Title: Studying the universe from 2 km underground: SNO and the new SNOLAB

Date: Mar 30, 2005 02:00 PM

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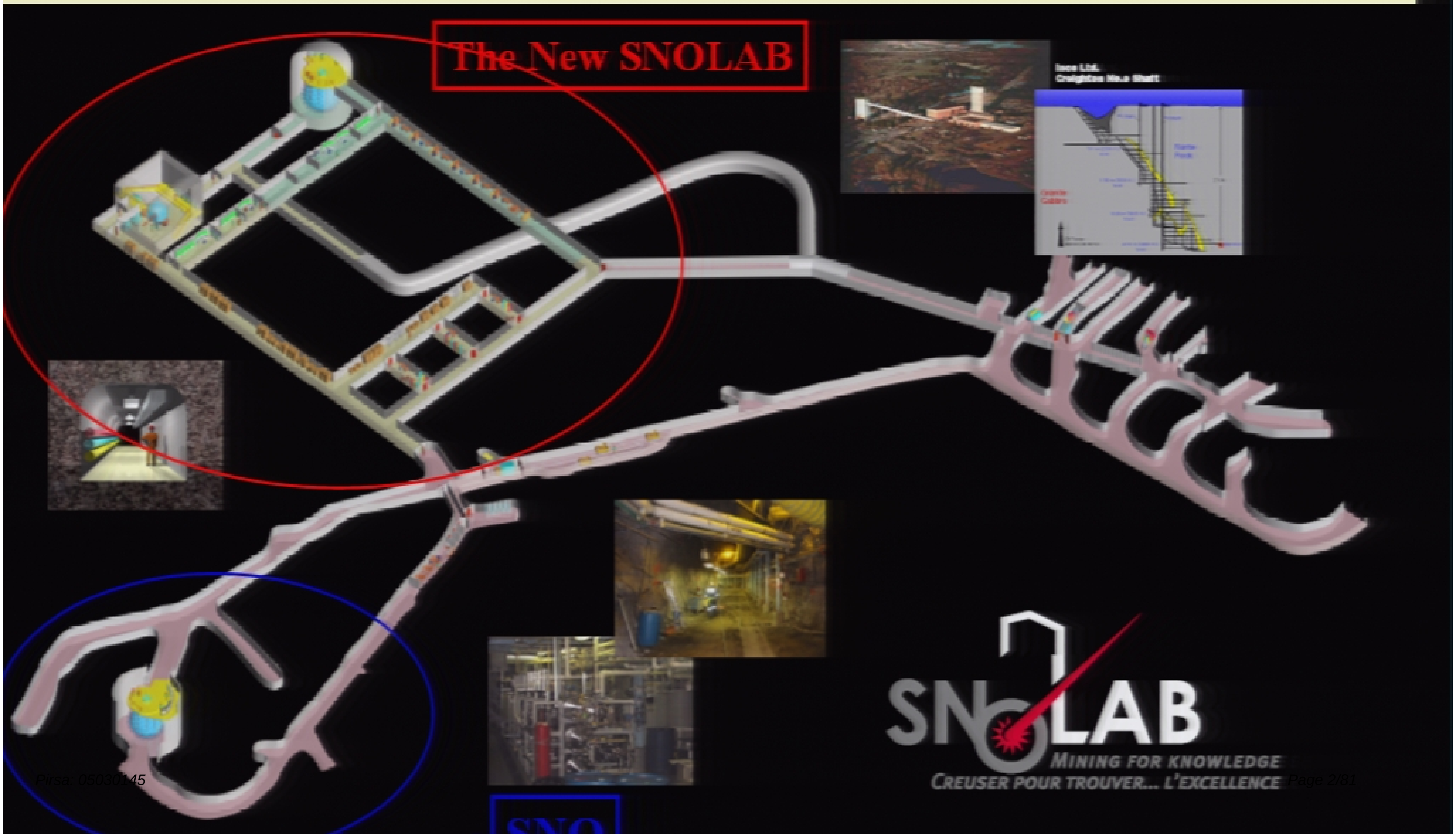
Abstract: By creating a location that is essentially free from radioactive background, sensitive measurements can be performed to test fundamental laws of physics with neutrinos from the Sun, Dark Matter particles left over from the Big Bang and rare forms of radioactivity. The Sudbury Neutrino Observatory (SNO) is a neutrino detector containing 1,000 tonnes of heavy water and situated 2,000 meters underground in INCO's Creighton Mine near Sudbury, Ontario. SNO has observed neutrinos from the core of Sun and has found clear evidence for neutrino flavor change. This requires modification of the Standard Model for elementary particles and confirms solar model calculations with great accuracy. The underground facility is now being expanded to create a long-term international facility for underground science (SNOLAB), where measurements of Dark Matter, Double Beta Decay and Solar Neutrinos will be performed with the lowest radioactive background available anywhere. The results for SNO and the future scientific program for SNO and SNOLAB will be described.

With the Sudbury Neutrino Observatory (SNO) and the new SNOLAB we have great new scientific opportunities in Neutrino Physics, Dark Matter detection, Double Beta Decay at the lowest background underground site in the world



Outline of Talk

- Neutrino Physics - Status
- Latest Results from SNO
- Future Objectives for SNO
- Prospects with the New SNOLAB
  - Many Letters of intent
  - Examples
    - Solar Neutrinos, Supernova Neutrinos
      - SNO +
    - Double Beta Decay
      - Majorana (Ge)
      - SNO ++ (Nd)
    - Dark Matter
      - Picasso (Fluorine)
      - DEAP (Argon)

Neutrino properties

What have we learned?

1) Evidence for neutrino flavor change:

- Atmospheric: Super-K
- Solar: SNO (Solar model independent test, supported by other measurements).
- Reactor: KamLAND observes neutrino disappearance with solar parameters.
- LSND?: To be addressed soon by MiniBoone
- Neutrino parameter limits set by many experiments: Reactor, Accelerator

2) Neutrino Mass:

- Mass differences from oscillations
- Mass Limit < 2.2 eV from tritium beta decay
- Double Beta Decay: Limits so far: Mass limit <~ 0.4 eV if Majorana particles.
- Limits from Astrophysics: CMB, Large Scale structure <~ 1 eV.

3) Number of light neutrinos:

- Z width: 2.981 +- 0.008 active types
- Limits on sterile neutrinos from solar, atmospheric measurements.
- Big Bang Nucleosynthesis: 3 active neutrino types

Neutrino properties

-The most favored explanation for the flavor change data
- to date is <u>Neutrino Oscillations</u>.

-Others are ruled out as dominant, but could be small sub-dominant
- Flavor Changing Neutral Currents,
- Resonant Spin Flavor Precession for solar neutrinos ...
- Violation of Equivalence Principle ......
- Mass Varying Neutrinos...

In the discussion to follow, we will concentrate on the favored basis of Neutrino Oscillations and consider the further information to be obtained on this basis.

Using the oscillation framework:

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

For three neutrinos:

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Maki-Nakagawa-Sakata-Pontecorvo matrix

(Double β decay only)

$$= \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & e^{-i\alpha_3/2+i\delta} \end{pmatrix}$$

Solar,Reactor | **Atmospheric** | **CP Violating Phase** | **Reactor,LBL** | **Majorana Phases**

where $c_{ij} = \cos\theta_{ij}$, *and* $s_{ij} = \sin\theta_{ij}$

Range defined for Δm_{12}, Δm_{23}

For two neutrino oscillation in a vacuum: (valid approximation in many cases)

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2(1.27\frac{\Delta m^2 L}{E})$$

Matter Effects – the MSW effect

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

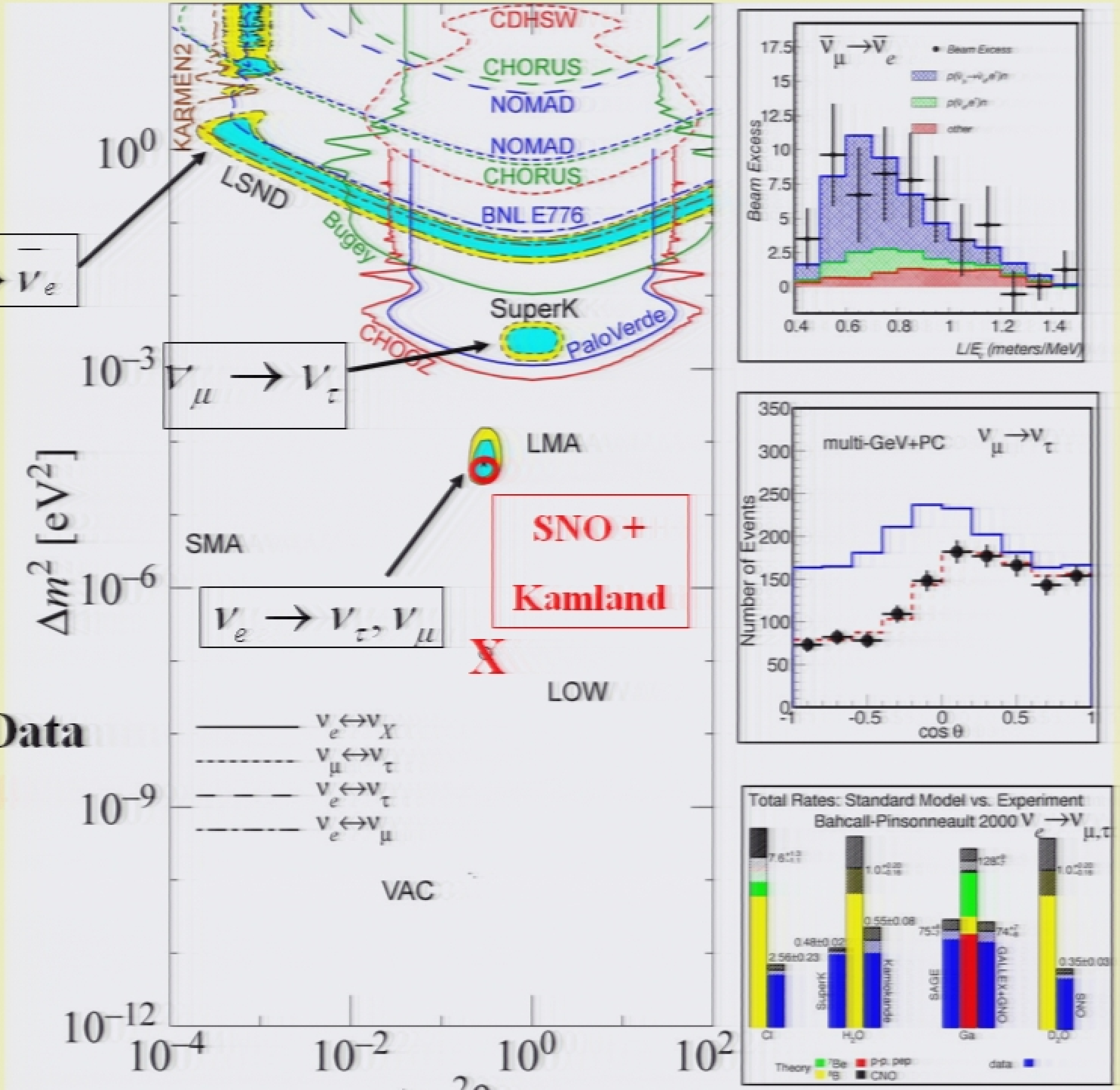
$$\mathrm{H} = \begin{bmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & -\frac{\Delta m^2}{4E}\cos 2\theta \end{bmatrix}$$

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

In the oscillation formula:

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

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



Neutrino Data
2004

LSND

Super-K

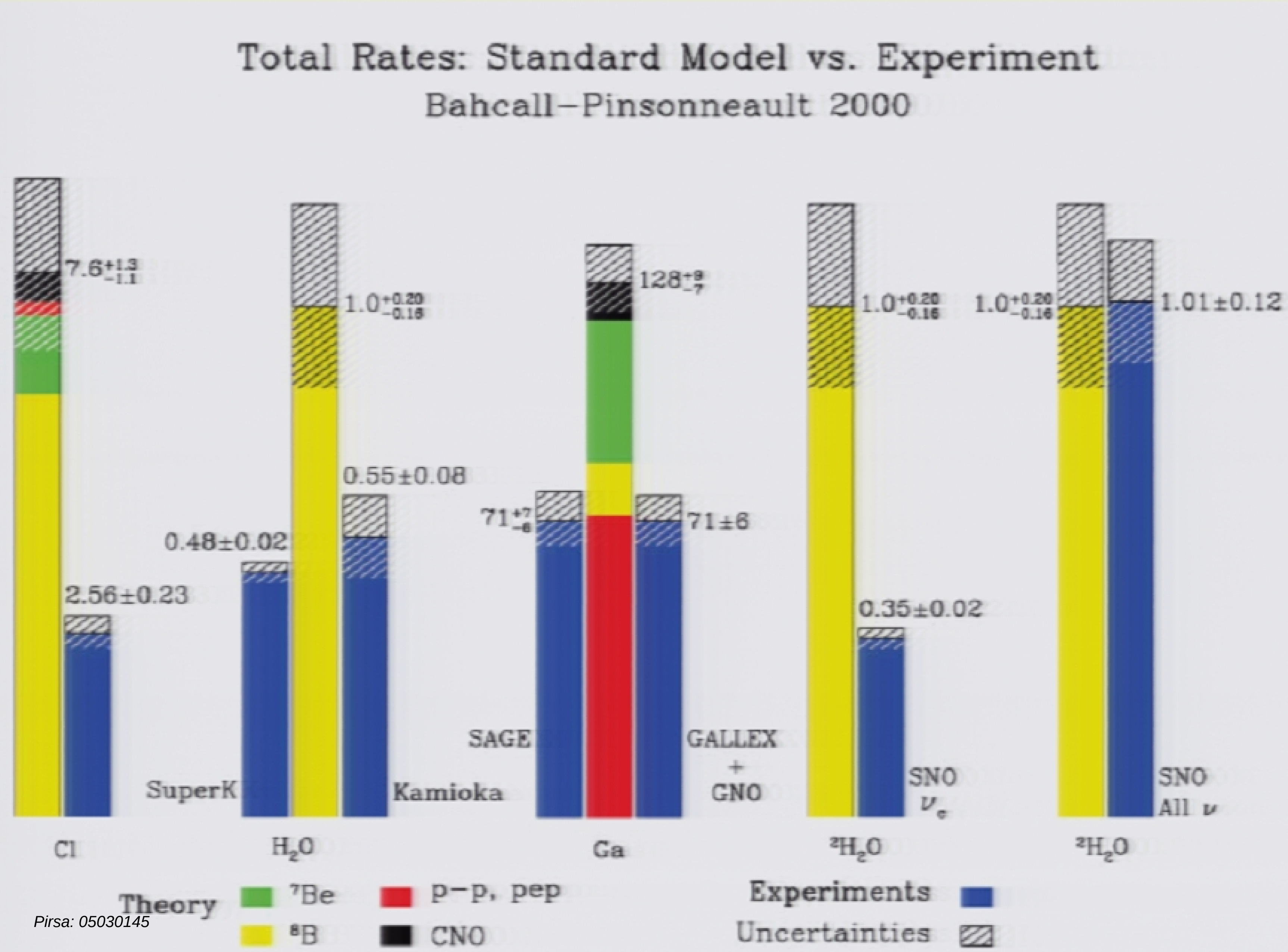
Δm_{23}

Solar

Δm_{12}

What have we learned?

Solar Neutrinos



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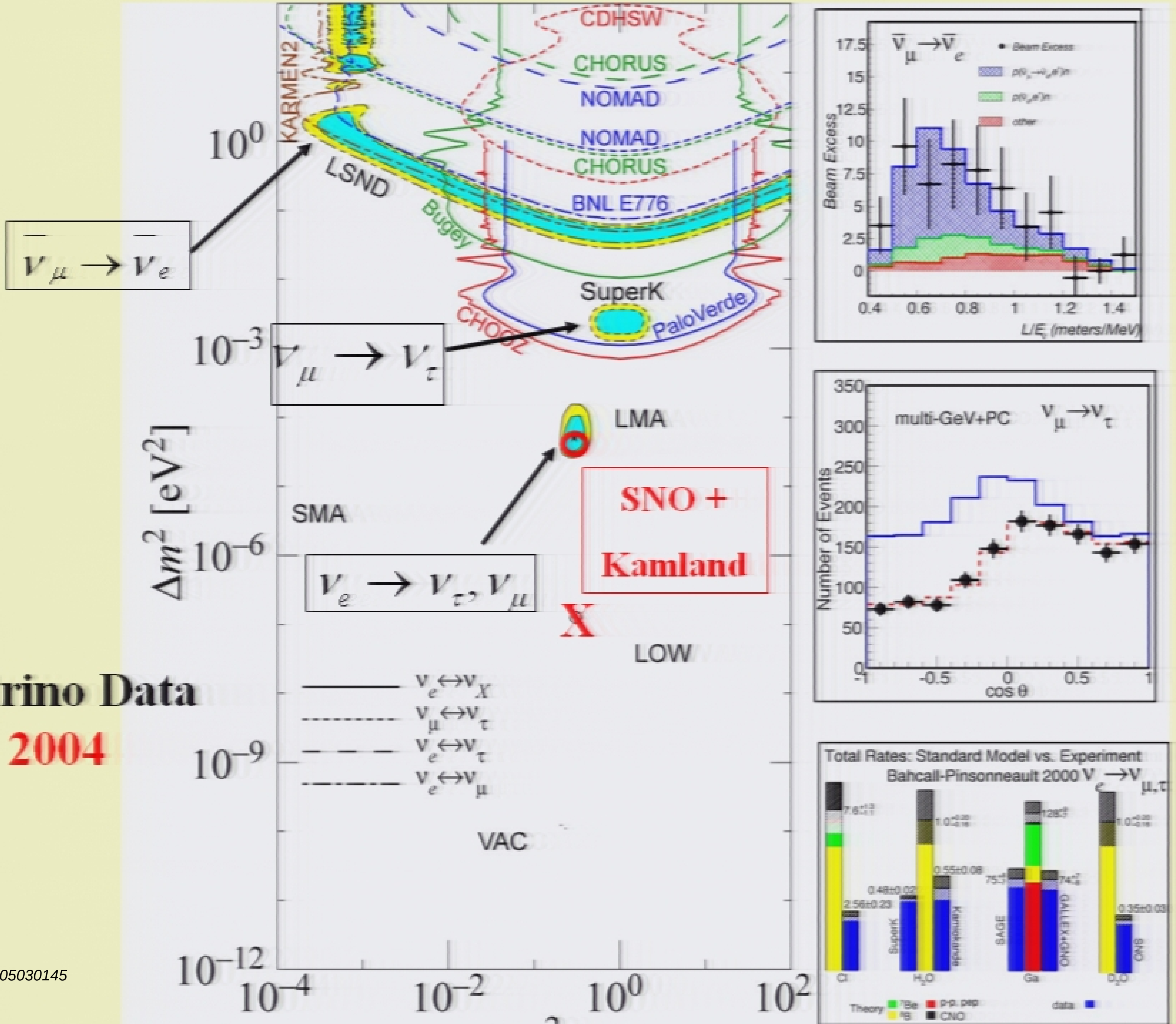

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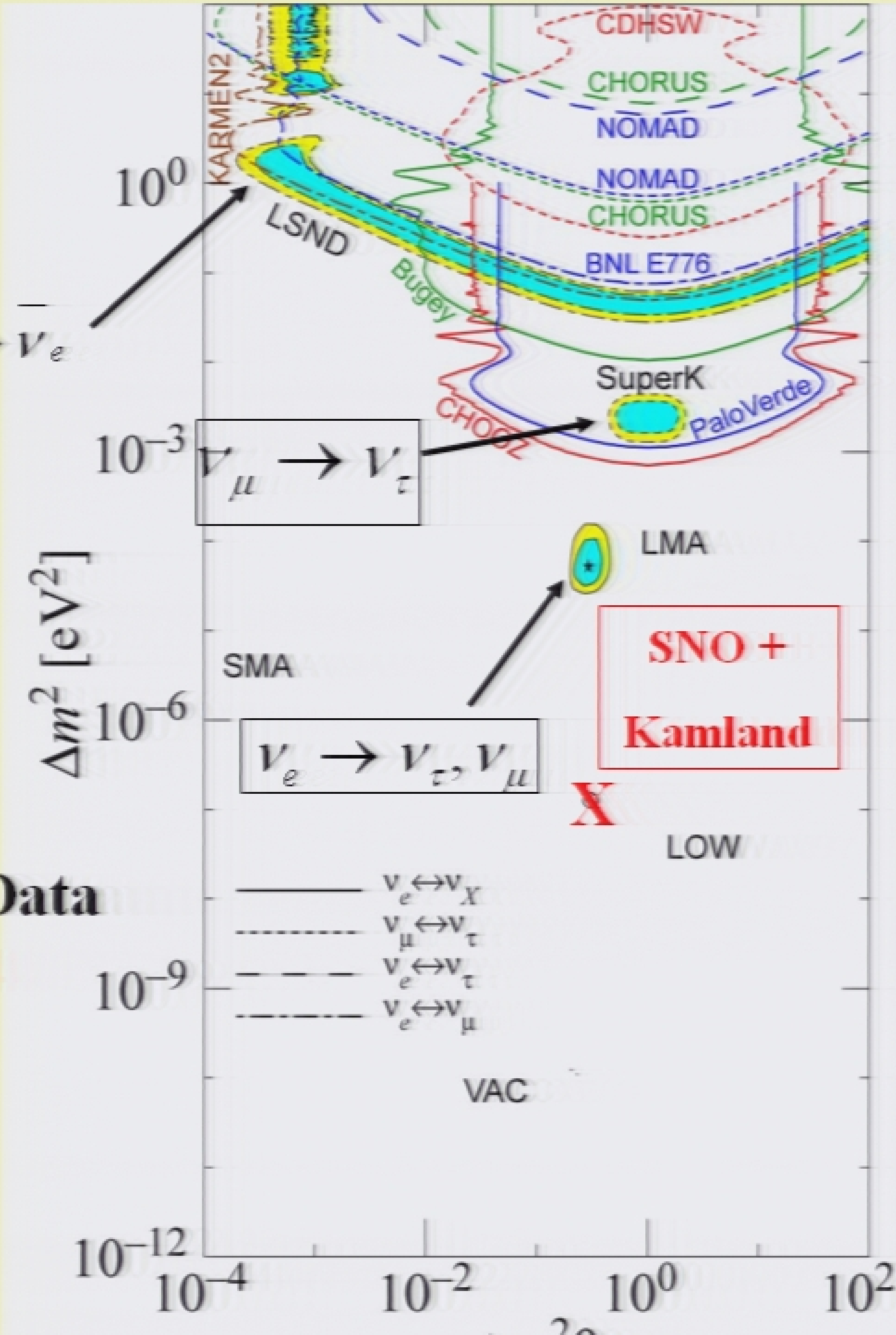

eutrino Data

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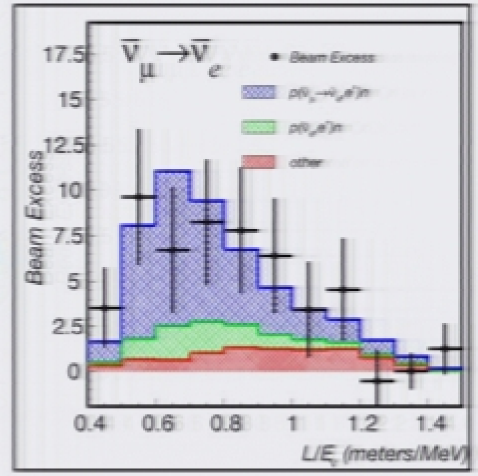
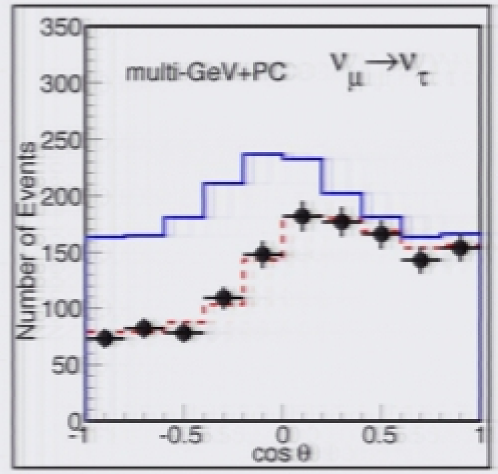


LSND



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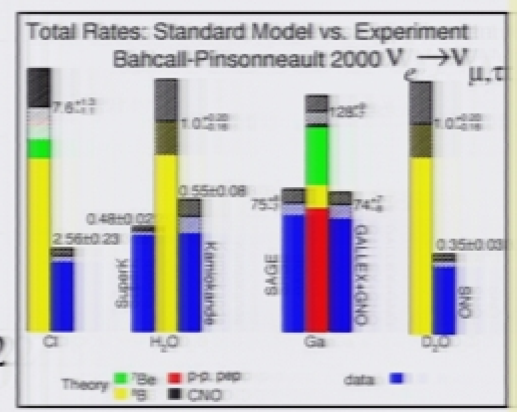
Δm_{23}



Solar

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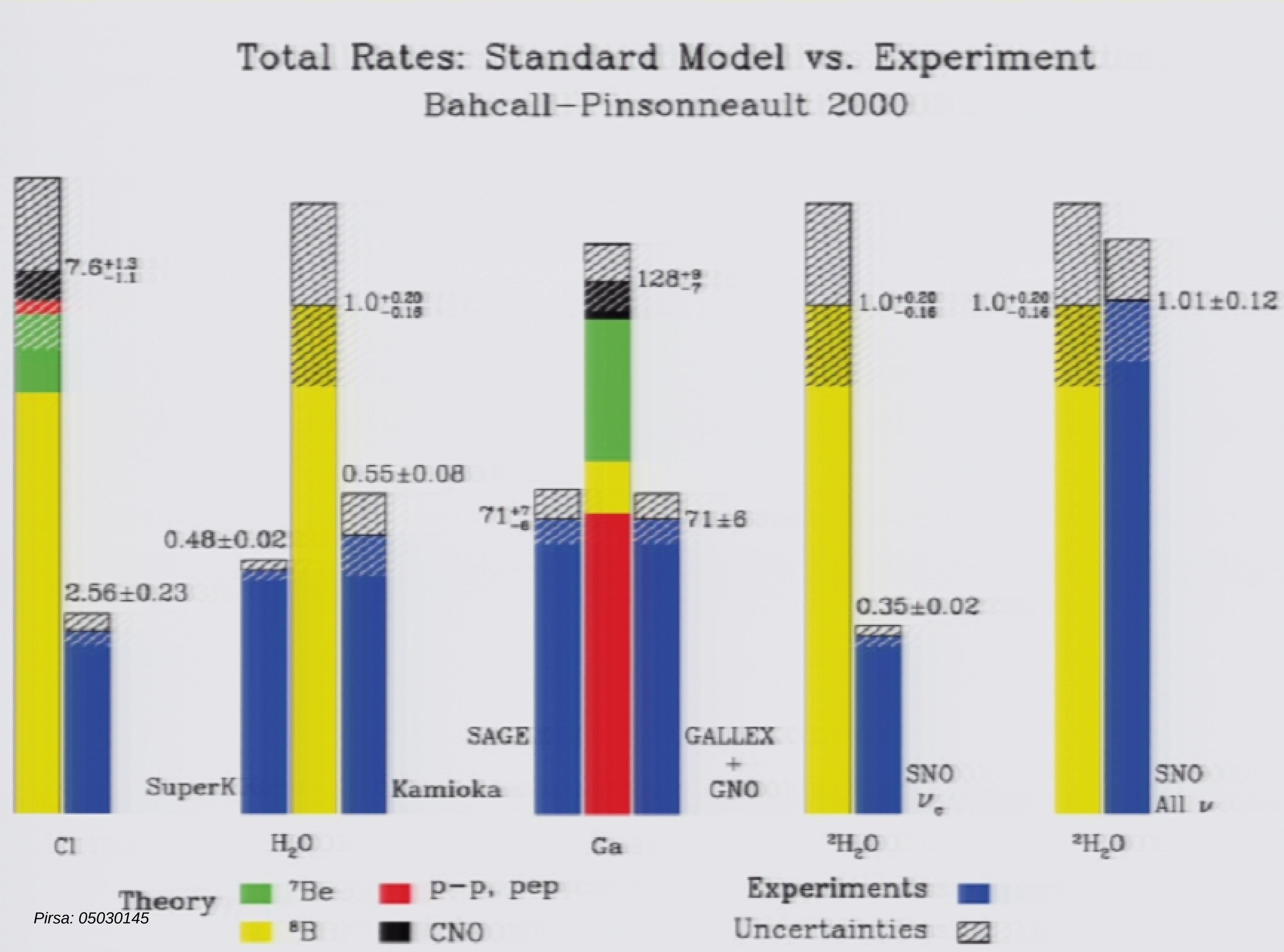
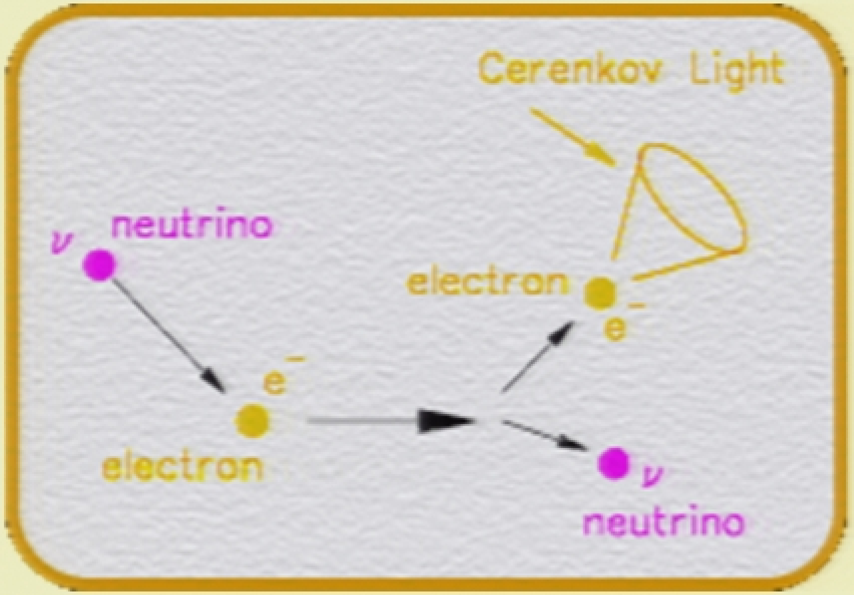


ν Reactions in SNO

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

- Both SK, SNO
- Mainly sensitive to ν_e, less to ν_μ and ν_τ
- Strong directional sensitivity



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

- Good measurement of ν_e energy spectrum
- Weak directional sensitivity $\propto$ 1-1/3cos(θ)
- ν_e only.

