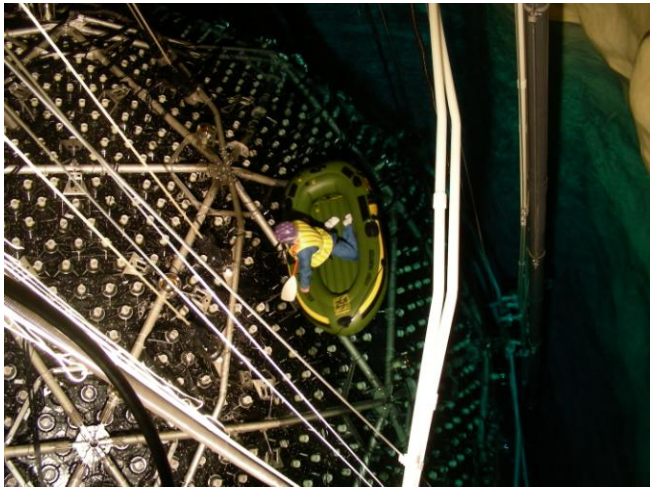
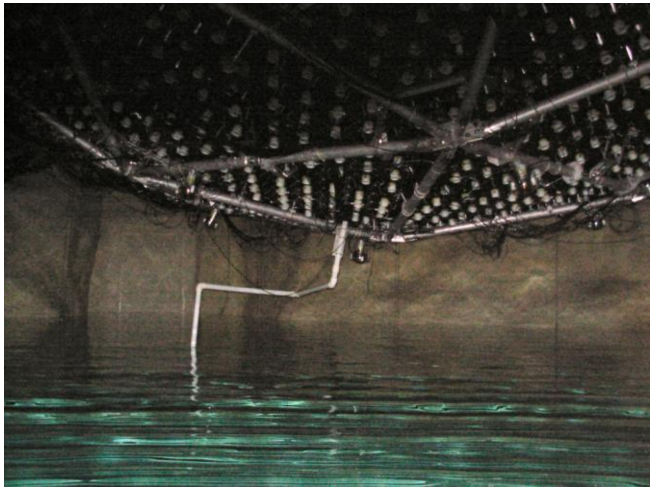
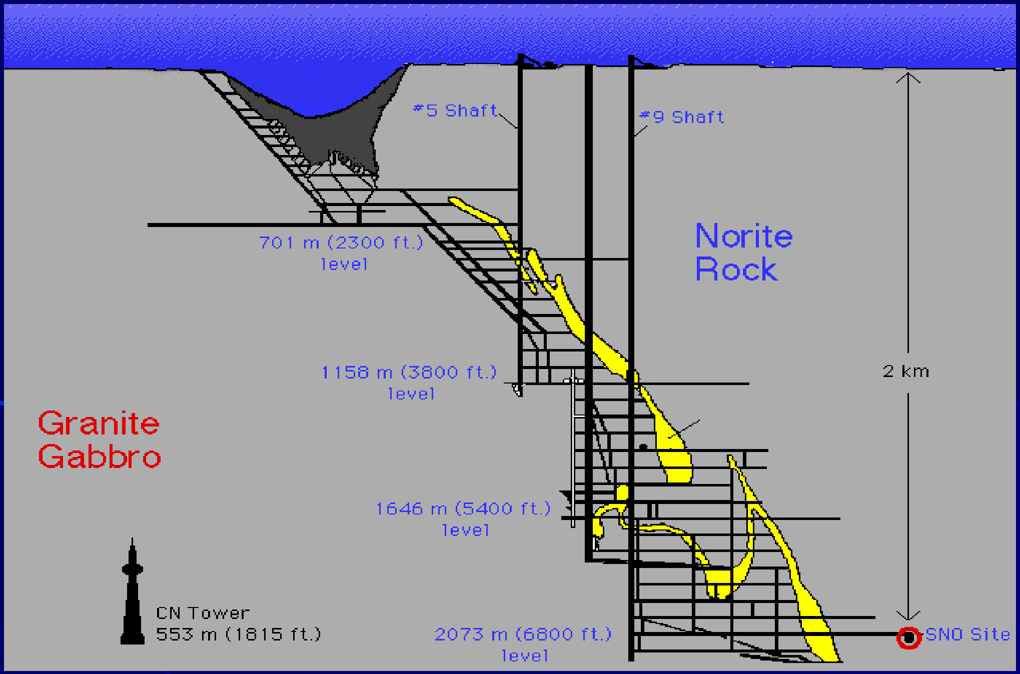


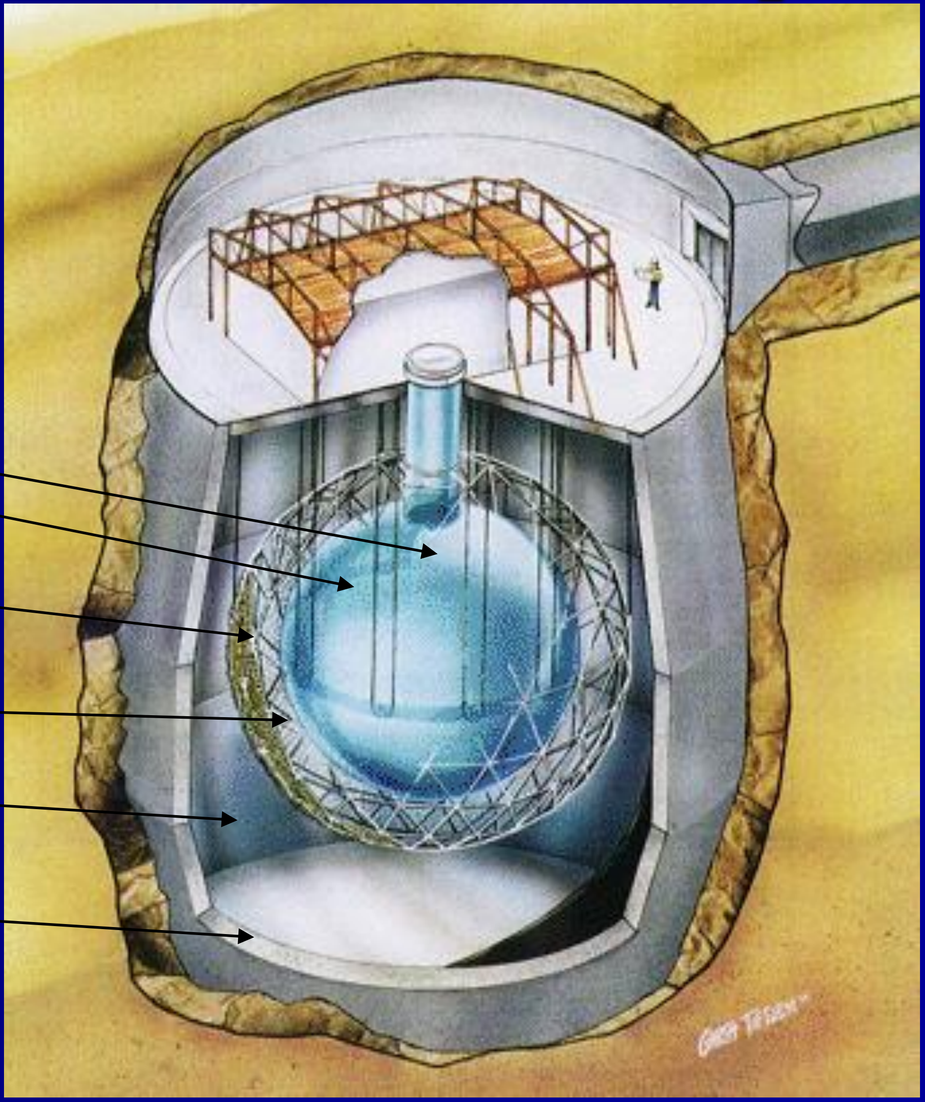



Double Beta Decay in SNO+

Mark Chen
Queen’s University
DBD09 and APS/JPS DNP, Waikoloa, Hawaii

Sudbury Neutrino Observatory





1000 tonnes D_2O

12 m diameter Acrylic Vessel

18 m diameter support structure; 9500 PMTs (~60% photocathode coverage)

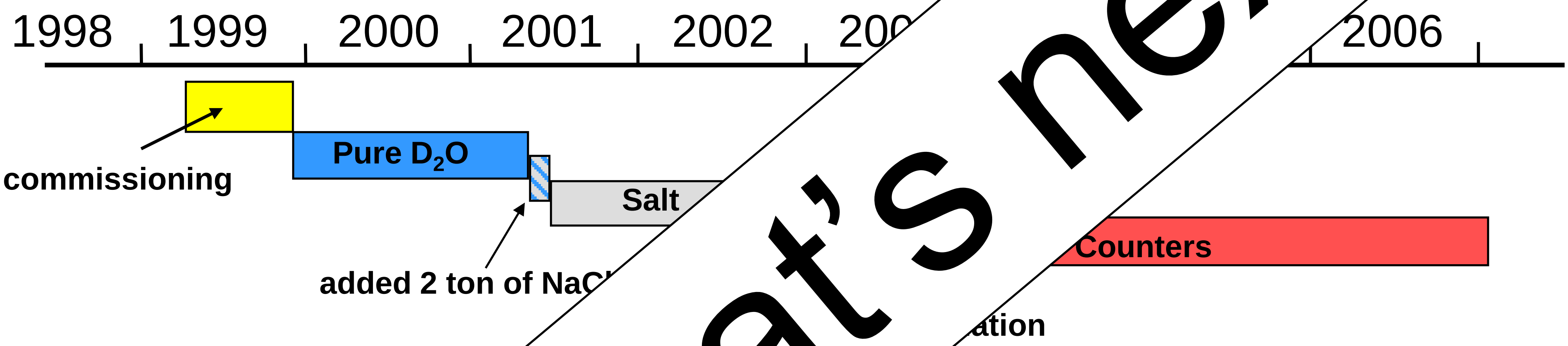
1700 tonnes inner shielding H_2O

5300 tonnes outer shielding H_2O

Urylon liner radon seal

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

SNO Timeline Summary



• pure D_2O phase discov ... ino flavors that are not ν_e

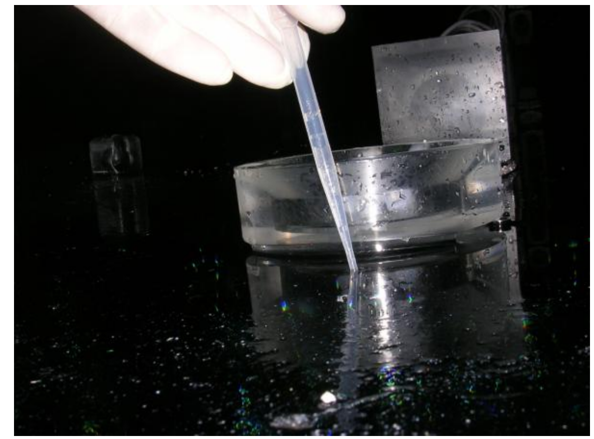
• salt phase moved ... ination of oscillation parameters; flux determination h ... t (thus could use it rigorously for more than just the ... day/night effect and spectral shape were studied a ... e ^8B solar neutrino flux

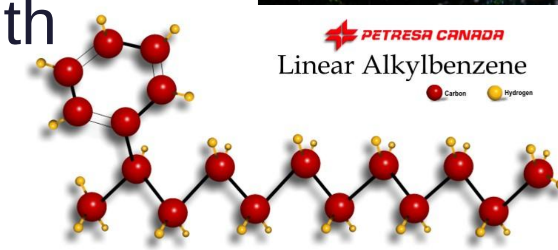
• P ... ffered CC and NC event-by-event separation, for im ... d cleaner spectral shape examination; analyses combining all th ... e in progress

so . . . what's next?

SNO+

- $300M of heavy water removed and returned to Atomic Energy of Canada Limited (every last drop)
- SNO detector to be filled with liquid scintillator
  - 50-100 times more light than Čerenkov
- linear alkylbenzene (LAB)
  - compatible with acrylic, undiluted
  - high light yield, long attenuation length
  - safe: high flash point, low toxicity
  - cheaper than other scintillators
- physics goals: *pep* and *CNO* solar neutrinos, geo neutrinos, reactor neutrino oscillations, supernova neutrinos, double beta decay with Nd





SNO+ Double Beta Decay

- …sometimes referred to as SNO++
- it is possible to add ββ isotopes to liquid scintillator, for example
  - dissolve Xe gas
  - organometallic chemistry (Nd, Se?, Te?, Mo?)
  - dispersion of nanoparticles (Nd_2O_3, TeO_2)
- we researched these options and decided that the best isotope and technique is to make a Nd-loaded liquid scintillator

Why ^{150}Nd?

