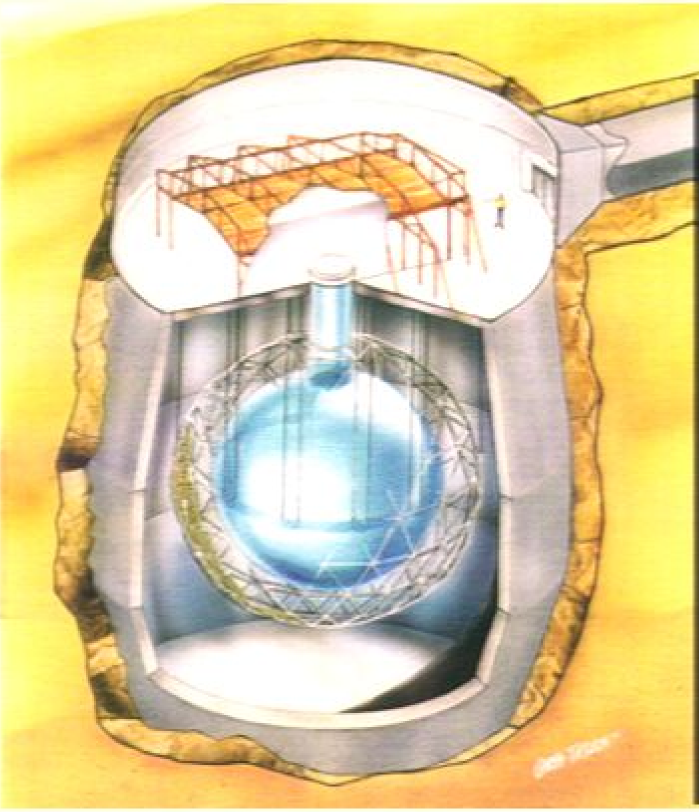
Title: SNO and the New SNOLAB Underground Facility

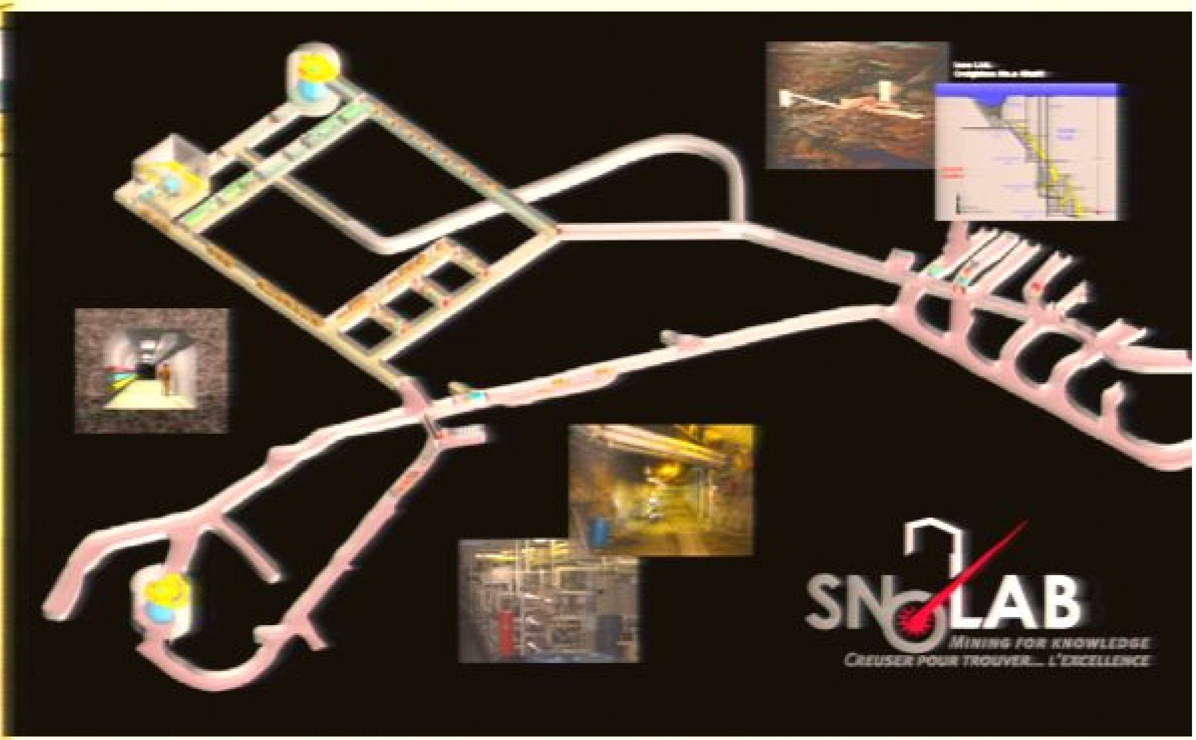
Date: Jun 06, 2008 02:30 PM

URL: http://pirsa.org/08060047

Abstract:

SNO and the New SNOLAB

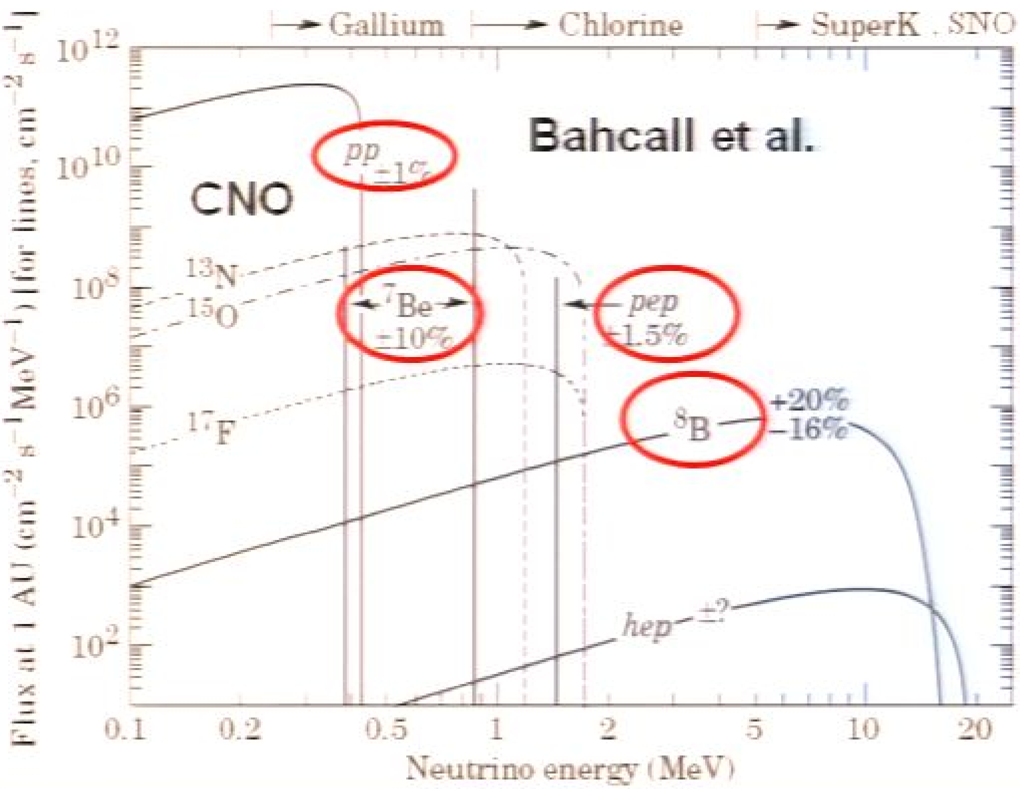




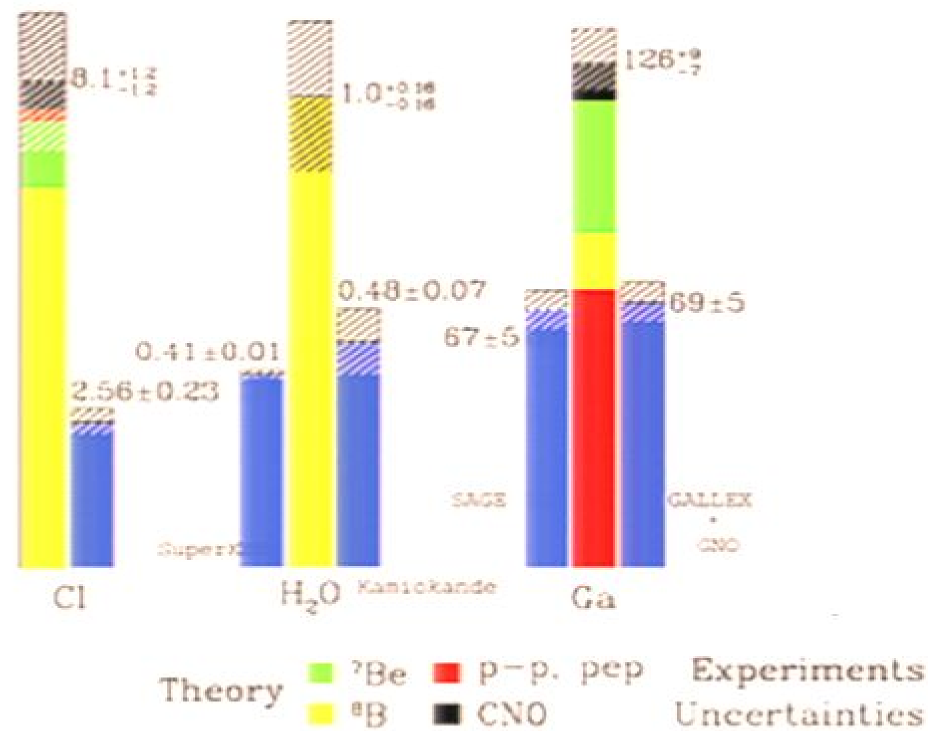
Art McDonald
Queen's University, Kingston, Ontario, Canada

SNO: Flavour Change for Solar Neutrinos

Solar Model Flux Calculations



Previous Experiments Sensitive Mainly to Electron Neutrinos



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Unique Signatures in SNO (D_2O)

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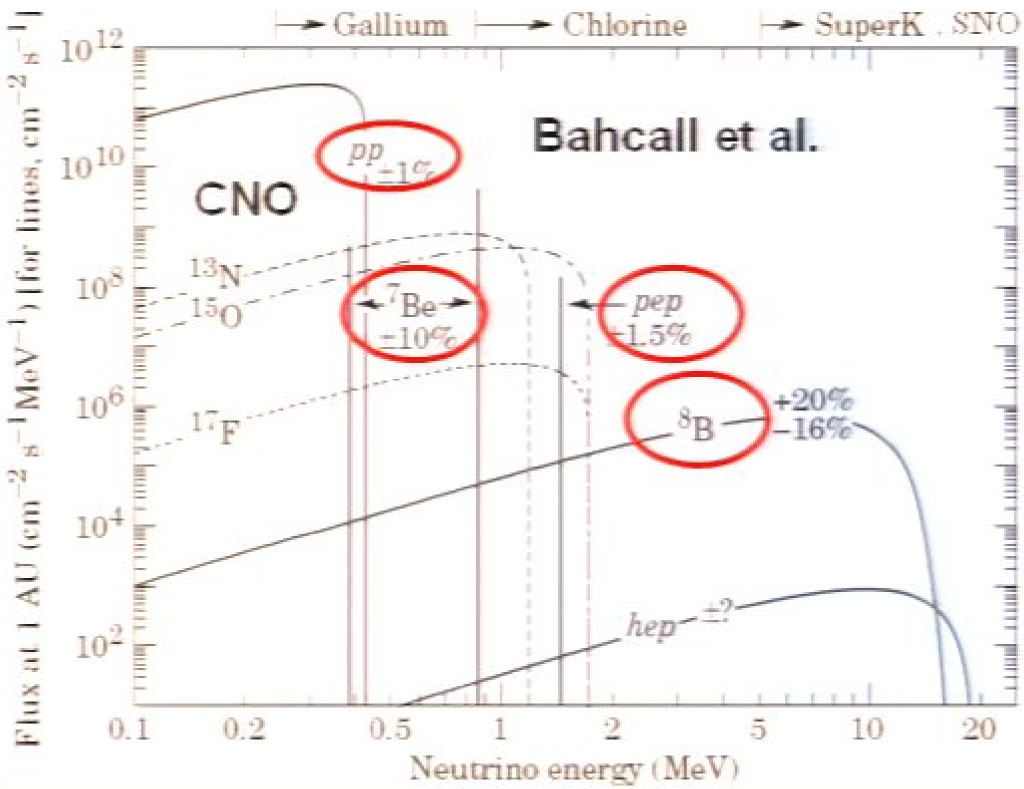

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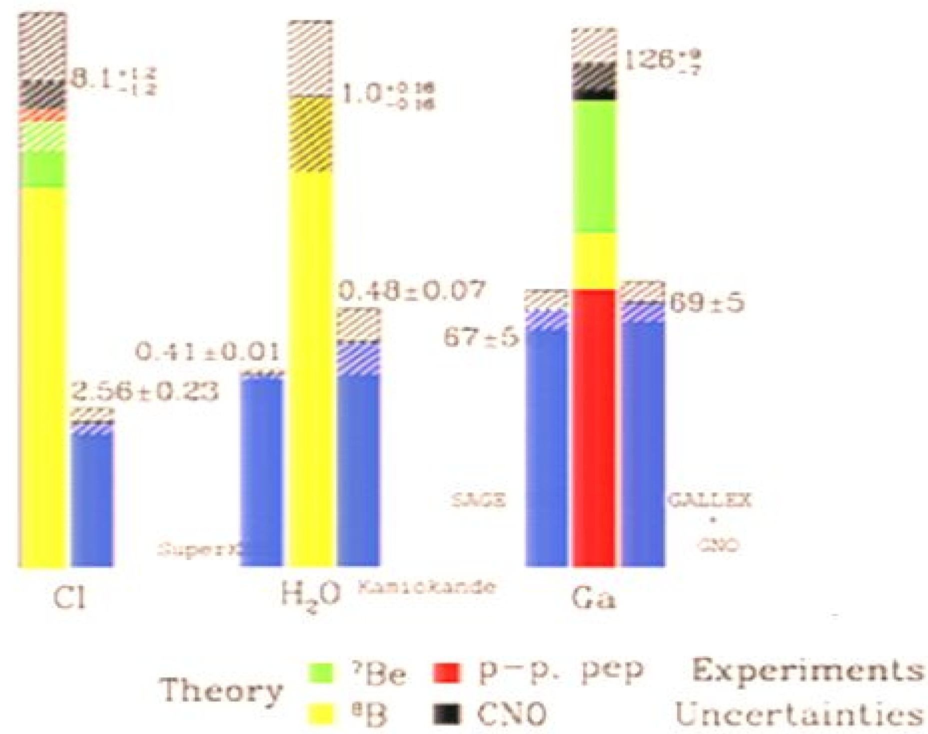

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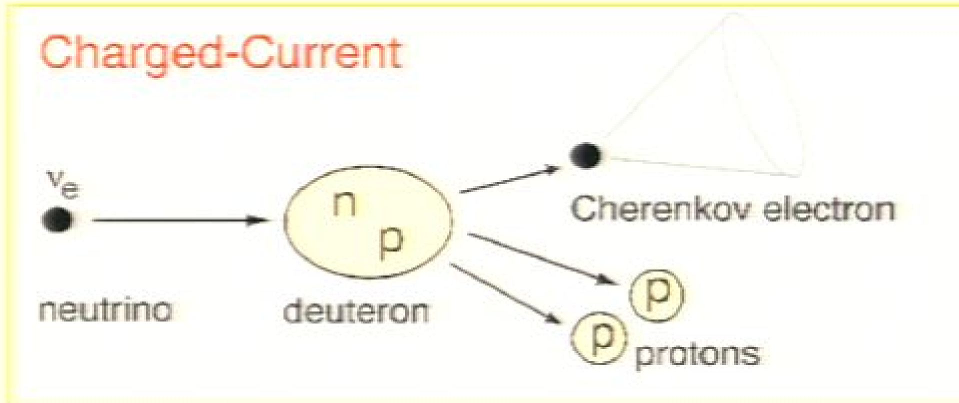
$\nu_e + d \rightarrow e^- + p + p$

$E_{thresh} = 1.4$ MeV

ν_e only



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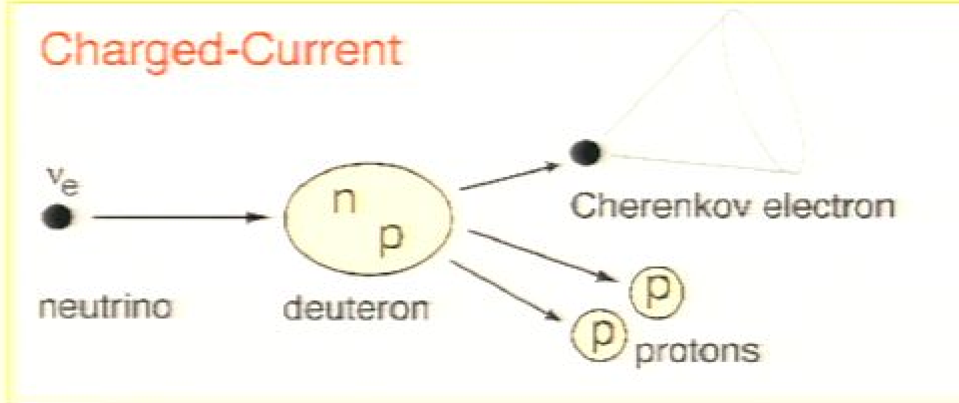

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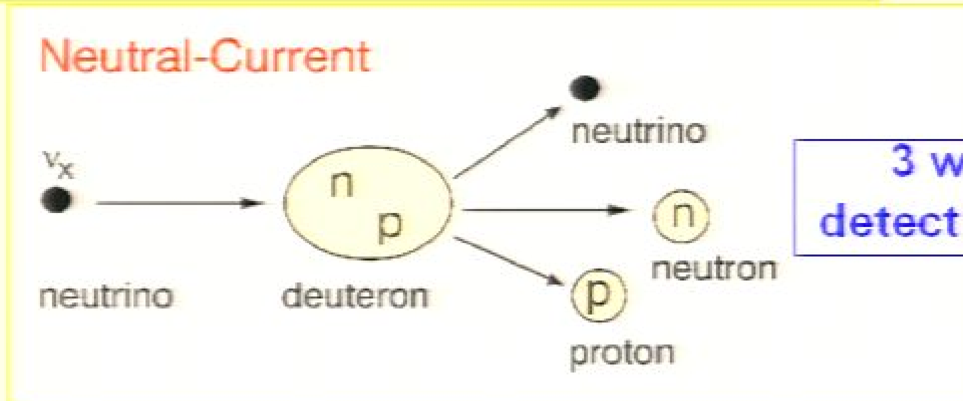
Equally sensitive to $\nu_e\ \nu_\mu\ \nu_\tau$



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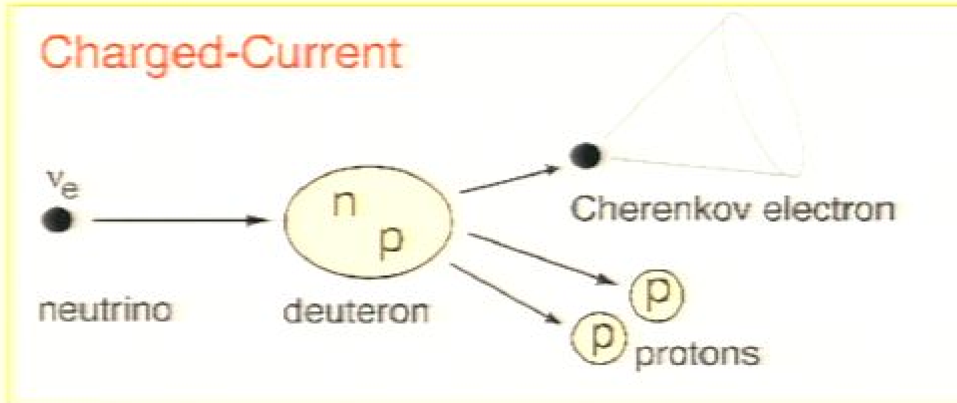

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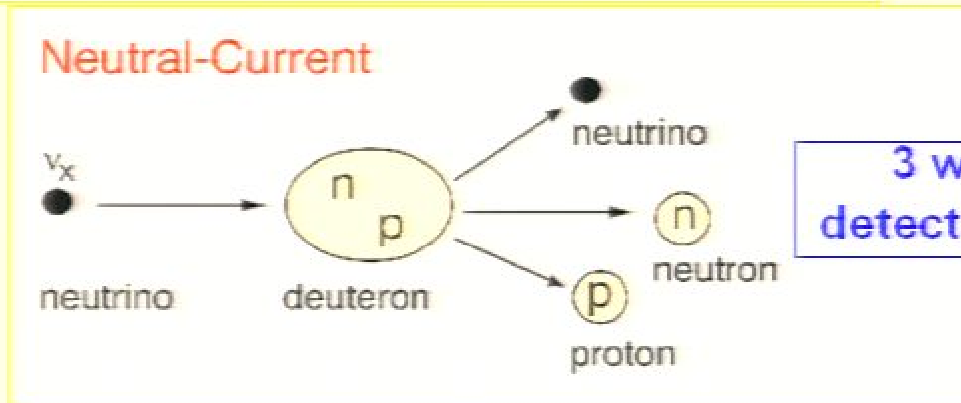

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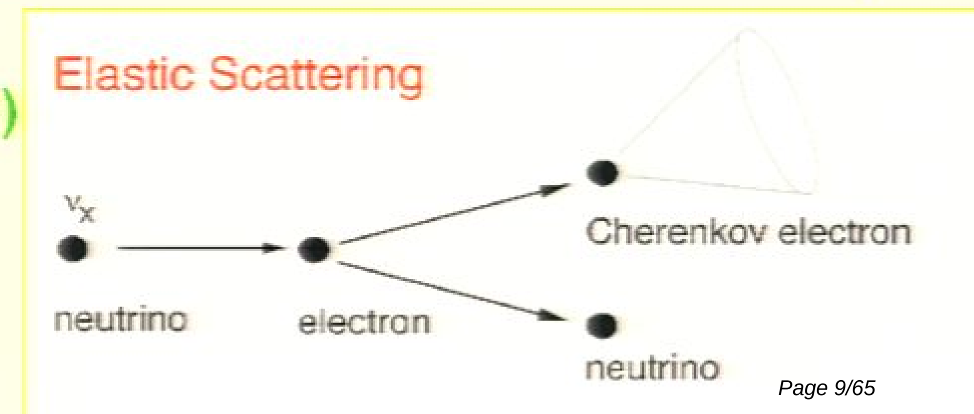
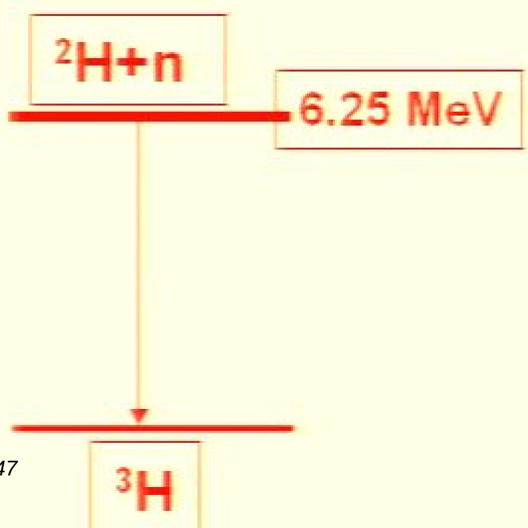


SNO: 3 neutron (NC) detection methods (systematically different)

Phase I (D_2O)
Nov. 99 - May 01

n captures on
$^2H(n,\gamma)^3H$
Effc. ~14.4%
NC and CC separation by energy, radial, and directional distributions



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July 01 - Sep. 03

2 t NaCl. n captures on
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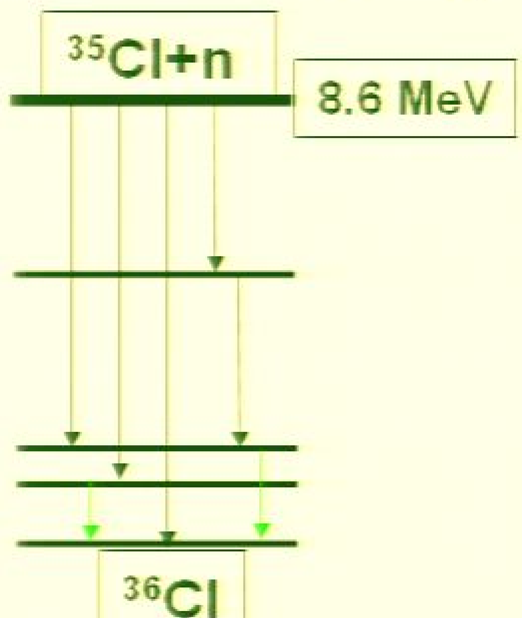
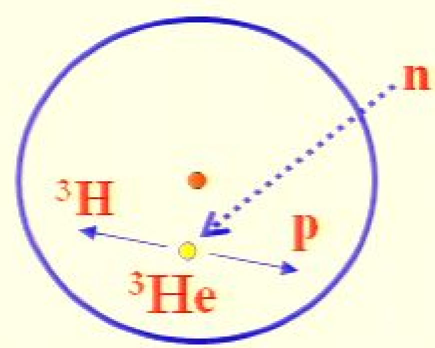


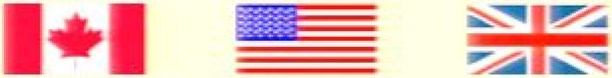
Phase III (^3He)
Nov. 04-Dec. 06

40 proportional counters
$^3He(n,p)^3H$
Effc. ~ 30% capture
Measure NC rate with entirely different detection system.



