

The SNO+ Experiment

R. Helmer

on behalf of the SNO+ collaboration

Neutrino Workshop

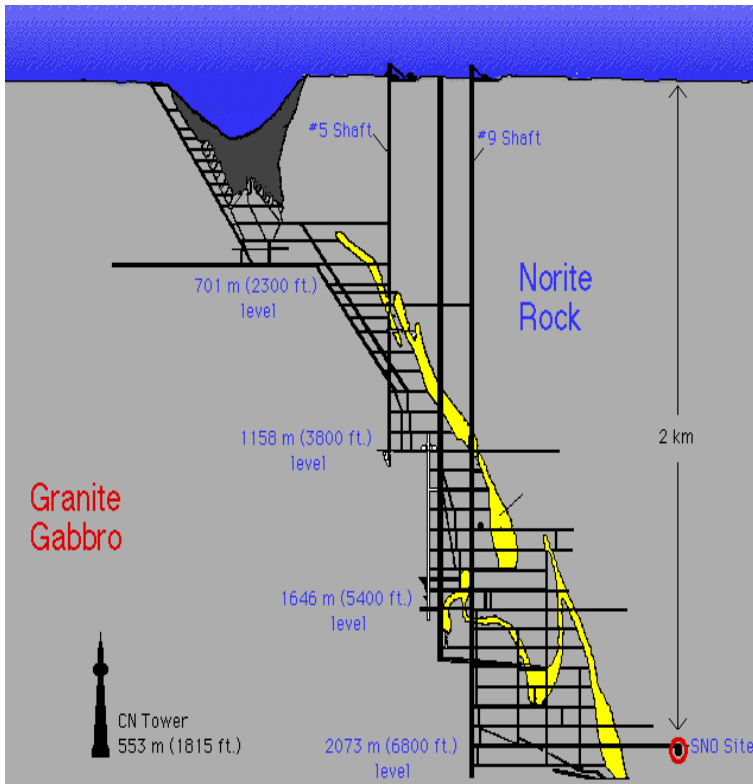
TRIUMF

Nov. 12-14, 2012

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

SNO Detector (reminder)

Vale's Creighton Mine



SNO Detector

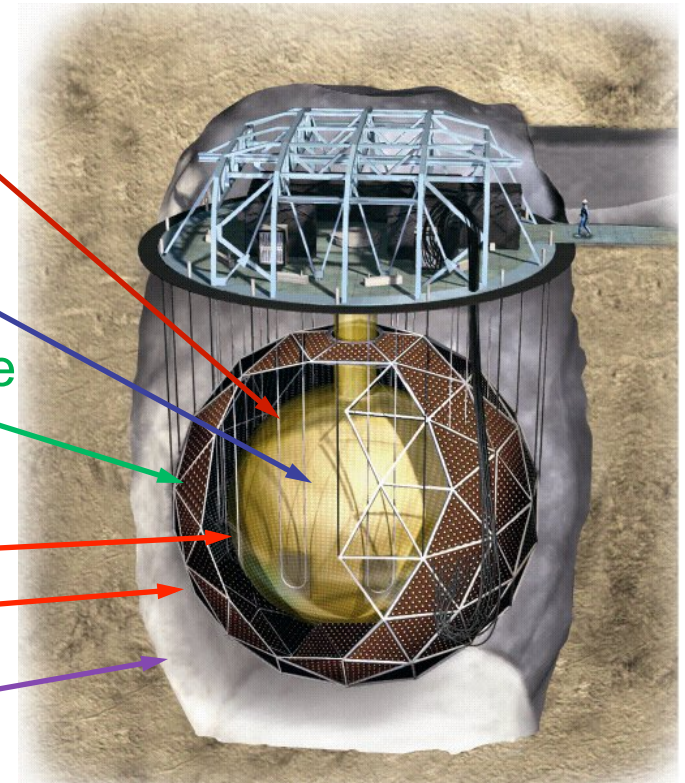
Acrylic Vessel
- 12 m diameter

Heavy water
- 1000 t D₂O

Phototube sphere
- ~ 9500 PMTs

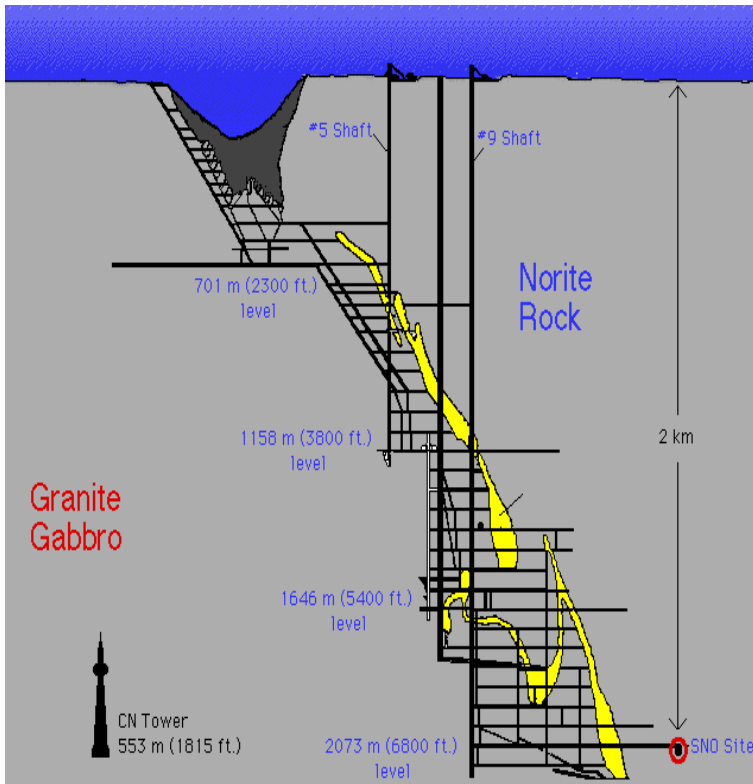
Water shielding
- 1700 t inner
- 5300 t outer

Urylon liner
- radon seal



Deep underground lab

Vale's Creighton Mine



Deep underground lab

SNO+ Detector

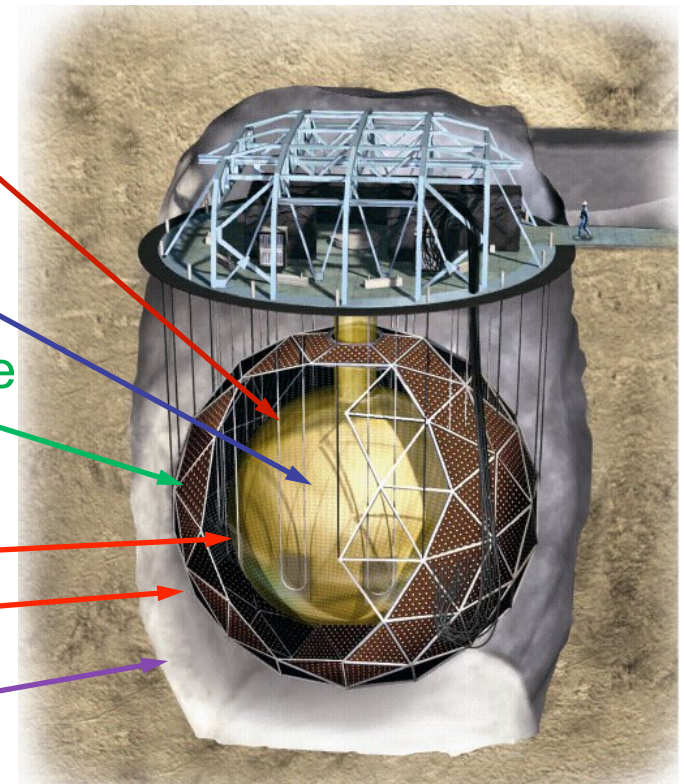
Acrylic Vessel
- 12 m diameter

Liquid scintillator
- 780 t LAB

Phototube sphere
- ~ 9500 PMTs

Water shielding
- 1700 t inner
- 5300 t outer

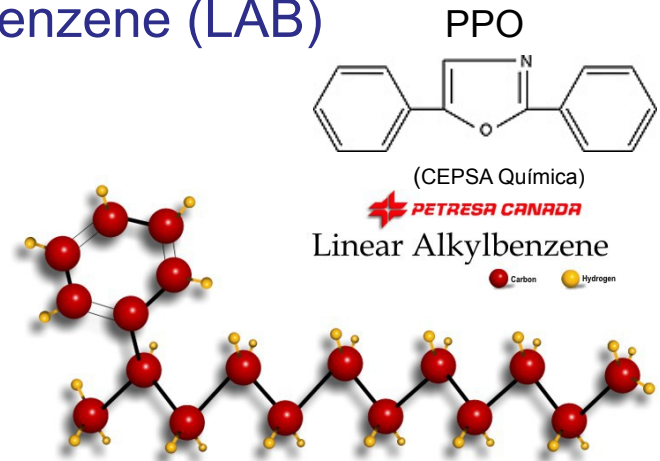
Urylon liner
- radon seal



Already exists!

