Solar fluxes from neutrino oscillation data

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I. The new solar problem

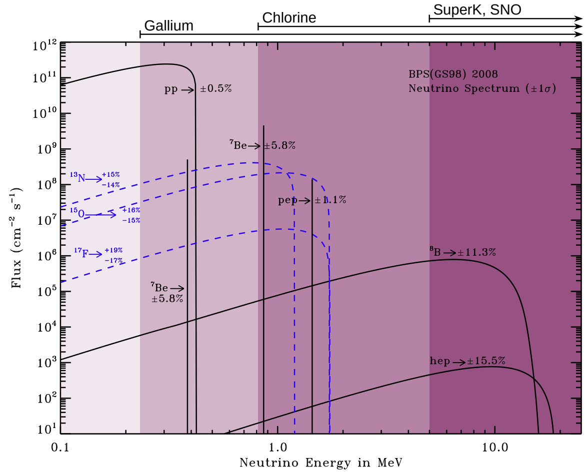
II. Solar neutrino fluxes

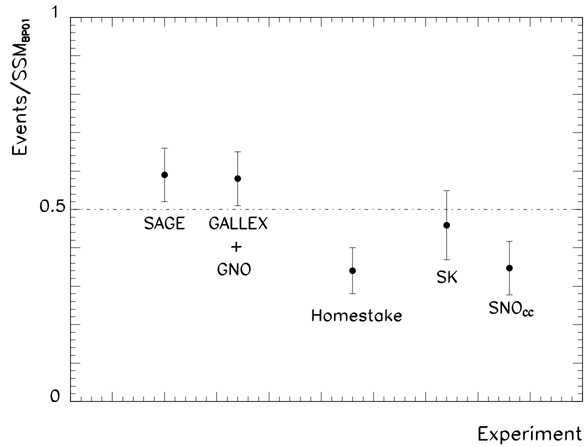
III. Neutrino oscillation parameters

Conclusions

The solar NEUTRINO problem

- Nuclear reactions in the core of the Sun produce *electron neutrinos*;
- during the last 40 years, a number of underground experiments has measured their flux in different energy windows;
- it is found that ALL the experiments observe a deficit of about $\mathbf{30 - 60\%}$;
- the deficit is NOT the same for all the experiments, hence the effect is **energy dependent**.
- it is **not possible** to reconcile the data with the Standard Solar Model (SSM) by simply readjusting the parameters of the model;
- solution: neutrino $\nu_e \to \nu_{\text{active}}$ oscillations;
- Effect well understood $\Rightarrow$ **PROBLEM SOLVED.**

