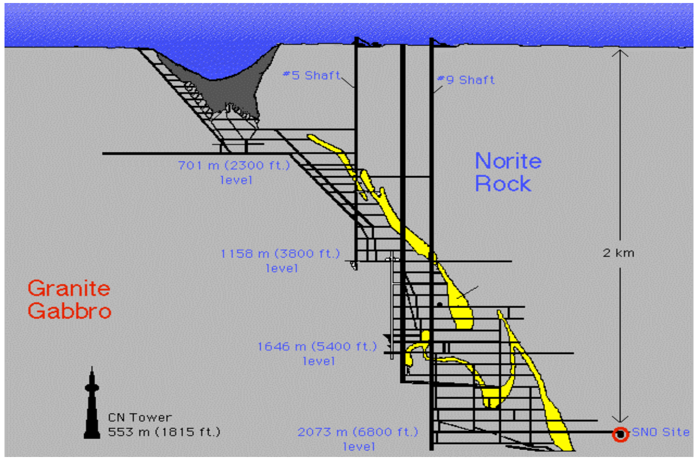
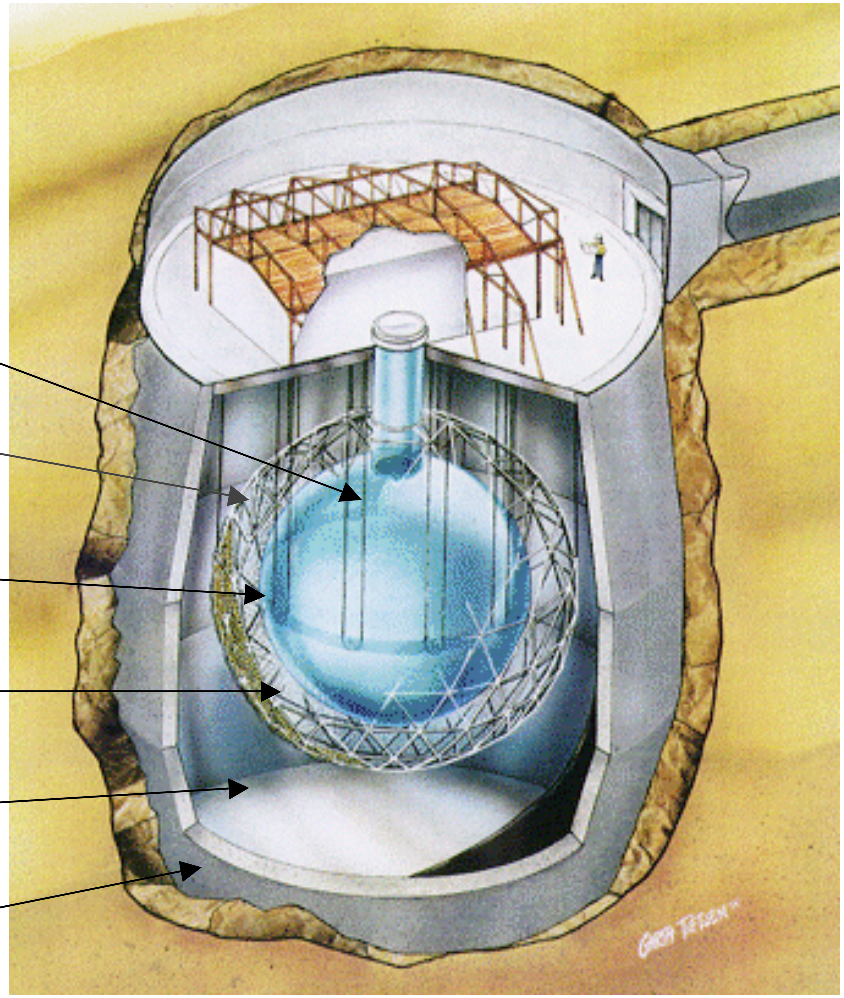
Present and future of SNO: SNO, SNO+ and SNOLAB

Aksel Hallin,Queen's University
for the SNO Collaboration
NDM, Paris, September 2006

Sudbury Neutrino Observatory





ν Reactions in SNO

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

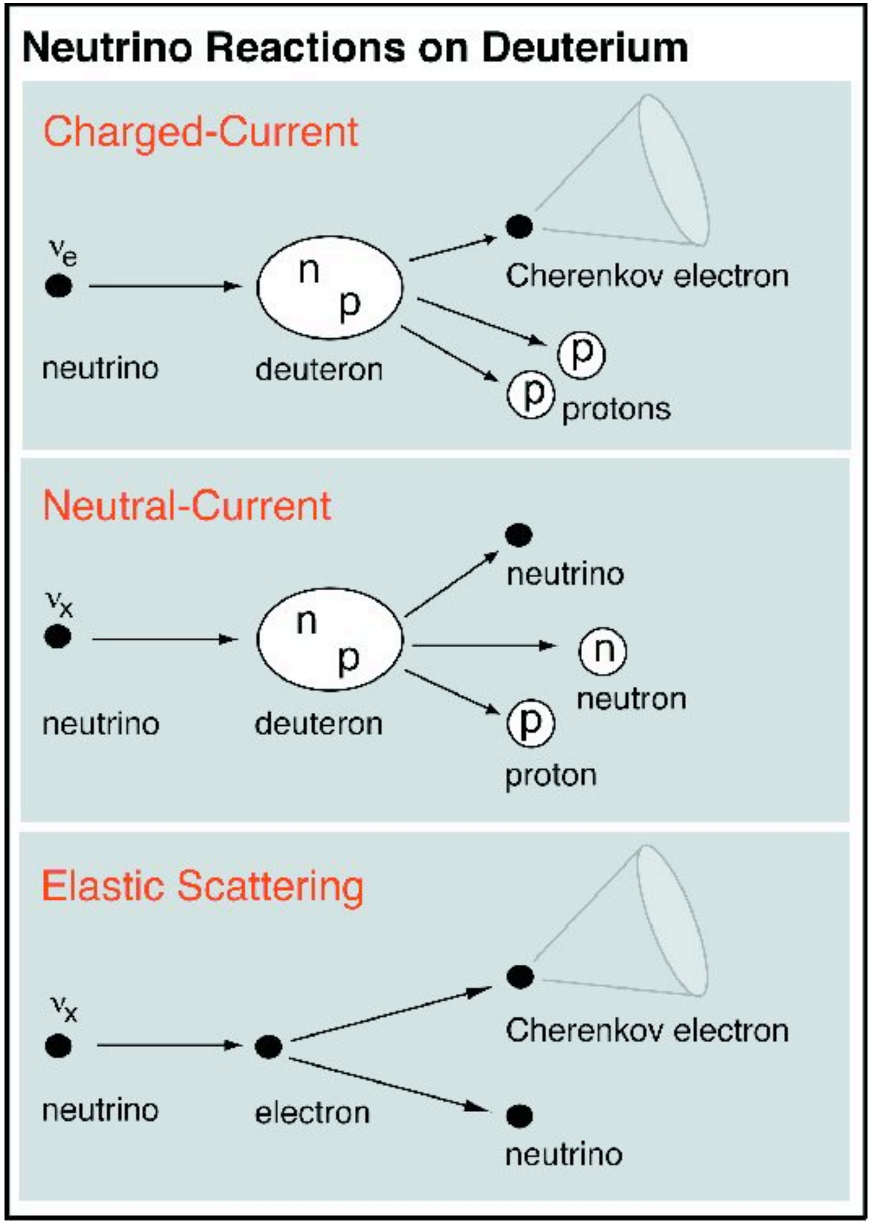
-Gives ν_e energy spectrum well
-Weak direction sensitivity $\propto$ 1-1/3cos(θ)
- ν_e only.

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

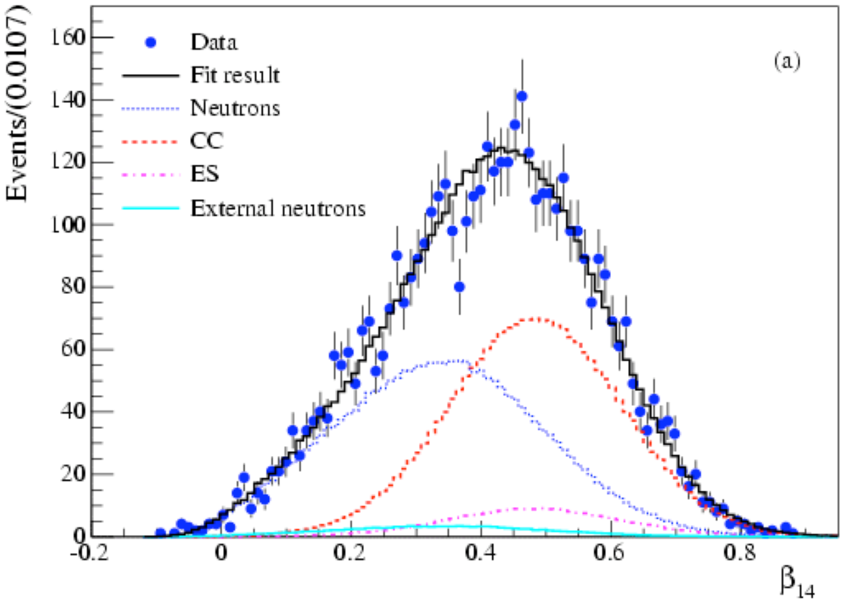
-Measure total ^8B ν flux from the sun.
- Equal cross section for all ν types

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

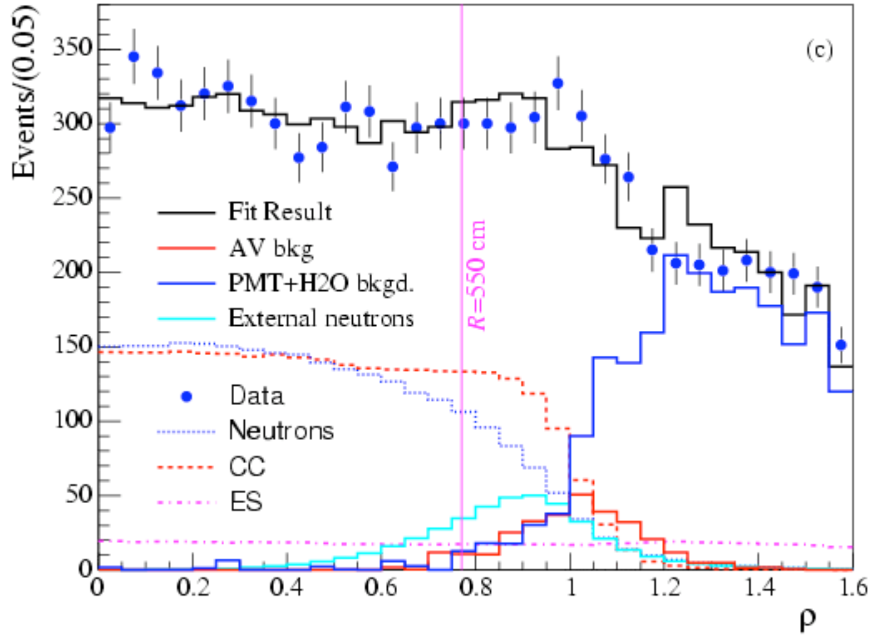
-Low Statistics
-Mainly sensitive to $\nu_{e,}$, some
-sensitivity to ν_μ and ν_τ
-Strong direction sensitivity



