Plan of Talks

1. The Standard Model and (a Little) Beyond
2. Neutrinos (Mainly) from Heaven
3. The Numbers and What They Tell Us
4. The Flavor Puzzle(s)
5. Leptogenesis

Plan of Talk III

The Numbers and What They Tell Us

1. Atmospheric Neutrinos (AN)
2. Reactor Neutrinos (RN)
3. Solar Neutrinos (SN)
4. New Physics
5. Grand Unified Theories (GUTs)

The Numbers...

Can I Detect AN?

Can I Detect AN?

Q. How many AN interact with a human?

$$N_{\rm int} = \Phi_\nu \times \sigma^{\nu p} \times N_p^{\rm human} \times T^{\rm human}$$

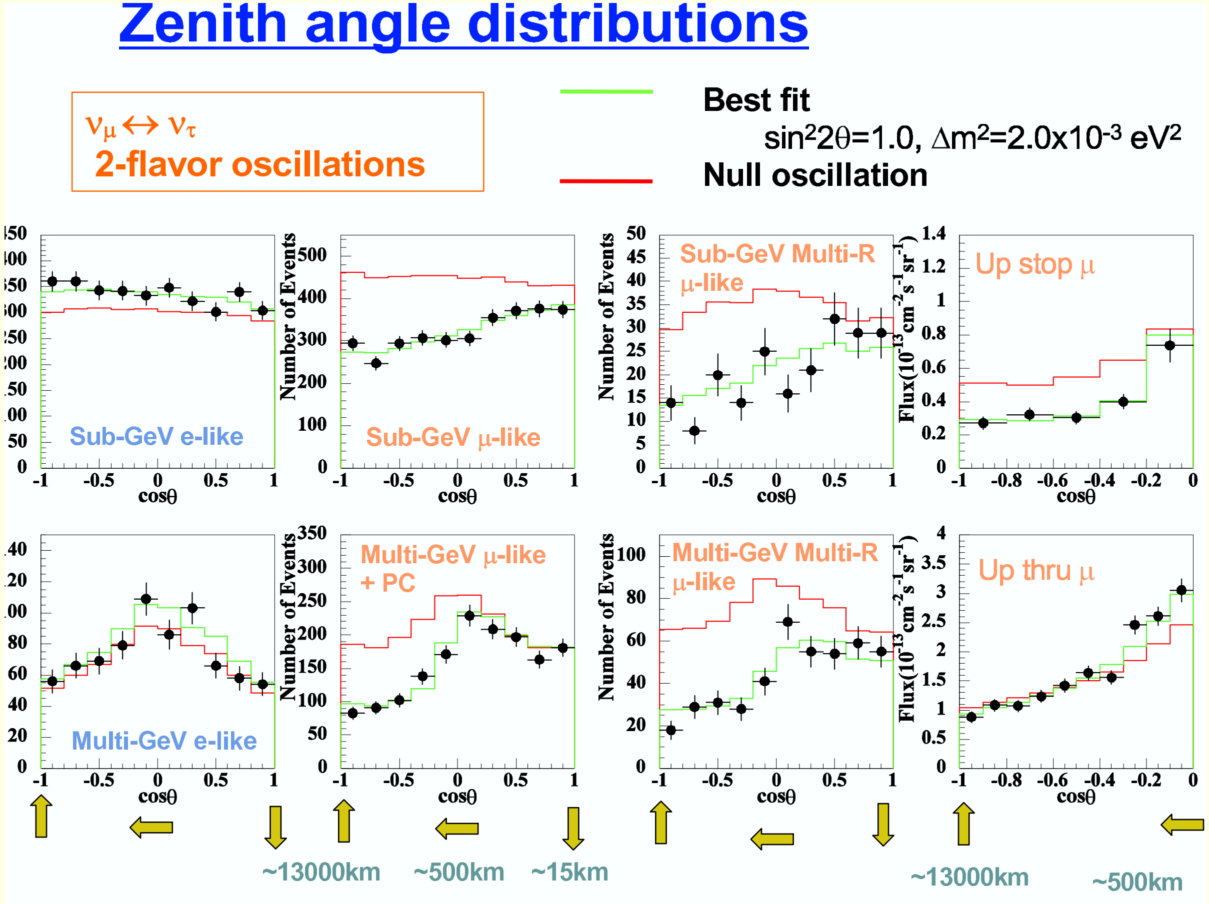
- $\Phi_\nu = \frac{1\ \nu}{{\rm cm}^2 \times {\rm sec}}$
- $\sigma_{\nu p} \sim 10^{-38}\ {\rm cm}^2$
- $N_p^{\rm human} = \frac{M^{\rm human}}{\rm gram} \times N_{\rm A} \sim 6 \times 10^{28}$
- $T^{\rm human} \sim 3 \times 10^9$ sec

