Exploring Solar Neutrinos
Recent Results and Future Opportunities

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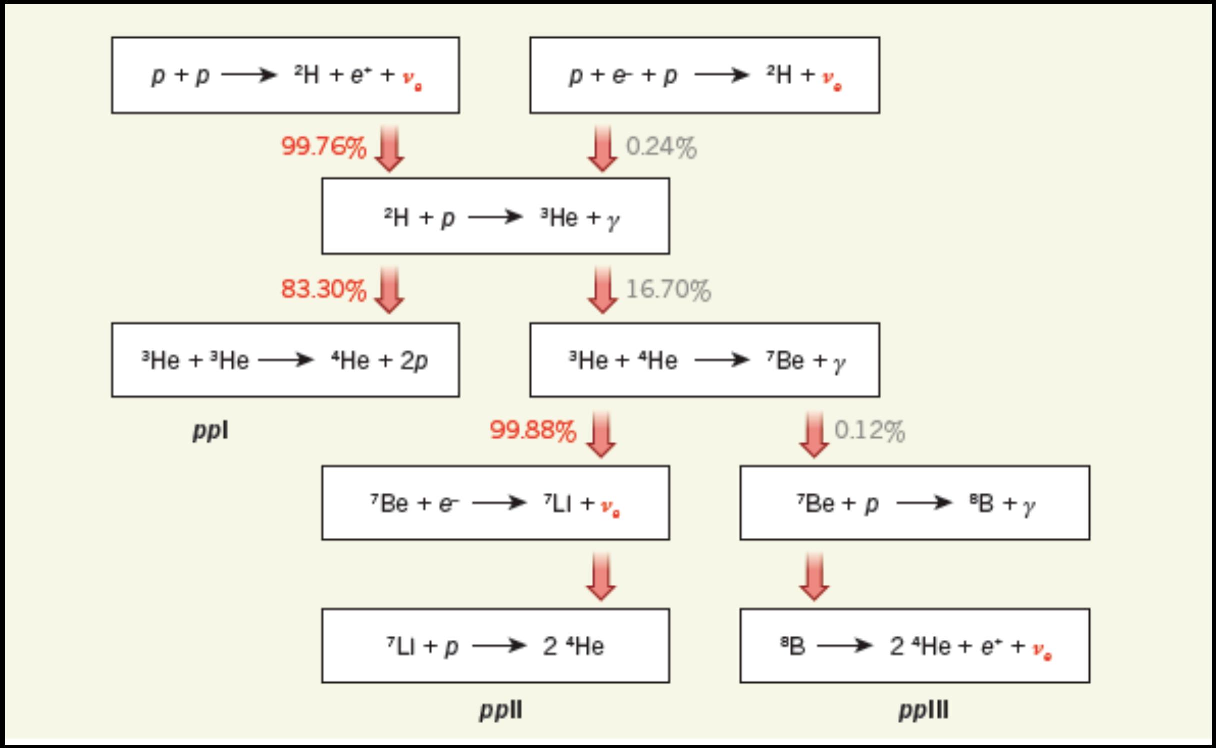
"Energy production in stars"

H. Bethe, Physical Review 55 434, March 1 1939 – 75 years ago.

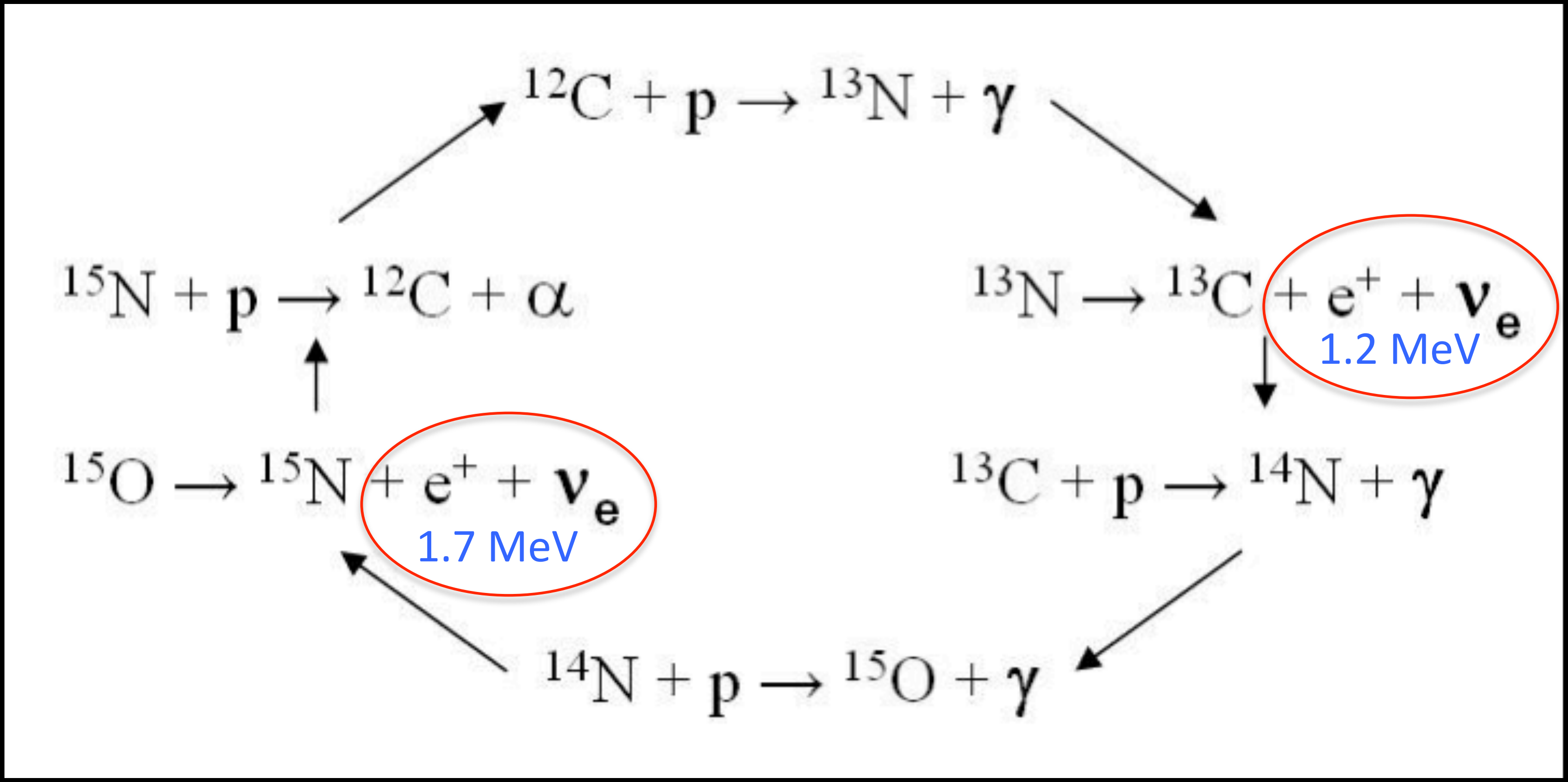


The pp chain

H. Bethe (1906-2005)

The CNO Cycle

Lights up most of the stars we see at night, but only 1% of Sun

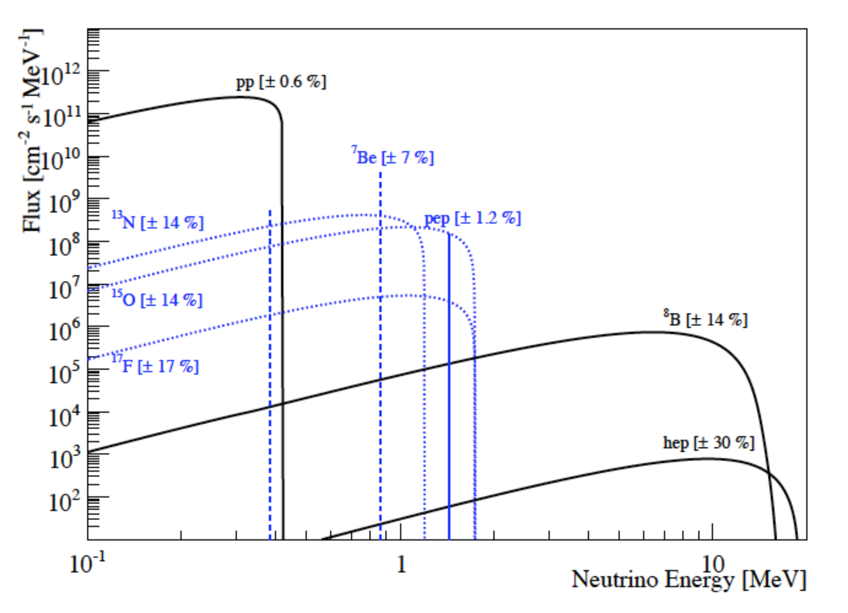


The CNO neutrino flux depends on ^{12}C abundance.

