Birth of Neutrino Astrophysics

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July 31, 2003

Tsukuba, Japan

For more details, see my review article;

"Observational Neutrino Astrophysics"; Physics Report, **220**

(1992) Nos.5&6, pp.229-482.

The content of this talk will appear shortly in Reviews of Modern Physics.

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

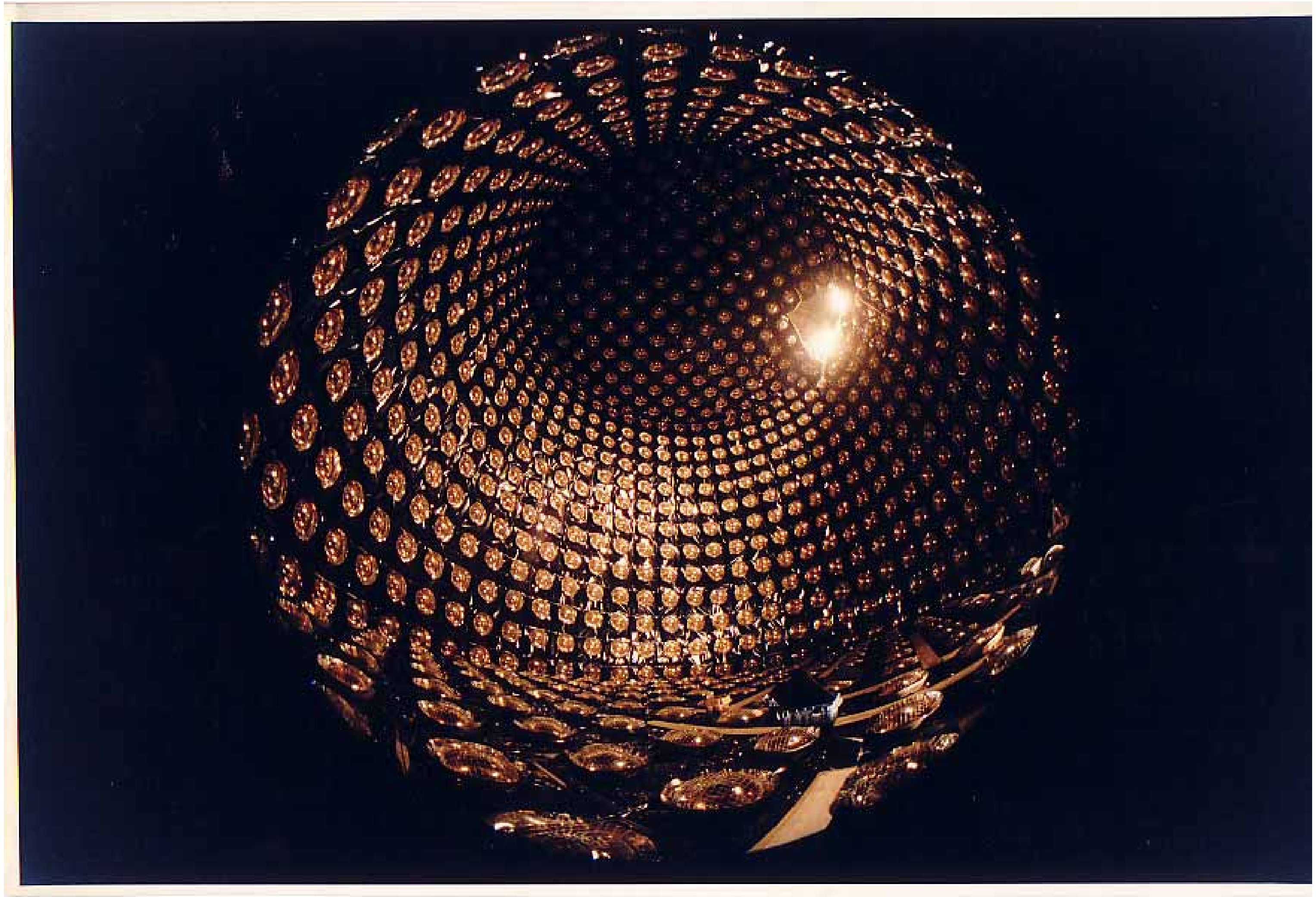
1) KamiokaNDE; Imaging Water Cerenkov,
   20% PMT coverage, 3,000tons,
   ca.3MUS$.
   Feasibility experiment.

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))

