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

DESY Seminar

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

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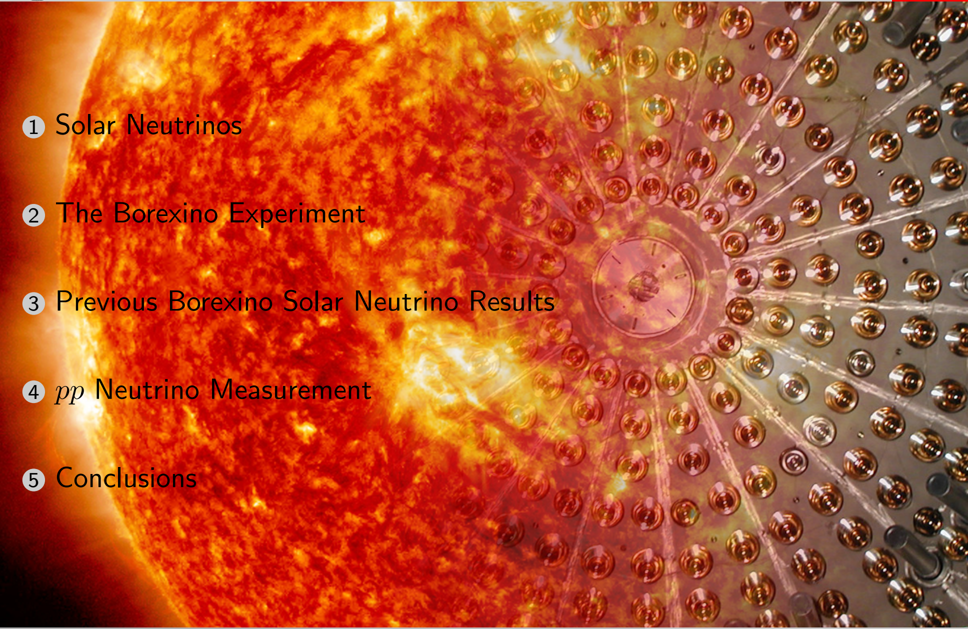
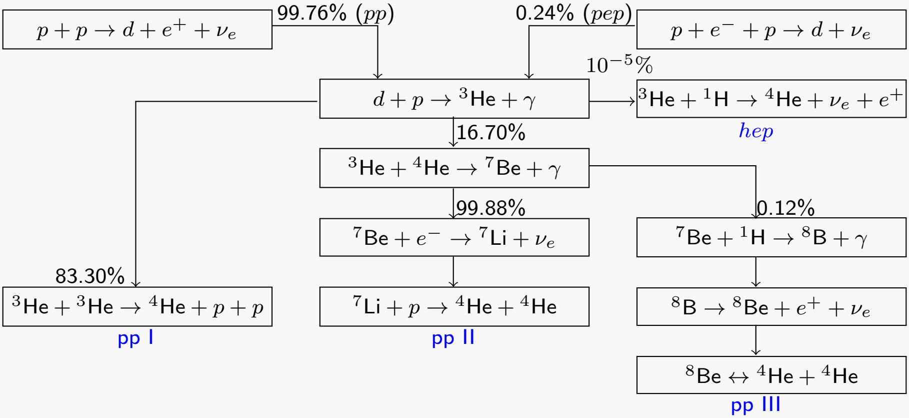
Overview



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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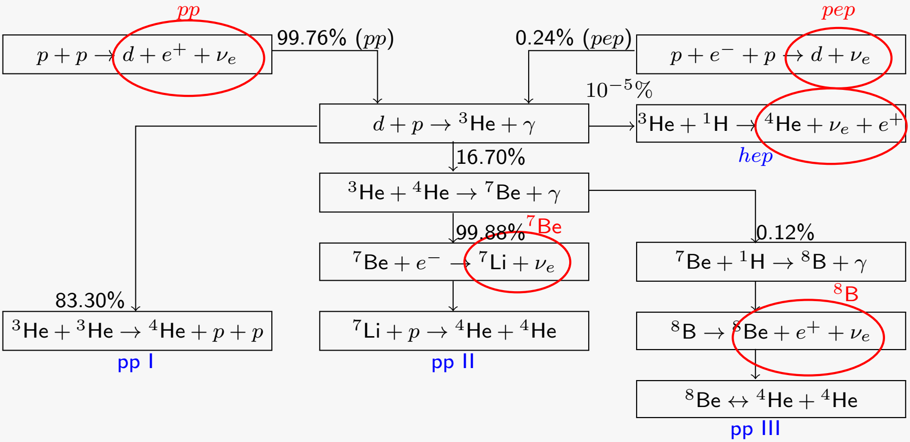

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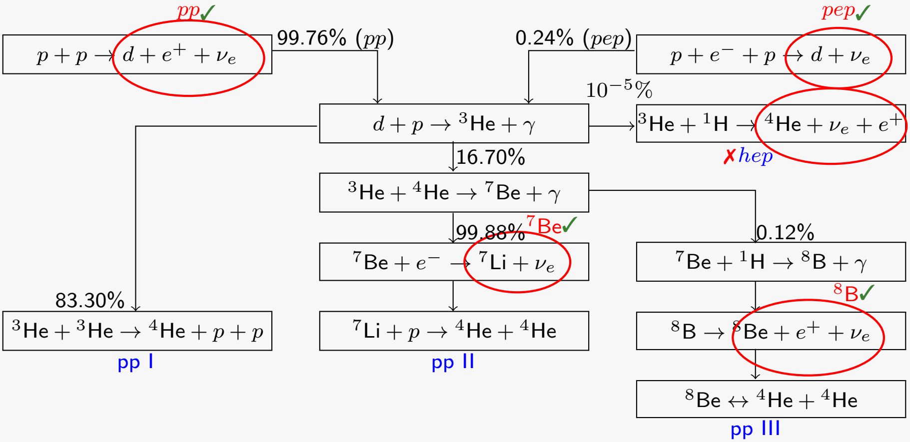

