Detection of neutrinos from the primary proton-proton fusion process in the Sun with Borexino

DESY Hamburg Seminar & DESY Zeuthen Physics Colloquium

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

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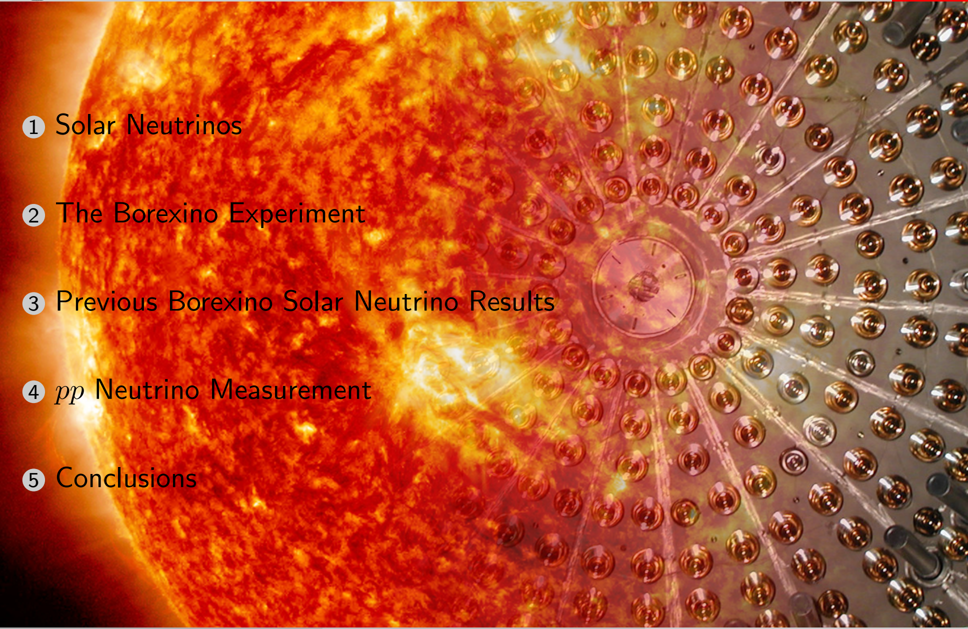
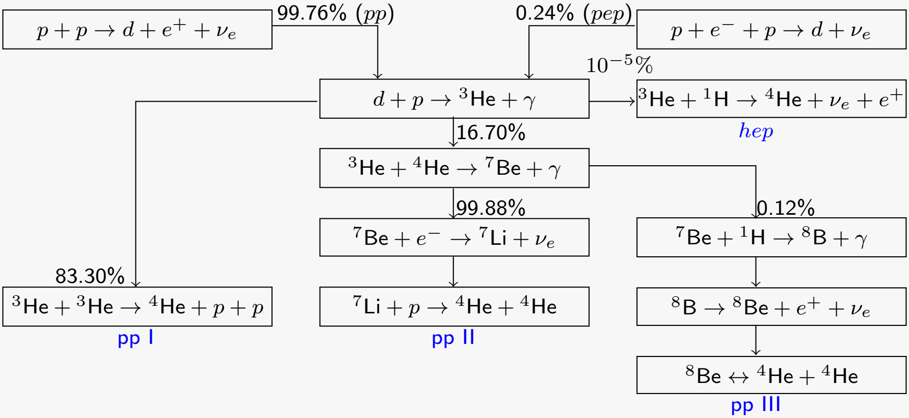
Overview



Solar Neutrinos: pp-chain

- Energy Production in the Sun: Fusion
- $4p \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e + 26.7\ \mathrm{MeV}$
- Main contribution: pp-chain



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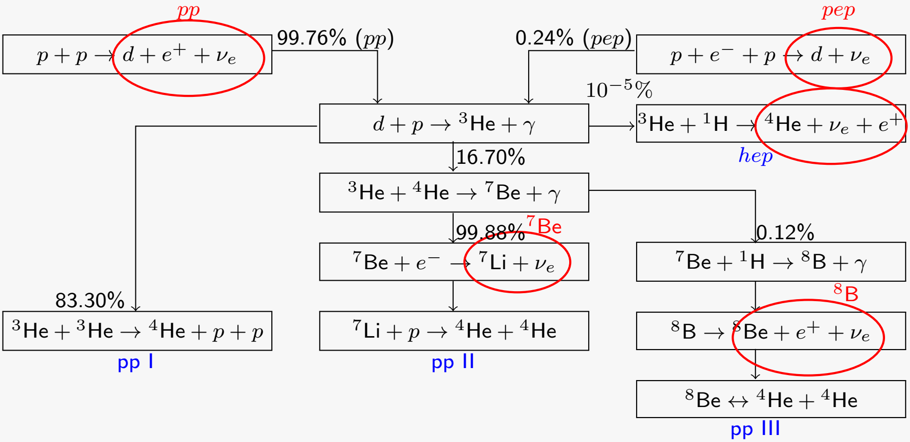

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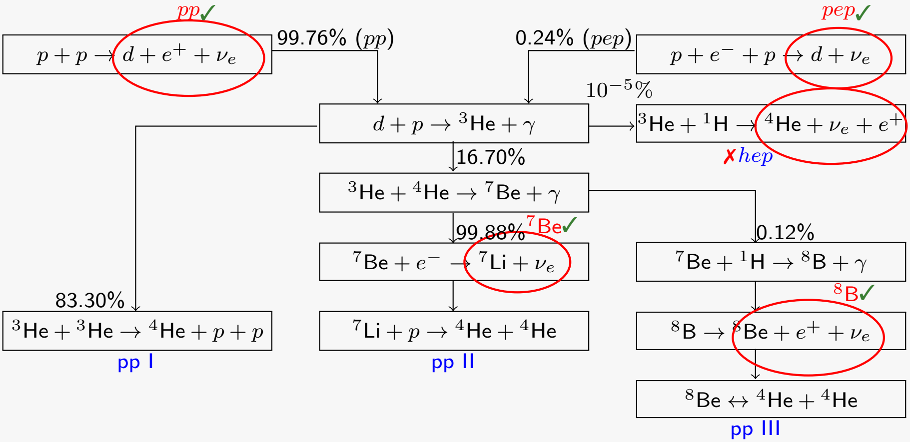

