Present status and prospects of Super-Kamiokande

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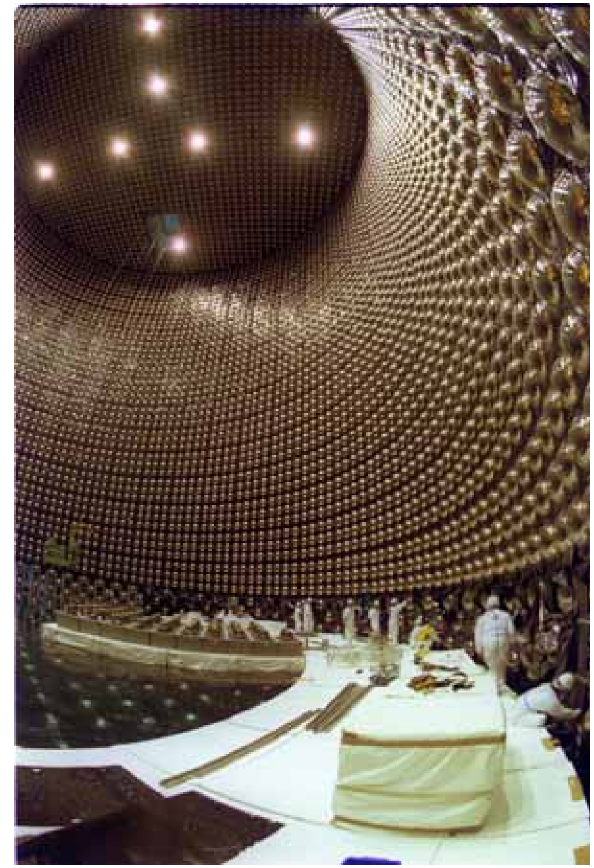
1. Super-Kamiokande detector
2. Atmospheric neutrinos
3. Solar neutrinos
4. Supernova relic neutrino search
5. Summary

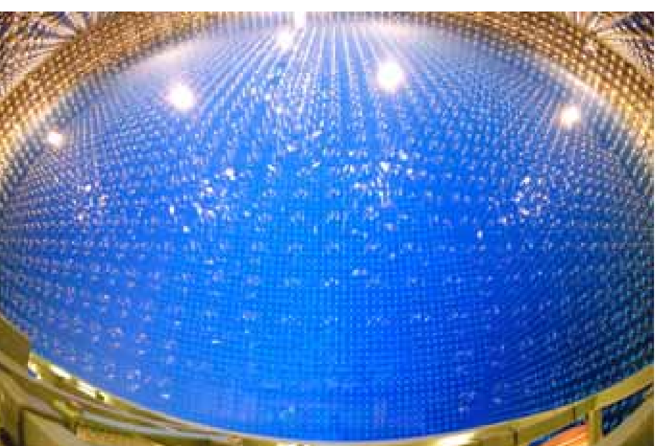
Full Reconstruction (October 2005 – April 2006)

~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.



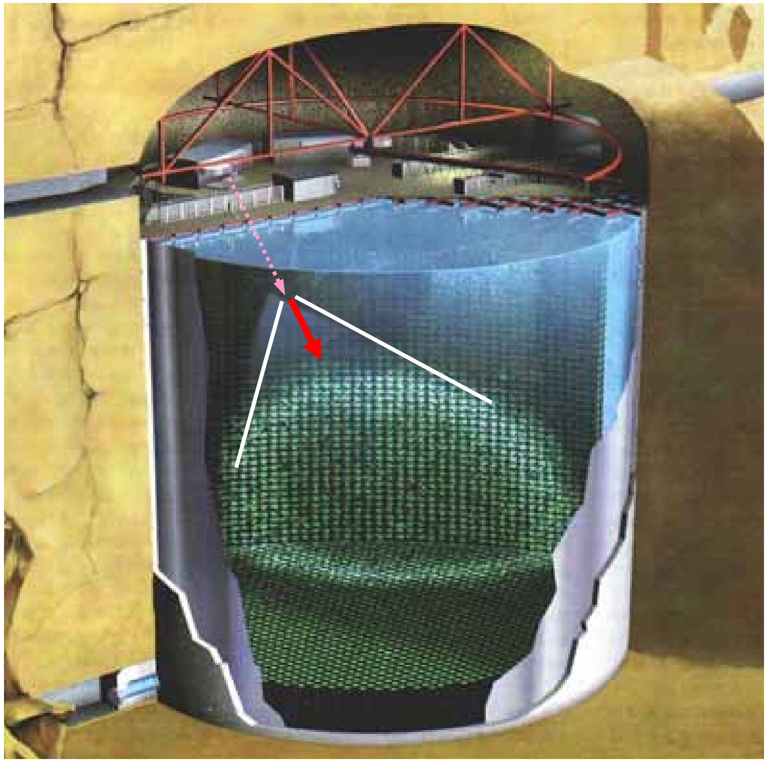
Mount PMTs on a floating floor.



Pure water was supplied and SK-III data taking has been running since July 11, 2006.
Fundamental calibrations done and data process ongoing.

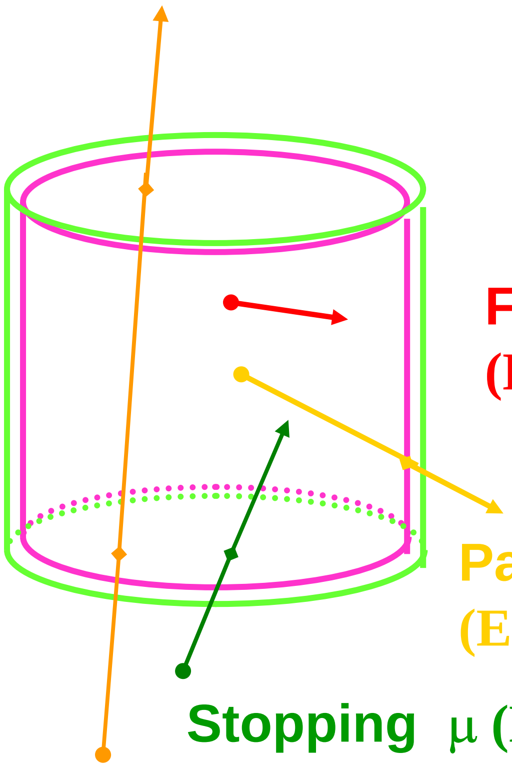
Observation of Atmospheric Neutrinos in Super-Kamiokande

Water Cherenkov detector



- 1000 m underground
- 50,000 ton (22,500 ton fid.)
- 11,146 20 inch PMTs (SK-I)
- 1,885 anti-counter PMTs

