From SNO to SNOLAB

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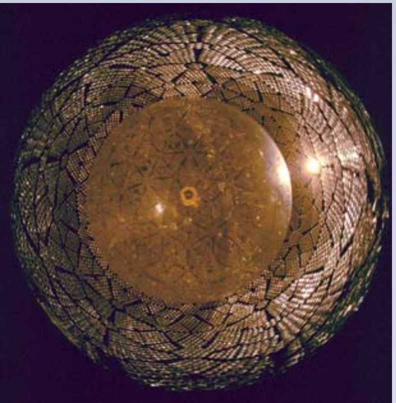


On behalf of the SNO Collaboration

The 10th ICATPP Conference
Villa Como, 8-12 October, 2007

Outline

- Introduction – Solar Neutrinos
- Sudbury Neutrino Observatory (SNO)
- Results and prospect
  - SNO Phases I (pure D_2O)
  - SNO Phase II (salt)
  - SNO Phase III (NCD)
- SNOLAB
  - Low energy solar neutrinos (SNO+)
  - Dark Matter (Picasso & DEAP)
  - Double beta decay (EXO)
- Summary and Conclusion

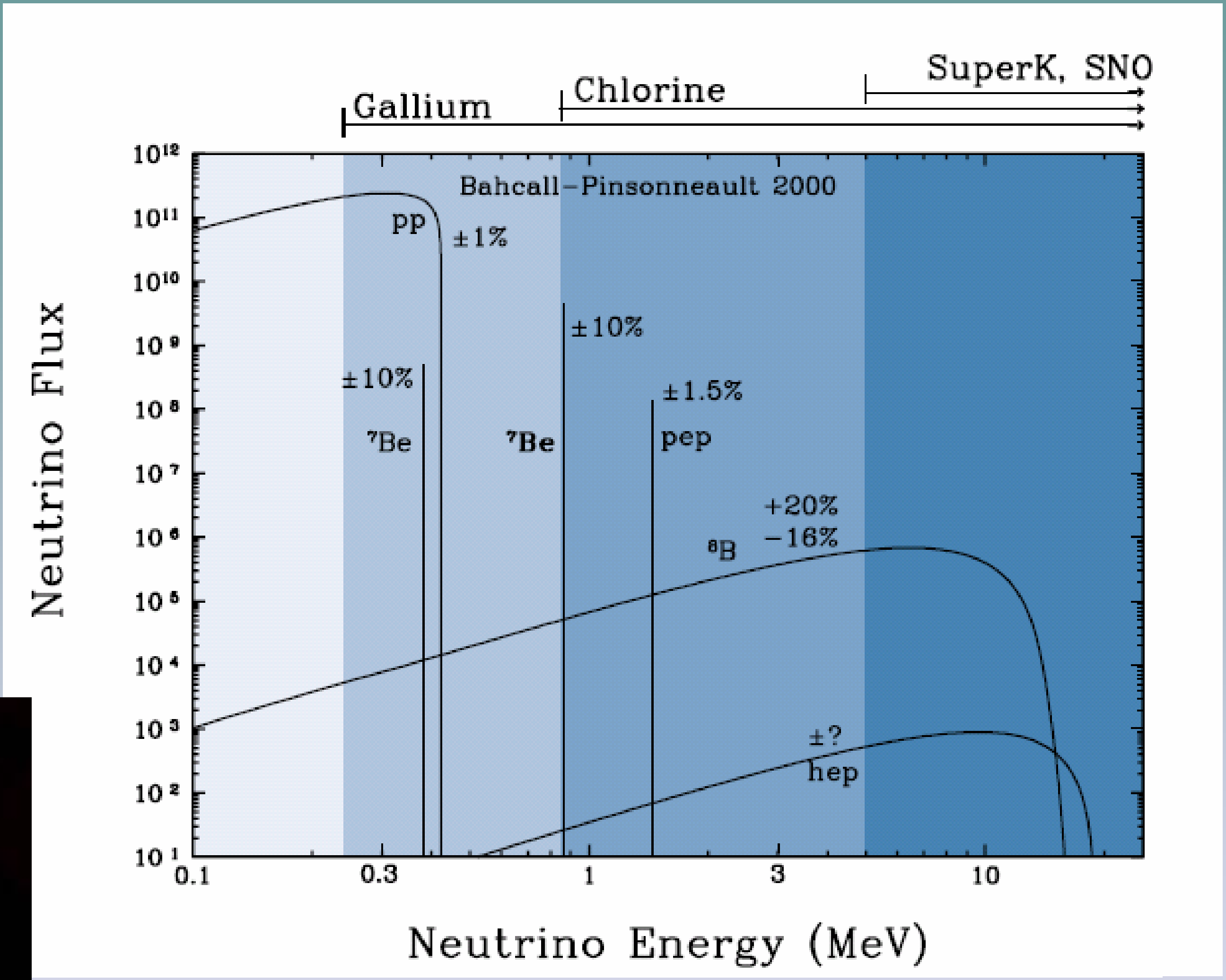
SNO Collaboration

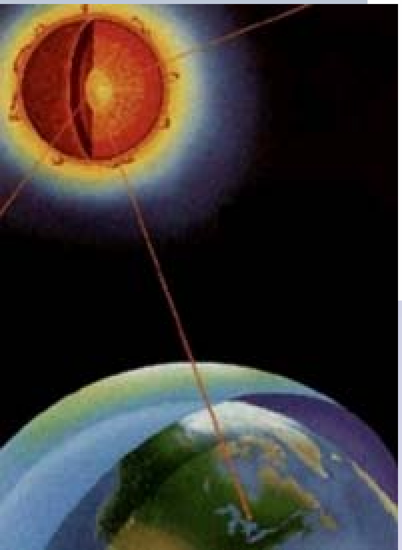
---Sudbury Neutrino Observatory

- Carleton University
- Laurentian University
- Queen’s University
- TRIUMF Laboratory
- University of British Columbia
- University of Guelph
- Oxford University

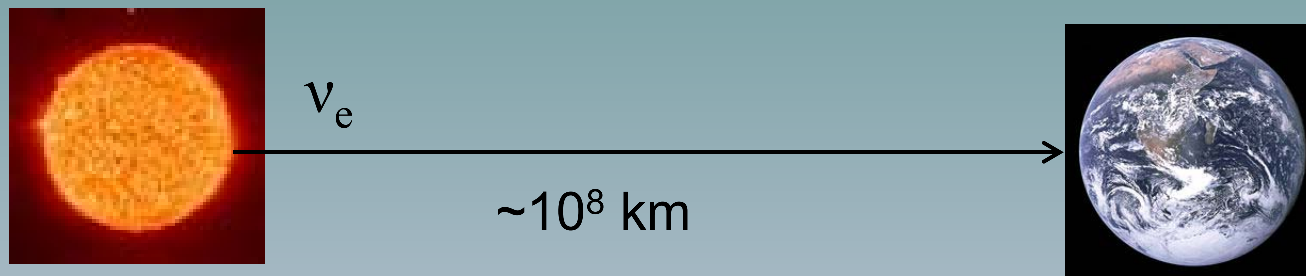
- Brookhaven National Laboratory
- Lawrence Berkeley National Laboratory
- Los Alamos National Laboratory
- University of Pennsylvania
- University of Texas at Austin
- University of Washington
- Massachusetts Institute of Technology
- LIP, Lisbon, Portugal

Solar Neutrinos





Solar Neutrino Problem (SNP)



Measured ≠ predicted

Neutrino reactions

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar}$$

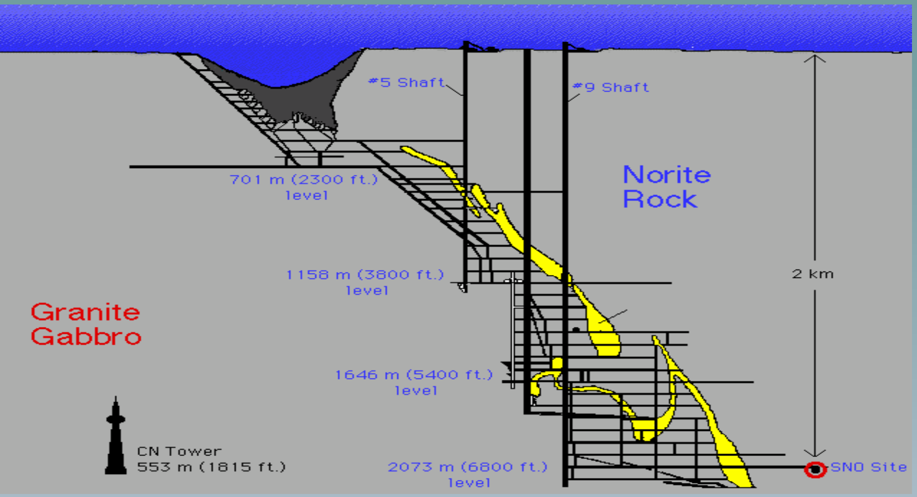
$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow e^- + {}^{71}\mathrm{Ge}$$

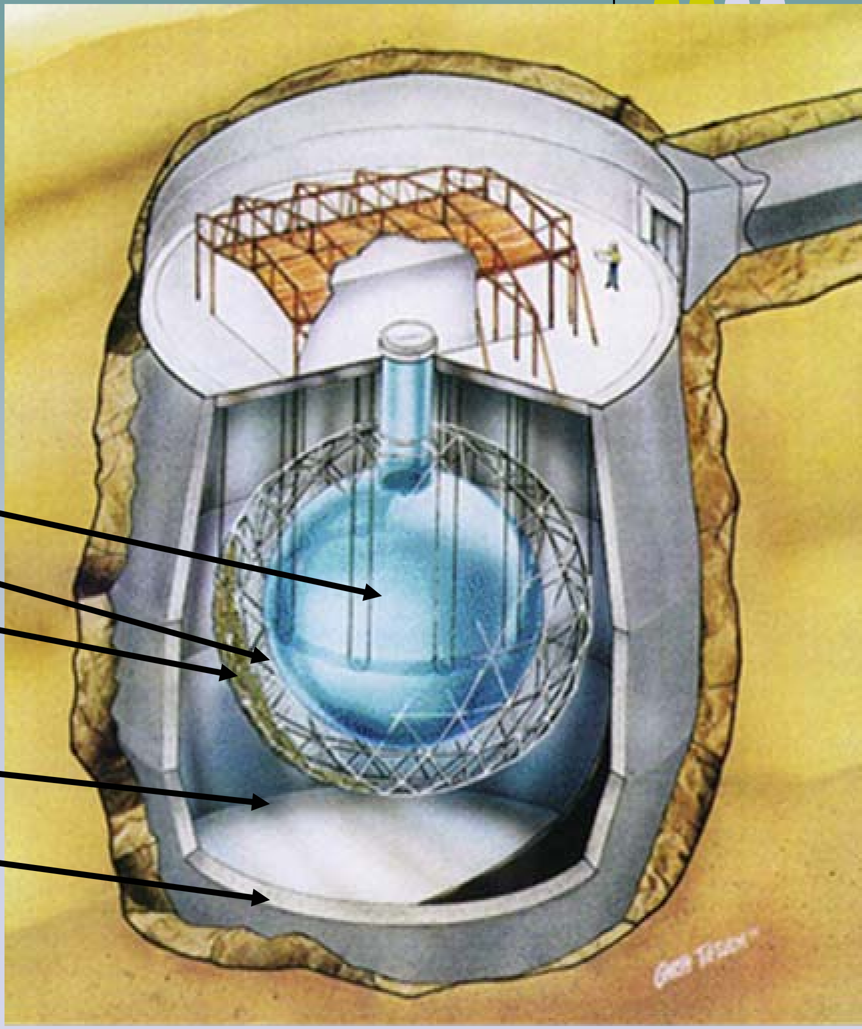
$$\nu_l + e^- \rightarrow \nu_l + e^-$$

Experiment	Medium	Threshold (MeV)	Measured/SSM
Homestake	Cl	0.814	[CC]=0.34±0.03
SAGE+GALLEX/GNO	Ga	0.2332	[CC]=0.52±0.03
SuperK	H_2O	7.0	[ES]=0.406±0.013

arXiv:hep-ph/0406294

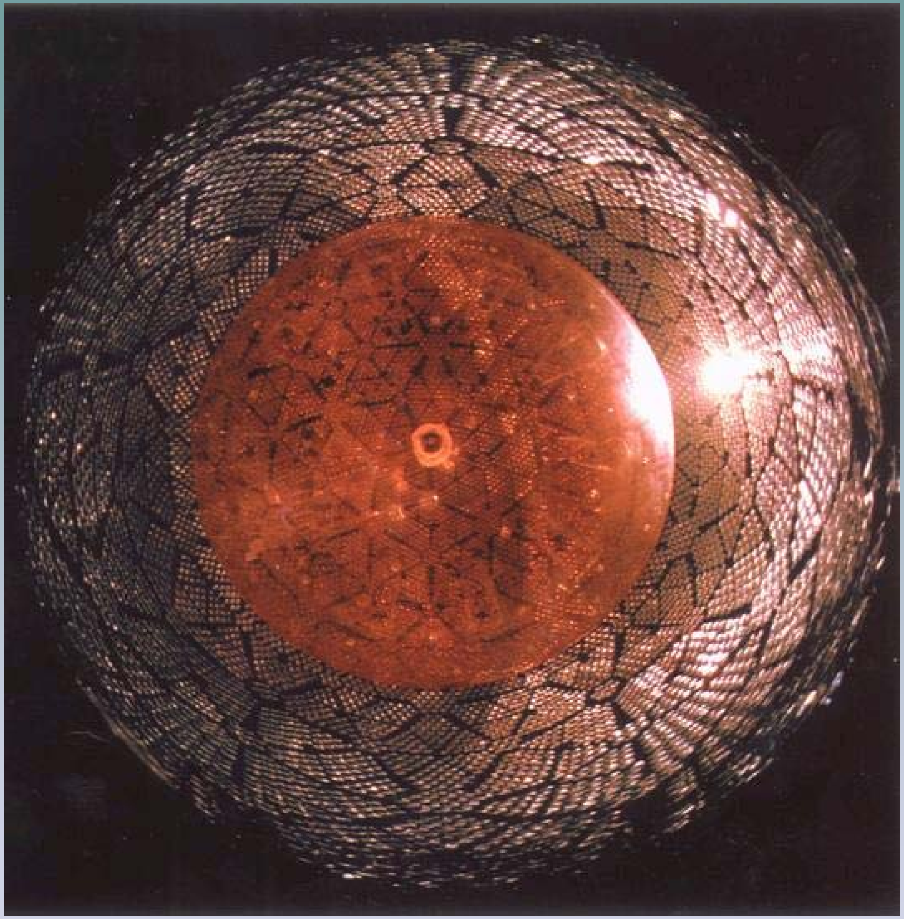
Sudbury Neutrino Observatory



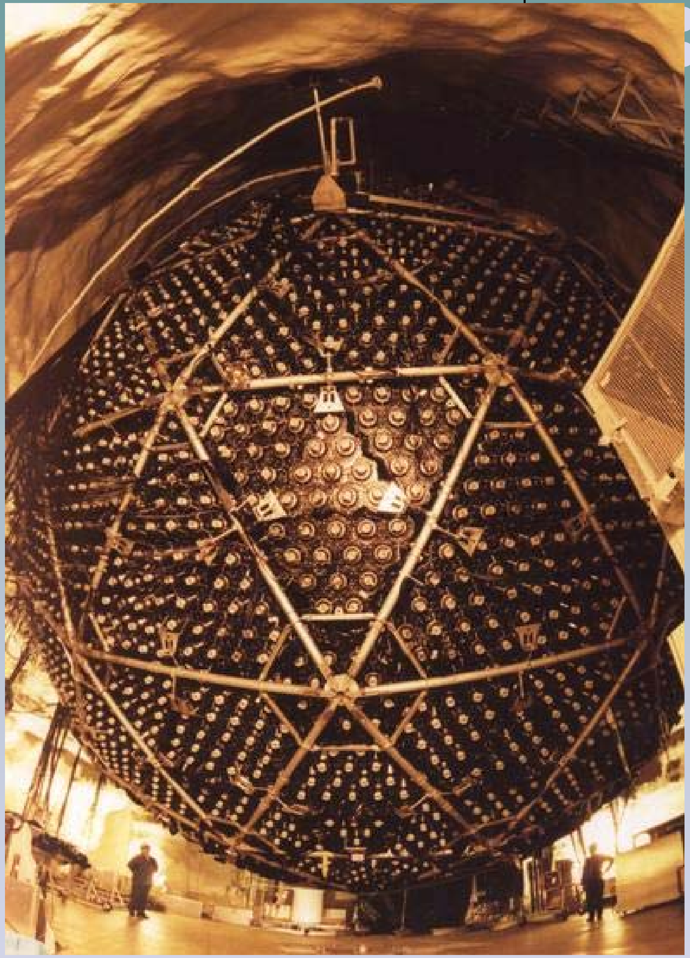


- 1,000 tons D2O.
- 6 m radius acrylic vessel.
- 9 m radius steel support structure
  9,500 PMTs , 54% coverage.
- 7,000 tonnes H2O shielding.
- Urylon liner and radon seal
- Low radioactive backgrounds materials are selected (e.g. U, Th).
- depth: 2092 m (~6010 m.w.e.) ~70 muons/day

The SNO Detector



View from the bottom of the SNO acrylic vessel and PMT array with a fish-eye lens

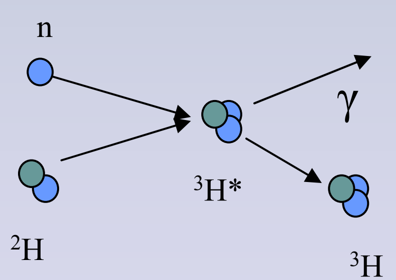


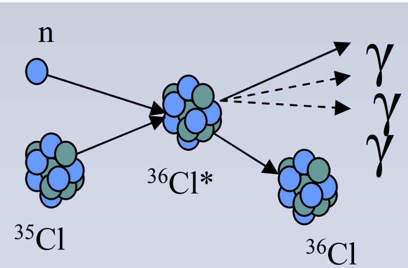
View of the SNO detector

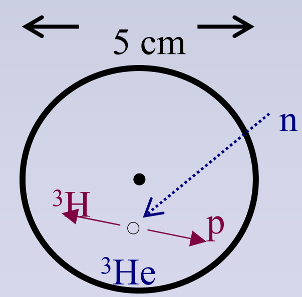
Three methods to detect the neutrons from the NC reaction in SNO

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

Phase I (D_2O) Nov. 99 - May 01	Phase II (Salt+D_2O) July 01 - Sep. 03	Phase III (^3He+D_2O) Nov. 04 - Nov. 06
	2t NaCl added	
n captures on Deuterium $^2H(n,\gamma)^3H$	n captures on Chlorine $^{35}Cl(n,\gamma)^{36}Cl$	n captures on ^3He counters $^3He(n,\gamma)^3H$
$\sigma = 0.0005b$ 6.25 MeV single γ PMT array readout	$\sigma = 44b$ 8.6 MeV multiple γs PMT array readout	$\sigma = 5330b$ 0.764 MeV(p,^3H) Independent readout
		Event by event separation

