Super-Kamiokande

(on the activities from 2000 to 2006 and future prospects)

M. Nakahata
for Neutrino and astroparticle Division

- Super-Kamiokande detector
- Atmospheric neutrinos
- Solar Neutrinos
- Proton decay search
- Supernova neutrinos

Super-Kamiokande collaboration

Institute	Country	(*)
ICRR, Univ. of Tokyo	Japan	28
Boston Univ.	USA	11
BNL	USA	1
Univ. of California, Irvine	USA	11
California State Univ.	USA	3
Chonnam Univ.	Korea	4
Duke Univ.	USA	4
Gifu Univ.	Japan	1
Univ. of Hawaii	USA	3
Indiana Univ.	USA	1
KEK	Japan	8
Kobe Univ.	Japan	1
Kyoto Univ.	Japan	2
LANL	USA	1
Louisiana State Univ.	USA	2
Univ. of Minnesota	USA	2
Miyagi Kyoiku Univ.	Japan	2
Nagoya Univ.	Japan	3
State Univ. of New York, Stony Brook	USA	7
Niigata Univ.	Japan	1
Okayama Univ.	Japan	4
Osaka Univ.	Japan	2
Seoul National Univ.	Korea	2
Shizuoka Univ.	Japan	1
Shizuoka Univ. of Welfare	Japan	1
SungKyunKwan Univ.	Korea	2
Tohoku Univ.	Japan	1
Tokai Univ.	Japan	3
Univ. of Tokyo	Japan	1
Tokyo Institute of Technology	Japan	1
Tsinghua Univ.	China	3
Warsaw Univ.	Poland	1
Univ. of Washington	USA	4

(*) Number of participants.

33 institutes, 122 physicists

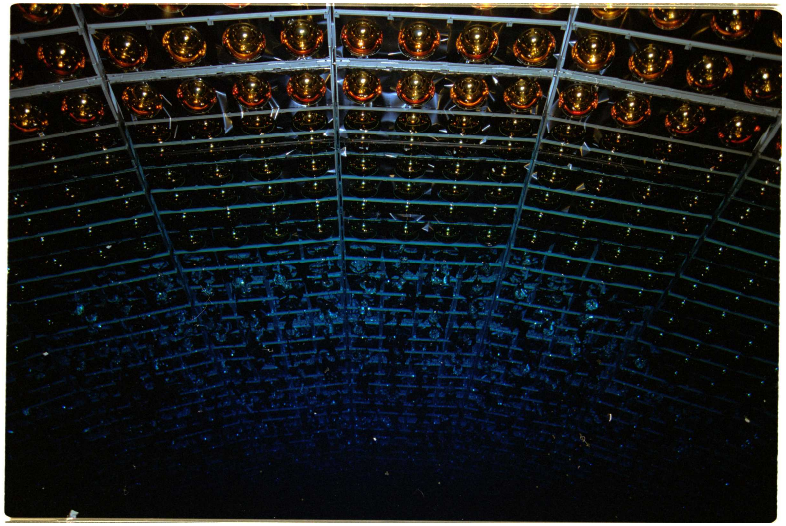
ICRR member:

Staff:	17	(faculty: 8, research assistant: 9)
PD:	4	
Students:	7	
Total	28	

History of Super-Kamiokande Detector

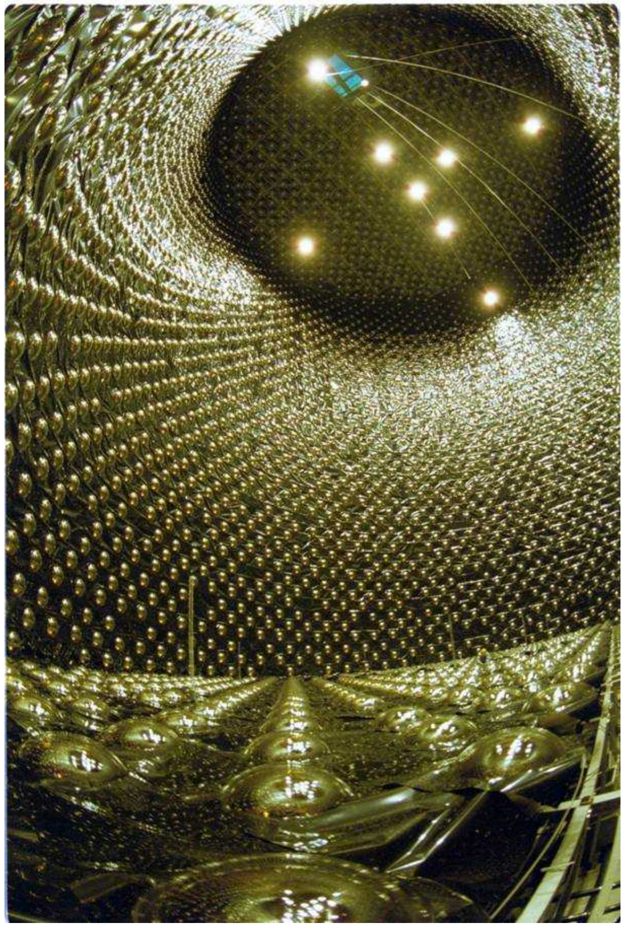
Year	Event	Phase	Number of ID PMTs (photocoverage)	Main results
1996	Start			
1997				
1998		SK-I	11,146 (40%)	Evidence for Atmospheric ν osc.
1999				
2000				Tau ν favor over sterile ν in atm. osc.
2001	Accident			Evidence for Solar ν osc.
2002	Partial Reconstruction			LMA by solar ν global analysis
2003		SK-II	5,182 (19%)	
2004				Atmospheric ν L/E
2005				K2K final results
2006	Full reconstruction			Atmospheric ν tau appearance
2007		SK-III	11,129 (40%)	
2008				

Accident and partial reconstruction



Accident on Nov.12, 2001.
6777 ID, 1100 OD PMTs were destroyed.

All PMTs were packed in acrylic and FRP cases to prevent shock-wave.



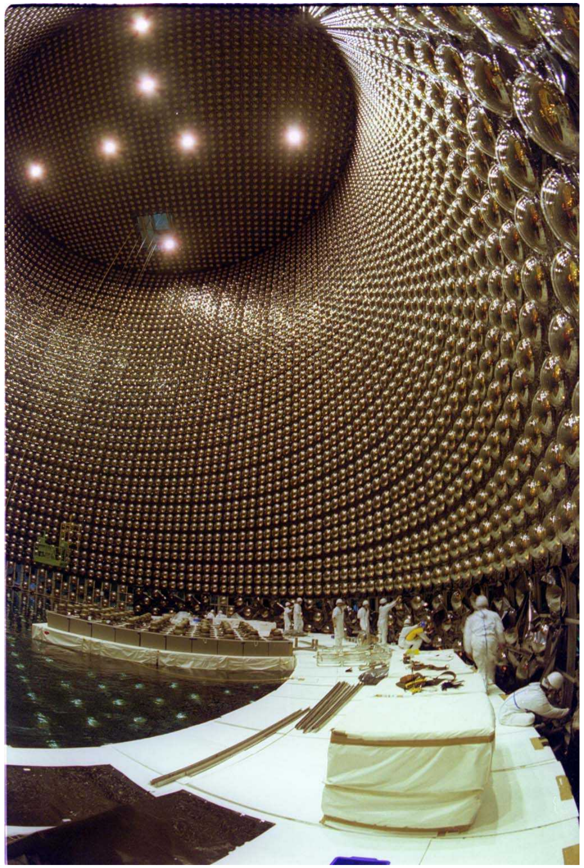
Reconstructed using remaining 5182 ID PMTs. OD was fully reconstructed (April-September 2002).

ID: Inner detector
OD: Outer detector

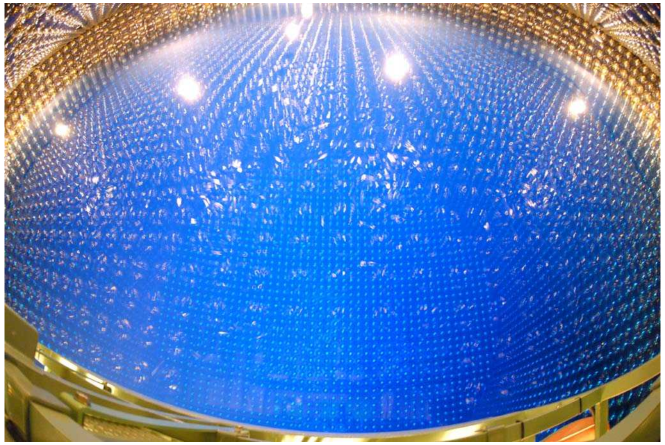
Full Reconstruction (October 2005 – April 2006)

~6000 ID PMTs were produced from 2002 to 2005 and were mounted from Oct.2005 to Apr.2006.

All those PMTs were packed in acryic and FRP cases.



Mount PMTs on a floating floor.



Pure water was supplied and SK-III data taking has been running since July 11, 2006.

Atmospheric neutrinos

Main Physics

Study of muon-neutrinos oscillations

Oscillation parameters (θ_{23}, Δm^2_{23}, θ_{13})

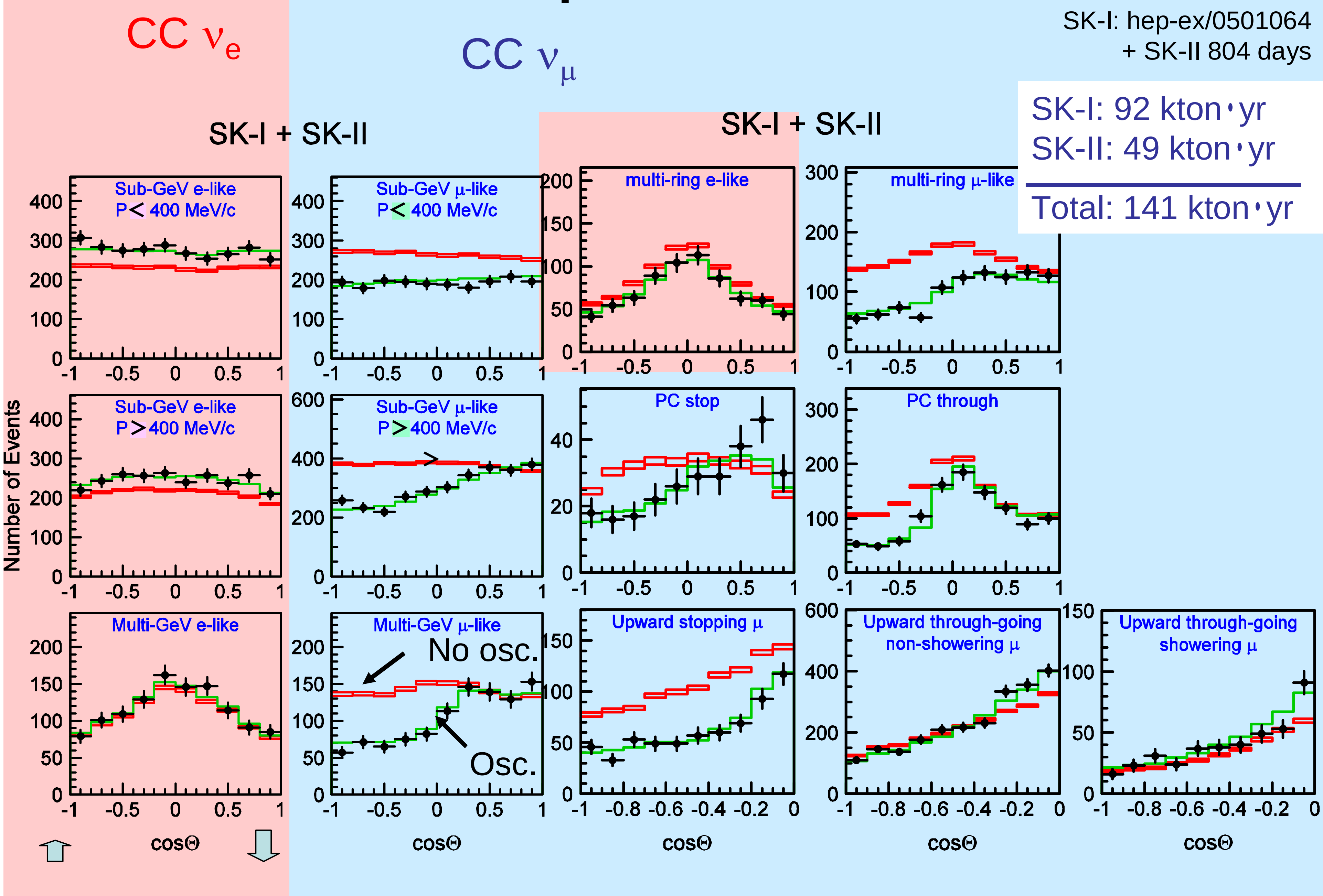
Oscillation mode ($\nu_\mu \rightarrow \nu_\tau$? $\nu_\mu \rightarrow \nu_{sterile}$?)

Oscillation signature (L/E dependence)

SK-I+II atmospheric neutrino data

SK-I: hep-ex/0501064
+ SK-II 804 days

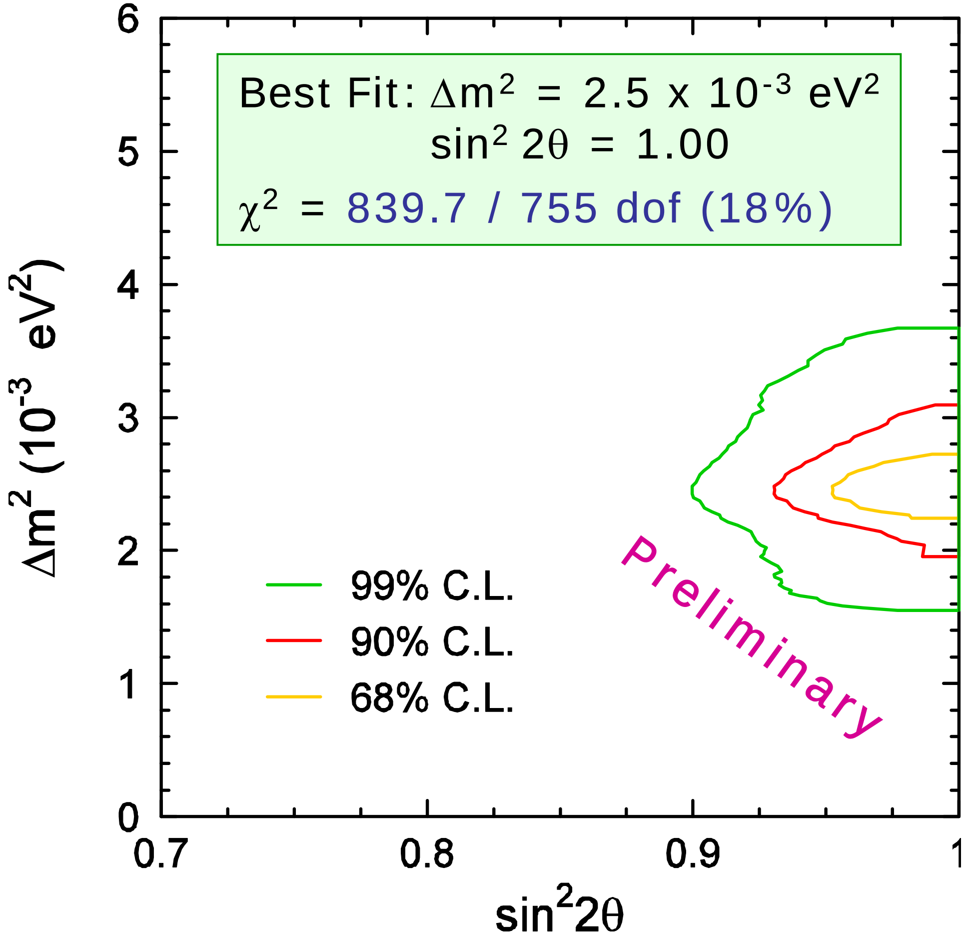
SK-I: 92 kton·yr
SK-II: 49 kton·yr
Total: 141 kton·yr



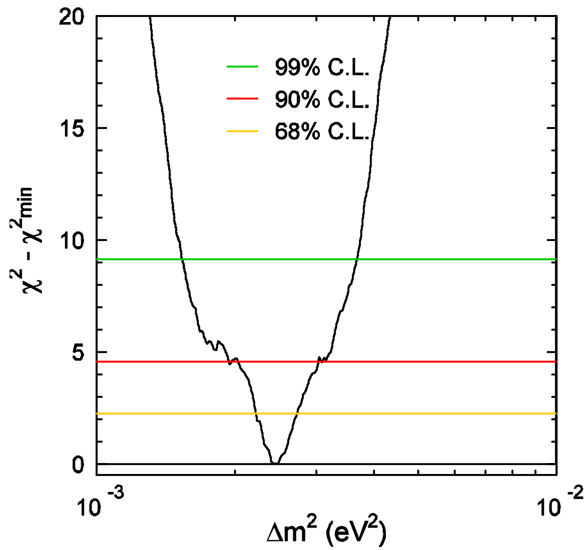
$\nu_\mu \rightarrow \nu_\tau$ 2 flavor analysis

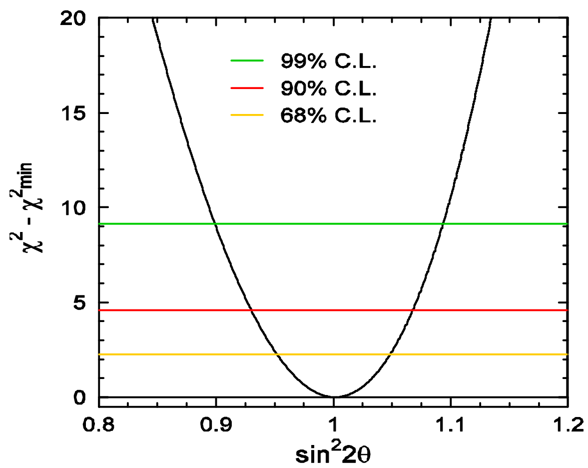
SK-I + SK-II

1489 days (SK-1)+ 804 days (SK-II)



