united nations educational, scientific and cultural organization

international atomic energy agency

the
abdus salam
international centre for theoretical physics

SMR.1508 - 4

SUMMER SCHOOL ON PARTICLE PHYSICS

16 June - 4 July 2003

NEUTRINO PHYSICS

Lecture II

S. PARKE
Fermilab
Batavia, IL
U.S.A.

strada costiera, 11 - 34014 trieste italy - tel. +39 0402240111 fax +39 040224163 - sci_info@ictp.trieste.it - www.ictp.trieste.it

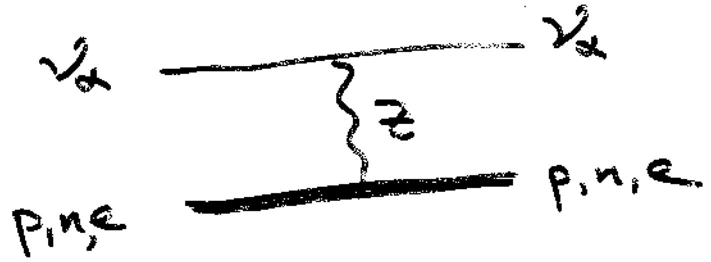
Solar Neutrinos

&

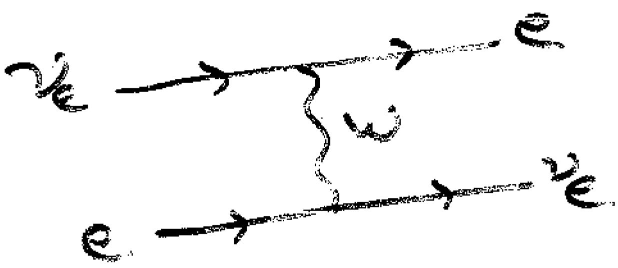
Neutrino Oscillations in Matter:

Neutrino Osc in Matter:

Extra contribution coming from the **FORWARD** scattering of neutrinos off matter:



BUT ν_e has another possibility:



Wolfenstein '78

Mikheyev + Smirnov '85

sterile neutrinos (ν_s) by def^n do not have such interactions.

$$H_{int} = \frac{G_F}{\sqrt{2}} \bar{e}\gamma^\mu(1-\gamma_5)\nu_e \; \bar{\nu}_e\gamma_\mu(1-\gamma_5)e$$

Fierz

$$= \frac{G_F}{\sqrt{2}} \underbrace{\bar{e}\gamma^\mu(1-\gamma_5)e}_{J_e^\mu} \cdot \underbrace{\bar{\nu}_e\gamma^\mu(1-\gamma_5)\nu_e}_{J_\nu^\mu}$$

In matter rest frame the electrons are non-relativistic and unpolarized

$$\bar{e}\gamma^\mu(1-\gamma_5)e \approx N_e \delta^{\mu 0}$$

$\uparrow$ # density

$$H_{int} = \frac{G_F}{\sqrt{2}} N_e \bar{\nu}_e\gamma^\mu(1-\gamma_5)\nu_e$$

$$= \sqrt{2} G_F N_e \bar{\nu}_{eL}\gamma^0 \nu_{eL}$$

Therefore $\Delta V = \begin{cases} +\sqrt{2}G_F N_e & \text{neutrinos} \\ -\sqrt{2}G_F N_e & \text{anti-neutrinos} \end{cases}$

harder more difficult easy

$$\sqrt{2}G_F N_e = \sqrt{2}G_F\left(\frac{Y_e\rho}{m_N}\right) = 3.82\times10^{-14}\,\text{eV}\left(\frac{Y_e}{0.5}\right)\left(\frac{\rho}{1\,\text{g cm}^{-3}}\right)$$

$$= 3.82\times10^{-8}\,\text{eV}^2/\text{MeV} \;\cdot\cdot$$

ν Type	Bkgd	ΔV
ν_e	e	$\frac{1}{\sqrt{2}} G_F (4 s_w^2 + 1)(N_e - N_{\bar{e}})$
$\nu_{\mu,\tau}$	e	$\frac{1}{\sqrt{2}} G_F (4 s_w^2 - 1)(N_e - N_{\bar{e}})$
$\nu_{e,\mu,\tau}$	n	$\frac{1}{\sqrt{2}} G_F (N_{\bar{n}} - N_n)$
$\nu_{e,\mu,\tau}$	p	$\frac{1}{\sqrt{2}} G_F (1 - 4 s_w^2)(N_p - N_{\bar{p}})$
ν_s	e, p, n	0

$s_w^2 \approx \frac{1}{4}$

Ordinary Matter:

$$V_e - V_{\mu,\tau} = \sqrt{2}\, G_F N_e$$

$$V_\mu - V_\tau = 0 \qquad \text{Vacuum}$$

$$\left.\begin{aligned} V_s - V_{\mu,\tau} &= \sqrt{2}\, G_F \frac{N_n}{2} \\ V_e - V_s &= \sqrt{2}\, G_F \left(N_e - \tfrac{1}{2} N_n\right) \end{aligned}\right\} \text{important } \nu_s \text{ phenom}$$

$$i\frac{d}{dt}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix} = \frac{1}{2}\begin{pmatrix}-\frac{\Delta m^2}{2E} & \\ & +\frac{\Delta m^2}{2E}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

rotate to flavor basis:

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \frac{1}{2}\begin{pmatrix}c_\theta & s_\theta\\ -s_\theta & c_\theta\end{pmatrix}\begin{pmatrix}-\frac{\Delta m^2}{2E} & \\ & \frac{\Delta m^2}{2E}\end{pmatrix}\begin{pmatrix}c_\theta & -s_\theta\\ s_\theta & c_\theta\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

$$= \frac{1}{2}\begin{pmatrix}-\frac{\Delta m^2}{2E}c_{2\theta} & \frac{\Delta m^2}{2E}s_{2\theta}\\ \frac{\Delta m^2}{2E}s_{2\theta} & +\frac{\Delta m^2}{2E}c_{2\theta}\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

add ~~extra term~~ matter

$$\sqrt{2}G_F N_e\begin{pmatrix}1 & 0\\ 0 & 0\end{pmatrix} = \frac{\sqrt{2}G_F N_e}{2}\left[\cancel{\begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix}} + \begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}\right]$$

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \frac{1}{2}\begin{pmatrix}-\frac{\Delta m^2}{2E}c_{2\theta} + \sqrt{2}G_F N_e, & \frac{\Delta m^2}{2E}s_{2\theta}\\ \frac{\Delta m^2}{2E}s_{2\theta}, & +\frac{\Delta m^2}{2E}c_{2\theta} - \sqrt{2}G_F N_e\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

Rewrite as

$$\frac{1}{2}\begin{pmatrix} -\frac{\Delta M_N^2}{2E} C_{2\theta_N} & \frac{\Delta M_N^2}{2E} S_{2\theta_N} \\ \frac{\Delta M_N^2}{2E} S_{2\theta_N} & +\frac{\Delta M_N^2}{2E} C_{2\theta_N} \end{pmatrix}$$

then it is trivial to diagonalize

$$\begin{pmatrix} \nu_1^N \\ \nu_2^N \end{pmatrix} = \begin{pmatrix} C_{\theta_N} & -S_{\theta_N} \\ S_{\theta_N} & C_{\theta_N} \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

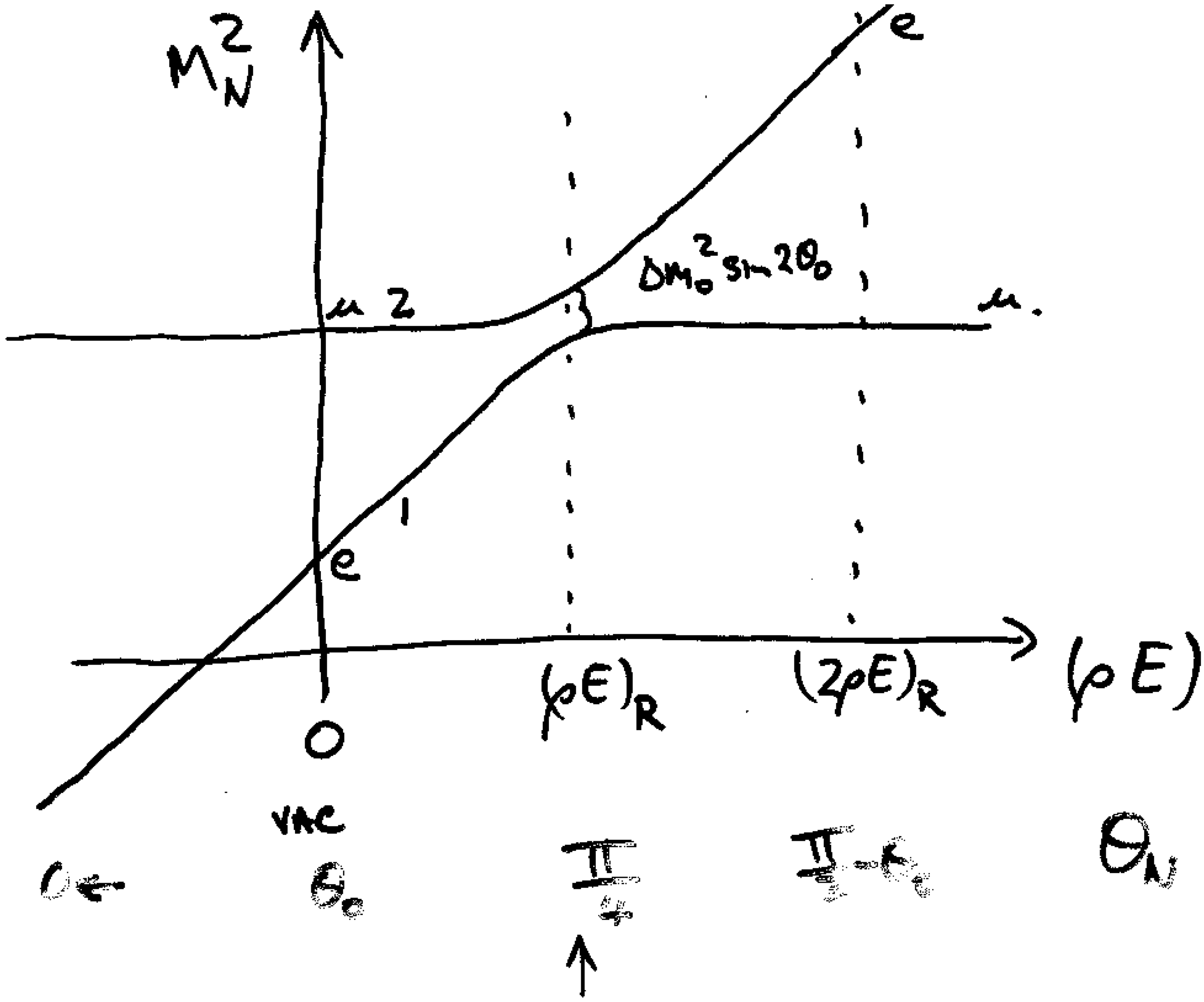
with eigenvalues $\pm \frac{\Delta M_N^2}{2E}$

$$\Delta M_N^2 C_{2\theta_N} = \Delta M_0^2 \cos 2\theta_0 - 2\sqrt{2} G_F N_e E$$

$$\cancel{\ast} \longrightarrow \quad \Delta M_N^2 S_{2\theta_N} = \Delta M_0^2 \sin 2\theta_0$$

$$\cancel{\ast} \longrightarrow \left(\Delta M_N^2\right)^2 = \left(\Delta M_0^2 C_{2\theta_0} - 2\sqrt{2} G_F N_e E\right)^2 + \left(\Delta M_0^2 S_{2\theta_0}\right)^2$$

IMPORTANT:



resonance

$$\Delta m_0^2 c_{2\theta_0} = 2\sqrt{2} G_F N_e E$$

$$L_R = \frac{4\pi E}{\delta m_N^2} = \frac{4\pi E}{\delta m_0^2 \sin 2\theta_0}$$

SLAC Summer School 1986 - Parke

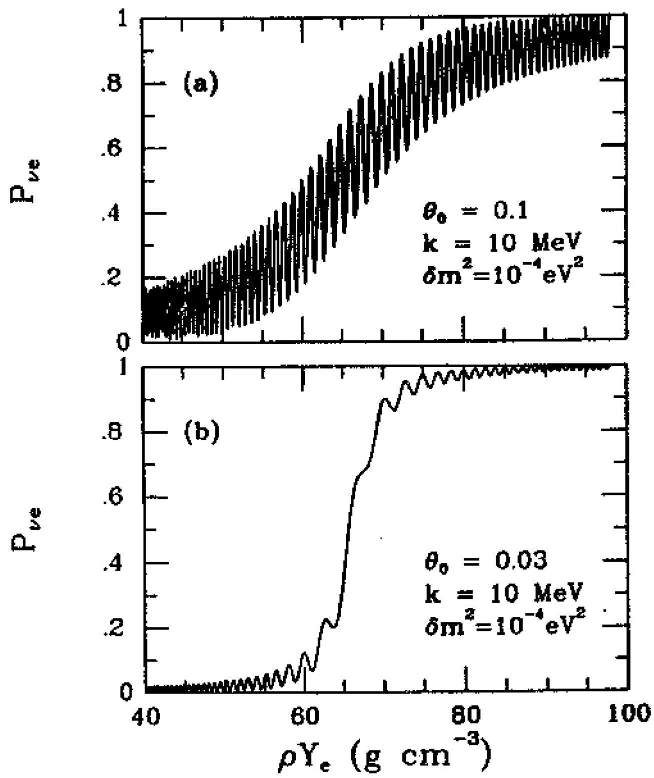


Figure (2a) and (2b): Electron neutrino probabilities as a function of electron density for an electron neutrino produced at the center of the Sun. For these values of θ_0 resonance crossing is adiabatic.

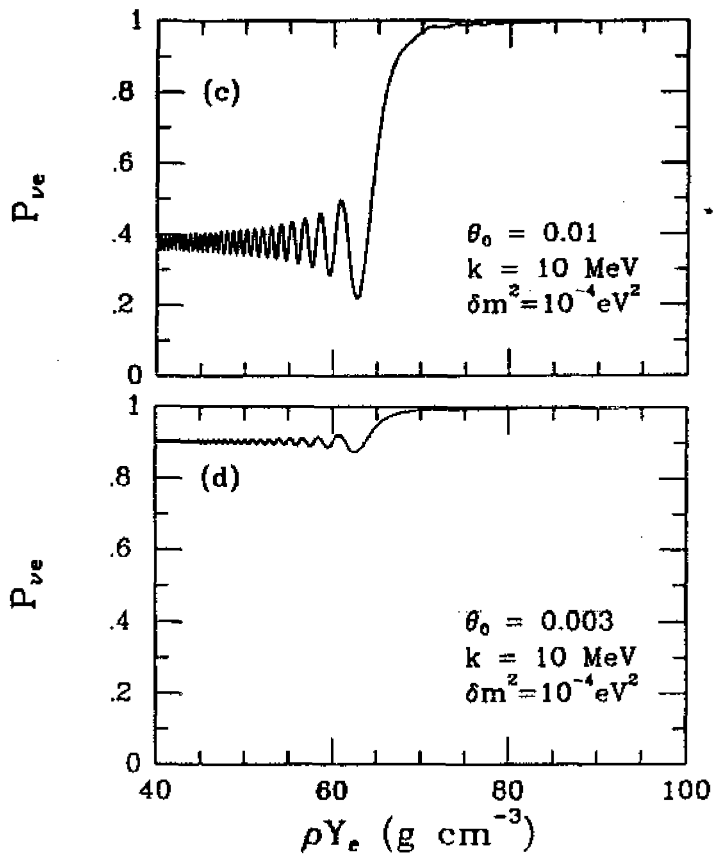


Figure (2c) and (2d): Electron neutrino probabilities as a function of electron density for an electron neutrino produced at the center of the Sun. For these values of θ_0 resonance crossing is non-adiabatic.

Constant Matter:

$$P_{\nu_e \to \nu_\mu} = \sin^2 2\theta_N \sin^2 \frac{\Delta m_N^2 L}{4E}$$

$$= \sin^2 2\theta_0 \left(\frac{\Delta m_0^2 L}{4E}\right)^2 \cdot \frac{\sin^2\left(\frac{\Delta m_N^2 L}{4E}\right)}{\left(\frac{\Delta m_N^2 L}{4E}\right)^2}$$

leading term as $L \to 0$

is identical to VACUUM CASE:

To see a difference:

$\Delta m_N^2 \neq \Delta m_0^2$ and $\frac{\Delta m^2 L}{4E} > \frac{\pi}{4}$

i.e. near first peak.

