Backgrounds in Borexino

A Long Quest for Solar Neutrinos with Low Background

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Measurements of Solar Neutrinos

A 50-year quest to suppress background for detecting rare neutrino signals

1. Radiogenic Detectors:

- Chlorine $^{37}Cl(\nu_e, e\text{-})^{37}Ar$: ^{7}Be, ^{8}B: → *Solar neutrino detected*
- GALLEX, SAGE $^{71}Ga(\nu_e, e^-)^{71}Ge$: pp, ^{7}Be, ^{8}B → *Too few pp neutrinos*
- *Neutrino produces radioactive atoms which counted off-line. This avoids many backgrounds.*

2. Large Water Cherenkov Detectors

- Kamiokande → *Solar neutrinos detected*, Super-K ^{8}B ν-e^- elastic scattering: →*Atm. Neut. Osc.*
- SNO charged+neutral currents with ^{8}B neutrinos: → *Solar Neutrino Oscillations*
- *^{8}B neutrinos with $E_\nu > 5$ MeV with directionality avoids many backgrounds except for neutrons.*

3. Liquid Scintillator Detectors:

- Borexino (2007-2017): *pp, pep , ^{7}Be, ^{8}B neutrinos detected.*
- Kamland (2013) ^{7}Be *neutrinos detected.*
- *With low threshold energy and no directionality, unprecedented, ultra-low background is needed*

Outline

- Talks of Gianpaolo Bellini, Barbara Caccianiga, and Davide Franco covered many features of the Borexino detector and data with emphasis on solar neutrino results.
- In my talk I will present a brief summary of some of the low-background methods that helped to made these results possible.

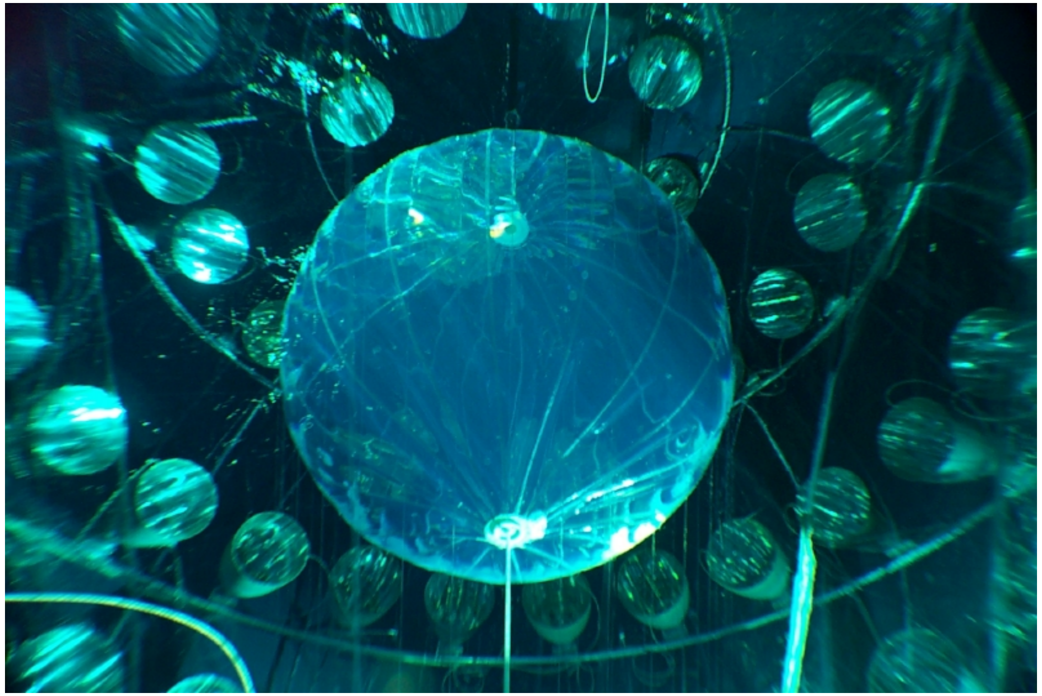
Detection of Solar Neutrinos in Borexino

A 27-year Quest for Low-Background

- **The Counting Test Facility Phase: 1992- 1996.**
  - Low background nylon vessel developed. ✓
    - Designed to operate directly in water for shielding. ✓
  - Scintillator purification methods developed. ✓
    - Distillation, water extraction, nitrogen stripping ✓
  - Key achievements. ✓
    - Low ^{14}C scintillator from petroleum products ✓
    - U, Th at $\sim 10^{-16}$ g/g. ✓
- **Borexino Phase 1: 1998-2010.**
  - Borexino design & construction 1998-2002 ✓
  - Legal problems due to spill: 2002-2004 ✓
  - Phase 1 Data 2007-2010 ✓
    - First measurement of ^{7}Be neutrinos. ✓
  - Inner Vessel Leak: a 2-year technical setback 2008✓
- **Borexino Phase 2: 2010-2016.**
  - Background reduced by scint. purification: 2010-11 ✓
    - [U], [Th]: 10^{-18} g/g → 10^{-19} g/g ✓
    - ^{85}Kr, ^{210}Bi reduced. ✓
  - Phase 2 Solar Neutrino Data: 2011-2016 ✓
    - First direct measurement of pp neutrinos. 2014 ✓
    - Full Bethe pp-chain measured: pp, pep, ^{7}Be, ^{8}B 2017. ✓
- **Borexino Phase 3: 2014 - 2017:**
  - Temperature stabilization with thermal insulation and active temperature control. ✓
  - Upgrade of water extraction system to improve removal of ^{210}Pb and ^{210}Po. ✓
  - CNO neutrino data with stable temperature.
  - CNO neutrino data with stable temperature and lower background.

The CTF Phase 1992-96

- A 4-ton scintillator detector with water shielding.
- Developed thick nylon vessel technology for containment of scintillator.
- Developed scintillator handling systems and on-line scintillator purification system.
- Made first measurement of ^{14}C in petroleum product: $^{14}C/^{12}C \sim 10^{-18}$ g/g.
  - Previous limit of F. Boehm: $< 10^{-13}$ g/g.
- Discovered radon background in water shield and cosmic-muon background.
- Employed 3D position reconstruction.
- Measured U and Th at level 10^{-16} g/g, which justified funding full-scale Borexino.
- Developed analysis software to understand internal scintillator background.
- Produced marriages among some young collaborators.



The CTF vessel, filled with scintillator, held down in water with strings, surrounded by an array of ~ 100 PMTs, in a large water tank, In Hall C, of LNGS, Italy

Borexino Phase 1: 1998-2010

Low-Background Strategy for Scintillator Based on CTF

- 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.
    - Observe 100's cpd probably due to water filling

- Purification of simple liquid scintillator
  - Pseudocumene (PC) & 1.5 g/l PPO
  - Distillation, water extraction, and N_2 gas stripping.
  - "Precision cleaning" methods developed and employed
    - Class-30 MIL-STD-1246C specification achieved for particulates in fluid handling system.

Nylon Scintillator Containment Vessel

Fabricated in special Princeton Low-Radon Cleanroom

First hermetically sealed cleanroom with low-radon air was developed to avoid surface radioactivity due to ^{222}Rn daughters:
➔ ^{210}Pb (22 yr).

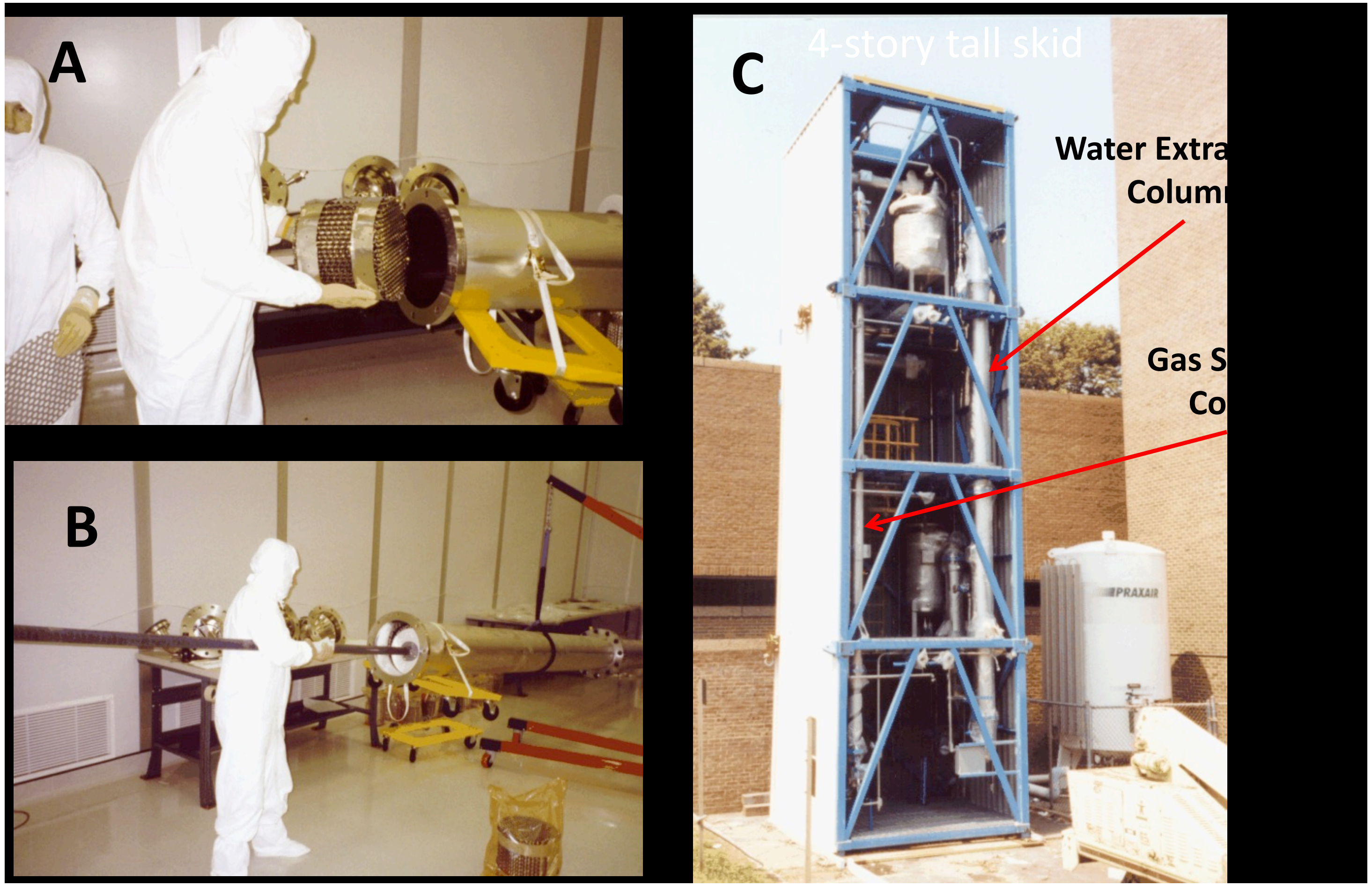
Fabrication time: > 1 yr
Low-radon cleanrooms are now more common in low-background research.