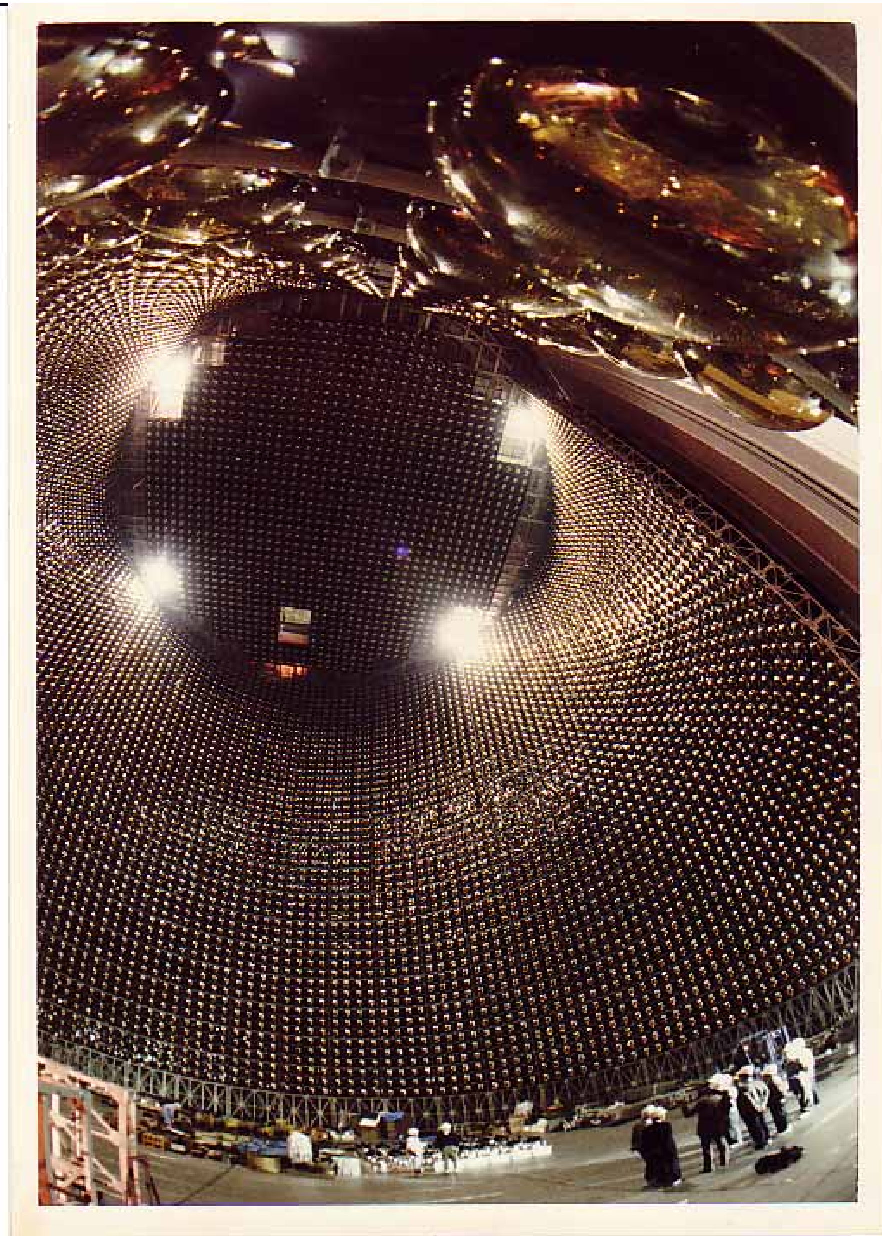
Fish-eye View of KamiokaNDE's Interior



50cmϕ PMT

which made the two detectors precision devices

Fish-Eye View of Super-KamiokaNDE's Interior

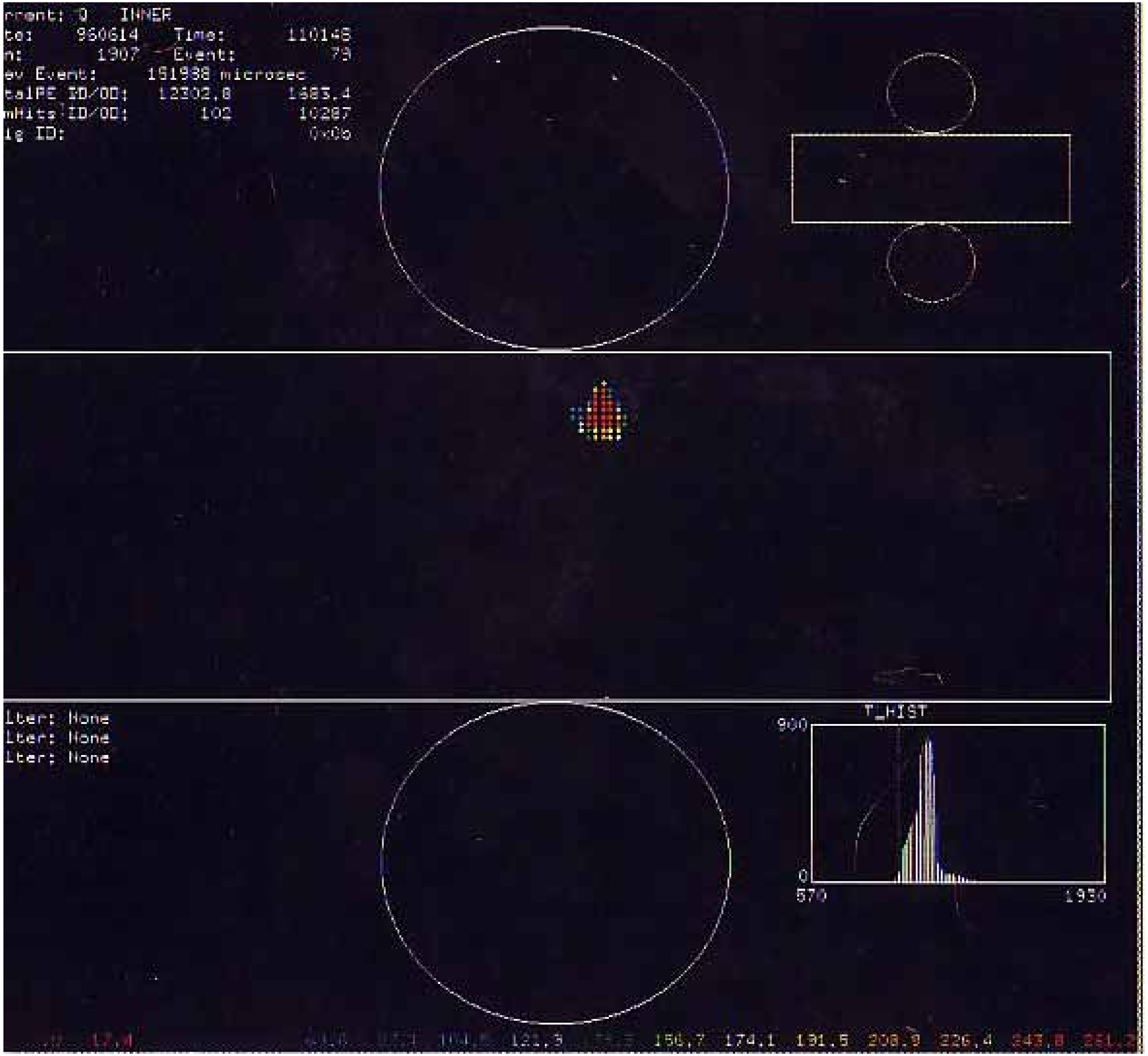


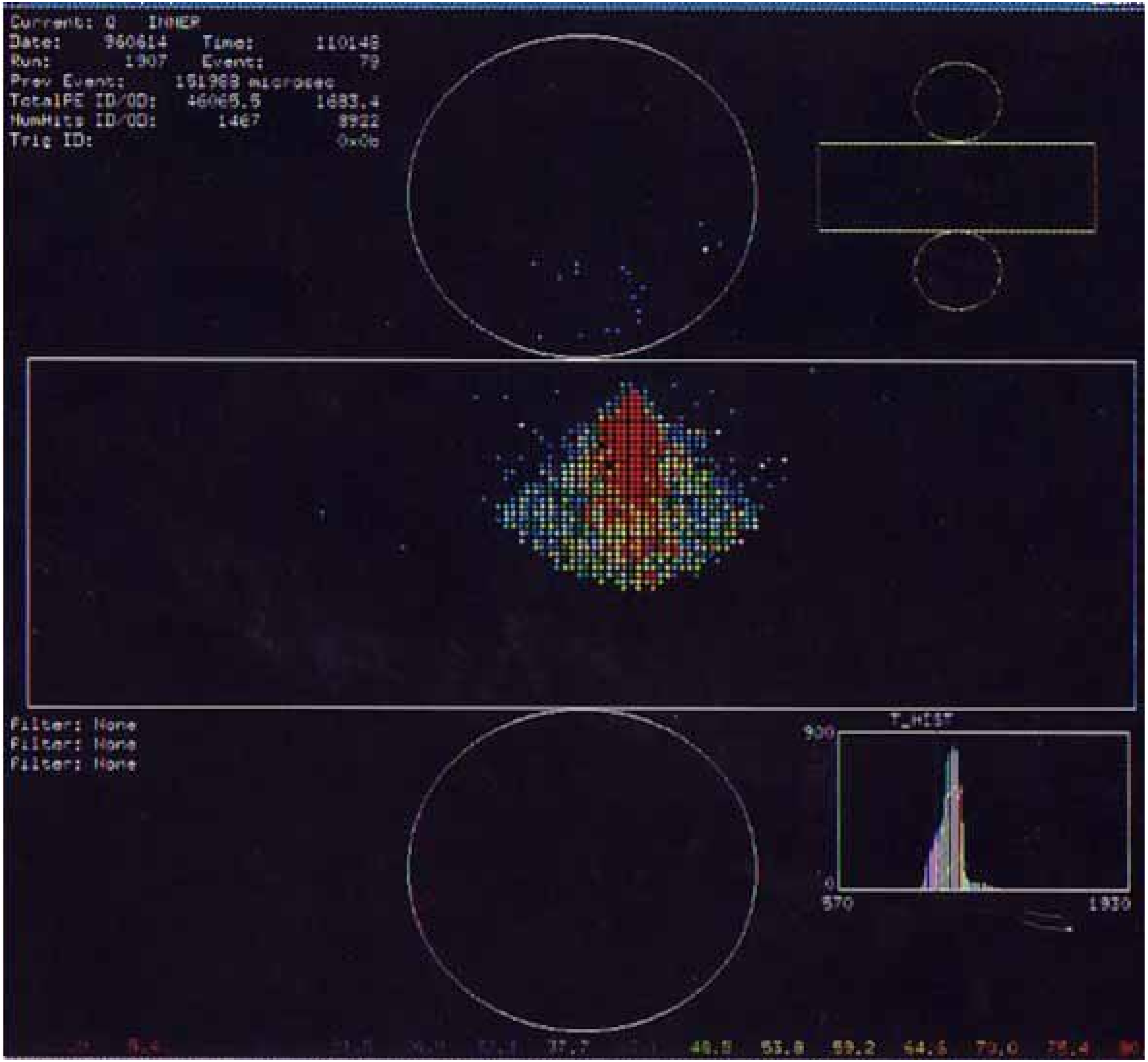
Detector Performances

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

2) Discrimination between electron and muon

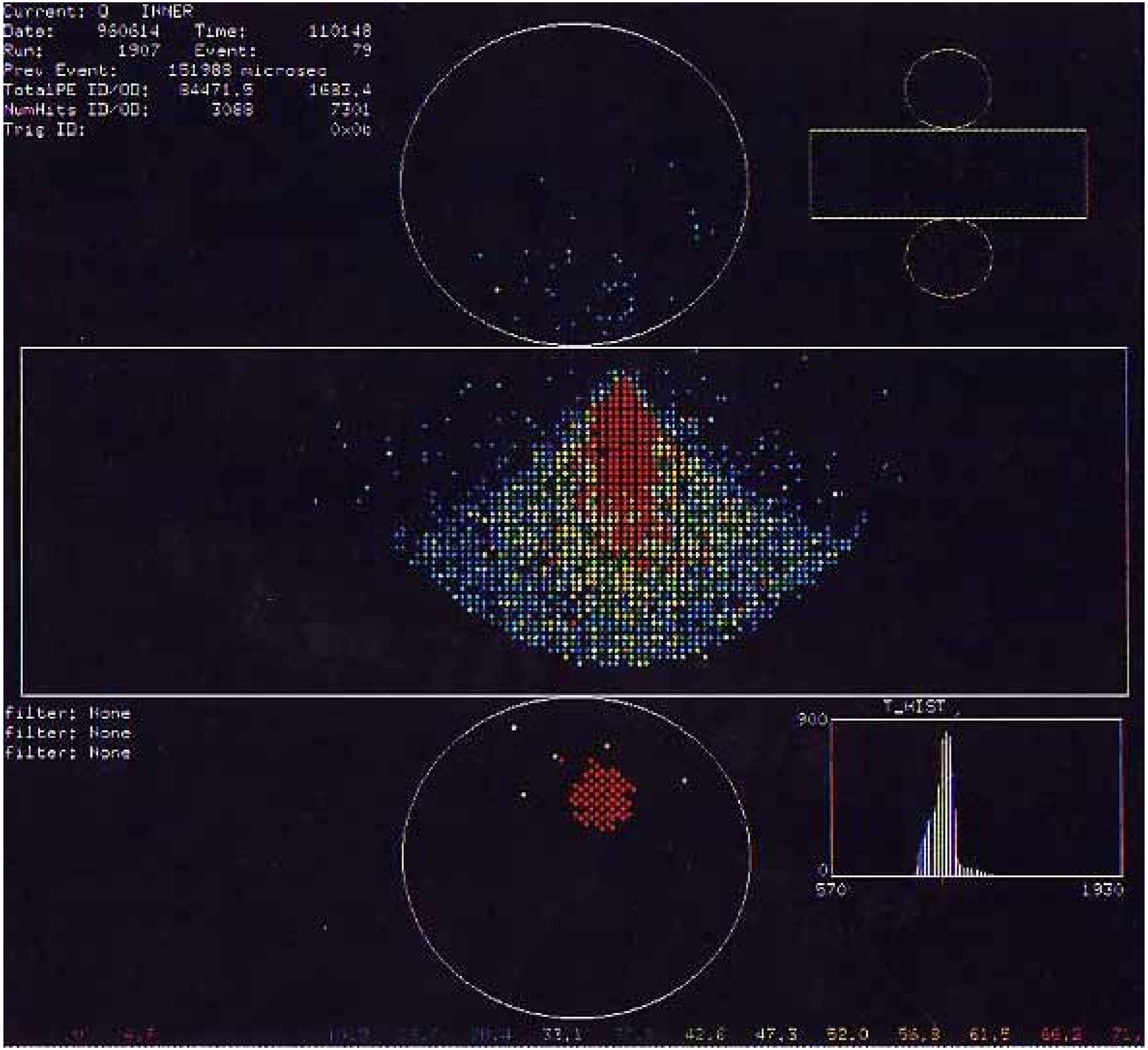
The μ has
just entered
the detector.