1-2 interactions per lifetime

Exposure(human) $\sim$ 10 Ton-Year

$\Longrightarrow$ **Need Huge (Kton-Year) Detectors**

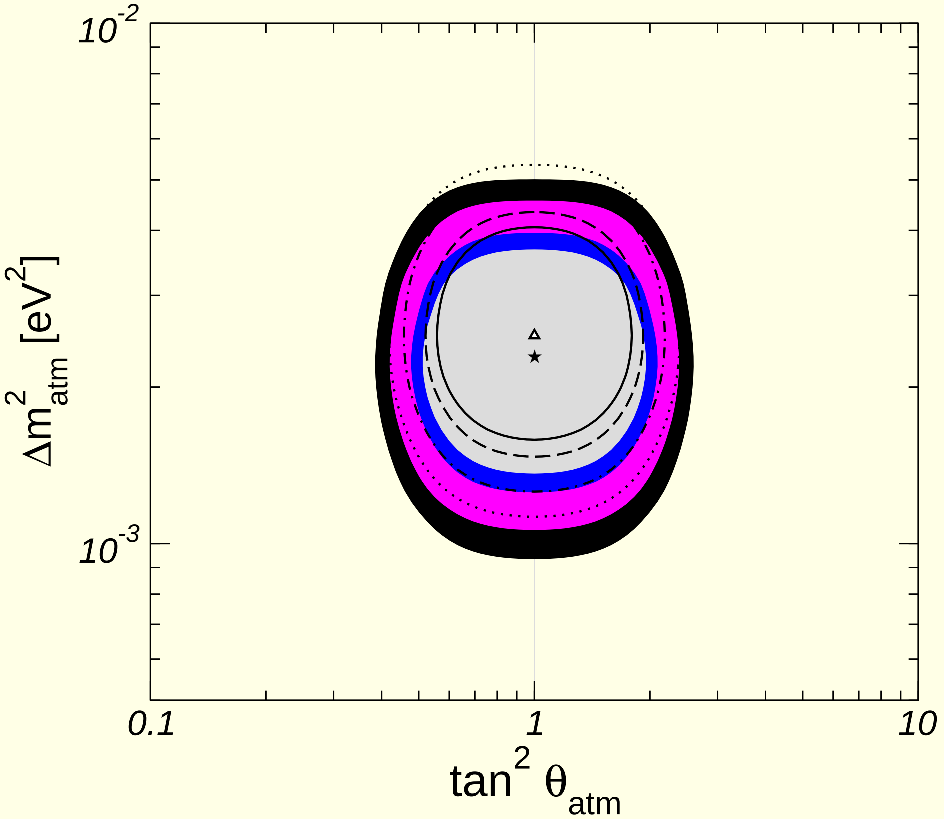
AN - results



Zenith angle distribution of SK

Saji, NOON2004

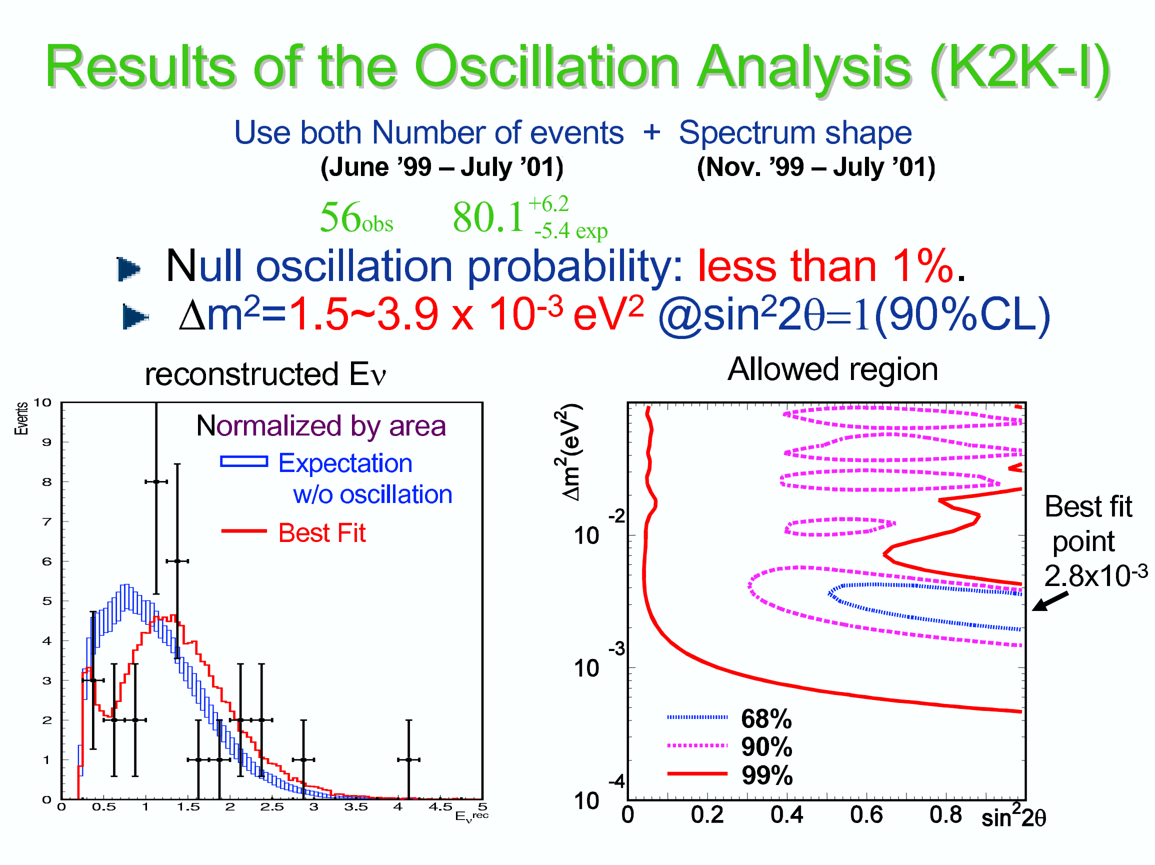
AN - theoretical interpretation



Allowed regions (at 90, 95, 99%, 3σ CL) from the analysis of the full data sample of AN for oscillation channel $\nu_\mu \to \nu_\tau$

