Neutrino Flux Measurements in SNO's Phase III

Sean McGee
University of Washington
for the SNO Collaboration

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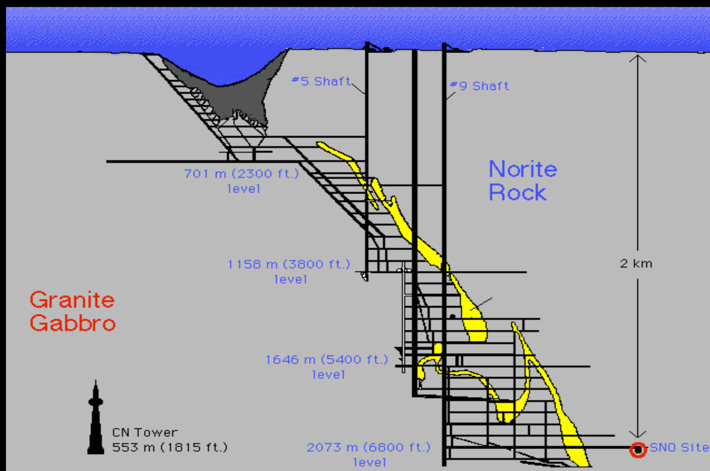
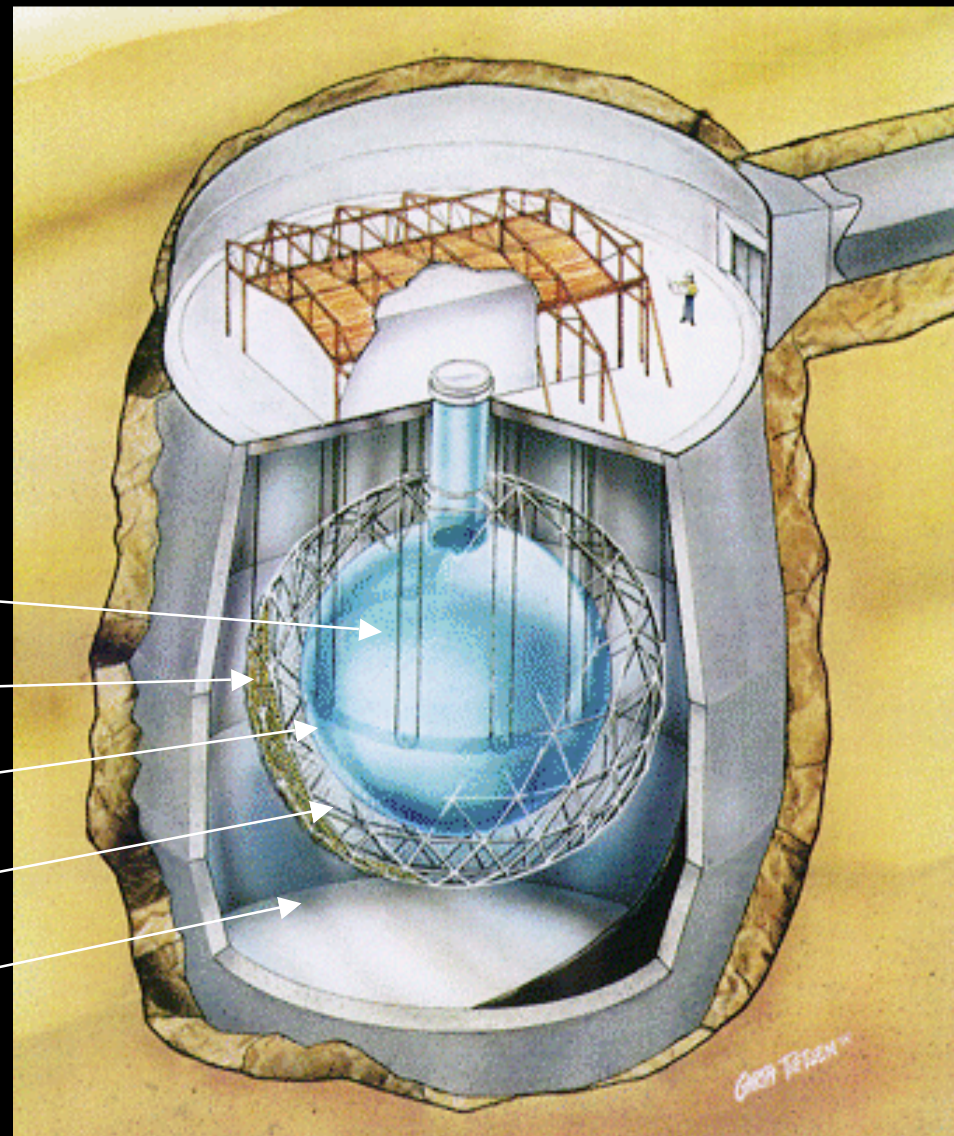
- Introduction
  - What is SNO
  - What is Phase III
- Signals and Backgrounds
- Preliminary Spectral Analysis
- Pulse Shape Analysis techniques being pursued
- Final days of SNO
- Future

Sudbury Neutrino Observatory





1000 tonnes D_2O

Support Structure for 9500 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

1700 tonnes Inner Shielding H_2O

5300 tonnes Outer Shield H_2O

2000 m below the surface (6000 m.w.e.)

Nucl. Inst. and Meth. A449, p172 (2000)

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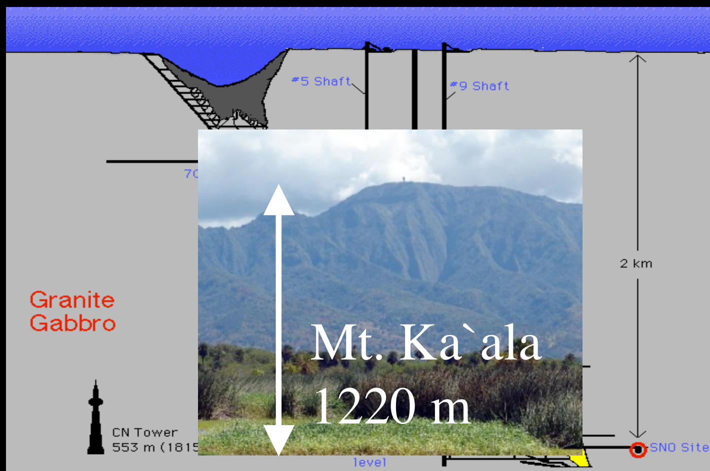

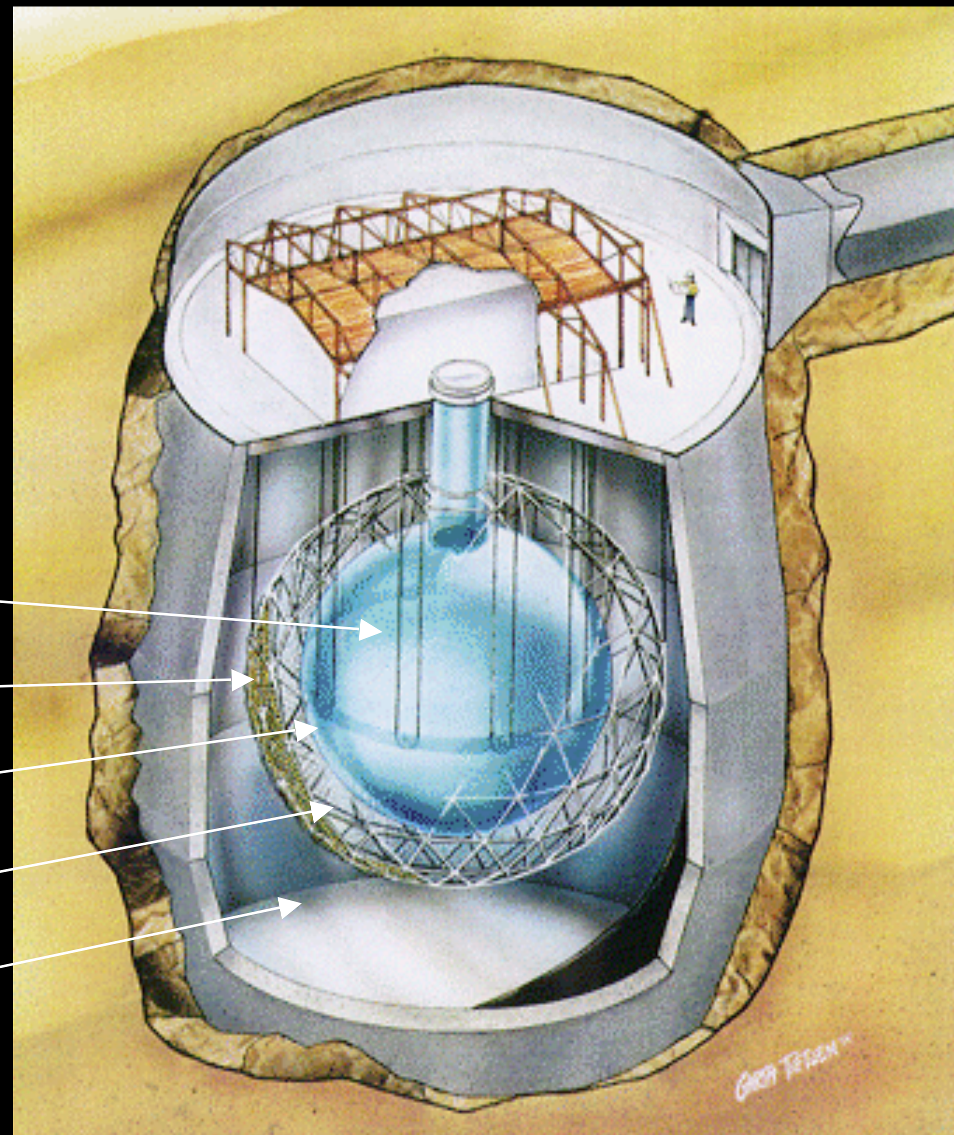

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ν Reactions in SNO

CC

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

- good measurement of ν_e energy spectrum
- some directional info ∝ (1 – 1/3 cosθ)
- ν_e only

