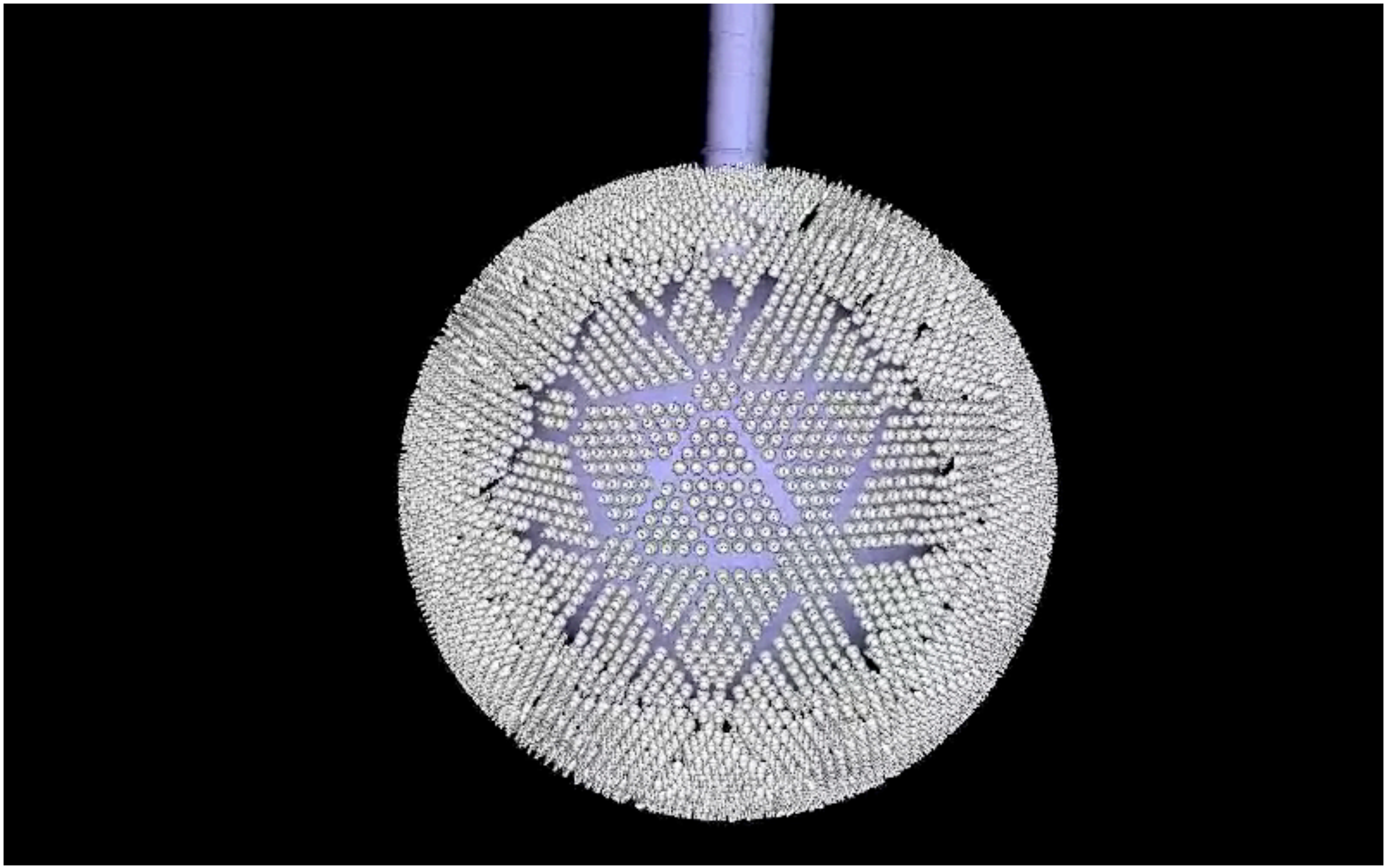
SNO and SNO+

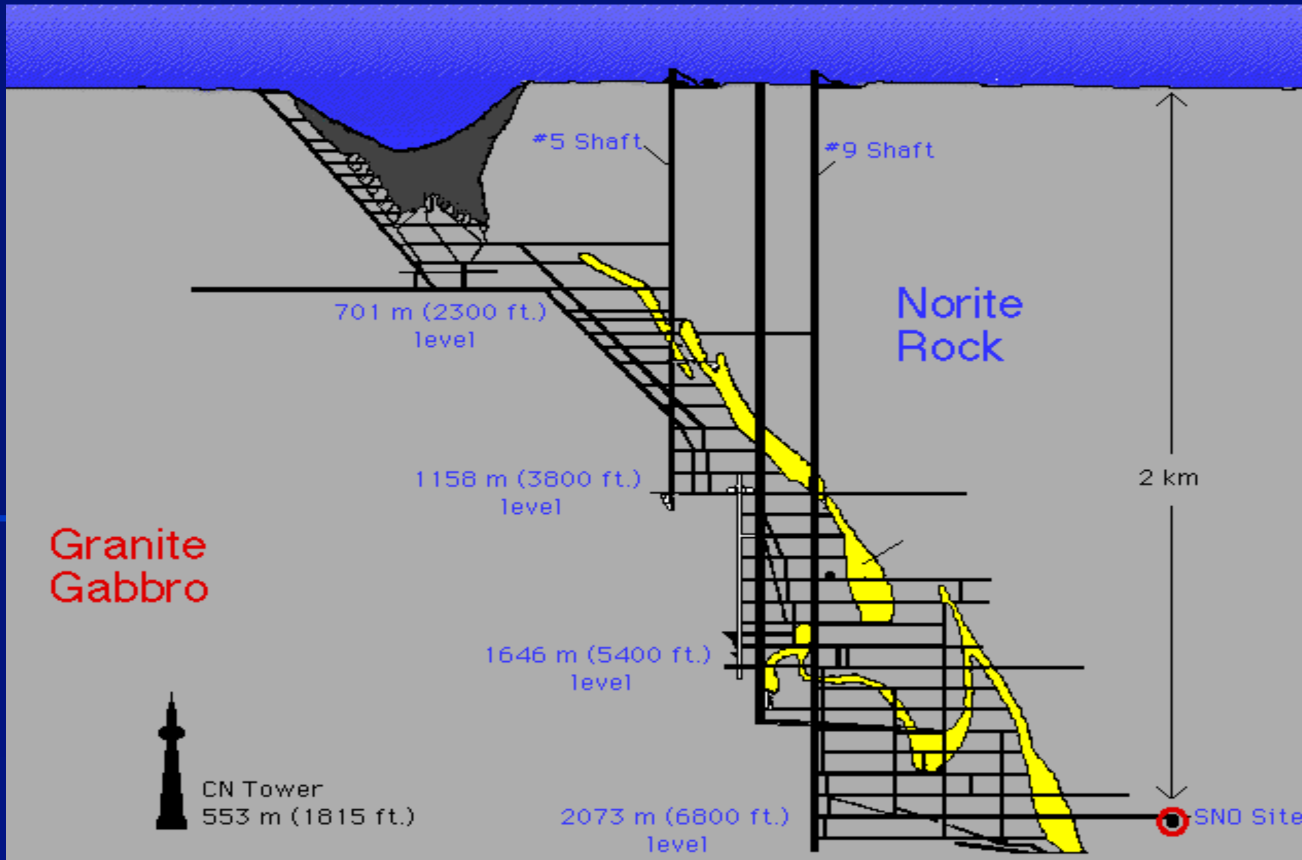
Mark Chen

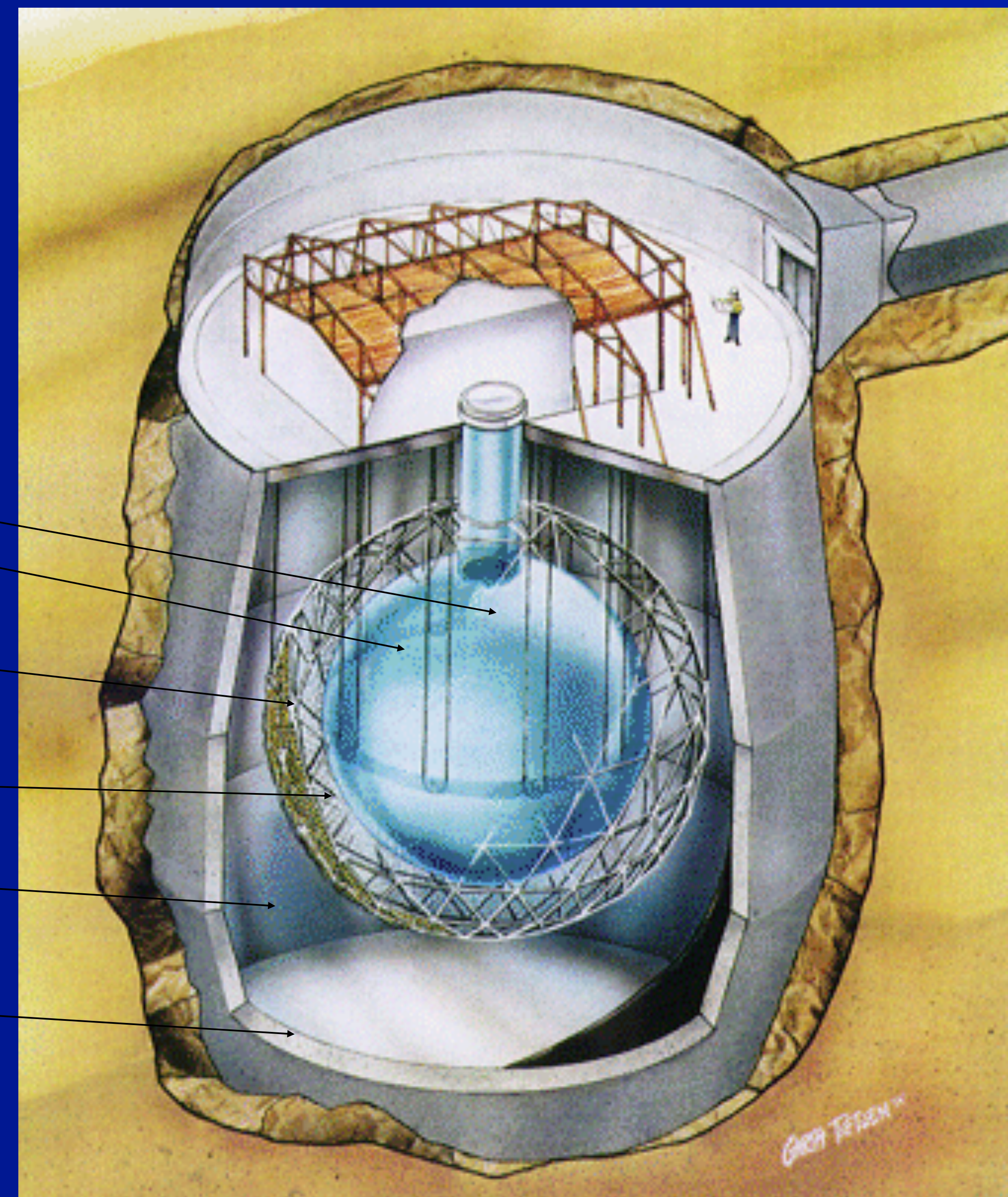
Queen's University and CIFAR



SNOLAB
NSERC CRSNG
Canada Foundation for Innovation
Fondation canadienne pour l'innovation
CIFAR
CANADIAN INSTITUTE for ADVANCED RESEARCH
Queen's UNIVERSITY

Sudbury Neutrino Observatory





1000 tonnes D_2O

12 m diameter Acrylic Vessel

18 m diameter PMT support structure; 9500 PMTs (~55% photocathode coverage)

1700 tonnes inner shielding H_2O

5300 tonnes outer shielding H_2O

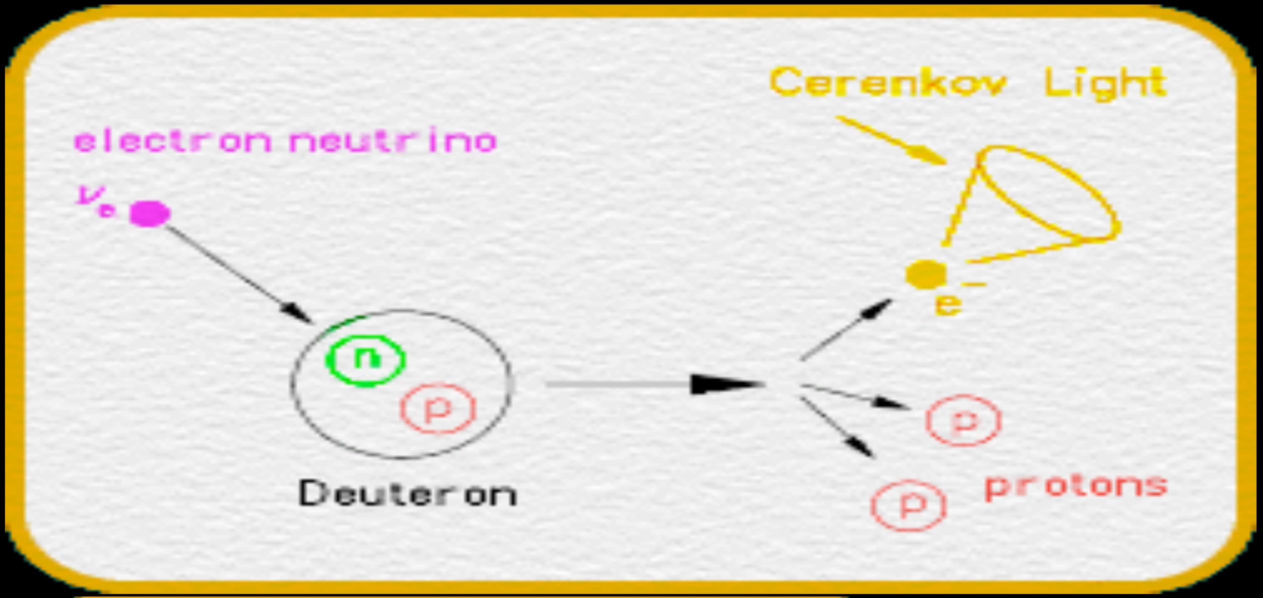
Urylon liner radon seal

depth: 2092 m (~6010 m.w.e.) ~70 muons/day

Neutrino Reactions in SNO

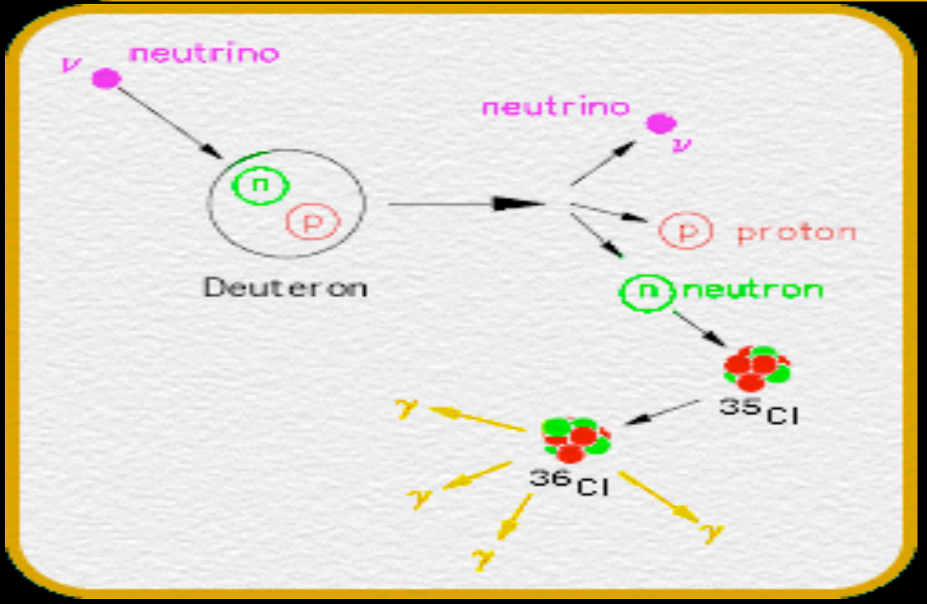
CC $\nu_e + d \rightarrow p + p + e^-$

- only detects ν_e
- good measurement of ν_e energy spectrum



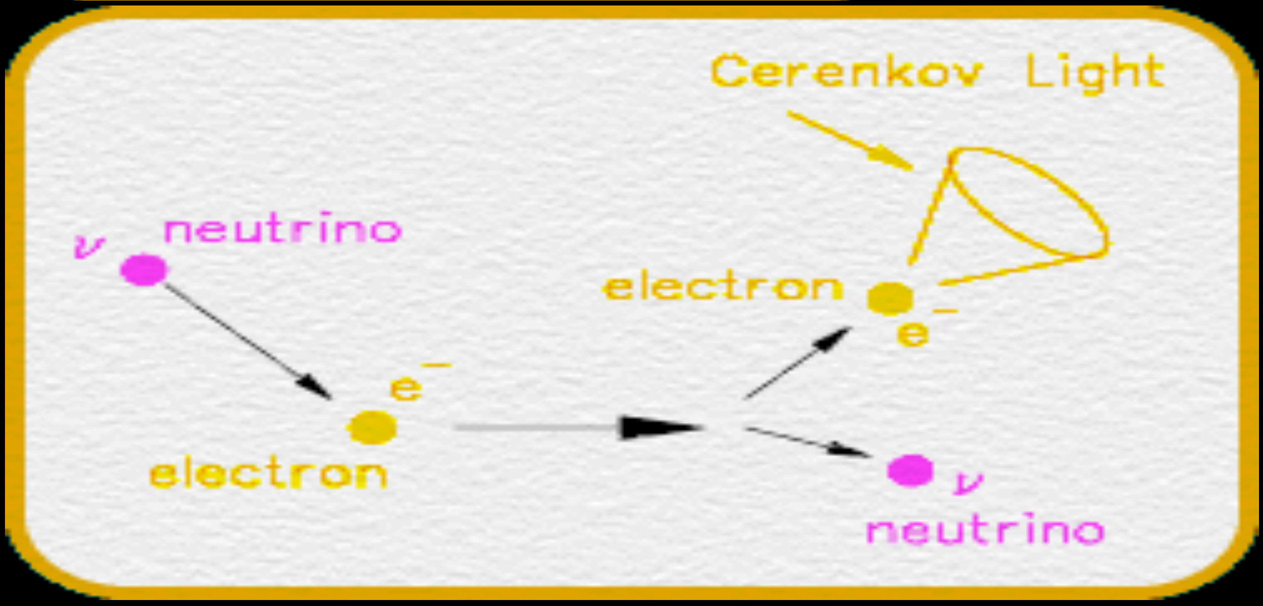
NC $\nu_x + d \rightarrow p + n + \nu_x$

- measures total ^8B ν flux from the Sun
- equal cross section for all ν flavours



ES $\nu_x + e^- \rightarrow \nu_x + e^-$

- mainly sensitive to ν_e
- strong directional sensitivity



SNO Neutral Current Trilogy

Pure D_2O	**Salt**	**^{3}He Counters**
Nov 99 – May 01	**Jul 01 – Sep 03**	**Nov 04 – Nov 06**
$n + d \rightarrow t + \gamma$	$n + {}^{35}Cl \rightarrow {}^{36}Cl + \Sigma\gamma$	$n + {}^3He \rightarrow t + p$
(E_γ = 6.25 MeV)	($E_{\Sigma\gamma}$ = 8.6 MeV)	proportional counters σ = 5330 b
	enhanced NC rate and separation	event-by-event separation
PRL **87**, 071301 (2001) PRL **89**, 011301 (2002) PRL **89**, 011302 (2002)	PRL **92**, 181301 (2004)	
PRC **75**, 045502 (2007)	PRC **72**, 055502 (2005)	PRL **101**, 111301 (2008)

"long" archival papers with complete details

PRC **81**, 055504 (2010)

combined analysis with
lower energy threshold

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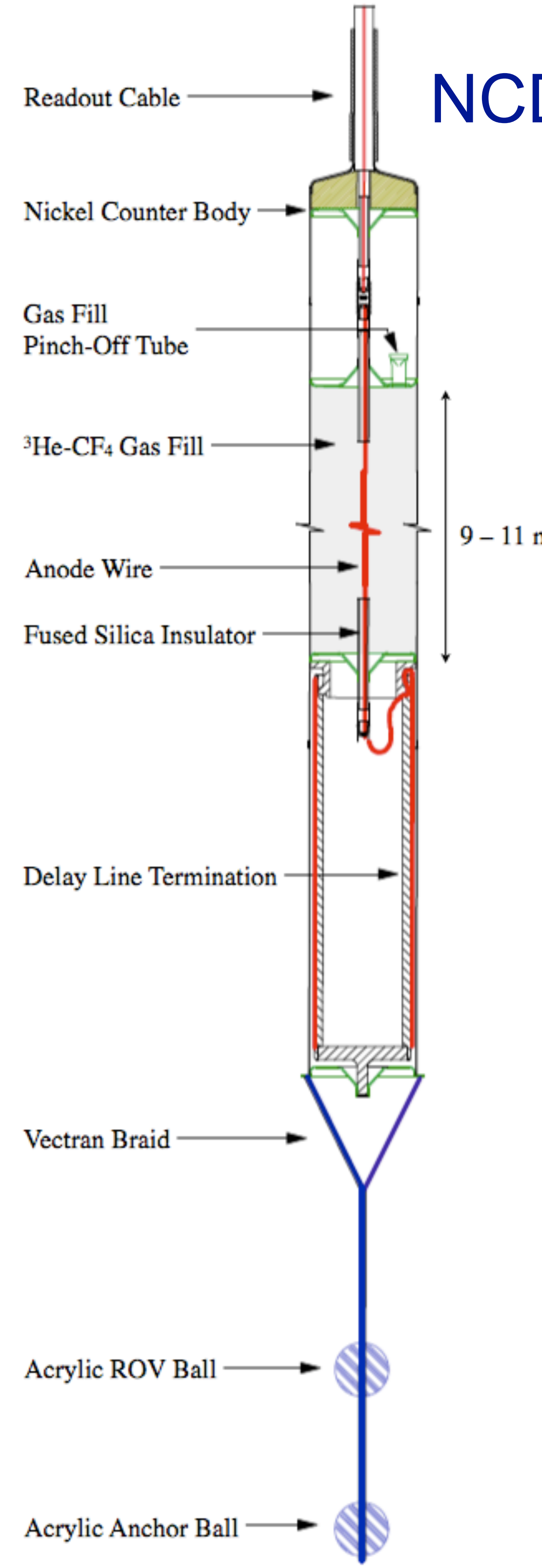
NCD



rs

SNO Neutral Current Trilogy

Pure D_2O

Nov 99 – May 01

$n + d \rightarrow t + \gamma$

(E_γ = 6.25 MeV)

