Recent Results from Super-Kamiokande and Sudbury Neutrino Observatory

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Neutrino Mass and Mixing

Two Generation Model

Source — Detector

$|\nu_e\rangle \xrightarrow{\quad L \quad} A_e\,|\nu_e\rangle + A_\mu\,|\nu_\mu\rangle$

ν_1, ν_2 mass eigenstates m_1, m_2

$$|\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

$$\Delta m^2 = m_1^2 - m_2^2$$

$$P_\mu = |A_\mu|^2 = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4 E_\nu}\right)$$

$$P_e = |A_e|^2 = 1 - \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4 E_\nu}\right)$$

$E_\nu = 1$ MeV, $\Delta m^2 = 1$ eV^2, $\longrightarrow$ $L = 1.24$ meters

($P_e \rightarrow$ minimum)

Length & Energy Scales

$E_\nu = 1$ MeV, $\Delta m^2 = 1$ eV^2, ⟶ L = 1.24 meters

($P_e \rightarrow$ minimm)

$E_\nu = 1$ GeV, $\Delta m^2 = 10^{-3}$ eV^2, L = 1240 km — Super-K

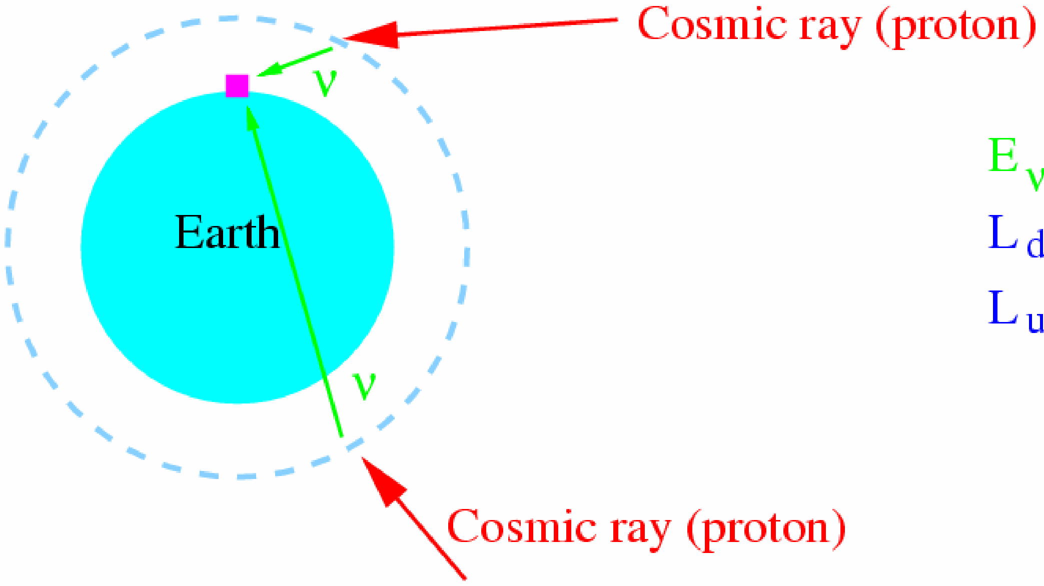
$E_\nu = 1$ MeV, $\Delta m^2 = 10^{-3}$ eV^2, L = 1.2 km — Chooz, Palo Verde