John Bahcall

Scintillator Purification System

Distillation, N_2 Stripping, Water Extraction @ ~1 ton/hr

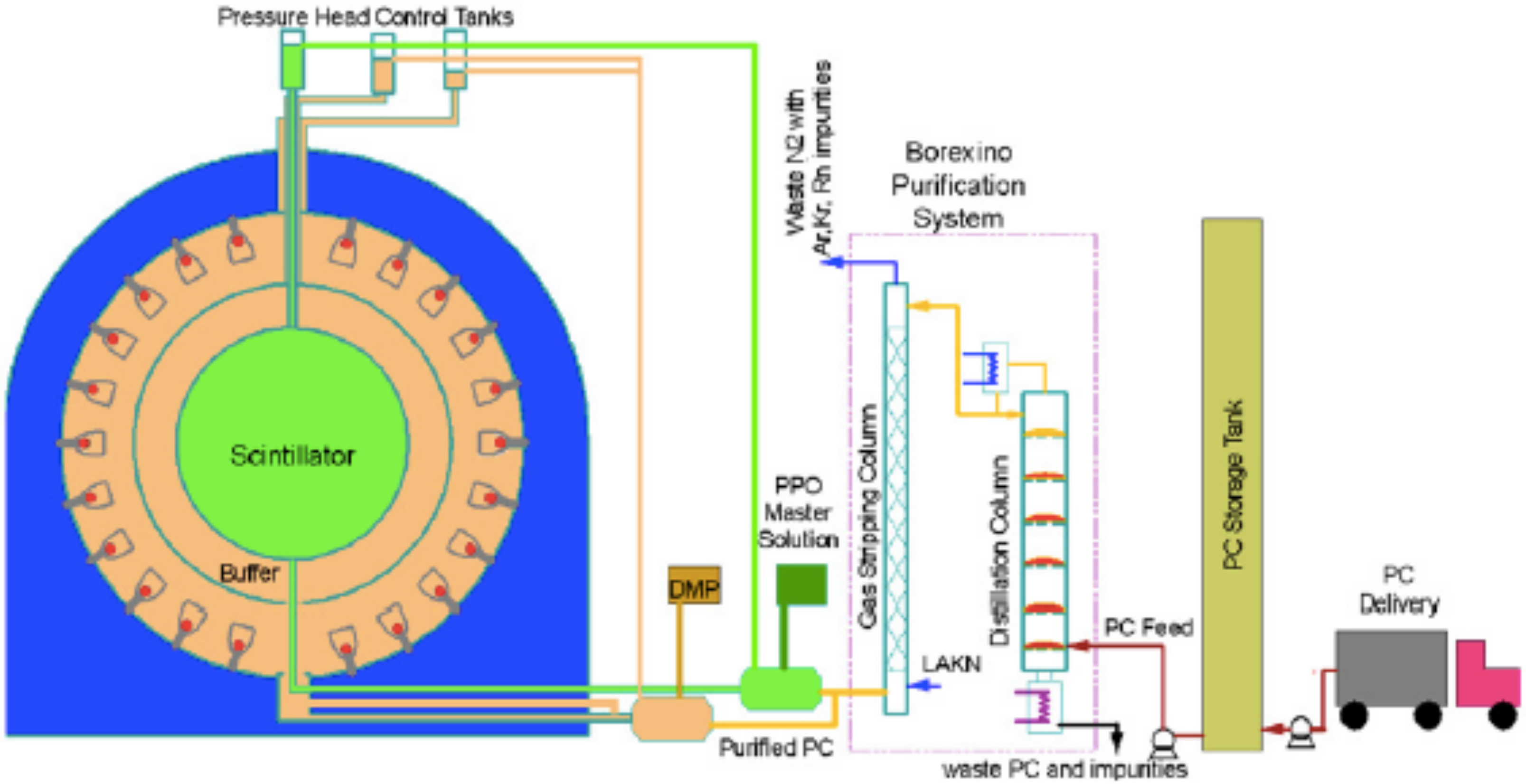
Precision Cleaned. Assembled in Princeton Low-radon Clean Room



Scintillator Purification and Filling

Distillation, Water Extraction and N_2 Stripping

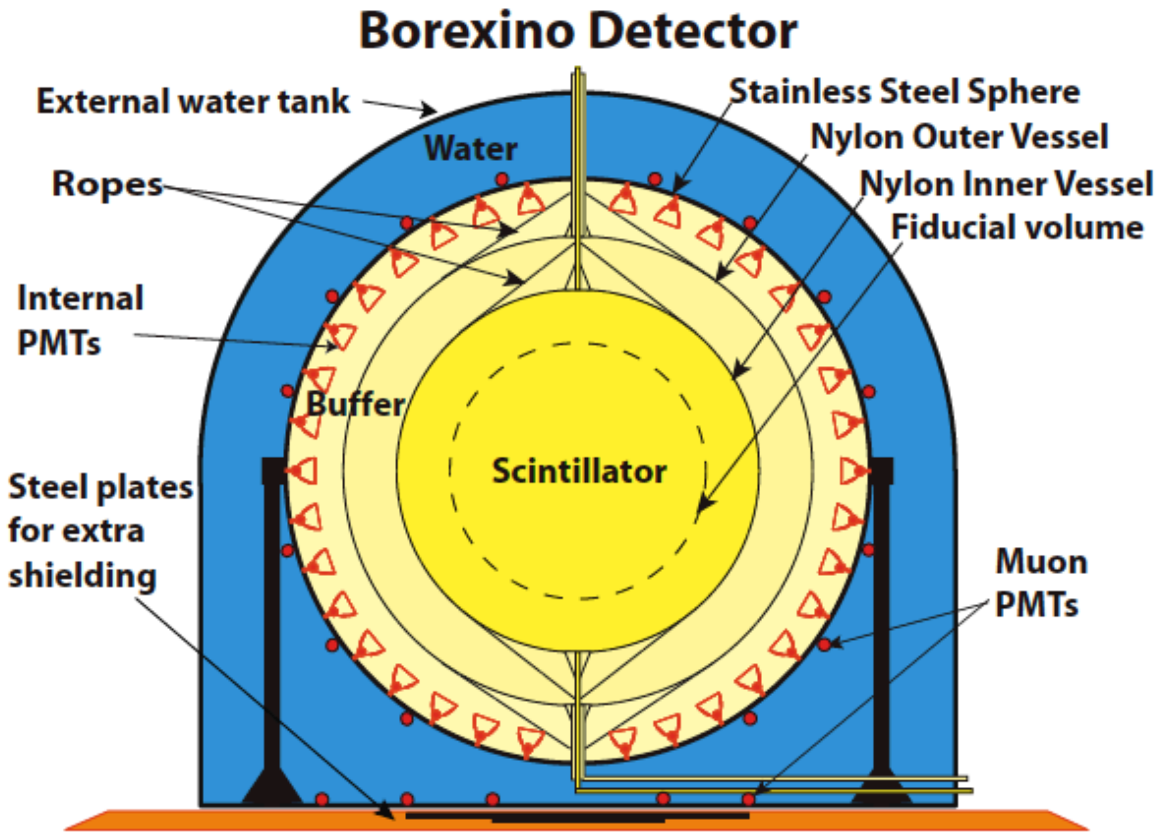
J. Benziger et al. / Nuclear Instruments and Methods in Physics Research A 587 (2008) 277–291



Borexino Detector

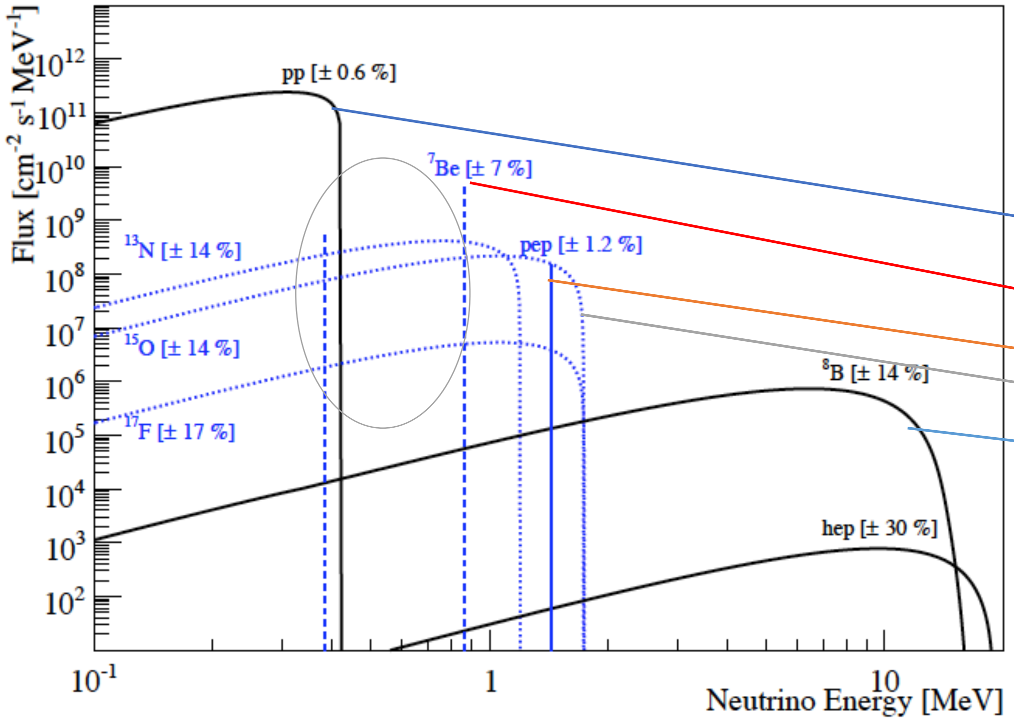
(All zones are active detectors with PMT read-out)

- **Shielding Against External Background**
  - Water: 2.25m
  - Buffer zones: 2.50 m
  - Outer scintillator zone: 1.25 m
- **Self-shielding within Liquid Scintillator**
  - Inner vessel scintillator: 300 ton
  - Fiducial volume: 100 ton
  - Scintillator shielding: 200 ton
- **Thin radio-pure nylon vessels**
  - Film extruded from special radio-pure pellets.
  - Vessels fabricated in first low-radon cleanroom.
  - Outer vessel to suppress radon from PMTs and SSS.
  - Small γ–background from nylon vessel
- **Stainless Steel Sphere:**
  - Supports PMT array with individual feedthroughs
  - Separates water and scintillator and resists buoyant force with several legs welded to pads on base of water tank.
- **Scintillator radio-purity:**
  - On-line precision cleaned purification systems produce ultra-low levels of U, Th, K in scintillator.

