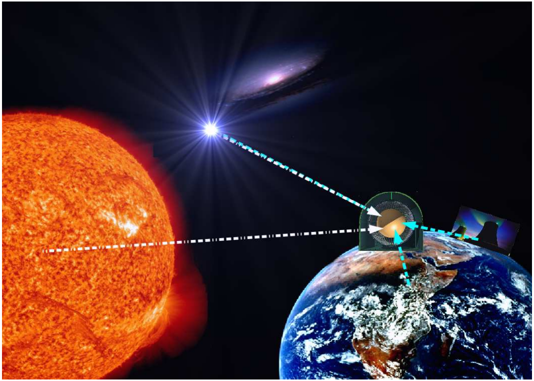
BOREXINO
Recent Solar And Terrestrial Neutrino Results



Werner Maneschg
on behalf of the Borexino Collaboration

Borexino: detector properties & design, and physics goals

Main properties:

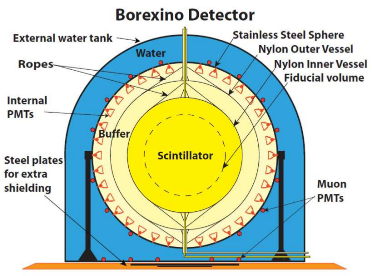
- Large volume organic liquid scintillator detector:
  - at LNGS (1.4 km overburden)
  - operational since May 2007
- Ultra low background (radiopurest environment ever measured)
- Real-time detection (time stamp and pulse shape for every event)
- Spectroscopy at low energies, typically between 0.1-15 MeV
- 3D position reconstruction

Main physics goals:

- Neutrinos from Sun
- Antineutrinos from Earth & reactors
- Sterile neutrinos (TH 23-07-15:13.5)
- SN-(anti)neutrinos & other exotic particles and processes

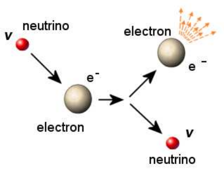
Nut shell profile:

1. Water tank (2100 m^3):
   - Absorption of environmental γ rays and neutrons
   - μ Cherenkov detector (208 PMTs)
2. Stainless Steel Sphere:
   - 2212 PMTs, 1350 m^3, R=6.85 m
3. 2 buffer layers: PC+DMP
   - Outer R_2=5.50 m, Inner R_1=4.25 m
   - Shielding from external γ rays
4. Scintillator: 270 tons of PC+PPO

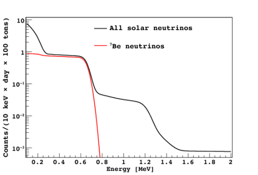


Neutrino and antineutrino detection with Borexino

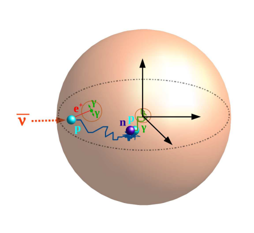
Neutrinos: elastic neutrino-electron scattering



- Mainly ν_e, but also ν_μ and ν_τ
- Compton-like formalism
  $\rightarrow$ Mono-energetic neutrino source has a Compton-like edge



Antineutrinos: inverse beta decay

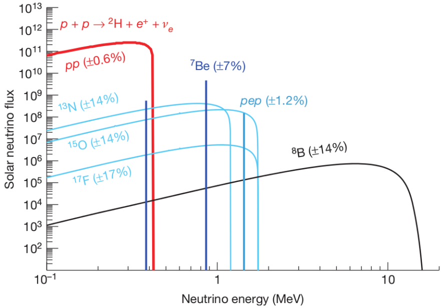


- Reaction: $\bar{\nu} + p \rightarrow n + e^+$
  (Threshold: E_ν=1.806 MeV)
- Prompt signal of positron annih.: $e^- + e^+ \rightarrow 2\gamma$
- Delayed neutron capture ($\tau \sim$255 μs) on H:
  $n + p \rightarrow D + 2.2\, MeV\, \gamma$
  $\rightarrow$ Energy intervals, space and time correlations
  $\rightarrow$ very efficient rejection method

Solar neutrino fluxes (according to Standard Solar Model predictions)

Neutrino fluxes at 1 AU:

from simulations by A. Serenelli et al., Astrophys. J. 743, 24 (2011)



Units: [$cm^{-2}s^{-1}MeV^{-1}$] for continuum neutrino sources, [$cm^{-2}s^{-1}$] for mono-energetic neutrino sources.