Event classification

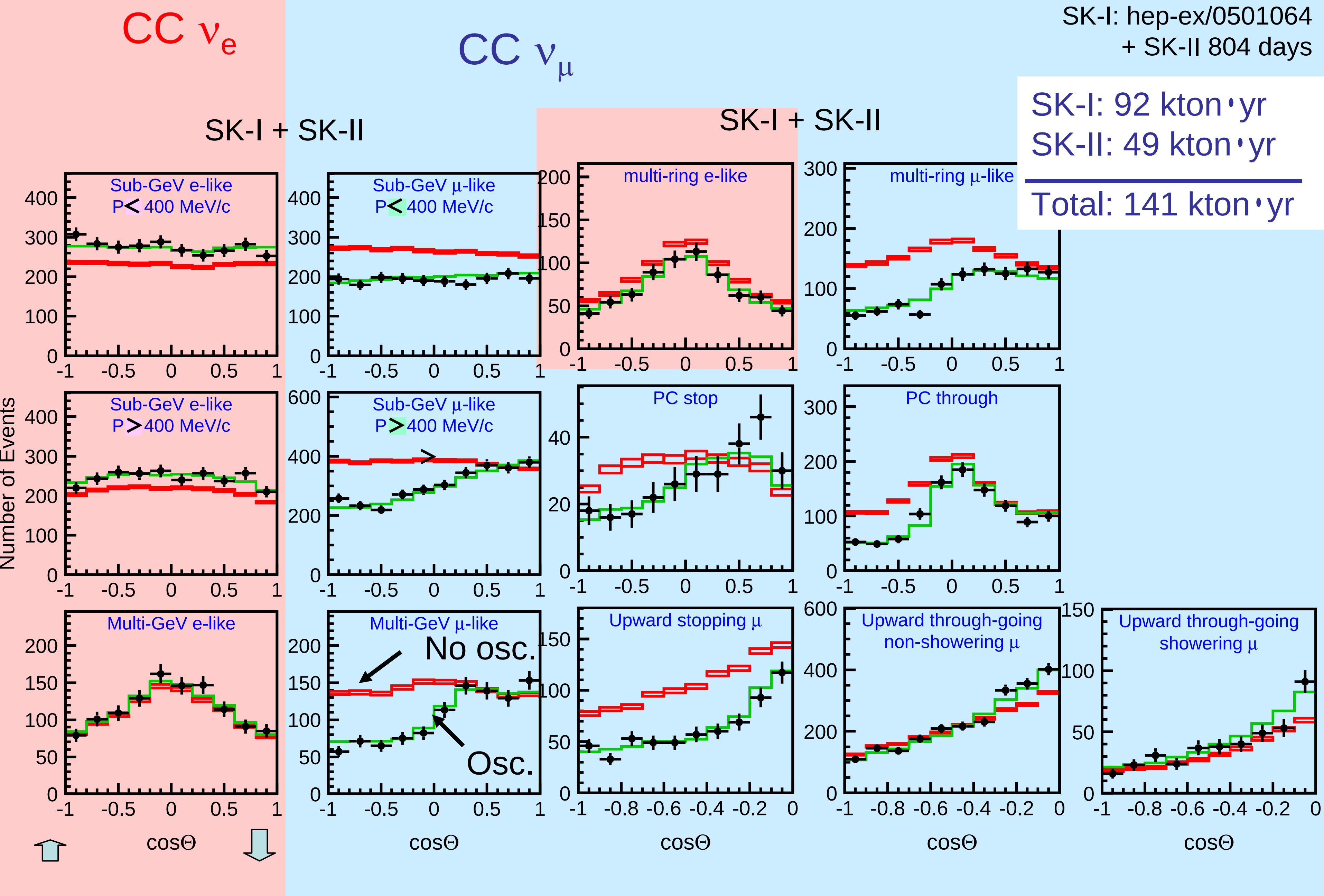


SK-I+II atmospheric neutrino data

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

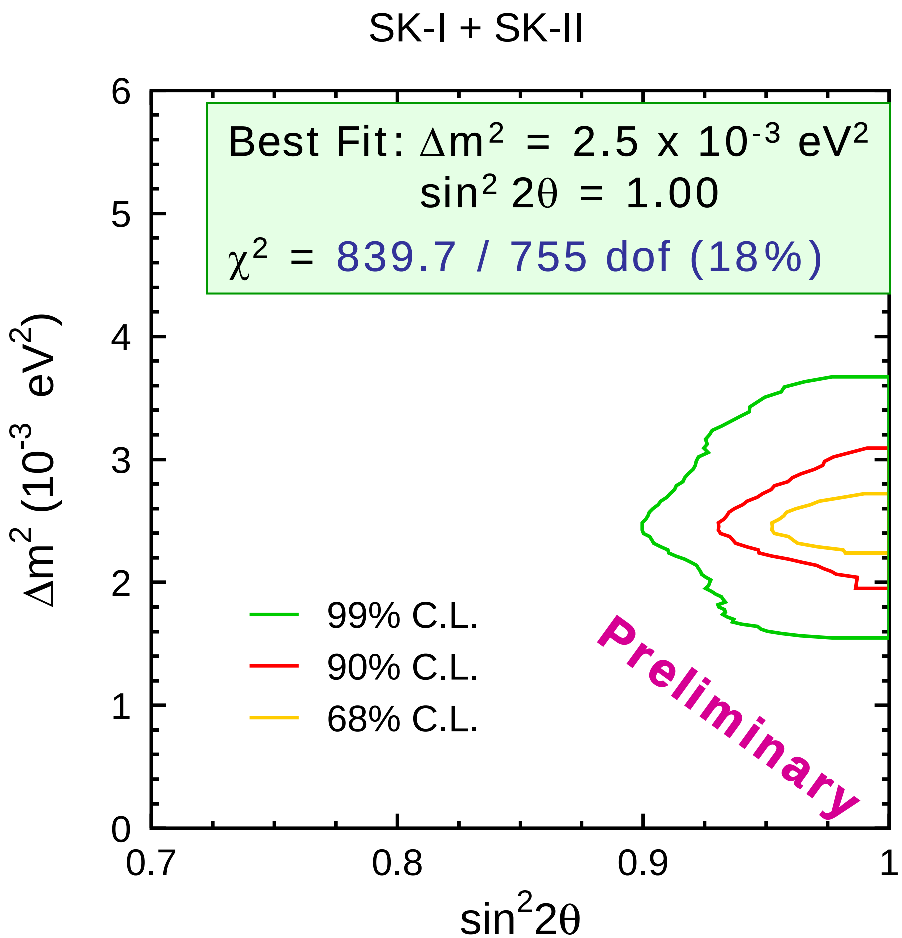
SK-I: 92 kton•yr
SK-II: 49 kton•yr

Total: 141 kton•yr

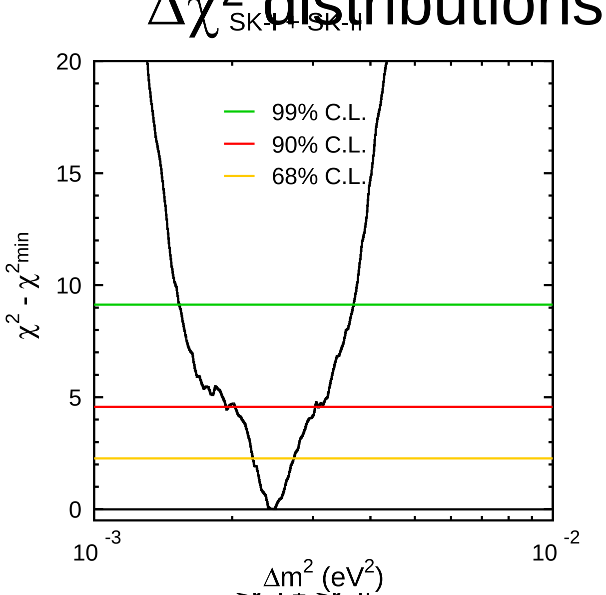


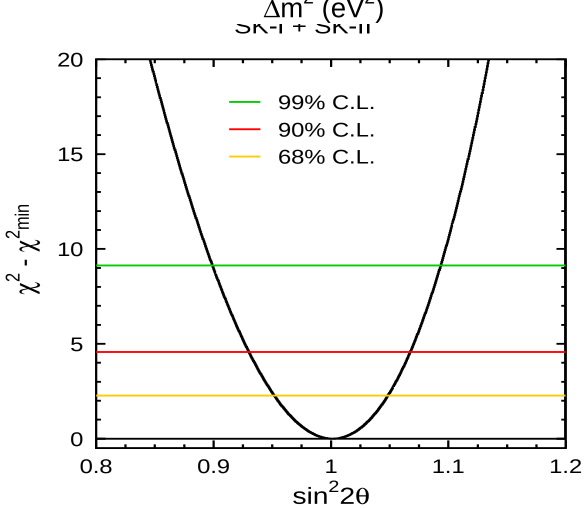
$\nu_\mu \rightarrow \nu_\tau$ 2 flavor analysis