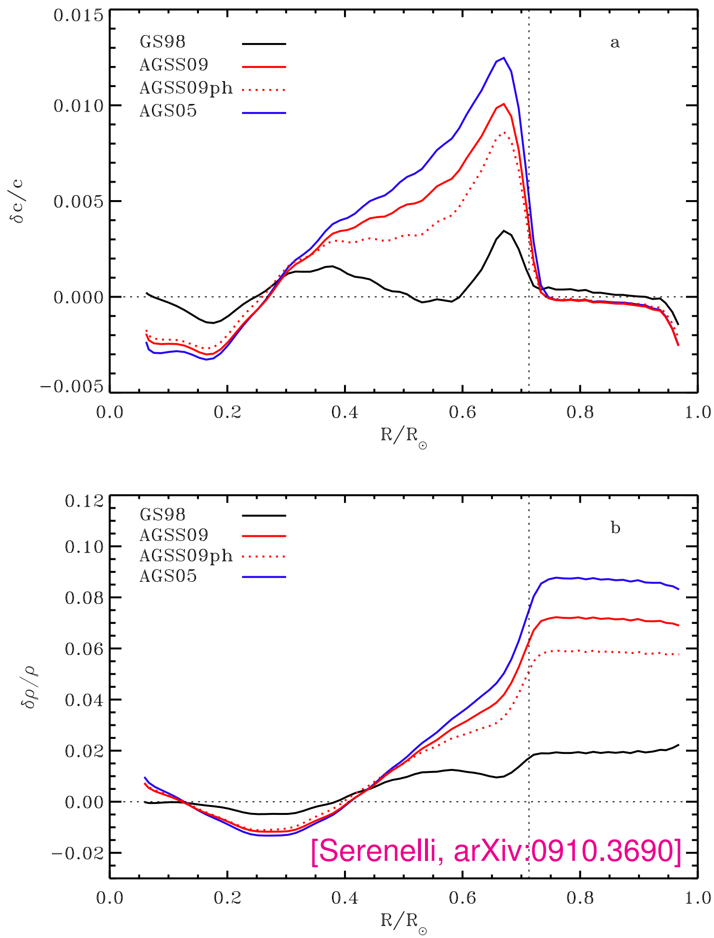




The solar ABUNDANCE problem

- The solar chemical composition is encoded in its surface spectrum;
- however, its extraction requires an accurate modelling of the solar atmosphere;
- two atmospheric models: old-1D (GS98) and new-3D (AGS05, AGSS09);
- the extracted surface composition is then extended to the bulk of the Sun;
- the chemical composition in the radiative zone determines the opacities, which in turn determine the internal solar structure;
- the structure of the solar interior is accurately measured by **helioseismology**;

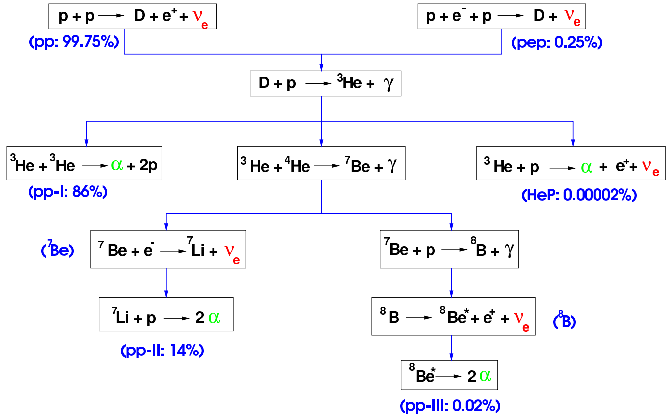
⇒ **new abundances from AGS models are incompatible with helioseismology.**

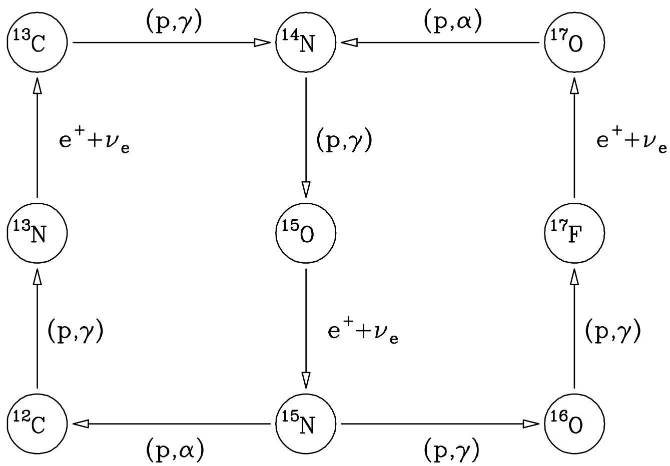


Neutrinos and solar abundances

- Neutrinos are produced in the core of the Sun through two different mechanisms: the pp chain and the CNO cycle;
- both give $4p \to ^4\text{He} + 2e^+ + 2\nu_e + \gamma$;
- the solar abundance problem is a discrepancy between the theory of stellar atmospheres and the theory of stellar interiors; neutrinos are not directly involved;
- however, the rate of the different nuclear reactions depend on the chemical composition **of the solar core**;
- in particular, CNO ν's are sensitive to the amount of "metals" (= anything but H & He);

⇒ solar neutrinos can provide direct information on the metallicity in the solar interior.





Reconstructing the neutrino fluxes

Flux	Φ_i^{ref} [cm^{-2} s^{-1}]
pp	5.97×10^{10}
^{7}Be	5.07×10^{9}
pep	1.41×10^{8}
^{13}N	2.88×10^{8}
^{15}O	2.15×10^{8}
^{17}F	5.82×10^{6}
^{8}B	5.94×10^{6}
hep	7.90×10^{3}