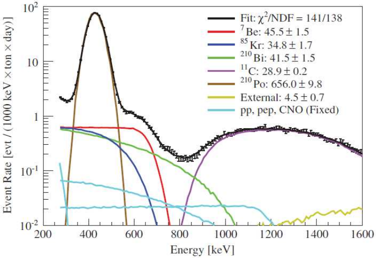
ν flux	GS98	AGSS09
pp	5.98(1±0.006)	6.03(1±0.006)
^{7}Be	5.00(1±0.07)	4.56(1±0.07)
pep	1.44(1±0.012)	1.47(1±0.012)
^{13}N	2.96(1±0.14)	2.17(1±0.14)
^{15}O	2.23(1±0.15)	1.56(1±0.15)
^{17}F	5.52(1±0.17)	3.40(1±0.16)
^{8}B	5.58(1±0.14)	4.59(1±0.14)

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

Solar neutrino measurements:
different obstacles: diff. background, detector response, energy threshold
sensitivity for different phenomena: neutrino osc. (incl. matter effects (MSW)), SSM metallicity scenarios

Solar ^{7}Be neutrino rate measurement

Averaged ^{7}Be-ν rate fitted with MC (ROI: 0.2-0.7 MeV)

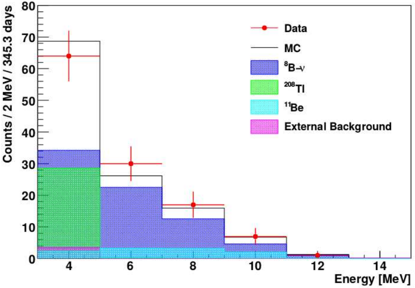


Results and remarks:

- Averaged rate: R=(46±1.5(stat)$^{+1.5}_{-1.6}$(sys)) c/d/100 ton (uncertainty ±5%)
  Comparison to SSM predictions:
  - Without osc.: (74±5) c/d/100 ton (5σ exclusion)
  - With osc.: 44 (High-met.) and 48 (Low-met.) c/d/100 ton
- **D**ay-**N**ight asymmetry: (N-D)/((N+D)/2) = 0.001±0.012(stat)±0.007(sys) (8.5 σ exclusion of LOW osc. solution)
- 7% Annual modulation: according to rate-vs-time analysis: T=(1.01±0.07) yr; ϵ=0.0398±0.0102 → expected value within 2 σ

Solar ^{8}B neutrino rate measurement

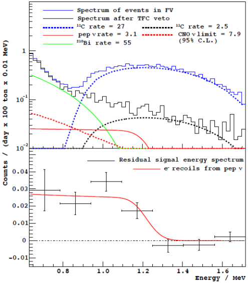
Data vs. MC of ^{8}B recoil energy spectrum (ROI: 3-15 MeV)



Results and remarks:

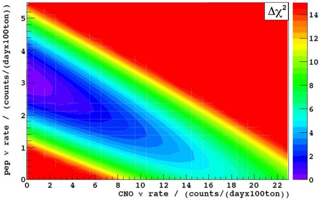
- Challenging: low neutrino rate, many small background components
- Rate above 3 MeV: 0.217±0.038(stat)±0.008(syst) c/d/100ton
- Flux at 1 AU: $(2.7\pm0.4\pm0.1)\times10^{6}$ cm^{-2} s^{-1}
  → good agreement with SuperKamiokaNDE and SNO
  → confirmation of MSW-LMA solution for oscillation in vacuum/matter
- Data set: used 488 d; new analysis with multiple statistics ongoing

Solar pep and CNO neutrino rate measurement



← pep/CNO recoil energy spectrum (ROI: 0.7-1.7 MeV)

