Plan of Lectures

I. Standard Neutrino Properties and Mass Terms (Beyond Standard)

II. Neutrino Oscillations

III. The Data and Its Interpretation

IV. Some Missing Pieces and the Meaning of All This

Plan of Lecture III

The Data and Its Interpretation

Atmospheric Neutrinos

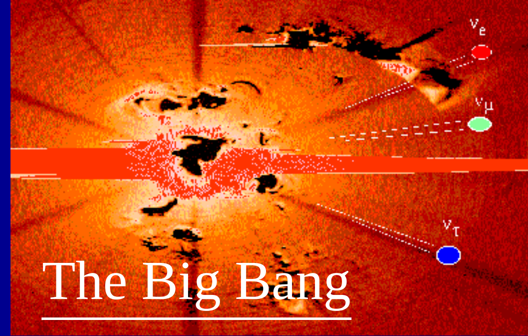
Reactor and Accelerator Neutrinos at Short Baselines

Solar Neutrinos

Long Baseline Reactor Neutrinos: KamLAND

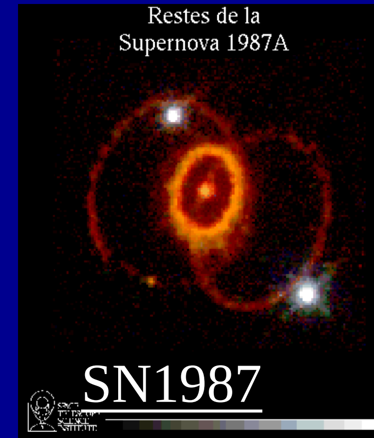
Fitting all Together (?)

Sources of ν's



$\rho_\nu = 330/\mathrm{cm}^3$

E_ν =0.0004 eV



$E_\nu \sim$ MeV

The Sun

ν_e

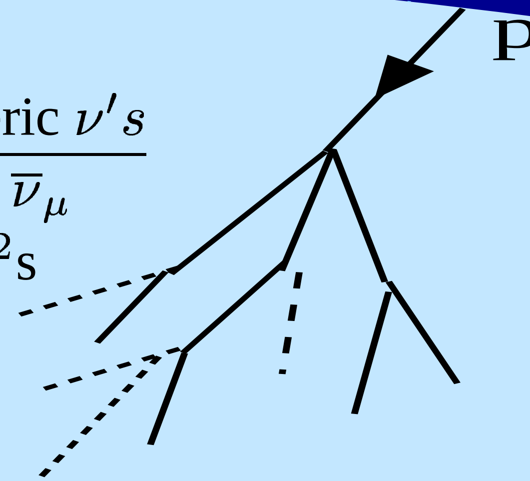
$\Phi_\nu^{Earth} = 6 \times 10^{10} \nu/\mathrm{cm}^2\mathrm{s}$

$E_\nu \sim$ 0.1–20 MeV

Atmospheric $\nu' s$

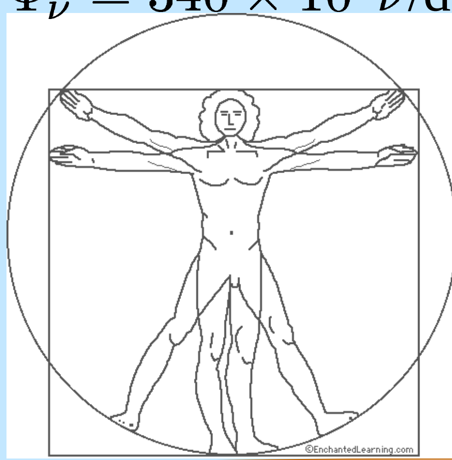
$\nu_e, \nu_\mu, \overline{\nu}_e, \overline{\nu}_\mu$

$\Phi_\nu \sim 1\nu/\mathrm{cm}^2\mathrm{s}$



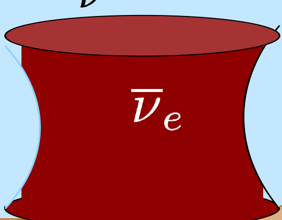
Human Body

$\Phi_\nu = 340 \times 10^6 \nu$/day



Nuclear Reactors

$E_\nu \sim$ few MeV



Fermilab
Discovering the Nature of Nature

CERN

～宇宙と物質の
起源と構造を探る～
KEK
高エネルギー加速器研究機構

Earth's radioactivity

$\Phi_\nu \sim 6 \times 10^6 \nu/\mathrm{cm}^2\mathrm{s}$

Accelerators

$E_\nu \simeq$ 0.3–30 GeV

ν Interactions

- Due to SM Weak Interactions

$$\sigma^{\nu p} \sim 10^{-38}\text{cm}^2 \frac{E_\nu}{\text{GeV}}$$

- Let's consider for example atmospheric $\nu' s$?

$$\Phi_\nu^{\text{ATM}} = 1\,\nu\,\text{per cm}^2\,\text{per second} \quad \text{and} \quad \langle E_\nu \rangle = 1\text{ GeV}$$

- How many interact?

$$N_{\text{int}} = \Phi_\nu \times \sigma^{\nu p} \times N_{\text{prot}}^{\text{human}} \times T_{\text{life}}^{\text{human}} \quad (M \times T \equiv \text{Exposure})$$

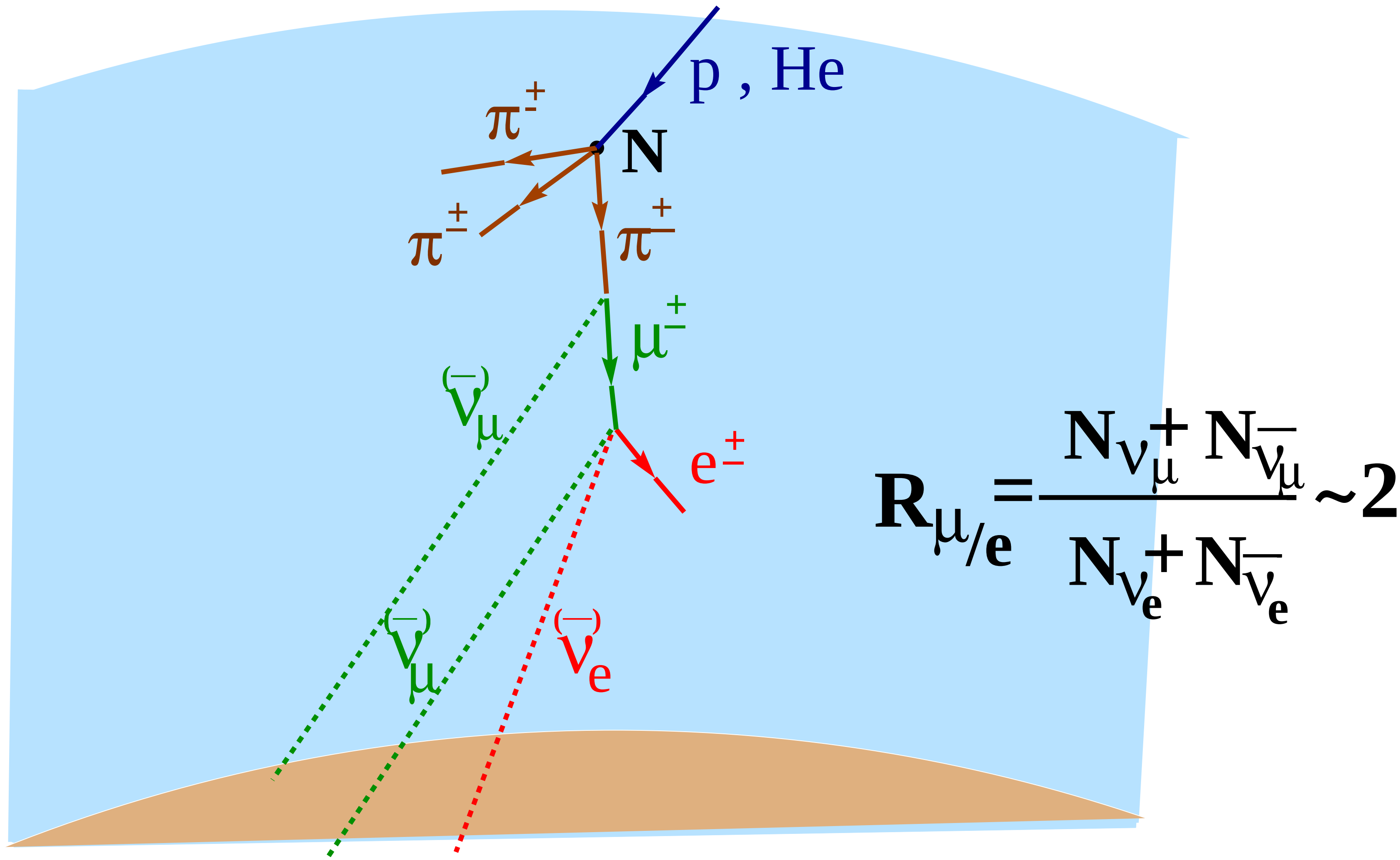
$$\left.\begin{array}{l} N_{\text{protons}}^{\text{human}} = \frac{M^{\text{human}}}{gr} \times N_A = 80\text{kg} \times N_A \sim 5 \times 10^{28}\text{protons} \\ T^{\text{human}} = 80\,\text{years} = 2 \times 10^9\,\text{sec} \end{array}\right\} \begin{array}{l}\text{Exposure}_{\text{human}} \\ \sim \text{Ton} \times \text{year}\end{array}$$

$$N_{\text{int}} = (5 \times 10^{28})\,(2 \times 10^9) \times 10^{-38} \sim 1\,\text{interaction per lifetime}$$

$\Rightarrow$ Need huge detectors with Exposure $\sim$ KTon $\times$ year

Atmospheric Neutrinos

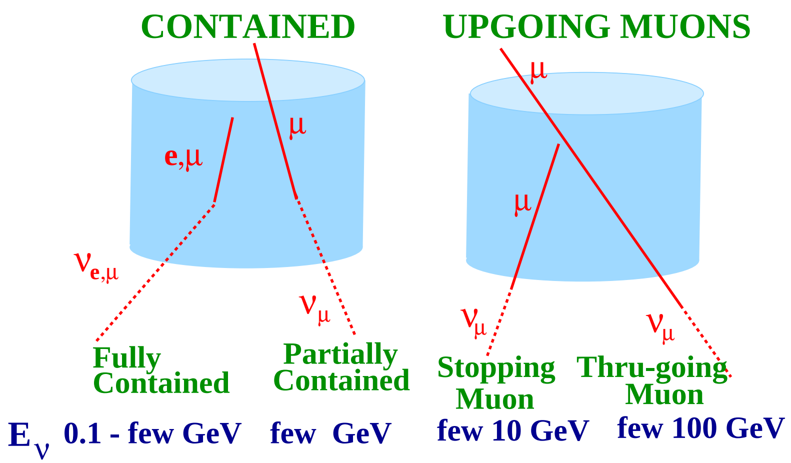
Atmospheric $\nu_{e,\mu}$ are produced by the interaction of cosmic rays (p, He ...) with the atmosphere



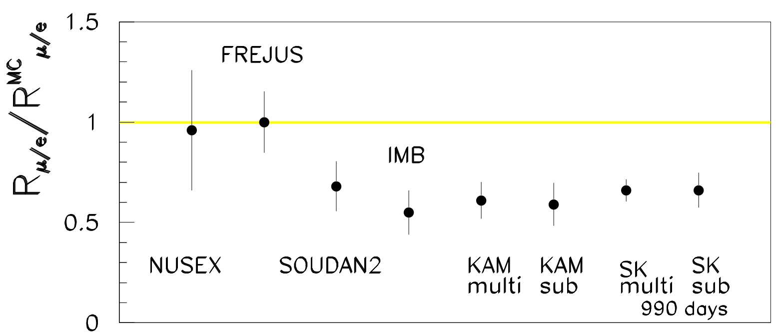
$$R_{\mu/e} = \frac{N_{\nu_\mu} + N_{\bar{\nu}_\mu}}{N_{\nu_e} + N_{\bar{\nu}_e}} \sim 2$$

