Solar Neutrinos with Borexino at LNGS

Current Results/Future Opportunities

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Borexino Collaboration

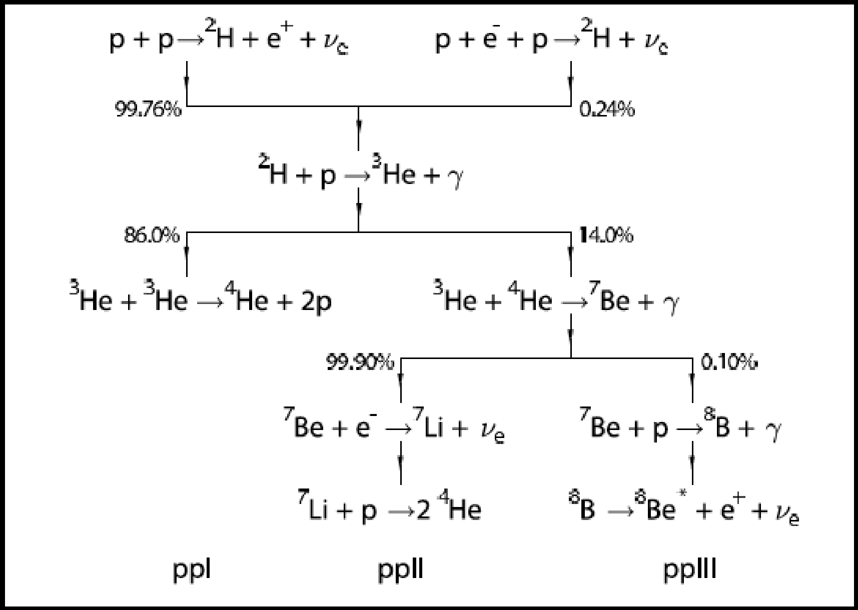
A 20+year successful collaboration between U.S. and Italian + European Groups

Borexino
Historical Highlights

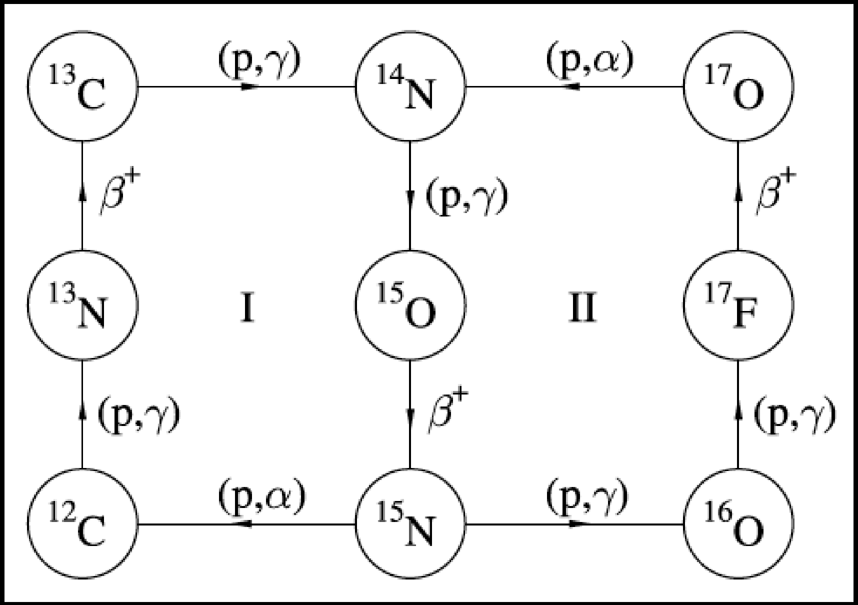
- 1989-92: Prototype CTF Detector started
- 1995-96: Low background in CTF achieved
- 1996-98: Borexino Funded INFN,NSF, German
- 1998-2002: Borexino construction
- August 16 2002: Accidental release of ~50 liter of liquid scintillator shuts down Borexino and LNGS
- 2002-2005: Legal & political actions: Princeton Lawyers
- 2005 Borexino Restarts Fluid Operations
- August 16, 2007 First Borexino Results on Web.