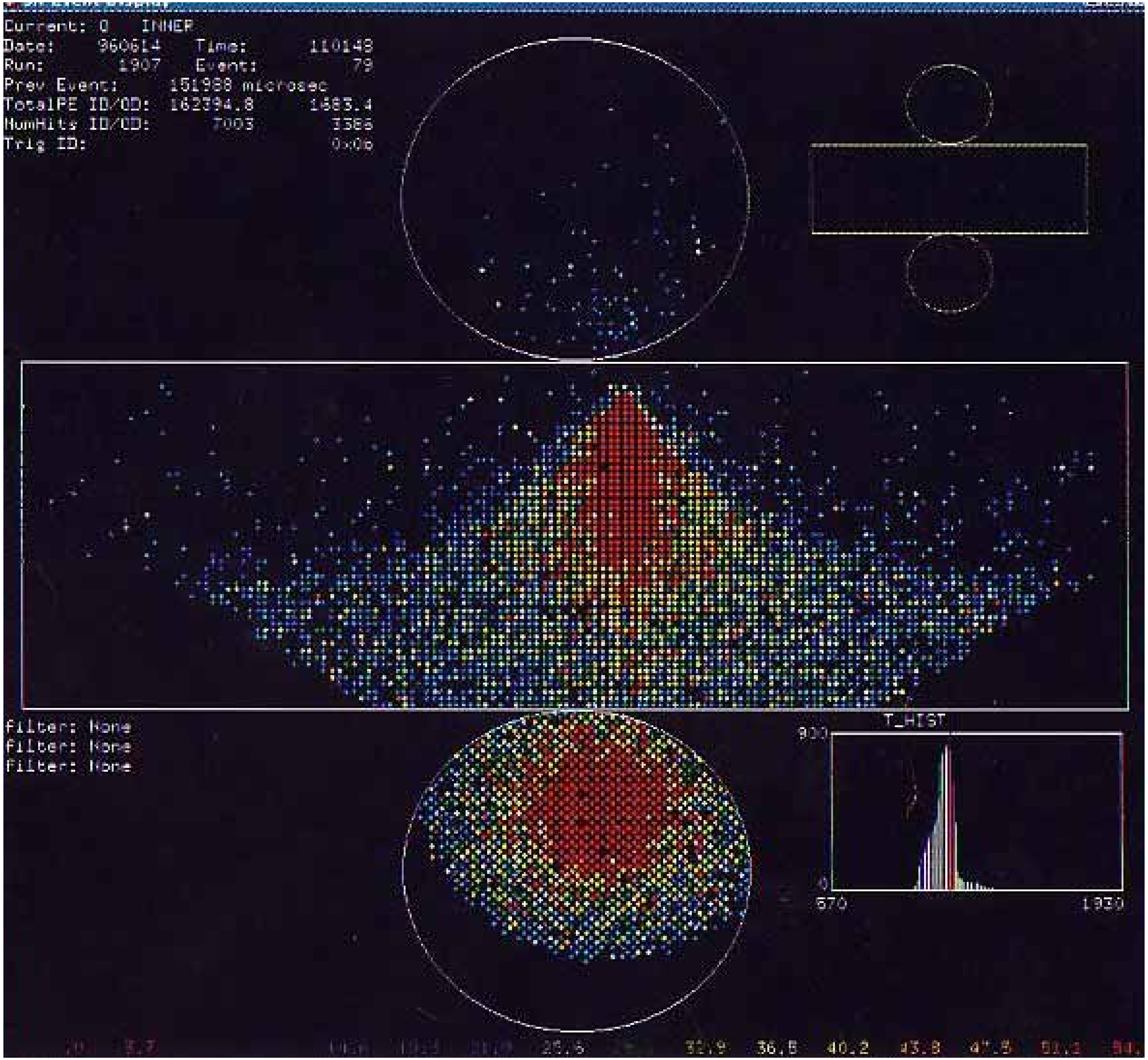


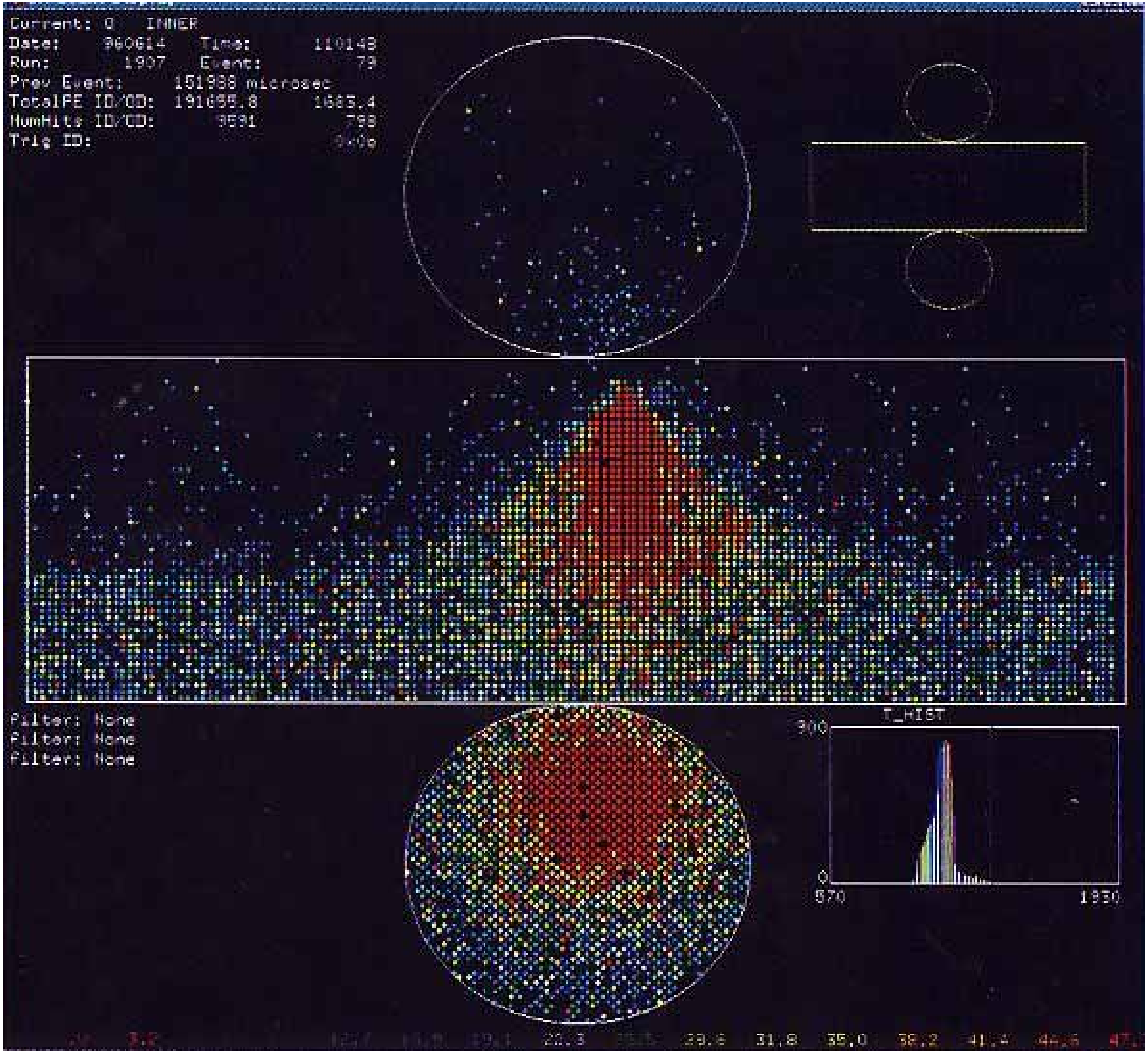


Current: 0 INNER
Date: 960614 Time: 110148
Run: 1907 Event: 79
Prev Event: 151968 microsec
TotalPE ID/OD: 46065.5 1683.4
NumHits ID/OD: 1467 8922
Trig ID:
Filter: None
Filter: None
Filter: None
T_HIST
900
0
570
1930

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




Current: 0 INNER
Date: 960614 Time: 110149
Run: 1907 Event: 79
Prev Event: 151988 microsec
TotalPE ID/OD: 162394.8 1683.4
NumHits ID/OD: 7003 3386
Trig ID: 0x0b
filter: None
filter: None
filter: None
T_HIST
900
0
570
1930
25.6
32.9
36.5
40.2
43.8
47.5
51.1


Current: 0 INNER
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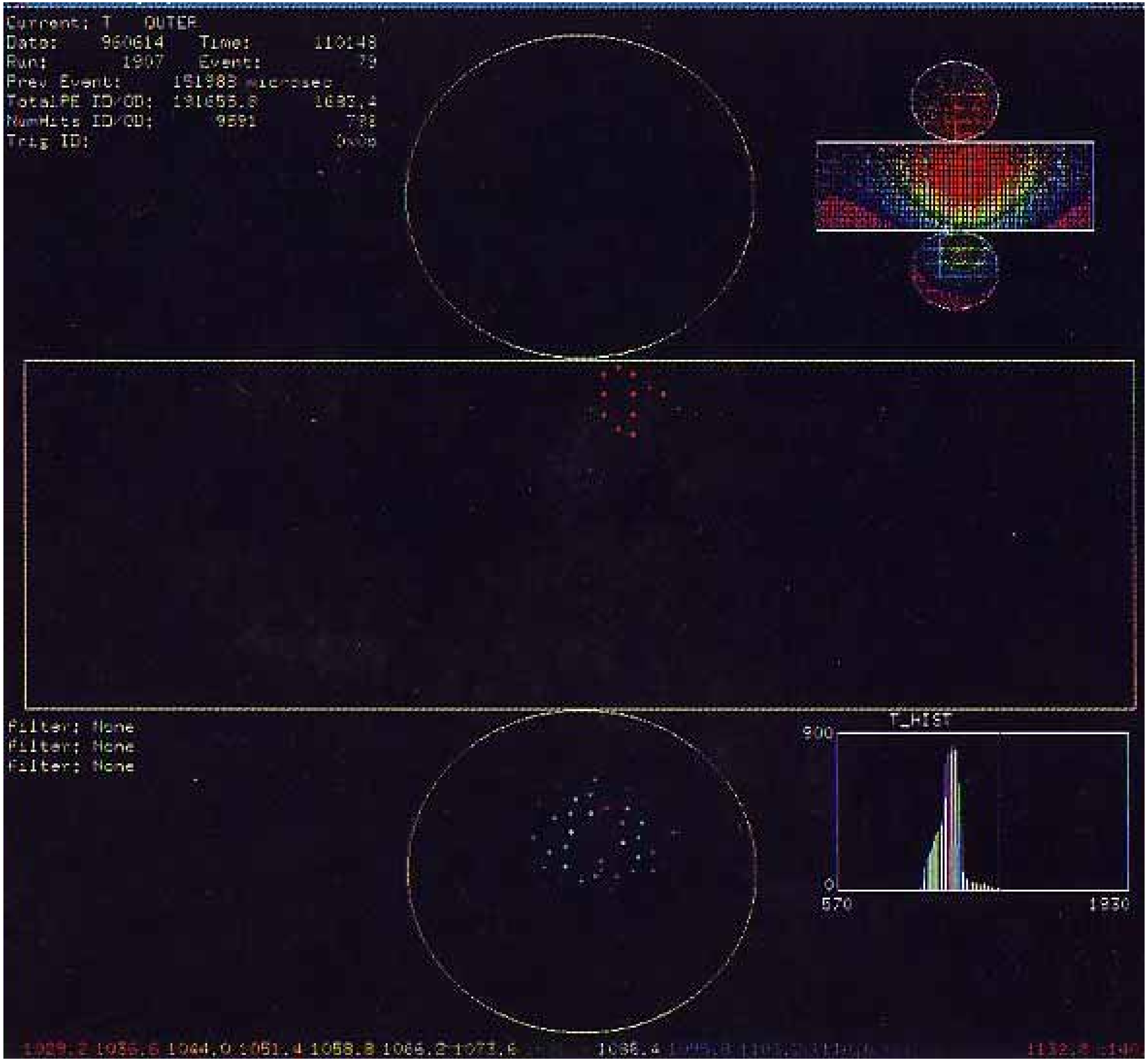
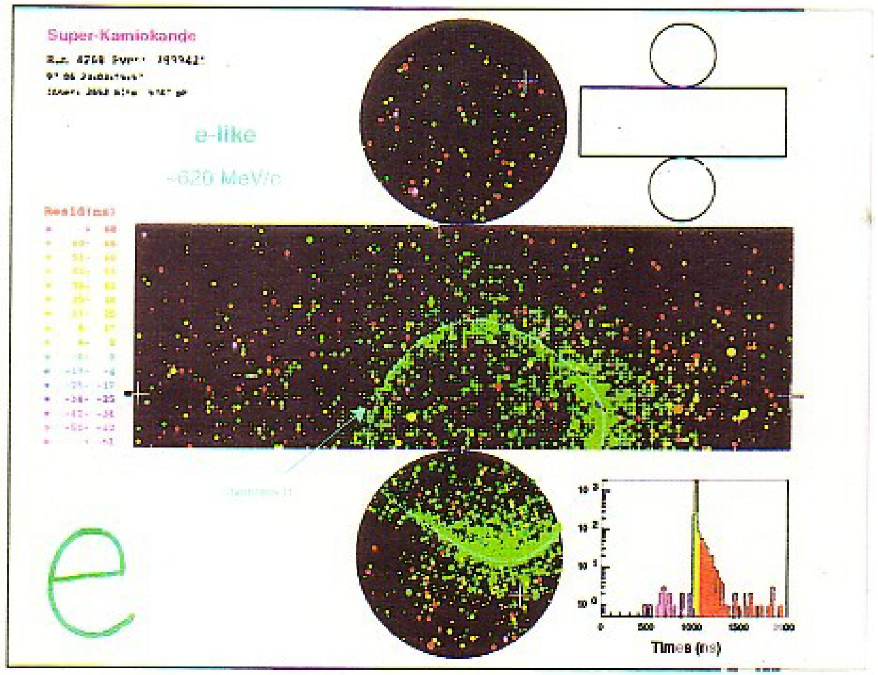
Run: 1907 Event: 79
Prev Event: 151988 microsec
TotalPE ID/OD: 191655.8 1685.4
NumHits ID/OD: 9591 798
Trig ID: 0x0b
Filter: None
Filter: None
Filter: None
T_HIST
300
0
570
1930
31.8
35.0
38.2
41.4