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

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

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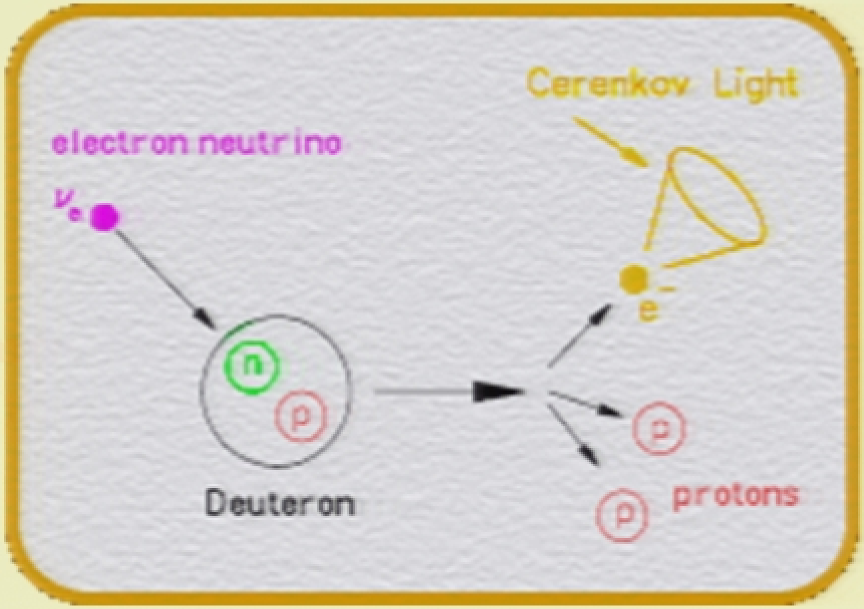

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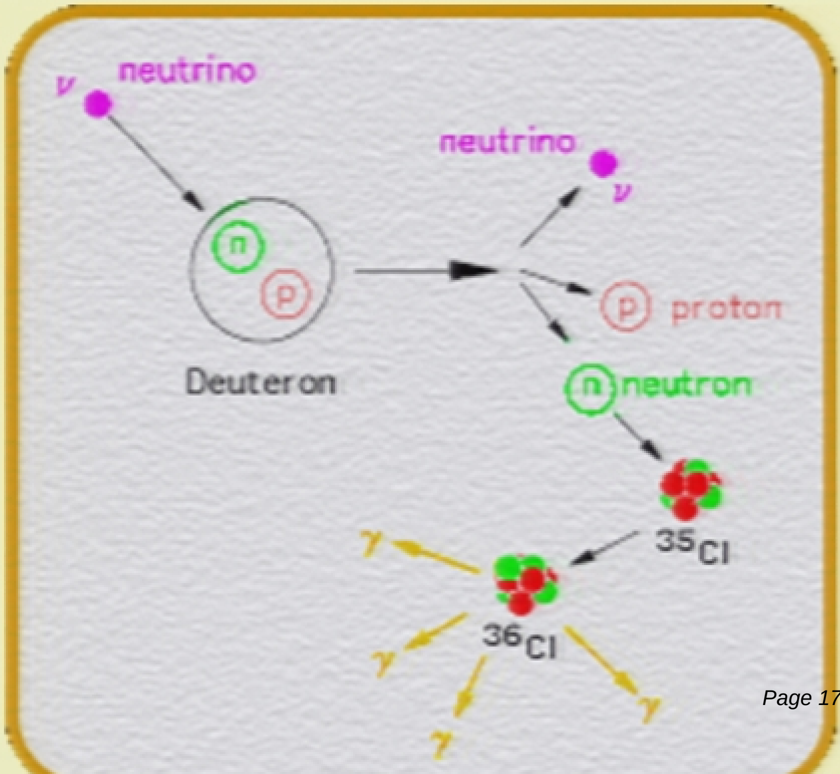

Solar Neutrino Physics From SNO

Flavor change + active neutrino appearance

$$\frac{\Phi_{CC}}{\Phi_{ES}} = \frac{\nu_e}{\nu_e + 0.15\,(\nu_\mu + \nu_\tau)}$$

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

Total ^{8}B Solar Neutrino Flux

$$\Phi_x = \Phi_{CC} + (\Phi_{ES} - \Phi_{CC}) \times (1/0.15)$$

$$\Phi_x = \Phi_{nc}$$

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Flavor change + active neutrino appearance

June 2001
(with SK)

$$\frac{\Phi_{CC}}{\Phi_{ES}} = \frac{\nu_e}{\nu_e + 0.15\,(\nu_\mu + \nu_\tau)}$$

3.3 σ

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Sept. 2003
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(With salt)

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> 7 σ

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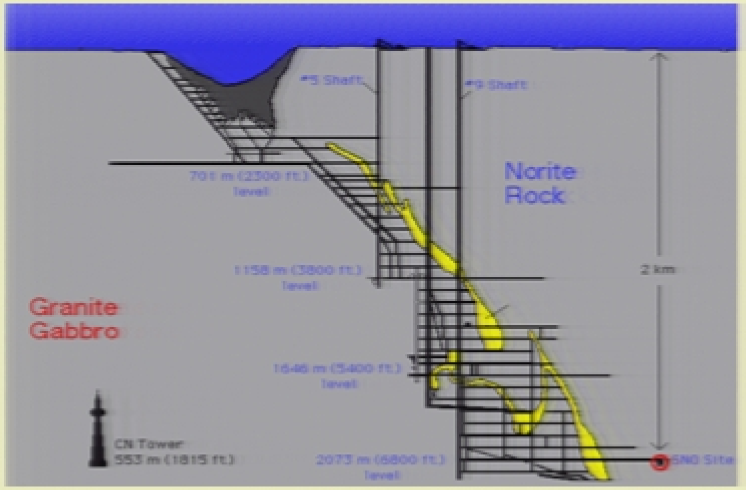
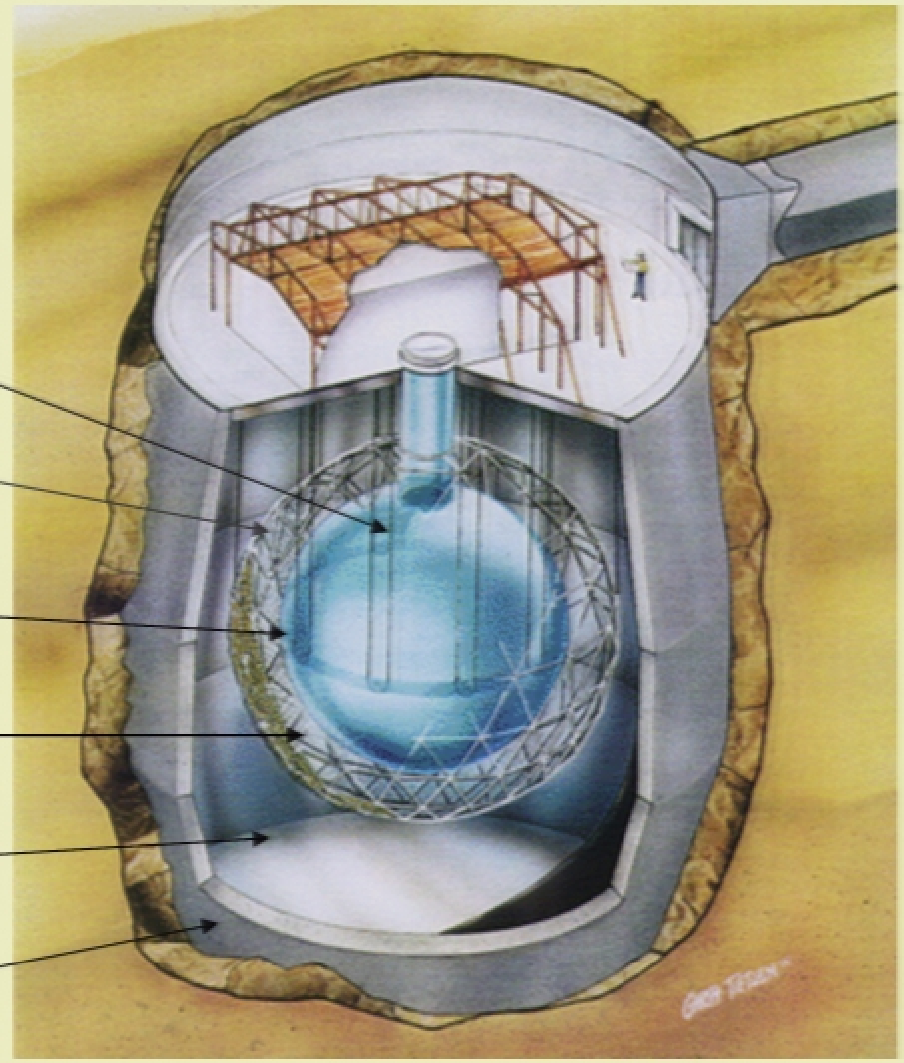
~10%

Sudbury Neutrino Observatory





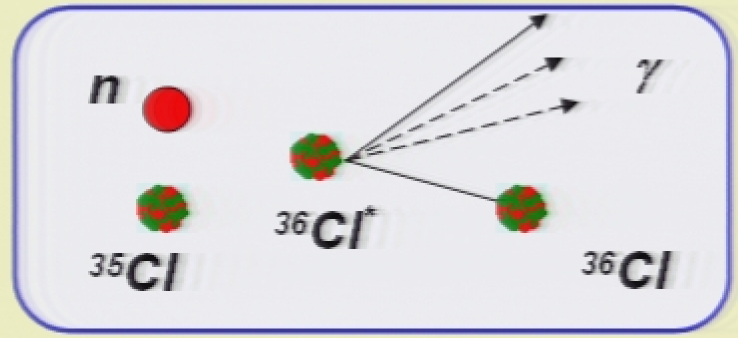
SNO Run Sequence

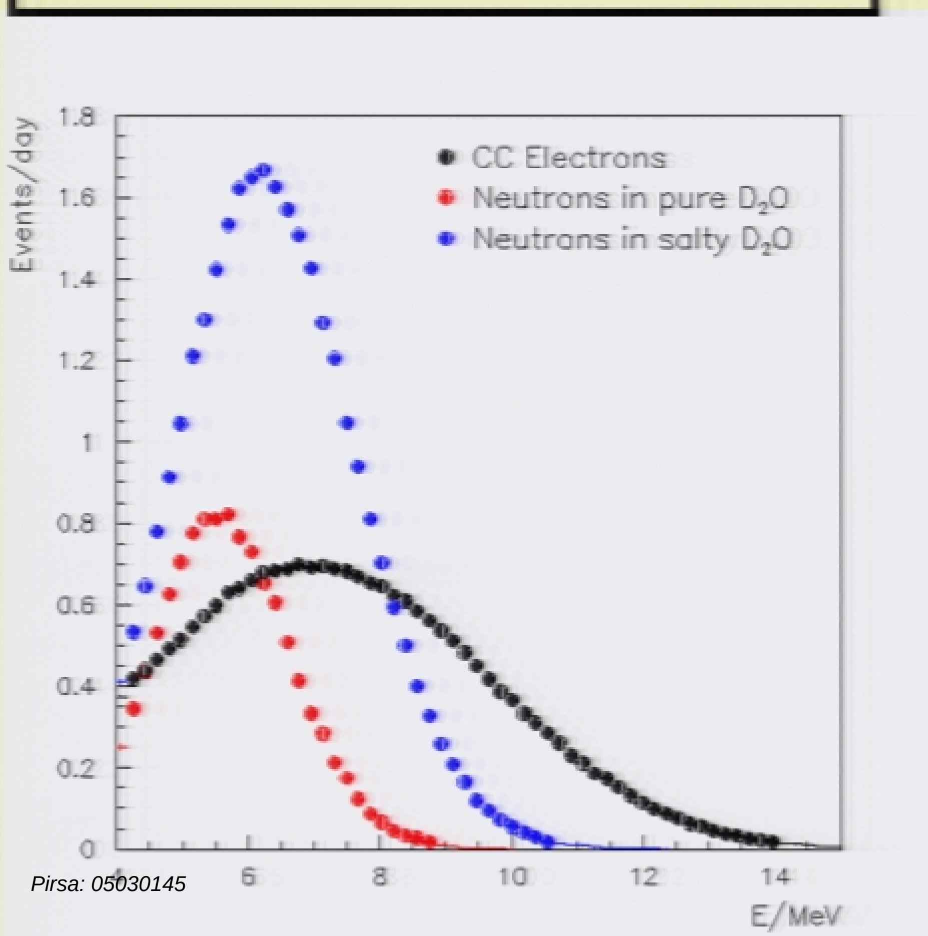
The Three Phases		Neutron Detection Method
Pure D_2O • Good CC sensitivity	Nov. 1999- May 2001	**Capture on D** $n + d \rightarrow t + \gamma \ldots \rightarrow e^-$ ($E_\gamma = 6.3$ MeV)
Added Salt in D_2O • Enhanced NC • sensitivity	June 2001 To Sept 2003	**Capture on Cl** $n + {}^{35}Cl \rightarrow {}^{36}Cl + \Sigma\gamma \ldots \rightarrow e^-$ ($E_{\Sigma\gamma} = 8.6$ MeV)
Neutral Current Detectors • ^{3}He proportional counters in the D_2O	Nov. 2004 to Dec. 2006	**Capture on ^{3}He** $n + {}^3He \rightarrow p + t$ **Event by event separation of CC and NC events**

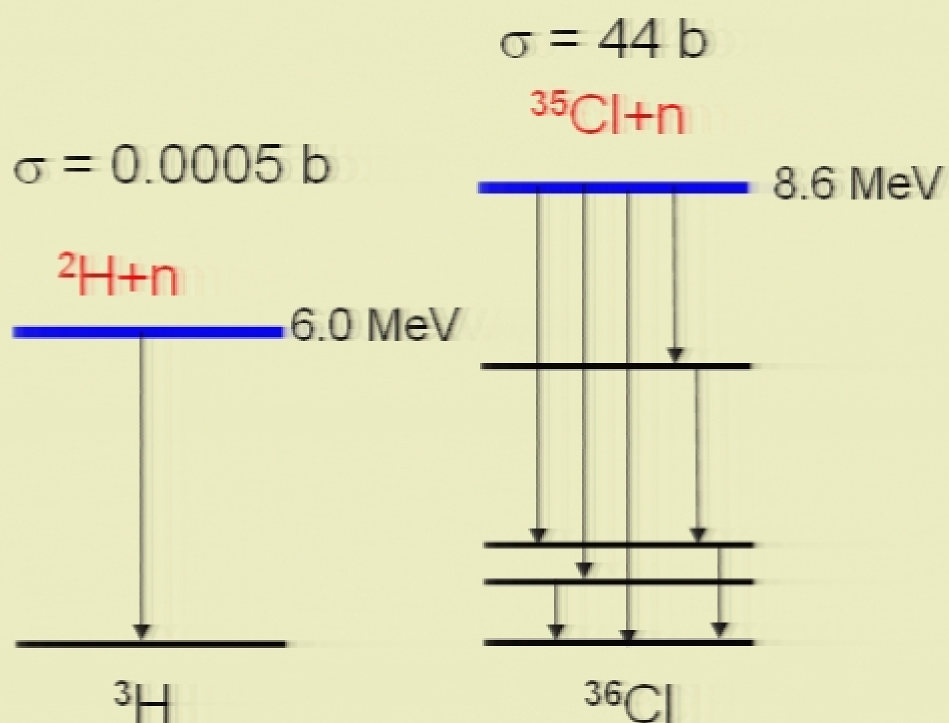
SNO Salt Phase:

Advantages of NaCl for Neutron Detection

- Higher capture cross section
- Higher energy release
- Many gammas (Isotropy)

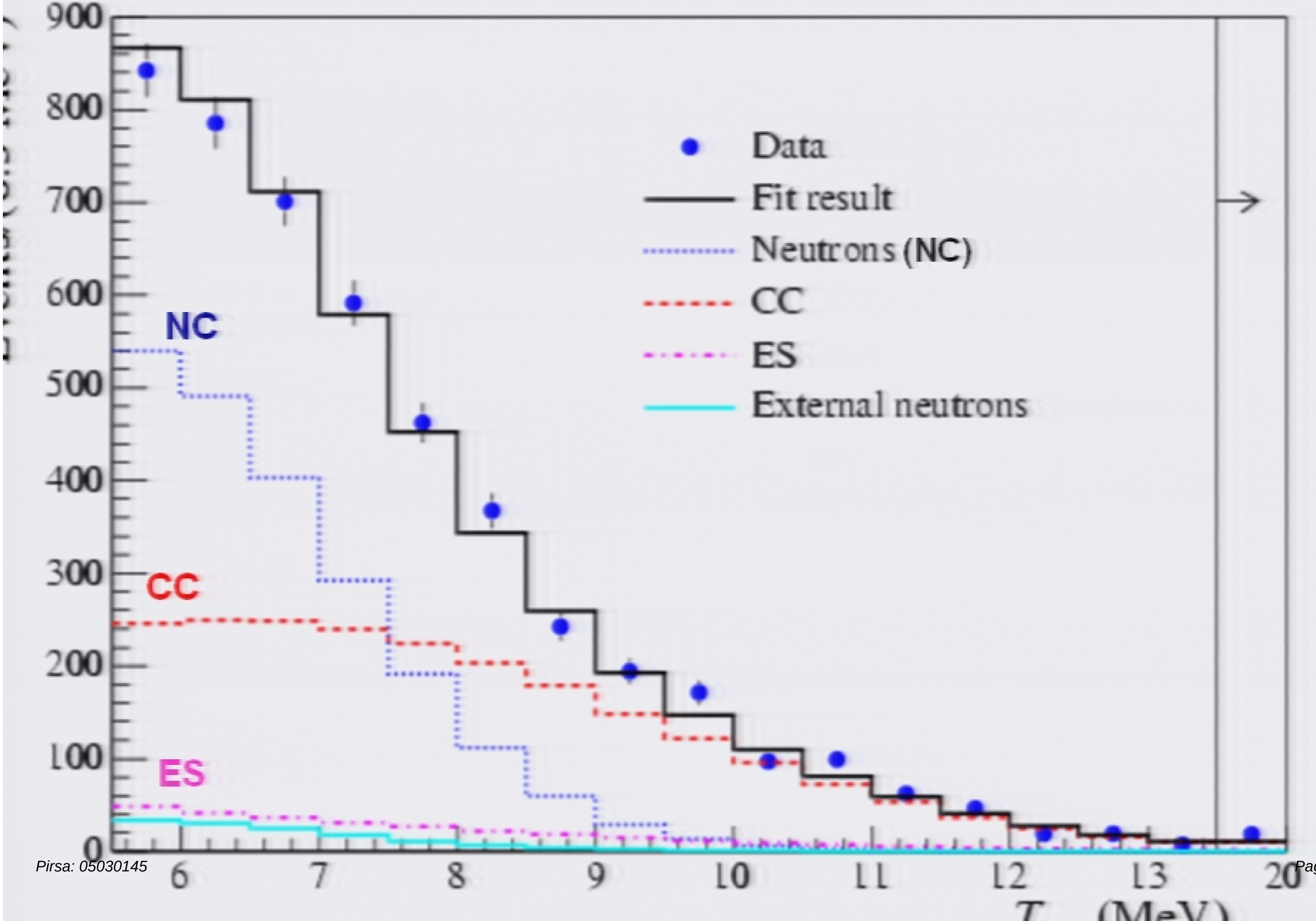




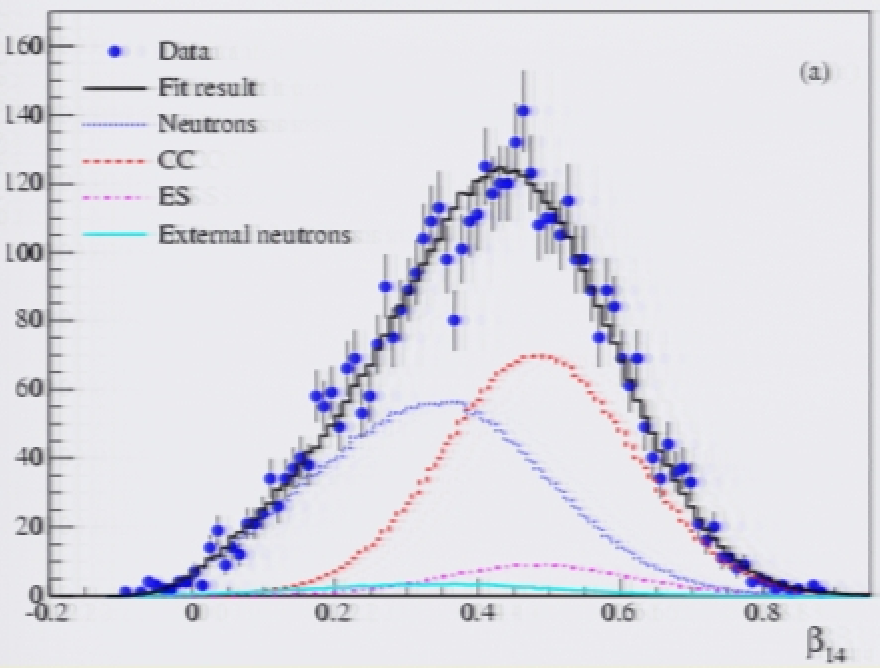


The latest SNO data: 361 live days with salt   hep-ex/0502021 (46 pages)