Solar Nuclear Fusion Cycles

The pp cycle

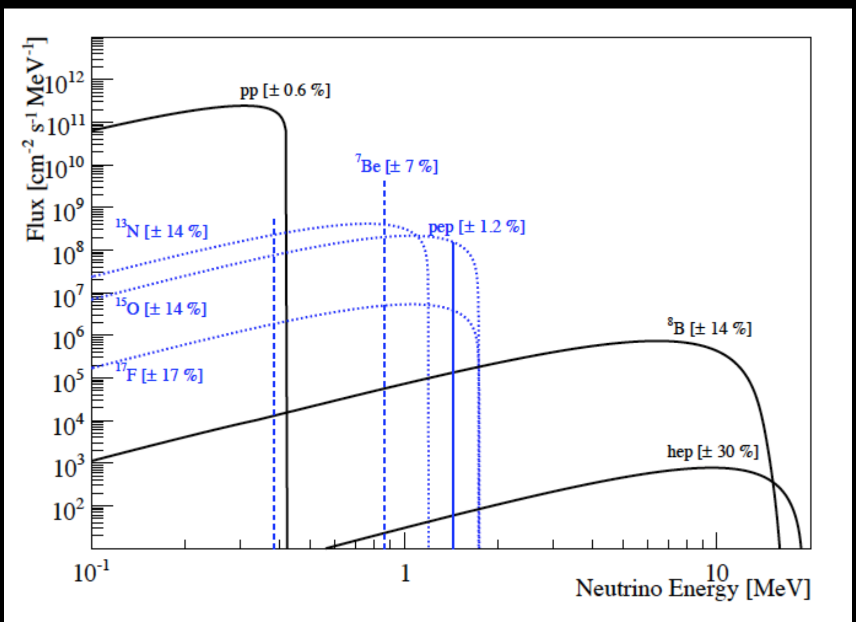


The CNO cycle

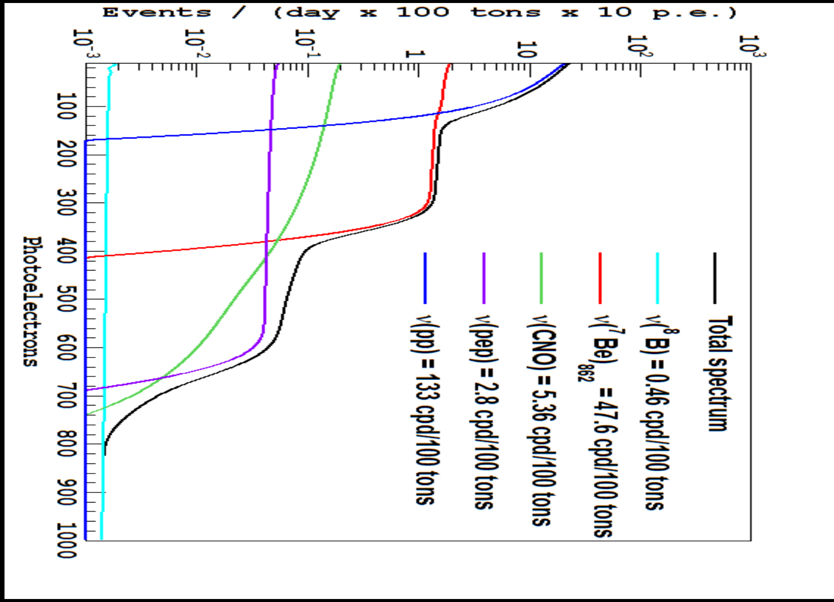


Solar Neutrino Spectra

Neutrino Energy Spectrum



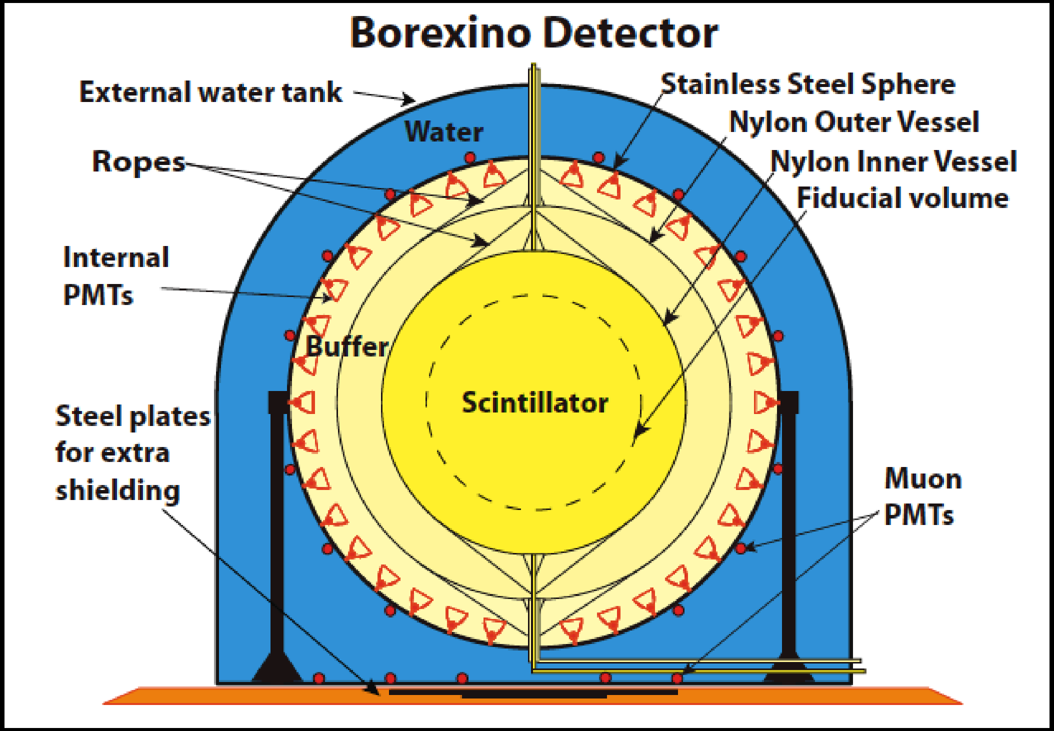
Neutrino-Electron Elastic Scattering Energy Spectrum