Solar Neutrinos: CNO-cycle

CNO I:

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

CNO II:

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

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

CNO I:

$$^{12}\text{C} + {}^{1}\text{H} \rightarrow {}^{13}\text{N} + \gamma$$
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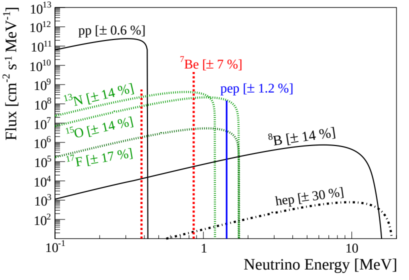
- CNO contribution to our Sun's energy production $< 1\%$ (theory)
- Major contribution for heavier stars

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} $[\text{cm}^{-2}\text{s}^{-1}]$	Low Z Φ_{AGSS09} $[\text{cm}^{-2}\text{s}^{-1}]$	$E_{\nu,\text{max}}$ [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

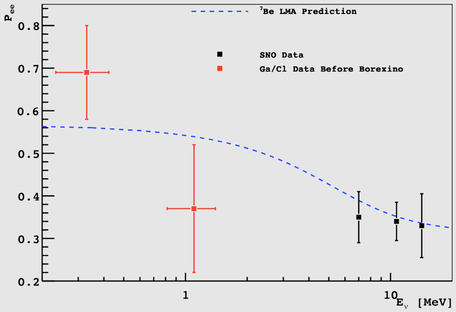
Interaction Rate

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

- 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

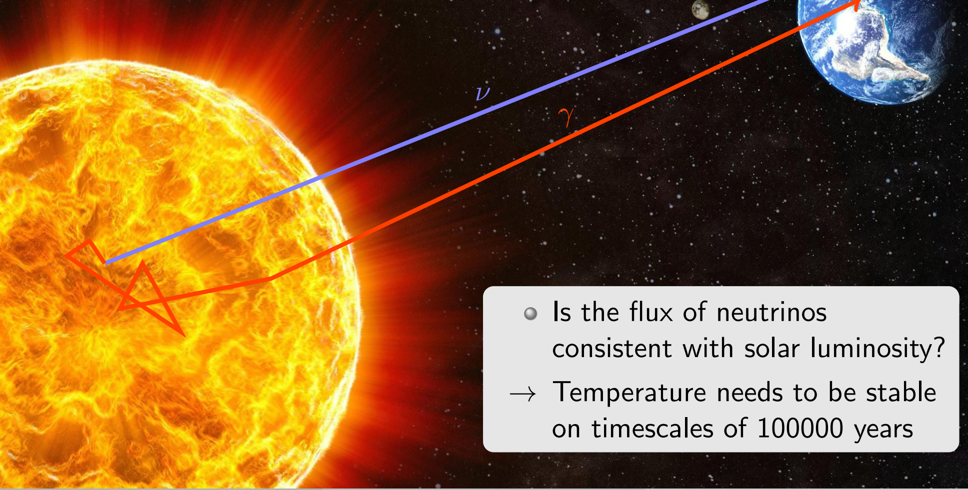
→ Very sensitive to different models

P_{ee} before Borexino



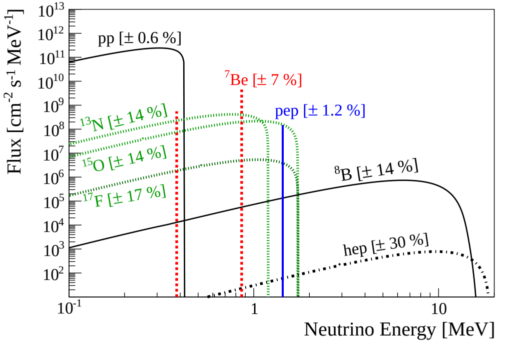
Solar Variability

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

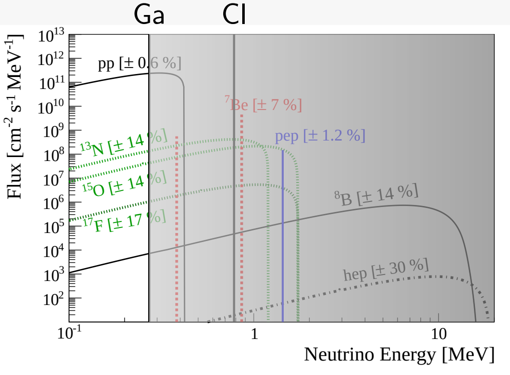


- Is the flux of neutrinos consistent with solar luminosity?

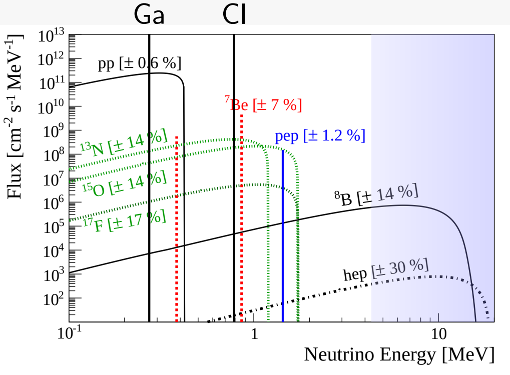
$\rightarrow$ Temperature needs to be stable on timescales of 100000 years


Flux [cm^{-2} s^{-1} MeV^{-1}]
Neutrino Energy [MeV]
pp [± 0.6 %]
^{7}Be [± 7 %]
pep [± 1.2 %]
^{13}N [± 14 %]
^{15}O [± 14 %]
^{17}F [± 17 %]
^{8}B [± 14 %]
hep [± 30 %]
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{-1}
1
10

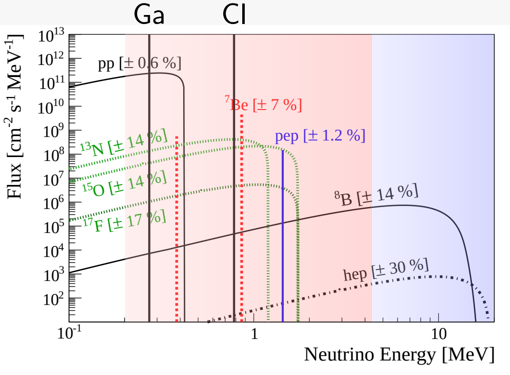
- Radiochemical experiments → no spectral measurement.



