Global Analysis of Solar Neutrinos

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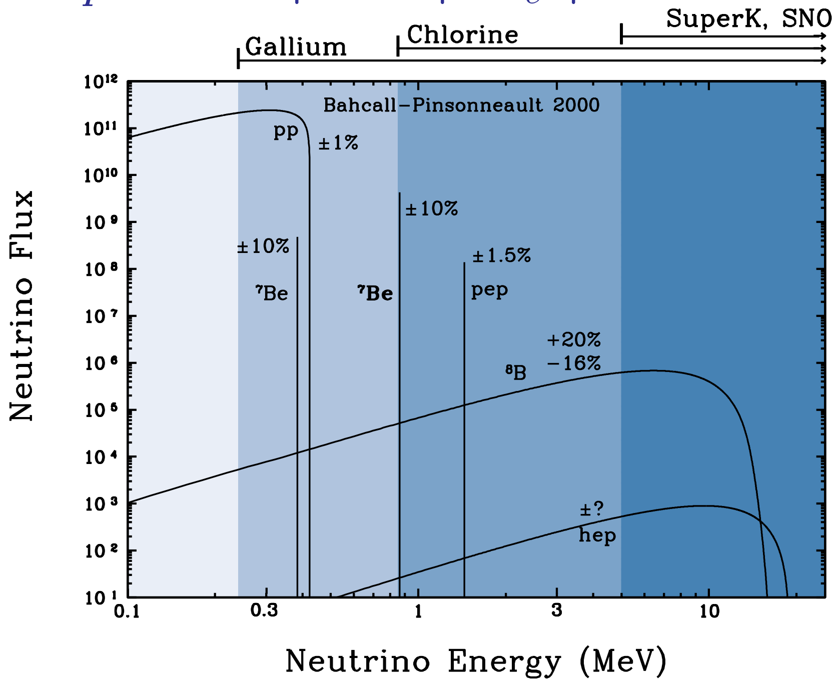
The Solar Neutrino Problem

Solar Neutrino Flux

Neutrinos are an essential byproduct of the thermonuclear energy generation process inside the Sun.

$$4p \rightarrow ^4He + 2e^+ + 2\nu_e + 28\text{MeV}$$



Solar Neutrino Experiments

The Cl experiment

- $^{37}Cl + \nu_e \rightarrow ^{37}Ar + e^-$ [E_{th} = 0.814 MeV]

The Ga experiment

- $^{71}Ga + \nu_e \rightarrow ^{71}Ge + e^-$ [E_{th} = 0.233 MeV]

The SK experiment

- $e^- + \nu_x \rightarrow e^- + \nu_x$, [$E_{th}$ = 5.0 MeV], (all flavors)

The SNO experiment

- $d + \nu_e \rightarrow p + p + e^-$, [$E_{th}$ = 5.0 MeV], (CC)
- $d + \nu_e \rightarrow p + n + e^-$, [$E_{th}$ = 5.0 MeV], (NC)(all flavors)
- $e^- + \nu_x \rightarrow e^- + \nu_x$, [$E_{th}$ = 5.0 MeV], (ES), (all flavors)

The Data

- The ratio of the observed solar neutrino rates to the SSM predictions.

experiment	$\frac{obsvd}{BPB00}$	composition
Cl	0.337 ± 0.029	B (75%), Be (15%)
Ga	0.553 ± 0.034	pp (55%), Be (25%), B (10%)
SK	0.465 ± 0.014	B (100%)
	(0.363)	
SNO(CC)	0.349 ± 0.021	B (100%)
SNO(ES)	0.473 ± 0.052	B (100%)
	(0.368)	

Observed flux < Theoretical Prediction

$\Downarrow$

$\boxed{\text{Solar Neutrino Problem}}$

- flat energy spectrum of recoil electrons above 5 MeV at SK
- very small day-night asymmetry at SK

$$\mathcal{A} = \frac{2(\phi_N - \phi_D)}{(\phi_N + \phi_D)} = 2.1 \pm 2.0 \pm 1.3\ \%$$

$\longrightarrow 0.96\sigma$ effect

- flat energy spectra of recoil electrons above 5 MeV at SNO

The Neutral Current Data

$$\boxed{\boxed{\text{SNO(NC)} = 1.008 \pm 0.123}}$$

$$\Downarrow$$

$$\boxed{\text{Evidence for flavor conversion at } 5.5\sigma}$$

$$\boxed{\mathcal{A}_{CC} = 7.0 \pm 4.9^{+1.3}_{-1.2}\ \%}$$

$$\boxed{\mathcal{A}_{NC} = -17.4 \pm 19.5^{+2.4}_{-2.2}\ \%}$$

Implications of the NC Data

- SNO Collaboration,
  nucl-ex/0204009
- V.Barger, D.Marfatia, K.Whisnant, B.P.Wood,
  hep-ph/0204253
- P.Creminelli, G.Signorelli, A.Strumia,
  hep-ph/0102234 (V3)
- A.Bandyopadhyay, S.Choubey, S.Goswami, D.P.Roy,
  hep-ph/0204286 and hep-ph/0203169
- J.N.Bahcall, M.C.Gonzalez-Garcia, C.Pena-Garay,
  hep-ph/0204314
- P.Aliani, V.Antonelli, M.Picariello, E.Torrente-Lujan,
  hep-ph/0205053
- A.Strumia, C.Cattadori, N.Ferrari, F.Vissani
  hep-ph/0205261
- P.C. de Holanda, A.Yu.Smrinov
  hep-ph/0205241
- Super-Kamiokande Collaboration,
  hep-ex/0205075
- G.L.Fogli,E.Lisi,A.Marrone,D.Montanino,A.Palazzo
  hep-ph/0206162

Model Independent Analysis

- No input from the Standard Solar Model for ^8B flux

- No assumption from particle physics model for ^8B supression probability

- Use just the data from SK and SNO

- ^8B survival probability independent of energy above 5 MeV
  $\Rightarrow$ The recoil electron energy spectrum at SK
  $\Rightarrow$ The recoil electron energy spectrum at SNO

$$R^{el}_{SK} = f_B P_{ee} + f_B r P_{ea}$$

$$R^{CC}_{SNO} = f_B P_{ee}$$

$$R^{NC}_{SNO} = f_B (P_{ee} + P_{ea})$$

- $f_B \Rightarrow^8 B$ normalization factor

- $r \Rightarrow$ ratio of the ν_μ to ν_e scattering cross-sections folded with the ^8B spectrum and averaged over energy

