Progress on SNO+

R. Helmer

on behalf of the SNO+ collaboration

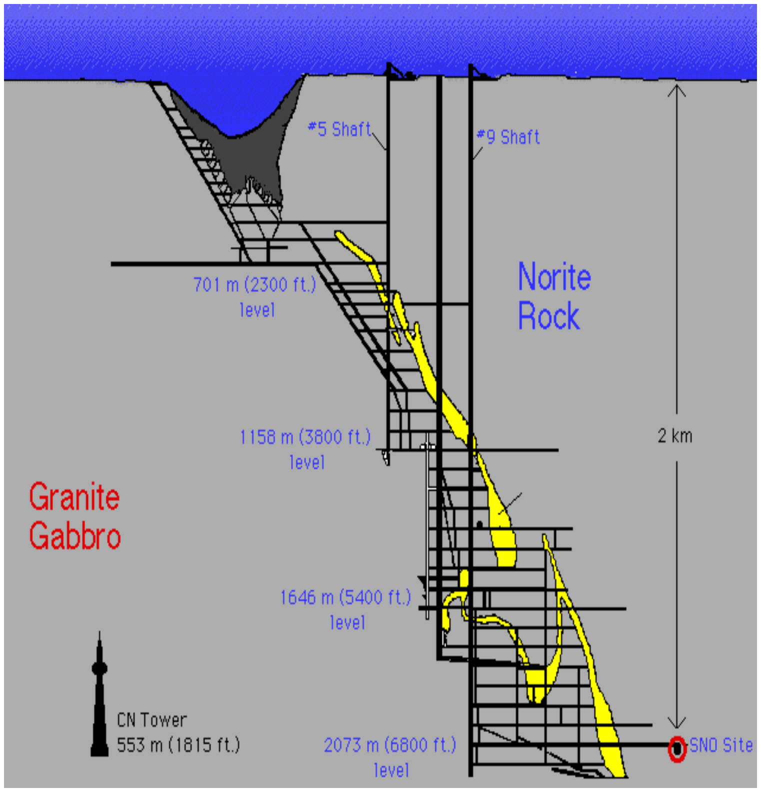
DBD11 Osaka Nov. 14-17, 2011

Outline

- SNO(+) detector
- Physics goals
- Detector changes and upgrades
- Calibration
- Schedule
- Summary

SNO+ Detector

Vale’s Creighton Mine



Deep underground lab

SNO+ Detector

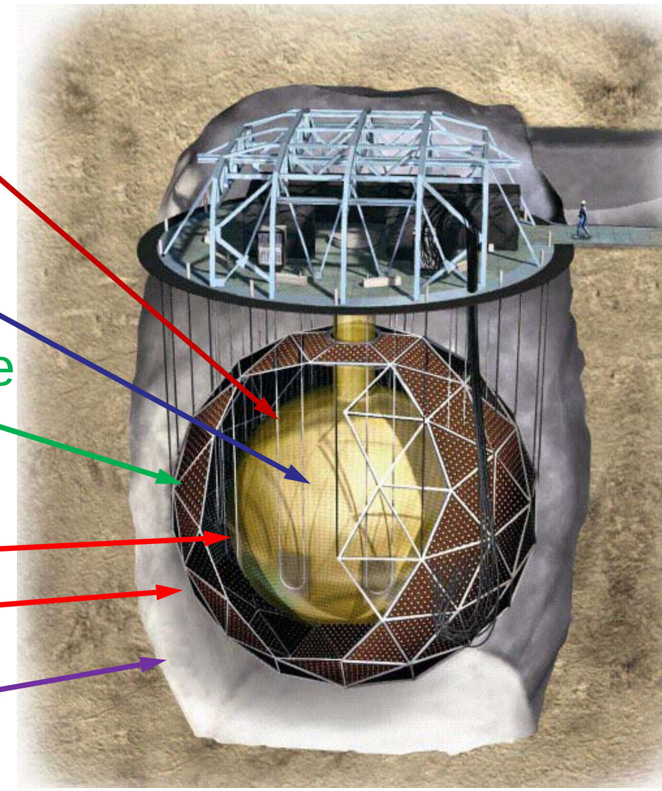
Acrylic Vessel
- 12 m diameter

Liquid scintillator
- 780 t LAB

Phototube sphere
- ~ 9500 PMTs

Water shielding
- 1700 t inner
- 5300 t outer

Urylon liner
- radon seal

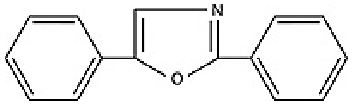


Already exists!

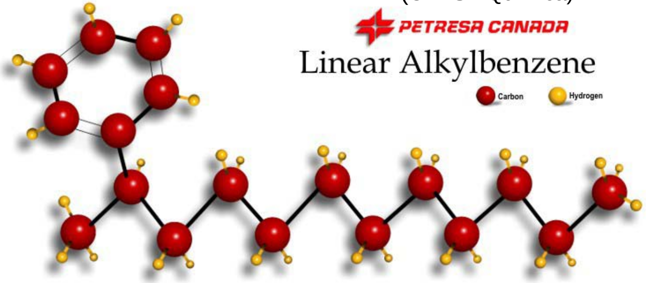
Liquid Scintillator

The scintillator cocktail of choice is Linear Alkylbenzene (LAB) with 2g/L of PPO

PPO



(CEPSA Química)

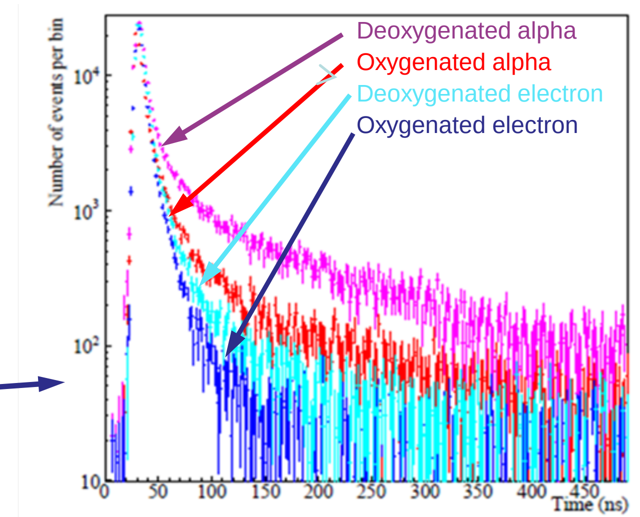


- developed by SNO+ collaborators (Queen's)
- chemically compatible with acrylic
- high flash point, low toxicity – SAFE !
- readily available – LAB is used in the production of detergents
- made in Canada, plant is < 700 km from SNOLAB
- Petresa LAB has the best optical quality of all the LABs SNO+ tested.
- Petresa willing to carry out special steps for SNO+
  - purge all process lines and vessels with boil-off N_2
  - flush with N_2 and dedicate all delivery trucks
- concentration of 2g/L PPO gives emitted light a wavelength distribution that matches the PMT response.

Petresa plant, Bécancour, QC

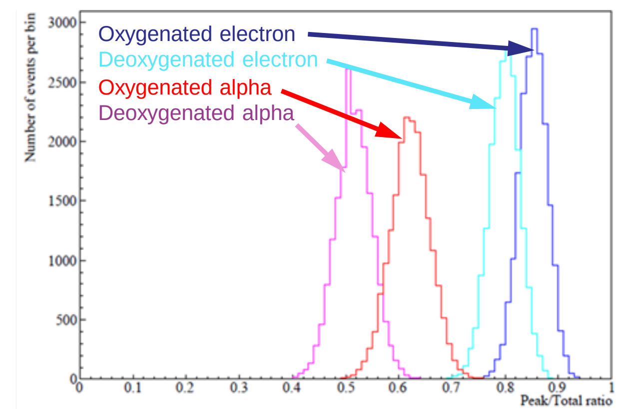
Scintillator Properties

Timing properties of the LAB-PPO scintillator were measured in a simple bench top experiment - see NIM A640 (2011) 119.



Effect of deoxygenating the scintillator on the timing spectra for alphas and electrons.

Ratio of a short time integration window over the peak of each event divided by a long time integration.



These data show the deoxygenated scintillator exhibits slightly better alpha/electron separation, and that it is possible to retain > 99.9% of the electrons while rejecting > 99.9% of the alphas.

Scintillator Properties

AmBe source

"Bucket" source

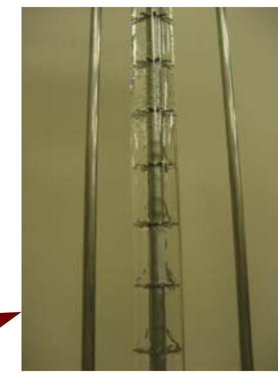
- container filled with LAB
- deployed in SNO water fill
- confirmed bench top results
- Birks' constant determined
- alpha quenching factors measured
- detector response was 480 hits/MeV

A separate measurement showed LAB light output is linear with energy [see NIM A654 (2011) 318]

The refractive index has also been measured. [see Phys. Scripta 03 (2011) 035701].

