SNO+ Double Beta Decay with Nd

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Sudbury
Neutrino
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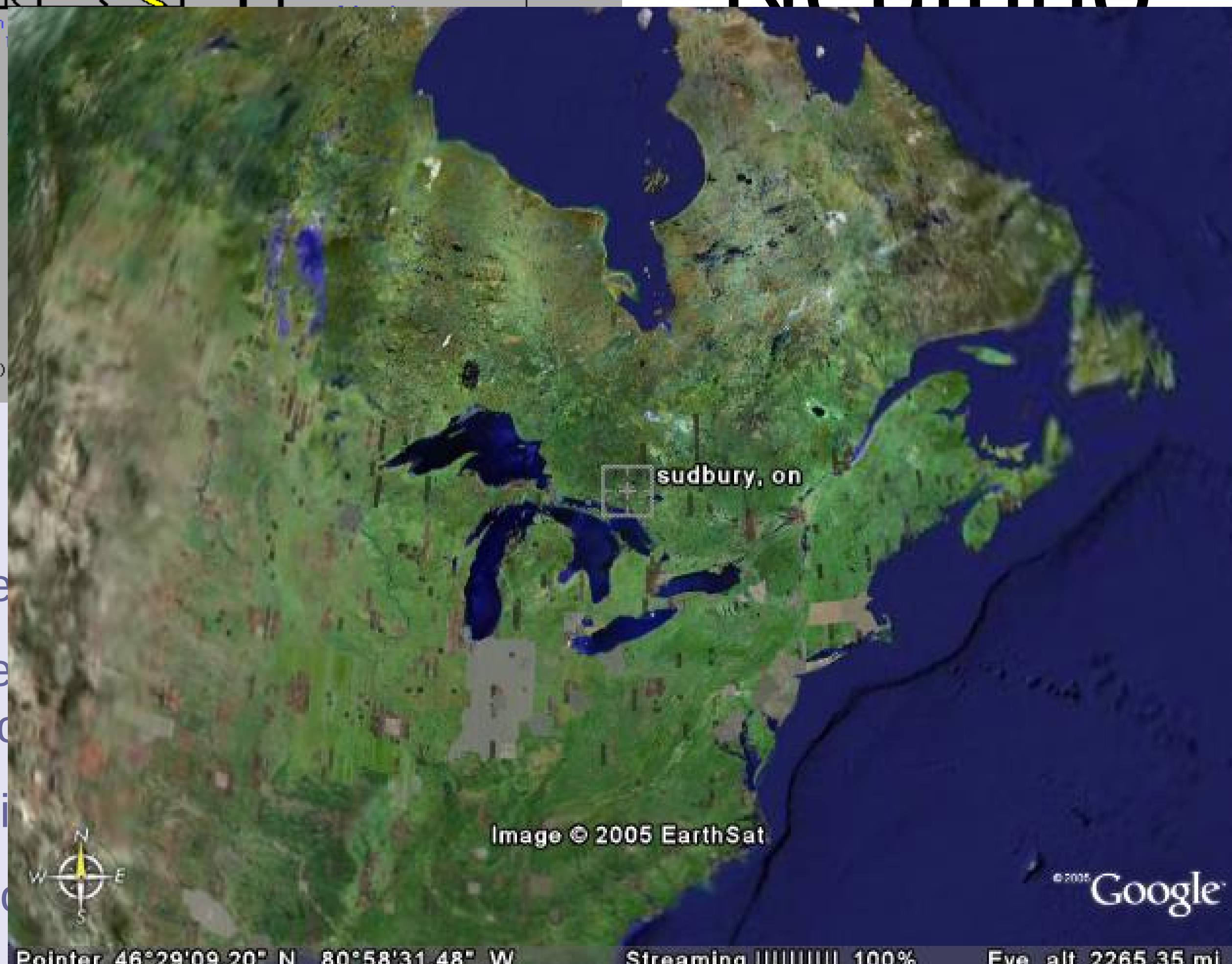


1000 tonnes

12 m diamete

18 m diamete
(~60% photoc

1700 tonnes i

5300 tonnes c

Urylon liner radon seal

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

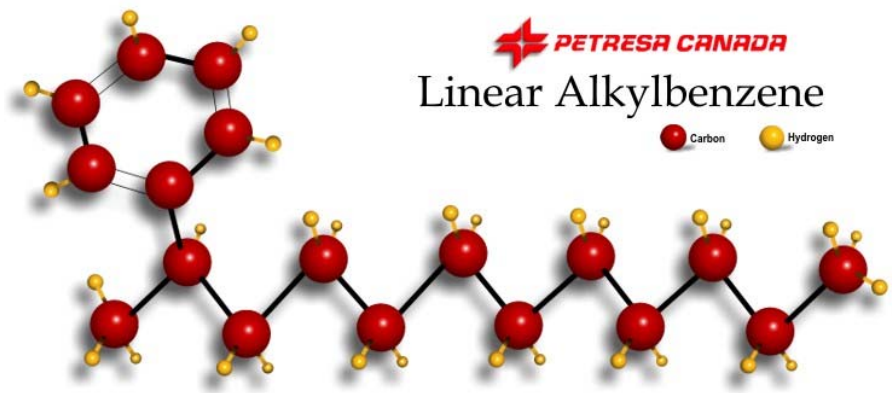
Heavy Water Returned

- the Sudbury Neutrino Observatory has finished taking data with heavy water
- the heavy water has been drained and returned to AECL
  - Nov 28, 2006
    - end of data taking and detector turned off
  - Jan 18, 2007
    - last NCD taken out
  - Jan 27, 2007
    - began removing D_2O from the neck
  - May 28, 2007
    - AV completely drained
      - using a submersible pump
      - plus entry into the AV using a bosun's chair
      - used pump hose to vacuum up the last D_2O
      - used syringe to get last ~200 mL

- we are moving on to SNO+ and are working to fill the detector with liquid scintillator

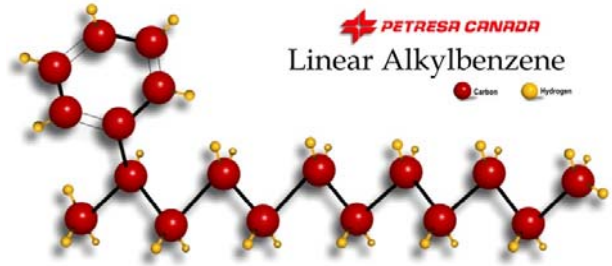
Fill with Liquid Scintillator

- SNO plus liquid scintillator physics program
  - *pep* and CNO low energy solar neutrinos
    - tests the neutrino-matter interaction, sensitive to new physics
  - geo-neutrinos
  - 240 km baseline reactor oscillation confirmation
  - supernova neutrinos
  - double beta decay