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

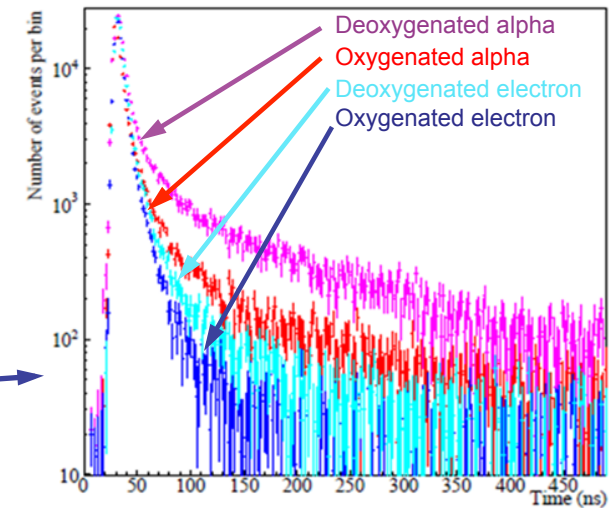
- developed by SNO+ collaborators (Queen's)
- chemically compatible with acrylic
- high flash point, low toxicity – SAFE !
- large light output – expect > 400 hits/MeV (9 hits/MeV in SNO)
- readily available – LAB is used in the production of detergents
- made in Canada, plant is < 700 km from SNOLAB
- 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 N₂
 - flush with N₂ and dedicate all delivery trucks
- concentration of 2g/L PPO gives emitted light a wavelength distribution that matches the PMT response.



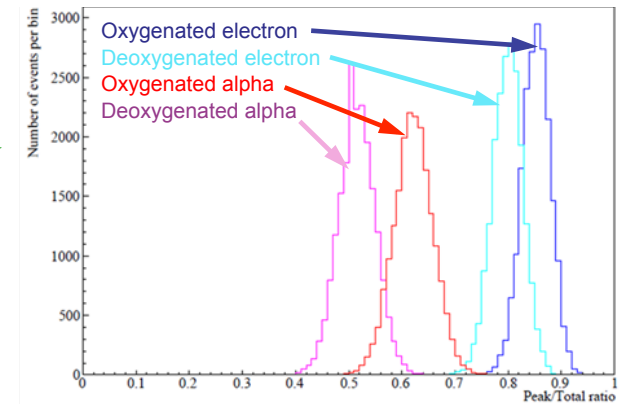
Petresa plant, Bécancour, QC

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.

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

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 $^{210,214}\text{Bi}$)

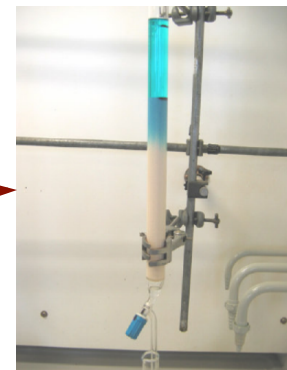
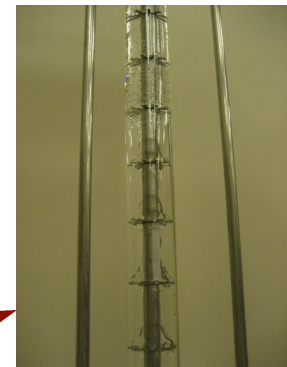
^{40}K : 1.3×10^{-18} g/g (~ 23 cpd)

^{85}Kr , ^{39}Ar : < 100 cpd

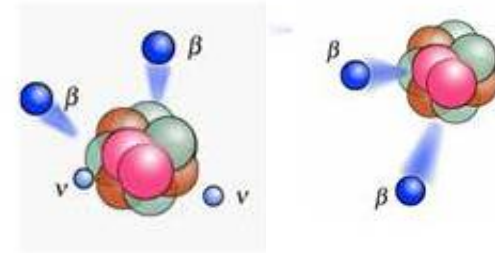
To achieve these goals the purification steps include:

- 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

Prototypes



Search for neutrinoless $\beta\beta$ -decay
(highest priority for SNO+)



Solar neutrinos:

- precise measurement of pep survival probability
- CNO and ^8B neutrinos



Reactor neutrinos:

- several reactors contribute to oscillations



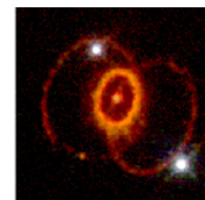
Geo neutrinos:

- Th, U distributions in earth's crust



Supernova neutrinos:

- hundreds of events



The search for neutrinoless $\beta\beta$ -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:

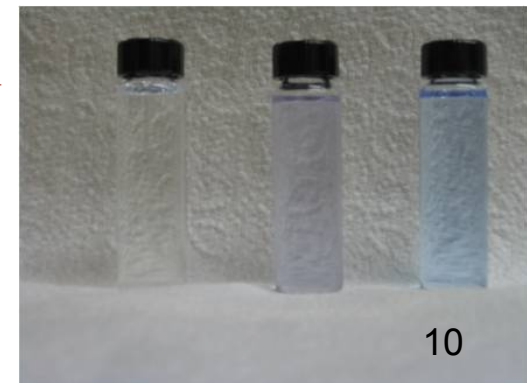
- has the largest phase space factor
- 33 x larger than ^{76}Ge
- has the second largest Q-value – above most backgrounds from natural radioactivity
- for the same effective Majorana neutrino mass, $0\nu\beta\beta$ in ^{150}Nd has the fastest calculated rate
- 1% Nd-loaded LAB has been stable over several years
- self-scavenge pH-controlled purification is effective at removing Th and other

radioisotopes

[see NIM A618 (2010) 124]

and optical transmission is improved

Isotope	$G^{0\nu}$ ($\times 10^{-15} \text{ y}^{-1}$)	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



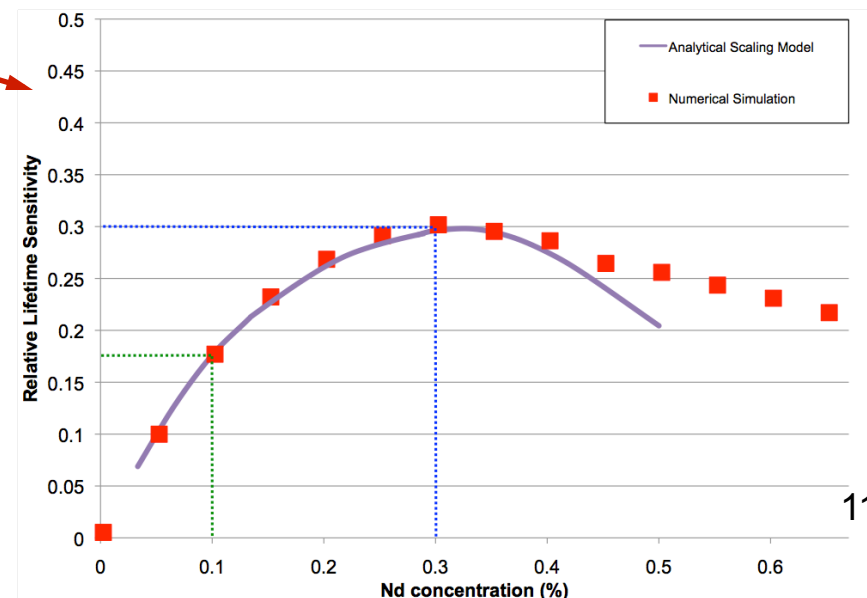
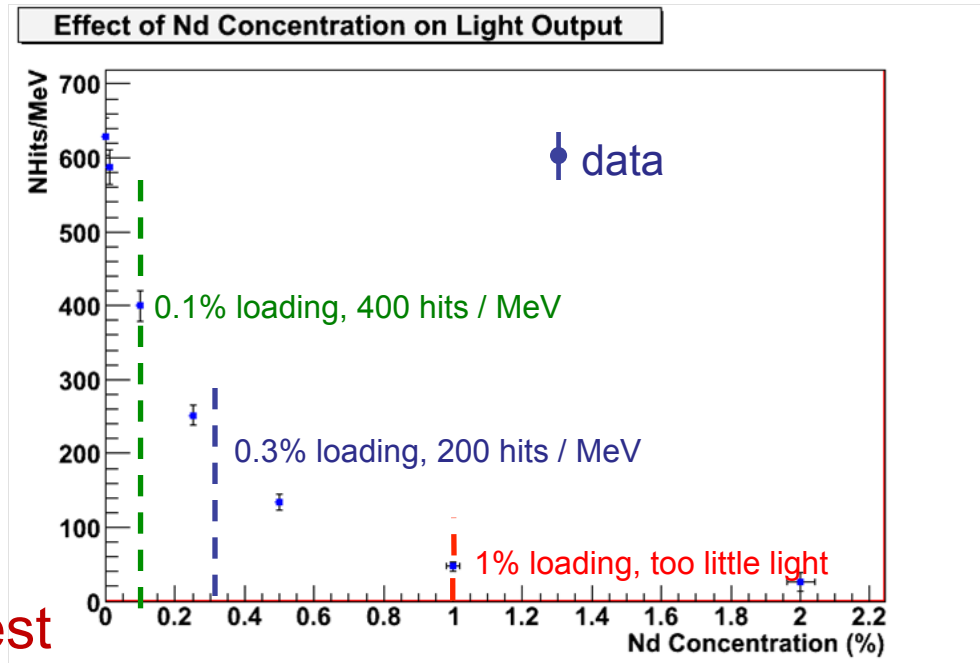
How much Nd?