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



$\Delta\chi^2$ distributions



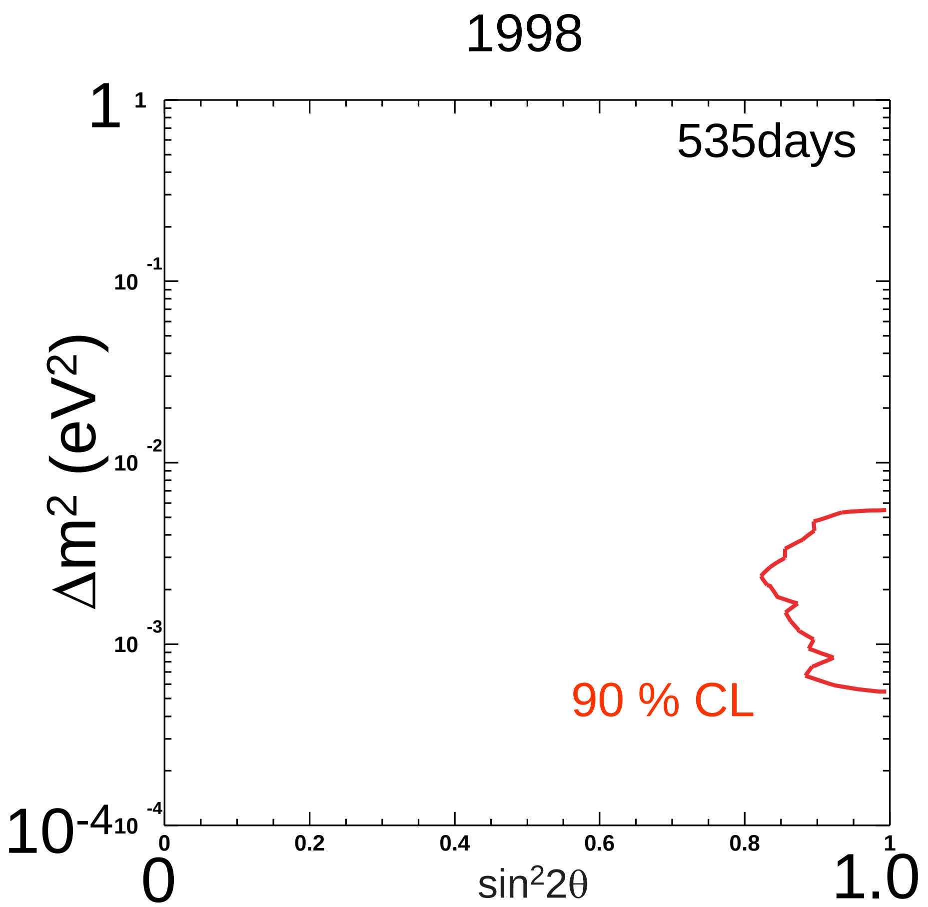


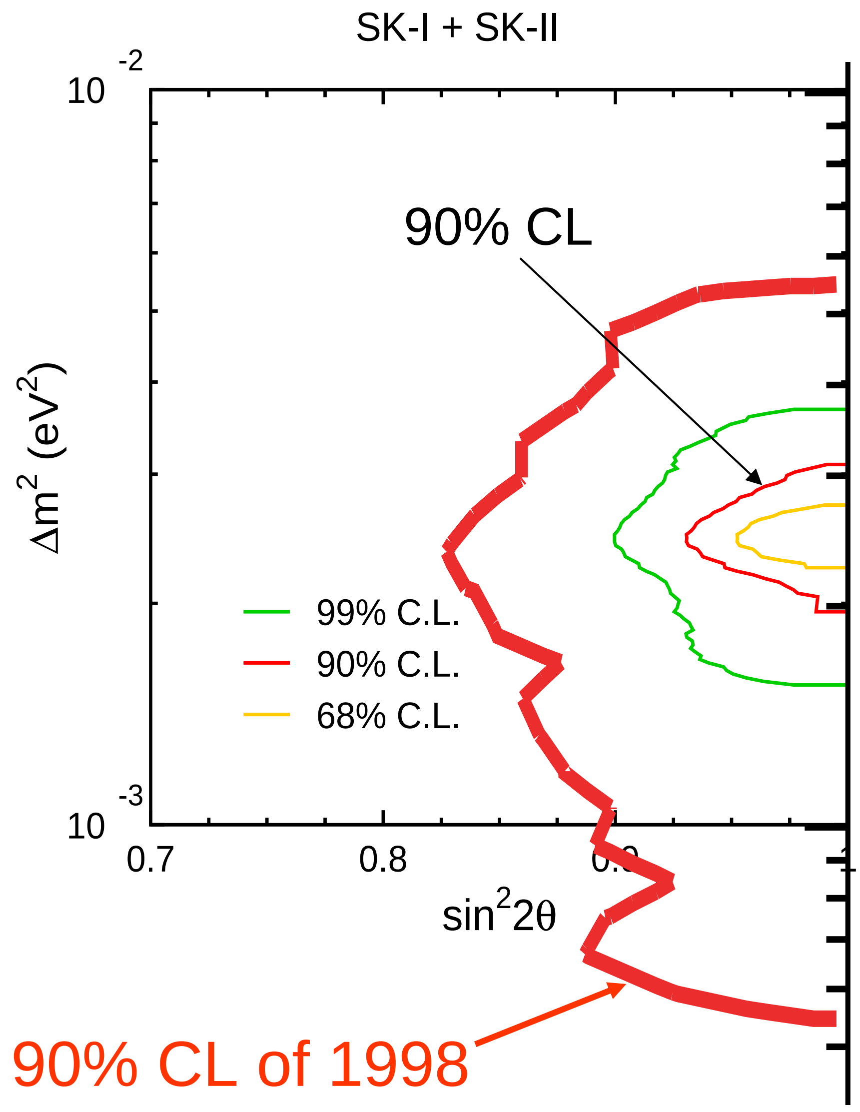
By using finer bins (370 bins both for SK-I and II), sensitivity for Δm^2 increased.

$1.9 \times 10^{-3}\ eV^2 < \Delta m^2 < 3.1 \times 10^{-3}\ eV^2$

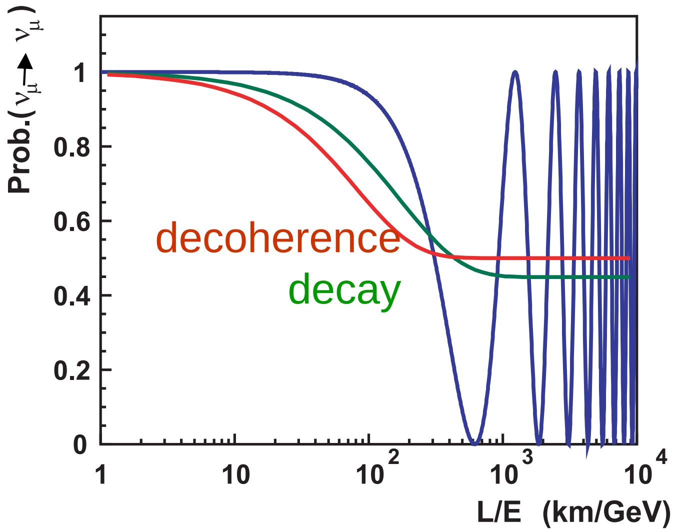
$\sin^2 2\theta > 0.93$ at 90% CL

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





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



oscillation

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

decoherence

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

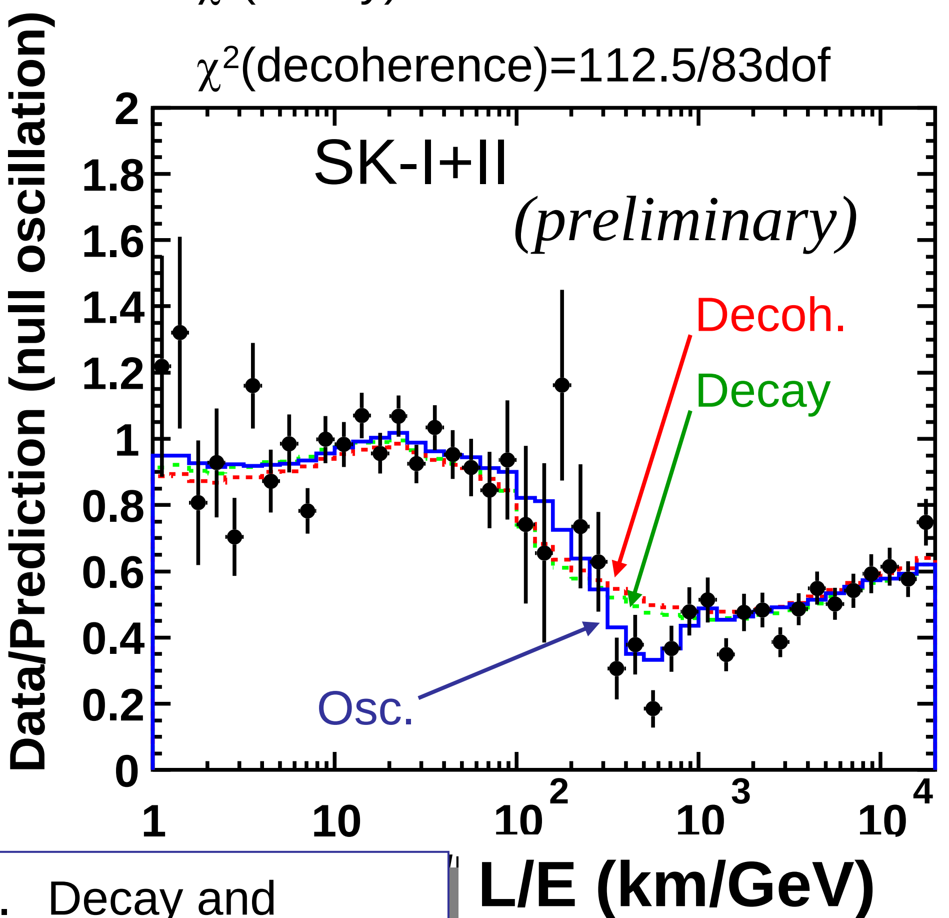
decay

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

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, respectively.

Future: Search for Non-zero θ_{13}: study of sub-dominant oscillations

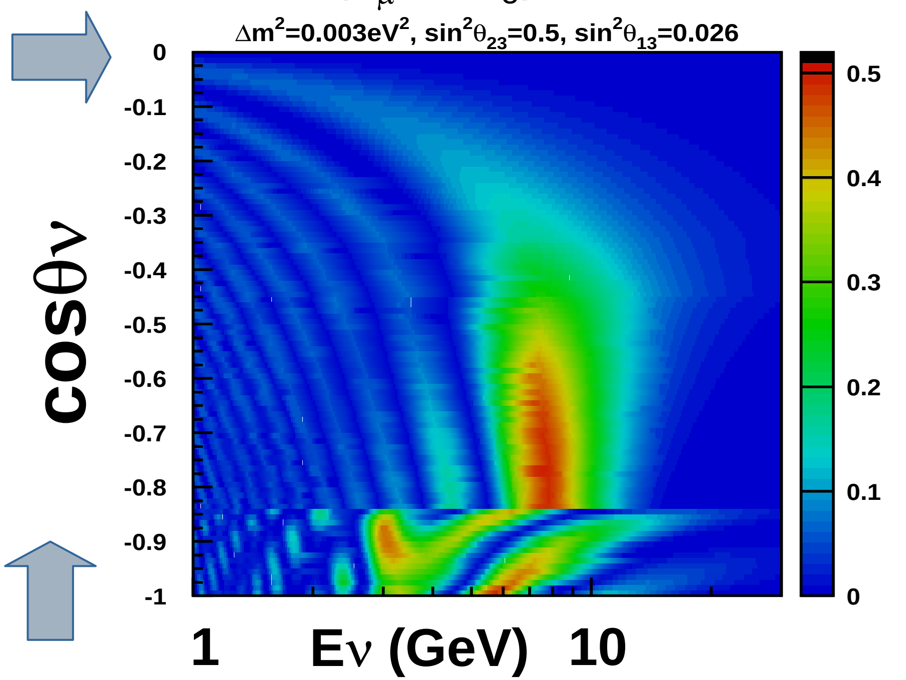
One mass scale dominance approx.