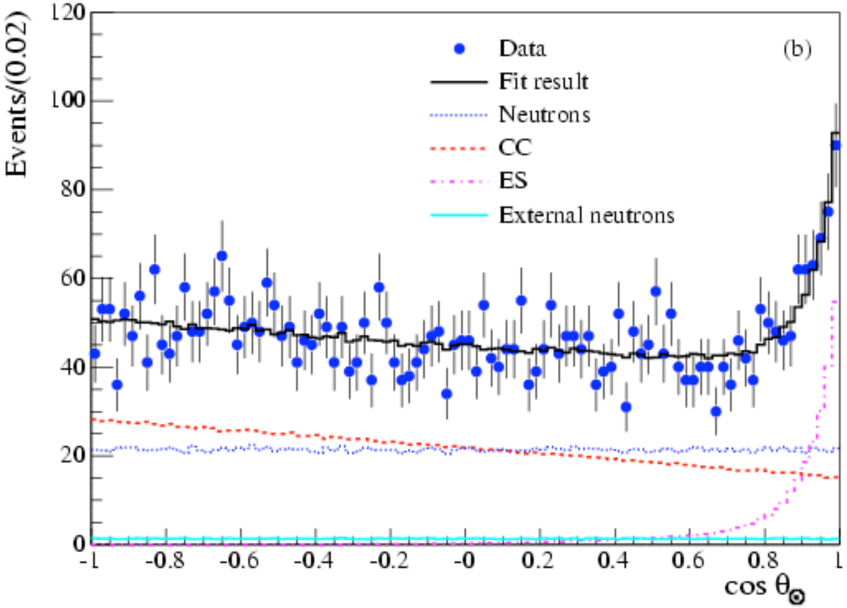
ISOTROPY: NC, CC separation



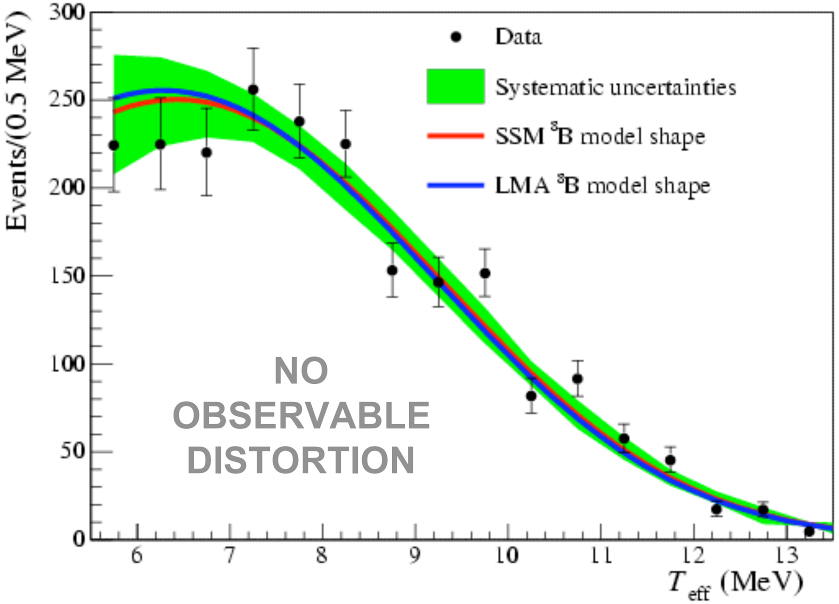
EVENTS VS VOLUME: Bkg < 10%

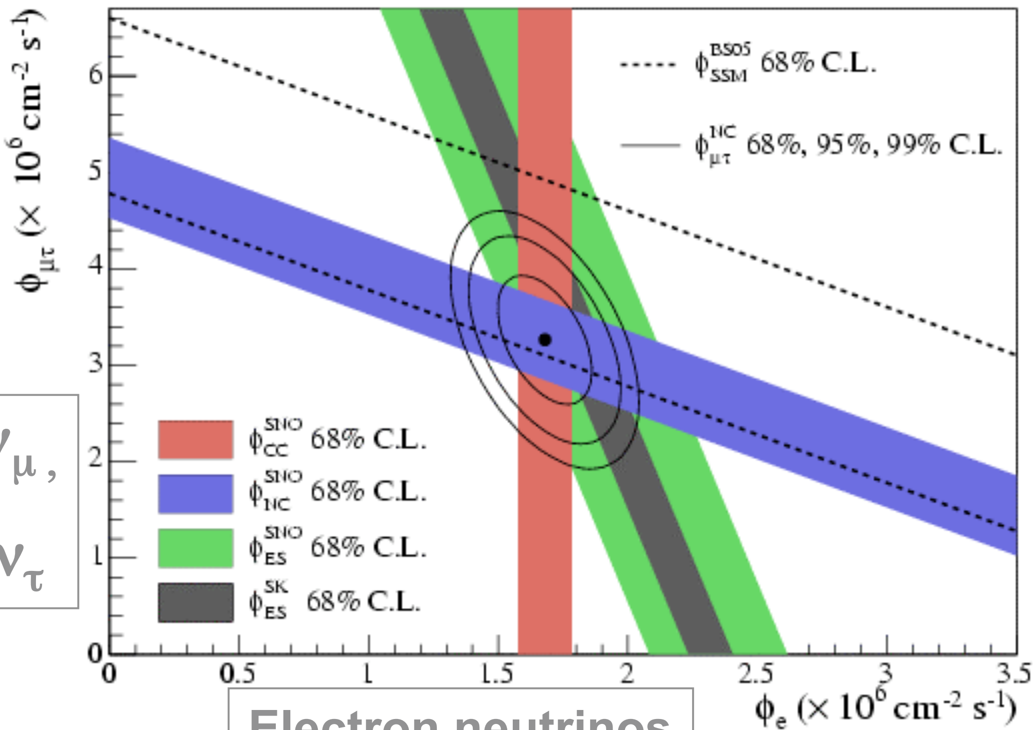


DIRECTION FROM SUN



ENERGY SPECTRUM FROM CC REACTION





ν_μ, ν_τ

Electron neutrinos

CC, NC FLUXES MEASURED INDEPENDENTLY

$$\phi_{CC} = 1.68\ ^{+0.06}_{-0.06}(\text{stat.})^{+0.08}_{-0.09}(\text{syst.})$$

$$\phi_{NC} = 4.94\ ^{+0.21}_{-0.21}(\text{stat.})^{+0.38}_{-0.34}(\text{syst.})$$

$$\phi_{ES} = 2.35\ ^{+0.22}_{-0.22}(\text{stat.})^{+0.15}_{-0.15}(\text{syst.})$$

(In units of $10^6\,\text{cm}^{-2}\text{s}^{-1}$)

The Total Flux of Active Neutrinos is measured independently (NC) and agrees well with solar model Calculations:

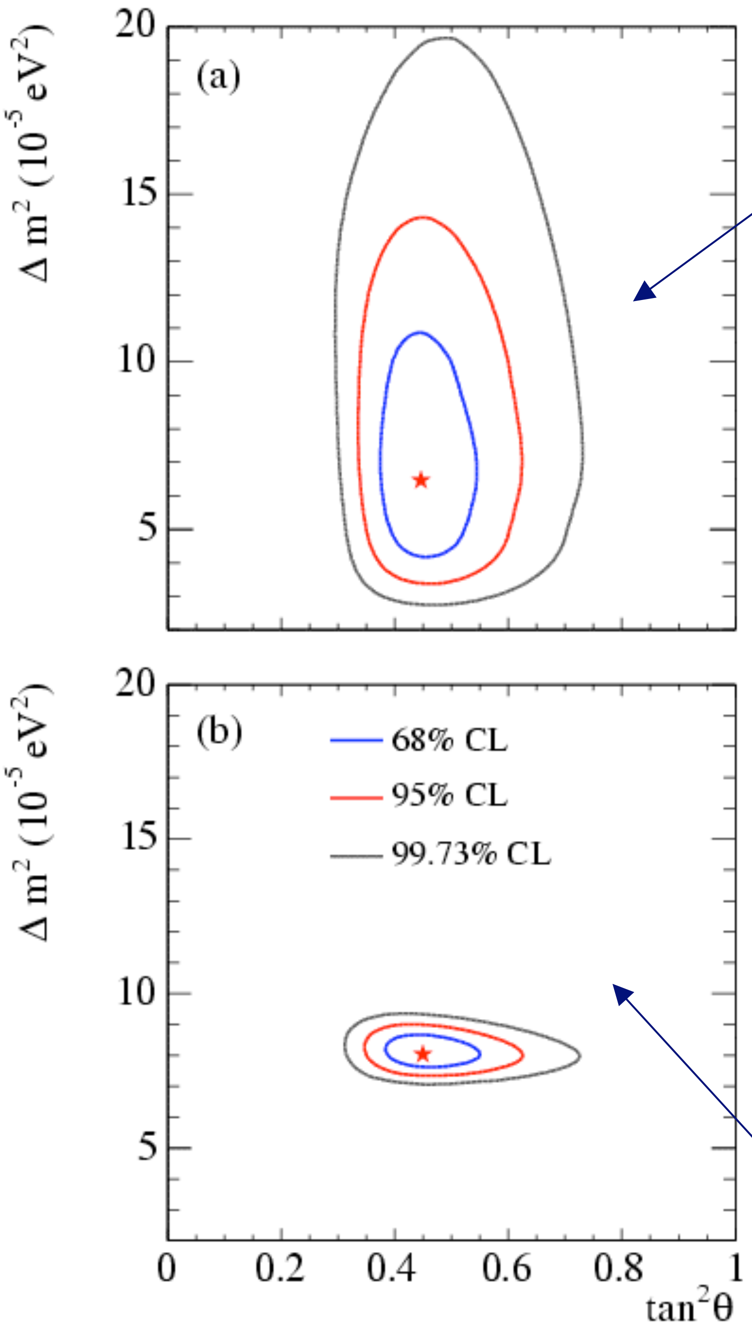
5.82 +- 1.3 (Bahcall et al),

5.31 +- 0.6 (Turck-Chieze et al)

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.34 \pm 0.023(\text{stat.})^{+0.029}_{-0.031} \approx \sin^2\theta_{12}$$

Improved accuracy for θ_{12}.

Flavor change is determined with > 7 σ



SOLAR ONLY AFTER NEW SNO SALT DATA

Large mixing Angle (LMA) region

- The solar results define the mass hierarchy ($m_2 > m_1$) through the Matter interaction (MSW)

- SNO: CC/NC flux defines $\tan^2\theta < 1$ (ie Non - Maximal mixing) by more than 5 standard deviations

LMA prediction for solar ν is for very small spectral distortion, small (~ 3 %) day-night asymmetry, as observed by SNO

SOLAR PLUS KAMLAND (assuming CPT) (Reactor $\bar{\nu}$'s)

Expect significant improvement with NCDs and combined results

HEP/DSNB Limits

$\phi < 2.3 \times 10^{4}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (90% CL) HEP (improved by 6.5)

$\phi < 70\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (90% CL) DSNB

Astrophysical Journal, 2006

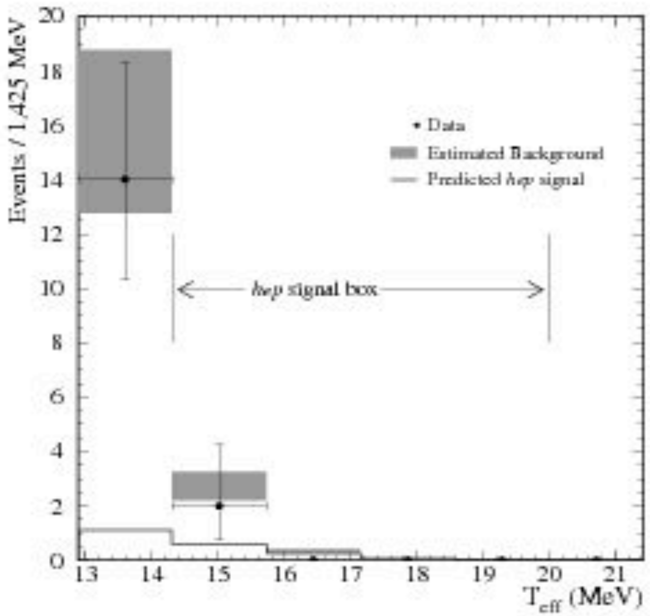


Fig. 5.— The distribution of events in the region of the ^{8}B endpoint. There are two events in the *hep* signal box 14.3 MeV $< T_{\mathrm{eff}} <$ 20 MeV. Also shown are the estimated number of background events, including the systematic uncertainty, and the standard solar model prediction for the *hep* signal.

Also, “Long D_2O paper” on way

SNO Phase III (NCD Phase)

- ^{3}He Proportional Counters ("NC Detectors")

  40 Strings on 1-m grid

  440 m total active length

Detection Principle

$$^{2}H + \nu_x \rightarrow p + n + \nu_x - 2.22\ \mathrm{MeV} \qquad \text{(NC)}$$

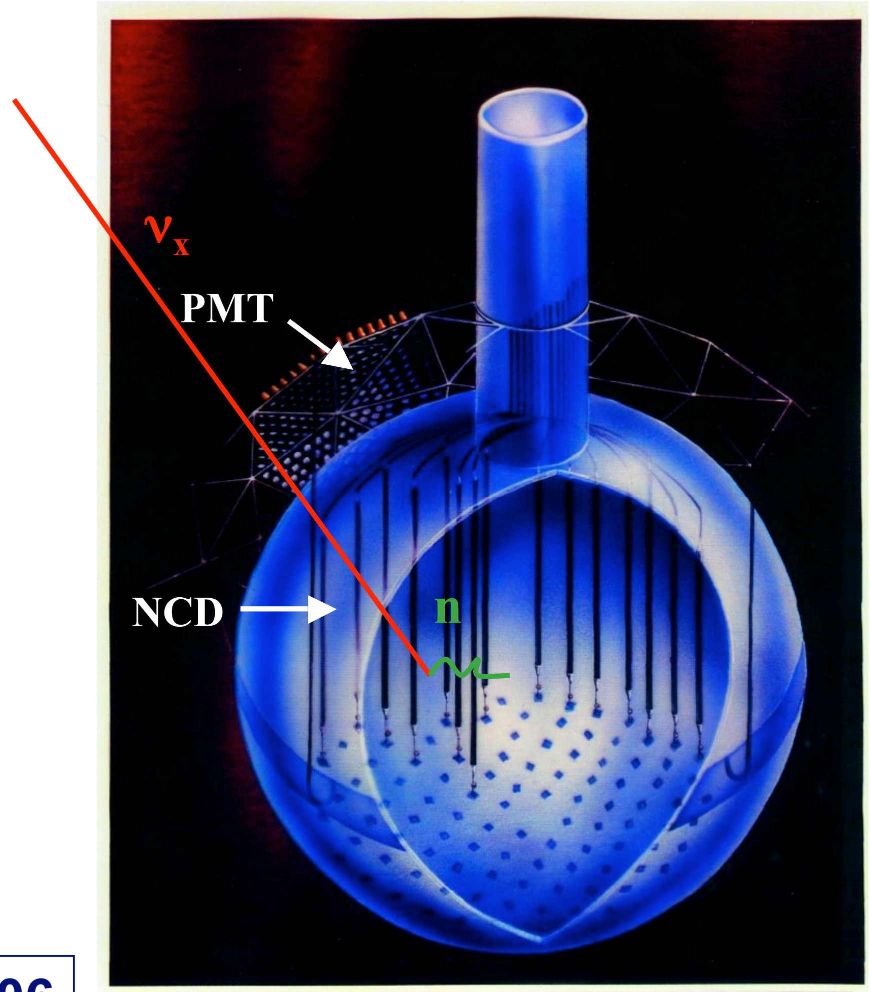
$$^{3}He + n \rightarrow p + {}^{3}H + 0.76\ \mathrm{MeV}$$

Physics Motivation

Event-by-event separation. Measure NC and CC in separate data streams.

Different systematic uncertainties than neutron capture on NaCl.