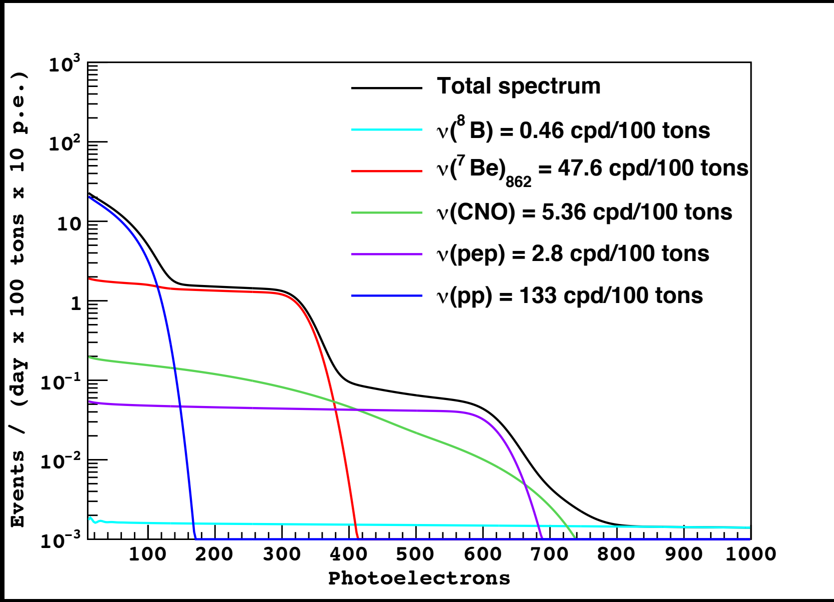
Rate depends on "metallicity", abundance of elements heavier than ^{4}He.

