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THE SOLAR NEUTRINO PUZZLE: PRESENT SITUATION AND FUTURE SCENARIOS

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EVIDENCES OF ν MASS AND OSCILLATIONS

- After a long and fascinating history ν still plays a central role in Standard Model physics and beyond
- Search for ν mass and oscillations:
  - (1) Direct kinematical Searches: β decays and neutrinoless double β decays (recent claim of ν mass discovery)
  - (2) Reactor and accelerator experiments:
    * (2a) Shortbaseline (SBL) exp. (CHORUS,NOMAD,etc.); no indication of oscillations
    * (2b)Longbaseline (LBL) reactor exp. (CHOOZ and Palo Verde); important limits on $\sin^2(2\theta)$, Δm^2
    * (2c) LSND: signal $\bar{\nu_\mu} \to \bar{\nu_e}$ oscillation; not confirmed; it would imply high $\Delta m^2 \to$ sterile ν
    * (2 d) LBL accelerator exp.
      · K2K ($L \simeq 250$ Km):confirm oscillations
      · Cern-G. Sasso project and Minos
  - (3) Atmospheric ν (SK,IMB,Soudan,Macro) $\nu_\mu \to \nu_\tau$ oscillation; $\Delta m^2 \simeq 1.5 - 4 \times 10^{-3} eV^2$, $\sin^2(2\theta) > 0.88$
  - (4) Solar ν

SOLAR ν EXPERIMENTS

- End 60s: 1st solar ν flux measurement at Homestake ($^{37}Cl + \nu_e \rightarrow ^{37}Ar + e^-$; $E_{thresh} \simeq 0.81 MeV$) ($\nu$ from ^8B, ^7Be ,pep, hep)
  - Measures a ν deficit $\geq 60\%$
  - What's happening to solar ν on their way to Earth?
  - Could the Solar Standard Model (SSM) be wrong ?
- Other experiments using Gallium β decay, SAGE and GALLEX/GNO ($E_{thresh.} \simeq 233 KeV$; sensitive also to pp neutrinos)
  - Confirm of Homestake indications: only 55% of expected signal
  - ν oscillations and theoretical implications: signal of new physics ?
- 90s Kamiokande and SK measure $\nu_e - e^-$ elastic scattering in H_2O (sensitive only to ^8B and hep)
  - confirmation of ν_e deficit. Study of day-night asymmetries, spectrum distortion and seasonal variations: constraints on mixing parameters
- 2001: First data from SNO

POST SNO SITUATION

SNO (Cherenkov with heavy water) 3 PROCESSES:

- (1) $\nu_e + d \rightarrow e^- + p + p$ CHARGED CURRENT (CC)
- (2) $\nu_x + e^- \rightarrow \nu_x + e^-$ ELASTIC SCATTERING (ES)
- (3) $\nu_x + p \rightarrow \nu_x + p$ NEUTRAL CURRENT (NC)

- From (CC) $\rightarrow$ direct measurement of $\Phi_{\nu_e} = 1.75 \times 10^6 cm^{-2} s^{-1}$ ($\simeq$ 35% of S.S.M.)
- From comparison with SNO ES and SK ES: clear indication of ν_e oscillation into active neutrinos (ν_μ, ν_τ)
- Measurement of total ν active flux:
  - Good agreement with S.S.M.
  - Sterile ν hypothesis disfavoured
- Important indications about possible solution of solar ν puzzle, but still there isn't a unique (crystal-clear) answer

OUR ANALYSIS

(hep-ph/0111418 and hep-ph/0112101)