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

The Sudbury Neutrino Observatory: SNO



Acrylic vessel (AV)
12 m diameter

1000 tonnes D_2O
($300 million)

1700 tonnes H_2O
inner shielding

5300 tonnes H_2O
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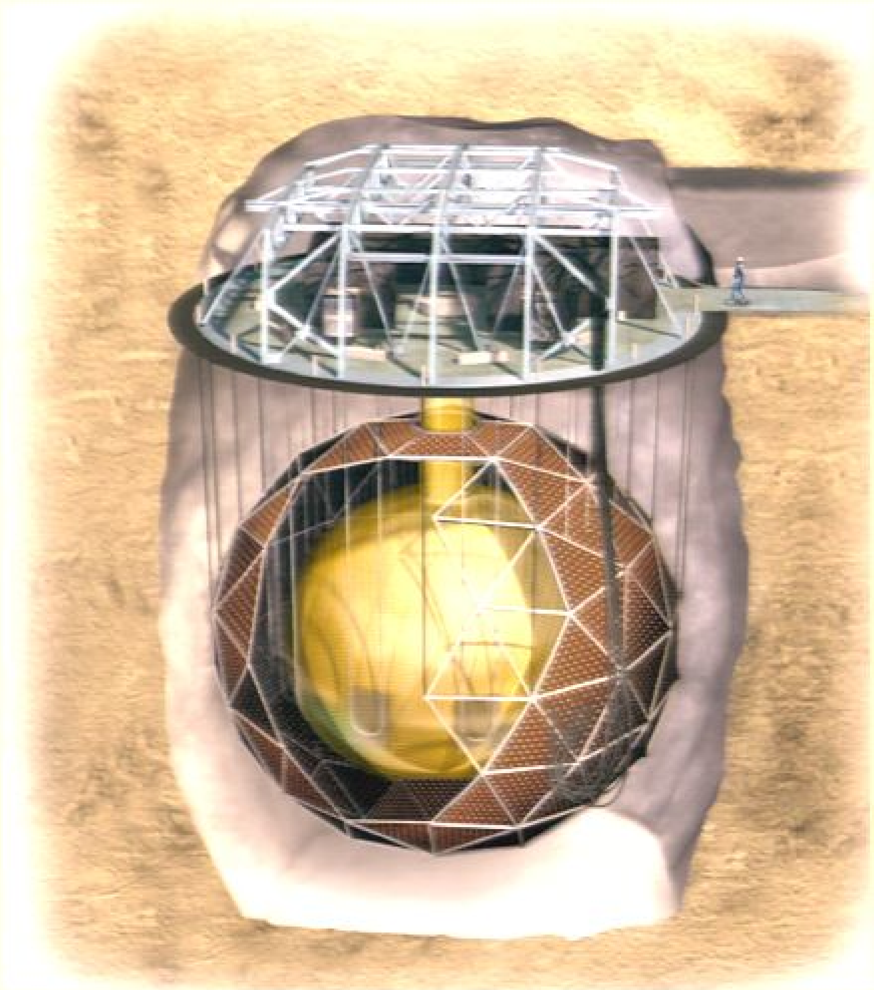
~9500 PMT's



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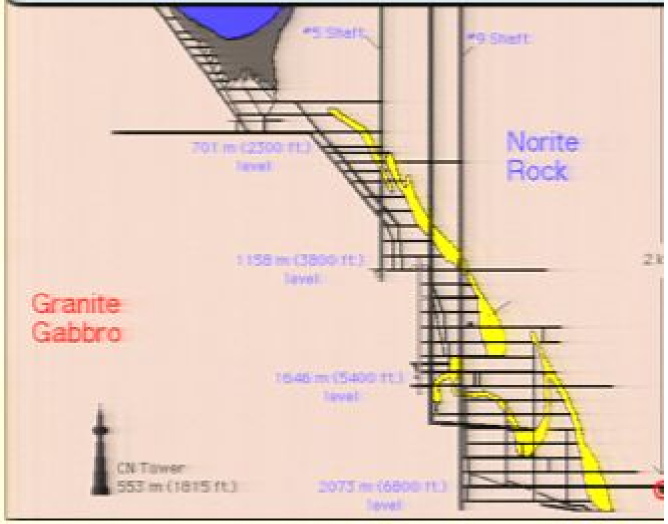

Creighton mine
Sudbury, CA

- Entire detector Built as a Class 2000 Clean room
- Low Radioactivity Detector materials

The heavy water has recently been returned and development work is in progress on SNO+ with liquid scintillator and ^{150}Nd additive

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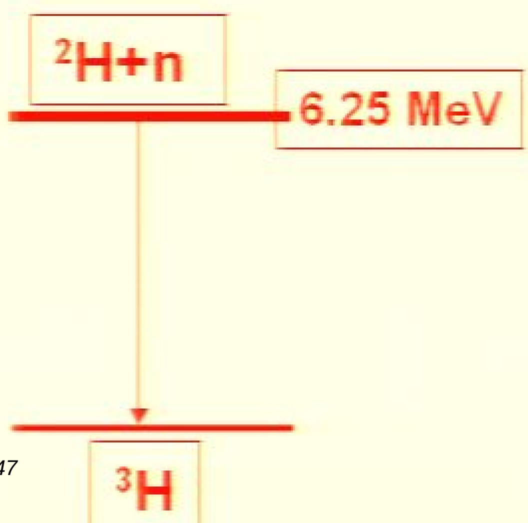

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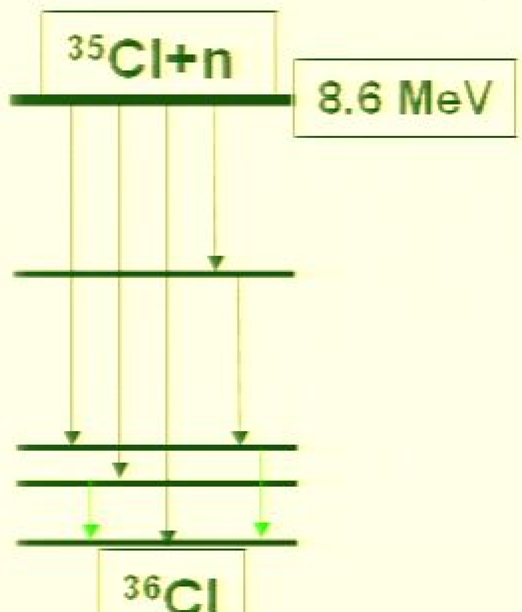

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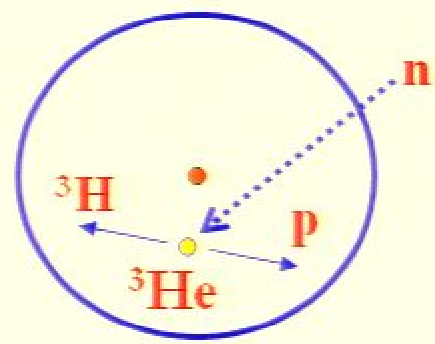

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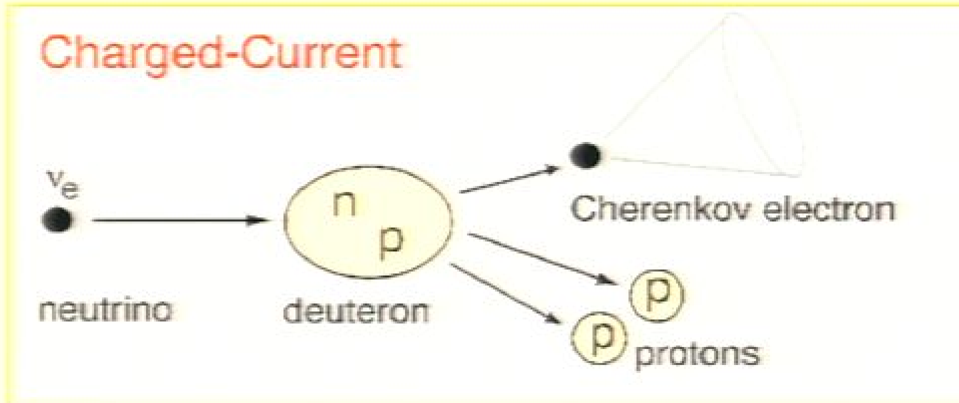

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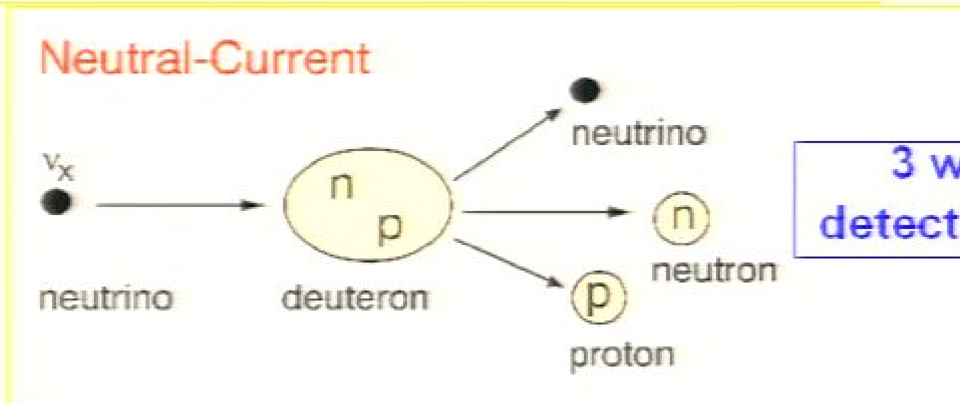

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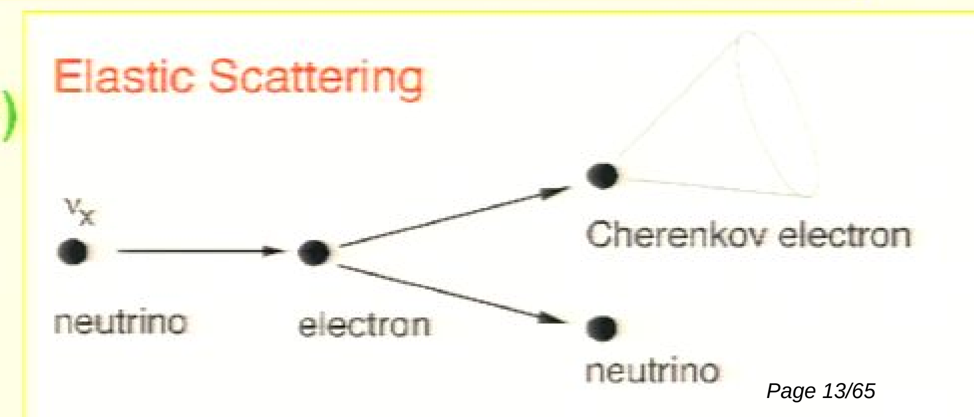

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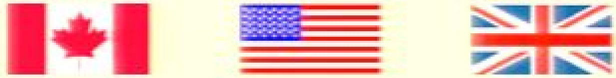

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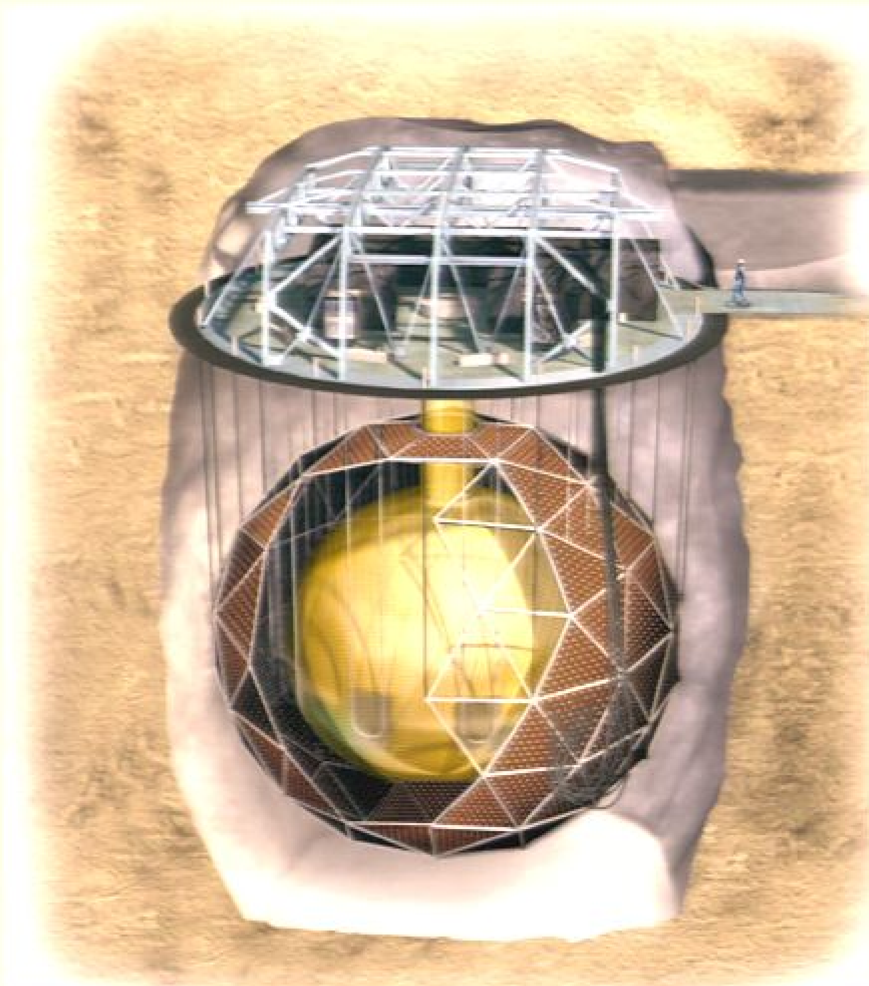

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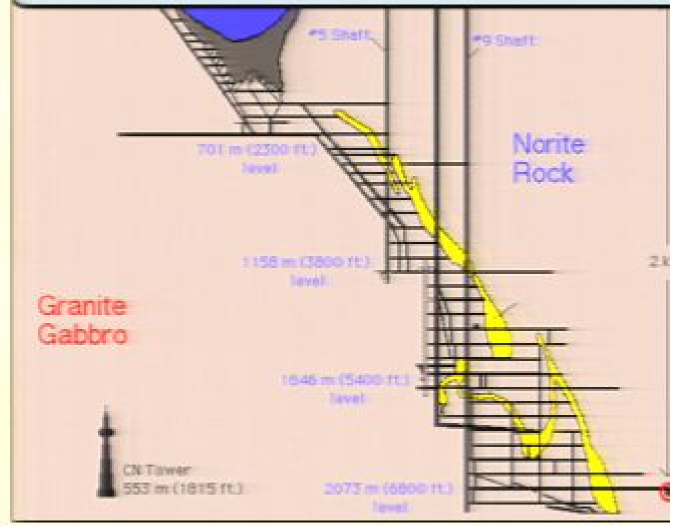

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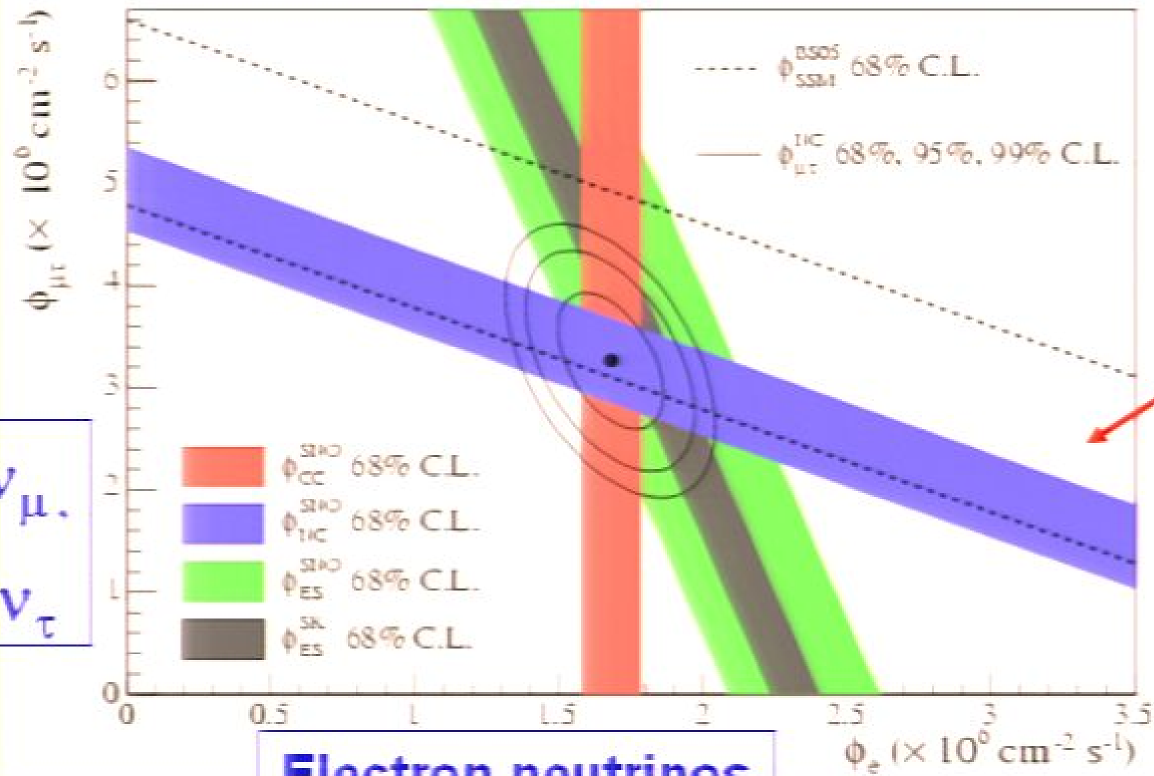

ν_μ, ν_τ

Electron neutrinos

SNO Results for Salt Phase

Flavor change determined by > 7 σ.

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

5.82 +- 1.3 (Bahcall et al),

5.31 +- 0.6 (Turck-Chieze et al

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

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

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(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

Using the oscillation framework:

If neutrinos have mass: $|\nu_l\rangle = \sum U_{li} |\nu_i\rangle$

For 3 Active neutrinos. (MiniBoone has recently ruled out LSND result

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Maki-Nakagawa-Sakata-Pontecorvo matrix

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Range defined for Δm_{12}, Δm_{23}

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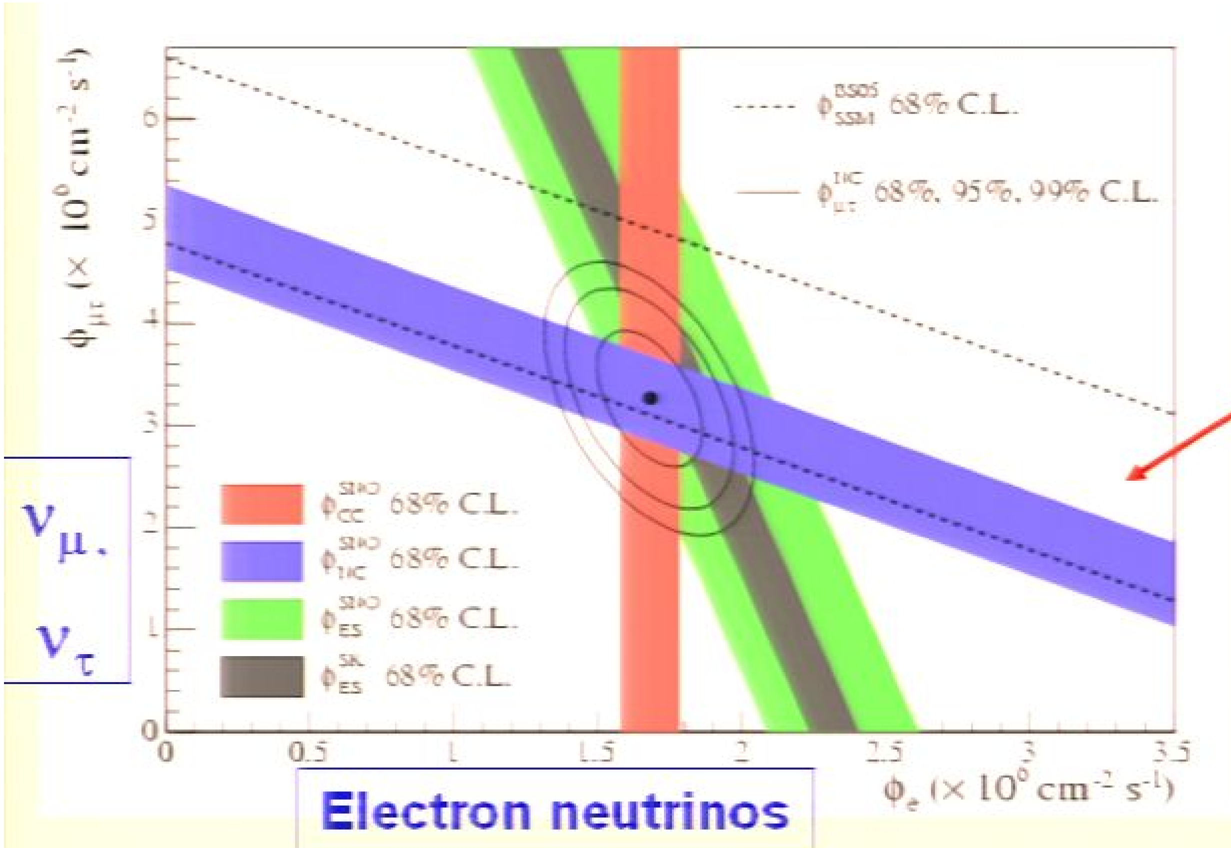

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Matter Effects – the MSW effect

(Mikheyev, Smirnov, Wolfenste

$$i\frac{d}{dt}\begin{bmatrix}\nu_e\\ \nu_x\end{bmatrix} = H\begin{bmatrix}\nu_e\\ \nu_x\end{bmatrix}$$

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

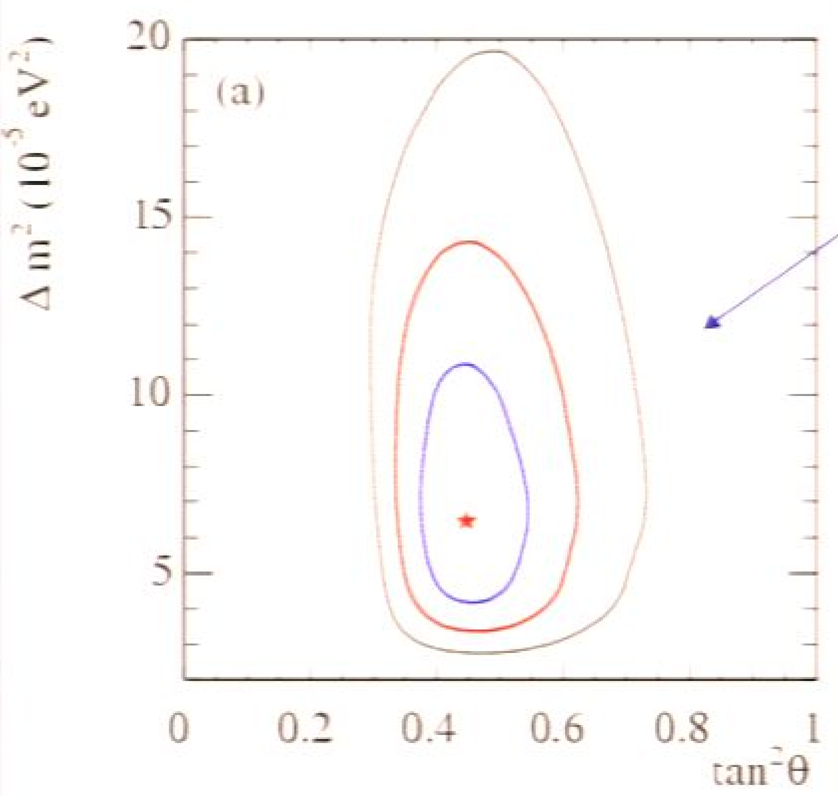
The extra term arises because solar ν_e have an extra interaction via W exchange with electrons in the Sun or Earth.