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

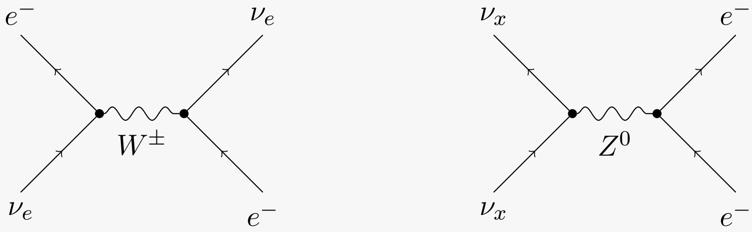


- Radiochemical experiments → no spectral measurement.
- Water Cherenkov detectors → $E > 3.5$ MeV
- Liquid Scintillator → $E > 200$ keV



Neutrino Detection in Liquid Scintillator

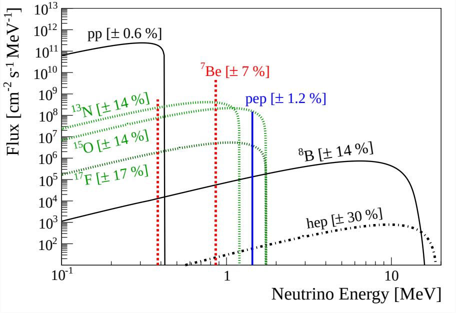
- Neutrino electron scattering
- Scintillation light produced by recoil electron
- Compton like energy transfer
- No energy threshold (limited by $^{14}\mathrm{C}$ background (156 keV))
- Cross-sections very well known!

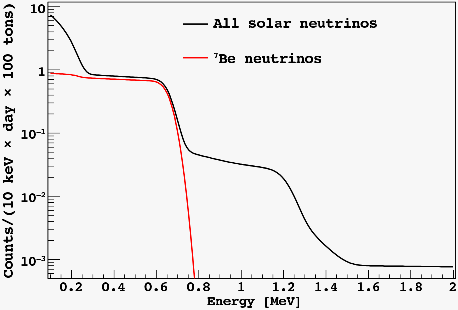


Compton-like energy transfer:

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

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





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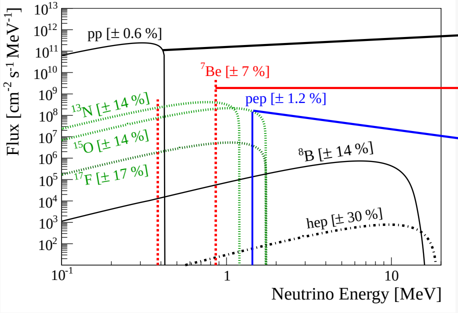
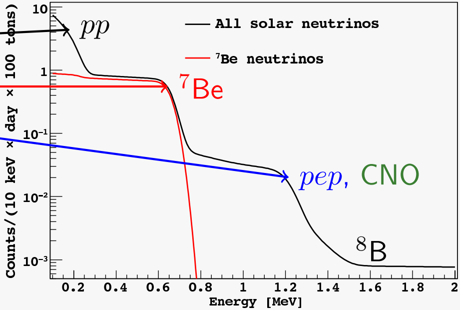
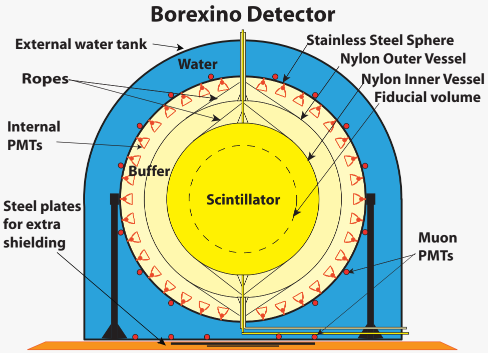






Steel dome: $\varnothing 18\,\text{m} - 16.9\,\text{m}$ high

Inner Detector

Graded shielding

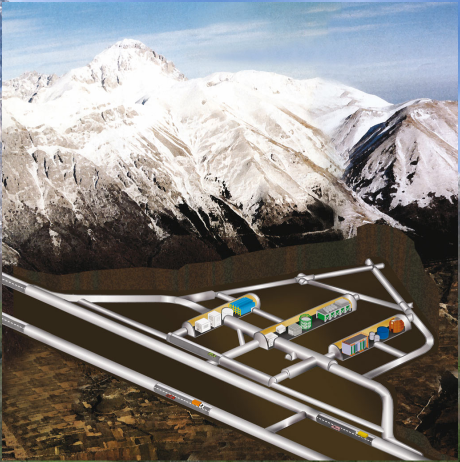
- 278 tons pseudocumene
- $\sim 1.5\,\text{g}/\ell$ PPO
- Two 125 µm nylon vessels ($\varnothing 8.5\,\text{m}$ and $11\,\text{m}$)
- Barrier against radon
- Buffer: light quencher DMP
- Stainless steel sphere ($\varnothing 13.7\,\text{m}$)
- 2212 inward facing 8" PMTs

