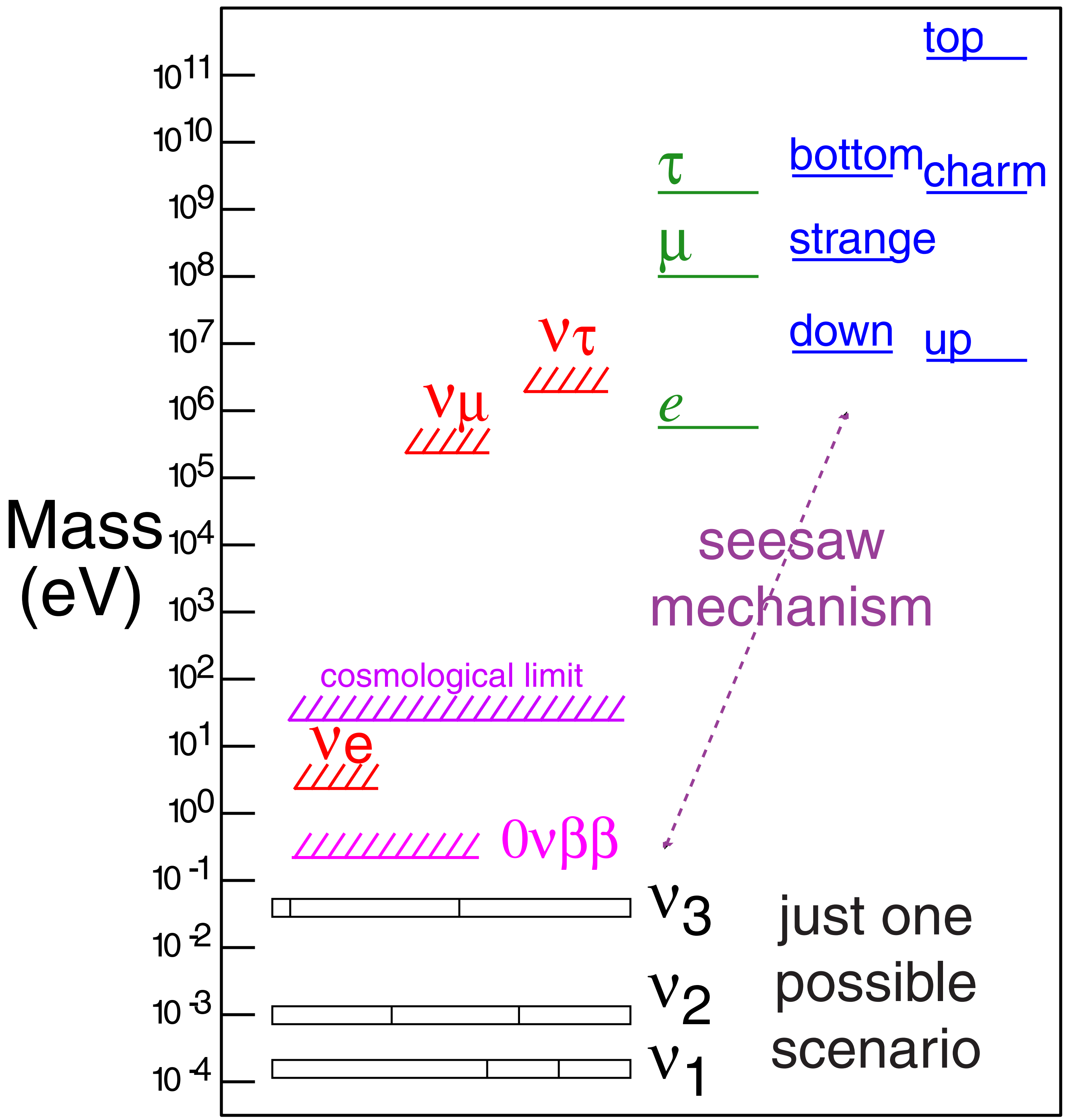
# NON-ACCELERATOR NEUTRINO EXPERIMENTS

Edward Kearns - Boston U.

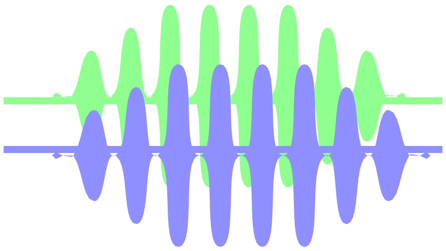
OSAKA 2000 XXX

## neutrino mass
## solar neutrinos
## atmospheric neutrinos

# Mass of Fundamental Particles



# Neutrino Oscillation

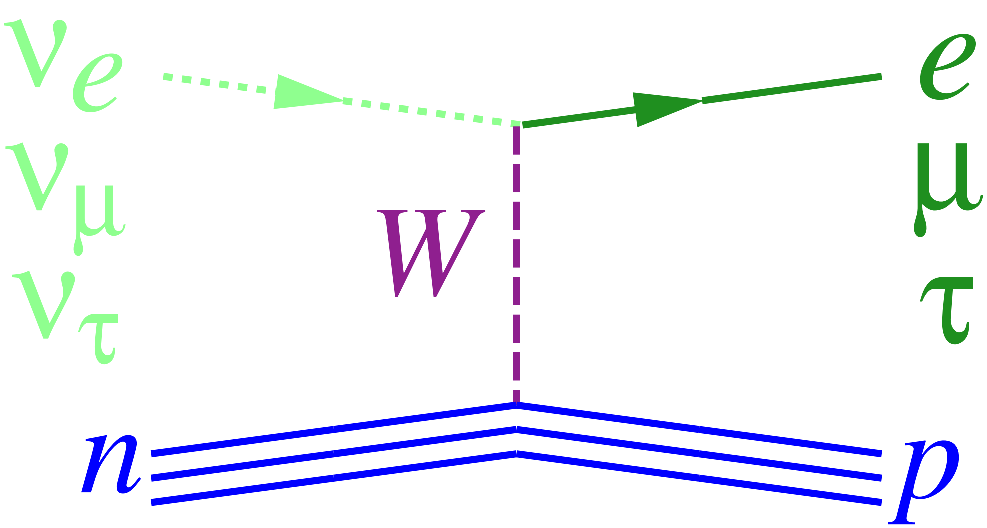


$$\nu_e = \nu_1 \cos\theta + \nu_2 \sin\theta$$

$$\nu_\mu = -\nu_1 \sin\theta + \nu_2 \cos\theta$$

$$P_{\nu\nu'} = \sin^2 2\theta \ \sin^2 \frac{1.27\,\Delta m^2 L}{E}$$

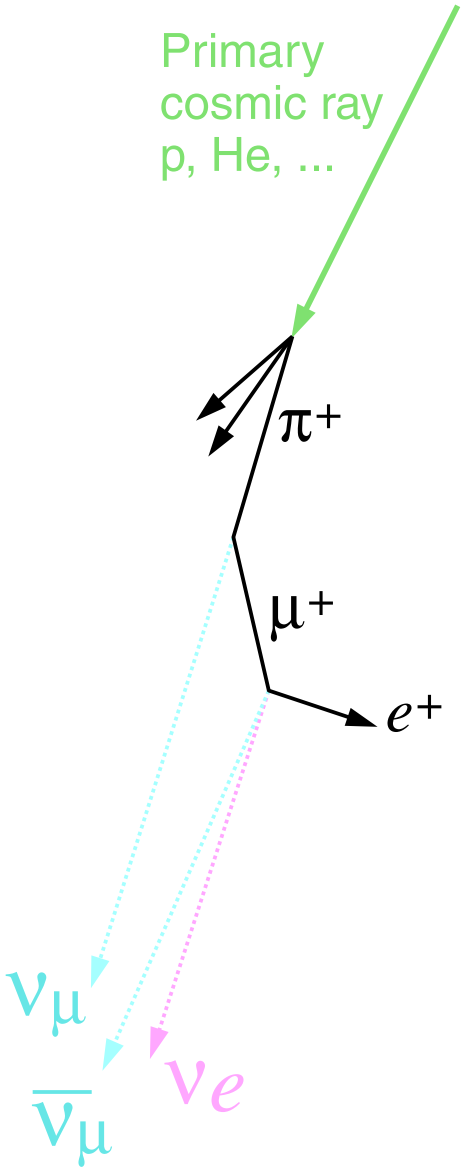
# Charged Current Interaction



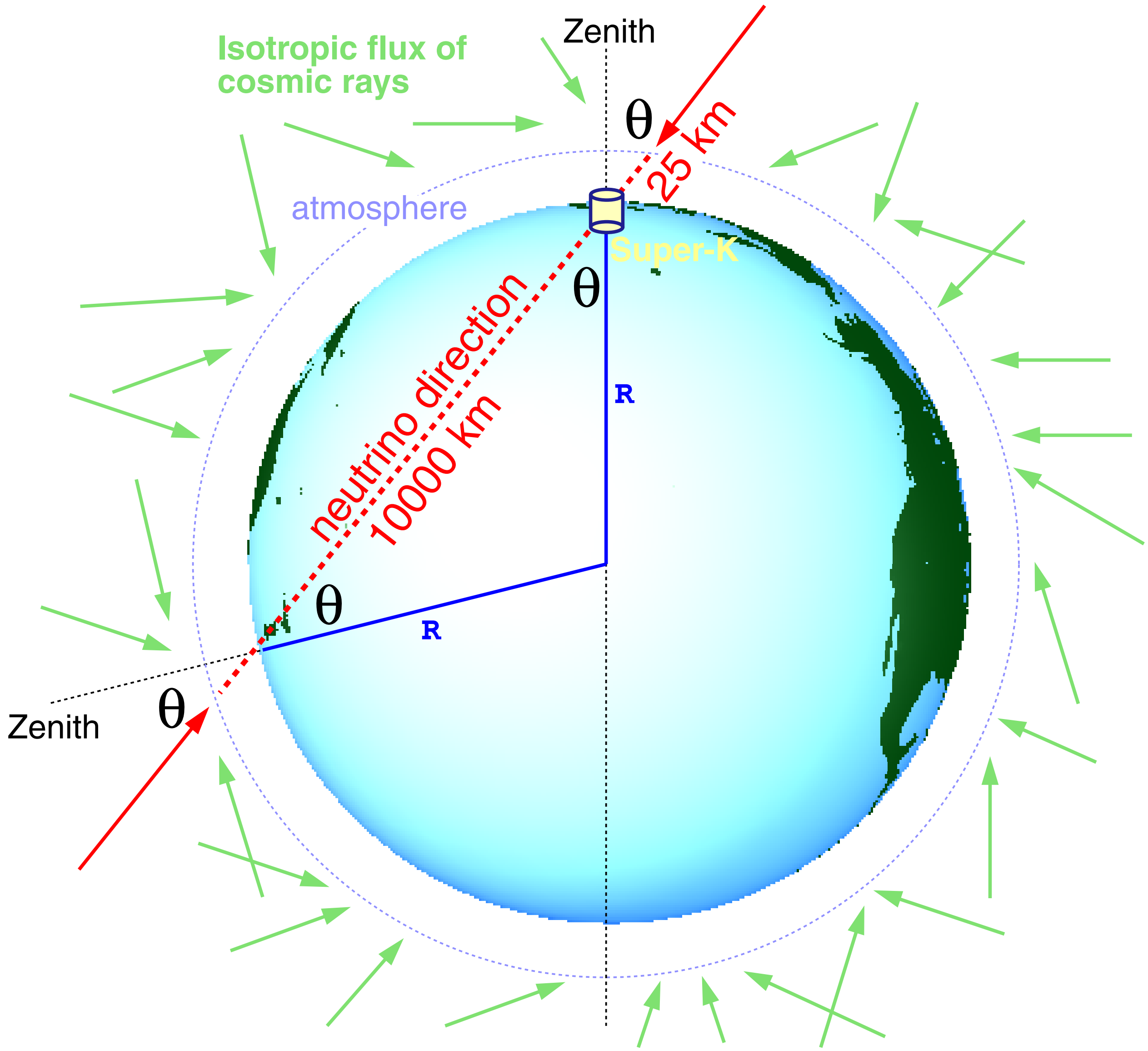

Reaction Threshold

| | |
|---|---|
| $e$ | $E_\nu > 1.5$ MeV |
| $\mu$ | $E_\nu > 110$ MeV |
| $\tau$ | $E_\nu >$ *3500* MeV |

# ATMOSPHERIC NEUTRINOS

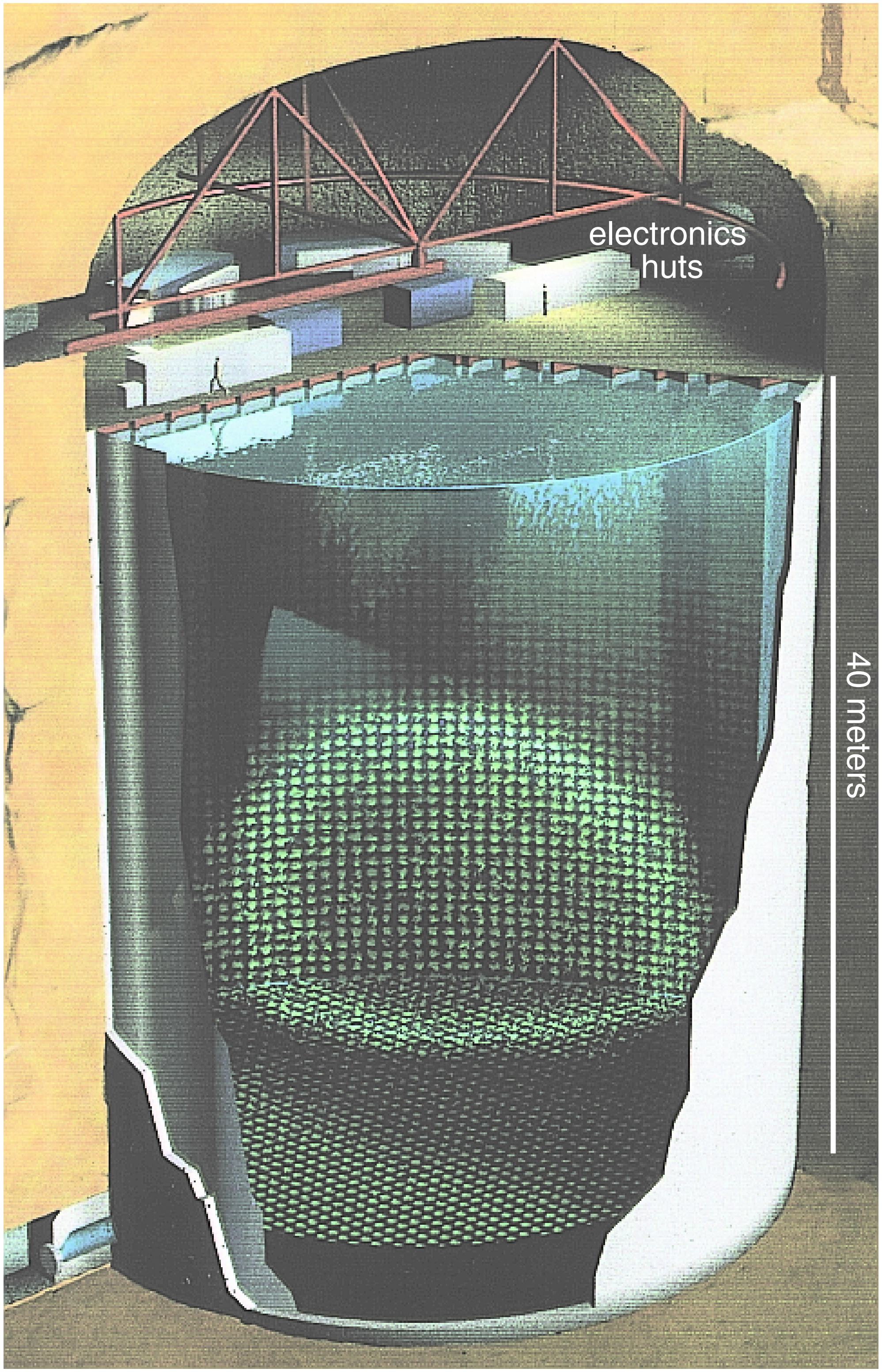



**Ratio of $\nu_\mu/\nu_e$ ~ 2**
**(for $E_\nu$ < few GeV)**




**Up-Down Symmetric Flux**
**(for $E_\nu$ > few GeV)**

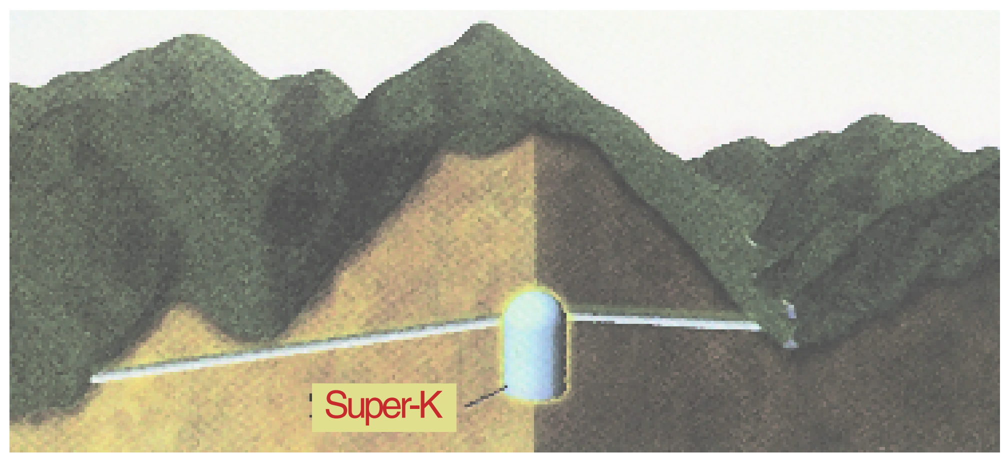
# Super-Kamiokande Detector




**Inner detector**
- 22.5 kton fiducial mass
- 11134 50cm photomultiplier tubes
- 40% photocathode coverage
- ~2 ns PMT timing resolution
- ~85 m water attenuation length

