Recent results from Borexino Phase-II solar neutrino program

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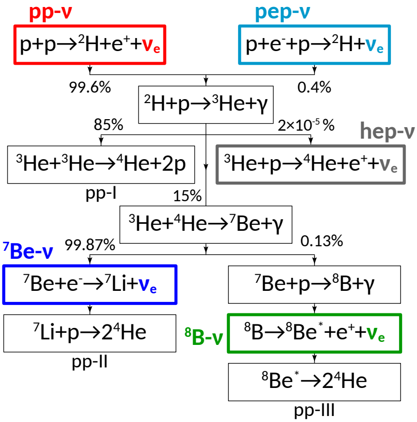
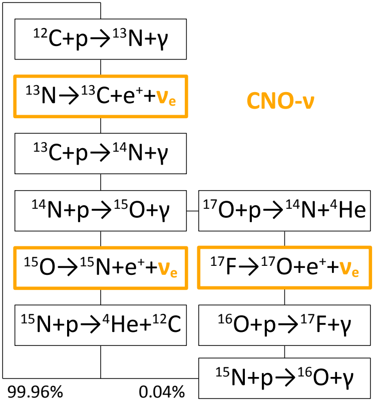
Production of neutrinos in the Sun

pp chain



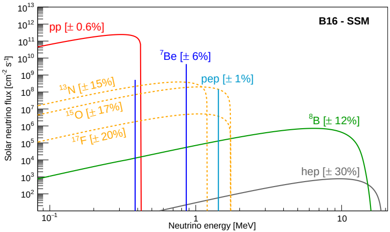
99% of solar energy

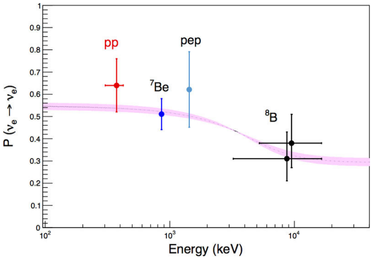
CNO cycle



dominant in heavier stars

What we can get from solar neutrino measurements





Solar physics:

- Solar neutrino fluxes
  - test of the SSM
  - test of the Sun stability
- Solar metallicity (abundance of heavy elements)

Neutrino physics:

- Neutrino oscillations in matter (MSW-effect)
  - oscillation parameters
  - day-night effect
- Non-standard neutrino properties

Solar metallicity problem

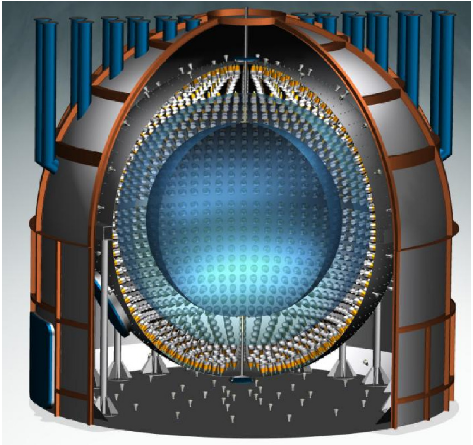
3D hydrodynamical models to determine abundances near the solar surface (assumed to be the same as in the core):

- GS98 (Grevesse & Sauval 1998)
- AGSS09 (Asplund et al. 2009) — worse agreement with helioseismology

Solar ν	GS98-HZ $[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	AGSS09-LZ $[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$
pp	$5.98\,(1 \pm 0.006) \times 10^{10}$	$6.03\,(1 \pm 0.005) \times 10^{10}$
$^{7}\mathrm{Be}$	$4.93\,(1 \pm 0.06) \times 10^{9}$	$4.50\,(1 \pm 0.06) \times 10^{9}$
pep	$1.44\,(1 \pm 0.009) \times 10^{8}$	$1.46\,(1 \pm 0.009) \times 10^{8}$
CNO	$4.88\,(1 \pm 0.11) \times 10^{8}$	$3.51\,(1 \pm 0.10) \times 10^{8}$
$^{8}\mathrm{B}$	$5.46\,(1 \pm 0.12) \times 10^{6}$	$4.50\,(1 \pm 0.12) \times 10^{6}$