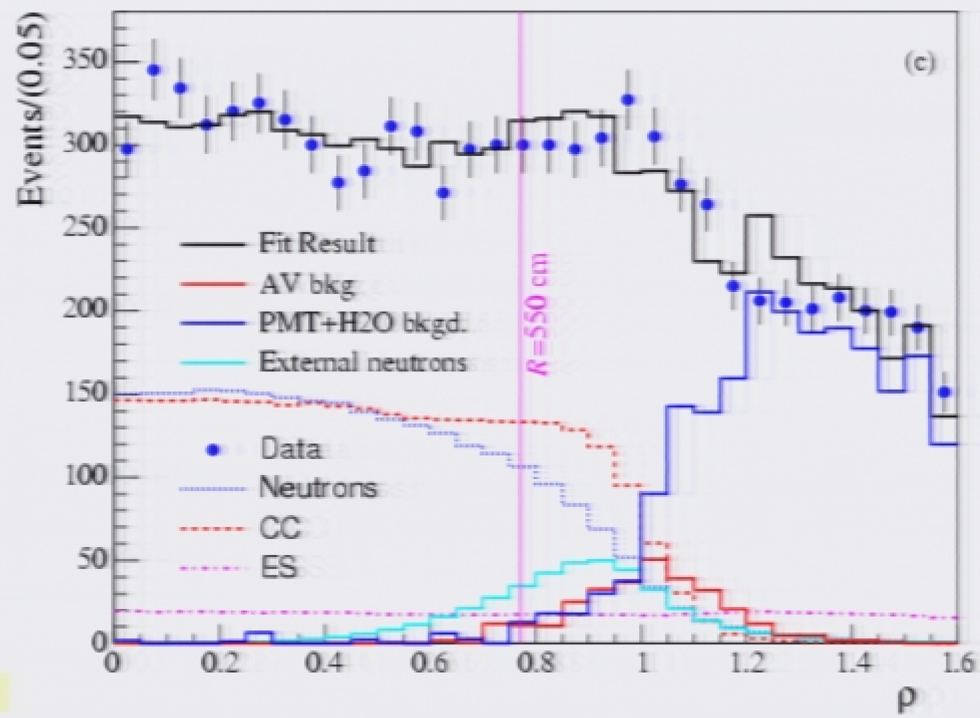
Total Spectrum



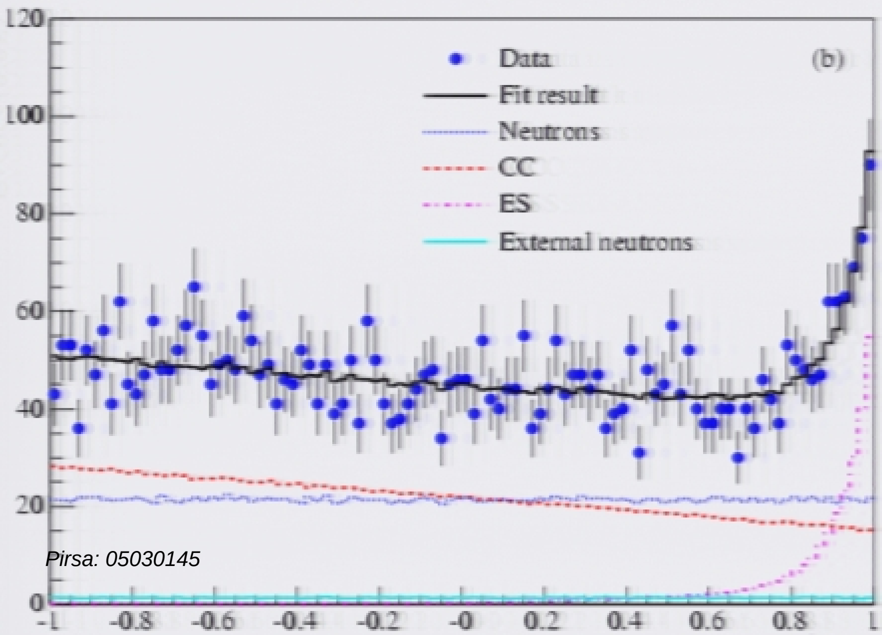
ISOTROPY



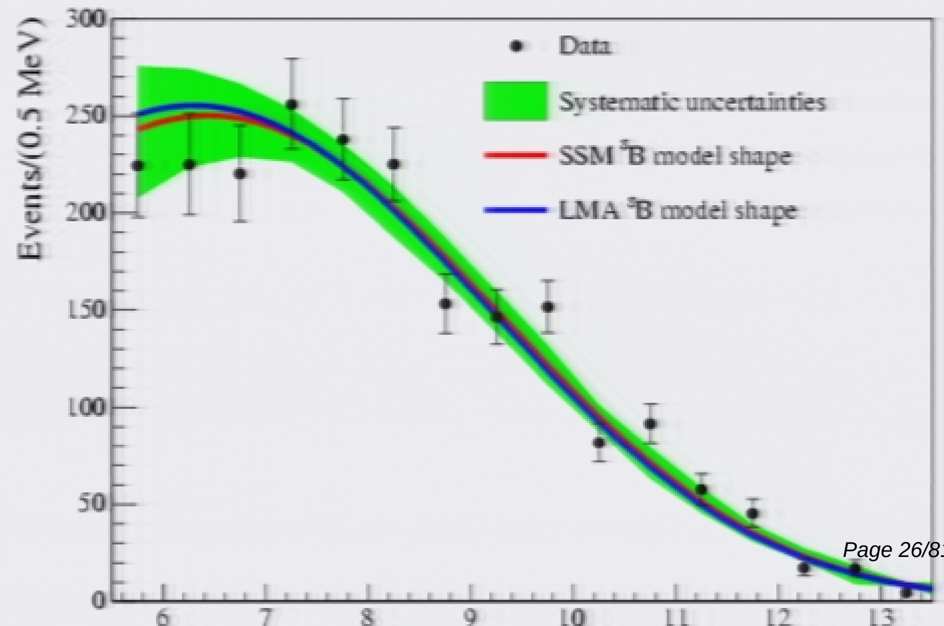
COUNTS VERSUS VOLUME



DIRECTION FROM SUN



ENERGY SPECTRUM FROM CC REACTION



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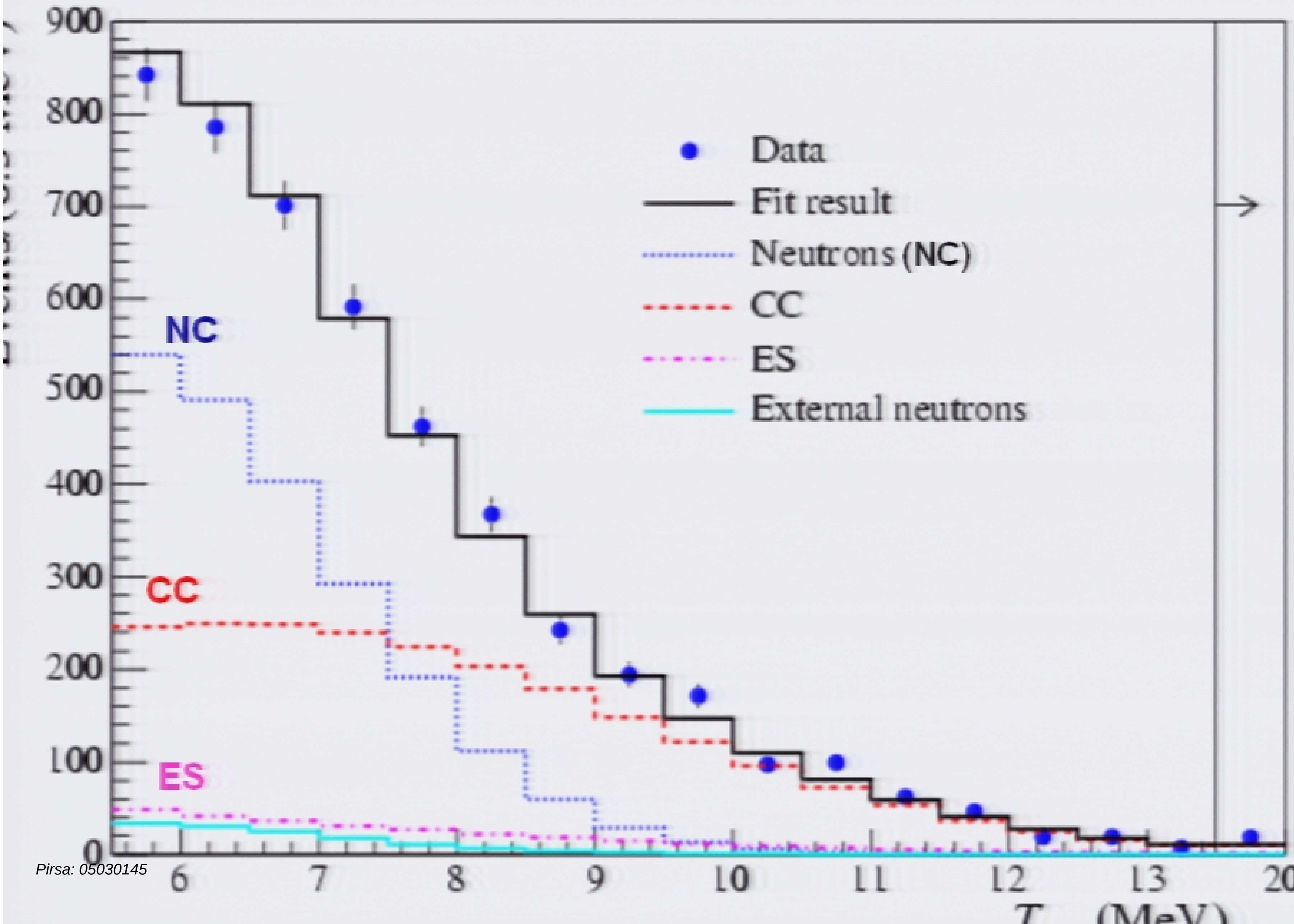

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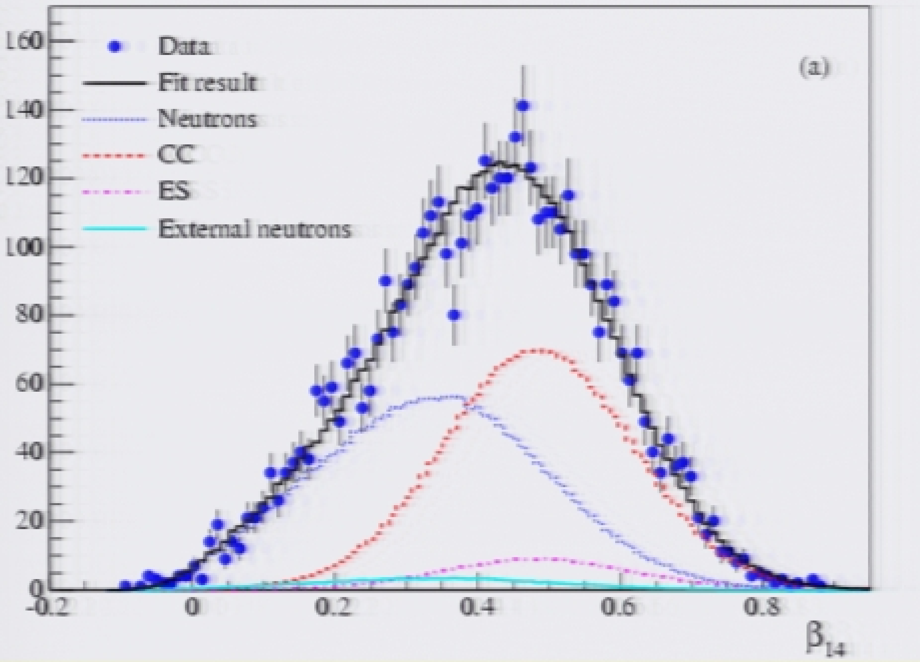

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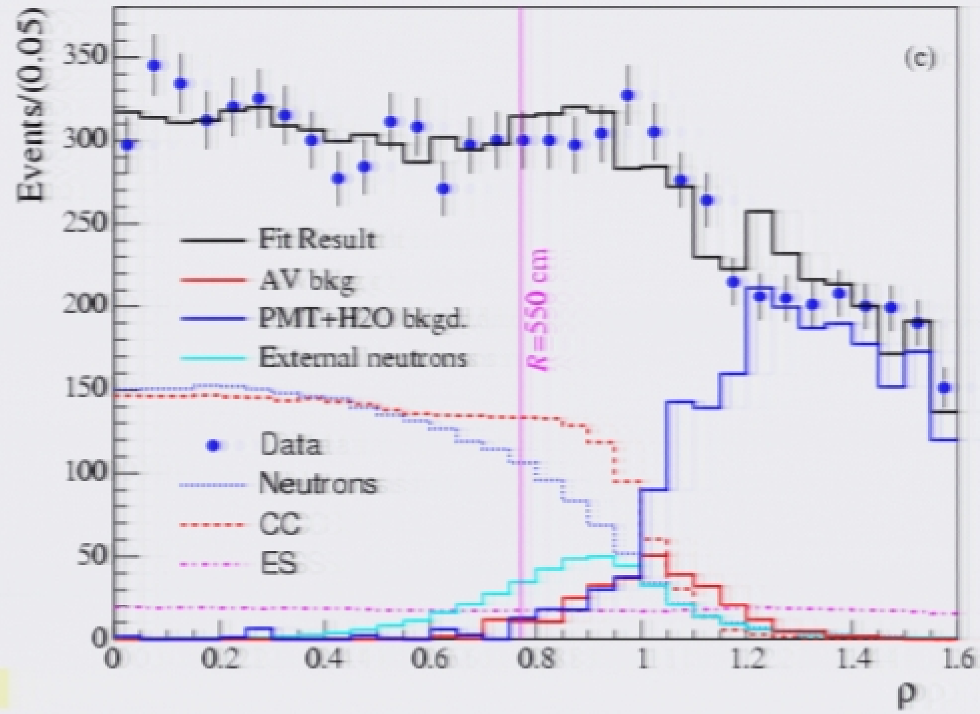

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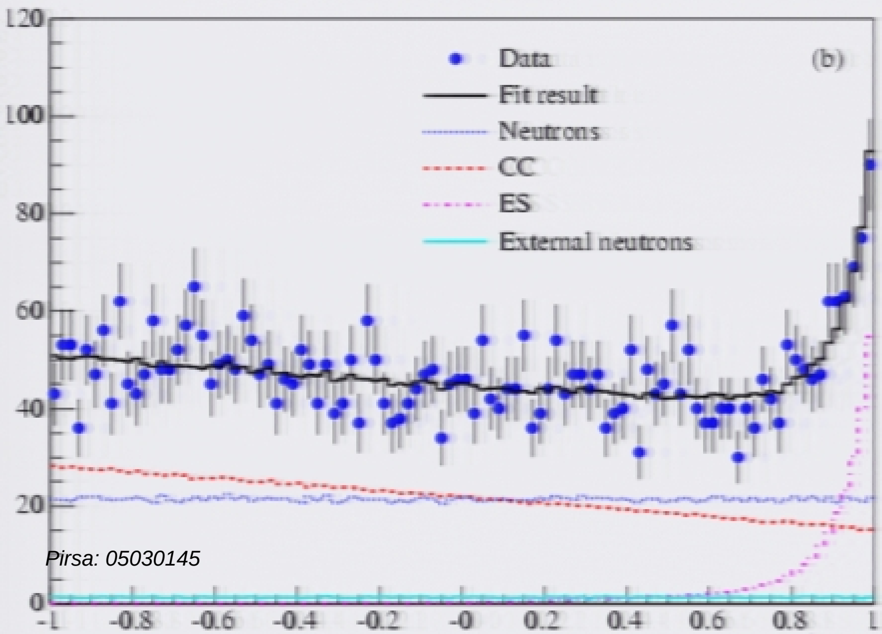

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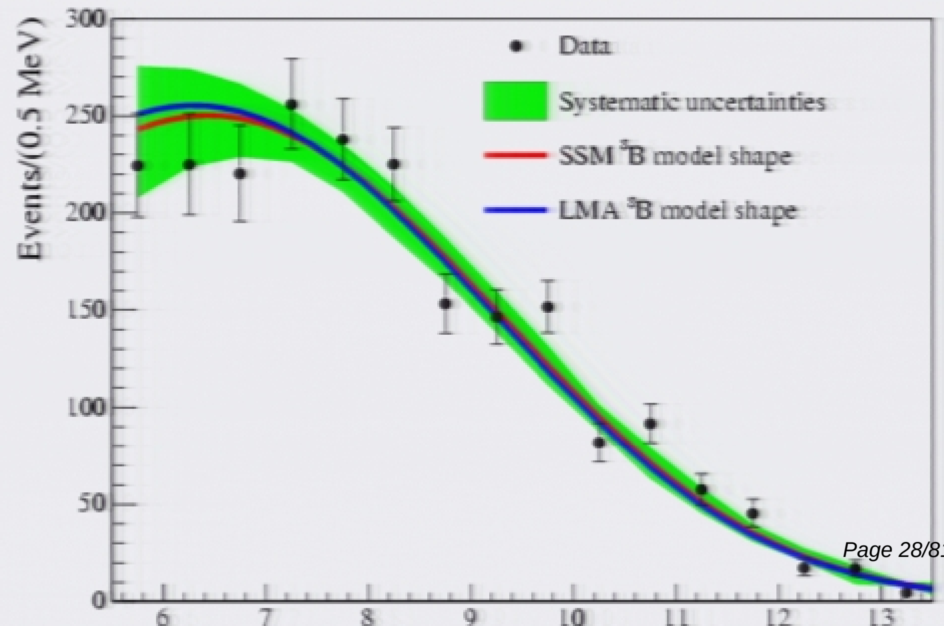


Day-Night Asymmetry

ν Regeneration in the Earth through MSW Interactions with elecctrons in the core, mantle?

Neutrino Trajectories at Night

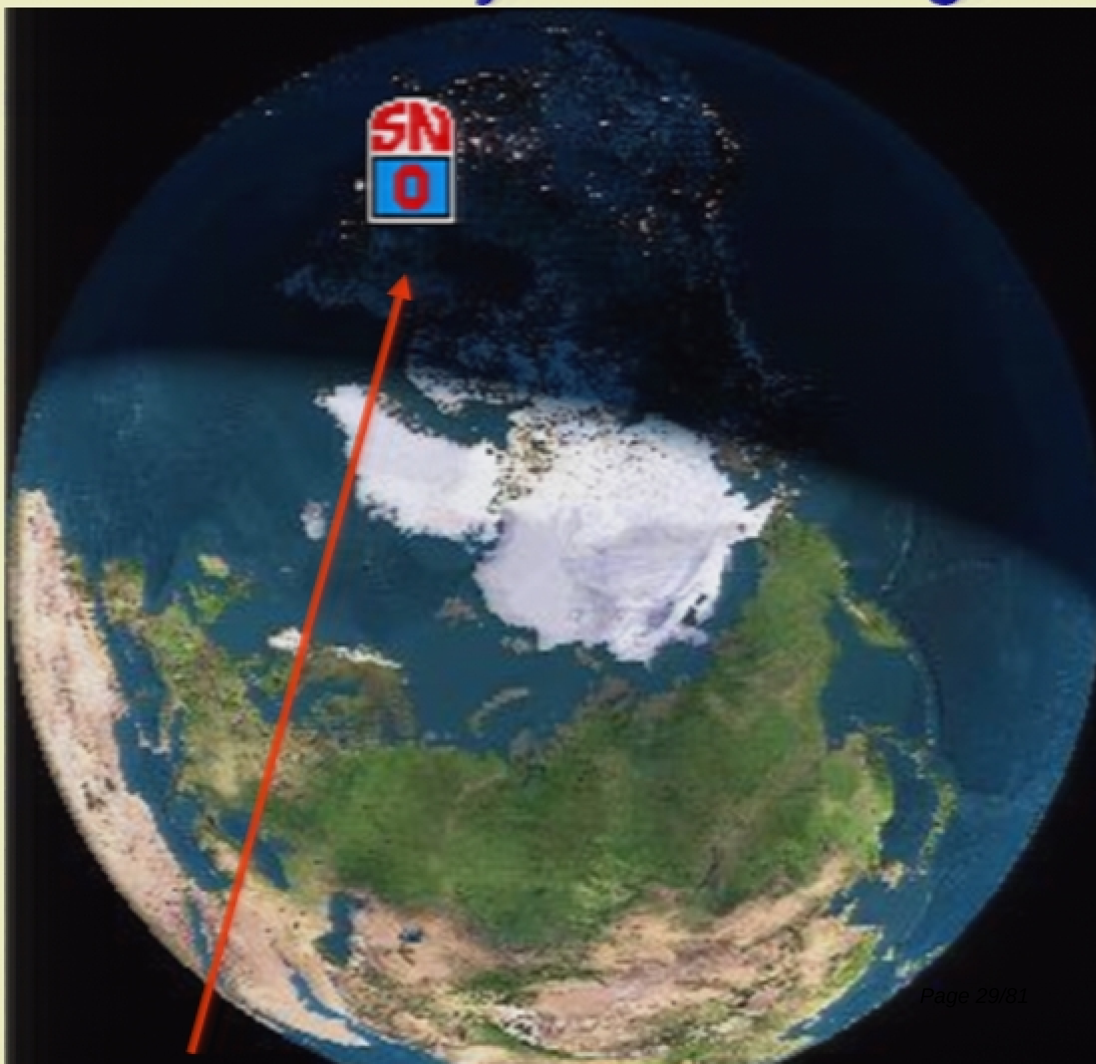
Certain oscillation scenarios predict a zenith angle dependence for the solar neutrino flux

Day Flux ≠ Night Flux ?

Measure the Asymmetry

$$\left(A \equiv \frac{2(N-D)}{N+D} \right)$$

Zenith Angle is the angle relative to the horizon



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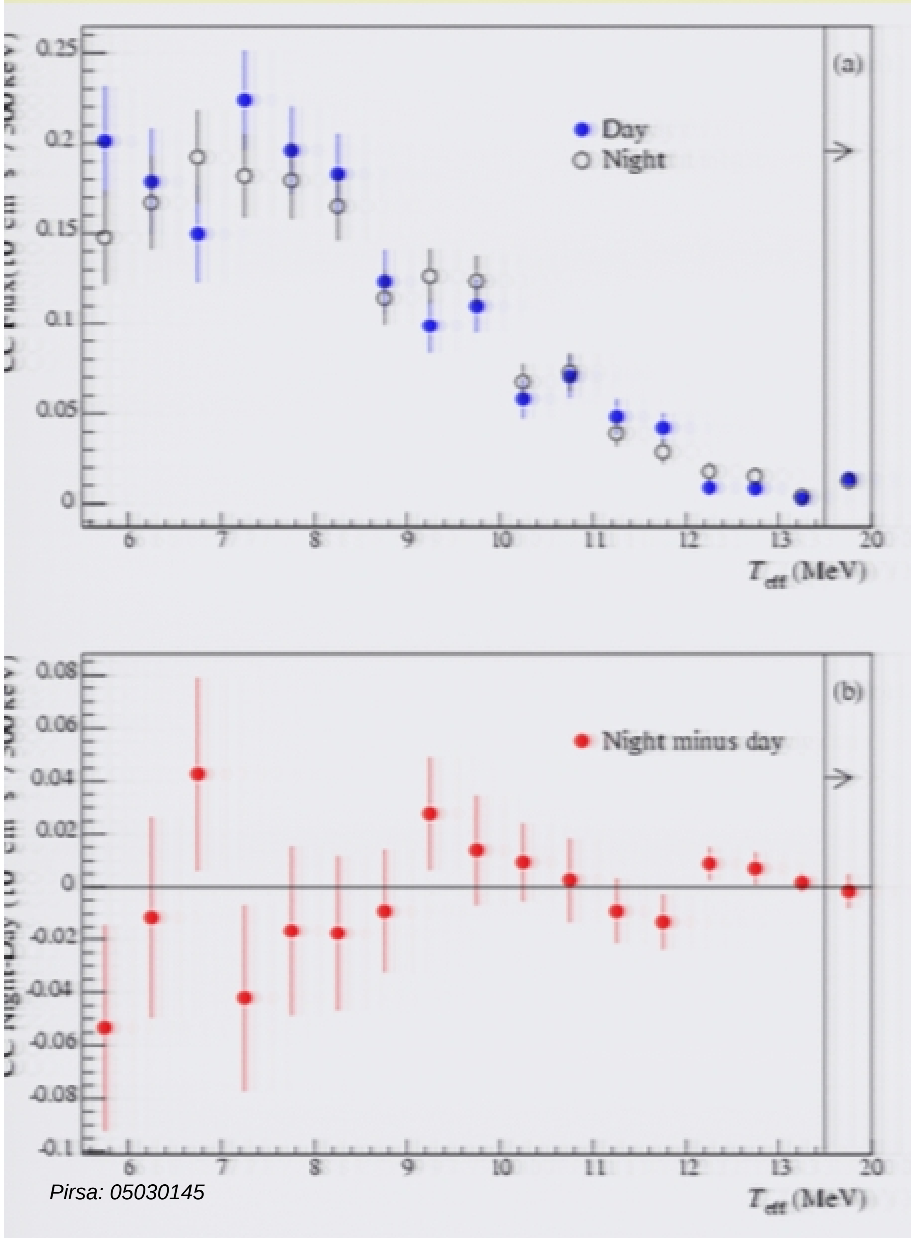


A_{CC}= -0.056 ± 0.074 (stat.) ± 0.051 (syst.)

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

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

Constraining A_{NC} to be zero:

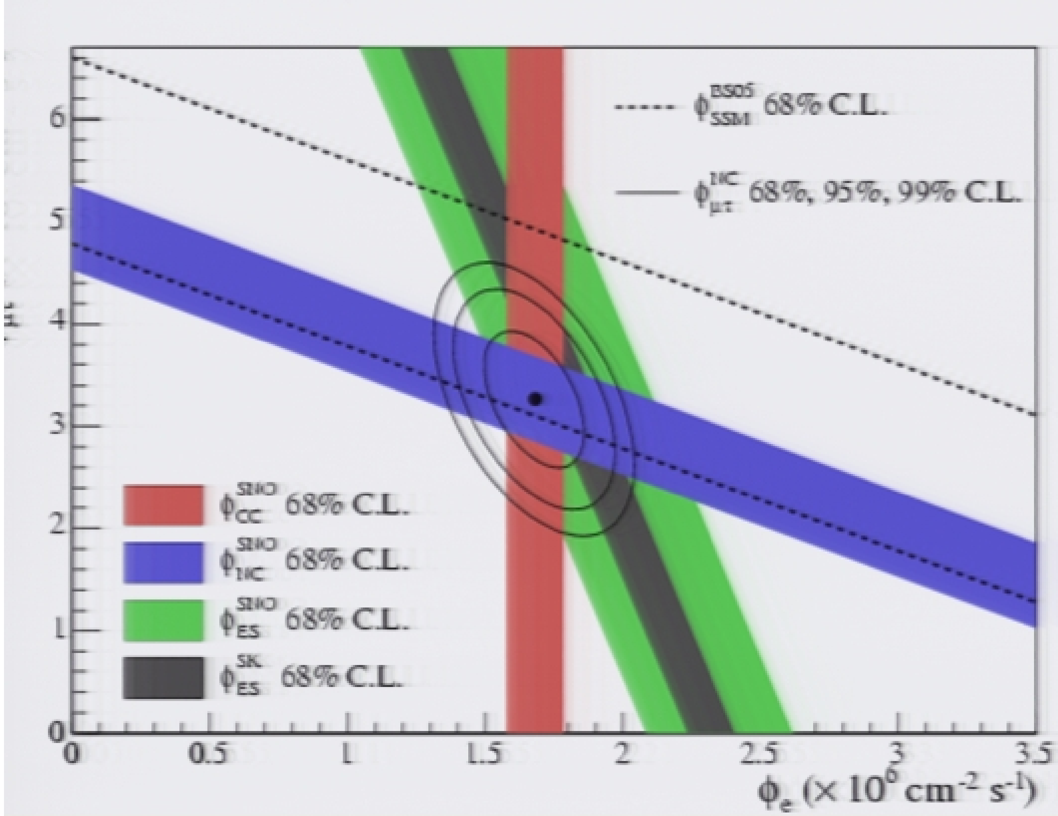
A_{CC}= -0.037 ± 0.063(stat.) ±0.032(syst.)