$\sin x \neq x$

VARYING DENSITY:

slowly – adiabatic (no hopping between eigenstates)

$$P(\nu_e \to \nu_e) = (1,0)\begin{pmatrix} c_0^2 & s_0^2 \\ s_0^2 & c_0^2 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} c_N^2 & s_N^2 \\ s_N^2 & c_N^2 \end{pmatrix}\begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$= (c_0^2, s_0^2)\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} c_N^2 \\ s_N^2 \end{pmatrix}$$

$$= c_0^2 c_N^2 + s_0^2 s_N^2$$

$$= \frac{1}{2}\left(1 + \cos 2\theta_0 \cos 2\theta_N\right)$$

for small θ_0 and high density ($\cos 2\theta_N = -1$)

Survival Probability

$$P(\nu_e \to \nu_e) = \sin^2\theta_0$$

FAST VARYING

(Allow for hopping)

$$P_{\nu_e \to \nu_e} = (\quad)\begin{pmatrix} & \\ & \end{pmatrix}\begin{pmatrix} 1-P_X & P_X \\ P_X & 1-P_X \end{pmatrix}\begin{pmatrix} & \\ & \end{pmatrix}\begin{pmatrix} \\ \end{pmatrix}$$

$$= \left(C_0^2 , S_0^2 \right) \begin{pmatrix} 1-P_X & P_X \\ P_X & 1-P_X \end{pmatrix} \begin{pmatrix} C_N^2 \\ S_N^2 \end{pmatrix}$$

$$= C_0^2 C_N^2 + S_0^2 S_N^2 - P_X C_0^2 \left(C_N^2 - S_N^2 \right) + P_X S_0^2 \left(C_N^2 - S_N^2 \right)$$

$$\boxed{P_{\nu_e \to \nu_e} = \frac{1}{2} + \left(\frac{1}{2} - P_X \right) \cos 2\theta_0 \cos 2\theta_N}$$

Parke '86

θ_0 small, and $\cos 2\theta_N = -1$, $P_X = 1$

$$P_{\nu_e \to \nu_e} = \cos^2 \theta_0$$

What is P_X ??

In linearized approx. solved by Landau-Zener 1932

$$P_X = \exp\left[-\frac{\pi}{2}\frac{\sin^2 2\theta_0}{\cos 2\theta_0}\frac{\Delta m^2/2E}{\left|\frac{d\ln N_e}{dt}\right|}\right]$$

Haxton '86
Parke '86

$$= \exp\left[-c\left\{\begin{matrix}\text{\# of oscillations}\\ \text{in Resonance region}\end{matrix}\right\}\right]$$

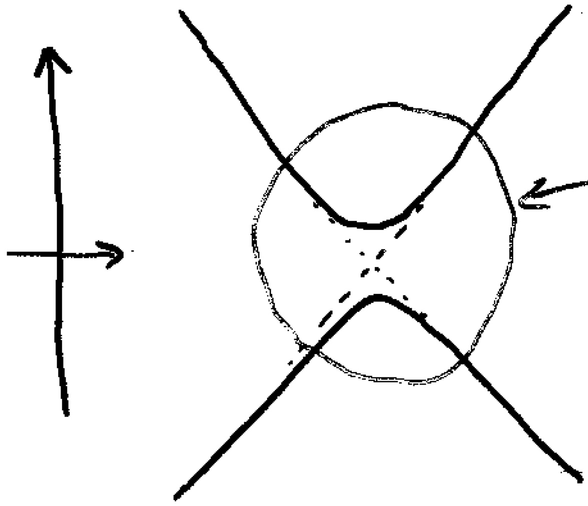
- many oscillations implies state can adjust hence $P_X \to 0$.
- "few" oscillations state cannot adjust hence P_X large.
- later came P_X for exponential densities – Petcov

Landau - Zener 1932

$$i \frac{d}{dt}\begin{pmatrix} u_1 \\ u_2 \end{pmatrix} = \begin{pmatrix} -vt & b \\ b & vt \end{pmatrix}\begin{pmatrix} u_1 \\ u_2 \end{pmatrix}$$

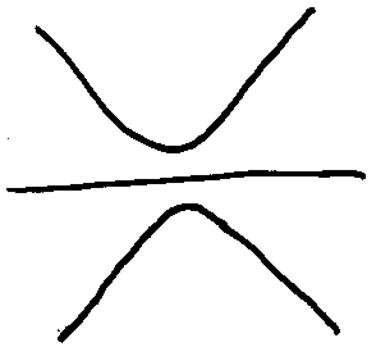
in terms of Weber f^{ns}

$$E_\pm = \pm\sqrt{b^2+v^2t^2}$$



where the action is:
— linearize the about this point.

MACRO



$$\begin{pmatrix} -vt & b/\sqrt{2} & 0 \\ \frac{b}{\sqrt{2}} & 0 & b/\sqrt{2} \\ 0 & b/\sqrt{2} & vt \end{pmatrix}$$

$$E_i = 0, \pm\sqrt{b^2+v^2t^2}$$

Sol^n "square" of above.

magnetic monopole
passing thru Hydrogen Atom
parke et al '83

$$\frac{\delta m^2}{2\sqrt{2}\, G_F N_e E_\nu} =$$

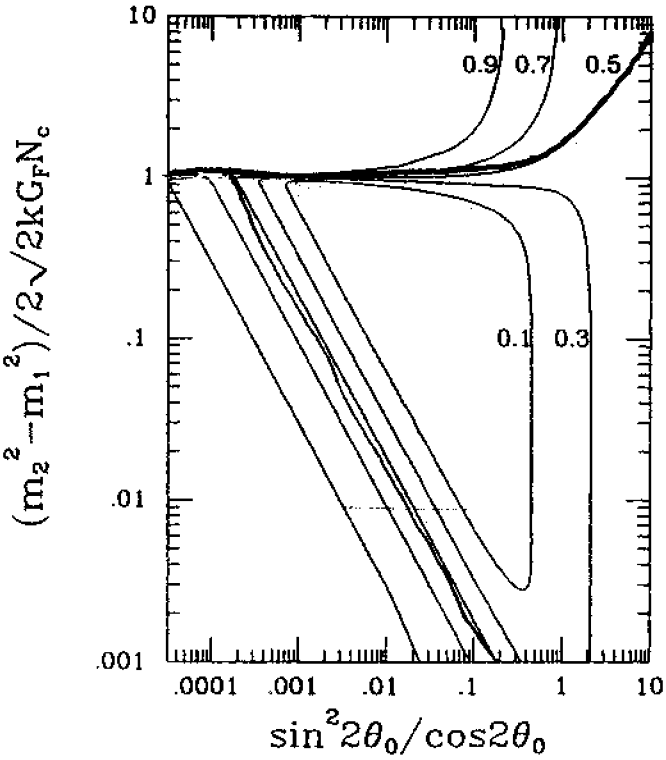
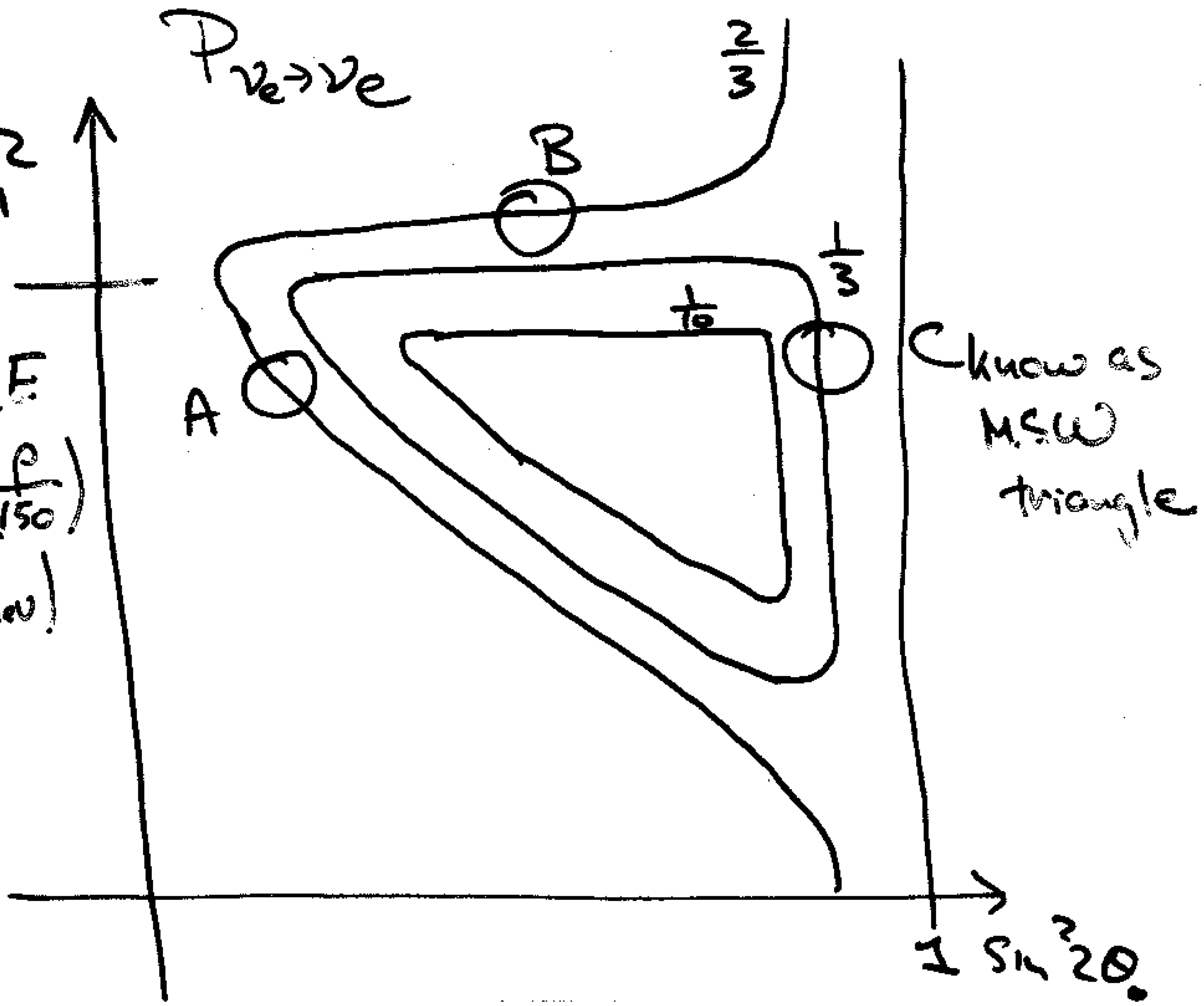


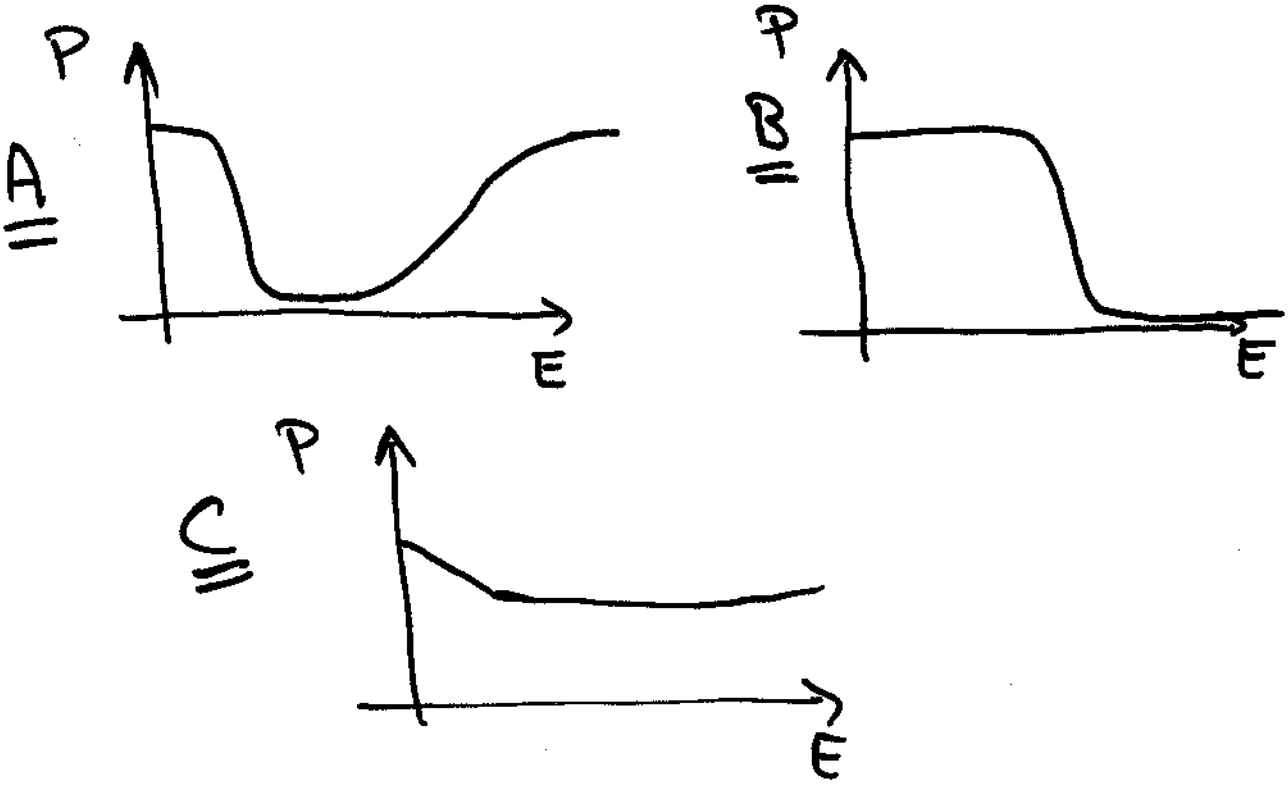
Figure (4): Electron neutrino survival probability contours for an exponential solar electron density profile and an electron neutrino produced at center of the Sun.

$$\overline{P}_{\nu_e} = \frac{1}{2} + \left(\frac{1}{2} - P_x\right) C_{\theta_0} C_{\theta_N} \, ;$$

