# Neutrino Oscillations:

## Solar

## and Atmospheric

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# ν Oscillations In Two Domains: Atmospheric and Solar

$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$ ν mass eigenstates ≠ flavor eigenstates

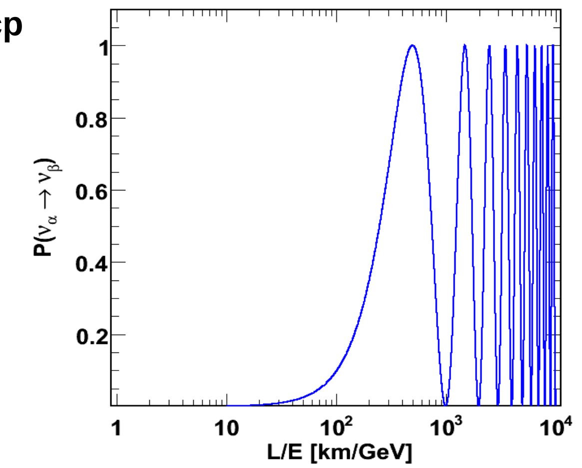
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

**Atmospheric** **Solar**

**Additionally two mass splittings: $\Delta m^2_{12}$, $\Delta m^2_{13}$, $\delta_{cp}$**

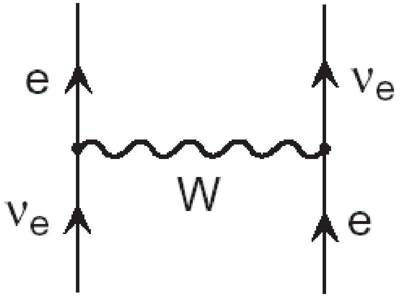
**To first order experiments are sensitive to oscillations between two active ν's:**

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right) \quad \left[\frac{eV^2\,km}{GeV}\right]$$



# Matter Effects : Constant Density

Only $\nu_e$




⇒ Creates an effective potential

$A = \sqrt{2}\, G_F N_e$ , $N_e$ = $e^-$ density

⇒ Alters $\nu_e \leftrightarrow \nu_\alpha$ oscillations

Two-ν system can be expressed in "matter" variables:

$$P(\nu_e \rightarrow \nu_\alpha) = \sin^2 2\theta_M \sin^2\left(\frac{1.27\,\Delta M^2 L}{E}\right)$$

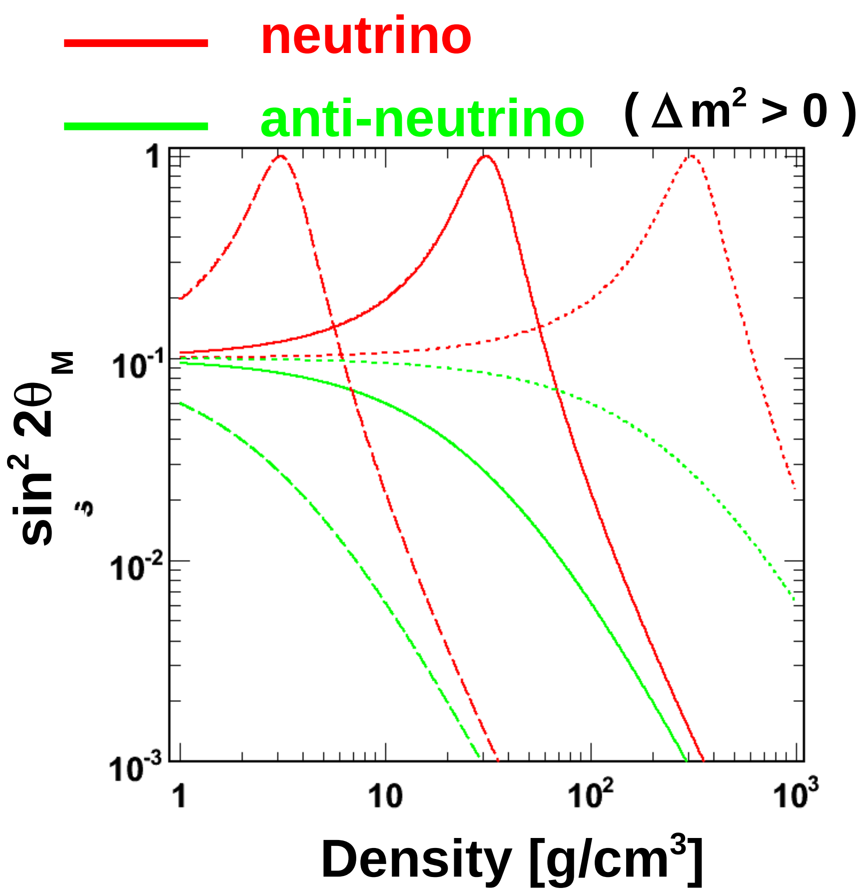
$$\Delta M^2 = \Delta m^2 \sqrt{\sin^2 2\theta + (\Gamma - \cos 2\theta)^2}$$

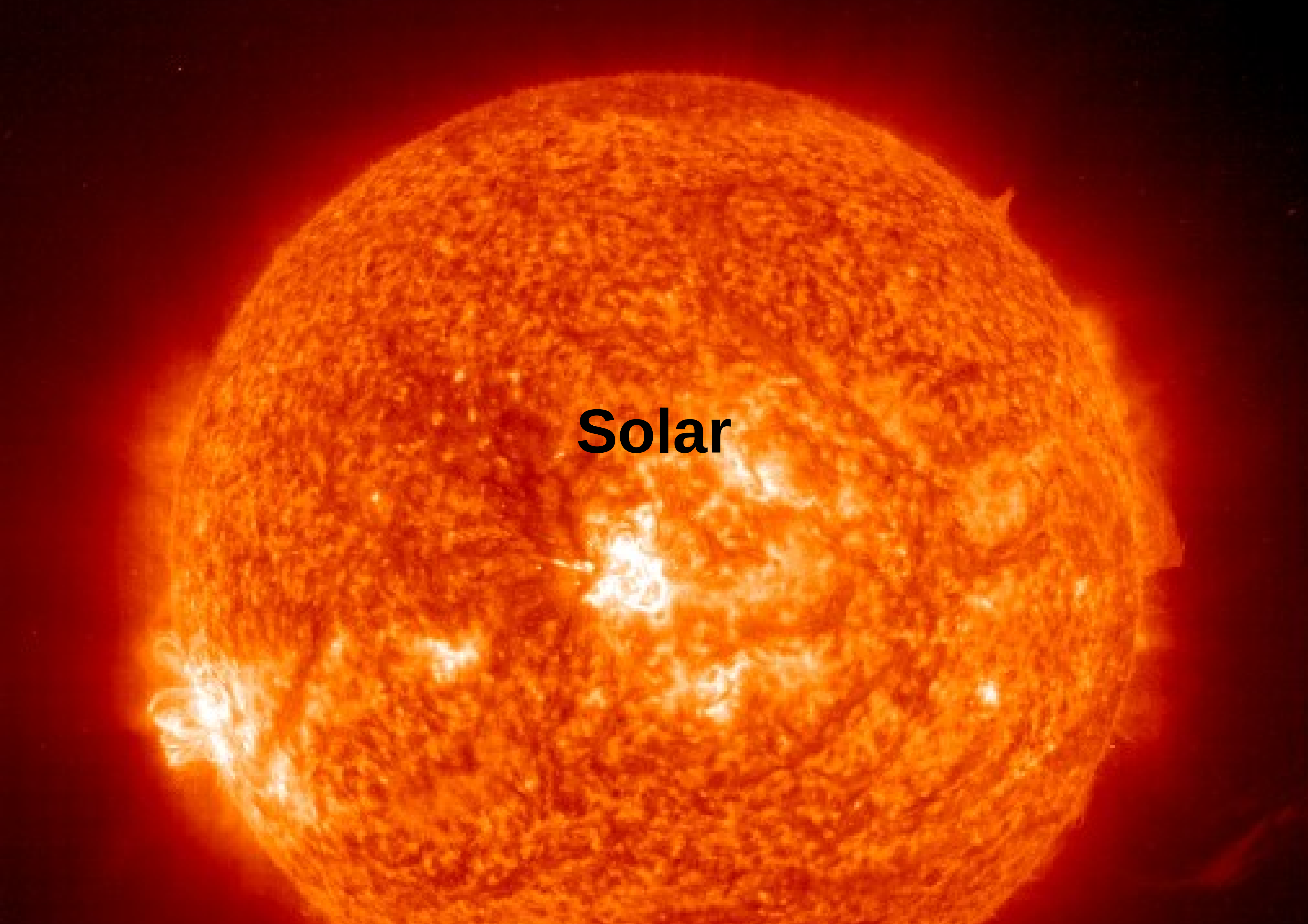
$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\Gamma - \cos 2\theta)^2}$$

Leads to a resonance condition

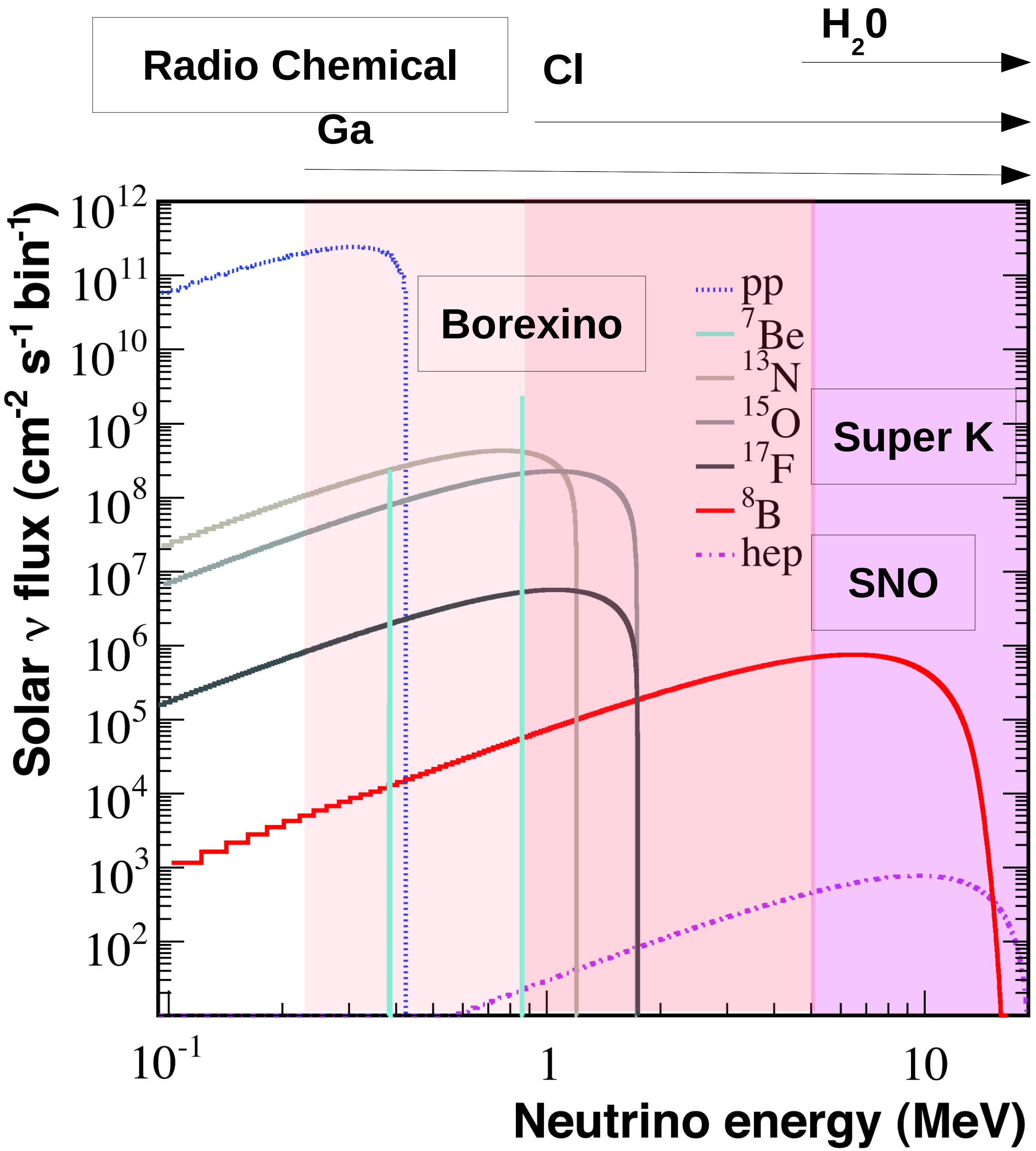
$$\Gamma = \pm 2\sqrt{2} G_f N_e E / \Delta m^2$$

At low densities and energies vacuum oscillations are recovered




Solar

# Standard Solar Model



# Radio-Chemical Experiments and the Solar ν Problem

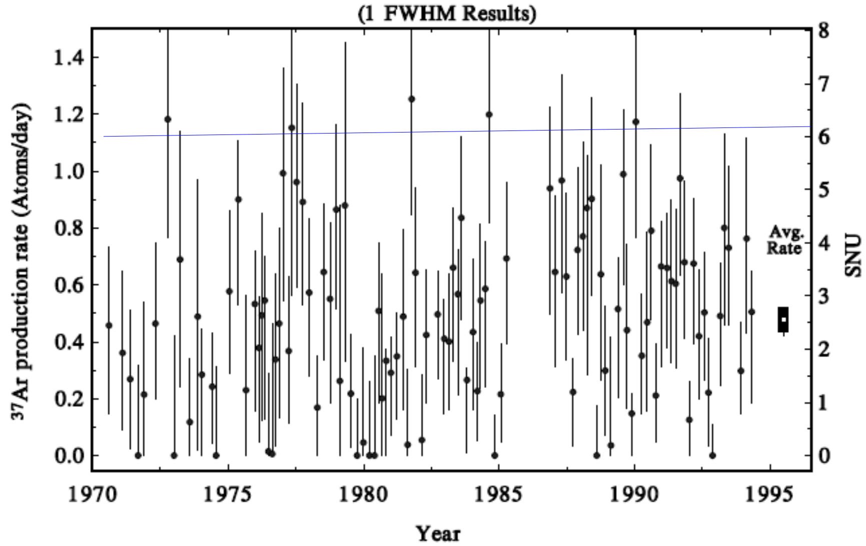
## Homestake experiment ( 1969- 1993)

