Solar Neutrinos: Interpretation of Results

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* Looking at the experimental results
* Profile of the effect
* Global solutions

* Leading and sub-leading
  U_e3 in solar neutrinos
  sterile component
* Spin-flavor Flip
* Non-standard neutrino interactions

Solar Neutrinos: 2000 - 2002

Breakthrough:
First direct evidence of
flavor conversion

Main conclusion:

Solar neutrinos undergo flavor conversion

$\nu_e \rightarrow \nu_\mu, \nu_\tau$ or/and $\bar{\nu}_\mu, \bar{\nu}_\tau$

Key word:

Appearance

- Appearance of the muon and tau neutrino flux from the Sun
- Non-electron neutrinos compose main part of the flux at high energies $E > 5$ MeV

Main issue: Mechanism of conversion?

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Profile of the Effect

V. S. Berezinsky, M. Lissia
G.L. Fogli, E. Lisi,
D.Montanino, A. Palazzo

Reconstructing the energy dependence
of the survival probability

1. SK/SNO
   SNO NC/CC → P_{ee}(> 5 MeV)

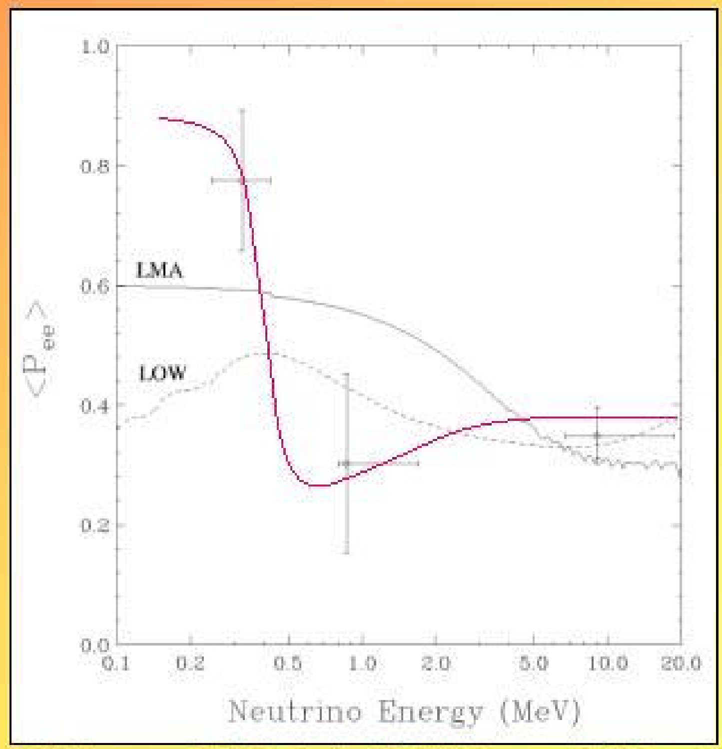
   Suppression of Boron neutrinos
   independently on SSM

2. Cl - SK/SNO
   over SSM → P_{ee}(0.8 - 1.5 MeV)

   Probability in the range of Be, CNO

3. Ga - Cl - SK/SNO
   over SSM → P_{ee}(0.2 - 0.4 MeV)

   Probability for pp neutrinos



V. Barger, D Marfatia, K. Whisnant B.Wood

Time variations

Day-Night

SK: $A_{DN} = - 2.1 \pm 2.0^{+1.3}_{-1.2}$ %

SNO (CC): $A_{DN} = - 7.0 \pm 4.9^{+1.5}_{-1.4}$ %

Weeks

Gallium experiments: ?

P.A. Sturrock, M.A. Webber
J. D. Scargle

Seasonal

SK: in agreement with geometrical (eccentricity effect)

SAGE:
Gallex, GNO: no statistically significant variations

11 years

Homestake: ?

SK: no

SAGE
GALLEX no

No strong identification in the fits: upper bounds play important role

SNO 2002: Implications

Q. R. Ahmad et al., SNO collaboration nucl-ex/0204009

1. V. Barger , D. Marfatia, K.Whisnant, B. P. Wood, hep-ph/0204253
2. A. Bandyopadhyay, S. Choubey, S. Goswami, D.P. Roy, hep-ph/0204286
3. P. Creminelli, G. Signorelli, A. Strumia, addendum n2 (April 22, 2002) hep-ph/0102234
4. J. N. Bahcall, M.C. Gonzalez-Garcia, C. Pena-Garay, hep-ph/0204314
5. P.Aliani, V. Antonelli, M. Picariello, E. Torrente-Lujan, hep--ph/0205053
   V. Antonelli (poster session)
6. M. Smy, SK collaboration

Global Fit

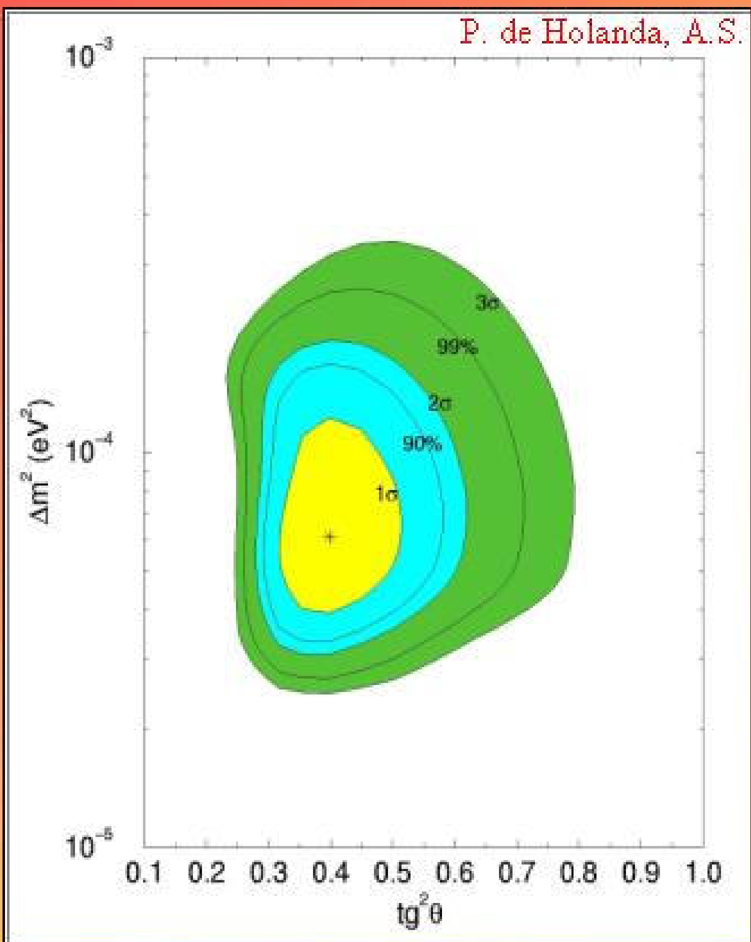
P. de Holanda, A.S.
hep-ph/0205241

Data	Neutrino fluxes	Neutrino model
- Homestake - SAGE - GNO+GALLEX (rates) - SuperKamiokande: Zenith spectra - SNO: Day and Night spectra	- BP2000 - Boron neutrino flux: $f_B = F_B / F_B^{SSM}$ free parameter - $F_{hep} = 0.93\ 10^4\ cm^{-2}\ c^{-1}$	Two neutrino mixing Oscillation parameters: Δm^2, $\tan^2\theta$

81 data points

79 d.o.f.

