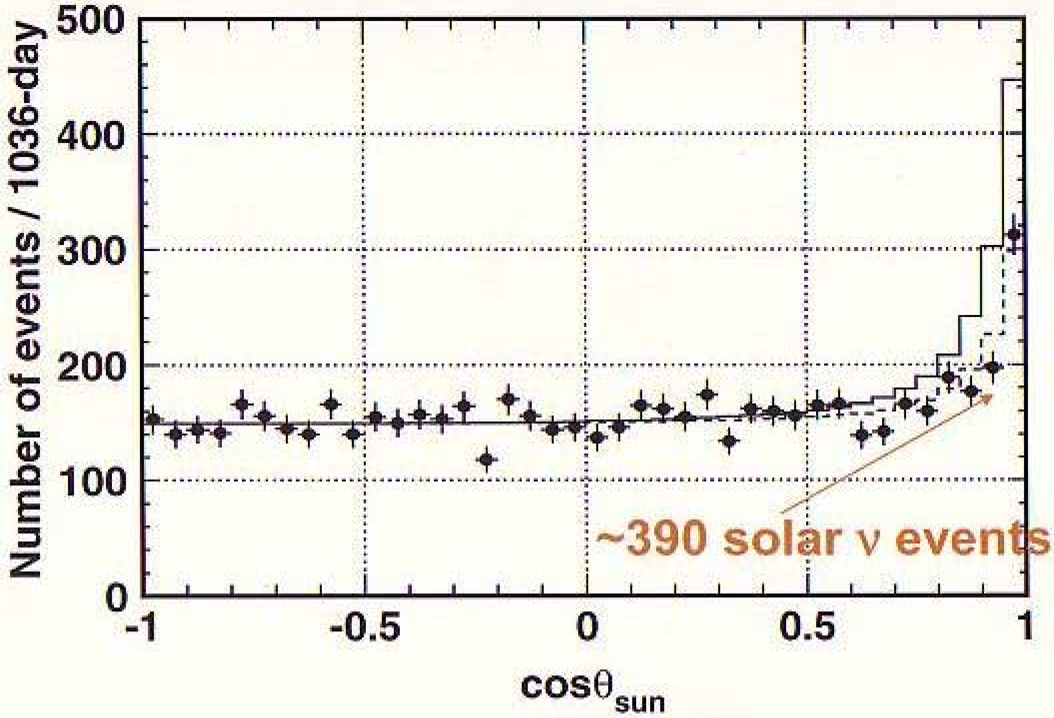
http://www.sns.ias.edu/~jnb/

Solar Neutrino Experiments

	Target	Data / SSM (BP98)
· Homestake	^{37}Cl	0.33 ± 0.03
· Kamiokande	e^- (water)	0.54 ± 0.07
· SAGE	^{71}Ga	0.52 ± 0.06
· GALLEX	^{71}Ga	0.59 ± 0.06
· SK	e^- (water)	0.475 ± 0.015

Solar neutrinos (Kamiokande-III)

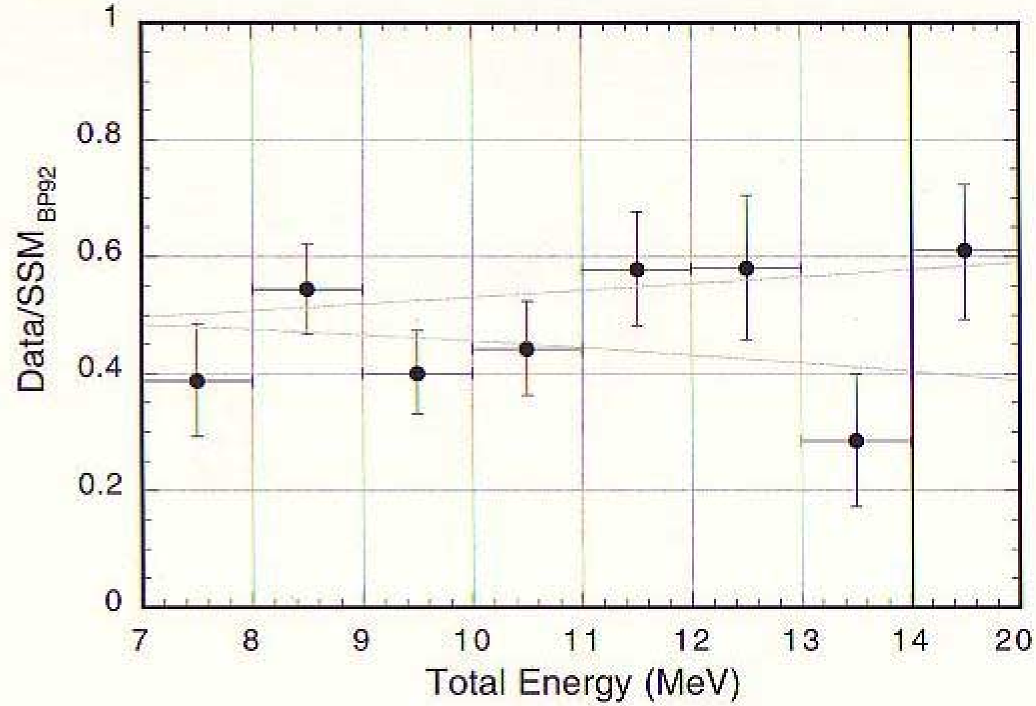
Dec. 28, 1990 – Feb. 6, 1995 (1036 days)



Y.Fukuda et al., Phys. Rev. Lett. 77 (1996) 1683

Energy spectrum of solar neutrino events

Kamiokande II and III (2079 days)



Based on ~600 solar ν events

Y.Fukuda et al., Phys. Rev. Lett. 77 (1996) 1683

The detector performance at the beginning of 1987.