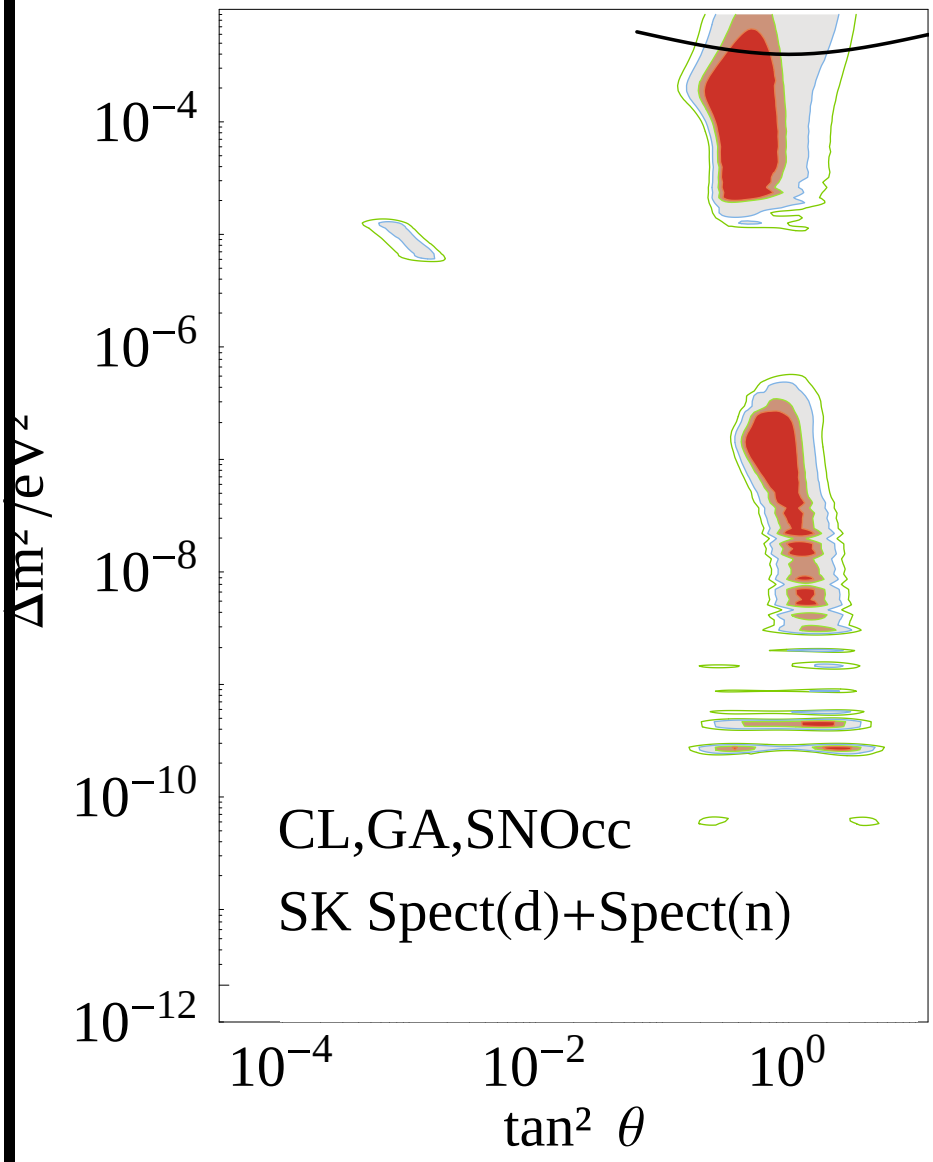
- Phenomenological study of all solar ν data including SNO and the recent SK data
- Inclusion of constraints from CHOOZ and atmospheric ν
- Aim of the analysis
  -determination of the allowed regions in the mixing parameters space
  -predictions for Borexino and SNO neutral current signal
- Strategy
  -ν oscillation hypothesis
  -bidimensional and tridimensional models
  -introduction in the hamiltonian of matter interaction term
  -comparison between computed signal and experimental results
  -statistical analysis withχ^2 method

STATISTICAL AND NUMERICAL ANALYSIS

- Determination of ν_e transition probability (including matter effects in Sun and Earth)
- Determination of response functions for each detector
- Computation of the ratio between the computed signal and the one predicted by SSM in absence of oscillation.
  $R_i^{th} = S_i^{th}/S_i^{SSM}$, i=Cl, Ga, SK, SNO
- Comparison with experimental ratio and χ^2 analysis
  - $\chi^2 = \chi^2_{global} + \chi^2_{spectrum}$
  - Introduction of 2 parameters to account for the uncertainties in flux normalization factor and in the bin correlation
- Determination of χ^2_{min} and search for the mixing parameters such that: $\Delta\chi^2 = \chi^2(\Delta m^2, \theta) - \chi^2_{min} < \chi^2_n(C.L.)$

