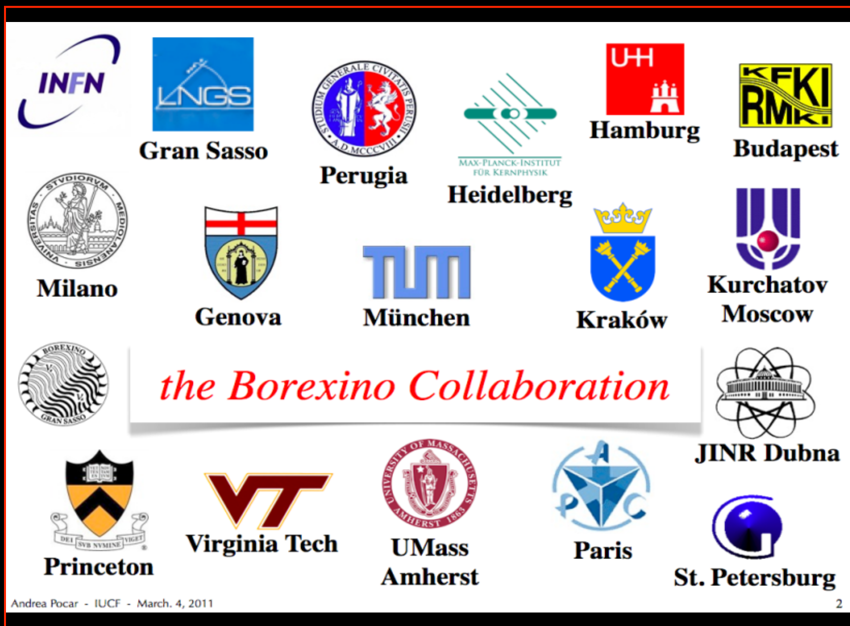
Solar Neutrinos with Borexino at LNGS

Current Results/Future Opportunities

Frank Calaprice

Princeton University

Borexino Collaboration

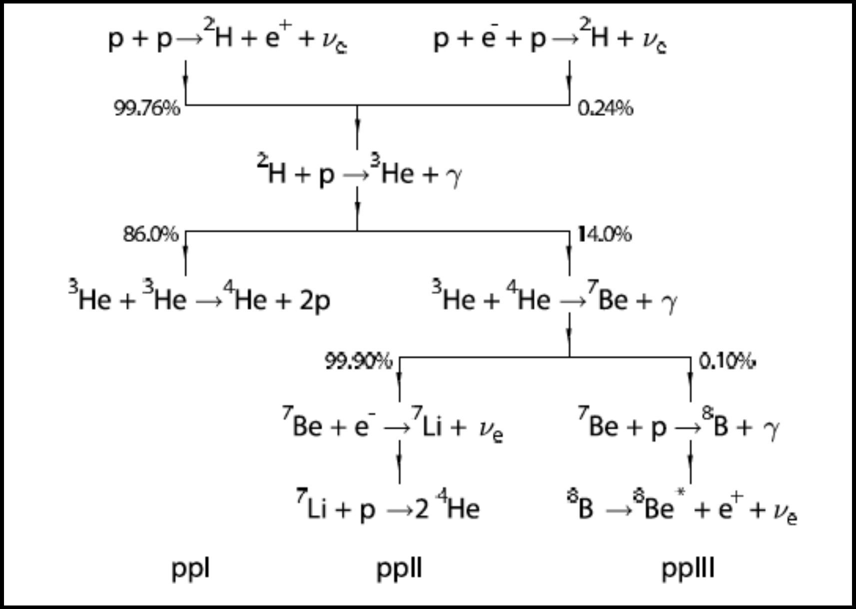


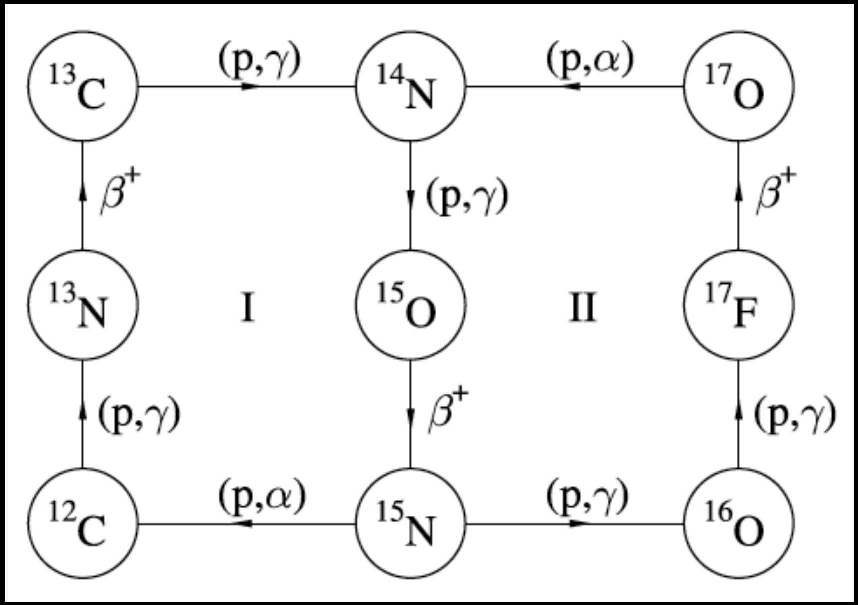
A 20^{+}year successful collaboration between U.S. and Italian + European Groups