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

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

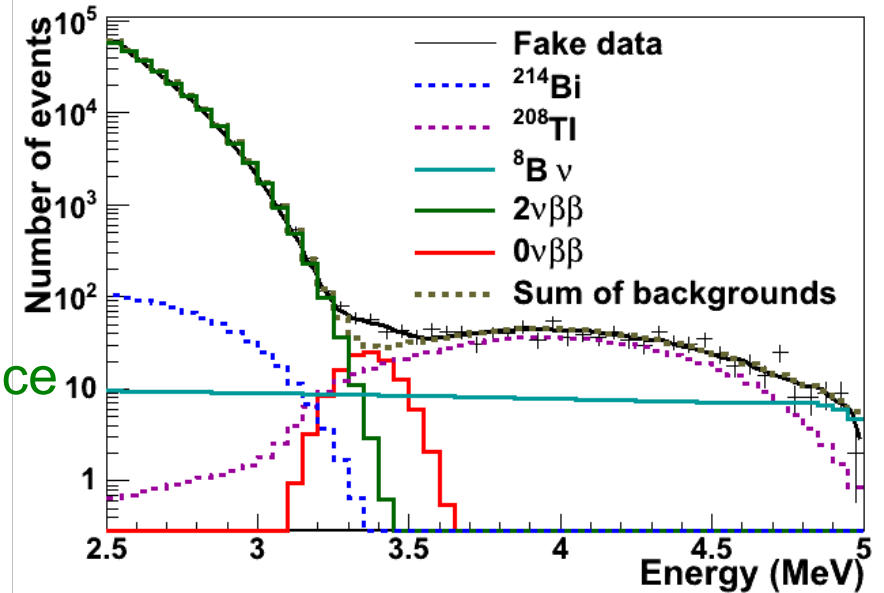
But optimization studies suggest 0.3% loading might be a better compromise between light output and statistics.

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



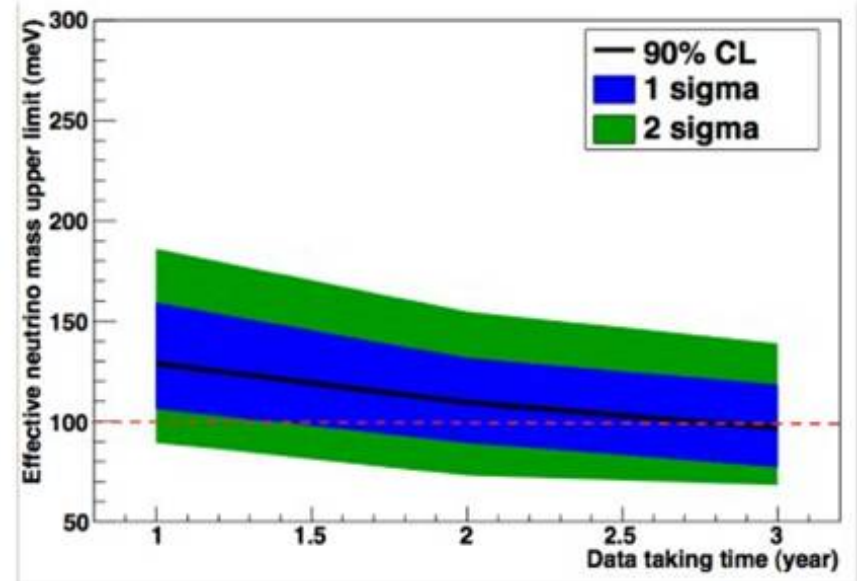
$\beta\beta$ -decay signal for 0.1% Nd loaded scintillator

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



The flux of pep neutrinos is a fundamental quantity in the Standard Solar Model.

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

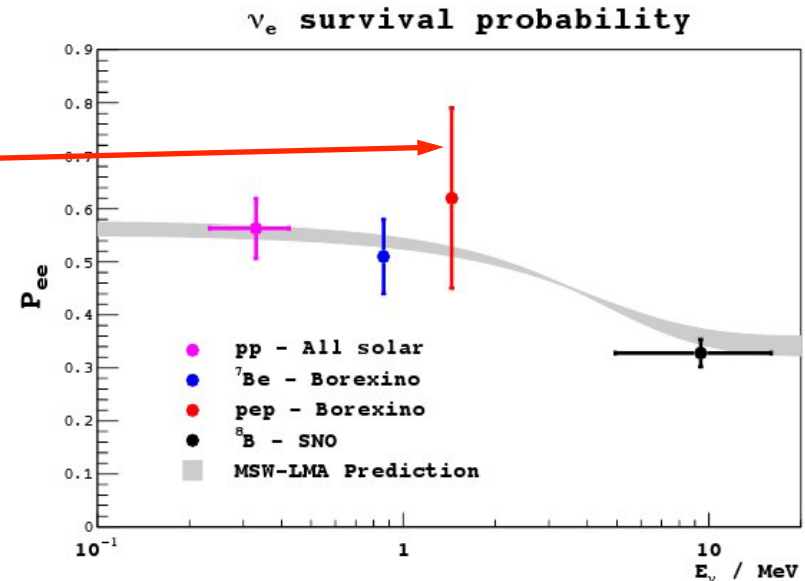
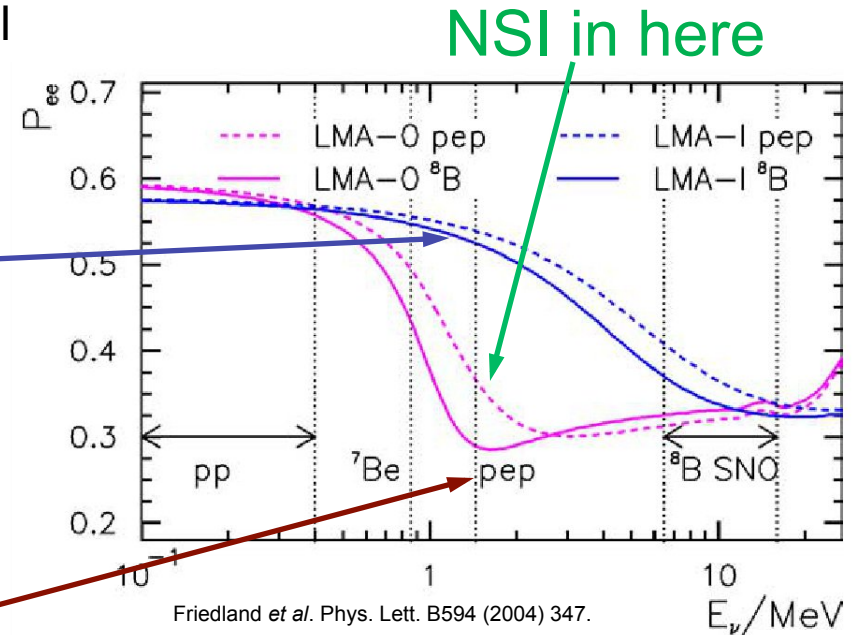
Transition region between is fertile ground:

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

The pep line lies nicely in this region.

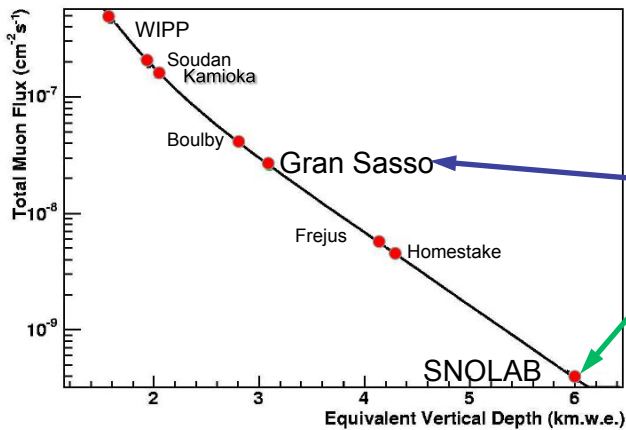
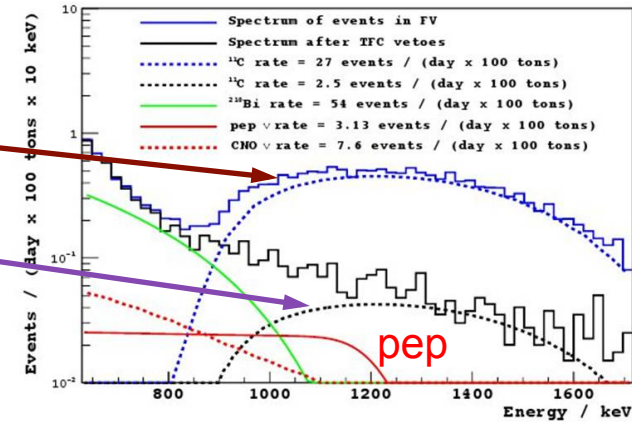
The Borexino Collaboration recently announced the first observation of pep neutrinos. The measured rate was $3.1 \pm 0.6(\text{stat}) \pm 0.3(\text{syst})$ counts/(day x 100 t).

So what can SNO+ do?



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.



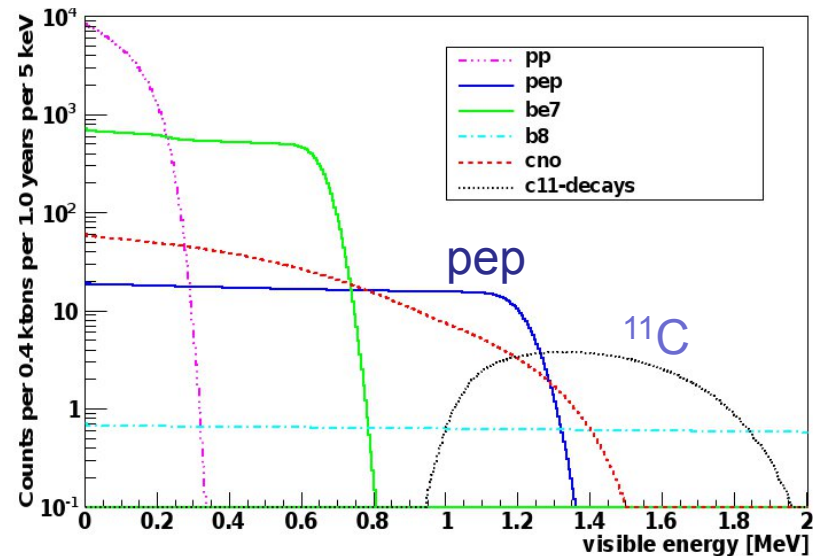
A reminder

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 $5\%/\sqrt{E}$ resolution, 400 t fid. vol.