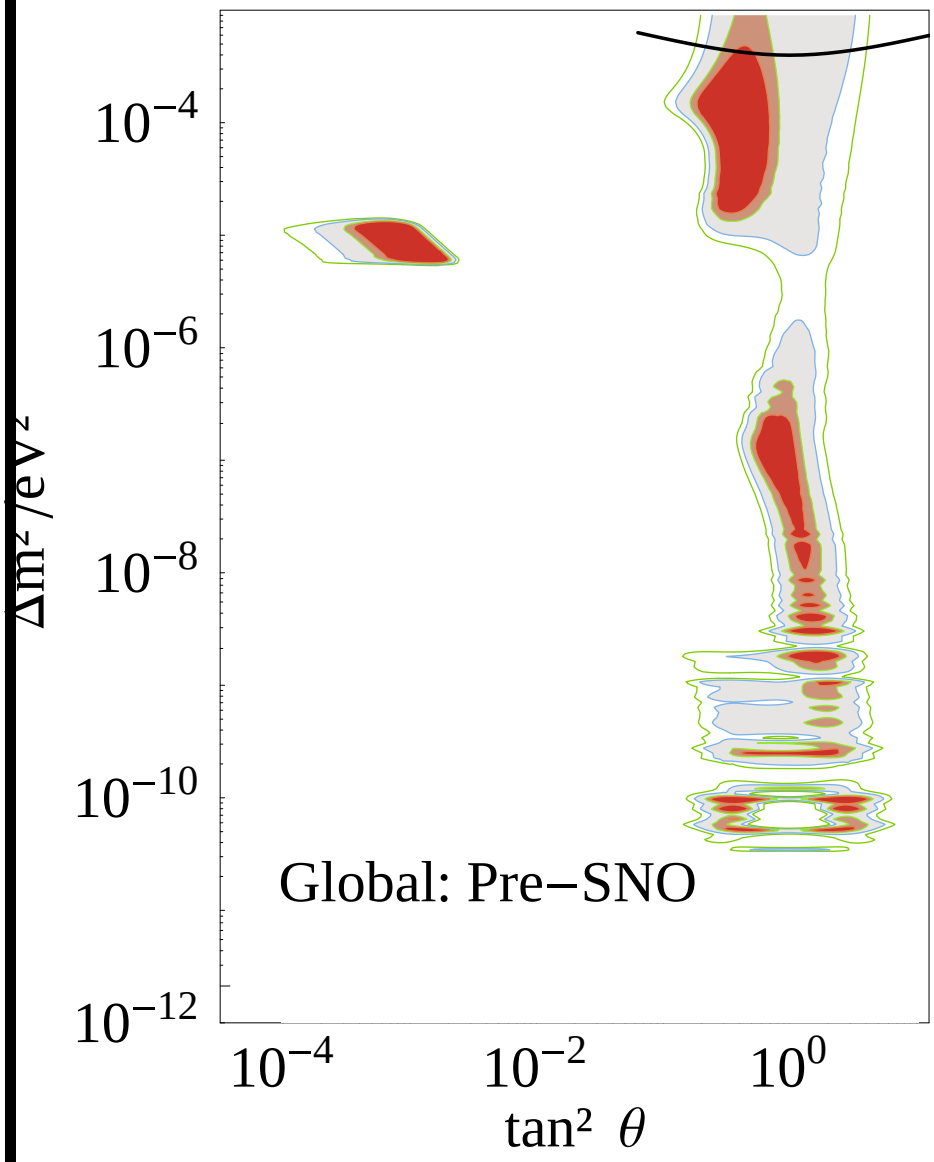
THE PRESENT SITUATION

- Results of the analysis including the data of the flux for Cl, Ga, SNO CC and of the SK energy bins.
- The different colored regions are the ones allowed by the data at different confidence levels (90%,95%,99% and 99.7% C.L.)
- The LMA and LOW solutions are the preferred ones (the absolute minimum is in the LMA region). The SMA and vacuum solutions are strongly disfavoured


10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
$\Delta m^2/eV^2$
CL,GA,SNOcc
SK Spect(d)+Spect(n)
10^{-4}
10^{-2}
10^{0}
$\tan^2\ \theta$

