Solar neutrino detection with Borexino: the pp chain and the CNO cycle

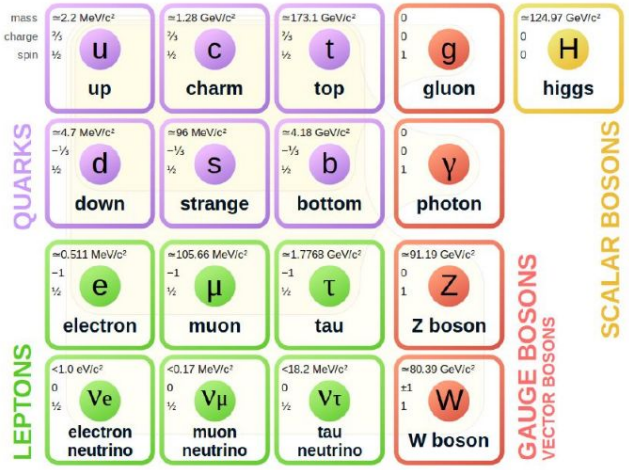
R. Biondi on behalf of BOREXINO Collaboration

HQL2021 - 13th September 2021

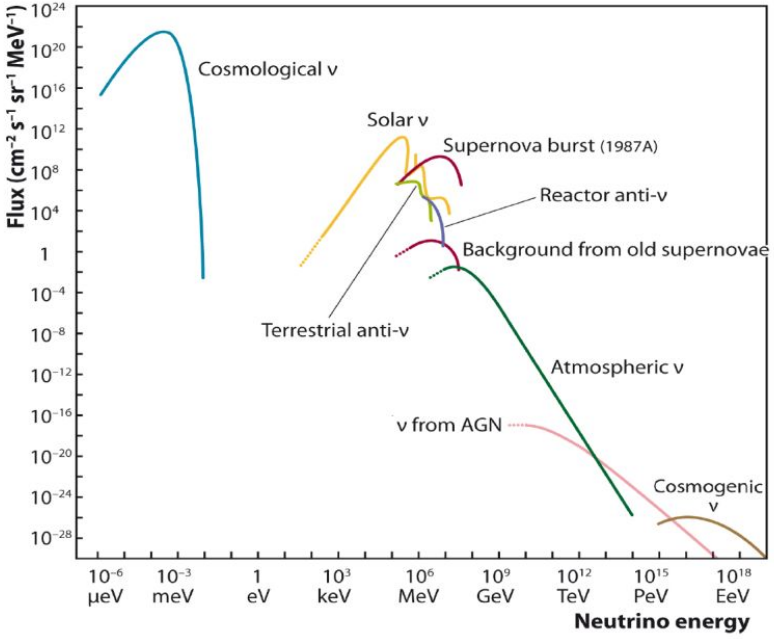
Neutrinos

SM neutral fermion with still unknown mass

- Able to change flavor (Neutrino Oscillations)
- Small Cross Sections (~$10^{-38\text{-}44}$ cm^2 at 1 MeV)



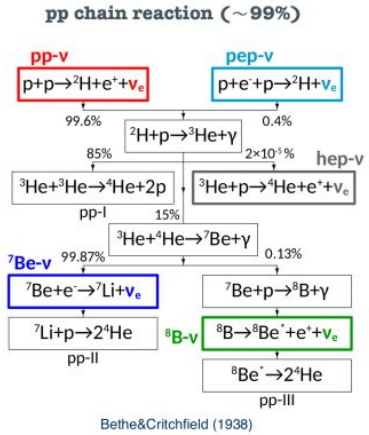
Natural and Artificial Sources

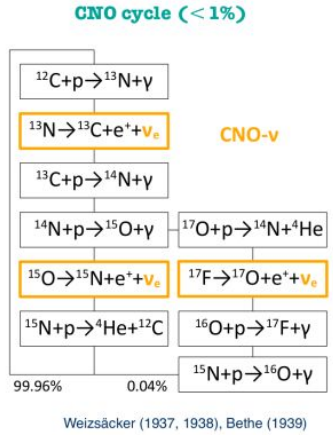


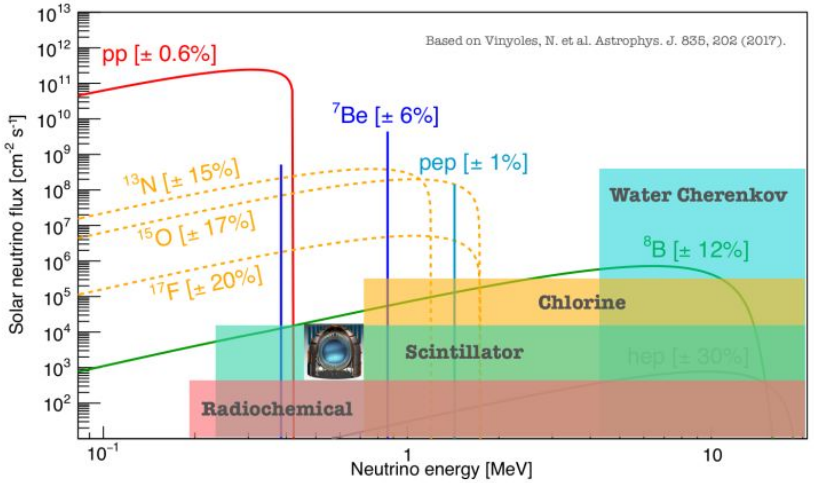
Solar Neutrinos

As we already know, the Sun is powered by **Nuclear Fusion**:

$$4\,p \rightarrow {}^{4}He + 2\,e^{+} + 2\,\nu_e \quad (\Delta E \simeq 26 MeV)$$