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

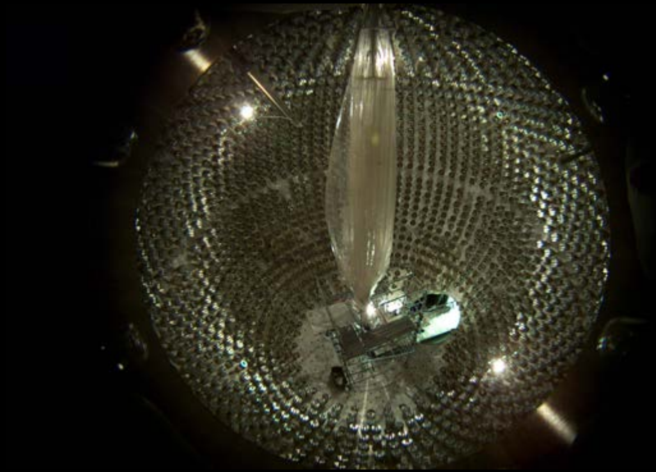


Fabrication of Nylon Vessel
Princeton Low Radon Cleanroom

John Bahcall

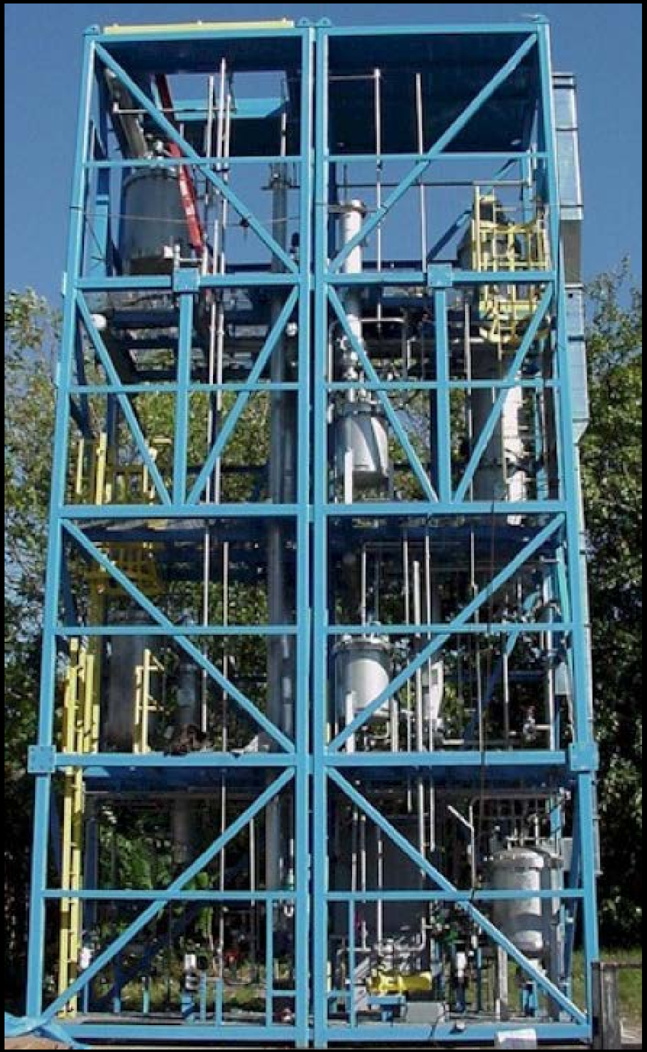
Vessel Installation / Inflation

- Despite laboratory upgrades and the ban on fluid use, work on Borexino progressed.
- 2004 was a watershed year: the scintillator containment vessels, built over one year at Princeton, were installed and inflated to spherical shape.



The Borexino Experiment: Purification Plants

- Main Purification Skids
  - distillation of PC to remove non-volatile contaminants
  - water extraction of charged ions
  - nitrogen stripping to remove undesirable gases (radioactive noble gases, oxygen)
- Skids for distillation of "master solution," refitted from CTF.



Borexino Energy Spectra

PRL 107 141302 (2011)

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

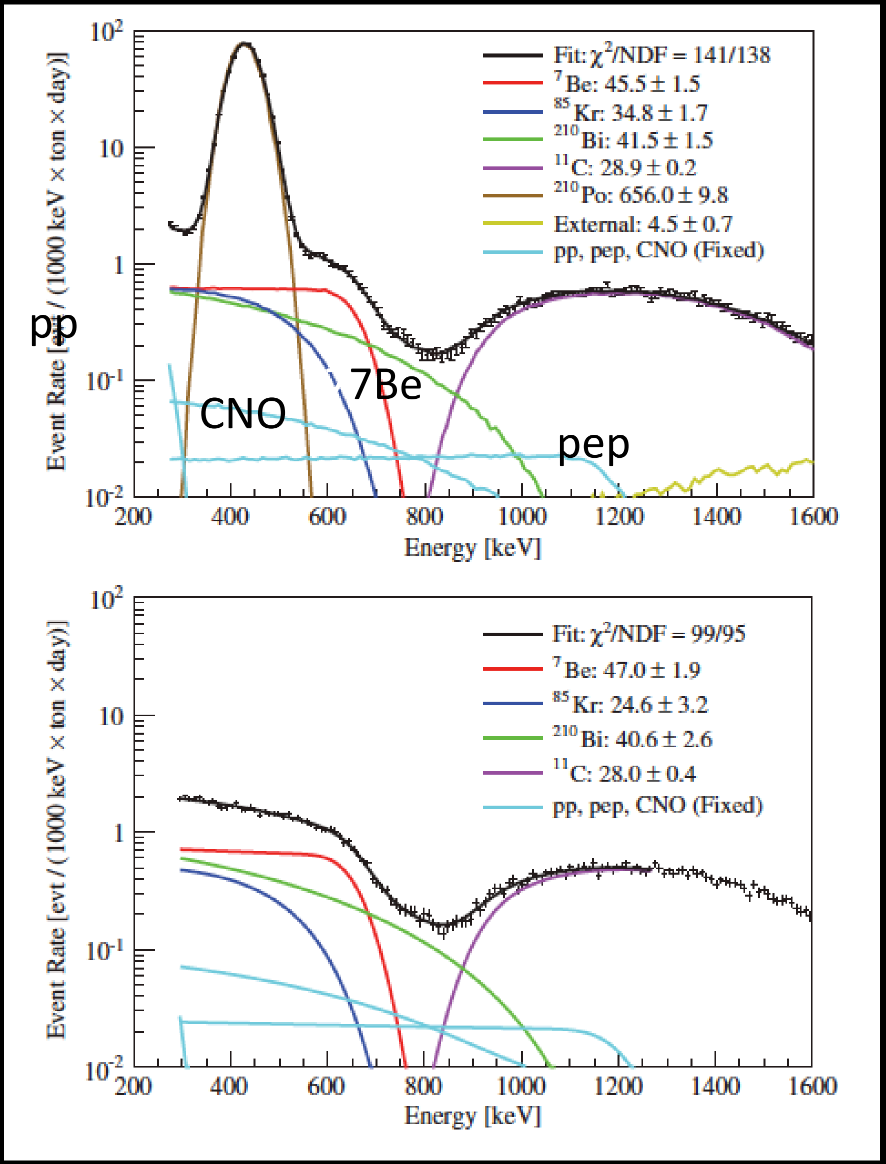
Prominent backgrounds are:

^{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

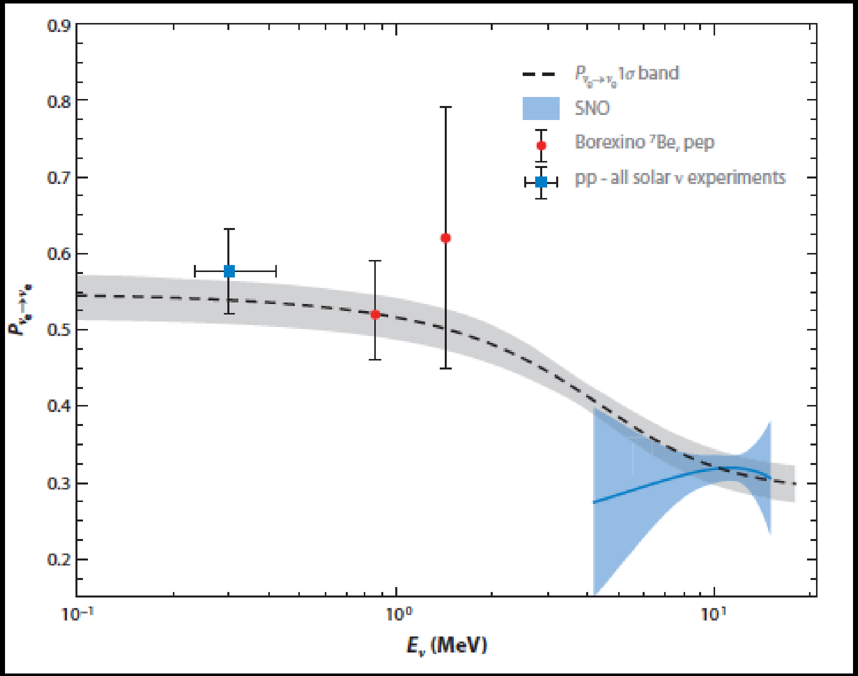
Pee = 1.0   no neutrino oscillations

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.

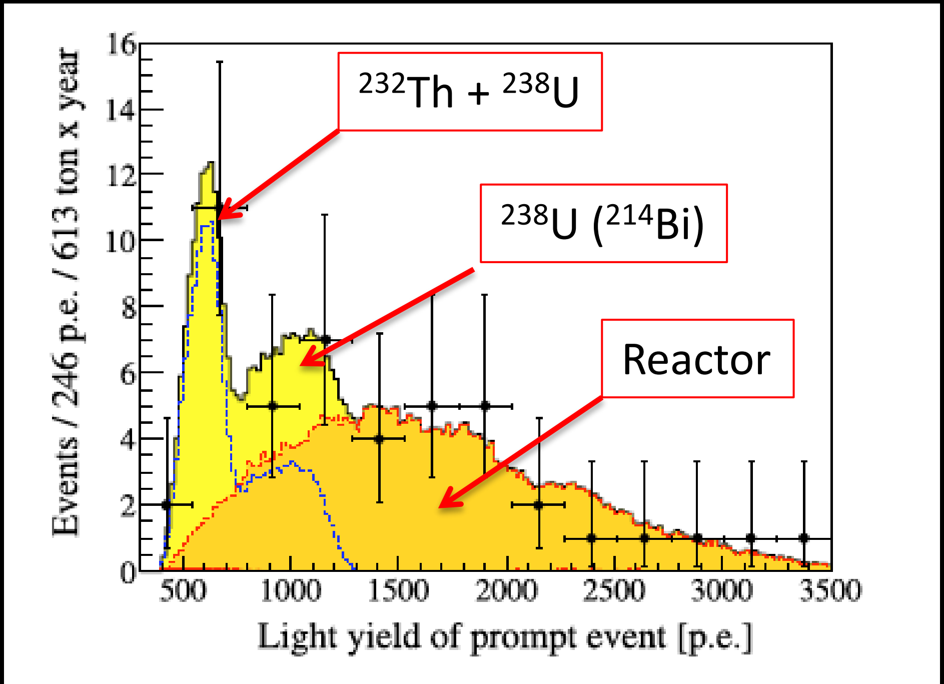
Improving pep, and low energy ^{8}B data motivated by sensitivity to new physics.



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 event in orange.
- Antineutrinos detected by delayed coincidences from changed current reaction
  - v+p -> e^+ + n
- Total 46 events detected
  - 14.3 ⌖ 4.4 geo-neutrinos
  - 31.2 ⌖ 6.5 reactor neutrinos



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)

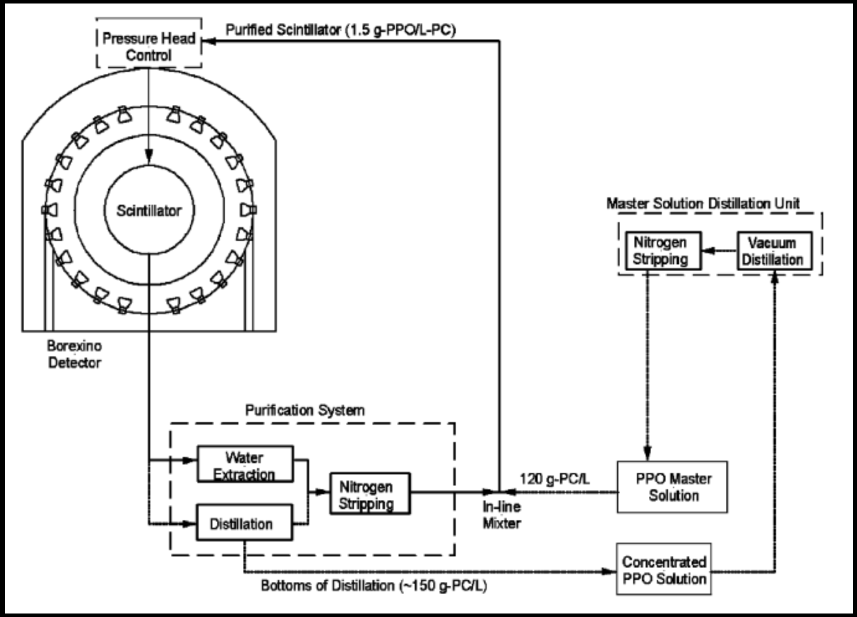
3. **Non-standard interactions in vacuum- matter oscillations transition.**