PRL **87**, 071301 (2001)

PRL **89**, 011301 (2002)

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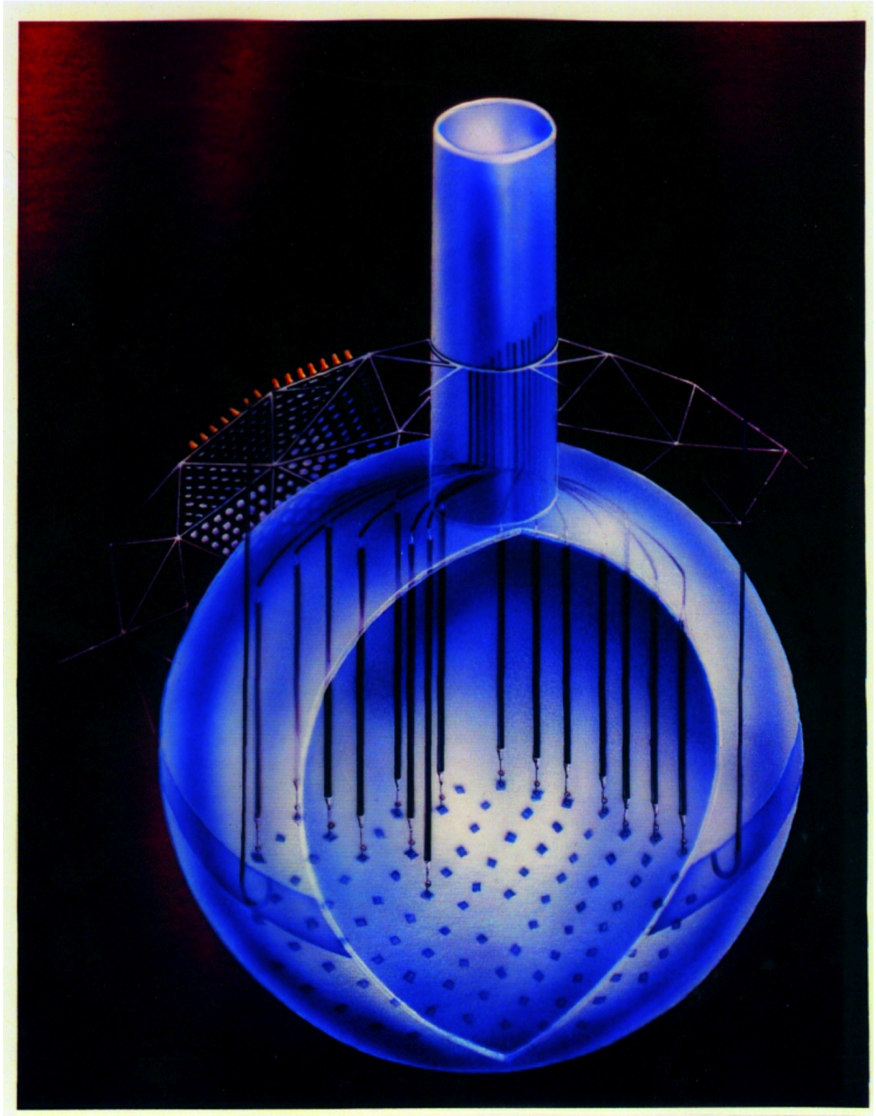


PRC **81**, 055504 (2010)

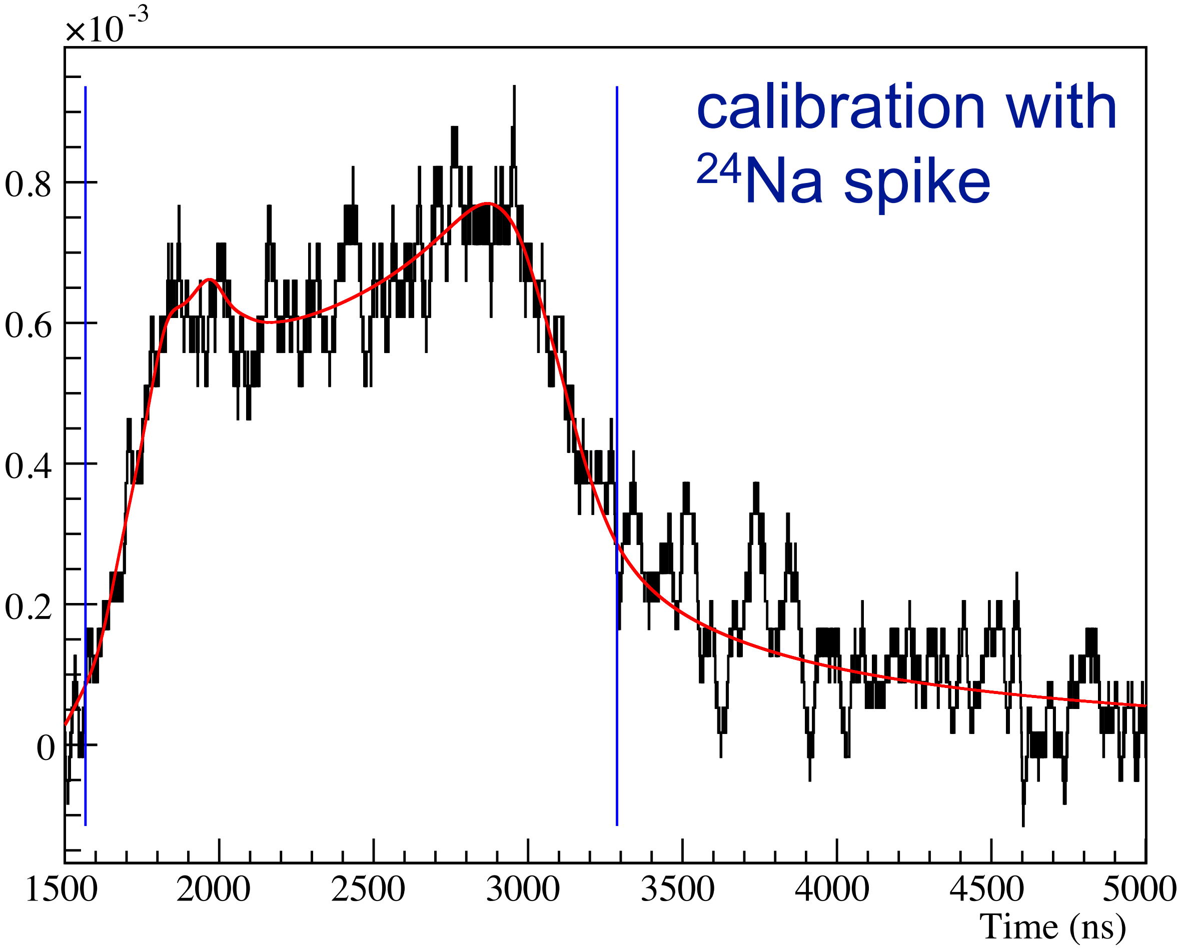
combined analysis with lower energy threshold

SNO Final Combined 3-Phase Analysis

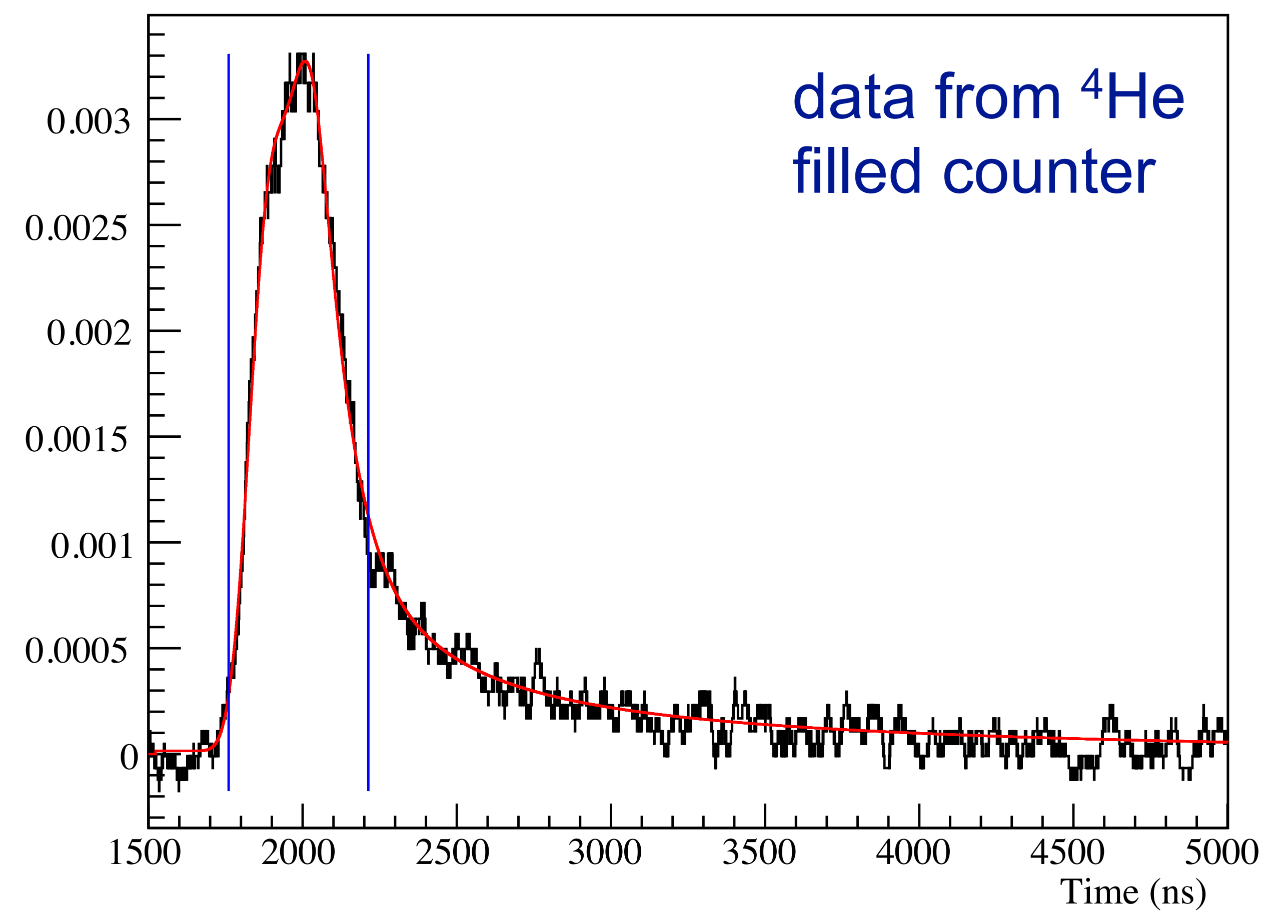
arXiv:1109.0763

- previous NCD analysis only used energy spectrum shape to distinguish neutrons from alphas
- new analysis used pulse shape differences to separate

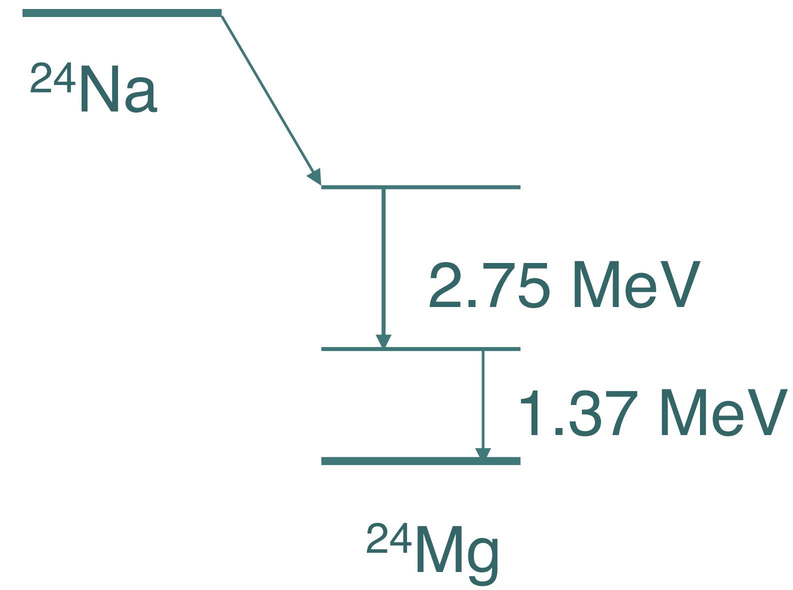
neutrons



alphas



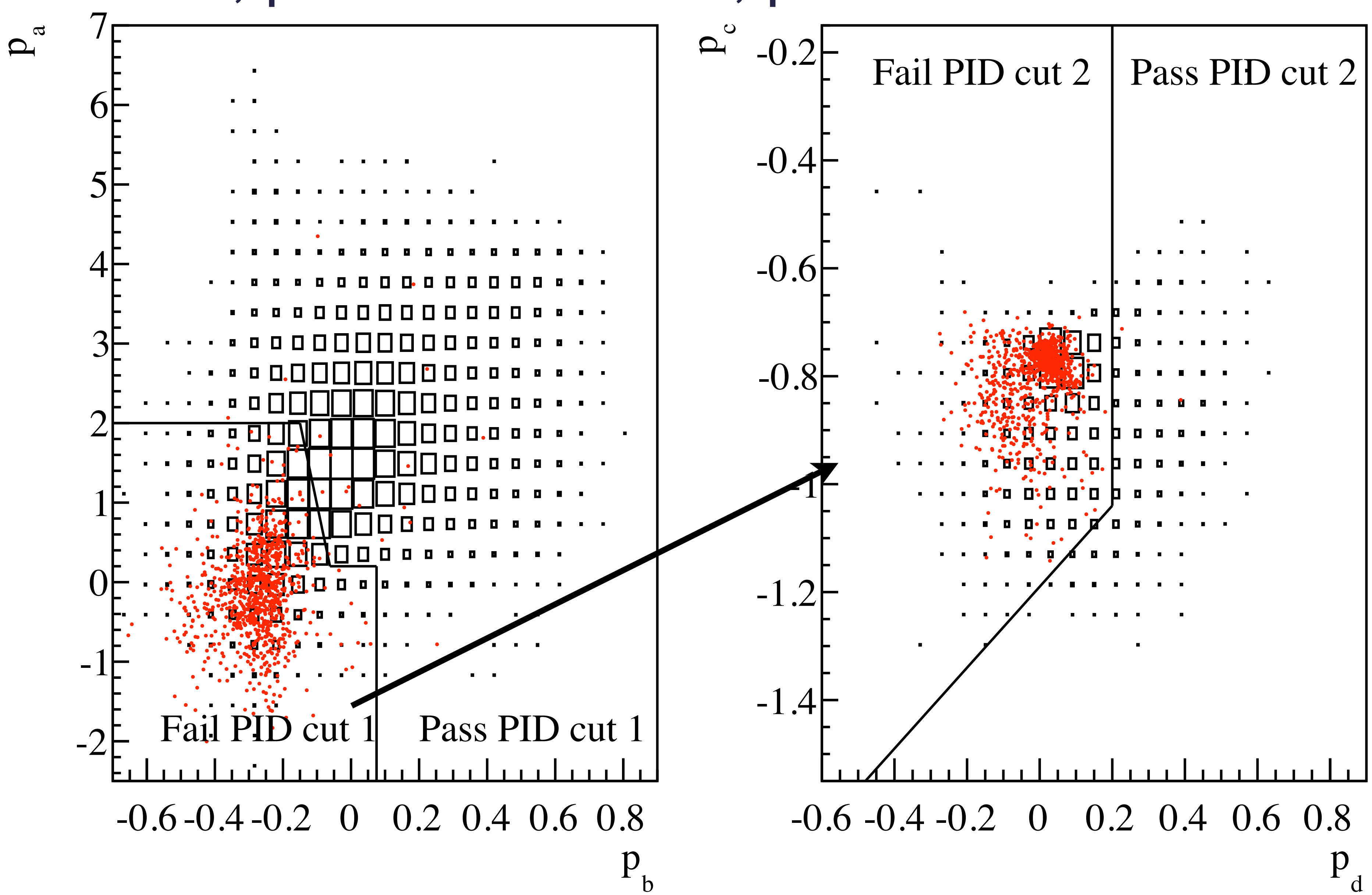
^{24}Na "neutron" spike



- ^{24}NaCl activated in a nuclear reactor
  - $t_{1/2}$ = 14.96 hr
- injected a small amount of this salt into the heavy water and mixed to achieve uniform distribution
- 2.75 MeV gamma ray produces neutrons via photodissociation of deuterons
- ...produces a uniform distribution neutron spike to calibrate the response of all the NCD ^{3}He counters, plus temporal and spatial variations of the neutron detection efficiency

Particle ID

- based upon fitting to libraries of known neutron and known alpha pulses
  - derived from simulation p_a
  - and from ^{24}Na neutron calibration and 4He alpha data, p_b
  - kurotosis, p_c and skewness, p_d



only events that failed PID cut 1 passed to PID cut 2

red dots = α
black boxes = n

Effect of Particle ID

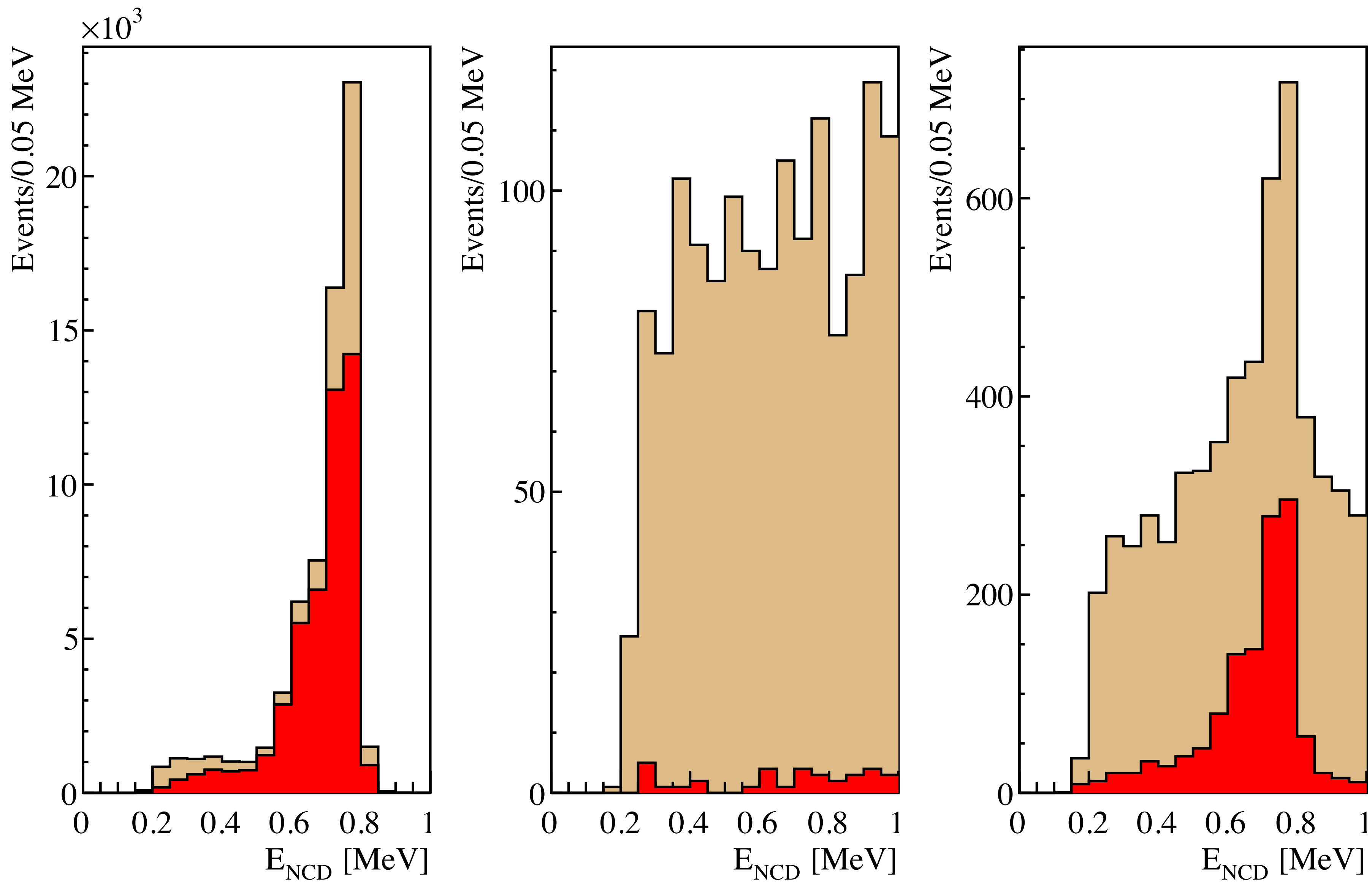


FIG. 5. E_{NCD} spectrum before (brown) and after (red) the particle identification cut. From left to right the plots are for ^{24}Na calibration data (neutrons), data from strings filled with ^{4}He (alphas), and data from strings filled with ^{3}He.