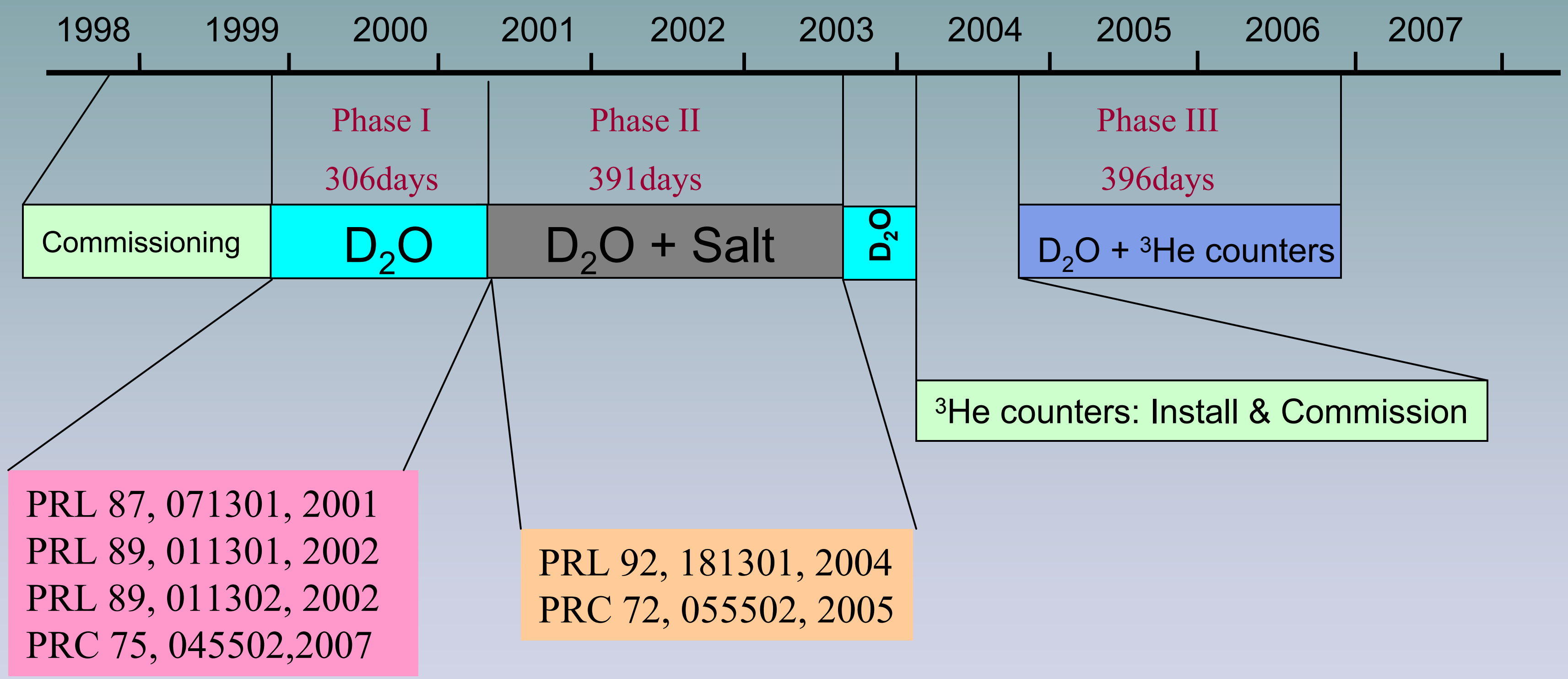






$n + {}^3He \rightarrow p + {}^3H$

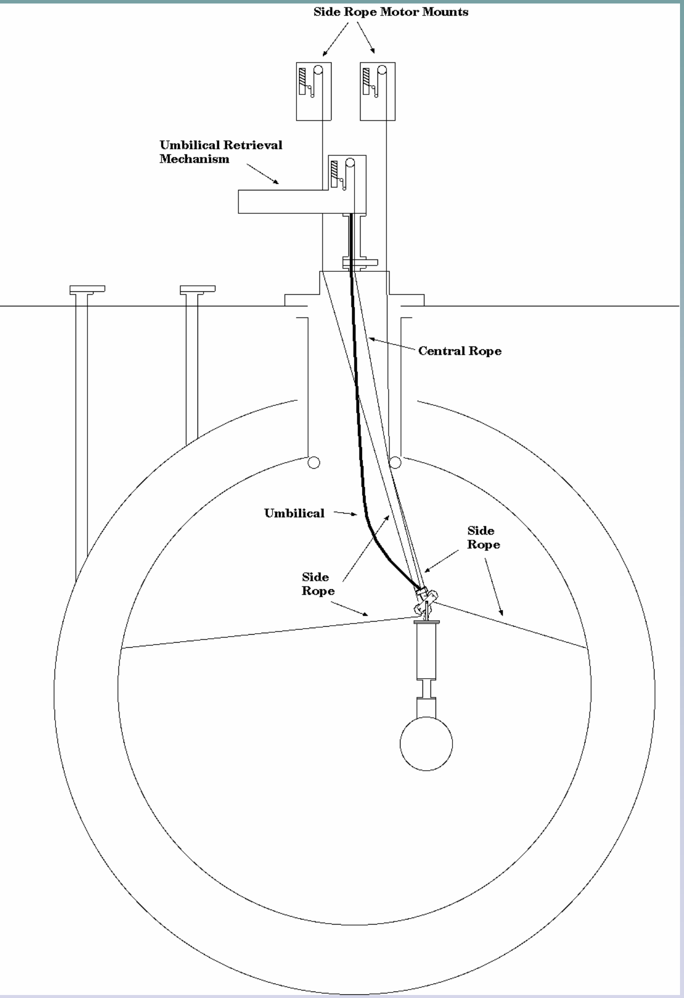
SNO timeline

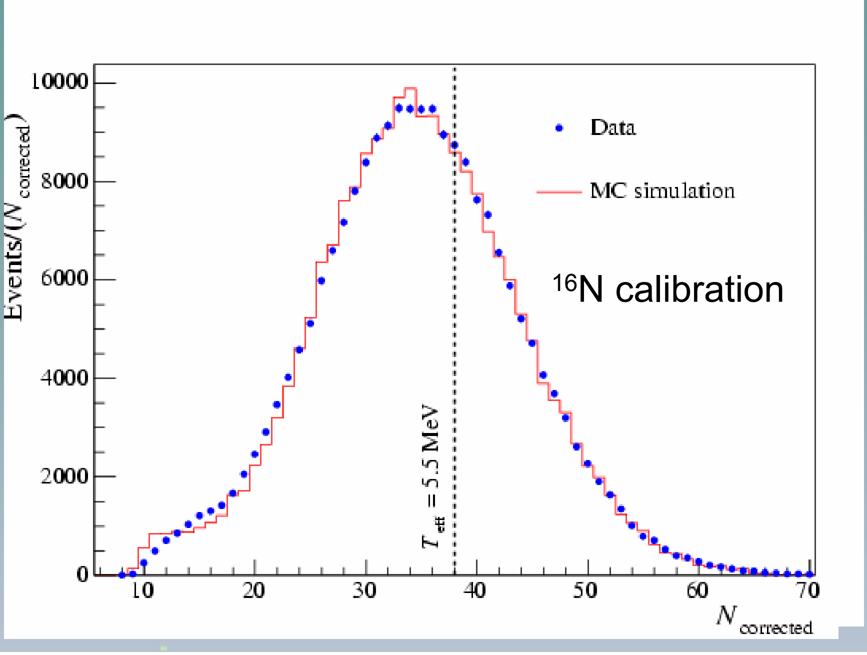


Total of ~1100 live days

Calibration of SNO detector

Phys. Rev. C 72, 055502 (2005)

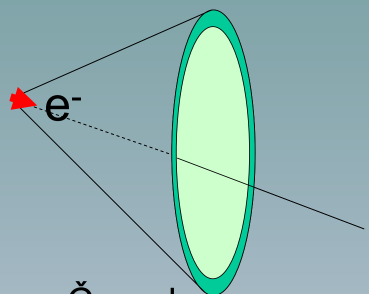




Calibration source	Details	Calibration
Pulsed nitrogen laser	337, 369, 385, 420, 505, 619 nm	Optical & timing calibration
^{16}N	6.13-MeV γ-rays	Energy & reconstruction
^{8}Li	β spectrum	Energy & reconstruction
^{252}Cf	neutrons	Neutron response
Am-Be	neutrons	Neutron response
^{3}H(p, γ)^{4}He ("pT")	19.8-MeV γ-rays	Energy linearity
U, Th	$\beta-\gamma$	Backgrounds
^{88}Y	$\beta-\gamma$	Backgrounds
Dissolved Rn spike	$\beta-\gamma$	Backgrounds
In-situ ^{24}Na activation	$\beta-\gamma$	Backgrounds

Neutrino detection

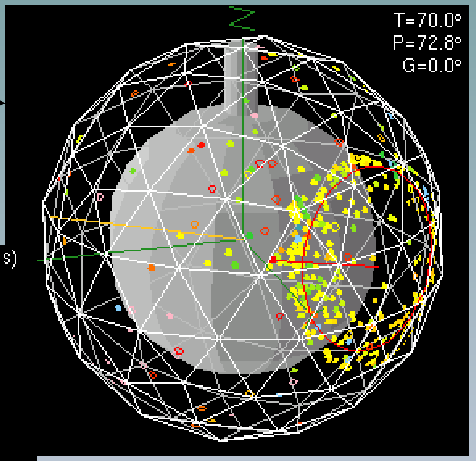
PMT array measurement:

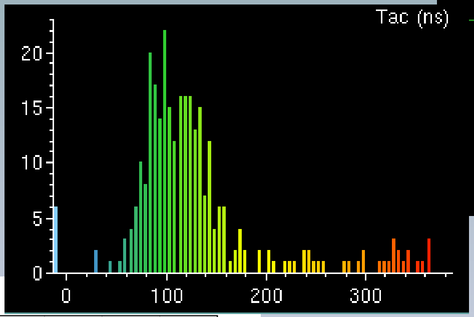


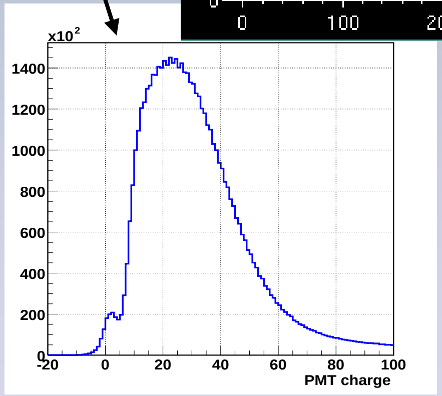
Čerenkov photons

Position
Time
Charge

PMT hits



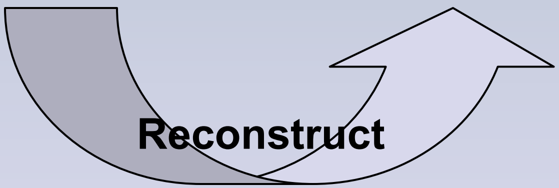




e^- from **CC** or **ES** reaction

Compton-scattered e^- of γs from *n*-capture (**NC** reaction) in the detector

vertex
direction energy

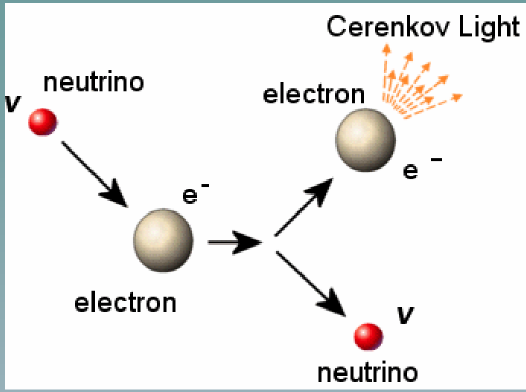


Neutrino reactions in SNO detector

ES

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

- Mostly sensitive to ν_e, some ν_μ,ν_τ
- Strong directional sensitivity



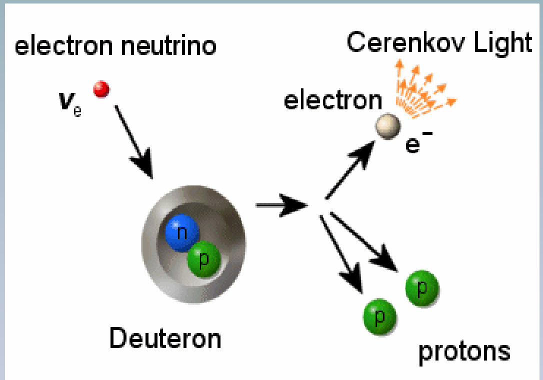
CC

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

-Q = 1.44 MeV

-Measure ν_e energy spectrum

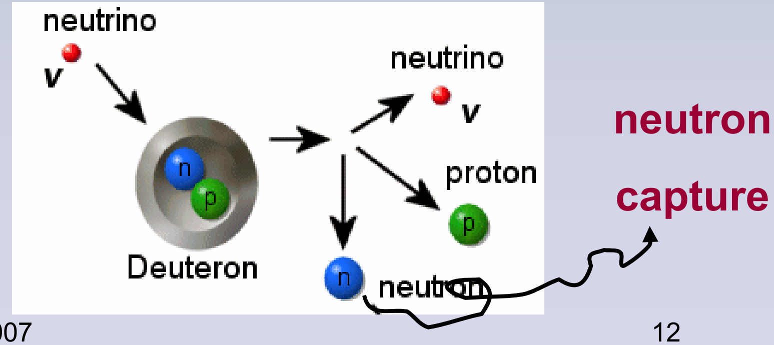
-Sensitive to ν_e only



NC

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

- Q = 2.22 MeV
- Equally sensitive to 3 active ν flavors
- Measures total ^8B ν flux (SNO only)



Key signatures for ν oscillations of SNO

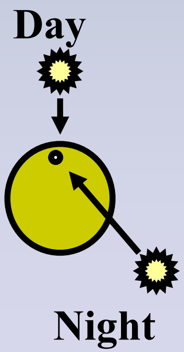
flavor change?

$$\frac{\Phi_{CC}}{\Phi_{ES}} = \frac{\nu_e}{\nu_e + 0.154(\nu_\mu + \nu_\tau)}$$

ES:
- Strong directional sensitivity, θ_{sun}
- Super-K precision measurement

$$\frac{\Phi_{CC}}{\Phi_{NC}} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau}$$

NC:
- Equally sensitive to 3 flavors
- Cross section uncertainties cancel



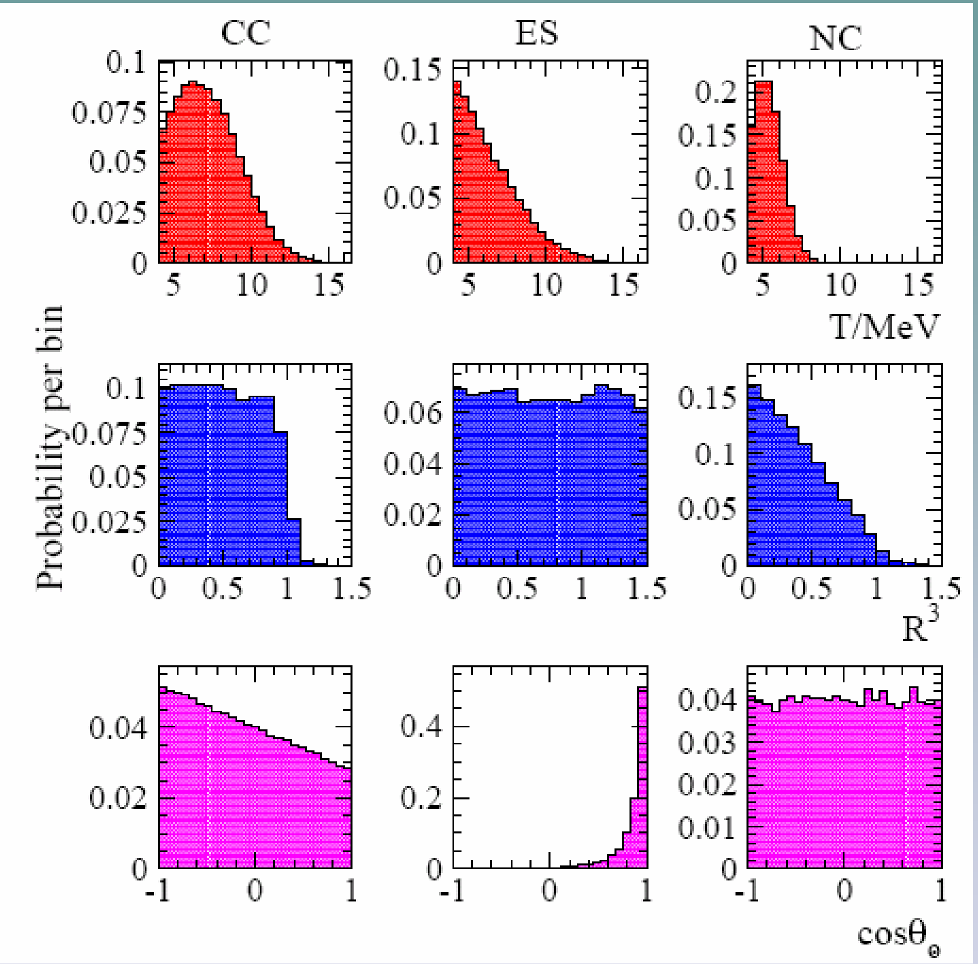
Φ_{day} vs Φ_{night}

Neutrino Signal Extraction from PMT Data

Energy Distribution

Radial Distribution (R^3, R_{AV}=1)

Solar Direction Distribution



Maximum likelihood statistical separation of the signals (PMT data).

The energy (top row), radial (middle row), and directional (bottom row) distributions used to build pdfs to fit the SNO signal data

D2O Phase

Results of the SNO Experiment

Phase I

Pure D_2O

Nov. 1999 - May 2001

Shape Constrained Neutrino Fluxes (D_2O)

Signal Extraction in Φ_{CC}, Φ_{NC}, Φ_{ES} with $E_{Theshold}$ > 5 MeV

$$\Phi_{cc}(\nu_e) = 1.76^{+0.06}_{-0.05}\text{(stat.)}^{+0.09}_{-0.09}\text{(syst.)} \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$$

$$\Phi_{es}(\nu_x) = 2.39^{+0.24}_{-0.23}\text{(stat.)}^{+0.12}_{-0.12}\text{(syst.)} \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$$

$$\Phi_{nc}(\nu_x) = 5.09^{+0.44}_{-0.43}\text{(stat.)}^{+0.46}_{-0.43}\text{(syst.)} \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$$

Signal Extraction in Φ_e, $\Phi_{\mu\tau}$

$$\Phi_e = 1.76^{+0.05}_{-0.05}\text{(stat.)}^{+0.09}_{-0.09}\text{(syst.)} \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$$

$$\Phi_{\mu\tau} = 3.41^{+0.45}_{-0.45}\text{(stat.)}^{+0.48}_{-0.45}\text{(syst.)} \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$$

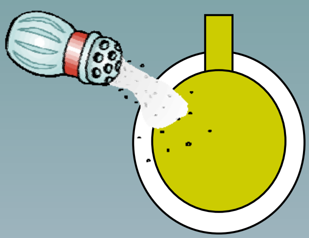
Phase II

2 tons NaCl added in D_2O

July 2001 - Sep. 2003

Phase II (SALT)

Phys. Rev. C 72, 055502 (2005)

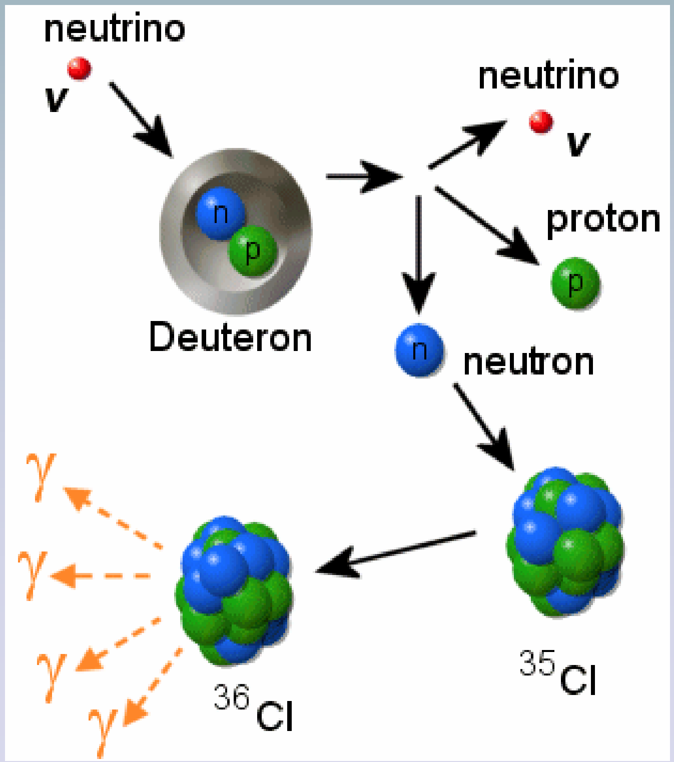


2 tons NaCl added into the D2O

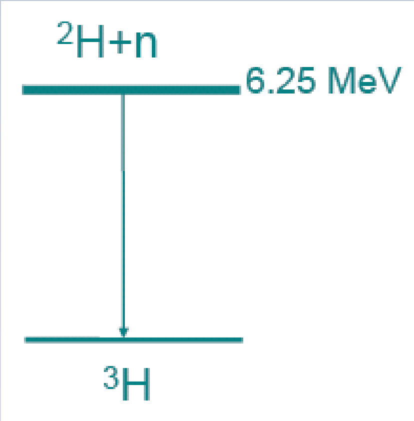
- Higher neutron capture cross section
- Higher energy release (totally 8.6MeV)
- Multiple gammas (averagely 2.5γs)

σ = 44 b

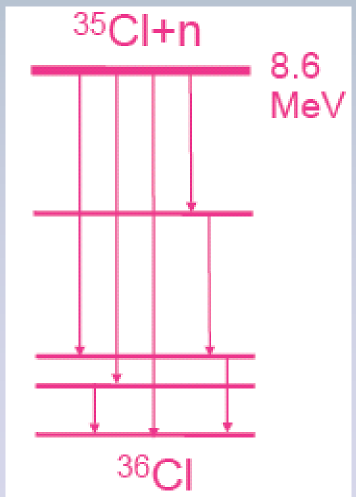
NC:



σ = 0.0005 b



Pure d2o

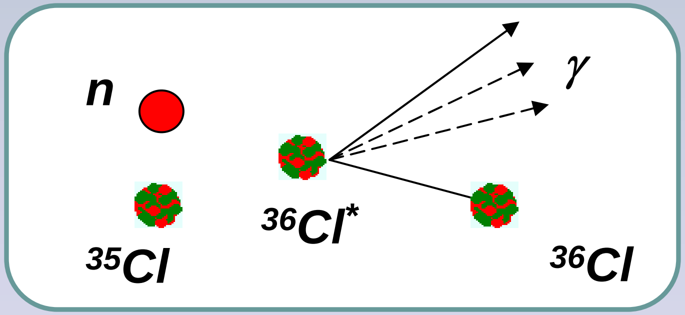


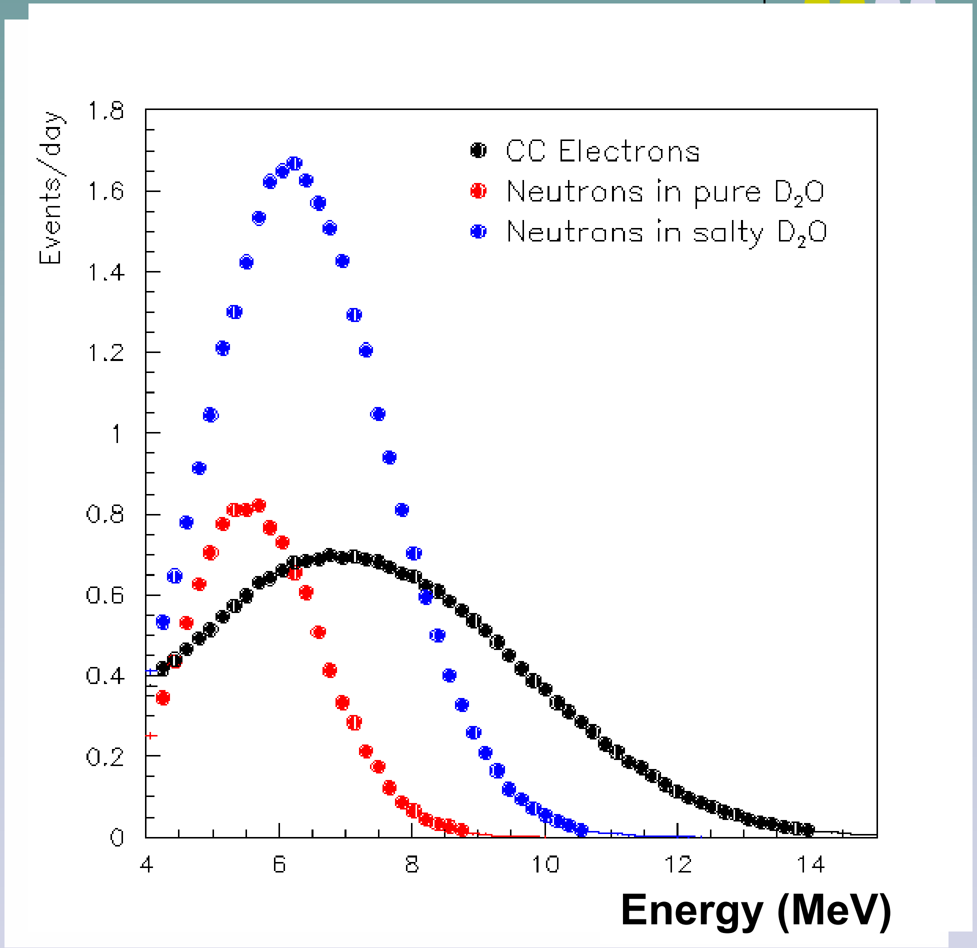
Salt added

A.Bellerive: Villa como, Oct. 2007

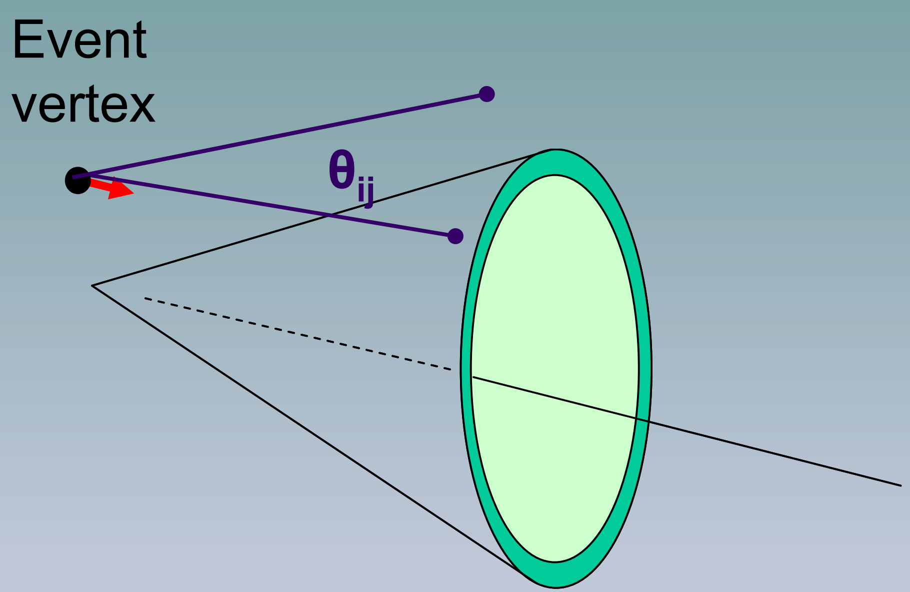
Advantages of Salt: more sensitive

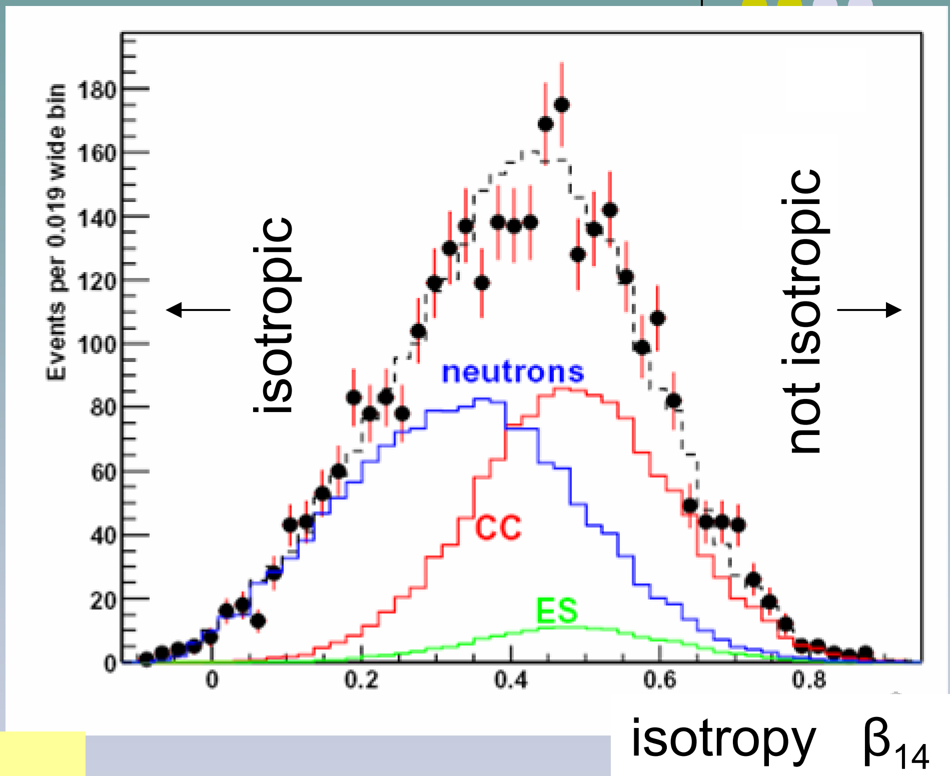
- Neutrons capturing on ^{35}Cl provide higher neutron energy above threshold.
- Higher capture efficiency
- Gamma cascade changes the angular profile.





Advantages of salt: event isotropy



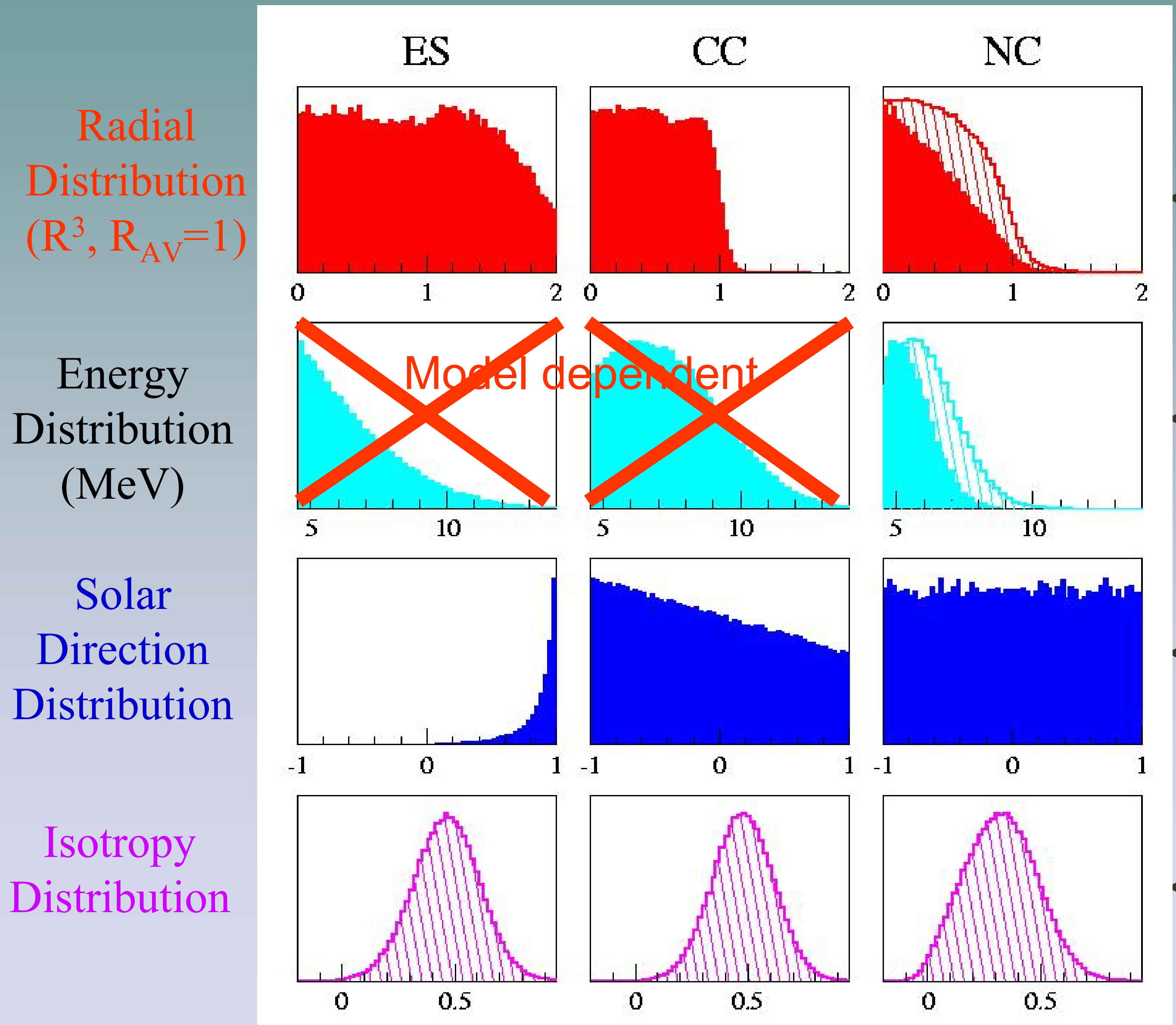


Isotropy variable, β_{14} , function of angles between each pair of hit PMTs (**θ_{ij}**) in event [similar to *thrust* in collider physics]

β_{14} powerful discriminating variable between NC and CC/ES events

Salt phase (July 2001 – September 2003)

$$n + {}^{35}\mathrm{Cl} \rightarrow {}^{36}\mathrm{Cl}^* \rightarrow {}^{36}\mathrm{Cl} + \gamma' s$$



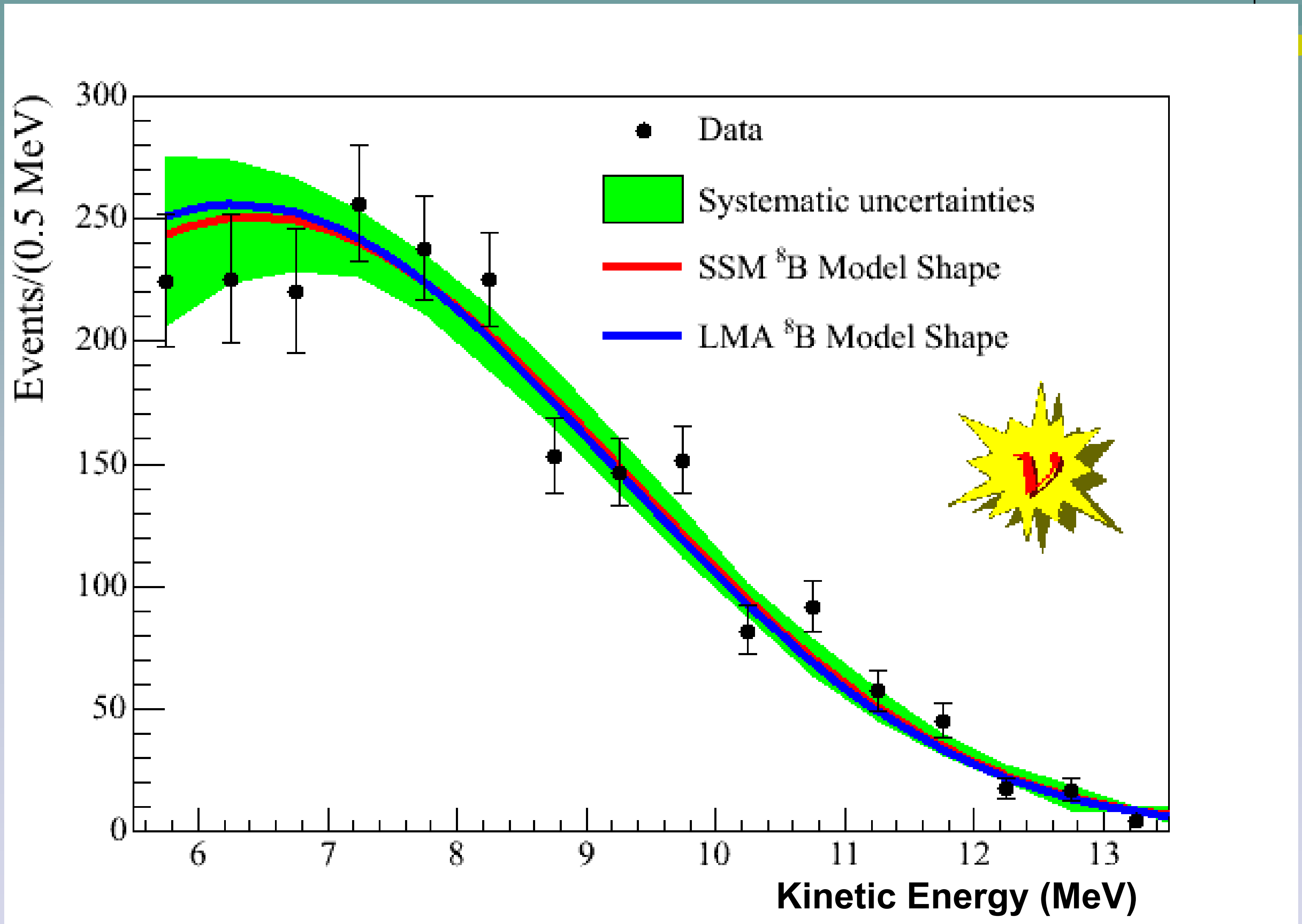
NC changed due to larger $\sigma_{n\gamma}$

NC shifted to higher energy

Unchanged

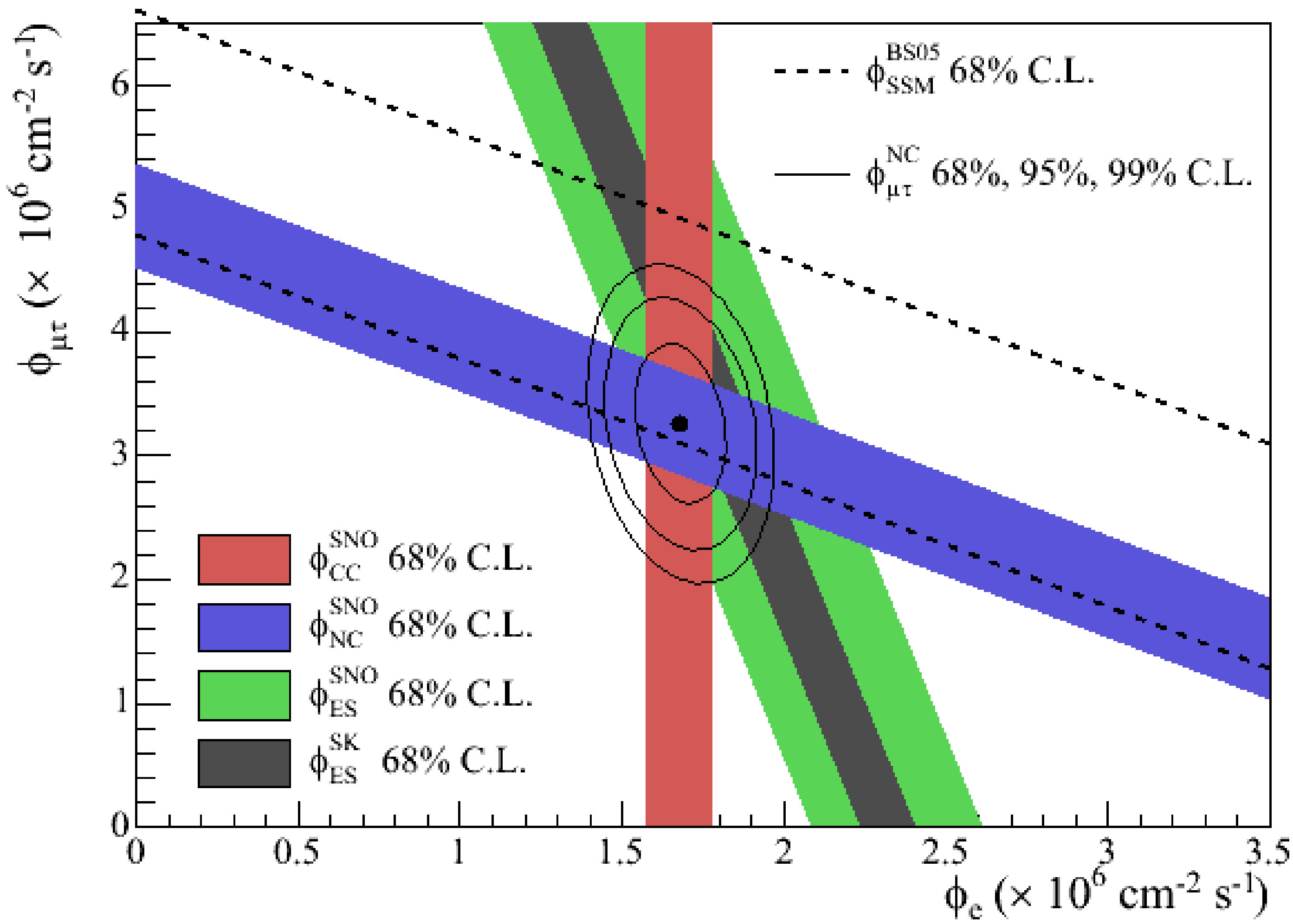
All new due to multiple γ's

Charged Current (CC=ν_e) Spectrum



Salt results & comparison to SSM

More precise salt results confirm D_2O results



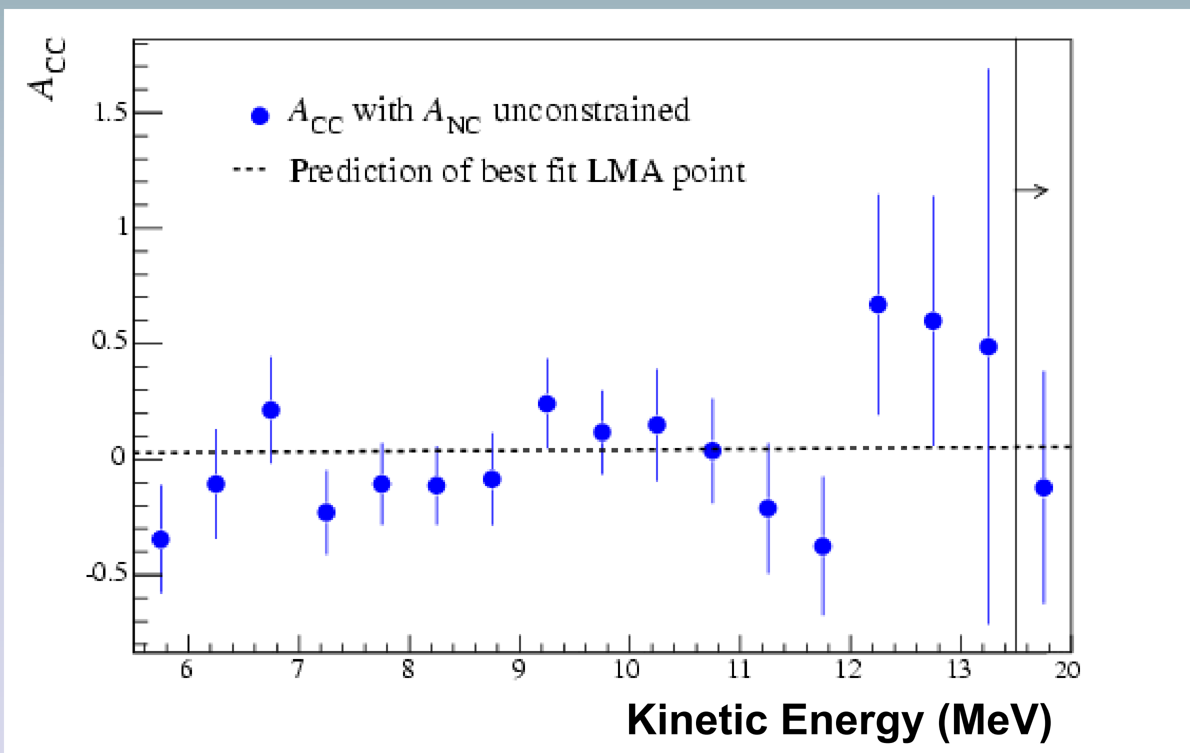
Day/Night Asymmetries

$$A_X = \frac{(\Phi_{night} - \Phi_{day})}{(\Phi_{night} + \Phi_{day})/2}$$

A_{CC}= -0.056 ± 0.074 (stat.) ± 0.051 (syst.)

A_{NC}= 0.042 ± 0.086(stat.) ± 0.067 (syst.)

A_{ES}= 0.146 ± 0.198(stat.) ± 0.032 (syst.)



A_{CC} and A_{NC} are correlated (ρ = -0.532)

In standard neutrino oscillations, A_{NC} should be zero…

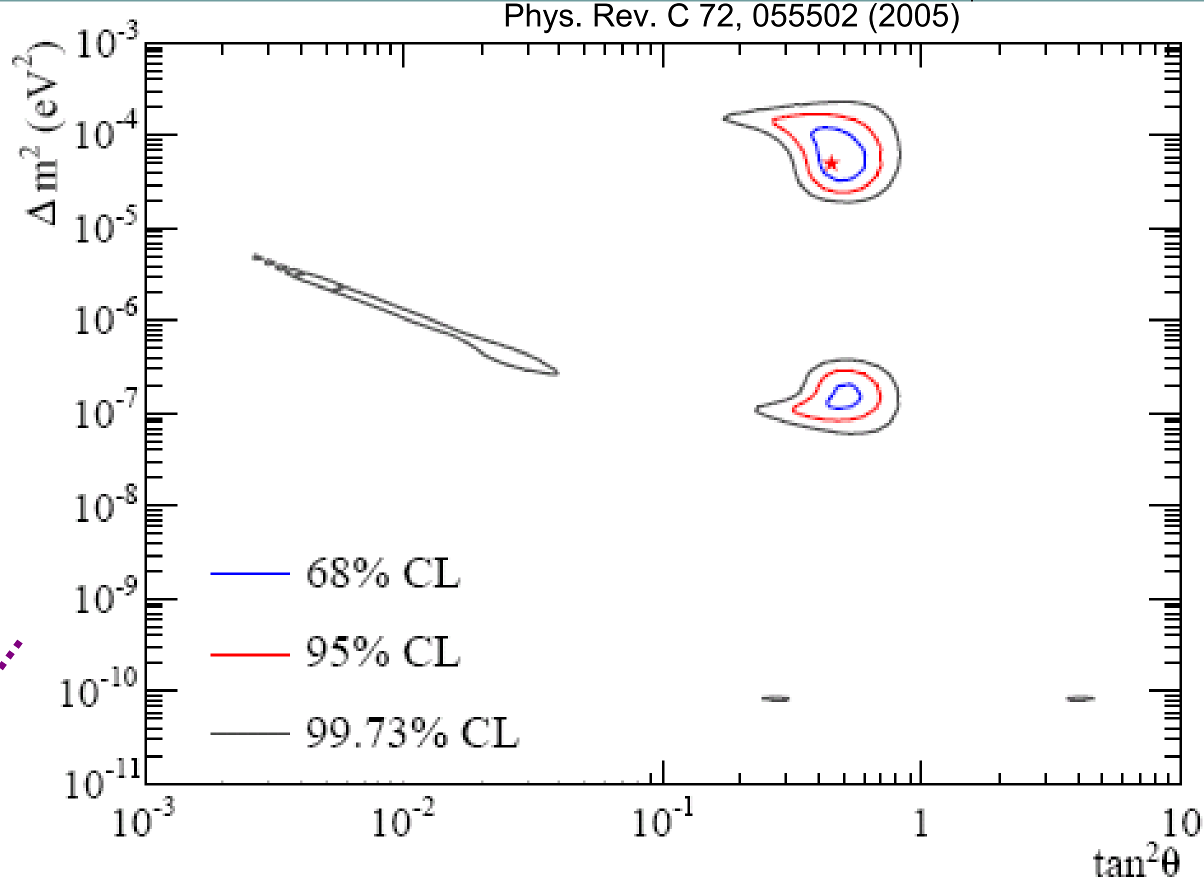
SNO Phase I & II (D_2O & salt)

Oscillation analysis

SNO-only neutrino oscillation analysis, including pure D2O and salt phase dataset.

