The MiMaNu Coll.

Solving the Solar Neutrino Problem

Updated Analysis

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Outline:

1. Brief Introduction to the **Solar Neutrino Problem**
2. Overview of different experimental results
3. What we have done: [References: `hep-ph/0112101` and `hep-ph/0111418`]
    - exclusion plots using all solar neutrino data
    - iso-signal predictions for Borexino, NC-SNO and kamLAND
4. Conclusions and Outlook . . .

. . . Brief Introduction to the **Solar Neutrino Problem. . .**

- **70s**: first solar-ν-flux measurement based on inverse β decay on ^{37}Cl at Homestake measures a ν deficit of approximately 70%!
  - What is happening to solar νs on their way to the earth?
  - Could the Standard Solar Model (SSM) be wrong?
- **80s- early 90s**: other experiments based on inverse β decay on Gallium, such as SAGE (1990), GallEX (1992) reproduce Homestake results.
  - Are νs undergoing flavor-changing (FC) oscillations as they reach the earth?
  - What are the theoretical implications of such FC oscillations?
  - Could this be one of the first indications of 'NEW PHYSICS'?
- **90s**: Kamiokande ($\simeq$ 1989) and SuperKamiokande (1998) measure ν_e elastic scattering in H_2O, still confirming ν_e deficit.
  - Real-time detection of 'directional neutrinos', making day-night analysis possible.
  - There is still no satisfying (i.e. converging) solution in the oscillations parameter space
- **2001**: results from SNO, detector capable of measuring elastic-scattering, charged-and neutral-current interactions of all active flavors in D_2O.
  - SNO measurement seems to strongly disfavor the small mixing angle (SMA) solutions to the solar ν problem.

What Next?

Borexino, KamLAND and NC-SNO will hopefully narrow down the allowed solutions in the parameter space.

Overview of different experimental results

Homestake: $^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e^-$

- 814 KeV threshold
- Measured the radioactivity of ^{37}Ar which was chemically extracted from ^{37}Cl.
- Measured $\underline{0.332 \pm 0.056}$ $S_{\text{Data}}/S_{\text{SSM}}$.

SAGE&GallEX/GNO: $^{71}\text{Ga} + \nu_e \rightarrow ^{71}\text{Ga} + e^-$

- 223 KeV threshold $\Rightarrow$ more neutrinos coming from the pp chain where 'captured'.
- same idea as Homestake.
- Measured $\underline{0.579 \pm 0.050}$ $S_{\text{Data}}/S_{\text{SSM}}$.

Kamiokande I-II & **SuperKamiokande** $\nu_e + e^- \rightarrow \nu_e + e^-$

- Best threshold: 5 MeV $\Rightarrow$ measured only neutrinos coming from the ^{8}B and hep chains. The threshold decreased considerably from Kamiokande to SuperKamiokande.
- Measured Cherenkov light emitted by the scattered electron.
- Measured $\underline{0.451 \pm 0.011}$ $S_{\text{Data}}/S_{\text{SSM}}$.

CC-SNO and **ES-SNO** $\nu_e + d \rightarrow e^- + p + p$ & $\nu_e + e^- \rightarrow \nu_e + e^-$

- 6.75 MeV threshold. As for SK, measured Cherenkov light emitted by electron produced in both interactions.
- CC measurement: $\underline{0.347 \pm 0.029}$ $S_{\text{Data}}/S_{\text{SSM}}$.

Expected results from KamLAND, NC-SNO and Borexino

Borexino $\nu_e + e^- \rightarrow \nu_e + e^-$

- Will measures monochromatic 0.862 MeV ^{7}Be νs.

NC-SNO $\nu_x + d \rightarrow \nu_x + n + p$

- Measurement of neutron-capture prompt, monochromatic γ rays at 6.25 MeV.
- Phase I: NC measurement in pure D_2O, results expected soon.
- Phase II: NC measurement enhanced by presence of NaCl (which increases the γ energy to 8.6 MeV). Taking data since May 28, 2001.

KamLAND $\bar{\nu}_e + p \rightarrow n + e^+$

- Reactor ν experiment using 16 Japanese commercial reactors as source of $\overline{\nu}_e$. The detector is similar to Borexino and might also measure *solar* ν elastic scattering processes.
- Detection and signal discrimination is 'fail-safe' coincidence measurement of prompt γ from the annihilation of the positron and delayed γ from the subsequent re-capture of the emitted neutron.