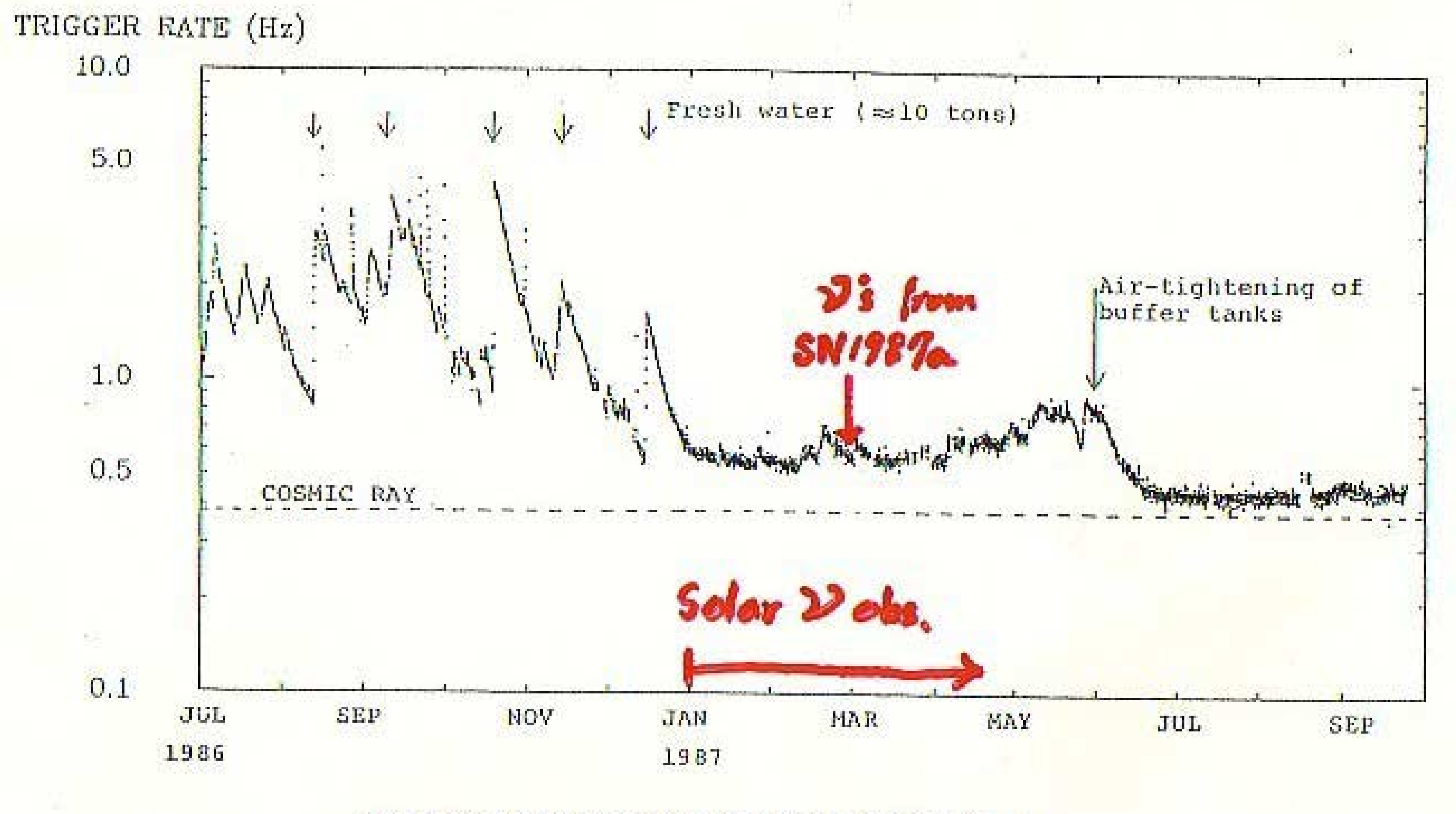
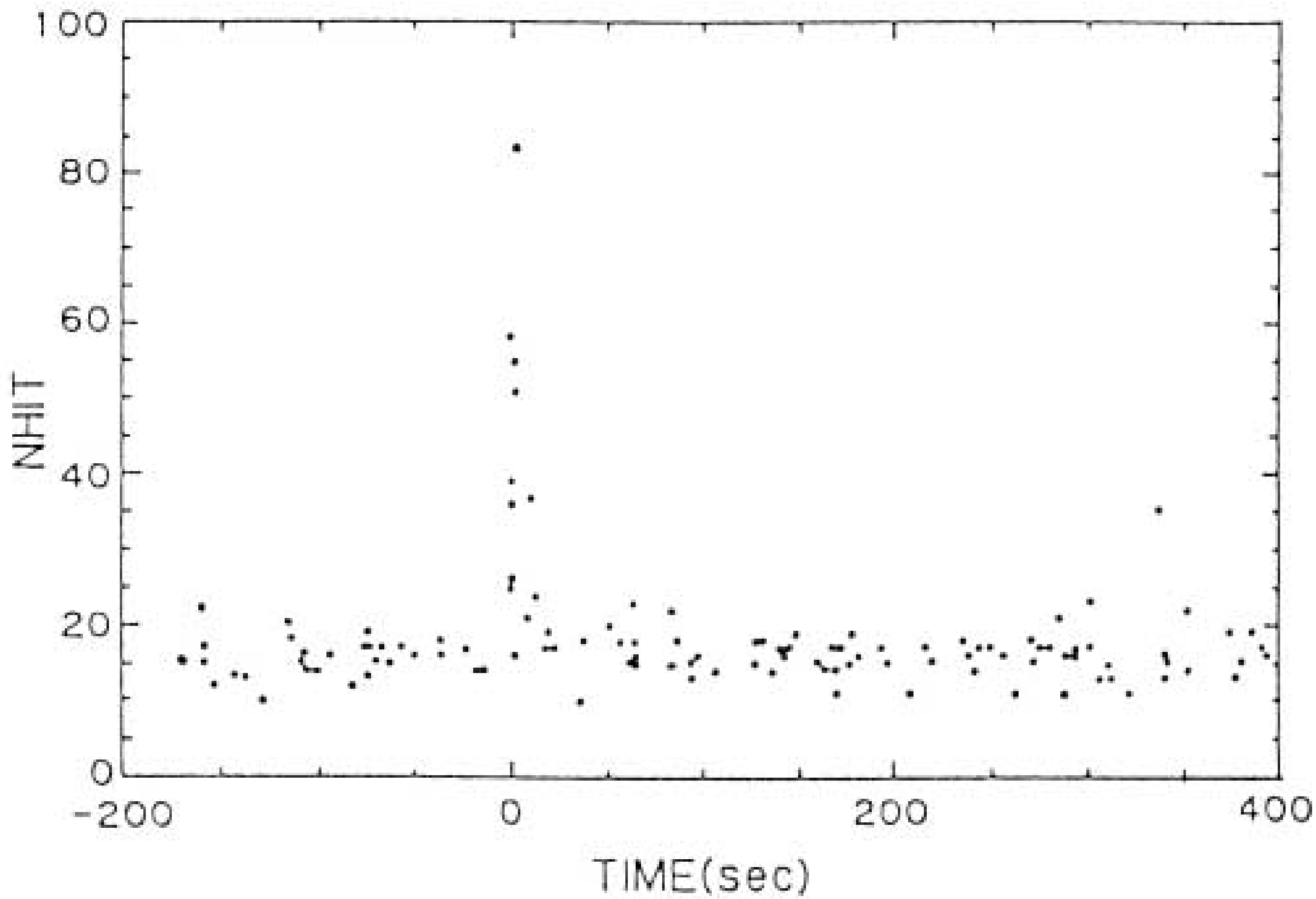