ApJ. 496 (1998) 505

$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{38}Ar$

**Measure:**

**2..56 SNU ,**
**SNU = 1 ev /s/ $10^{36}$atoms**



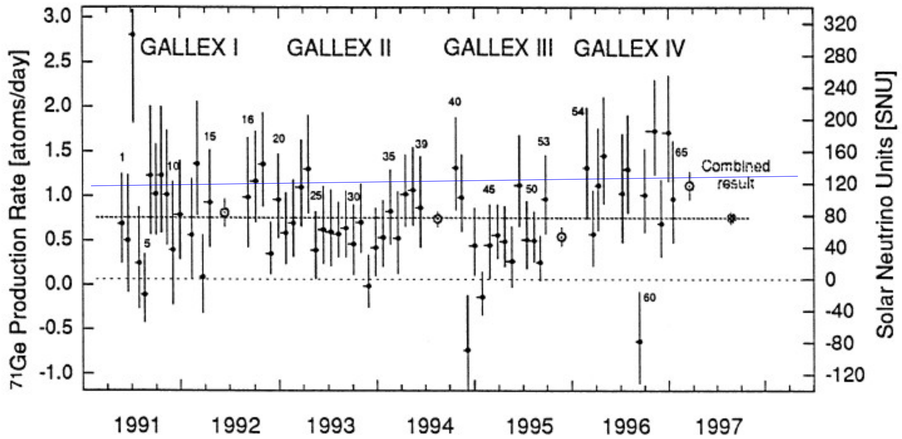

**Solar Model Predictions:**
**9.3, Bahcall, , 6.3 Turk-Chieze, 7.6 Sacman**

## Gallex / GNO

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

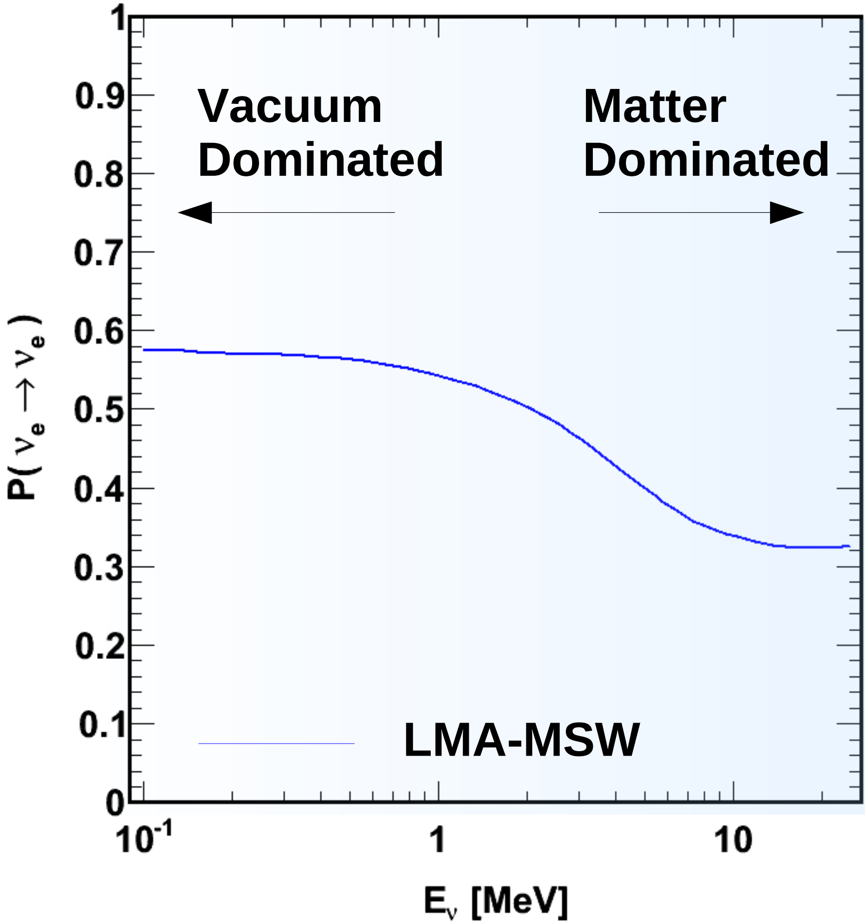
**Observed rate : 77.5 ± 6.2 SNU**
**vs. 130 from SSM**

**SAGE : 66 ± 7 SNU**




Phys. Lett. B 447(1999) 127

# Solar MSW : LMA




$A_R$ = Matter potential at resonance

$A_0$ = Matter potential at creation

**Three Domains for Solar $\nu$:**
**"adiabatic regime"**

**i) $A_0 \ll A_R$ : low E or low $\rho$**

Never cross resonance region,
Vacuum oscillations dominant

$P_{ee} = 1 - \frac{1}{2} \sin^2 2\theta$ > ½

**ii ) $A_0 < A_R$ : $\nu$ born near resonance**

Vacuum + Matter oscillation effects

$P_{ee} = 1/2\,[\,1 + \cos 2\theta_{m,0} \cos 2\theta\,]$

**iii ) $A_0 > A_R$ : $\nu$ born above resonance**

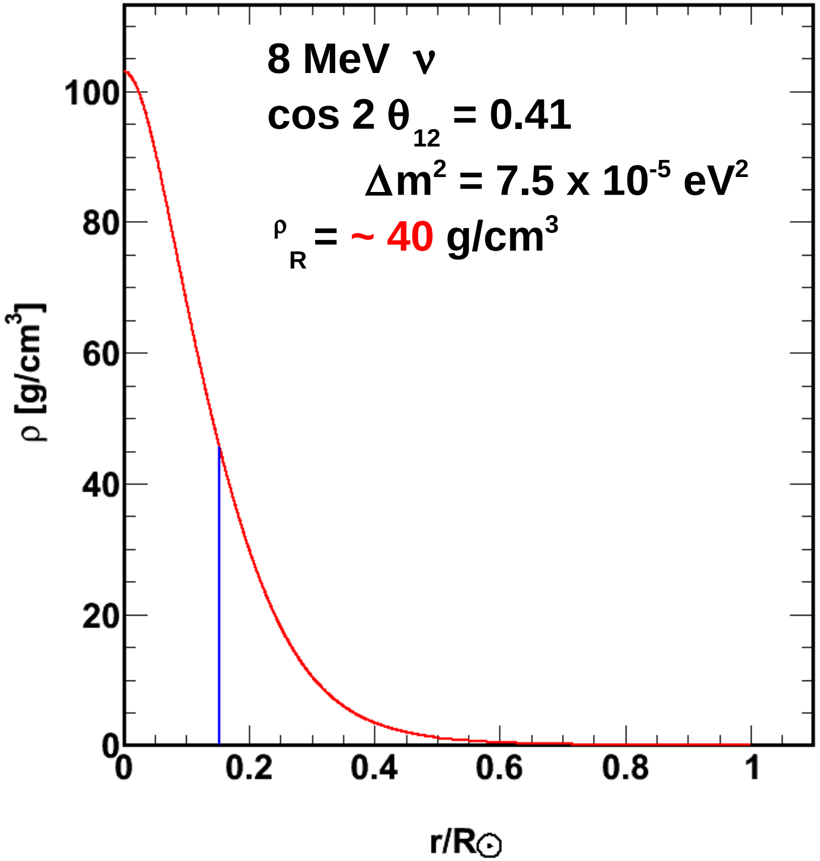
Cross resonance, $\cos^2\theta_{m,0} \sim -1$

Mixing at birth is suppressed

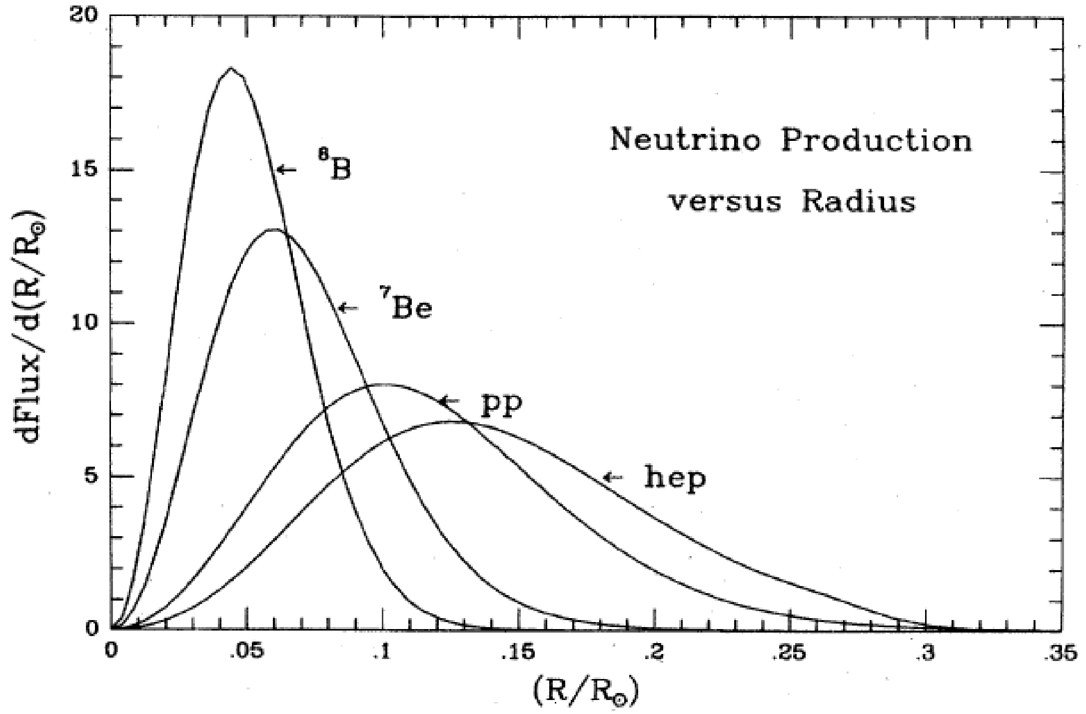
$P_{ee} = \sin^2 2\theta = |\langle \nu_e | \nu_2 \rangle|^2$

# Solar MSW : LMA (2 )

Solar matter profile



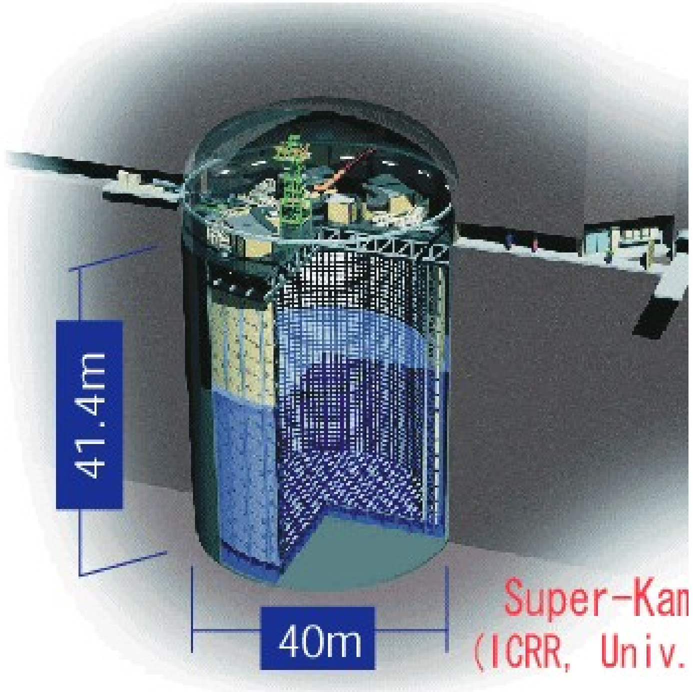

Bahcall Rev. Mod. Phys 60 (1988)



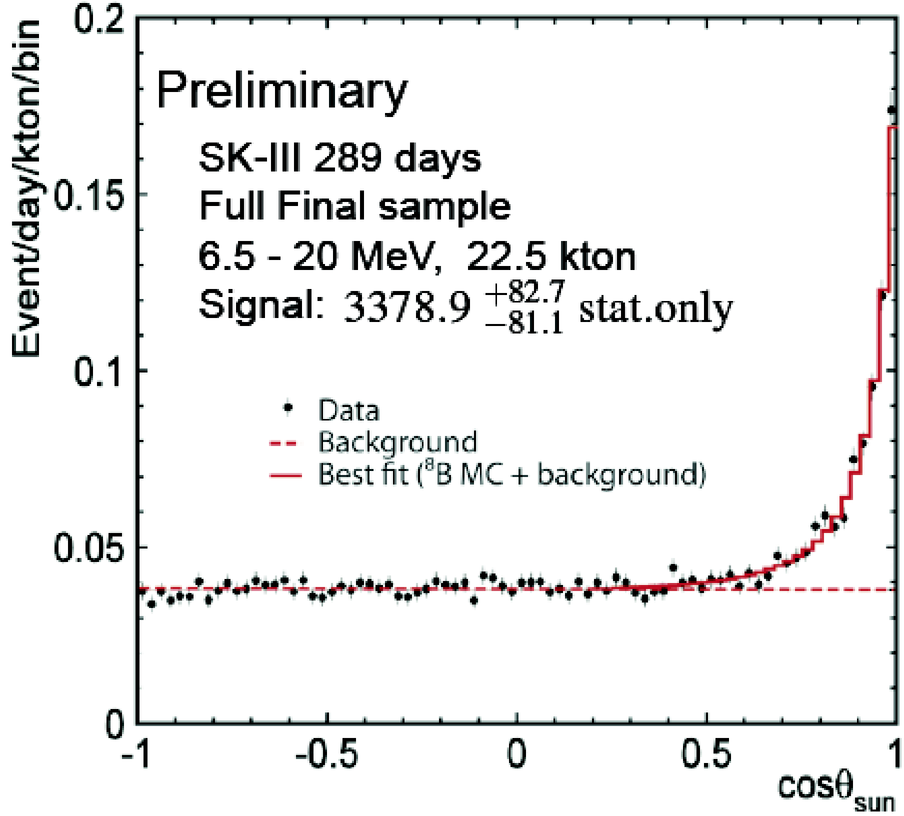

**As a function of density the location of the matter resonance is inversely proportional to the ν energy**

**⇒ Solar ν's probe all of the MSW-LMA regions**

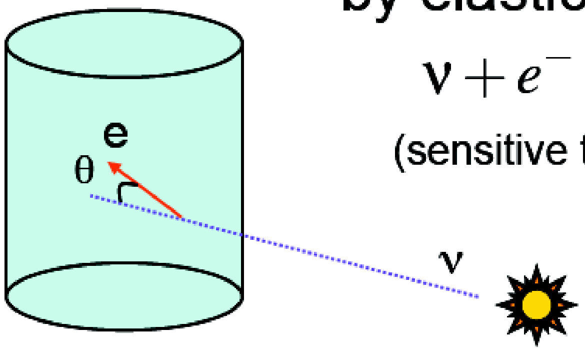
# Super-Kamiokande (Super-K): Solar ν's




SK-III solar : see B. Yang




$^8$B neutrino measurement by elastic scattering:




$$\nu + e^- \rightarrow \nu + e^-$$

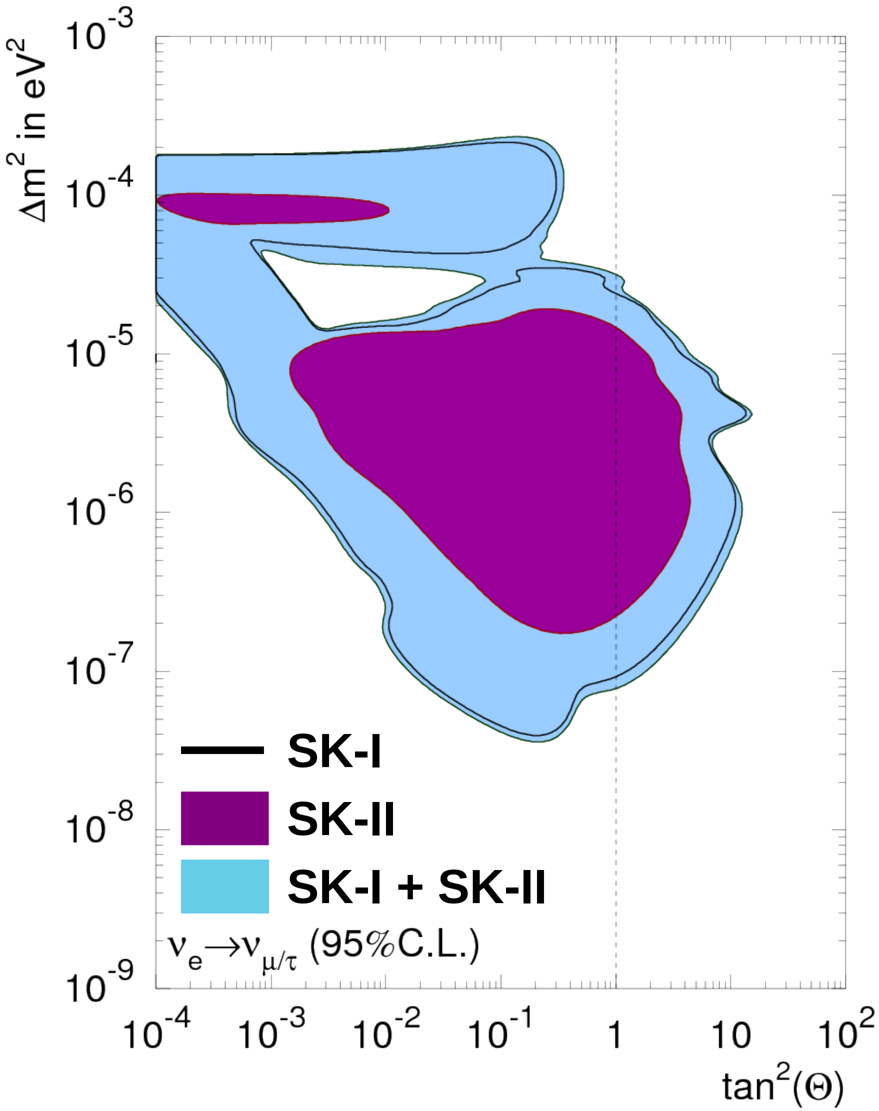
(sensitive to all ν flavors)

- **Reconstruct direction to the sun**
  - **Measure $^8$B flux**
  - **Day / Night and Seasonal variations**
- **2.38 ± 0.05 x $10^{-6}$ $cm^{-2}$ $s^{-1}$**
- **Data/ SSM = 0.465 ± 0.005**

# Super-Kamiokande ( SK Only )

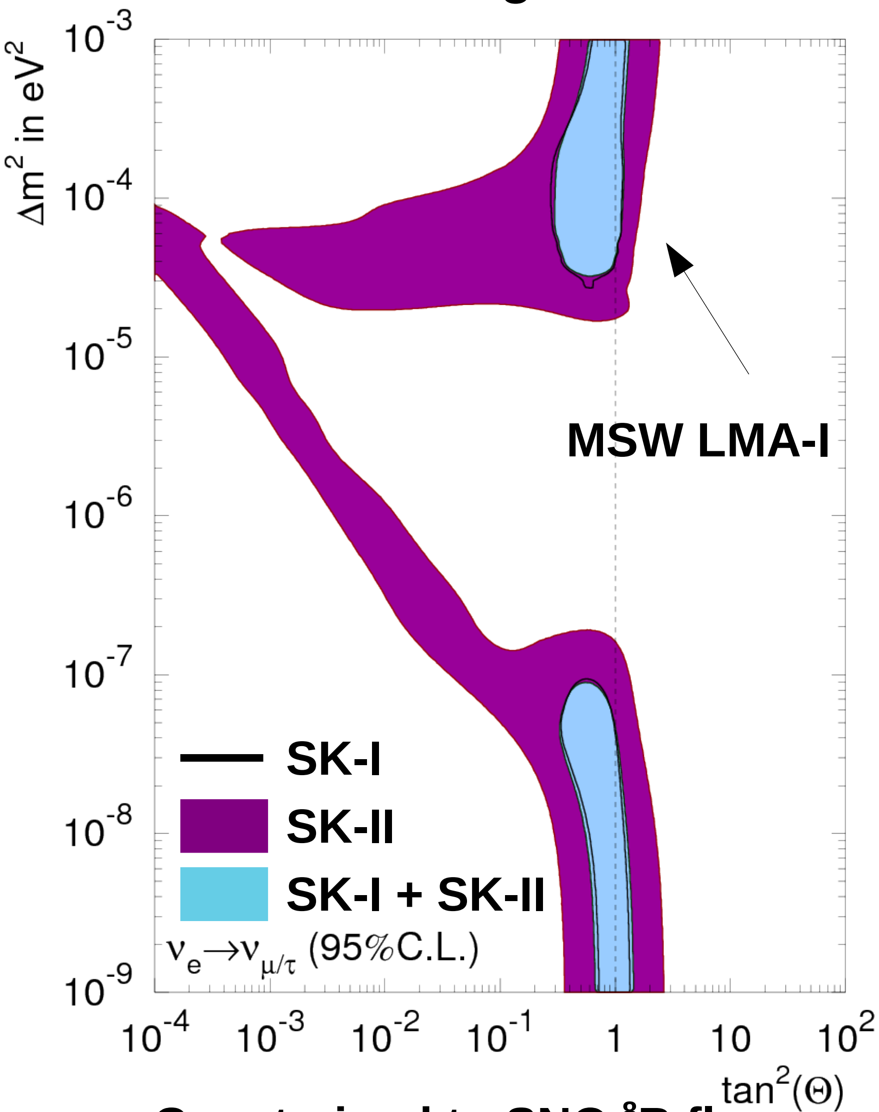
Phys.Rev.**D78**:032002 (2008)

## Exclusion Contours




**Best Fit:: tan² θ = 0.4   δm² = 6.0 x 10⁻⁵ eV²**

## Allowed Regions

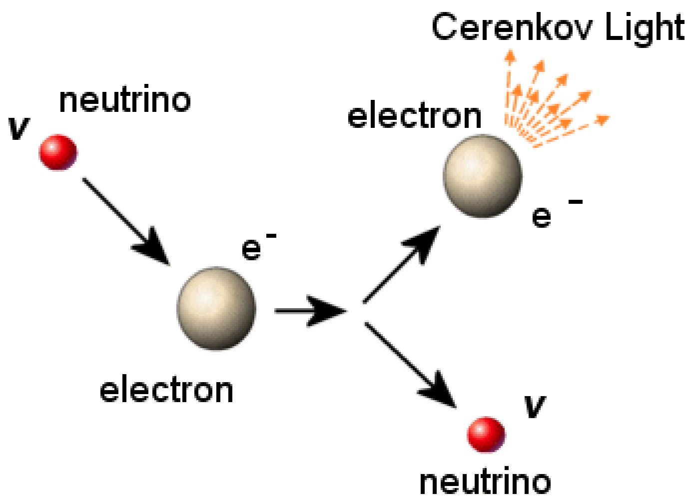



**Constrained to SNO $^{8}$B flux**

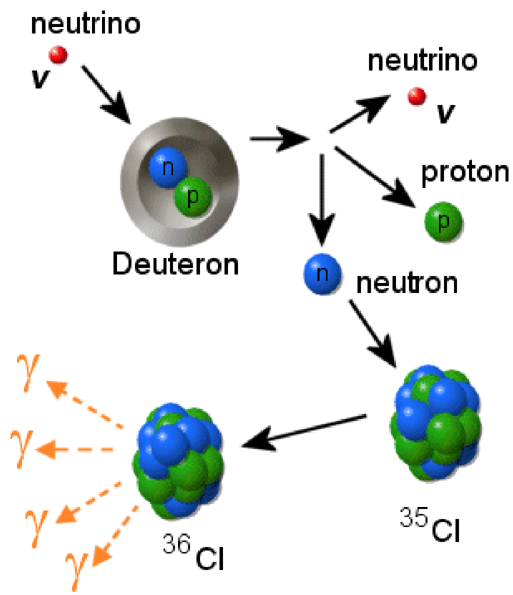
(S.N. Ahmed et al., PRL**92** (2004) 181301)

# Sudbury Neutrino Observatory - SNO

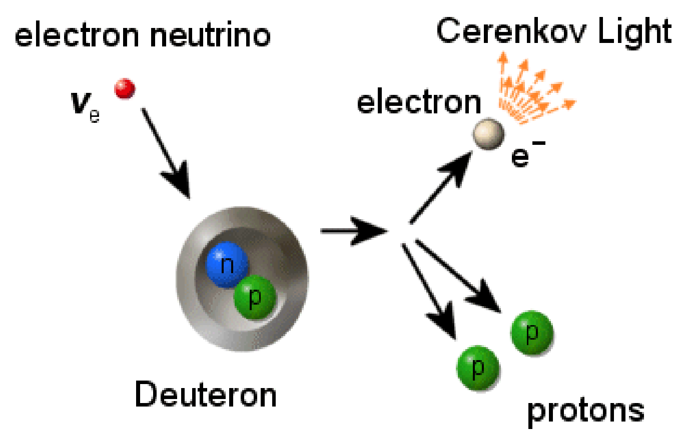
## Elastic Scattering (ES)




## Neutral Current (NC)

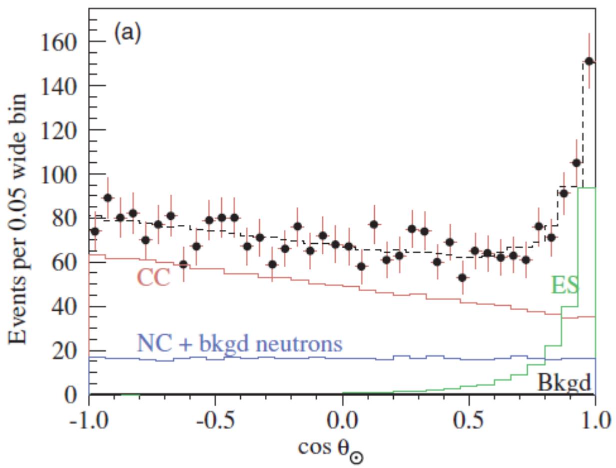



## Charged Current (CC)




( only $\nu_e$ at solar E)

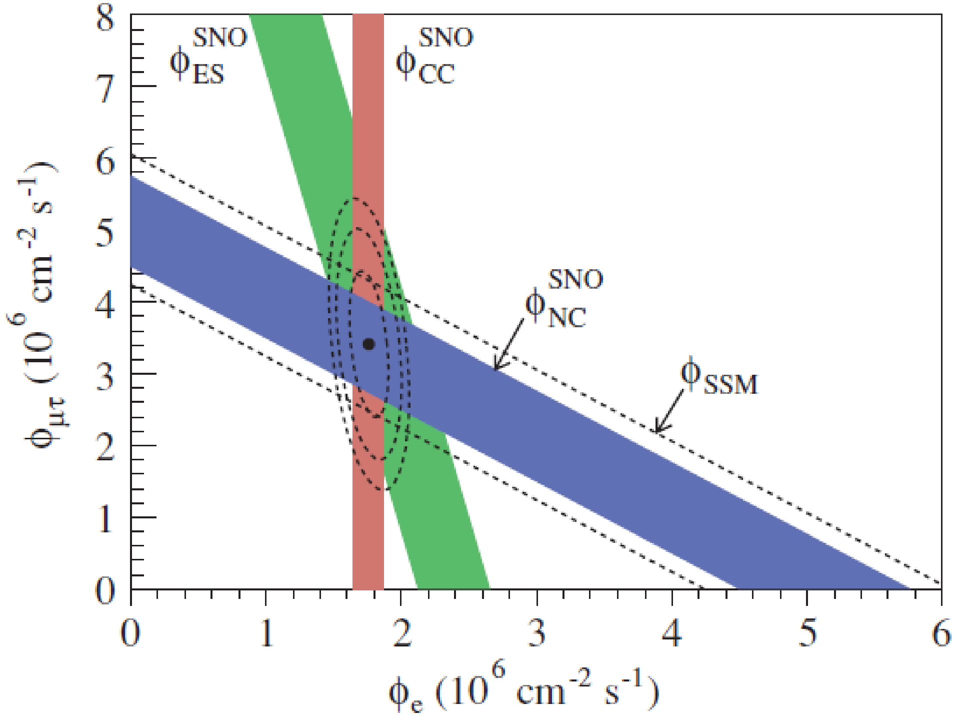
**Cherenkov imaging experiment using $D_2O$ (1 kton)**