Atmospheric Neutrinos: Data

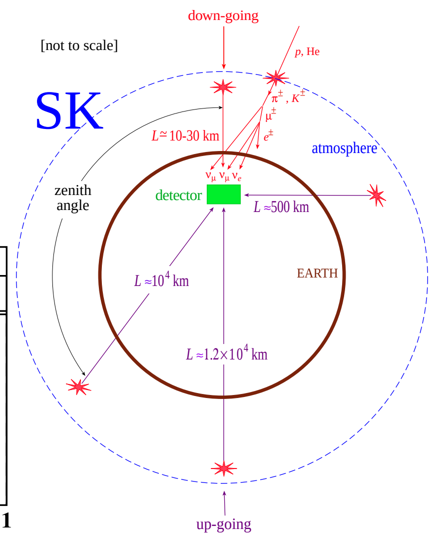
EVENT CLASSIFICATION



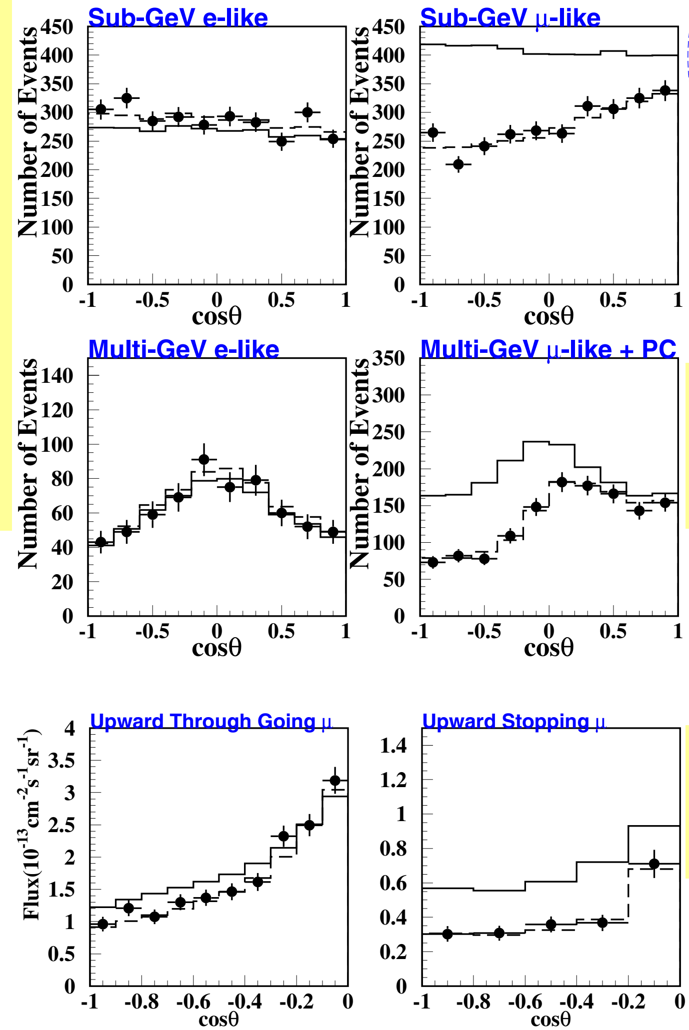
- Total Rates for Contained Events



- Angular Distribution at SK



ν_e in agreement with SM



→ Deficit grows with L

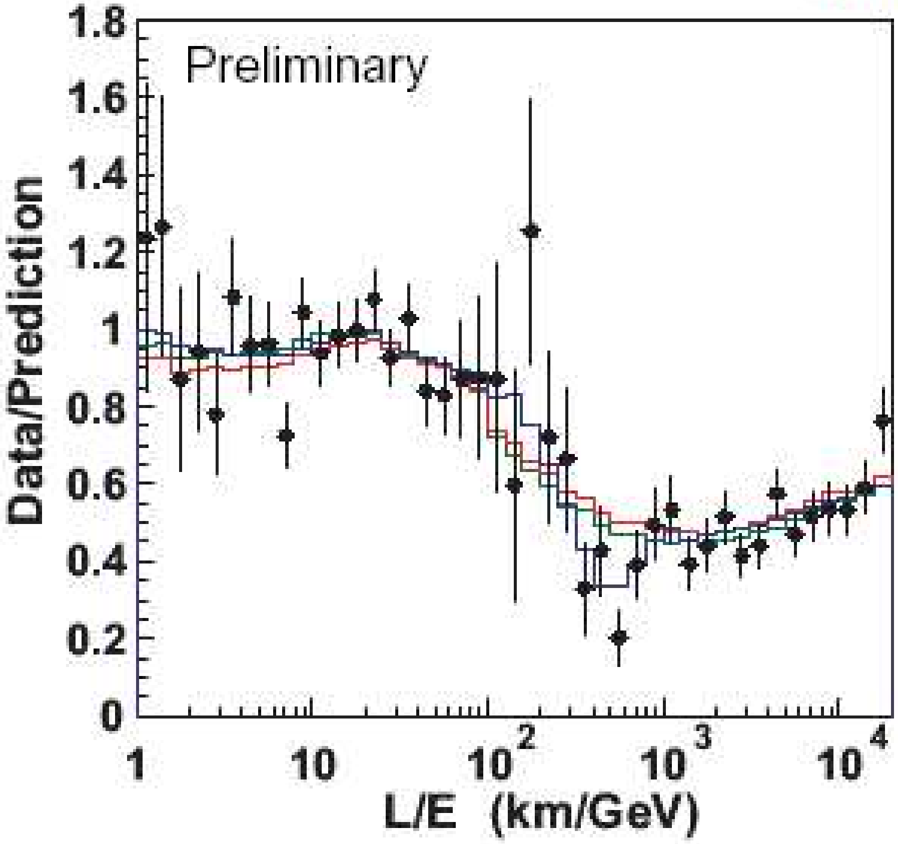
→ Decreases with E

Juan's Figure

Oscillation $\chi^2_{min}=37.8/40$ d.o.f

Decay $\chi^2_{min}=49.2/40$ d.o.f $\rightarrow \Delta\chi^2=11.4$

Decoherence $\chi^2_{min}=52.4/40$ d.o.f $\rightarrow \Delta\chi^2=14.6$



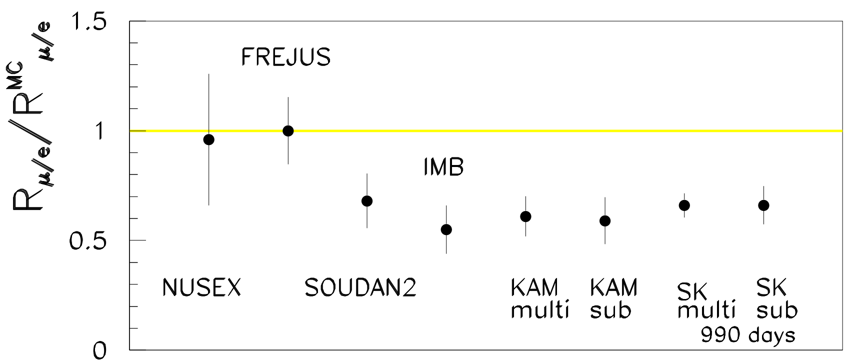
3.4 σ to ν decay

3.8 σ to ν decoherence

First dip observed in data cannot be explained by alternative hypotheses

Atmospheric ν Oscillations: Parameter Estimate

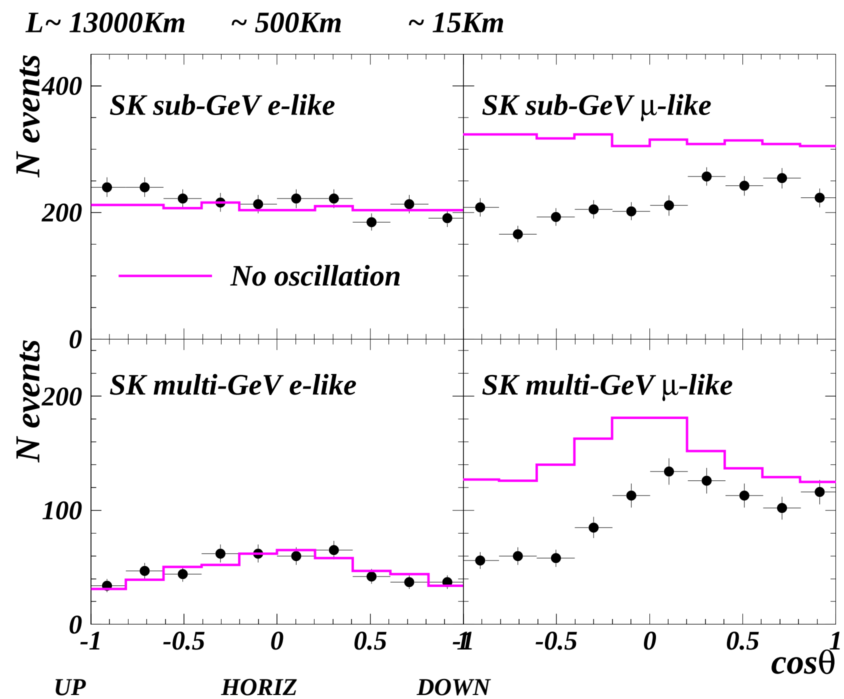
- From Total Contained Event Rates:



$$\langle P_{\mu\mu} \rangle = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{2E}$$
$$\sim 0.5 - 0.7$$

$$\Rightarrow \sin^2 2\theta \gtrsim 0.6$$

- From Angular Distribution:



For $E \sim 1$ GeV deficit at $L \sim 10^2 - 10^4$ Km

$$\frac{\Delta m^2(\mathrm{eV}^2) L(\mathrm{km})}{2E(\mathrm{GeV})} \sim 1$$

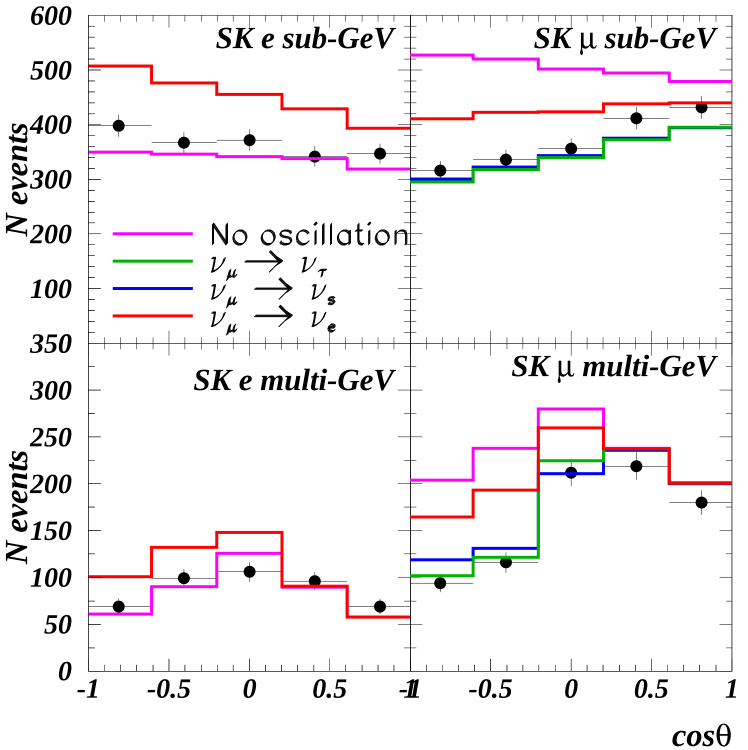
$$\Rightarrow \Delta m^2 \sim 10^{-4} - 10^{-2} \mathrm{eV}^2$$

Atmospheric ν Oscillation Analysis

- Three possible oscillation channels: $\nu_\mu \to \nu_X \quad X = e, \tau,$ sterile