Non-Neutron, Non-Alpha

- "unknown unknowns" [D. Rumsfeld] were quantified
- neutron energy pdf comes from ^{24}Na spike calibration
- alpha energy pdf ought to be satisfactorily described with zeroth-order polynomial (in the neutron energy region)
- from SNO's Phase III paper
  - "Low-energy instrumental background events were found on two strings that were excluded from the analysis. Distributions of these events were used to fit for possible additional contamination in the data on the rest of the array."
- we don't see spurious pulses on the good NCD counters; but how do we set a limit on the quantity of a possible unknown pulse?
  - by allowing arbitrary (but non-conspiratorial) pulse shapes to distort the alpha background energy pdf
  - we describe this in our new Combined 3-Phase Analysis

$$P_\alpha(E) = p_0[P_0(E) + \sum_{n=1}^{N_{\max}} p_n P_n(E)]$$

Polynomial Fit to Alpha Energy pdf

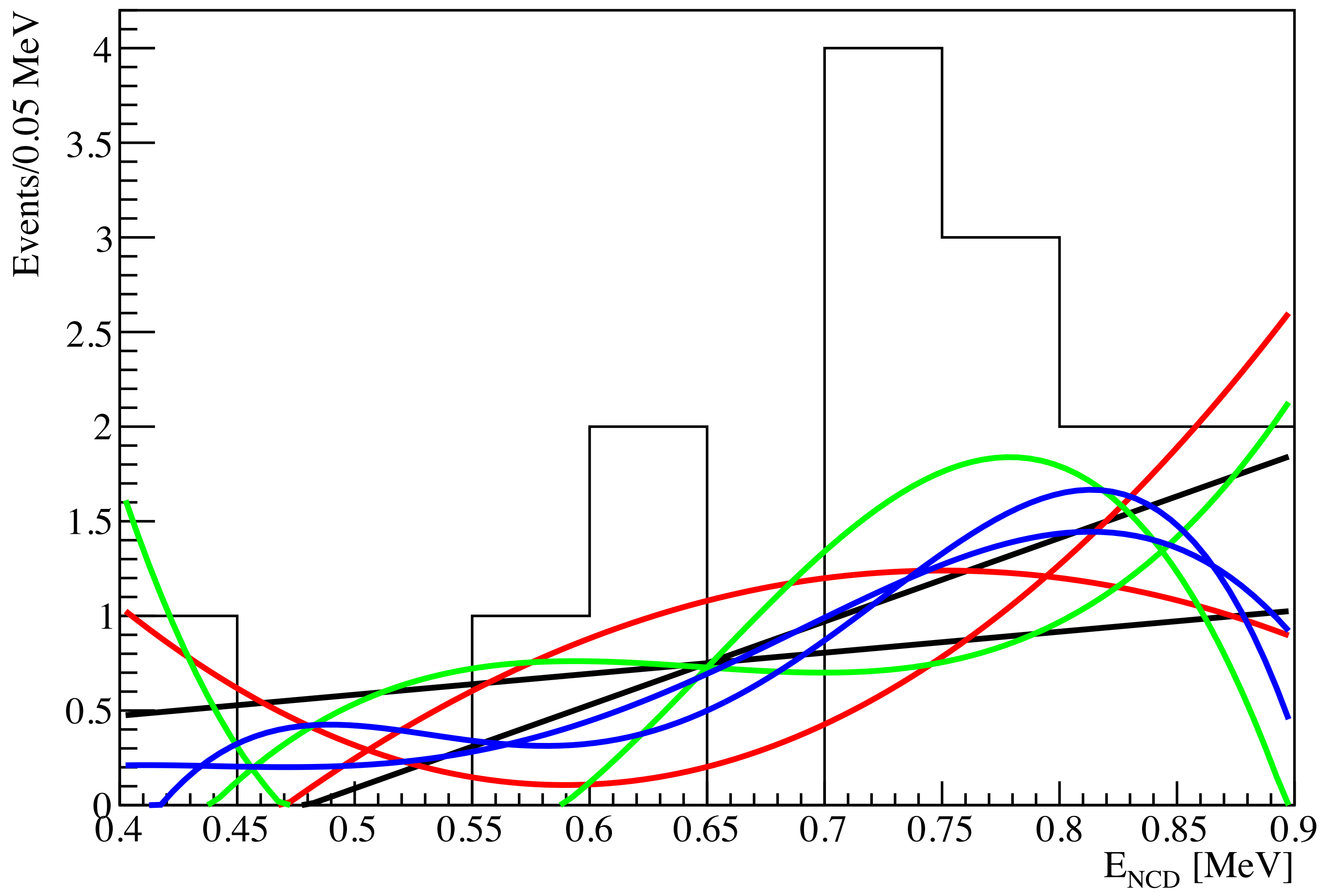


FIG. 8. E_{NCD} spectrum for events on the strings filled with ^{4}He after the particle identification cut. The black, red, green, and blue lines, respectively, show the PDFs used to simulate alpha events for N_{max} equal to one, two, three, and four.

NCD Fit Results

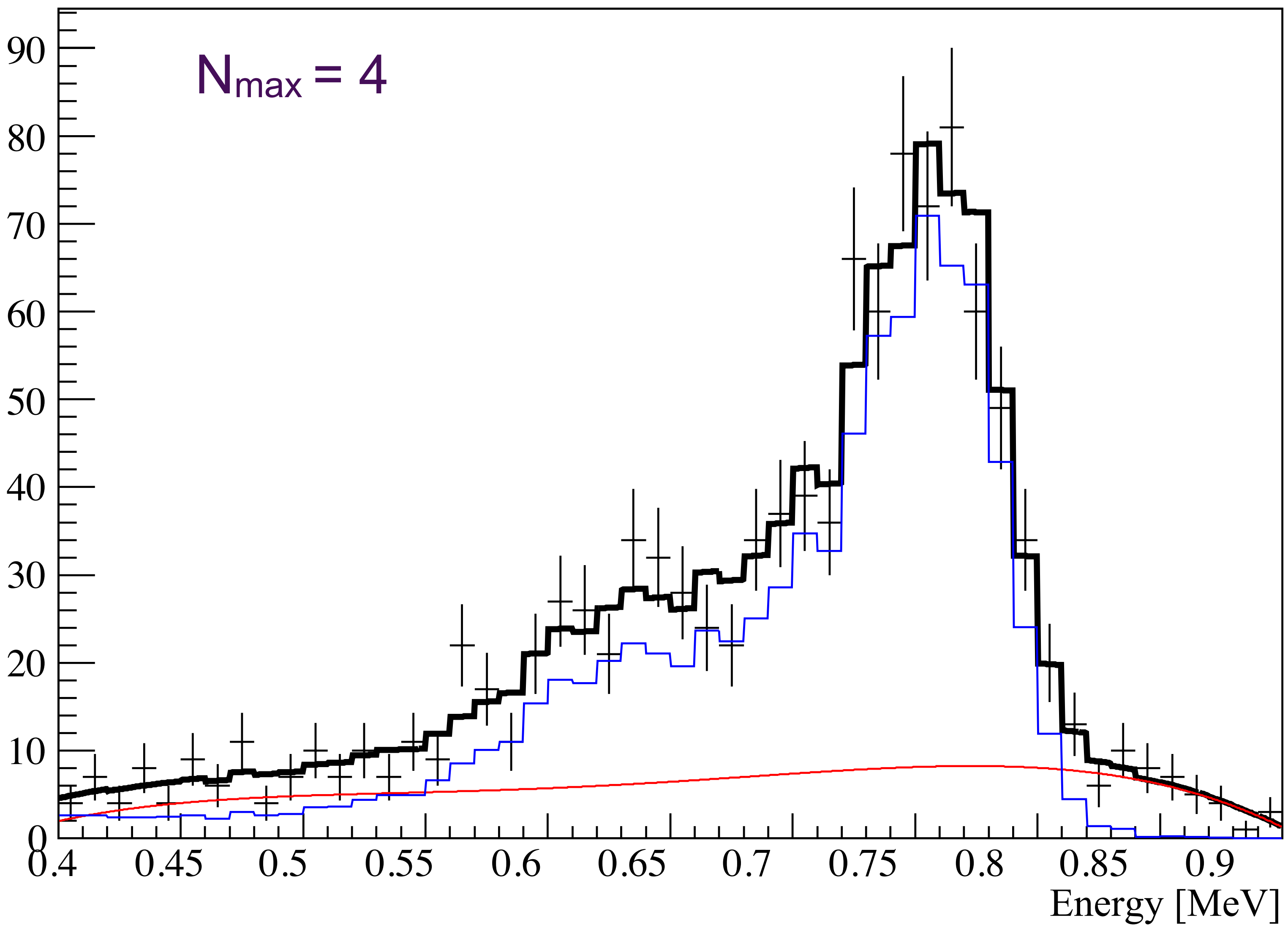


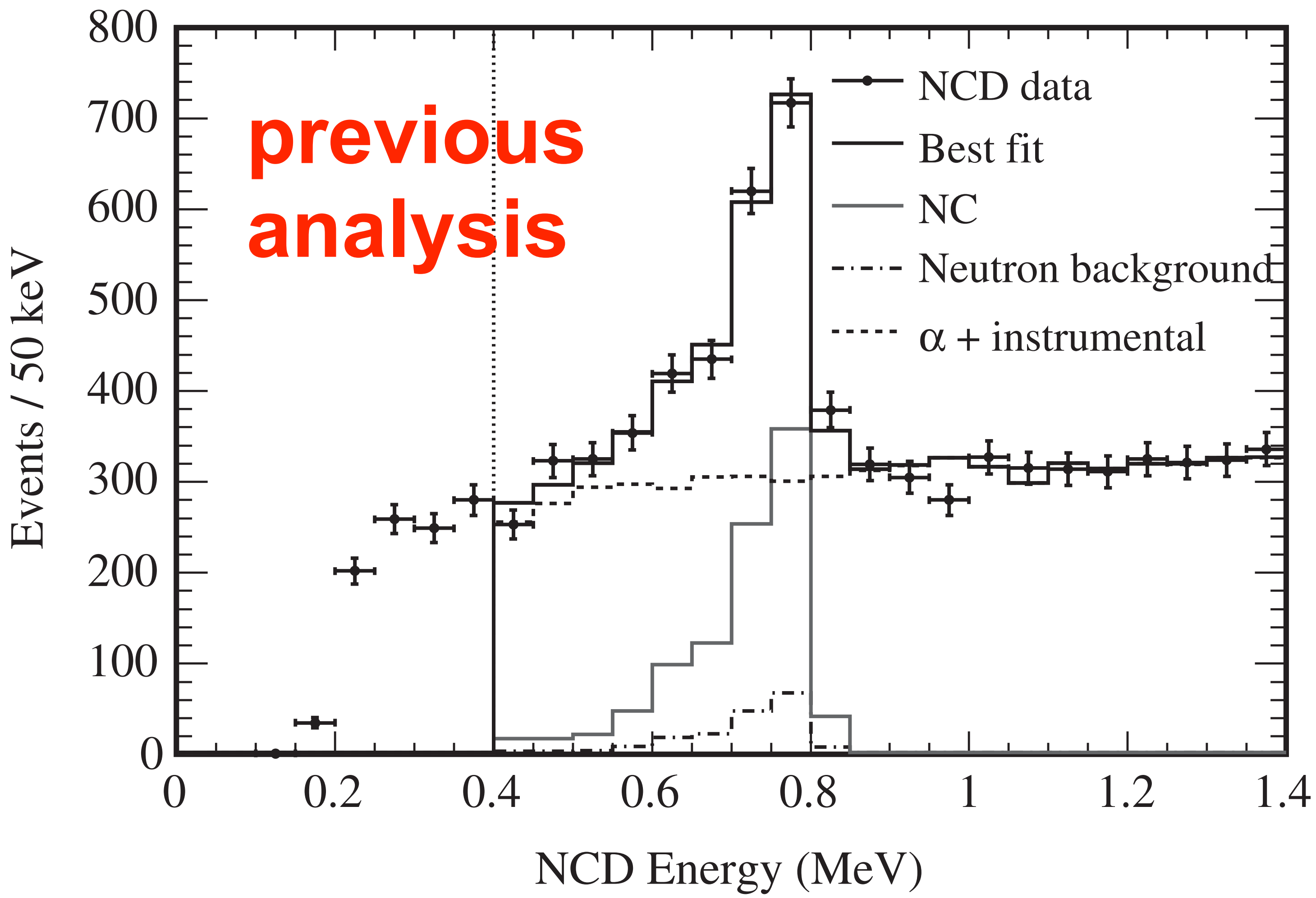
FIG. 9. The fitted $E_{\rm NCD}$ spectrum after the particle identification cut. The thick black line is the best fit. The blue and red lines are the best fitted neutron and alpha spectra, respectively.

$N_{\rm max}$	χ^2/NDF	Stat. uncertainty
0	54.92/48	4.2%
1	56.72/47	4.2%
2	47.63/46	5.5%
3	41.78/45	6.5%
4	40.20/44	6.9%
5	40.34/43	9.4%
6	40.41/42	9.2%

1115 ± 79
neutrons observed by the NCD array

polynomial fit technique includes alpha energy systematics

NCD Fit Results



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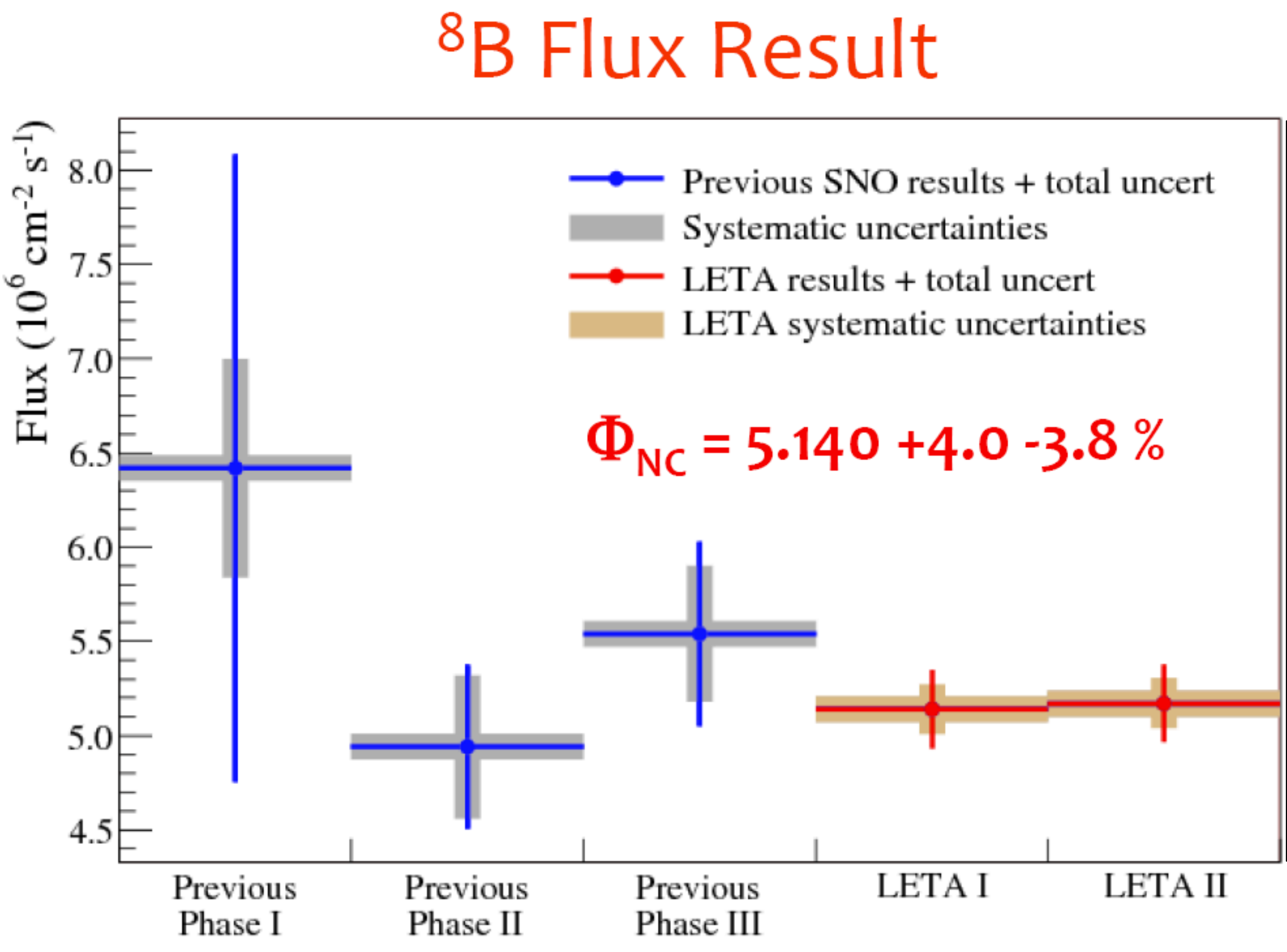
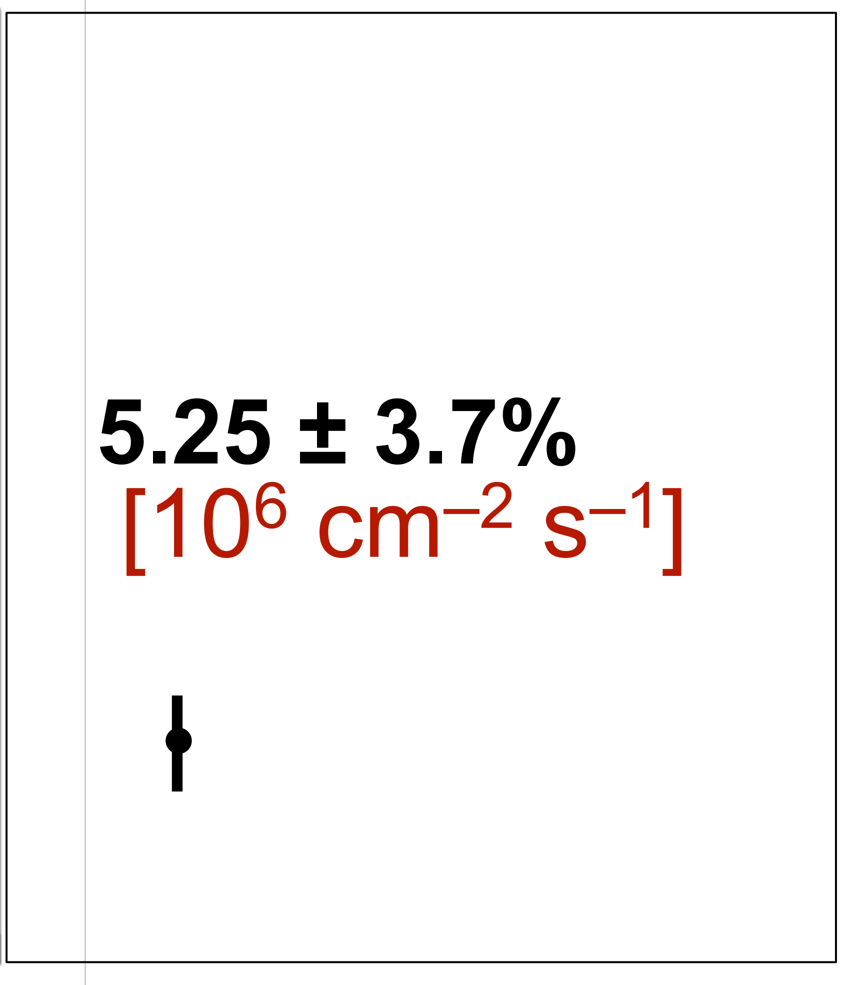
Final SNO Total ^8B Solar Neutrino Flux from NC





Combined 3-Phase

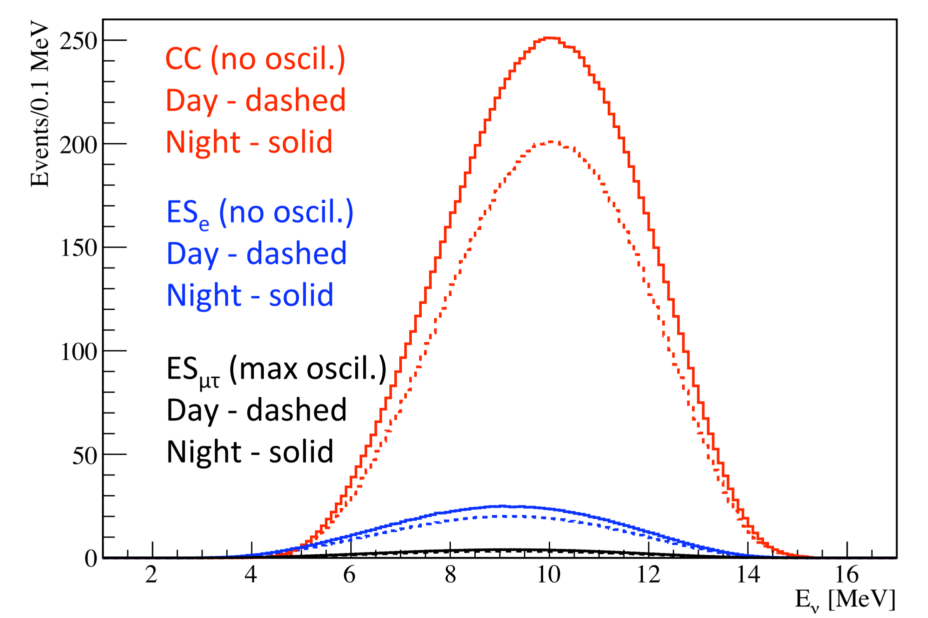
Oscillation Analysis

- combined CC, ES data from all three phases plus the new, combined NC total ^{8}B flux
- survival probability and day/night asymmetry are gently-varying functions of energy (in the LMA region)