What we have done (hep-ph/0111418 and hep-ph/0112101)

1. Phenomenological study of all solar ν data including SNO and recent SK results

2. Inclusion of CHOOZ and atmospheric neutrino constraints on the solar-neutrino parameter space $\left(\Delta m^2_{12}, \tan^2\theta_{12}\right)$.

3. Strategy:
   - ν oscillation hypothesis;
   - bidimensional and tridimensional models;
   - introduction of matter effects in the hamiltonian;
   - comparison between computed signal and experimental results;
   - statistical χ^2 analysis.

4. Aim of the analysis:
   - determination of the allowed regions in the mixing parameter space;
   - Predictions for Borexino, SNO-NC and kamLAND signals.

Global Rates: situation Prior to SNO results (< August 2001)

Solution	Δm^2	$\tan^2\theta$	χ^2_m/n	g.o.f.
SMA	0.118E-04	0.721E-03	0.74	38.97%
VAC	0.970E-10	0.256E+01	0.86	35.37%
LOW-VAC	0.110E-08	0.205E+01	0.92	33.75%
VAC	0.686E-10	0.341E+00	1.01	31.49%
LOW-VAC	0.310E-08	0.155E+01	1.64	20.03%
VAC	0.104E-09	0.935E+00	1.87	17.15%
LMA	0.125E-03	0.341E+00	1.91	16.70%

- **SMA** 'wins' over **LMA** solution.
- Many excellent twin-**LOW** and twin-**VAC** solutions.
- At 90% C.L. solutions with $\tan^2\theta_{12} \sim 1$ are indistinguishable.

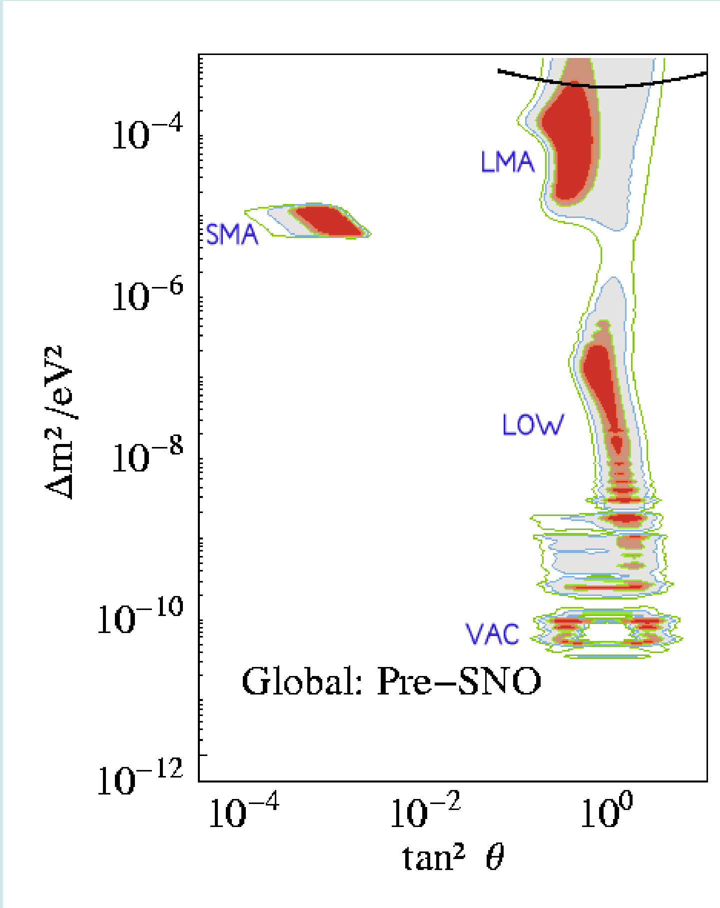

Figure 1: pre-SNO global analysis. Global rates for SuperKamiokande, Homestake, GallEX-SAGE-GNO included.

Global Rates: situation after SNO results (> August 2001)

Solution	Δm^2	$\tan^2\theta$	χ^2_m/n	g.o.f.
VAC	0.686E-10	0.361E+00	0.52	59.45 %
LOW-VAC	0.191E-08	0.164E+01	1.03	35.70%
LMA	0.125E-03	0.382E+00	1.12	32.63 %
VAC	0.891E-09	0.183E+01	1.61	19.89%
LOW	0.122E-06	0.707E+00	2.04	13.00%
SMA	0.118E-04	0.853E-03	2.32	9.83%

- With the introduction of SNO-CC results, the **SMA** solution is no longer favored over the **LMA** solution.
- The **LMA**, **LOW** and **VAC** are clearly separated.