LMA MSW



- **Best fit point:**

$$\Delta m^2 = 6.2\ 10^{-5}\ eV^2$$
$$\tan^2\theta = 0.40$$
$$f_B = 1.06$$

- **1σ - intervals:**

$$\Delta m^2 = (4 - 12)\ 10^{-5}\ eV^2$$
$$\tan^2\theta = 0.32 - 0.51$$

- **3σ - bounds:**

$$\Delta m^2 < 3.3\ 10^{-4}\ eV^2$$

$$\tan^2\theta < 0.80$$

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How large is the Large mixing

Upper bound on mixing angle controlled by

$$\frac{CC}{NC} \sim \sin^2\theta$$

$$Q_{Ar} \sim f_B \sin^2\theta$$

$$Q_{Ge} \sim 1 - 0.5 \sin^2 2\theta$$

P. de Holanda, A.S.

- $$\tan^2\theta < \begin{cases} 0.51 & 1\sigma \\ 0.62 & 2\sigma \\ 0.79 & 3\sigma \end{cases}$$
- 3σ - bounds from different analyses:

$$\tan^2\theta < \begin{cases} 0.55 & \text{SNO} \\ 0.64 & \text{Barger et al} \\ 0.89 & \text{Bahcall et al} \end{cases}$$

Deviation from maximal

$$\varepsilon = 0.5 - \sin^2\theta$$

$$\varepsilon > 0.06\,, \quad 3\sigma$$

$$\varepsilon > \lambda = \sin^2\theta_C$$

Expansion parameter — Cabibbo angle

Maximal mixing:

Accepted at 4σ

For maximal mixing

$$\frac{NC}{CC} < 2 \quad (-2.2\,\sigma)$$

$$Q_{Ge} \sim 64 \text{ SNU} \quad (-1.8\,\sigma)$$

$$Q_{Ar} \sim 3.2 \text{ SNU} \quad (+2.8\,\sigma) \qquad (f_B = 0.85)$$

Important implications for theory

Double beta decay, determination of the absolute scale of neutrino masses

How high is the high Dm2

Upper bound on Δm^2

Implications for
- measurements of Δm^2
- future LBL experiments
- determination of CP violation phase
- theory of neutrino mass

The upper bound is controlled by

- Day-Night asymmetry:

  $A_{DN} \sim (\Delta m^2)^{-1}$

- NC/CC
- Q_{Ar}

P. de Holanda, A.S.

- $$\Delta m^2 < \begin{cases} 1.2\ 10^{-4}\ eV^2, & 1\sigma \\ 1.9\ 10^{-4}\ eV^2, & 2\sigma \\ 3.4\ 10^{-4}\ eV^2, & 3\sigma \end{cases}$$

- 3σ - bounds:

$$\Delta m^2 < \begin{cases} 1.9\ 10^{-4}\ eV^2, & \text{SNO} \\ 2.3\ 10^{-4}\ eV^2, & \text{Barger et al} \\ 3.7\ 10^{-4}\ eV^2, & \text{Bahcall et al} \end{cases}$$

- At maximal allowed value $\Delta m^2 \sim 3.4\ 10^{-4}\ eV^2$

  $A_{DN}^{ES} \sim 0.01\ \%$ $A_{DN}^{CC} \sim 0.01\%$

  NC/CC ~ 2

  $Q_{ar} \sim 3.25$ SNU

HLMA?

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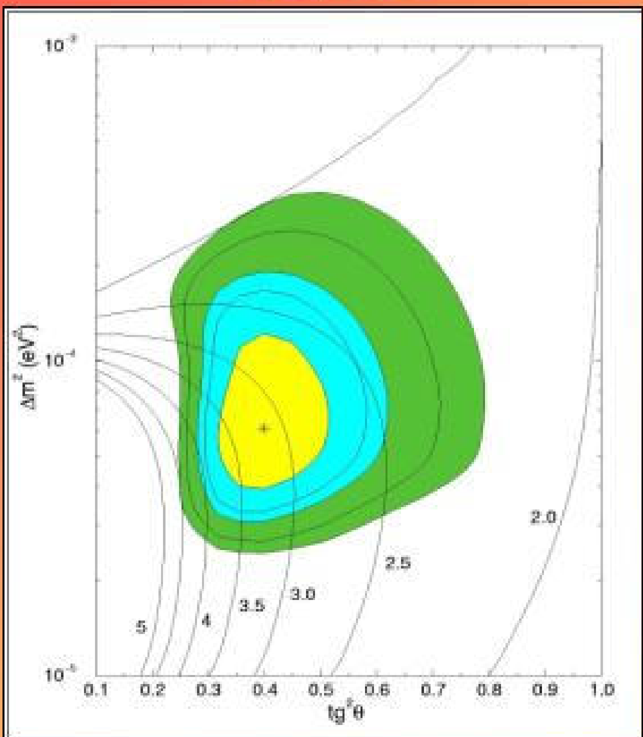
Grids of predictions