**Outer detector**
- optically isolated veto and shield
- 1800 20cm pmts recovered from IMB

**Location**
- Kamioka zinc mine, Japan
- 1 km under mountain (2700 m.w.e.)



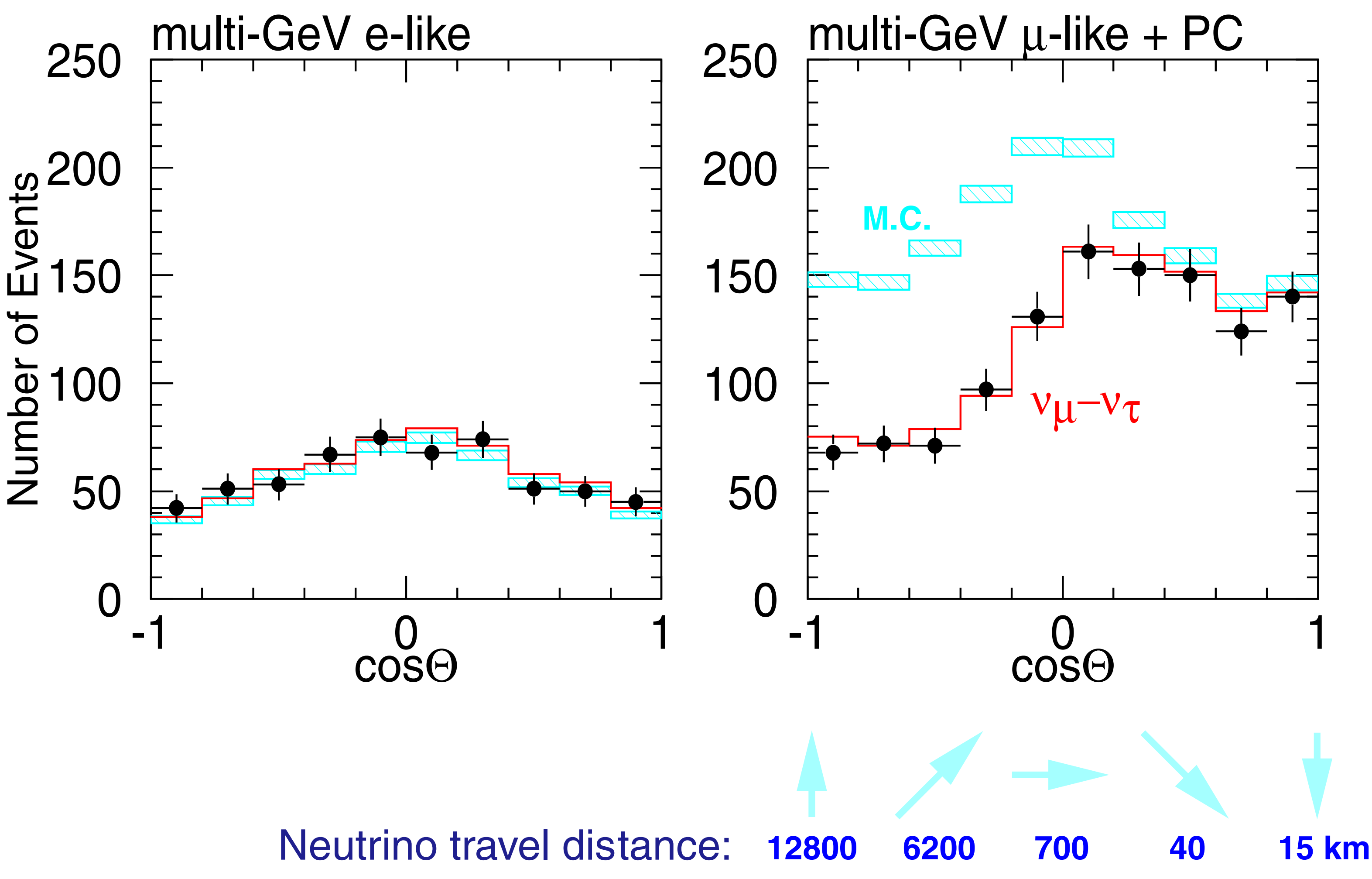
# Super-K Evidence for Neutrino Oscillation

**sub-GeV:**

$$\frac{(N_\mu/N_e)_{DATA}}{(N_\mu/N_e)_{M.C.}} = 0.652 \pm \underset{stat.}{0.019} \pm \underset{sys.}{0.051}$$

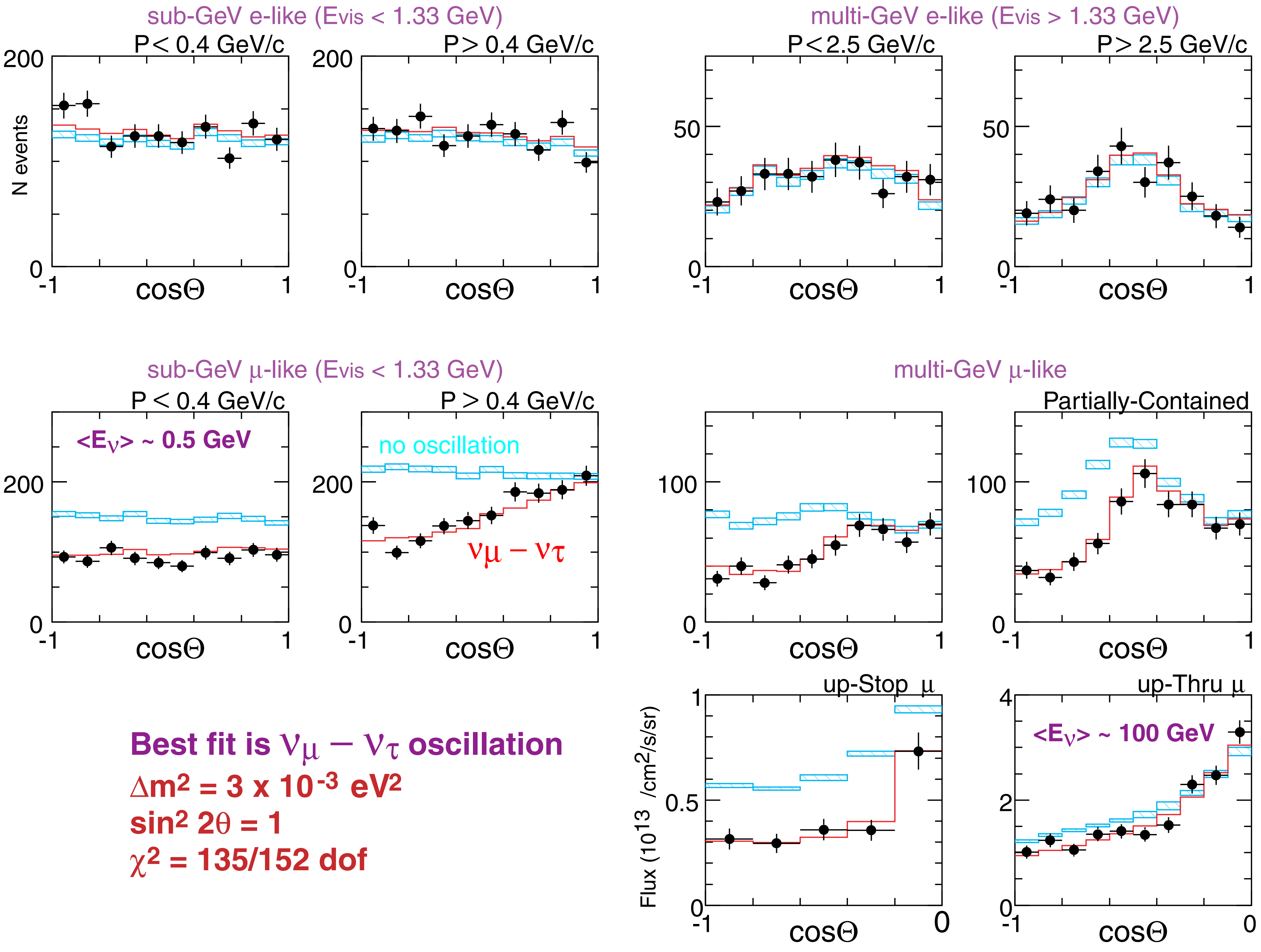
**multi-GeV ($\mu$-like):**

$$\frac{N_{UP} - N_{DOWN}}{N_{UP} + N_{DOWN}} = -\,0.296 \pm \underset{stat.}{0.032} \pm \underset{sys.}{0.01}$$




Neutrino travel distance:

# Fit to Super-K Atmospheric Neutrinos over 3 Decades in Energy



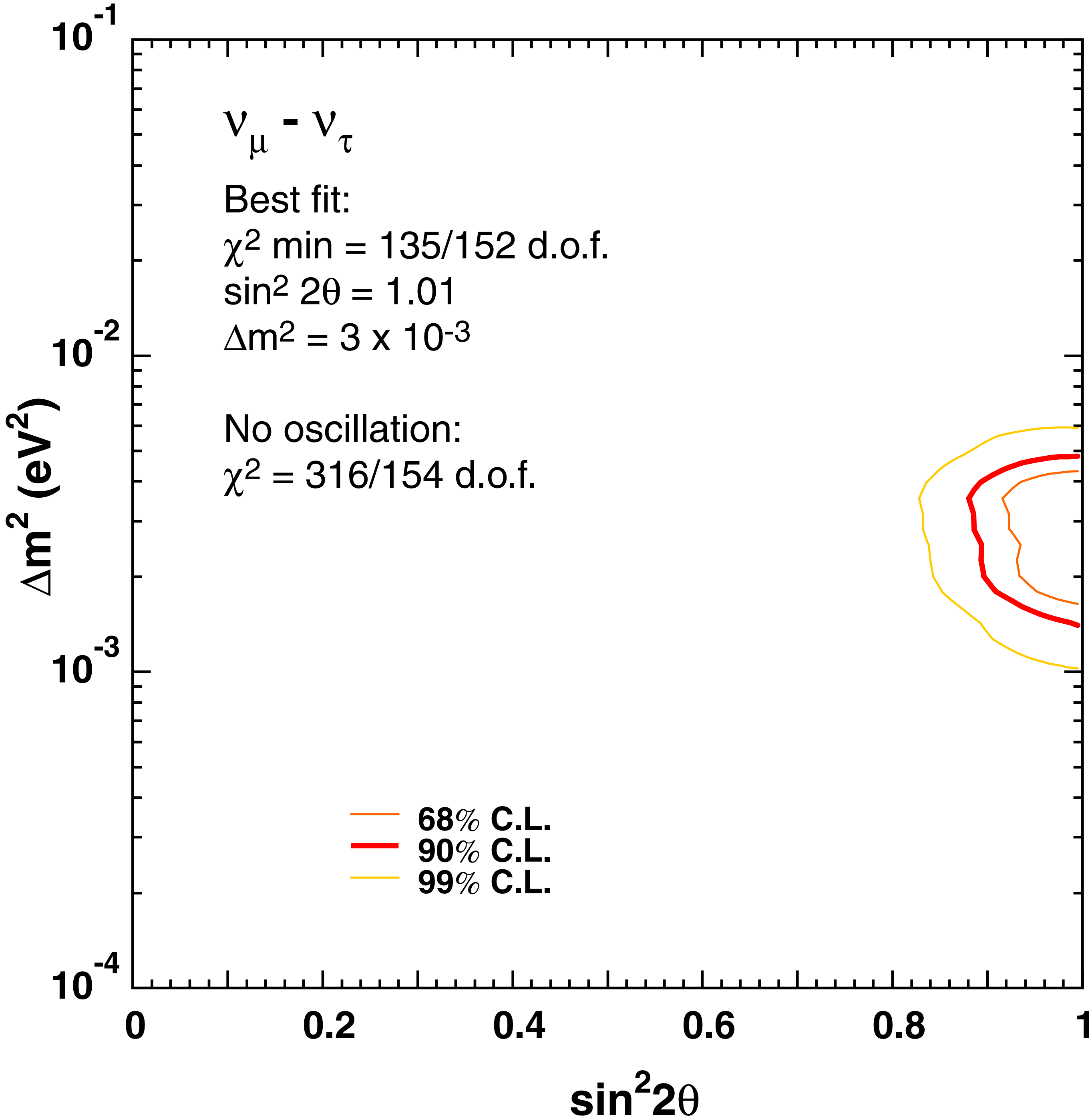

**Best fit is $\nu_\mu - \nu_\tau$ oscillation**

**$\Delta m^2 = 3 \times 10^{-3}$ eV$^2$**

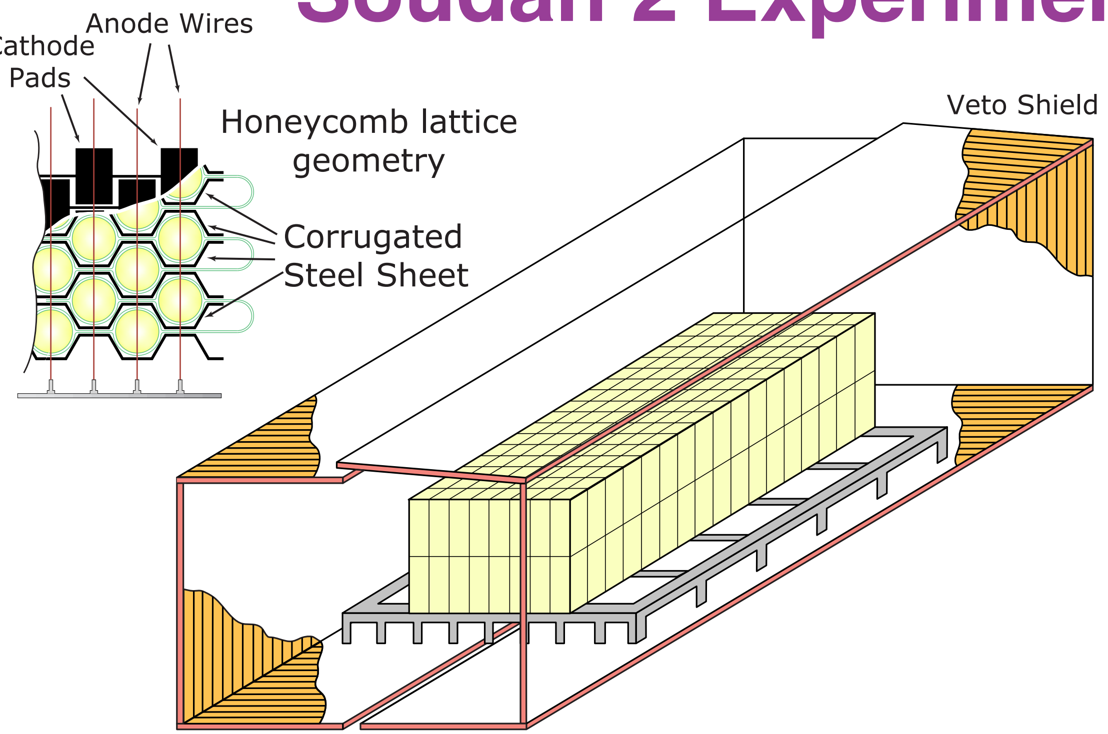
**$\sin^2 2\theta = 1$**

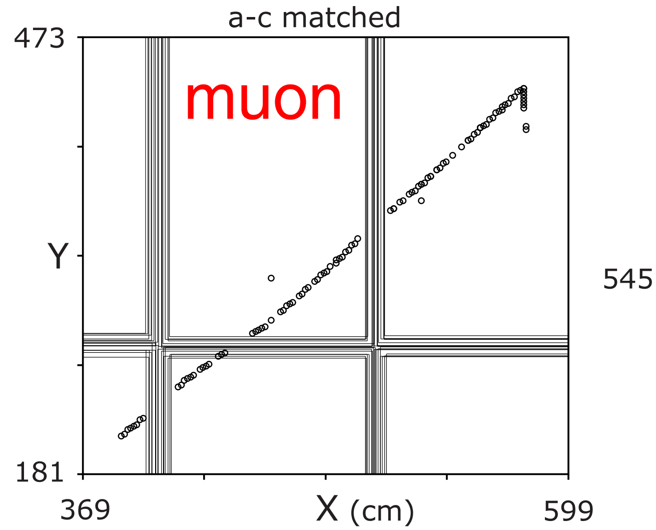
**$\chi^2 = 135/152$ dof**

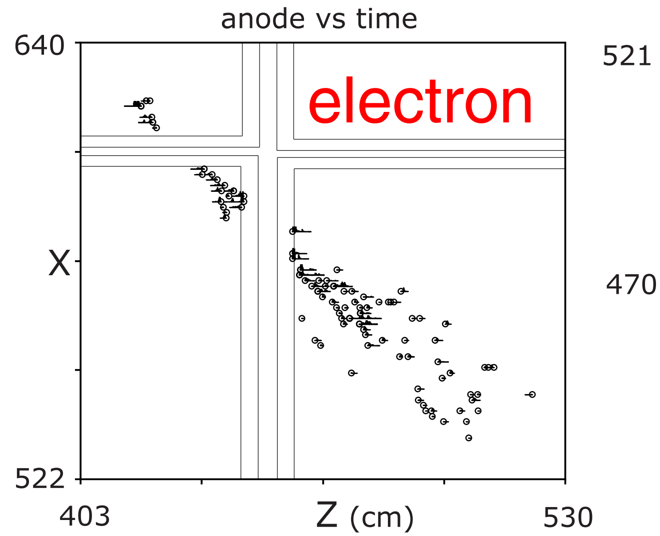
# Super-K Best Fit and Contours



# Soudan 2 Experiment




Soudan Mine (Minnesota), 2100 m.w.e.
iron tracking calorimeter
high geomagnetic latitude
5.1 kt-yr, 326 contained interactions
~24% background subtraction using veto events

$$R = \frac{(\mu/e)_{DATA}}{(\mu/e)_{M.C.}} = 0.68 \pm 0.11_{stat} \pm 0.06_{sys}$$