The ^{8}B flux was free in the fit; hep solar neutrinos were fixed at 9.3×10^3 cm^{-2} s^{-1}.

Phys. Rev. C 72, 055502 (2005)



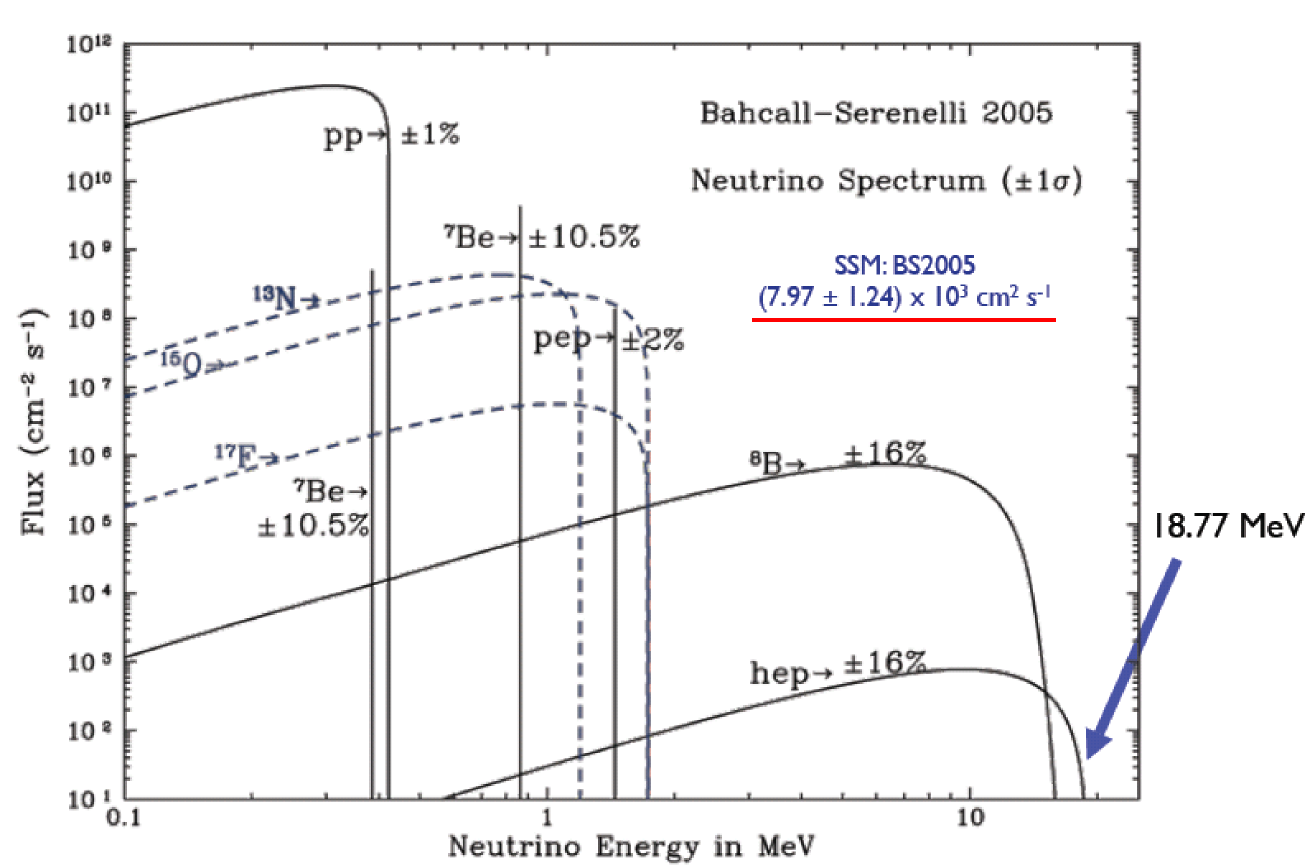
Oscillation analysis	Δm^2 (10^{-5} eV^2)	$\tan^2\theta$
SNO-only	$5.0^{+6.2}_{-1.8}$	$0.45^{+0.11}_{-0.10}$
Global solar	$6.5^{+4.4}_{-2.3}$	$0.45^{+0.09}_{-0.08}$
Solar plus KamLAND	$8.0^{+0.6}_{-0.4}$	$0.45^{+0.09}_{-0.07}$

- Contains Cl, Sage, Gallex/GNO and SK-1 zenith data
- 8B flux free in fit, hep flux fixed to 9:3 $\times 10^3$ cm^{-1}s^{-1}

SNO hep Solar Neutrino analysis

Pure D_2O dataset **hep reaction in the pp chain:**

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



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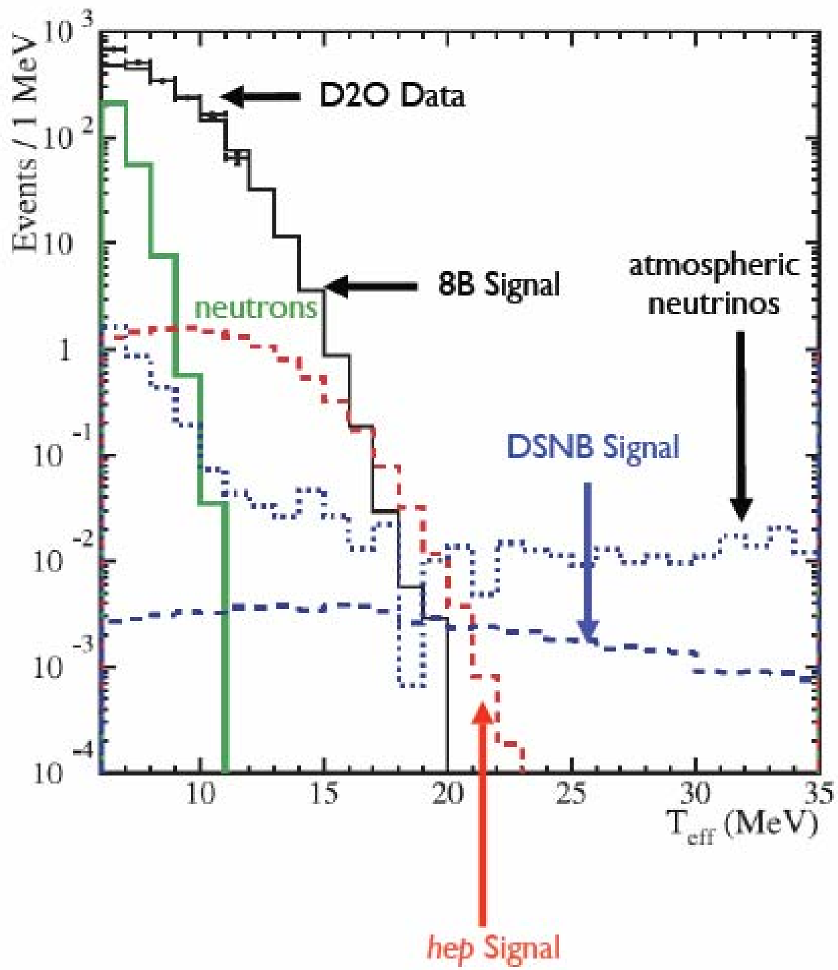
SNO hep and DSNB ν analysis

DSNB: Diffuse Supernova Neutrinos



→Both signals lie in the region between ^{8}B solar neutrinos and atmospheric neutrinos

→Search by counting number of events within a predefined energy window or signal box …

hep neutrinos

- Dominant background is ^{8}B solar neutrinos
- Normalize with low-energy fit with account for neutrino oscillations ($6 < T_{eff} < 12$ MeV)

DSNB neutrinos

- Dominant background is atmospheric neutrinos
- Signal region $21 < T_{eff} < 35$ MeV

Pure D2O dataset

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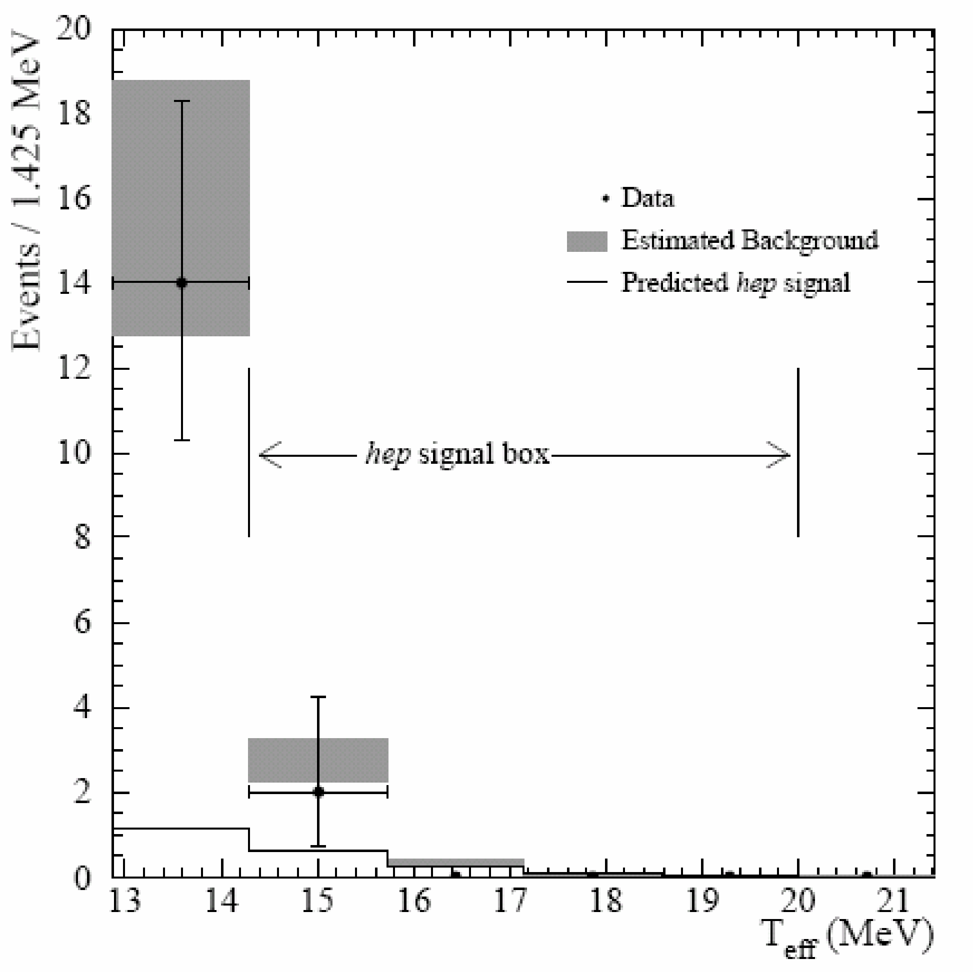
SNO hep and DSNB ν analysis

Pure D2O dataset



***hep* neutrinos**

- 2 events in signal box
- consistent with expected backgrounds
- Φ_{hep} < 2.3 x 10^4 cm^{-2}
  - 90% confidence level upper
  - 2.9 times SSM prediction
  - 6.5 times better than SK limit

DSNB neutrinos

- 0 events in signal box
- 0.18 background events expected
- Φ_{DSNB}< 70 cm^{-2} for 22.9<E_ν<36.9 MeV
  - 90% confidence level upper limit
  - average of 5 models
  - 10^2 better than previous MB limit

Astrophys.J. 653 (2006) 1545-1551

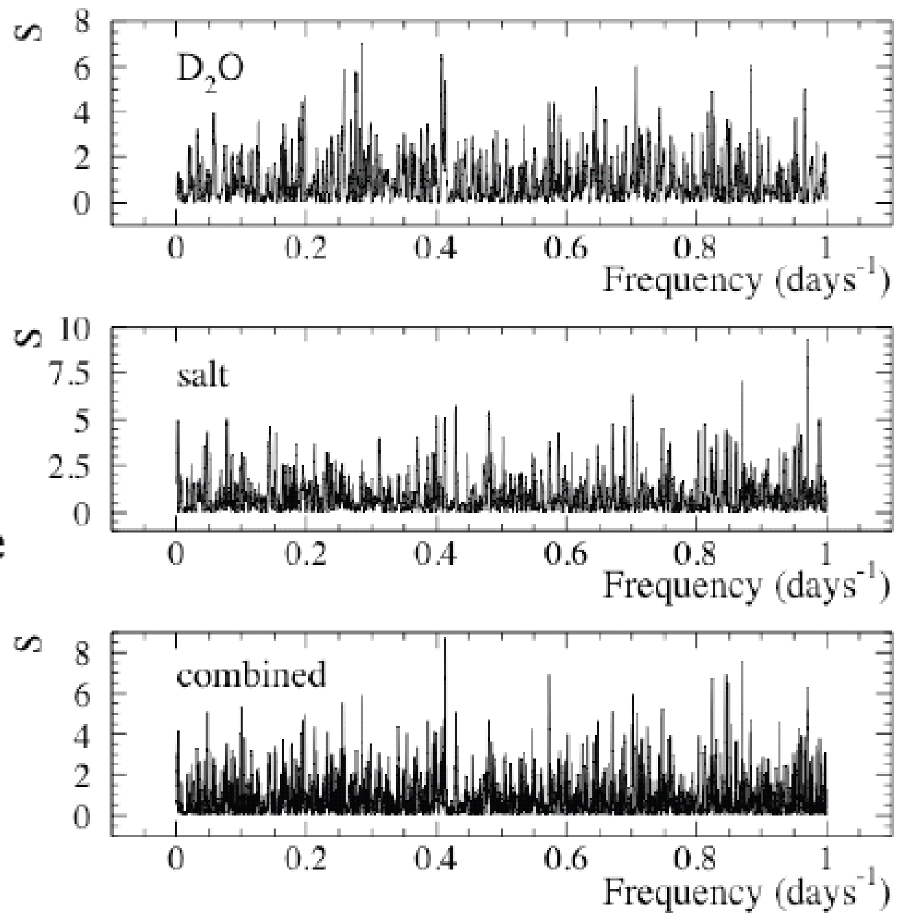
Periodicity Analysis of SNO Data

A periodicity analysis on the D_2O and salt data sets was performed using both a Lomb-Scargle periodogram and an unbinned maximum likelihood fit (PRD 72 052010, 2005)

For the combined data sets, the largest peak occurs at a period of 2.4 days, with a statistical significance of S=8.8

Monte Carlo shows that 35% of simulated data sets give a peak at least this large

No statistically significant periodicity was found



Phys. Rev. D 72, 052010 (2005)

Results from the SNO Experiment

Phase III

^{3}He Proportional Counters

Nov. 2004 - Nov. 2006:

SNO Phase III (^{3}He Proportional Counters)

^{3}He Proportional Counters (“NC Detectors”)

Detection Principle

$$^2H + \nu_x \rightarrow p + n + \nu_x - 2.22\ \text{MeV} \qquad \text{(NC)}$$
$$^3He + n \rightarrow p + {}^3H + 0.76\ \text{MeV}$$

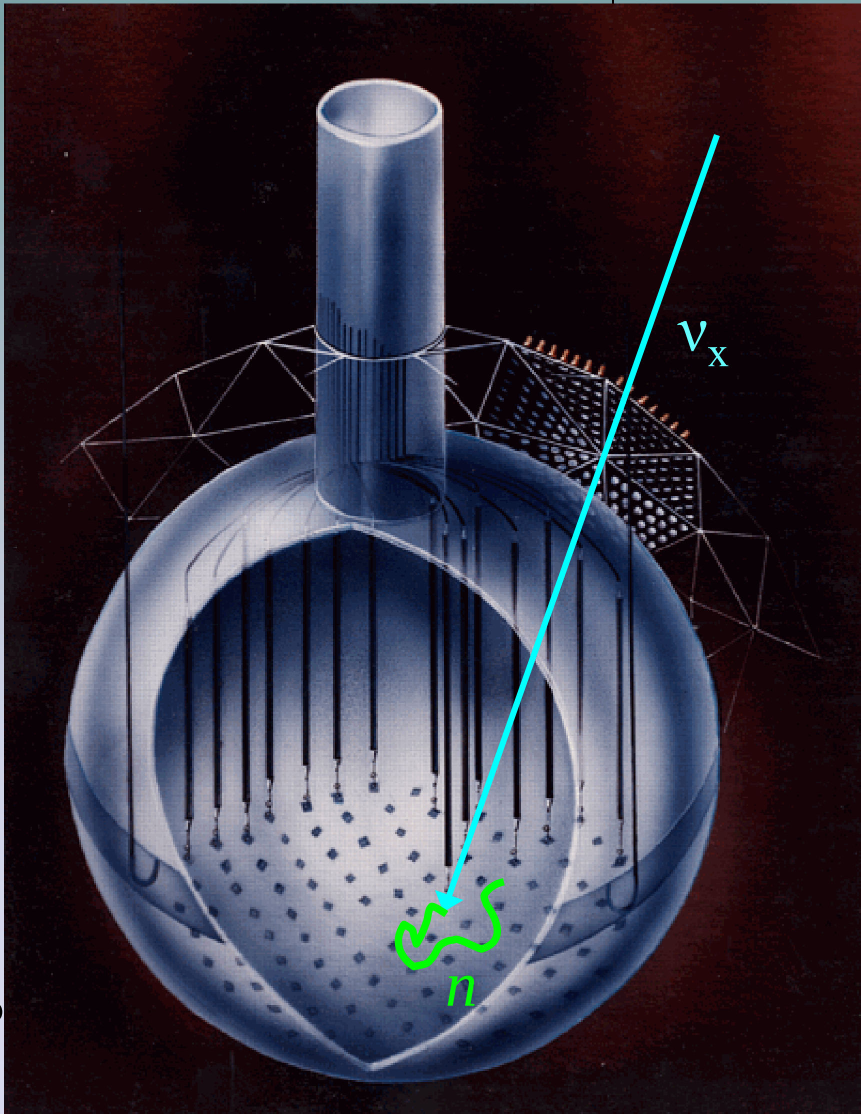
40 Strings on 1-m grid

398 m total active length

Physics Motivation

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

Different systematic uncertainties than neutron capture on NaCl.