$E_\nu = 1$ MeV, $\Delta m^2 = 10^{-5}$ eV^2, L = 125 km — KamLAND

Kamioka Liquid scintillator Anti-Neutrino Detector

Super – Kamiokande

Atmospheric Neutrino Oscillations

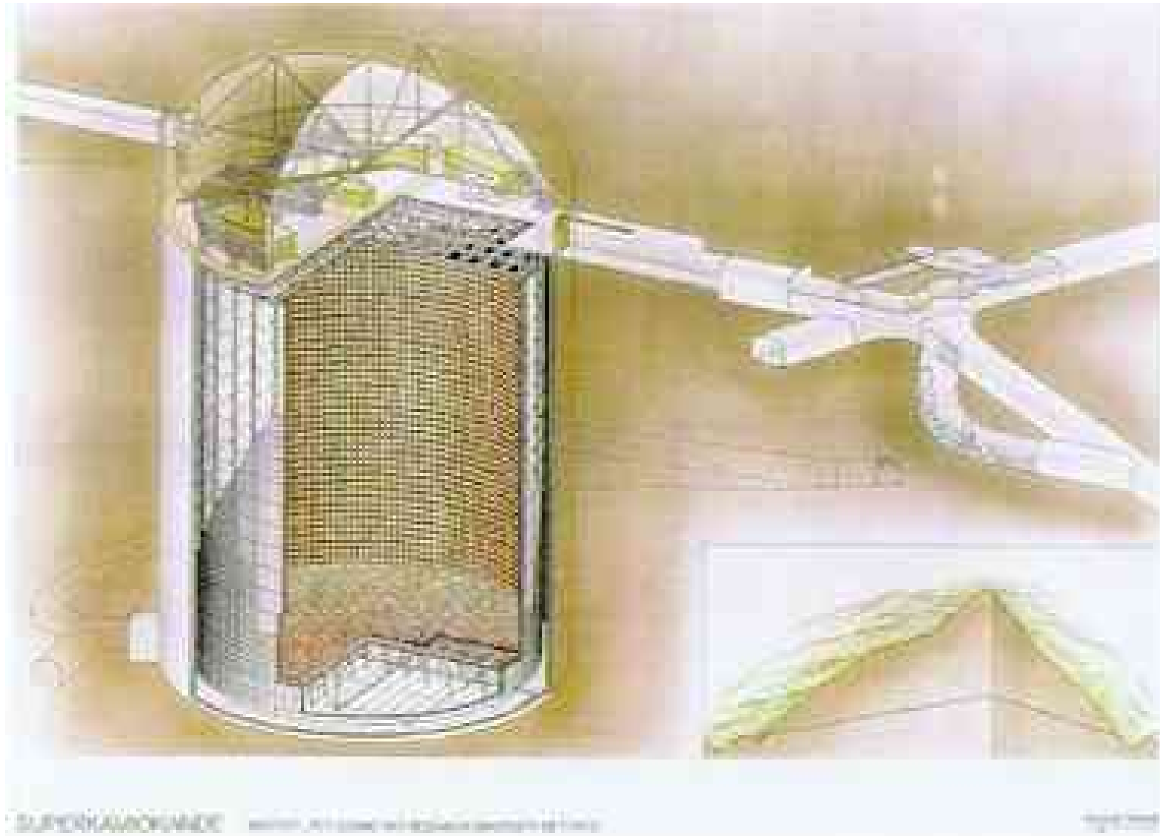


$E_{\nu} \sim 0.5 – 5$ GeV

$L_{down} \sim 100$ km

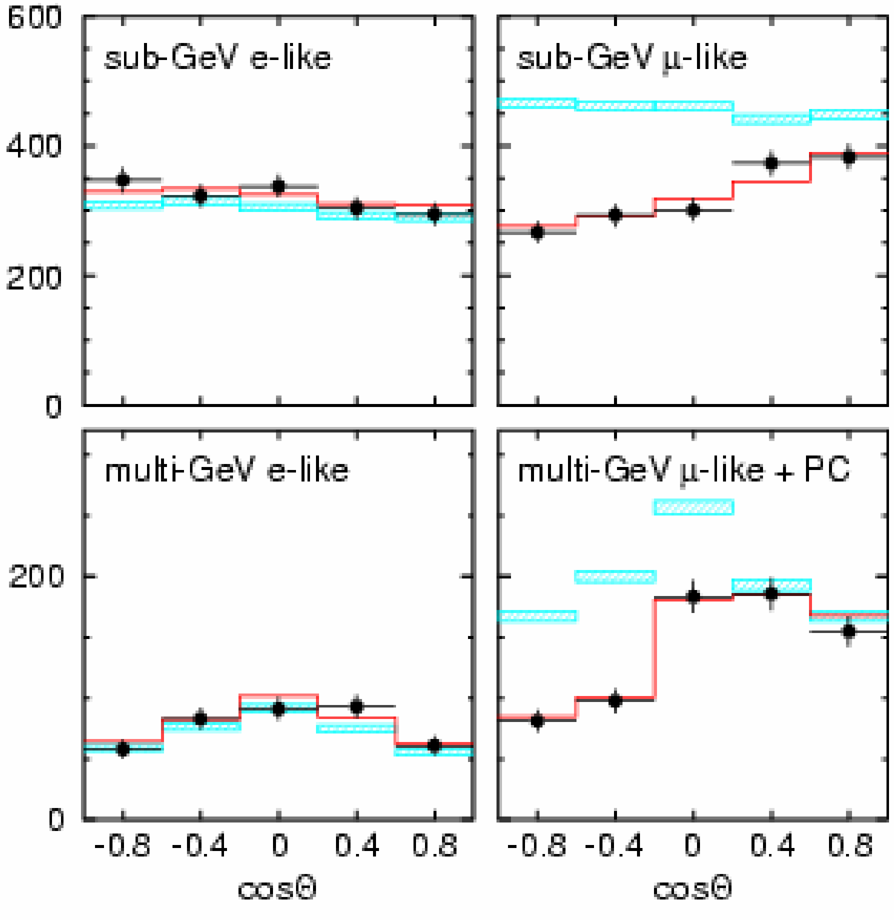
$L_{up} \sim 10{,}000$ km

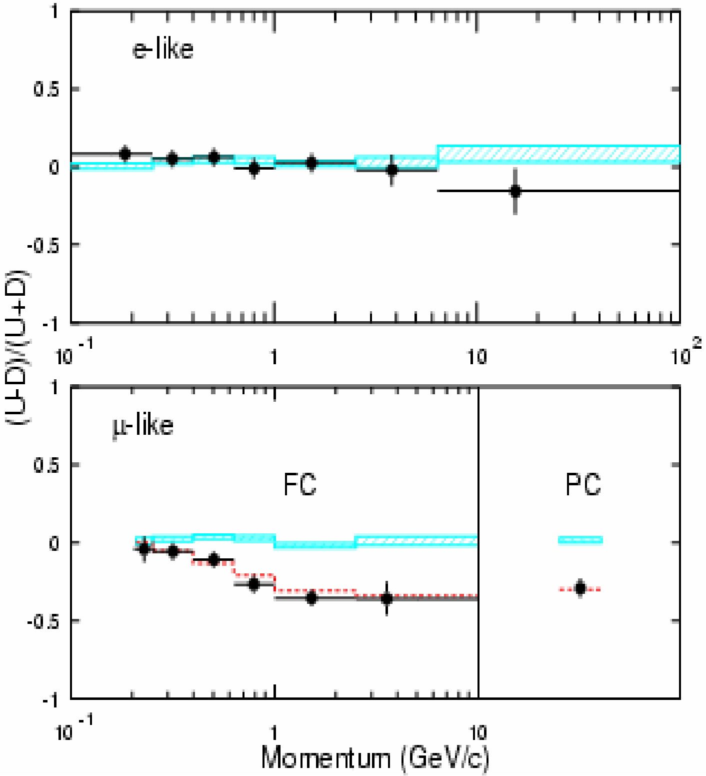
Super-Kamiokande



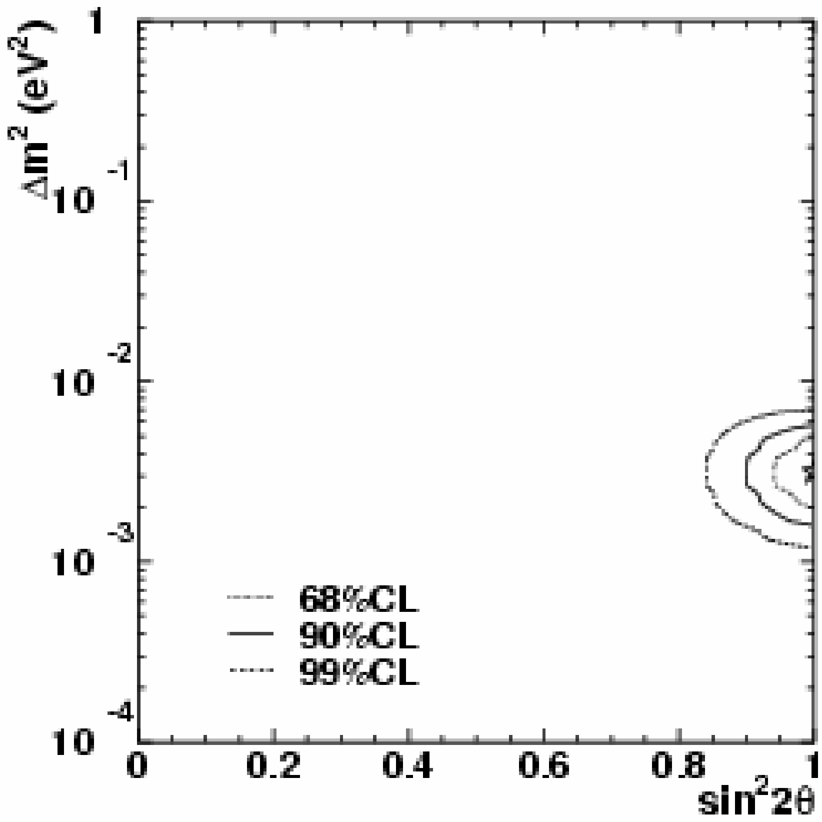
30 kton H_2O Cherenkov
11000 20" PMT's

Super-K Atmospheric ν Results





Super-K Atmospheric ν Results
Neutrino Oscillation Interpretation

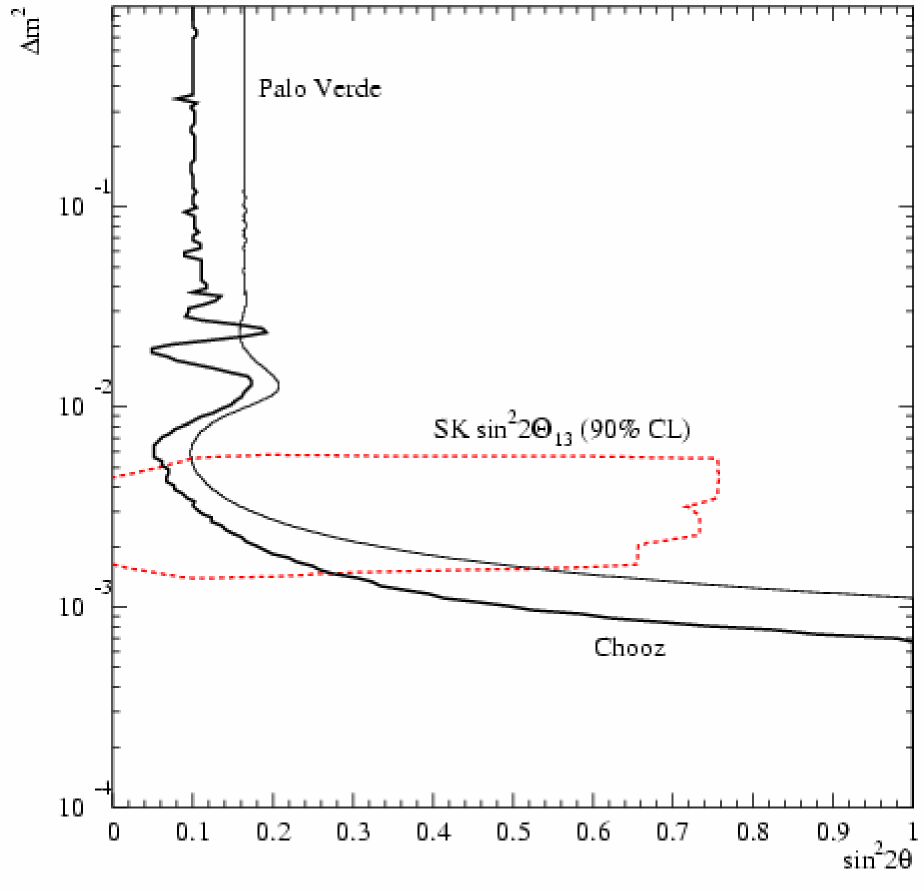


$\Omega_\nu > 0.001$

→ K2K, MINOS

Super-K Atmospheric ν Results

Oscillation to ν_e disfavored



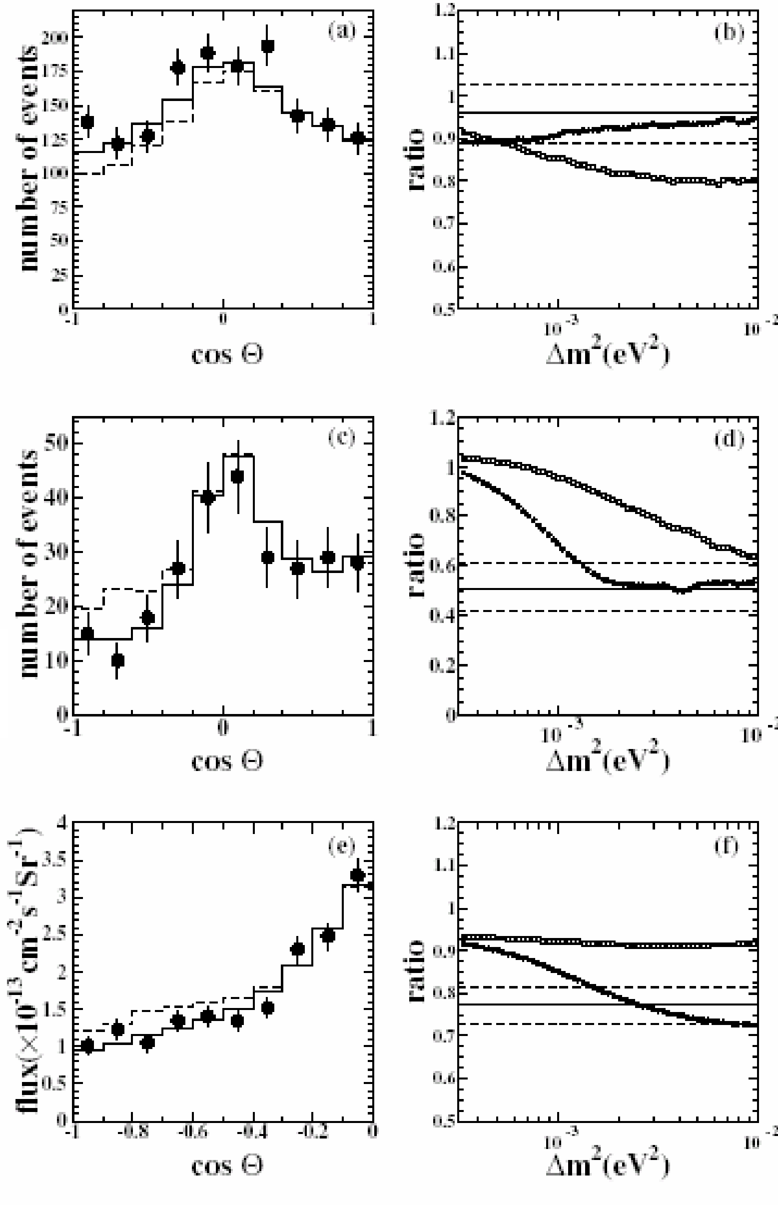
$\nu_\mu \to \tau$ neutrino ? $\nu_\mu \to$ sterile neutrino ?

multi-ring →

partially contained →

through,upward →

τ: solid
sterile: dashed



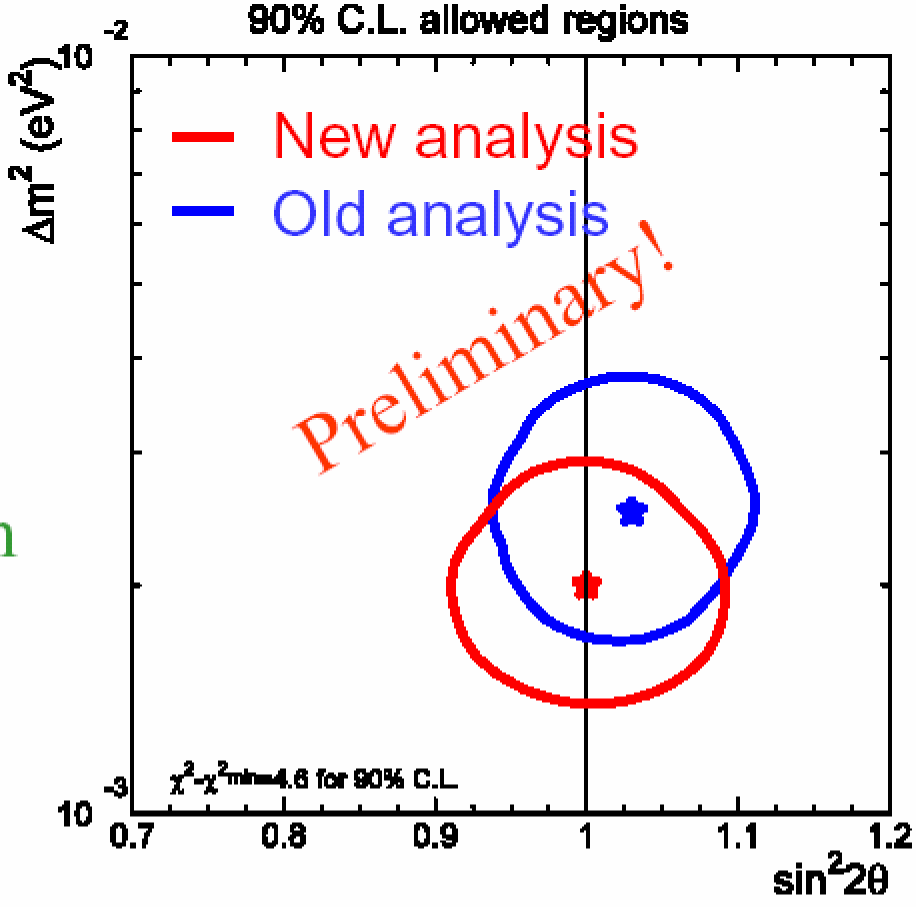
τ s

s τ

s τ

New analysis results of atmospheric neutrinos in Super-Kamiokande (2003)

- Neutrino flux (hep-ph/0203272)
  (Honda 1995(1D) Honda 2001(3D))
- Neutrino interaction model
  (several improvements, agree better with K2K near-detector data)
- Improved detector simulation
- Improved event reconstruction

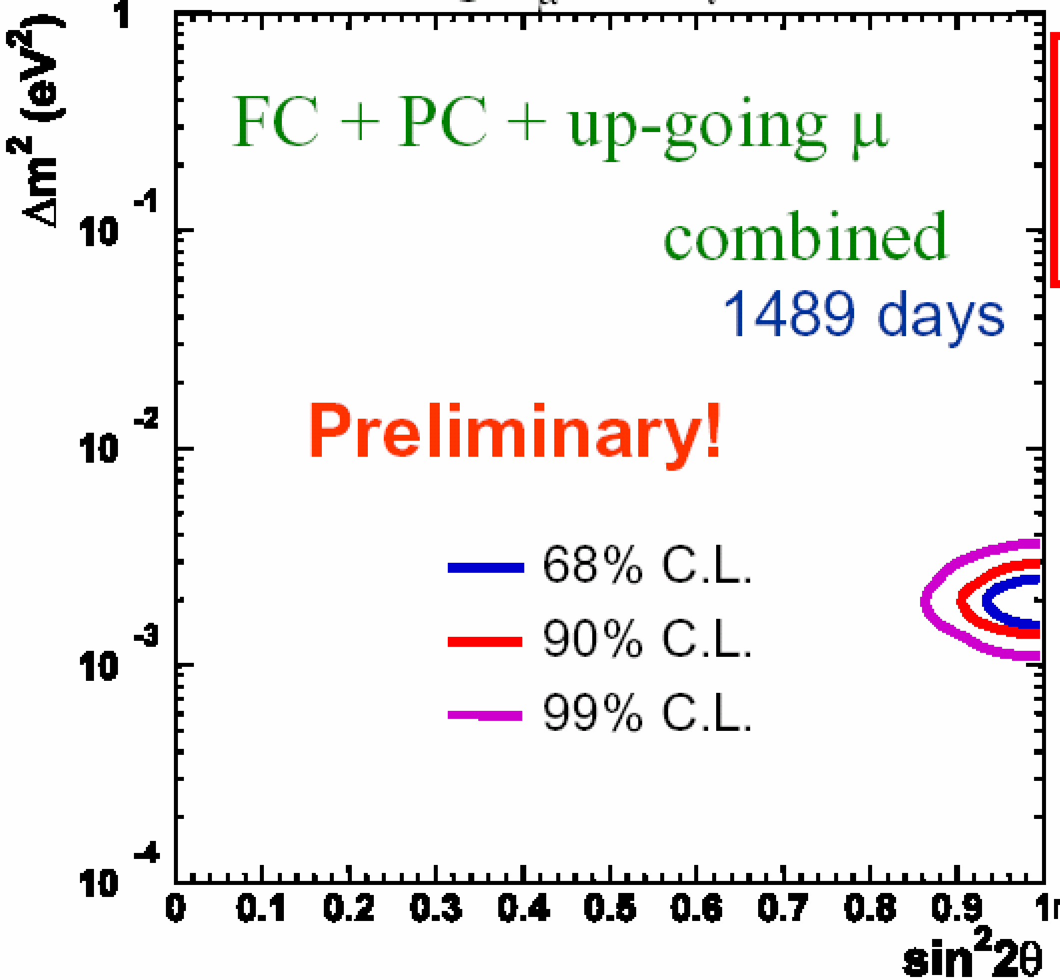


Each change contributes to the shift in the allowed (Δm^2) region.