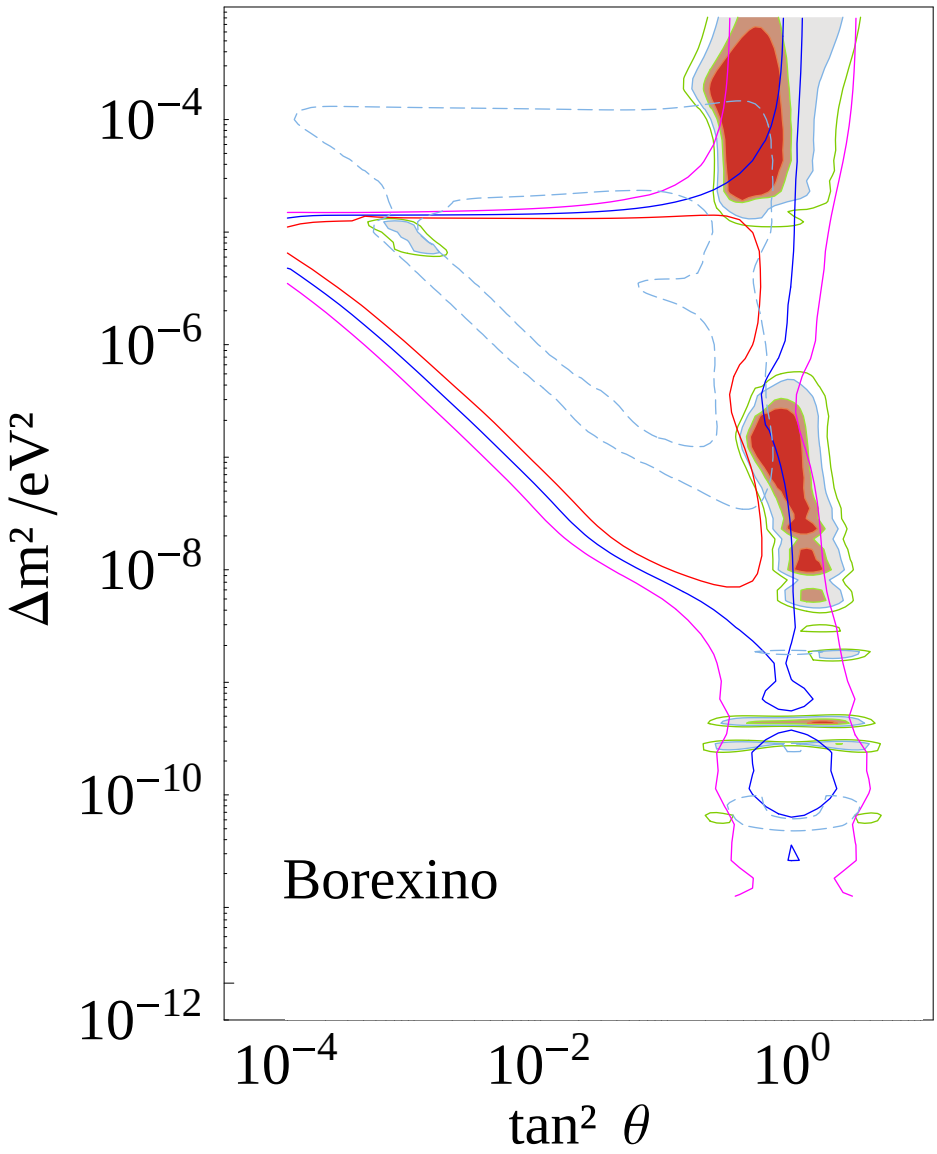
THE PRE SNO SITUATION

- Results of the analysis excluding the data from SNO and from SK energy specrum
- In this case the regions are not well separated and the SMA solution would be possible and even favoured


10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
$\Delta m^2/eV^2$
Global: Pre−SNO
10^{-4}
10^{-2}
10^{0}
$\tan^2\ \theta$