- 3.37 MeV endpoint (2nd highest of all ββ isotopes)
  - above most backgrounds from natural radioactivity
- largest phase space factor of all ββ isotopes
  - 56 kg ^{150}Nd equivalent to (considering only the phase space)
    - ~220 kg of ^{136}Xe
    - ~230 kg of ^{130}Te
    - ~950 kg of ^{76}Ge
- isotopic abundance 5.6%

  0.1% w/w natural Nd-loaded liquid scintillator in 1000 tonnes has 56 kg of ^{150}Nd compared to 37 g in NEMO-III
- cost $NdCl_3$ is ~$86,000 for 1 tonne
- upcoming experiments use Ge, Xe, Te; Cd and Se proposed…we can deploy a large amount of Nd

Need to Know NME to Estimate Rate

- ^{150}Nd has a fast rate but uncertainty in the NME
  - calculations such as QRPA assumed spherical nuclei; do not take into account the large deformation seen in ^{150}Nd and its daughter nucleus ^{150}Sm
- our approach is experimentally motivated
  - for what is known ^{150}Nd is an attractive candidate
  - we have a technique to deploy a considerable quantity of Nd in a detector
  - complementarity with other experiments

Recent Progress: DBD Nuclear Deformation Studies

Nuclear deformation and neutrinoless double-β decay of ^{94,96}Zr, ^{98,100}Mo, ^{104}Ru, ^{110}Pd, ^{128,130}Te and ^{150}Nd nuclei in mass mechanism

arXiv:0805.4073v4

K. Chaturvedi[1,2], R. Chandra[1,3], P. K. Rath[1], P. K. Raina[3] and J. G. Hirsch[4]

Two–neutrino double beta decay of deformed nuclei within QRPA with realistic interaction

Mohamed Saleh Yousef, Vadim Rodin,* Amand Faessler, and Fedor Šimkovic†

Deformation and the Nuclear Matrix Elements of the Neutrinoless $\beta\beta$ Decay

J. Menéndez and A. Poves

Departamento de Física Teórica and IFT-UAM/CSIC, Universidad Autónoma de Madrid, E-28049, Madrid, Spain

E. Caurier and F. Nowacki

IPHC, IN2P3-CNRS/Université Louis Pasteur BP 28, F-67037, Strasbourg Cedex 2, France

Deformed Results From Chaturvedi et al.

- used Projected Hartree-Fock-Bogoliubov framework
- NME smaller by factor of 2.6 compared to Rodin et al. 2007 spherical RQRPA

The $(\beta^-\beta^-)_{0\nu}$ decay of ^{94,96}Zr, ^{98,100}Mo, ^{104}Ru, ^{110}Pd, ^{128,130}Te and ^{150}Nd isotopes for the $0^+ \to 0^+$ transition is studied in the Projected Hartree-Fock-Bogoliubov framework. In our earlier work, the reliability of HFB intrinsic wave functions participating in the $\beta^-\beta^-$ decay of the above mentioned nuclei has been established by obtaining an overall agreement between the theoretically calculated spectroscopic properties, namely yrast spectra, reduced $B(E2{:}0^+ \to 2^+)$ transition probabilities, quadrupole moments $Q(2^+)$, gyromagnetic factors $g(2^+)$ as well as half-lives $T_{1/2}^{2\nu}$ for the $0^+ \to 0^+$ transition and the available experimental data. In the present work, we study the $(\beta^-\beta^-)_{0\nu}$ decay for the $0^+ \to 0^+$ transition in the mass mechanism and extract limits on effective

Deformed QRPA

- spherical QRPA study fixes g_{pp} to reproduce $2\nu\beta\beta$ experimental half-life
- new study examines deformation of ^{150}Nd;
- g_{pp} changes in deformed QRPA analysis
- Rodin tells me he's working on $M^{0\nu}$ calc

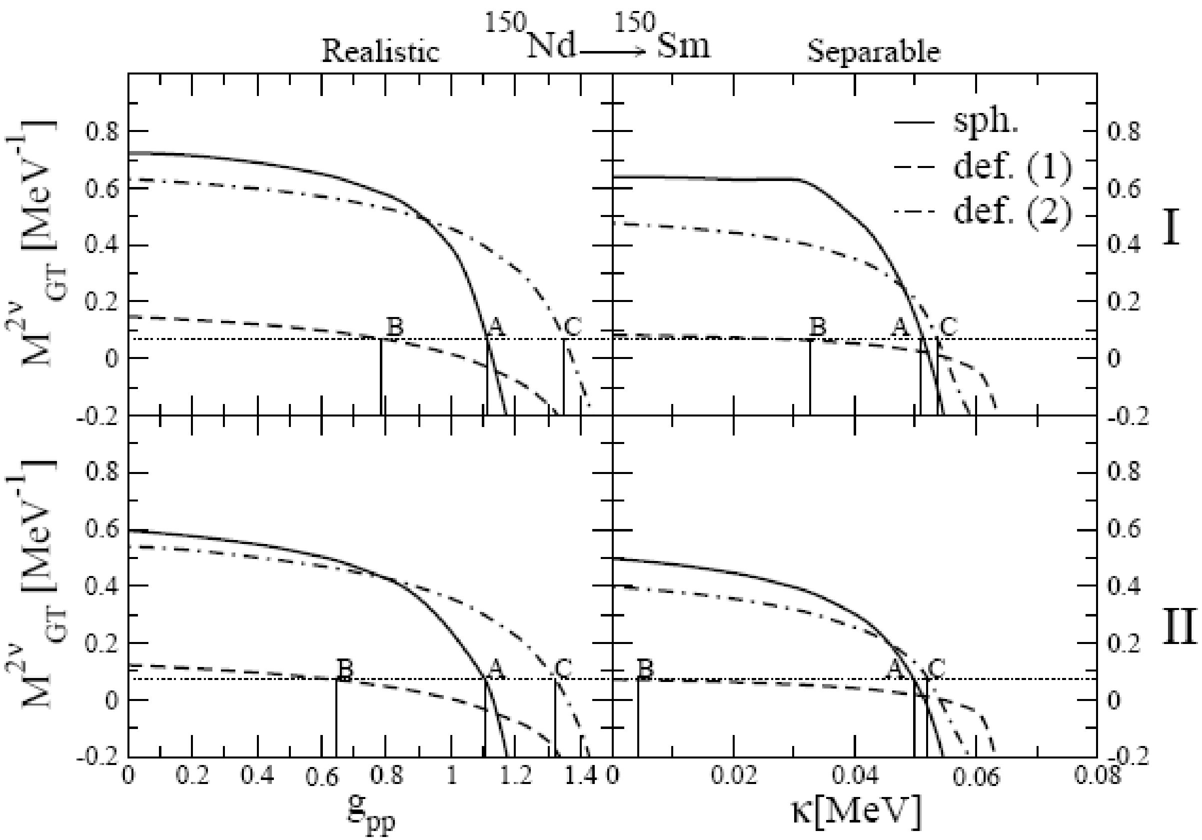
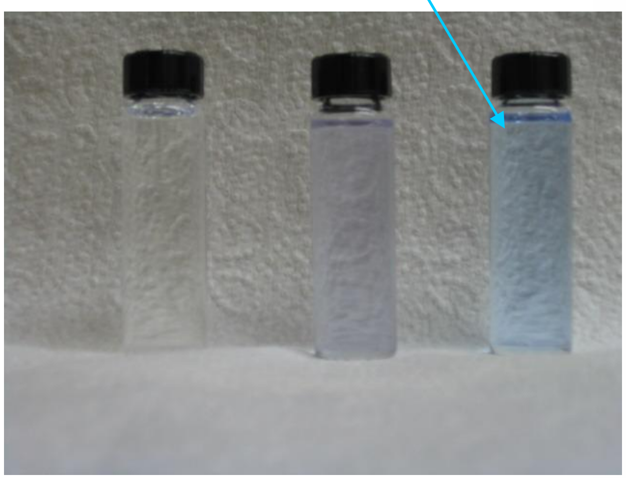


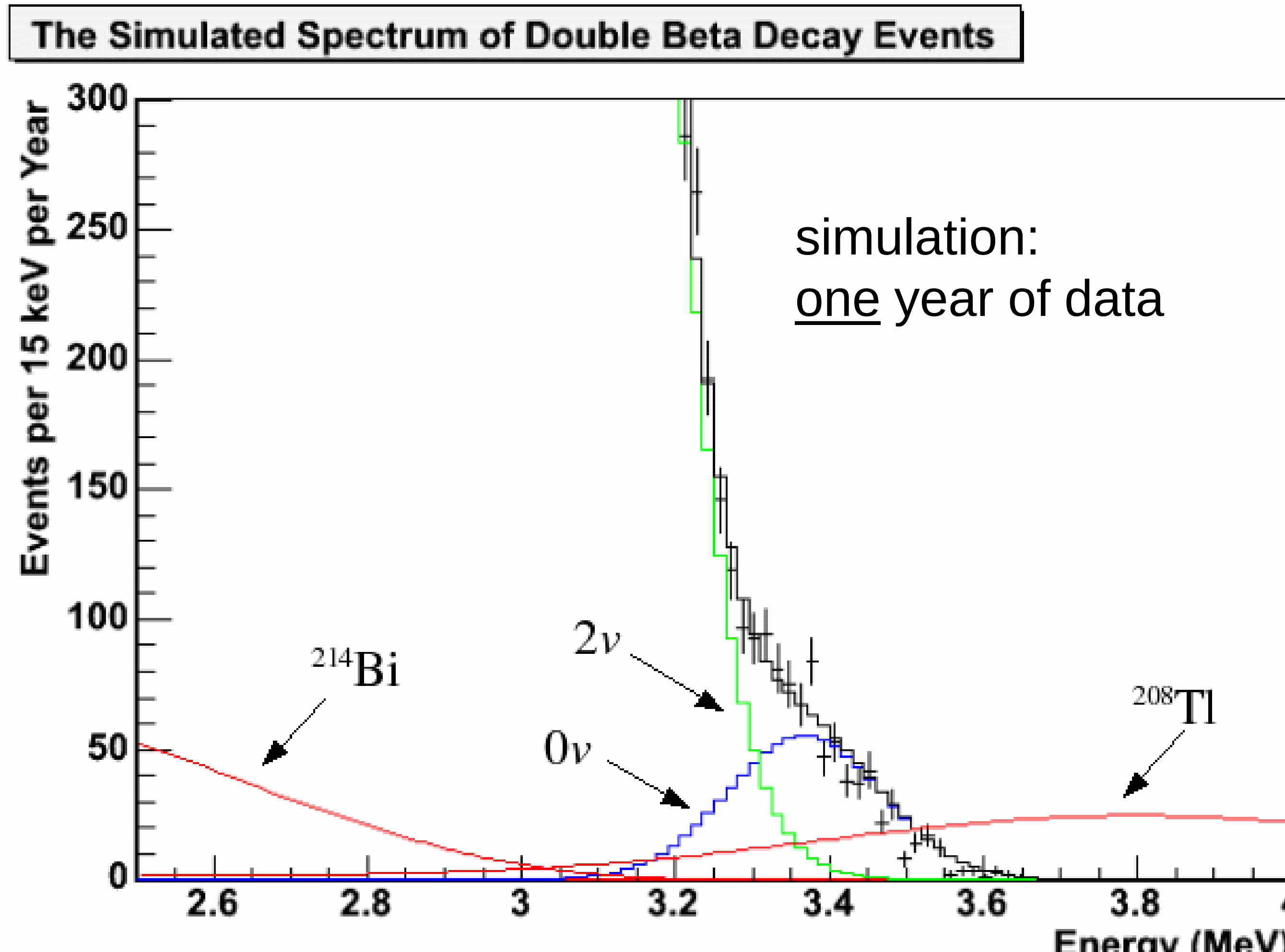
FIG. 6: The same as in Fig. 5, but for ^{150}Nd→^{150}Sm decay with 2 different sets of deformation parameters: from Ref. [21] (β_2(^{150}Nd)= 0.37, β_2(^{150}Sm)= 0.23, "def. (1)") and from Ref. [28] (β_2(^{150}Nd)= 0.24, β_2(^{150}Sm)= 0.21, "def. (2)").