Gonzalez-Garcia, NOON2004

K2K - results and interpretation



Accelerator ν_μ's with $E \sim 1.3\ GeV$ and $L \sim 250$ km

Ishii, NOON2004

RN - results

Reactor $\overline{\nu}_e$'s with $E \sim$ few MeV:

- CHOOZ

  $L \sim 1$ km

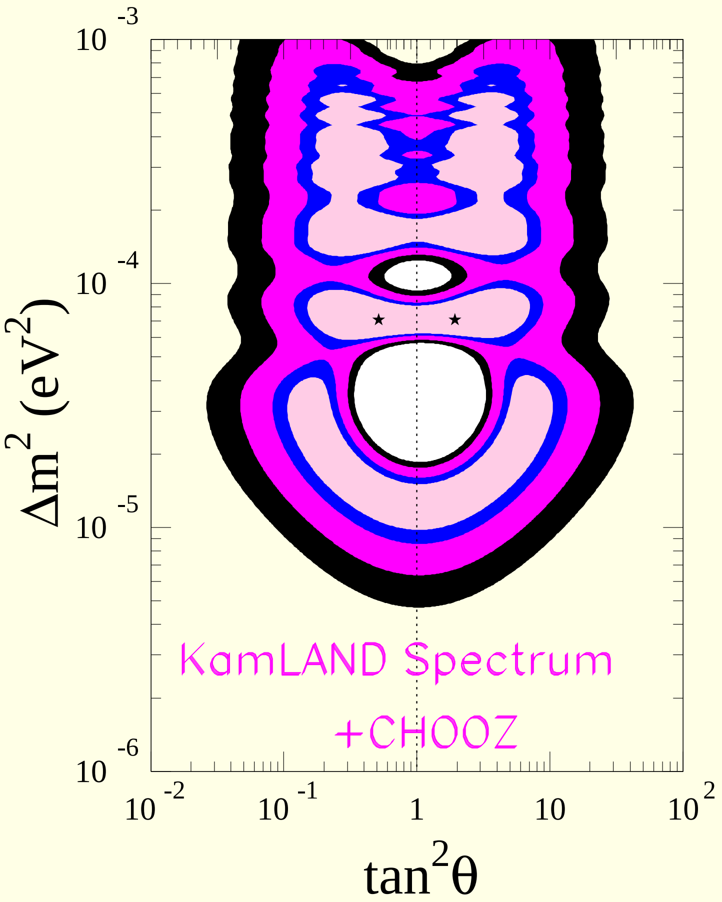
  $$\boxed{\frac{N_{\rm obs}}{N_{\rm no-osc}} = 1.01 \pm 0.028 \pm 0.027}$$

- KamLAND

  $L \sim 180$ km

  $$\boxed{\frac{N_{\rm obs}}{N_{\rm no-osc}} = 0.611 \pm 0.085 \pm 0.041}$$

RN - theoretical interpretation



Allowed regions (at 90, 95, 99%, 3σ CL) from the analysis of KamLAND and CHOOZ data

Gonzalez-Garcia, NOON2004

SN - The total flux

1	Chlorine	0.30 ± 0.03
1	Sage + Gallex/GNO	0.53 ± 0.03
44	Super-Kamiokande	0.403 ± 0.013
	SNO I CC	0.30 ± 0.02
34	SNO I NC	0.88 ± 0.11
	SNO I ES	0.41 ± 0.04
1	SNO II CC	0.28 ± 0.02
1	SNO II NC	0.89 ± 0.08
1	SNO II ES	0.38 ± 0.05

The beginning: Bahcall, Davis (1964)

SN - SNO (Phase I)

$$\nu_e + \mathrm{d} \rightarrow \mathrm{p} + \mathrm{p} + \mathrm{e}^- \qquad \phi_{\mathrm{CC}} = 1.76^{+0.06+0.09}_{-0.05-0.09}$$

$$\nu_a + \mathrm{d} \rightarrow \mathrm{p} + \mathrm{n} + \nu_a \qquad \phi_{\mathrm{NC}} = 5.09^{+0.44+0.46}_{-0.43-0.43}$$

$$\nu_a + \mathrm{e}^- \rightarrow \nu_a + \mathrm{e}^- \qquad \phi_{\mathrm{ES}} = 2.39^{+0.24+0.12}_{-0.23-0.12}$$

SN - SNO (Phase I)

$$\nu_e + \mathrm{d} \to \mathrm{p} + \mathrm{p} + \mathrm{e}^- \qquad \phi_{\mathrm{CC}} = 1.76^{+0.06+0.09}_{-0.05-0.09}$$

$$\nu_a + \mathrm{d} \to \mathrm{p} + \mathrm{n} + \nu_a \qquad \phi_{\mathrm{NC}} = 5.09^{+0.44+0.46}_{-0.43-0.43}$$

$$\nu_a + \mathrm{e}^- \to \nu_a + \mathrm{e}^- \qquad \phi_{\mathrm{ES}} = 2.39^{+0.24+0.12}_{-0.23-0.12}$$