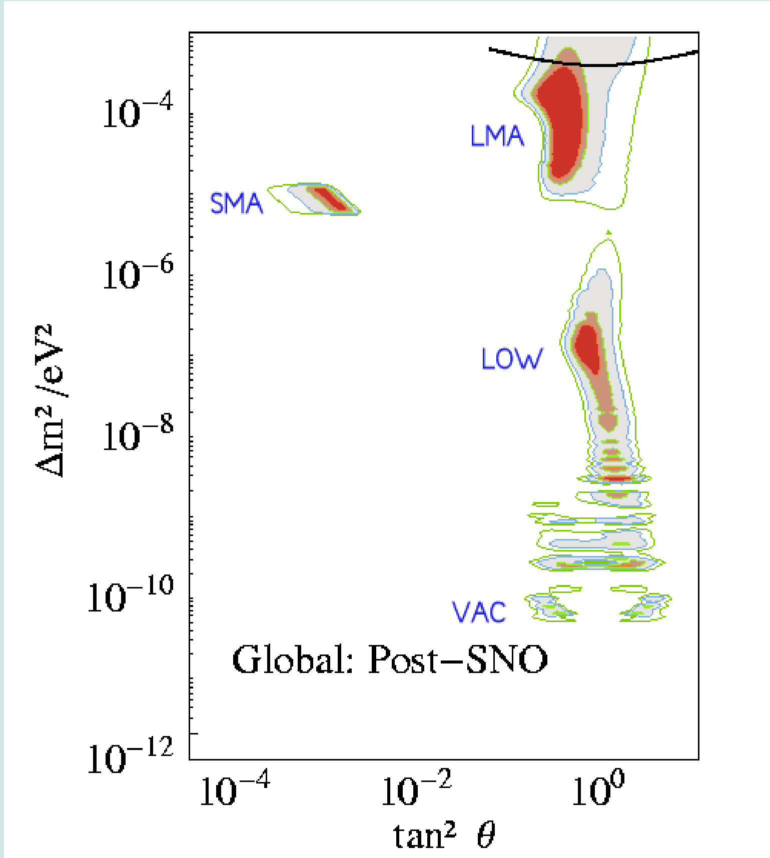

Figure 2: Global analysis, including SNO

Note: From the comparison of SNO-ES and SK-ES: clear indication of ν_e oscillations into *active* flavors.

SK spectrum analysis for fixed ^{8}B flux

Solution	Δm^2	$\tan^2\theta$	χ^2_m/n	g.o.f.
LOW-VAC	0.191E-08	0.164E+01	0.73	88.97%
LMA	0.670E-04	0.427E+00	0.77	84.38%
LOW	0.122E-06	0.668E+00	0.82	77.90%
LOW-VAC	0.382E-08	0.138E+01	0.83	76.78%
VAC	0.891E-09	0.173E+01	0.85	73.10%
LOW-VAC	0.877E-08	0.131E+01	0.87	70.65%
VAC	0.274E-09	0.242E+01	0.88	68.00%
LOW	0.175E-07	0.117E+01	0.88	67.96%
LOW-VAC	0.110E-08	0.258E+00	0.89	67.30%
VAC	0.891E-09	0.478E+00	0.91	63.08%
VAC	0.274E-09	0.382E+00	0.91	62.85%
SMA	0.118E-04	0.763E-03	1.03	42.03%
SMA	0.729E-05	0.126E-02	1.04	39.89%
VAC	0.686E-10	0.244E+00	1.07	35.78%

- With the inclusion of the SK spectrum and day-night analysis, the **LMA** solution gains even more credibility over **SMA**.

