Knowing the Universe from a Hole in the Ground

Particle-Astrophysics Research
at
SNO & SNOLab

The Present

The Sudbury Neutrino Observatory (SNO)

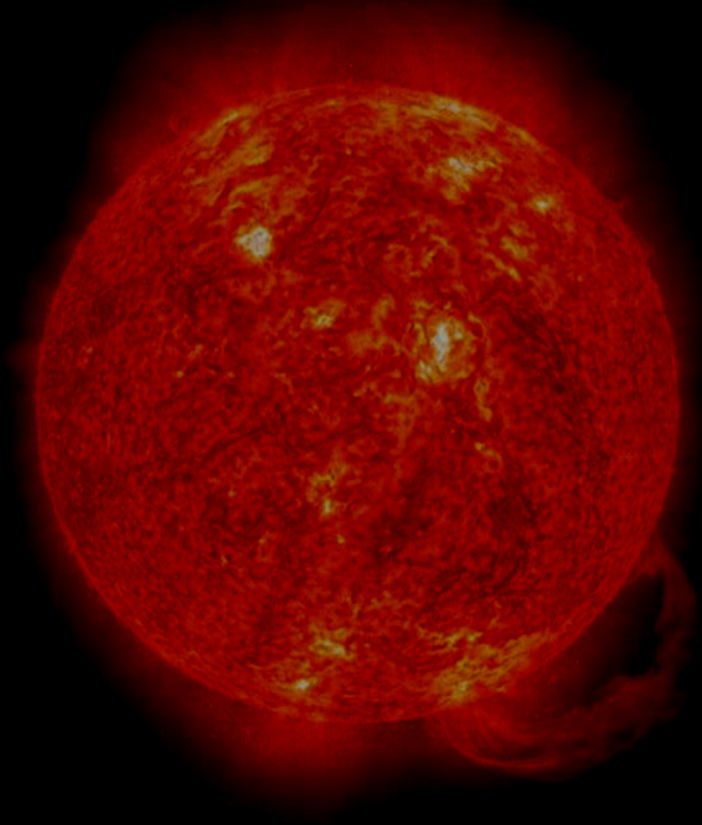
- The Solar Neutrino Problem
- The SNO Experiment
- Results from SNO and Implications

The Future

SNOLab

- Status
- Physics program

Tony Noble
Queen's University



Solar Neutrino Physics

Solar Neutrino Production

$p + p \rightarrow {}^2H + e^+ + \nu$ — 99.77%

$p + e^- + p \rightarrow {}^2H + \nu$ — 0.23%

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

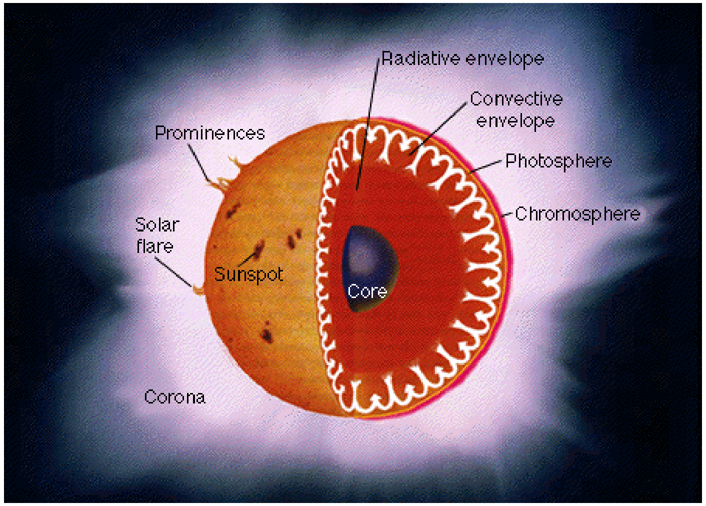
84.92%: $^3He + {}^3He \rightarrow \alpha + 2p$

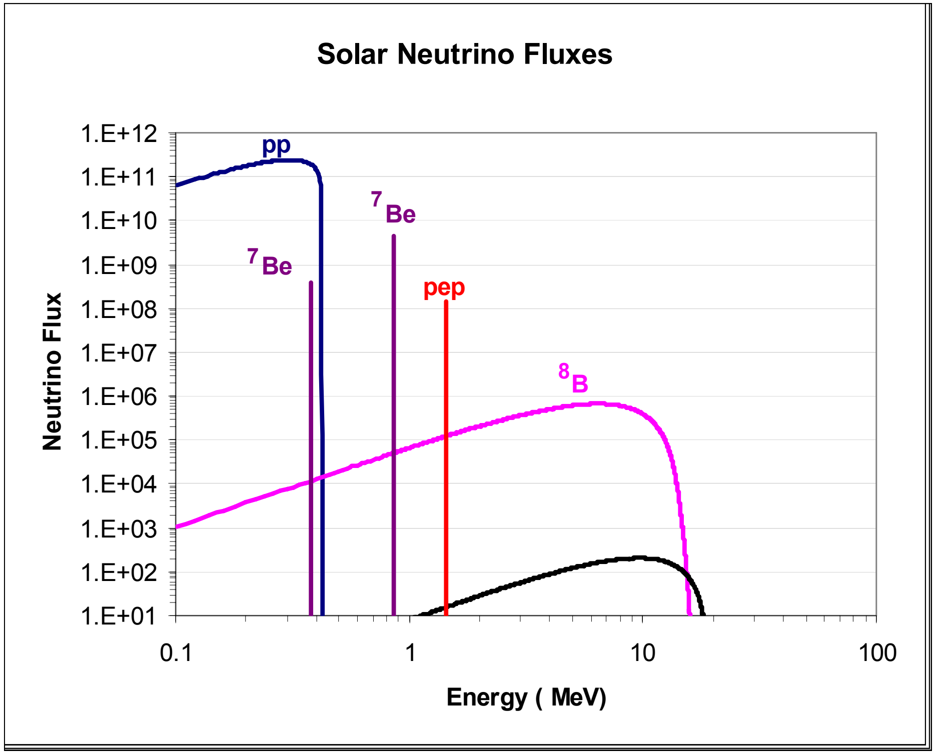
15.08%: $^3He + \alpha \rightarrow {}^7Be + \gamma$

10^{-5}%: $^3He + p \rightarrow \alpha + e^+ + \nu$

15.07%: $^7Be + e^- \rightarrow {}^7Li + \gamma + \nu$ → $^7L + p \rightarrow 2\alpha$

$^7Be + p \rightarrow {}^8B + \gamma$ → 0.01%: $^8B \rightarrow 2\alpha + e^+ + \nu$





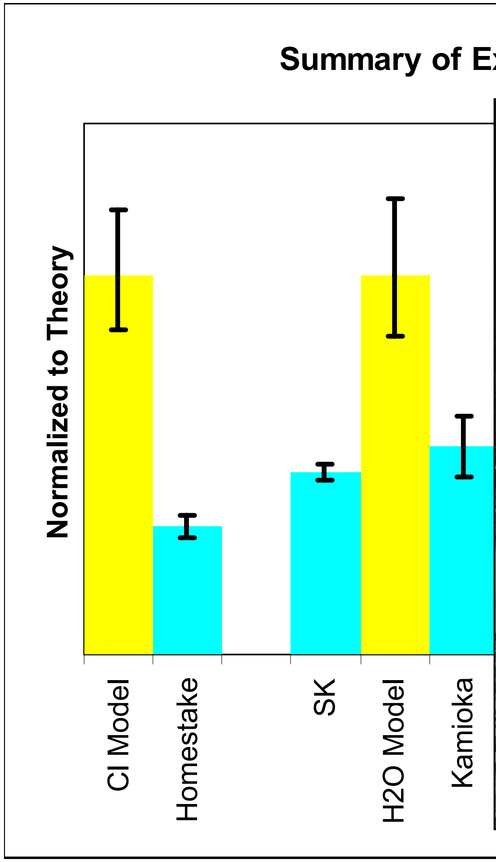
The Solar Neutrino Problem

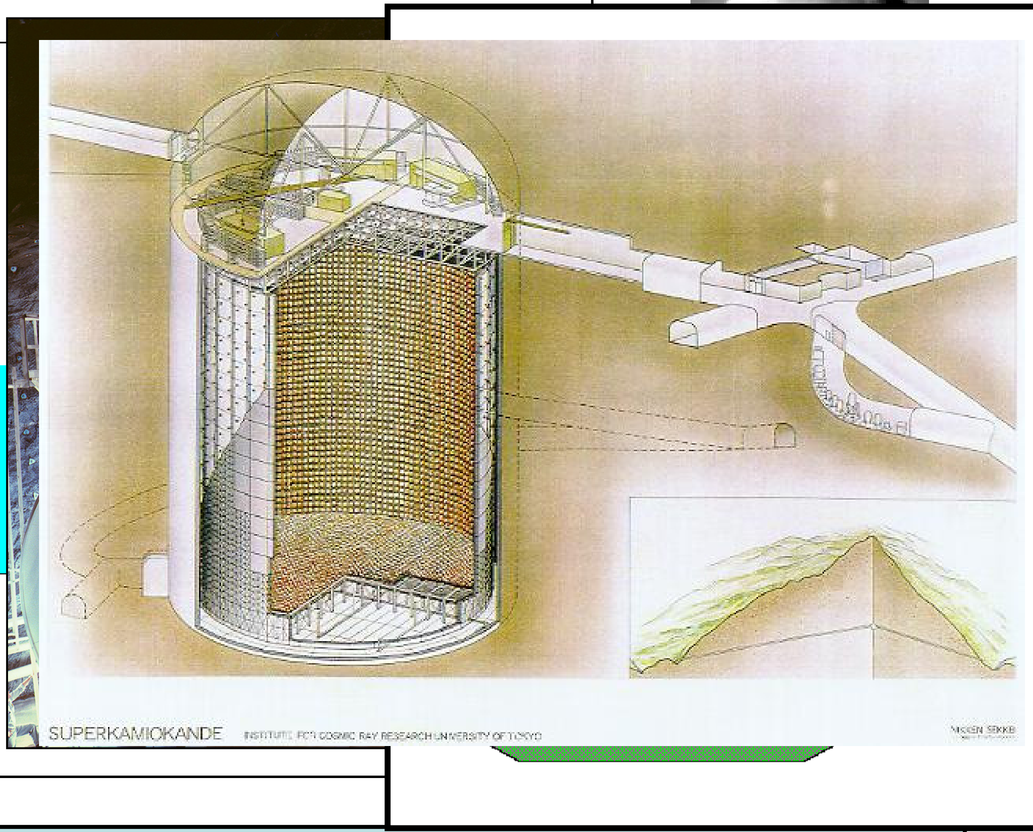
GALLEX/GNO

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

Masatoshi Koshiba

Nobel Prize in Physics, 2002





Either: Solar Models are Incomplete or Incorrect

Or: Neutrinos undergo Flavor Changing Oscillations or other new physics.

Neutrino Oscillations

The lepton mixing matrix (MNSP) is

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

And flavour eigenstates are a mixture of mass eigenstates.

The states evolve with time as

$$\nu_e = U_{e1} e^{-iE_1 t} \nu_1 + U_{e2} e^{-iE_2 t} \nu_2 + U_{e3} e^{-iE_3 t} \nu_3$$

The survival probability is given as:

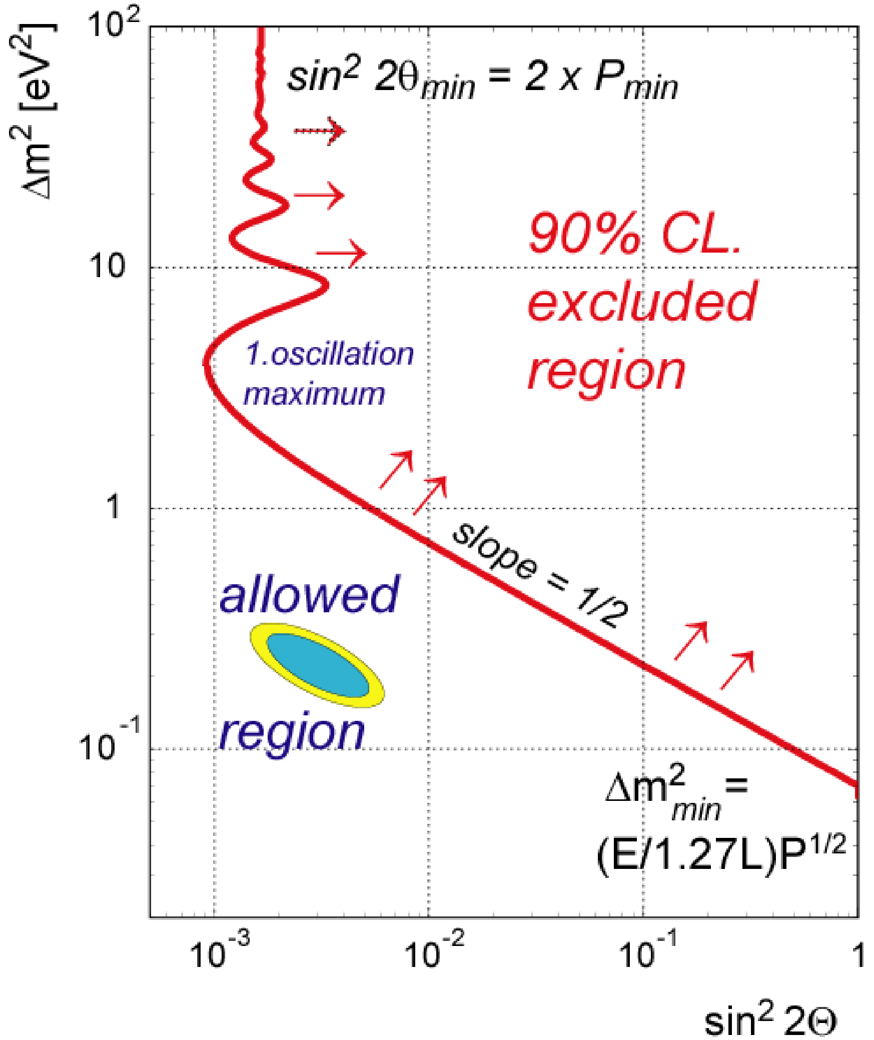
$$P_{\mu e} \sim \sin^2(2\theta) \sin^2(1.27 \Delta m^2 L / E)$$

Physics:

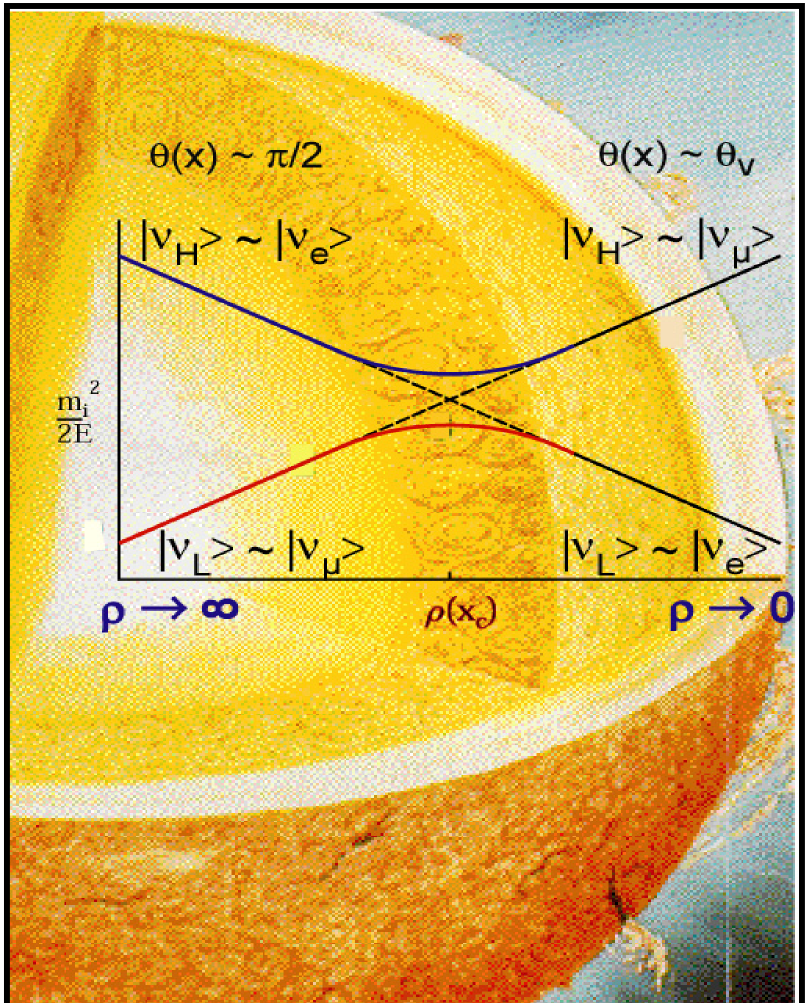
Δm^2 & $\sin^2(2\theta)$

Experiment:

Distance (L) & Energy (E)



The Mikheyev-Smirnov-Wolfenstein (MSW) Effect



- Matter effects enhance oscillations in the sun, since ν_e and $\nu_{\mu\tau}$ interact differently with matter. (ν_e interact with electrons via W exchange)
- Solar neutrino flux detected on Earth consists of $\nu_e + \nu_{\mu,\tau}$

To understand the Solar Neutrino Problem:

- Need a detector that measures the total flux of neutrinos, not just ν_e
- The detector should be very large, to see just a few neutrinos per day.
- The detector must be ultra ultra clean. As radioactivity can mimic a neutrino event.
- The detector must be located very deep, to get away from cosmic rays on the surface.

→ Sudbury Neutrino Observatory

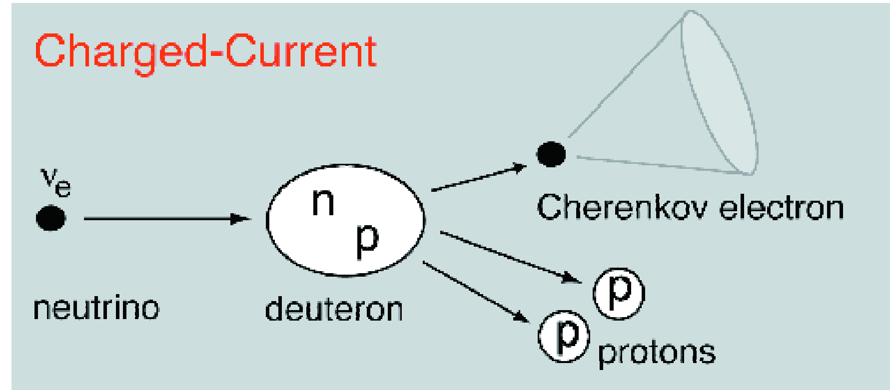
Using D_2O

The SNO Experiment

Neutrino Reactions in SNO

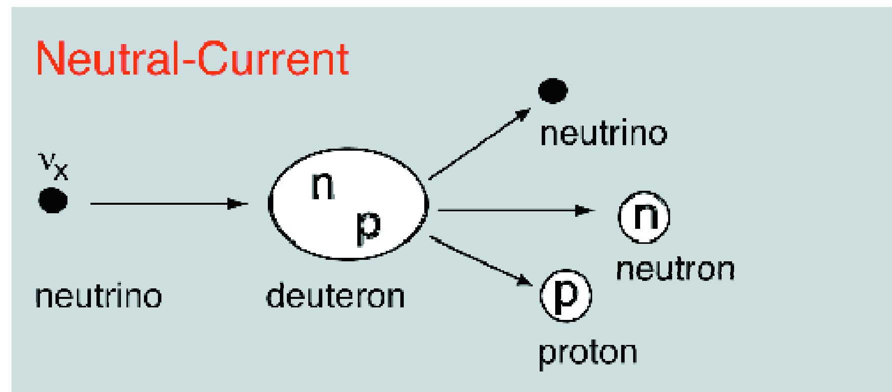
CC $\nu_e + d \rightarrow p + p + e^-$

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



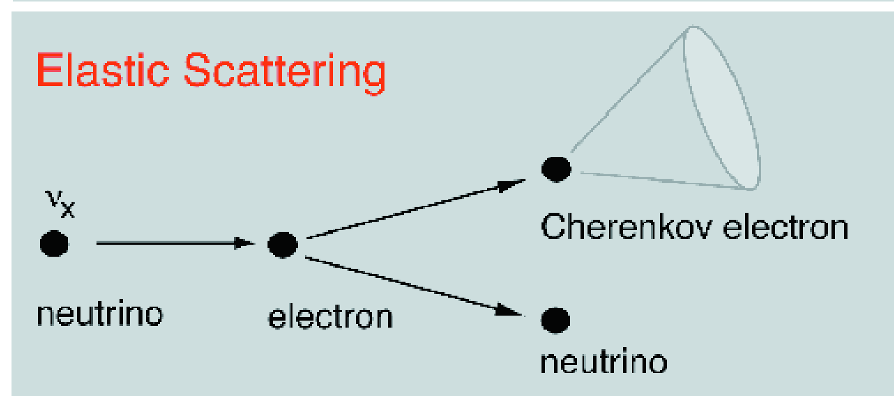
NC $\nu_x + d \rightarrow p + n + \nu_x$

- Q = 2.22 MeV
- measures total ^{8}B 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



What Makes SNO Unique?

- SNO's key measurement is its ability to simultaneously measure the electron (CC) and total (NC) neutrino flux:

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

- Charged current/neutral current ratio is direct test of neutrino oscillations, independent of knowing the absolute flux.