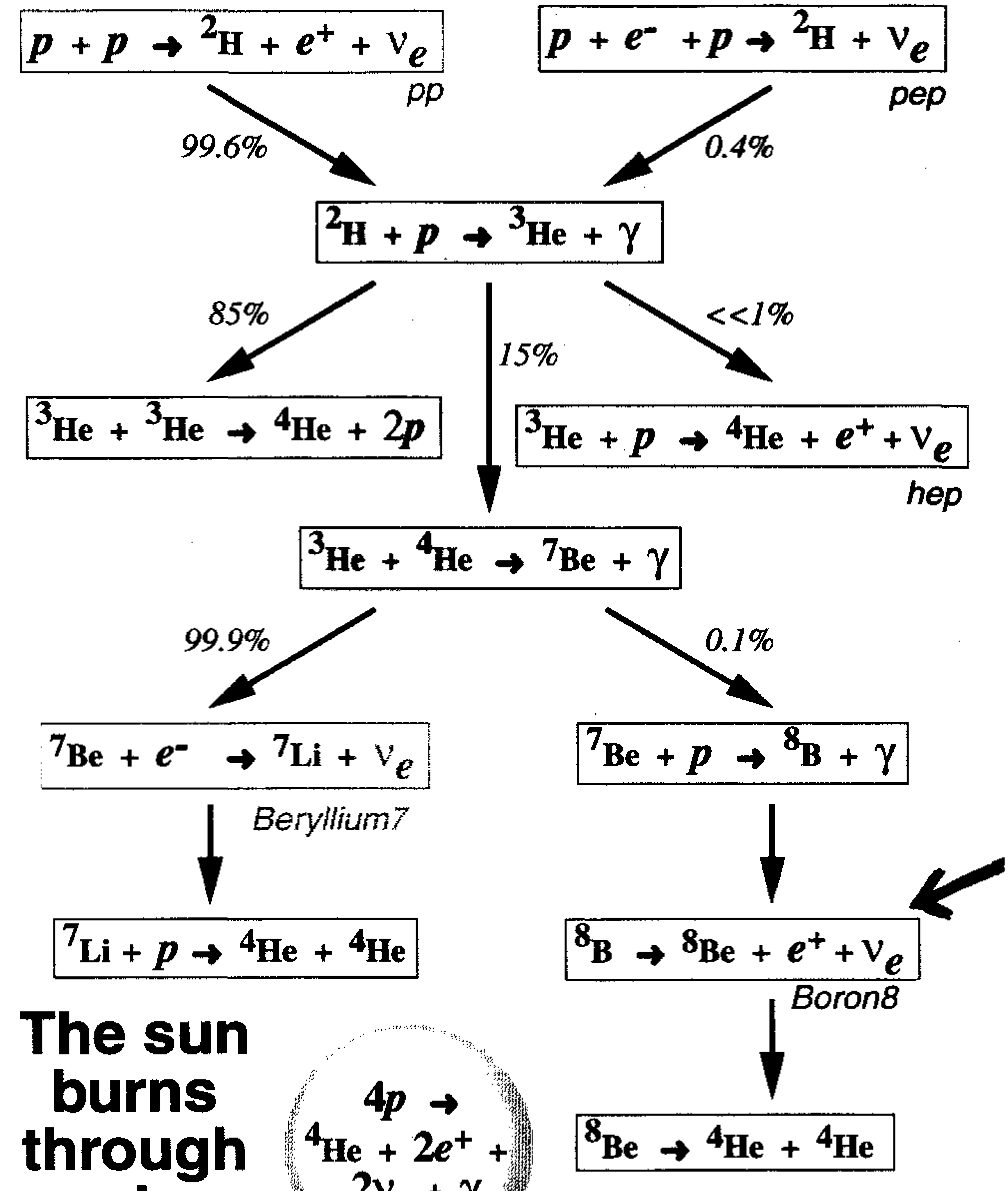
$$P_x = \exp\left\{ -\pi^2 \frac{L_R}{W_R} \right\}$$

$$\Delta m^2 c_{2\theta_0} = 2\sqrt{2}\, G_F N_e E \simeq 10^{-4}\,\mathrm{eV}^2 \left(\frac{\rho}{150}\right)\left(\frac{E}{10\,\mathrm{MeV}}\right)$$





SOLAR NEUTRINOS:



$$4p + 2e^- \rightarrow {}^4He + 2\nu_e + 26.7\,\text{MeV}$$

Solar Neutrinos

- $4p + 2e^- \rightarrow {}^4He + 2\nu_e + 26.7\,\text{MeV}$

  $1\,\nu_e$ for every 13.4 MeV

- Earth's surface $\mathcal{L}_\odot = 0.1350$ joules/cm^2/sec

- 1 joule equals 6×10^{18} eV

- flux of ν_e at earth $\begin{pmatrix} \text{day} \\ + \\ \text{night} \end{pmatrix}$

$$= \frac{0.1350 \times 6 \times 10^{18}}{13.4 \times 10^{6}} \ \#/\text{cm}^2/\text{sec}$$

$$= 6 \times 10^{10}\ /\text{cm}^2/\text{sec} \ !$$

Using solar νs' to probe the Sun

1946 Pontecorvo,1949 Alvarez

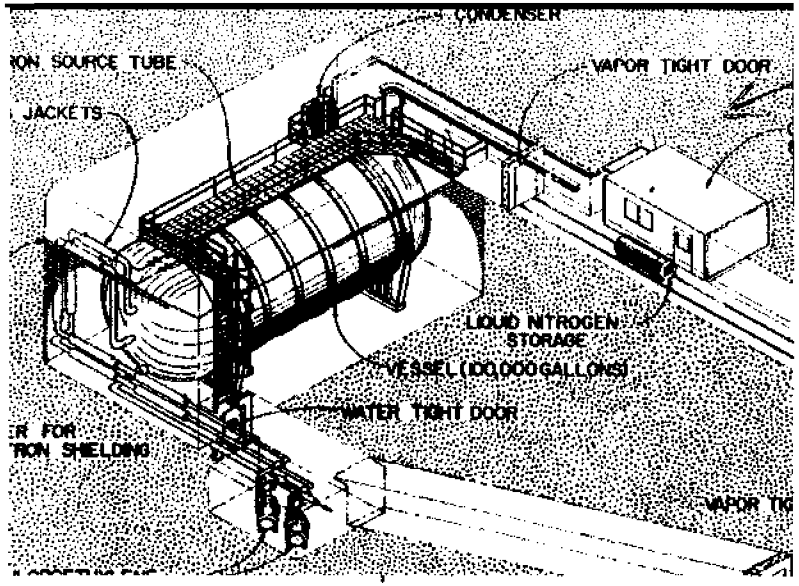
$^{37}Cl + \nu_e \rightarrow\ ^{37}Ar + e^-$

1960's

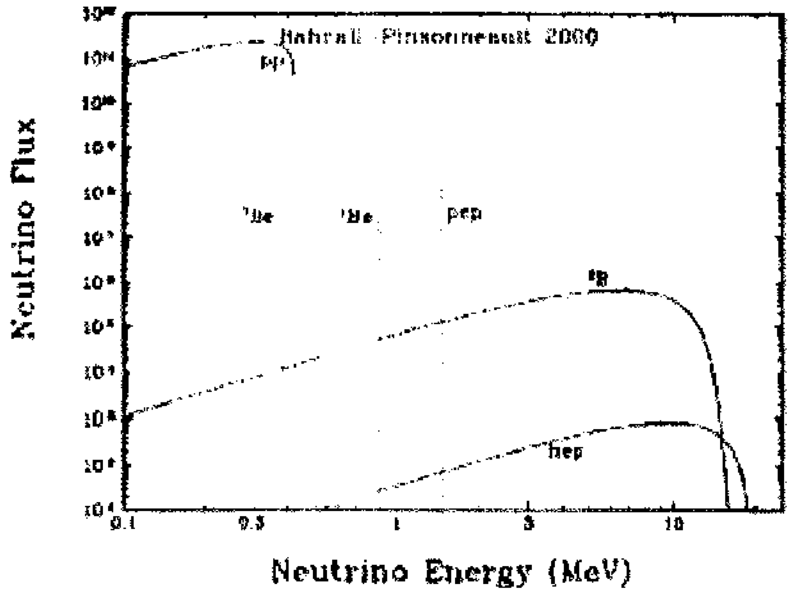
Ray Davis, builds Chlorine detector

John Bahcall, generates SSM & ν flux predictions

"…to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars..."



3



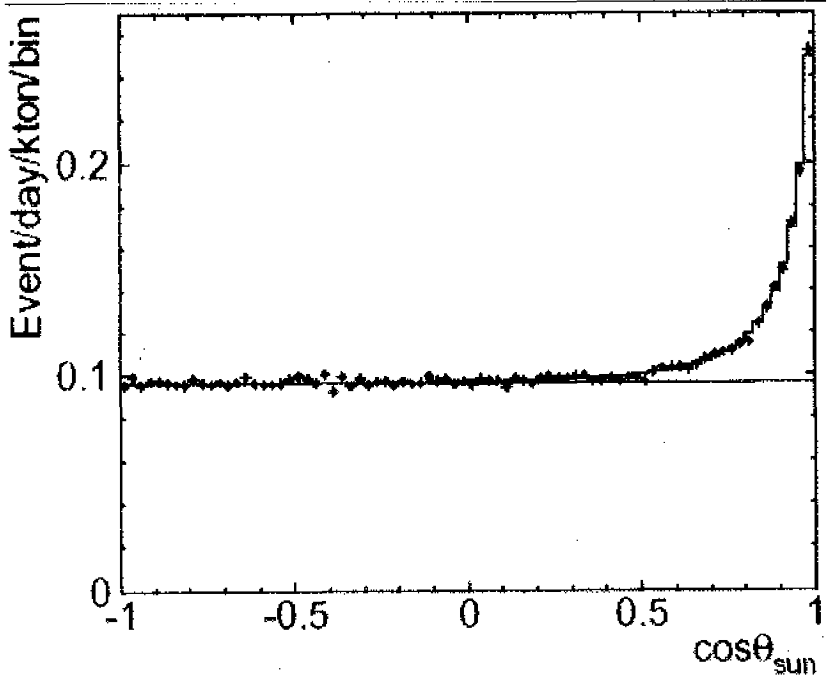
Super-Kamiokande

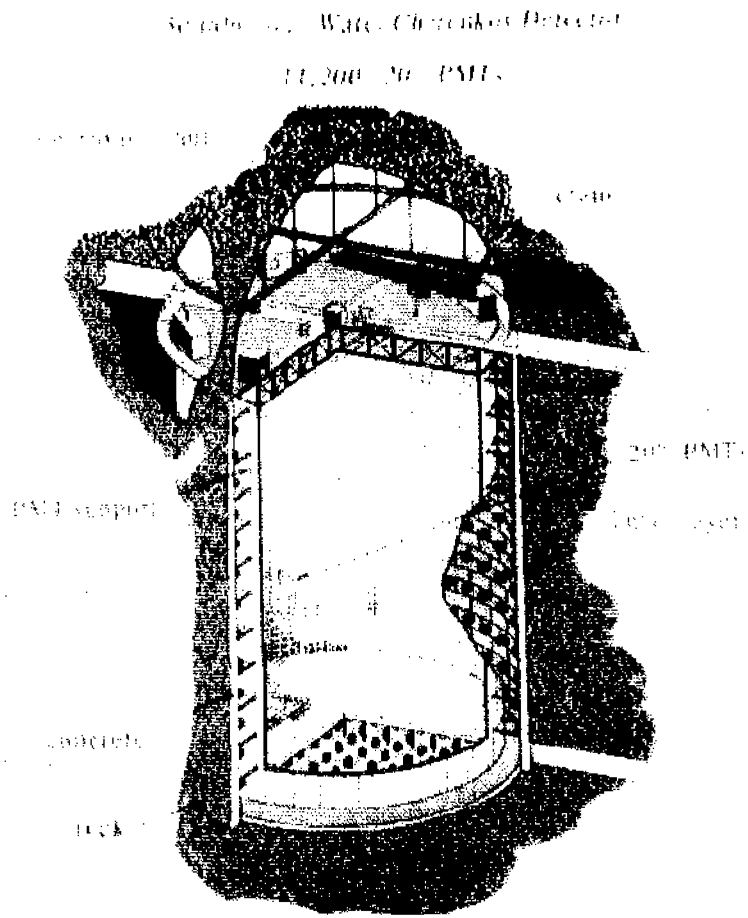
(hep-ex/0103032)

Elastic Scattering: $\nu_x + e^- \longrightarrow \nu_x + e^-$

$$\Phi^{ES} = 2.32 \pm \underset{(stat)}{0.03}\ \underset{(sys.)}{{}^{+0.08}_{-0.07}} \quad (10^6\ cm^{-2}\ s^{-1})$$

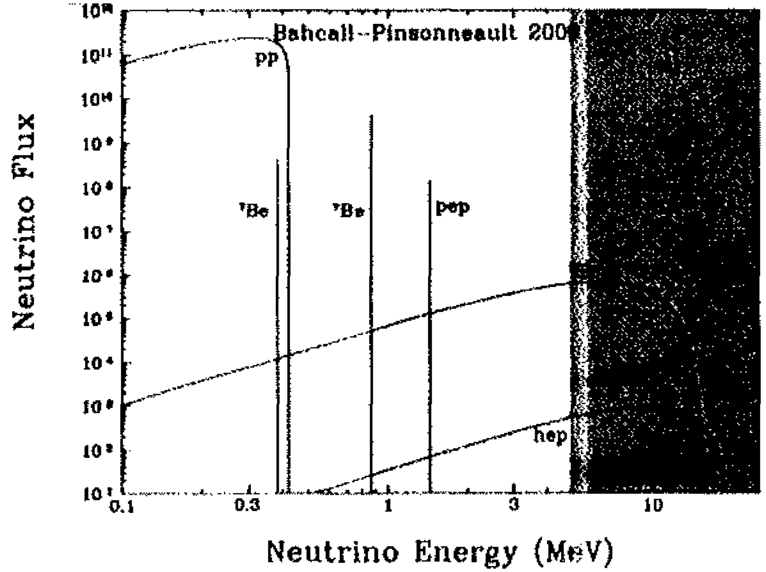
$$\text{Data/SSM} = 0.451 \pm \underset{(stat)}{0.005}\ \underset{(sys.)}{{}^{+0.016}_{-0.014}}$$





Gallium Measurements

$$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$$

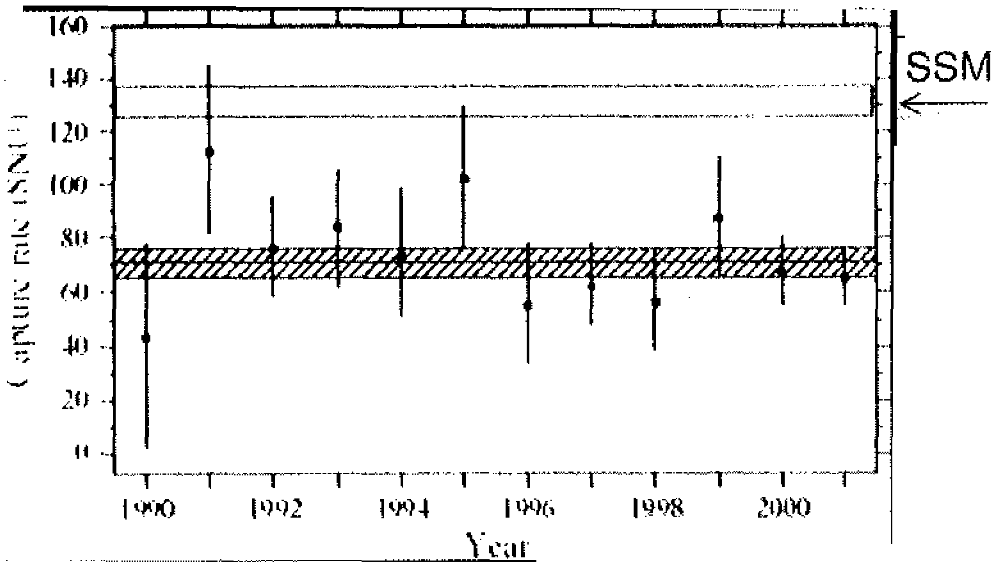


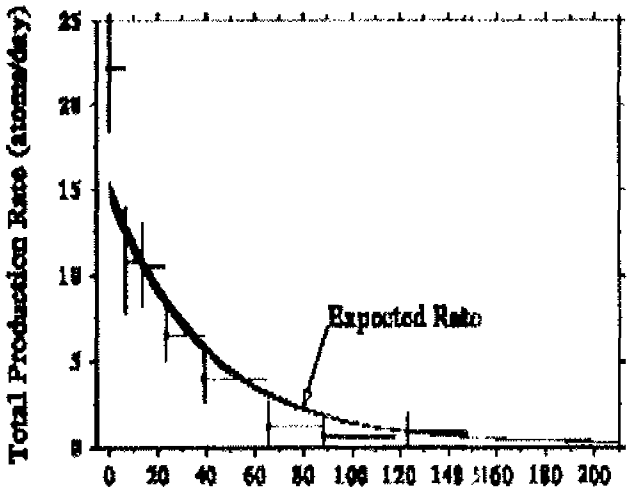
Two independent experiments

SAGE **Data/SSM = 0.55 ± 0.05**

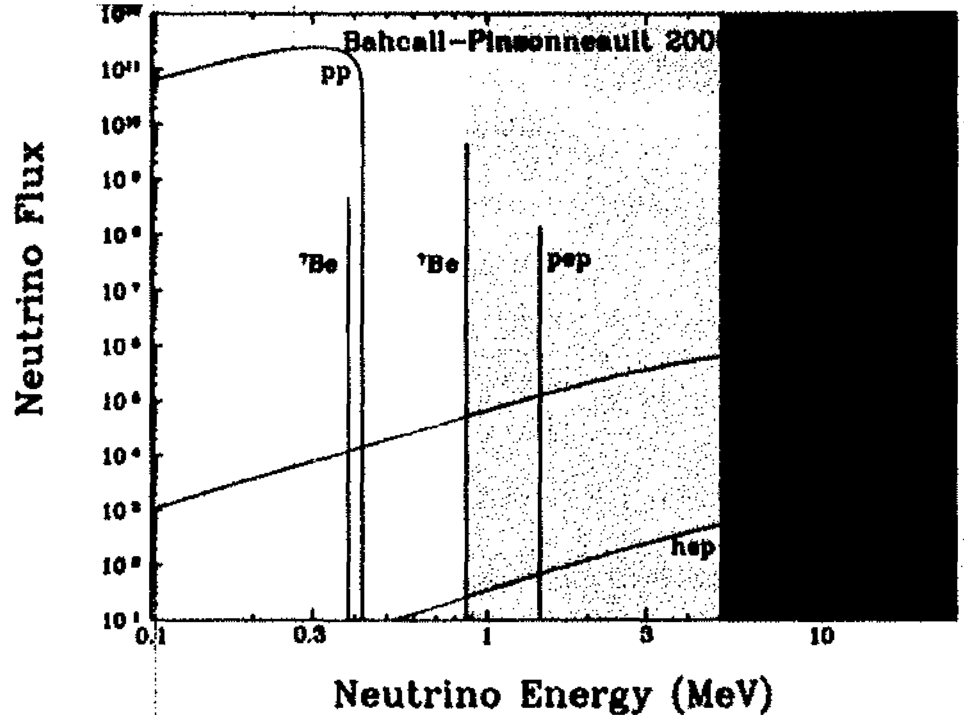
GALLEX Data/SSM = 0.57 ± 0.05

Latest SAGE results (astro-ph/0204245)





Solar ν Flux Measurement Results



$\int \nu$ flux

$\sim 6.5 \cdot 10^{10}/cm^2/s$

Experiment	Year	Detection Reaction	Ratio Exp/BP2000
Chlorine (127 t)	1970-1995	$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$	0.34 ± 0.03
Kamiokande (680t)	1986-1995	$\nu_x + e^- \rightarrow \nu_x + e^-$	0.54 ± 0.08
SAGE (23 t)	1990-	$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$	0.55 ± 0.05
Gallex + GNO (12 t)	1991-	$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$	0.57 ± 0.05
SuperK (22kt)	1996-	$\nu_x + e^- \rightarrow \nu_x + e^-$	$0.451^{+0.017}_{-0.015}$

Astrophysical Solutions?