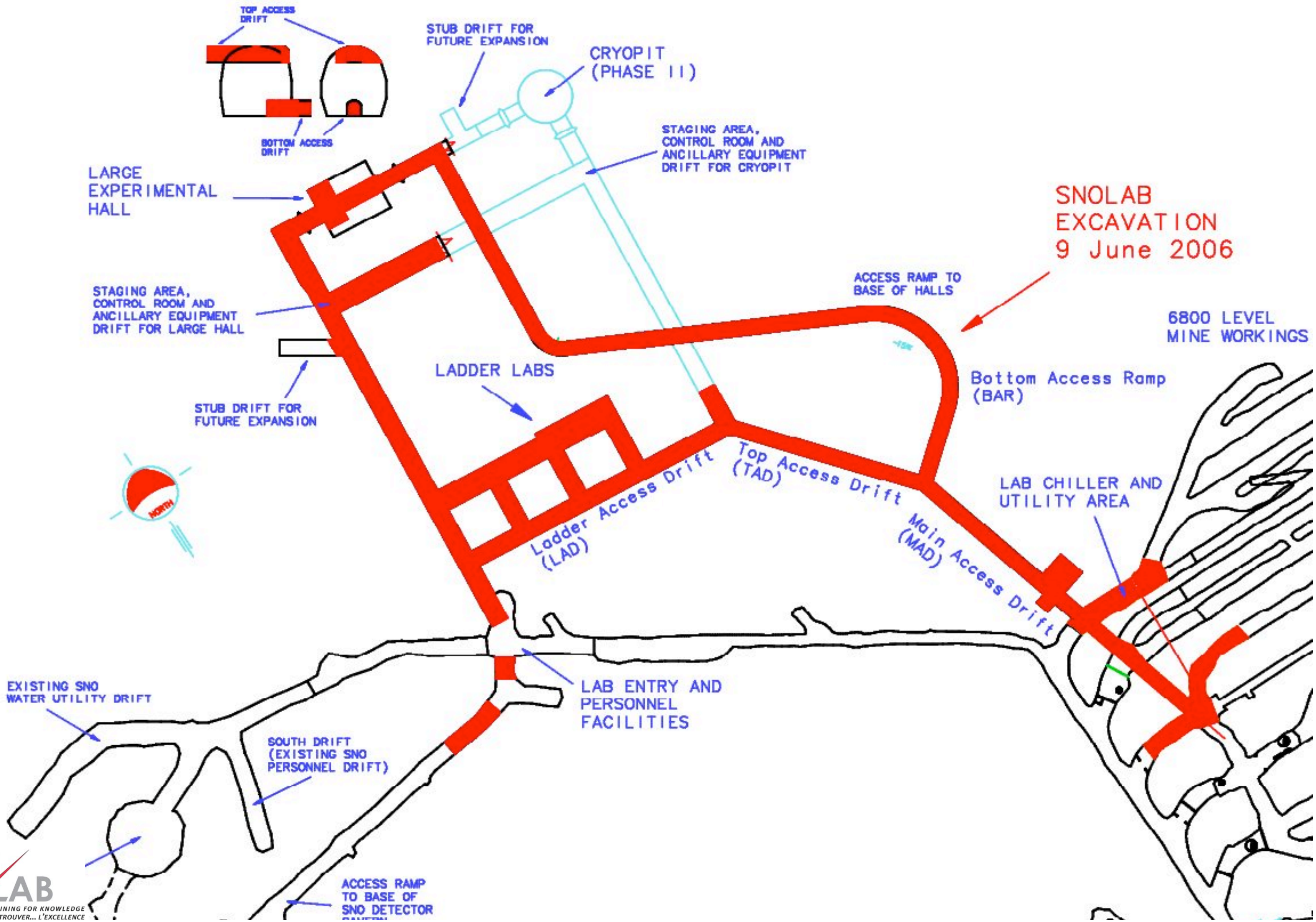
NCD array removes neutrons from CC, calibrates remainder. CC spectral shape.



Production Data: Nov. 2004 – Nov. 2006

Underground Facilities

SNOLAB Excavation Status

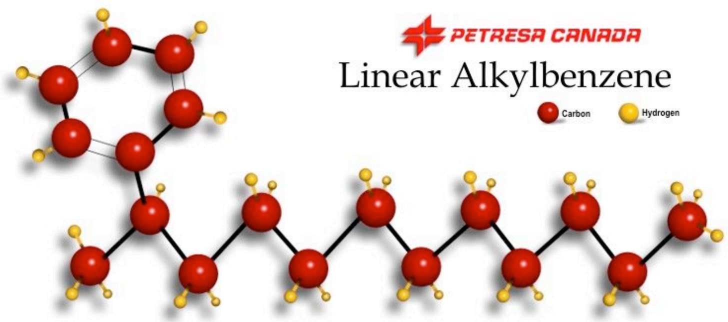


SNOLAB
Mining for knowledge
Creuser pour trouver... l'excellence

SNO+: SNO + Liquid Scintillator

Uses investment in SNO to build large multipurpose low background detector

- Double beta decay
- Low energy neutrino oscillations
- Precision solar neutrino measurement
- Geoneutrinos
- Reactor antineutrino oscillation measurement
- Active veto for large future dark matter or double beta decay measurements
- Supernova detector
- Large detector for ultrasensitive radiopurity measurements.



SNO+ Collaboration

Queen's
M. Chen, M. Boulay, X. Dai, E. Guillian, A. Hallin, P. Harvey, C. Hearns, C. Kraus, C. Lan, A. McDonald, V. Novikov, S. Quirk, P. Skensved, A. Wright, U. Bissbort

Carleton
K. Graham

Laurentian
D. Hallman, C. Virtue

Trent
J. Jury

SNOLAB
B. Cleveland, F. Duncan, R. Ford, I. Lawson

Brookhaven National Lab
D. Hahn, M. Yeh, A. Garnov,

Idaho State University
K. Keeter

University of Texas at Austin
J. Klein

University of Pennsylvania
G. Beier (for Nd double beta decay)

LIP Lisbon
J. Maneira, N. Barros, S. Andringa

Technical University Munich
L. Oberauer, F. v. Feilitzsch (for Nd double beta decay)

Sussex
K. Zuber

a subset of the SNO collaboration will continue with SNO+

- potential collaborators from outside SNO (Italy, Russia) have indicated some interest

Double Beta Decay: SNO++

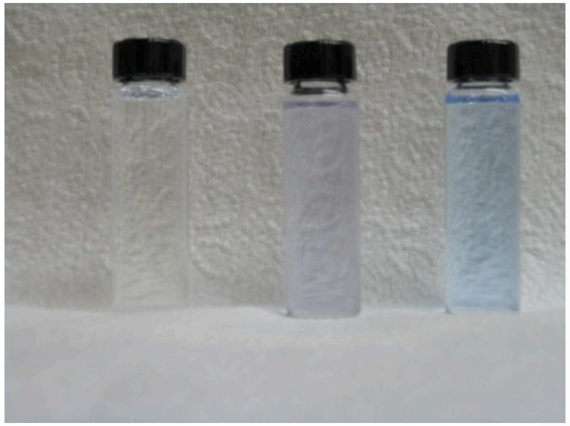
- SNO plus liquid scintillator plus double beta isotopes: SNO++
- add $\beta\beta$ isotopes to liquid scintillator
  - dissolved Xe gas (2%)
  - organometallic chemical loading (Nd, Se, Te)
  - dispersion of nanoparticles (Nd_2O_3, TeO_2)

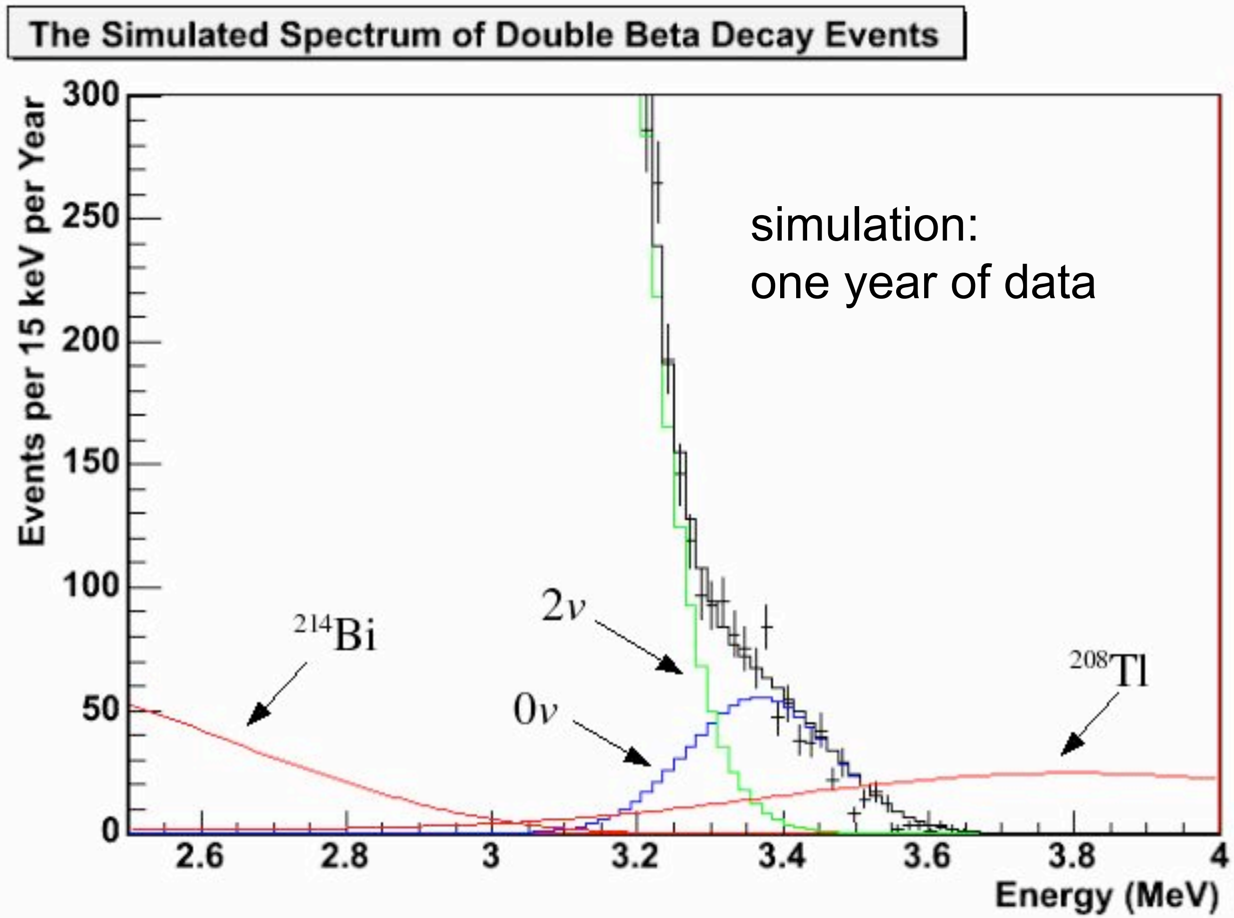
- enormous quantities (high statistics) and low backgrounds help compensate for the poor energy resolution of liquid scintillator
- possibly source in–source out capability

Test $<m_\nu> = 0.4$ 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++

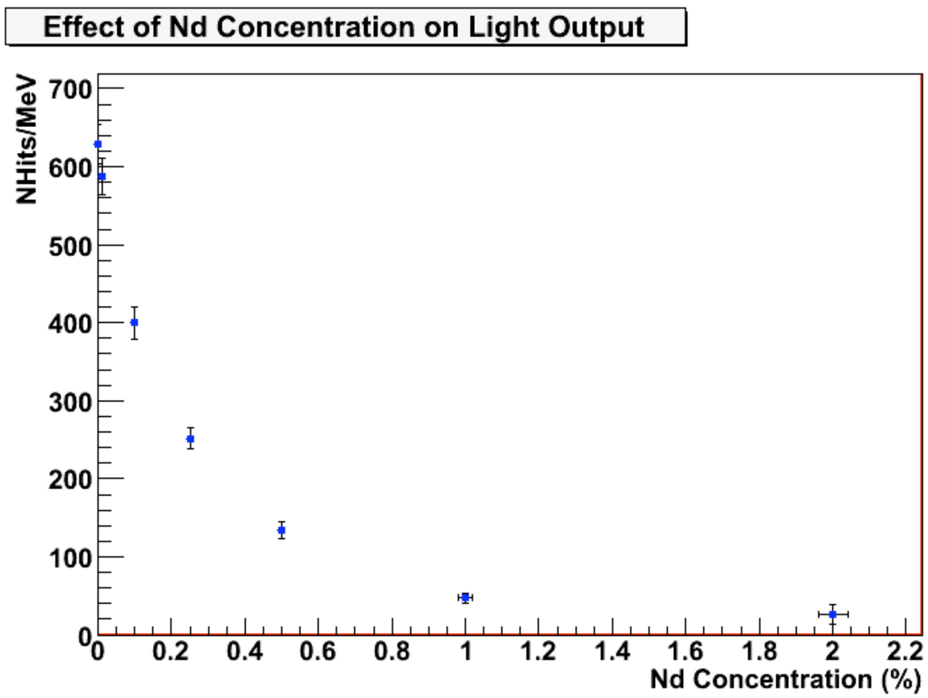




maximum likelihood statistical test of the shape to extract 0ν and 2ν components…~240 units of $\Delta\chi^2$ significance after only 1 year!

Enriched Nd Scintillator

- 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



SNO++ Double Beta Sensitivity

- insensitive to internal radon backgrounds
- insensitive to external backgrounds (2.6 MeV gamma)
- internal Th is the main concern
  - and 2ν background, of course
- homogeneous, well defined background model
- for m_ν = 50 meV, 0ν signal is ~60 events/yr in the upper-half of the peak, with S:B about 1:1
  - based upon KamLAND Th levels in scintillator and known 2ν double beta decay backgrounds
  - gives a 5σ exclusion of 50 meV after one year
- …shows the advantage of huge amounts of isotope, thus high statistics

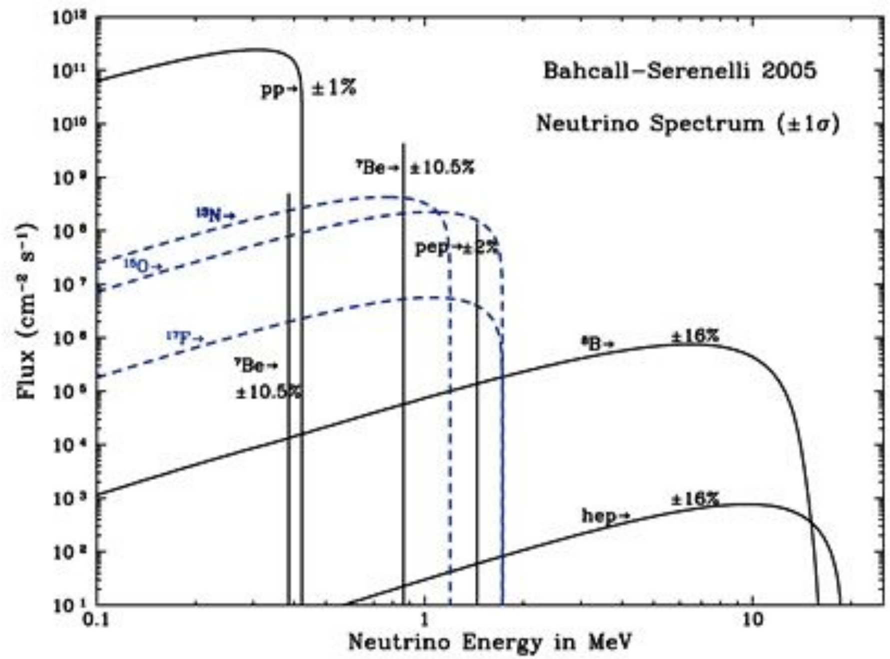
Nd-150 Consortium

- SuperNEMO and SNO+, MOON and DCBA have joined together to try 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 (to 2.5% from 0.7%) in several hundred hours (i.e. about 1 week)