No Oscillations:

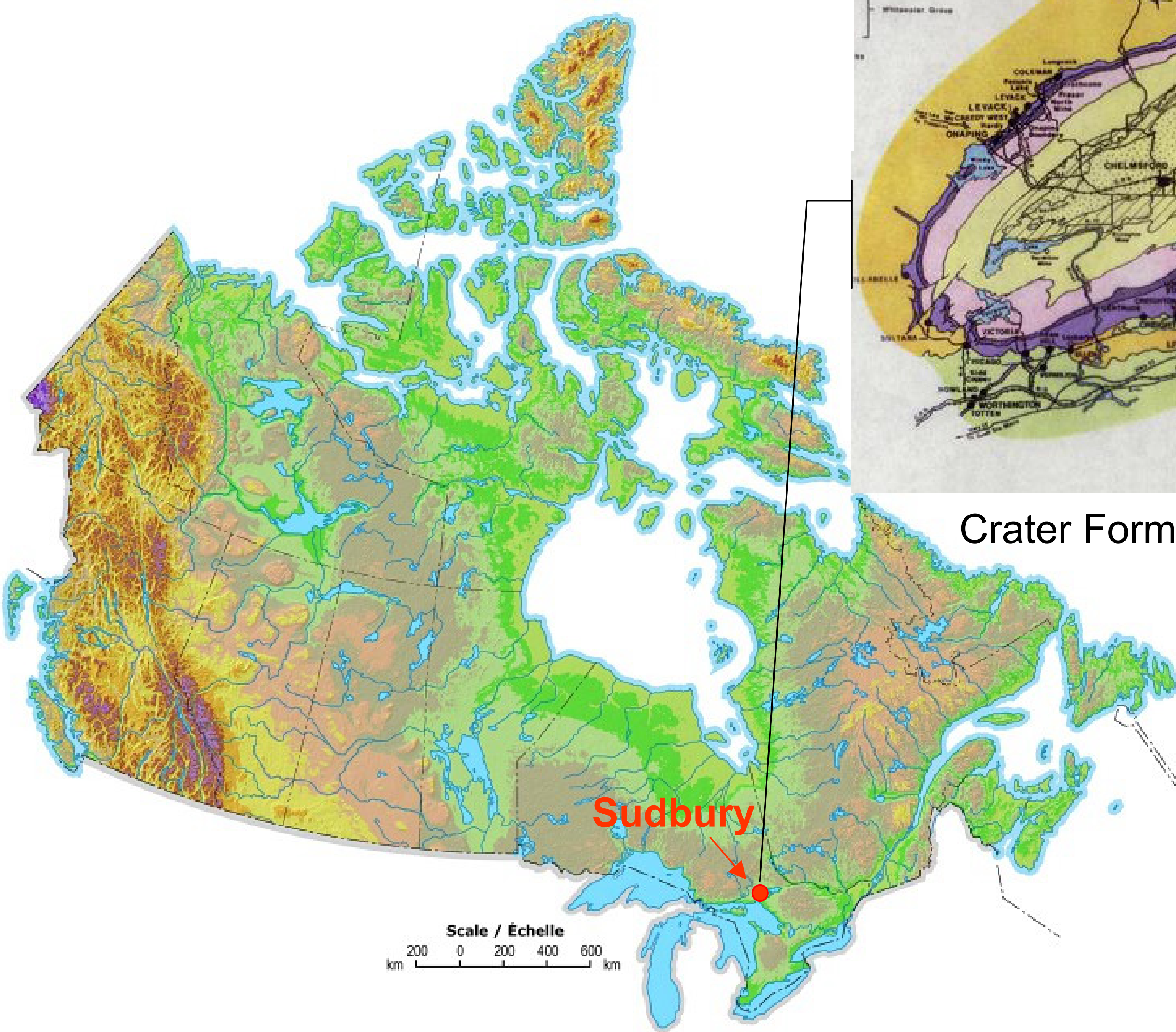
$$\frac{\nu_e}{\nu_e + \cancel{\nu_\mu} + \cancel{\nu_\tau}} = 1$$

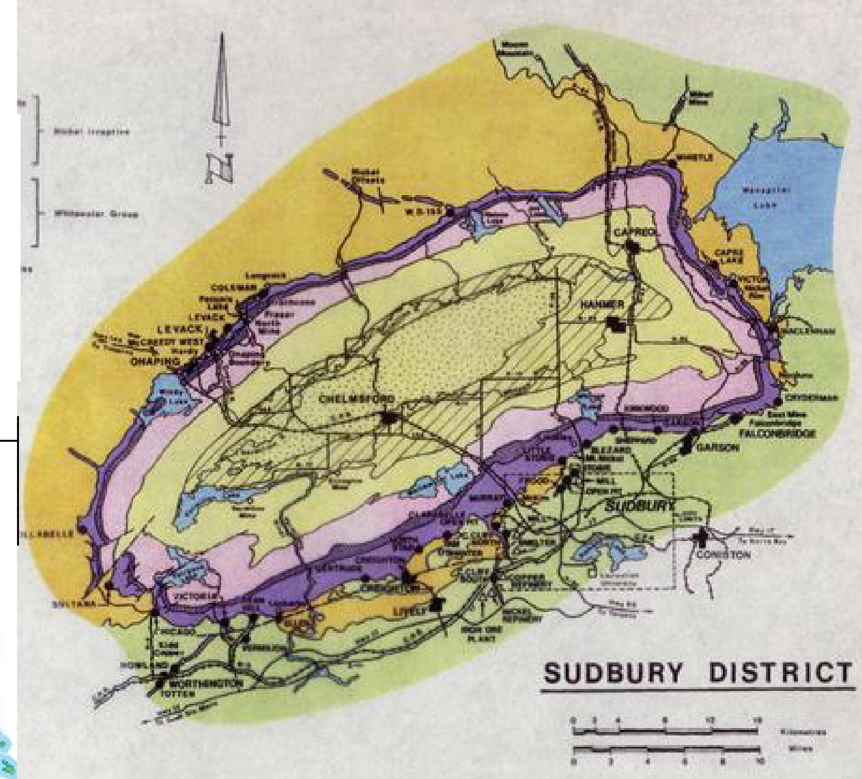
Oscillations:

$$\frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau} < 1$$

SNO Detector

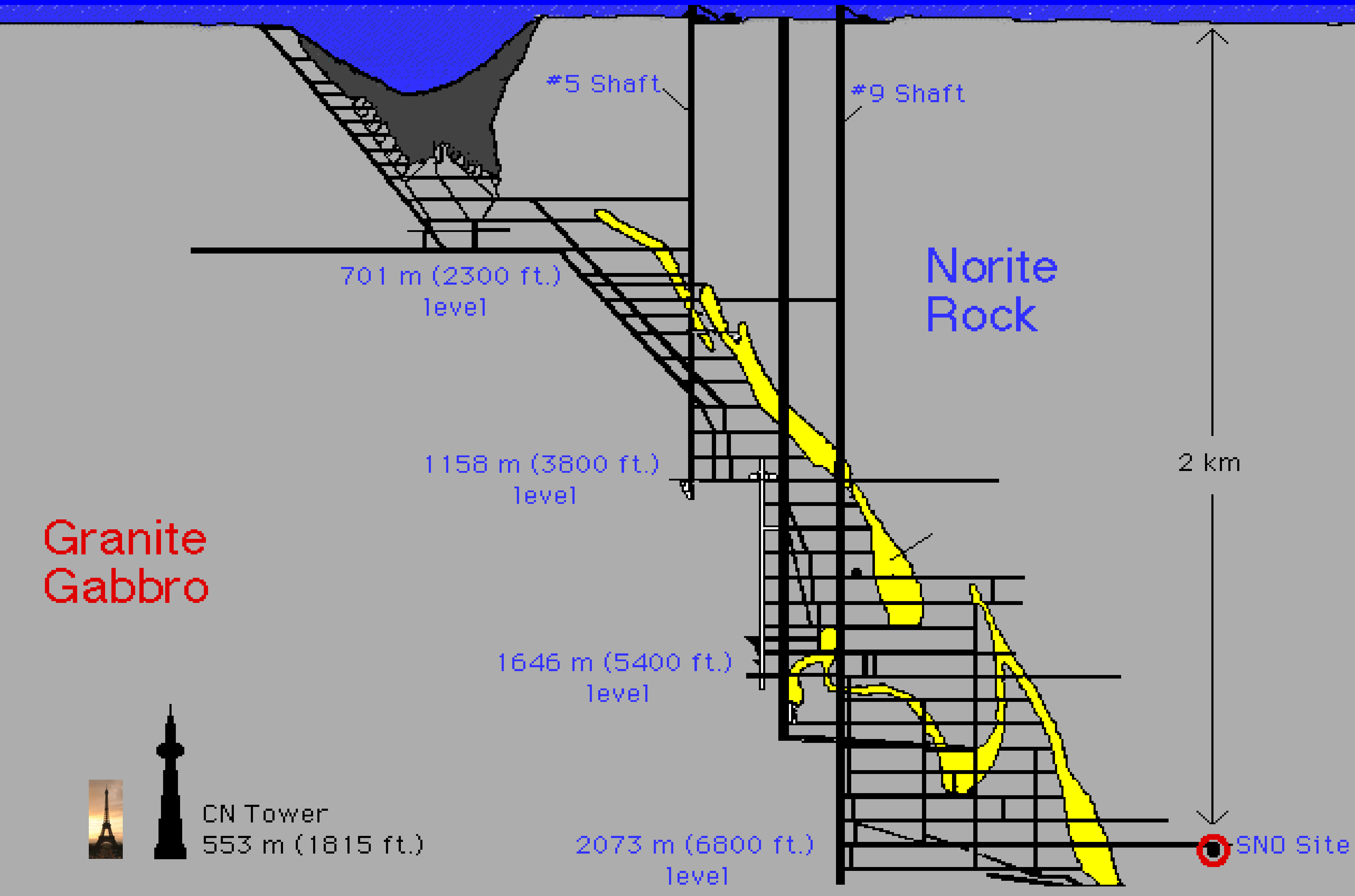
Location of SNO:





Crater Formed by Meteor Strike

SNO: The Sudbury Neutrino Observatory



Sudbury Neutrino Observatory

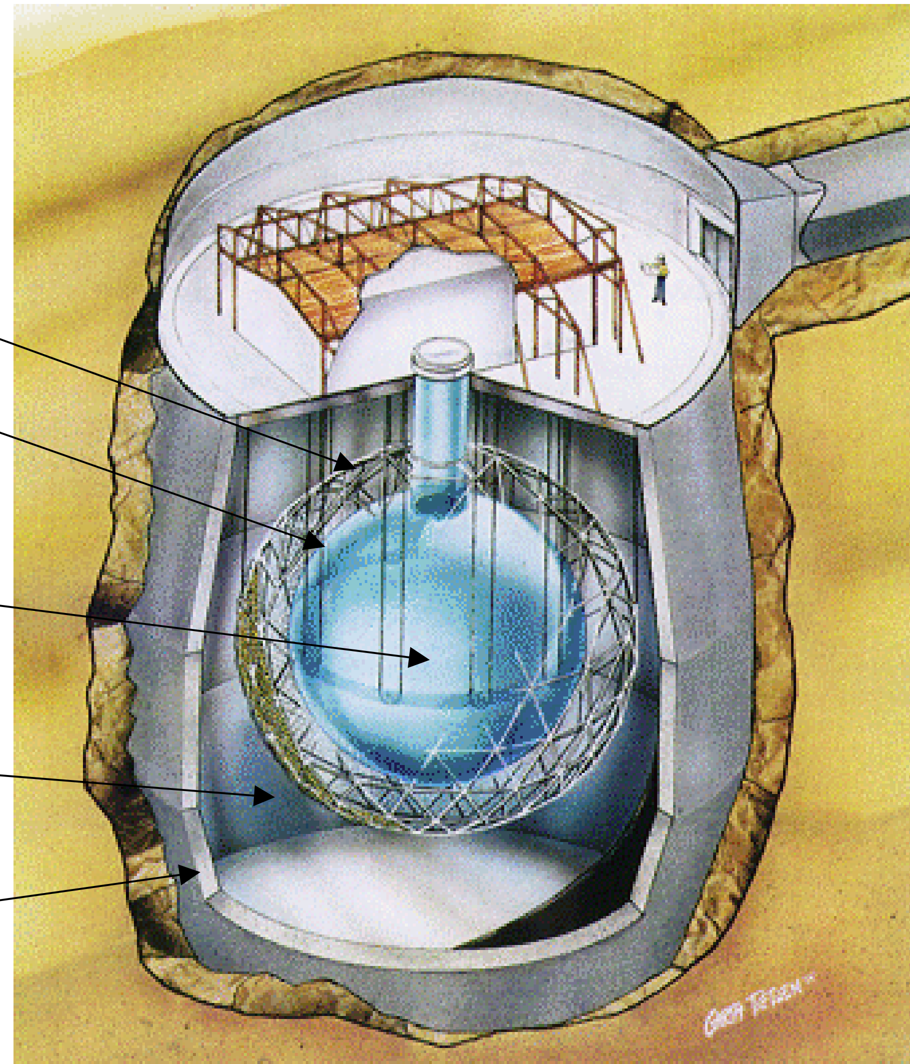
9456 20 cm Photo Multiplier Tubes

Acrylic Vessel, 12 m diameter

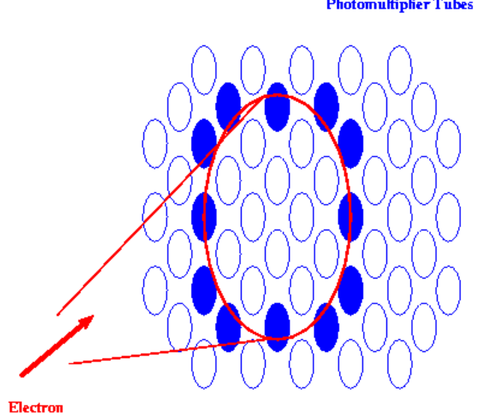
1000 Tonnes D_2O

7000 Tonnes H_2O

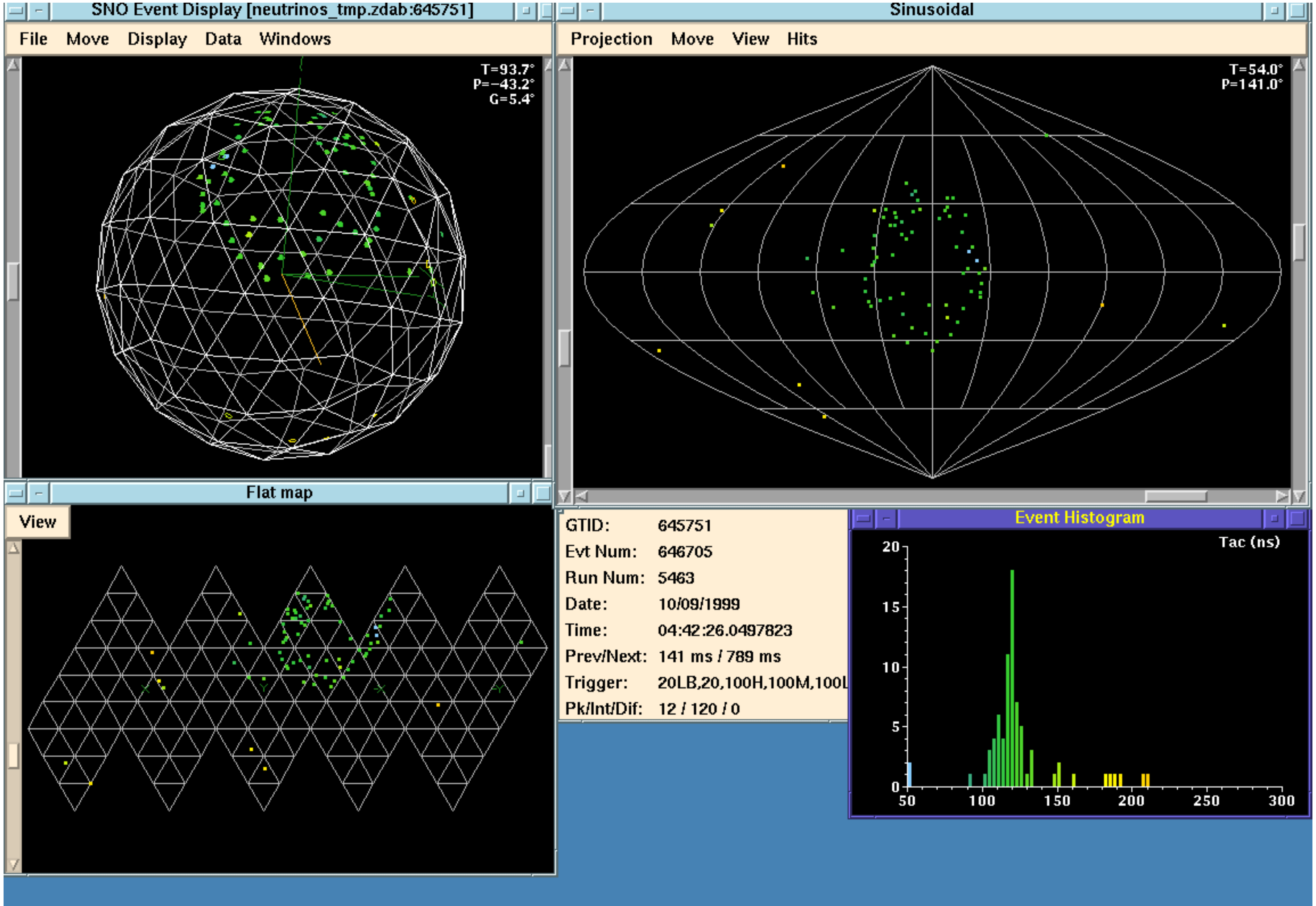
Urylon Liner and Radon Seal



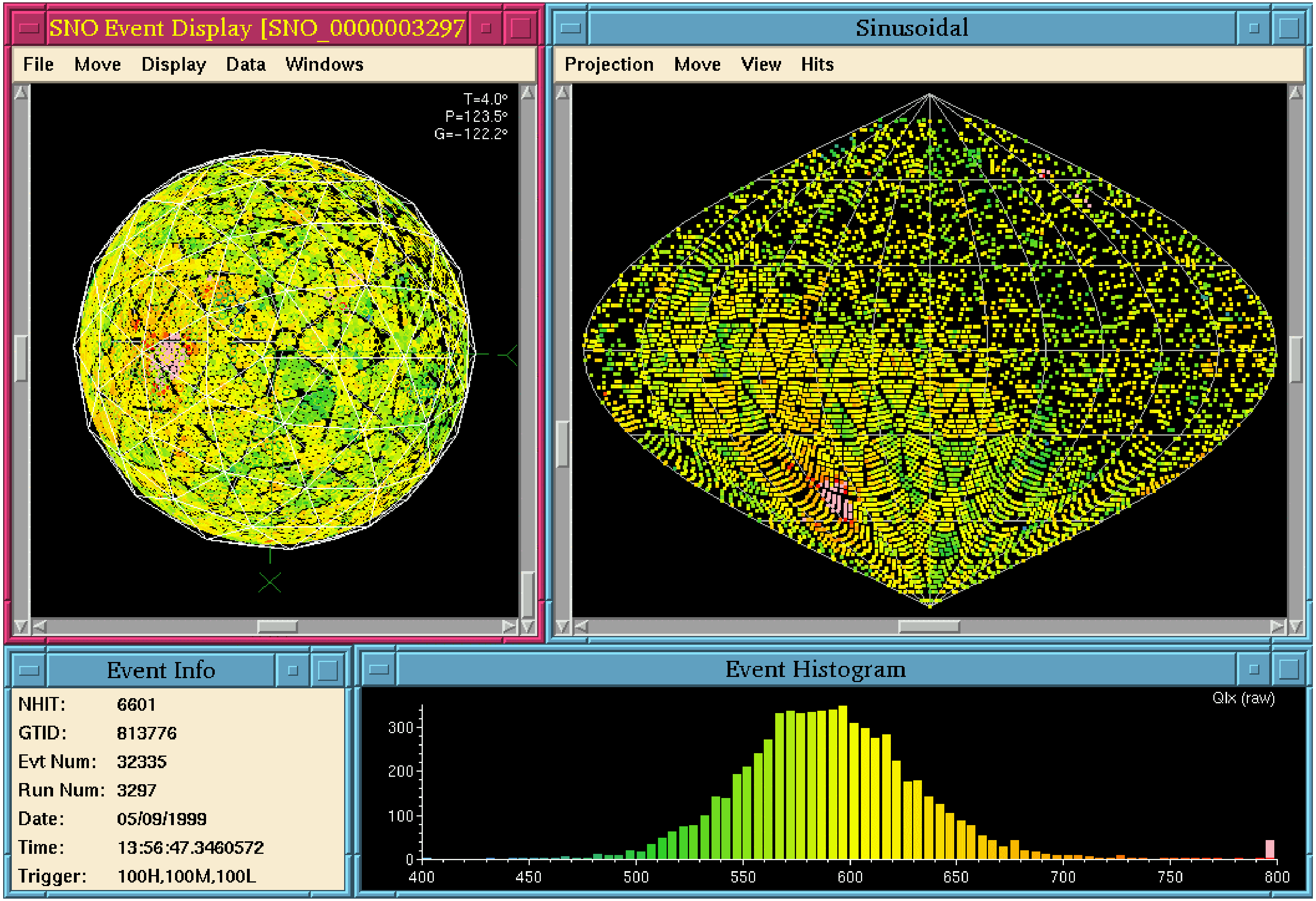
The SNO Detector during Construction



NEUTRINO EVENT DISPLAYED ON SNO COMPUTER SYSTEM



THESE ARE THE COSMIC RAYS WE HAVE GONE UNDERGROUND TO AVOID

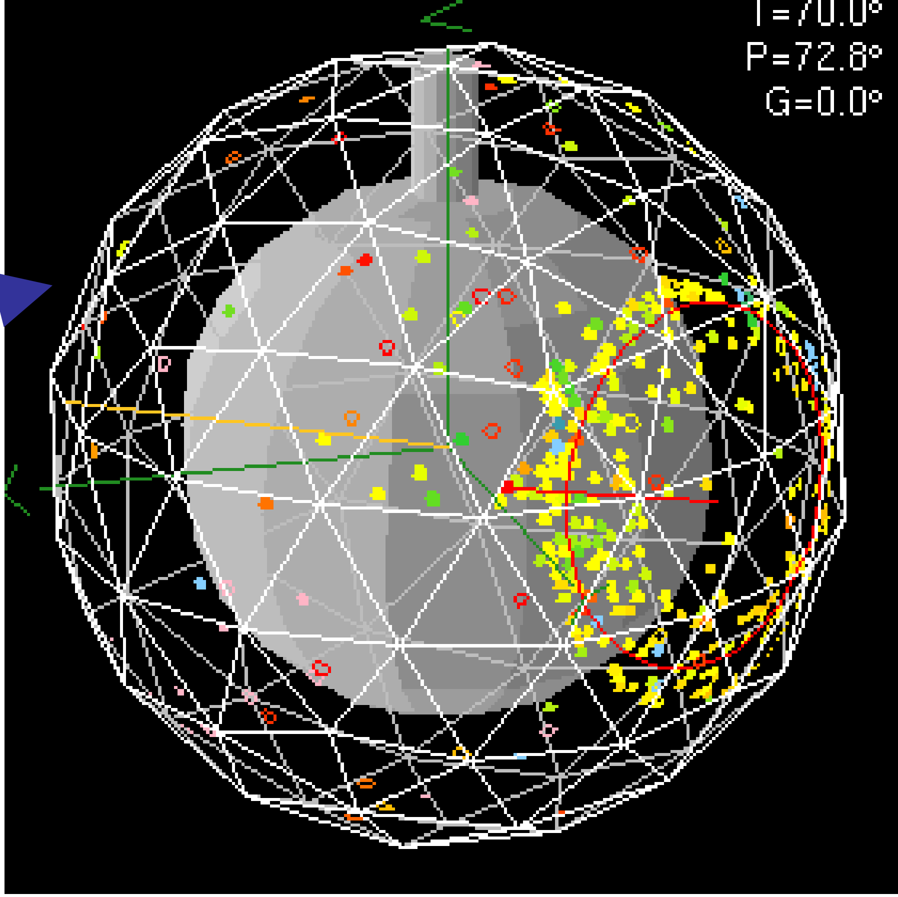


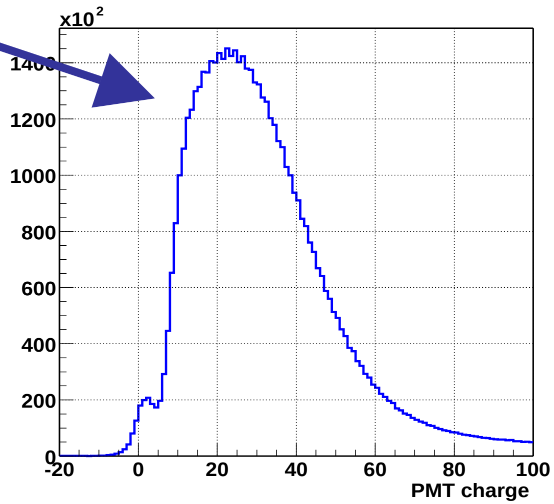
AT OUR DEPTH THEY ONLY HAPPEN A FEW TIMES AN HOUR