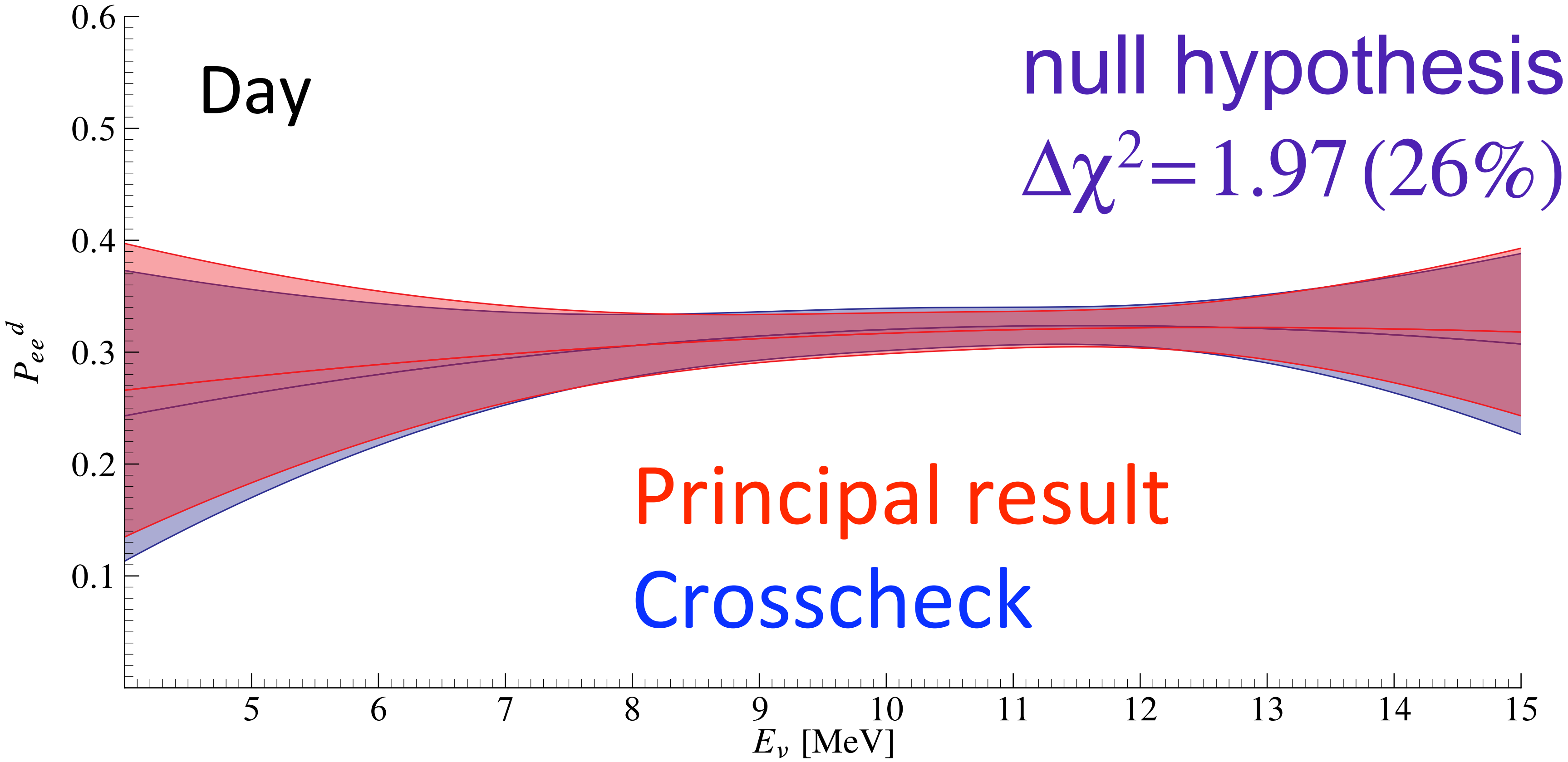
$$P_{ee}^{Day}(E_\nu) = c_0 + c_1(E_\nu - 10) + c_2(E_\nu - 10)^2$$

$$P_{ee}^{Asym}(E_\nu) = a_0 + a_1(E_\nu - 10),\ E_\nu \text{ in MeV}$$

polynomial expanded around 10 MeV since that is the neutrino energy with the maximum detected count rate (^{8}B energy spectrum, cross section, SNO threshold)



SNO-Determined P_{ee} and D/N Shapes



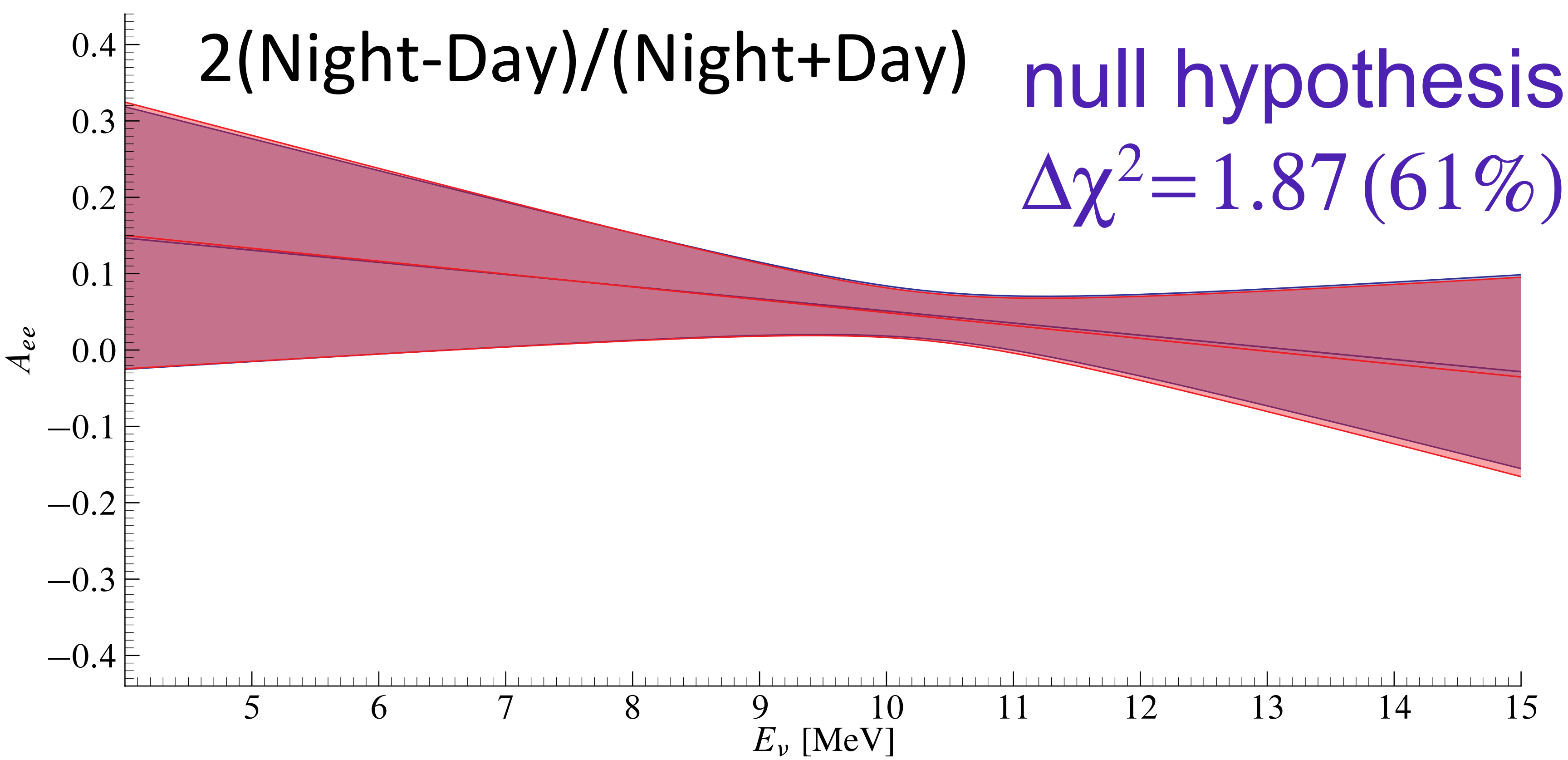
$$c_0 = 0.317 \pm 0.016 \pm 0.009$$

$$c_1 = 0.0039^{+0.0065}_{-0.0067} \pm 0.0045$$

$$c_2 = -0.0010 \pm 0.0029^{+0.0014}_{-0.0016}$$

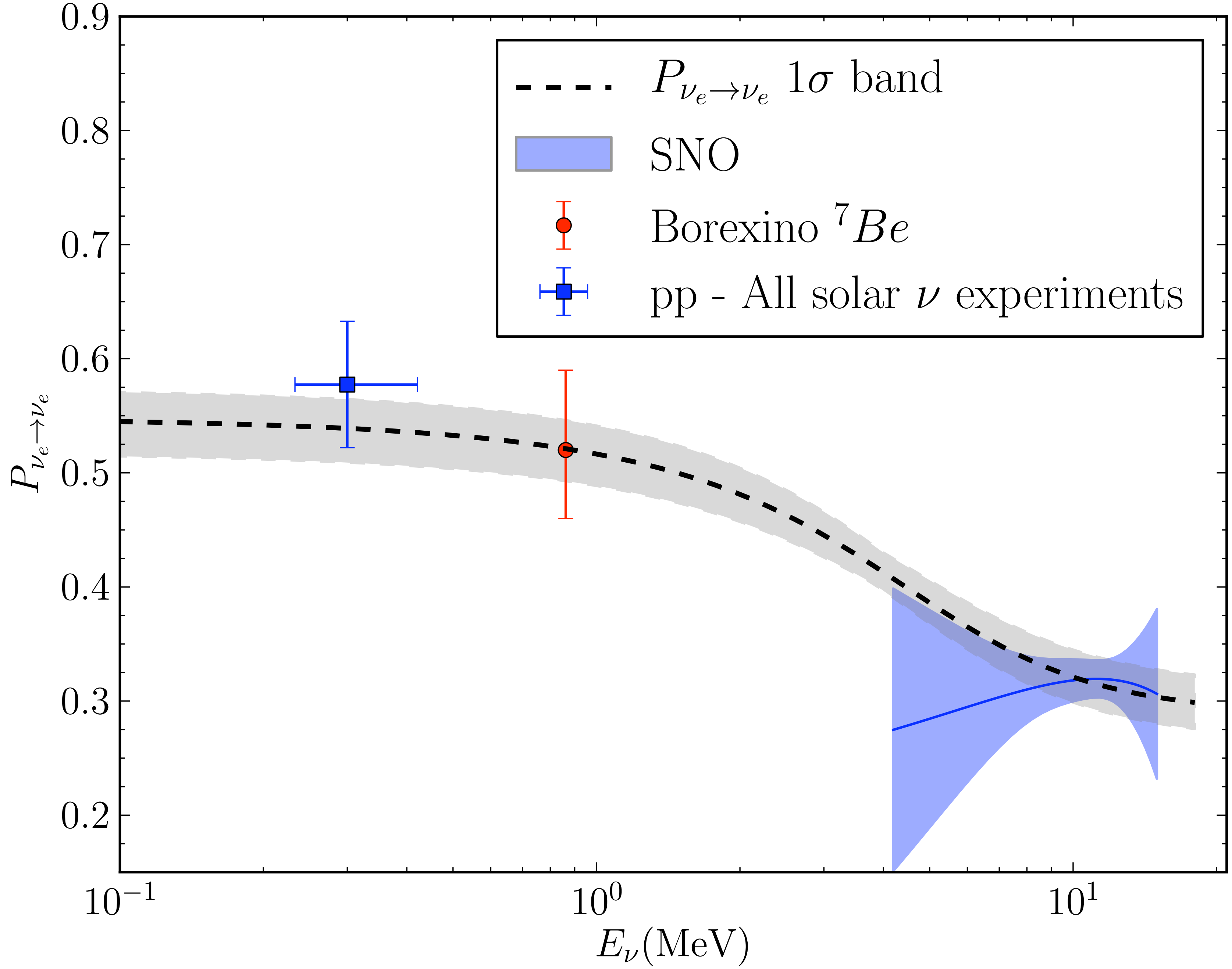
$$a_0 = 0.046 \pm 0.031^{+0.014}_{-0.013}$$

$$a_1 = -0.016 \pm 0.025^{+0.010}_{-0.011}$$

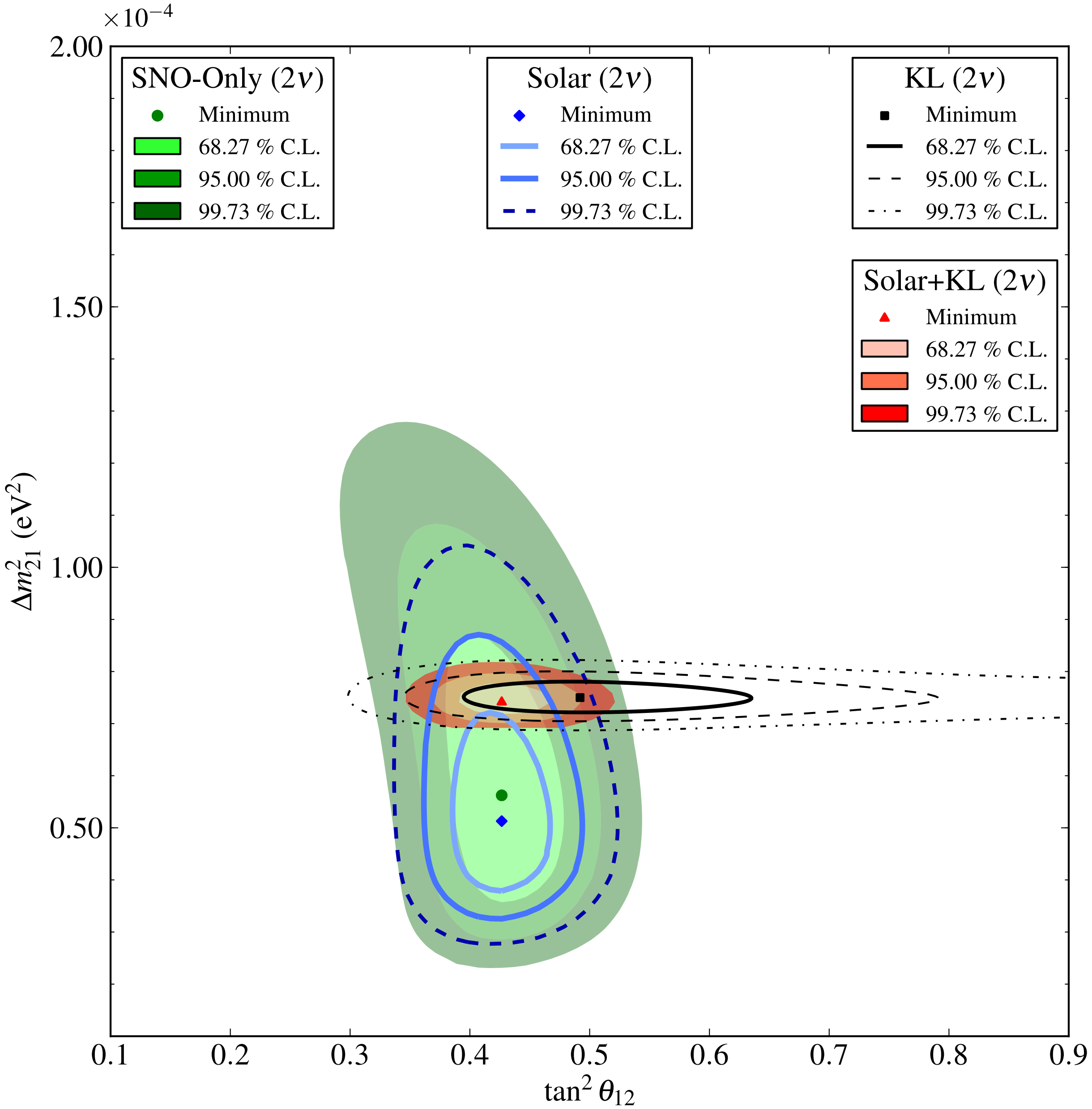


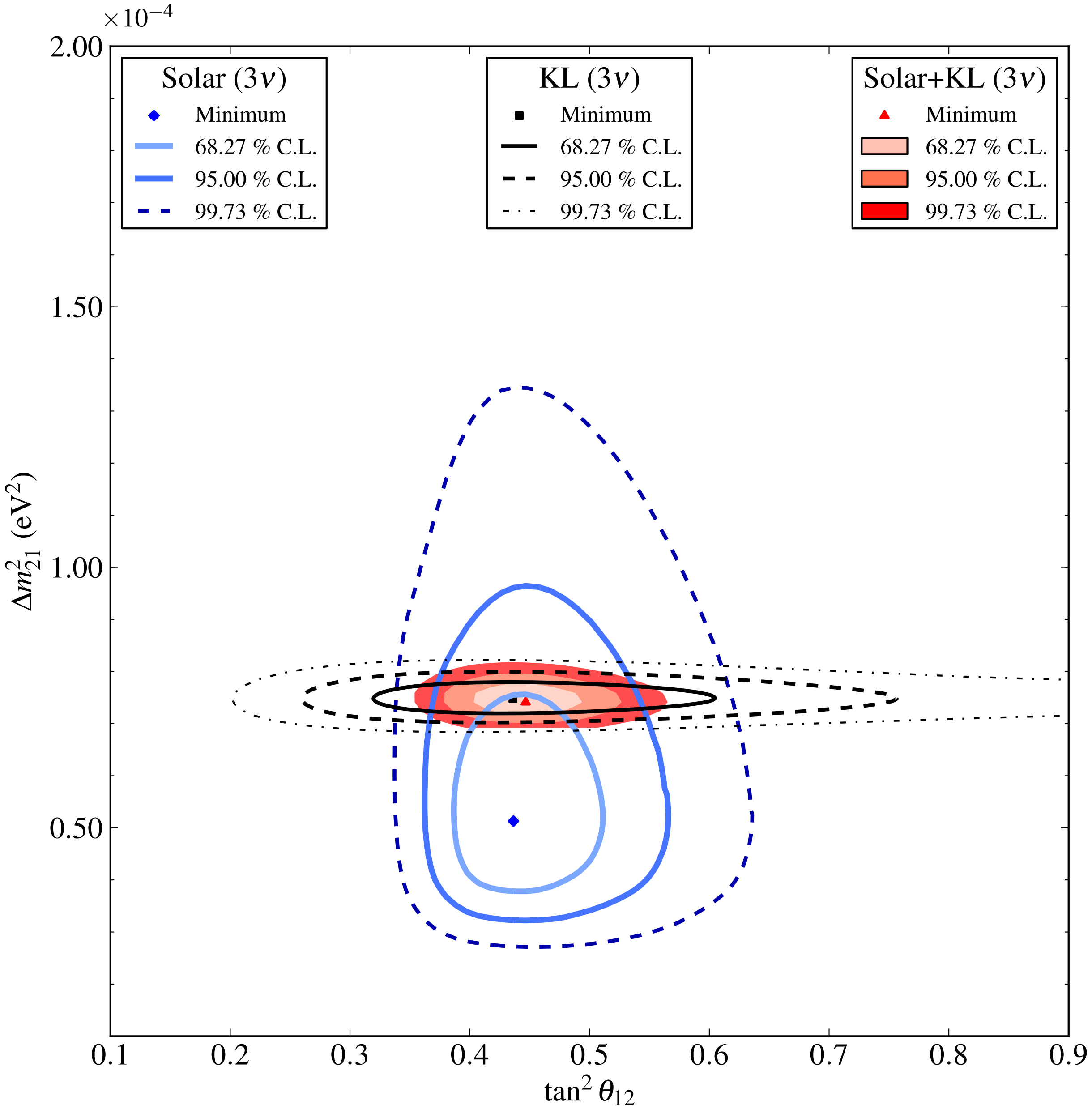
Approximately 20% improvement over previous analysis.