SSM Energy Generation

$p + p \rightarrow {}^2H + e^+ + \nu_e$ $\quad$ $p + e^- + p \rightarrow {}^2H + \nu_e$

$\downarrow$

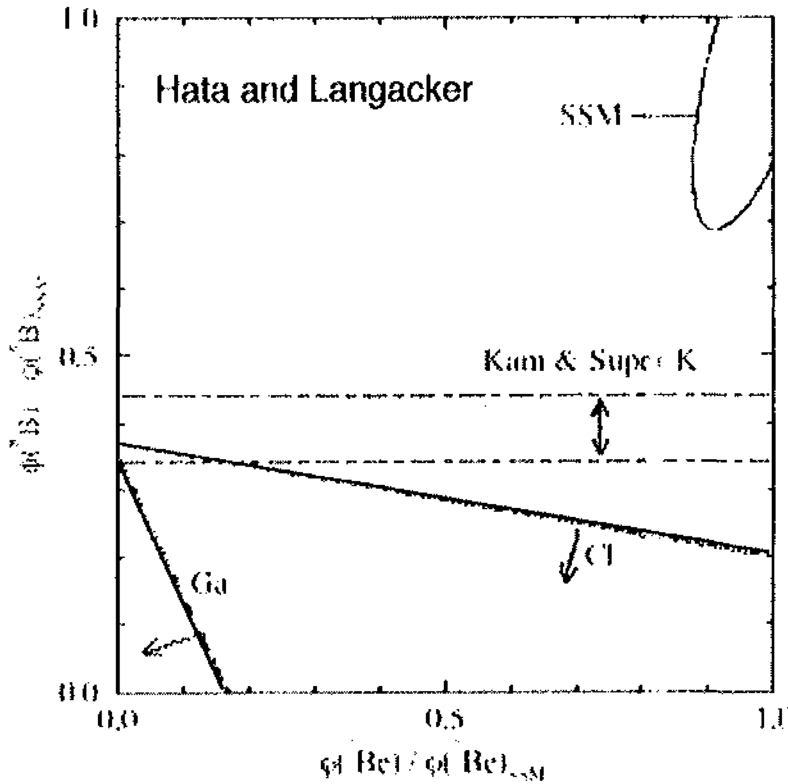
${}^2H + p \rightarrow {}^3He + \gamma$

${}^3He + {}^3He \rightarrow {}^4He + 2p$ $\quad$ ${}^3He + p \rightarrow \alpha + e^+ + \nu_e$

${}^3He + \alpha \rightarrow {}^7Be + \gamma$

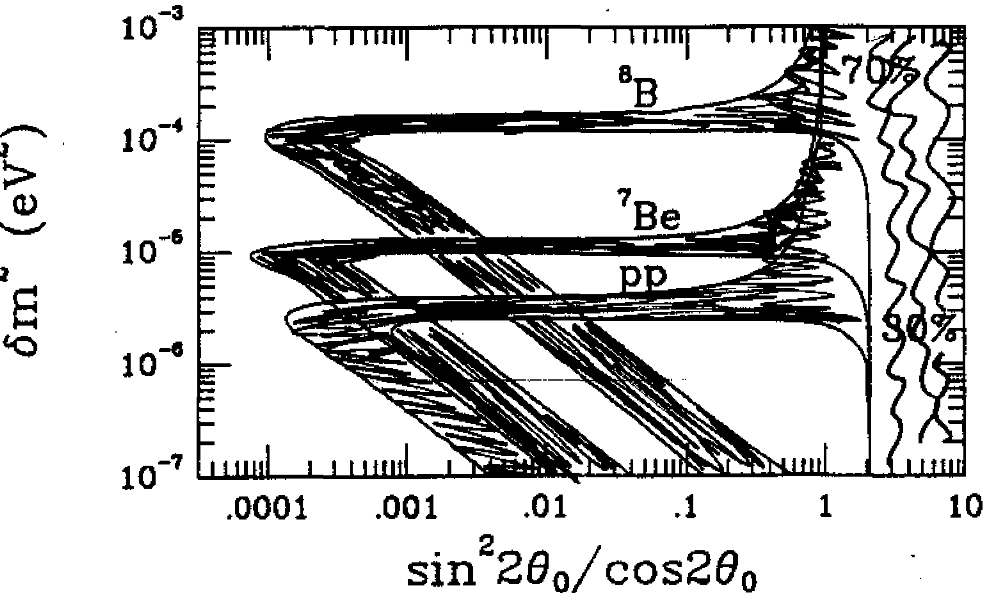
${}^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e$ $\quad$ ${}^7Be + p \rightarrow {}^8B + \gamma$

${}^7Li + p \rightarrow \alpha + \alpha$ $\quad$ ${}^8B \rightarrow 2\,\alpha + e^+ + \nu_e$



The data are incompatible with standard and non-standard solar models

(For a model independent analysis see Heeger and Robertson, PRL 77 (1996) 3720)

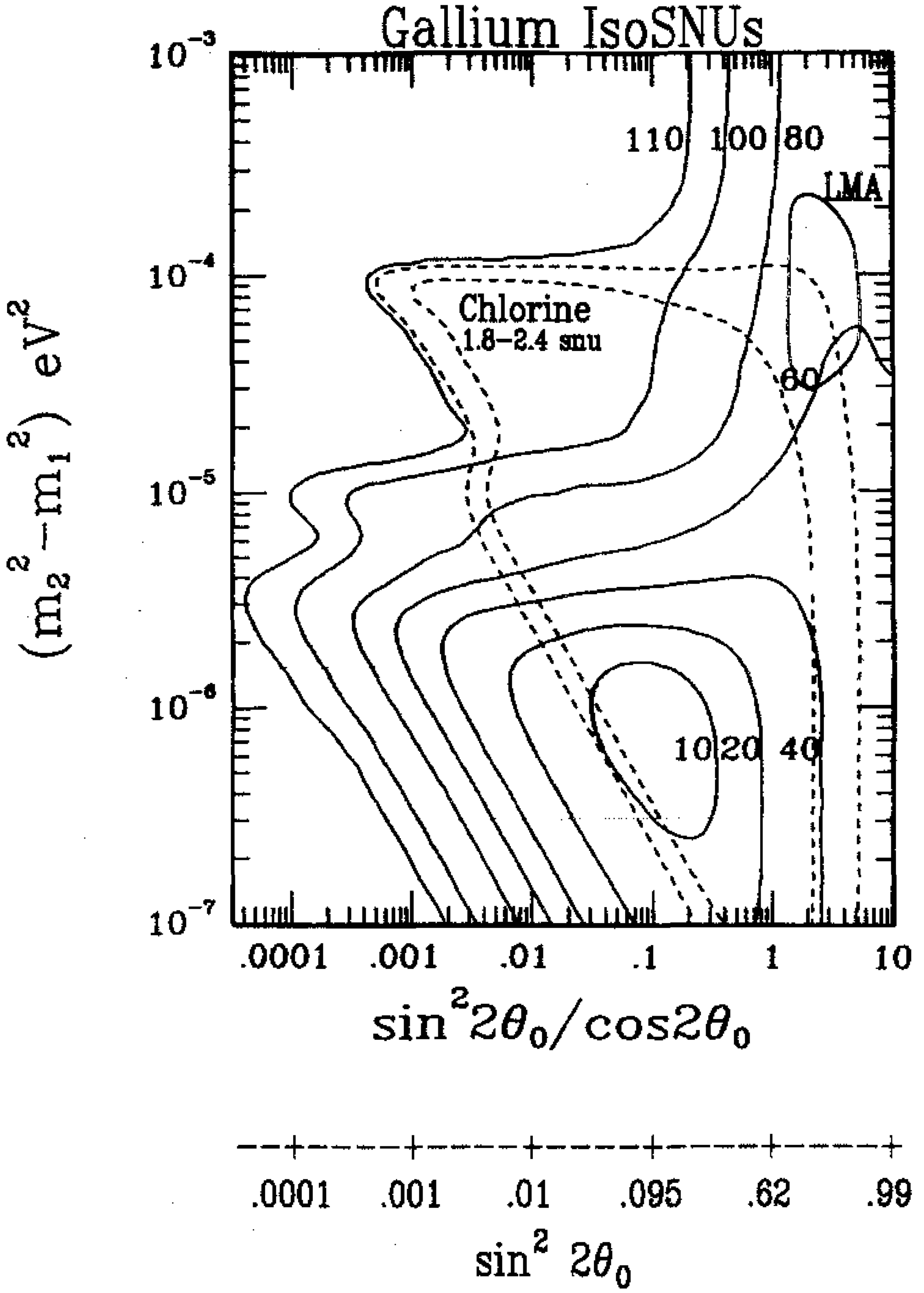


30-70% for

^{8}B

^{7}Be

PP

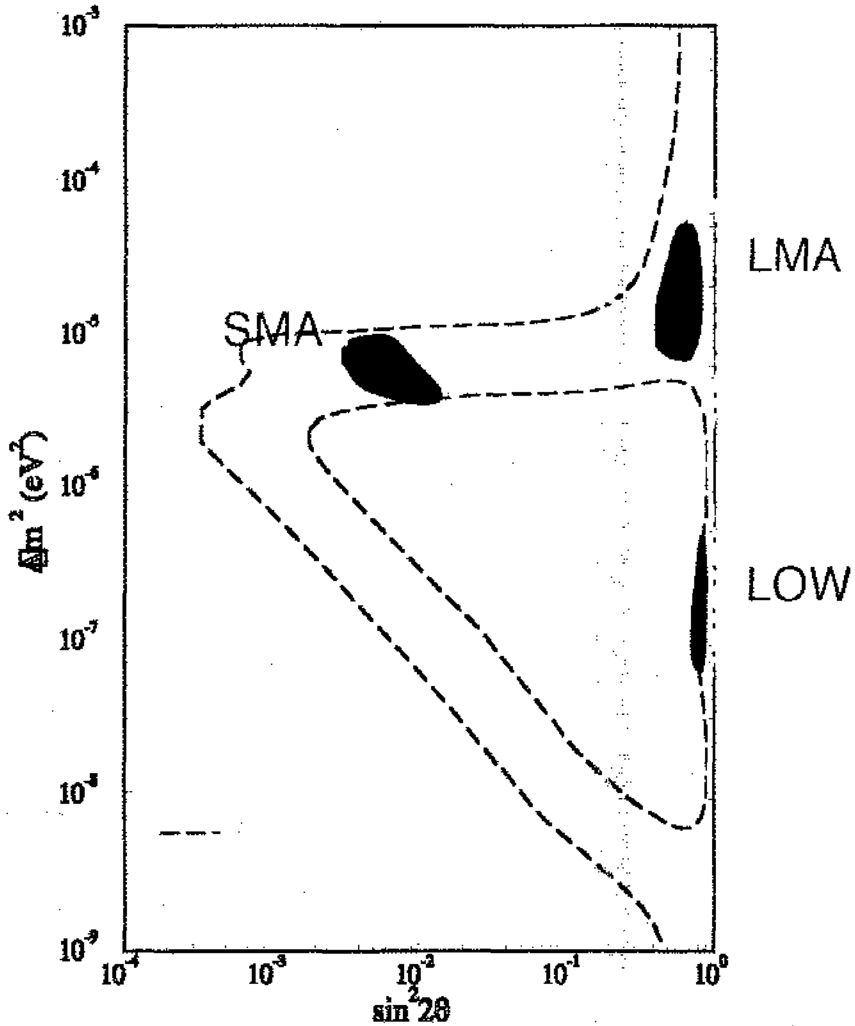


S. Parke and T. Walker – PRL 57, 2322 (1986)
--based on analytic results of
S. Parke – PRL 57, 1275 (1986)

Matter Enhanced ν Oscillations

MSW gives a dramatic extension of oscillation sensitivity to potential regions in Δm^2

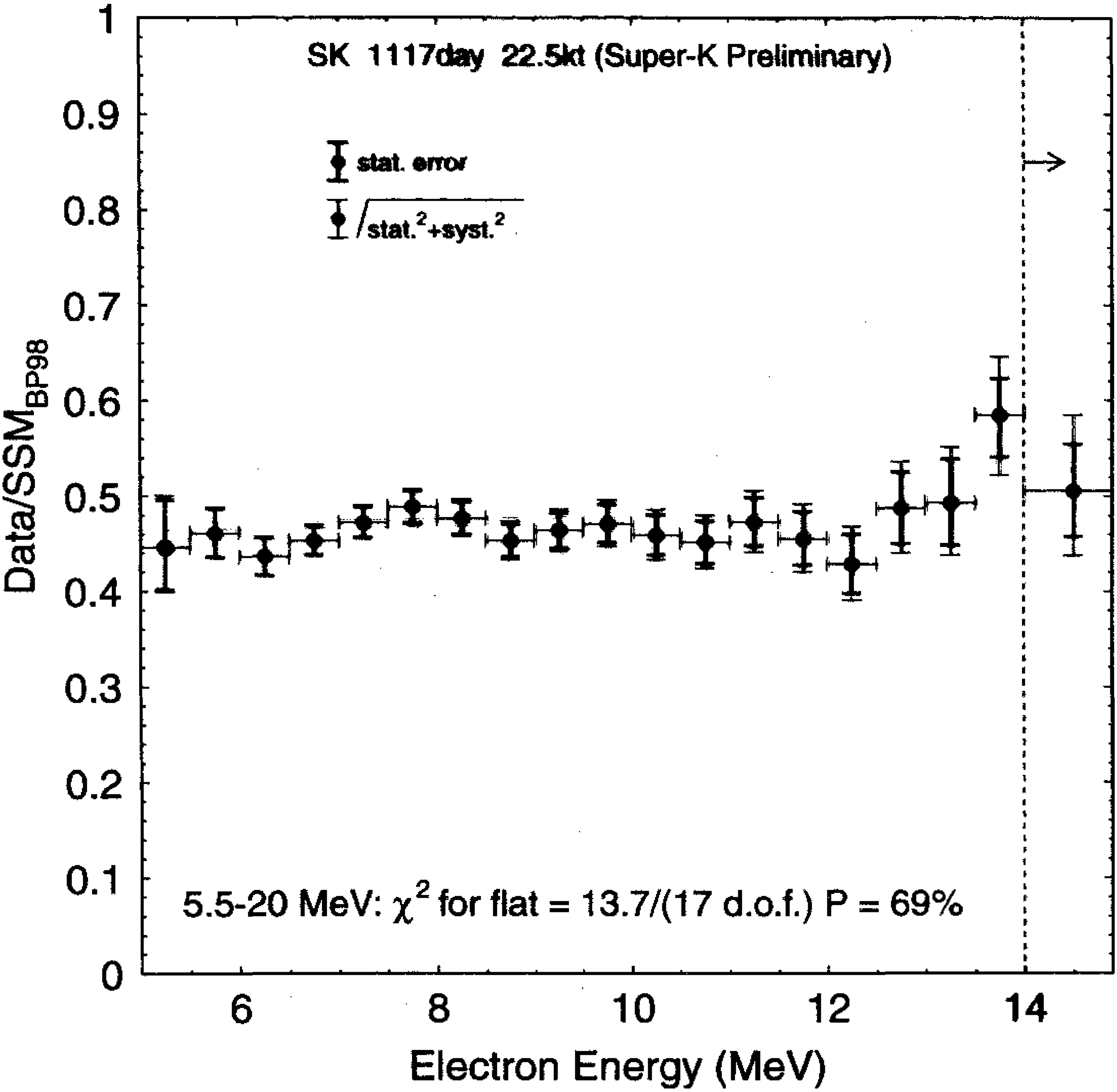
Solar ν data are consistent with the MSW hypothesis.