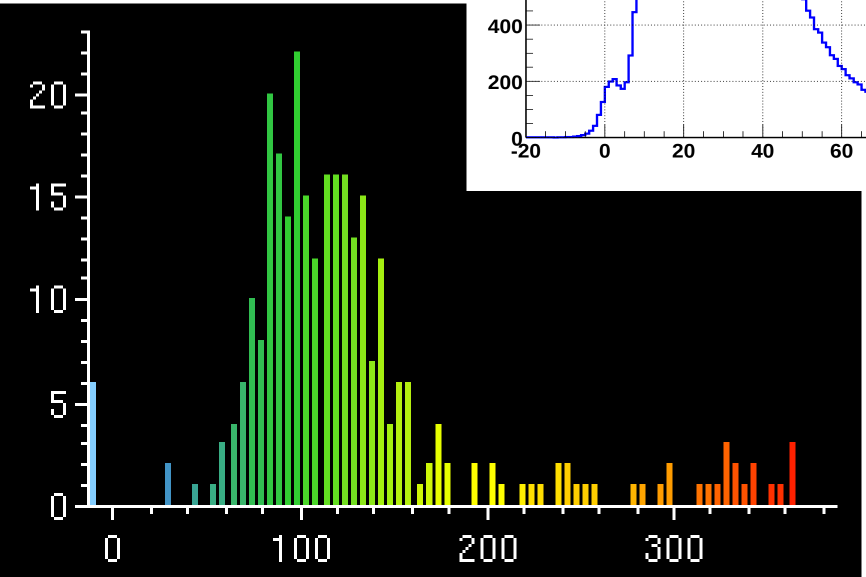
What We Measure:

PMT Measurements

- -position
- -charge
- -time







Reconstructed Event

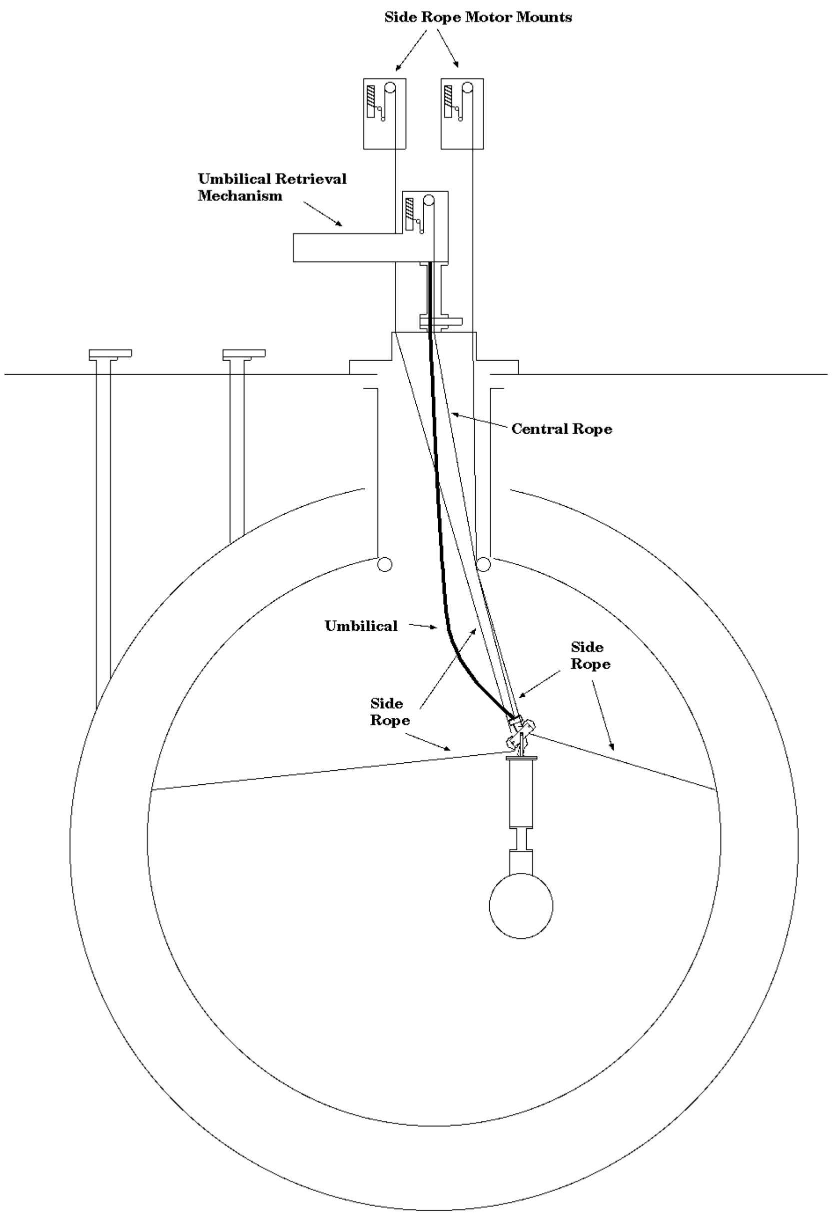
- -event vertex
- -event direction
- -energy
- -isotropy

Detector Calibration

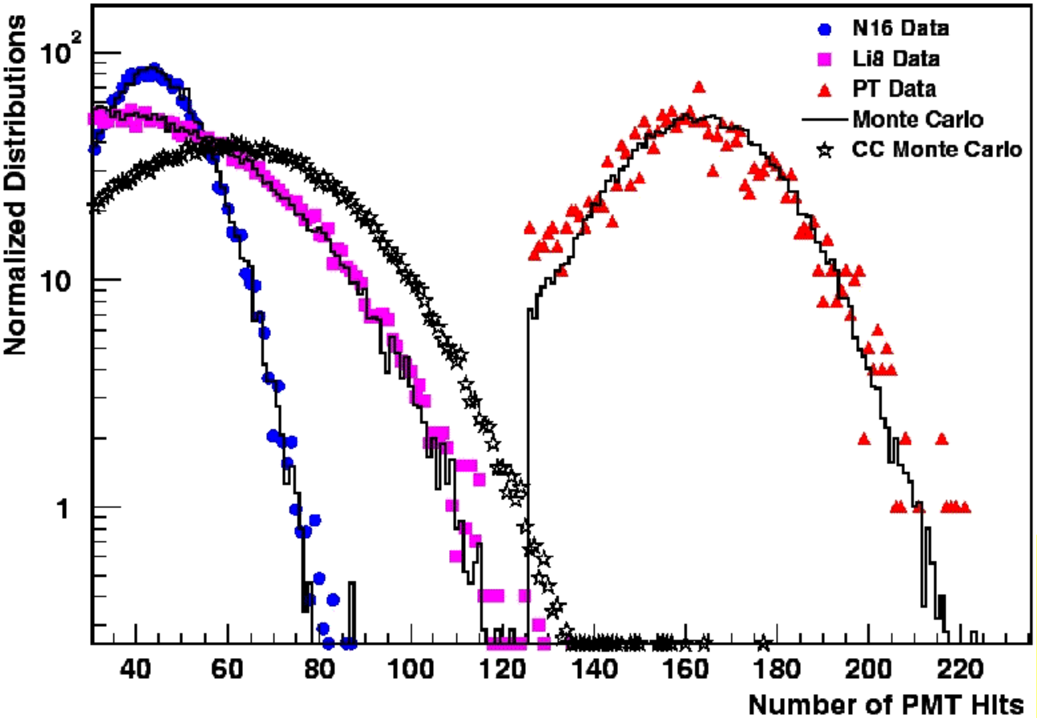
&

Backgrounds

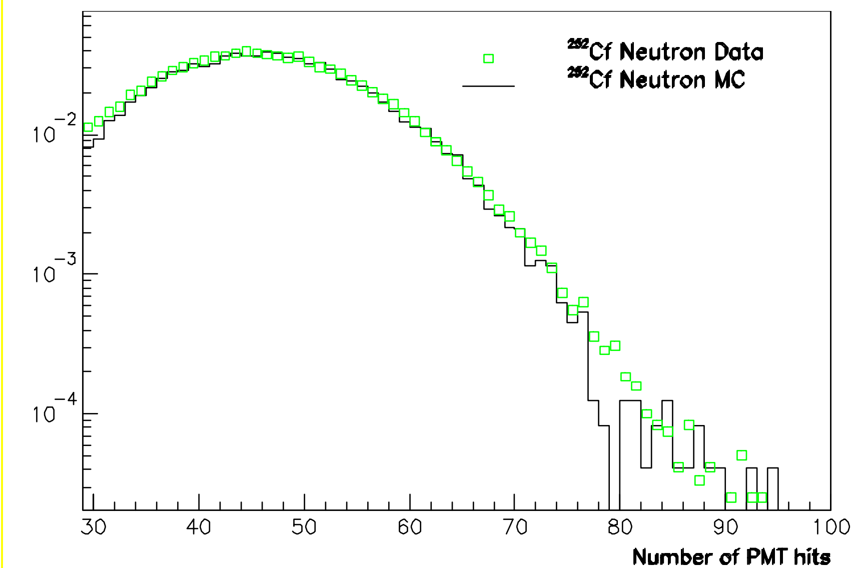
Optical Calibration: “Laser Ball”



SNO Energy Calibrations



^{252}Cf neutrons

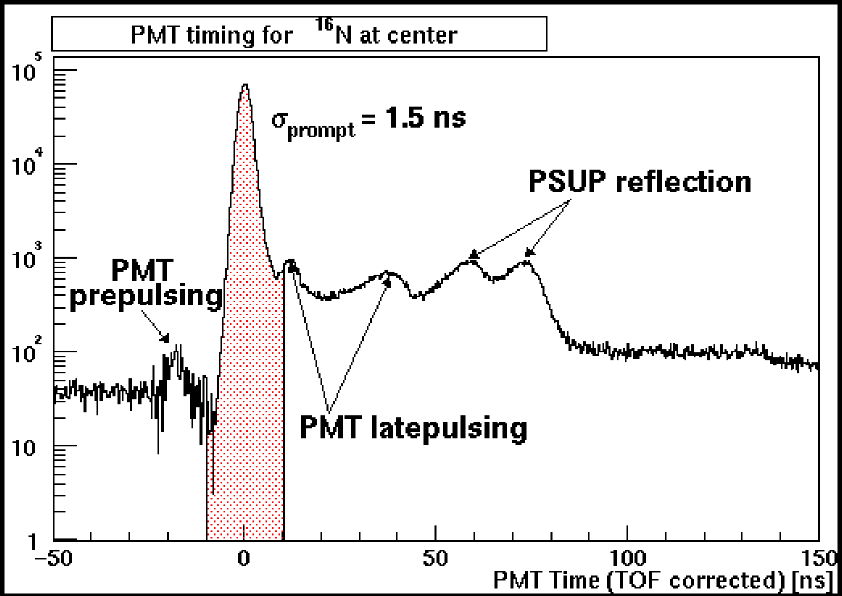


β's from ^{8}Li

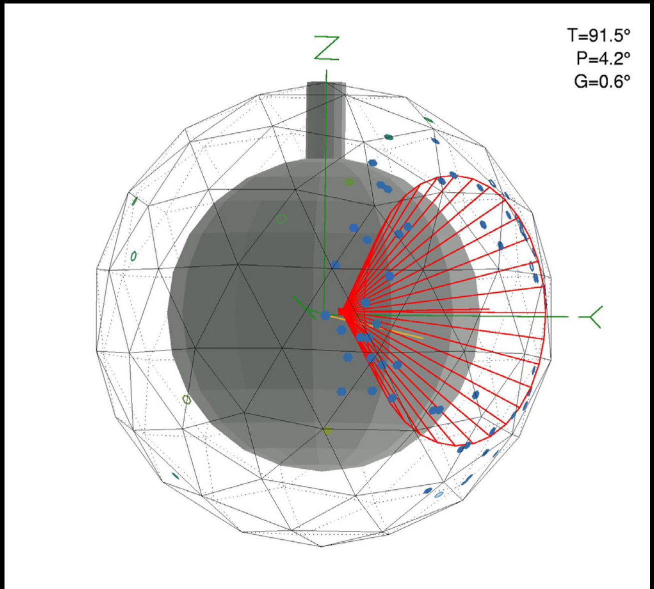
γ's from ^{16}N and t(p,γ)^{4}He

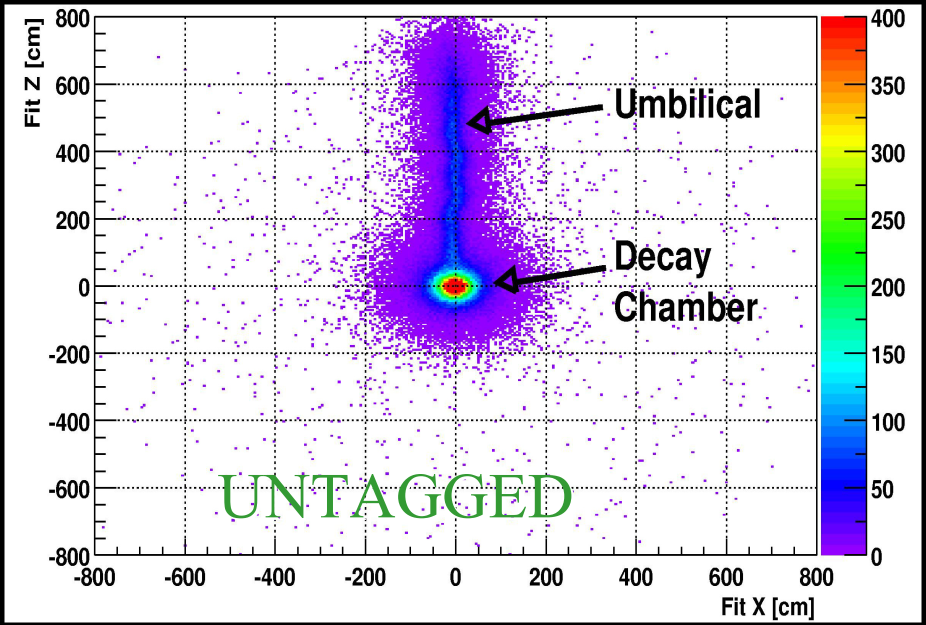
Vertex Reconstruction

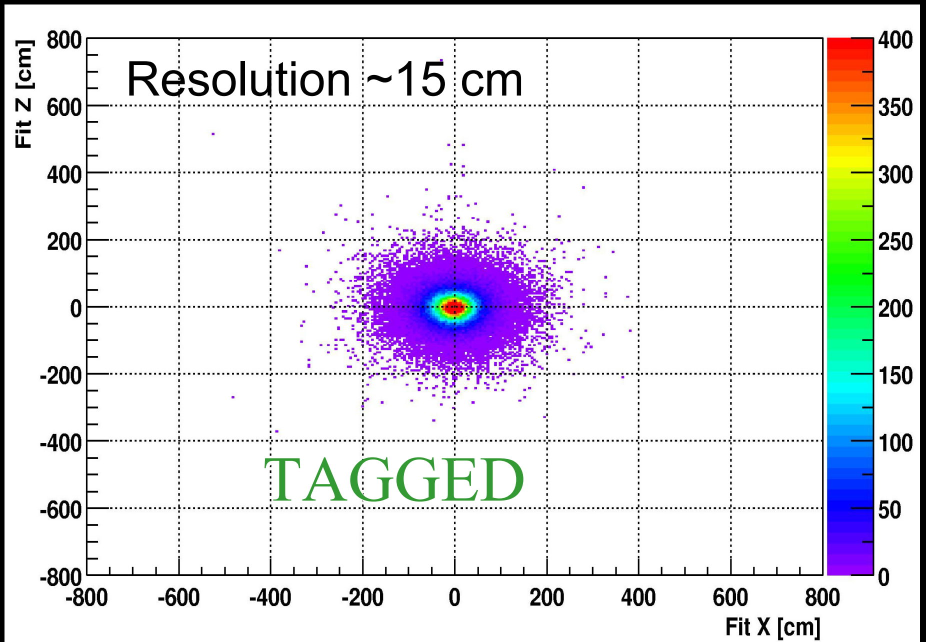
^{16}N 6.13 MeV γ $\left\{^{16}O(n,p)^{16}N\right\}$



PMT times used to reconstruct event position

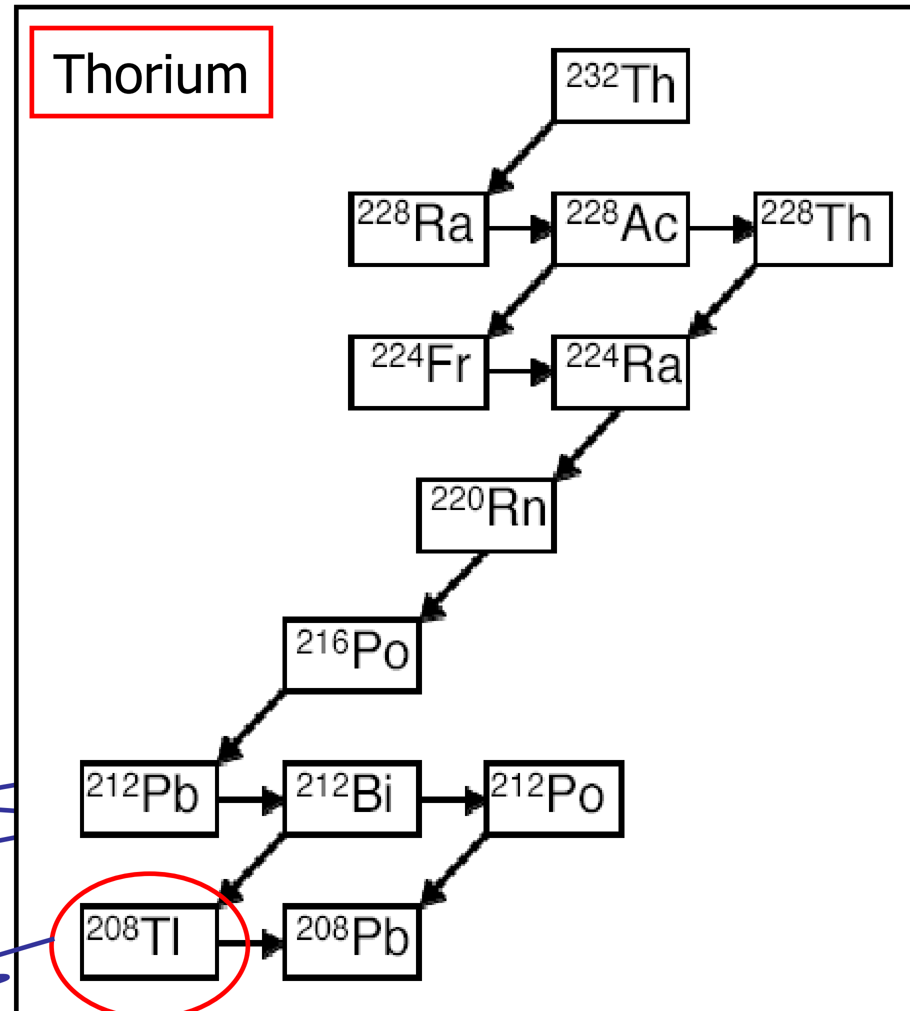




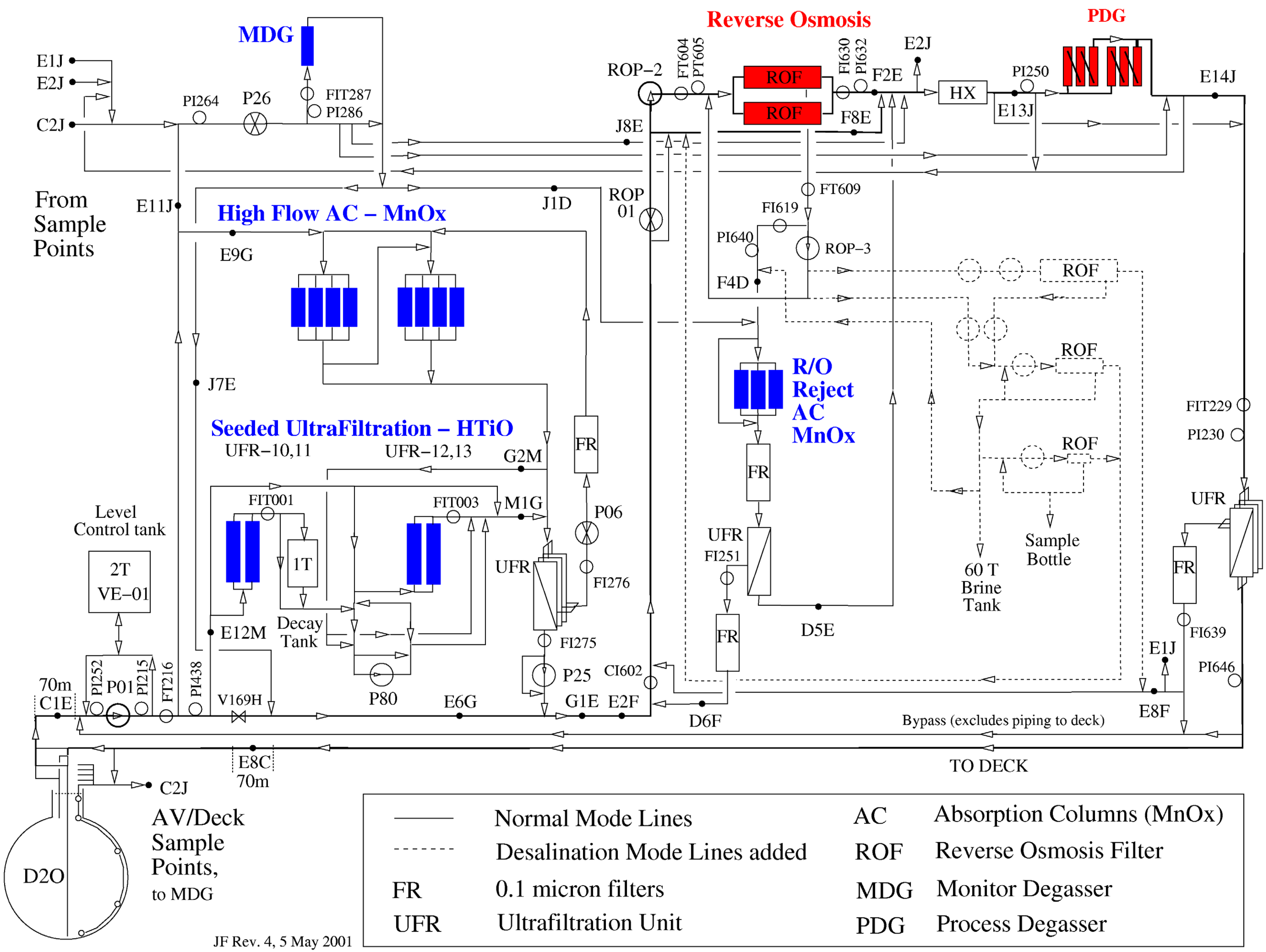


An Ultraclean Environment

- Highly sensitive to any γ above neutral current threshold (2.2 MeV).
- Threshold limited by low energy background radiation. (β, γ)
- Sensitive to ^{238}U and ^{232}Th decay chains and ^{40}K