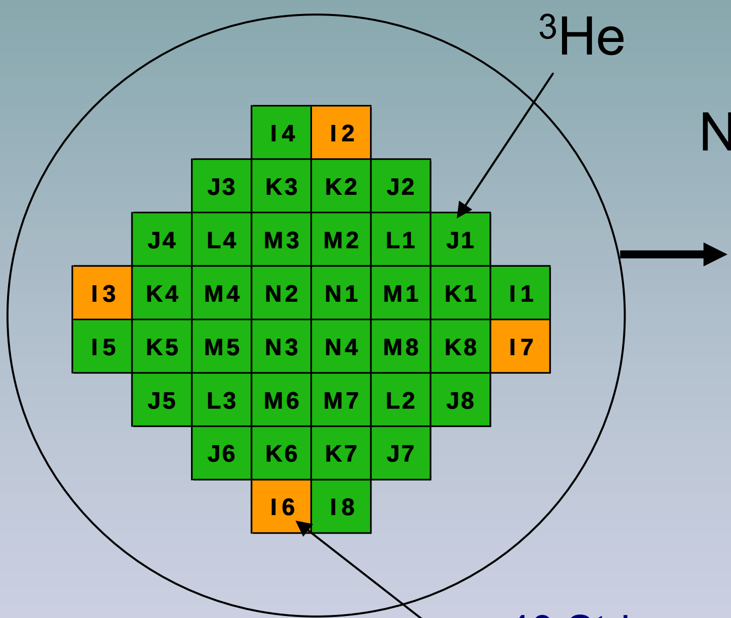
SNO Phase III (^{3}He Proportional Counters)

	D_2O unconstrained	D_2O constrained	Salt unconstrained	^{3}He
NC,CC	-0.950	-0.520	-0.521	~0
CC,ES	-0.208	-0.162	-0.156	~-0.2
ES,NC	-0.297	-0.105	-0.064	~0

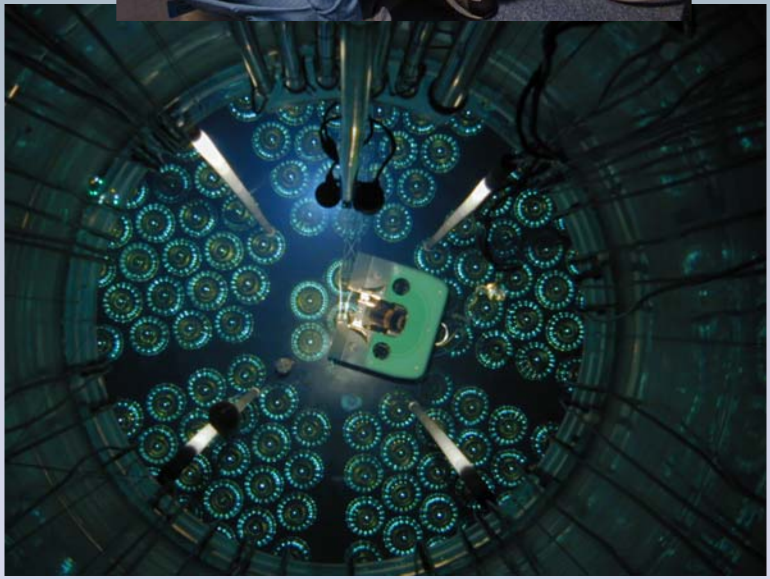
Correlation Coefficients between the CC, ES, and NC events

SNO Phase III (^{3}He Proportional Counters)

The positions of the NCD strings projected onto the plane of the AV equator



Installation of the NCD strings



40 Strings on 1-m grid

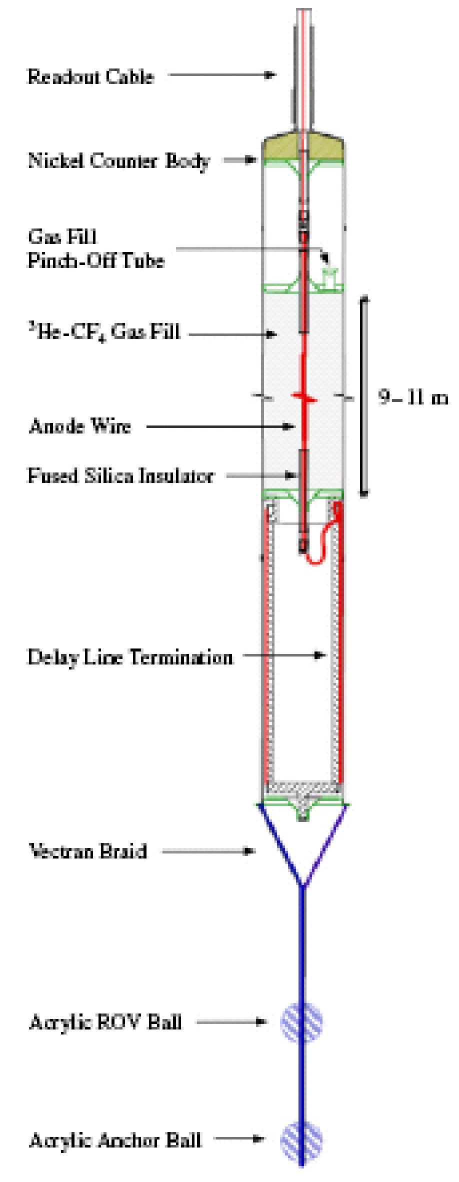
398 m total active length

36 ^{3}He Strings and 4 ^{4}He strings for determination of α background

NIM A 579 (2007) 1054–1080

SNO Phase III (^{3}He Proportional Counters)

- Proportional counters detect neutrons via: $n + {}^3He \rightarrow p + {}^3H$
- Low radioactivity CVD nickel, 5 cm diameter, 0.36 mm thick
- Gas is 85% ^{3}He and 15% CF_4, at ~ 2.5 atm
- Anchored to the bottom of SNO on a 1-meter square grid
- 40 strings, each 9 to 11 meters long, 398 meters total length
- 50 µm copper anode wire at 1950 V



Schematic of an NCD string

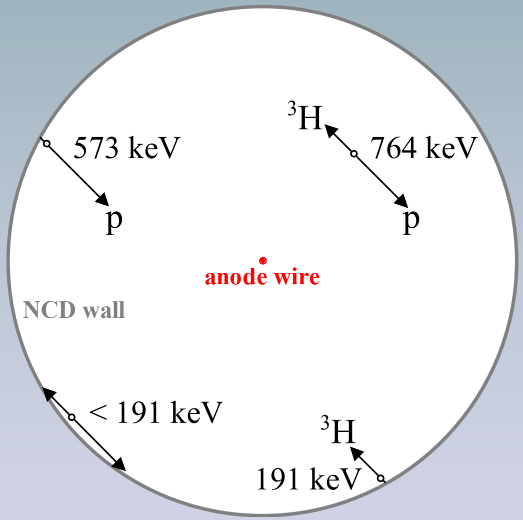
NIM A 579 (2007) 1054–1080

SNO Phase III (^{3}He Proportional Counters)

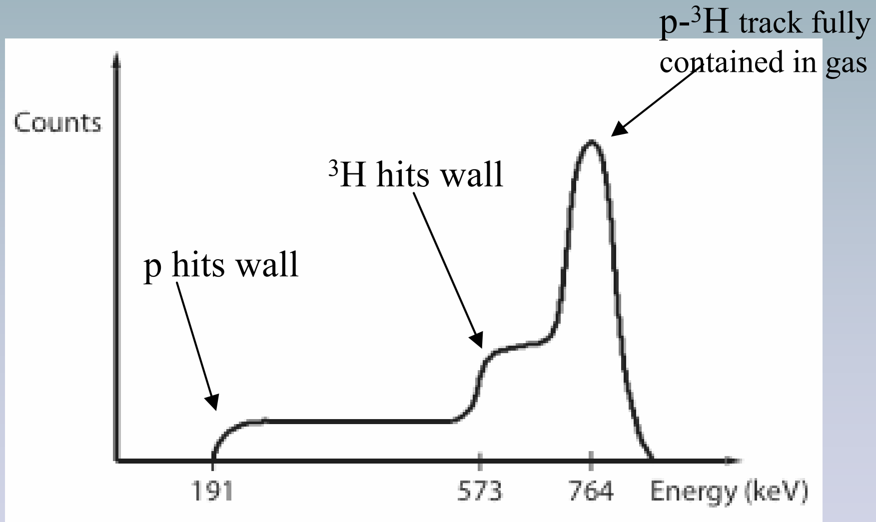
Neutron Capture in the NCDs

~ 1200 n captures per year in NCDs from solar ν

n + ^{3}He $\rightarrow$ p + ^{3}H   (Q = 764 keV)



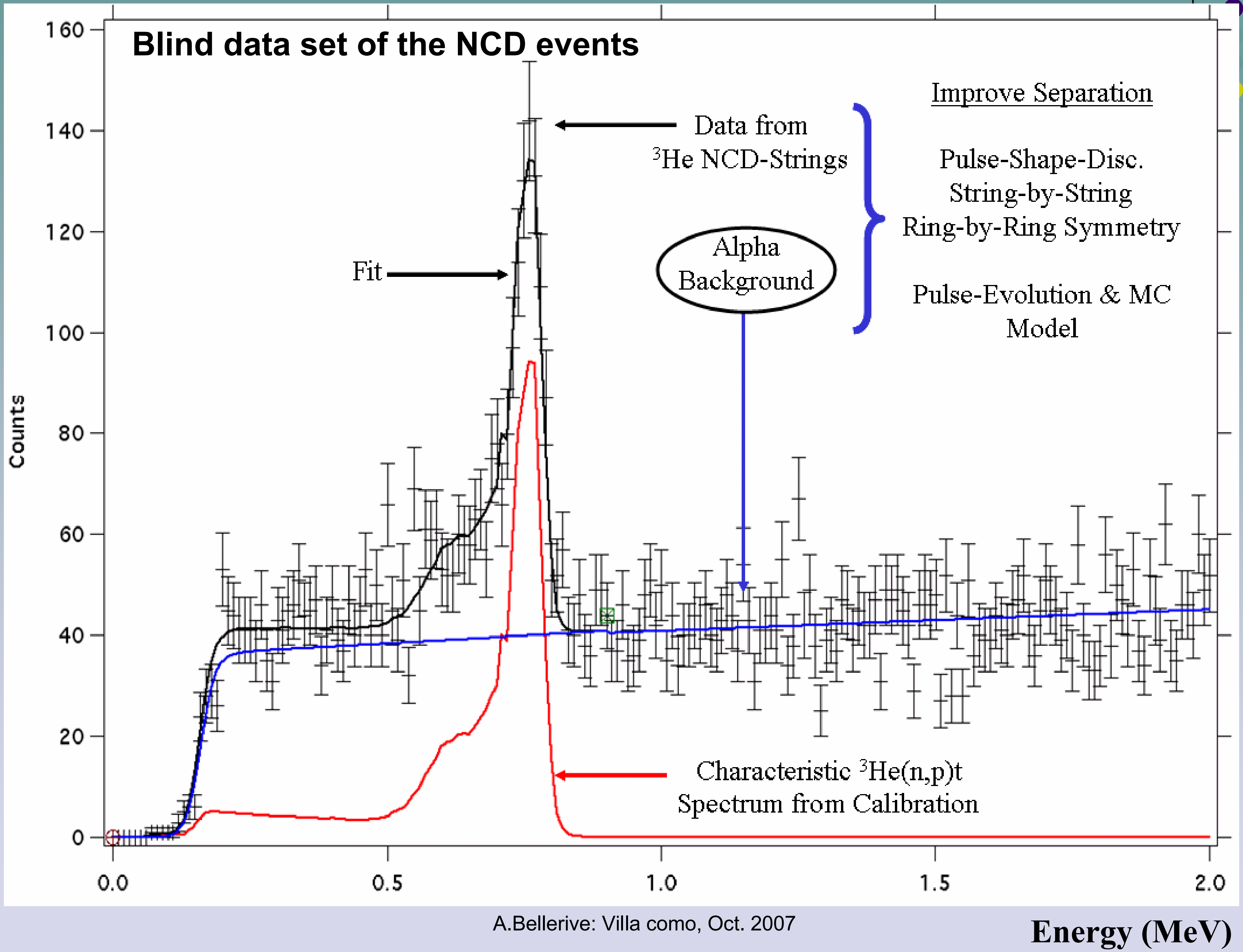
End view of an NCD with representative ionization tracks.



Idealized energy spectrum in a ^{3}He proportional counter.

NIM A 579 (2007) 1054–1080

SNO Phase III (^{3}He Proportional Counters)



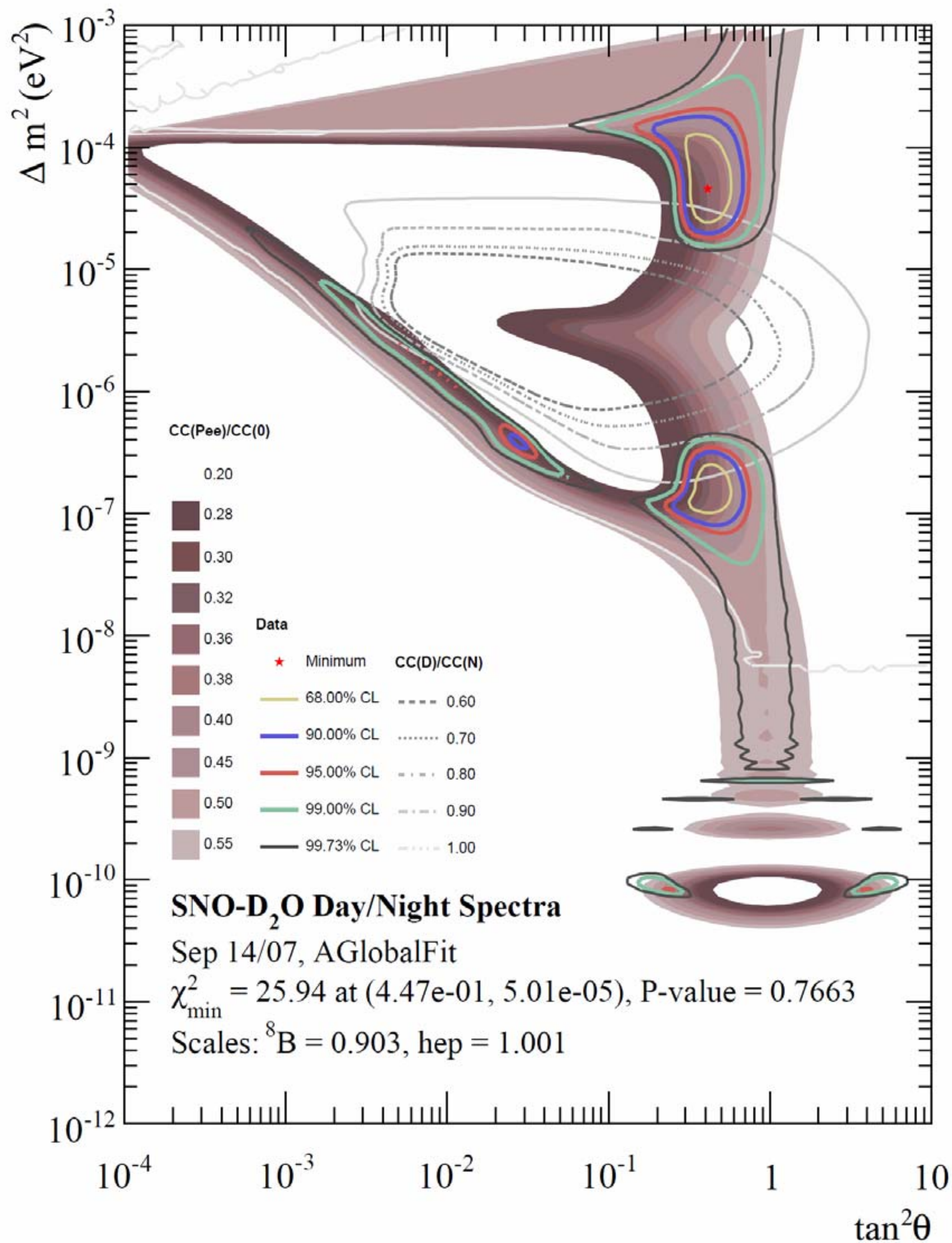
SNO Sensitivity

Future

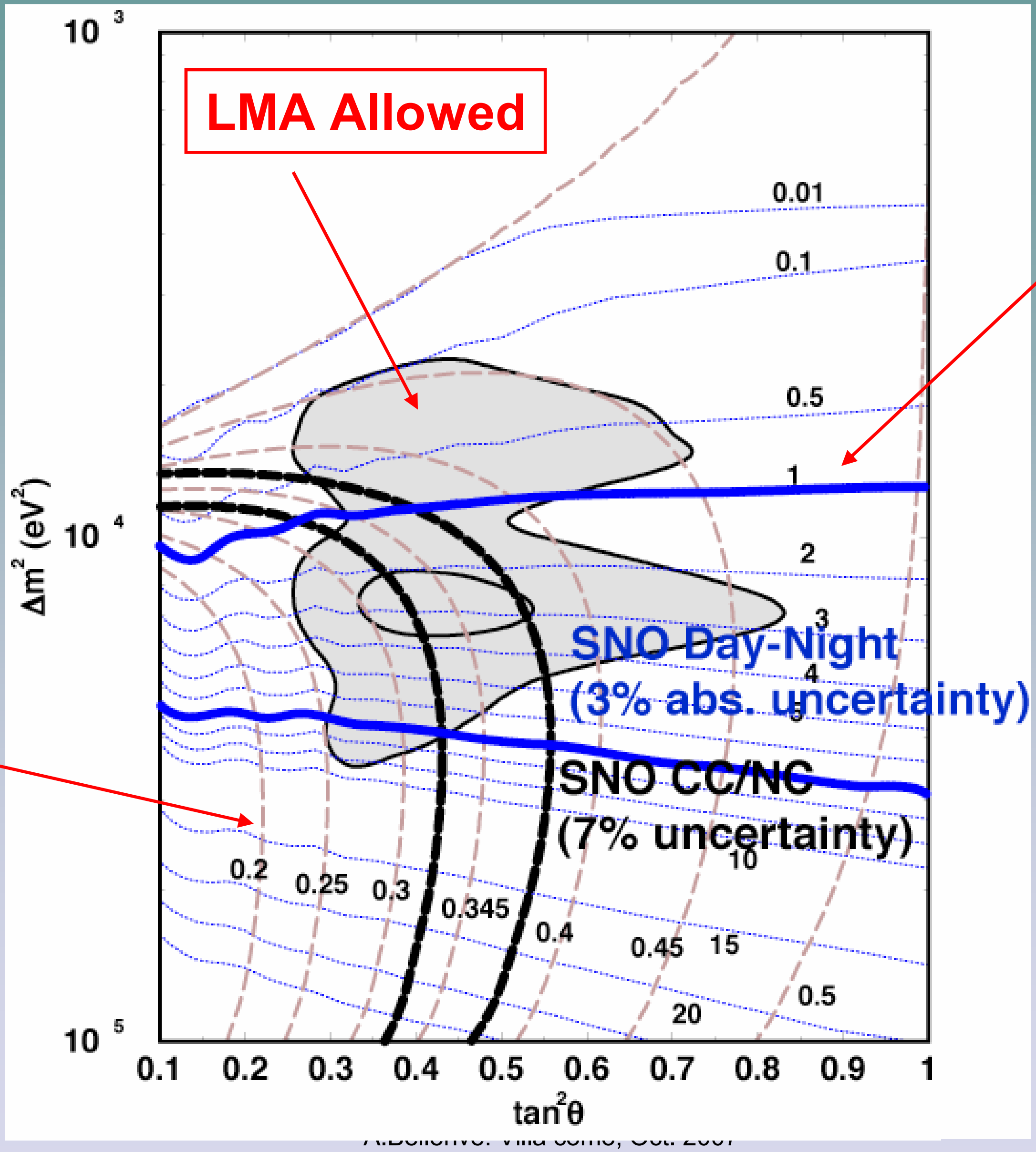
Ratio CC/NC ★

Day-night

Combination of information from three phases!



What SNO might tell us in the future…



Day – Night Contours (%)

CC/NC Contours

hep-ph/0212270
hep-ph/0204253

Summary

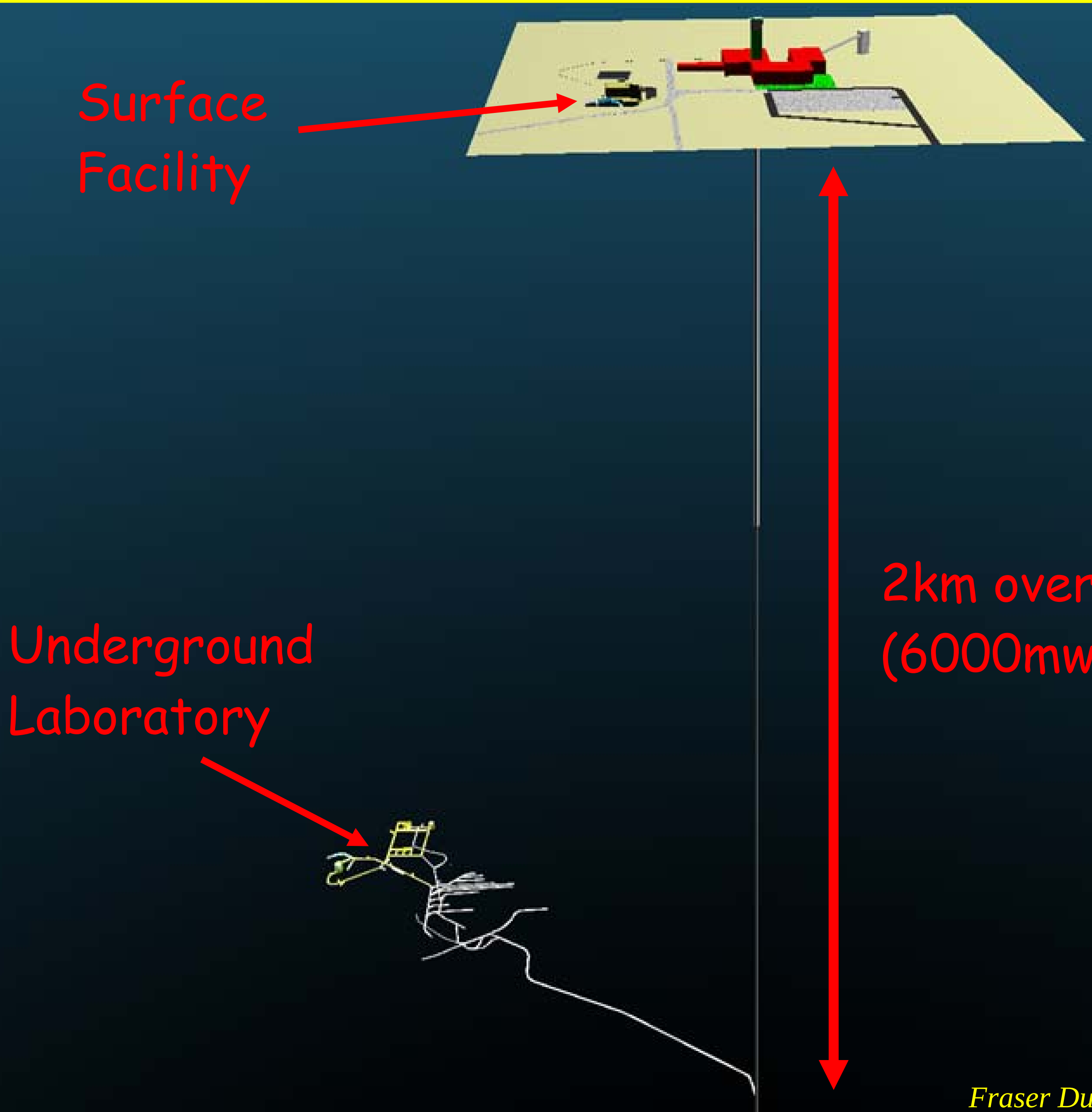
What we have:

- ^{8}B neutrino results from first two phases, including fluxes, spectrum, D/N asymmetry
- search for periodicity in data
- hep and diffuse SN neutrino results

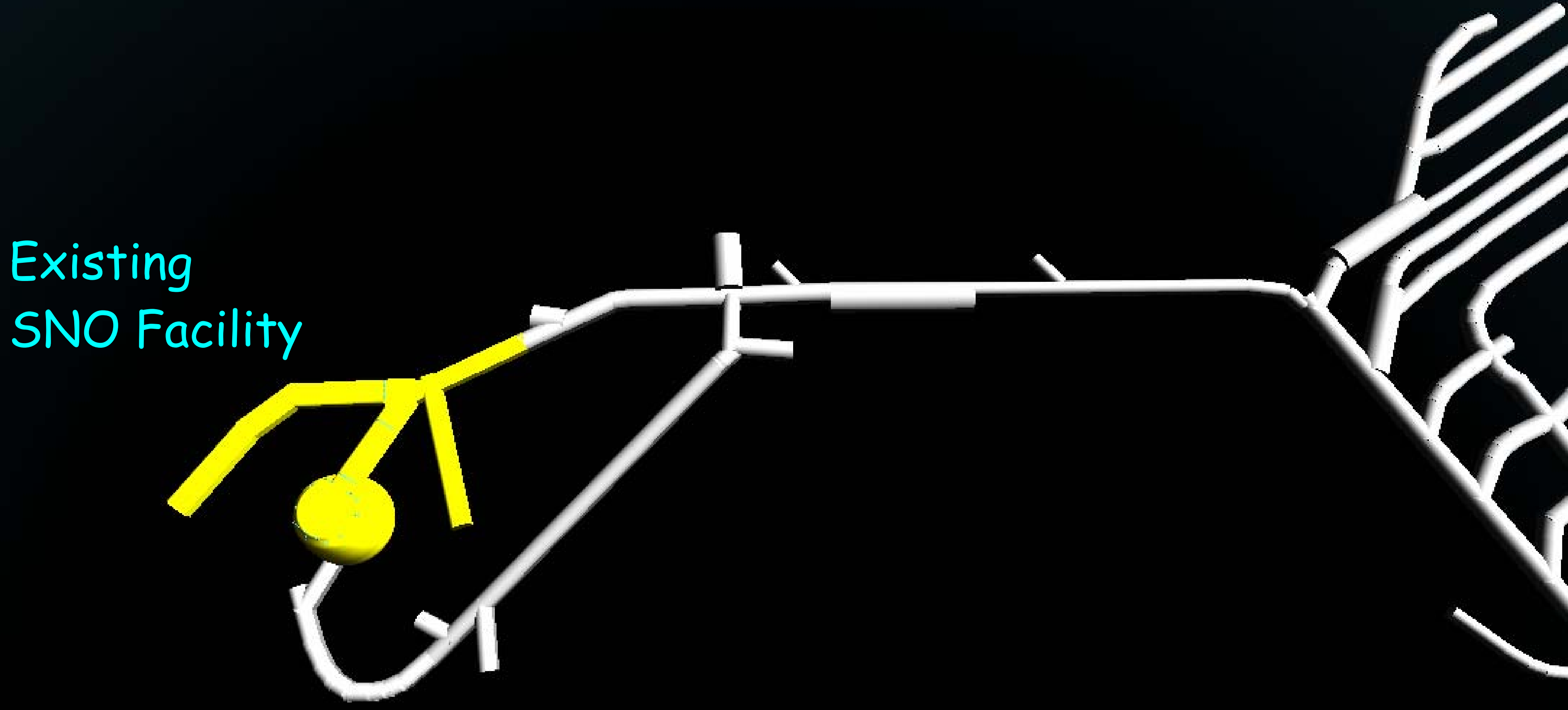
What is next:

- First results from NCD phase
- Low energy threshold analysis for phase I and II
- muon and atmospheric analysis
- other results
- COMBINATION OF ALL THREE PHASES !