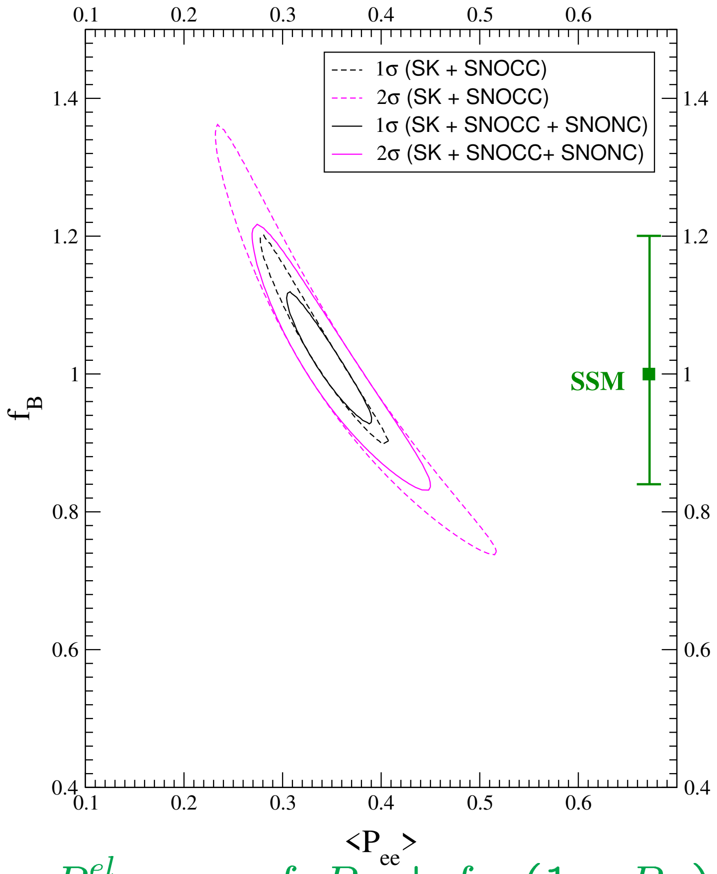
$$\boxed{R^{NC}_{SNO} = R^{CC}_{SNO} + (R^{el}_{SK} - R^{CC}_{SNO})/r}$$

$$\Downarrow$$

$$1.05 \pm 0.15$$

DATA$\Rightarrow$ ($R^{NC}_{SNO} = 1.01 \pm 0.12$)