Solar Neutrino Spectra

Neutrino Energy Spectrum

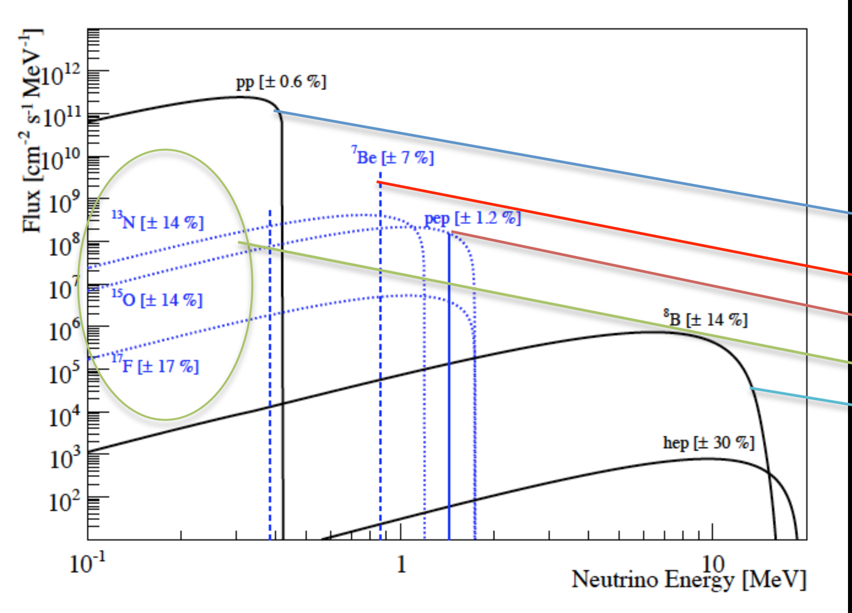


Neutrino-Electron Elastic Scattering Energy Spectrum

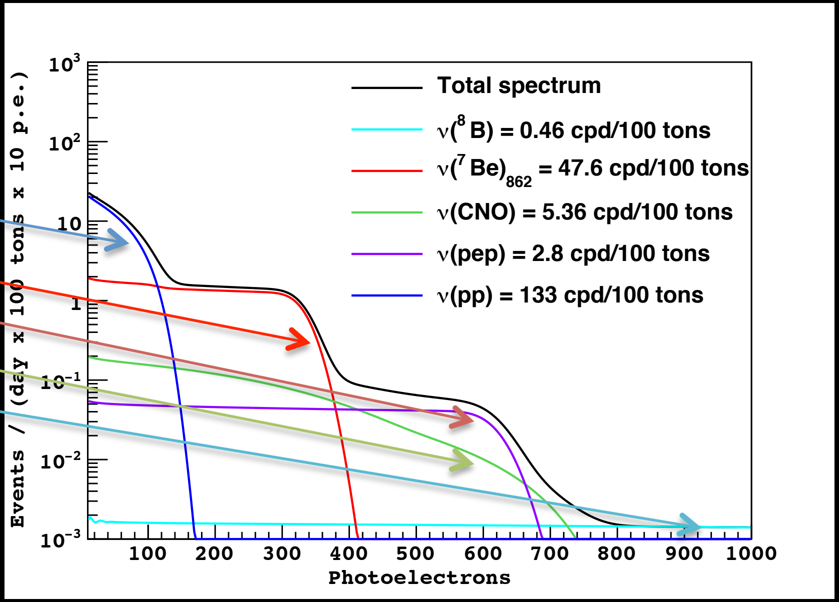


Solar Neutrino Spectra

Neutrino Energy Spectrum



Neutrino-Electron Elastic Scattering Energy Spectrum



X2 for keV

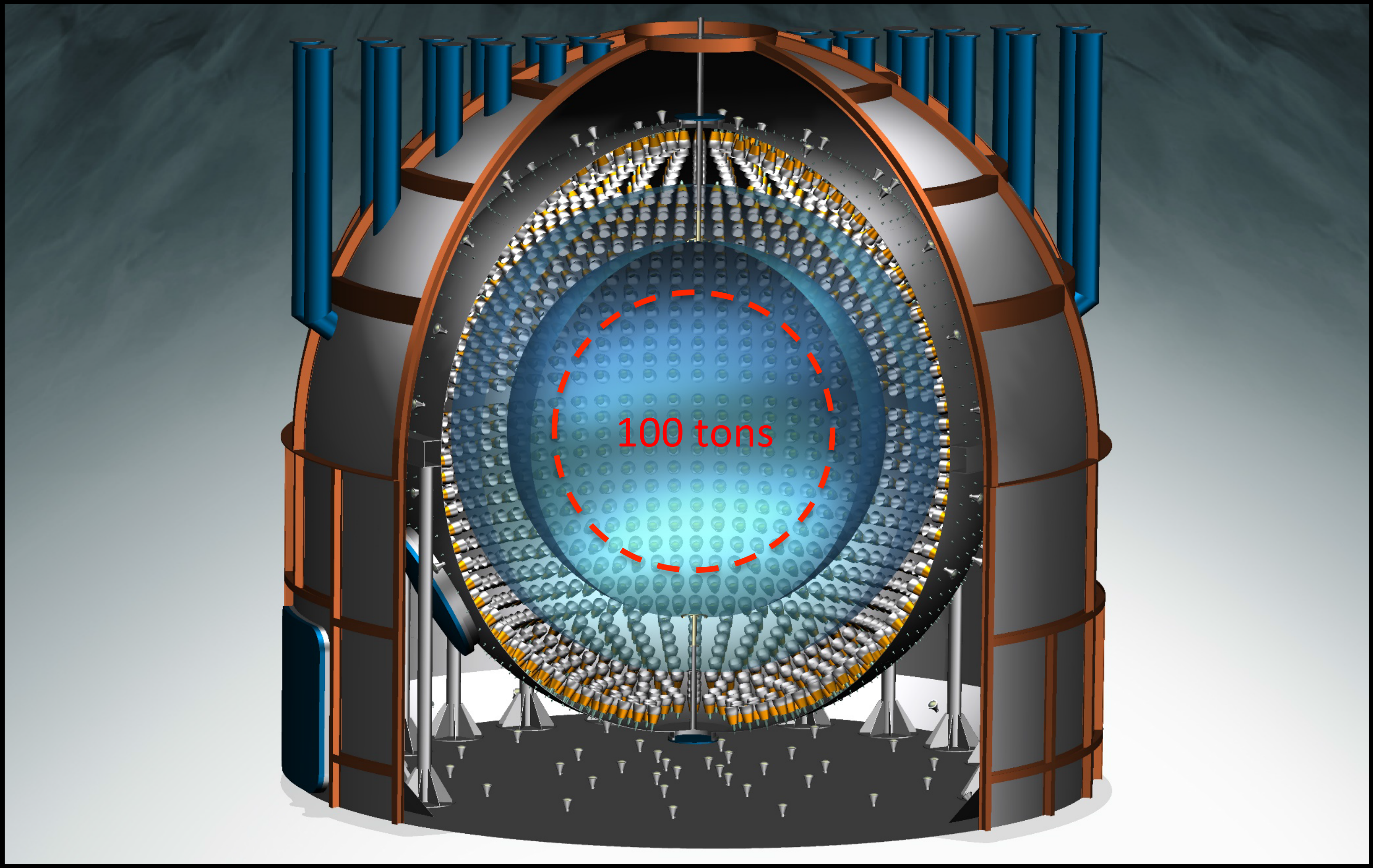
Detection of Solar Neutrinos

1. Radiogenic Detectors:
   - Chlorine $^{37}Cl(\nu_e, e-)^{37}Ar$: ^{7}Be, ^{8}B: ➔ Solar neutrino problem
   - GALLEX, SAGE $^{71}Ga(\nu_e, e^-)^{71}Ge$: pp, ^{7}Be, ^{8}B
2. Water Cherenkov Detectors
   - Kamiokande ^{8}B $(\nu+e^-)$ elastic scattering- directionality
   - Super-K ^{8}B $(\nu+e^-)$ elastic scattering - directionality
   - SNO charged + neutral currents ^{8}B➔ Neutrino Oscillations
3. Liquid Scintillator Detectors: $\nu+e^-$ elastic scattering
   - Borexino I (2007-2010) ^{7}Be, pep , ^{8}B ν's
   - Kamland (2013) ^{7}Be ν's
   - Borexino II (2014) pp ν's

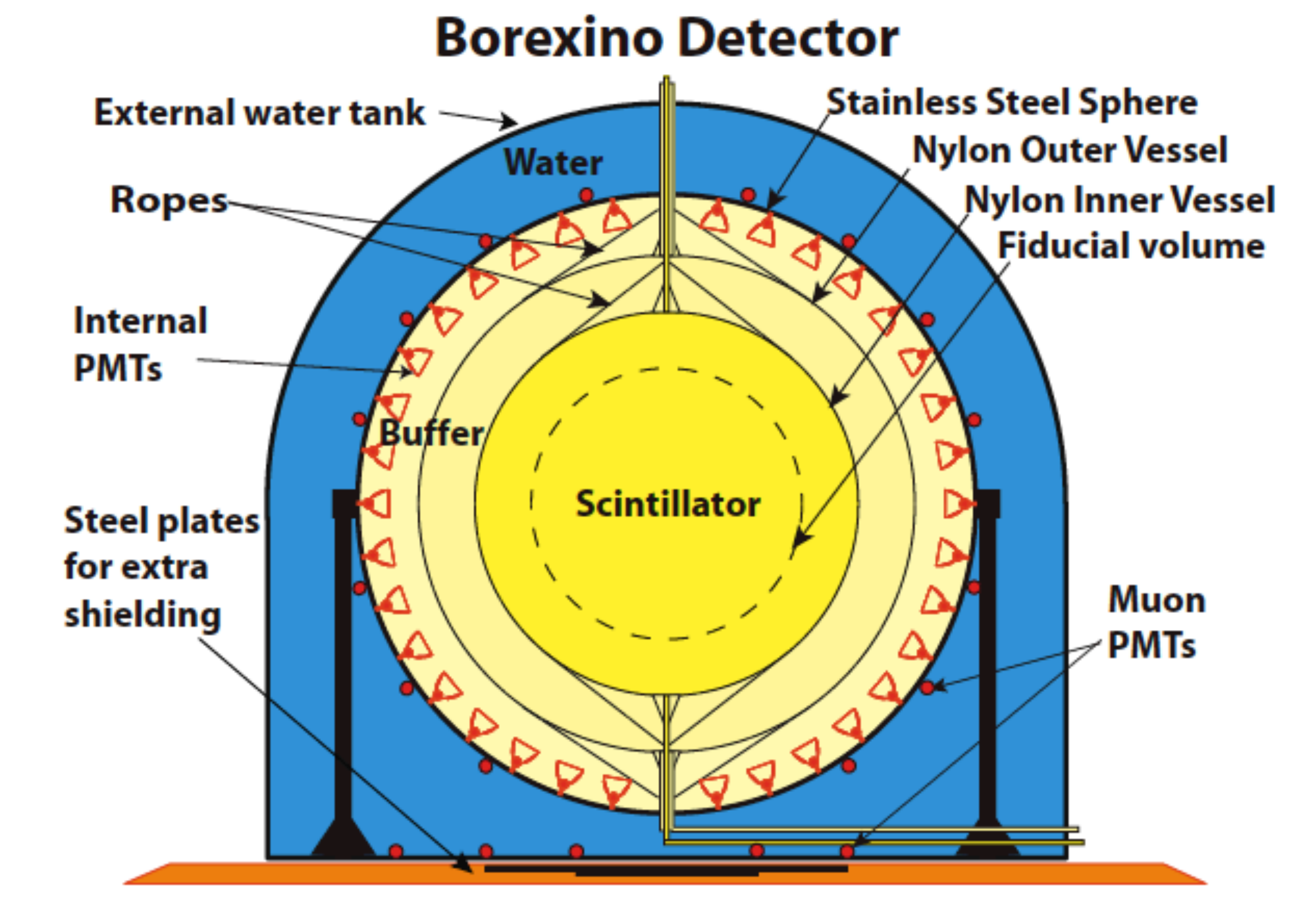
Liquid Scintillator Detectors

- Elastic scattering: $\nu + e^- \rightarrow \nu + e^-$
- Measure energy spectrum with $\Delta E/E \sim 5\%$ @ 1 MeV
- Position of event by photon time-of-flight:
- No directionality.
- Sensitive to α, β, γ and all other backgrounds.
  - α's (^{210}Po) separated by pulse shape discrimination PSD
- Background strategy:
  - Suppress background with active shielding.
  - Use energy spectrum to separate signal and background
  - PSD also useful for e+ background.

Borexino Liquid Scintillator Detector



To achieve low background, Borexino uses thick layers of active shielding, thin radiopure nylon vessels to contain scintillator, and purification methods to remove radioactivity from scintillator.



Shielding Against External Background.

Water:	2.25m
Buffer zones:	2.5 m
Outer scintillator zone:	1.25 m

Low-Background Strategy

- Water, Buffers(2) and Scintillator Self-Shielding
  - Designed to suppress external backgrounds
  - Scintillator and vessel radioactivity are left as the main background sources.
- Scintillator Containment Vessel
  - Nylon balloon with small mass and low radioactivity.
  - Built in low-radon cleanroom to avoid dust and ^{210}Pb (22 yr)
  - Expect ~ 1cpd ^{210}Pb due to radon exposure during construction.
- Purification of simple liquid scintillator
  - Pseudocumene (PC) & 1.5 g/l PPO
  - Distillation, water extraction, and N_2 gas stripping.
  - Precision cleaning methods employed.

Nylon Scintillator Containment Vessel

Fabricated in Low-Radon Cleanroom

John Bahcall

First hermetically sealed cleanroom with low-radon air.

Reduces radioactivity due to dust and ^{222}Rn daughters

★ ^{210}Pb (22 yr)

Nylon film developed for low background use.
Fabrication: > 1 yr

Performance of Nylon Vessels

✓Low rate of gamma rays from vessel.

✓Low rate of radioactivity from dirty particulates on surface.

