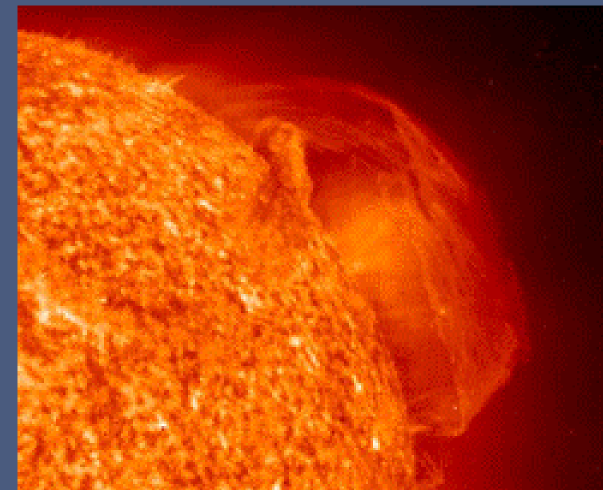
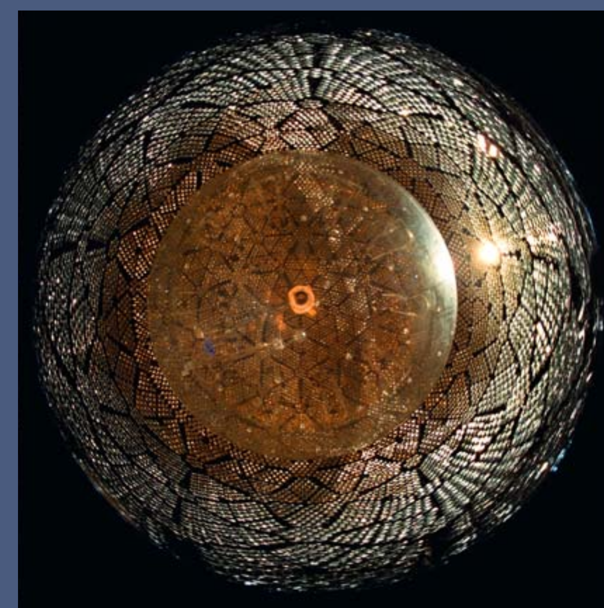
Multiple Personality Neutrinos from the Sun



Alain Bellerive
Canada Research Chair in Particle Physics
Carleton University

On behalf of the SNO Collaboration



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Outline

- Introduction
  - ❖ Where and How!?!
  - ❖ Fundamental Forces of Nature
  - ❖ Standard Model of Elementary Particles
  - ❖ Tools: Particle Detectors
- Electroweak Reactions
- Solar Neutrino Physics
- Long Standing Solar Neutrino Problem/Solution
- Experimental Apparatus: SNO
- Results on Neutrino Oscillations
- Future of Particle Astrophysics in Canada
- Summary and Conclusion

Where and How !?!

Everybody in Physics at CUPC:

- *Fun – Curious – Passion*
- *Applied or Pure*
- *Experimental or Theoretical*

Underground Science:

- *Neutrinos – Dark Matter*
- *New Opportunities with SNOLAB*
- *Institutions: Carleton, Guelph, Laurentian, Queen's, TRIUMF, UBC, and Université de Montréal.*

High Energy Physics:

- *BaBar - ATLAS - ZEUS – NLC - ν Factory*
- *CERN-SLAC-Cornell-DESY-FNAL-BNL-KEK*
- *Institute of Particle Physics (IPP)*

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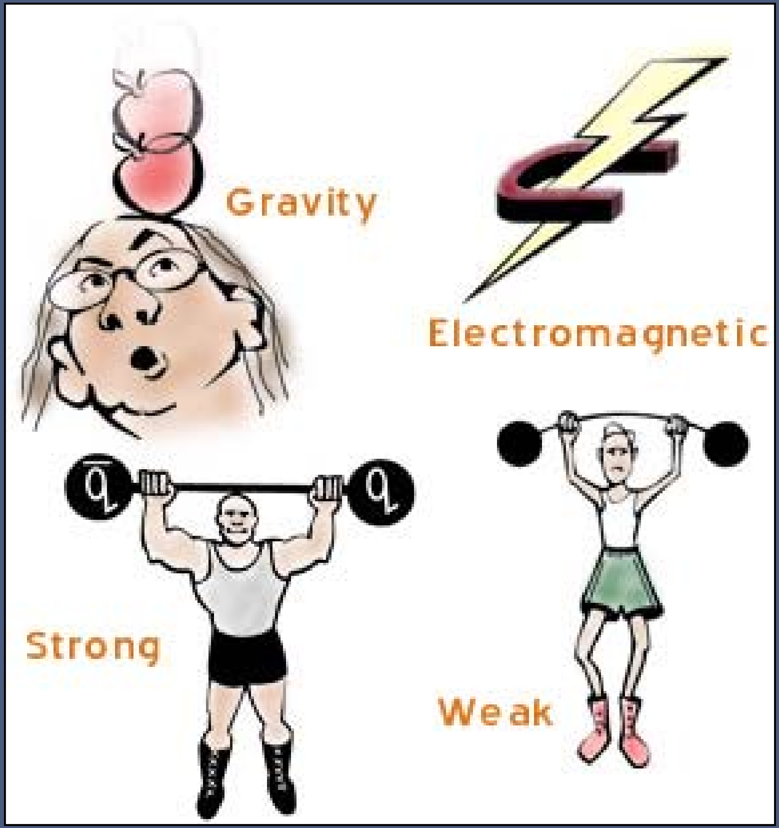
The First Piece:

- Fundamental Forces
- Standard Model
- Particle Detectors

Fundamental Forces

Gravity: Gravity governs the attraction between two massive objects. It is negligible at the subatomic scale.



Electromagnetic: Most of us are familiar with electric and magnetic phenomena.

Strong: In the Standard Model, hadrons (neutrons & protons) are considered to be made of quarks bound together by the strong force.

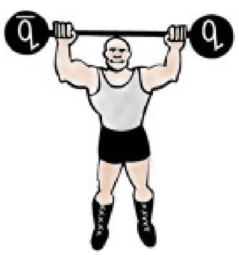
Weak: The weak interaction is more subtle! It is responsible for the instability of some nuclei via β-decay (*e.g.* n -> p e ν).

Interaction	Particle	Range (m)	Coupling
EM	photon	infinity	10^{-2}
Strong	gluon	10^{-15}	1
Weak	W & Z	10^{-18}	10^{-6}

Elementary Particles

Fermions		Bosons	
Leptons and Quarks	Spin = $\frac{1}{2}$	Spin = 1*	Force Carrier Particles
Baryons (qqq)	Spin = $\frac{1}{2}, \frac{3}{2}, \frac{5}{2}\ldots$	Spin = 0, 1, 2...	Mesons ($q\bar{q}$)

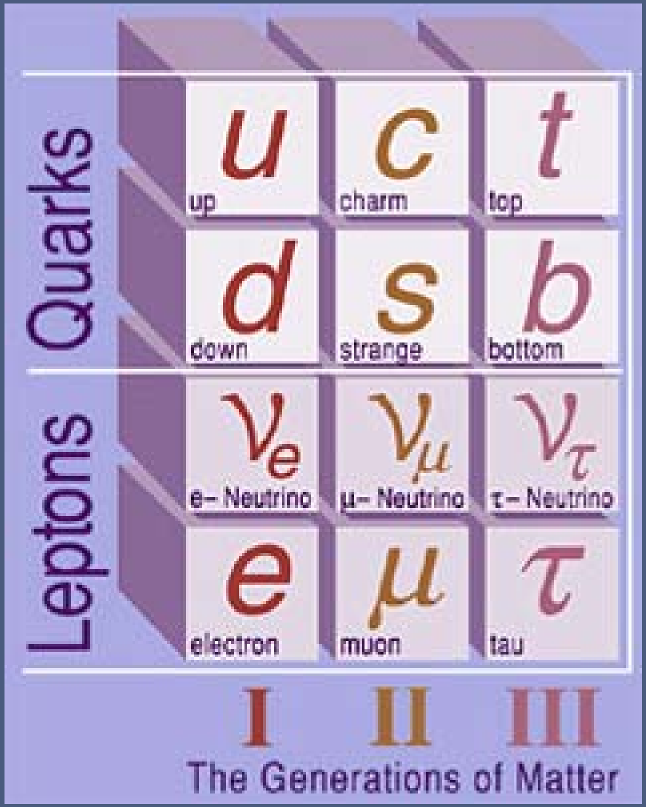


	Gravity	Weak	Electromagnetic	Strong
		Electroweak		
Carried by →	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on →	All Massive	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

Standard Model

The Standard Model provides a general description of the physics currently accessible with modern particle accelerators. The minimal Standard Model postulates that matter is composed of fundamental spin-½ quarks and spin-½ leptons interacting via spin-1 bosons.



Quarks and leptons can be sub-divided into families which interact via the exchange of weak vector bosons

Quark Sector

$Q = +2/3$

$Q = -1/3$

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

Lepton Sector

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

$Q = -1$

$Q = 0$

Electroweak Lagrangian:

L = L(weak NC) + L (em NC) + L(weak CC)

$$L(\text{em NC}) = \mathrm{e}\, J_\mu^{\text{em}} A^\mu$$

$$L(\text{weak NC}) = \frac{g}{\cos\theta_W}\left(J_\mu^0 + \sin^2\theta_W J_\mu^{\text{em}}\right) Z^\mu$$

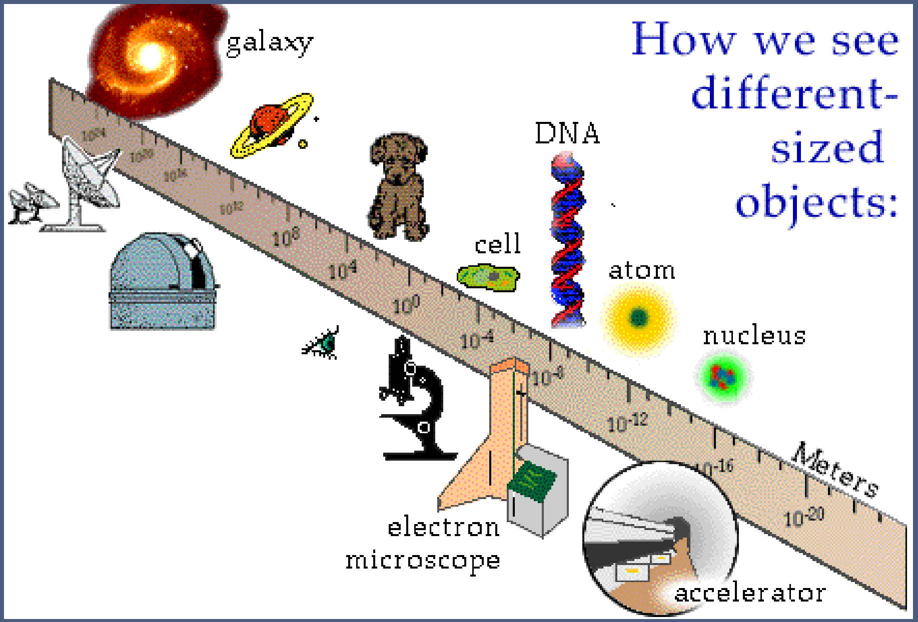
$$L(\text{weak CC}) = \frac{g}{\sqrt{2}}\left(J_\mu^+ W^{\mu-} + J_\mu^- W^{\mu+}\right)$$

Open Questions in Particle Physics

In the theoretical framework of the Standard Model, there are presently two fundamental open questions at the forefront of particle physics

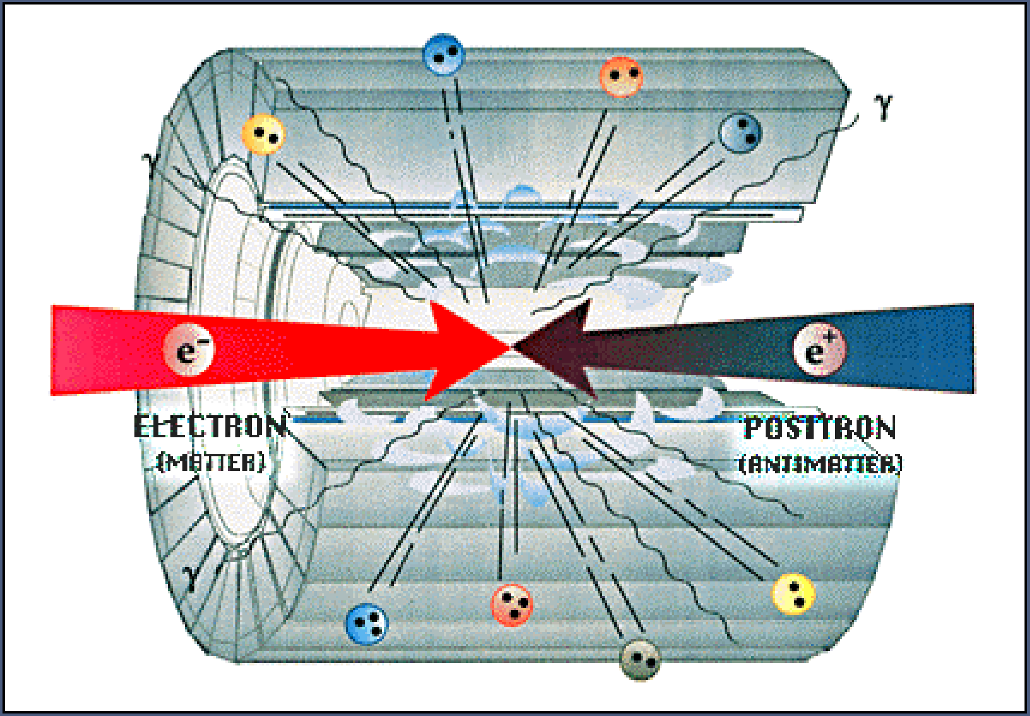
1) The **first inquires about the origin of mass generated in the electroweak sector via the <u>Higgs mechanism</u>.**

2) The other deals with the origin of <u>quark & neutrino mixing</u>, and CP violation.