$$\nu_\mu \to \nu_e$$

The angular distribution for Contained



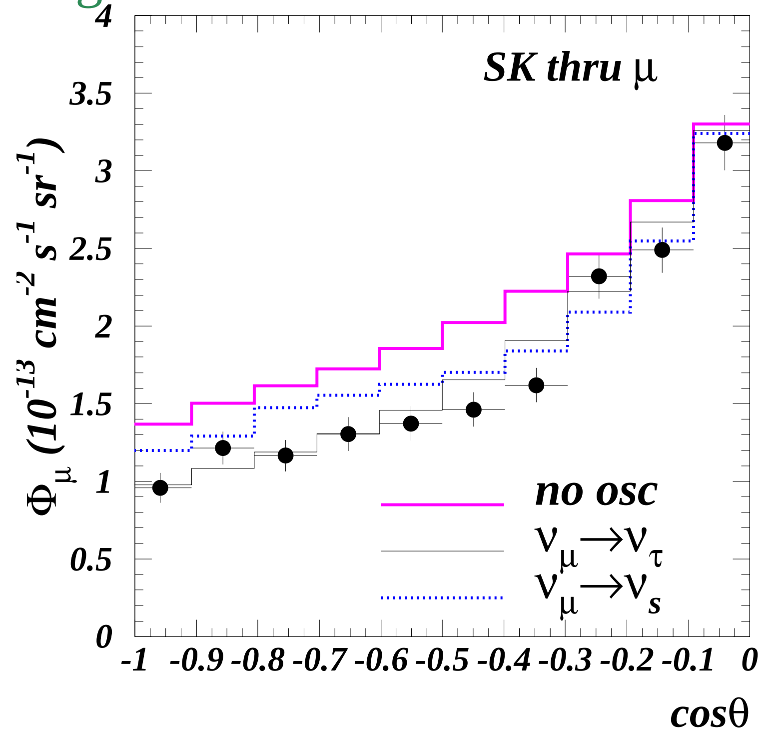
Not enough up-down asymmetry for μ's

Excess of e-like events

Ruled out

$$\nu_\mu \to \nu_{\rm sterile}$$

The angular distribution for Thru-Going μ

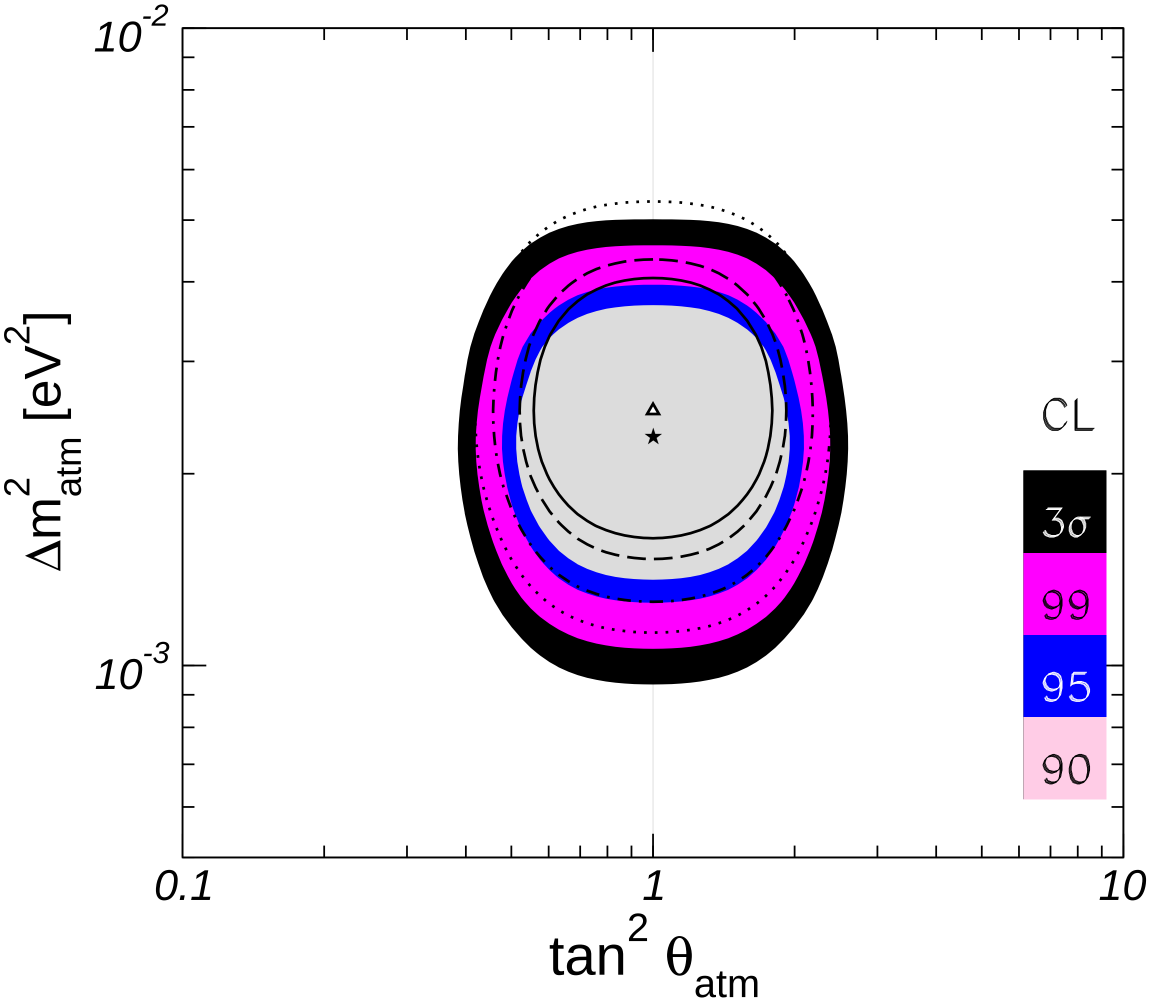


Matter effects $\Rightarrow$

Flatter distribution for $\nu_\mu \to \nu_s$

Not good fit to data

Atmospheric ν Oscillation Solution: $\nu_\mu \to \nu_\tau$



Best fit:

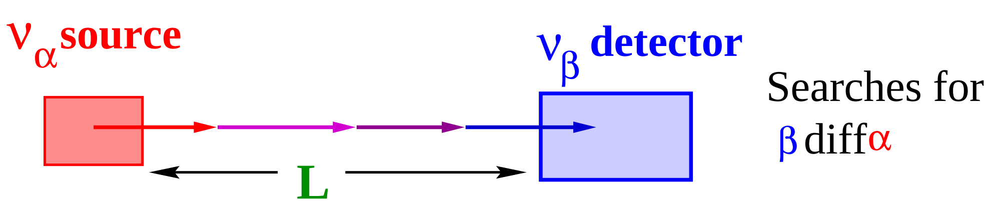
$\Delta m^2 = 2.2 \times 10^{-3}$ eV^2

$\tan^2\theta = 1$

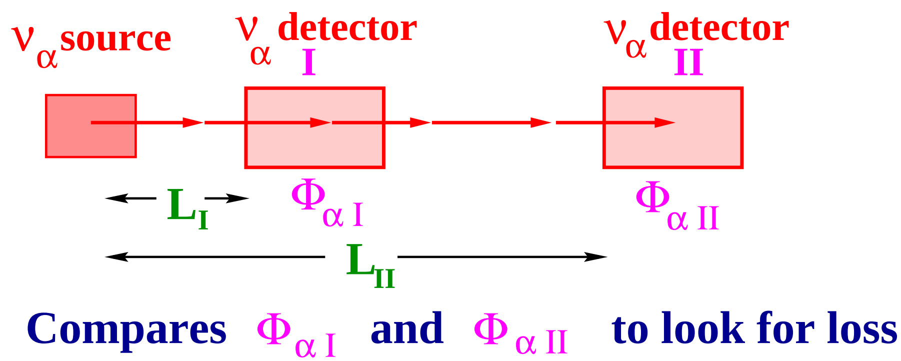
ν Oscillations: Lab Searches at Short Distance

- In laboratory experiments ν source: Accelerator or Nuclear Reactor

Appearance Experiment



Disappearance Experiment



Experiment	$\langle \frac{E/MeV}{L/m} \rangle$		α	β
CCFR	100	FNAL	ν_μ, ν_e	ν_τ
E531	25	FNAL	ν_μ, ν_e	ν_τ
Nomad	13	CERN	ν_μ, ν_e	ν_τ
Chorus	13	CERN	ν_μ, ν_e	ν_τ
E776	2.5	BNL	ν_μ	ν_e
Karmen2	2.5	Rutherford	$\bar\nu_\mu$	$\bar\nu_e$
LSND	3	Los Alamos	$\bar\nu_\mu$	$\bar\nu_e$

Experiment	$\langle \frac{E/MeV}{L/m} \rangle$		α
CDHSW	1.4	CERN	ν_μ
BugeyIII	0.05	Reactor	$\bar\nu_e$
Chooz	0.005	Reactor	$\bar\nu_e$

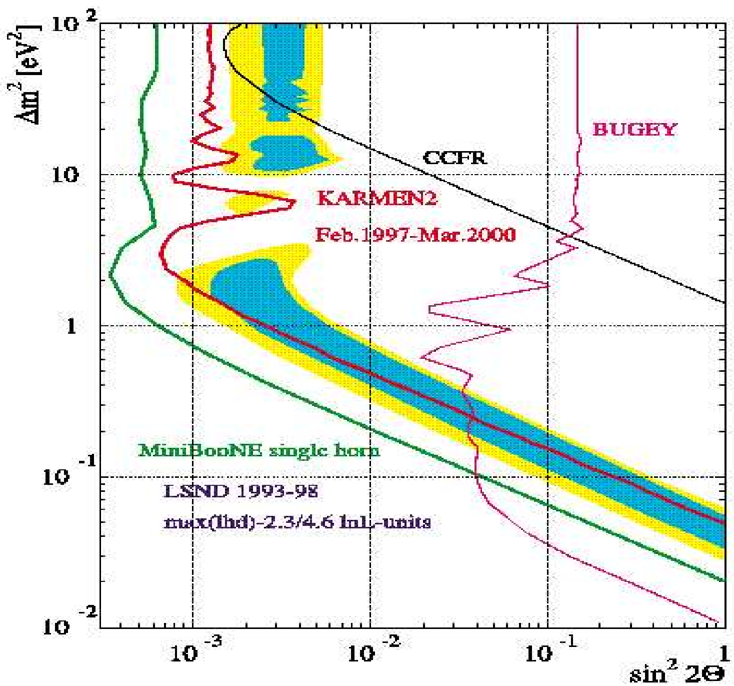
LSND

- The only short distance signal for oscillation: $L = 30$ m with $\langle E_\nu \rangle \sim 30$ MeV
- Used the proton beam of Los Alamos $p + Target \to \pi^+ + X$

$$\pi^+ \to \nu_\mu \, \mu^+$$

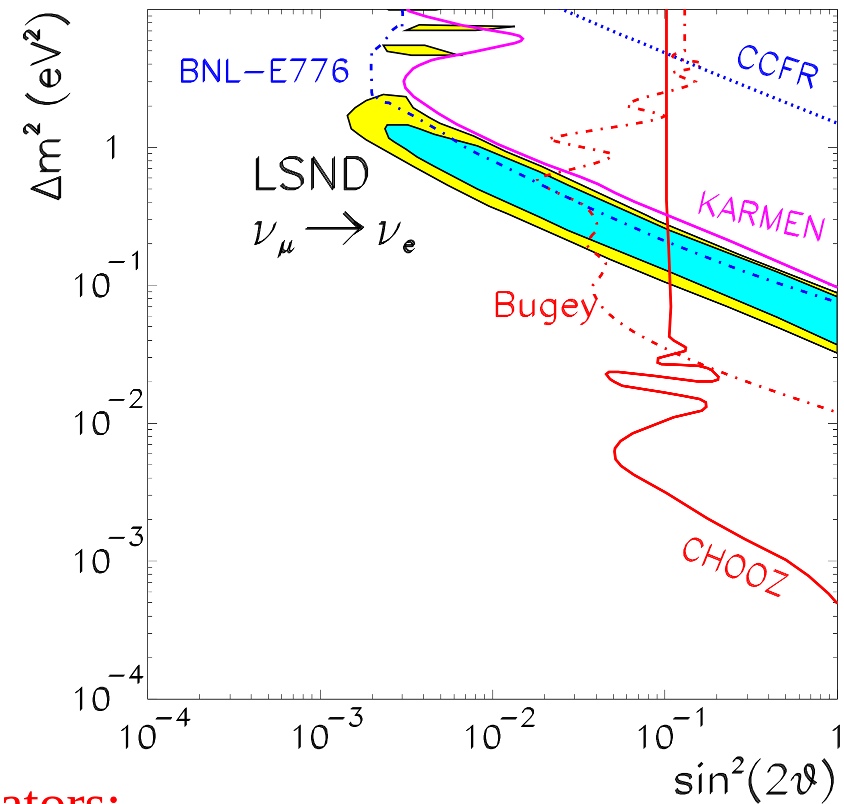
$$\mu^+ \to e^+ \, \nu_e \, \overline{\nu_\mu}$$

- observed $\overline{\nu_\mu} \to \overline{\nu_e}$ with probability $\langle P_{e\mu} \rangle = (0.26 \pm 0.07 \pm 0.05)\%$



- $Karmen$ which searched for the same signal and did not observe oscillations.
- $MiniBoone$ in Fermilab is running to solve this.

Summary of $\nu_\mu \to \nu_e$ at Short Baseline

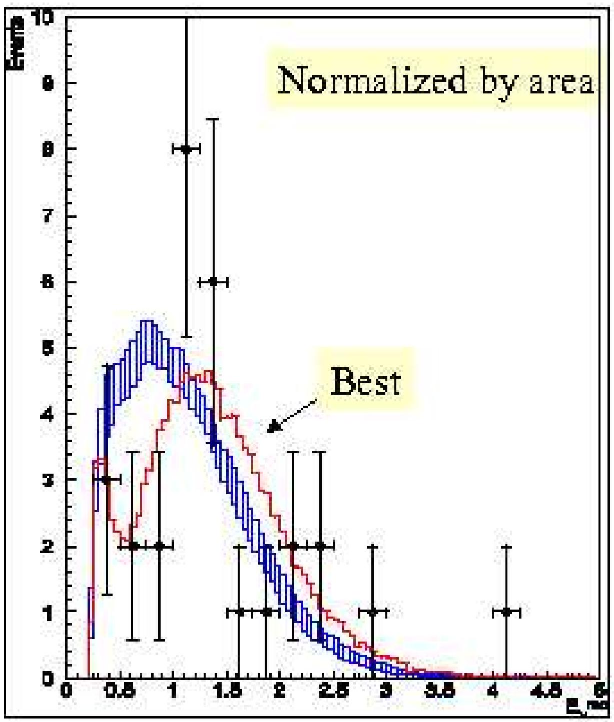


- Reactor disappearance experiments
  - $\Rightarrow$ Lower E and longer L
  - $\Rightarrow$ are more sensitive to lower Δm^2
- Accelerator appearance experiments
  - $\Rightarrow$ higher E shorter L more precision
  - $\Rightarrow$ better limits on mixing
- To reach small $\Delta m^2 \gtrsim 10^{-4}$ eV^2
  - $\Rightarrow$ very large L and intermediate E
  - $\Rightarrow$ Long Baseline Experiments at Accelerators:
- To reach smaller $\Delta m^2 \gtrsim 10^{-5}$ eV^2 $\Rightarrow$ Long Baseline Experiments at Reactors