Scintillator Purification

Prototypes



SNO+ gains from the experiences of:

- Borexino (achieved better than SNO+ goals) and
- KamLAND (developed successful purification techniques)
- SNO+ uses the same construction, purification techniques and materials as Borexino, hence
  - ➢ should achieve same background levels

The target levels are:

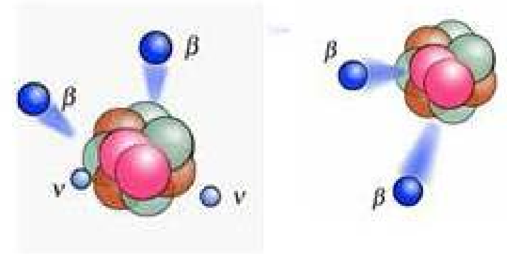
Th: 10^{-17} g/g (~ 3 cpd for ^{208}Tl and ^{228} Ac)
U: 10^{-17} g/g (~ 9 cpd for ^{210,214}Bi)
^{40}K: 1.3 x 10^{-18} g/g (~ 23 cpd)
^{85}Kr, ^{39}Ar: < 100 cpd

To achieve these goals the purification steps include:

- multistage distillation (removes heavy metals, improves UV transparency)
- N_2/water vapour gas stripping using a packed gas stripping tower (removes Rn, Kr, Ar, O_2)
- water extraction (removes K, Ra, Bi)
- metal scavenging (removes Ra, Bi, Pb; also can be used to assay ^{210}Bi, ^{210}Pb - useful when looking for CNO neutrinos)
- microfiltration

Physics Program

Search for neutrinoless ββ-decay



Solar neutrinos:

- precise measurement of pep survival probability
- CNO neutrinos

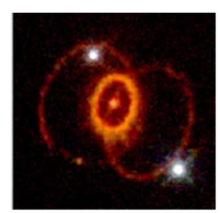
Reactor neutrinos:

- several reactors contribute to oscillations

Geo neutrinos:

- Th, U distributions in earth’s crust

Supernova neutrinos:



- hundreds of events

Neutrinoless ββ-decay

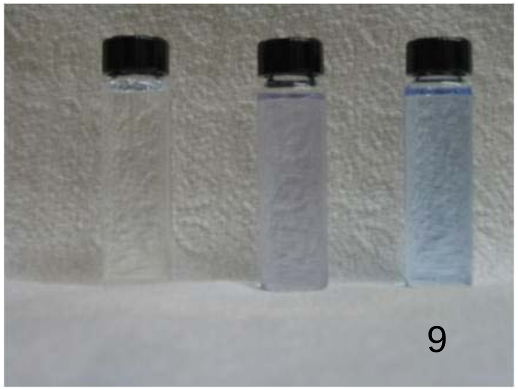
The search for neutrinoless ββ-decay is a high priority within the community to :

- establish whether neutrinos are Dirac or Majorana particles
- probe neutrino masses at the level of tens of meV

^{150}Nd is an excellent candidate:

Isotope	$G^{0\nu}$ (x 10^{-15} y^{-1})	Q-value (MeV)	Abundance %
^{48}Ca	75.8	4.27	0.2
^{76}Ge	7.6	2.04	7.8
^{82}Se	33.5	3.00	9.2
^{76}Zr	69.7	3.35	2.8
^{100}Mo	54.5	3.03	9.6
^{116}Cd	58.9	2.80	7.5
^{130}Te	52.8	2.53	34.5
^{136}Xe	56.3	2.48	8.9
^{150}Nd	249.0	3.37	5.6

- has the largest phase space factor
  - 33 x larger than ^{76}Ge
- has the second largest Q-value – above most backgrounds from natural radioactivity
- for the same effective Majorana neutrino mass, the 0νββ rate in ^{150}Nd is the fastest
- 1% Nd-loaded LAB has been stable over several years
- self-scavenge pH-controlled purification is effective at removing Th and other radioisotopes [see NIM A618 (2010) 124] and optical transmission is improved



Neutrinoless ββ-decay

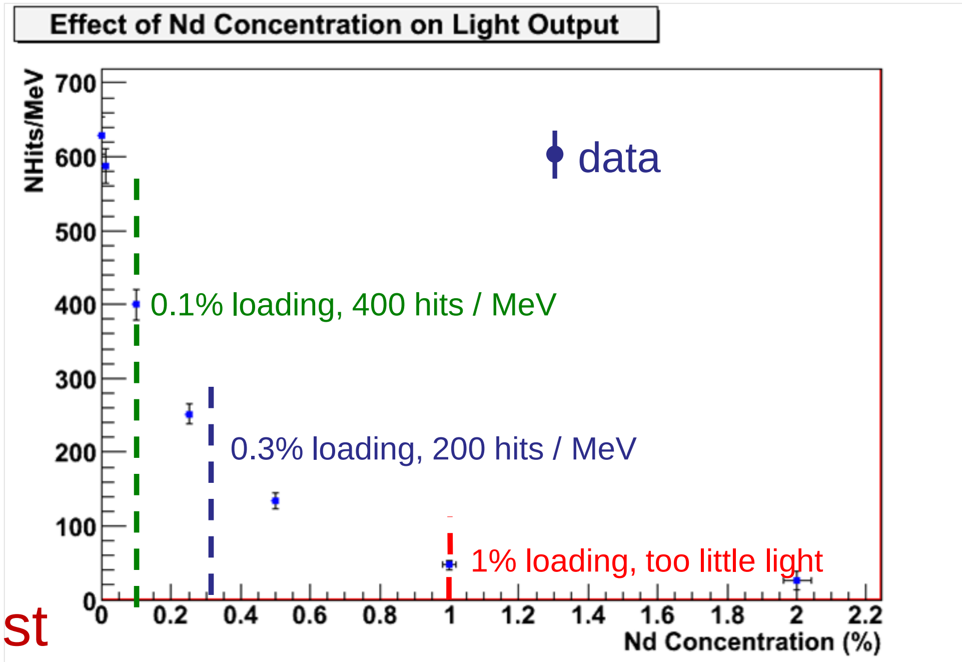
How much Nd?

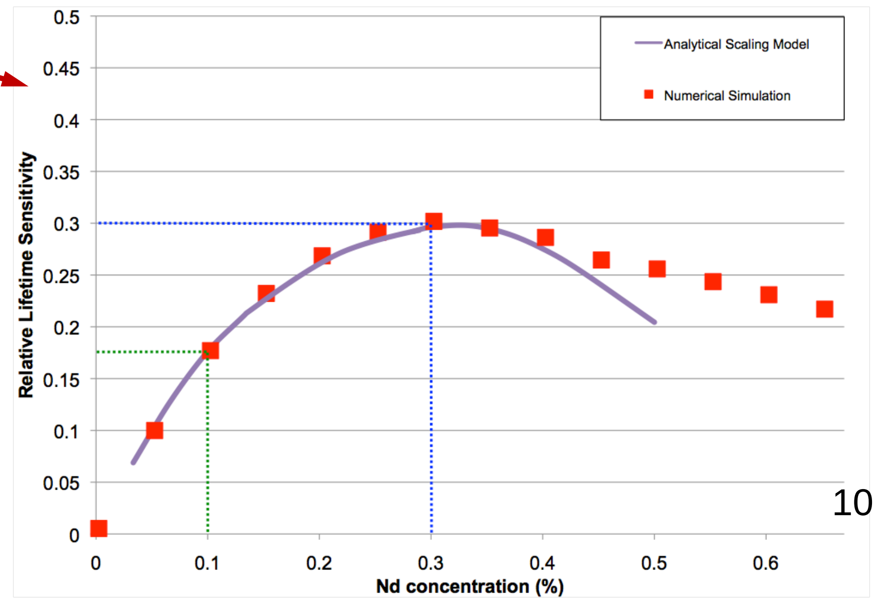
Although 1% loading is stable, there is too little light.

Default loading is 0.1%
(43.6 kg of ^{150}Nd)

But optimization studies suggest 0.3% loading might be a better compromise between light output and statistics.