In the oscillation formula:

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{(\omega - \cos 2\theta)^2 + \sin^2 2\theta}$$

$$\omega = -\sqrt{2}G_F N_e E / \Delta m^2$$

MSW effect can produce an energy spectrum distortion and flavor regeneration in Earth giving a Day-night effect. If observed, matter interactions define the mass heirarchy.

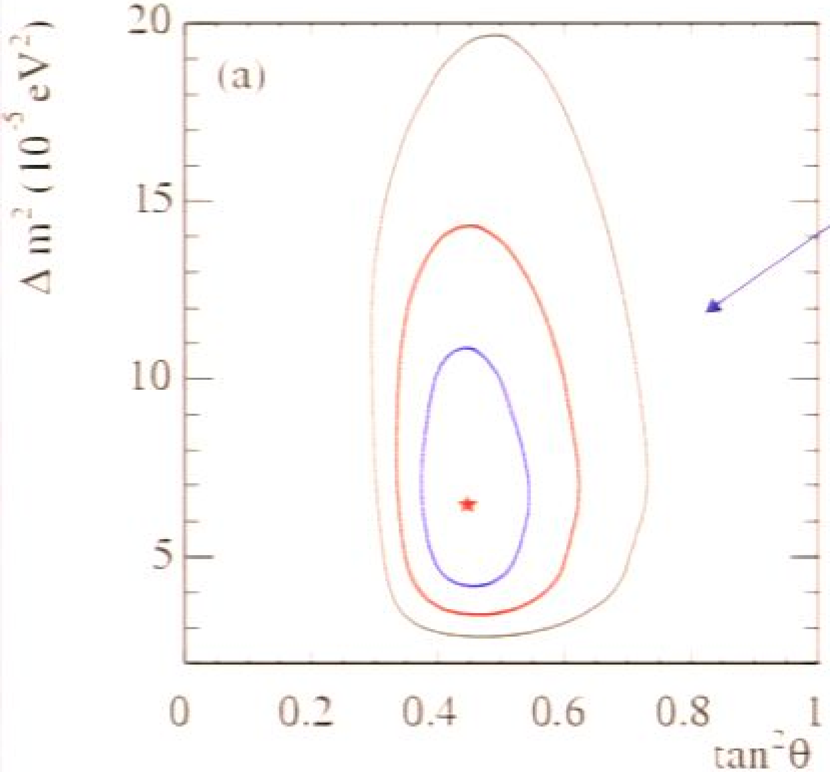


SOLAR ONLY AFTER SNO SALT DATA

MSW: 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 $\tan^2\theta_{12} < 1$ (ie Non - Maximal mixing by more than 5 standard deviations**



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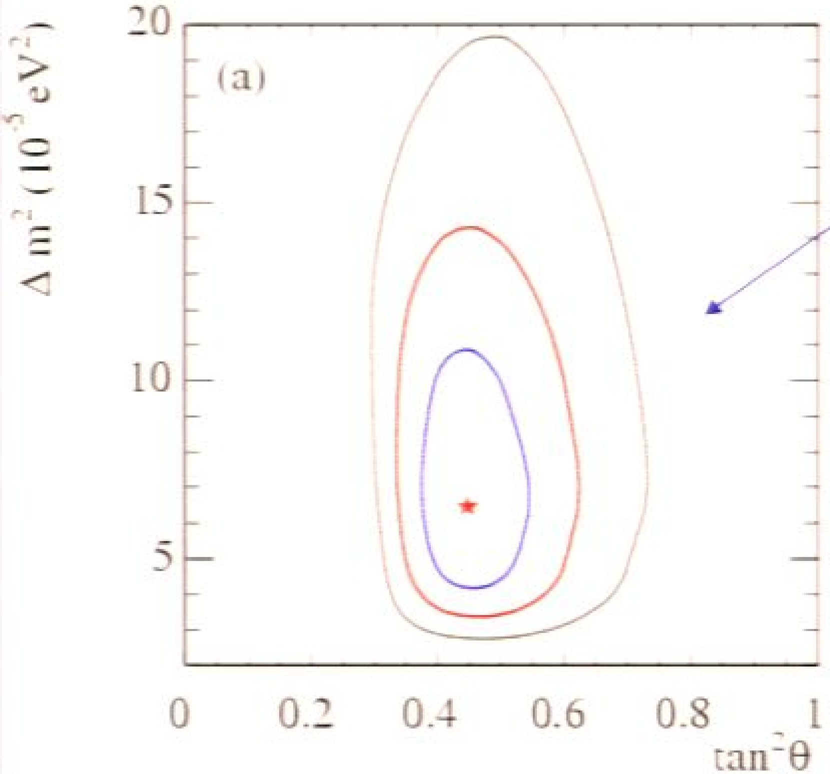
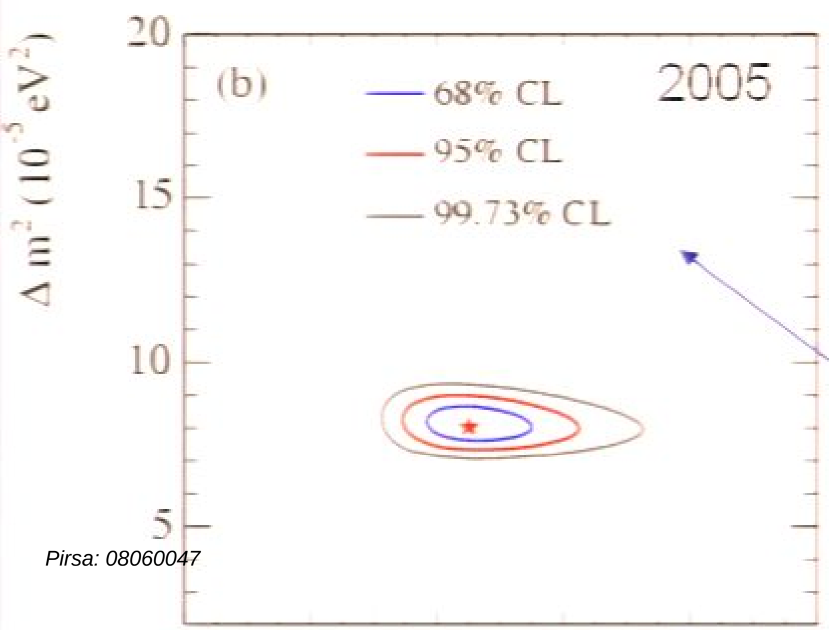
LMA for solar ν predicts very small spectral distortion, small (~ 3 %) day-night asymmetry, as observed by SK, SNO

$$\text{Asym}_{\text{salt} + D_2O} = 0.037 \pm 0.040$$





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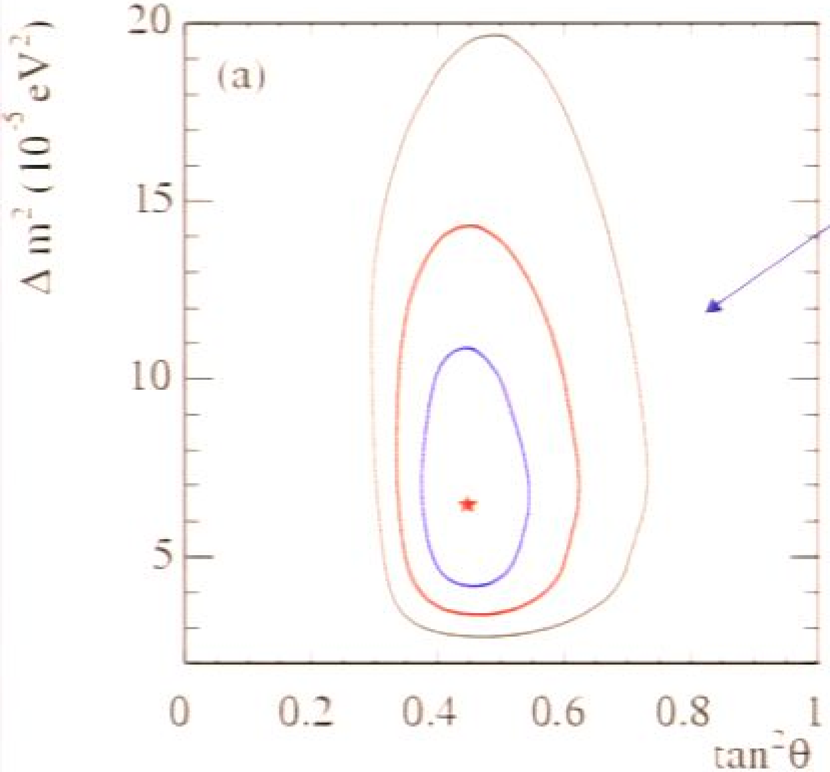

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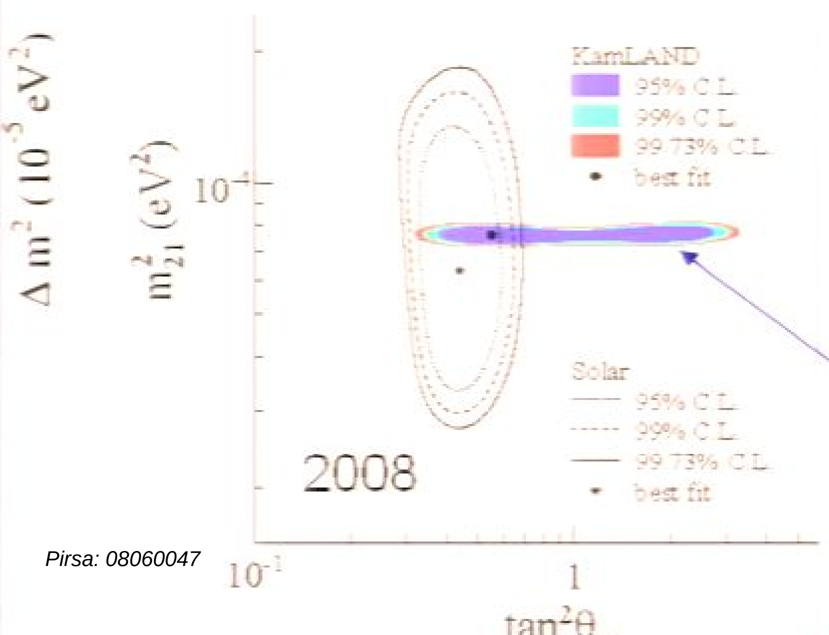

SOLAR PLUS

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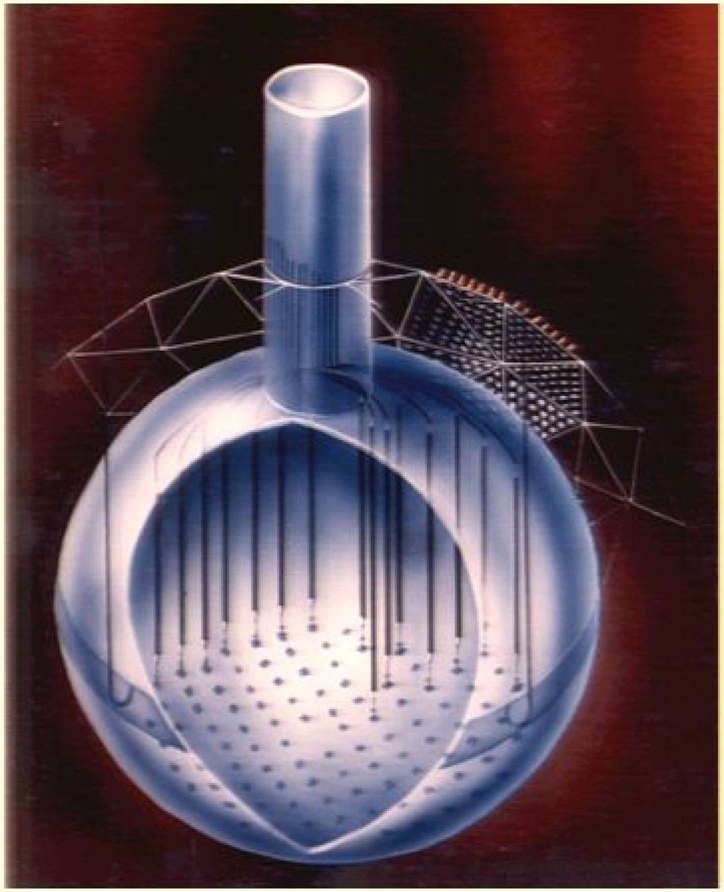
Final Phase: SNO Phase III

Neutral-Current Detectors (NCD):
An array of ^{3}He proportional counters

40 strings on 1-m grid
~440 m total active length



- Search for spectral distortion
- Improve solar neutrino flux by breaking the CC and NC correlation (ρ = -0.53 in Phase II):

CC: Cherenkov Signal $\Rightarrow$ **PMT Array**

NC: n+^{3}He $\Rightarrow$ **NCD Array**

- Improvement in θ_{12}, as

$$\frac{\phi^{CC}}{\phi^{NC}} \approx \sin^4\theta_{13} + \cos^4\theta_{13}\sin^2\theta_{12}$$

Correlations	D_2O unconstrained	D_2O constrained	Salt unconstrained	NCD
NC.CC	-0.950	-0.520	-0.521	-0.19
CC.ES	-0.208	-0.162	-0.156	0.2
ES.NC	-0.297	-0.105	-0.064	-0.02

Blind Analysis

Phase III production data taking Dec 2004 to Dec 2006. D_2O now removed

Chemical Vapor Deposition:

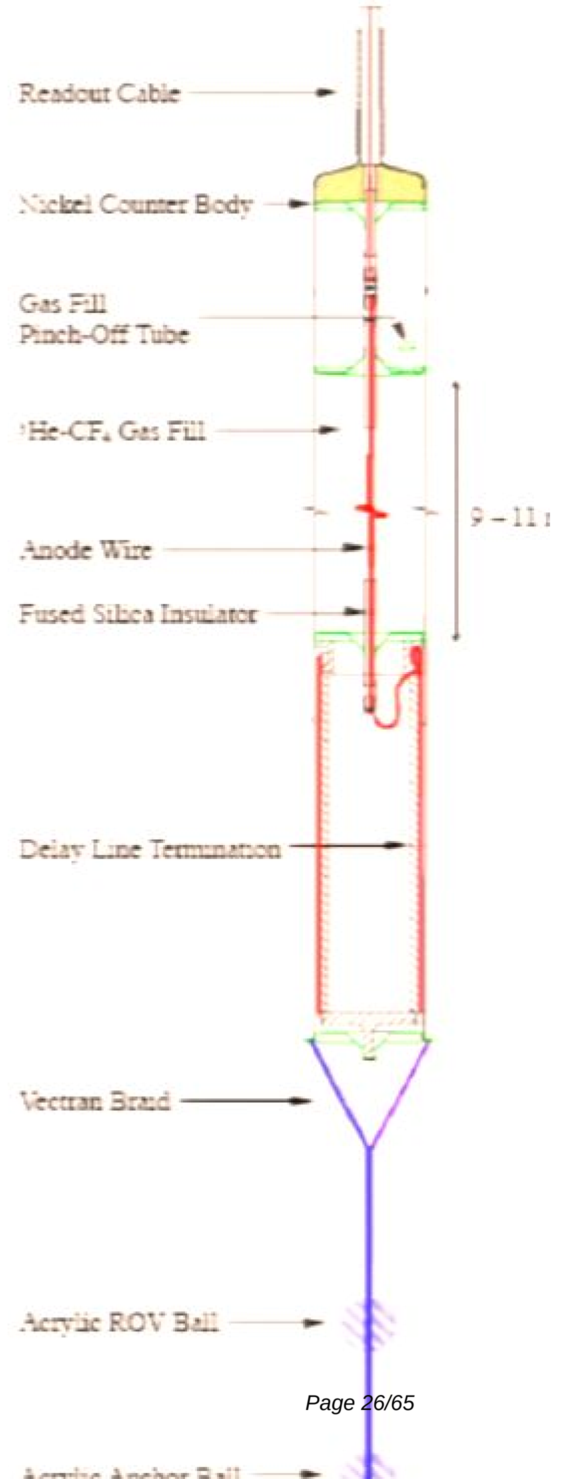
$Ni + 4CO \leftrightarrow Ni(CO)_4$

Strong, ultrapure Ni shapes.

Background alpha rate < $\frac{1}{100}$ best previous.

$$\mathrm{gTh/gNCD} = 3.43^{+1.49}_{-2.11} \times 10^{-12}$$

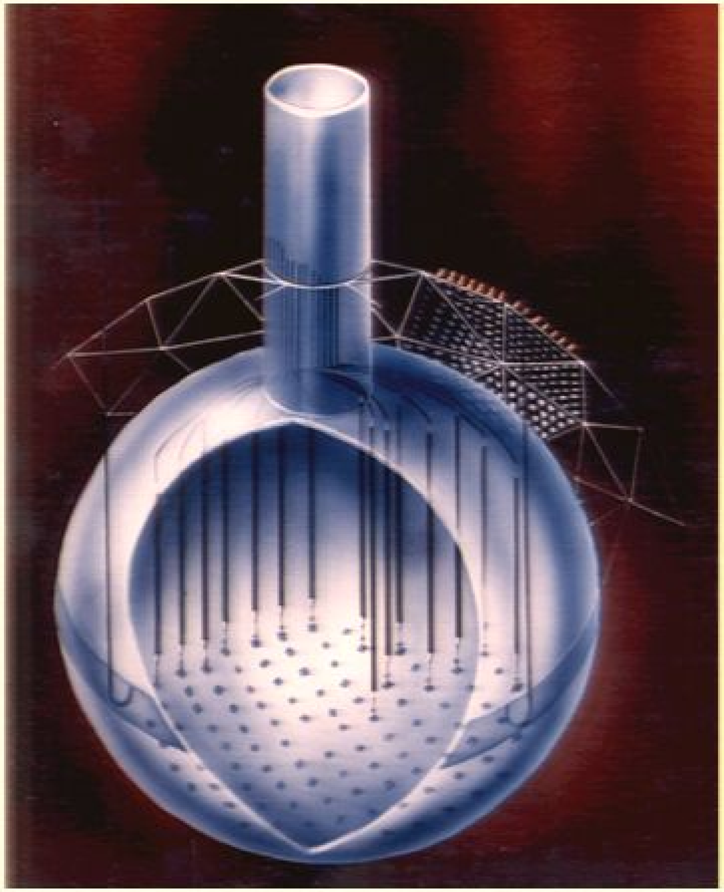
$$\mathrm{gU/gNCD} = 1.81^{+0.80}_{-1.12} \times 10^{-12}$$



Final Phase: SNO Phase III

Neutral-Current Detectors (NCD):
An array of ^{3}He proportional counters

40 strings on 1-m grid
~440 m total active length



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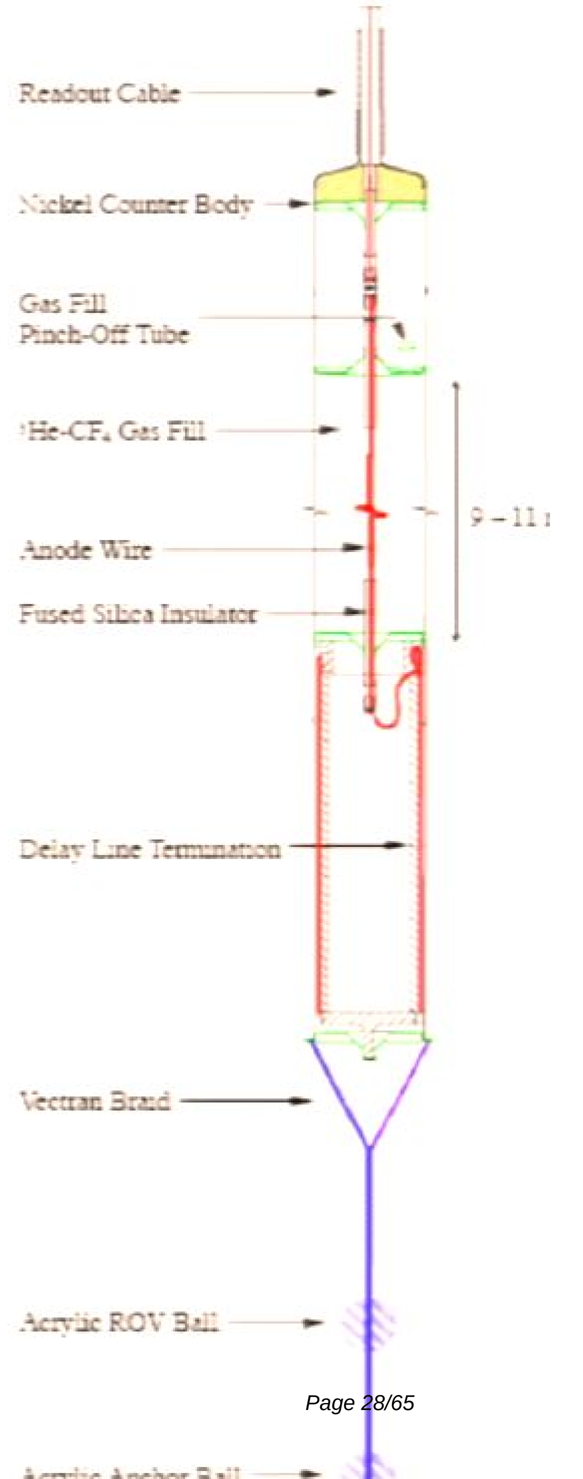
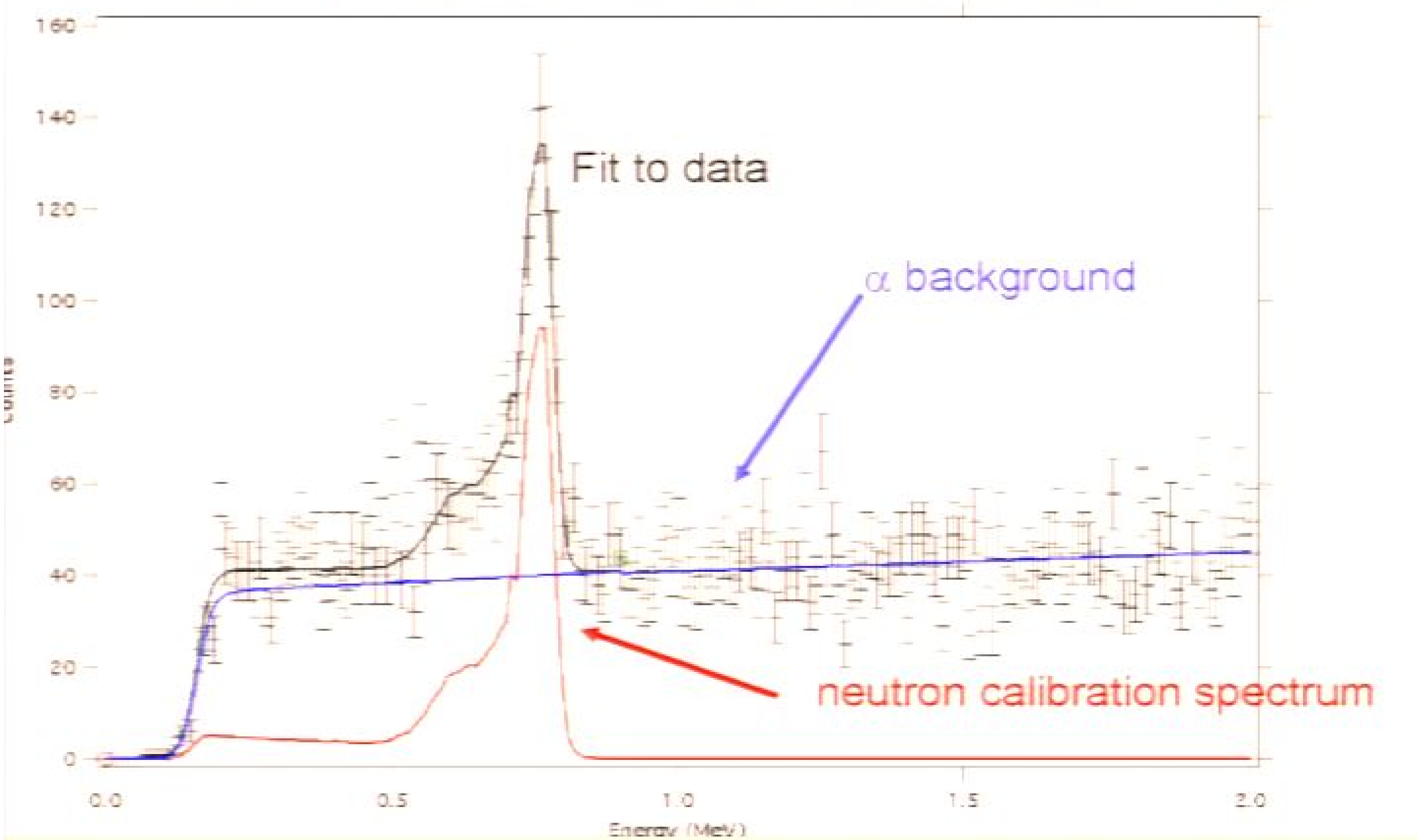