Re-Purification of BX Scintillator 2010-2011

- **Future Solar Program requires lower background.**
  - ^{210}Bi < CNO (5 cpd/100t) might allow separation of CNO and ^{210}Bi spectra.
- **From 2007 to 2010 the ^{210}Bi background increased.**
  - ^{210}Bi rate: 15 → 70 cpd/100t (cause: scintillator operations, other?)
  - ^{85}Kr rate: 30 cpd/100t (constant)
- **To reduce background, scintillator was re-purified using two processes:**
  - Water extraction to remove ^{210}Pb (^{210}Bi) and other similar (e.g., ^{226}Ra)
  - Nitrogen stripping to remove ^{85}Kr and other volatiles.
- **Six purification operations were done, each of about 1 month duration.**
  - Each operation processed all 320 m^3 scintillator in the detector once.
  - Data were acquired to evaluate backgrounds after each operation.

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)

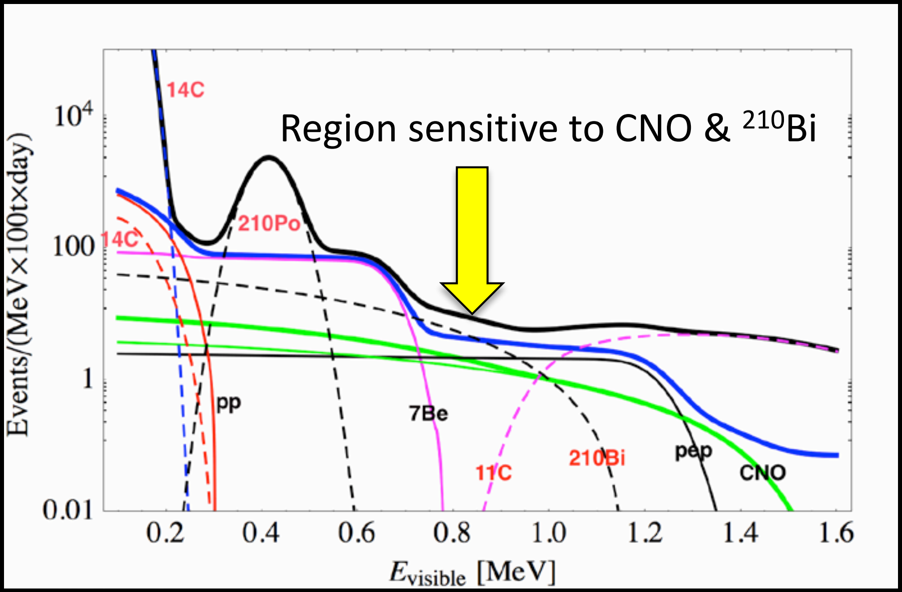


Results of 6 cycles of Re-purification

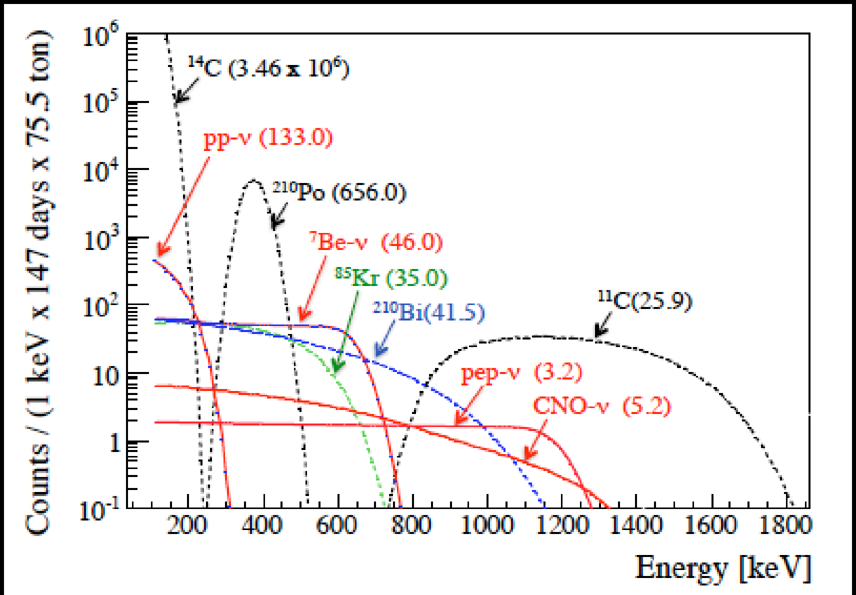
- ^{85}Kr: 30 cpd/100t → < 5 cpd/100t
- ^{210}Bi: 70 cpd/100t → 20 ± 5 cpd/100t
- ^{210}Po: Essentially not reduced! Why?
- ^{238}U (^{226}Ra): [(53 ± 5) → (1.6 ± 0.6)] x 10^{-19} g/g
  ^{214}Bi-^{214}Po Reduction factor = 33. 7 events/100t/yr.
- ^{232}Th: [(3.8 ± 0.8 → < 1.2] x 10^{-18} g/g (95% CL)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

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.