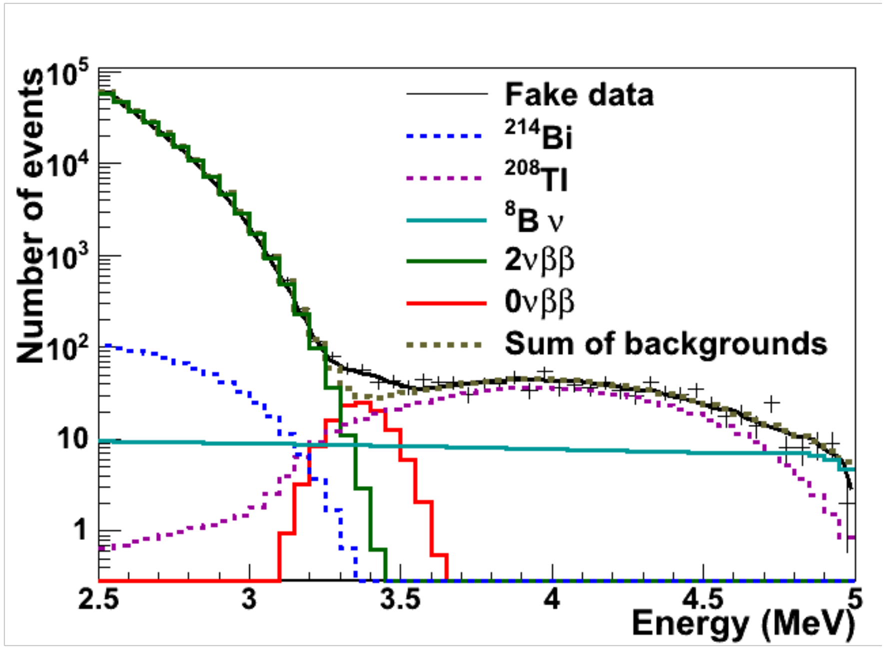
So slowly increase the Nd concentration – Nd signal and background will increase but detector backgrounds will stay the same.





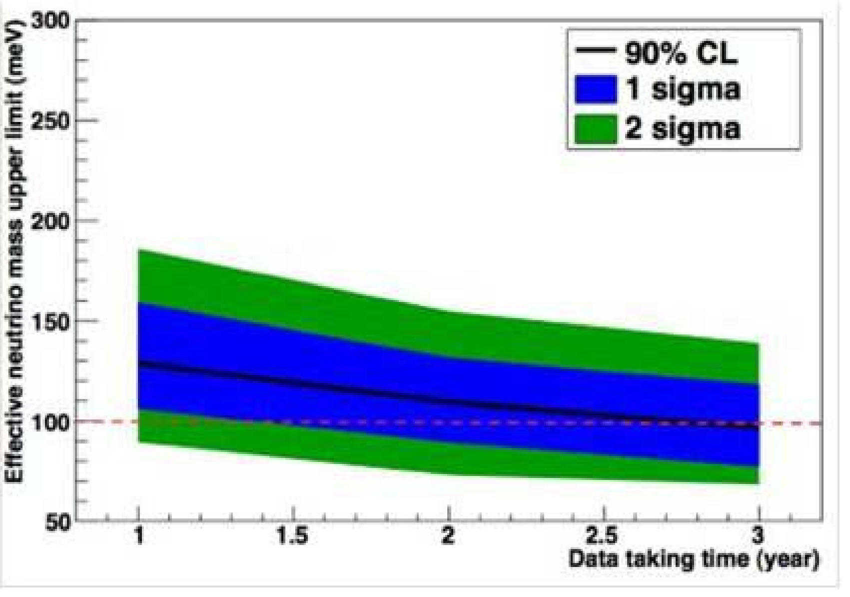
Neutrinoless ββ-decay

ββ-decay signal for 0.1% Nd loaded scintillator



- signal at the level of Klapdor (Phys. Lett. B 586 (2004) 198.)
- ~ 2 years live time
- ^{214}Bi can be tagged and removed
- constrain ^{208}Tl with ^{212}Bi ⟶ ^{212}Po delayed coincidence

Neutrino mass sensitivity for 0.3% Nd loading.



- IBM-2 [Phys. Rev. C 79 (2009) 044301] nuclear m.e. values for Nd were used
- radioactivity backgrounds at the levels achieved by Borexino
- cosmogenic backgrounds included; pile-up under study

Solar pep Neutrinos

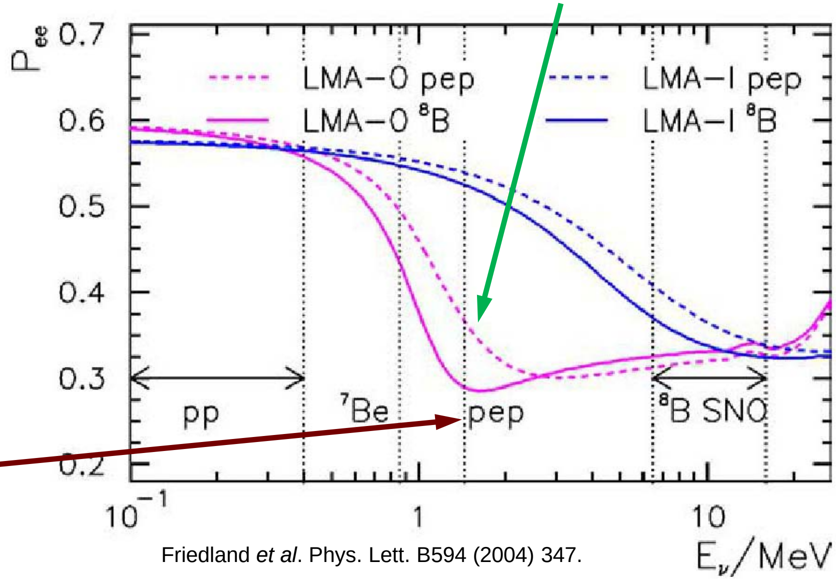
Solar neutrino oscillations are governed by vacuum effects at pp energies and by matter effects at ^{8}B energies.

Transition region between is fertile ground:

- just to observe the shift
- to look for nonstandard interactions.

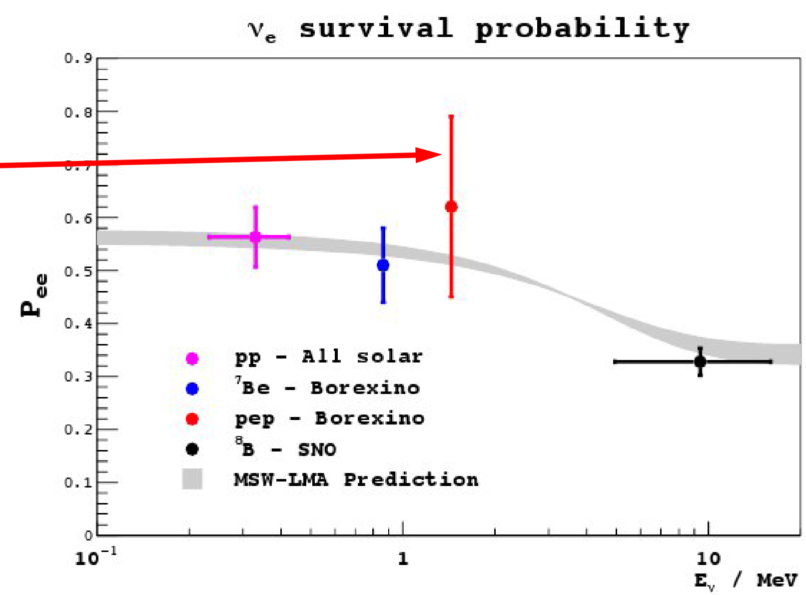
The pep line lies nicely in this region.

NSI in here



Friedland *et al*. Phys. Lett. B594 (2004) 347.

The Borexino Collaboration recently announced the first observation of pep neutrinos. The measured rate was 3.1±0.6(stat)±0.3(syst) counts/(day x 100 t).



Chiavarra at PIC2011, see also arXiv:1110.3230

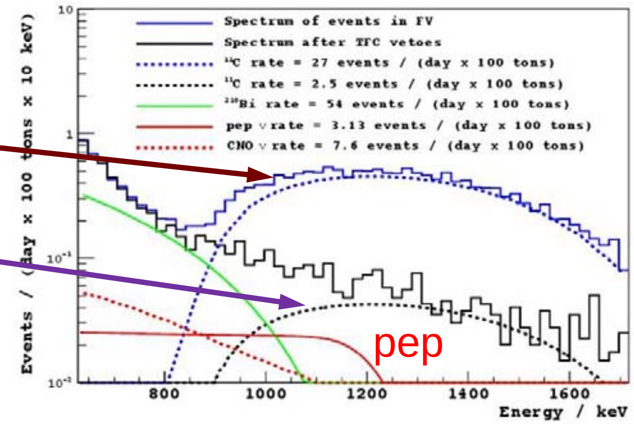
So what can SNO+ do?

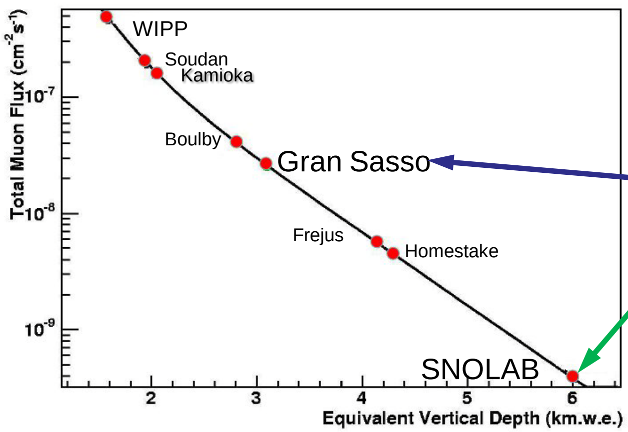
TRIUMF SNO+

Solar pep Neutrinos

Main background to the Borexino pep measurement is the high rate of decay of cosmogenically produced ^{11}C.