from Yousef, Rodin, Faessler, Šimkovic, arXiv:0806.0964v2

The SNO+ Double Beta Concept

0ν: 1000 events per year with 1% natural Nd-loaded liquid scintillator in SNO++

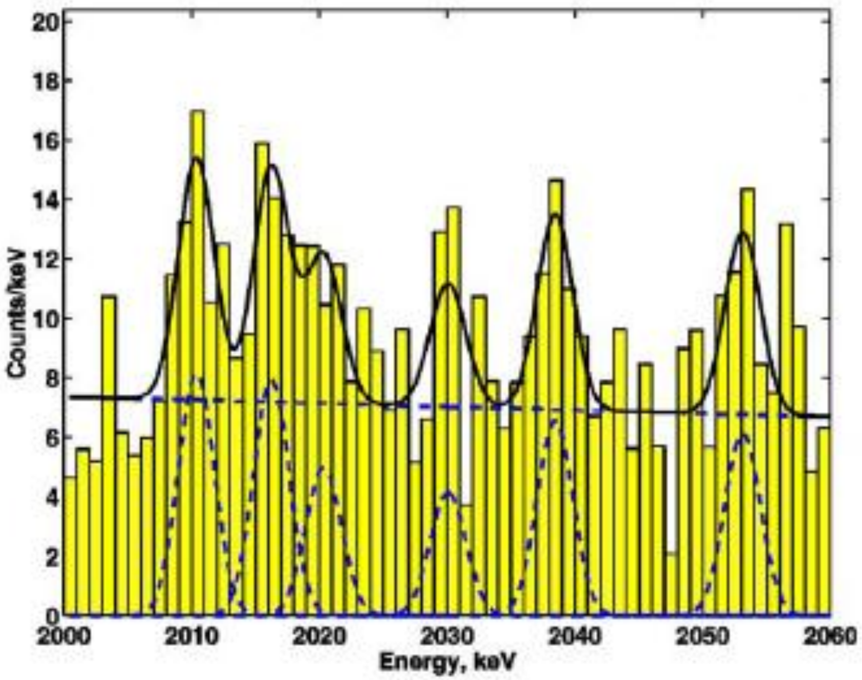




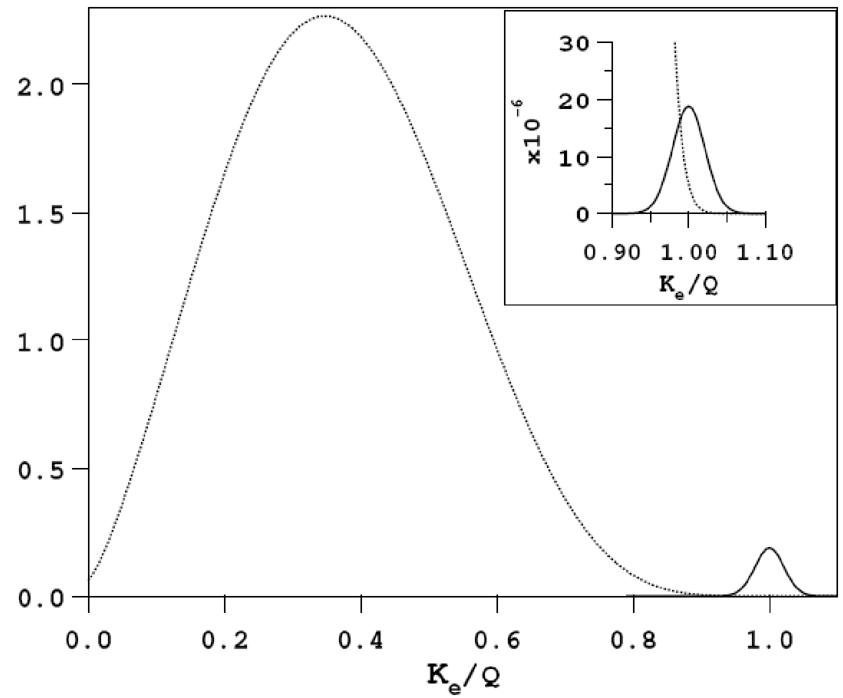
$0\nu\beta\beta$ Signal for $<m_\nu> = 0.150$ eV, ~500 kg ^{150}Nd

DBD: Why Good Energy Resolution is Needed?

- to separate $0\nu\beta\beta$ from $2\nu\beta\beta$
- to separate $0\nu\beta\beta$ signal from other gamma lines



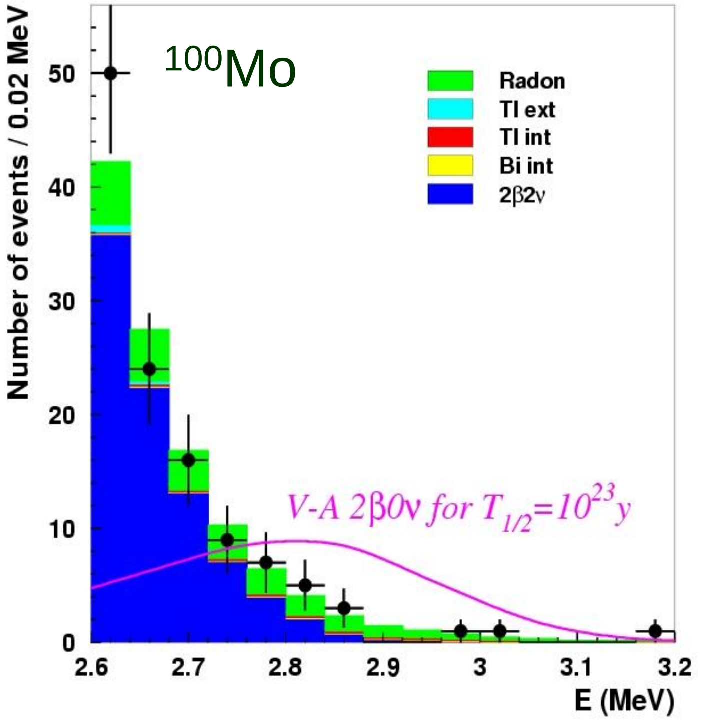
from H.V. Klapdor-Kleingrothaus et al.



from S. Elliott and P. Vogel

Can You Live With Worse Resolution?

- to separate $0\nu\beta\beta$ from $2\nu\beta\beta$
  - YES! by fitting the endpoint shape…resolution is less important when fitting spectral shapes than simply counting signal and background events in an energy bin
  - this is already done (e.g. NEMO-3)
- to separate $0\nu\beta\beta$ signal from other gam
  - YES! if there are no background gamm
- how to achieve zero (low) γ backgrounc
  - use B-field tracking detector: identify β^{-}
    or
  - choose a high Q-value isotope abov
    with an ultra-low background detect

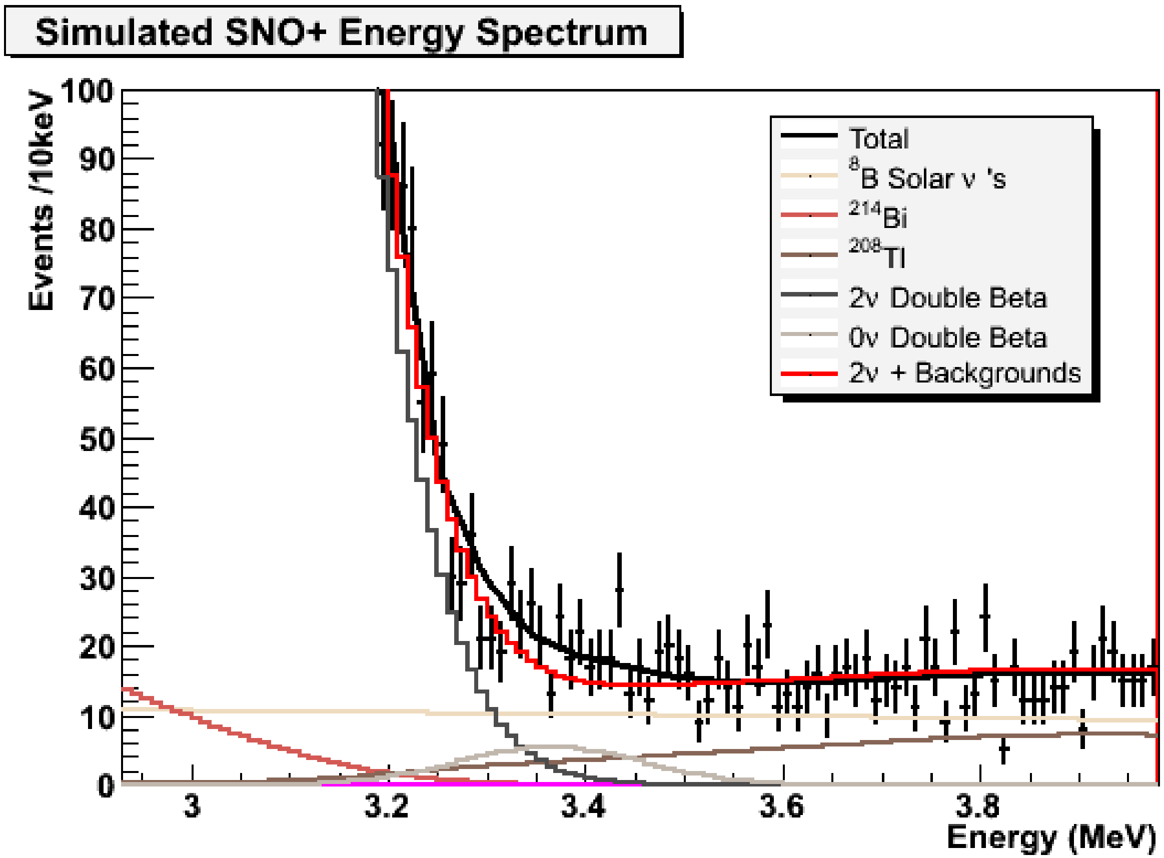


from F. Piquemal

What Do Scintillators Offer?

- “economical” way to build a detector with a **large** amount of isotope
- several isotopes can be considered
- ultra-low background environment can be achieved (e.g. phototubes stand off from the scintillator, self-shielding of fiducial volume)
- with a liquid scintillator, possibility to purify *in-situ* to further reduce backgrounds
- possible source-in, source-out capability

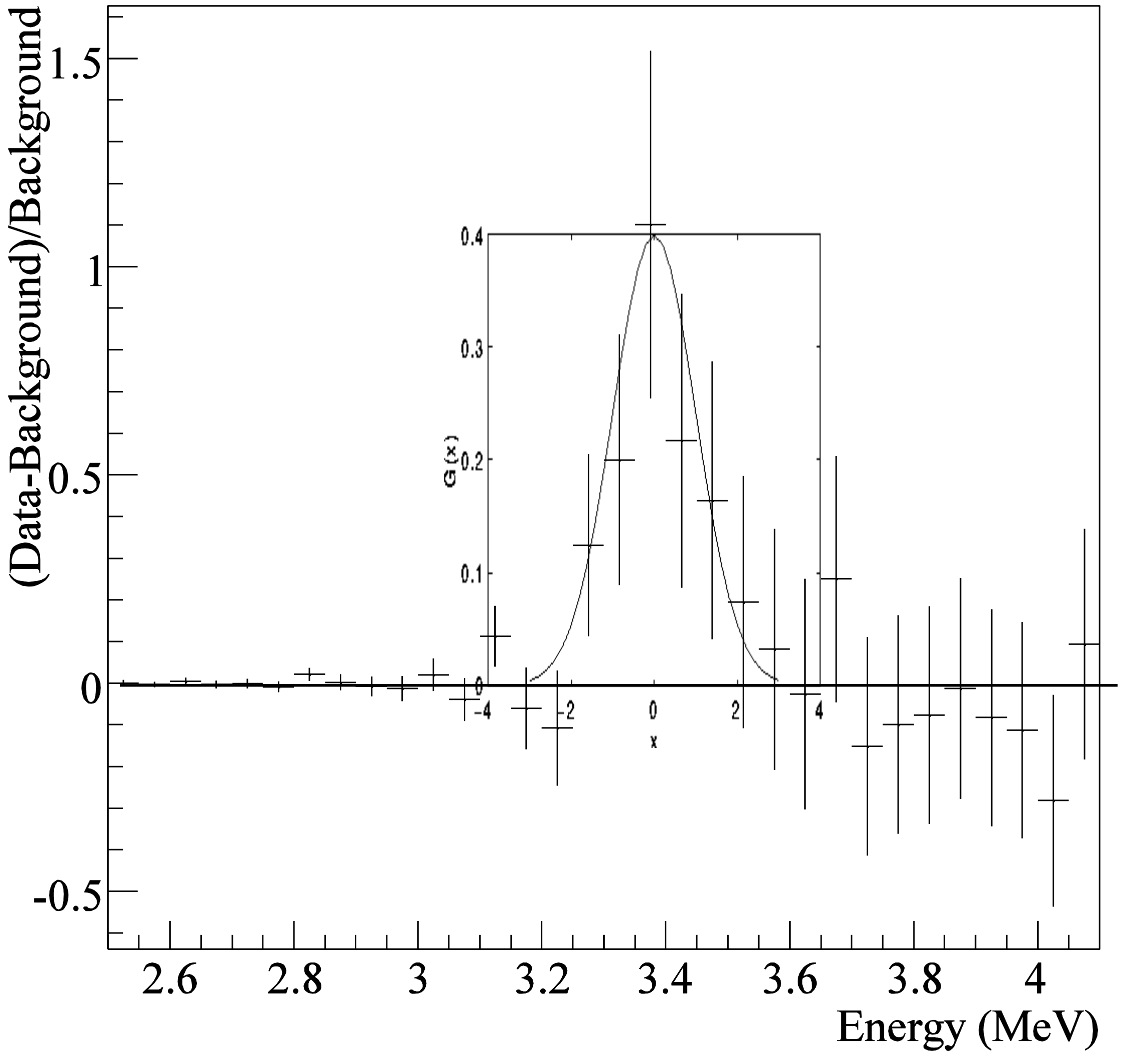
56 kg of ^{150}Nd and $\langle m_\nu \rangle$ = 100 meV



