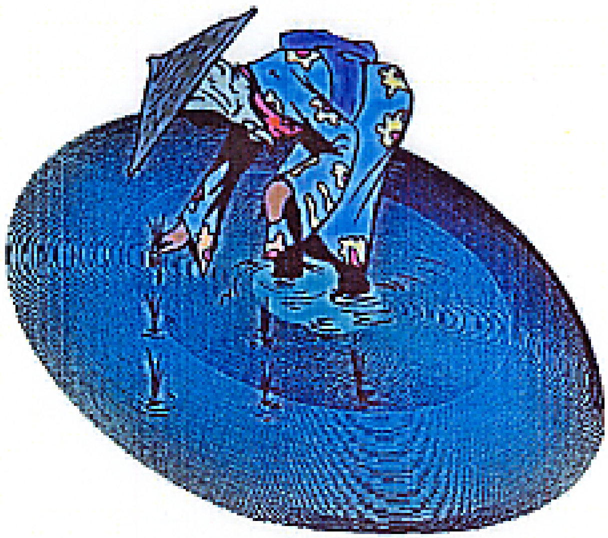
Neutrinos in the Land of the Rising Sun



Oscillation Results from Super–Kamiokande–I

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University of California, Irvine

NuCosmo02

Fermilab October 17, 2002

Super-Kamiokande Collaboration

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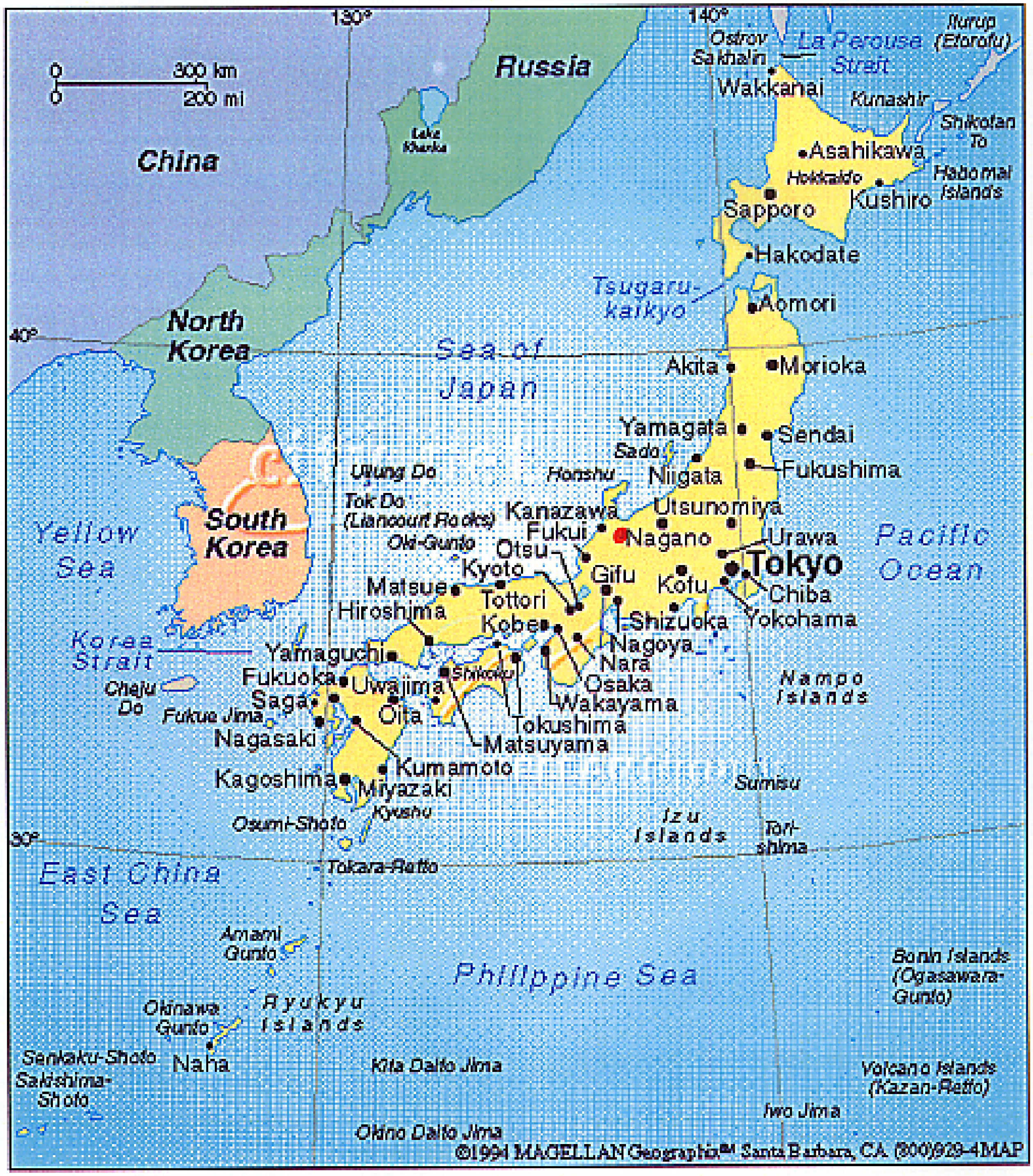

130°
140°
40°
30°
0 300 km
0 200 mi
Russia
China
Lake Khanka
North Korea
South Korea
Yellow Sea
Korea Strait
Cheju Do
Sea of Japan
Ullung Do
Tok Do (Liancourt Rocks)
Oki-Gunto
Ostrov Sakhalin
La Perouse Strait
Iturup (Etorofu)
Kunashir
Shikotan To
Habomai Islands
Wakkanai
Asahikawa
Hokkaido
Sapporo
Kushiro
Hakodate
Tsugaru-kaikyo
Aomori
Akita
Morioka
Yamagata
Sendai
Sado
Niigata
Fukushima
Honshu
Utsunomiya
Kanazawa
Fukui
Nagano
Urawa
Pacific Ocean
Tokyo
Otsu
Kyoto
Gifu
Kofu
Chiba
Matsue
Tottori
Hiroshima
Shizuoka
Yokohama
Kobe
Nagoya
Yamaguchi
Nara
Shikoku
Fukuoka
Uwajima
Osaka
Nampo Islands
Saga
Wakayama
Fukue Jima
Oita
Tokushima
Nagasaki
Matsuyama
Kumamoto
Kagoshima
Miyazaki
Sumisu
Kyushu
Osumi-Shoto
Izu Islands
Tori-shima
East China Sea
Tokara-Retto
Amami Gunto
Philippine Sea
Bonin Islands (Ogasawara-Gunto)
Okinawa Gunto
Ryukyu Islands
Senkaku-Shoto
Naha
Sakishima-Shoto
Kita Daito Jima
Volcano Islands (Kazan-Retto)
Iwo Jima
Okino Daito Jima
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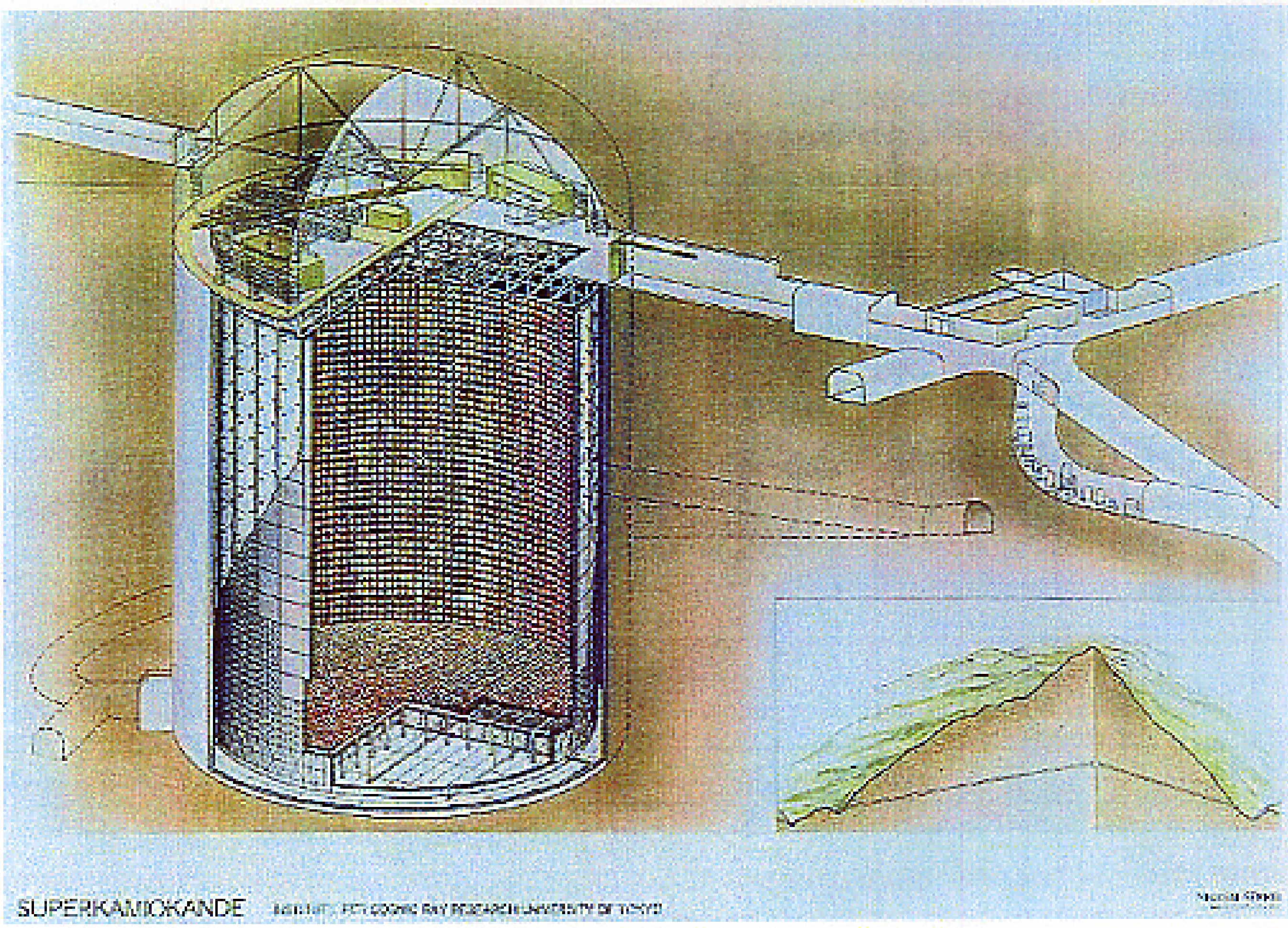
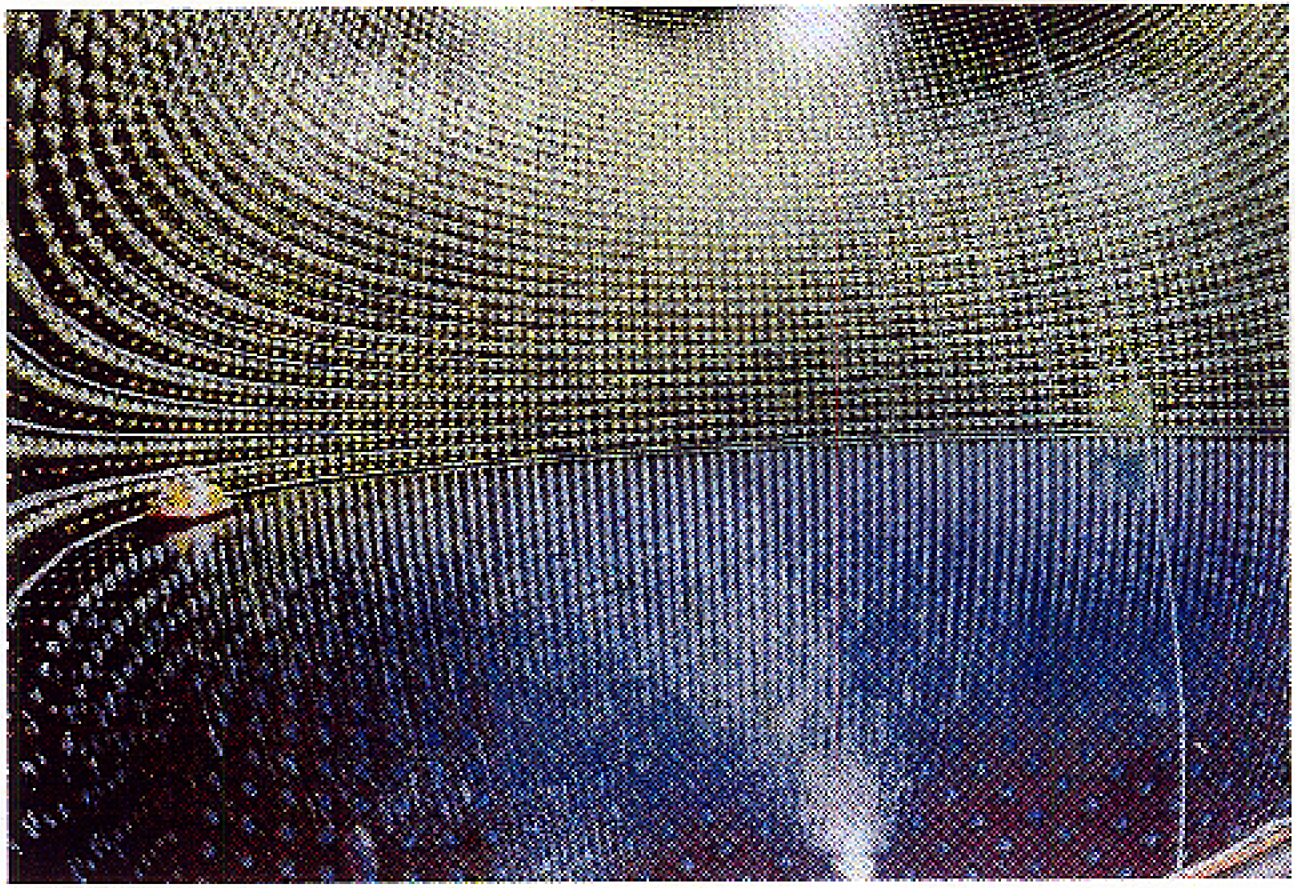

SUPERKAMIOKANDE



Properties of neutrino oscillations

- The mathematics of neutrino oscillations gives us:

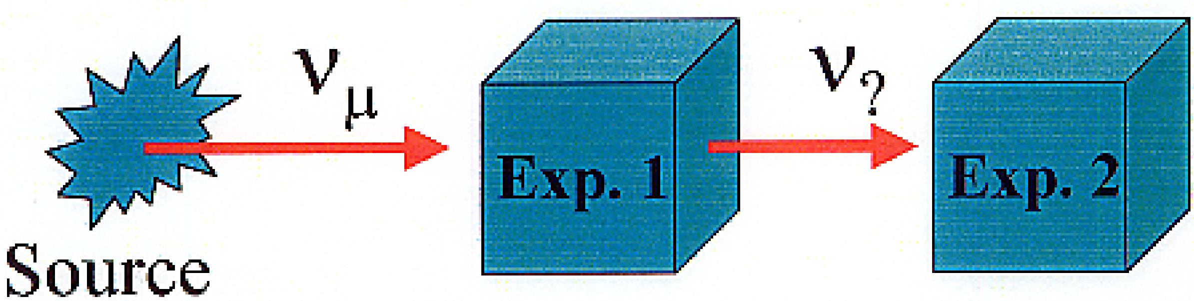
Neutrino energy

$$\text{Oscillation distance} \sim \frac{E}{\Delta M^2}$$

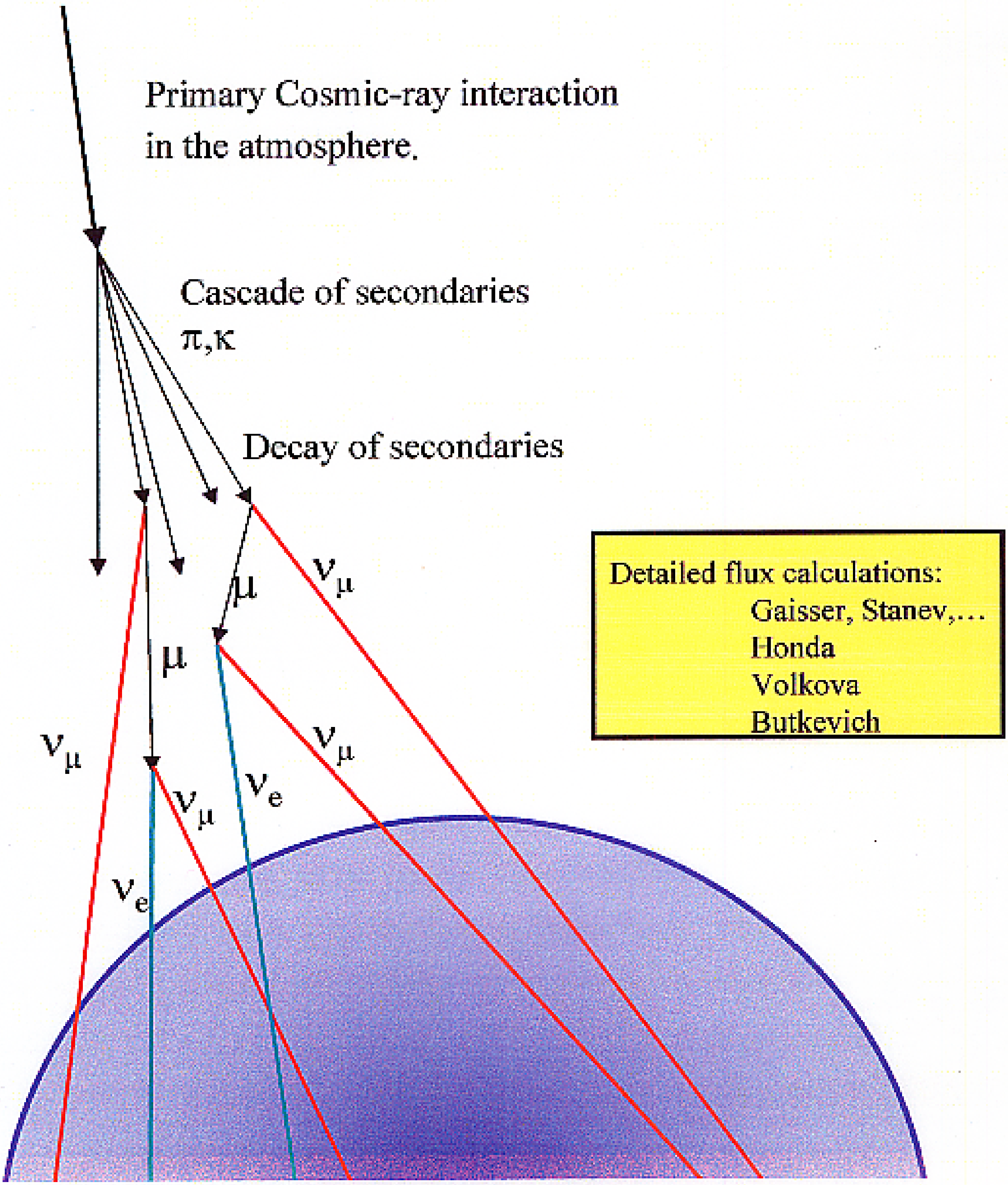
$(m_1^2 - m_2^2)$

If $\Delta M^2 = 0$ NO Oscillations

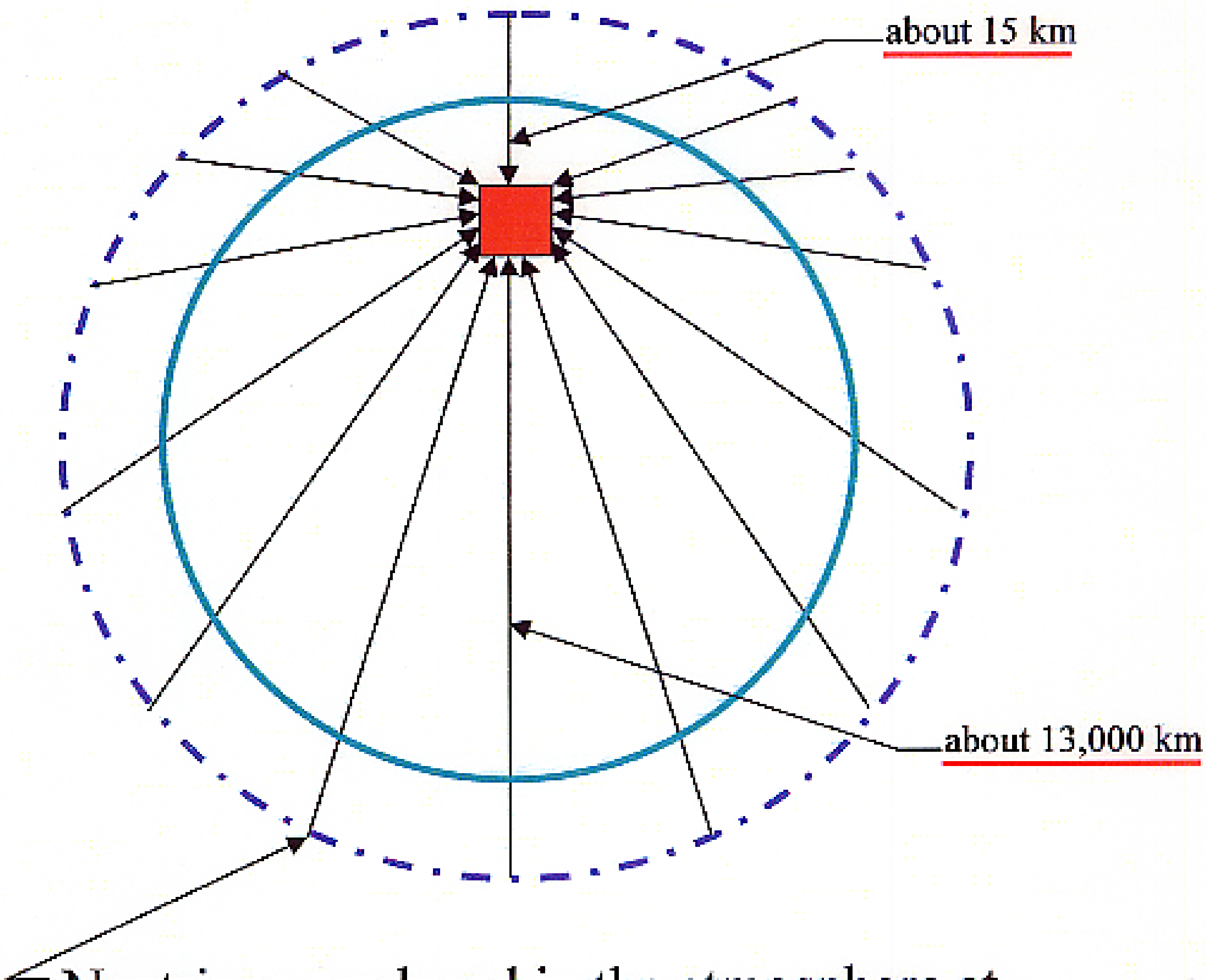
 - This means small ΔM^2 ➡ long oscillation distance.
 - Can search for oscillations by doing experiments at different distances from the source.



Atmospheric Neutrinos



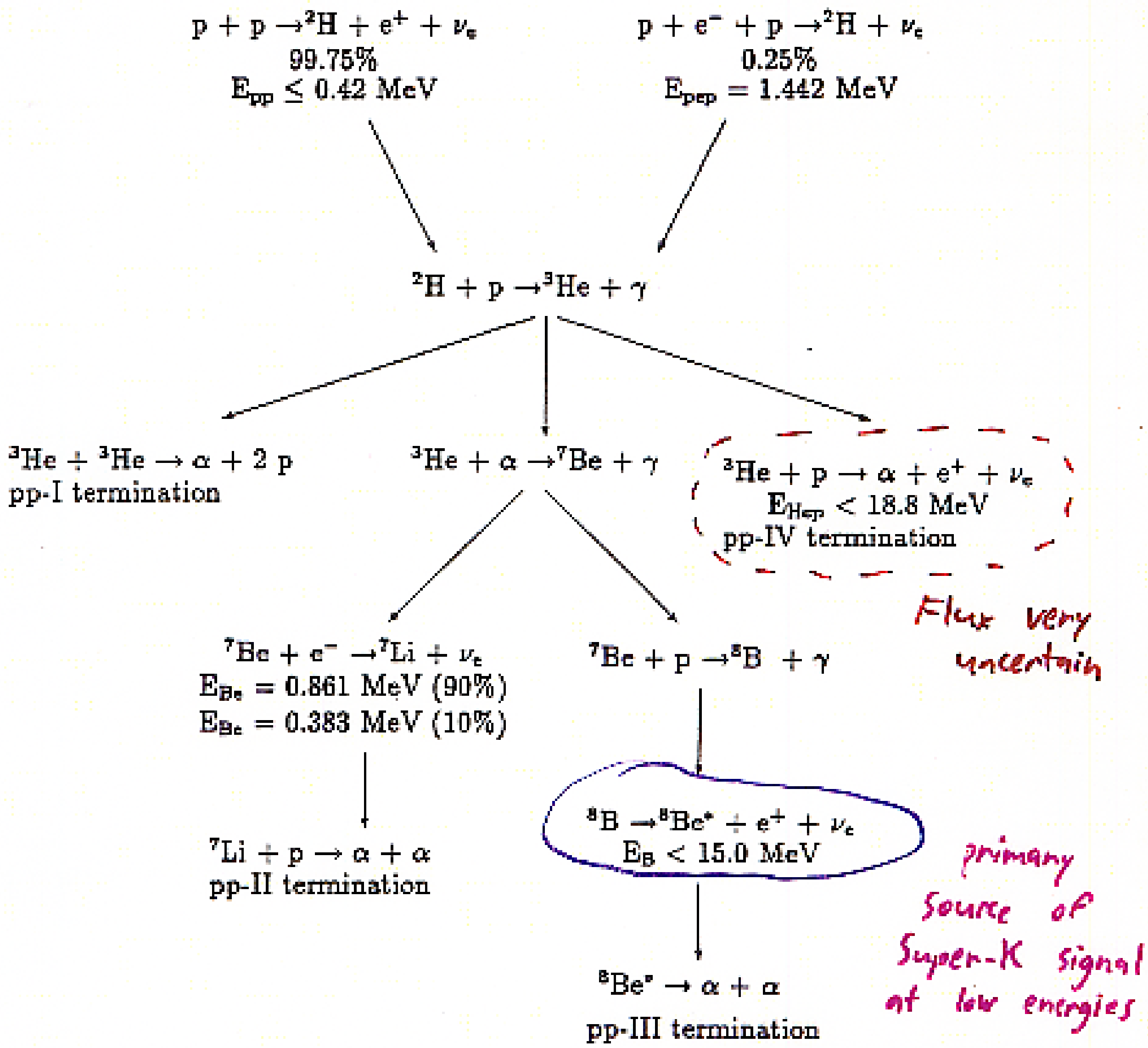
Study ν_μ and ν_e as a function of distance traveled



Neutrinos produced in the atmosphere at ~15 km altitude...

travel through the earth and interact in the detector.

