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Neutrino Oscillations

Supervisor:
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Outline

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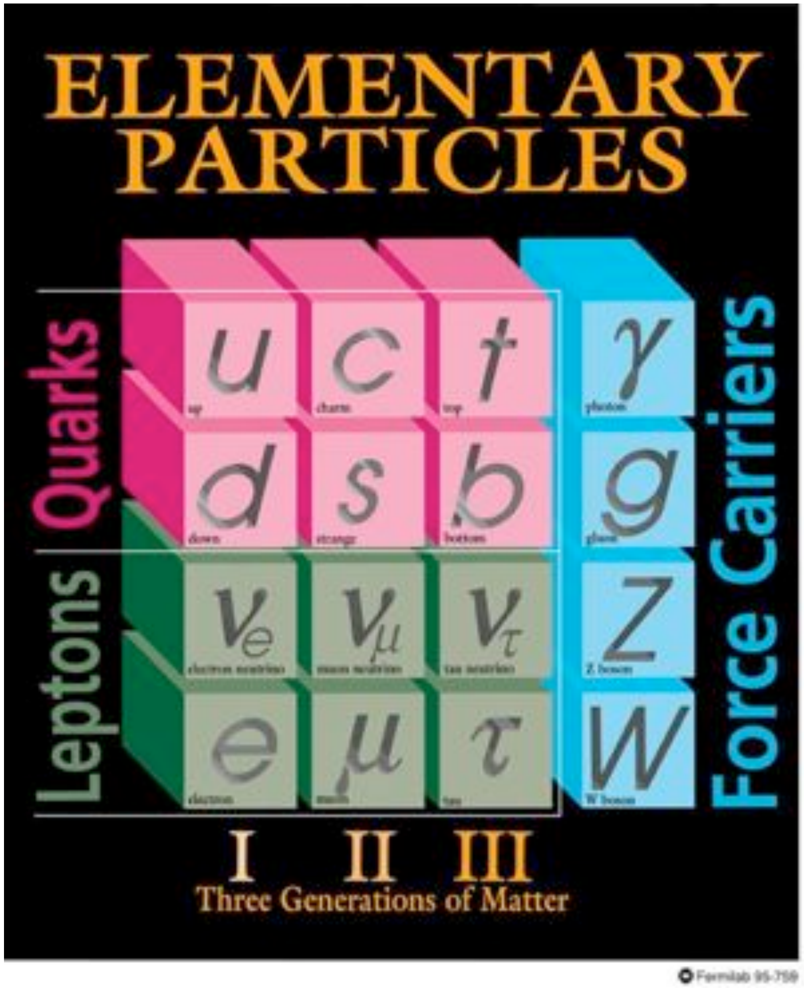
The Neutrino

- Introduced 1931 by Pauli
- Left-handed Fermion
- Spin 1/2
- Lepton
- Flavored:
  - e (1956)
  - μ (1962)
  - τ (2000)
- Weak Interaction
- Cross Section: ~$10^{-45}m^2$

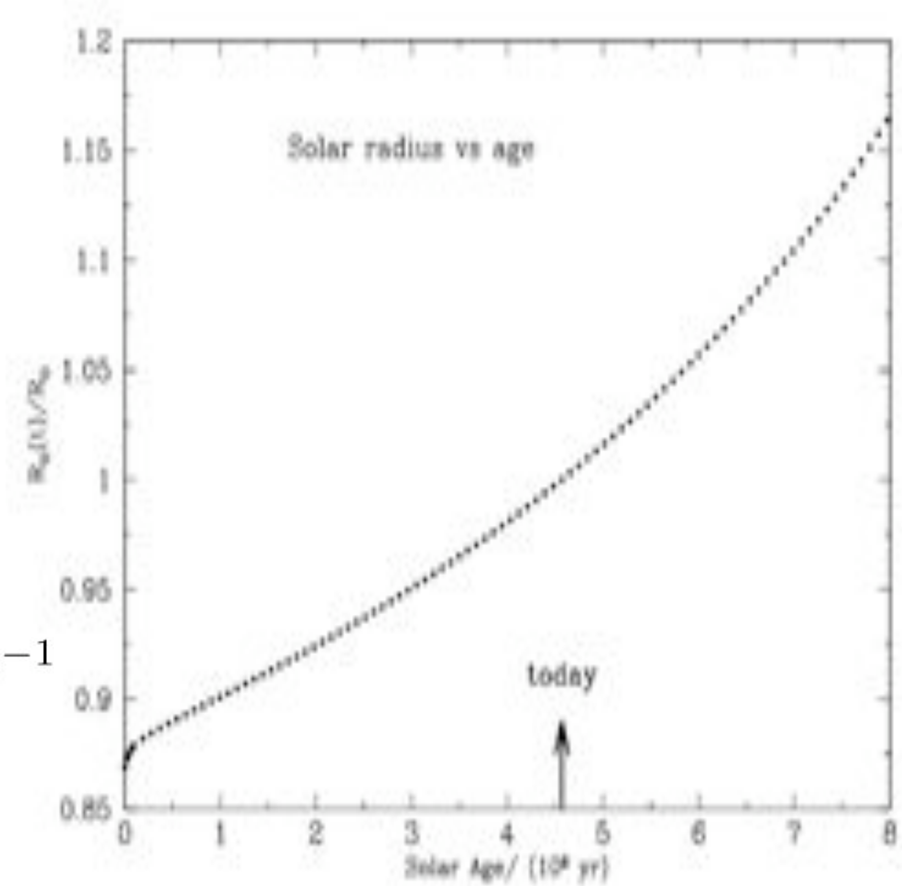


The Standard Solar Model

- Includes Standard Model
- I.e. Luminosity and Radius
  - Age dependent
- Nuclear Fusion
- Particle Propagation in the Sun
- Predicts Neutrino Flux:

$$\phi_{SSM}^{Homestake}(\nu) = 7.6^{+1.3}_{-1.1} \times 10^6 cm^{-2} s^{-1}$$

- …



Neutrino Production in the Sun

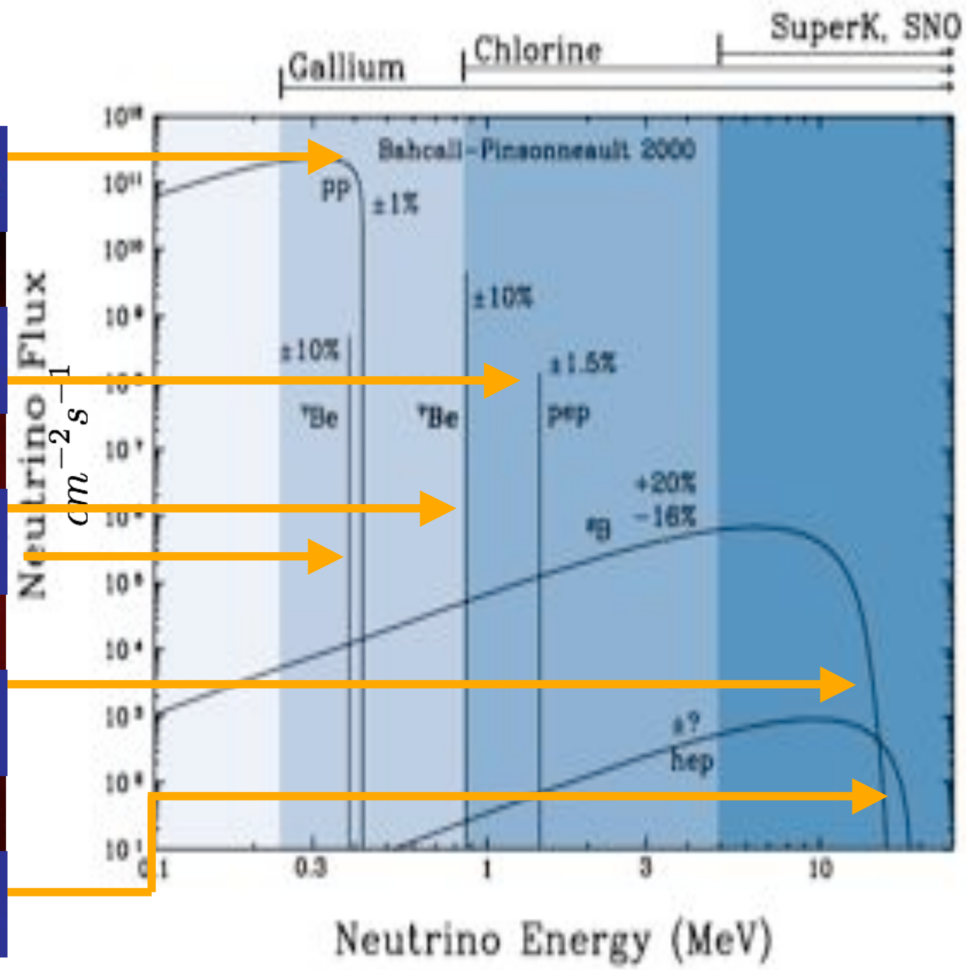
$p + p \rightarrow {}^2H + e^+ + \nu_e$ ≤ 0.423

$p + e^- + p \rightarrow {}^2H + \nu_e$ 1.445

${}^7Be + e^- \rightarrow {}^7Li + \nu_e$ $\begin{cases} 0.863 & 90\% \\ 0.385 & 10\% \end{cases}$

${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$ < 15

${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$ <18.8



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Outline

- The Standard (Solar) Model
- Detecting Neutrinos
- The Solar Neutrino Problem
- Neutrino Oscillations
- Neutrino Interactions
- **S**udbury **N**eutrino **O**bservatory
- Data Collection & Results
- Conclusions & Outlook

Detecting Neutrinos

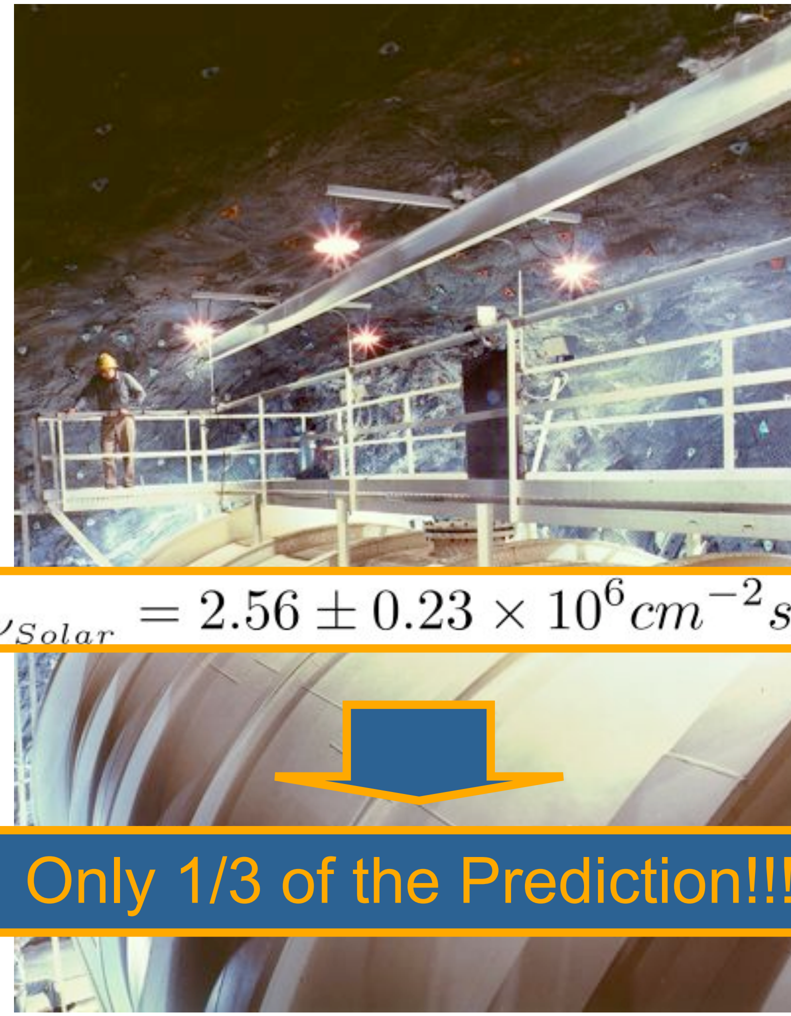
- **1960 - Today:**

  The Homestake Experiment
  - Raymond Davis (Part of Nobel Price 2002)
  - Total Solar Neutrino Flux
  - 1478 m below Surface
  - 615 Tons C_2Cl_4 (Percloroethylene)

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

→ 814 keV Threshold Energy

→ Most sensitive to *pep* Reaction



$$\phi_{\nu_{Solar}} = 2.56 \pm 0.23 \times 10^6 cm^{-2} s^{-1}$$

Only 1/3 of the Prediction!!!