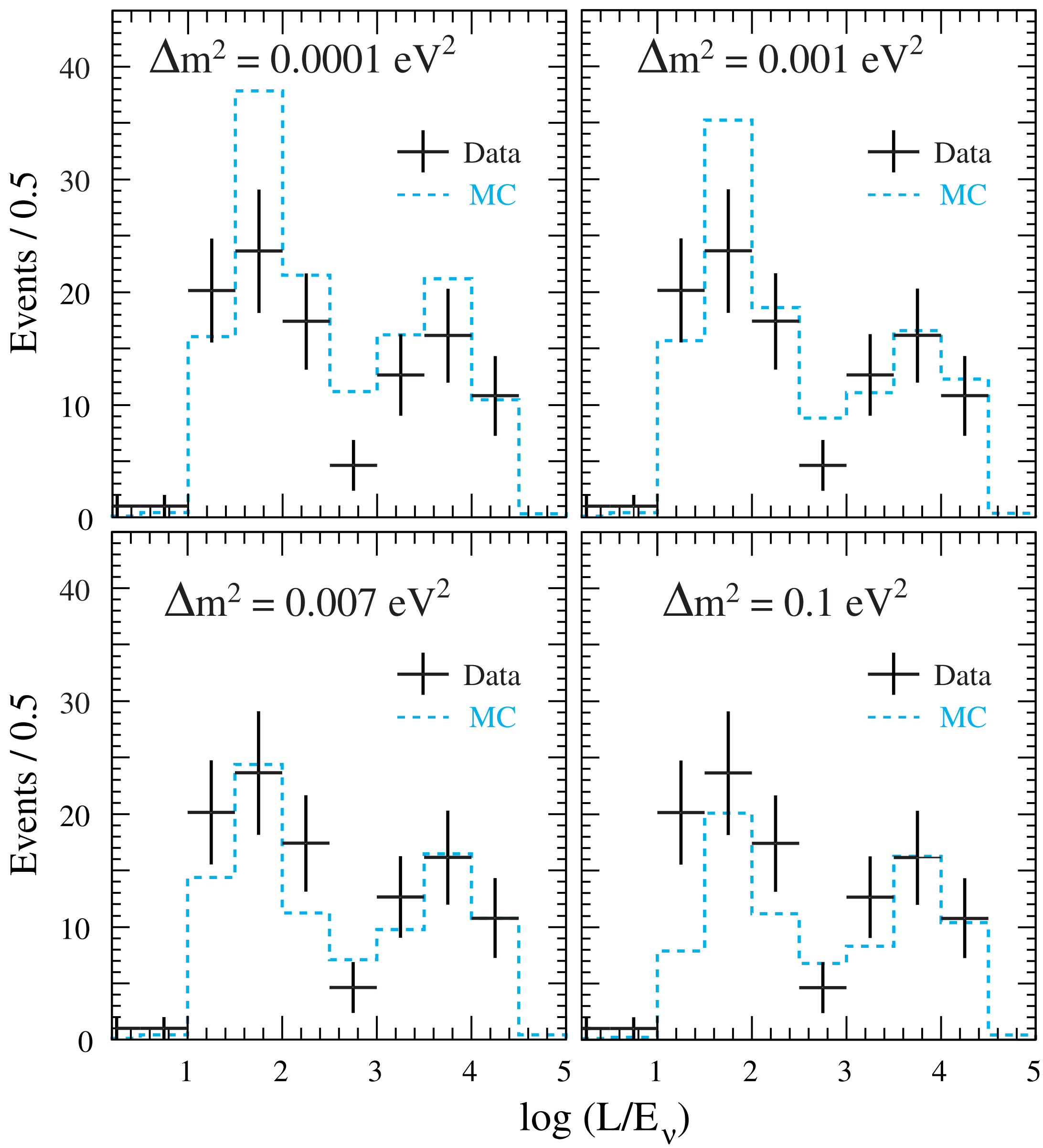
# Soudan 2 high resolution analysis

*Pearce/Peterson*

quasi-elastic
- p > 150 MeV/c if recoil present
- Evis > 600 MeV otherwise

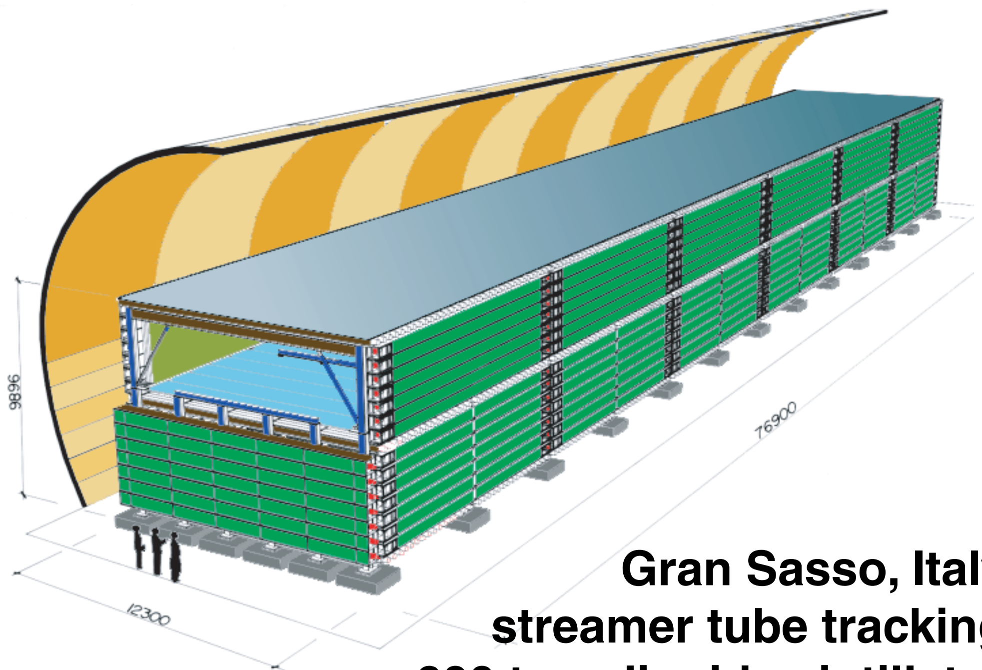
high energy multi-prongs

20-30° pointing, log(L/E) resolution ~0.5

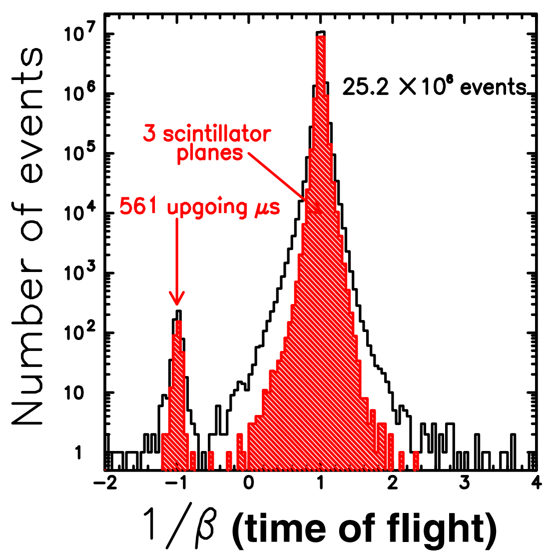


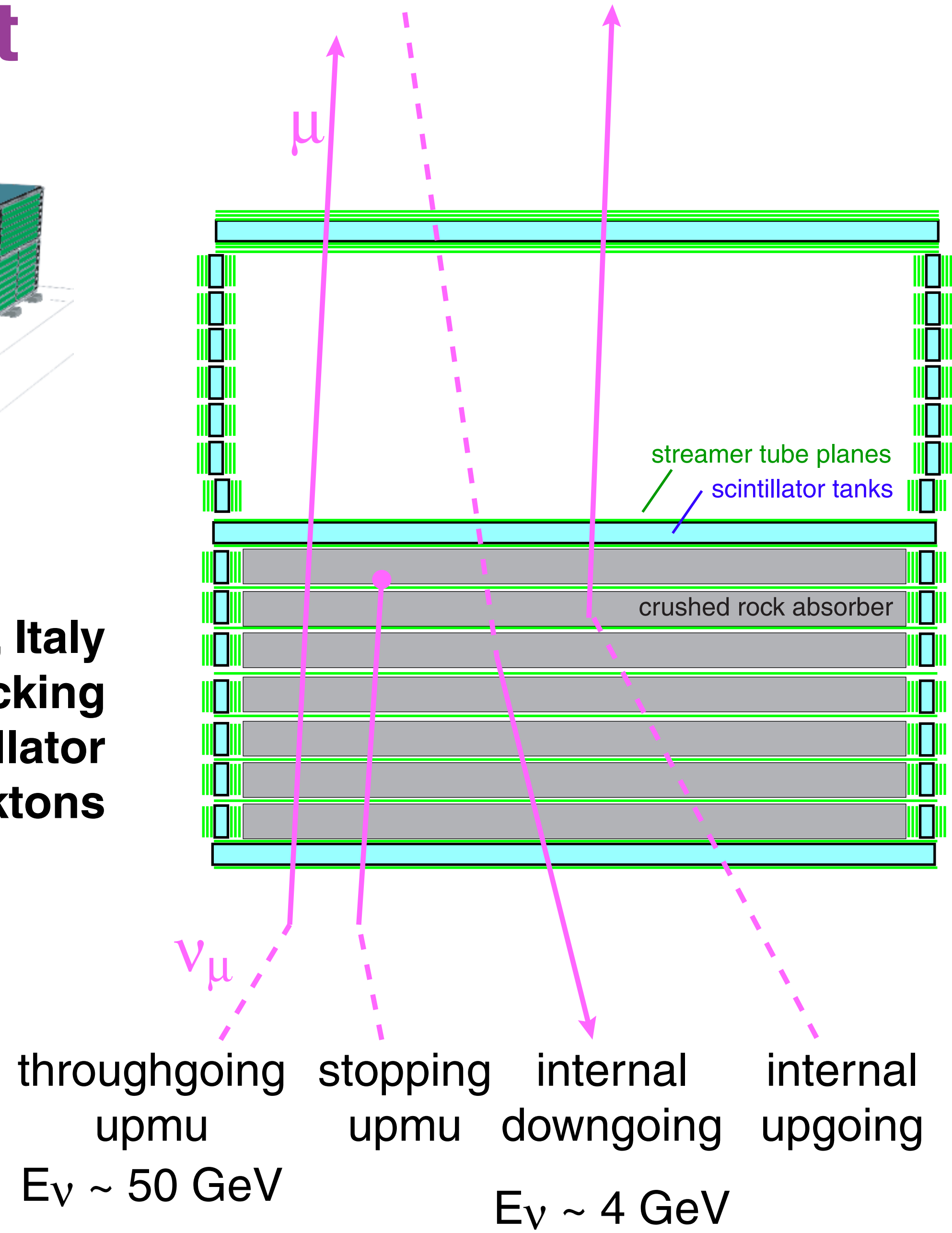

best fit: $\sin^2 2\theta = 0.9$, $\Delta m^2 = 8 \times 10^{-3}\ eV^2$

# MACRO Experiment

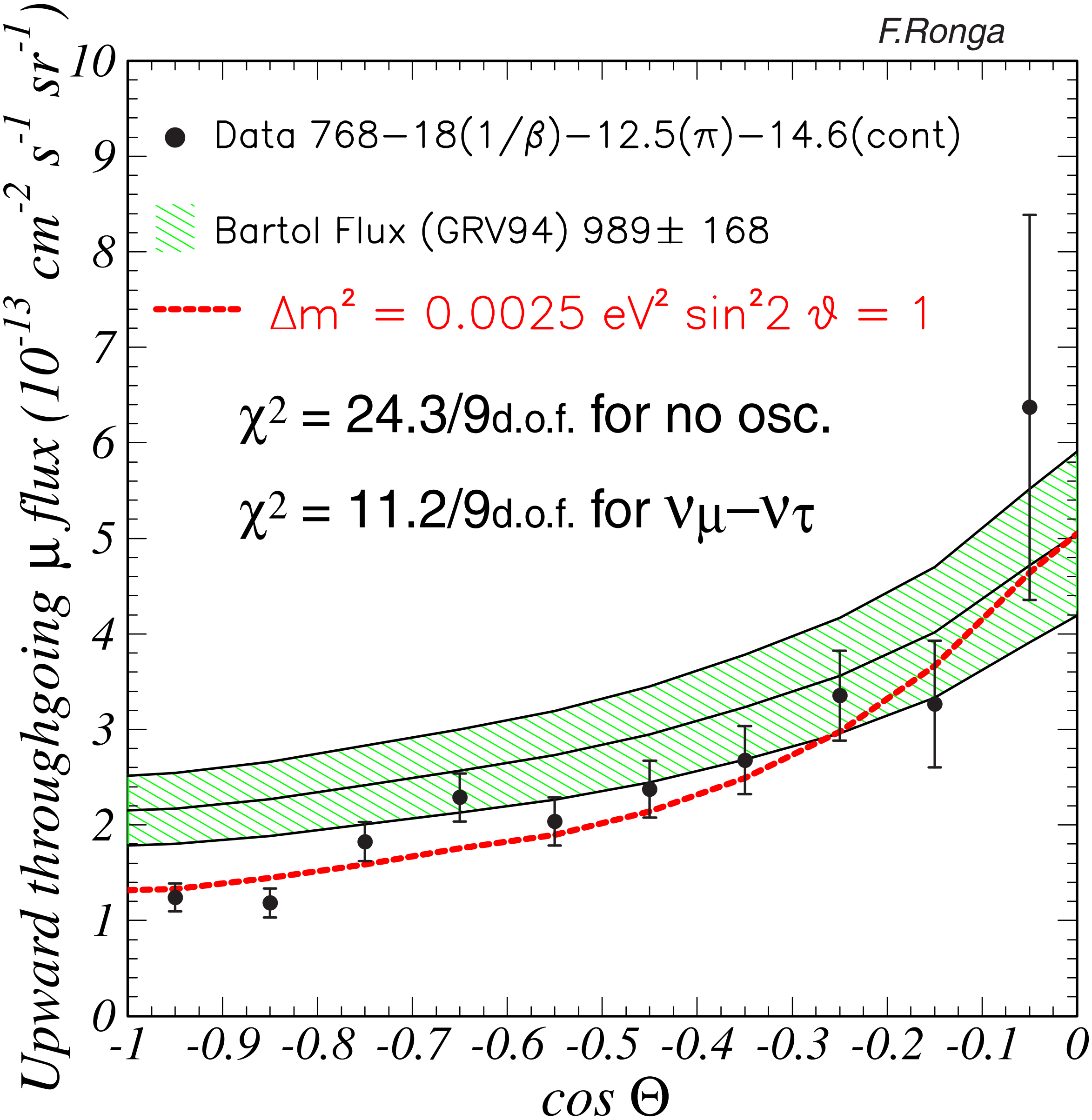



**Gran Sasso, Italy**
**streamer tube tracking**
**600 tons liquid scintillator**
**detector mass ~5.3 ktons**



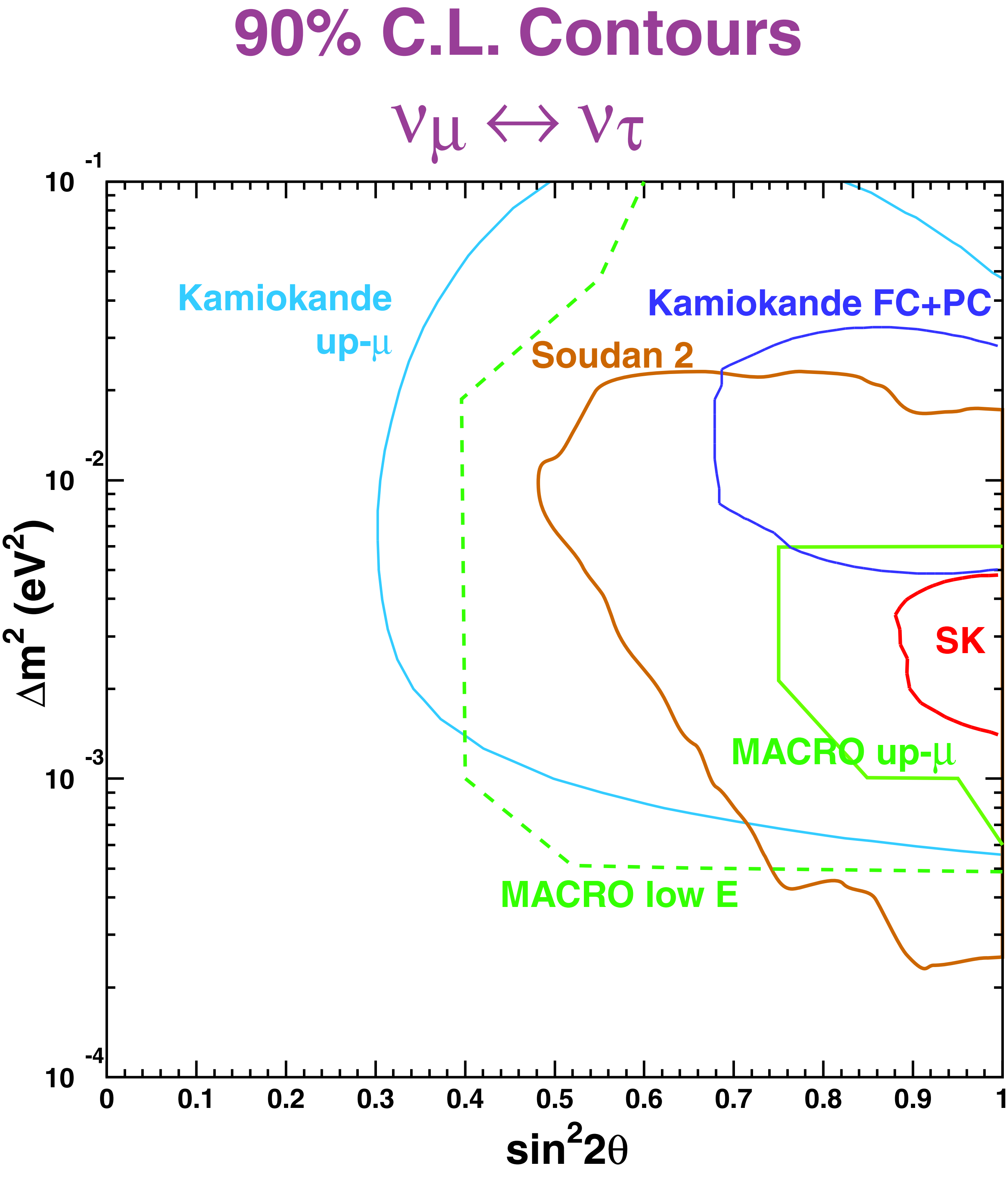



# MACRO Up-μ Results

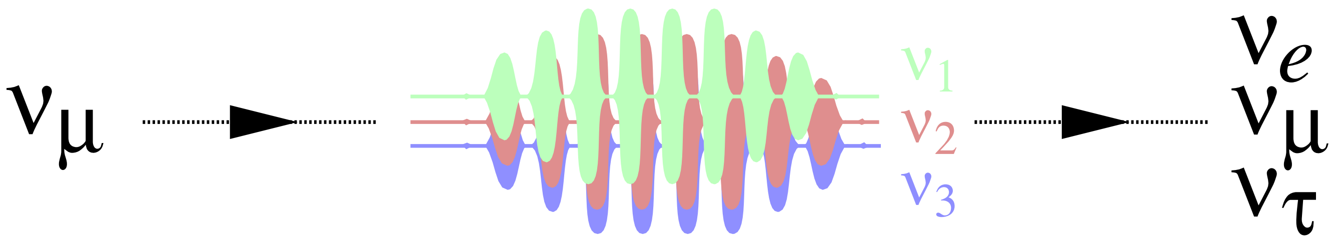



| | DATA/M.C. |
|---|---|
| thru-upmu | $0.73 \pm 0.03 \pm 0.04 \pm 0.12$ |
| internal upgoing | $0.55 \pm 0.04 \pm 0.06 \pm 0.14$ |
| int.down+up-stop | $0.70 \pm 0.04 \pm 0.07 \pm 0.18$ |
| | *stat sys theo* |