Other backgrounds not shown.



Simulation of the impact of SNO+ pep measurement

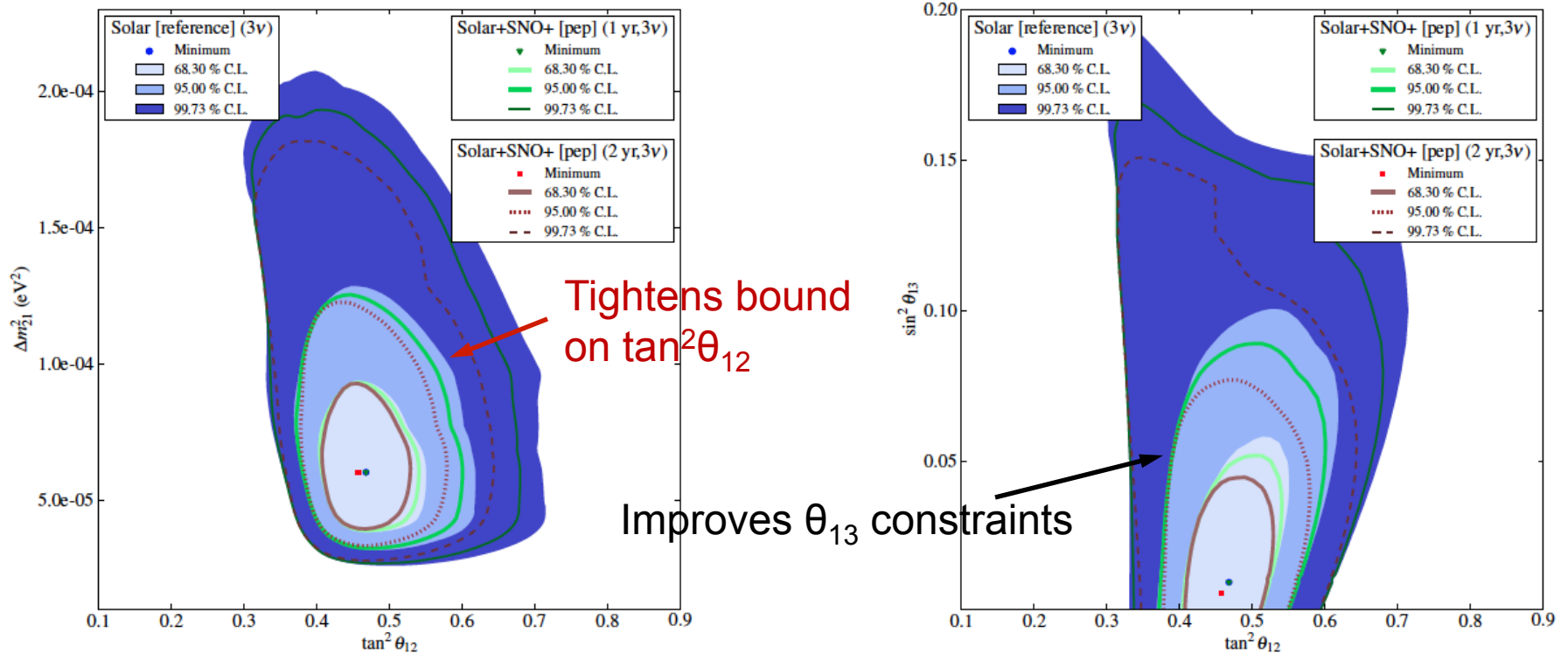
Energy range 0.2 - 6.5 MeV, 50% fid. vol.

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

$\Delta m_{12}^2 = 6.02 \times 10^{-5} \text{ eV}^2$

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

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



A recent downward revision of solar metal abundances from solar surface measurements 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%!

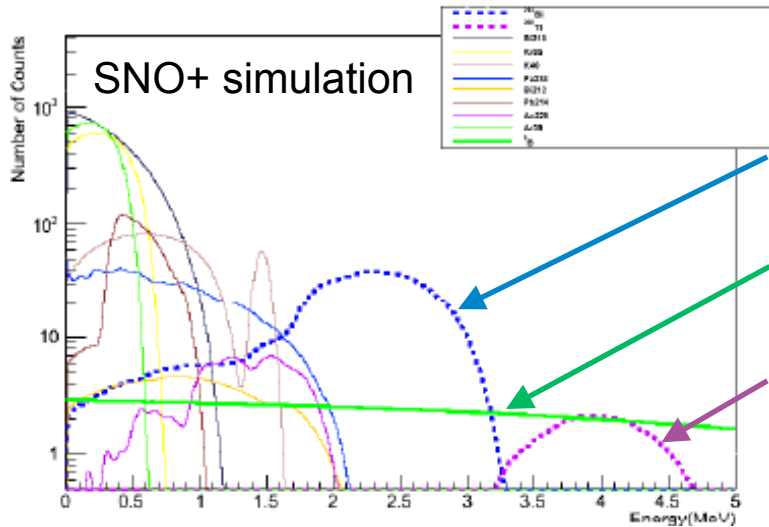
Borexino has recently set an upper limit on the CNO flux. SNO+ should do better because it is larger and has a lower ^{11}C background.

Predicted neutrino fluxes
high Z low Z

Source	BPS08(GS)	BPS08(AGS)	Difference
<i>pp</i>	5.97(1 ± 0.000)	6.04(1 ± 0.005)	1.2%
<i>pep</i>	1.41(1 ± 0.011)	1.45(1 ± 0.010)	2.8%
<i>hep</i>	7.90(1 ± 0.15)	8.22(1 ± 0.15)	4.1%
^7Be	5.07(1 ± 0.00)	4.55(1 ± 0.00)	10%
^8B	5.94(1 ± 0.11)	4.72(1 ± 0.11)	21%
^{13}N	2.88(1 ± 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	8.40 ^{+0.87} _{-0.88}	0.80 ^{+0.80} _{-0.70}	
Ga	127.9 ^{+8.1} _{-8.2}	120.5 ^{+6.0} _{-7.1}	

Window from 2 – 5 MeV

Previously measured at low energies by Borexino and KamLand



^{214}Bi , $Q_\beta = 3.3 \text{ MeV}$

- reject with $^{214}\text{Bi} \rightarrow ^{214}\text{Po} \rightarrow ^{210}\text{Pb}$ coincidence

^8B neutrinos

^{208}Tl , $Q_\beta \sim 5 \text{ MeV} + \gamma\text{s}$

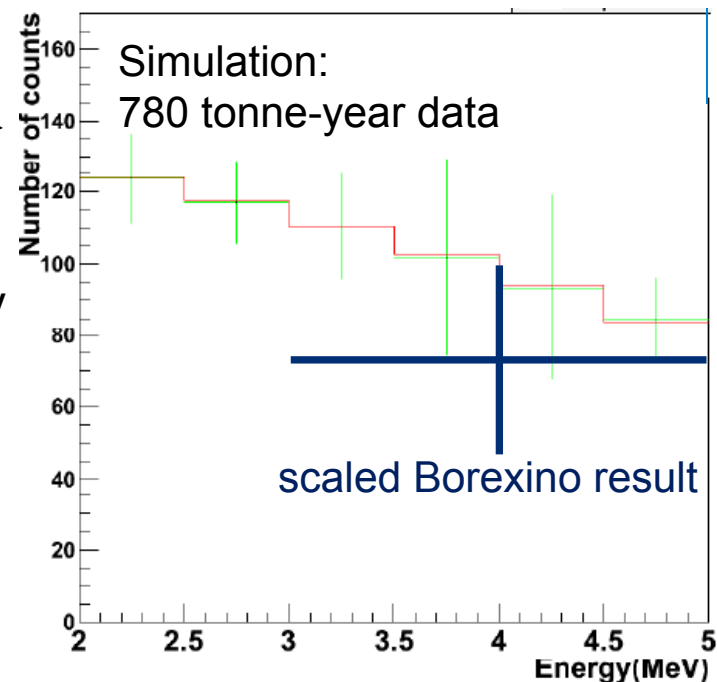
- constrain by $^{212}\text{Bi} \rightarrow ^{212}\text{Po} \rightarrow ^{208}\text{Pb}$ coincidence

Simulation includes:

- 99.8% ^{214}Bi rejection
- ^{208}Tl background constrained in the fit by a $\pm 25\%$ uncertainty

Note:

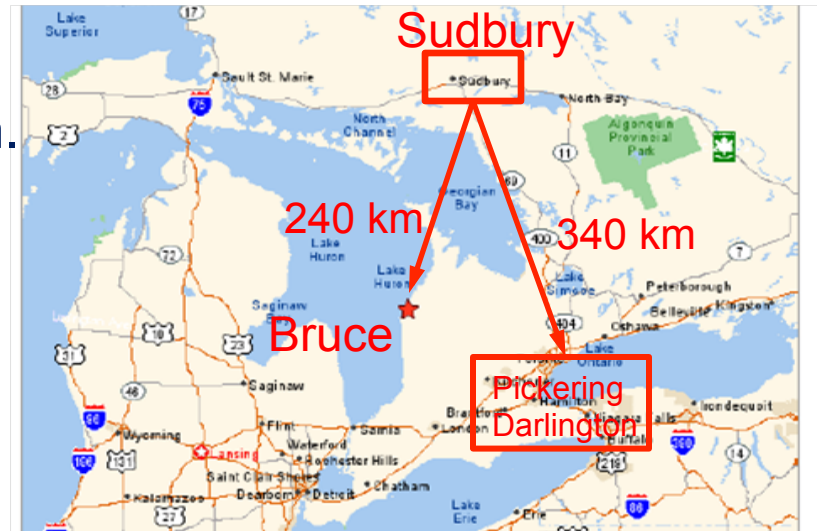
- less cosmogenic background in SNO+ than in KamLand
 - Borexino 5 X smaller than SNO+
- SNO+ can make a bin-by-bin comparison



KamLAND observed antineutrinos from 53 reactors, average baseline 180 km, firmly established the MSW-LMA solution.