$\Delta\chi^2$ distributions

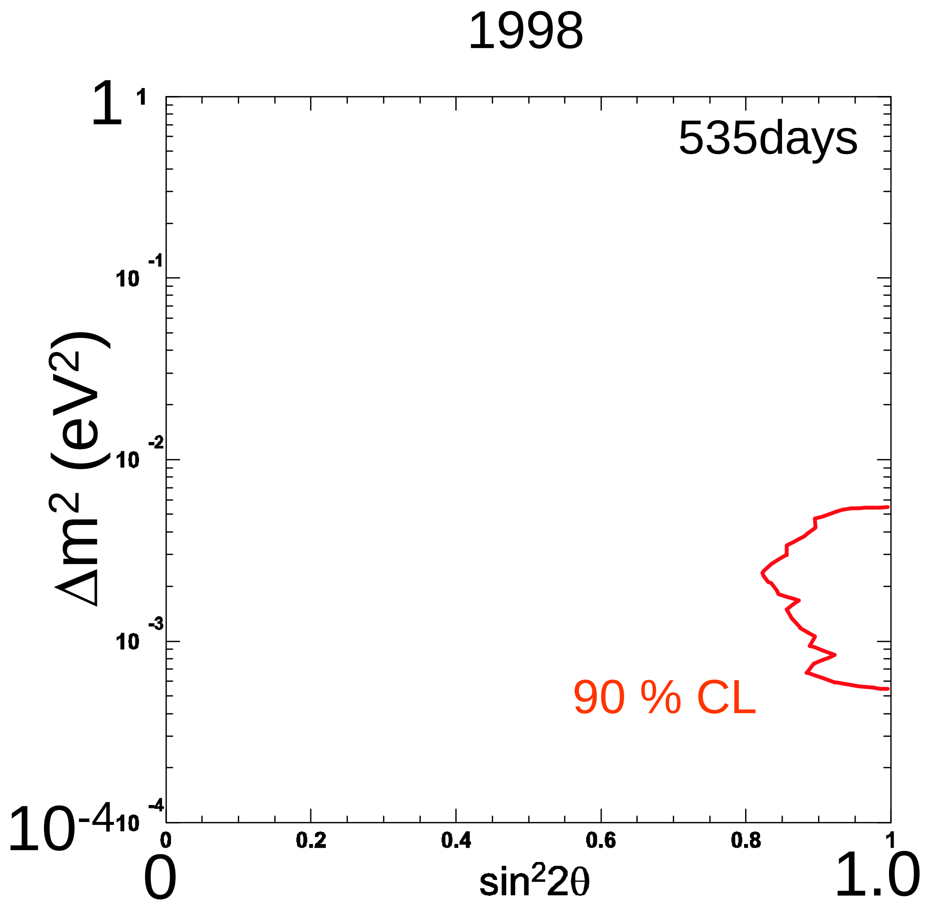


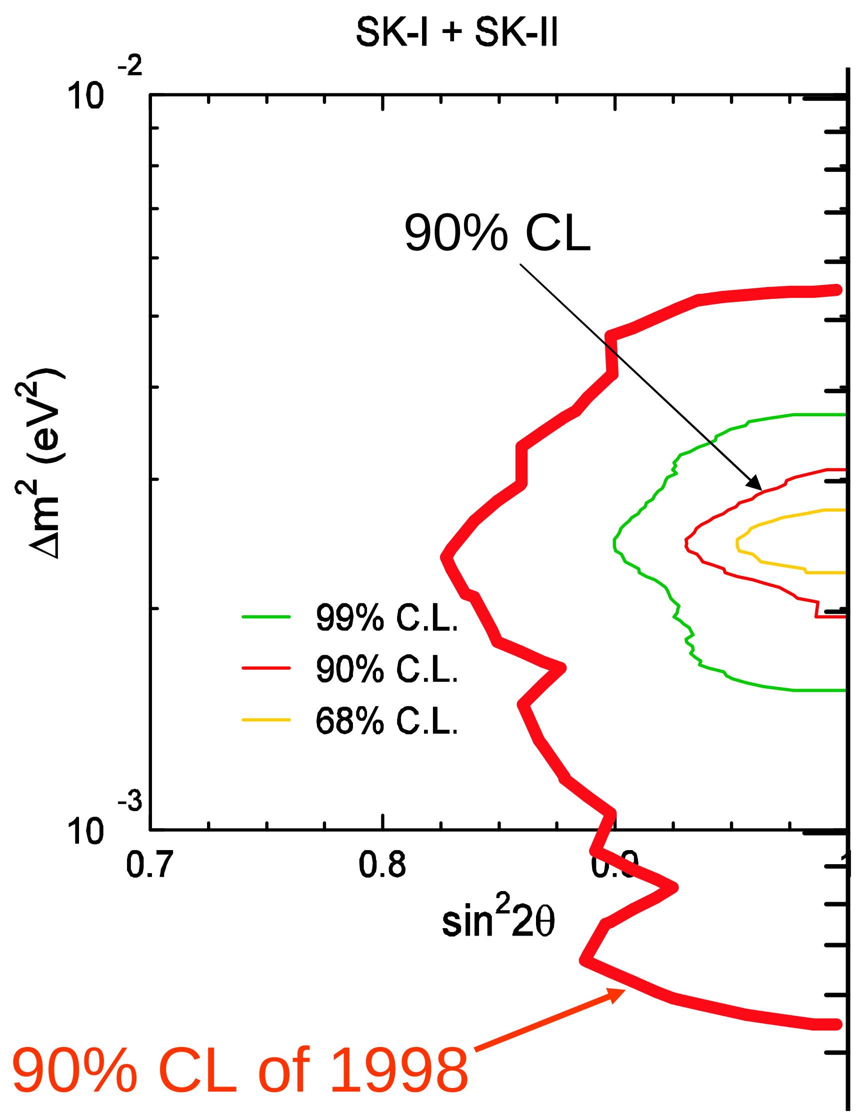


1.9×10^{-3} eV^2 < Δm^2 < 3.1×10^{-3} eV^2

$\sin^2 2\theta > 0.93$ at 90% CL

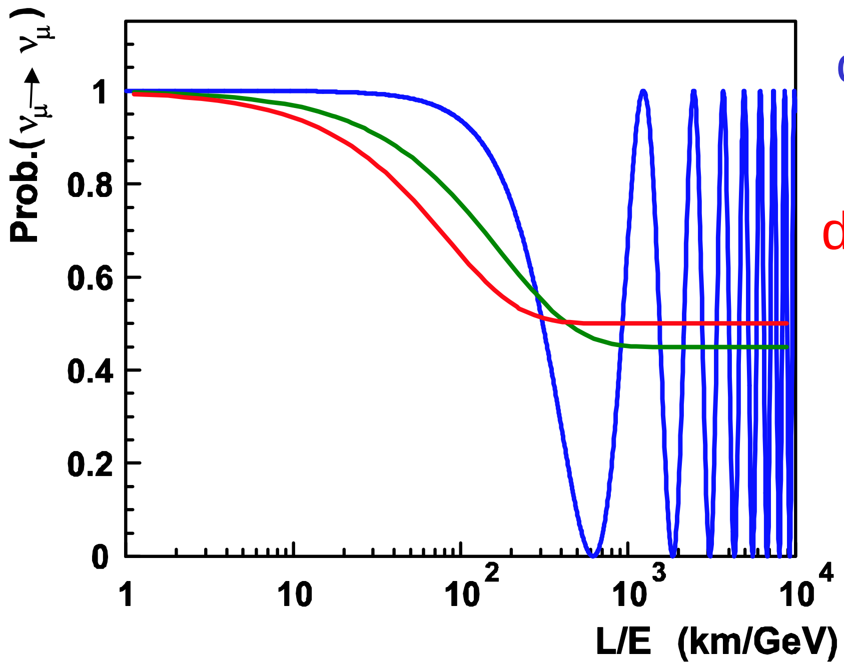
Oscillation results 1998 vs. (SK-I+SK-II)





L/E analysis

SK collab. hep-ex/0404034



oscillation

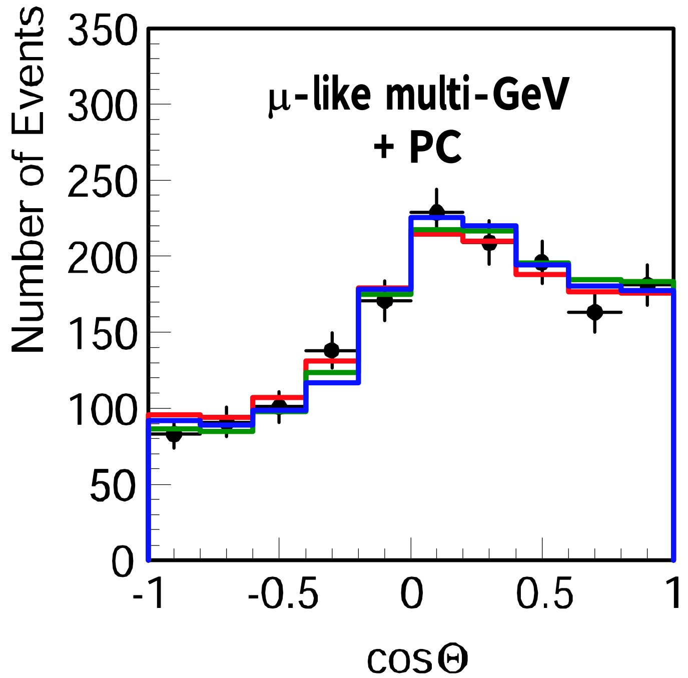
$$P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2(1.27 \frac{\Delta m^2 L}{E_\nu})$$

decoherence

$$P_{\mu\mu} = 1 - \frac{1}{2} \sin^2 2\theta \cdot (1 - \exp(-\gamma_0 \frac{L}{E}))$$

decay

$$P_{\mu\mu} = (\cos^2\theta + \sin^2\theta \cdot \exp(-\frac{m}{2\tau}\frac{L}{E}))^2$$

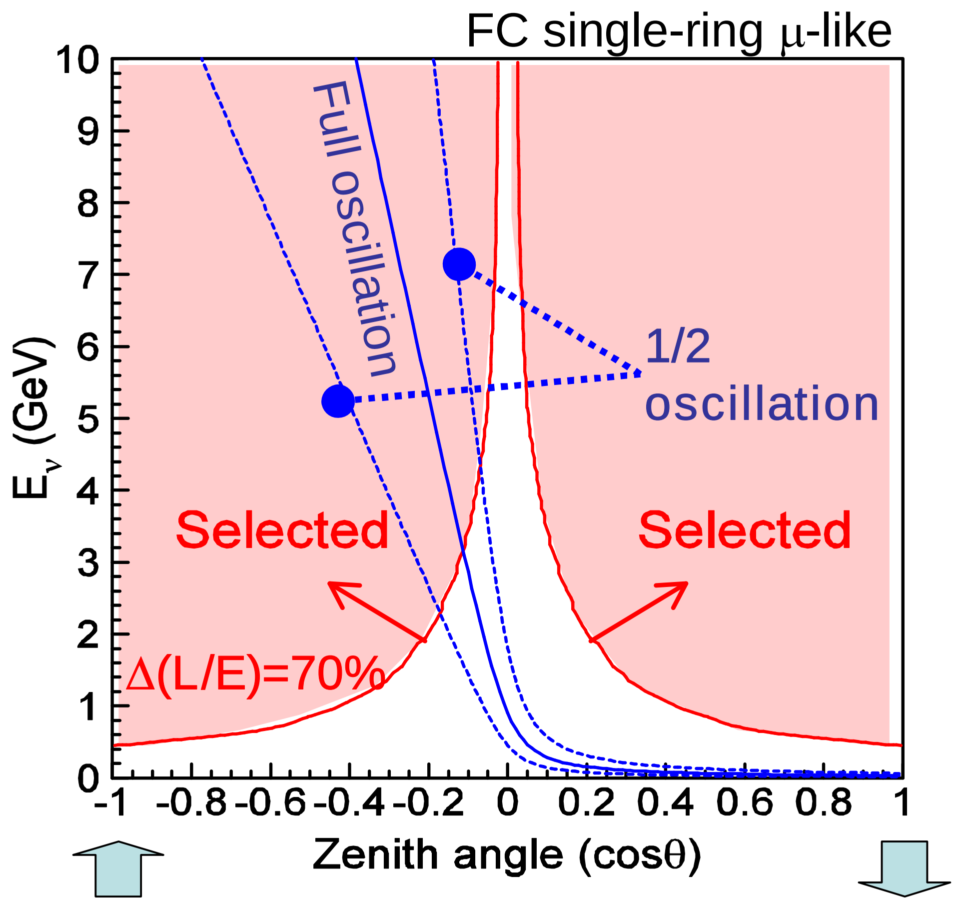


Should observe this dip!

→ Further evidence for oscillations

→ Better determination of oscillation parameters, especially Δm^2

Selection criteria



Select events with high L/E resolution

(Δ(L/E) < 70%)

Events are not used, if:

★horizontally going events

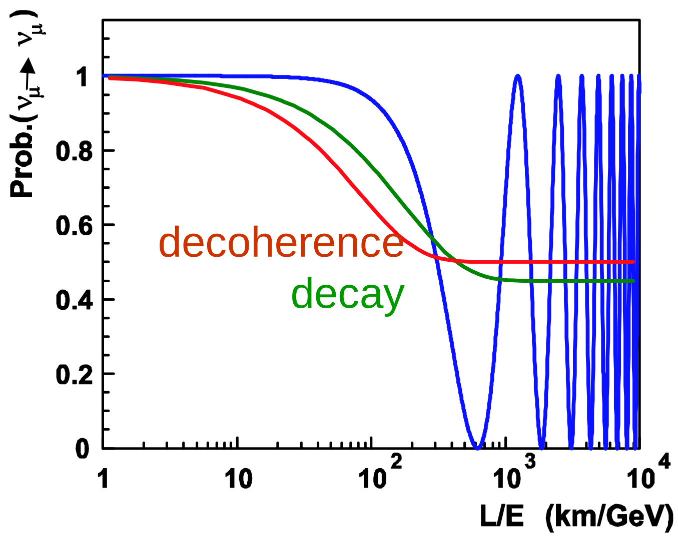
★low energy events

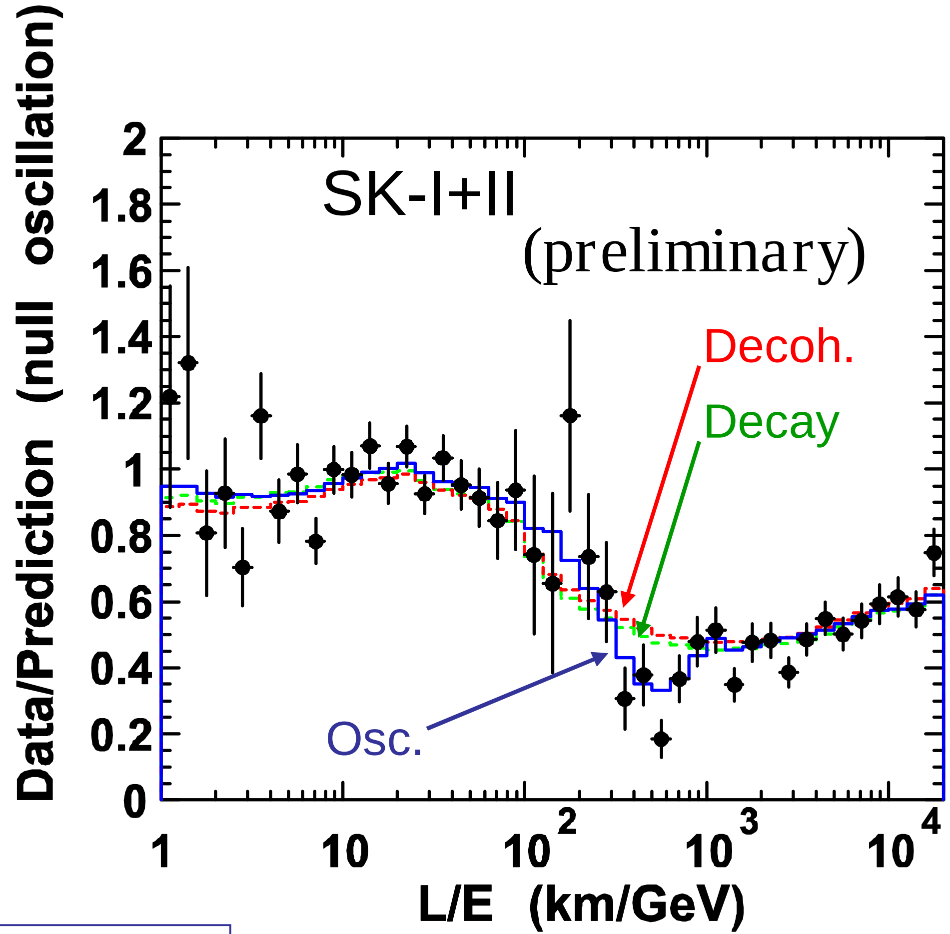
Similar cut for: FC multi-ring μ-like,

OD stopping PC, and

OD through-going PC

SK-I+II L/E analysis and non-oscillation models





χ^2(osc)=83.9/83dof

χ^2(decay)=107.1/83dof

χ^2(decoherence)=112.5/83dof

Oscillation gives the best fit to the data.
Decay and decoherence models disfavored by 4.8 and 5.3 σ, resp.

Oscillation to ν_τ or $\nu_{sterile}$?

μ-like data show zenith-angle and energy dependent deficit of events, while e-like data show no such effect.

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

Propagation

$\nu_\mu \rightarrow \nu_\tau$: No matter effect

$\nu_\mu \rightarrow \nu_s$: With matter effect

→ For $\sin^2 2\theta = \sim 1$, matter effect suppresses oscillation at higher energy.