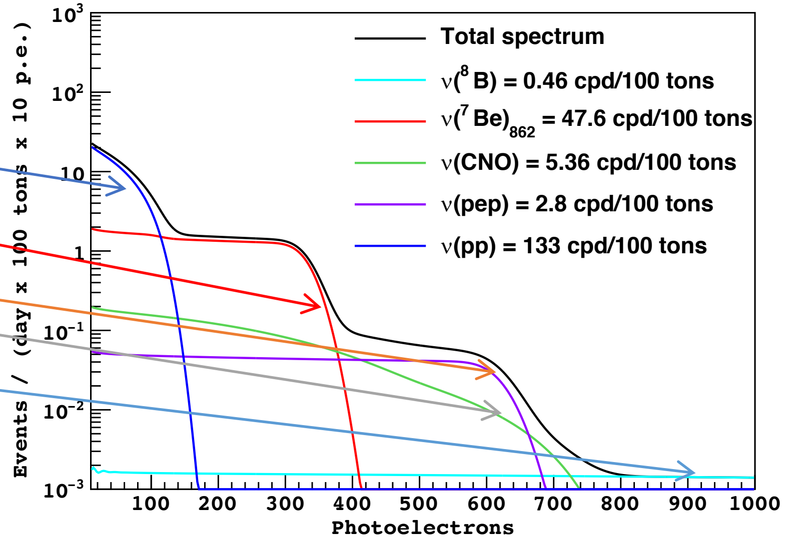


Solar Neutrino Spectra

Neutrino Energy Spectrum



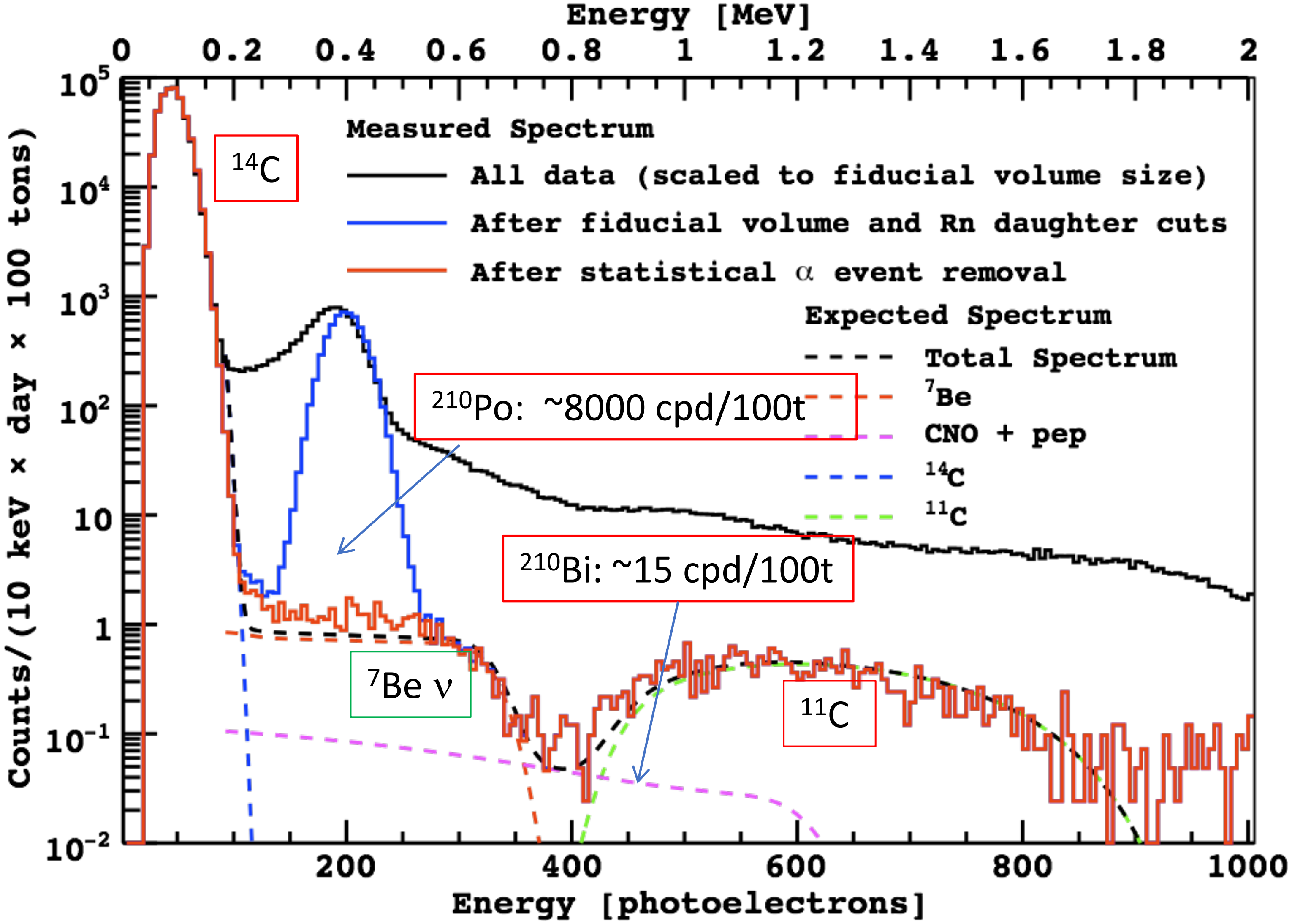
Neutrino-Electron Elastic Scattering Energy Spectrum



X2 for keV

Phase 1 Spectrum after 6 weeks of Data-2007

Clear ^{7}Be ν signal, but mysterious rates for ^{210}Pb(22y)-^{210}Bi(5d)-^{210}Po(138d)

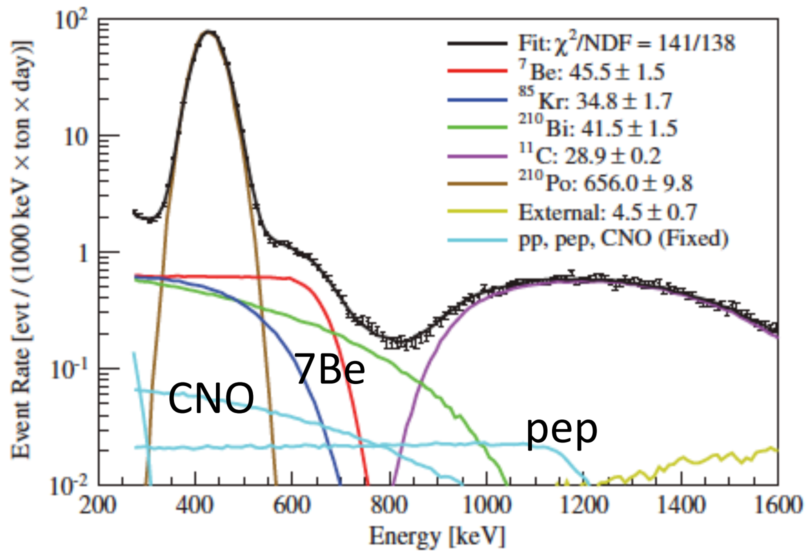


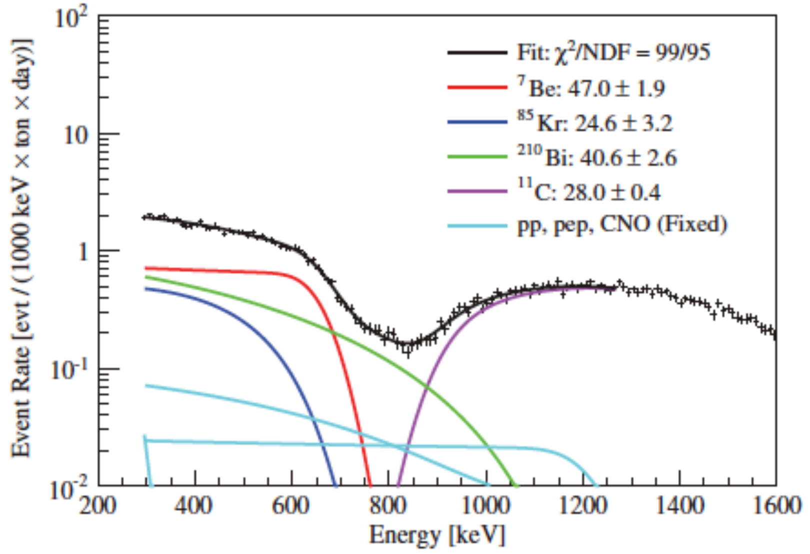
Phase I Energy Spectra

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

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

- **Clear ^{7}Be signal**
  - Box-like spectrum shape easily fit for measurement of ^{7}Be solar neutrinos with accuracy of 5%.
- **Prominent backgrounds:**
  - ^{210}Po ^{210}Bi ^{85}Kr, ^{11}C, & ^{14}C (not shown)
- **^{210}Bi (^{210}Pb) increased to ~40 cpd/100t**
  - Scintillator operations to reduce leak in Scintillator Vessel increased ^{210}Po and ^{210}Pb.
- **^{210}Po increased, then decayed to ~650 cpd/100t.**
  - Separated by α/β pulse shape discrimination.
- **pep and CNO obscured by ^{210}Bi**
  - Box spectrum and cuts to reduce the ^{11}C. (muon track, neutron, other) yielded pep measurement.
  - CNO more difficult- still underway.