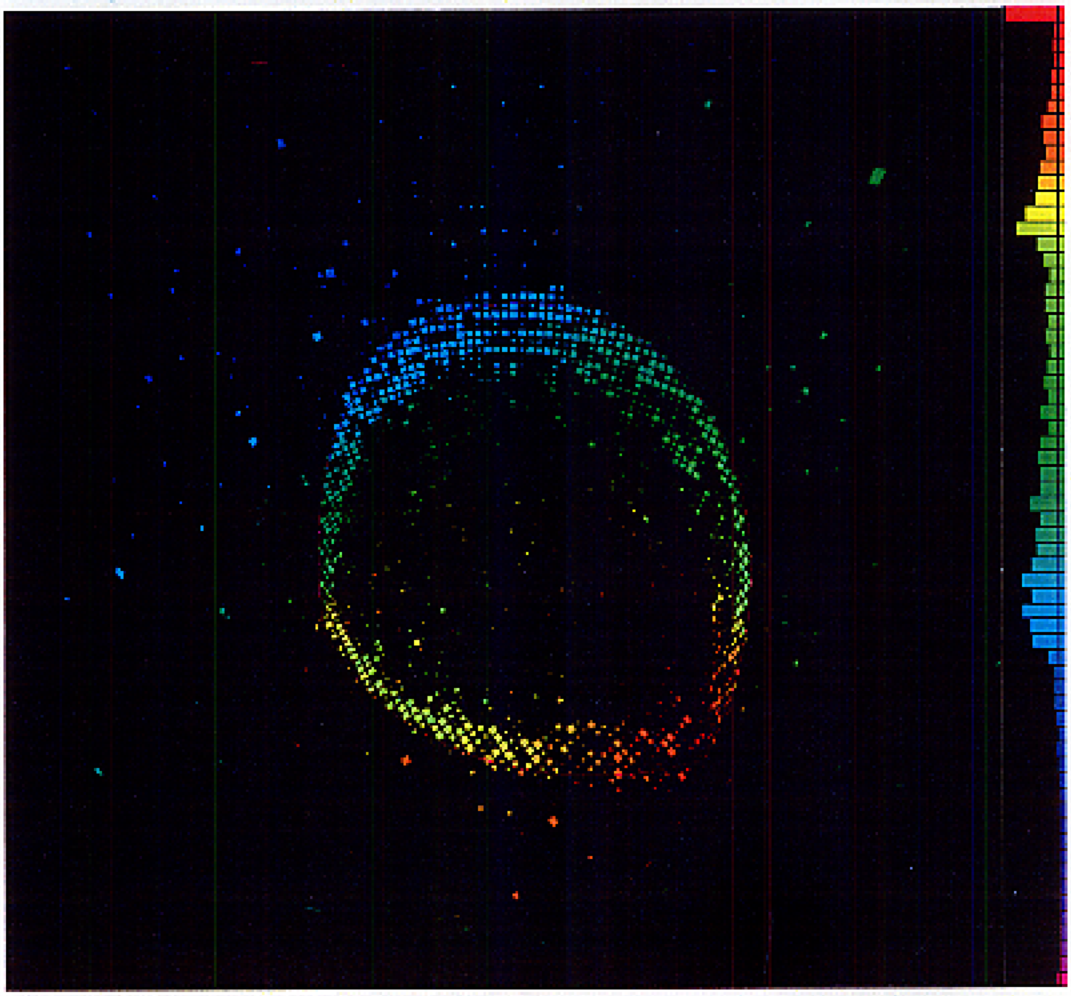
Solar Neutrinos



The PP chain involved in hydrogen burning in the Sun

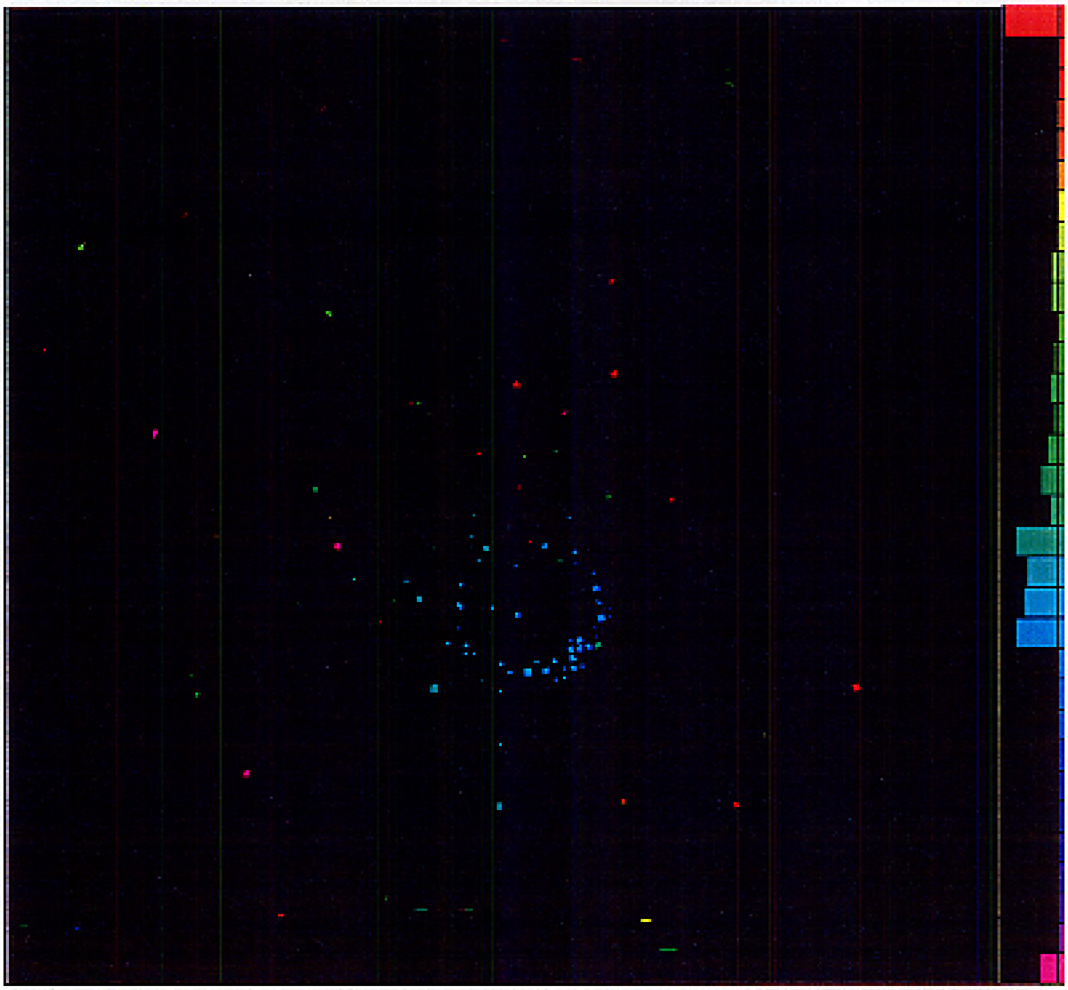
In Super-K: $\nu_e + e^- \to \nu_e + e^-$

Look for recoil electron's Čerenkov light

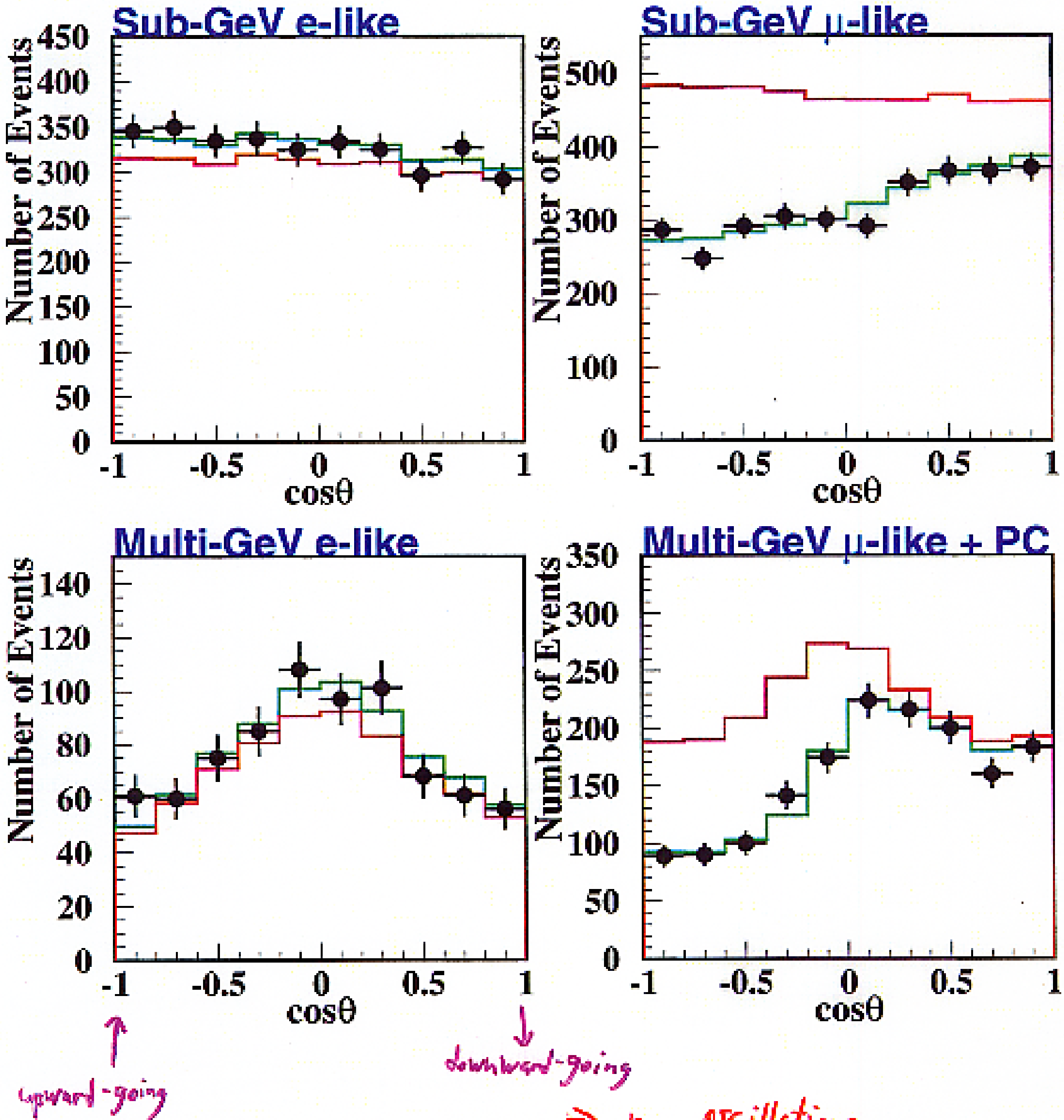


A 603 MeV Muon From An

Atmospheric Neutrino Interaction

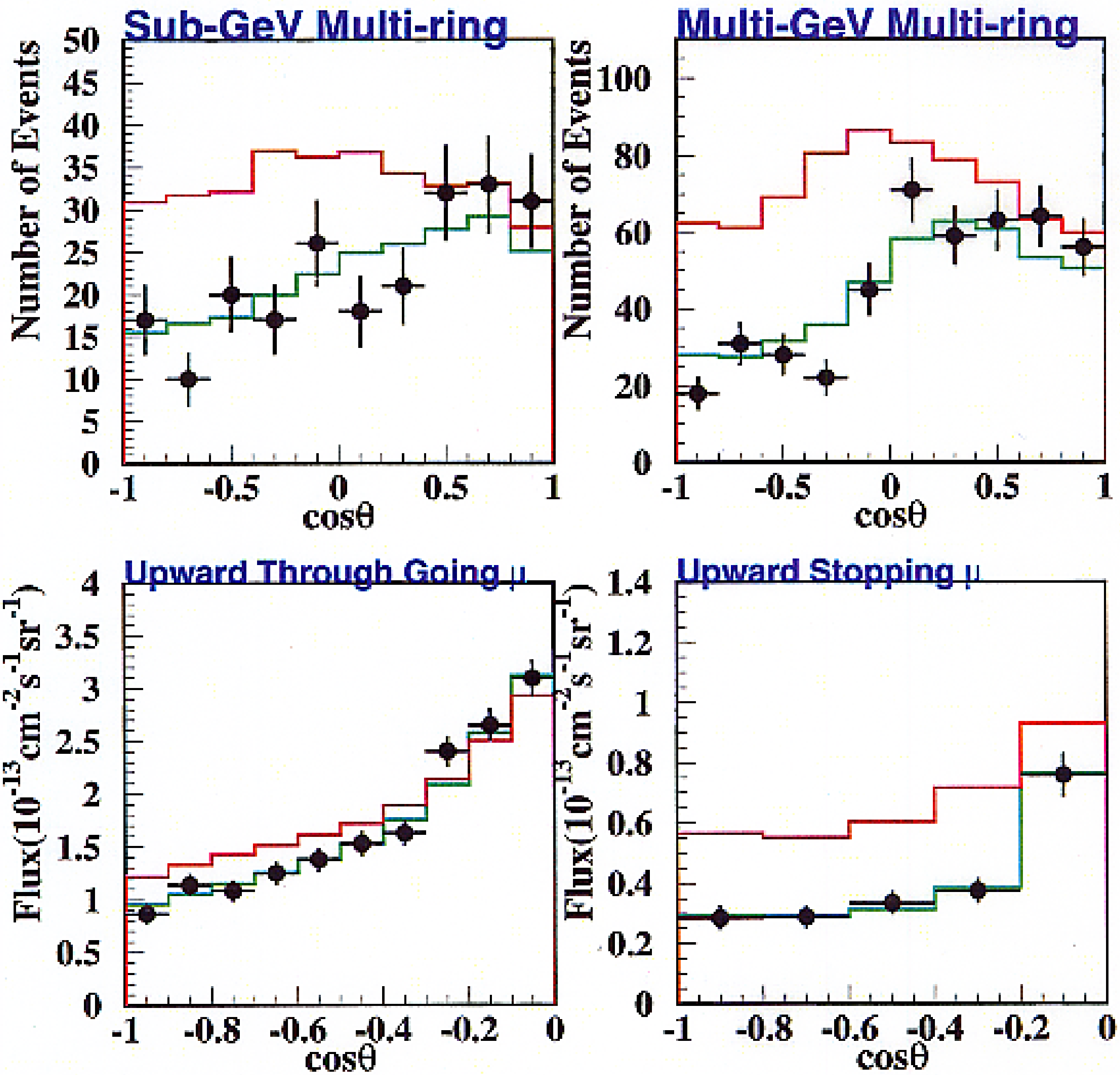


A 12.5 MeV Solar Neutrino Event



— ⇒ no oscillations

— ⇒ $\sin^2 2\theta = 1.0$, $\Delta m^2 = 2.5 \times 10^{-3}\ eV^2$



— = no oscillations

— = (1.0, 2.5×10^{-3} eV^2)

Results of Oscillation Analysis (FC + PC + Upmu)

- **Assuming $\nu_\mu \leftrightarrow \nu_\tau$ Oscillation**

  Best Fit:

  $\chi^2\text{min} = 162.7 / 170$ d.o.f

  at $(\sin^2 2\theta, \Delta m^2) = (1.03, 2.5\times10^{-3}\ \text{eV}^2)$

  (including unphysical region)

  $\chi^2\text{min} = 163.2 / 170$ d.o.f

  at $(\sin^2 2\theta, \Delta m^2) = (1.00, 2.5\times10^{-3}\ \text{eV}^2)$

  (physical region)