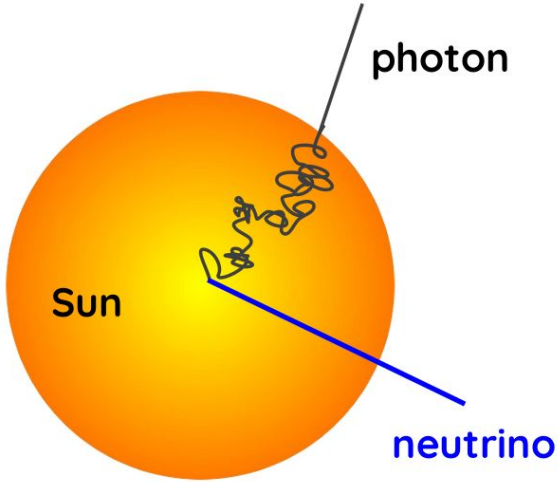
This reactions produce a total neutrino flux at Earth of: **~ 10^{11} cm $^{-2}$ s $^{-1}$** .

A window into the core of the Sun

Precise measurement of the different components of the Solar Neutrino Flux can be used to address many interesting topics in **Astroparticle Physics**.

Photons and Neutrinos are both produced in the Sun's core:

- **Photons interact continuously with the plasma:** no information on direction and energy(10^5 years to reach the photosphere)
- **Neutrinos escape undisturbed:** direction and energy are kept (8 minutes to reach the Earth)



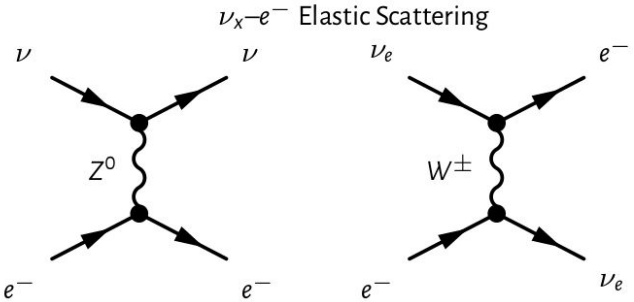
Solar Neutrinos can be used to:

- Test of the solar (stellar) models
- Detailed study of solar–ν fluxes (Solar metallicity)
- Non-standard interactions
- Neutrino magnetic moment

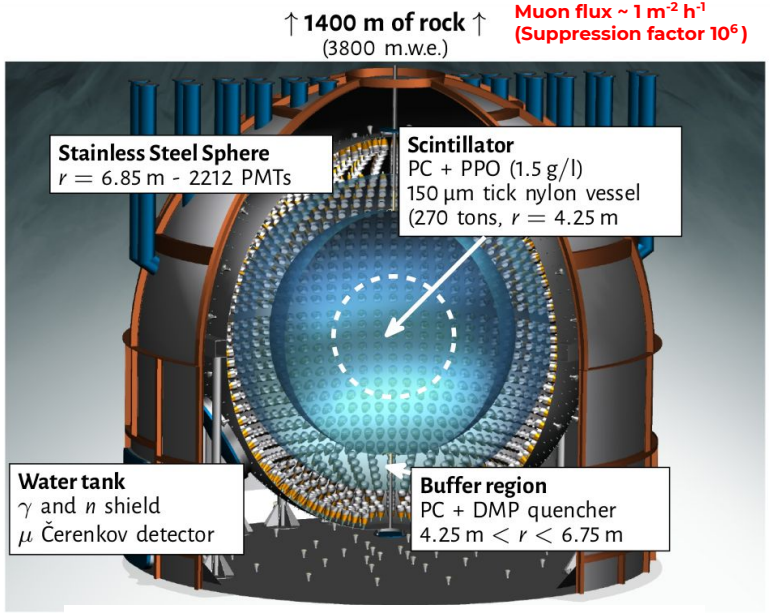
And much more…

Borexino Detector

Borexino is an **ultrapure liquid scintillator experiment** located in the LNGS which is able to detect light emitted in elastic scattering between solar neutrinos and the electrons of the scintillating material.



- Light Yield ~550 p.e./MeV ΔE/E ~ 6%/(E[MeV])$^{1/2}$
- Position reconstruction based on time of flight resolution: ~11 cm at 1 MeV (Phase-III).
- ν-induced electron recoils are indistinguishable from β and γ background



	Requirement	Result Phase-II
^{238}U	1×10^{-16} g/g	$< 9.5 \times 10^{-20}$ g/g
^{232}Th	1×10^{-16} g/g	$< 5.7 \times 10^{-19}$ g/g
^{210}Po	< 100 cpd/100ton	~ 50 cpd/100ton
^{210}Bi		~ 20 cpd/100ton
^{14}C	1×10^{-18} g/g	~ 2×10^{-18} g/g

The Long History of Borexino

Thermal insulation

2008 — 2010 — 2012 — 2014 — 2016 — 2018 — 2020

Phase I	Purification Campaign	Phase II	Phase III

Solar neutrinos

- ^{7}Be: 1st observation + Precise measurement ($\pm$5%)
- *pep*: 1st observation
- ^{8}B: low-threshold measurement
- CNO: best upper limit

Other studies

- geo-ν evidence $> 4.5\sigma$
- Limits on rare processes

Solar neutrinos

- *pp*: 1st measurement
- ^{7}Be: Seasonal modulation
- Simultaneous meas. of low-*E* solar-ν (*pp*, *pep*, ^{7}Be, CNO limit)
- ^{8}B: improved low-thrs meas.