Outer Detector

2100 tons ultra pure water

- Active shielding
- 208 PMTs $\Rightarrow$ Cherenkov veto

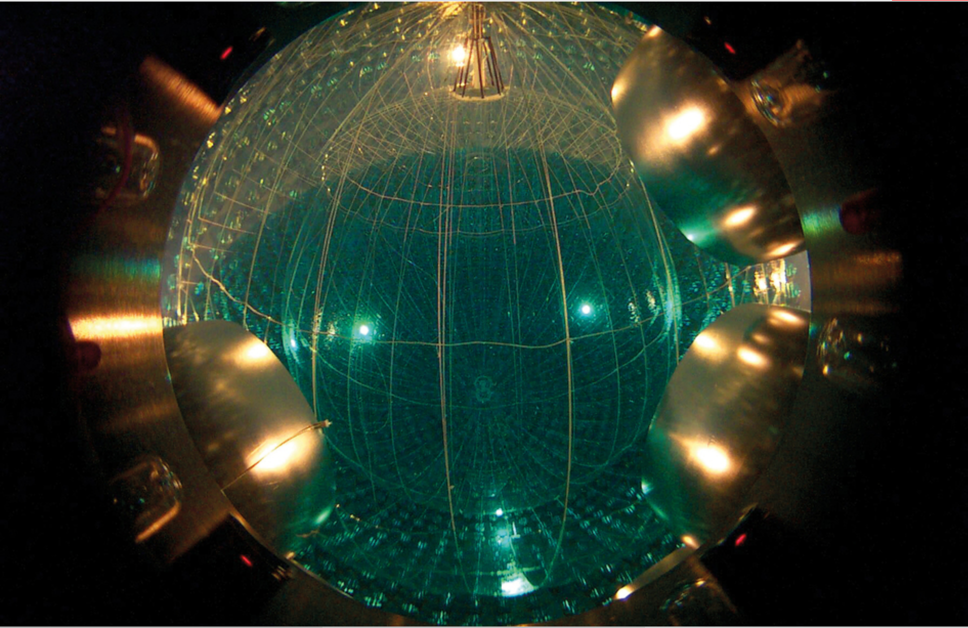
Borexino Detecor Site



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

INFN

LNGS

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

UHH

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TUM
TECHNISCHE UNIVERSITÄT MÜNCHEN

APC

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VT

Data Taking Campaigns

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

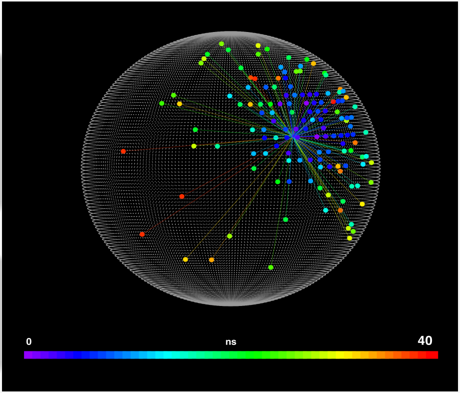
- Number of detected photoelectrons

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

Spatial reconstruction

- photon arrival time pattern (tof)