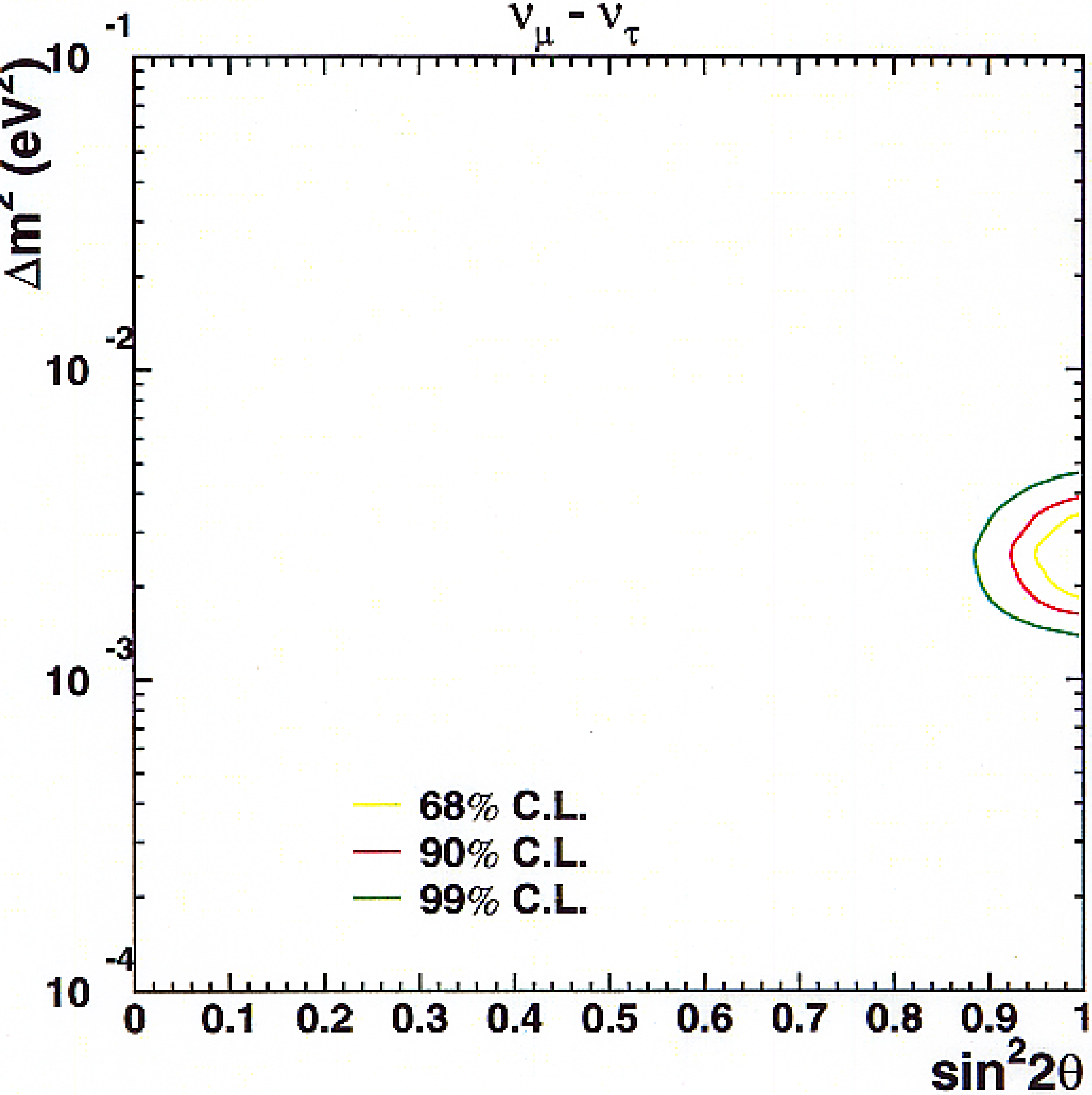
  90% confidence level allowed region:

  $\sin^2(2\theta) > 0.92$

  $1.6 \times 10^{-3}\ \text{eV}^2 < \Delta m^2 < 3.9 \times 10^{-3}\ \text{eV}^2$

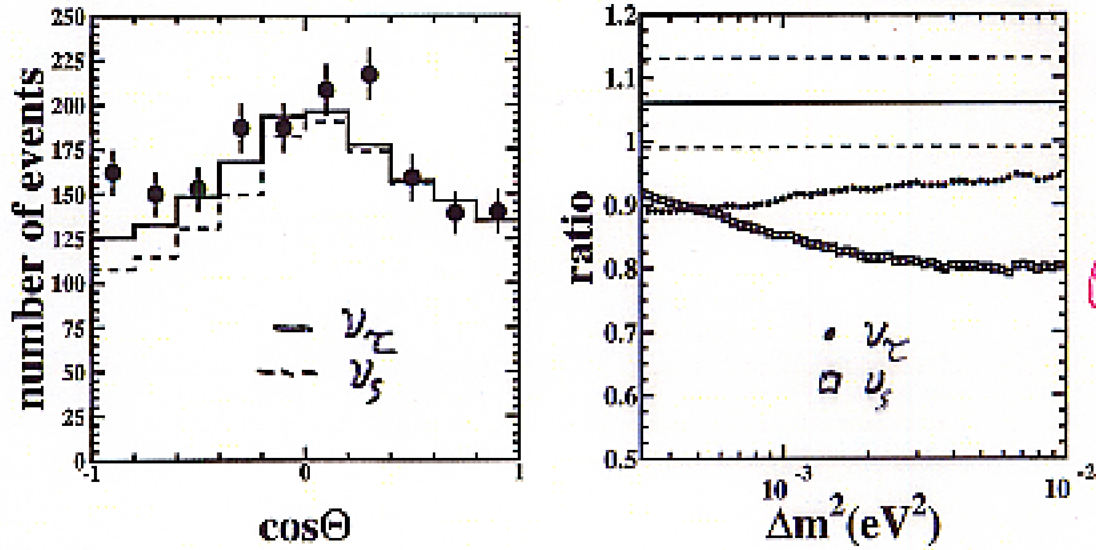
- **Assuming Null Oscillation**

  $\chi^2\text{min} = 456.5 / 172$ d.o.f



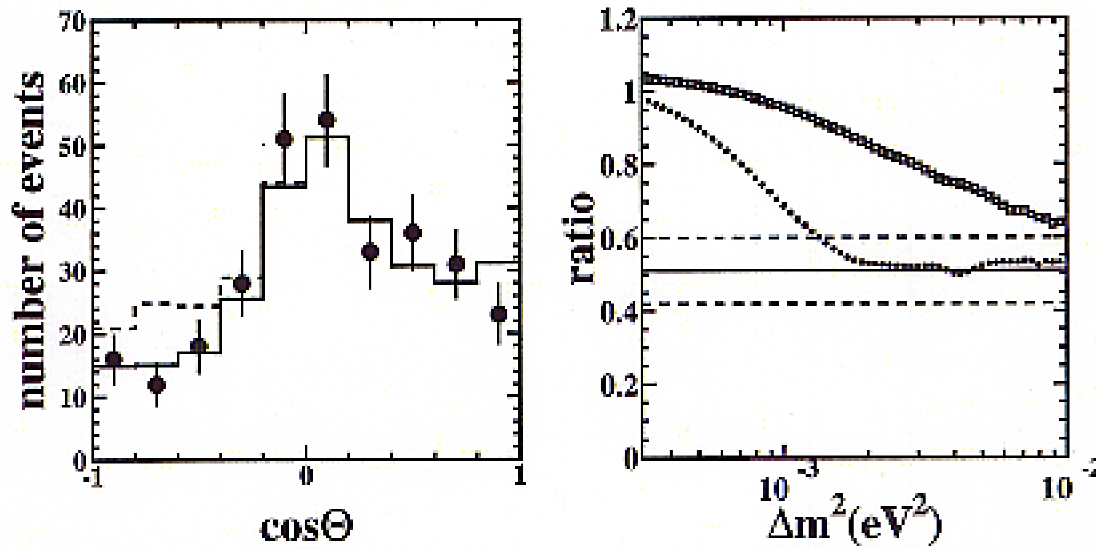
$\nu_\mu - \nu_\tau$
Δm^2 (eV^2)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
$\sin^2 2\theta$
68% C.L.
90% C.L.
99% C.L.

$\nu_\mu \rightarrow \nu_\tau$ or $\nu_{sterile}$?



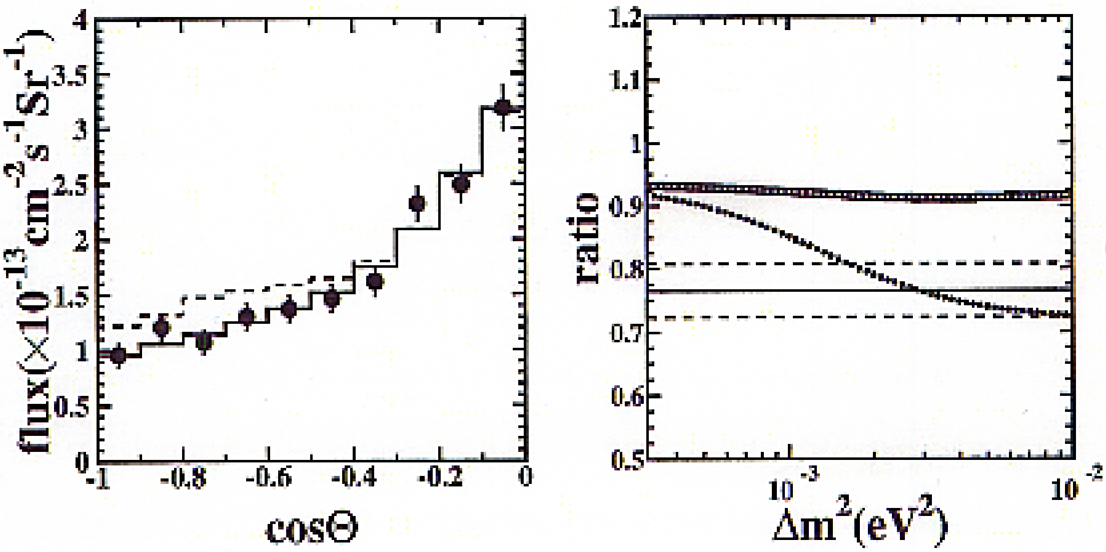
NC Enhanced Sample

(Multi-ring Data)



Matter Effect Study

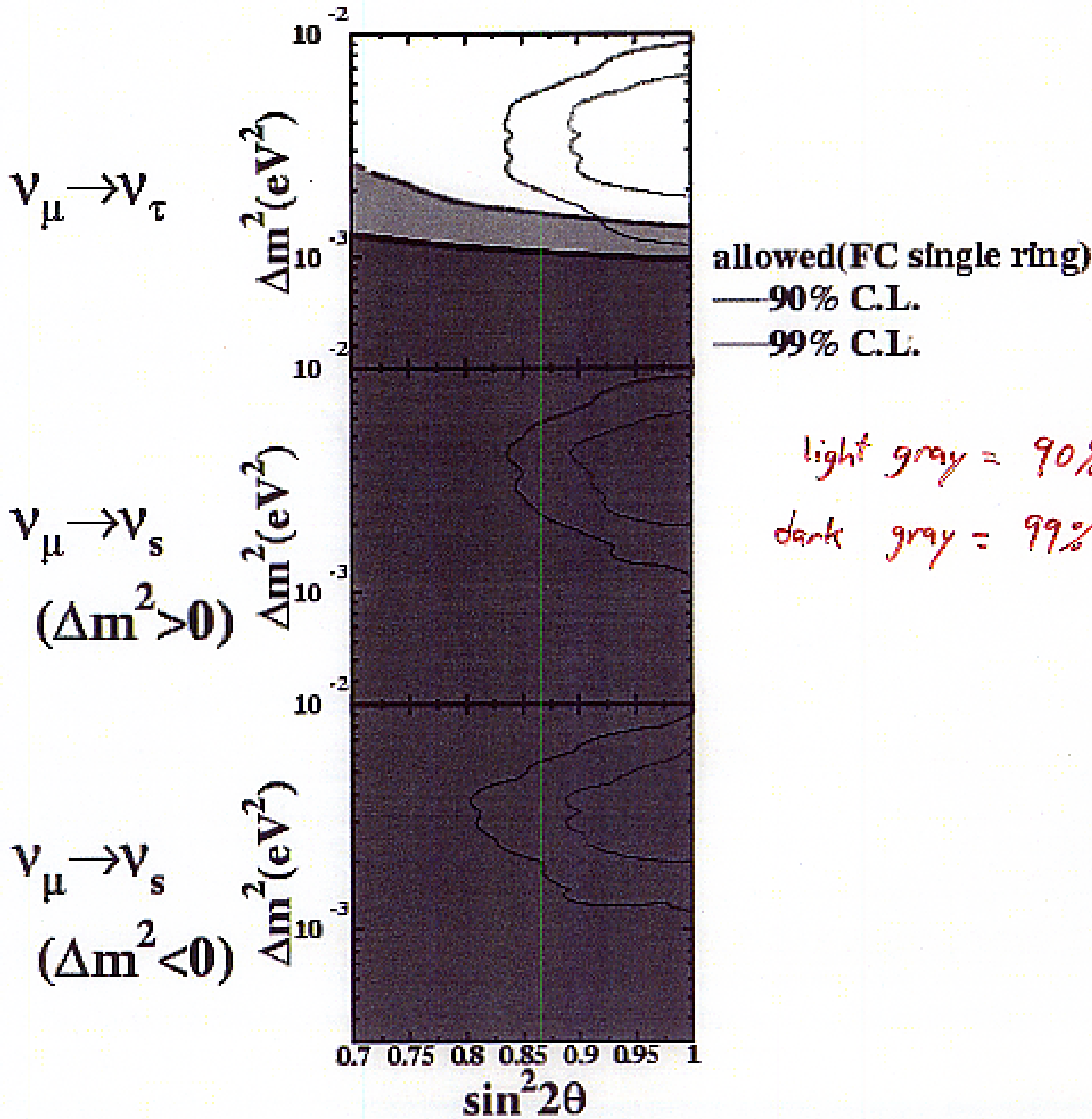
(PC Data)