Transitions to Active Flavor

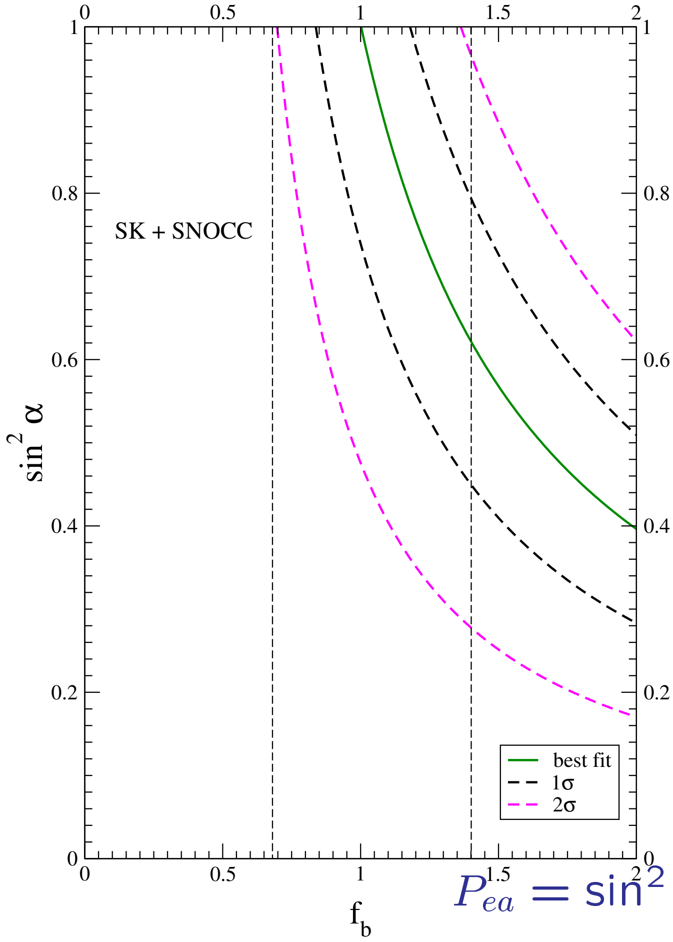


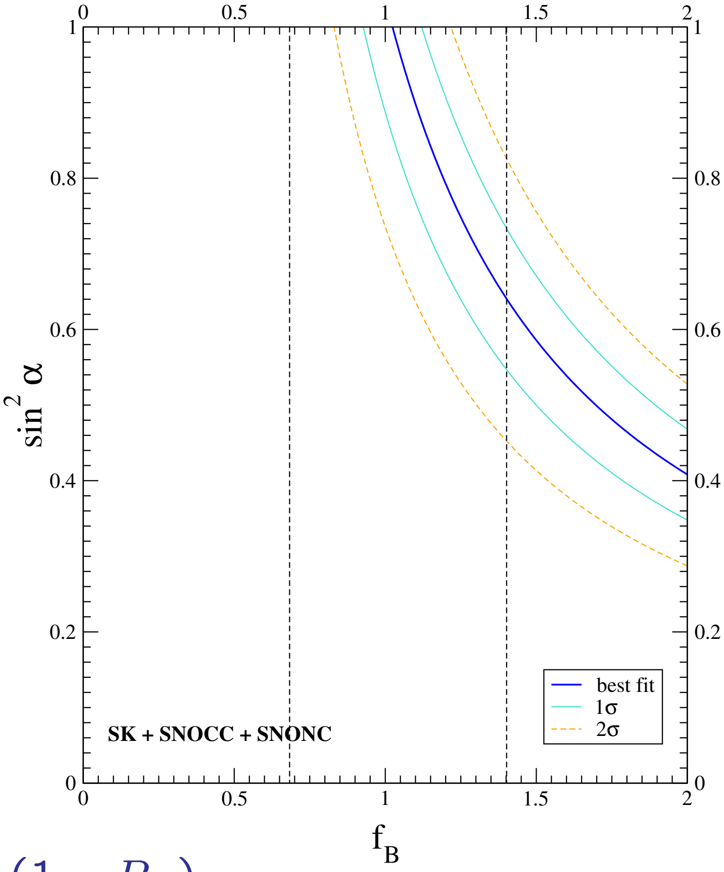
$$
\begin{aligned}
R^{el}_{SK} &= f_B P_{ee} + f_B r (1 - P_{ee}) \\
R^{CC}_{SNO} &= f_B P_{ee} \\
R^{NC}_{SNO} &= f_B
\end{aligned}
$$

- SK and SNO CC can uniquely determine f_B and P_{ee}
- but error is large due to
  - low sensitivity of SK to f_B
  - strong anticorrelation of P_{ee} and f_B through R^{CC}_{SNO}
- Inclusion of SNO NC reduces the error
- Absolutly consistent with BPB2000 SSM

Transitions to Active+Sterile Species

$$\nu_e \to \nu = \nu_a \sin\alpha + \nu_s \cos\alpha$$





$$P_{ea} = \sin^2\alpha(1 - P_{ee})$$

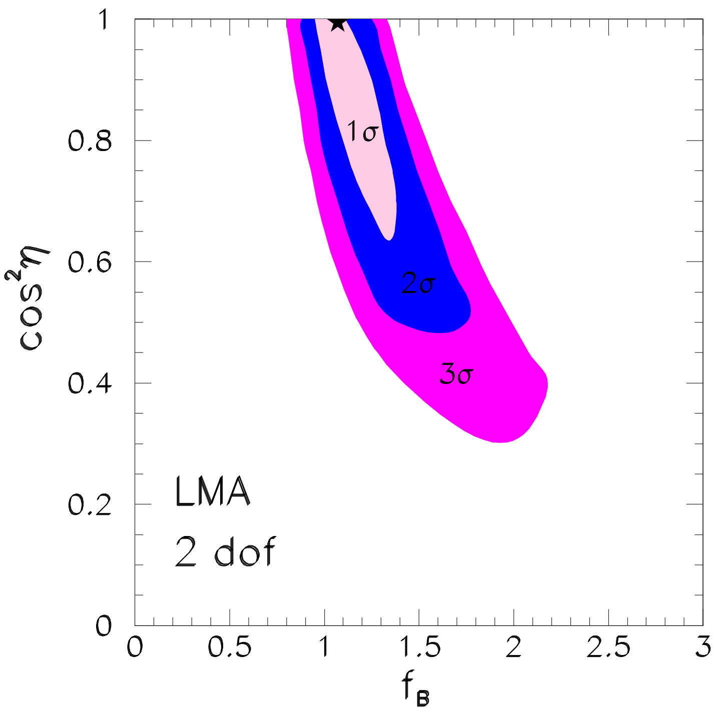
$$\begin{aligned} \sin^2\alpha(f_B - R^{CC}_{SNO}) &= (R^{el}_{SK} - R^{CC}_{SNC})/r, \\ \sin^2\alpha(f_B - R^{CC}_{SNO}) &= R^{NC}_{SNO} - R^{CC}_{SNO}. \end{aligned}$$

- For each value of $\sin^2\alpha$ we determine f_B from a weighted average of the two equations
- Data is totally compatible with pure $\nu_e - \nu_{active}$ transitions
- Data is totally inconsistent with pure $\nu_e - \nu_{sterile}$ transitions
- From the $1\sigma(2\sigma)$ upper limit of SSM and $1\sigma(2\sigma)$ lower limit of f_B we get a lower limit on $\sin^2\alpha > 0.68(0.45)$

Bounds on Sterile from Oscillation Analysis

- J.N. Bahcall, M.C.Gonzalez-Garcia, C.Pena-Garay, hep-ph/0204194

- For each point in the $\cos^2\eta - f_B$ plane they minimize the χ^2 with respect to Δm^2 and $\tan^2\theta$