$\rightarrow \Delta x \sim 10$ cm @ 1 MeV



- Particle identification by pulse shape

Event Selection

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

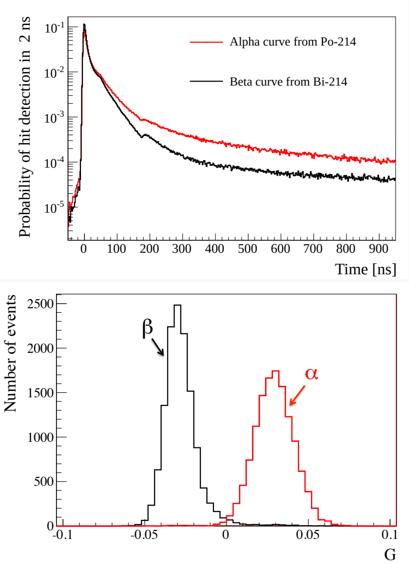
α–β discrimination

- 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



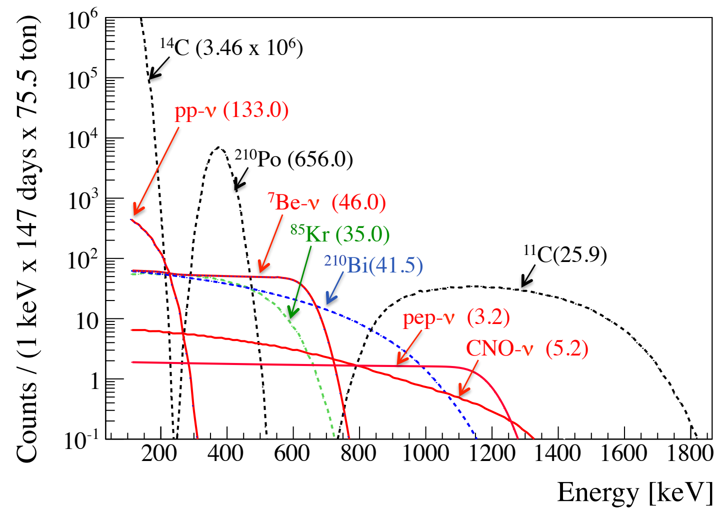
Radiopurity

High radiopurity is the key to success

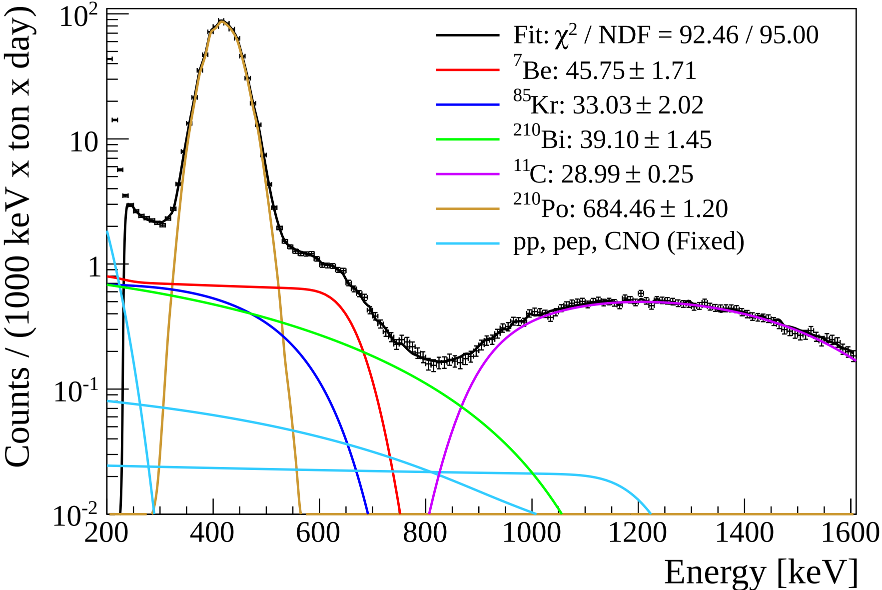
- ^{14}C inherent to the scintillator
- Dedicated prototype in the 90s (CTF)
- Careful choice and handling of all gasses, liquids and materials
- **World record radiopurity levels reached**

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

Expected Signal and Major Background



^{7}Be Interaction Rate



Rate

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

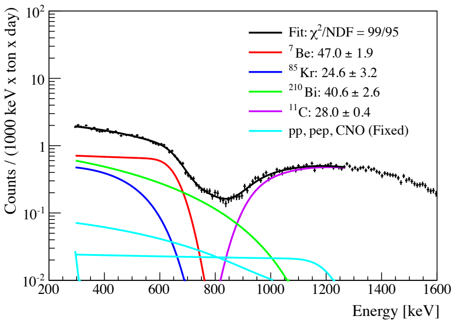
Flux

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

Survival Probability

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

741 days:



Phys. Rev. Lett. 107 (2011) 141302

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

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

^{8}B Neutrino Flux

Rate $E > 3$ MeV

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

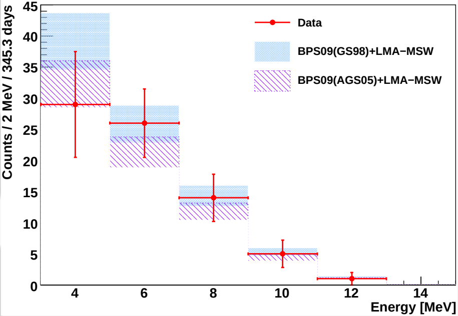
Flux

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

Survival Probability

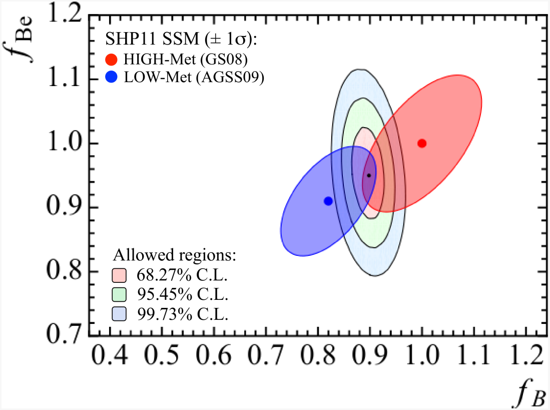
$$P_{ee} = 0.29 \pm 0.10$$

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



Phys.Rev. D82 (2010) 033006

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:

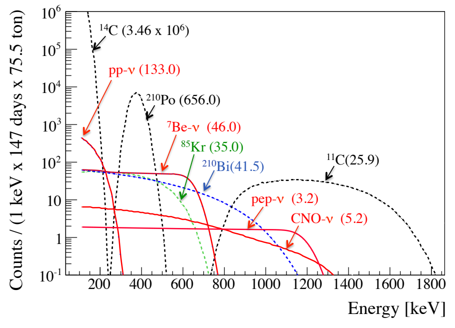
- $f_{\mathrm{Be}} = 0.91 \pm 0.06$
- $f_{\mathrm{B}} = 0.82 \pm 0.11$

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

Main contribution

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

- $\tau_{1/2} = 20.3\ \mathrm{min}$
- 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

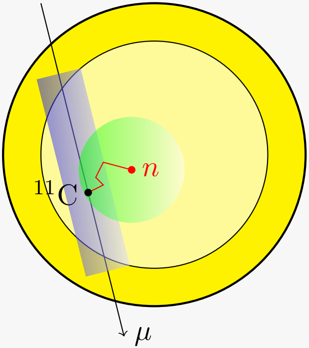
- Borexino: ≈ 4000 muons per day

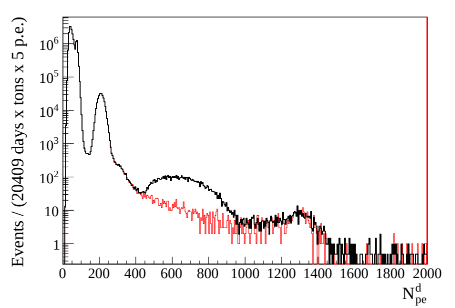
Three-fold coincidence

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

Reduction of ^{11}C background

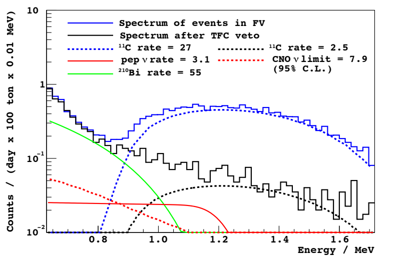
- TFC reduces 89.4 % of ^{11}C
- β^+/β^- pulse shapes
- Boosted decision tree