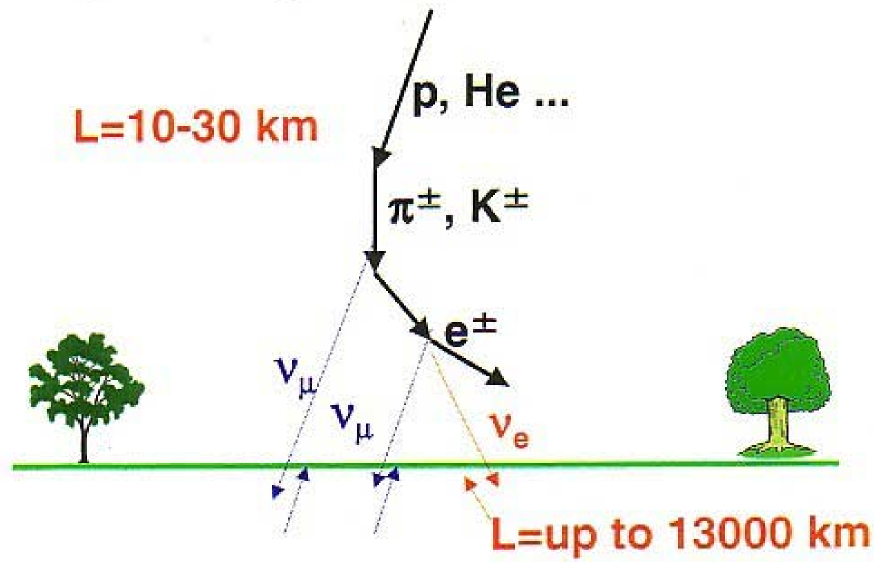
Fig. 3.20. The early performance of the KAM-II detector.

The observed signal of the supernova neutrino burst. It was immediately confirmed by IMB experiment in USA. The combined results, T_ν of 4.5MeV and the total ν energy output of $3x10^{53}$erg gave strong support to the theoretical model.



ν_μ/ν_e has to be 2 or larger

Atmospheric neutrinos



$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} = \sim 2$$ @ low energy ($E_\nu < 1$ GeV)

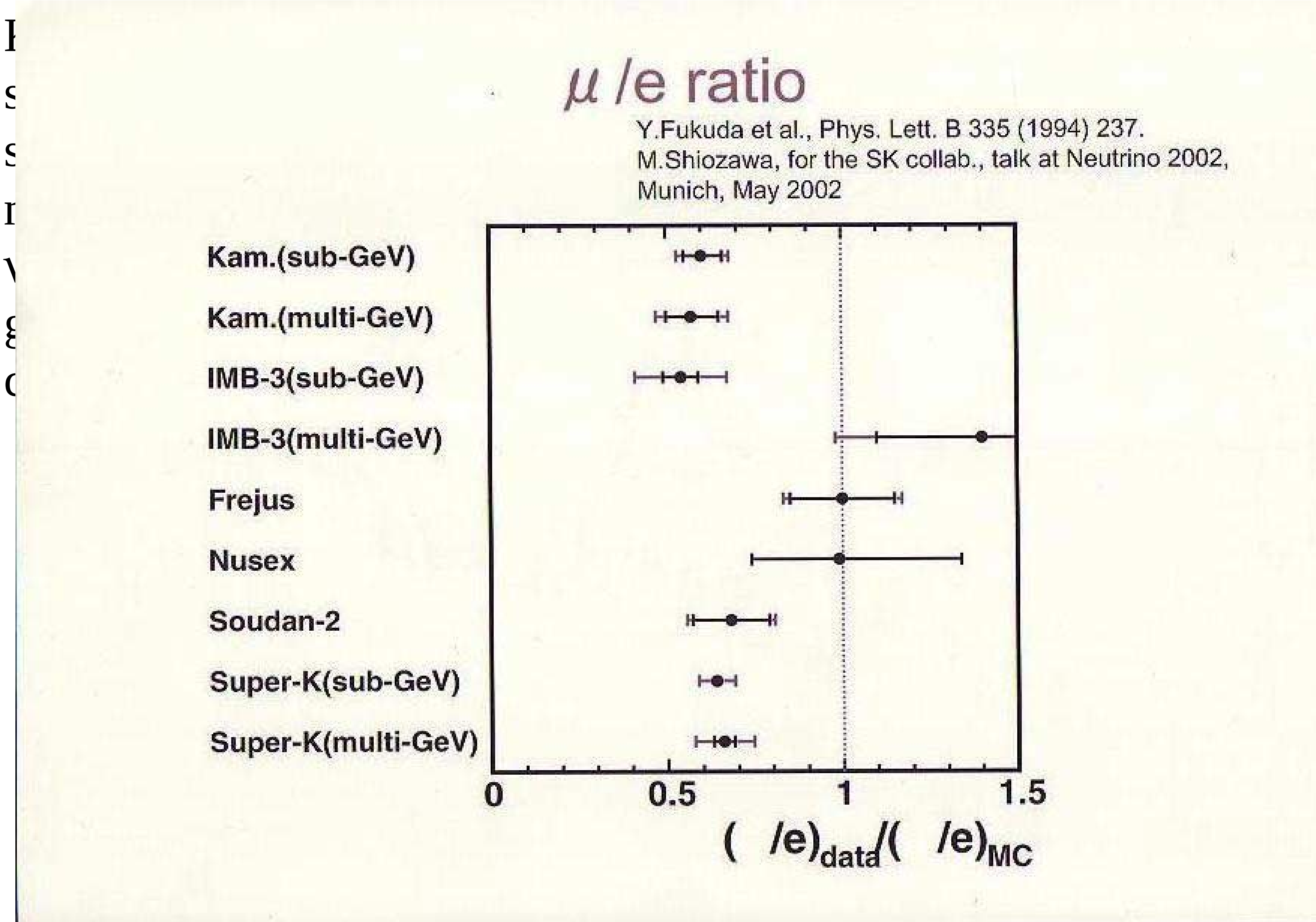
$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \nearrow$$ @ high energy

Error in flux~25%, double ratio~5%

Neutrino oscillations :

$$\Rightarrow \left(\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}\right)_{data} \Big/ \left(\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}\right)_{MC} \neq 1$$

I
s
s
r
V
g
c



μ /e ratio
Y.Fukuda et al., Phys. Lett. B 335 (1994) 237.
M.Shiozawa, for the SK collab., talk at Neutrino 2002, Munich, May 2002
Kam.(sub-GeV)
Kam.(multi-GeV)
IMB-3(sub-GeV)
IMB-3(multi-GeV)
Frejus
Nusex
Soudan-2
Super-K(sub-GeV)
Super-K(multi-GeV)
0
0.5
1
1.5
(/e)data/(/e)MC

The Neutrino Oscillation

Consider 2 neutrino case for simplicity.