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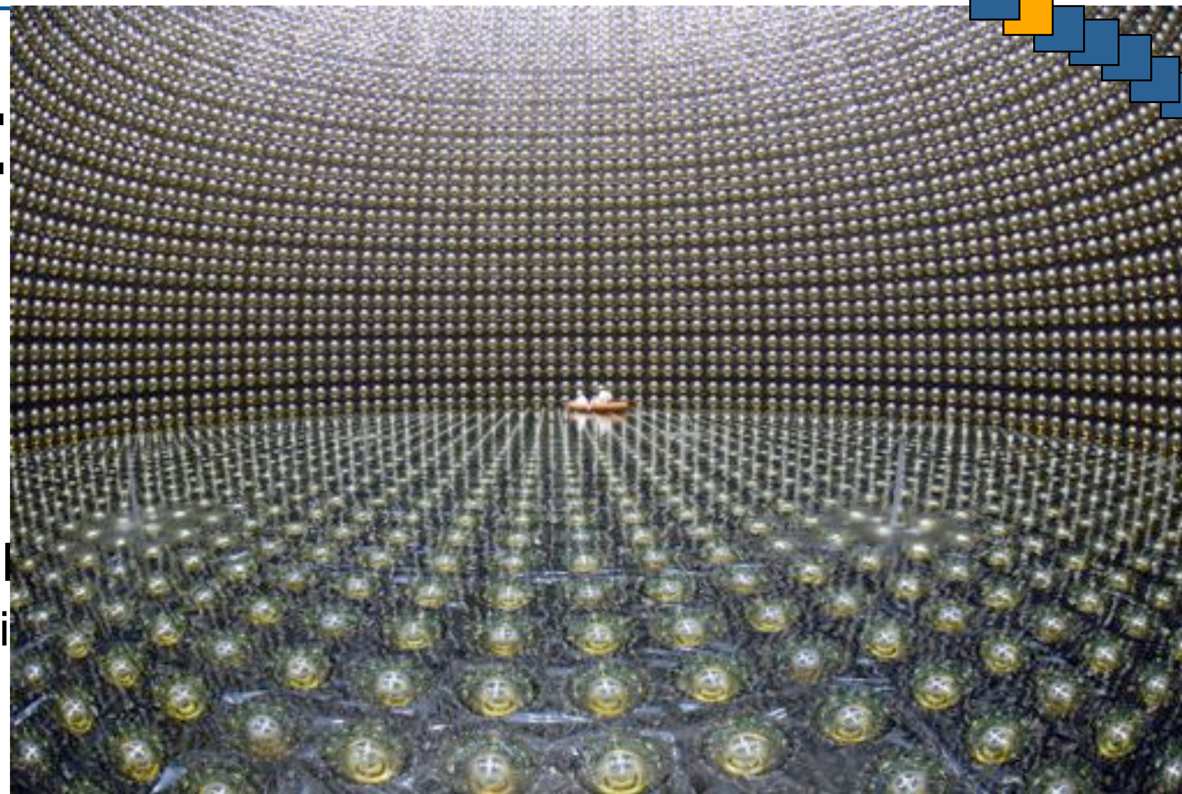
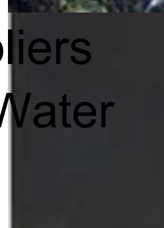
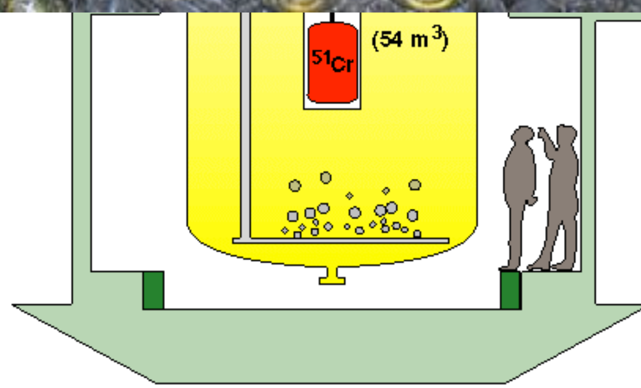
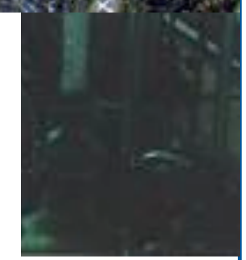
History:



- **1990 - 2000:**
  SAGE
  – 50 Tons of Gallium
- **1991-1997:**
  GALLEX → Now: Gl
  – 101 Tons Galliumtri
- **1996- Today:**
  Super Kamiokande
  – 11.200 Photomultipliers
  – 50.000 Tons Pure Water
- **1999 - Today:**
  Sudbury Neutrino Observa
  – 1.000 Tons D_2O







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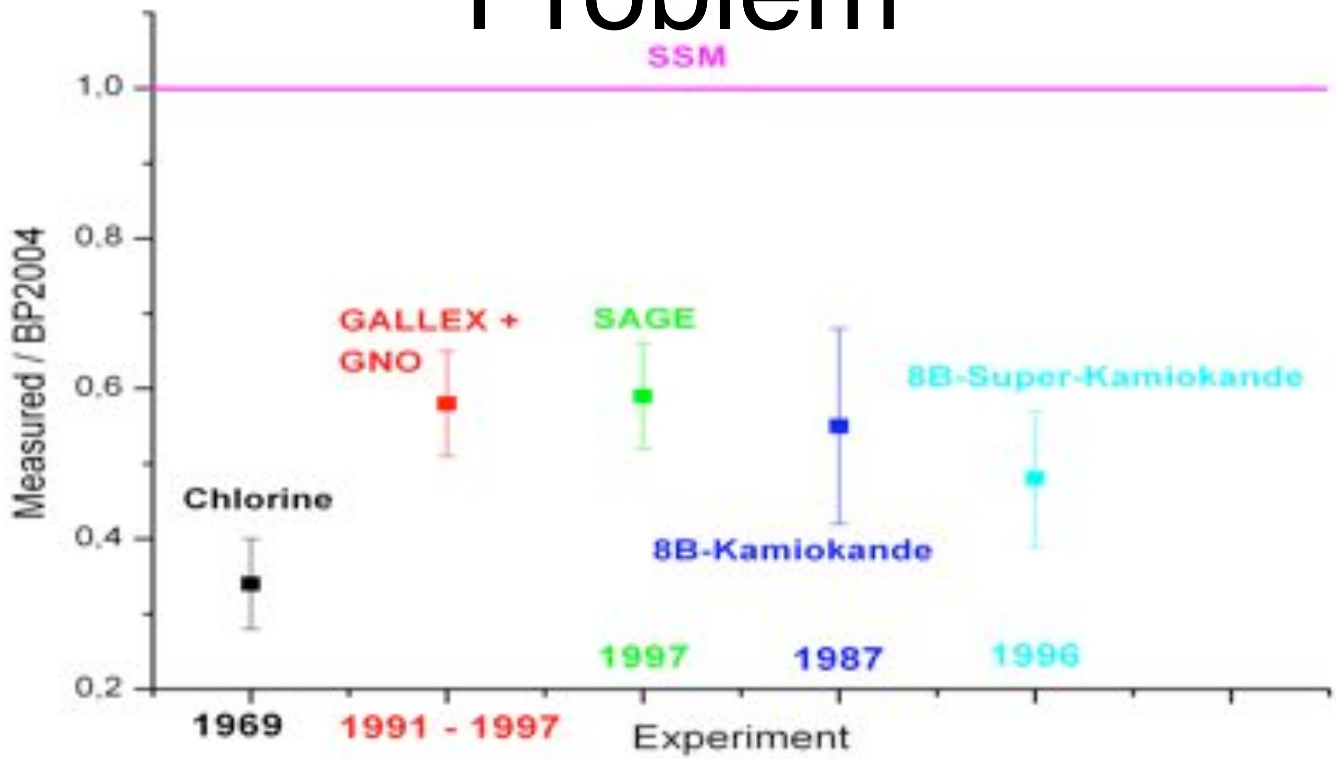
The Solar Neutrino Problem



- Up to 70% of the predicted υ_e's missing!
- Some Mechanism must have changed their Flavor!

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Neutrino Oscillations

Three Neutrino Analysis

- Weak Eigenstates (n=3):

$$|\nu_\alpha(t)\rangle = \sum_{i=1}^{n} U^*_{\alpha i} |\nu_i(t)\rangle$$

Mass Eigenstates

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

Pontecorvo-Maki-Nakagawa-Sakata matrix

- Transition Prob

$$1.27\frac{\Delta m^2_{\alpha\beta}}{\mathrm{eV}^2}\frac{L/E}{m/\mathrm{MeV}}$$

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The Goal

- Comparison of the relative Seize and Rates of three exclusive Signals
- Charged Current Reaction
  - Sensitive only to ν_e's
- Electron Scattering
  - Sensitive to ν_e's and $\nu_{\mu\tau}$'s
- Neutral Current Reaction
  - Equally sensitive to all Neutrino Flavors

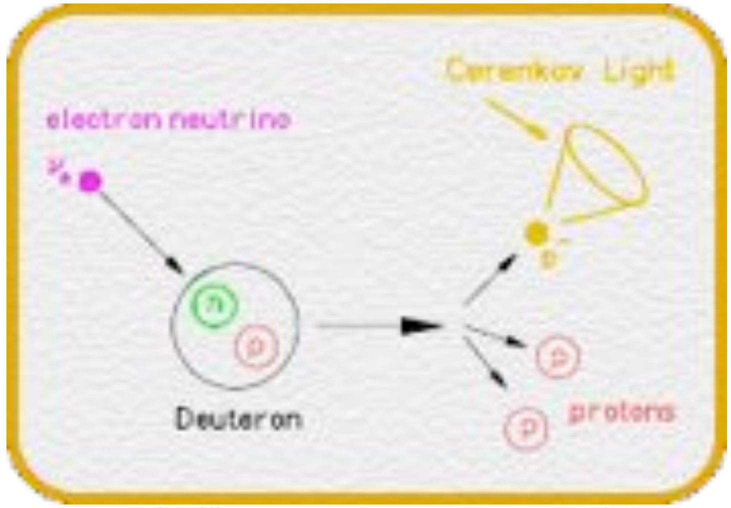
→ Derive $\phi(\nu_e)$ and $\phi(\nu_{\mu\tau})$ from the total detected Flux

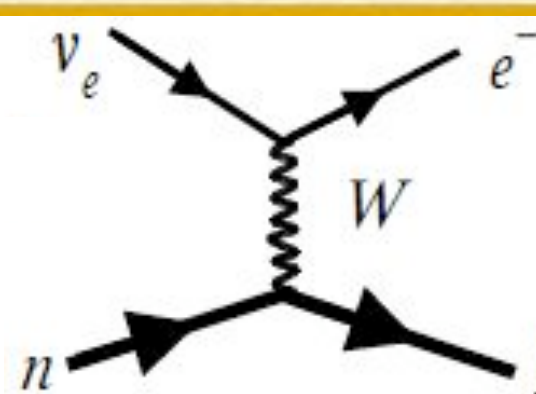
Charged Current (CC) Reaction

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

- W boson exchanged
- e^- ejected at speed of light
- Amount of light ~ energy
- SSM predicts 30 events per day

$$\Rightarrow \quad \phi_{CC} = \phi(\nu_e)$$

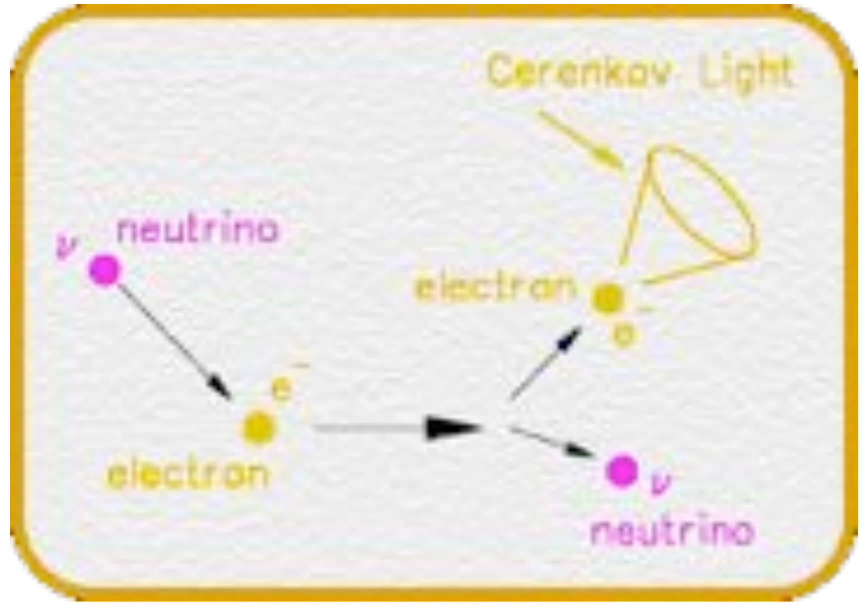


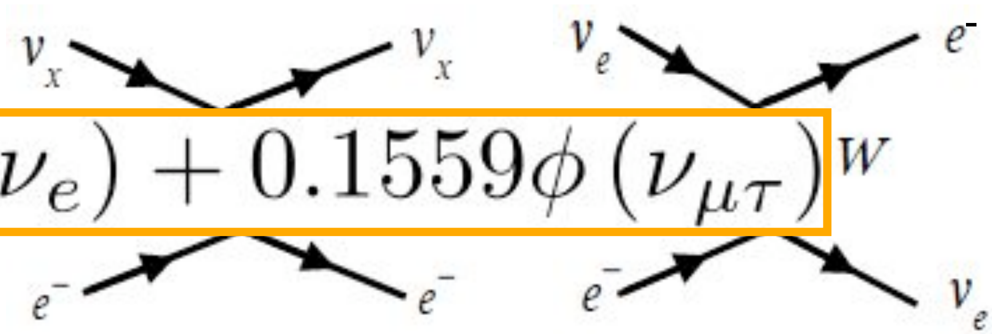


Electron Scattering (ES)