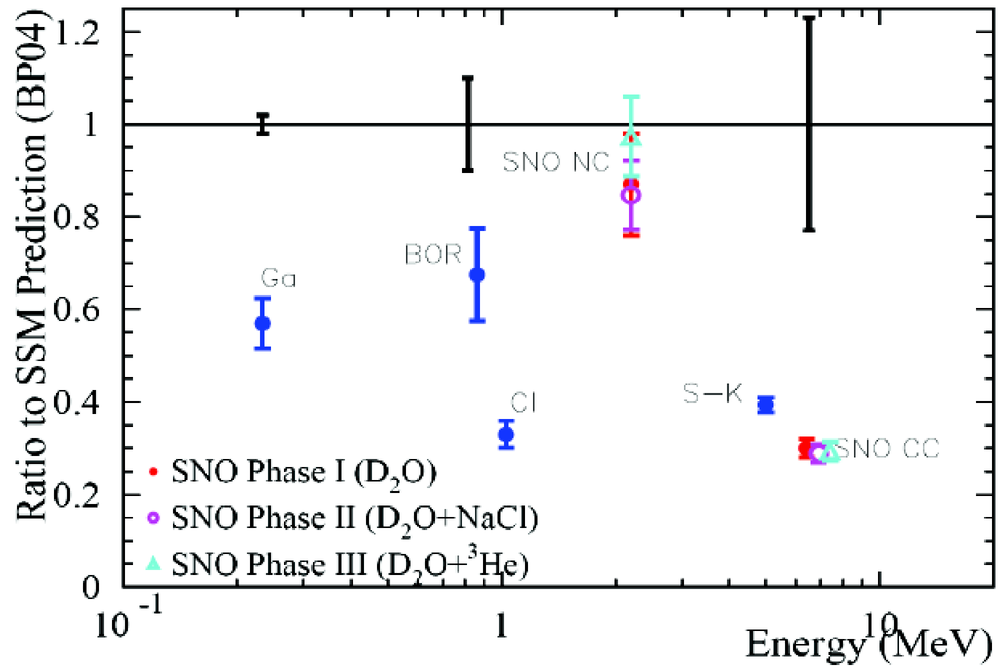



**Independent measurements of $\nu_e$ component and total active $\nu_x$ component of the solar $^8B$ flux**

# SNO $^{8}$B Fluxes

B. Ahramin et al., Phys. Rev. C **75** 04552 (2007)



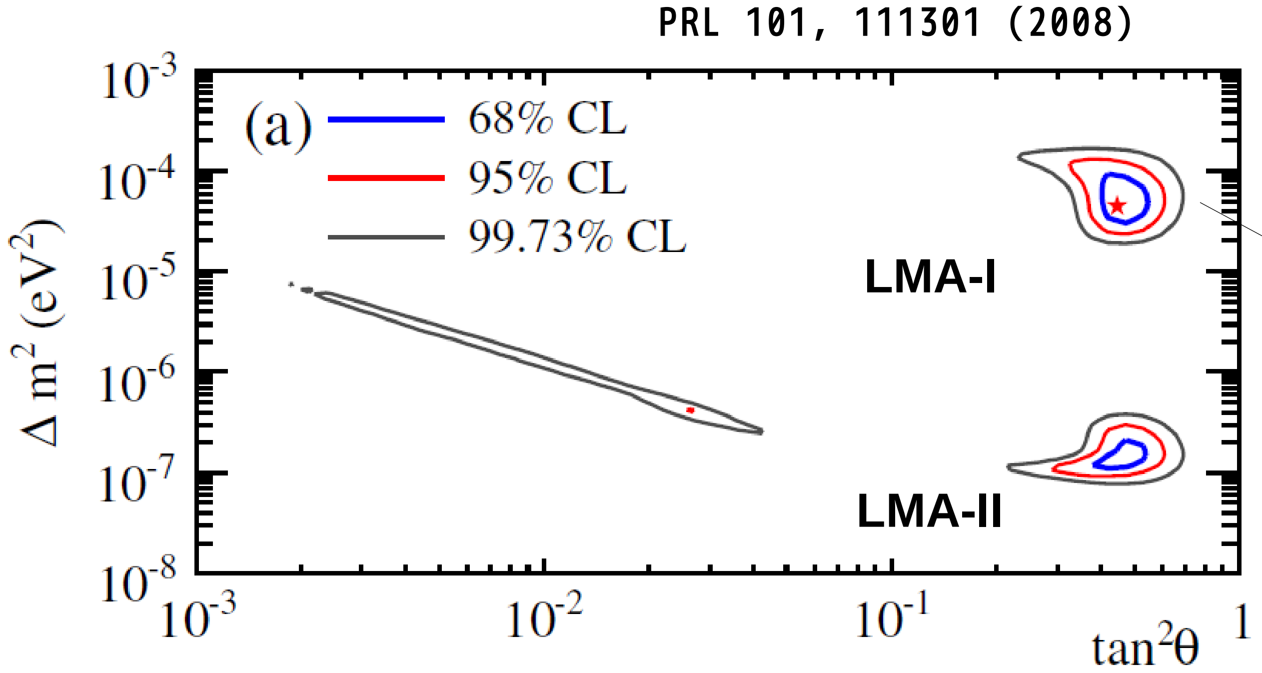

**ES flux is well below the standard solar model prediction**

**Consistent with observations from other solar experiments**

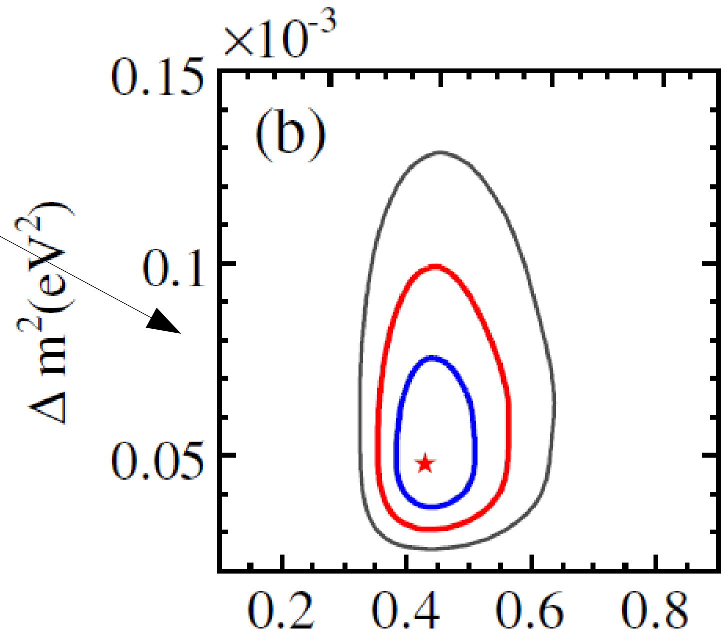
**NC flux agrees well with the SSM prediction**

**Strong evidence that non-$\nu_e$ neutrinos make up solar flux...**

# SNO : Oscillation Contours




SNO Only ($D_2$0, salt, NCD)

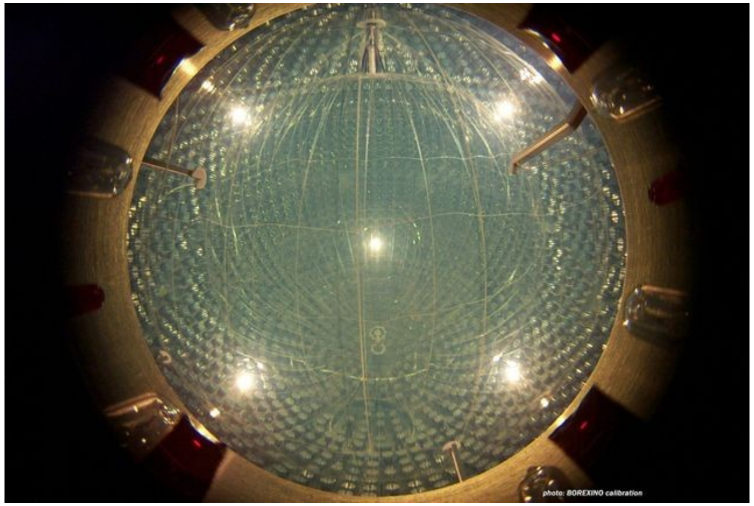



SNO + Solar Experiments

**Best Fit:**
**SNO Only:** $\tan^2\theta = 0.447$ $\delta m^2 = 4.57 \times 10^{-5}$ eV$^2$
**SNO + Solar:** $\tan^2\theta = 0.437$ $\delta m^2 = 4.90 \times 10^{-5}$ eV$^2$

**Global solar neutrino data favor the MSW-LMA solution to solar neutrino problem ... more precision with reactor experiments**

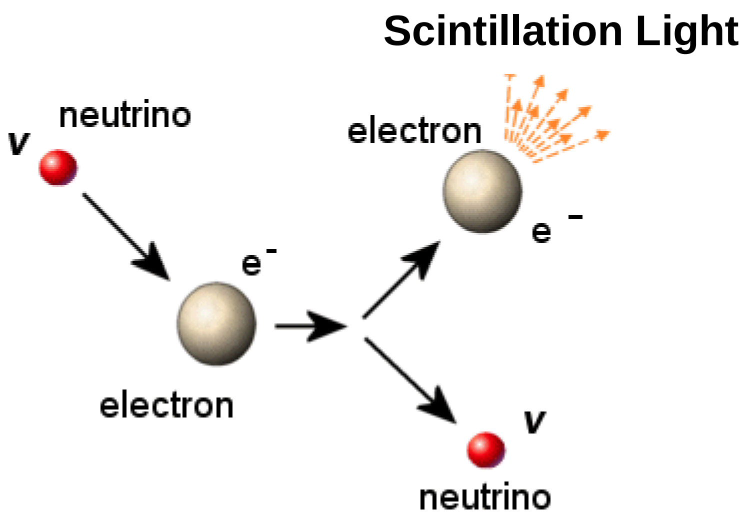
# Borexino : 7Be Flux Measurement



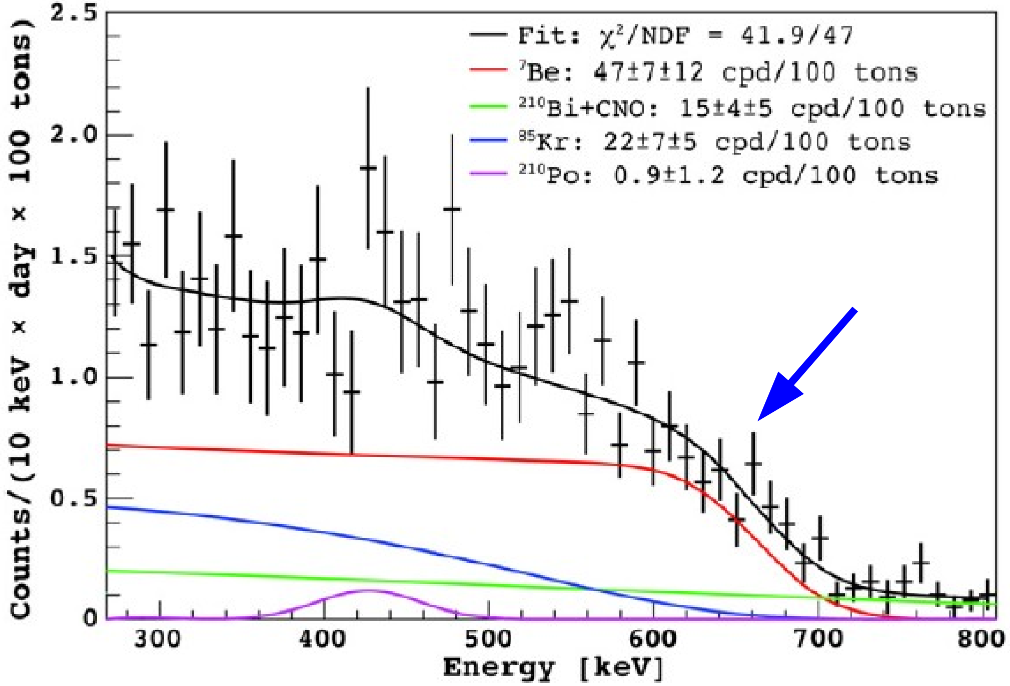

~ 300 ton liquid scintillator experiment
No directionality: Scattered $e^-$ indistiguishable from BG $e^-$
low background essential

Measure $^7$Be ν ( 865 KeV ) ~ 10% of flux
Also sensitive to $^8$B ν

Elastic Scattering (ES)

