What next LNGS

Prospettive per il ruolo scientifico dei LNGS

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Problemi aperti in fisica dei neutrini solari e sviluppi futuri

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Status of solar neutrino physics

Solar neutrino results continue to be interesting for astroparticle and elementary particle physics.

Recently:

- **1st measurement of pp ν flux** by **Borexino** (G. Bellini et al., Nature 512 (2014) 383)

  $\Phi_{\nu,\,pp}$= (6.6 ± 0.7) x 10^{10} cm^{-2} s^{-1} , agreement both with high and low Z SSM.

- **Confirmation of the LMA** oscillation solution:

- **SK IV data** (combined with prev. 3 phases) (A. Renshaw 1403.4575[hep.ex] and Phys. Rev. Lett 112 (2014) 09185) slightly favoured spectrum distortion and **upturn in low E spectrum** predicted and not yet observed **and** measured Day-Night asymmetry ≠ 0 at 2.7 σ at 68% C.L. . **Needs** for **additional studies** with **more statistics** (see later).
- **Borexino data**: absence of D-N asymmetry in ^{7}Be signal:

A_{DN}=0.001 ± 0.012(stat)±0.007(syst) (G.Bellini et al., PRD 89 (2014) 112007), agreement with LMA.

- Present knowledge of the **mixing and oscillation parameters**

$\sin^2\theta_{12}$=0.308 ± 0.017; $\sin^2\theta_{13}$(NH)=(2.34 ±0.19)$\cdot 10^{-2}$; $\sin\theta_{13}$(IH) =(2.40 ±0.20)$\cdot 10^{-2}$

$$\Delta m^2 = 7.54^{+0.26}_{-0.22} \cdot 10^{-5}\,eV^2$$

Only LMA region survives after Borexino data (+ previous experiments)

- **Determination of fluxes**

Solar neutrino fluxes

- **^{8}B solar ν flux determination**

(above 3.5 MeV) improved quite recently with the combined analysis of **SNO** 3 phases (Phys. Rev. C 88 (2013) 025501) :

$$\varphi_{^8B} = 5.25 \pm 0.16(\text{stat})^{+0.11}_{-0.13}(\text{syst}) \cdot 10^{6}\,\text{cm}^{-2}\text{s}^{-1}$$

- **SuperKamiokande** recently, including also SK IV (hep-ex:1403.4575), found a flux value on the detector equal to: $(2.37 \pm 0.015(\text{stat.}) \pm 0.04(\text{syst.})) \cdot 10^{6}\text{cm}^{-2}\text{s}^{-1}$.
- **Borexino**,with a lower **E threshold (3 MeV)** got (PRD 82 (2010) 033006) an equivalent unoscillated flux of $(2.4 \pm 0.4(\text{stat}) \pm 0.1(\text{syst})) \cdot 10^{6}\text{cm}^{-2}\text{sec}^{-1}$, **comparable** with SNO and SK.

- **^{7}Be ν flux: dominated by Borexino**

$\phi_{7Be}(\nu_e) = (3.10 \pm 0.15) \cdot 10^{9}\ \text{cm}^{-2}\text{sec}^{-1}$ (PRL 107 (2011) 141302; PRD 89 (2014) 112007)

- KamLAND measured a flux for the 0.862 MeV ^{7}Be line (89.6% of total ^{7}Be ν flux) of $(3.26 \pm 0.50) \cdot 10^{9}\ \text{cm}^{-2}\text{s}^{-1}$ (arXiv:1405.6190 [hep-ex]) .