↓ pep vs. CNO rate

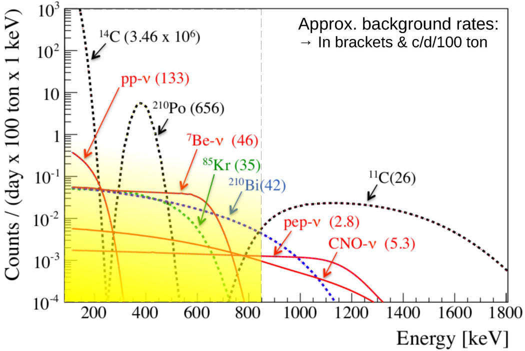


Results and remarks:

- Main background cosmogenic ^{11}C: S/B$\sim$1:10
  → Apply a threefold coincidence method (90% ^{11}C red., 50% exposure loss)
  → Apply pulse shape BDT algorithm for β^+/β^- separation
- Other background: ^{210}Bi, ^{40}K, external γ-rays (2.6 MeV from ^{208}Tl),...
- pep: first evidence; Including the MSW effect and LMA solution: DATA/SSM(AG98)= 1.1 ± 0.2
- CNO: best upper limit to date; DATA/SSM(AG98)<1.5; new analysis ongoing
- Solar Metallicity problematics not yet solved (needs ^{210}Bi understanding)

Towards the detection of solar pp neutrinos

pp recoil energy spectrum (ROI: 0.05-0.27 MeV)



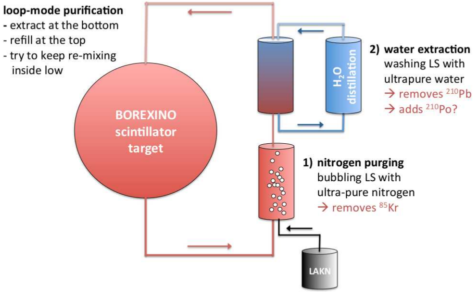
pp neutrinos:

Endpoint energy E_{mx}:
$0 < E_{mx} < 420$ keV
$\rightarrow E_{rec} < 264$ keV
Energy threshold E_{th}:
Borexino: $E_{th} \sim 50$ keV
Radiochem. experiments:
$E_{th} \sim 233$ keV

Main obstacles:

- Above ~240 keV: decays of ^{85}Kr, ^{210}Bi (^{210}Pb daughter)
- Below ~240 keV: decays of ^{14}C, ^{14}C pile-ups

Reduction of the ^{85}Kr and ^{210}Bi background in Borexino



Scintillator purification campaigns:
Period: 2010/06-2011/08
6 full cycles

Background rates before / after purification:

Nuclide	Phase I rate or mass fr.	Phase II rate or mass fr.	Spec's (analysis dep.) rate or mass fr.
^{85}Kr	(31 ± 5) c/d/100 t	<7 c/d/100 t (95% C.L.)	few 10 c/d/100 t (^{7}Be,pp)
^{210}Bi	~70 c/d/100 t	~25 c/d/100 t	few 10 (^{7}Be,pp) / few c/d/100 t (CNO)
^{210}Po	~6000 c/d/100 t *	~200 c/d/100 t *	100 c/d/100 t (pp)
^{238}U	$(1.6\pm0.1)\times10^{-17}$ g/g	$<9.7\times10^{-19}$ g/g (95% C.L.)	$<10^{-16}$ g/g (7Be)
^{232}Th	$(6.8\pm1.5)\times10^{-18}$ g/g	$<1.2\times10^{-18}$ g/g (95% C.L.)	$<10^{-16}$ g/g(7Be)

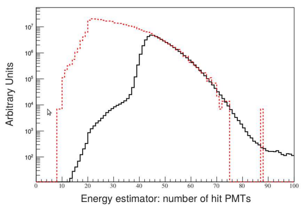
* ^{210}Po (τ=138 d): Phase I: 2007.05, Phase II: 2013.05 (end of pp data set period)