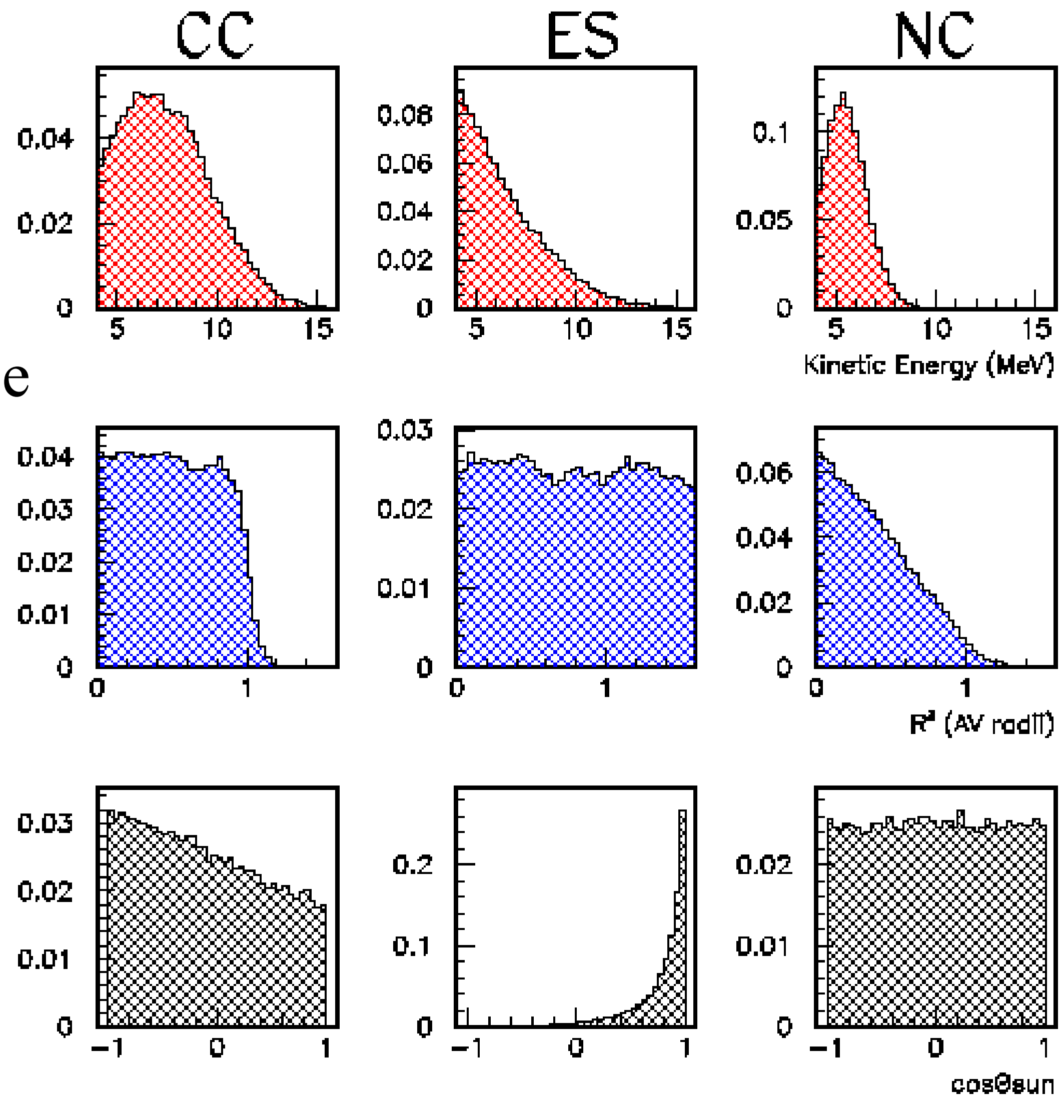
SNO D_2O Assay and Purification Systems



Results and Implications

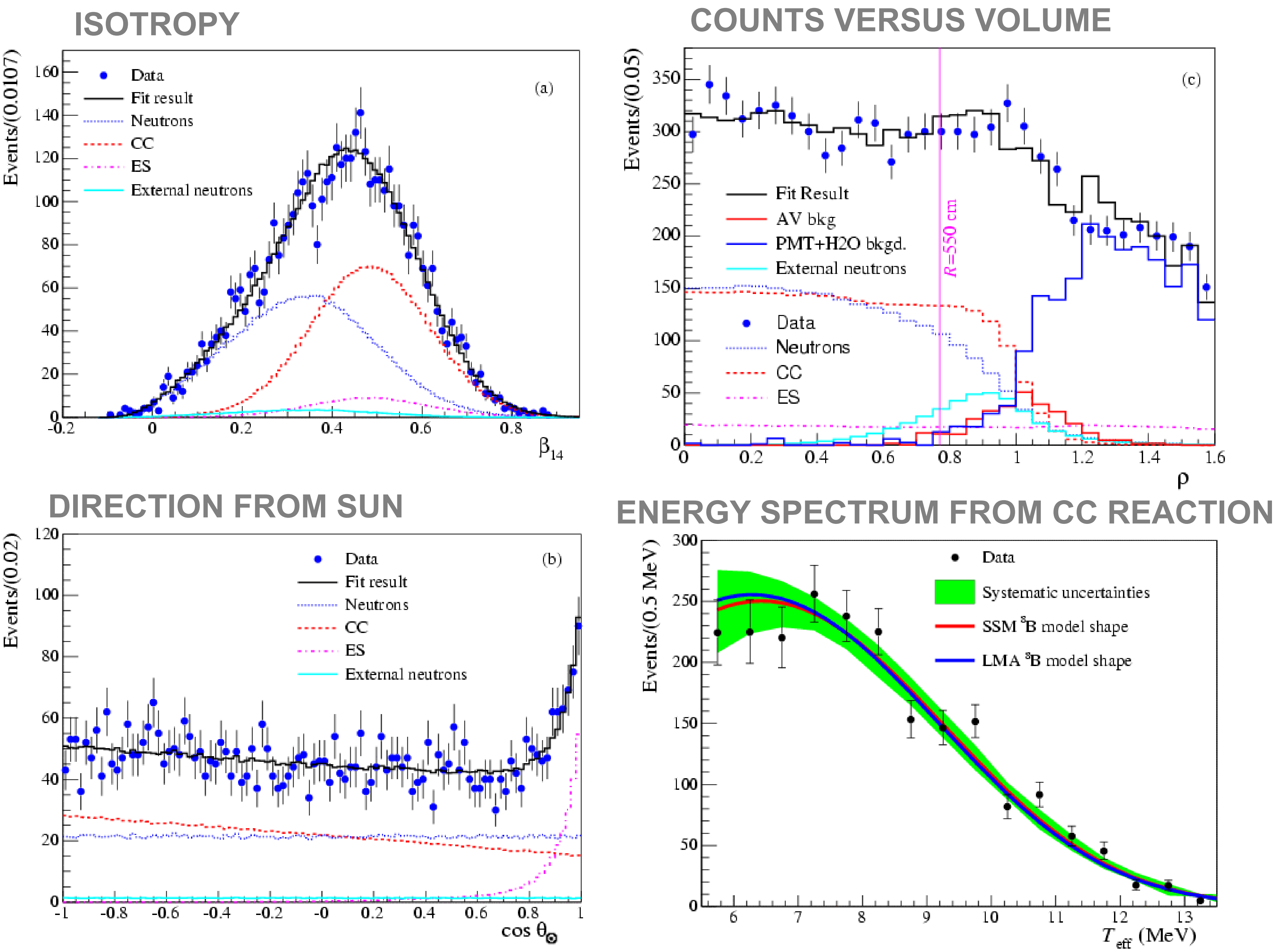
Extraction of CC, ES, NC Signals (Pure D2O)

To extract the CC, ES, NC signal SNO performs a Maximum likelihood statistical separation of these signals based on distributions of the SNO observables.



Data Analysis:

Multivariate Likelihood Fit



ISOTROPY
Events/(0.0107)
Data
Fit result
Neutrons
CC
ES
External neutrons
(a)
β14
COUNTS VERSUS VOLUME
Events/(0.05)
(c)
Fit Result
AV bkg
PMT+H2O bkgd.
External neutrons
R=550 cm
Data
Neutrons
CC
ES
ρ
DIRECTION FROM SUN
Events/(0.02)
Data
Fit result
Neutrons
CC
ES
External neutrons
(b)
cos θ⊙
ENERGY SPECTRUM FROM CC REACTION
Events/(0.5 MeV)
Data
Systematic uncertainties
SSM 8B model shape
LMA 8B model shape
T eff (MeV)

Three Phases of SNO.
(Different methods to measure NC)

D_2O (Done)

NC sensitivity
ε_n~14.4%

$n + {}^2H \rightarrow {}^3H + \gamma$

$E_\gamma = 6.25$ MeV

Long neutron path length. Lower energy signal. Fewer events

Nov. 1999- May 2001

Salt (Done)

Enhanced NC sensitivity
ε_n~40%

$n + {}^{35}Cl \rightarrow {}^{36}Cl + \sum\gamma$

$E_{\sum\gamma} = 8.6$ MeV

Short neutron path, well defined vertex, more energy, more events.

June 2001 - Sept 2003

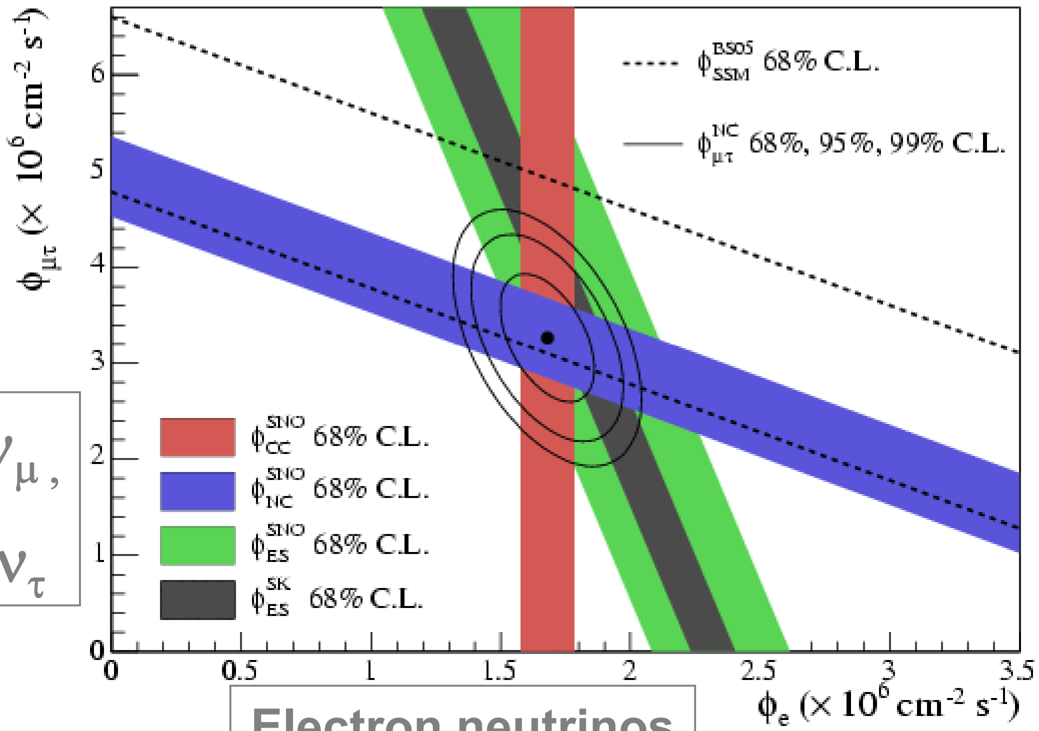
NCD (Now)

Neutral Current Detectors
ε_n~30% capture

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

Measure NC rate with entirely different detection system. CC and NC decoupled.

Nov. 2004 to Dec. 2006



ν_μ, ν_τ

Electron neutrinos

Salt Phase Results

NC flux is in agreement with,

And more accurate than

Solar models for ^{8}B flux.

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

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

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

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

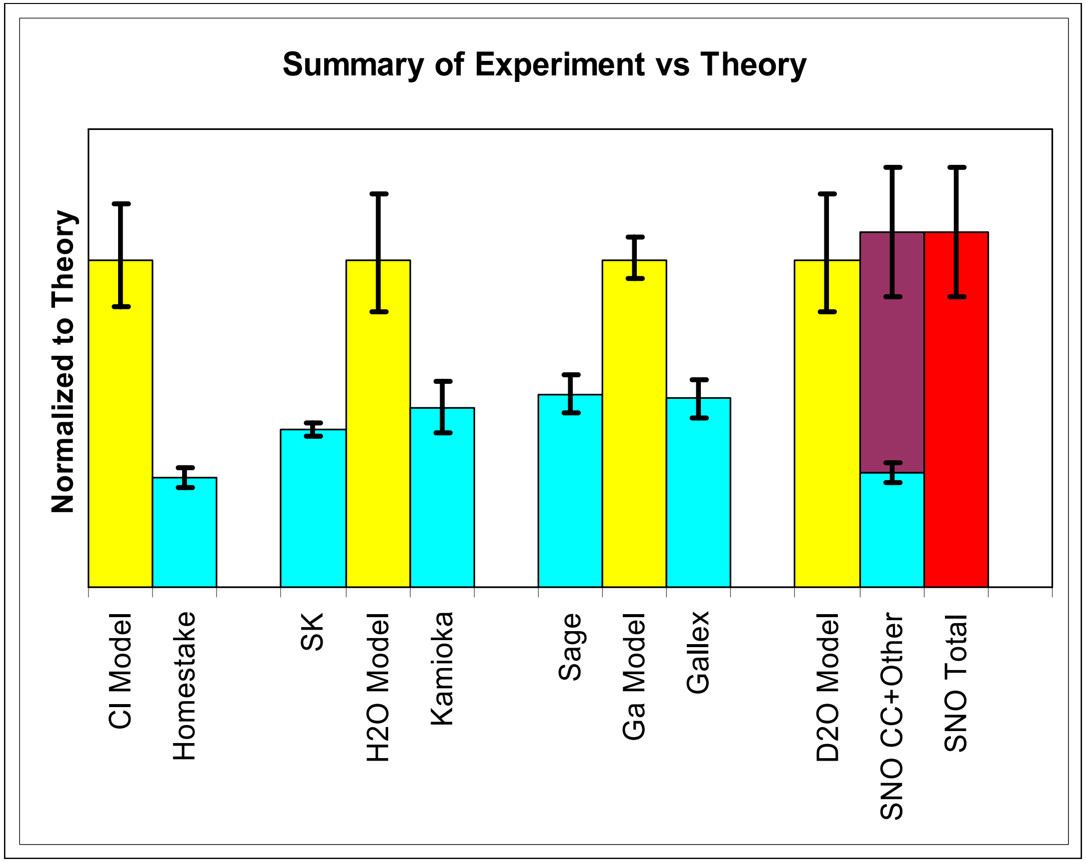
$$\frac{\phi_{CC}}{\phi_{NC}} = 0.34 \pm 0.023(\text{stat.})^{+0.029}_{-0.031}$$

Electron Neutrinos are only 1/3 of total,

Flavor change is determined with > 7 σ

Neutrino Flavor Change is Beyond the Standard Model of Particle Physics

The Solar Neutrino Problem



SNO Solution: Neutrinos undergo Flavor Changing Oscillations

John Bachall. Institute for Advanced Study. Princeton

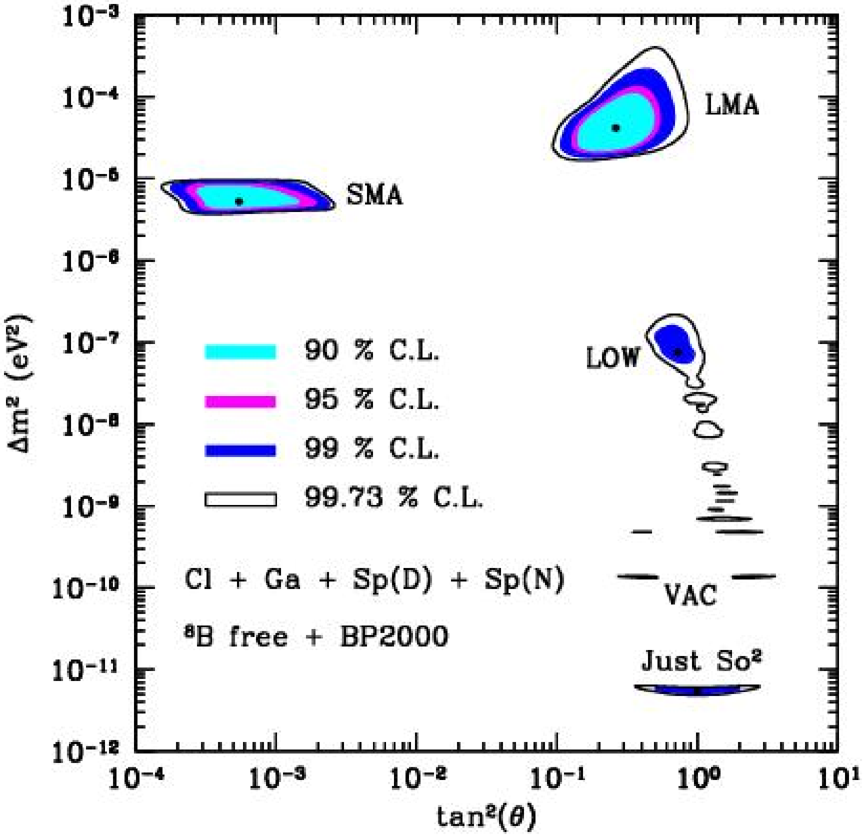
For 30 years has been unwavering in his calculation for the flux of neutrinos from the sun.

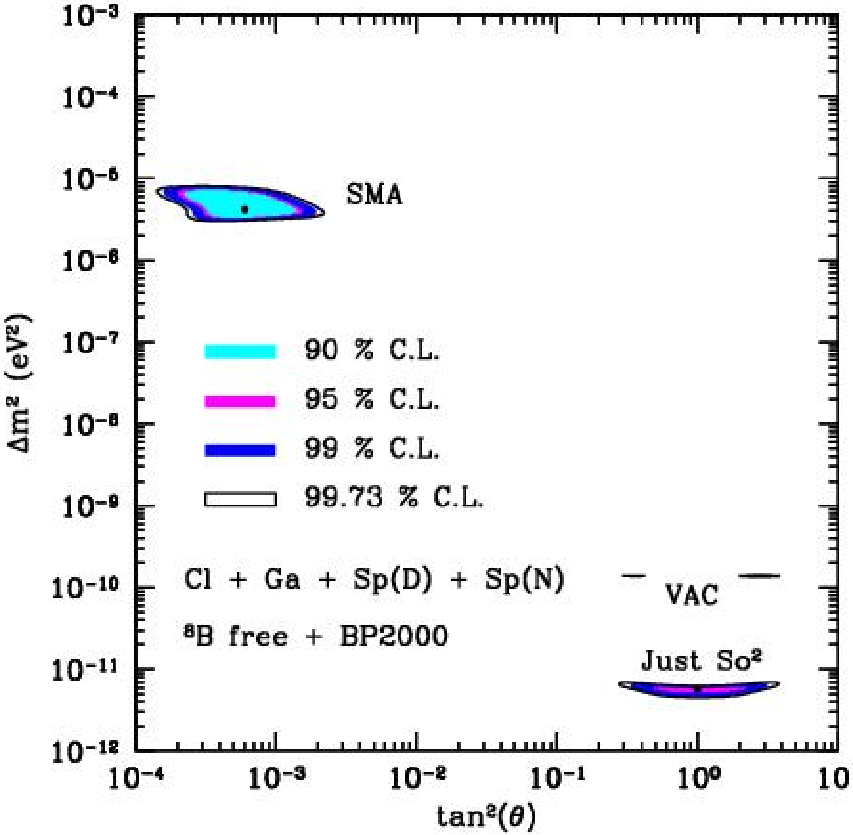
This in the face of empirical evidence to the contrary.

Until the SNO results proved him correct:

‘I feel vindicated. The DNA evidence is in after 30 years’

Previously Allowed Solutions for Solar Neutrino Oscillations

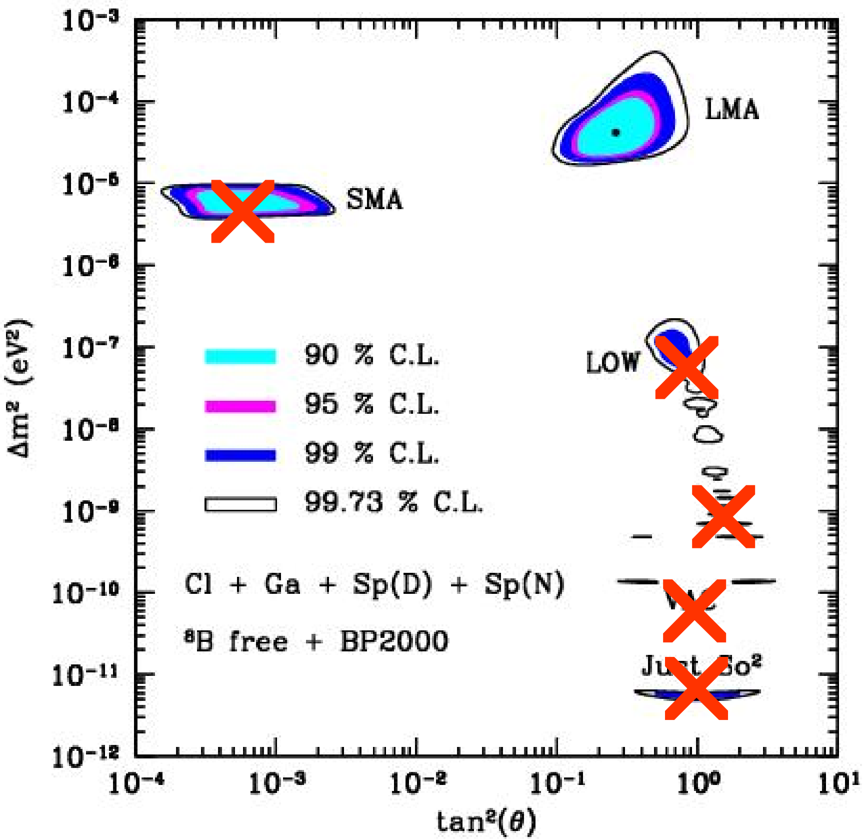


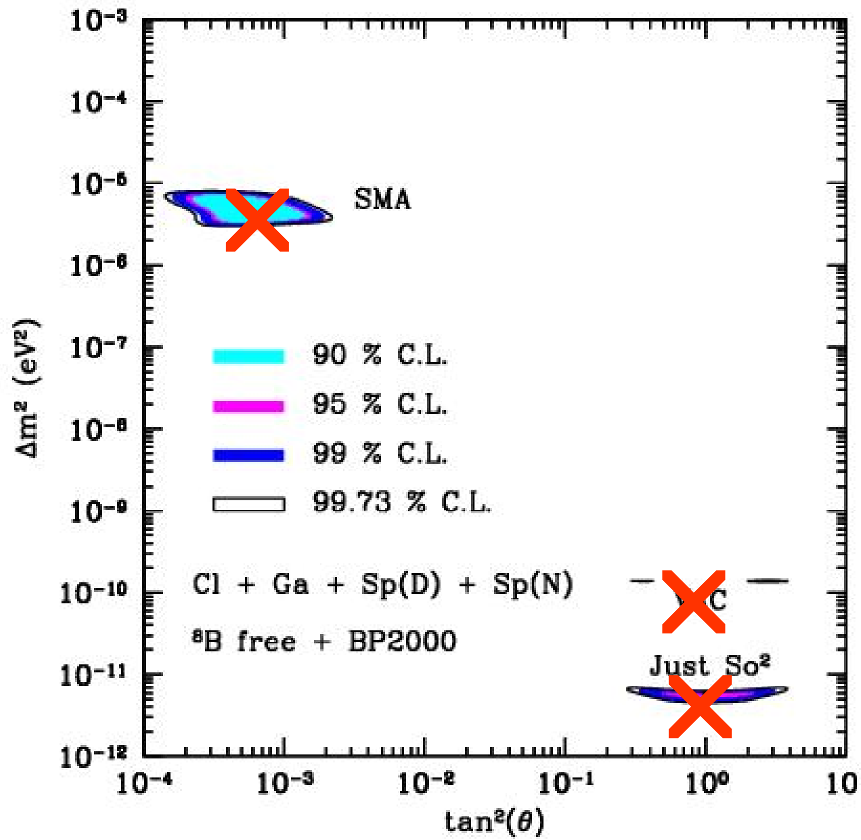


To Active Neutrinos

To Sterile Neutrinos

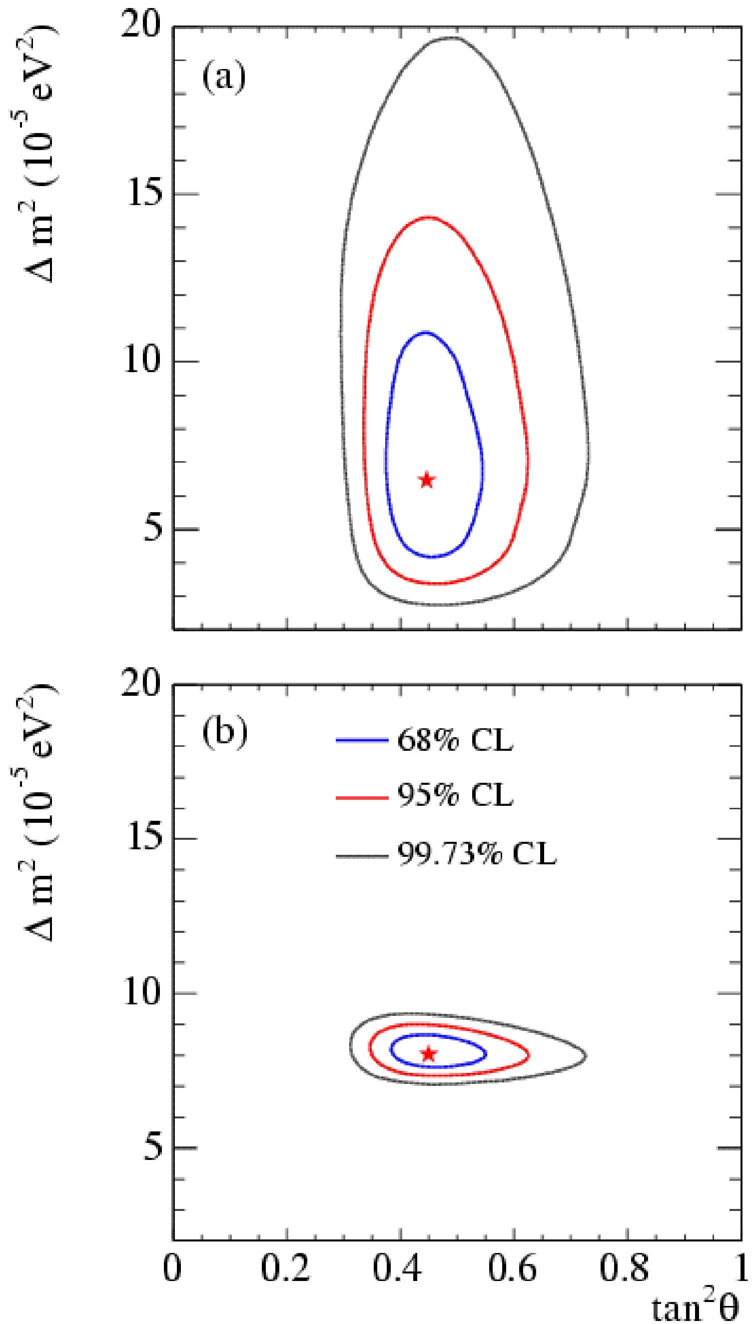
SNO Results favour LMA





To Active Neutrinos

To Sterile Neutrinos



Large mixing Angle (LMA) region

SOLAR ONLY

SOLAR PLUS KAMLAND (Reactor ν's)

The 1-2 neutrino oscillation parameters are now becoming well defined.