Borexino Phase I Solar Neutrinos

Milestone in Low Background Counting

✓ ^{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

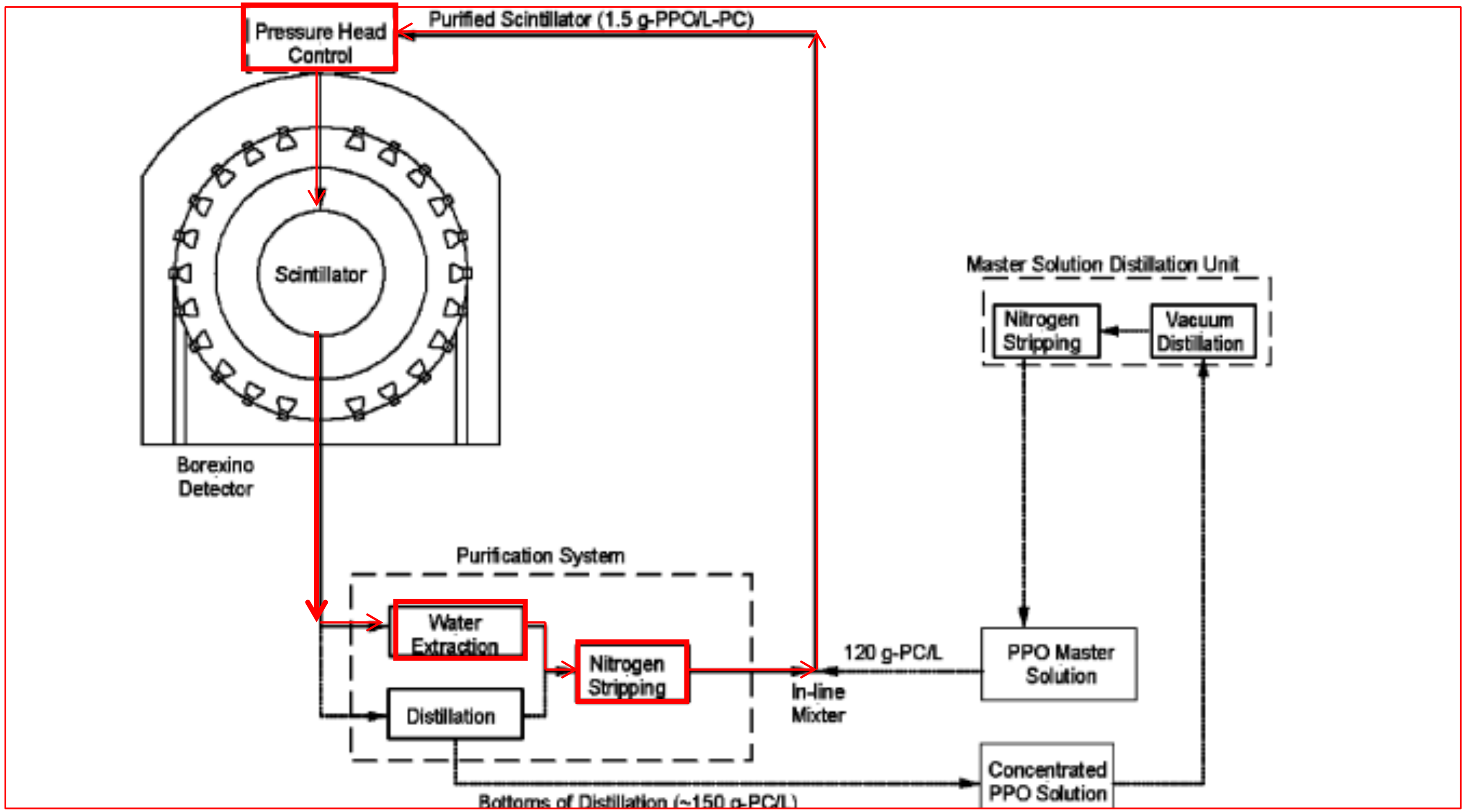
Direct Measurement of Neutrinos in pp-chain

✓ CNO limit:	< 7.9 cpd/100t		PRL	2012
CNO expected:	3, 5 cpd/100t for LM, HM.			

Borexino Phase 2: 2010-2016

Borexino Re-Purification Systems

Water Extraction or Distillation followed by N_2 Stripping



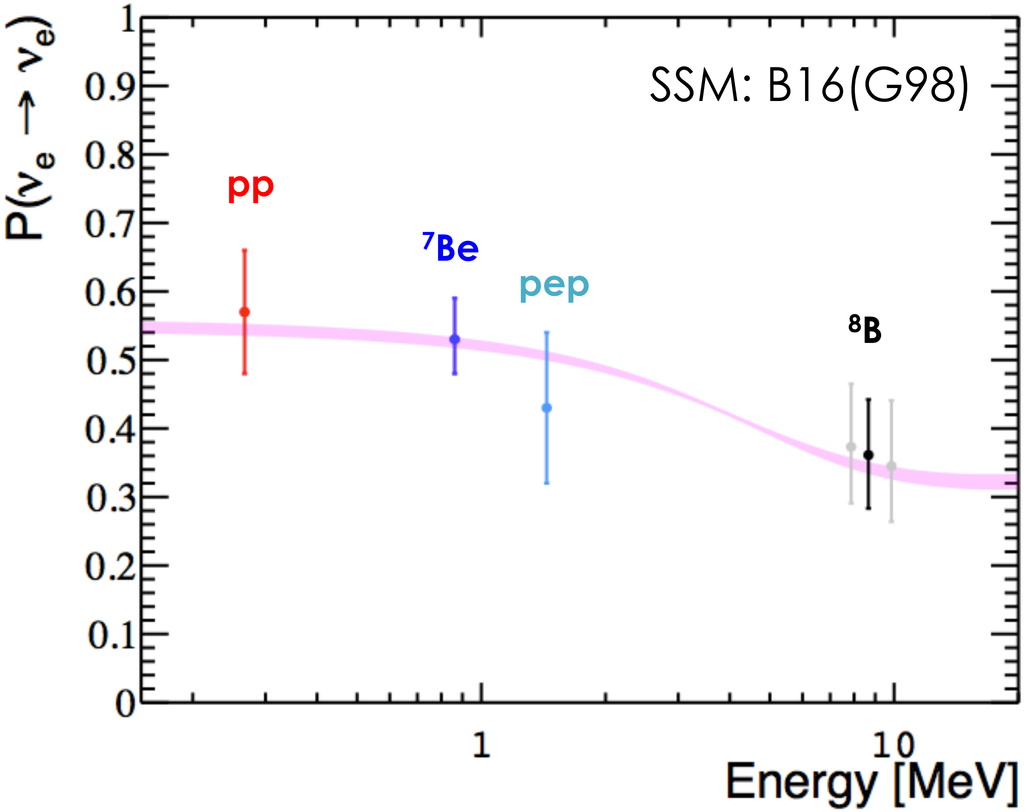
Background Reduction by Scintillator Purification for Phase 2

- Scintillator re-purification was carried out from July 13, 2010 to August 11, 2011.
- Six cycles of "water extraction" and "nitrogen tripping" were used to remove non-volatile and volatile radioactive impurities.
  - Each cycle purified the full 300 m^3 of scintillator in a "loop" flow mode.
- Scintillator purification was successful in lowering backgrounds, and set the stage for acquiring Phase 2 data.
- The ^{210}Po was not satisfactory. Plant contamination to reduce DMP in buffers to reduce vessel leak, followed by inadequate cleaning, is suspected as a major cause.
- More recent studies revealed that ^{210}Pb, and especially ^{210}Po, are not removed efficiently from ground water by standard water purification systems.
  - New facilities to produce ultrapure water by fractional distillation have since been installed.

Isotope	Initial impurity	Final impurity
^{85}Kr	30 cpd/100t	<5 cpd/100t
	Reduced: >6	
^{238}U (^{226}Ra) ^{214}Bi - ^{214}Po	5.3×10^{-18} gU/g Reduced: >77	$<8\times10^{-20}$ gU/g <0.8 c/100t/y
^{238}U (^{226}Ra) ^{214}Bi - ^{214}Po	5.3×10^{-18} gU/g Reduced: >77	$<8\times10^{-20}$ gU/g <0.8 c/100t/y
^{232}Th ^{212}Bi-^{212}Po	$3.8(8)\times10^{-18}$ gTh/g Reduced: >3	$<1\times10^{-18}$ gTh/g <0.8 c/100t/y
^{210}Bi	70 cpd/100t Reduced: x4	17.5 cpd/100t
^{210}Po	Increased in first 2 cycles 20 →45 cpd/t Plant contaminants?	Decreased during Cycles 4-6 return to ~20 cpd/t and decaying.

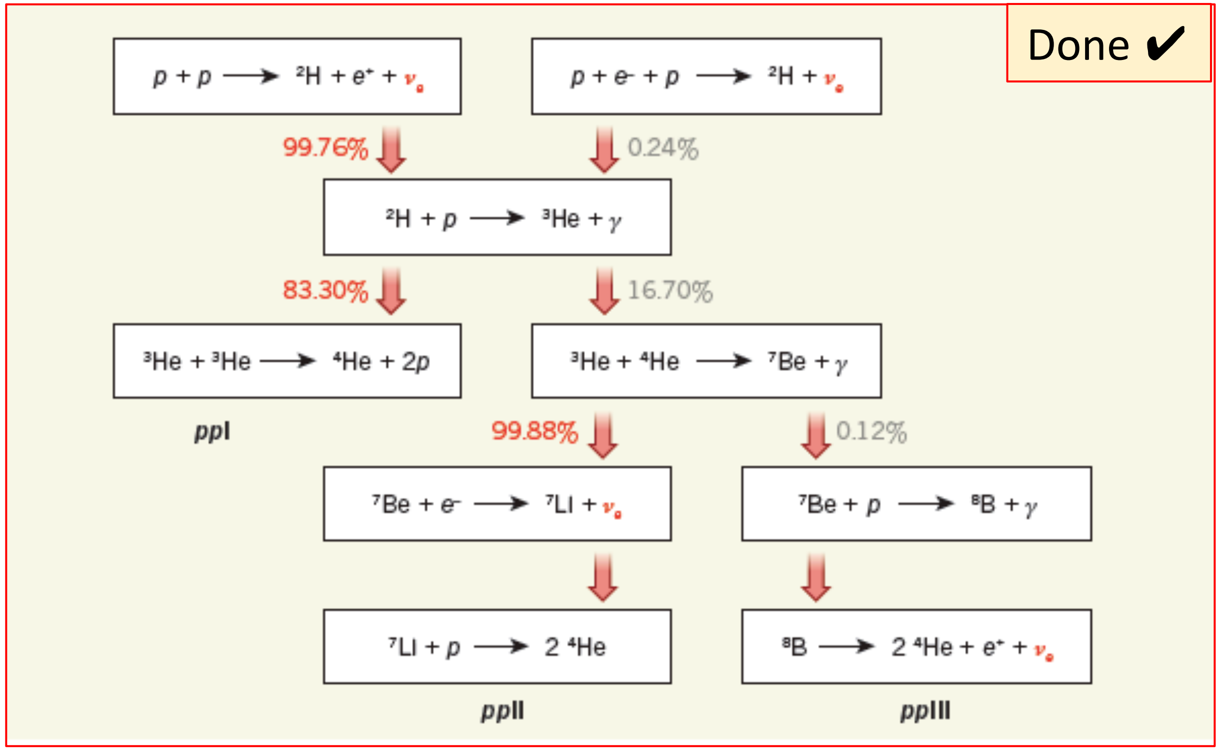
Borexino Phase 2
Solar Neutrino Measurements