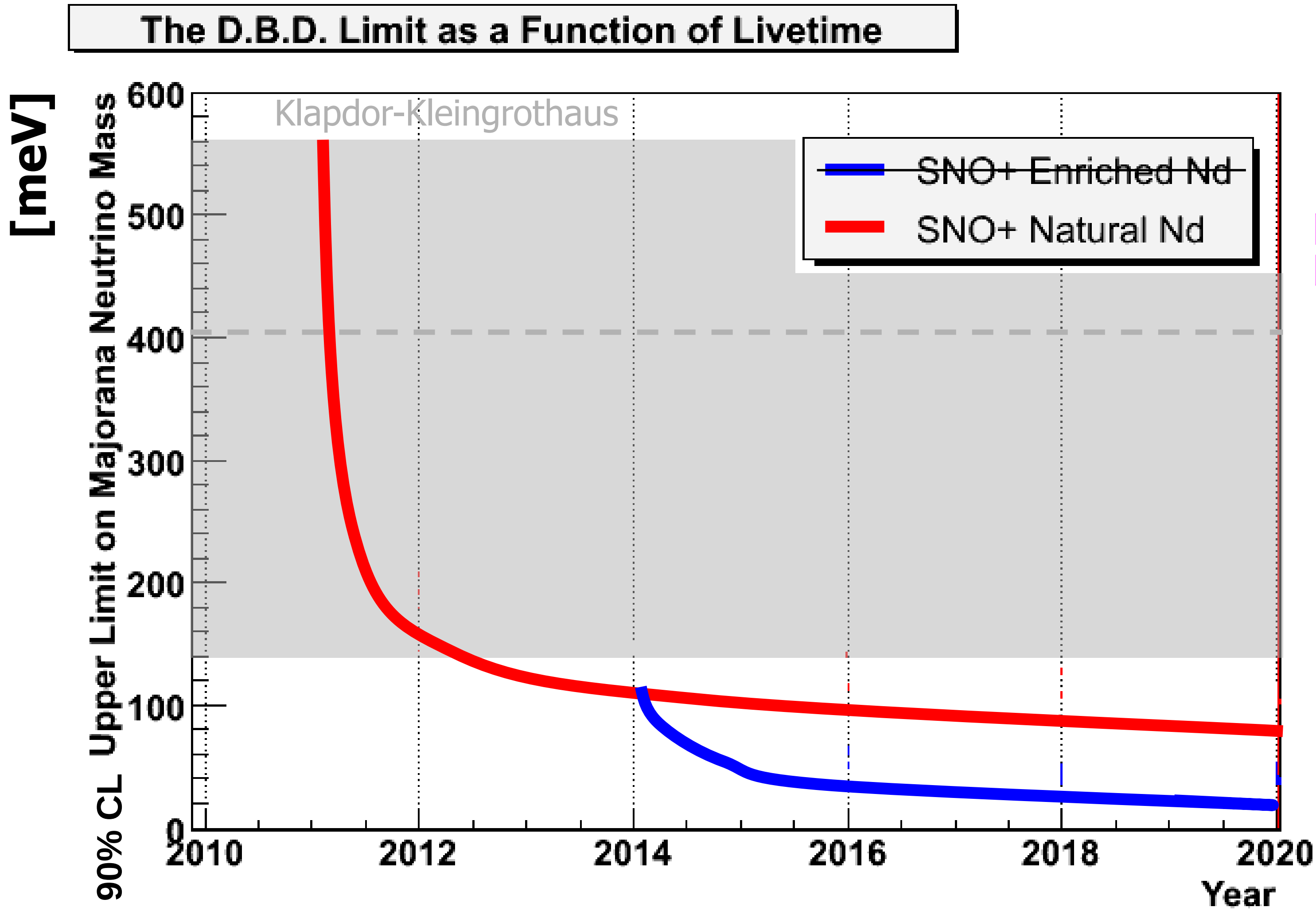
- 6.4% FWHM at Q-value
- 3 years livetime
- U, Th at Borexino levels
- 5σ sensitivity
- note: the dominant background is ^{8}B solar neutrinos!
- ^{214}Bi (from radon) is almost negligible
- ^{212}Po-^{208}Tl tag (3 min) might be used to veto ^{208}Tl backgrounds; ^{212}Bi-^{212}Po (300 ns) events constrain the amount of ^{208}Tl

SNO+ DBD Residual Plot

- 1 kilotonne-year
- $<m_\nu>$=270 meV
- 0.1% wt/wt Nd-loaded LS in SNO+



SNO+ ββ Sensitivity



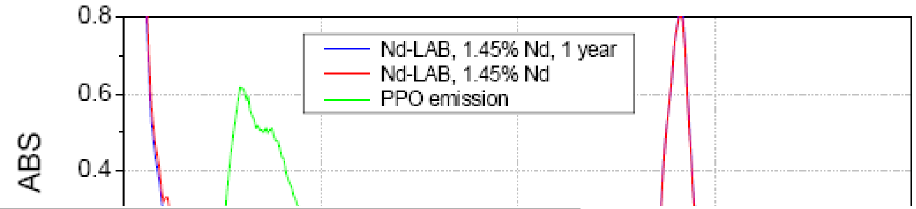
Nd enrichment possibilities are being explored

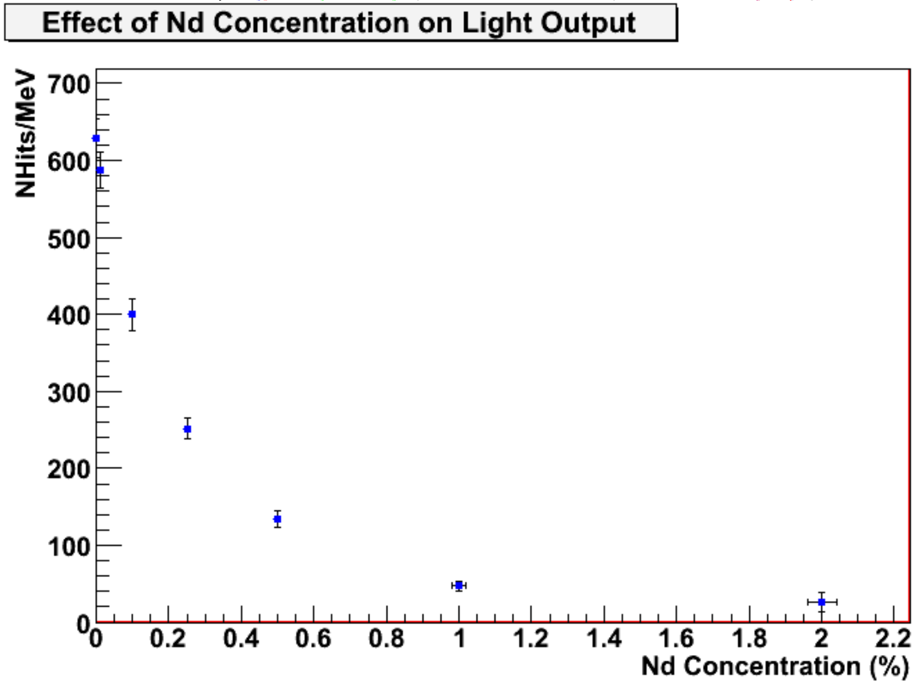
SNO+ Operating Plan:

- ☐ Natural Nd in 2011
- ☐ ~~Enriched Nd in 2014~~
- ☐ 50% fiducial volume
- ☐ 75% livetime

^{150}Nd SNO+ R&D Summary

- stable Nd-loaded liquid scintillator
- scintillation optical properties studied
- developed purification techniques to rer
- target background levels achievable wit
- no long-live
- studied effe
- physics sen
  - will reach
  - down to
- SNO+ plans
  phase





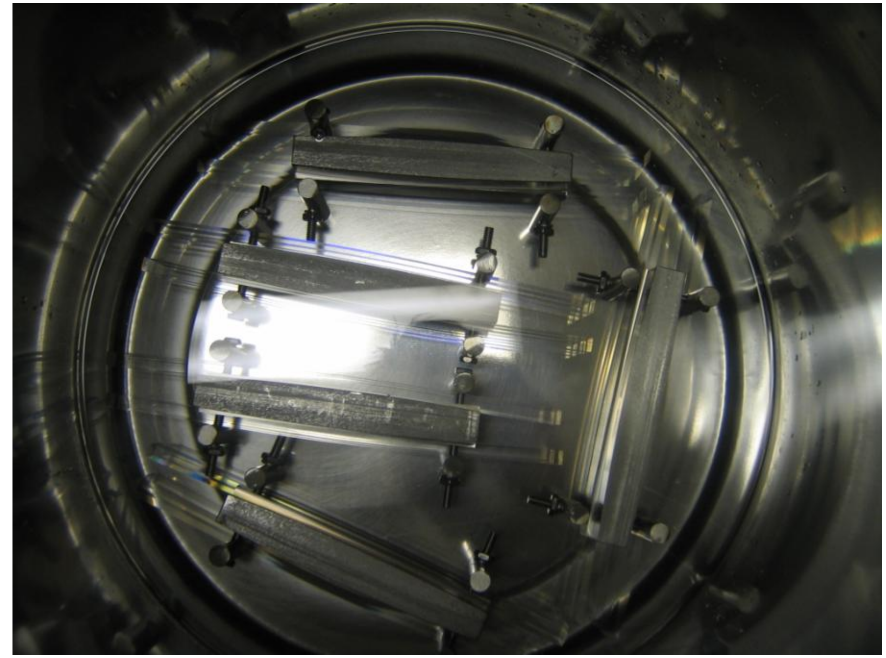
Turning SNO into SNO+

- to do this we need to:
  - buy the liquid scintillator
  - install hold down ropes for the acrylic vessel
  - build a liquid scintillator purification system
  - make a few small repairs
  - minor upgrades to the cover gas
  - minor upgrades to the DAQ/electronics
  - change the calibration system and sources

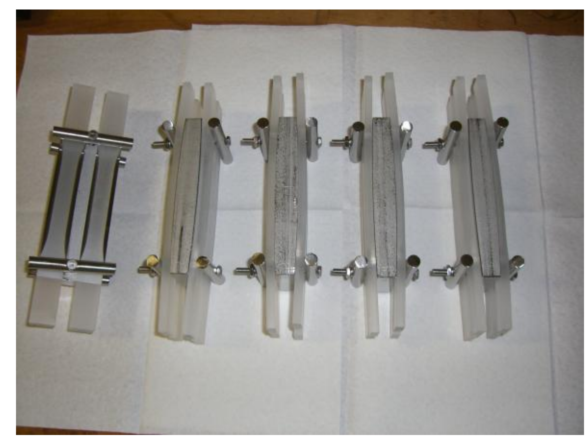
Scintillator R&D

List of T

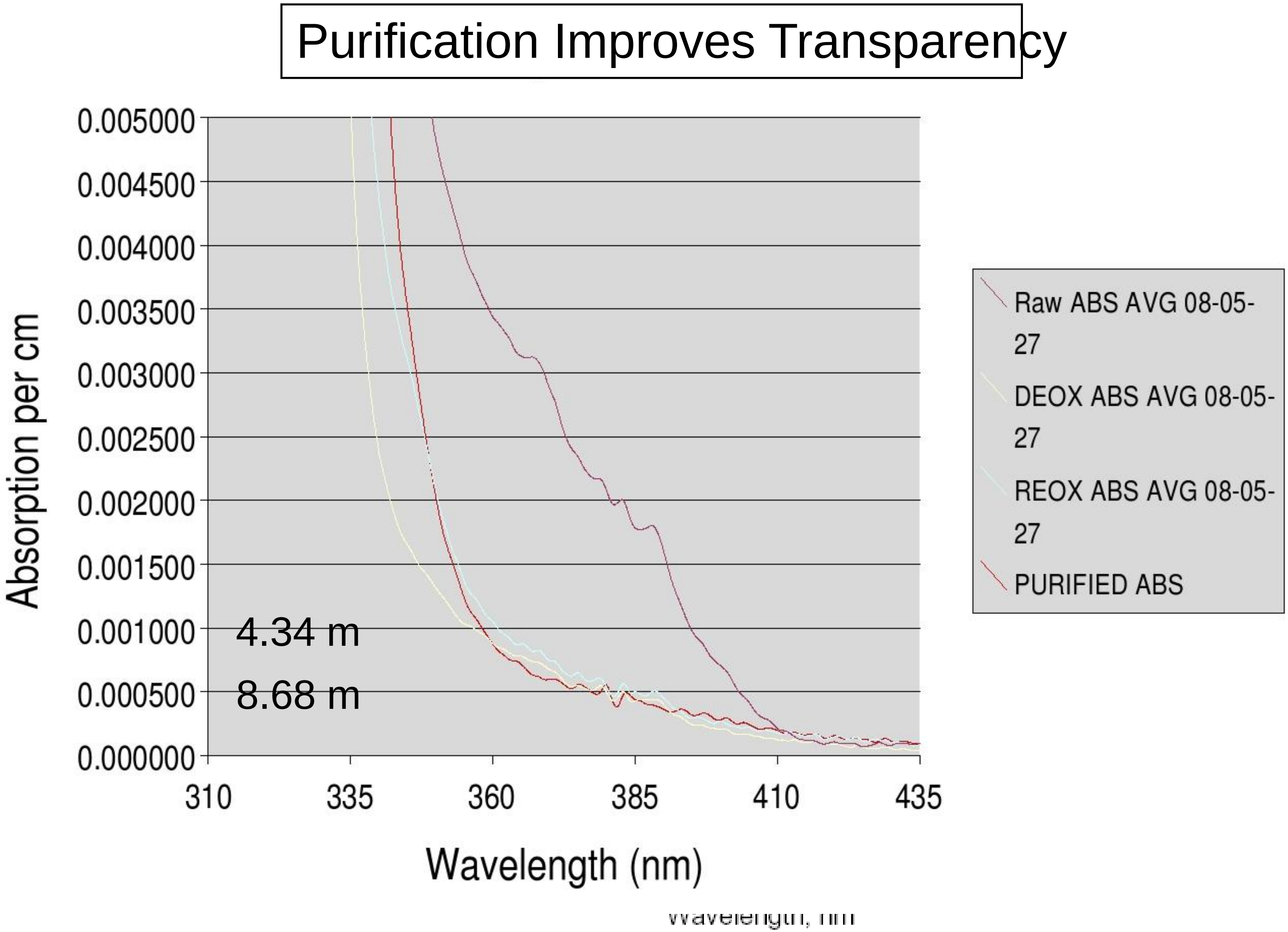
- acryl
- light
- atten
- comp
- LAB- y
- scinti
- alpha ion
- quen
- buck e
  SNO
- meta