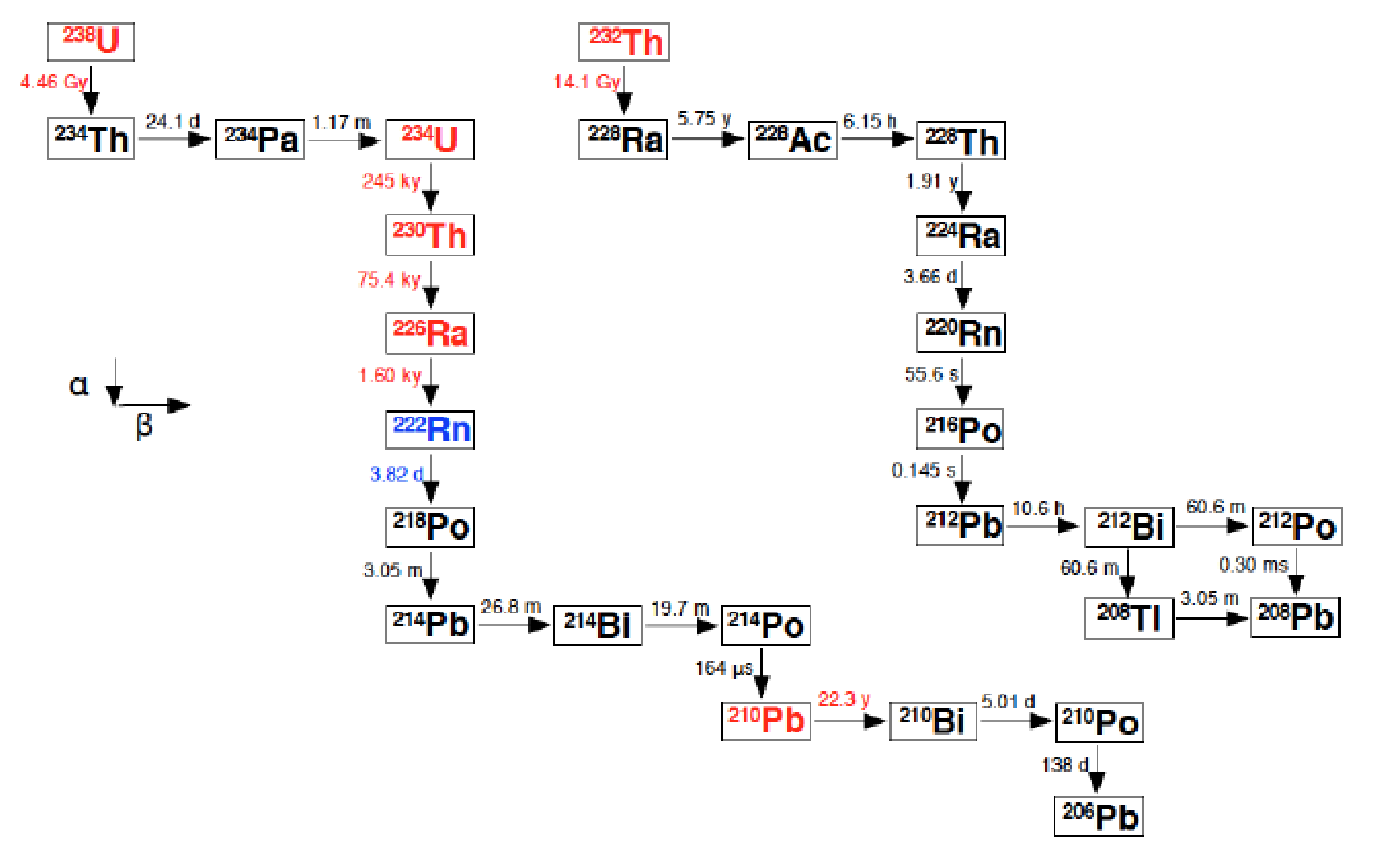
Water Extraction Worked!

CNO needs lower background.

^{210}Pb (^{210}Bi) and ^{210}Po found in “Purified Water” used for Water Extraction

New method developed to remove ^{210}Po.

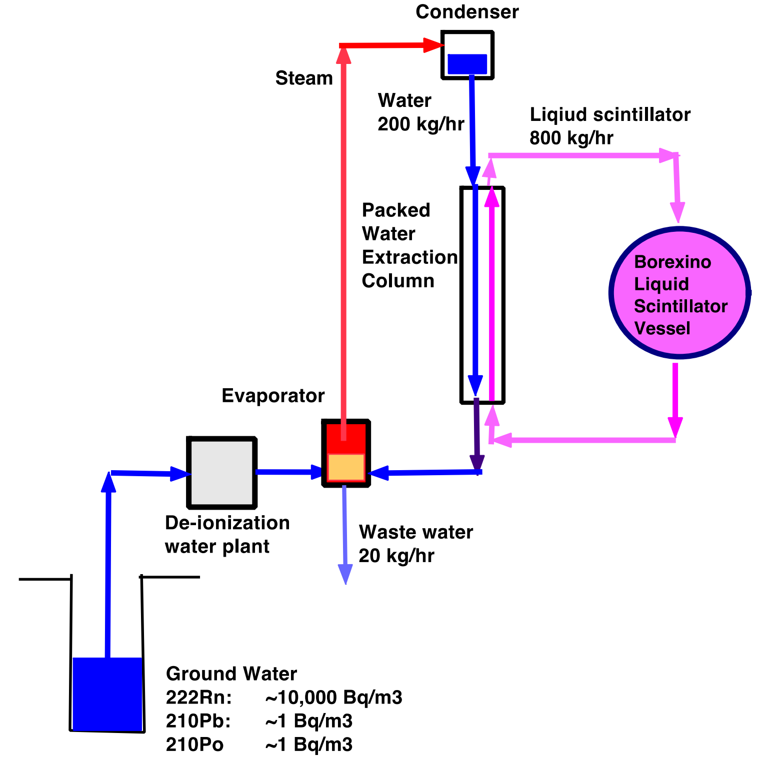
A Primer on U and Th Decay Chains



A lower ^{210}Bi rate compared to ^{210}Po implies a chemical separation process that removes Pb more efficiently than Po.