- 5.3σ signal for solar $\nu_e \to \nu_{\mu,\tau}$ transformation

$$\boxed{\phi_{\mu,\tau} = (3.41^{+0.66}_{-0.64}) \times 10^6 \ \mathrm{cm}^{-2}\mathrm{s}^{-1}}$$

- Confirmation of the standard solar model

$$\boxed{\frac{\phi_{\mathrm{NC}}}{\phi_{\mathrm{SSM}}} = 1.01 \pm 0.12}$$

- Consistency check

$$\phi_{\mathrm{NC}} = [\phi_{\mathrm{ES}} - (1 - r)\phi_{\mathrm{CC}}]/r, \quad (r \equiv \sigma_{\mu,\tau}/\sigma_e)$$

SNO: SSM Test and Consistency Check

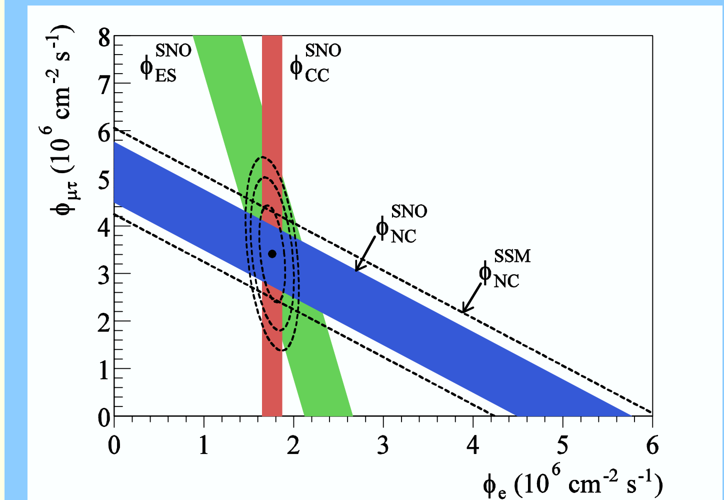
Flux Results – Pure D_2O Phase

$$\Phi_e = 1.76^{+0.05}_{-0.05}(stat.)^{+0.09}_{-0.09}(syst.)\times 10^6\,\mathrm{cm}^{-2}s^{-1}$$

$$\Phi_{\mu\tau} = 3.41^{+0.45}_{-0.45}(stat.)^{+0.48}_{-0.45}(syst.)\times 10^6\,\mathrm{cm}^{-2}s^{-1}$$

5.3 σ effect

Neutrinos Massive



Constrained Fit for flavour change test

$$\Phi_{SSM} = 5.05^{+1.01}_{-0.81}$$

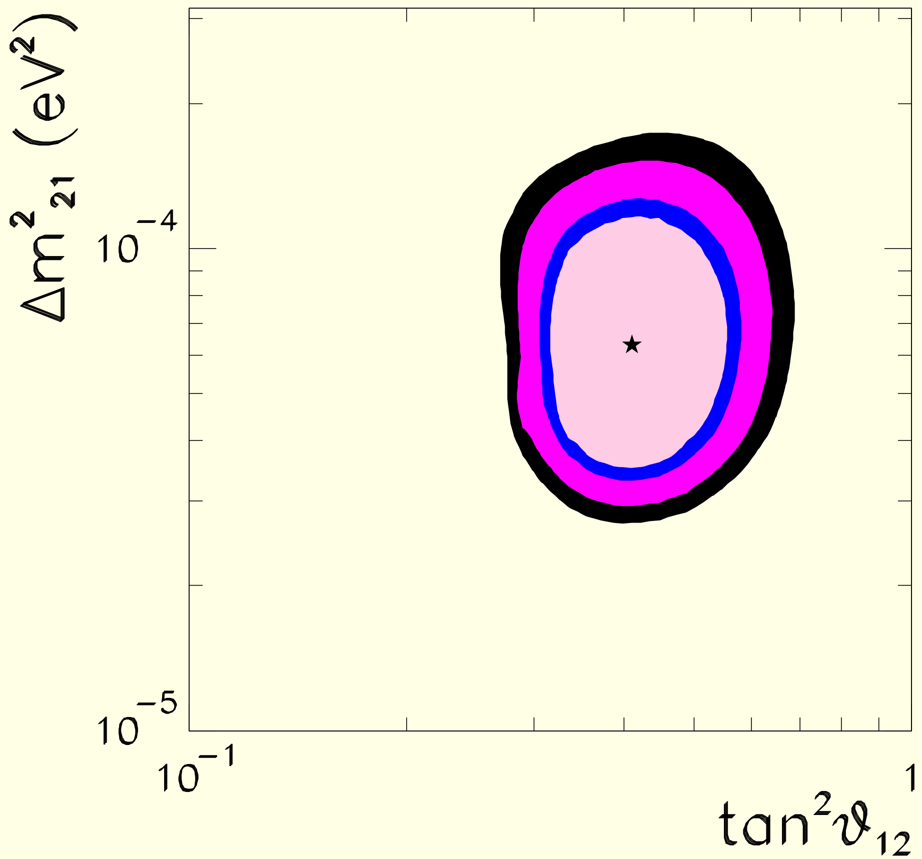
$$\Phi_{SNO} = 5.09^{+(0.44\oplus 0.46)}_{-(0.43\oplus 0.43)}$$