Neutrino	Phase 2
pp	144±16% (2014). 134±9.6% (2017)
^{7}Be	48.3 ± 2.7 %
pep	2.5 ± 18 %
^{8}B	0.220 +0.015,-0.016(stat) ± 0.006 (syst)

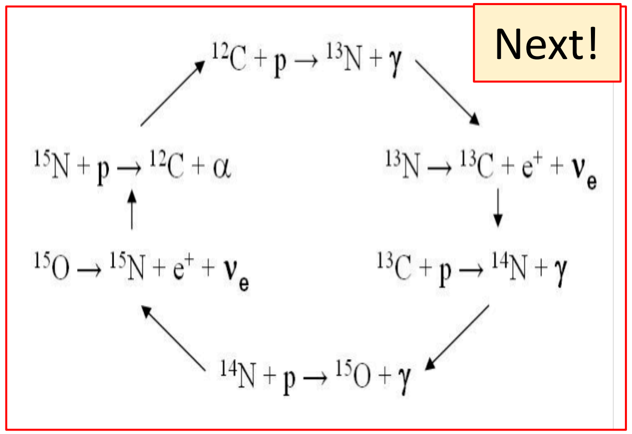


"Energy production in stars"

H. Bethe, Physical Review 55 434, March 1 1939 – 78 years ago.



The pp chain



The CNO Cycle

H. Bethe (1906-2005)
"Smiling in Heaven"

Borexino Phase 3 Solar Program
CNO Neutrinos and Solar Metallicity

Measuring CNO Neutrinos

- Detecting presence of CNO neutrinos will be another Borexino first and a major accomplishment.
- Measuring CNO can determine if the metallicity is high or low.
- The continuous CNO spectrum is similar to that of ^{210}Bi; separating them by a fit to the spectrum is difficult.
- Strategy suggested by F.L Villante, A. Ianni, F. Lombardi, G. Pagliaroli, F. Vissani, Phyd. Letts. B **701** 336 (2011)

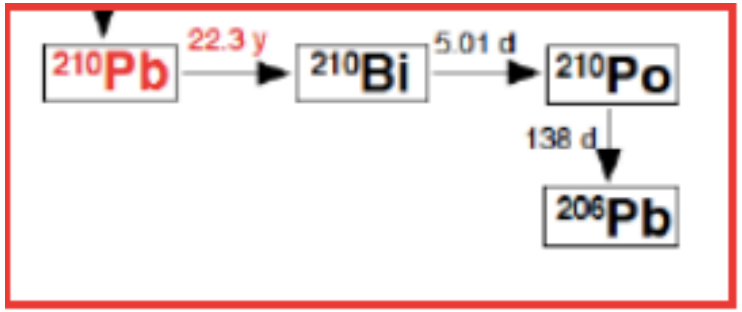
Establish secular equilibrium in ^{210}Pb decay chain in FV.

- Then measure ^{210}Po alpha decay with PSD to determine the ^{210}Bi rate.

Reduce the ^{210}Bi (^{210}Pb) background rate for higher accurate rate.

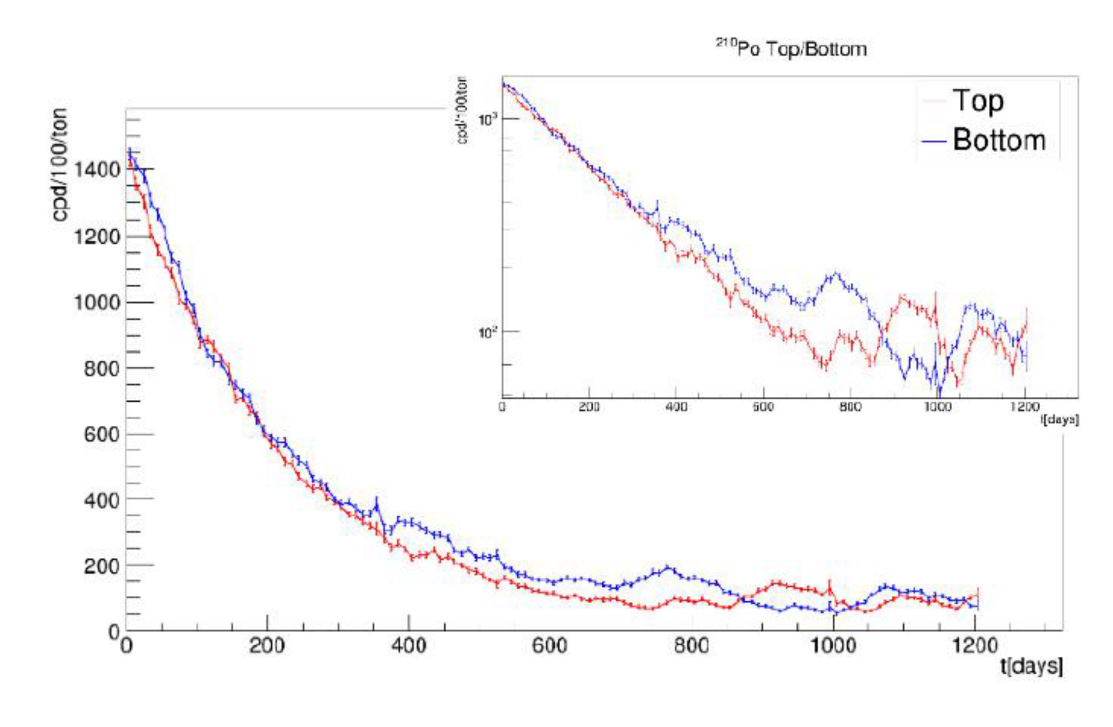
- Purification system was recently upgraded for this.

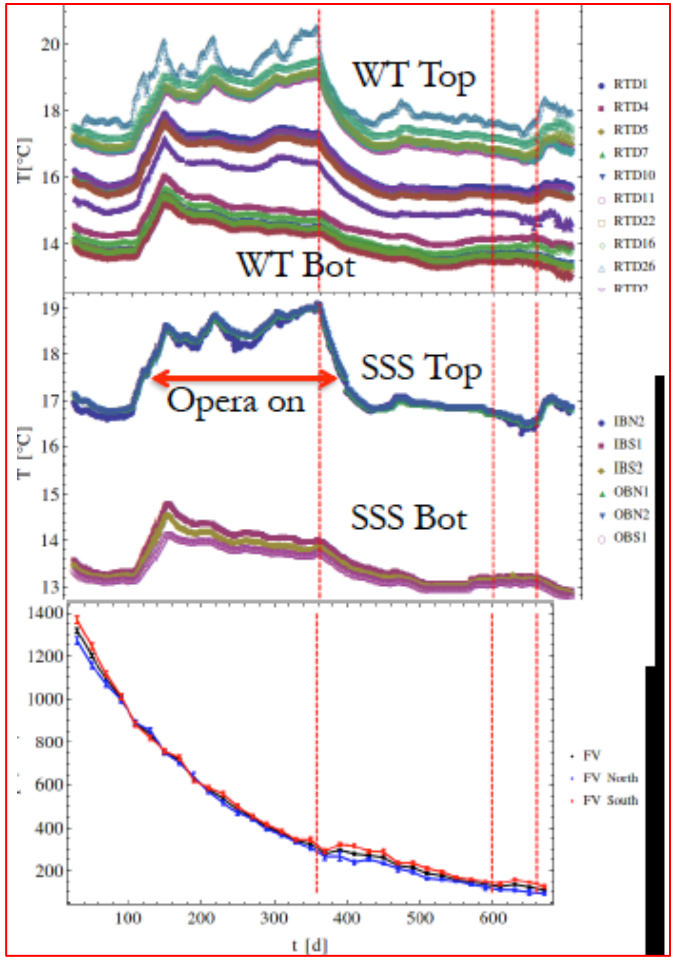
Decay chain of ^{210}Pb-^{210}Bi-^{210}Pb



- The A=210 nuclei in the FV of the scintillator will be in secular equilibrium after a time long compared to the 138-d half-life of ^{210}Po.
- Secular equilibrium in FV can be difficult to achieve if convection currents can carry ^{210}Po from the scintillator vessel surface into the FV
- Suppressing temperature changes and associated convection currents is an essential requirement