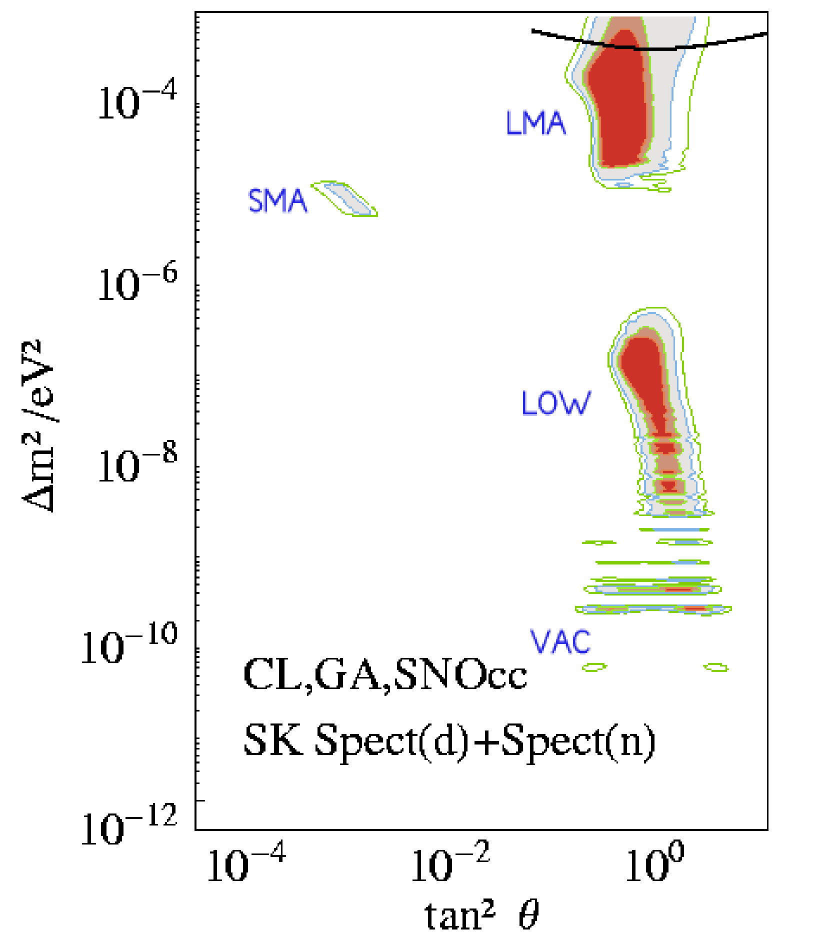

Figure 3: Analysis including SK spectrum, Homestake and GallEX-SAGE total rates

SK spectrum analysis with varying ^8B flux

Solution	Δm^2	$\tan^2\theta$	χ^2_m/n	g.o.f.
LOW-VAC	0.191E-08	0.164E+01	0.73	89.00%
LOW-VAC	0.191E-08	0.173E+01	0.73	89.00%
VAC	0.588E-09	0.183E+01	0.78	83.56%
LMA	0.670E-04	0.427E+00	0.77	84.47%
VAC	0.274E-09	0.271E+01	0.79	81.86%
LOW-VAC	0.382E-08	0.146E+01	0.80	80.94%
LOW	0.122E-06	0.748E+00	0.81	79.97%
VAC	0.274E-09	0.323E+00	0.81	78.93%
LOW-VAC	0.110E-08	0.231E+00	0.82	78.13%
LOW-VAC	0.877E-08	0.138E+01	0.83	76.74%
VAC	0.111E-09	0.449E+01	0.92	60.56%
VAC	0.111E-09	0.206E+00	0.93	60.33%
SMA	0.118E-04	0.807E-03	1.03	42.08%
SMA	0.729E-05	0.126E-02	1.04	39.89%