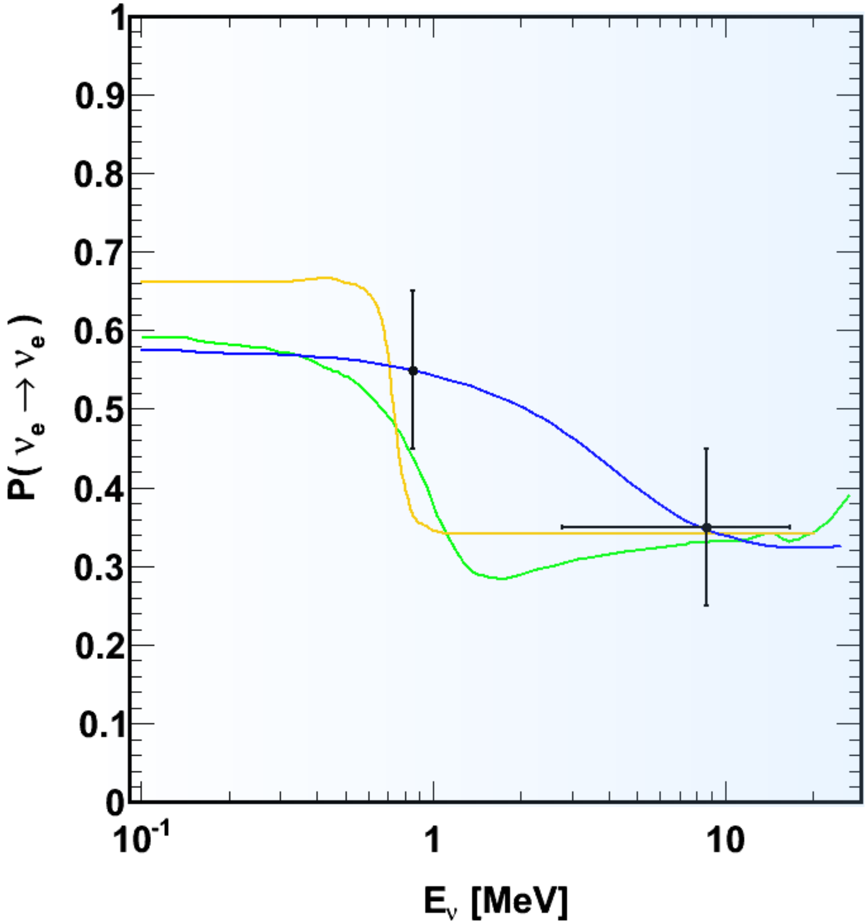



Physics Letters B 658 (2008) 101-108



# Borexino Results

arxiv: 0808.2868v11




Borexino

LMA-MSW

NSI Friedland PLB594

MaVan Barger et. al, PRL 95

$P_{ee}(^7Be) / P_{ee}(^8B) = 1.8\ \sigma$

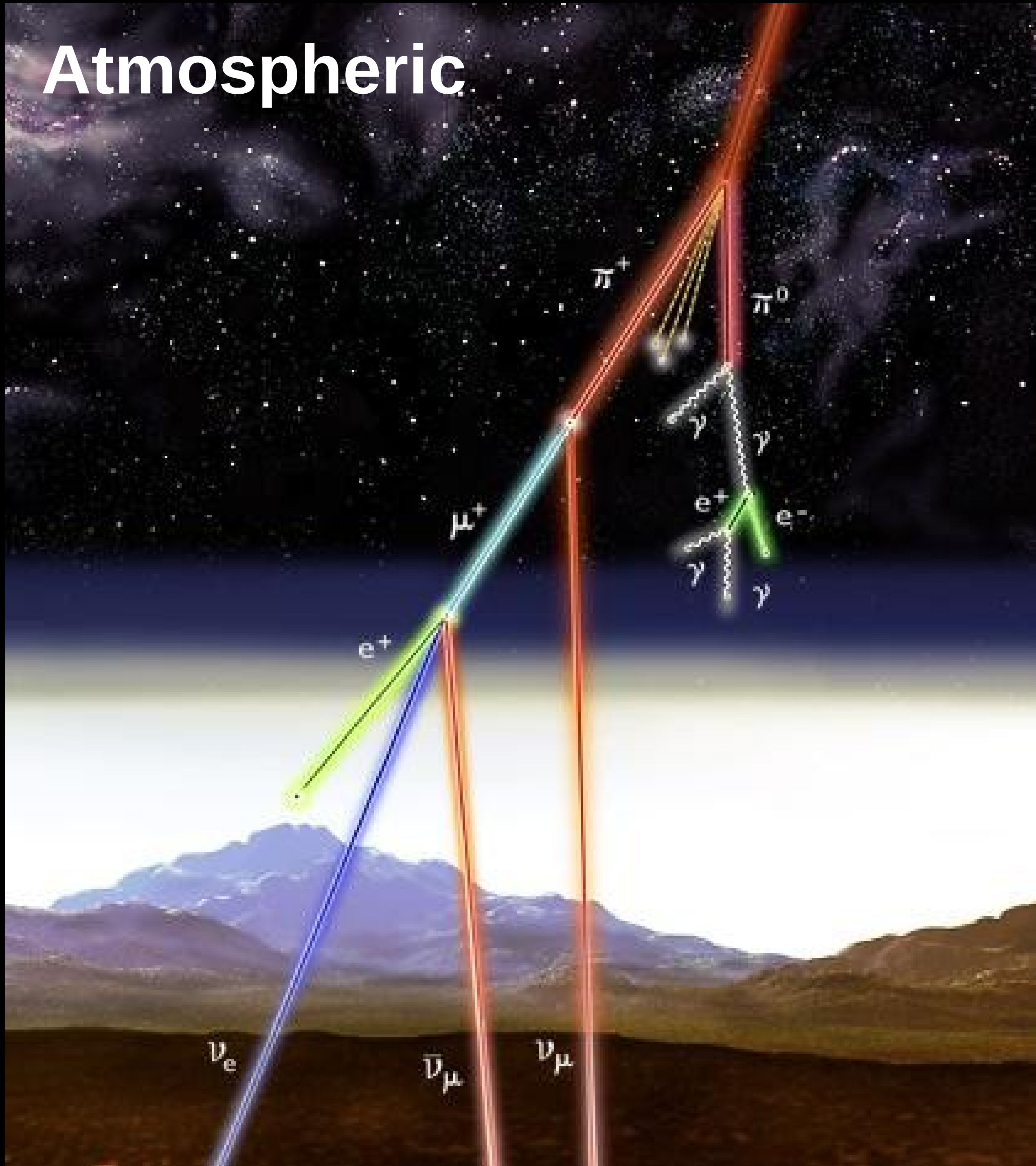
Physics Letters B 658 (2008) 101-108

$^7$Be $\Phi$ : 47 ± 7 ± 12 ev / d /100t vs: unosc 74 ± 4 ev/d/100t

$^8$B $\Phi$ ( > 2.8 MeV) : 2.65 ± 0.44 ± 0.18 x $10^{-6}$ cm$^{-2}$ s$^{-1}$

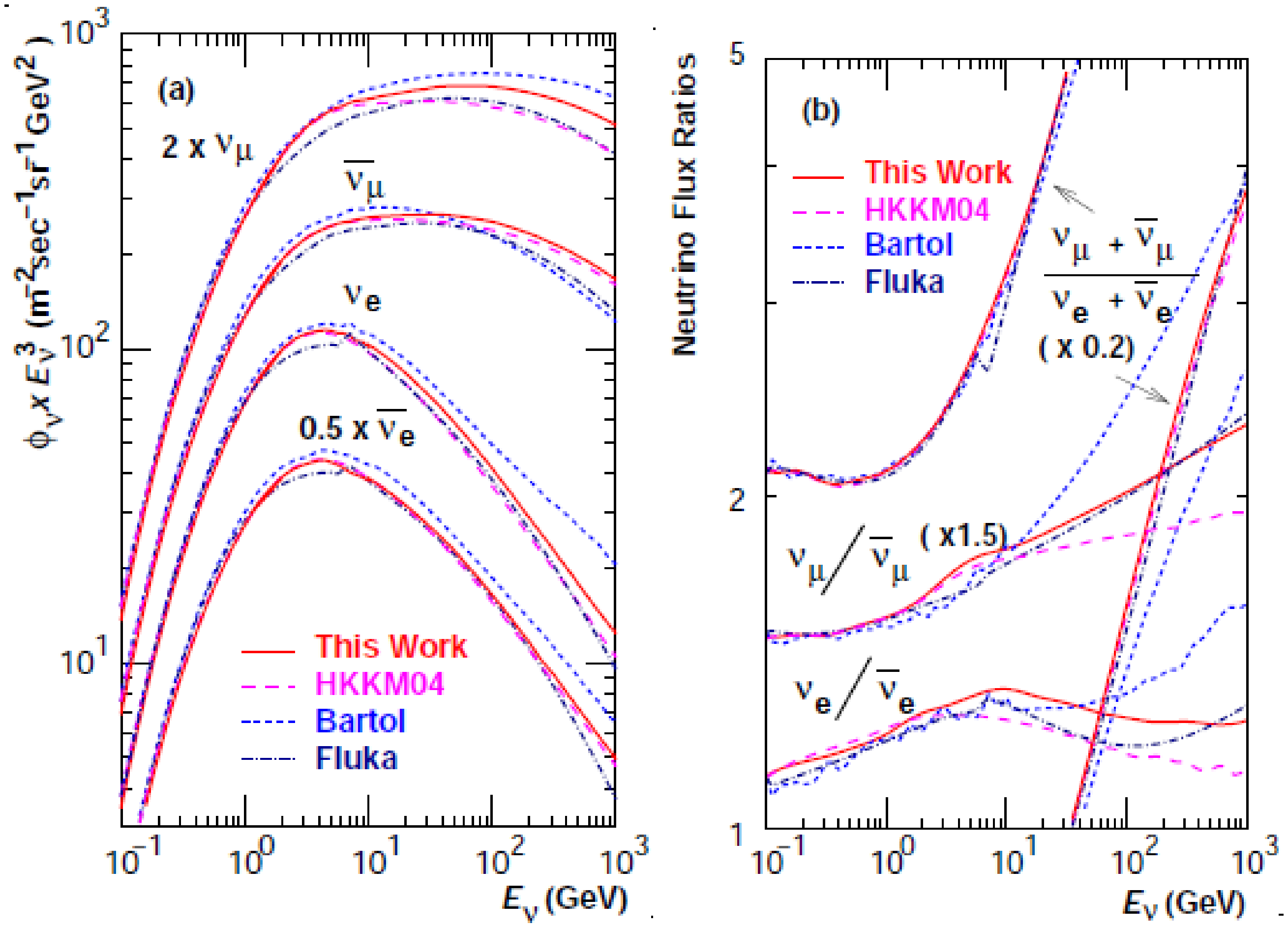
**Borexino data is consistent with the MSW-LMA parameter space**

# Atmospheric



# Atmospheric ν Fluxes

M. Honda, et. Al Phys.Rev.D75:043006,2007




Flux is isotropic about the Earth

- Large variation in ν pathlength ~ 10 - $10^4$ km

Spanning several energy decades

At energies E < 10 GeV flux ratio $\nu_\mu / \nu_e \sim 2$

Large Variation in L/E
Good for osc. studies

# Atmospheric ν Anomaly

**Taken from Fogli PhysRevD.52.2775**

$H_20$

| Experiment | Refs. | Total exposure (kt yr) | Simulated exposure (kt yr) | μ-like events Data | μ-like events BGS | e-like events Data | e-like events BGS |
|---|---|---|---|---|---|---|---|
| Kamiokande sub-GeV | [3] | 7.7 | 43 | 234 | 396.0 | 248 | 257.2 |
| Kamiokande multi-GeV (FC) | [3] | 8.2 | 51 | 31 | 40.4 | 98 | 70.8 |
| Kamiokande multi-GeV (FC+PC) | [3] | 8.2+6.0 | 51+40 | 135 | 165.8 | 98 | 70.8 |
| IMB | [4],[5] | 7.7 | 33 | 182 | 344.5 | 325 | 339.4 |
| Fréjus (FC) | [6],[7] | 1.56 | 10 | 66 | 90.0 | 56 | 66.8 |
| Fréjus (all) | [6],[7] | 1.56 | 10 | 108 | 125.8 | 57 | 70.6 |
| NUSEX | [8] | 0.74 | ~15 | 32 | 36.8 | 18 | 20.5 |

Fe

**Detectors with a water target saw evidence for $\nu_\mu$ disappearance**

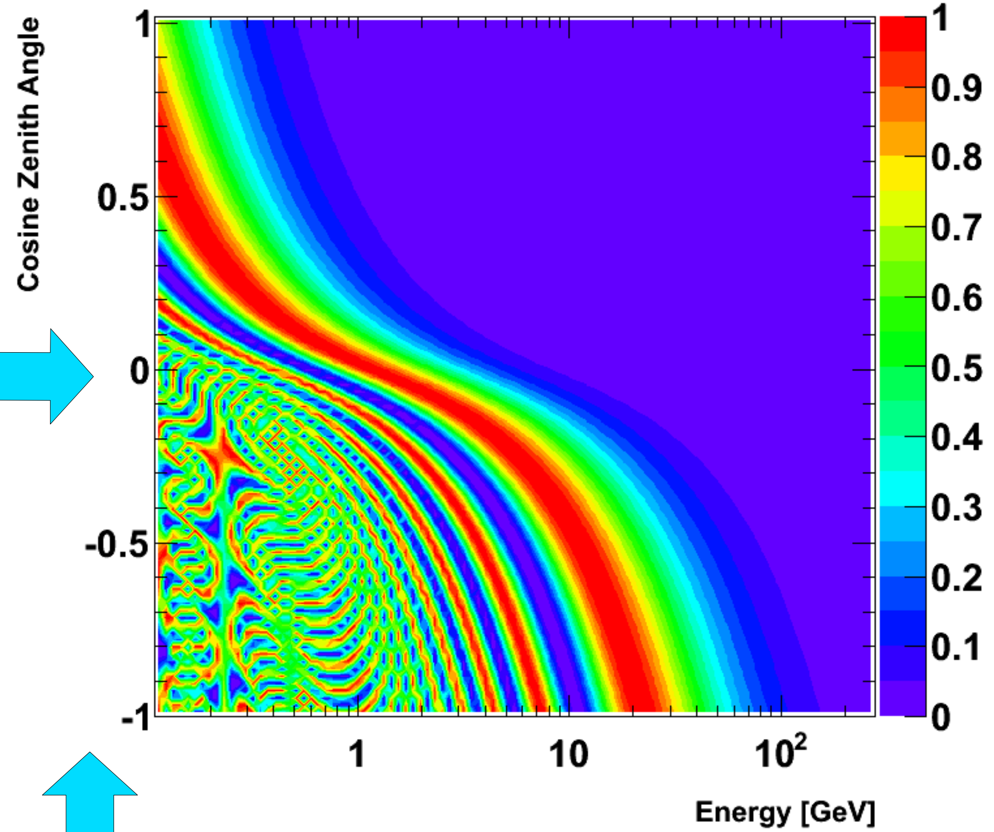
**Iron based detector signatures were more consistent with no oscillation**

**No strong deviation found in $\nu_e$ samples**

# Oscillation interpretation

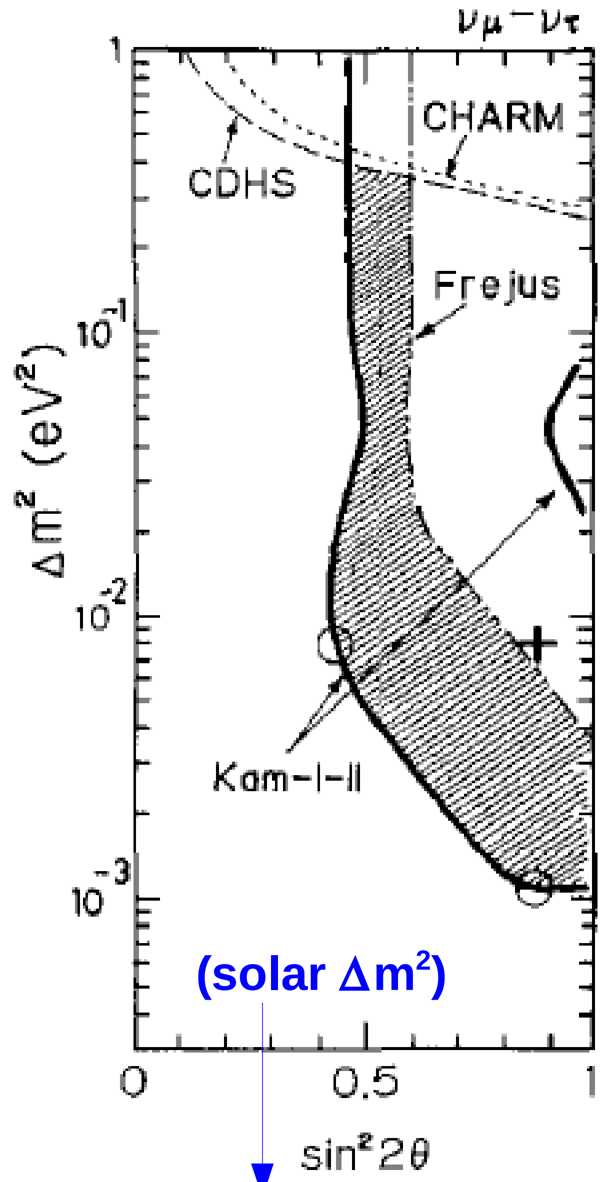
Two flavor oscillations: $\nu_\mu \rightarrow \nu_\tau$