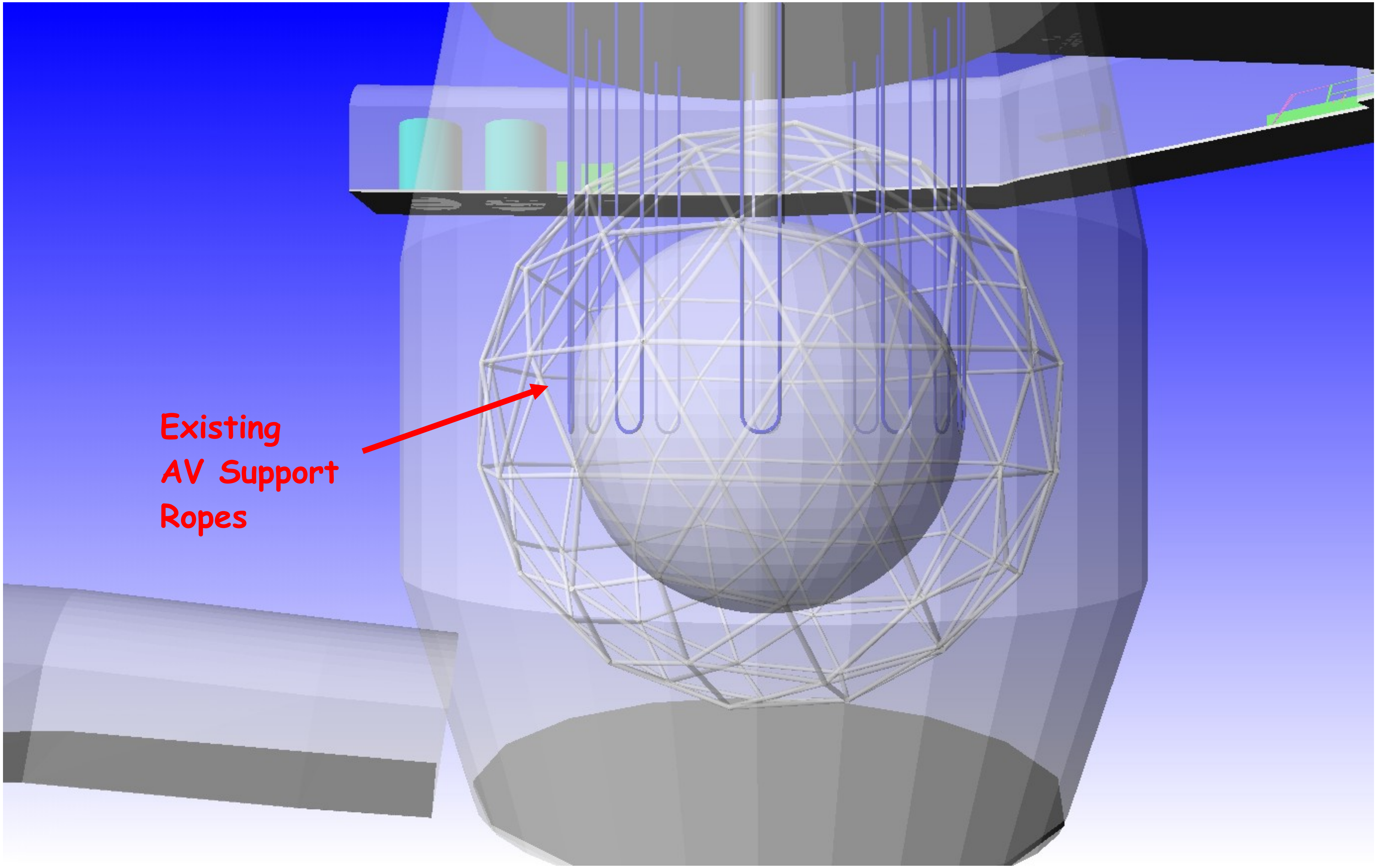
SNO+ Liquid Scintillator

- "new" liquid scintillator developed
  - linear alkylbenzene
    - compatible with acrylic, undiluted
    - high light yield
    - pure (light attenuation length in excess of 20 m at 420 nm)
    - low cost
    - high flash point 130°C safe
    - low toxicity safe
    - smallest scattering of all scintillating solvents investigated
    - density ρ = 0.86 g/cm^3
    - metal-loading compatible

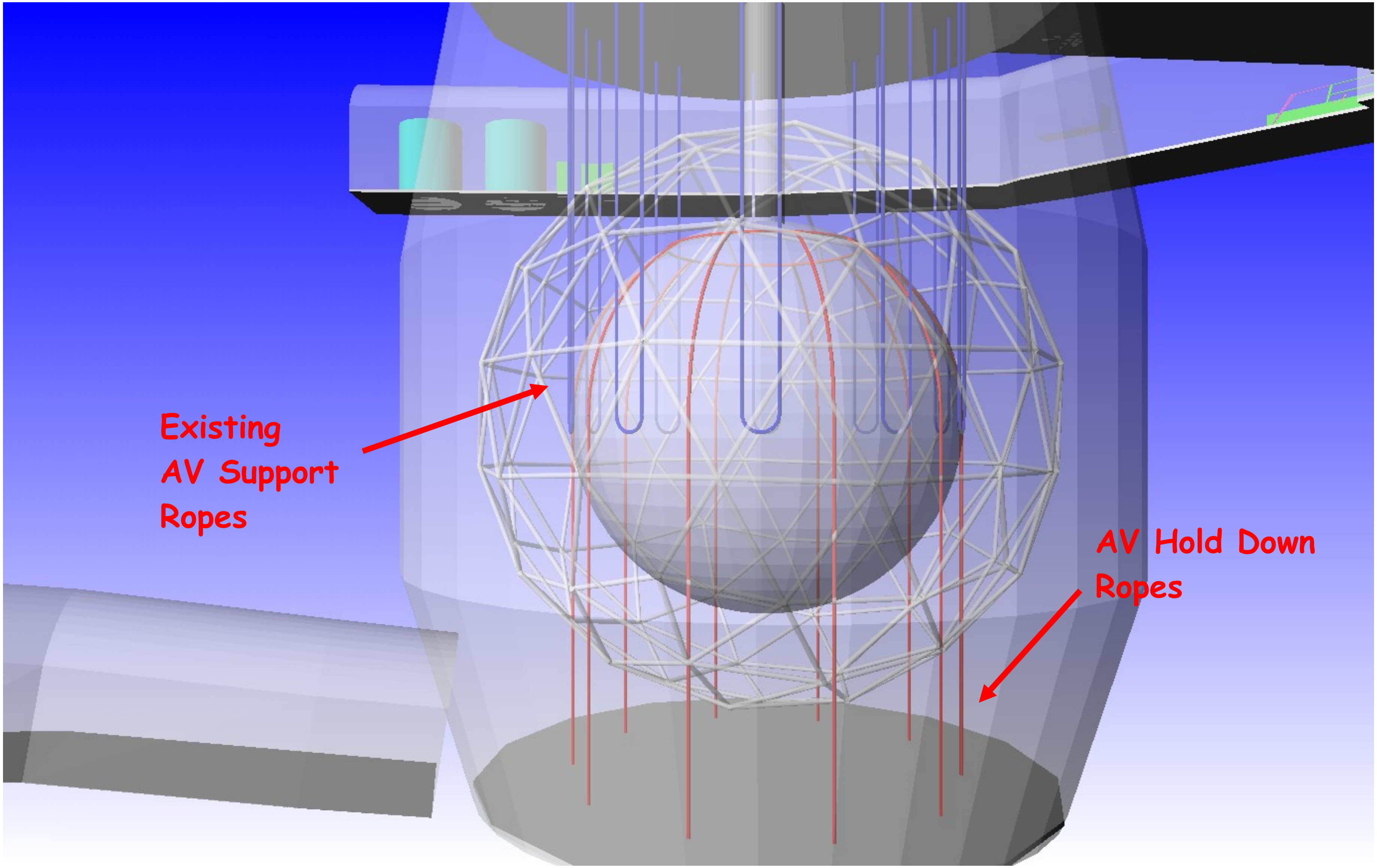


  - SNO+ light output (photoelectrons/MeV) will be approximately 3-4× that of KamLAND
    - ~900 p.e./MeV for 54% PMT area coverage

SNO+ AV Hold Down



SNO+ AV Hold Down



Steps Required: SNO → SNO+

- AV hold down
- liquid scintillator procurement
- scintillator purification
- minor upgrades
  - cover gas
  - electronics
  - DAQ
  - calibration

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)
  - 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

table from F. Avignone Neutrino 2004

$$\overline{\eta} \equiv \langle G^{0\nu} |\mathcal{M}^{0\nu}|^2 \rangle \times 10^{13}$$

Isotope	$\overline{\eta}$
^{48}Ca	0.54
^{76}Ge	0.73
^{82}Se	1.70
^{100}Mo	10.0
^{116}Cd	1.30
^{130}Te	4.20
^{136}Xe	0.28
^{150}Nd	57.0

^{150}Nd

- 3.37 MeV endpoint
- $(9.7 \pm 0.7 \pm 1.0) \times 10^{18}$ yr 2$\nu\beta\beta$ half-life measured by NEMO-III