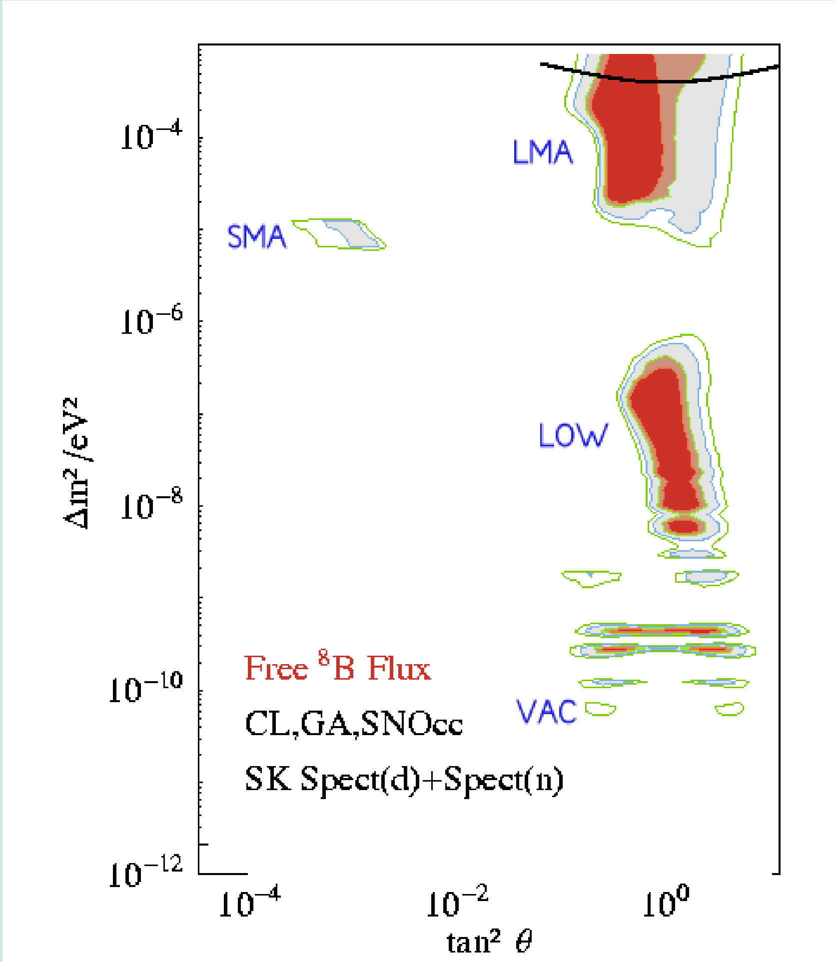

Figure 4: SK Spectrum analysis with unconstrained ^8B flux. Minimization with respect to Φ confirms SSM predictions.

- introduction of two parameters to account for uncertainties in the flux normalization factor and bin-correlations.