SNO NCD Signals

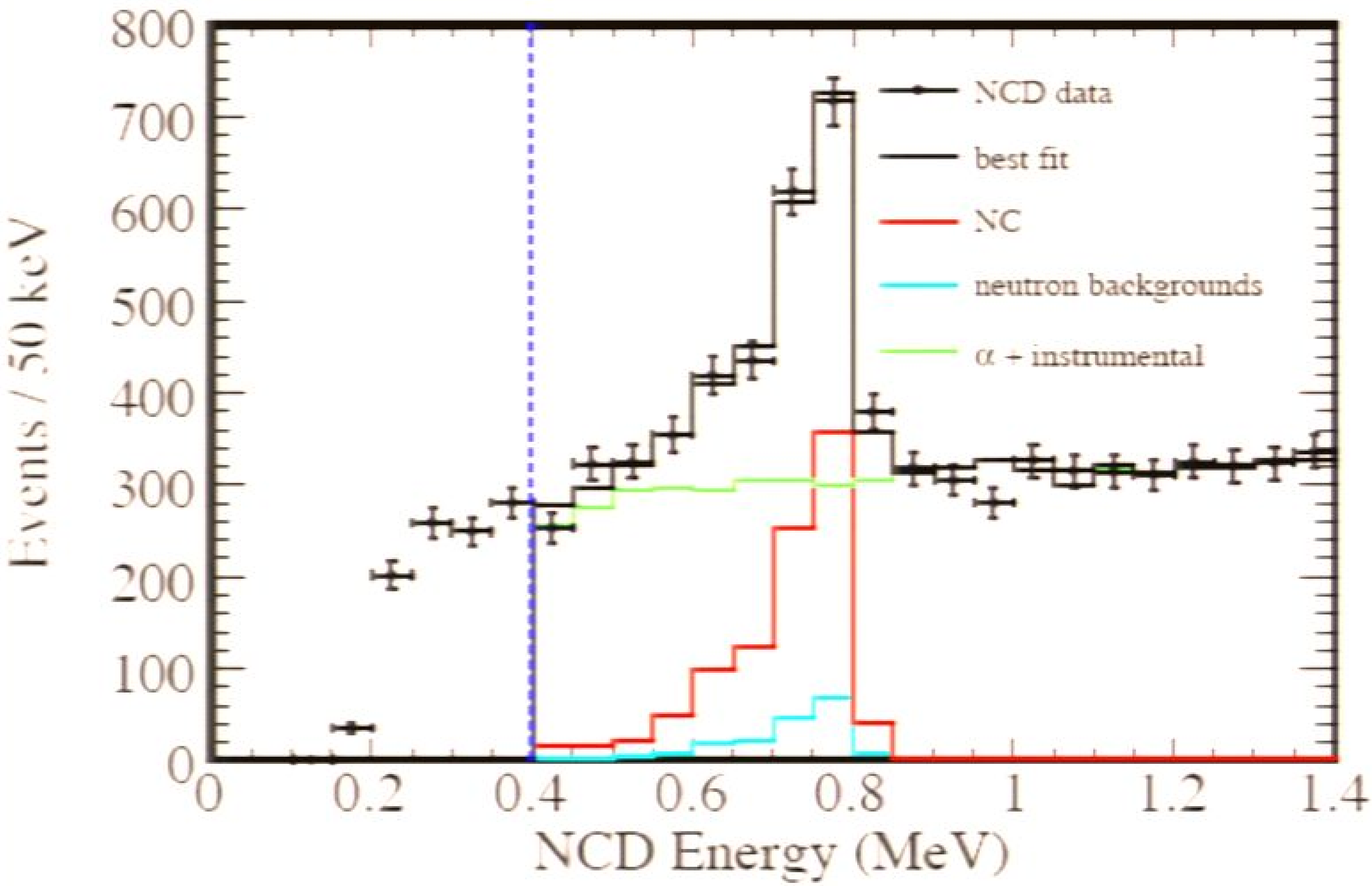
$n + {}^{3}He \rightarrow p + {}^{3}H \quad (q=768\ keV)$

Blind Data: Include hidden fraction of neutrons that follow muons and omit an unknown fraction of candidate events



Very low Background. About one count per 2 hours in region of interest. Can be reduced by a factor of more than 20 by pulse shape discrimination.

Neutrons from solar neutrino interactions



NC Signal:
983 ± 77

Neutron background:
185 ± 25

Alphas and Instrumentals
6126 ± 250
(0.4 to 1.4 MeV)

NEW SNO PAPER: (Yesterday)
arXiv:0806.0989v1 [nucl-ex]

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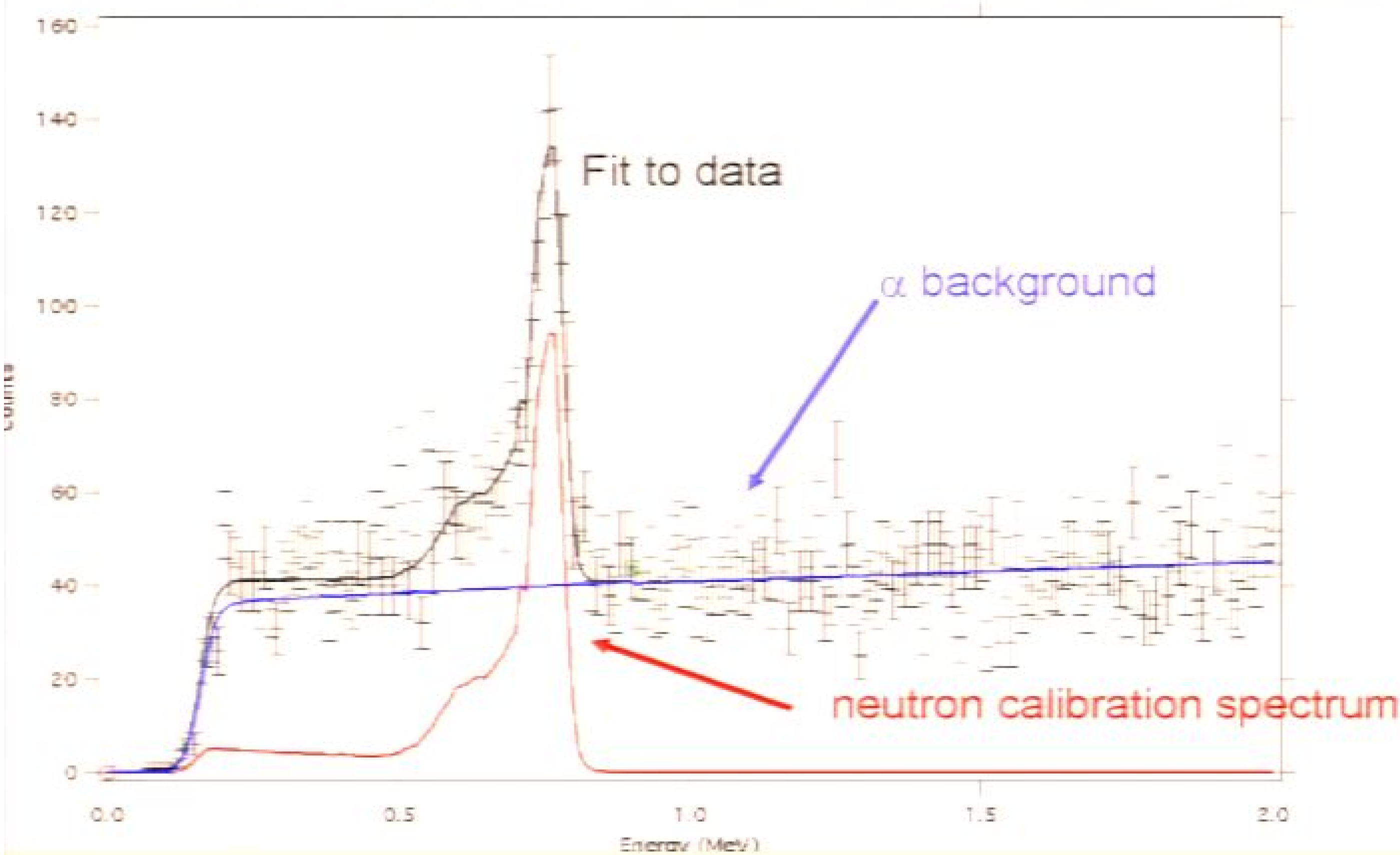

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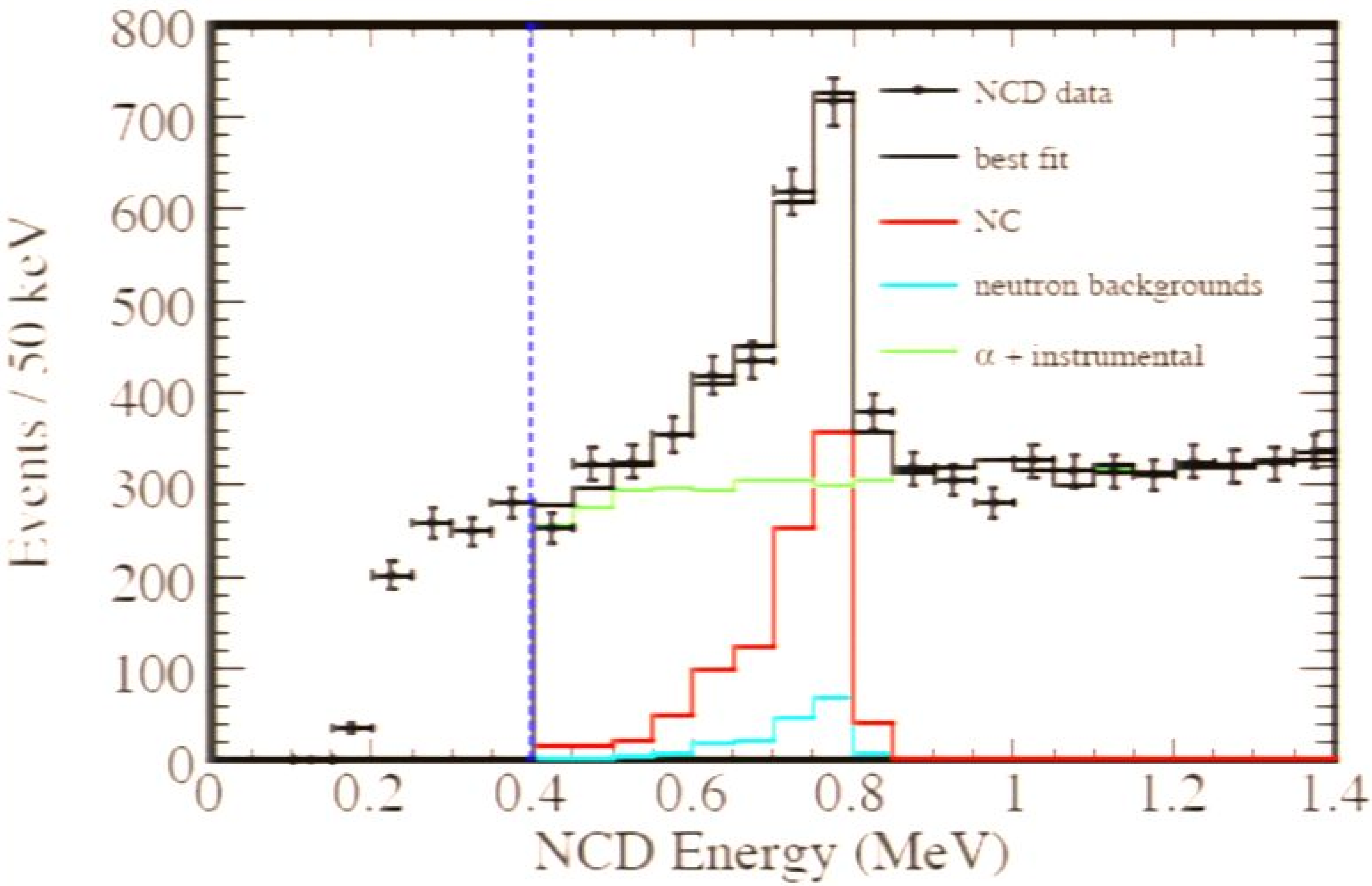

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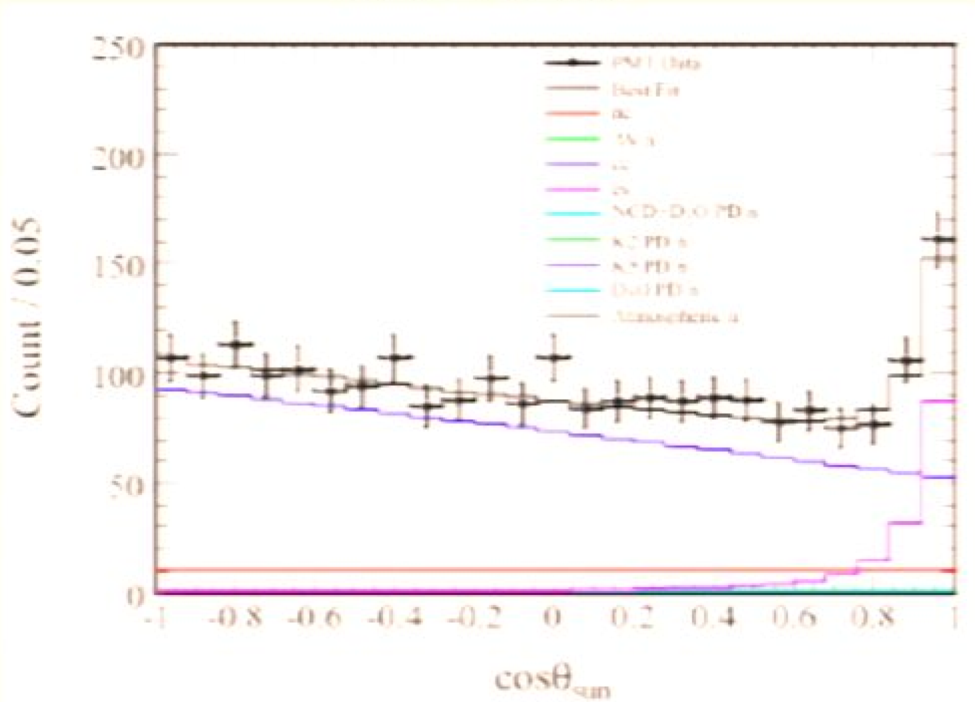
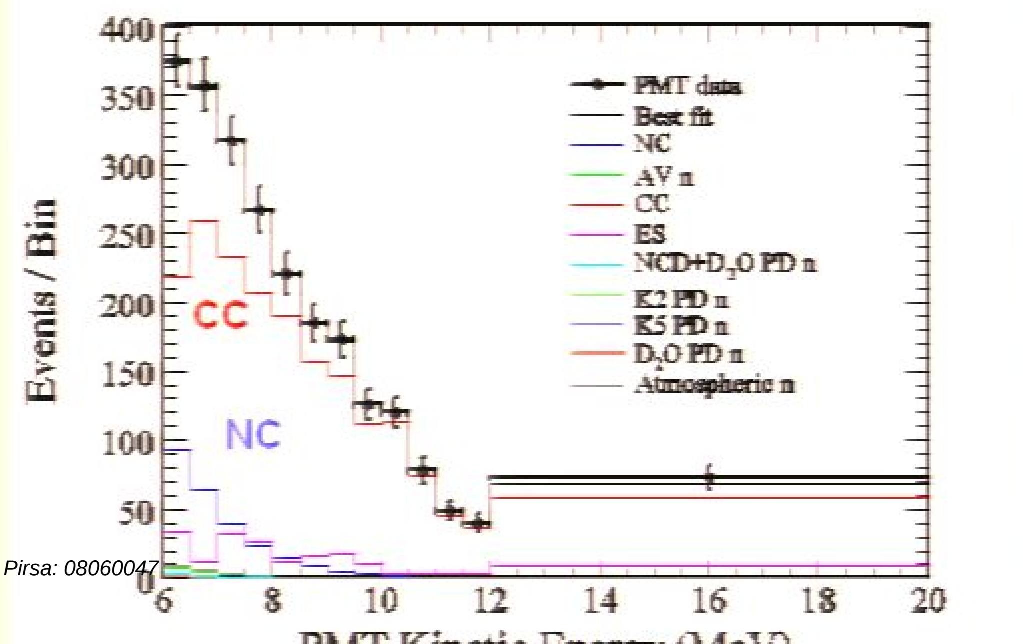


PMT Distributions $\cos(\theta_{sun})$, Energy



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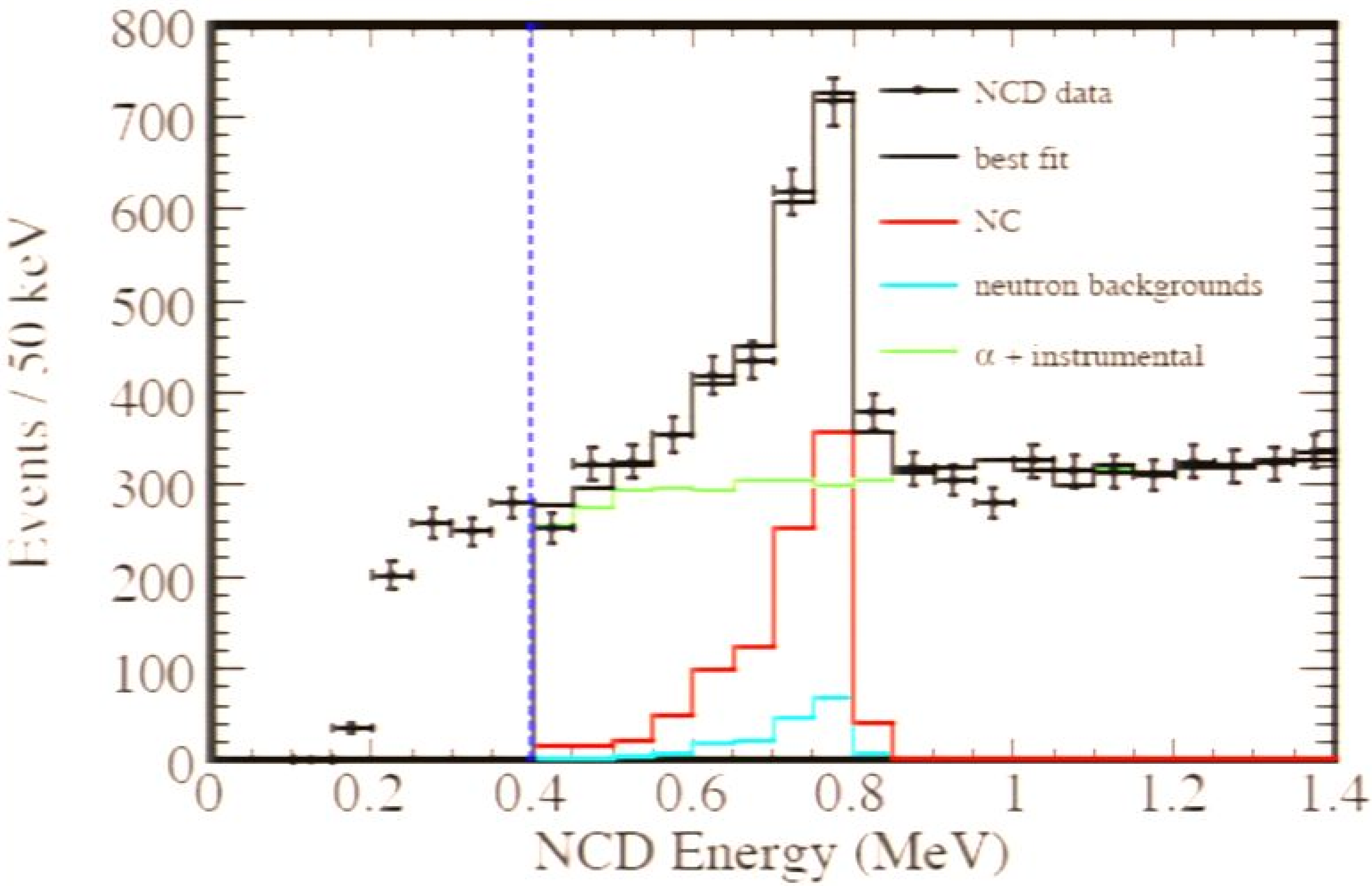

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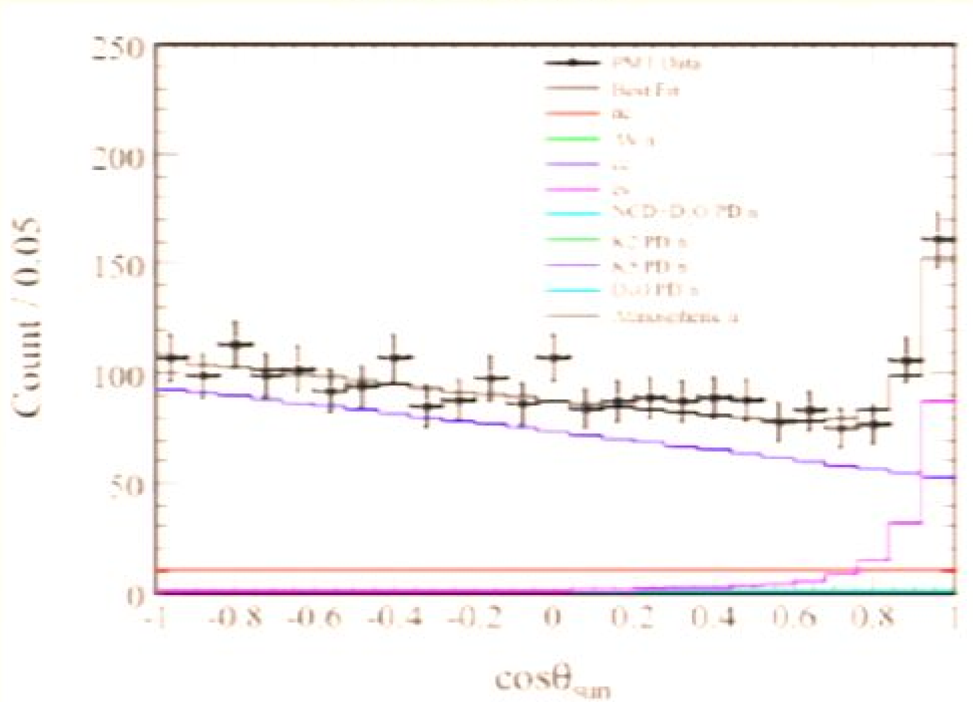
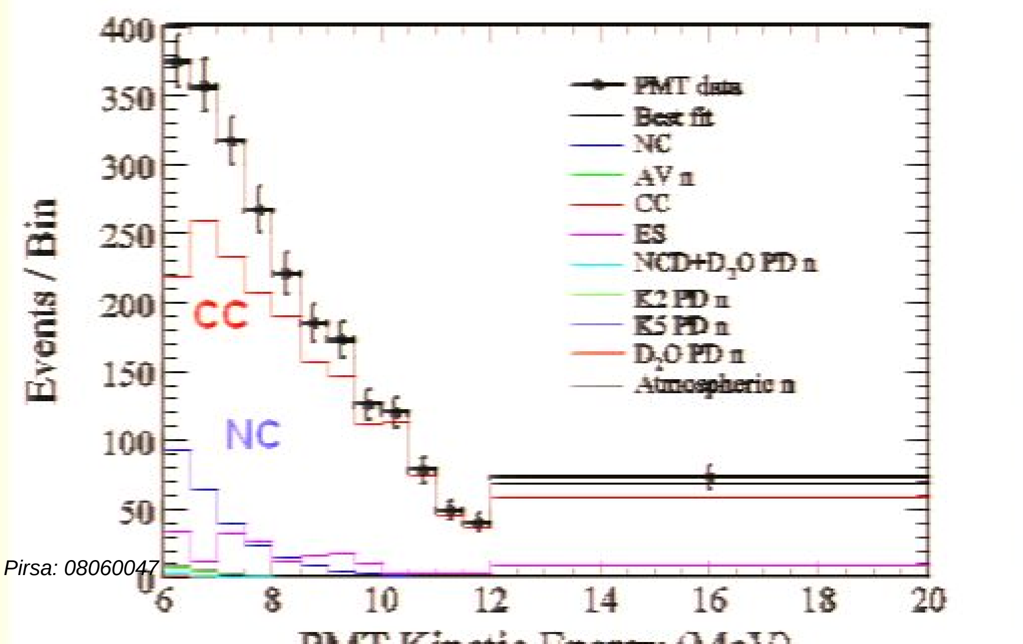
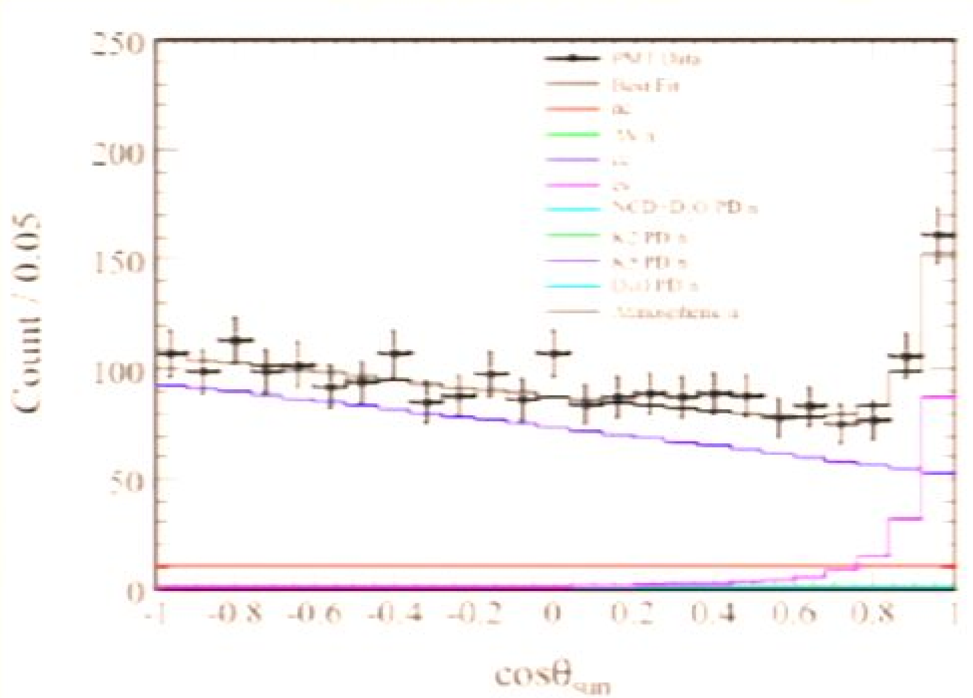