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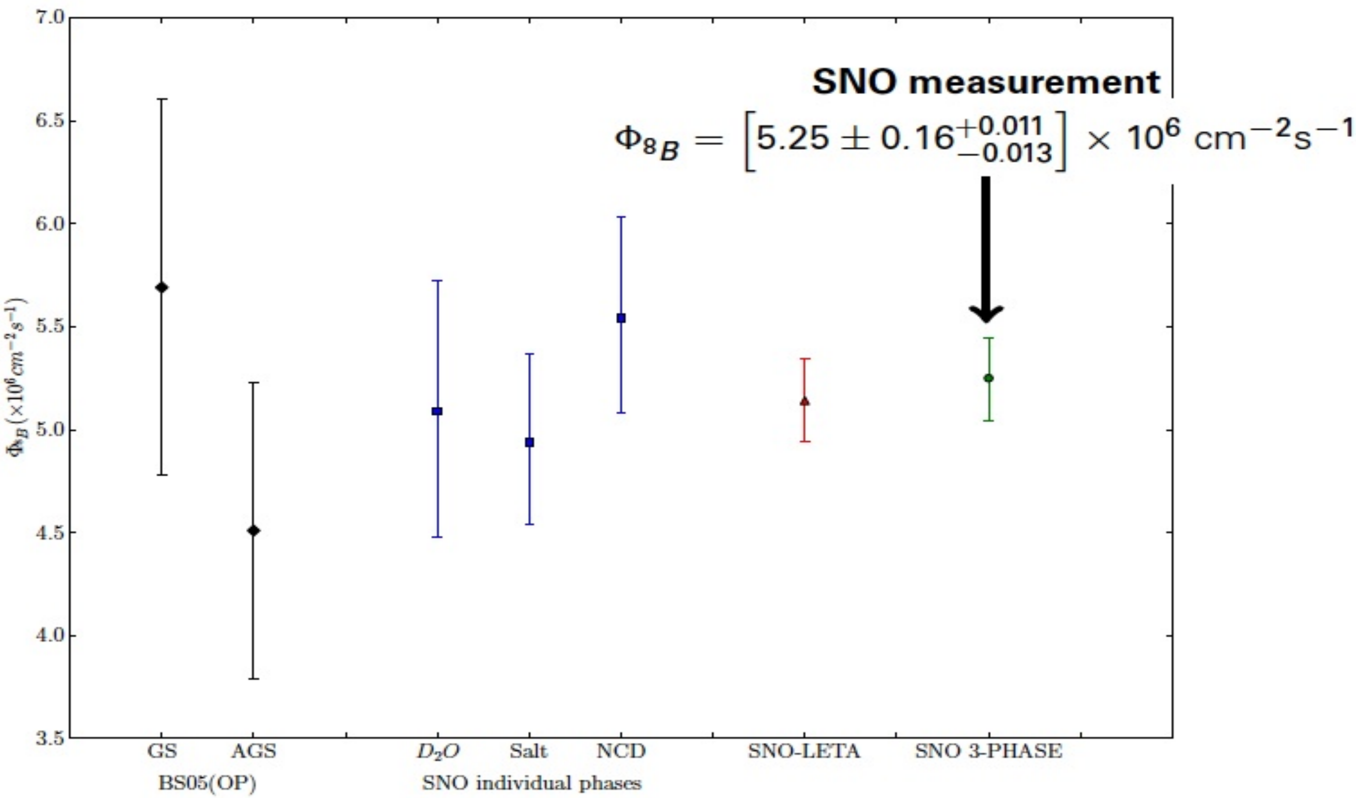
Improvement in ^{8}B solar ν flux determination with different phases of the SNO experiment and comparison with the SSM.



Taken from SNO Collaboration publications.

Solar neutrino fluxes II

- **Recent great step forward: Borexino 1st direct measurement of pp ν (0–420 keV), main component of the pp-chain:**

$\phi_{pp}(\nu_e) = (6.6 \pm 0.7)\cdot 10^{10}\ cm^{-2}s^{-1}$

(inter. rate 144 ± 13(stat)±10 (syst) c.p.d. per 100 tons). **Agreement with SSM**.

- **pep and CNO neutrinos**

Despite their relevance (in SSM pep ν flux strongly constrained by luminosity and link to pp; CNO cycle essential for solar core metallicity and important to fuel stars in various evolution phases) … **not directly detected till 2011**.

- e^- recoil spectrum from **pep ν**: Compton like shoulder with 1.22 MeV end point. Very low interaction rate (few c.p.d/(100 tons));

Bckg reduction (in 1-2 MeV E region) very challenging. Mainly: cosmogenic ^{11}C (β^+ ; E released between 1.02 and 1.98 MeV).

- **CNO**: continous spectra, with endpoints among 1.19 and 1.74 MeV (N,O, F).

Results by Borexino (PRL 108 (2012)051302):

pep ν: rate=3.1±0.6(stat)±0.3(syst) [c/(day·100tons]; ϕ =(1.6 ±0.3)•10^8 cm^{-2} s^{-1}.

CNO ν : $\phi < 7.7\cdot 10^8\ cm^{-2}\ s^{-1}$

High Z and low Z SSM

- The agreement between the Solar Standar Model (SSM) and the solar data has been compromised by the downward **revision of the solar surface heavy-element content** from (Z/X) = 0.0229 [GS98] to (Z/X) = 0.0165 [AGS05], leading to a strong **discrepancy between the SSM and the helioseismology** results.

- In 2009 revision of solar photospheric abundances, using three dimensional hydrodynamical solar atmosphere model and improved radiative transfer and opacities, gave [AGSS09] (Z/X) = 0.0178.