Solar Nuclear Fusion Cycles

The pp cycle

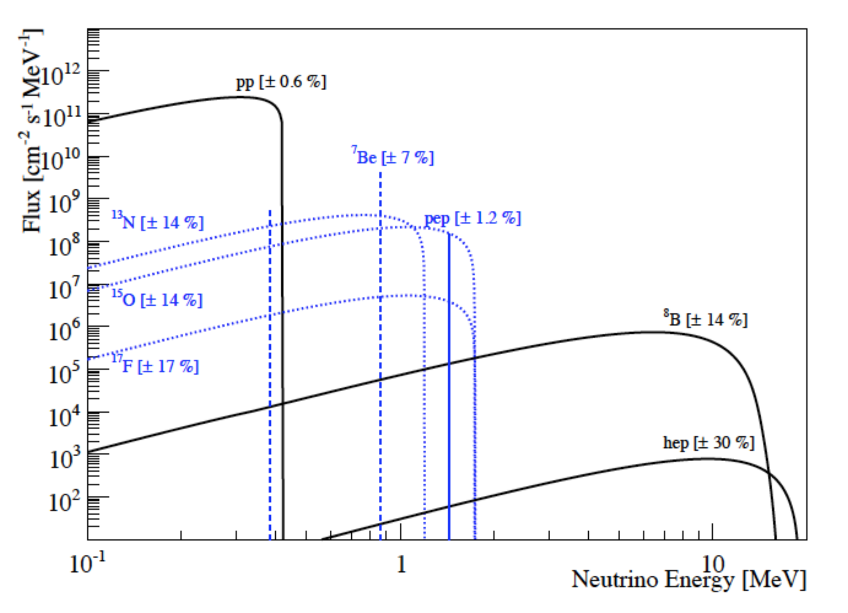
The CNO cycle



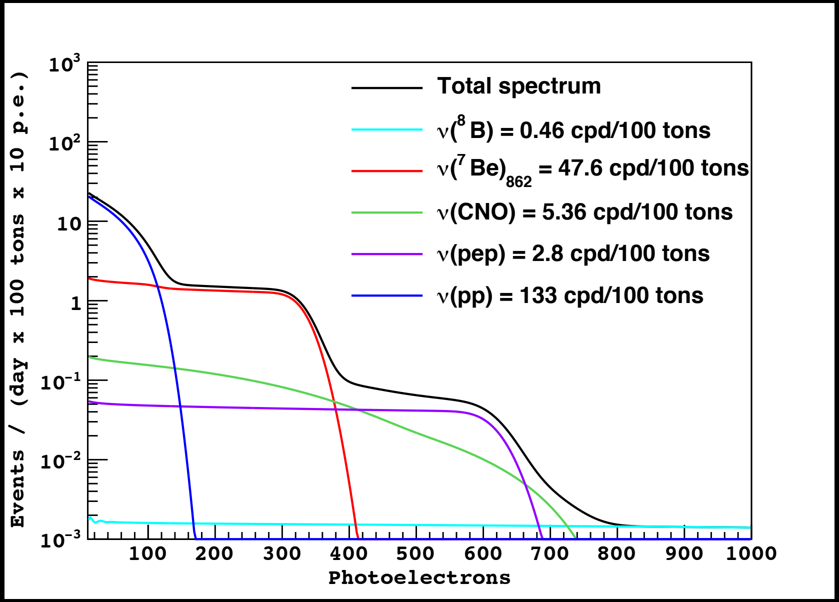


Solar Neutrino Spectra

Neutrino Energy Spectrum

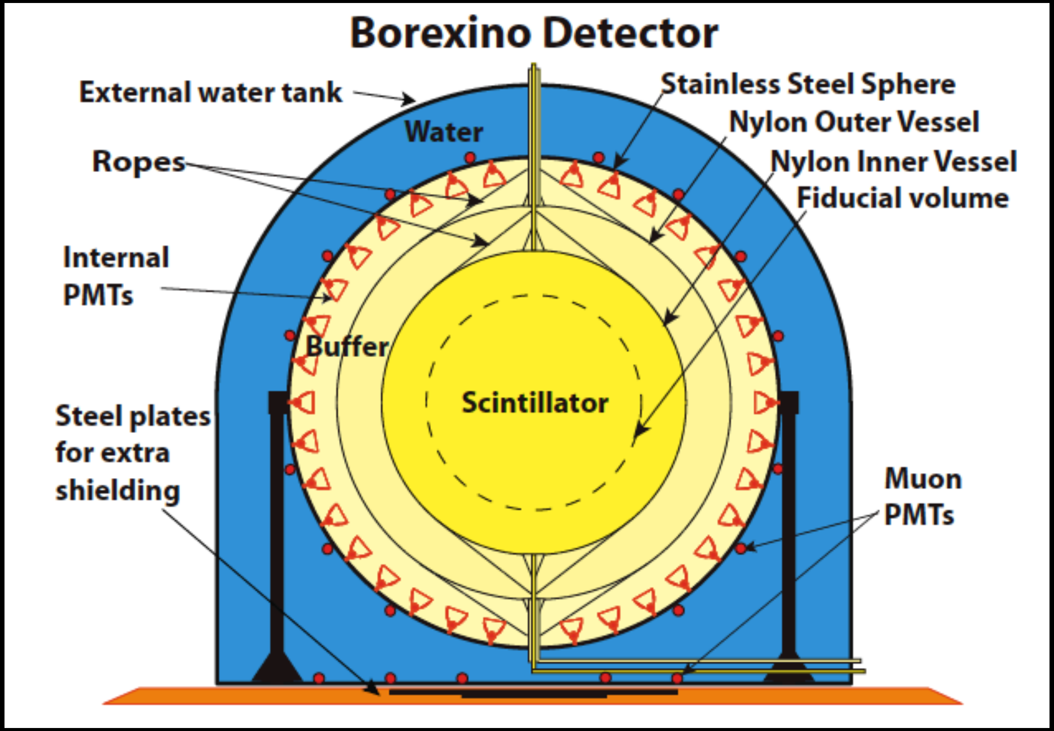


Neutrino-Electron Elastic Scattering Energy Spectrum



Overview of the Borexino Detector
(Mostly Active Shielding)

- Shielding Against Ext. Backgnd.
  - Water: 2.25m
  - Buffer zones: 2.5 m
  - Outer scintillator zone: 1.25 m
- Main backgrounds: in Liq. Scint.
  - $^{14}C/^{12}C$
    - 10^{-18} g/g. cf. 10^{-11} g/g in air CO_2
  - U, Th impurities
  - ^{222}Rn daught (^{210}Pb, ^{210}Bi, ^{210}Po)
  - ^{85}Kr
- Light yield (2200 PMT's)
  - Detected: 500 p_e/MeV (~4%)
- Pulse shape discrimination.
  - Alpha-beta separation



Borexino Energy Spectra

PRL 107 141302 (2011)

Data are based on 740.7 live days between May 16, 2007 and May 8, 2010.