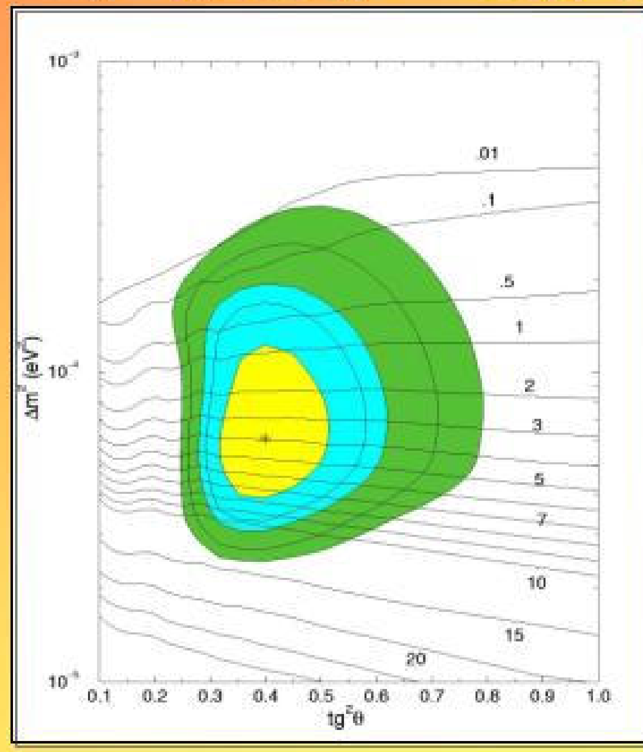
NC / CC



NC/CC (b.f.) = 3.15

3σ: ~ - (2.0 - 4.5) %

Day-Night asymmetry, %



A_{DN}^{CC} (b.f.) = - 3.9 %

3σ: - (~ 0 - 14) %

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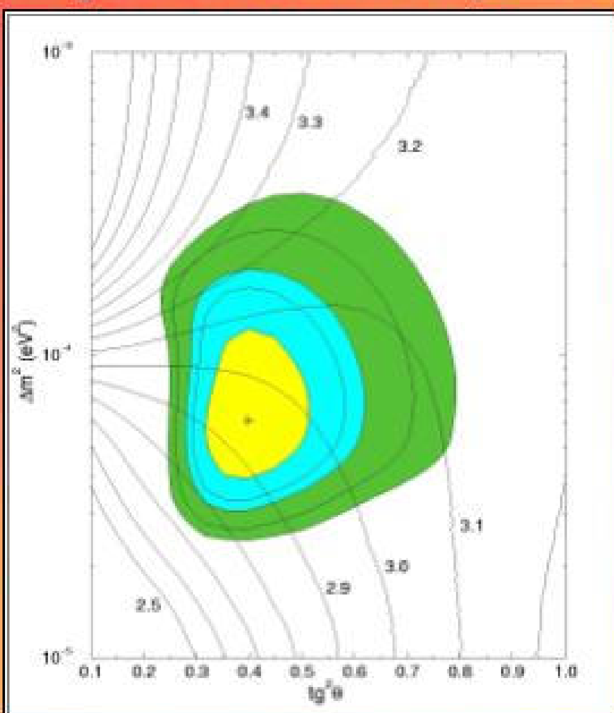
Grids of predictions

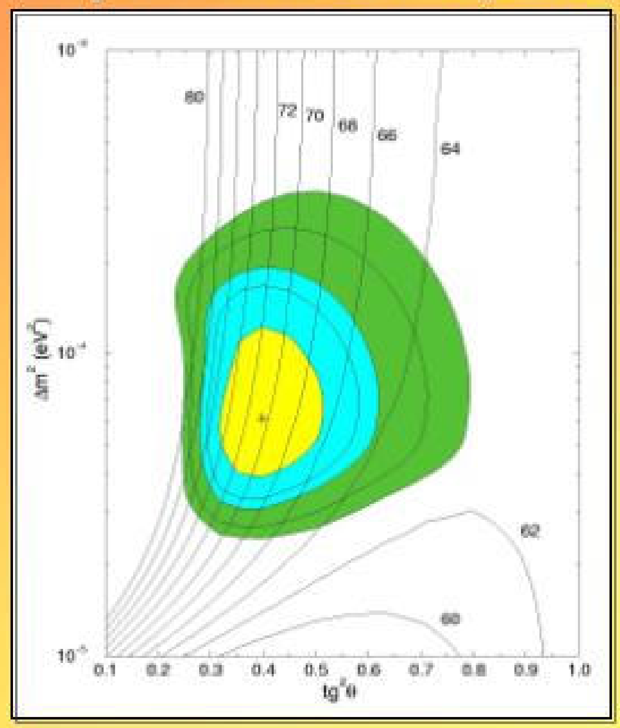
Ar-production rate, SNU



b.f.: $Q_{Ar} = 2.95$ SNU

3σ: $Q_{Ar} = (2.7 - 3.35)$ SNU

Ge-production rate, SNU



b.f.: $Q_{Ge} = 70.5$ SNU

3σ: $Q_{Ge} = (63 - 84)$ SNU

Alternatives?

LMA

RSFP

in convective zone

in radiative zone

non-RSFP

LOW

VO-QVO

FCNC


Alternatives?
RSFP
KamLAND
radiative
zone
non-RSFP
LOW
QVO
FCNC
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LOW disappears?

Best fit point

$\Delta m^2 = 0.93 \; 10^{-7} \; eV^2$
$\tan^2\theta = 0.63$
$f_B = 0.91$

χ^2 / d.o.f = 78.9/78

χ^2 (LOW) - χ^2 (LMA) = 13.2

➡ Accepted at 99.89% CL
Does not appear at 3σ - level

Features of the fit

Day - Night asymmetries:

A_{DN}^{CC} = 3.6 % A_{DN}^{ES} = 2.7 %

Zenith spectra at SK: important for quality of the fit

Rates:

Q_{Ar} = 3.1 SNU

Q_{Ge} = 66.5 SNU

NC/CC = 2.35

SMA: any chance?

Best fit point

$\Delta m^2 = 5.0 \; 10^{-6} \; eV^2$
$\tan^2\theta = 5.0 \; 10^{-4}$
$f_B = 0.58$

χ^2 / d.o.f = 99.9/79
χ^2 (LOW) - χ^2 (LMA) = 34.2
⇨ Appears at 5.5σ - level

For $\tan^2\theta = 1.5 \; 10^{-3}$
χ^2 / d.o.f = 105/79

Features

Reasonable fit of SK data
Very bad fit of the day and night spectra at SNO

A_{DN}^{CC} = - 0.86 %
3σ lower boron neutrino flux

NC/CC ~ 1.4

⇨ Suppressed contribution of the NC events to the total rate distortion of spectrum

Excluded, unless some systematic error will be found in the SNO or/and SK results

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VO-QVO

- **Best fit point**

$\Delta m^2 = 4.5 \; 10^{-10} \; eV^2$
$\tan^2\theta = 2.06$
$f_B = 0.72$

In the ``dark'' side: some matter effect is present

χ^2 / d.o.f = 76.1/79

χ^2 (QVAC) - χ^2 (LMA) = 10.4

→ accepted at 3σ - level:

Spot in the parameters plane

- **Features**

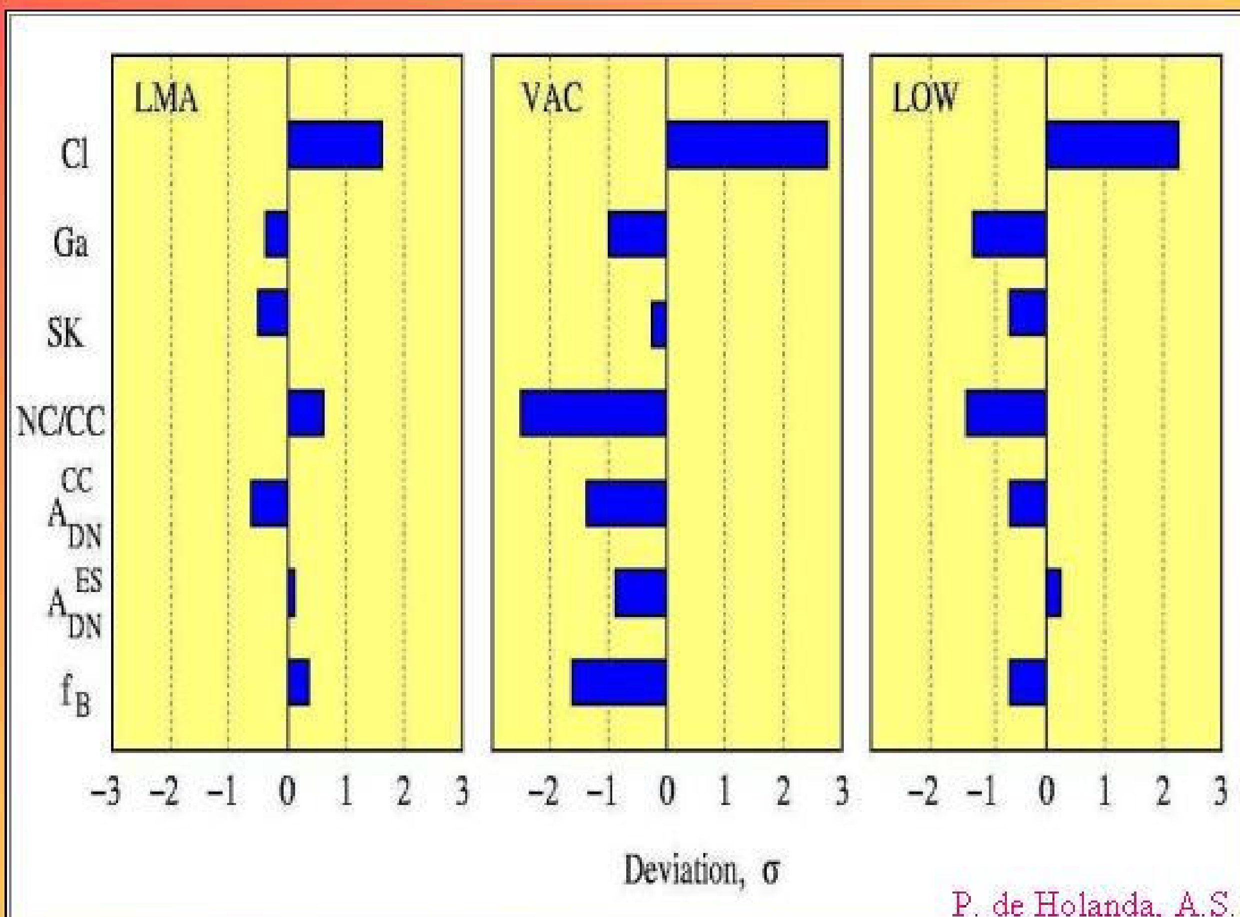
- no D-N asymmetry
- 2σ- lower boron neutrino flux

SSM restriction on f_B
exclusion at 3σ -level

Q_{Ar} = 3.2 SNU
Q_{Ar} = 67.5 SNU

NC/CC = 1.86

Pull-off diagrams



D-N Asymmetry: SK vs. SNO

$$A_{ND}^{CC} = \left(1 + \frac{r}{(1 - r)\,P}\right) A_{ND}^{ES}$$

Bahcall
Krastev, A.S

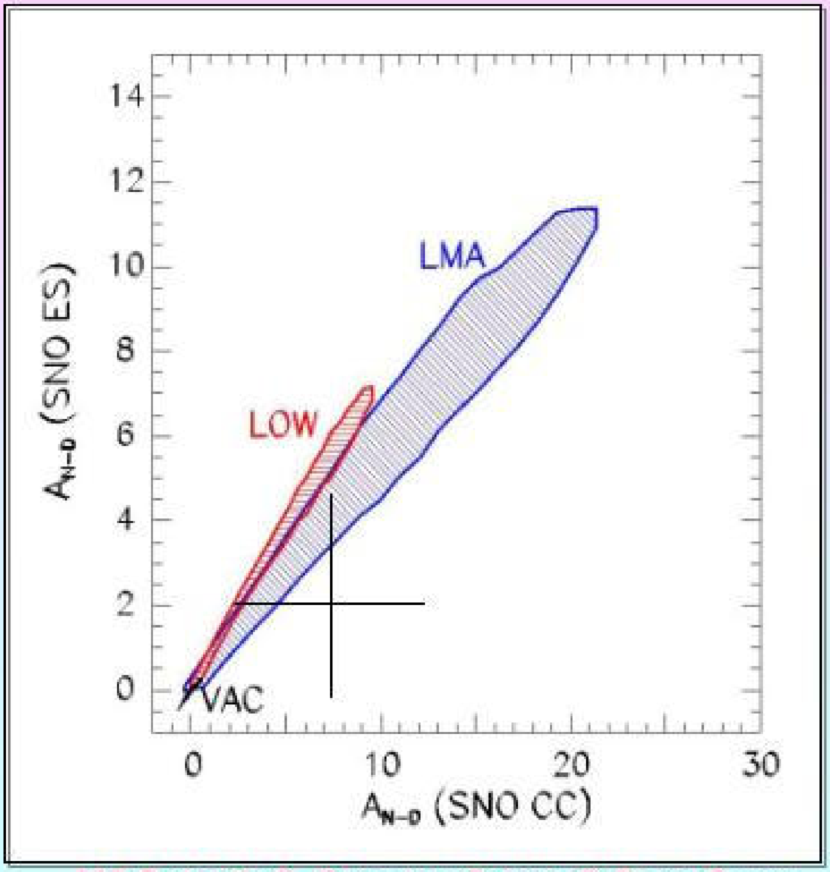
``dumping'' factor
for ES

P is the averaged survival probability
$P \sim \sin^2\theta$ (LMA, LOW)

$r = \sigma(\nu_\mu e) / \sigma(\nu_e e)$

The asymmetry in ES is suppressed due to effect of ν_μ/ν_τ neutrinos

The effect is significant (in spite of smaller cross-section) since the ν_μ/ν_τ flux is 2 - 4 larger than ν_e-flux



J.N. Bahcall, C. Gonzalez-Garcia, C. Pena-Garay

Leading and sub-Leading

LMA or ...?