kamLAND expected signal analysis

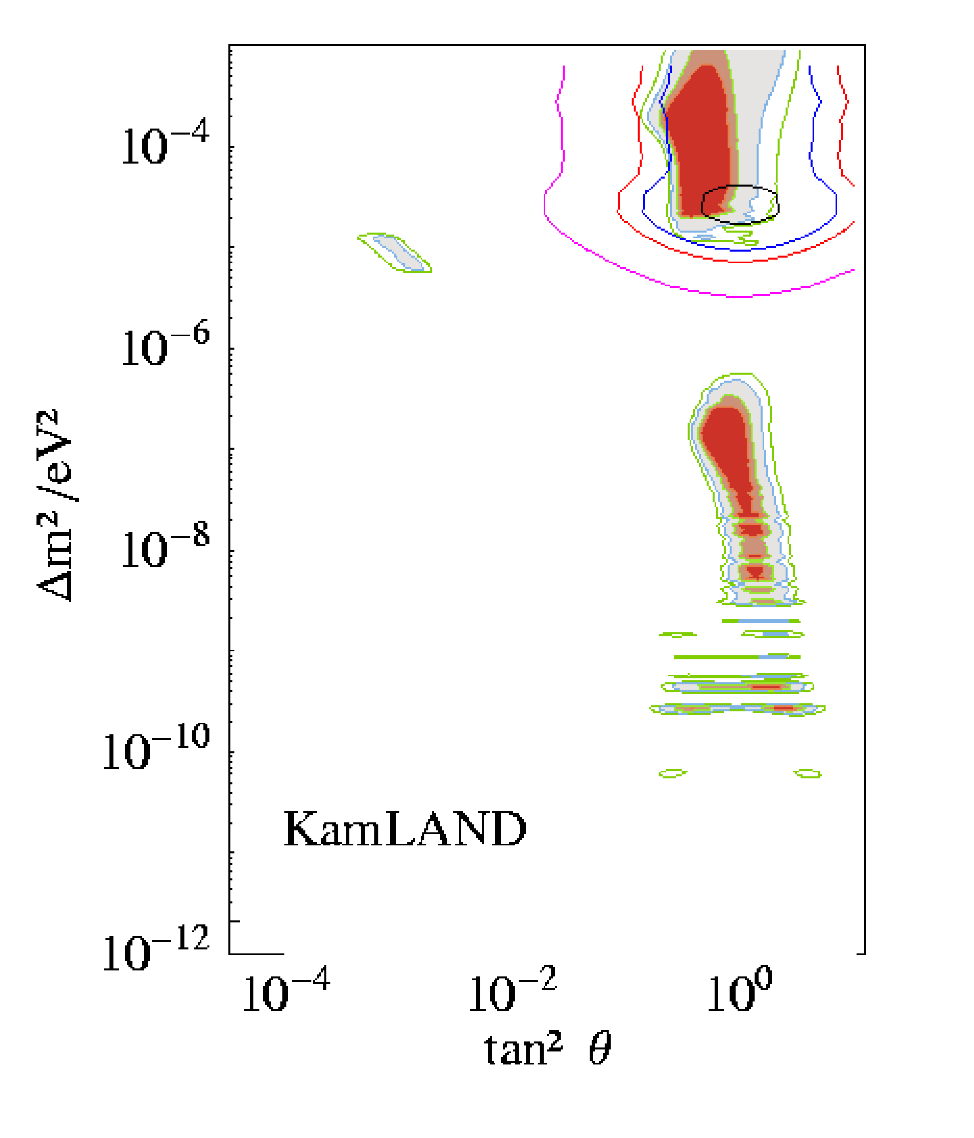

Figure 5: kamLAND iso-signal lines and Spectrum-analysis allowed regions

- $S_{\rm Data}/S_{\rm SSM}$=0.95
- $S_{\rm Data}/S_{\rm SSM}$=0.8
- $S_{\rm Data}/S_{\rm SSM}$=0.7

Signal is only sensitive to the **LMA** region. The smaller it becomes, the smaller the allowed region ⇒ we will be able to determine with high accuracy the value of Δm^2_{12}.

Soon to come, SNO-NC results. Signal analysis

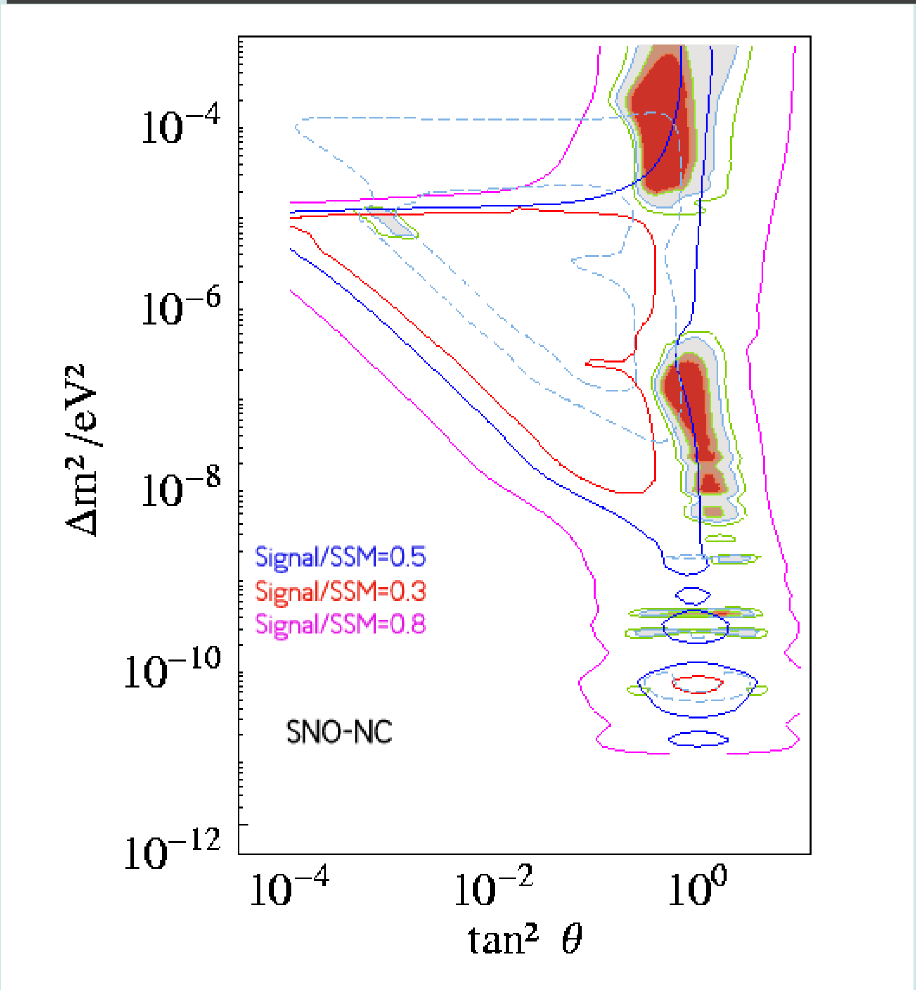

Figure 6: caption

1 0.8< $S_{\mathrm{Data}}/S_{\mathrm{SSM}}$: Apparantly no solution to the solar neutrino problem!