Tools to study subatomic particles

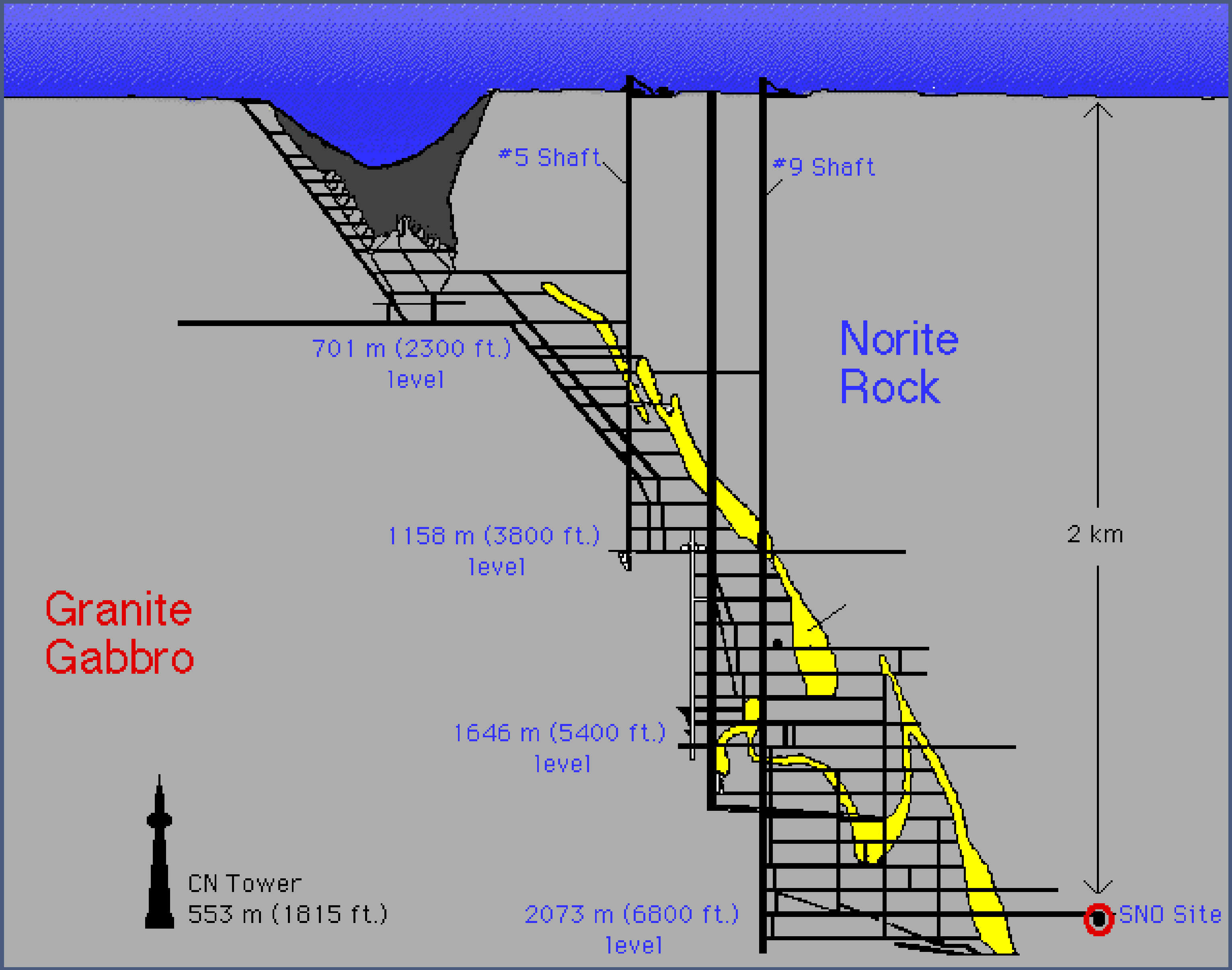
$$\Delta x \, \Delta p \approx \hbar$$



1) Multipurpose detectors operating at high energy accelerators

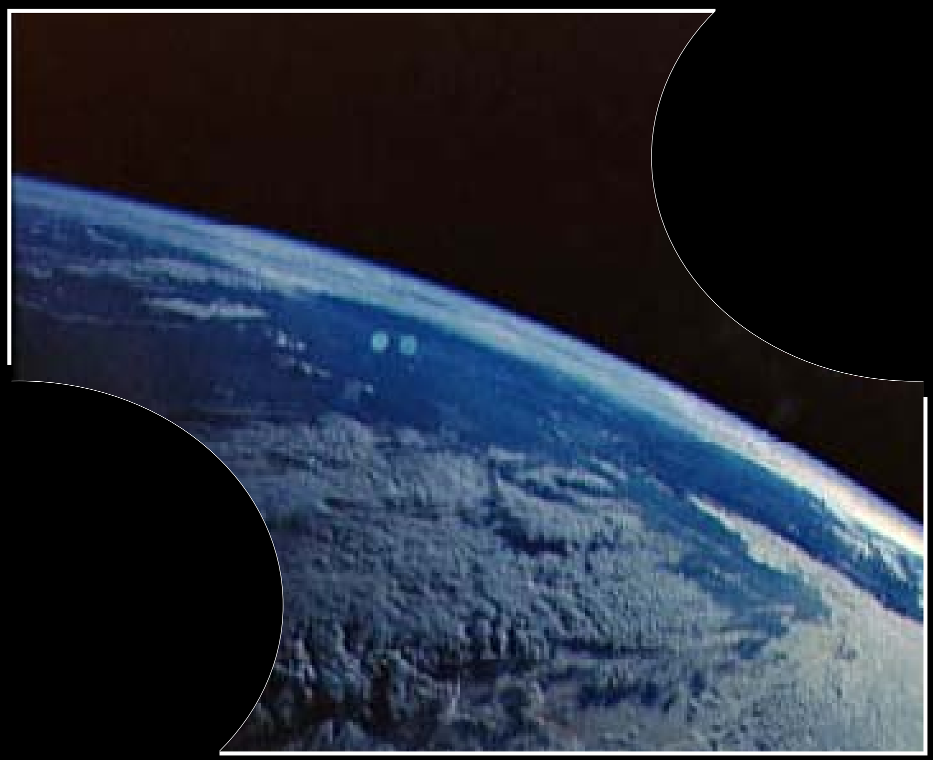
e.g. BaBar - ATLAS

2) Underground laboratories: *e.g.* Sudbury



The Second Piece:

Electroweak Reactions

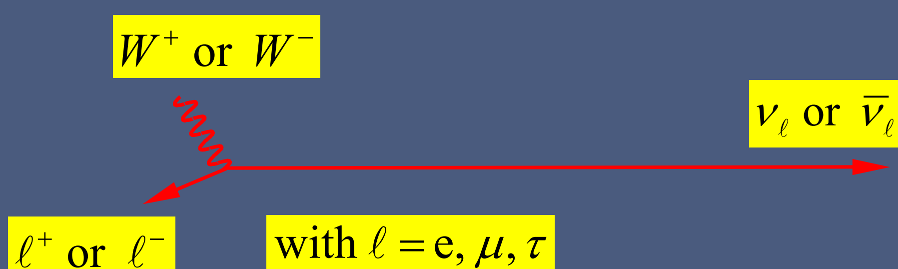


Electroweak Interactions

$$L(\text{em NC}) = e\, J_\mu^{\text{em}} A^\mu$$

with $f = \text{e}, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau, \text{u}, \text{c}, \text{t}, \text{d}, \text{s}, \text{b}$

$$L(\text{weak NC}) = \frac{g}{\cos\theta_{\text{W}}}\left(J_\mu^0 + \sin^2\theta_W J_\mu^{\text{em}}\right) Z^\mu$$



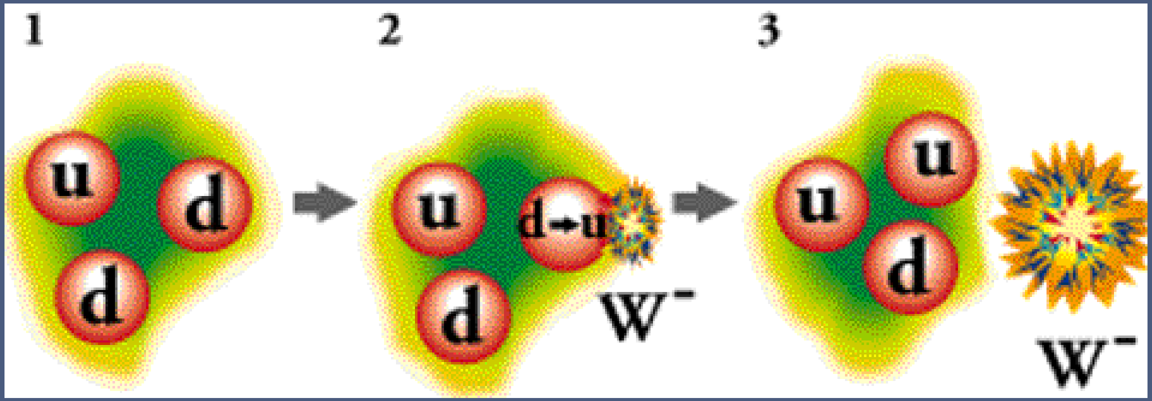
with $\ell = \text{e}, \mu, \tau$

with $q = \text{u}, \text{c}, \text{t}$ and $\text{q}' = \text{d}, \text{s}, \text{b}$

$$L(\text{weak CC}) = \frac{g}{\sqrt{2}}\left(J_\mu^+ W^{\mu-} + J_\mu^- W^{\mu+}\right)$$

Electroweak Reactions

$$n \rightarrow p\, e^{-}\, \overline{\nu}_e$$

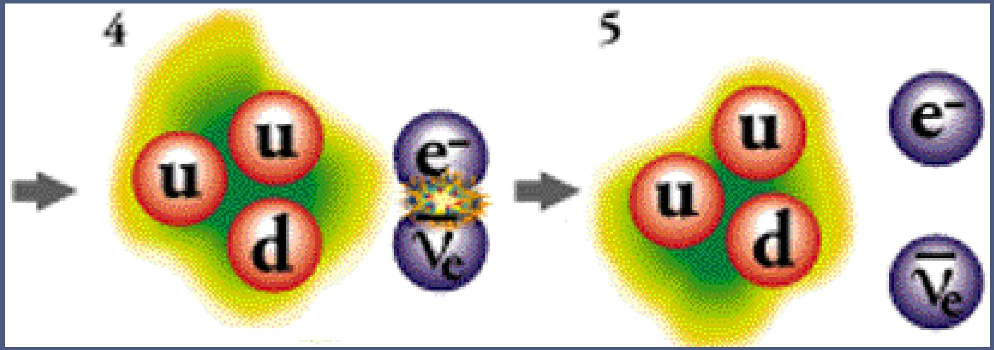


1) The neutron (charge = 0) is made of up, down, down quarks.

2) One of the down quarks is transformed into an up type quark….

Since the down quark has a charge of -1/3 and and the up quark has a charge of 2/3, it follows that this process is mediated by a **virtual** W^- particle.

3) The new up quark rebounds away from the emitted W^-. The neutron now has become a proton.



In this decay the W^- particle, which carries away a (-1) charge; thus charge is conserved!

4) An electron and antineutrino emerge from the virtual W- boson.

5) The proton, electron, and the antineutrino move away from one another.

Quark Mixing (CKM)

- Define a quark mixing matrix which relates the mass and weak eigenstates

Quark Mixing Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- In the minimal Standard Model CP violation in the quark sector is built in the CKM matrix since the elements of *V* are complex

$$V_{ij} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Neutrino Mixing

- Just as in the quark sector, it is possible to define a neutrino mixing matrix which relates the mass and weak eigenstates

Mixing Matrix

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

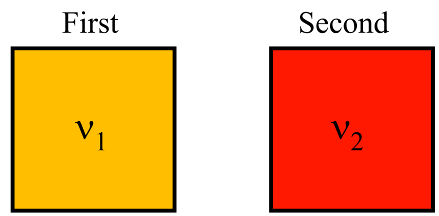
- In the minimal Standard Model there is no mixing... →

$$U_{\alpha i} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

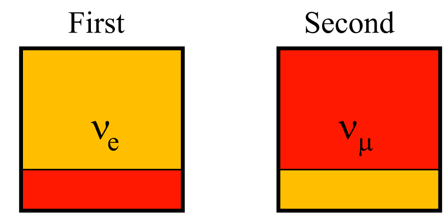
Neutrino Oscillations

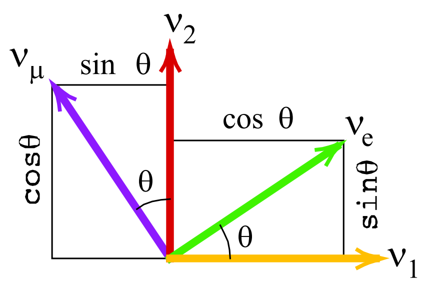
Neutrino States

Mass States



Weak States



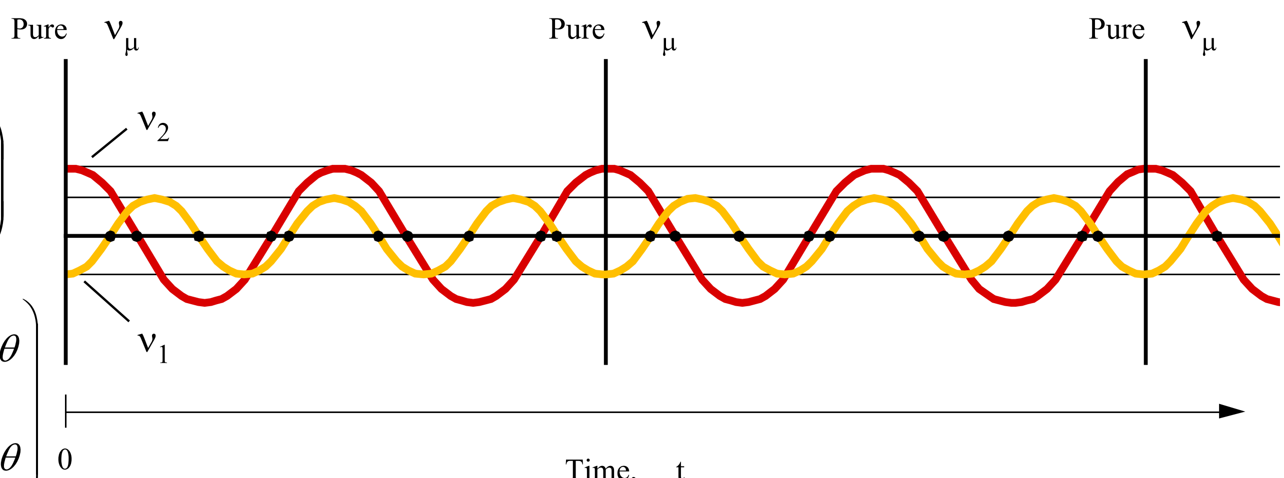


$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Time Evolution

$$i\frac{d}{dt}\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \frac{1}{2}\mathrm{T}\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

$$\mathrm{T} = \begin{pmatrix} -\frac{\Delta m^2}{2E}\cos 2\theta & \frac{\Delta m^2}{2E}\sin^2\theta \\ \frac{\Delta m^2}{2E}\sin^2\theta & \frac{\Delta m^2}{2E}\cos 2\theta \end{pmatrix}$$



Neutrino Oscillations:

$$\Delta m^2 = \left| m_2^2 - m_1^2 \right|$$

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

- Physics:

  Δm^2 & $\sin(2\theta)$

- Experiment:

  Distance (L) & Energy (E)