Allowed region in Super-Kamiokande atmospheric ν data (2003)

(complete SK-I data-set)

Assuming $\nu_\mu \rightarrow \nu_\tau$ oscillation



90% CL allowed region
$\sin^2 2\theta > 0.9$
$1.3 \times 10^{-3} < \Delta m^2 < 3.0 \times 10^{-3}$ eV^2

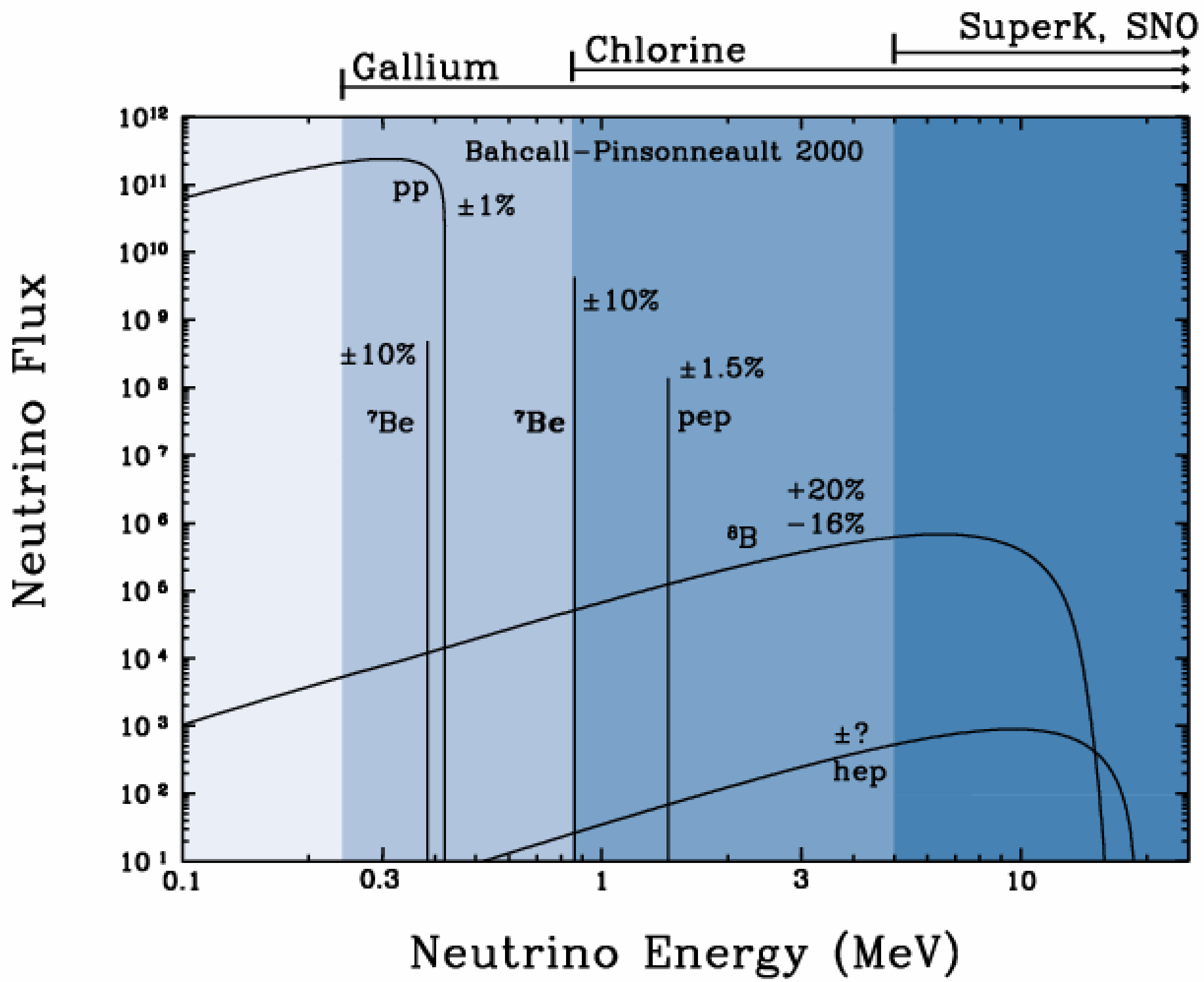
Best fit
$(\sin^2 2\theta, \Delta m^2)$
$= (1.0, 2.0 \times 10^{-3}$ eV$^2)$

$\chi^2_{min} = 170.8/170$ d.o.f.

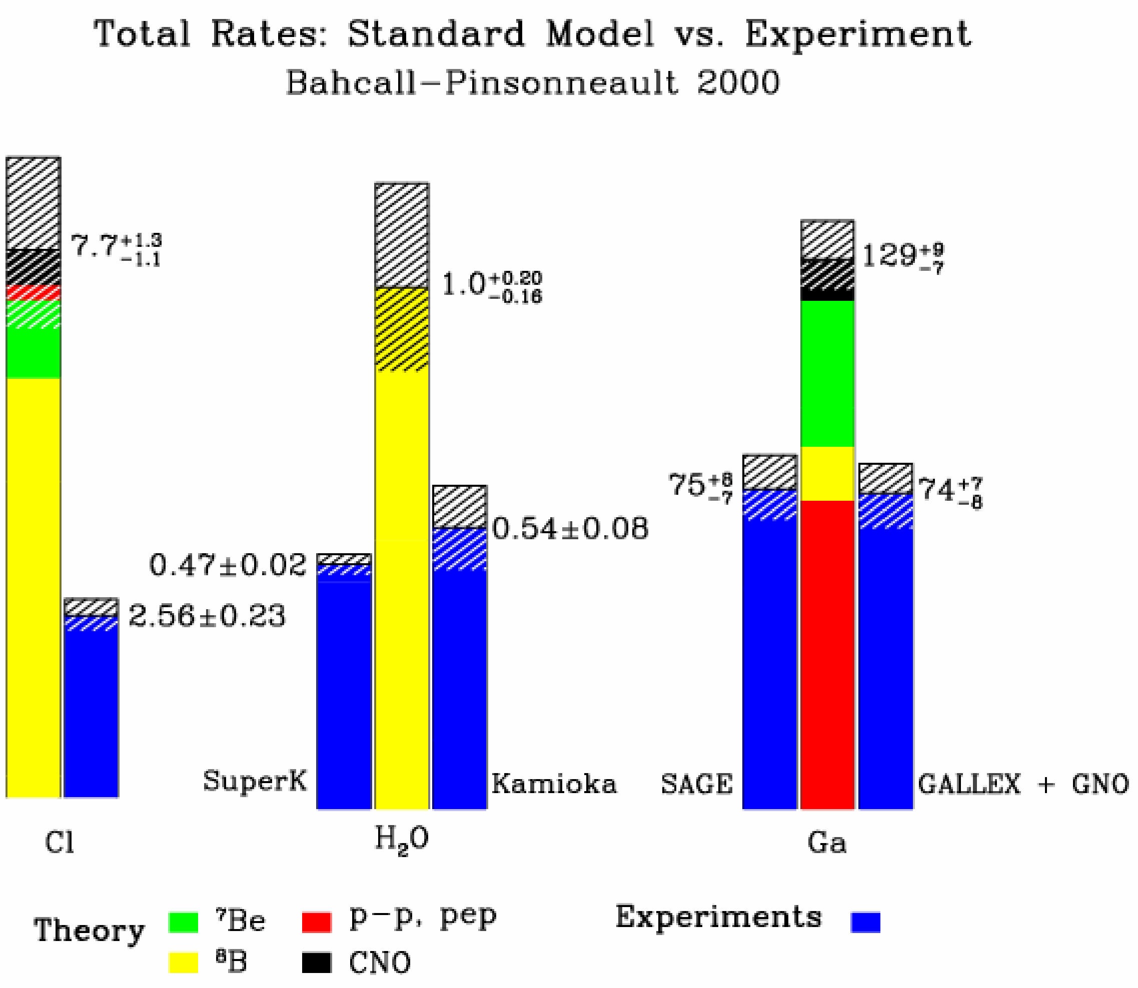
Assuming null oscillation

$\chi^2 = 445.2/172$ d.o.f.

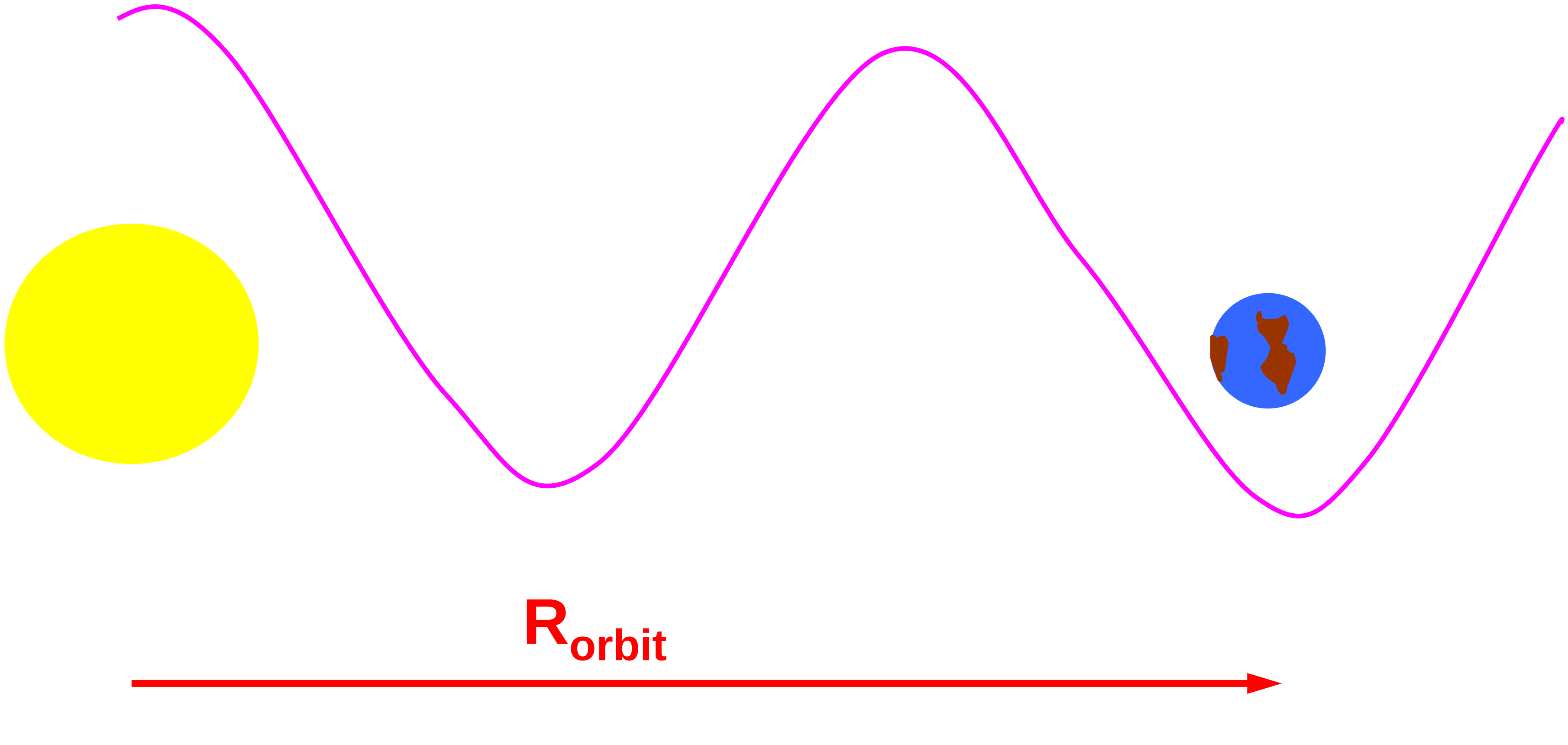
Solar Neutrino Energy Spectrum



More missing neutrinos…



Neutrino Oscillations?