SNO+ situated 240 km from one 6.3 GW station and 340 km from two ~ 3.3 GW stations.

Expect about 90 events/year (oscillated).

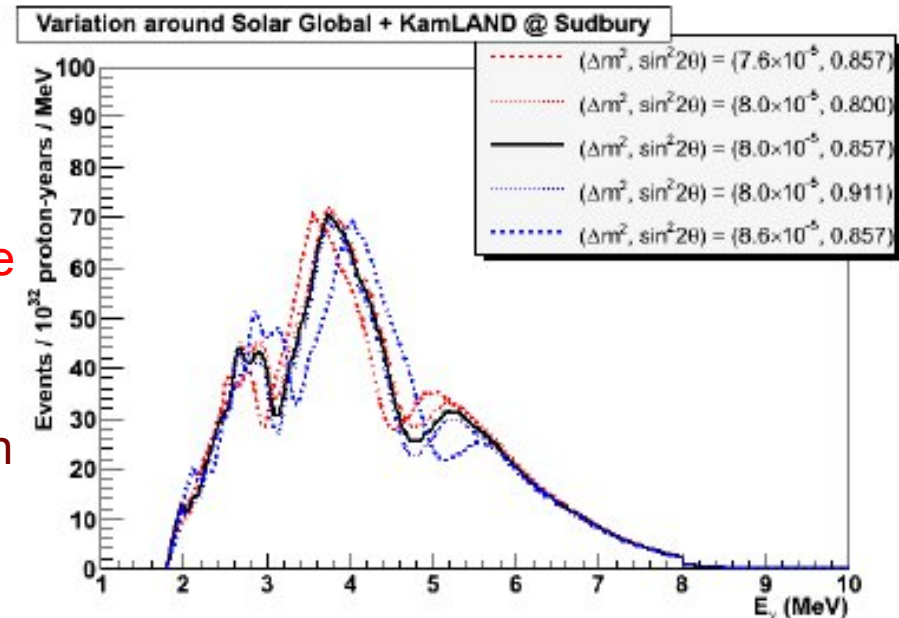


The oscillation maximum from Bruce is pushed to higher energies than in KamLAND (constant L/E).

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

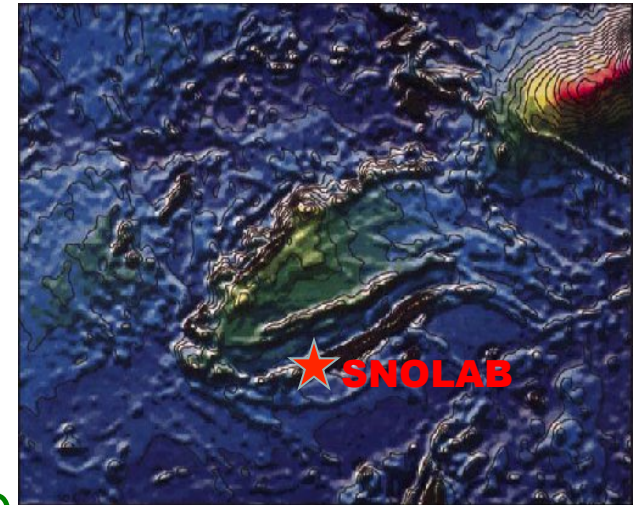
It so happens that the spectral features line up such that the peak in the spectrum is quite sensitive to Δm^2 .

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



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?



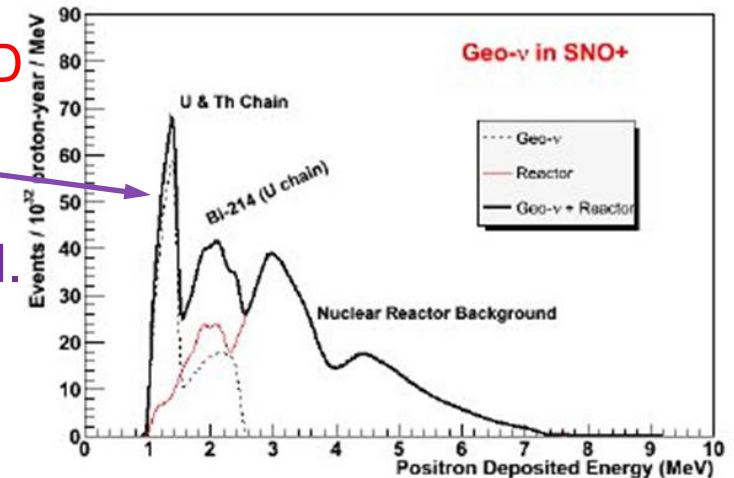
Evidence for geo neutrinos first seen at KamLAND.

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.



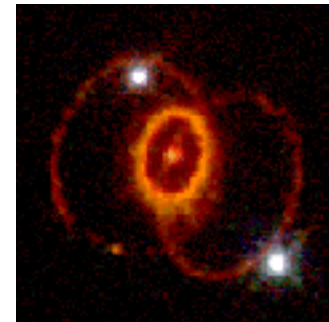
SN1987A

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



Type II SN at 10 kpc

SNEWS: SNO+ will be a member

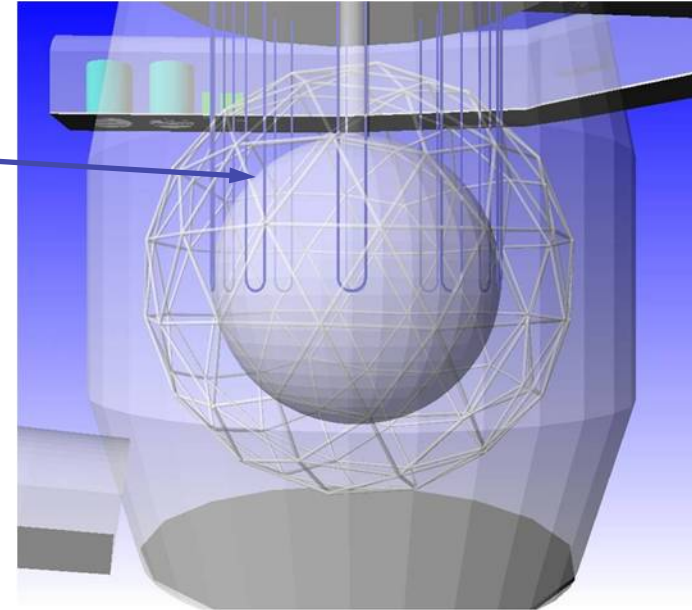
Although re-using the SNO detector for a new experiment is a good idea, it does not come for free!

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

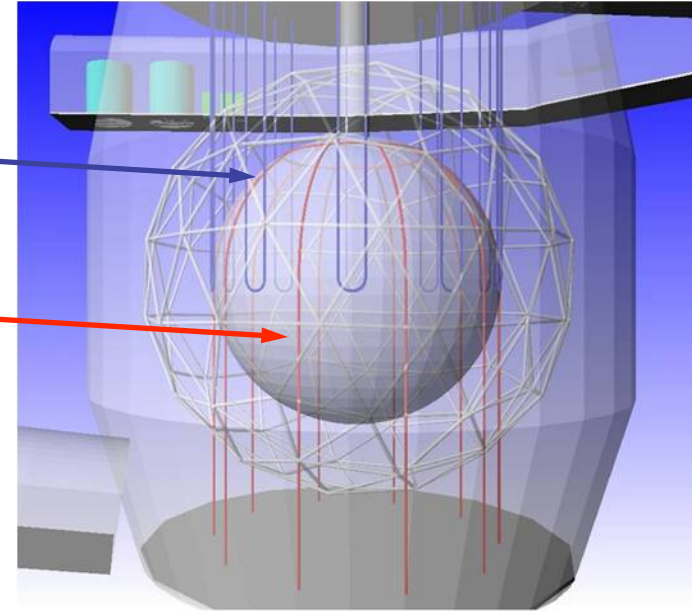
In SNO the acrylic vessel filled with heavy water had to be held up.



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

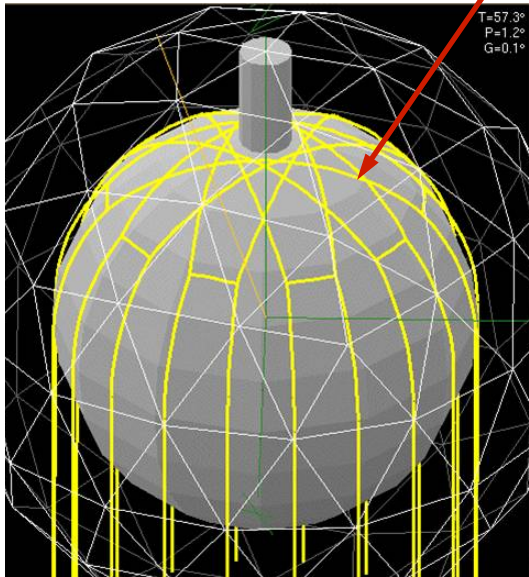
In SNO+ the vessel filled with LAB has to be held down.