NC

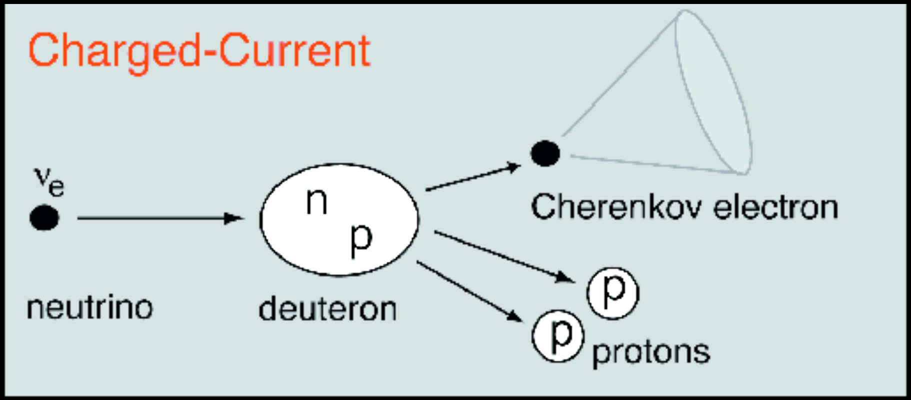
$$\nu_x + d \rightarrow p + n + \nu_x$$

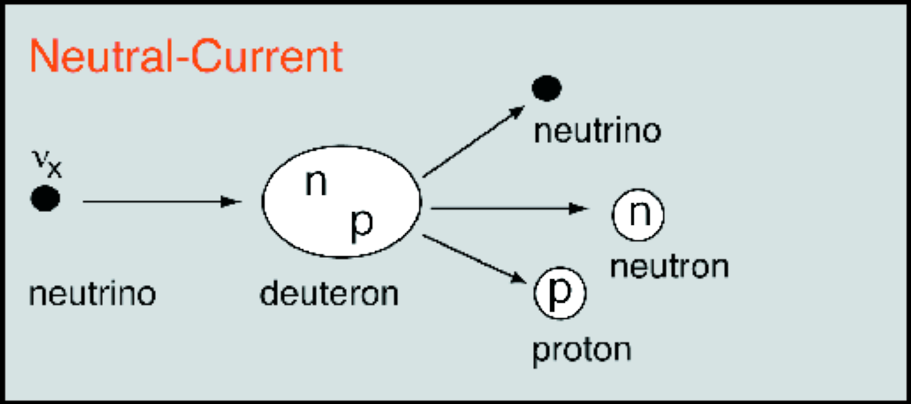
- measures total ^8B ν flux from the Sun
- equal cross section for all ν types

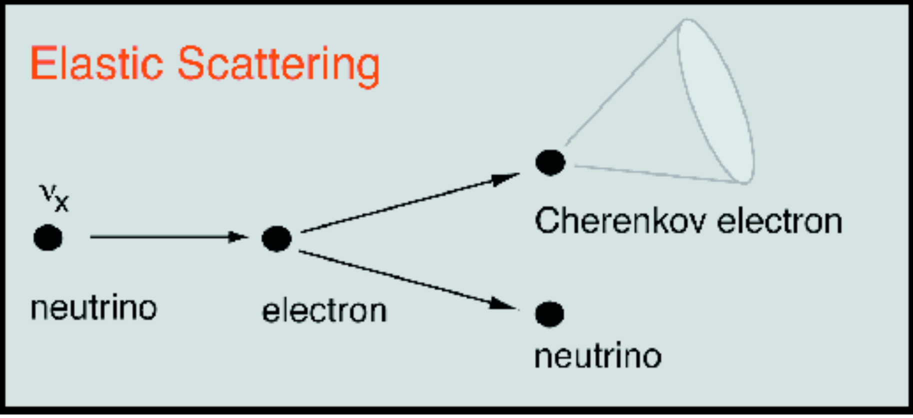
ES

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

- low statistics
- mainly sensitive to ν_e, some ν_μ and ν_τ
- strong directional sensitivity







SNO Run Sequence

I. Pure D_2O	CC, ES, some NC $n + d \rightarrow t + \gamma$ ... ($E\gamma$ = 6.25 MeV, $\varepsilon_n \sim 14\%$) Nov. 2, 1999 to May 28, 2001 "strong evidence for flavor transformation of solar ν_e"

SNO Run Sequence

I. Pure D_2O	CC, ES, some NC
II. D_2O+NaCl (2 tonnes dissolved salt)	CC, ES, enhanced NC $n + {}^{35}Cl \rightarrow {}^{36}Cl + \sum\gamma$ ($E_{\Sigma\gamma}$= 8.6 MeV, $\varepsilon_n \sim$ 41% above threshold) isotropy of shower used for better NC event separation

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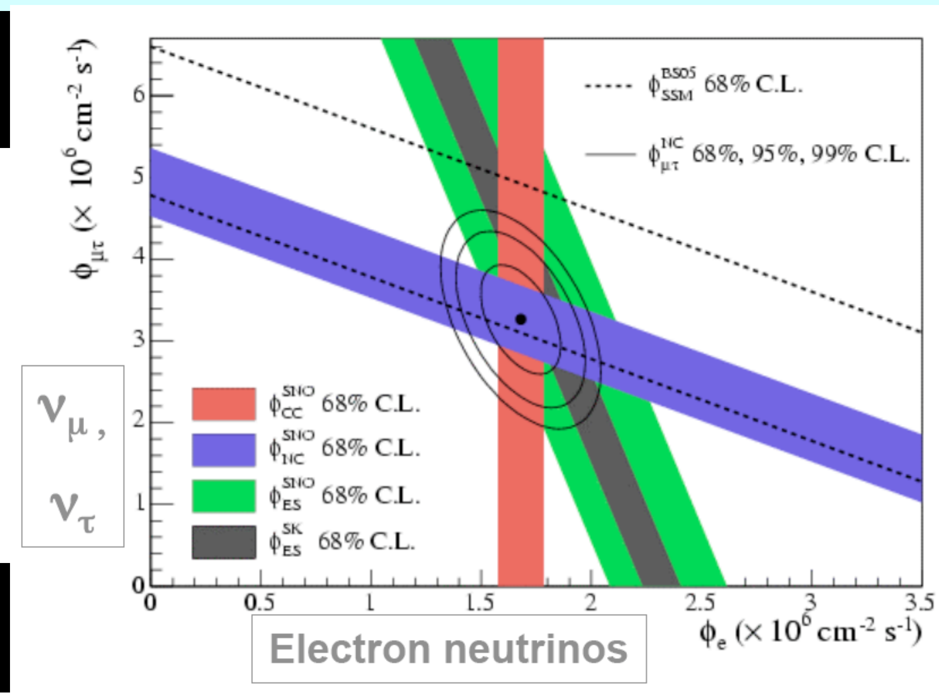
$$\phi_{CC} = 1.68 \ {}^{+0.06}_{-0.06}(\text{stat.})^{+0.08}_{-0.09}(\text{syst.})$$

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

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

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



SNO Run Sequence

I. Pure D_2O	CC, ES, some NC
II. D_2O+NaCl	CC, ES, enhanced NC
III. D_2O+NCDs	CC, ES, NC
(^{3}He proportional counters)	$n + {}^3He \rightarrow p + t$
	$\varepsilon_n \sim 26\%$ NC and CC signals uncorrelated (event by event separation)

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	$\varepsilon_n \sim 26\%$
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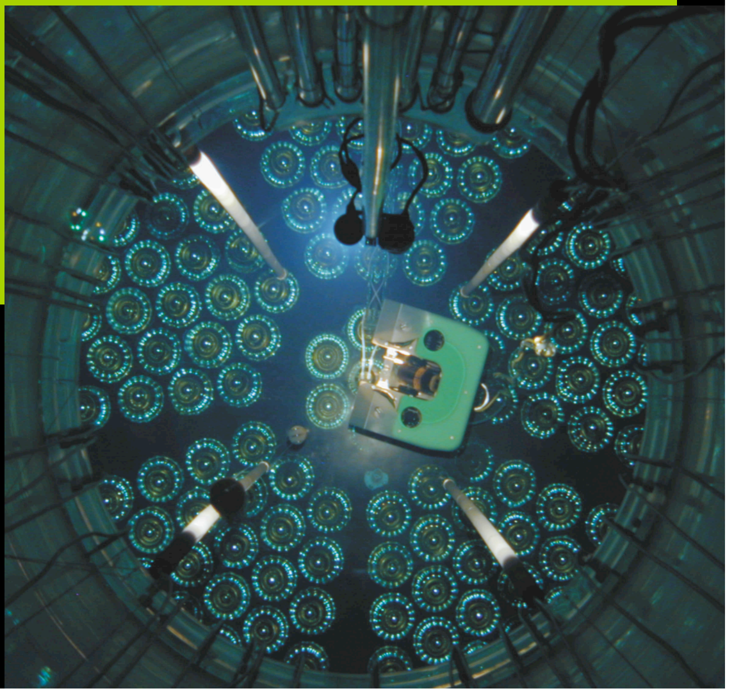
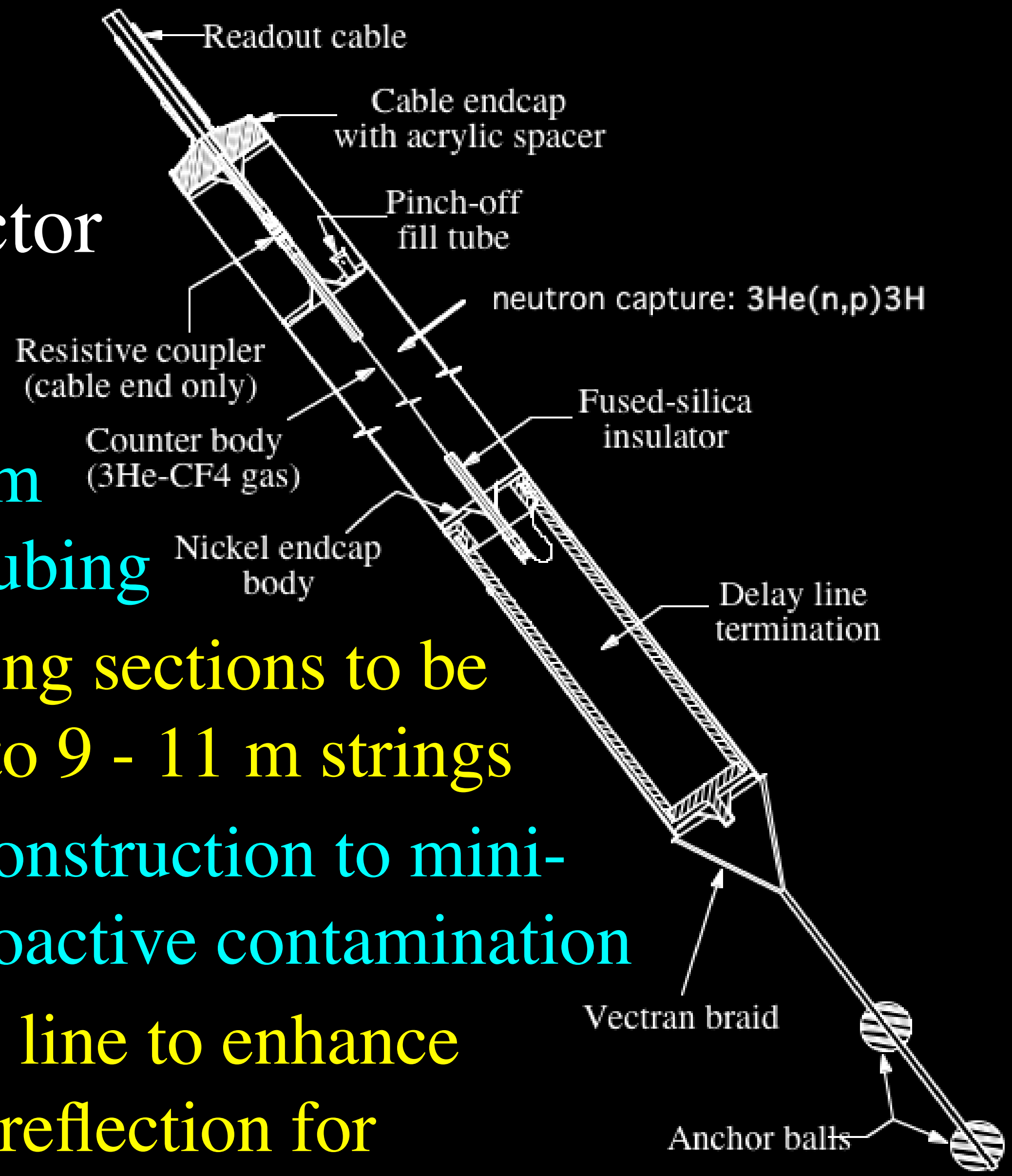
Effectively a different experiment!