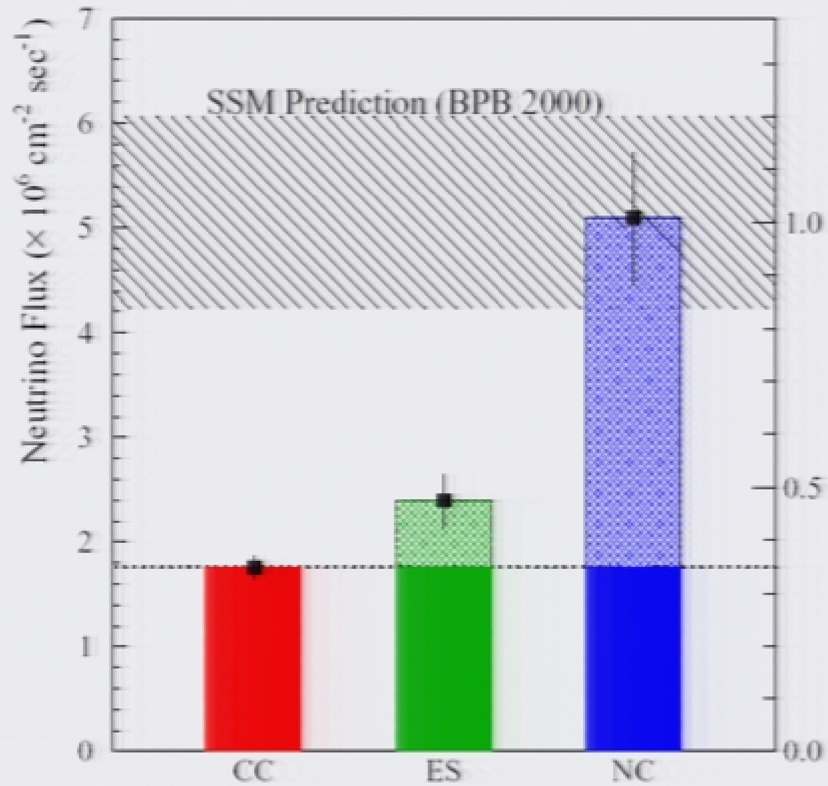
A_{ES}= 0.153 ± 0.198(stat.) ±0.030(syst.)

Combine this with the analogous

ACC from the salt phase:

$$A_{salt\ +D_2O} = 0.037 \pm 0.040$$





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

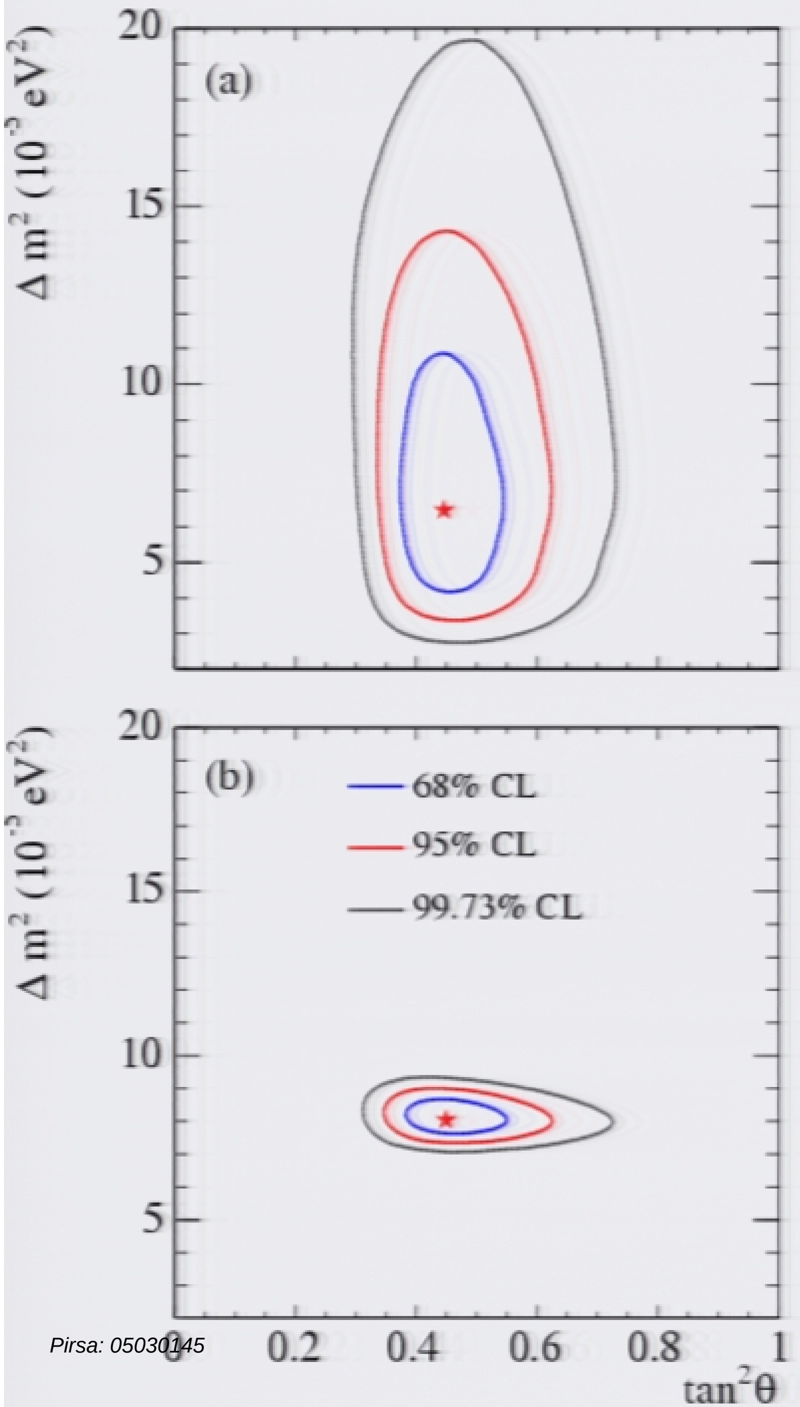
$$\phi_{NC} = 4.94 \ ^{+0.21}_{-0.21}(\text{stat.})^{+0.38}_{-0.34}(\text{syst.})$$

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

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

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

NC flux is in agreement with,
And more accurate than
Solar models for ^{8}B flux.



Large mixing Angle (LMA) region

SOLAR ONLY

SOLAR PLUS KAMLAND

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.

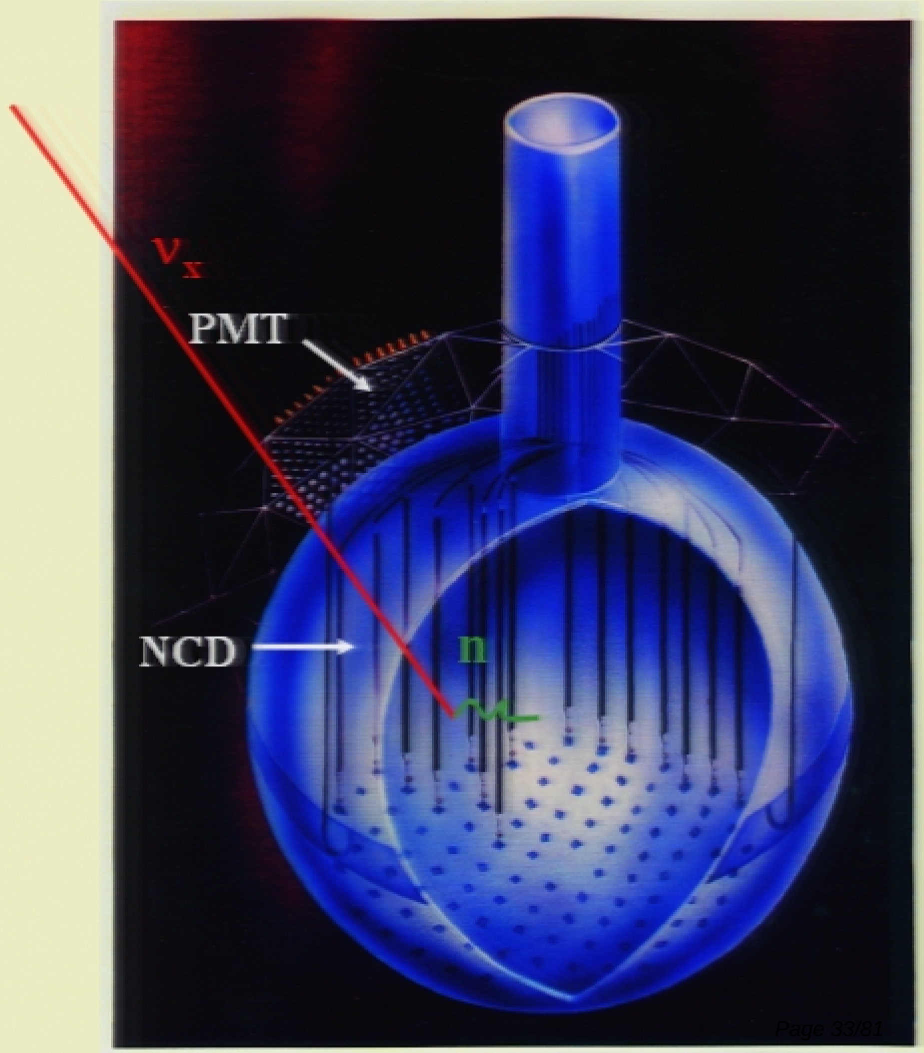
LMA prediction is for very small spectral distortion, small (~ 3 %) day-night asymmetry

SNO Phase III (NCD Phase)- Began Nov '04

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

40 Strings on 1-m grid

440 m total active length



Detection Principle

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

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

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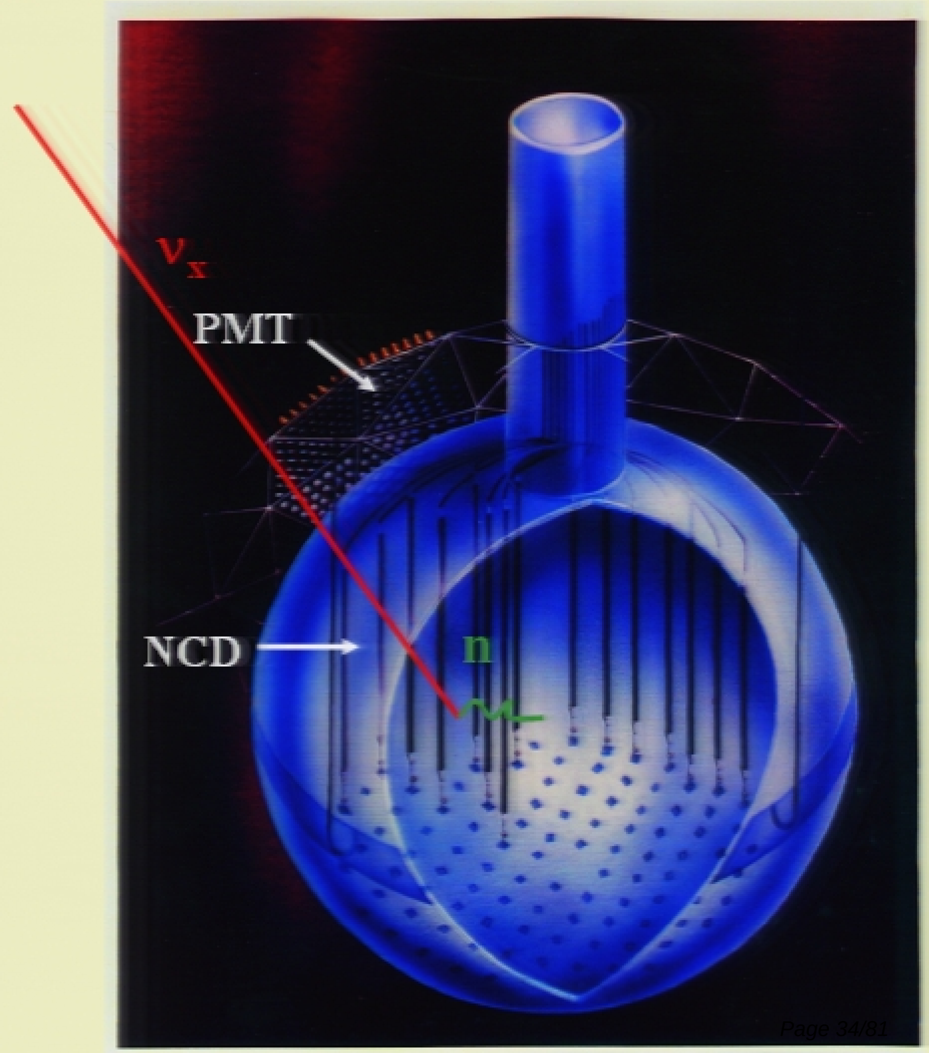


Detection Principle

$$^2H + \nu_x \rightarrow p + n + \nu_x - 2.22\ MeV \quad (NC)$$

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

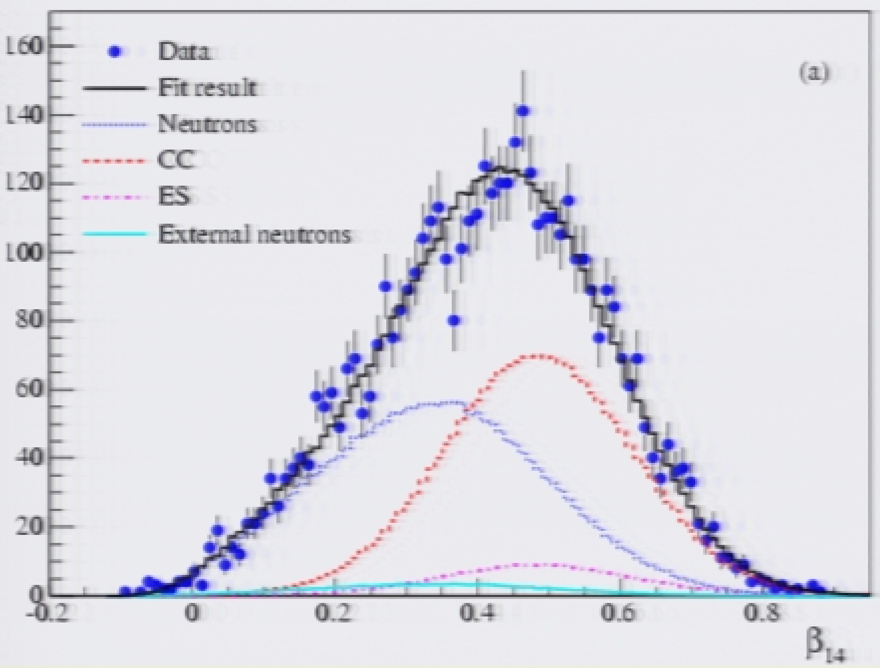
Physics Motivation

Event-by-event separation. Measure NC and CC in separate data streams. Better Flux accuracy (NC/CC).

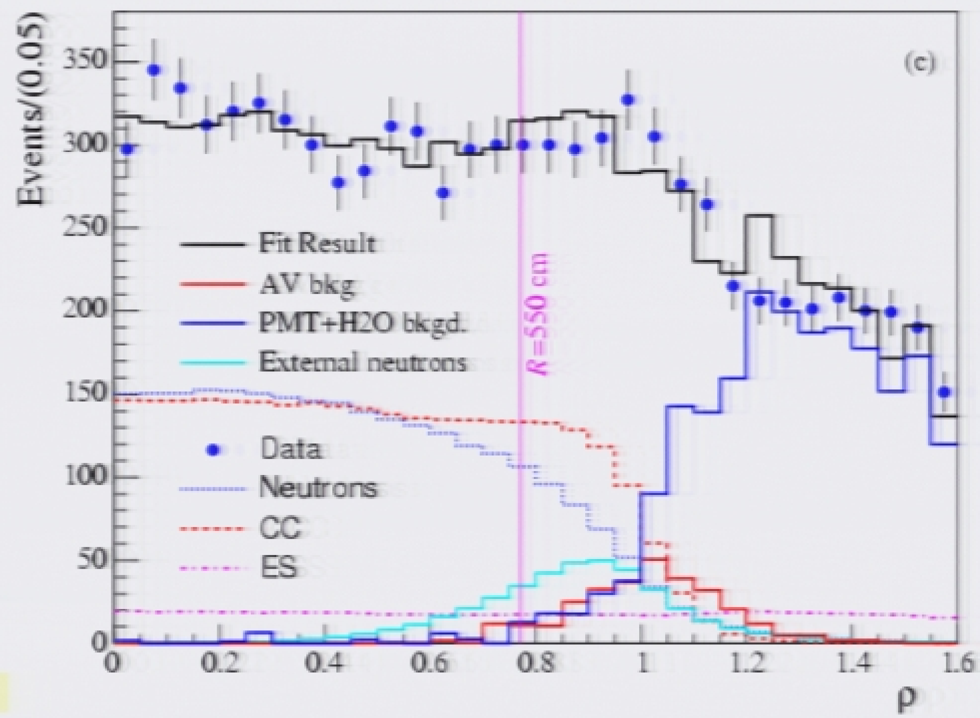
Different systematic uncertainties than neutron capture on NaCl.

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

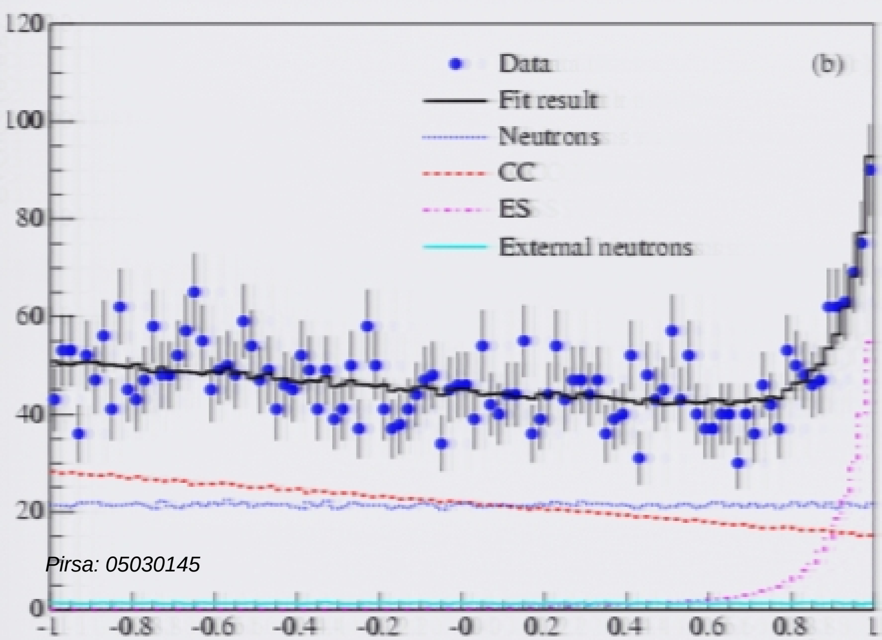
ISOTROPY



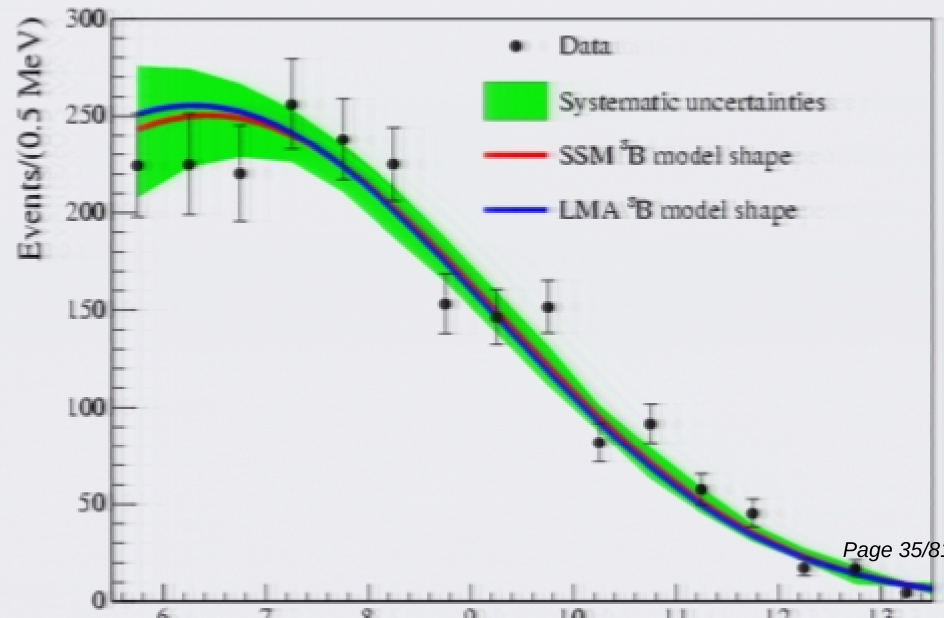
COUNTS VERSUS VOLUME



DIRECTION FROM SUN



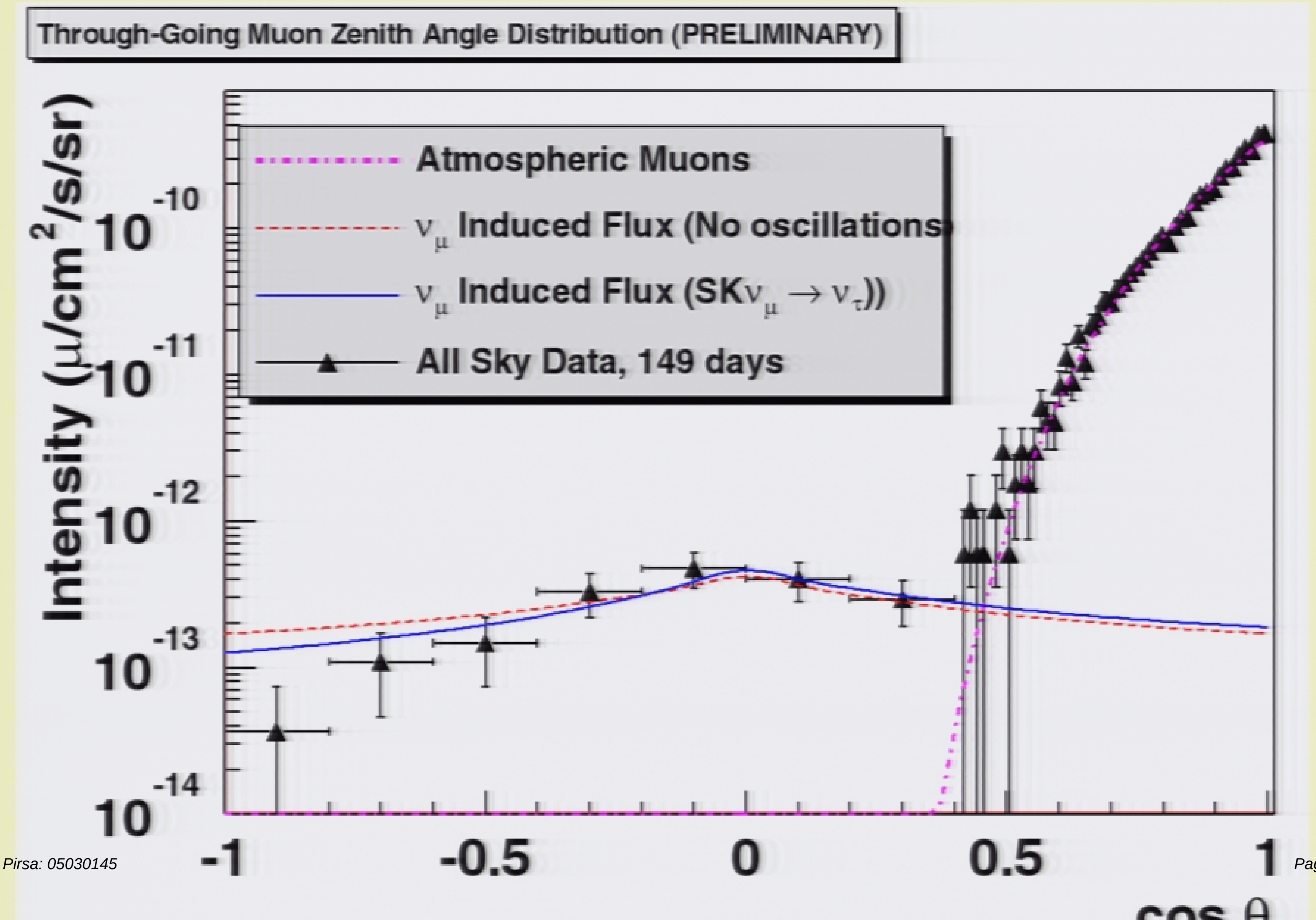
ENERGY SPECTRUM FROM CC REACTION



SNO Physics Program

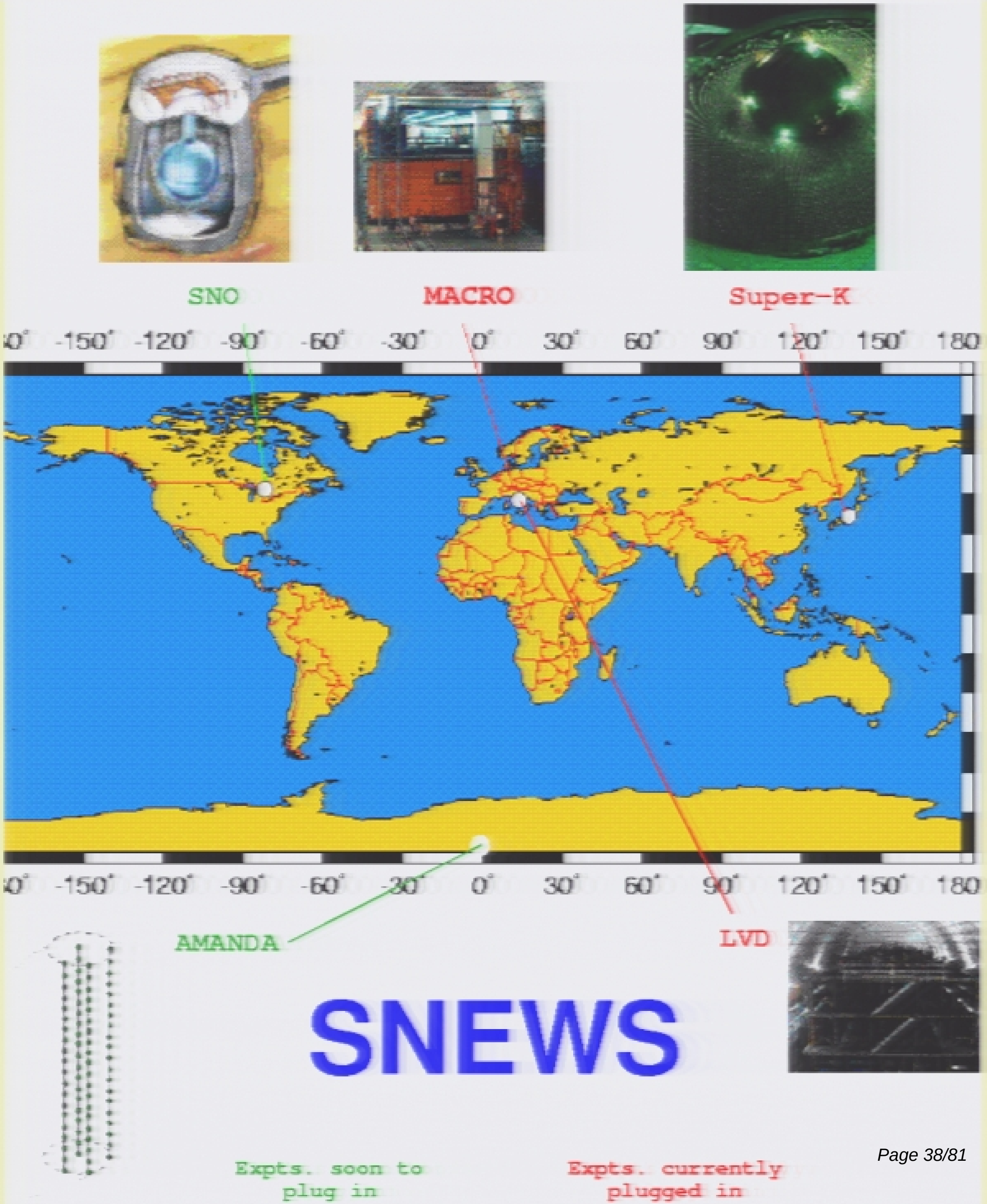
- **Solar Neutrinos**
  - → Electron Neutrino Flux
  - → Total Neutrino Flux
  - → Electron Neutrino Energy Spectrum Distortion (Predicted ~10 %)
  - → Day/Night effects (Predicted ~ 4 %)
  - → Seasonal variations
- **Atmospheric Neutrinos & Muons**
  - → Downward going cosmic muon flux
  - → Upward going muons and angular dependence
- **Supernova Watch**
- **Antineutrinos**
- **Nucleon decay ("Invisible" Modes: N → $\nu\nu\nu$)**

SNO Muon & Atmospheric Neutrino Analysis



Supernovae and SNO:

For an event at the Center of the Galaxy SNO would observe 1000 events evenly Distributed among Electron, mu, tau Neutrinos.