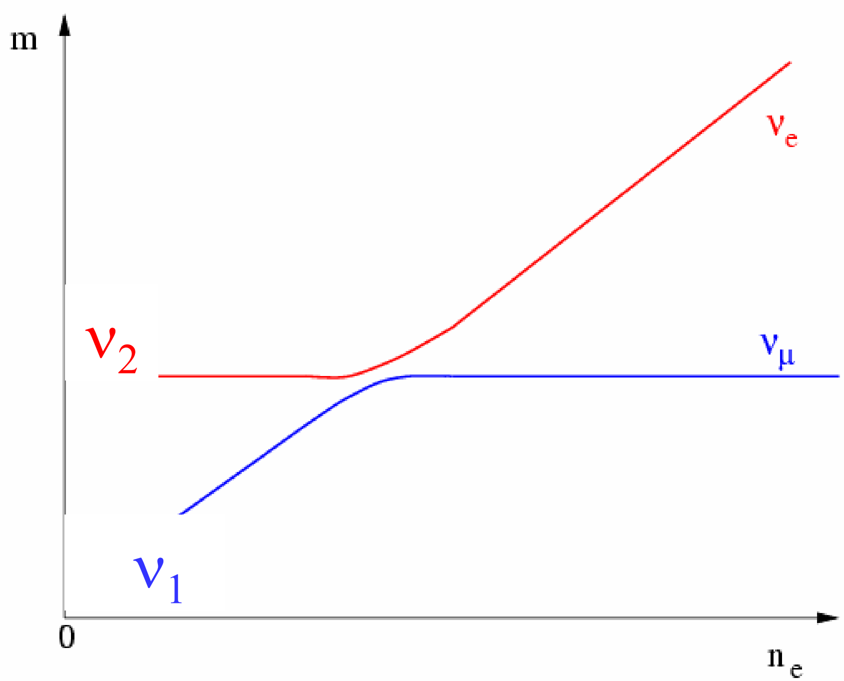


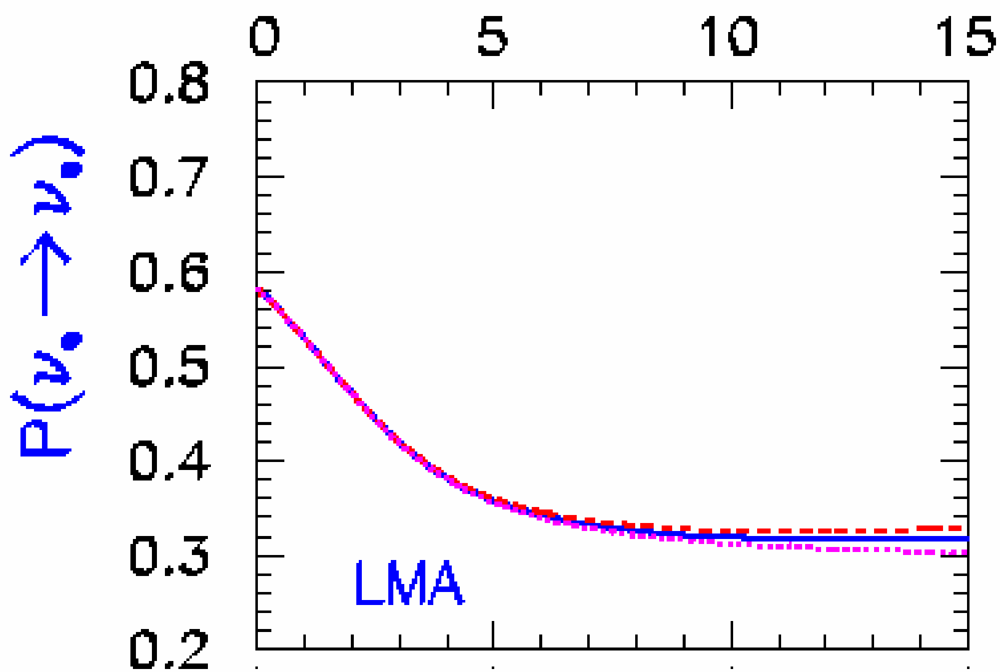
"Just So ??? "

Matter Enhanced Oscillation (MSW)

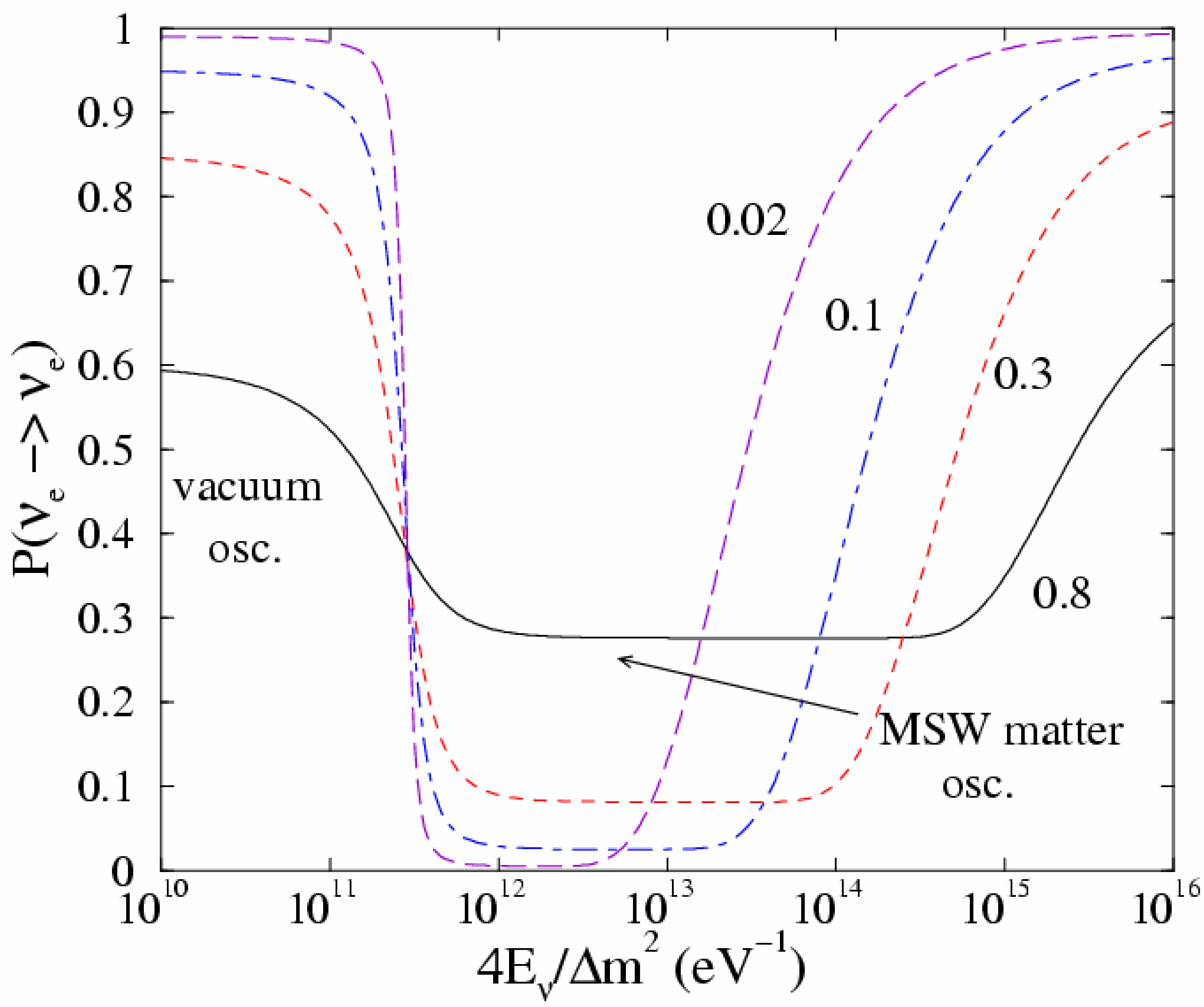
Mikheyev, Smirnov, Wolfenstein

$$\mathcal{H} = \mathcal{H}_V + \mathcal{H}_M(r)$$
$$= \frac{\Delta m^2_\odot}{4E}\begin{bmatrix} -\cos 2\theta_\odot & \sin 2\theta_\odot \\ \sin 2\theta_\odot & \cos 2\theta_\odot \end{bmatrix} + \begin{bmatrix} V(r) & 0 \\ 0 & 0 \end{bmatrix}$$
$$V = \sqrt{2}\, G_F N_e$$