- Strategy: perform a solar model indepenent analysis of both solar and terrestrial neutrino data in the framework of 3ν mixing;
- aim: to dertermine both the flavor parameters and all the solar neutrino fluxes with a mimimum set of theoretical priors;
- 11 parameters: θ_{12}, θ_{13}, Δm^2_{21} and 8 reduced fluxes $f_i = \Phi_i/\Phi_i^{\text{ref}}$;
- imposed physical conditions:
  - fluxes must be positive: $\Phi_i \geq 0$
  - the number of nuclear reactions terminating the pp-chain should not exceed the number of nuclear reactions which initiate it: $\Phi_{^7\text{Be}} + \Phi_{^8\text{B}} \leq \Phi_{\text{pp}} + \Phi_{\text{pep}}$
  - the $^{14}\text{N}(p,\gamma)^{15}\text{O}$ reaction must be the slowest process in the main branch of the CNO-cycle: $\Phi_{^{15}\text{O}} \leq \Phi_{^{13}\text{N}}$
  - the CNO-II branch must be subdominant: $\Phi_{^{17}\text{F}} \leq \Phi_{^{15}\text{O}}$
  - pep & pp have the same nuclear matrix element: $f_{\text{pep}}/f_{\text{pp}} = 1.008 \pm 0.010$

The luminosity constraint

- Apart from **neutrinos**, nuclear reactions in the solar core also produce **energy**;
- changing the rate of a given reaction scales the corresponding **energy yield** and **neutrino flux** by the same factor;
- the total amount of energy produced by the Sun is well known;
- imposing this as a constraint results in a further condition on the neutrino fluxes:

$$\sum_{i=1}^{8} \alpha_i \, \Phi_i = \frac{L_\odot}{4\pi \, (\text{A.U.})^2} = 8.5272 \times 10^{11} \, \text{MeV} \, \text{cm}^{-2} \, \text{s}^{-1}$$

- or, in terms of the reduced fluxes:

$$\sum_{i=1}^{8} \beta_i \, f_i = 1 \qquad \text{with} \qquad \beta_i \equiv \frac{\alpha_i \Phi_i^{\text{ref}}}{L_\odot / [4\pi \, (\text{A.U.})^2]}$$

- in what follows we will present results both **with** and **without** imposing the luminosity constraint.

Flux	α_i [MeV]	β_i
pp	13.0987	9.171×10^{-1}
^{7}Be	12.6008	7.492×10^{-2}
pep	11.9193	1.971×10^{-3}
^{13}N	3.4577	1.168×10^{-3}
^{15}O	21.5706	5.439×10^{-3}
^{17}F	2.363	1.613×10^{-5}
^{8}B	6.6305	4.619×10^{-5}
hep	3.7370	3.462×10^{-8}

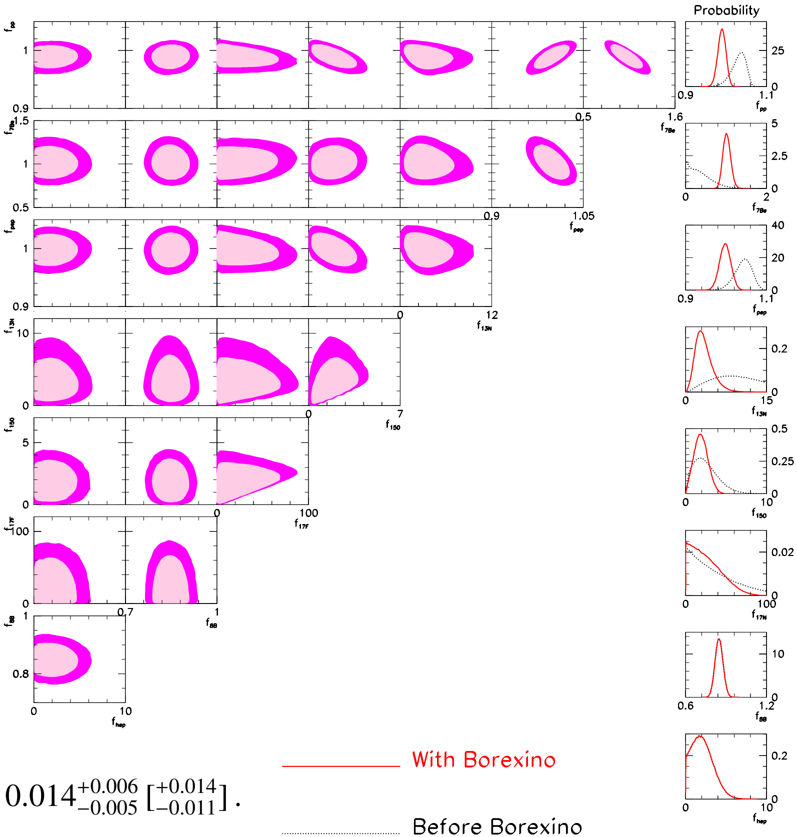
Results with the luminosity constraint

- Best-fit fluxes:

$$f_{pp} = 0.990^{+0.010}_{-0.009}\,[^{+0.023}_{-0.030}]\,,$$
$$f_{^7Be} = 1.00^{+0.10}_{-0.09}\,[^{+0.25}_{-0.21}]\,,$$
$$f_{pep} = 0.998 \pm 0.014\,[\pm 0.04]\,,$$
$$f_{^{13}N} = 2.7^{+1.7}_{-1.2}\,[^{+5.6}_{-2.4}]\,,$$
$$f_{^{15}O} = 1.8 \pm 0.9\,[^{+2.2}_{-1.8}]\,,$$
$$f_{^{17}F} \leq 32\,[72]\,,$$
$$f_{^8B} = 0.85 \pm 0.03\,[\pm 0.08]\,,$$
$$f_{hep} = 1.7^{+1.3}_{-1.4}\,[^{+3.8}_{-1.7}]\,,$$

- oscillation parameters:

$$\Delta m^2_{21} = 7.6 \pm 0.2\,[\pm 0.5] \times 10^{-5}\ \mathrm{eV}^2\,,$$
$$\sin^2\theta_{12} = 0.33 \pm 0.02\,[\pm 0.05]\,,$$
$$\sin^2\theta_{13} = 0.02 \pm 0.012\,[^{+0.03}_{-0.02}]\,,$$



- solar luminosity:

$$\frac{L_{\text{pp-chain}}}{L_\odot} = 0.986^{+0.005}_{-0.006}\,[^{+0.011}_{-0.014}] \iff \frac{L_{\text{CNO}}}{L_\odot} = 0.014^{+0.006}_{-0.005}\,[^{+0.014}_{-0.011}]\,.$$

Results without the luminosity constraint

- Best-fit fluxes:

$$
\begin{aligned}
f_{\text{pp}} &= 0.98^{+0.16}_{-0.15}\,[^{+0.47}_{-0.40}]\,,\\
f_{^7\text{Be}} &= 1.01^{+0.10}_{-0.09}\,[^{+0.27}_{-0.22}]\,,\\
f_{\text{pep}} &= 0.98^{+0.16}_{-0.15}\,[^{+0.47}_{-0.40}]\,,\\
f_{^{13}\text{N}} &= 2.7^{+1.8}_{-1.3}\,[^{+5.7}_{-2.5}]\,,\\
f_{^{15}\text{O}} &= 1.9 \pm 1.0\,[^{+2.3}_{-1.9}]\,,\\
f_{^{17}\text{F}} &\leq 34\,[79]\,,\\
f_{^8\text{B}} &= 0.85 \pm 0.03\,[\pm 0.08]\,,\\
f_{\text{hep}} &= 1.7^{+1.3}_{-1.4}\,[^{+3.8}_{-1.7}]\,,
\end{aligned}
$$

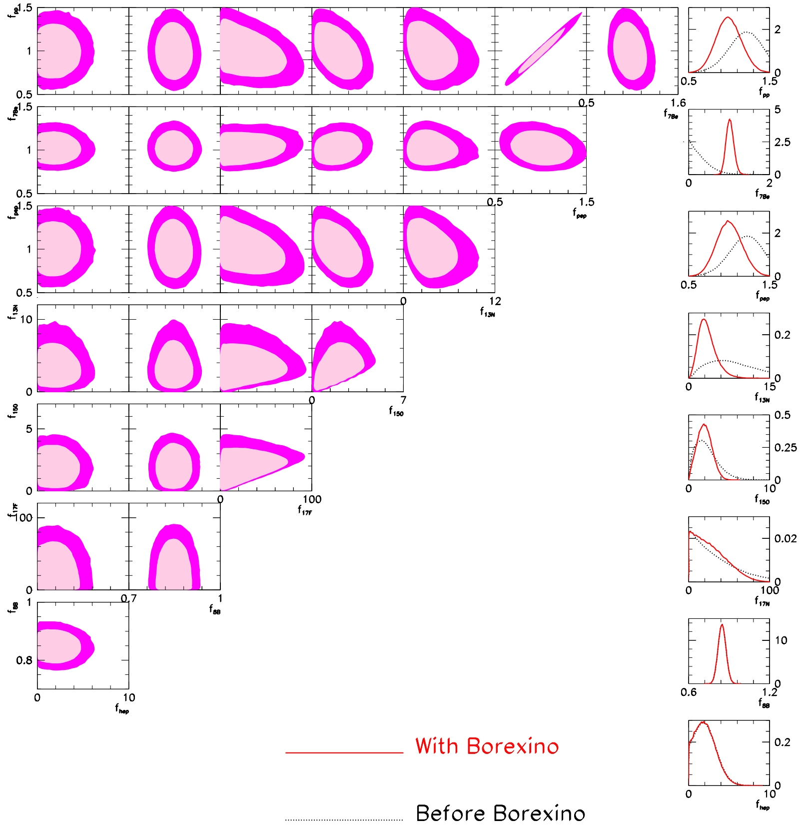
- solar luminosity:

$$
\frac{L_{\text{pp-chain}}}{L_\odot} = 0.98^{+0.15}_{-0.14}\,[\pm 0.40]\,,
$$

$$
\frac{L_{\text{CNO}}}{L_\odot} = 0.015^{+0.005}_{-0.007}\,[^{+0.013}_{-0.014}]\,,
$$

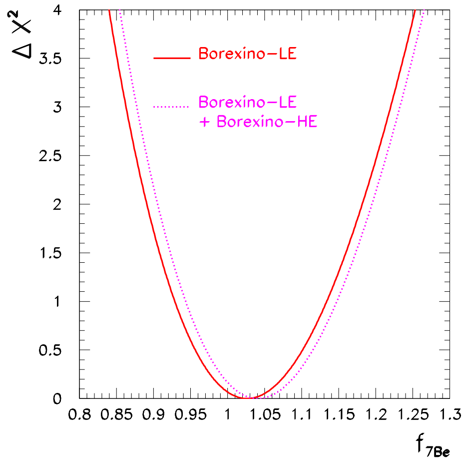
- from which we derive:

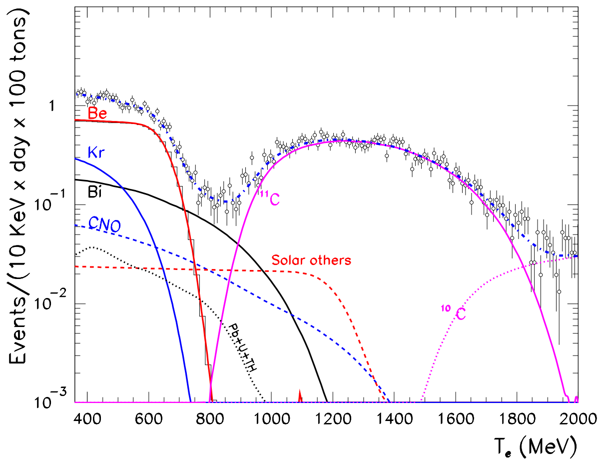
$$
\frac{L_\odot(\text{neutrino-inferred})}{L_\odot} = 1.00 \pm 0.14\,[^{+0.37}_{-0.34}]\,.
$$



The Borexino experiment

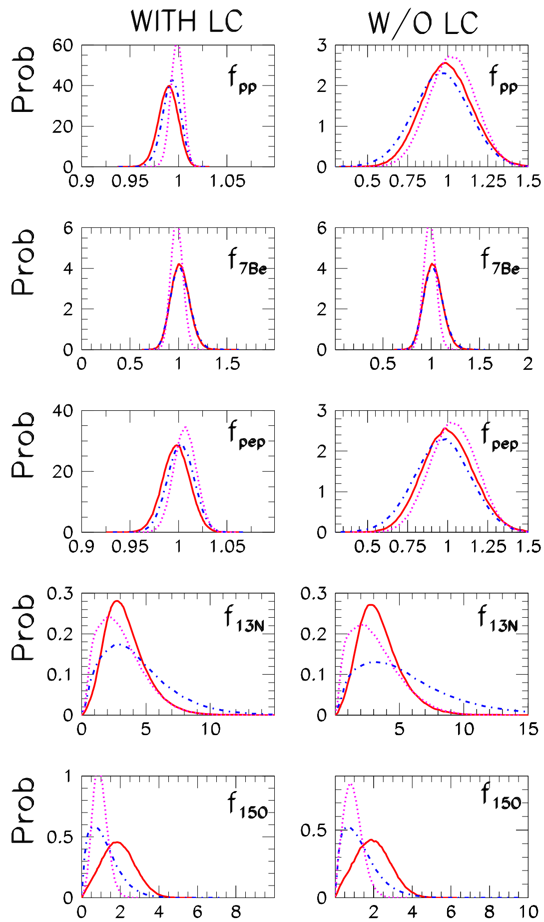
- Borexino has provided a unique measurement of solar neutrinos at low energy [arXiv:0805.3843];
- however, the official analysis only focuses on the extraction of ^{7}Be, and treats CNO neutrinos as “background”;
- this is inconsistent with our approch, which aims at a joint determination of **all** the fluxes on the same footing;
- hence, we have performed our own analysis of the Borexino spectrum;
- backgrounds:
  - ^{14}C is removed by a cut $T_e \geq 365$ keV;
  - ^{238}U, ^{214}Pb are assumed to be known;
  - ^{85}Kr, ^{210}Bi, ^{11}C, ^{10}C are left free and fitted;
- our fit is in excellent agreement with the results of the Borexino collaboration.