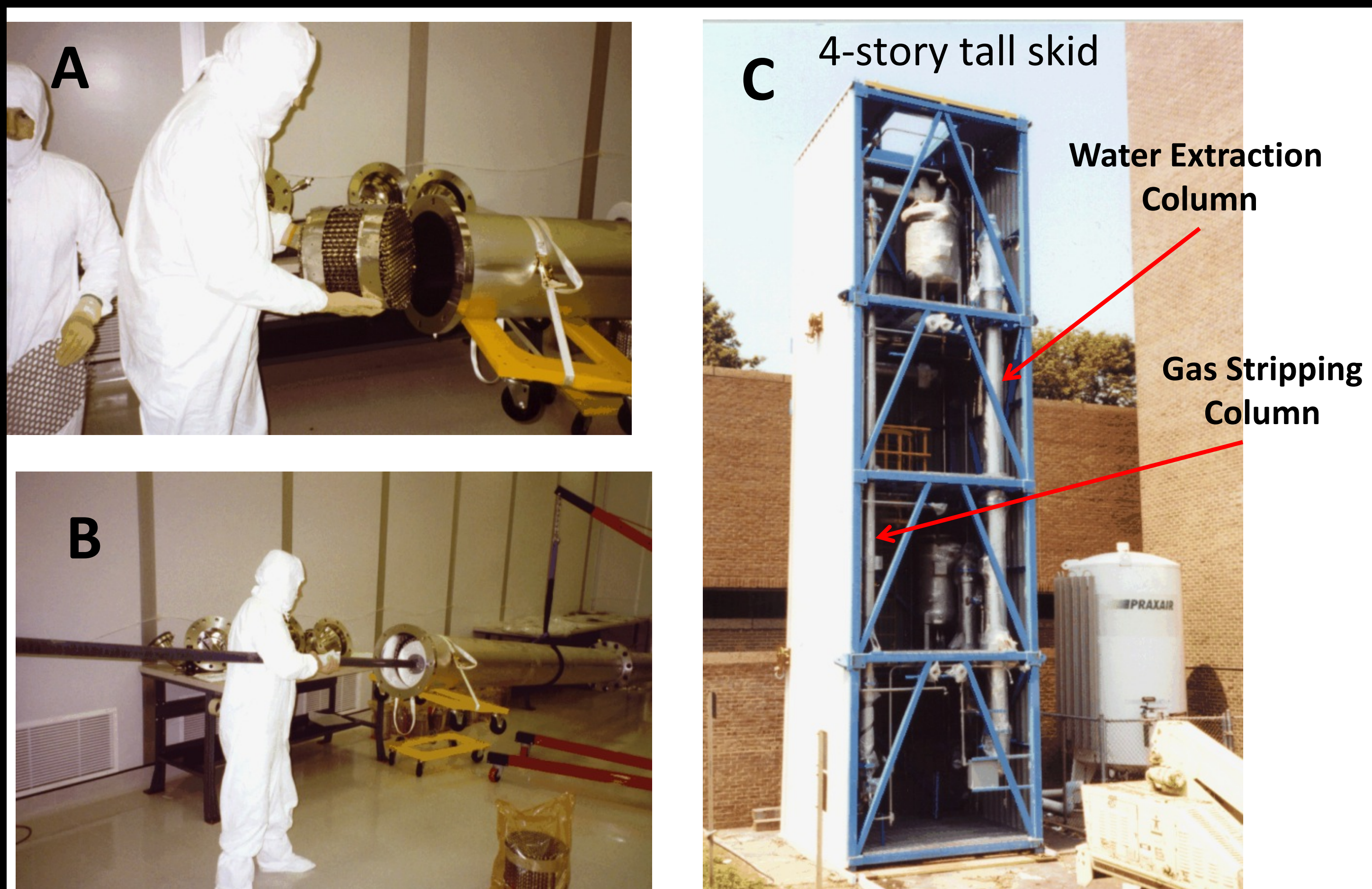
- Clean vessel wtih only ~ 10cpd of ^{214}Bi-^{214}Po near vessel

✕ High rate of ^{210}Pb on nylon surface.

- Much higher rate than expected from exposure to low-radon air during fabrication. We have 100's decays/day
- Water used for first filling is likely source.
    - Poor removal of radon daughers in ground water by standard water purification systems.

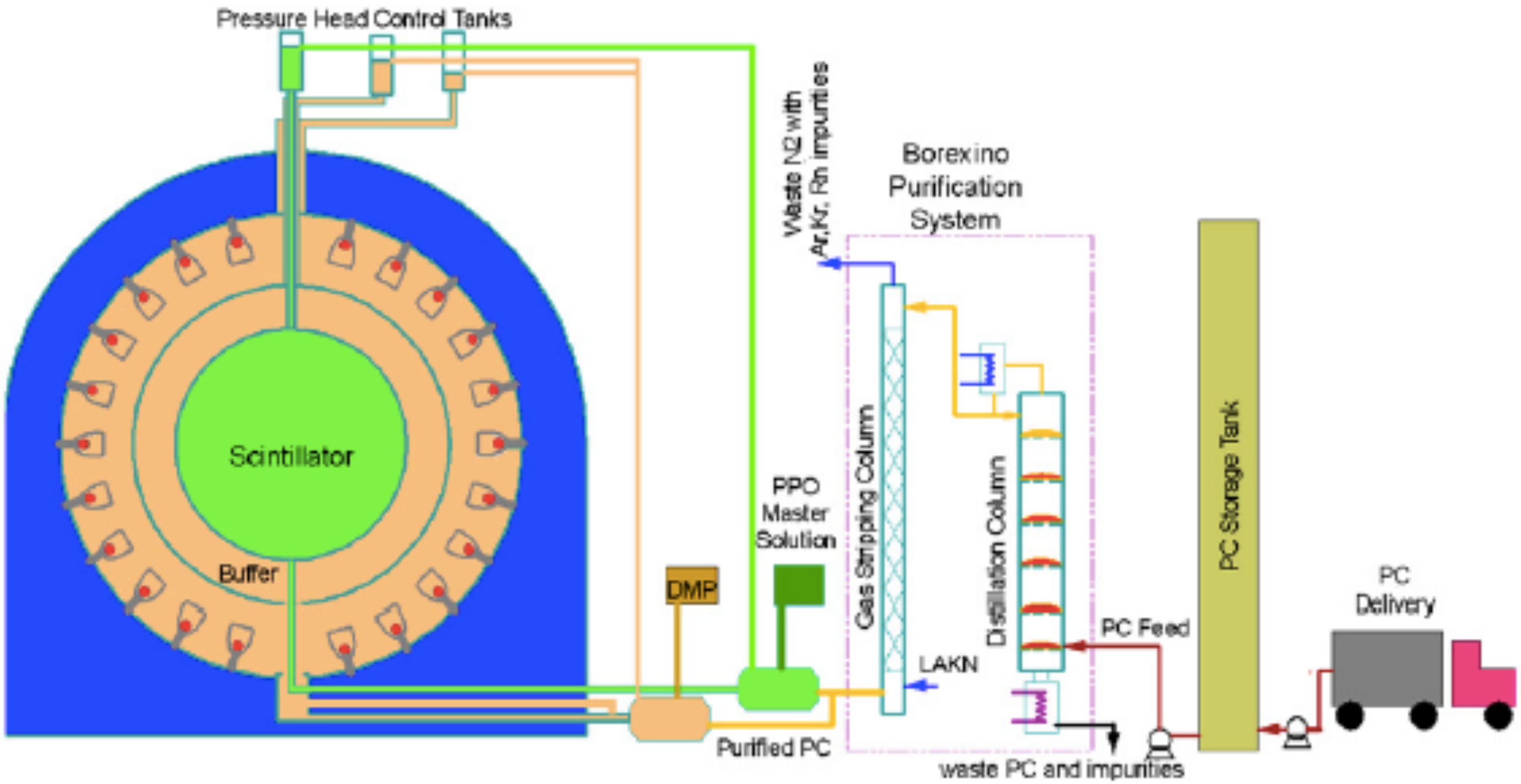
Scintillator Purification System

Distillation, N_2 Stripping, Water Extraction @ ~1 ton/hr
Precision Cleaned. Assembled in Low-radon Clean Room