IU/(ID+US) = 0.59 ±0.07 *cf* 0.75 ±0.06 (no osc)

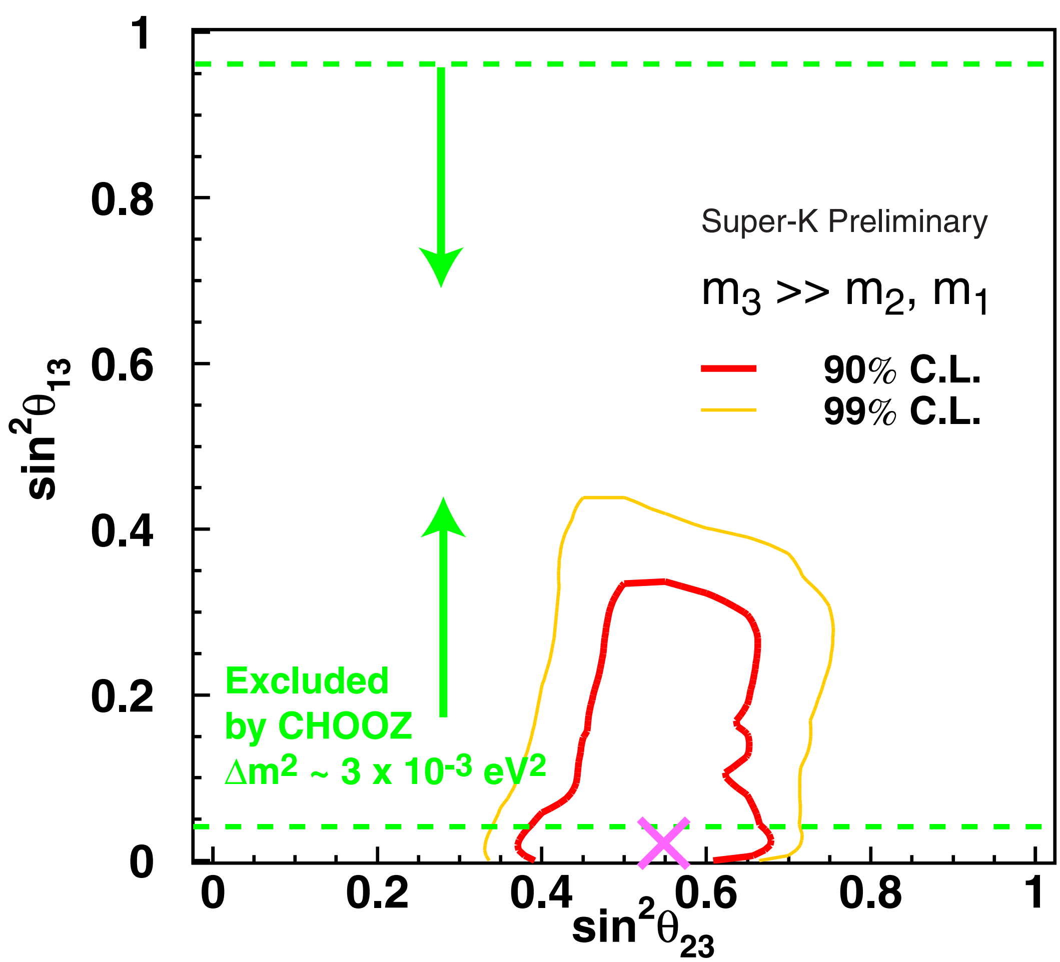

90% C.L. Contours
$\nu_\mu \leftrightarrow \nu_\tau$
Kamiokande
up-μ
Kamiokande FC+PC
Soudan 2
SK
MACRO up-μ
MACRO low E
$\Delta m^2$ (eV$^2$)
$\sin^2 2\theta$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

# 3 Flavor Oscillations




$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

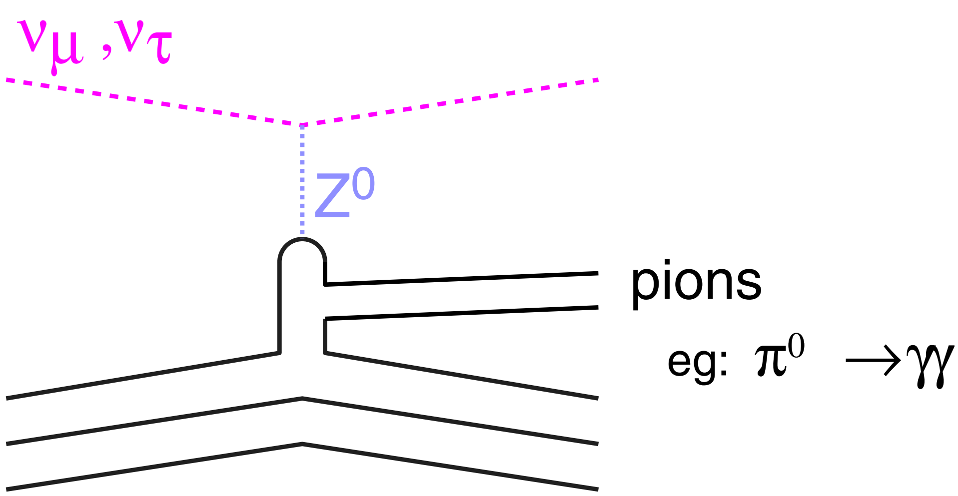
$$P_{ab} = \delta_{ab} - 4 \sum_{i<j} U_{ai} U_{bj} U^*_{aj} U^*_{bi} \sin^2 \frac{1.27\, \Delta m^2_{ij} L}{E}$$



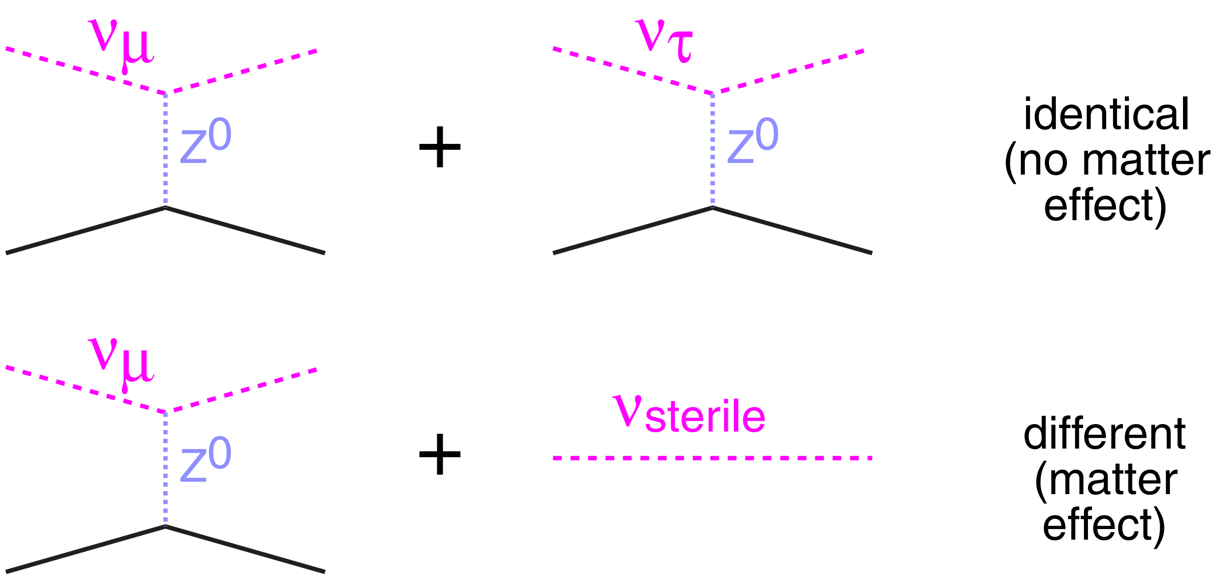

**SK best fit consistent with pure $\nu_\mu - \nu_\tau$ mixing**

# Experimental signatures to resolve $\nu_\mu - \nu_\tau$ versus $\nu_\mu - \nu_{sterile}$

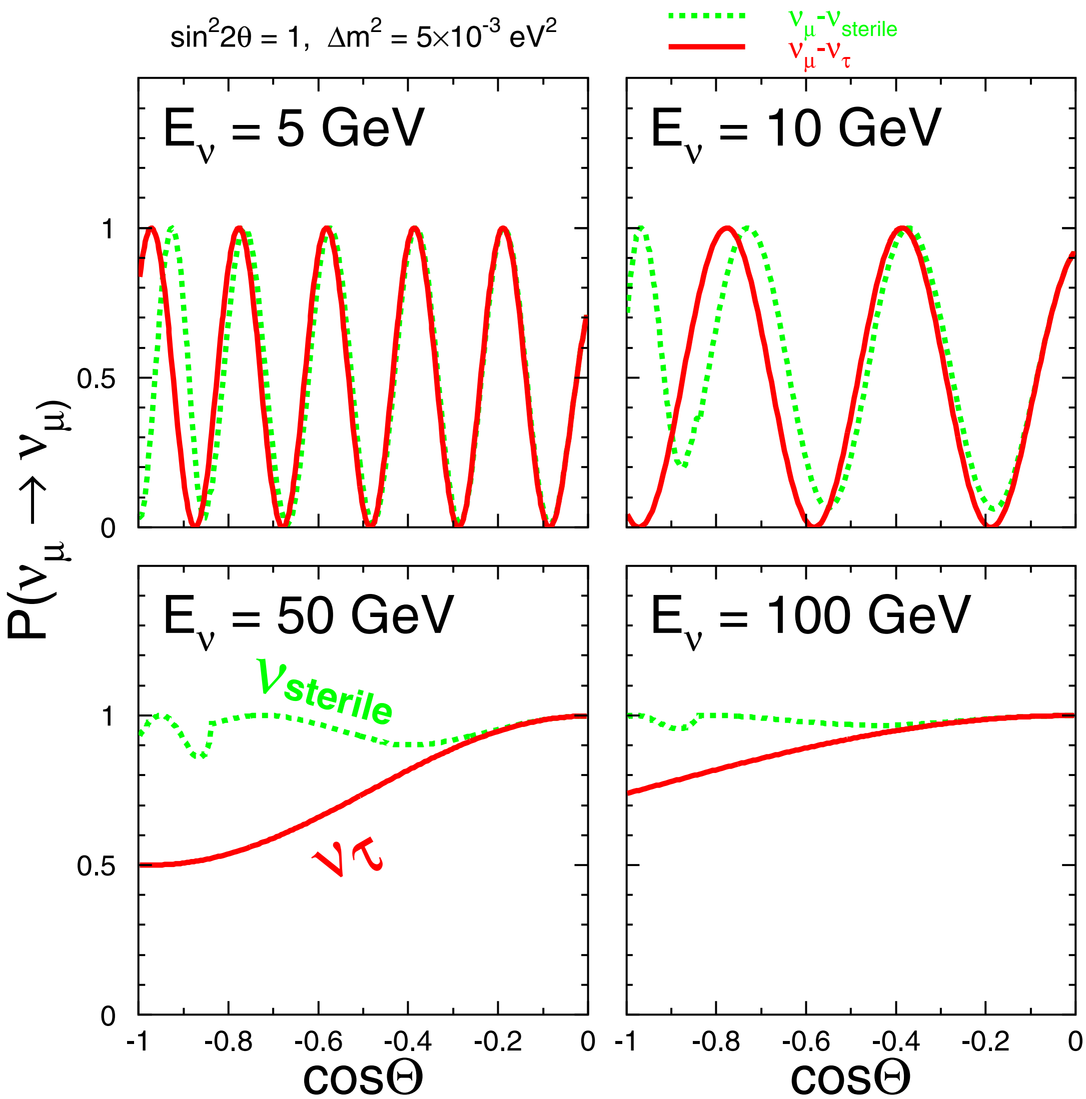
① Neutral Current: missing for $\nu_\mu - \nu_{sterile}$




② Matter effects: present for $\nu_\mu - \nu_{sterile}$



# $\nu_\mu - \nu_{sterile}$ Matter Effects




$$\sin^2 2\theta \longrightarrow \frac{\sin^2 2\theta}{(A - \cos 2\theta)^2 + \sin^2 2\theta}$$

$$\Delta m^2 \longrightarrow \frac{\Delta m^2}{\sqrt{(A - \cos 2\theta)^2 + \sin^2 2\theta}}$$

$$A = \mp \frac{\sqrt{2}\, E_\nu\, G_F\, n}{\Delta m^2}$$

small $E_\nu$, $|A| << 1$ no matter effects $\rightarrow$ vacuum oscillation

large $E_\nu$, $|A| >> 1$ oscillation is suppressed

$|A| \sim 1$ in earth for $E_\nu = 5$ GeV x $\Delta m^2 (10^{-3}\ \text{eV}^2)$

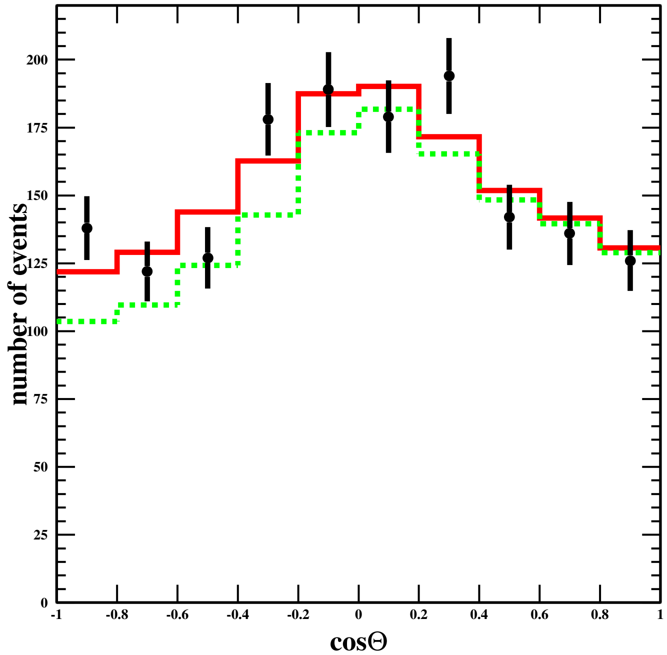
# Evidence that atmospheric $\nu$ oscillation

is $\nu_\mu - \nu_\tau$ (solid red line)

not $\nu_\mu - \nu_{sterile}$ (dotted green line)

*T.Toshito*

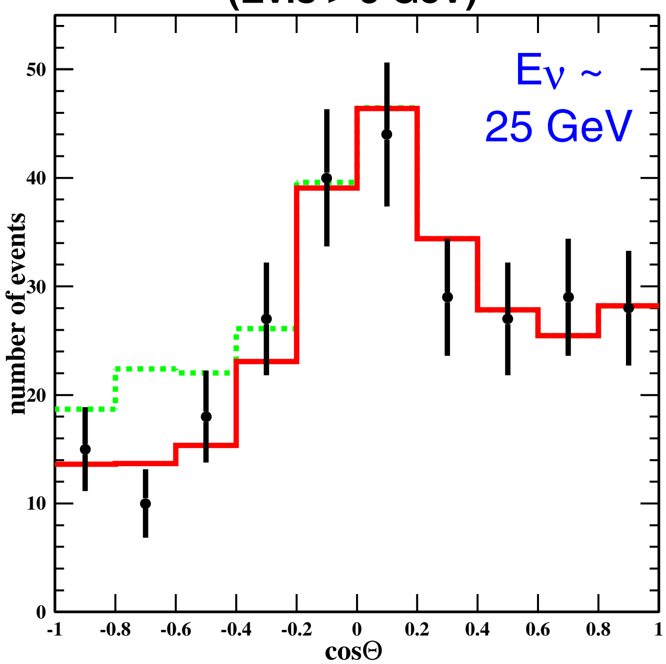
### N.C. enriched multi-ring



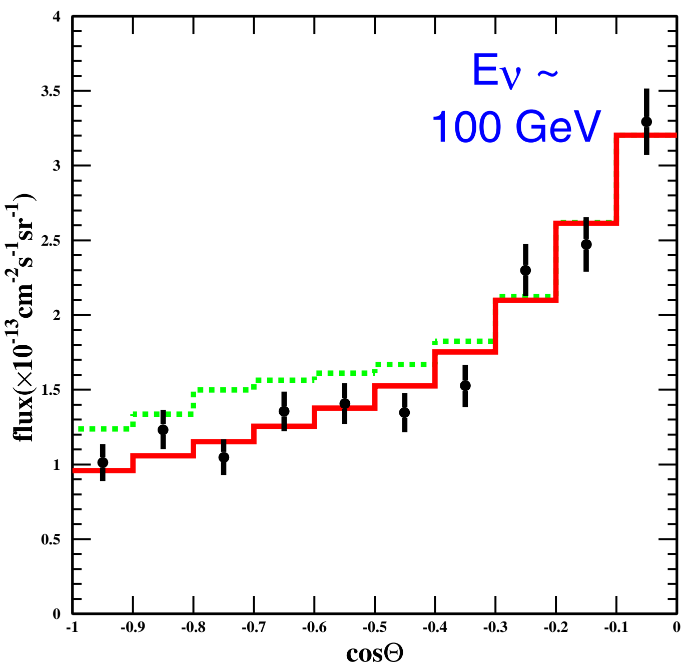

← ① Neutral Current Enhanced Sample

② High Energy Events with Matter Effects

### Partially Contained
(Evis > 5 GeV)




### Throughgoing Up-μ




↑ upgoing direction

$\nu_\mu - \nu_\tau$ preferred at 99% C.L.