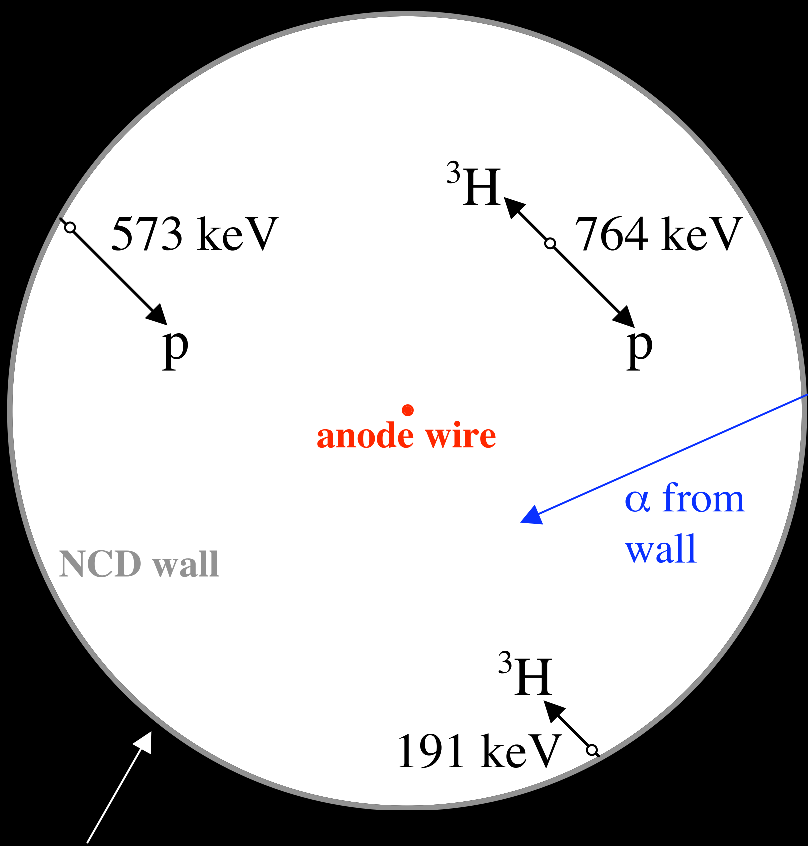
NCD

Neutral Current Detector

- 85% ^{3}He, 15% CF_4
- Constructed from 5.1 cm diameter CVD nickel tubing
- 200, 250 and 300 cm long sections to be welded underground into 9 - 11 m strings
- open-ended electrical construction to minimize materials and radioactive contamination
- 89 ns (round trip) delay line to enhance separation of pulse and reflection for z-position determination of events



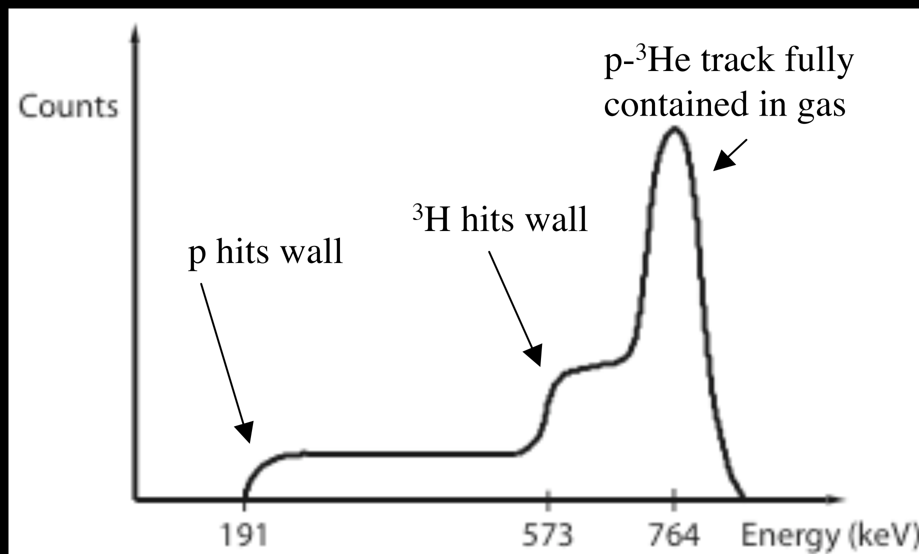
Neutral Current Detectors (cont.)



Cross section of an NCD

- NCD array:
  - 36 ^{3}He (signal)
  - 4 ^{4}He (control)
- $^{3}He + n \rightarrow {}^{1}H + {}^{3}H$

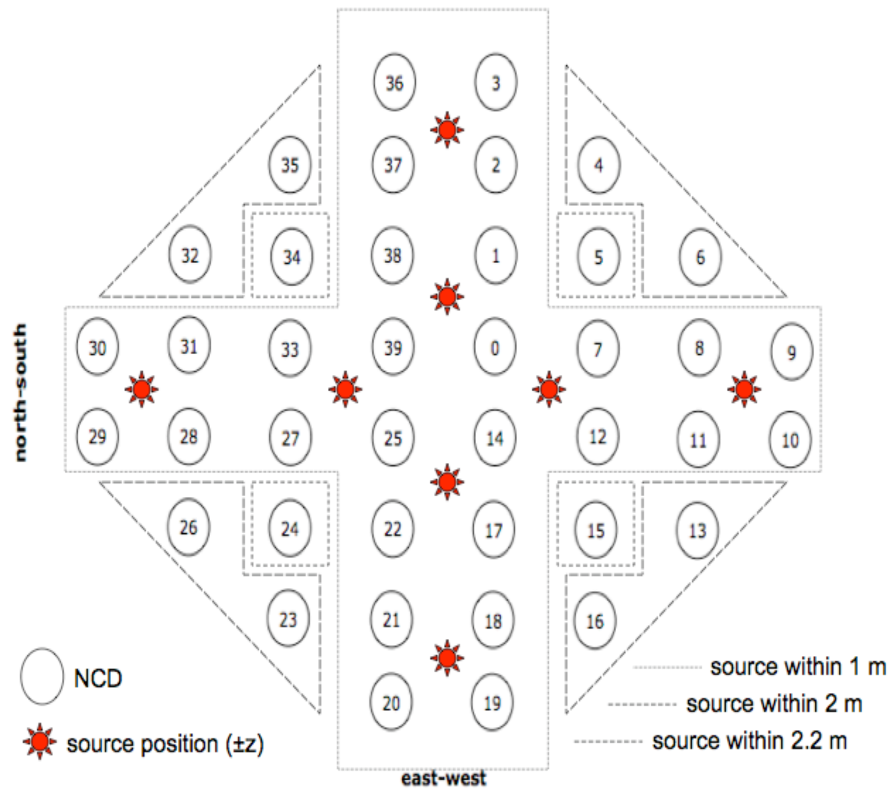
  (Q = 764 keV)
- Primary background is α from surface Po and embedded U and Th



NCD Calibrations

- Multiple AmBe sources (67 n/s hottest)
- Rate cross-calibrated with known ^{252}Cf source each calibration (know rate to < 1%)
- Point source effectively populates one region of NCD (z dependence)
- Used to calibrate the MC at discrete points
- MC is then used to determine the array efficiency

sample AmBe source run plan



NCD array deployed in a 1 x 1 meter grid

NCD Calibrations

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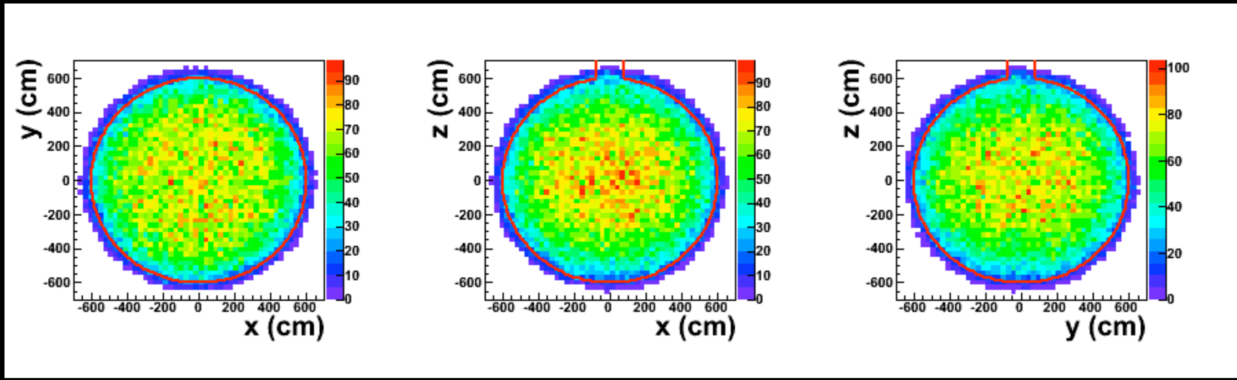
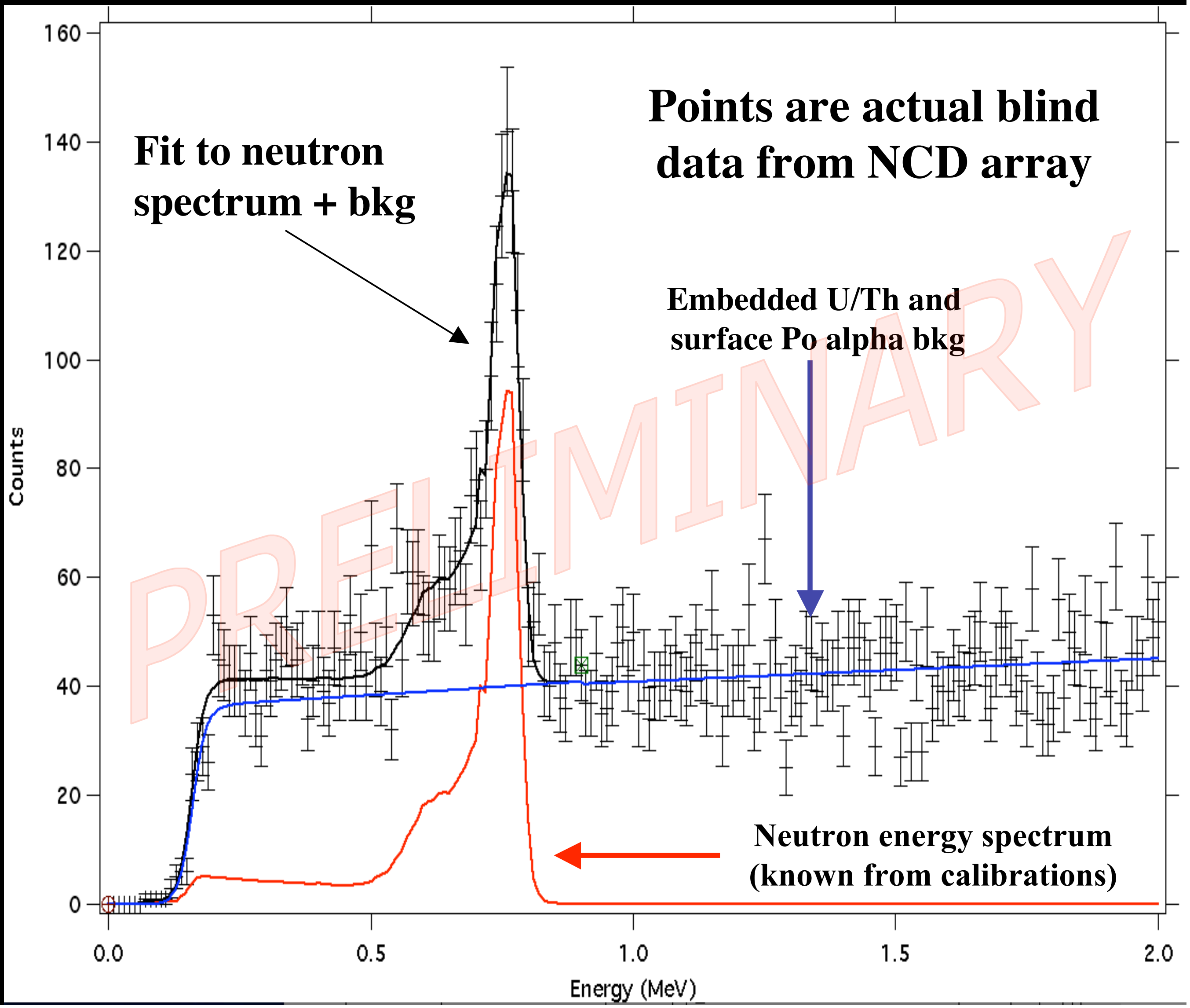
- Check MC and get neutron efficiency from dispersed source
- Injected 14 kBq ^{24}Na (overall NCD rate started at 0.3 Hz after mixing)
- 2.7 MeV γ photo-disintegrates deuteron
- 15 hr half-life
- Returned to normal running after 9 days