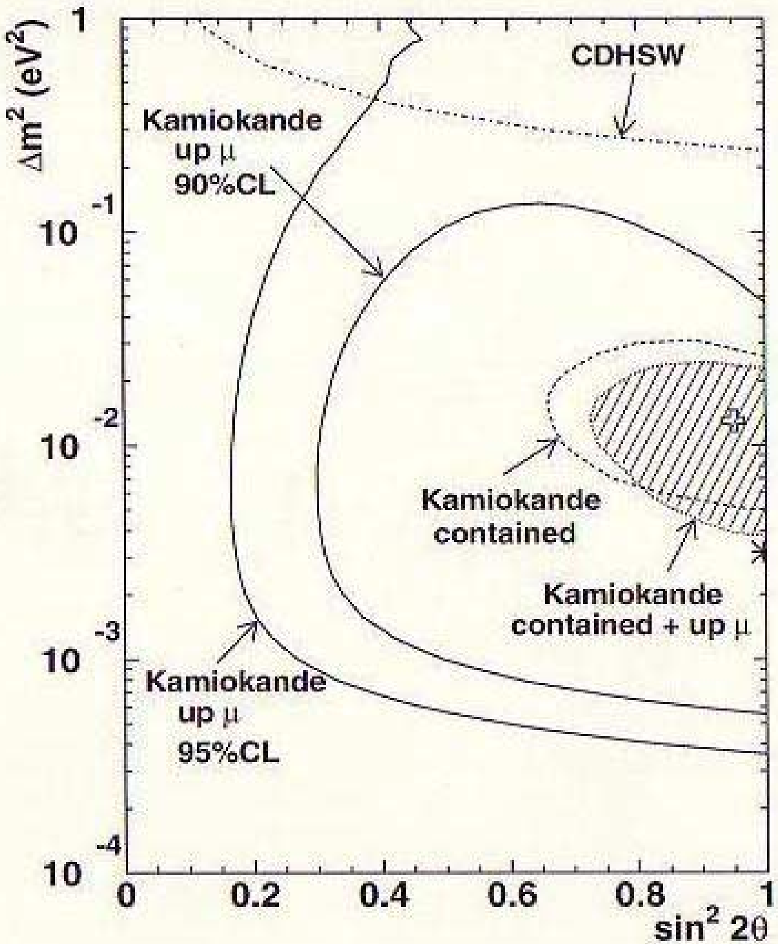
The weak eigenstate ψ_μ is a superposition of

ψ_{m1} and $\psi_{m2,;}$ namely $\psi_\mu = \psi_{m1} \cos\theta + \psi_{m2} \sin\theta$ with a parameter θ, the angle between ψ_μ and ψ_{m1} .

The two states, ψ_{m1} and ψ_{m2}, make beat with the frequency proportional to E_1-E_2 =m_1^2-m_2^2 Δm^2, since E~p+(m^2/2p),thereby changing the relative intensity of ψ_{m1} and ψ_{m2}.

This causes a partial transformation of ψ_μ to ψ_τ.

Allowed parameter region by the Kamiokande atmospheric neutrino mesasurement

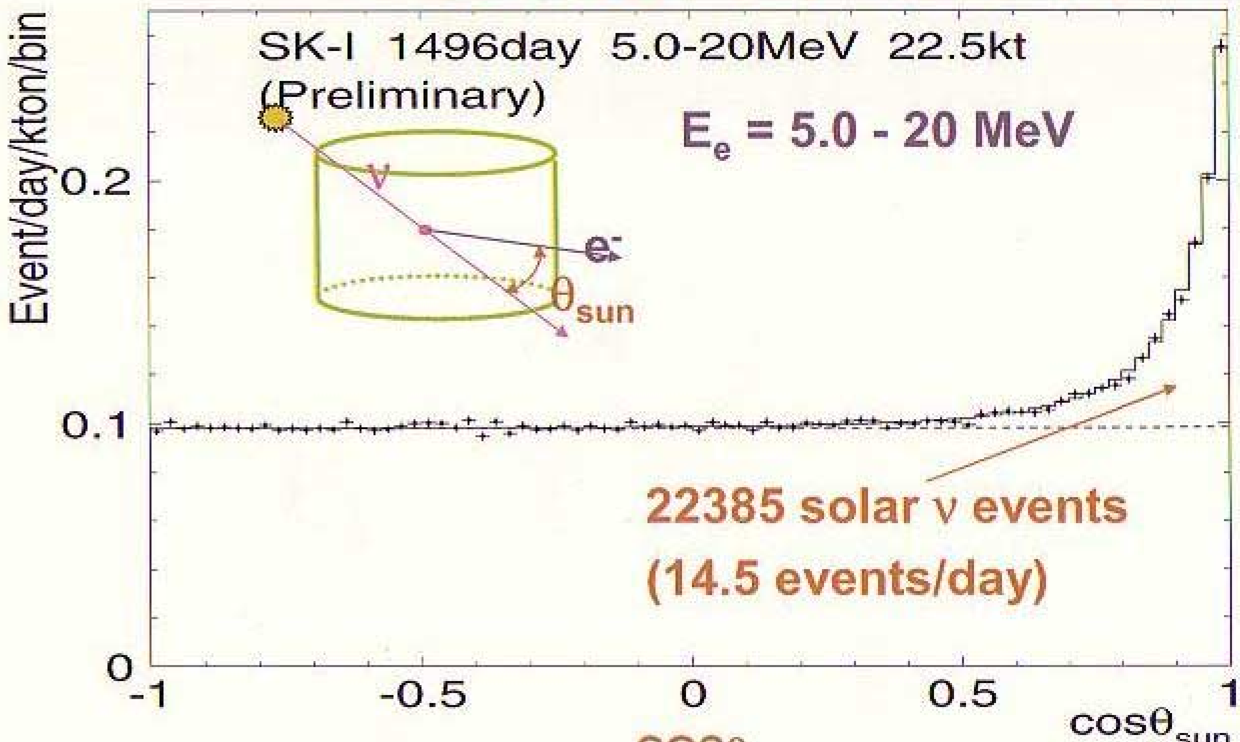


Super-KamiokaNDE Accomplished Three things so far.

1) Established the solar neutrino observation with much better statistics.
2) Firmly established, at more than 9σ, the non-zero masses of ν's and their oscillations.
3) Non-observation of nucleon decays is giving more stringent restriction on the possible type of future grand unified theory.