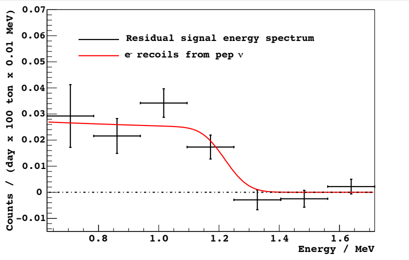




pep and CNO neutrino fluxes

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



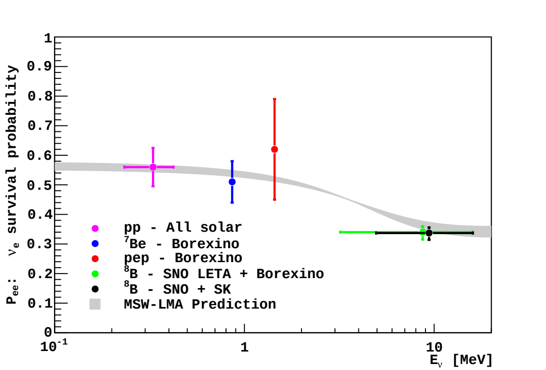


pep results:

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

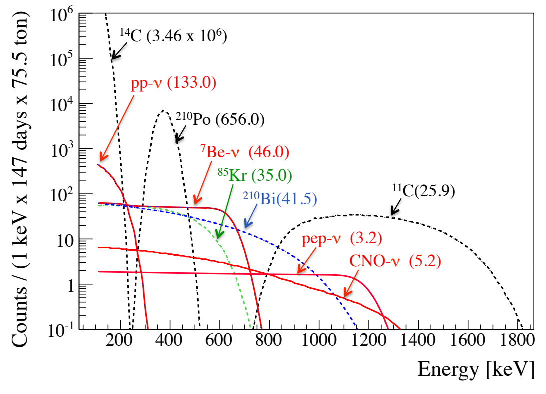
Limit on CNO rate

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



What's missing?

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



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

Loop-mode purification

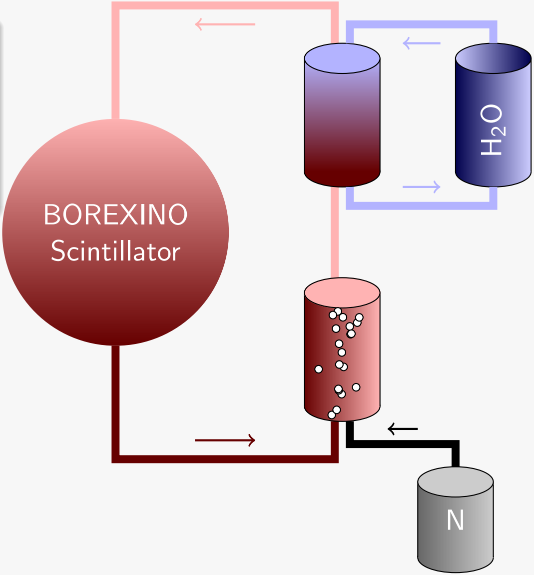
- Extract at the bottom
- Refill at the top
- Try to keep re-mixing inside low

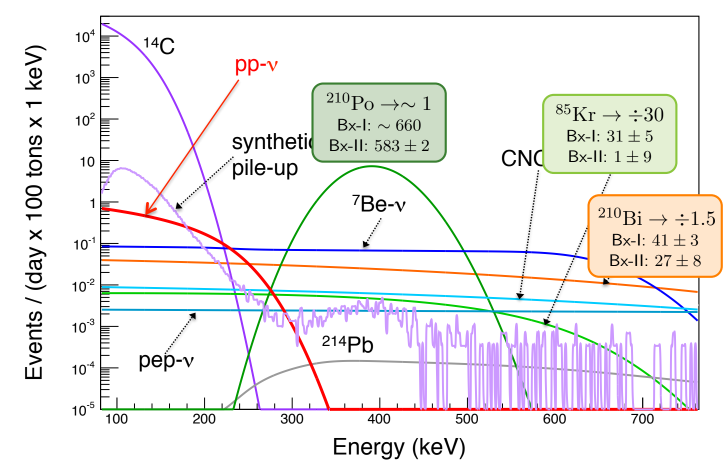
1. Nitrogen purging
   - Bubbling LS with ultra-pure nitrogen

   → removes ^{210}Pb

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

   → removes ^{85}Kr




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

Approaching ^{14}C

- 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

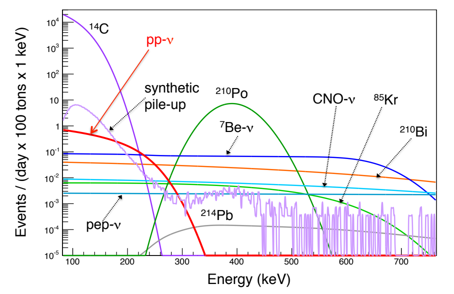
- Mostly below threshold

$\rightarrow$ hard to fit spectral shape

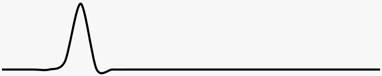
$\rightarrow$ actual decay rate?