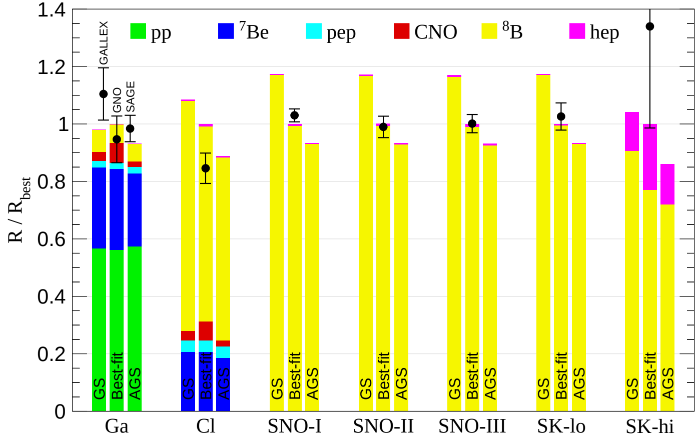
The role and potential of Borexino

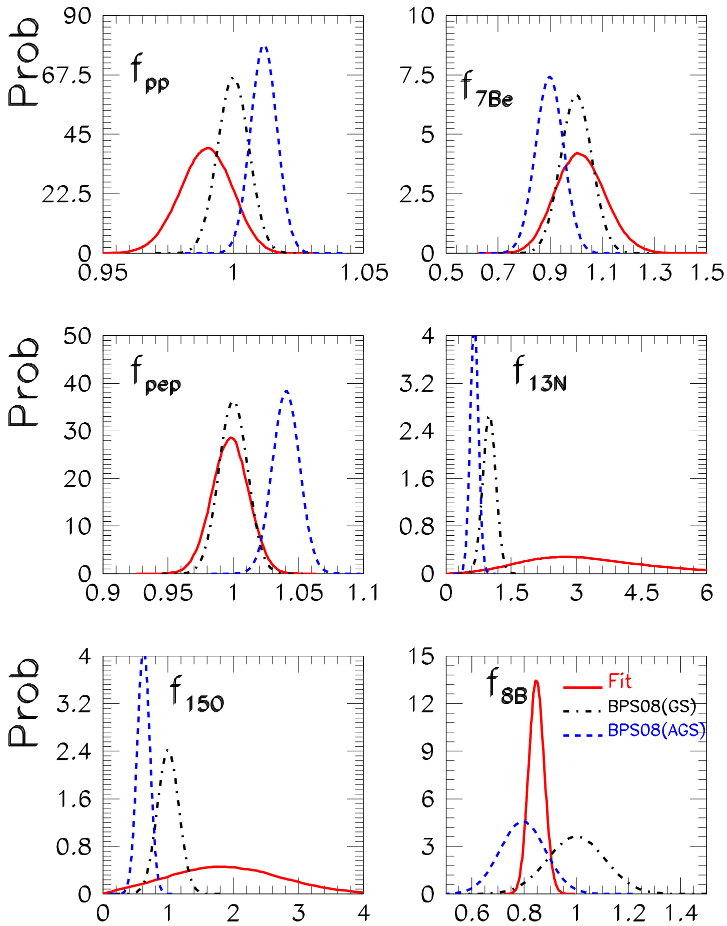
- Three types of fit:
  - solid: present, full-spectrum;
  - dash-dotted: present, ^{7}Be line only;
  - dotted: future (no ^{11}C, stat $\times 2$, sys / 3);
- use of spectral info irrelevant for ^{7}Be;
- CNO improves ⇒ Borexino can see them, even with unknown ^{210}Bi background;
- CNO also important for Chlorine and Gallium:
  - Gallium mainly sensitive to ^{13}N (lower E_ν);
  - Chlorine mainly sensitive to ^{15}O (higher E_ν);
- Gallium excess ⇒ ^{13}N always larger than 1;
- Chlorine deficit ⇒ ^{15}O senses tension with Borexino;
- future data will improve fluxes, but not dramatically.