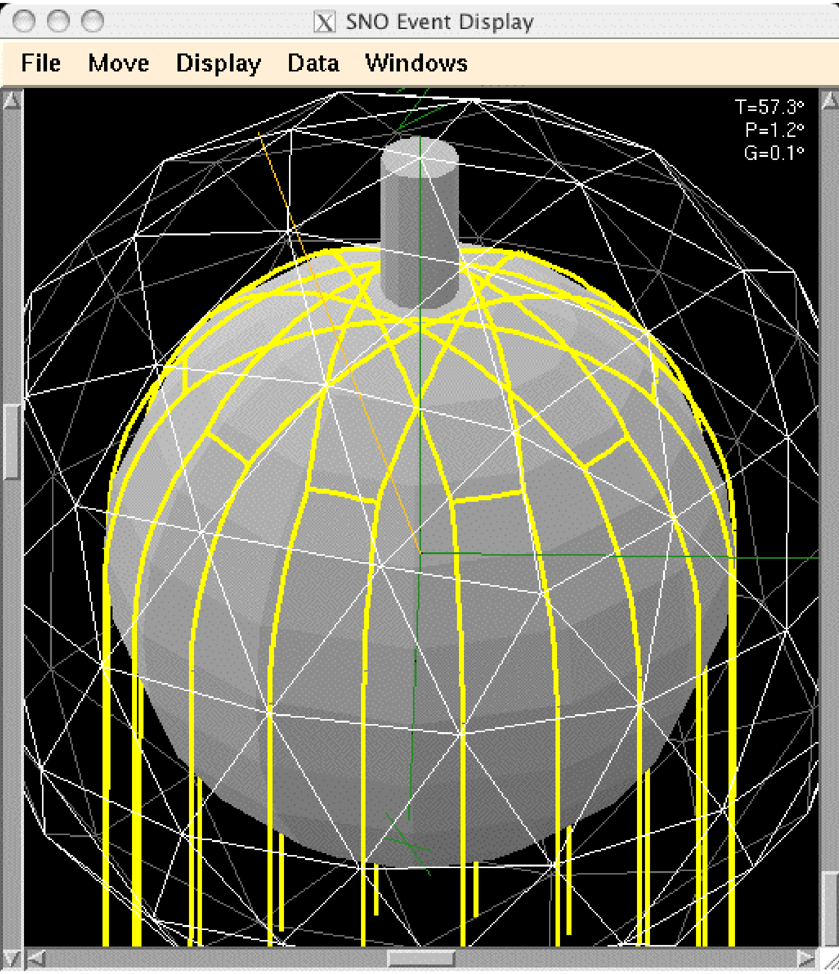
ASTM D543 “Standard Practices for Evaluating the Resistance of Plastics to Chemical Reagents”

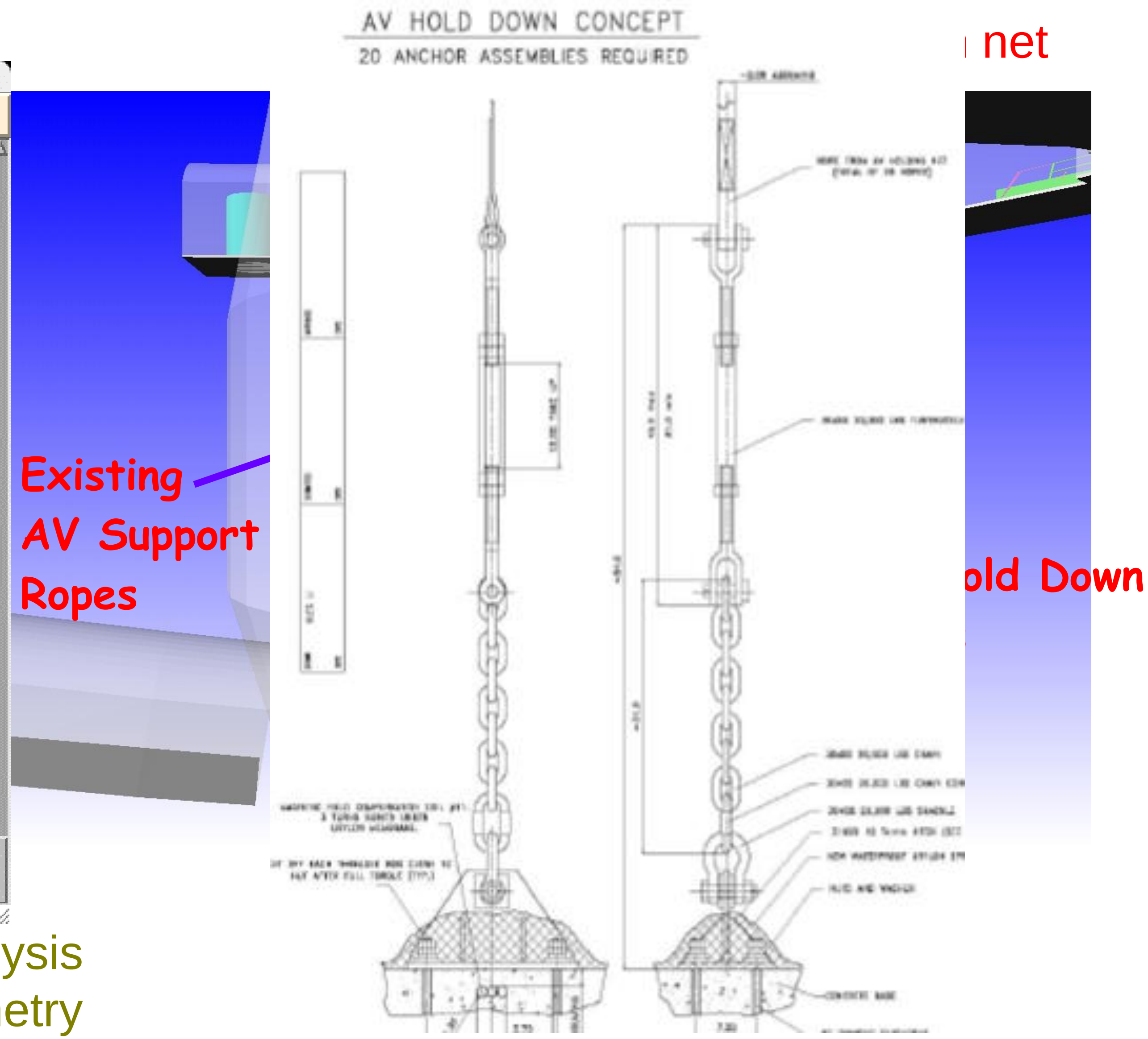


LAB Light Attenuation Length



SNO+ Rope Hold Down Net

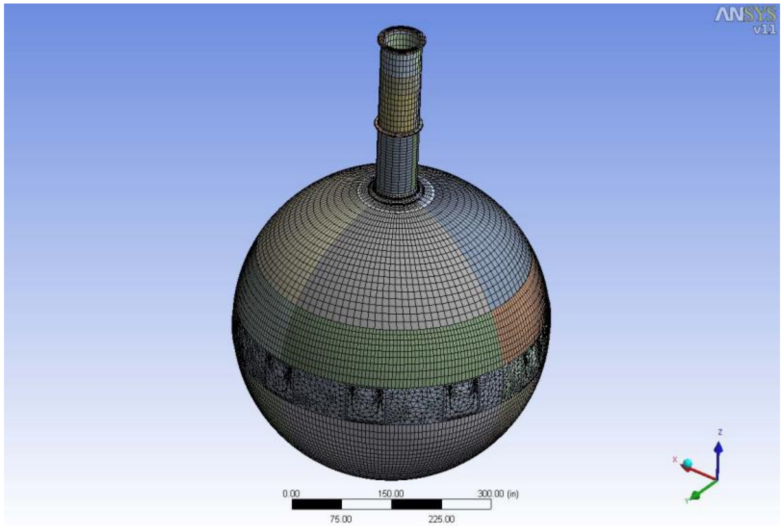


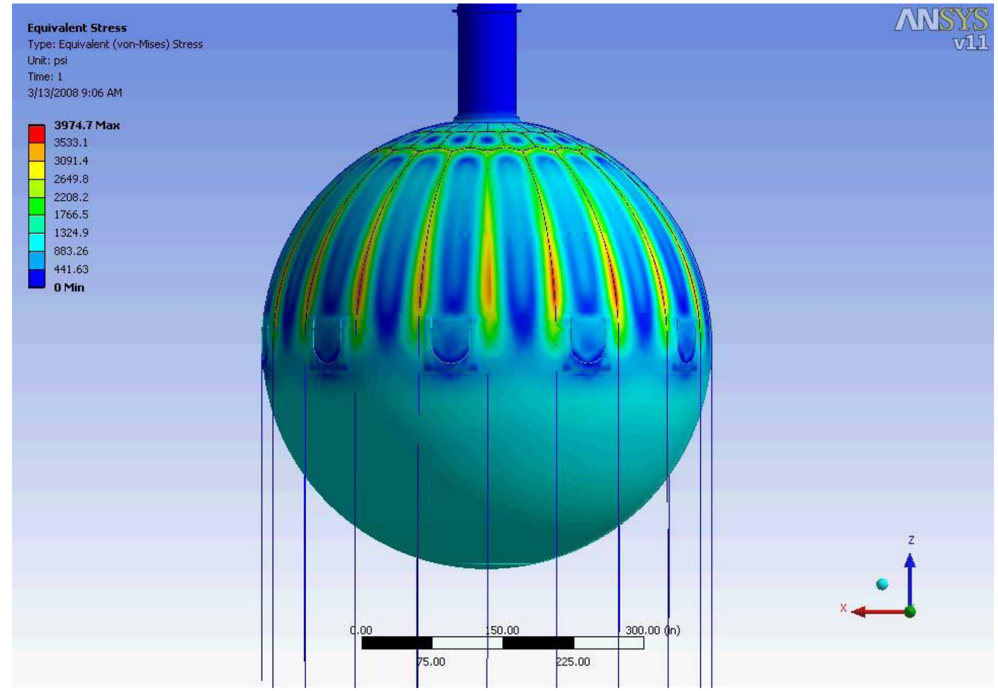


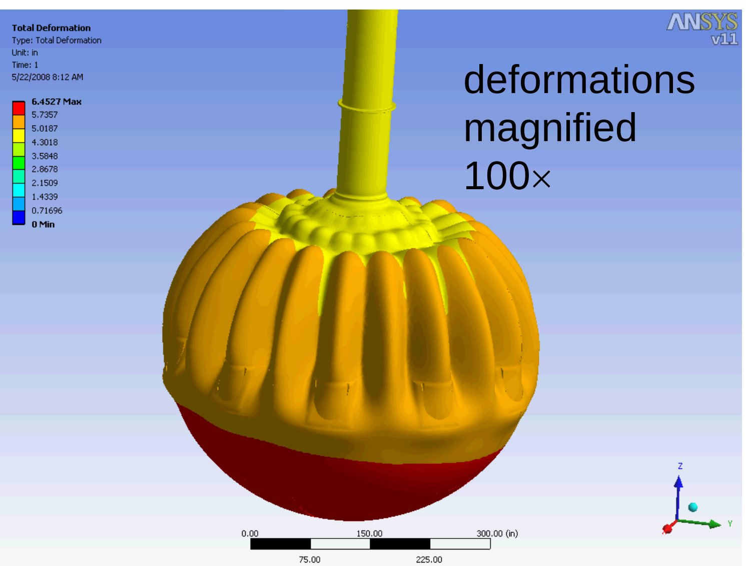
- buckling and finite element analysis
- visualization of net-PSUP geometry

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

Buckling and Finite Element Analysis



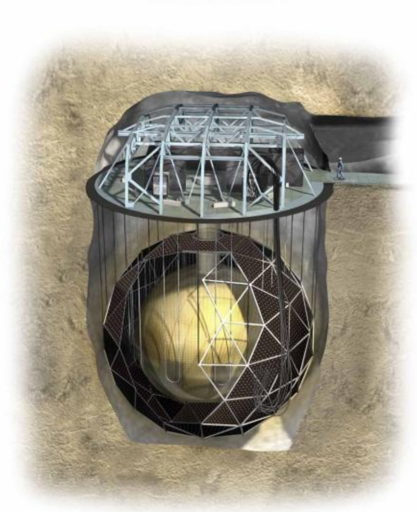




- stresses below SNO limit of 600 psi
- considered extreme case with **empty AV** surrounded by water outside: **does not buckle**