- forms pile-up due to hight rate

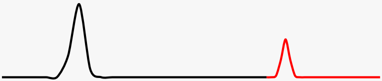
$\rightarrow$ additional signals in pp-region



- length of Bx tigger gate is 16 μs

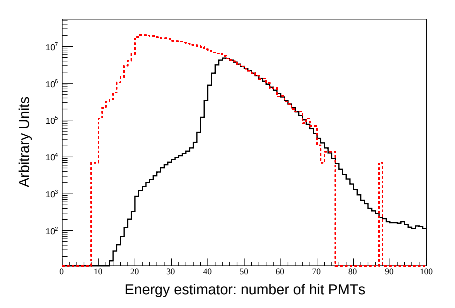


- at low probability, a second event is included → mostly ^{14}C



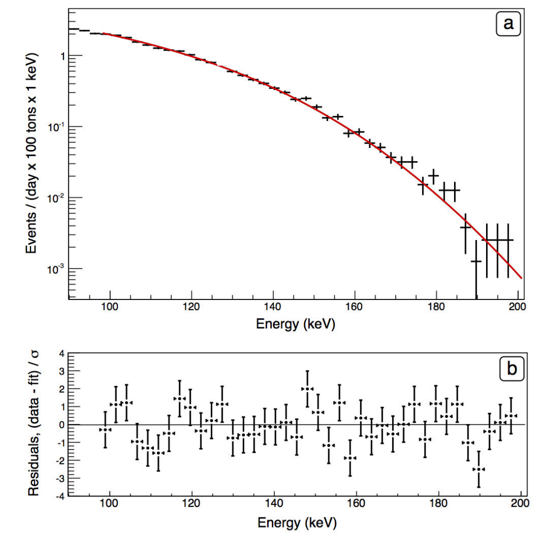
- trigger threshold does not apply to second event

→ undistorted spectrum!



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

Fit to ^{14}C Rate



- 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

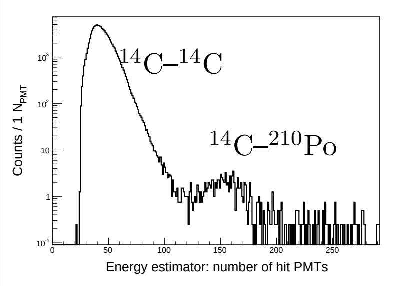
- Corresponding ^{14}C/^{12}C isotopical abundance is $(2.7 \pm 0.1) \times 10^{-18}$ g/g

^{14}C-Pile-Up

Synthetic method: overlay of

- Random event
- ^{14}C event

- Reconstructed using regular procedure



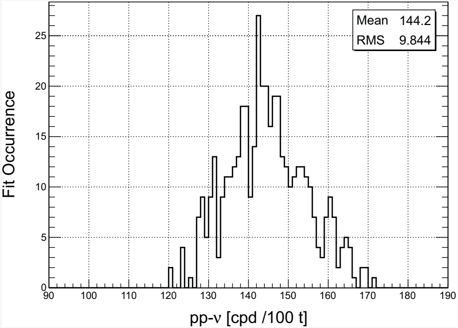
Standard Fit

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

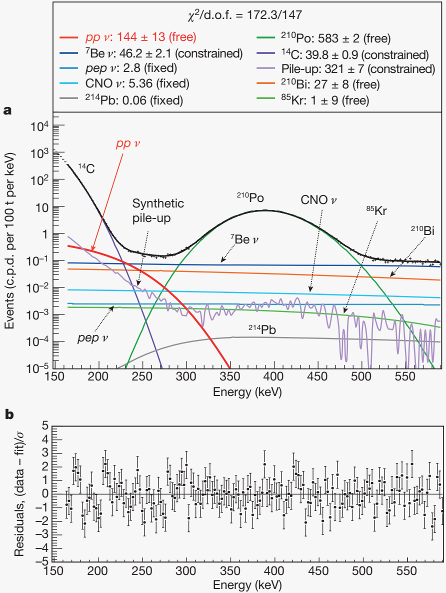
- Energy estimator: N_p
- Range: [60-220 N_p] (corresponds to 165-590 keV)
- Free spectral components: ^{14}C, ^{210}Bi, ^{210}Po, pp, ^{85}Kr
- Constrained spectral components: ^{7}Be (paper central value)
- Fixed spectral components: pep+CNO+^{8}B (SSM/LMA(HM))
- Energy scale variables: LY free, quenching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

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

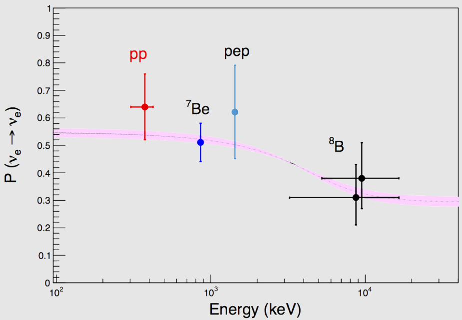
Outlook

- 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

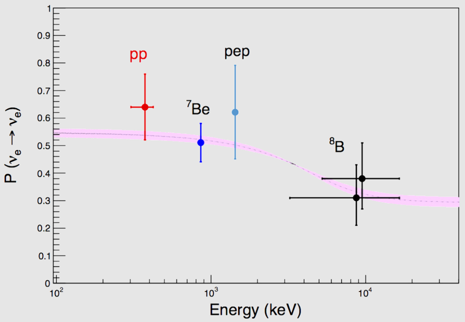
- Long-term: bigger detector needed
- LENA design: 50 kt detector possible – 200 CNO neutrinos per day
- JUNO: 20 kt soon starting construction in China

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.

Borexino data only



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Thank You!