CNO I:

$$^{12}\mathrm{C} + {}^{1}\mathrm{H} \rightarrow {}^{13}\mathrm{N} + \gamma$$
$$^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + e^{+} + \nu_e$$
$$^{13}\mathrm{C} + {}^{1}\mathrm{H} \rightarrow {}^{14}\mathrm{N} + \gamma$$
$$^{14}\mathrm{N} + {}^{1}\mathrm{H} \rightarrow {}^{15}\mathrm{O} + \gamma$$
$$^{15}\mathrm{O} \rightarrow {}^{15}\mathrm{N} + e^{+} + \nu_e$$
$$^{15}\mathrm{N} + {}^{1}\mathrm{H} \rightarrow {}^{12}\mathrm{C} + {}^{4}\mathrm{He}$$

CNO II:

$$^{15}\mathrm{N} + {}^{1}\mathrm{H} \rightarrow {}^{16}\mathrm{O} + \gamma$$
$$^{16}\mathrm{O} + {}^{1}\mathrm{H} \rightarrow {}^{17}\mathrm{F} + \gamma$$
$$^{17}\mathrm{F} \rightarrow {}^{17}\mathrm{O} + e^{+} + \nu_e$$
$$^{17}\mathrm{O} + {}^{1}\mathrm{H} \rightarrow {}^{14}\mathrm{N} + {}^{4}\mathrm{He}$$
$$^{14}\mathrm{N} + {}^{1}\mathrm{H} \rightarrow {}^{15}\mathrm{O} + \gamma$$
$$^{15}\mathrm{O} \rightarrow {}^{15}\mathrm{N} + e^{+} + \nu_e$$

- CNO contribution to our Sun's energy production $< 1\%$ (theory)
- Major contribution for heavier stars

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CNO II:

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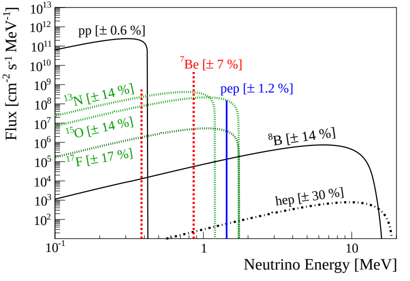
Why are Solar (pp) Neutrinos Interesting?

1. Test our understanding of energy generation in the Sun
   - Conventional observation limited to surface
   - pp accounts for 99.76% of deuterium synthesis

   $\rightarrow$ determines rate of solar energy generation
2. Oscillation physics
   - Measurement of ν_e survival probabilities
3. Tests of solar variability
   - Test assumption that neutrino flux is consistent with solar luminosity

Solar abundance problem

- Metallicity Z
- Helioseismic data: metal-rich core
- SSM: homogenious primordial Sun



Name	High Z Φ_{GS98} [cm^{-2}s^{-1}]	Low Z Φ_{AGSS09} [cm^{-2}s^{-1}]	$E_{\nu,\max}$ [MeV]
pp	5.98×10^{10}	6.03×10^{10}	0.422
pep	1.44×10^{8}	1.47×10^{8}	$1.442^{\dagger}$
hep	7.91×10^{3}	8.18×10^{3}	18.8
^{7}Be	5.00×10^{9}	4.56×10^{9}	$0.861^{\dagger}/0.384^{\dagger}$
^{8}B	5.58×10^{6}	4.59×10^{6}	16.34
^{13}N	2.96×10^{8}	2.17×10^{8}	1.199
^{15}O	2.23×10^{8}	1.56×10^{8}	1.732

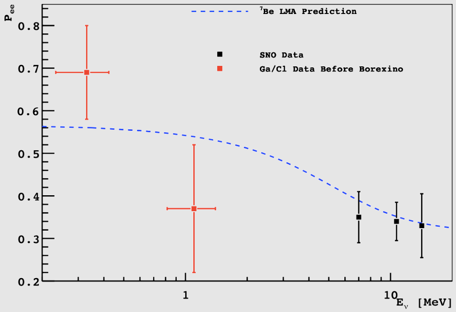
Interaction Rate

$$R_\nu = N_e \int dE \frac{d\Phi}{dE}(P_{ee}\sigma_e + (1 - P_{ee})\sigma_{\mu,\tau})$$

- Oscillations affected by matter effects (MSW effect)
- Oscillation survival probability P_{ee} energy dependent
- Transition region between vacuum- and matter dominated oscillations at a few MeV

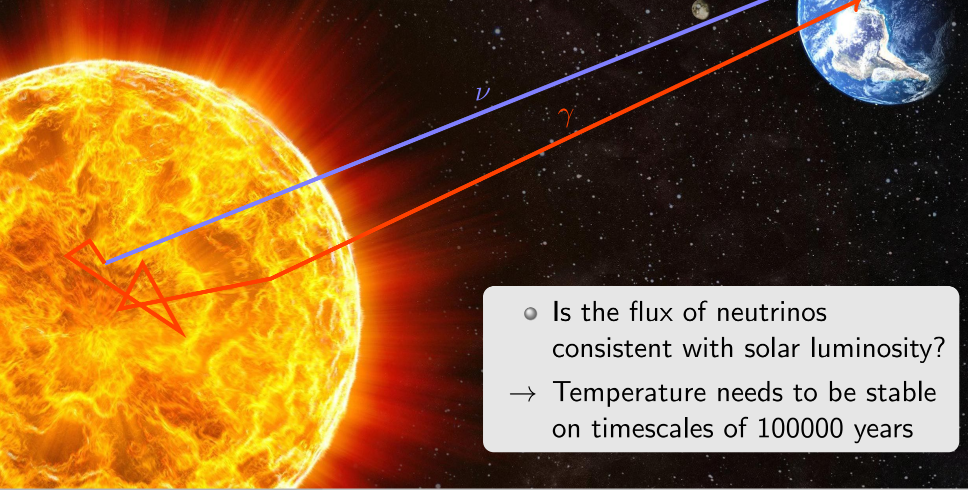
→ Very sensitive to different models

P_{ee} before Borexino



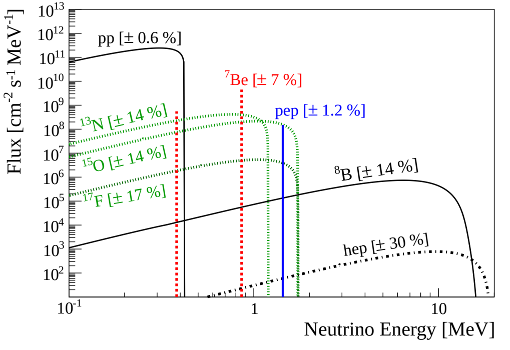
Solar Variability

- Light emitted during fusion takes > 100000 years to get to the surface of the Sun
- Neutrinos can leave the core unhindered

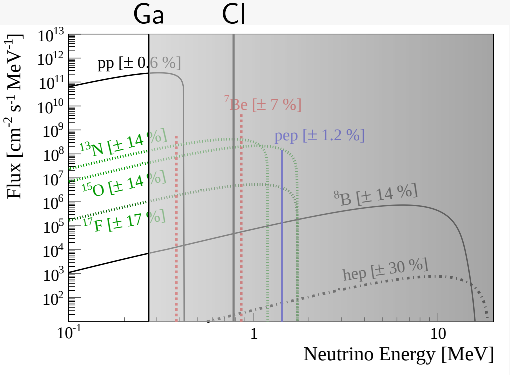


- Is the flux of neutrinos consistent with solar luminosity?