Without Constraint

$$\Phi_{SNO} = 6.42^{+(1.57\oplus 0.55)}_{-(1.57\oplus 0.58)}$$

Graham, NOON2004

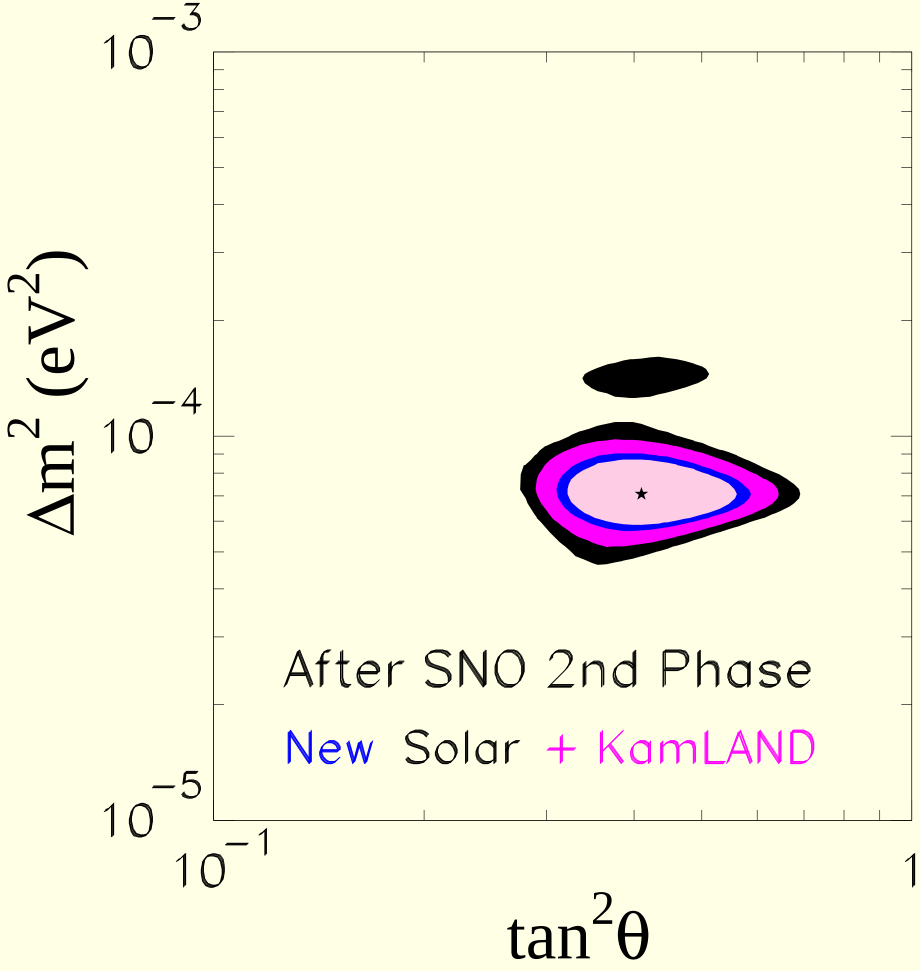
SN - theoretical interpretation



Allowed regions (at 90, 95, 99%, 3σ CL) from the analysis of solar neutrino data

Gonzalez-Garcia, NOON2004

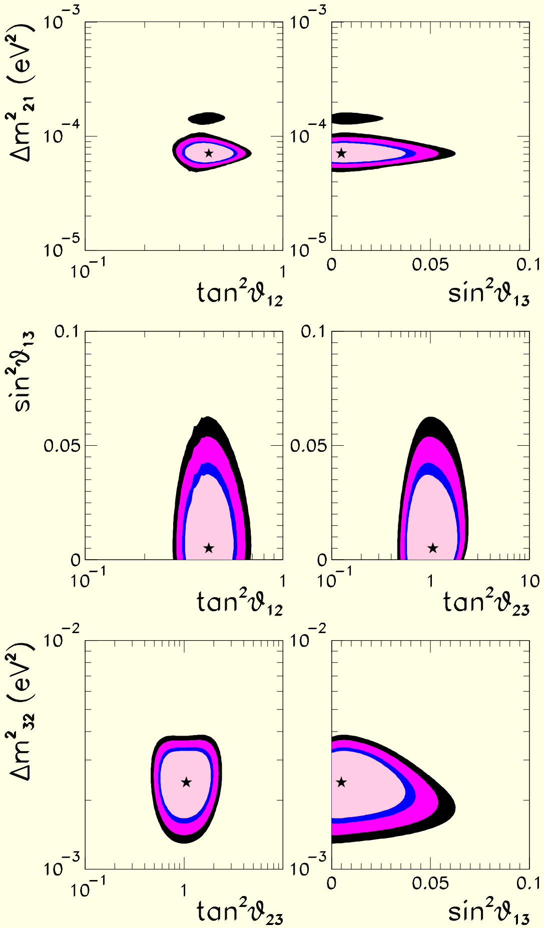
SN + RN - theoretical interpretation



Allowed regions (at 90, 95, 99%, 3σ CL)