$P(\nu_\mu \rightarrow \nu_\tau)$




Upward going events have opportunity to oscillate away

Phys. Lett. B 280 (1992) 146

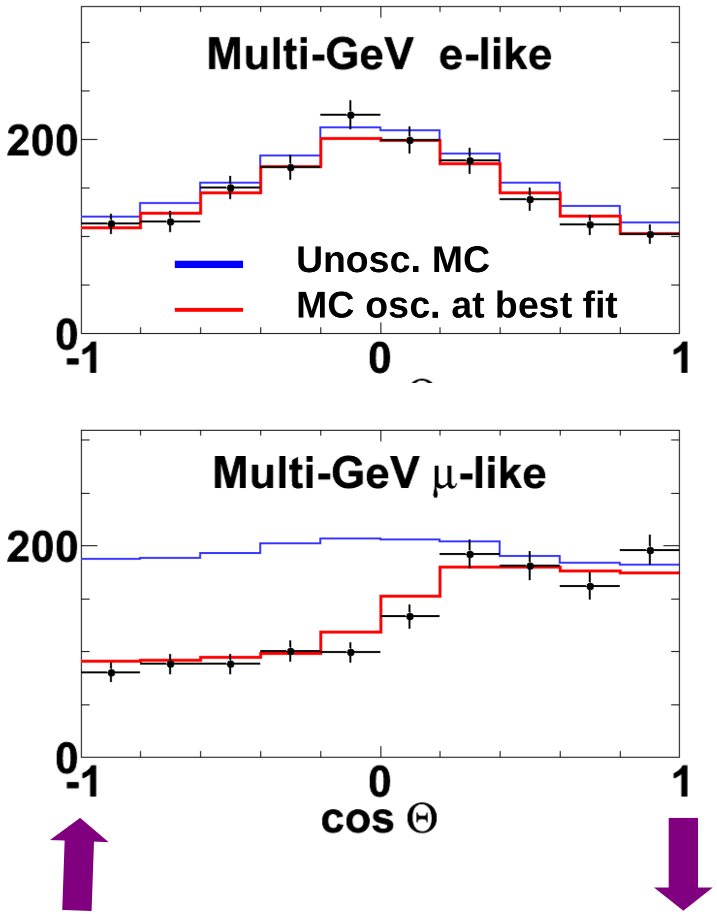


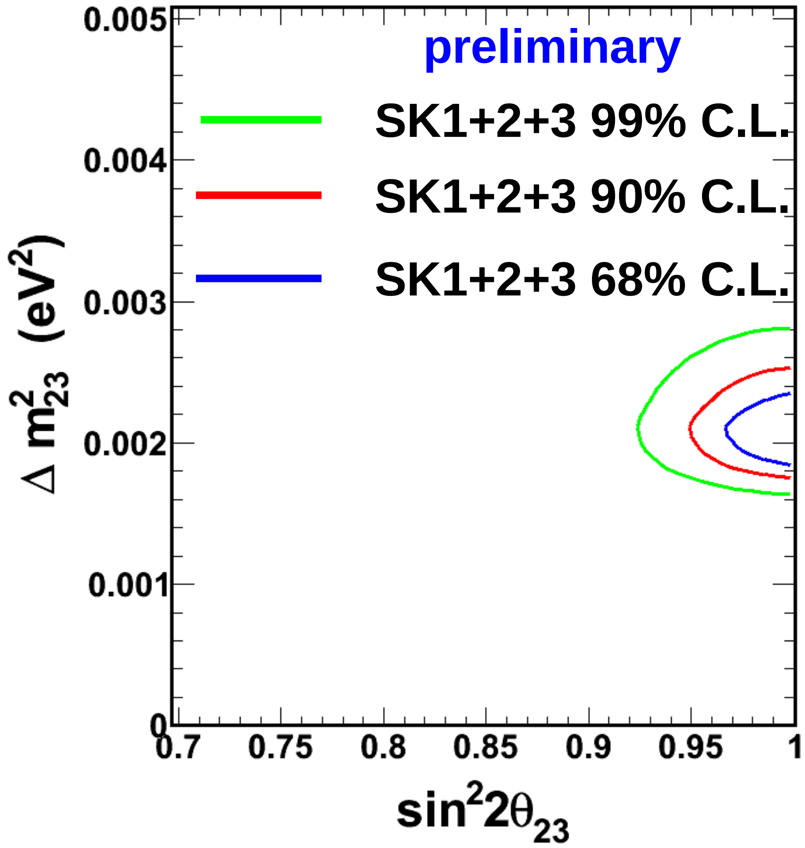

(solar $\Delta m^2$)

# Super-Kamiokande: Atmospheric ν

- High statistics
  - > 28,000 ν events

SK-I + II + III  2806 days



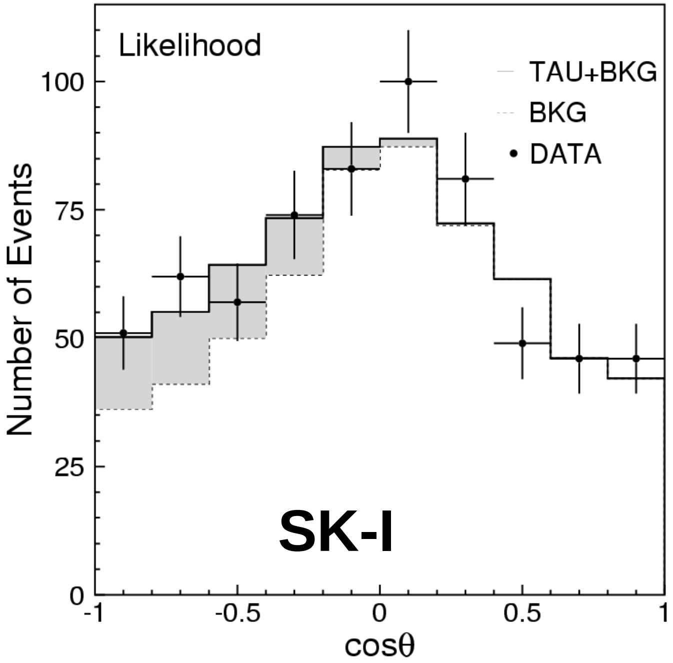

**Best Fit: (physical):**

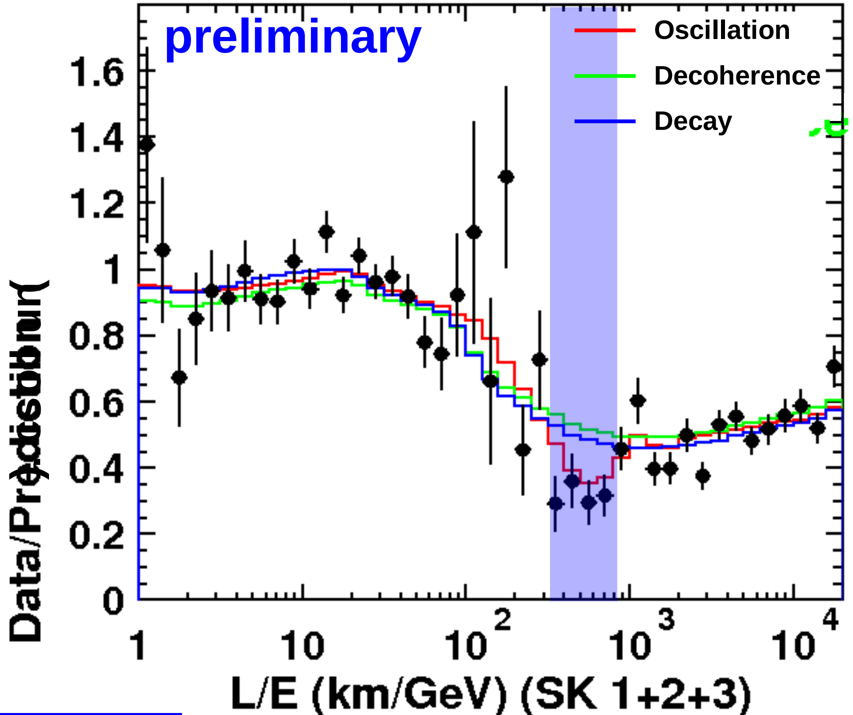
$\Delta m^2 = 2.1 \times 10^{-3}\ eV^2$

$\sin^2 2\theta = 1.0$

$\chi^2 = 468 / 418$d.o.f

# Where are the Super-K $\nu_\mu$ going?




| Model | Limit / Exclusion |
|---|---|
| $\nu_\mu \rightarrow \nu_s$ | 7.2 σ (SK-I + SK-II) |
| Sterile admixture (2+2) | 23% allowed |
| Decay ( $\sin^4\theta + \cos^4\theta\, e^{-\alpha L/E}$) | 17 σ |
| Decay ( $\sin^2\theta + \cos^2\theta\, e^{-\alpha L/E})^2$ | 3.9 σ |
| Decoherence | 4.4 σ |
| LIV Limit | $1.2\times10^{-24}$ |
| CPTV Limit (GeV) | $0.9\times10^{-23}$ |
| MaVaNs | 3.5 – 3.8 σ (SK-I) |

No pure sterile

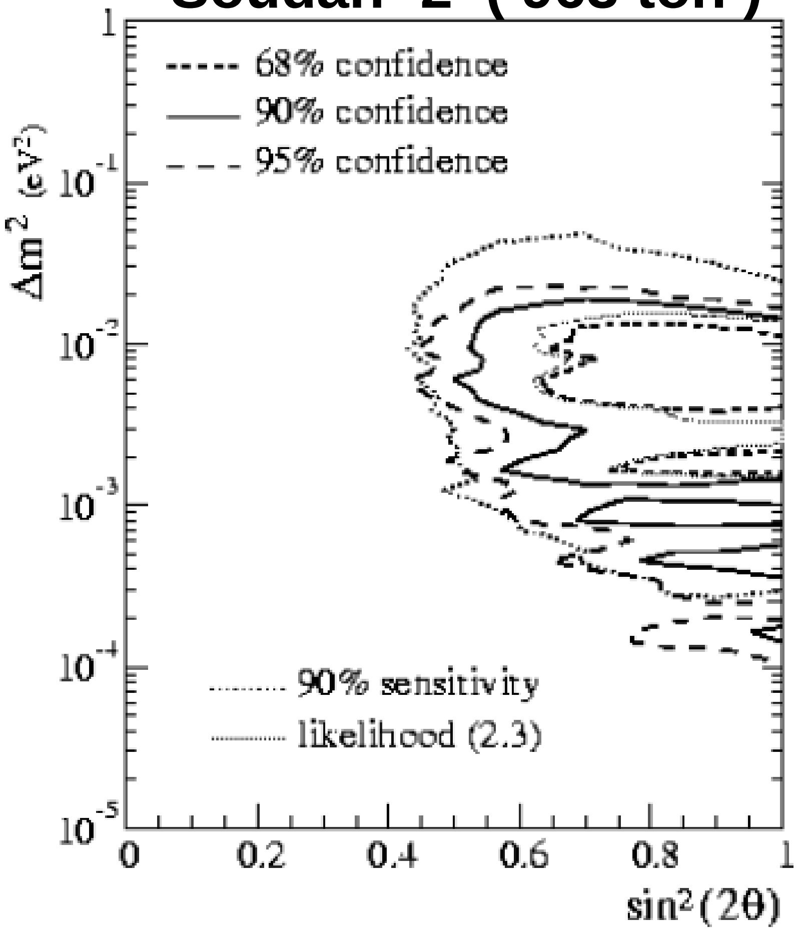
What about $\theta_{13}$ ?

What about $\theta_{23}$ 's octant?