Low Energy Solar Neutrinos

- complete our understanding of neutrinos from the Sun

  pep, CNO, ^{7}Be



p-p Solar Fusion Chain

$p + p \rightarrow {}^2H + e^+ + \nu_e$ $\quad$ $p + e^- + p \rightarrow {}^2H + \nu_e$

$^2H + p \rightarrow {}^3He + \gamma$

$^3He + {}^3He \rightarrow {}^4He + 2\,p$ $\quad$ $^3He + p \rightarrow {}^4He + e^+ + \nu_e$

$^3He + {}^4He \rightarrow {}^7Be + \gamma$

$^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e$ $\quad$ $^7Be + p \rightarrow {}^8B + \gamma$

$^7Li + p \rightarrow \alpha + \alpha$ $\quad$ $^8B \rightarrow 2\,\alpha + e^+ + \nu_e$

CNO Cycle

$^{12}C + p \rightarrow {}^{13}N + \gamma$ $\quad$ $^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$

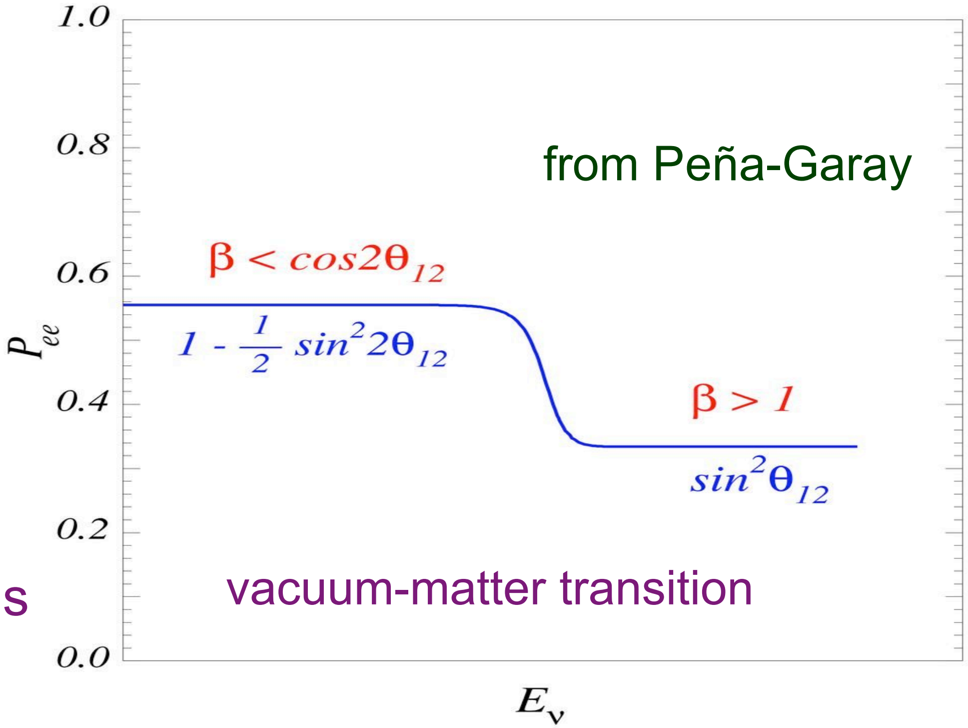
$^{13}C + p \rightarrow {}^{14}N + \gamma$

$^{14}N + p \rightarrow {}^{15}O + \gamma$ $\quad$ $^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$

$^{15}N + p \rightarrow {}^{12}C + \alpha$

Neutrino-Matter Interaction

- best-fit oscillation parameters suggest MSW occurs
- but we have no direct evidence of MSW
  - day-night effect not observed
  - no spectral distortion for ^8B ν's
- testing the vacuum-matter transition is sensitive to new physics



for $\Delta m^2 = 8 \times 10^{-5}$ eV^2, $\theta = 34°$
N_e at the centre of the Sun →
E is 1-2 MeV

$$\begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}$$

Survival Probability Rise

SSM pep flux:

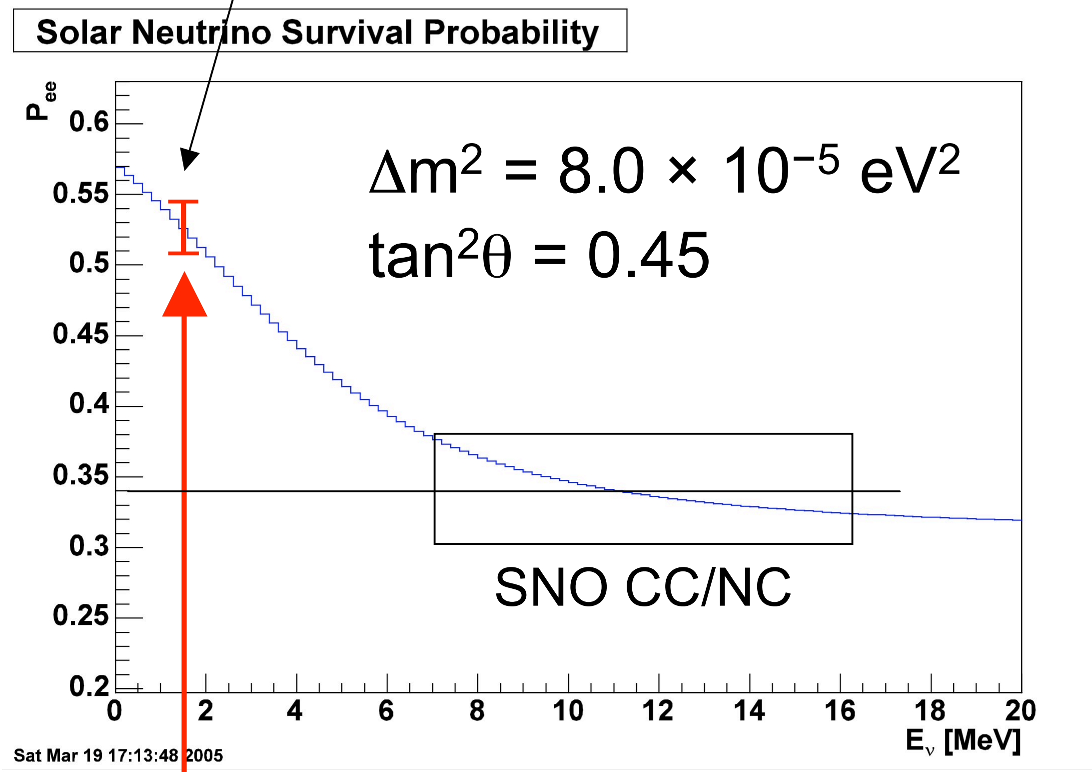
uncertainty ±1.5%

known source → precision test

improves precision on θ_{12}
solar Δm^2 measurement

sensitive to new physics:
- non-standard interactions
- solar density perturbations
- mass-varying neutrinos
- CPT violation
- large θ_{13}
- sterile neutrino admixture

stat + syst + SSM errors estimated



pep ν

observing the rise confirms MSW and that we know what's going on

New Physics

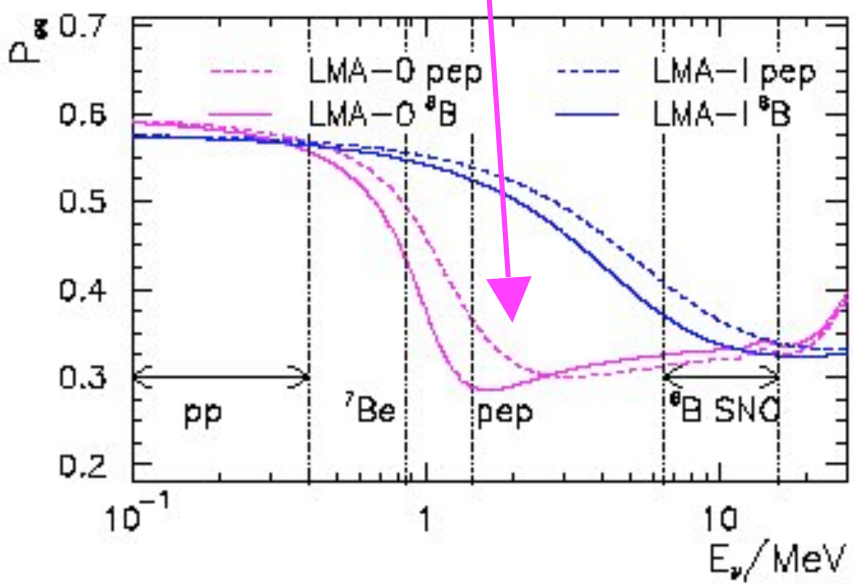
$$L^{NSI} = -2\sqrt{2}G_F(\bar{\nu}_\alpha \gamma_\rho \nu_\beta)(\epsilon_{\alpha\beta}^{f\tilde{f}L}\bar{f}_L\gamma^\rho \tilde{f}_L + \epsilon_{\alpha\beta}^{f\tilde{f}R}\bar{f}_R\gamma^\rho \tilde{f}_R) + h.c. \quad (1)$$

NC non-standard Lagrangian

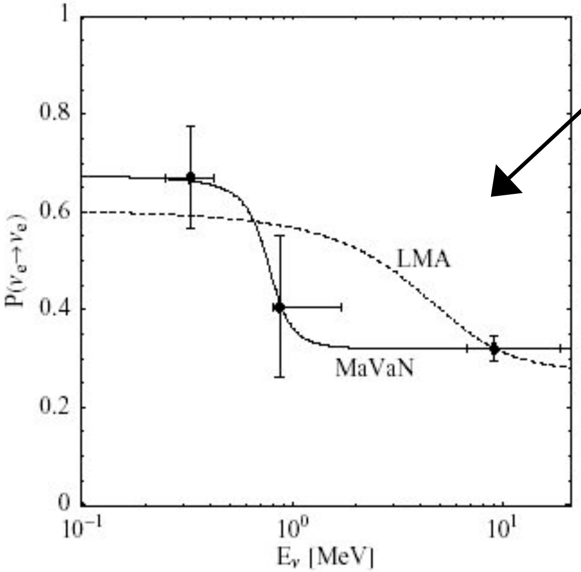
$\epsilon_{12} = -2\,\epsilon_{e\tau}\sin\theta_{23} = -0.25$ $\quad |\varepsilon_{\tau e}^{dP}| < 0.5$

CHARM limit

- non-standard interactions
- MSW is linear in G_F and limits from ν-scattering experiments $\propto g^2$ aren't that restrictive
- mass-varying neutrinos



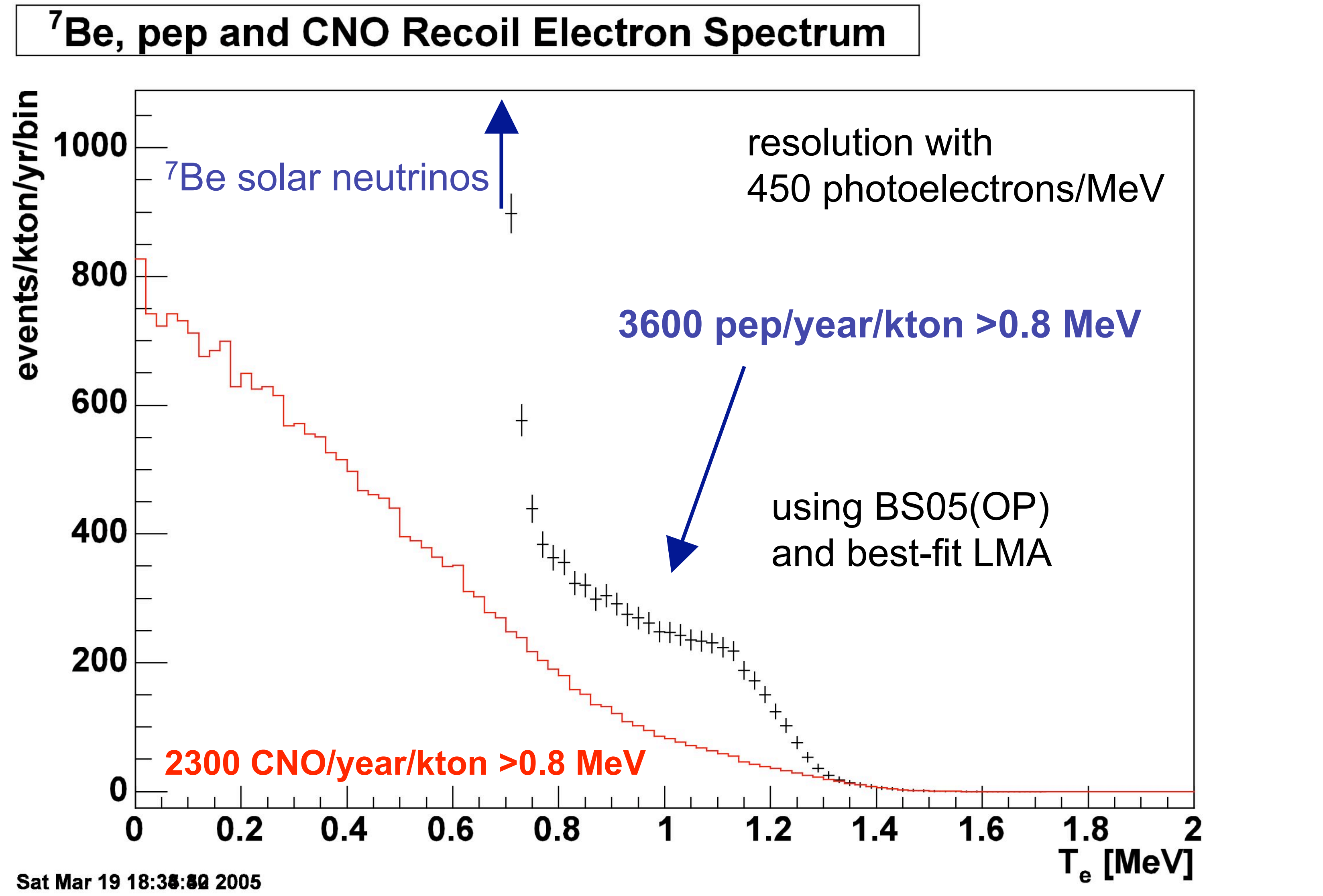
Friedland, Lunardini, Peña-Garay, hep-ph/0402266