Water Extraction and Nitrogen Stripping Performed 2010-2011

- Contacting high purity water with scintillator can remove radioactive impurities from the scintillator.
  - Works best if impurities have higher affinity for water, e.g., polar species, but can also be effective if not.
- For water extraction, we use LNGS ground water purified by the following:
  - Reverse osmosis and Ion-exchange (de-ionization water plant)
  - Single stage evaporator distillation.
- Ground water has high levels of radioactivity.
  - ICPMS studies show that ^{238}U, ^{232}Th, ^{40}K are removed effectively by de-ionization.
  - ^{222}Rn is very high (10,000 Bq/ton), but can removed by de-gasification, e.g. N2 stripping.
  - Radon daughters ^{210}Pb, ^{210}Bi, and ^{210}Po had not been studied until recently.
  - New data show that de-ionization processes are not very effective in removing ^{210}Pb and ^{210}Po.
  - The main radioactivity in Borexino de-ionized water is ^{210}Pb and ^{210}Po.



The water extraction system.

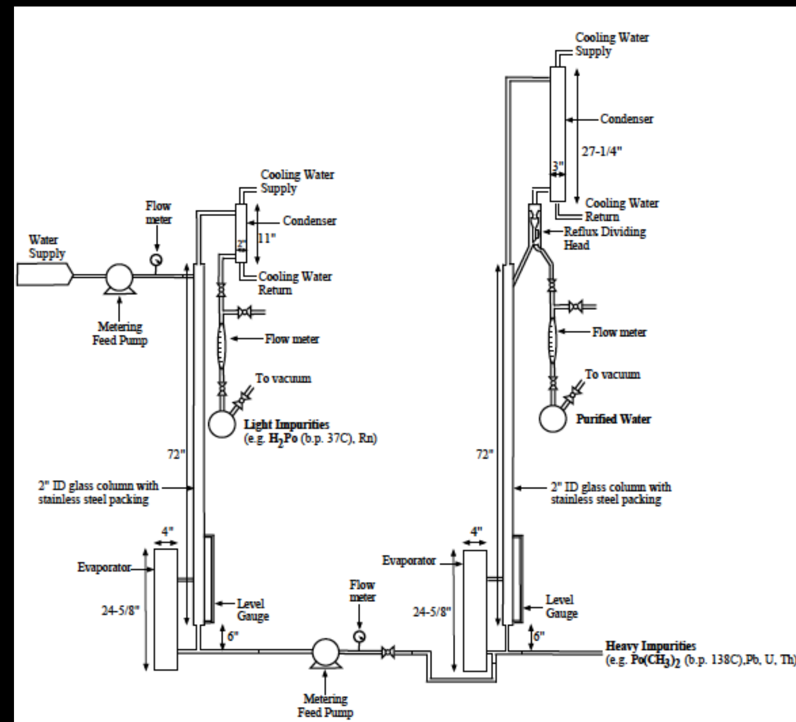
N_2 stripping column used in series

Volatile Polonium Compounds?

- ^{210}Po compounds were thought to be non-volatile, and would be removed by distillation.
- Recent studies provide evidence that some of the ^{210}Po in well water is a 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 Nuclear Chemistry 272, 413 (2007)
- Dimethyl polonium: Boiling point ~138 C (est.)
- Poor removal of ^{210}Po by de-ionization and ineffective distillation due to volatile polonium compound could explain problems Borexino has had with this isotope.

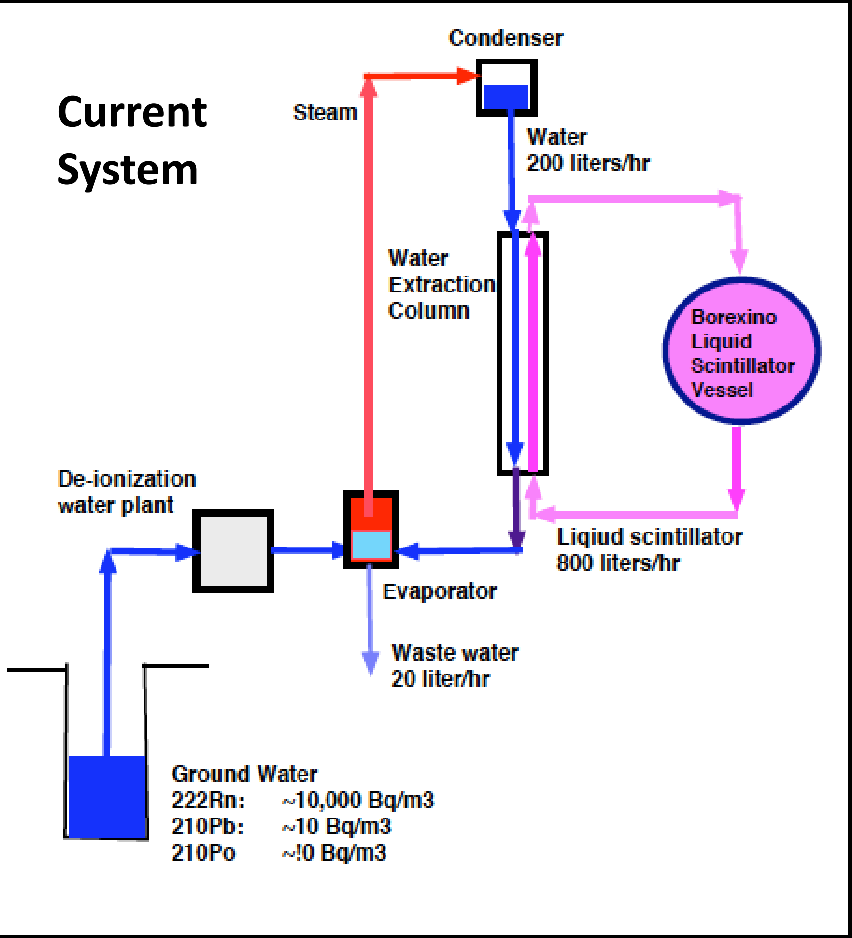
New Distillation System to Remove ^{210}Po and ^{210}Pb from Ground Water.