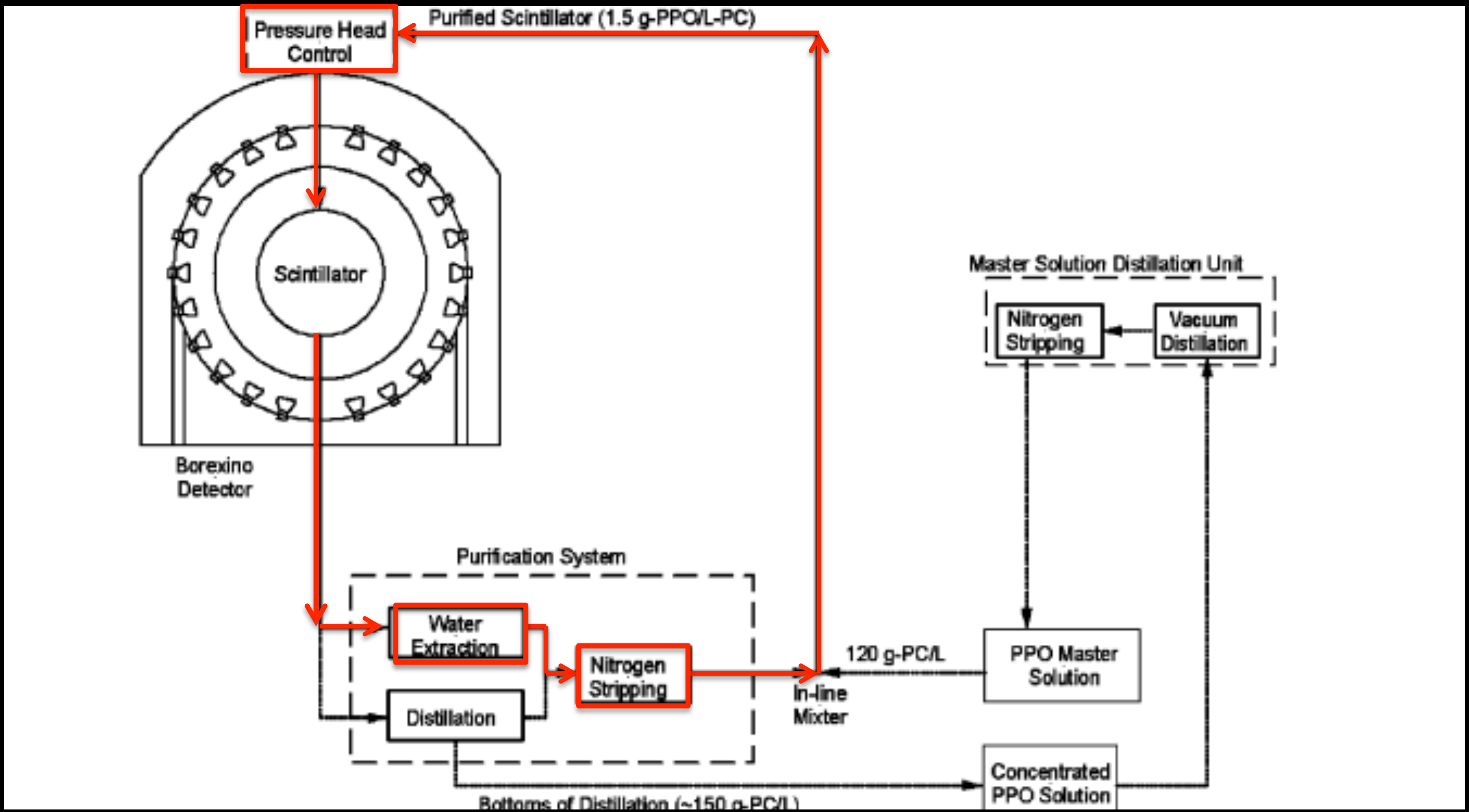
Pseudocumene Purification During Filling Operations.

J. Benziger et al. / Nuclear Instruments and Methods in Physics Research A 587 (2008) 277–291



Borexino Re-Purification Systems

Water Extraction or Distillation followed by N_2 Stripping



Performance of Scintillator Purification

- Distillation system
  - ✓ Achieved low radioactivity after first purification
    - ✓ Low level of ^{210}Pb ~ 15 cpd/100t
    - ✗ Poor for ^{210}Po: ~ 8000 cpd/100t (Why? It may be water.)
- N_2 stripping
  - ✓ Removed ^{85}Kr during scintillator re-purification.
- Water extraction (Re-purification)
  - ✓ Reduced ^{238}U and ^{232}Th upper chain.
  - ✓ Moderate reduction of ^{210}Pb
  - ✕ Poor removal of ^{210}Po (again ^{210}Po in water)

Borexino Phases I & 2

Phase I   2007 - 2010

Scintillator purified while filling.

Measured ^{7}Be, pep, ^{8}B neutrinos

Phase II   2010 - 2014

Background Reduced by Scintillator Re-purification

Measurement of pp neutrinos

Phase I Energy Spectra

^{7}Be-result: PRL 107 141302 (2011)

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

Prominent backgrounds:

^{210}Po ^{210}Bi ^{85}Kr, ^{11}C & ^{14}C (not shown)

CNO obscured mainly by ^{210}Bi.

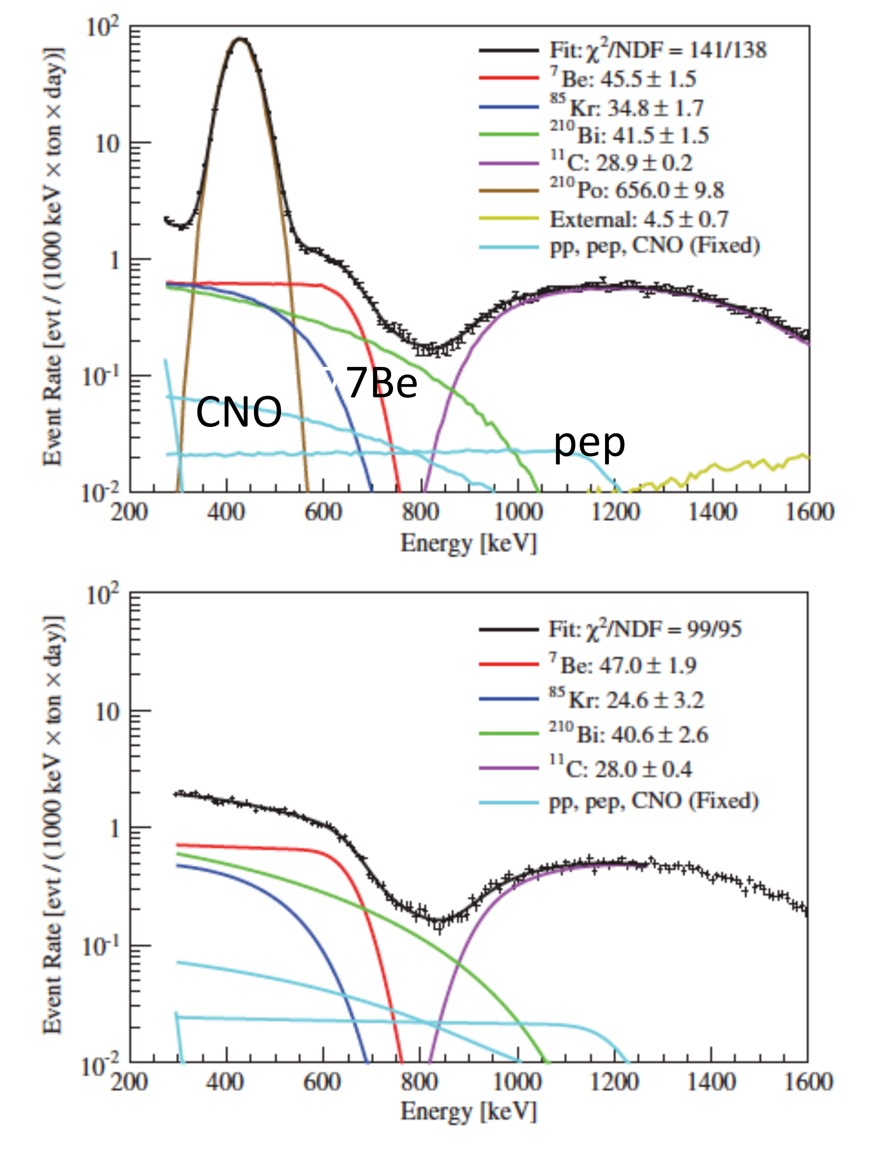
The pep was measured by applying cuts to reduce the ^{11}C. (muon track, neutron, other)

^{210}Po α-rate very high ~8000 cpd/100t

Rejected by α/β pulse shape discrimination.