SNOLAB


Surface
Facility
2km overburden
(6000mwe)
Underground
Laboratory

SNOLAB



SNOLAB

Phase I

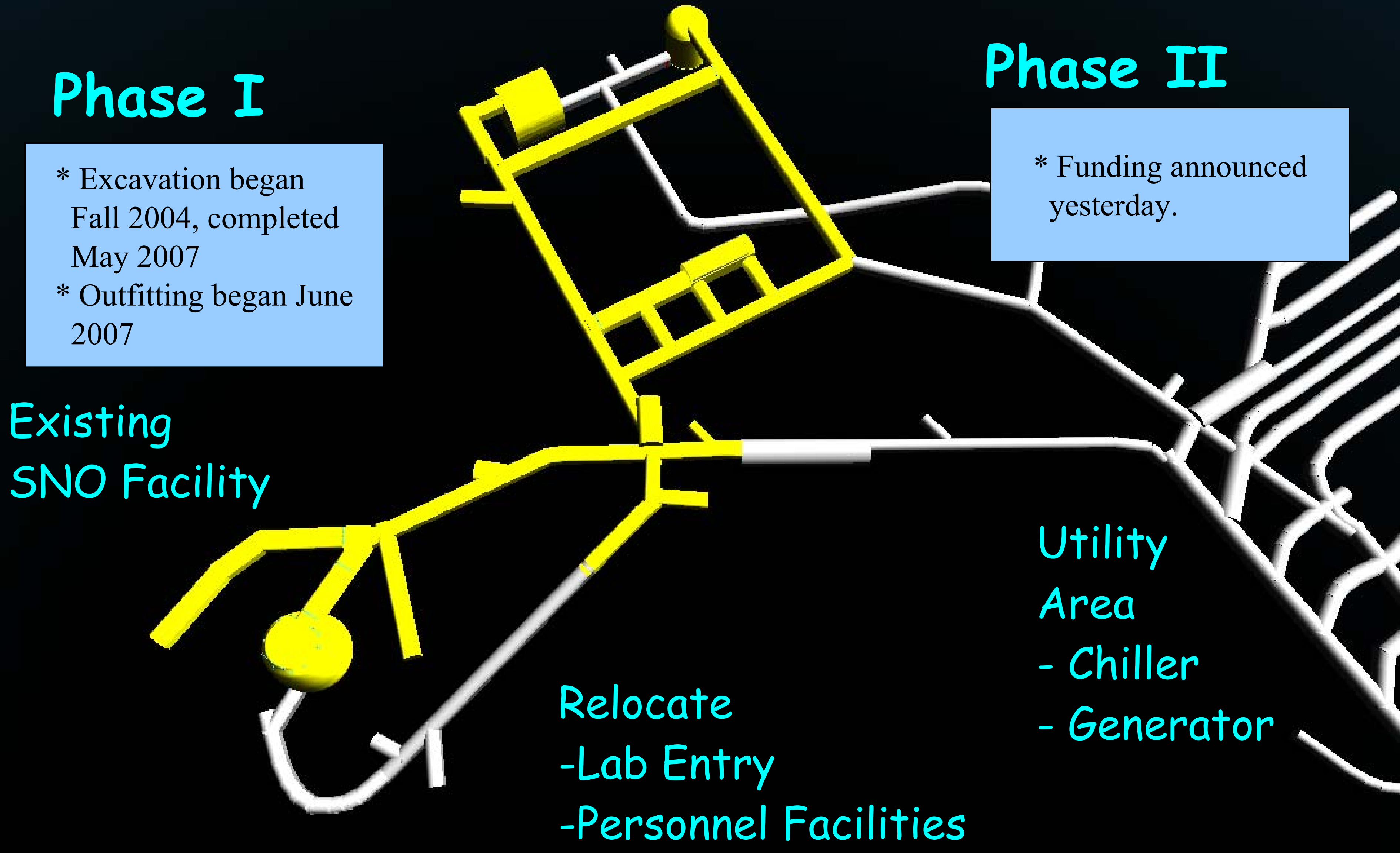
SNOLAB

Phase I

* Excavation began Fall 2004, completed May 2007
* Outfitting began June 2007

Phase II

* Funding announced yesterday.



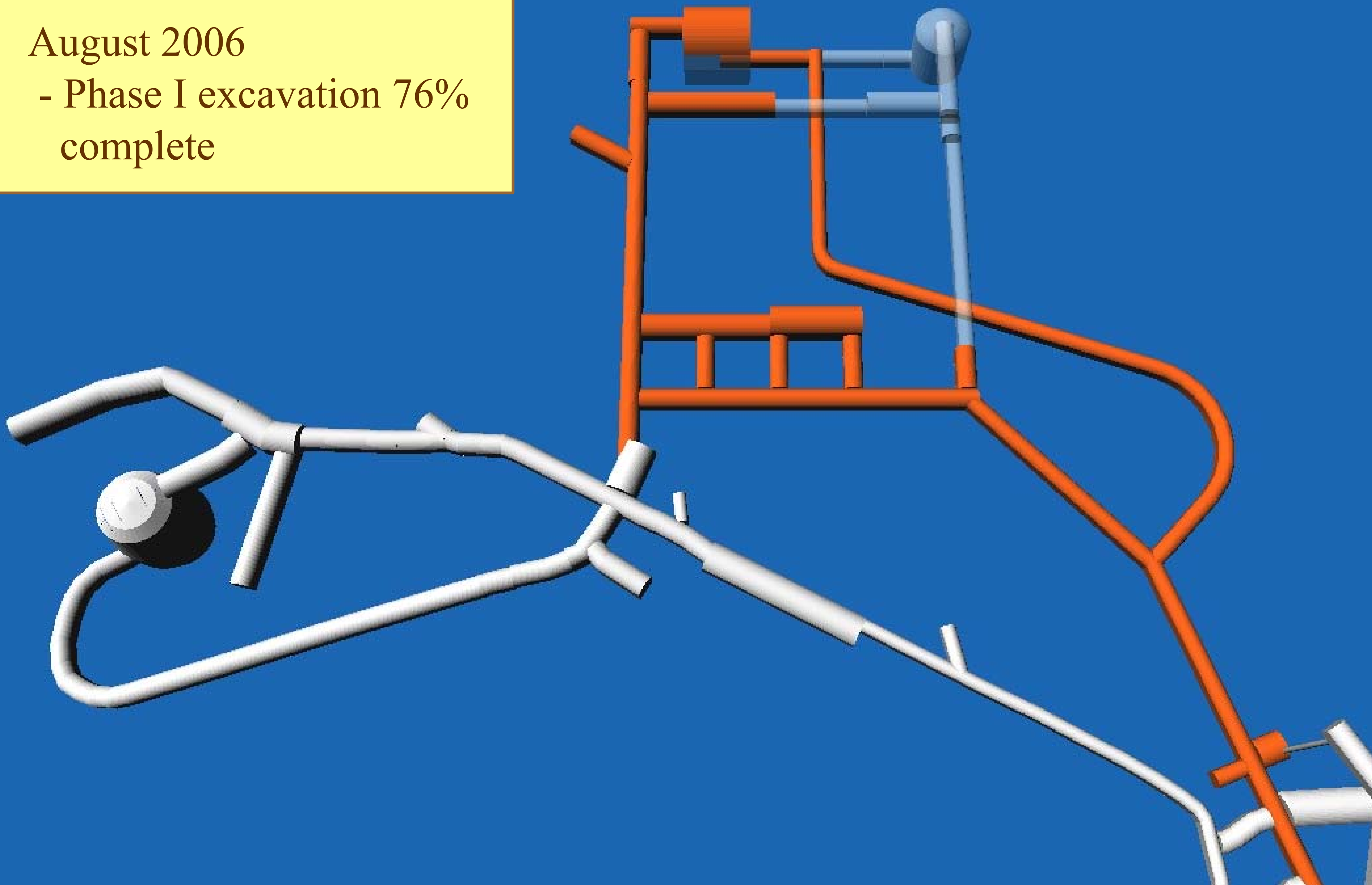
Laboratory Space

	Excavation Area	Excavation Volume	Clean Rm Area	Clean Rm Volume	Laboratory Area	Laboratory Volume
Existing	20,049 ft^2 1,863 m^2	582,993 ft^3 16,511 m^3	12,196 ft^2 1,133 m^2	470,360 ft^3 13,321 m^3	8,095 ft^2 752 m^2	412,390 ft^3 11,679 m^3
Existing + Phase I	65,340 ft^2 6,072 m^2	1,367,488 ft^3 38,728 m^3	41,955 ft^2 3,899 m^2	1,049,393 ft^3 29,719 m^3	26,117 ft^2 2,427 m^2	837,604 ft^3 23,721 m^3
Existing + Phase I&II	77,636 ft^2 7,215 m^2	1,647,134 ft^3 46,648 m^3	53,180 ft^2 4,942 m^2	1,314,973 ft^3 37,241 m^3	32,877 ft^2 3,055 m^2	1,043,579 ft^3 29,555 m^3

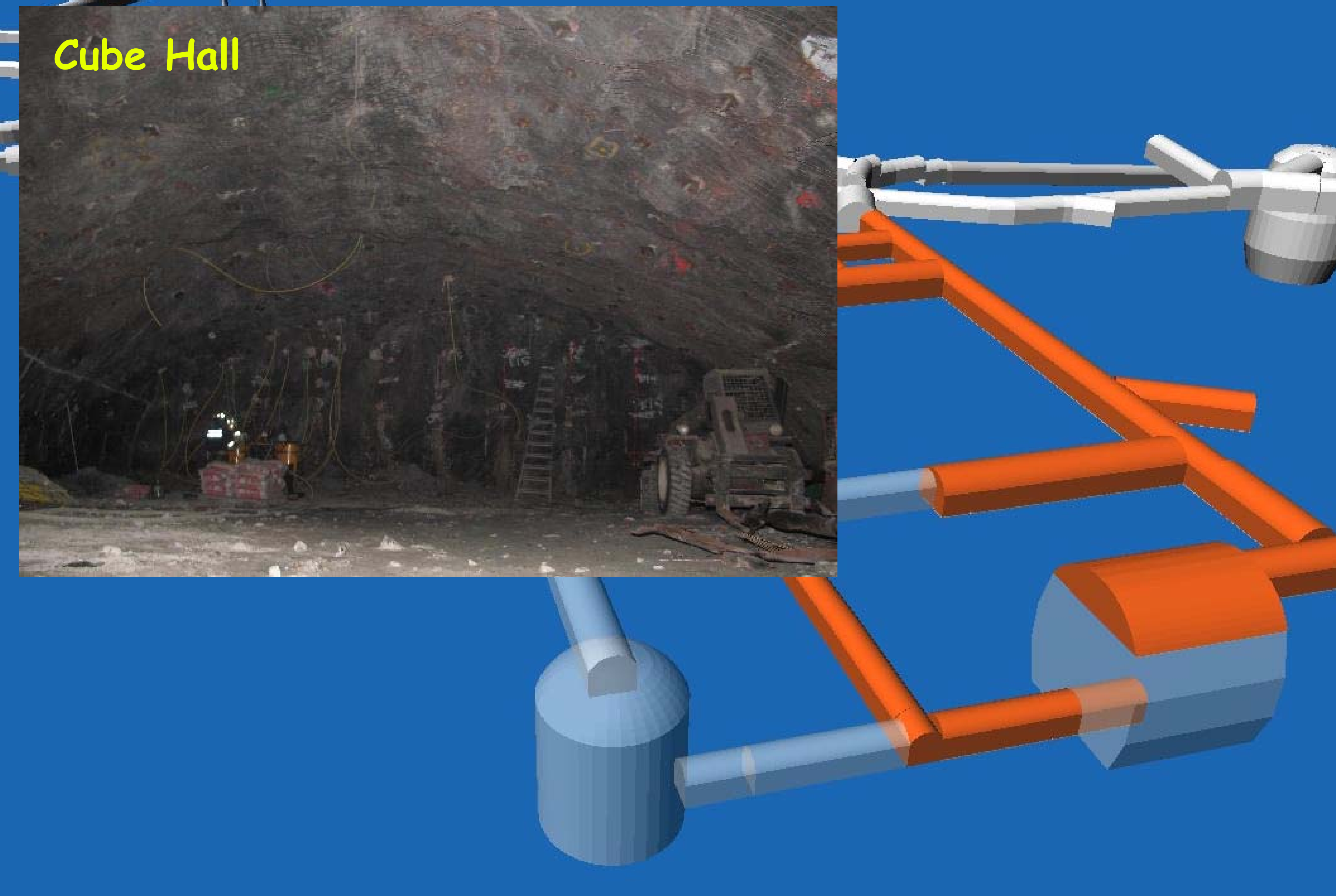
CLASS 2000 Clean Room Laboratory Space

Excavation Status: August 2006

August 2006
- Phase I excavation 76% complete



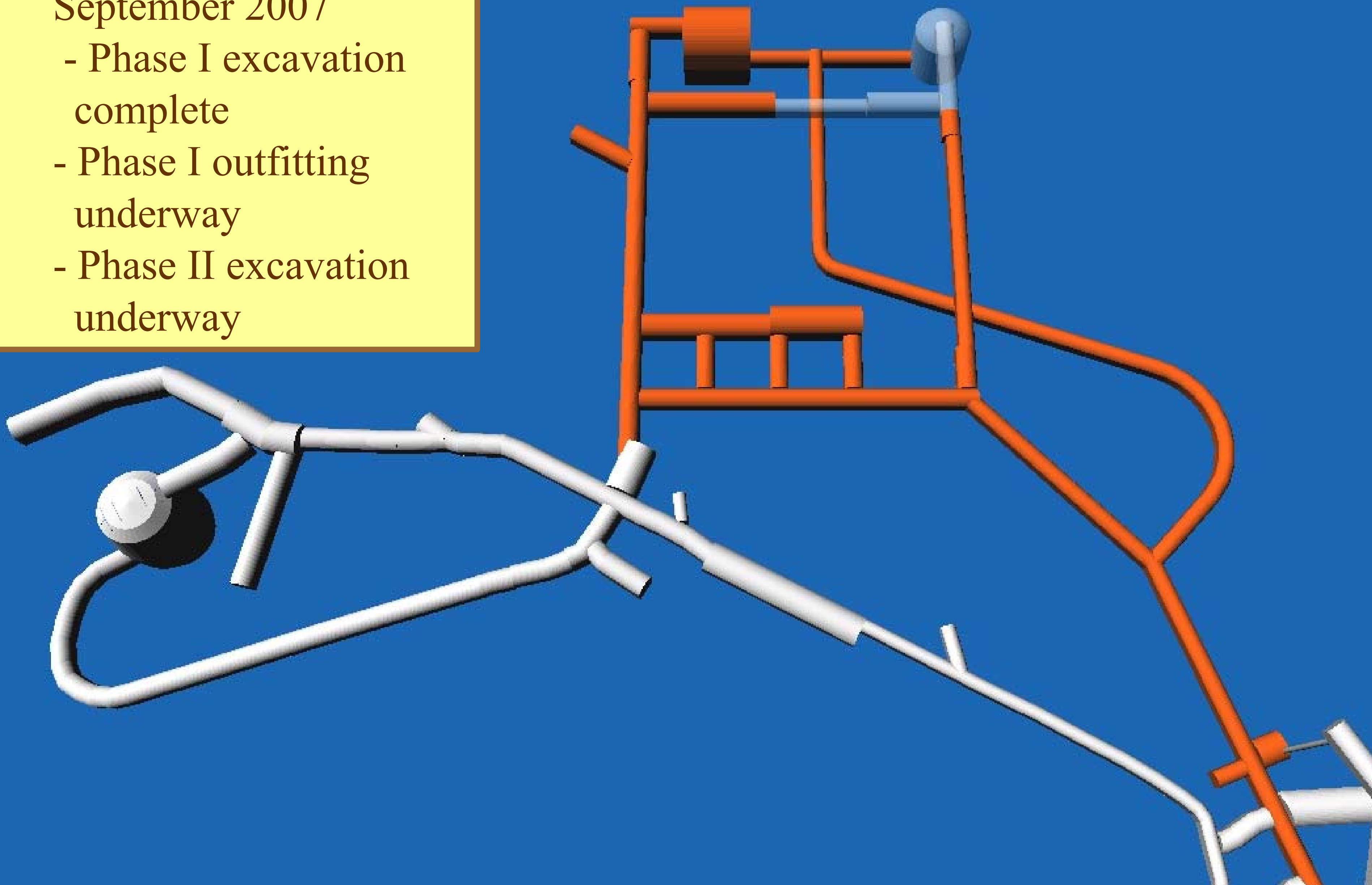
Excavation Status: August 2006

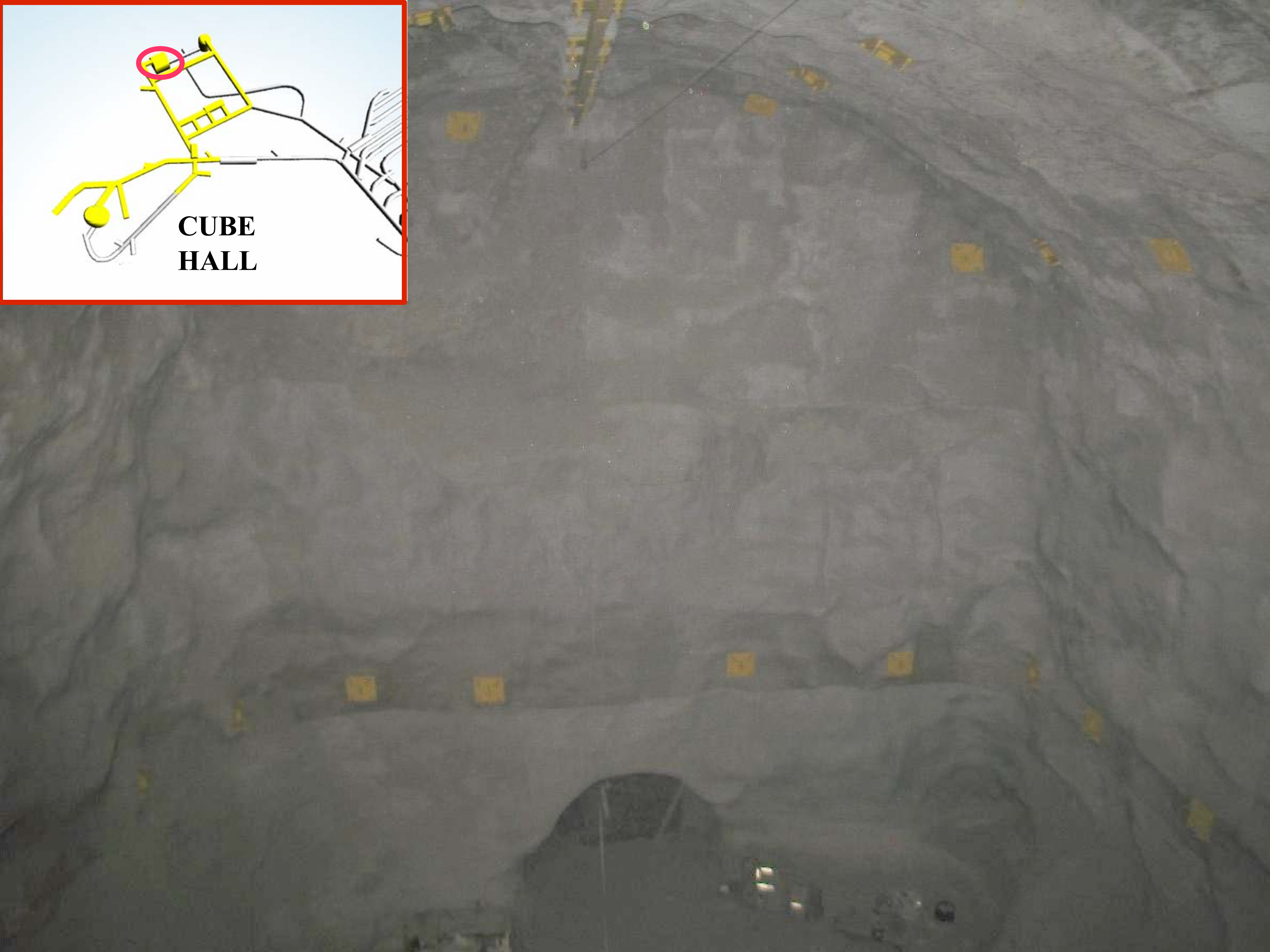


Excavation Status: August 2006

Excavation Status: Today

September 2007
- Phase I excavation complete
- Phase I outfitting underway
- Phase II excavation underway