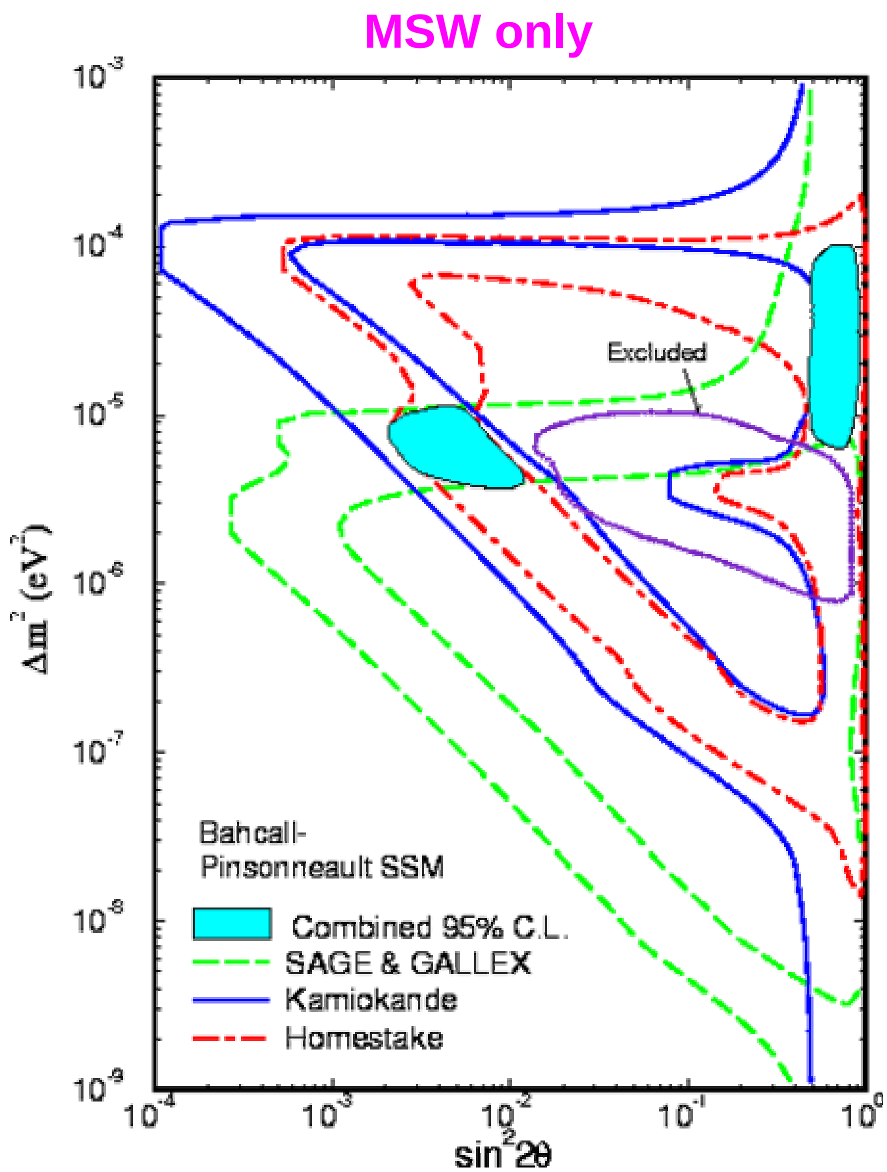




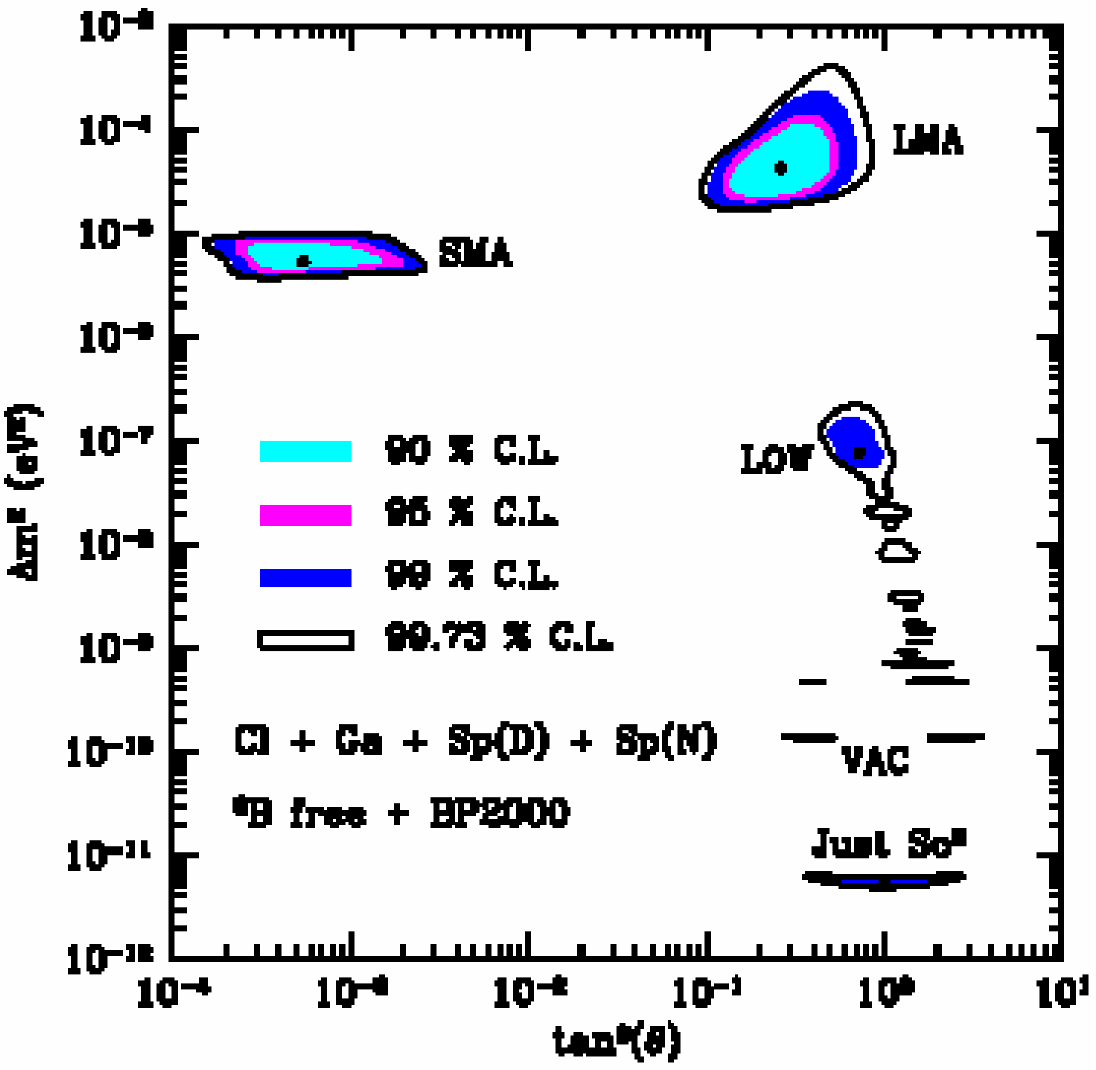
Neutrino Oscillations in the Sun



Solar Neutrino Results

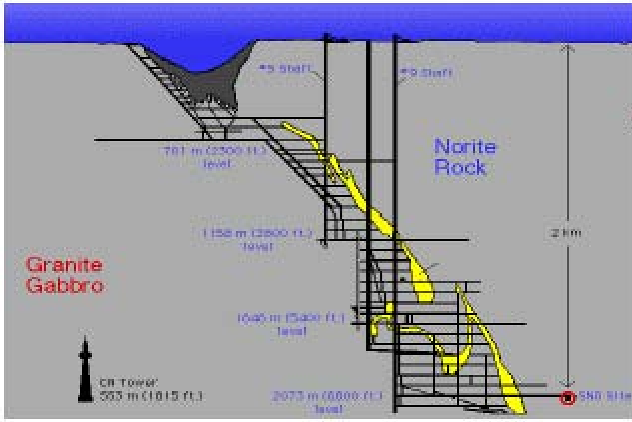


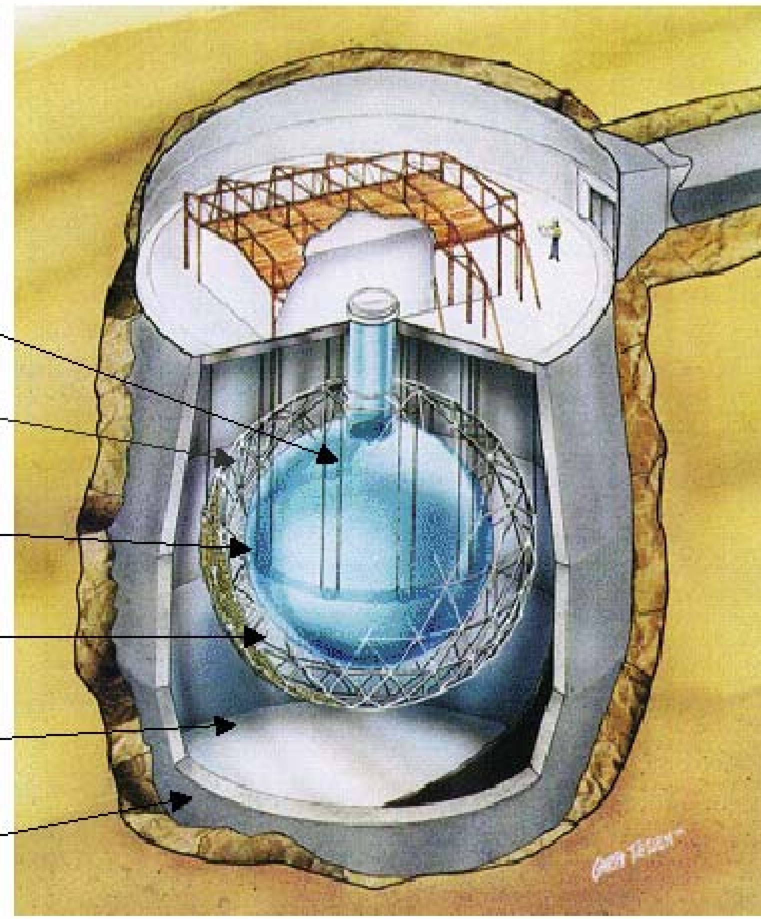
Solar Neutrino Results



(Bahcall, Krastev and Smirnov, 2001)

Sudbury Neutrino Observatory





1000 tonnes D_2O

Support Structure for 9500 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

1700 tonnes Inner Shielding H_2O

5300 tonnes Outer Shield H_2O

Urylon Liner and Radon Seal

ν Reactions in SNO

CC $\nu_e + d \Rightarrow p + p + e^-$

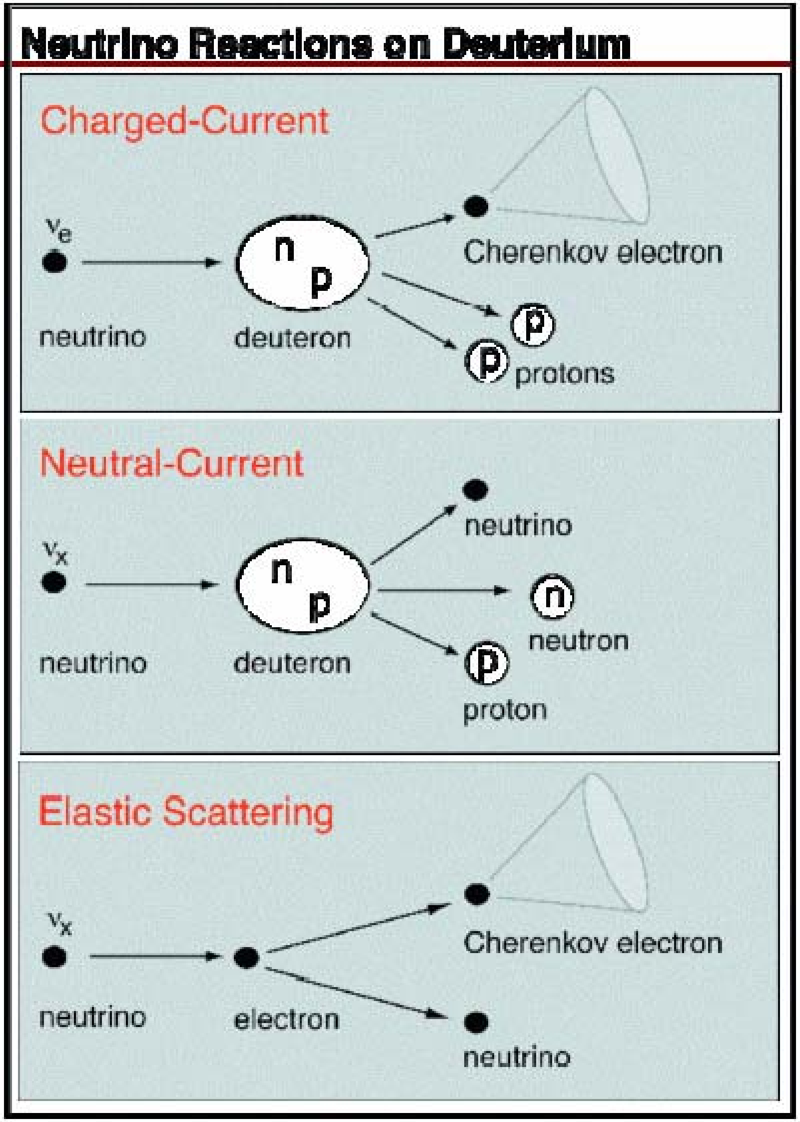
-Gives ν_e energy spectrum well
-Weak direction sensitivity $\propto$ 1-1/3cos(θ)
- ν_e only.

NC $\nu_x + d \Rightarrow p + n + \nu_x$

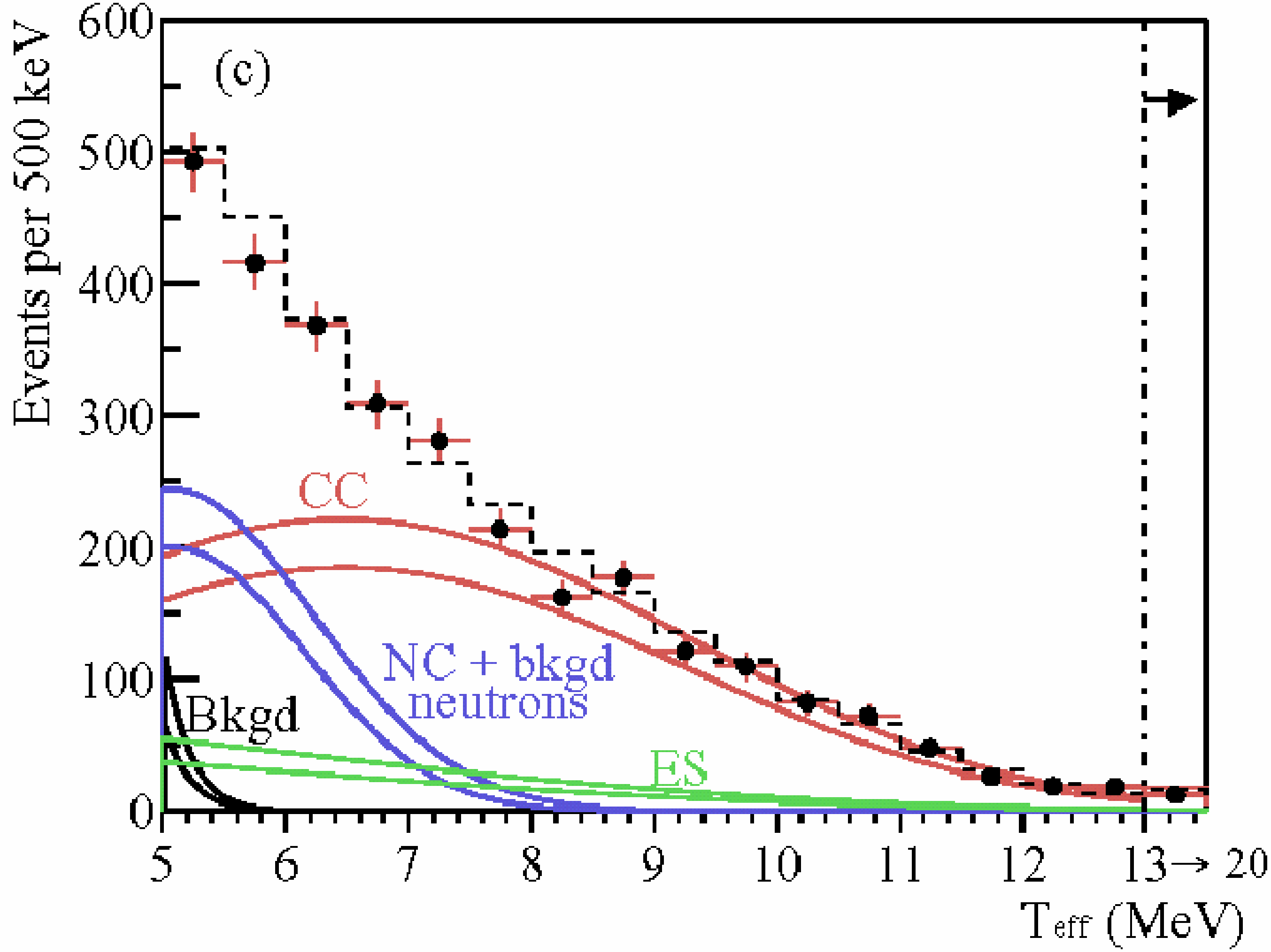
-Measure total ^{8}B ν flux from the sun.
- Equal cross section for all ν types