Analysis cuts reduce this rate to a manageable level, but at a cost of half the rate of good events.





A reminder

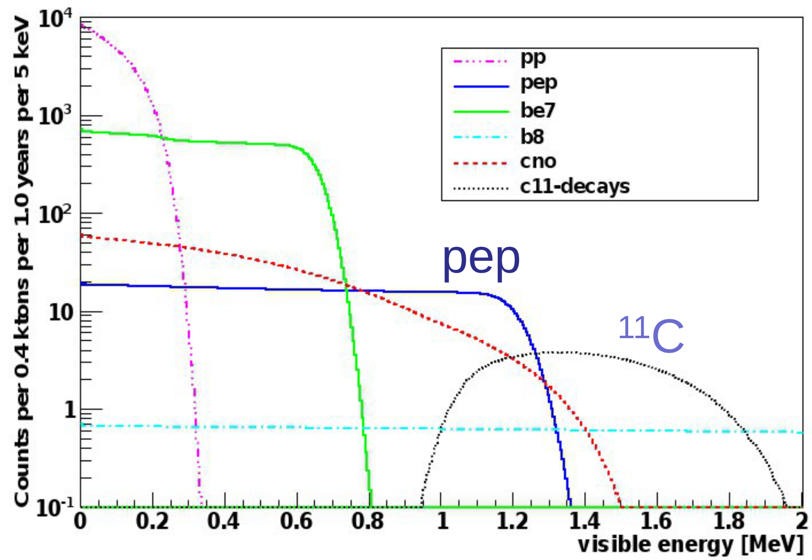
Gran Sasso is at a depth of 3000 mwe compared with SNOLAB at 6000 mwe.

SNO+ is deep! – many fewer muons.

SNO+ has lower background and larger size – can make a precision measurement.

Spectra were analytically generated for one year exposure, with 5%/√E resolution, 400 t fid. vol.

Other backgrounds not shown.



Solar pep Neutrinos

Simulation of the impact of SNO+ pep measurement

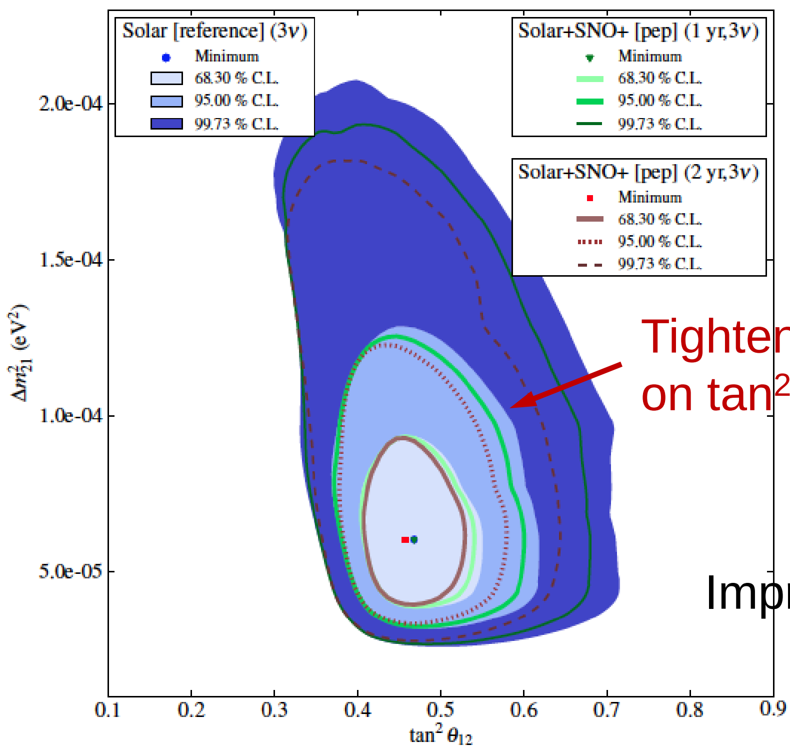
Energy range 0.2 - 6.5 MeV, 50% fid. vol.

Assumes $\tan^2\theta_{12} = 0.468$

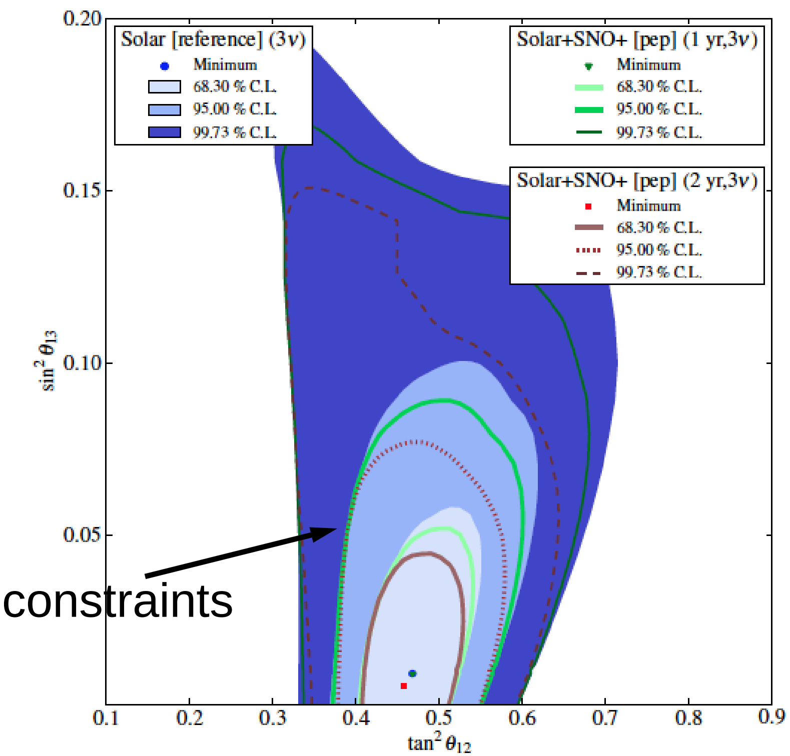
$\Delta m^2_{12} = 6.02 \times 10^{-5}\ eV^2$

$\sin^2\theta_{13} = 0.01$

Does not include latest Borexino results or large θ_{13}



Tightens bound on $\tan^2\theta_{12}$



Improves θ_{13} constraints

Solar CNO Neutrinos

A recent downward revision of solar metal abundances has led to

- better agreement with heavy element abundances in the interstellar medium
- but poorer agreement with helioseismology data

Solar model predicted CNO fluxes are greatly affected by solar elemental abundances. The predicted fluxes differ by > 30%!

Borexino has recently set an upper limit on the CNO flux. SNO+ should do better because it is larger and has a lower ^{11}C background.

Predicted neutrino fluxes

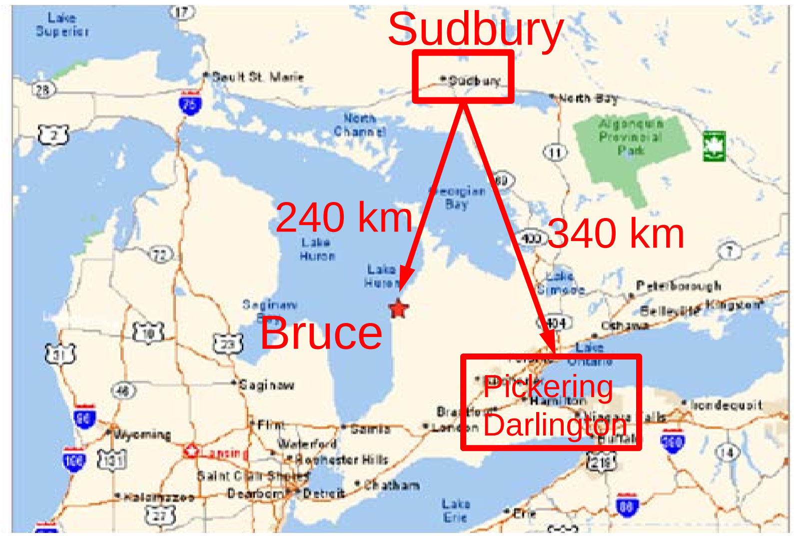
high Z   low Z

Source	BPS08(GS)	BPS08(AGS)	Difference
pp	$5.97(1 \pm 0.006)$	$6.04(1 \pm 0.005)$	1.2%
pep	$1.41(1 \pm 0.011)$	$1.45(1 \pm 0.010)$	2.8%
hep	$7.90(1 \pm 0.15)$	$8.22(1 \pm 0.15)$	4.1%
^{7}Be	$5.07(1 \pm 0.06)$	$4.55(1 \pm 0.06)$	10%
^{8}B	$5.94((1 \pm 0.11)$	$4.72(1 \pm 0.11)$	21%
^{13}N	$2.88(1 \pm 0.15)$	$1.89(1 ^{+0.14}_{-0.13})$	34%
^{15}O	$2.15(1 ^{+0.17}_{-0.16})$	$1.34(1 ^{+0.16}_{-0.15})$	31%
^{17}F	$5.82(1 ^{+0.19}_{-0.17})$	$3.25(1 ^{+0.16}_{-0.15})$	44%
Cl	$8.46^{+0.87}_{-0.88}$	$6.86^{+0.69}_{-0.70}$	
Ga	$127.9^{+8.1}_{-8.2}$	$120.5^{+6.9}_{-7.1}$	

Reactor Neutrinos

KamLAND observed antineutrinos from 53 reactors at an average baseline of 180 km and firmly established the MSW-LMA solution to the SNP.