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



Drilling holes for the anchor bolts

Hold down rope net overlays the vessel



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



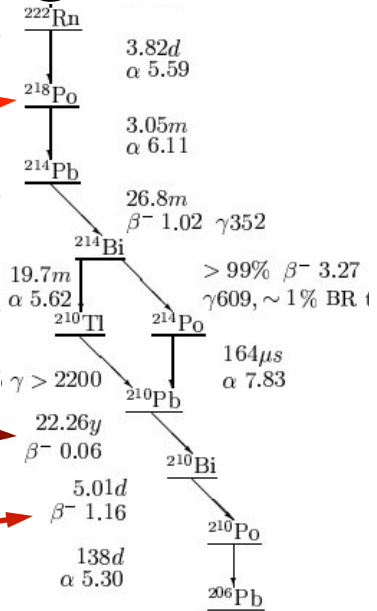
Mine air - laden with radon. \longrightarrow

^{218}Po electrostatically attracted to AV. \longrightarrow

^{218}Po α -decay daughters implanted into the acrylic. \longrightarrow

Long-lived ^{210}Pb - could be leached into the LAB. \longrightarrow

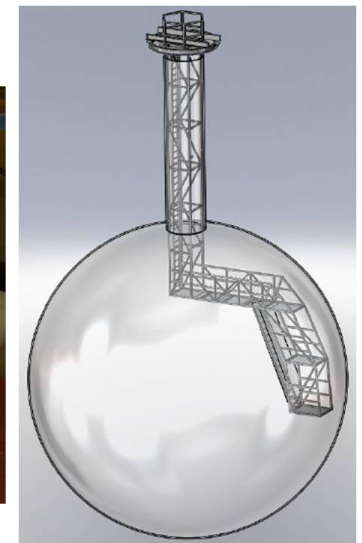
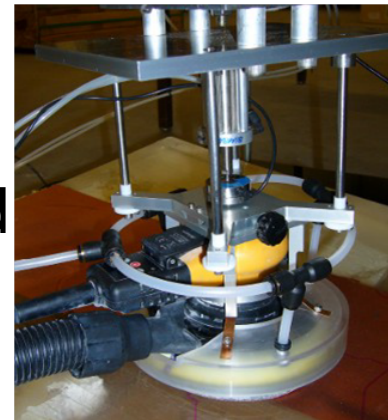
The β -decay spectrum of ^{210}Bi is nearly degenerate with the CNO spectrum. \longrightarrow



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 2 μm will be removed.



More on sanding

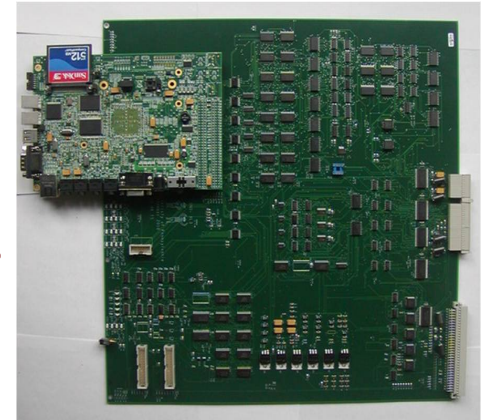
However:

- readiness of sanding was stuck at 95%
- collaboration's priority is double-beta decay and ^{210}Pb background only a problem for CNO measurement
- some ^{210}Pb will leach into water during water fill, though might be at a slow rate
- some could leach into LAB – purification system might remove it
- could be implanted so deeply into AV it won't leach out
- can evaluate during $\beta\beta$ running, other mitigation strategies could be employed, if necessary

Thus don't sand for now.

Differences between SNO and SNO+

- much more light/MeV (400 hits vs. 9)
- lower threshold \longrightarrow 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

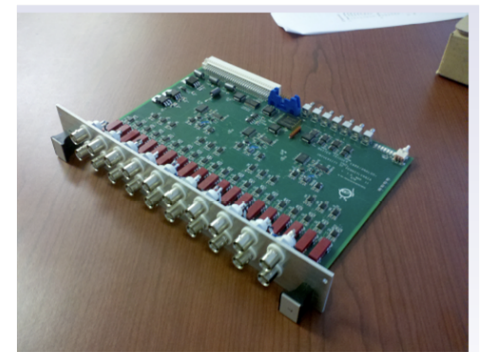


Increase data bandwidth by putting local intelligence in each crate. Data are digitized and stored on ML403 board.

New card to sum triggers from all crates.

Sums voltage rather than current.

Digitized by CAEN digitizer.



Several other boards being refurbished.

Optical Calibration

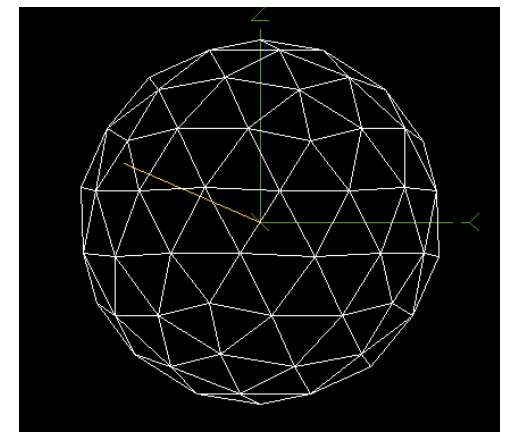
The laserball was the workhorse for the optical calibration of SNO and was deployed monthly.

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.

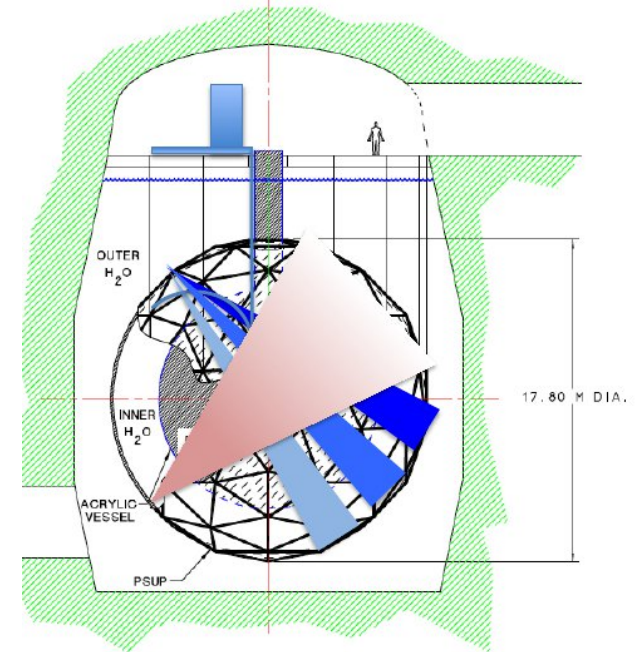


Light will be emitted with varying:

- wavelength
- opening angle
- position
- direction

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

- **Tellie** – monitor timing (T_0 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.



^{60}Co – 0.32 MeV β , 2.5 MeV summed γ

- energy scale, multivertex reconstruction, pile-up

^{48}Sc – 0.66 MeV β , 3.3 MeV summed γ , close to Nd $0\nu\beta\beta$ end point

- energy scale, reconstruction, position dependence, Nd absorption

^8Li (Čerenkov source)

- only Čerenkov light in detector, no scintillation
- PMT efficiency, LAB absorption/re-emission timing

AmBe – n, 4.4 MeV γ

- Lght yield, neutron propagation, reconstruction, Nd absorption

^{16}N – 6 MeV γ

- 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

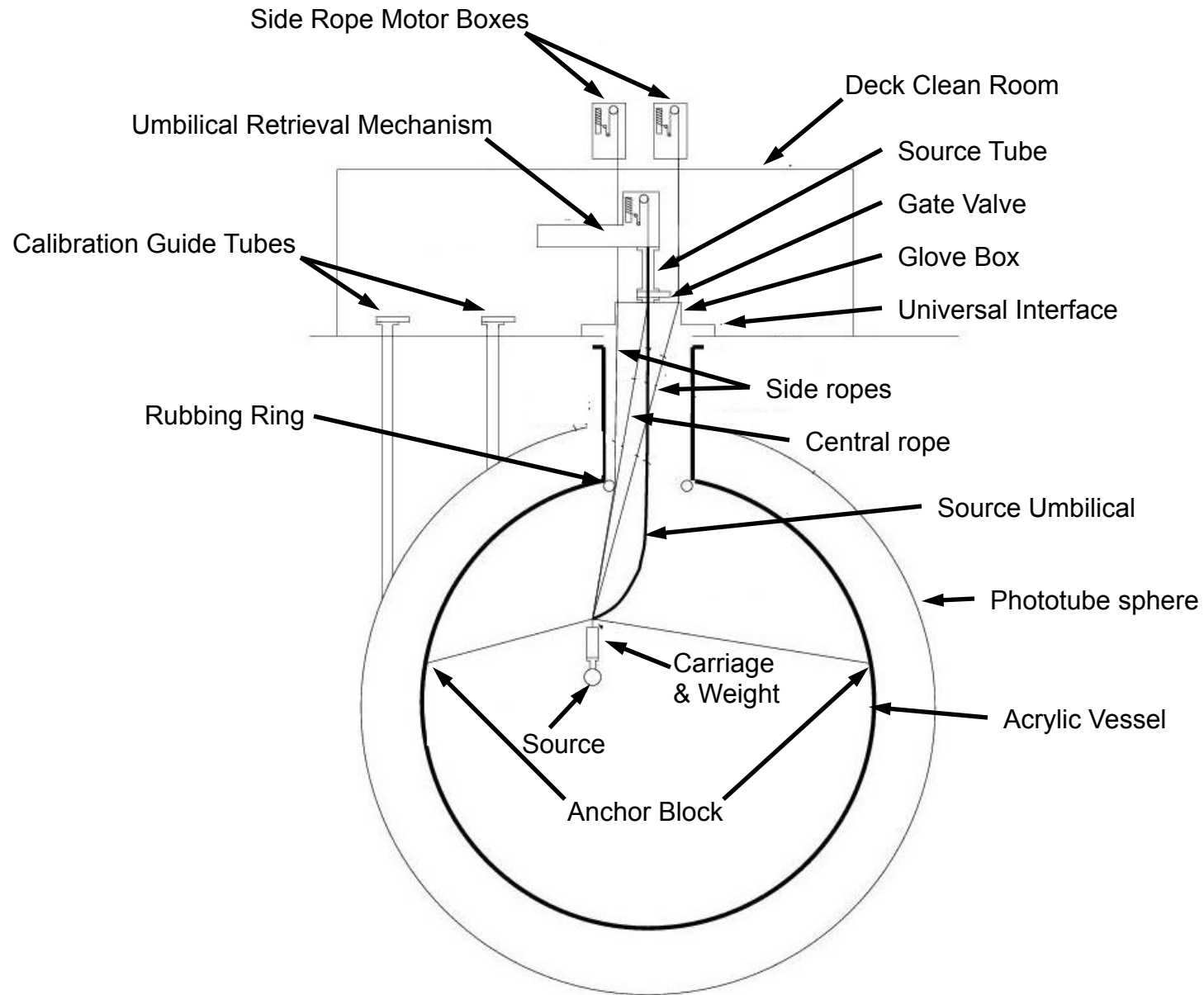
- energy scale, reconstruction, position dependence