Which Standard Solar Model?

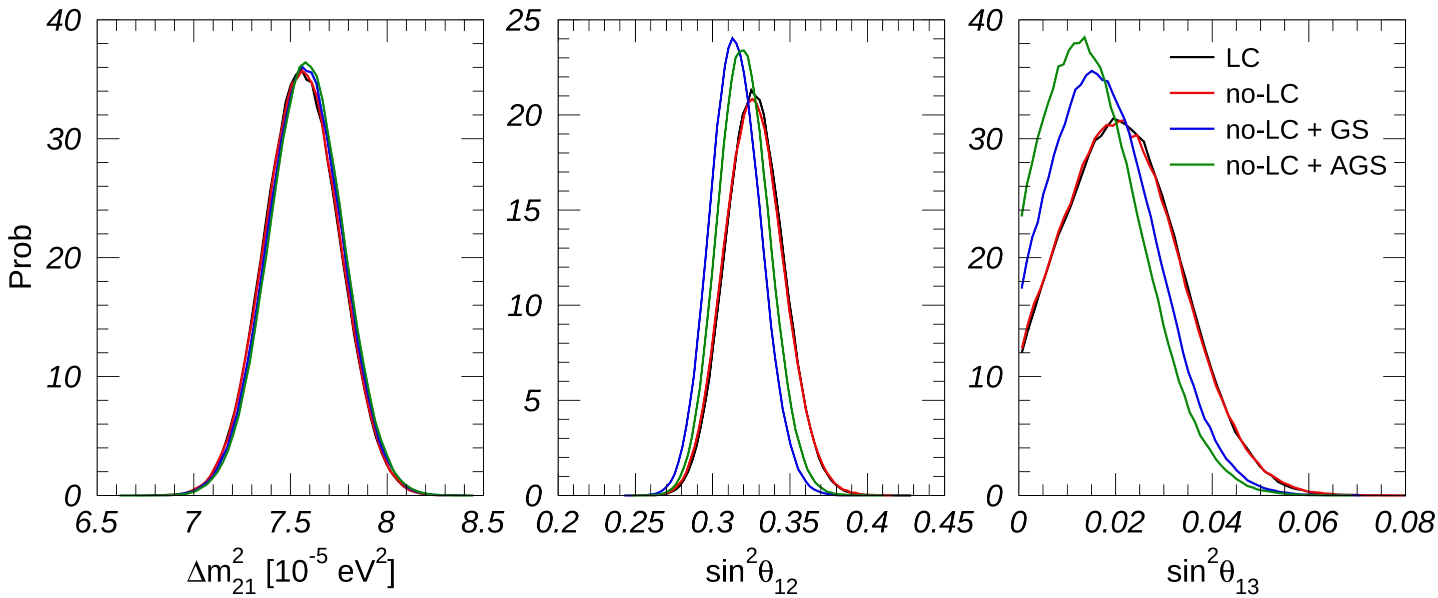
- Present data inconclusive because:
  - no clear preference for a given model;
  - not enough sensitivity anyway;
- statistical test: $P_{\text{agr}} = \begin{cases} 43\% \text{ for GS,} \\ 20\% \text{ for AGS;} \end{cases}$
- wishlist: measure CNO at $\mathcal{O}(30\%)$ level.





Connection with the oscillation parameters

- Imposing the luminosity constraint has no effect on the oscillation parameters;
- Δm^2_{21} completely dominated by KamLAND ⇒ insensitive to the SSM's details;
- conversely, the preferred range of θ_{12} and θ_{13} depends on the SSM.