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

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

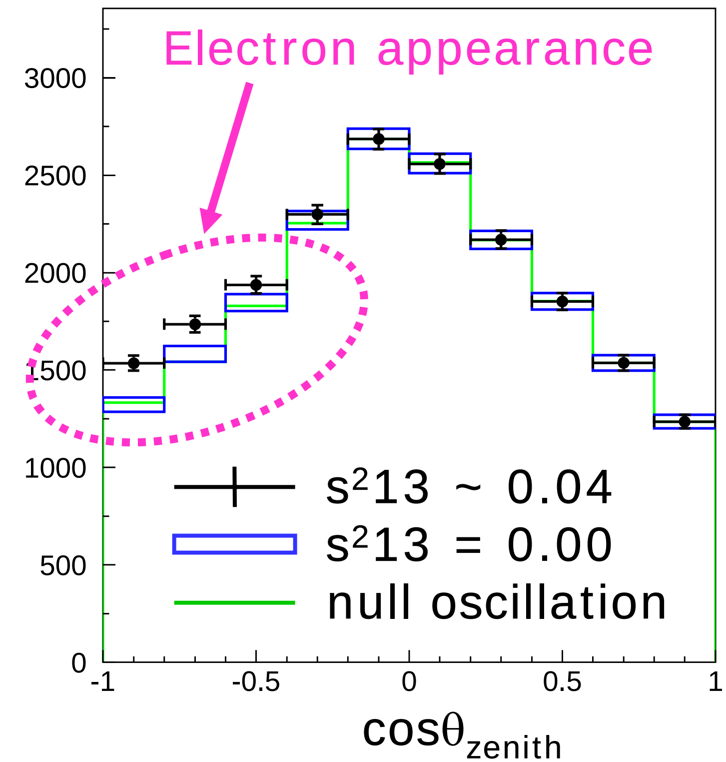
only 3 parameters

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



Simulation (4.5 Mton·yr)

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

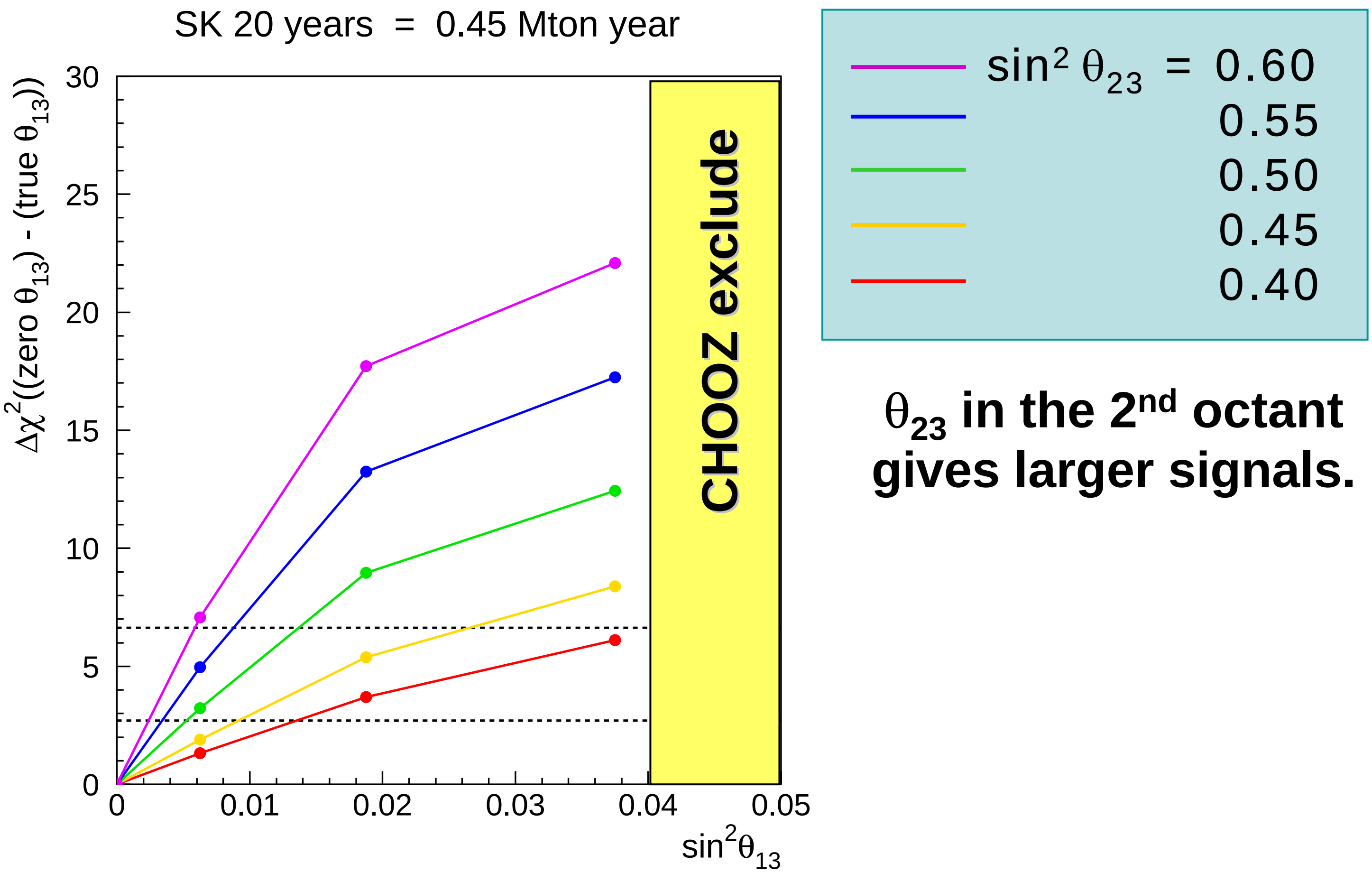


Using finely binned data, look for enhancement at certain energies and angles due to electron neutrino resonance in the earth.

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 ~ 0.6
$s^2\theta_{13}$=0.00~0.04
δcp=45º
Δm^2_{12}=8.3e-5
Δm^2_{23}=2.5e-3



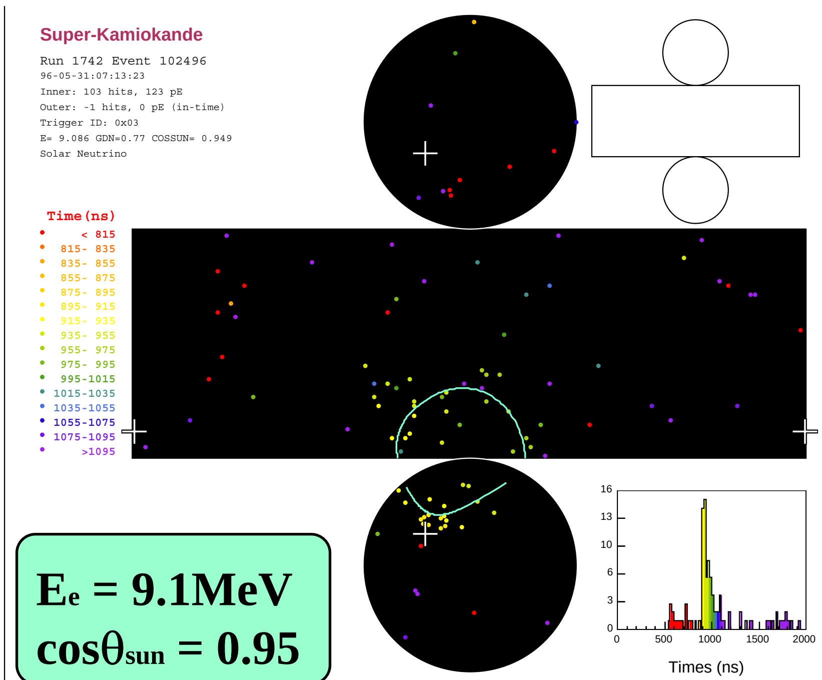
θ_{23} in the 2nd octant gives larger signals.

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

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.