Using the oscillation framework:

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

For three neutrinos:

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Maki-Nakagawa-Sakata-Pontecorvo matrix

(Double β decay only)

$$= \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & e^{-i\alpha_3/2+i\delta} \end{pmatrix}$$

Solar,Reactor | **Atmospheric** | **CP Violating Phase** | **Reactor,LBL** | **Majorana Phases**

Range defined for Δm_{12}, Δm_{23}

where $c_{ij} = \cos\theta_{ij}$, and $s_{ij} = \sin\theta_{ij}$

For two neutrino oscillation in a vacuum: (valid approximation in many cases)

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 (1.27 \frac{\Delta m^2 L}{E})$$

What can we learn?

Neutrino Properties

- Detailed Study of LSND: (MiniBoone) 3 Neutrino types or more?

- Improvement in (or confirmation of) parameters to date:
  Δm_{12}^2, Δm_{23}^2, θ_{12}, θ_{23}.

- Determination of unknown parameters:
  - θ_{13}
  - CP Violating Phase δ
  - Mass hierarchy

- Dirac or Majorana (Majorana Phases)

- Mass scale

What can we learn?

-Improvements in (confirmation of) parameters to date:
Δm_{12}^2, Δm_{23}^2, θ_{12}, θ_{23}.

- Δm_{12}^2, θ_{12} :
  - Reactor neutrinos: Kamland (Confirm LMA, improve parameters).
  - Solar Neutrinos: SNO+ , Borexino, Kamland.
  - Low Energy Solar neutrino measurements (pp): CLEAN, LENS

- Δm_{23}^2, θ_{23} :
  - Long baseline Accelerator: K2K, MINOS, CNGS
    - Confirm atmospheric (K2K near 99% confidence)
    - Observe oscillation pattern (dip)
    - Observe tau appearance

What can we learn?

Neutrino Properties

- Determination of unknown parameters:

- Reactor Neutrino Disappearance for θ_{13} :
  Double Chooz, Braidwood, Daya Bay, KASKA

- Long Baseline accelerator: T2K, NOVA... Neutrino Factories

  - θ_{13}

  - m_2 , m_3 Mass Hierarchy:
    - Study Matter Effects

  - CP Violating Phase δ:
    - Must have large θ_{13}
      - Compare $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$

$\nu_\mu \Rightarrow \nu_e$ oscillation experiment

A. Cervera et al., Nuclear Physics B 579 (2000) 17 – 55, expansion to second order in $\theta_{13}, \frac{\Delta_{12}}{\Delta_{23}}, \frac{\Delta_{12}}{A}, \Delta_{12}L$

$$P(\nu_\mu \to \nu_e) = P_1 + P_2 + P_3 + P_4$$

$$P_1 = \sin^2\theta_{23}\sin^2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2\sin^2\frac{B_\pm L}{2}$$

1st Generation: θ_{13}

$$P_2 = \cos^2\theta_{23}\sin^2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2\sin^2\frac{AL}{2}$$

$$P_3 = J\cos\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

$$P_4 = J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

$\nu_\mu \to \nu_e$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2}{2E_\nu};$$

$$A = \sqrt{2}G_F n_e;$$

$$B_\pm = |A \pm \Delta_{13}|;$$

$$J = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

Matter Effects: Mass Hierarchy

Θ_{13} must be finite to enable CP violation measurements

CP: Compare $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$

- Dirac or Majorana (Majorana Phases)

- Double Beta Decay

- Observation implies Majorana neutrinos if CPT is good.
- Effective Mass inferred depends on Majorana phases

$$|\langle m \rangle| = \left| |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_2} m_2 + |U_{e3}|^2 e^{i\alpha_3} m_3 \right|$$

- Next generation experiments could get to ~0.05 eV i.e. $\sim\sqrt{\Delta m^2_{Atm}}$

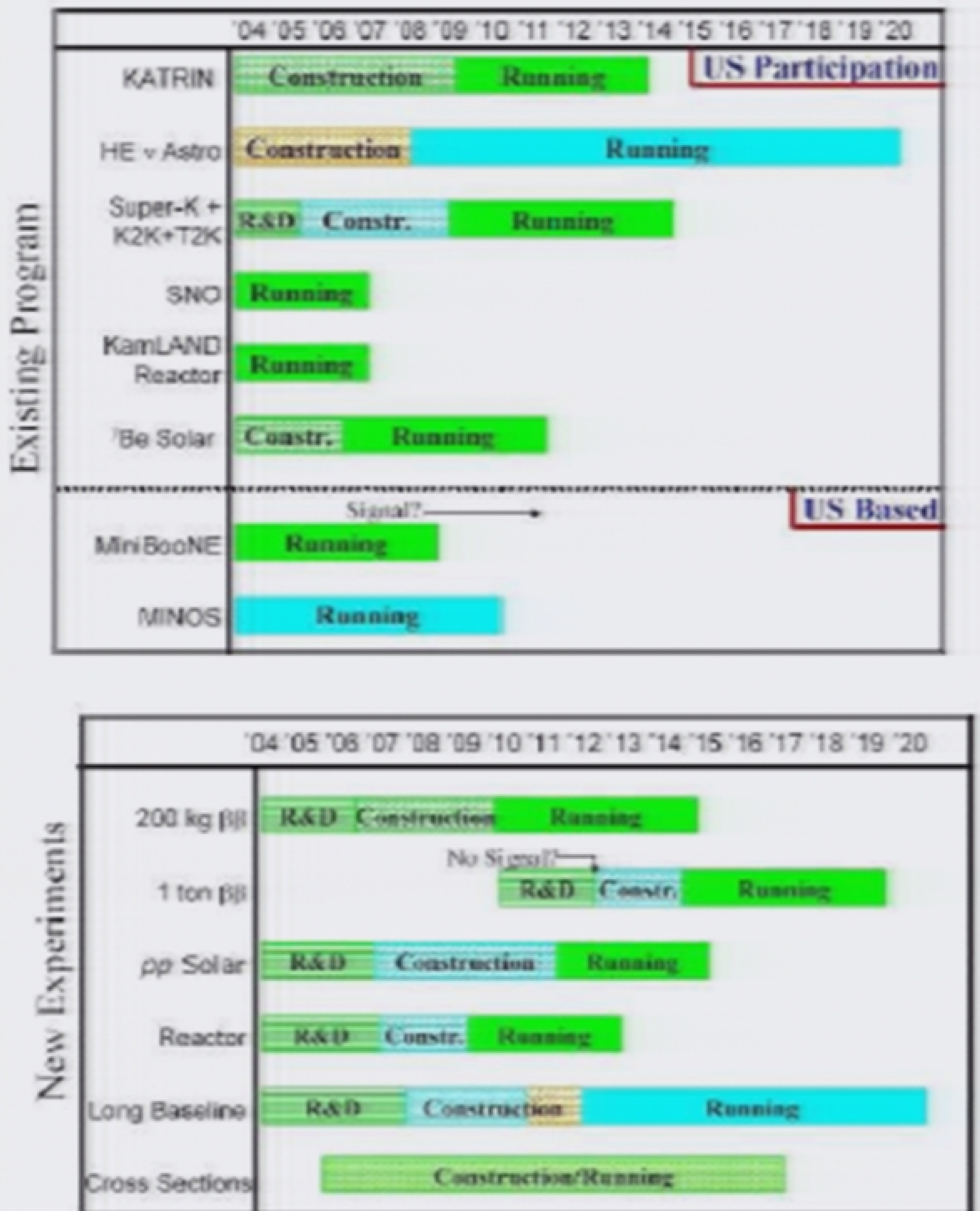
- Mass scale

- Tritium Beta Decay

$$|\langle m \rangle| = \left| |U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 + |U_{e3}|^2 m_3 \right|$$

- Next generation experiment (KATRIN) could get to ~ 0.3 eV: (Overall mass scale ??)

US Review, Planning For Neutrino Physics



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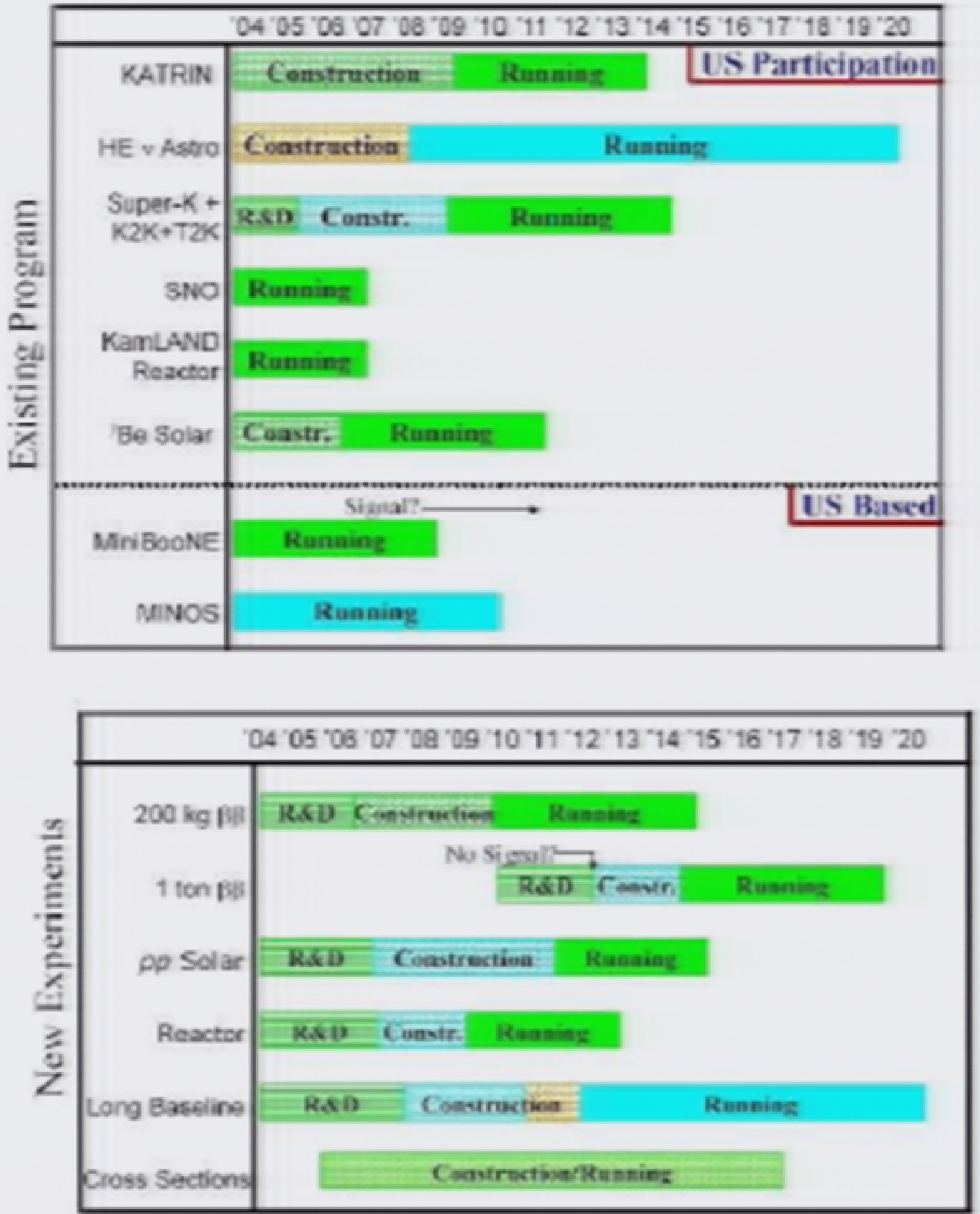


New International Underground Science Facility
At the Sudbury site: SNOLAB

Proposal ($ 38M) funded by Canada Foundation for Innovation, 2002
Further Support: ($ 10 M)
Northern Ontario Heritage Foundation, Ontario Innovation Trust, FEDNOR

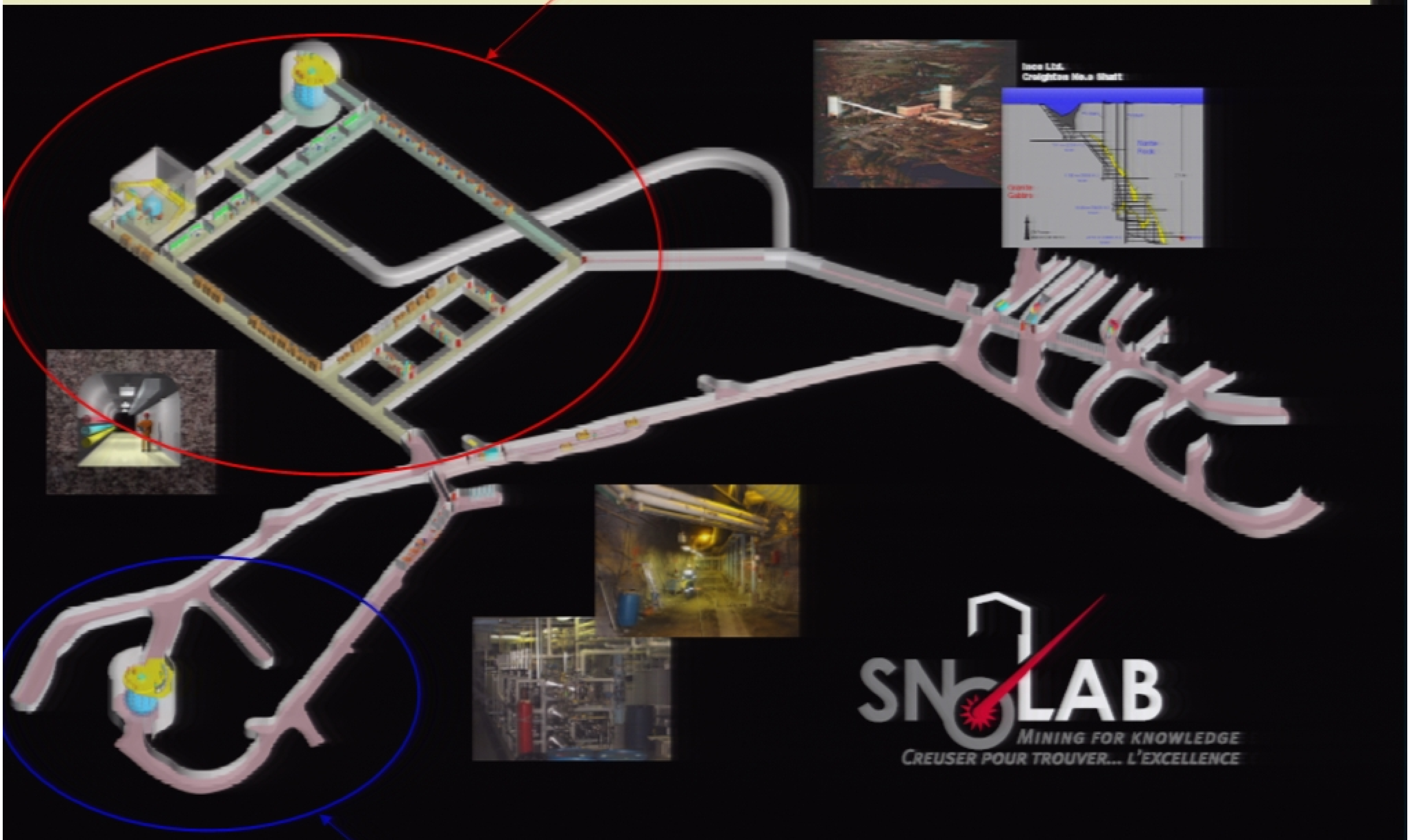
To pursue:

- 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

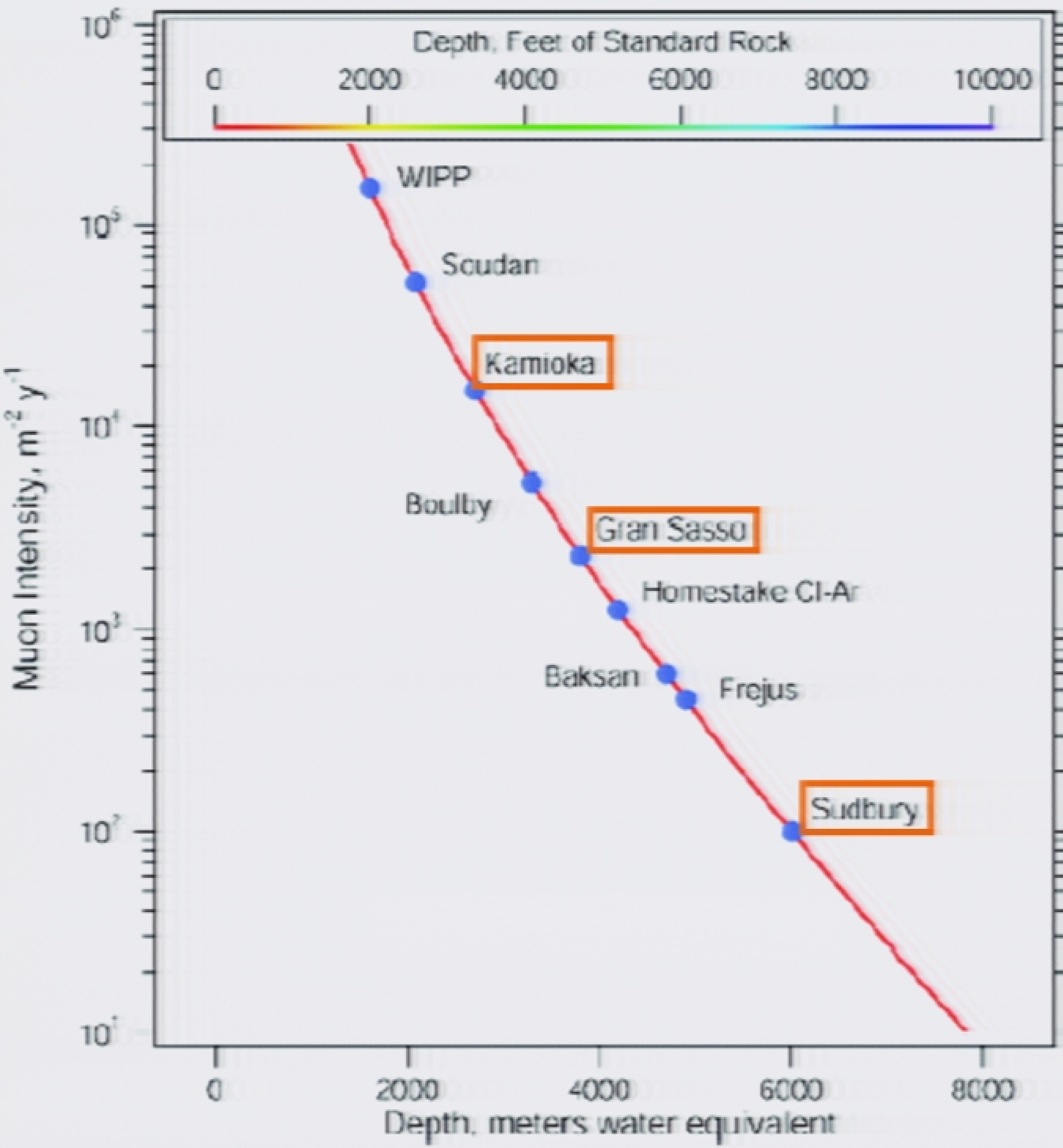
- Double Beta Decay:
  - More accuracy for neutrino masses.
  - Are Neutrinos Majorana particles?
  - Leptogenesis…

The New SNOLAB



SNO

Surface facility as of March 11, 2005


Depth, Feet of Standard Rock
0
2000
4000
6000
8000
10000
WIPP
Scudan
Kamioka
Boulby
Gran Sasso
Homestake Cl-Ar
Baksan
Frejus
Sudbury
Muon Intensity, m^{-2} y^{-1}
Depth, meters water equivalent

Letters of Interest for SNOLAB

Solar Neutrinos:

Liquid Ne: CLEAN (also Dark Matter)

Liquid Scintillator: SNO+ (also Double Beta Decay, Reactor Neutrinos, Geoneutrinos, Supernovae)

Liquid Helium (also Dark Matter)

Dark Matter:

Silicon Bolometers: CDMS

Liquid Xe: ZEPLIN, XENON

Gaseous Xe: DRIFT

Freon Super-saturated Gel: PICASSO

Timing of Liquid Argon Scintillation: (DEAP)

Neutrinoless Double Beta Decay:

Ge Crystals: Individual cryostats (Majorana) or Large Liquid Nitrogen bath

Liquid Xe: EXO

CdTe: COBRA

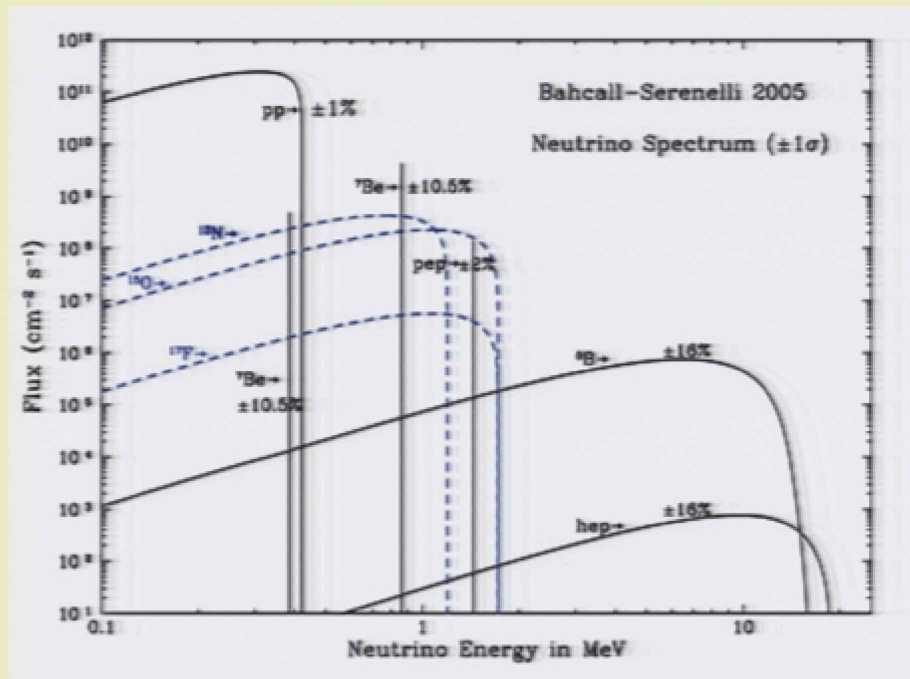
SNO+ (Fill with Liquid Scintillator)

Principal Investigator: Mark Chen, Queen's

- SNO plus liquid scintillator → physics program
  - *pep* and CNO low energy solar neutrinos
    - tests the neutrino-matter interaction, sensitive to new physics
  - geo-neutrinos
  - 240 km baseline reactor oscillation confirmation
  - supernova neutrinos
  - double beta decay?
  - ...