Curiously, ^{210}Pb was very low, ~10 cpd/100t.

Break in secular equilibrium in A= 210?



Phase I spectrum with backgrounds

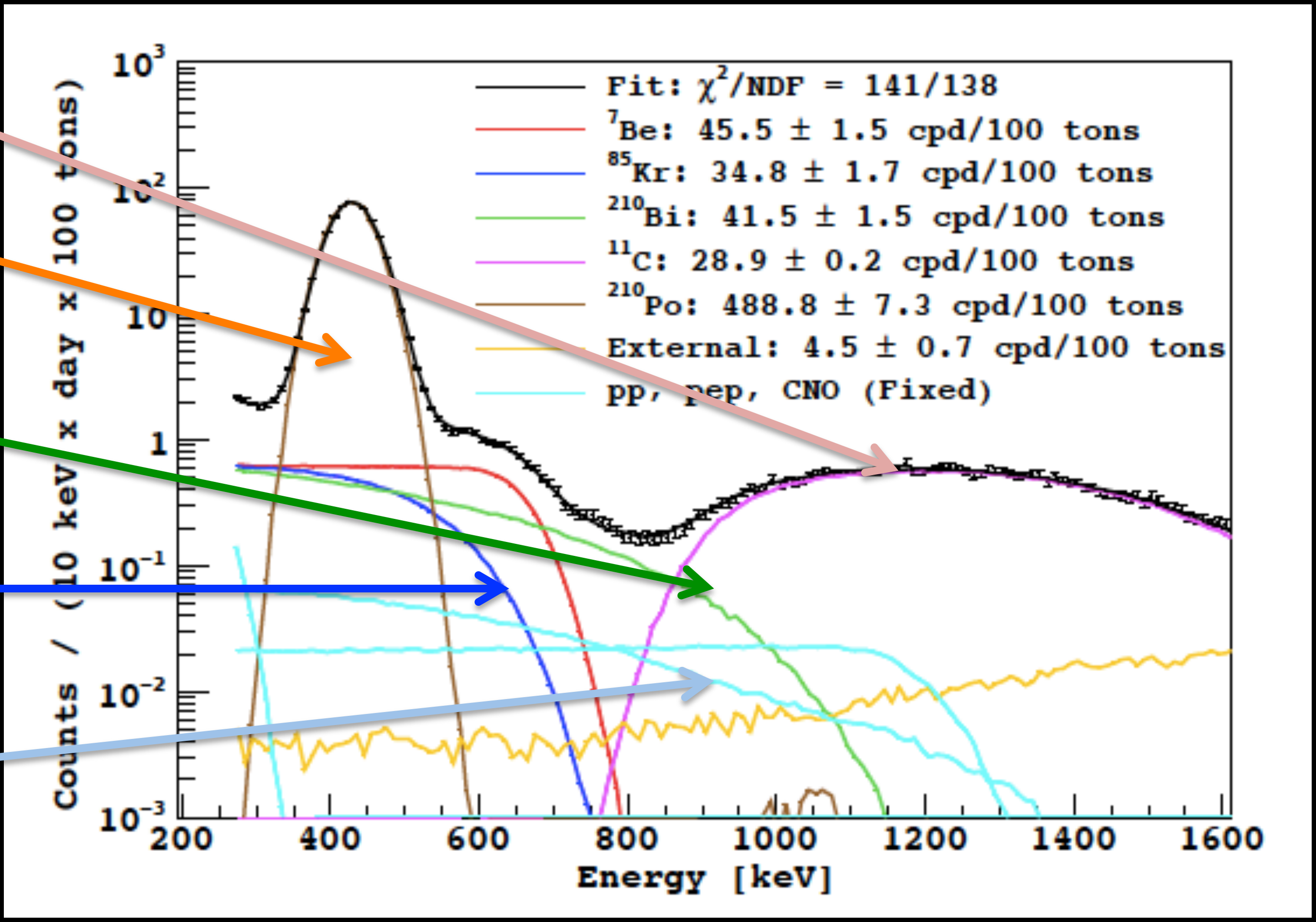
^{11}C

^{210}Po

^{210}Bi

^{85}Kr

CNO

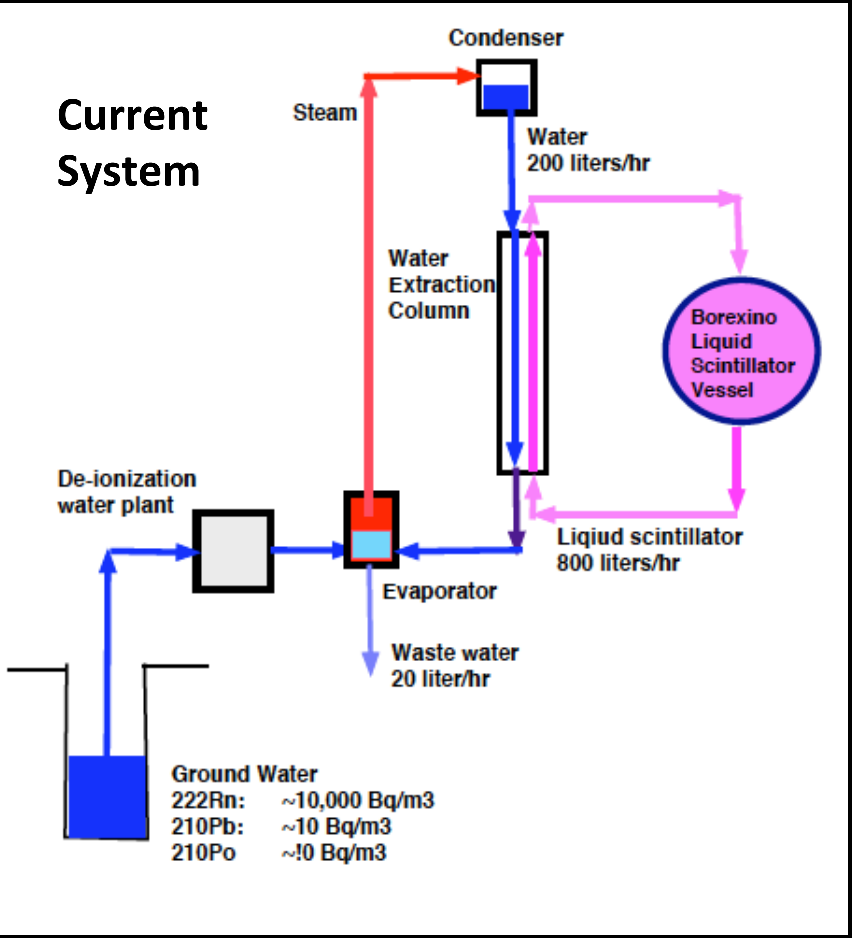


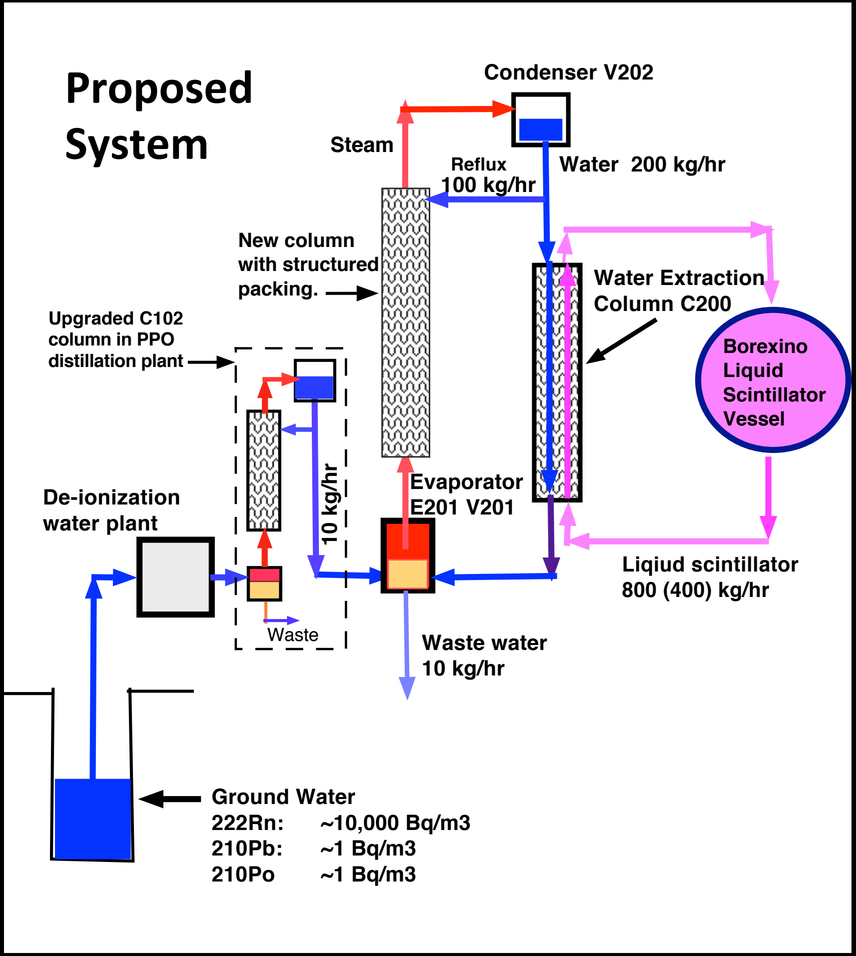
Phase II

- Scintillator Re-purification 2010-2011
  - Water extraction
  - N_2 stripping
- Data acquistion 2011-2014.
- Analysis of data for pp- neutrinos

Borexino Water Extraction Systems

Current & upgraded systems with 2 new fractional distillation columns



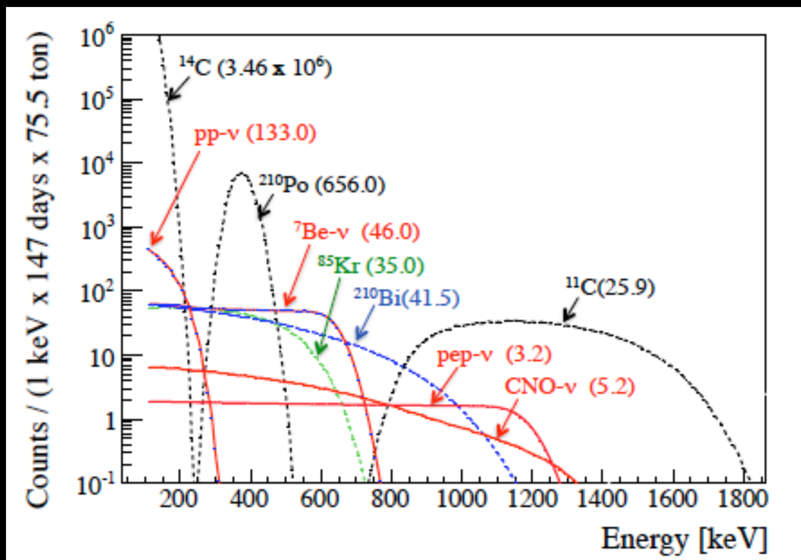


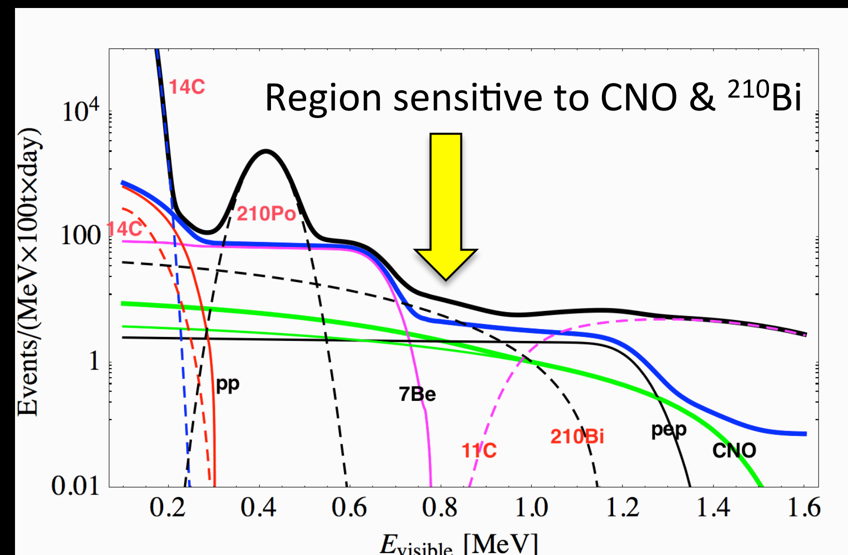