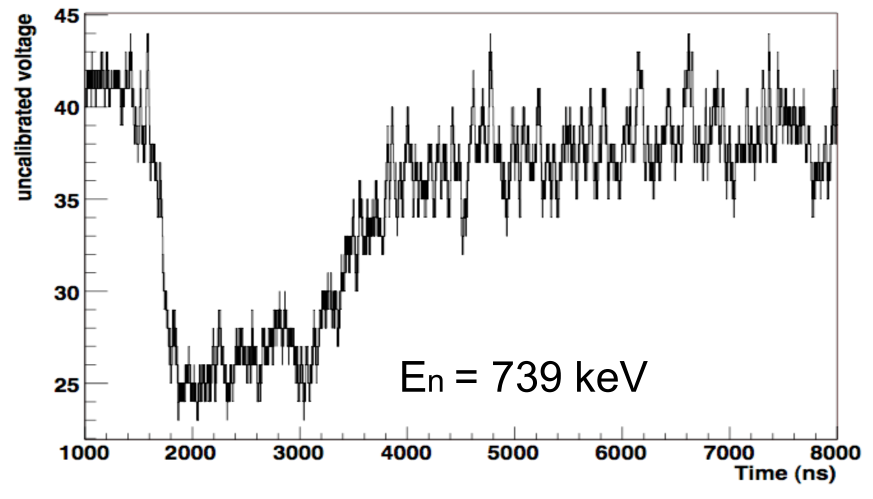
Spectral Analysis

- Neutron signal clearly evident
- Distribution of radioactivity affects the bkg spectrum in ROI
- 4 ^{4}He strings to measure bkg
- May be able to improve S/B in ROI with Pulse Shape Analysis (PSA) techniques

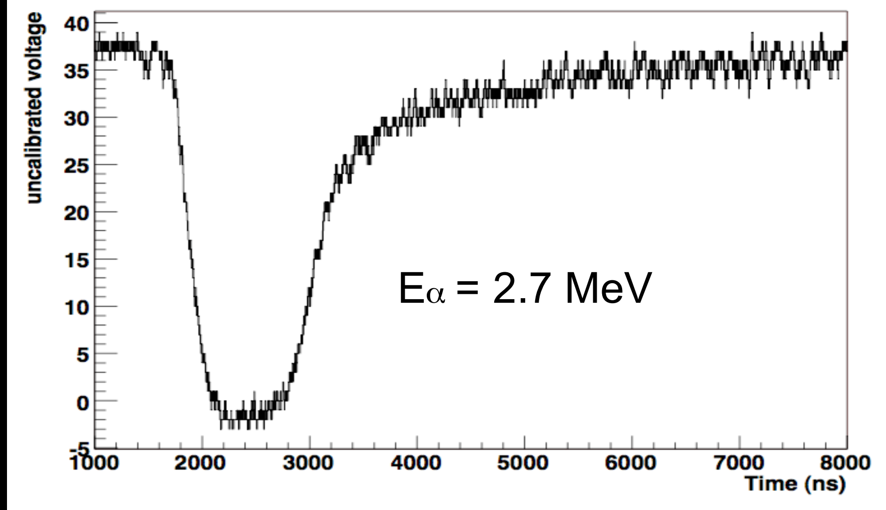


Some NCD Pulse Shapes

proton-triton track perpendicular to anode



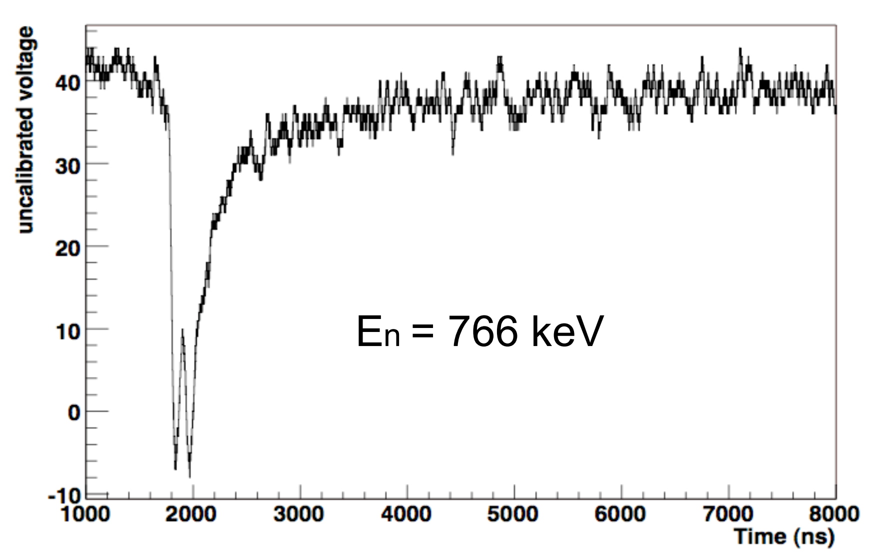
Embedded alpha pulse shape



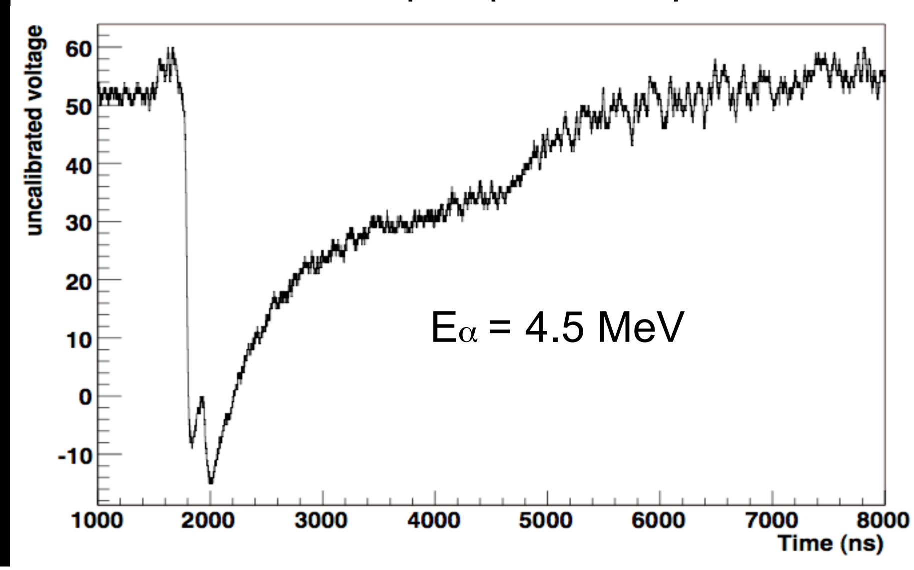
neutrons

alphas

proton-triton track parallel to anode



Surface alpha pulse shape



NCD PSA Paths

- Brute Force (slow)
  - Grid fit on library of real or MC pulses
  - Can use pulse energy to constrain grid region
  - Compare goodness of fit between α and n hypotheses
  - CPU intensive
  - Alpha data important

- Parameter Based (fast)
  - Use pulse parameters to distinguish signal from background
    - Collection Function method
    - Decision Tree method
  - Need large set of real pulses or MC to set cuts or train discriminators
  - Alpha data important

Both paths would produce pdf's of α or n likelihood.