Other studies

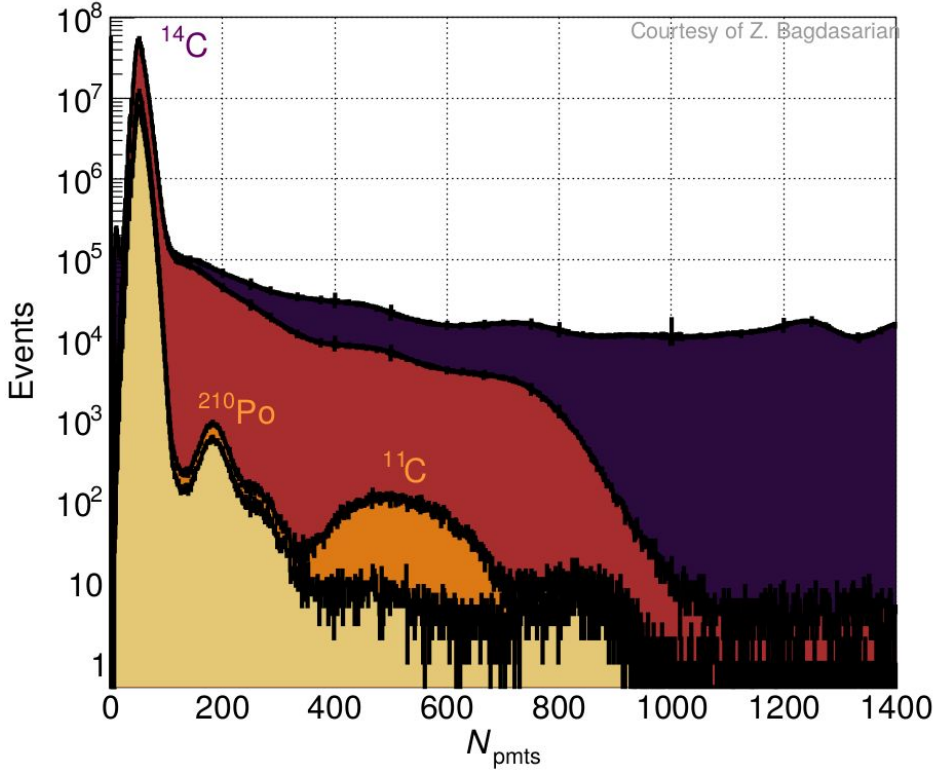
- μ_ν limit
- Non-standard interactions
- geo-ν update

Solar neutrinos

The quest for CNO neutrinos

"Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun"
Borexino Collaboration
Nature 587 (2020) 577-582

The Spectra of Borexino



Full Spectrum

Muon cut

$\approx$ 4300 μ/day crossing ID

Removes μ, μ-induced n and cosmogenics

Fiducial Volume cut

Reduction of external and surface background

^{11}C suppression (TFC cut)

μ–n pairs coincidences

+ space-time correlation with β-like ev.

$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$

n capture ~ 260μs

n+p → d+γ (2.2 MeV)

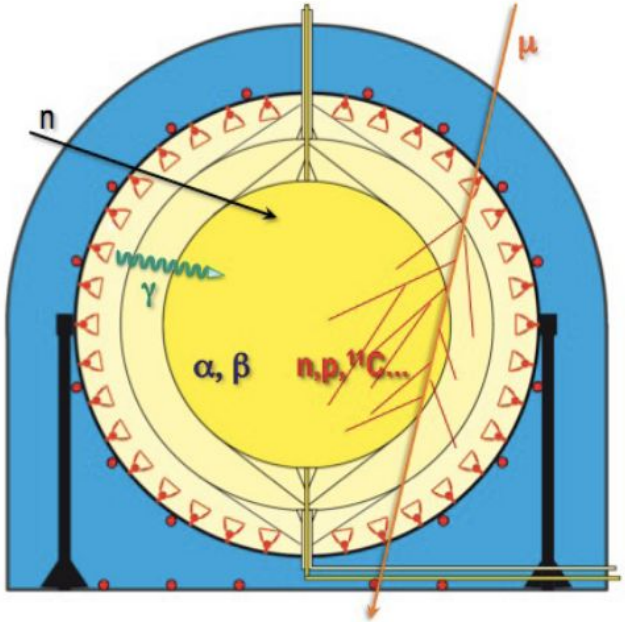
β^+ decay ~ 30 min

${}^{11}C \rightarrow {}^{11}C + e^+ + \nu_e$

Residual Background

The detection of solar neutrinos is possible only if **extreme low background** requirements are reached.