But Temperature Stability of Borexino in Hall C is Poor





Thermal Insulation of Water Tank

Reduces Temperature Changes & Convective Currents that Move ^{210}Po into FV

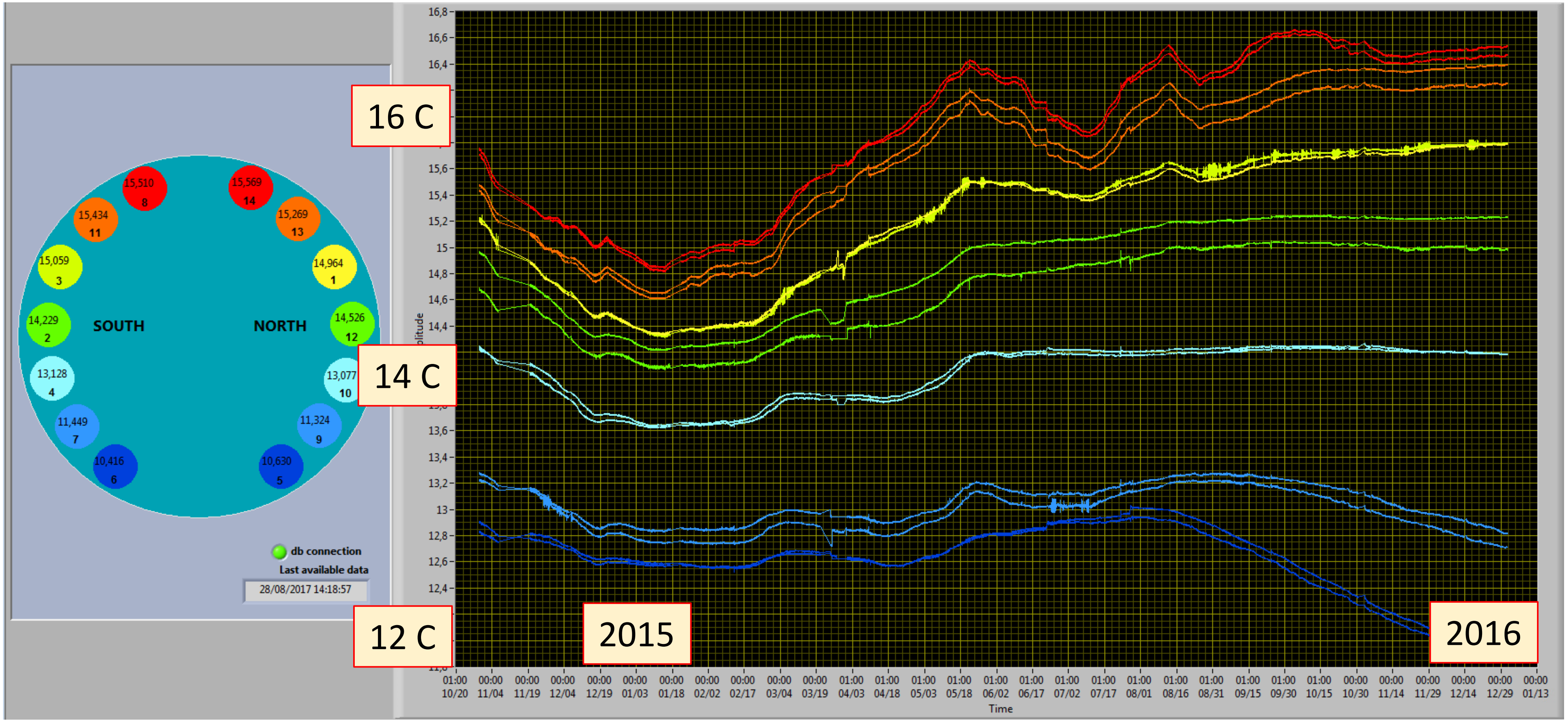
Rockwool: 20 cm thickness

k = 0.03 W/m/K

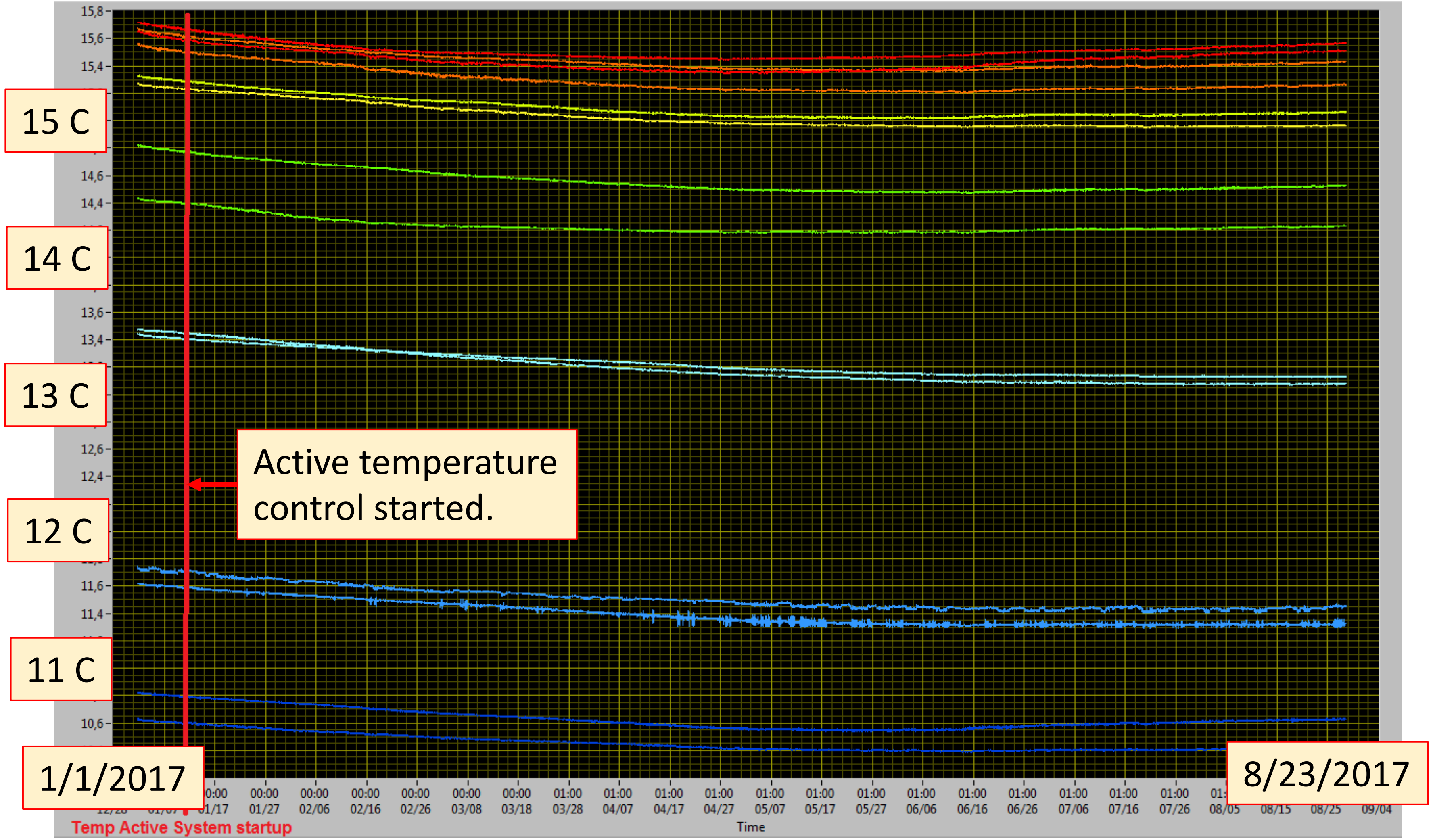
Before Insulation

During Insulation

Outer Buffer 2014-2015



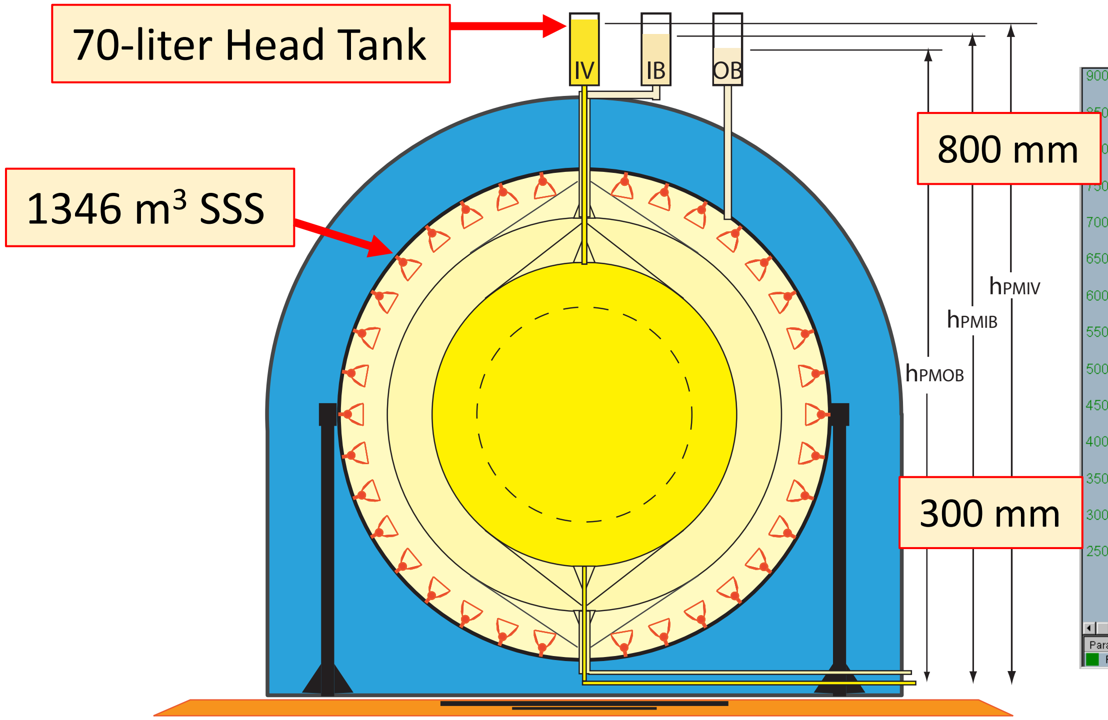
Outer Buffer Temperatures 2017



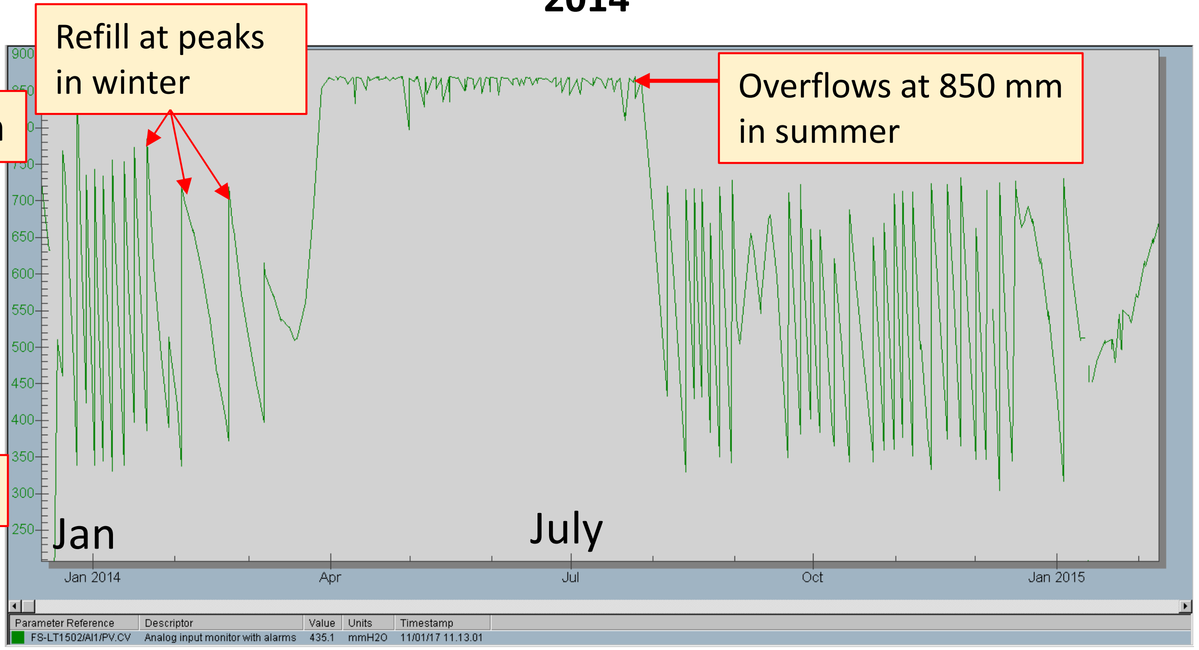
Head Tank Level

Sensitive to Scintillator Temperature Changes of 0.01 C