Comparing to the MSW LMA Solution

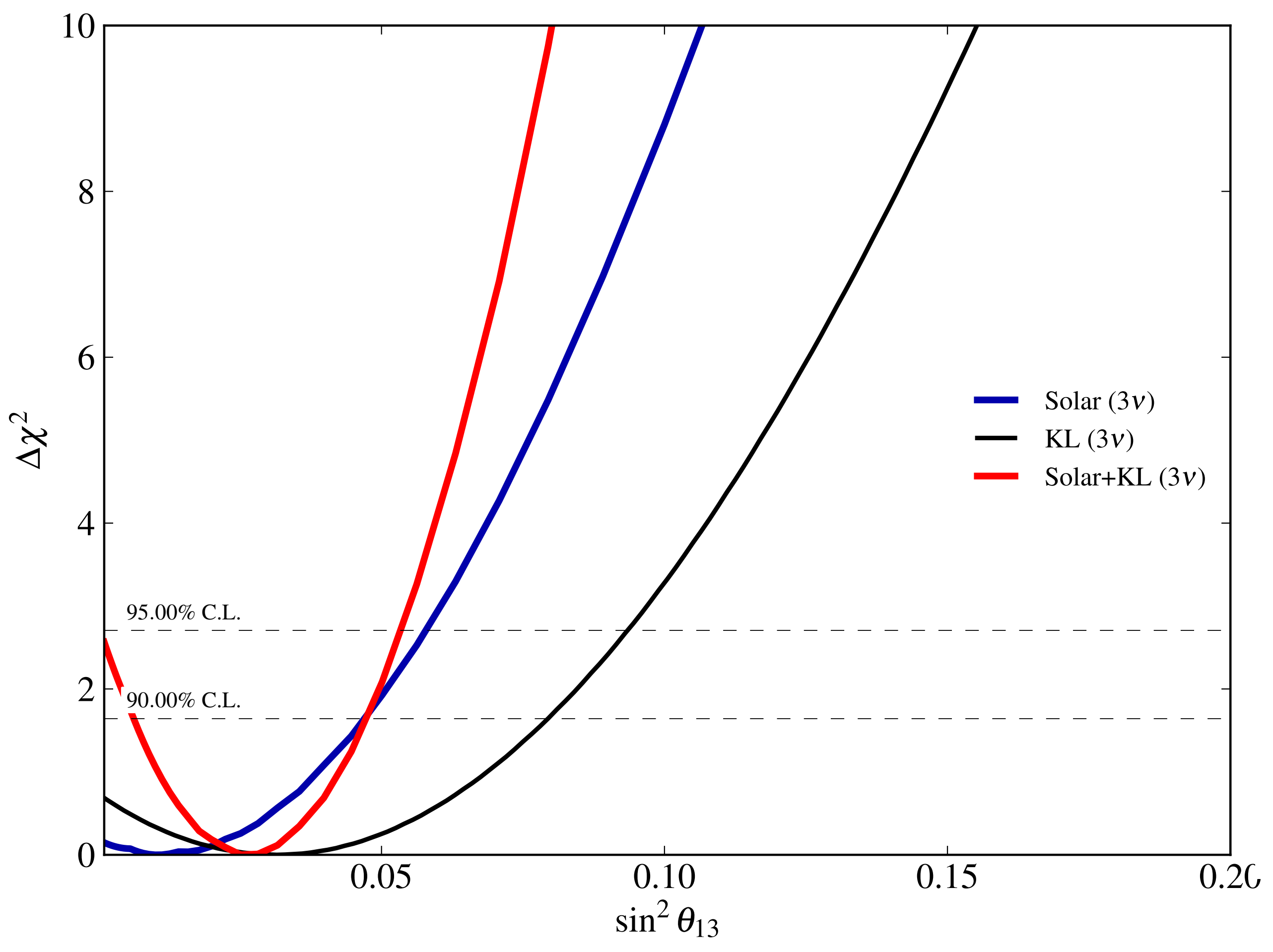


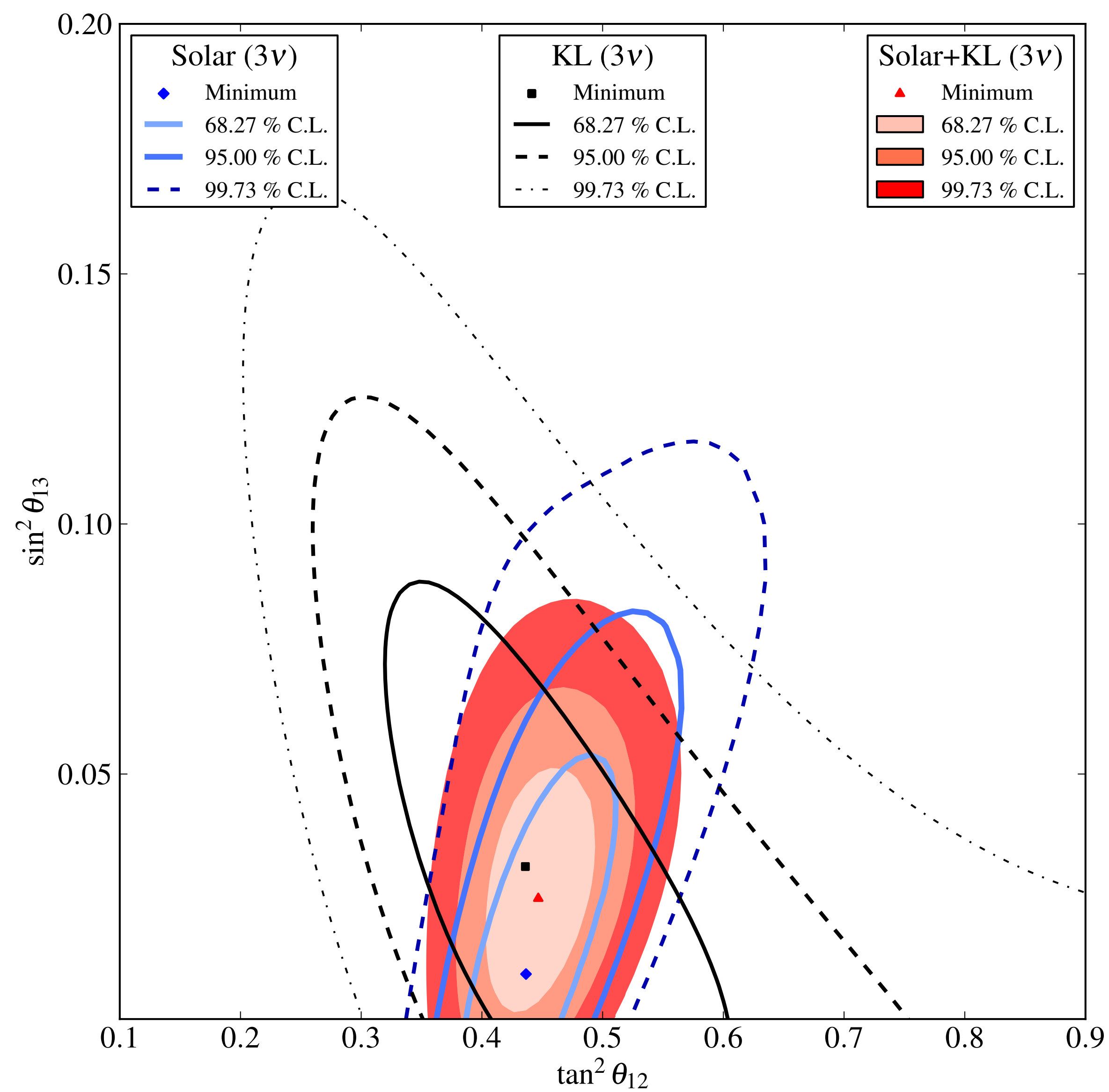
Global Solar Plus KamLAND



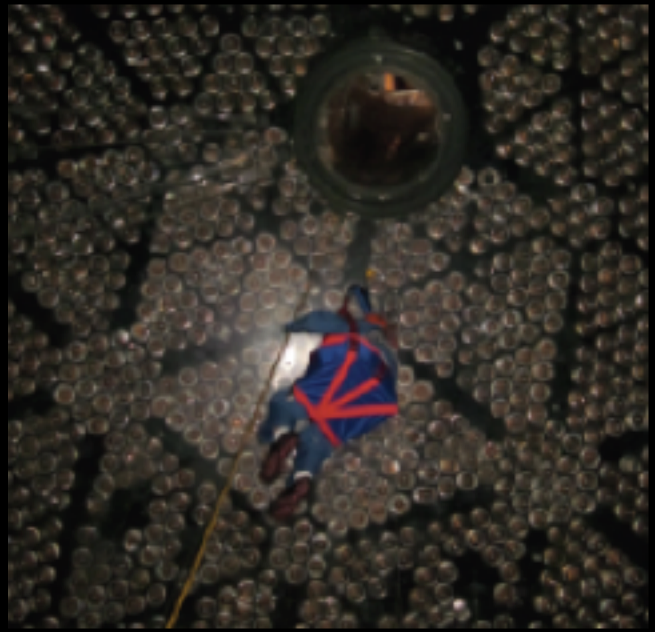


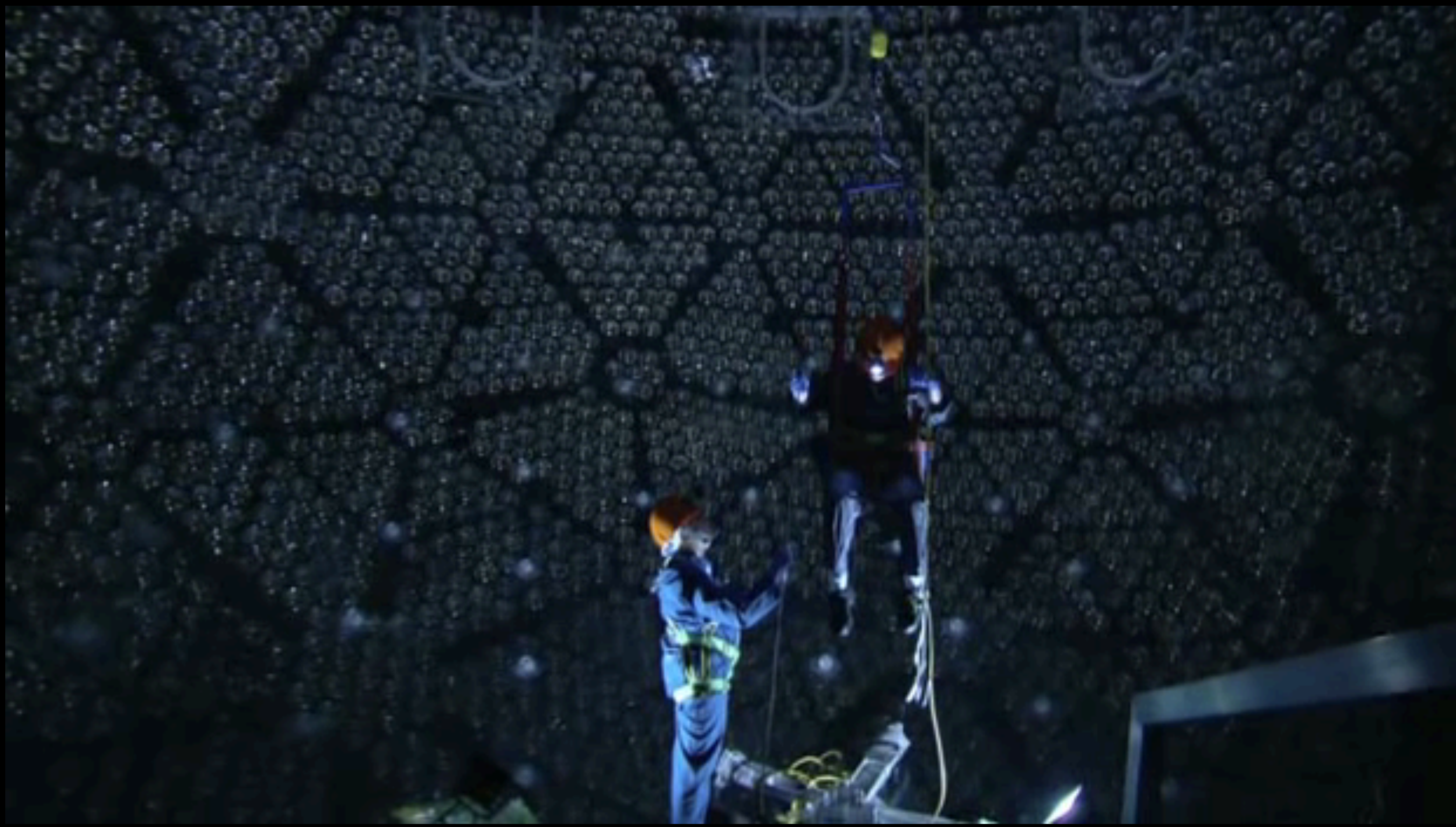
SNO's θ13
3-Flavour Analysis

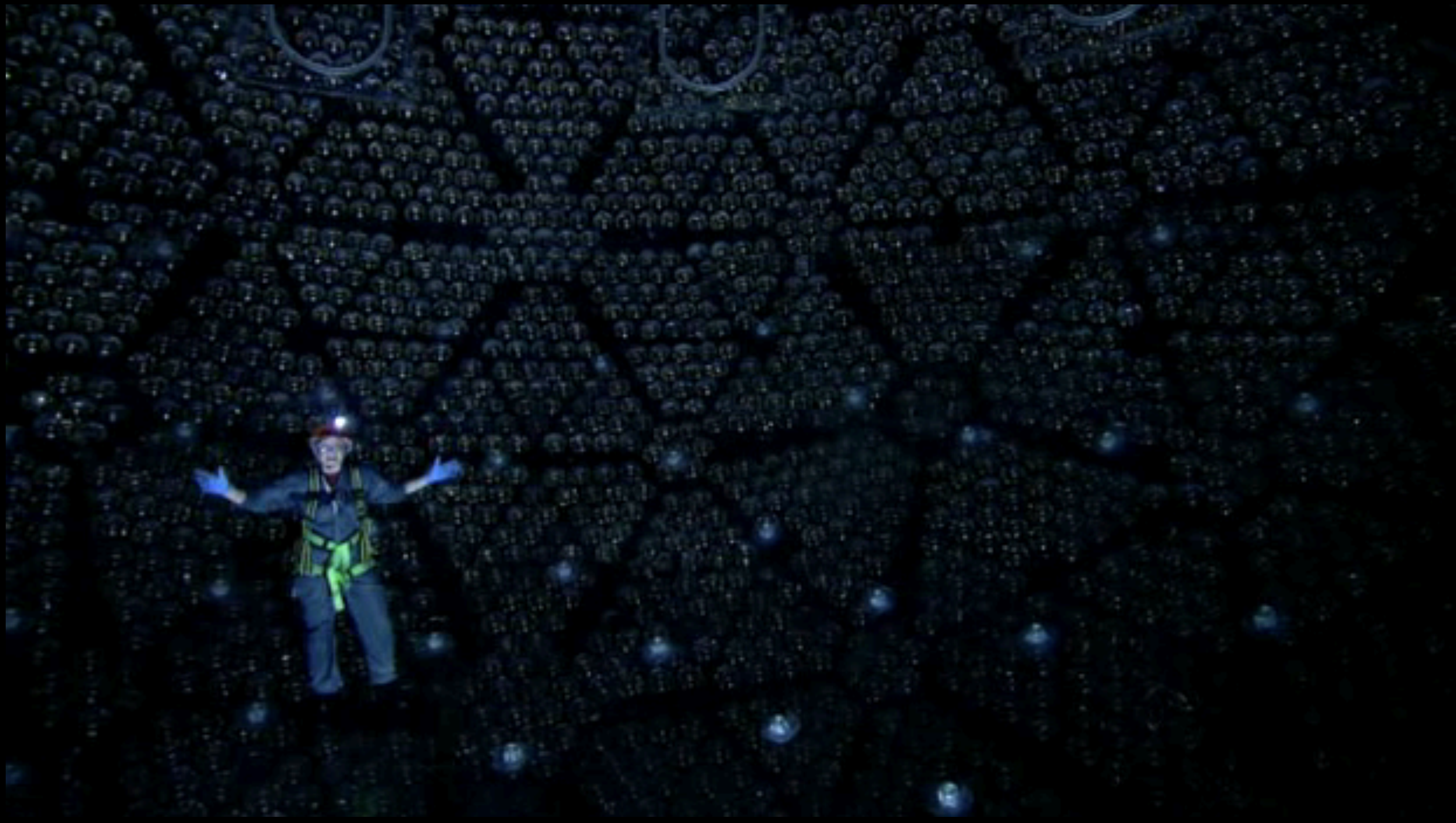




SNO+









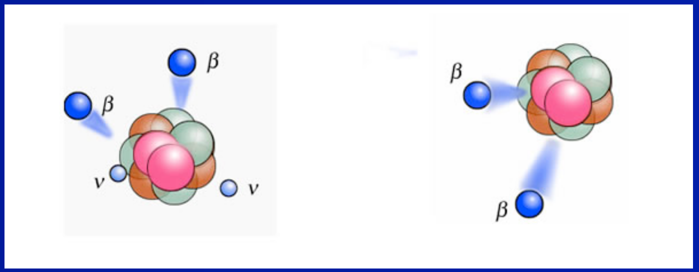


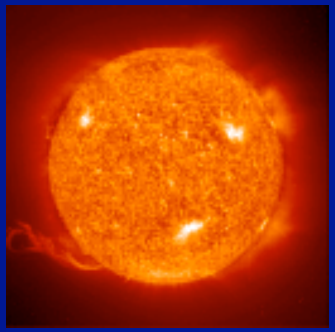
SNO+ Collaboration

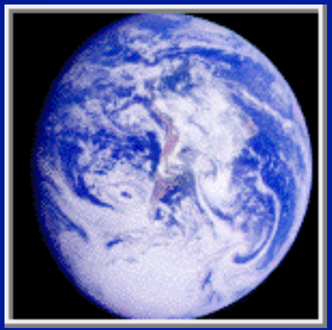
Queen's, Alberta, Laurentian, SNOLAB, TRIUMF
BNL, Penn, Washington, AASU, BHSU, UNC
Oxford, Sussex, QMUL, Leeds, Liverpool, Sheffield
LIP Lisbon
TU-Dresden

SNO+ Physics Program

- search for neutrinoless double beta decay
- neutrino physics
  - –solar neutrinos
  - –geo antineutrinos
  - –reactor antineutrinos
  - –supernova neutrinos