Backup

6 Additional Slides
- Borexino
- LENA
- JUNO

MSW effect

$$x \equiv \frac{2\sqrt{2}G_F N_e E_\nu}{\Delta m^2}$$

Effective mass splitting

$$\Delta m_m^2 \equiv \Delta m^2 \sqrt{\sin^2 2\theta + (\cos 2\theta - x)^2}$$

Effective mixing angle

$$\sin^2 2\theta_m \equiv \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - x)^2}$$

$$P_{\alpha\to\beta} = \sin^2(2\theta_m)\sin^2\left(1.27\frac{\Delta m_m^2 L\,[\text{km}]}{E\,[\text{GeV}]}\right)$$

- $x < \cos 2\theta \Rightarrow$ Vacuum dominated oscillations
- $x > 1 \Rightarrow$ Matter effects dominate ($\theta_m \to 90°$)
- Intermediate region: resonance with maximal mixing ($\theta_m \to 45°$)

Gatti Parameter

- Binned reference shape based on measured α and β distributions
- n normalized bins with values r_α and r_β
- Measured binned time distribution of an event: $e(t_n)$

Gatti Parameter G:

$$G = \sum_n e(t_n) w(t_n)$$

with

$$w(t_n) = \frac{r_\alpha(t_n) - r_\beta(t_n)}{r_\alpha(t_n) + r_\beta(t_n)}$$

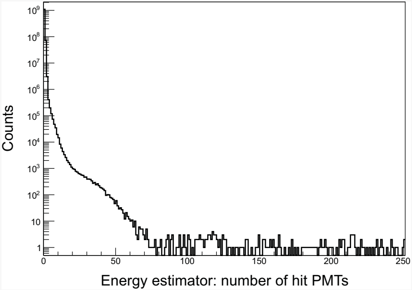
^{14}C-Pile-Up

Alternative method:

- Random triggers (16 µs, 0.5 Hz)
- Sliced in 230 ns time windows

→ Randomly sampled signal

- Pile-up: combination of any spectral component with such a spectrum



Egg shaped cavern

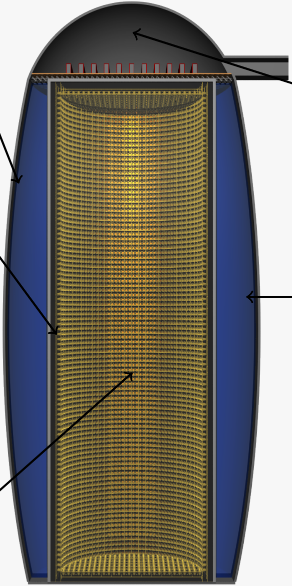
- $\updownarrow$ 120 m
- $\varnothing >$ 36 m

Detector Tank

- concrete wall
- cylindrical – $\updownarrow =$ 100 m $\varnothing =$ 32 m
- $\sim$ 32000 12" PMTs

Target

- 50 kt scintillator



Top cavern

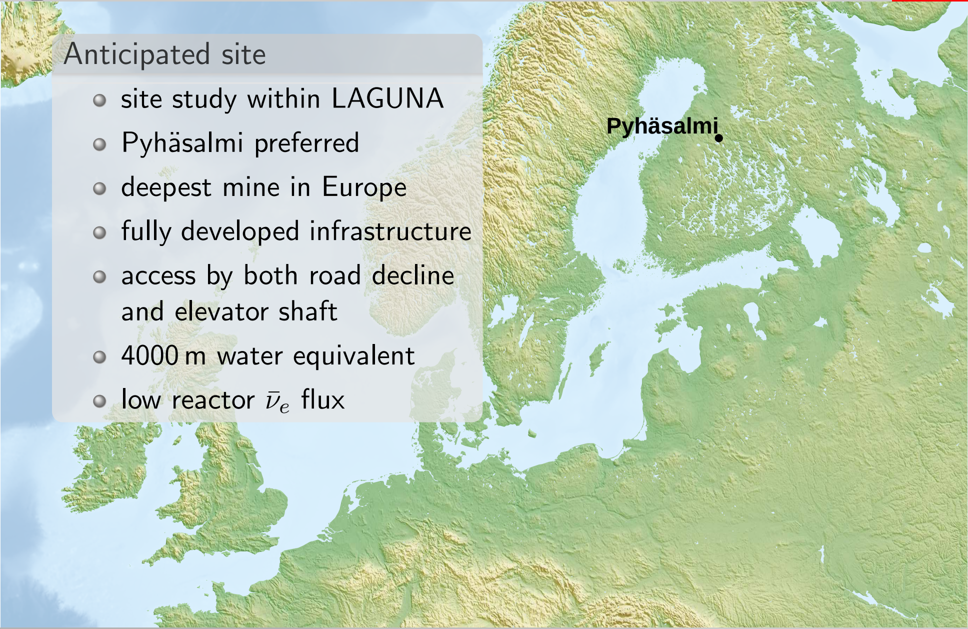
- access to top deck
- external muon veto

Water-filled cavern

- $\sim$ 2000 12" PMTs
- veto for inclined muon tracks
- shielding for fast neutrons

Anticipated site

- site study within LAGUNA
- Pyhäsalmi preferred
- deepest mine in Europe
- fully developed infrastructure
- access by both road decline and elevator shaft
- 4000 m water equivalent
- low reactor $\bar{\nu}_e$ flux



LENA Site

Anticipated site

- site study within LAGUNA
- Pyhäsalmi preferred
- deepest mine in Europe
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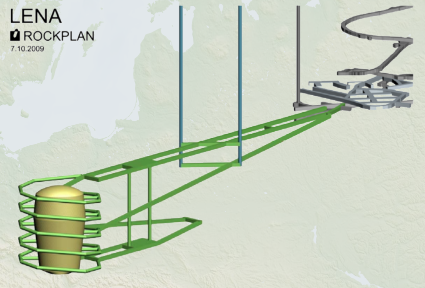
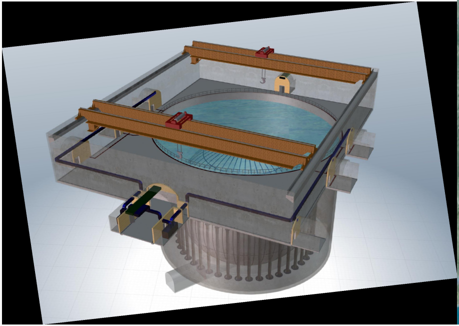
LENA @ Pyhäsalmi



Jiangmen Underground Neutrino Observatory



- Main goal: Mass Hierarchy - solar program under investigation
- Collaboration formed this June
- Start of civil engineering end 2014
- Begin of data taking 2020

JUNO Detector