Solar neutrinos (Super－Kamiokande)

May 31, 1996 – July 13, 2001 (1496 days)



COSθ_sun

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

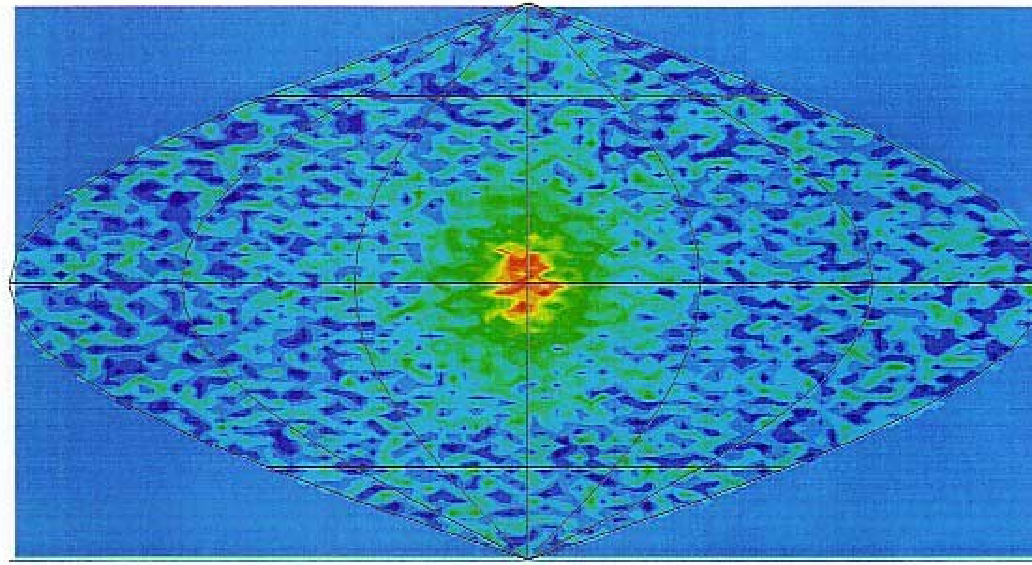
$$\frac{\text{Data}}{\text{SSM(BP2000)}} = 0.465 \pm 0.005^{+0.016}_{-0.015}$$

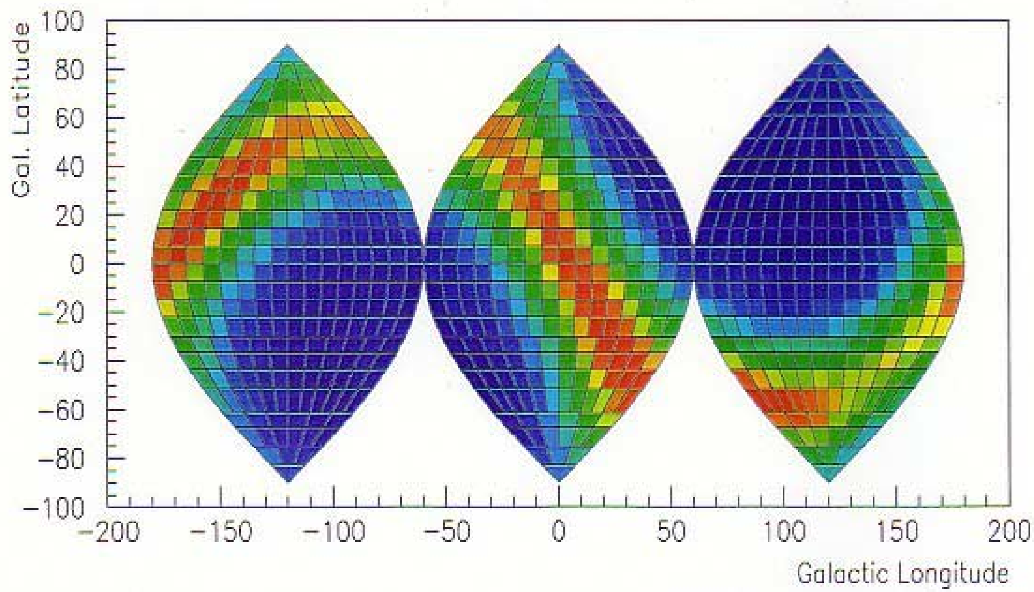
(BP2000: 5.05×10^6 /cm^2/sec)

The Sun as seen by ν's and its orbit in the Galactic coordinate.

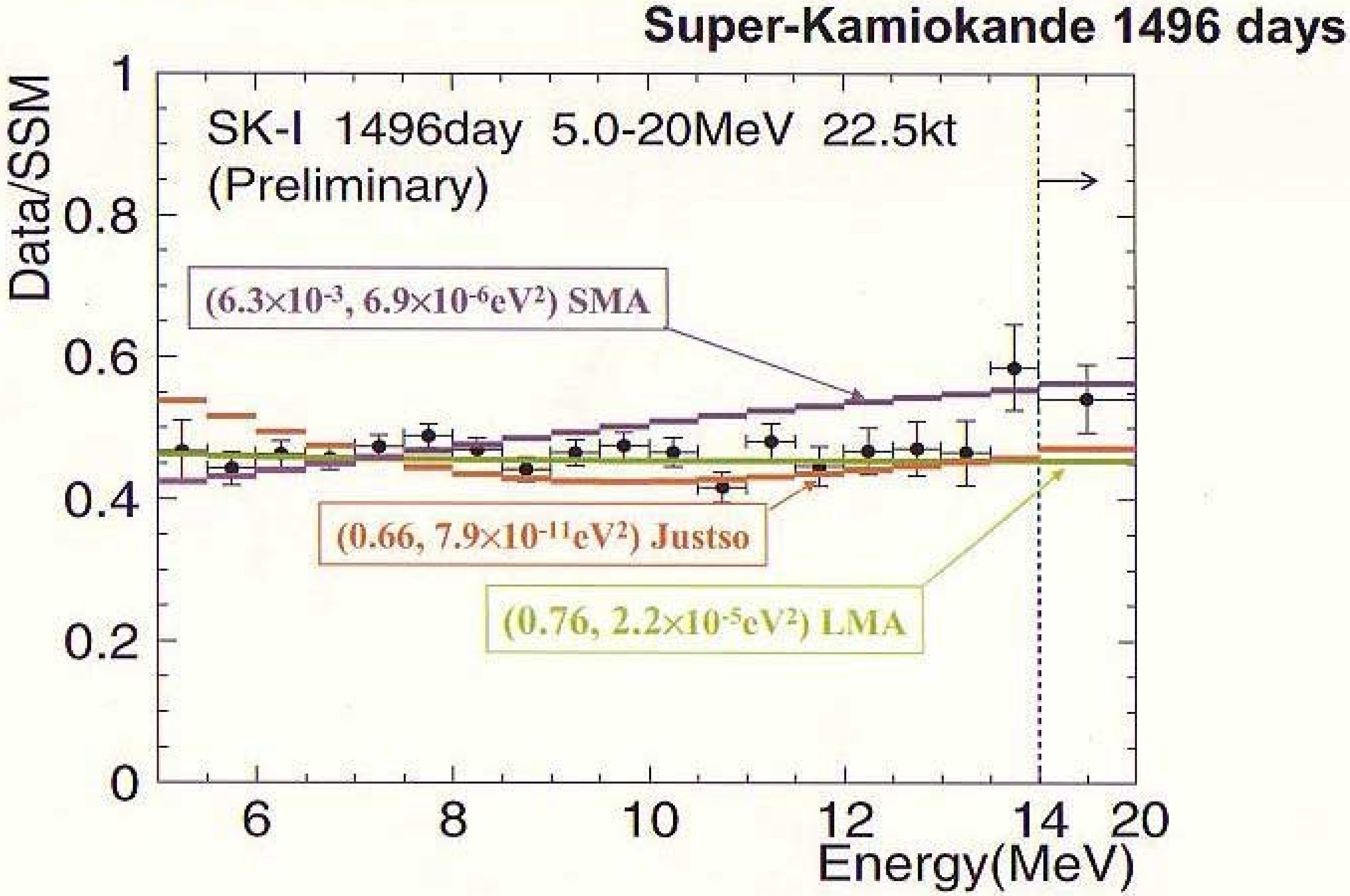
You have to excuse the poor angular resolution because the neutrino astrophysics is still in its infantile stage.