# Summary: Atmospheric Neutrinos

**Neutrino oscillation scenario is best explanation for the data**

- high statistical significance
- agreement between experiments
- mu-tau oscillation favored
- awaiting confirmation and precise measurement by long baseline experiments

improve flux calculations to get best estimate of mixing (supplementary to long baseline expts)

- 3D calculations of cosmic ray shower
- new measurements of primary flux
- improve hadronic model (HARP expt)

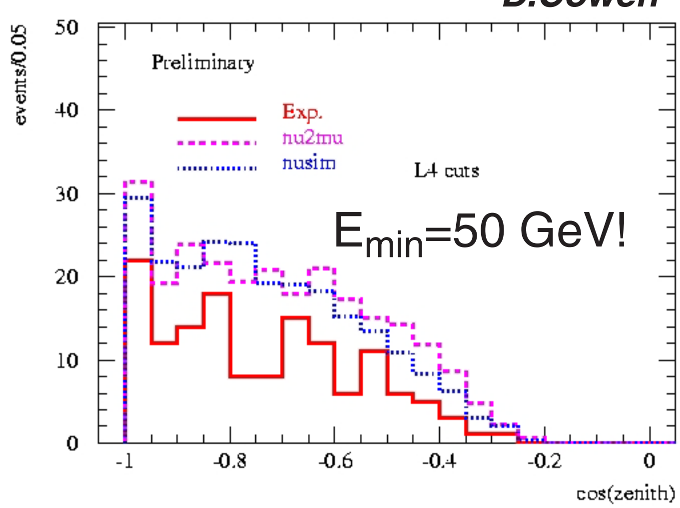
*D.Cowen*

new experiments:

AMANDA →

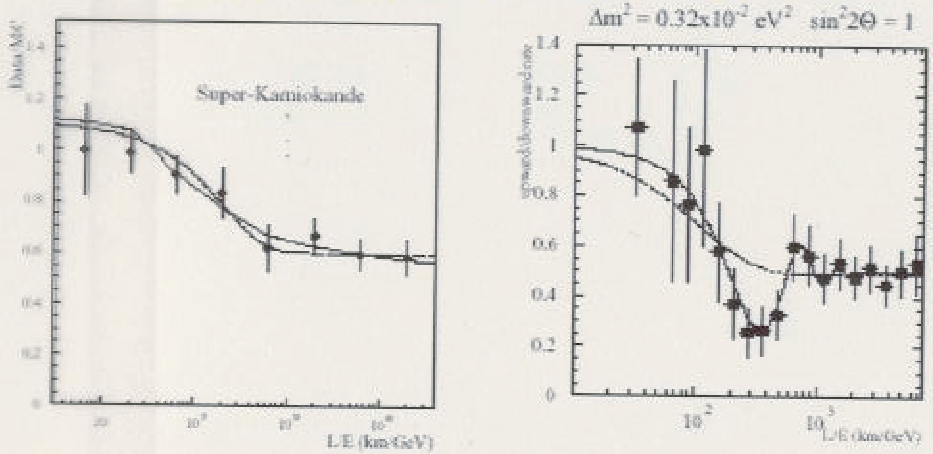
ICARUS

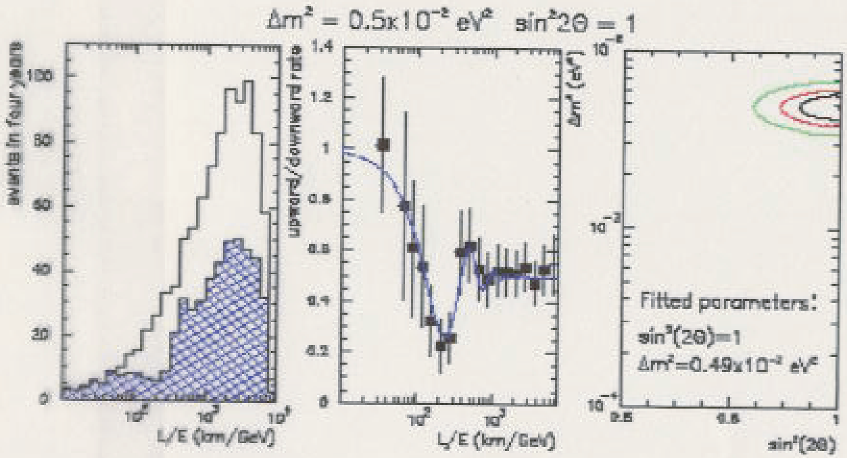
MONOLITH



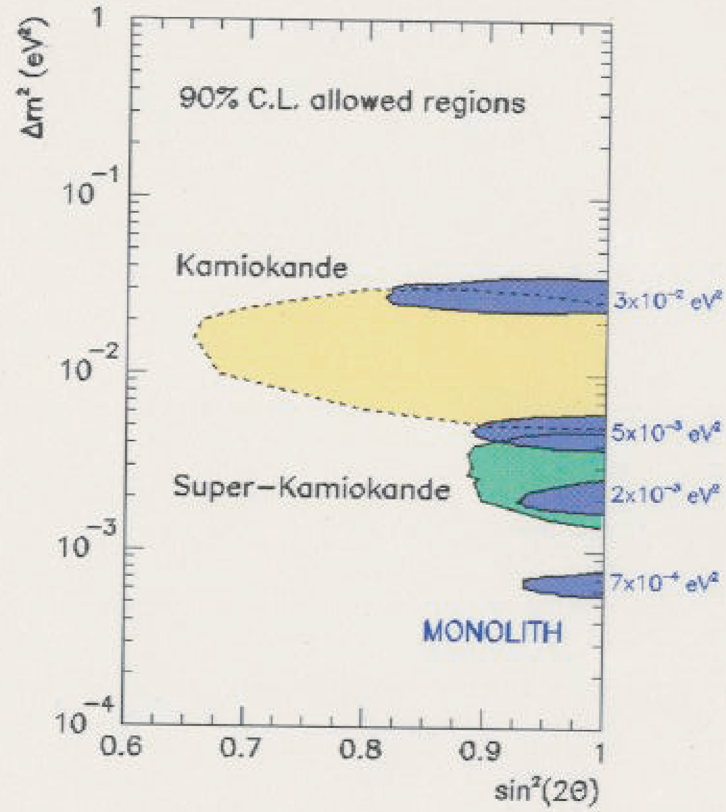
# Monolith Sensitivity – 4 years

The oscillation pattern as seen in SuperKamiokande and expected in Monolith for $\Delta m^2 = 3.2 \times 10^{-3}$ $eV^2$



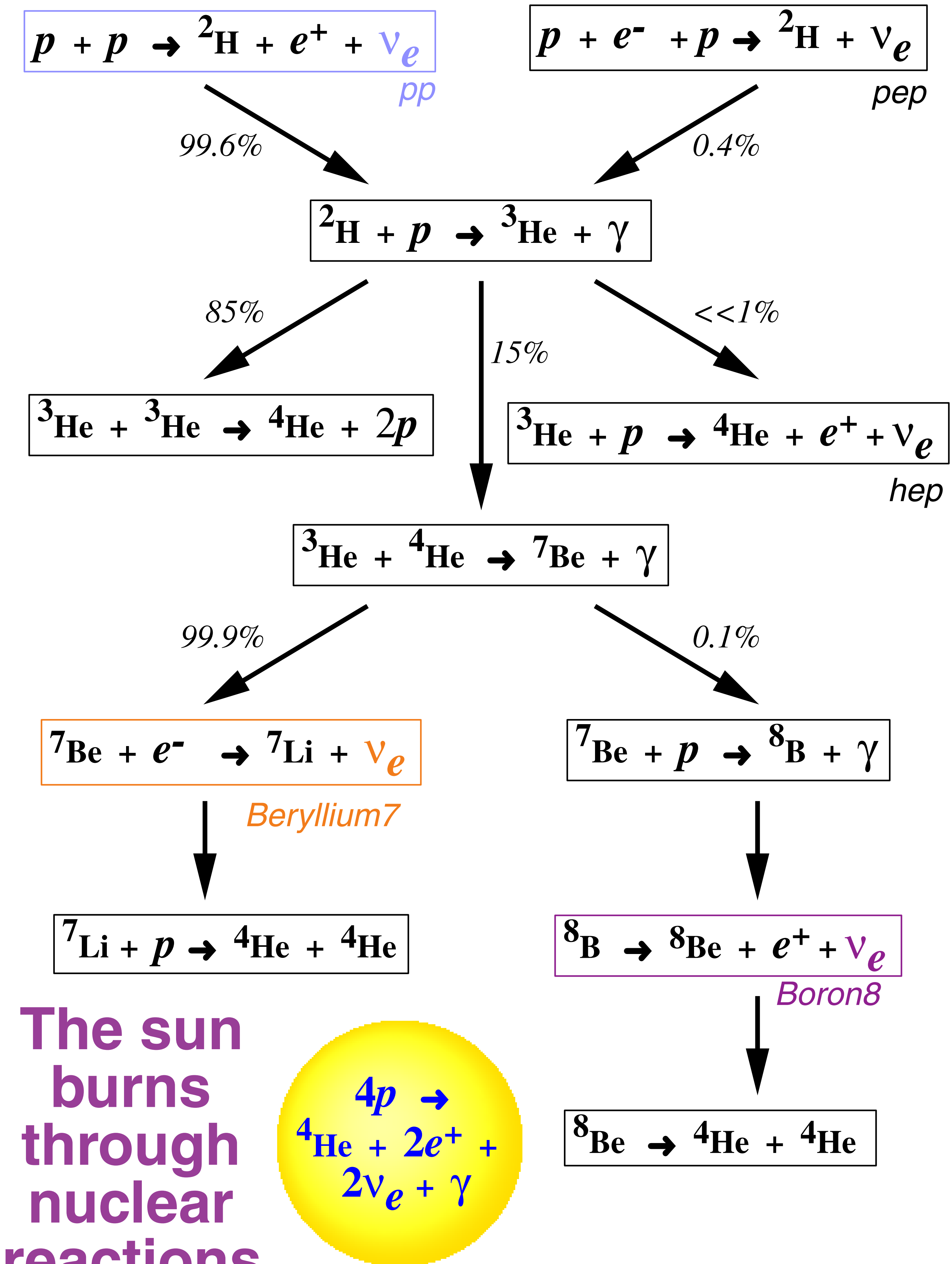




*L/E* distributions and oscillation pattern for $\Delta m^2 = 5 \times 10^{-3}$ $eV^2$



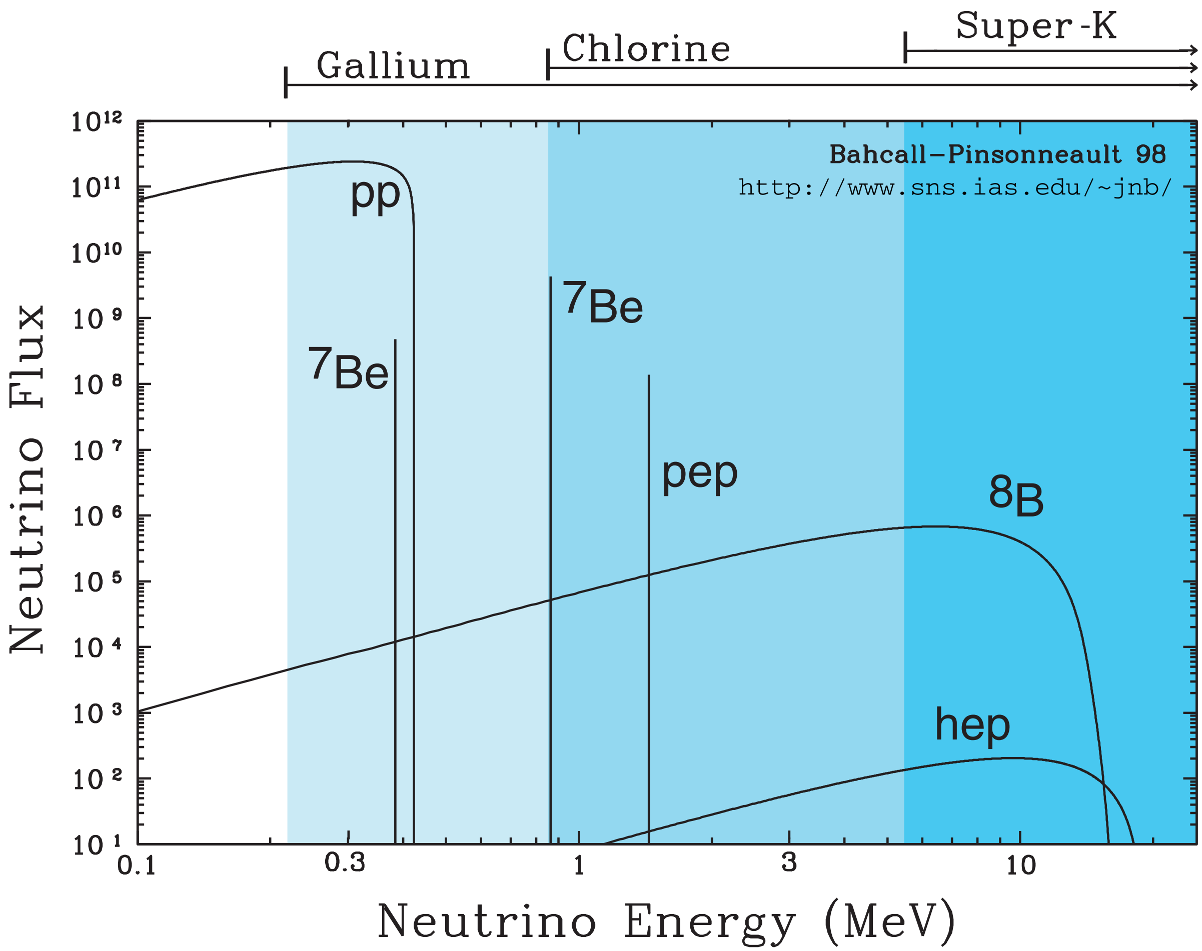

The superior *L/E* resolution will allow detection of the first oscillation period. It will also result in a substantial improvement in the measurement of $\Delta m^2$.

*S. Ragazzi, July 2000*

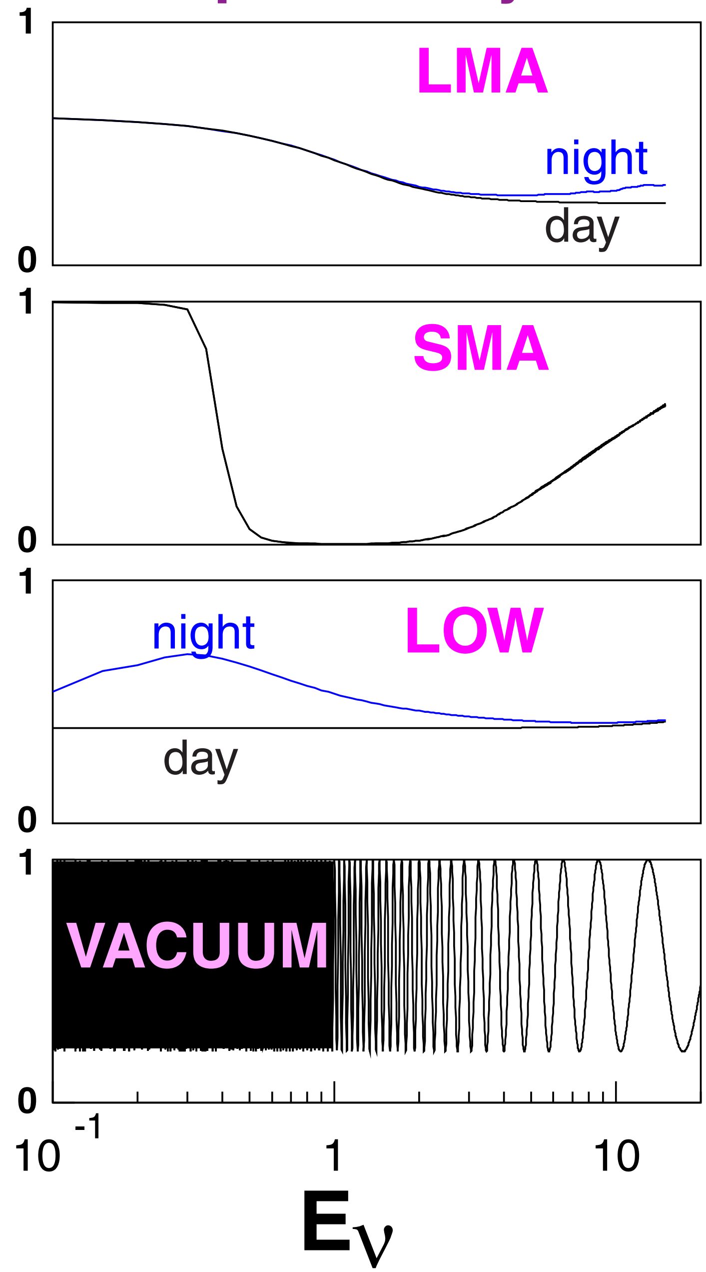


p + p → ²H + e⁺ + νe
pp
p + e⁻ + p → ²H + νe
pep
99.6%
0.4%
²H + p → ³He + γ
85%
15%
<<1%
³He + ³He → ⁴He + 2p
³He + p → ⁴He + e⁺ + νe
hep
³He + ⁴He → ⁷Be + γ
99.9%
0.1%
⁷Be + e⁻ → ⁷Li + νe
Beryllium7
⁷Be + p → ⁸B + γ
⁷Li + p → ⁴He + ⁴He
⁸B → ⁸Be + e⁺ + νe
Boron8
⁸Be → ⁴He + ⁴He
The sun burns through nuclear reactions
4p → ⁴He + 2e⁺ + 2νe + γ