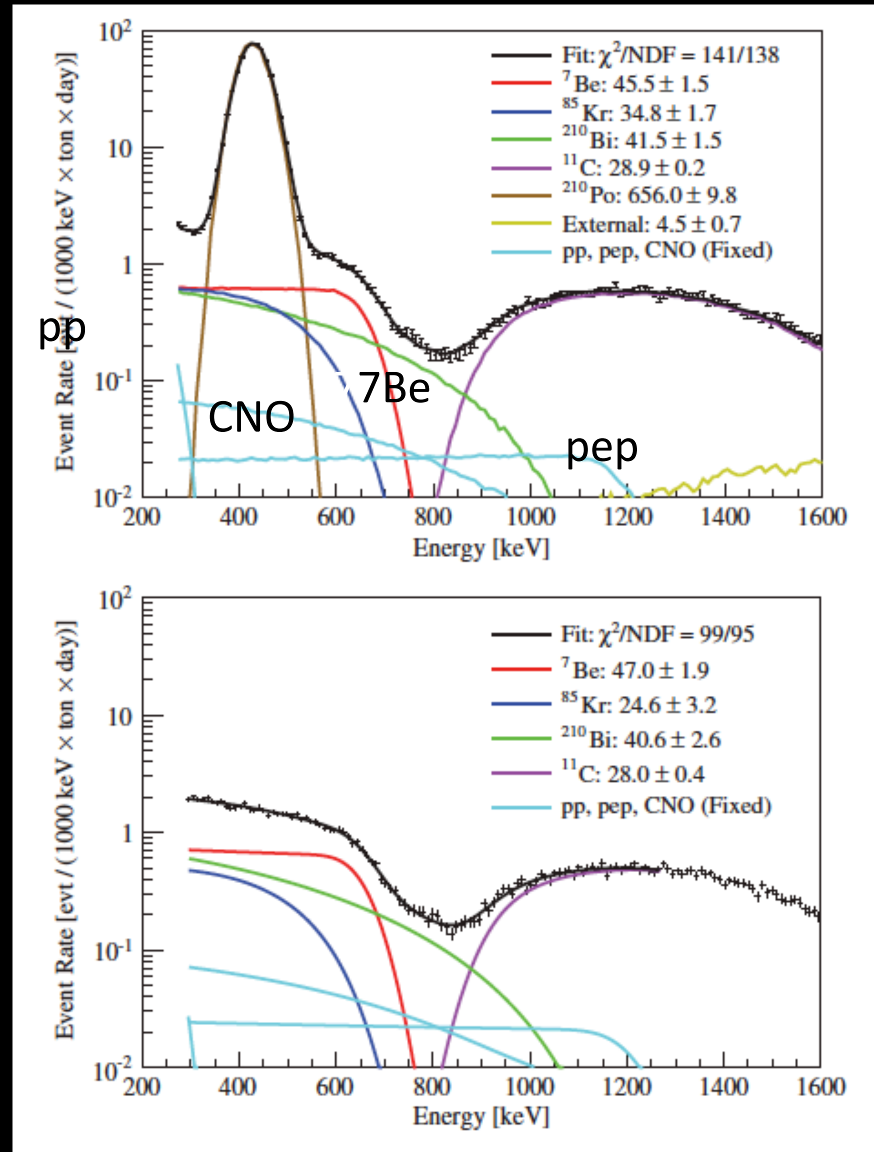
Prominent backgrounds are:

^{210}Po ^{210}Bi ^{85}Kr & ^{14}C (not shown)

CNO obscured mainly by ^{210}Bi due to similar shape.

The ^{210}Po alpha rate was very high but saved by alpha/beta pulse shape discrimination.

The pep was measured by applying cuts to reduce the ^{11}C background.



Borexino Neutrino Measurements

Solar Neutrino rates (cpd/t)

- ^{7}Be: 0.460 ± 0.023 — Phys. Rev. Lett. 107 141302 (2011)
- ^{8}B: 0.0022 ± 0.0004 — Phys. Rev. D 82, 033006 (2010)
- pep: 0.031 ± 0.005 — Phys. Rev,. Lett. 108, 051302 (2012)

Geo-neutrinos

- Total 14.3 ± 4.4 events — Phys. Letts. B722, 295 (2013)