- **External:** γs and n from environment and detector materials (PMTs and SSS, mostly)
- **Internal:** α and β emitters dissolved in the scintillator ^{14}C, ^{238}U, ^{232}Th, ^{40}K, ^{39}Ar, ^{7}Be, ^{85}Kr, ^{210}Pb, ^{210}Po
- **Cosmogenic:** residual muon flux and background from muon–induced long living isotopes (^{11}C, ^{8}He, ^{9}C, ^{9}Li)

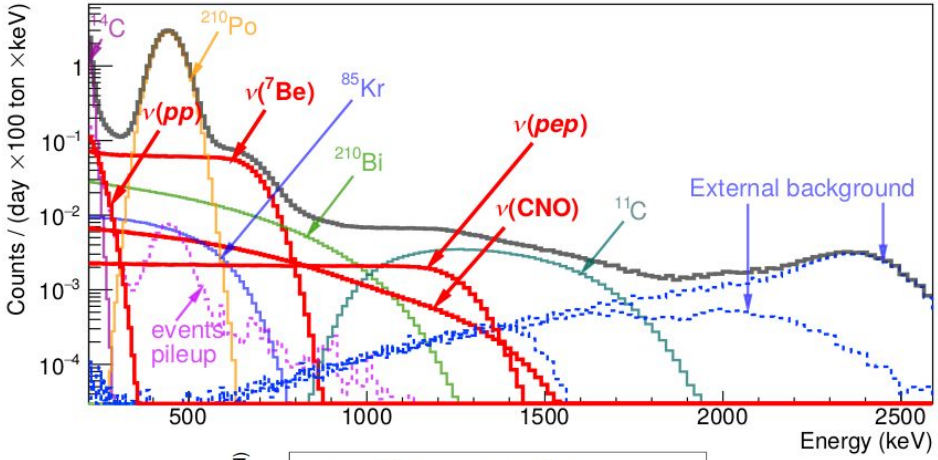


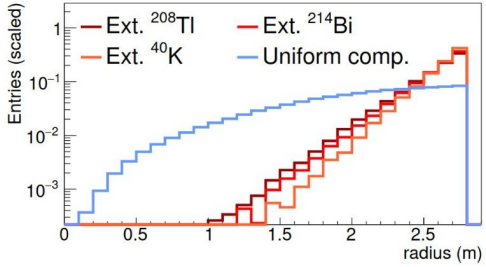
Migrating Contaminants: Internal background components can detaching from Nylon Vessel and transported by convection reach the Fiducial Volume ^{210}Po, ^{222}Rn.

Residual Spectra

From this spectra, the Rate of the different components, Solar Neutrinos and Backgrounds can be extracted via a **Multi-Variate Spectral Fit**, that takes into accounts also the radial distribution of the events.

- Simultaneous fit of **Energy**, **Radial Position** and **Pulse Shape** of the events
- Reference distributions based on accurate MC simulations (~1% precision)
- Fit parameters: **Interaction Rates** (also Response Function parameters)





$$\mathcal{L}_{\mathrm{MV}}(\vec{\theta}) = \mathcal{L}_{\mathrm{TFC\text{-}tag}}(\vec{\theta}) \cdot \mathcal{L}_{\mathrm{TFC\text{-}sub}}(\vec{\theta}) \cdot \mathcal{L}_{\mathrm{PS}}(\vec{\theta}) \cdot \mathcal{L}_{\mathrm{RD}}(\vec{\theta}).$$

pp- Chain Results

Multivariate Fit performed on different Energy Range:

- **LER** 0.19 - 2.93 MeV
- **HER** 3.2 - 16 MeV
- **HER-I** 3.2 - 5.7 MeV
- **HER-II** 5.7 - 16 MeV

From LER we extract the pp, pep and ^{7}Be neutrino rates.

CNO rate constrained to HZ-SSM and LZ-SSM predictions

^{8}B rate is obtained by fitting the radial distribution in HER

Nature volume 562, pages 505–510 (2018)