- **Two different versions of the SSM** survive:

- high metallicity (or **high Z**) and low metallicity (**low Z**) SSM, predicting **different values of solar neutrino fluxes** (mainly CNO ν)

Estimates for different solar ν fluxes

Flux	GS98	AGSS09	Solar
pp	5.98·(1±0.006)	6.03·(1±0.006)	$6.05\cdot(1^{+0.003}_{-0.011})$ DIRECT 6.6 • (1 ± 0.11)
pep	1.44·(1±0.012)	1.47·(1±0.012)	$1.46\cdot(1^{+0.010}_{-0.014})$ DIRECT 1.6 • (1 ±0.19)
^{7}Be	5.00·(1±0.07)	4.56·(1±0.07)	$4.82\cdot(1^{+0..05}_{-0.04})$
^{8}B	5.58·(1±0.13)	4.59·(1±0.13)	5.20·(1±0.04)
^{13}N	2.96·(1±0.15)	2.17·(1±0.13)	≤ 6.7 (to update)
^{15}O	2.23·(1±0.16)	1.56·(1±0.15)	≤ 3.2 (to update)
^{17}F	5.52·(1±0.18)	3.40·(1±0.16)	≤ 5.9 (to update)

Units in $cm^{-2}\ s^{-1}$: 10^{10} (*pp*), 10^{9} (^{7}Be), 10^{8} *(pep,*^{13}N,^{15}O*)*,10^{6} (^{8}B, ^{17}F)

Partially taken from Astrophys. J. 705 (2009) L123 and from Adv. High Energy Phys. 2013 (2013) 351926

Open "problems" in solar ν physics

- Improvement of the **accuracy** of the **very low E part** of the spectrum: pp and pep:

- **<u>Borexino</u>** (possible improvement with increased statistics and reduction of ^{210}Bi background for pep);
- **<u>SNO+</u>** (advantage from the detector mass, about 3 times larger, and the location, 2 times deeper underground than Borexino, with a significant reduction of ^{11}C background. Possible pep measurement with 5% accuracy),
- **<u>next generation of multipurpose experiments</u>** (planned for $0\nu2\beta$ decays and dark matter searches, but suitable also to study the lower E part of solar ν spectrum).

Requirements: very large detector masses and high levels of radiopurity.

Examples: new techniques with organic scintillators and ''noble liquid detectors''

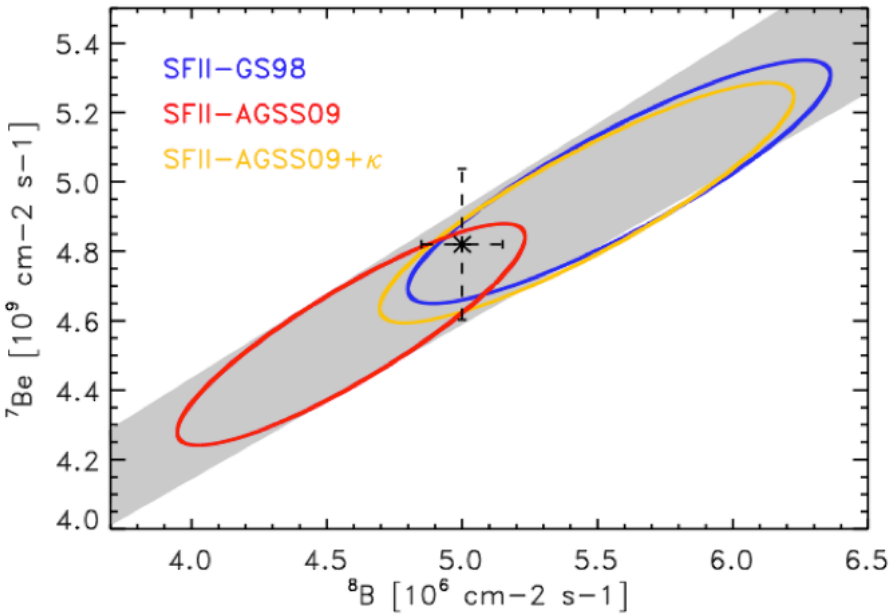
- **The metallicity problem.**

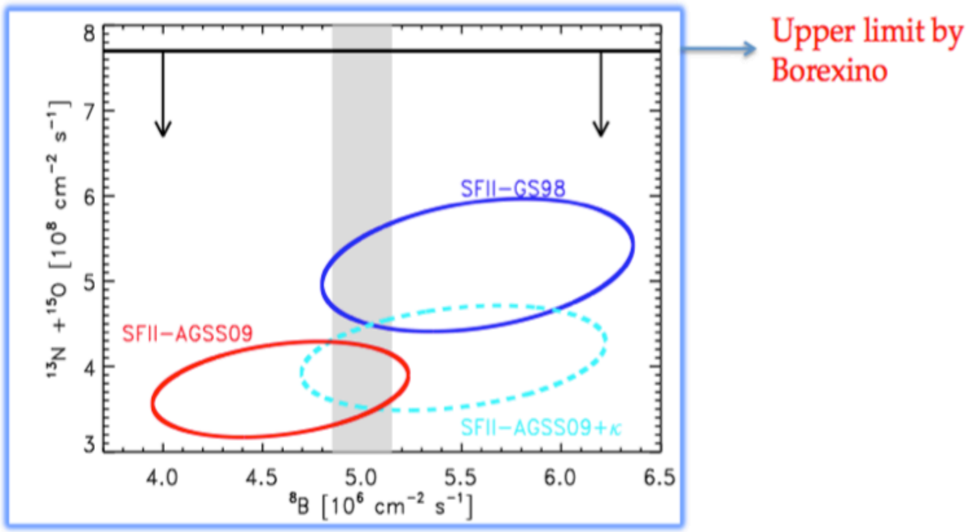
- **Test** with higher statistical significance **of the LMA** oscillation **pattern.**