CUBE
HALL


CUBE
HALL


LADDER
LABS


LADDER
LABS


LADDER
LABS


NO FORK
SNO
ingēnia
Lab
Entrance

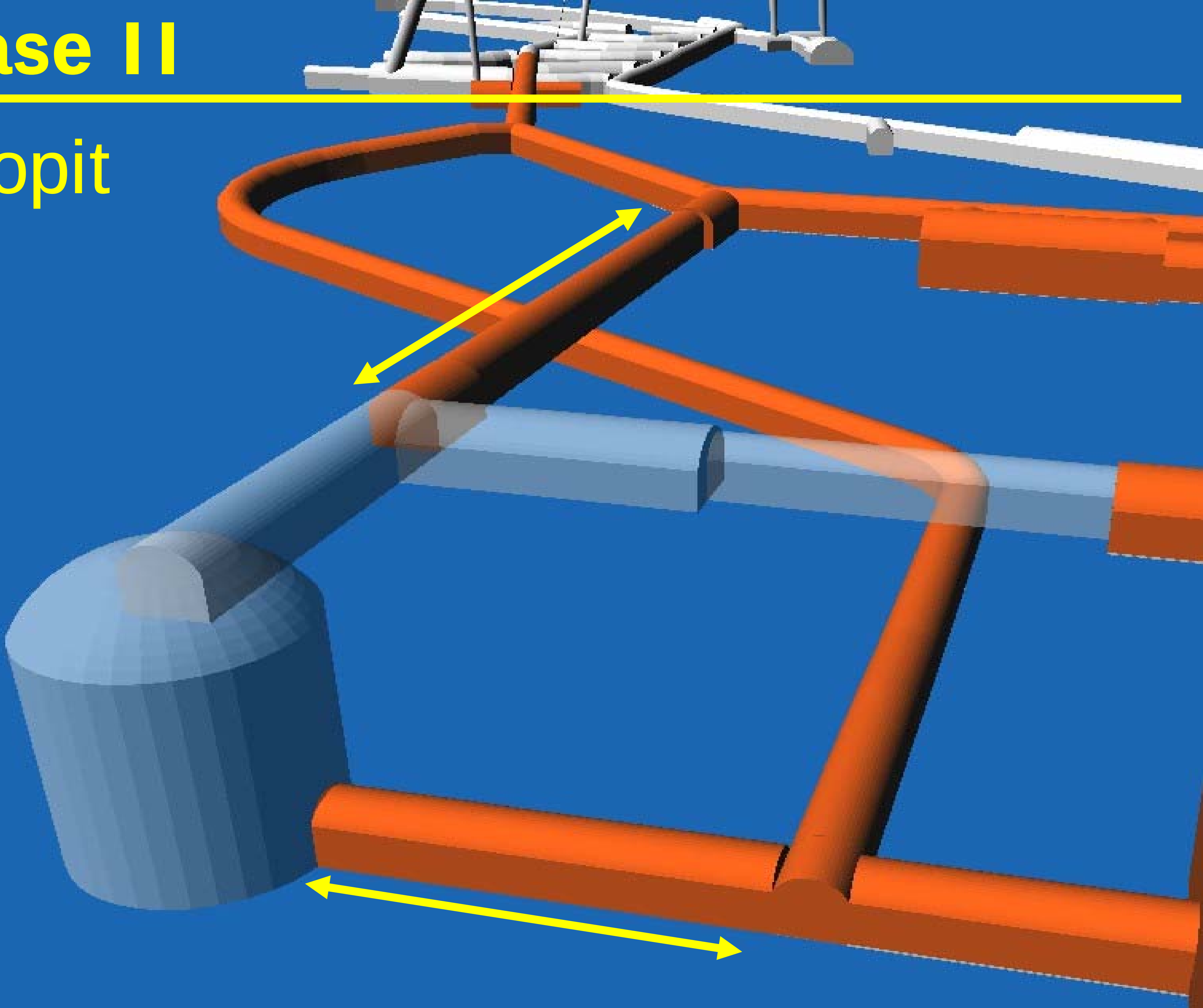

CAUTION
MEN WORKING ABOVE
Comstock
Personnel Area

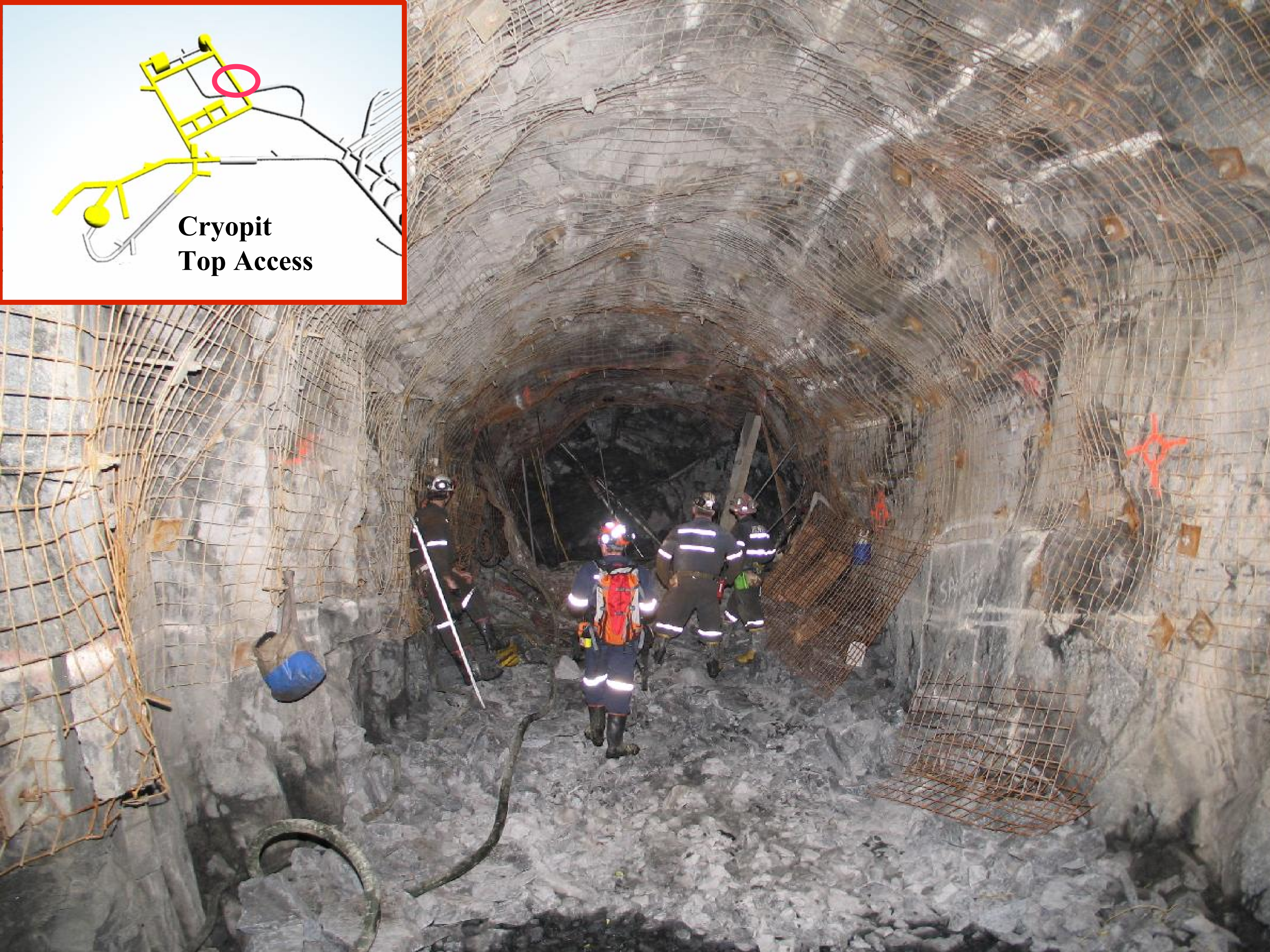

Personnel
Area


Personnel
Area

Phase II

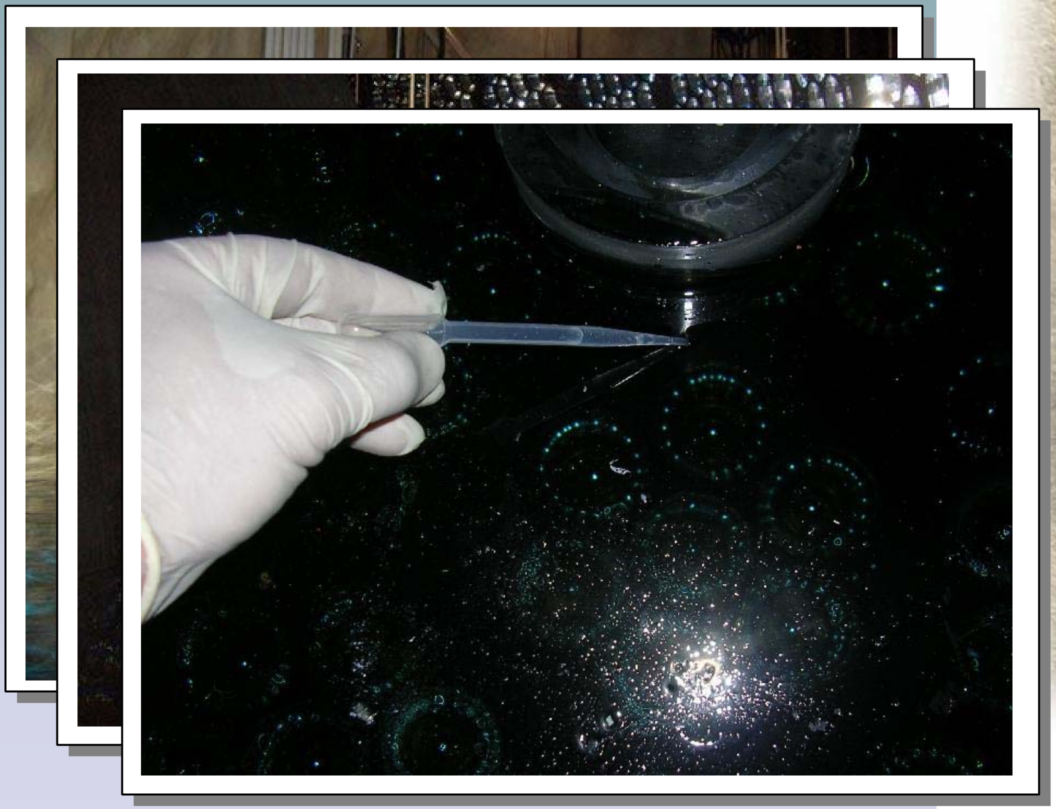
Cryopit

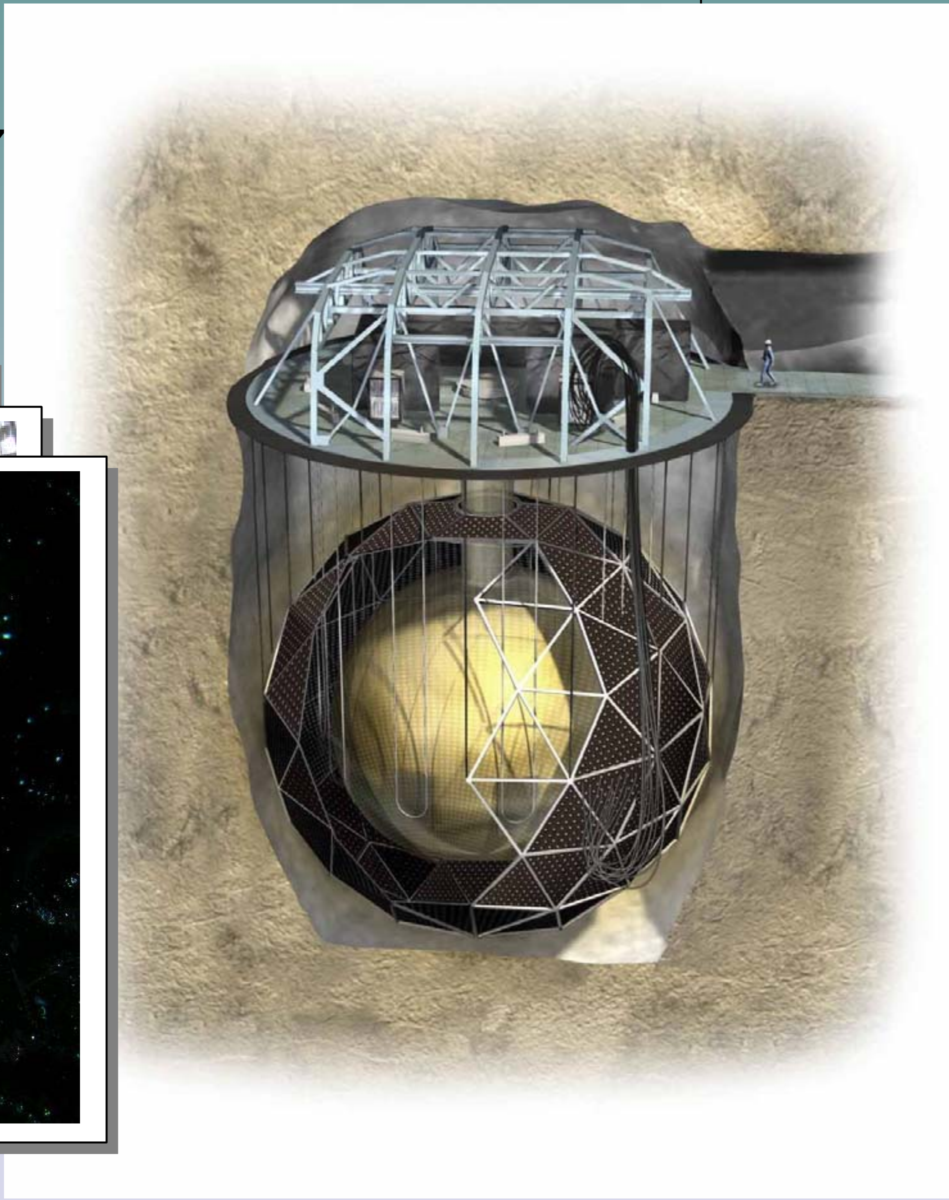



Cryopit
Top Access

SNO

- Ended data taking 28 Nov 2006
- Most heavy water returned June 2007
- Finish decommissioning end of 2007





Carleton UNIVERSITY

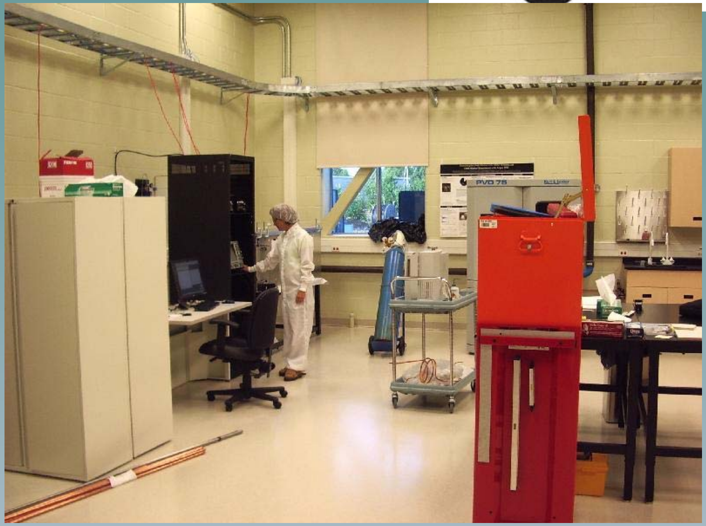
SNOLAB

MINING FOR KNOWLEDGE

CREUSER POUR TROUVER... L'EXCELLENCE

Surface Facilities

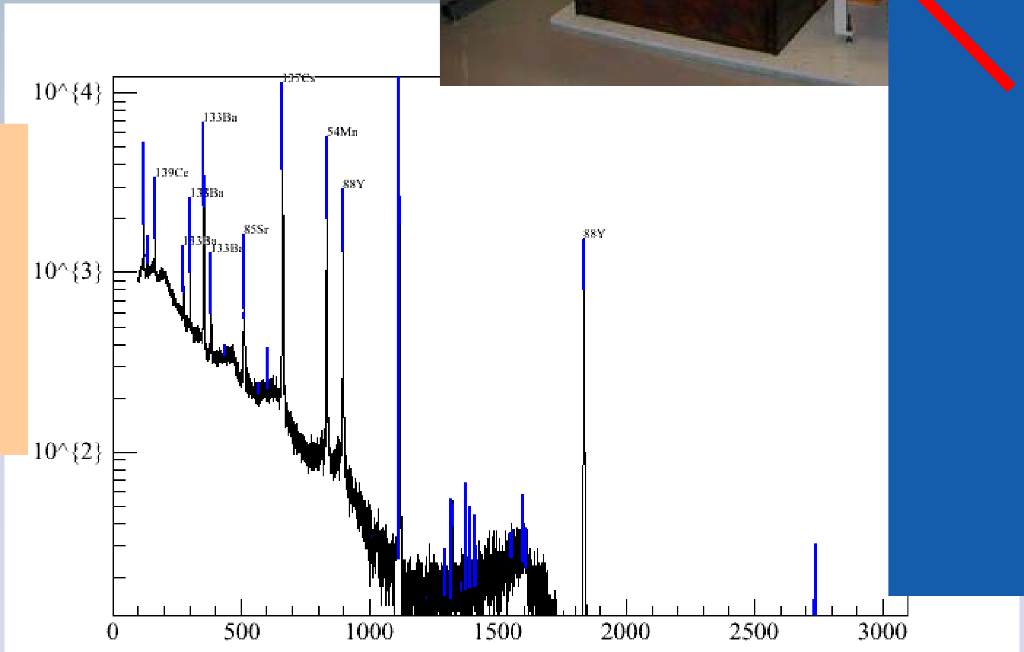
- Site: 4,700 ft^2 CLASS 1000 Clean Room Laboratories, IT Infrastructure (high speed off site), Office, Meeting Rms, Control Rms, Material handling.
- Laurentian Water Facility: Intended for spike work not appropriate for site. Will have Ultra Pure Water facility, Low BG counting



Material Screening

Ge Gamma Counter

- Low Background Counting available for the experiments.
- 1 liter sample sizes
- Presently being used by SNO, EXO, DEAP/CLEAN, PICASSO



Element	Sensitivity
K	0.5 ppm
Th	1.4 ppb
U	0.28 ppb

Material Screening

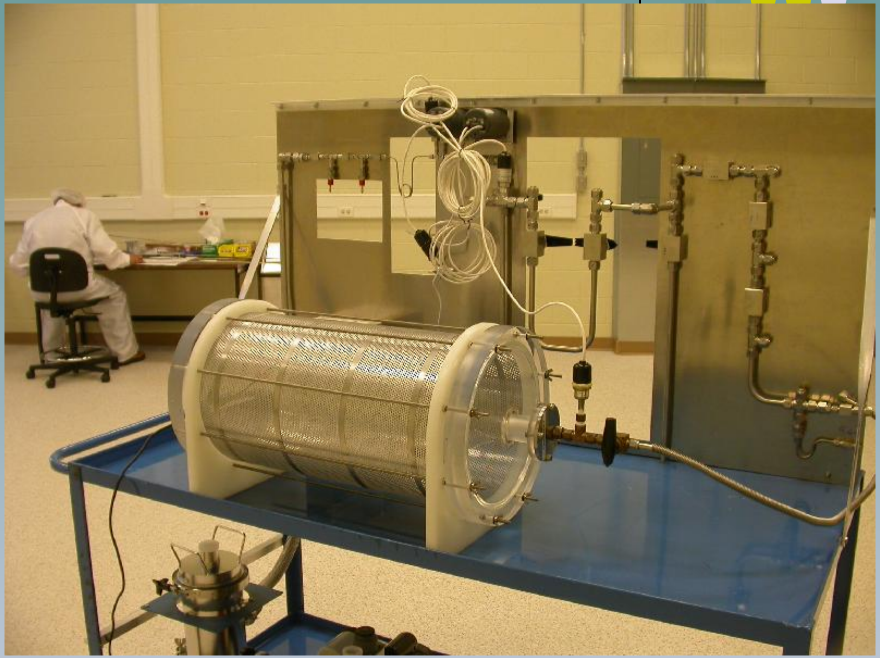
ESC (Electrostatic Counter)

- 8 counters on site.
- Self contained samples connected directly to the recirculating loop. Other samples placed in polypropolyne cylinders with N_2 or Ar gas recirculated through chamber.
- Turnaround time 1 month (3 months notice recommended)
  - 2 weeks/sample + 2 weeks for background.

Radionuclide	Sensitivity
^{222}Rn (U)	20 atoms/day
^{220}Rn (Th)	10 atoms/day
^{219}Rn (Ac)	50 atoms/day

Material Screening

- **Radon Emanation Chambers**
  - Used extensively for counting materials used in the SNO experiment.
  - sensitivity ~50 decays per day.
- **ICP-MS**
  - Association with facility at NRC (National Research Council) ICP-MS facility in Ottawa.
  - Tuned to maximize sensitivity to U and Th at sub ppt levels. K limits to > 100 ppb.