RESEARCH ARTICLE

Table 2 | Borexino experimental solar-neutrino results

Solar neutrino	Rate (counts per day per 100 t)	Flux ($cm^{-2} s^{-1}$)	Flux–SSM predictions ($cm^{-2} s^{-1}$)
pp	$134 \pm 10^{+6}_{-10}$	$(6.1 \pm 0.5^{+0.3}_{-0.5}) \times 10^{10}$	$5.98(1.0 \pm 0.006) \times 10^{10}$ (HZ) $6.03(1.0 \pm 0.005) \times 10^{10}$ (LZ)
^{7}Be	$48.3 \pm 1.1^{+0.4}_{-0.7}$	$(4.99 \pm 0.11^{+0.06}_{-0.08}) \times 10^{9}$	$4.93(1.0 \pm 0.06) \times 10^{9}$ (HZ) $4.50(1.0 \pm 0.06) \times 10^{9}$ (LZ)
pep (HZ)	$2.43 \pm 0.36^{+0.15}_{-0.22}$	$(1.27 \pm 0.19^{+0.08}_{-0.12}) \times 10^{8}$	$1.44(1.0 \pm 0.01) \times 10^{8}$ (HZ) $1.46(1.0 \pm 0.009) \times 10^{8}$ (LZ)
pep (LZ)	$2.65 \pm 0.36^{+0.15}_{-0.24}$	$(1.39 \pm 0.19^{+0.08}_{-0.13}) \times 10^{8}$	$1.44(1.0 \pm 0.01) \times 10^{8}$ (HZ) $1.46(1.0 \pm 0.009) \times 10^{8}$ (LZ)
$^{8}B_{HER-I}$	$0.136^{+0.013+0.003}_{-0.013-0.003}$	$(5.77^{+0.56+0.15}_{-0.56-0.15}) \times 10^{6}$	$5.46(1.0 \pm 0.12) \times 10^{6}$ (HZ) $4.50(1.0 \pm 0.12) \times 10^{6}$ (LZ)
$^{8}B_{HER-II}$	$0.087^{+0.080+0.005}_{-0.010-0.005}$	$(5.56^{+0.52+0.33}_{-0.64-0.33}) \times 10^{6}$	$5.46(1.0 \pm 0.12) \times 10^{6}$ (HZ) $4.50(1.0 \pm 0.12) \times 10^{6}$ (LZ)
$^{8}B_{HER}$	$0.223^{+0.015+0.006}_{-0.016-0.006}$	$(5.68^{+0.39+0.03}_{-0.41-0.03}) \times 10^{6}$	$5.46(1.0 \pm 0.12) \times 10^{6}$ (HZ) $4.50(1.0 \pm 0.12) \times 10^{6}$ (LZ)
CNO	<8.1 (95% C.L.)	$<7.9 \times 10^{8}$ (95% C.L.)	$4.88(1.0 \pm 0.11) \times 10^{8}$ (HZ) $3.51(1.0 \pm 0.10) \times 10^{8}$ (LZ)
hep	<0.002 (90% C.L.)	$<2.2 \times 10^{5}$ (90% C.L.)	$7.98(1.0 \pm 0.30) \times 10^{3}$ (HZ) $8.25(1.0 \pm 0.12) \times 10^{3}$ (LZ)

Measured neutrino rates (second column): for *pp*, ^{7}Be, *pep* and CNO neutrinos we quote the total counts without any threshold; for ^{8}B and hep neutrinos we quote the counts above the corresponding analysis threshold. Neutrino fluxes (third column) are obtained from the measured rates assuming the MSW-LMA oscillation parameters[19], standard neutrino–electron cross-sections[27] and a density of electrons in the scintillator of $(3.307 \pm 0.003) \times 10^{31}$ electrons per 100 t. All fluxes are integral values without any threshold. The result for *pep* neutrinos depends on whether we assume HZ or LZ SSM predictions to constrain the CNO neutrino flux. The last column shows the fluxes predicted by the SSM for the HZ or LZ hypotheses[18].

Absence of the pep neutrinos is rejected with >5σ significance

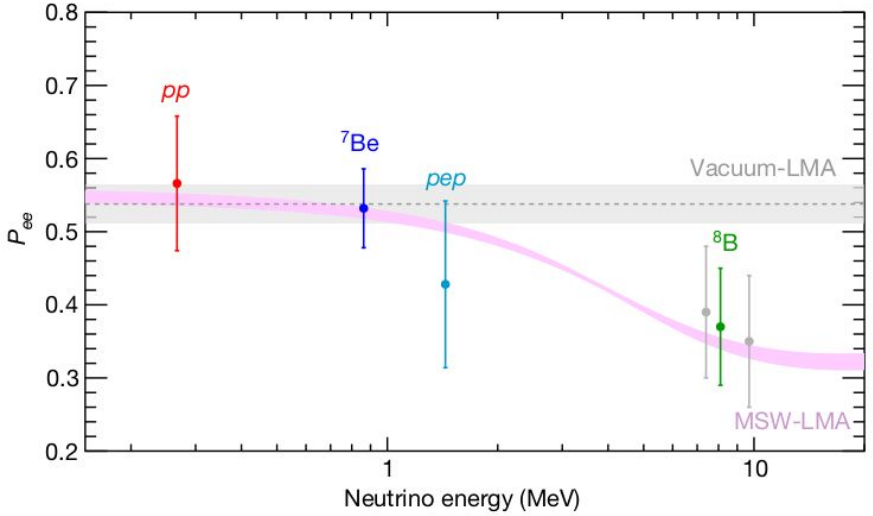
Data from 2007 to 2018

ν_e Survival probability

Interaction rates of pp, ^{7}Be, pep and ^{8}B neutrinos can be used to infer the ν_e survival probability at different energies.

Assuming the HZ-SSM fluxes and standard ν_e cross-sections we obtain the survival probabilities for each solar-neutrino component:

The quoted errors include the uncertainties on the SSM solar-neutrino flux predictions.



Borexino provides the most precise measurement of the P_{ee} in the LER and is the only experiment that can **simultaneously test neutrino flavour conversion both in the vacuum and in the matter-dominated regime**.