ES $\nu_x + e^- \Rightarrow \nu_x + e^-$

-Low Statistics
-Mainly sensitive to ν_e, some
-sensitivity to ν_μ and ν_τ
-Strong direction sensitivity



Total spectrum (NC + CC + ES)

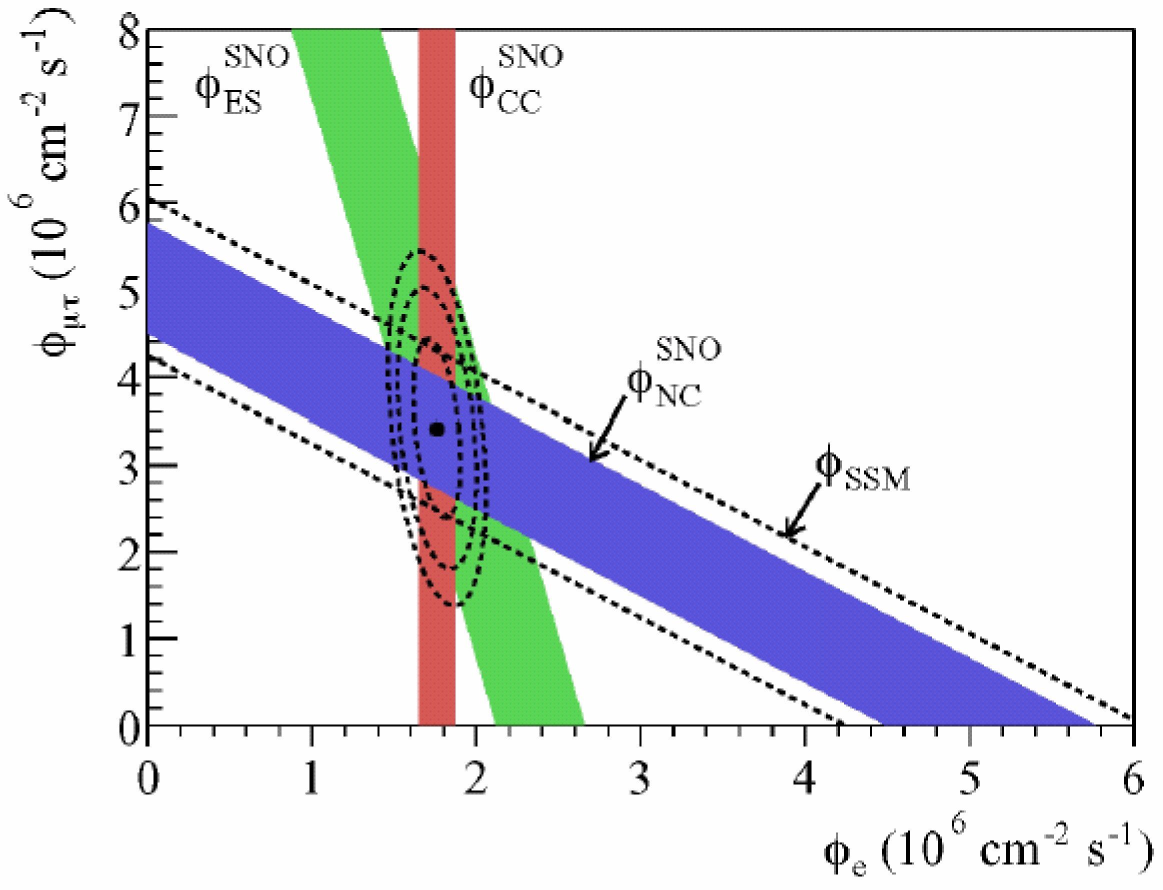


Neutrino Flavor Composition of ^{8}B Flux

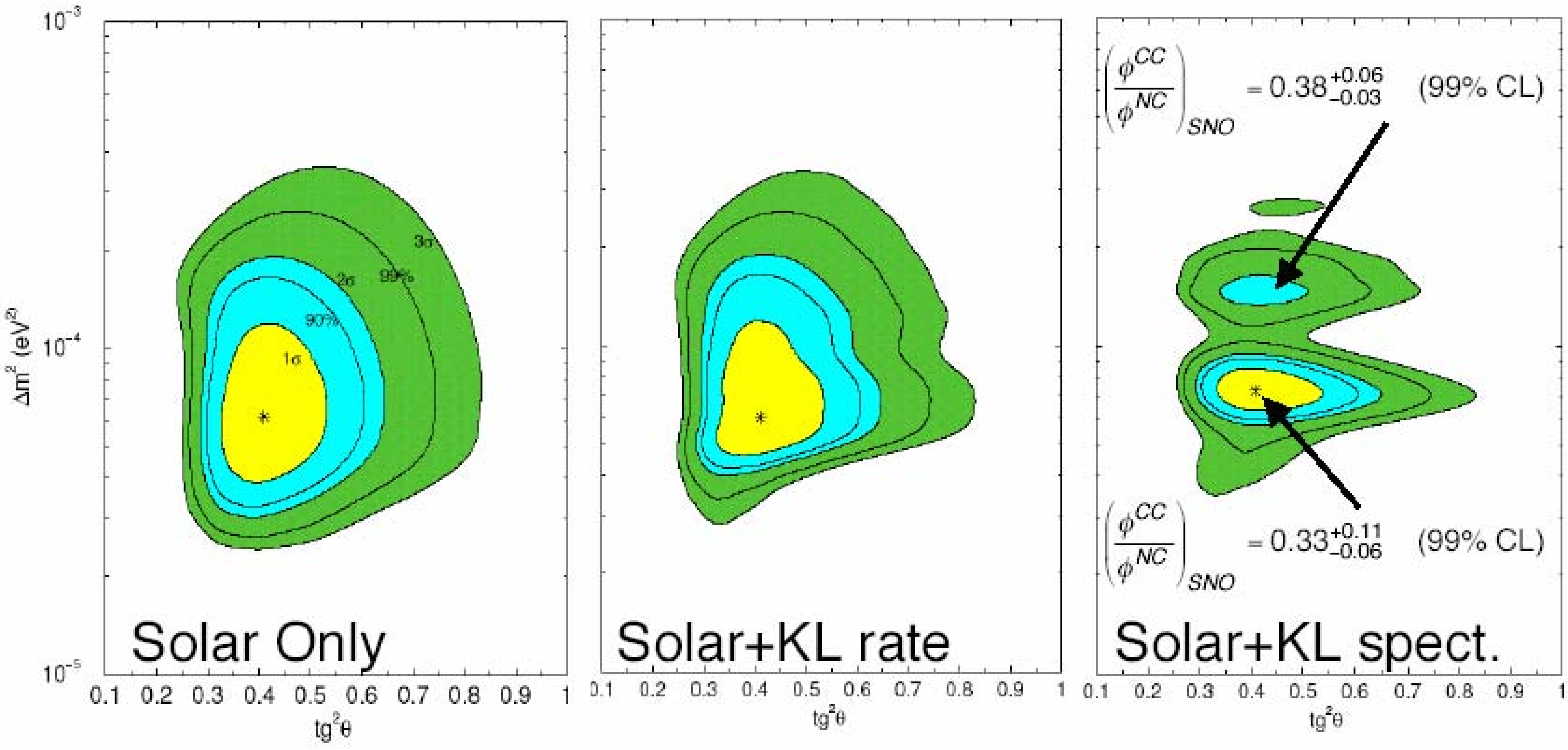
Fluxes

(10^6 cm^{-2} s^{-1})

ν_e:	1.76(11)
$\nu_{\mu\tau}$:	3.41(66)
ν_{total}:	5.09(64)
ν_{SSM}:	5.05



$\tan^2\theta_{12}$-Δm_{12}^2

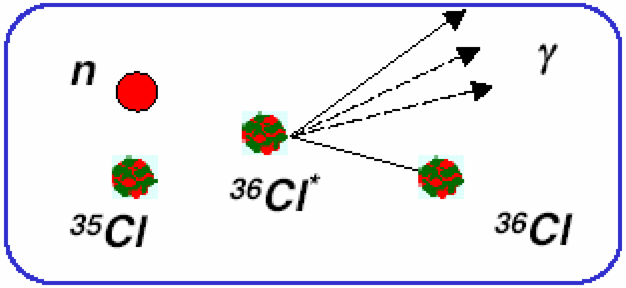


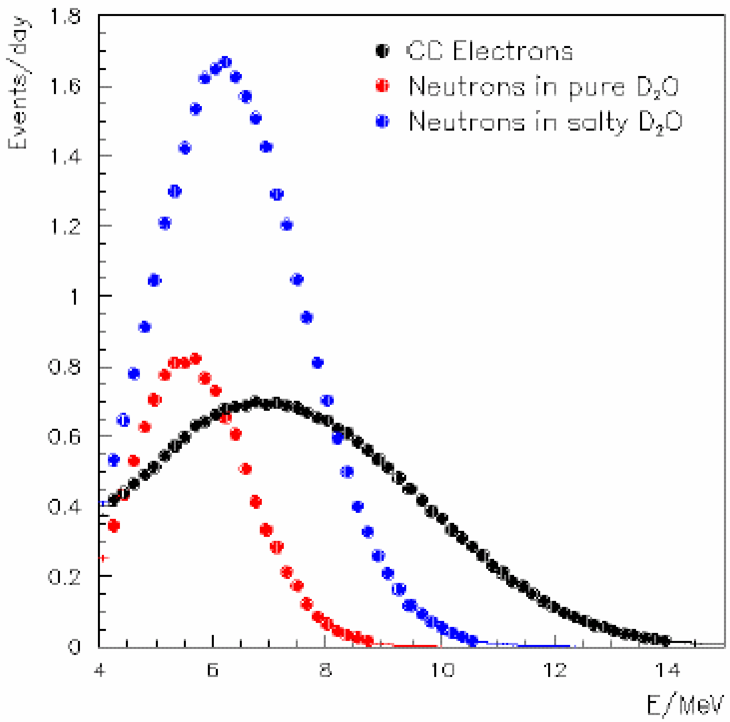
de Holanda & Smirnov, hep-ph/0205241, hep-ph/0212270

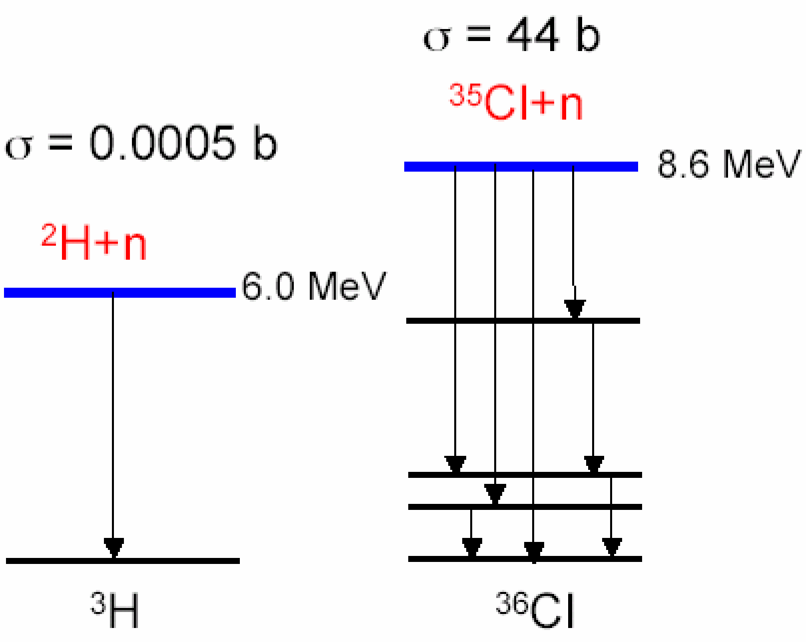
(Assume CPT)