Results of Re-purification by Water Extraction

- ^{85}Kr: 30 cpd/100t → < 5 cpd/100t
- ^{238}U (^{226}Ra): [(530 ± 50) → < 8 x 10^{-20} gU/g
  ^{214}Bi-^{214}Po Reduction factor > 77 (< 0.8 count/100t/yr).
- ^{232}Th: [(3.8 ± 0.8 → < 1.0] x 10^{-18} gTh/g
  ^{212}Bi-^{212}Po Reduction factor > 3. (< 0.8 count./100t/yr)
- ^{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.

Backgrounds before & after Water Extraction + N_2 Stripping

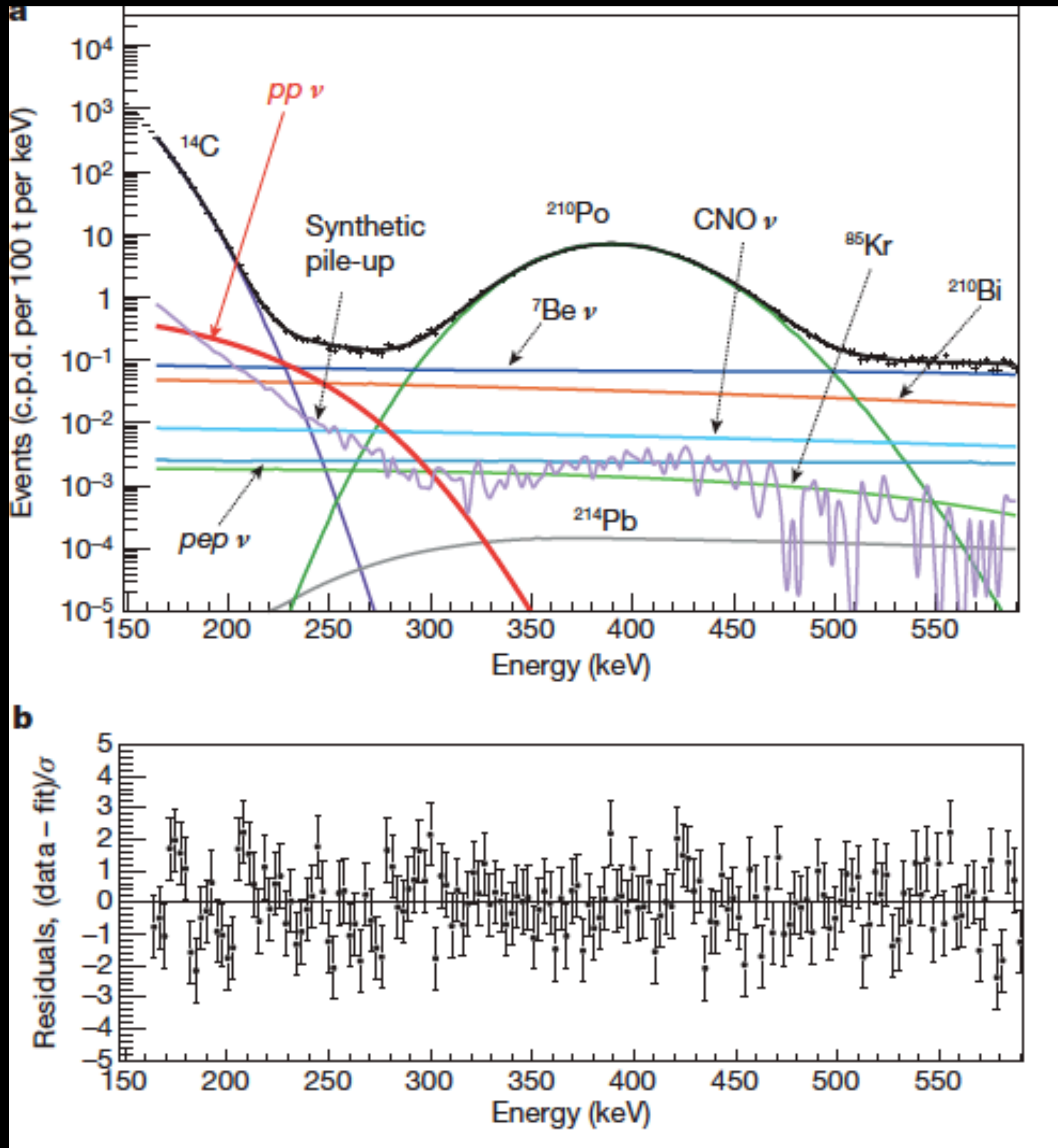




Before re-purification 2008-2010
Rates in parentheses are in cpd/100t.
Without ^{11}C cuts. See arXiv1308.0443v1.