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

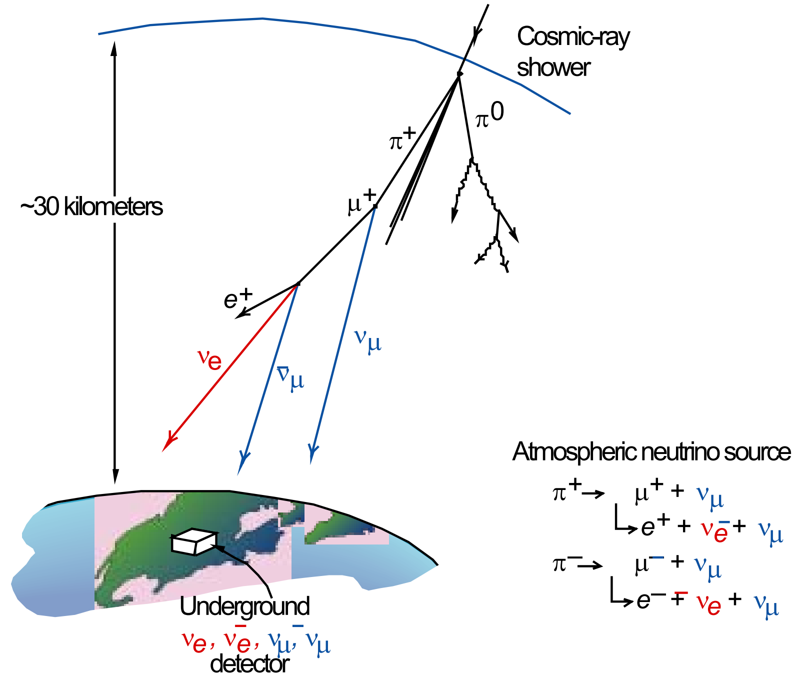
The state evolve with time or distance

Evidence for Neutrino Oscillations

First evidence of neutrino oscillation

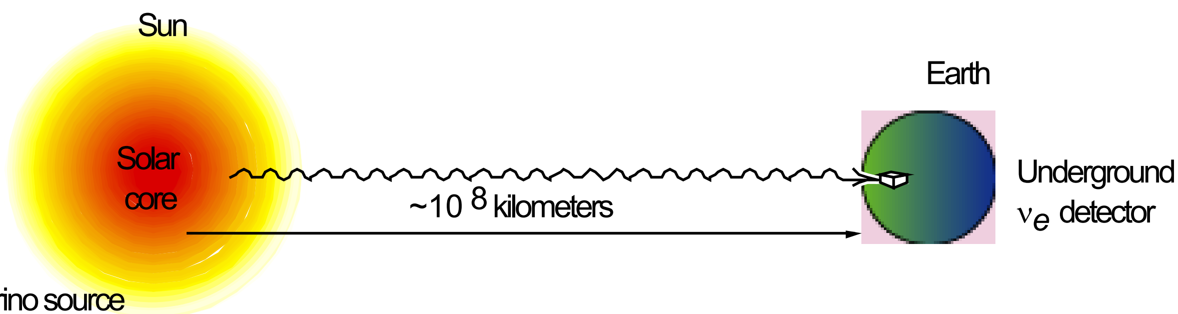
$$\frac{\nu_\mu}{\nu_e} \neq 2$$

Atmospheric Neutrinos
high energies



Solar Neutrinos
low energies

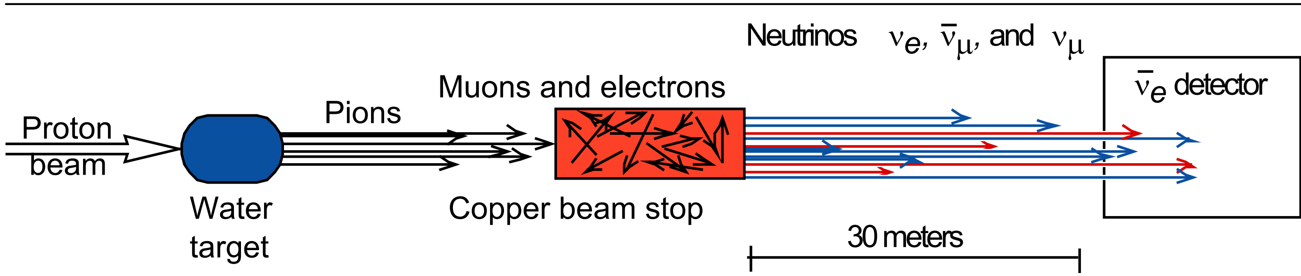
Today's talk !!!



Primary neutrino source
$p + p \rightarrow D + e^+ + \nu_e$

Beamstop Neutrinos
tunable energies

Future!



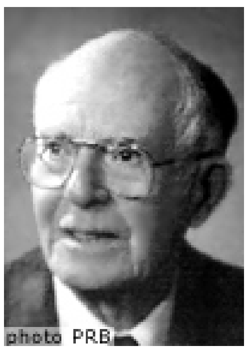
Arranging the Pieces:

Solar Neutrino Physics

The Nobel Prize in Physics 2002

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"



Raymond Davis Jr.

Masatoshi Koshiba

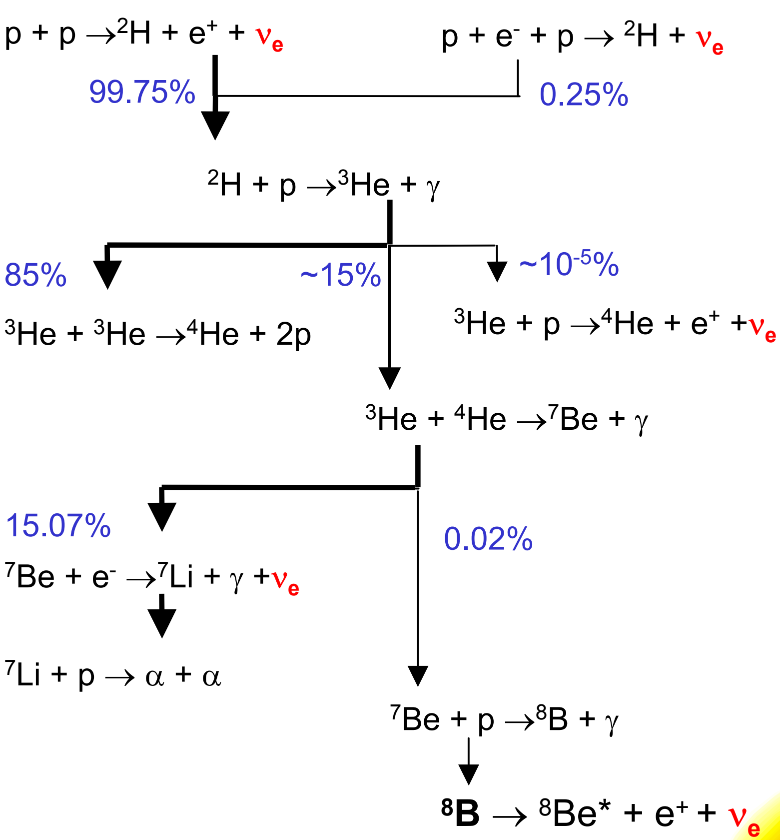
Riccardo Giacconi

The work of Davis and Koshiba has led to unexpected discoveries and a new, intensive field of research, *neutrino-astronomy.*

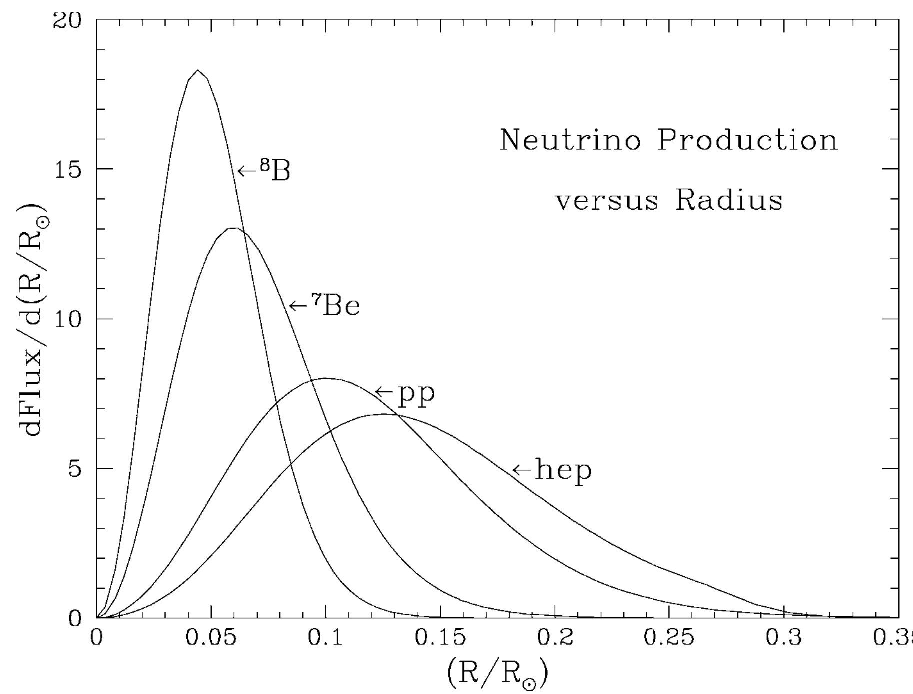
Giacconi constructed the first X-ray telescopes, which have provided us with completely new – and sharp – images of the universe.

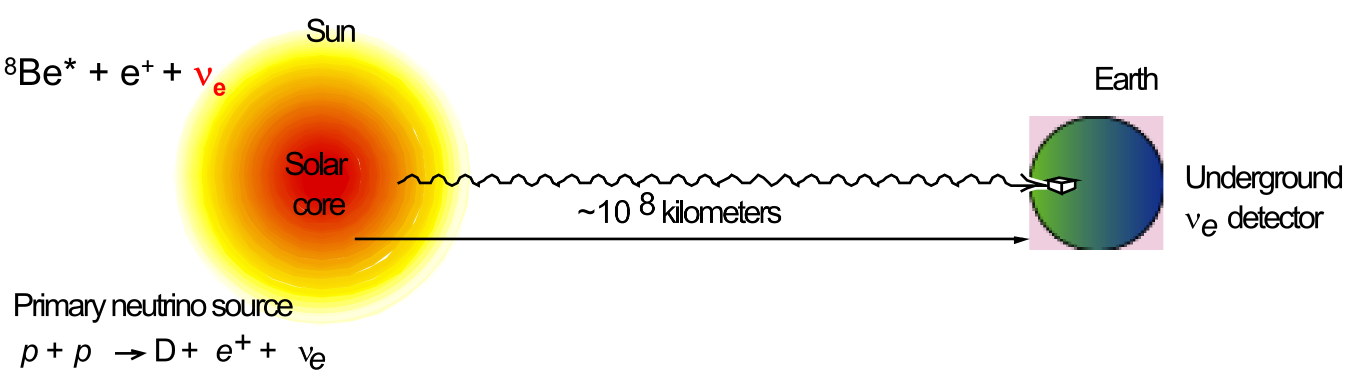
Neutrino Production in the Sun

Light Element Fusion Reactions



Neutrino Production Radius





Neutrino from the Sun

- Our sun emits around $2 \times 10^{+38}$ neutrinos per second.
- The earth receives more than 100 billions neutrinos per second and cm^2. This huge raining is undetected by the five senses of the homo sapiens.

Neutrino Detectors

- Underground, undersea or under ice, the experimental apparatus detect either the Cerenkov light emitted when a neutrino interact with the water or the transformation of atoms under neutrino interaction.

Strategy

- Deep and clean = low background.
- HUGE = Neutrino have small probability of interacting!

Using solar νs' to probe the Sun

1946 Pontecorvo, 1949 Alvarez

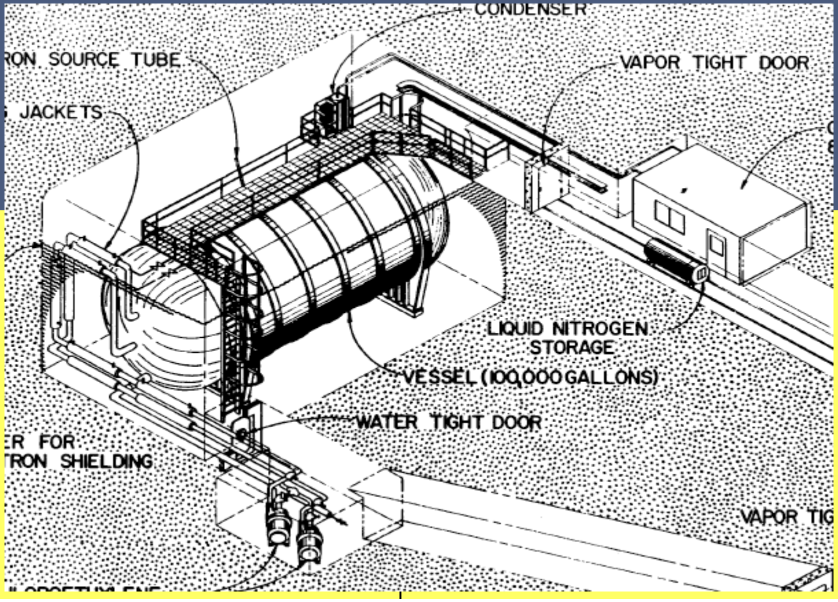
$^{37}Cl + \nu_e \rightarrow\ ^{37}Ar + e^-$

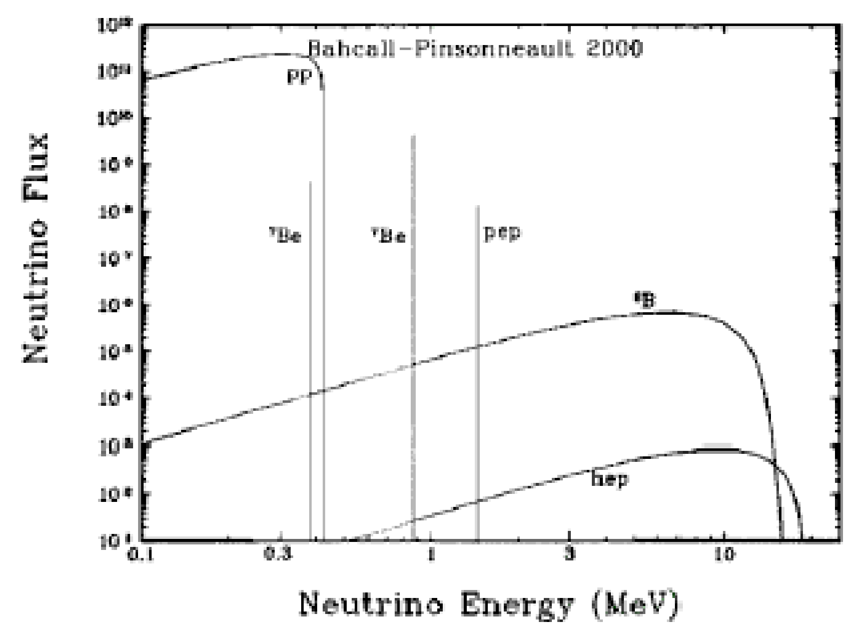
1960's

Ray Davis, builds Chlorine detector

John Bahcall, generates SSM & ν flux predictions

"…to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars..."





Super-Kamiokande

(hep-ex/0103032)

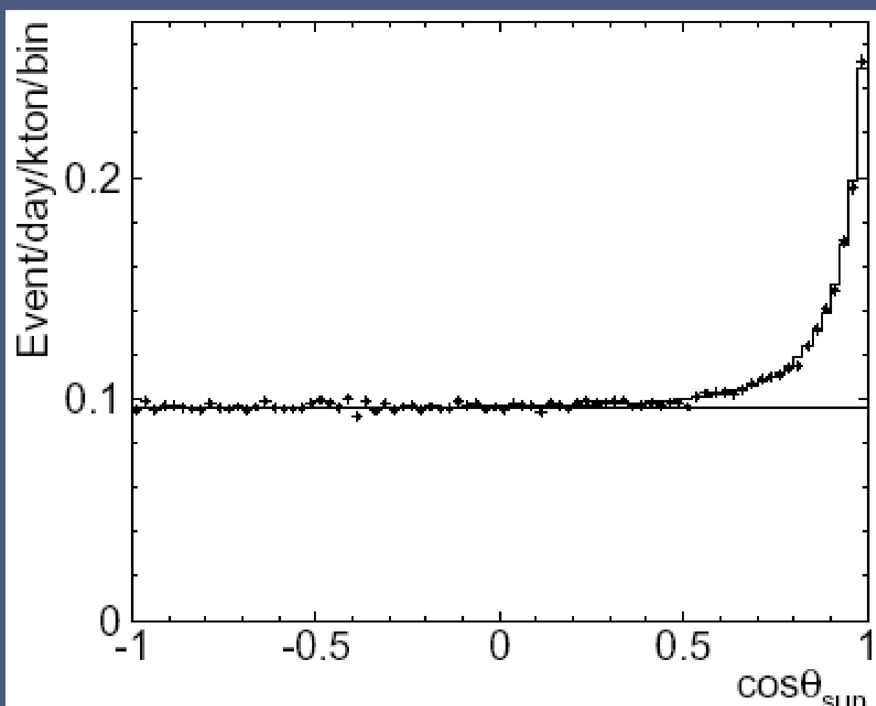
Elastic Scattering: $\nu_x + e^- \rightarrow \nu_x + e^-$ (mainly ν_e)