- Study of the ^{8}B flux in the region around 3 MeV and look for the ''spectrum upturn'' in the vacuum-matter transition region.
- Study of Day-Night asymmetry with ^{8}B

The solar metallicity problem

Theoretical predictions, in different SSM versions (high Z, low Z and low Z with increased opacity), and experimental results for the ^{7}Be and ^{8}B ν and the main components of CNO cycle. Taken from A. M. Serenelli, "A special Borexino event - Borexino Mini-Workshop", Sept. 5 2014





- Need to **measure CNO neutrinos**, but difficult to extract the very low signal from background, mainly due to ^{210}Bi and ^{11}C.
- Due to the ambiguity metallicity-opacity, important to **complement** also **with the accurate determination of ^{7}Be and/or ^{8}B flux.**
- Difficulty of the measurements and possibilities for present and future experiments (Borexino, SNO+, others).

The ^{7}Be determination

- ^{7}**Be** determination **up to now** essentially **from Borexino (5% accuracy).** KL central value slightly higher but a 15% of indetermination.

- Other **future possibilities** (in addition to new measurements from Borexino (and SNO+)) ?

- JUNO: oscillation reactor anti-neutrino experiment, with medium baseline (50 km), under construction in China. Designed to study the mass hierarchy. **Very big liquid scintillator** (20 ktons, more than 50 times bigger than Borexino): **can contribute to solar ν physics?**

- **Advantages**

- Very **big** detector **mass** (20 kt) → High ν **interaction rate**

- Very **good energy resolution**: $\sigma(E)/\sqrt{E} = 3\%$

- **Difficulty**

- Suppression of the **background**. High **radiopurity levels** required.

Experiment relatively close to the sea level: attention to **cosmogenic background** (mainly for ^{8}B observation.)

- Radiopurity levels required probably comparable with the Borexino ones.

The high ν inter. rate and the very high E resolution could make possible an accurate measurement of ^{7}Be neutrino flux

ν anomalous magnetic moment: measurement from ^{7}Be

- **In the S. M. $\mu_\nu \leq 10^{-20}\,\mu_B$**, with $\mu_B = e/(2\,m_e)$. A significant **deviation** from this value **would be** a **signal of new physics**.
- **Comparison with experimental results**:
- **from reactor antineutrino experiments** (Gemma, TEXONO, MUNU) : $\approx 3 \times 10^{-11}\,\mu_B$
- **from astrophysics** indirect limits even more stringent (almost 1 order of magnitude lower)
- **Borexino results**:

  $\mu_{\nu,\text{eff.}} \leq 5.4 \times 10^{-11}\,\mu_B$; $\mu_{\nu_e} \leq 7.3 \times 10^{-11}\,\mu_B$
- **Further improvements (if possible)** could make these measurement competitive with other techniques

Future Solar ν physics: ^{8}B

- Improvement in **^{8}B ν flux** measurement potentially useful **for metallicity problem and opacity/metallicity ambiguity** .

- **Day-Night asymmetry**

From SK and SNO fit A_{DN} = (-2.9 ± 1.0)%, in agreement with LMA, but high E resolution could help in **making** the result **statistically more robust**.

- Detailed study of **low E (around 3 MeV) ^{8}B spectrum** could confirm (or contradict) the recent SK hint of the presence in the spectrum of an upturn (predicted by the standard oscillation paradigm) in the **transition from matter enhanced to vacuum dominated regions.**

- Liquid scintillator technology allows the measurements of ^{8}B ν down to ≈ 3 MeV.

- **Possible Background problems**.

Main backgrounds for "low" E ^8B

- **Internal background**:

mainly 2.6 MeV γ-rays from **^{208}Tl**: can be kept under control;

- Background by **radio elements in the vessel**: fiducial volume cut;
- **Main problem** : **cosmogenic isotopes** produced in situ

^{11}C: the suppression with TFC and other techniques could be not enough due to the high starting level, but it doesn't affect the spectrum above 3 MeV.

^{10}C : reduction with TFC of signals between muons and cosmogenic neutrons.

^{11}Be: most dangerous, comparable with the signal and subtracted statistically using time profile with respect to the muon.