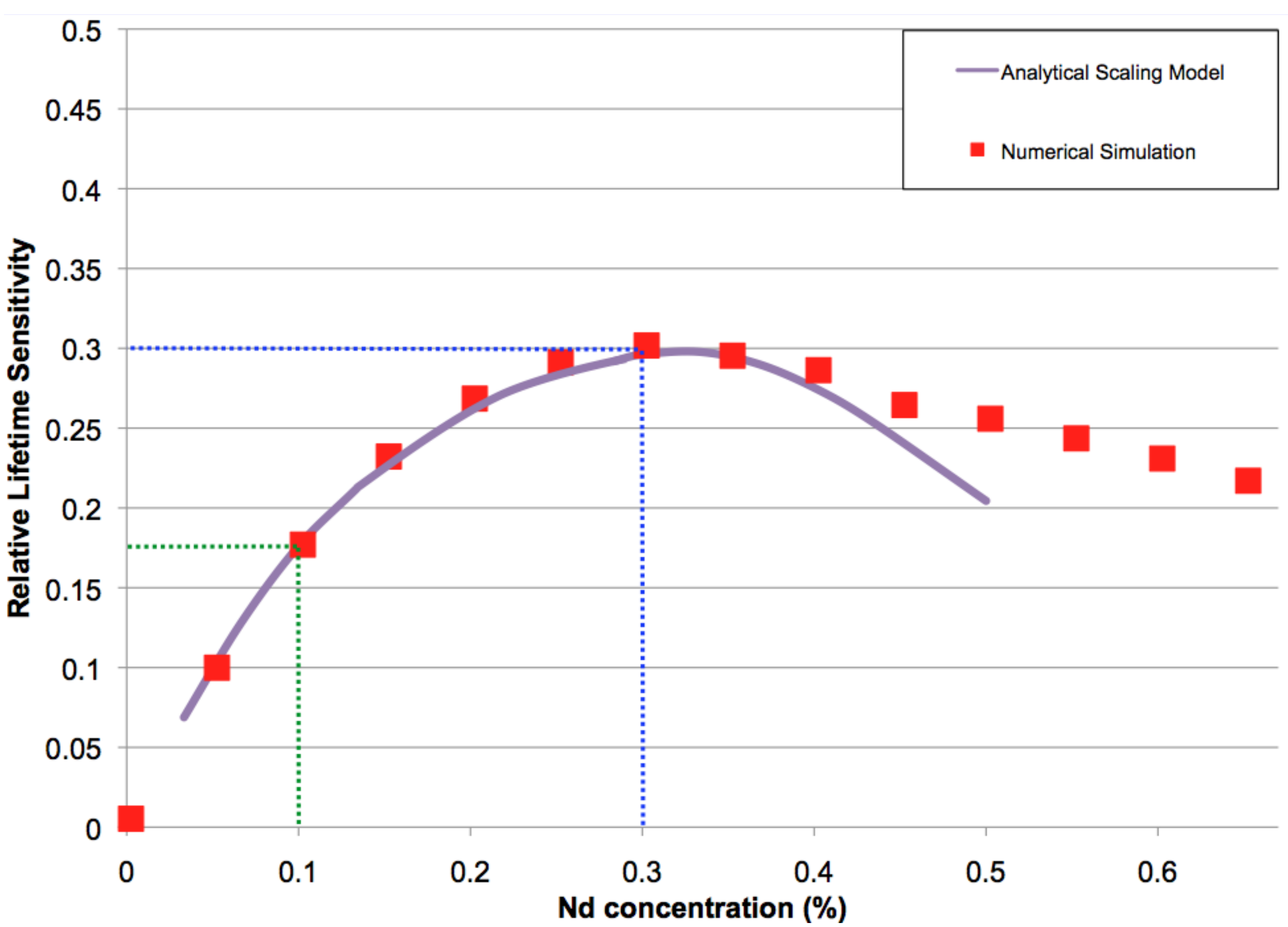


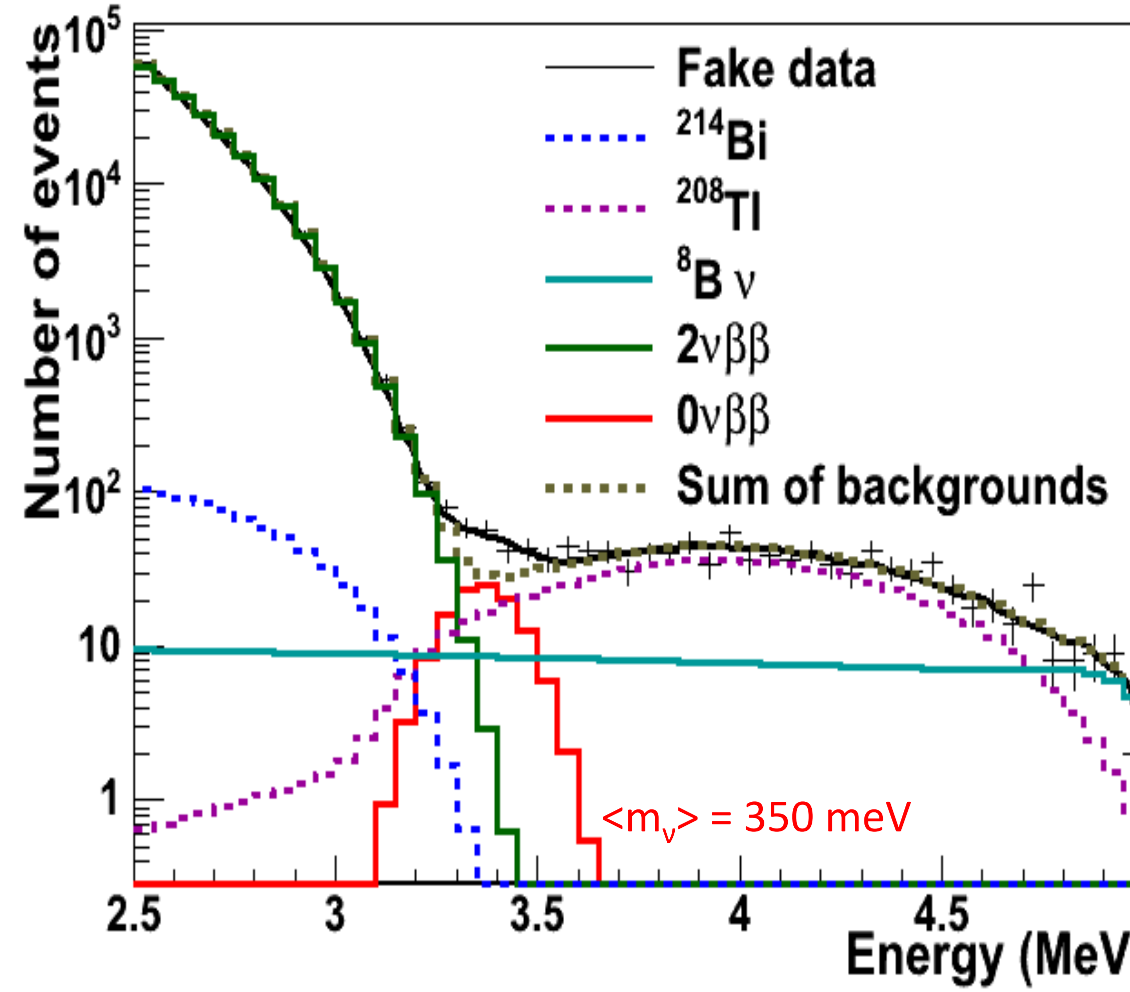


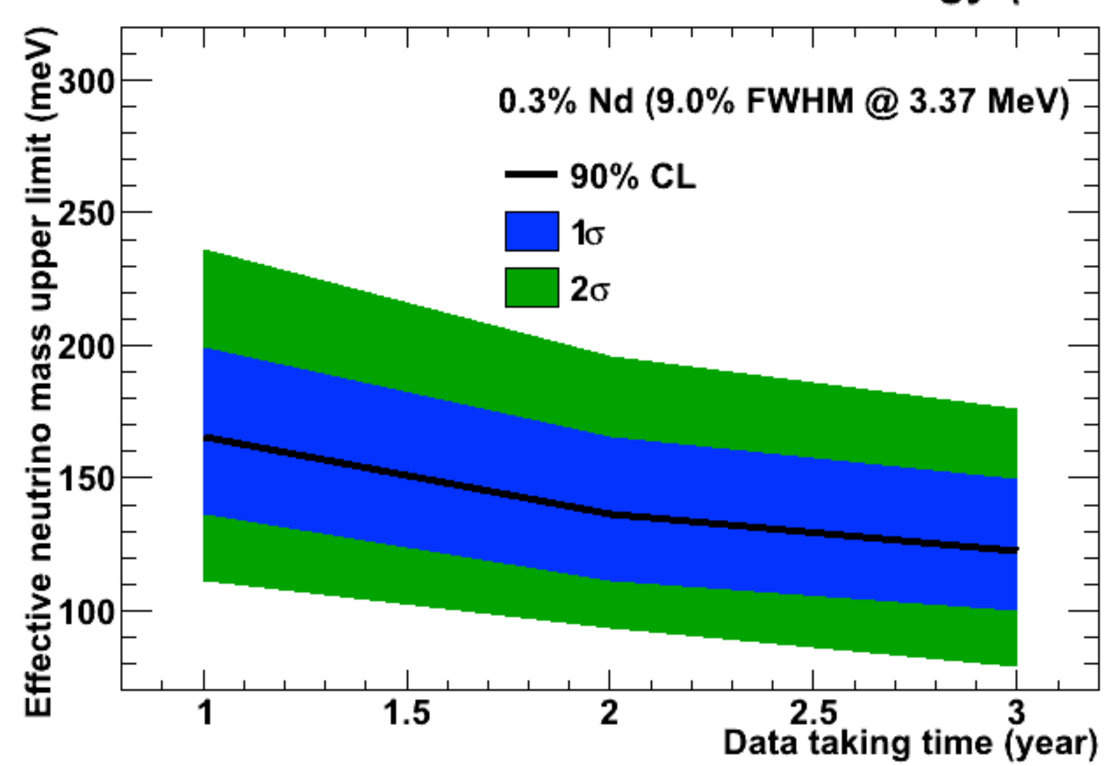
SNO+ Physics Goals

Double Beta Decay with ^{150}Nd

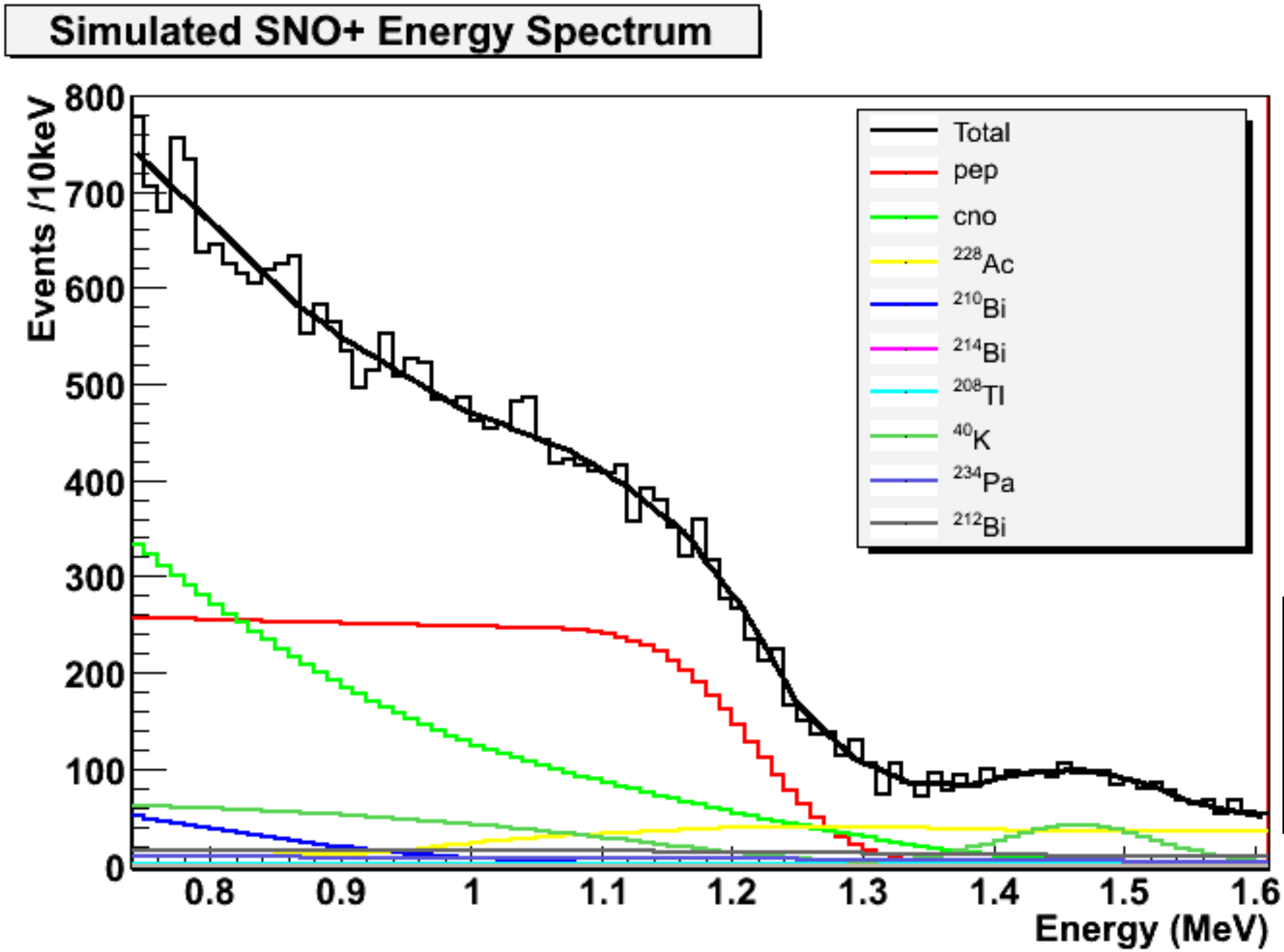
- 44 kg ^{150}Nd (0.1% loading)
- investigating 0.3% loading, found to be the optimum amount
- pursuing Nd isotope enrichment possibilities







SNO+ pep and CNO Solar Neutrino Signals



an accurate measurement of the rate of pep solar neutrino interactions:

$$R = \Phi\, P_{ee}\, \sigma$$

flux is calculated in SSM to ±1.5%; cross section is known (ν-e scattering)

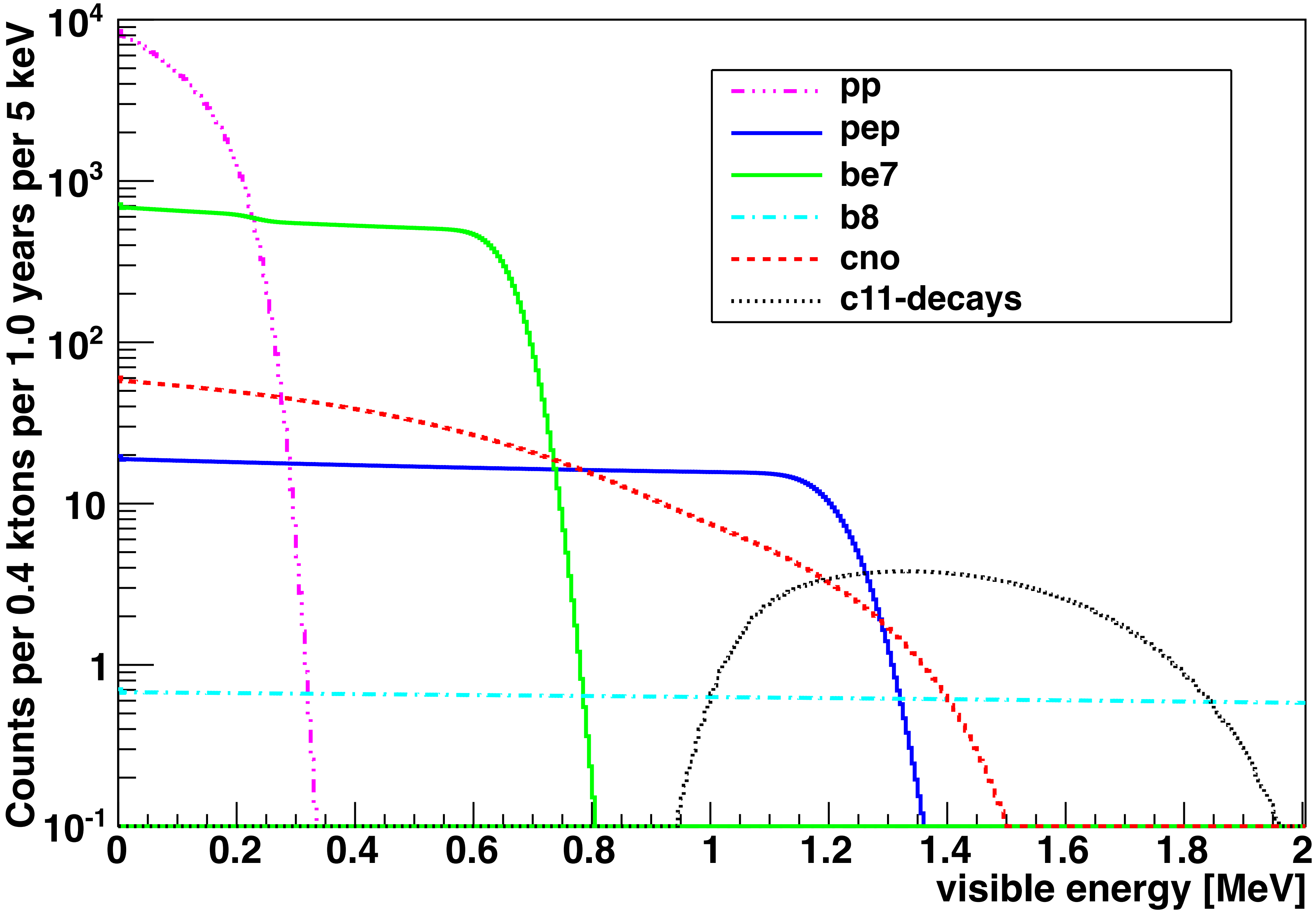
➔ yields an accurate measure of the survival probability

CNO measurement uncertainty: ±7% statistical after 3 years

3600 *pep* events/(kton·year), for electron recoils >0.8 MeV

<u>±5% total uncertainty</u> after 3 years (including systematic and SSM)

^{11}C Background – Not a Concern



muon rate in SNO+ will be 70 muons/day

backgrounds scale pretty much with muon flux

will be relatively easy to tag and further eliminate ^{11}C backgrounds following muons, at this rate

Turning SNO into SNO+

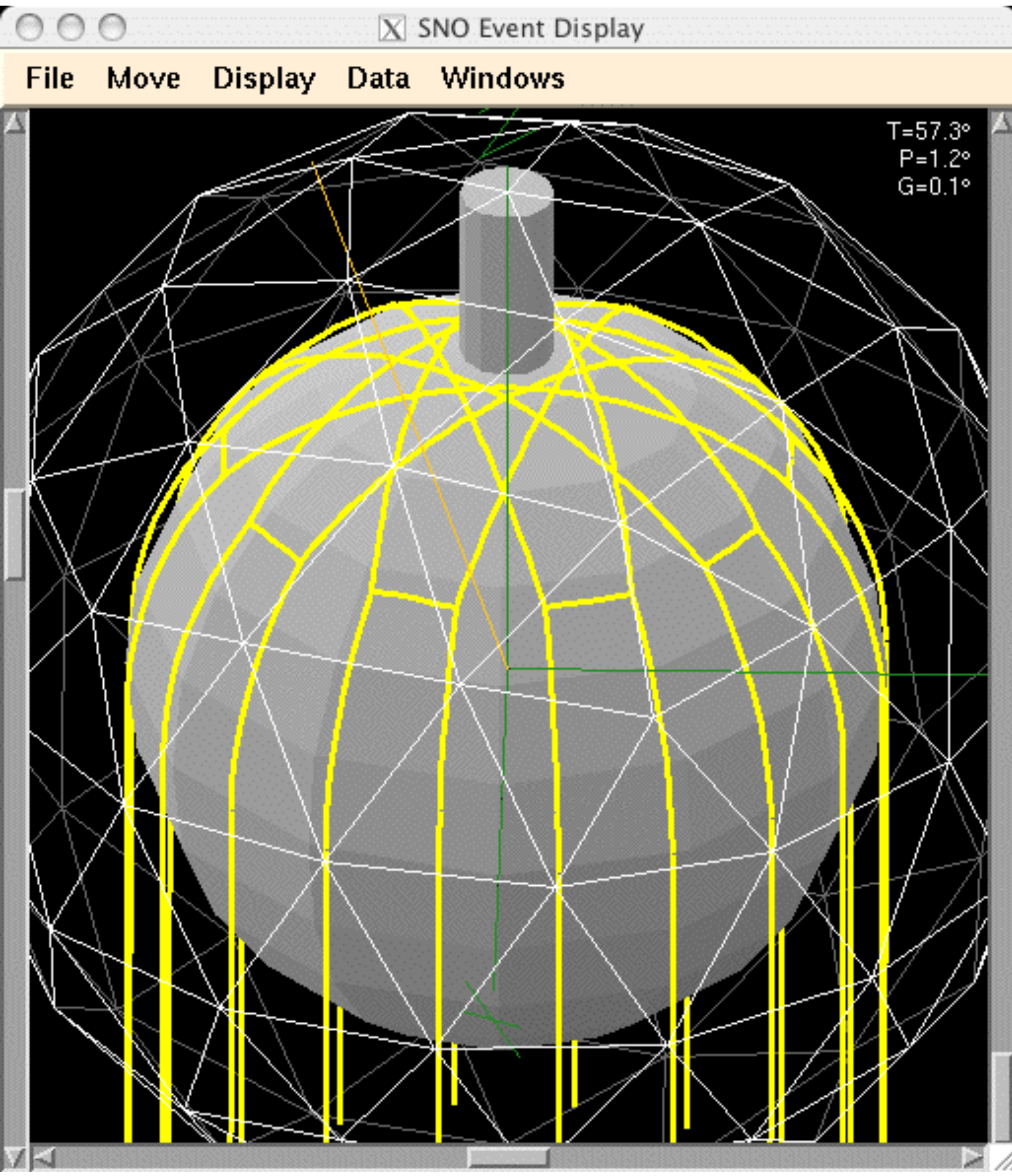
- to do this we need to:
  - buy the liquid scintillator
  - install hold down ropes for the acrylic vessel
  - build a liquid scintillator purification system
  - clean up inside the Acrylic Vessel (remove radon daughters)
  - minor upgrades to the cover gas
  - minor upgrades to the DAQ/electronics
  - change the calibration system and sources

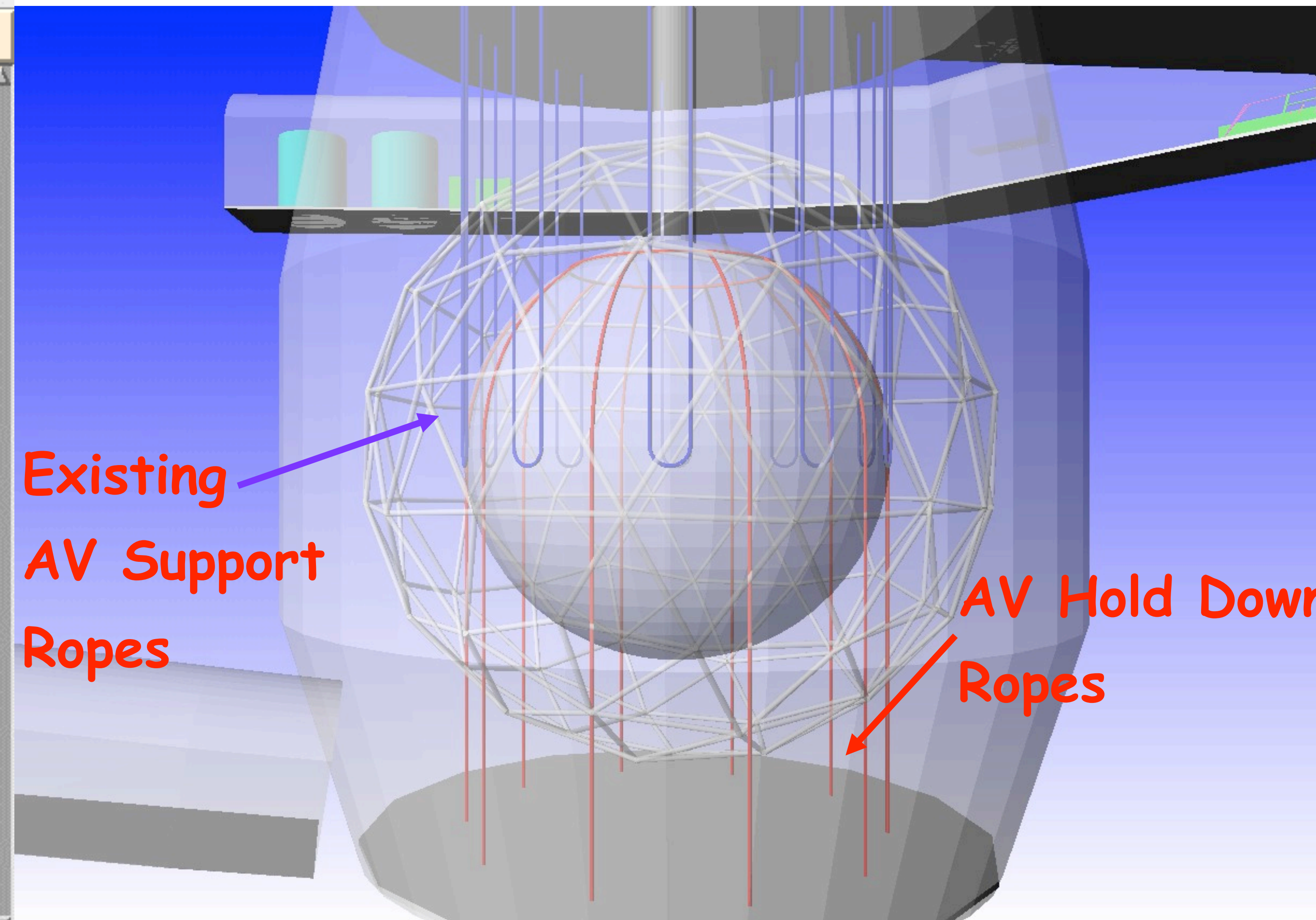
SNO+ Status

- buy the liquid scintillator
  - ***preparing to receive scintillator for filling in early 2013***
- install hold down ropes for the acrylic vessel
  - cavity hold down anchors and new floor complete
  - new rope net delivered to site, preparing for installation in the next few weeks
- build a liquid scintillator purification system
  - many components being fabricated, for installation in 2012
- clean up inside the Acrylic Vessel (remove radon daughters)
  - preparing to install inside AV access tower
- minor upgrades to the cover gas underway
- upgrades to the DAQ/electronics
  - new electronics installed; running with new DAQ
  - preparing for water-filled commissioning in mid-2012
- change the calibration system and sources