2 0.5< $S_{\mathrm{Data}}/S_{\mathrm{SSM}}$ <0.8 **LMA** strongly favored. **SMA** excluded. Some **LOW-VAC** solutions possible.

3 0.3< $S_{\mathrm{Data}}/S_{\mathrm{SSM}}$ <0.5 **LOW-LMA** solutions favored. **SMA** still marginally allowed.

4 $S_{\mathrm{Data}}/S_{\mathrm{SSM}}$ <0.3: only **SMA** solution remains.

Borexino expectations: what will we learn from this new experiment?

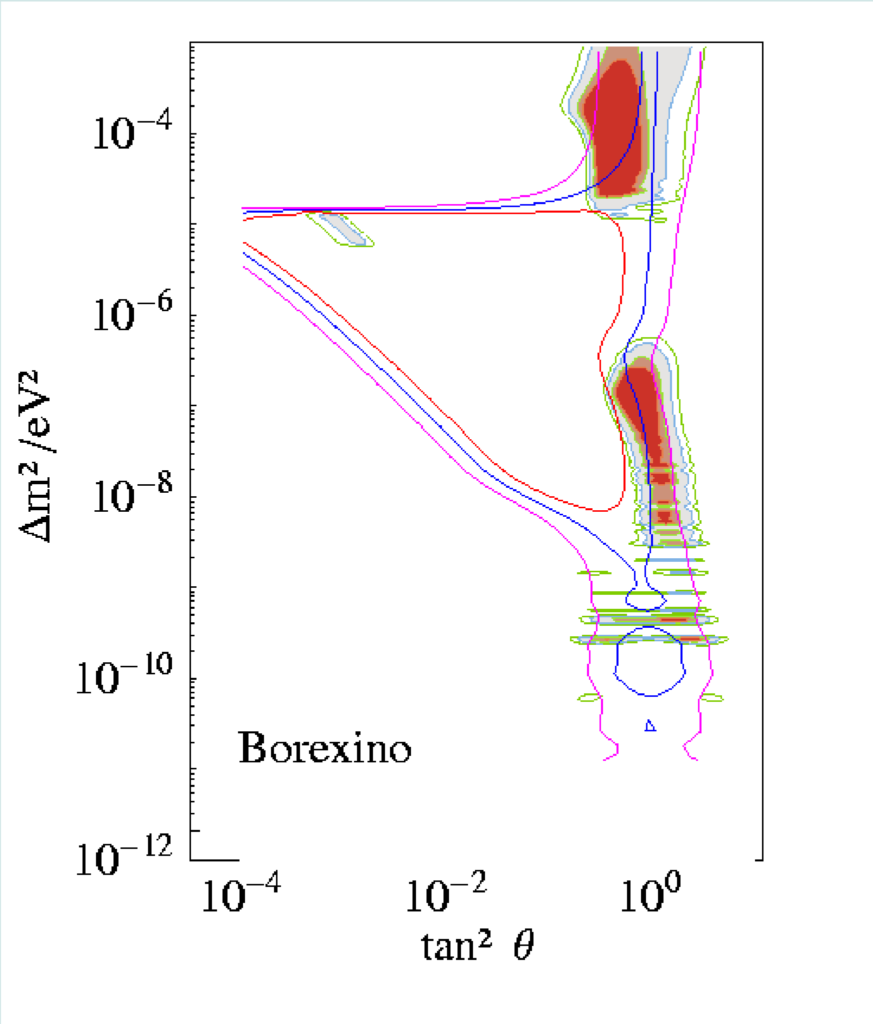

Figure 7: Borexino expected signal

- $S_{\mathrm{Data}}/S_{\mathrm{SSM}}=0.7$
- $S_{\mathrm{Data}}/S_{\mathrm{SSM}}=0.6$
- $S_{\mathrm{Data}}/S_{\mathrm{SSM}}=0.5$