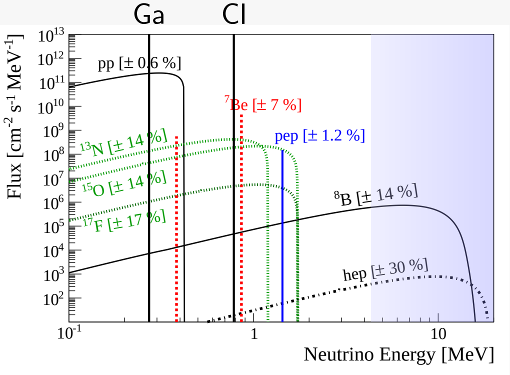
$\rightarrow$ Temperature needs to be stable on timescales of 100000 years


pp [± 0.6 %]
7Be [± 7 %]
pep [± 1.2 %]
13N [± 14 %]
15O [± 14 %]
17F [± 17 %]
8B [± 14 %]
hep [± 30 %]
Flux [cm-2 s-1 MeV-1]
Neutrino Energy [MeV]
10-1
1
10

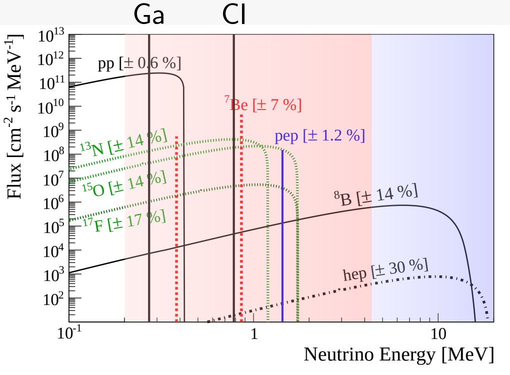
- Radiochemical experiments → no spectral measurement.



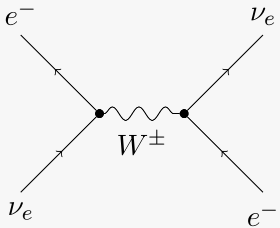
- Radiochemical experiments → no spectral measurement.
- Water Cherenkov detectors → $E > 3.5$ MeV

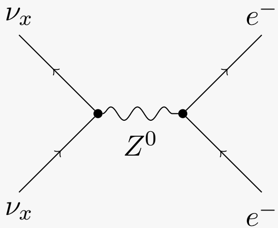


- Radiochemical experiments $\rightarrow$ no spectral measurement.
- Water Cherenkov detectors $\rightarrow$ $E > 3.5$ MeV
- Liquid Scintillator $\rightarrow$ $E > 200$ keV



- Neutrino electron scattering
- Scintillation light produced by recoil electron
- Compton like energy transfer
- No energy threshold (limited by $^{14}\mathrm{C}$ background (156 keV))
- Cross-sections very well known!

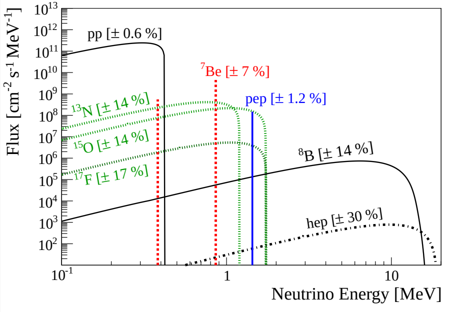


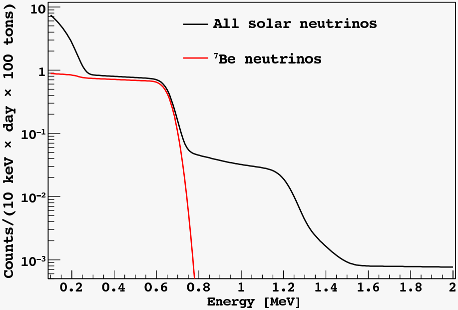


Compton-like energy transfer:

$$T_e^{max} = \frac{E_\nu}{1 + \frac{m_e c^2}{2E_\nu}}$$

- 862 keV mono-energetic ^{7}Be neutrinos $\rightarrow T_e^{max} = 665$ keV





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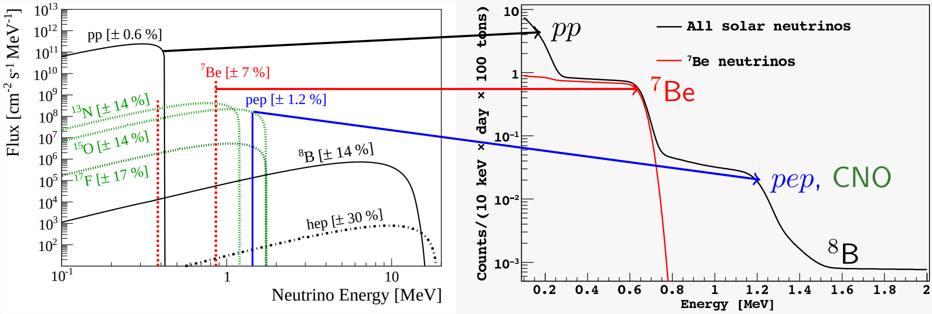
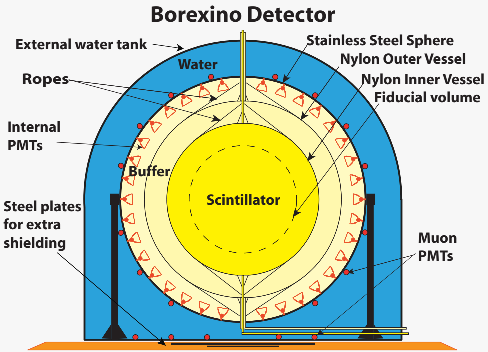