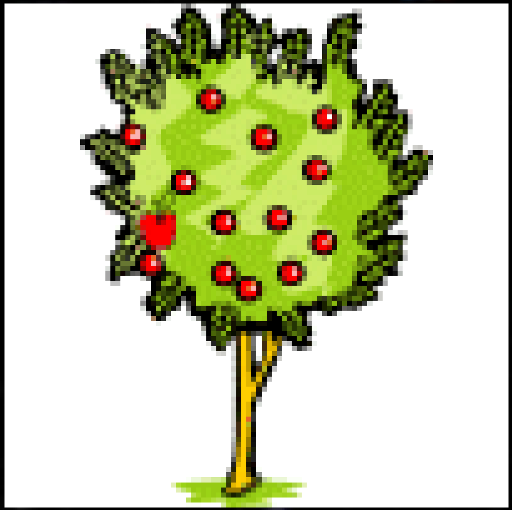
- Note that the solar results define the mass hierarchy ($m_2 > m_1$) through the Matter interactions (MSW).

- Also, $\tan^2\theta < 1$ (Maximal mixing) by more than 5 standard deviations.

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

What did we learn so far ?

1 Neutrinos are changing from one flavour to another between the sun and the earth!



Imagine an apple falls off a tree, when it lands on the ground, it's a banana!
Thirty year old puzzle about neutrinos has been solved.

2 Neutrinos must have a finite mass. New physics !

3 Our model of how the Sun burns is very accurate.

4 The mass of neutrinos alone is not enough to cause a "Big Crunch"

5 Neutrino masses are insufficient to account for Dark Matter.

The Current (Last) Phase of SNO

From Discovery to Precision:
The Neutral Current Detectors

Array of ^{3}He counters

Move into next phase of SNO
40 Strings implanted on 1-m grid

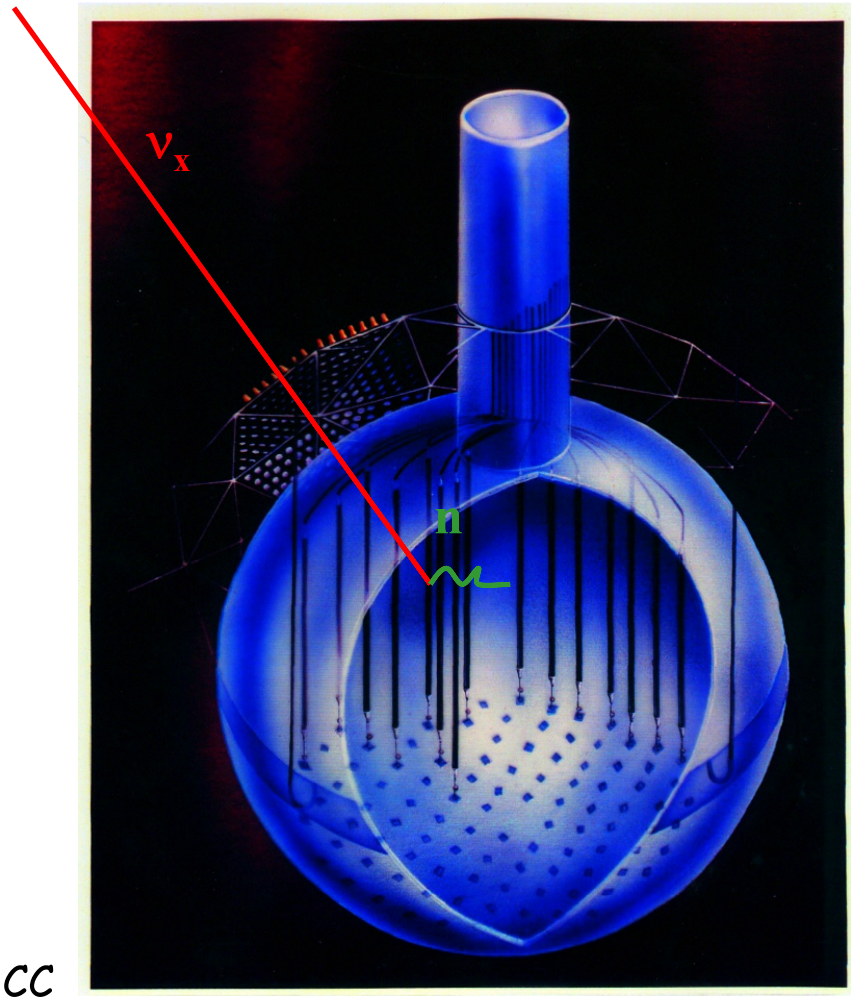
Detection Principle

(NC) $^2H + \nu_x \rightarrow p + n + \nu_x$

$\searrow$ $^3He + n \rightarrow p + {}^3H$ (NCD)

(CC) $^2H + \nu_e \rightarrow p + p + e^-$

$\searrow$ e^- - Cherenkov light (PMT)



Physics Motivation

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

Different systematic uncertainties
than neutron capture on NaCl, D_2O

NCD array removes neutrons from CC, Better CC spectral shape at the lowest energy.

What will we learn from NCD's ?

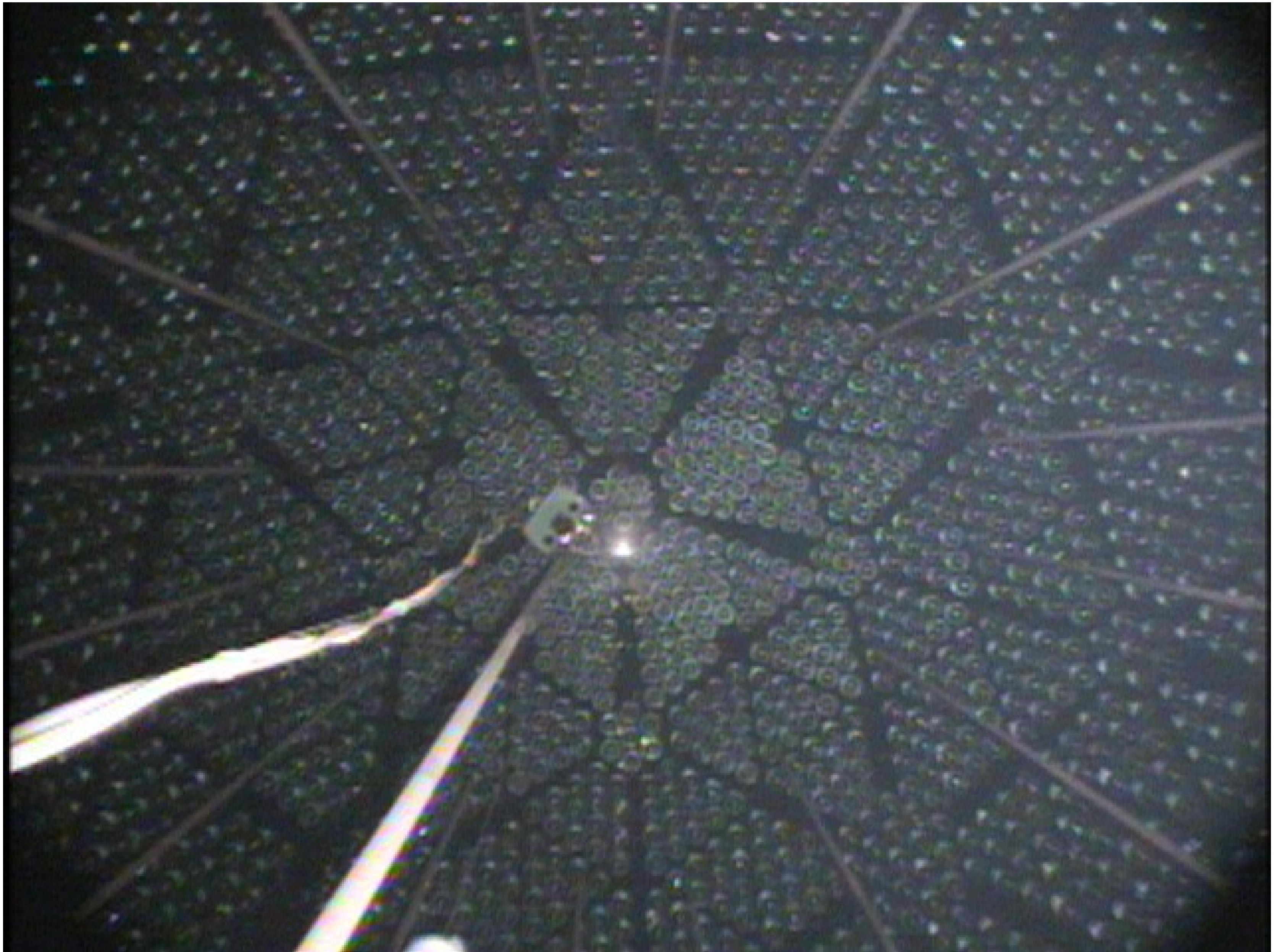
1 Use a blind analysis to confirm that what we measured in the pure D_2O and salt phase were correct, using a completely different method with different systematic errors. :

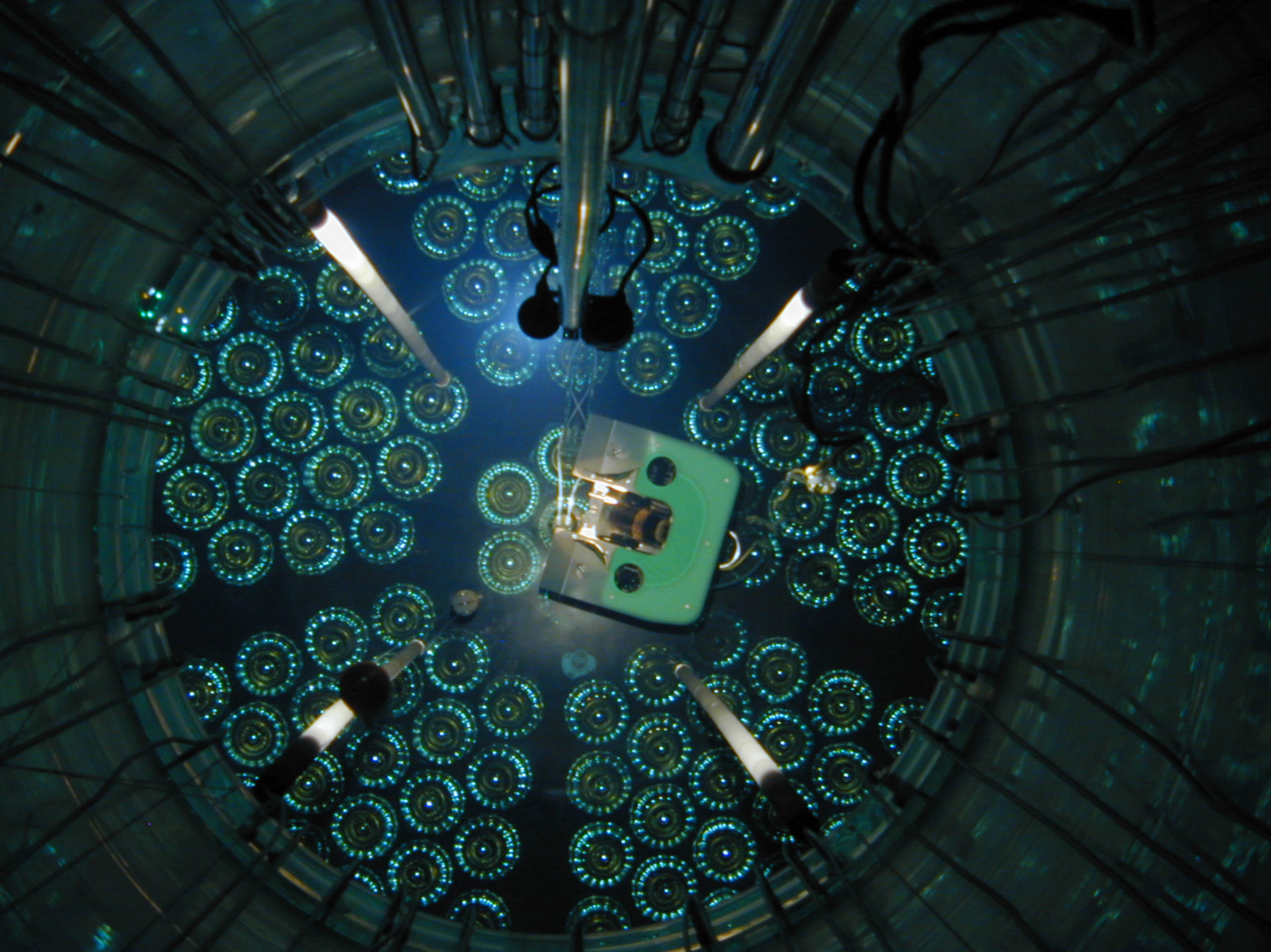
2 Improve the precision of the measurements.

- Reduce error on $\sin^2(2\theta_{12})$ by ~ 2
- Improvement on $\cos^4(\theta_{13})$
- Correlation-free measurement of NC/CC
- Search for explicit MSW signature: shape (syst), day/night (stat)
- Flux of ^8B neutrinos
- Flux of hep neutrinos
- Supernova live

Neutral Current Detectors deployed,

Production running since November, 2004





SNO with D_2O will finish data taking December, 2006.

Is there a future programme at SNO for Particle Astrophysics?

Or mission accomplished?

May 2003, visiting troops in Iraq

Related problems in Particle Astrophysics:

Basic properties of Matter:

- Absolute mass of the neutrino
- Is neutrino Dirac or Majorana?
- CP violation & matter/antimatter asymmetry.
- Mixing angles. MNSP matrix

Stellar Processes:

Supernovae, ultrahigh energy cosmic rays, …

Composition of the Universe

(Dark Matter, Dark Energy,…)

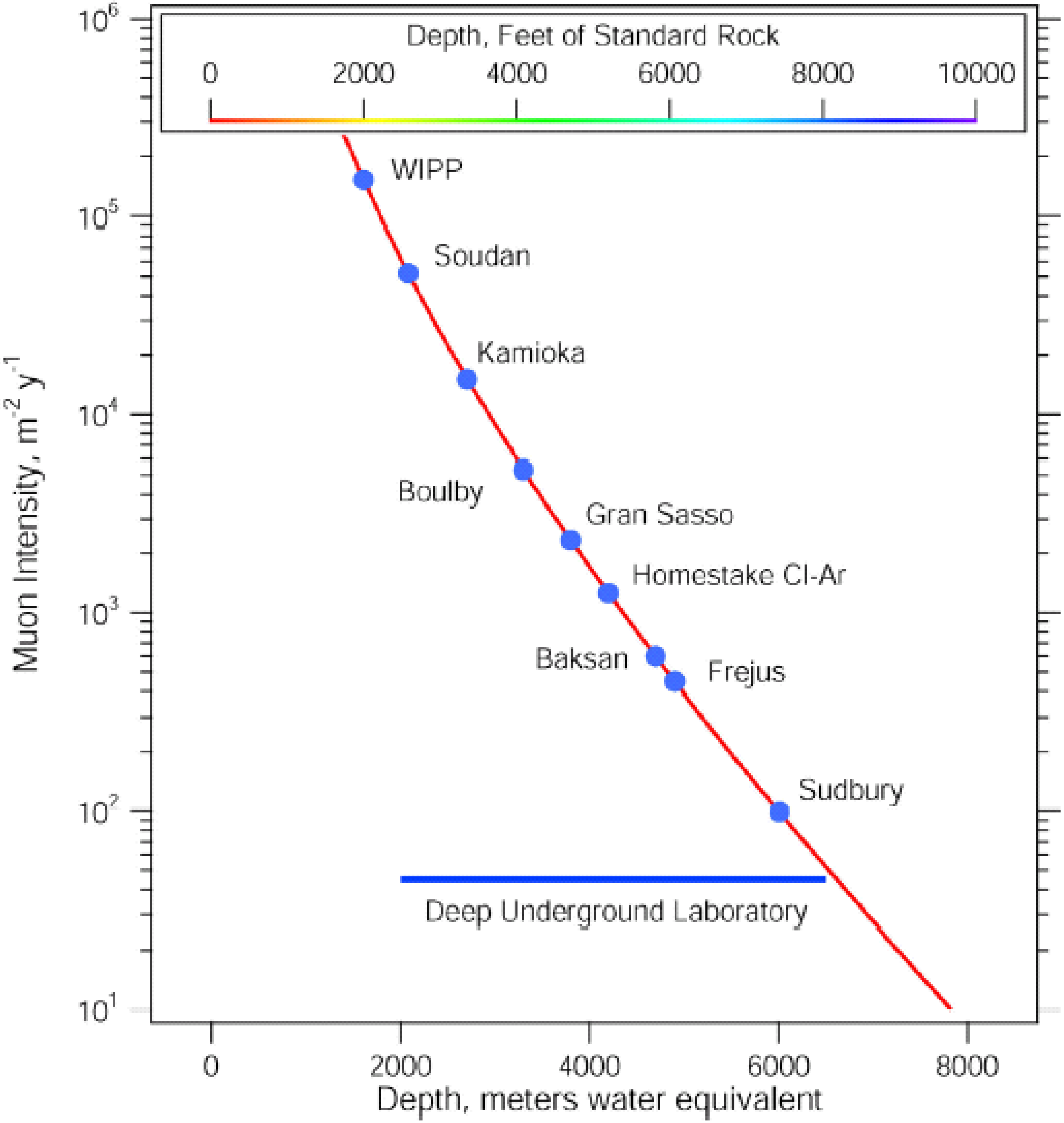
Dark Matter, Neutrinoless Double Beta Decay, Supernovae, and Low-Energy Solar Neutrinos, are best studied in a clean, deep underground facility.