U_e3

sterile neutrino

decay

Leading or sub-Leading?

magnetic moment

non-standard interactions

hybrid solutions?

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Solar neutrinos and U_e3

- Context: 3ν scheme solar + atmospheric $\Delta m^2_{13} >> 2EV$

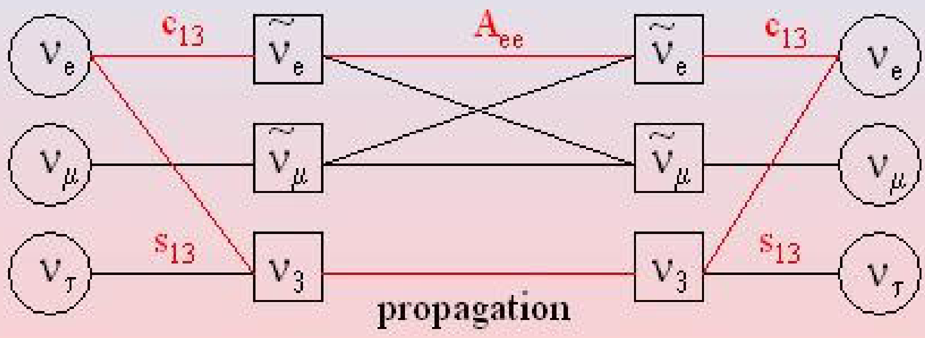
- Propagation basis: $(\nu_e\ \nu_\mu\ \nu_\tau) \Rightarrow (\tilde{\nu}_e\ \tilde{\nu}_\mu\ \nu_3)$

$\tilde{\nu}_e = (U_{e1}\ \nu_1 + U_{e2}\ \nu_2)/\sqrt{1 + U_{e3}^2}$

$\tilde{\nu}_\mu = (U_{e1}\ \nu_2 - U_{e2}\ \nu_1)/\sqrt{1 + U_{e3}^2}$

$\Rightarrow$ ν_3 - ``decouples'' producing averaged oscillation effect
$\tilde{\nu}_e - \tilde{\nu}_\mu$ mix, and convert

- scheme of transition



projection

- $P_{ee} = \cos^4\theta_{13}\, P_2 + \sin^4\theta_{13}$

where $P_2 = P(\tilde{\nu}_e \to \tilde{\nu}_e) = |A_{ee}|^2$

is determined by Δm^2_{12} $\tan^2\theta_{12} = \frac{U_{e2}^2}{U_{e1}^2}$ $V = \cos^2\theta_{13}\, V_e$

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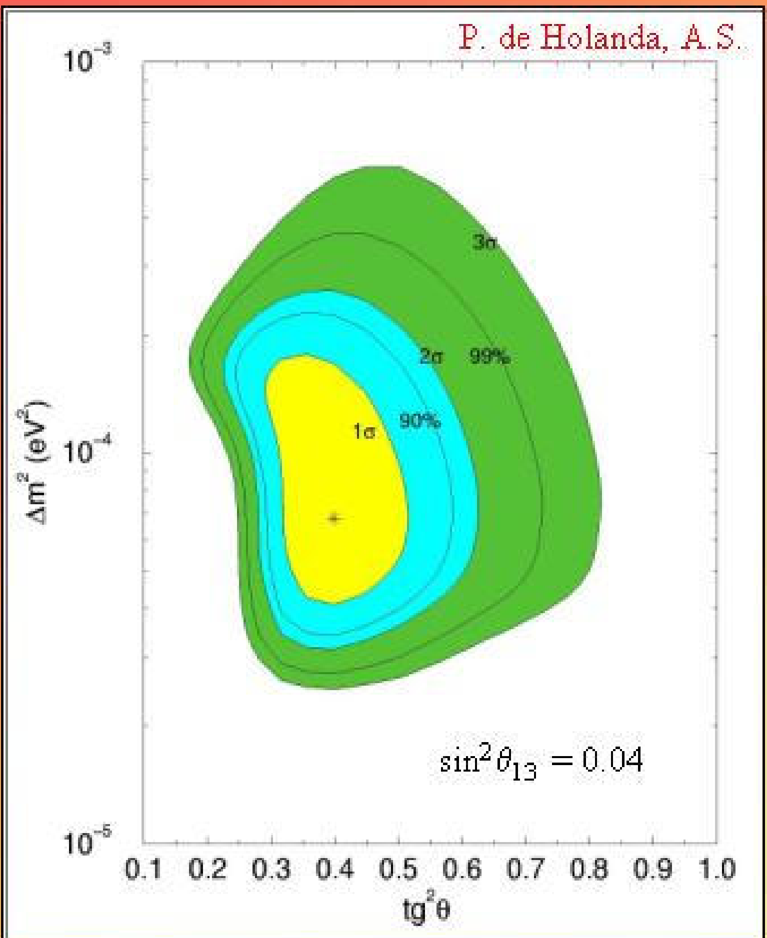
LMA and U_e3



- Best fit point:

$\Delta m^2 = 6.8\ 10^{-5}\ eV^2$
$\tan^2\theta = 0.40$
$f_B = 1.096$

- χ^2 /d.o.f. = 67.3/79

$\Delta\chi^2 = 1.7$

θ_{13} worsen the LMA fit

- 3σ - bounds:

$\Delta m^2 < 5.4\ 10^{-4}\ eV^2$

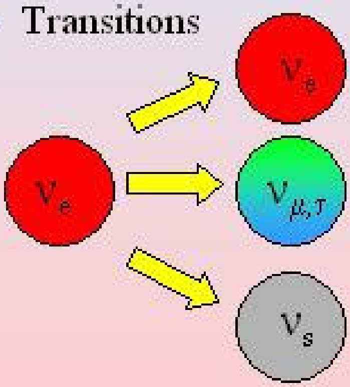
$\tan^2\theta < 0.82$

Nu_s and solar neutrinos

- Pure oscillations $\nu_e - \nu_s$ are excluded at about 5σ level
- Oscillations $\nu_e - \nu_x$ where

$$\nu_x = \cos\eta\ \nu_{\mu,\tau} + \sin\eta\ \nu_s$$

- Transitions



P_{ee}

$(1 - P_{ee}) \cos^2\eta$

$(1 - P_{ee}) \sin^2\eta$

- Matter potential is modified:

$$V = \sqrt{2}\, G_F \left(n_e - \sin^2\eta\ \frac{n_n}{2}\right)$$

- Fluxes detected by different reactions

charged currents:

$$\Phi_{CC} = f_B\ P_{ee}$$

neutral currents:

$$\Phi_{NC} = f_B\,[1 - (1 - P_{ee}) \sin^2\eta\,]$$

neutrino-electron scattering

$$\Phi_{ES} = f_B\,[P_{ee} - r\,(1 - P_{ee}) \cos^2\eta\,]$$

where f_B is the boron neutrino flux

$$r = \sigma(\nu_\mu\, e) / \sigma(\nu_e\, e)$$

Degeneracy of parameters:

two combinations $f_B P_{ee}$ $f_B\,(1 - P_{ee})\cos^2\eta$

Barger et al,

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Bound on sterile

Global fit of the solar neutrino data

For each pair of values of
$\cos^2\eta$ and f_B
χ^2 is minimized with respect to
Δm^2, $\tan^2\theta$

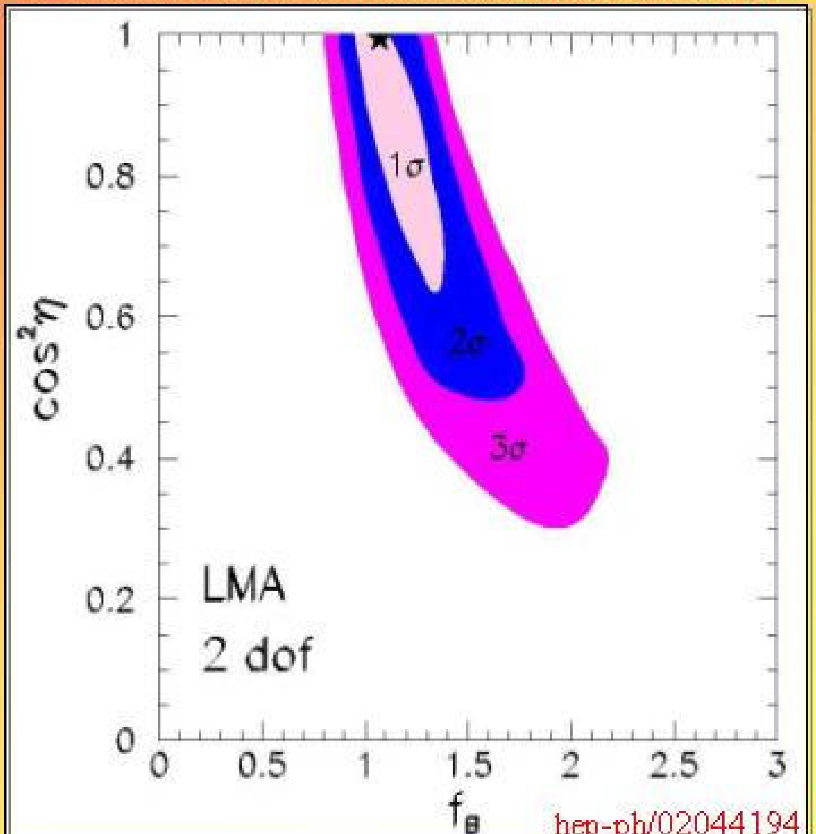
⇨ $\chi^2(\cos^2\eta, f_B)$

χ^2_{min}

$\sin^2\eta = 0, \quad f_B = 1.07$

$$\sin^2\eta < \begin{cases} 0.35, & 1\,\sigma \\ 0.70, & 3\,\sigma \end{cases}$$

J.N.Bahcall, M.C. Gonzalez-Garcia, C Pena-Garay



hep-ph/02044194

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Spin-Flavor Precession

Resonance spin-flavor precession:
unique possibility to reconcile

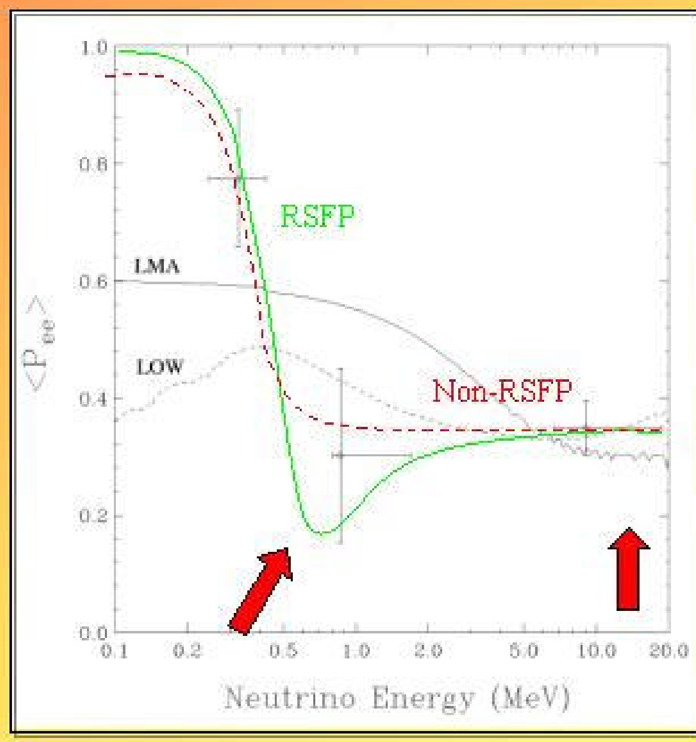
Strong suppression at intermediate energies ⟷ no distortion at high energies

C.S.Lim, W. J. Marciano
E. Kh. Akhmedov

Non-resonance spin flavor precession:
profile similar to LMA

O.G. Miranda, C. Pena-Garay, T.I. Rashba,
V. B. Semikoz, J. W. F. Valle, hep-ph/0108145