Electron Neutrino Survival Probabilities

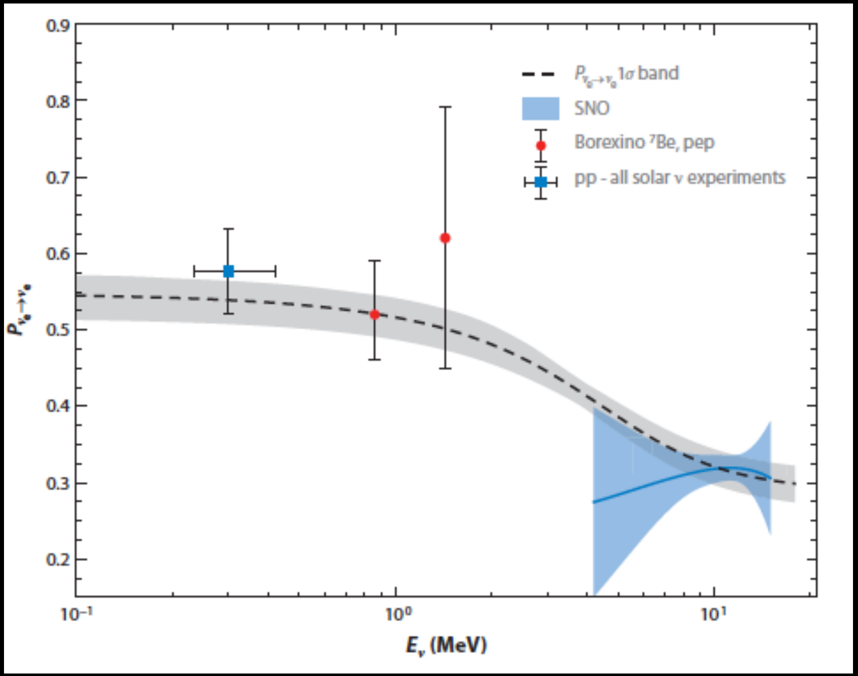
Pee = 1.0   no neutrino oscillations

The MSW predicted transition from vacuum to matter-enhanced oscillations generally agrees with measurements of pp, ^{7}Be, pep, and ^{8}B neutrinos.

The centroid of SNO's ^{8}B low threshold data falls below the MSW curve with decreasing energy, but the significance is not high.

The transition region is sensitive to new physics. e.g non-standard interactions, sterile neutrinos.

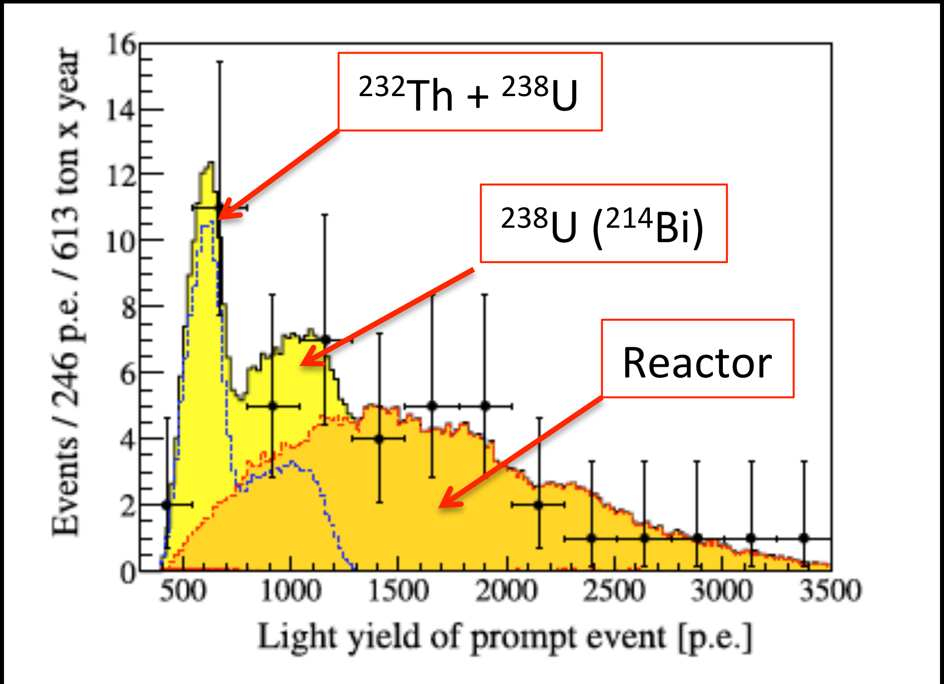
Improving pep, and low energy ^{8}B data motivated by sensitivity to new physics.



W.C. Haxton, R.G. Hamish Robertson, and Aldo M. Serenelli, Annu. Rev. Astron. Astrophys. 2013. 51:21–61

Geo-neutrinos

- Geo-neutrino data from 1353 days of data.
  - Physics Letters B 722 (2013) 295–300
- Geo-neutrino events in yellow; reactor events in orange.
- Antineutrinos detected by delayed coincidences from changed current reaction
  - ν+p -> e^+ + n
- Total 46 events detected
  - 14.3 ± 4.4 geo-neutrinos
  - 31.2 ± 6.5 reactor neutrinos



Success!

- Borexino delivered its original goal of measuring ^{7}Be neutrinos with 5% accuracy.
- Lower backgrounds than originally sought allowed measurements of ^{8}B and pep neutrinos and geo-neutrinos.
  – Original goal: [U], [Th] ~ 5×10^{-16} g/g
  – Achieved: [U], [Th] ~ 2×10^{-17}, < 7×10^{-18} g/g
  – Background: 20 – 70 times lower than sought!

What's next?

- Lower background by scintillator re-purification.
- Solar program: detect all solar neutrinos!
  - pp neutrinos
  - CNO detection or upper limit
  - Improve accuracy of ^{7}Be, pep
- SOX source experiment
  - Short baseline neutrino oscillations

Future Solar Neutrino Program

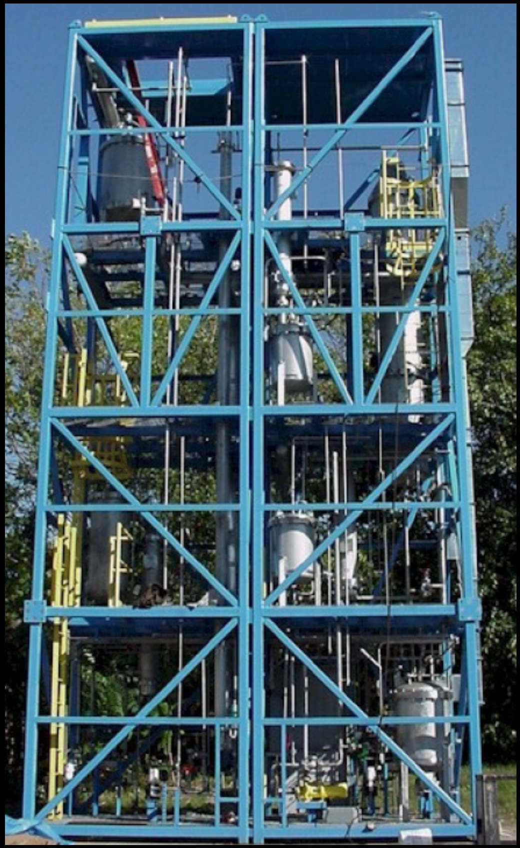
1. **Detect/Measure CNO neutrinos**
   - Confirm proton burning process for stars more massive than Sun.
   - CNO neutrino rate determines C, N abundances in core.
     - Clarify the "solar metallicity problem"
     - Haxton, Serenelli, and others suggest planetary accretion could explain difference in metal abundance in photospheric and helioseismology data.
     - High metalicity rate would support such possibilities.