Gonzalez-Garcia, NOON2004

A three generation analysis



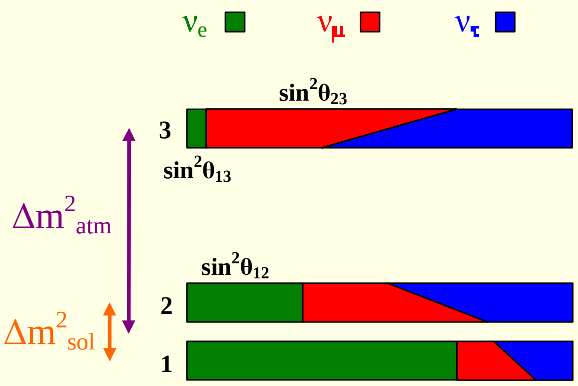
Allowed regions (at 90, 95, 99%, 3σ CL)

Gonzalez-Garcia + Pena-Garay, PRD68:093003, 2003 [hep-ph/0306001]

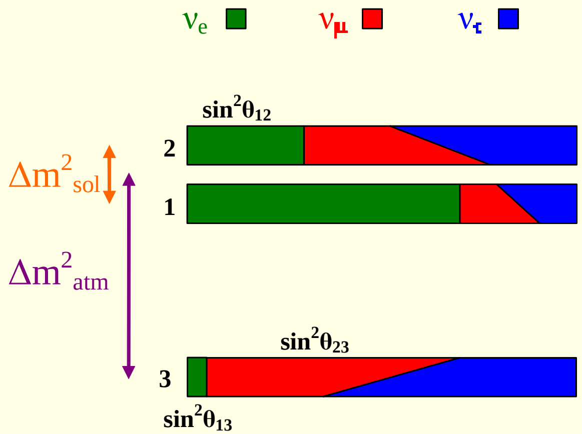
Allowed Ranges for Neutrino Parameters

	Best fit	3σ range
Δm^2_{32} $[eV^2]$	2.4×10^{-3}	$(1.4 - 3.4) \times 10^{-3}$
Δm^2_{21} $[eV^2]$	7.1×10^{-5}	$(5.2 - 9.8) \times 10^{-5}$
$\tan^2\theta_{23}$	1.0	$0.49 - 2.2$
$\tan^2\theta_{12}$	0.42	$0.29 - 0.64$
$\sin^2\theta_{13}$	0.006	≤ 0.054

Mixing and Hierarchy



Normal Hierarchy



Inverted Hierarchy

$$\sin^2\theta_{12} = 0.3, \quad \sin^2\theta_{13} = 0.05, \quad 0.33 < \sin^2\theta_{23} < 0.67$$

What we do not know

- The spectrum:
  Hierarchical or Degenerate?
- The hierarchy:
  Normal or Inverted?
- $|U_{e3}|$:
  Small or Tiny?

...and What They Tell Us

New Physics

> The Standard Model is NOT
> the complete picture of Nature

New Physics

> The Standard Model is NOT the complete picture of Nature

Most likely, the SM is only a low energy effective theory and lepton number is broken at some high energy scale

A specific realization: The See-Saw Mechanism

Heavy SM-singlet fermions, $M \gg \Lambda_{\text{EW}}$

$$\mathcal{L} = Y \phi^\dagger \overline{\nu_L} \nu_R + M \nu_R \nu_R \implies M_\nu = \begin{pmatrix} 0 & Y\langle\phi\rangle \\ Y\langle\phi\rangle & M \end{pmatrix}$$

$$\implies m_\nu = \frac{Y^2 \langle\phi\rangle^2}{M}$$

The Scale of New Physics

- SM = low energy effective theory
- $\mathcal{L}_{\rm NR} \sim \frac{1}{\Lambda_{\rm NP}} \phi\phi L L$

$\Longrightarrow$

$$\boxed{\Lambda_{\rm NP} \sim \frac{\langle\phi\rangle^2}{m_\nu}}$$

- AN: $m_\nu \gtrsim 0.04\ eV$

$\Longrightarrow$

$$\boxed{\Lambda_{\rm NP} \lesssim 10^{15}\ GeV}$$

The Scale of New Physics

- SM = low energy effective theory
- $\mathcal{L}_{\rm NR} \sim \frac{1}{\Lambda_{\rm NP}} \phi\phi L L$

$\Longrightarrow$

$$\boxed{\Lambda_{\rm NP} \sim \frac{\langle\phi\rangle^2}{m_\nu}}$$

- AN: $m_\nu \gtrsim 0.04\ eV$

$\Longrightarrow$

$$\boxed{\Lambda_{\rm NP} \lesssim 10^{15}\ GeV}$$

1. There is new physics at a scale well below the Planck scale
2. The upper bound is intriguingly close to the GUT scale

GUT

Why Believe in GUT?

1. Coupling unification
2. Multiplet unification
3. Flavor unification

GUT

Why Believe in GUT?

1. Coupling unification
2. Multiplet unification
3. Flavor unification

Why Be Cautious About GUT?