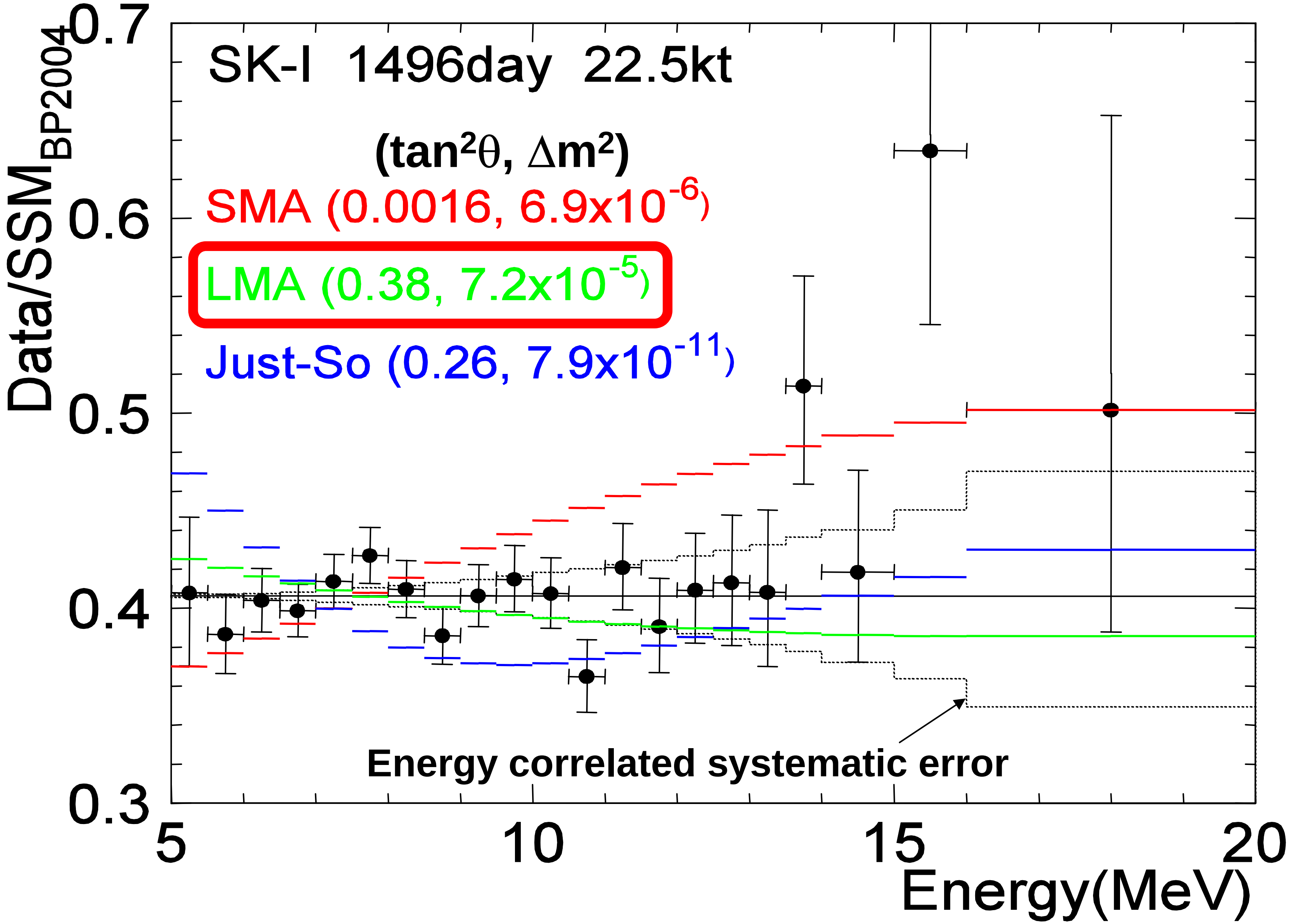
Typical event

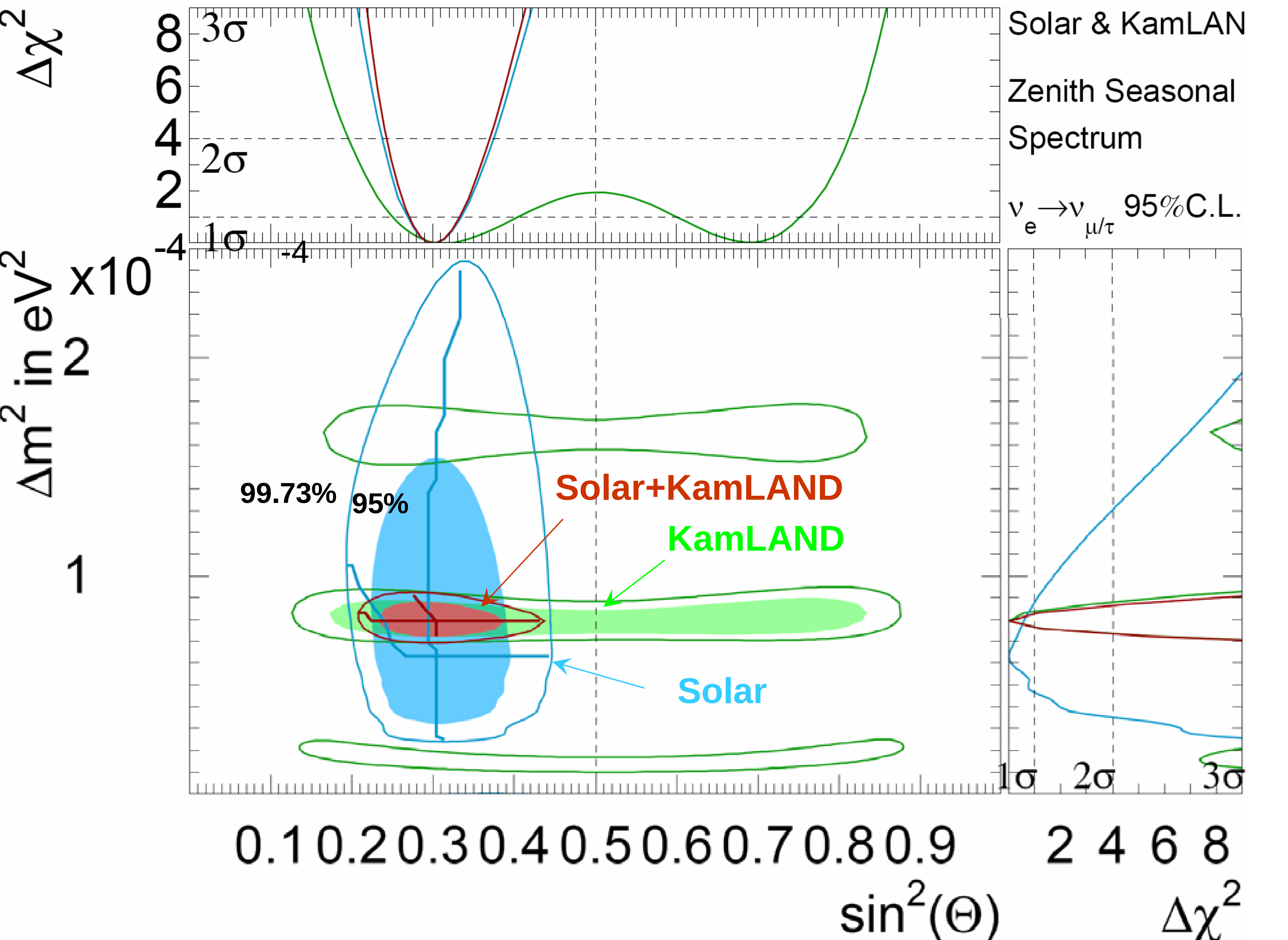


E_e = 9.1MeV
$\cos\theta_{sun}$ = 0.95

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

Energy spectrum of SK-I

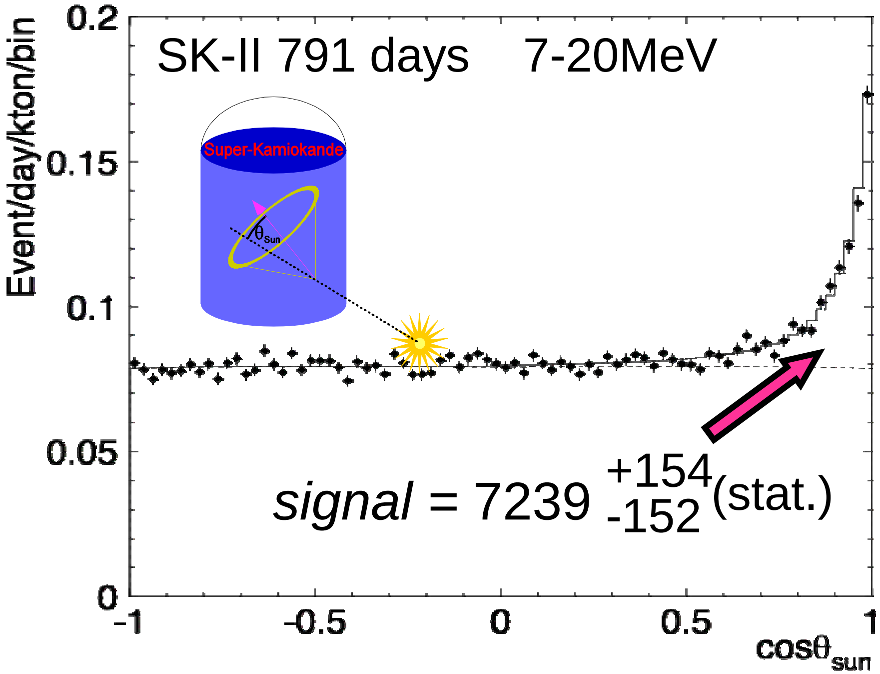




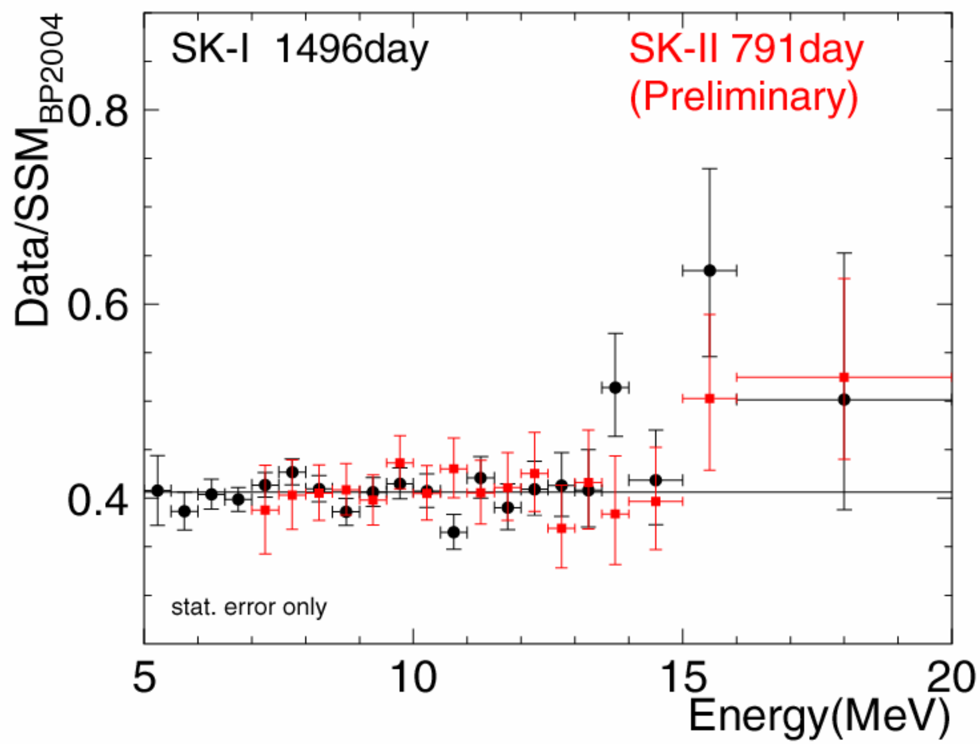
Solar & KamLAN
Zenith Seasonal
Spectrum
$\nu_e \rightarrow \nu_{\mu/\tau}$ 95%C.L.
$\Delta\chi^2$
8
6
4
2
3σ
2σ
1σ
Δm^2 in eV^2 $x10^{-4}$
-4
2
1
99.73%
95%
Solar+KamLAND
KamLAND
Solar
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
$\sin^2(\Theta)$
1σ 2σ 3σ
2 4 6 8
$\Delta\chi^2$