- isotopic abundance 5.6%

  1% natural Nd-loaded liquid scintillator in SNO+ has 560 kg of ^{150}Nd compared to 37 g in NEMO-III

- cost: \$1000 per kg for metallic Nd; cheaper is $NdCl_3$…\$86 per kg for 1 tonne

SNO+ Double Beta Decay

- a liquid scintillator detector has poor energy resolution; but enormous quantities of isotope (high statistics) and low backgrounds help compensate
- large, homogeneous liquid detector leads to well-defined background model
  - fewer types of material near fiducial volume
  - meters of self-shielding
- possibly source in–source out capability

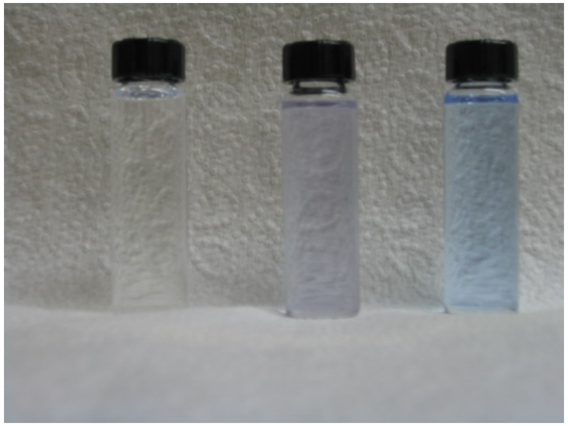
Nd-Loaded Scintillator

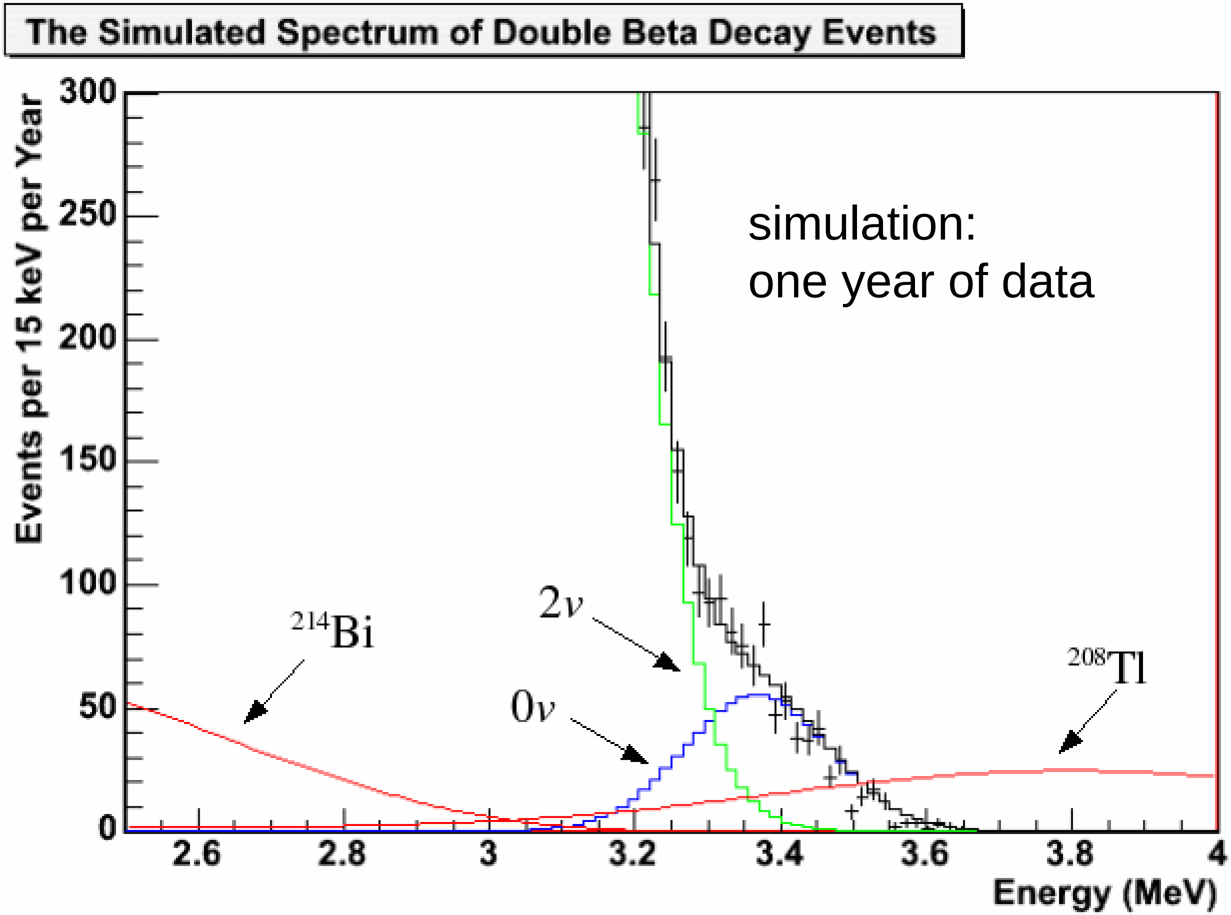
- using the carboxylate technique that was developed originally for LENS and now also used for Gd-loaded scintillator
- we successfully loaded Nd into pseudocumene and in linear alkylbenzene (>1% concentration)
- with 1% Nd loading (natural Nd) we found very good neutrinoless double beta decay sensitivity…

Test $<m_\nu> = 0.150$ eV

Klapdor-Kleingrothaus et al., Phys. Lett. B **586,** 198, (2004)

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





maximum likelihood statistical test of the shape to extract 0ν and 2ν components…~240 units of $\Delta\chi^2$ significance after only 1 year!

Nd-LS Synthesis

- solvent-solvent extraction method to synthesize metal-loaded liquid scintillator
- this method was used to make Nd-LS at both BNL and Queen's laboratories

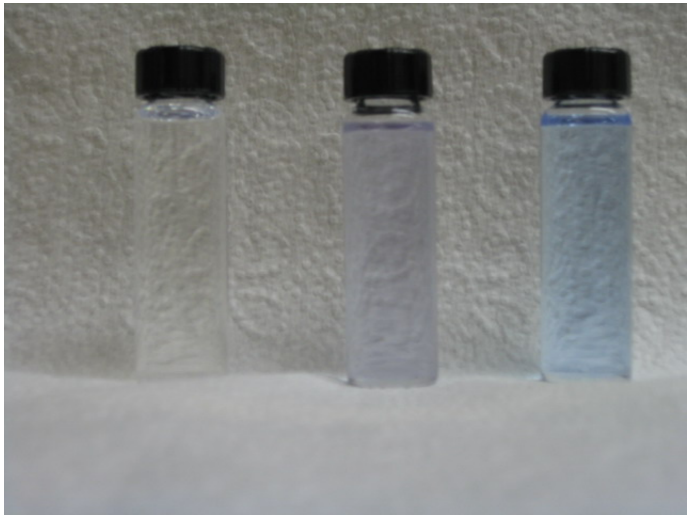
linear alkylbenzene (LAB)