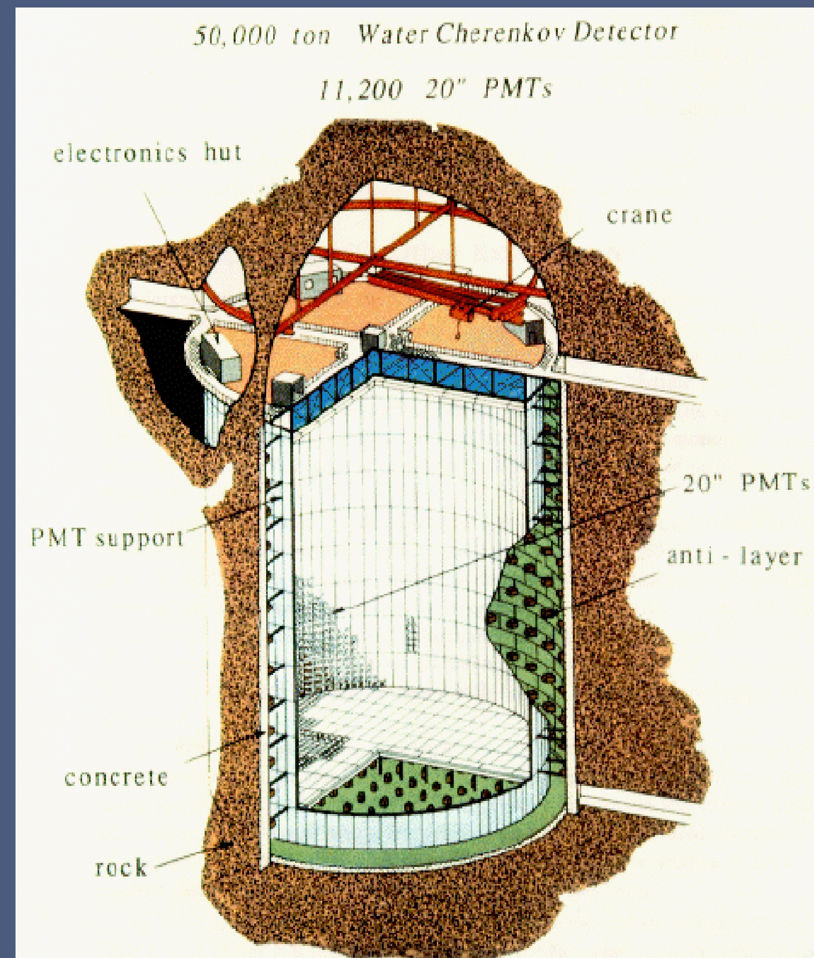
$$\Phi^{ES} = 2.32 \pm 0.03 \, {}^{+0.08}_{-0.07} \quad (10^6 \text{ cm}^{-2} \text{ s}^{-1})$$

(stat) (sys.)

$$\text{Data/SSM} = 0.451 \pm 0.005 \, {}^{+0.016}_{-0.014}$$

(stat) (sys.)





Gallium Measurements

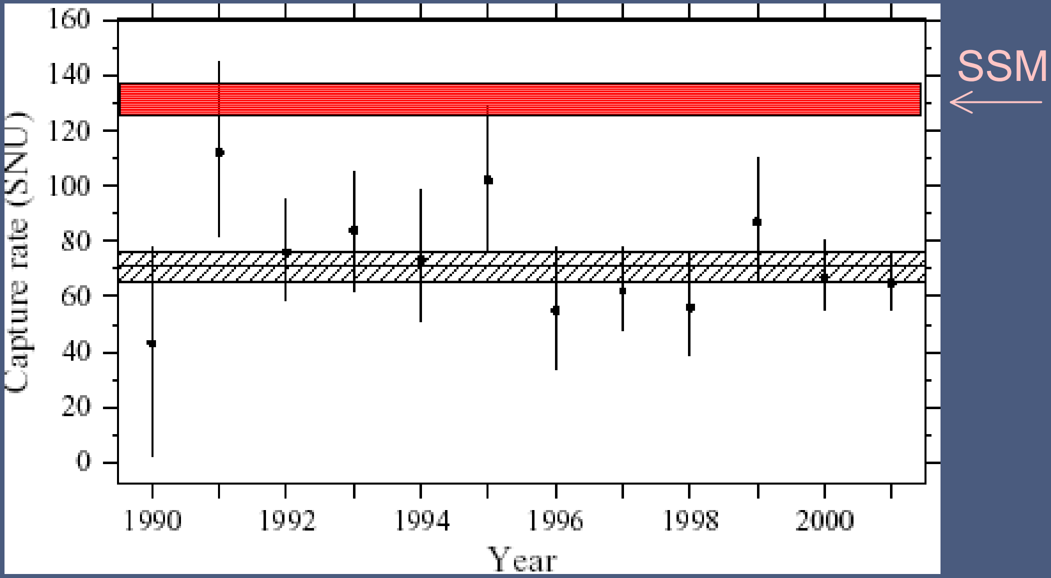
$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$

Two independent experiments

SAGE **Data/SSM = 0.55 ± 0.05**

GALLEX **Data/SSM = 0.57 ± 0.05**

Latest SAGE results (astro-ph/0204245)

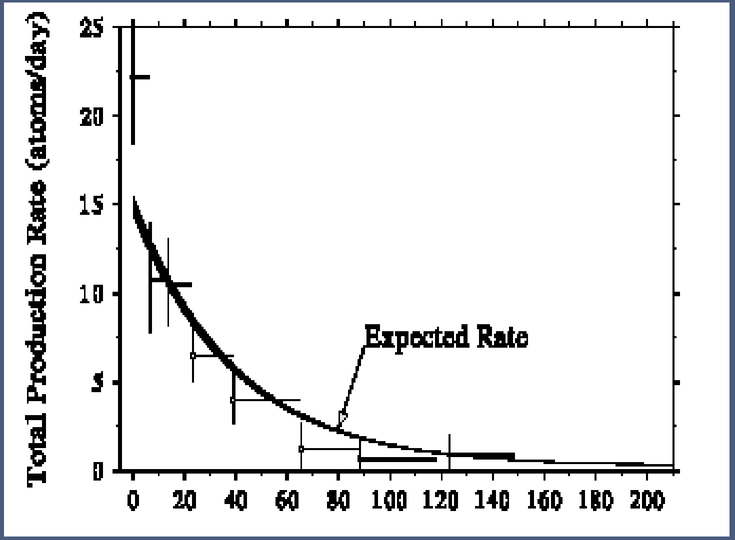


Both Expts Performed
ν source tests

$^{51}Cr + e^- \rightarrow {}^{51}V + \nu_e$

SAGE Source Test

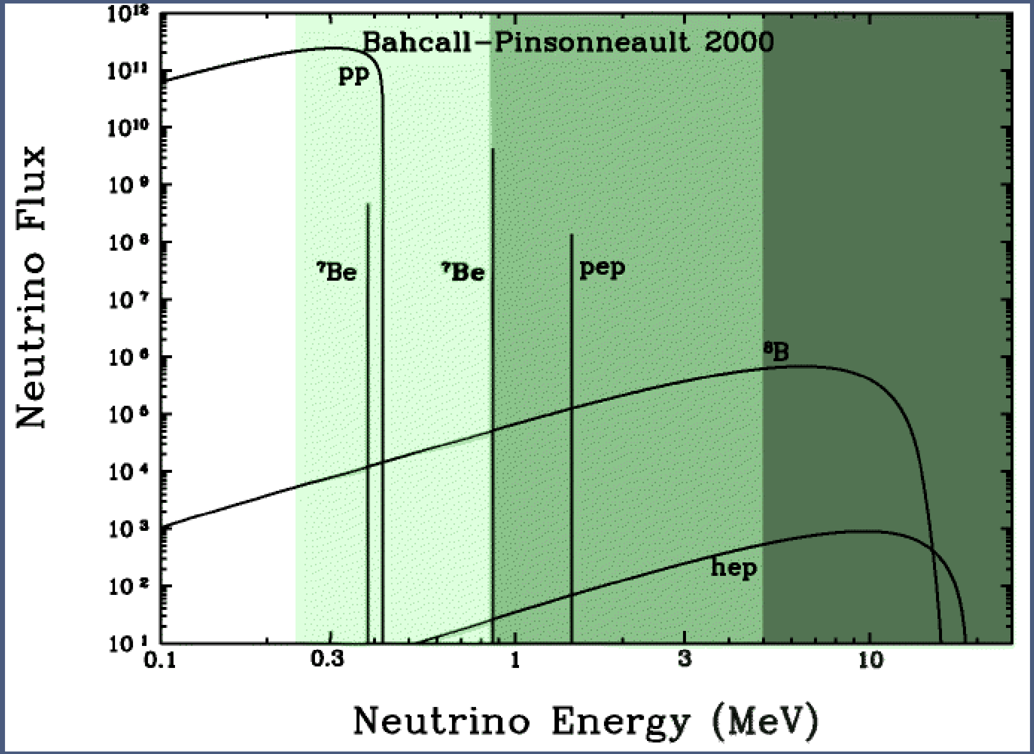
$R(\sigma_{mea}/\sigma_{th})$=0.95±.12±.03



Solar ν Flux Measurement Results

$\int \nu$ flux

$\sim 6.5 \cdot 10^{10}/cm^2/s$



Experiment	Year	Detection Reaction	Ratio Exp/BP2000
Chlorine (127 t)	1970-1995	$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$	0.34 ± 0.03
Kamiokande (680t)	1986-1995	$\nu_x + e^- \rightarrow \nu_x + e^-$	0.54 ± 0.08
SAGE (23 t)	1990-	$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$	0.55 ± 0.05
Gallex + GNO (12 t)	1991-	$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$	0.57 ± 0.05
SuperK (22kt)	1996-	$\nu_x + e^- \rightarrow \nu_x + e^-$	$0.451^{+0.017}_{-0.015}$

Astrophysical Solutions?

SSM Energy Generation

$p + p \rightarrow {}^2H + e^+ + \nu_e$ $\quad$ $p + e^- + p \rightarrow {}^2H + \nu_e$

$\downarrow$

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

${}^3He + {}^3He \rightarrow {}^4He + 2p$ $\quad$ ${}^3He + p \rightarrow \alpha + e^+ + \nu_e$

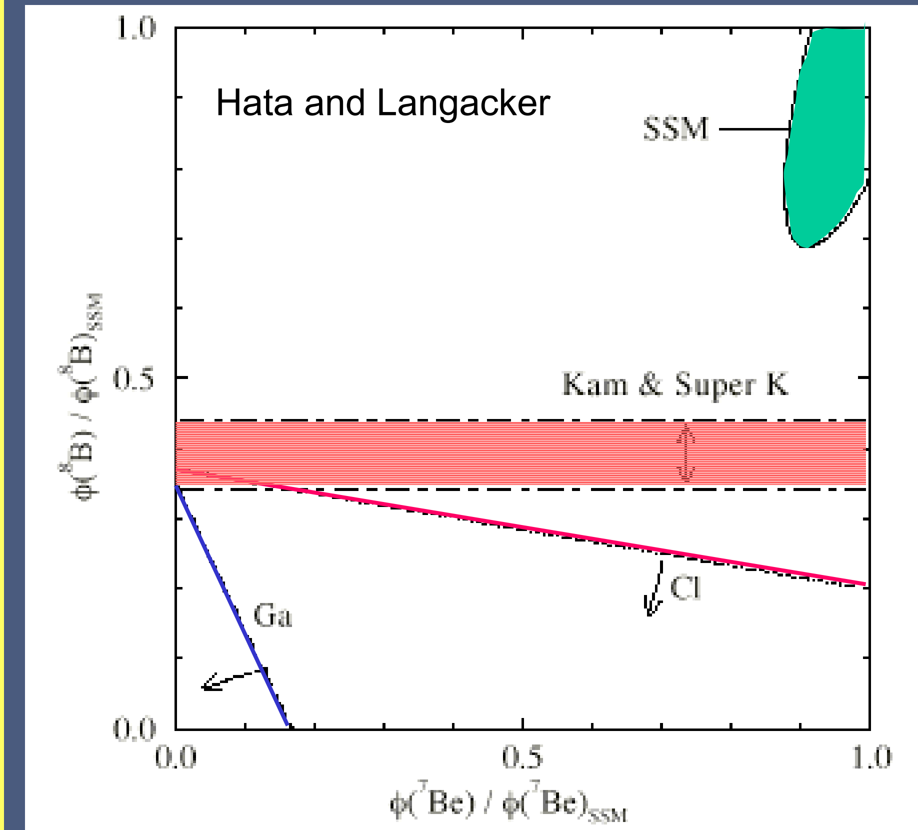
$\downarrow$

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

${}^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e$ $\quad$ ${}^7Be + p \rightarrow {}^8B + \gamma$

$\downarrow$ $\quad$ $\downarrow$

${}^7Li + p \rightarrow \alpha + \alpha$ $\quad$ ${}^8B \rightarrow 2\,\alpha + e^+ + \nu_e$



The data are incompatible with the Standard Solar Model !!!

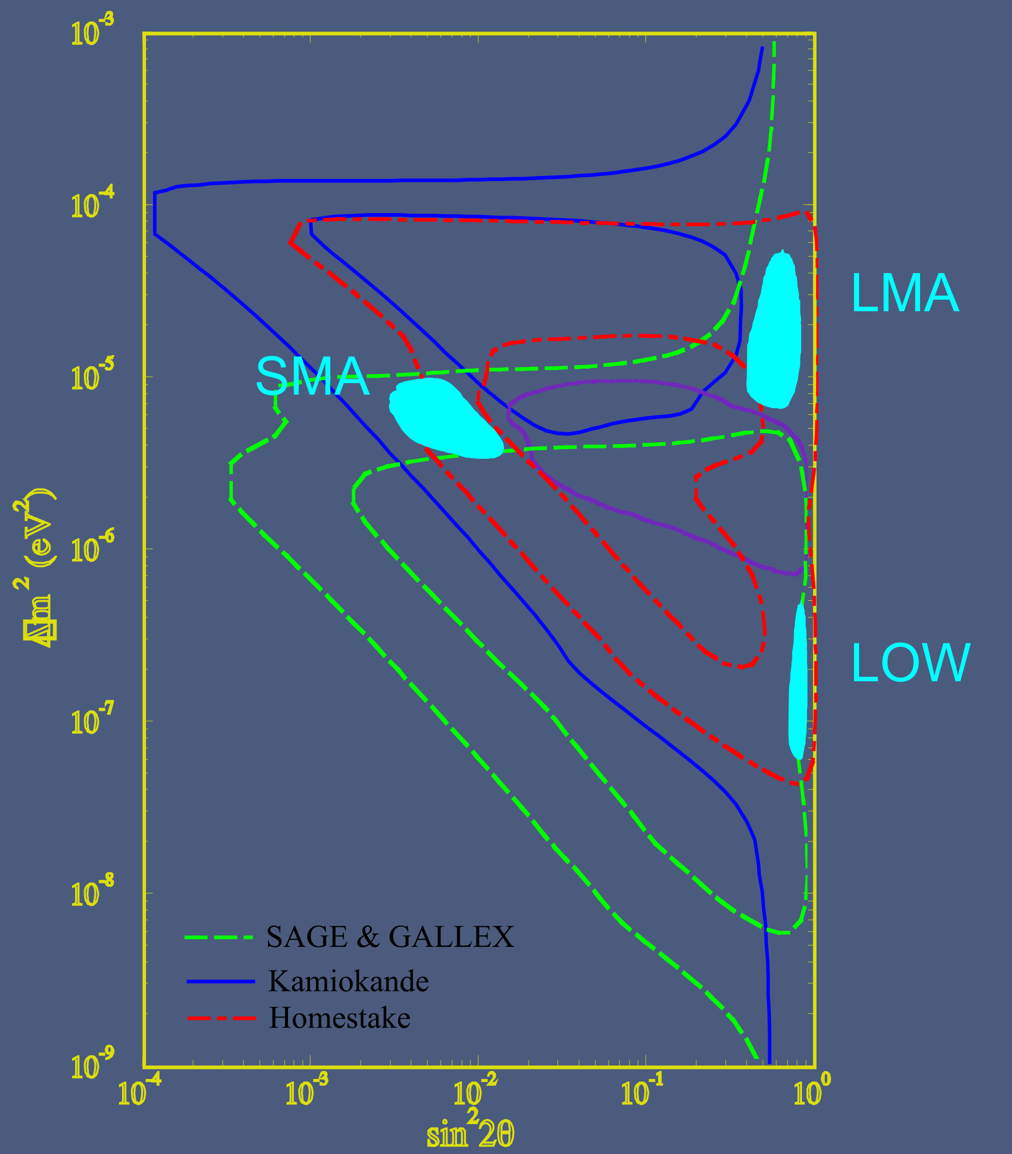
Look at Δm^2 versus $\sin^2 2\theta$

Data give a dramatic extension of oscillation sensitivity to very large values of Δm^2

Solar ν data are not consistent with vacuum oscillations between the sun and the earth!