μ_ν = (0.3 - 1) 10^{-11} μ_B
$B_{max} \sim$ 100 kG
Specific B(r) dependence



Resonance region

VVO region

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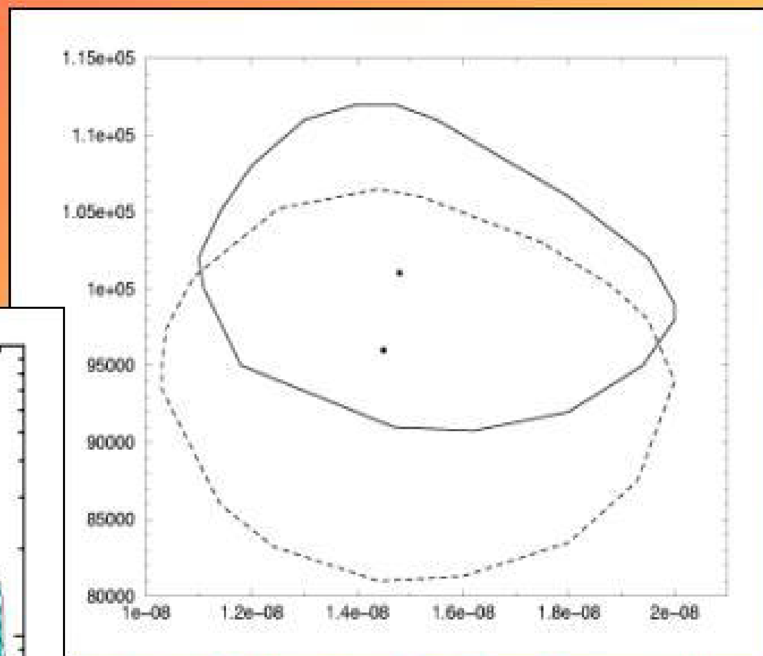
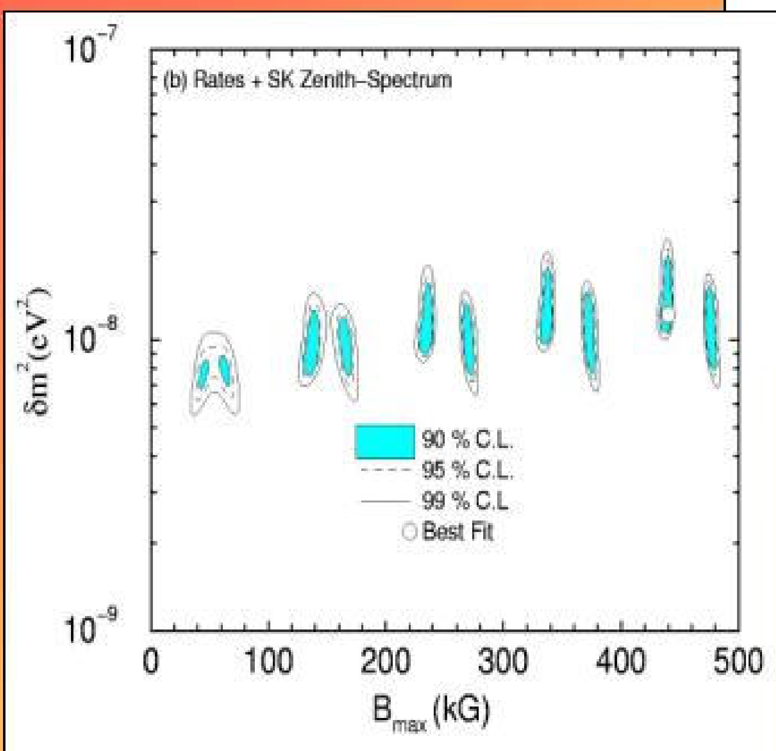
Solutions



E. Kh. Akhmedov, J. Pulido, Astropart. Phys. 13 (2000)



A.M. Gago et al, Phys. Rev. D65:073012 (2002)

$\Delta m^2 = (1 - 2)\ 10^{-8}\ eV^2$

$B_{max} > 80$ kG

Time variations of signals

A. Friedland, A Gruzinov
hep-ph/0202095

Generic consequence of the SFP in the convective zone

Time variations of signals

11 years
annual
semiannual
27 days

No significant variations of neutrino signals have been found

- Surface magnetic field: 11 years variations

  There is no model with: Constant large scale field in the convective zone and Variations of surface field

- Large scale field in the convective zone → Convective mixing → Should be seen at the surface

- Equatorial gap / Eccentricity of the Earth orbit → Semiannual variations

  Voloshin
  Vysotsky
  Okun

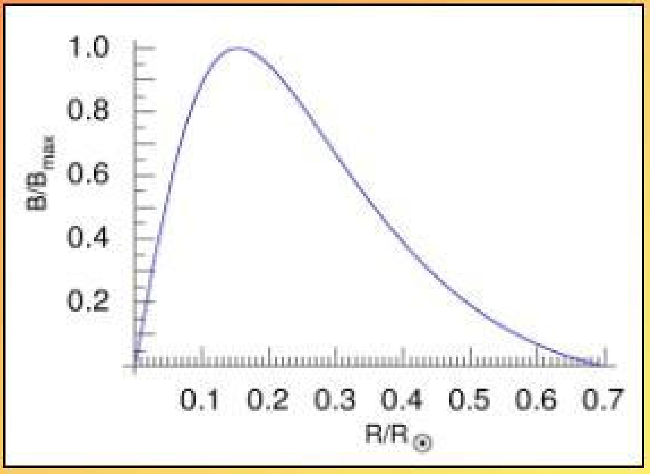
Spin-Flip in the radiative zone

A. Friedland, A Gruzinov, hep-ph/0202095

Strong relic field in the radiative zone
frozen configuration ⇨ constant

B = (0.4 - 0.6) MG

toroidal



Mixing in the production point

Survival probability:

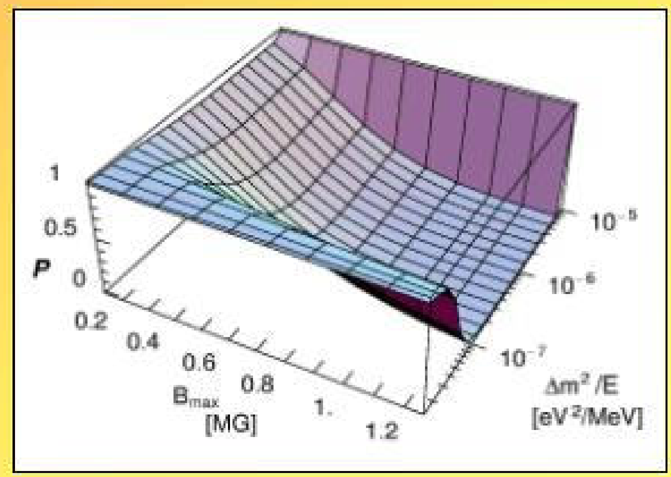
$P_{ee} = 0.5 \; [1 - (1 - 2P_c) \cos 2\theta_0 \,]$