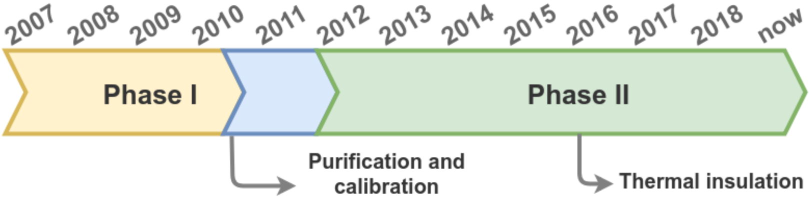
Direct metallicity measurement: solar neutrino fluxes (especially CNO)

Borexino detector



- **Location:** Laboratori Nazionali del Gran Sasso (Italy)
- **Primary goal:** measurements of solar neutrino fluxes at low energies
- **Energy threshold:** $\sim$ 150 keV (recoil electrons)
- **Energy resolution:** $\sim 5\%$ @ 1 MeV
- **Abundance of ^{238}U and ^{232}Th:** $< 10^{-19}$ g/g

Data sets



Energy regions

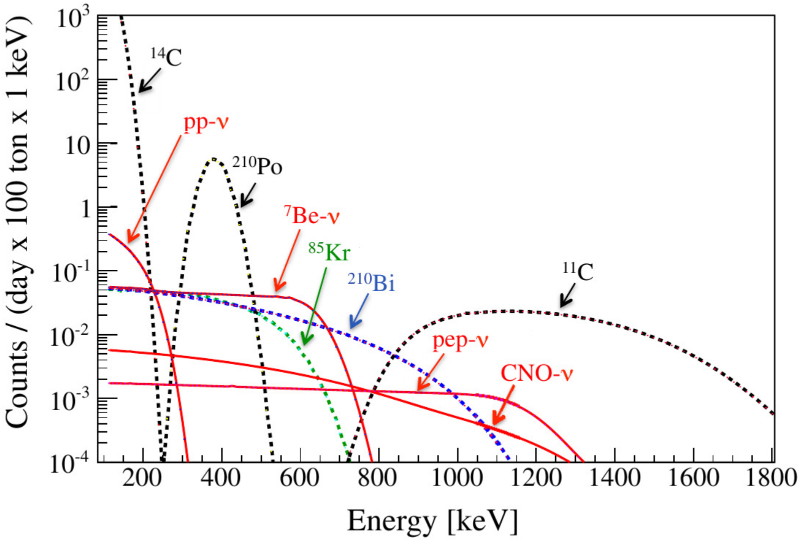
Low Energy Region (LER)

- 0.19–2.93 MeV
- Dec 2011 – May 2016 (2191.51 days)
- Fiducial mass 71.3 t
- *pp*, $^{7}\mathrm{Be}$, *pep*, CNO

High Energy Region (HER-I/II)

- 3.2–5.7/5.7–16 MeV
- Jan 2008 – Dec 2016 (2062.4 days)
- Fiducial mass 227.8/266 t
- $^{8}\mathrm{B}$

LER spectrum composition



event-by-event selection is nearly impossible → **spectral fit is needed**

LER analysis: background rejection

Muon veto:

- 2 ms after crossing the outer detector
- 300 ms after crossing the inner detector

Fiducial volume:

- $R < 2.8$ m
- $-1.8 < z < 2.2$ m

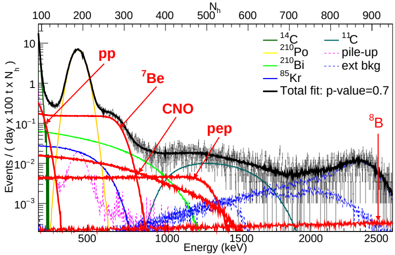
^{11}C cut: three-fold coincidence (TFC)

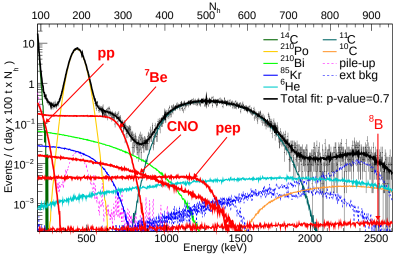
- muon event
- neutron capture
- β^+ decay of ^{11}C