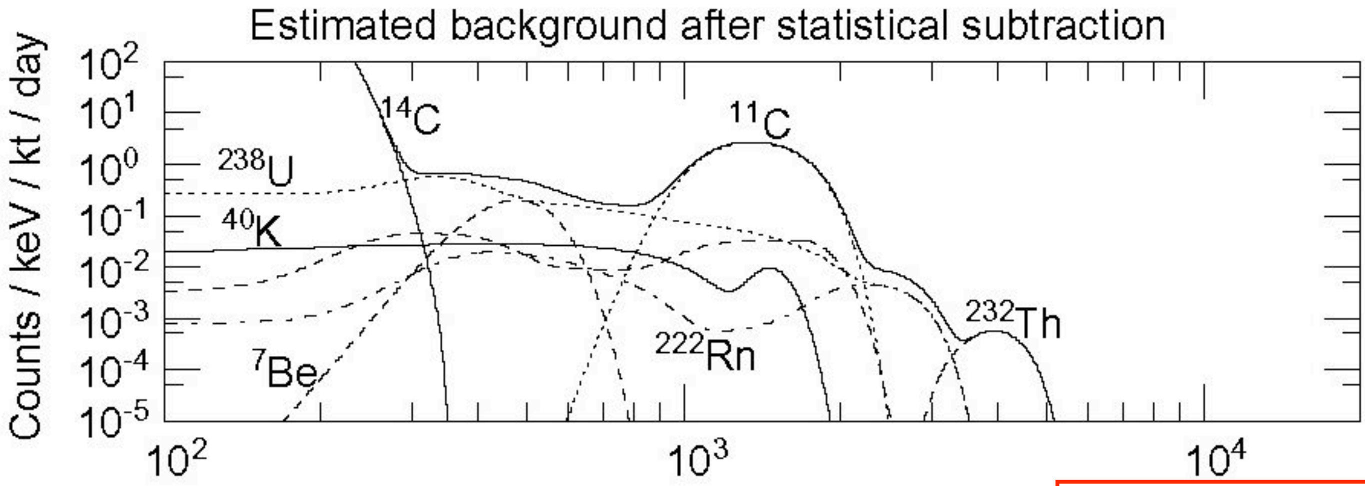
pep solar neutrinos are at the "sweet spot" to test for new physics

Barger, Huber, Marfatia, hep-ph/0502196

Event Rates (Oscillated)

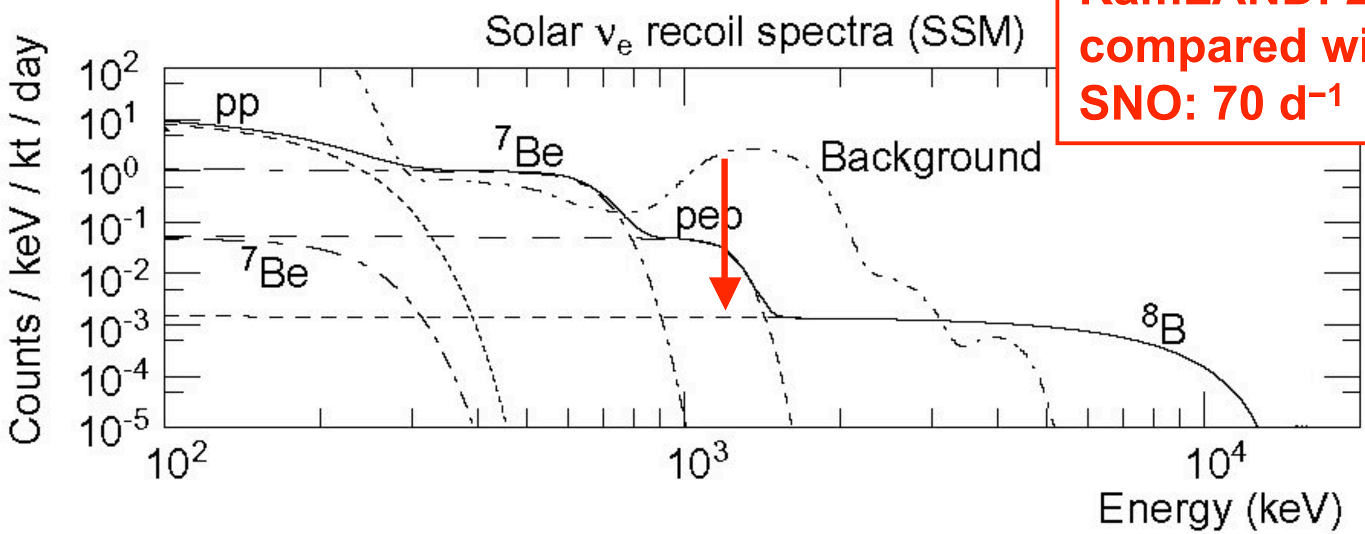


^{11}C Cosmogenic Background



these plots from the KamLAND proposal

muon rate in KamLAND: 26,000 d^{-1} compared with SNO: 70 d^{-1}



SNO+ solar summary

SNOLAB is a deep site where the *pep* solar neutrinos could be measured *with precision*

pep solar neutrinos are *sensitive to new physics* affecting neutrino propagation in matter

first observation of the CNO solar neutrinos would be important for astrophysics

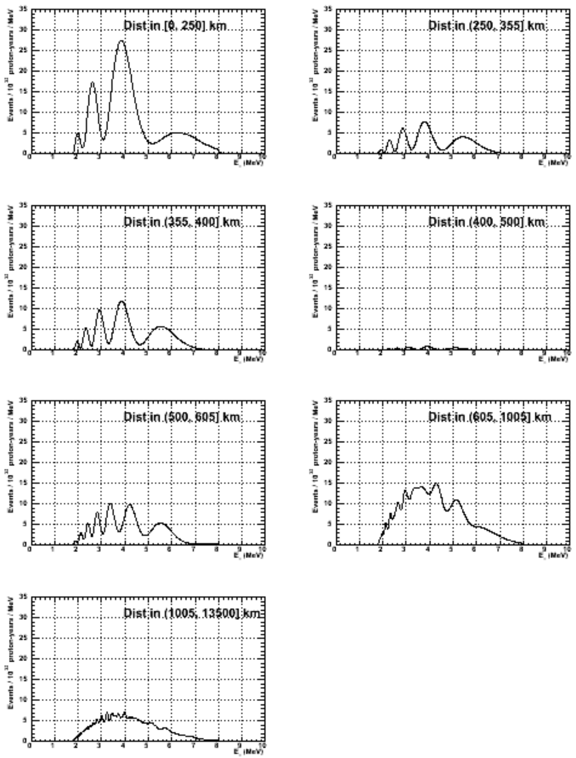
Reactor Antineutrinos

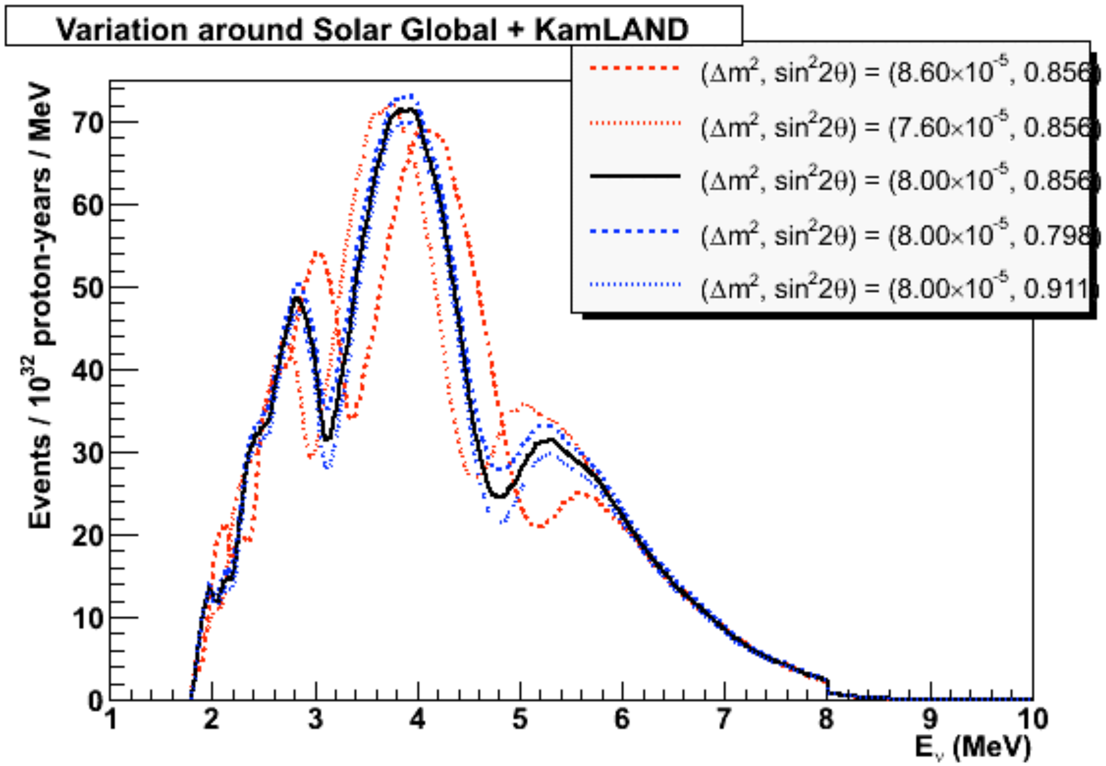
- SNO+ can confirm reactor neutrino oscillations
- an interesting test!
  - move KamLAND’s spectral distortion to higher energies by going to a slightly longer baseline

Reactor Oscillations

antineutrino events: $\bar{\nu}_e + p \rightarrow e^+ + n$

Kamland: 850 events/10^{32} proton-years
SNO: 180 events/10^{32} proton-years





Baselines: 240 and 340 km

Geo-Neutrinos

- can we detect the antineutrinos produced by natural radioactivity in the Earth?

radioactive decay of heavy elements (uranium, thorium) produces antineutrinos

$\bar{\nu}_e$

assay the entire Earth by looking at its "neutrino glow"

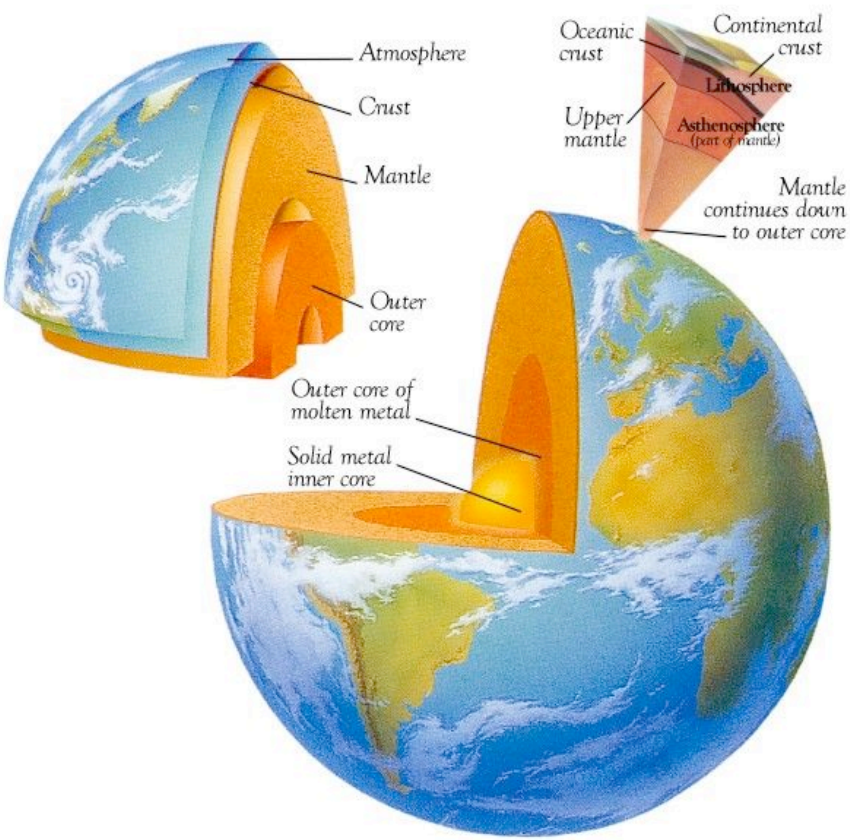
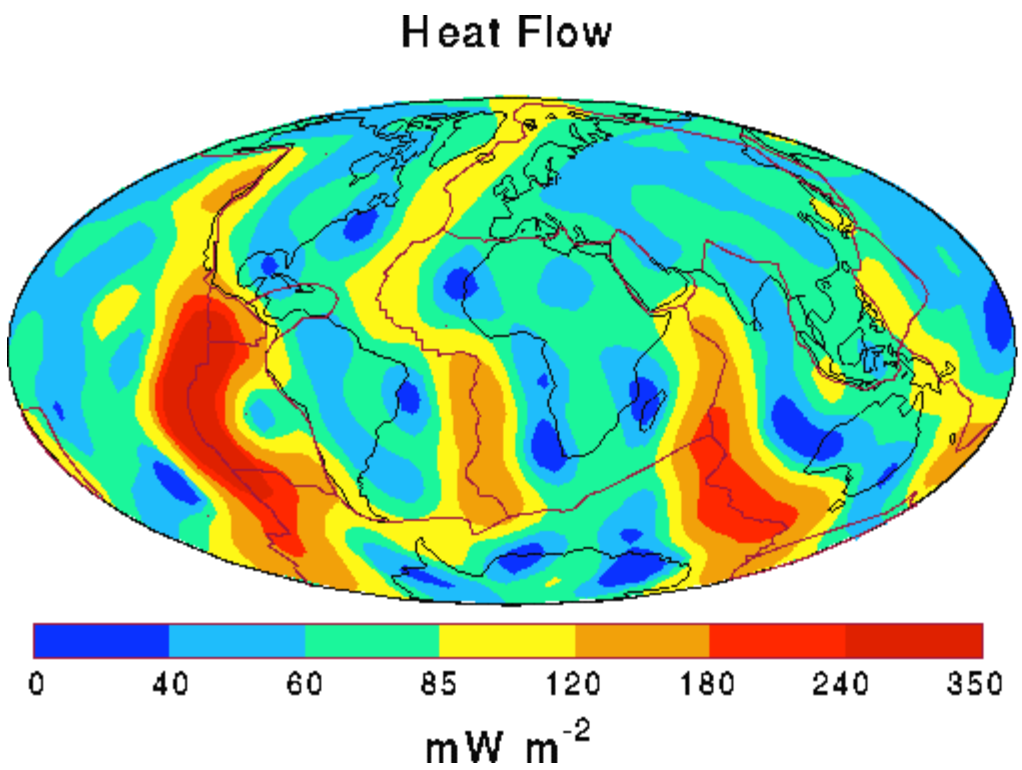


Image by: Colin Rose, Dorling Kindersley

Earth's Heat Flow

- models of Earth's heat sources suggest that radioactivity contributes 40-100% towards Earth's total heat flow



the radiogenic portion is not that well known!