2. **Improve accuracy of ^{7}Be and pep measurements.**
   - Neutrino rates could provide accurate prediction of power produced by solar nuclear fusion reactions.
   - Comparing neutrino-related power to total solar luminosity could reveal new physics? Sterile neutrino tension? (H. Robertson)

3. **Non-standard interactions in vacuum- matter oscillations transition.**

Going for lower background…

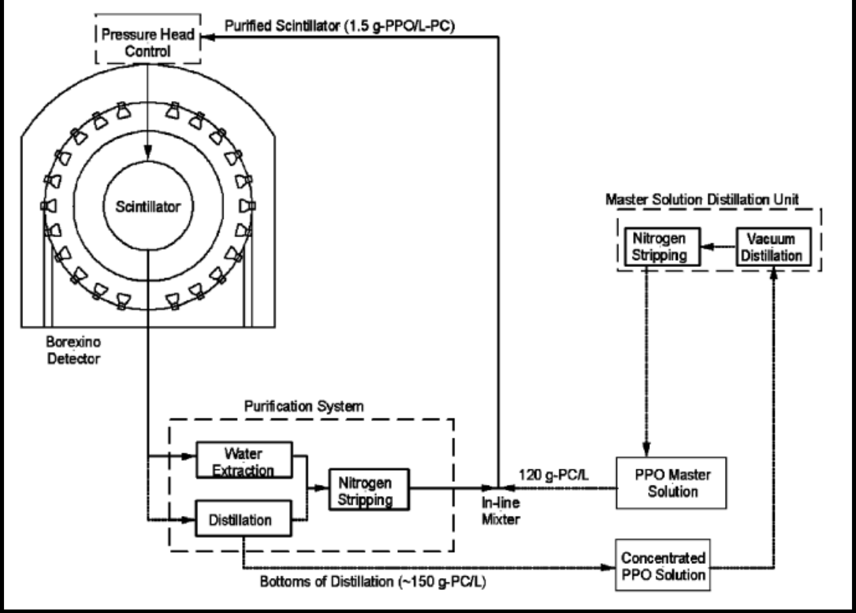
- Initial background was achieved by in-line purification as detector was being filled.
  - Distillation, nitrogen stripping and water extraction/ distillation of PPO.
- Same purification system was built for re-purification in loop mode.
- 2010: Re-purification started to achieve lower background.



The scintillator purification "skids"

Background Reduction with Loop Purification of Liquid Scintillator

- "Loop" purification is achieved by draining fluid from bottom of vessel, passing it through purification system, and returning to the top.
- Processes available are:
  - Water extraction or distillation
  - Nitrogen stripping (^{85}Kr)