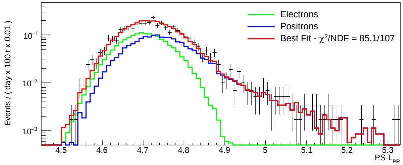
LER analysis: multivariate approach

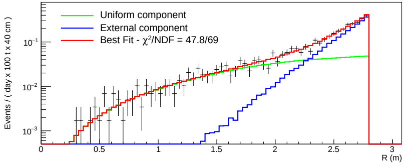
Simultaneous fit of TFC-subtracted, TFC-tagged, pulse shape and radial distributions:

$$\mathcal{L} = \mathcal{L}_{TFC-sub} \cdot \mathcal{L}_{TFC-comp} \cdot \mathcal{L}_{PS} \cdot \mathcal{L}_{RD}$$









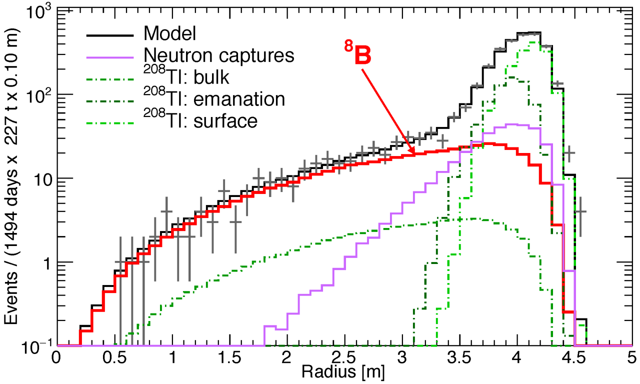
HER analysis

Muon veto:

- 6.5 s after crossing the inner detector

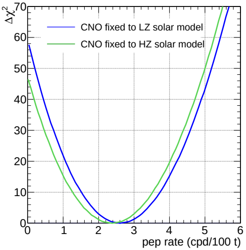
Fiducial volume:

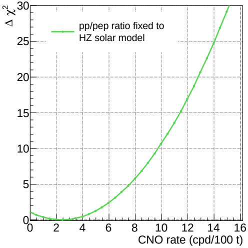
- $R < 2.5$ m (HER-I)



Results: solar neutrino fluxes

Solar ν	Borexino experimental results		B16(GS98)-HZ	B16(AGSS09)-LZ
	Rate [cpd/100 t]	Flux [$\mathrm{cm^{-2}s^{-1}}$]	Flux [$\mathrm{cm^{-2}s^{-1}}$]	Flux [$\mathrm{cm^{-2}s^{-1}}$]
pp	$134 \pm 10\ ^{+6}_{-10}$	$(6.1 \pm 0.5\ ^{+0.3}_{-0.5}) \times 10^{10}$	$5.98\,(1 \pm 0.006) \times 10^{10}$	$6.03\,(1 \pm 0.005) \times 10^{10}$
^{7}Be	$48.3 \pm 1.1\ ^{+0.4}_{-0.7}$	$(4.99 \pm 0.13\ ^{+0.07}_{-0.10}) \times 10^{9}$	$4.93\,(1 \pm 0.06) \times 10^{9}$	$4.50\,(1 \pm 0.06) \times 10^{9}$
pep (HZ)	$2.43 \pm 0.36\ ^{+0.15}_{-0.22}$	$(1.27 \pm 0.19\ ^{+0.08}_{-0.12}) \times 10^{8}$	$1.44\,(1 \pm 0.009) \times 10^{8}$	$1.46\,(1 \pm 0.009) \times 10^{8}$
pep (LZ)	$2.65 \pm 0.36\ ^{+0.15}_{-0.24}$	$(1.39 \pm 0.19\ ^{+0.08}_{-0.13}) \times 10^{8}$	$1.44\,(1 \pm 0.009) \times 10^{8}$	$1.46\,(1 \pm 0.009) \times 10^{8}$
CNO	< 8.1 (95% C.L.)	$< 7.9 \times 10^{8}$ (95% C.L.)	$4.88\,(1 \pm 0.11) \times 10^{8}$	$3.51\,(1 \pm 0.10) \times 10^{8}$
^{8}B	$0.223\ ^{+0.015}_{-0.016}\ ^{+0.006}_{-0.006}$	$(5.68\ ^{+0.39}_{-0.41}\ ^{+0.03}_{-0.03}) \times 10^{6}$	$5.46\,(1 \pm 0.12) \times 10^{6}$	$4.50\,(1 \pm 0.12) \times 10^{6}$
hep	< 0.002 (90% C.L.)	$< 2.2 \times 10^{5}$ (90% C.L.)	$7.98\,(1 \pm 0.30) \times 10^{3}$	$8.25\,(1 \pm 0.12) \times 10^{3}$