- At $1\sigma(2\sigma) \Rightarrow \sin^2\alpha > 0.65(0.48)$

- Agrees well with the bounds obtained from our Model Independent analysis

Model Dependent Analysis

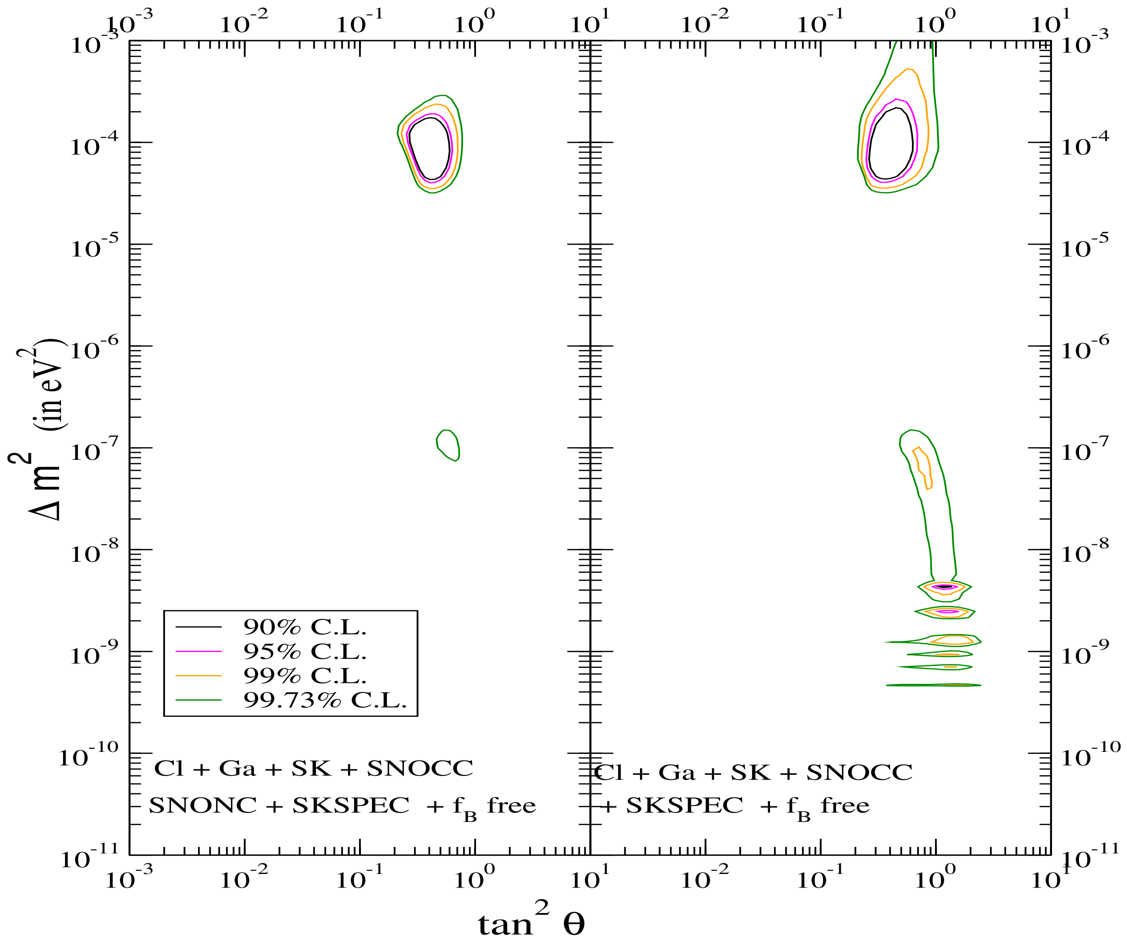
- Assume a two-generation, $\nu_e - \nu_{active}$ oscillation model for the neutrinos
- Analyse the global solar neutrino data using latest SK, CC, NC, Ga, Cl and SK zenith angle spectrum data with f_B free
- The spectrum over-all normalization (X_n) is kept free to avoid double counting of the SK rate
- Anti-correlations between the CC and NC rates are taken into account
- Use ^8B flux and uncertainty from the SNO NC data, thereby reducing the error from (16-20%) as in SSM to 12% as in data
- Use the SSM predictions for all the other fluxes and uncertainties from BPB2000
- Use full unified solar neutrino survival probability including vacuum as well as matter effects (both in sun and earth)

$$\chi^2 = \chi^2_R + \chi^2_S$$
$$\chi^2_{R/S} = \sum_{i,j} \left(X_n F_i^{th} - F_i^{exp}\right) (\sigma_{ij}^{-2})_{R/S} \left(X_n F_j^{th} - F_j^{exp}\right)$$

($X_n = 1$ for χ^2_R, $X_n =$ free for χ^2_S)

Nature of Solution	Δm^2 in eV^2	$\tan^2\theta$	f_B	χ^2_{min} of fit	Goodness
LMA	6.07×10^{-5}	0.41	1.05	40.57	65.99 %
LOW	1.02×10^{-7}	0.60	0.91	50.62	26.14%
VO	4.43×10^{-10}	1.1	0.80	56.11	12.39%
SMA	5.05×10^{-6}	1.68×10^{-3}	0.98	70.97	0.81%

Impact of SNO NC on Parameter Space



- LOW appears only at 3σ
- Values of Δm^2 above 3×10^{-4} disfavored
- VO-QVO and Just-So not allowed at 3σ
- Maximal Mixing is disfavored at 3σ
- SMA further disfavored
- Dark Side solutions are gone $\Rightarrow$ $\Delta m^2 > 0$

Allowed Range of Parameters

- LMA
  - $3\sigma \Rightarrow$

$$3.16 \times 10^{-5} eV^2 \leq \Delta m^2 \leq 2.9 \times 10^{-4} eV^2$$

$$0.21 \leq \tan^2\theta \leq 0.78$$

  - $1\sigma \Rightarrow$

$$5.0 \times 10^{-5} eV^2 \leq \Delta m^2 \leq 1.46 \times 10^{-4} eV^2$$

$$0.3 \leq \tan^2\theta \leq 0.54$$

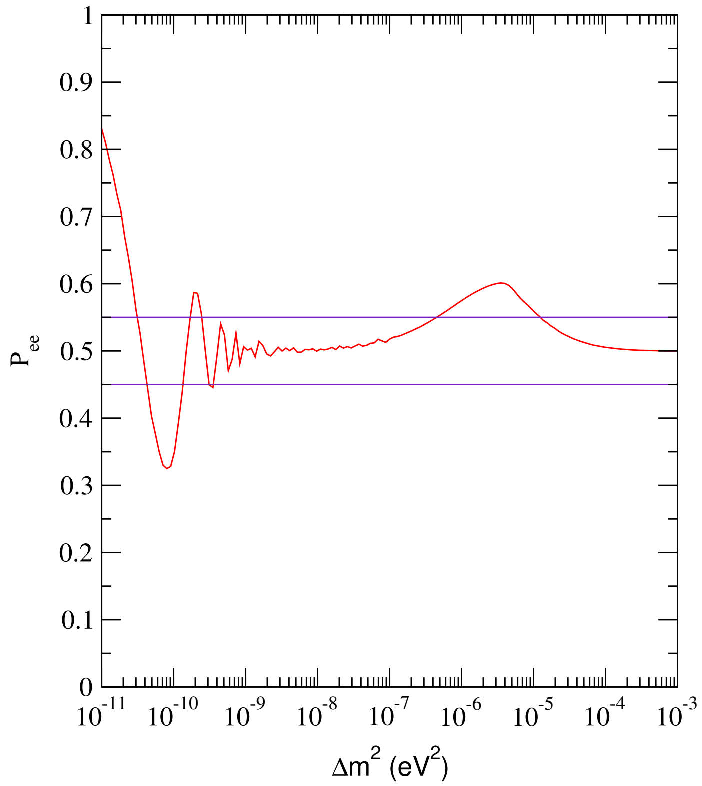
Upper bound on Δm^2 from solar neutrinos is now better than that from CHOOZ ($\Delta m^2 < 8 \times 10^{-4}$ eV^2) as the NC data restricts $f_B \sim 1$