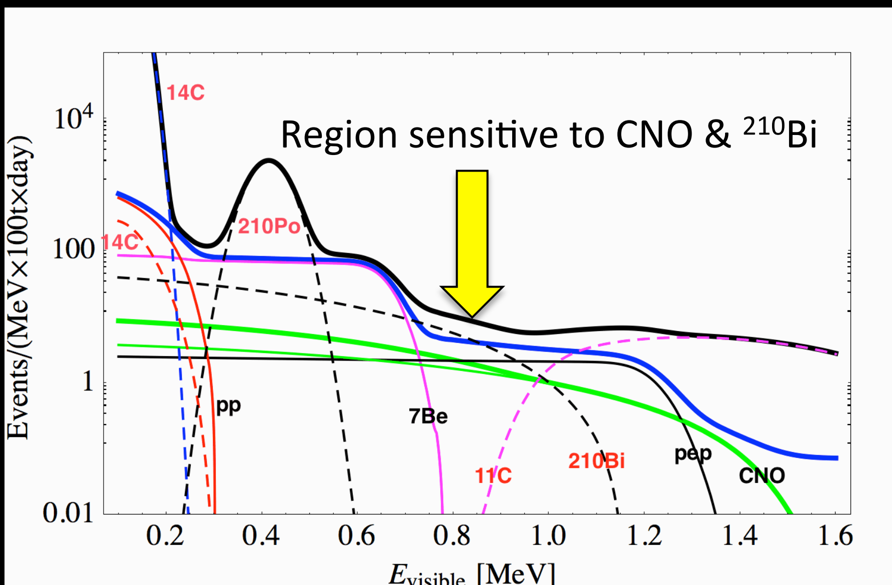


Results of 6 cycles of Re-purification

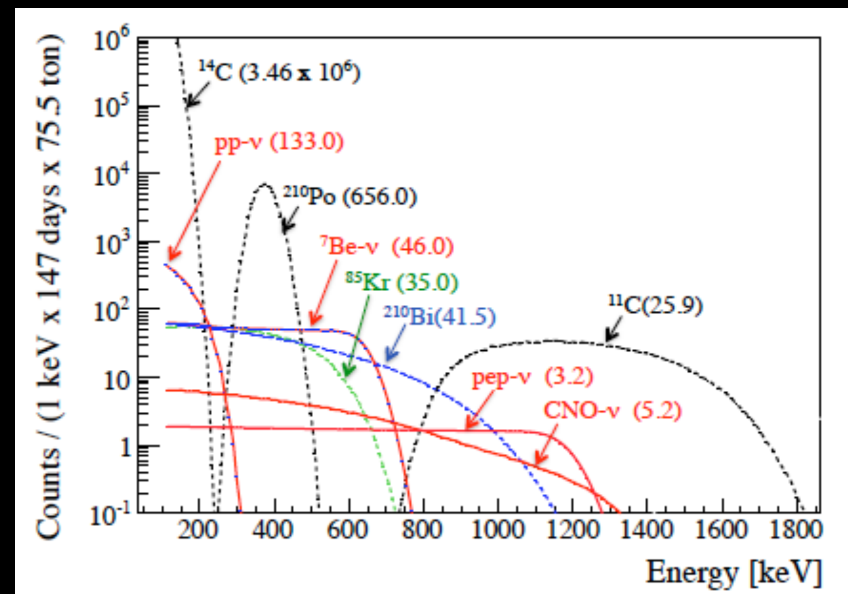
- ^{85}Kr: 30 cpd/100t → < 5 cpd/100t
- ^{238}U (^{226}Ra): [(53 ± 5) → (1.6 ± 0.6)] x 10^{-19} g/g
  - ^{214}Bi-^{214}Po: Reduction factor = 33. 7 events/100t/yr.
- ^{232}Th: [(3.8 ± 0.8 → < 1.2] x 10^{-18} g/g (95% CL)
  - ^{212}Bi-^{212}Po: Reduction factor > 3. 2 ev./100t in 600 d
- ^{210}Bi: 70 cpd/100t → 20 ± 5 cpd/100t
- ^{210}Po: Essentially not reduced! Why?

Rates before purifcation are based on 153.6 ton-yr exposure taken in 740.7 d between May 16, 2007 and May 8, 2010. See Borexino Coll. arXiv 1308.0443v1.

Backgrounds after & before Water Extraction + N_2 Stripping



After re-purification 2012-2013
(with ^{11}C cuts)



Before re-purification 2008-2010
Without ^{11}C cuts. See arXiv1308.0443v1.

Water Extraction Worked!!

- With current background we will make improvements in ^{7}Be and pep measurements, and improve the upper limit on CNO.
- However, lower background is needed for a strong thrust toward CNO and precise ^{7}Be and pep measurements.

“Purified” Water Surprises

- LNGS round water has relatively high levels of ^{222}Rn (10,000 Bq/m^3) and its daughters ^{210}Pb-^{210}Bi-^{210}Po (1-10 Bq/m^3)

- The inability to remove ^{210}Po and some problems with ^{210}Pb led to investigations of the water.

- Surprise #1
  – Water purification by de-ionization is not very effective in removing ^{210}Pb, and especially not effective for ^{210}Po.

- Surprise #2
  – ^{210}Po has a volatile compound that is not removed by simple distillation.

Surprise #1

- Reduction of ^{210}Pb (^{210}Bi) was inferred from ICPMS measurements of stable ^{208}Pb.
  - ^{208}Pb reduced by x 700 by de-ionization (modest)
  - Typical reduction is $x10^{5\text{-}6}$ for ionized salts.
- Reduction of ^{210}Po was measured by direct counting of alphas, using deposition on silver.
  - ^{210}Po reduced by X10 by de-ionization (very poor!)

Surprise #2

- Publications claim that some ^{210}Po in well water is a in volatile compound produced by biological (bacteria) processes:
  - "Bio-Volatilization of Polonium: Results from Laboratory Analyses", N. HUSSAIN, T. G. FERDELMAN, T. M. CHURCH, Aquatic Geochemistry 1: 175-188, 1995
  - "Impact of microorganism on polonium volatilization", N. Momoshima, et. al. J. Radioanalytical and Nucl. Chem. 272, 413 (2007)
- Dimethyl polonium: Boiling point ~138 C (est.)
- Poor removal of ^{210}Po by de-ionization and distillation due to volatile polonium compound could explain long-standing problems Borexino has had with this isotope.

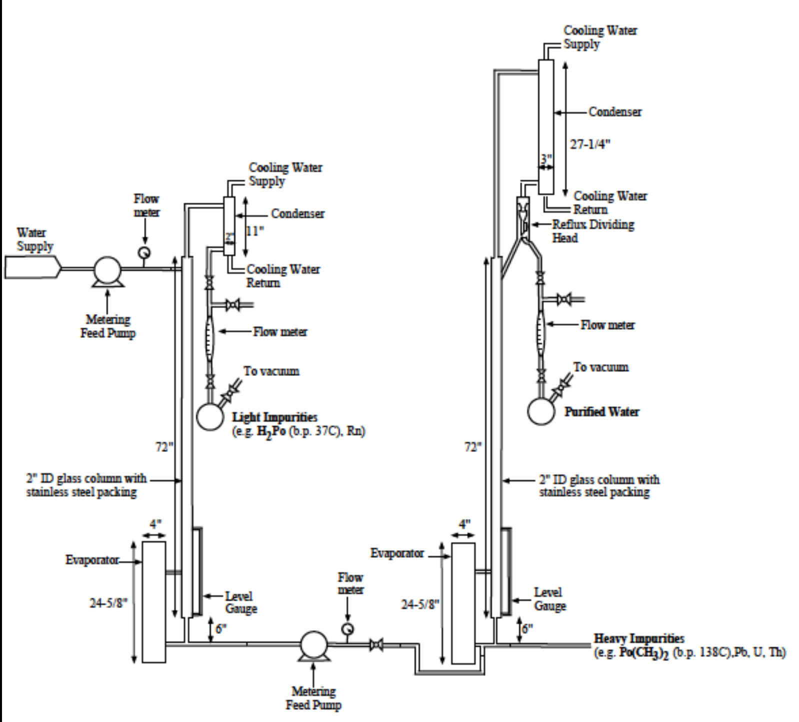
Historical Problems with ^{210}Po

- Poor removal of ^{210}Po by de-ionization and distillation due to volatile polonium compound explains long-standing problems.