Borexino: day-night asymmetry and signal analysis

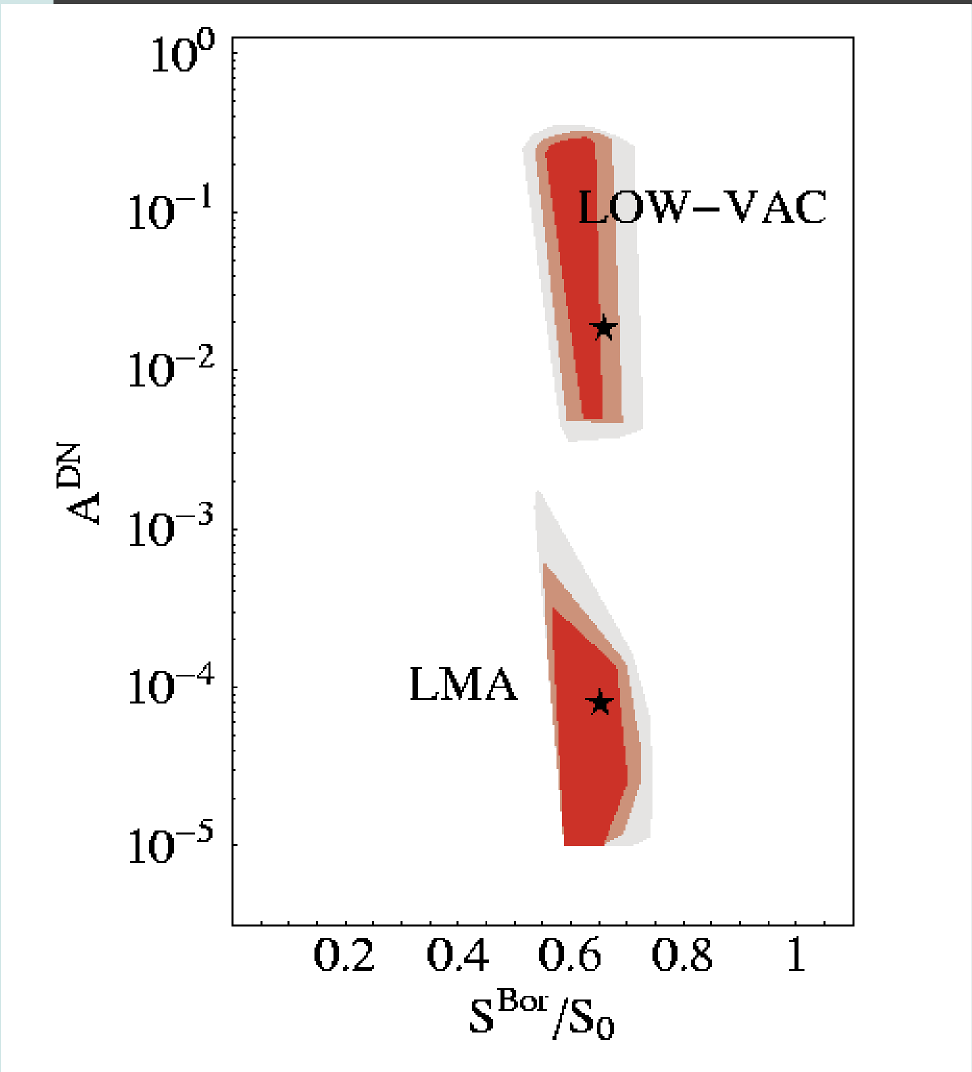

Figure 8: caption

1 if $S_{\mathrm{Data}}/S_{\mathrm{SSM}} < 0.5$, only SMA solution remains!

2 if $S_{\mathrm{Data}}/S_{\mathrm{SSM}} > 0.5$ both LOW and LMA solutions are possible. The day-night asymmetry plot then allows us to distinguish among the two solutions. In particular, the allowed regions narrow down as the signal approaches 0.7.

3 To discriminate between the LOW and LMA solutions, accuracy of 5-10 % would be required.

Conclusions and Outlook...

- Including CC-SNO result, the previousely allowed regions shrink and the SMA solution is strongly disfavored.
- NC-SNO results will help discriminate between **SMA** and **LOW-**-**LMA** solutions.
- Borexino will then be able to distinguish between the **LMA** and **LOW** solutions.
- If *the* solution lies in the LMA region, kamLAND will determine with unprecedent precision the 'real' value of Δm^2_{12}.
- **Work in progress**:
  - atmospheric neutrinos!
  - Sterile νs and seasonal variations in Borexino