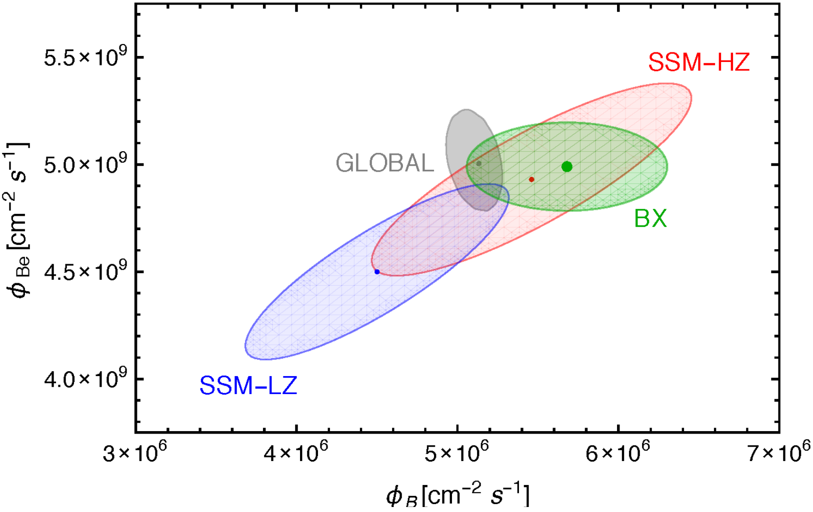




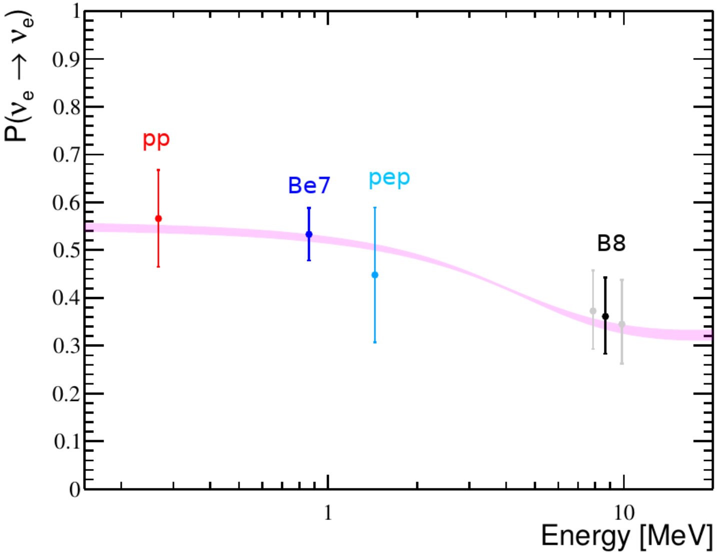
More than 5σ significance!

$\Phi(pp)/\Phi(pep) = 47.7 \pm 1.2$

Solar metallicity



Compatibility with the MSW-LMA solution (HZ assumed)



Summary

- The first simultaneous analysis of *pp*, *pep* and $^{7}\mathrm{Be}$ solar neutrino fluxes
- The first complete study of solar neutrinos
- $\Phi_{^{7}\mathrm{Be}}$ with unprecedentedly high precision (2.8%)
- First 5σ evidence of *pep* neutrinos
- updated limit on CNO neutrino flux and measurements of *pp* and ^{8} neutrinos
- First hint towards high metallicity

See detail in our papers:

- entire pp-chain: Nature 562 (2018) no. 7728, 505-510
- $^{8}\mathrm{B}$ in details: arXiv:1707.09279 [hep-ex]
- *pp*, $^{7}\mathrm{Be}$, *pep* and CNO in details: arXiv:1709.00756 [hep-ex]