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

- e^- direction correlated to incident neutrino
- Dominated by e^- neutrinos by factor of 6.5
- SSM predicts 3 events per day



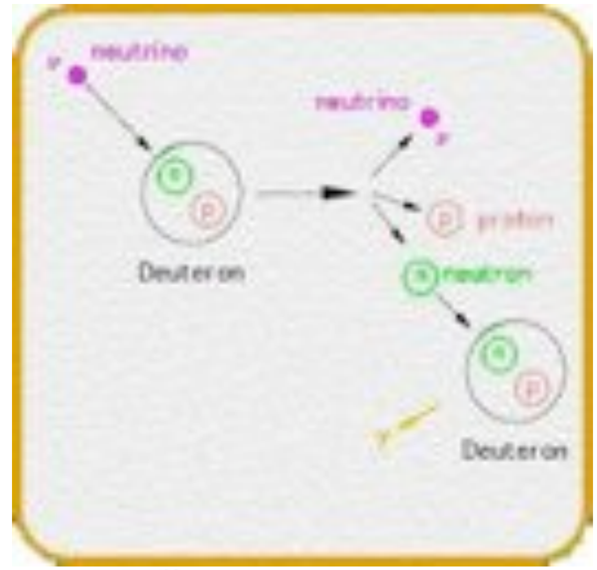


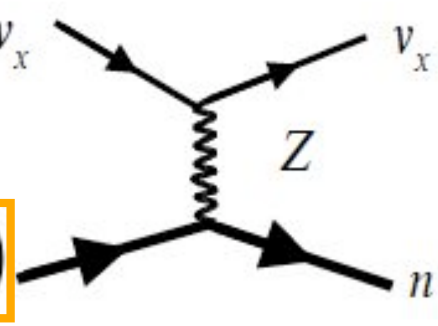
$$\phi_{ES} = \phi(\nu_e) + 0.1559\phi(\nu_{\mu\tau})$$

Neutral Current (NC) Reaction

$$\nu_x + d \longrightarrow p + n + \nu_x$$

- Releases single 6.35 MeV Photon
- As Charged Current: Unique to Heavy Water
- Equally sensitive to all Flavors
- Direct Measurement of Flux of all Neutrinos
- Cross Section only 0.5 mb





$$\phi_{NC} = \phi(\nu_e) + \phi(\nu_{\mu\tau})$$

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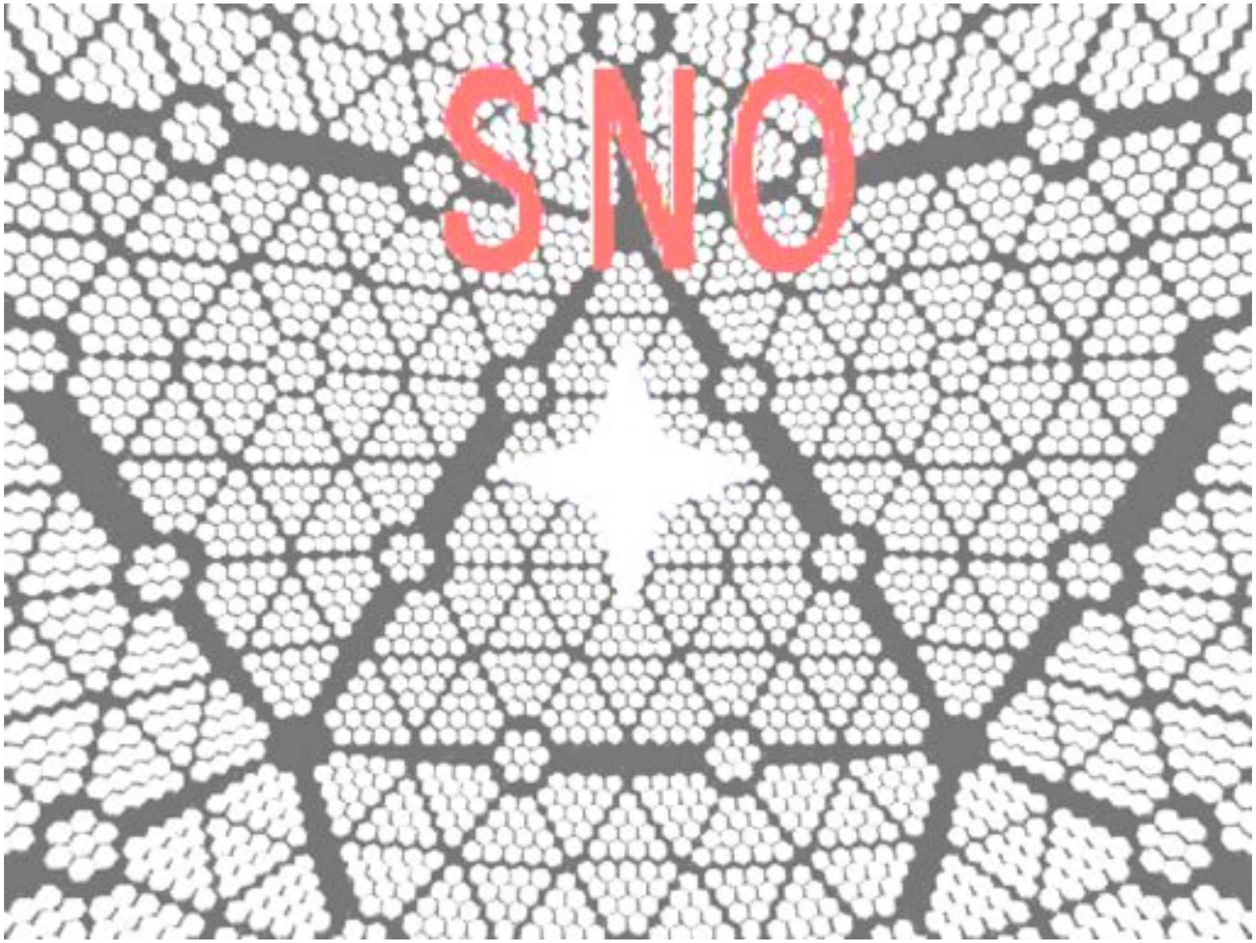
The Solution



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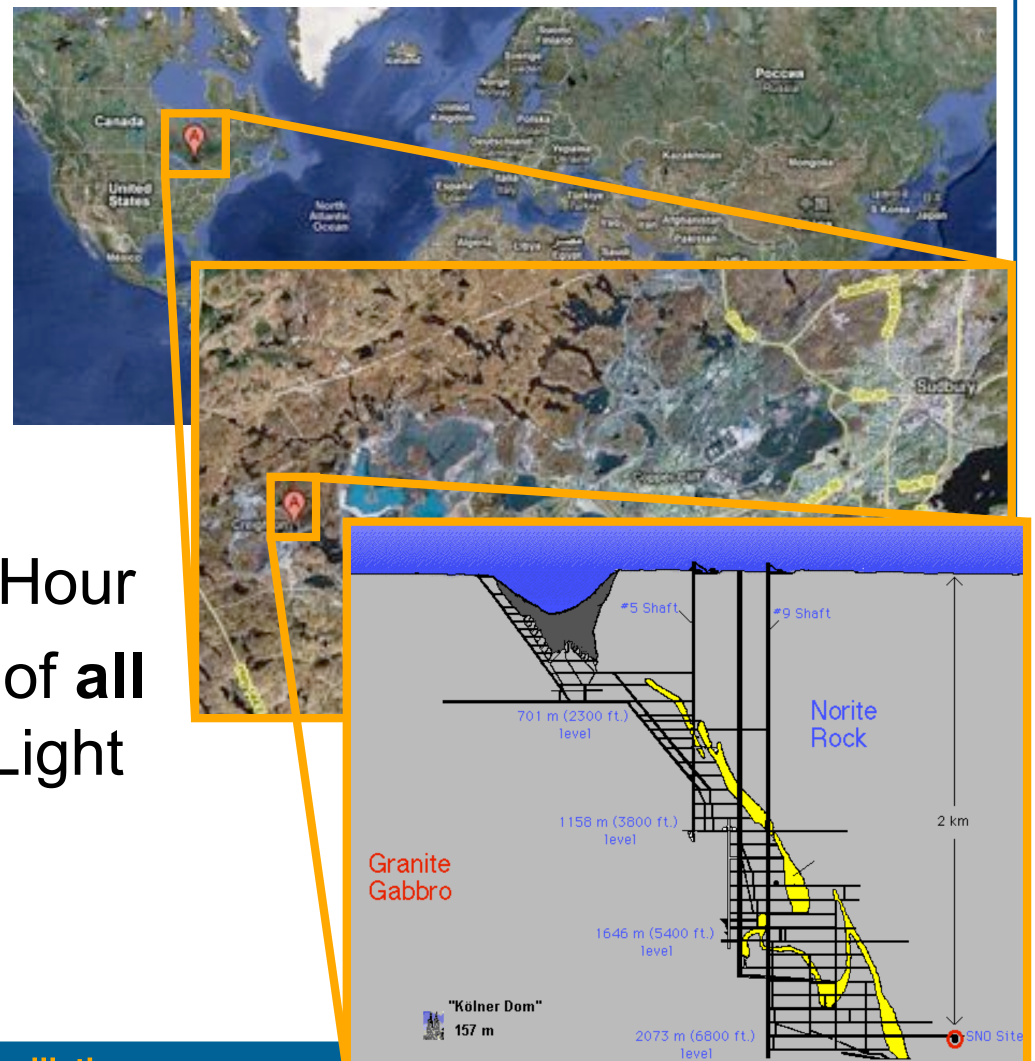
Outline

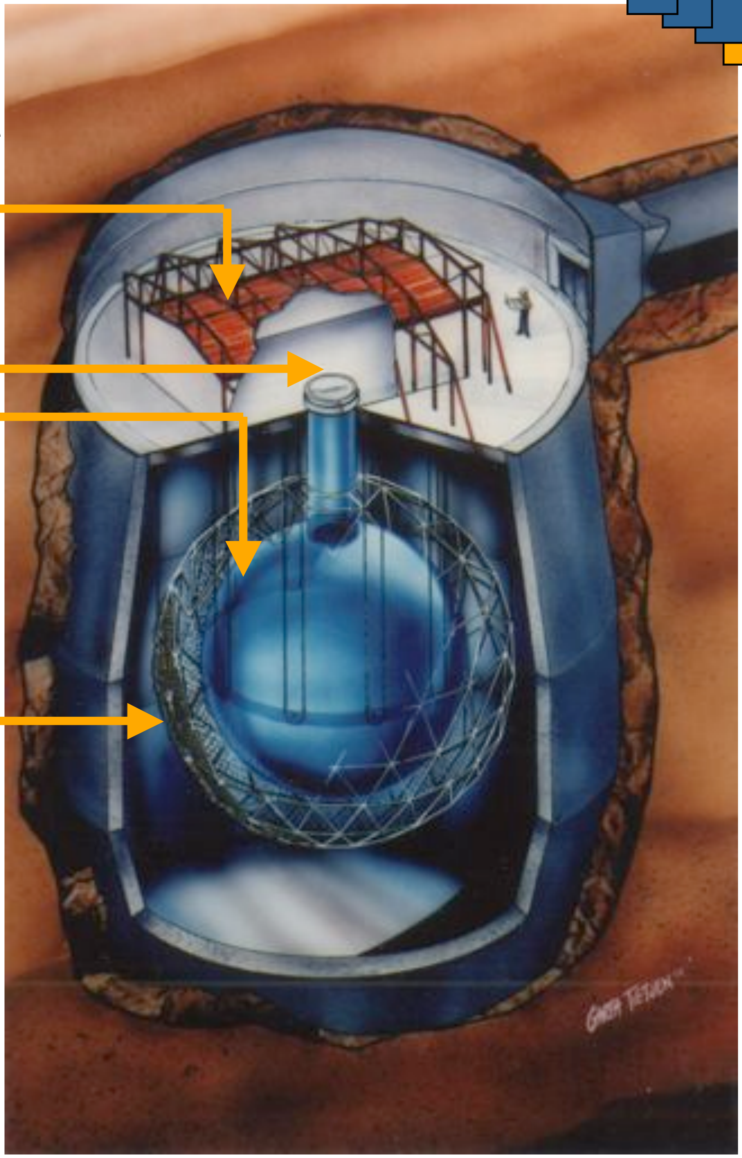
Sudbury **N**eutrino **O**bservatory

- Located in Canada
  - Near Sudbury, Ontario
  - 1730 m below Sea Level
- Construction of SNO finished in 1999
- → About 3 cosmic μ‘s per Hour
- Identifies Neutrino Flux of **all** Flavors via Cherenkov Light