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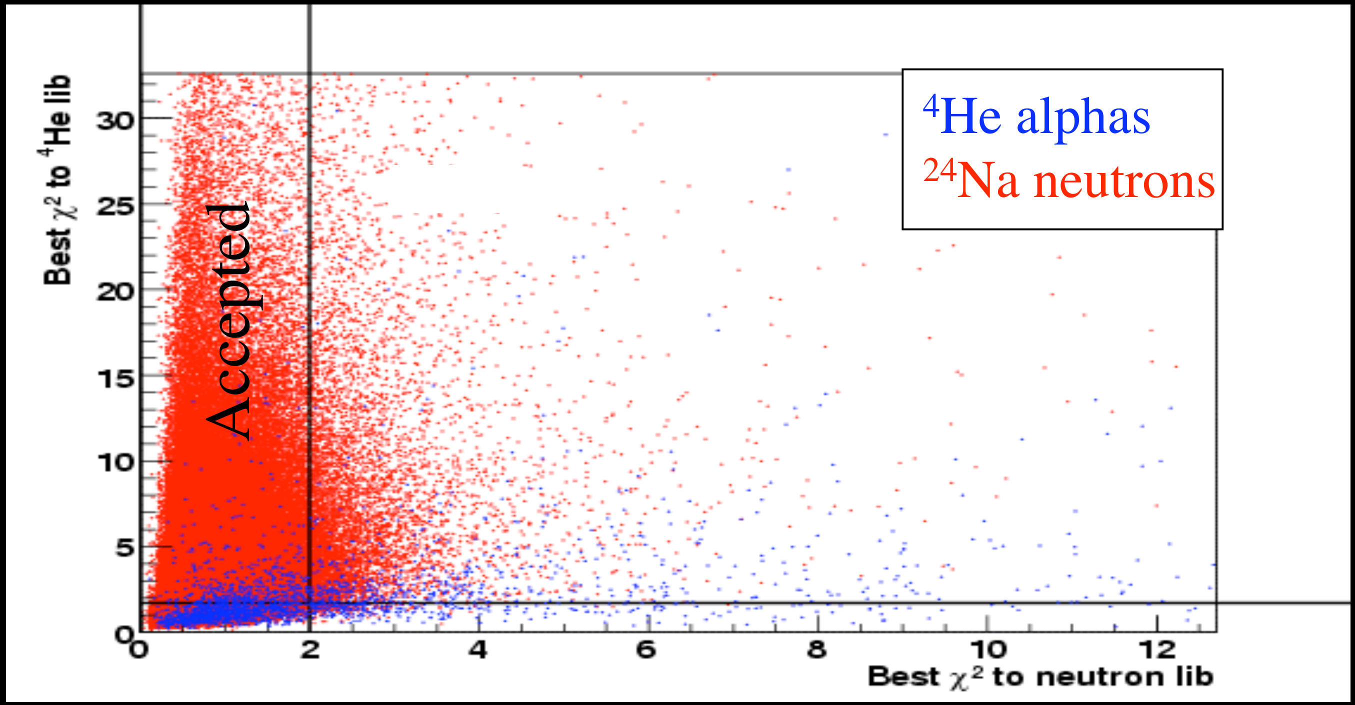
Both paths would produce pdf's of α or n likelihood.

Of course, SNO also pursuing a CC analysis with PMT data!

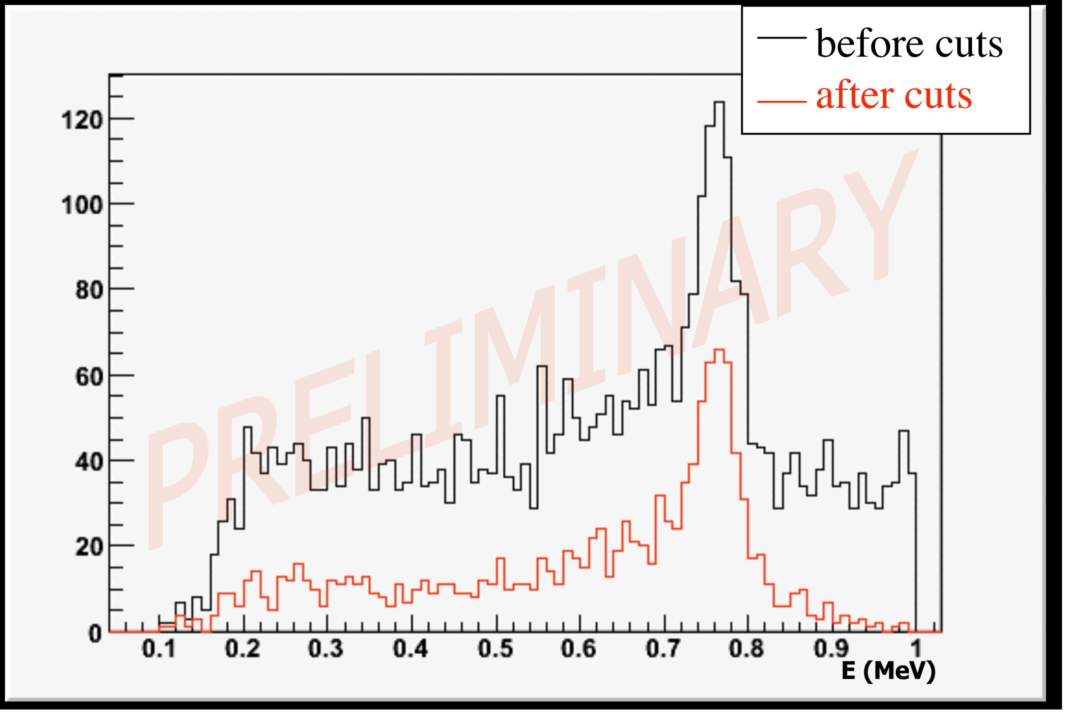
Grid Fit (Brute Force Method)

- Libraries of neutron and alpha pulses are constructed
- Real data currently being used
  - ^{24}Na calibration runs for signal (27,000 events)
  - ^{4}He string data for background (1,600 events)
- All pulses are normalized and re-binned
- Pulses are shifted to allow for different trigger positions
- Best χ^2 to each library is found

Results



- Make 2D cut in χ^2 space
  - 76% of neutrons accepted
  - 84% of alphas rejected
- Improvement in signal-to-background ratio in ROI



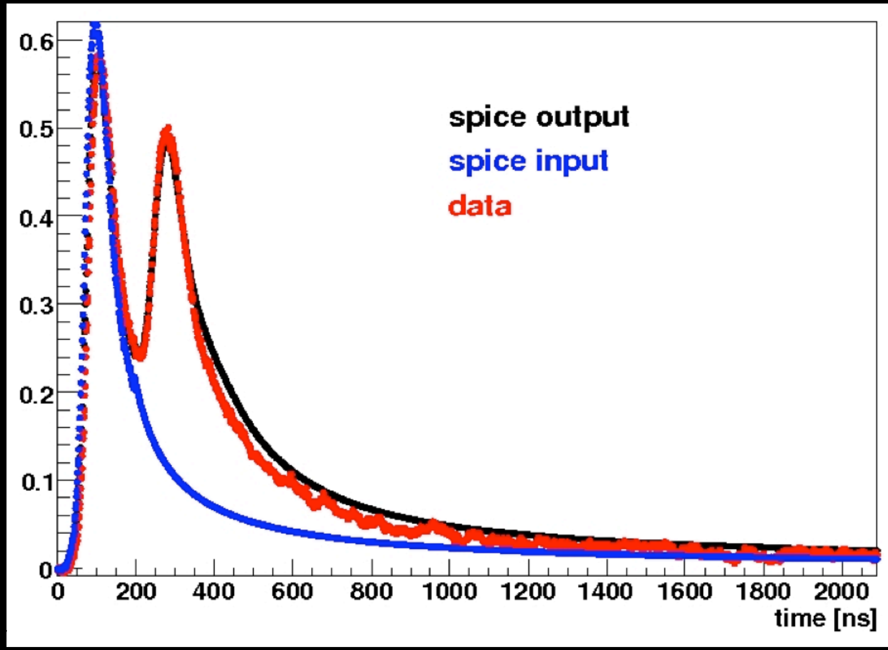
Collection Function Technique

- Derive avalanche signal due to one electron $D(\tau)$

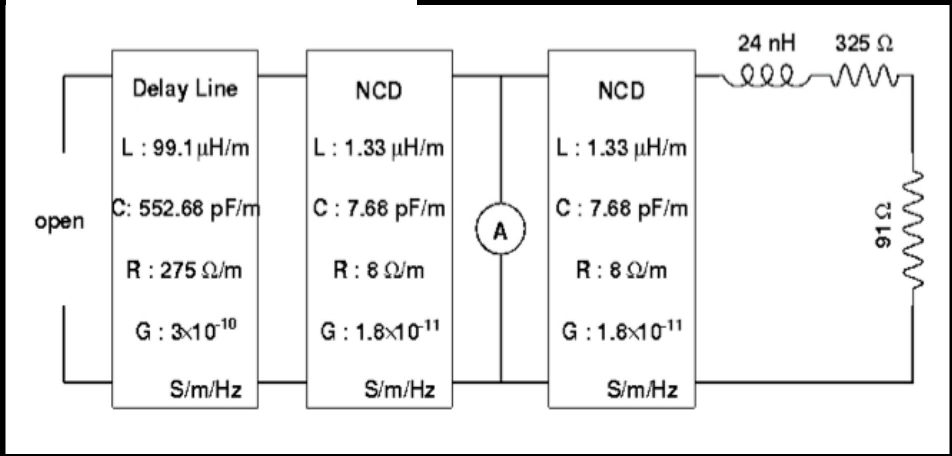
- Model propagation of signal in the NCD (SPICE) $I[D(\tau), z]$

- Pulse shape is just sum of all ionization collected at anode

$$S(t) = \int_0^t C(\tau) I[D(t-\tau), z] d\tau$$



SPICE model



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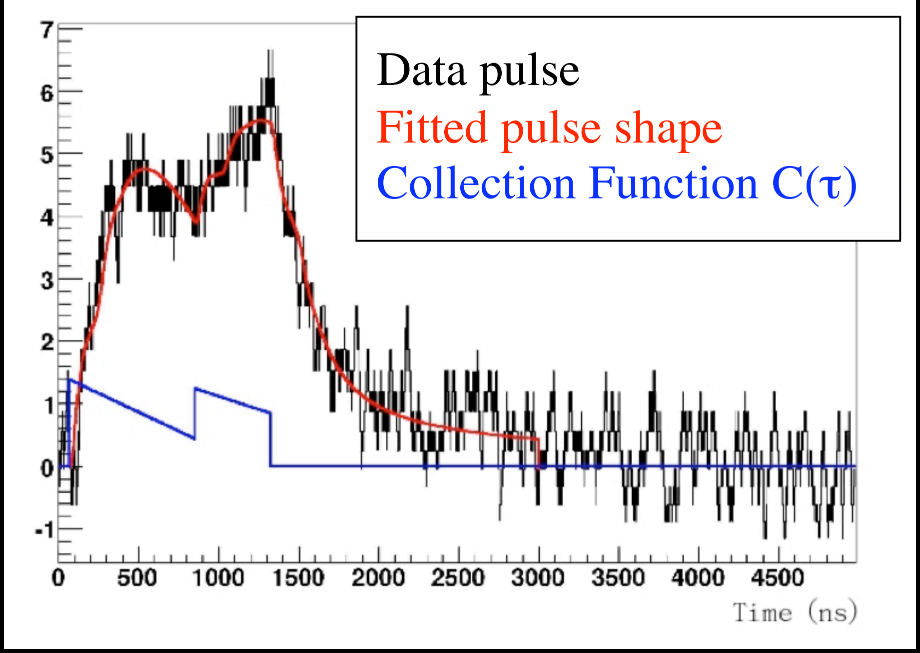
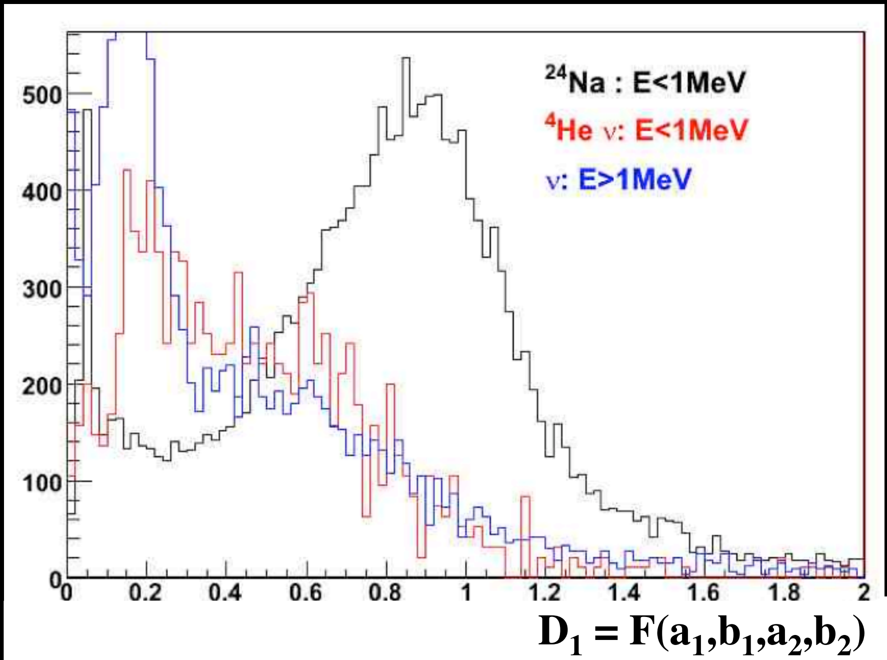