Inside AV Boating

no crazing or deterioration of acrylic seen

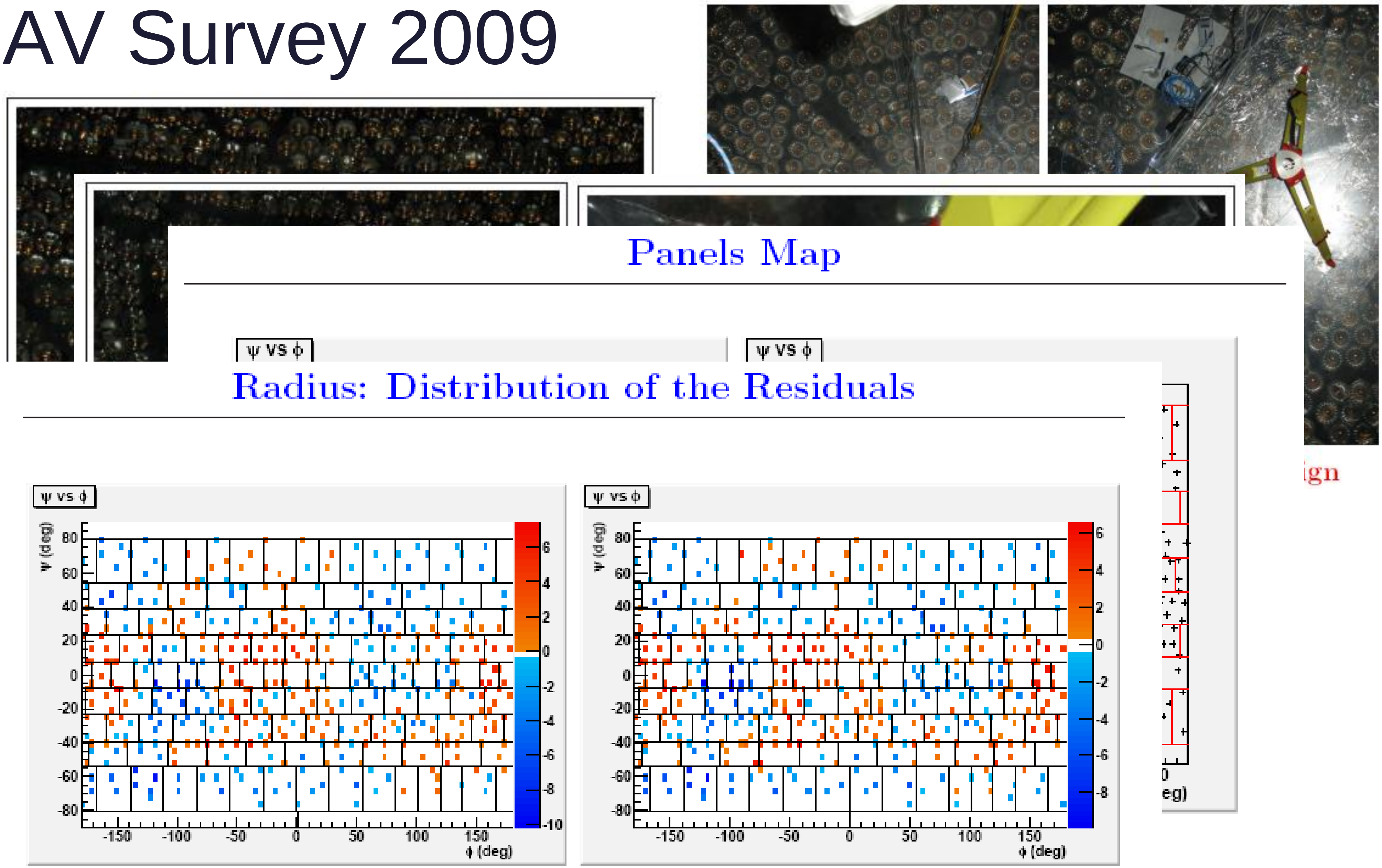


- boating has taken place *inside* the acrylic vessel
  - to attach survey targets
  - inspection for engineering re-certification
- many inspections in the outer detector and cavity

outside PSUP boating

not heavy water!

AV Survey 2009



First Campaign Second Campaign

deviation from perfect sphere in mm

Deviations from Sphericity (2009 Survey)

Radius: Row by Row

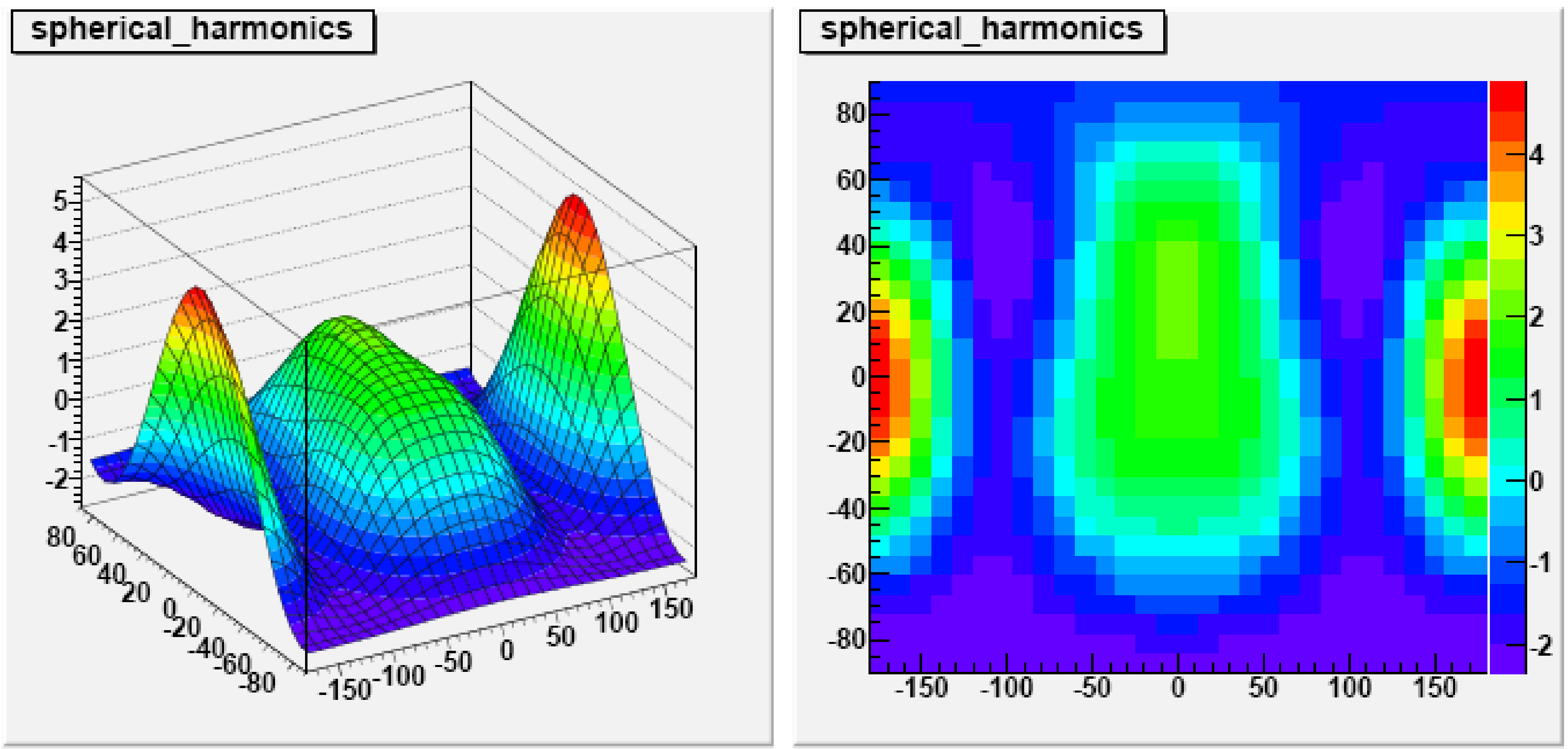
Rows	Combined data sets		
	Radius (cm)	Min. Dev. (mm)	Max. Dev. (mm)
110	600.838 ± 0.400	-3.36 ± 10.41	$+5.74 \pm 10.34$
108	600.773 ± 0.272	-5.41 ± 7.85	$+3.68 \pm 7.88$
106	602.326 ± 0.160	-5.05 ± 5.37	$+5.47 \pm 5.37$
104	601.379 ± 0.072	-8.40 ± 3.85	$+4.09 \pm 3.43$
102	601.136 ± 0.019	-10.15 ± 2.33	$+6.39 \pm 2.53$
103	601.108 ± 0.050	-9.33 ± 2.94	$+6.82 \pm 2.95$
105	600.946 ± 0.120	-4.99 ± 4.50	$+6.94 \pm 4.51$
107	601.439 ± 0.240	-5.20 ± 6.58	$+5.47 \pm 6.87$
109	601.329 ± 0.415	-5.00 ± 10.10	$+5.07 \pm 9.89$
101	597.812 ± 0.024	-8.87 ± 2.34	$+7.19 \pm 2.66$
All*	601.142 ± 0.007	-10.26 ± 1.94	$+7.09 \pm 2.10$

*: 101 not included

as before, SNO AV is spherical to better than 0.5”

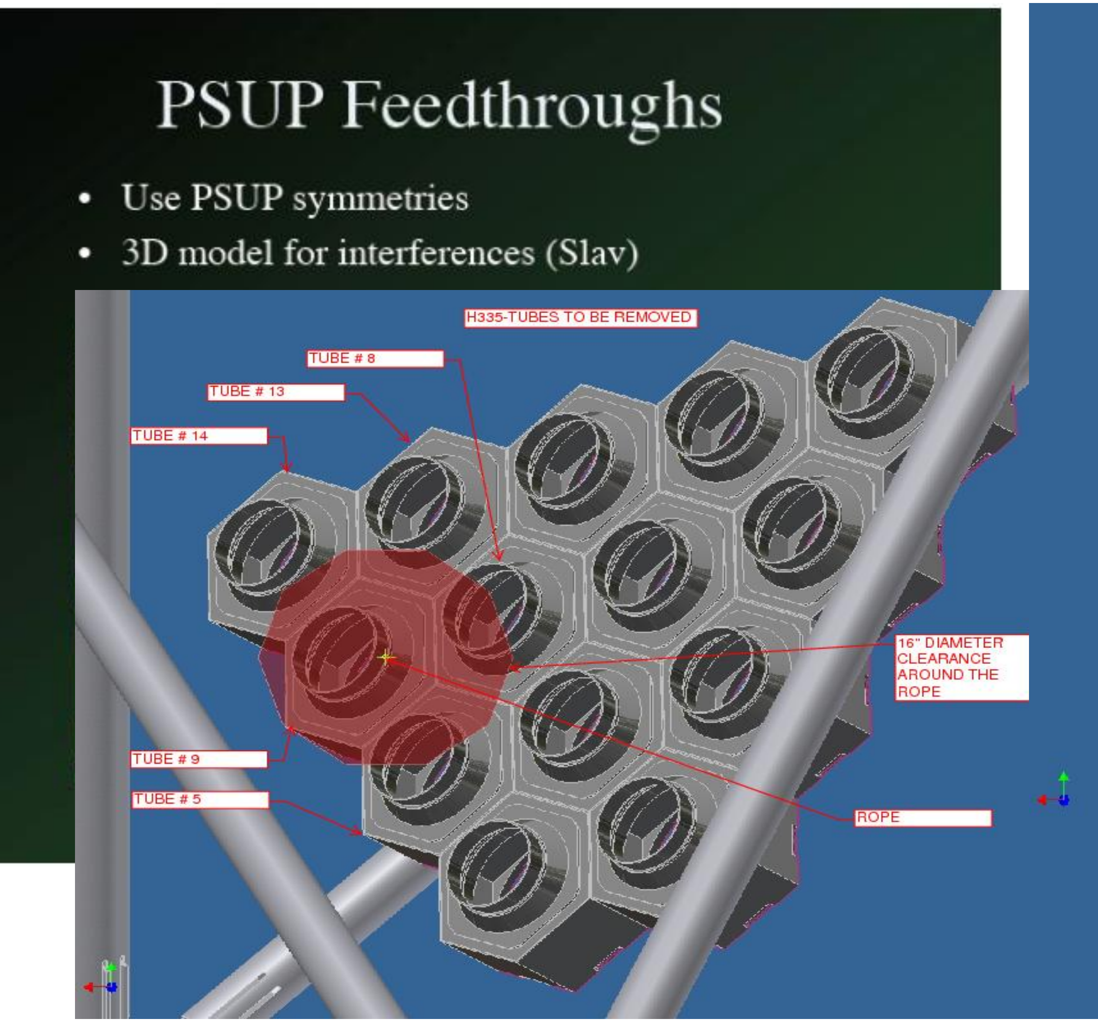
Detailed Survey Results to be Added to FEA

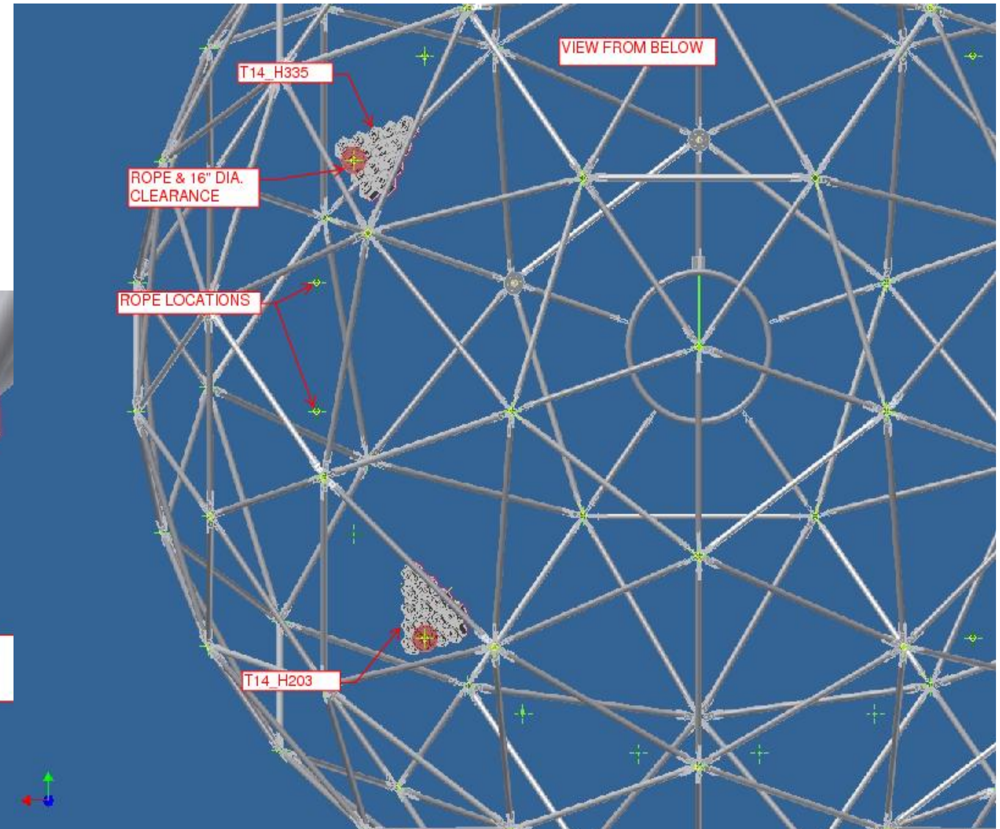
Radius: Spherical Harmonics



we are putting measured deviations into the FEA; re-run stress and buckling analysis