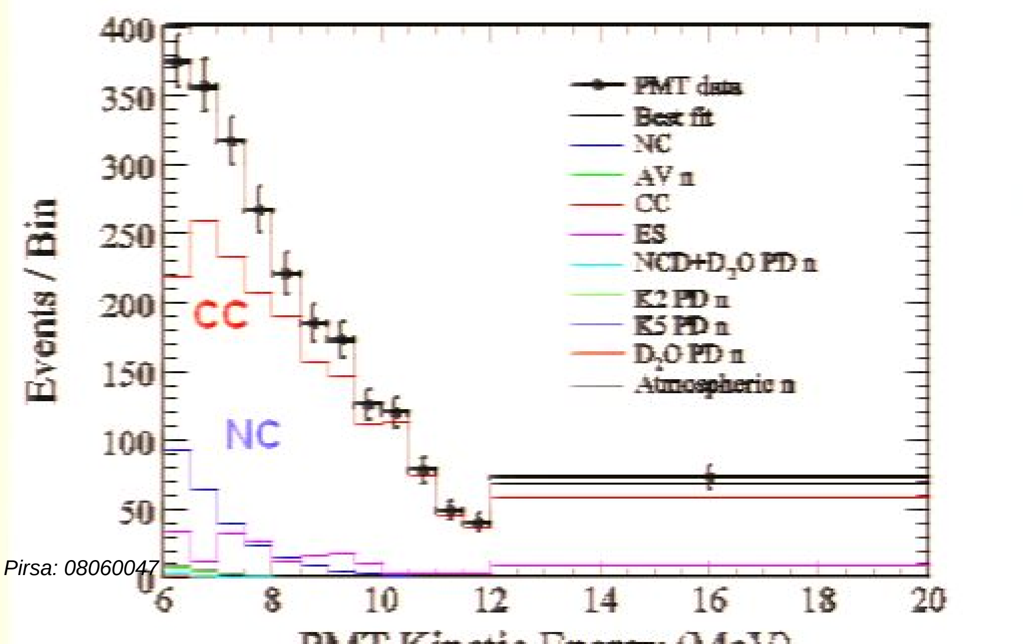
PMT Distributions $\cos(\theta_{sun})$, Energy

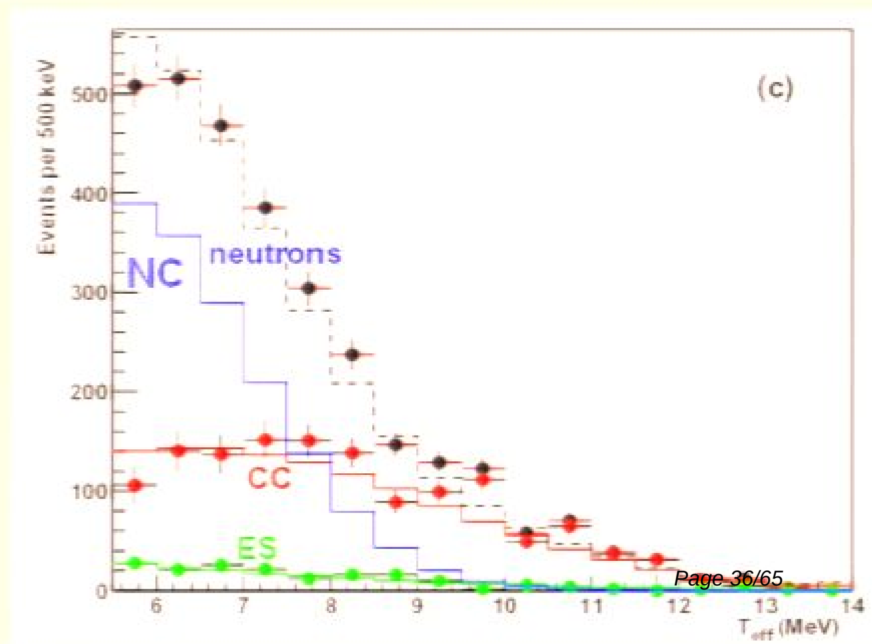
NCD Phase



PMT Distributions $\cos(\theta_{sun})$, Energy

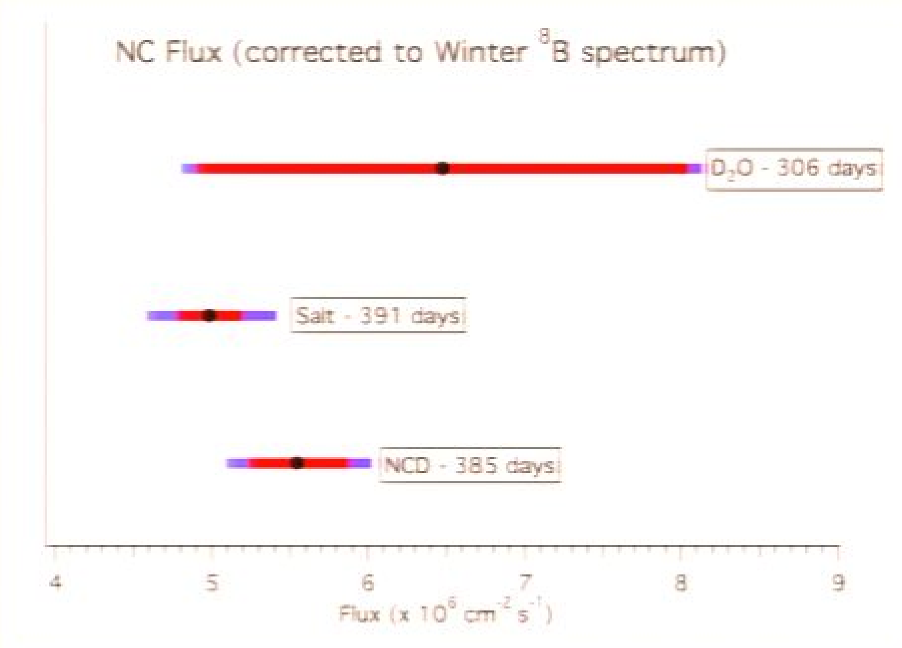
Data from salt phase

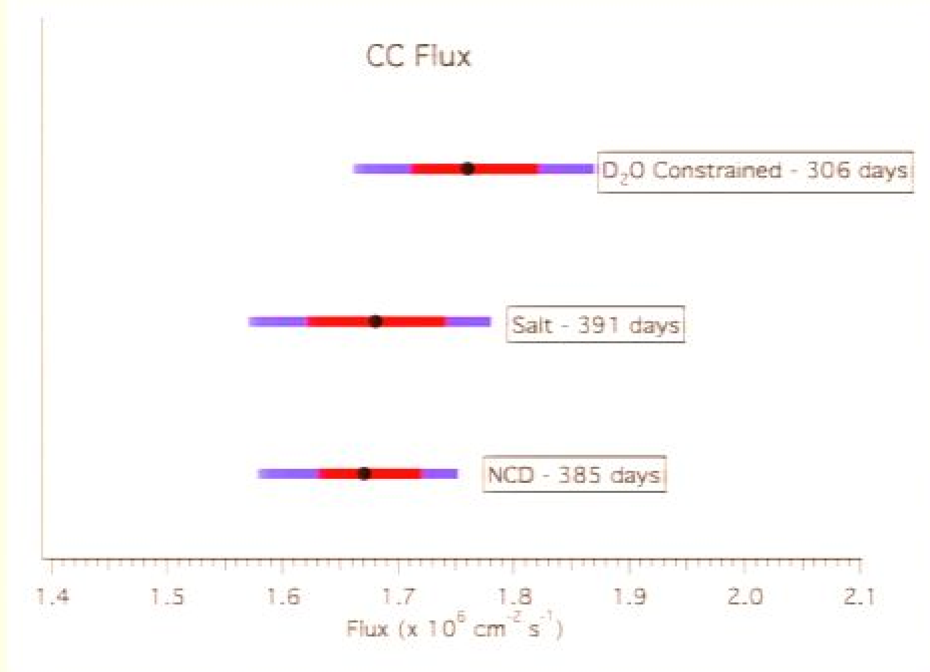




SNO Fluxes: 3 Phases

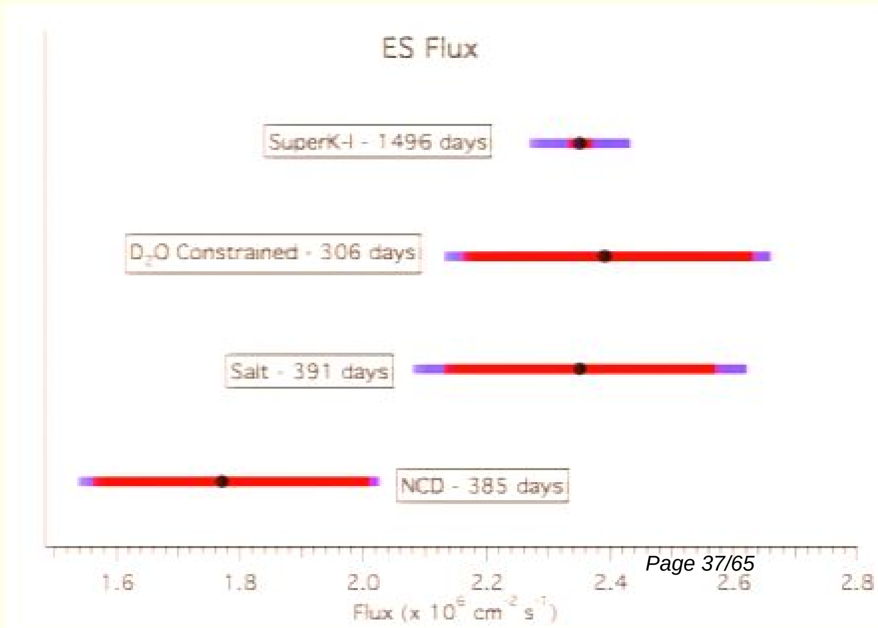
stat   stat + sys





$$\frac{\phi_{CC}^{SNO}}{\phi_{NC}^{SNO}} = 0.301 \pm 0.033 \text{ (total)}.$$

p-value for consistency of NC/CC/ES in the salt & NCD phases + D2O NC(unconstr) is 32.8%



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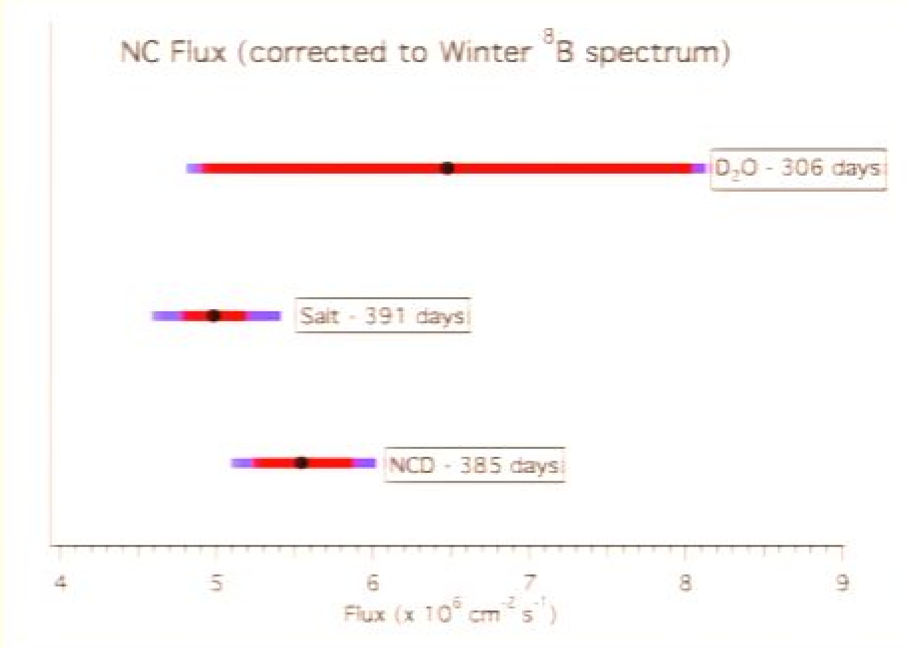
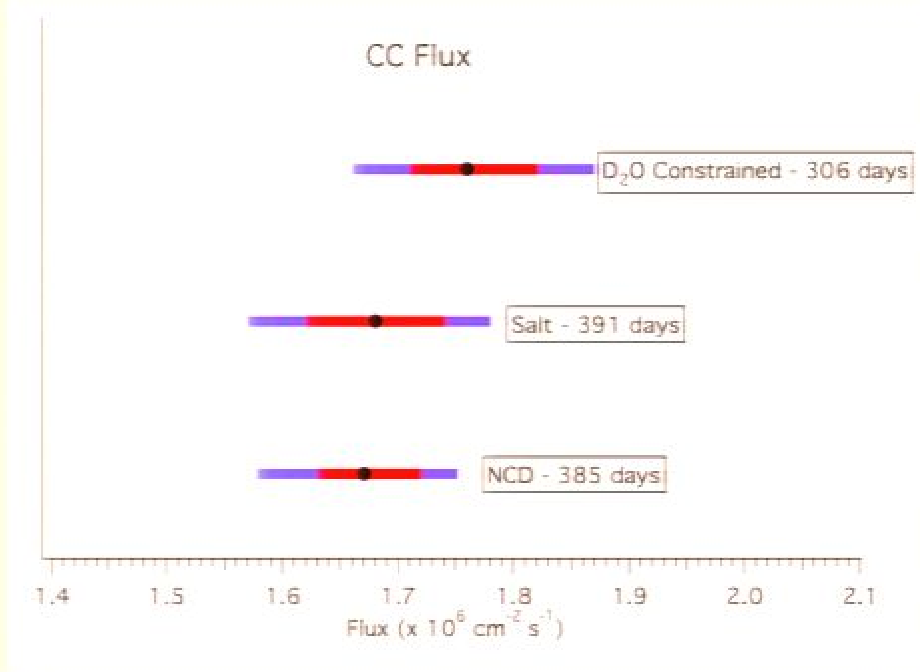
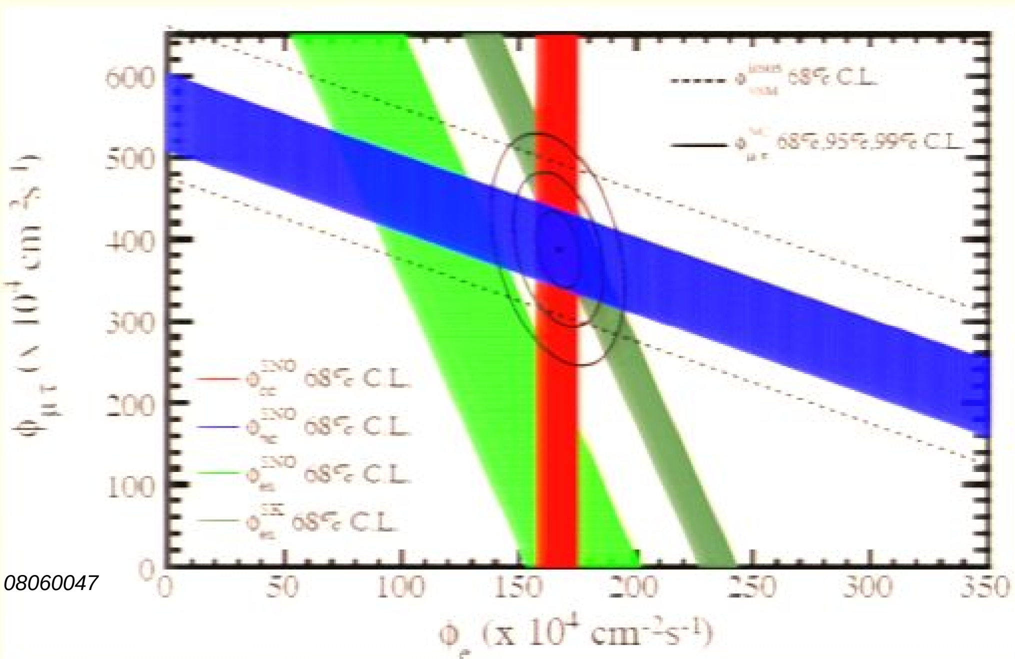
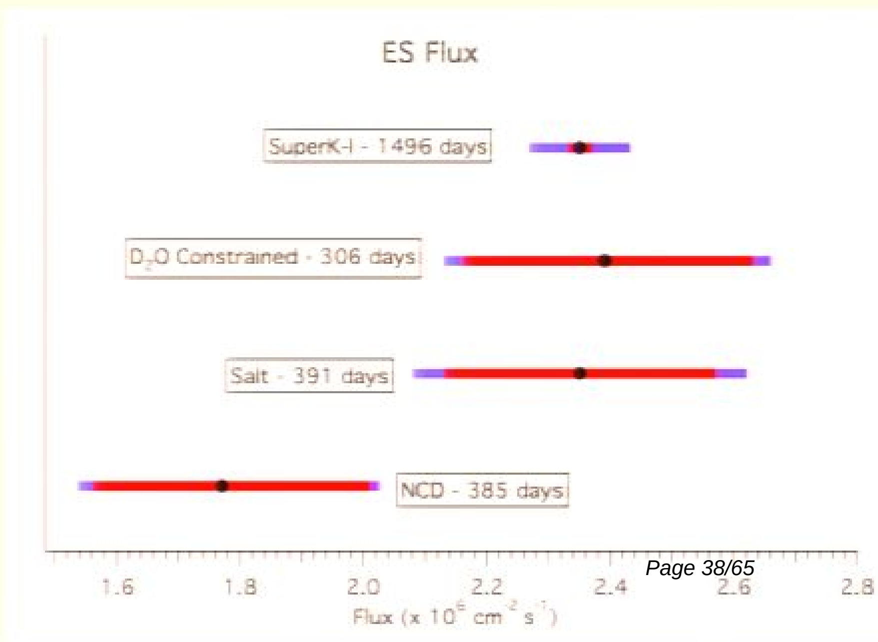
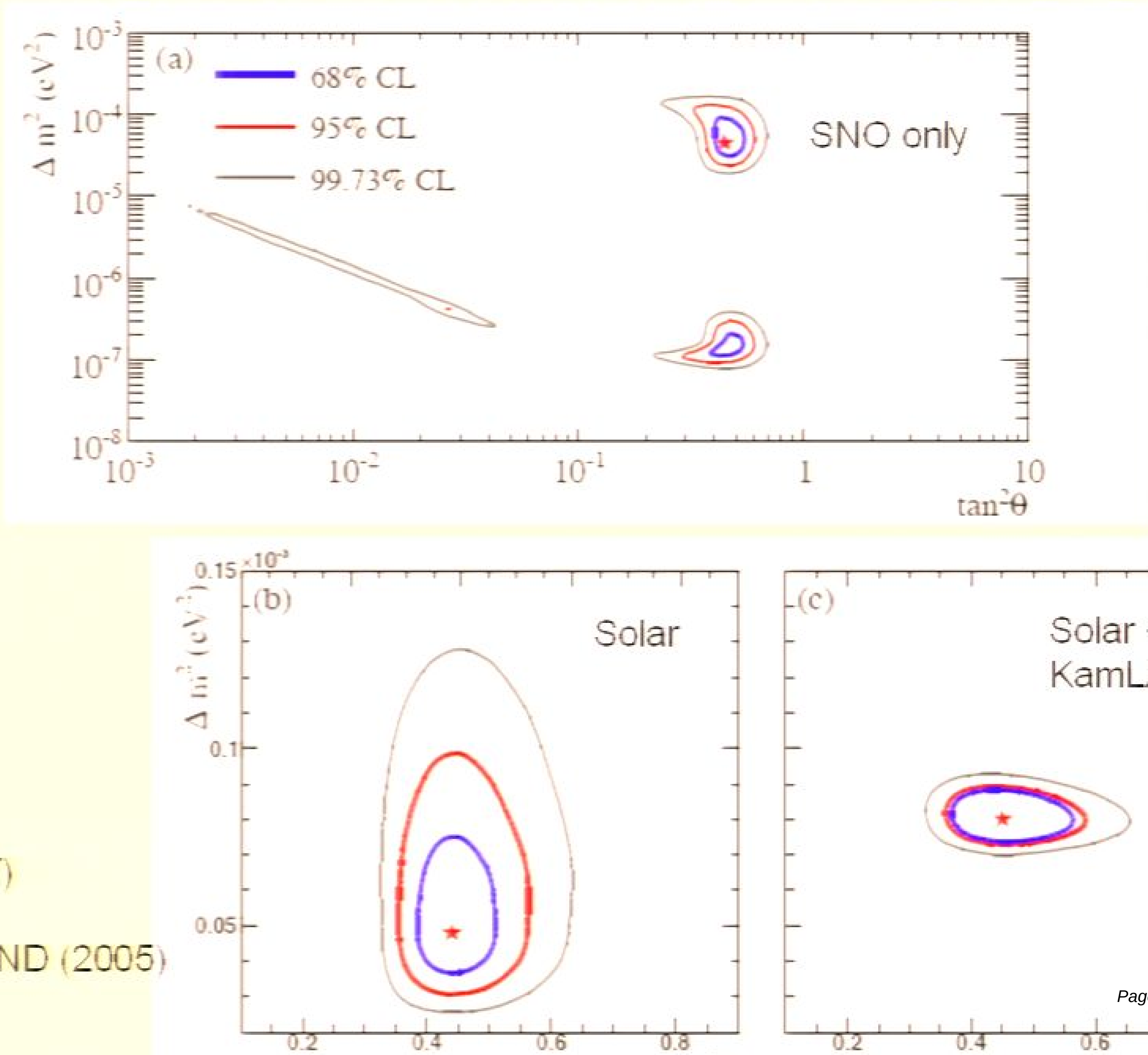








2-Neutrino Oscillation Contours



Cl-Ar
Super-K
SAGE
Gallex
GNO
SNO
Borexino (2007)

766 t-y KamLAND (2005)

Solar + KamLAND fit results

$$\Delta m^2 = 7.94^{+0.42}_{-0.26} \times 10^{-5} \text{ eV}^2$$

$$\phi_{8B} = 0.873\,\phi_{8B(BSB05-OP)}$$

$$\theta = 33.8^{+1.4}_{-1.3} \text{ degrees}$$

$$\theta = 33.9^{+2.4}_{-2.2} \text{ deg (previous)}$$

2-neutrino mixing model.
Marginalized 1-σ uncertainties.