$$S(t) = \int_0^t C(\tau) I[D(t-\tau), z] d\tau$$

- Fit shape to extract C(τ) "Collection Function"

$$C(\tau) = \begin{cases} 0 & : \tau < t_0 \\ a_1 + b_1\tau & : t_0 \leq \tau < t_1 \\ a_2 + b_2\tau & : t_1 \leq \tau < t_2 \\ 0 & : t_2 \leq \tau \end{cases}$$

Collection Function Technique



- Investigate combinations of Collection Function parameters $F(a_1,b_1,a_2,b_2)$ to optimize separation of signal and background
- Improved S/B in ROI

$$S(t) = \int_0^t C(\tau) I[D(t-\tau), z] d\tau$$

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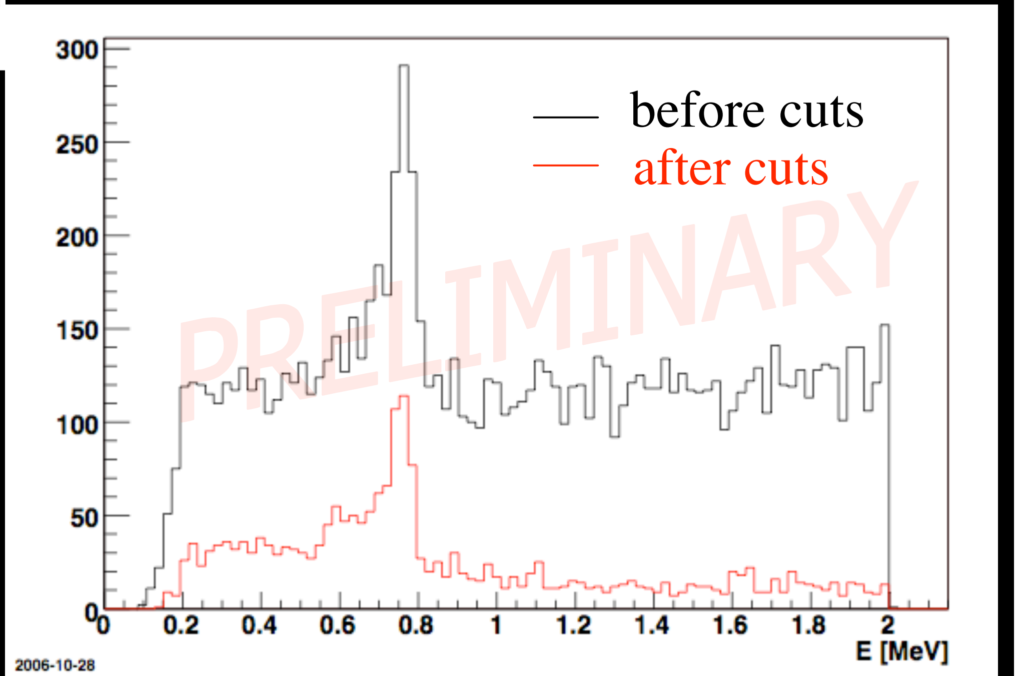


Discriminant (Boosted Decision Tree)

Motivation

- Decision trees promise better results than Fisher discriminants
- More transparent than Neural Nets
- Decision trees are a “majority vote” of a set of N yes/no cuts
- Promise (or claims):
  - Deal well with many input variables (> 100)
  - Deal well with highly correlated variables
  - Less sensitive to training than a net
- Decision trees used by BaBar, D0, MiniBooNE, and now available in ROOT (I. Narsky’s code available at: sourceforge.net/projects/statpatrec)

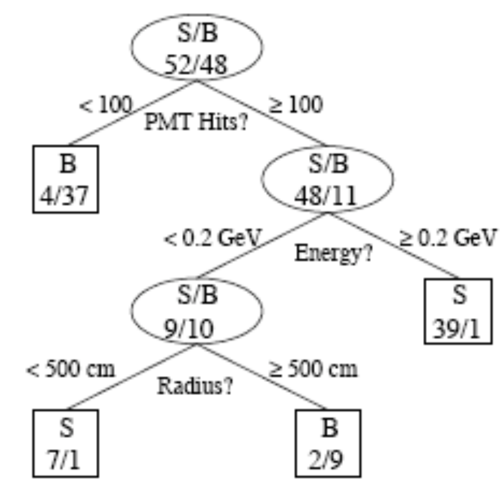


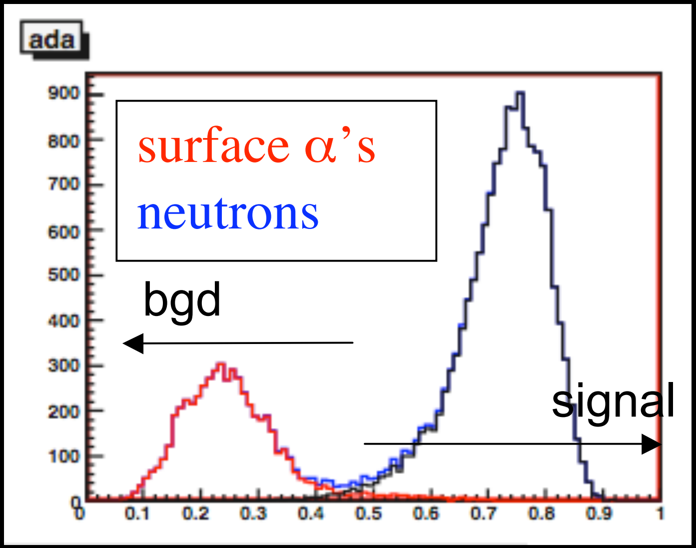
Figure 1: Schematic of a decision tree.

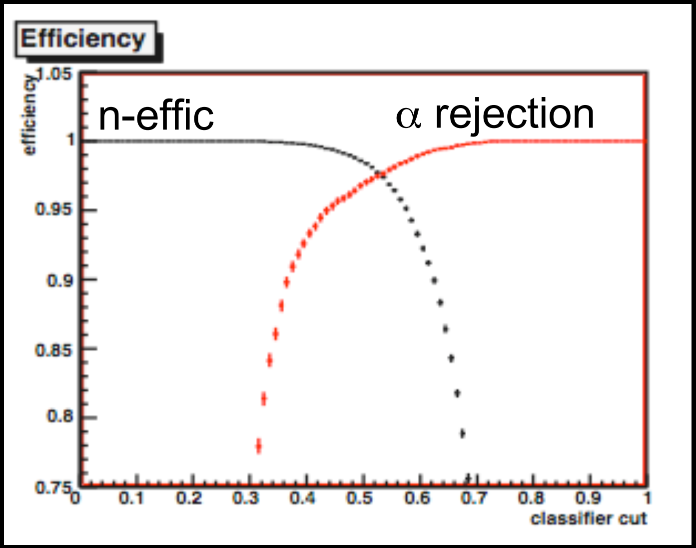
arXiv:physics/0508045

<u>Boosting</u>: feedback mechanism to boost the weights of misclassified training events.

AdaBoost Decision Tree seems to be best classifier.

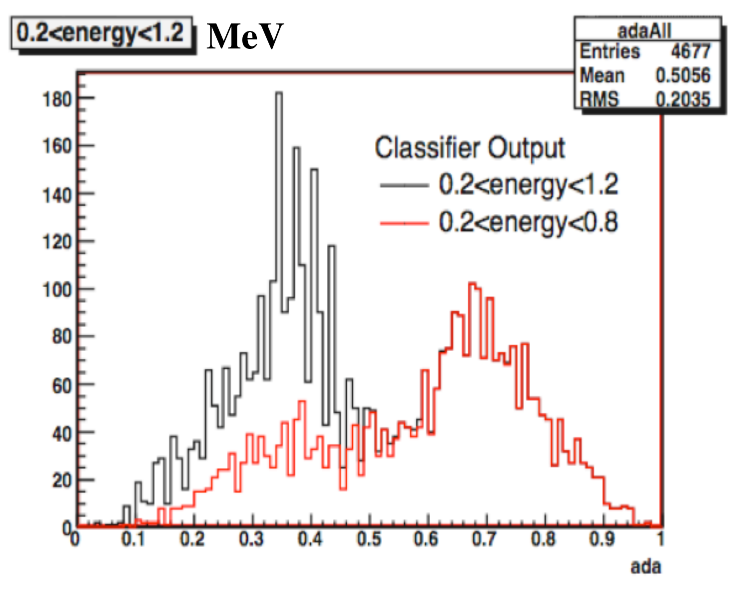
Discriminant (Boosted Decision Tree)