PSUP Panel Feedthroughs

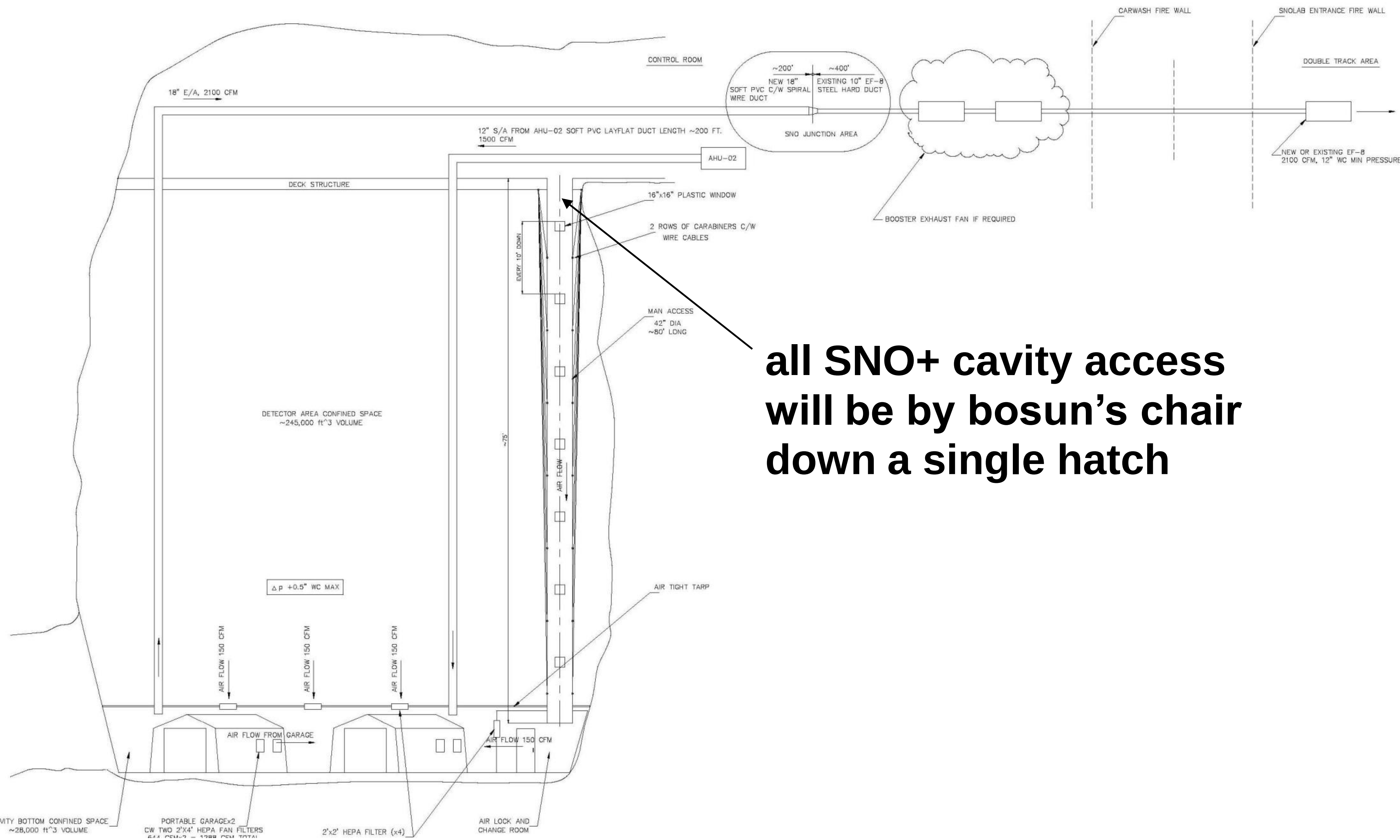




PSUP feedthroughs being designed; detailed installation plan nearing completion

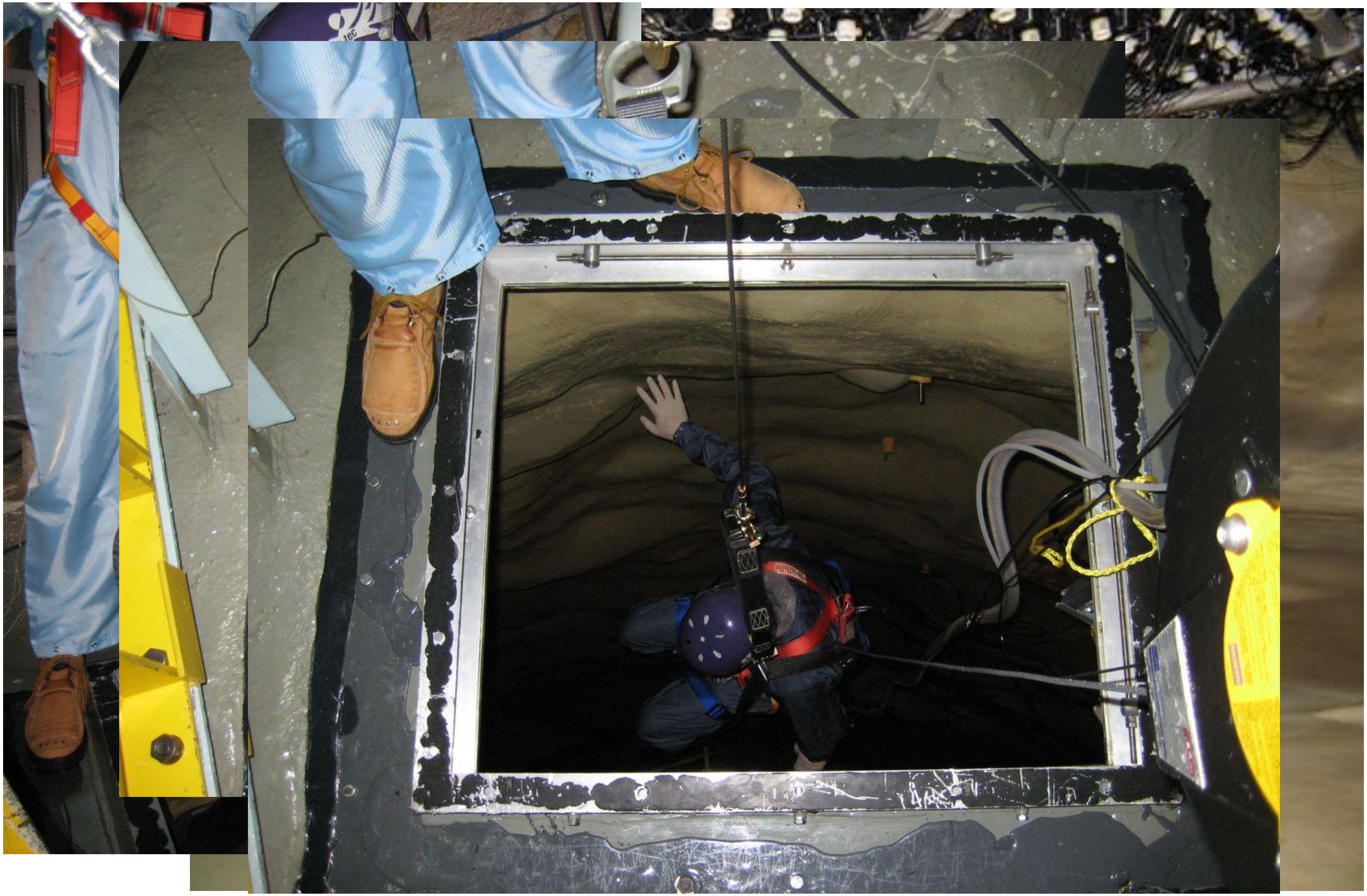
AIR HANDLING FLOWSHEET

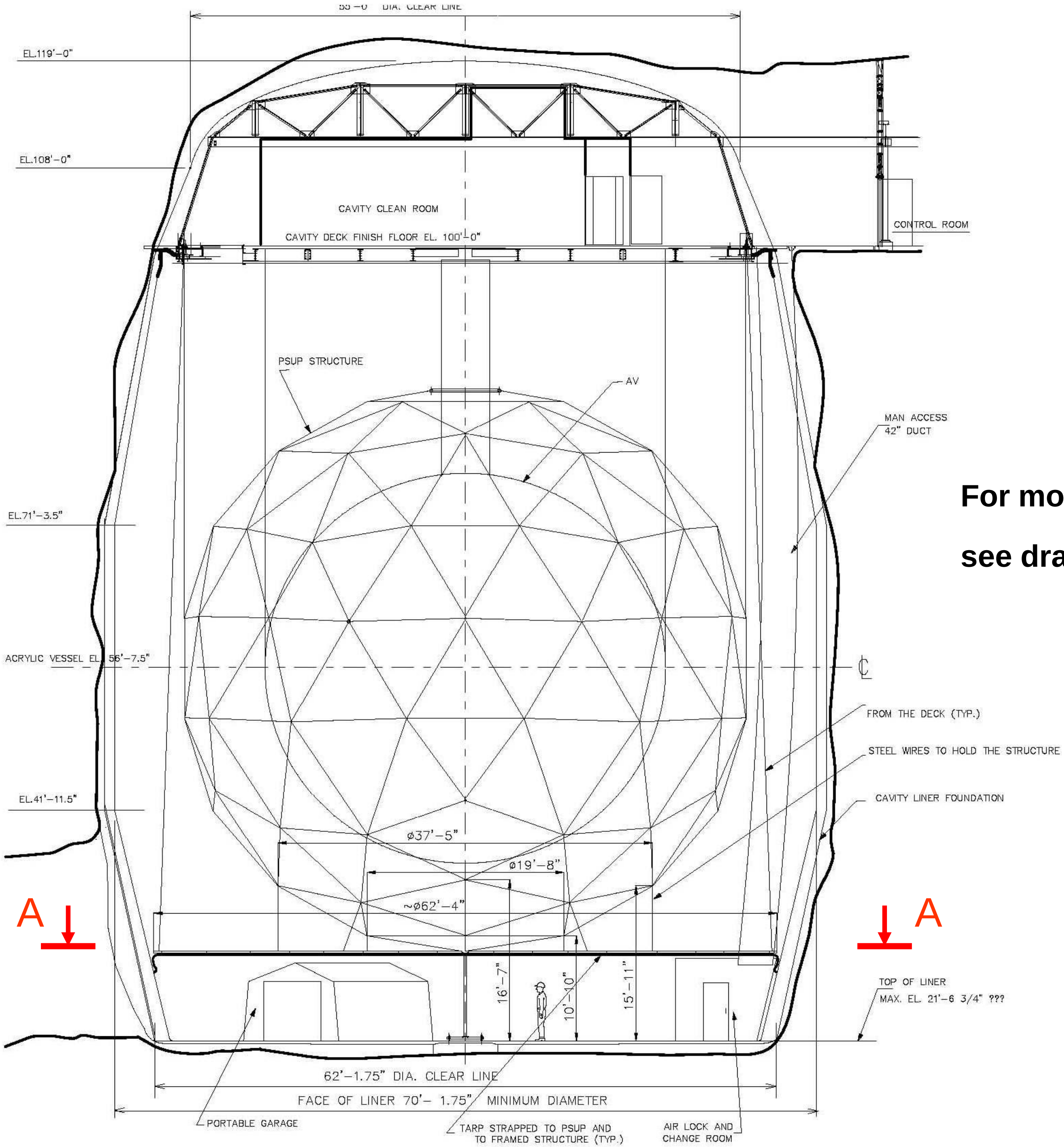
(see drawing # SLDO-SNP-FL-2001-01)