Steel dome: ⌀18 m – 16.9 m high

Inner Detector

Graded shielding

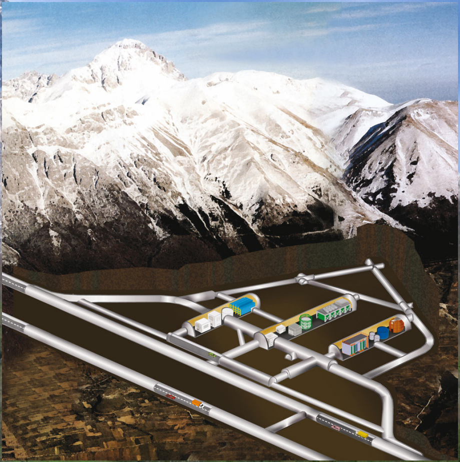
- 278 tons pseudocumene
- $\sim 1.5\,\mathrm{g}/\ell$ PPO
- Two 125 µm nylon vessels (⌀8.5 m and 11 m)
- Barrier against radon
- Buffer: light quencher DMP
- Stainless steel sphere (⌀13.7 m)
- 2212 inward facing 8" PMTs

Outer Detector

2100 tons ultra pure water

- Active shielding
- 208 PMTs ⇒ Cherenkov veto

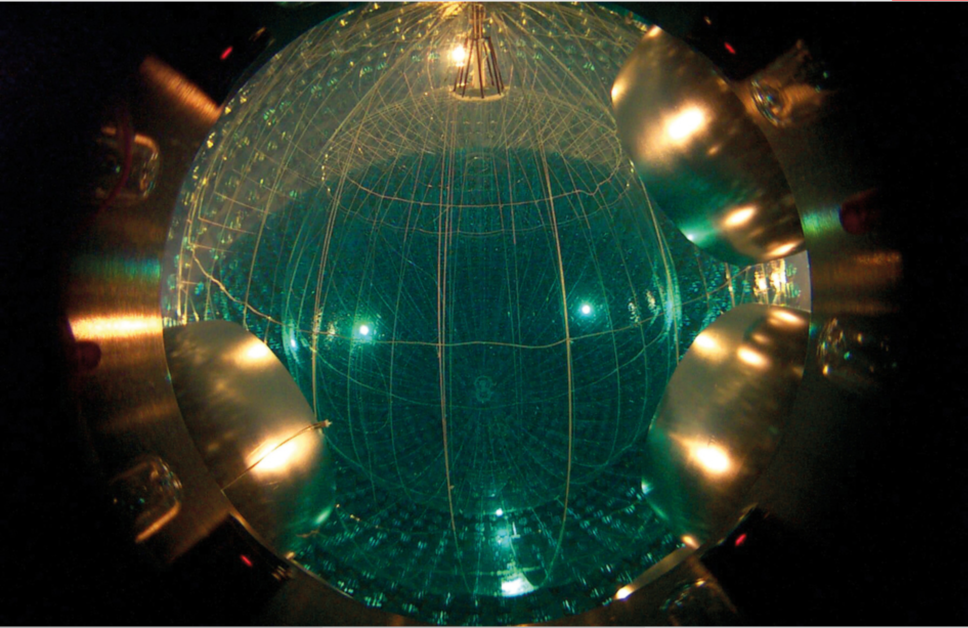
Borexino Detecor Site



LNGS Underground Lab

- Located at Gran Sasso
- 1400 m of rock shielding
- 3800 m.w.e.
- 1.2 muons per m^2 and hour

A View Inside



22 Institutes from 6 Countries

Phase I – May 2007 - May 2010

- First observation of $^7\mathrm{Be}$ neutrinos
- Day-night asymmetry
- $^8\mathrm{B}$ neutrinos
- pep neutrinos
- Limit on CNO
- geo-neutrinos
- Muon seasonal variations
- Limits on rare processes

Purification campaigns

- May 2010
- Aug-Oct 2011

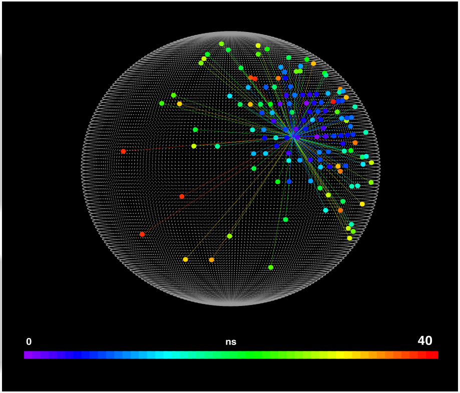
Phase II – ongoing since 2012

- pp neutrinos
- CNO neutrinos
- Short baseline oscillations (SOX)

All phases

Neutrons and other cosmogenics, $^7\mathrm{Be}$ seasonal variations, update on geo-ν

- Scintillation light emitted isotropically
- Record time t and charge q of all hit PMTs



Energy reconstruction

- Number of detected photoelectrons

$\rightarrow$ $\Delta E/E \sim 5\%$ @ 1 MeV

Spatial reconstruction

- photon arrival time pattern (tof)

$\rightarrow$ $\Delta x \sim 10\,\mathrm{cm}$ @ 1 MeV

- Particle identification by pulse shape

Dark rate 400-500 kHz

Trigger threshold

25 PMTs detect light within 100 ns
$\rightarrow$ Trigger rate: ~ 30 Hz

- No coincidence with muon events
  - 300 ms veto (ID)
  - 2 ms (OD)
- Clusters of hit PMTs within 230 ns gate

Four energy estimators

- N_p: Number of PMTs that detect light
- N_h: Number of detected hits
- N_{pe}: Number of photoelectrons (pe)
- N_{pe}^d: Correction of dark-noise

- Normalization to number of live channels $f_{eq}(t)$
- Response functions to true energy deposit
  - correct for event position
  - particle specific quenching
- Roughly 500 pe per MeV

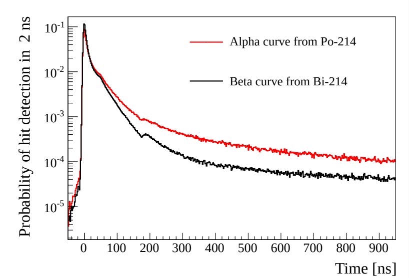
α–β discrimination

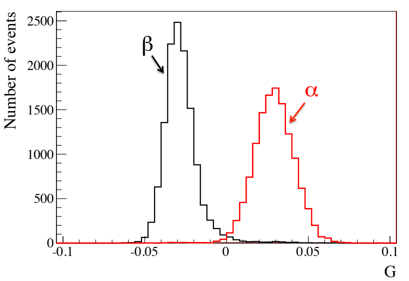
- Time distribution of emitted photons depends on particle type
- Simple discrimination: tail-to-total ratio
- More advanced: *Gatti*-filter