Interaction

$\nu_\mu \rightarrow \nu_\tau$: With Neutral Current

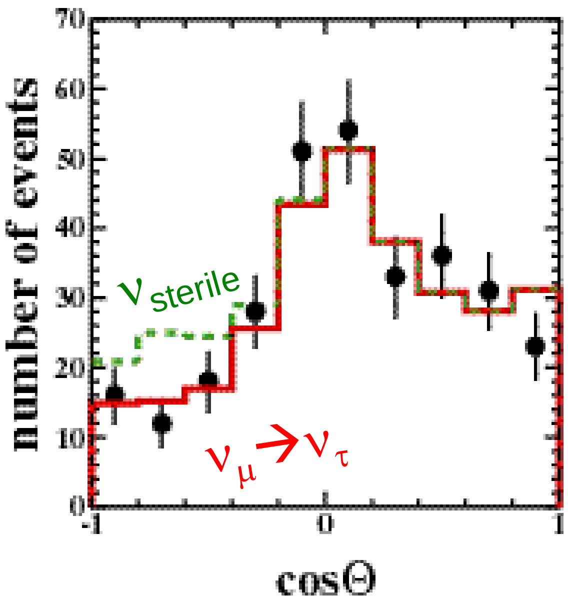
$\nu_\mu \rightarrow \nu_s$: W/O Neutral Current

→ Check upward-going NC events

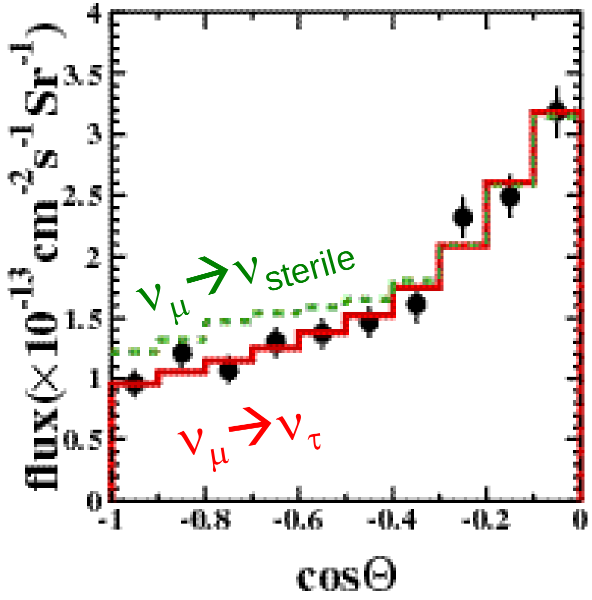
Testing $\nu_\mu \rightarrow \nu_\tau$ vs. $\nu_\mu \rightarrow \nu_{sterile}$

Matter effect

High E PC events (Evis>5GeV)

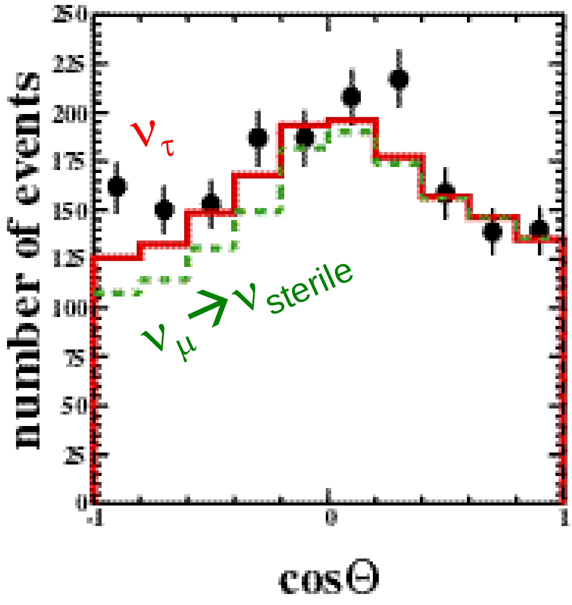


Up through muons



Neutral current

Multi-ring e-like, with Evis >400MeV



→ Pure $\nu_\mu \rightarrow \nu_{sterile}$ excluded

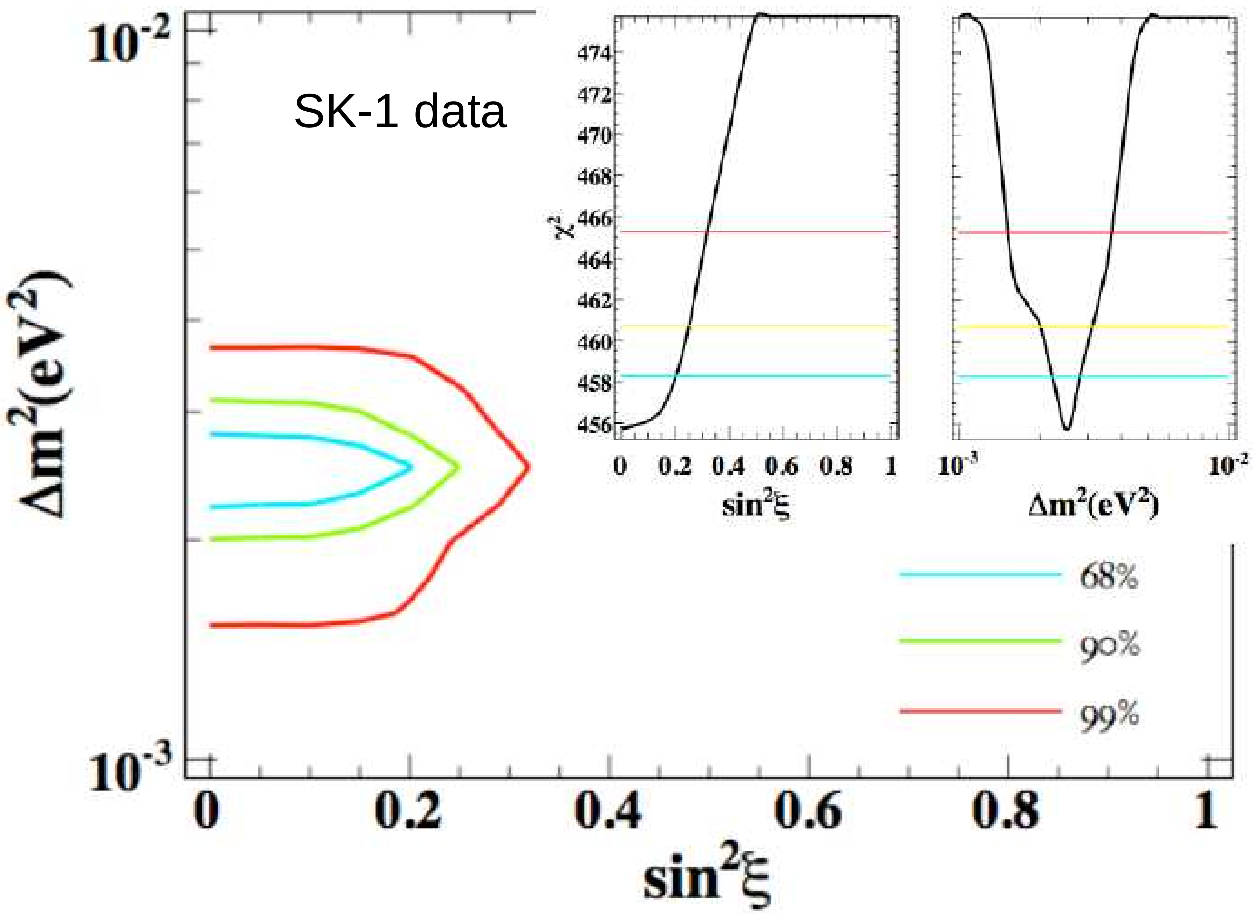
(PRL85,3999 (2000))

Limit on oscillations to $\nu_{sterile}$

$\nu_\mu \rightarrow (\sin\xi \cdot \nu_{sterile} + \cos\xi \cdot \nu_\tau)$

If pure $\nu_\mu \rightarrow \nu_\tau$, $\sin^2\xi=0$

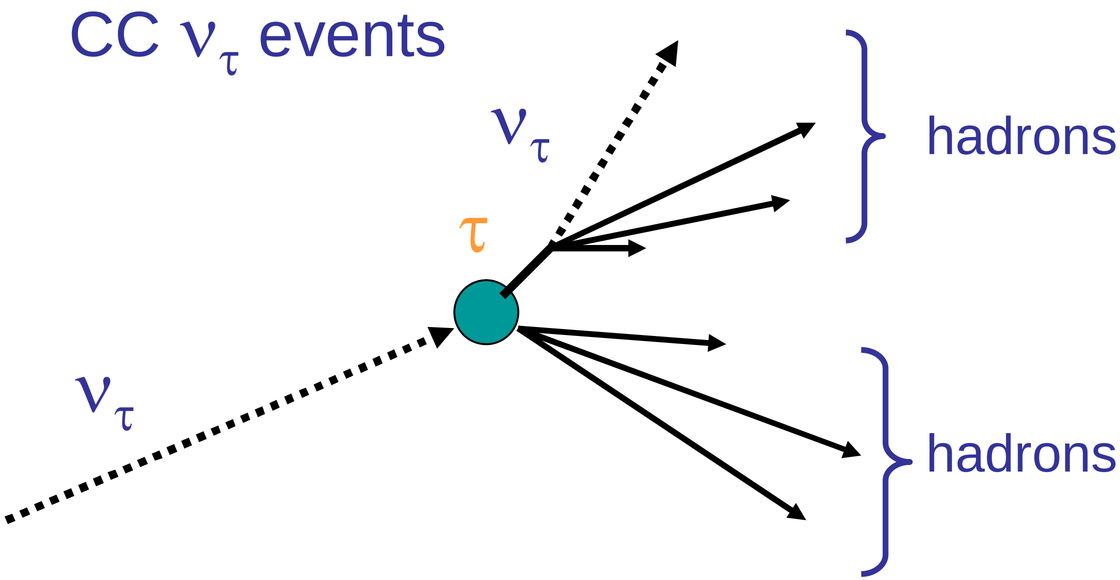
If pure $\nu_\mu \rightarrow \nu_{sterile}$, $\sin^2\xi=1$

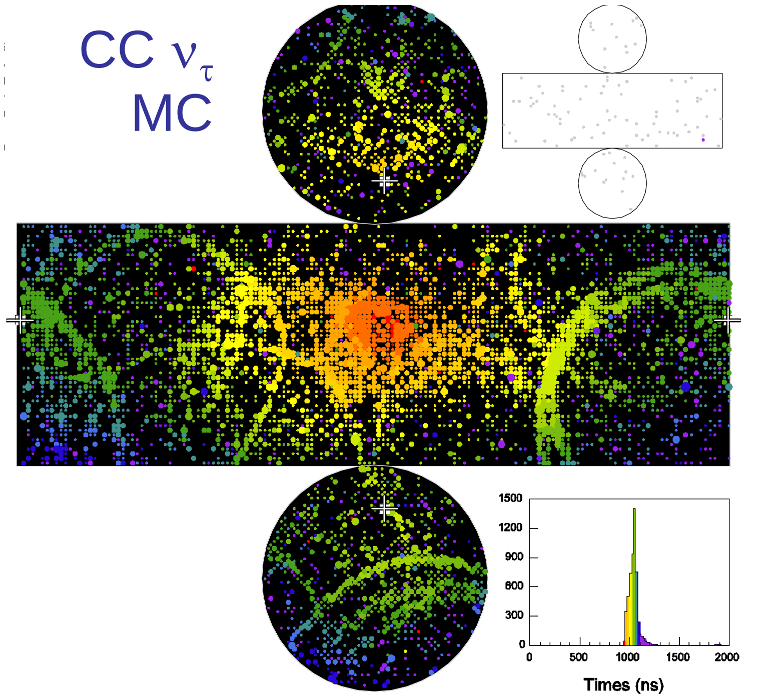


Consistent with pure $\nu_\mu \rightarrow \nu_\tau$

SK collab. draft in preparation

Search for CC ν_τ events (SK-I)





Signature of CC ν_τ events

- Higher multiplicity of Cherenkov rings
- More $\mu \rightarrow e$ decay signals
- Spherical event pattern

Likelihood and neural network analysis

Only ~ 1.0 CC ν_τ FC events/kton·yr

(BG (other ν events) ~ 130 ev./kton·yr)

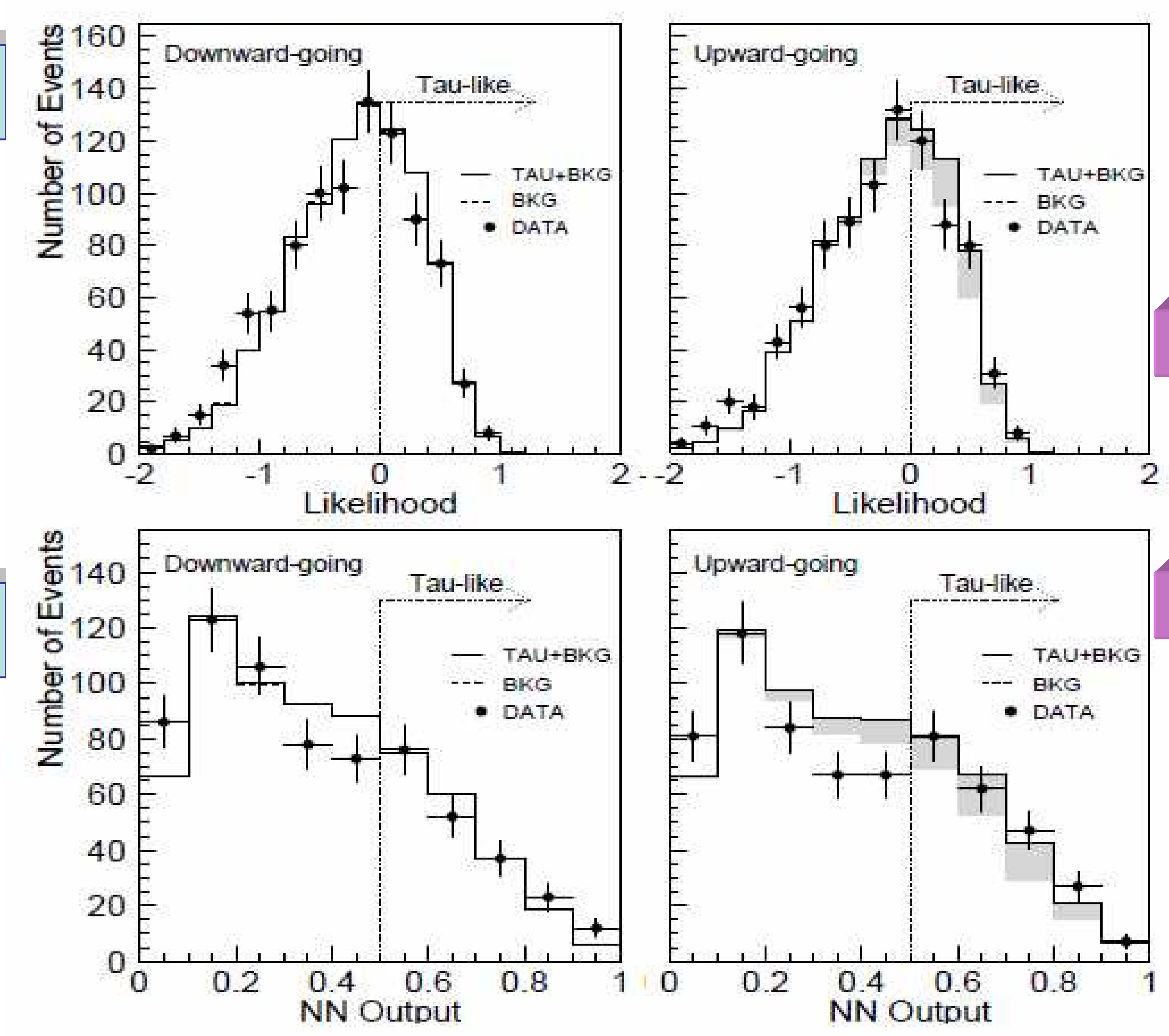
Likelihood / neural-net distributions

Pre-cuts: E(visible) >1.33GeV, most-energetic ring = e-like

Down-going (no ν_τ) | Up-going

Likelihood

Neural-net

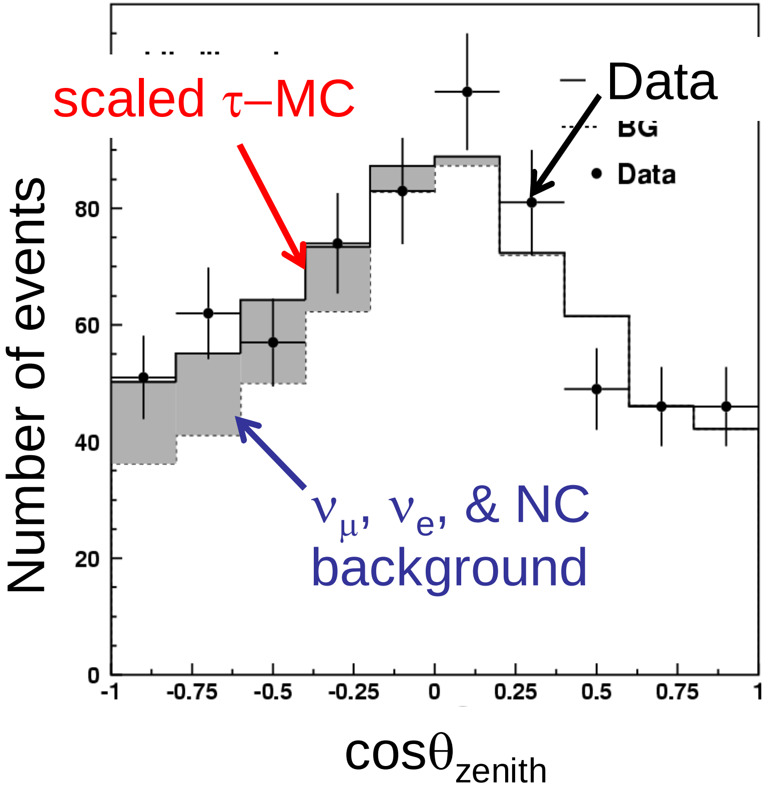


Zenith-angle

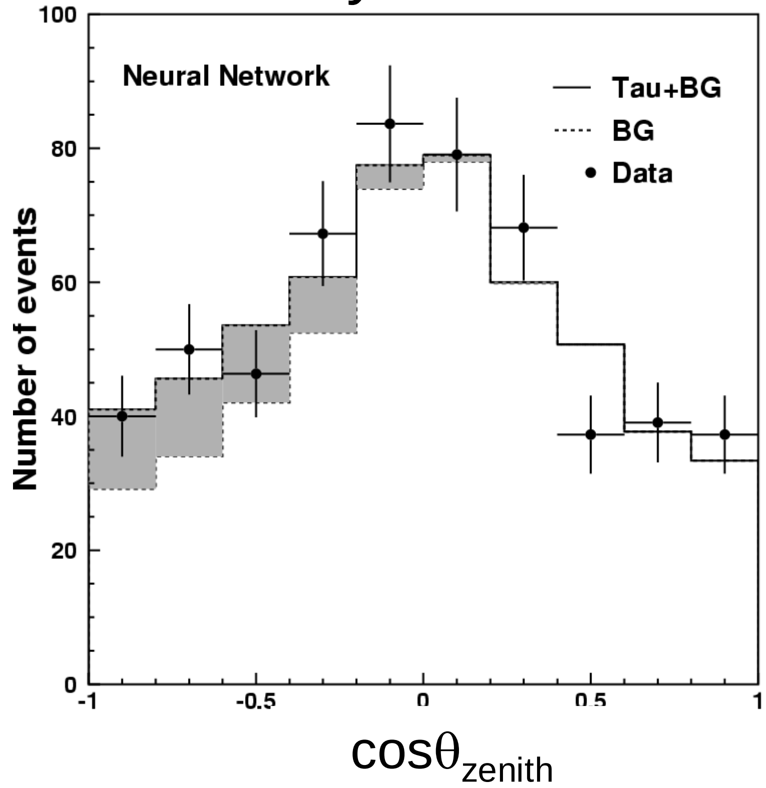
Zenith angle dist. and fit results

Hep-ex/0607059

Likelihood analysis



NN analysis



Fitted # of τ events	138±48(stat) +15 / -32(syst)	134±48(stat) +16 / -27(syst)
Expected # of τ events	78±26(syst)	78±27 (syst)

Zero tau neutrino interaction is disfavored at 2.4σ.