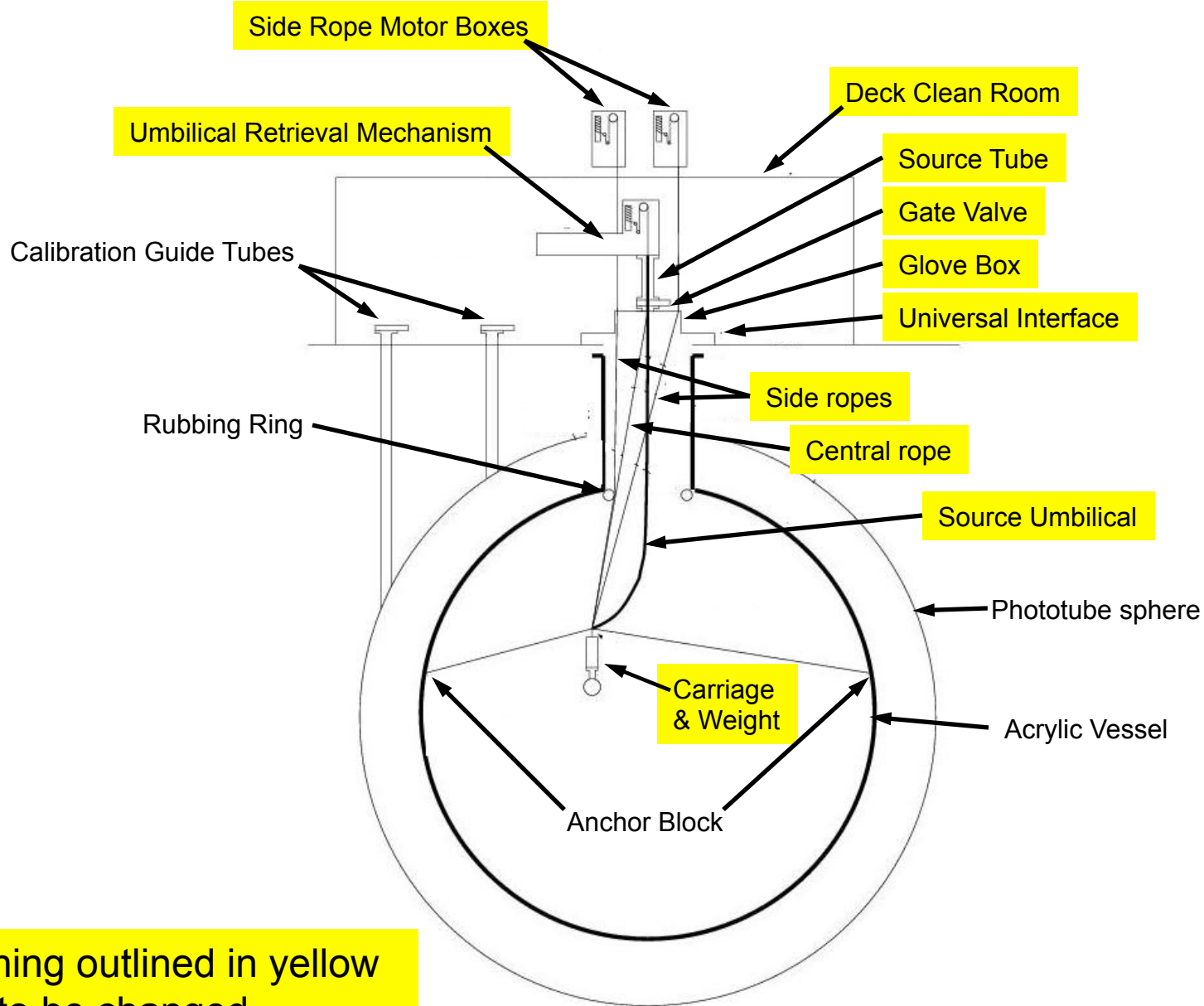
camera system – six cameras spaced around the phototube sphere

- 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





Everything outlined in yellow needs to be changed.

SNO glove box and UI

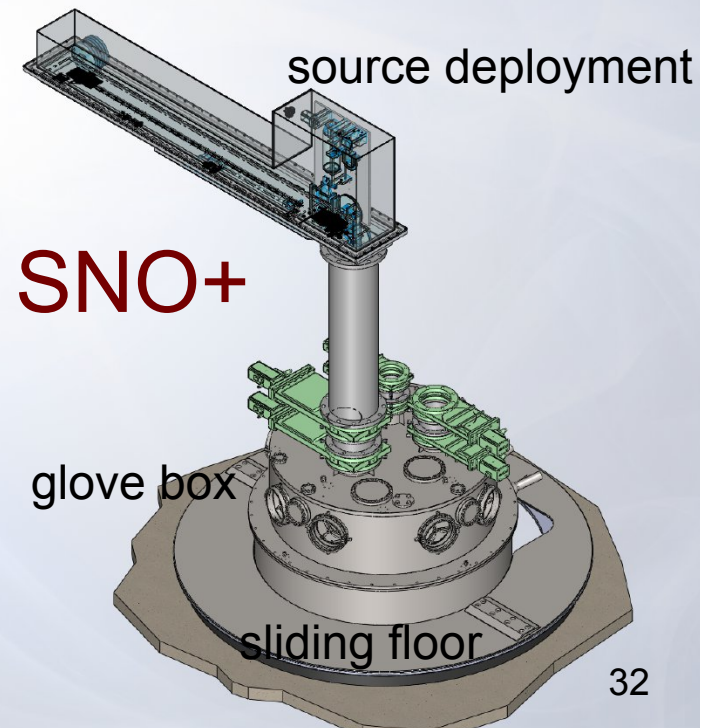
- gaskets and single O-rings to seal against mine air
- a single cover gas system for D_2O and H_2O

Radioactivity requirements for SNO+ are much more stringent.

Mine air must not get in.

Leak rate goal is $< 2 \times 10^{-6}$ 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