The accuracy on θ_{12} will improve with new data: Kamland, Borexino, SNO LETA

Neutrino phenomenology examples:
(Smirnov summary at Neutrino 2008)
Tri-Bi-Maximal Mixing: 35.2 deg
Quark-Lepton Complementarity: 32.2 deg
($\theta_{12} + \theta_{Cabbibo}$ = 45 deg)

This work:

- NCD results agree well with previous SNO phases. Minimal correlation with CC. Different systematics.
- New precision on θ

Future solar analysis:

- LETA (Low Energy Threshold Analysis)
- 3-neutrino analysis
- *hep* flux
- Day-night, other variations
- Muons, atmospheric ν

SNO Physics Program

- **Solar Neutrinos (6 papers to date)**
  - → **Electron Neutrino Flux**
  - → **Total Neutrino Flux**
  - → **Electron Neutrino Energy Spectrum Distortion**
  - → **Day/Night effects**
  - → **hep neutrinos** hep-ex 0607010
  - → **Periodic variations: [Variations < 8% (1 dy to 10 yrs)]** hep-ex/0507079
- **Atmospheric Neutrinos & Muons**
  - → **Downward going cosmic muon flux**
  - → **Atmospheric neutrinos: wide angular dependence [Look above horizon]**
- **Supernova Watch (SNEWS)**
- **Limit for Solar Electron Antineutrinos**

  hep-ex/0407029
- **Nucleon decay ("Invisible" Modes: N →$\nu\nu\nu$)**

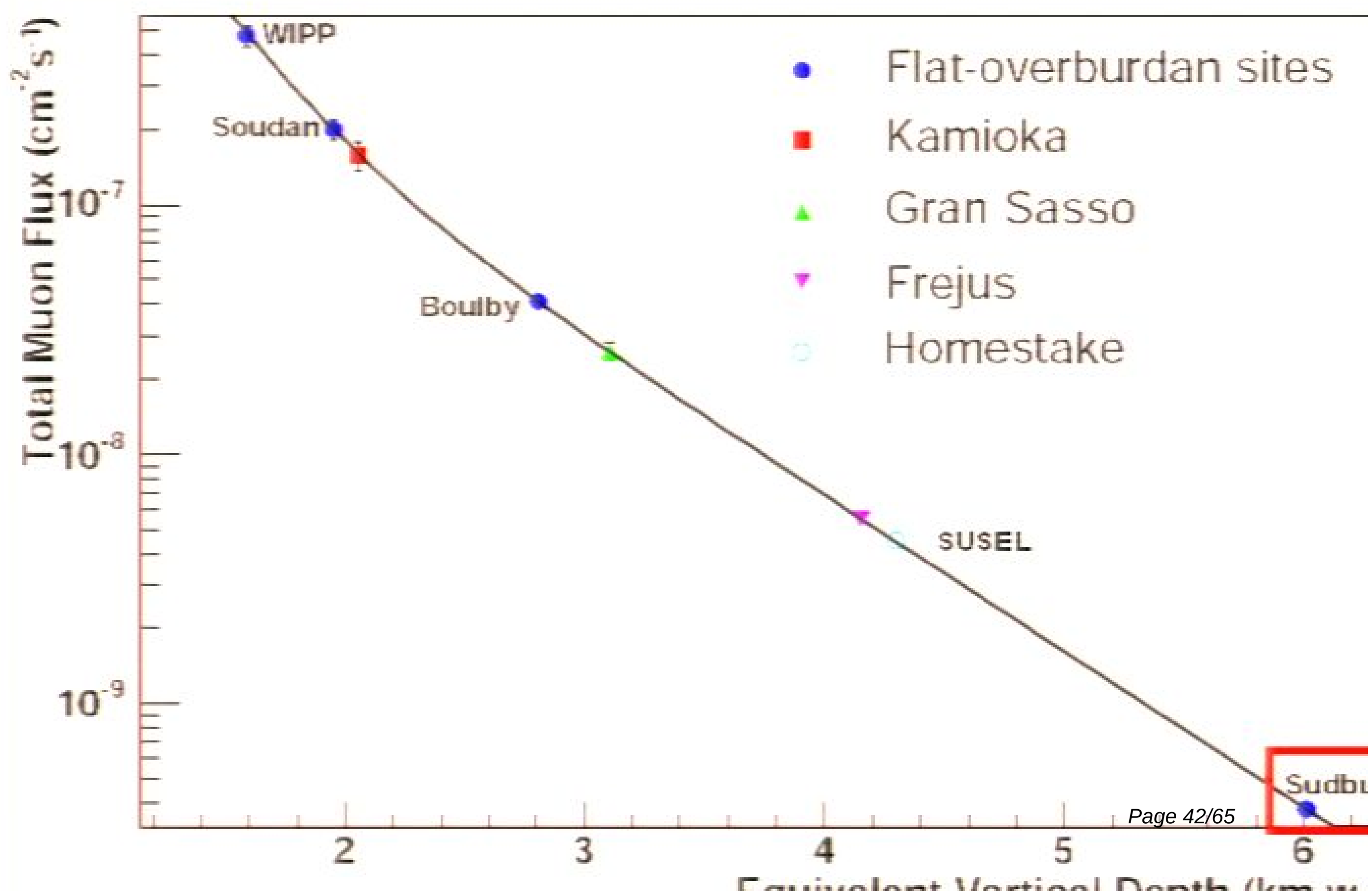
  Phys.Rev.Lett. 92 (2004) **[Improves limit by 1000]**
- **Supernova Relic Electron Neutrinos** hep-ex 0607010

New International Underground Facility: SNOLAB

Phase 1 Experimental area: Available 2008
Cryopit addition: Excavation completed. Available early 2009.
Total additional excavated volume in new lab: 2 times SNO volume.

For Experiments that benefit from a very deep and clean lab:

- ν - less Double Beta Decay
- Dark Matter
- Solar Neutrinos
- Geo – neutrinos
- Supernova ν `s



Letters of Intent/Interest for SNOLAB

Dark Matter:

Timing of Liquid Argon/Neon Scintillation: DEAP-1 (7 kg), MINI-CLEAN (360 kg), DEAP/CLEAN (3.6 Tonne)

Freon Super-saturated Gel: PICASSO

Silicon Bolometers: SUPER-CDMS (25 kg)

6 th Workshop and
Experiment Review Committe
Aug 22, 23, 2007
www.snolab.ca
RED IMPLIES APPROVED FOR SITING

Neutrino-less Double Beta Decay:

^{150}Nd: Organo-metallic in liquid scintillator in SNO+

^{136}Xe: EXO (Gas or Liquid) (Longer Term)

CdTe: COBRA (Longer Term)

Solar Neutrinos:

Liquid Scintillator: SNO+ (also Reactor Neutrinos, Geo-neutrinos)

Liquid Ne: CLEAN (also Dark Matter) (Longer Term)

SuperNovae:

SNO+: Liquid scintillator: HALO: Pb plus SNO ^{3}He detectors.

SNOLAB

70 to 800 times lower
μ fluxes than
Gran Sasso, Kamioka.

All Lab Air: Class < 2000

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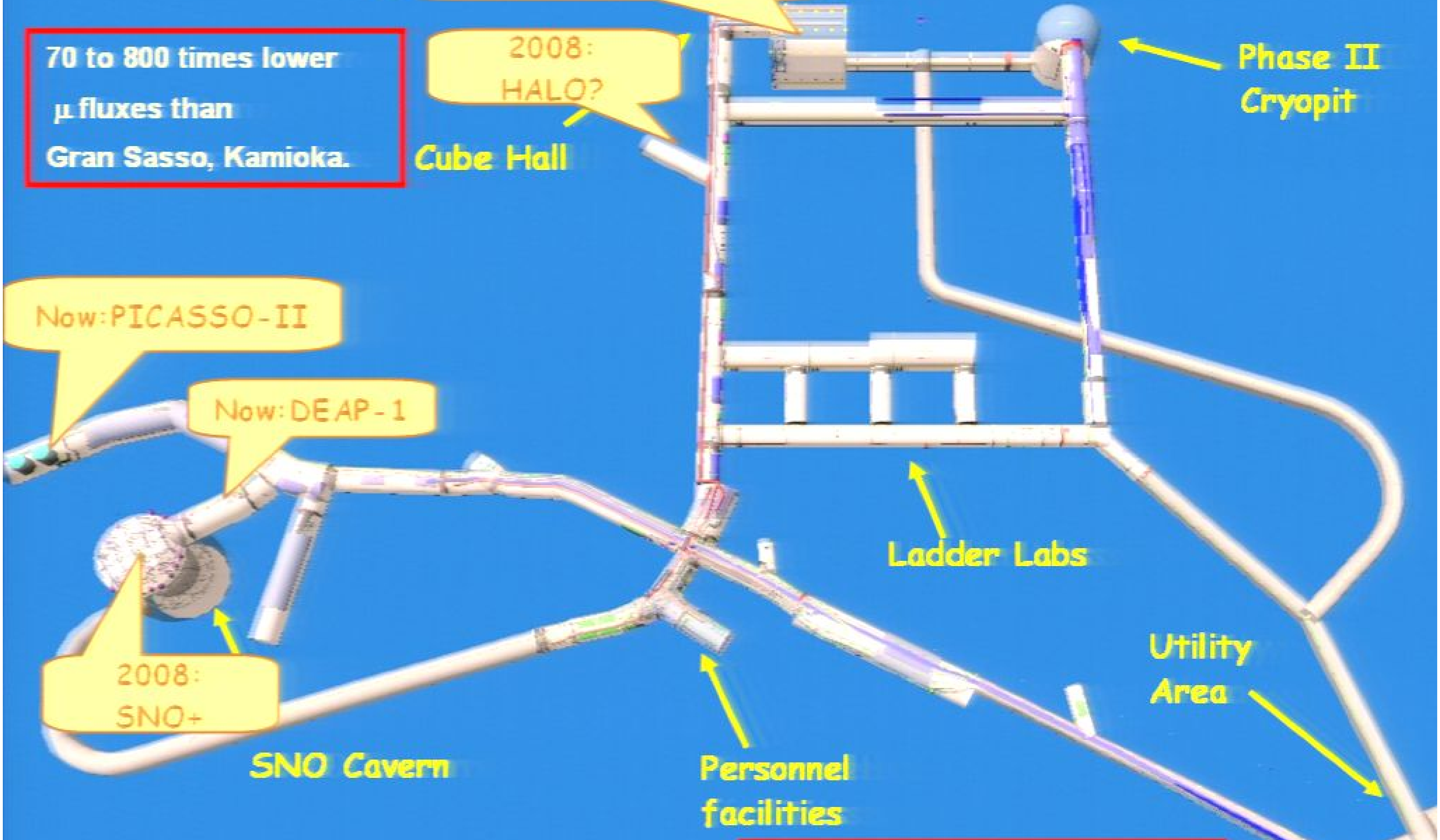
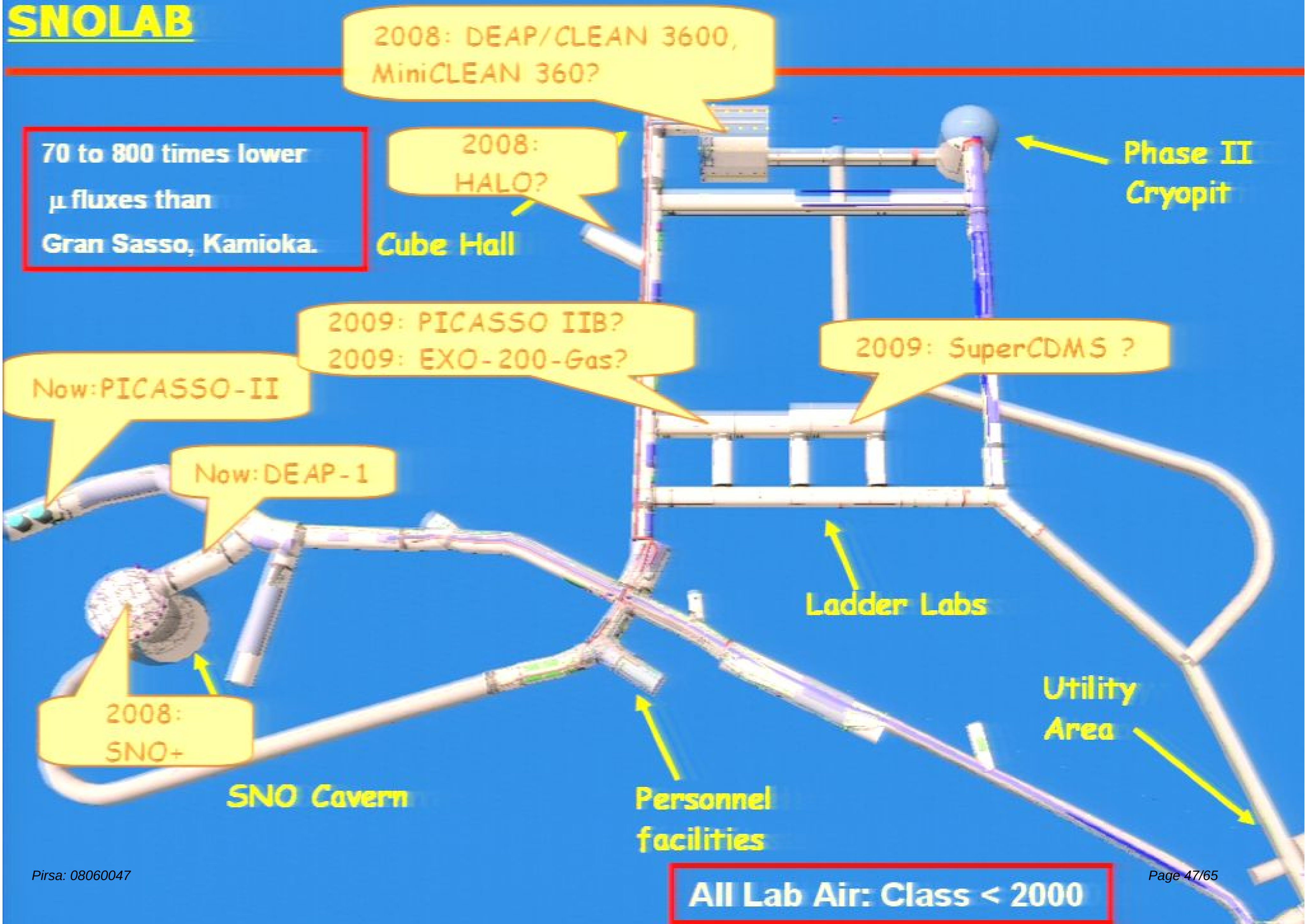
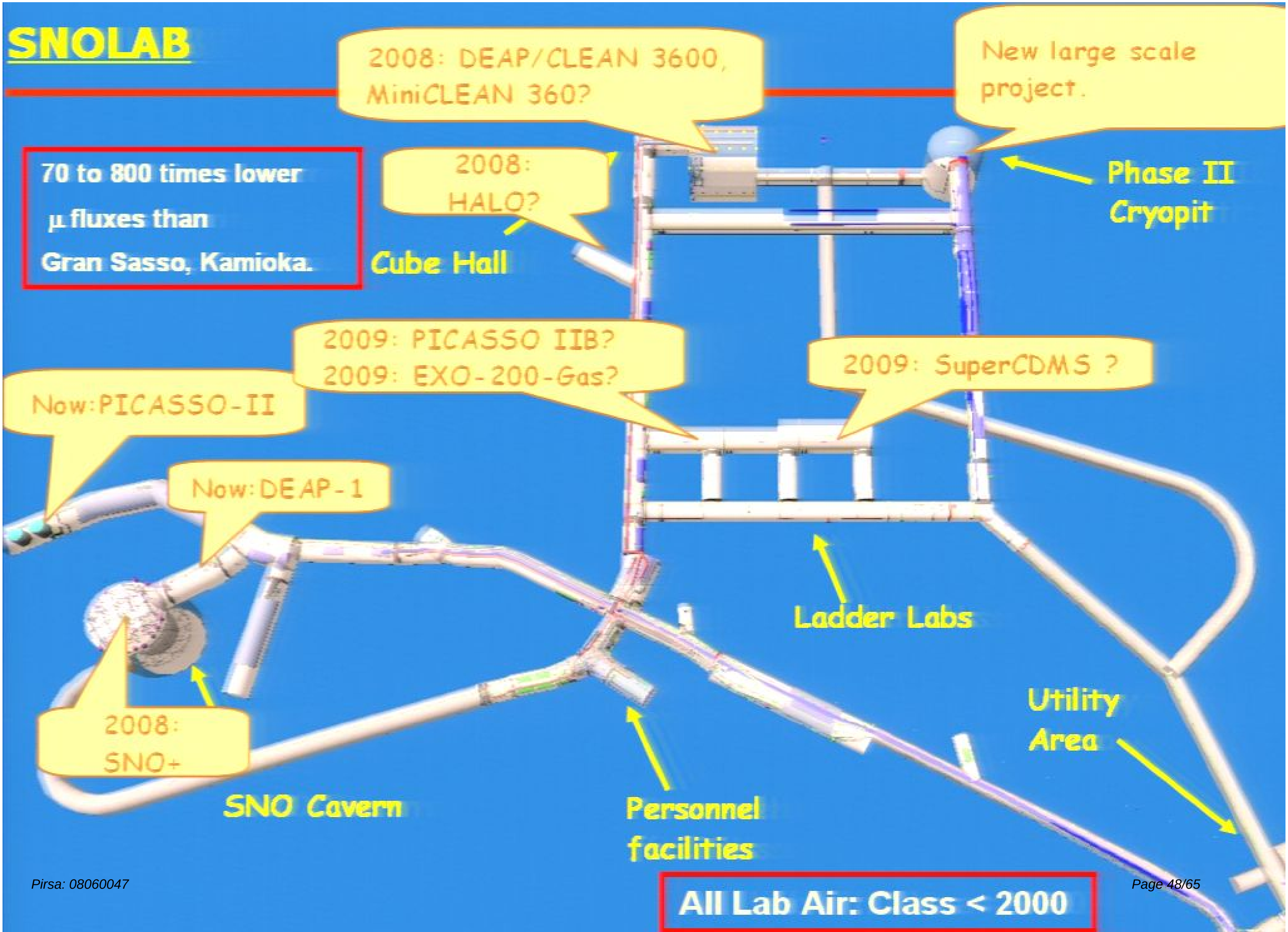


All Lab Air: Class < 2000

SNOLAB


2008: DEAP/CLEAN 3600,
MiniCLEAN 360?
70 to 800 times lower
μ fluxes than
Gran Sasso, Kamioka.
2008:
HALO?
Cube Hall
Phase II
Cryopit
2009: PICASSO IIB?
2009: EXO-200-Gas?
2009: SuperCDMS ?
Now:PICASSO-II
Now:DEAP-1
Ladder Labs
2008:
SNO+
SNO Cavern
Personnel
facilities
Utility
Area
All Lab Air: Class < 2000

SNOLAB



70 to 800 times lower
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2008: DEAP/CLEAN 3600,
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New large scale
project.
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HALO?
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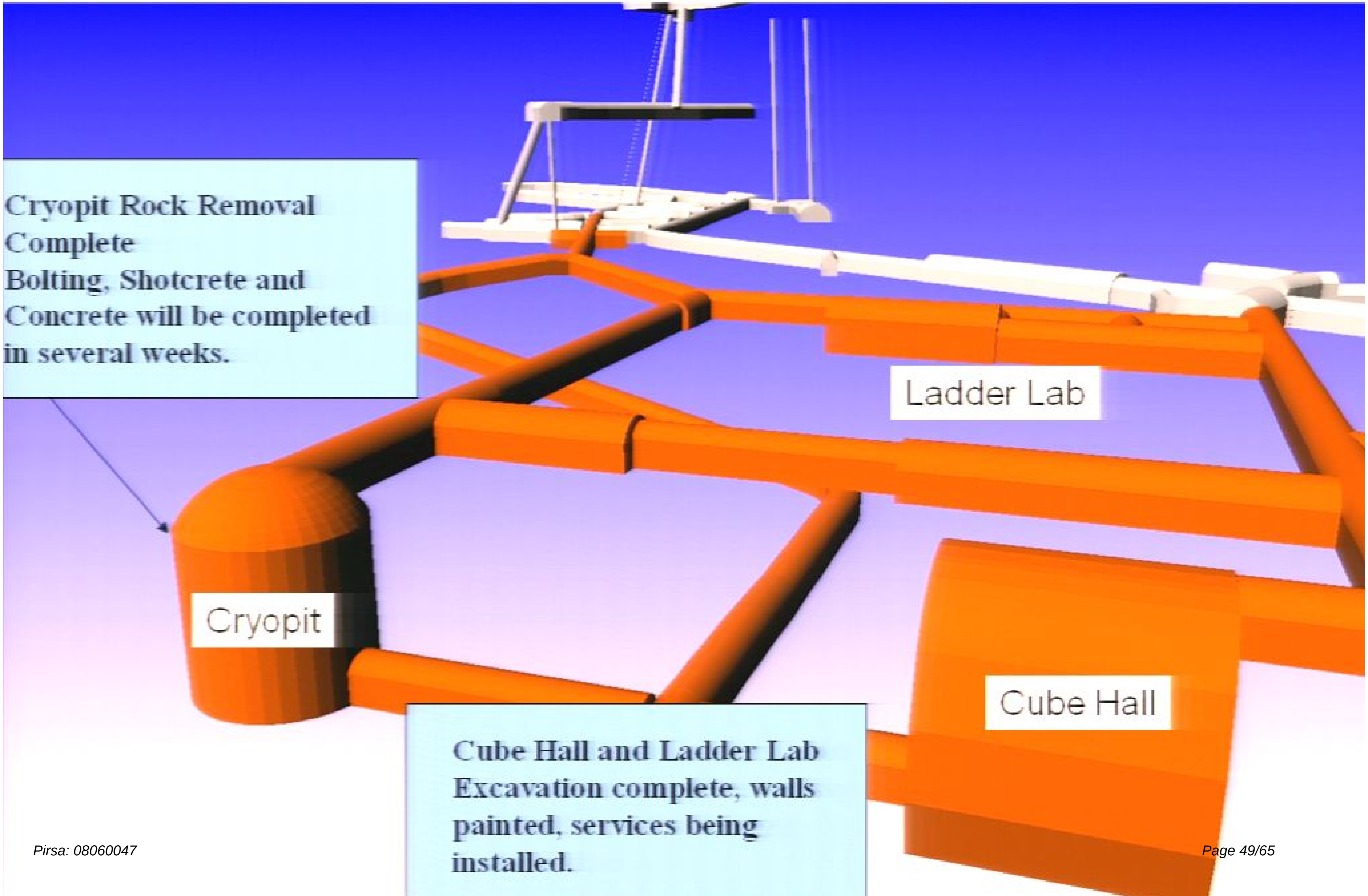
SNO+
SNO Cavern
Ladder Labs
Utility
Area
Personnel
facilities
All Lab Air: Class < 2000

Excavation Status

Cryopit Rock Removal Complete
Bolting, Shotcrete and Concrete will be completed in several weeks.



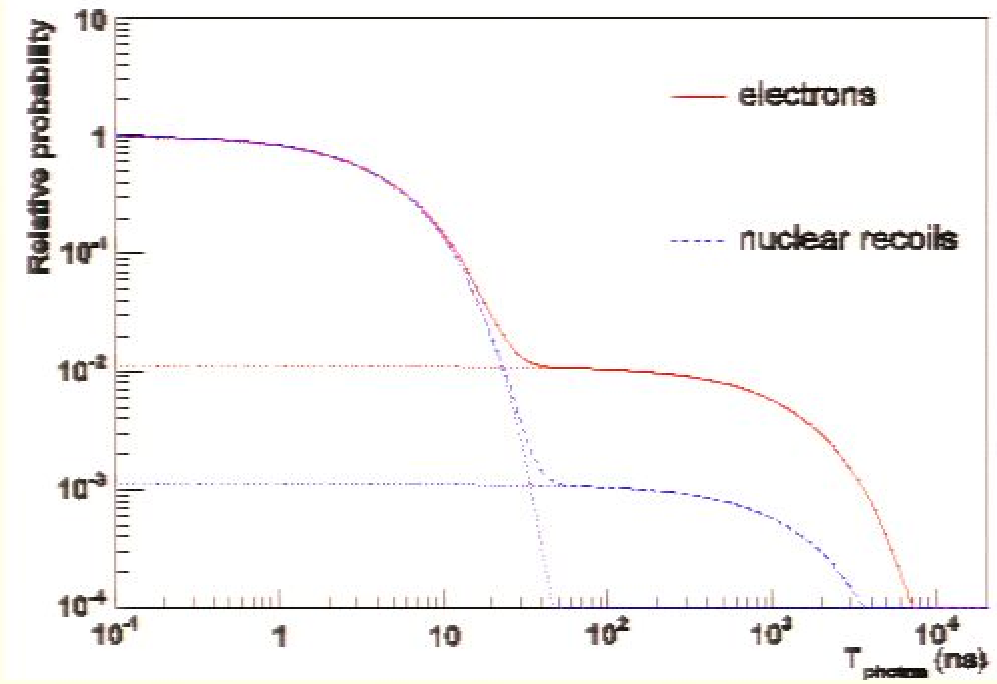
Cube Hall and Ladder Lab Excavation complete, walls painted, services being installed.