1. Initial filling of Borexino (water was used on PPO)
   - ^{210}Po (6000 cpd/100t), ^{210}Pb(~15 cpd/100t)
2. Water extraction:
   - Not effective to remove ^{210}Po
   - Reasonably effective to remove ^{210}Pb

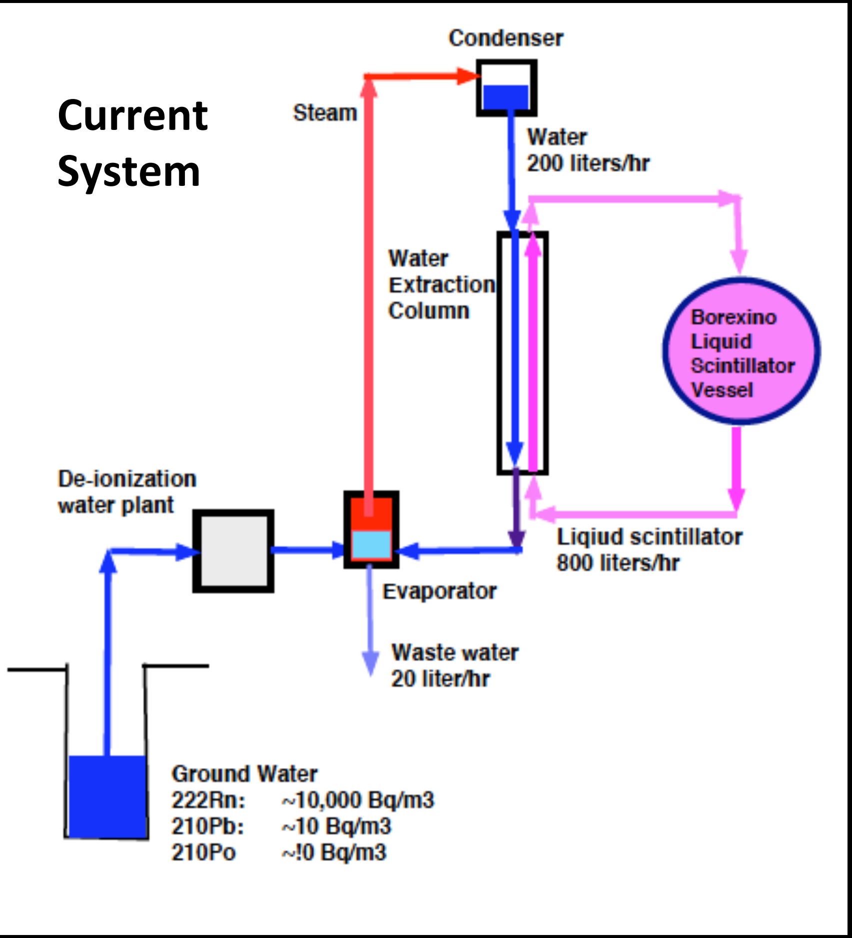
New Distillation System Tested to Remove ^{210}Po and ^{210}Pb from Water.

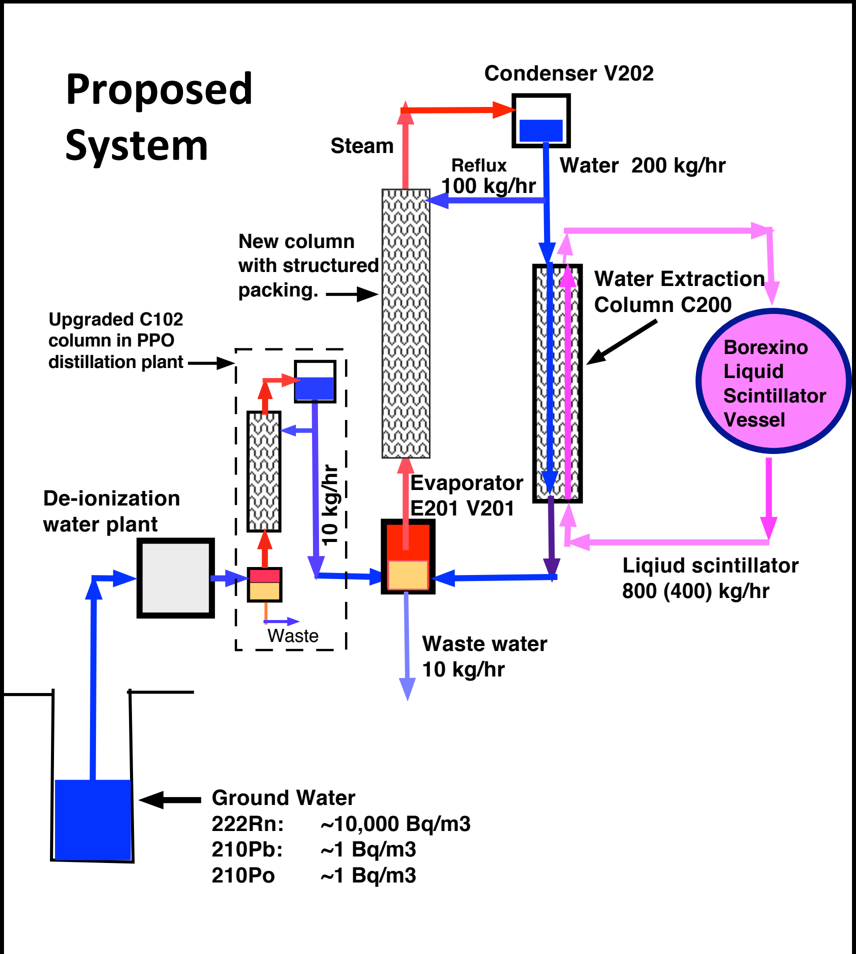
- A small-scale distillation system was designed are tested at Princeton to remove dimethyl polonium from ground water.
  - A tall column with structured packing and high reflux was designed for x1000 reduction.
- Princeton well water, noted for its high radon levels, made it easy to measure the polonium before and after distillation.
- Results:
  - When system was operated as simple evaporator, the ^{210}Po was not separated. Explains many problems.
  - When operated with full column and high reflux, the output water showed no measurable ^{210}Po.
  - Reduction factor > 300.