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

Entering the SNO Cavity – Bosun's Chair

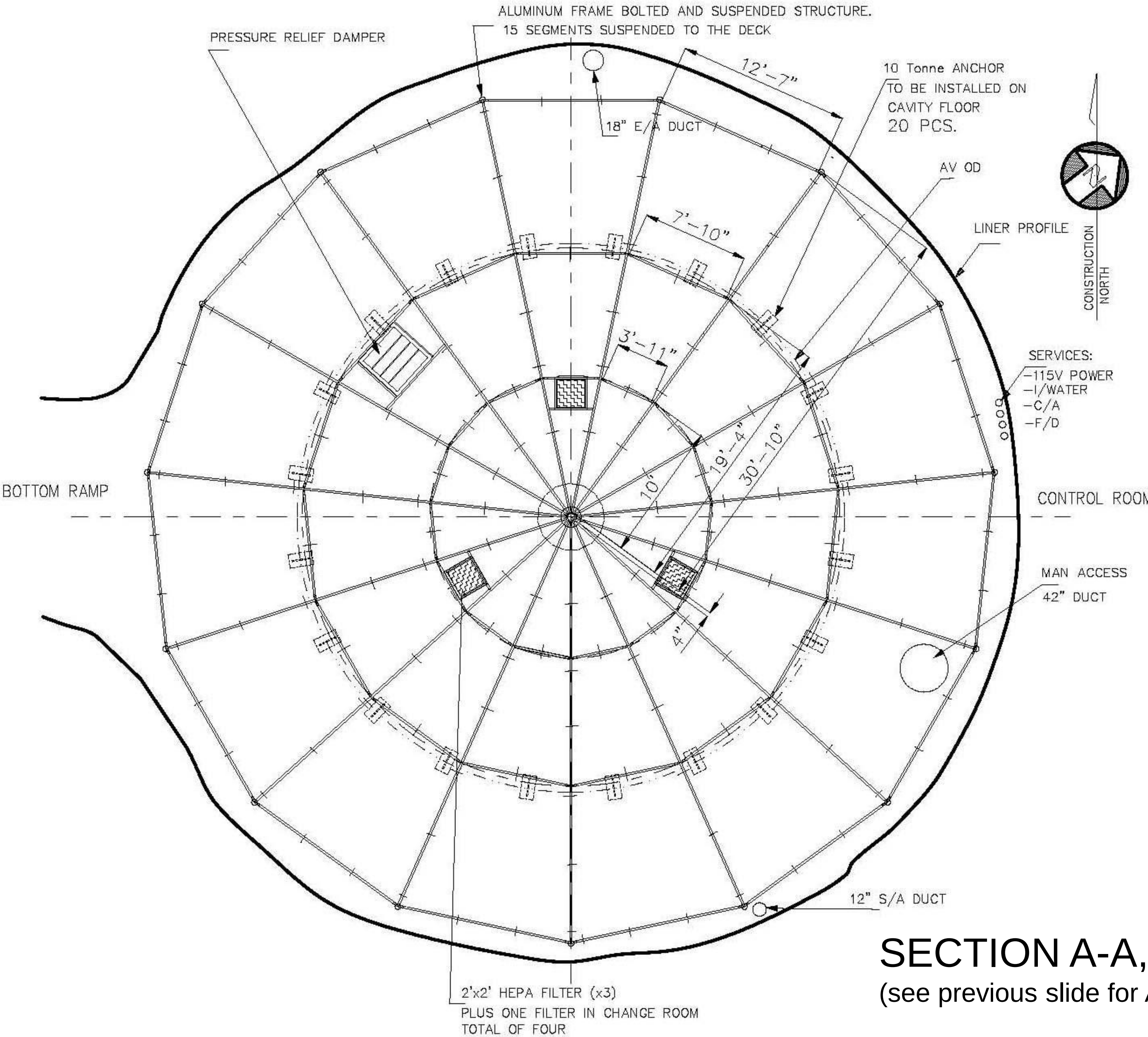




For more UMBRELLA structure details

see drawing # SLDO-SNP-2000-01

UMBRELLA FRAME STRUCTURE



SECTION A-A, tarp not shown

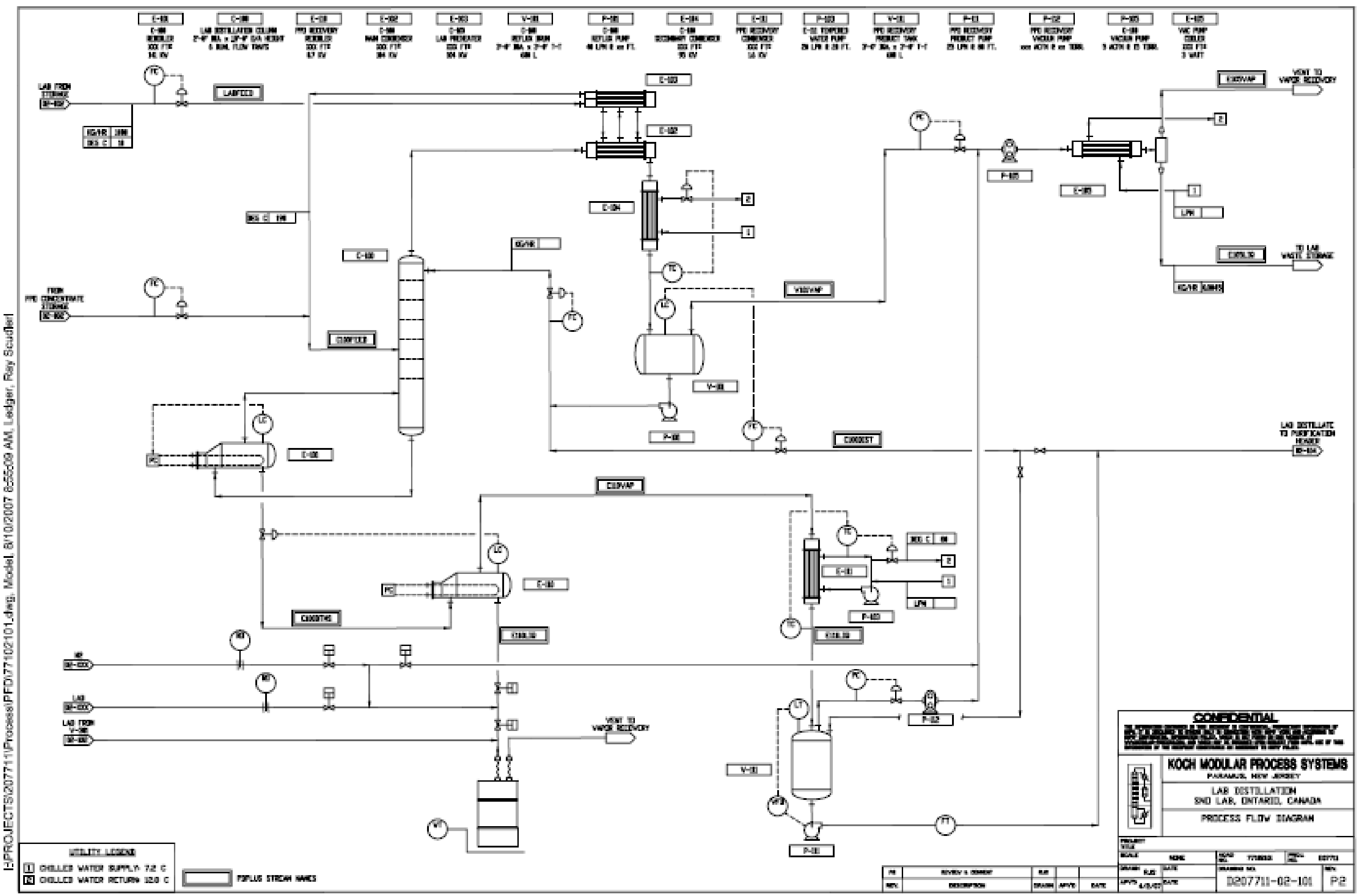
(see previous slide for A-A location)

Scintillator Purification and Process Systems

designed by KMPS (who built the successful Borexino system)

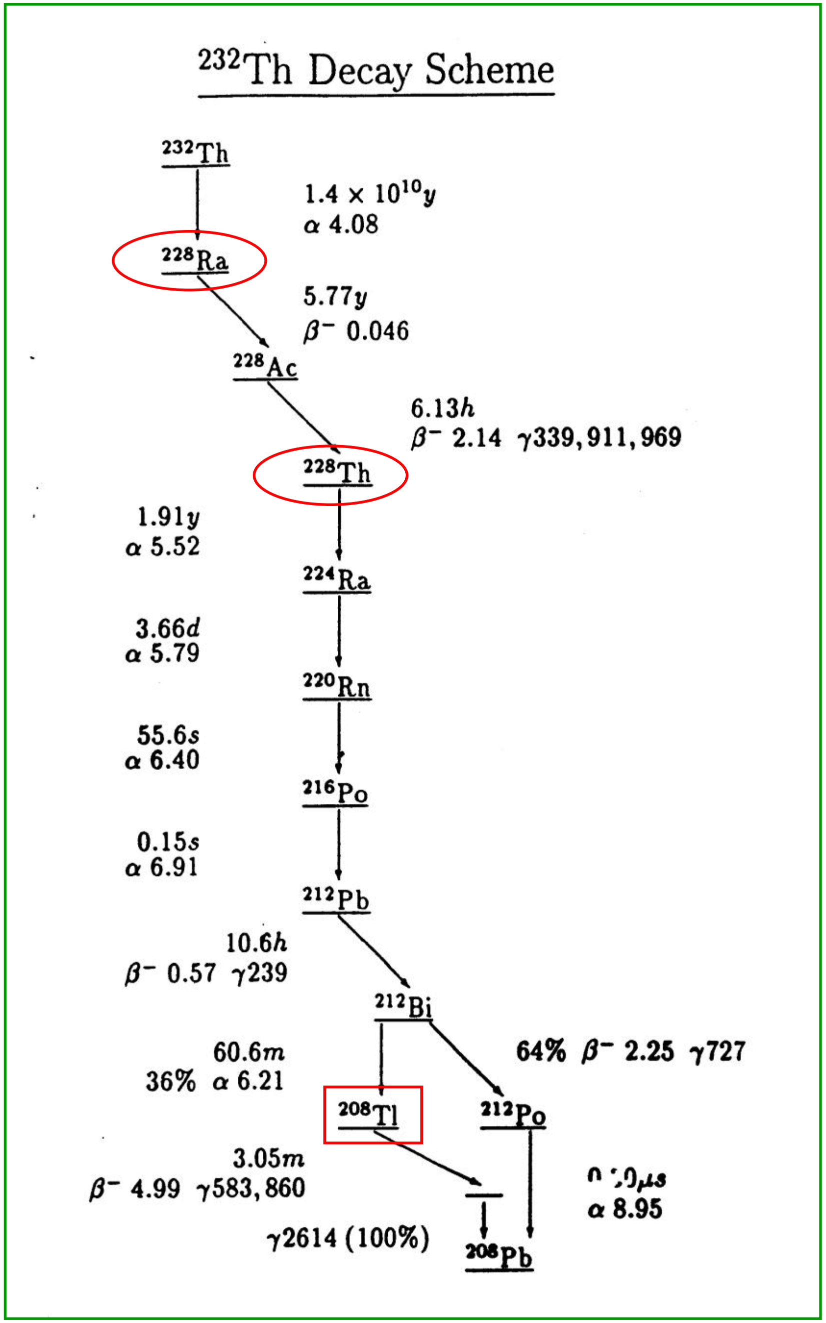
purific

Nd-loa



Nd Radiopurity

- raw $NdCl_3$ salt measurement:
  - ^{228}Th at 32±25×10^{-9} g ^{232}Th/g Nd
- purification target:
  - ^{228}Th and ^{228}Ra in 10 tonnes of 10% Nd (in form of $NdCl_3$ salt) down to <1 ×10^{-14} g ^{232}Th/g Nd
- reduction factor of >10^{6} required!!!
- recall: SNO purified salted heavy water down to ~10 $^{-15}$ g/g level!!



Spike Test Results: Extraction Efficiencies of Th and Ra in 10% $NdCl_3$ using HZrO and $BaSO_4$

Purification method	Adsorbent Conc	Extraction efficiency	
		228Th	226Ra
HZrO mixed-in	0.1 mg/g Zr 0.44 mg/g Zr **0.82 mg/g Zr**	<5% 99.06±0.22% **99.89±0.02%**	<10% 30.7±5.7% 30.1±9.0%
BaSO4 mixed-in	1.0 mg/g Ba	9.5±4.7%	63.4±1.9%
BaSO4 co-precipitation	0.49 mg/g Ba **1.39 mg/g Ba**	20.4±4.4% 62.8±2.3%	97.2±0.2% **99.89±0.03%**

factor of 1000 purification per pass achieved for both Th and Ra!

Status of SNO+

- 2008-2010 funded by NSERC for final designs and initial construction plus operating grants for Alberta, Laurentian and Queen's $2.6M
- Sep 2008: FedNor Innovation funds received $380k
- >$11M proposal (SNO+ portion) submitted to CFI LEF/NIF competition: October 2008
- approved in June 2009
- construction of hold-down net, cavity liner, anchors: designs and initial construction commenced in 2009 and will proceed into 2010
- contracts for scintillator procurement in Q3 2009
- orders for construction of purification plant Q3 2009
- scintillator process and purification system delivered for installation end of Q2 2010
- early 2011 → process and purification systems installed, ready for scintillator filling
- commissioning and data taking in 2011

SNO+ Collaboration

- **University of Alberta:** A. Bialek, P. Gorel, A. Hallin, M. Hedayatipoor, C. Krauss
- **Brookhaven National Laboratory:** R. Hahn, Y. Williamson, M. Yeh
- **Dresden University of Technology:** K. Zuber
- **Black Hills State University:** K. Keeter
- **Armstrong Atlantic State University:** J. Secrest
- **Laurentian University:** O. Chkvorets, E.D. Hallman, S. Korte, M. Schumaker, C. Virtue
- **University of Leeds:** S. Bradbury, J. Rose
- **University of Liverpool:** N. McCauley
- **LIP Lisbon:** S. Andringa, N. Barros, J. Maneira
- **University of North Carolina:** M. Howe, J. Wikerson
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- **Queen Mary University of London:** J. Wilson-Hawke
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