(organic phase) **$Nd(RCOO)_3$**

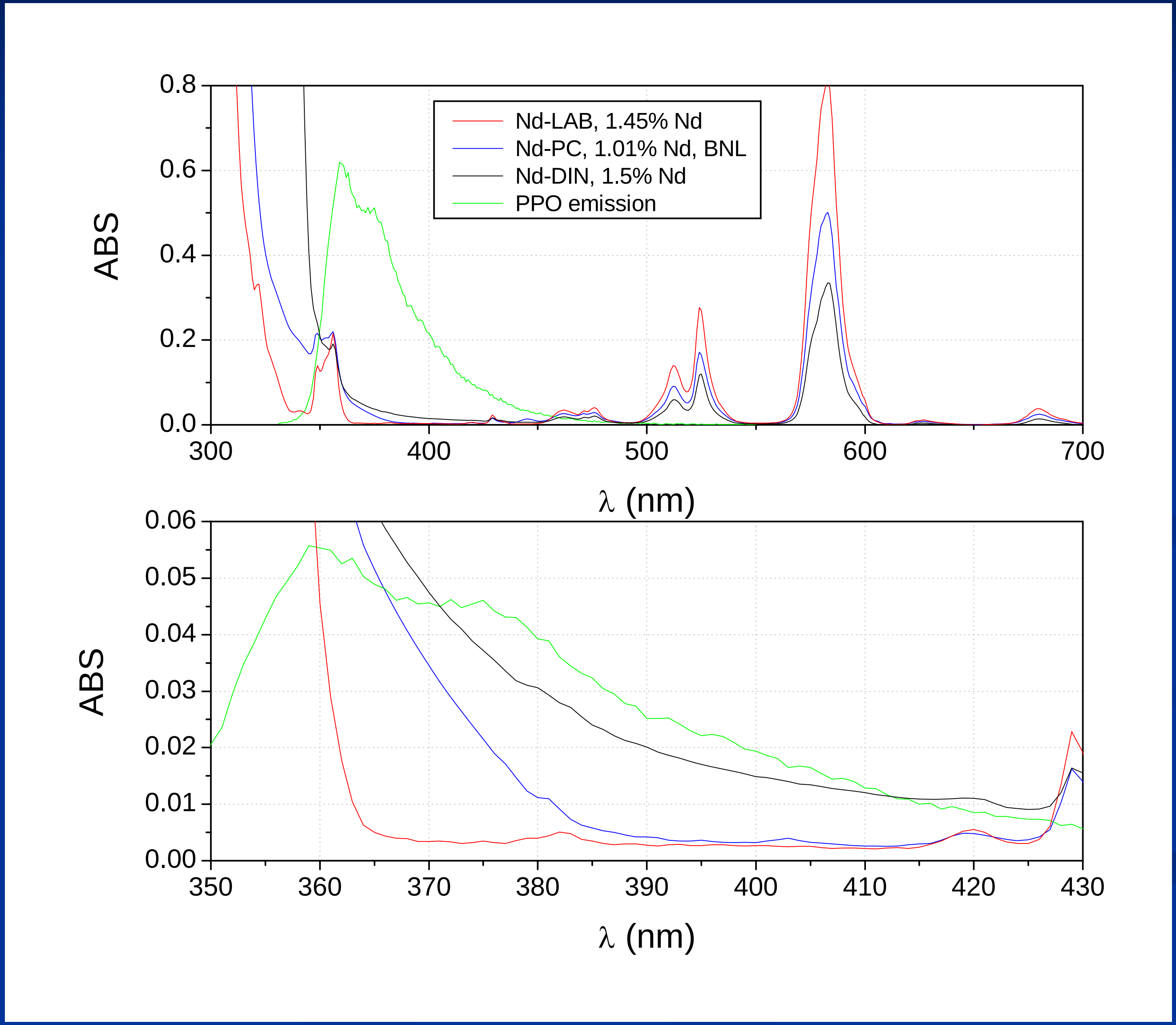
(aqueous phase)

$Nd^{3+}(Cl^-)_3 + 3RCOO^- \rightarrow Nd(RCOO)_3$

$NH_3 + RCOOH \rightarrow NH^{4+} + RCOO^-$



Nd in Various Scintillation Solvents



Light Output from Nd Scintillator

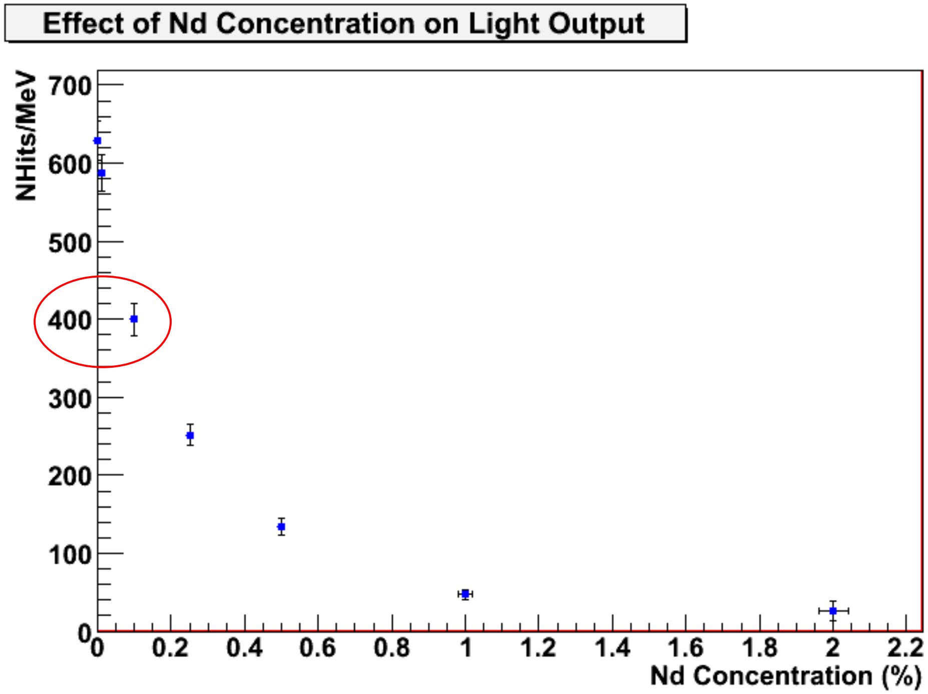
- you can see that 1% Nd-loaded scintillator is blue
  - because Nd absorbs light
- fortunately it is blue
  - it means the blue scintillation light can propagate through
- but, not enough light output in SNO+ if using 1% Nd loading

- BUT, with enriched Nd (e.g. enrich to 56% ^{150}Nd up from 5.6%) could have the same neutrinoless double beta decay sensitivity using 0.1% Nd loading…

Light Output and Concentration

- at 1% loading (natural Nd), there is too much light absorption by Nd
  - 47±6 pe/MeV (from Monte Carlo)