- Need definitive proof
- Appearance measurement
- Independent of SSM

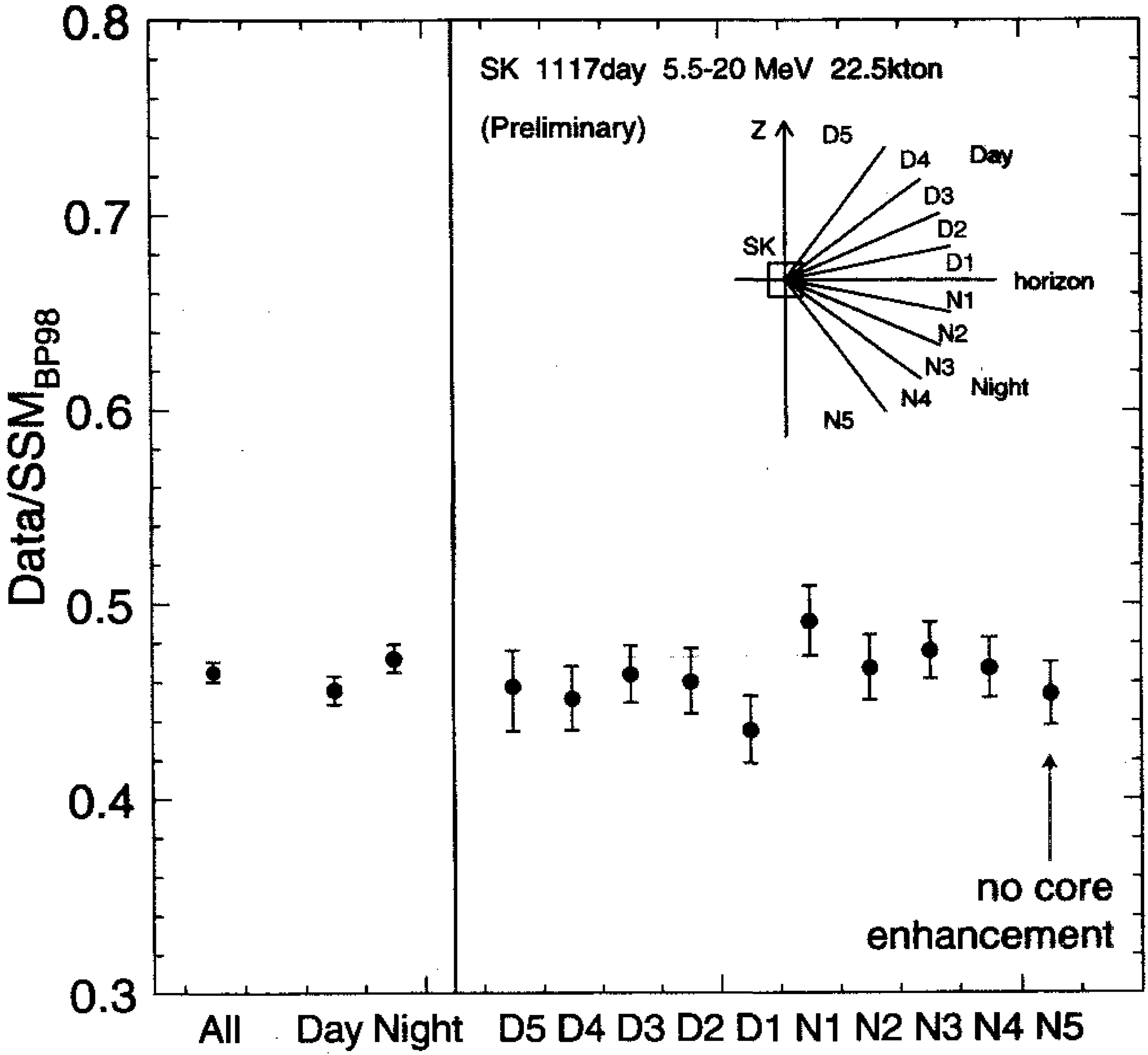
Nu'98 SK presented E_ν spectrum – LMA preferred.

Super-K Solar ν Energy Spectrum



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

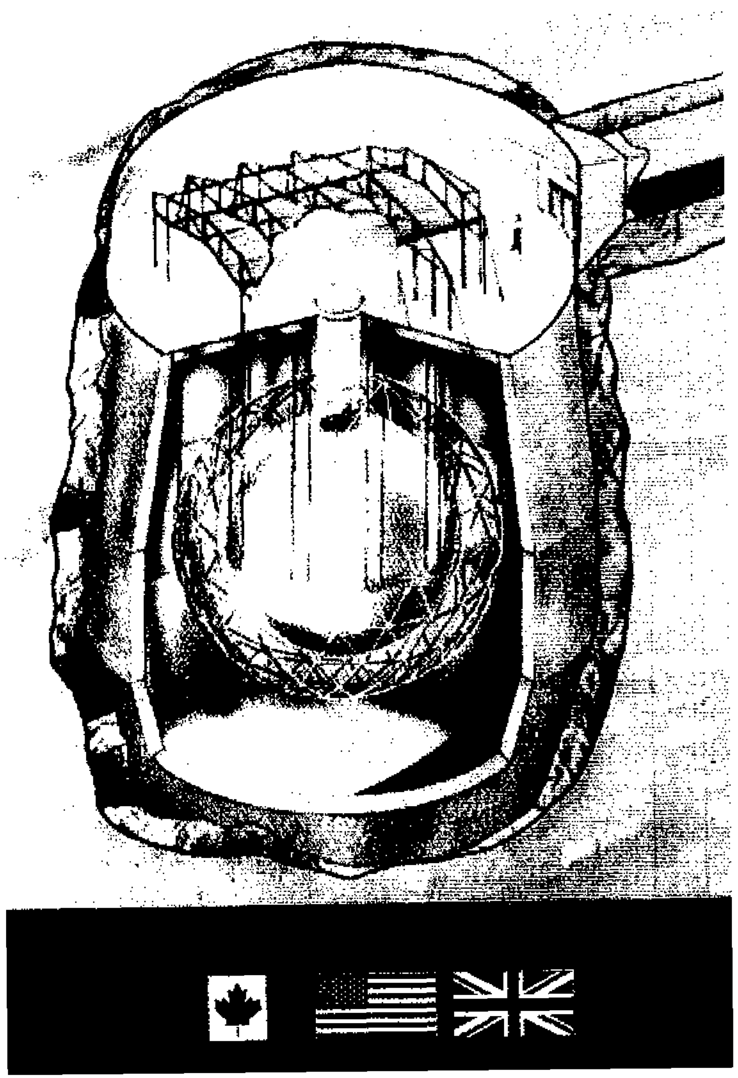
Super-K Day-Night Result



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

1.3σ effect

The Sudbury Neutrino Observatory



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

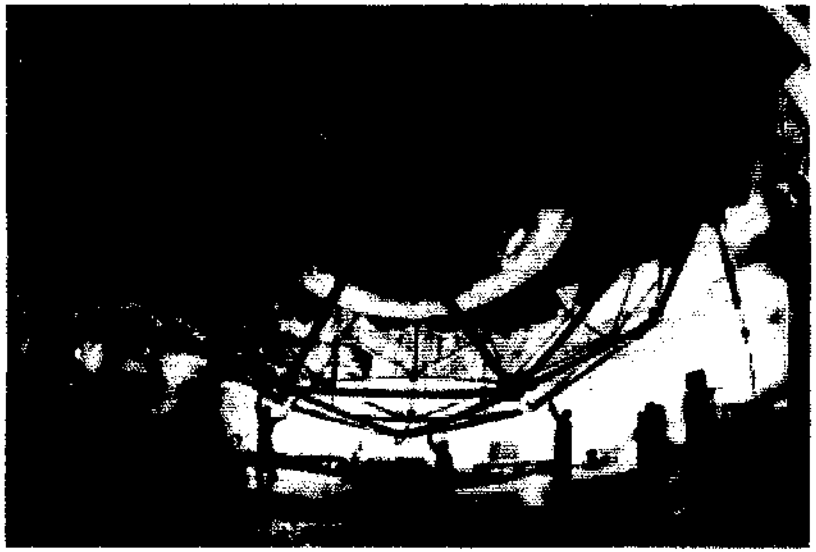
-Good sensitivity to ν_e energy spectrum
-Weak directional sensitivity $\propto$ 1-1/3cos(θ)
- ν_e only.

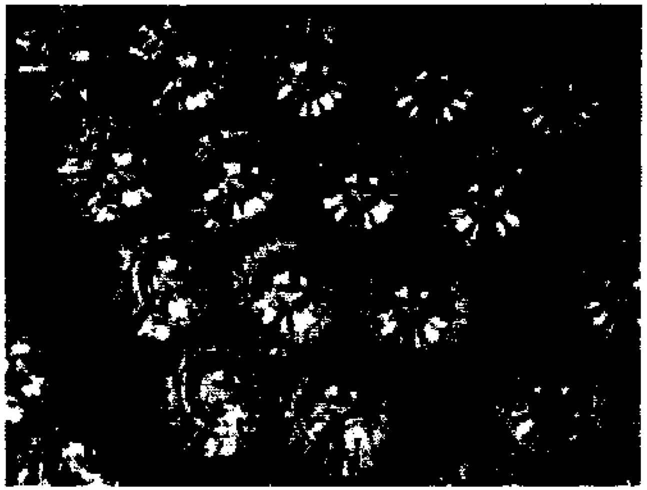
- Measure total ^8B ν flux from the sun.
- Equal cross section for all ν types
- 2.2 MeV Threshold, Integrated $E > E_{th}$

ES

-Low Statistics
-Dominant contribution (5/6) from ν_e,
smaller (`1/6) contributions from ν_μ & ν_τ
-Strong directional sensitivity

The SNO Detector during Construction





Key signatures for unexpected ν Flavors

Measure total flux of solar neutrinos vs. the pure ν_e flux

Direct Evidence for ν flavor change

$$\frac{\Phi_{cc}}{\Phi_{es}} = \frac{\nu_e}{\nu_e + 0.154(\nu_\mu + \nu_\tau)}$$ June 2001

$$\frac{\Phi_{cc}}{\Phi_{nc}} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau}$$ **April 2002**

Potential signal For ν oscillations Φ_{day} **vs** Φ_{night} **April 2002**

ν Reactions in SNO

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

Produces Cherenkov Light Cone in D_2O

-Good measurement of ν_e energy spectrum
-Weak directional sensitivity $\propto$ 1-1/3cos(θ)
- ν_e only.

D_2O Only Phase

n captures on deuteron
$^2H(n, \gamma)^3H$
Observe 6.25 MeV γ

- Measure total ^8B ν flux from the sun.
- Equal cross section for all ν types
- 2.2 MeV Threshold, Integrated $E > E_{th}$

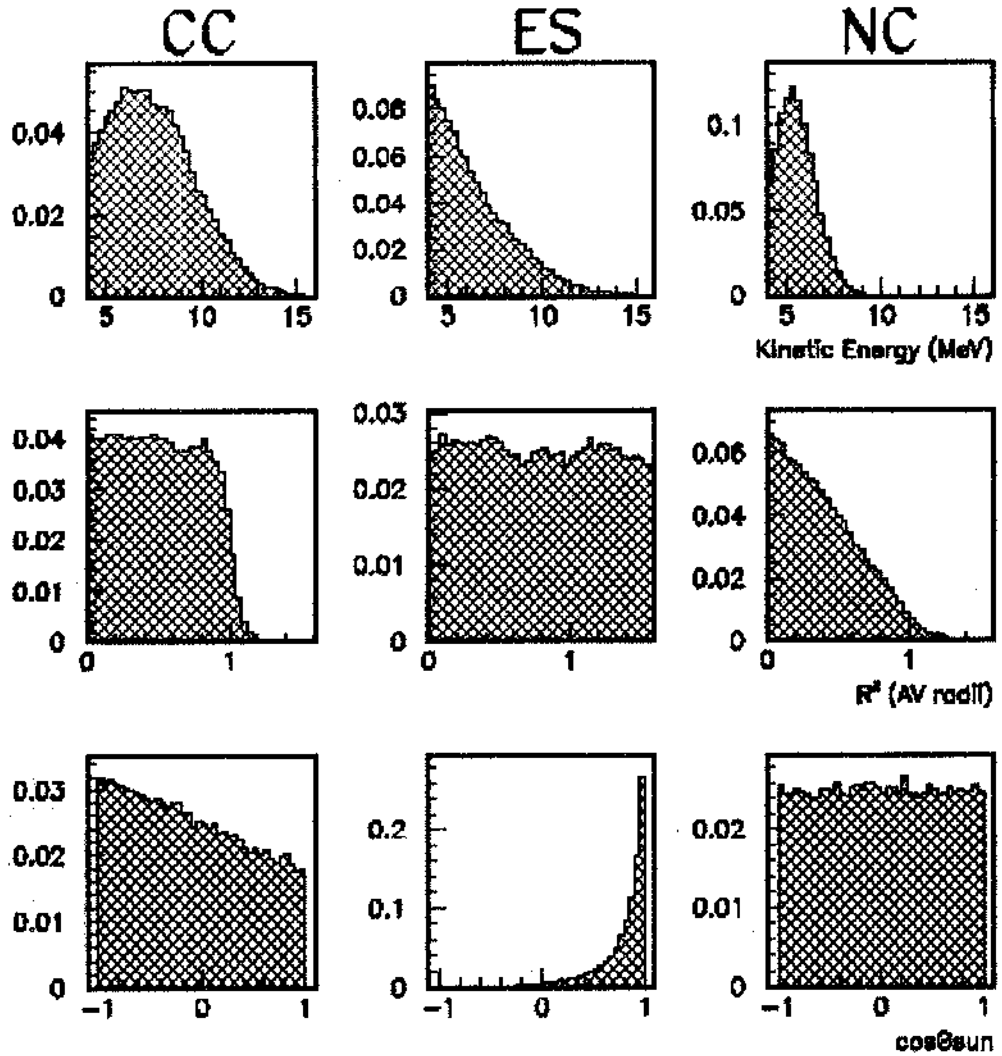
ES

Produces Cherenkov Light Cone in D_2O

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

Extraction of CC, ES, NC Signals

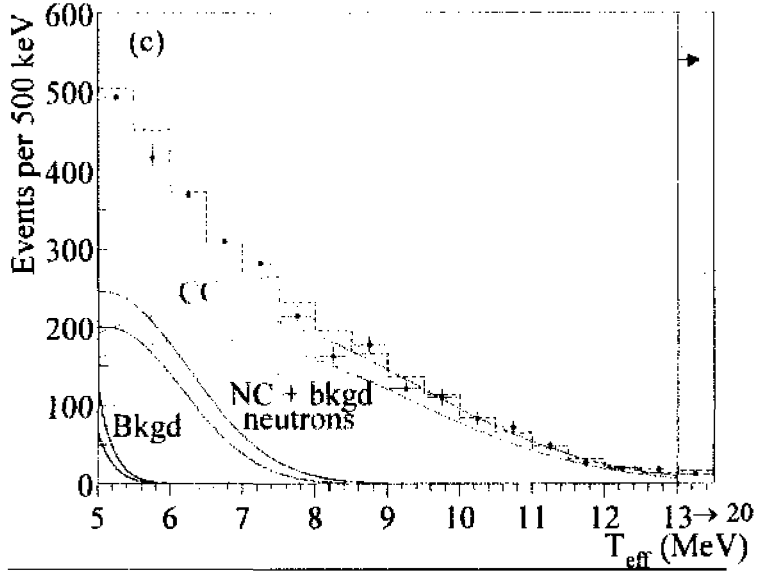
To extract the CC, ES, NC signal SNO performs a Max-likelihood statistical separation of these signals based on distributions of the SNO observables.