# Standard Solar Model Energy Spectrum




## ν survival probability




**Flux measured / Flux predicted**

**= 0.58 ± 0.06**
**Gallium**

**= 0.33 ± 0.09**
**Chlorine**

**= 0.47 ± 0.01**
**Water**

# Flux Measurements

gallium

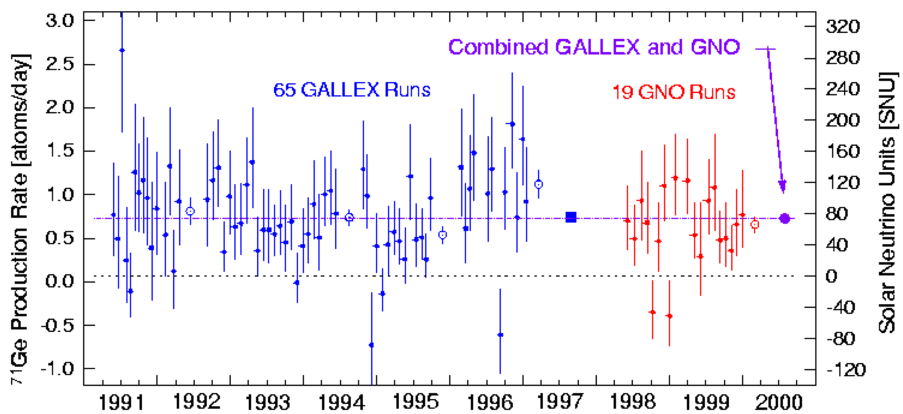
**SAGE** $75.4^{+7.8}_{-7.4}$ **SNU**

**Gallex + GNO** $74.1^{+6.7}_{-6.8}$ **SNU**

*C.Cattadori*

*GNO goals:*
*long time record of pp neutrinos with accuracy of 5 SNU*

*30t → 60t → 100t Ga*




**Theory (BP98)** $129^{+8}_{-6}$ **SNU**

chlorine

**Homestake** 2.56 ± 0.16 ± 0.16 **SNU**

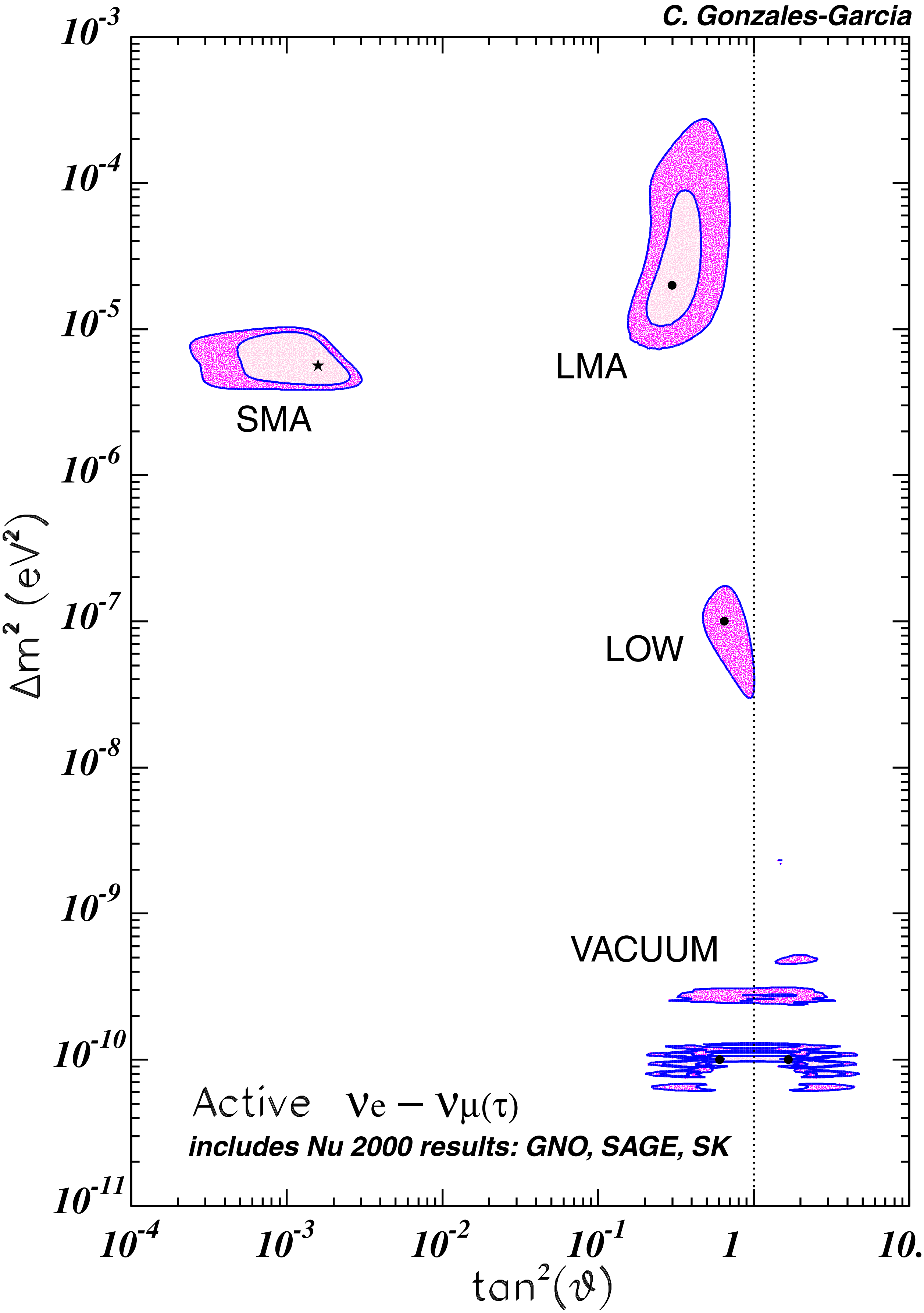
**Theory (BP98)** $7.7^{+1.2}_{-1.0}$ **SNU**

water

**Super-K** $2.40 \pm 0.03^{+0.08}_{-0.07}$ $10^6 cm^{-2}s^{-1}$

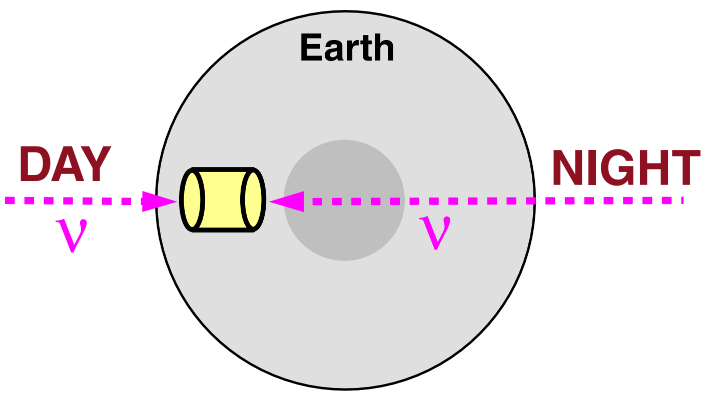
**Theory (BP98)** $5.15 \pm 0.98$ $10^6 cm^{-2}s^{-1}$

# Global Fit to Measured Flux
## from Ga, Cl, $H_2O$ Experiments

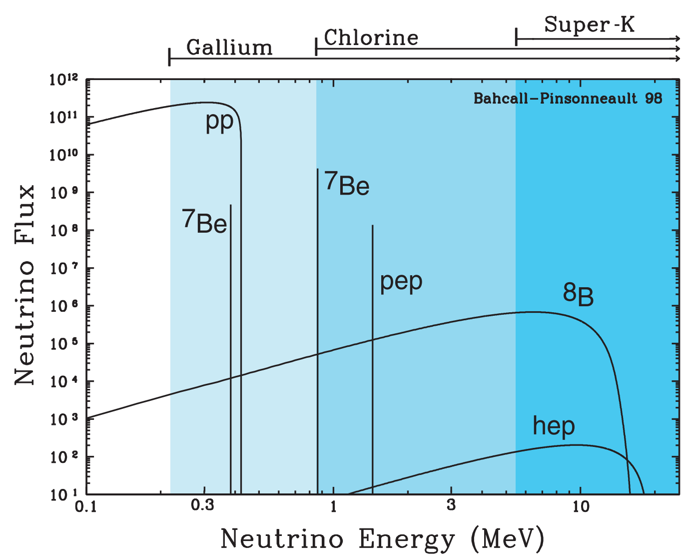


# Goal of 2nd-generation solar experiments is "SMOKING GUN" evidence of ν-oscillation

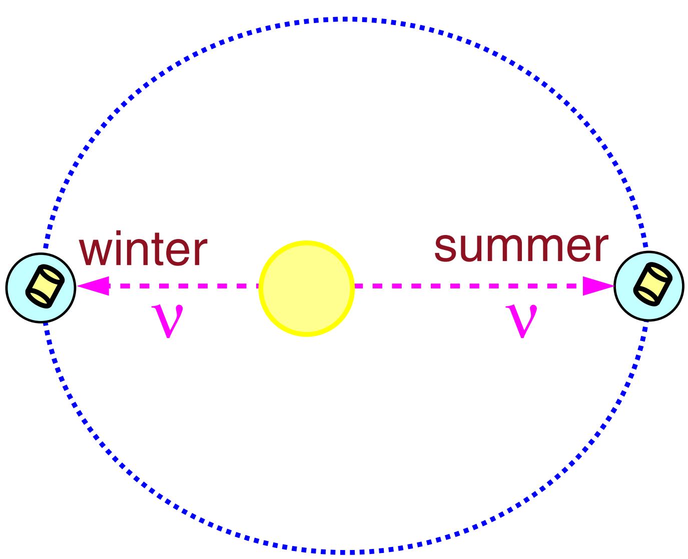
## Matter-effect regeneration



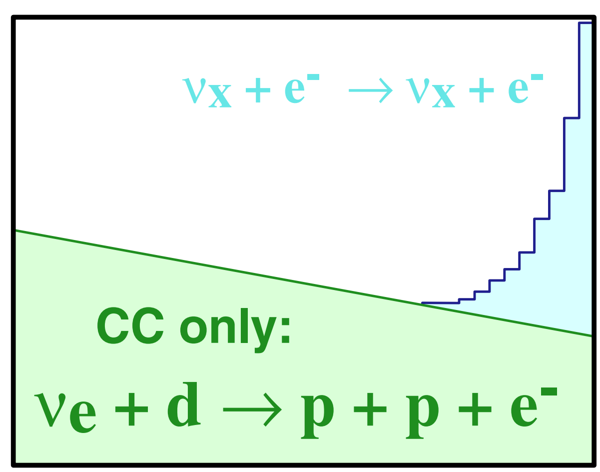

## Energy spectrum distortion




## Seasonal flux variation




## Neutral current / charged current




NC: $\nu_x + d \rightarrow \nu_x + p + n$

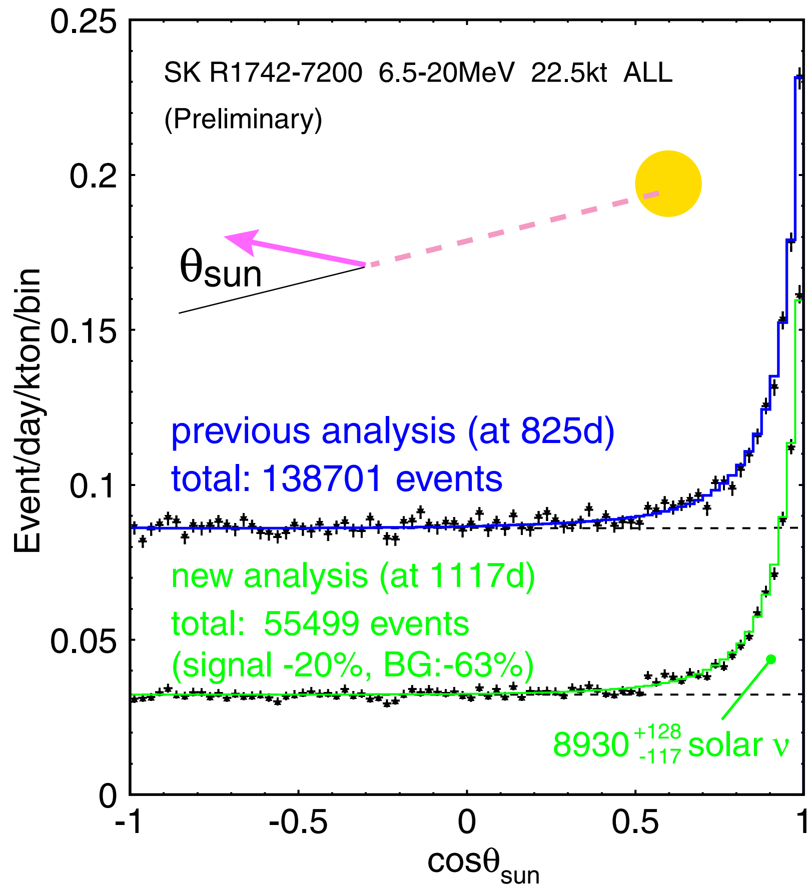
# Super-K Results - What's New

*Y.Takeuchi*

- **825 days → 1117 days (35% increase)**
- **Improved analysis: more BG rejection**

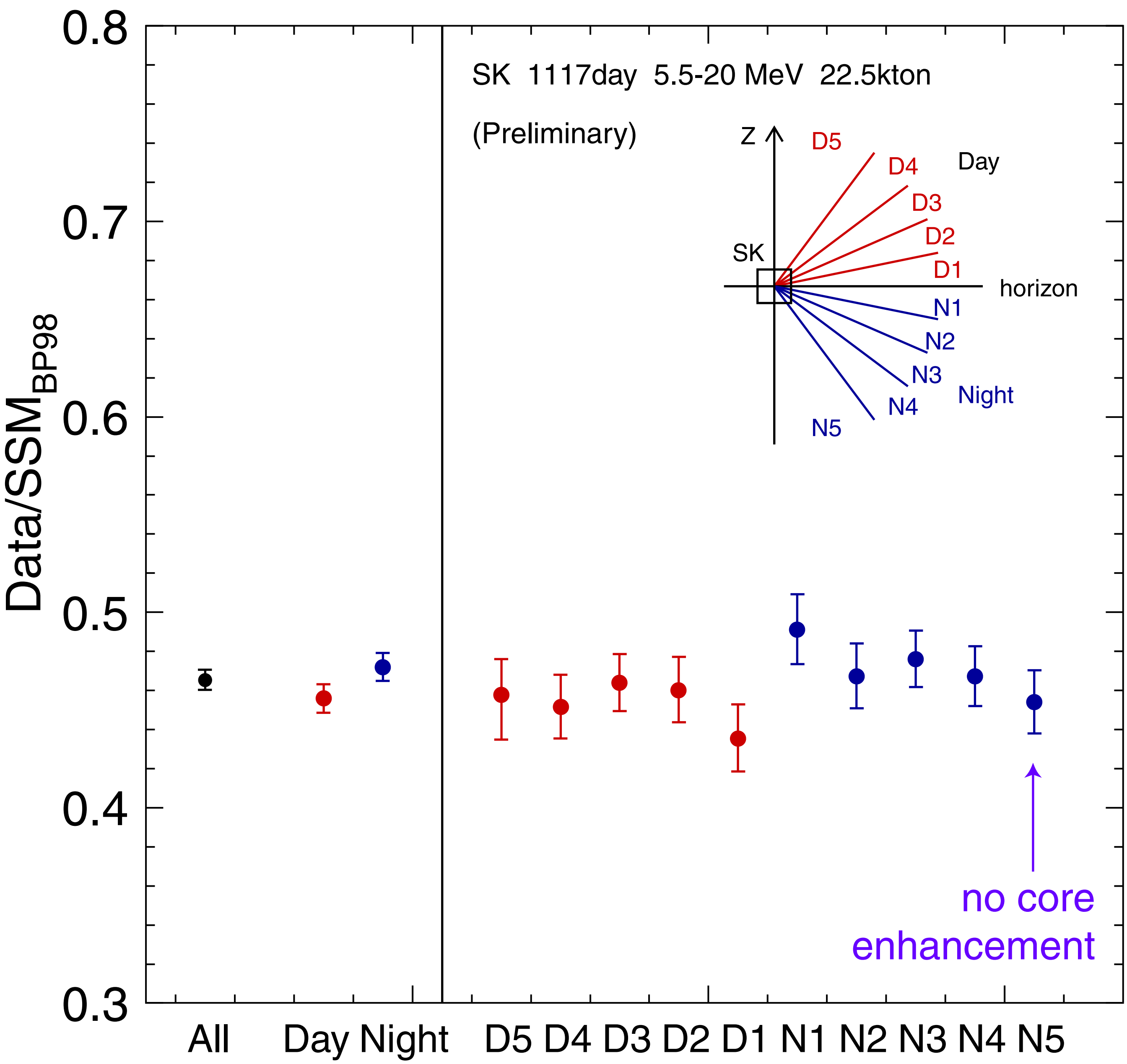
  **Reprocess all data combining SLE + LE**

  (previously, super-low-energy trigger + analysis was different for lowest energy bins)




- **M.C. retune (shifts energy scale 0.27%)**
- **Re-evaluate systematic uncertainties**
- **New data 5.0-5.5 MeV (not used in fits yet)**