Gatti Parameter - Simplified

- Comparison of binned and normalized time distribution to reference data

Real data





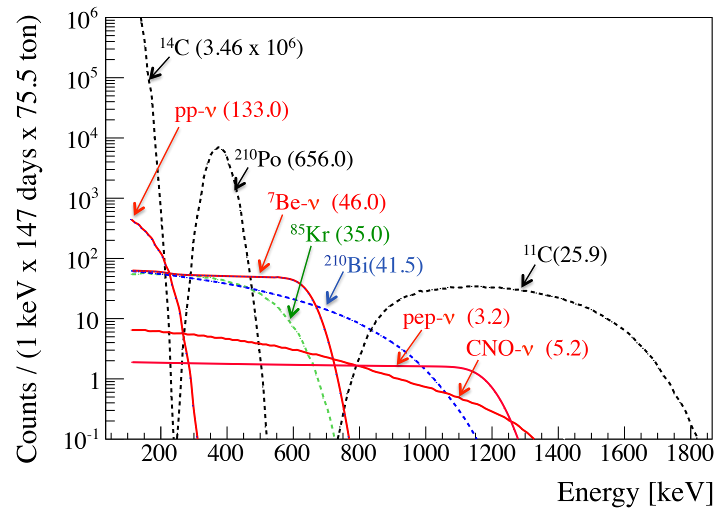
Radiopurity

High radiopurity is the key to success

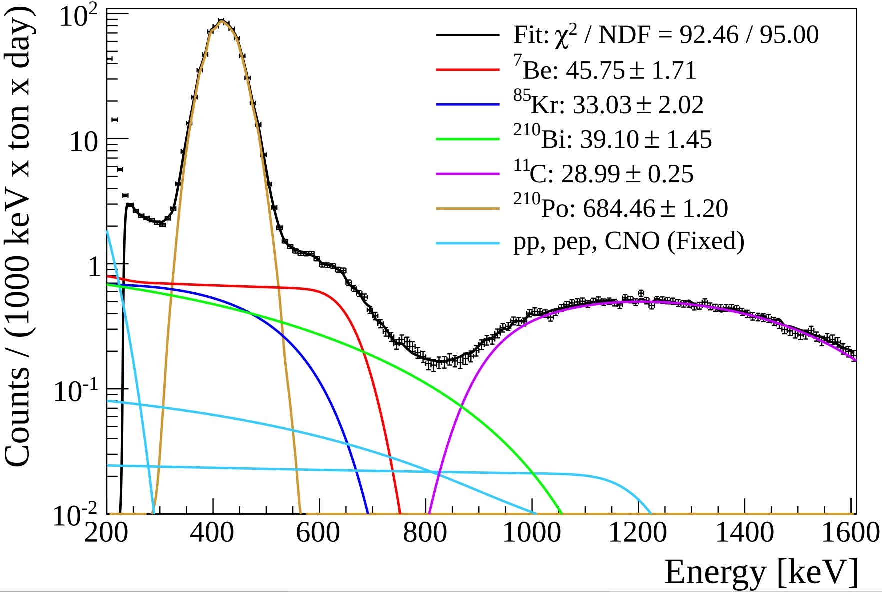
- $^{14}\mathrm{C}$ inherent to the scintillator
- Dedicated prototype in the 90s (CTF)
- Careful choice and handling of all gasses, liquids and materials
- **World record radiopurity levels reached**

Isotope	Phase I	Rate [cpt/100 t]	Method
$^{238}\mathrm{U}$	$(5.3 \pm 0.5) \times 10^{-18}$ g/g	(0.57 ± 0.05)	measured (Bi-Po)
$^{232}\mathrm{Th}$	$(3.8 \pm 0.8) \times 10^{-18}$ g/g	(0.13 ± 0.03)	measured (Bi-Po)
$^{14}\mathrm{C}/^{12}\mathrm{C}$	$(2.69 \pm 0.06) \times 10^{-18}$ g/g	$(3.46 \pm 0.09) \times 10^{6}$	measured (CTF)/Fit
$^{40}\mathrm{K}$	$\leq 0.04 \times 10^{-18}$ g/g	< 0.42	Fit
$^{85}\mathrm{Kr}$	(30 ± 5) cpd/100 t	$(30.4 \pm 5.3 \pm 1.5)$	measured (^{85}Rb β-γ)
$^{39}\mathrm{Ar}$	$\ll {}^{85}\mathrm{Kr}$	~ 0.4	estimated from ^{85}Kr
$^{210}\mathrm{Po}$	(70) 1 dpd/100 t	$5 \times 10^{2} - 8 \times 10^{3}$	Fit
$^{210}\mathrm{Bi}$	(20) 70 dpd/100 t	$(41.0 \pm 1.5 \pm 2.3)$	Fit

Expected Signal and Major Background



^{7}Be Interaction Rate



^{7}Be Interaction Rate - Results

Rate

$$46.0 \pm 1.5(\mathrm{stat})^{+1.5}_{-1.6}(\mathrm{sys})/\mathrm{d} \cdot 100\mathrm{t}$$

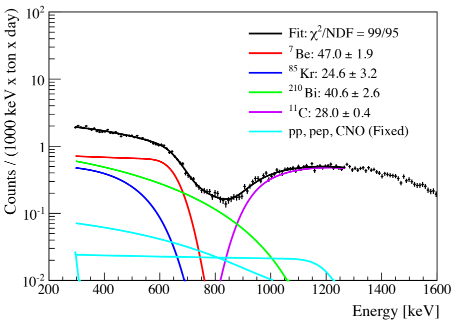
Flux

$$\phi_{\mathrm{Be}} = (3.10 \pm 0.15) \times 10^{9}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Survival Probability

$$P_{ee} = 0.51 \pm 0.07 \quad \text{at} \quad 0.862\,\mathrm{MeV}$$

741 days:



Phys. Rev. Lett. 107 (2011) 141302

^{7}Be Day-Night Assymetry excluded (Phys. Lett. 707, 1 (2011) 22-26)

$$A_{DN} = \frac{N - D}{(N + D)/2} = 0.001 \pm 0.012(\mathrm{stat}) \pm 0.007(\mathrm{sys})$$