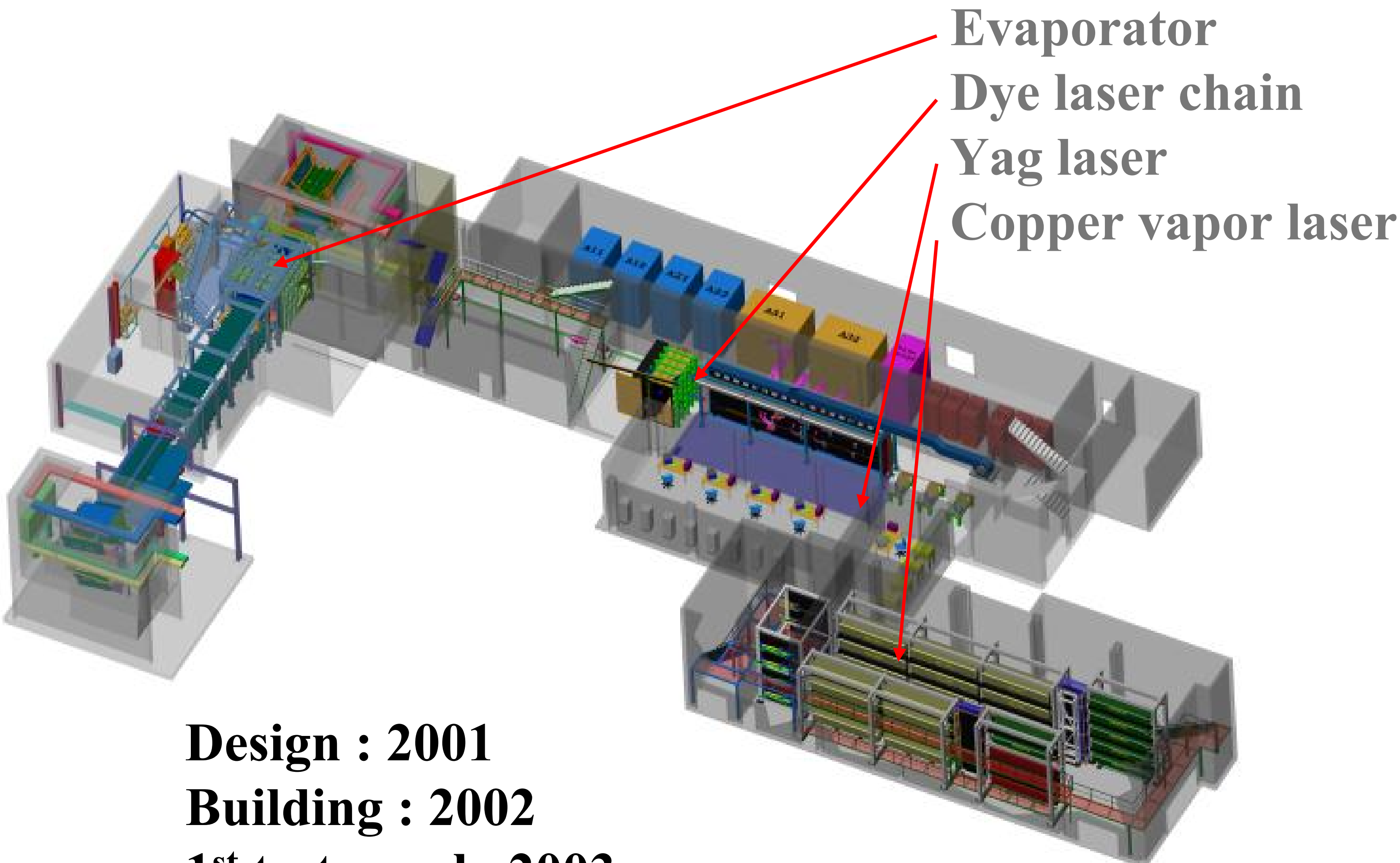
- at 0.1% loading (isotopically enriched to 56%) our Monte Carlo predicts
  - 400±21 pe/MeV (from Monte Carlo)
  - good enough to do the experiment



Nd-150 Consortium

- SuperNEMO and SNO+, MOON and DCBA are supporting efforts to maintain an existing French AVLIS facility that is capable of making 100's of kg of enriched Nd
  - a facility that enriched 204 kg of U (from 0.7% to 2.5%) in several hundred hours

2000-2003 Program : Menphis facility



Design : 2001
Building : 2002
1st test : early 2003
1st full scale exp. : june 2003

AVLIS for ^{150}Nd is Known

Development of the laser isotope separation method (AVLIS) for obtaining weight amounts of highly enriched ^{150}Nd isotope

A.P. Babichev, I.S. Grigoriev, A.I. Grigoriev, A.P. Dorovskii, A.B. D'yachkov, S.K. Kovalevich, V.A. Kochetov, V.A. Kuznetsov, V.P. Labozin, A.V. Matrakhov, S.M. Mironov, S.A. Nikulin, A.V. Pesnya, N.I. Timofeev, V.A. Firsov, G.O. Tsvetkov, G.G. Shatalova

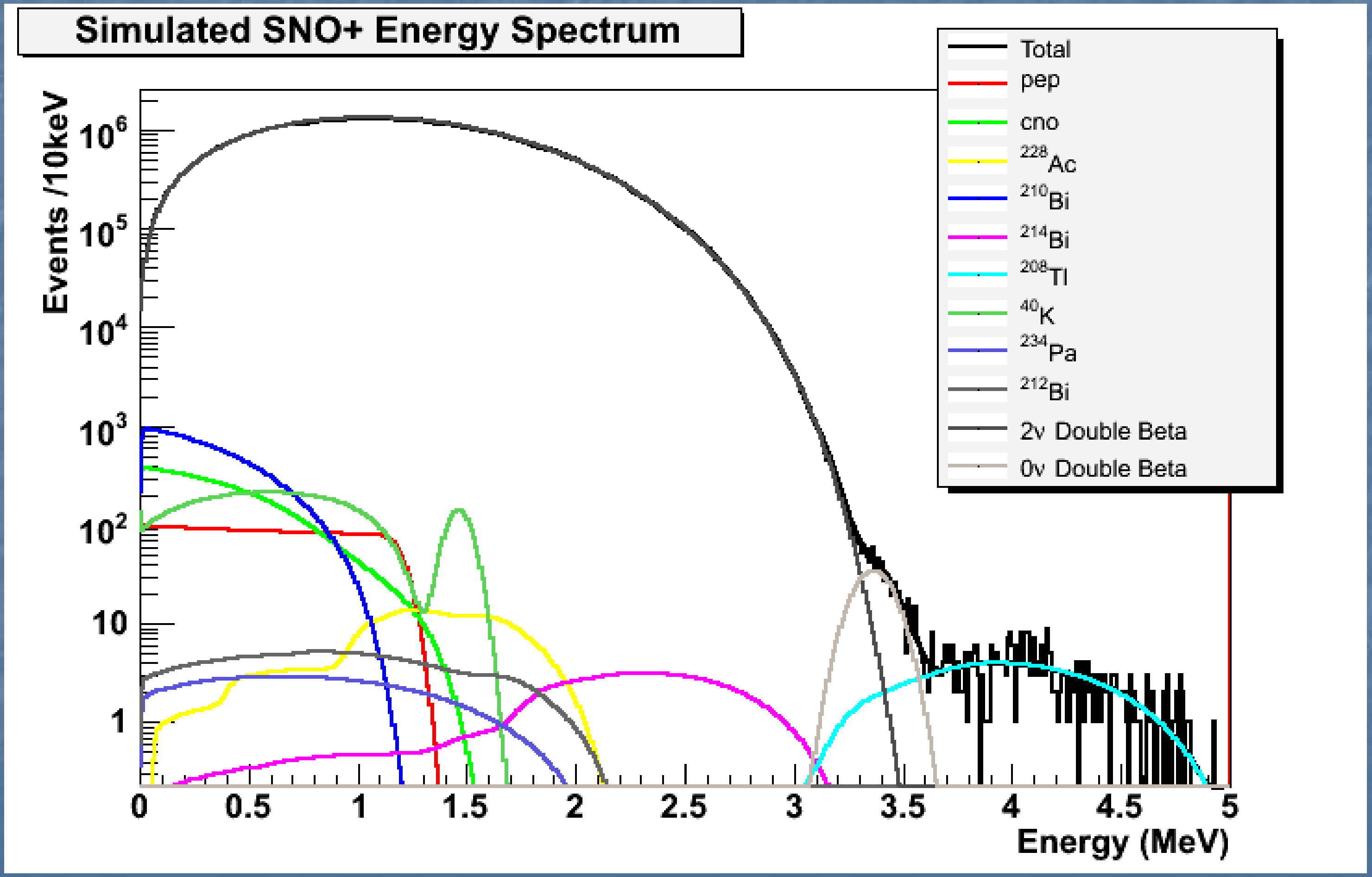
Summary So Far…

- SNO+ plans to deploy 0.1% Nd-loaded liquid scintillator
  - ~500 kg of ^{150}Nd if enriched Nd
  - 56 kg of ^{150}Nd if natural Nd
- light output: 400 pe/MeV corresponds to 6.4% resolution FWHM at ^{150}Nd Q-value
- why Nd?
  - high Q-value is above most backgrounds
  - Ge: Majorana and GERDA
  - Xe: EXO, XMASS
  - Te: CUORE
  - Mo: MOON
  - Ca: CANDLES
  - Se: SuperNEMO
  - Cd: C0BRA
  - Nd: SNO+
- how we search for double beta decay?
  - fit 2ν and 0ν **known** spectral shapes along with **knowable** background shapes (mainly from internal Th)

Your Questions Anticipated

- what neutrino mass sensitivity ?
- long-term stability of Nd liquid scintillator?
- radio-purity of Nd?
- schedule?