P_c is the level crossing probability

$P_{ee} \sim 0.3$ ⇨ the flip should be non-adiabatic

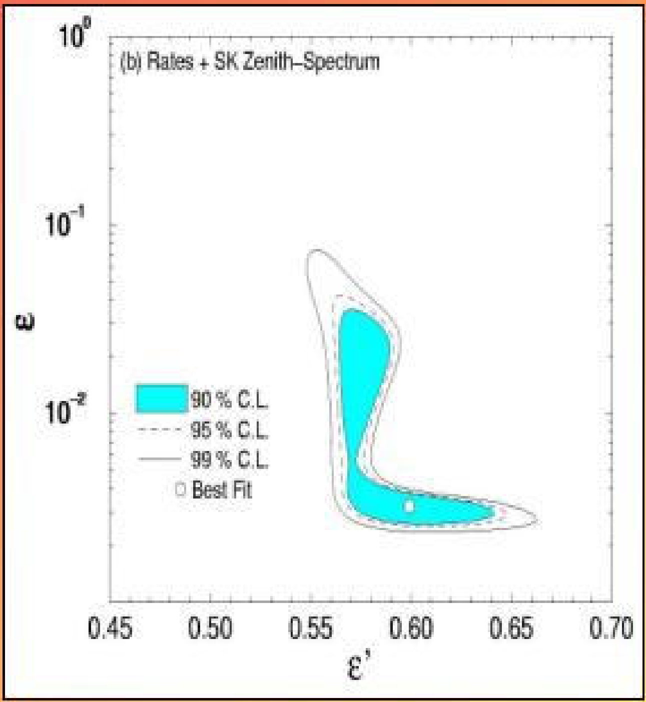
Non-trivial to avoid distortion of spectrum

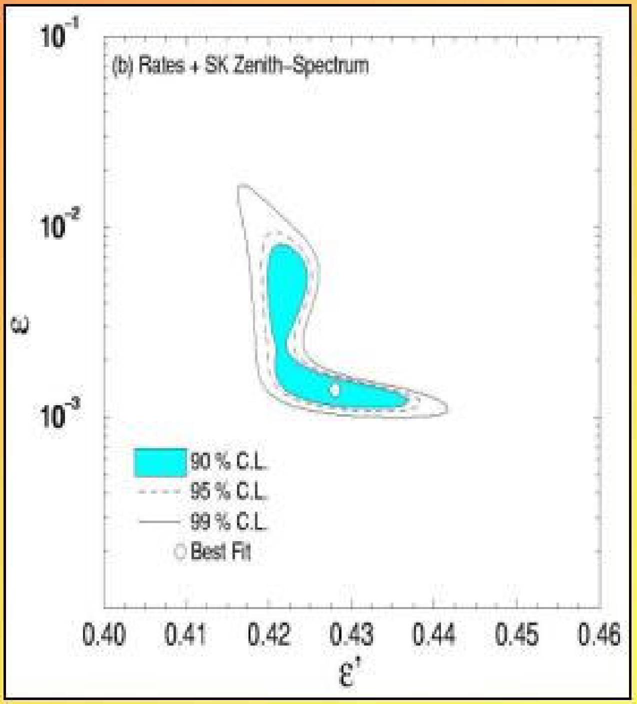
$\Delta m^2 = (1.5 - 5.0)\, 10^{-6}\, eV^2$



Solutions

A.M. Gago, et al, hep-ph/0112060





Very good fit

Too large value of ε'

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Non-standard neutrino interactions

L. Wolfenstein

Dynamics

Level splitting: $H = \sqrt{2}\ G_F\ [n_e(r) - \varepsilon' n_f(r)]$

Mixing: $H = \sqrt{2}\ G_F\ \varepsilon\ n_f(r)$

$f =$ u, d

No dependence of probability on energy

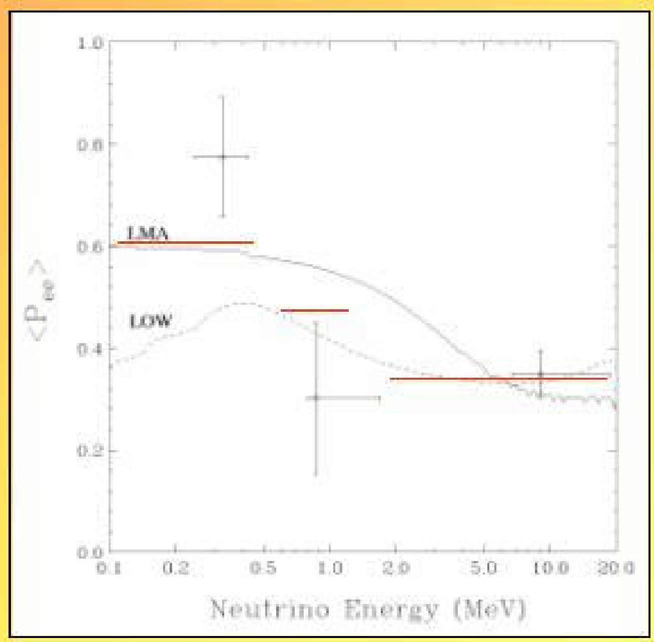
$P_{ee} = \text{const}$

Dependence on energy appears due to difference of productions regions for pp, Be, B neutrinos:

In the production region

n(pp) < n(Be) < n(B)

The larger density the stronger conversion



Summary (before KamLAND)

- LMA gives the best fit

  $\Delta m^2 = (5 - 7)\, 10^{-5}\ \mathrm{eV}^2$
  $\tan^2\theta = 0.35 - 0.45$

- With new SNO data important upper bound

  $\tan^2\theta < 0.8 \quad (3\,\sigma)$

  Implications for double beta decay absolute mass scale, theory

- Sub-leading effects: U_{e3} produces small effect
  Sterile component is further restricted: $\sin^2\eta < 0.35$
  Searches for new Δm^2

- LOW and VO survive at $\sim 3\sigma$ level SMA is excluded at $\sim 5\sigma$

- A number of other possible mechanisms which can reproduce the energy profile of the effect

  Time variations?

- Solutions based on neutrino spin-flip in the solar magnetic fields or on non-standard flavor changing interactions give good description of data

- Hybrid solutions ?