SNOLAB 2008 - …

Scientific Program

Low Energy Neutrinos

- SNO+ (SNO filled with liquid scintillator)

Search for Cold Dark Matter

- Picasso
- DEAP

Investigation of Double-Beta Decay

- Enriched Xenon Observatory (EXO)
- SNO+ (upgrade Nd loaded)

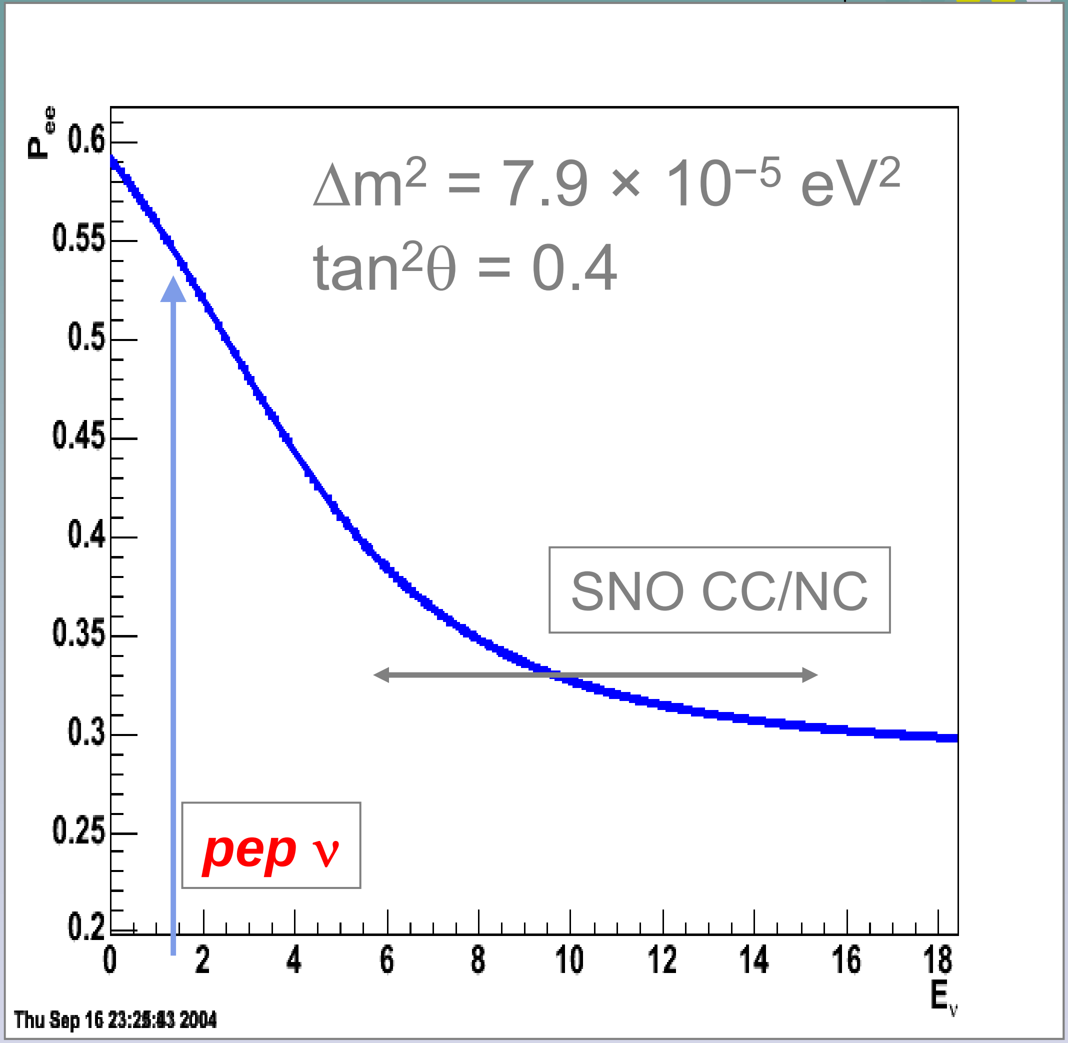
SNO++: Survival Probability

pep flux:

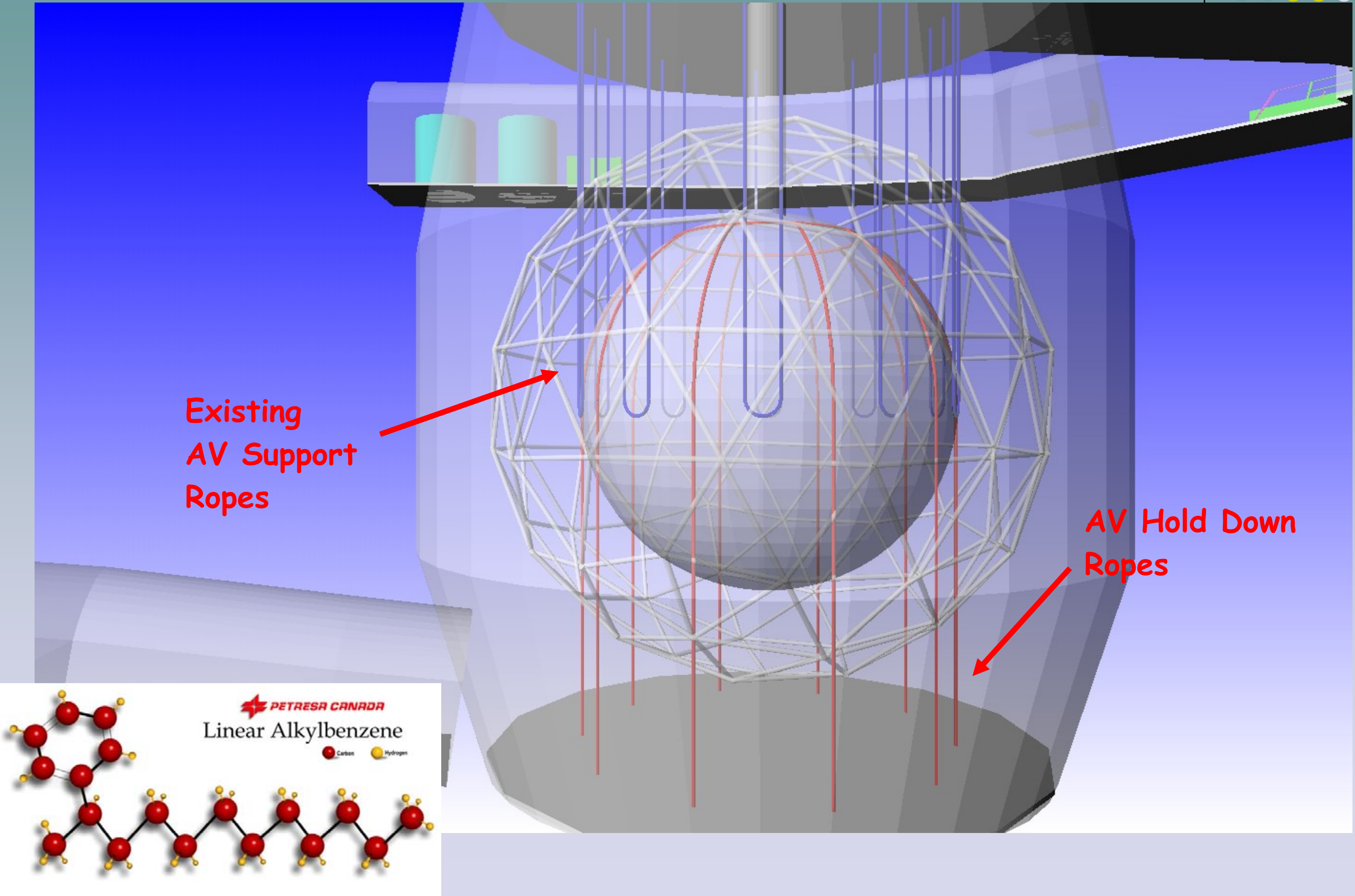
Uncertainty ±1.5%

Allows precision test of the Solar Standard Model & the LMA matter enhanced oscillation scenario

Real-time low energy ν's experiments are the ultimate probe of the Sun

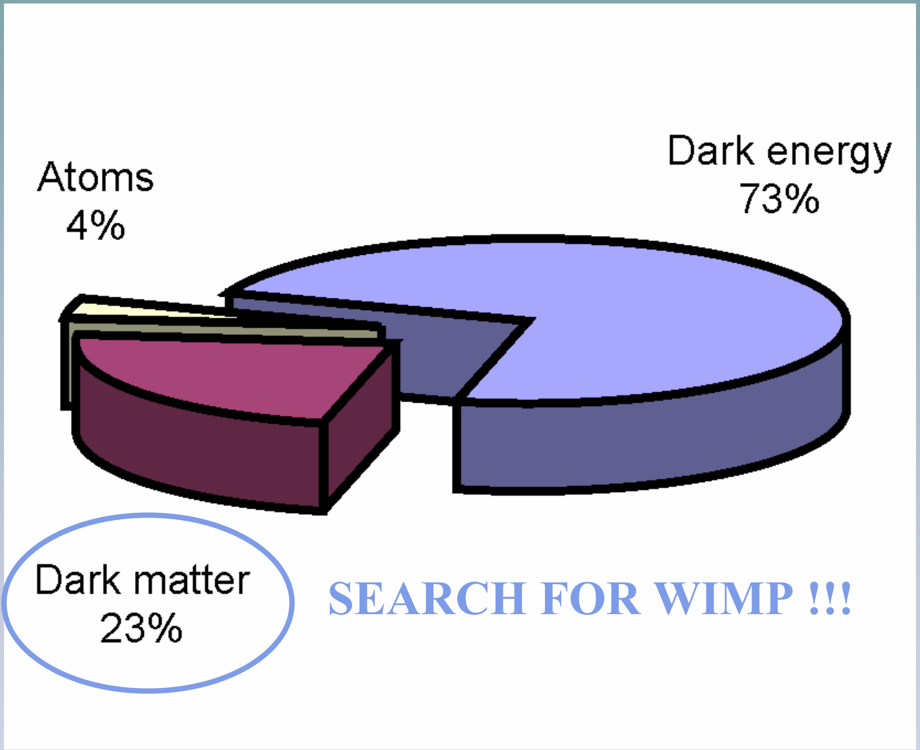


SNO+ liquid scintillator



The Cosmic Connections

Energy budget of Universe



96% is a mystery!

WIMP Direct Detection Tools

DM

CHARGE

Semiconductors : Ge,Si

TPC

LIGHT

NaI, CsI, CaF_2, Liq. Ar & Xe

HEAT

Cryogenic detectors :
Al_2O_3, LiF

Superheat

Freon

Active Background Rejection

Cryogenic detectors

LIGHT + PSD

NaI, Liq.Xe : UK/NAIAD, DAMA,
ZEPLIN-I, **DEAP/CLEAN**

CHARGE HEAT

Ge , Si : CDMS, EDELWEISS

LIGHT HEAT

$CaWO_4$, BGO : CRESST, Rosebud

LIGHT CHARGE + PSD

Liq.-GasXe : ZEPLIN-II

Superheat

Freon : **PICASSO**, SIMPLE

CHARGE + TPC

Xe : DRIFT

Neutralino Interaction with Matter

Spin dependent interaction – axial coupling

Picasso

Target nuclei

Isotope	Spin	Unpaired	λ^2
^{7}Li	3/2	p	0.11
^{19}F	**1/2**	**p**	**0.863**
^{23}Na	3/2	p	0.011
^{29}Si	1/2	n	0.084
^{73}Ge	9/2	n	0.0026
^{127}I	5/2	p	0.0026
^{131}Xe	3/2	n	0.0147

- Small freon droplets in polymerized gel at room T° droplets overheat
- A particle hit vaporizes the droplet:
  - phase transition event
  - an acoustic shock wave detected with piezoelectric transducers

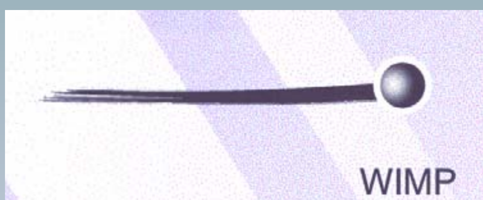
Picasso at SNOLAB

Remotely controled from U de Montréal

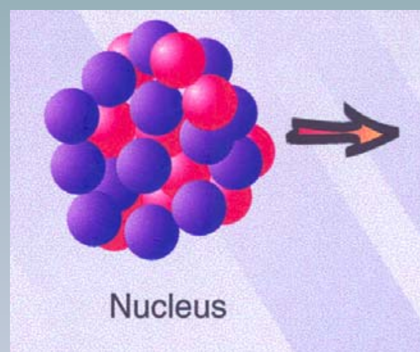
Neutralino Interaction with Matter

Spin independent interaction – scalar coupling

⇒ heavy nuclei



$M_{WIMP} \sim 100$ GeV

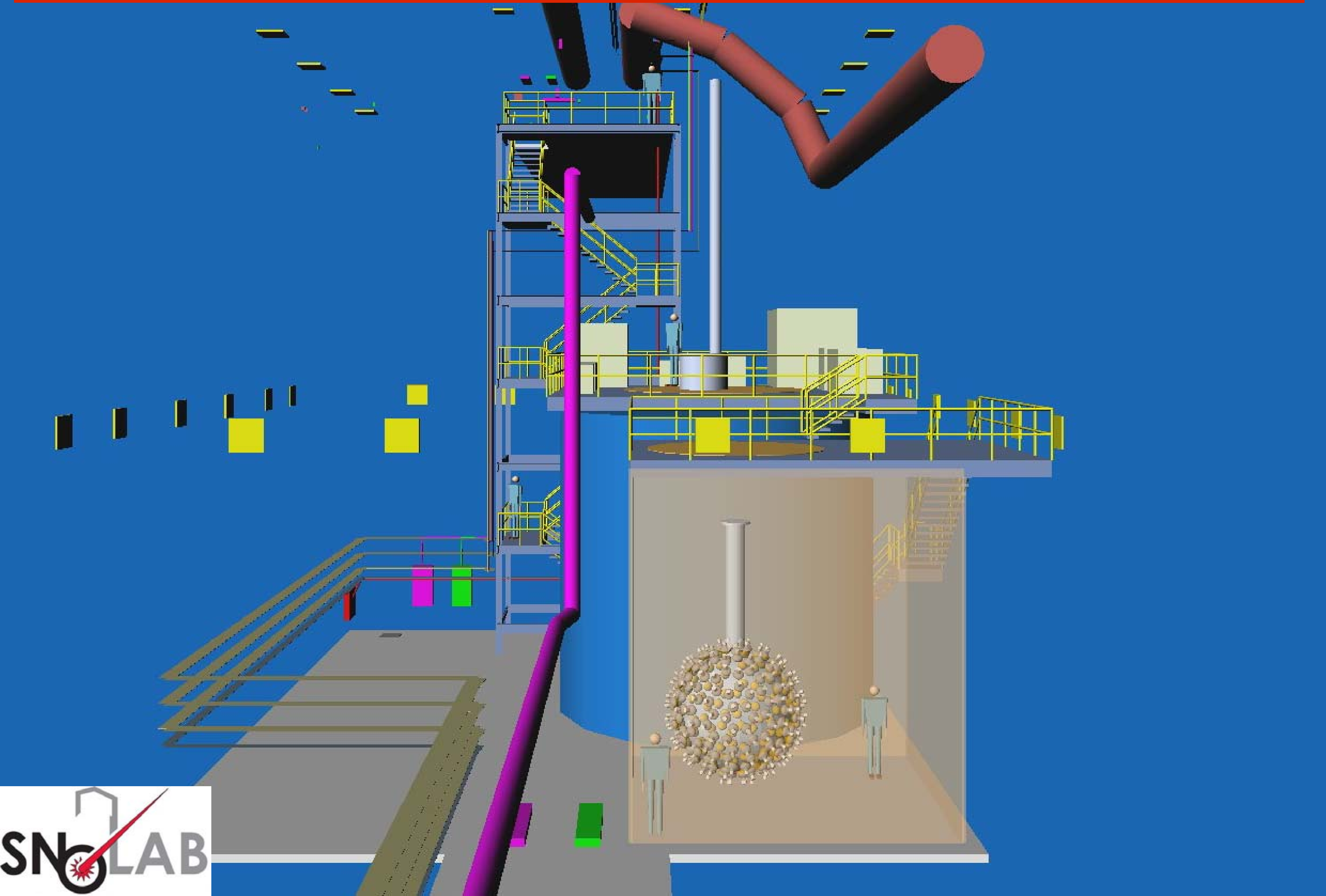


$M_{Recoil} < 100$ keV

- ➔ Require Low-E Threshold
- ➔ Require Large Target Mass
- ➔ Ultra-Low Background

DEAP/CLEAN… sensitivity

DEAP Experimental Hall

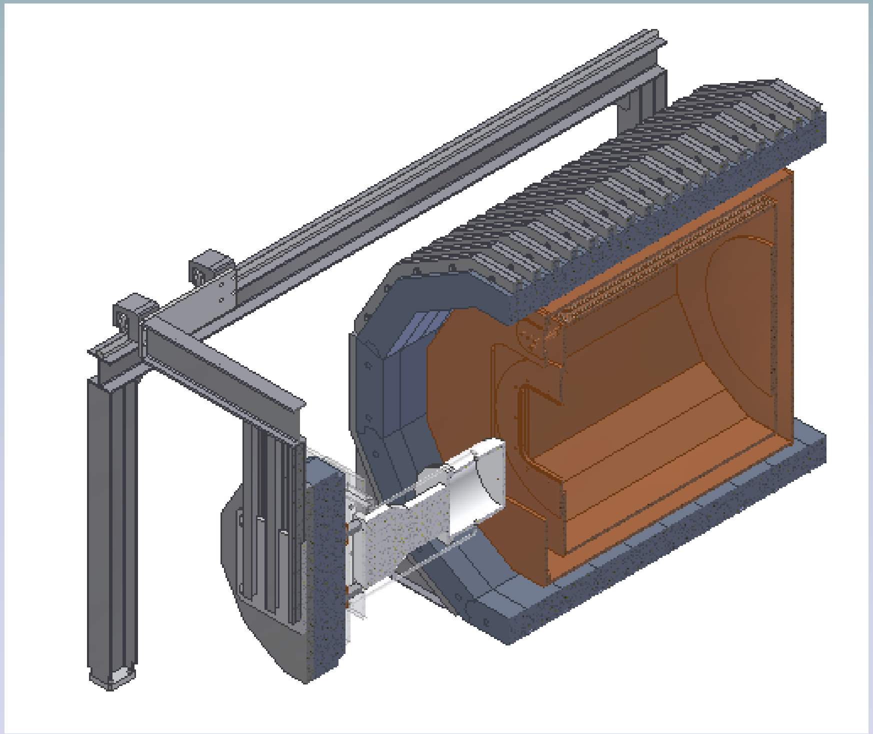


SNOLAB

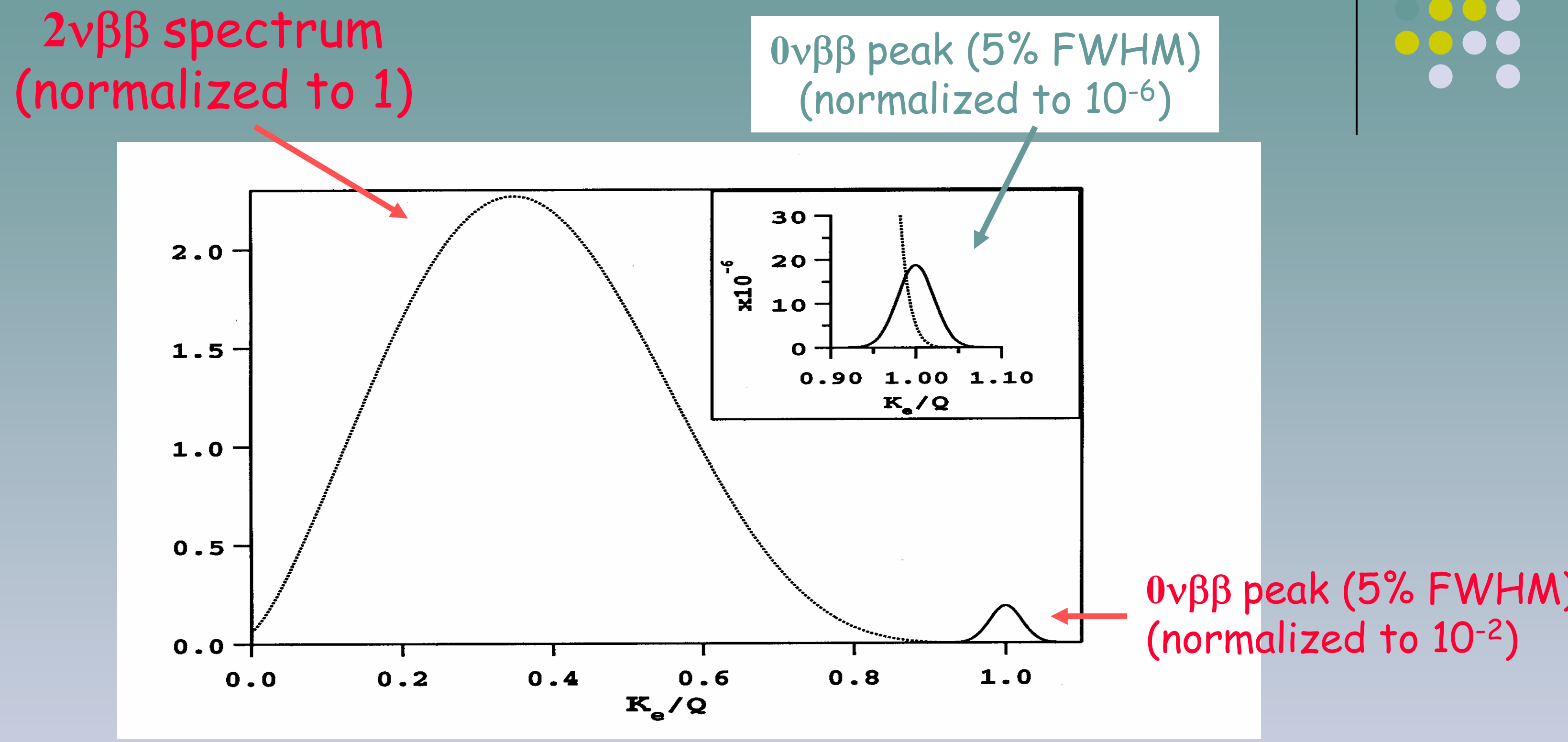
ββ decay proposals at SNOLAB

Enriched Xenon Observatory
EXO

SNOLAB



Background due to SM $2\nu\beta\beta$ decay



Summed electron energy in units of the kinematic endpoint (Q)

from S.R. Elliott and P. Vogel, Ann.Rev.Nucl.Part.Sci. **52** (2002) 115.

The only effective tool here is energy resolution

Conclusion

What we have:

Great Physics out of SNO

What is next:

Exciting future for SNOLAB

Thanks