SNO+ Rope Hold Down Net

sketch of hold down net



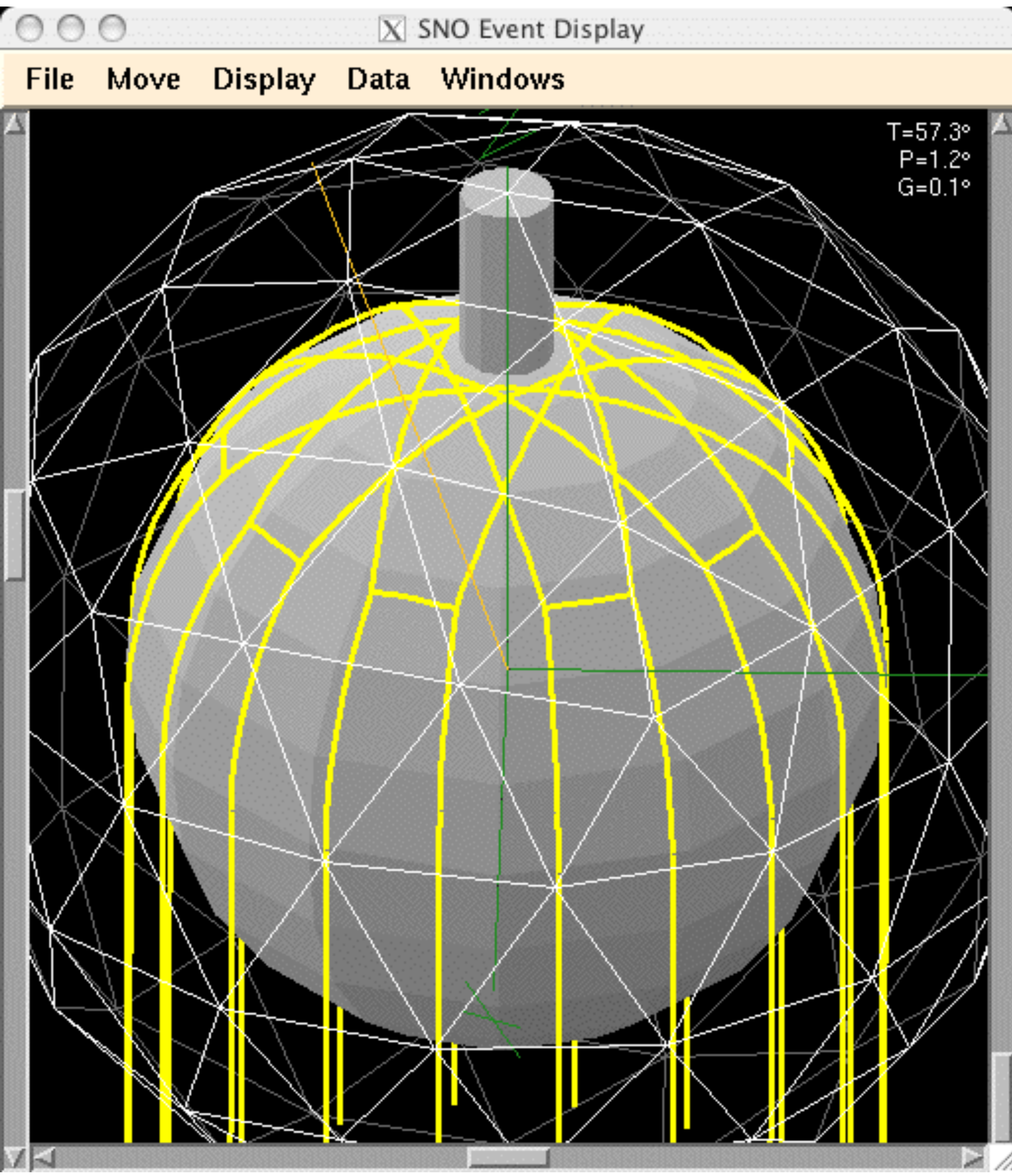


rope tension calculation and visualization of net-PSUP geometry

SNO+ ropes will be Tensylon: low U, Th, K ultra-high molecular weight polyethylene

SNO+ Rope Hold Down Net

sketch of hold down net



rope tension calculation and
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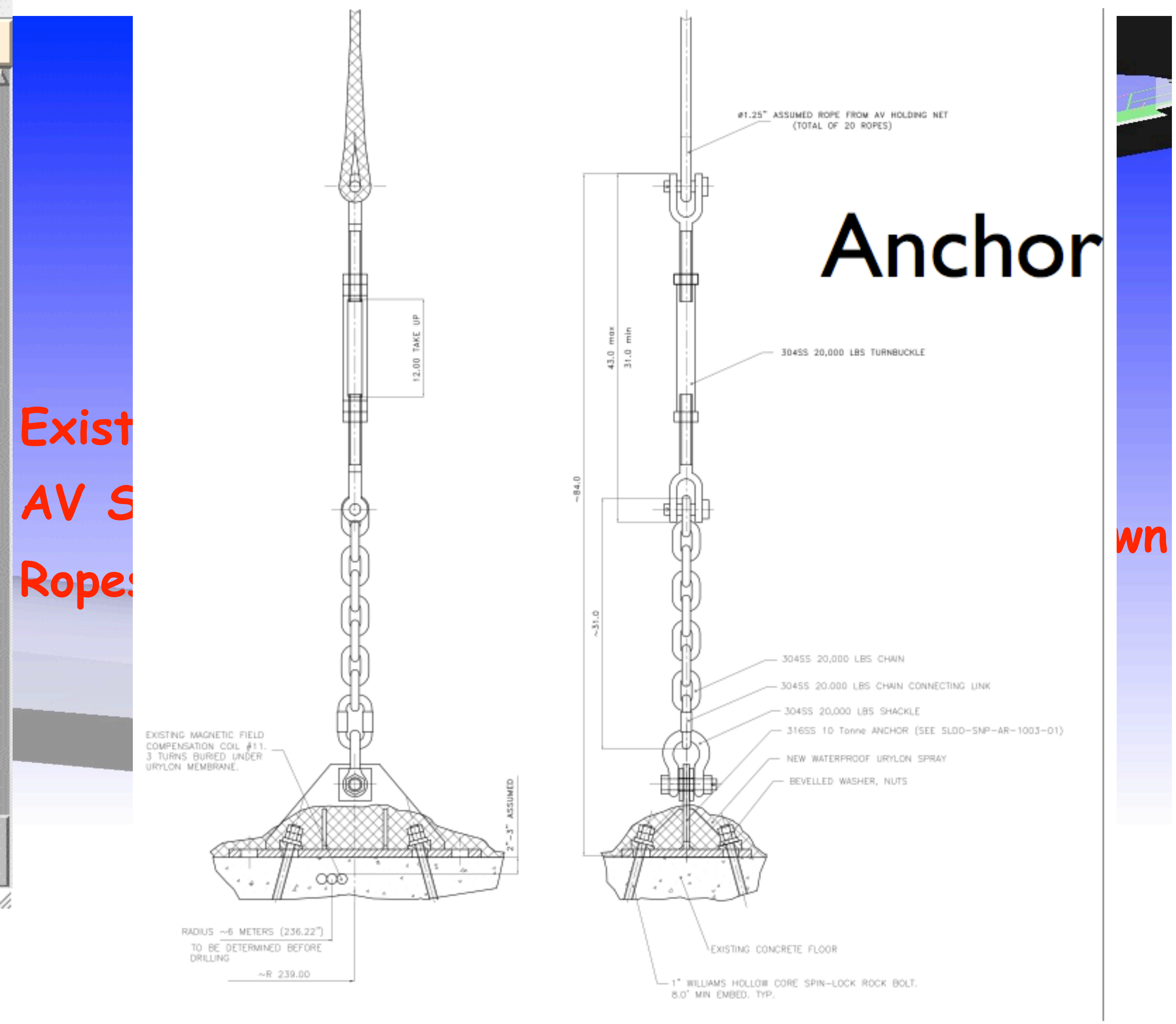
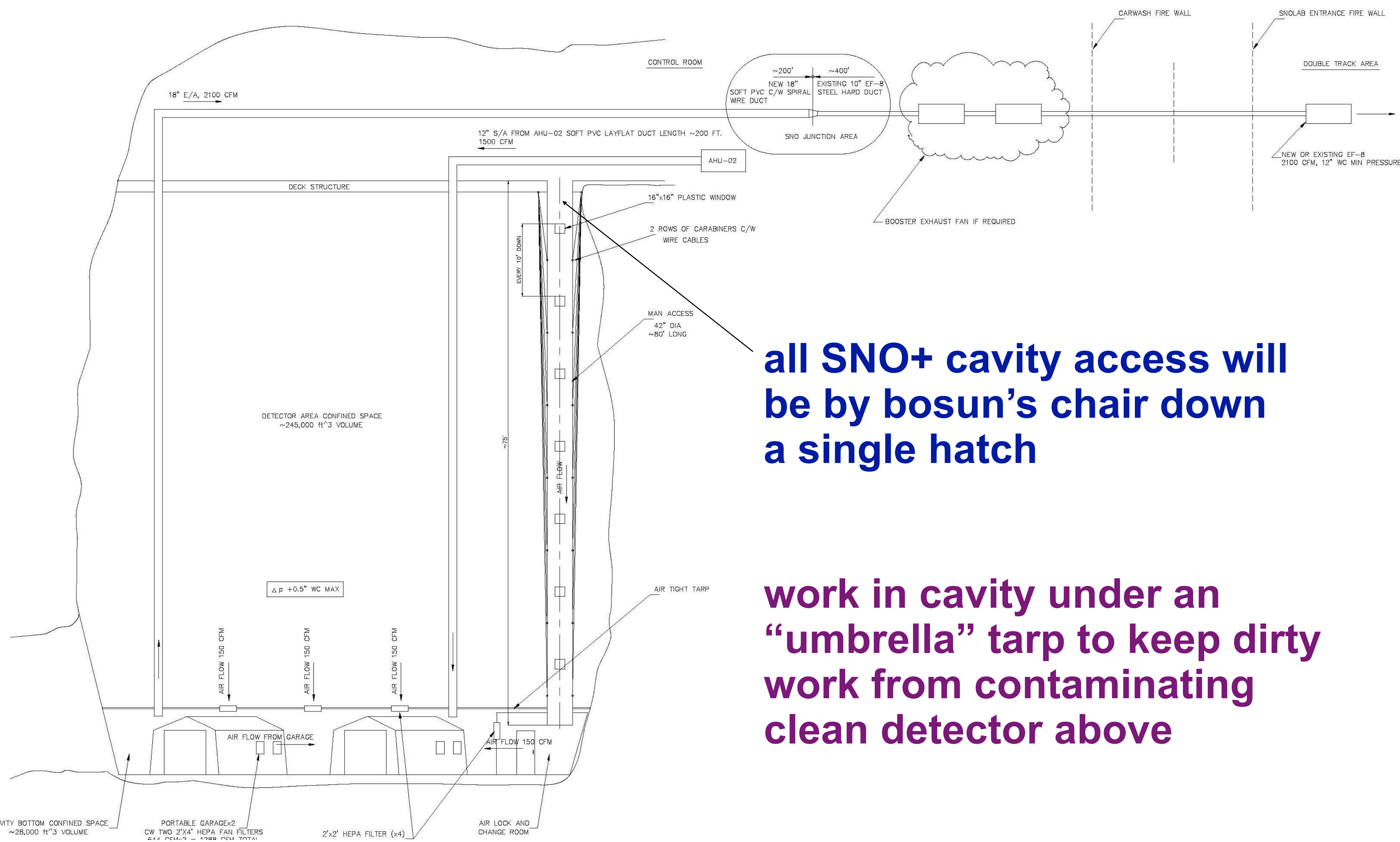


SNO+ ropes will be Tensylon: low U, Th, K ultra-high molecular weight polyethylene

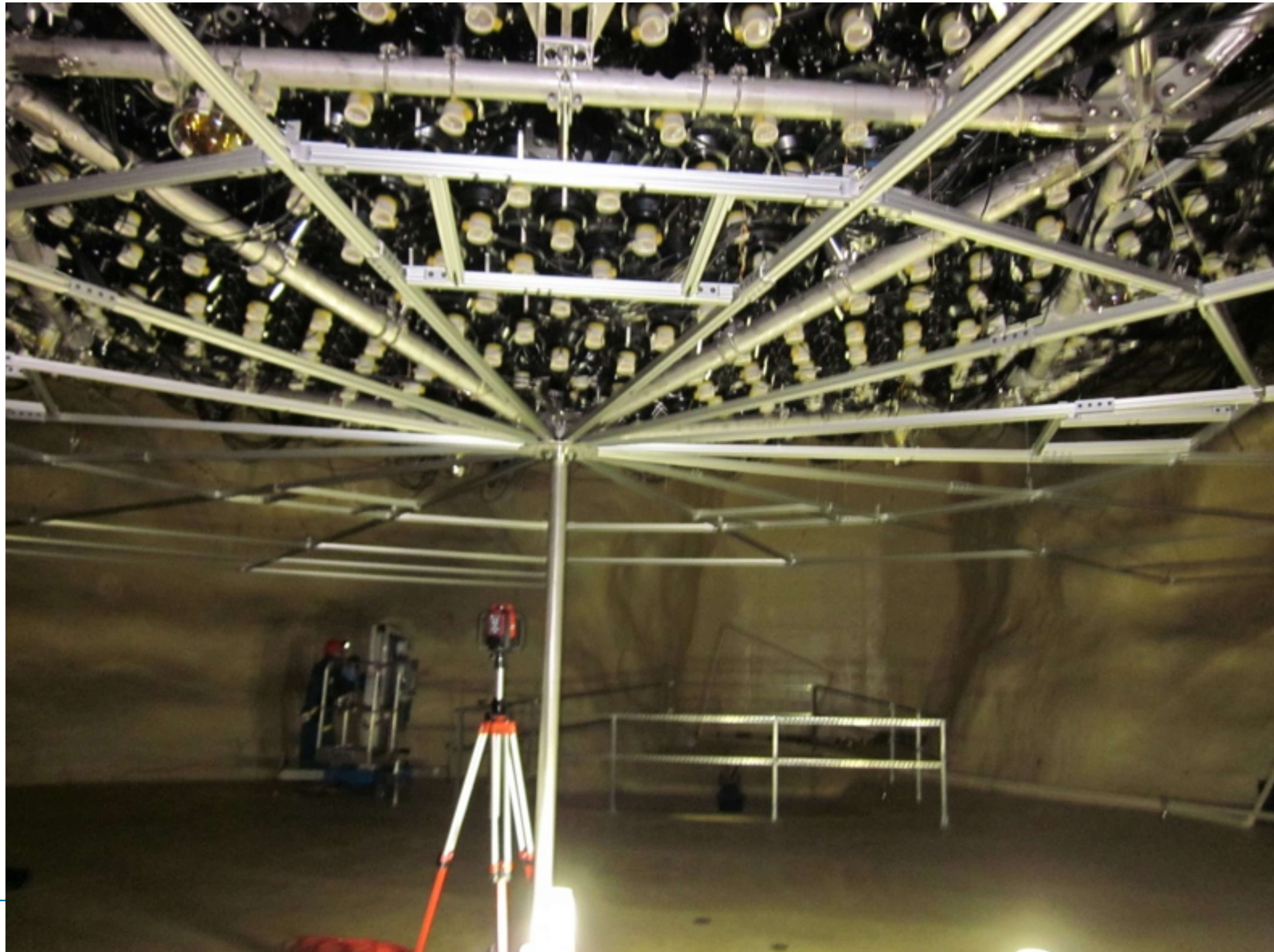
AIR HANDLING FLOWSHEET
(see drawing # SLDO-SNP-FL-2001-01)



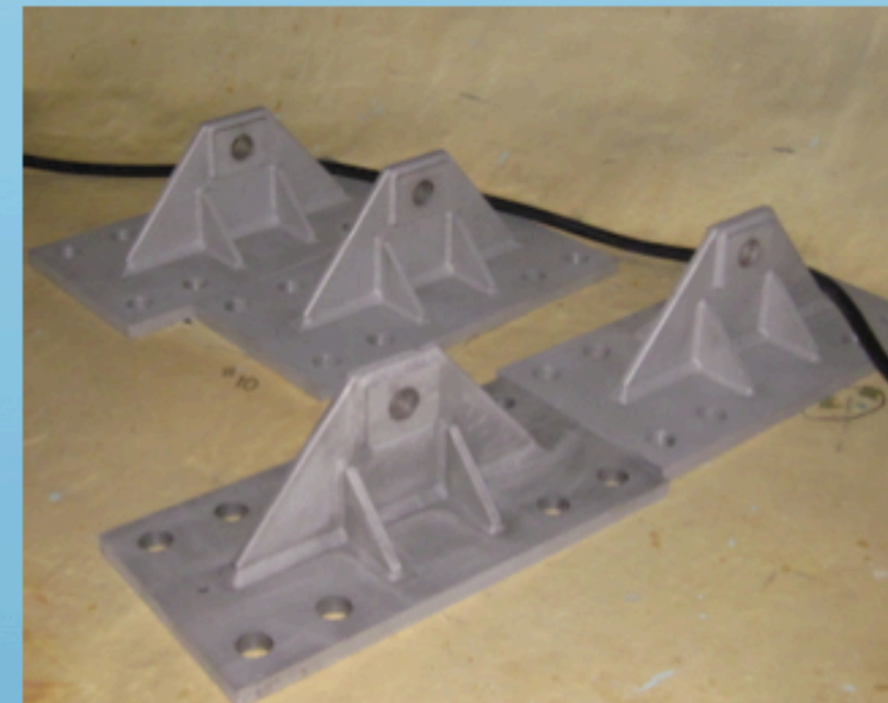
all SNO+ cavity access will be by bosun's chair down a single hatch

work in cavity under an "umbrella" tarp to keep dirty work from contaminating clean detector above

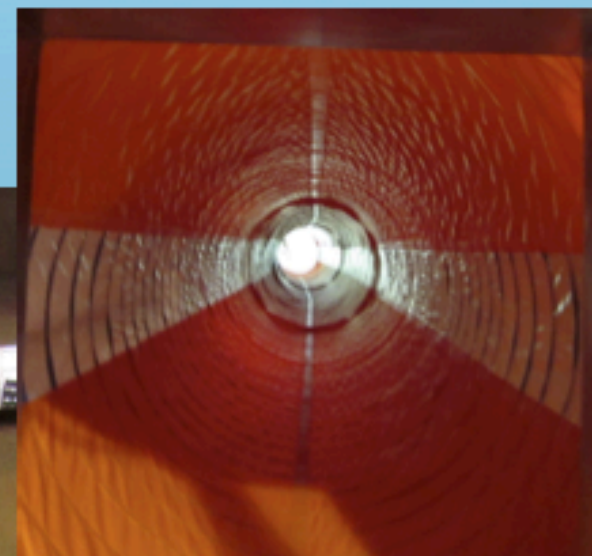
The Umbrella



February 15th 2011



access tube



Drilling Inside the SNO+ Cavity

drilling to install anchors for the hold-down net

in the SNO+ cavity, under the umbrella

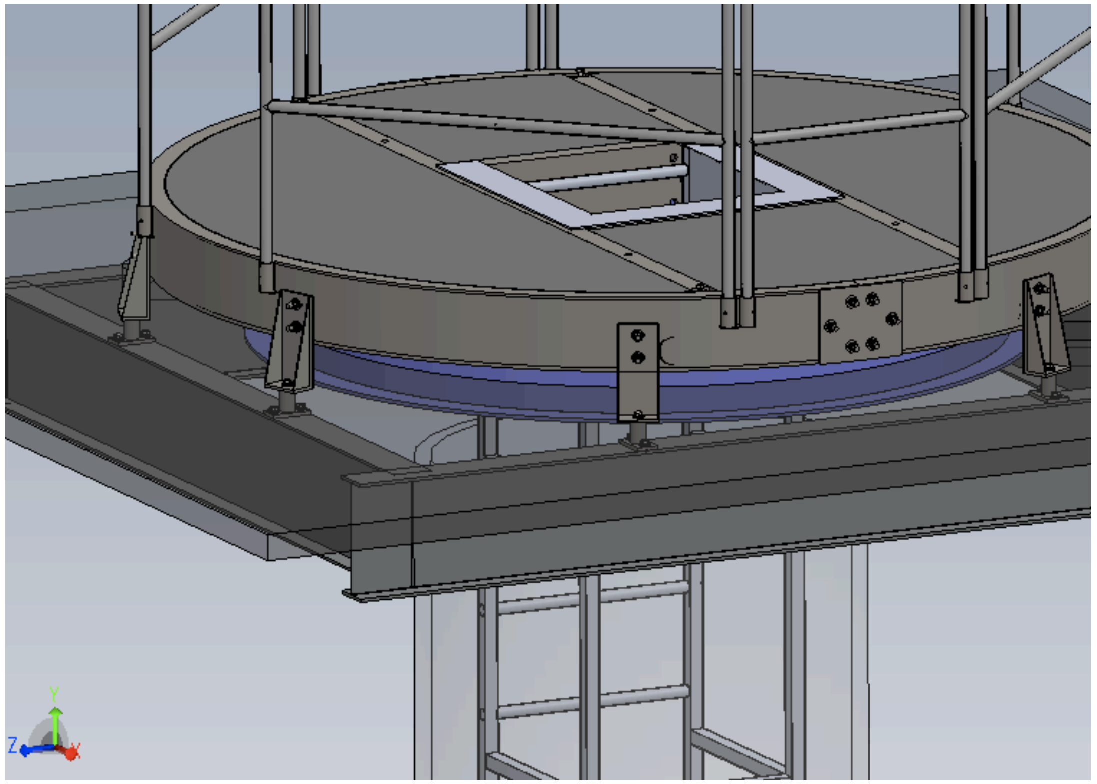
All Done!