Low Energy Solar Neutrinos

- precision survival probability measurement: *pep*
- observe rise in survival probability at lower energies: lower energy ^{8}B, ^{7}Be, *pep*
- testing the vacuum-matter transition is sensitive to new physics



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

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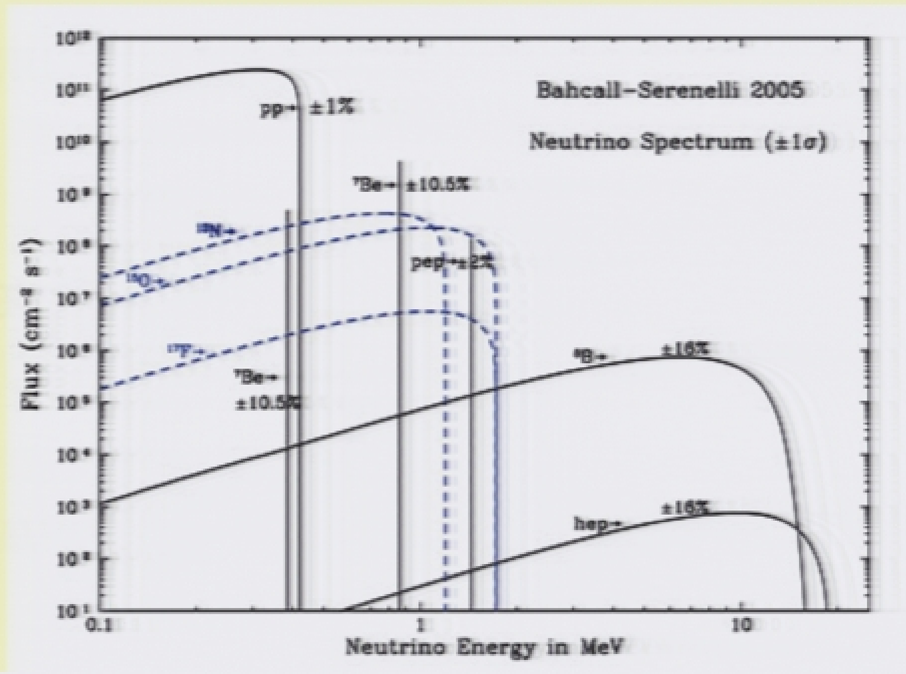

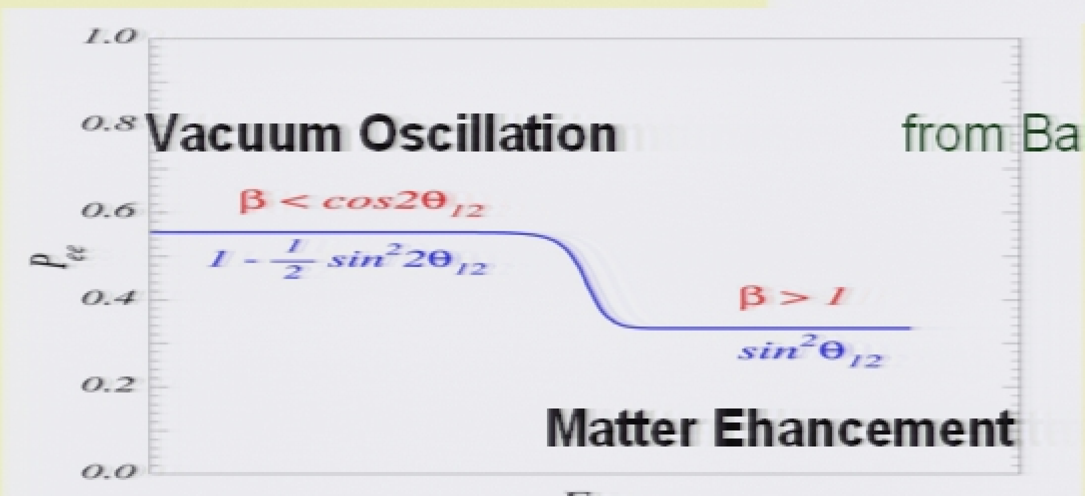

from Bahcall, Peña-Garay

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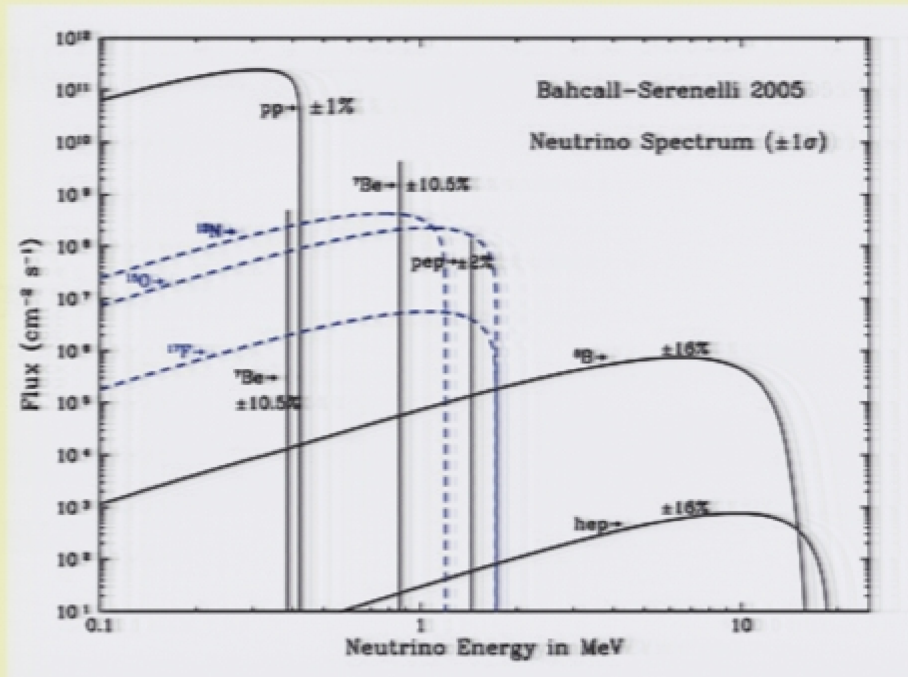

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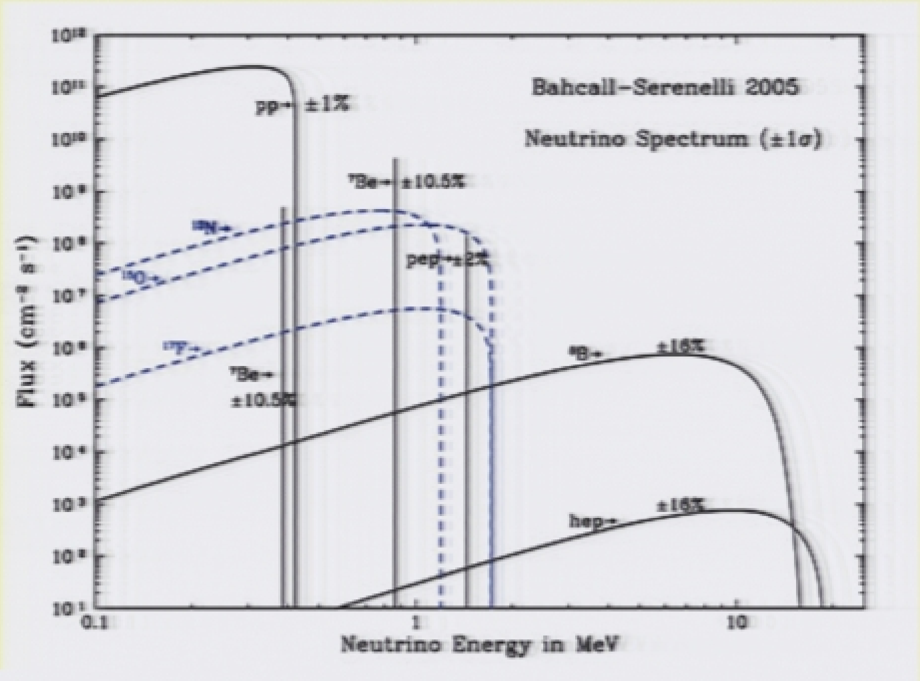

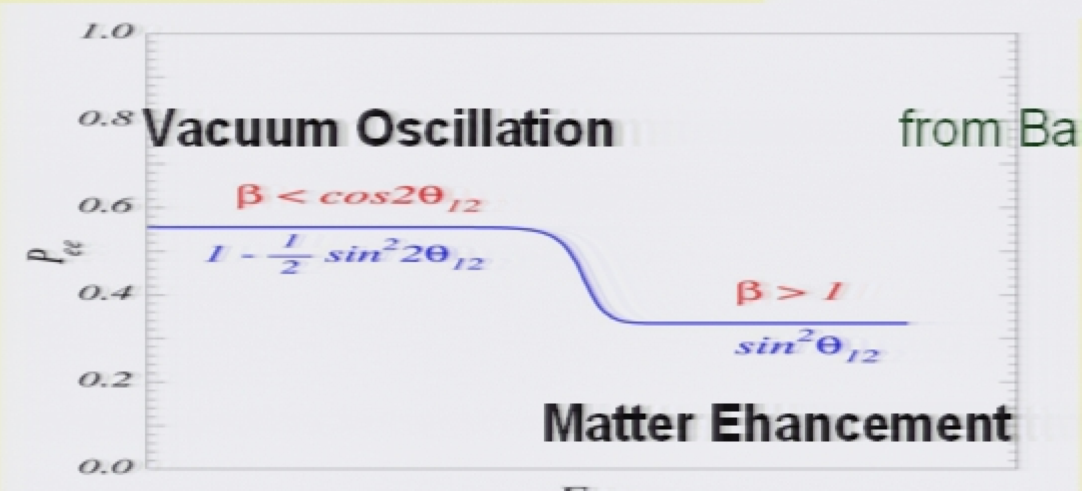

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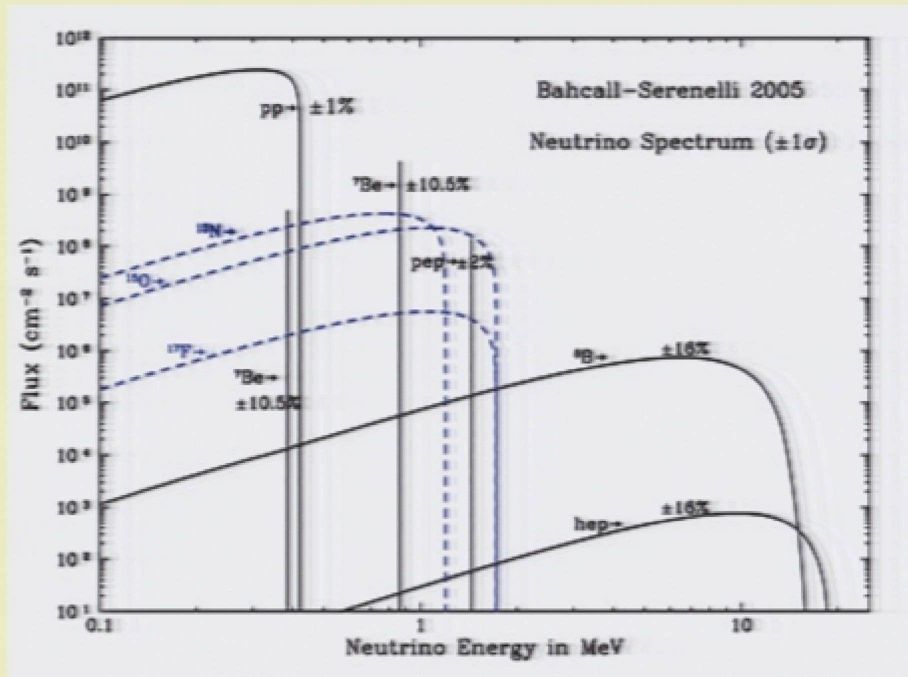

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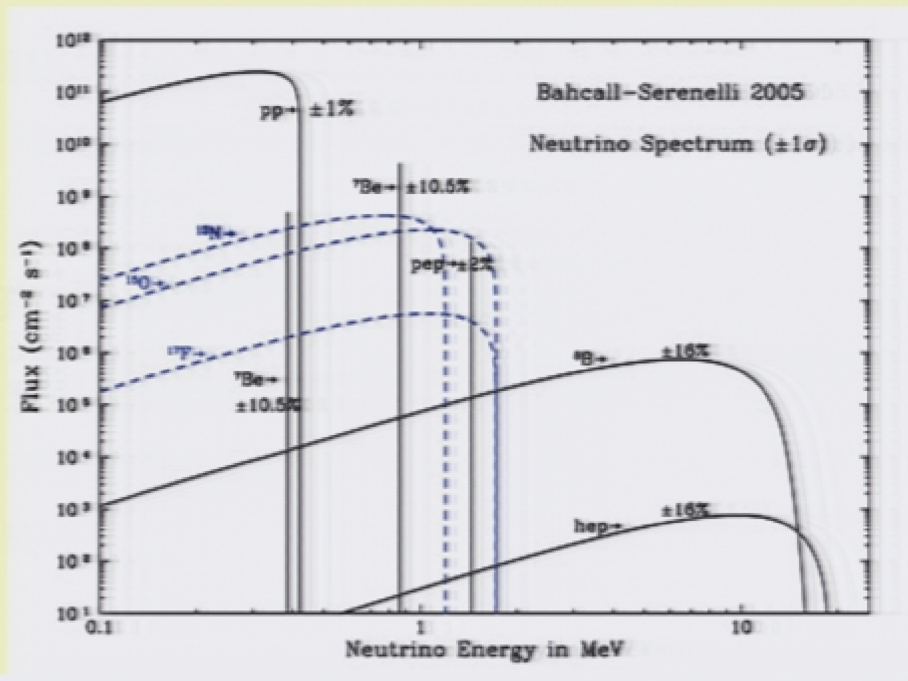
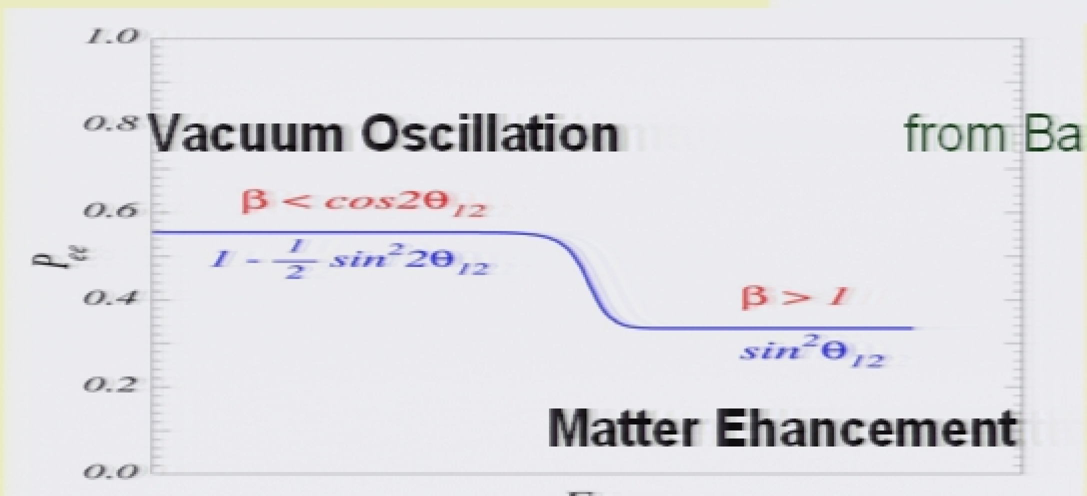




from Bahcall, Peña-Garay

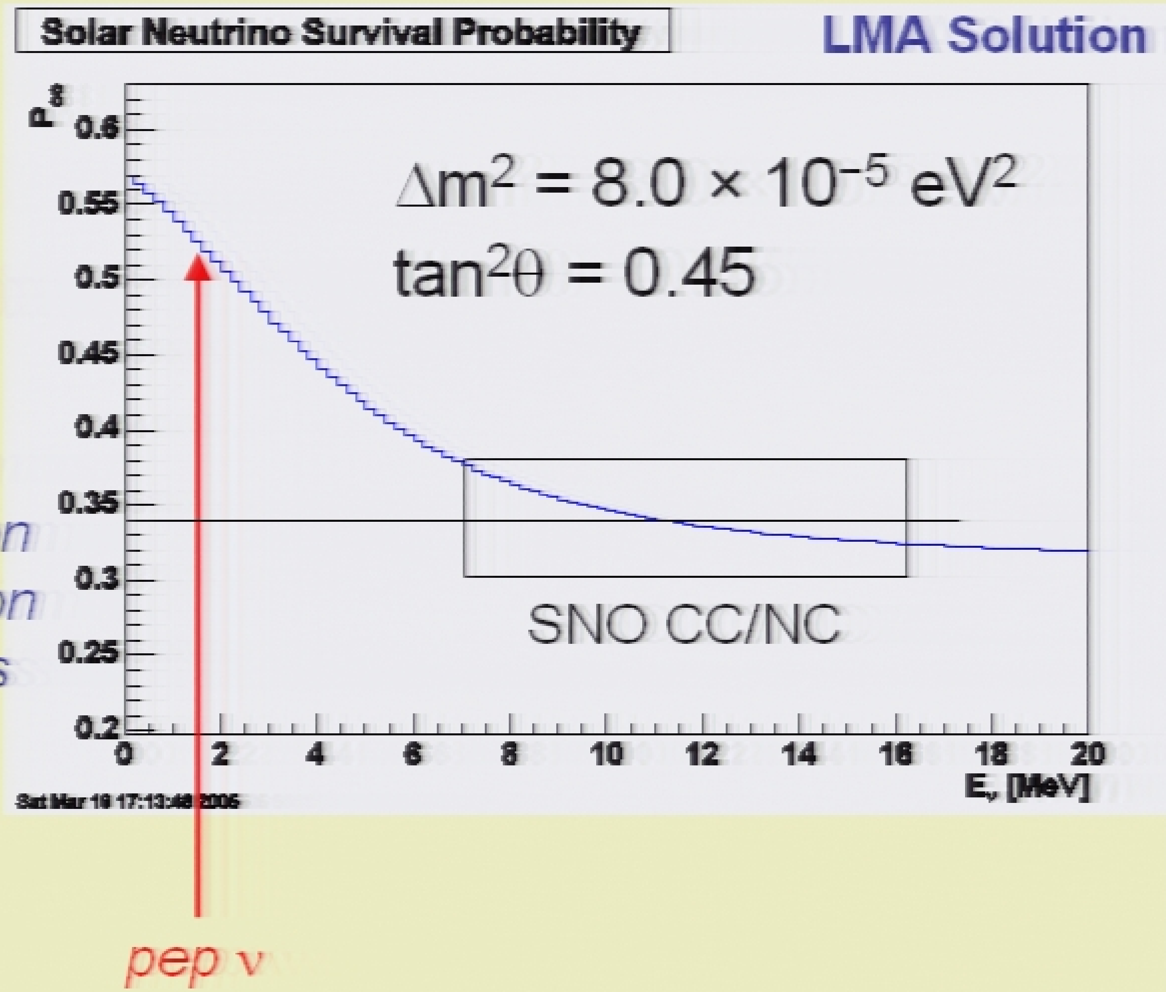
Survival Probability Rise

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

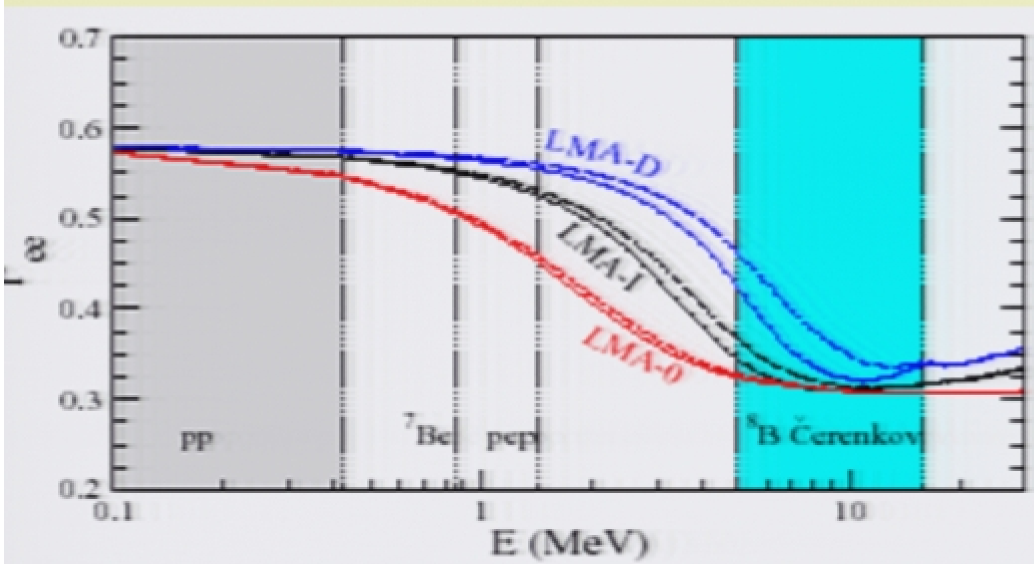


sensitive to new physics:

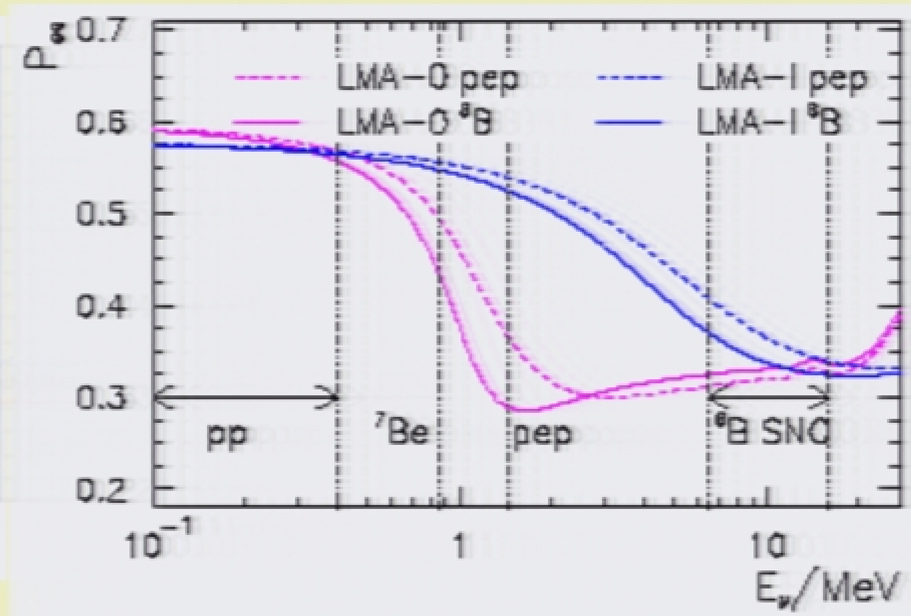
- non-standard interactions
- mass-varying neutrinos
- CPT violation
- large θ_{13}
- sterile neutrino admixture

DISTORTIONS FROM:

Non-Standard Interactions?

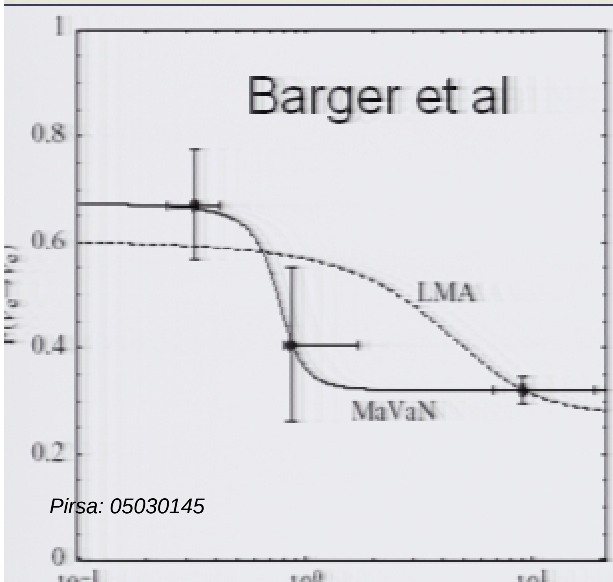


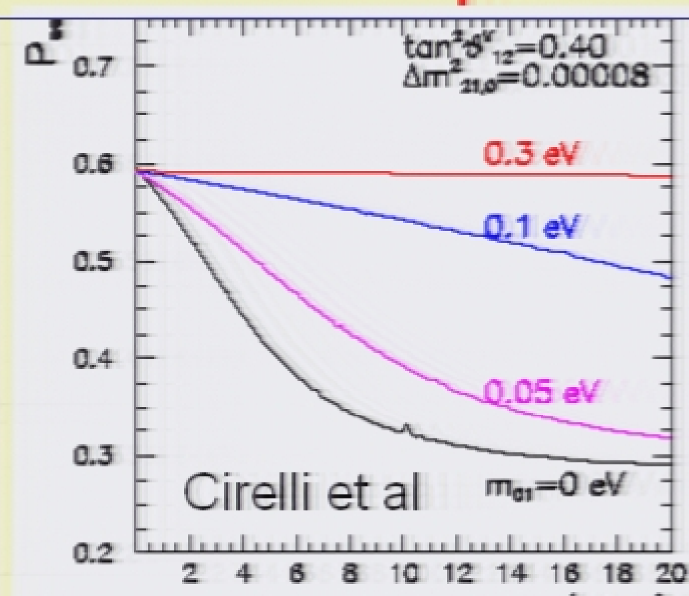
Miranda, Tórtola, Valle



Friedland, Lunardini, Peña-Garay

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



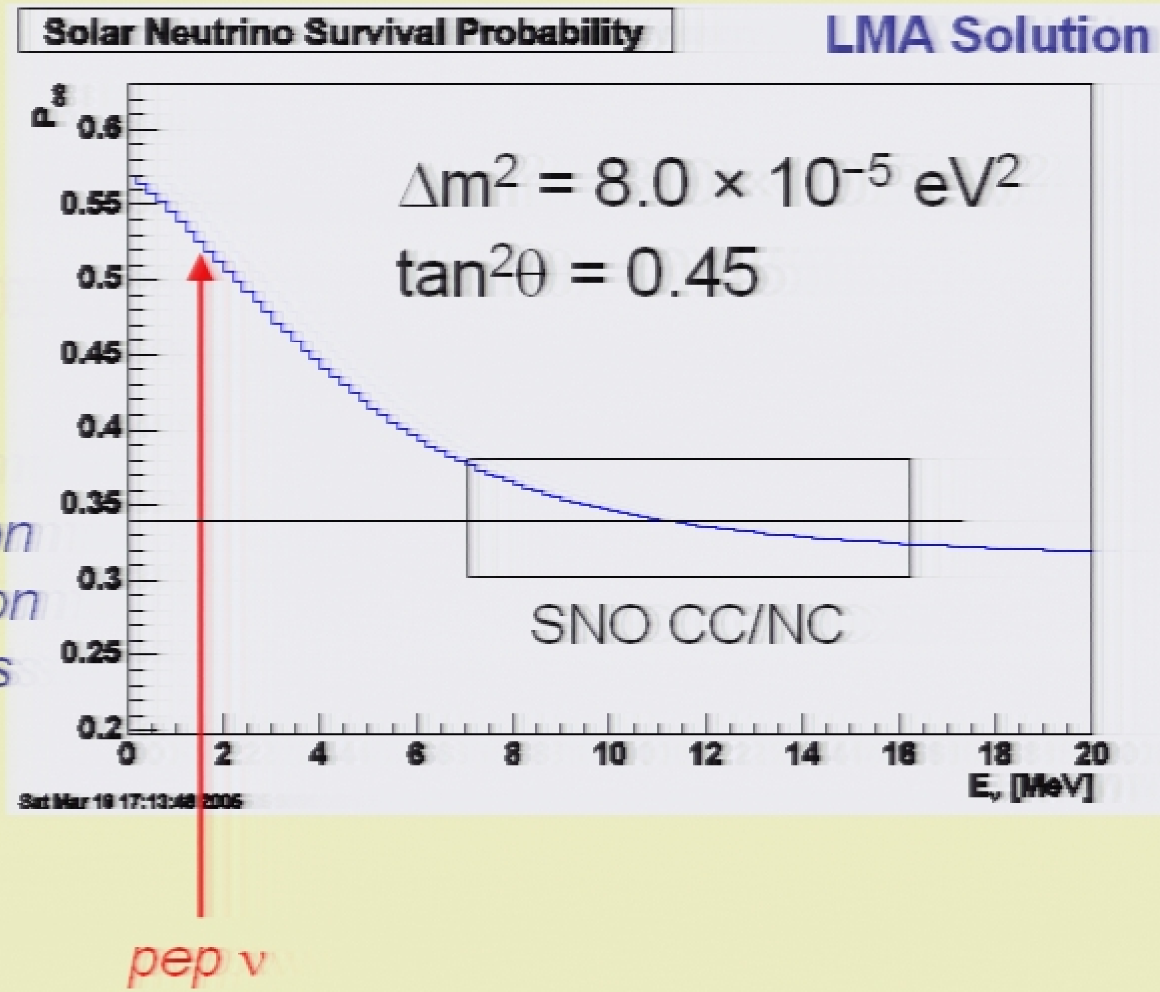


Also, distortion Effects from sterile Neutrinos: Smirnov et al

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



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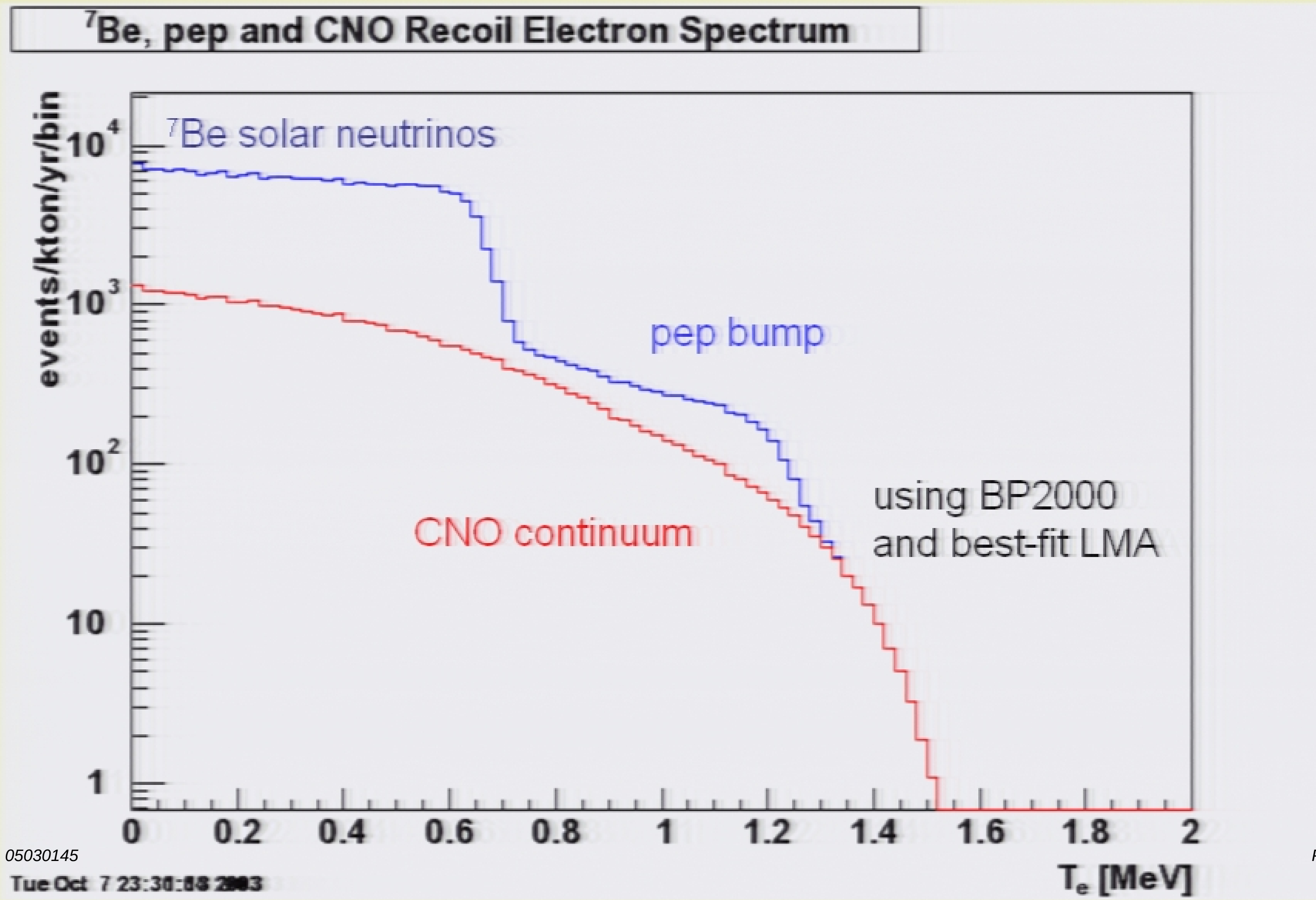
- sterile neutrino admixture