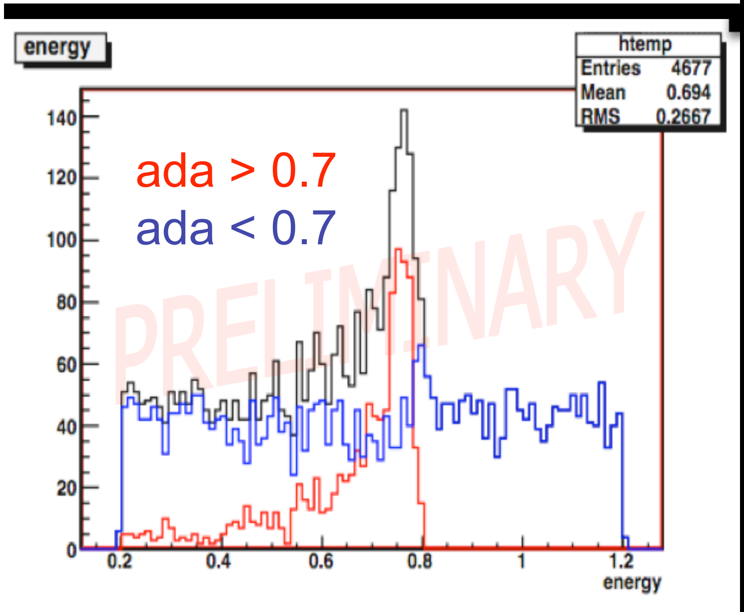




- Need large sample of signal and background to train discriminator
  - Neutrons are easy
  - Limited number of alphas
- Easy (for us) to get sample of ^{210}Po (surface) alphas
- Use pulse shape parameters as inputs:
  - Pulsewidth
  - "Risetime"
  - Moments (Skewness, Kurtosis)
- Classifier works well in this limited case
  - 99% neutron efficiency
  - 95% surface alpha rejection

Discriminant (Boosted Decision Tree)





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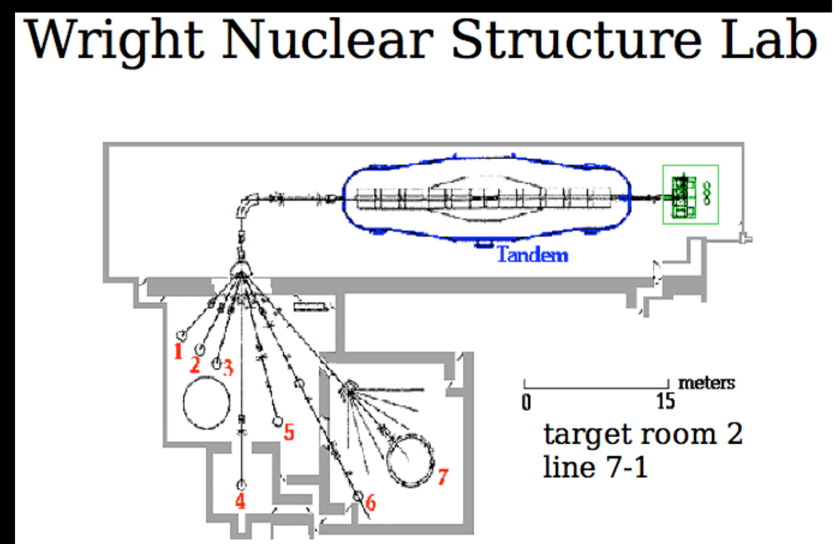
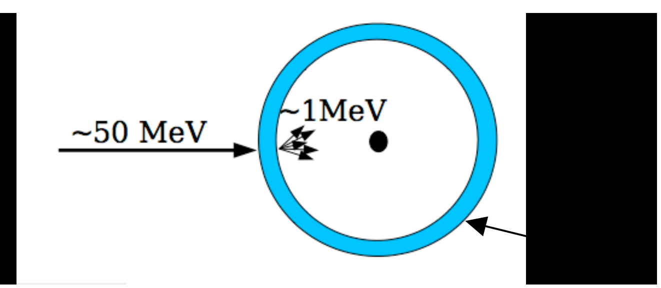
- Classifier works well in this limited case
  - 99% neutron efficiency
  - 95% surface alpha rejection
- Classifier trained with predominantly surface alphas still discriminates real data well
- Should improve with large sample of embedded alphas

The “Yale α Sample”

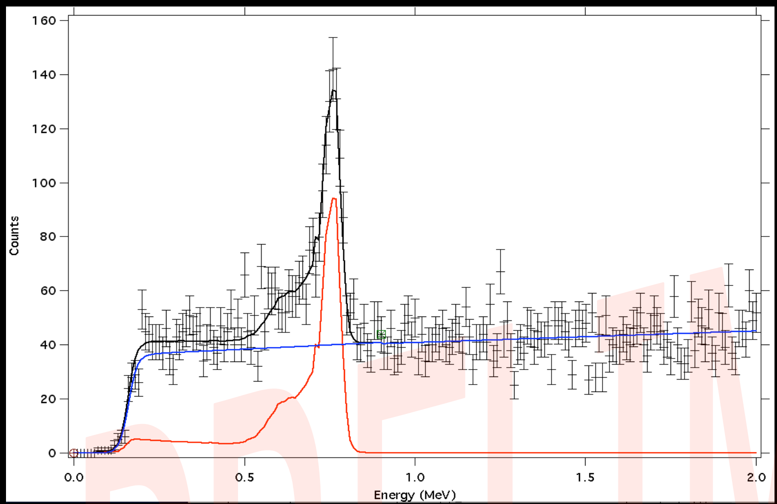
- Conceived and organized by MIT collaborators
- 4 days of data-taking: April 24-27, 2006
- Was necessary to etch NCD to get adequate wall thickness
- Varying orientation and tilt to simulate alpha emission from wall
- Covered entire energy range necessary (100 keV - few MeV)
- Large sample (10^5 α’s)
- Can be used to augment α sample or confirm α MC

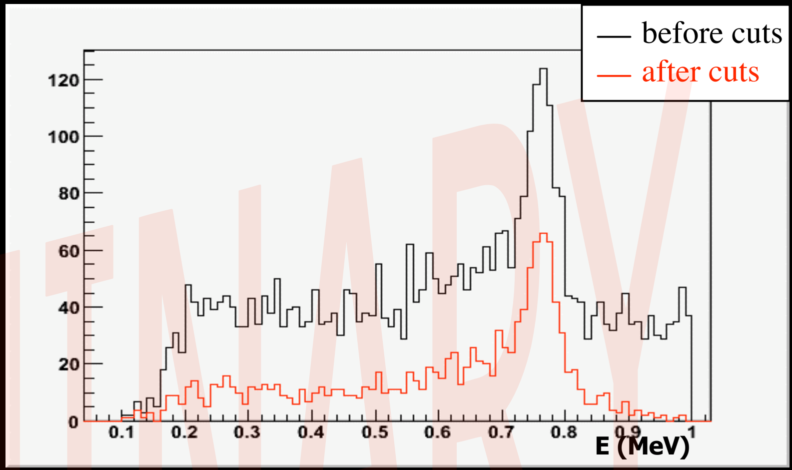


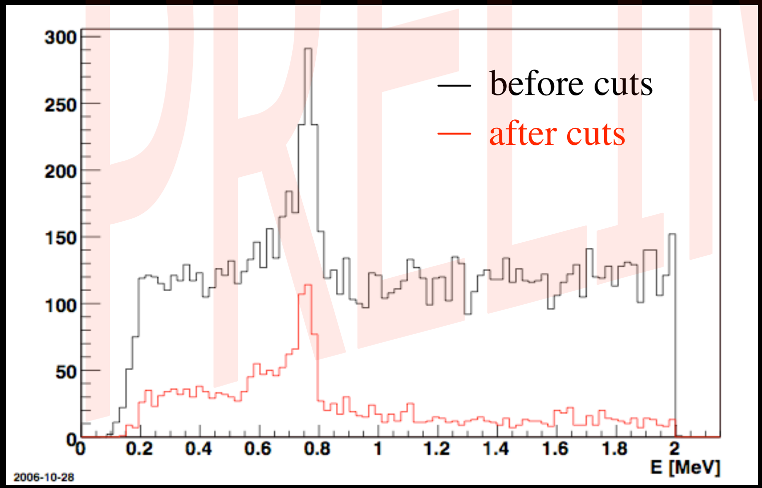


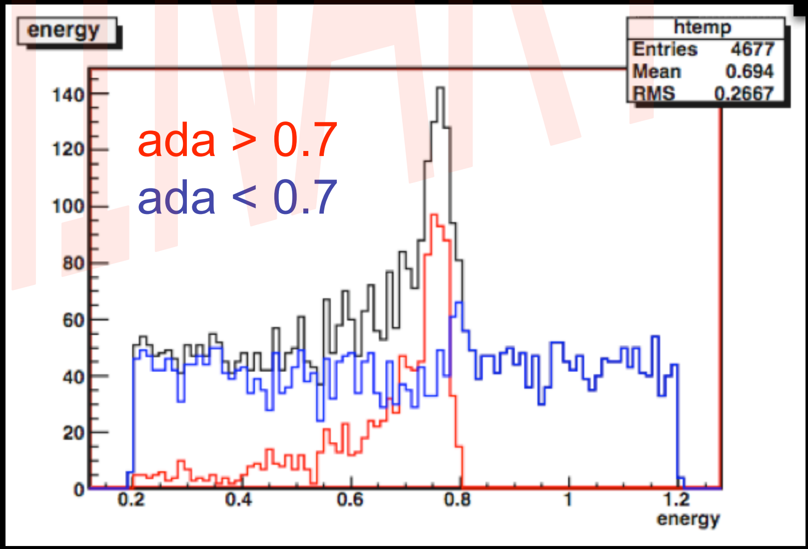
Summary

- PSA methods being refined, but early results show good signal-to-background improvement





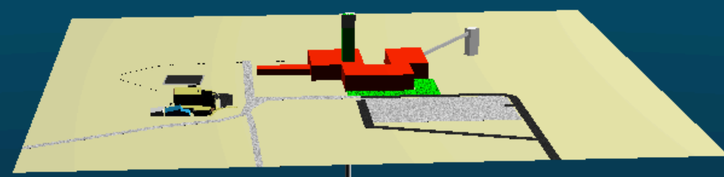




SNO Schedule

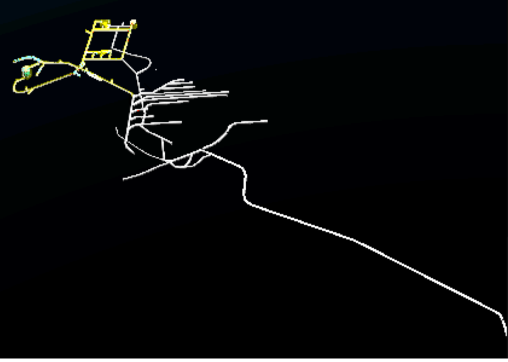
- Data-taking to be completed at the end of November 2006.
- NCD removal would commence shortly thereafter.
- Over 400 days of live-time will have been logged in Phase III.
- Heavy water returned to Canadian government throughout 2007.