SNO+ Double Beta Spectrum

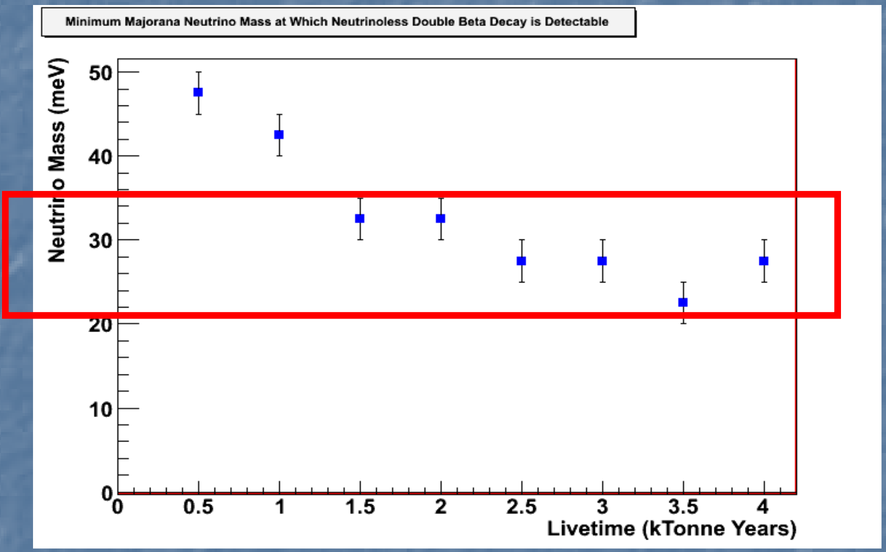


1 yr, 500 kg isotope, m_{ν} = 150 meV

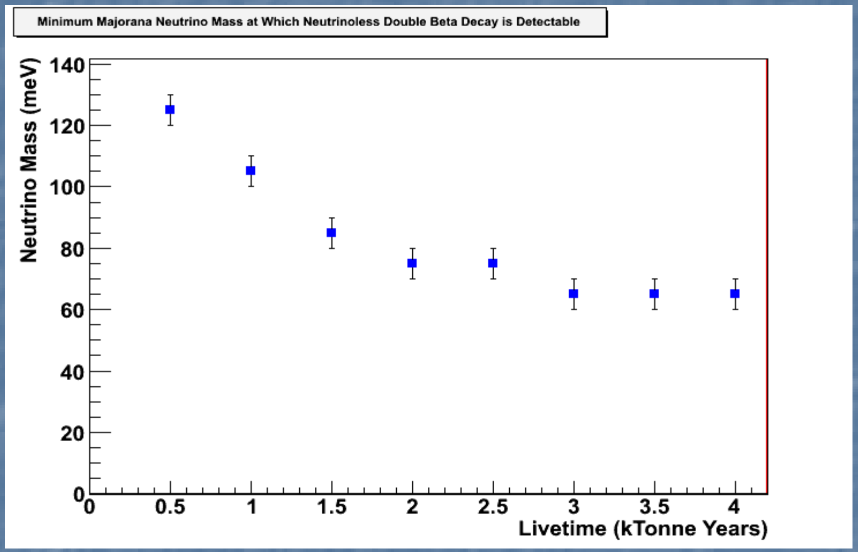
Statistical Sensitivity in SNO+

corresponds to 0.1% natural Nd LS in SNO+

500 kg isotope

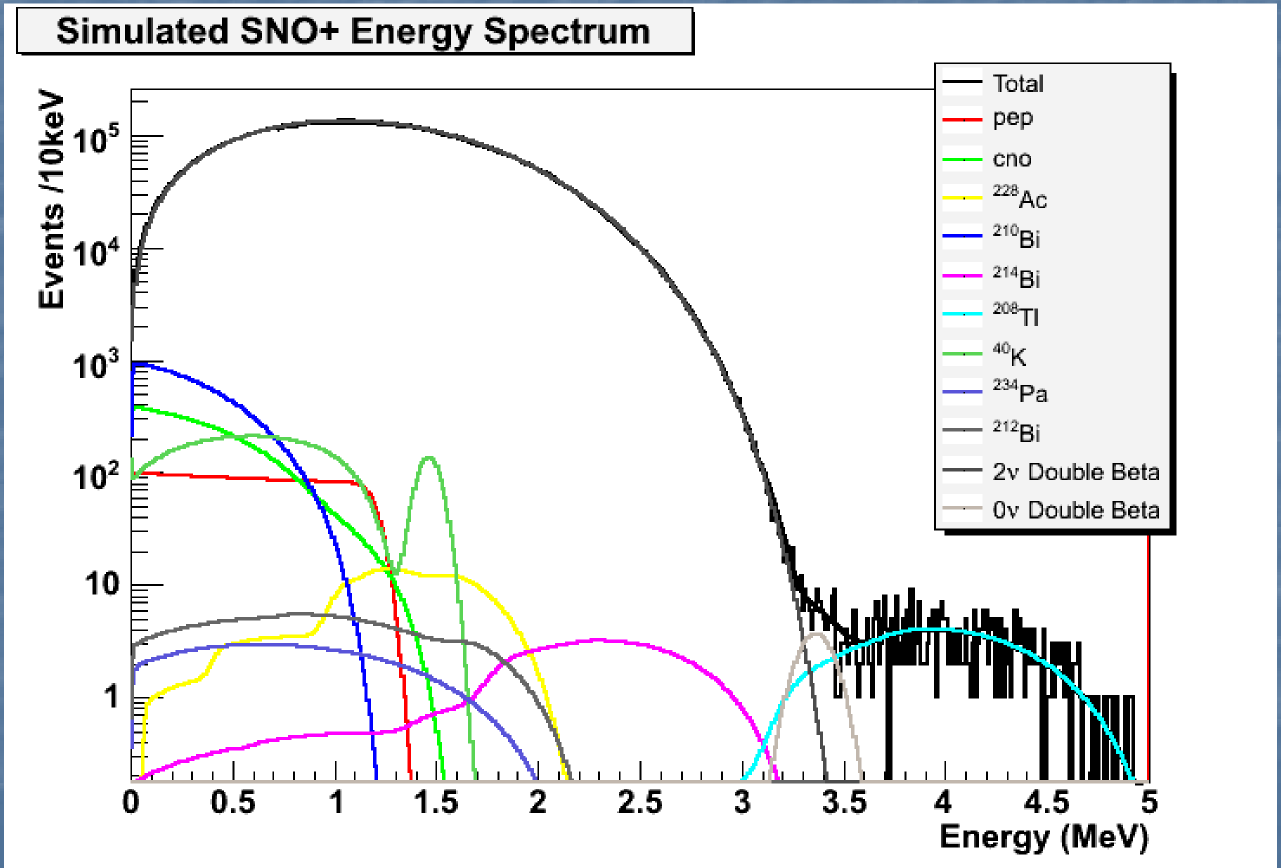


56 kg isotope



- 3 sigma detection on at least 5 out of 10 fake data sets
- $2\nu/0\nu$ decay rates are from Elliott & Vogel, Ann. Rev. Nucl. Part. Sci. **52**, 115 (2002)