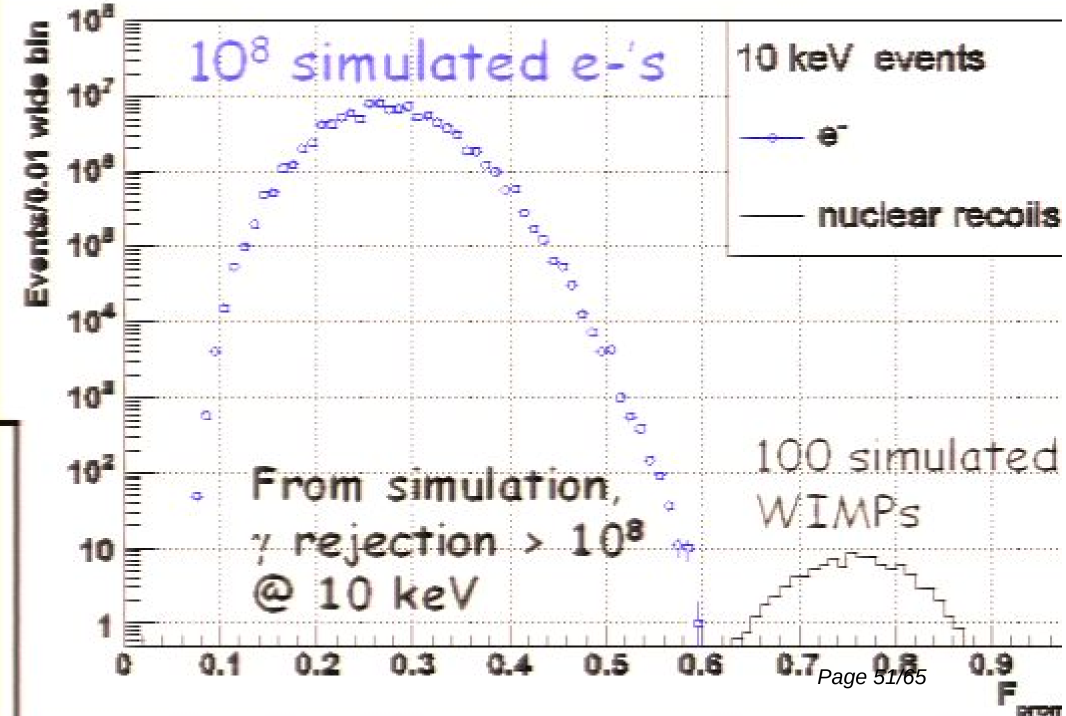

Cube Hall

DEAP/CLEAN: 1 Tonne Fiducial Liquid Argon Dark Matter (WIMP) detector

- Scintillation time spectrum for Ar enables nuclear recoils from WIMP collisions to be separated from betas and gammas from ^{39}Ar background using only scintillation light.

- DEAP and CLEAN collaborations have come together to build new detectors with a simple and easily scaled technology at SNOLAB.



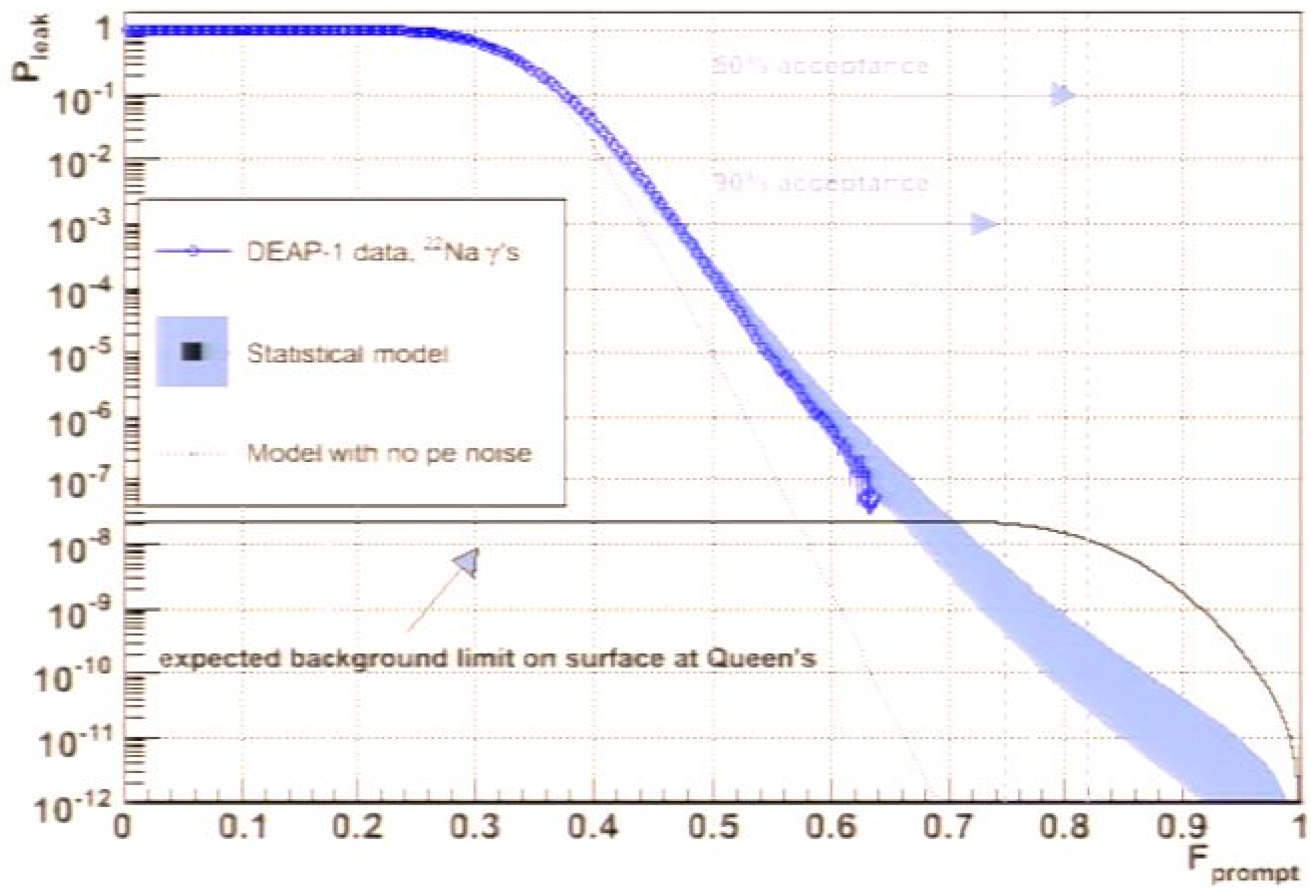


Queen's, Alberta, Carleton, Laurentian, SNOLAB, TRIUMF, LANL, Yale, Boston, South Dakota, New Mexico, North Carolina, Texas, NIST Boulder, MIT

M.G. Boulay & A. Hime astro-ph/0411358

DEAP-1 (7 kg Ar) discrimination tests using 511 keV gammas

Ran DEAP-1 on surface to background limit (6 x 10^{-8} PSD) , moved to SNOLAB
Now running underground for Pulse Shape Discrimination studies and DM sear

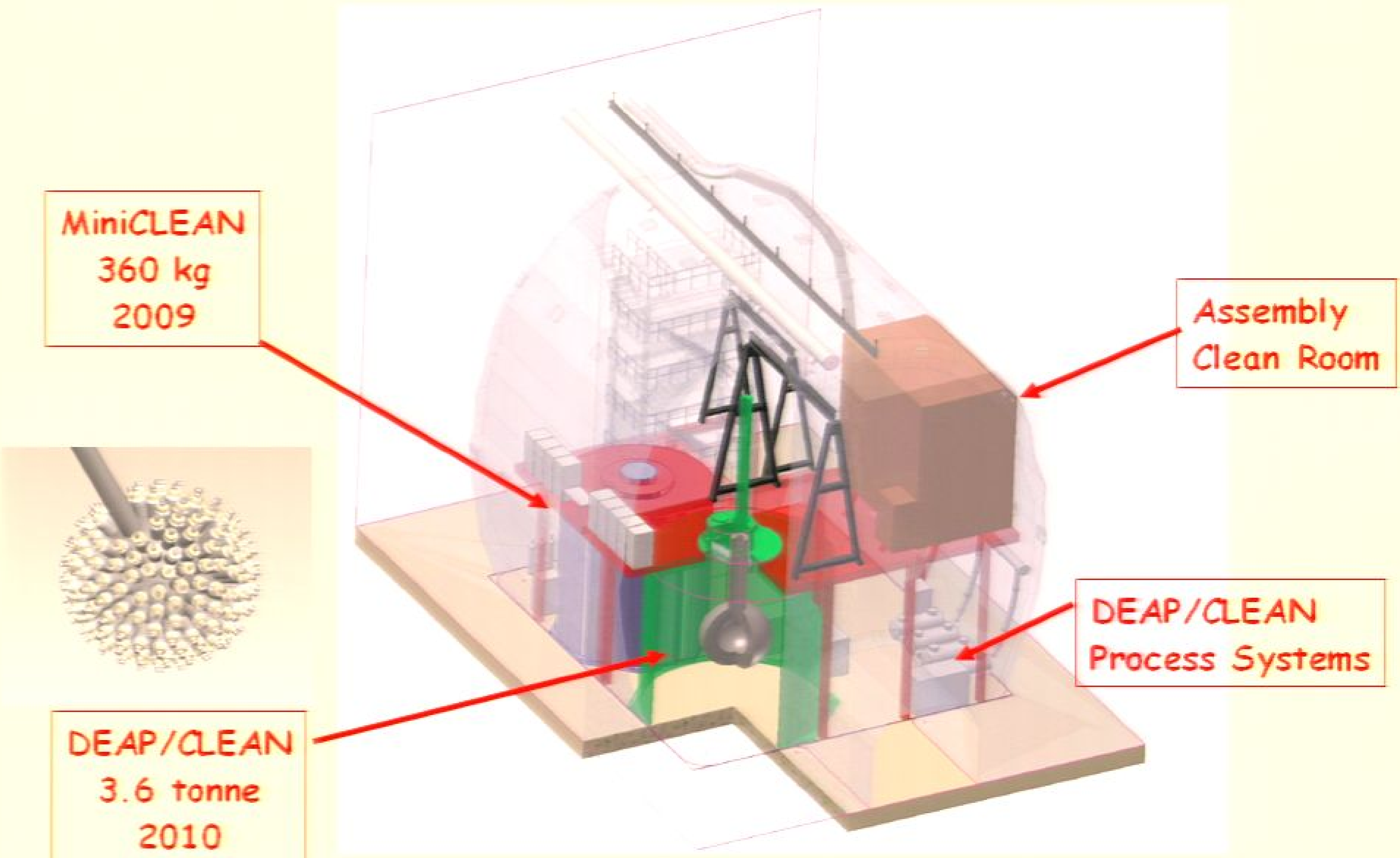


PSD agrees with statistical model over seven orders of magnitude.

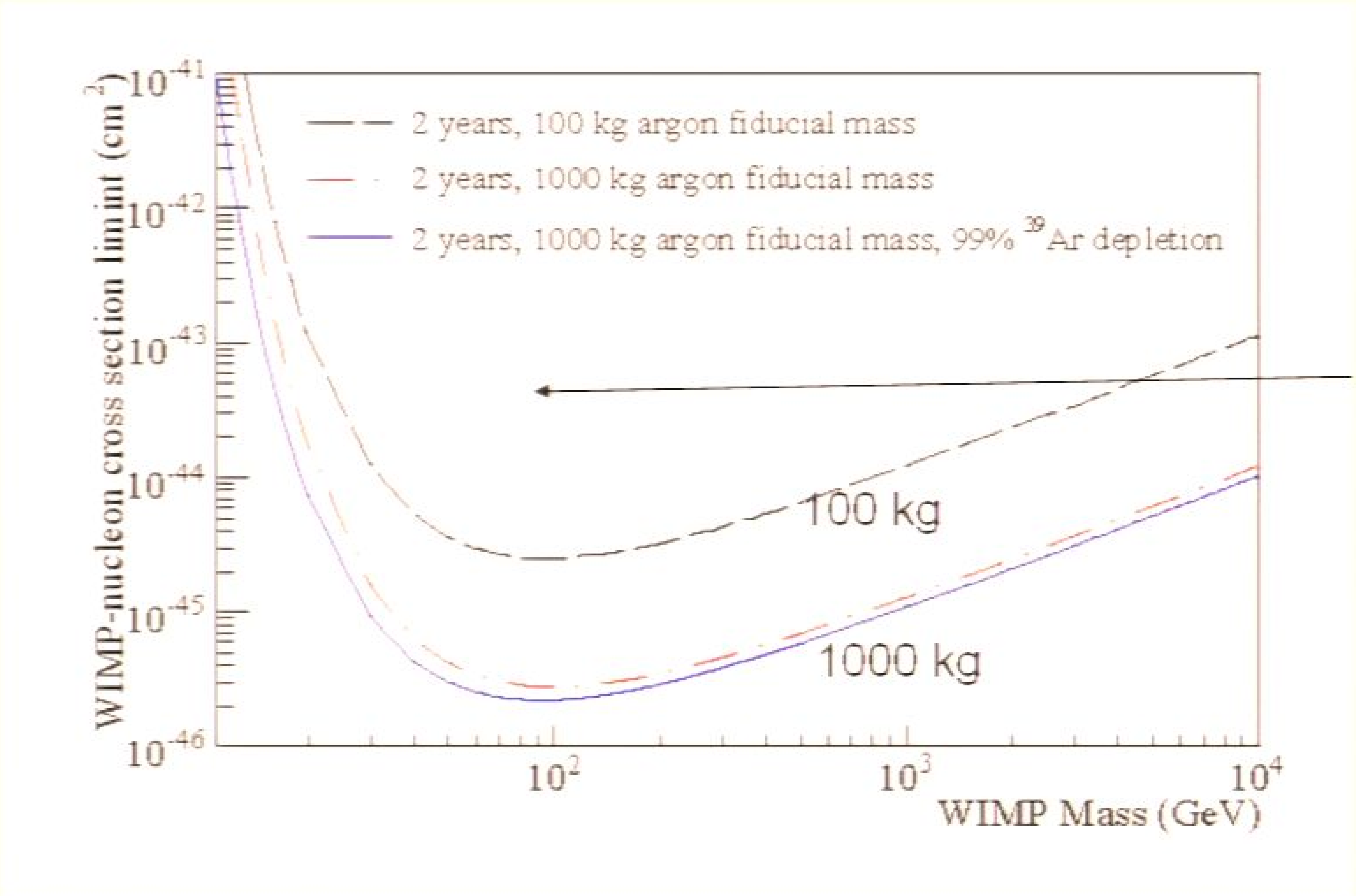
Projection:
Light alone is sufficient for 10^9 background reduction neede for 1 tonne DM experiment with natural Ar.

PSD already OK for 1 tonne fiducial Ar if depleted x 20 in ^{39}Ar. (See Galbiati et a

Cube Hall


MiniCLEAN
360 kg
2009
Assembly
Clean Room
DEAP/CLEAN
Process Systems
DEAP/CLEAN
3.6 tonne
2010

WIMP Sensitivity with liquid argon



Present Experimental Limits
~ 5 x 10^{-44}
CDMS, XENO

(However, als
DAMA periodi
signal
at ~ 10^{-42})

Schedule: Mini-CLEAN (360 kg): 100 kg Fiducial: 2009,

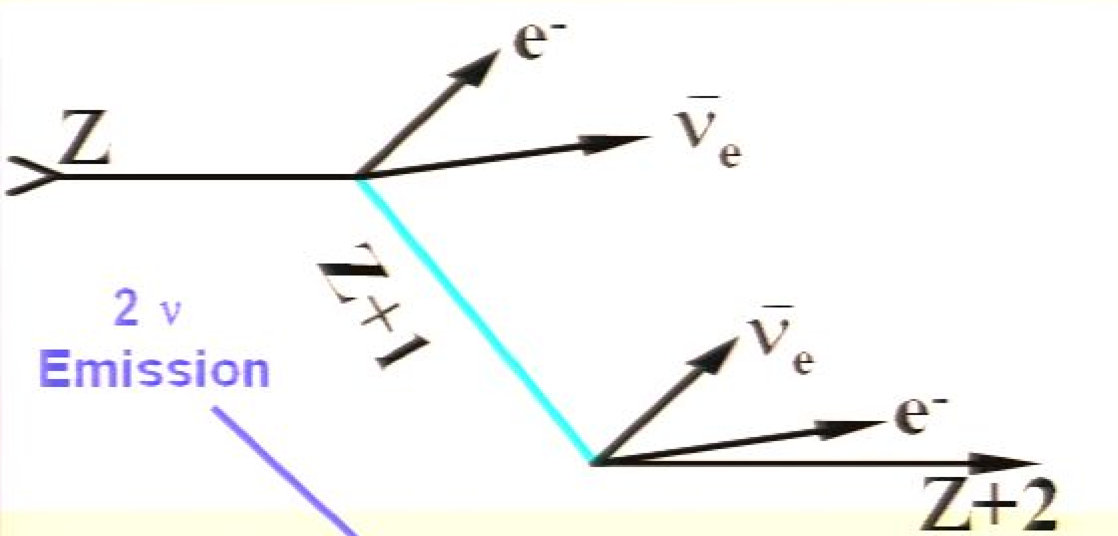
DEAP/CLEAN (3600 kg): 1000 kg Fiducial: starting 2010

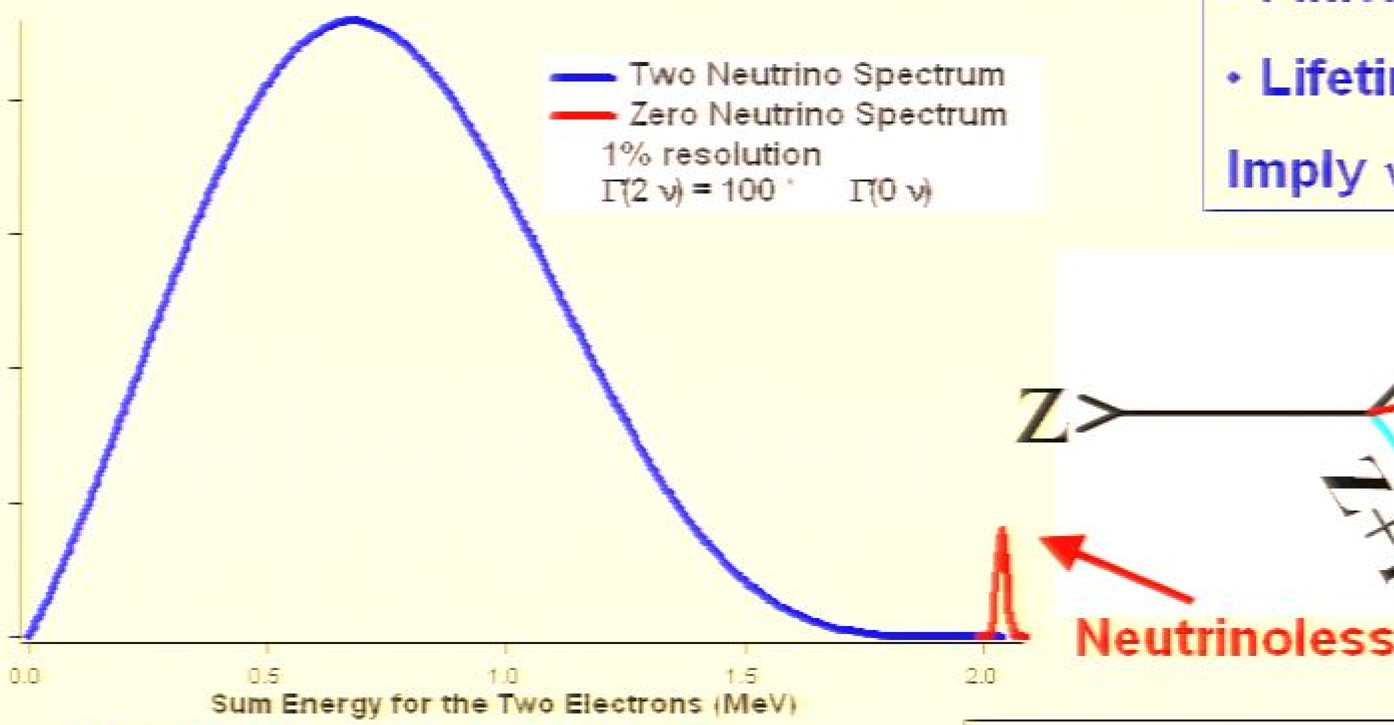
Neutrinoless Double β Decay

Requires:

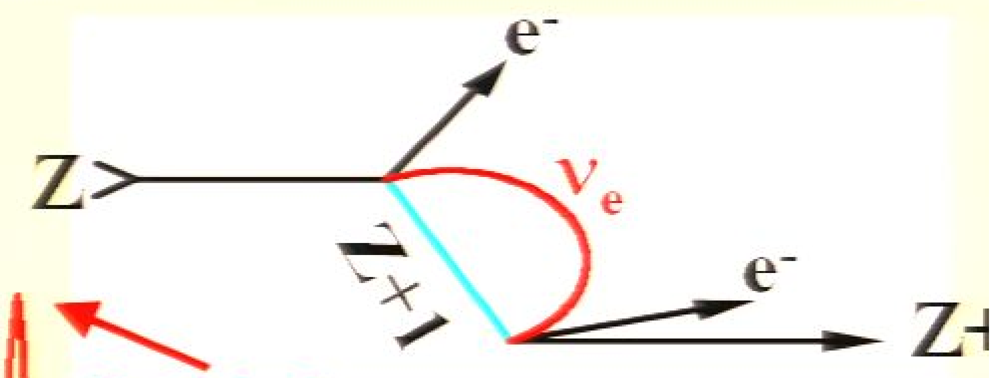
- Neutrino = Anti-neutrino (Majorana particles)
- Finite ν mass
- Lifetimes > ~10^{26} years

Imply ν mass < 0.1 eV





Summed Electron Energy



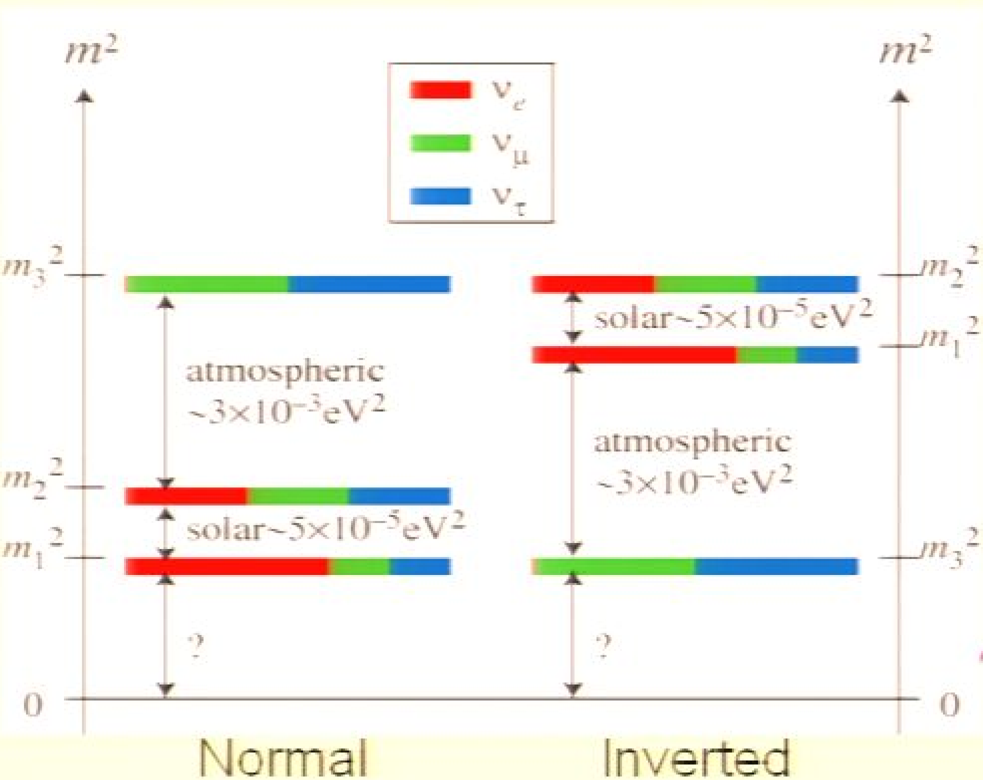
$$T_{1/2} = F(Q_{\beta\beta}, Z)\ |M^{0\nu}|^2 \langle m_{\nu\beta\beta} \rangle^2$$