^{8}B Neutrino Flux

Rate $E > 3$ MeV

$$0.22 \pm 0.04(\text{stat}) \pm 0.01(\text{sys})/\text{d} \cdot 100\text{t}$$

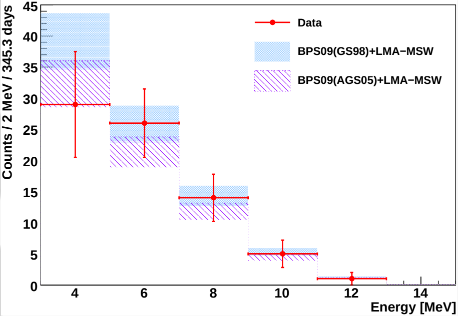
Flux

$$\phi_{\text{B}} = (2.4 \pm 0.4 \pm 0.1) \times 10^6 \ /\text{cm}^2\text{s}$$

Survival Probability

$$P_{ee} = 0.29 \pm 0.10$$

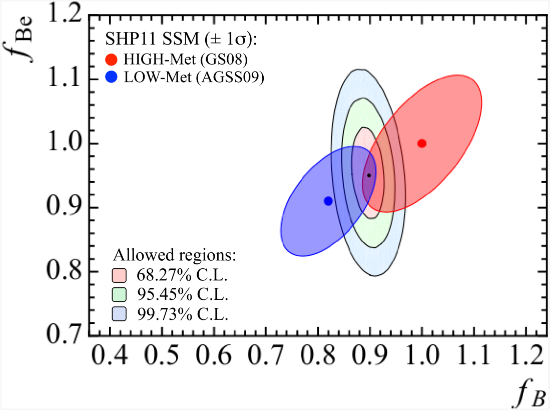
at $< E >= 8.9\,\text{MeV}$



Phys.Rev. D82 (2010) 033006

SSM Metallicity

arXiv:1308.0443



Reduced flux

$$f_i = \frac{\phi_{\mathrm{true}}}{\phi_{\mathrm{SSM}}}$$

High metallicity hypothesis:

- $f_{\mathrm{Be}} = 1.00 \pm 0.07$
- $f_{\mathrm{B}} = 1.00 \pm 0.14$

Low metallicity hypothesis:

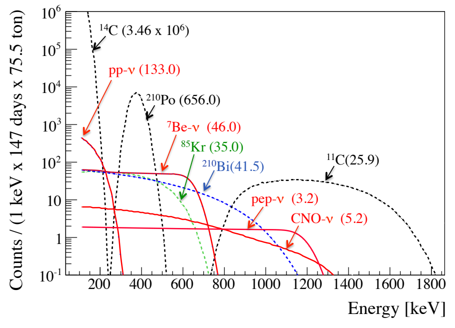
- $f_{\mathrm{Be}} = 0.91 \pm 0.06$
- $f_{\mathrm{B}} = 0.82 \pm 0.11$

- ^{7}Be and ^{8}B data cannot discriminate models
- $\Rightarrow$ CNO measurement needed!

Main contribution

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

- $\tau_{1/2} = 20.3$ min
- Not related to incident muon
- β^+-decay $Q = 0.96$ MeV
- $\rightarrow$ 1–2 MeV visible energy
- covers CNO and pep range



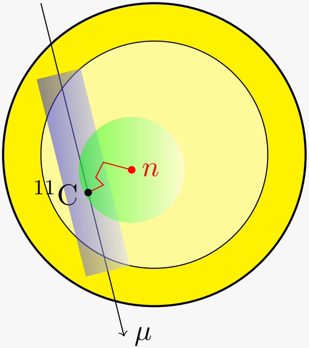
$\Rightarrow$ Need to go deep underground to reduce muon flux

- Borexino: ≈ 4000 muons per day

Reducing ^{11}C

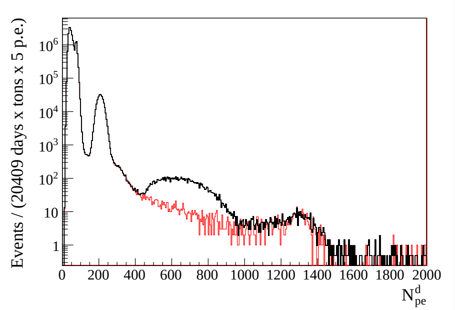
Three-fold coincidence

- Cylinder around muon track
- Sphere around captured neutron
- Veto for 2 h
- 48.5% exposure remains

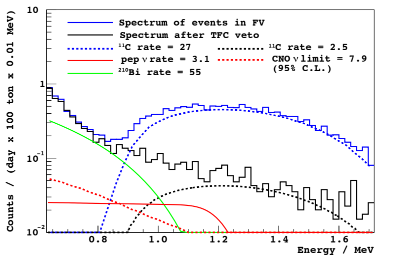


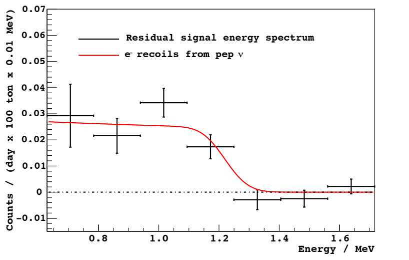
Reduction of ^{11}C background

- TFC reduces 89.4 % of ^{11}C
- β^+/β^- pulse shapes
- Boosted decision tree



First measurement of *pep* solar neutrino rate (Phys. Rev. Lett. 108 (2012) 051302)



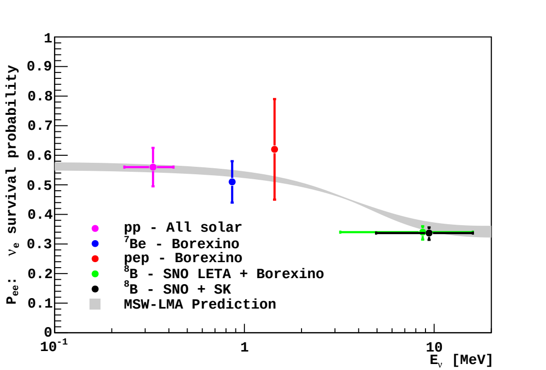


pep results:

- $R = (3.1 \pm 0.6 \pm 0.3)\,\mathrm{cpd}/100\,\mathrm{t}$
- $\phi = (1.6 \pm 0.3) \times 10^8\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- $P_{ee} = 0.62 \pm 0.17$ at 1.44 MeV

Limit on CNO rate

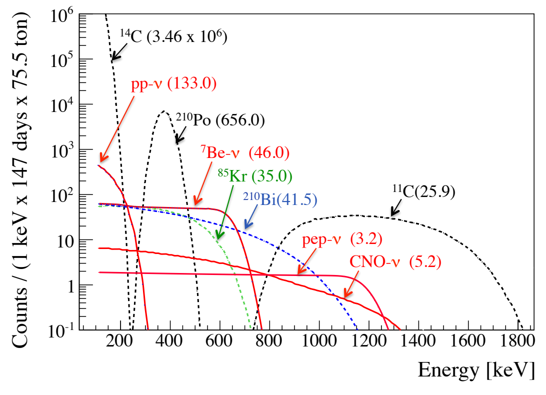
- Best limit so far
- $\phi_{\mathrm{CNO}} < 7.7 \times 10^8\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$



What's missing?