SNO+ is situated 240 km from one 6.3 GW station (as of 2012) and 340 km from two ~ 3.3 GW stations.



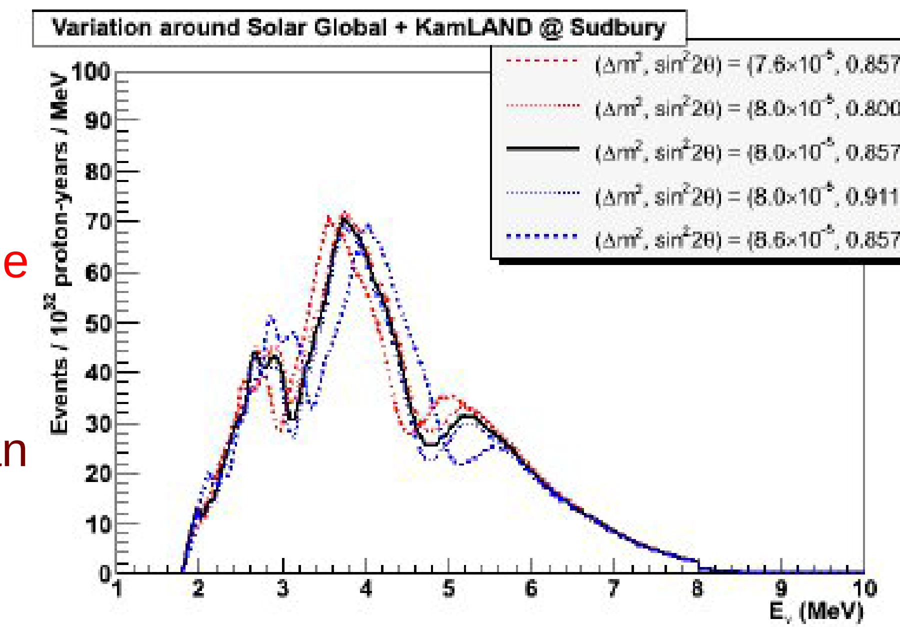
Expect about 90 events/year (oscillated).

The oscillation maximum from Bruce is pushed to higher energies than in KamLAND (constant L/E).

Distance to the other reactors is such that the second oscillation maximum appears.

It so happens that the spectral features line up such that the peak in the spectrum is quite sensitive to Δm^2.

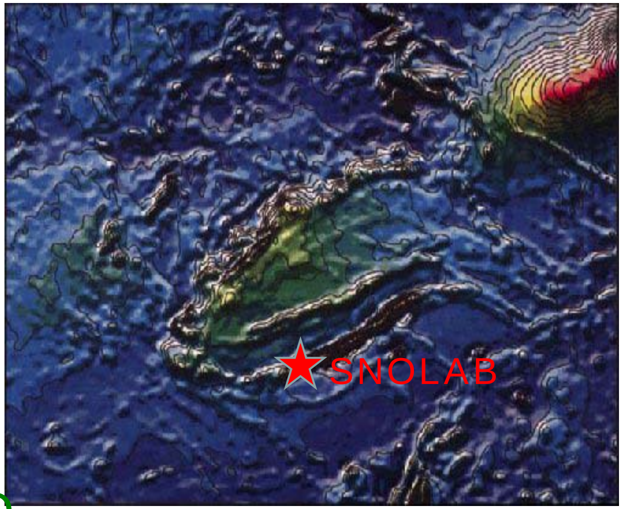
Sensitivity projections show that SNO+ can surpass the current KamLAND limits in about 3½ years of running.



Geo Neutrinos

SNO+ is located in the middle of ancient, thick, continental crust, an ideal location to help answer some of the open questions about Earth's natural radioactivity:

- how much U and Th is in the crust?
- how much is in the mantle?
- is BSE model consistent with geo neutrino data?

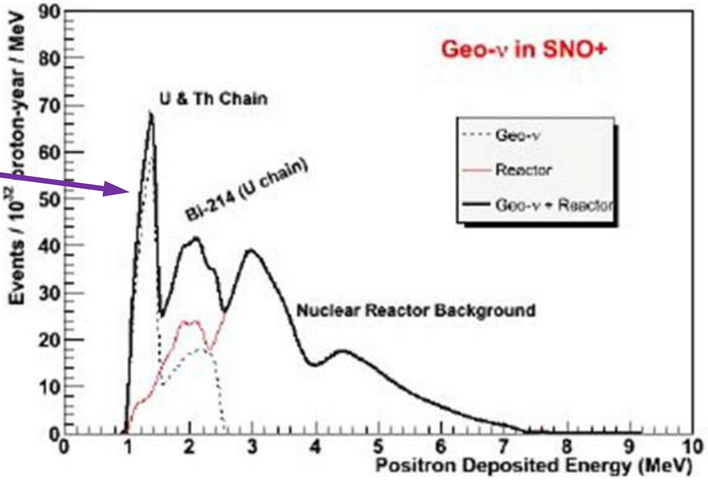


Evidence for geo neutrinos first seen at KamLAND.

SNO+ should see a cleaner signal because of lower background from nuclear reactors:

- reactor/signal ~ 0.9 (SNO+), 4.4 for KamLAND

Spectrum shows that geo neutrinos are quite distinct from the reactor neutrinos, and that U and Th neutrinos can be separately identified.



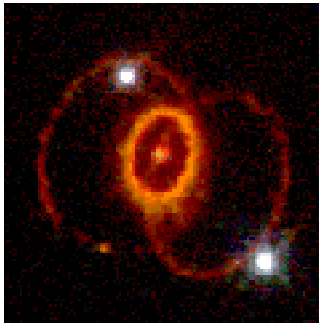
SNO+ expects to detect about 54 events per year in the geo neutrino window; about 25 will come from reactor background.

Supernova Neutrinos

SN1987A

- observed by Kamiokande and IMB (water Čerenkov)
- provided important information about the mechanisms of supernova explosion

A liquid scintillator detector has a larger variety of reactions available – should provide even more information.



SNO+ could observe:

CC:	$\bar{\nu}_e + p \longrightarrow n + e^+$	260 events
	$^{12}C(\nu_e,e^-)^{12}N$	30
	$^{12}C(\bar{\nu}_e,e^+)^{12}B$	10
NC:	$^{12}C(\nu_x,\nu_x)^{12}C_{15.11}$	60
	$\nu_x + p \longrightarrow \nu_x + p$	270
ES:	$\nu_x + e \longrightarrow \nu_x + p$	12

Type II SN at 10 kpc

SNEWS: SNO+ will be a member

Changes and Upgrades

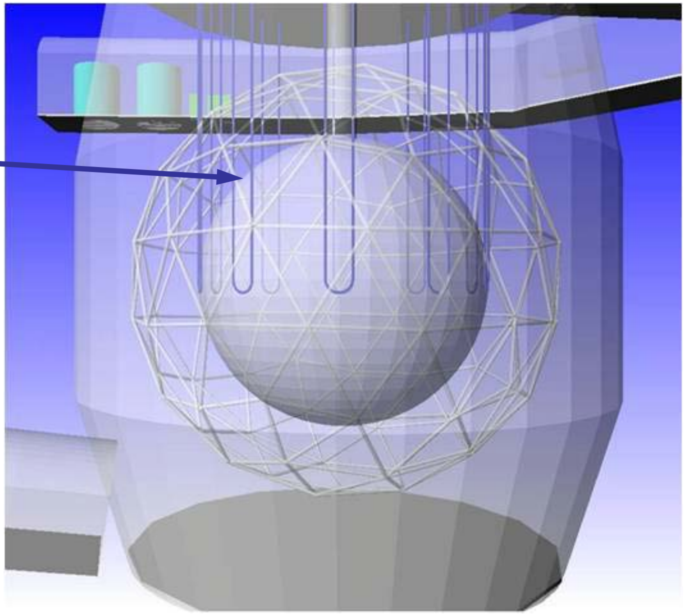
Although re-using the SNO detector for a new experiment is a good idea, it does not come for free!