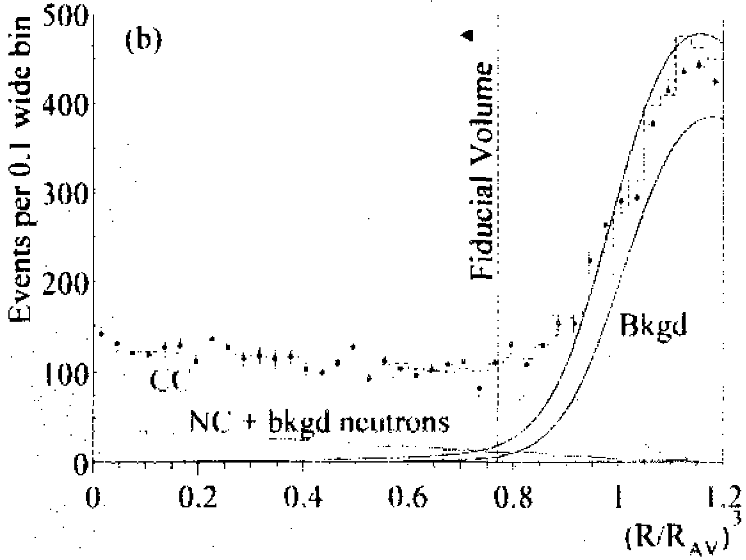


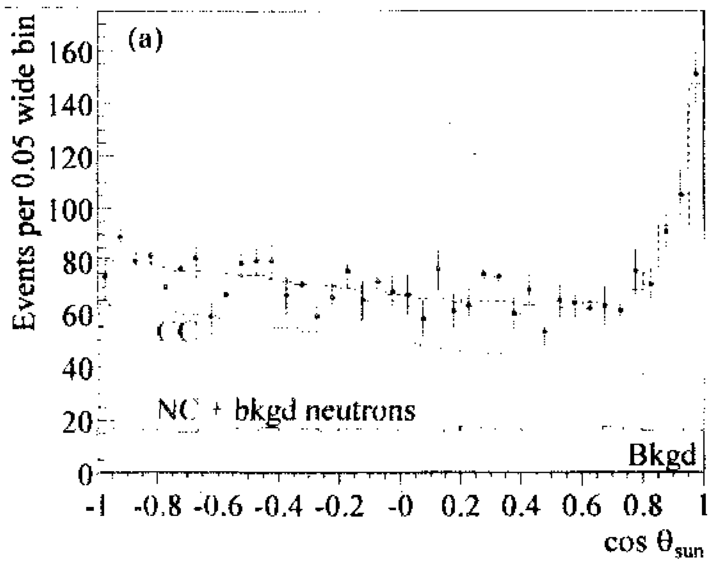
Shape Constrained Signal Extraction Results

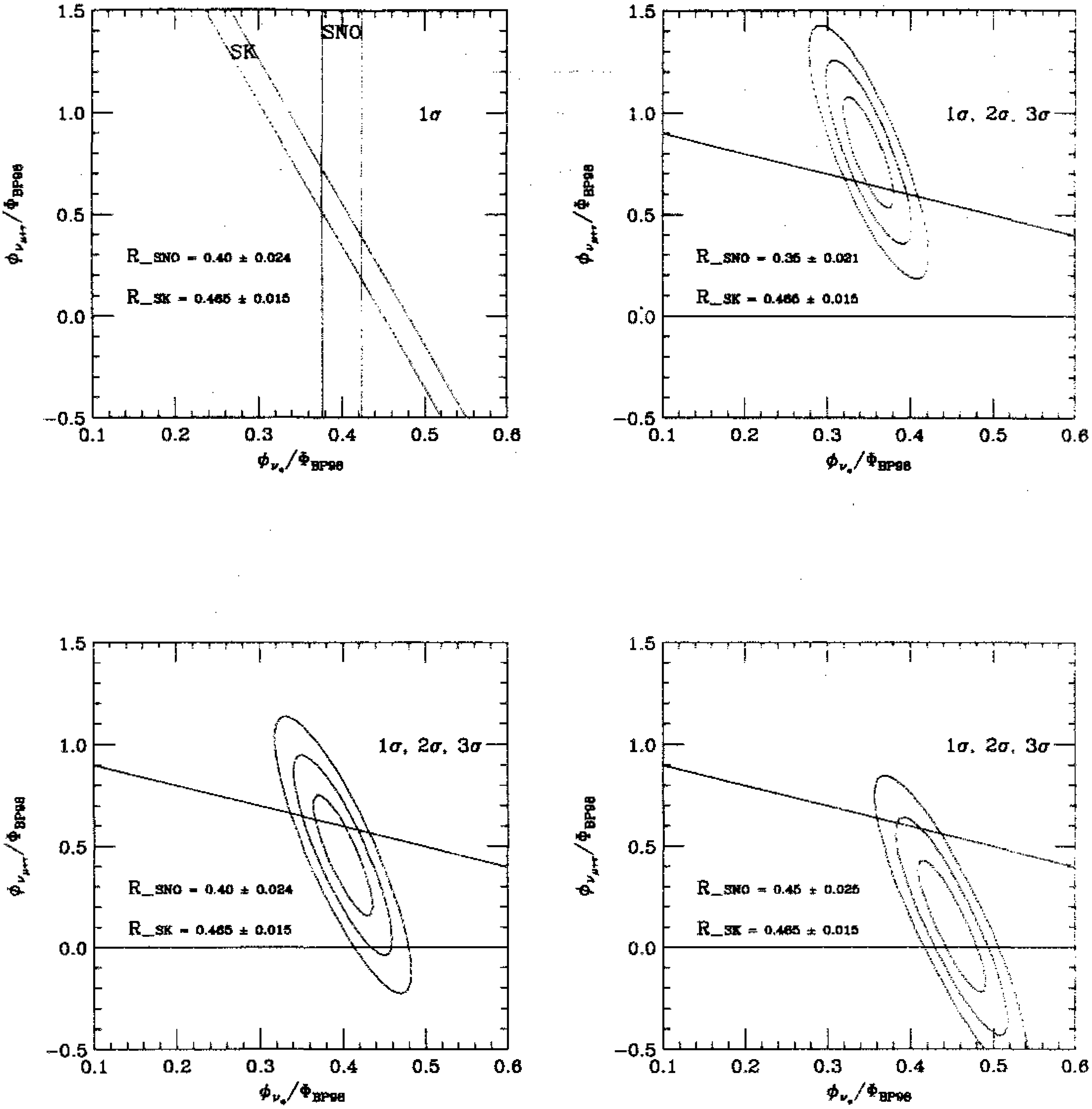
#EVENTS

CC	$1967.7^{+61.9}_{+60.9}$
ES	$263.6^{+26.4}_{+25.6}$
NC	$576.5^{+49.5}_{+48.9}$









SNO
SK
1σ
R_SNO = 0.40 ± 0.024
R_SK = 0.465 ± 0.015
1σ, 2σ, 3σ
R_SNO = 0.35 ± 0.021
R_SK = 0.465 ± 0.015
1σ, 2σ, 3σ
R_SNO = 0.40 ± 0.024
R_SK = 0.465 ± 0.015
1σ, 2σ, 3σ
R_SNO = 0.45 ± 0.025
R_SK = 0.465 ± 0.015
ϕ_{ν_e}/Φ_{BP98}
$\phi_{\nu_{\mu+\tau}}/\Phi_{BP98}$

Neutrino Flavor Composition of ^{8}B Flux

Fluxes

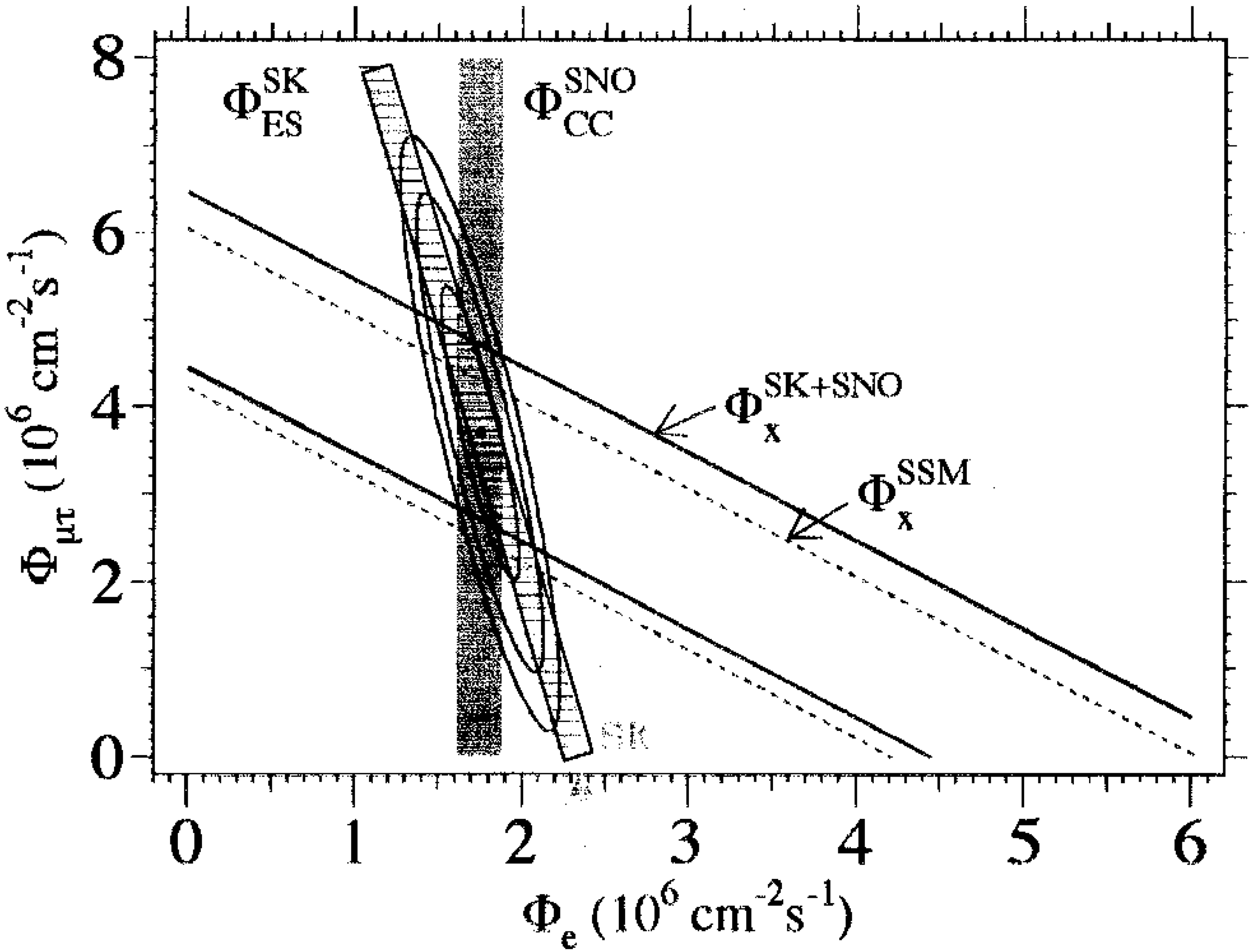
(10^6 cm^{-2} s^{-1})

ν_e: 1.75(15)

$\nu_{\mu\tau}$: 3.69(113)

ν_{total}: 5.44(99)

ν_{SSM}: 5.05

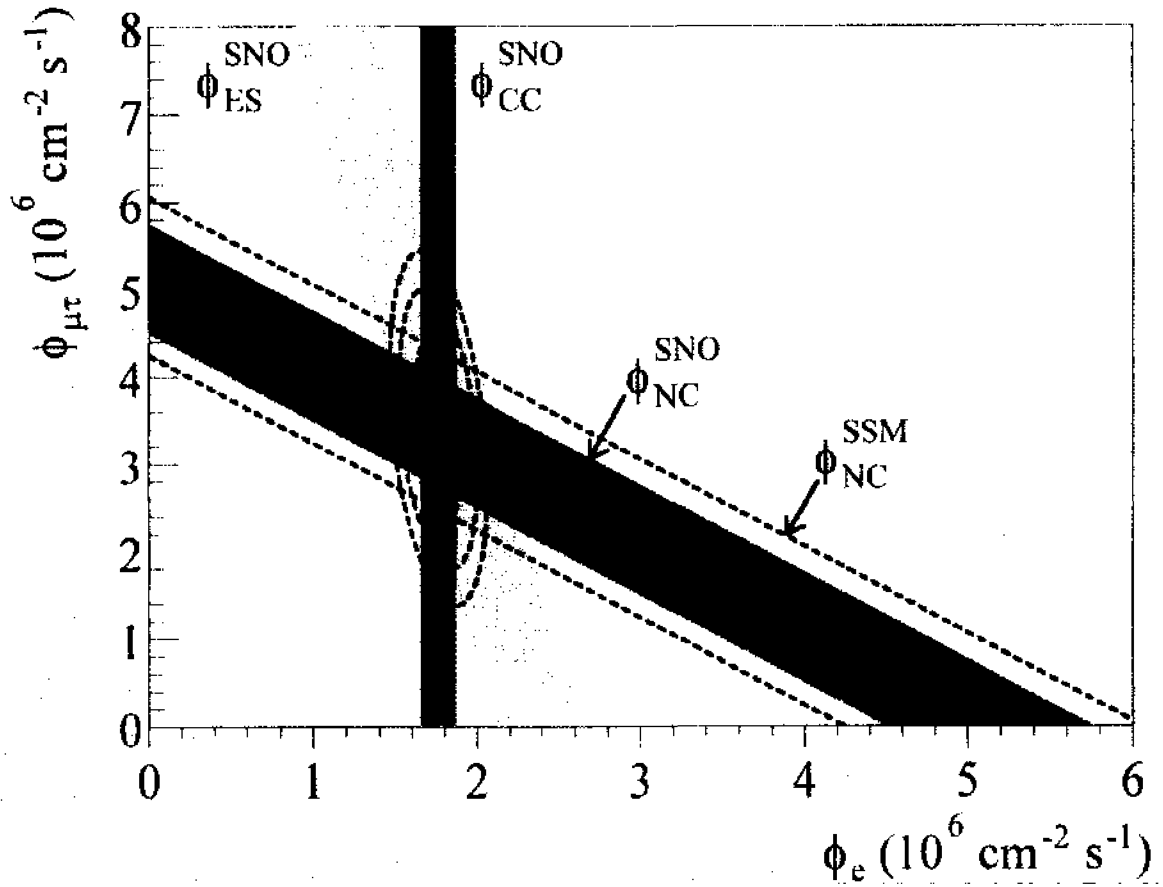


$\phi_{CC} = \phi_e$

$\phi_{ES} = \phi_e + 0.154\,\phi_{\mu,\tau}$

SNO NC in D_2O Conclusions

~ 2/3 of initial solar ν_e are observed at SNO to be $\nu_{\mu,\tau}$

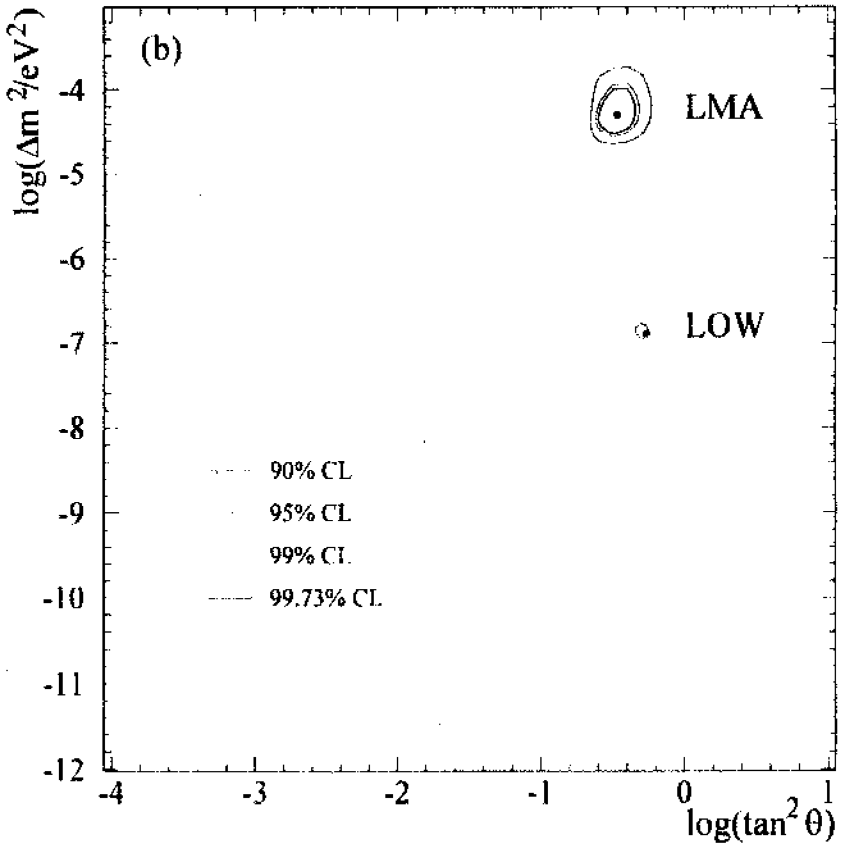


$\Phi_{ssm} = 5.05^{+1.01}_{-0.81}$ $\Phi_{sno} = 5.09^{+0.44\ +0.46}_{-0.43\ -0.43}$