0.1% Natural Nd Loading

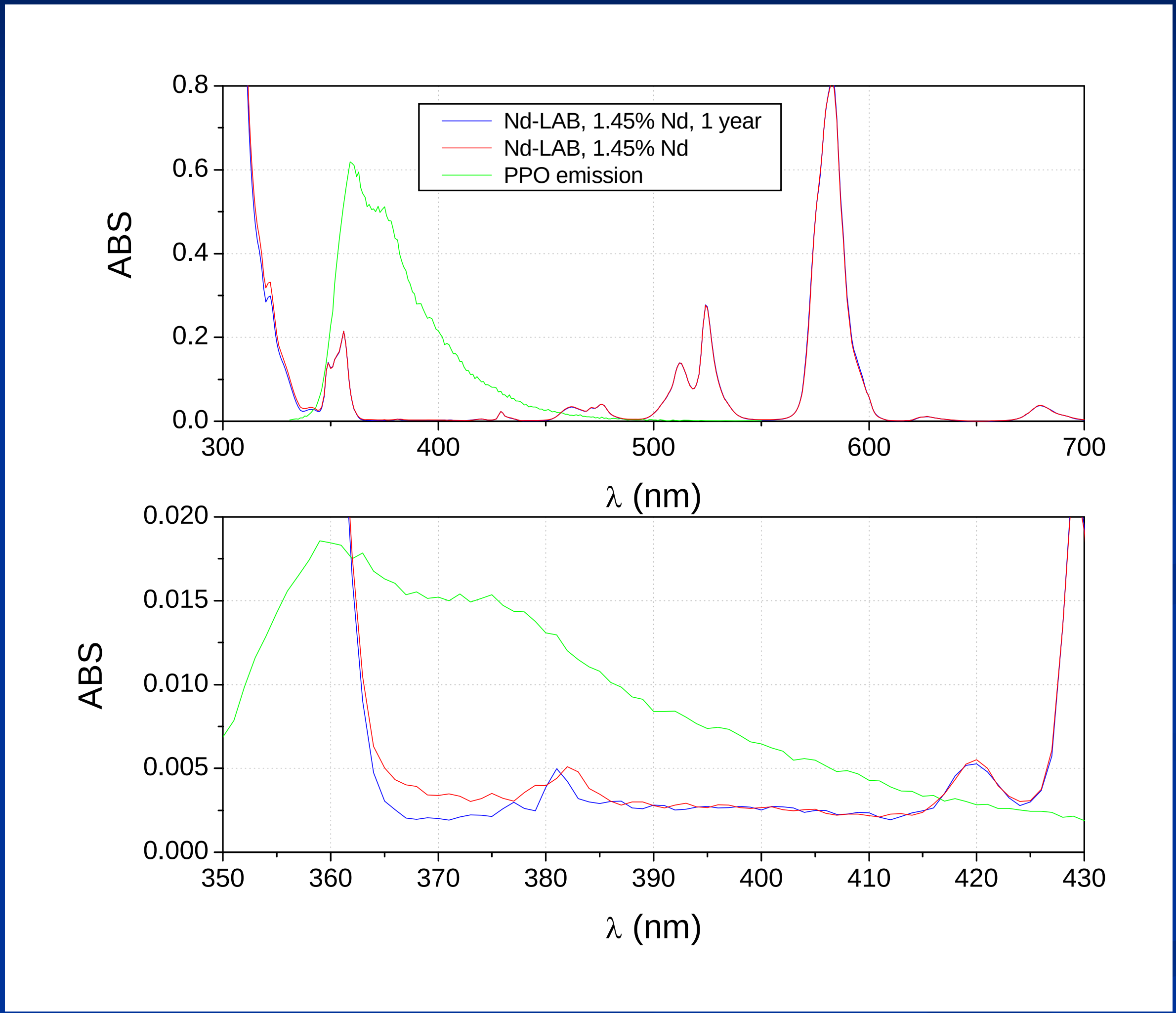


1yr, 1000kg natural, 150meV

Statistical Sensitivity

- for 50% enriched ^{150}Nd (0.1% Nd LS in SNO+)
  - 3σ statistical sensitivity reaches 30 meV
  - 5σ sensitivity of 40 meV after 3 years
  - assumed background levels (U, Th) in the Nd LS to be at the same level as KamLAND scintillator
  - systematic error in energy response will likely be the limit of the experiment and not the statistics
  - preliminary studies show that we can understand the energy resolution systematics at the level required to preserve sensitivity down to 50 meV

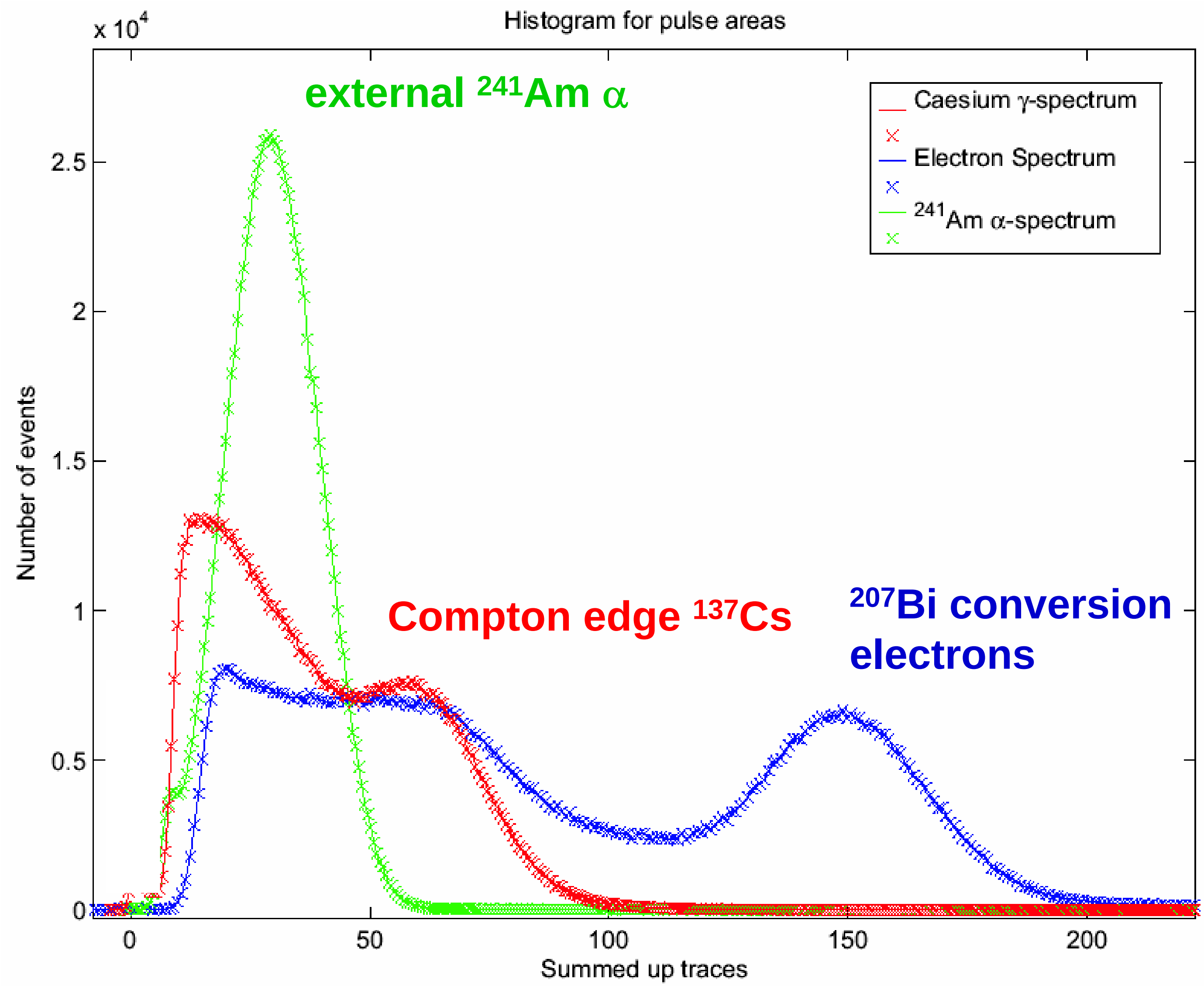
Stability of Nd-LAB



no change in optical properties after >1 year

Nd LS Works!