Many changes and upgrades are needed:

- the way in which the acrylic vessel is supported must be changed
- the vessel must be cleaned and free of radioactivity
- upgrades are needed for the electronics and DAQ
- new process systems are required
- different calibration sources and hardware are needed
- the vessel must be sealed to prevent the ingress of radon
- the liquid scintillator must be developed and procured
- Nd must be purchased and purified

AV Support Ropes

In SNO the acrylic vessel filled with heavy water had to be held up.

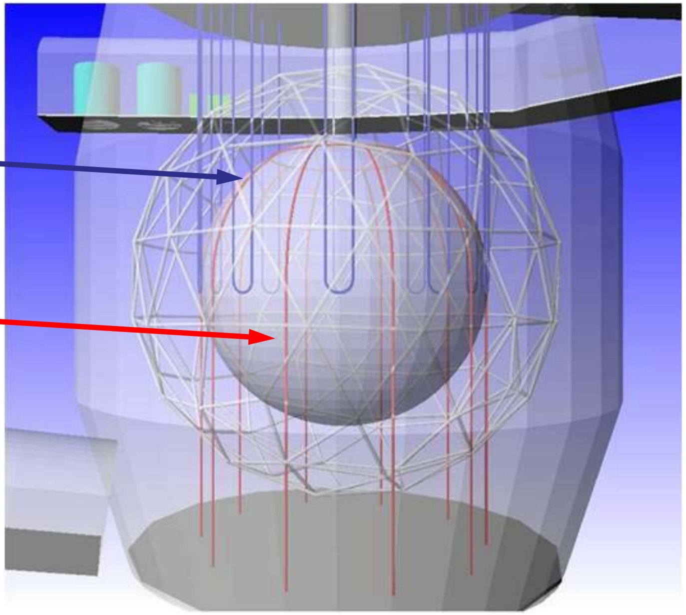


AV Support Ropes

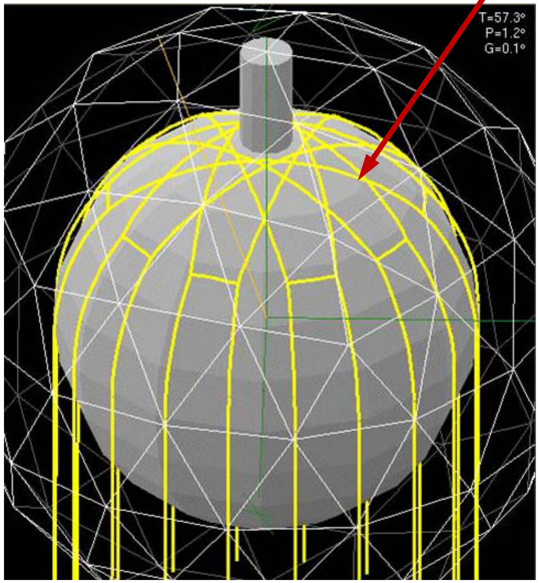
In SNO the acrylic vessel filled with heavy water had to be held up.

In SNO+ the vessel filled with LAB has to be held down.

Up ropes were vectran, need to be replaced as well – 30 times too much potassium. All ropes will be fabricated from tensylon.



Hold down rope net overlays the vessel



Umbrella keeps dust off the vessel and phototube sphere during construction.

Drilling holes for the anchor bolts

Acrylic Vessel Sanding

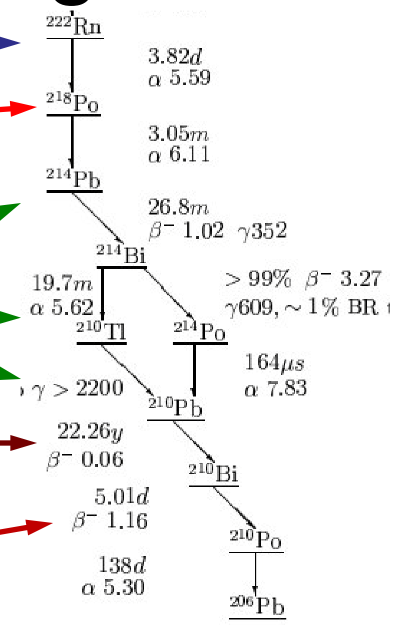
Mine air is laden with radon.

^{218}Po can be electrostatically attracted to the AV walls.

Some ^{218}Po α-decay daughters will recoil and be implanted into the acrylic.

Eventually get long-lived ^{210}Pb, which could be leached into the LAB.

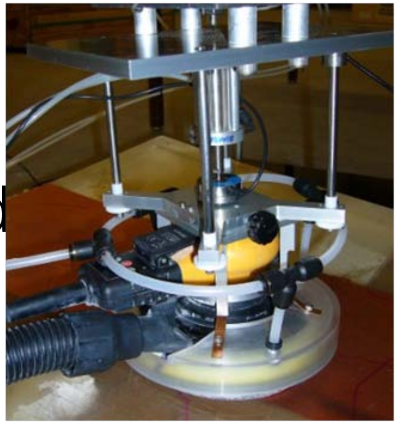
The β-decay spectrum of ^{210}Bi is nearly degenerate with the CNO spectrum.

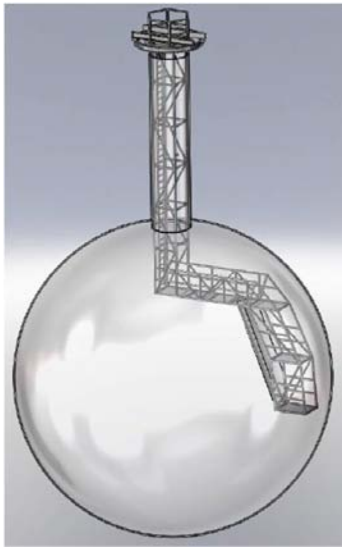


Earlier studies at the end of SNO showed several times more Po α decays from above the water level than from below.

The inside of the AV has been exposed to mine air for several years – hence sand the inside.

About 20 μm will be removed.

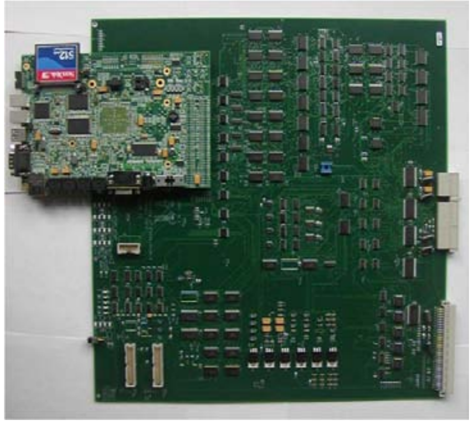




Electronics

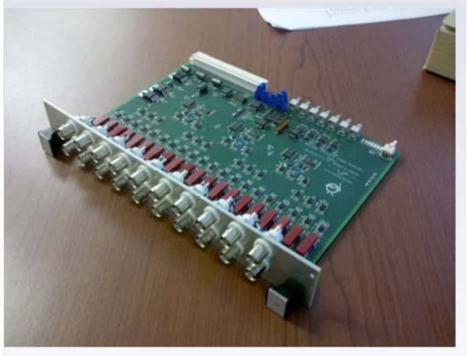
Differences between SNO and SNO+

- much more light/MeV (400 hits vs. 9)
- lower threshold → higher event rate
  - 3.5 kBytes/s in SNO vs. 120 kBytes/s in SNO+
  - max sustained rate 300 kBytes/s vs. 2 Mbytes/s
    - not enough bandwidth in SNO electronics
    - too much current for SNO trigger sum
- more isotropic distribution of light



Increase data bandwidth by putting local intelligence in each crate. Data are digitized and stored on ML403 board.

New card to sum triggers from all crates.
Sums voltage rather than current.
Digitized by CAEN digitizer.



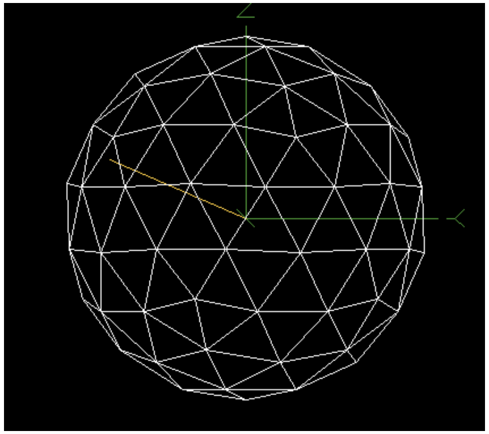
Several other boards being refurbished.

Optical Calibration

The laserball was the workhorse for the optical calibration of SNO and was deployed monthly.