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

pp-neutrino spectral fit & Residuals 165-590 keV



Spectral fit for pp neutrinos and backgrounds.

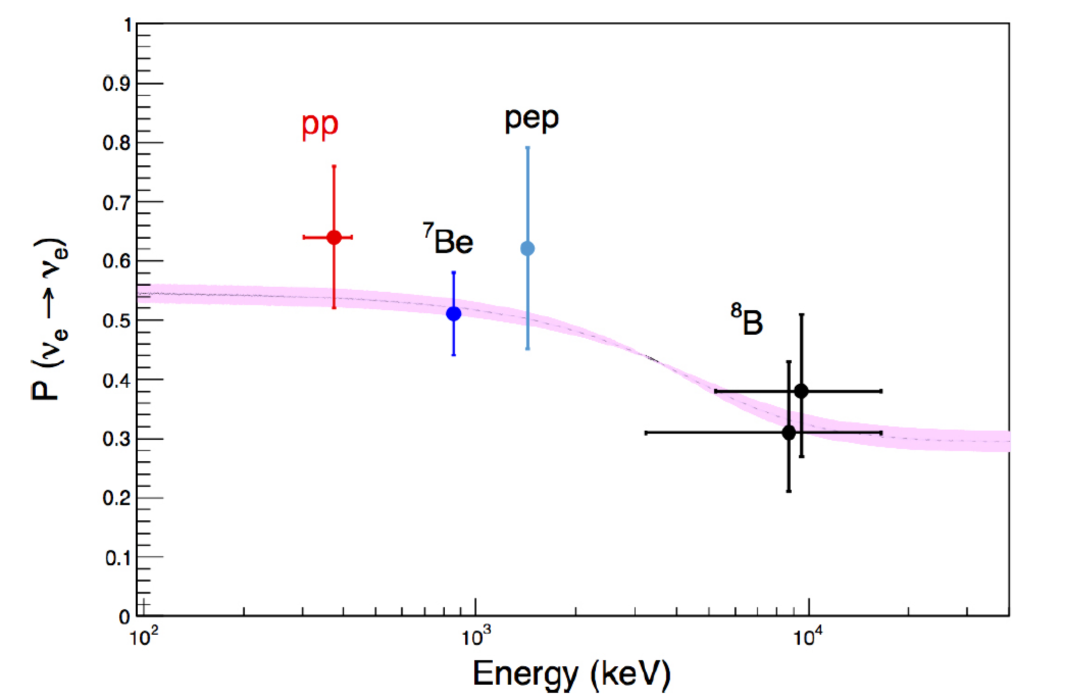
Table 1 | Results from the fit to the energy spectrum

Parameter	Rate ± statistical error (c.p.d. per 100 t)	Systematic error (c.p.d. per 100 t)
pp neutrino	144 ± 13	±10
^{85}Kr	1 ± 9	±3
^{210}Bi	27 ± 8	±3
^{210}Po	583 ± 2	±12

The best-fit value and statistical uncertainty for each component are listed together with its systematic error. The χ^2 per degree of freedom of the fit is χ^2/d.o.f. = 172.3/147.

Borexino Measurements

✓ ^{7}Be	46.0	cpd/100t	± 5%.	PRL	2011
✓ ^{8}B (> 3 MeV)	0.22	cpd/100t	± 19%	PRD	2010
✓ pep	3.1	cpd/100t	± 22%	PRL	2012
✓ CNO limit:	< 7.9	cpd/100t		PRL	2012
✓ pp	144	cpd/100t	± 16%	Nature	2014



Borexino I & II Results

- First spectroscopic measurement of the pp-neutrinos from the keystone p-p fusion reaction.
- Measurements of four pp-chain neutrinos prove that the Sun derives its power from the pp-chain
  - Neutrino luminosity agrees with photon luminosity within uncertainty.
- Rates agree with the Standard Solar Model and neutrino oscillations described by MSW theory.
  - Survival probability shows transition from vacuum to matter-effect neutrino oscillations.

Future goals for Borexino III

1. CNO measurement.
   – Rate differs 30% between high and low metallicity
2. Improve accuracy for pp, ^{7}Be, pep, ^{8}B
   – Probe for non-standard interactions
   – Refine MSW transition, vacuum to matter oscillation.
   – Neutrino luminosity check.
3. Requirements:
   – Solve mystery of A=210 backgrounds (✓?)
   – Lower ^{210}Bi background with temperature control and re-purification.

Summary

- Borexino developed a low background liquid scintillator detector that made possible direct spectroscopic measurements of solar neutrinos.
- Phase I produced the ^{7}Be, pep, and ^{8}B data after initial filling of the detector.
- Phase II produced the pp-neutrino data after background reduction by scintillator re-purificiation.
- Phase III started in 2015 with continuing efforts toward even lower backgrounds that could allow a measurement of CNO neutrinos.
- Results from Phase III could yield the best data and provide a better understanding of neutrino physics and the Sun.

Borexino Collaboration

• Astroparticle and Cosmology Laboratory	Paris, France
• Gran Sasso Science Insitute	L'Aquila, Italy
• INFN Laboratori Nazionali del Gran Sasso	Assergi, Italy
• INFN e Dipartimento di Fisica dell'Universita Genoa	Genoa, Italy
• INFN e Dipartimento di Fisica dell'Universita Milano	Milano, Italy
• INFN e Dipartimento di Chimica dell'Universita Perugia	Perugia, Italy
• Insitute for Nuclear Research	Gachina, Russia
• Institut fur Experimnetalphysik, Universitat Hamburg	Haamburg, Germany
• Institute of Physics, Jagellonian University	Cracow, Poland
• Joint Institute for Nuclear Research	Dubna, Russia
• Kuchatov Institute	Moscow, Russia
• Max-Planck Institute fuer Kernphysik	Heidelberg, Germany
• Princeton University	Princeton NJ, USA
• Technische Universitat	Muenchen, Germany
• University of Massachusettes at Amherst	Amherst MA, USA
• University of Moscow	Moscow, Russia
• Virginia Polytechnic Institute and State University	Blacksburg VA, USA

91 Participants, 17 Insitutions, 6 Countries

The End

Radioactivity in purified water-

A plausible explanation of our background problems

1. Ground water at LNGS has high level of ^{222}Rn and its progeny, ^{210}Pb and ^{210}Po.
2. Standard water purification systems based on reverse osmosis and ion exchange were found to remove ^{210}Pb and ^{210}Po with low efficiencies.
3. Distillation removes ^{210}Pb, but not ^{210}Po.
   - ^{210}Po in ground water is processed biologically by micro-organism into volatile dimethyl polonium.
   - With estimated boiling point of 138 C, the ^{210}Po is difficult to remove from water by simple distillation.

^{210}Pb and ^{210}Po Mysteries Explained?

1. Borexino was first filled with water irctly from the water purification system without distillation.
   - This water was contaminated with ^{210}Pb and ^{210}Po and would have contaminated the nylon vessel with ^{210}Pb, as observed.
2. The PPO was purified by water extraction and distillation before it was mixed with PC to make the scintillator.
   - The water would have introduced both ^{210}Po and ^{210}Pb, and distillation would have removed the ^{210}Pb.
   - The two operations would leave the scintillator with a high level of ^{210}Po, and low level of ^{210}Pb, as observed.
3. The failure of water extraction to reduce ^{210}Po in scintillator could have been due to ^{210}Po in the water.