- LOW
  - $3\sigma \Rightarrow$

$$7.3 \times 10^{-8} eV^2 \leq \Delta m^2 \leq 1.5 \times 10^{-7} eV^2$$

$$0.46 \leq \tan^2\theta \leq 0.73$$

Maximal Mixing

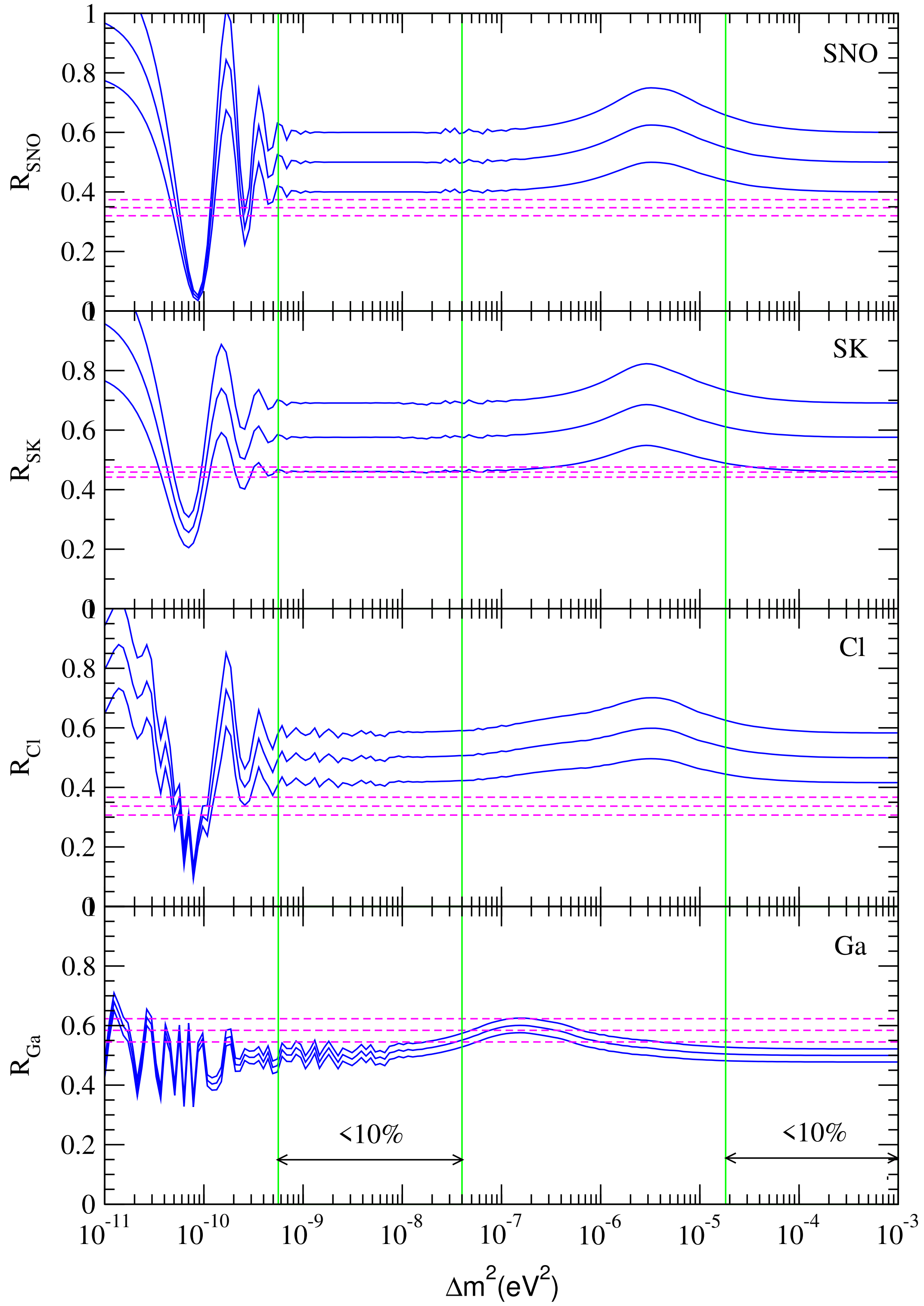


$$P_{ee}^{\odot} = \frac{1}{2} + \frac{1}{2}(1 - 2P_J) \cos 2\theta \cos 2\theta_m$$