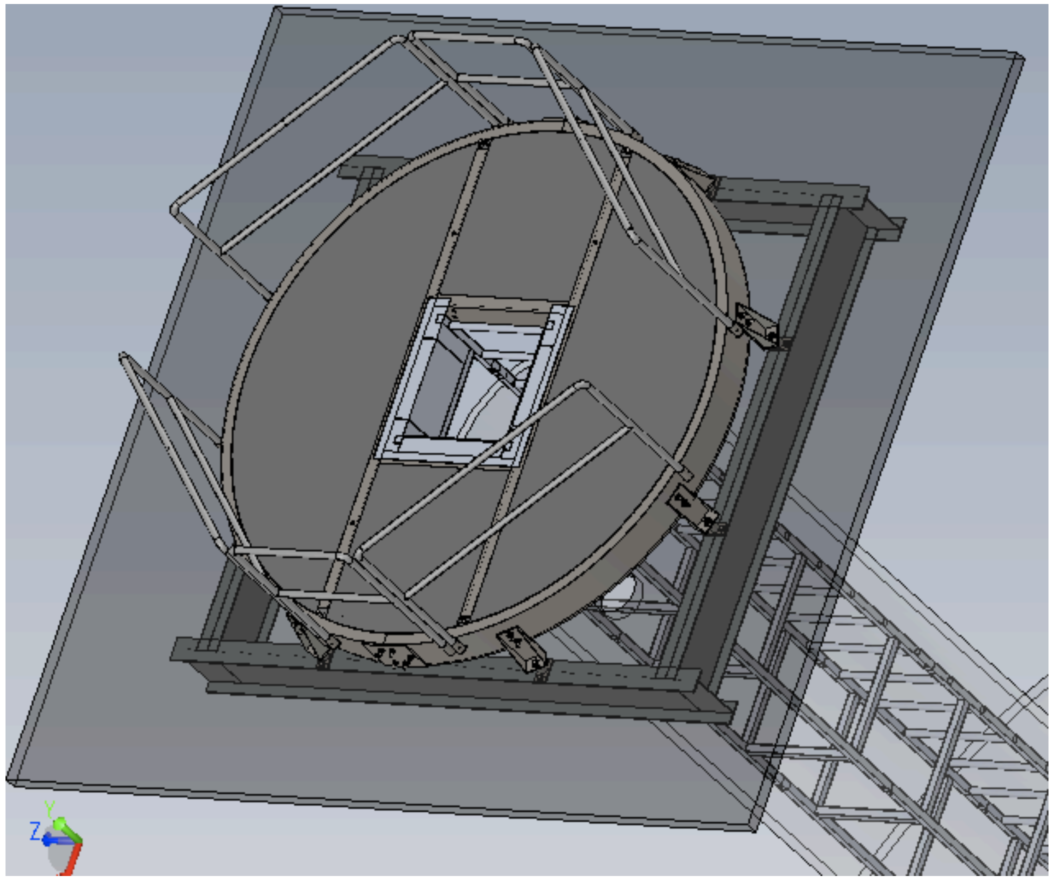
All Done!

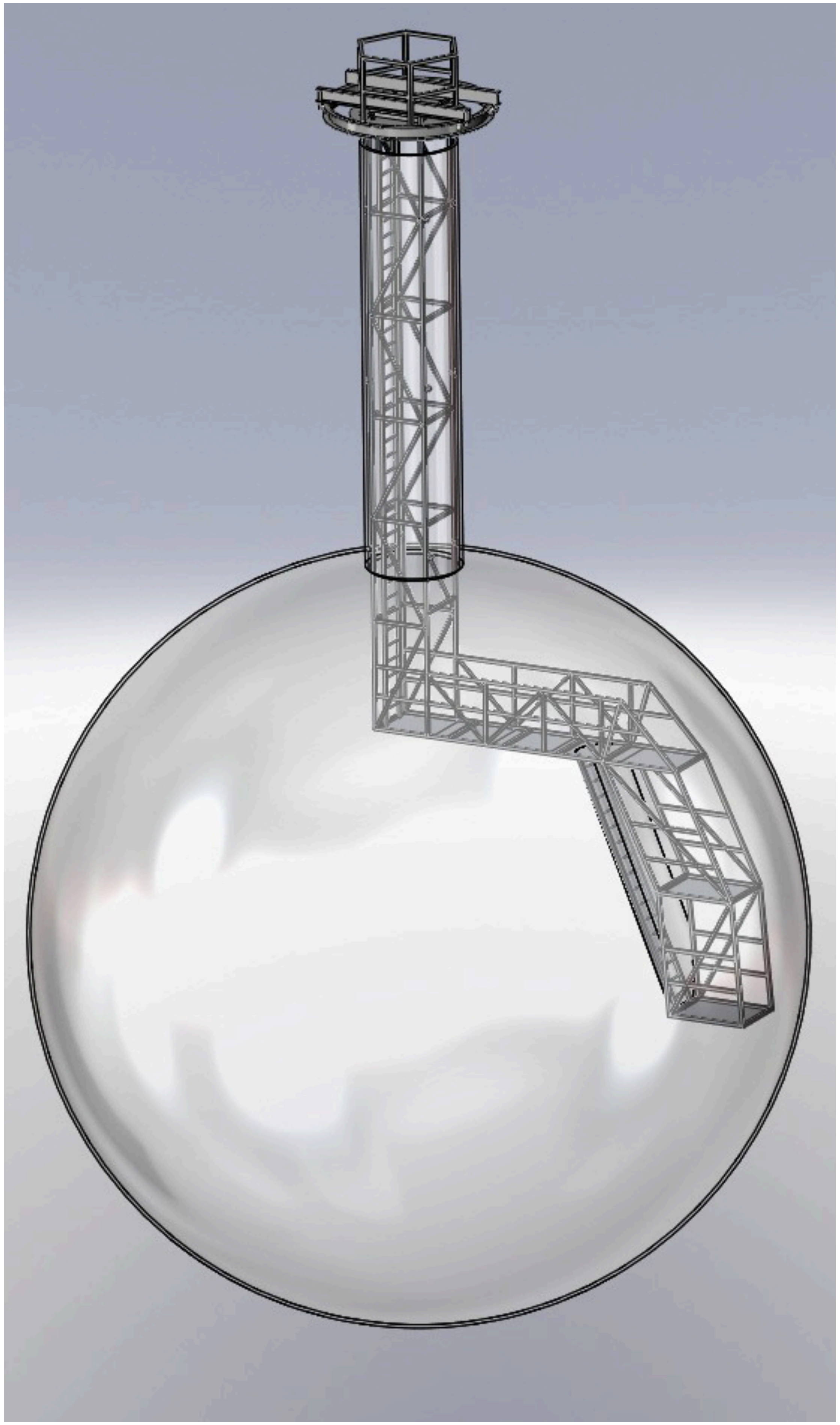
New SNO+ Floor Liner

new floor liner sprayed including up the sides of the walls and over the anchor plates

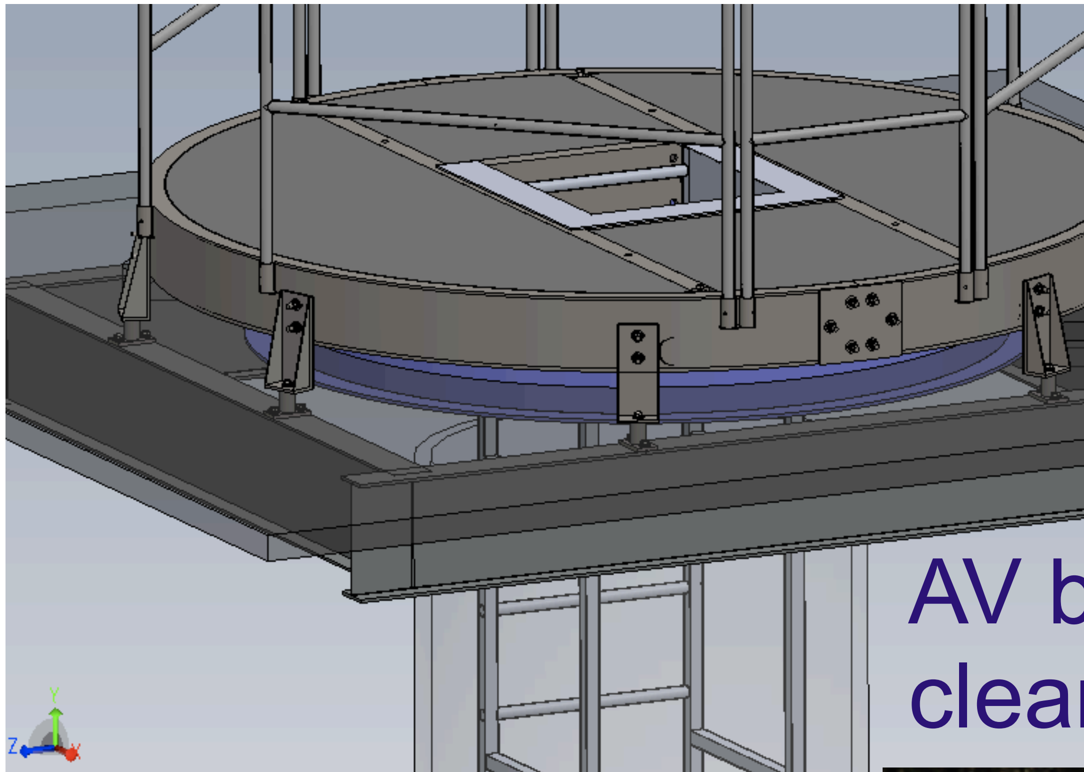
AV Sanding Tower

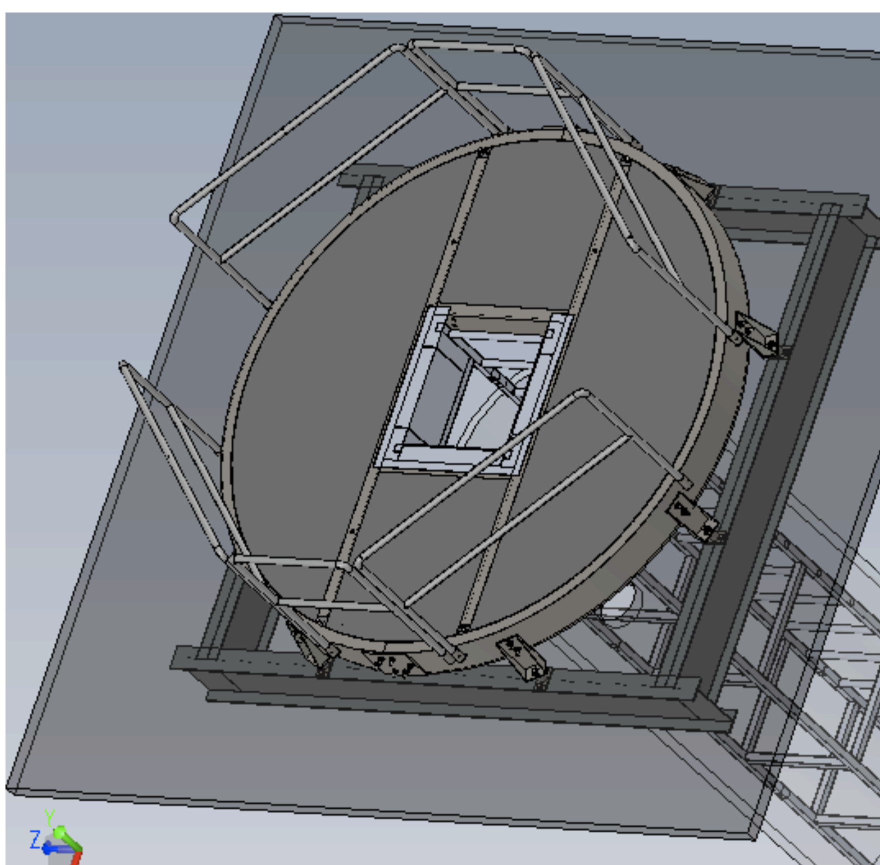




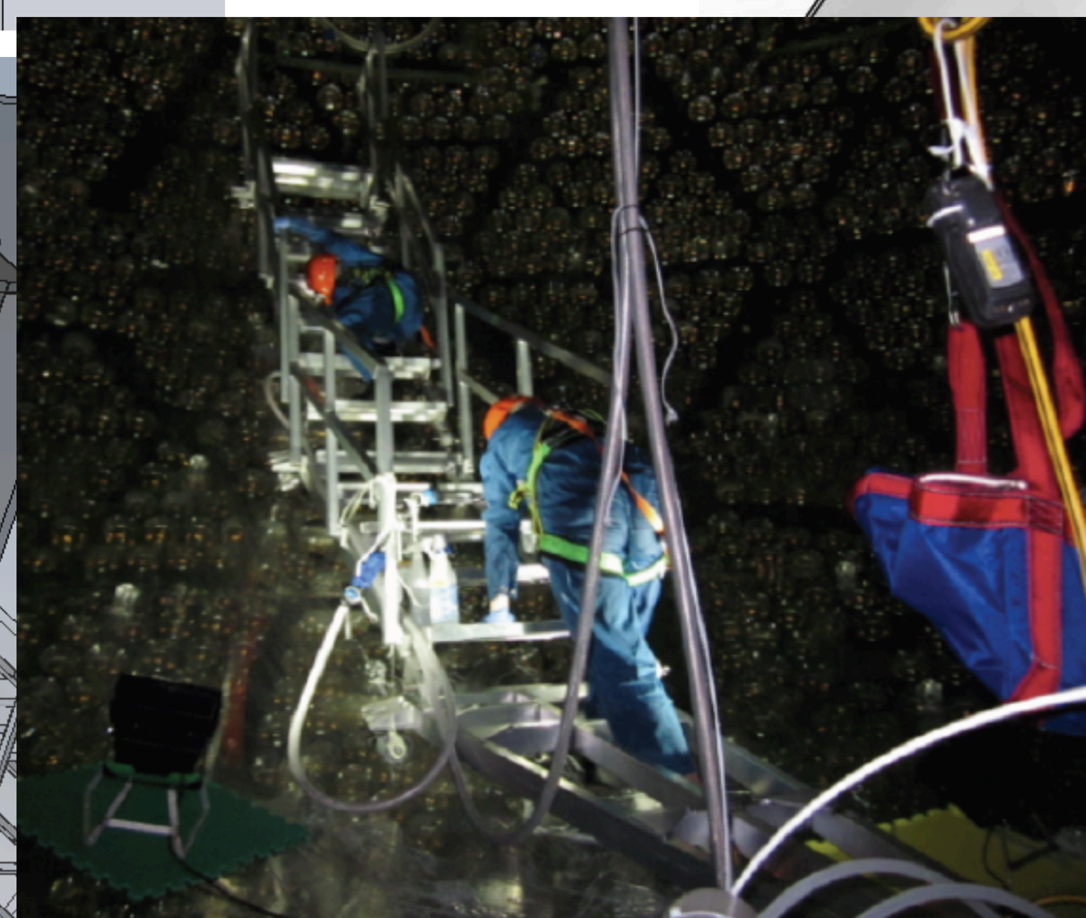


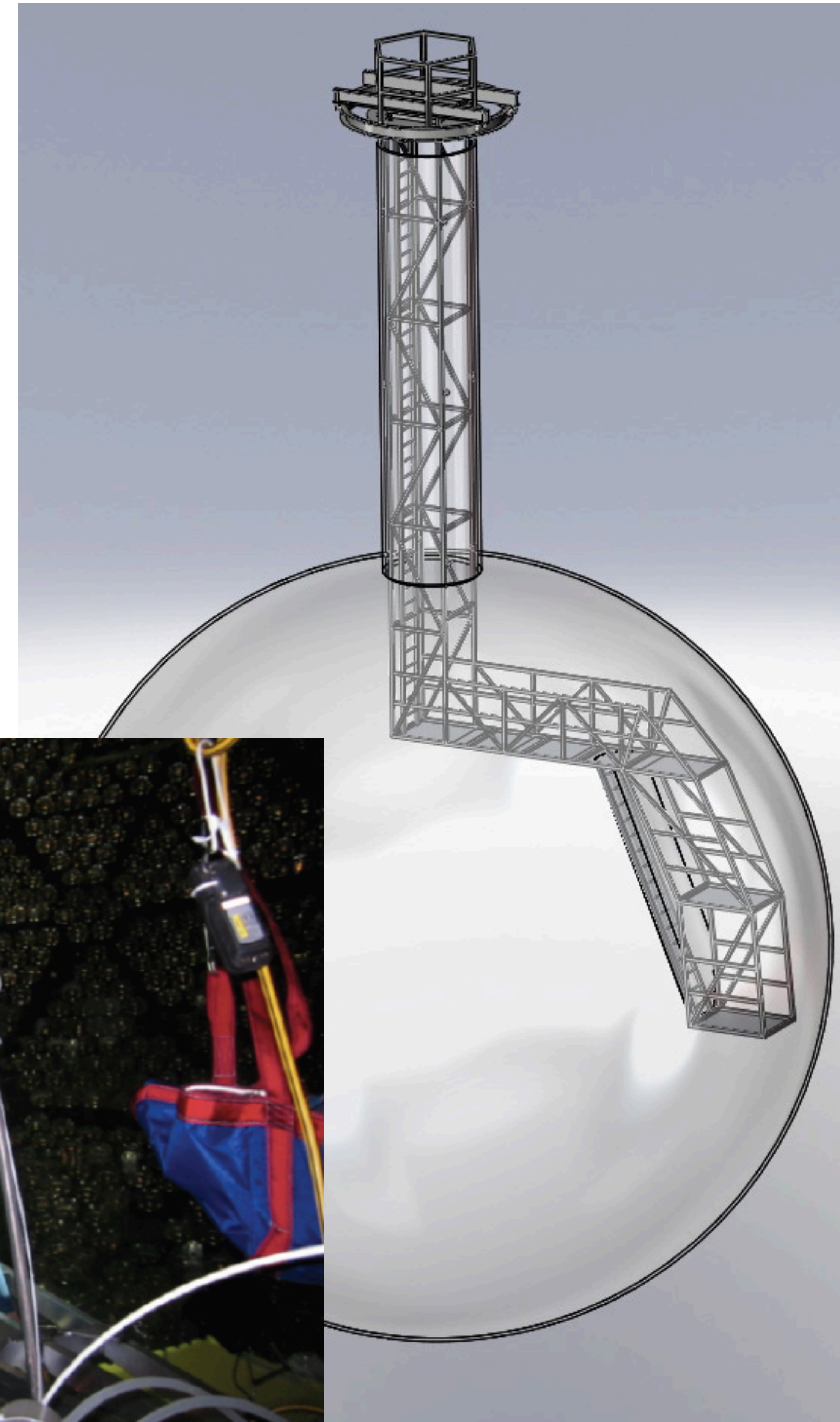
AV Sanding Tower





AV bottom
cleaning ladder





Summary

- SNO final, combined analysis of all 3 phases complete
- SNO+ is under construction
  - major project milestones achieved: hold down net and electronics
- water fill of the detector cavity will start soon
  - boating work to install cameras and calibration fibres
- water-filled commissioning of the electronics in mid-2012
- scintillator purification plant ready for scintillator fill in early 2013

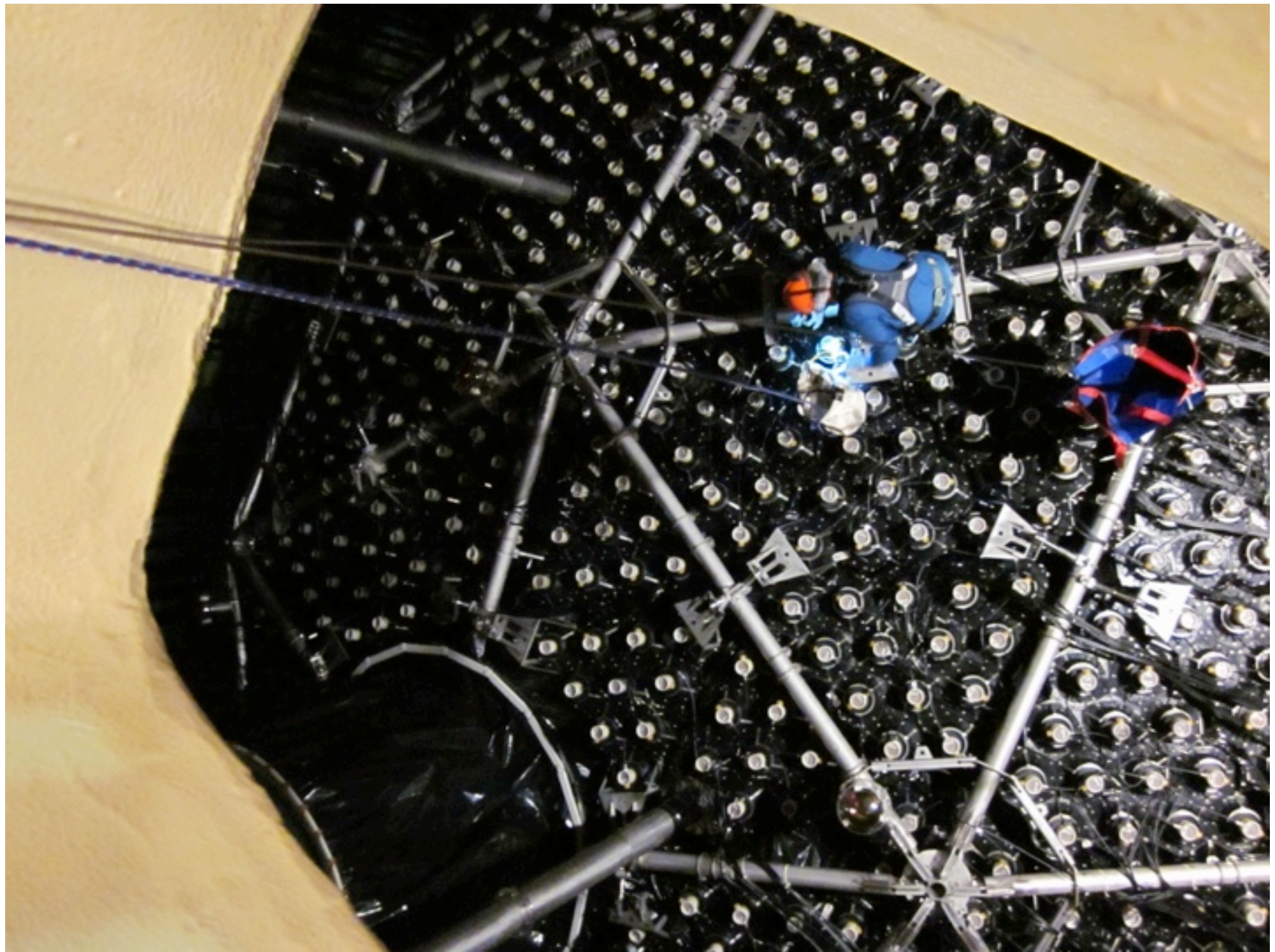


photo of access to the top of the PMT structure