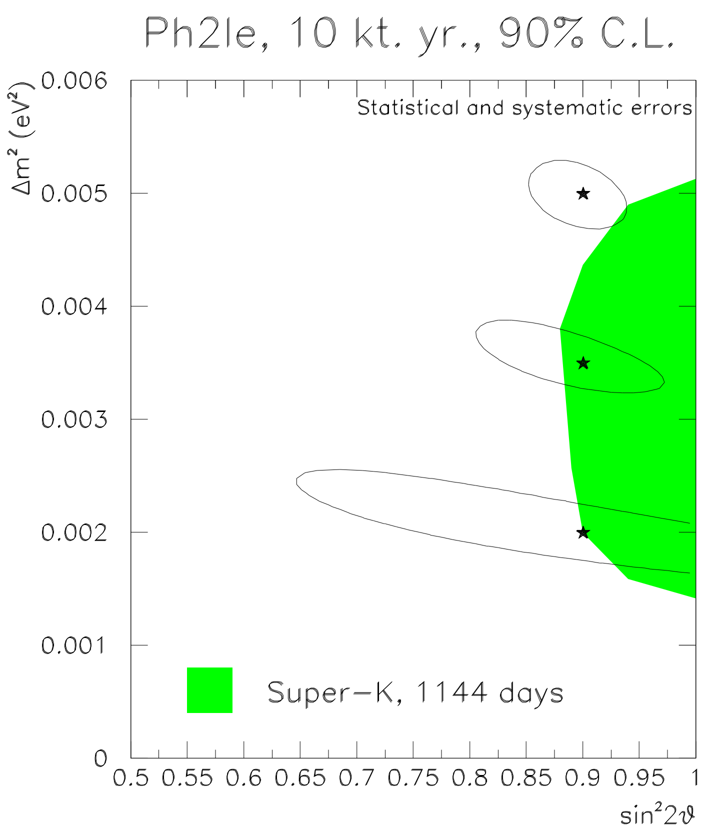
ATM Test: Long Baseline Experiments

K2K	ν_μ at KEK	Kamiokande	L=250 km
MINOS	ν_μ at Fermilab	Soundan	L=730 km
Opera/Icarus	ν_μ at CERN	Gran Sasso	L=740 km

K2K confirms



MINOS: Precision measurement



CNGS: OPERA/ICARUS τ appearance searches

Solar Neutrinos: Fluxes

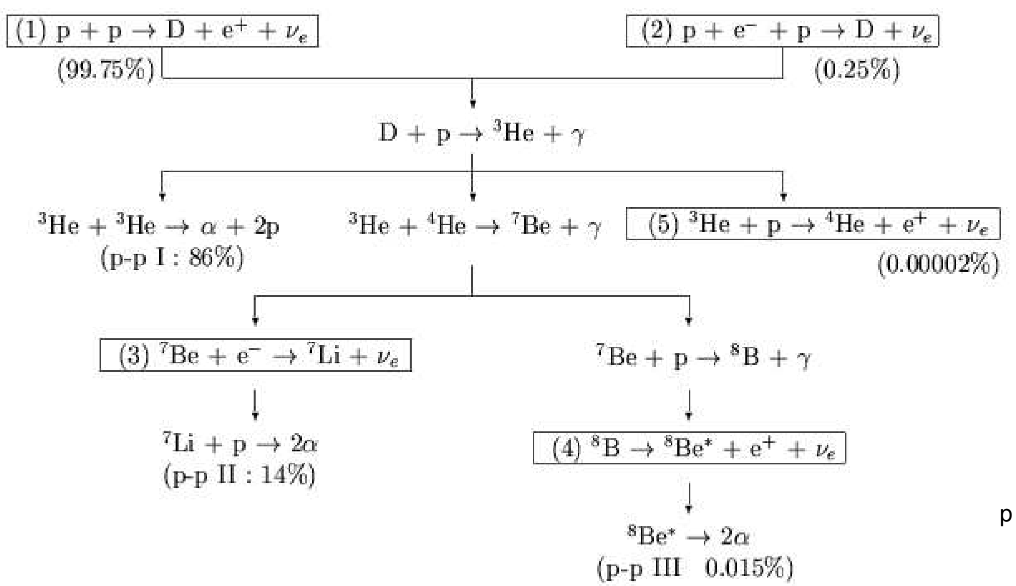
- The Sun shines converting protons into α, e^+ and $\nu' s$

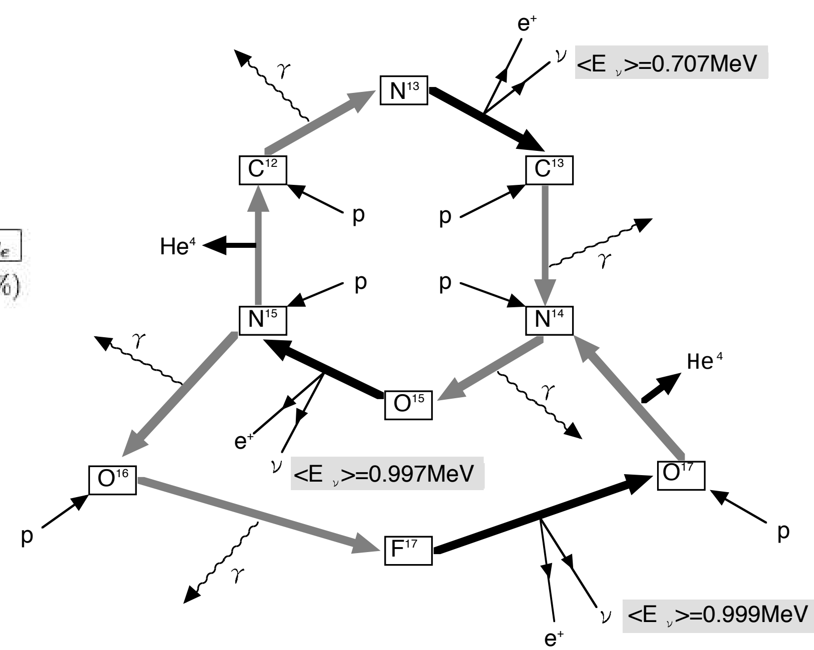
  $4\,p \;\rightarrow\; {}^4He \,+\, 2\,e^+ \,+\, 2\,\nu_e \,+\, \gamma$

  $4m_p - m_{{}^4He} - 2m_e \simeq 26$ MeV Thermal energy mostly in γ

- Two major chains of nuclear reactions

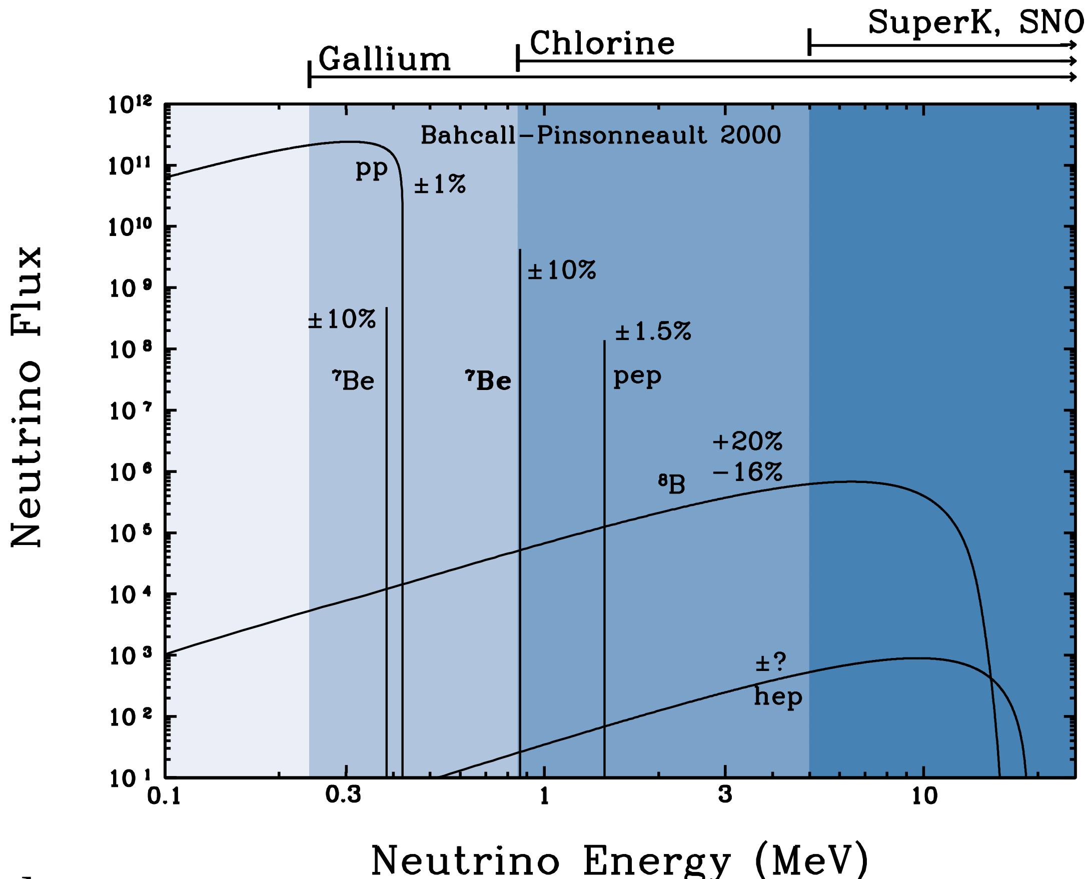
  pp chain: CNO cycle:





- Present Solar Model $\Rightarrow$ *pp*-chain dominates by 99%

Solar Neutrinos: Fluxes



- Most Relevant Fluxes :

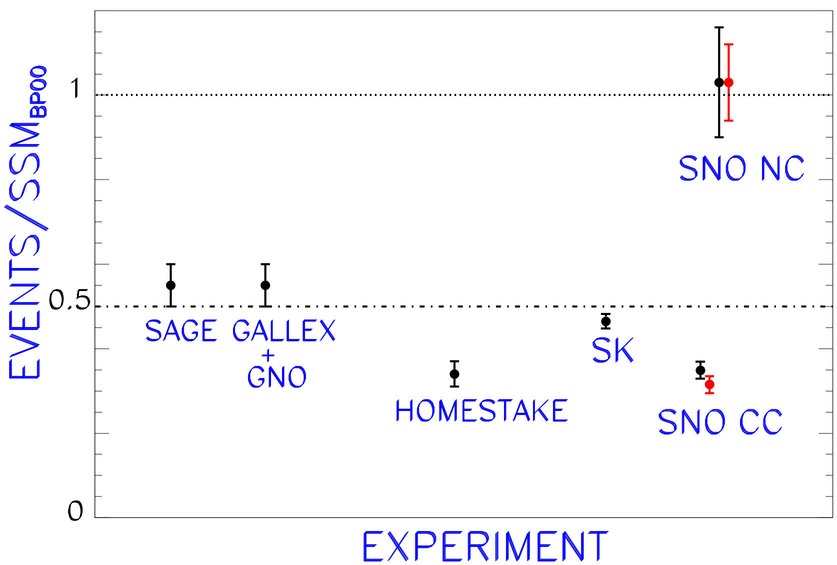
  - At SK, SNO and Chlorine, ^{8}B neutrinos: 20% accuracy in total flux
    At $1/10^5$ spectrum independent of solar physics

  - At Ga, pp neutrinos : Best determined by SSM (1%)

  - At Chlorine, also ^{7}Be neutrinos

Solar Neutrinos: Data

	Experiment	Detection	Flavour	$E_{\rm th}$ (MeV)	$\frac{\rm Data}{\rm BP00}$
radio-chemical	Homestake	$^{37}{\rm Cl}(\nu,e^-)^{37}{\rm Ar}$	ν_e	$E_\nu > 0.81$	0.35 ± 0.06
	Sage + Gallex+GNO	$^{71}{\rm Ga}(\nu,e^-)^{71}{\rm Ge}$	ν_e	$E_\nu > 0.23$	0.55 ± 0.05
real time	Kam ⇒ SK	ES $\nu_x e^- \to \nu_x e^-$	$\nu_e, \nu_{\mu/\tau}$ $\left(\frac{\sigma_{\mu\tau}}{\sigma_e} \simeq \frac{1}{6}\right)$	$E_e > 5$	0.46 ± 0.09
	SNO	CC $\nu_e d \to p p e^-$	ν_e	$T_e > 5$	0.315 ± 0.02
		ES $\nu_x e^- \to \nu_x e^-$	$\nu_e, \nu_{\mu/\tau}$	$T_e > 5$	0.44 ± 0.06
		NC $\nu_x d \to \nu_x d$	$\nu_e, \nu_{\mu/\tau}$	$T_\gamma > 5$	1.03 ± 0.09



Experiments measuring mostly ν_e find deficit

Deficit is energy dependent

Deficit disappears in NC⇒ Confirmation of SSM

$$\frac{\Phi_{^8\rm B}^{\rm SNO,NC}}{\Phi_{^8\rm B}^{\rm SSM}} = 1.03 \pm 0.09$$

Solar Neutrinos: Flavour Conversion Evidence

SK and SNO measure $\Phi_{^8\mathrm{B}}$ in different reactions

$$\begin{array}{lll} \mathrm{ES} \;\; \nu_x e^- \to \nu_x e^- & \Phi_{^8\mathrm{B}}^{\mathrm{SK,ES}} & = (2.35 \pm 0.08) \times 10^6 \;\mathrm{cm}^{-2}\mathrm{s}^{-1} \\ \mathrm{CC} \;\; \nu_e d \to p p e^- & \Phi_{^8\mathrm{B}}^{\mathrm{SNO,CC}} & = (1.59 \pm 0.11) \times 10^6 \;\mathrm{cm}^{-2}\mathrm{s}^{-1} \\ \mathrm{NC} \;\; \nu_x d \to \nu_x d & \Phi_{^8\mathrm{B}}^{\mathrm{SNO,NC}} & = (5.21 \pm 0.47) \times 10^6 \;\mathrm{cm}^{-2}\mathrm{s}^{-1} \end{array}$$