Future: Search for Non-zero θ_{13}

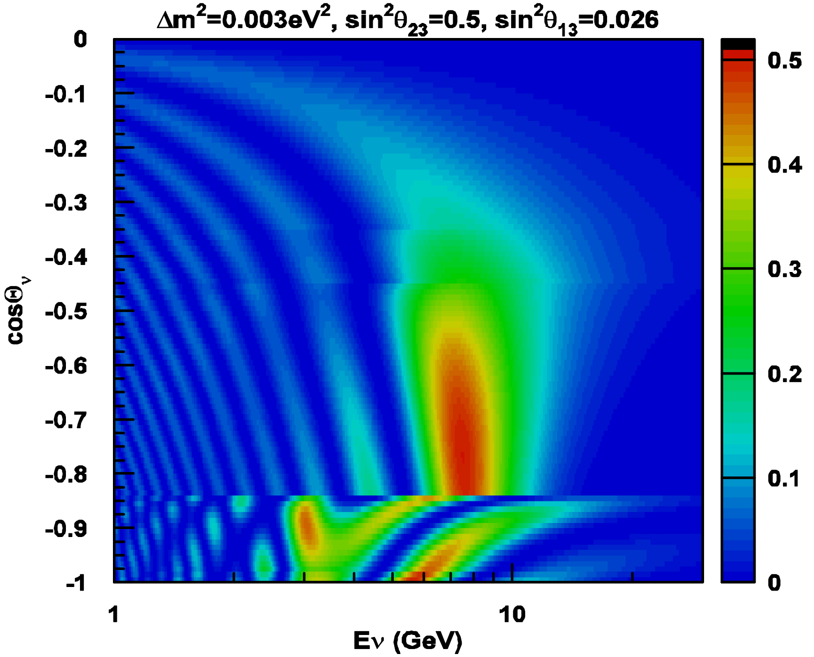
One mass scale dominance approx.

$\Delta m^2_{12} \sim 0$, $\Delta m^2_{13} \sim \Delta m^2_{23} = \Delta m^2$

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

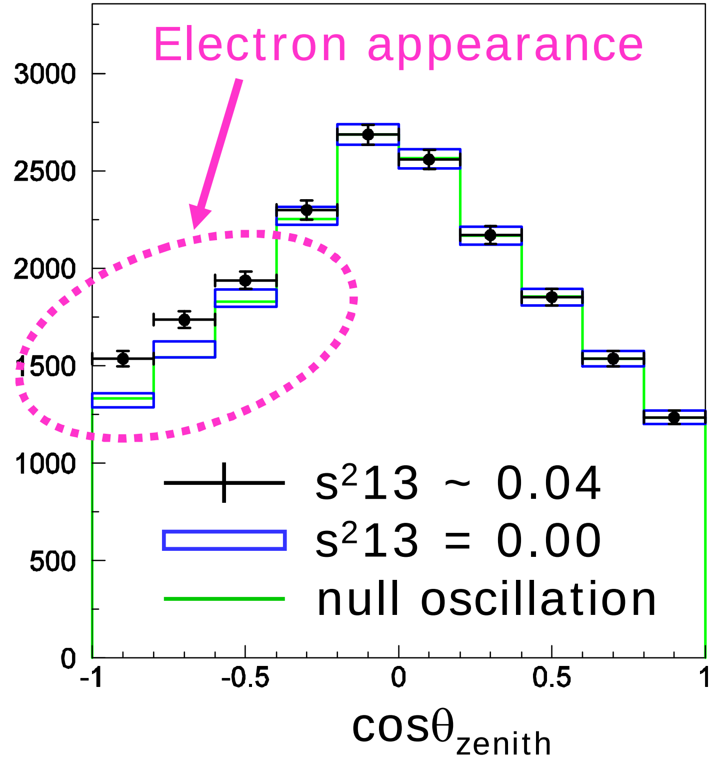
only 3 parameters

P($\nu_\mu \to \nu_e$) at SK



Simulation (4.5 Mton·yr)

1+multi-ring, e-like, 2.5~5 GeV/c

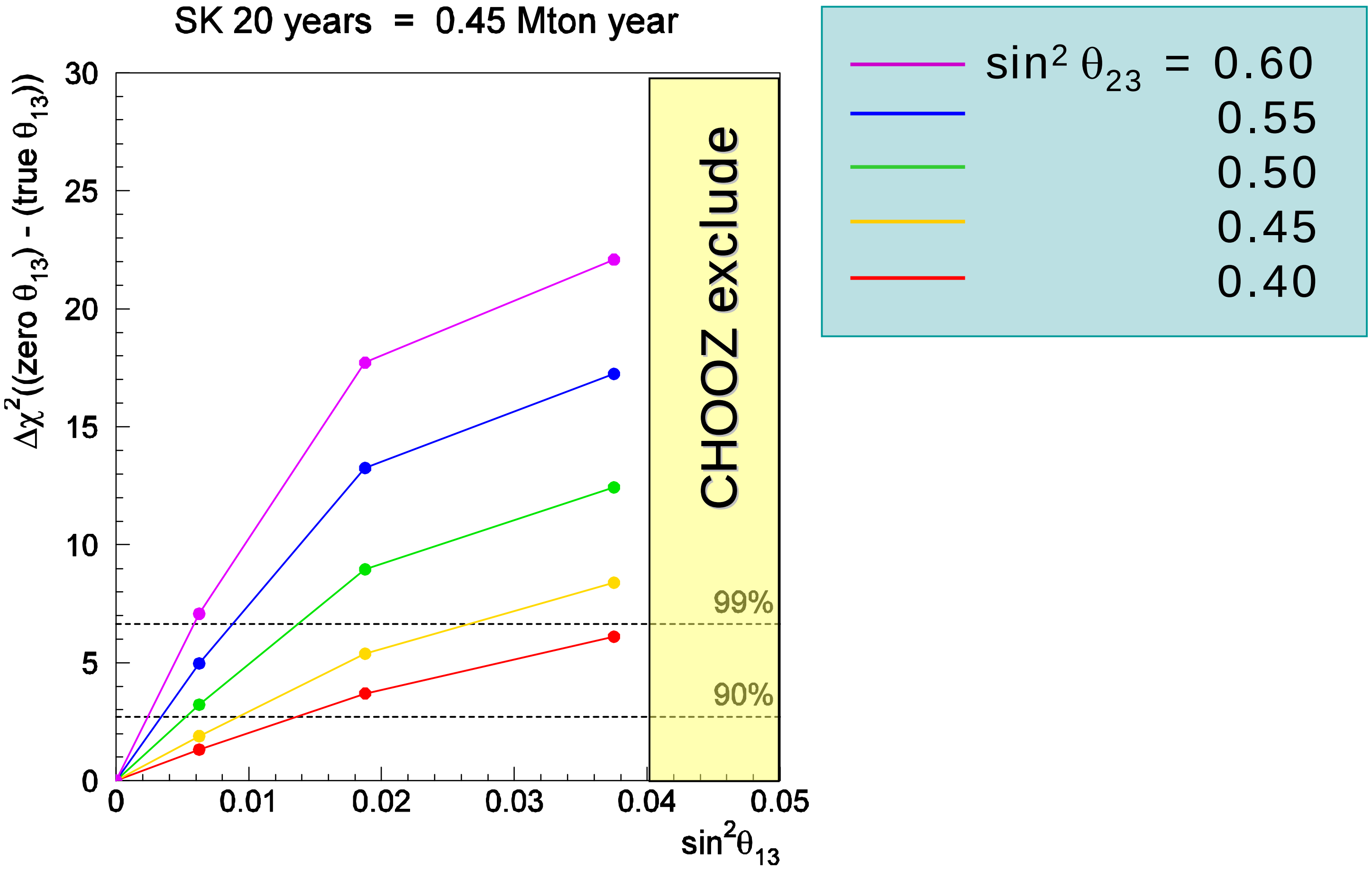


Using finely binned data, look for enhancement at certain energies and angles due to electron neutrino resonance in earth.

Future: Search for non-zero θ_{13}

Sensitivity of 20 years' SK data

$s^2 2\theta_{12}=0.825$
$s^2\theta_{23}=0.4 \sim 0.6$
$s^2\theta_{13}=0.00 \sim 0.04$
$\delta cp=45^o$
$\Delta m^2_{12}=8.3e-5$
$\Delta m^2_{23}=2.5e-3$



If θ_{13} is close to CHOOZ limit, non-zero θ_{13} can be observed by atmospheric neutrinos.

Summary of Atmospheric neutrino analysis

- **Activities from 2000 to 2006**
  - Allowed parameter region was improved:
    - $1.9 \times 10^{-3}\ \mathrm{eV}^2 < \Delta m^2 < 3.1 \times 10^{-3}\ \mathrm{eV}^2$
    - $\sin^2 2\theta > 0.93$ at 90% CL
  - L/E dependence of neutrino oscillation was observed.
  - $\nu_\mu \rightarrow \nu_\tau$ favors over $\nu_\mu \rightarrow \nu_{sterile}$
  - Tau appearance with 2.4 σ level.
- **Future prospects**
  - Search for non-zero $\theta 13$. If $\theta 13$ is close to CHOOZ limit, it could be observed by atmospheric neutrinos.

Solar neutrinos

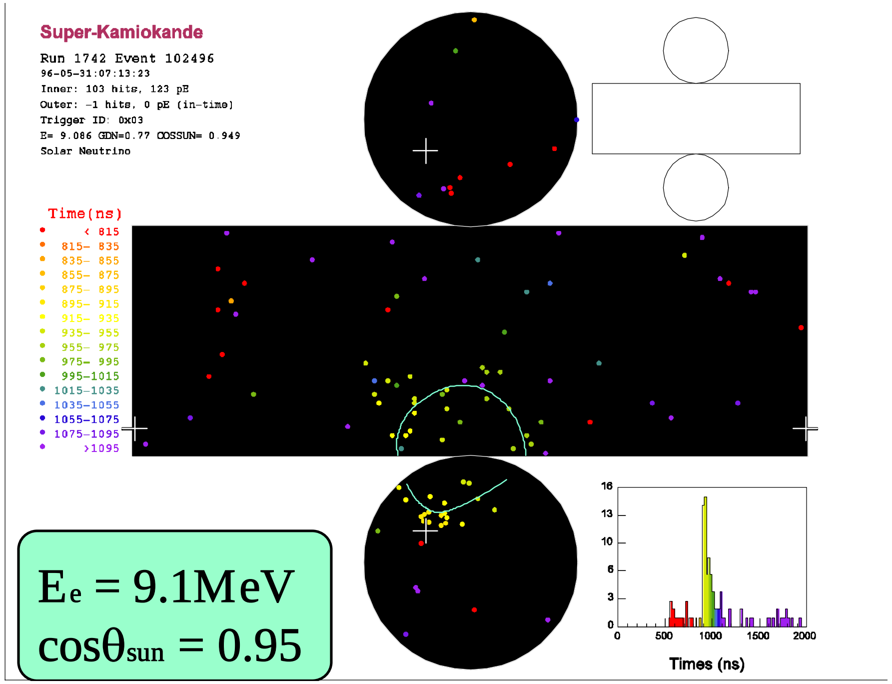
Main Physics

High statistics measurement of ^8B solar neutrinos to
(1) solve "solar neutrino problem"
(2) measure oscillation parameters (θ_{12}, Δm^2_{12})

Solar neutrino measurement in SK

- ^{8}B neutrino measurement by $\nu + e^- \rightarrow \nu + e^-$
- Sensitive to ν_e, ν_μ, ν_τ $\sigma(\nu_{\mu(\tau)}+e^-) =\sim 0.15 \times \sigma(\nu_e+e^-)$
- High statistics ~15ev./day with E_e > 5MeV
- Real time measurement. Studies on time variations.
- Studies on energy spectrum.
- Precise energy calibration by LINAC and ^{16}N.

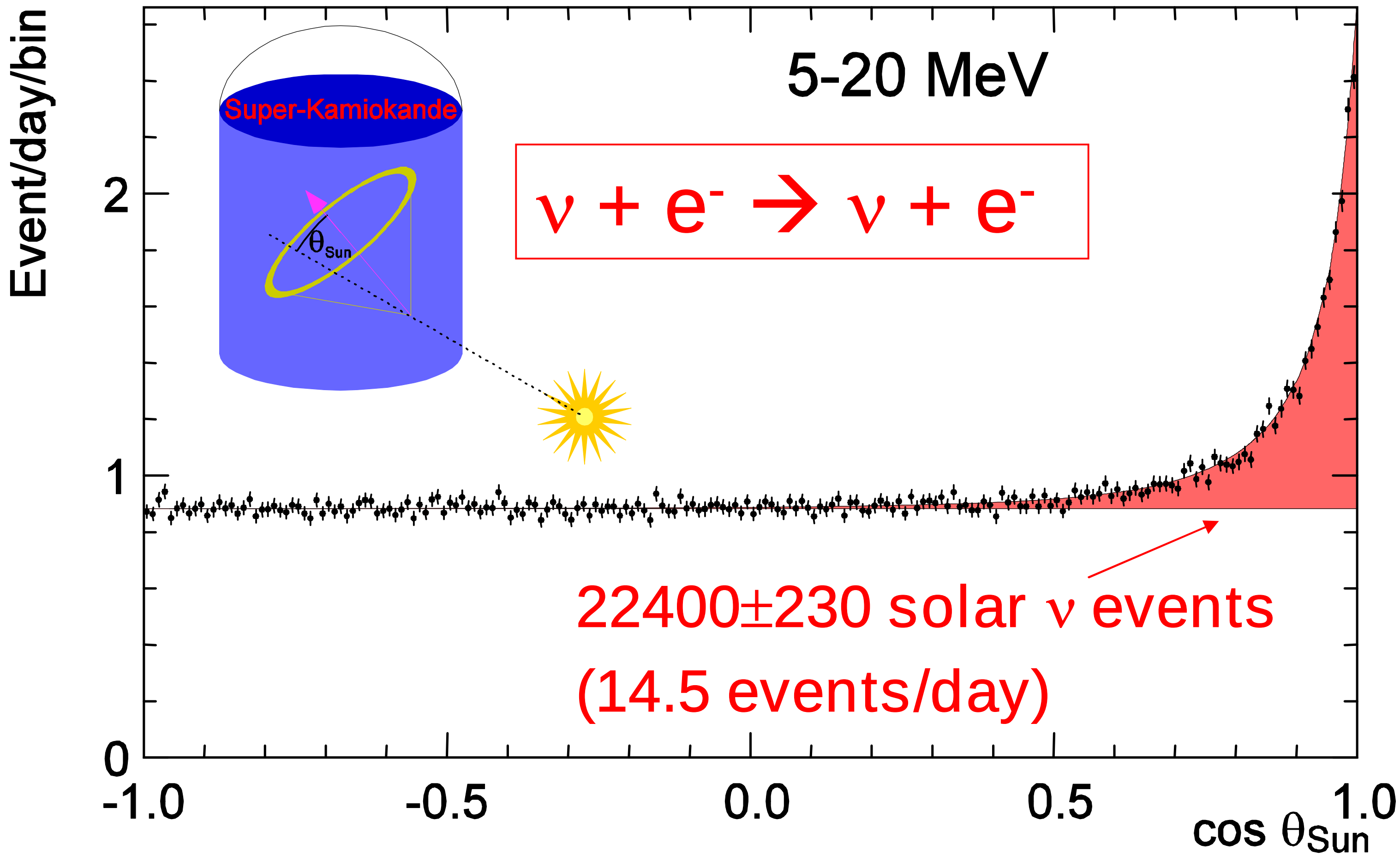
Typical event



- Timing information
  ➡ vertex position
- Ring pattern
  ➡ direction
- Number of hit PMTs
  ➡ energy

Super-Kamiokande-I solar neutrino data

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



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

$$\frac{\text{Data}}{\text{SSM(BP2004)}} = 0.406 \pm 0.004 \, ^{+0.014}_{-0.013}$$

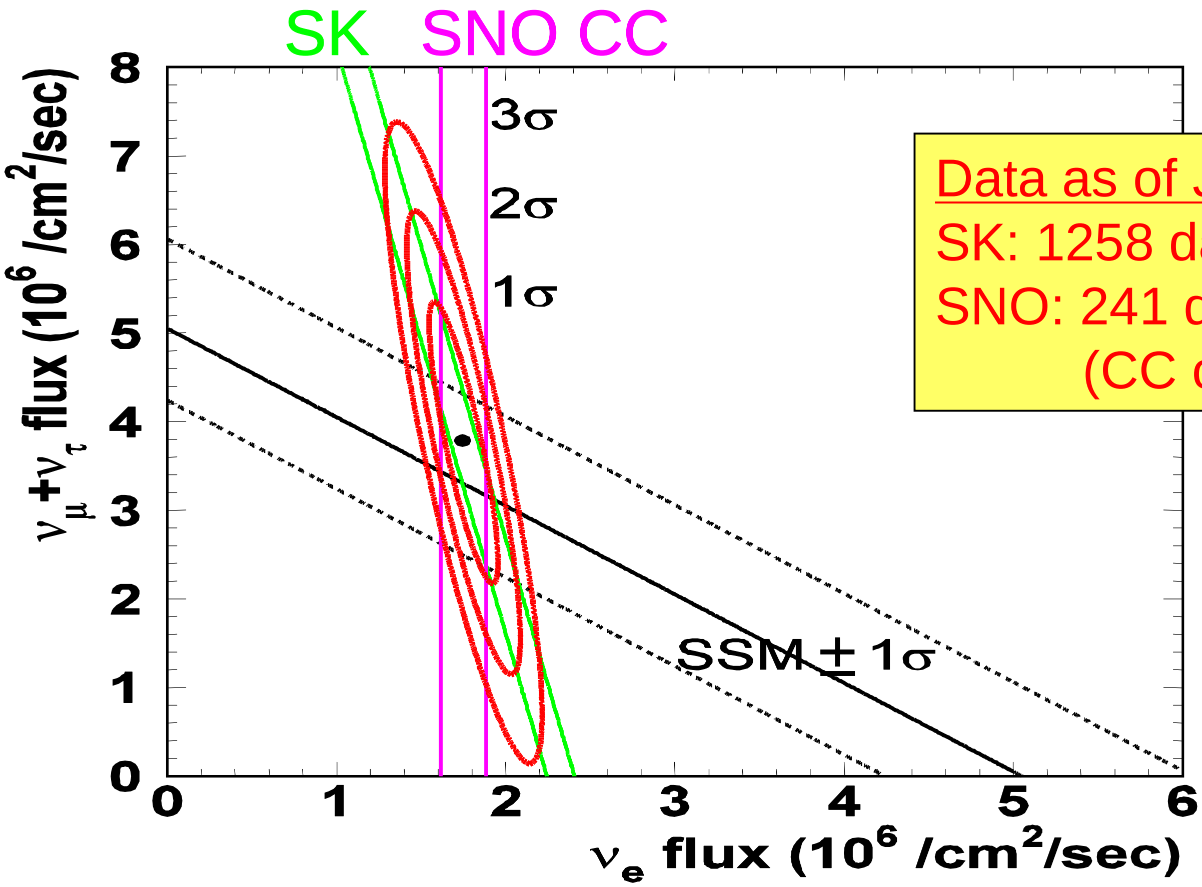
(Data/SSM(BP2000) = 0.465 ±0.005 +0.016/-0.015)