SK-II solar neutrino analysis

Event direction



Energy spectrum



Consistent with SK-I

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

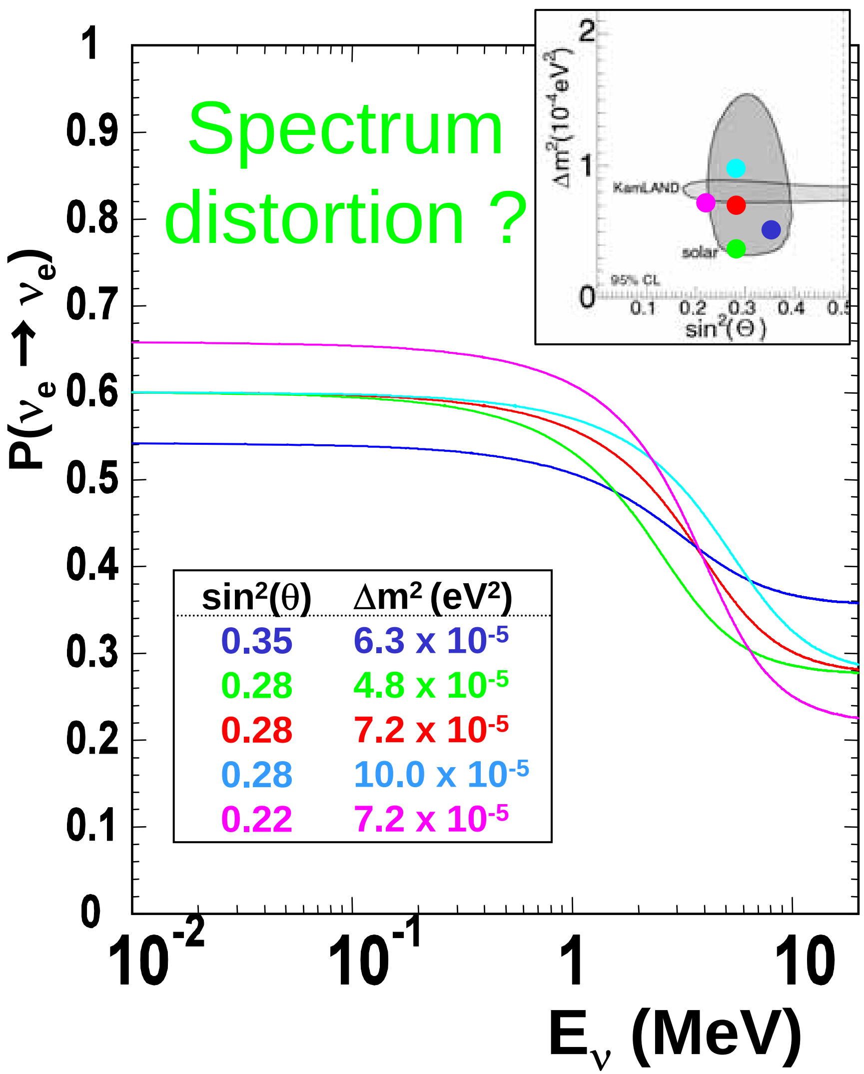
SK-I result: 2.35 +/-0.02(stat.) +/-0.08(syst.)

Future prospects: precise spectrum measurement

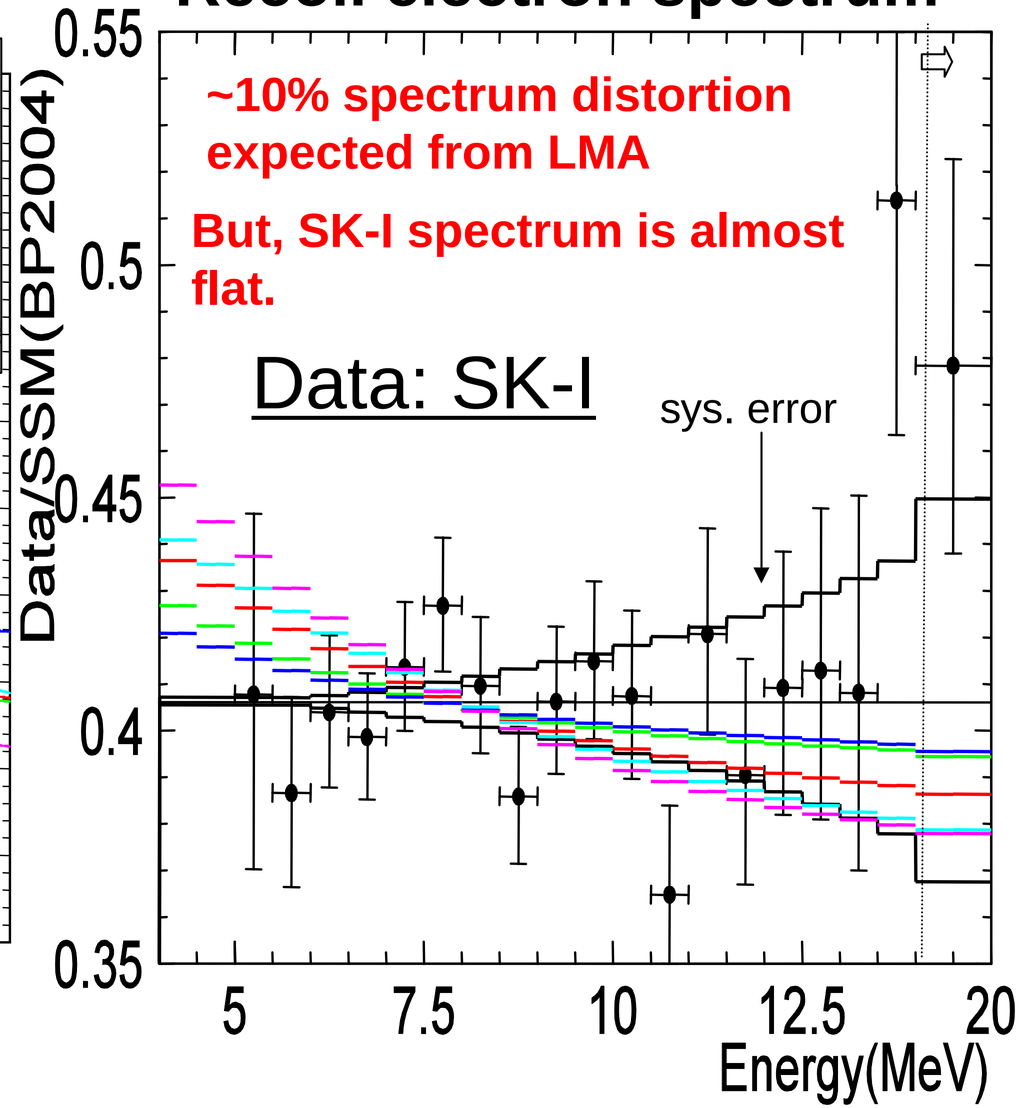
E <1 MeV: Vacuum $\theta_m \rightarrow \theta_V$ → $P=1-(1/2)\sin^2 2\theta$

E >a few MeV: Adiabatic $P=\cos^2\theta\cos^2\theta_m+\sin^2\theta\sin^2\theta_m$ → $P=\sin^2\theta$ $(\theta_m \rightarrow \pi/2)$