New International Underground Science Facility At the Sudbury site: SNOLAB

- Proposal ($ 38M) funded by Canada Foundation for Innovation: Complete in 2007
- Surface Laboratory ($ 10 M) complete in July, 2005

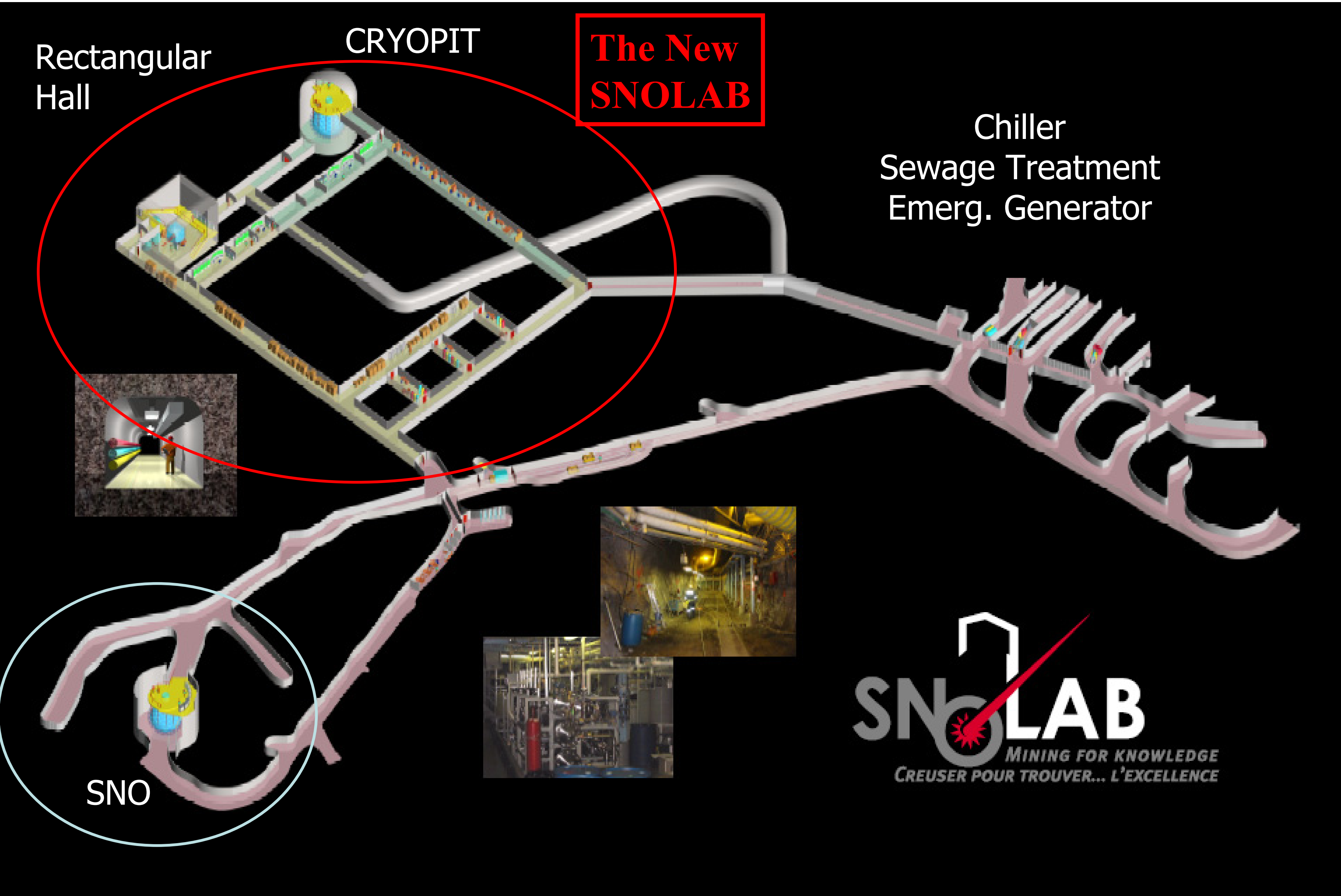
To pursue:

- Low energy solar neutrinos:
  - Future observations from a possible SNO+ detector
    - Solar Neutrinos
    - Geo - neutrinos
    - Supernova Neutrinos
    - Reactor Neutrinos
- Dark Matter (WIMPS)
  - Measurements of nuclear recoils with ultra-low background
  - 25 % of the Universe.
- Double Beta Decay:
  - More accuracy for neutrino masses.
  - Are Neutrinos their own Anti-particles (Majorana particles)?
  - Leptogenesis…

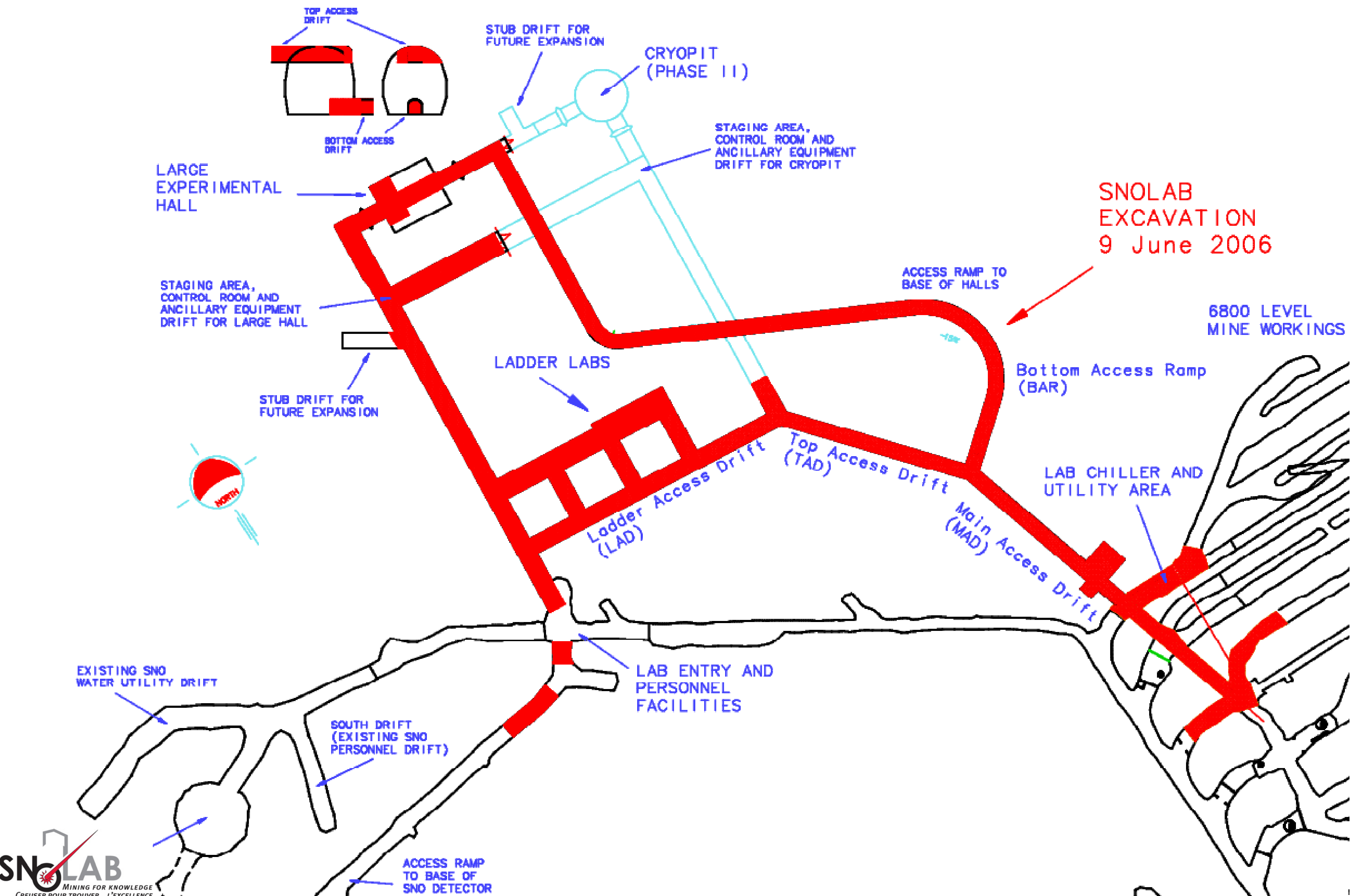


Depth, Feet of Standard Rock
0
2000
4000
6000
8000
10000
WIPP
Soudan
Kamioka
Boulby
Gran Sasso
Homestake Cl-Ar
Baksan
Frejus
Sudbury
Deep Underground Laboratory
Muon Intensity, m-2 y-1
10^6
10^5
10^4
10^3
10^2
10^1
0
2000
4000
6000
8000
Depth, meters water equivalent

New Underground Research space



SNOLAB Excavation Status




10,912 LBS

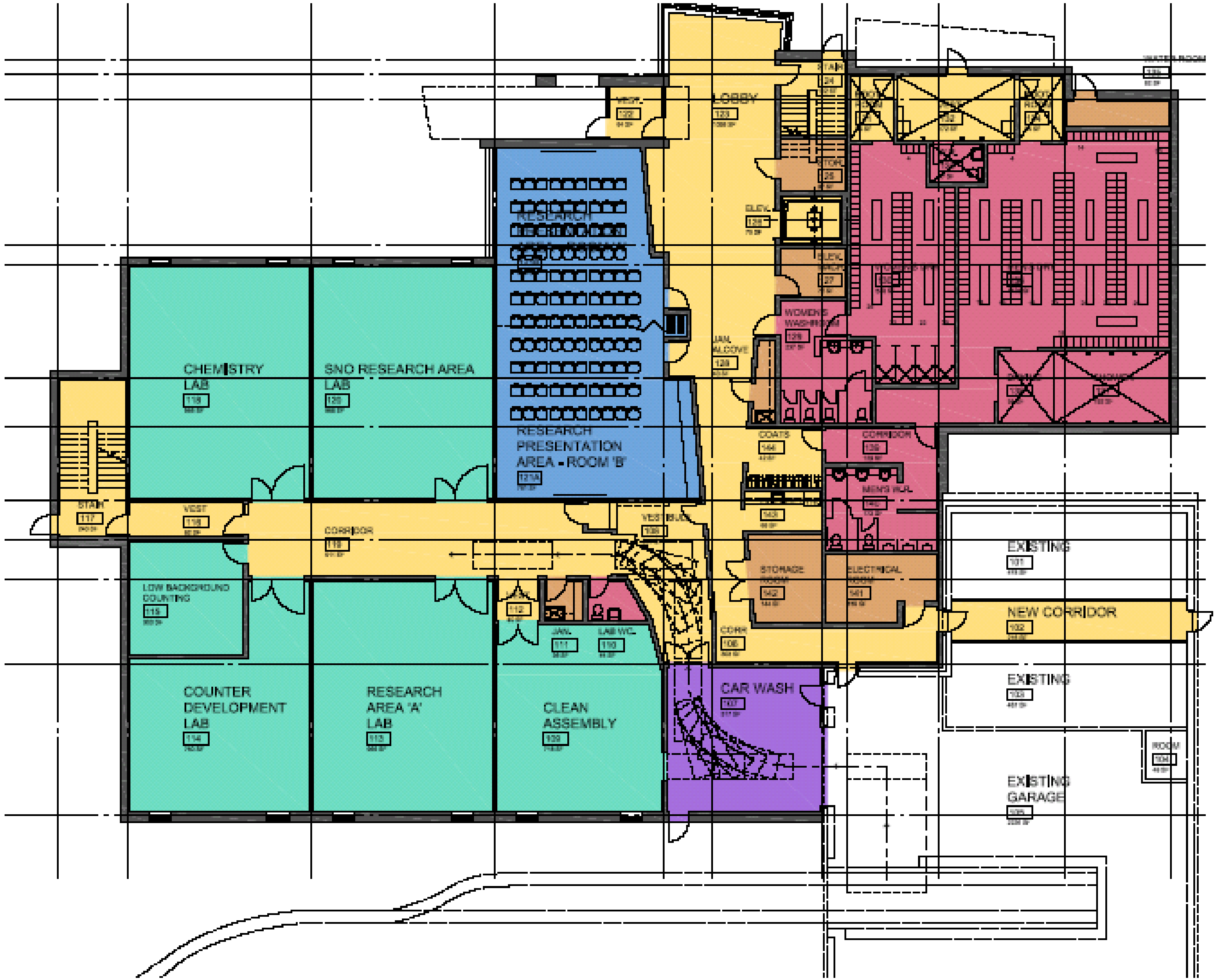
Ladder Labs

Nicholls
Yallowega
Bélanger
architects - architectes

Sudbury Neutrino Observatory
SNOLAB Surface Facility

existing photo

Surface Facility



CHEMISTRY LAB
118
SNO RESEARCH AREA LAB
120
RESEARCH PRESENTATION AREA - ROOM 'B'
121B
LOBBY
123
STAIR
117
VEST
116
CORRIDOR
119
LOW BACKGROUND COUNTING
115
COUNTER DEVELOPMENT LAB
114
RESEARCH AREA 'A' LAB
113
CLEAN ASSEMBLY
109
CAR WASH
107
ELEV.
JAN. ALCOVE
WOMEN'S WASHROOM
COATS
CORRIDOR
MEN'S W.R.
VESTIBULE
STORAGE ROOM
ELECTRICAL ROOM
CORR
JAN.
LAB W.C.
EXISTING
101
NEW CORRIDOR
102
EXISTING
103
EXISTING GARAGE

Surface Facility

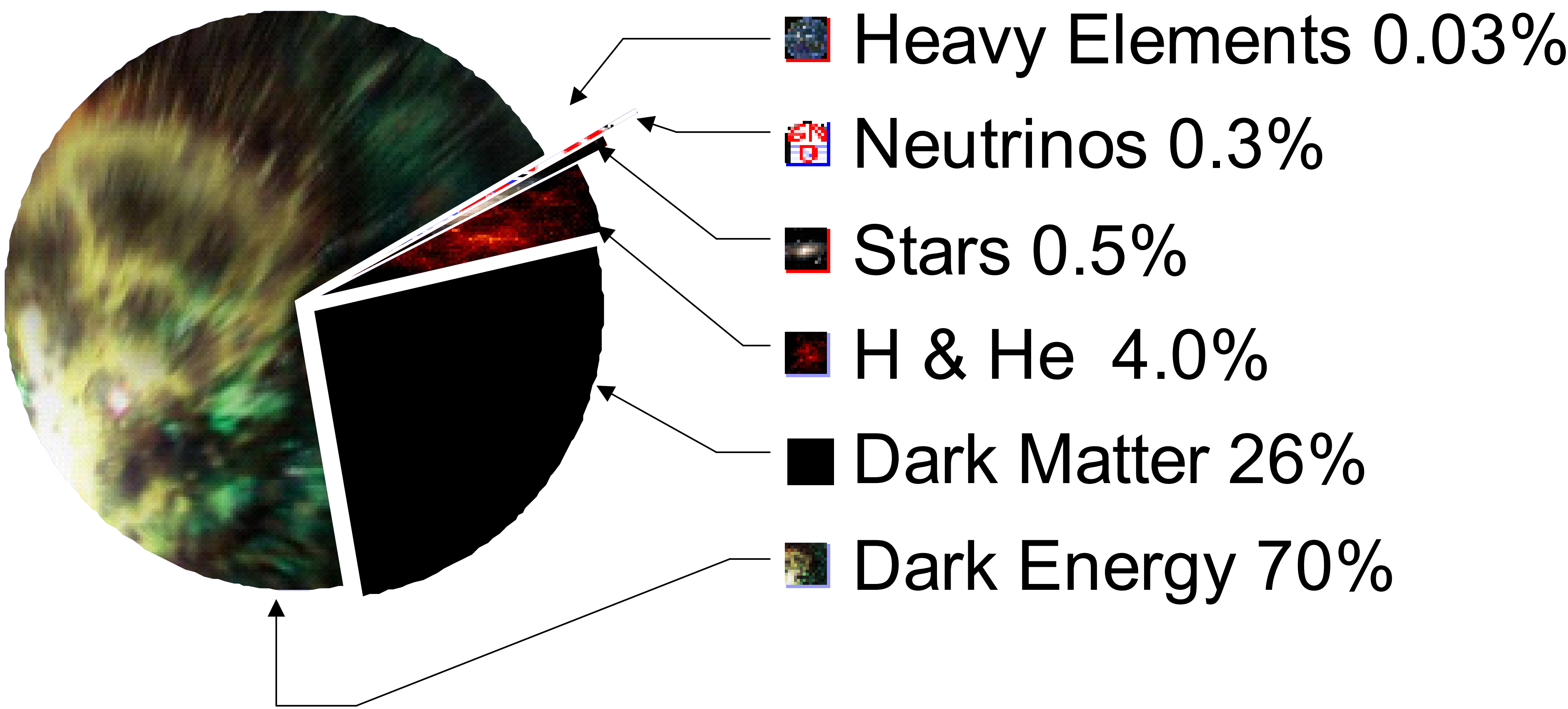
- Complete
- The SNO Experiment is operational in the building (laboratories, control room)
- New experiments starting to work in the building

Physics Program:

Dark Matter Searches

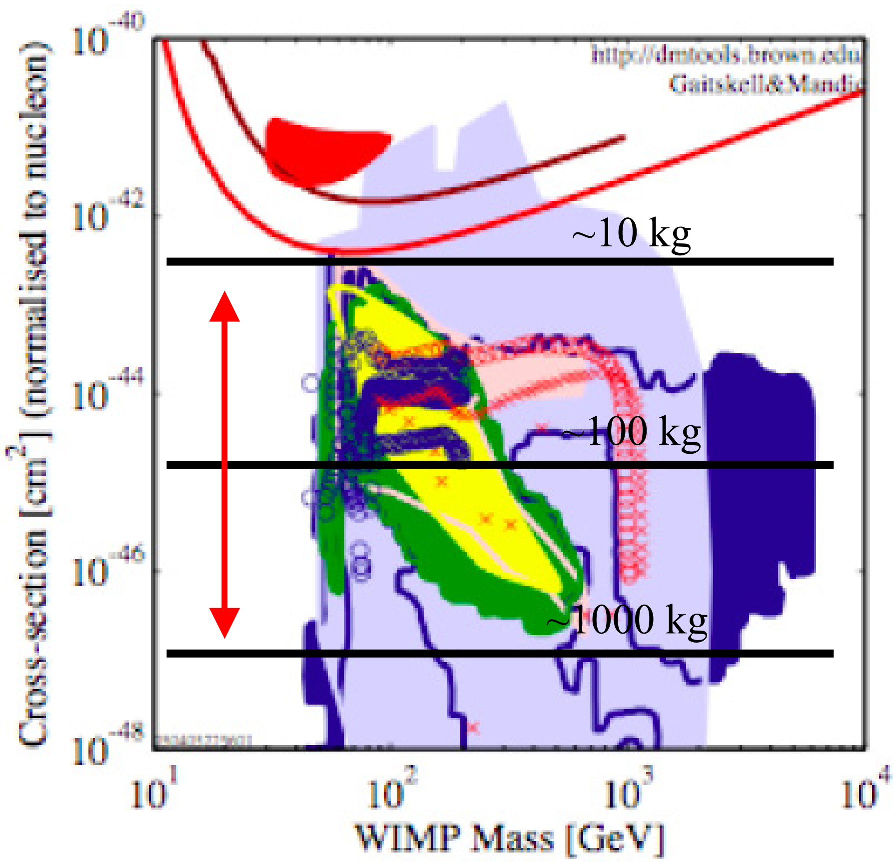
- Super CDMS – near term
- PICASSO & DEAP – next generation

Composition of the Universe

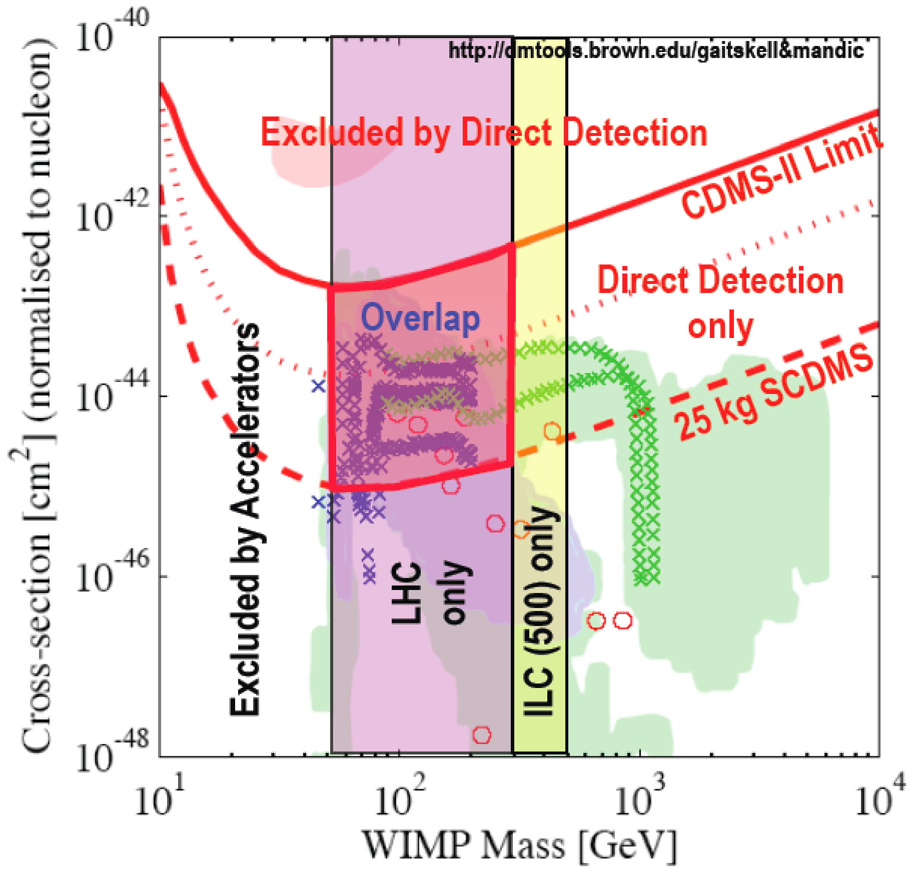


At SNOLAB we can address the nature of "Exotic Dark Matter" very well

Where should we look?



Complementarity with Accelerator Program

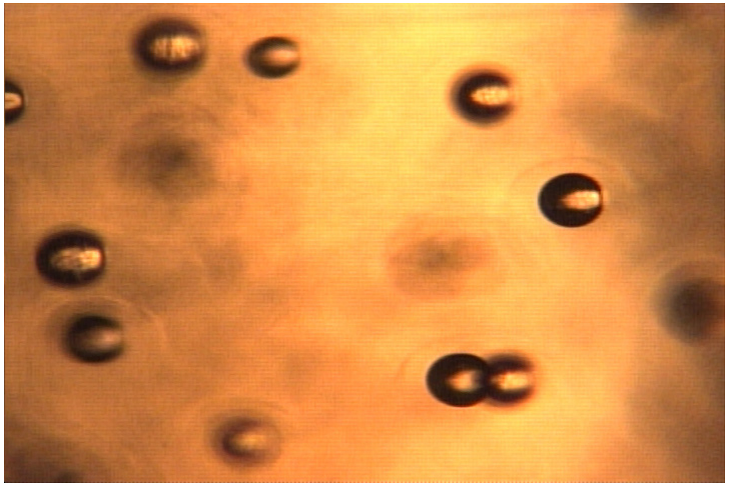


Favored candidate: WIMP(weakly interacting massive particle). Supersymmetry predicts candidates.

Canadian Dark Matter Experiment: Picasso

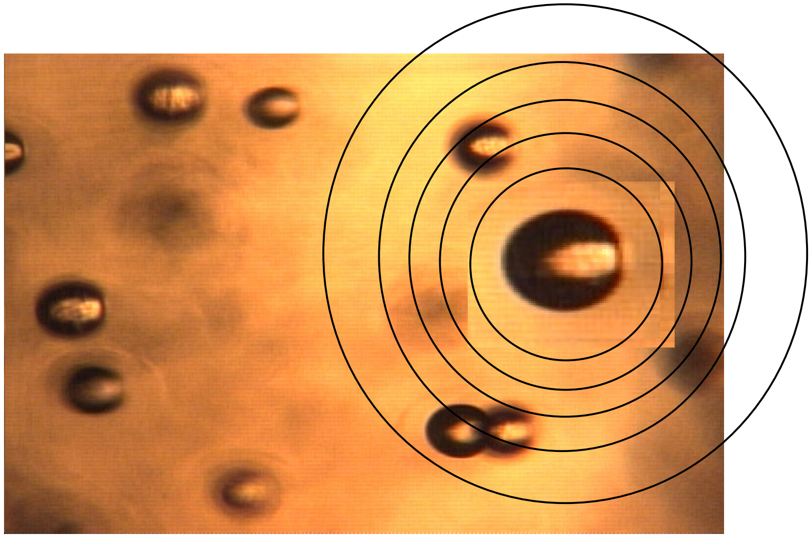
Superheated Droplet Detector

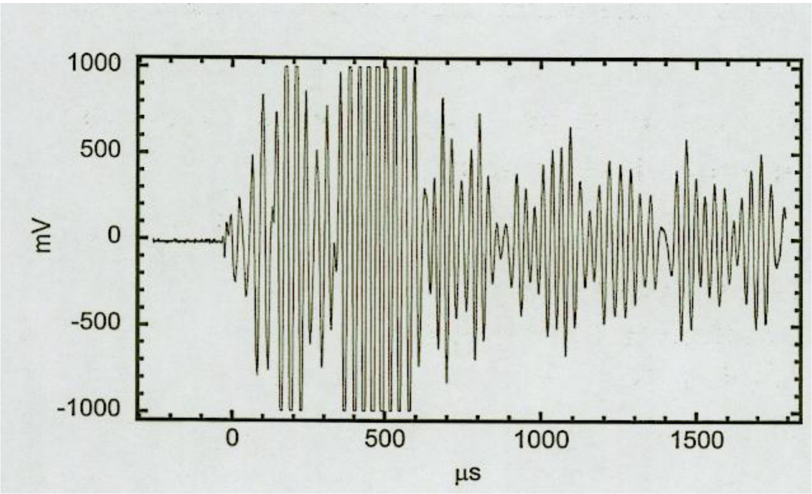
- Detector consists of tiny (5 to 100 μm) halocarbon liquid droplets (C_3F_8, C_4F_{10}...) embedded in a gel.
- The droplets are superheated - maintained at a temperature higher than their boiling point.