The Sun by Neutrinograph





Energy spectrum of solar neutrino events

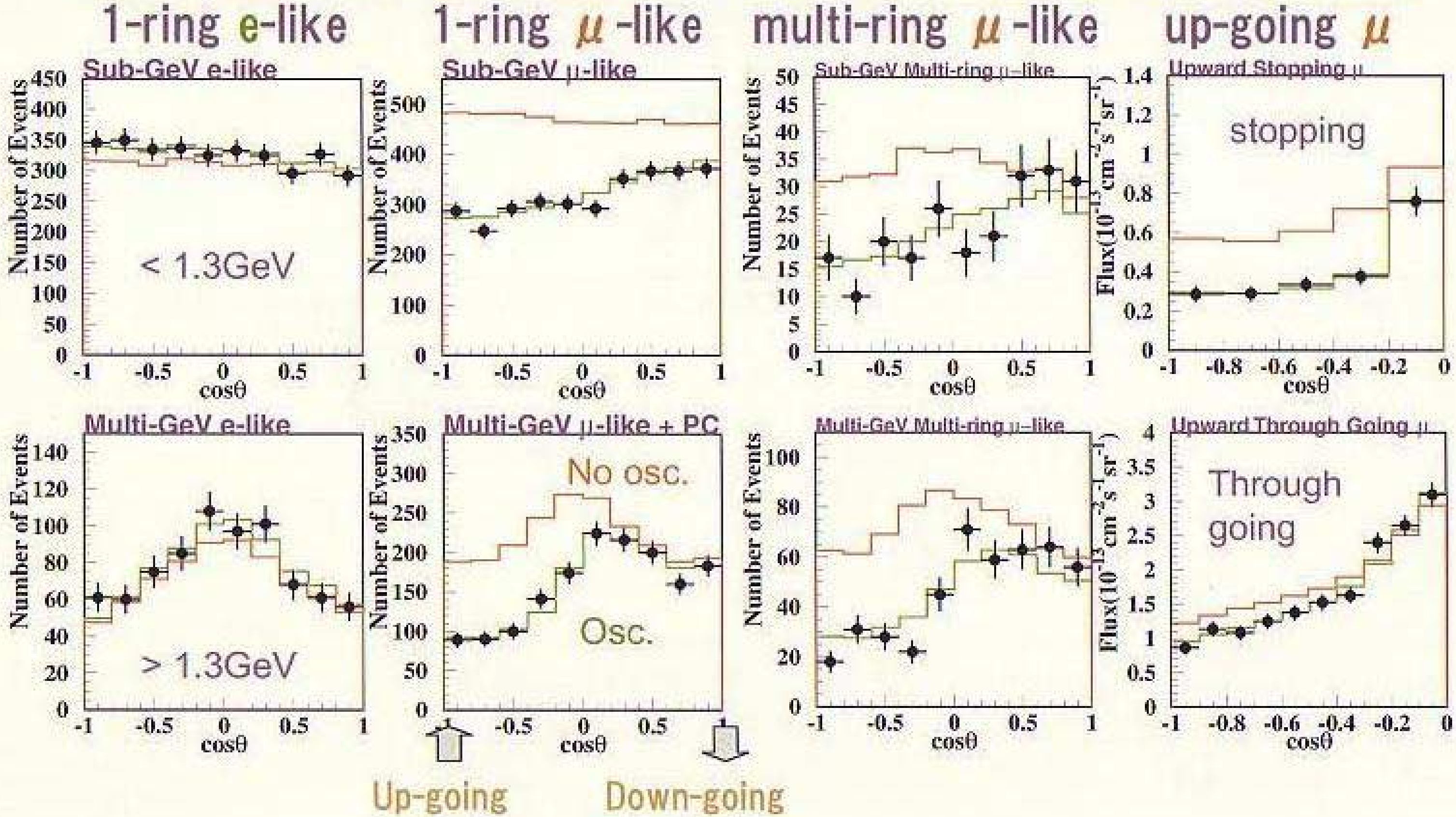


Bad fit to SMA and Just-so solutions.

Atmospheric neutrino results from SK-1

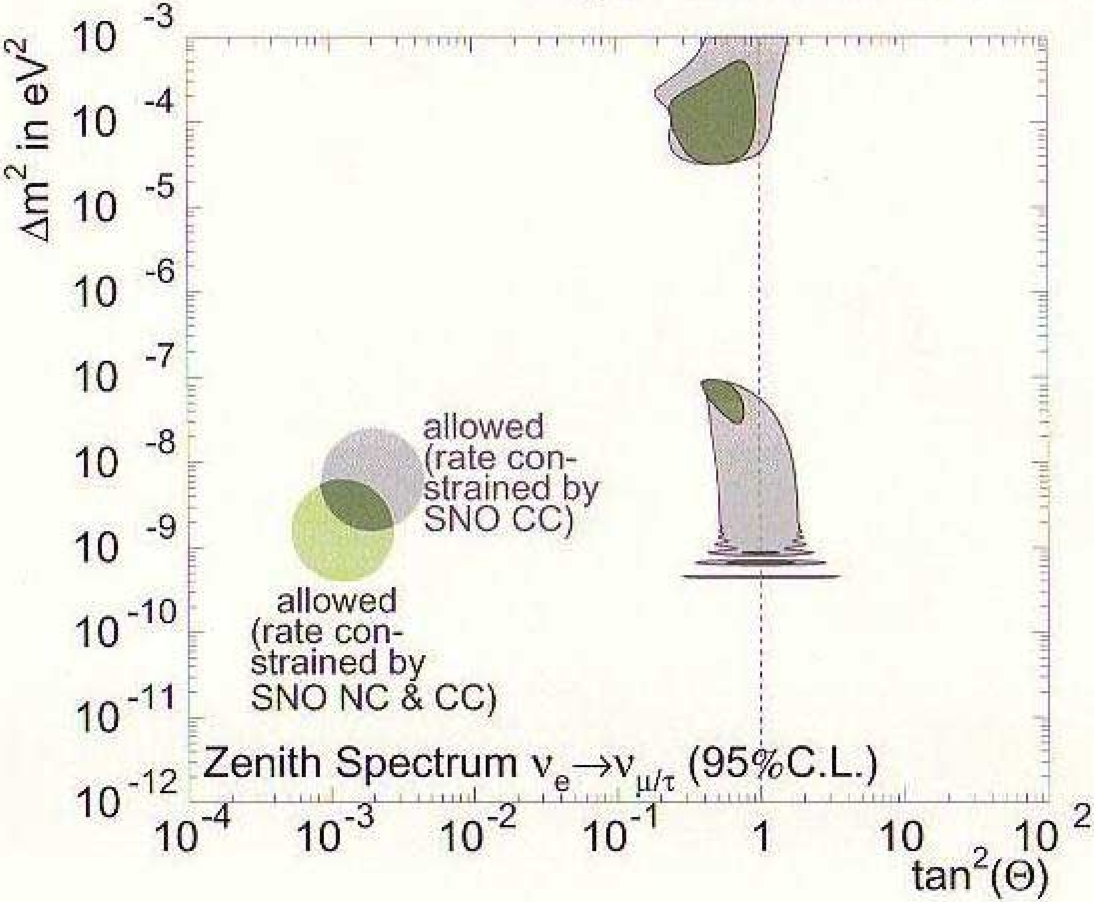
M.Shiozawa, for the SK collab., talk at Neutrino 2002, Munich, May 2002