Borexino data **disfavour the vacuum-LMA hypothesis at 98.2% C.L.** (Likelihood ratio) and are in excellent agreement with the expectations from the MSW-LMA paradigm

Probing the Sun's core

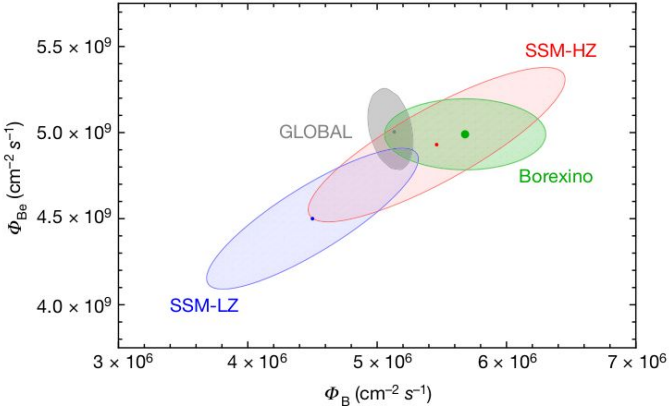
The neutrino fluxes can be used to derive the power generated by nuclear reactions in the Sun's core: $L = (3.89\ ^{+0.35}_{-\ 0.42}) \times 10^{33}$ erg s^{-1} (photon luminosity: $L = (3.846 \pm 0.015) \times 10^{33}$ erg s^{-1})

This confirm the Nuclear origin of the energy of the Sun

We derive the ratio **R I/II = 2Φ(^{7}Be)/[Φ(pp) − Φ(^{7}Be)]** between the ^{3}He -^{4}He and the ^{3}He -^{3}He fusion rates, which quantifies the relative intensity of the two primary terminations of the pp chain (pp-II and pp-I), We find R I/II = $0.178^{+0.027}_{-0.023}$ in agreement with predictions from SSM

Exploiting the fact that ^{7}Be and ^{8}B fluxes are very different in the HZ and LZ SSMs Borexino measurements can be used to test **Solar Metallicity**

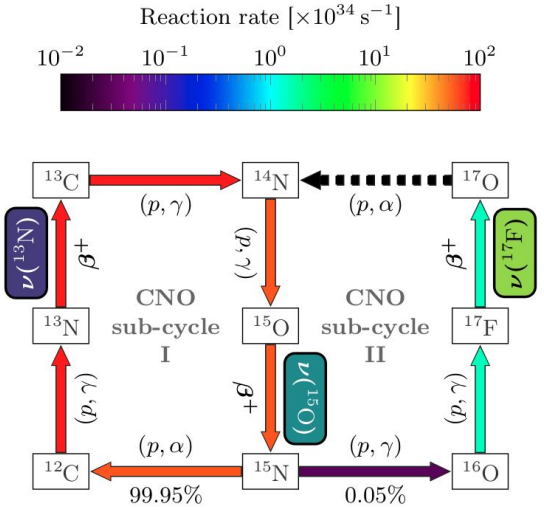
Borexino results are compatible with the temperature profiles predicted by both HZ- and LZ-SSMs. **Assuming HZ to be true, Borexino data disfavour LZ at 96.6% C.L.** (Likelihood ratio)

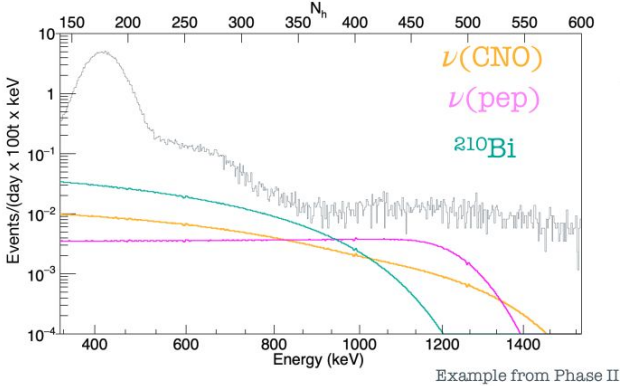


New Challenge: CNO Neutrinos

Why CNO neutrino detection is so important?

- Proof energy production in stars via CNO cycle.
- Expected to be dominant in stars heavier than the sun.
- Sensitive to Sun metallicity (discriminate between HZ and LZ)





Example from Phase II

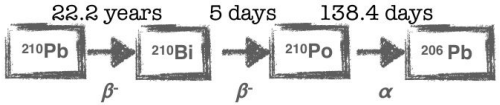
The challenge:

- Low rate of CNO neutrinos: ~ 3 – 5 cpd/100 ton.
- Shape similar to ^{210}Bi and ν(pep).

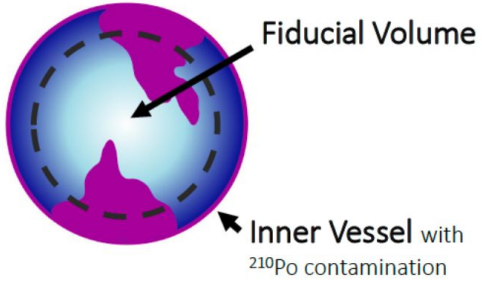
Strong correlation between the three species that needs independent constraints of the two backgrounds to disentangle them from the CNO signal.