ν_e survival probability

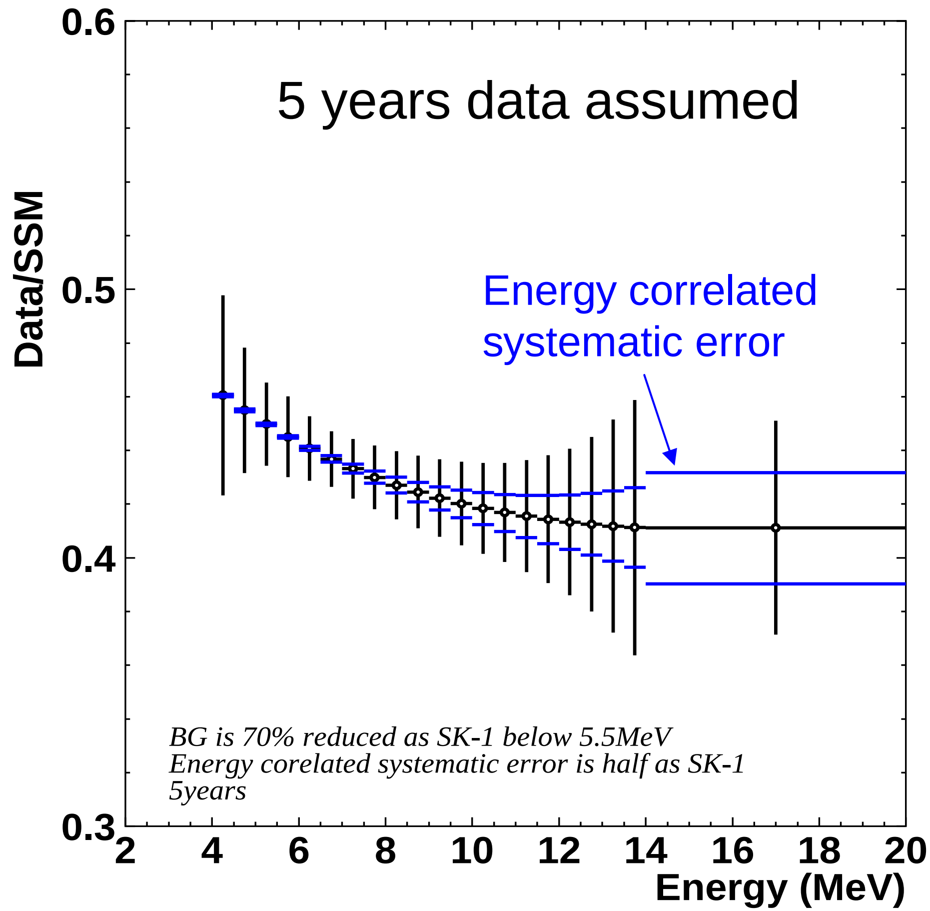


Recoil electron spectrum

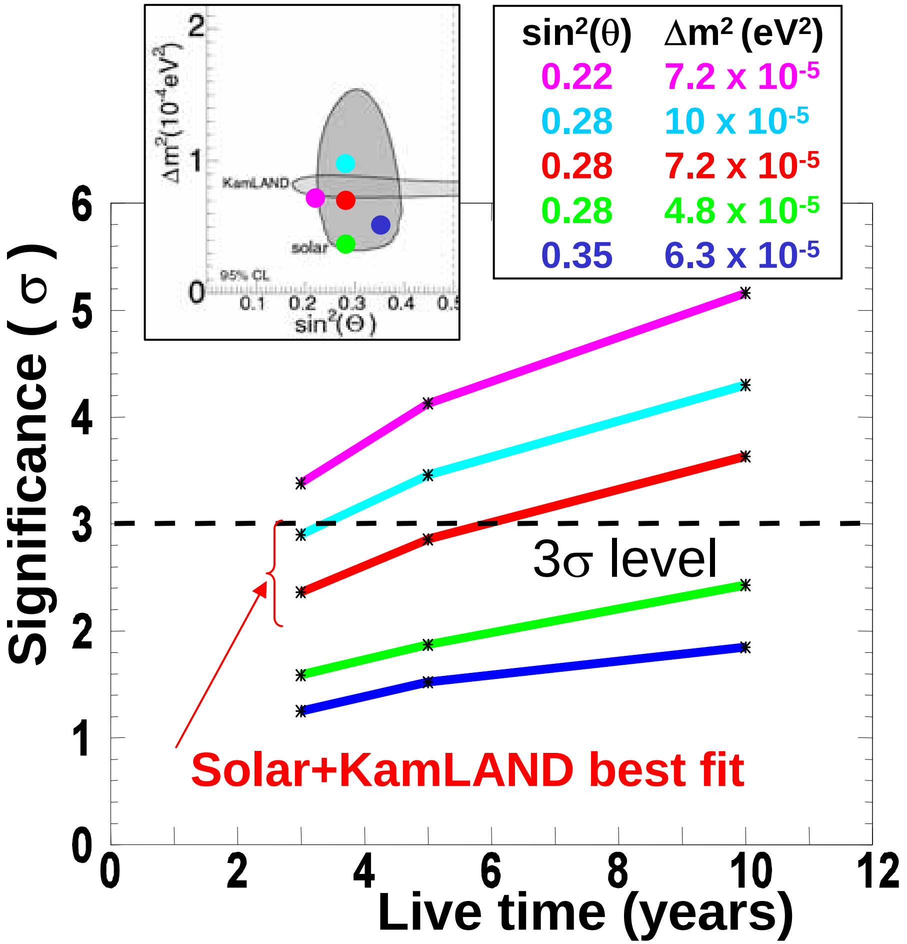


Future propsects: expected sensitivity of SK-III

Expected spectrum in SK-III



Statistical significance



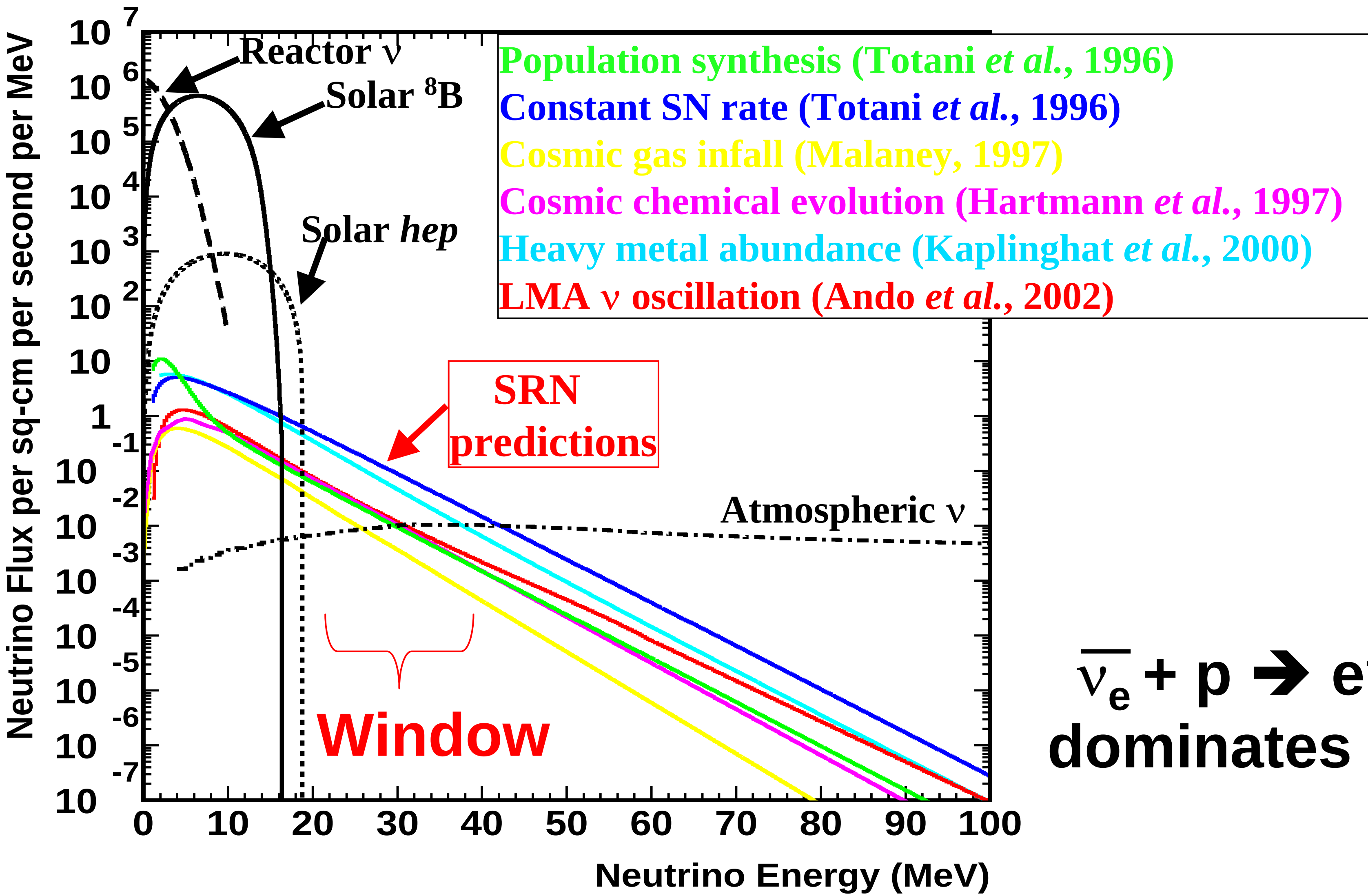
Assumption:

Correlated systematic error: x 0.5

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

(> 5.5MeV is same as SK-I)