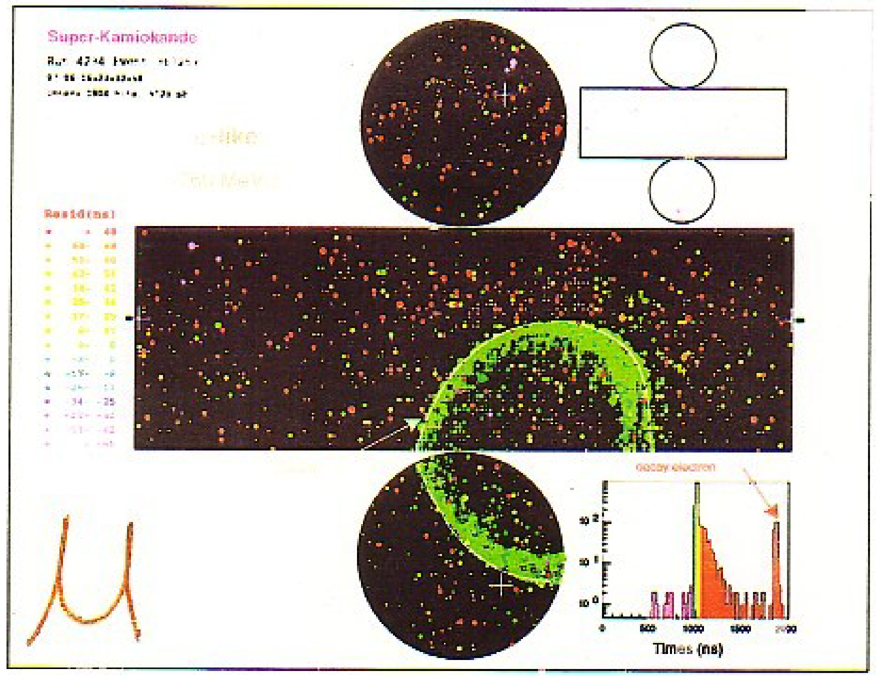
The data of the outer anti-counter are shown, while the inner data are moved to the top right.



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.



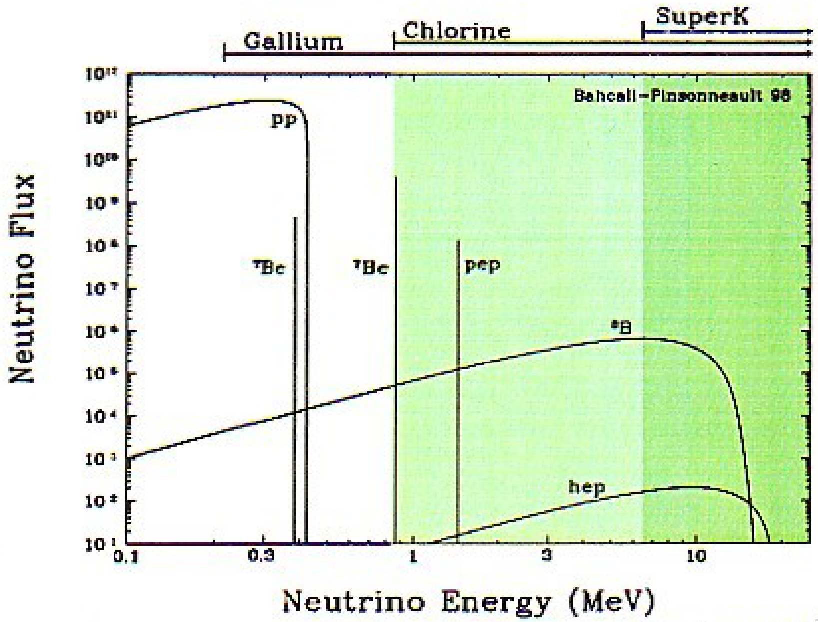


4 Accomplishments of KamiokaNDE

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)



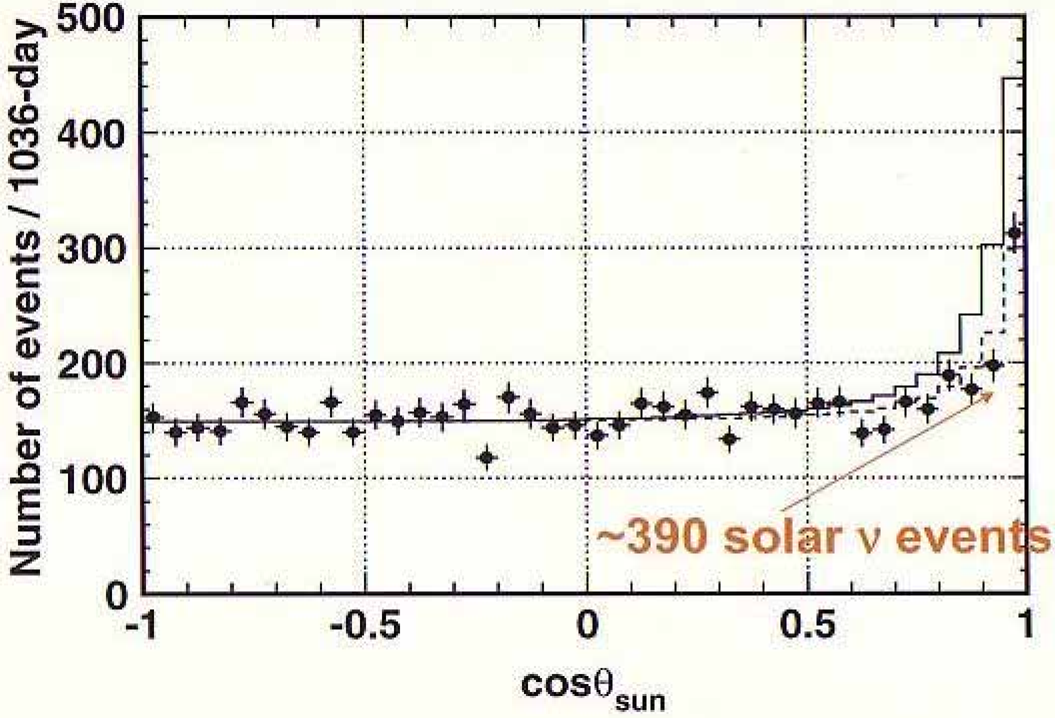
http://www.sns.ias.edu/~jnb/

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)

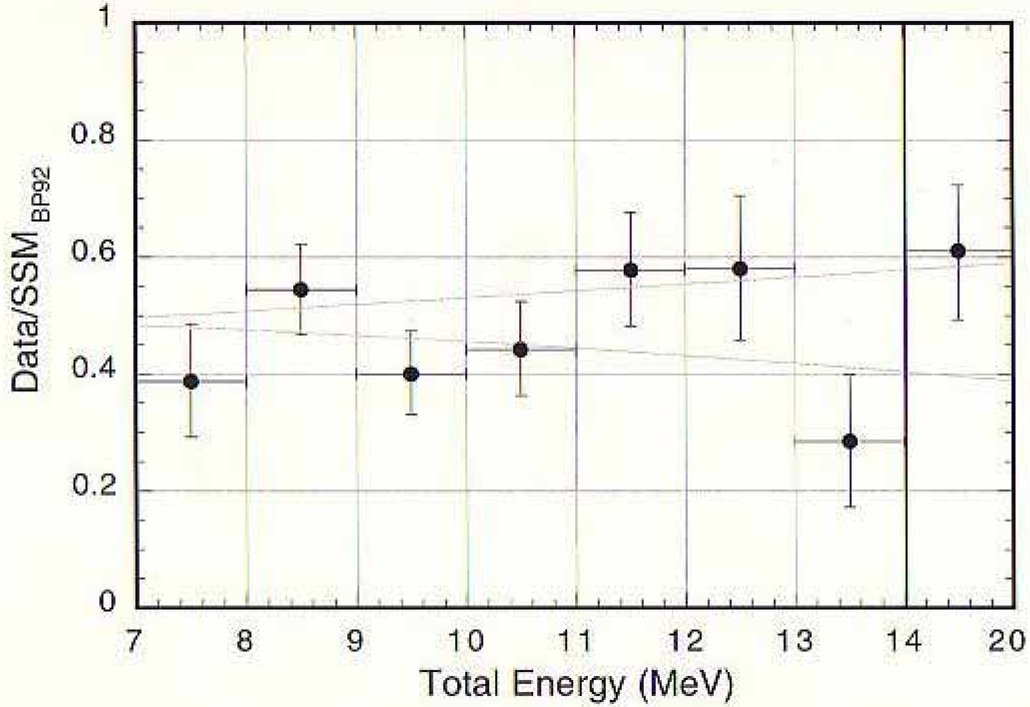
Dec. 28, 1990 – Feb. 6, 1995 (1036 days)



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.