Evidence for solar neutrino oscillation by SK and SNO (June 2001)

SK ϕ_{ES} = 2.32±0.03+0.08/-0.07 [x10^6/cm^2/s] $\phi_{ES} = \phi_e + 0.15\,\phi_{\mu,\tau}$

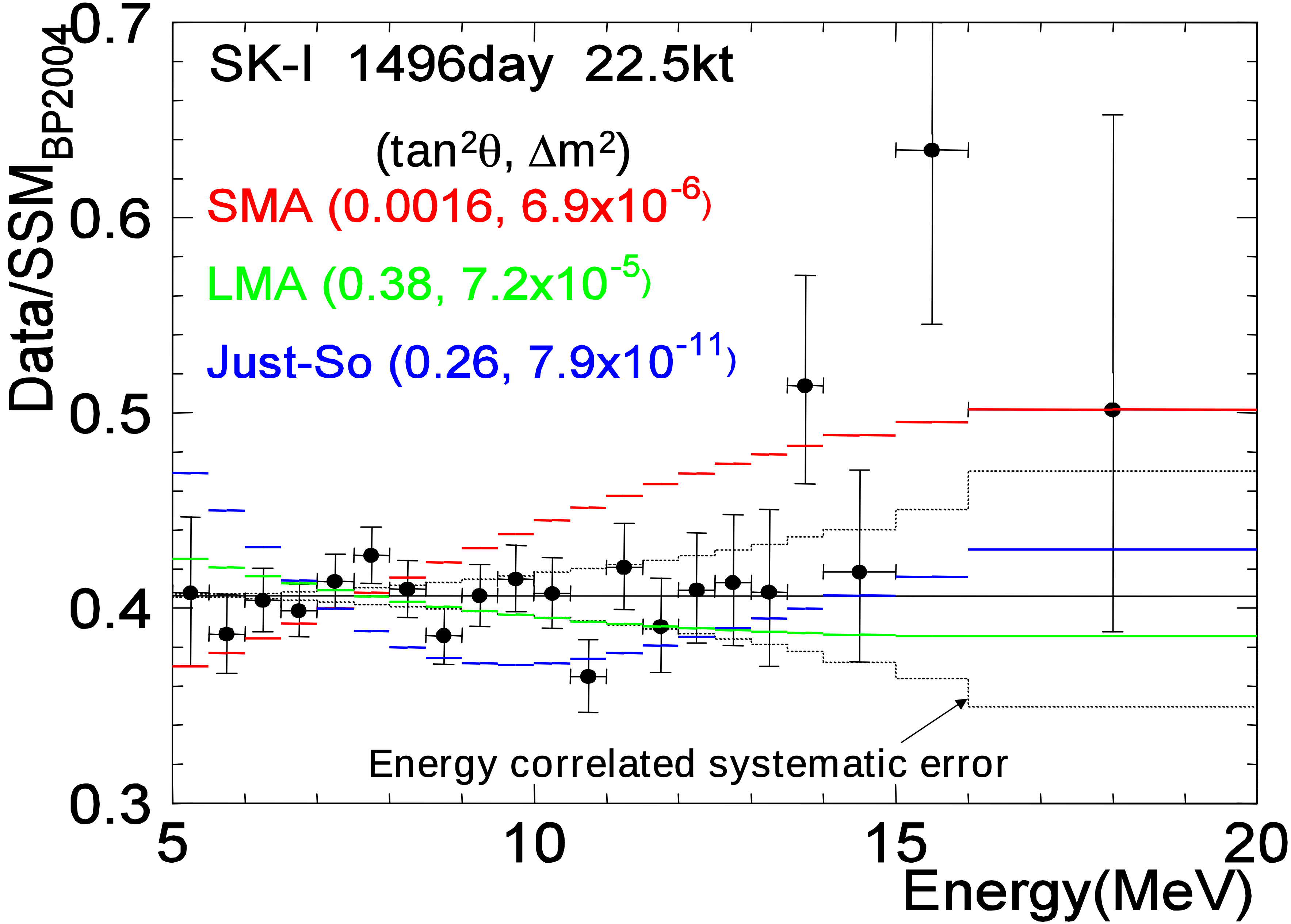
SNO ϕ_{CC} = 1.75±0.07+0.12/-0.11 $\phi_{CC} = \phi_e$

Obtained total flux: ϕ_{exp} = 5.5±1.4 (cf. $\phi_{SSM(BP2000)}$ = 5.05+1.0/-0.8)

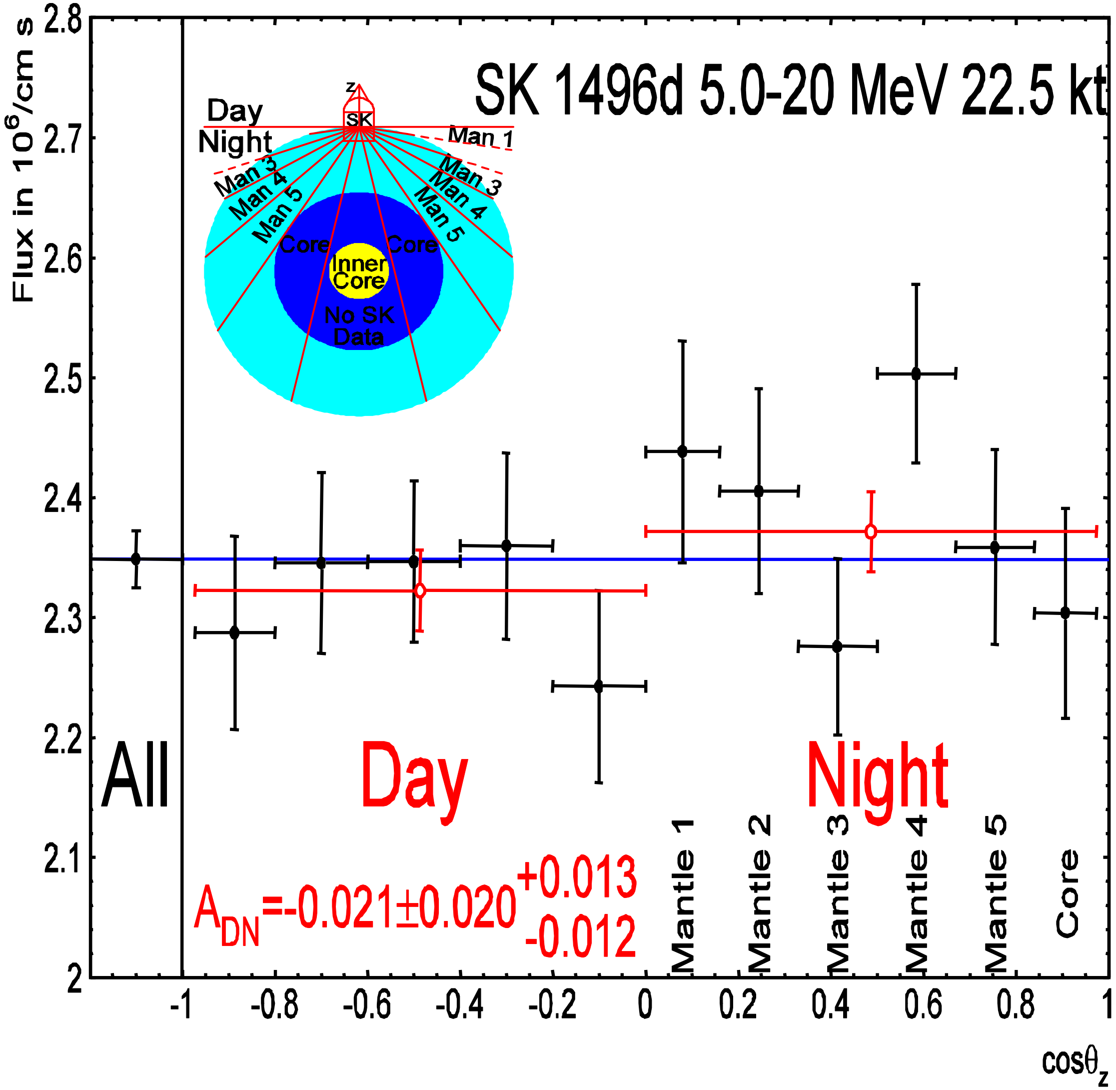


Data as of June 2001
SK: 1258 days of SK-I
SNO: 241 days of pure D2O (CC only)

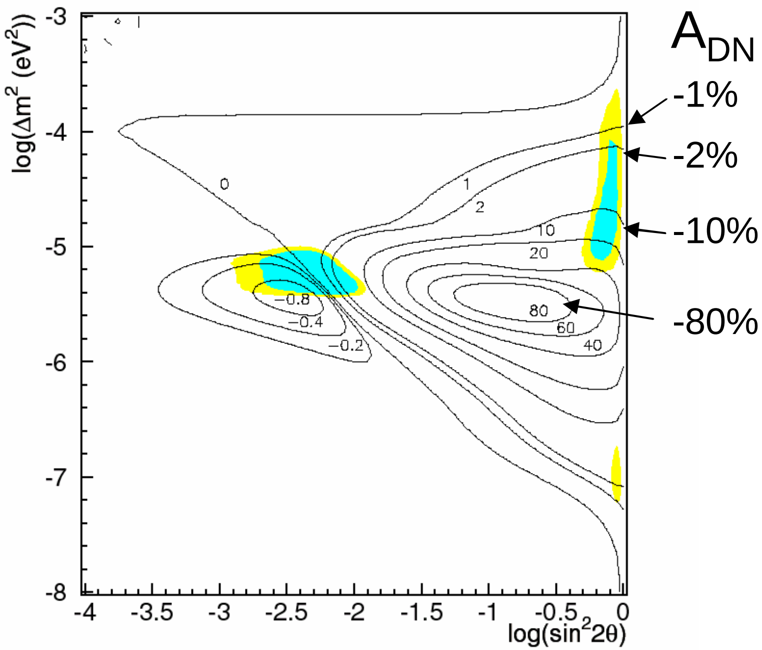
Energy spectrum of SK-I



SK-I day/night difference

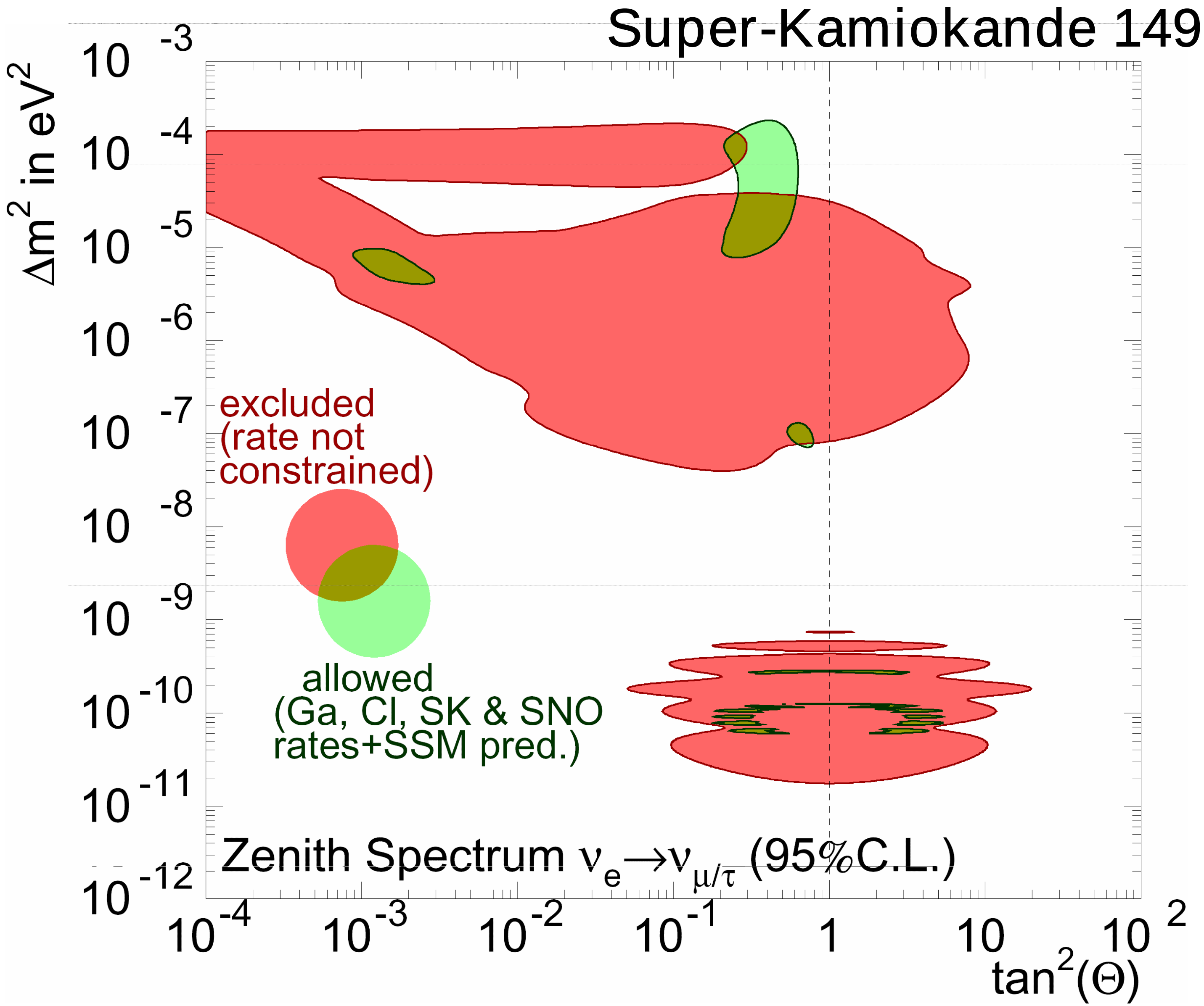


Expected D/N asymmetry



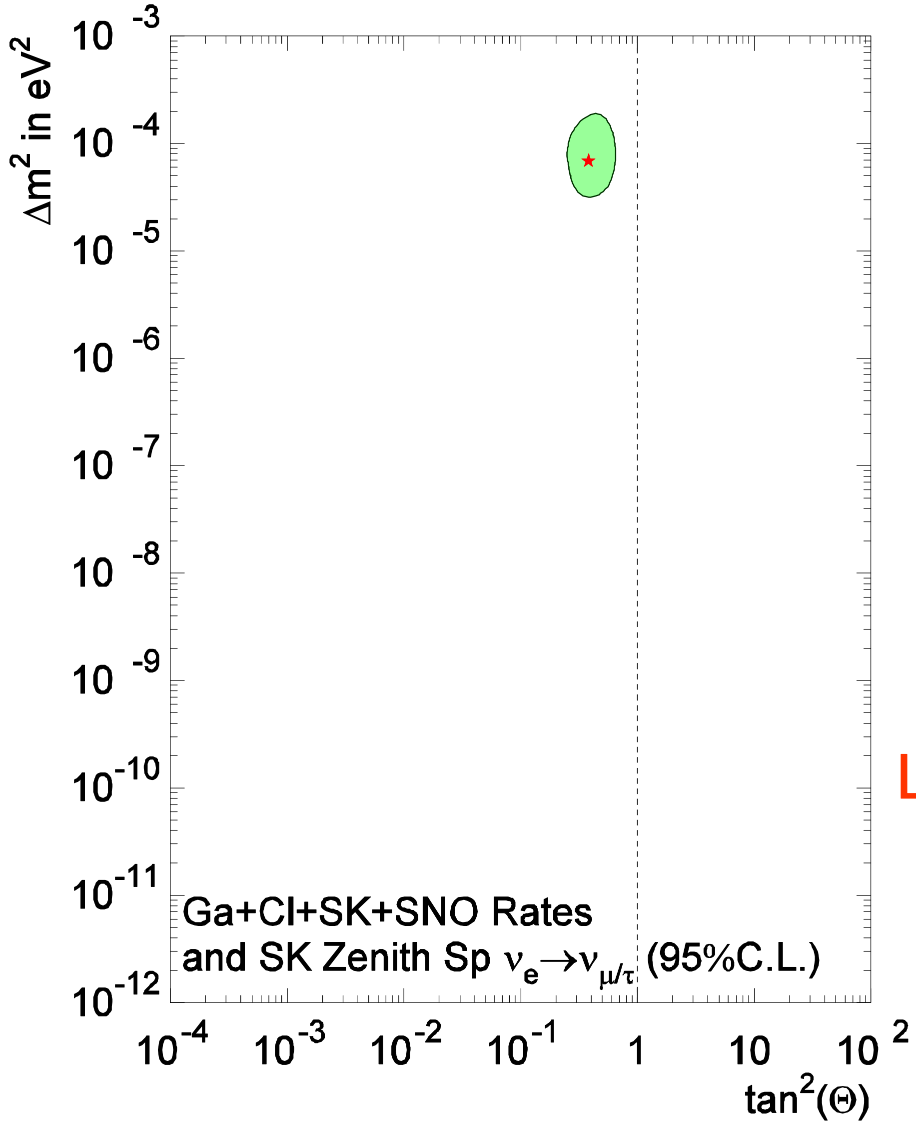
$$A_{DN} = \frac{(\text{Day-Night})}{(\text{Day+Night})/2}$$

Excluded region by energy spectrum and day/night



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

Allowed region combined with all solar neutrino data

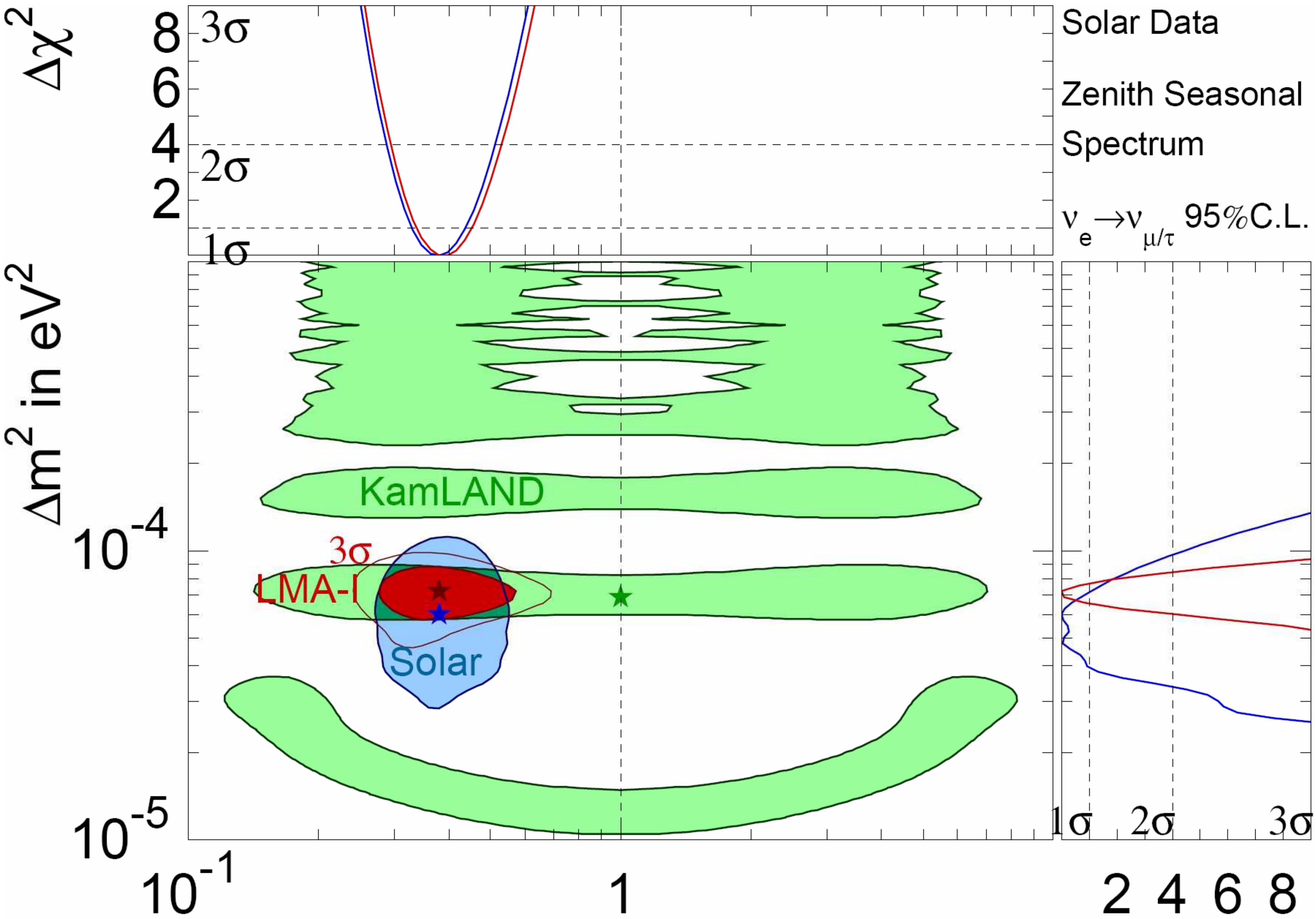


- Rates: Homestake (Cl), GALLEX (Ga), SAGE (Ga), SK (H2O), SNO CC+NC (D2O)
- Zenith spectra from SK: energy spectra of electrons at 7 zenith angle bins (day + 6 nights)

LMA is favored with 99 % CL.