Search for supernova relic neutrinos

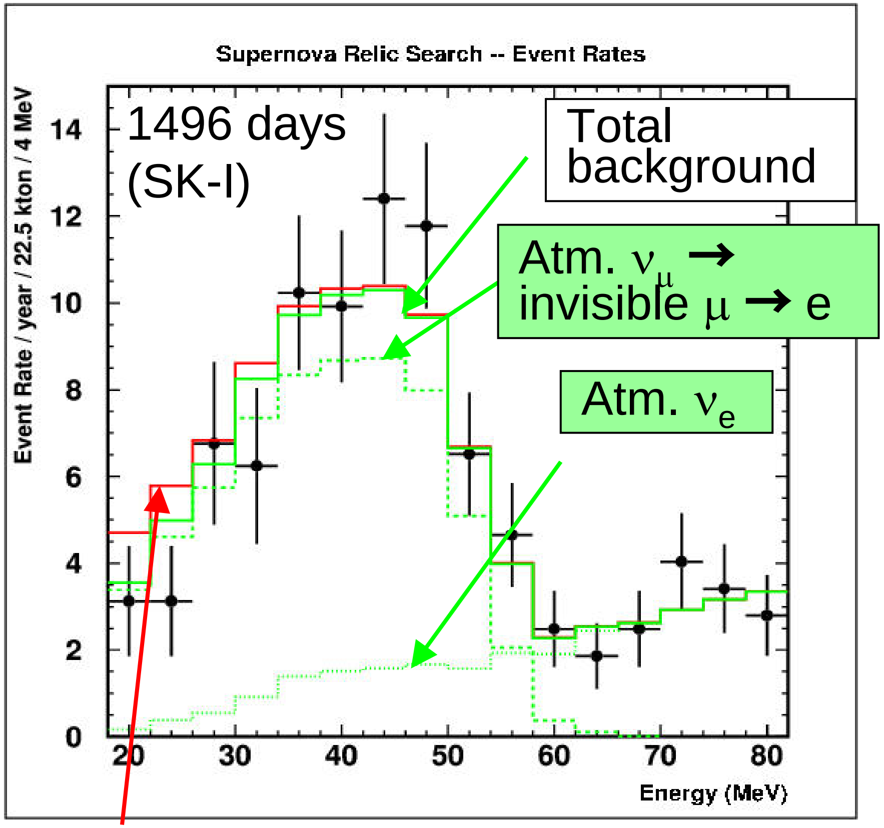


$\overline{\nu}_e + p \rightarrow e^+ + n$ dominates in SK

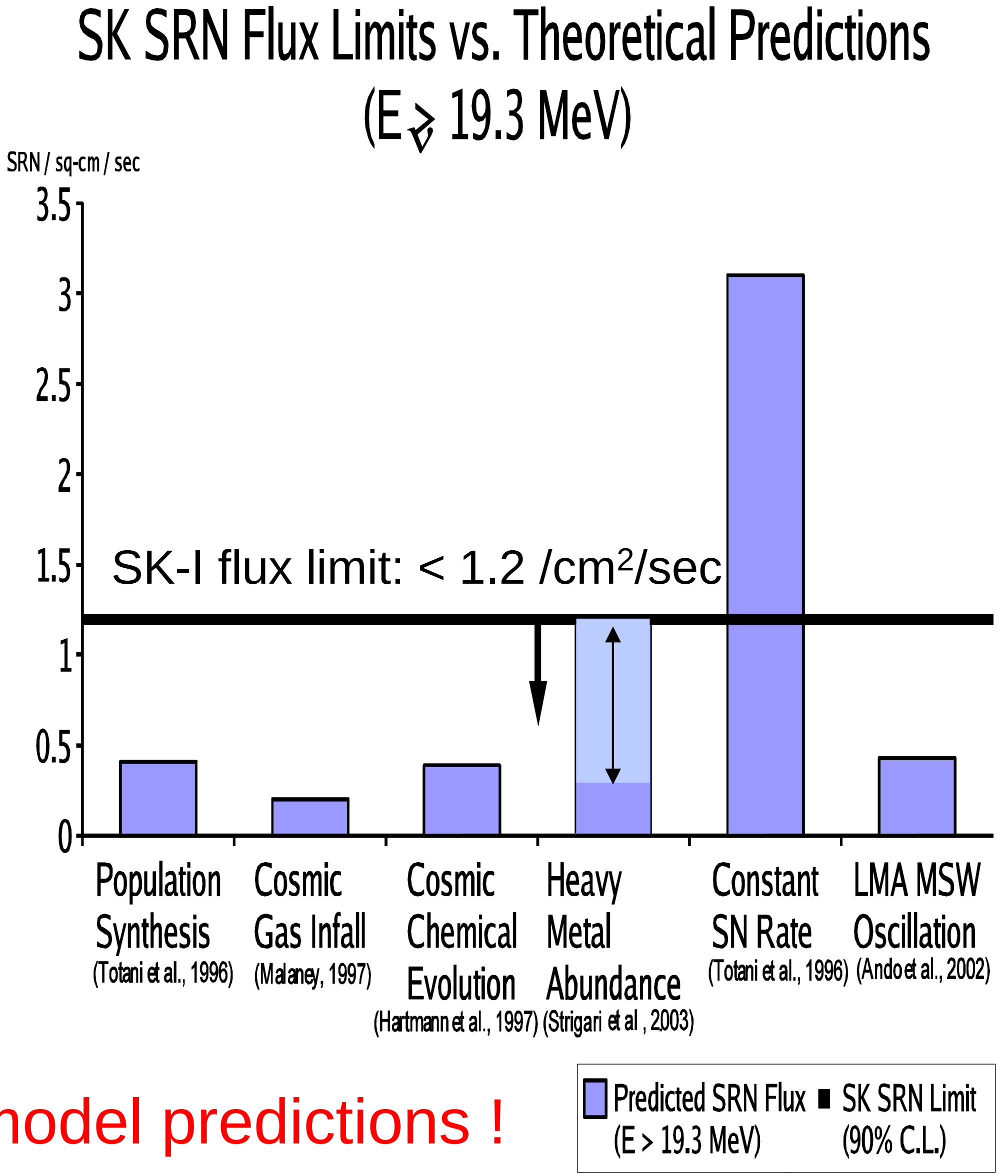
Spallation B.G. below ~18 MeV

Search for supernova relic neutrinos in SK-I

Energy spectrum (>18MeV)

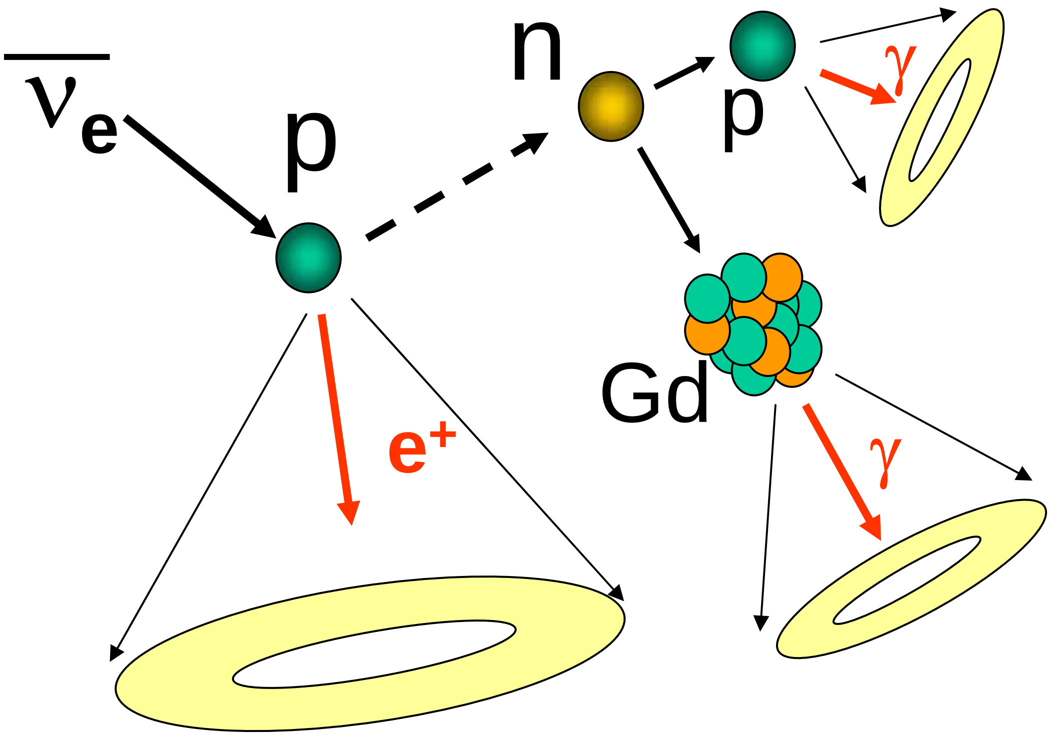


90% CL limit of SRN



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

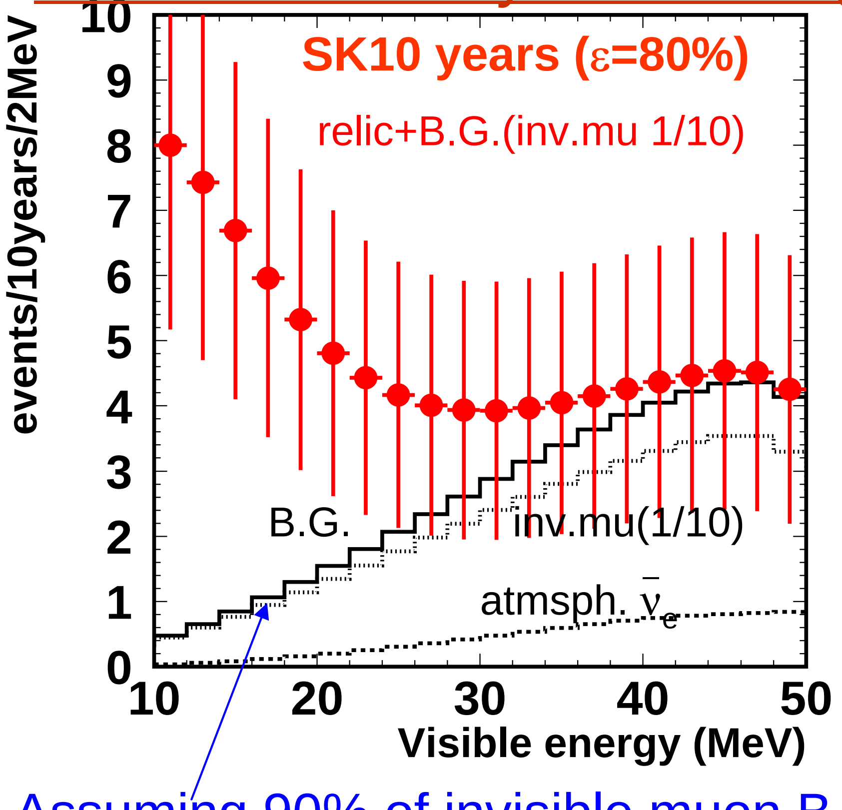
(ref. Vagins and Beacom)

$\overline{\nu}_e$ 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.

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

- Atmospheric neutrinos
  - Allowed parameter region was improved:
    - $1.9 \times 10^{-3}\ eV^2 < \Delta m^2 < 3.1 \times 10^{-3}\ eV^2$, $\sin^2 2\theta > 0.93$ @90% CL
  - L/E dependence of neutrino oscillation was observed.
  - Search for non-zero $\theta 13$. If $\theta 13$ is close to CHOOZ limit, it could be observed by atmospheric neutrinos.
- Solar neutrinos
  - Evidence for solar ν osc. by comparing SK and SNO in 2001.
  - LMA sol. was obtained by solar global analysis @99% CL
  - ~10% distortion in the energy spectrum for the LMA solution.

    By lowering bg in low E region, it should be observed in 5-7y.
- Supernova relic neutrinos
  - Flux < 1.2 /cm^2/s (E>18 MeV, SK-I) Close to theor. pred.
  - Improved search for SRN neutrinos by neutron tagging.