**SK-I+II+III in detail: see: J.L. Raaf talk**

# Soudan and MACRO Atmospheric ν

## Soudan -2 ( 963 ton )



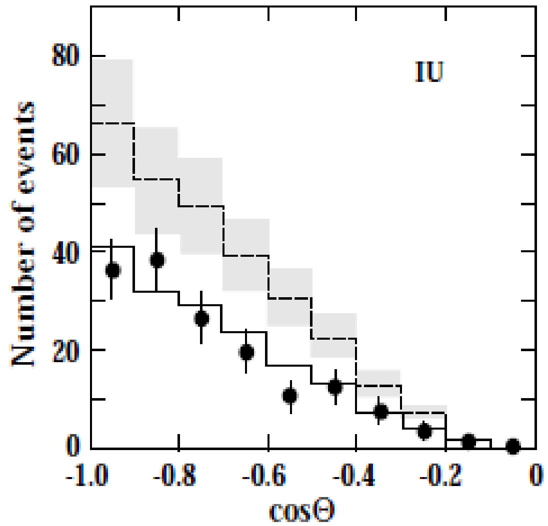

M. Sanchez Ph1ys. Rev. D68 (2003) 113004

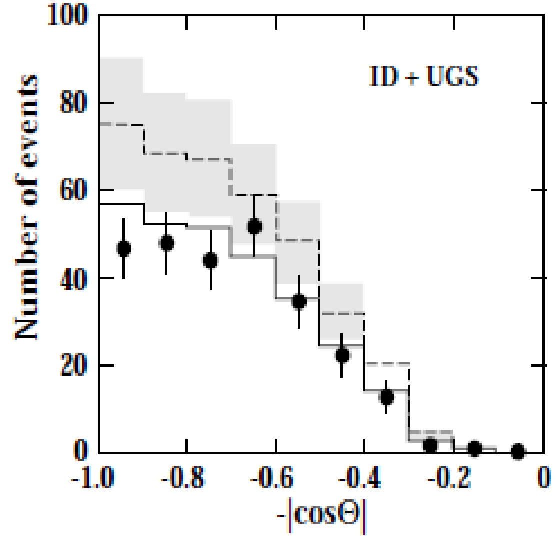
**Best Fit::**

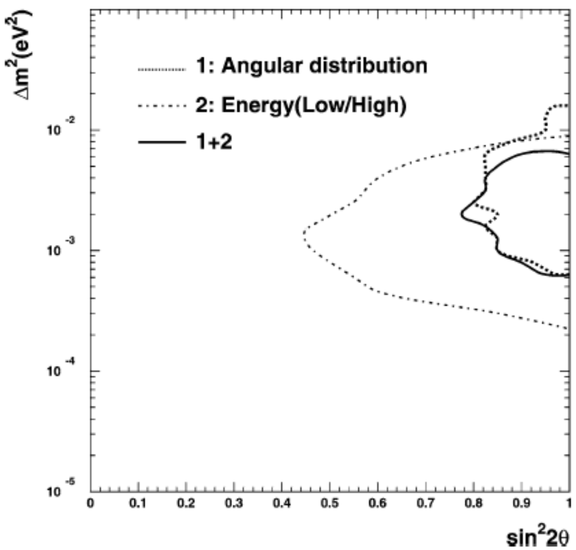
$\Delta m^2 = 5.2 \times 10^{-3}$ eV$^2$

$\sin^2 2\theta = 0.97$

## MACRO




**Best Fit: :**

$\Delta m^2 = 2.3 \times 10^{-3}$ eV$^2$

$\sin^2 2\theta = 1.0$

**Confirmation of a consistent oscillation picture**

**⇒more precision with beam experiments**

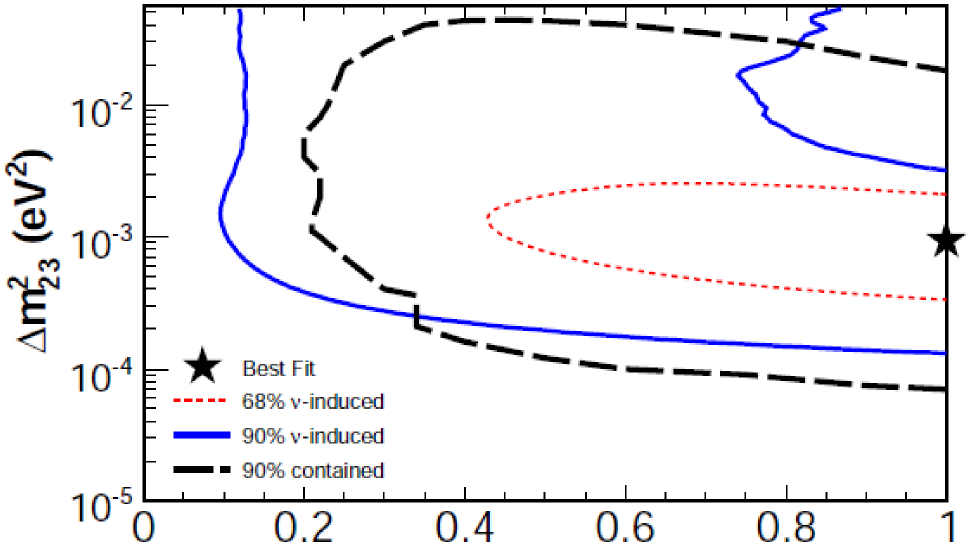
# MINOS – Atmospheric ν's

Search for ν-induced muon events in the MINOS far detector

Magnetized: event by event separation of $\mu^-$ and $\mu^+$

Total : 140 events in 854 d

Phys.Rev.D75:092003,2007





Double Ratio:

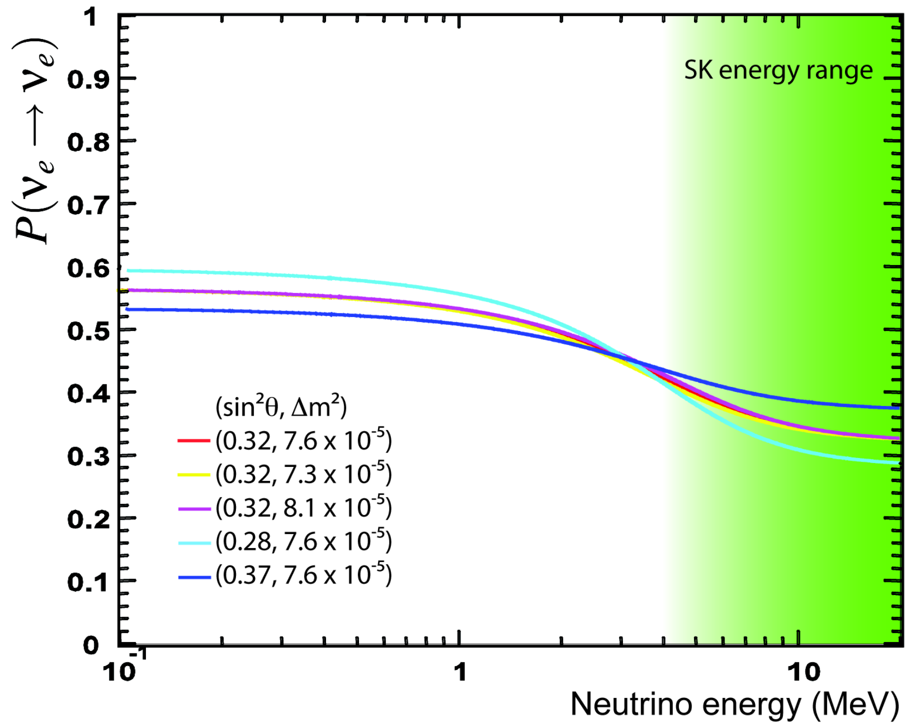
$R$ = 0.65 ± 0.09 (sys)

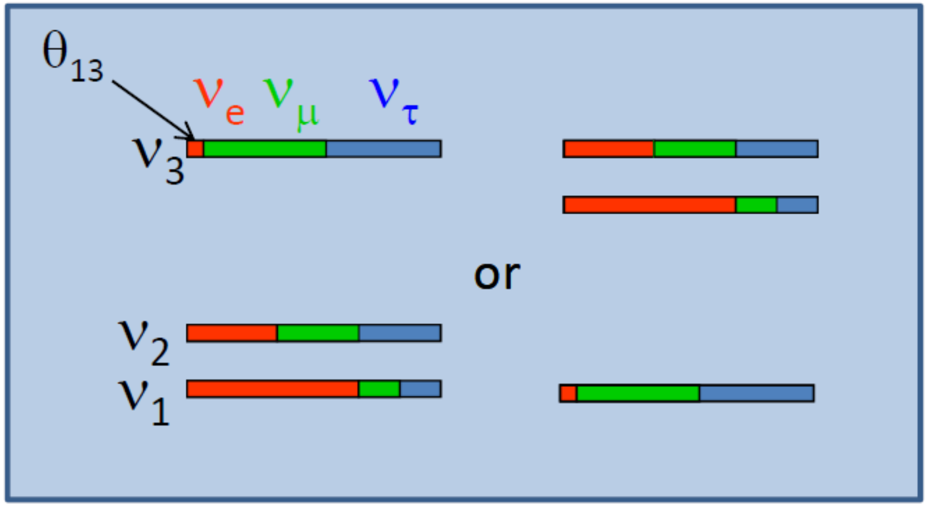
CPT Double Ratio:

$R_{cpt} = (\mu^-/\mu^+)\,\text{data} / (\mu^-/\mu^+)\,\text{MC} = 0.72^{+0.24}_{-0.18}\,(\text{stat.})\,^{+0.08}_{-0.04}$

**Consistent with no CPT Violation**

# The Future




**Solar upturn?**
**Earth regeneration effects?**
**Day/Night ?**

**$\theta_{13}$ > ?**
**Mass Hierarchy ?**
**$\theta_{23}$ Octant**

# Future : Observe all effects !

**SNO**

Low Energy Threshold analysis (3.5 MeV )
Improved oscillation parameters?
Solar upturn?

**Super-Kamiokande**

Low energy solar upturn?
Earth regeneration effects and Day / Night asymmetry ?
Continued atmospheric running...

**SNO+**

Observe pep and CNO neutrinos : Probe intermediate MSW region ?

**LENS , CLEAN (others )**

Observe pp neutrinos : see M. Pitt's LENS talk in Neutrinos IV

**INO**

Sensitivity to mass hierarchy ?
$\theta_{13} > 0$ ?

... and more ...

# Summary

- Observations of natural ν sources have consistently yielded fewer events than would be expected in models where ν mass is zero
  - across various ν energies and detector targets

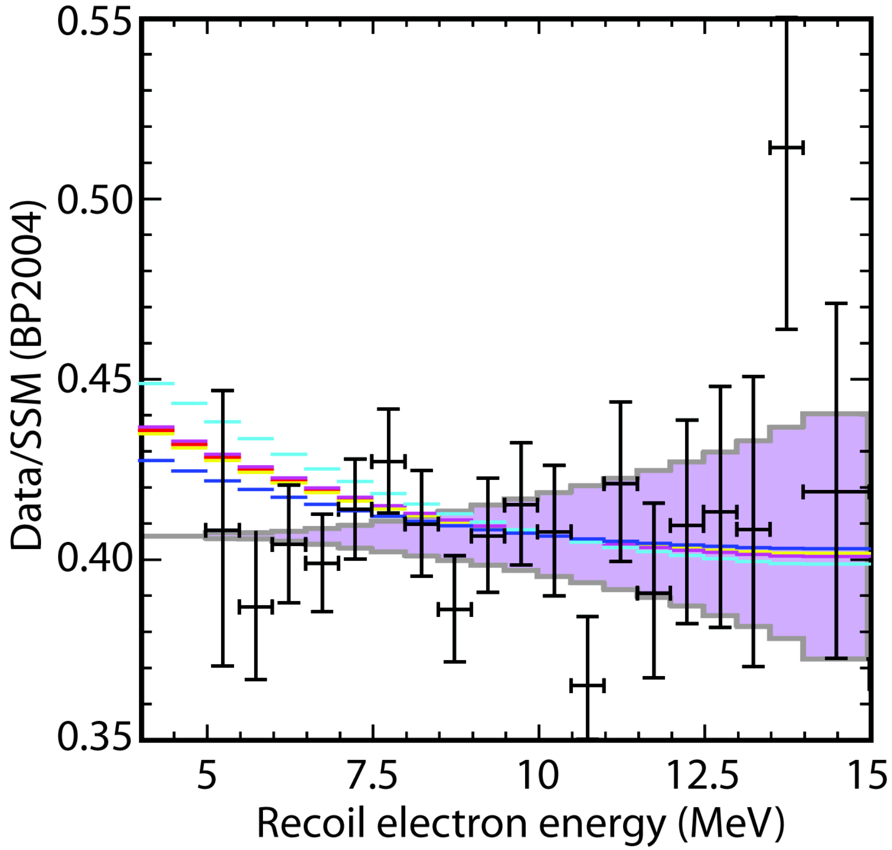
- Resolving these discrepancies lead to the discovery of ν mass and ν oscillations in two different regimes "solar" and "atmosheric"
  - $\Delta m^2_{atm} / \Delta m^2_{solar} = \sim 30 - 40$
  - Large angle mixing

- The observations of solar and atmospheric neutrinos have confirmed ν oscillation scenarios and are increasingly constraining the values of these oscillation parameters
  - Additional information from reactor and accelerator experiments further improves these measurements ( see M.Bishai, other talks here)
  - Still plenty of questions remain to explored