Constraint on ^{210}Bi and v(pep)

v(pep) flux: from global fit to solar neutrino data and imposing the pp/pep ratio, the solar luminosity constraint and the oscillation parameters: **v(pep) = (2.74 ± 0.04) cpd/100t**



^{210}Bi rate: can be constrained from its daughter nucleus ^{210}Po decay rate, assuming secular equilibrium, their rate is equal and ^{210}Po events can be easily selected: they produce **monoenergetic α** (clear gaussian peak, pulse shape discrimination)



The quest for CNO is turned into the quest of ^{210}Bi through ^{210}Po

Stability challenges: ^{210}Po intrinsic rate is perturbed by the presence of convective motions, that contaminate the FV with additional ^{210}Po from the Vessel. To avoid this, we needed to stabilize experimental hall temperature and insulate the detector, and then find the region in the FV where the **rate of ^{210}Po is at its minimum**. In this region, the ^{210}Po contamination in the FV is negligible and so we can infer the intrinsic ^{210}Po rate and hence the ^{210}Bi rate.

Considering systematic uncertainties on the ^{210}Bi uniformity in the FV we have the following Upper limit: **R(^{210}Bi) ≤ (11.5 ± 1.3)cpd/100t**

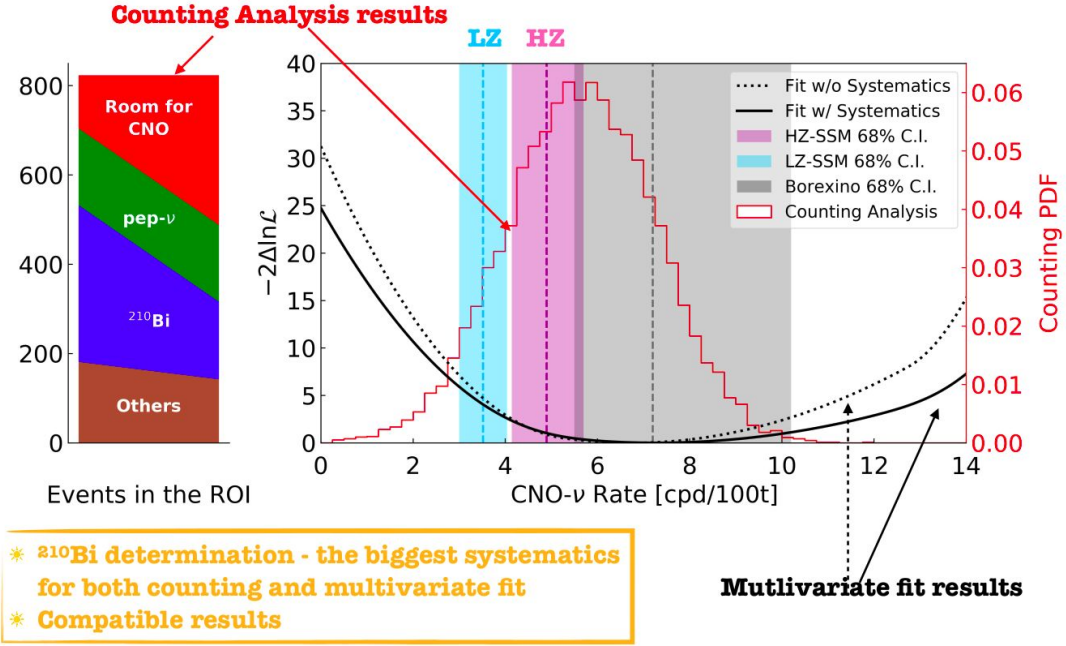
Results

Dataset: July 2016 - February 2020
Exposure: 1071,95 days x 71.3 tons.

Using the previously determined constraints in the Multivariate (Energy and Position only) Monte Carlo Spectral Fit we can determinate CNO rate

Taking into account **systematics** from fit configuration, ^{210}Bi shape, ^{11}C spectrum deformation and detector response. We can build up a profile-likelihood

The results has been confirmed by a simpler **Counting Analysis**



v(CNO) = 7.2 $^{+2.9}_{-1.7}$ (stat) cpd/100t

Conclusions

The final results on CNO rate in Borexino detector is: **R(CNO) = $7.2^{+3.0}_{-1.8}$ cpd/100t (stat. + sys.)** that correspond to 5.1σ significance of the CNO observation (profile-likelihood)

This correspond to a flux of neutrinos on Earth of: **F(CNO) = $7.0^{+3.0}_{-2.0}$ × 10^{8} cm^{-2} s^{-1}**

The No CNO hypothesis excluded with **≥ 5 σ** significance @ 99% C.L.
(hypothesis test based on a profile likelihood test statistic)

With this outcome Borexino has completely unraveled the two processes powering the Sun the **pp Chain** and the **CNO Cycle**