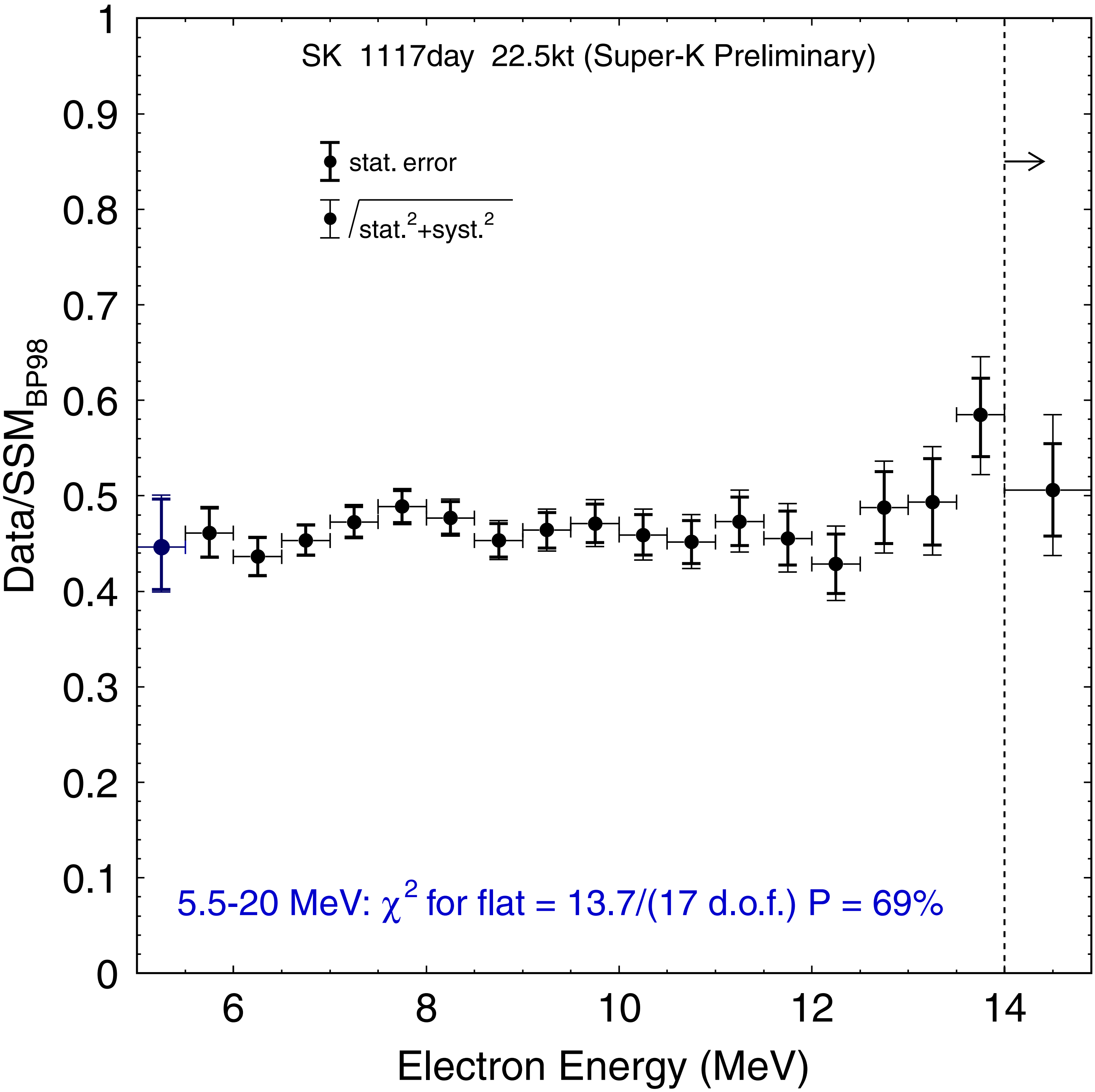
# Super-K Day-Night Result




$$\frac{D - N}{(D+N)/2} = -0.034 \pm 0.022^{+0.013}_{-0.012}$$

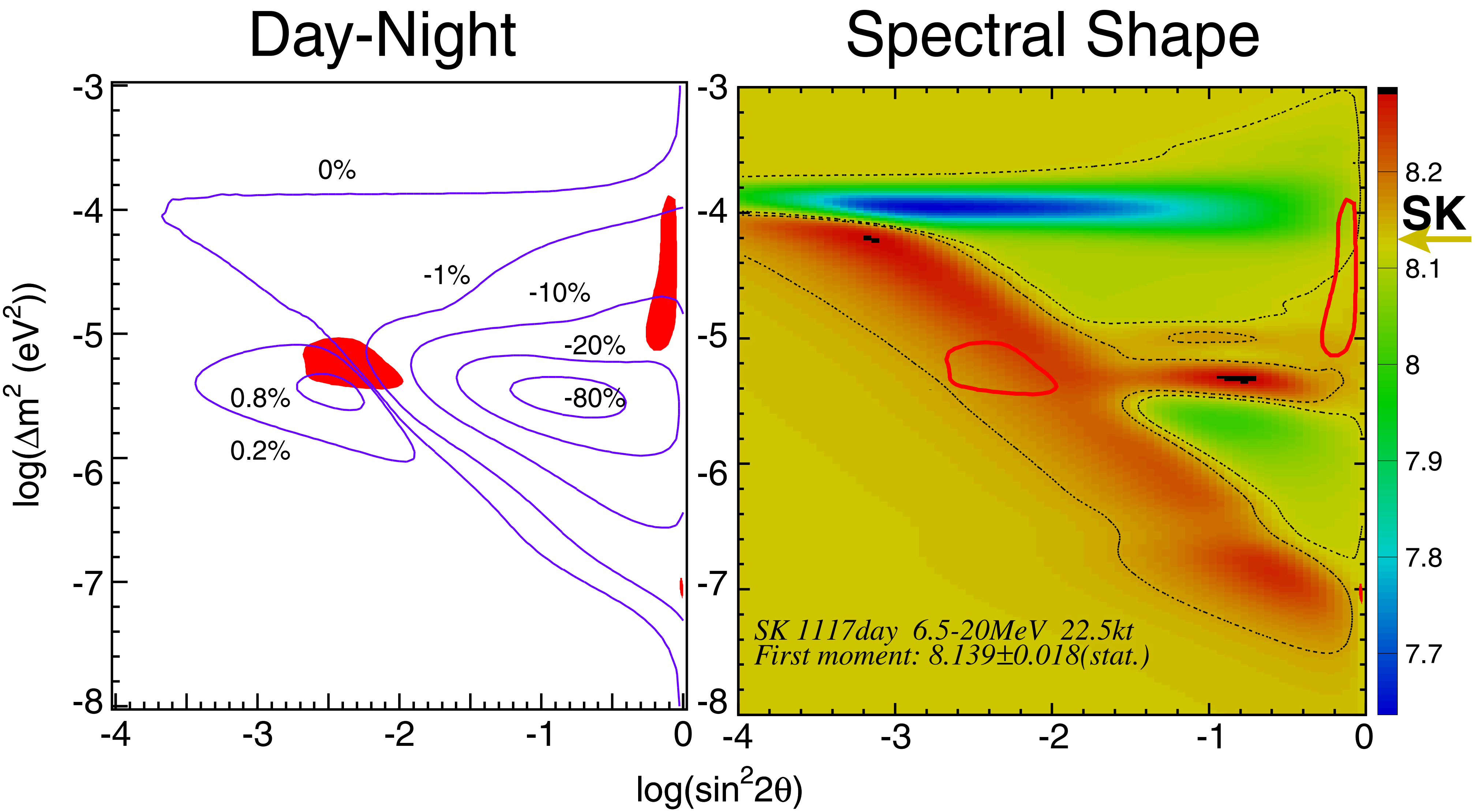
1.3σ effect

# Super-K Solar ν Energy Spectrum



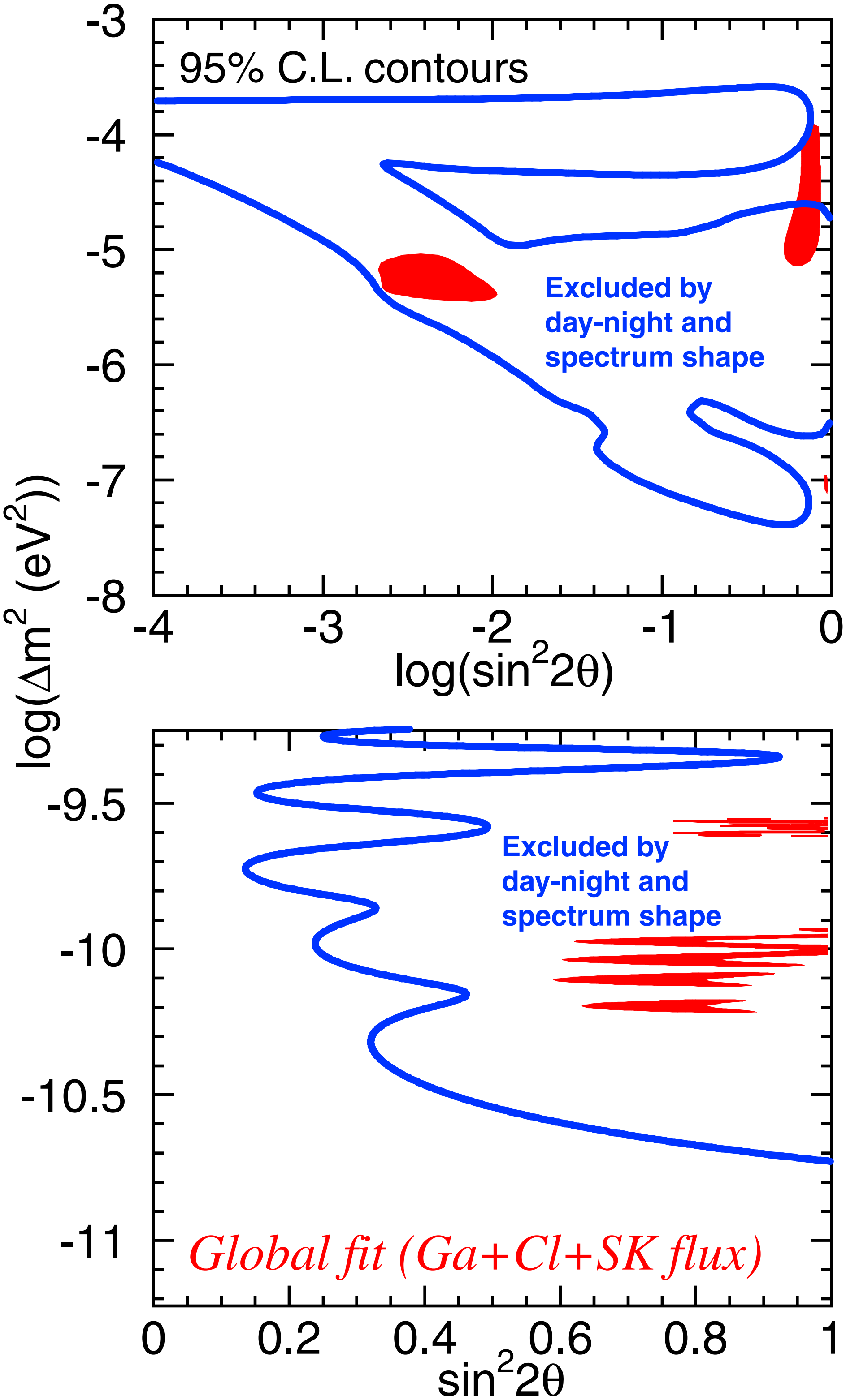

**no evidence for spectral distortion**
**high energy end consistent with 5x SSM Hep flux**

# Smoking Gun Expectations:



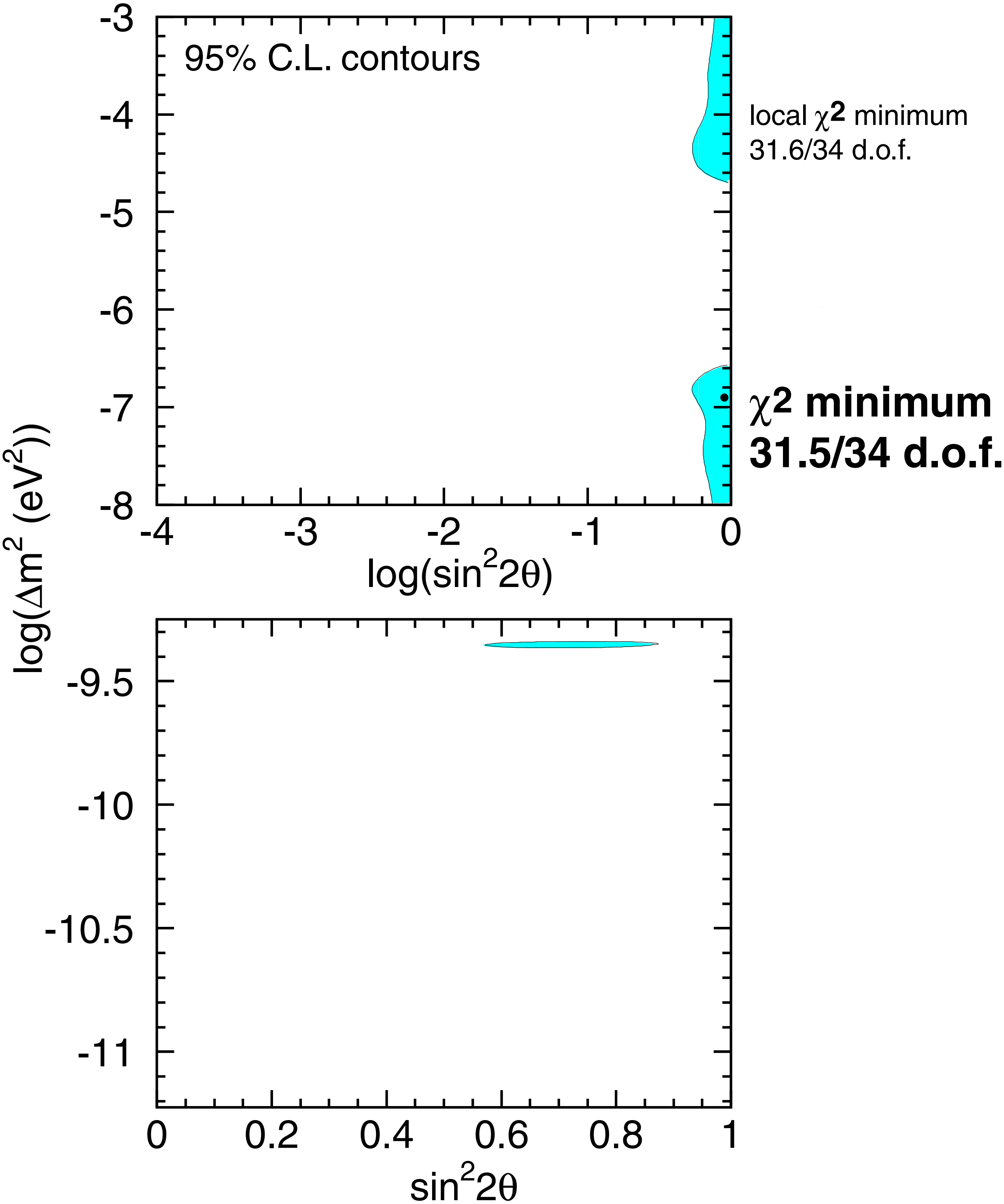

**first moment: <Ee>**
(Bahcall & Krastev)
SK value = 8.14 ± 0.02

# Super-K Flux Independent Analysis



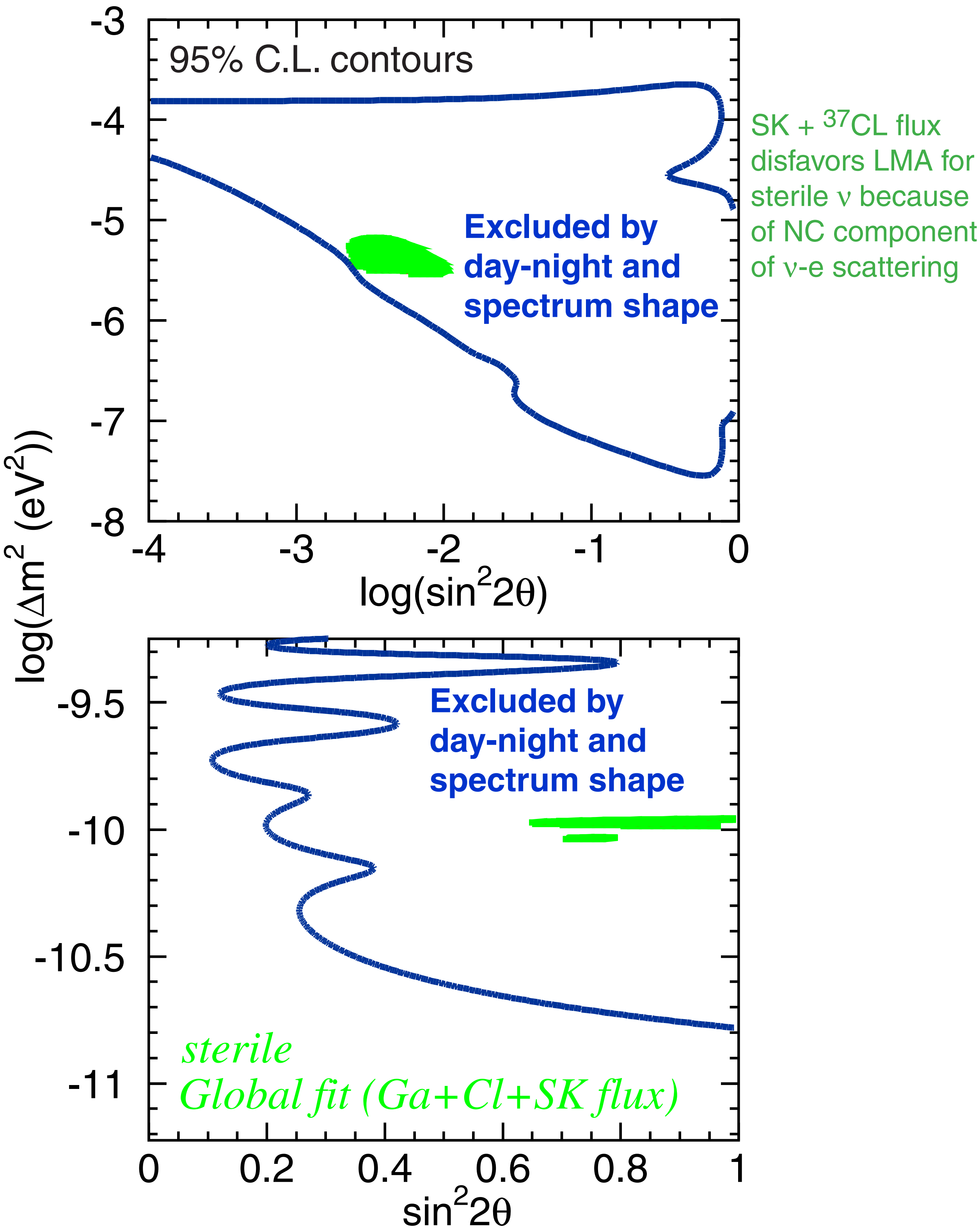
# Super-K Allowed Regions

day-night + spectrum shape + BP98 flux constraint




Large mixing is favored by Super-K data

# SK data disfavors sterile neutrino solution




**caveat: this analysis relies on two-flavor mixing**

**4-ν mixing with partial sterile component allowed *(O.Yasuda)***

# SNO

## Sudbury Neutrino Observatory

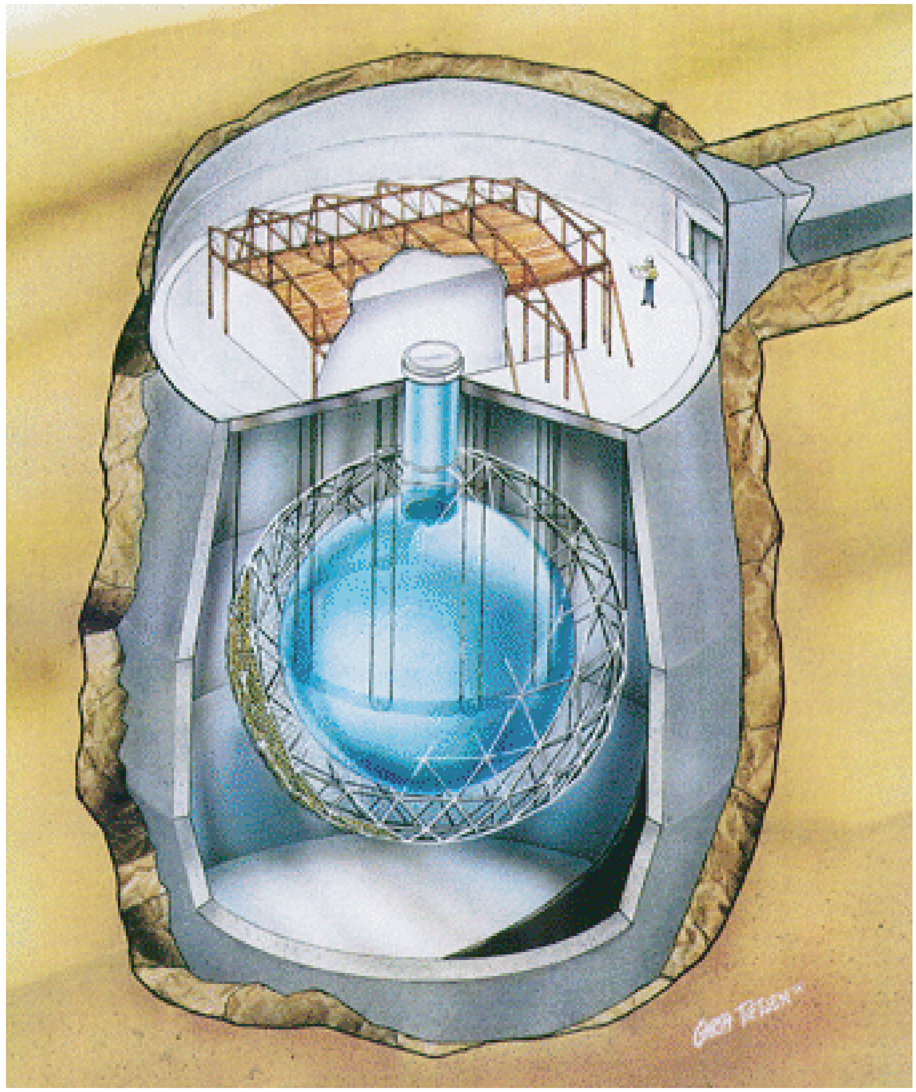
**2073 m depth**

**(~70 $\mu$/day)**

**1 kton $D_2O$**

**9500 20-cm PMTs**

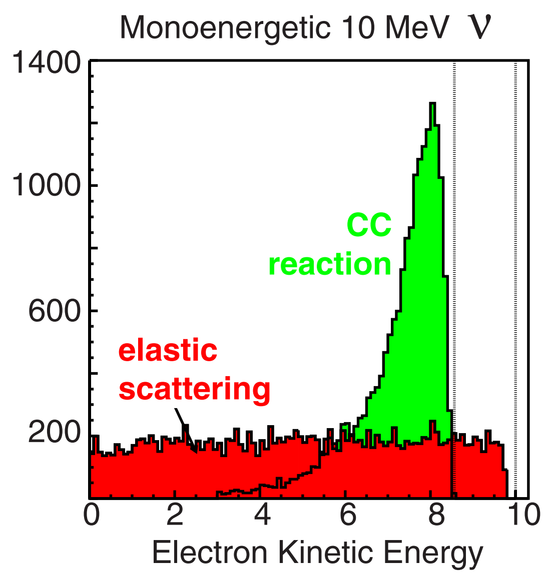
**began detecting $\nu$s May 1999**



**ES** $\nu_x + e^- \rightarrow \nu_x + e^-$
**directional**

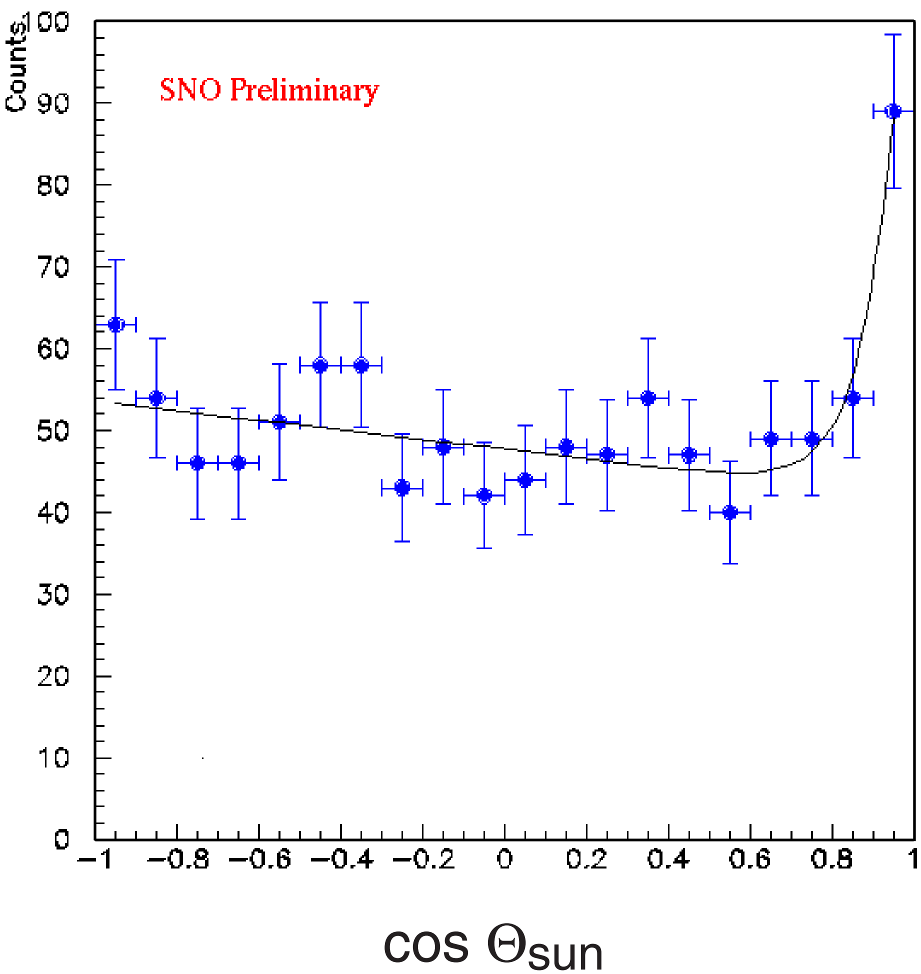
**CC** $\nu_e + d \rightarrow p + p + e^-$
**energy response →**

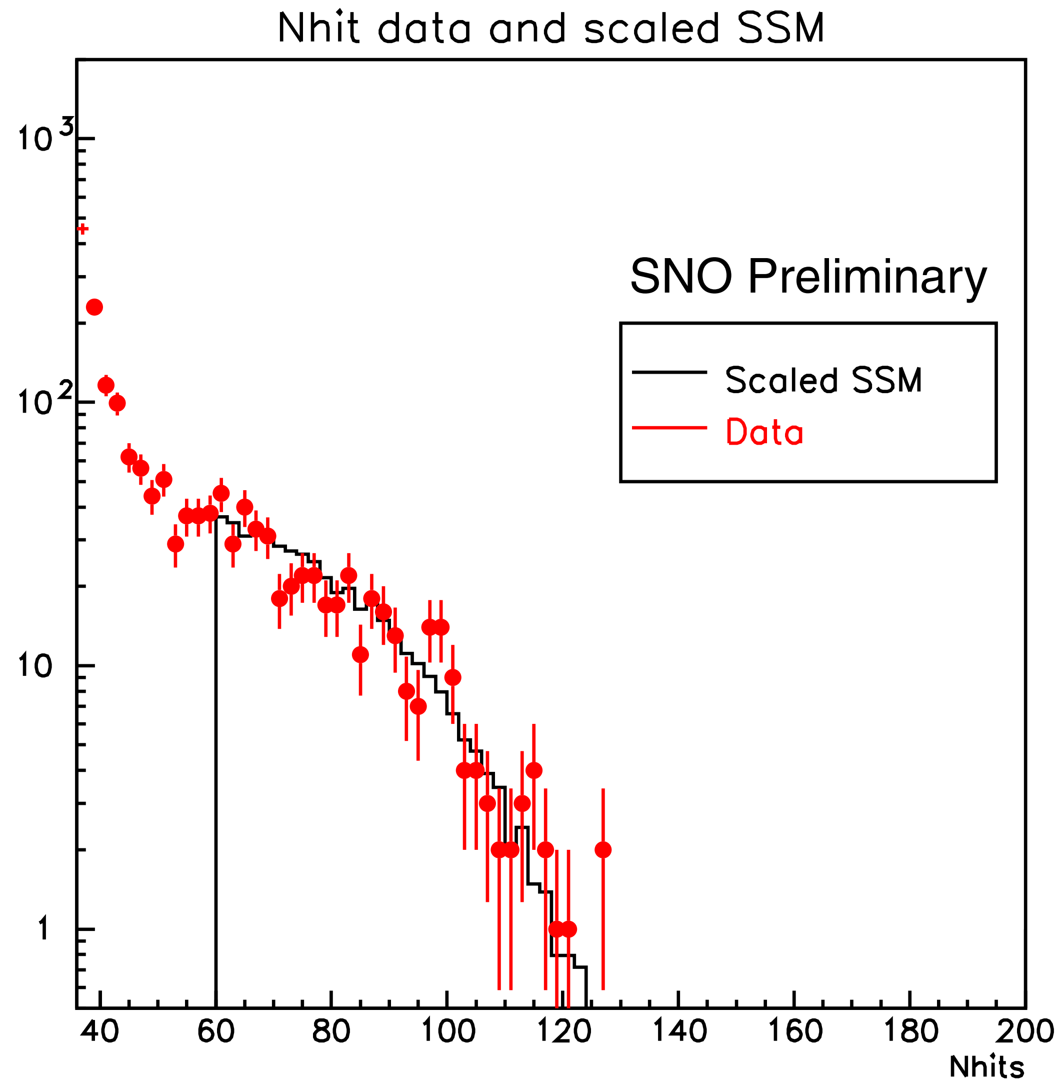
**NC** $\nu_x + d \rightarrow \nu_x + p + n$
**n capture**
- **on deuterium**
- **on $^{35}Cl$ salt**
- **with $^{3}He$ proportional counters**