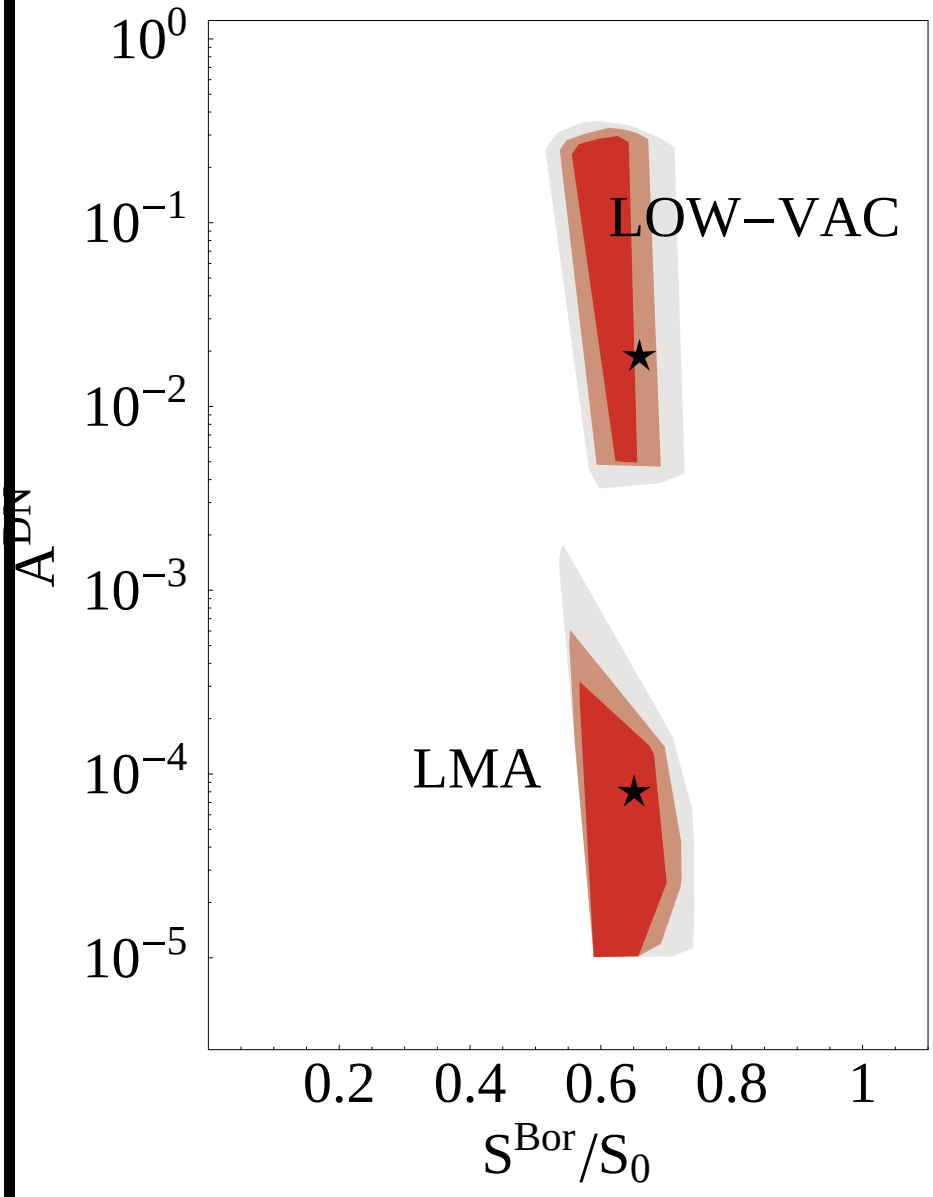
Borexino perspectives: Total signal analysis

- Contour lines corresponding to different possible values of the total signal of Borexino normalized to the SSM expected value. The full lines in the picture correspond to a Borexino signal equal to 0.5 (internal line), 0.6 and 0.7 .
- Superimposed there are the different regions allowed by the other experiment (see previous pictures).
- The SMA solution is well distinguished (the values of Borexino signal is ≤ 0.5). To discriminate between LMA and LOW a $5 - 10\%$ accuracy would be required


10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
Δm^2 /eV^2
Borexino
10^{-4}
10^{-2}
10^{0}
tan^2 θ