* In the SSM with SM interaction all results should be equal

$$\Phi_{^8\mathrm{B}}^{\mathrm{ES,SK}} = \Phi_{^8\mathrm{B}}^{\mathrm{CC,SNO}} \Rightarrow 3.2\sigma \text{ out}$$

$$\Phi_{^8\mathrm{B}}^{\mathrm{NC,SNO}} = \Phi_{^8\mathrm{B}}^{\mathrm{CC,SNO}} \Rightarrow 7\sigma \text{ out}$$

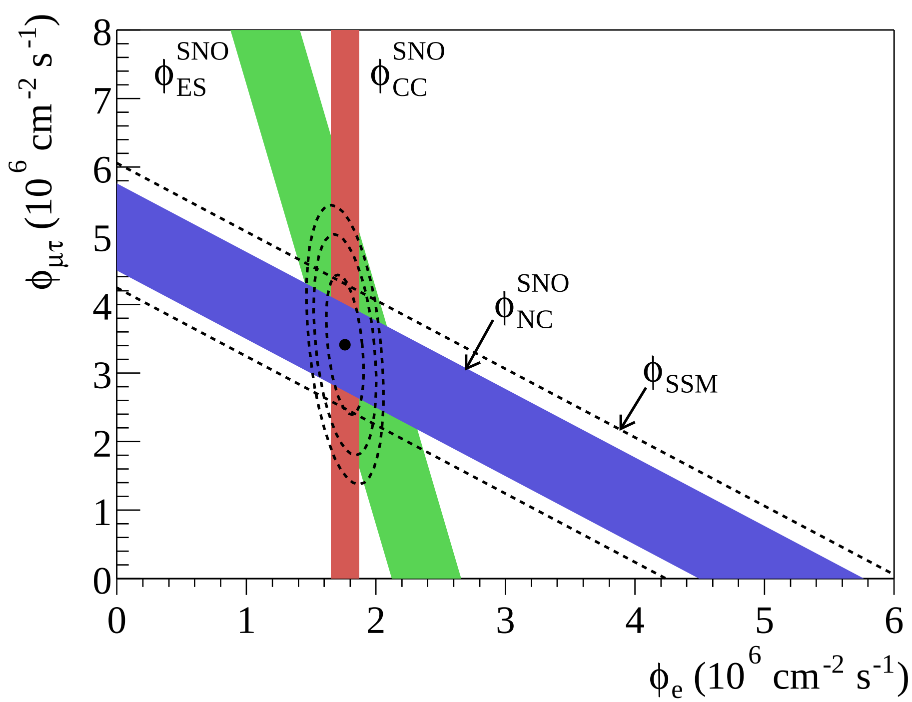
* If flavour conversion everything fits perfectly:

$$\Phi^{\mathrm{CC}} = \Phi_e$$

$$\Phi^{\mathrm{ES}} = \Phi_e + r\,\Phi_{\mu\tau}$$

$$\Phi^{\mathrm{NC}} = \Phi_e + \Phi_{\mu\tau}$$

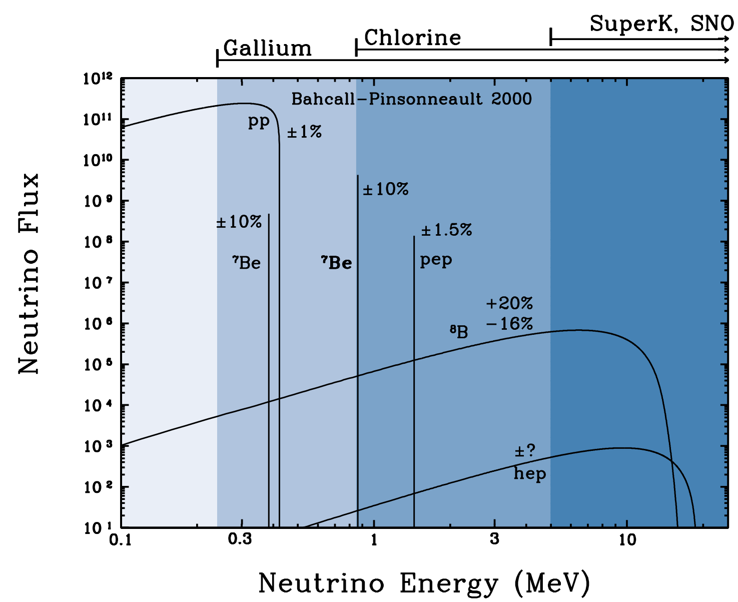
$$\left(r = \frac{\sigma_{\mathrm{ES}}(\nu_e)}{\sigma_{\mathrm{ES}}(\nu_\mu)} \simeq \frac{1}{6} \right)$$



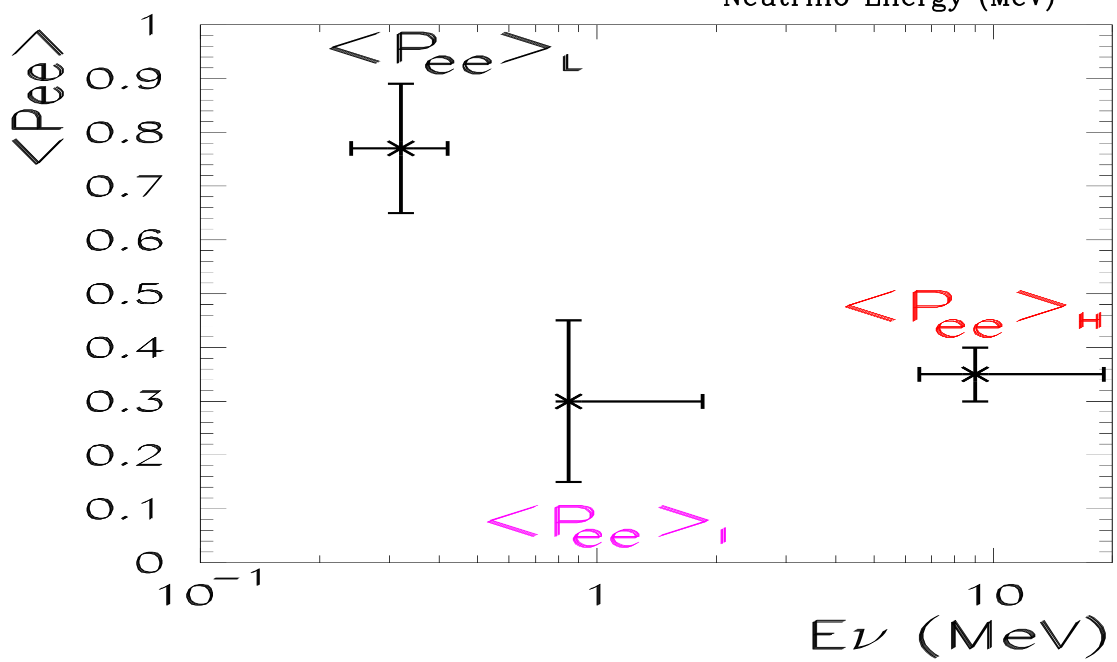
Solar Neutrinos: Flavour Conversion Probabilities

- Fitting the observed rates:

	$\frac{\text{Data}}{\text{SSM}}$	R_{th}
Cl	0.35 ± 0.06	$0.76\ f_B\ \langle P_{ee}\rangle_H\ +\ 0.24\ \langle P_{ee}\rangle_I$
Ga	0.55 ± 0.05	$0.1\ f_B\ \langle P_{ee}\rangle_H\ +\ 0.36\ \langle P_{ee}\rangle_I\ +\ 0.54\ \langle P_{ee}\rangle_L$
SK	0.46 ± 0.09	$f_B[\langle P_{ee}\rangle_H\ +\ \frac{1}{6}\ (1 - \langle P_{ee}\rangle_H)]$
SNO CC	0.35 ± 0.07	$f_B\ \langle P_{ee}\rangle_H$
NC	1.01 ± 0.23	f_B

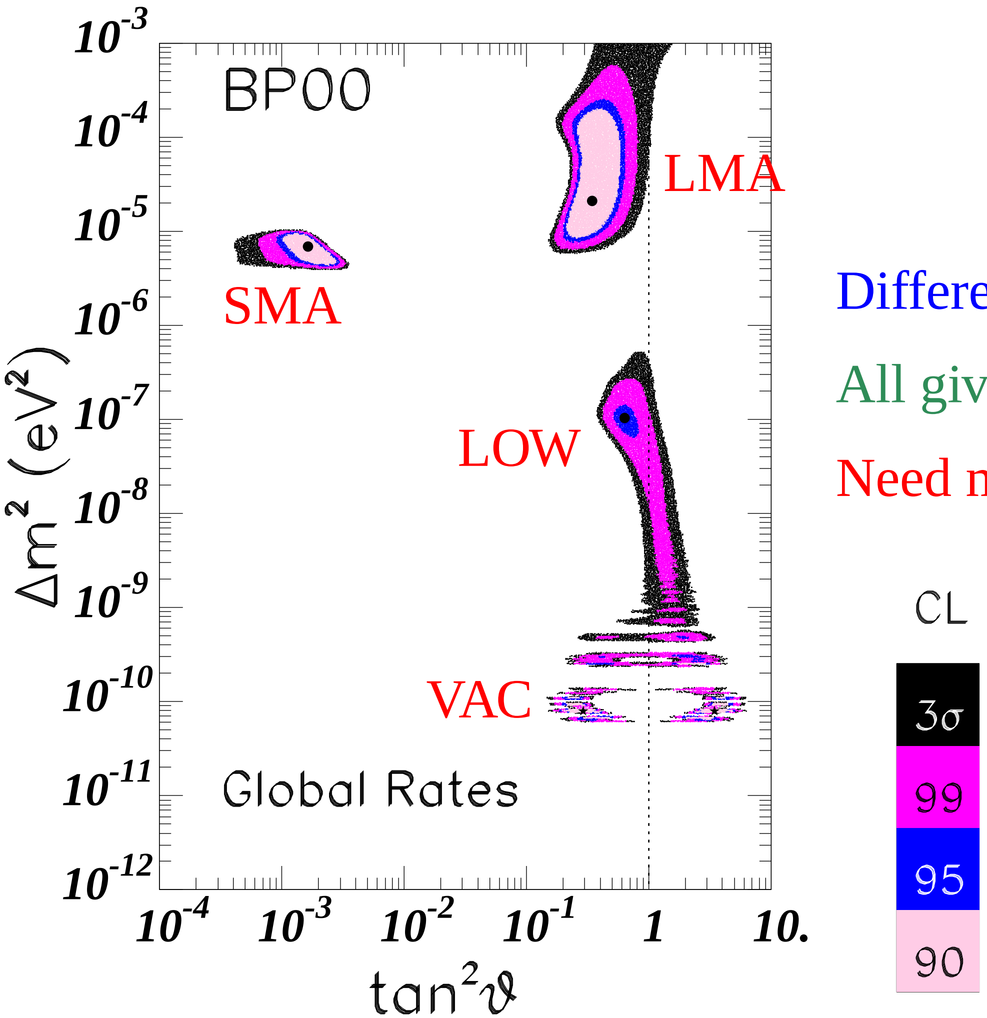


- The ν_e survival probability :



Solar Neutrinos: Oscillation Solutions

Allowed regions by Fit to Total Rates: Cl, Ga, SK and SNO CC



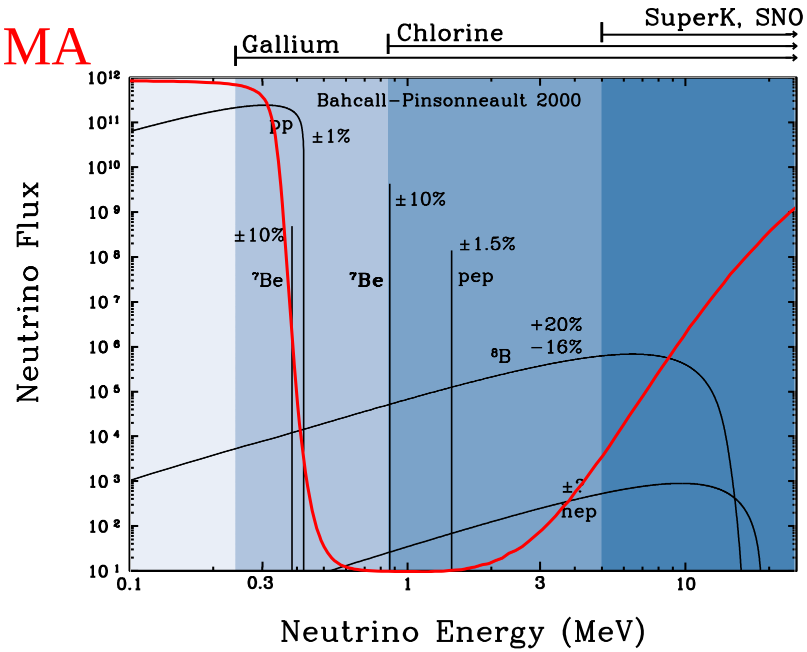
Different regimes can explain the Total Rates