Small prototype distillation system with two 6-foot column 2 l/hr capacity.
Students : B.Russell, C. Aurup, W. Taylor

Current & Proposed Upgraded Water Extraction Systems

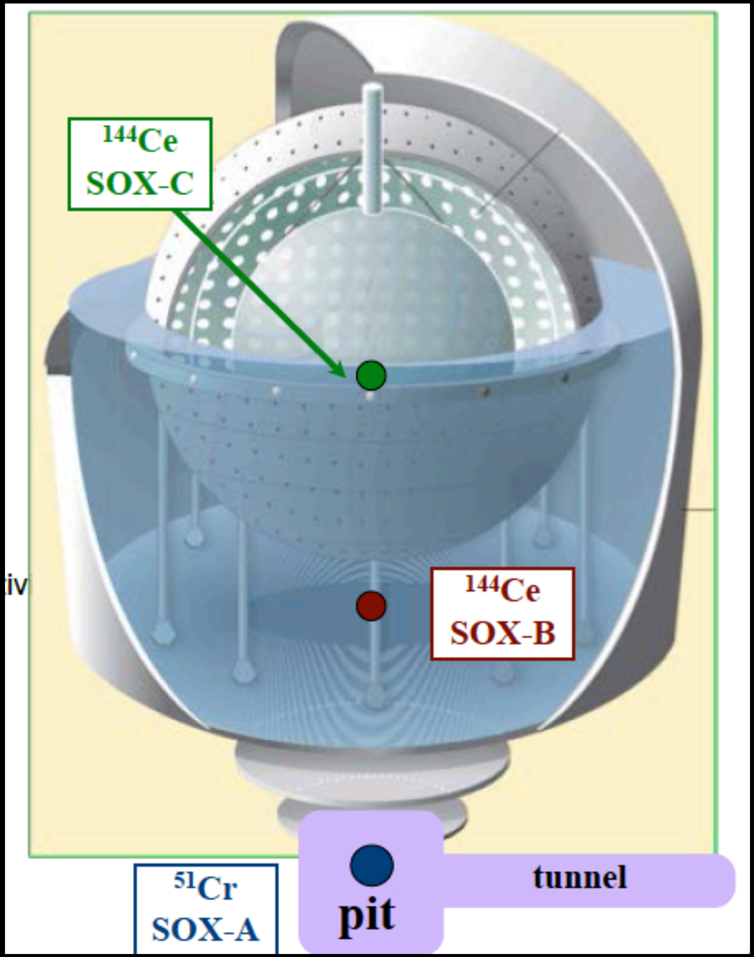




The Borexino SOX Experiment

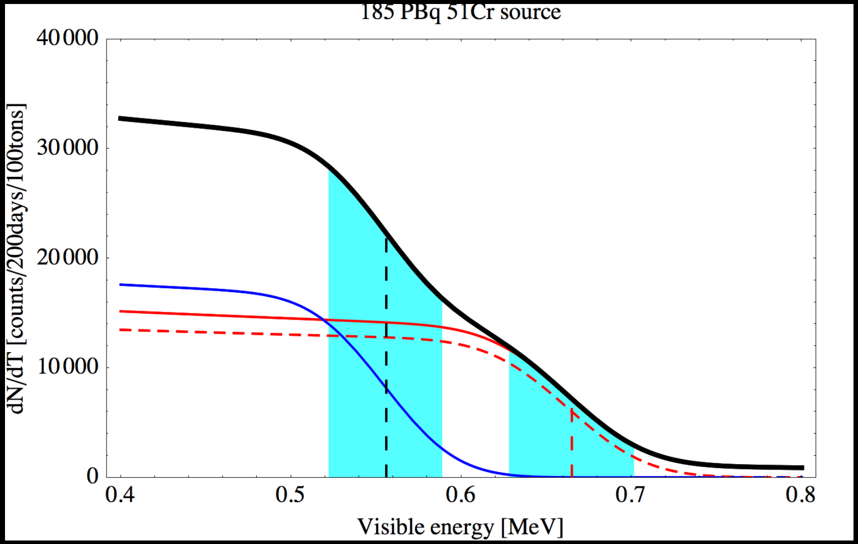
Short distance ν_e Oscillations with BoreXino

- The SOX-A experiment will deploy a 10 MCi ^{51}Cr source below Borexino to search for short baseline neutrino oscillations, due to sterile neutrinos.
- The lower background needed for solar neutrinos will benefit SOX with higher sigmal/background ratio.
- The mono-energetic ^{51}Cr neutrino will benefit the solar program by providing an excellent energy calibration
- SOX-A is funded by the European Research Council.



SOX ^{51}Cr Source and Solar Neutrinos

- The SOX ^{51}Cr source will provide a precise energy calibration for the ^{7}Be measurement.
- The 2.7% uncertainty due to the energy scale will be reduced significantly (<1%).
- With lower background, and more accurate energy calibration, a 3% measurement of the ^{7}Be rate could be possible.
- Uncertainty in pep will also be reduced significantly.



Main systematic errors in ^{7}Be measurment:

Fiducial volume:	+0.5/-1.3 %
Energy response:	2.7%
Fit methods:	2.0%
Statistical uncertainty:	3.3%

Status of Solar/Neutrino Science

- Bethe's pp fusion cycle
  - Observed 3 of the 4 neutrinos.
  - pp still not detected.
  - Precise comparison of neutrino & EM luminosity needed.
- Neutrino oscillations
  - Solar neutrinos consistent with MSW theory
  - Precise data on Vacuum-matter effect transition needed.
- CNO physics
  - Solar metallicity problem still unexplained
- A precision phase of Borexino is coming.
  - Stay tuned- it could address outstanding issues.

The End