Event Rates (Oscillated)

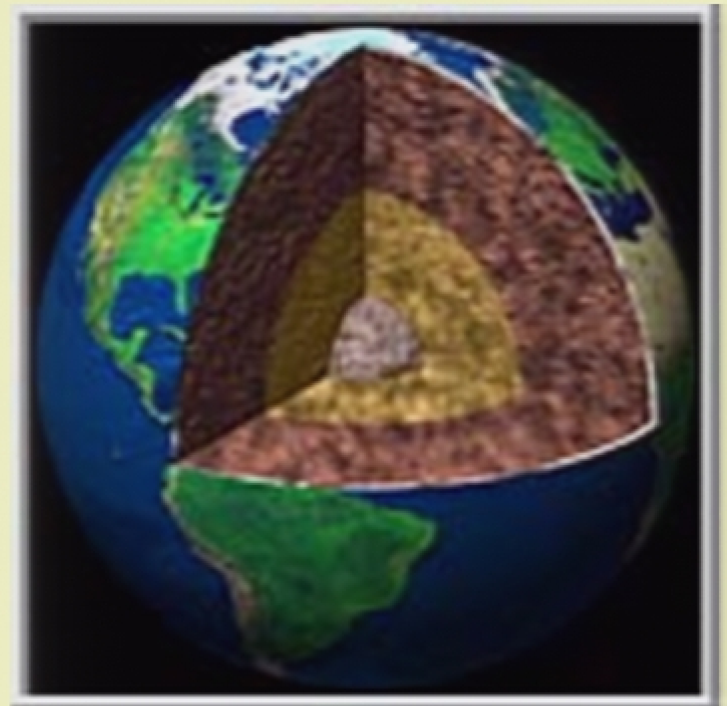


pep Solar ν Backgrounds

- ^{11}C cosmogenic production
  - $t_{1/2}$ = 20 min makes this difficult to veto at shallower depths
  - positron decay guarantees >1 MeV energy deposited, right in the *pep* ν–e⁻ recoil window
  - but at SNO depths, muon rate is small enough to allow easy tagging (or even tolerate this background without veto)
- CNO neutrinos are a "background"
  - good energy resolution desired to see clear "recoil edge" for monoenergetic *pep* ν
  - clearly interesting, for astrophysics, first observation of CNO ν ?
- radiopurity requirements challenging
  - ^{40}K, ^{210}Bi (Rn daughter)
  - ^{85}Kr, ^{210}Po (seen in KamLAND) not a problem since *pep* signal is at higher energy than ^{7}Be
  - U, Th not a problem if can achieve KamLAND-level purity

Antineutrino Geophysics

- can we detect antineutrinos from β^- decay of U and Th in the Earth's mantle and crust?
- knowing Earth's total radioactivity would be very important for geophysics
  - understanding thermal history of the Earth
  - thought to account for ~40% to 100% of Earth's total heat flux (i.e. poorly constrained)
  - dominant heat source driving mantle convection
- how much in the mantle and the crust?



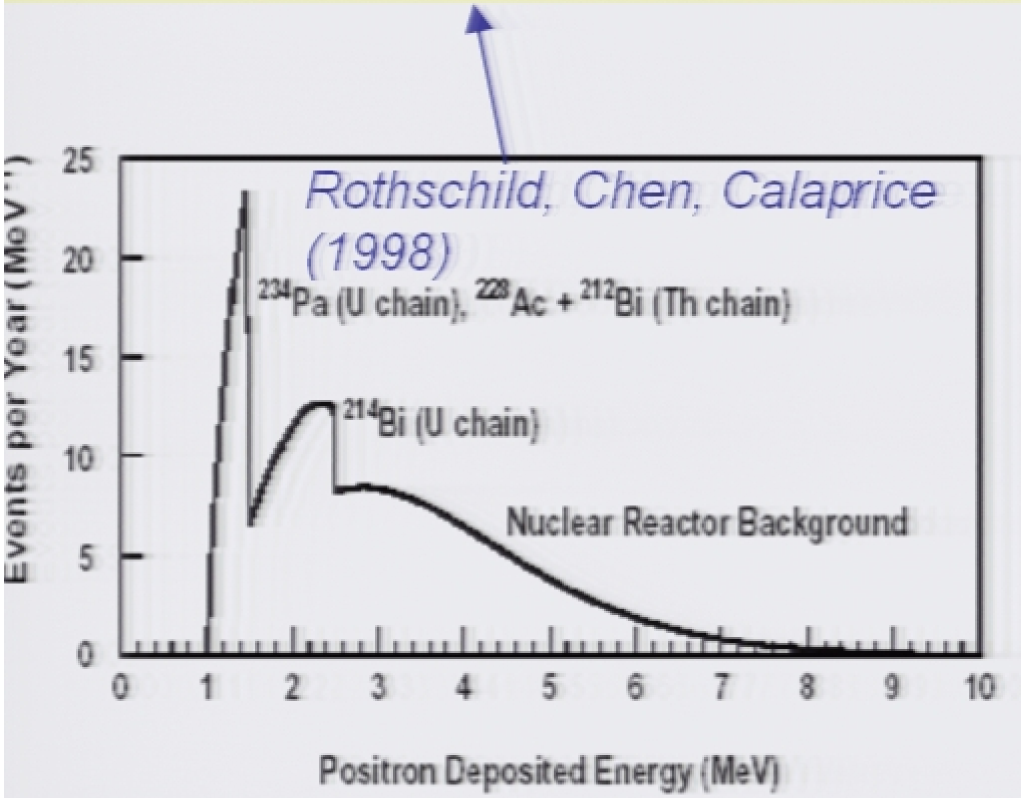
$\bar{\nu}_e + p \rightarrow e^+ + n$

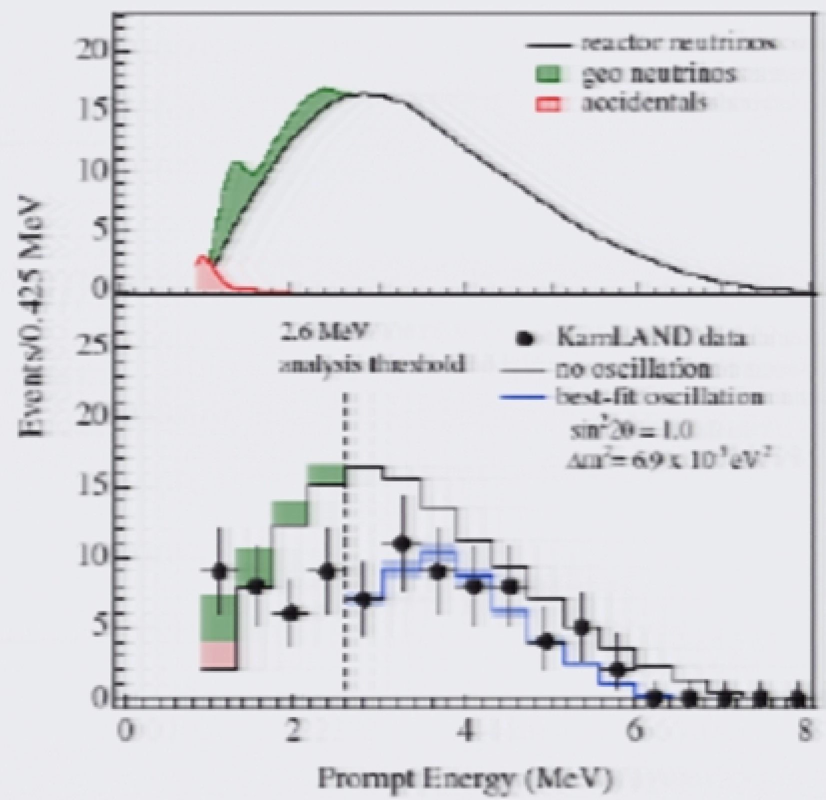
delayed coincidence

Geo-Neutrino Signal

terrestrial antineutrino event rates:

- Borexino: 10 events per year (280 tons of C_9H_{12}) / 29 events reactor
- KamLAND: 29 events per year (1000 tons CH_2)
- Sudbury: 64 events per year (1000 tons CH_2) / 87 events reactor





above plot for Borexino… geo/reactor ratio at Sudbury would be twice as high

KamLAND: $^{13}C(\alpha,n)$ a problem?

Supernova Neutrinos

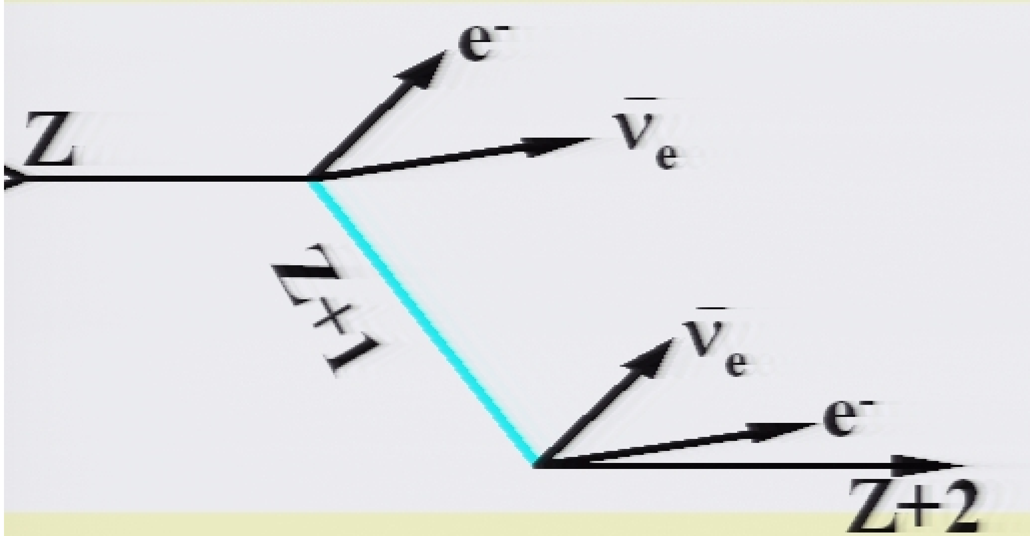
- 1 kton organic liquid scintillator would maintain excellent supernova neutrino capability
  - $\bar{\nu}_e$ + p [large rate]
  - $\bar{\nu}_e$ + ^{12}C (CC)
  - ν_e + ^{12}C (CC)
  - ν_x NC excitation of ^{12}C (NC)
  - ν_x + p elastic scattering (NC) [large rate]

  see Beacom *et al.*, PRD **66**, 033001(2002)

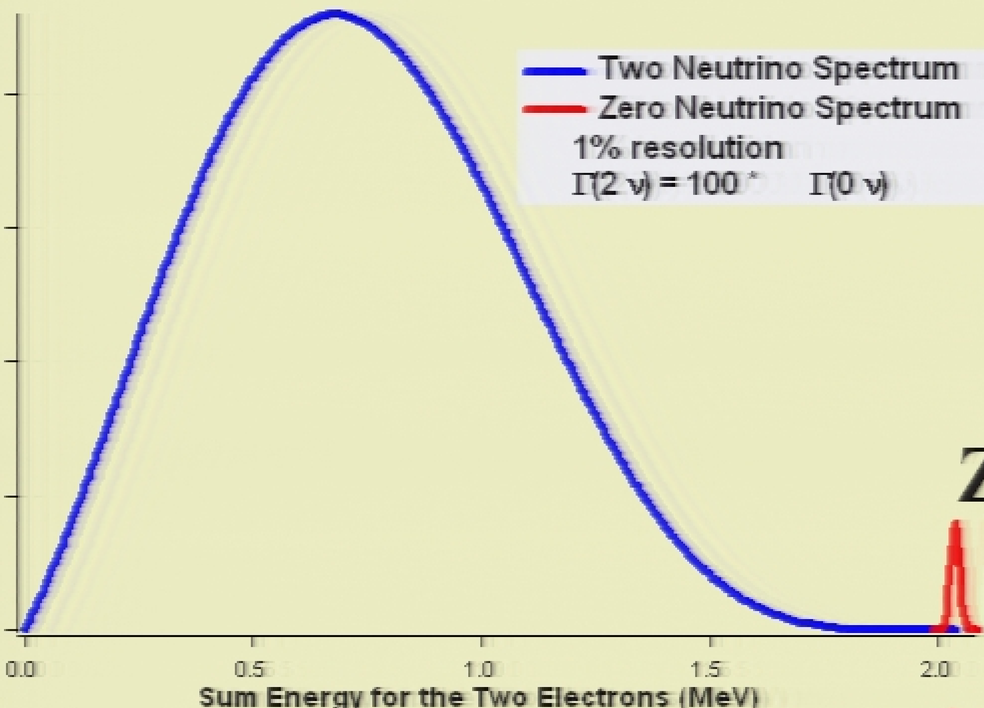
Overall ~ 400 events for a supernova at galactic center

SNO+… An Extension of SNO Science

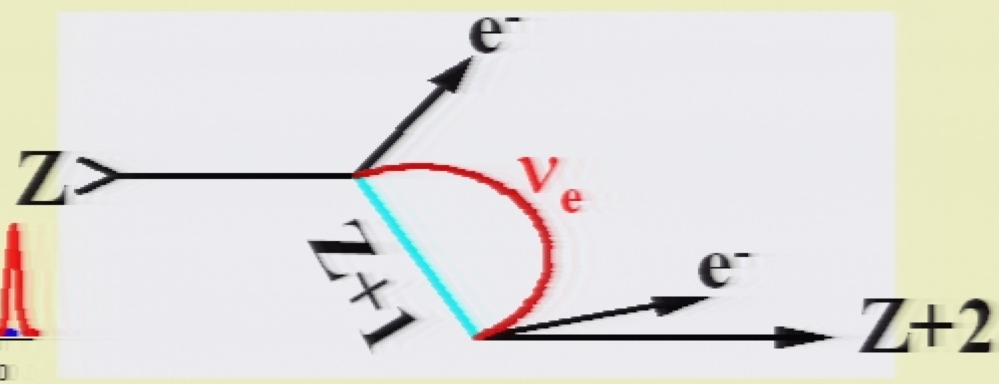
- new physics in a timely way.
- lower energy ^{8}B and *pep* are a great opportunity to test the neutrino-matter interaction
- SNO+ is well positioned to make these measurements (depth, geology, appropriate distance to reactors, low backgrounds)
- requirements
  - liquid scintillator procurement (interaction with acrylic)
  - mechanics of new configuration (density of LS)
  - Acrylic Vessel certification
  - fluid handling and safety systems
  - scintillator purification



ββ Decay



Requires Massive Majorana Neutrino
ΔL=2

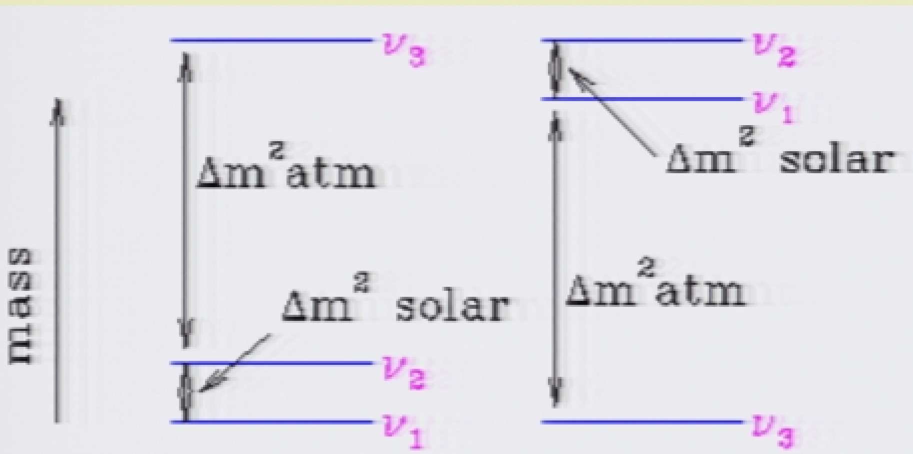


Endpoint Energy

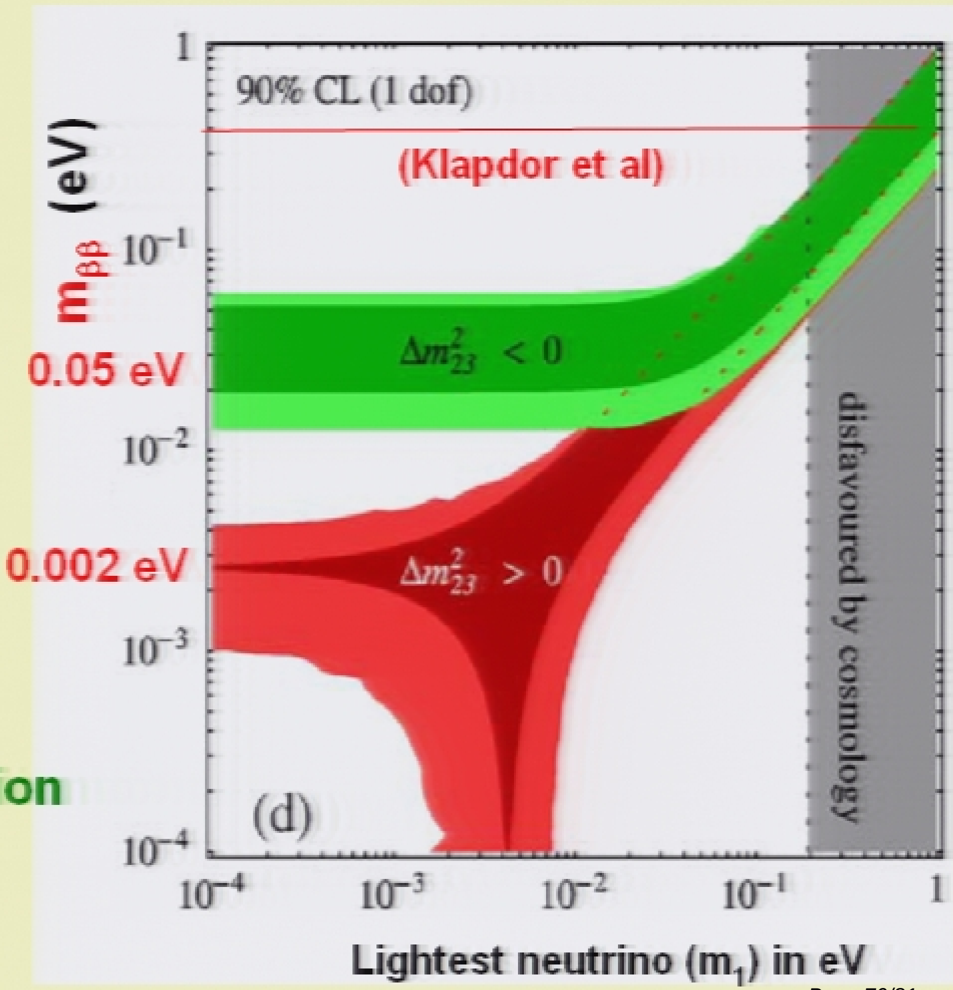
Measuring Effective Mass

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

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



normal hierarchy   inverted hierarchy



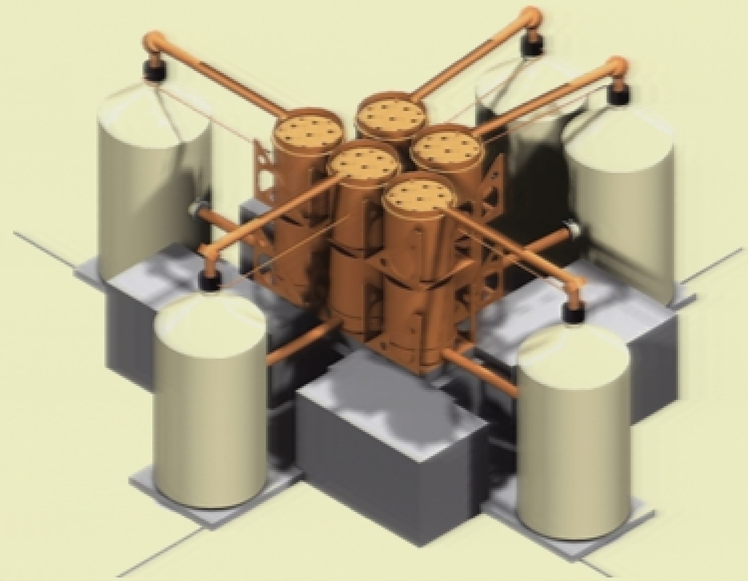
Key requirements: Mass, > ~ 200 kg

Very low backgrounds, Good resolution

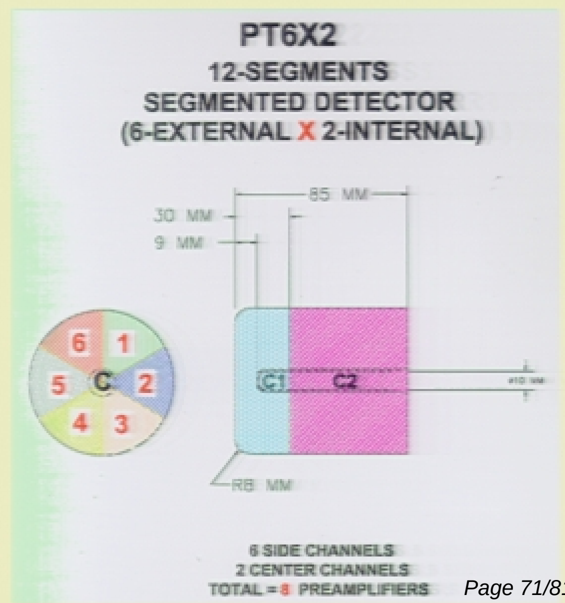
Many Candidate Nuclei:

Ge, Xe, Te, Ca, Se, Mo, Cd, Nd

Example: Majorana



- 200 kg enriched 86% ^{76}Ge
- many crystals, each segmented
- advanced signal processing
- require special low background materials
- need deep underground location
- effective low background shielding (active?...Liquid Ar?)