Plot as of May 2002

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

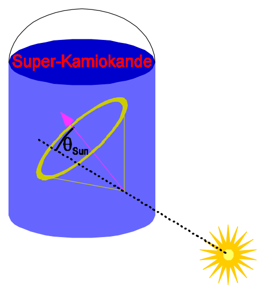


Plot after KamLAND first result

SK-II solar neutrino analysis

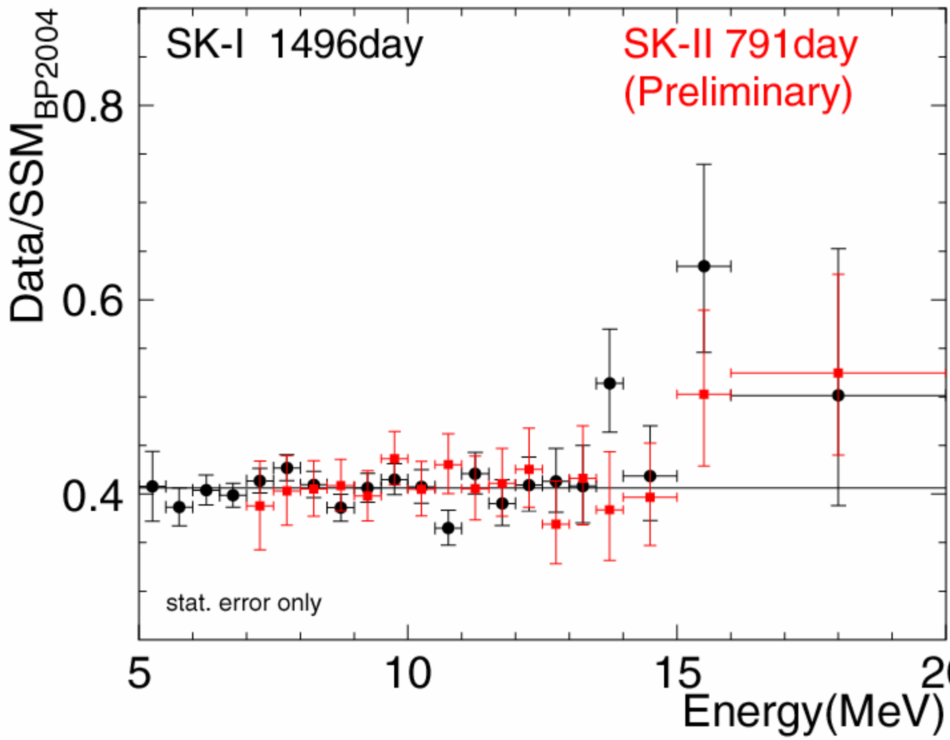
Event direction

SK-II 791 days   7-20MeV



signal = 7239^{+154}_{-152} (stat.)

Energy spectrum



Consistent with SK-I

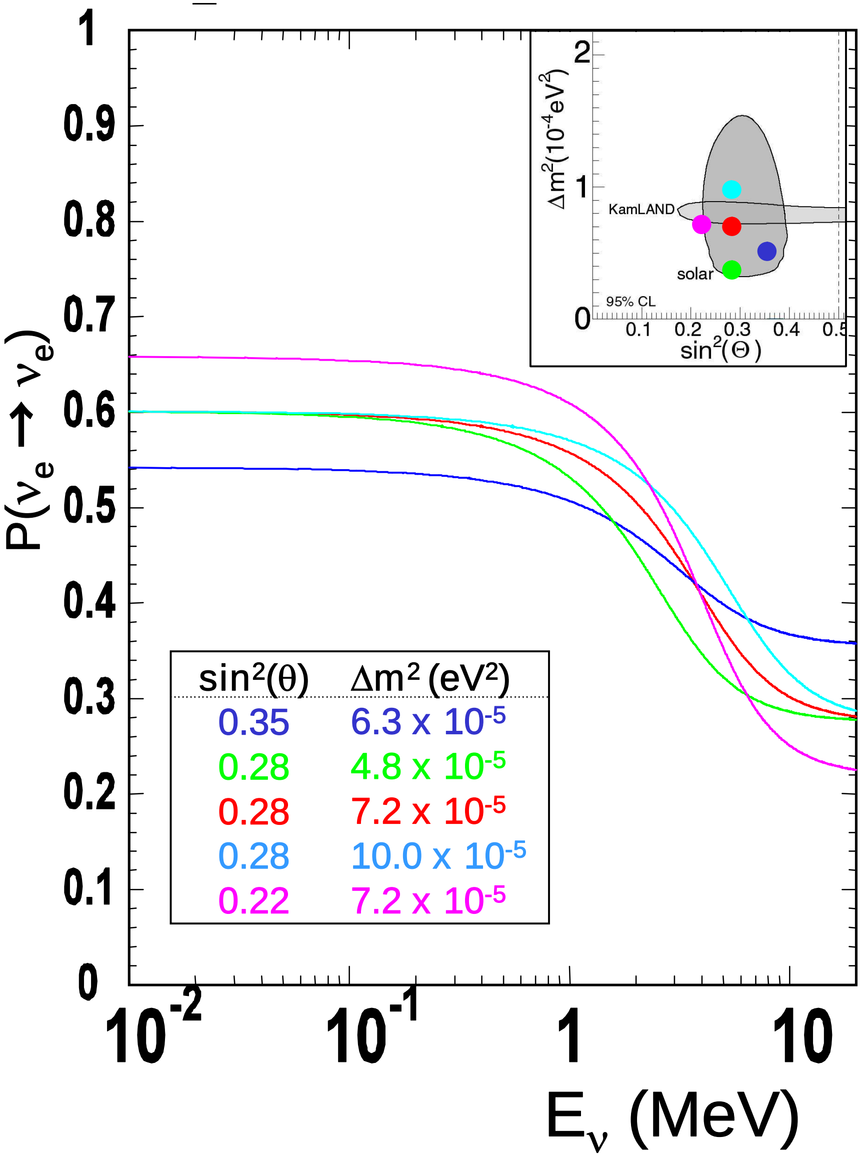
flux = 2.38 ±0.05 (stat.) +0.16/-0.15(sys.) $\times 10^6/cm^2/sec$

SK-I result: 2.35 +/-0.02(stat.) +/-0.08(syst.)

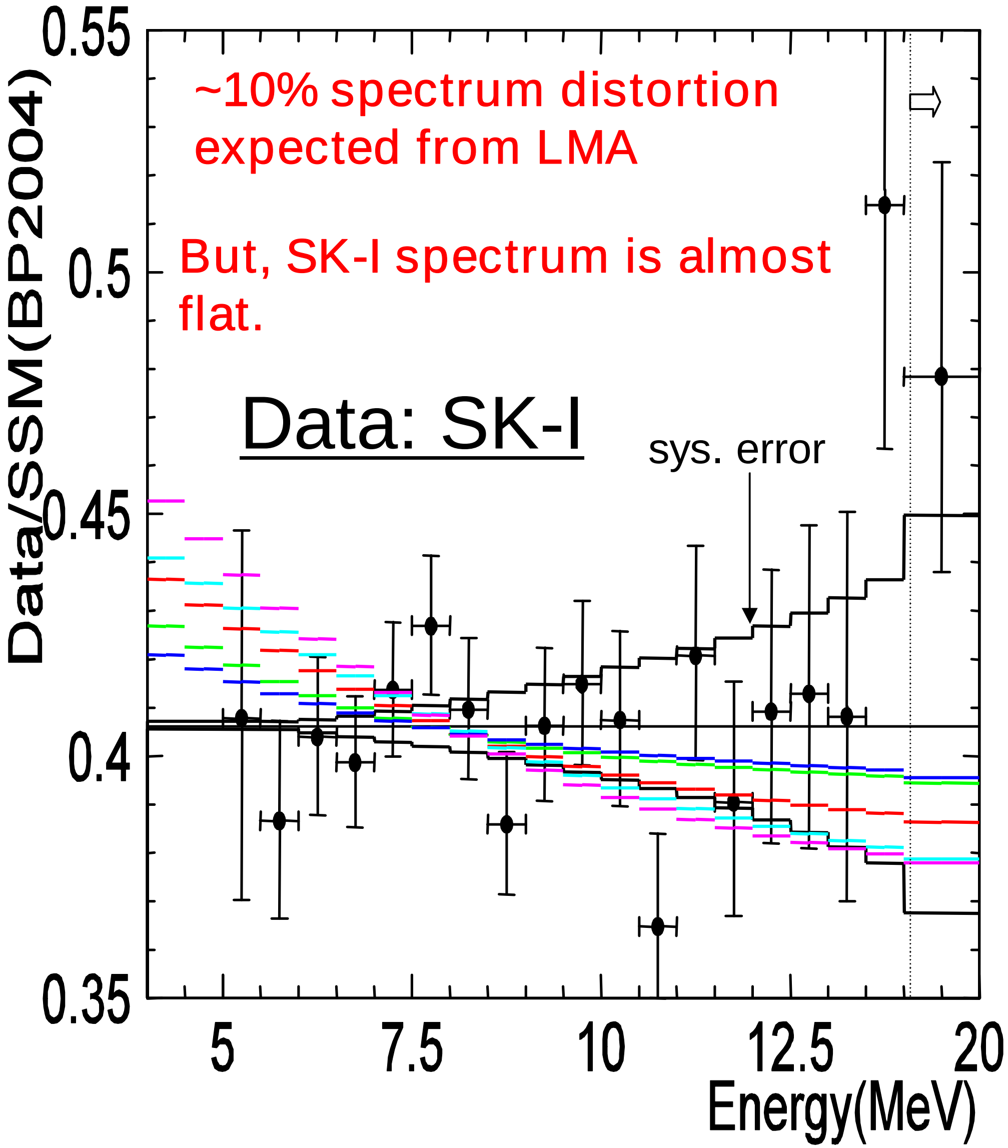
Future prospects: precise spectrum measurement

Is there spectrum distortion ?

ν_e survival probability

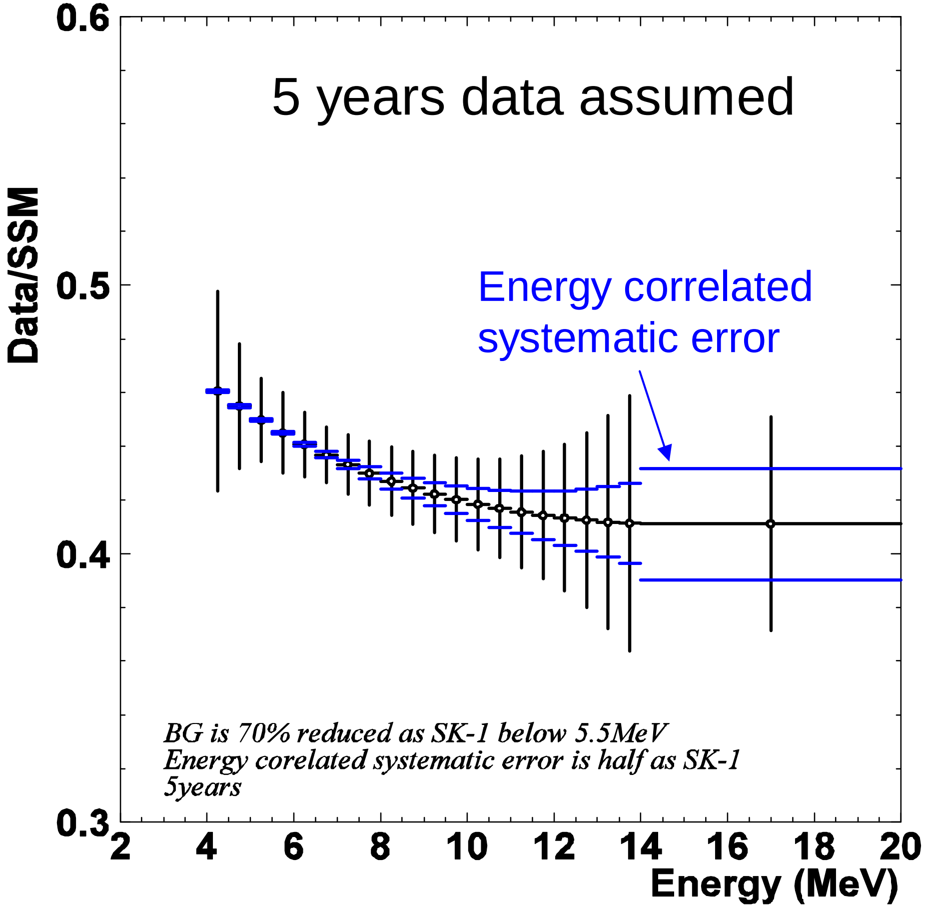


Recoil electron spectrum

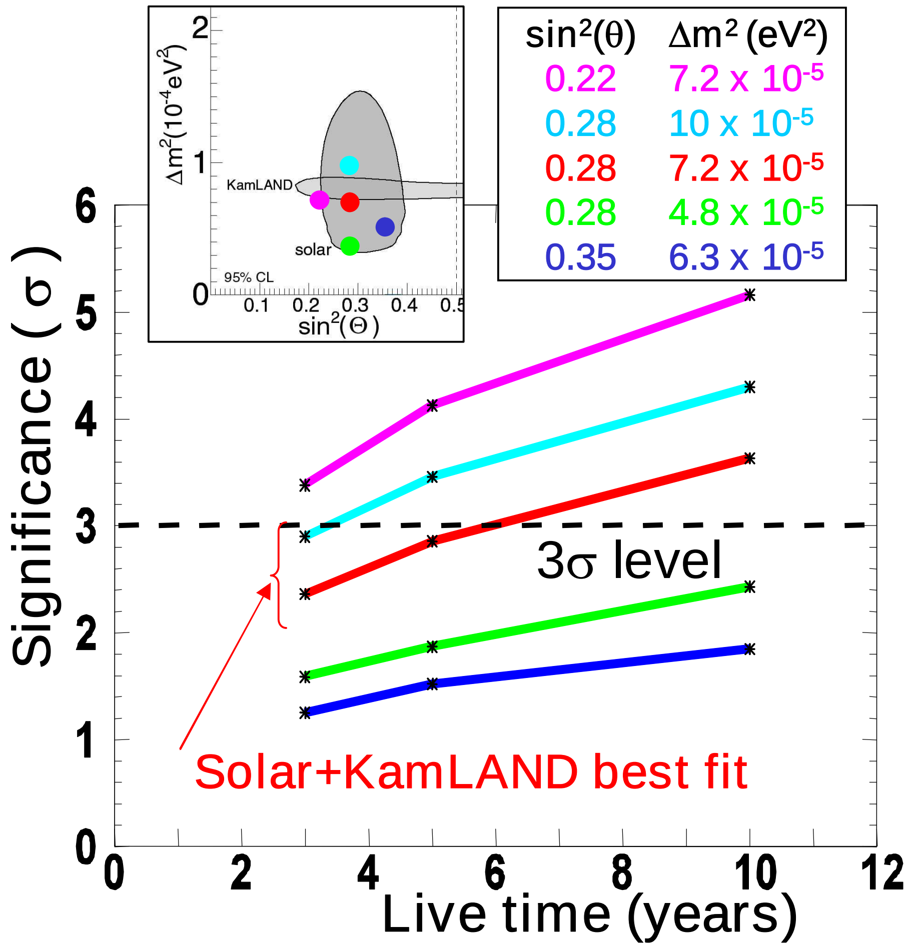


Future propsects: expected sensitivity of SK-III

Expected spectrum in SK-III



Statistical significance



Assumption:

Correlated systematic error: x 0.5

4.0-5.5MeV background : x 0.3 of SK-I

(> 5.5MeV is same as SK-I)

Summary of Solar neutrino analysis

Activities from 2000 to 2006

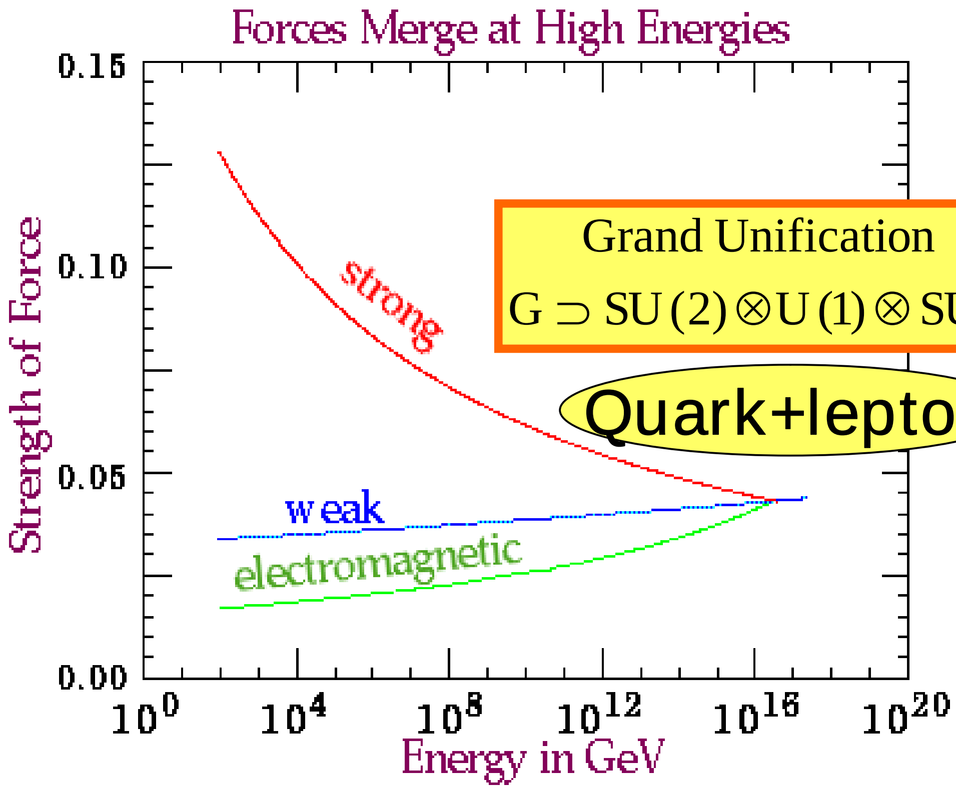
- Evidence for solar neutrino oscillation by comparing SK and SNO data in 2001.
- The flat energy spectrum and small day/night value of SK favored LMA solution.
- LMA solution was obtained by solar global analysis (SK, SNO, radiochemical) with 99% CL.
- SK-II data is consistent with SK-I data.