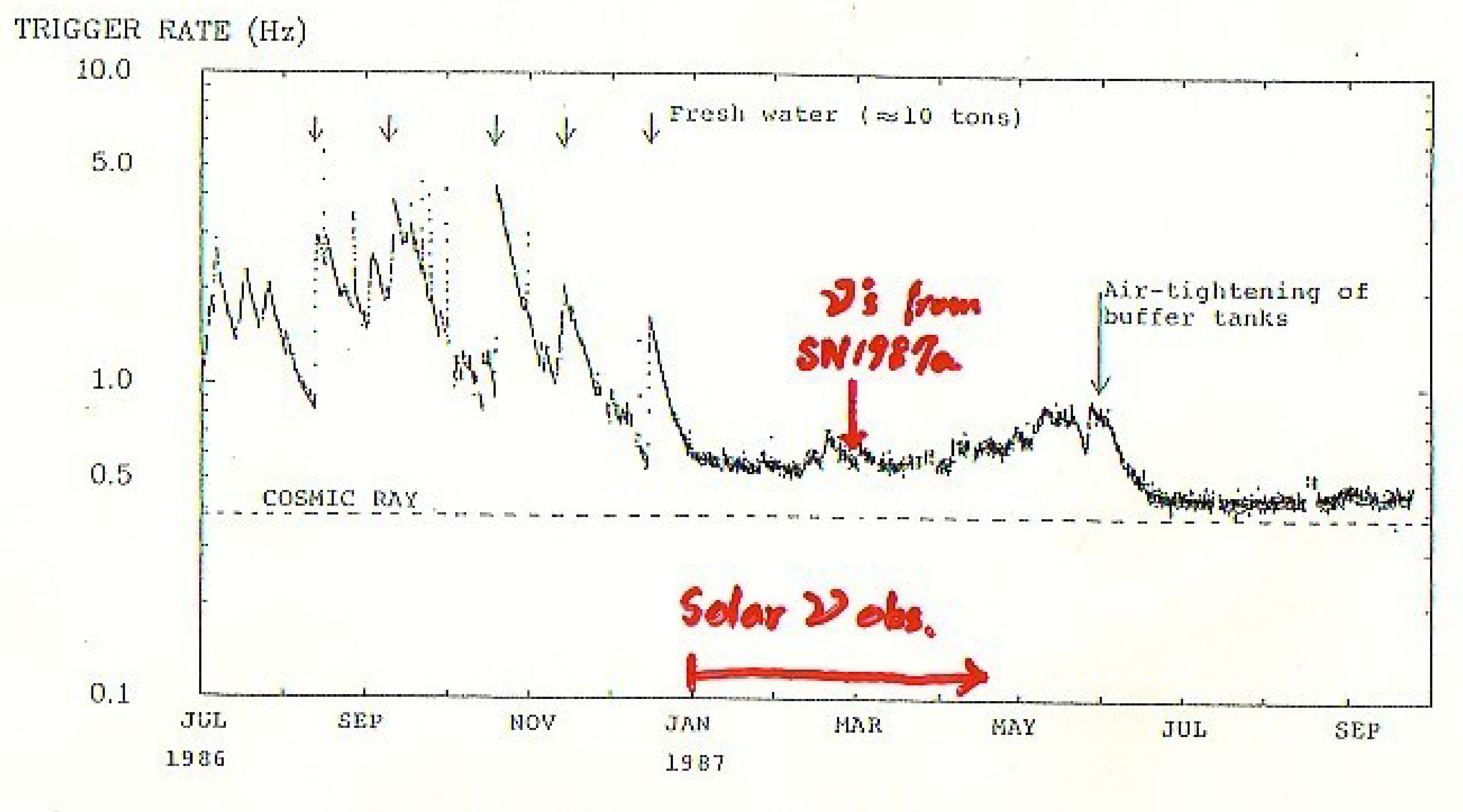
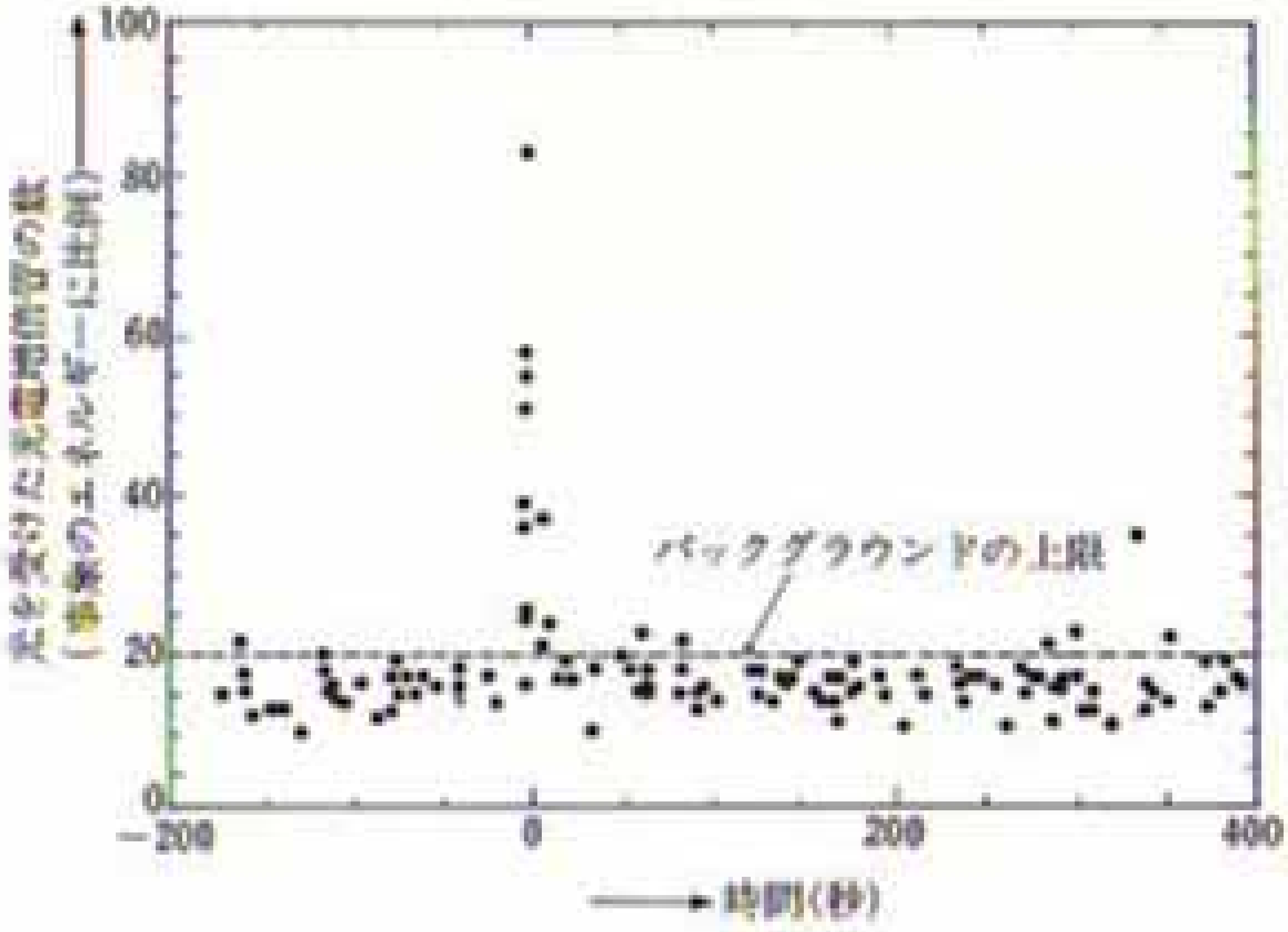
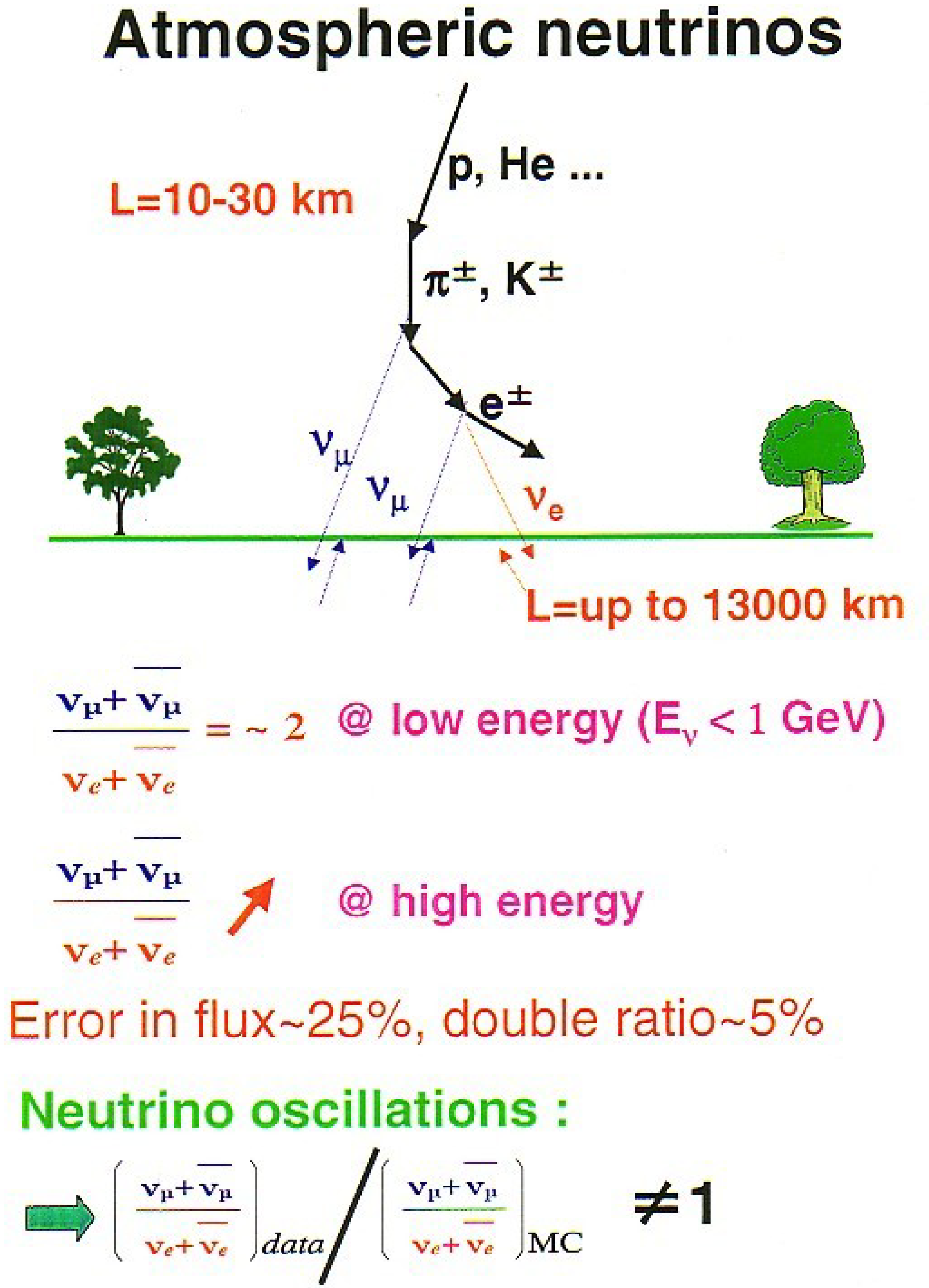


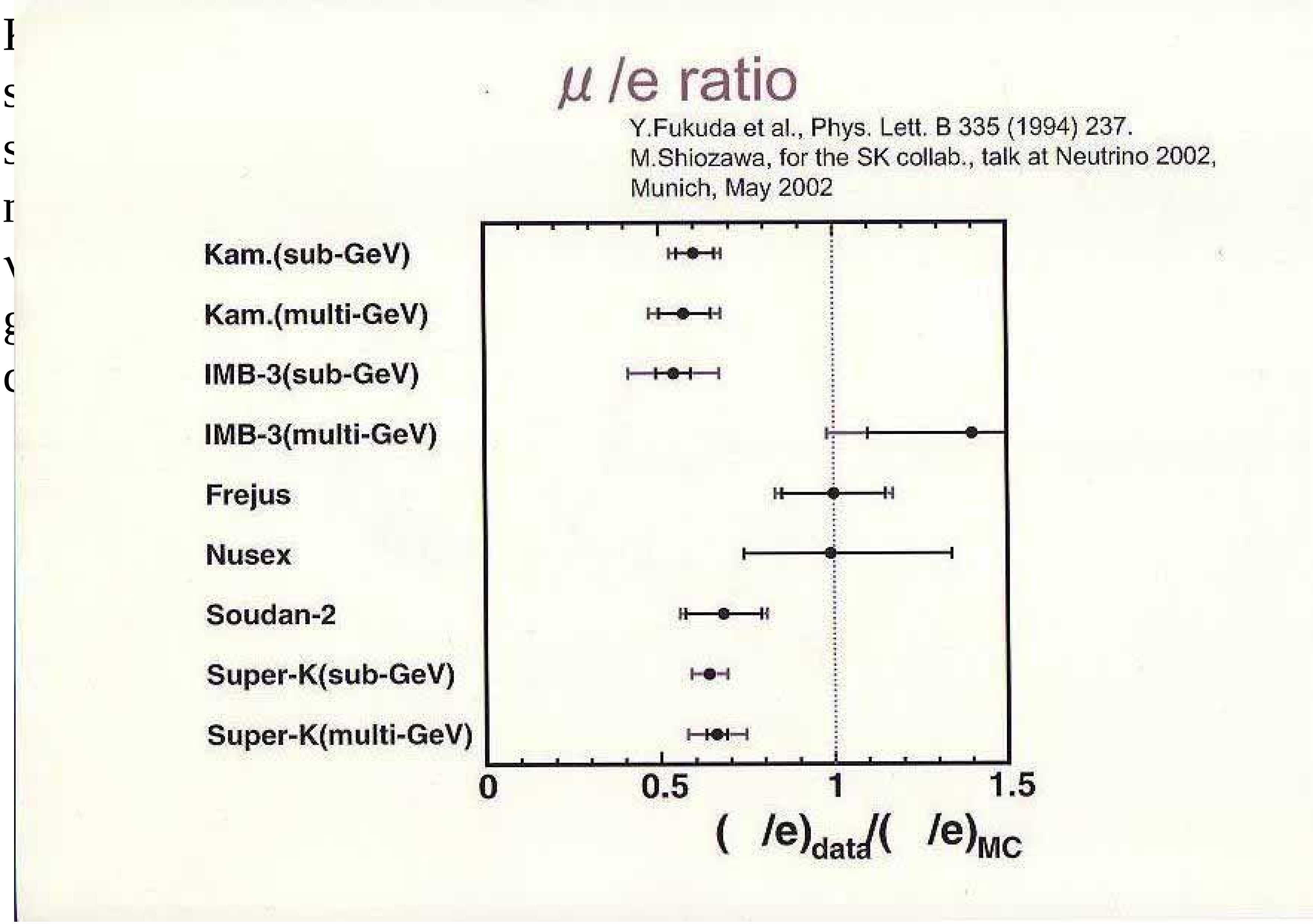
Fig. 3.20. The early performance of the KAM-II detector.