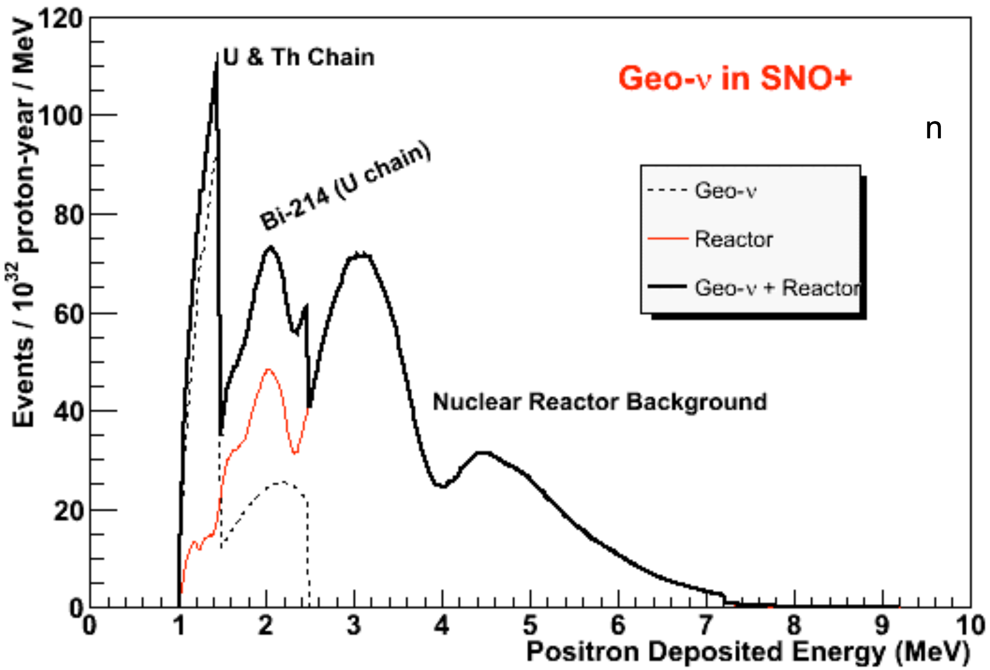
geophysicists want to understand Earth's thermal history

H.N. Pollack, S.J. Hurter and J.R. Johnson, *Reviews of Geophysics* **31**(3), 267-280, 1993

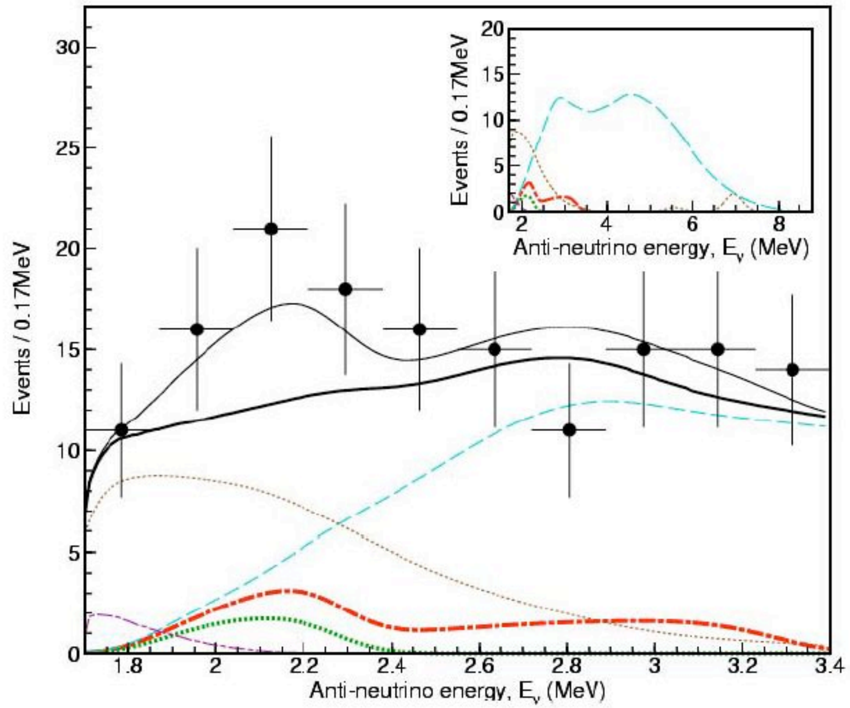
Geo-Neutrino Signal

antineutrino events $\overline{\nu}_e + p \rightarrow e^+ + n$:

- KamLAND: 33 events per year (1000 tons CH_2) / 142 events reactor
- SNO+: 44 events per year (1000 tons CH_2) / 38 events reactor

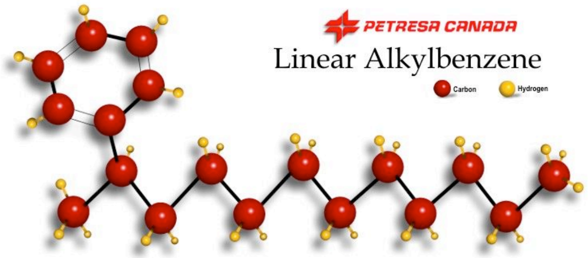


SNO+ geo-neutrinos and reactor background



<u>KamLAND</u> geo-neutrino detection…July 28, 2005 in Nature

SNO+ Technical Progress



- liquid scintillator identified
  - 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
    - low toxicity
    - smallest scattering of all scintillating solvents investigated
    - density ρ = 0.86 g/cm^3
  - SNO+ light output (photoelectrons/MeV) will be approximately 4× that of KamLAND

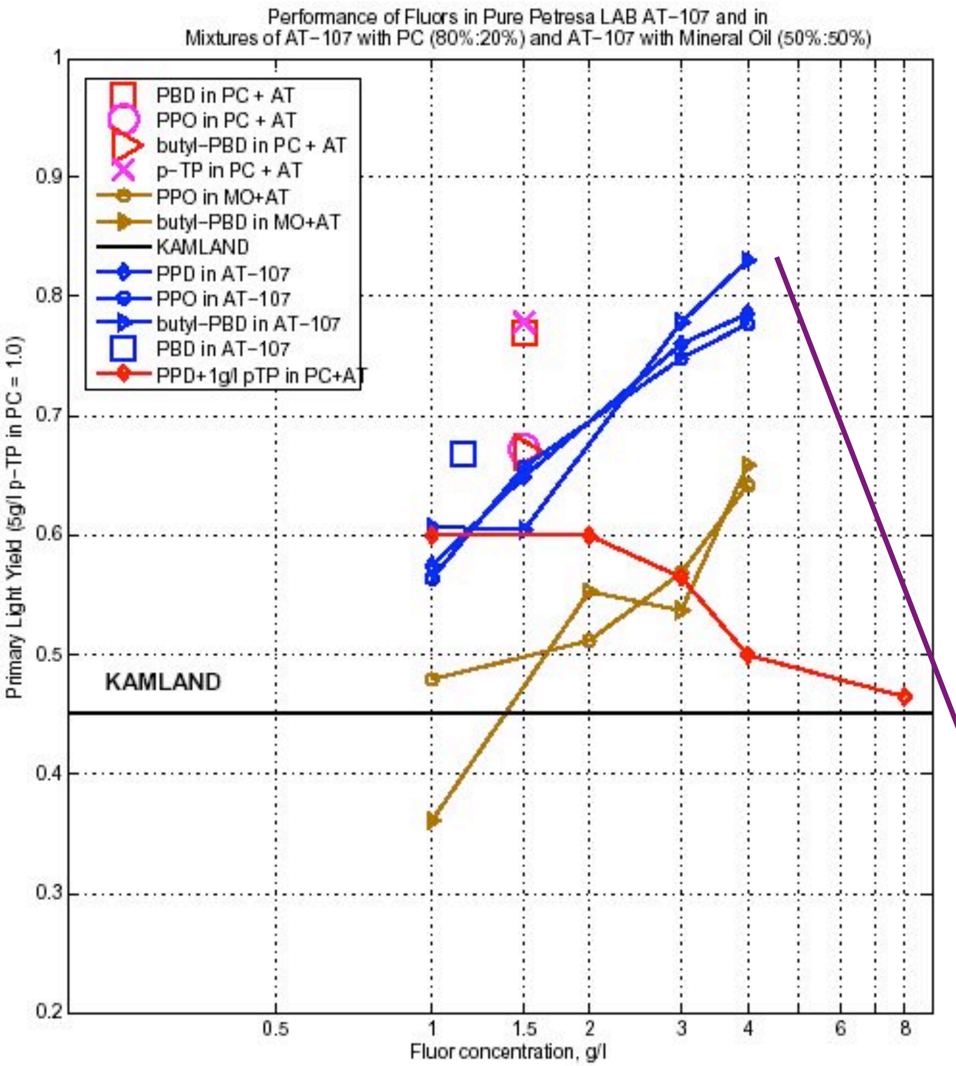
SNO+ Monte Carlo

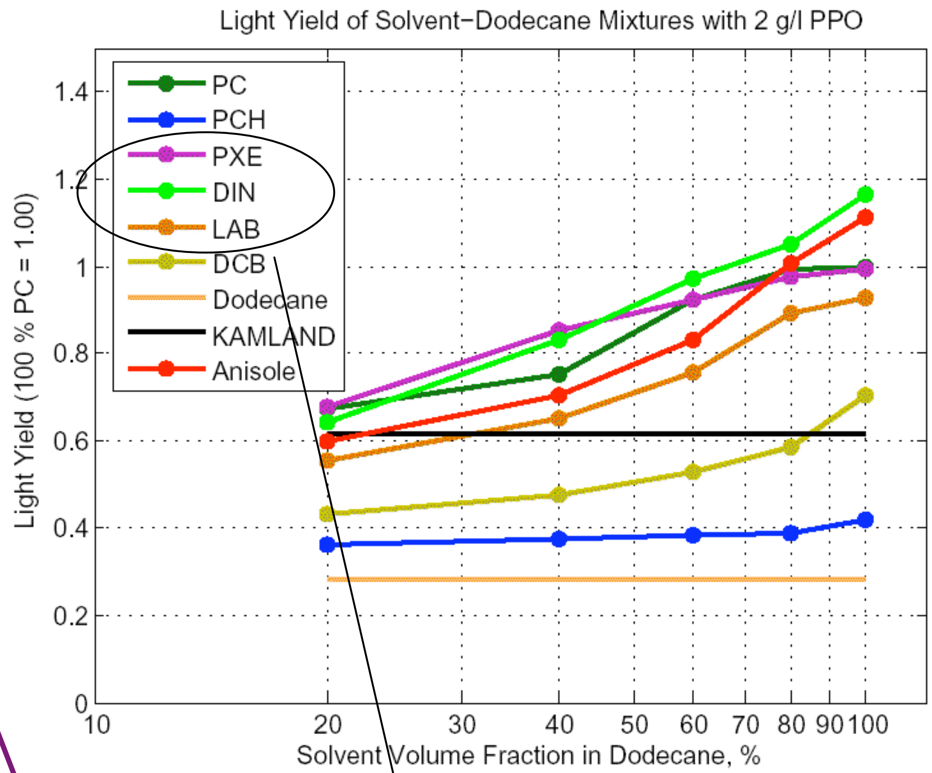
- light yield simulations

KamLAND scintillator in SNO+	629 ± 25 pe/MeV
above no acrylic	711 ± 27 pe/MeV
KamLAND scintillator and 50 mg/L bisMSB	826 ± 24 pe/MeV
above no acrylic	878 ± 29 pe/MeV
KamLAND (20% PC in dodecane, 1.52 g/L PPO)	~300 pe/MeV for 22% photocathode coverage