1489day FC+PC data + 1678day upward going muon data



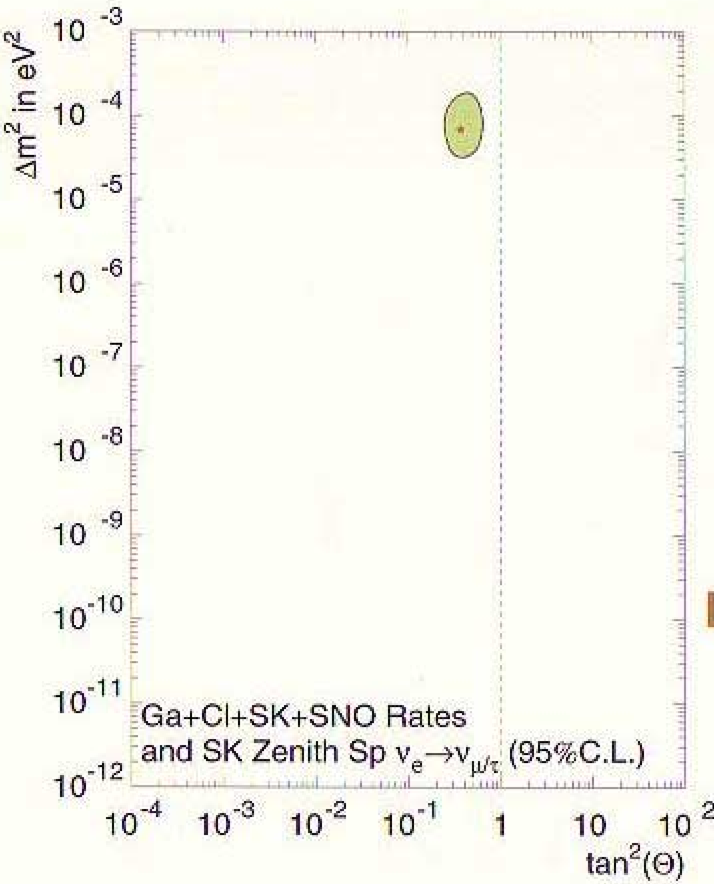
Allowed region combined with SNO data

Super-Kamiokande 1496 days



S.Fukuda et al., Phys. Lett. B 539 (2002) 179

Allowed region combined with all solar neutrino data



- **Rates: Homestake (Cl), GALLEX (Ga), SAGE (Cl), SK (H2O), SNO CC+NC (D2O)**
- **Zenith spectra from SK: energy spectra of electrons at 7 zenith angle bins (day + 6 nights)**

LMA is the most likely solution.

S.Fukuda et al., Phys. Lett. B 539 (2002) 179

Implications of Non-zero Neutrino Masses

1) The right handed neutrinos have to exist. Standard Theory has to be modified and SU(5) is discarded as possible GUT.

2) Very low energy neutrinos will make the total reflection at very low temperature. Very nice for the future possibility of observing the 1.9K Cosmic Neutrino Background.

For the sake of giving proper credit, shown here Is the author list of the supernova neutrino observation.

VOLUME 58, NUMBER 14 PHYSICAL REVIEW LETTERS 6 APRIL 1987

Observation of a Neutrino Burst from the Supernova SN1987A

K. Hirata,[a] T. Kajita,[a] M. Koshiba,[a,b] M. Nakahata,[b] Y. Oyama,[b]
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Department of Physics, University of Niigata, Niigata 950-21, Japan

E. W. Beier, L. R. Feldscher, S. B. Kim, A. K. Mann, F. M. Newcomer, R. Van Berg, and W. Zhang
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and

B. G. Cortez[d]
California Institute of Technology, Pasadena, California 91125
(Received 10 March 1987)

A neutrino burst was observed in the Kamiokande II detector on 23 February 1987, 7:35:35 UT (± 1 min) during a time interval of 13 sec. The signal consisted of eleven electron events of energy 7.5 to 36 MeV, of which the first two point back to the Large Magellanic Cloud with angles 18° ± 18° and 15° ± 27°.

PACS numbers: 97.60.Bw, 14.60.Gh, 95.85.Sz, 97.60.Jd

Here is the author list of the oscillation paper.