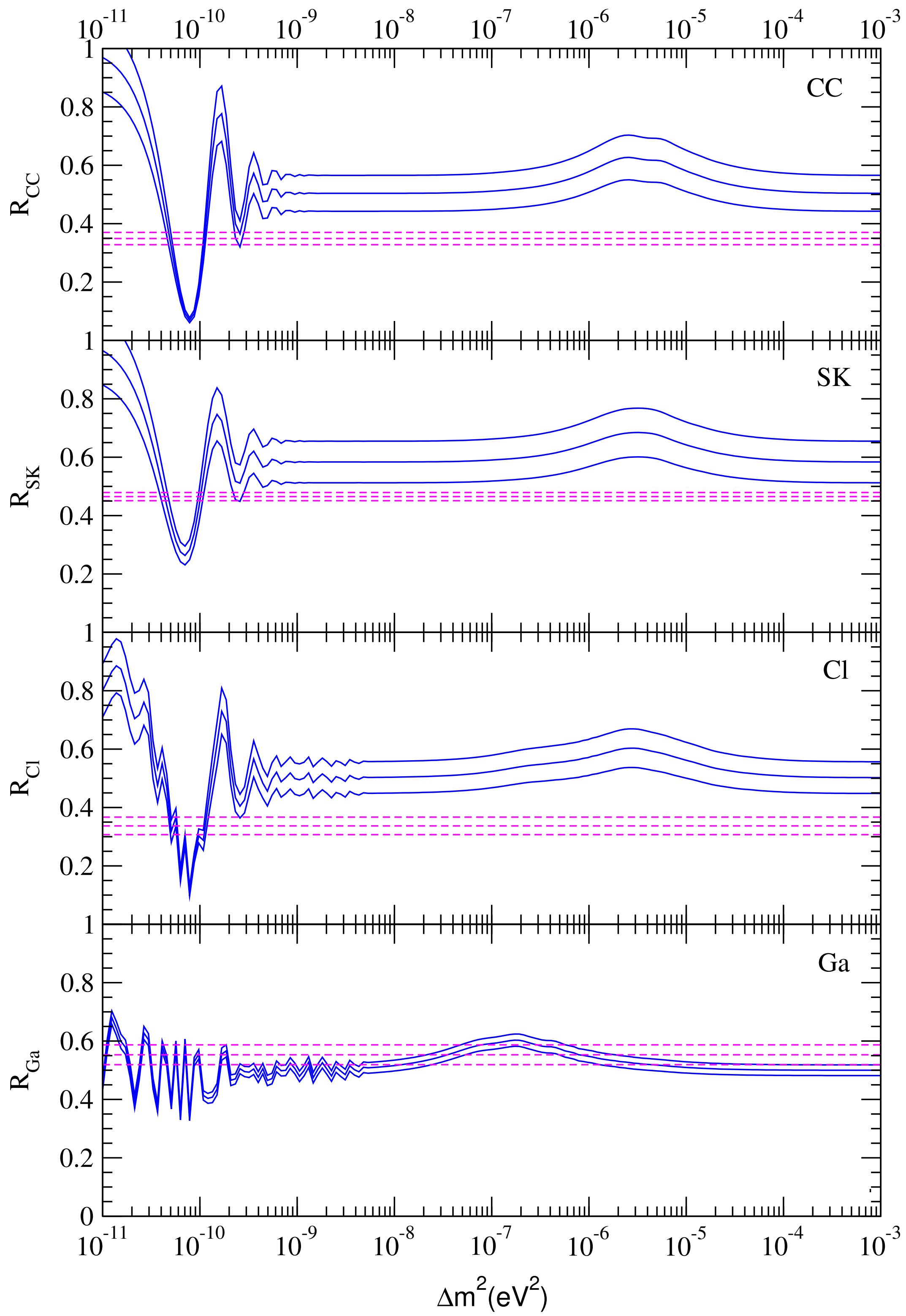
$$\cos 2\theta = 0 \Rightarrow P_{ee}^{\odot} = \frac{1}{2}$$

$$\boxed{\text{Matter does not matter}}$$

$$P_{ee} = \frac{1}{2} + f_{reg}$$



- Predicted Rates at Maximal Mixing for $\pm 1\sigma$ BPB2000



- Predicted Rates at Maximal Mixing for $\pm 1\sigma$ NC Rate

Status of the LOW solution

- SNO Collaboration: nucl-ex/0204009

(SNO D/N spectrum and 1258 days SK D/N spectrum)

$$\chi^2_{LOW} - \chi^2_{LMA} = 10.7$$

- Barger et al: hep-ph/0204253

(SNO D/N spectrum and 1496 days SK D/N spectrum)

$$\chi^2_{LOW} - \chi^2_{LMA} = 9.2$$

- Creminelli et al: hep-ph/0102234 (v3)
  Strumia el al: hep-ph/0205261

(CC and NC rates and 1496 days SK zenith angle spectrum)

$$\chi^2_{LOW} - \chi^2_{LMA} = 8.1$$

- Bandopadhyay et al: hep-ph/0204286

(CC and NC rates and 1496 days SK zenith angle spectrum)

$$\chi^2_{LOW} - \chi^2_{LMA} = 10.05$$

- Bahcall et al: hep-ph/0204314

(CC and NC rates and 1496 days SK zenith angle spectrum)

$$\chi^2_{LOW} - \chi^2_{LMA} = 8.8$$

- Holanda, Smirnov: hep-ph/0205241

(SNO D/N spectra and 1496 days SK zenith angle spectra)

$$\chi^2_{LOW} - \chi^2_{LMA} = 13.3$$

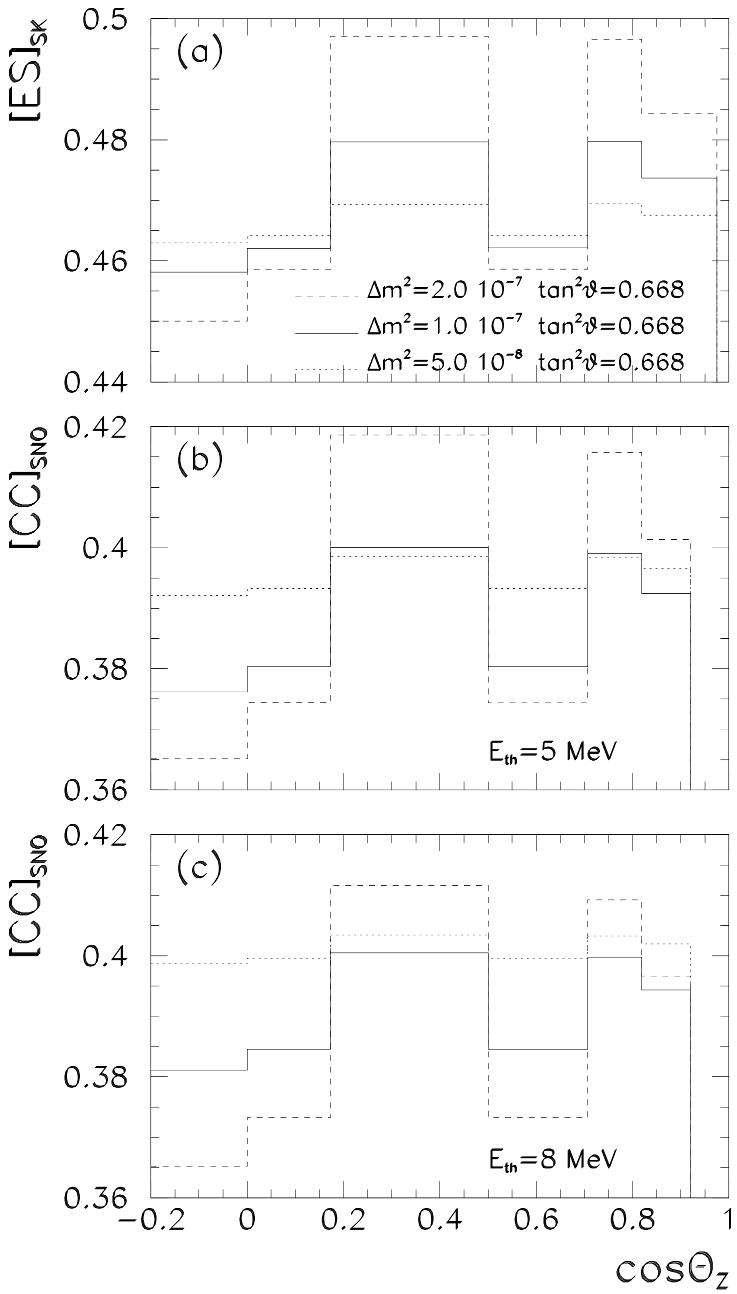
- Super-Kamiokande Collaboration: hep-ex/0205075