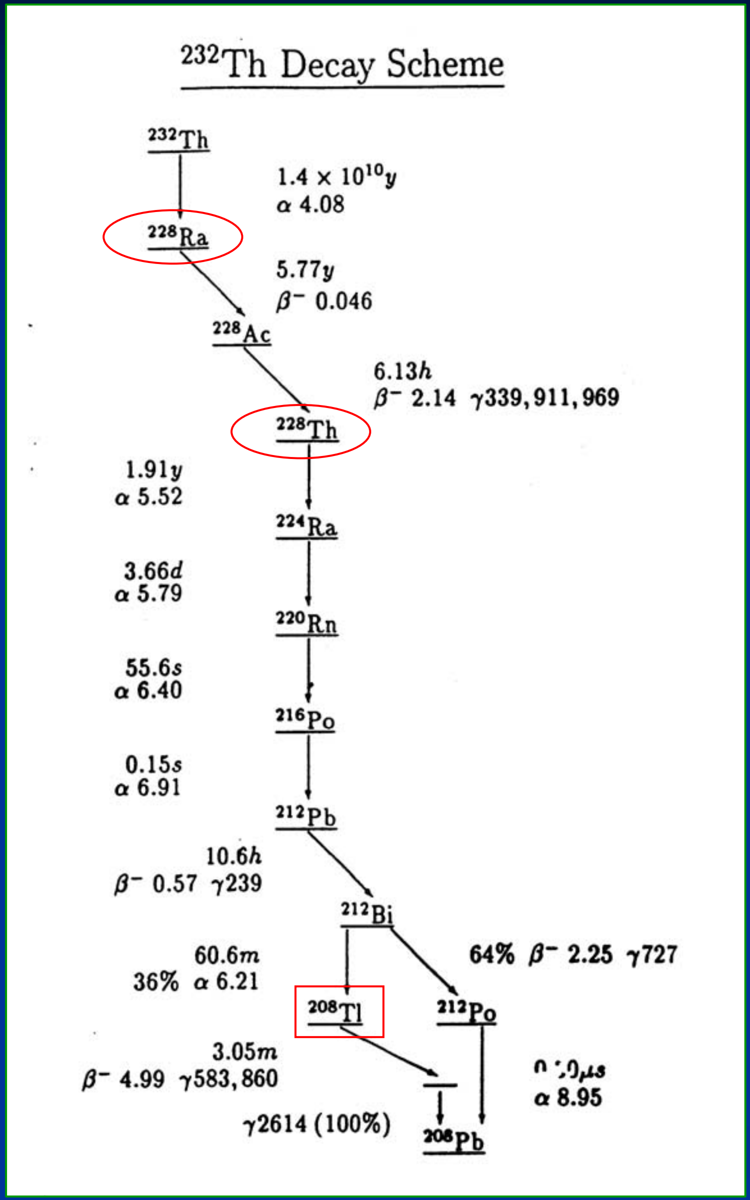
small Nd-LS detector with α, β, γ sources demonstrates it works as scintillator



Nd Purification

- **$NdCl_3$ needs to be purified**
- putting Nd into the organic accomplishes purification (U, Th don't get loaded into the liquid scintillator)
- Nd liquid scintillator: after synthesis it is possible to perform online loop purification

- ^{150}Nd enrichment also removes unwanted Th



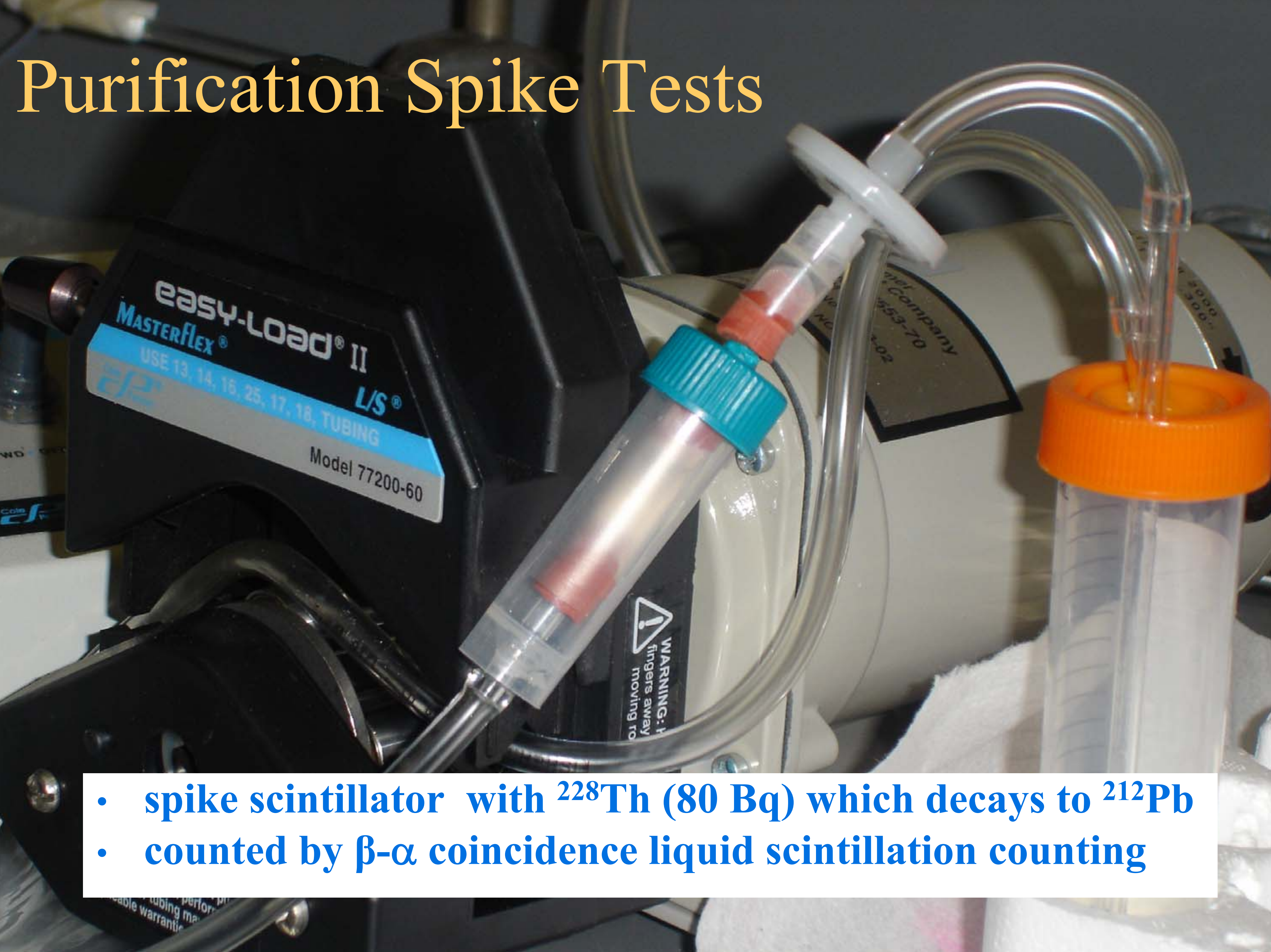
Radio-purification goals:

- ^{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**

- Raw $NdCl_3$ salt measurement: ^{228}Th equivalents to **32±25×10^{-9}** g ^{232}Th/g Nd

A reduction of >10^{6} is required!!!

Purification Spike Tests



- spike scintillator with ^{228}Th (80 Bq) which decays to ^{212}Pb
- counted by β-α coincidence liquid scintillation counting

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

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

SNO+ “broad-brush” schedule

- 2007: SNO+ finalize design
- 2008: funded, SNO+ installation
- 2009: fill and run with pure scintillator
- 2010: add Nd
- 2011: below 100 meV sensitivity reached if natural Nd and below 50 meV reached if enriched Nd

SNO+ Nd: Summary

- good sensitivity and very timely
- homogeneous liquid, well defined background model
  - large volume gives self-shielding
  - Q-value is above most backgrounds
    - thus “insensitive” to internal radon backgrounds
    - thus insensitive to “external” backgrounds (2.6 MeV γ)
- Th, Ra purification techniques are effective
- huge amounts of isotope, thus high statistics, can work for double beta decay search
  - but requires exquisite calibration and knowledge of detector response

SNO+ Collaboration

Queen's
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new collaborators are welcome!