Because of the stringent radiopurity requirements and risk of contamination, we don't want to deploy it as often in SNO+.

Therefore, it will be augmented by the Ellie system - (Tellie, Smellie, Amellie) – LED driven fibres mounted on the phototube sphere to monitor:



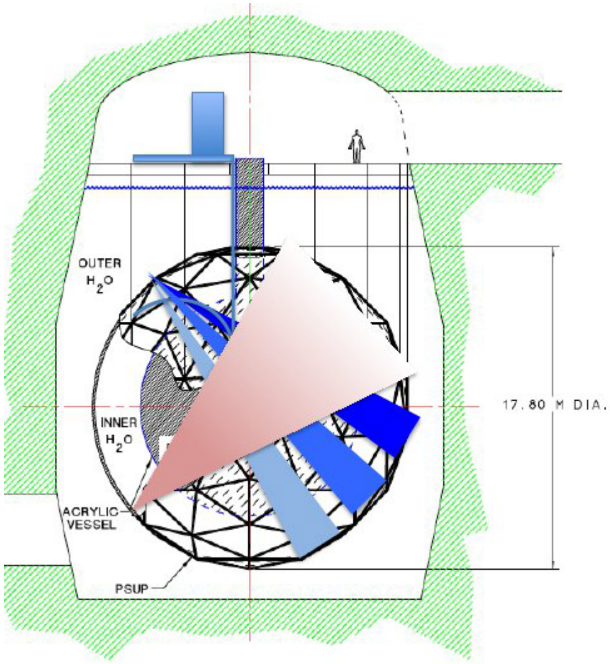
- PMT timing calibration and gain
- scattering and attenuation lengths

in real time with less risk of contamination.

Optical Calibration - ELLIE

Light will be emitted with varying:

- wavelength
- opening angle
- position
- direction



Each system is tuned to monitor a specific aspect of the detector response:

- Tellie – monitor timing (T0 and time walk) and gain calibration of the PMTs.
- Amellie – measure light attenuation in detector volume using wide angle beams.
- Smellie – measure scattering within the detector volume using collimated beams at several wavelengths.

Other Calibration Sources

^{60}Co – 0.32 MeV β, 2.5 MeV summed ɣ
- energy scale, multivertex reconstruction, pile-up

^{48}Sc – 0.66 MeV β, 3.3 MeV summed ɣ, close to Nd 0νββ end point
- energy scale, reconstruction, position dependence, Nd absorption

^{8}Li (Čerenkov source)
- only Čerenkov light in detector, no scintillation
- PMT efficiency, LAB absorption/re-emission timing

AmBe – n, 4.4 MeV ɣ
- Lght yield, neutron propagation, reconstruction, Nd absorption

^{16}N – 6 MeV ɣ
- energy scale, sacrifice and contamination, check detector model in water fill

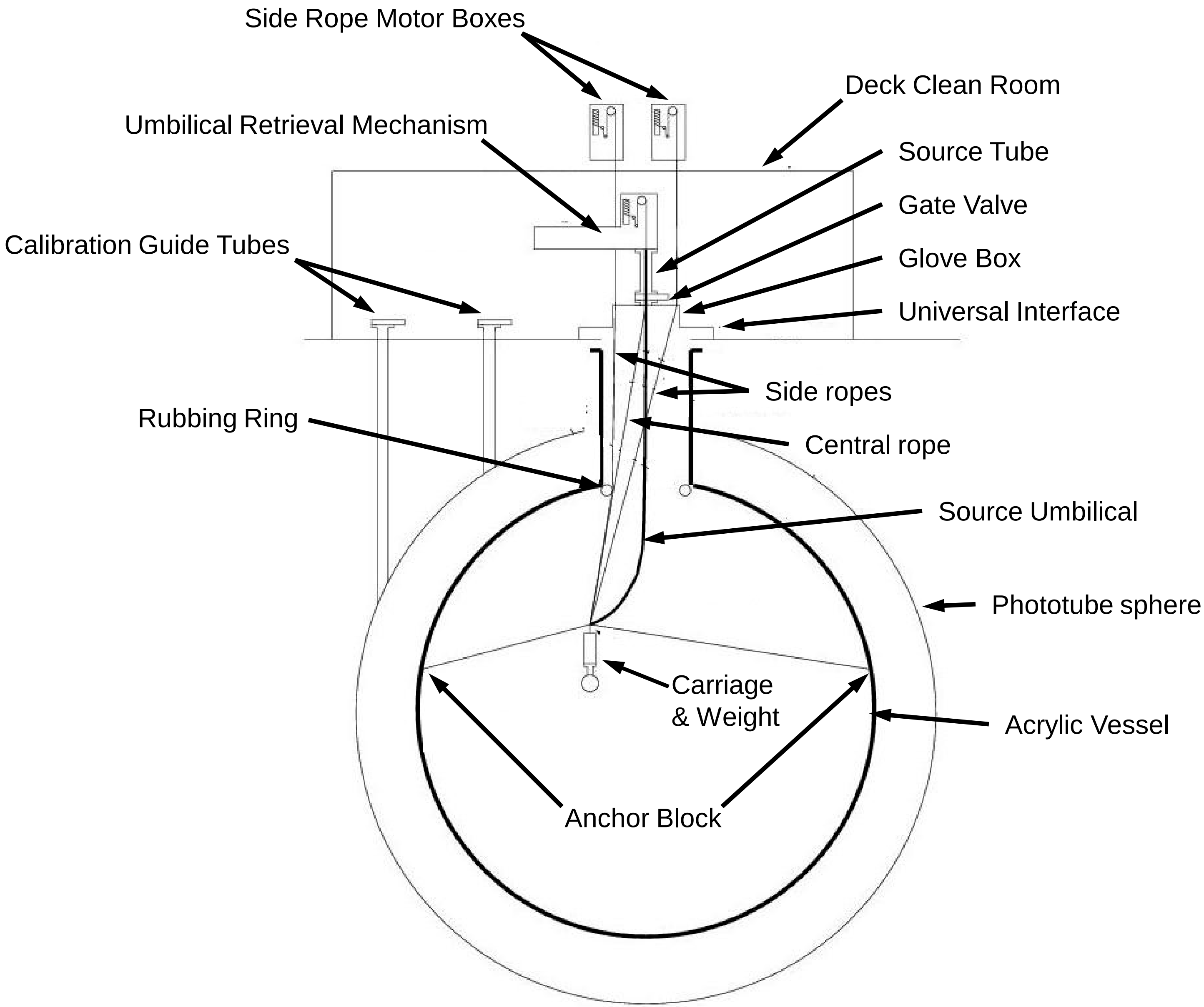
radon source ball
- alpha quenching, beta response, scintillator timing response

low energy gamma source – to be determined
- energy scale, reconstruction, position dependence

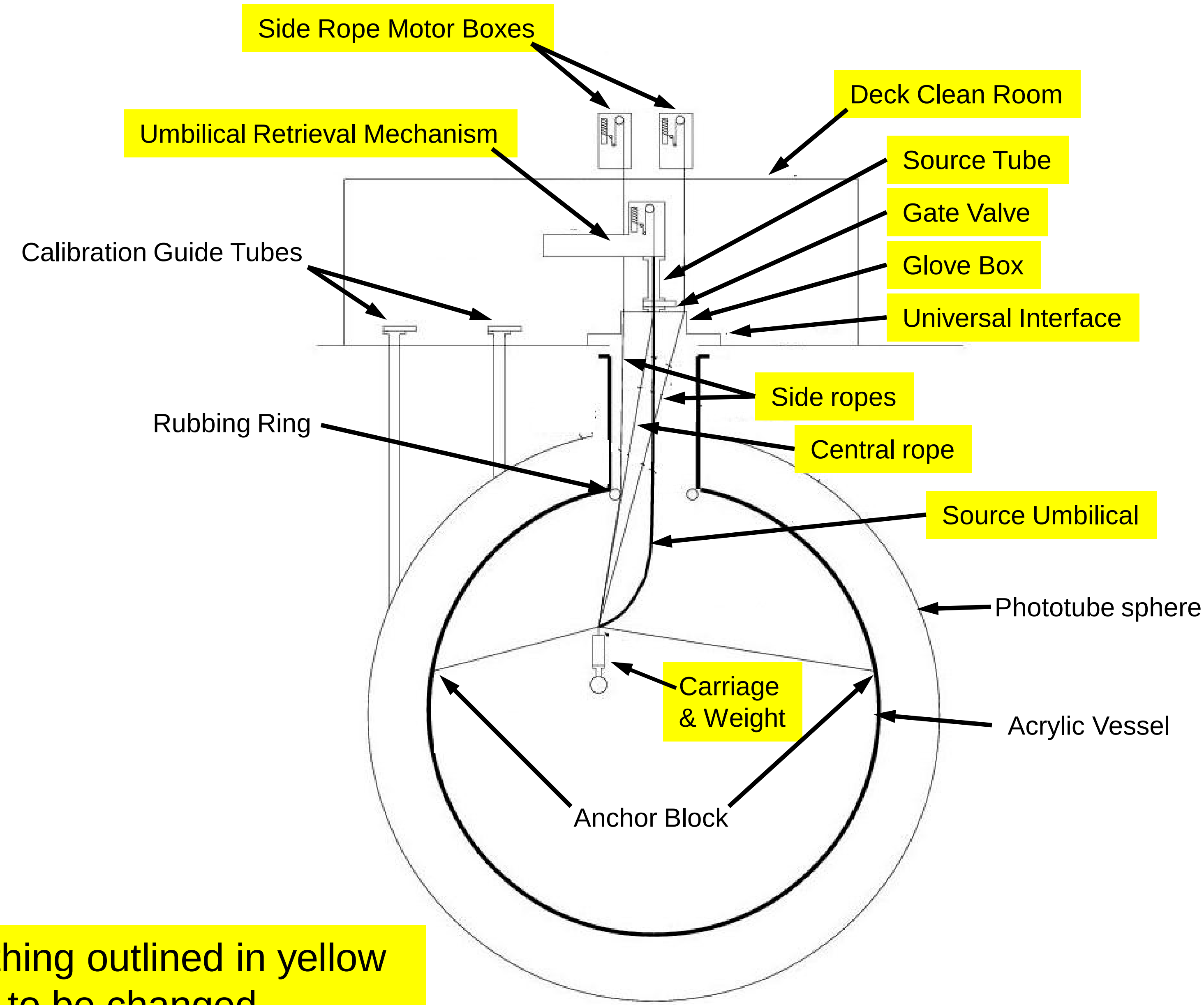
camera system – six cameras spaced around the phototube sphere
- locate sources within 1 cm (5 cm in SNO), monitor AV position