SNO Conclusions

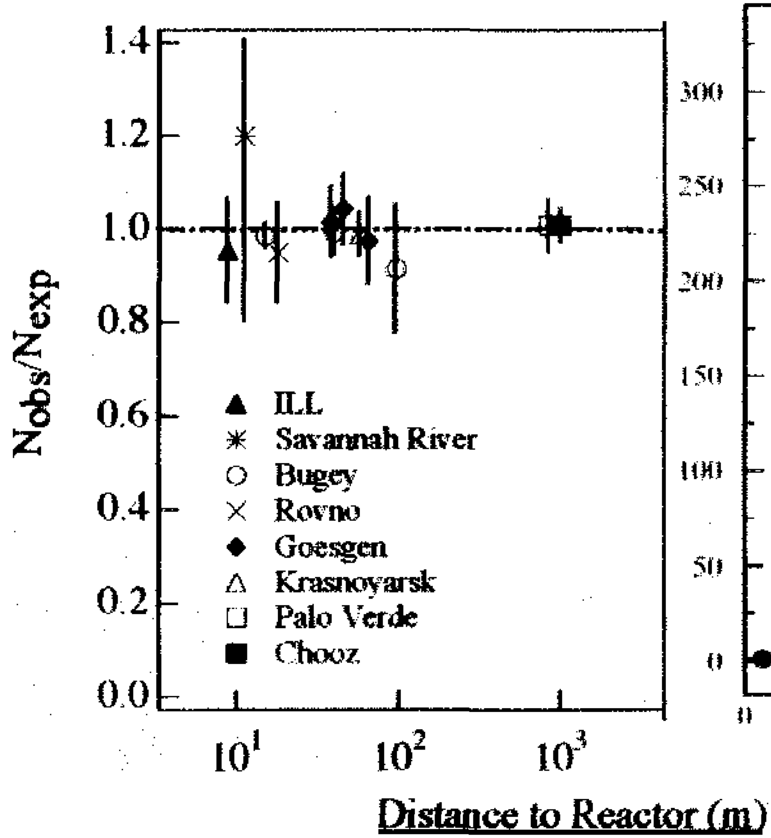
- First NC flux measurements - clear evidence that the majority of ν_e produced in the Sun are transformed to ν_μ and/or ν_τ
  - Null hypothesis - "No Weak Flavor Mixing" ruled out at 5.3 σ
  - Lowest Detection threshold yet for a real-time solar ν detector
  - Total ^8B flux measurement agrees well with Solar Models
  - Data in good agreement with previous SNO - SK CC/ES result
- First measurements of the Day-Night Asymmetries
  - SNO Data consistent with MSW oscillation interpretation
  - combined with global solar neutrino data favors LMA solution
  - "Dark side" solutions not allowed, indicating $m\nu_2 > m\nu_1$

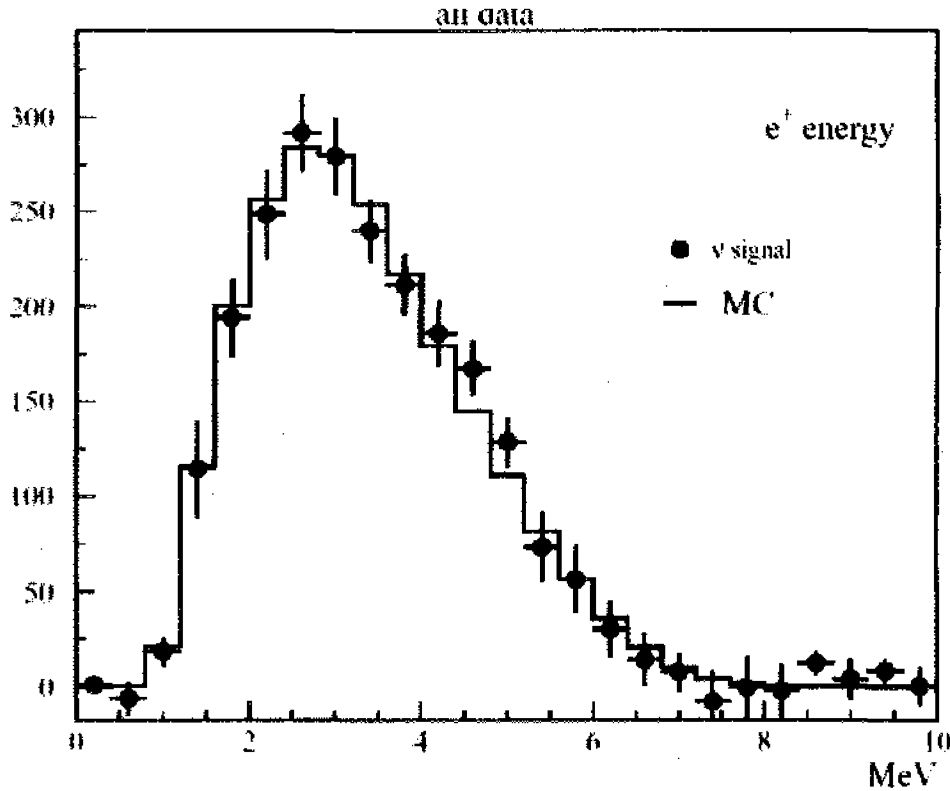
Combining All Experimental and Solar Model information



Reactor ν_e oscillation searches

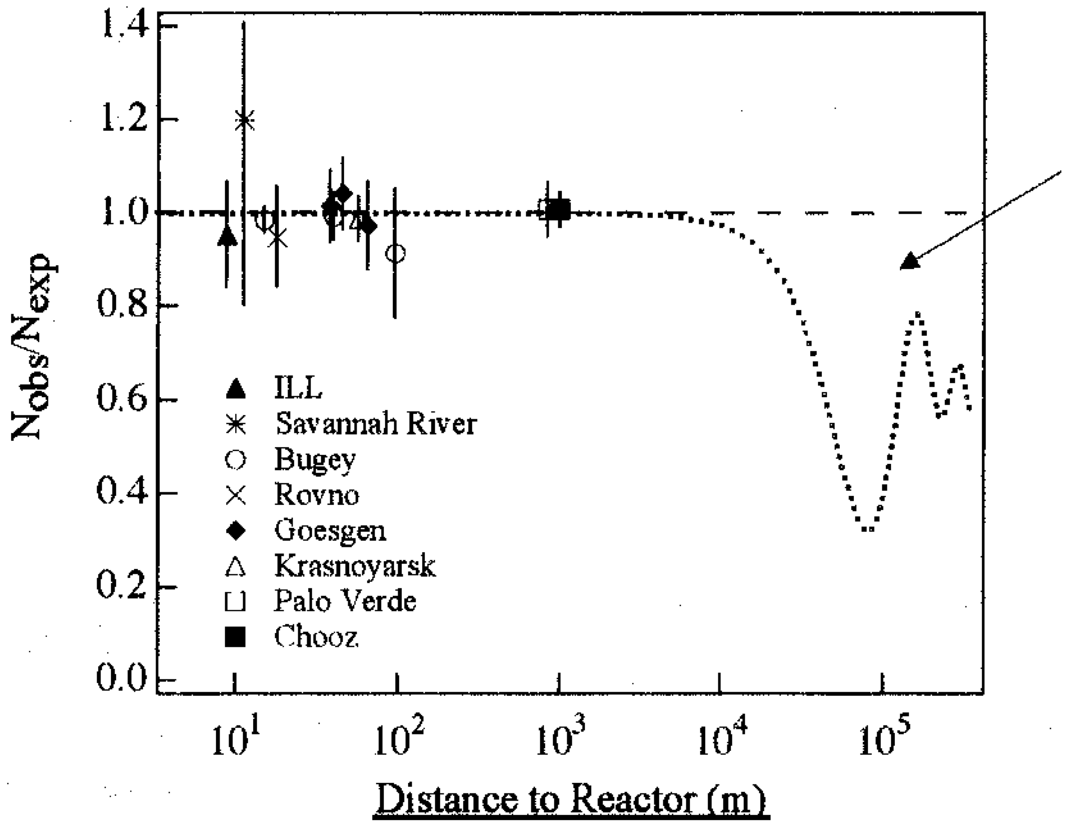
1956 Reines & Cowan $\bar{\nu}_e + p \Rightarrow n + e^+$

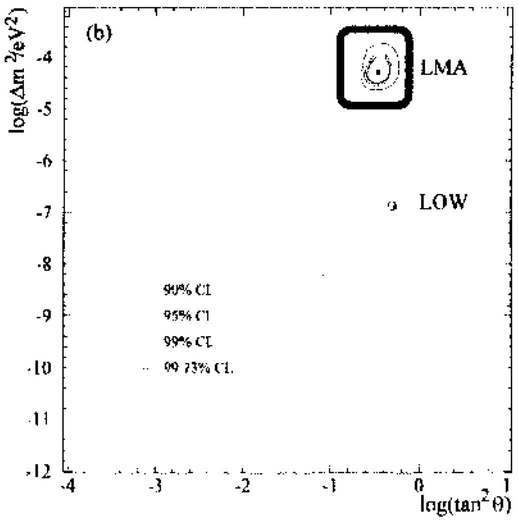




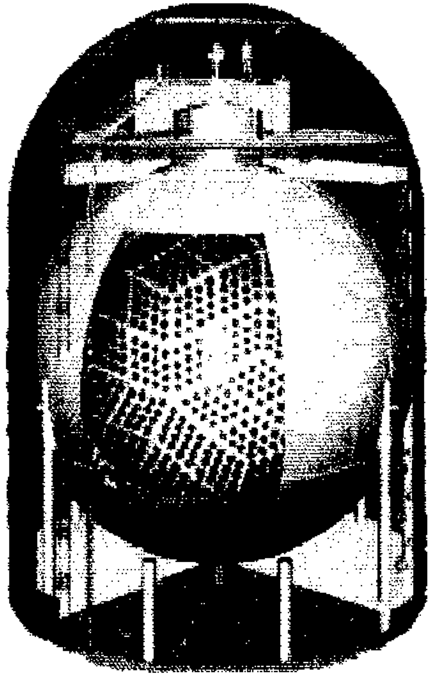
Solar neutrino LMA implication

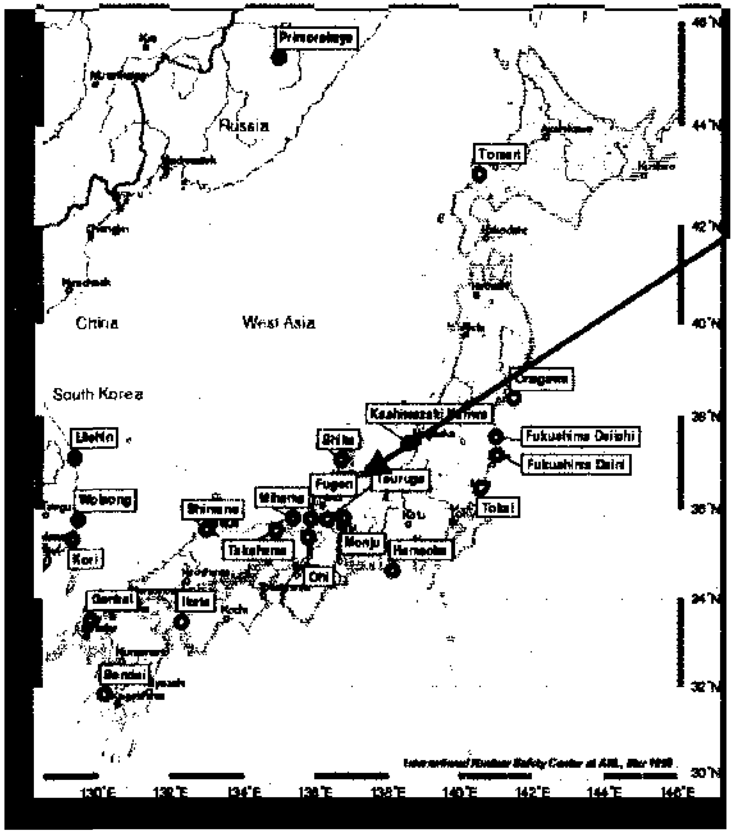
Reactor experiments optimum at ~180 km





KamLAND - Kamioka Liquid Scintillator Anti-Neutrino Detector



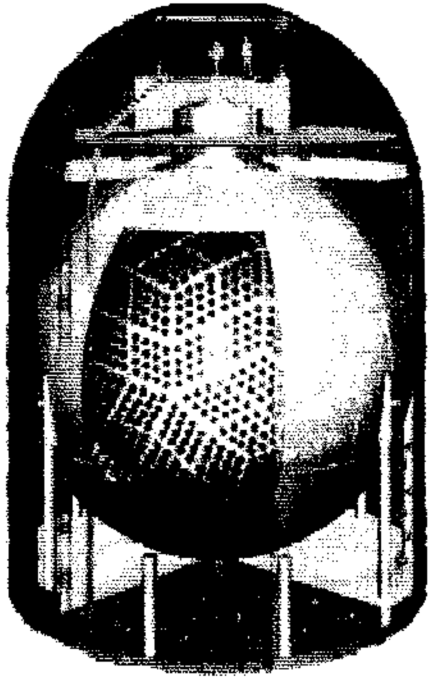


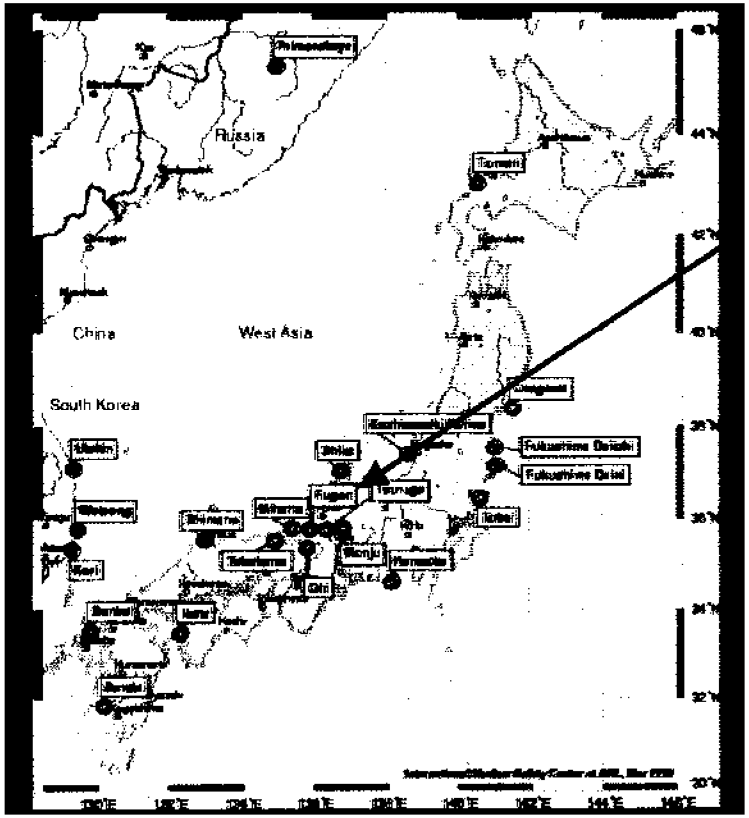
16 complexes - 10% of world's nuclear power