Rate and spectral shape of the ^{14}C background in Borexino

$^{14}C/^{12}C$: 10^{-18} g/g

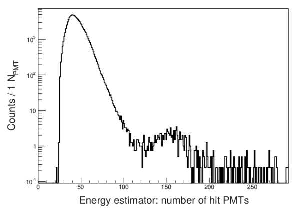
Pure ^{14}C β spectrum

- Trigger problem:
  - Total rate: $\sim$30 Hz for E_{th} $\sim$50 keV
  - ^{14}C expected rate: (10-100) c/s/100ton
  - Aquisition window: 16μs;
  - Events with E close to E_{th}: often problematic
- Solution for ^{14}C close to E_{th}: Trigger with two random events: 2. event (^{14}C) unaffected by E_{th}
  $\rightarrow$ Spectral shape threshold: 100 keV $\rightarrow$ 50 keV
  $\rightarrow$ ^{14}C rate: (40$\pm$1) c/s/100ton



^{14}C pile-ups

- Pile-up problem:
  - ^{14}C overlap with PMT dark rate, ^{14}C, ^{210}Po
  $\rightarrow$ Spectral shape hardly known
  $\rightarrow$ Position reco. largely fails
  Expected rate: (6-600) c/d/100ton)
- Solution: Generate 'synthetic' pile-ups:
  - Overlap artificially uncorrelated data with regular events
  $\rightarrow$ ^{14}C pile-up rate: (154$\pm$10) c/d/100ton



Solar pp neutrino rate measurement (August 2014)


ARTICLE

doi:10.1038/nature13702

Neutrinos from the primary proton–proton fusion process in the Sun

Borexino Collaboration*

Nature, Vol. 512, August 28, 2014

Results and remarks:

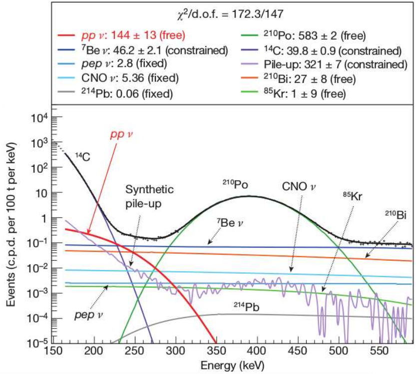
- Rate:
  144±13(stat)±10(sys) c/d/100 ton
  (10σ exclusion of pp ν absence)
- Robustness of analysis:

Parameter	Systematics:
energy estimator	±7%
fit energy range	
data selection	
pile-up evaluation	
fiducial mass	±2%

- Check of residual background

Measured recoil energy spectrum

Fit in (165-590) keV

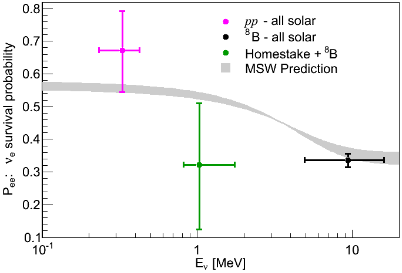


Rates in [c/d/100 ton], except for ^{14}C [c/s/100 ton]

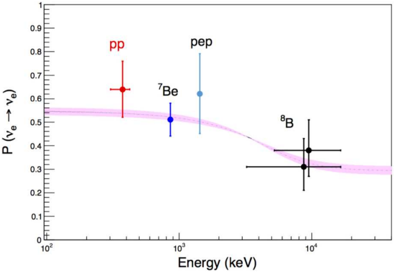
Solar neutrino oscillations in vacuum/matter

Electron neutrino survival probability:

Before Borexino:



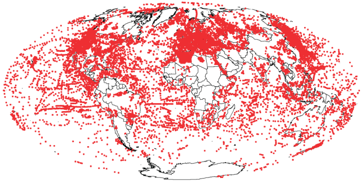
Borexino alone (2014/08):



Borexino results:

- Borexino data standalone confirm MSW - Large-Mixing-Angle solution
- Further improvements expected from:
  - Data sets with more statistics/lower systematics (pp, pep, ^{8}B)
  - Potentially first direct detection of the CNO neutrino rate