Extensive materials testing program – any material that can contact the LAB is tested for radon emanation and leaching of radioactive or other impurities

Calibration Source Deployment Hardware



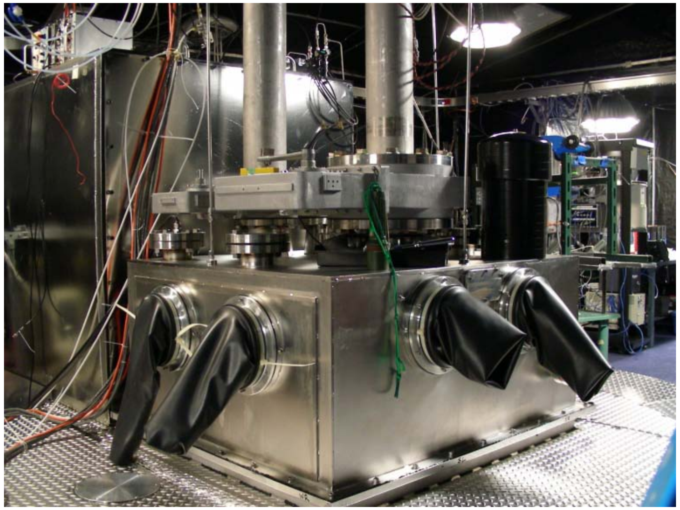
Calibration Source Deployment Hardware



Everything outlined in yellow needs to be changed.

Universal Interface Region

SNO glove box and UI



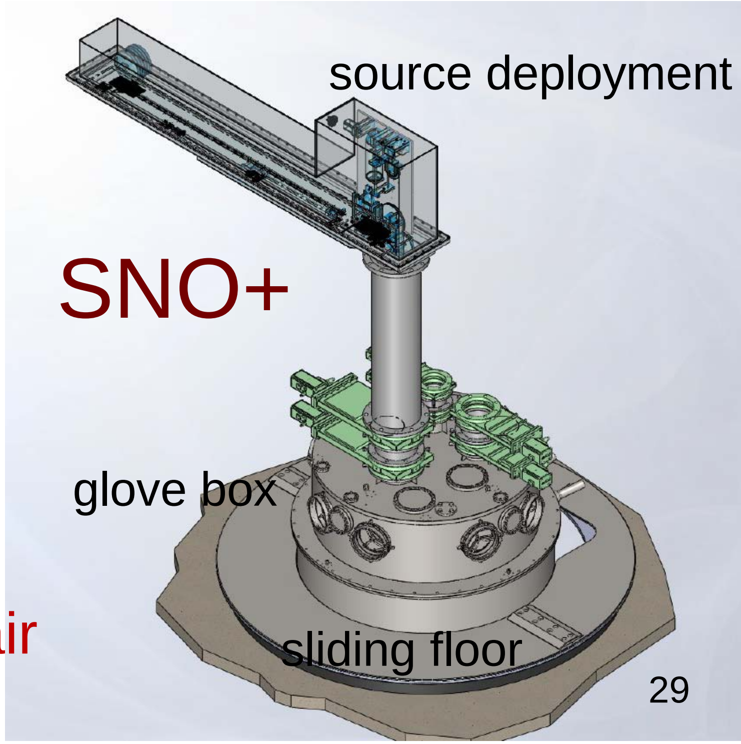
- gaskets and single O-rings to seal against mine air
- a single cover gas system for D_2O and H_2O

Radioactivity requirements for SNO+ are much more stringent.

Mine air must not get in.

Leak rate goal is < 2 x 10^{-6} mbar.L/s

- seals are double O-ring or ConFlat
- UI is double O-ringed sealed to AV
- calibration sources will be kept either in deployment mechanism or storage box and will not be exposed to mine air
- separate cover gas systems



Approximate Timeline

Jan. 2012 – air fill – commission new electronics and DAQ

May 2012 – Aug 2012 - water fill

Aug 2012 – Feb 2013 - water fill data

- commission new hardware
- check PMT mapping – some PMTs have been repaired/moved
- re-establish optical model of the detector
- get background estimates and channel efficiencies
- develop energy/position reconstruction
- tune data cleaning cuts
- some physics – nucleon decay

Feb 2013 – May 2013 – scintillator fill

May 2013 - ? – run pure scintillator (a few months)

- understand detector's scintillator response
- repeat most water fill activities
- more physics - low energy solar data

When happy, start Nd introduction and 0νββ-decay experiment

Summary

The original proposal was to re-use the SNO detector, filled with liquid scintillator, to make a measurement of pep neutrinos.

It was quickly realized that measurements of CNO, reactor, and geo neutrinos would come along for free.

Hundreds of events will be observed in the event of a supernova in the Galaxy.

And as well as all that, a double beta-decay experiment will be carried out.

A nice reincarnation of the detector that was originally used to unambiguously establish flavour change of electron neutrinos from the sun!

The SNO+ Collaboration

University of Alberta A. Bialek, P. Gorel, A. Hallin,
M. Hedayatipoor, C. Krauss, Z. Petriw, L. Sibley, J. Soukup
Armstrong Atlantic State University J. Secrest
Black Hills State University K. Keeter
Brookhaven National Laboratory W. Beriguete, R. Hahn, S. Hans, L. Hu, R. Rosero, M. Yeh,
Y. Williamson
Technical University of Dresden N. Barros, V. Lozza, B. von Krosigk, F. Krüger, P. Schrock, K. Zuber
Laurentian University D. Chauhan, E. D. Hallman, C. Kraus, M. Schwendener, T. Shantz, C. Virtue
University of Leeds S. Bradbury, J. Rose
LIP Lisboa + Coimbra S. Andringa, J. Carvalho, L. Gurriana, A.Maio, J. Maneira
University of Liverpool N. McCauley
University of North Carolina at Chapel Hill M. Howe, J. Wilkerson
Oxford University S. Biller, I. Coulter, P. Jones, N. Jelley, A. Reichold
University of Pennsylvania E. Beier, R. Bonventre, W. J. Heintzelman, J. Klein, P. Keener,
R. Knapik, A. Mastbaum, G. Orebi Gann, T. Shokair, R. Van Berg
Queen Mary, University of London J. Wilson, F. di Lodovici
Queen's University S. Asahi, M. Boulay, M. Chen, K. Clark, N. Fatemi-Ghomi, P. J. Harvey,
C. Hearns, A. McDonald, A. Noble, H. M. O'Keeffe, T. Sonley, E. O'Sullivan, P. Skensved, I. Takashi
SNOLAB C. Beaudoin, G. Bellehumeur, O. Chkvorets, B. Cleveland, F. Duncan, R. Ford, N. Gagnon,
C. Jillings, S. Korte, I. Lawson, T. O'Malley, M. Schumacher, E. Vásquez-Jáuregui
University of Sheffield J. McMillan
University of Sussex E. Falk, S. Fernandes, J. Hartnell, G. Lefeuvre, S. Peeters, J. Sinclair, R. White
TRIUMF R. Helmer
University of Washington S. Enomoto, J. Kaspar, J. Nance, D. Scislowski, N. Tolich,
H. Wan Chan Tseung