Advantages of NaCl for Neutron Detection

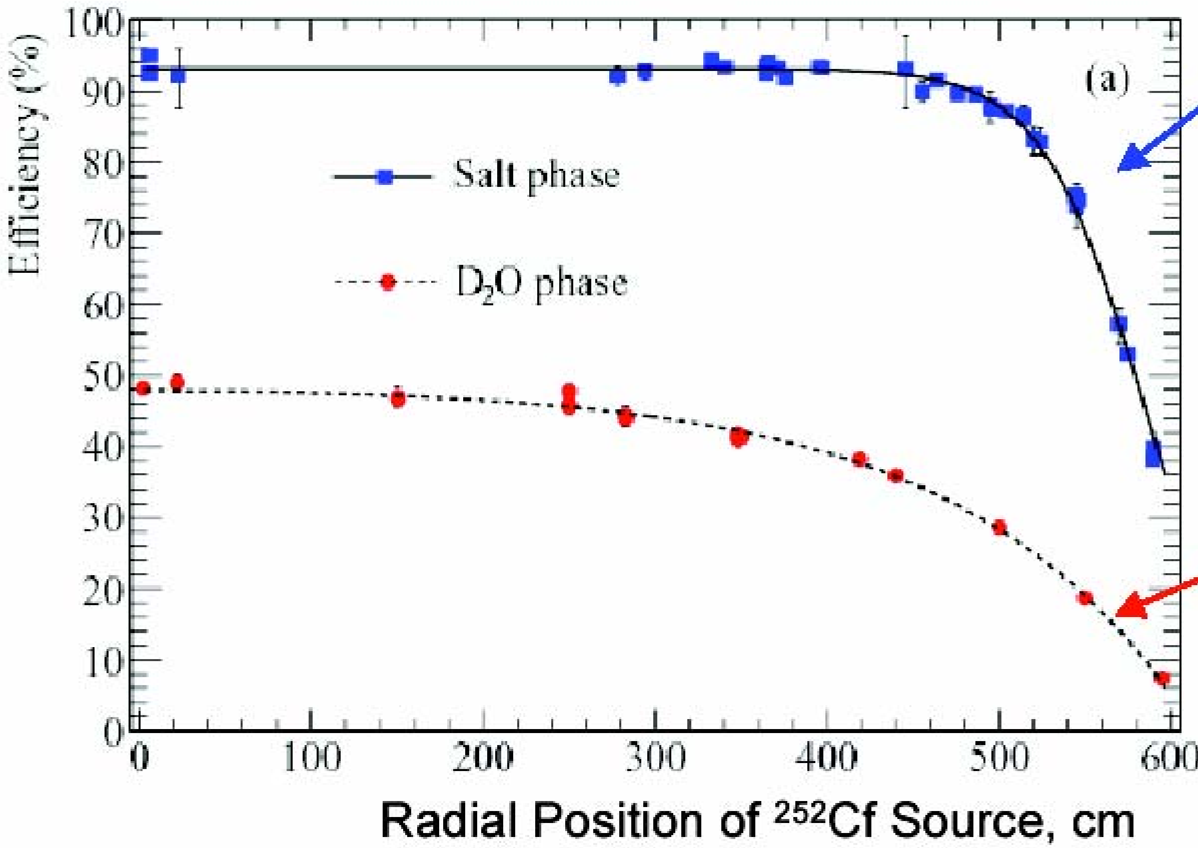
- Higher capture cross section
- Higher energy release
- Many gammas







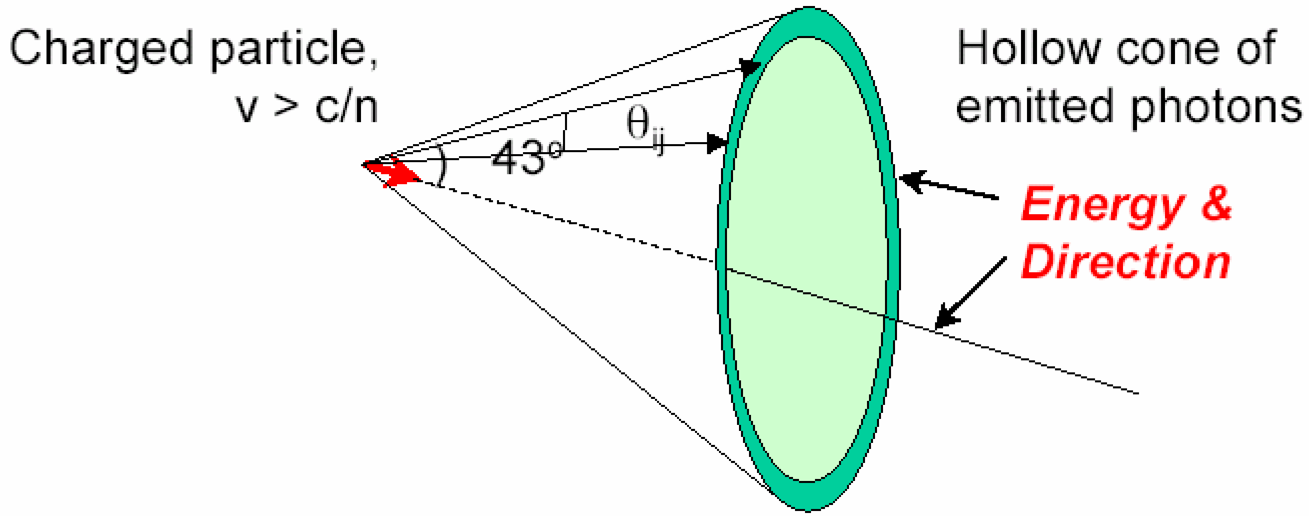
Neutron Capture Efficiency in SNO



$^{35}Cl(n,\gamma)^{36}Cl$
Average Eff. =
0.399
$T_e \geq 5.5$ MeV and
$R_\gamma \leq 550$ cm

$^{2}H(n,\gamma)^{3}H$
Average Eff. =
0.144
$T_e \geq 5.0$ MeV and
$R_\gamma \leq 550$ cm

Cherenkov light and β_{14}

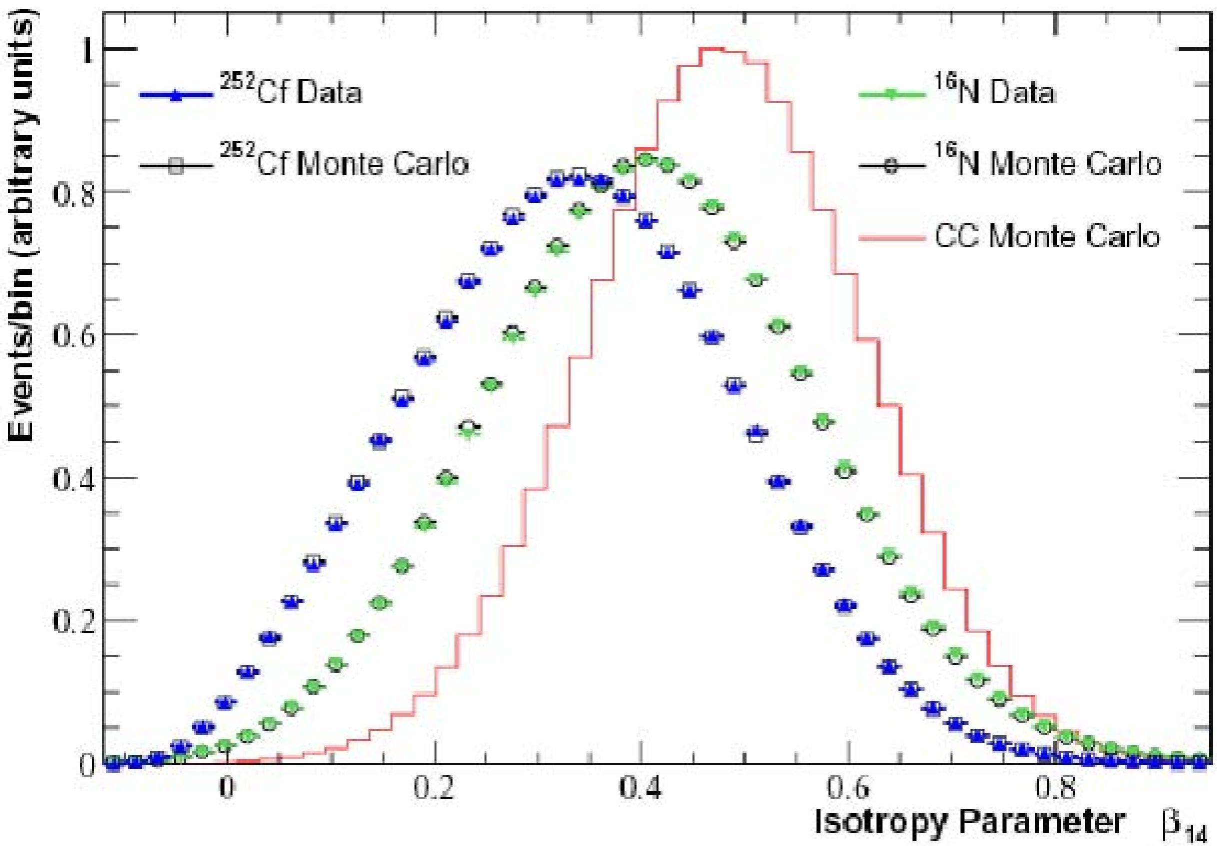


$$\beta_1 = \frac{2}{N(N-1)} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} cos\theta_{ij}$$

$$\beta_4 = \frac{2}{N(N-1)} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{1}{64}(9 + 20cos2\theta_{ij} + 35cos4\theta_{ij})$$

$$\beta_{14} = \beta_1 + 4\beta_4$$

Use of β_{14} to distinguish neutrons and e^-



β_{14} Distributions for SNO Salt Data

Data from July 26, 2001 to Oct. 10, 2002

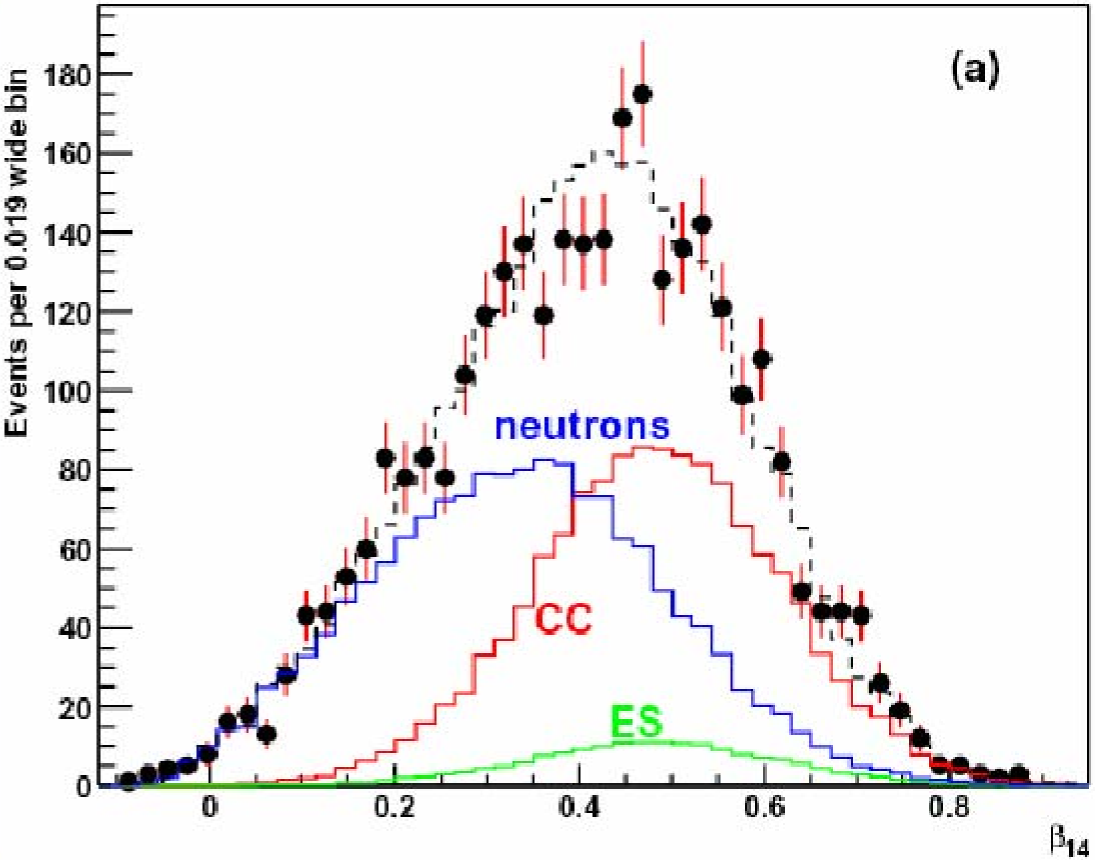
254.2 live days

3055 candidate events:

1339.6 $^{+63.8}_{-61.5}$ CC

1344.2 $^{+69.8}_{-69.0}$ NC

170.3 $^{+23.9}_{-20.1}$ ES



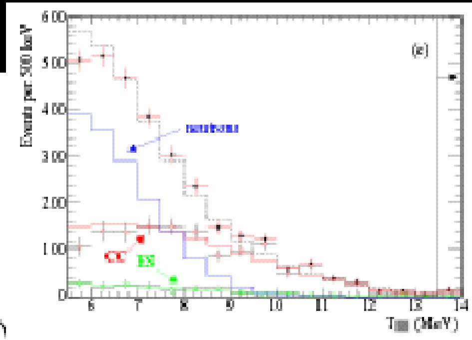
SNO Results: "Salt" phase

Shape of ^{8}B spectrum in CC and ES not constrained:

$$\phi_{CC}^{SNO} = 1.59^{+0.08}_{-0.07}(\text{stat})^{+0.06}_{-0.08}(\text{syst})$$

$$\phi_{ES}^{SNO} = 2.21^{+0.31}_{-0.26}(\text{stat}) \pm 0.10\ (\text{syst})$$

$$\phi_{NC}^{SNO} = 5.21 \pm 0.27\ (\text{stat}) \pm 0.38\ (\text{syst})$$

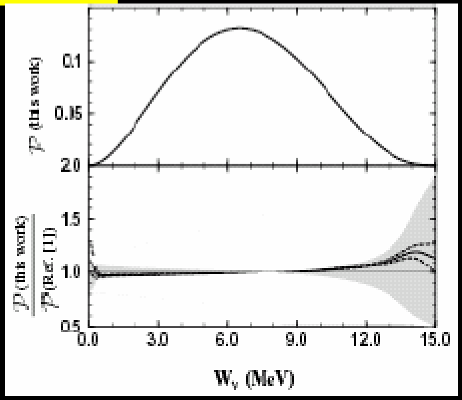


Standard (Ortiz et al.) shape of ^{8}B spectrum in CC and ES:

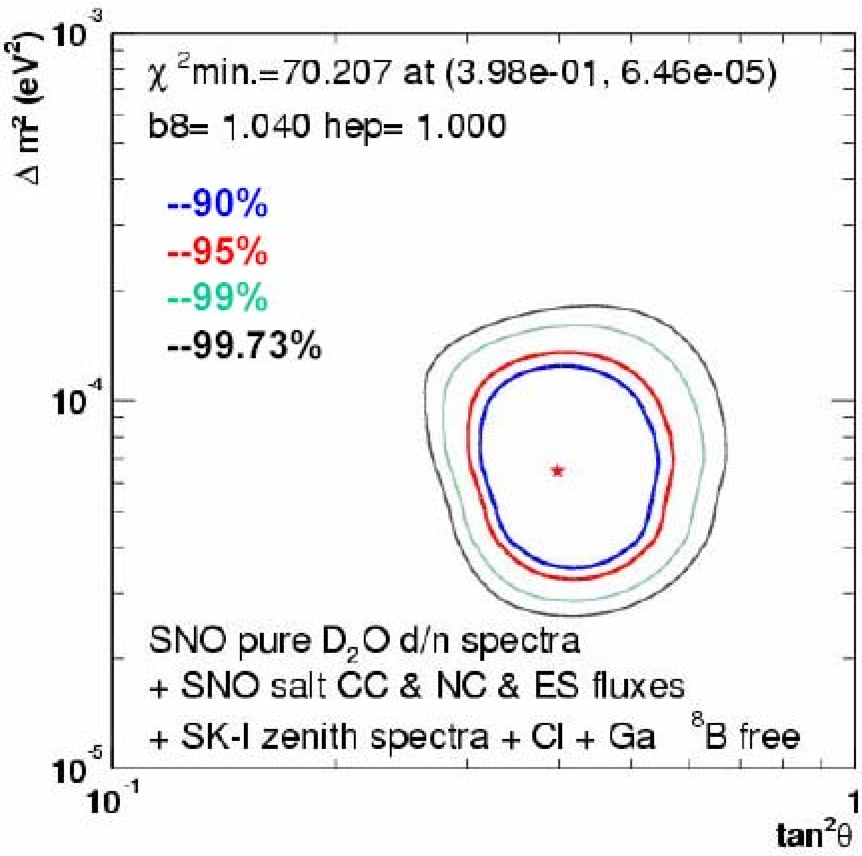
$$\phi_{CC}^{SNO} = 1.70 \pm 0.07(\text{stat.})^{+0.09}_{-0.10}(\text{syst.})$$

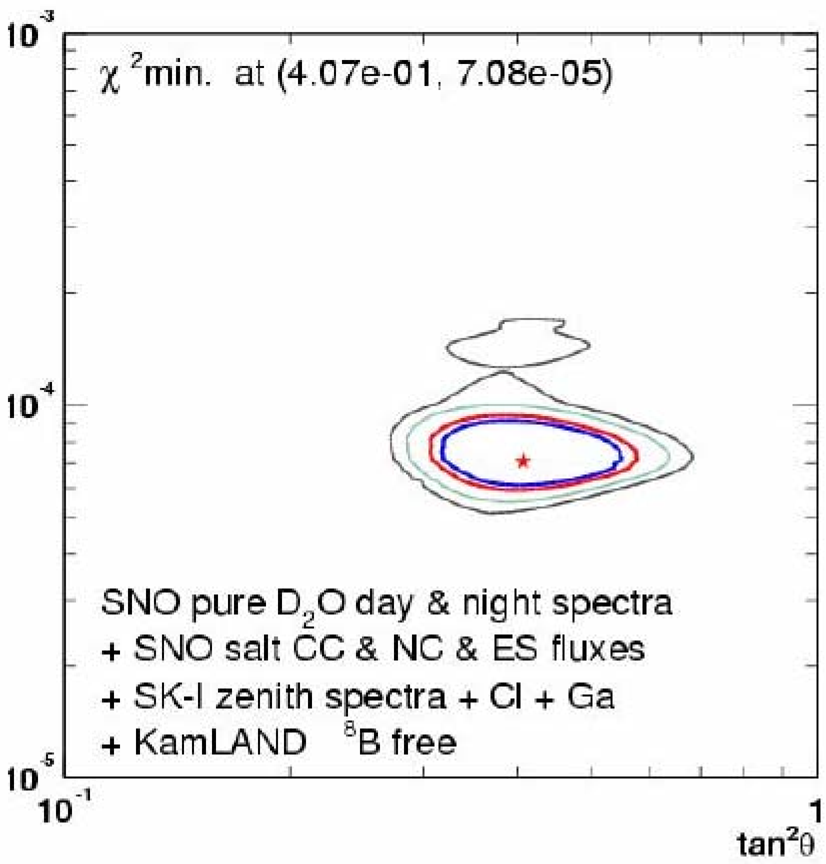
$$\phi_{ES}^{SNO} = 2.13^{+0.29}_{-0.28}(\text{stat.})^{+0.15}_{-0.08}(\text{syst.})$$

$$\phi_{NC}^{SNO} = 4.90 \pm 0.24\ (\text{stat.})^{+0.29}_{-0.27}(\text{syst.})$$

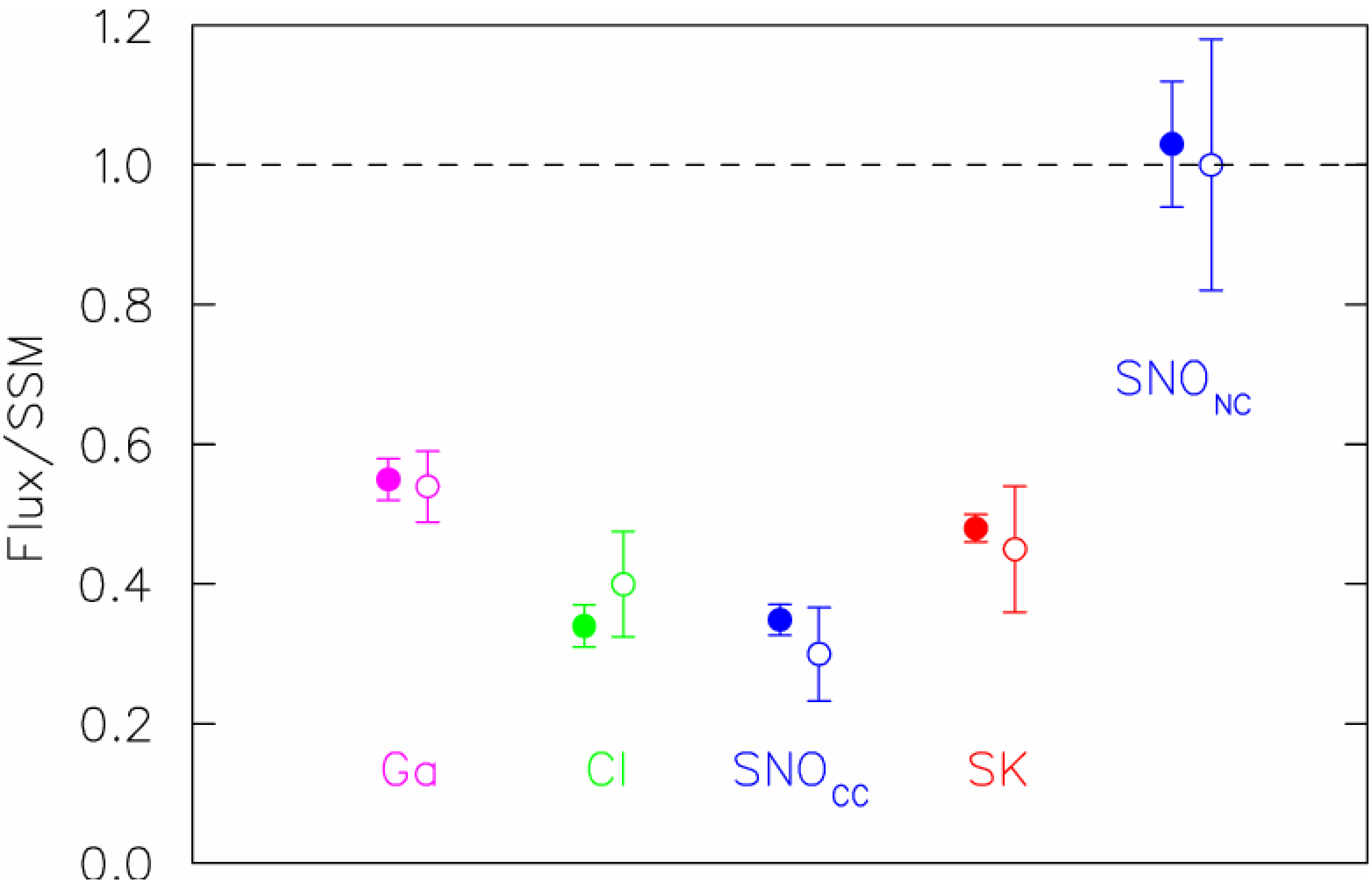


Global Analysis with SNO "Salt" phase





Open circles: combined best fit
Closed circles: experimental data



Results from Solar and Atmospheric Neutrino Experiments

- ν's transform flavor

- Atmospheric ν data explained extremely well by oscillations

  - looks like primarily ν_μ to ν_τ conversion
  - mixing angle θ_{23} is very large, possibly maximal
  - $\Delta m^2 \sim 2 \times 10^{-3}$ eV^2

- Solar ν_e change primarily to other active ν's

  - if oscillations, mixing angle θ_{12} is large but not maximal
  - if oscillations, $\Delta m^2 \sim 7 \times 10^{-5}$ eV^2
  - matter predicted to play a role in transformation

Maki - Nakagawa - Sakata Matrix

$$U_{MNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}$$

$$\times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

Future Reactor Experiment!

CP violation