SNO+ has 54% PMT coverage; acrylic vessel only diminishes light ouput by ~10%

LAB Scintillator Optimization





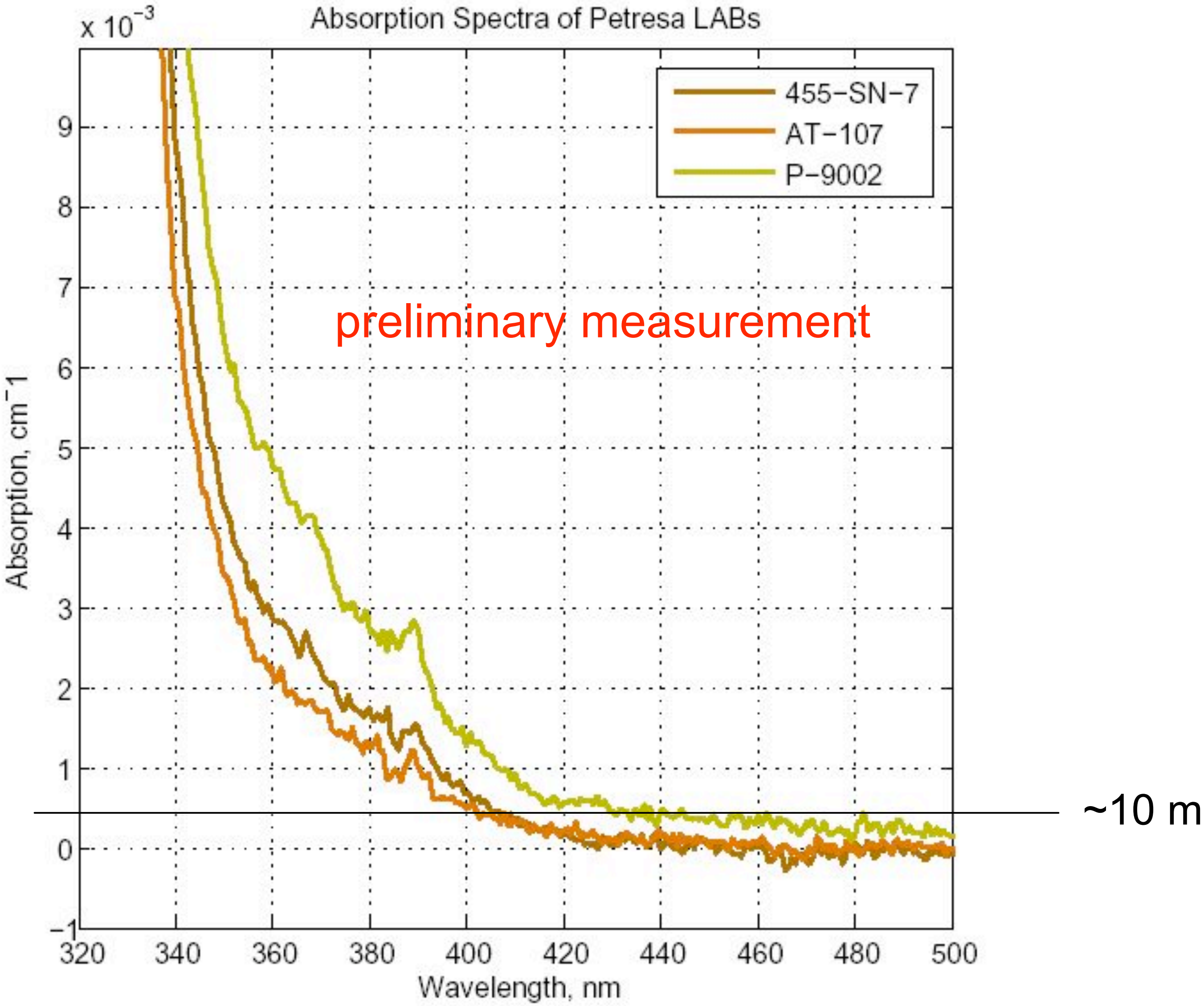
“safe” scintillators

LAB has 75% greater light yield than KamLAND scintillator

Light Attenuation Length

Petresa LAB as received

attenuation length exceeds 10 m

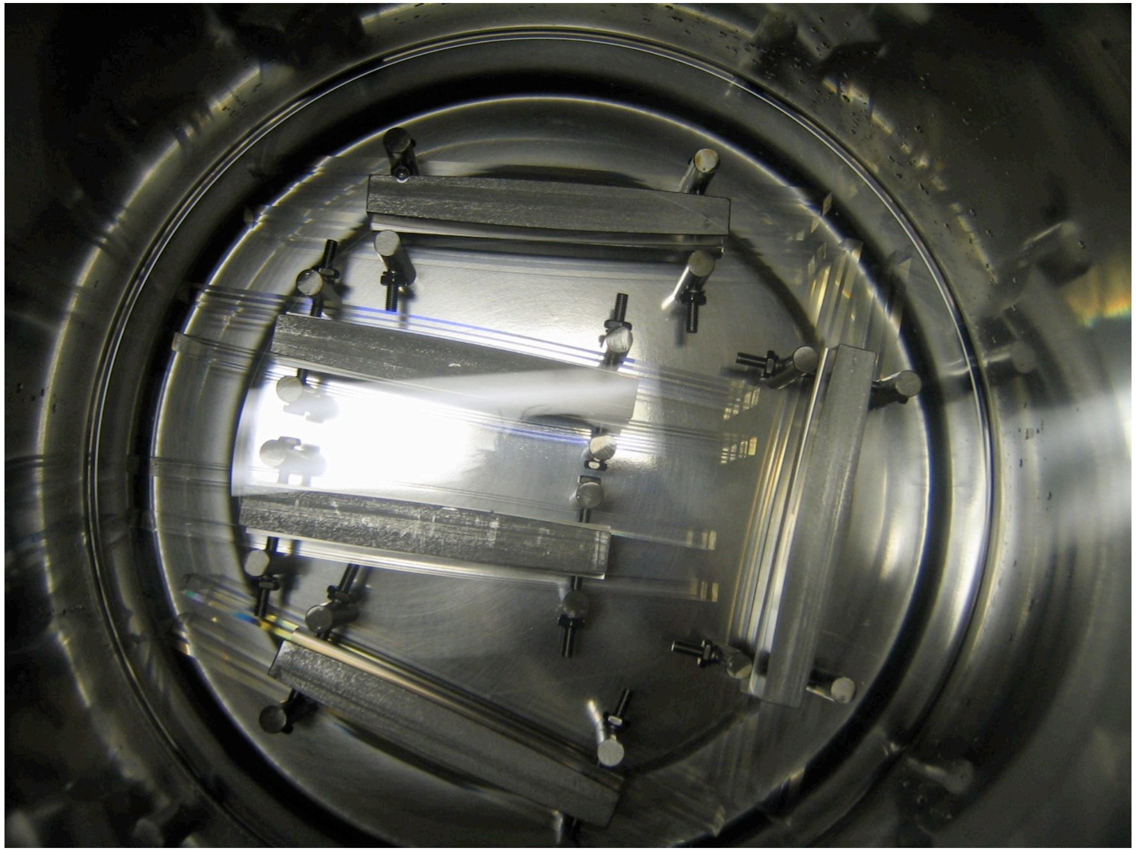


Scintillator Purification

- optical
  - at BNL and at Queen's
    - improves light attenuation length, removing impurities that absorb light, especially at lower wavelengths
  - alumina column and vacuum distillation both work
- radioactivity (e.g. ^{210}Pb)
  - at Queen's
    - alumina: 98-99% extraction efficiency
    - distillation: >99.9% extraction efficiency, single pass

Scintillator-Acrylic Compatibility

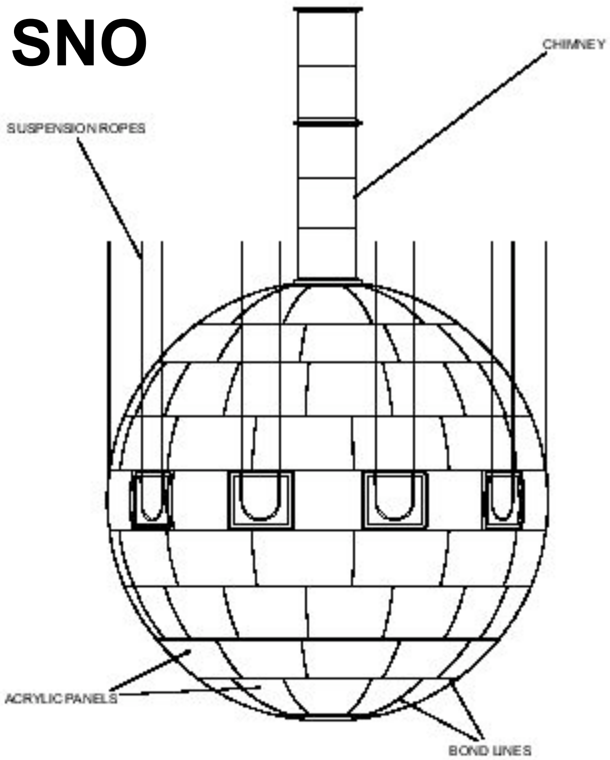
- ASTM D543 “Standard Practices for Evaluating the Resistance of Plastics to Chemical Reagents”



Acrylic Vessel Hold-down

- “rope net” being designed to hold down 15% density difference
- alternative: machine reverse rope grooves in existing belly plates

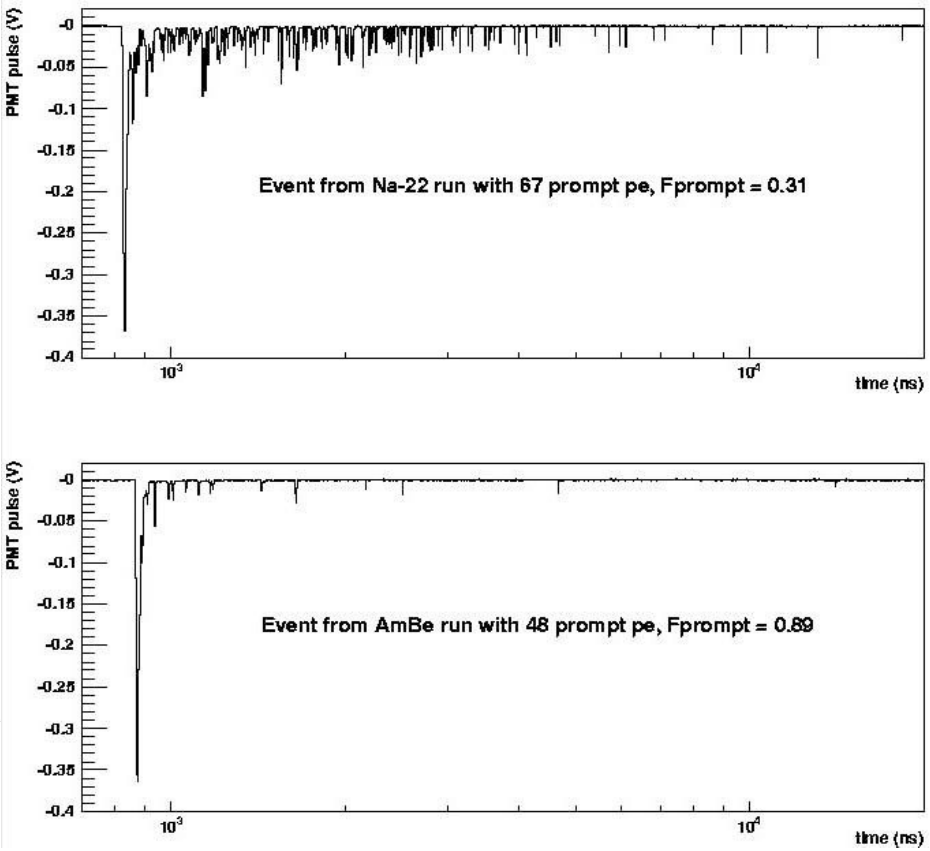
SNO

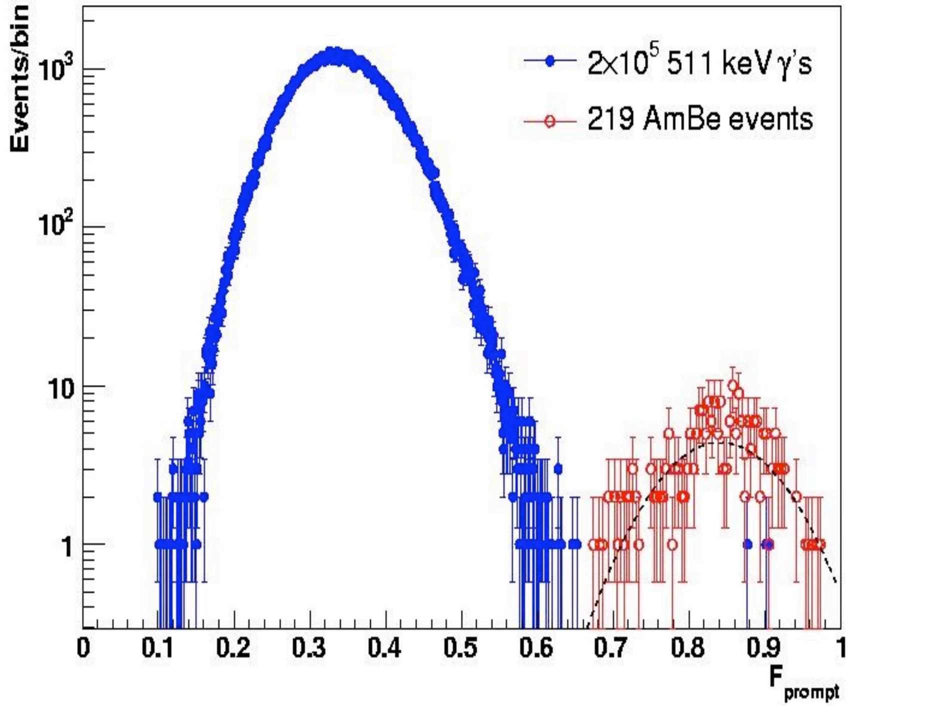


SNO+

DEAP - Dark matter Experiment with Argon and Pulse-shape-discrimination

M.G.Boulay and A.Hime, Astroparticle Physics 25, 179 (2006)





Concept Demonstrated Experimentally at LANL

DEAP-0

IV'rth SNOLAB Workshop, August (2005)

www.snolab2005.snolab.ca

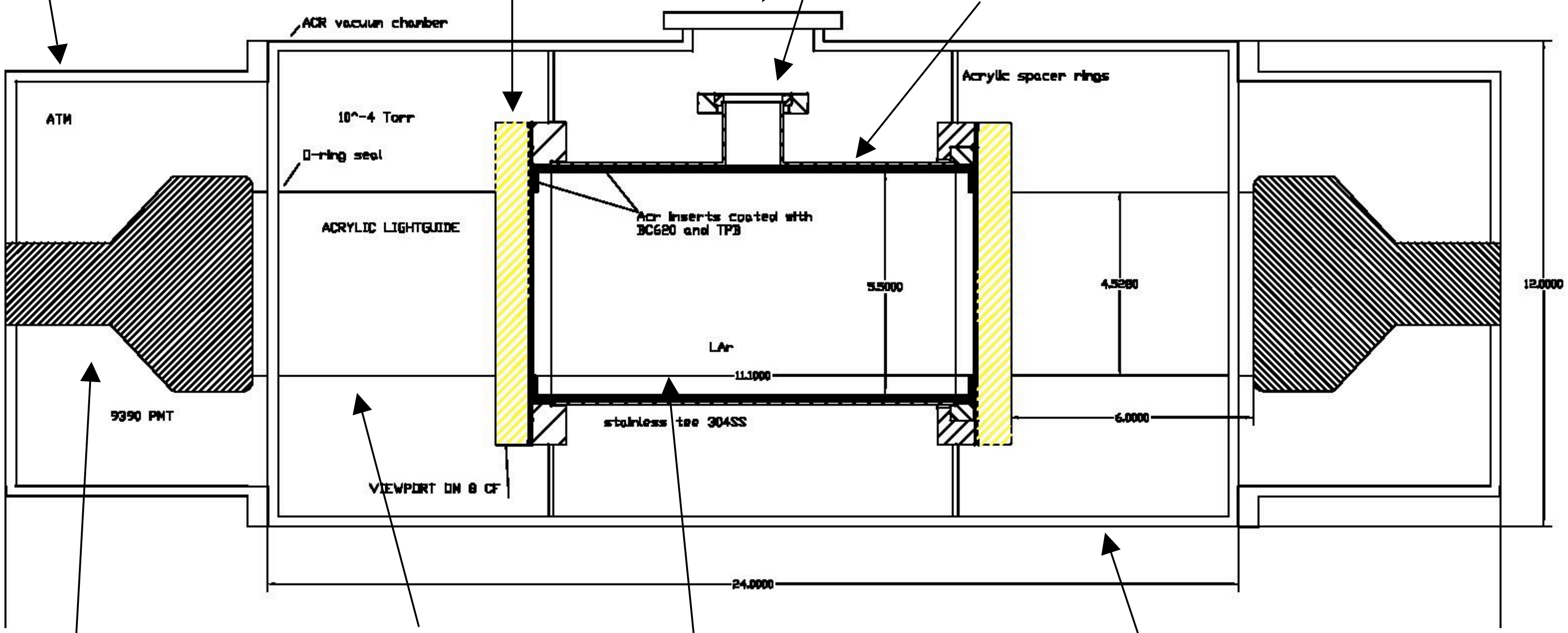
DEAP-1 (being constructed at Queen's)