Matter Effect Study

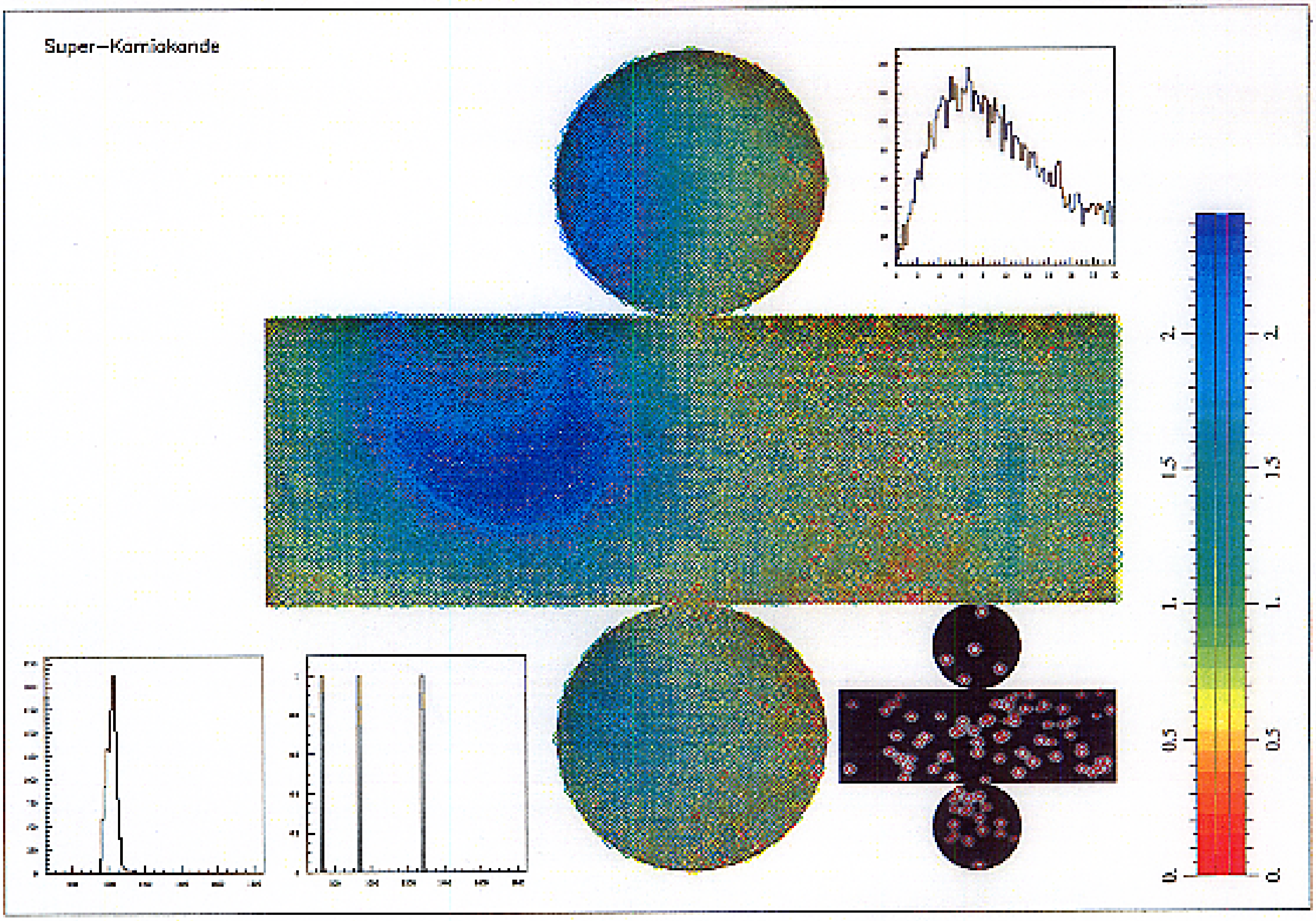
(Up-μ)

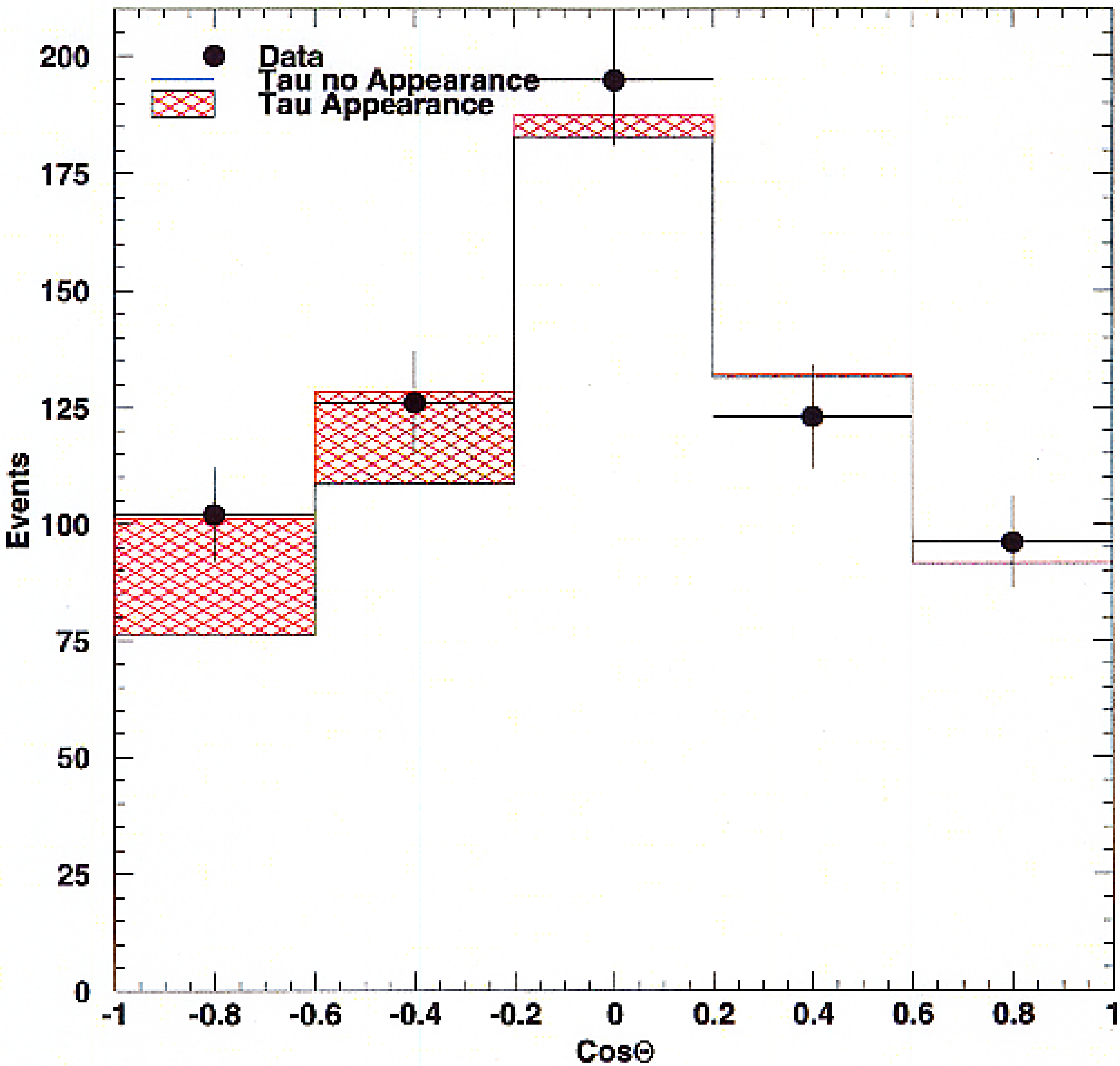
excluded region from combined analysis(multi+PC+upμ) (1289days)

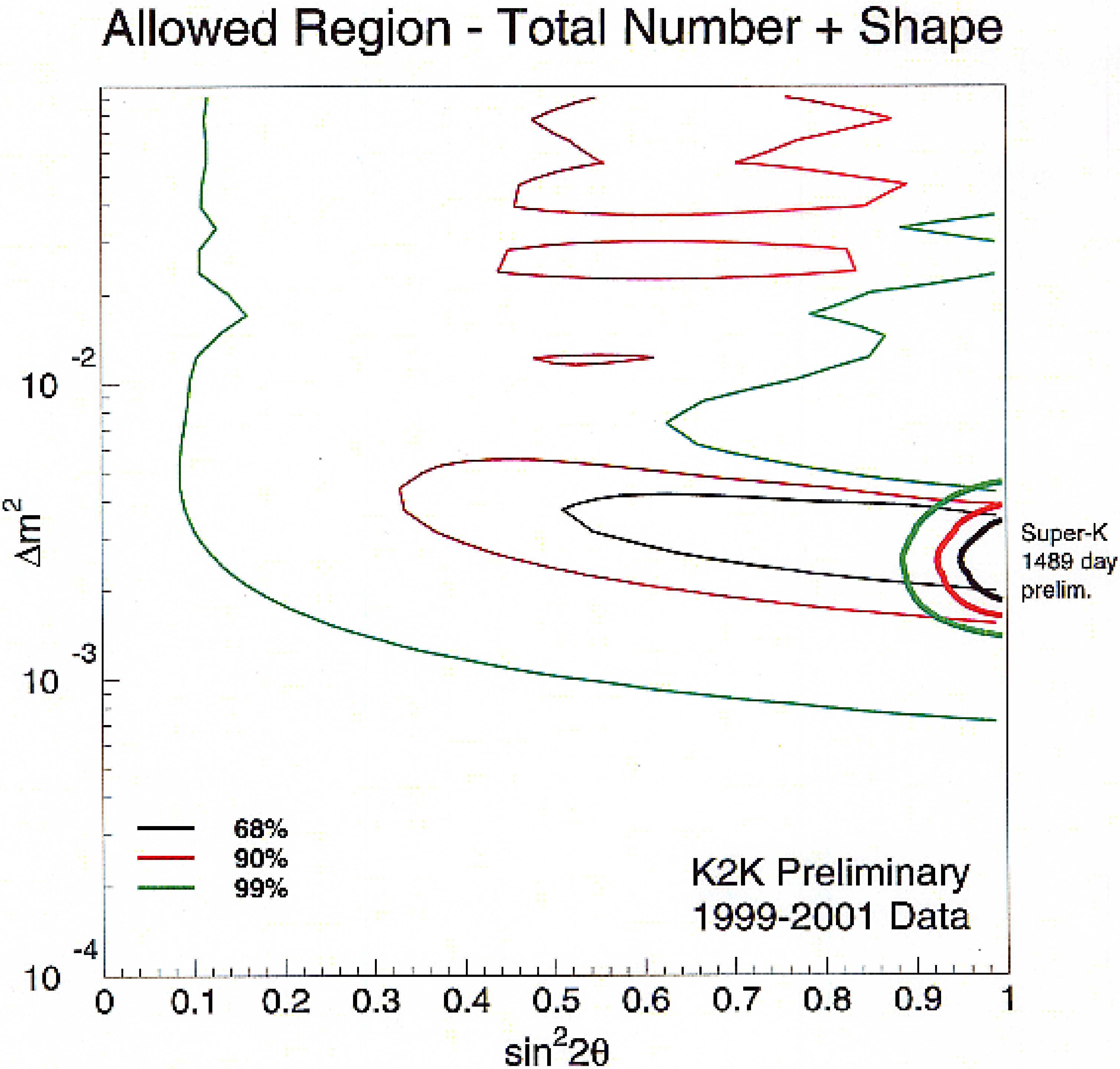


light gray = 90% excluded

dark gray = 99% excluded


Super-Kamiokande
0.
0.5
1.
1.5
2.

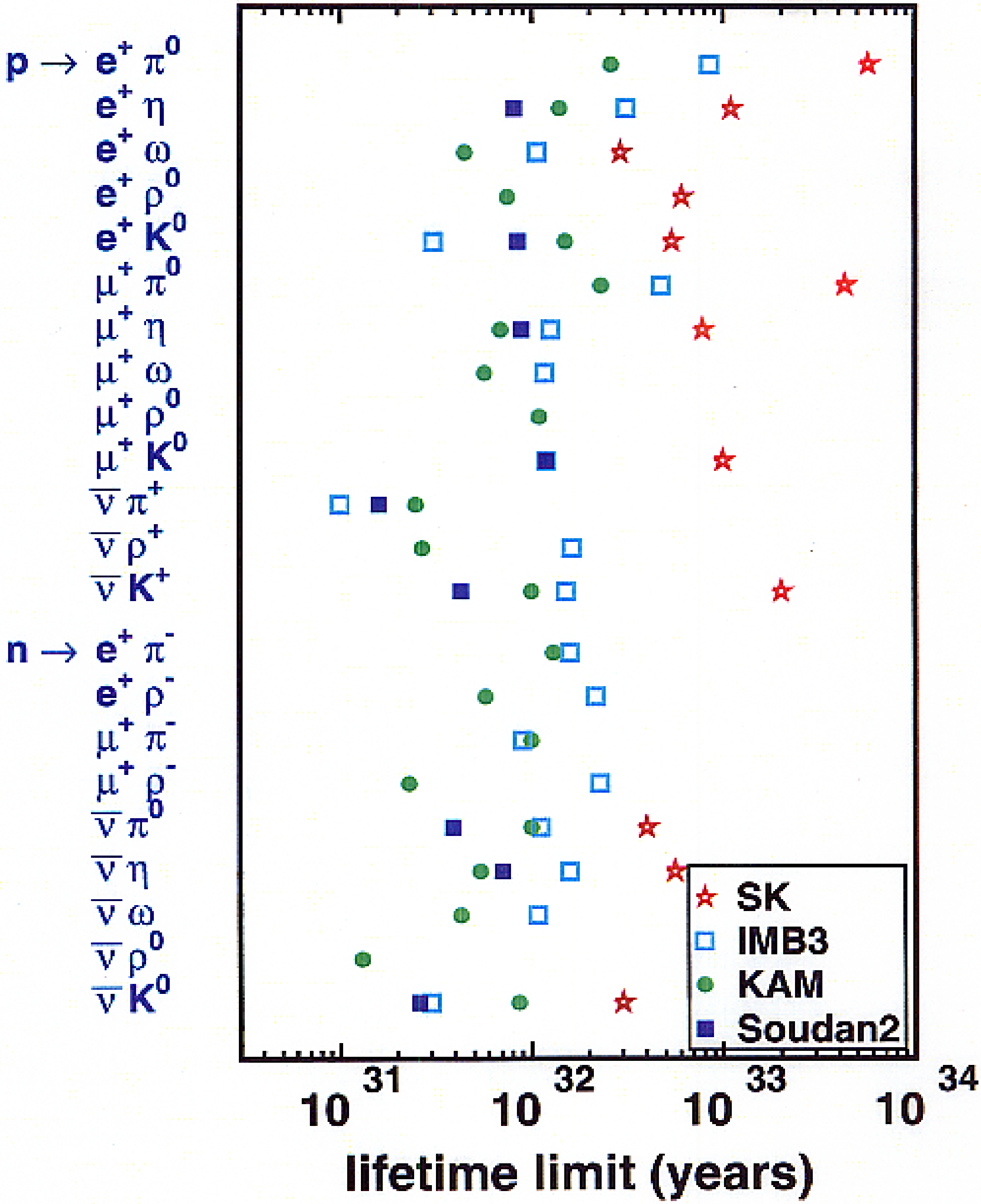

Data
Tau no Appearance
Tau Appearance
Events
Cos Θ
200
175
150
125
100
75
50
25
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1



Allowed Region - Total Number + Shape
Super-K
1489 day
prelim.
68%
90%
99%
K2K Preliminary
1999-2001 Data
10^{-2}
10^{-3}
10^{-4}
Δm^2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
$\sin^2 2\theta$

Summary of Nucleon Decay Searches

mode	exposure (kt• yr)	εB_m (%)	observed event	B.G.	τ/B limit (10^{32} yrs)
$p \to e^+ + \pi^0$	92	43	0	0.2	57
$p \to \mu^+ + \pi^0$	92	32	0	0.4	43
$p \to e^+ + \eta$	45	17	0	0.3	11
$p \to \mu^+ + \eta$	45	12	0	0	7.8
$n \to \bar{\nu} + \eta$	45	21	5	9	5.6
$p \to e^+ + \rho$	61	6.8	0	0.6	6.1
$p \to e^+ + \omega$	61	3.3	0	0.3	2.9
$p \to e^+ + \gamma$	70	71	0	0.1	73
$p \to \mu^+ + \gamma$	70	60	0	0.2	61
$p \to \bar{\nu} + K^+$	92				20
$K^+ \to \nu\mu^+$ (spectrum)		33	--	--	5.5
prompt $\gamma + \mu^+$		8.7	0	0.3	12
$K^+ \to \pi^+\pi^0$		6.5	0	0.9	8.6
$n \to \bar{\nu} + K^0$	79				3.0
$K^0 \to \pi^0\pi^0$		9.6	25	33.8	3.2
$K^0 \to \pi^+\pi^-$		4.6	10	6.7	1.1
$p \to e^+ + K^0$	70				5.4
$K^0 \to \pi^0\pi^0$		11.8	1	1.4	8.8
$K^0 \to \pi^+\pi^-$					
2-ring		6.2	6	1.0	1.5
3-ring		1.4	0	0.2	1.4
$p \to \mu^+ + K^0$	70				10
$K^0 \to \pi^0\pi^0$		6.1	0	1.1	6.2
$K^0 \to \pi^+\pi^-$					
2-ring		5.3	0	1.5	5.4
3-ring		2.8	1	0.2	1.8



p → e+ π0
e+ η
e+ ω
e+ ρ0
e+ K0
μ+ π0
μ+ η
μ+ ω
μ+ ρ0
μ+ K0
ν̄ π+
ν̄ ρ+
ν̄ K+
n → e+ π-
e+ ρ-
μ+ π-
μ+ ρ-
ν̄ π0
ν̄ η
ν̄ ω
ν̄ ρ0
ν̄ K0
SK
IMB3
KAM
Soudan2
10 31
10 32
10 33
10 34
lifetime limit (years)

High Energy Summary

So, where do we stand with Super–K's atmospheric neutrinos?