SNOLAB



- Outgrowth of the highly successful SNO project
- Proposal in 2001
- Funding in 2002

- Surface facility
  - Groundbreaking 2004
  - Occupancy 2005
- Underground
  - Tunneling commenced Nov 2004
  - Completion (wait for it)



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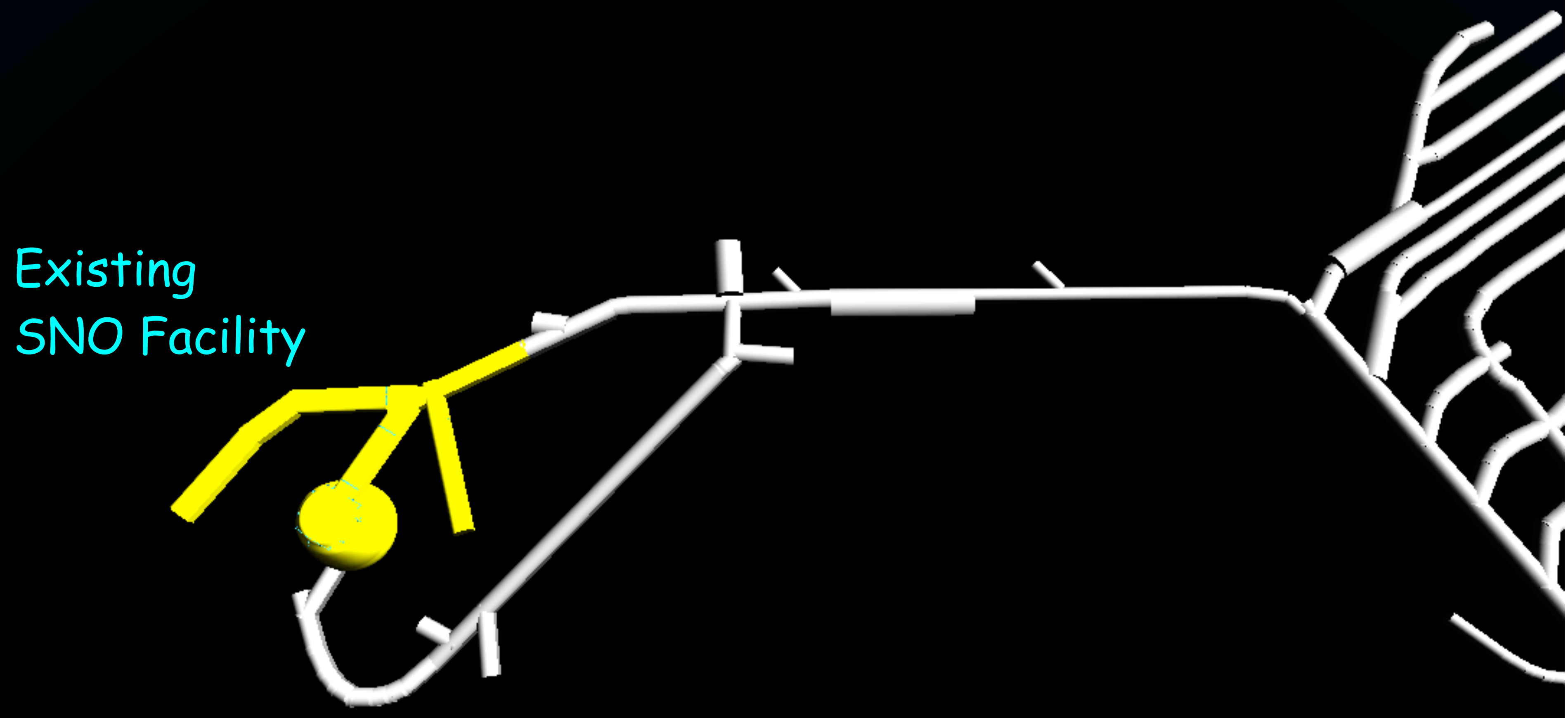
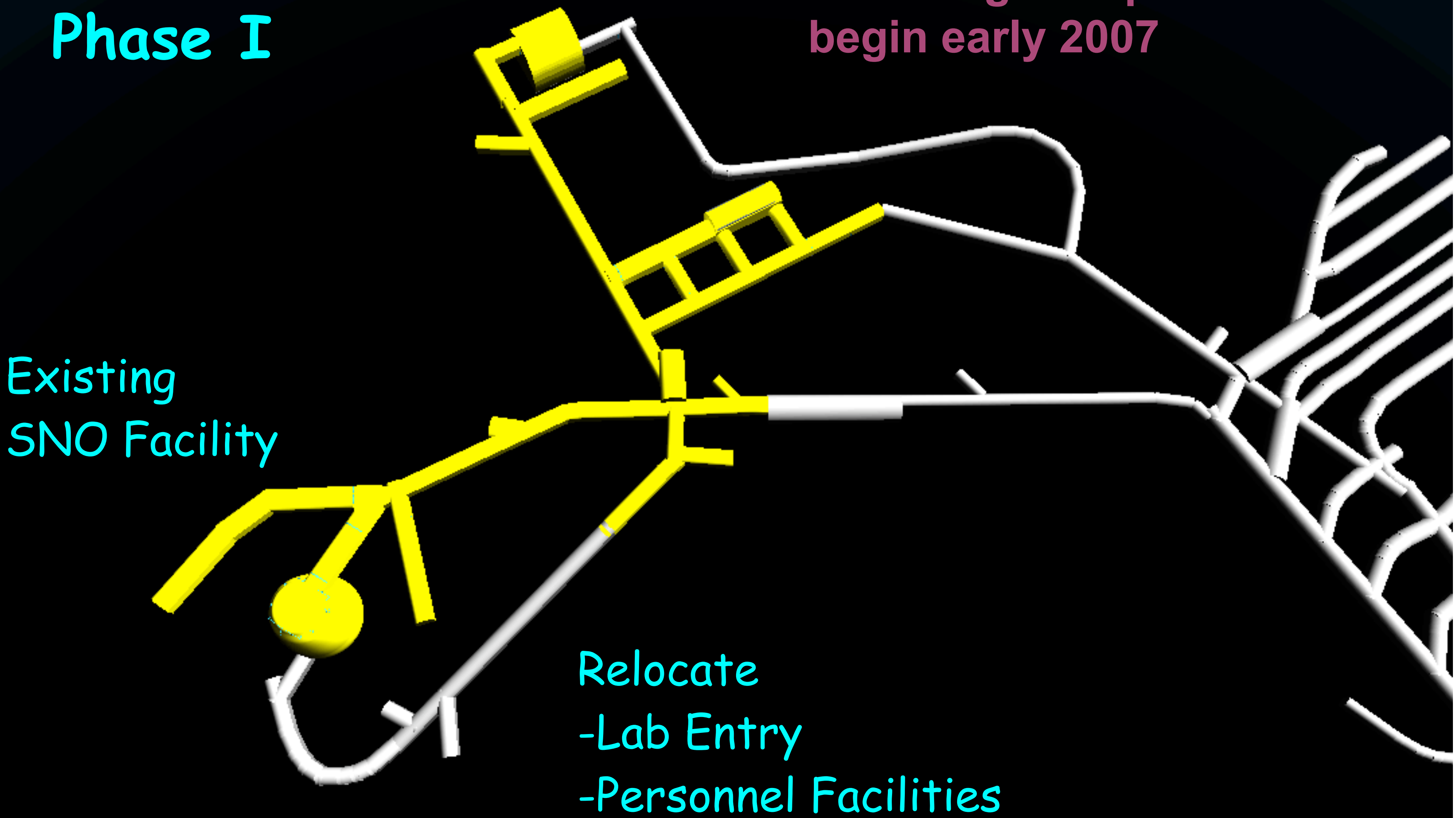


SNOLAB

Phase I

- Outfitting is expected to begin early 2007



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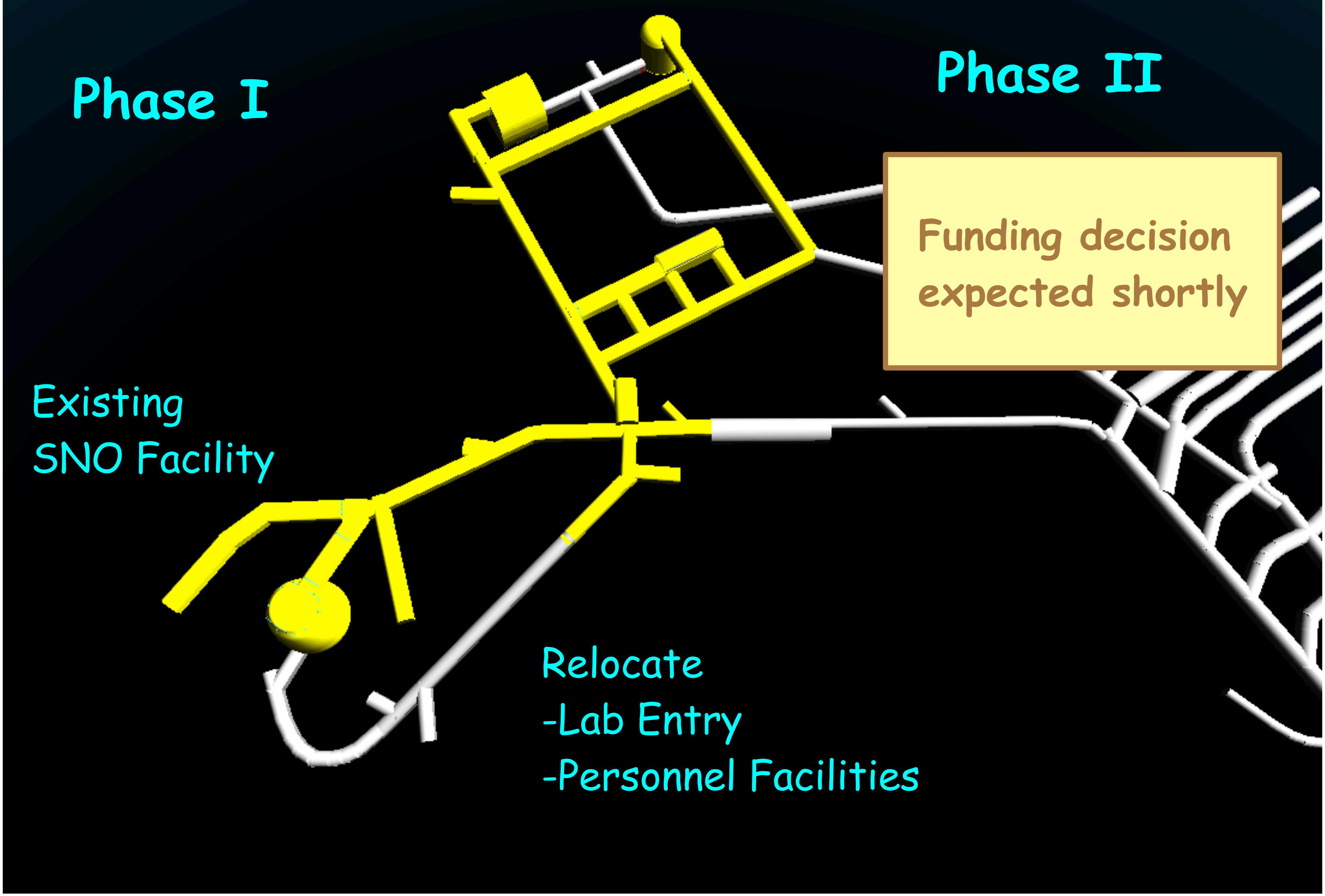
Phase I
Phase II
Funding decision expected shortly
Existing SNO Facility
Relocate
-Lab Entry
-Personnel Facilities