Detector Layout

- Four Neck Photomultiplier Tubes
- Deployment System
- Acrylic Vessel
  - 12 m Diameter
  - 1000 Tons of $D_2 0$
  - Surrounded by 1700 Tons of light Water
- Support Sphere
  - 9456 20-cm Photomultiplier Tubes
  - 54% of 4π
  - Surrounded by 5700 Tons of light Water
  - 91 outward facing Photomultiplier Tubes
  - 23 inward facing Photomultiplier Tubes



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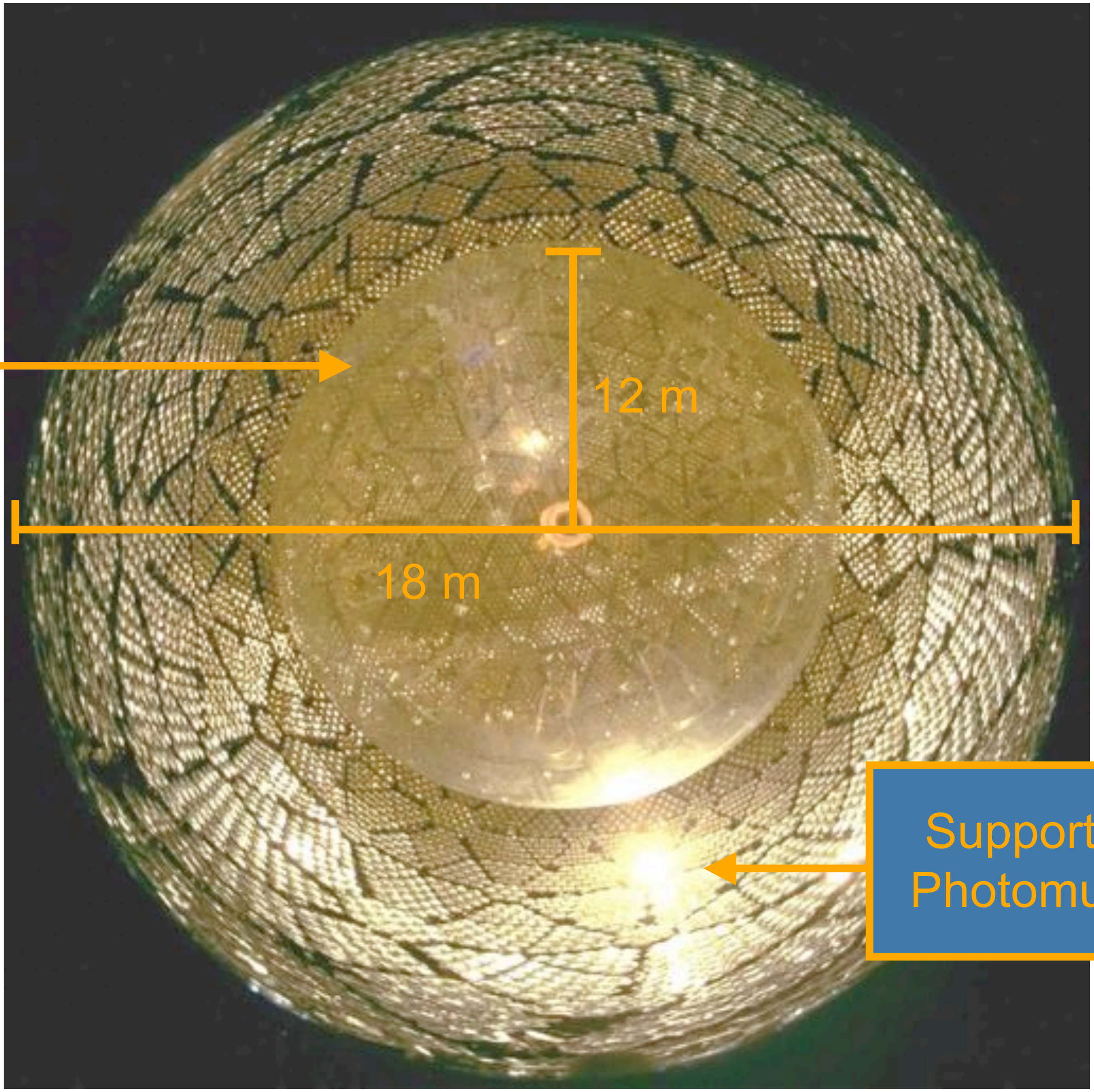
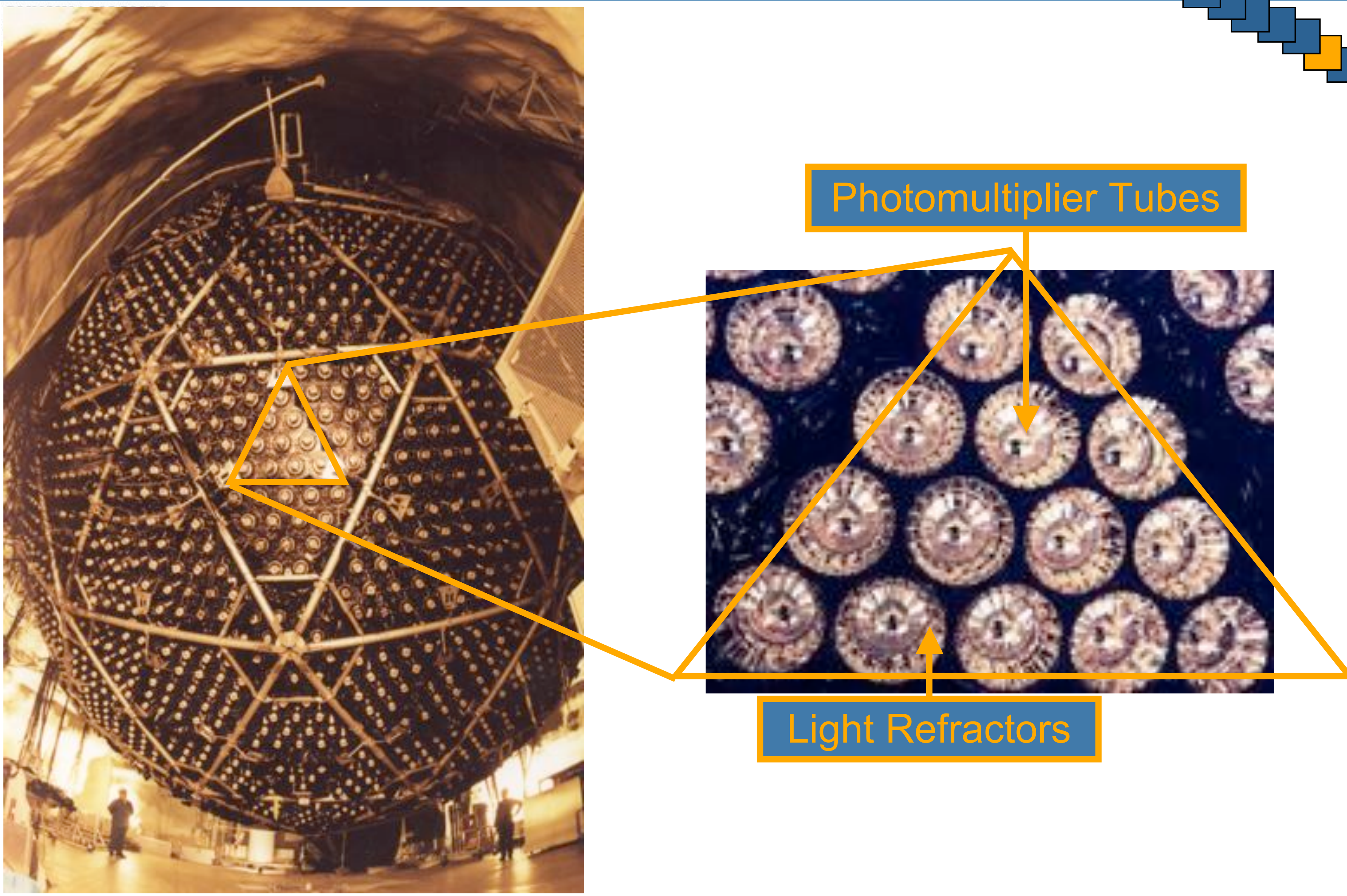
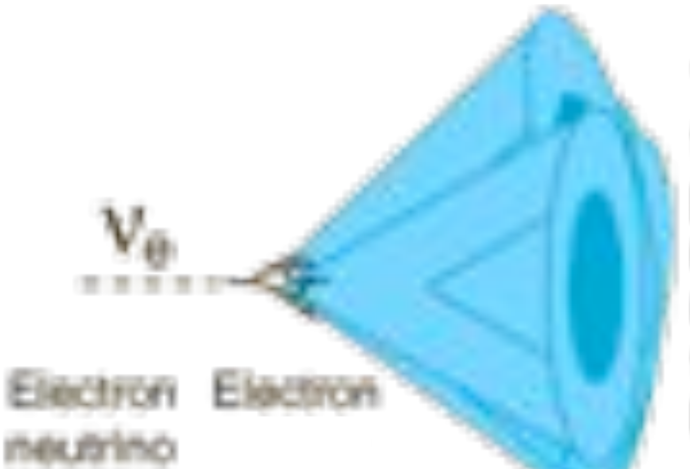