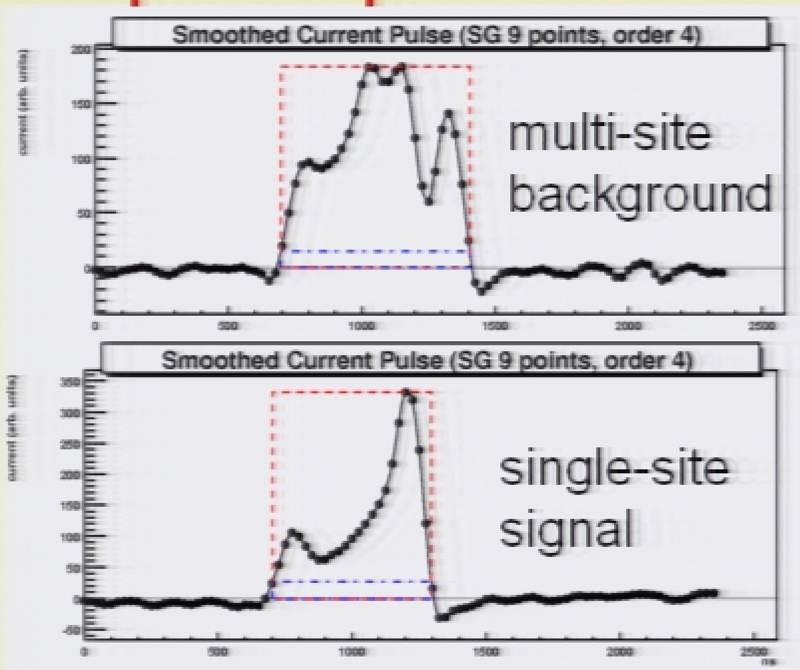
Few keV resolution at $Q_{\beta\beta}$ = 2039 keV
known technology → should be few surprises

sensitivity to few 10^{27} years
$m_\nu \sim 0.05$ eV

US, Canada, Russia collaboration

Majorana

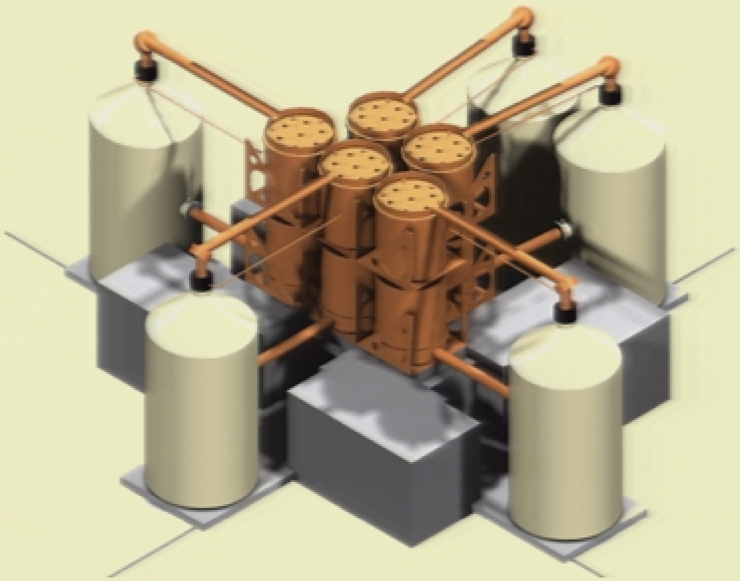
Use pulse shape discrimination



site electroformed copper

source	B $\frac{10^{-3}\text{cts}}{\text{keV}\cdot\text{kg}\cdot\text{y}}$	B after bkg. rej. $\frac{10^{-3}\text{cts}}{\text{keV}\cdot\text{kg}\cdot\text{y}}$	B after add. det. segm. $\frac{10^{-3}\text{cts}}{\text{keV}\cdot\text{kg}\cdot\text{y}}$
ext. γ from ^{208}Tl, ^{228}U	1	0.4	0.2
ext. neutrons	≤ 0.05	≤ 0.03	≤ 0.02
ext. muons	≤ 0.1	≤ 0.05	≤ 0.03
internal ^{68}Ge	12	1.1	0.3
internal ^{60}Co	2.5	0.8	0.2
^{222}Rn in LN/LAr	0.2	≤ 0.1	≤ 0.1
^{208}Tl, ^{228}U in holder mat.	≤ 1	≤ 0.1	≤ 0.1
surface contamination	≤ 0.6	≤ 0.1	≤ 0.1

Example: Majorana



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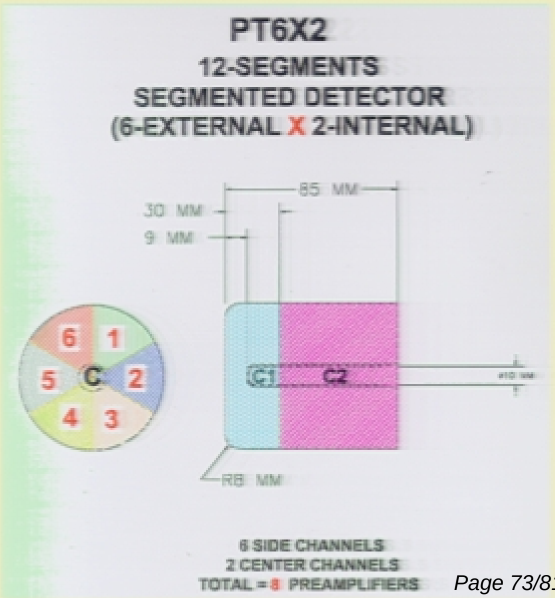


US, Canada, Russia collaboration

EXO

- 10 ton gas or liquid TPC filled with enriched ^{136}Xe (80%)
- $\beta\beta$ decay produces $^{136}Ba^{++}$
- measure electrons with TPC
- tag Ba to eliminate backgrounds (optical spectroscopy)
- purify gas/liquid in-situ
- in principle easily scalable

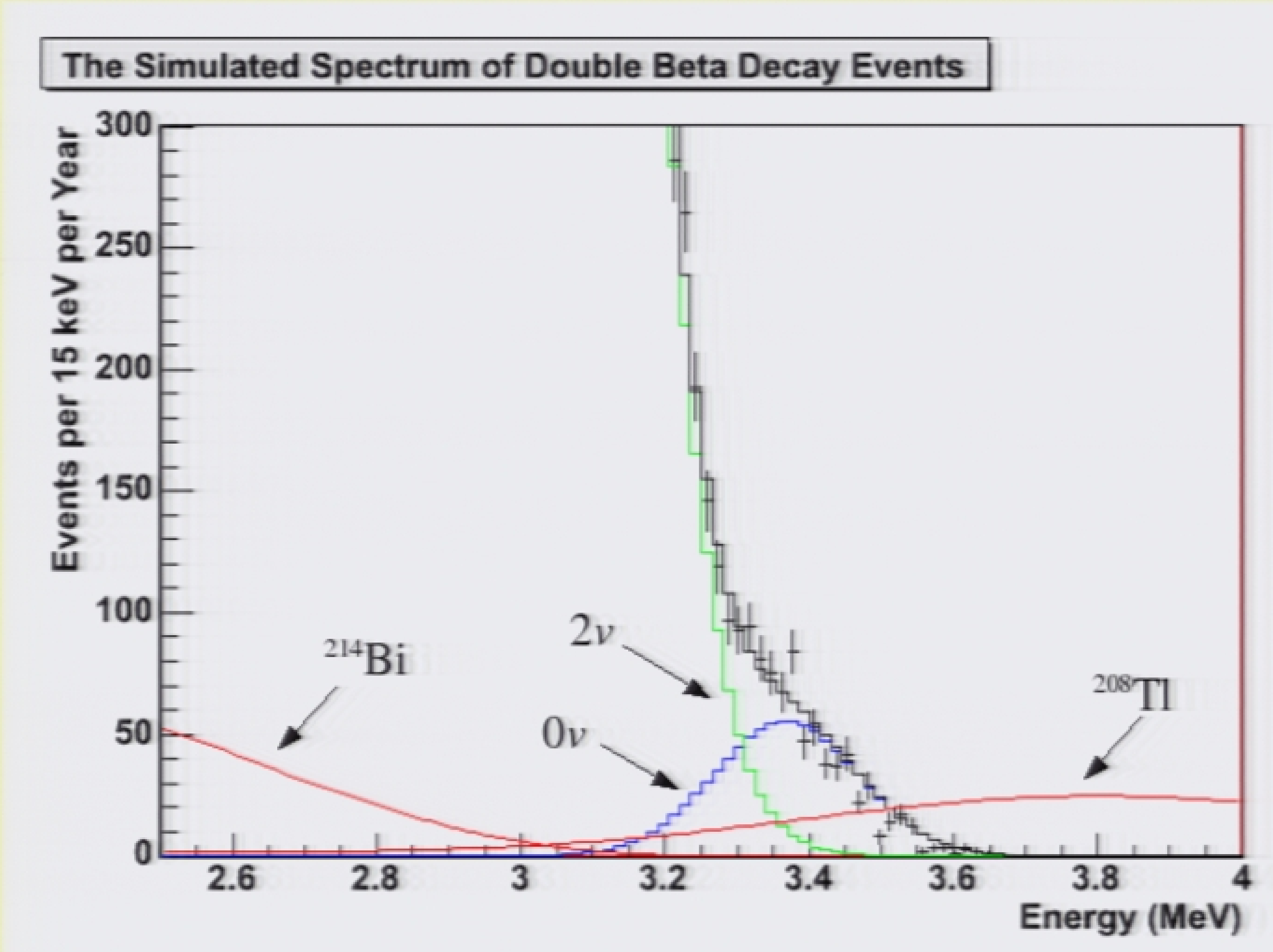
Isotope	Det mass (kg)	Enrich. (%)	Eff. (%)	Measur. time (yr)	Background	$T_{1/2}^{0\nu\beta\beta}$ (yr)	$<m_\nu>$ QRPA	(eV) NSM
$^{136}Xe^{*}$	1000	80	70	5	0 + 1.8 events	$8.3 \cdot 10^{26}$	0.051	0.14
$^{136}Xe^{**}$	10000	80	70	10	0 + 5.5 events	$1.3 \cdot 10^{28}$	0.013	0.037

SNO++ (Nd Double Beta Decay)

0ν: 1057 events per year with 1% natural Nd-loaded liquid scintillator in SNO++.

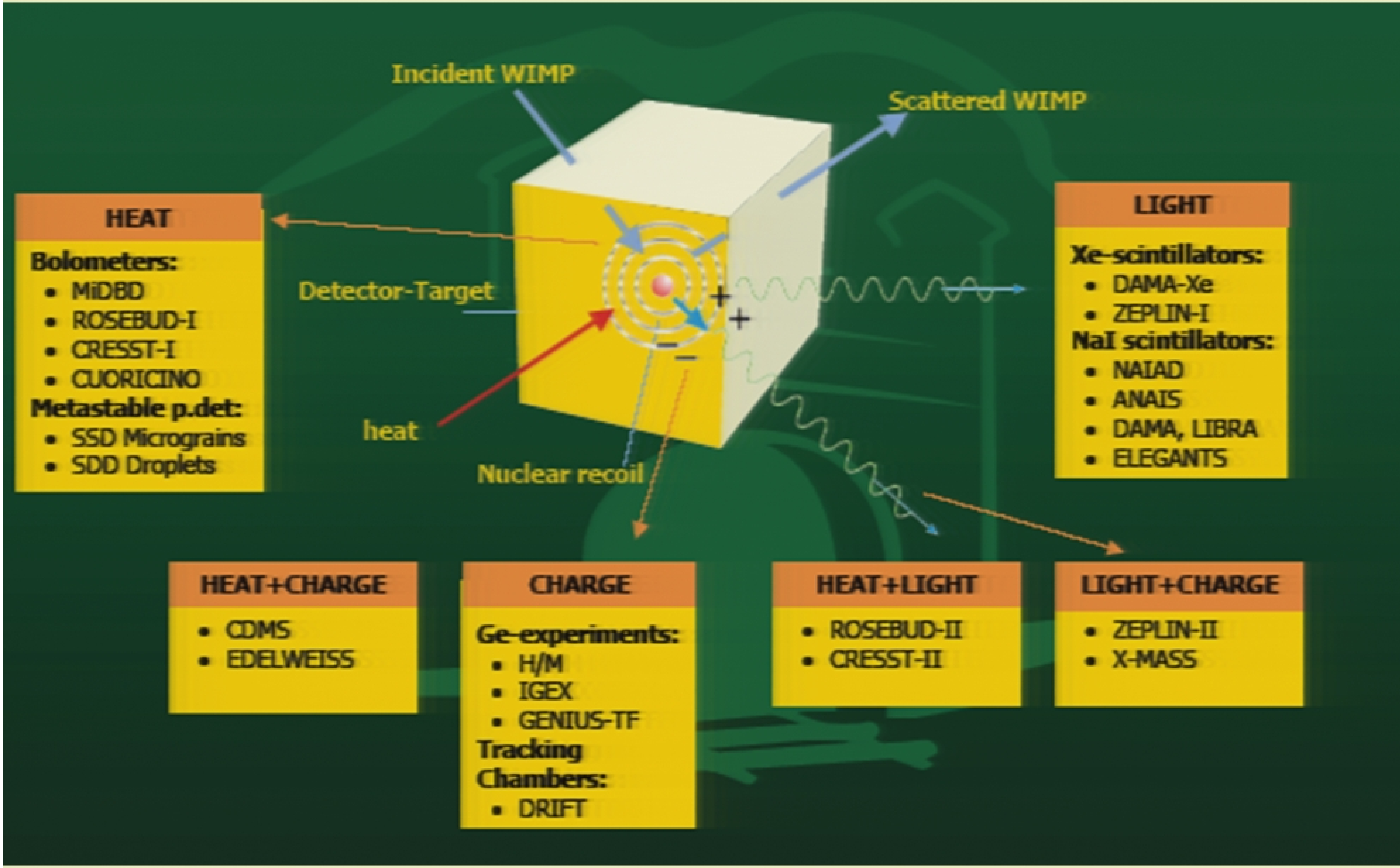
Simulation assuming light output similar to Kamland.

Very preliminary simulation:
one year of data
$m_\nu = 0.15$ eV



Direct Measurements of Dark Matter

Figure: Angel Morales

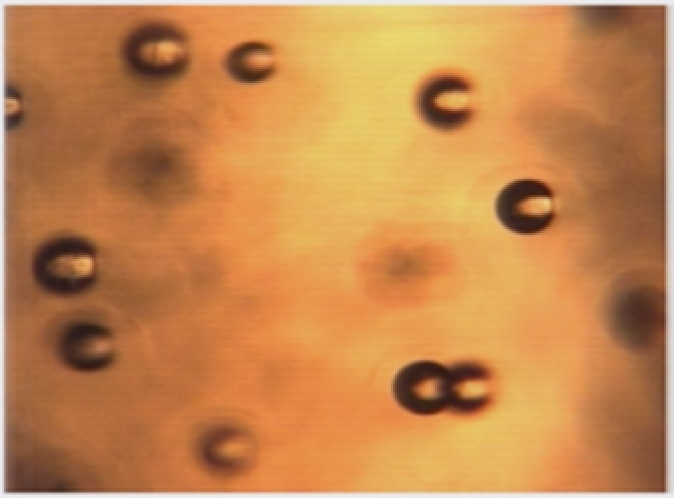


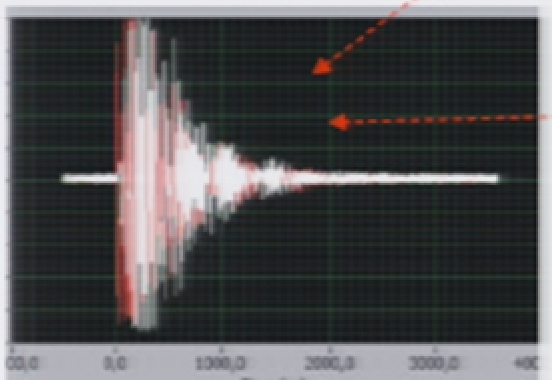
Neutrons can be a major problem, but at SNOLAB, this background is

The Superheated Droplet Detector

- droplets superheated at ambient T & P
- 50 to 100μm droplets of carbofluorides dispersed in polymerised gel
- active liquids:

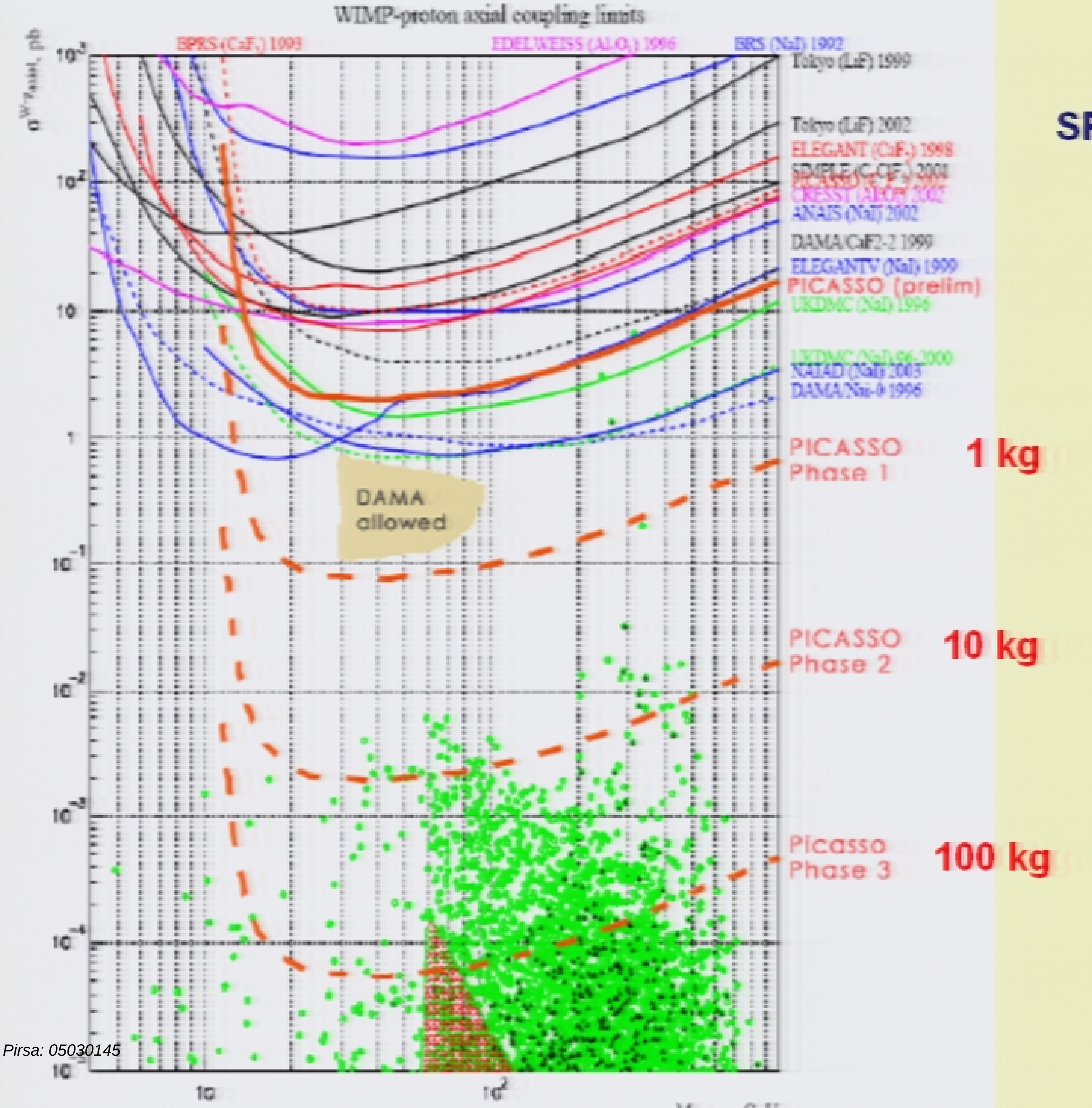
  C_4F_{10} (T_b=-1.7 °C) , C_3F_8 (T_b=-36.7 °C)
- …used for n-dosimetry (BTI-Chalk River)
- Recoil energy threshold E_{rec} = O(keV)
- insensitive to β, γ and cosmic μ radiation





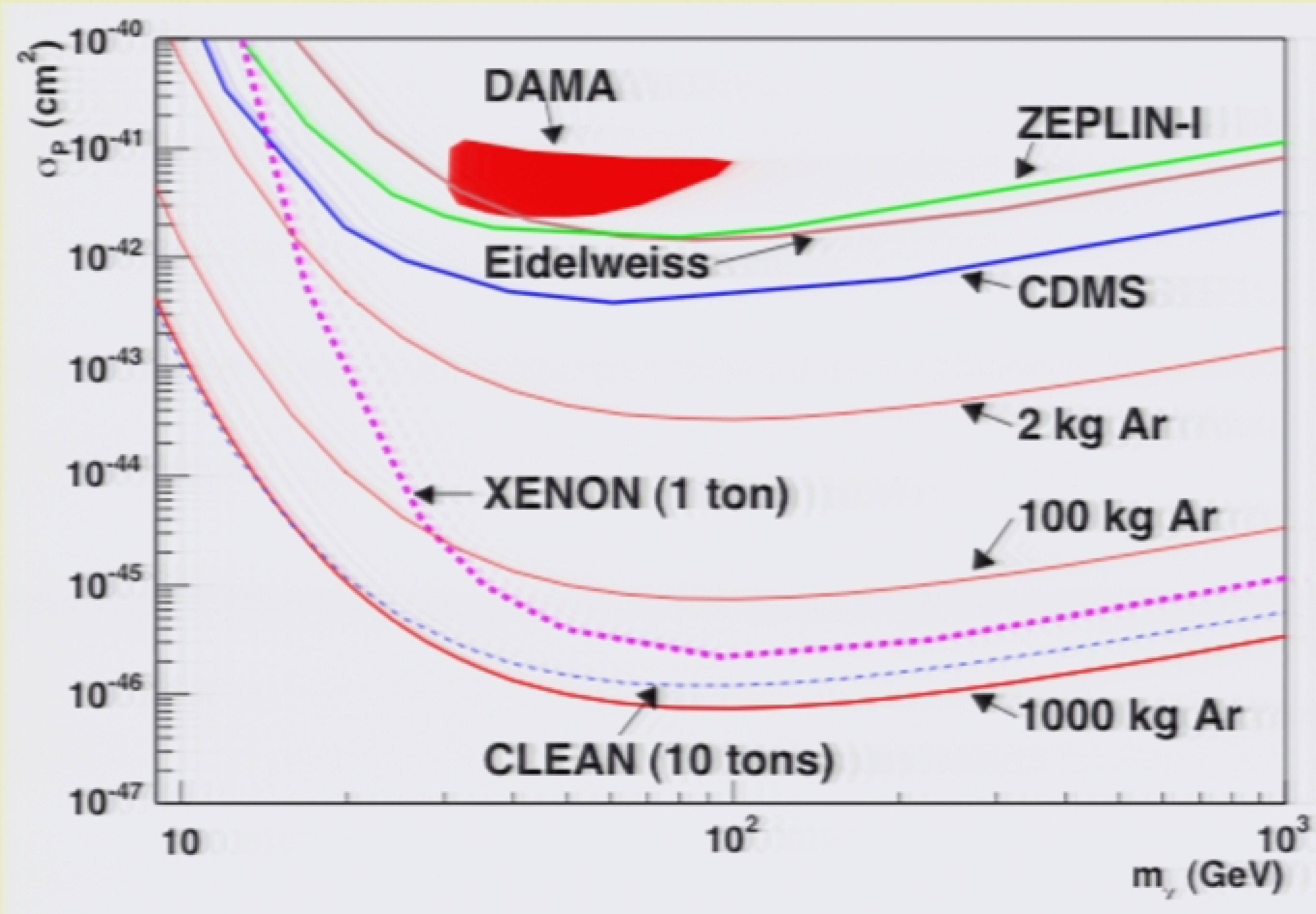
Montreal, Queen's

Indiana, Pisa, BTI



SPIN - DEPENDENT INTERACTION

Spin Independent Interaction



} Where we Are

} Some Future Expts.

Liquid Ar scintillation M.G. Boulay & A. Hime, astro-ph/0411358

CONCLUSIONS

- Cleanliness is next to deepliness…
- Many basic neutrino properties have been defined and we have now entered the precision phase.
- Particle Astrophysics is a great way to study both astro, and particle physics.
- Canada will have some wonderful opportunities in the near future with SNOLAB.

The SNO Collaboration

S. Gil, J. Heise, R.L. Helmer, R.J. Komar, T. Kutter,
S. M. Oser, C.W. Nally, H.S. Ng, R. Schubank,
Y. Tserkovnyak, T. Tsui, C.E. Waltham, J. Wendland
University of British Columbia

J. Boger, R. L Hahn, R. Lange J.K. Rowley, M. Yeh
Brookhaven National Laboratory

I. Blevis, A. Bellerive, X. Dai, F. Dalnoki-Veress, R. S. Dosanjh,
W. Davidson, J. Farine, D.R. Grant, C. K. Hargrove,
R. J. Hemingway, I. Levine, K. McFarlane, H. Mes, C. Mifflin,
V.M. Novikov, M. O'Neill, E. Rollin, M. Shatkay, C. Shewchuk,
O. Simard, D. Sinclair, N. Starinsky, G. Tesic, D. Waller
Carleton University

T. Andersen, M. Bergevin, K. Cameron, M.C. Chon, P. Jagam,
J. Karn, H. Labranche, J. Law, I.T. Lawson, B. G. Nickel,
R. W. Ollerhead, J. J. Simpson, N. Tagg, J.X. Wang
University of Guelph

B. Aharmim, J. Bigu, J.H.M. Cowan, J. Farine,
F. Fleurot, N. Gagnon, E. D. Hallman, R. U. Haq, J. Hewett,
J.G. Hykawy, G. Jonkmans, A. Kruger, S. Luoma,
A. Roberge, E. Saettler, M.H. Schwendener,
H. Seifert, R. Tafirout, C. J. Virtue
Laurentian University

Y. D. Chan, X. Chen, C. A. Currat, M.C.P. Isaac, K. M. Heeger,
K. T. Lesko, A.D. Marino, E.B. Norman, C.E. Okada, A.W. P. Poon,
S. S. E. Rosendahl, A. R. Smith, A. Schuelke, R. G. Stokstad
Lawrence Berkeley National Laboratory

M. G. Boulay, T. J. Bowles, S. J. Brice, M. R. Dragowsky, S. R. Elliott,
M. M. Fowler, A. Goldschmidt, A. Hime, J. Heise, K. Kirch, G. G. Miller,
P. Thornewell, R. G. Van de Water, J. B. Wilhelmy, J. M. Wouters.
Los Alamos National Laboratory

R.G. Allen, G. Buhler, H.H. Chen*
University of California

J. D. Anglin, M. Bercovitch, W. F. Davidson, R. S. Storey*

J. C. Barton, S. D. Biller, R. A. Black, R. Boardman, M. G. Bowler,
J. Cameron, B. T. Cleveland, G. Doucas, J. A. Dunmore, A. P. Ferraris,
H. Fergani, K.Frame, H. Heron, C. Howard, N. A. Jelley, A. B. Knox,
M. Lay, J. C. Loach, W. Locke, J. Lyon, N. McCaulay, S. Majerus,
G. McGregor, M. Moorhead, M. Omori, S. J. M. Peeters, C. J. Sims,
N. W. Tanner, R. Taplin, M. Thorman, P. T. Trent,
D. H. Wan Chan Tseung, N. West, J. R. Wilson, K. Zuber
Oxford University

E. W. Beier, D. F. Cowen, J. Deng, M. Dunford, E. D. Frank,
W. Frati, W. J. Heintzelman, P.T. Keener, C. C. M. Kyba,
N. McCauley,D. S. McDonald, M.S.Neubauer,
F. M. Newcomer,V. L. Rusu, R. Van Berg, P. Wittich.
University of Pennsylvania

M.M. Lowry, Princeton University

S.N. Ahmed, E. Bonvin, M. G. Boulay, M. Chen, E. T. H. Clifford,
Y. Dai, F. A. Duncan, E. D. Earle,H. C. Evans, G.T. Ewan, R. J. Ford,
B. G. Fulsom, K. Graham, W. B. Handler, A. L. Hallin, A. S. Hamer*,
P. J. Harvey, R. Heaton, J. D. Hepburn, C. Jillings, M. S. Kos,
L. L. Kormos, R. Kouzes, C. B. Krauss, A. V. Krumins, H. W. Lee,
J. R. Leslie, R. MacLellan, H. B. Mak, J. Maneira, A. B. McDonald,
W. McLatchie, B. A. Moffat, A. J. Noble, C. Ouellet, T. J. Radcliffe,
B.C. Robertson, P. Skensved, B. Sur. Y. Takeuchi, M. Thomson
Queen's University

D.L. Wark, Oxford U. and Rutherford Laboratory

R.L. Helmer, TRIUMF

A.E. Anthony, J.C. Hall, J.R. Klein
University of Texas at Austin

Q. R. Ahmad, M. C. Browne, T.V. Bullard, T. H. Burritt, G. A. Cox,
P. J. Doe, C. A. Duba, S. R. Elliott, R. Fardon, J. A. Formaggio,
J.V. Germani, A. A. Hamian, R. Hazama, K. M. Heeger, M. A. Howe,
S. McGee, R. Meijer Drees, K. K. S. Miknaitis, N. S. Oblath, J. L. Orrell,
K. Rielage, R. G. H. Robertson, K. Schaffer, M. W. E. Smith,
T. D. Steiger, L. C. Stonehill, B. L. Wall, J. F. Wilkerson.
University of Washington

C. Milton, B. Sur, AECL, Chalk River