But only circumstantial evidence

- Need definitive proof
- Appearance measurement
- Independent of SSM



Beyond the Standard Model - ν mass & mixing

Vacuum Oscillations

If neutrinos have mass then the lepton mixing matrix (MNSP) is expressed as

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

and flavor eigenstates are a mixture of mass eigenstates.

Then

$$\nu_e = U_{e1}\nu_1 + U_{e2}\nu_2 + U_{e3}\nu_3$$

and the state evolves with time or distance

$$\nu_e = U_{e1}e^{-iE_1 t}\nu_1 + U_{e2}e^{-iE2t}\nu_2 + U_{e3}e^{-iE_3 t}\nu_3$$

where $E_i^2 = p^2 + m_i^2$

(See B. Kayser hep-ph/0104147 for a nice introduction)

Matter Enhanced Oscillations (MSW)

Neutrinos in matter can acquire an effective mass through scattering.

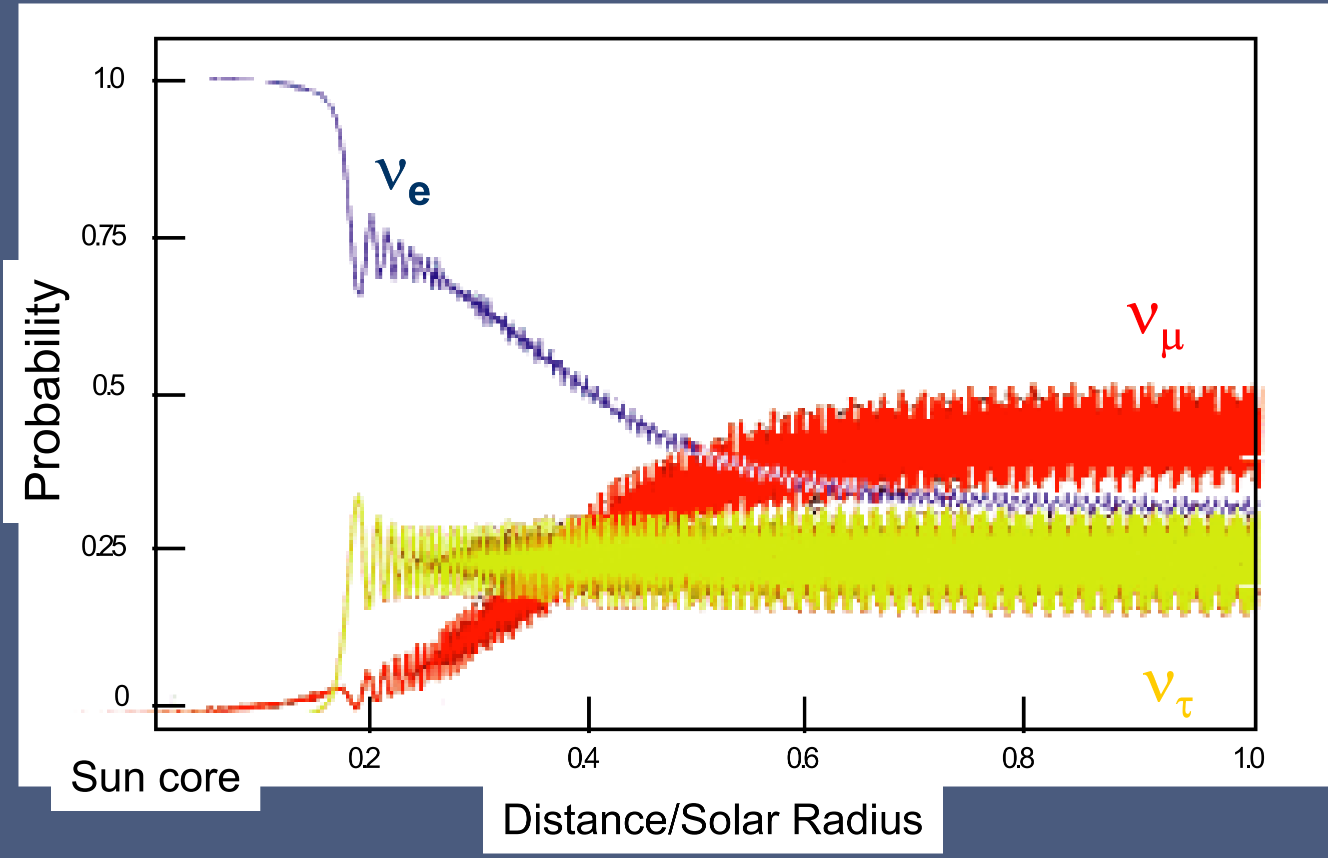
Normal matter contains many electrons, but no muons or taus, so ν_e can undergo both CC and NC scattering.

MSW Oscillations are dependent on the ν energy and the density of the material, hence one can observe spectral energy distortions.

Matter-Enhanced Neutrino Oscillations in the Sun

Neutrinos produced in weak state ν_e

$\Rightarrow$ Superposition of mass states $\nu_{1,2,3}$



→ Superposition of mass states changes through the MSW resonance effect

→ Solar neutrino flux detected on Earth consists of $\nu_e + \nu_{\mu,\tau}$

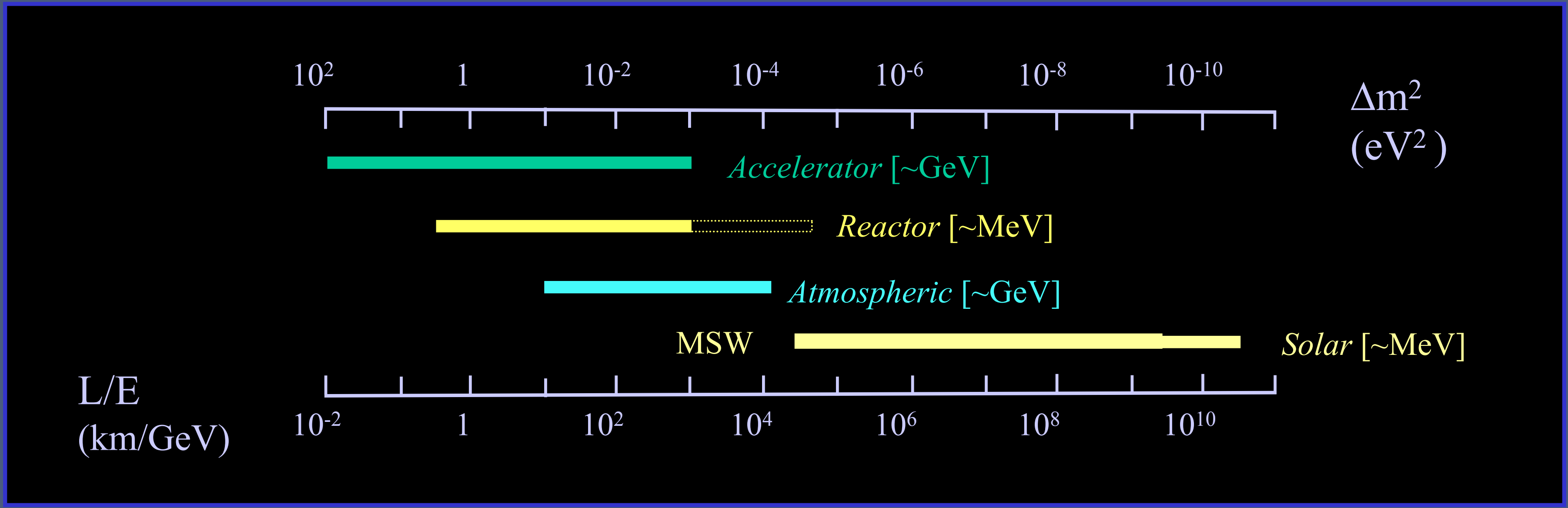
Sensitivity to ν oscillations

Vacuum Oscillations

- Different types of experiments sensitive to different aspects of oscillation space

MSW Oscillations

- For ν′s in matter can acquire an effective mass through scattering, enhancing oscillations.



Somewhere in the Depths of Canada...

Sudbury Neutrino Observatory

2092 m to Surface (6010 m w.e.)

PMT Support Structure, 17.8 m
9456 20 cm PMTs
~55% coverage within 7 m

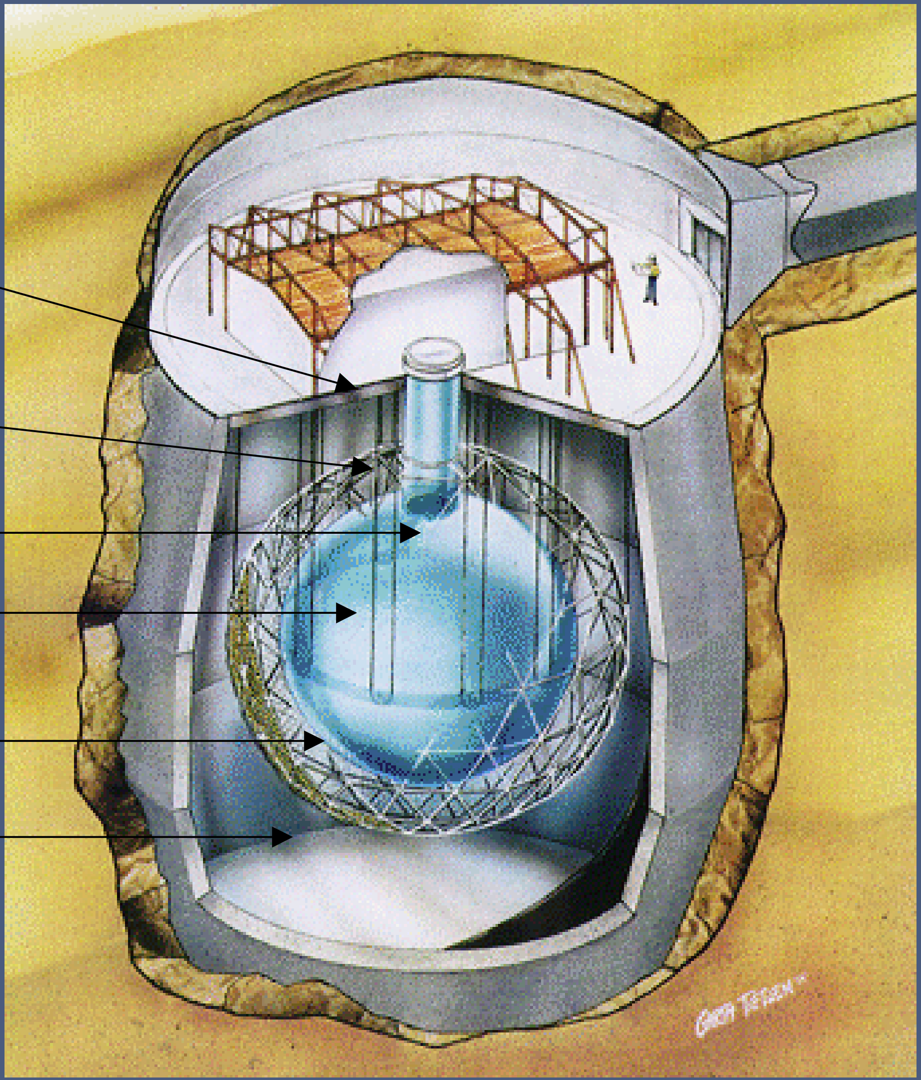
Acrylic Vessel, 12 m diameter

1000 tonnes D_2O

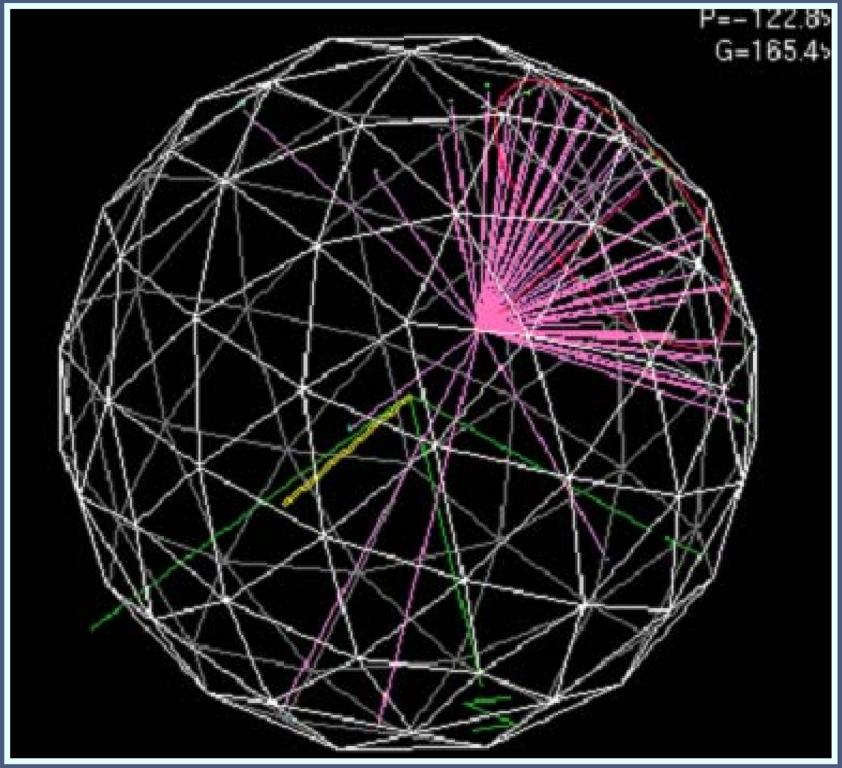
1700 tonnes H_2O, Inner Shield

5300 tonnes H_2O, Outer Shield

Urylon Liner and Radon Seal



Solar Neutrino Events in SNO



SNO
Heavy Water
Cherenkov Detector

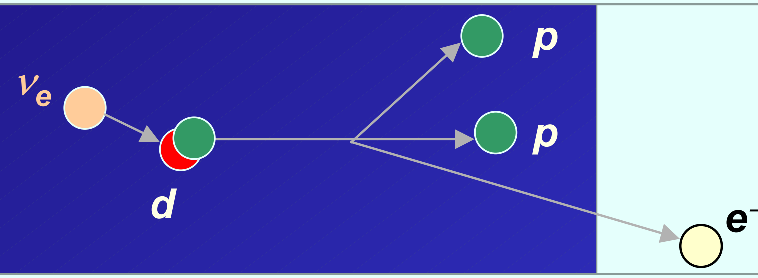
Cherenkov Light

When a particle travels through a medium such that its velocity *v* is greater that the velocity of light in the medium *c/n*, radiation is emitted. The radiation is confined to a **CONE** around the direction of the incident particle.