- Lower threshold on $^8\mathrm{B} - \nu$ to see upturn in transition region
- CNO measuremnt
- Direct pp neutrino measurement

Challanges for the pp measurement



- pp end point $422\,\mathrm{keV} \rightarrow$ recoil energy $< 261\,\mathrm{keV}$
- ^{14}C β-decay spectral shape: end point $156\,\mathrm{keV}$
- ^{14}C pile-up
- ^{85}Kr and ^{210}Bi reach similar level in ROI

Loop-mode purification

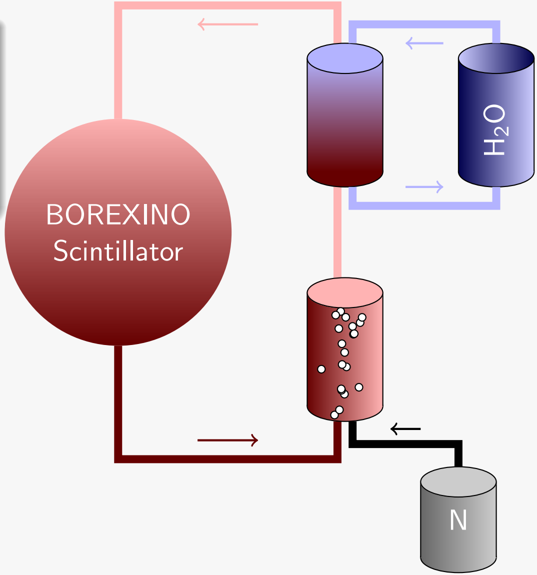
- Extract at the bottom
- Refill at the top
- Try to keep re-mixing inside low

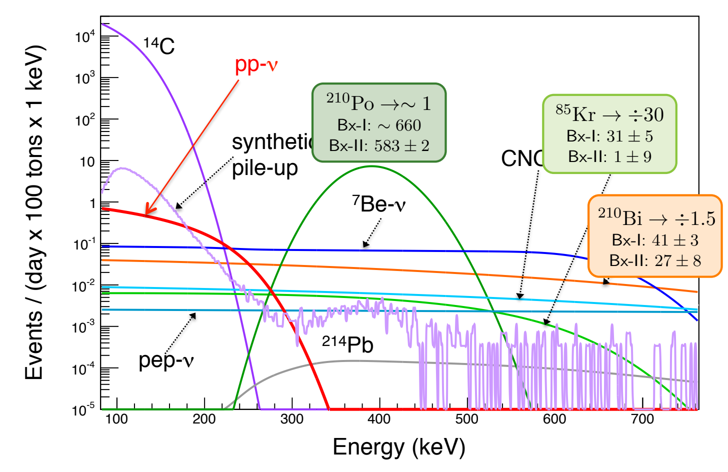
1. Nitrogen purging
   - Bubbling LS with ultra-pure nitrogen

   → removes ^{210}Pb

   → adds ^{210}Po ?
2. Water extraction
   - Washing LS with ultra-pure water

   → removes ^{85}Kr




Events / (day x 100 tons x 1 keV)
Energy (keV)
^{14}C
pp-ν
synthetic
pile-up
^{210}Po →∼ 1
Bx-I: ∼ 660
Bx-II: 583 ± 2
^{85}Kr → ÷30
Bx-I: 31 ± 5
Bx-II: 1 ± 9
CNO
^{7}Be-ν
^{210}Bi → ÷1.5
Bx-I: 41 ± 3
Bx-II: 27 ± 8
^{214}Pb
pep-ν

- Intrinsic to the scintillator (pseudocumene – C_9H_{12})
- Very low concentration ($^{14}C/^{12}C \sim 2.7 \times 10^{-18}$)

$\rightarrow$ still $\sim 10^2$ Bq in 100 tons

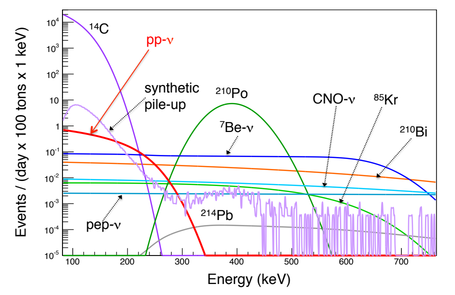
- Mostly below threshold

$\rightarrow$ hard to fit spectral shape

$\rightarrow$ actual decay rate?

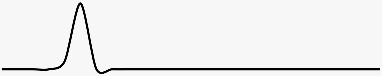
- forms pile-up due to hight rate

$\rightarrow$ additional signals in pp-region

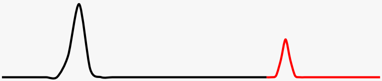


True ^{14}C spectrum based on random events

- length of Bx tigger gate is 16 μs

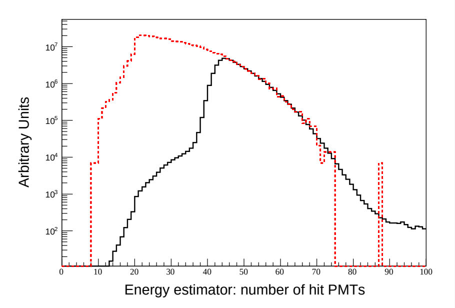


- at low probability, a second event is included → mostly ^{14}C

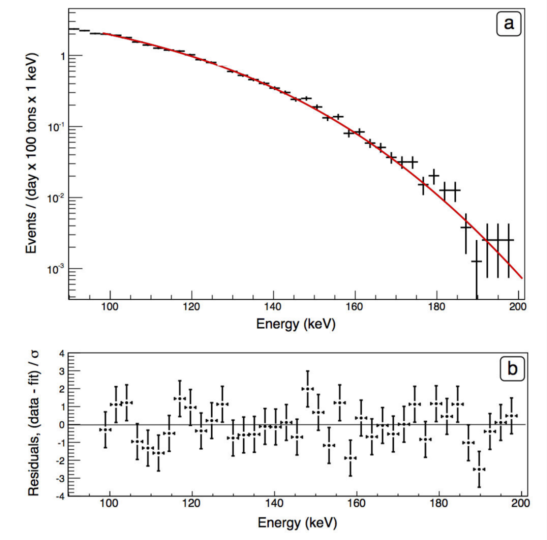


- trigger threshold does not apply to second event

→ undistorted spectrum!