Description of Earth's interior



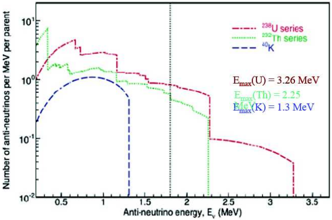
Bulk Silicate Earth model (BSE)

- Describes the 'Primitive Mantel's chem. comp. before crust differentiation, but after metal core separation
- Prediction of radiogenic heat (with local-dependent variations):
  - Crust: ~7 TW
  - Mantle: 1-19 TW
    (differing for BSE-submodels)
  - Core: 0 TW

  → Probe with geo-$\bar{\nu}$'s:
  Expected rate in Borexino:
  ~10 c/yr/270 ton

Geophysics

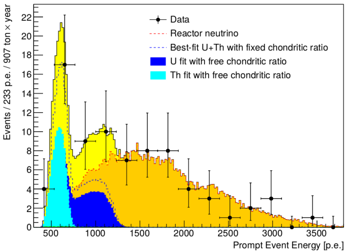
- Earth heat: (47±2) TW,
  from 40000 deep bore-holes
  integrated over surface:
  ~0.09 W/m^2
  (↔ Solar constant: 342 W/m^2)
  → Potential origin: radiogenic heat, primordial planetary contraction
- Seismology: insight of structure/ density, but not chem. composition
  → Further messengers:
  Petrologic/meteoritic samples and
  $\bar{\nu}$'s from U & Th decays ('geo-$\bar{\nu}$')



Geo-neutrino rate measurement with Borexino (June 2015)

Main background components (after 2 s muon rejection cut)

- Accidental coincidences
- Short-lived cosmogenic isotopes: e.g. β+n decay of ^{9}Li-^{8}He
- (α,n) reactions: in scintillator and in buffer
- Untagged muons, fast neutrons, spontaneous fission decays in PMTs
- Reactor-antineutrinos:
  → Same signiture as geo-$\bar{\nu}$'s; only spectral disentaglement possible
  → Calculation of reactor-$\bar{\nu}$ signal: 446 cores worldwide (196 European), weighted mean baseline 1170 km, exact duty cycles and fuel composition (<IAEA and EDF)



Results from 5.63 yr dataset

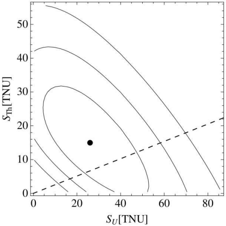
- Exposure: (907±44) ton×year
- 77 $\bar{\nu}$ candidates found:
  Unbinned likelihood fit with fixed chrondritic ratio Th/U=3.9:
  - Geo-$\bar{\nu}$: $(23.7^{+5.7}_{-6.6})$ ev, $(43.5^{+12.1}_{-10.7})$ TNU*
  - Reactor-$\bar{\nu}$: $(52.7^{+7.8}_{-8.5})$ ev, $(96.6^{+16.4}_{-15.1})$ TNU*
    → Agrees well with expect. incl. osc.
  - 3 main background components (S/B∼100)

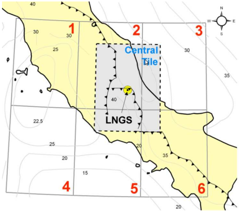
*TNU = Terrestial Neutrino Unit=1 ev/yr/10^{32} protons

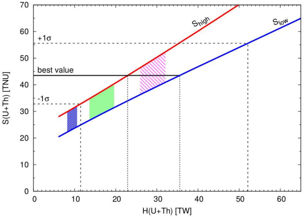
Implications for terrestrial radiogenic heat production

U/Th identification and local distribution:

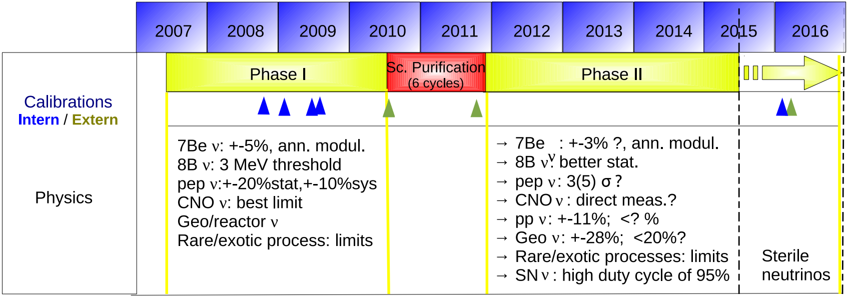
- Geo-$\bar{\nu}$ signal of $(43.5^{+12.1}_{-10.7})$ TNU: rejects null-hypothesis with $5.9\,\sigma$
- Separation of Th/U: If Th/U ratio is kept free in the fit:
  → S(Th)/S(U)≈0.6, within $1\,\sigma$ in agreement with chrondritic model pred.
  S(Th)/S(U)=0.3
- Localisation of U/Th in crust/mantle:
  1. Geological survey to deduce local crust contribution: (9.7±1.3) TNU
  2. BSE models to deduce total crust contribution: (23.4±2.8) TNU
  3. BSE models to deduce mantle contribution = total-crust: $(20.9^{+15.1}_{-10.3})$ TNU
     → Null-hypothesis of mantle contribution rejected at 98% C.L.
- Total radiogenic heat (Th+U+K): (33^{+28}_{-20}) TW (BSE model dependent)
  → In well agreement with terrestrial power output of (47±2) TW







Summary: Physics highlights and future goals



Plans for next years:

- Improved precision of present results of solar pp, pep, ^{7}Be and ^{8}B ν's, as well as geo- and reactor-$\bar{\nu}$; ...
- CNO ν's: Last undetected of the **'Big Five'**: improve limit or try to quote a rate ('solar metallicity puzzle')
- Sterile neutrino search with ^{144}Ce $\bar{\nu}$ and ^{51}Cr ν sources (**SOX**)
- Supernova $\nu/\bar{\nu}$'s: BX member of **SNEWS**, keep high duty cycle of 95% (low E-threshold)

'Big Five'

Further reading

- **Solar neutrinos**
  - 7Be rate @ ±17% precision: C. Arpesella at al., First real time detection of 7Be solar neutrinos by Borexino, Phys. Lett. B 658 (2008) 101-108
  - 7Be rate @ ±10% precision: C. Arpesella at al., Direct measurement of the 7Be solar neutrino flux with 192 days of Borexino data, Phys. Rev. Lett. 101 (2008) 091302
  - 7Be rate @ ±5% precision: G. Bellini et al., Precision measurement of the 0.862 MeV 7Be solar neutrino interaction rate in Borexino, Phys. Rev. Lett. 107 (2011) 141302
  - 7Be day-night asym.: G. Bellini at al., Absence of day-night asymmetry of 862 keV 7Be solar neutrino rate in Borexino and MSW oscillation parameters, Phys. Lett. B 707 (2012) 22-26
  - 7Be annual mod.: G. Bellini at al., Final results of Borexino Phase-I on low-energy solar-neutrino spectroscopy, Phys. Rev. D 89 (2014) 112007
  - pep rate & CNO limit: G. Bellini at al., First Evidence of pep Solar Neutrinos by Direct Detection in Borexino, Phys. Rev. Lett. 108 (2012) 051302
  - 8B rate: G. Bellini at al., Measurement of the solar 8B neutrino rate with a liquid scintillator target and 3 MeV energy threshold in the Borexino detector, Phys. Rev. D 82 (2010) 033006
  - pp rate: G. Bellini at al., Neutrinos from the primary proton-proton fusion process in the Sun, Nature 512, August 28, 2014
- **Geo-Antineutrinos:**
  - rate @ ±40% precision: G. Bellini et al., Observation of Geo-Neutrinos: Phys. Lett. B 687 (2010) 299-304
  - rate @ ±32% precision: G. Bellini et al., Measurement of geo-neutrinos from 1353 days of Borexino, Phys. Lett. B 722 (2013) 295-300
  - rate @ ±28% precision: M. Agostini et al., Spectroscopy of geo-neutrinos from 2056 days of Borexino data, arXiv: 1506.04610v2 (hep-ex) June 2015, accepted for publication in Phys. Rev. D