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.

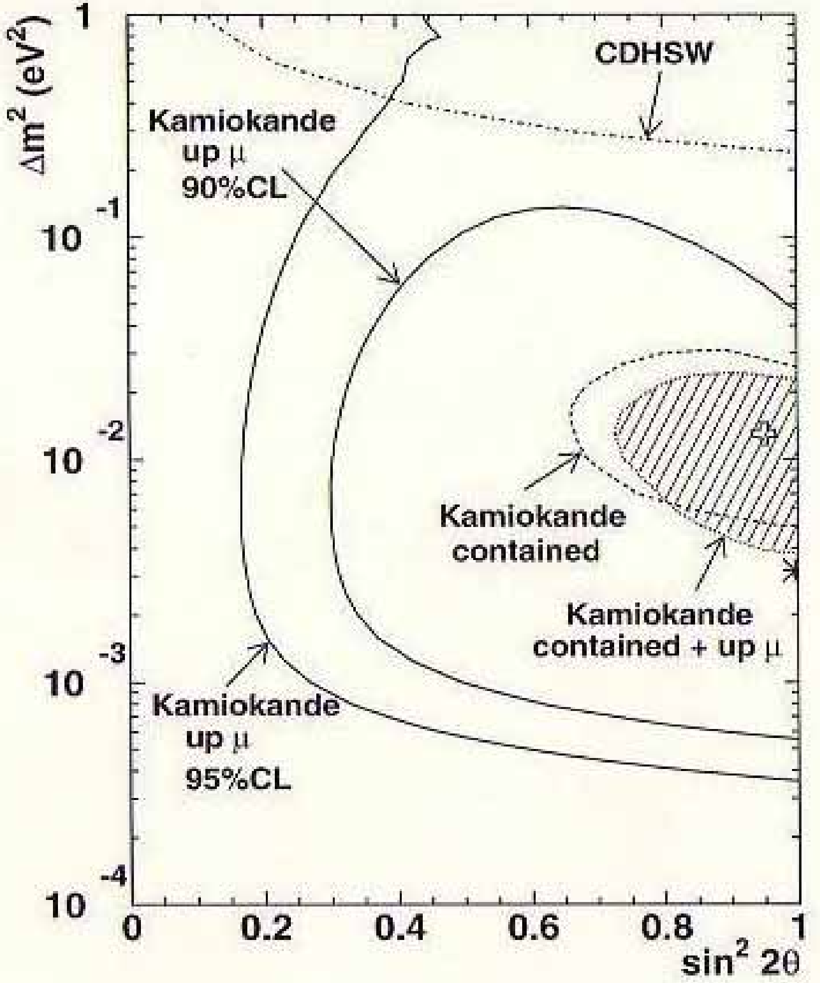


ν_μ/ν_e has to be 2 or larger




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

Allowed parameter region by the Kamiokande atmospheric neutrino mesasurement



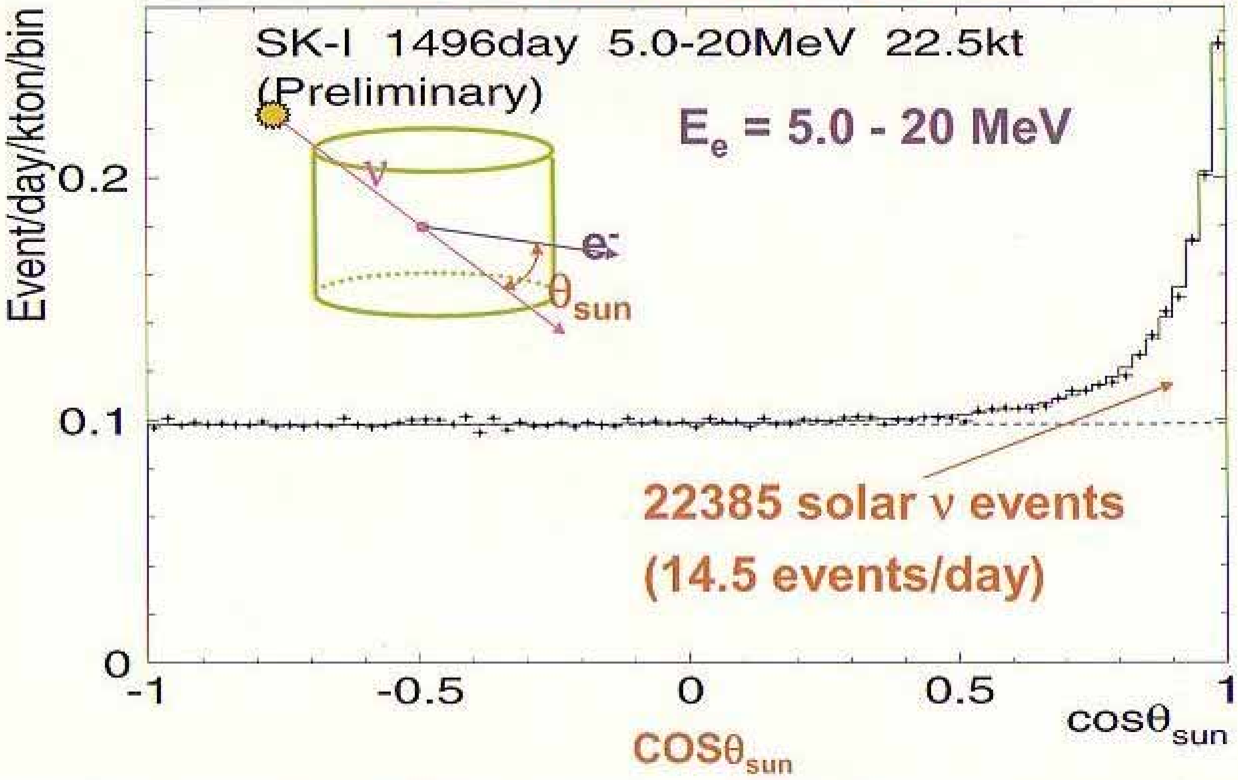
Observational Neutrino Astrophysics;
M. Koshiba,
Phys. Report, **220** Nos.5&6 (1992) 229-482.

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)



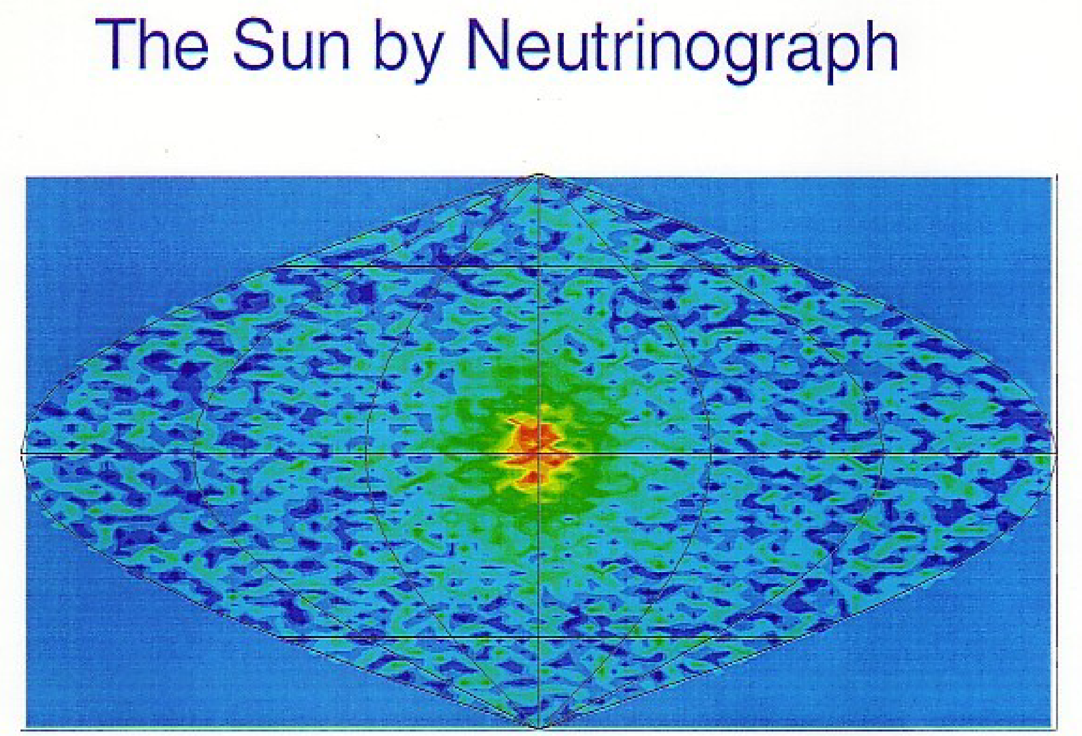
^{8}B flux : 2.35 ± 0.02 ± 0.08 [x 10^6 /cm^2/sec]

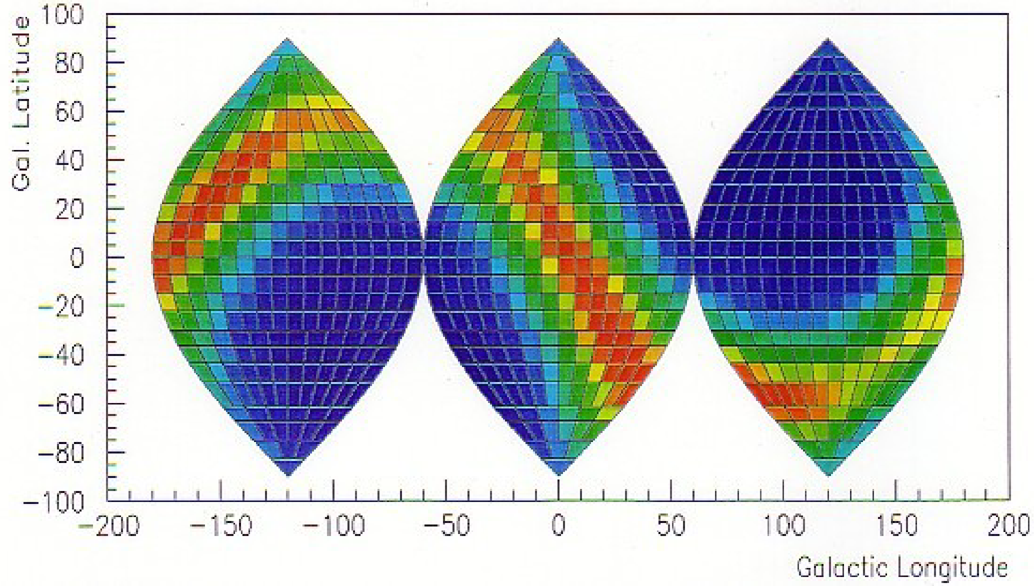
$$\frac{\text{Data}}{\text{SSM(BP2000)}} = 0.465 \pm 0.005 ^{+0.016}_{-0.015}$$