Picasso

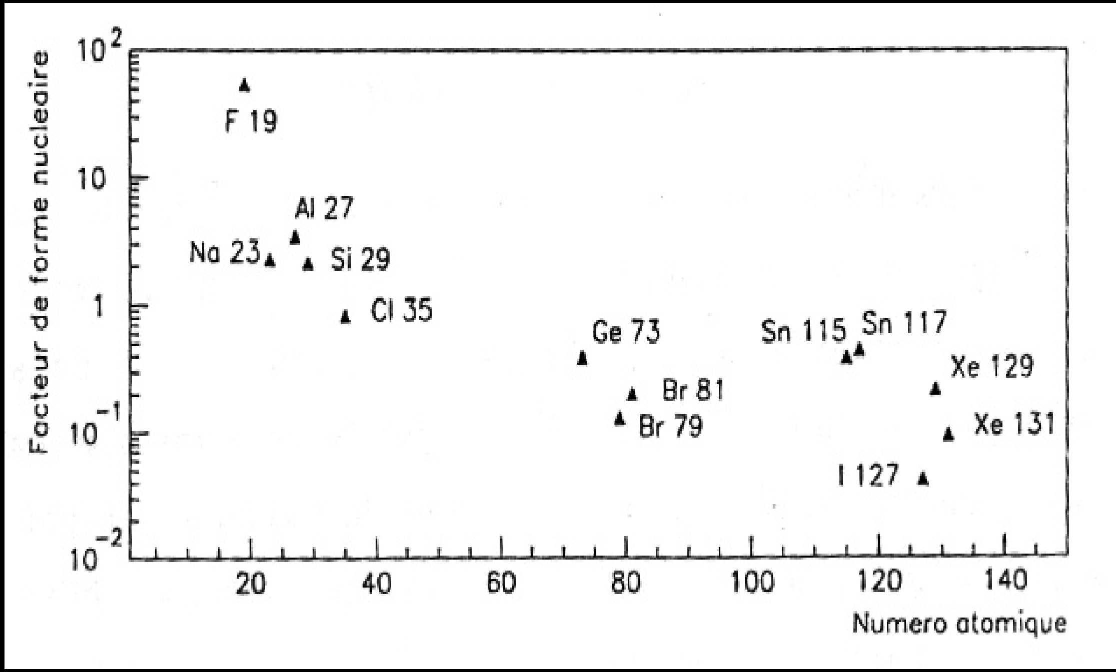
- WIMP induced nuclear recoils deposit a spike of heat into droplet. This causes droplet to evaporate rapidly.
- The evaporating bubble creates a sound shock wave, which can be recorded by a sensitive piezo-electric microphone.
- ~ Insensitive to β, γ, radiation, and other MIPS
- Low Threshold. ~ 5 to 10 keV E_n





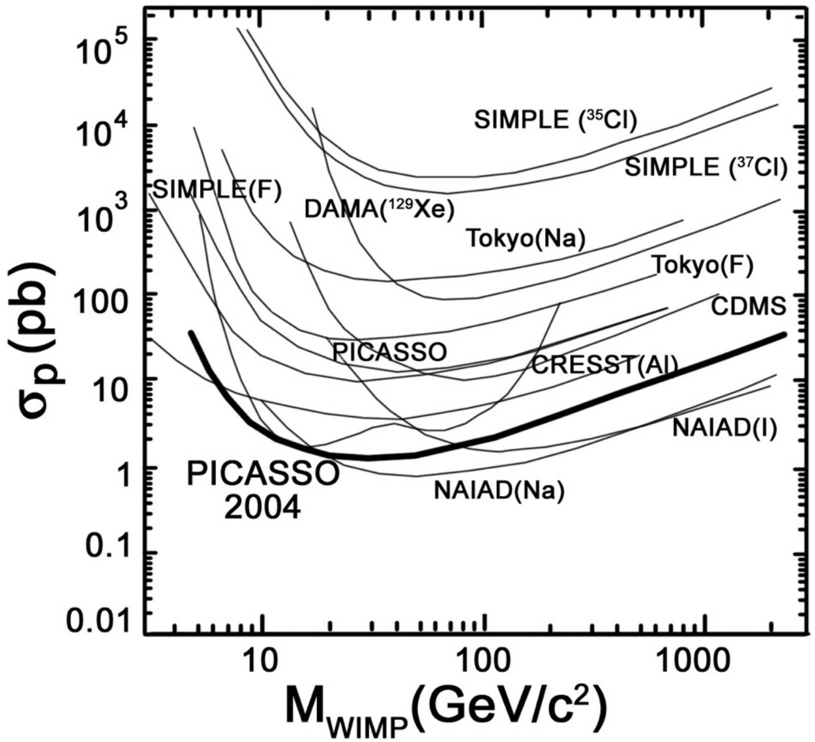
Advantages of this Technique

- **Favorable spin-dependent neutralino cross section on ^{19}F**



Probe of the <u>Spin Dependent</u> Sector

- **Droplets superheated at ambient T & P**
- **Threshold as low as E_n = 5 to 10 keV**
- **Insensitive to β, γ and cosmic μ radiation at operational T & P**

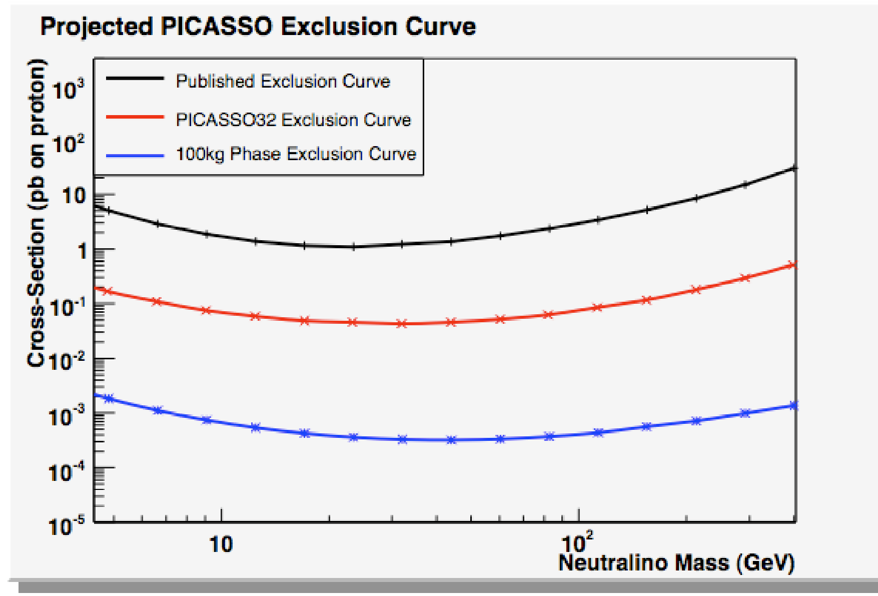


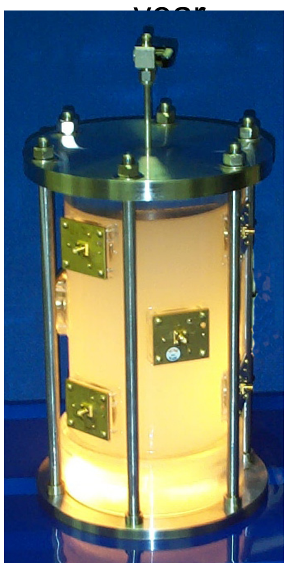
PICASSO Results

- Based on 3 detectors (1L each) with an active mass of 7.45g, 6.62g and 5.35g
- Exposure of 1.98 kgd
- Peak sensitivity of σp=1.31 pb for a WIMP with 29 GeV mass
- Phys.Lett.B624:186-194, 2005

PICASSO *PhaseII*

- 32 4.5 L detectors with a total active mass of >2 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

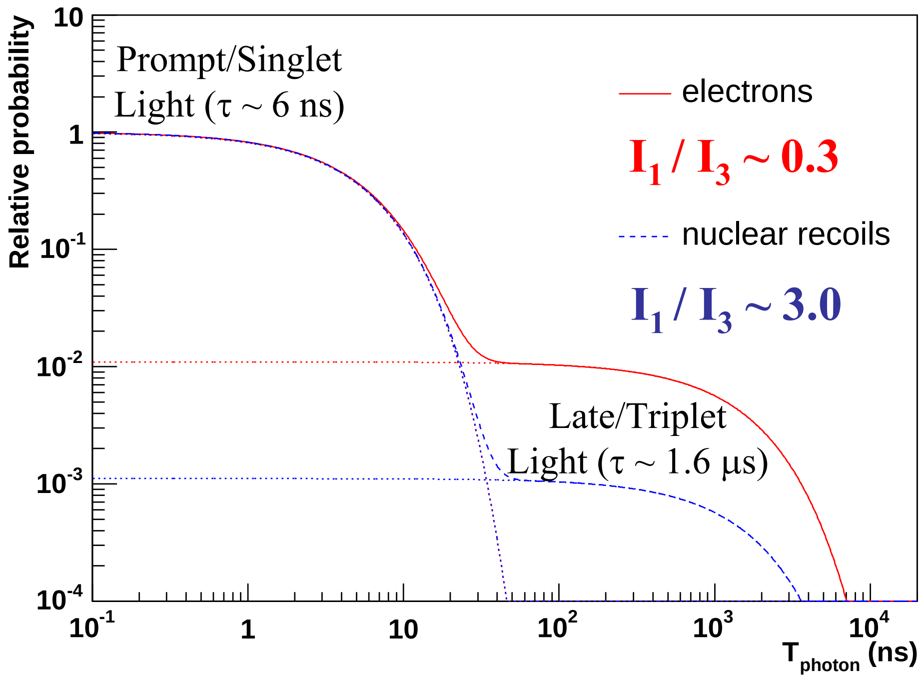


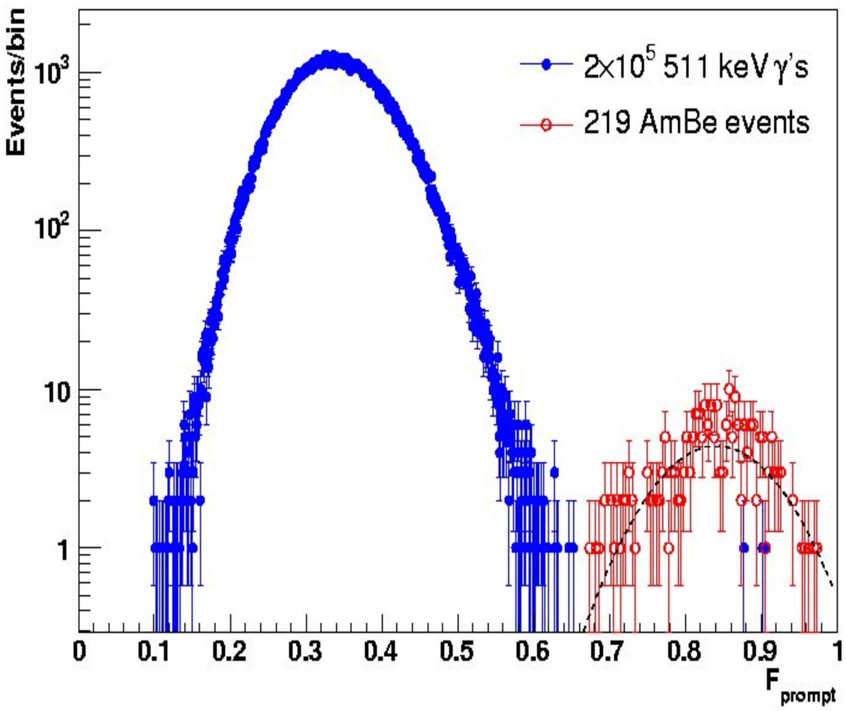


- Exciting new experiment at SNOLAB
- Hope to show that superheated droplet technique is feasible for large scale experiment
- Expect new, improved limits from PICASSO phase II by next year

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

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





Spin Independent:

Concept Demonstrated Experimentally at LANL
DEAP-0

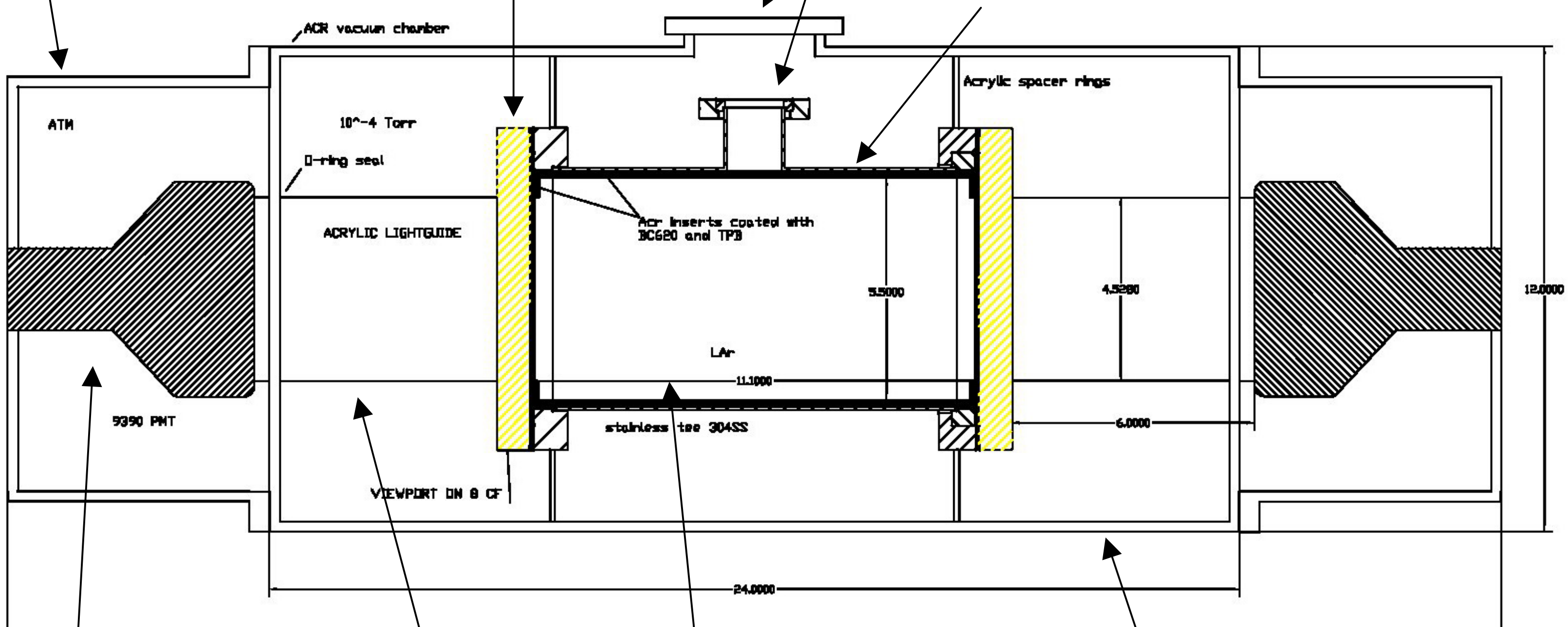
DEAP-1 (being constructed at Queen's)

Neck connects to vacuum and
Gas/liquid lines

Quartz windows

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

Physics Program:

Low Energy Solar Neutrinos

(Clean, SNO+)

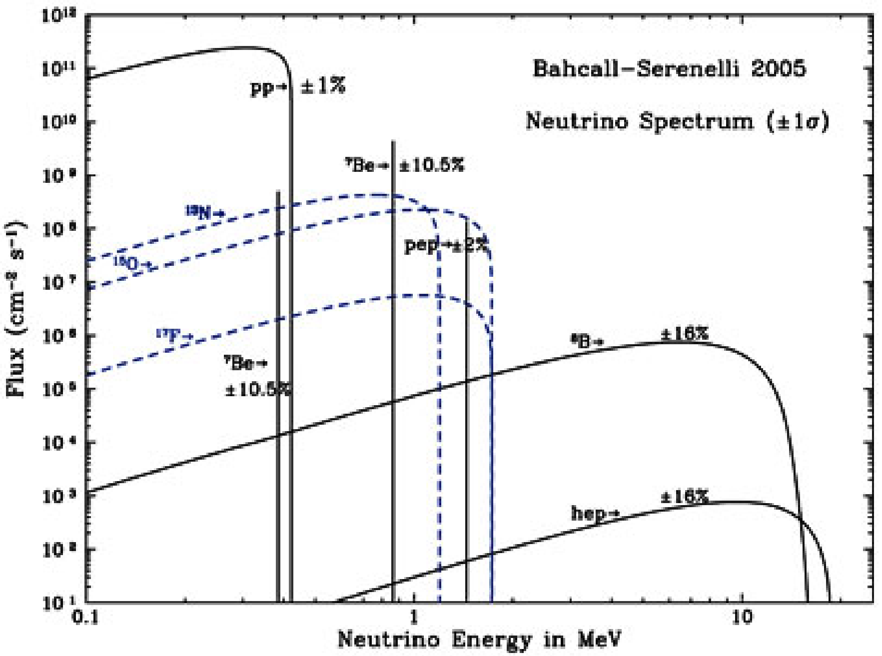
Low Energy Solar Neutrinos and Neutrino Oscillations:
SNO+ (SNO with scintillator)

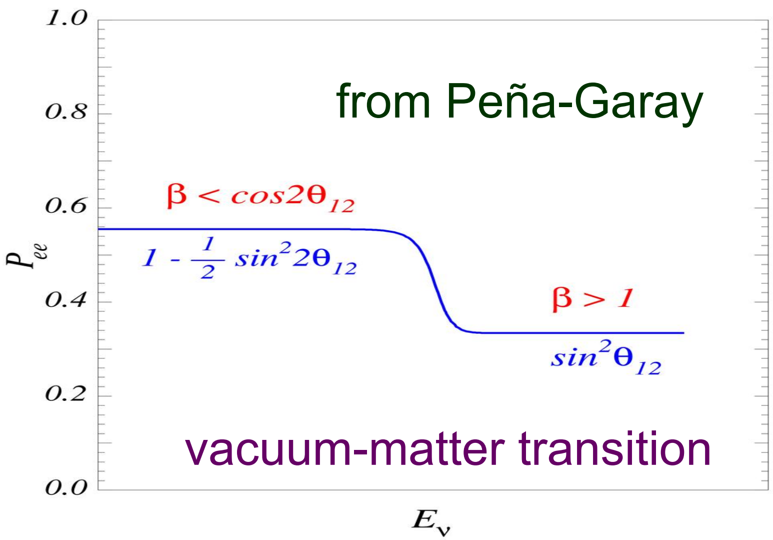
- complete our understanding of neutrinos from the Sun

pep, CNO, ^{7}Be

(complementary to nuclear astrophysics measurements)

- explore the neutrino-matter interaction which is sensitive to new physics





- best-fit oscillation parameters suggest MSW occurs
- but we have no direct evidence of MSW
  - day-night effect not observed
  - no spectral distortion for ^{8}B ν's

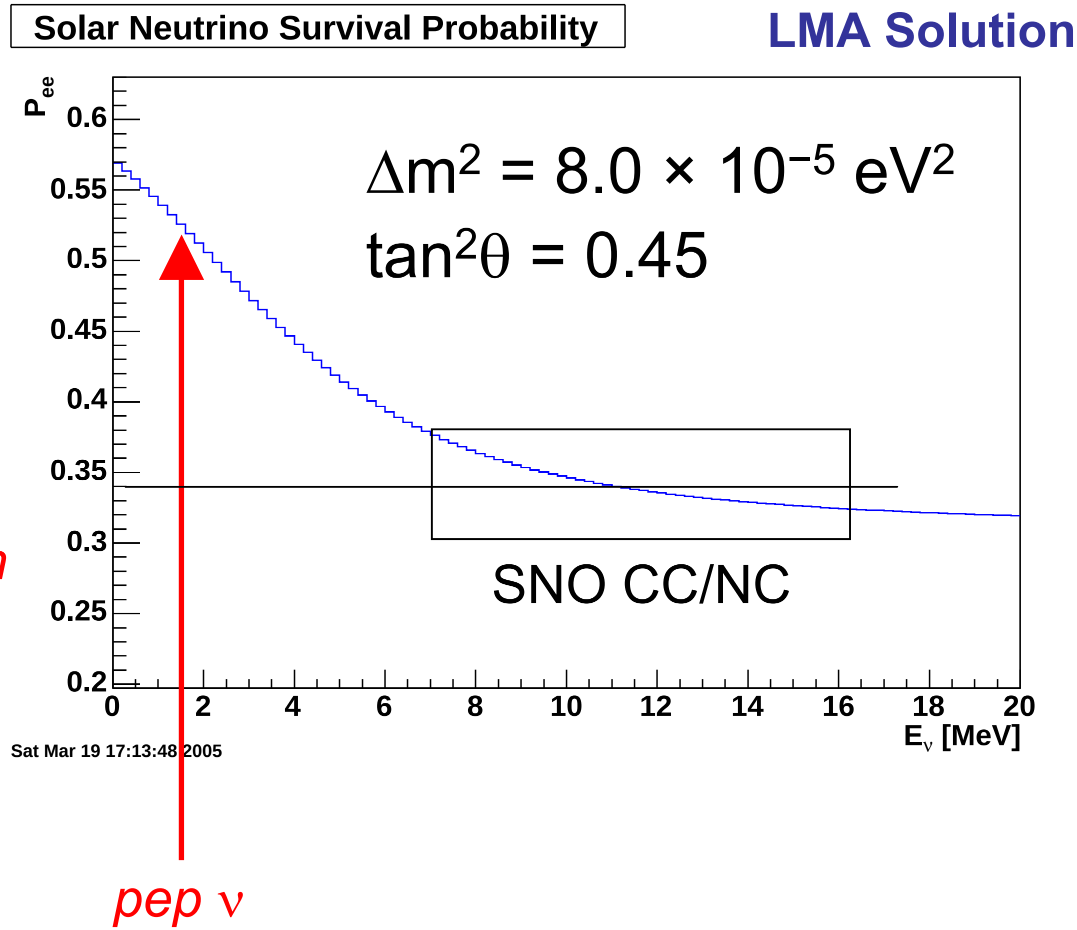
Survival Probability Rise

SSM pep flux:

uncertainty ±1.5%

allows precision test

transition from matter to vacuum dominance…test the extrapolation of the "simplest neutrino oscillation model" coupled with solar models

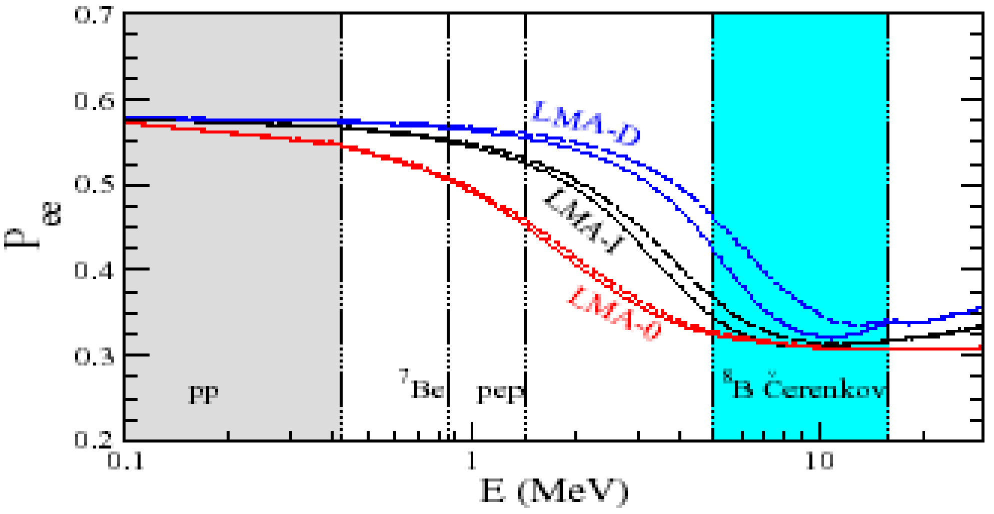


sensitive to new physics:

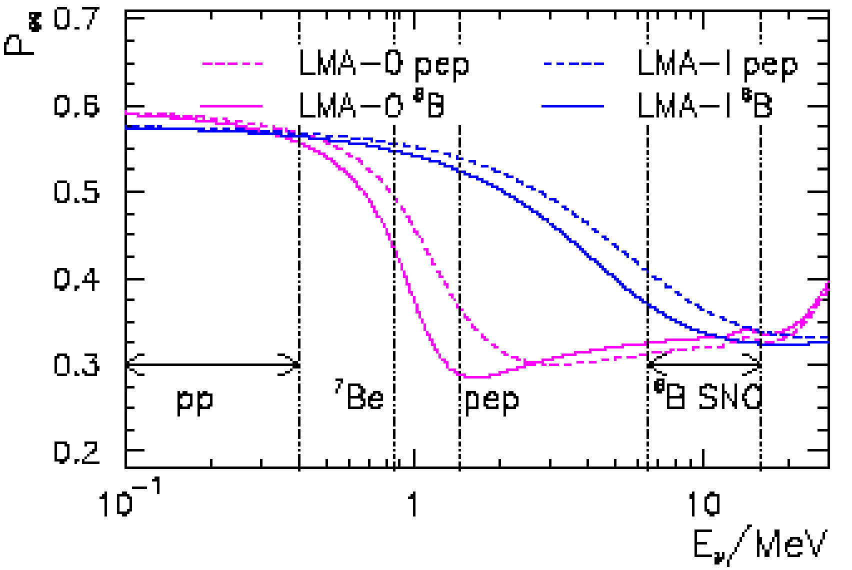
- non-standard interactions
- mass-varying neutrinos
- CPT violation
- large θ_{13}
- sterile neutrino admixture

DISTORTIONS FROM:

Non-Standard Interactions?