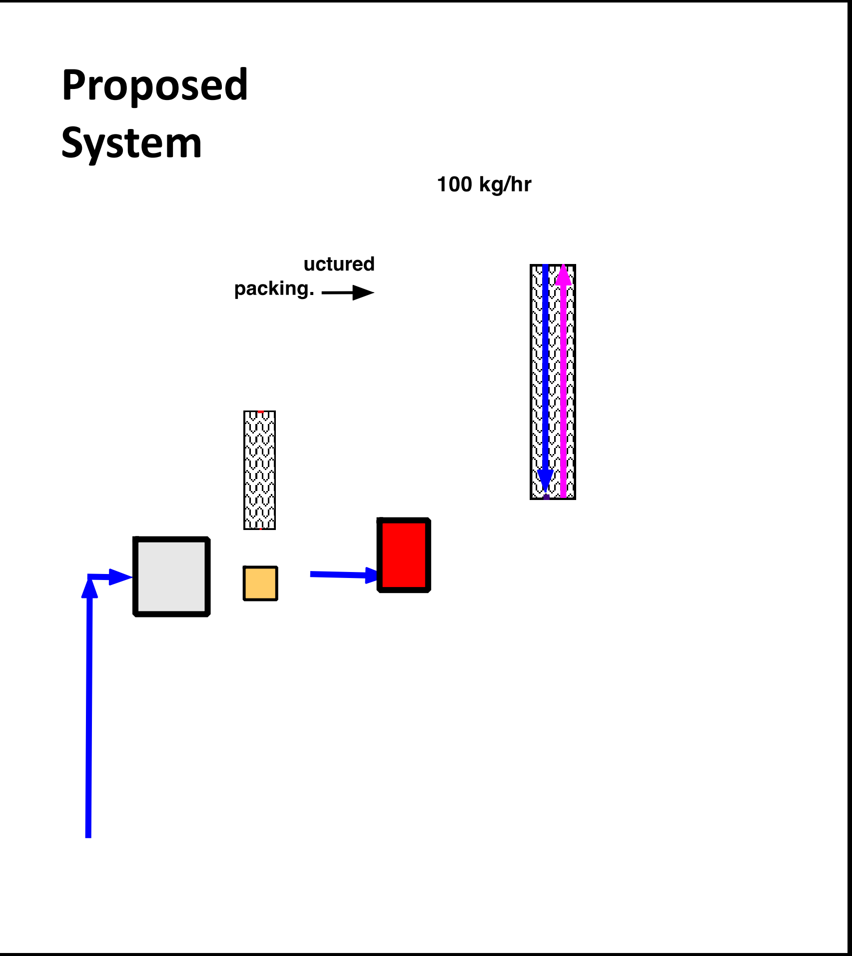
- A small-scale distillation system was designed are tested at Princeton to remove dimethyl polonium from ground water.
  - A tall column with structured packing and high reflux was designed for x1000 reduction.
- Princeton well water, noted for its high radon levels, made it easy to measure the polonium 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





Summary/Conclusions

- **Initial scintillator purification produced low backgrounds in Borexino.**
  - Solar neutrino rates measured: ^{7}Be, pep, ^{8}B
  - High ^{210}Po background was compensated with alpha/beta pulse shape discrimination.
- **Future research toward CNO and pp neutrinos, requires lower background.**
- **Scintillator re-purification worked!**
- **Discovered that de-ionization systems are ineffective on ^{210}Pb and ^{210}Po.**
- **Confirmed presence of volatile polonium, and removed it with fractional distillation.**
- **Water extraction with better water can reduce backgrounds and set stage for CNO.**

Status of Solar/Neutrino Science

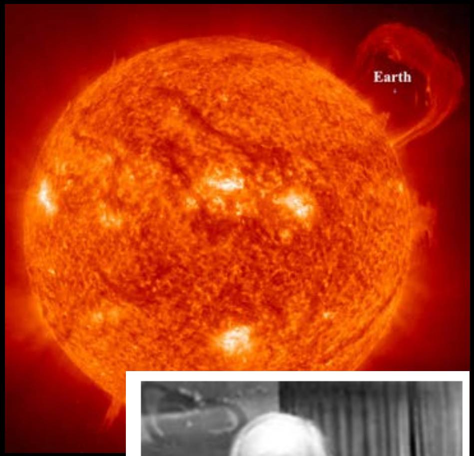
- Bethe’s pp fusion cycle
  - Observed 3 of the 4 neutrinos.
- Neutrino oscillations
  - Solar neutrinos consistent with MSW theory
  - Vacuum-matter effect transition study still needed.
- CNO physics
  - Solar metallicity problem still unexplained
  - Future contribution from Borexino?

The Princeton-Gran Sasso Summer School

- Education of our youth is very important.
- The Princeton-GS summer school brought 20-40 Italian high school students to Princeton for a month of study and cultural experiences.
- The program continued for nine successful years trying to spark interest in science.
- Inspired by Bruce Springsteen “Dancing in the dark- …you can’t start a fire without a spark…”

This photo from 2005

What makes the Sun shine?

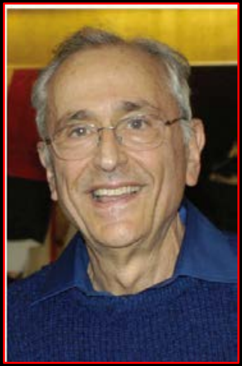


- Pre-scientific:
  - Deities and sacred bodies: Helios (Greek), etc
  - Giant flaming metal ball
    - Anaxagoras: imprisoned for suggesting it wasn't Helios
- Scientific based ideas:
  - Gravity (19'th century)
  - Nuclear (20'th century)
- Solar Metallicy Problem
  - More surprises??

Han Bethe
1906-2005

Bruno Pontecorvo
1913-1993

Ray Davis
1914-2006



John Bahcall
1935-2005

The End