(BP2000: 5.05 x 10^6 /cm^2/sec)

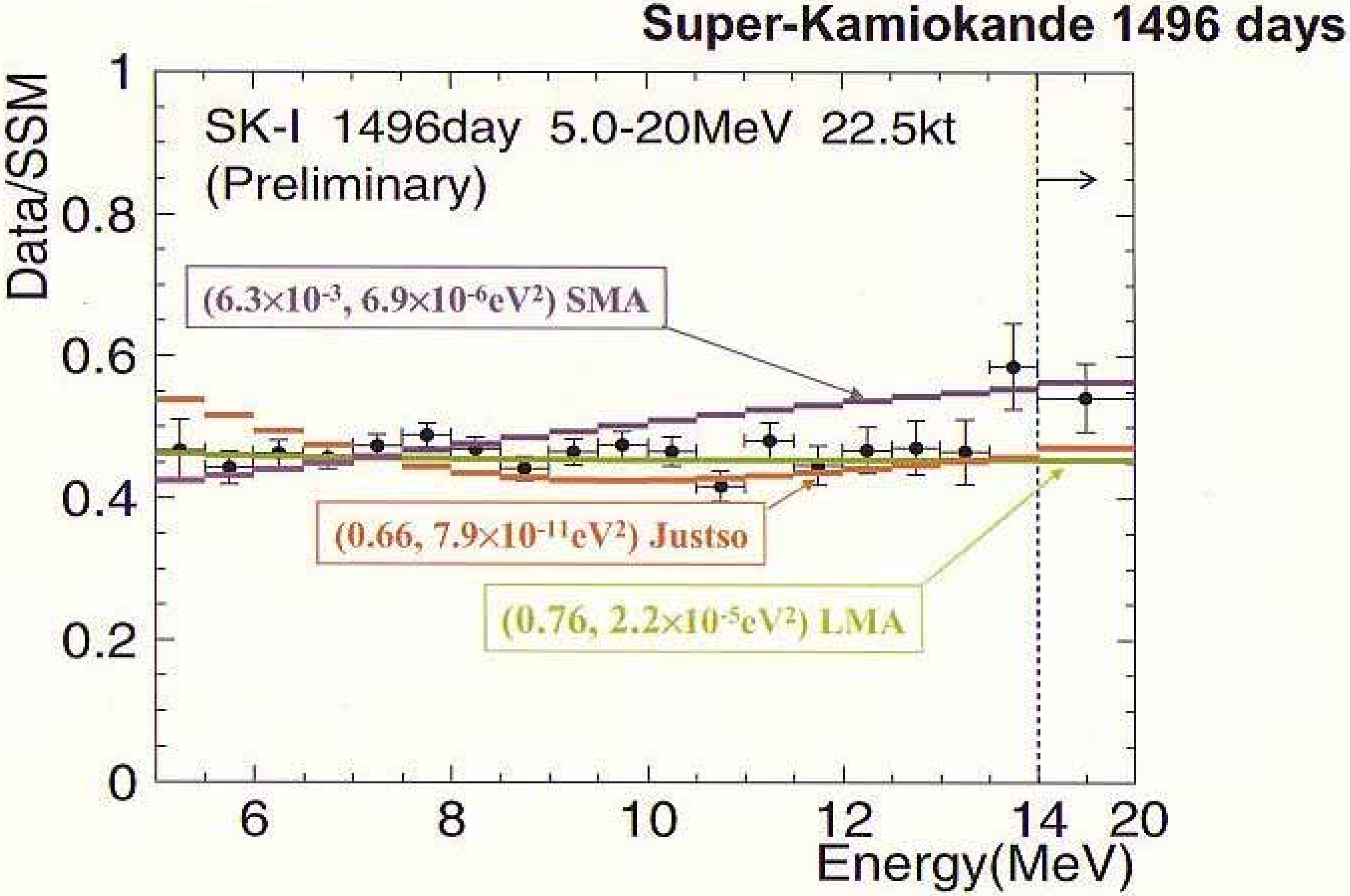
The Sun as seen by ν's and its orbit in the Galactic coordinate.

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





Energy spectrum of solar neutrino events

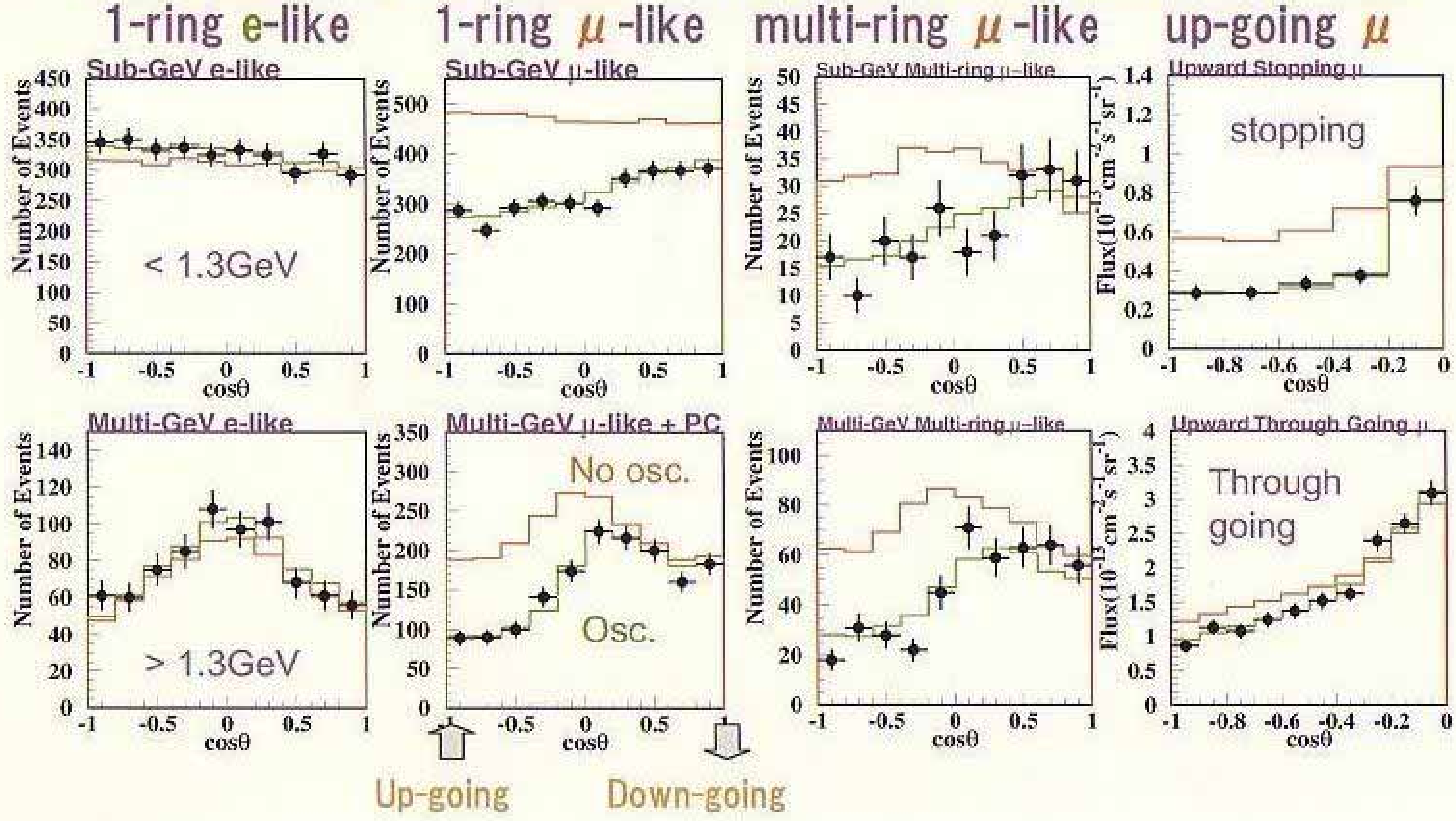


Bad fit to SMA and Just-so solutions.

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



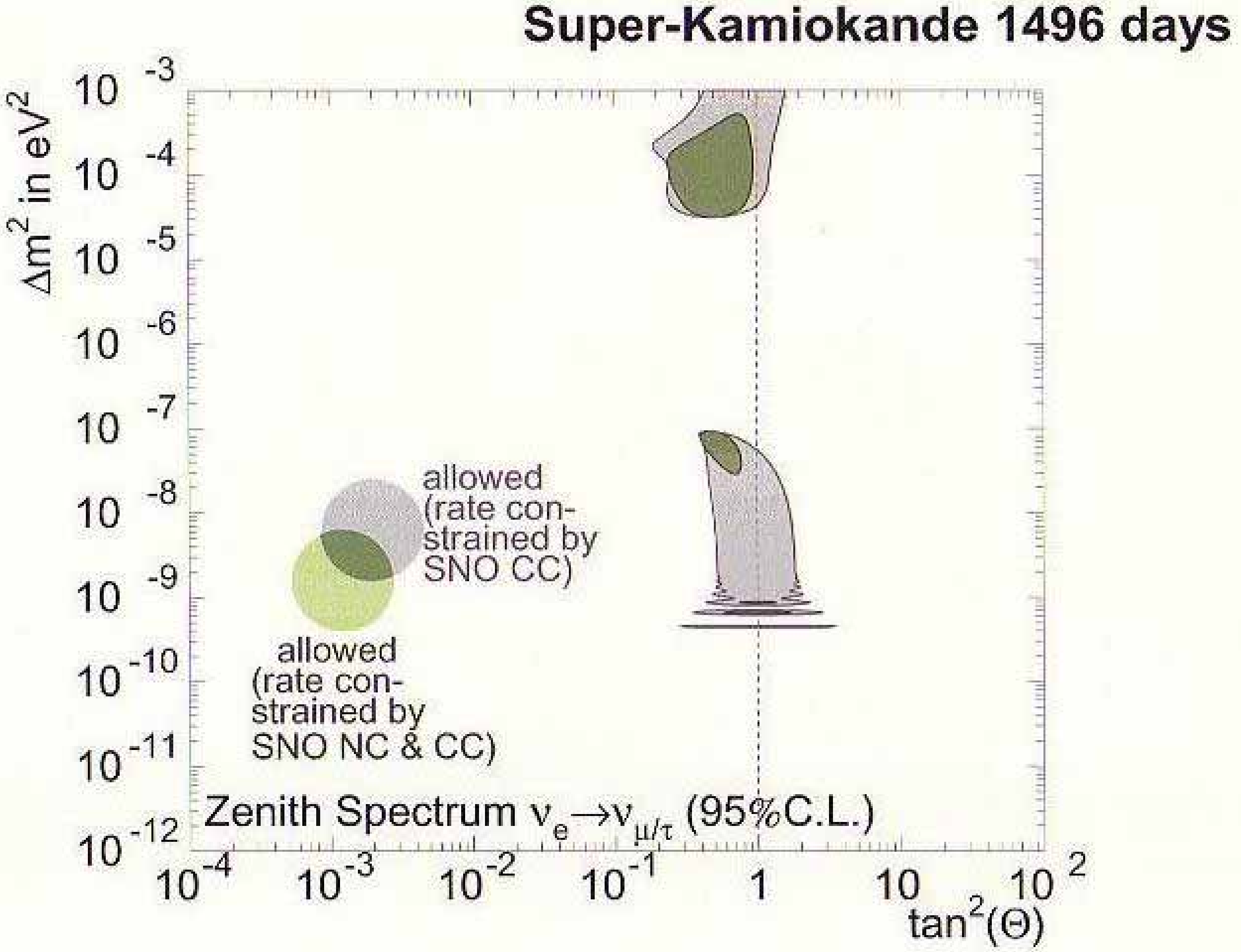
The Neutrino Oscillation

Consider 2 neutrino case for simplicity.