1. Proton decay
2. Doublet-Triplet splitting
3. Flavor splitting
4. Supersymmetry

AN: Three New Facts in Favor of GUT

1. $m_\nu \neq 0$

In SO(10): 1. Singlet fermions exist 2. M_ν related to M_u

$\Longrightarrow \quad m_\nu \neq 0$

AN: Three New Facts in Favor of GUT

1. $m_\nu \neq 0$

In SO(10): 1. Singlet fermions exist 2. M_ν related to M_u

$\Longrightarrow \quad m_\nu \neq 0$

2. $m_\nu \sim 0.05\ eV$

In SO(10): 1. $M_\nu^{\text{Dirac}} = M_u$ 2. $\Lambda_{SO(10)} \sim 10^{16}\ GeV$

$\Longrightarrow \quad m_{\nu_3} \sim \frac{m_t^2}{\Lambda_{SO(10)}} \sim 10^{-3}\ eV$

AN: Three New Facts in Favor of GUT

1. $m_\nu \neq 0$

In SO(10): 1. Singlet fermions exist 2. M_ν related to M_u

$\Longrightarrow \quad m_\nu \neq 0$

2. $m_\nu \sim 0.05\ eV$

In SO(10): 1. $M_\nu^{\rm Dirac} = M_u$ 2. $\Lambda_{SO(10)} \sim 10^{16}\ GeV$

$\Longrightarrow \quad m_{\nu_3} \sim \frac{m_t^2}{\Lambda_{SO(10)}} \sim 10^{-3}\ eV$

3. $|V_{\mu 3}| \sim 1$

In SU(5): 1. $M_\ell = M_d^T$ (2. $|V_{cb}| \sim 0.04$, $m_s/m_b \sim 0.03$)

$\Longrightarrow \quad |V_{\mu 3} V_{cb}| \sim m_s/m_b \quad \Longrightarrow \quad |V_{\mu 3}| \sim 1$

Summary

- The numbers:

$$\begin{aligned} \Delta m^2_{32} &\sim 2.4 \times 10^{-3}\ eV^2, \quad \Delta m^2_{21} \sim 7.1 \times 10^{-5}\ eV^2, \\ \tan^2\theta_{23} &\sim 1.0, \quad \tan^2\theta_{12} \sim 0.42, \quad \sin^2\theta_{13} \le 0.054. \end{aligned}$$

- The main lessons for theory:
  - There is New Physics
  - Most likely, the SM is only a low energy effective theory
  - $\Lambda_{\rm NP} \sim 10^{15}\ GeV\ (\ll m_{\rm Pl})$
  - The results ($m_\nu \neq 0$, $m_3 \sim 10^{-2}\ eV$, $|V_{\mu 3}| \sim 1$) fit GUT expectations nicely

Supersymmetry (with R-Parity)

MSSM

- $B - L$ = accidental symmetry $\Longrightarrow$ $m_\nu = 0$

MSSM=LEET

- $\frac{1}{\Lambda_{\rm NP}} LL\phi\phi$ allowed (R_p conserving) $\Longrightarrow$ $m_\nu \neq 0$ but small
- The supersymmetric partner of see-saw neutrino masses: Sneutrino-antisneutrino mixing $\Longrightarrow$ sneutrino oscillations

Grossman + Haber (1997)

MSSM+N

- Interesting new mechanisms (a-la Giudice-Masiero mechanism for suppressing μ) for $m_N \sim m_{3/2}$ but very light m_ν

Arkani-Hamed et al (2000); Borzumati et al (2000)

Supersymmetry without R-Parity

A Generic Problem

Naively, one mass at $\Lambda_{\rm EW}$ and two suppressed only by a loop factor.

- Must have a mechanism to ensure approximate lepton symmetry.

An Interesting Point

Many different sources for neutrino masses, allowing hierarchy simultaneously with large mixing.

1. μ and B misaligned: $\frac{m_2}{m_3} \sim \frac{g^2}{64\pi^2}$.
2. μ and B aligned at a high scale: RGE-induced misalignment gives appropriate hierarchy.
3. Only trilinear couplings (λ and λ') significant: $\frac{m_2}{m_3} \sim \frac{m_\tau^2}{3m_b^2}$.

Extra Dimensions

Large Extra Dimensions

If there is no $\Lambda_{NP} \gg$ TeV, the see-saw mechanism cannot be implemented
$\Longrightarrow$ There better be no singlet fermions confined to the brane.

(i) Coupling to bulk fermions: Arkani-Hamed et al (2002), Dienes et al (1999)

$$m_\nu^{\rm Dir} = \frac{Y\langle\phi\rangle}{\sqrt{V_n M_*^n}} = Y\langle\phi\rangle \frac{M_*}{M_{\rm Pl}}$$