Head Tank Level Measurement

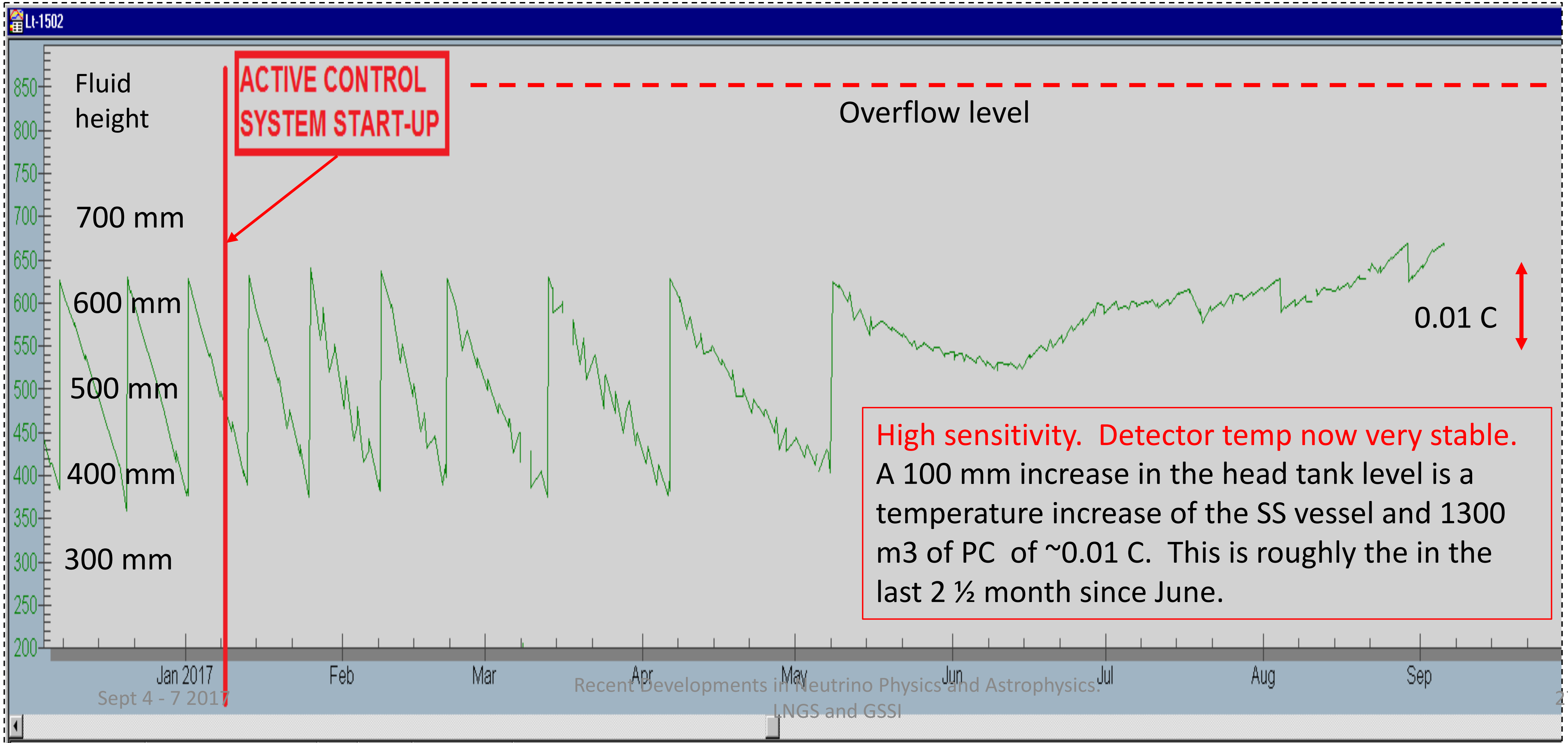


2014



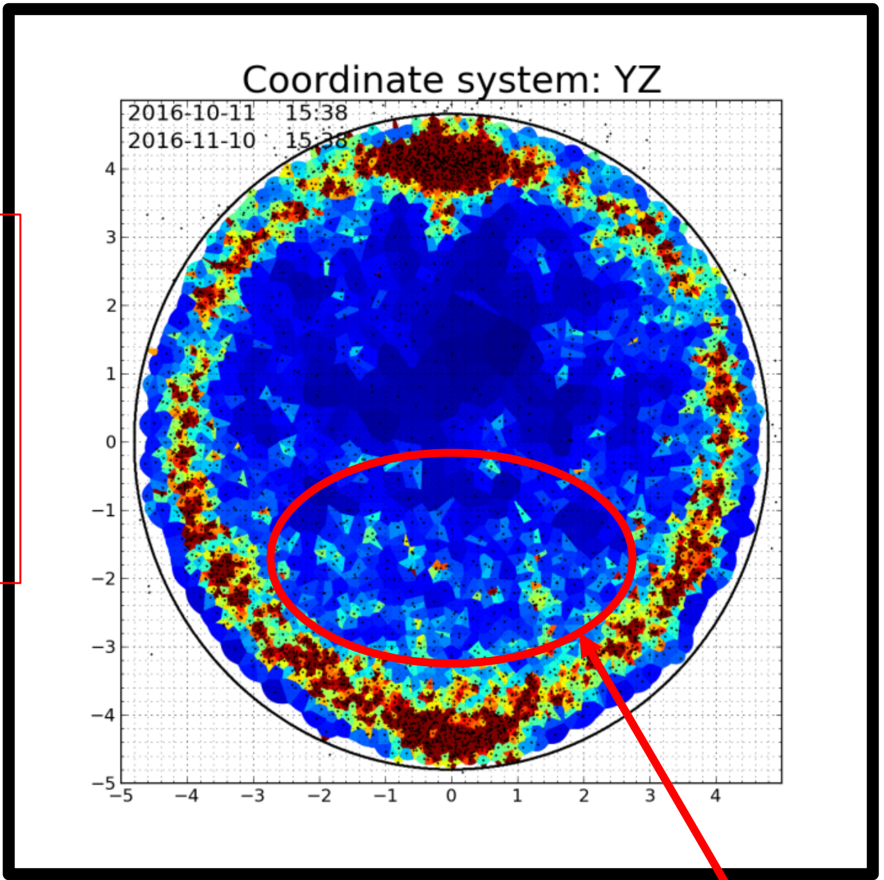
Head Tank Level 2017

Very Stable for ~2 ½ months, helped by warm summer

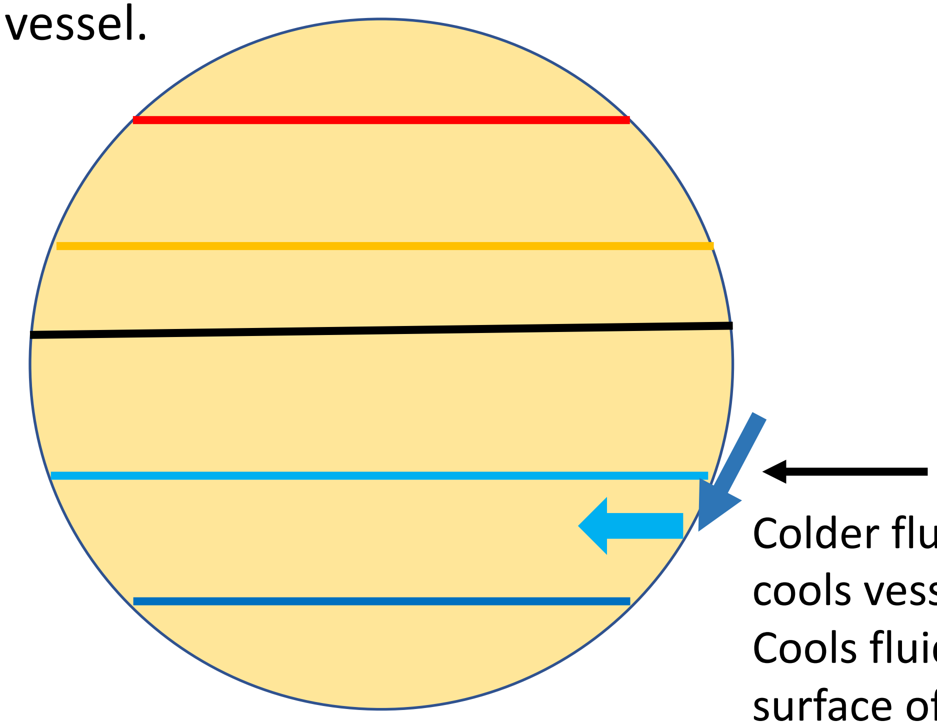


Time Dependence of Temperatures Causes Convective Flow of Fluids

Figure of ^{210}Po activity from Marcin W., Marcin M., and Xenon N.



- Decreasing temperature at the vessel surface will cause fluid inside vessel at inner surface to move down along vessel pushing fluid down and away from vessel.