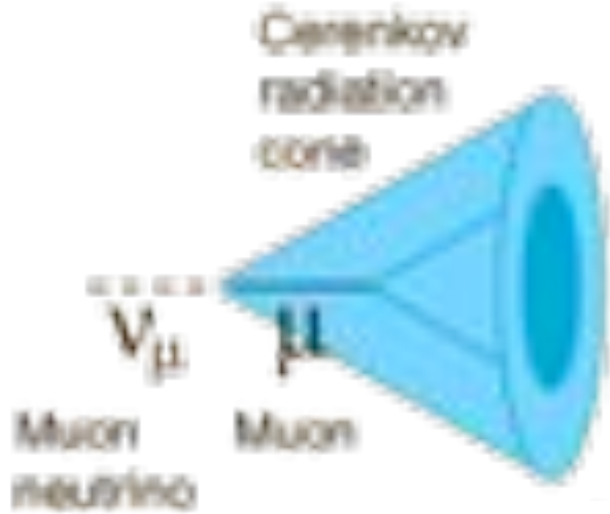

Photomultiplier Tubes
Light Refractors

Particle Identification

ν_e Event ⟷ Muon Event



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



$$\nu_\mu + d \rightarrow p + p + \mu^-$$

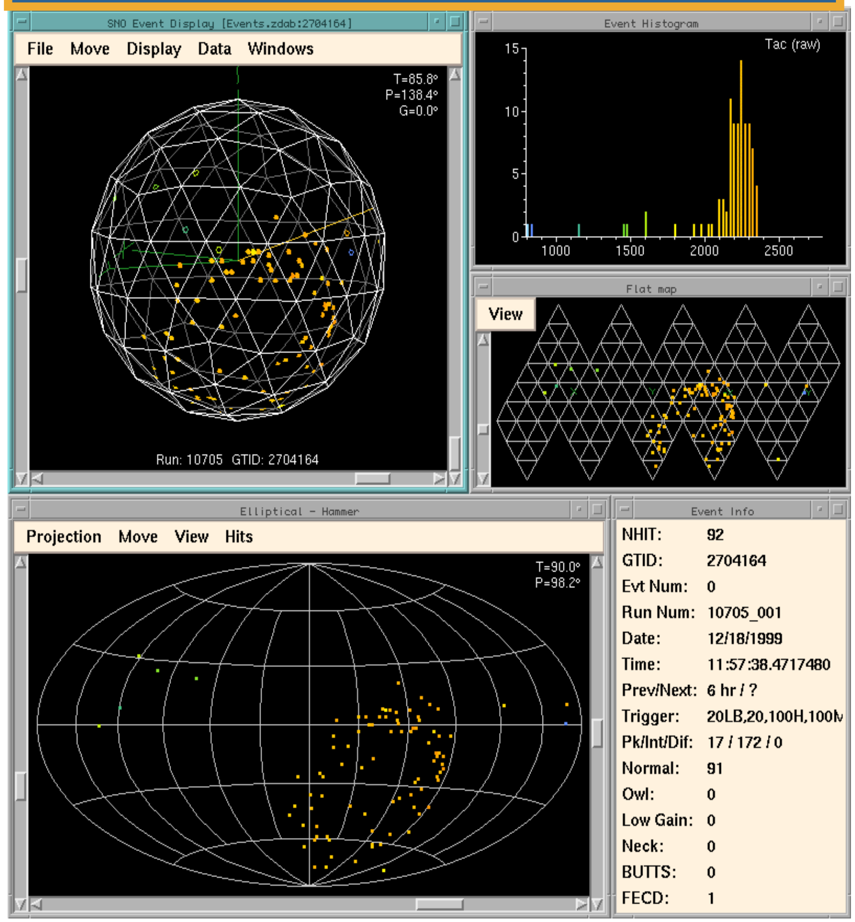
- Compton Scattering
- Multiple Cones

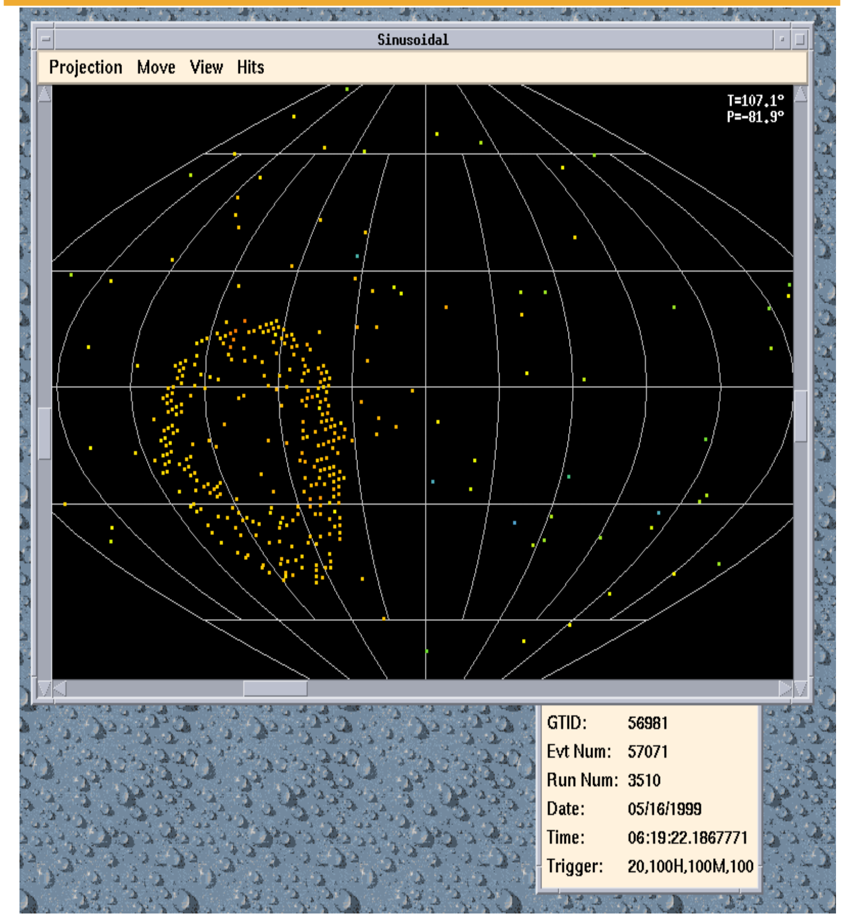
→ Diffuse Cherenkov Ring

- Sharp-edged Cherenkov Ring

How does an event look like?

ν_e Event	Muon Event





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Analysis Strategy

- Measure Sum of all Fluxes

Maximum Likelihood Fit

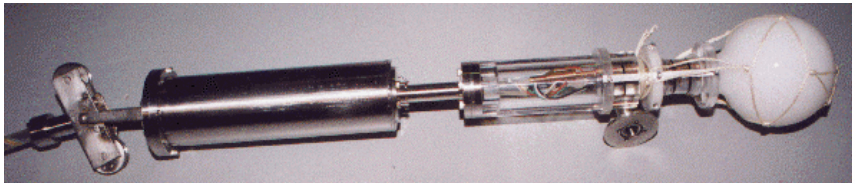
- Single Fluxes as free Parameters

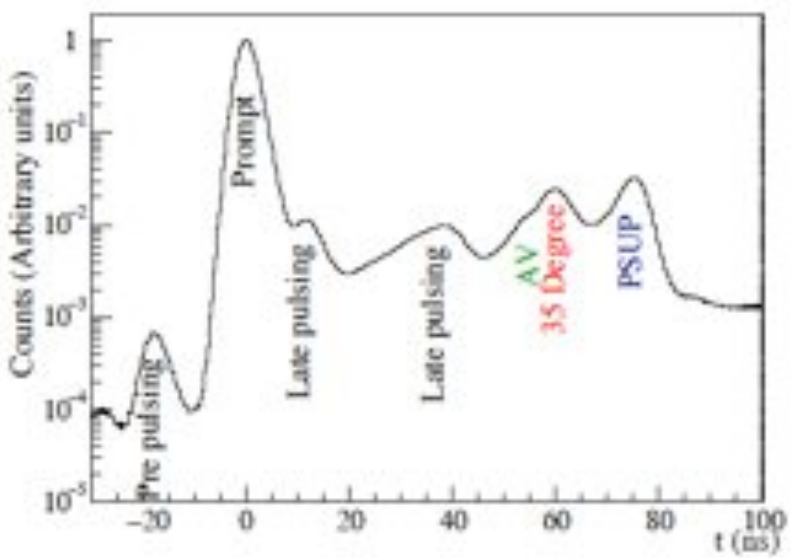
- Model must include:
  - Neutrino Interactions
  - Propagation of Particles and Optical Photons
  - Behavior of the DAQ
  - Detector Changes
  - Acceptance Corrections, Capture Efficiency,…

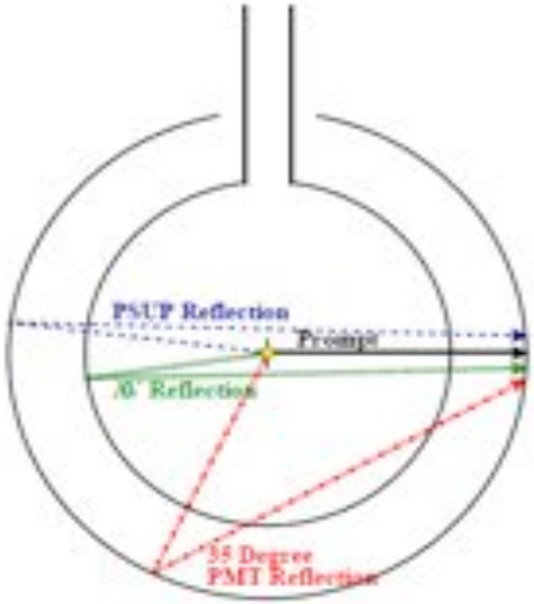
Calibration

- Calibration at Different Positions
- Different Radioactive Sources, i.e. ^{16}N
  - 6.13 MeV Photons
- Multi-Wavelength Laser
  - PMT Timing

Laser Ball







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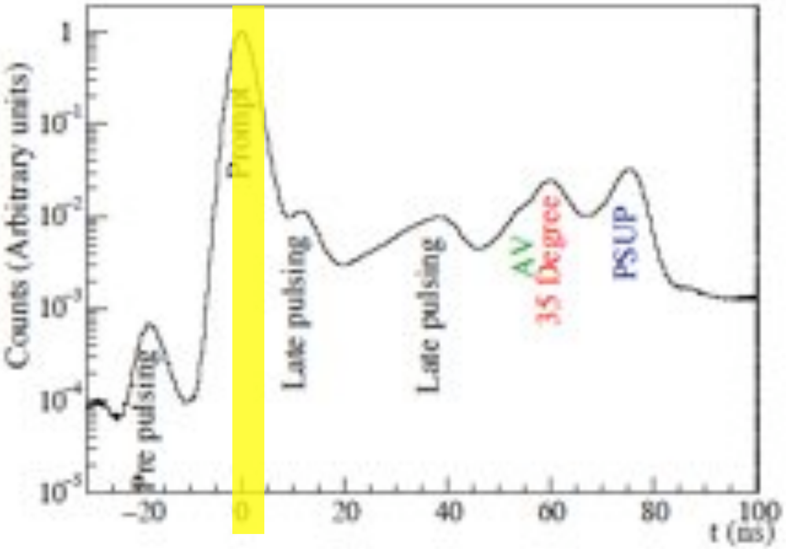
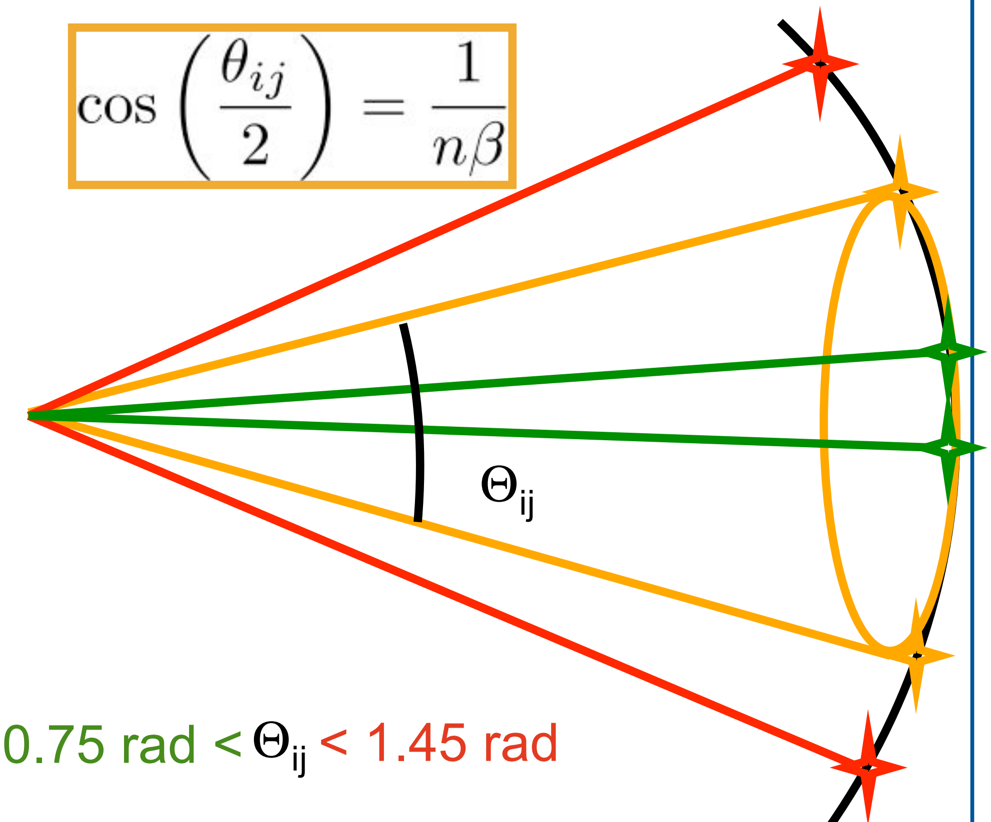
Cherenkov Light Characteristics