$$\chi^2_{LOW} - \chi^2_{LMA} = 9.0$$

- G.L.Fogli,E.Lisi,A.Marrone,D.Montanino,A.Palazzo : hep-ph/0206162

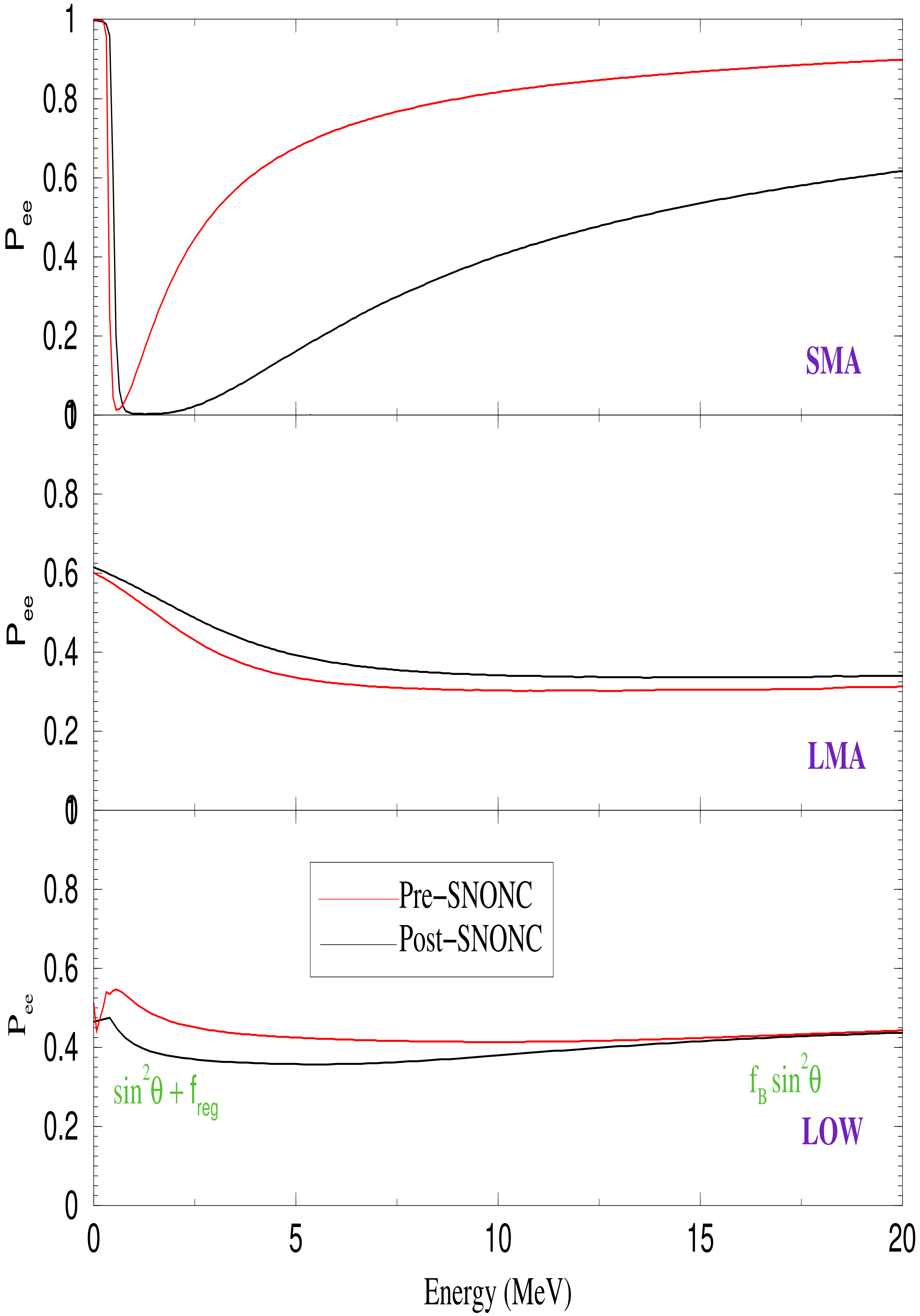
$$\chi^2_{LOW} - \chi^2_{LMA} = 8.4$$

• M.C.Gonzalez-Garcia, C.Pena-Garay, A.Yu.Smrinov
Phys. Rev. **D63**, 113004 (2001)