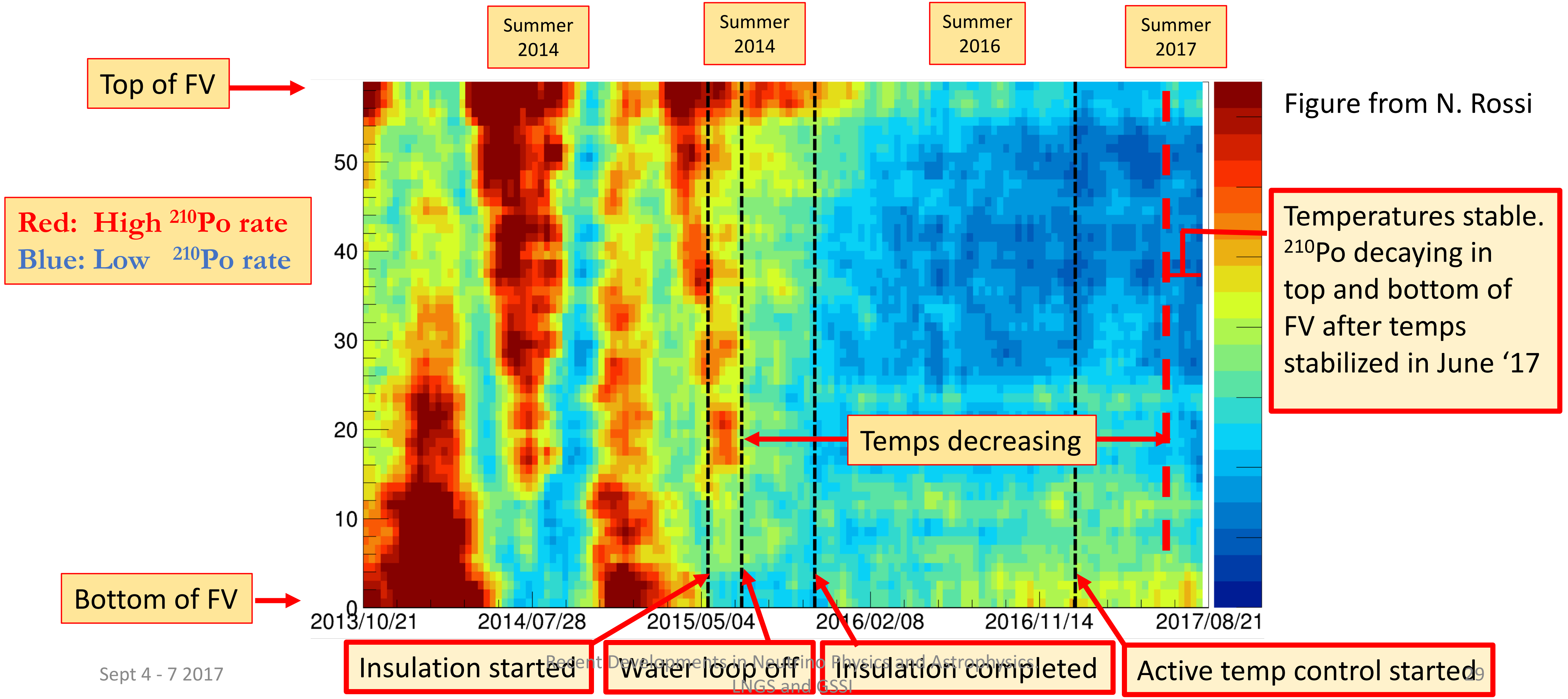


Colder fluid here cools vessel which Cools fluid on inner surface of vessel

^{210}Po at vessel surface gets pushed away from vessel into here as colder fluid moves in.

^{210}Po rate in Fiducial Volume Cubes vrs. Time

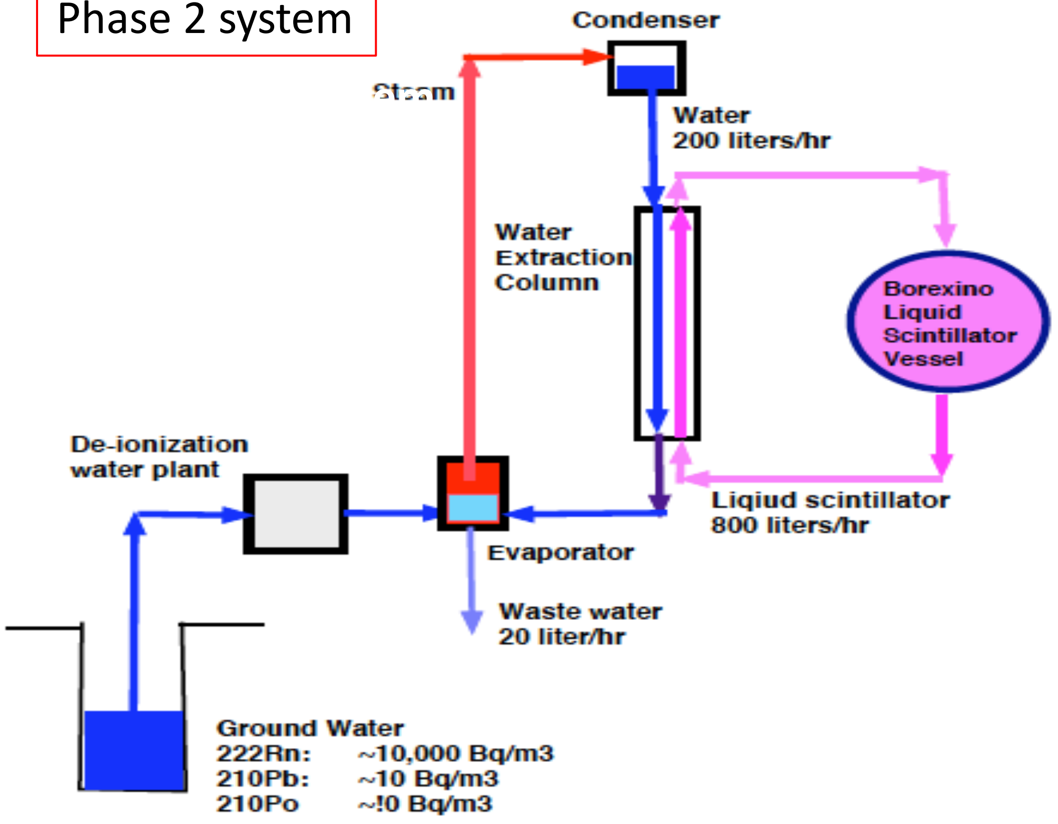
Summer 2017: Stable temperatures achieved, convective currents slowed, ^{210}Po decaying.
Is this a Borexino Milestone toward a CNO measurement?



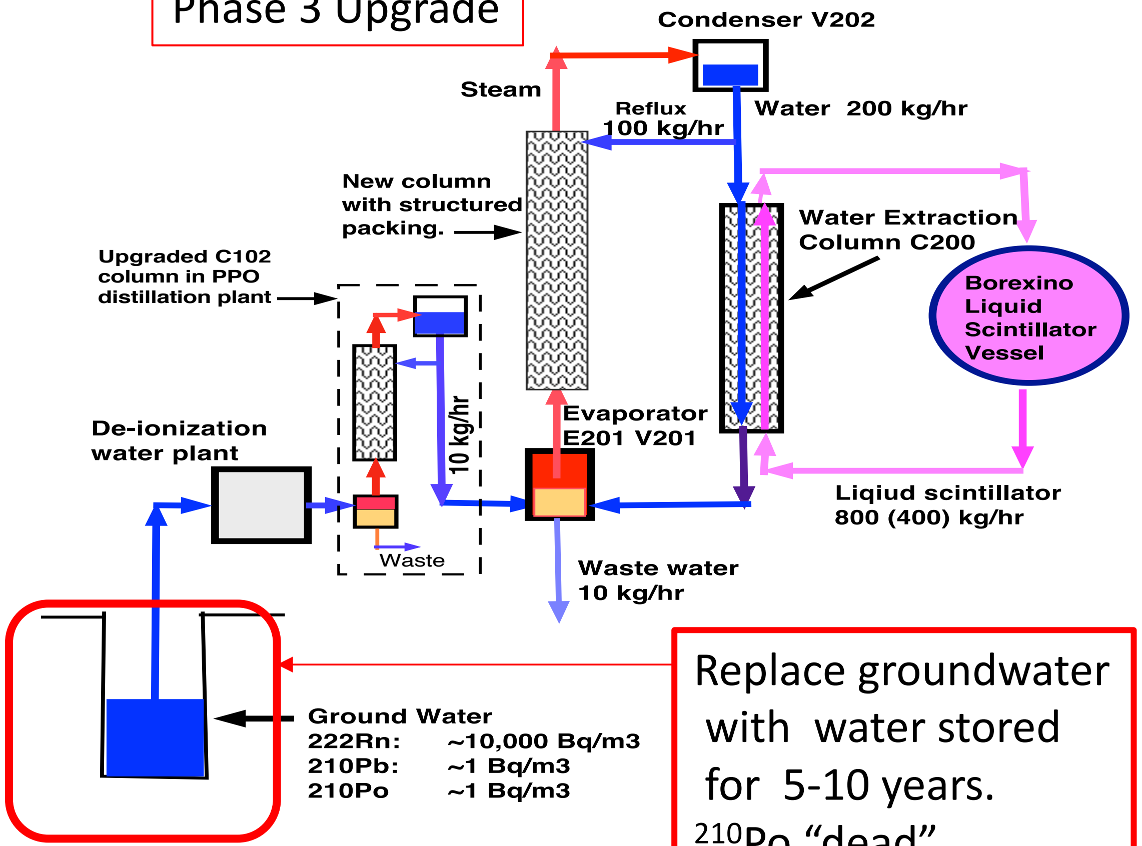
Borexino Water Extraction System

Previous and upgraded system with new fractional distillation columns

Phase 2 system



Phase 3 Upgrade



Replace groundwater with water stored for 5-10 years. ^{210}Po “dead”

Conclusions and Thanks

- Borexino achieved unprecedented low backgrounds that made it possible to measure the four neutrinos in Bethe's pp-chain.
- Recent improvements in the detector temperature stability and scintillator purification methods may make it possible to observe Bethe's CNO neutrinos.
- Many colleagues, researchers, and technical staff contributed to this effort. I thank them for the excellent work they did. I wish I had time to cite all of them individually here.
- Let me at least express personal thanks to:
  - Borexino co-founders Gianpaolo Bellini and Franz von Feilitsch,
  - Current and former Princeton colleagues, Jay Benziger, Cristiano Galbiati, Bruce Vogelaar, and Aldo Ianni
  - Princeton engineering staff Andrea Ianni, and Augusto Goretti.
  - The long NSF support, managed well by staffers Brad Keister and Jim Whitmore

The End