All give similar $\langle P_{ee}\rangle_L$, $\langle P_{ee}\rangle_I$,$\langle P_{ee}\rangle_H$

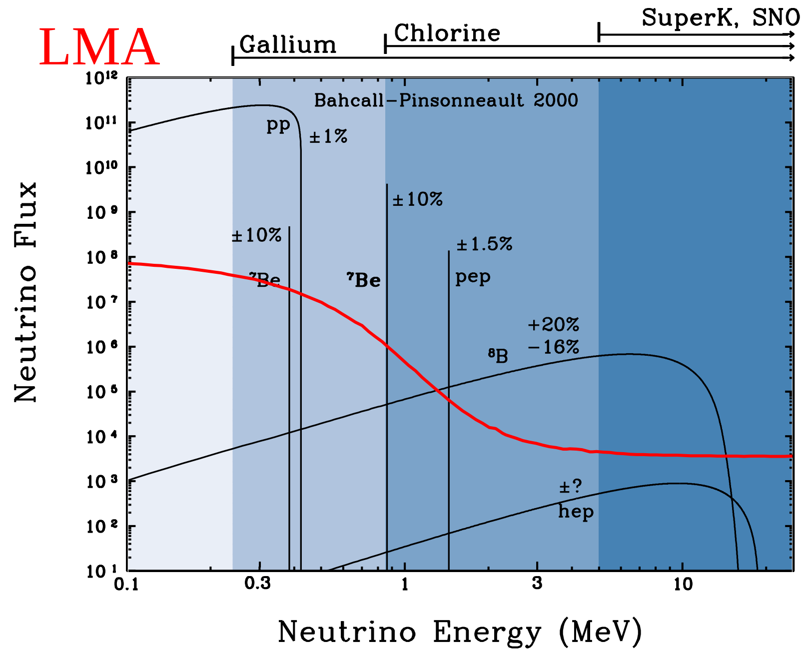
Need more observables to discriminate

Energy Dependence of P_{ee} for Different Solutions

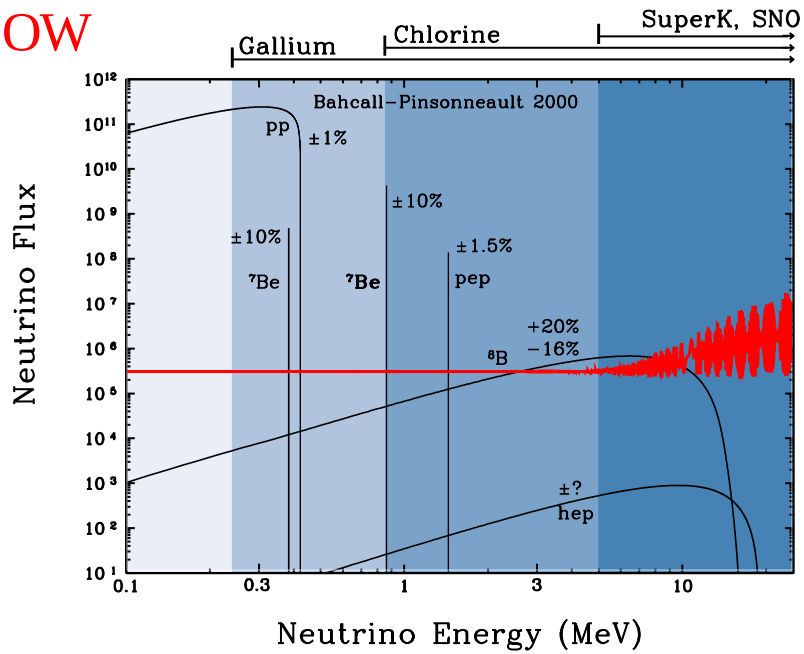
SMA



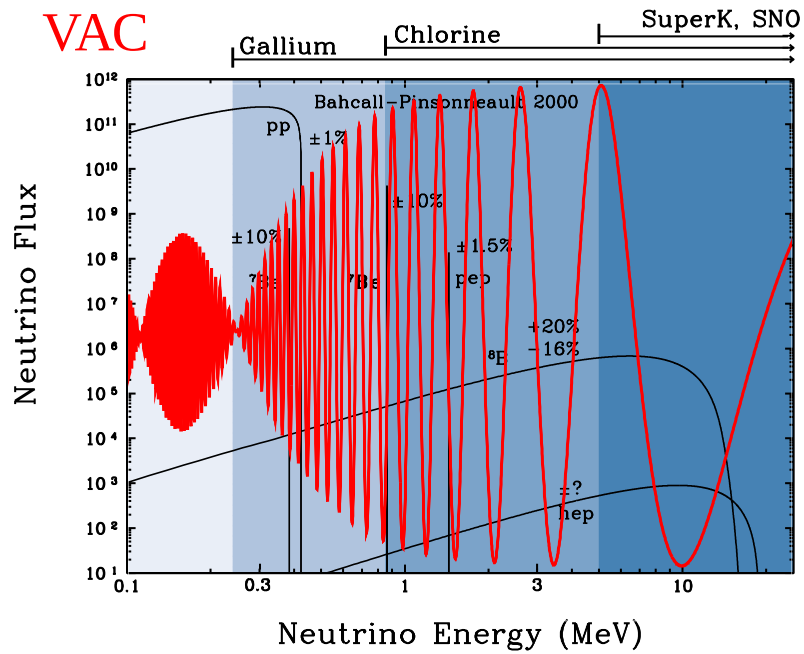
LMA



LOW



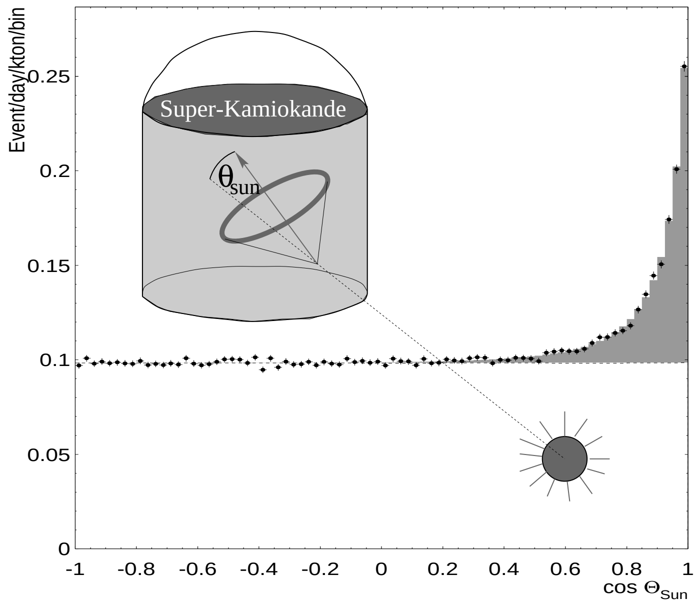
VAC



- Real Time experiments can also give information on Energy and Direction of $\nu's$ and can search for Energy and Time variations of the effect

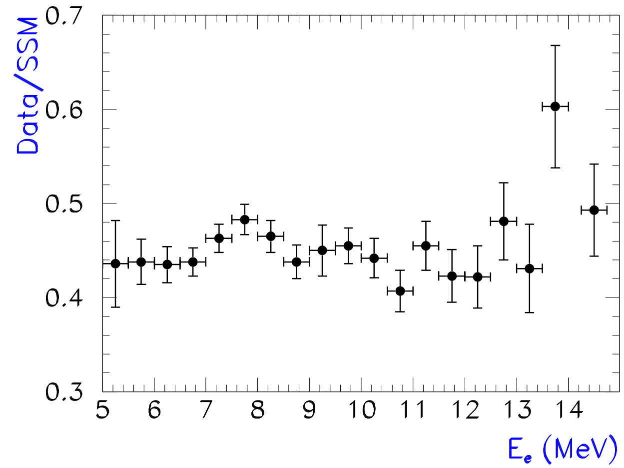
- From SK (Confirmed by SNO)

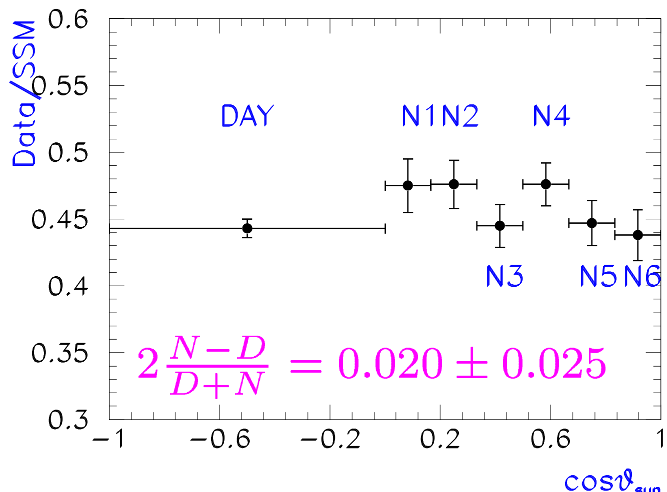
ν's come from the SUN



No Energy Distorsion

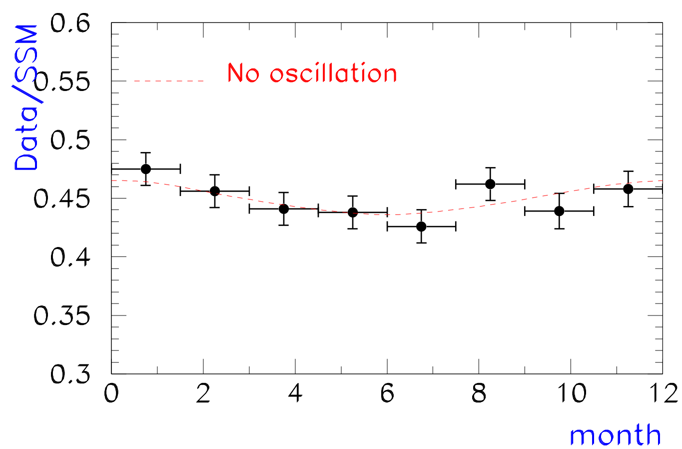
Deficit indep $E_\nu \gtrsim 5$ MeV





No Earth Matter Effect:

Small Day-Night Asymmetry

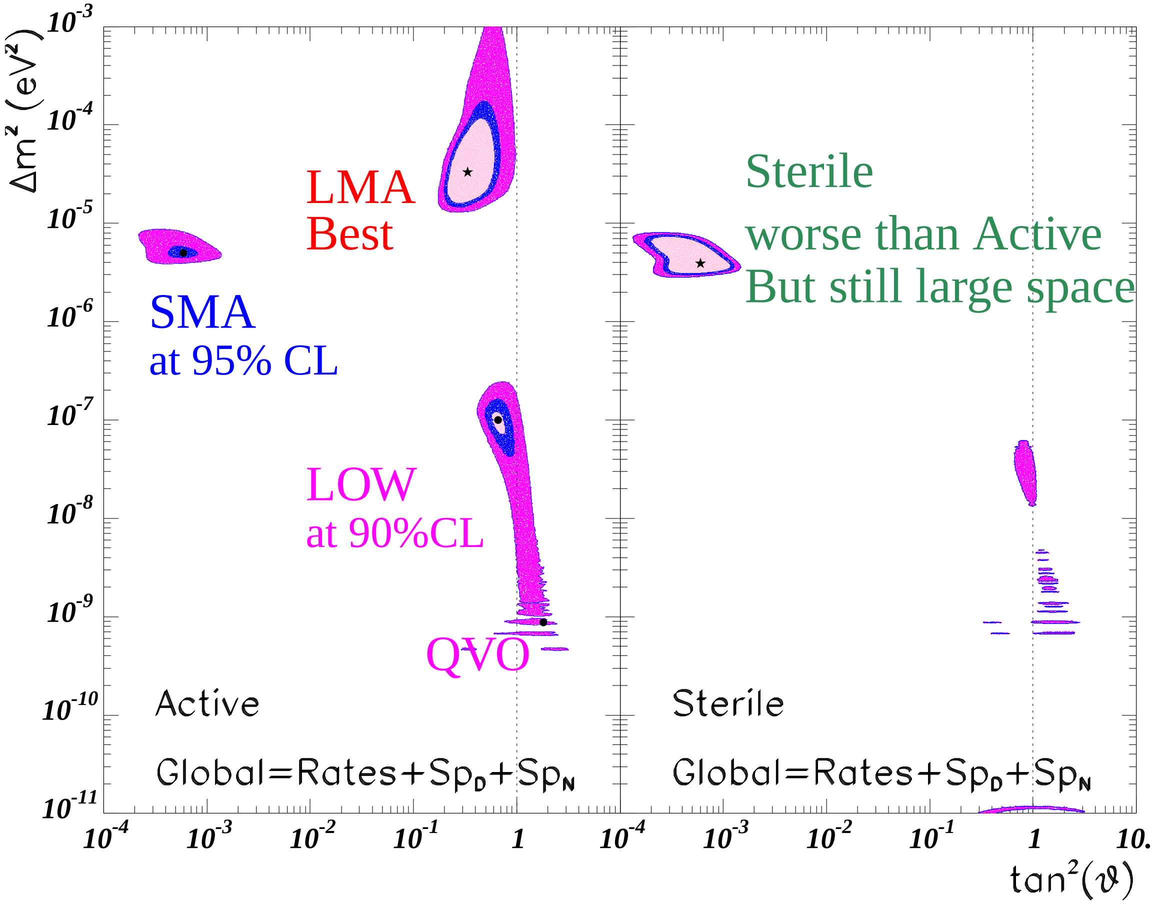


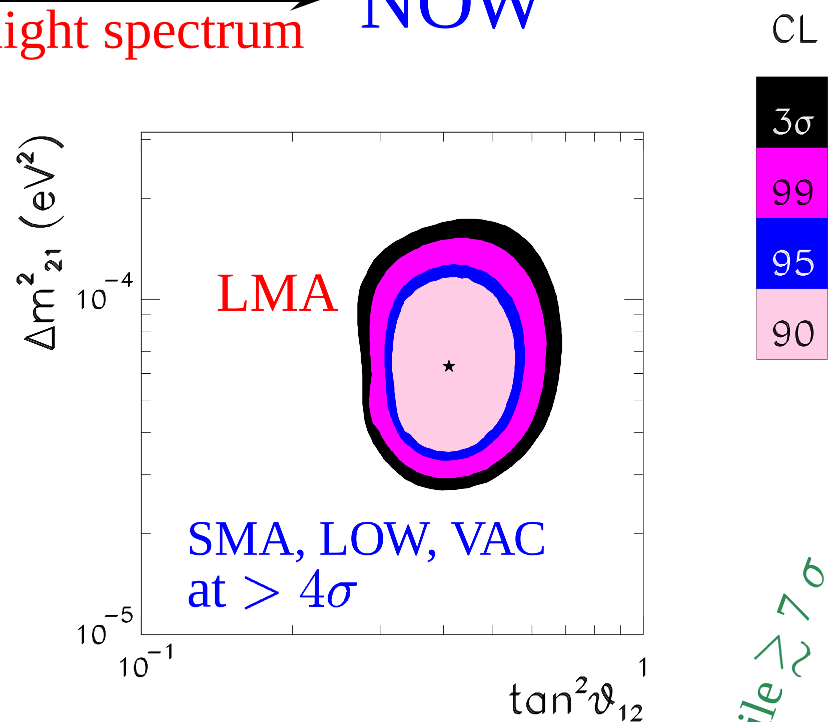
Seasonal Variation

Nothing beyond $1/R^2$

Solar Neutrinos: Oscillation Solutions

4 YEARS AGO $\xrightarrow[\text{New SNO day-night spectrum}]{\text{Detailed SK E and t dependence}}$ NOW





Sterile $\gtrsim 7\sigma$

Best fit:

$\Delta m^2 = 6.8 \times 10^{-5}$ eV^2

$\tan^2\theta = 0.42$

Terrestrial Test of LMA: KamLAND

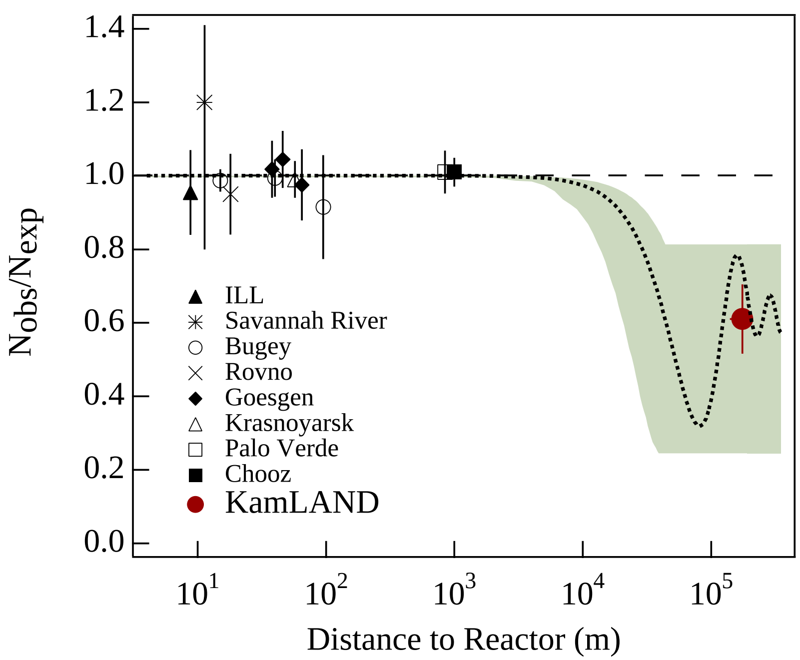
- Search on $\overline{\nu_e}$ at L$\sim$ 180 km reactors, $E_{\overline{\nu}}\sim$ few MeV: $\bar{\nu}_e + p \to n + e^+$

  –K. Eguchi et al., hep-ex/0212021 145 days of data.

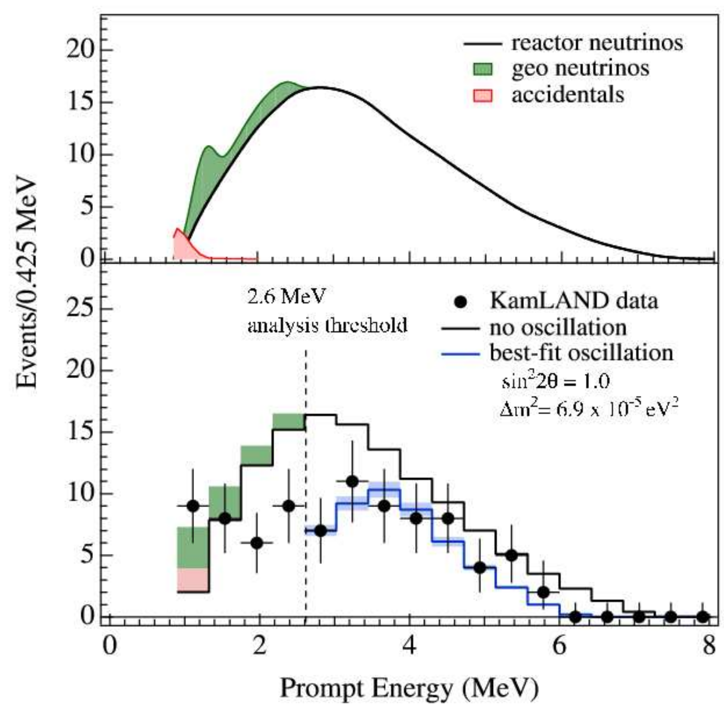
  –Analysis threshold : $E_{\rm vis} = E_\nu - (M_n - M_p) + m_e \simeq E_\nu - 0.8\ {\rm MeV} > 2.6\ {\rm MeV}.$

- 54 Observed events of 86.8 $\pm$ 5.6 Expected (1 background).

$$R_{\rm KamLAND} = 0.611 \pm 0.085({\rm stat}) \pm 0.041({\rm sys})$$



Energy spectrum observed

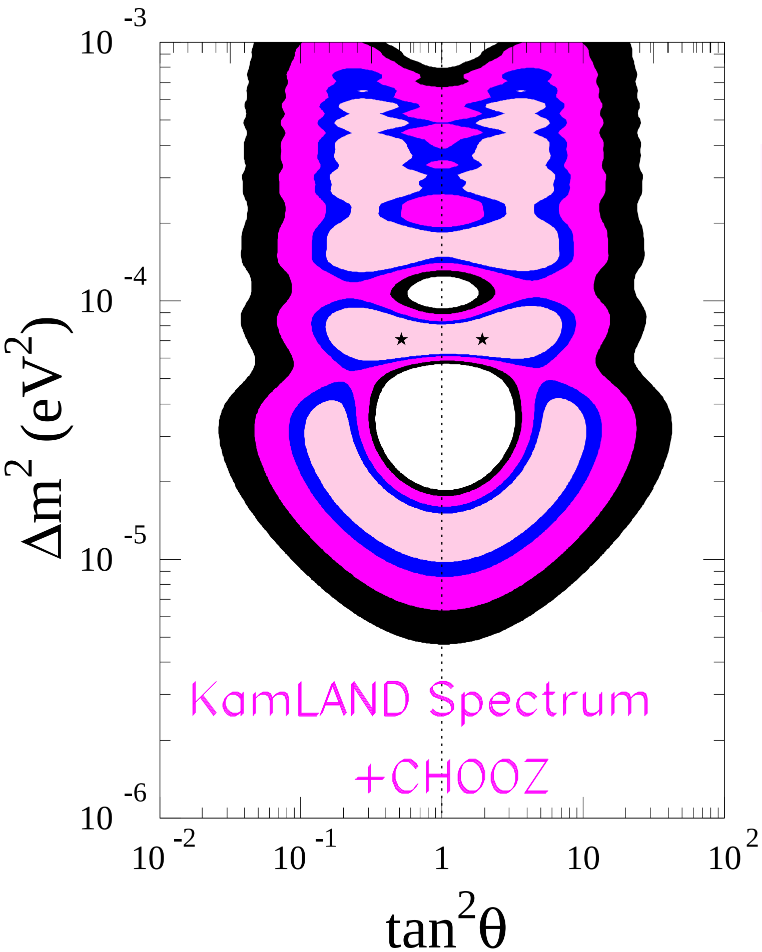


Test of LMA: KamLAND Oscillation Analysis

Analysis of $\bar{\nu}_e \not\to \bar{\nu}_e$: $P_{\bar{e}\bar{e}} = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$

– No matter effects: $\theta \equiv \frac{\pi}{2} - \theta$

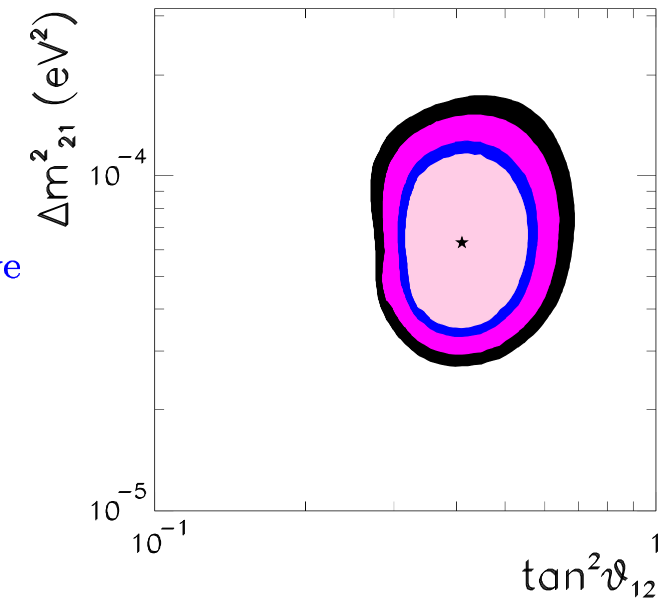
– Disappearance: No information about active or sterile osc.



$\Delta\bar{m}^2$	$\tan^2\bar{\theta}$	$\Delta\chi^2_{min}$
7.1×10^{-5}	5.2×10^{-1}	0.0
1.7×10^{-4}	3.5×10^{-1}	1.6
1.5×10^{-5}	3.7×10^{-1}	3.0

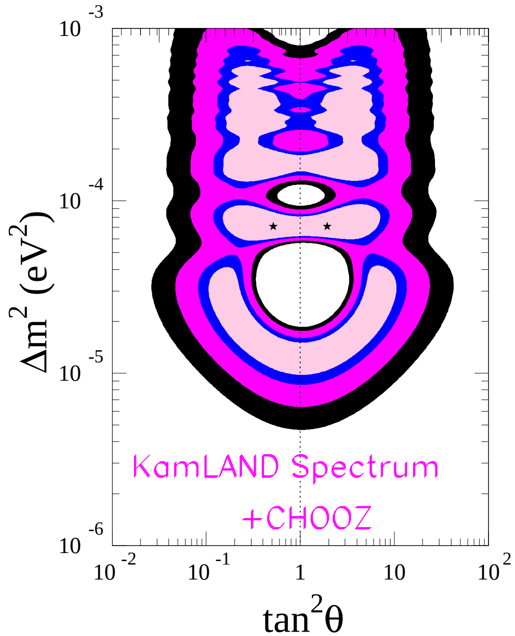
Solar

$\nu_e \to \nu_{\text{active}}$



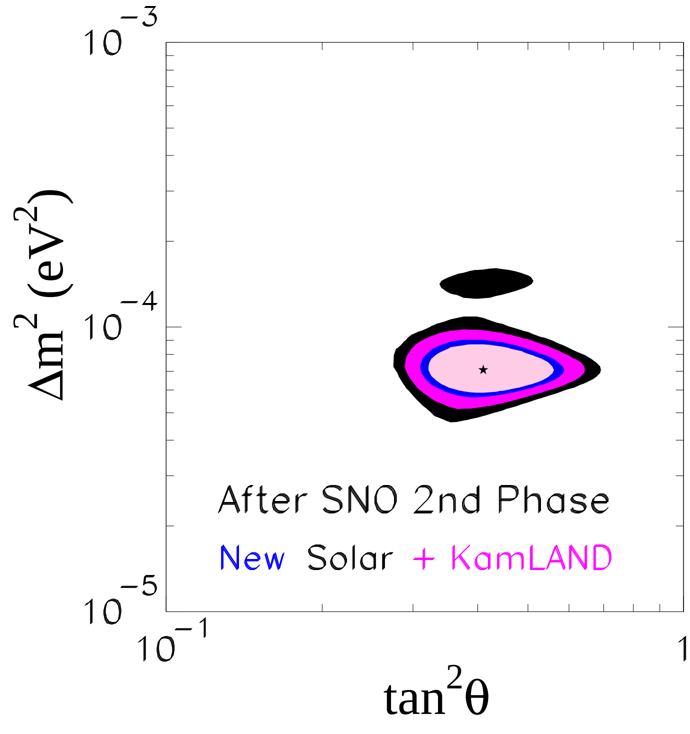
+ KamLAND

$\bar{\nu}_e \not\to \bar{\nu}_e$



ν_e oscillation parameters compatible with $\bar{\nu}_e$: CPT $\Rightarrow P_{ee} = P_{\bar{e}\bar{e}}$

$$\chi^2_{\text{global}} = \chi^2_{\text{solar}}(\Delta m^2, \tan^2\theta) + \chi^2_{\text{KamLAND}}(\Delta m^2, \tan^2\theta)$$