$$-2.5ns \rightarrow +0.5ns$$

$$\cos\left(\frac{\theta_{ij}}{2}\right) = \frac{1}{n\beta}$$



$$t_{Cut} = \frac{N_{InTime}}{N_{Total}} > 0.55$$

0.75 rad < Θ_{ij} < 1.45 rad

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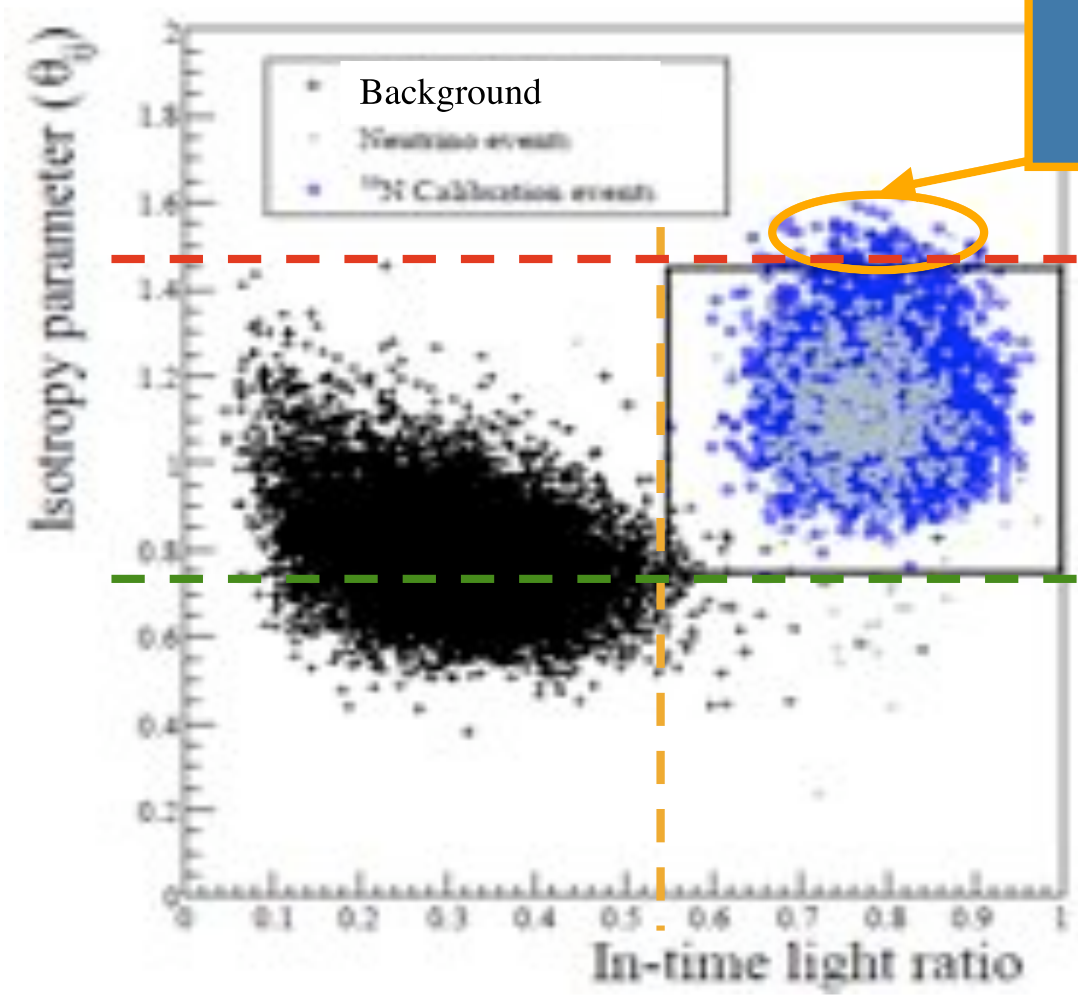
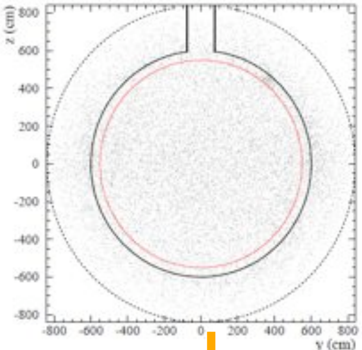
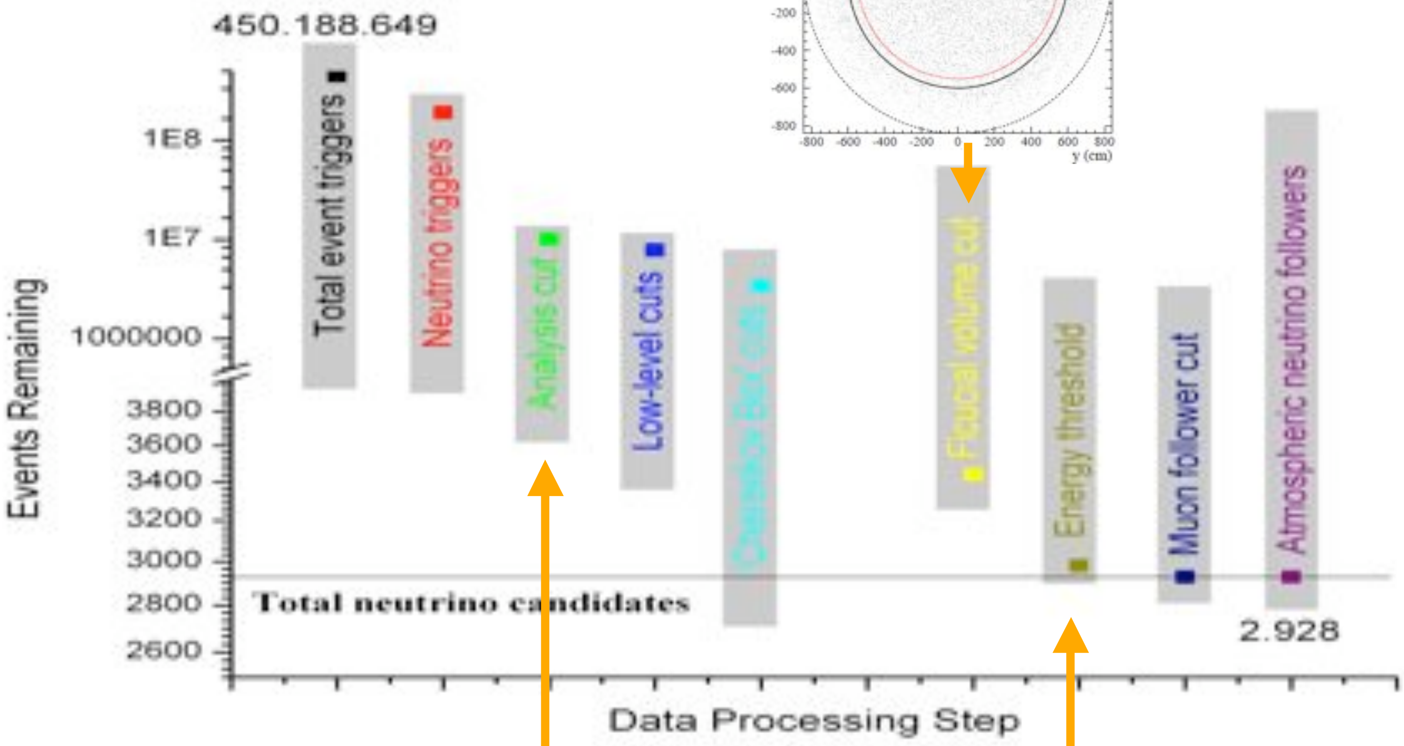
“Cherenkov Box“ Cuts



Incorrect reconstructed Tracks

Data Collection & Cuts





$N_{hit} > 21$

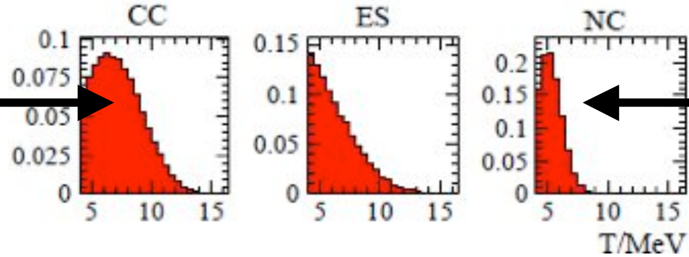
$T_{eff} > 5$ MeV

Extraction of the Signals

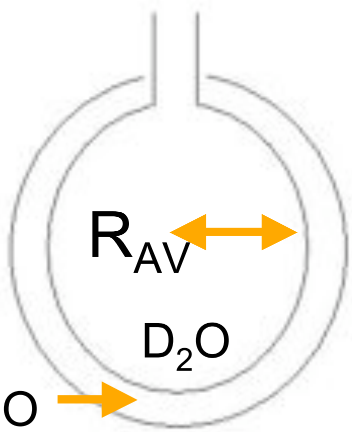
Effective Kinetic Energy

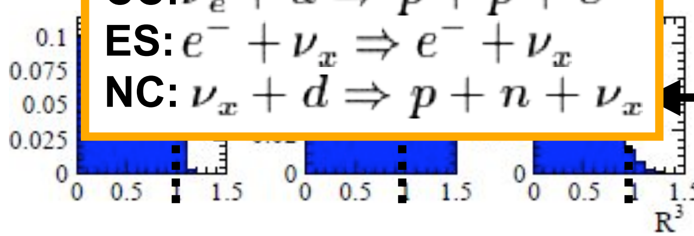
^{8}Be Spectrum

6.25 MeV



CC: $\nu_e + d \Rightarrow p + p + e^-$
ES: $e^- + \nu_x \Rightarrow e^- + \nu_x$
NC: $\nu_x + d \Rightarrow p + n + \nu_x$



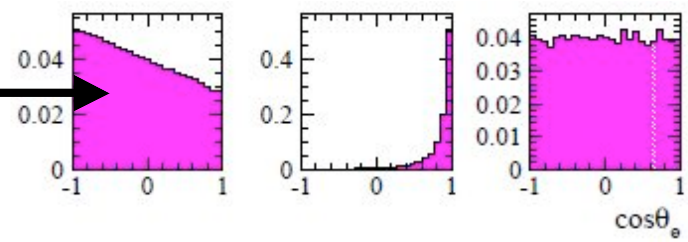


CC: $\nu_e + d \Rightarrow p + p + e^-$
ES: $e^- + \nu_x \Rightarrow e^- + \nu_x$
NC: $\nu_x + d \Rightarrow p + n + \nu_x$

$$R^3 \equiv \left(\frac{R_{fit}}{R_{AV}}\right)^3 = 1.0$$

Reconstructed Direction of the Event

$$\propto 1 - \frac{1}{3}\cos(\Theta_\odot)$$



CC: $\nu_e + d \Rightarrow p + p + e^-$
ES: $e^- + \nu_x \Rightarrow e^- + \nu_x$
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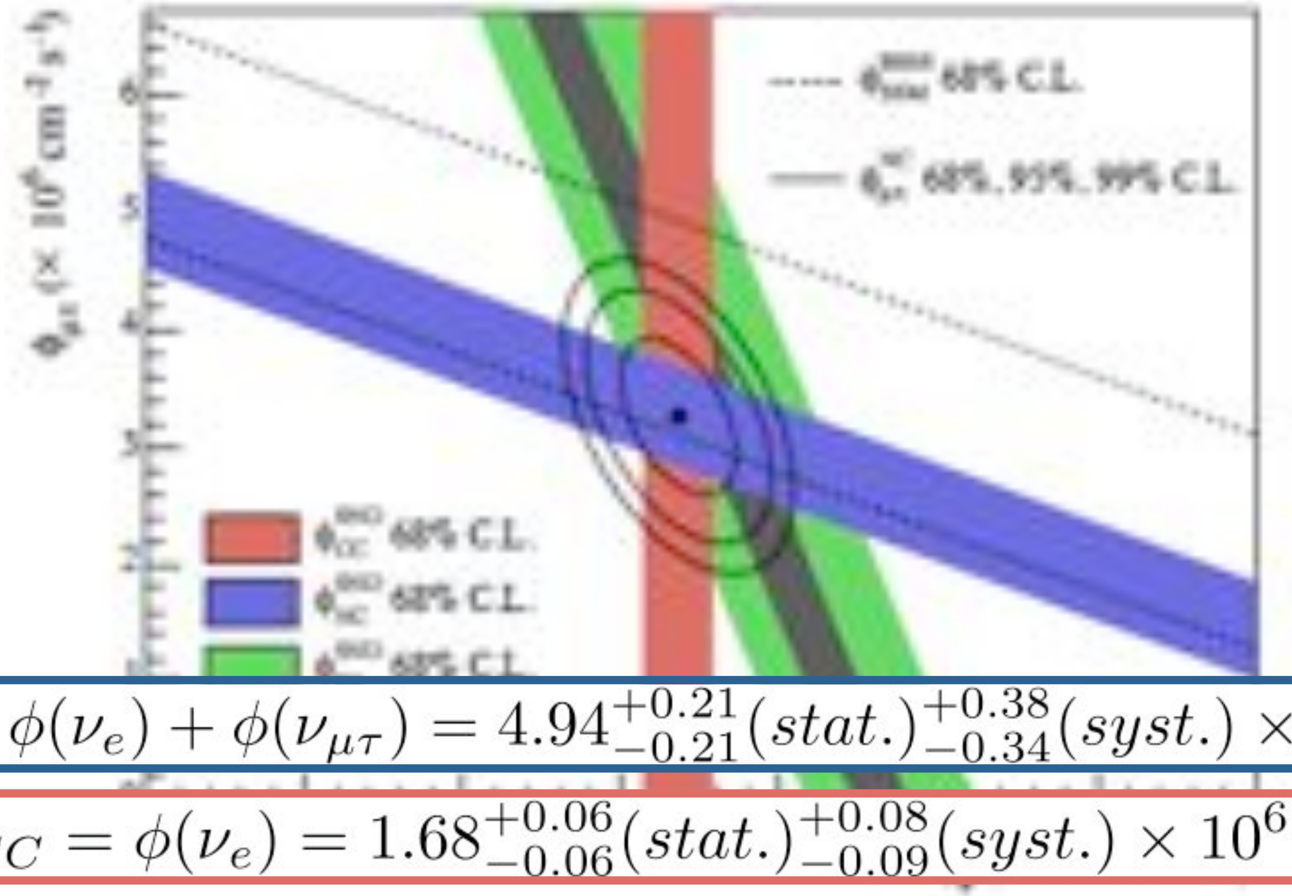
Results