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. Barszczxak,[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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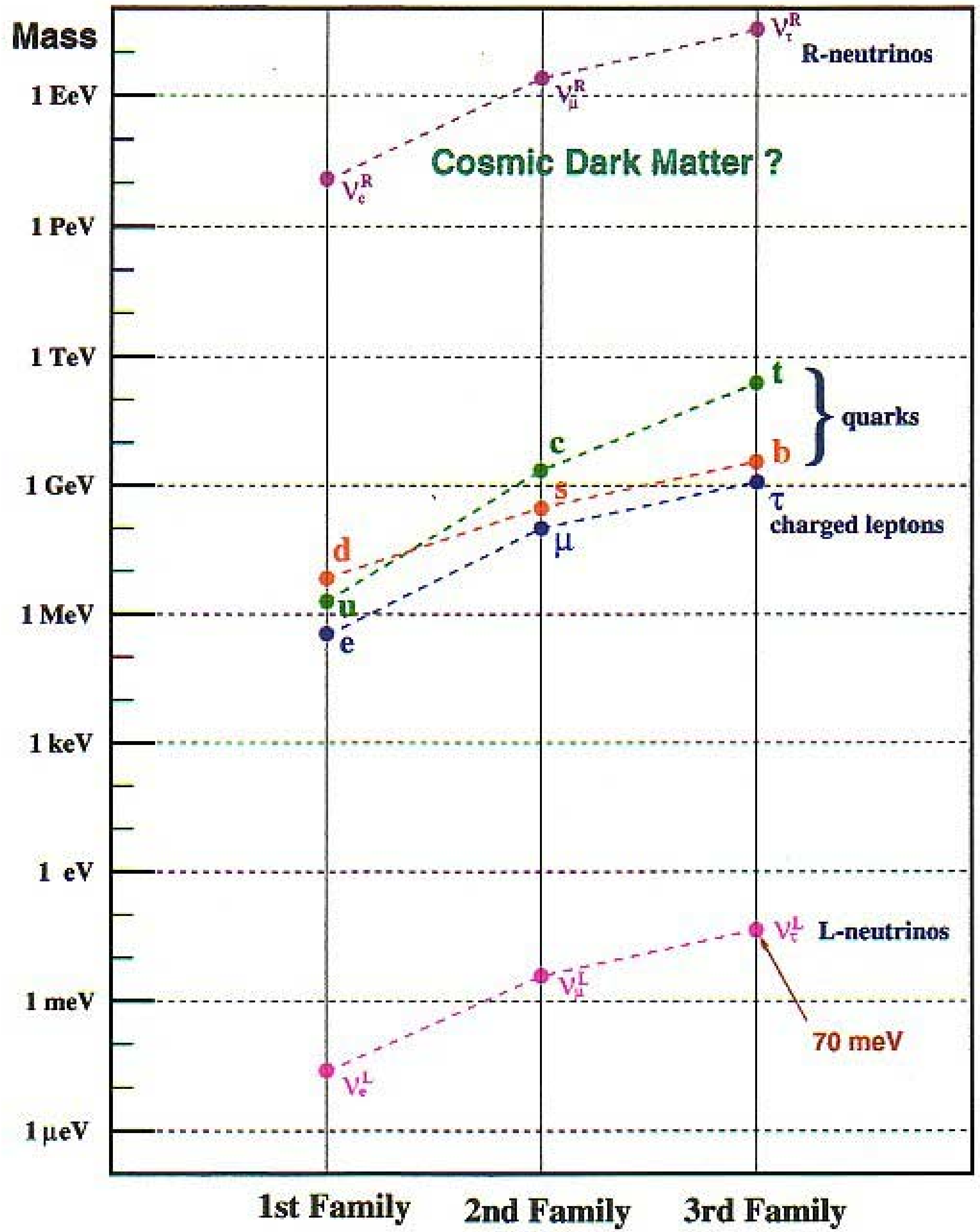
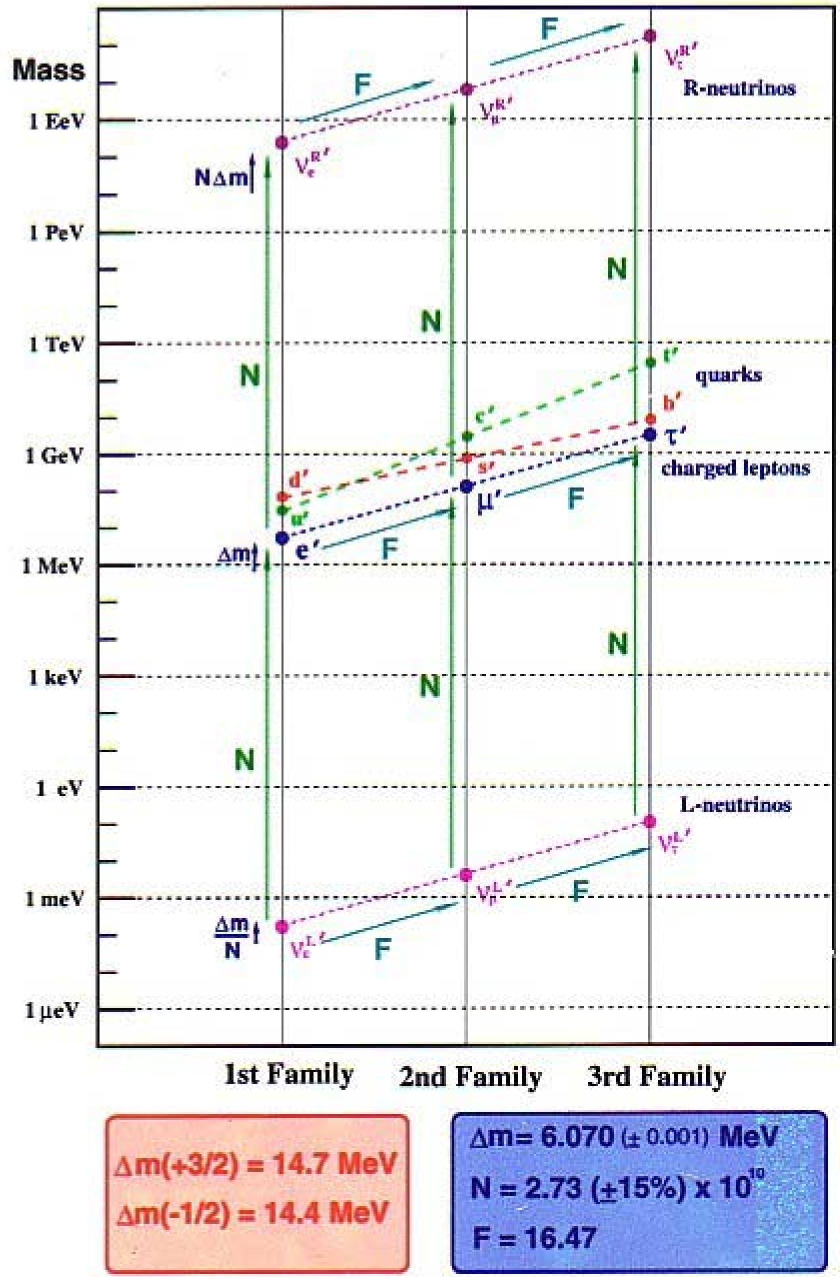
For fun

From the Δm^2's obtained, we can get a possible mass spectra of elementary particles using the See-Saw mechanism. And if we consider a small electromagnetic mass shift occurred in one of the phase changes in the very early Universe, we get the nice regularity as seen in the last slide.

Anyone of you challenge to explain this regularity?


Mass
1 EeV
1 PeV
1 TeV
1 GeV
1 MeV
1 keV
1 eV
1 meV
1 μeV
ν_τ^R
ν_μ^R
ν_e^R
R-neutrinos
Cosmic Dark Matter ?
t
c
b
s
d
u
quarks
τ
μ
e
charged leptons
ν_τ^L
ν_μ^L
ν_e^L
L-neutrinos
70 meV
1st Family
2nd Family
3rd Family


Mass
1 EeV
1 PeV
1 TeV
1 GeV
1 MeV
1 keV
1 eV
1 meV
1 μeV
R-neutrinos
quarks
charged leptons
L-neutrinos
F
N
NΔm
Δm
Δm/N
1st Family
2nd Family
3rd Family
Δm(+3/2) = 14.7 MeV
Δm(-1/2) = 14.4 MeV
Δm= 6.070 (± 0.001) MeV
N = 2.73 (±15%) x 10^10
F = 16.47

Thank you for your patience.

M. Koshiba