The SNO detector observes the following interactions:

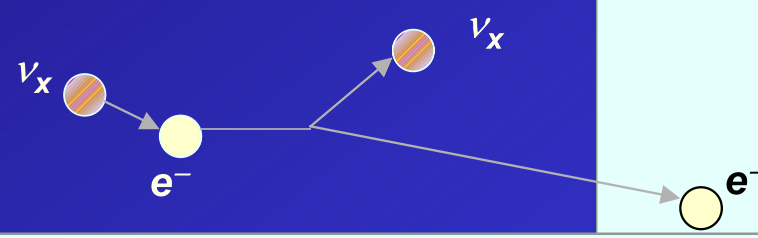
CC Charged Current

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



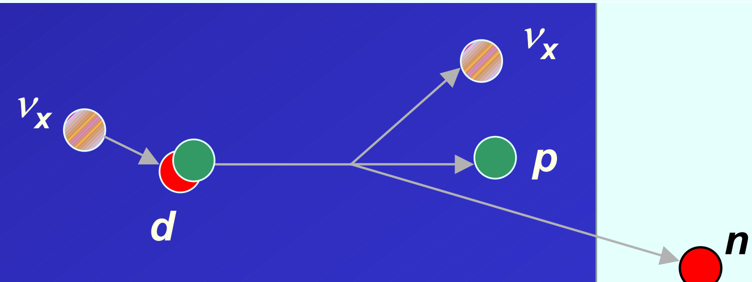
ES Elastic Scattering

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



NC Neutral Current

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



$x = e, \mu, \tau$

Detected Particle

ν Reactions in SNO

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

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

-Low Statistics
-Mainly sensitive to ν_e, some sensitivity to ν_μ and ν_τ
-Strong directional sensitivity

Danger !

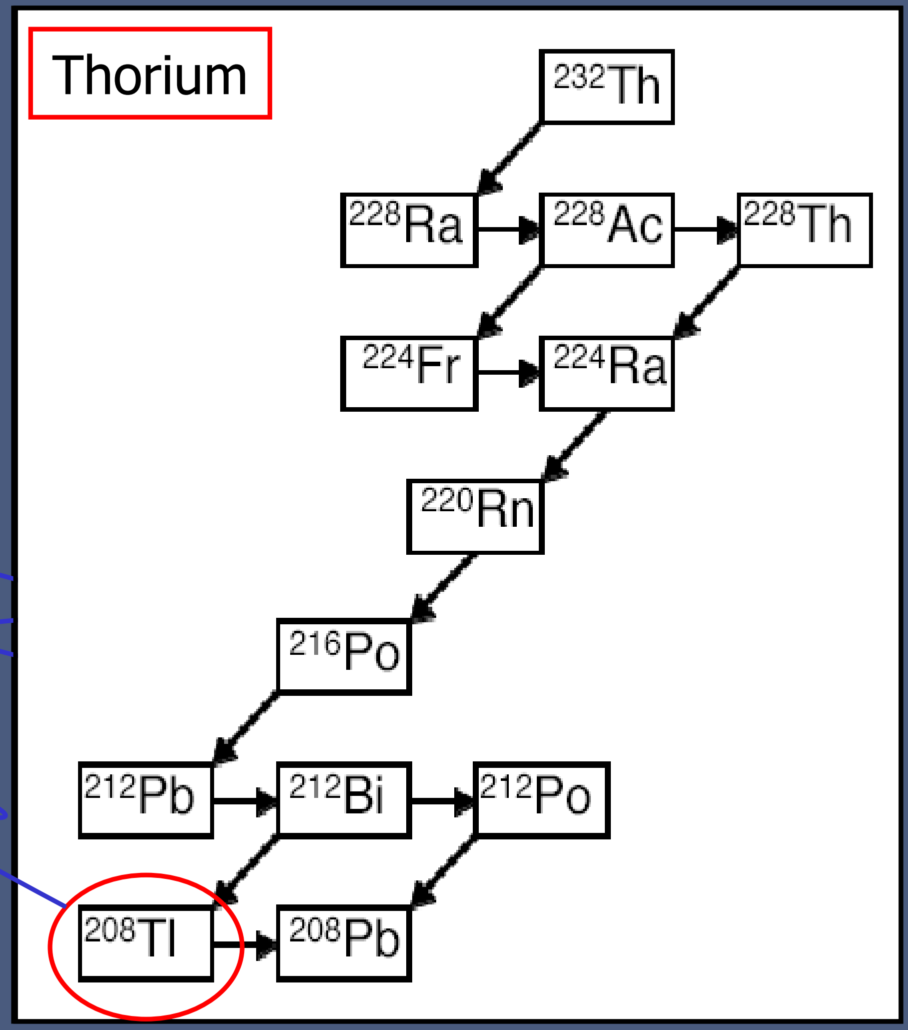
A 2.2 MeV photon can break the deuterium and mimic a NC event

An Ultraclean Environment

- Highly sensitive to any γ above neutral current (2.2 MeV) threshold.

3.27 MeV β

2.615 MeV γ



- Sensitive to ^{238}U and ^{232}Th decay chains

Measuring U/Th Content

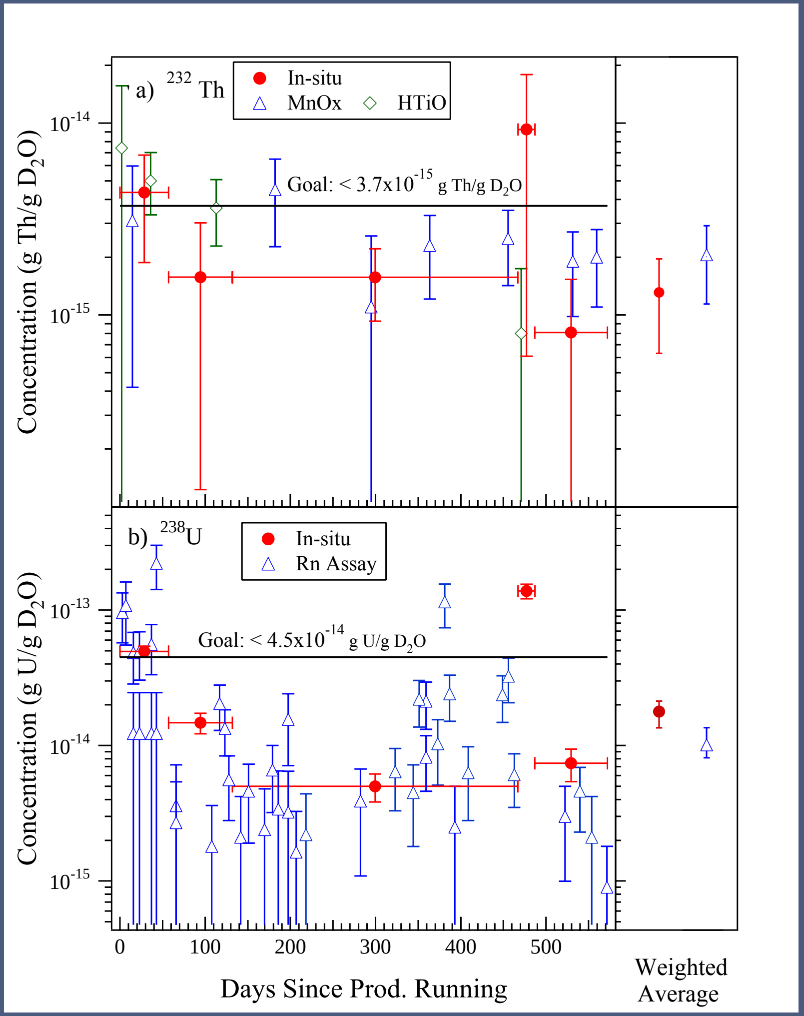
Purification System

- Clean D_2O and H_2O to pristine condition
- Monitor the water on-line

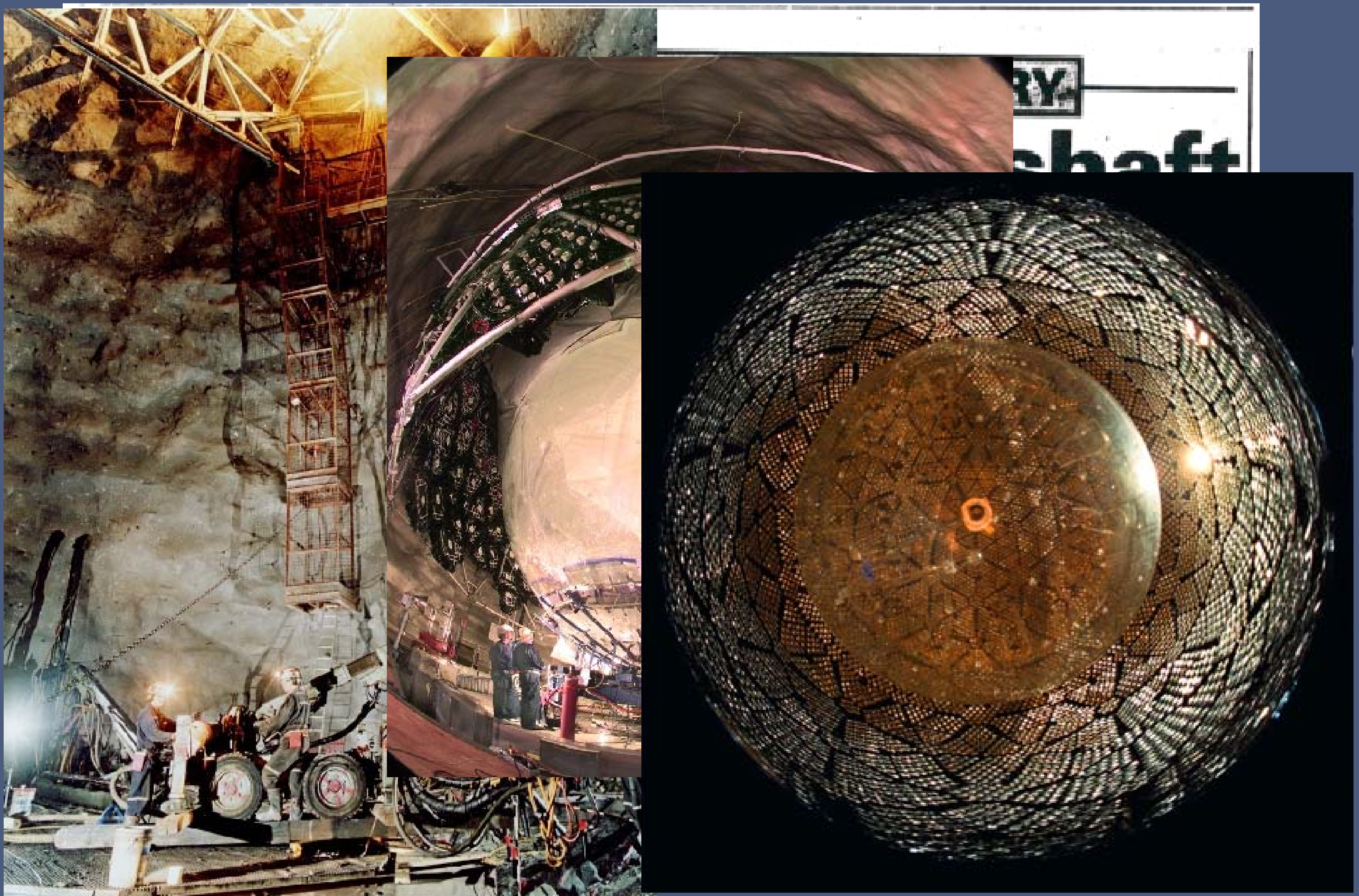
Background Measurement

- Ion exchange (^{224}Ra, ^{226}Ra)
- Membrane Degassing (^{222}Rn)

	D_2O	H_2O/AV
Neutron Events	44^{+8}_{-9}	27^{+8}_{-8}

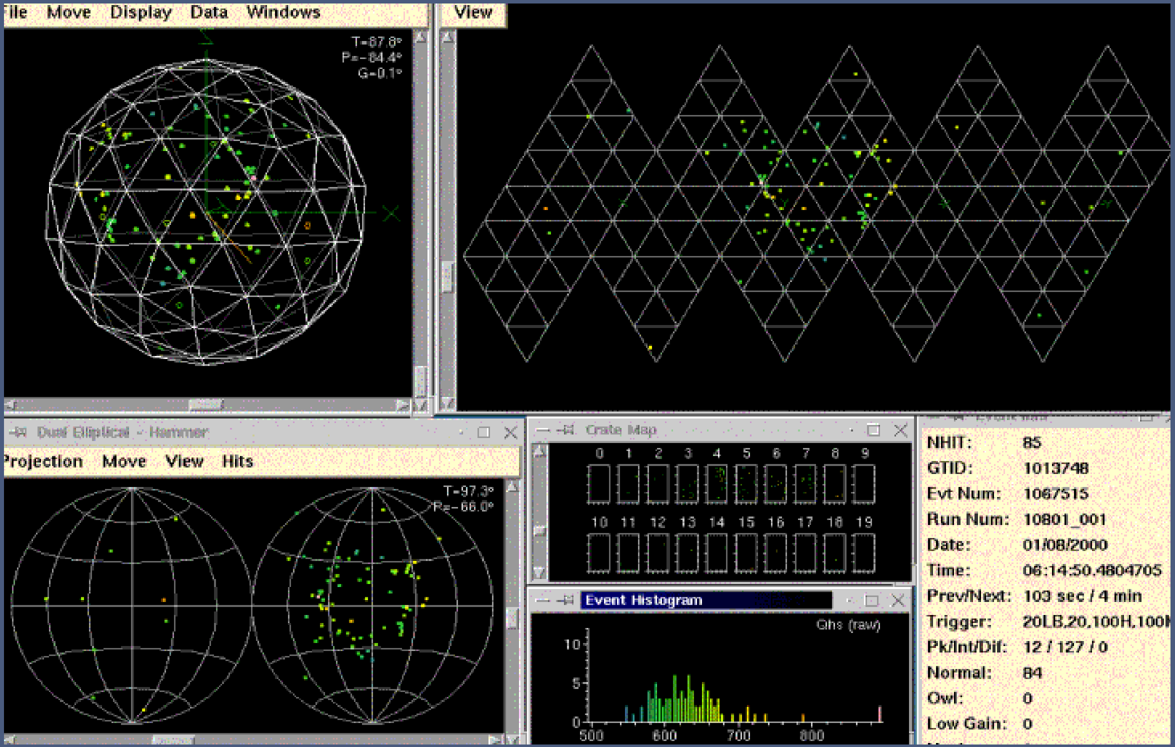


The SNO Detector during Construction



SNO observables - event by event

PMT Information: Positions, Charges, Times



Event Reconstruction

Vertex, Direction, Energy, Isotropy

ν Reactions in SNO

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

Produces Cherenkov Light Cone in D_2O

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

D_2O Only Phase

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

- Measure total ^8B ν flux from the sun.
- Equal cross section for all ν types
- 2.2 MeV Threshold, Integrated $E > E_{th}$