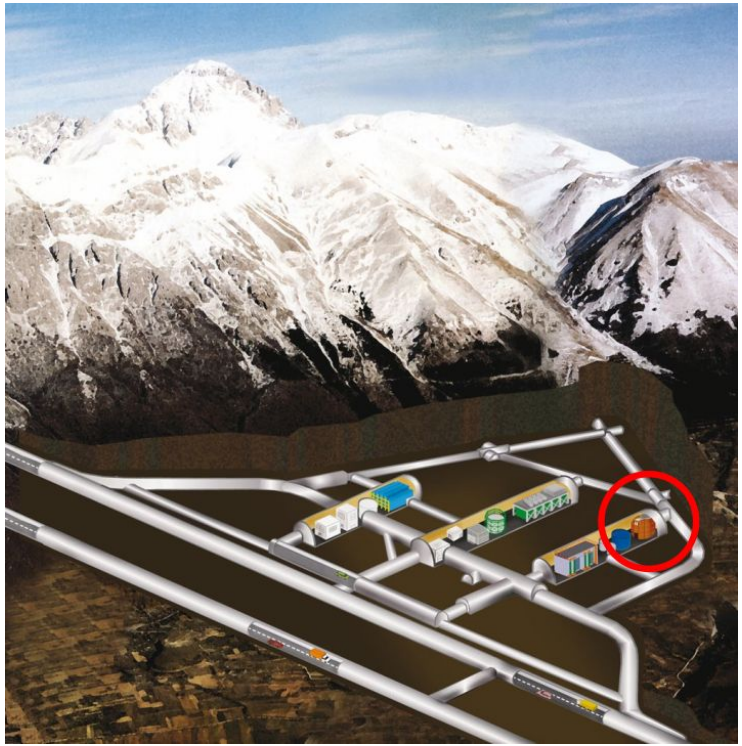
Unfortunately, the long and successful story of BOREXINO is coming to an end, it will be decommissioned by the end of the year.

It has been an amazing journey...

Thank you!

Backup

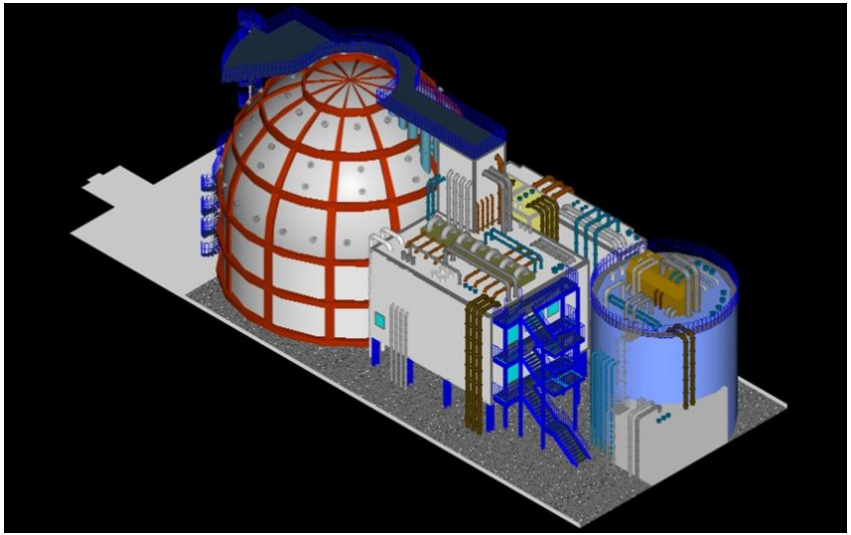
Borexino Location



Laboratori Nazionali del Gran Sasso – INFN (Hall C)

Rock: 3.800 m.w.e.

Muon flux ~ 1 m^{-2} h^{-1} (Suppression factor 10^6)

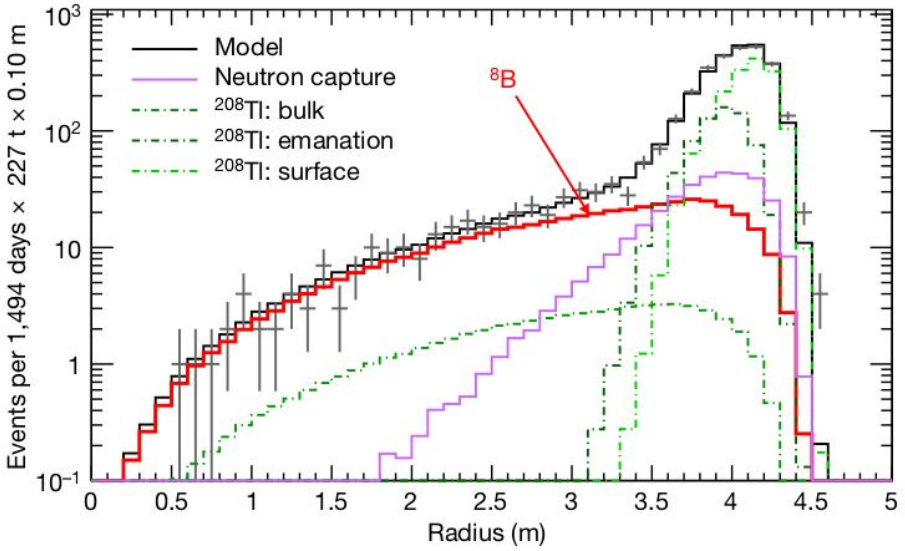


^{8}B Radial Fit and hep upper limit

Expected flux for proton capture reaction of ^{3}He (hep) is more than two orders of magnitude smaller than that of ^{8}B neutrinos.

Despite their higher end-point energy, this signal in Borexino is extremely small and covered by background, particularly cosmogenic ^{11}Be decays ^{8}B neutrinos.

In the energy region 11–20 MeV we find 10 ± 3 events, consistent with the expected background.



We obtain an upper limit for the hep neutrino flux of 2.2×10^{5} cm^{-2} s^{-1} (90% C.L.) to be compared with the expected flux 7.98 × 10 3 cm^{-2} s^{-1} (8.25 × 10^{3} cm^{-2} s^{-1}) assuming the HZ (LZ) SSM.