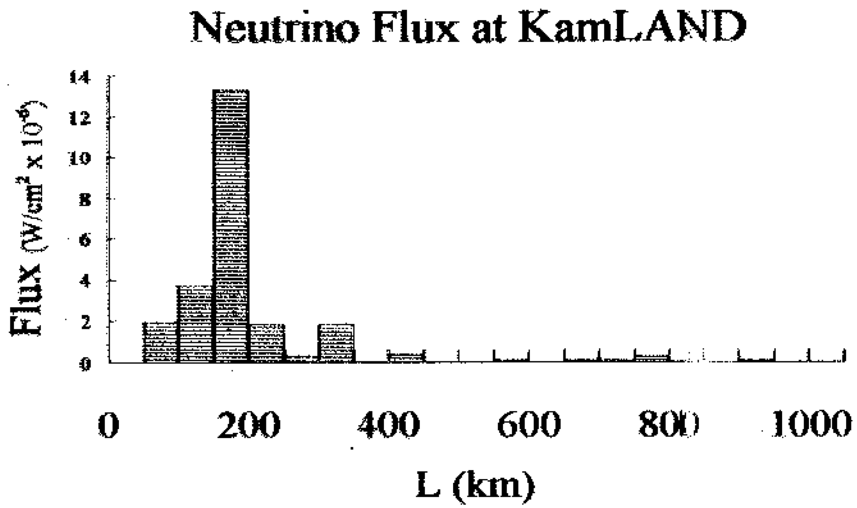
3 GW reactor: ~8 • 10^{20} $\overline{\nu}_e$/s

L ~140 - 210 km

KamLAND - Kamioka Liquid Scintillator Anti-Neutrino Detector

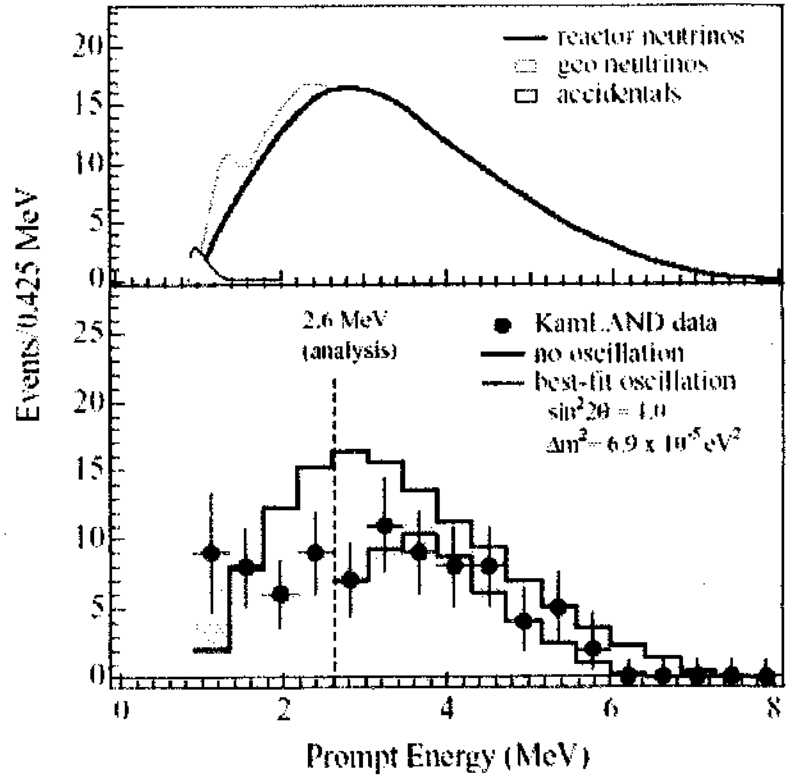


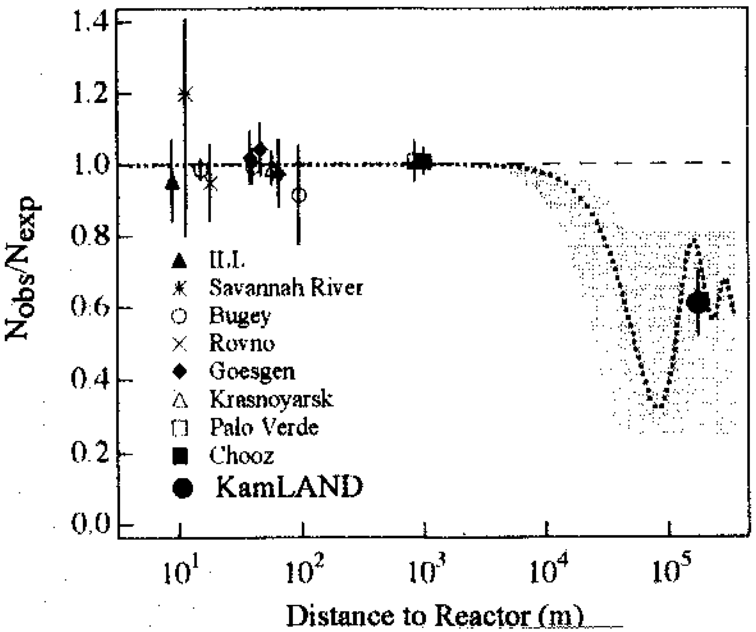




KamLAND first results (hep-ex/0212021)

- Data summary
  - 145.1 live days
  - Observed: 54
  - Expected: 86.8 ± 5.6
  - Background 1 ± 1



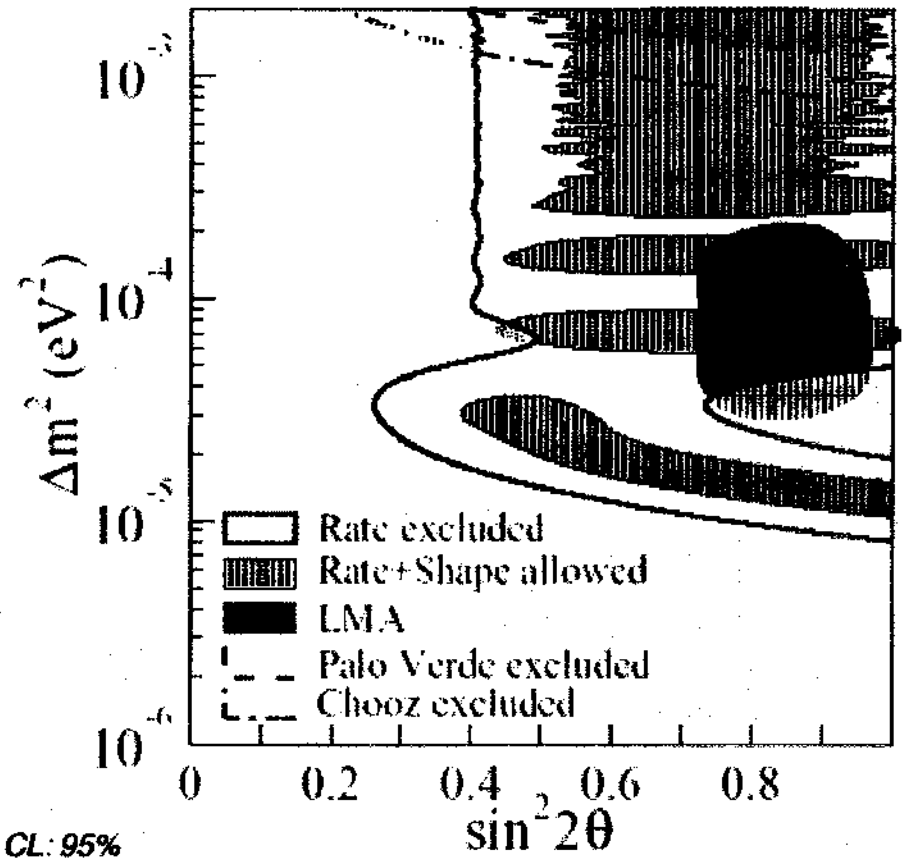


Measured survival probability differs from 1 by 4.1 σ

Probability that result is consistent with no oscillation hypothesis < 0.05%

Evidence of ν_e oscillations

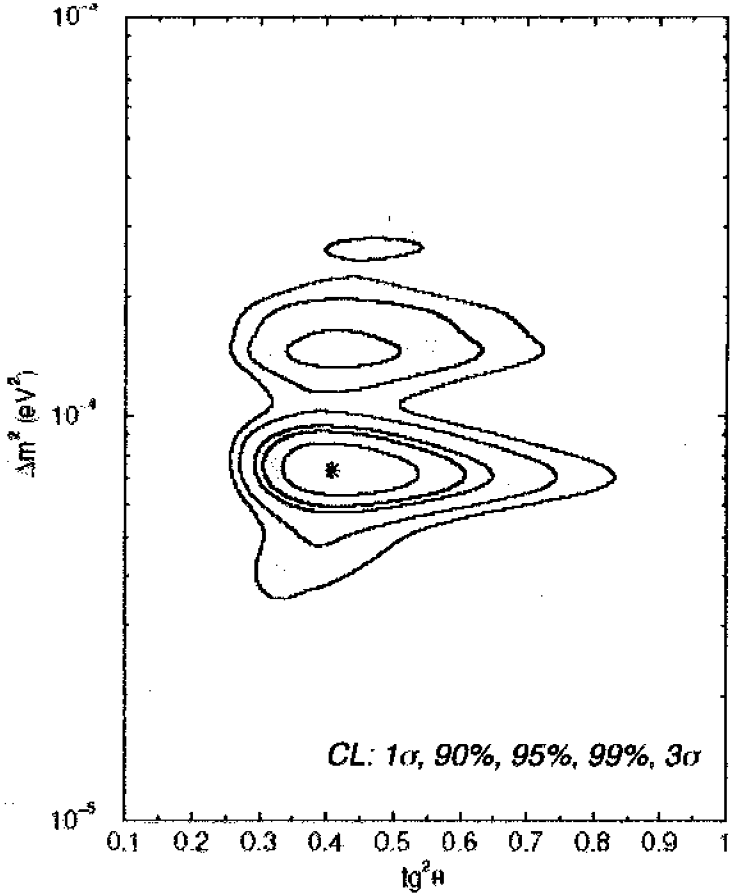
KamLAND with LMA shown



CL: 95%

hep-ex/0212021

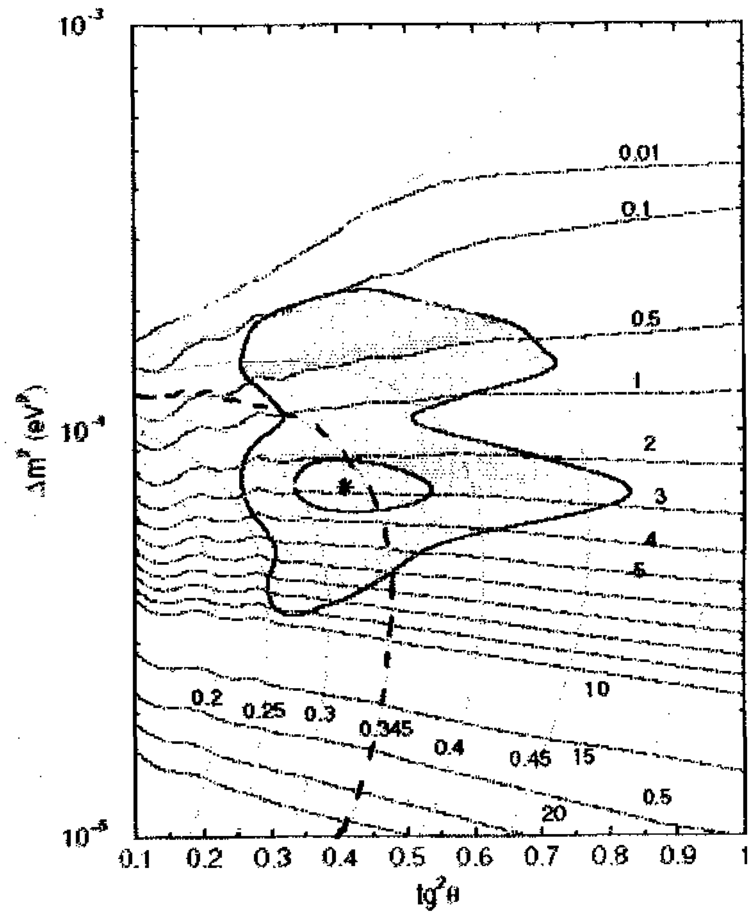
Global fit
(de Holanda and Smirnov)



hep-ph/0212270

Impact of precision SNO

- Improved NC/CC measurement will yield an improved θ_{12} value
  - D_2O: unconstrained ~30%
  - Salt: perhaps 10-15%
  - NCD: potentially ~5 %
- Note KamLAND should improve on Δm_{12}
- Possible chance to observe Day/Night asymmetry and hence direct oscillation siganl



de Holanda and Smirnov
hep-ph/0212270

Next generation Solar Neutrinos

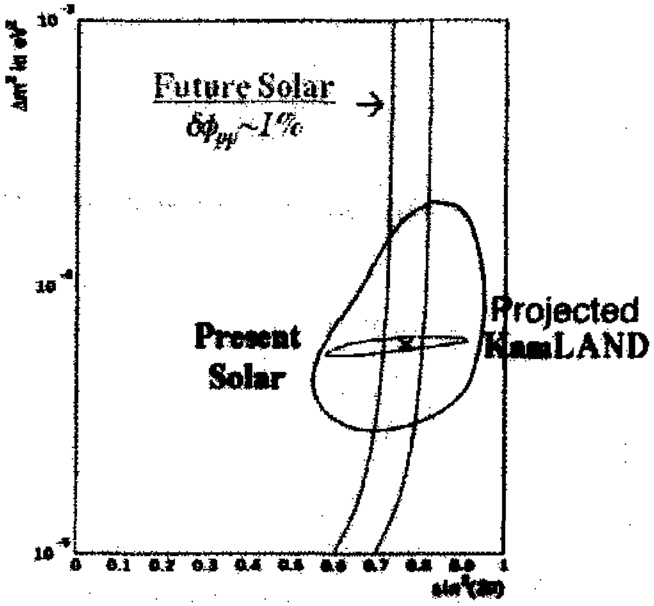
Charged-Current Experiments:

[illegible]

Goal: Measure [illegible] component of [illegible]

[illegible]

[illegible]



Elastic Scattering Experiments:

[illegible] TPC

[illegible]

Goal: Measure [illegible]

Solar Neutrinos + KamLAND:

- Strong evidance for matter enhanced (MSW) neutrino oscillations

$$\nu_e \leftrightarrow \nu_\mu, \nu_\tau$$

$$P_{\nu_e \to \nu_e} = 1 - \sin^2 2\theta_\odot \sin^2 \frac{\delta m_\odot^2 L}{4E}$$

$$P_{\nu_e \to \nu_\mu, \nu_\tau} = \sin^2 2\theta_\odot \sin^2 \frac{\delta m_\odot^2 L}{4E}$$

with $\delta m_\odot^2 \sim 7$ or $15 \times 10^{-5}\ eV^2$

$\sin^2 2\theta_\odot \sim 0.85$

What's Next Solar / KamLAND:

- SNO salt data
  enhanced NC signal
- SNO Day v. Night (?)
- Improved results from
  KamLAND.

  (currently ½ signal
  due to reactor shut down)

$$\underline{\underline{\sin^2 2\theta = 0.86}}$$

Vacuum/Reactor:

$$P_{\nu_e \to \nu_e} = 1 - \tfrac{1}{2}\sin^2 2\theta$$

$$= \tfrac{1}{2} + \tfrac{1}{2}\cos^2 2\theta$$

$$= 0.57$$

Matter/Solar:

$$P_{\nu_e \to \nu_e} = \tfrac{1}{2} + \tfrac{1}{2}\cos 2\theta_0 \cos 2\theta_N$$

if production is at $\theta_N \to \pi/2$ $\quad \cos 2\theta_N = -1$

$$= \tfrac{1}{2}(1 - \cos 2\theta_0) = \sin^2\theta_0$$

DIFFERENT

$$= 0.31$$

Strong evidence our picture (oscillations) is correct!!