n captures on deuteron
$^2H(n, \gamma)^3H$
Observe 6.25 MeV γ

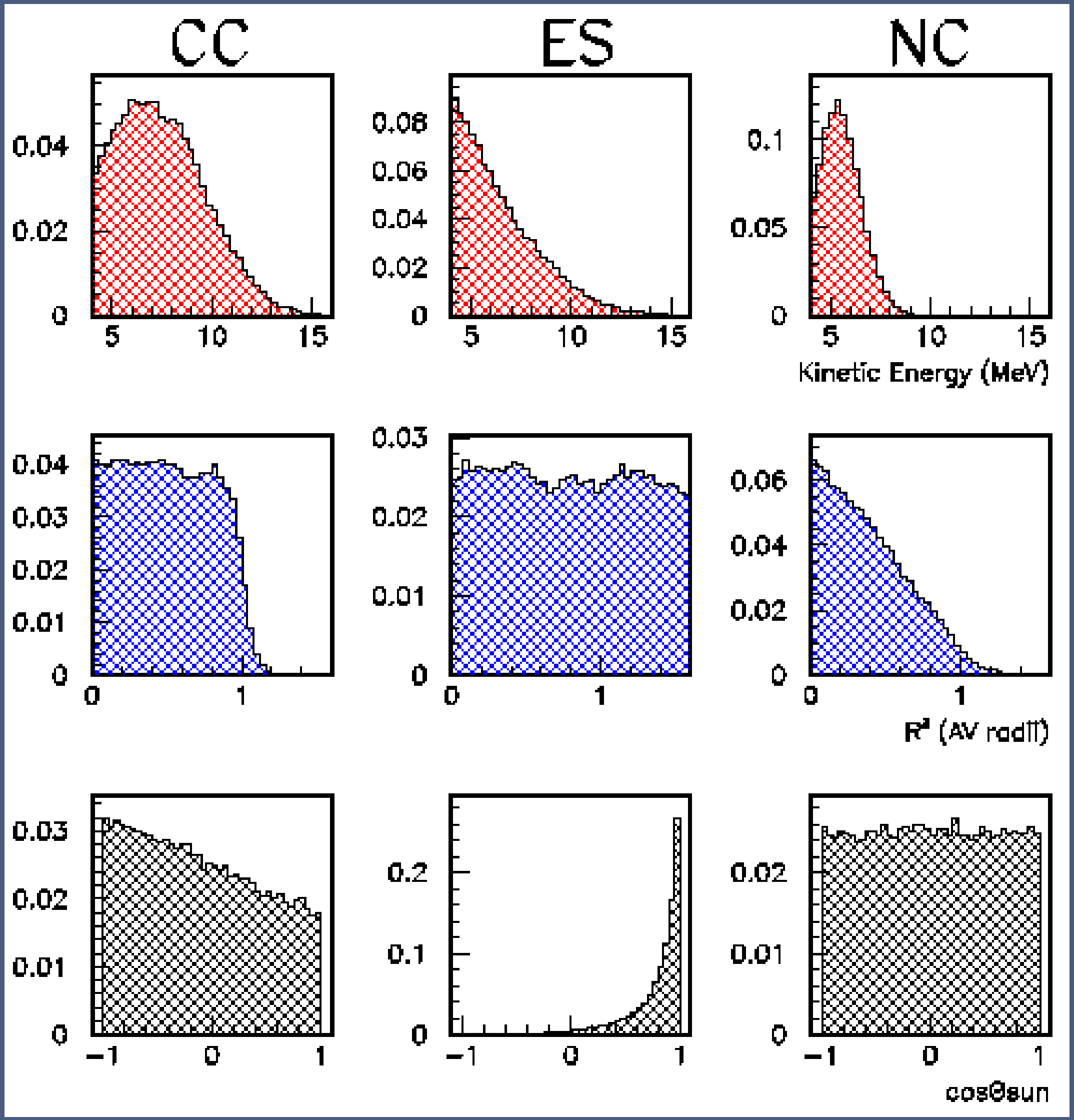
ES $\nu_x + e^- \Rightarrow \nu_x + e^-$

Produces Cherenkov Light Cone in D_2O

-Low Statistics
-Mainly sensitive to $\nu_{e,}$, some sensitivity to ν_μ and ν_τ
-Strong directional sensitivity

Extraction of CC, ES, NC Signals

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



Data Analysis:

Mutivariate Likelihood Fit

Global View:

SNO Results

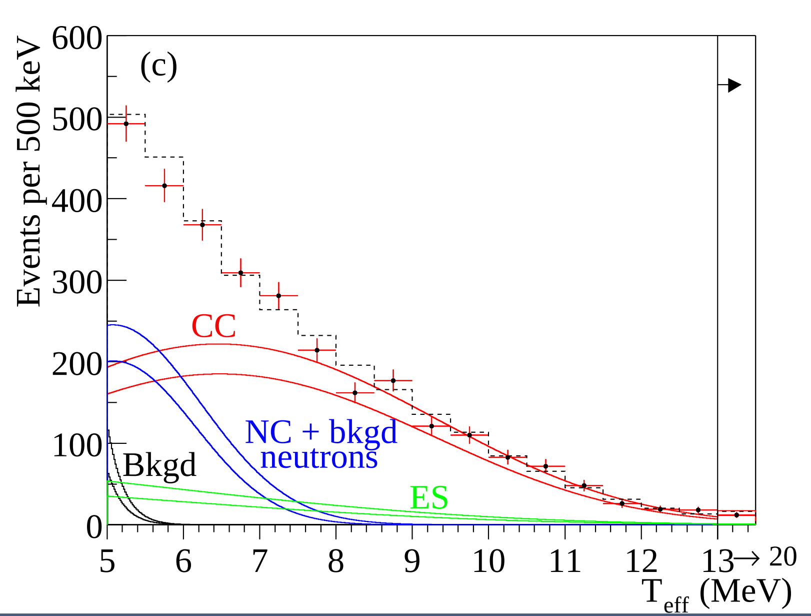
Shape Constrained Signal Extraction Results

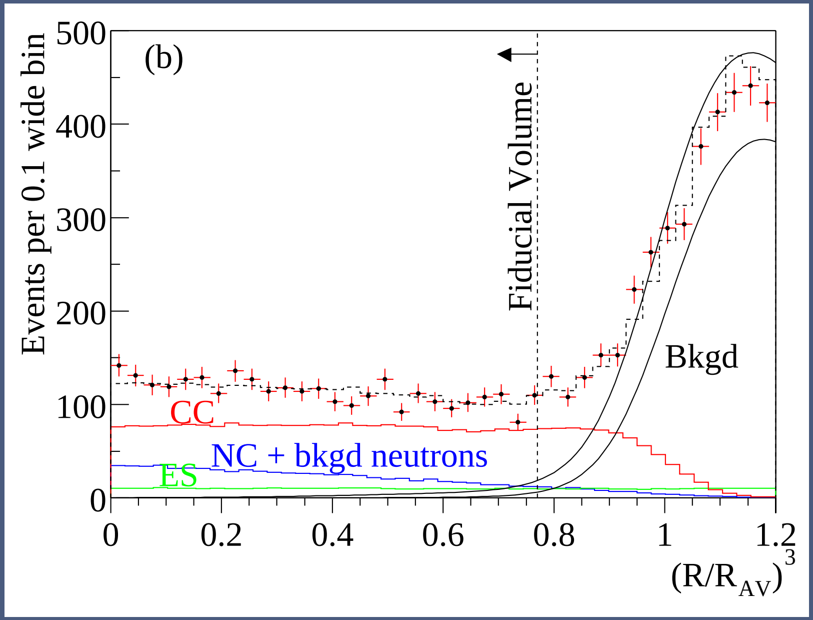
#EVENTS

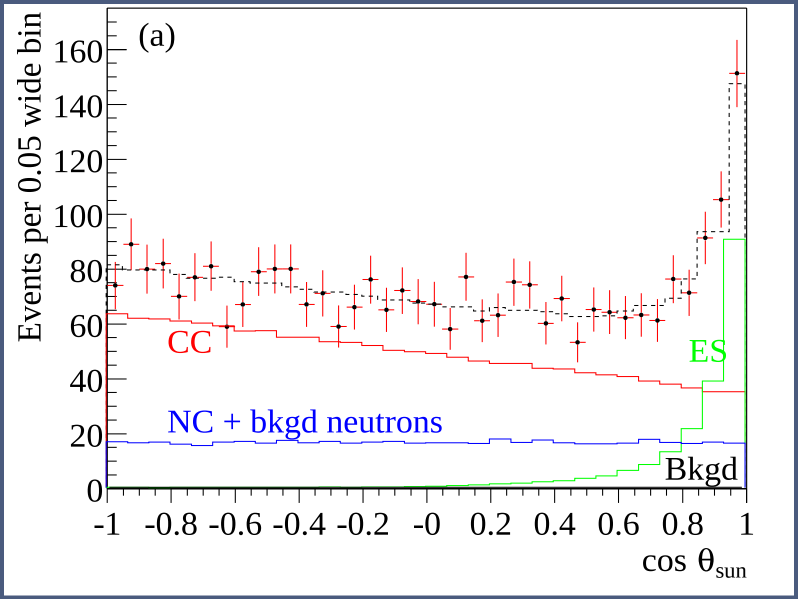
CC 1967.7 $^{+61.9}_{+60.9}$

ES 263.6 $^{+26.4}_{+25.6}$

NC 576.5 $^{+49.5}_{+48.9}$







Shape Constrained Neutrino Fluxes

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

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

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

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

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

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

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

The Solar Neutrino Problem

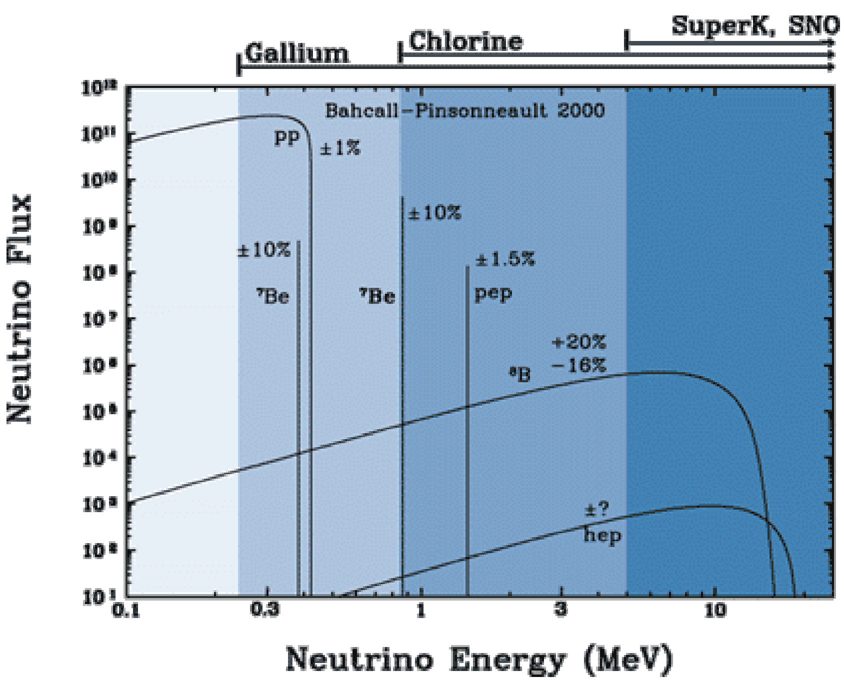


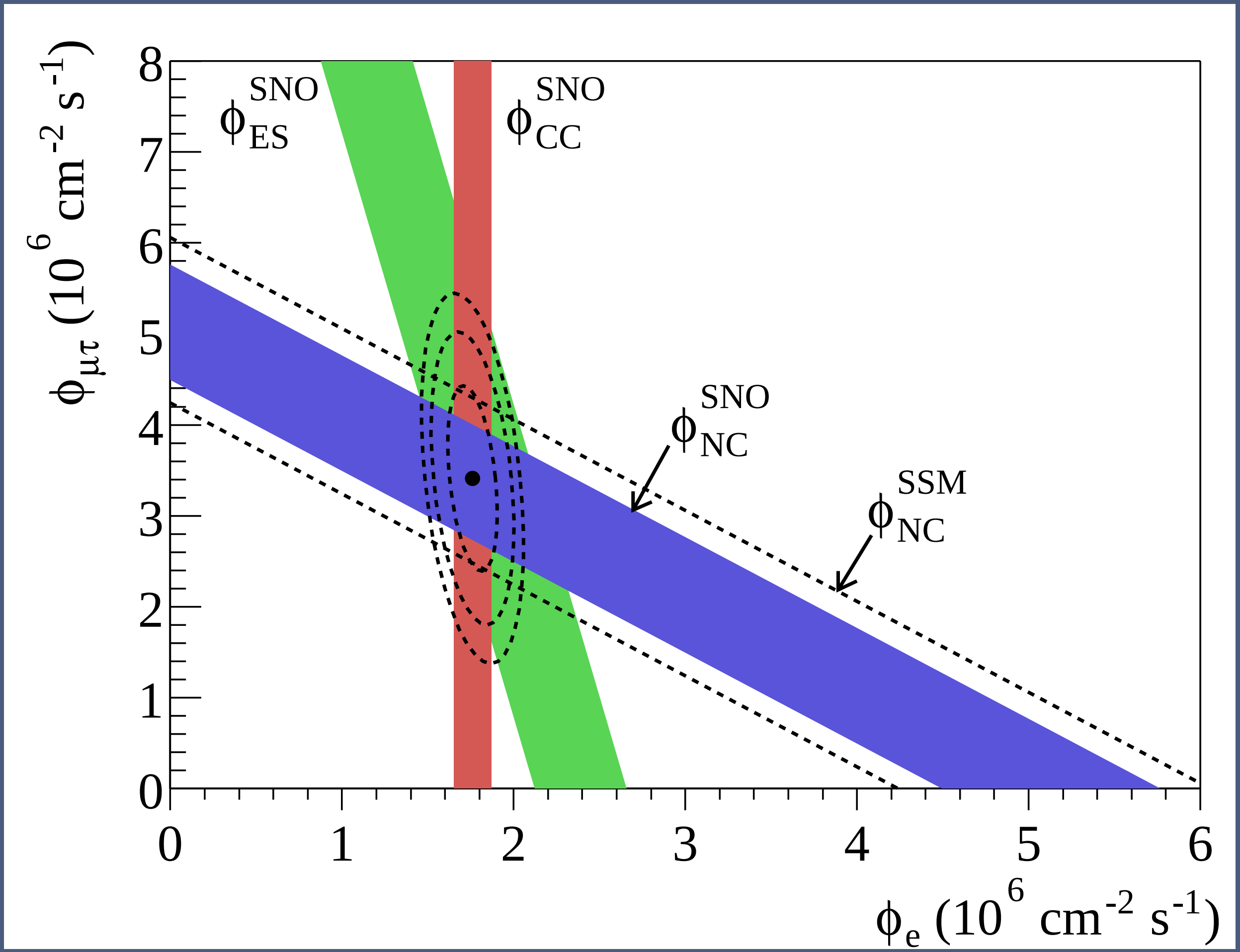
Figure by J. Bahcall

Experiment	Exp/SSM
•SAGE+GALLEX/GNO	0.58
•Homestake	0.33
•Kamiokande+SuperK	0.46
•SNO CC (June 2001)	0.35
SNO NC (April 2002)	~1

SNO CC vs NC implies flavor change, which can then explain other experimental results.

SNO NC in D_2O Conclusions

~ 2/3 of initial solar ν_e are observed at SNO to be $\nu_{\mu,\tau}$



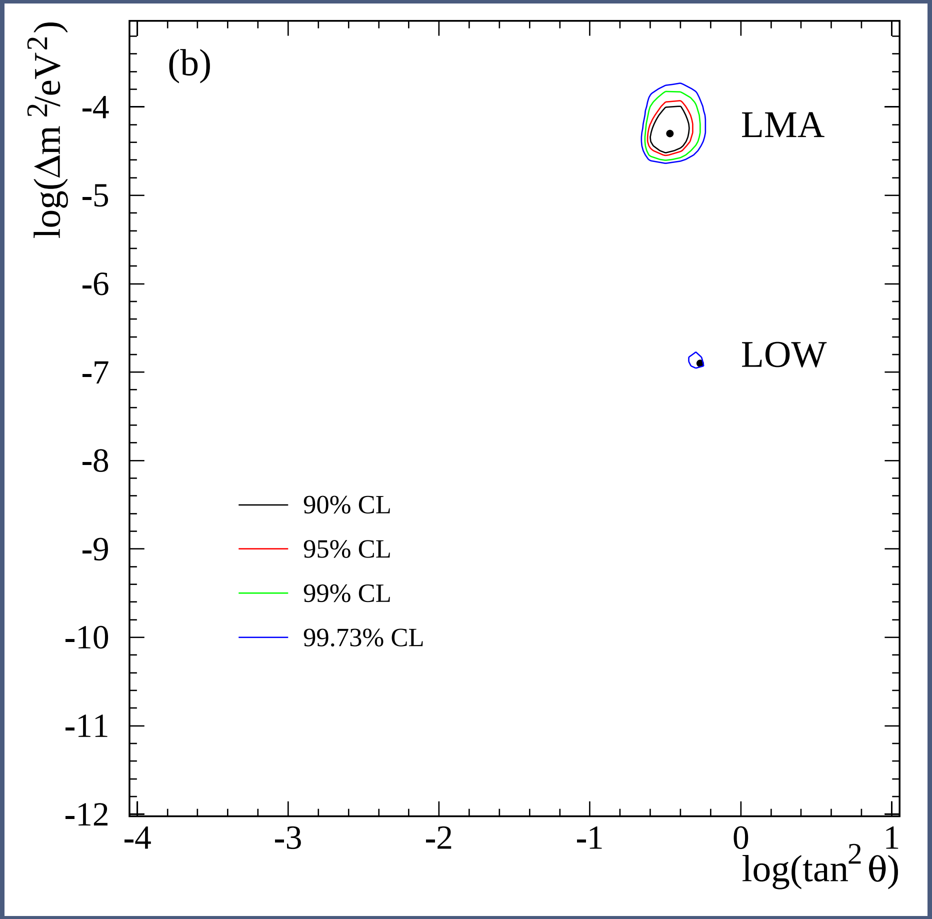
Flavor change at 5.3 σ level.