# First Results from SNO

*J.Klein*




**+ excellent agreement between $^{16}N$ calibration source and Monte Carlo**

**~10 hits per MeV**

# Borexino

*M. Pallavicini*

**300 tons of liquid scintillator**

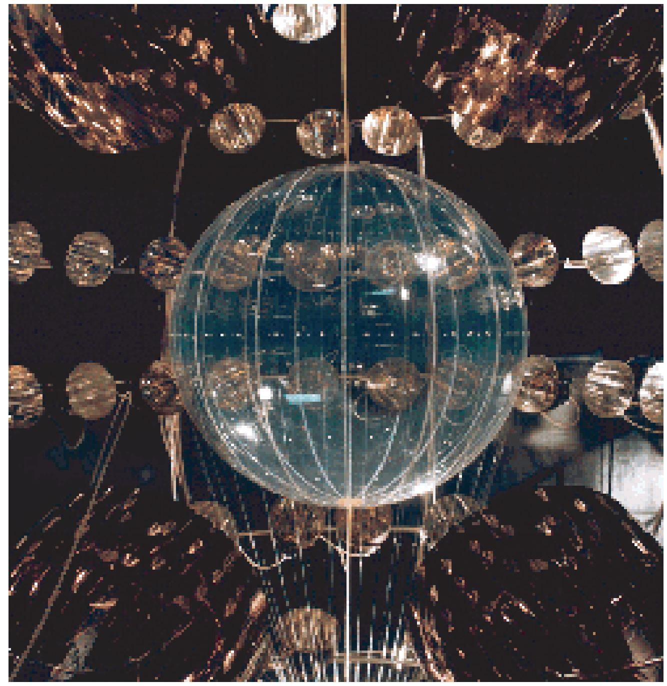
**demonstrated $10^{16}$ g/g U/Th**

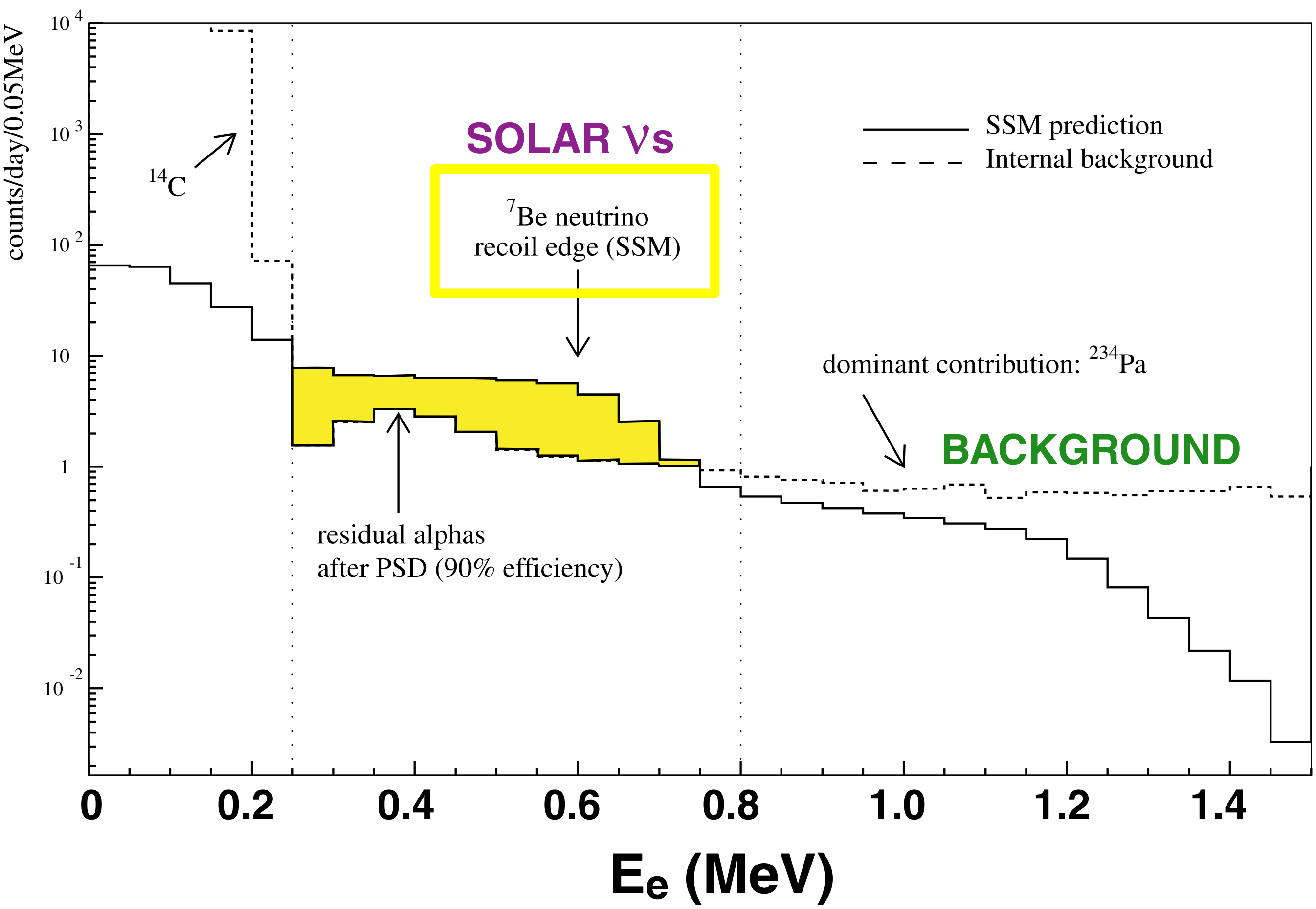
**study 862 keV $^{7}$Be line**

**55 events/day $\nu - e$ scattering**

**possible large seasonal variations**

**start in late 2001**





# Future Solar ν Experiments

## goal: low threshold sensitivity to pp ν

| | neutrino electron scattering |
|---|---|
| Heron | superfluid liquid He - rotons+UV |
| CLEAN | liquid Ne (or He) - scintillation + WLS + PMTs |
| Xenon | liquid Xe viewed by PMTs |
| Hellaz | pressurized He TPC (directionality) |

| | radiochemical → realtime |
|---|---|
| LENS | $^{176}$Yb + scintillator |
| MOON | $^{100}$ Mo + scintillator |
| Gd | $^{160}$Gd + scintillator |

*S.Schoenert*

http://www-sk.icrr.u-tokyo.ac.jp/lownu/

# Summary: Solar Neutrinos

Long standing solar neutrino
puzzle still unsolved
... but under attack.

NEW: Super-K spectrum+day/night
asymmetry FAVORS large mixing
of electron neutrino. No smoking
gun for neutrino oscillation, however.

Awaiting first results from
SNO and Borexino

new experiments:
find a viable realtime pp neutrino expt.
KamLAND prospects look good (LMA)

**Overall:** sterile neutrino
explanation of 3-oscillation
signatures (atm./solar/LSND)
under pressure.