→ The zenith angle dependence of the number of ν_μ's provides clear evidence for neutrino oscillations and therefore for massive neutrinos.

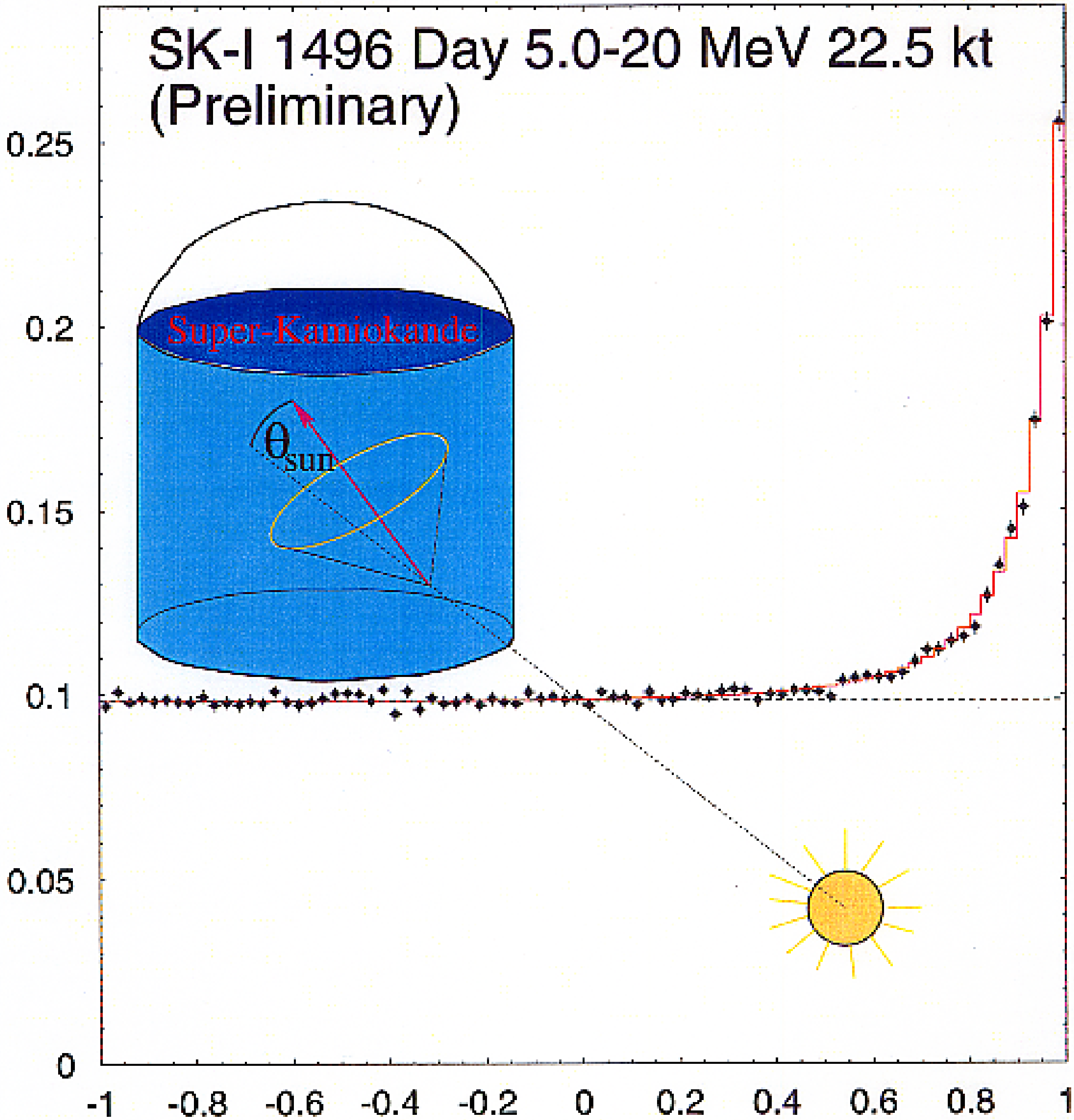
→ Oscillations into a sterile neutrino are completely ruled out at better than the 99% level, while oscillations into ν_τ are fully allowed.

→ Tau appearance? Maybe, but two sigma will be tough to beat.

→ No evidence of proton decay so far.

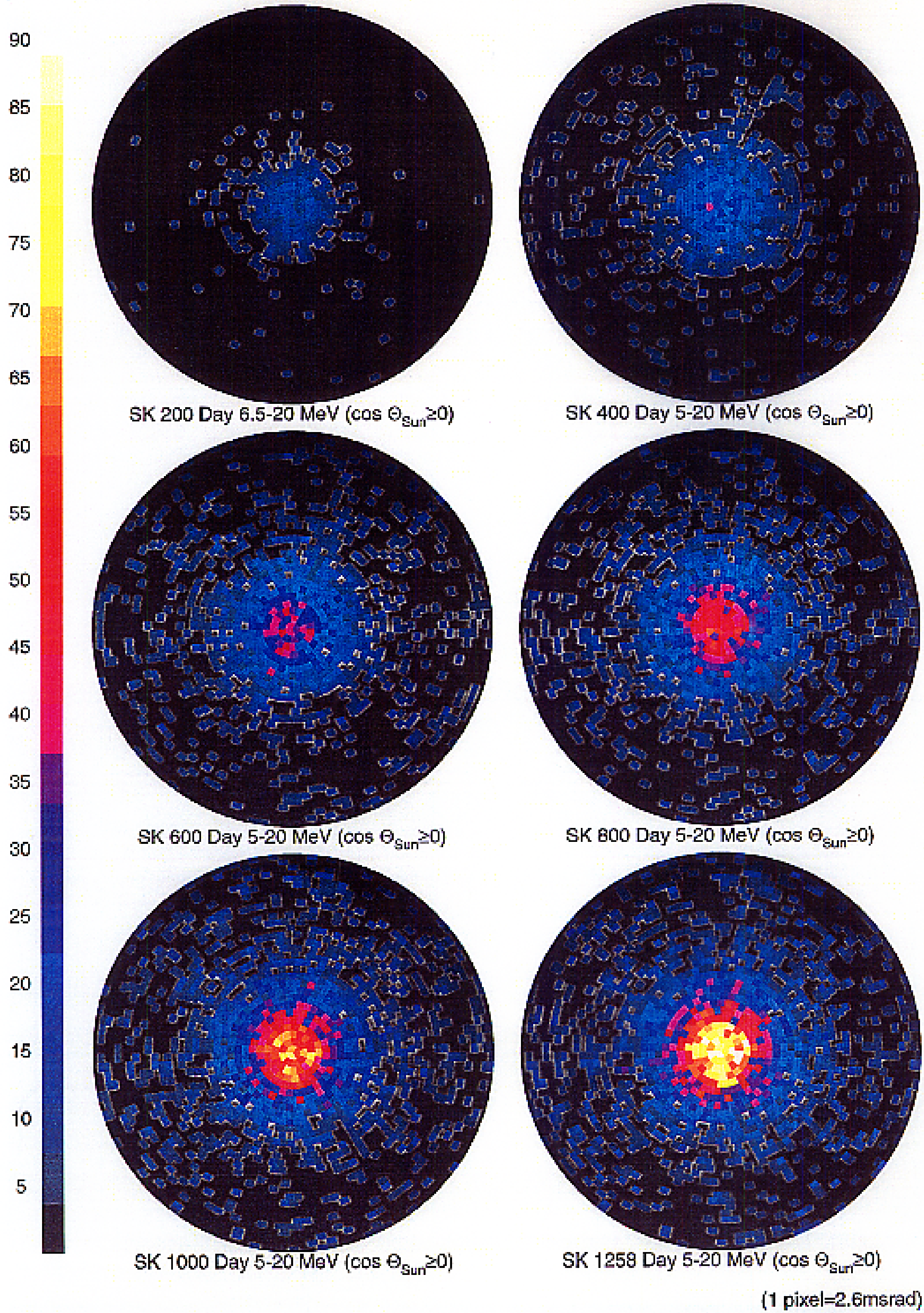
→ K2K has collected 50% of its planned data and already disfavors the null-oscillation solution at the two sigma level. Data-taking will continue at the end of 2002.

Solar Peak >5 MeV



SK reached its design threshold!

Michael B. Smy, UC Irvine


90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
SK 200 Day 6.5-20 MeV ($\cos\Theta_{Sun}\geq 0$)
SK 400 Day 5-20 MeV ($\cos\Theta_{Sun}\geq 0$)
SK 600 Day 5-20 MeV ($\cos\Theta_{Sun}\geq 0$)
SK 800 Day 5-20 MeV ($\cos\Theta_{Sun}\geq 0$)
SK 1000 Day 5-20 MeV ($\cos\Theta_{Sun}\geq 0$)
SK 1258 Day 5-20 MeV ($\cos\Theta_{Sun}\geq 0$)
(1 pixel=2.6msrad)

Neutrino Rate

1496 Day Final Sample:

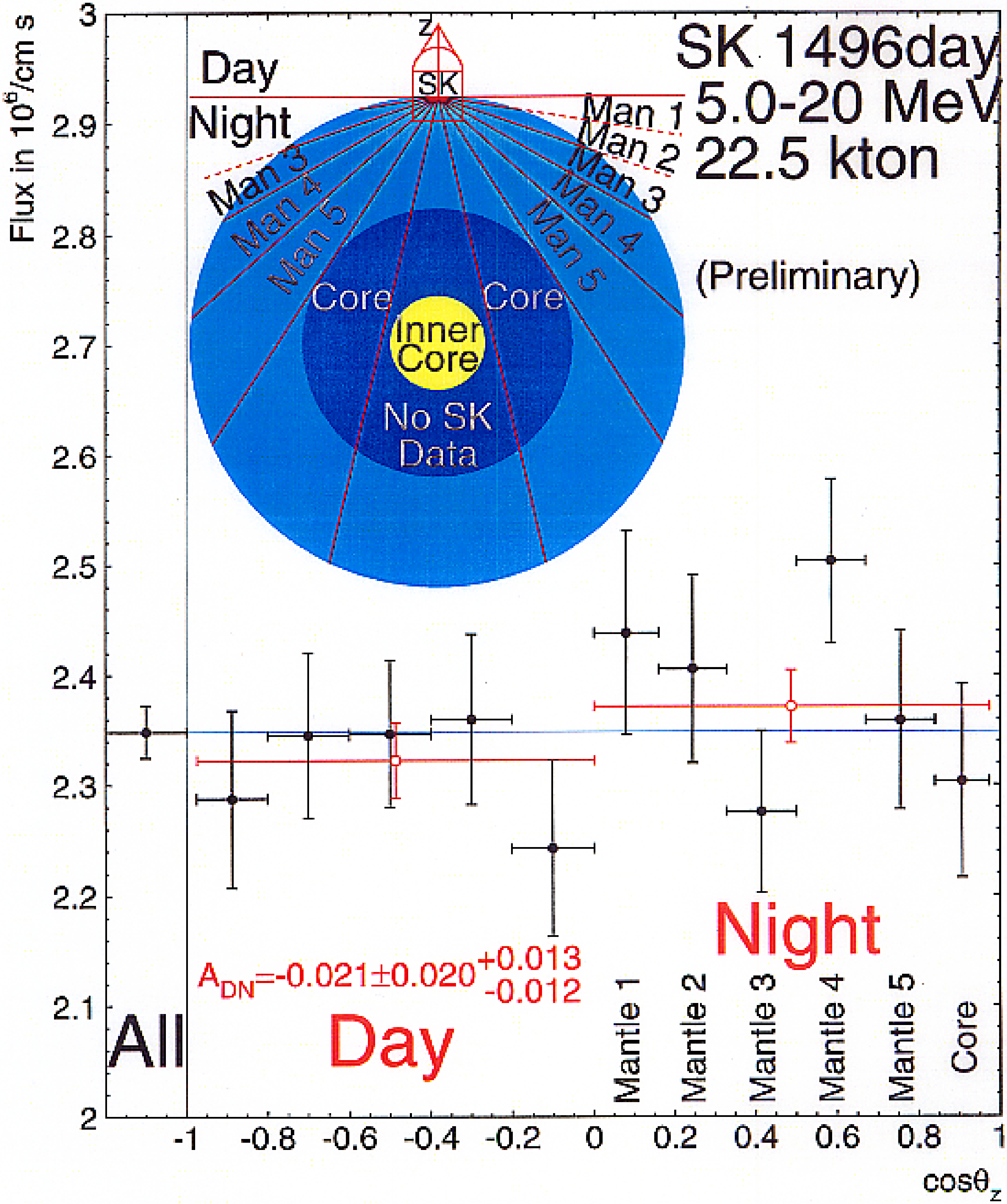
- 287,000 events
- 22,400 solar neutrino events

Expect:

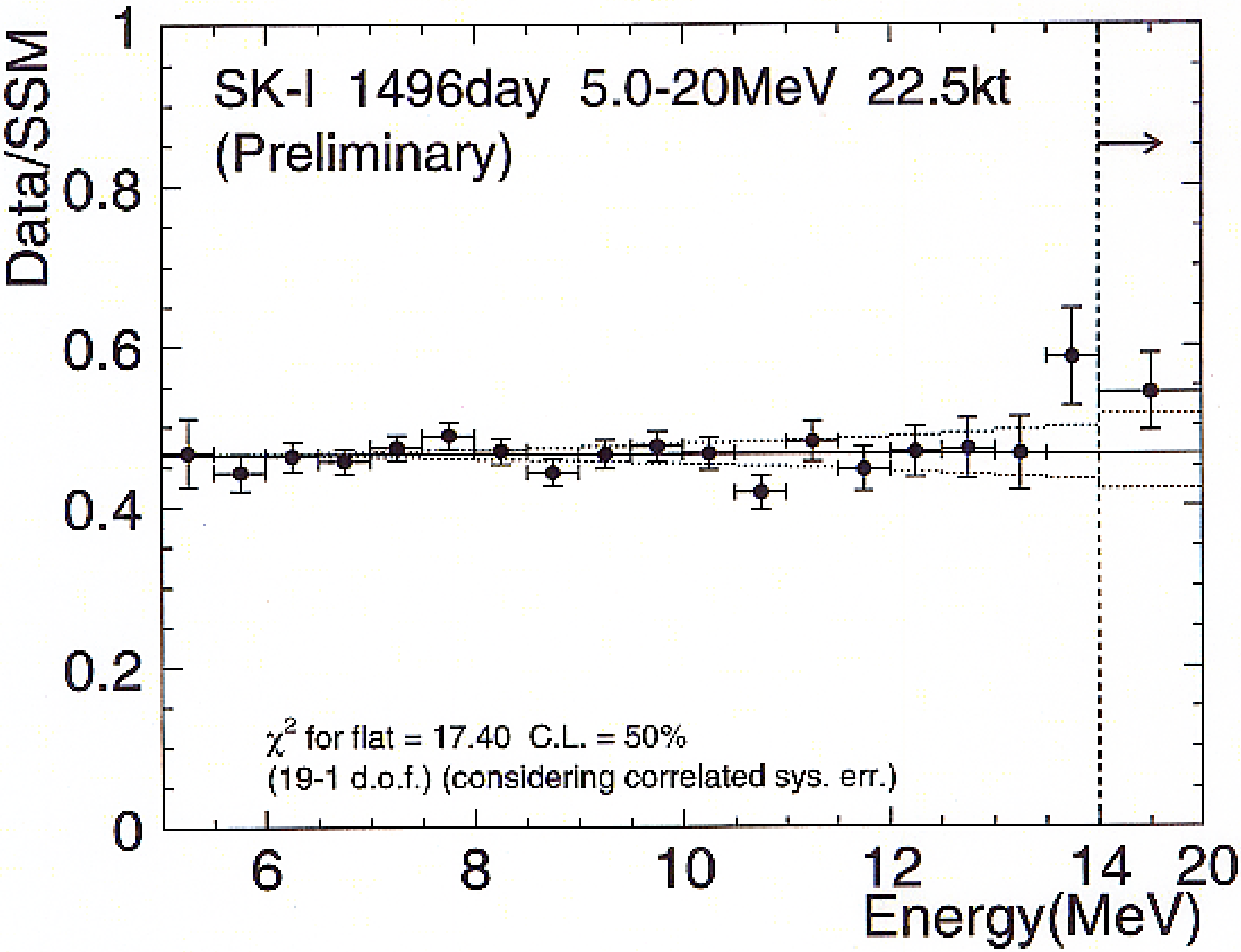
- 48,200 solar neutrino events (from SSM)
- 16,700 $e-$type solar neutrino events (from SNO)
- about 5,700 $\mu/\tau-$ type solar neutrino events!

Flux:

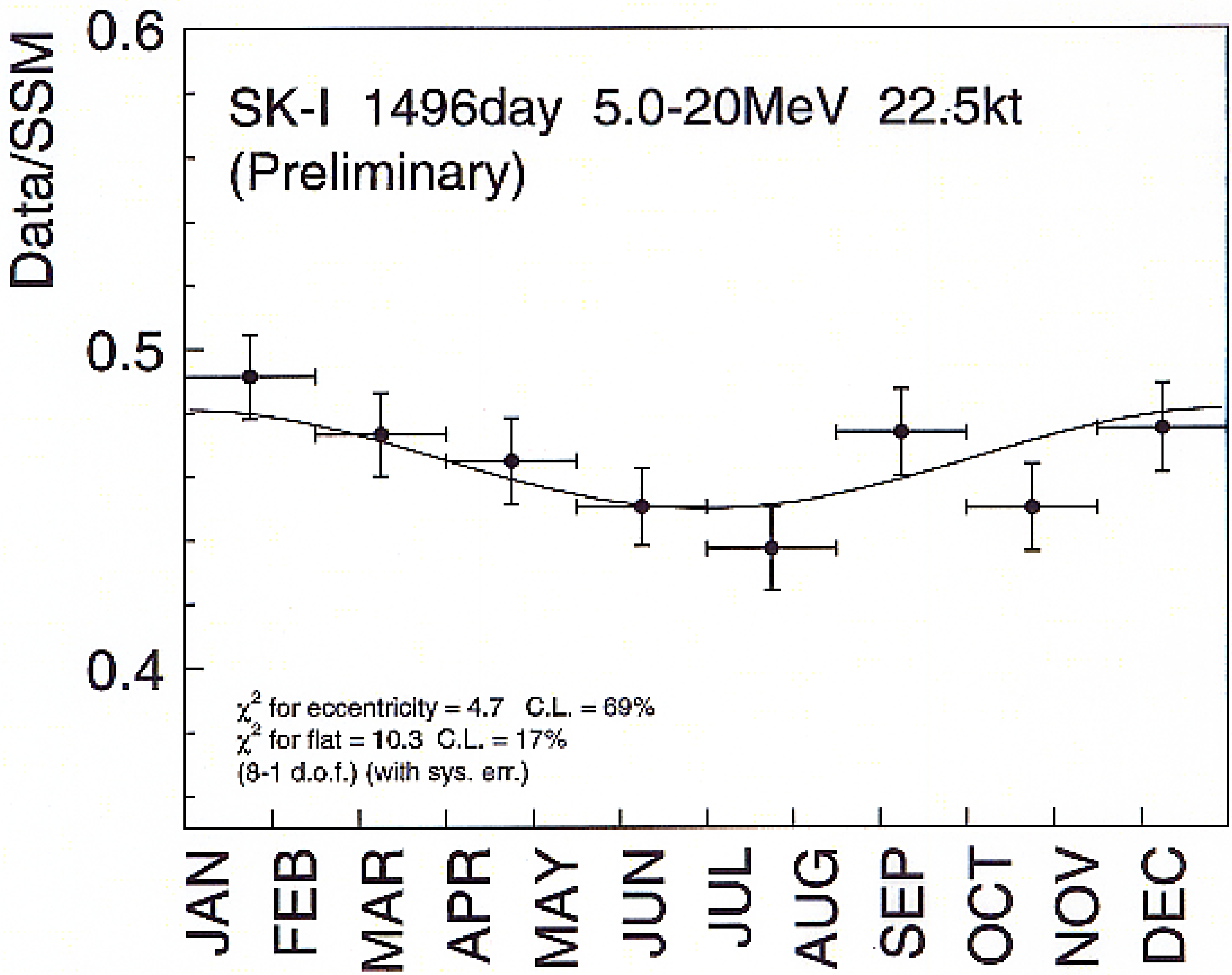
- flux is $2.35 \pm 0.02(\text{stat.}) \pm 0.08(\text{sys.}) \times 10^6/\text{cm}^2 \cdot \text{s}$
- or $0.465 \pm 0.005(\text{stat.})^{+0.016}_{-0.015}(\text{sys.}) \times \text{SSM}$



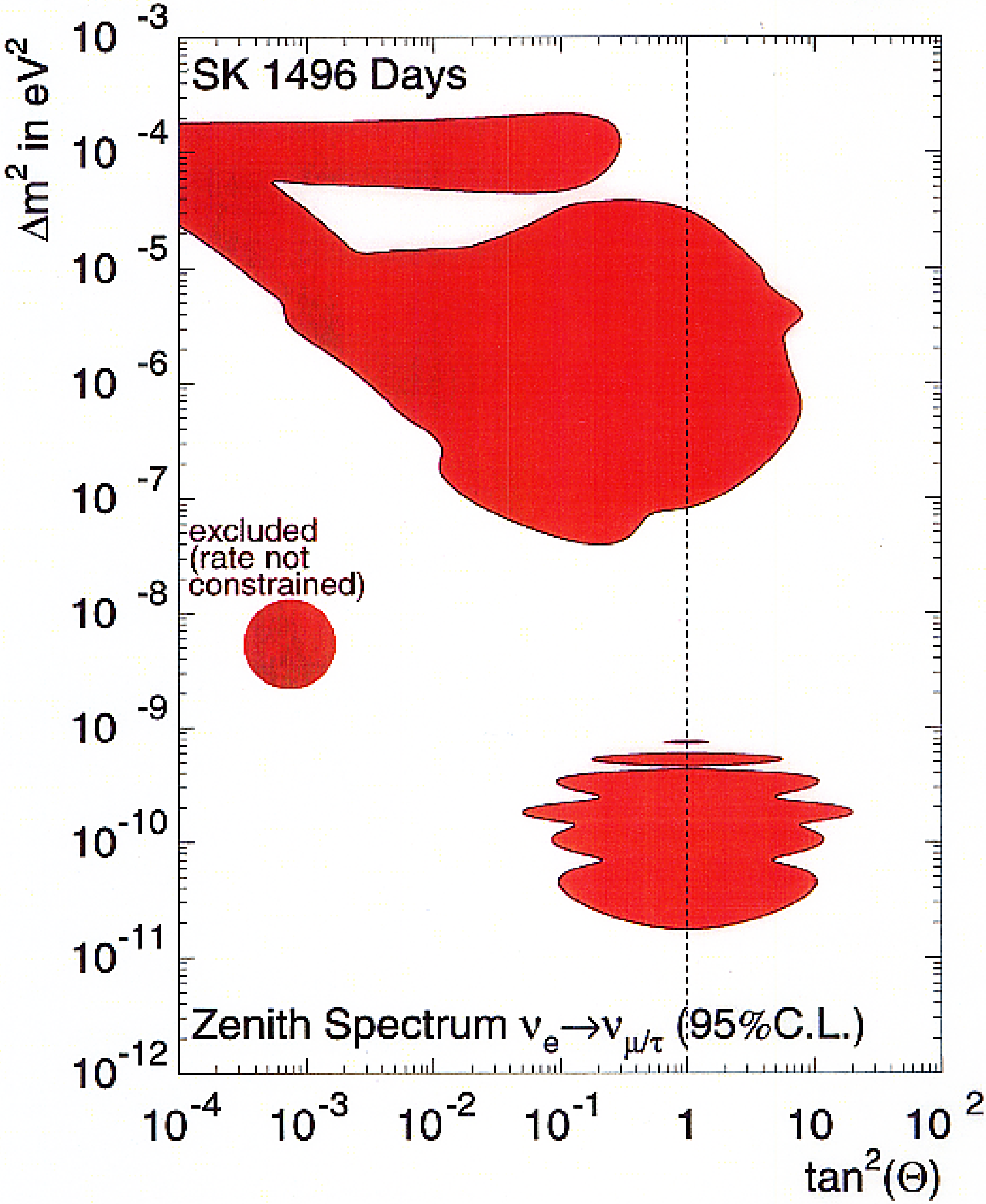
SK 1496day
5.0-20 MeV
22.5 kton
(Preliminary)
Day
Night
SK
z
Man 1
Man 2
Man 3
Man 4
Man 5
Core
Inner Core
No SK Data
A_DN=-0.021±0.020 +0.013 -0.012
All
Day
Night
Mantle 1
Mantle 2
Mantle 3
Mantle 4
Mantle 5
Core
Flux in 10^6/cm s
cosθz



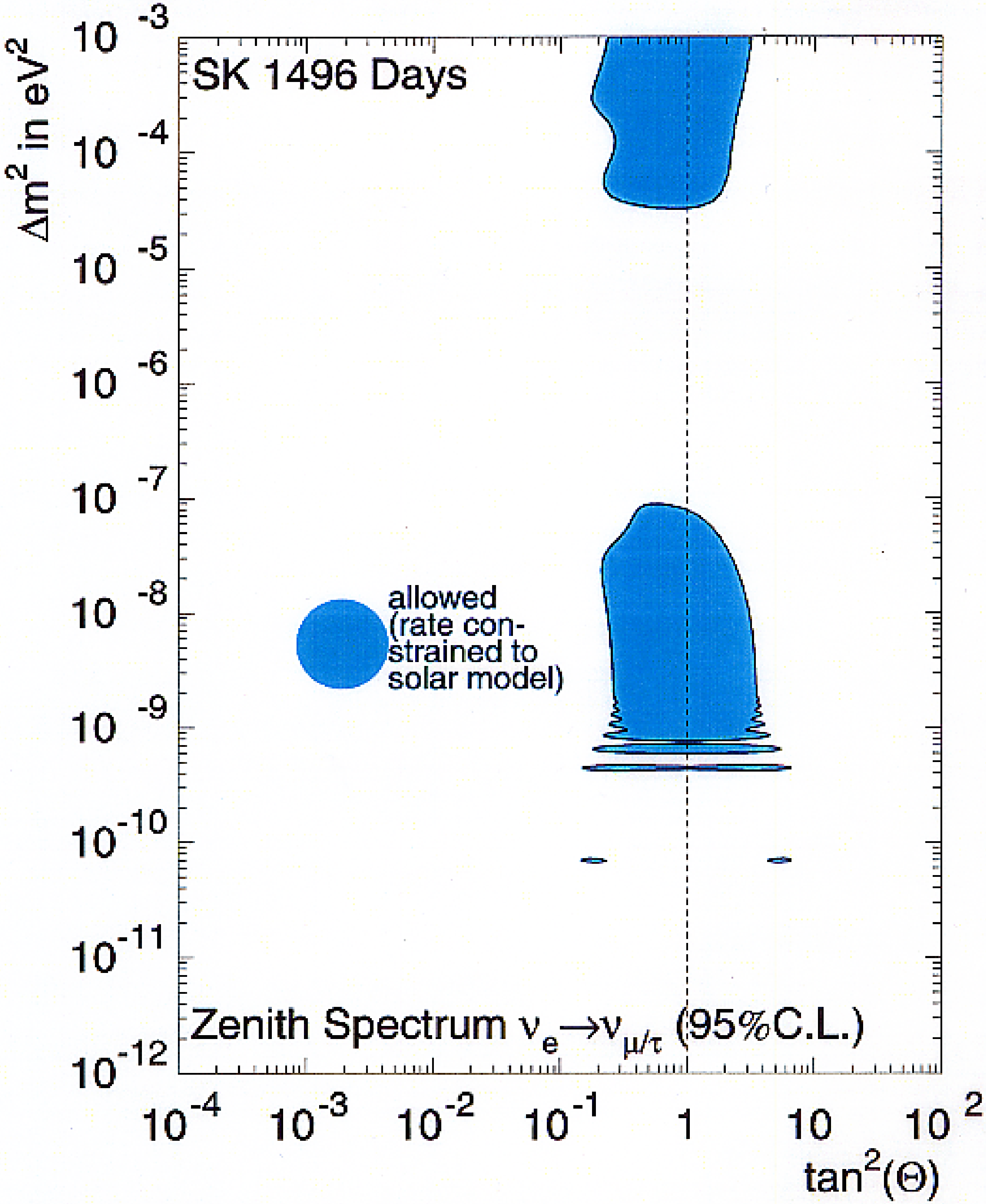
SK-I 1496day 5.0-20MeV 22.5kt
(Preliminary)
Data/SSM
1
0.8
0.6
0.4
0.2
0
6
8
10
12
14
20
Energy(MeV)
χ² for flat = 17.40 C.L. = 50%
(19-1 d.o.f.) (considering correlated sys. err.)