Sum of all the fluxes agrees with SSM.

$\Phi_{ssm} = 5.05^{+1.01}_{-0.81}$ $\Phi_{sno} = 5.09^{+0.44}_{-0.43}{}^{+0.46}_{-0.43}$

Physics Interpretation ν Oscillations

Combining All Experimental and Solar Model information



SNO - Current Status and Future Plans

The Salt Phase

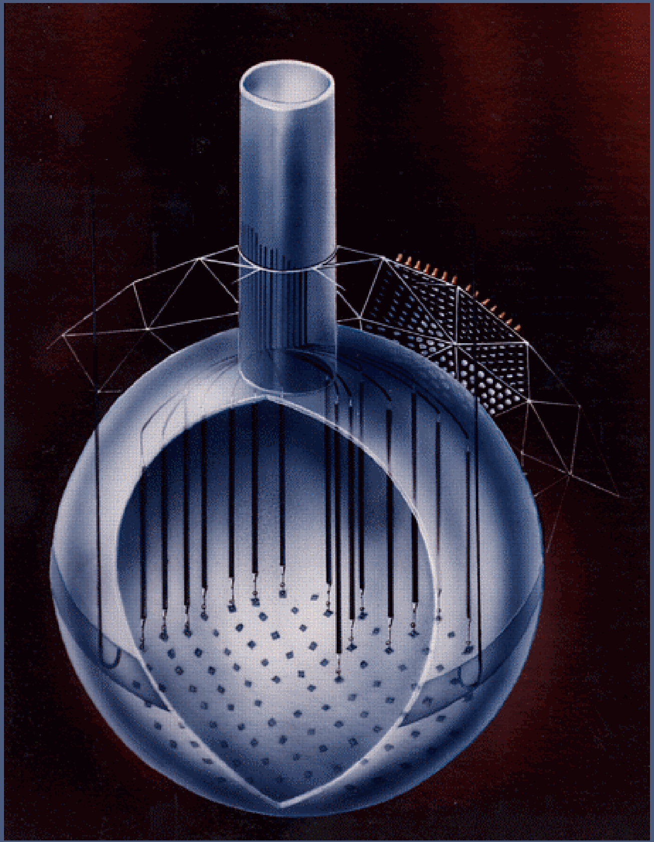
$n + {}^{35}\mathrm{Cl} \rightarrow {}^{36}\mathrm{Cl} + \Sigma\gamma \ldots \rightarrow e^{-}$ $(E_{\Sigma\gamma} = 8.6\ \mathrm{MeV})$

- Higher n-capture efficiency
- Higher event light output
- Event isotropy differs from e^-
- Running since June 2001
- Opportunities for graduate studies and coop projects

Neutral Current Detectors

$n + {}^{3}\mathrm{He} \rightarrow p + t$

- Event by event separation



Future Prospects for SNOLAB

CFI International Venture: 39 millions for new cavern at the 6800 ft level !!!

Sudbury, Canada

Going Underground...

- **Search for DARK MATTER**
- **SNO´ with wavelength shifters to measure to B^8 spectrum (LMA vs LOW)**
- **New neutrino experiments**
- **Intensive field of research**

SNO Conclusions

- First NC Flux measurements yield clear evidence that the majority of ν_e produced in the Sun are transformed to ν_μ and/or ν_τ
  - Null hypothesis - “No Weak Flavor Mixing” ruled out at 5.3 σ
  - Lowest Detection threshold yet for a real-time solar ν detector
  - Total ^8B flux measurement agrees well with Solar Models
  - Data in good agreement with previous SNO - SK CC/ES results

Enhanced NC measurement, with NaCl underway since June 2001

Need to confirmed solar neutrino oscillation with salt data (underway)

Measure the energy spectrum of $\nu_e$and possible energy distortion

Rule out LOW and study day/night asymmetry and season variation

NOT OVER: SNOLAB provides new opportunities for underground science and particle astrophysics in Canada *http://www.physics.carleton.ca/~alainb/*

http://www.ocip.carleton.ca

Broader Implications

Solar neutrinos and Atmospheric neutrinos demonstrate that neutrinos have mass and the Standard Model of Nuclear and Particle Physics is incomplete.

- Unlike the Quark Sector where the CKM mixing angles are small, the lepton sector exhibits large mixing
- The ν masses and mixing may play significant roles in determining structure formation in the early universe as well as supernovae dynamics and the creation of the elements

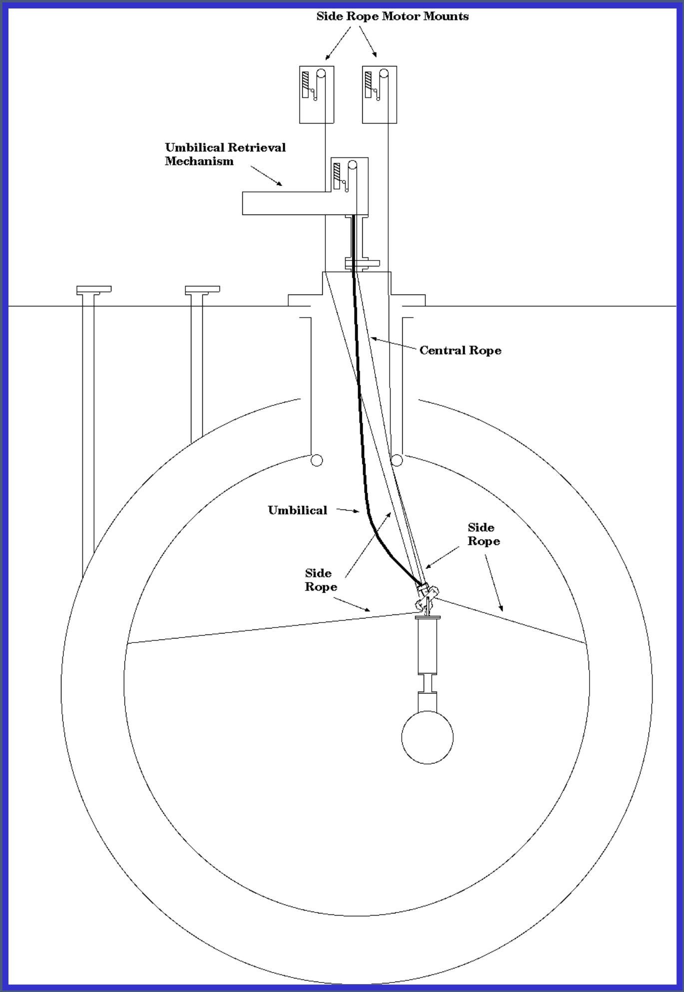
The coming decade should be an exciting time for neutrino physics helping delineate the "New" Standard Model that will include neutrino masses and mixing.

- Precision measurements of the leptonic mixing matrix
- Determination of Neutrino mass
- Investigation of lepton sector CP and CPT properties

Sources of Calibration

- Use detailed Monte Carlo to simulate events
- Check simulation with large number of calibrations:

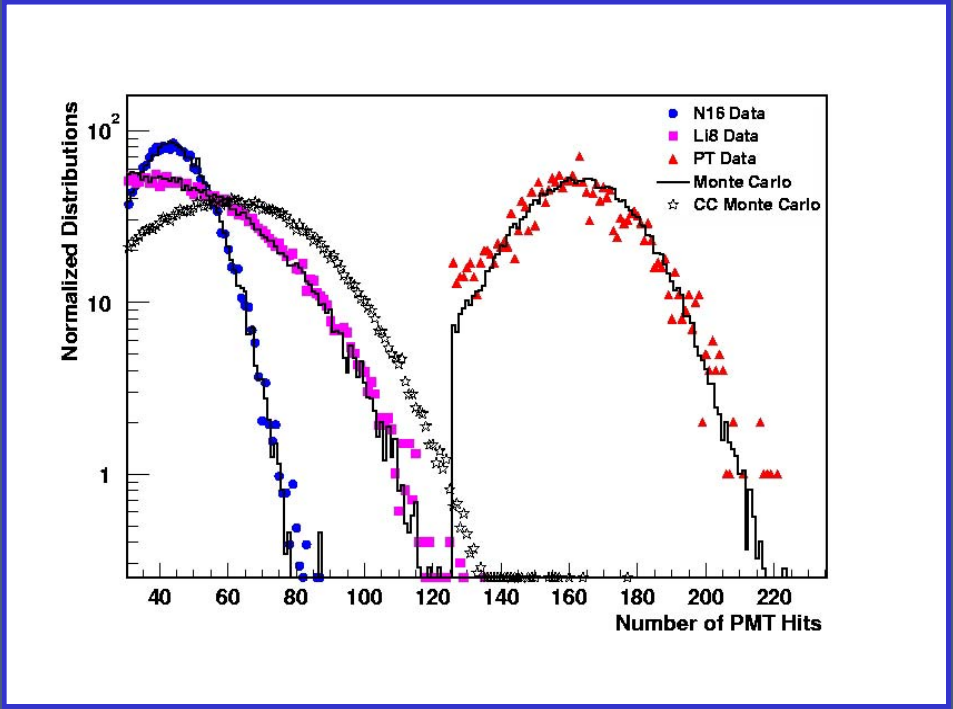
Calibration	Simulates...
Pulsed Laser	337-620 nm optics
^{16}N	6.13 MeV γ's
$^{3}H(p,\gamma)^{4}He$	19.8 MeV γ's
^{8}Li	<13.0 MeV β's
^{252}Cf	neutrons
U/Th	^{214}Bi & ^{208}Tl β-γ's



Energy Calibration

- Track energy response both in position and throughout the livetime of the detector
- Use ^{16}N , ^{8}Li, and (p,t) sources to calibrate across different energies and positions across the detector
- Energy uncertainty: <u>+</u>1.21%

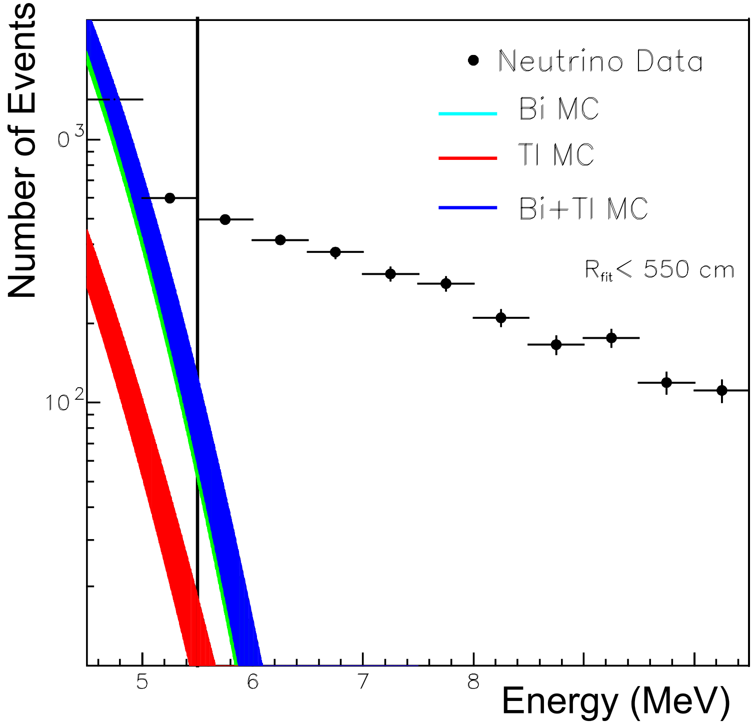
Data vs Monte Carlo

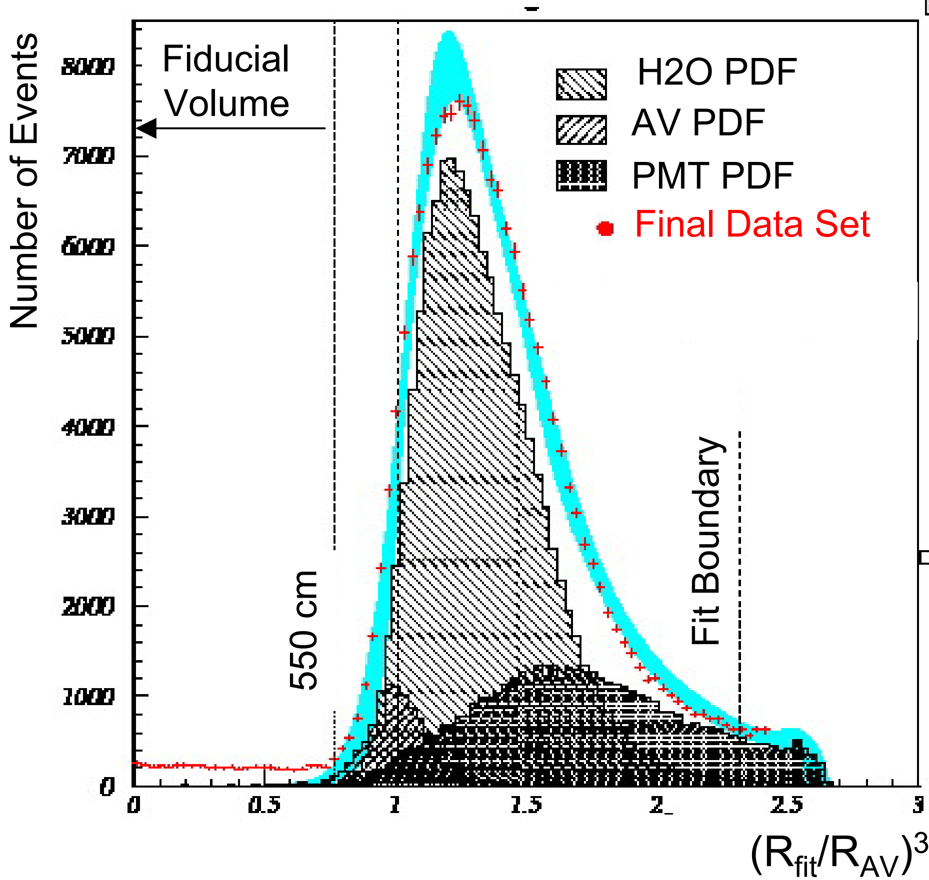


Cherenkov Background

Fit to Cherenkov backgrounds above 4.5 MeV outside fiducial volume

→ Extrapolate into fiducial volume





Events in Data Set	**2928**
Cherenkov Background Events	
D_2O	**20** +13/-6
H_2O	**3** +4/-3
Acrylic Vessel	**6** +3/-6
PMTs	**16** +11/-8

What About Neutrino Mass?