Future prospects

- Precise measurement of energy spectrum.
  ~10% distortion is expected for the LMA solution.
  By lowering background in lower energy region, it should be observed in 5-7 years.

Proton decay search

Physics

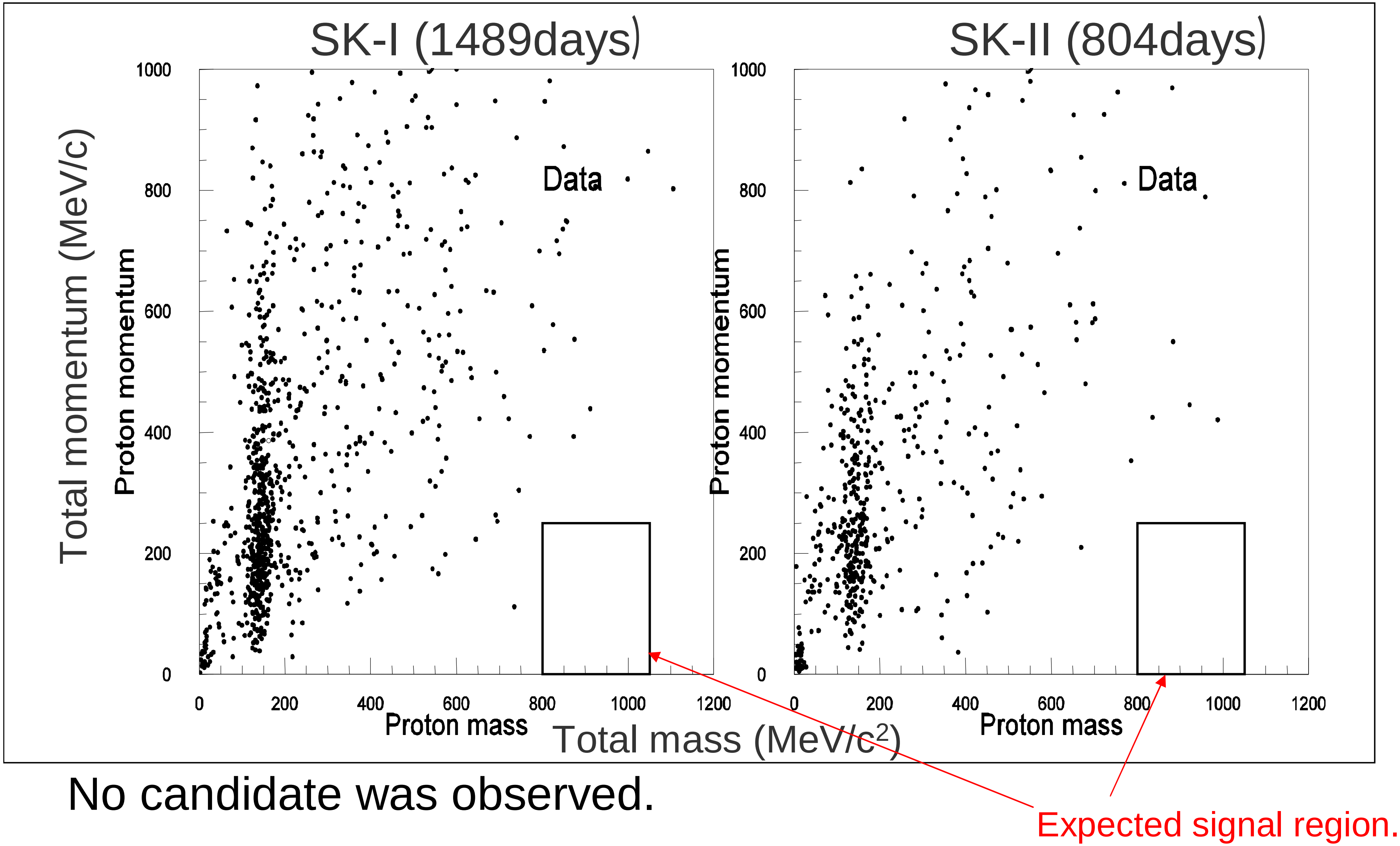


Grand Unification

$G \supset SU(2) \otimes U(1) \otimes SU(3)$

Quark+lepton → **Establish GUT**

Proton decay search ($p \rightarrow e^+\pi^0$)

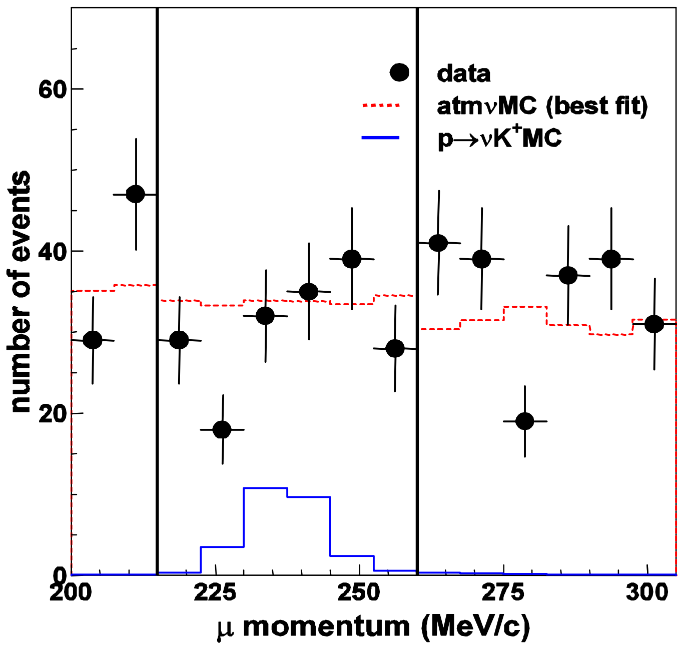


No candidate was observed.

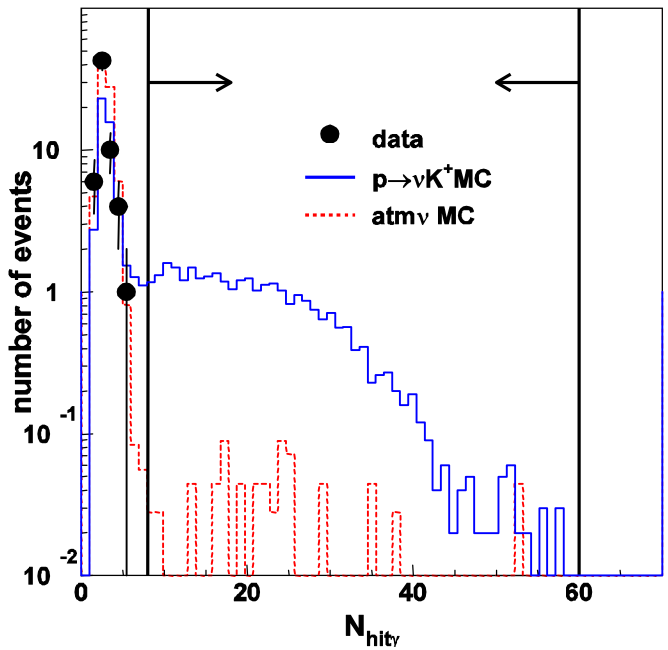
Life time limit ($p \rightarrow e^+\pi^0$)：>8.4 x 10^{33} years

Proton decay search ($p \rightarrow \nu K^+$)

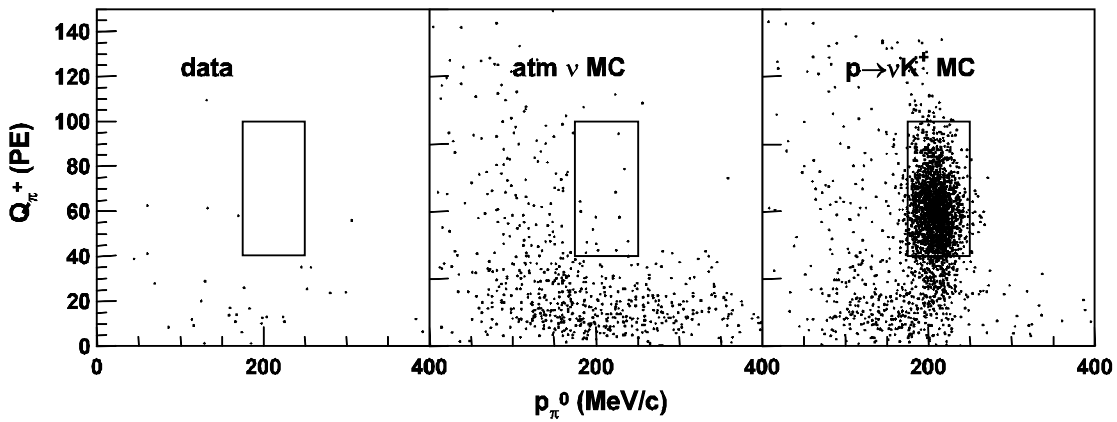
μ^+ shape method



Prompt γ method



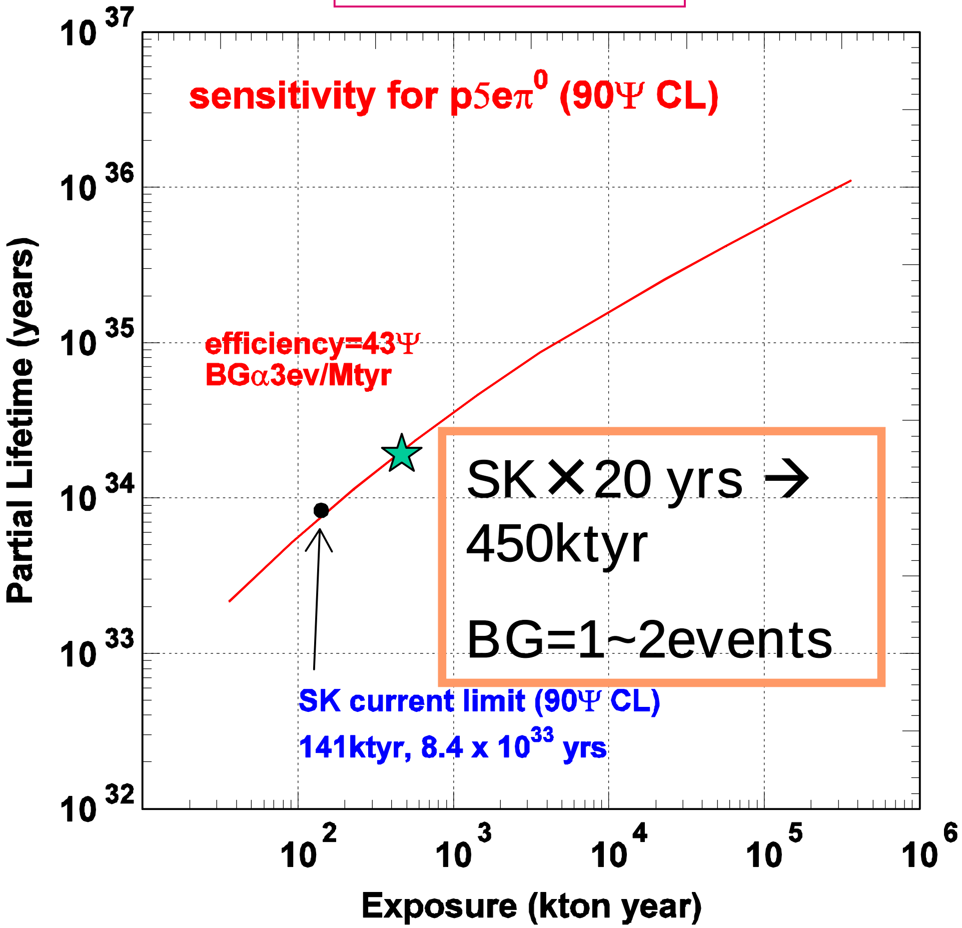
$K^+ \rightarrow \pi^+\pi^0$ method



Combine those methods,
Lifetime: >2.3 x 10^{33} years

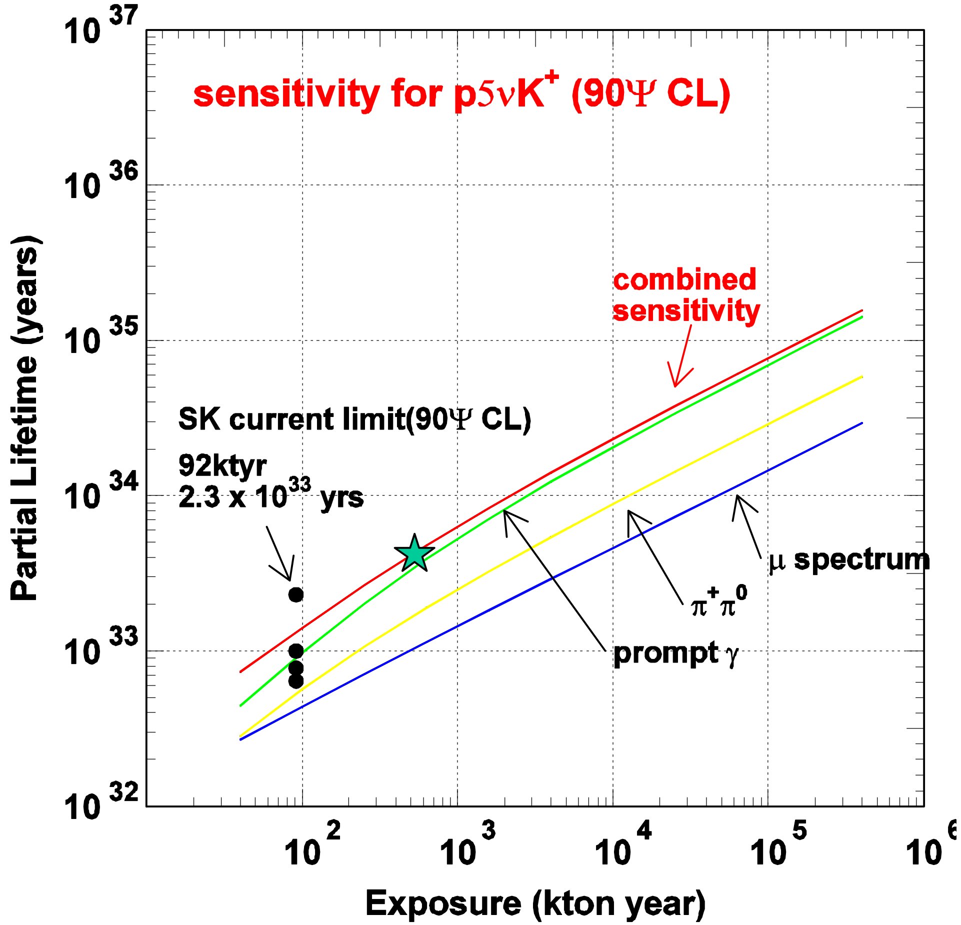
Sensitivity of future SK

$p \rightarrow e^+\pi^0$



τ /B → 2 × 10^{34} yrs
(SK 20yrs, 90%CL)

$p \rightarrow \nu K^+$



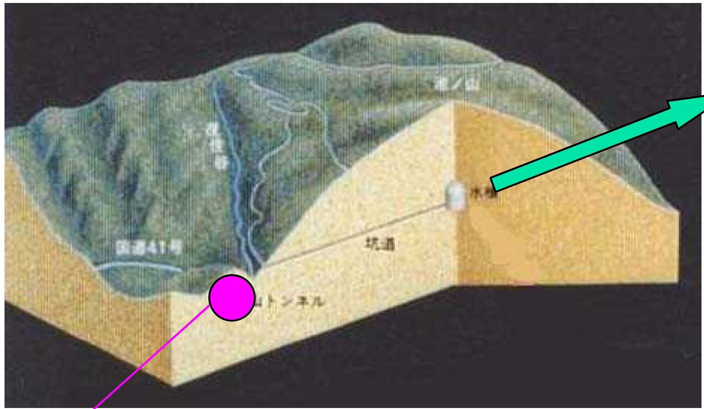
τ /B → 4 × 10^{33} yrs
(SK 20yrs, 90%CL)

Supernova neutrinos

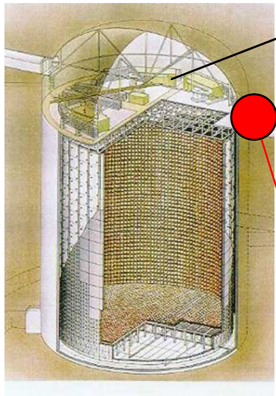
Physics

- High statistics supernova events at neutrino burst (~8000 events at 10kpc) to investigate detailed mechanism of supernova burst.
- Supernova relic neutrinos (SRN) to study star formation in the universe.