Neutrino oscillations: where we are

- **Updated** global 6-parameter fit (including δ_{CP}):
  - **Solar**: **Cl** + **Ga** + **SK-I** + **SNO-leta (I+II)** + **SNO-III** + **BX-low** + **BX-high**;
  - **Atmospheric**: SK-I + SK-II + **SK-III**;
  - **Reactor**: Chooz + **KamLAND**;
  - **Accelerator**: K2K + Minos-DIS + **Minos-APP**;
- BPS09(GS): best-fit and 1σ (3σ):

$$\theta_{12} = 34.4 \pm 1.0 \left({}^{+3.2}_{-2.9}\right), \quad \Delta m^2_{21} = 7.59 \pm 0.20 \left({}^{+0.61}_{-0.69}\right) \times 10^{-5}\ \text{eV}^2,$$

$$\theta_{23} = 42.8\,{}^{+4.7}_{-2.9} \left({}^{+10.7}_{-7.3}\right), \quad \Delta m^2_{31} = \begin{cases} -2.36 \pm 0.11\ (\pm 0.37) \times 10^{-3}\ \text{eV}^2, \\ +2.46 \pm 0.12\ (\pm 0.37) \times 10^{-3}\ \text{eV}^2, \end{cases}$$

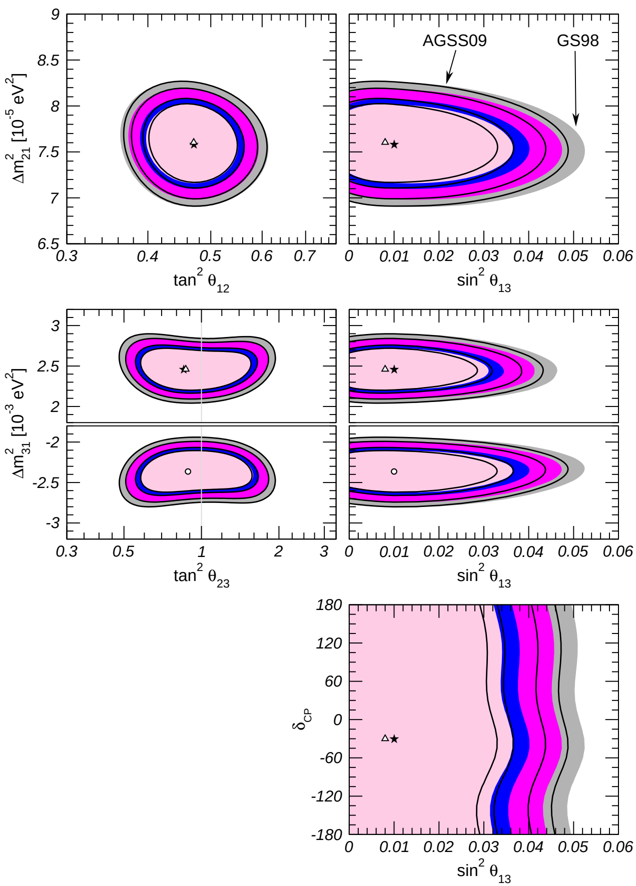
$$\theta_{13} = 5.6\,{}^{+3.0}_{-2.7}\ (\leq 12.5), \quad \delta_{CP} \in [0, 360];$$

- BPS09(AGSS): same as above except:

$$\theta_{12} = 34.5 \pm 1.0 \left({}^{+3.2}_{-2.8}\right), \quad \theta_{13} = 5.1\,{}^{+3.0}_{-3.3}\ (\leq 12.0);$$

- "$\theta_{13} \neq 0$":

Solar model	Sol+Kam	Global
BPS09(GS)	1.26σ	1.31σ
BPS09(AGSS)	1.05σ	1.17σ



⇒ **Full details and future: → next talk**

[Gonzalez-Garcia, MM & Salvado, arXiv:1001.4524 v3]

- We have performed a solar model independent analysis of solar and terrestrial neutrino data in the framework of three neutrino oscillations;
- we have fitted the normalization of the 8 solar neutrino fluxes together with the relevant oscillation parameters;
- main results:
  - the neutrino-inferred luminosity perfectly agrees with the measured one and it is known with a 1σ uncertainty of 14%;
  - the low value of the ^{8}B flux at SK and SNO points towards low metallicity models;
  - the measurement of ^{7}Be in Borexino favor high metallicity models;
  - altogether there is a slight preference for models with higher metallicities;
- the largest difference between the models lies on the CNO fluxes that give predictions which differ by about 30%. This is the level of precision required to achieve a statistically meaningful discrimination between the models.

⇒ [Gonzalez-Garcia, MM & Salvado, JHEP 05 (2010) 072, arXiv:0910.4584]
[Gonzalez-Garcia, MM & Salvado, JHEP 04 (2010) 056, arXiv:1001.4524]