(ii) Lepton number breaking on a distant brane: Arkani-Hamed et al (2002)

$$m_\nu^{\rm Maj} \sim \frac{\langle\phi\rangle^2}{M_*} e^{-mr}$$

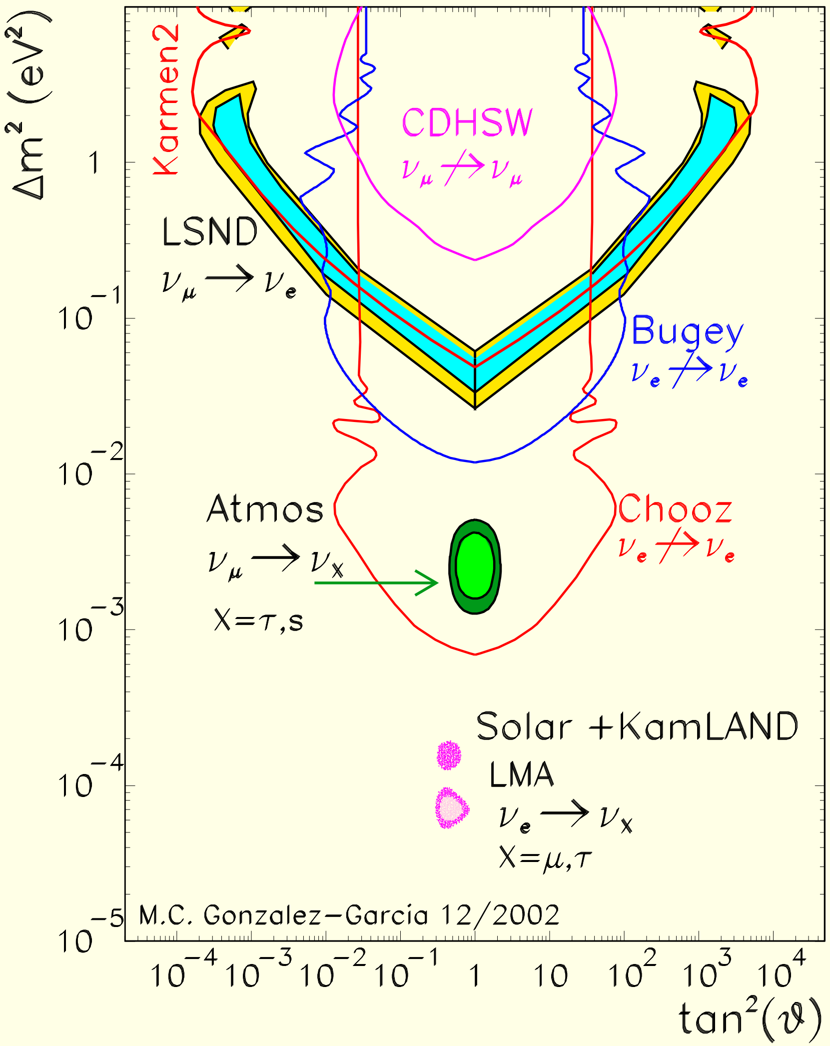
The Randall-Sundrum Scenario

(iii) Warp factor suppression: Grossman + Neubert (2000)

If the zero-mode of a bulk, singlet neutrino (of mass m) is located on the hidden brane,

$$m_\nu \sim \langle\phi\rangle \left(\frac{\langle\phi\rangle}{M_{\rm Pl}}\right)^{m/k-1/2}$$

Summary of Experimental Searches

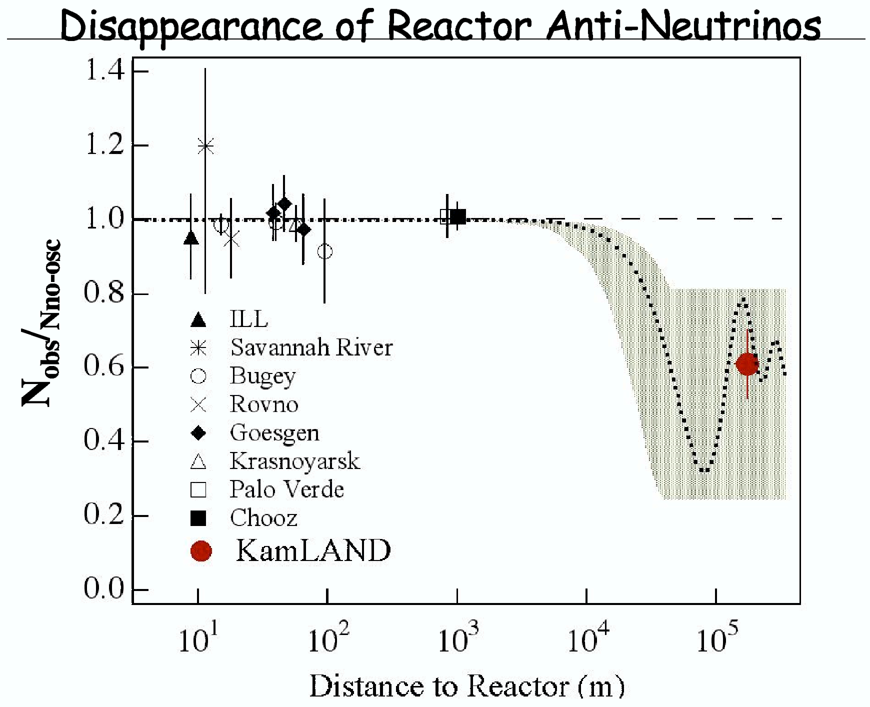


RN - results

Expected
86.8 + 5.6

Background
1 + 1

Observed
54



$N_{obs}/N_{no\text{-}osc}$ = 0.611 ± 0.085 (stat) ± 0.041 (syst)

Reactor $\overline{\nu}_e$'s with $E \sim\ MeV$ and $L \sim 1$ km (CHOOZ) or $\sim$ 200 km (KamLAND)

KamLAND - results