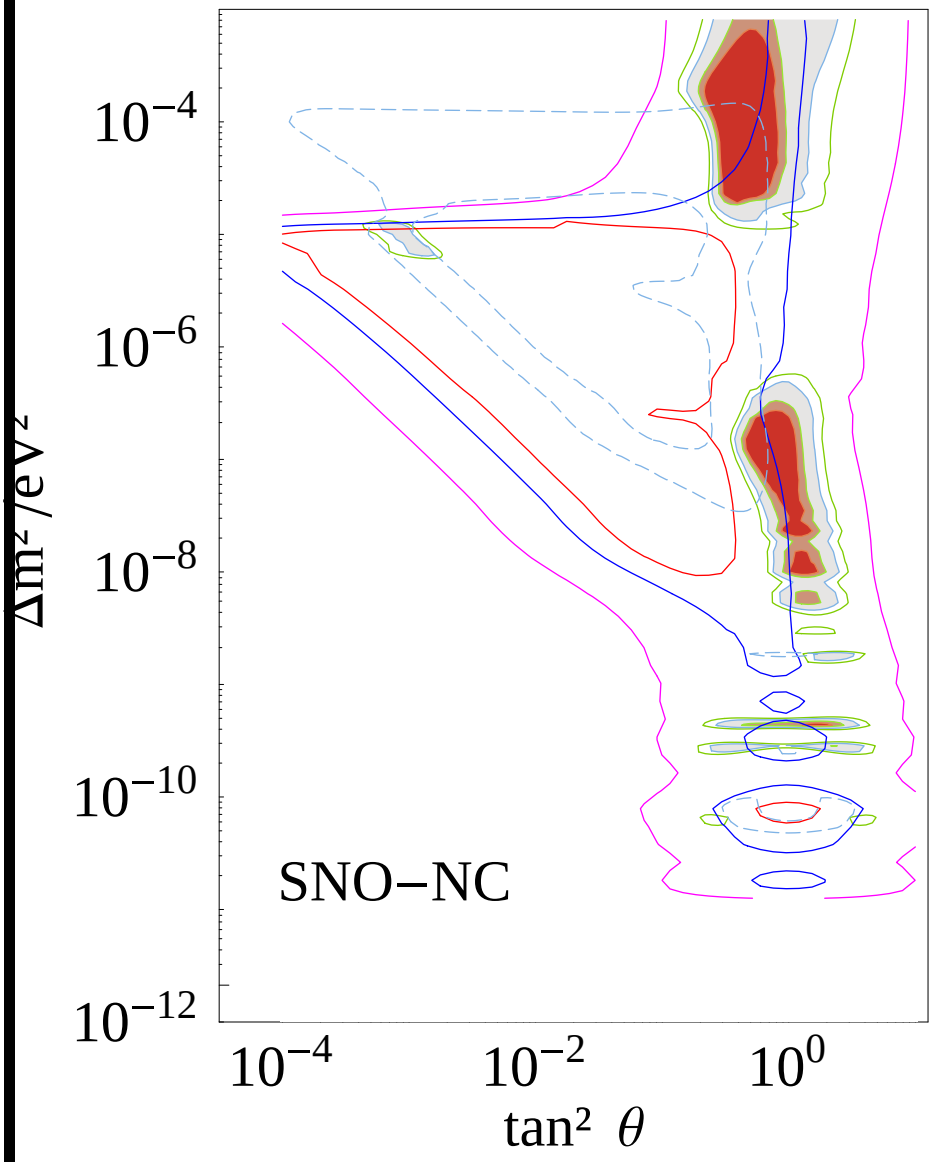
The Day-Night asimmetry at Borexino

- Values of the day-night asymmetry predicted for Borexino. Clear distinctin between the LMA and LOW solutions
- High possibility of discriminating between the different possible solutions of solar neutrino puzzle with a combined study of total signal and day-night asimmetry at Borexino


10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
A^{DN}
LOW−VAC
LMA
0.2
0.4
0.6
0.8
1
S^{Bor}/S_0

SNO NC

- Analysis of the predicted value of the total signal for SNO NC. Plot similar to the one of Borexino
- Comments about SNO NC and Kamland potentiality


10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
$\Delta m^2/eV^2$
SNO–NC
10^{-4}
10^{-2}
10^{0}
$\tan^2\ \theta$

COMMENTS AND CONCLUSIONS

- Updated phenomenological analysis including all solar neutrino data and giving predictions for new experiments
- Clear indications that neutrinos are really massive and oscillating, but still there is no unique solution of the solar neutrino puzzle. LMA solution favoured and SMA and vacuum solutions strongly disfavoured
- Predictions for Borexino and SNO NC possibility of discriminating between different solutions
- Statistical subtelties
- Future developments (work in progress):
  - General analysis in presence of sterile ν and study of seasonal variations
  - Extension of the analysis to atmospheric neutrinos