Thank you

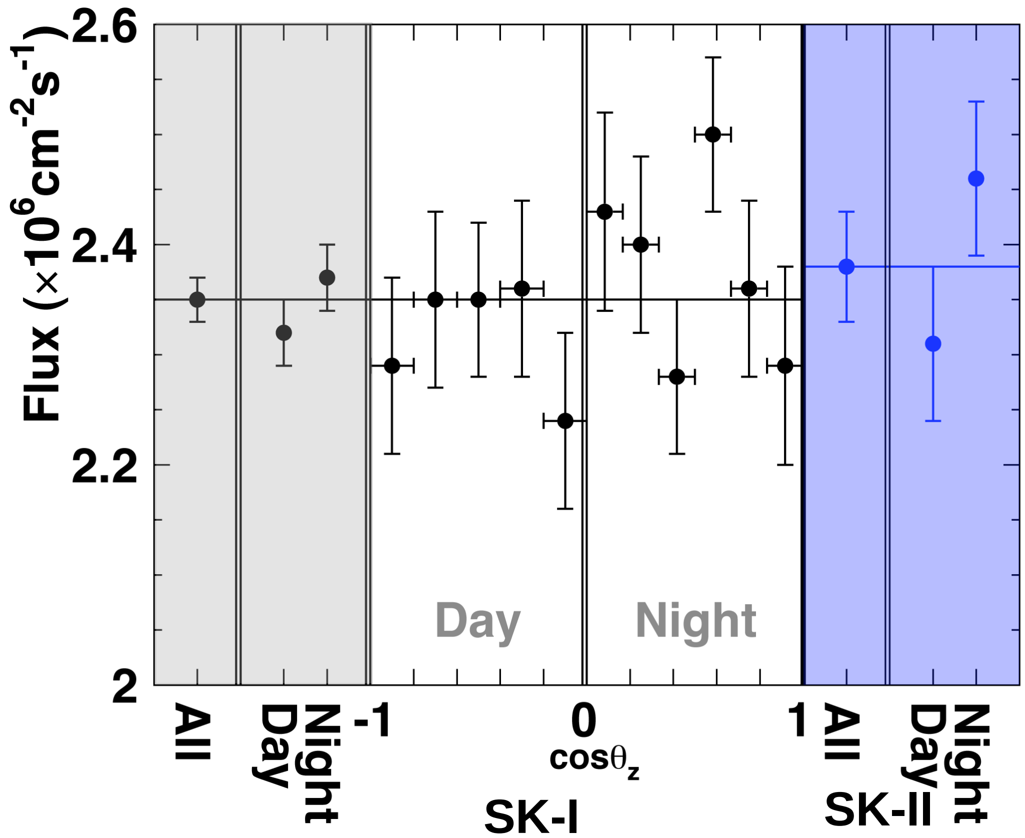
# Supplements

# The Future of Super-K Solar ν studies

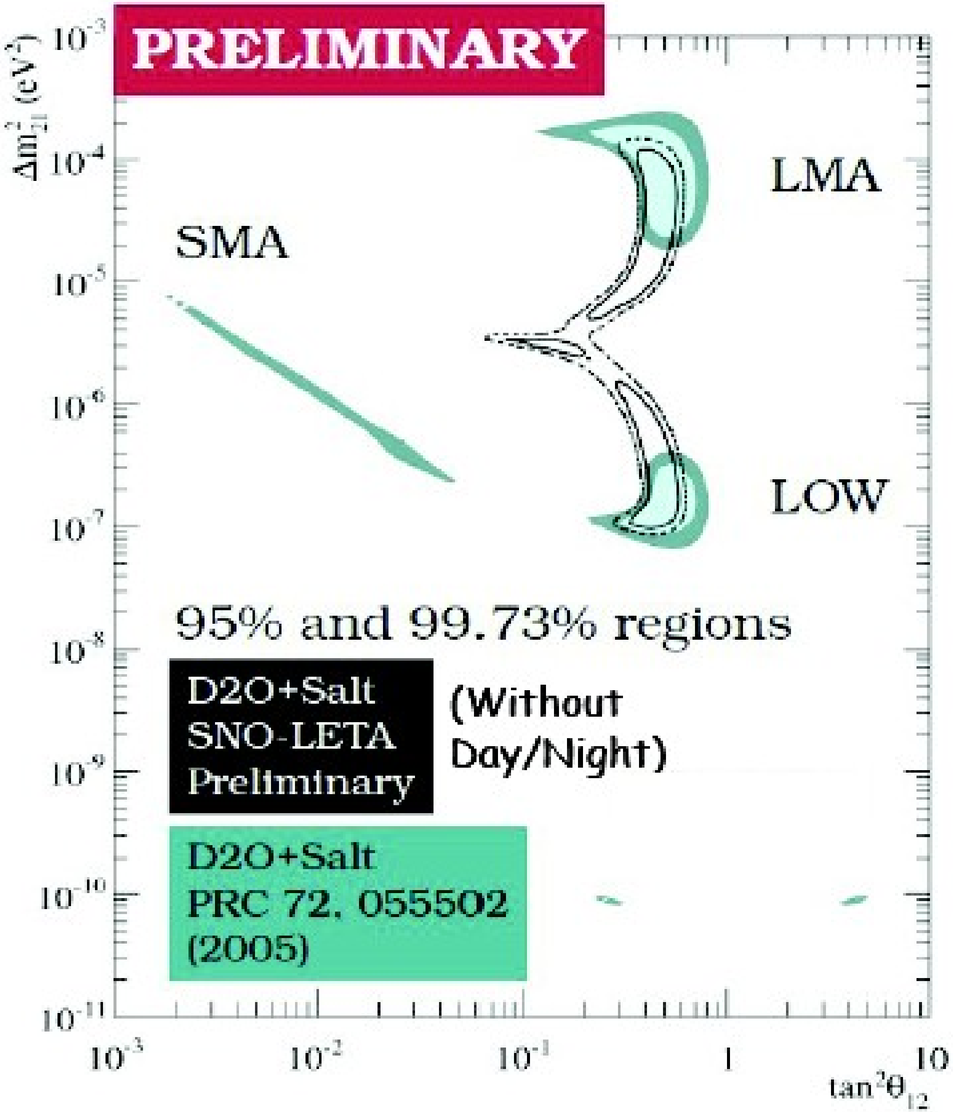



- Low energy upturn should be visible in the SK data ?

- Regeneration effects, Day/Night asymmetry



# SNO - Low Energy Threshold Analysis




- Reduce bacgrounds and lower analysis threshold to 3.5 MeV
- Two and Three flavor contours with KamLAND data
  - Improved solar parameters?
  - Information on $\theta_{13}$ ?
- Direct extraction of survival probability
  - MSW upturn effects?

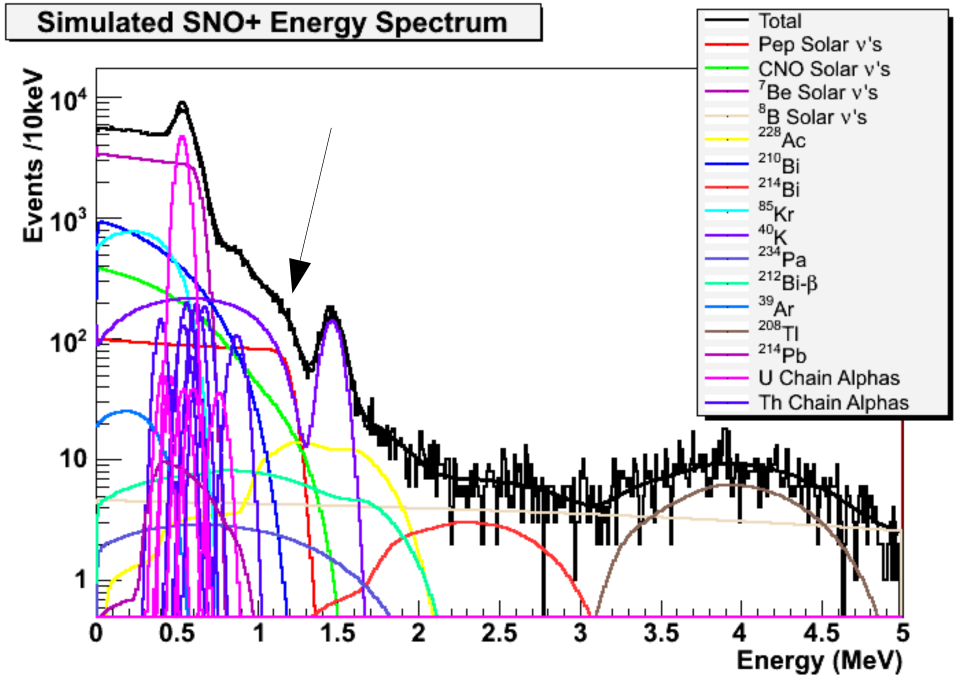
# SNO+

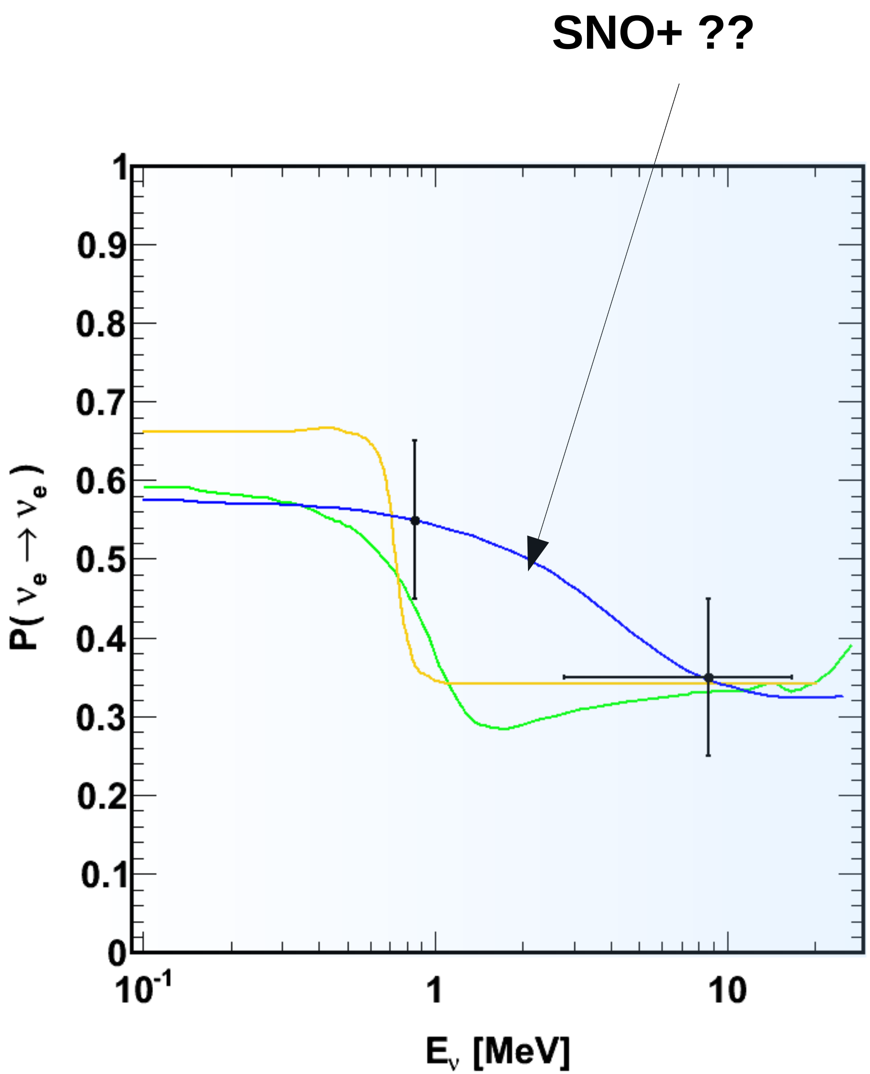
**An experiment to fill the SNO acrylic vessel with liquid scintillator to study:**

**Geo-ν, 0ν β−decay**

**pep and CNO ν - Energy shoulder 1.4 MeV**

**→ Probe MSW transition region**

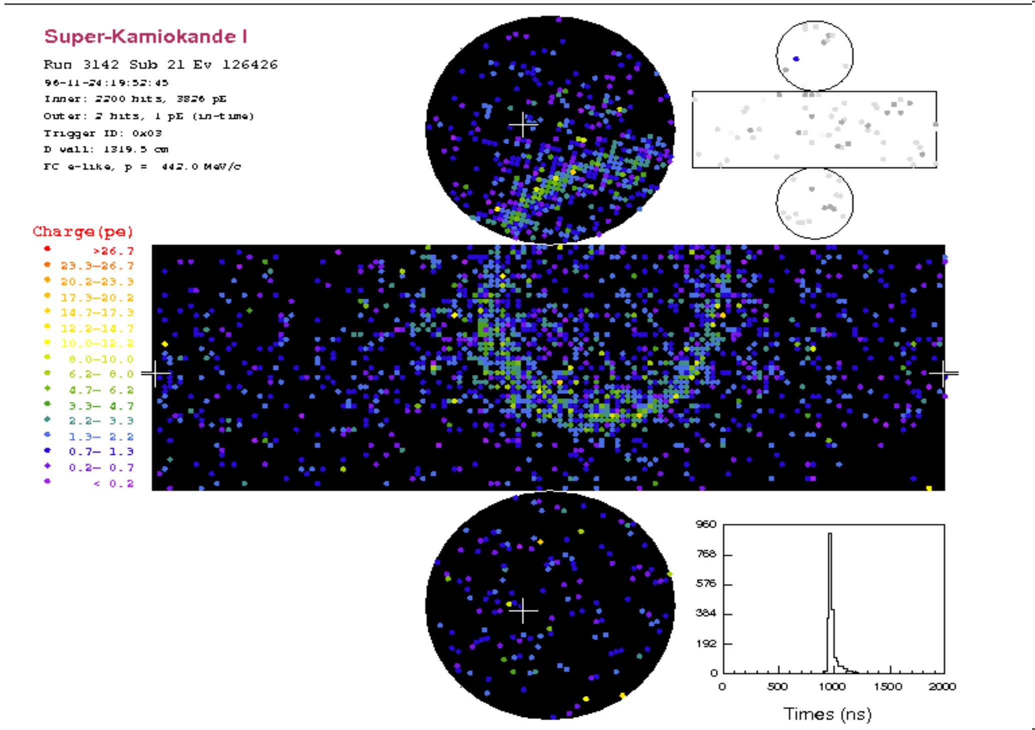


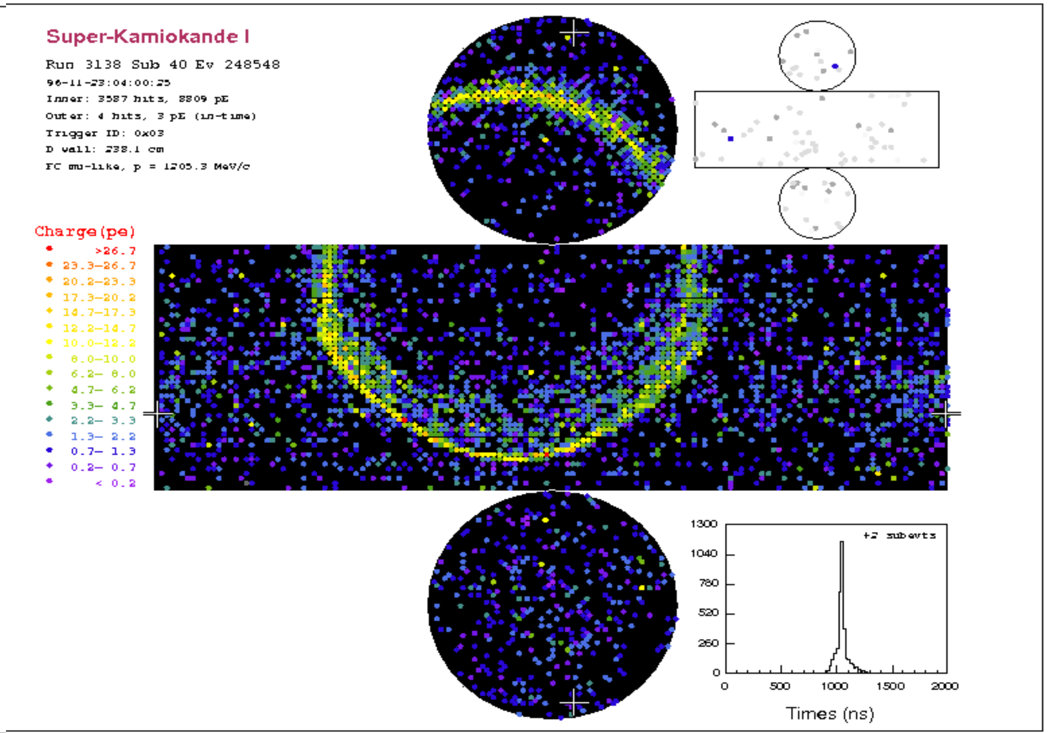




**See Also : Precision Measurement of the Low Energy Solar Neutrino Spectrum with the LENS Experiment : M. Pitt neutrino-IV**

# Two Fully Contained events from the SK-I Data

**e-like** | **μ-like**



# SK-I + SK-II + SK-III Data (preliminary)