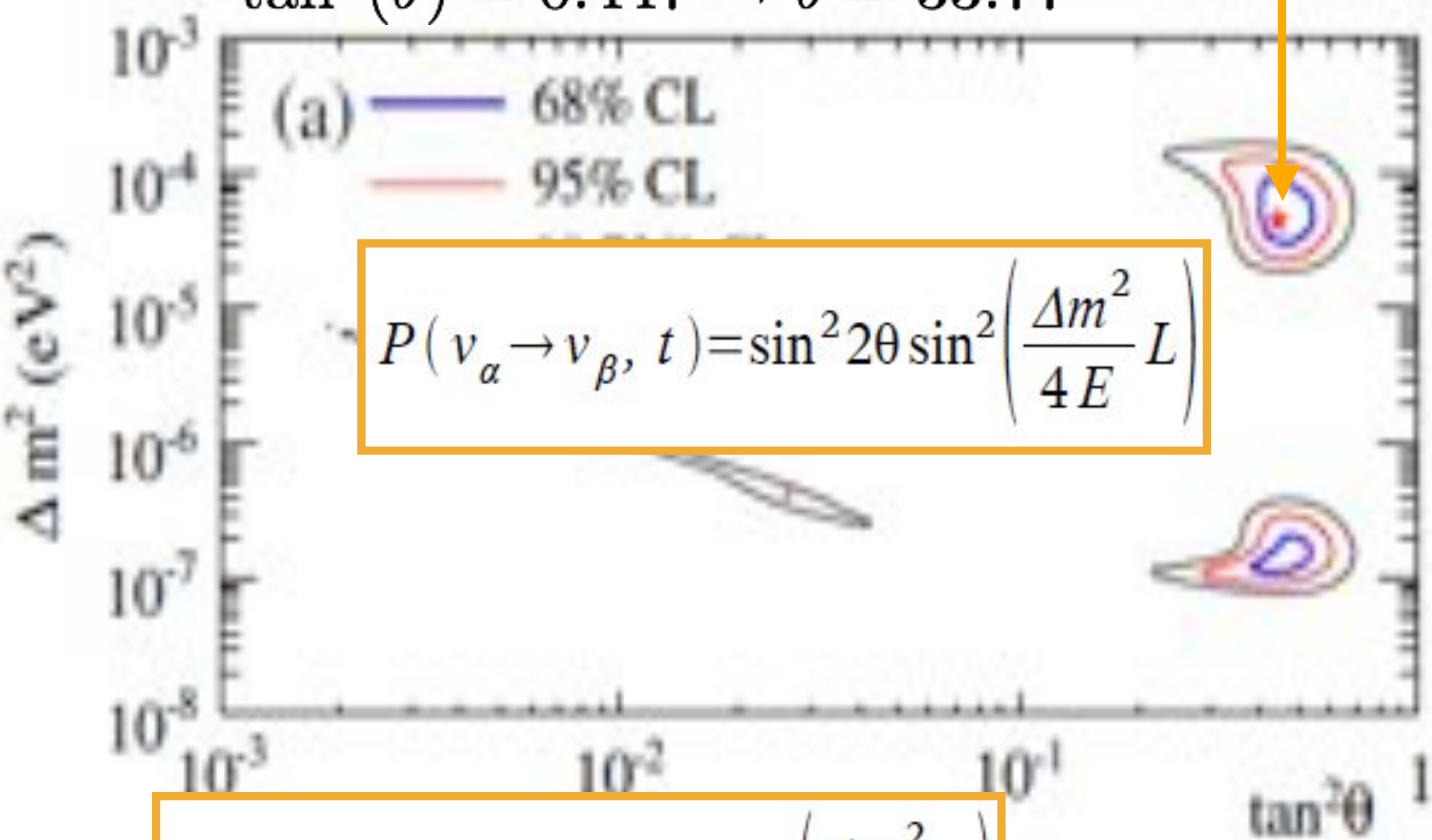
$$\phi_{NC} = \phi(\nu_e) + \phi(\nu_{\mu\tau}) = 4.94^{+0.21}_{-0.21}(stat.)^{+0.38}_{-0.34}(syst.) \times 10^6 cm^{-2} s^{-1}$$

$$\phi_{CC} = \phi(\nu_e) = 1.68^{+0.06}_{-0.06}(stat.)^{+0.08}_{-0.09}(syst.) \times 10^6 cm^{-2} s^{-1}$$

$$\phi_{ES} = \phi(\nu_e) + 0.1559\phi(\nu_{\mu\tau}) = 2.35^{+0.22}_{-0.22}(stat.)^{+0.15}_{-0.15}(syst.) \times 10^6 cm^{-2} s^{-1}$$

Mixing Parameters

$$\Delta m^2 = 4.57 \times 10^{-5} eV^2$$
$$\tan^2(\theta) = 0.447 \rightarrow \theta = 33.77$$



$$P(\nu_\alpha \rightarrow \nu_\beta, t) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$

$$P(\nu_\alpha \rightarrow \nu_\beta, t) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$

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Conclusions & Outlook

- Solar Neutrino Problem

$$\phi_{SSM}\left(\nu\left({}^{8}B\right)\right) = 5.05\left(^{+0.20}_{-0.16}\right) \times 10^{6} cm^{-2} s^{-1}$$

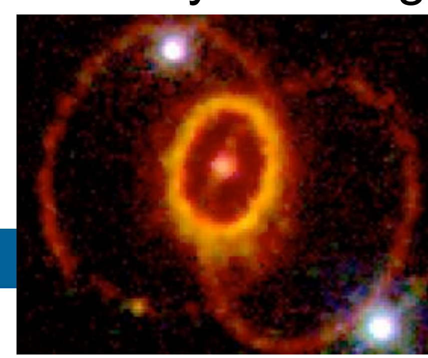
  - ✓ Solved by SNO!!!

$$\phi_{NC} = 4.94^{+0.21}_{-0.21}(stat.)^{+0.38}_{-0.34}(syst.) \times 10^{6} cm^{-2} s^{-1}$$

- Neutrino Interaction Understood (?)
  - ✓ Neutrino Oscillations
  - ✓ Day-Night-Asymmetry
- Neutrinos have Mass!!!

$$m_{\nu_e} < 460eV\ (68\%\ C.L.)$$
$$m_{\nu_\mu} < 0.19MeV\ (90\%\ C.L.)$$
$$m_{\nu_\tau} < 18.2MeV\ (95\%\ C.L.)$$

- Improved *hep* Neutrino Search
- New Fitting Algorithms and Techniques
- BOREXINO Detector for Low Energies
- Supernova Early Warning System



Sources

- B.Aharmim *et al.* (SNO Collaboration), arXiv:nucl-ex/0610020v1
- B. Aharmim *et al.* (SNO Collaboration), Phys. Rev. Lett. 101, 111301 (2008)
- B. Aharmim *et al.* (SNO Collaboration), arXiv:nucl-ex/0502021v1
- M.C. Gonzalez-Garcia, arXiv:hep-ph/0202058v3
- C. Howard (SNO Collaboration), arXiv:0906.0040v1
- http://www.sno.phy.queensu.ca/
- http://www.sns.ias.edu/~jnb/
- http://www.physi.uni-heidelberg.de/~uwer/lectures/ParticlePhysics/vorlesung.html

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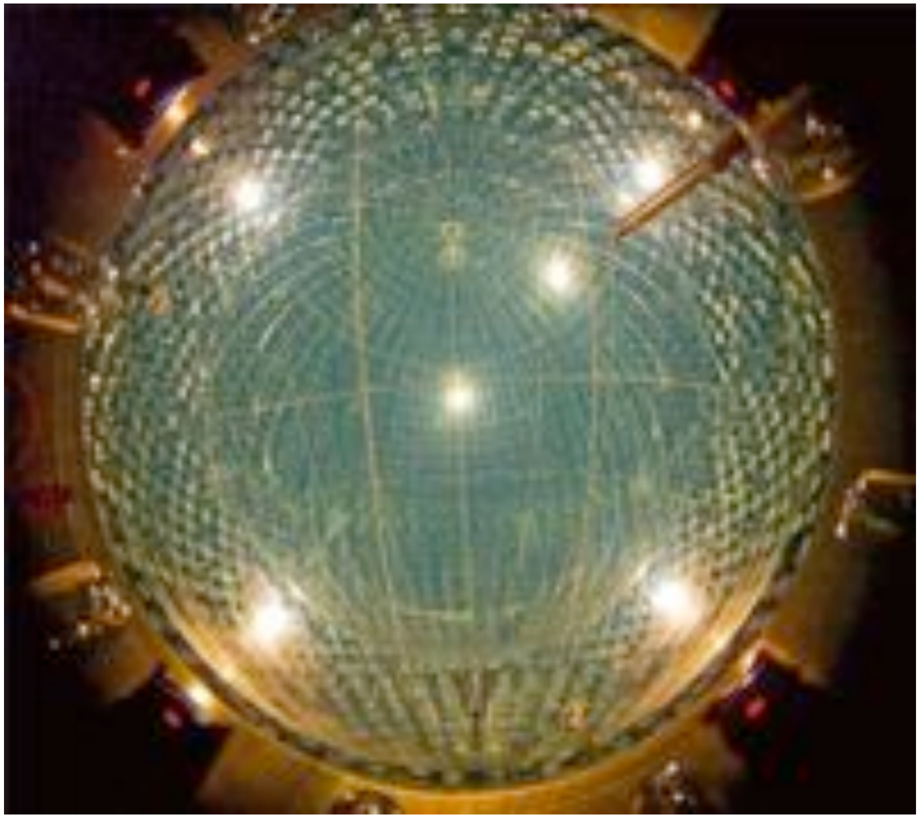
Pictures

- http://www.bnl.gov/bnlweb/raydavis/pictures.htm
- http://wwwlapp.in2p3.fr/neutrinos/anexp.html#gallex
- http://borex.lngs.infn.it/
- http://ewiserver.npl.washington.edu/sage/
- http://www.lancs.ac.uk/ug/ovens/Sun_SOHO_image.jpg
- http://www.sns.ias.edu/~jnb/
- http://hyperphysics.phy-astr.gsu.edu/hbase/Relativ/imgrel/cerenkov.gif
- http://cerncourier.com/cws/article/cern/39162
- http://home.fnal.gov/~carrigan/pillars/Standard_model_chart.png

BOREXINO

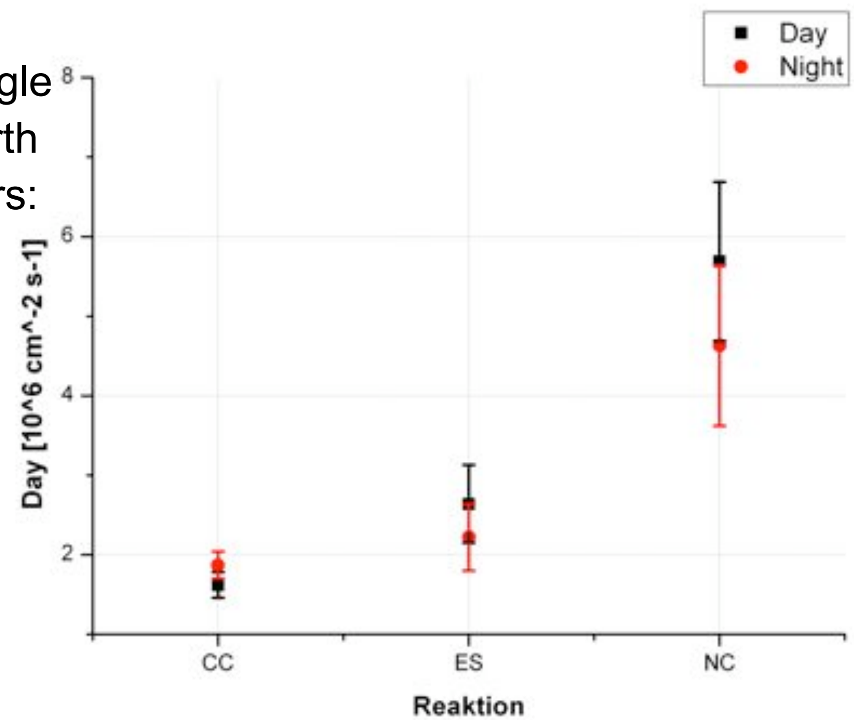
- 278 Tons of
  Liquid Scintillator
- Nylon Vessel (125 μm)
- 2212 20-cm Photomultipliers
- 13.7 m Diameter Support Sphere
- Running since May 2007
- **Measuring 0.862 MeV ^{7}Be ν's**
- **Found Transitions between High (^{8}B)-and**



See CERN Courier, Vol. 49, #5, p. 13

Day-Night-Asymmetry

- Would be strong Evidence for Neutrino Oscillation
- Observable spectral Distortions
  - Dependence on Solar Zenith Angle
  - Interaction with Matter in the Earth
  - Change of Oscillation Parameters:
    - Path Length
    - Electron Density