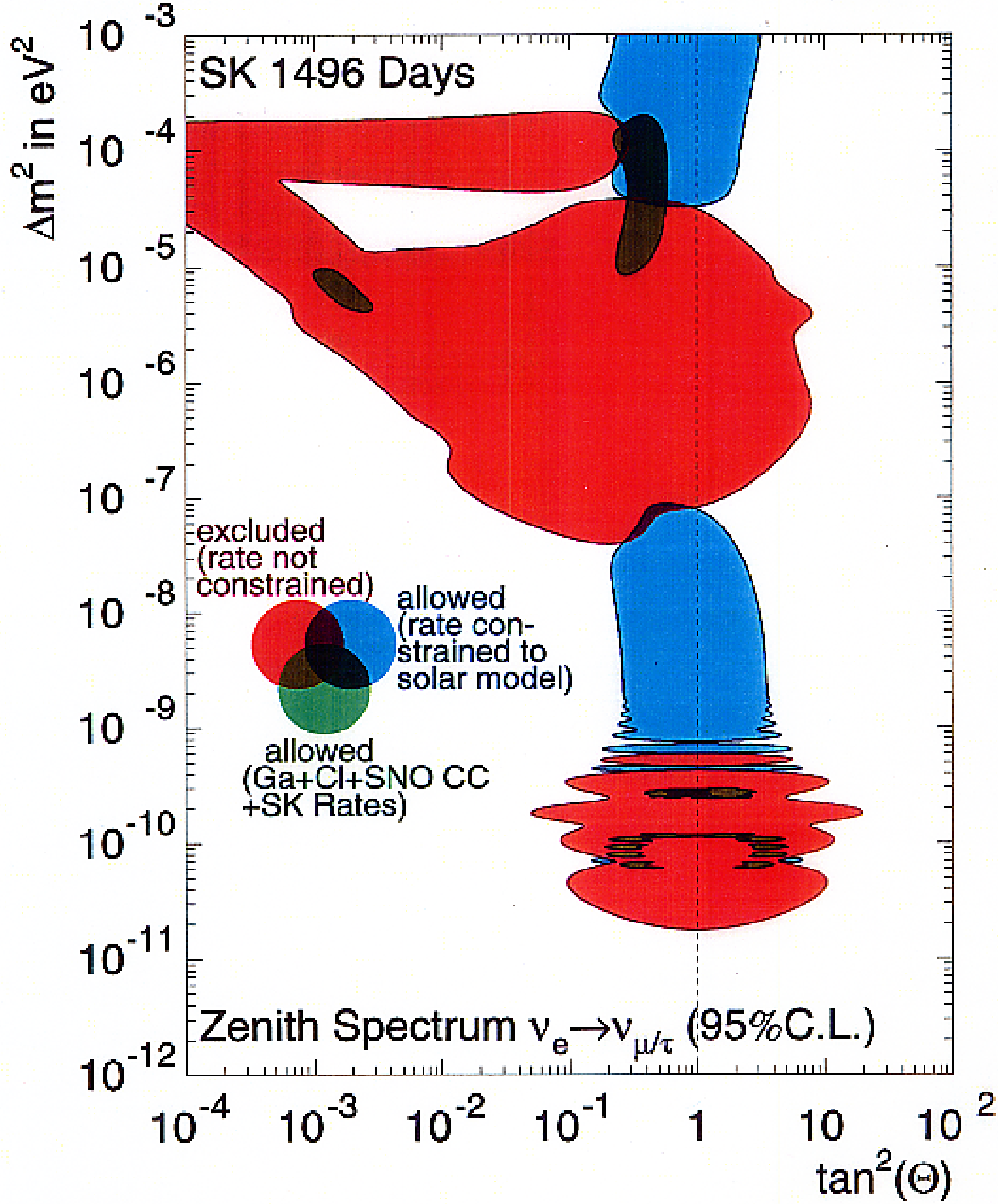
Data/SSM
0.6
0.5
0.4
SK-I 1496day 5.0-20MeV 22.5kt
(Preliminary)
χ² for eccentricity = 4.7 C.L. = 69%
χ² for flat = 10.3 C.L. = 17%
(8-1 d.o.f.) (with sys. err.)
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

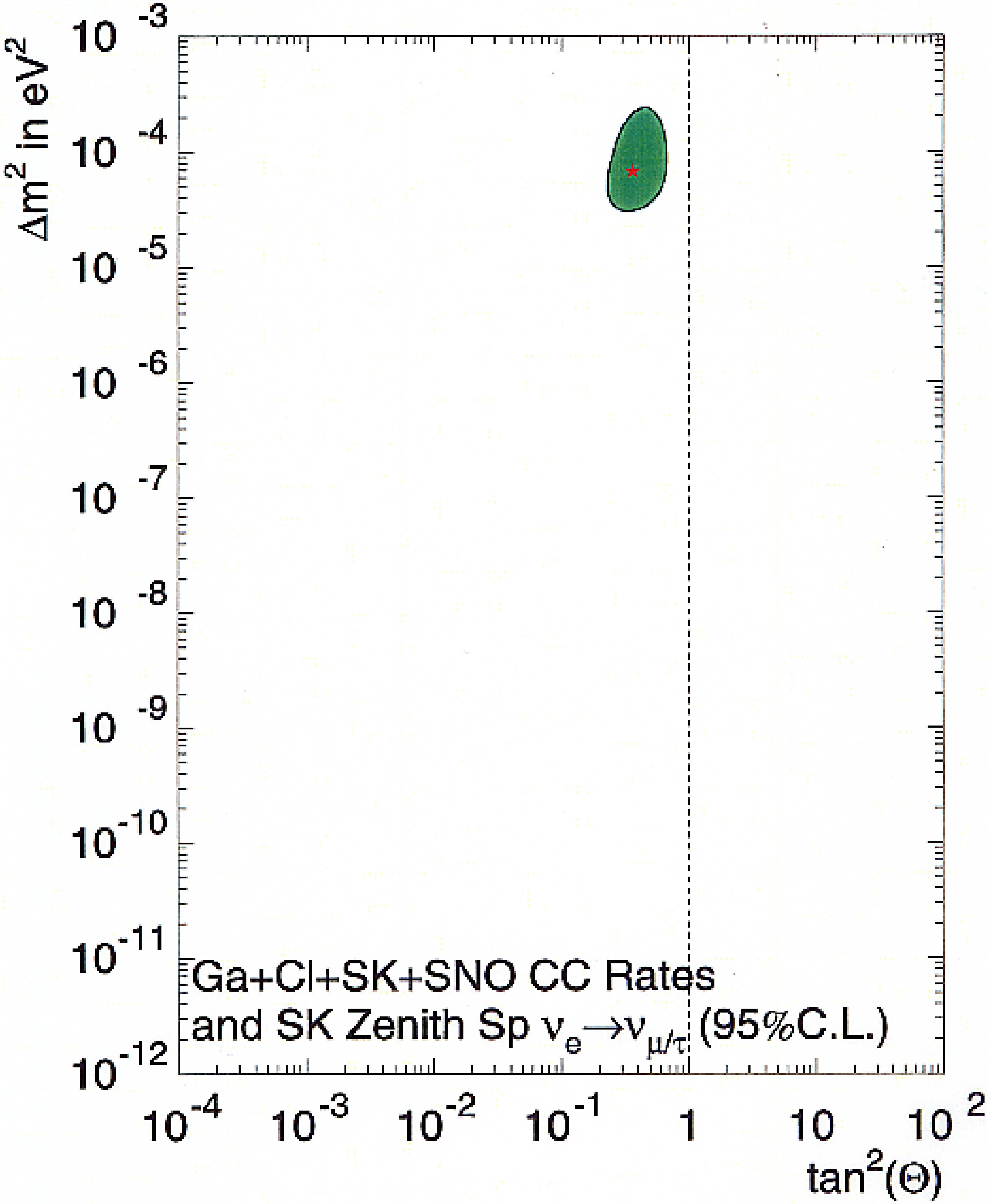


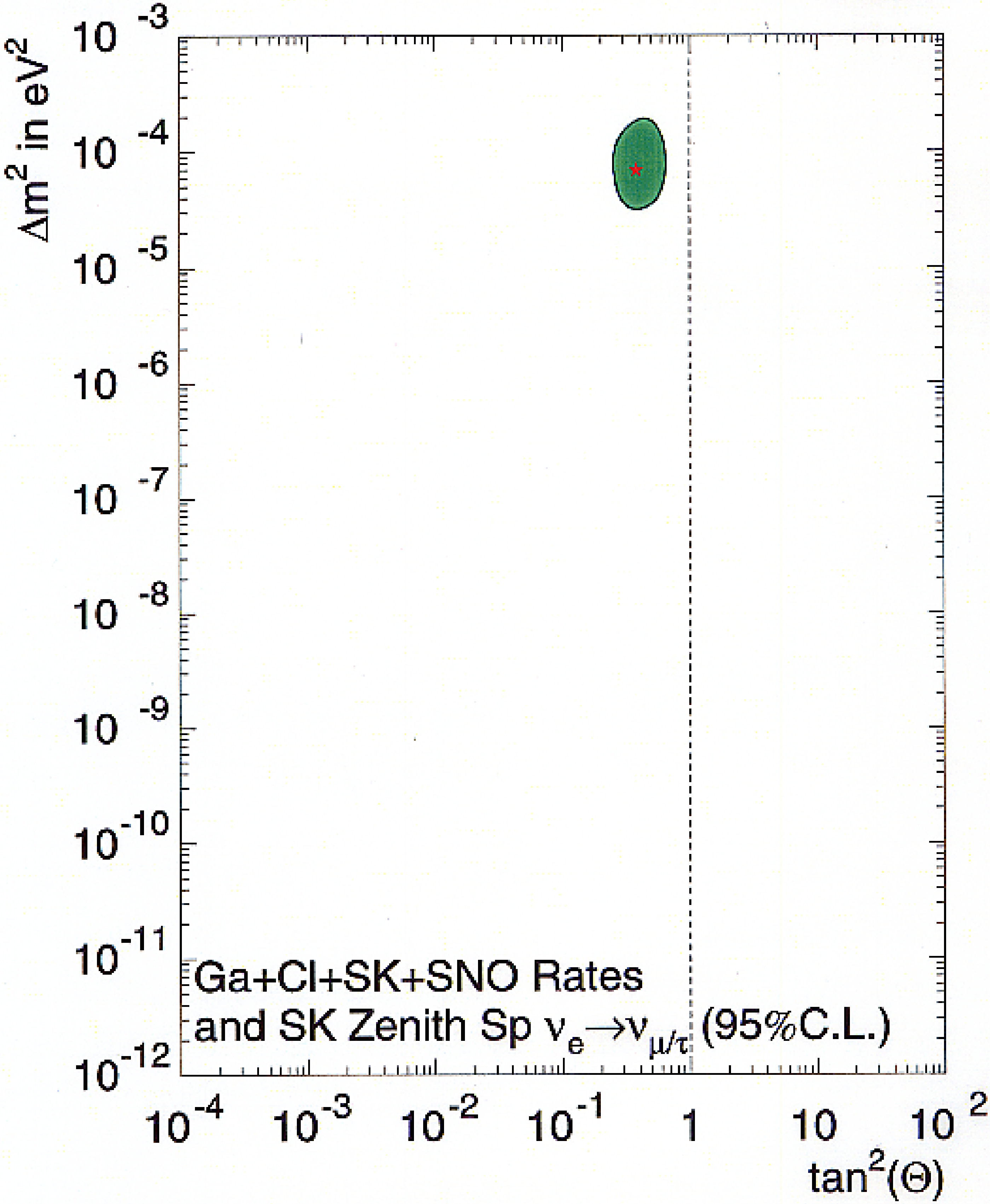
SK 1496 Days
excluded
(rate not
constrained)
Zenith Spectrum $\nu_e \rightarrow \nu_{\mu/\tau}$ (95%C.L.)
Δm^2 in eV^2
$\tan^2(\Theta)$
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}



Δm^2 in eV^2
SK 1496 Days
allowed
(rate con-
strained to
solar model)
Zenith Spectrum $\nu_e \rightarrow \nu_{\mu/\tau}$ (95%C.L.)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\Theta)$


SK 1496 Days
excluded
(rate not
constrained)
allowed
(rate con-
strained to
solar model)
allowed
(Ga+Cl+SNO CC
+SK Rates)
Zenith Spectrum $\nu_e \rightarrow \nu_{\mu/\tau}$ (95%C.L.)
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}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\Theta)$


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}
Ga+Cl+SK+SNO CC Rates
and SK Zenith Sp $\nu_e \rightarrow \nu_{\mu/\tau}$ (95%C.L.)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\Theta)$



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}
Ga+Cl+SK+SNO Rates
and SK Zenith Sp $\nu_e \rightarrow \nu_{\mu/\tau}$ (95%C.L.)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\Theta)$

Summary and Outlook

So, where do we stand with Super–K's solar neutrinos?

→ For active species, we have entirely excluded both the Small Mixing Angle MSW oscillation region and the "Just–So" vacuum oscillation regions at the 95% confidence level.

→ We've uniquely selected large mixing, and it appears that the LMA region is where to look for oscillations. KamLAND will do this within the next two years.

→ Oscillations into a purely sterile neutrino are completely ruled out at the 95% level everywhere in phase space.

What's Next?

Within the next year or so, we will be publishing new results on:

→ Supernova Relic Neutrinos

→ $\overline{\nu_e}$'s from the Sun

→ Neutrino Magnetic Moment

→ Galactic Supernova Rate

Super–K will be back online by January 1st, 2003. We look forward to continuing our high-statistics solar observations, with a number of enchancements, through an entire solar cycle.