• No peaks observed in the zenith angle spectrum of SK

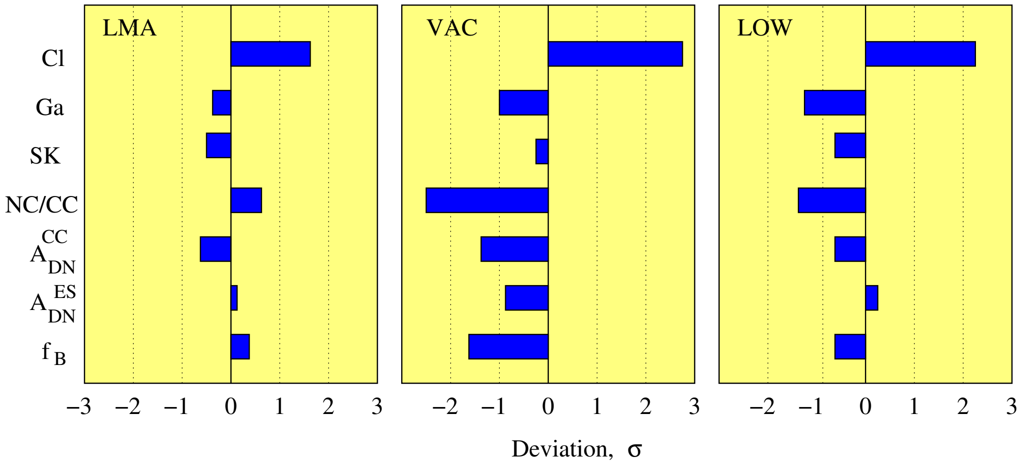
• SK disfavors large values of $\Delta m^2 \gtrsim 10^{-7}$ eV^2



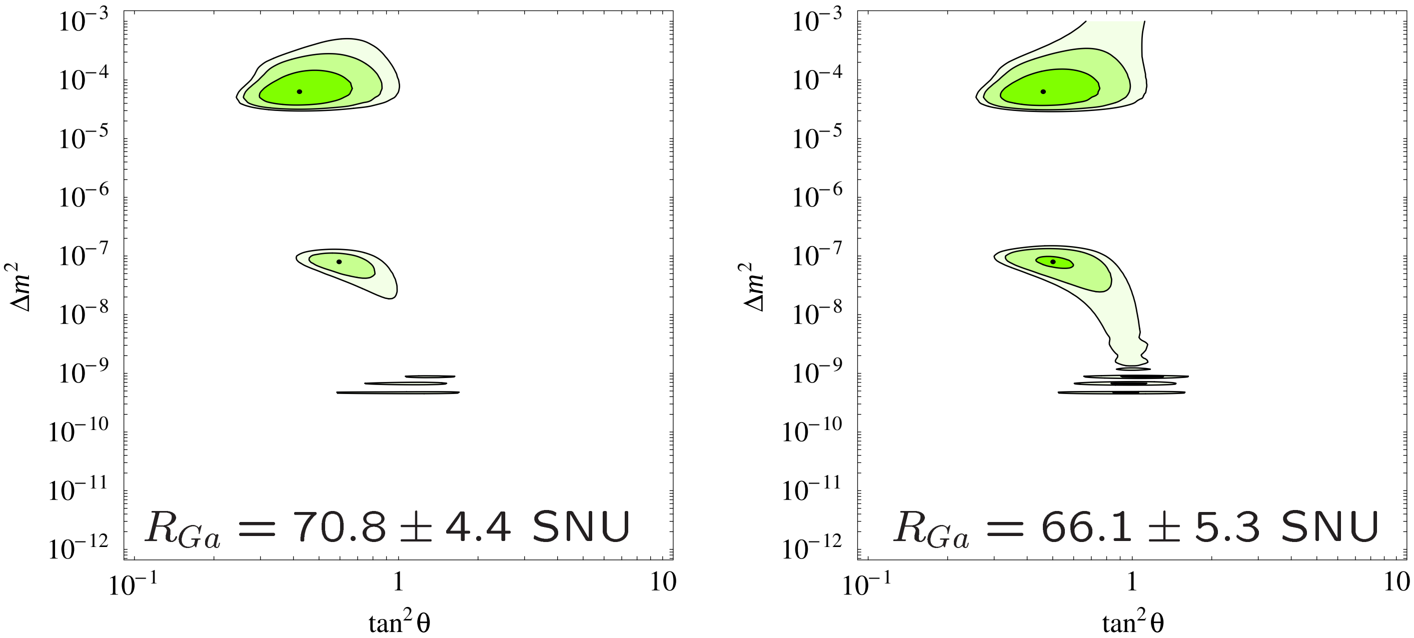
SMA
LMA
LOW
Pre−SNONC
Post−SNONC
$\sin^2\theta + f_{reg}$
$f_B \sin^2\theta$
P_{ee}
Energy (MeV)

- P.C.de Holanda, A.Yu.Smirnov, hep-ph/0205241

$$D_K = (K_{bf} - K_{exp})/\sigma_K$$



- A.Strumia, C.Cattadori, N.Ferrari, F.Vissani, hep-ph/0205261



- LOW improves for the latest GNO rate

Summary

The latest SNO NC data when combined with the data from other experiments

- 8σ signal for neutrino oscillations

- Rules out transitions to pure sterile states at 5.5σ

•Transitions to mixed state still allowed with $< 32\%(65\%)$ sterile mixture at $1\sigma(2\sigma)$

- f_B and P_{ee} further constrained

- SMA further disfavored

- VO-QVO and Just-So not allowed at 3σ

- LOW allowed at only 3σ

- Maximal mixing is disfavored at 3σ

- LMA survives as the only solution to the solar neutrino problem with $3.16 \times 10^{-5} \leq \Delta m^2 \leq 2.9 \times 10^{-4}$ and $0.21 \leq \tan^2\theta \leq 0.78$ at 3σ

- KamLAND should see a rate ~ 0.5 along with spectral distortion to confirm LMA. [Bahcall,Gonzalez-Garcia,Pena-Garay, hep-ph/0204314]

- Borexino should see a rate ~ 0.64 and no day-night asymmetry to confirm LMA. LOW solution predicts a minimum day-night asymmetry $\sim 12\%$ in Borexino. This can be used to further disfavor LOW. [Bahcall,Gonzalez-Garcia,Pena-Garay, hep-ph/0204314]