Quartz windows

Neck connects to vacuum and
Gas/liquid lines

11" x 6" (8" CF) tee

poly PMT supports



6" acrylic guide

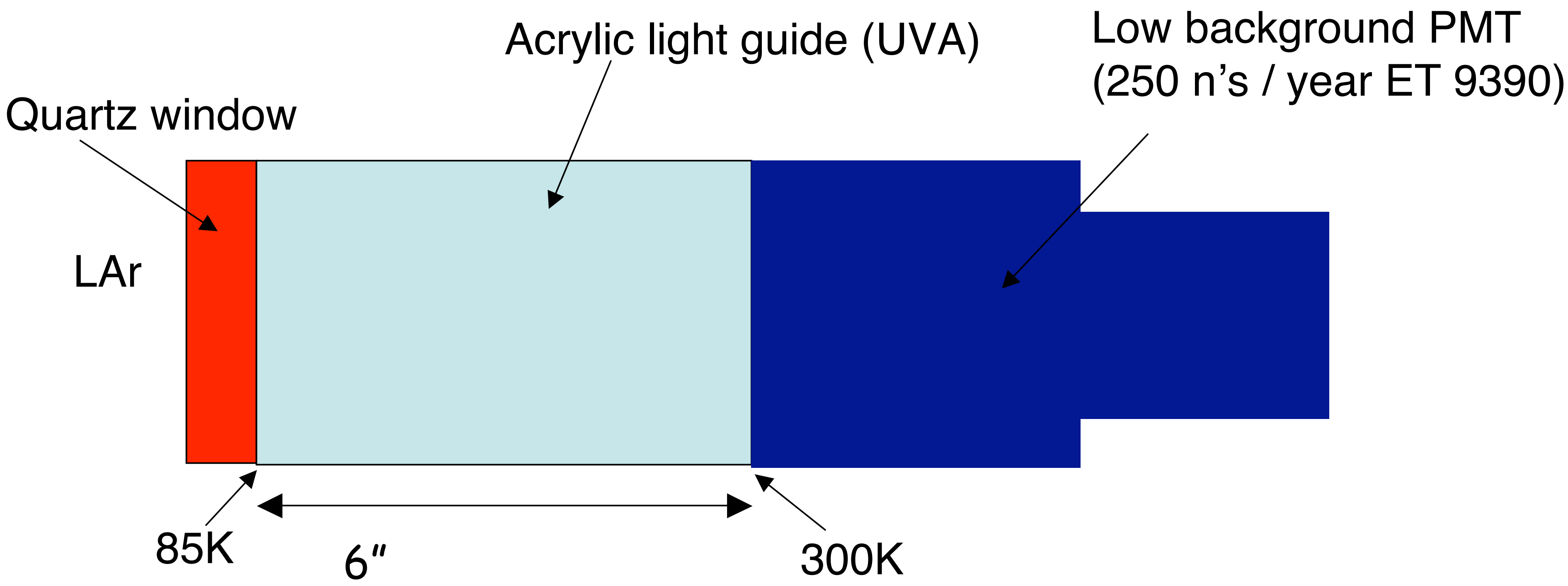
Acrylic vacuum chamber

ET 9390B PMT 5"

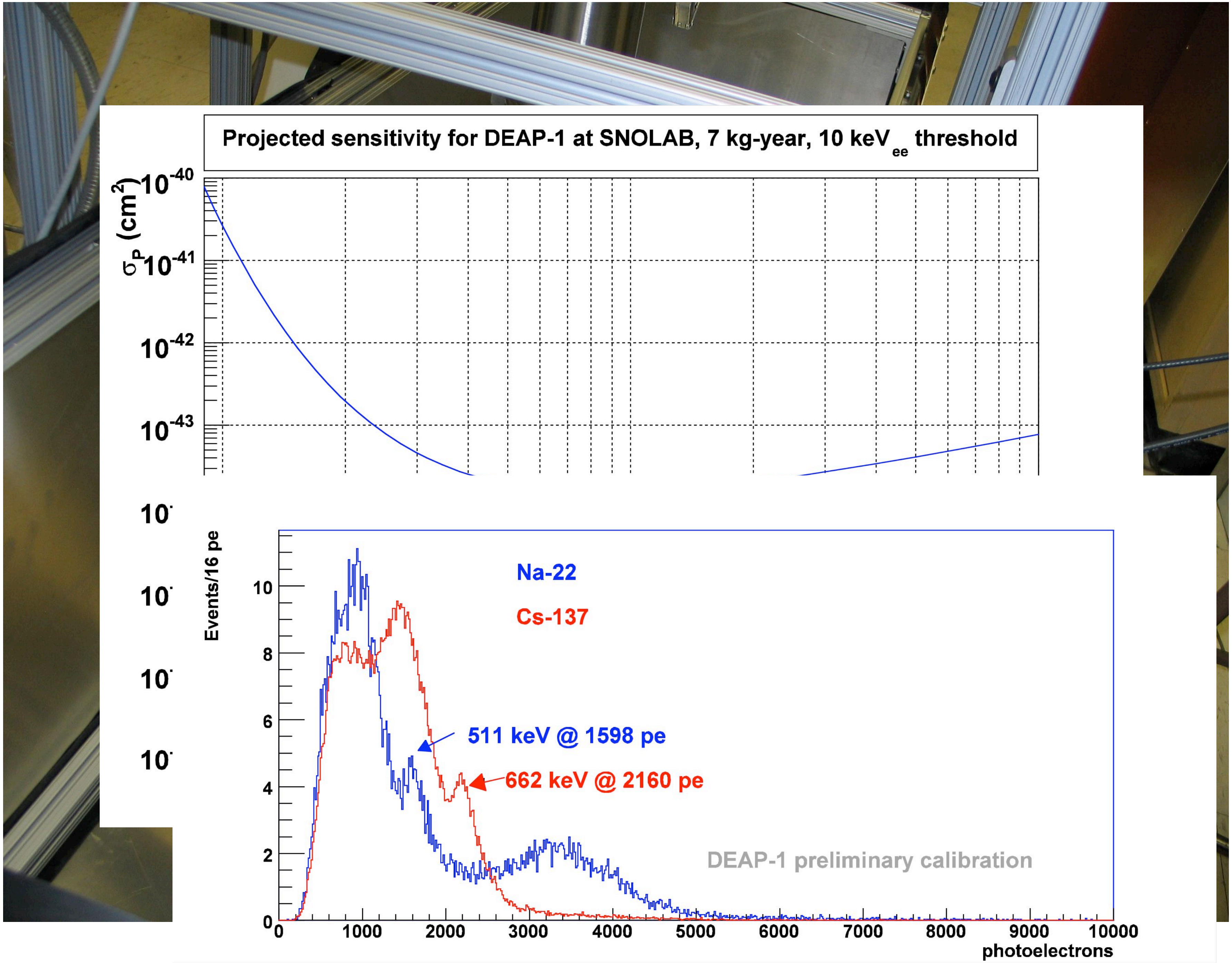
7 kg LAr

inner surface 97% diffuse reflector,
Covered with TPB wavelength shifter

Photon detection for DEAP-1

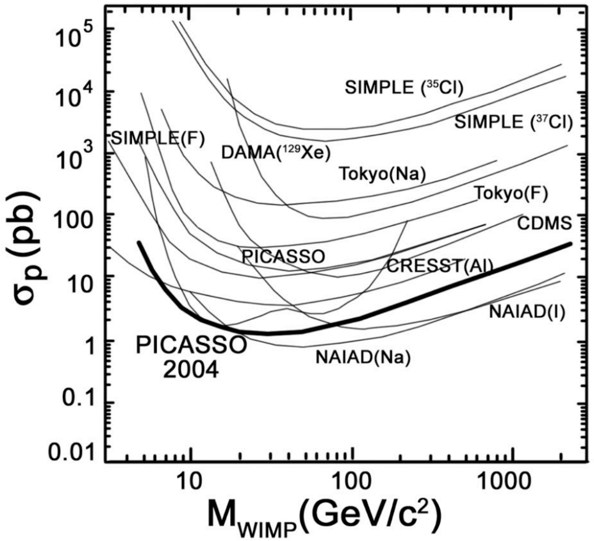


Acrylic guide backs off PMT to reduce (α,n) neutron backgrounds, and to reduce thermal load on room-temperature PMTs.

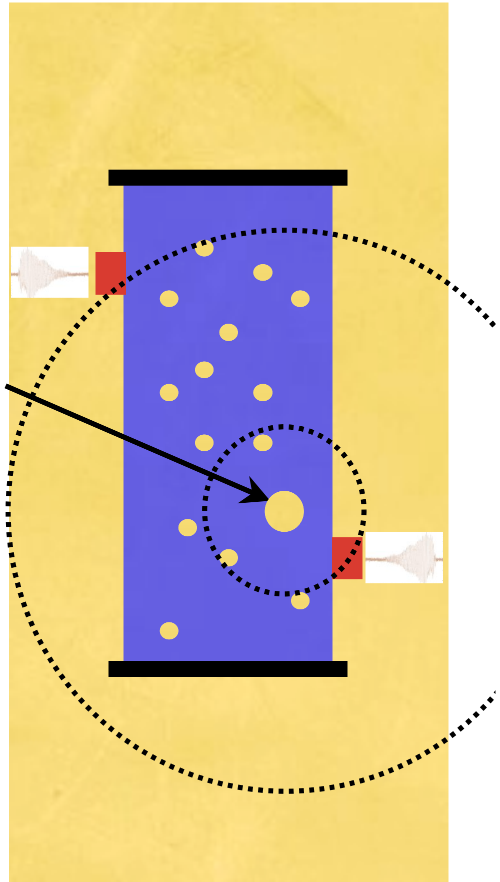


Projected sensitivity for DEAP-1 at SNOLAB, 7 kg-year, 10 keV$_{ee}$ threshold
σ_P (cm^2)
10^{-40}
10^{-41}
10^{-42}
10^{-43}
Events/16 pe
Na-22
Cs-137
511 keV @ 1598 pe
662 keV @ 2160 pe
DEAP-1 preliminary calibration
photoelectrons
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000

PICASSO *RESULTS*

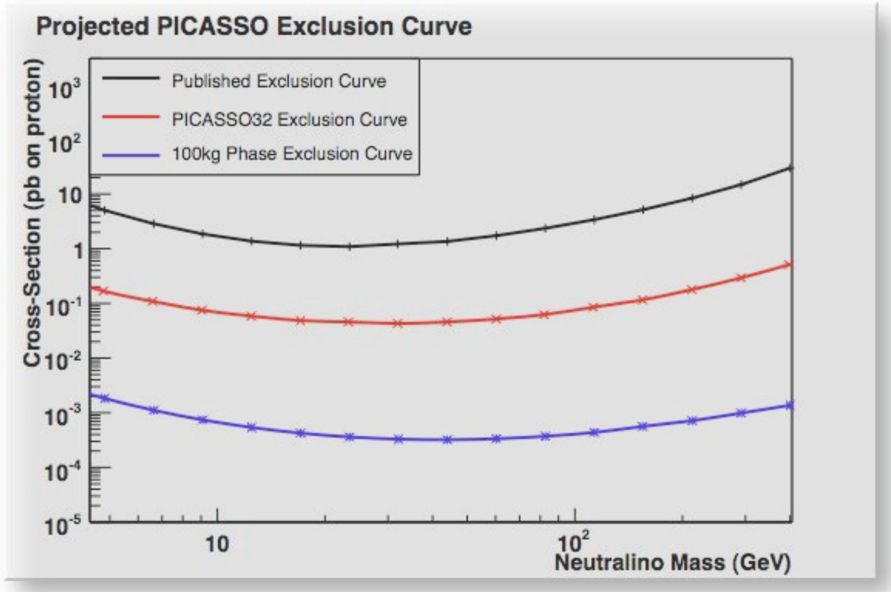


- PICASSO uses superheated droplet technique
- Based on 3 detectors (1L each) with an active mass of 7.45g, 6.62g and 5.35g
- Exposure of 1.98 kgd
- Best in spin-dependent sector
- Peak sensitivity of σ_p=1.31 pb for a WIMP with 29 GeV mass
- Phys.Lett.B624:186-194, 2005 / NIM A 555 184-204, 2005



PICASSO *PhaseII*

- 32 x 4.5 L detectors with a total active mass of $\approx$ 2.6 kg.
- 10x larger droplet size and (hopefully) 10x better purification will reduce background by factor 100 (answer within weeks after deployment)
- Finished development and installation of new neutron shield, support structure, temperature control, pressure system
- Phase II DAQ, calibration devices and full set of detectors will be deployed later this year



- Exciting new experiment at SNOLAB
- Hope to show that superheated droplet technique is feasible for large scale experiment
- Expect new, improved limits from PICASSO phase II by next year