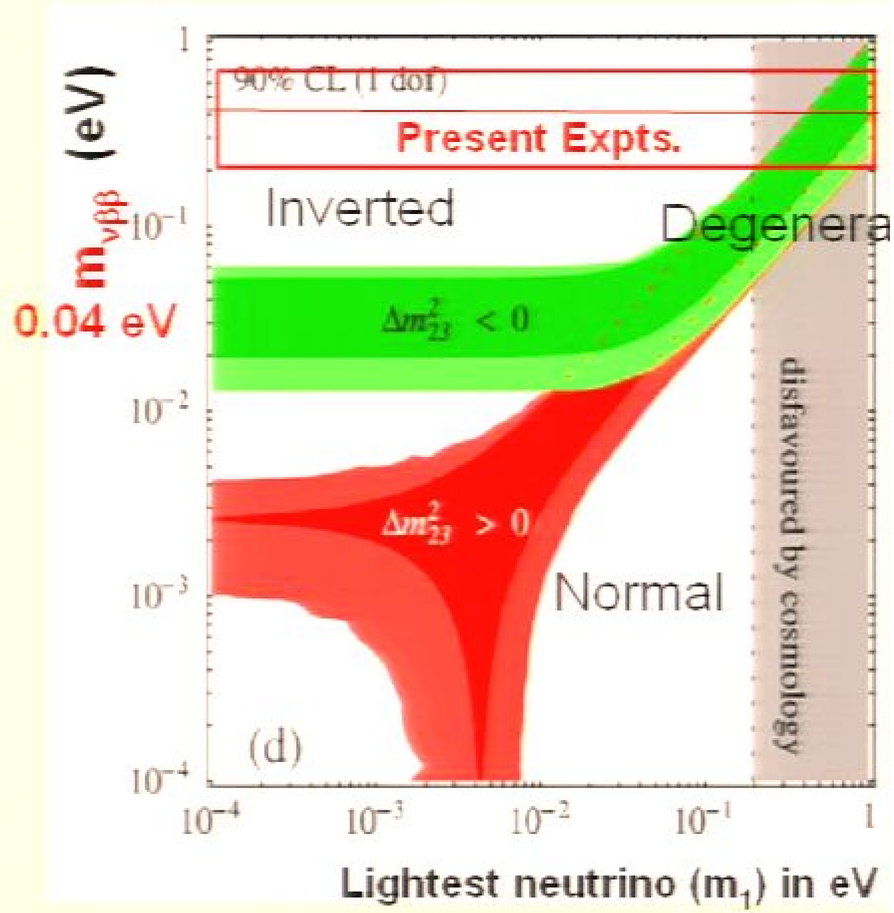
Measuring Effective ν Mass

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

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

Mass Hierarchies





Want sensitivity <~ 0.04 eV

large mass/low background

INTERESTING FOR LEPTOGENES

SNO+: Neutrino-less Double Beta Decay: ^{150}Nd

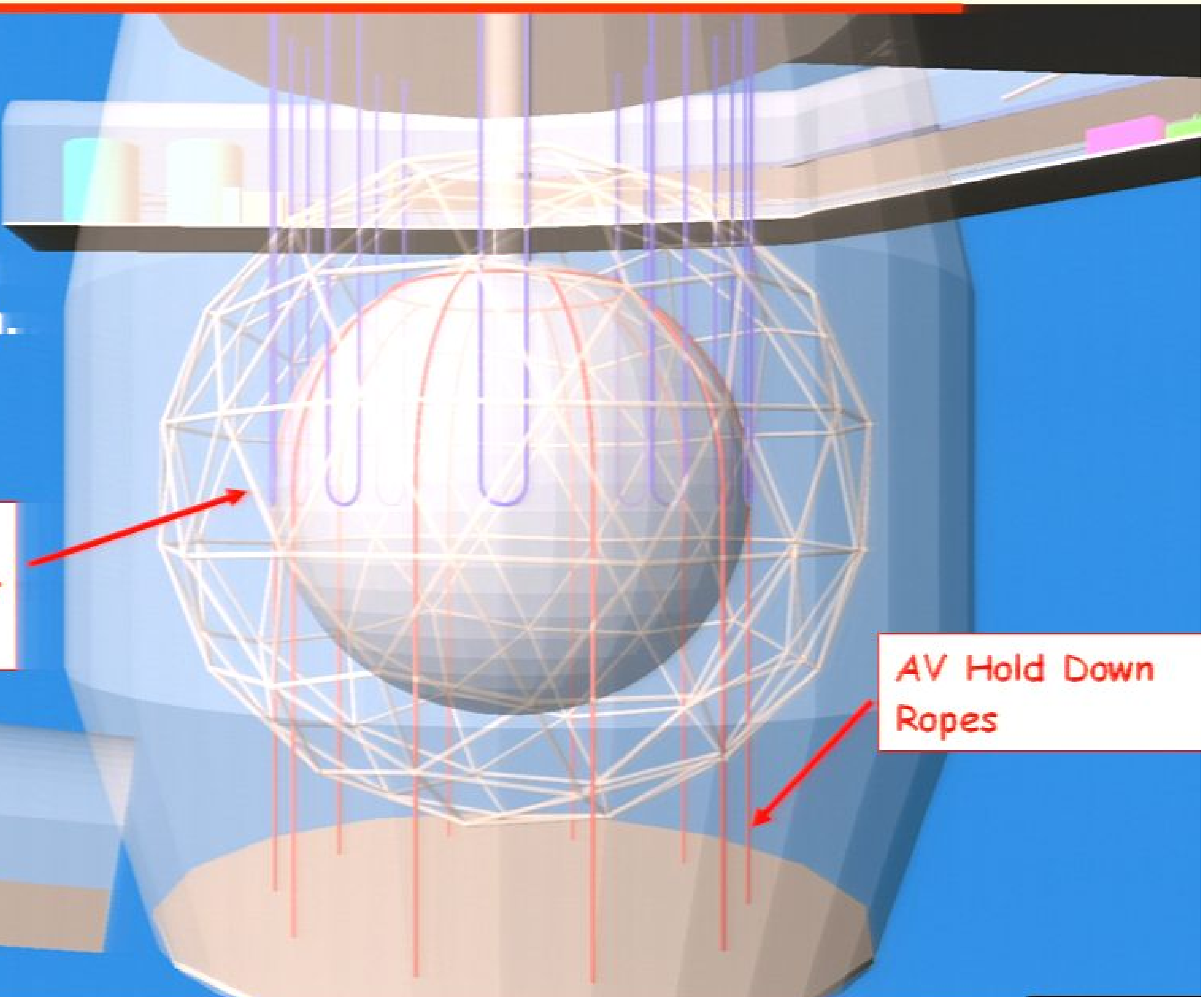
- Nd is one of the most favorable double beta decay candidates with large phase space due to high endpoint: 3.37 MeV.
- Ideal scintillator (Linear Alkyl Benzene) has been identified. More light output than Kamland, Borexino, no effect on acrylic.
- Nd metallic-organic compound has been demonstrated to have long attenuation lengths, stable for more than a year.
- 1 tonne of Nd will cause very little degradation of light output.
- Isotopic abundance 5.6% (in SNO+ 1 tonne Nd = 56 kg ^{150}Nd)
- Collaboration to enrich ^{150}Nd using French laser isotope facility Possibility of hundreds of kg of isotope production.
- SNO+ Capital proposal to be submitted Oct. 2008.
- Plan to start with natural Nd in 2010.
- Other physics: CNO solar neutrinos, pep solar neutrinos to study neutrino properties, geo-neutrinos, supernova search.

(No ^{11}C background at this depth.)

Queen's, Alberta, Laurentian, SNOLAB, BNL, Washington, Penn, Texas, LIP Lisbon, Idaho State, Idaho Nat Lab, Oxford, Sussex, TU Dresden

Main Engineering Changes for SNO+ : Scint. Purification, AV Hold Dowr

The organic liquid is lighter than water so the Acrylic Vessel must be held down.

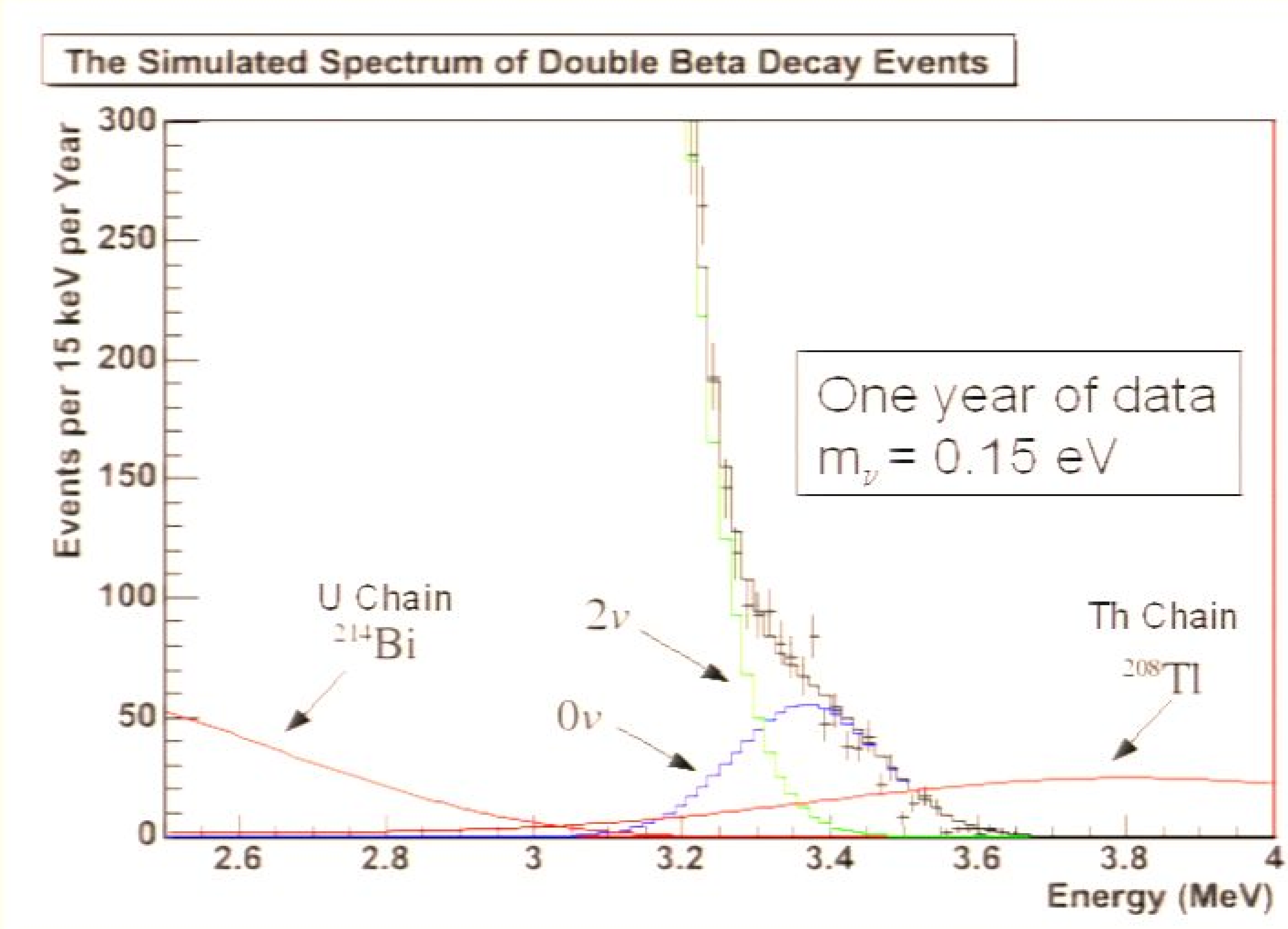


Otherwise, the existing detector, electronics etc. are unchanged.

SNO+ (^{150}Nd ν - less Double Beta Decay)

0ν: 1057 events per year with 500 kg ^{150}Nd-loaded liquid scintillator in SNO+.

Simulation assuming light output and background similar to Kamland.



Sensitivity Limits (3 yrs): Natural Nd (56 kg isotope): $m_{\nu\beta\beta}$ ~ 0.1 eV

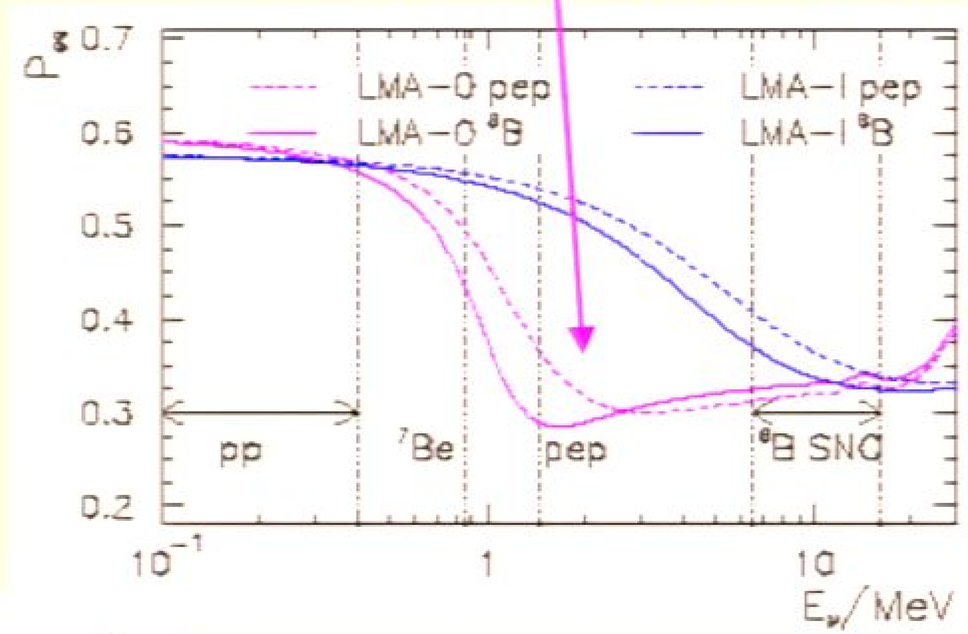
500 kg enriched ^{150}Nd: $m_{\nu\beta\beta}$ ~ 0.04 eV

New Physics

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

NC non-standard Lagrangian

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



- non-standard interactions
- mass-varying neutrinos

Barger, Huber, Marfatia, hep-ph/0502196

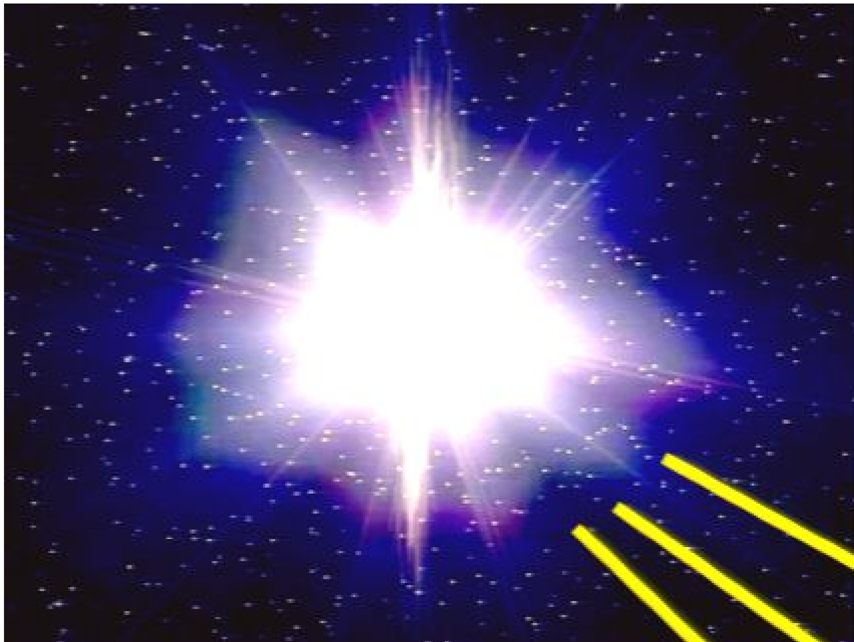
MSW

~ =

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

Sterile Neutrinos: de Holanda a
Smirnov hep-ph/0307266

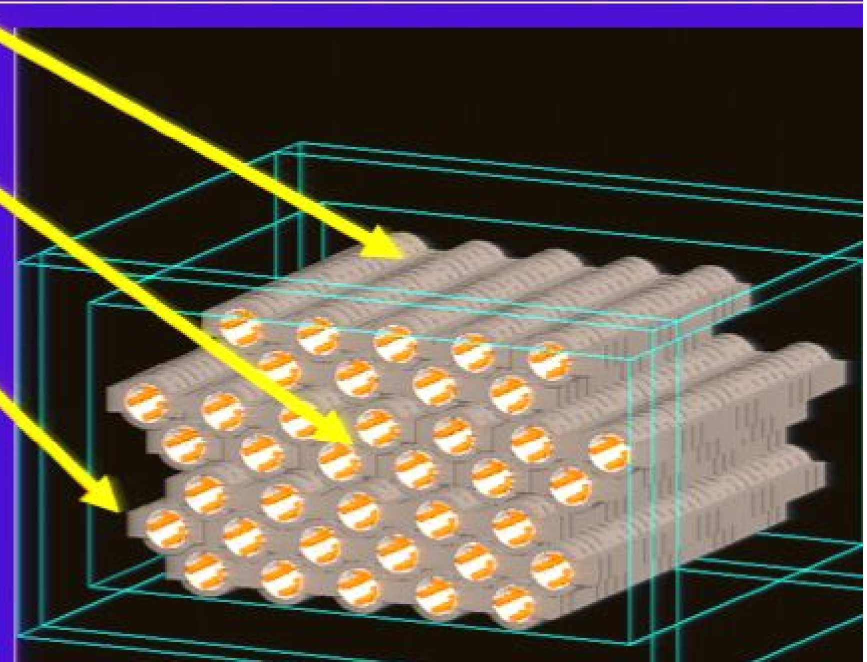
pep, ^{7}Be solar neutrinos are at an excellent energy to test for new physics



H elium
A nd
L ead
O bservatory

Pb: Most sensitivity to electron neutrin
~ 50 events for SN at center of Galaxy.

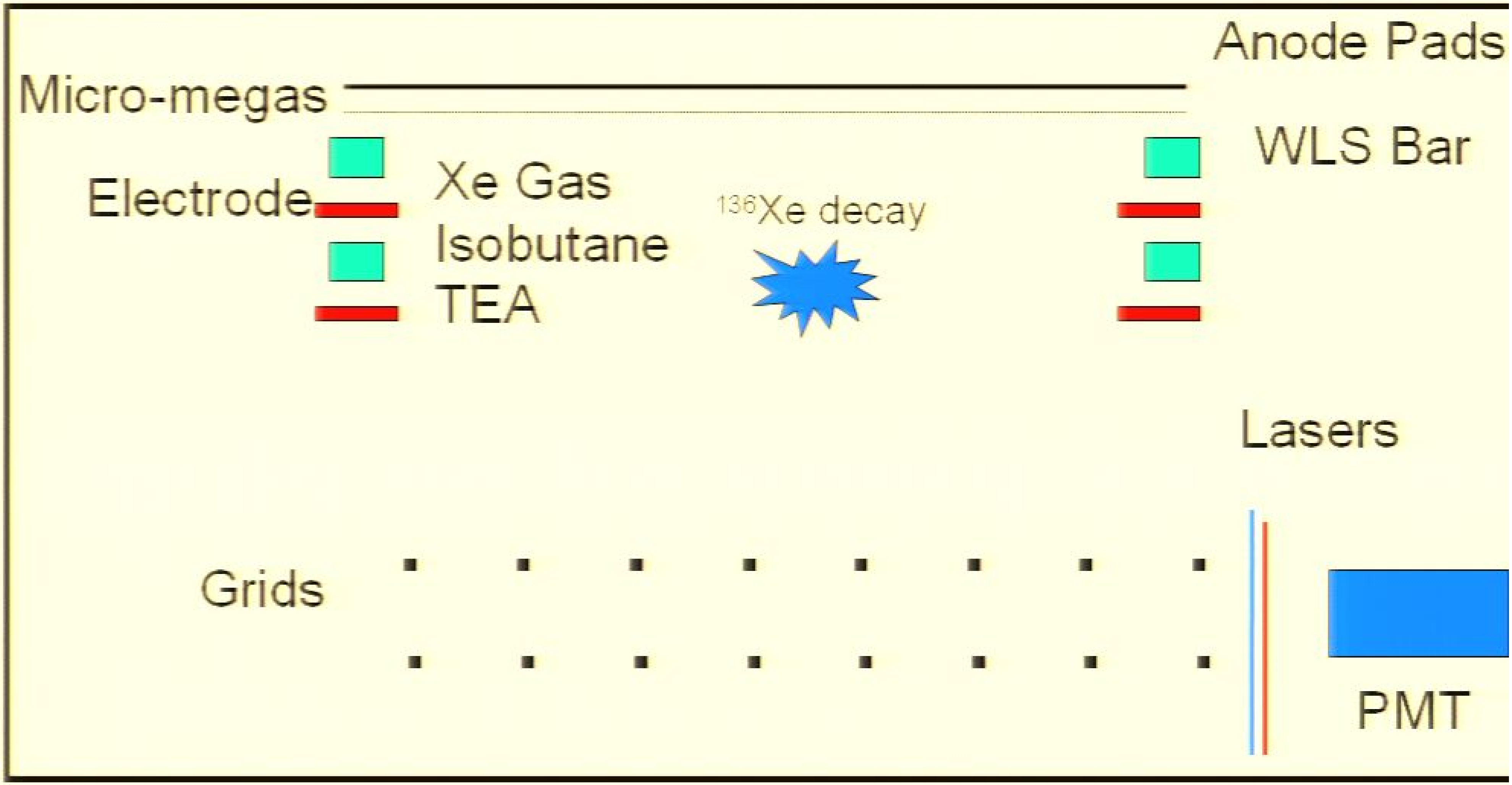
A lead detector for supernova neutrinos in SNOLAB



Laurentian, TRIUMF, SNOLAB, LANL, Washington, Duke, Minnesota, Digipen IT

HALO-1: 80 tons of existing Pb

R&D in Canada: EXO-gas double beta counte

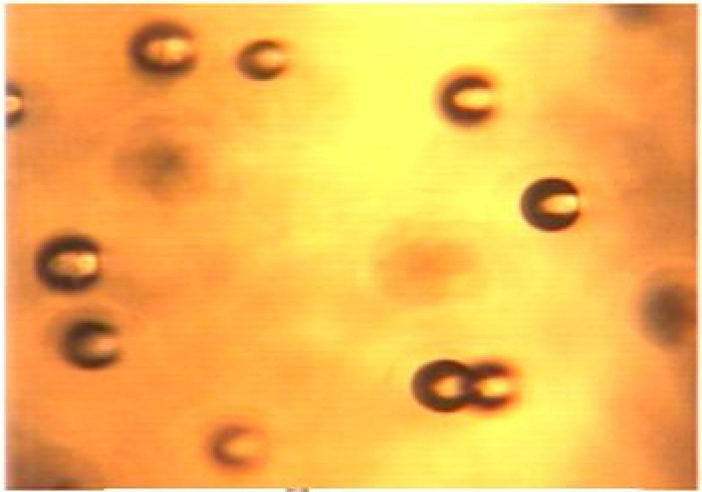


For 200 kg, 10 bar, box is 1.5 m on a side

EXO-gas Canada: Carleton, Laurentian

WIMP-Nucleus Spin-Dependent Interaction

The Superheated Droplet Detector

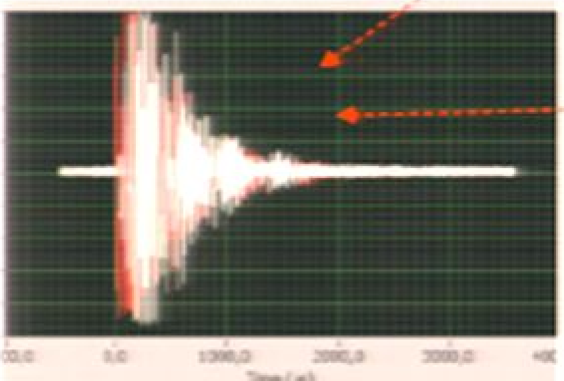


- droplets superheated at ambient T & P
- 50 to 100μm droplets of carbofluorides dispersed in polymerised gel
- active liquids:
  C_4F_{10} (T_b=-1.7 °C) , C_3F_8 (T_b=-36.7 °C)
- …used for n-dosimetry (BTI-Chalk River)
- Recoil energy threshold E_{rec} = O(keV)
- insensitive to β, γ and cosmic μ radiation

Fluorine is very sensitive for the spin-dependent interaction

Montreal, Queen's

Indiana, Pisa, BTI



Acoustic Signal

Up to 2.6 kg being run in 2007-08

SUMMARY

Scientific:

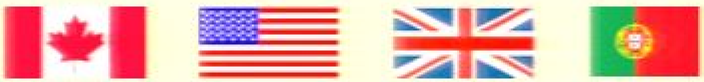
• SNO is complete, further papers to come over next year.

• SNOLAB excavation is complete, final room outfitting being completed.

• Several experiments are running in existing clean space.

• A number of other experiments have been approved for siting in the near future for neutrinos, double beta decay, Dark Matter.

The SNO Collaboration



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