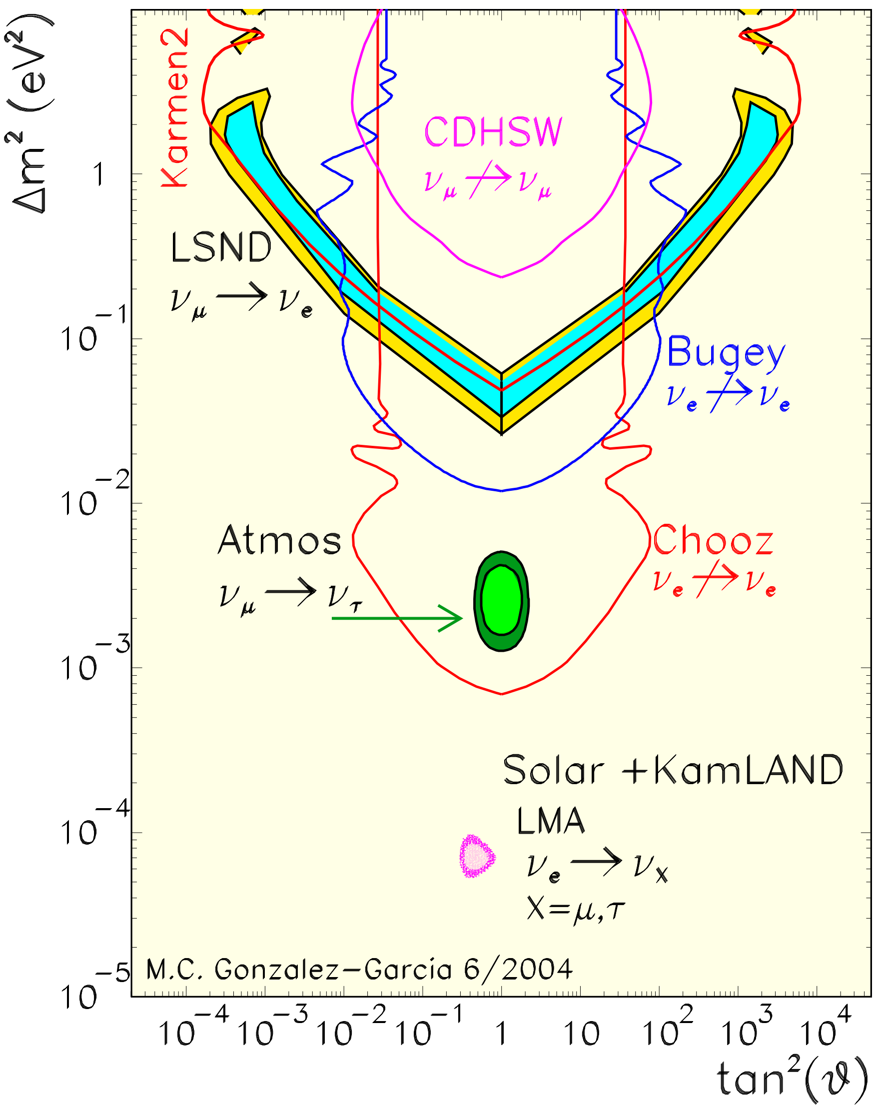


Best fit:

$\Delta m^2 = 7.1 \times 10^{-5}$ eV^2

$\tan^2\theta = 0.42$

Two Neutrino Oscillations: Summary



- How to fit all this together?

– 3 oscillation signals in 3 different scales

$$\Delta m^2_{\rm SOLAR} \ll \Delta m^2_{\rm ATM} \ll \Delta m^2_{\rm LSND}$$

– Mixing of $\nu_e, \nu_\mu, \nu_\tau \to$ 2 mass diff

$\to$ Explain only two evidences:

For example Solar + Atmos

- Theorists have tried hard to fit LSND in:

– Adding a fourth *sterile* neutrino

– Breaking CPT...

...but nothing works well

The Naked True:

If Miniboone finds a signal we have no good theory of what to do

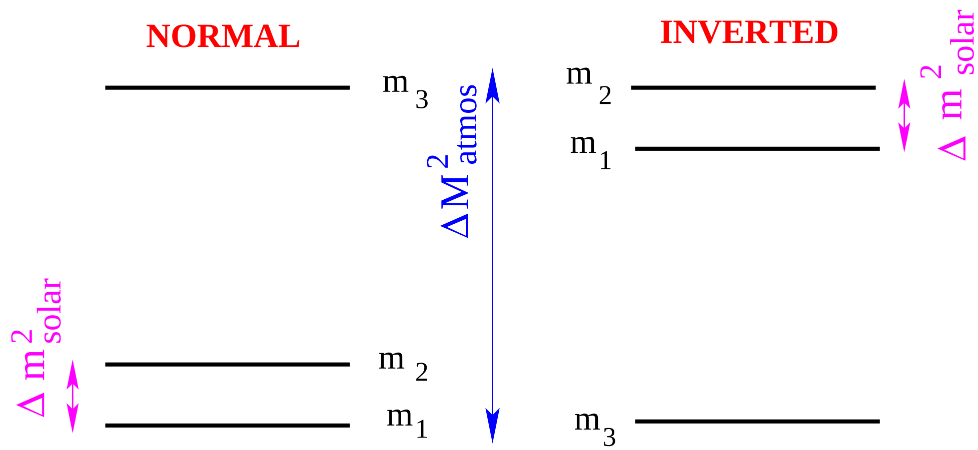
Ergo I am going to ignore LSND

Solar+Atmospheric+Reactor+LBL 3ν Oscillations

U: 3 angles, 1 CP-phase
+ (2 Majorana phases)

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Two mass schemes



2ν oscillation analysis $\Rightarrow \Delta m^2_{21} = \Delta m^2_{\odot} \ll \Delta M^2_{atm} \simeq \pm\Delta m^2_{32} \simeq \pm\Delta m^2_{31}$

Generic 3ν mixing effects:

– Interference of two wavelength oscillations

– Effects due to θ_{13}

– Difference between Inverted and Normal

– CP violation due to phase δ

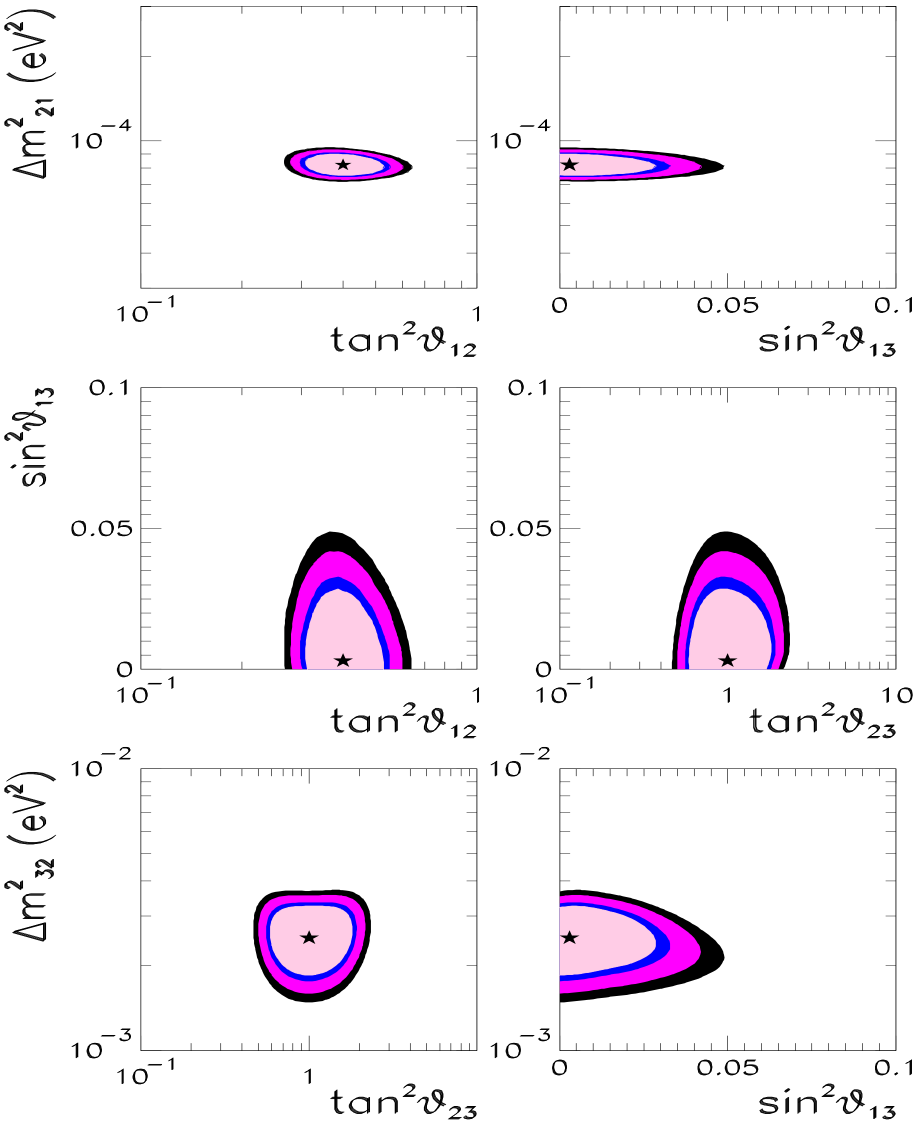
In Present Data:

2 wavelengths *Unobservable*
θ_{13} *Only a limit*
N versus I *Below sensitivity*
CP violation *Unobservable*

- But all these 3ν effects within reach of planned experiments

Global Analysis: Three Neutrino Oscillations

Projected allowed regions (2dof)



Best Fit:

$\Delta m^2_{21} = 7.1 \times 10^{-5}$ eV^2

$\tan^2\theta_{12} = 0.42$

$\sin^2\theta_{13} = 0.006$

$\Delta m^2_{31} = 2.4 \times 10^{-3}$ eV^2

$\tan^2\theta_{23} = 1.0$

Global Analysis: Three Neutrino Oscillations

The emerging: $|U_{\rm LEP}| = \begin{pmatrix} 0.73-0.89 & 0.44-0.66 & <0.24 \\ 0.23-0.66 & 0.24-0.75 & 0.51-0.87 \\ 0.06-0.57 & 0.40-0.82 & 0.48-0.85 \end{pmatrix}.$

with structure

$$|U_{\rm LEP}| \simeq \begin{pmatrix} \frac{1}{\sqrt{2}}(1+\mathcal{O}(\lambda)) & \frac{1}{\sqrt{2}}(1-\mathcal{O}(\lambda)) & \epsilon \\ -\frac{1}{2}(1-\mathcal{O}(\lambda)+\epsilon) & \frac{1}{2}(1+\mathcal{O}(\lambda)-\epsilon) & \frac{1}{\sqrt{2}} \\ \frac{1}{2}(1-\mathcal{O}(\lambda)-\epsilon) & -\frac{1}{2}(1+\mathcal{O}(\lambda)-\epsilon) & \frac{1}{\sqrt{2}} \end{pmatrix} \quad \begin{matrix} \lambda \sim 0.2 \\ \epsilon \lesssim 0.2 \end{matrix}$$

very different from quark's

$$|U_{\rm CKM}| \simeq \begin{pmatrix} 1 & \mathcal{O}(\lambda) & \mathcal{O}(\lambda^3) \\ \mathcal{O}(\lambda) & 1 & \mathcal{O}(\lambda^2) \\ \mathcal{O}(\lambda^3) & \mathcal{O}(\lambda^2) & 1 \end{pmatrix} \qquad \lambda \sim 0.2$$

Summary III

- The Data:

$$\Delta m^2_{31} \sim 2.4 \times 10^{-3}\ \text{eV}^2$$
$$\tan^2\theta_{23} \sim 1.0$$
$$\Delta m^2_{21} \sim 7.1 \times 10^{-5}\ \text{eV}^2$$
$$\tan^2\theta_{12} \sim 0.42$$
$$\sin^2\theta_{13} \lesssim 0.05$$

- U_{LEP} is very different from U_{CKM}
- If MiniBooNE confirms LSND, we lack an explanation
- Where are we going? What is the meaning of all this?

Tomorrow