Phases 1 - 3

Phase 1

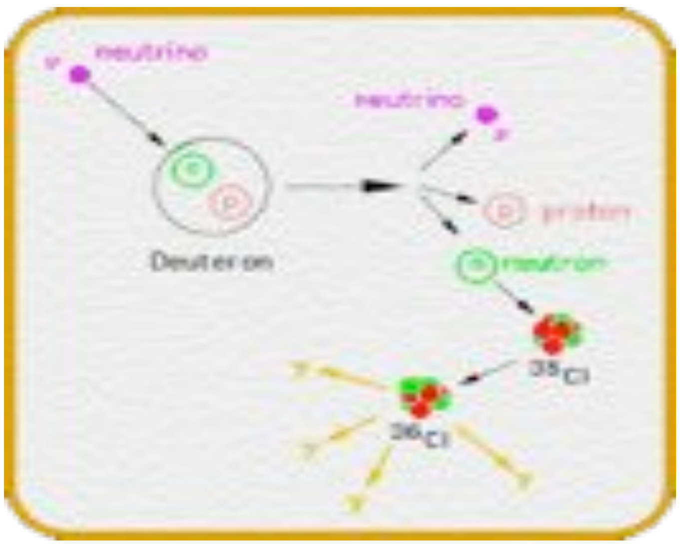
Detector filled with D_2O

Nov. 1999 - May 2001

Phase 2: Salt-Water-Phase

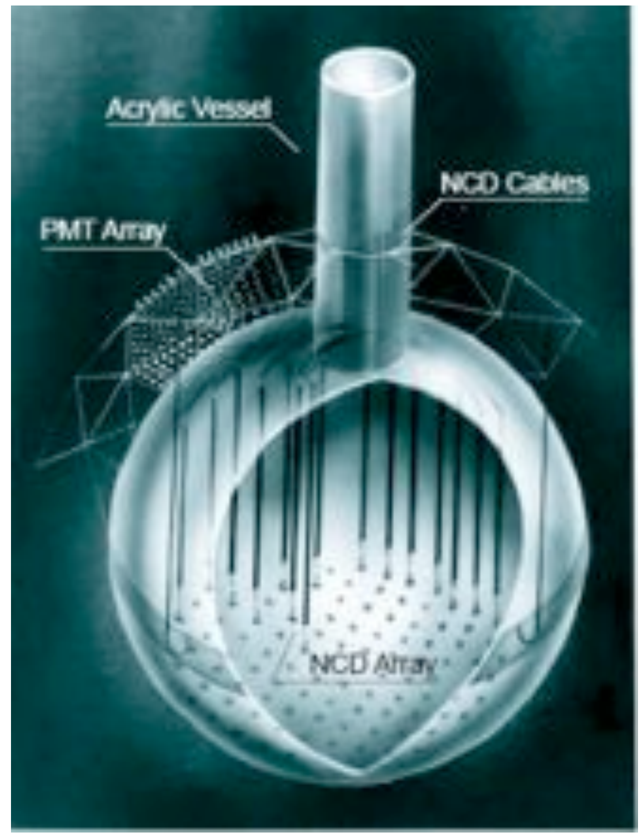
2 Tons NaCl

Jun. 2004 - Oct. 2003

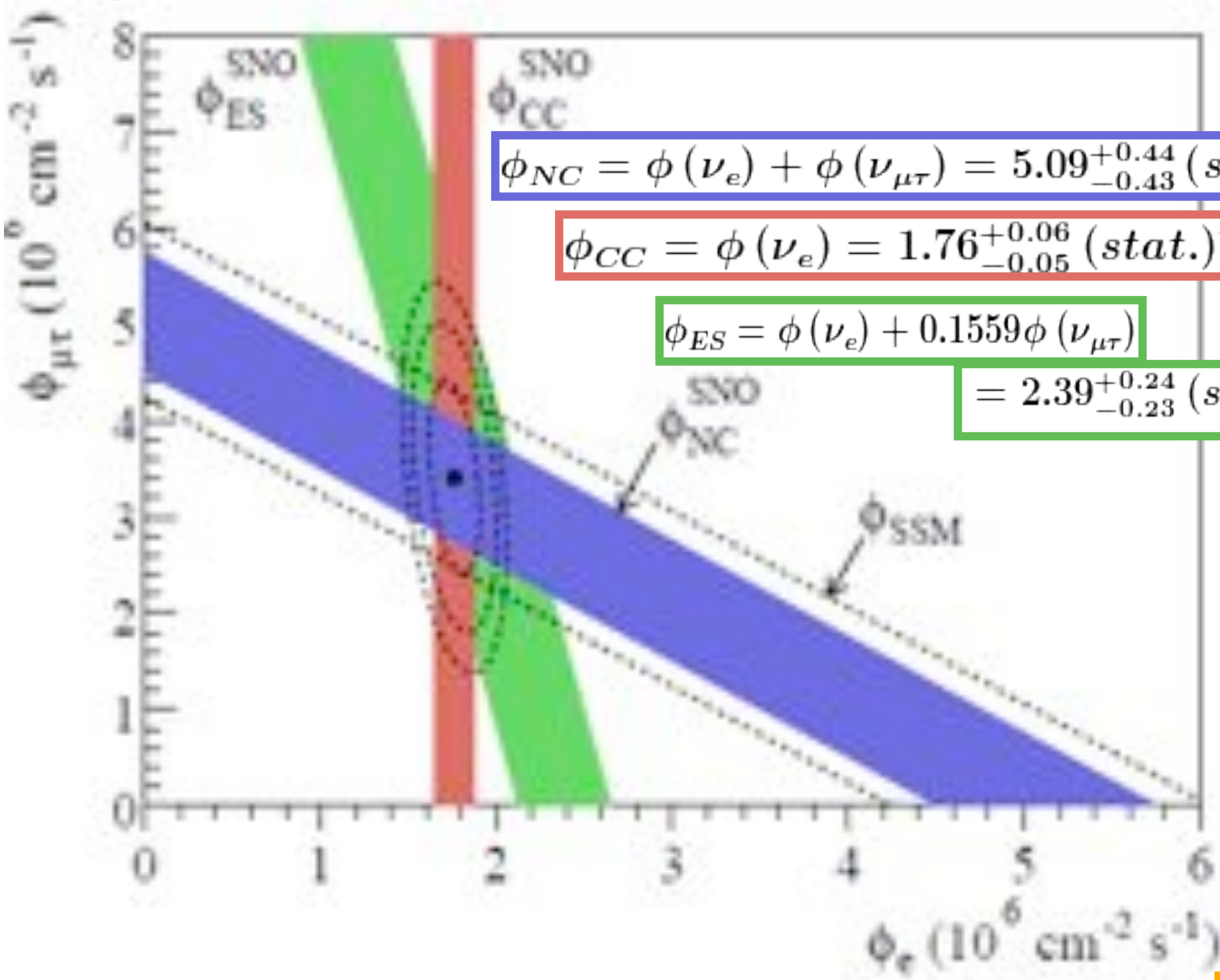


Phase 3: Neutral Current Detectors

Nov. 2004 - Nov. 2008



Phase I: Results



$$\phi_{NC} = \phi(\nu_e) + \phi(\nu_{\mu\tau}) = 5.09^{+0.44}_{-0.43}\,(stat.)^{+0.46}_{-0.43}\,(syst.) \times 10^6 cm^{-2}s^{-1}$$

$$\phi_{CC} = \phi(\nu_e) = 1.76^{+0.06}_{-0.05}\,(stat.)^{+0.09}_{-0.09}\,(syst.) \times 10^6 cm^{-2}s^{-1}$$

$$\phi_{ES} = \phi(\nu_e) + 0.1559\phi(\nu_{\mu\tau})$$

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

CC: $\nu_e + d \Rightarrow p + p + e^-$
ES: $e^- + \nu_x \Rightarrow e^- + \nu_x$
NC: $\nu_x + d \Rightarrow p + n + \nu_x$

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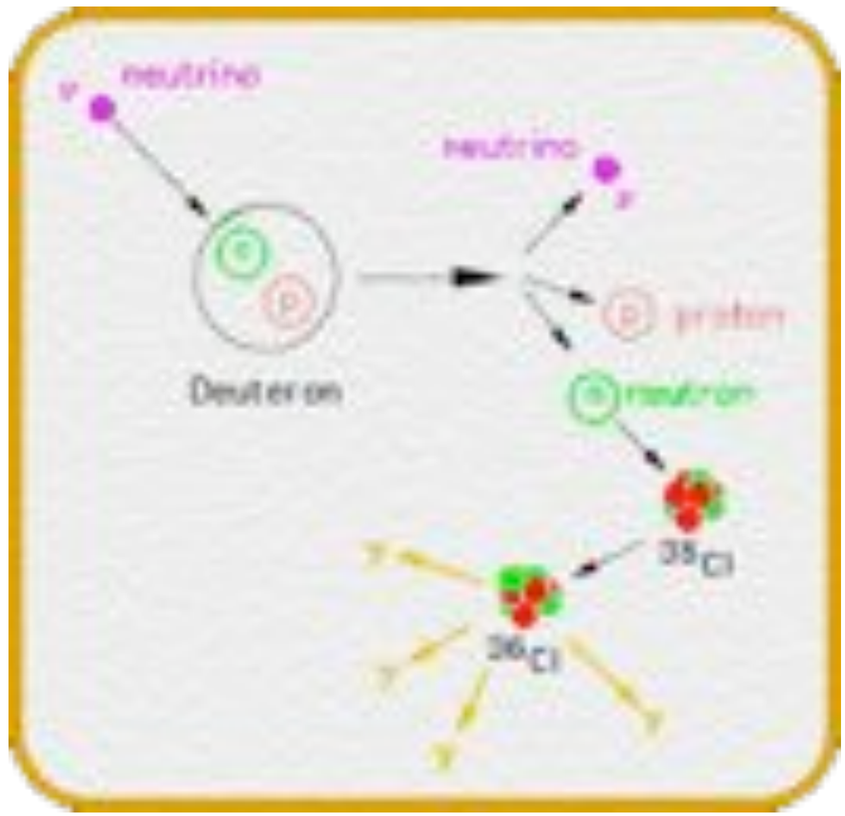
Phase 2: Adding NaCL

- June 2001 until October 2003
- Adding ~2000 kg of NaCl
  - Cross Section of ^{35}Cl is 44 b
  - Total Energy Released 8.6 MeV
  - Multiple Gamma Rays
- Enhances:
  - Neutron Capture Efficiency three-fold
  - Peak shifts 1 MeV Upward
  - Different Isotropy of PMTs



Total Flux Measurement more precise

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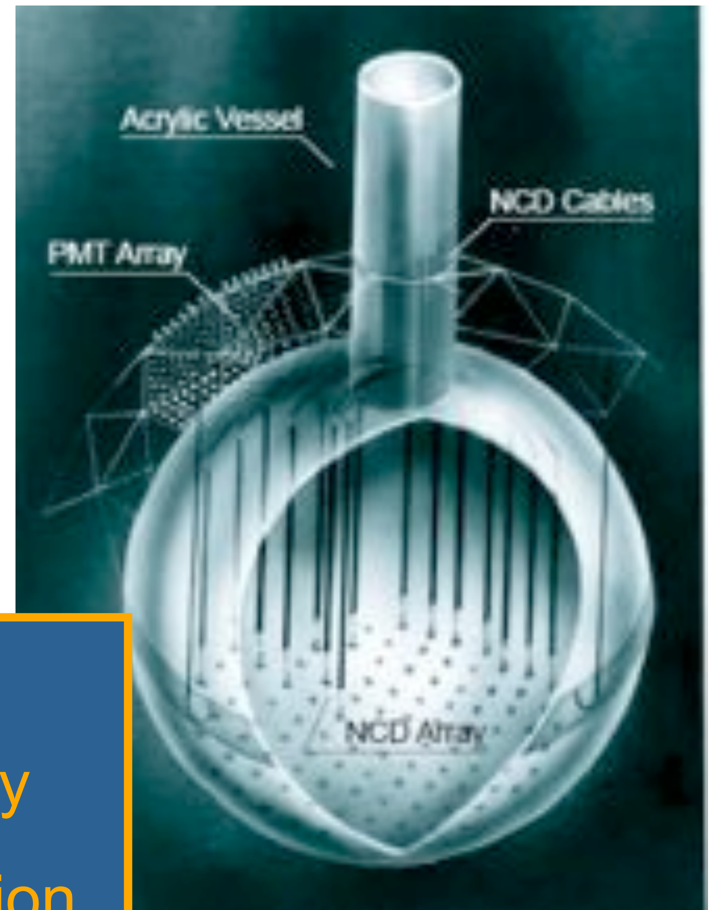
Phase 3: Neutral Current Detection (NCD)

- Nov. 2004 until Nov. 2006
- Again filled with D_2O
- 36 „Strings“ of ^{3}He Counters
  - Ultra pure Nickel
- Four ^{4}He Strings
  - Background Detection



- Neutral Current Flux suppressed

+ Improved Mixing Angle Uncertainty

+ Event by Event Particle Identification

Results Compared