- spectrum of 1st triggers
- spectrum of random in-gate events



- Fit using the theoretical ^{14}C β-emission shape
- Only events with $\Delta t > 8\,\mu$s after trigger to avoid PMT afterpulses

40 ± 4 Bq per 100 tons

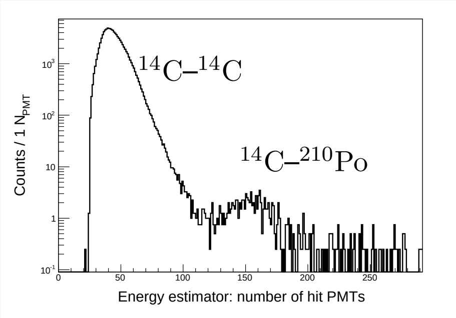
- Corresponding ^{14}C/^{12}C isotopical abundance is $(2.7 \pm 0.1) \times 10^{-18}$ g/g

^{14}C-Pile-Up

Synthetic method: overlay of

- Random event
- ^{14}C event

- Reconstructed using regular procedure



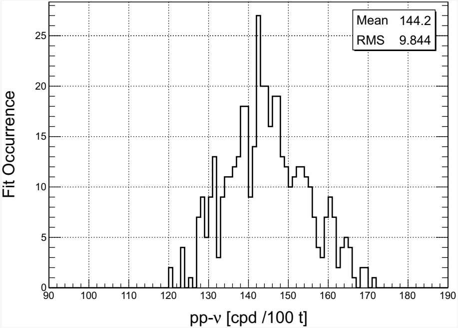
Standard Fit

Data from January 2012 to May 2013 (408 days)
Reduced threshold (20 PMTs) starting from 15.02.2013

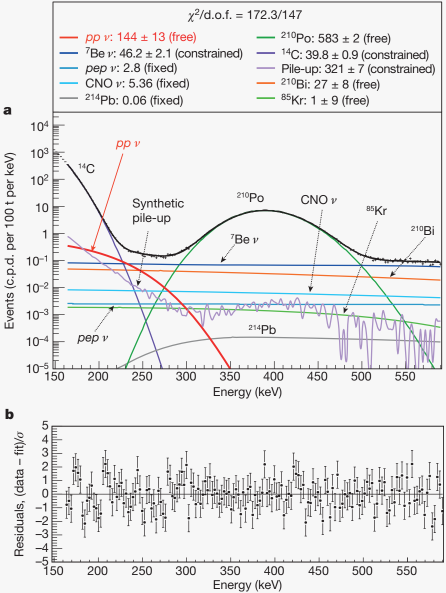
- Energy estimator: N_p
- Range: [60-220 N_p] (corresponds to 165-590 keV)
- Free spectral components: ^{14}C, ^{210}Bi, ^{210}Po, pp, ^{85}Kr
- Constrained spectral components: ^{7}Be (paper central value)
- Fixed spectral components: pep+CNO+^{8}B (SSM/LMA(HM))
- Energy scale variables: LY free, quenching fixed, f_{eq} calculated
- Synthetic pile-up constrained

Different values obtained by varying fit conditions

- Fit energy range
- Energy estimator
- Data selection criteria
- Pile-up evaluation method



RMS gives an estimate of the systematic error



Systematic uncertainties

- energy estimator
- fit energy range
- data selection
- pile-up avaluation

} 7%

- fiducial mass 2%

Resulting pp-rate

$$144 \pm 13_{(\text{stat})} \pm 10_{(\text{sys})}/\text{d} \cdot 100\,\text{t}$$

The absence of pp solar neutrinos is excluded @ $10\,\sigma$

Nature 512, 383–386
28 August 2014
doi:10.1038/nature13702

Interpreting the Result

1. Survival probability
   - $P_{ee} = 0.612 \pm 0.133$ measured
   - $P_{ee} = 0.543 \pm 0.013$ expected
2. pp neutrino flux measurement, verification of the SSM
   - $(6.42 \pm 0.85) \times 10^{10}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ measured
   - $(5.98 \pm 0.04) \times 10^{10}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ expected (high Z)
   - $(6.03 \pm 0.04) \times 10^{10}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ expected (low Z)
3. Solar variability
   - Solar fusion long-term stability confirmed

Outlook

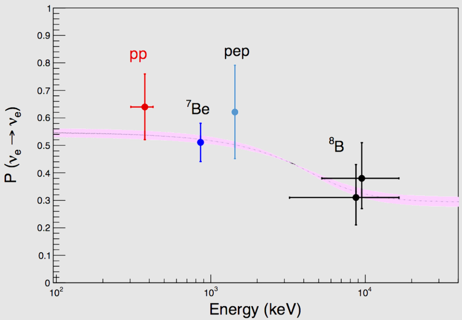
- Precision pep neutrino measurement ($> 3\sigma$) (2015)
- Measurement or stronger limits on CNO (2015)
- $^{7}\mathrm{Be}$ neutrino flux at 3% (2016-17)
- Geo-neutrinos with higher statistics (2016-17)
- $^{8}\mathrm{B}$ neutrino flux with $4\times$ higher statistics (aiming 10%) (2016-17)
- SOX will test reactor antineutrino anomaly
  - Search for sterile neutrinos with an intense $\bar{\nu}_e$ source
  - Measurement of neutrino magnetic moment
  - Search for non standard ν interactions

Beyond Borexino

- Long-term: bigger detector needed
- LENA design: 50 kt detector possible – 200 CNO neutrinos per day
- JUNO: 20 kt soon starting construction in China

Conclusions

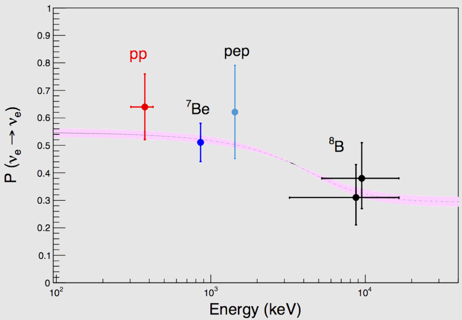
Borexino data only



- Borexino performed first real-time measurement of the solar pp-neutrino flux.
- Broad range of solar ν fluxes (^{7}Be, ^{8}B, pep, CNO, pp) and geo neutrinos.
- Unprecedented radiopurity.
- pp result confirms vacuum oscillation probabilities.
- Full agreement with standard solar model.

Conclusions

Borexino data only



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Thank You!