The weak eigenstate ψ_μ is a superposition of ψ_{m1} and ψ_{m2}.with a parameter θ, the angle between ψ_μ and ψ_{m1} . Since $E \sim p+(m^2/p)$ The two states, ψ_{m1} and ψ_{m2}, make beat with the frequency proportional to $\Delta m^2 = m_1^2 - m_2^2$, thereby changing the relative intensity.

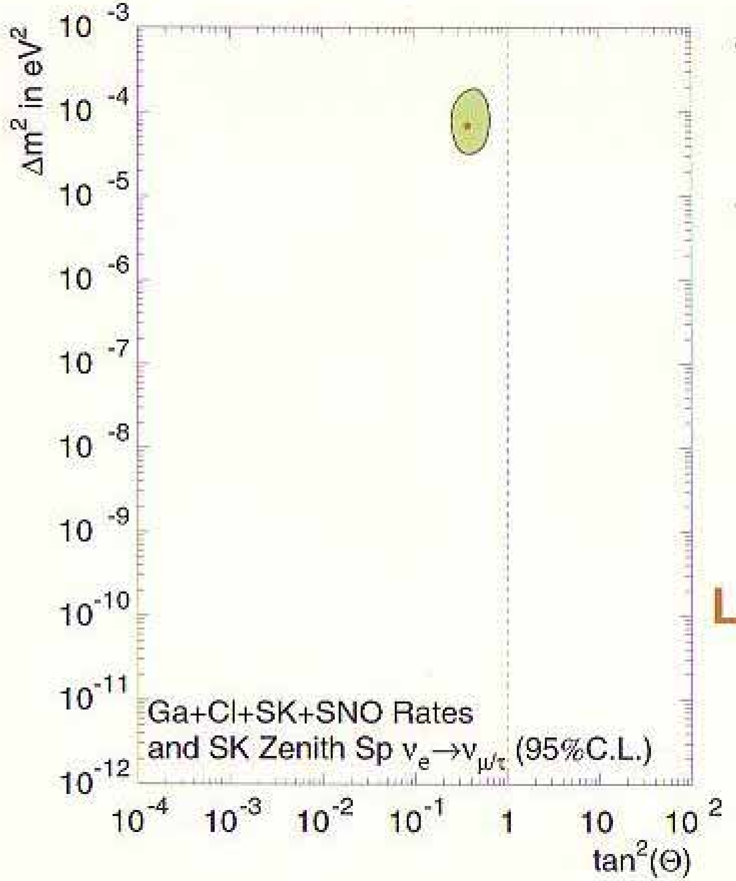
This causes a partial transformation of ψ_μ to ψ_τ.

Allowed region combined with SNO data



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)

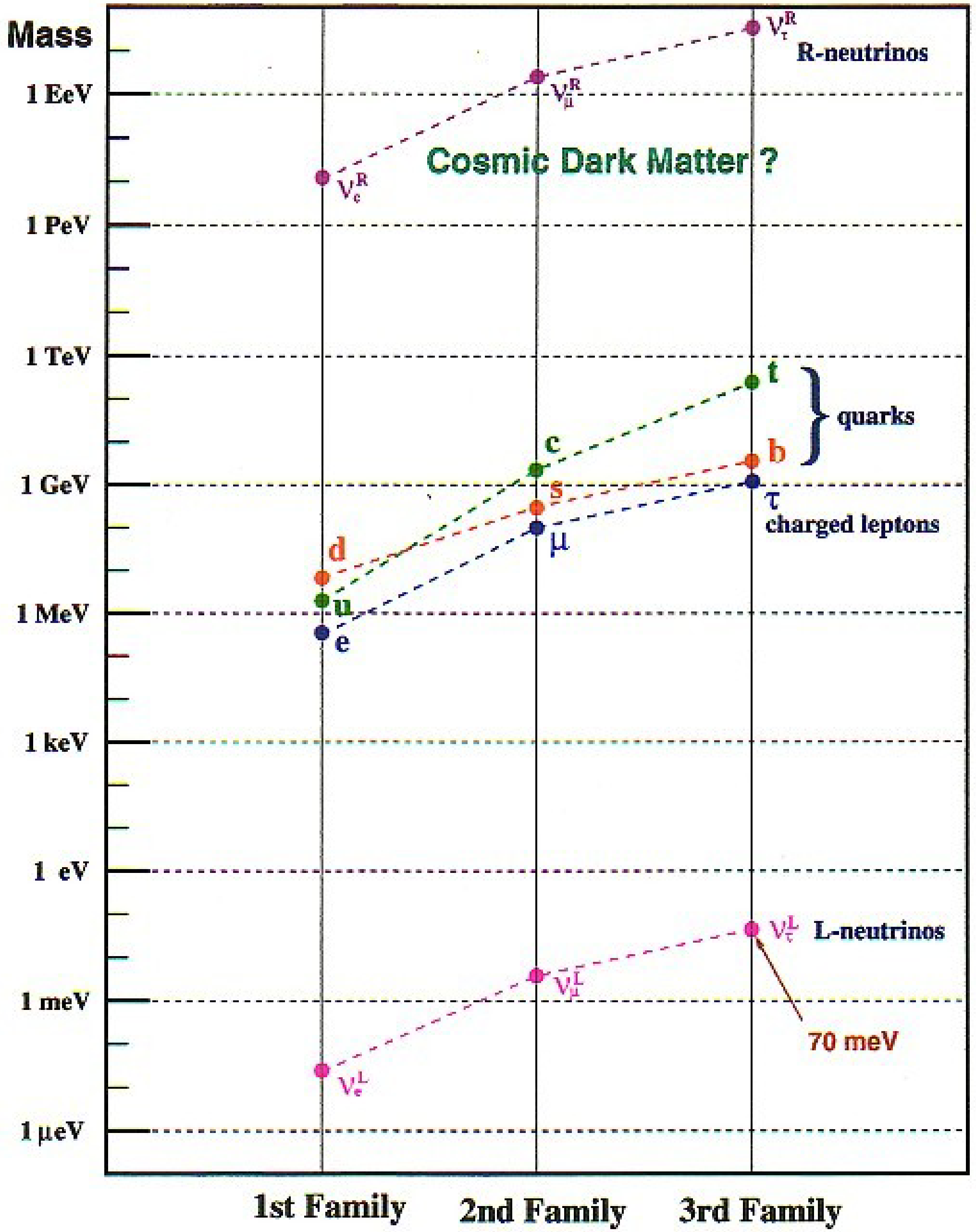
is discarded as possible GUT.

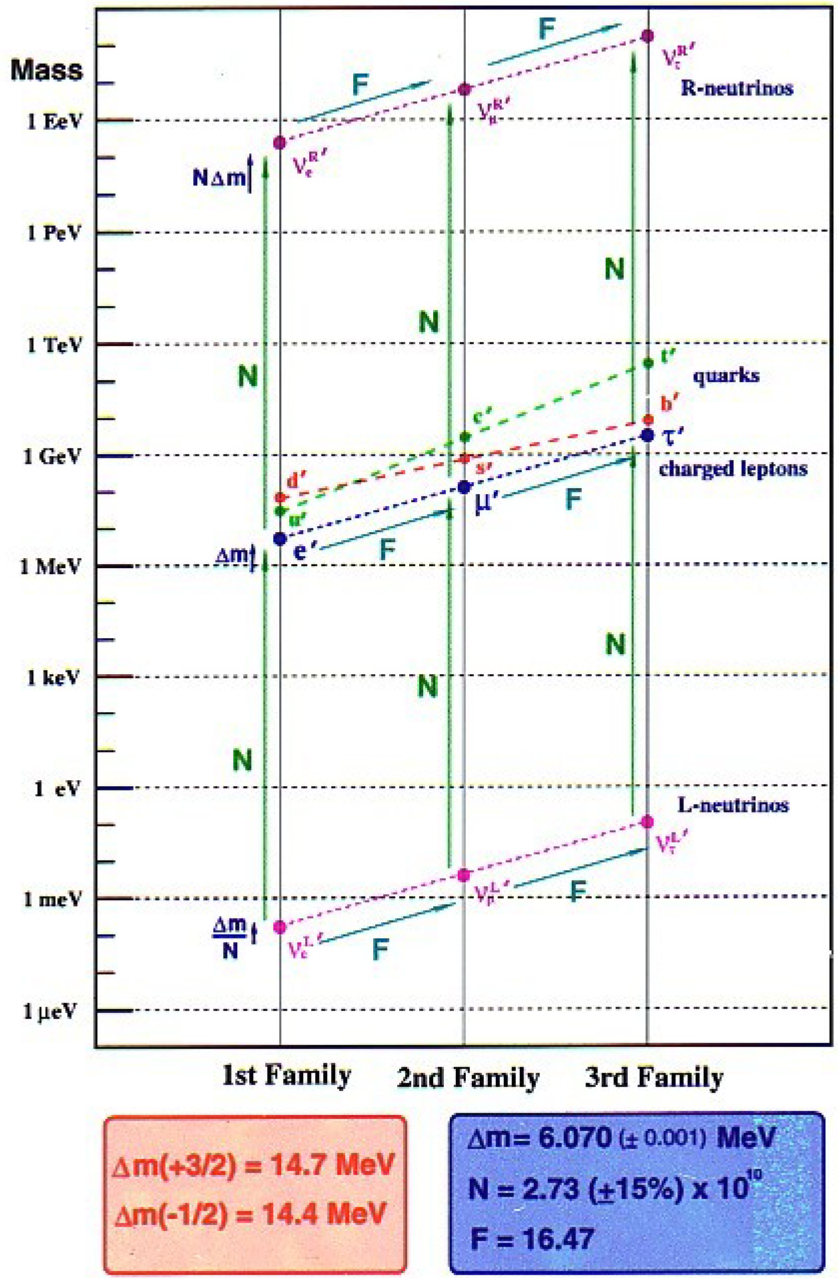
2) Very low energy neutrinos will make the total reflection at very low temperature. Very nice for the future possibility of observing the 1.9K Cosmic Neutrino Background.

For 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
R-neutrinos
Cosmic Dark Matter ?
t
c
b
s
d
u
e
μ
τ
quarks
charged leptons
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
NΔm
Δm
Δm/N
N
F
ν_e^{R'}
ν_μ^{R'}
ν_τ^{R'}
t'
b'
τ'
c'
s'
μ'
d'
u'
e'
ν_e^{L'}
ν_μ^{L'}
ν_τ^{L'}
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