Supernova burst search (online)



Offline computer



Data Acquisition system

Online host computer

A few minutes later

Supernova watch computer

If a candidate is found

ALARM

Notify to shift person

Check vertex distribution and event pattern

Send signal to SNEWS

SNEWS: (SuperNova Early Warning System)

Current members: SK, SNO, AMANDA/Ice Cube, LVD

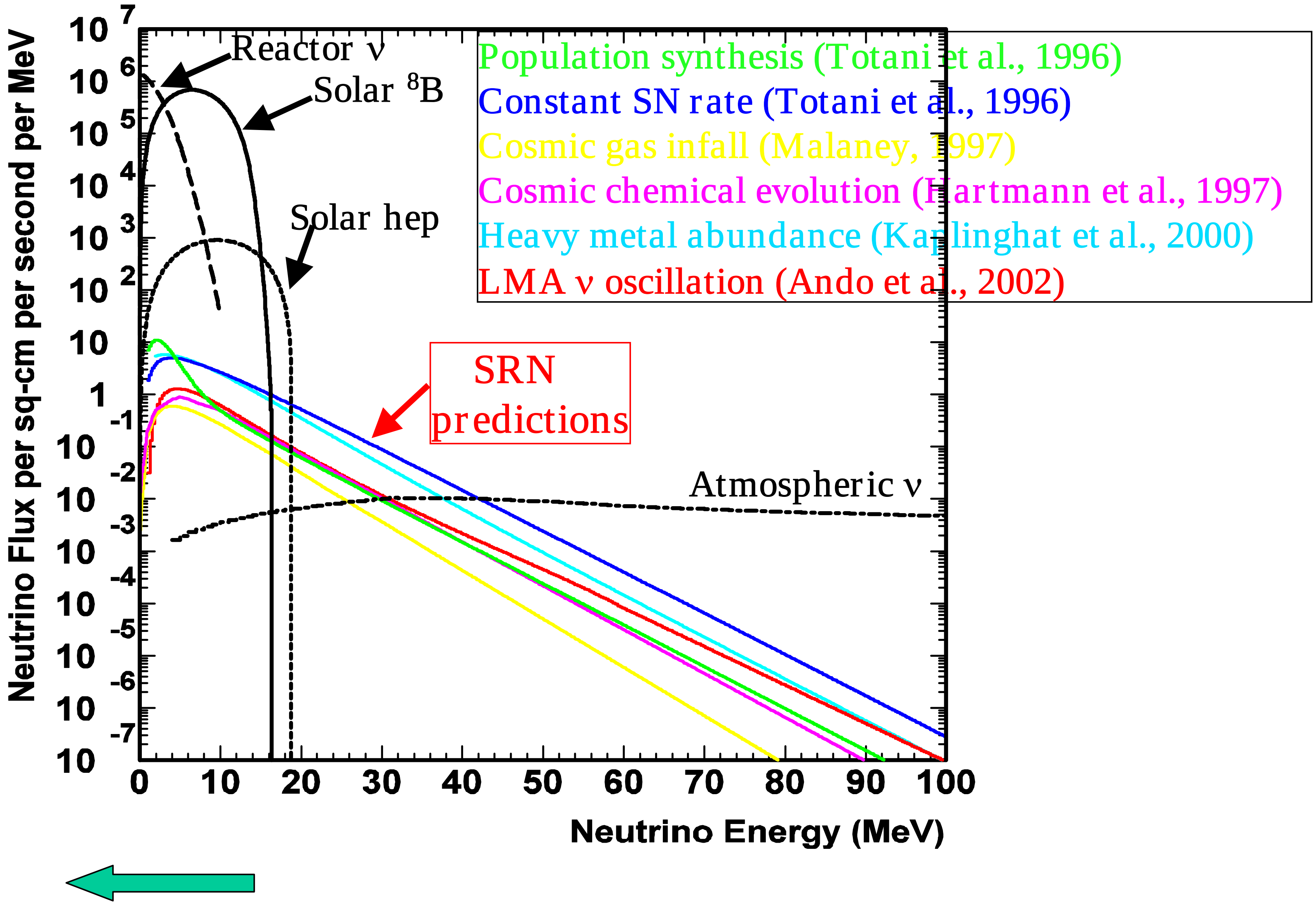
Selection criteria:

- $\geq$ 25 ev. within 10 sec.
- Rmean > 7.5m

Rmean: averaged distance between event vertices. This cut reject spallation and flasher backgrounds.

Alarm rate was about once per ~10 days. (specification of SNEWS).
They were due to PMT flashers and multiple spallation events.
No real galactic supernova was found during SK-I and SK-II.

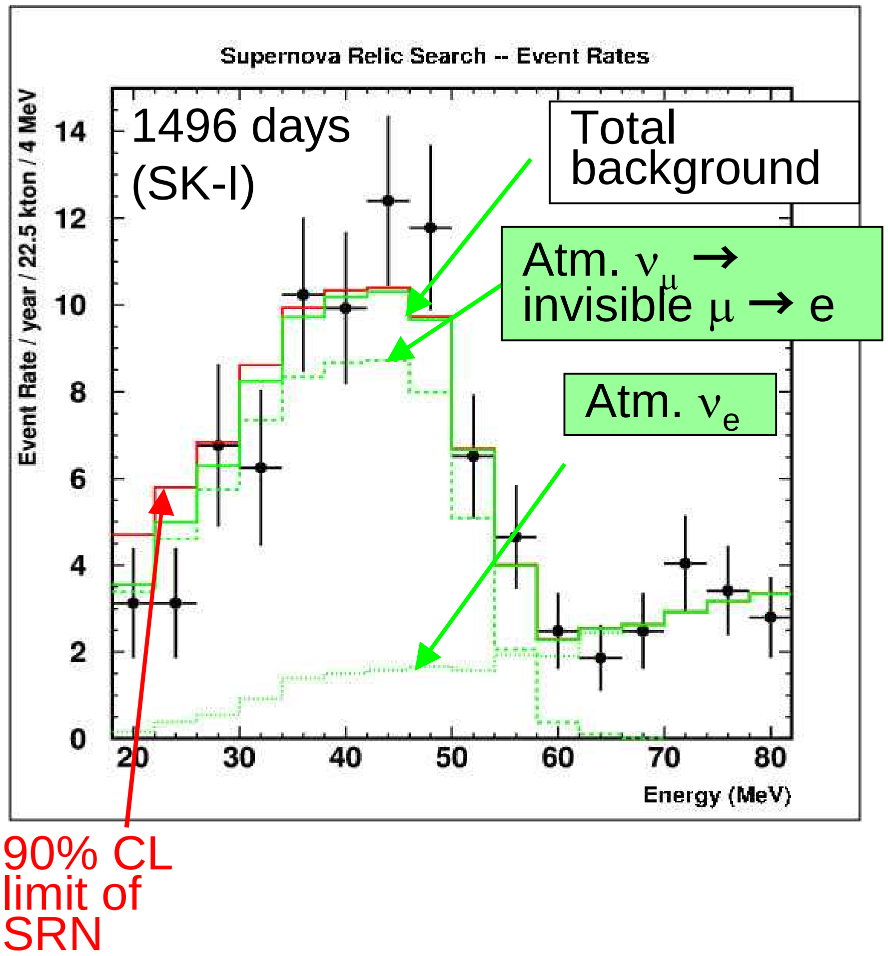
Search for supernova relic neutrinos



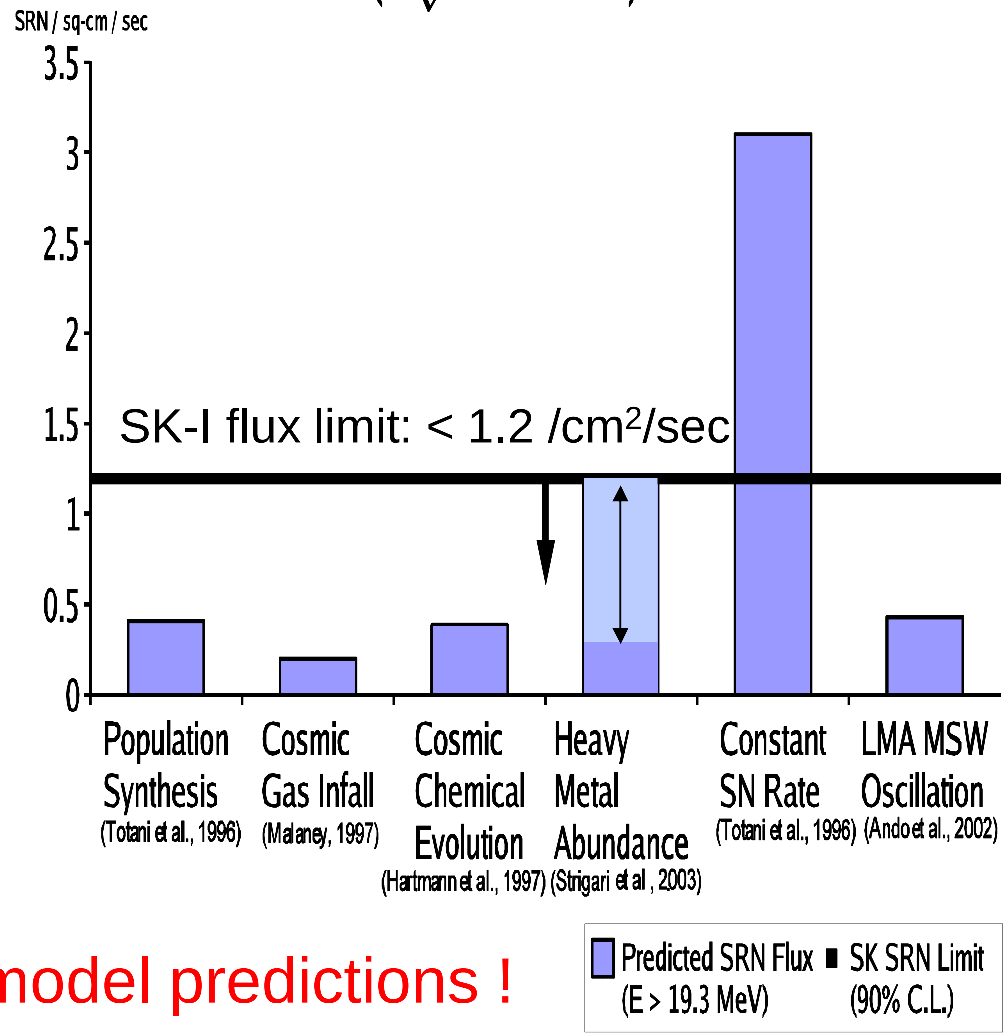
Spallation B.G. below ~18 MeV

Search for supernova relic neutrinos in SK-I

Energy spectrum (>18MeV)

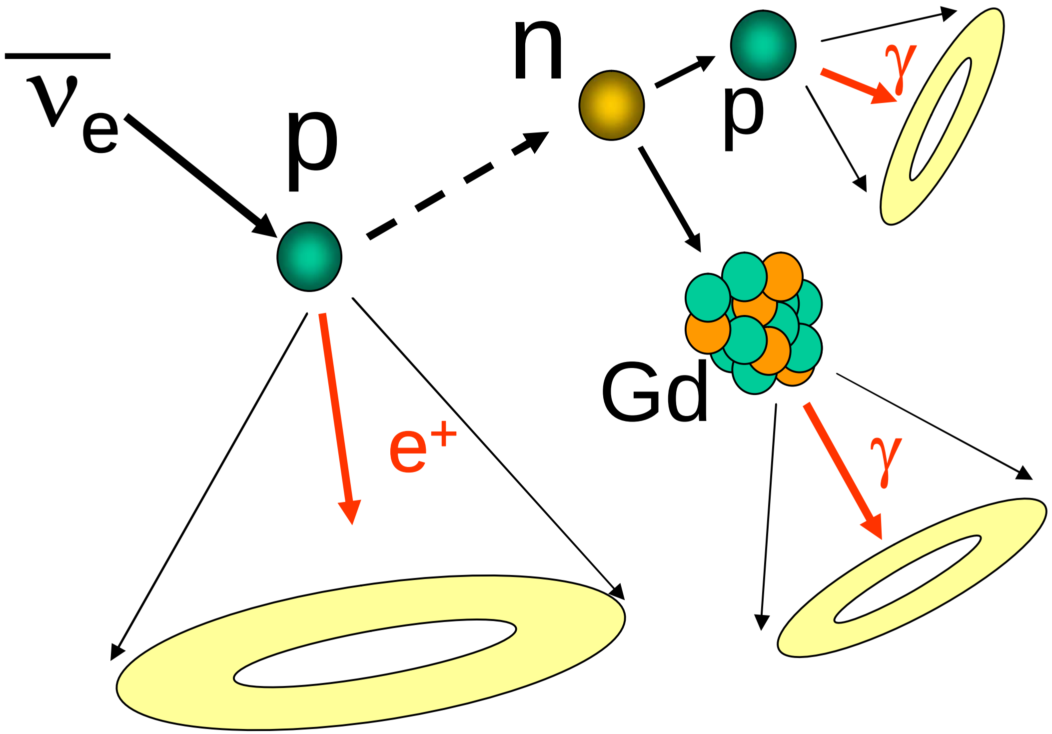


SK SRN Flux Limits vs. Theoretical Predictions ($E_{\bar\nu} > 19.3$ MeV)



SK limit is close to the model predictions !

Future: Possibilities of $\overline{\nu}_e$ tagging



Positron and gamma ray vertices are within ~50cm.

Possibility 1

n+p→d + γ

2.2MeV γ-ray

ΔT = ~ 200 μsec

Number of hit PMT is about 6 in SK-III

Possibility 2

n+Gd →~8MeV γ

ΔT = several 10th μsec

Add 0.2% $GdCl_3$ in water

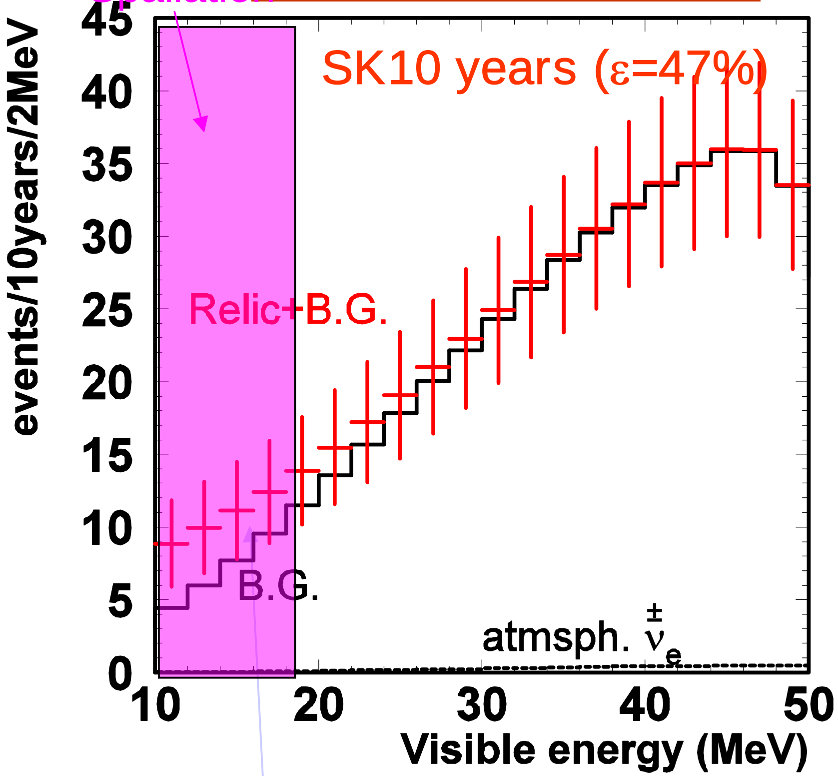
(ref. Vagins and Beacom)

$\overline{\nu}_e$ could be identified by delayed coincidence.

Possibility of SRN detection

Relic model: S.Ando, K.Sato, and T.Totani, Astropart.Phys.18, 307(2003) with flux revise in NNN05.

No B.G. reduction

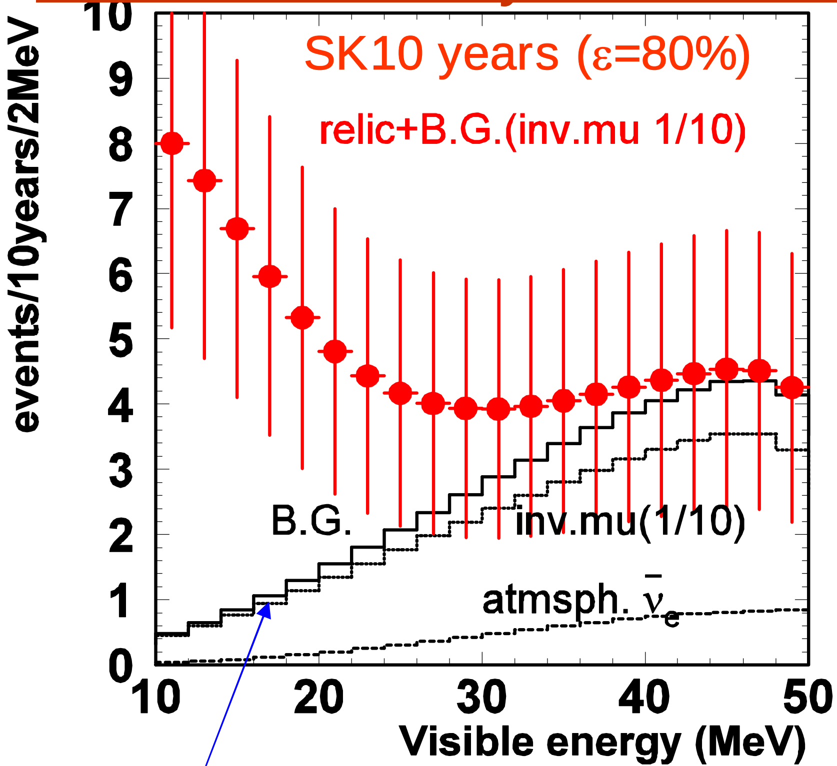


Hard to distinguish

Statistically <1σ excess
(10yrs, E_{vis} =18-30 MeV)

~1.2σ for SK20yrs

B.G. reduction by neutron tagging



Assuming 90% of invisible muon B.G. can be reduced by neutron tagging.

Assuming 80% detection efficiency.

Signal: 22.7, B.G. 13.1(E_{vis} =15-30 MeV)

Signal: 44.8, B.G. 14.7(E_{vis} =10-30 MeV)

Summary of proton decay

- **Activities from 2000 to 2006**
  - Lifetime lower limit was obtained:
    - $p \rightarrow e^+\pi^0$: >8.4 x 10^{33} yrs
    - $p \rightarrow \nu K^+$: >2.3 x 10^{33} yrs
- **Future prospects**
  - $p \rightarrow e^+\pi^0$: >2 x 10^{34} yrs, $p \rightarrow \nu K^+$: >4 x 10^{33} yrs for 20 yrs data

Summary of supernova neutrinos

- **Activities from 2000 to 2006**
  - Supernova burst search has in online and offline analyses. No candidate was found.
  - SRN Flux limit: < 1.2 /cm^2/sec for E>18 MeV by SK-I data. It is close to theoretical predictions.
- **Future prospects**
  - Improved search for SRN neutrinos by neutron tagging.