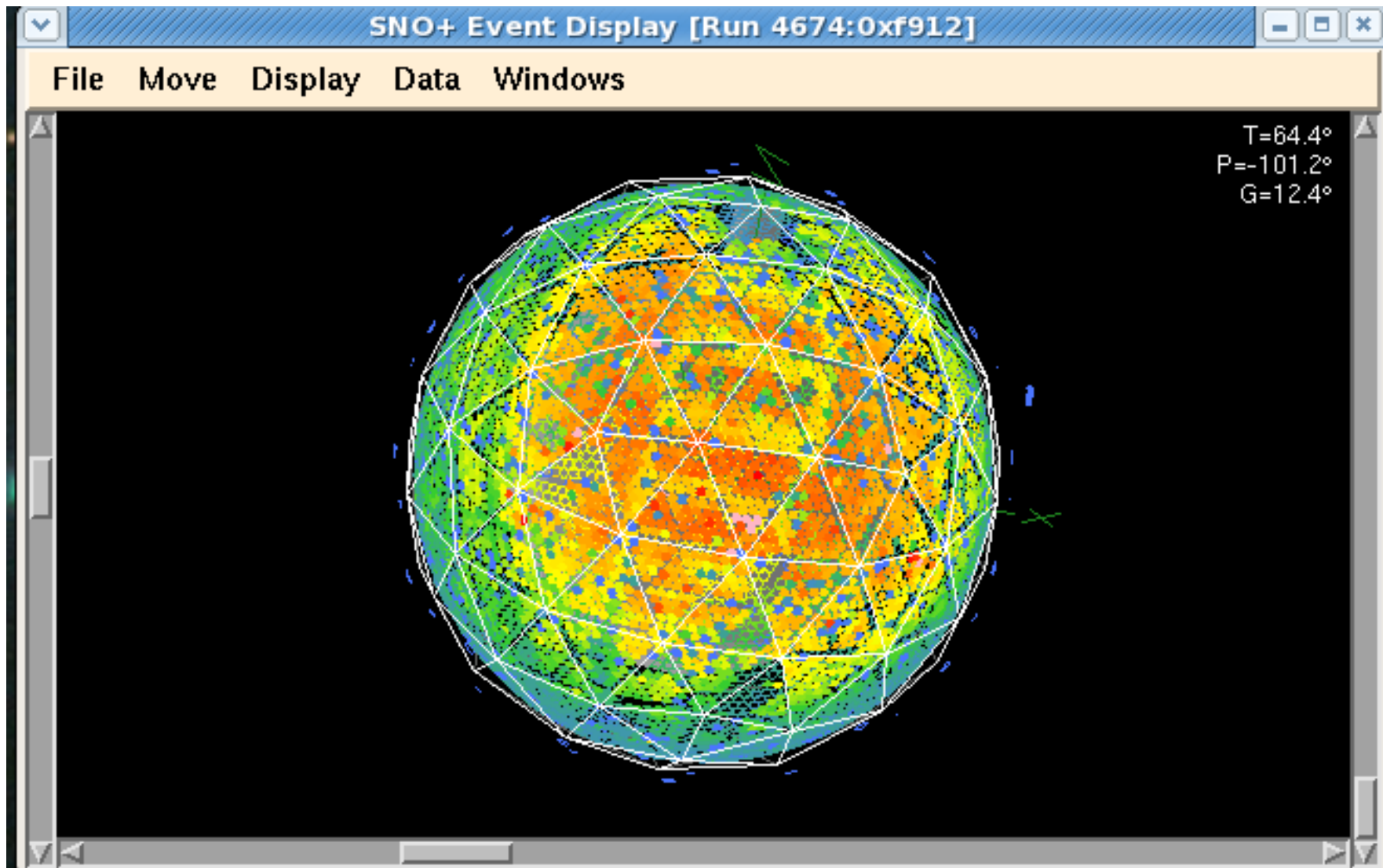


Approximate Timeline



Oct 2012 – air fill – commission new electronics and DAQ

Ladder inside the acrylic vessel





Approximate Timeline

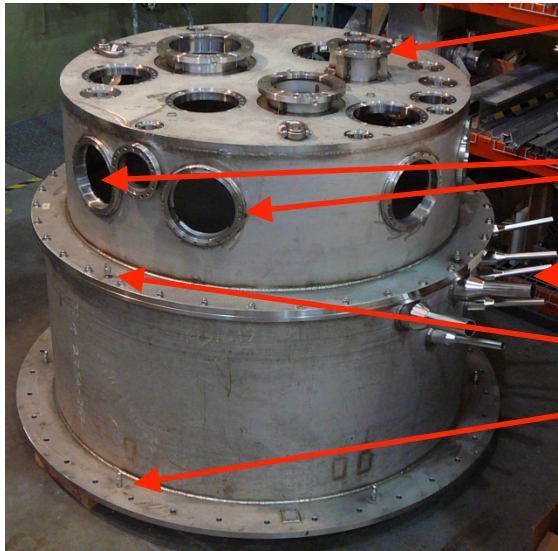


Oct 2012 – air fill – commission new electronics and DAQ

Nov 2012 – Jan 2013 - clean AV, install remaining new equipment

Universal Interface

Sits on top of acrylic vessel neck



ports for inserting calibration sources and for monitoring status of equipment inside acrylic vessel

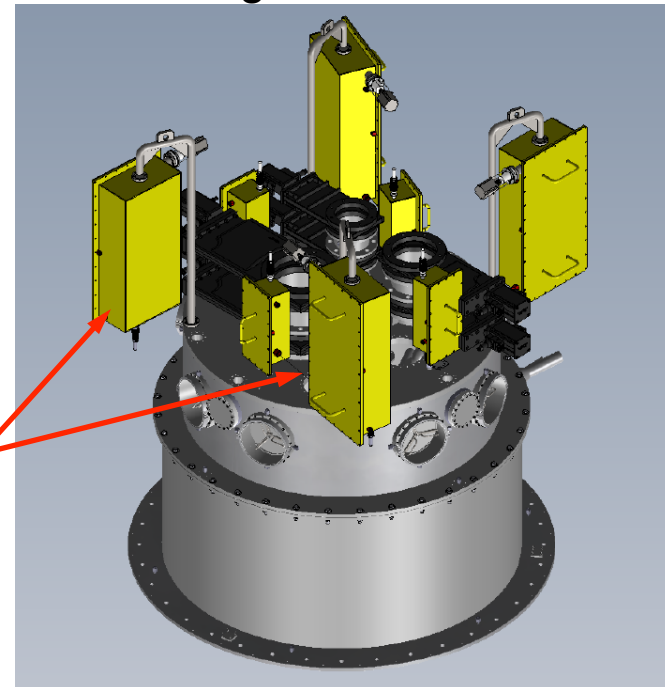
glove ports for attaching ropes used to position calibration sources

pipes for introducing liquid into AV

ports for pumping space between double o-ring seals

Designed and fabricated at TRIUMF

Finished product will include motor boxes used to adjust rope tensions and lengths (currently being designed).



Oct 2012 – air fill – commission new electronics and DAQ

Nov 2012 – Jan 2013 - clean AV, install remaining new equipment

Feb 2013 – Apr 2013 - water fill

May 2013 – Oct 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

Nov 2013 – Jan 2014 – scintillator fill

Feb 2014 - ? – 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 $0\nu\beta\beta$ -decay experiment

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. Hearn,

A. McDonald, A. Noble, H. M. O'Keefe, T. Sonley, E. O'Sullivan, P. Skensved, I. Takashi, A. Wright

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

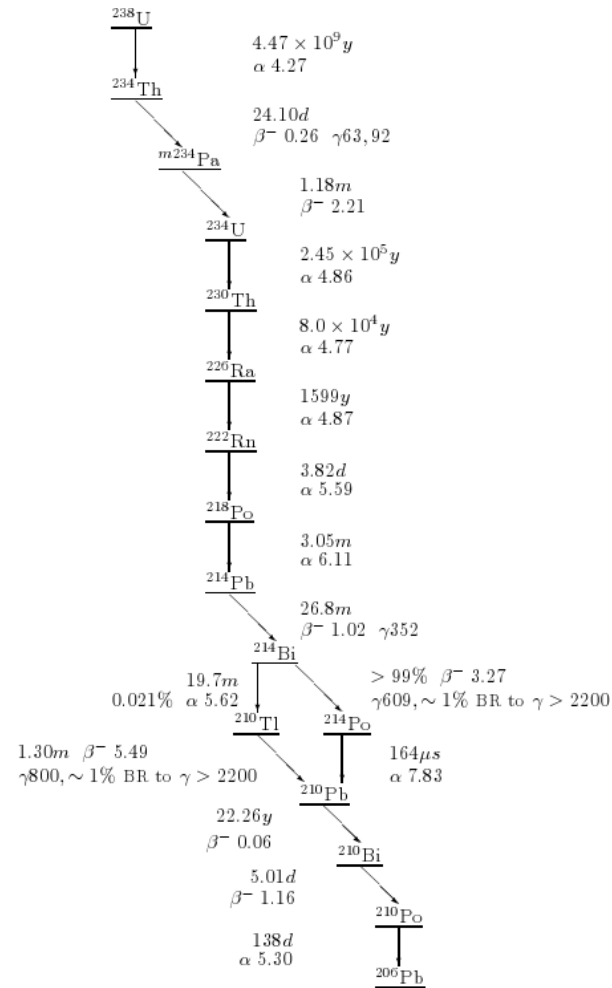
University of Sussex E. Falk, S. Fernandes, J. Hartnell, G. Lefeuvre, S. Peeters, J. Sinclair, R. White

TRIUMF R. Helmer

University of Washington S. Enomoto, J. Kaspar, J. Nance, D. Scislowski, N. Tolich,

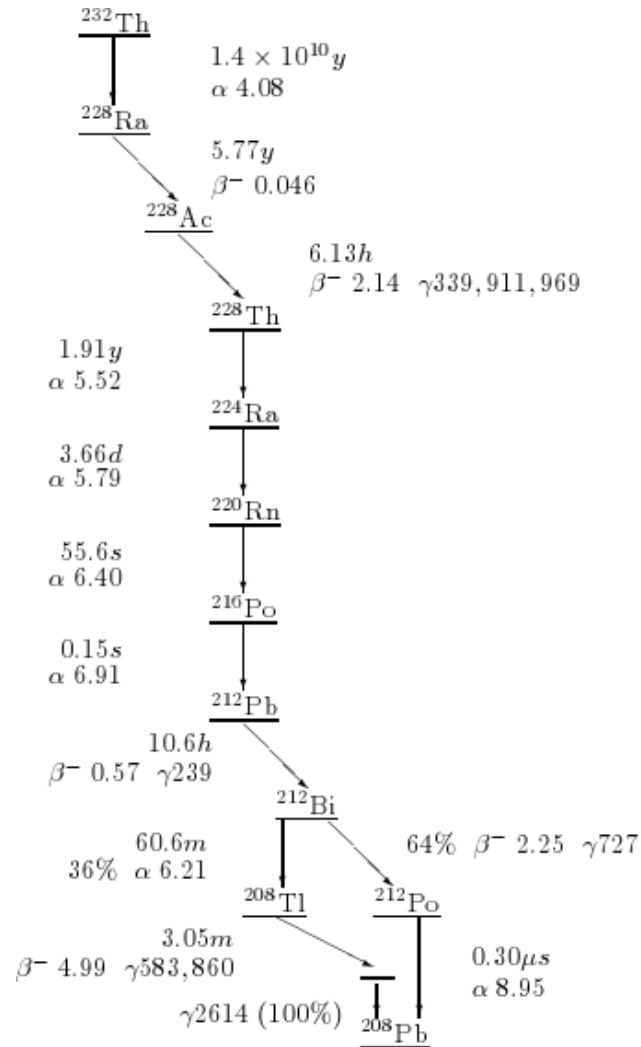
H. Wan Chan Tseung

^{238}U decay chain



Q-values for beta and alpha decays are given in MeV
Gamma energies are in keV

^{232}Th decay chain



Q-values for beta and alpha decays are in MeV
 Gamma energies are in keV