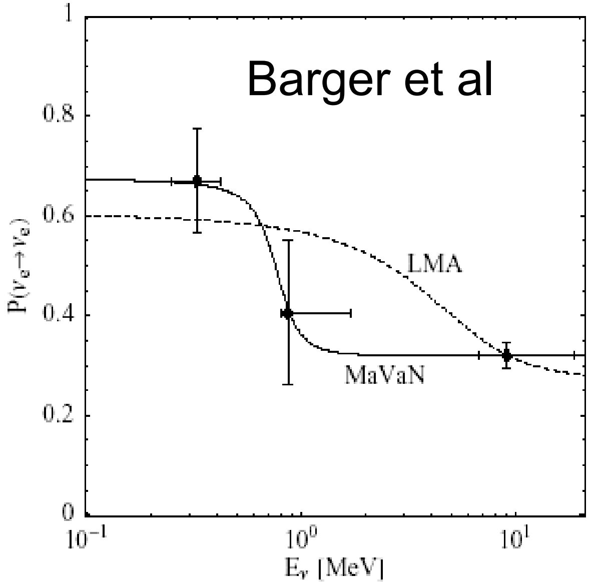


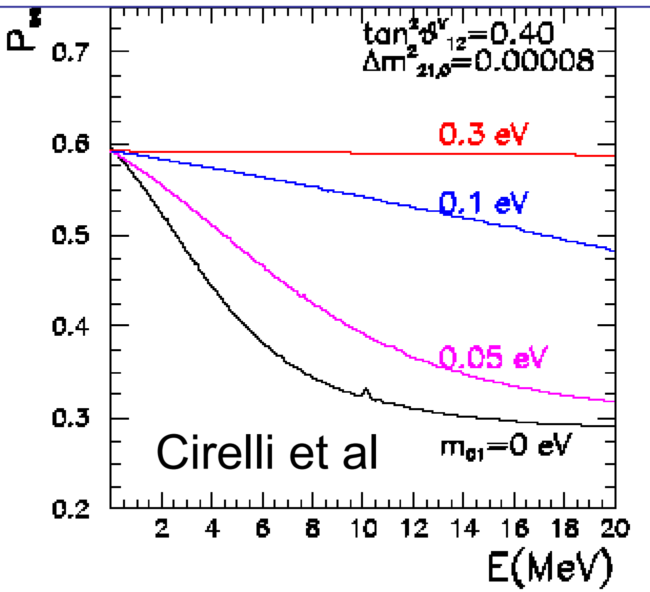
Miranda, Tórtola, Valle



Friedland, Lunardini, Peña-Garay

Mass-Varying Neutrinos? Fardon et al astro-ph/0309800





Also, distortion effects from sterile Neutrinos: Smirnov et al

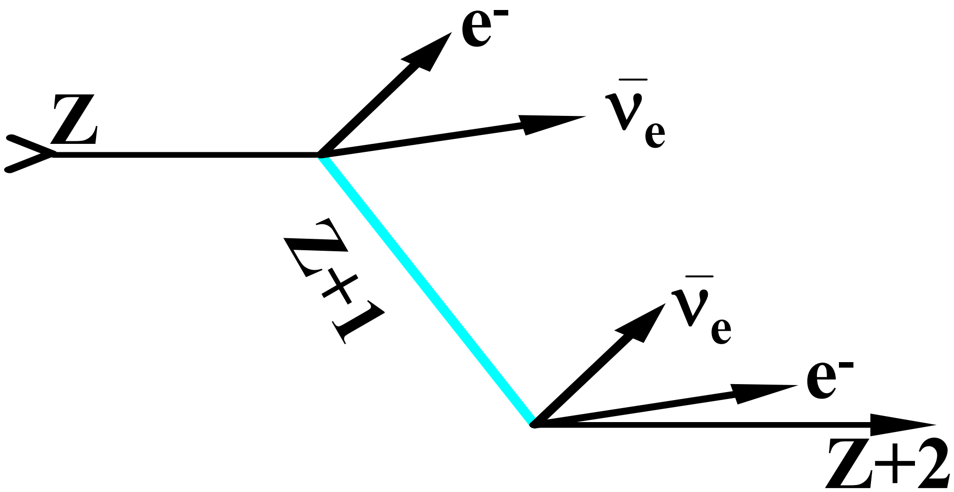
Physics Program:

$0\nu\beta\beta$

Neutrinoless Double Beta Decay

- Majorana / Gerda? – Germanium
- EXO - Xenon
- SNO+

ββ Decay

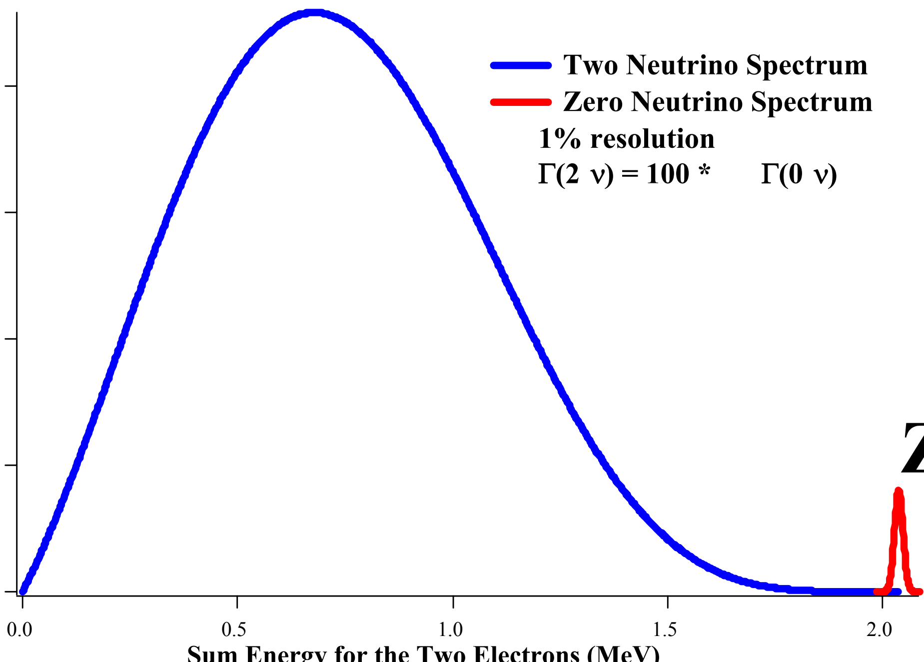


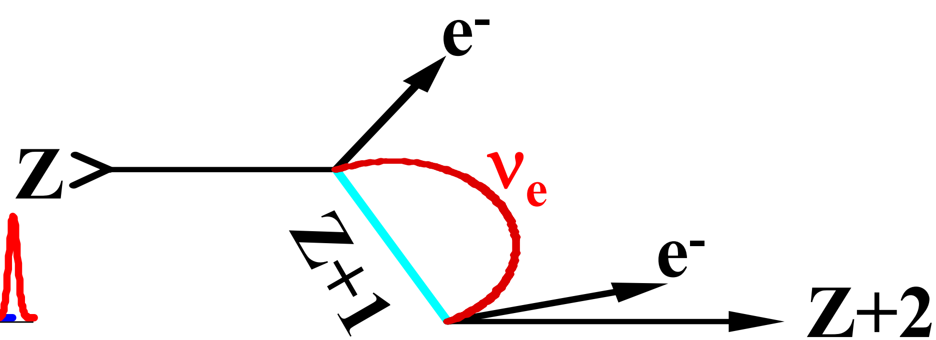
Requires Massive Majorana Neutrino
ΔL=2

Neutrino Masses ?

Majorana or Dirac?

CP Violation and Leptogenesis?



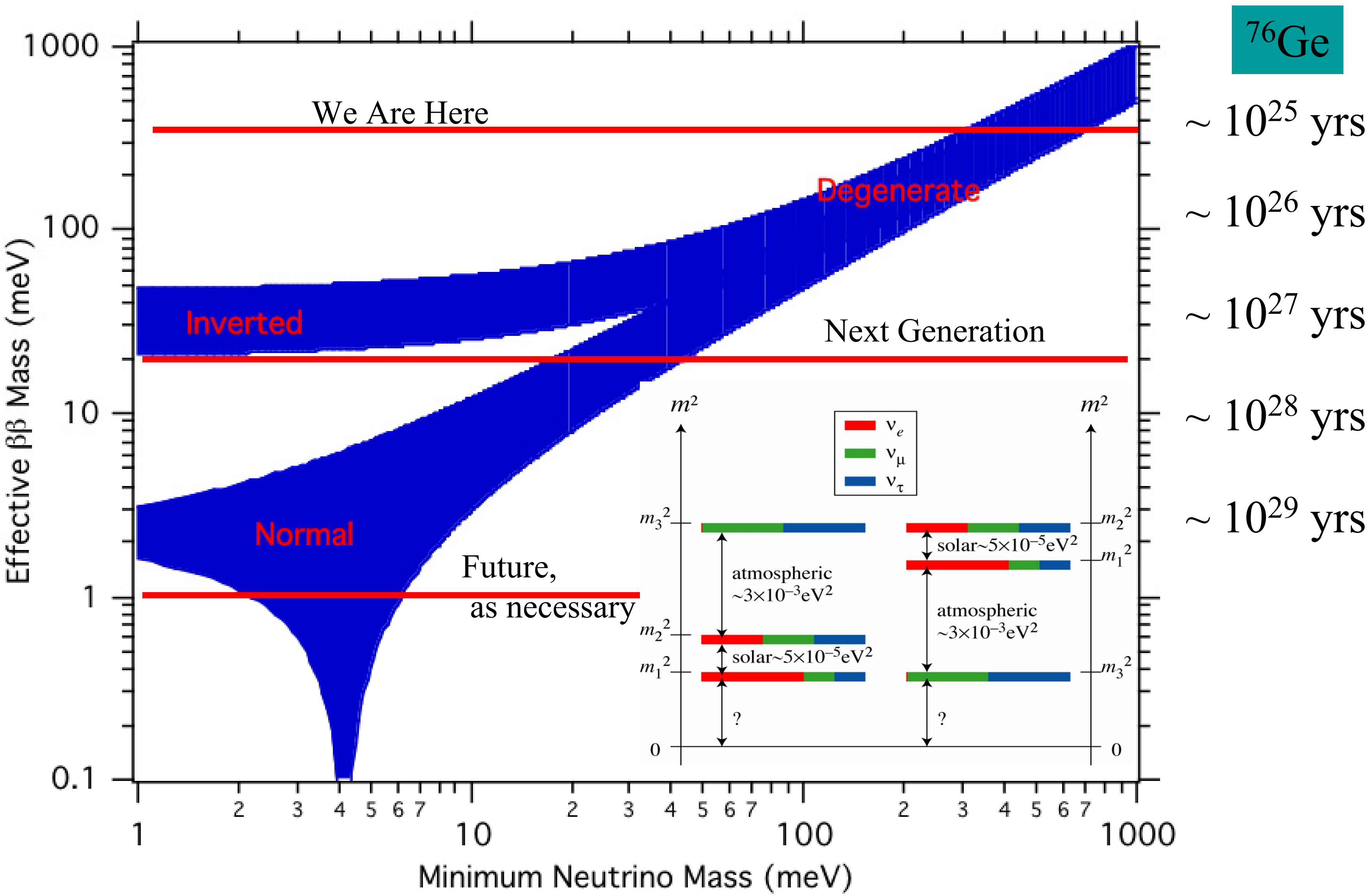


Endpoint Energy

Allowed Phase Space for a Majorana Neutrino Mass

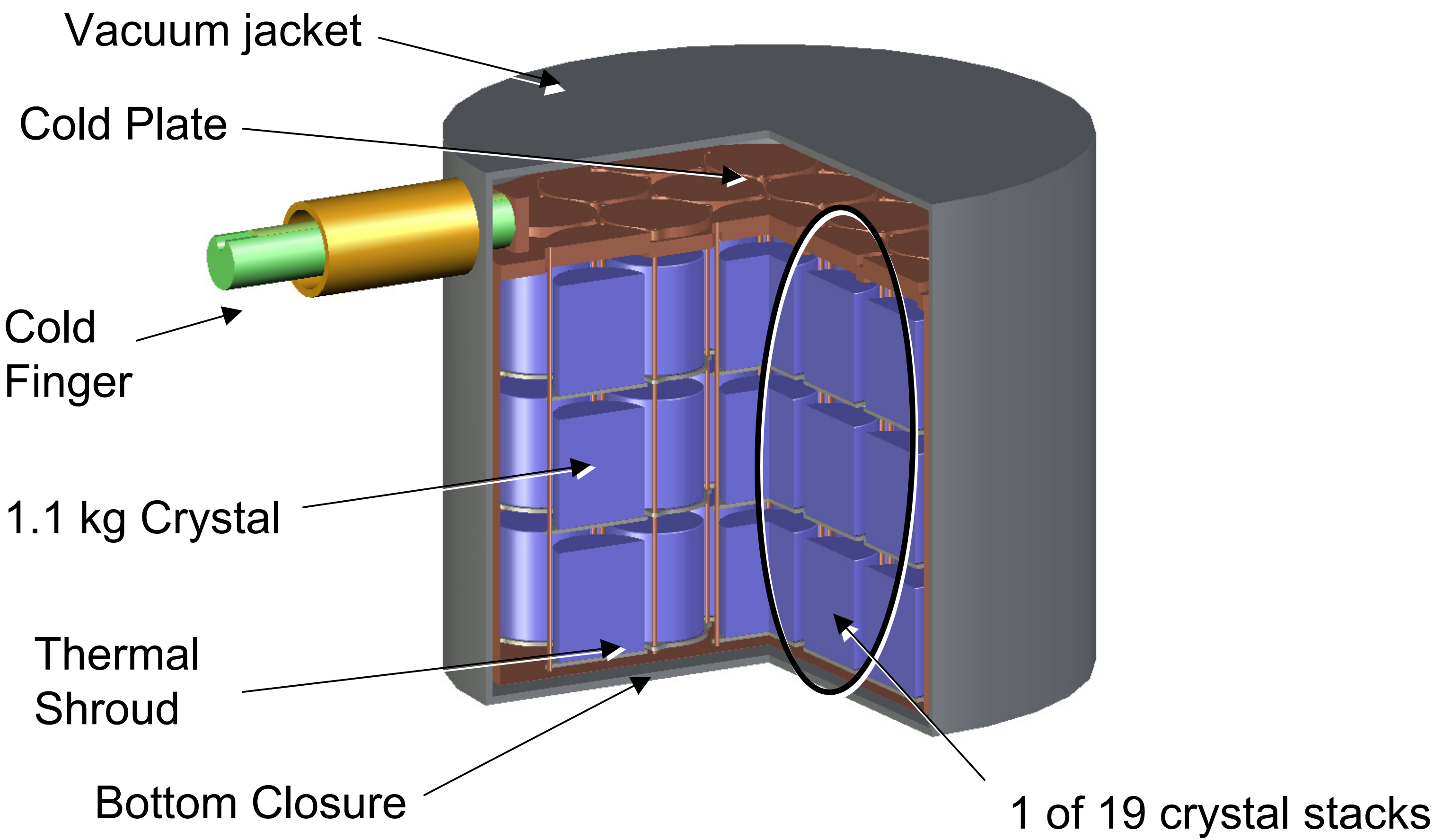
$$m_{\beta\beta} = |\sum_i U_{ei}^2 \, m_i|$$

$$m_{\beta\beta} = |m_1 \cos^2\theta_{13}\cos^2\theta_{12} + m_2\, e^{2i\alpha} \cos^2\theta_{13}\sin^2\theta_{12} + m_3\, e^{2i\beta} \sin^2\theta_{13}|$$



Double Beta Decay: Majorana

- 57 crystal module (60 kg)
  - Conventional vacuum cryostat made with electroformed Cu.
  - Reduce backgrounds with segmentation, PSD, underground electroforming, deep site, minimizing cryostat material, ultra-pure shield



Double Beta Decay: SNO++

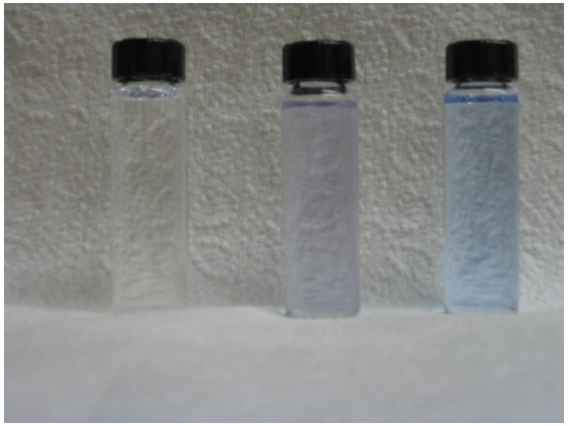
- SNO plus liquid scintillator plus double beta isotopes: SNO++
- add $\beta\beta$ isotopes to liquid scintillator
  - dissolved Xe gas (2%)
  - organometallic chemical loading (Nd, Se, Te)
  - dispersion of nanoparticles (Nd_2O_3, TeO_2)

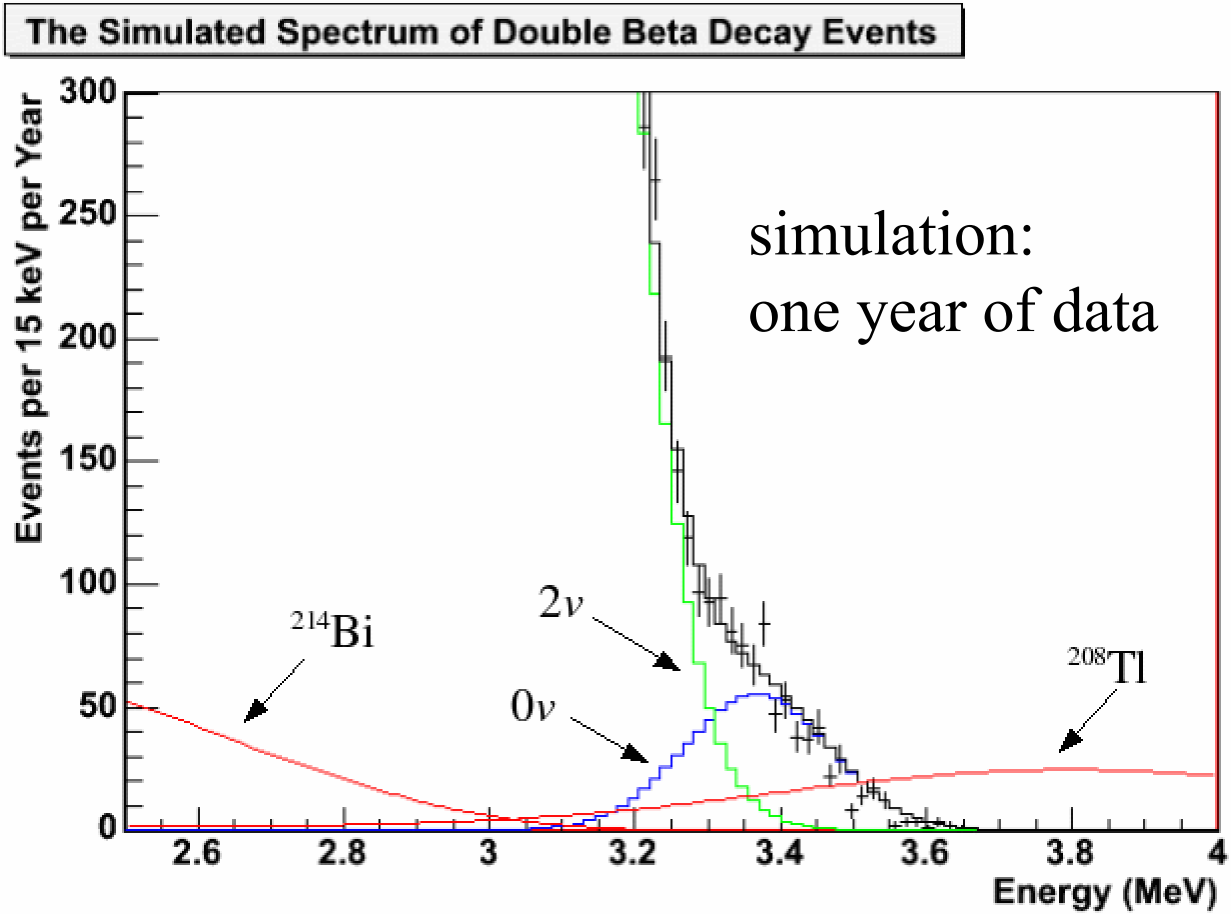
- enormous quantities (high statistics) and low backgrounds help compensate for the poor energy resolution of liquid scintillator
- possibly source in–source out capability

Test $<m_\nu> = 0.150$ 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!

Conclusions

The Sudbury Neutrino Observatory (SNO)

- Has solved the Solar Neutrino Problem
- Neutrinos are massive and oscillate
- Mixing angles and masses becoming well known
- Has implications on evolution and formation of the universe.

SNOLab

- Surface Facility Complete
- Underground facility completion in 2007
- A rich and exciting physics program is envisioned

V SNOLab workshop. Aug 21, 22 2006. Sudbury, Canada. www.snolab.ca

Sudbury Nightlife