Results and Prospects From The Sudbury Neutrino Observatory

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SSI Topical Conference – 8/6/2003

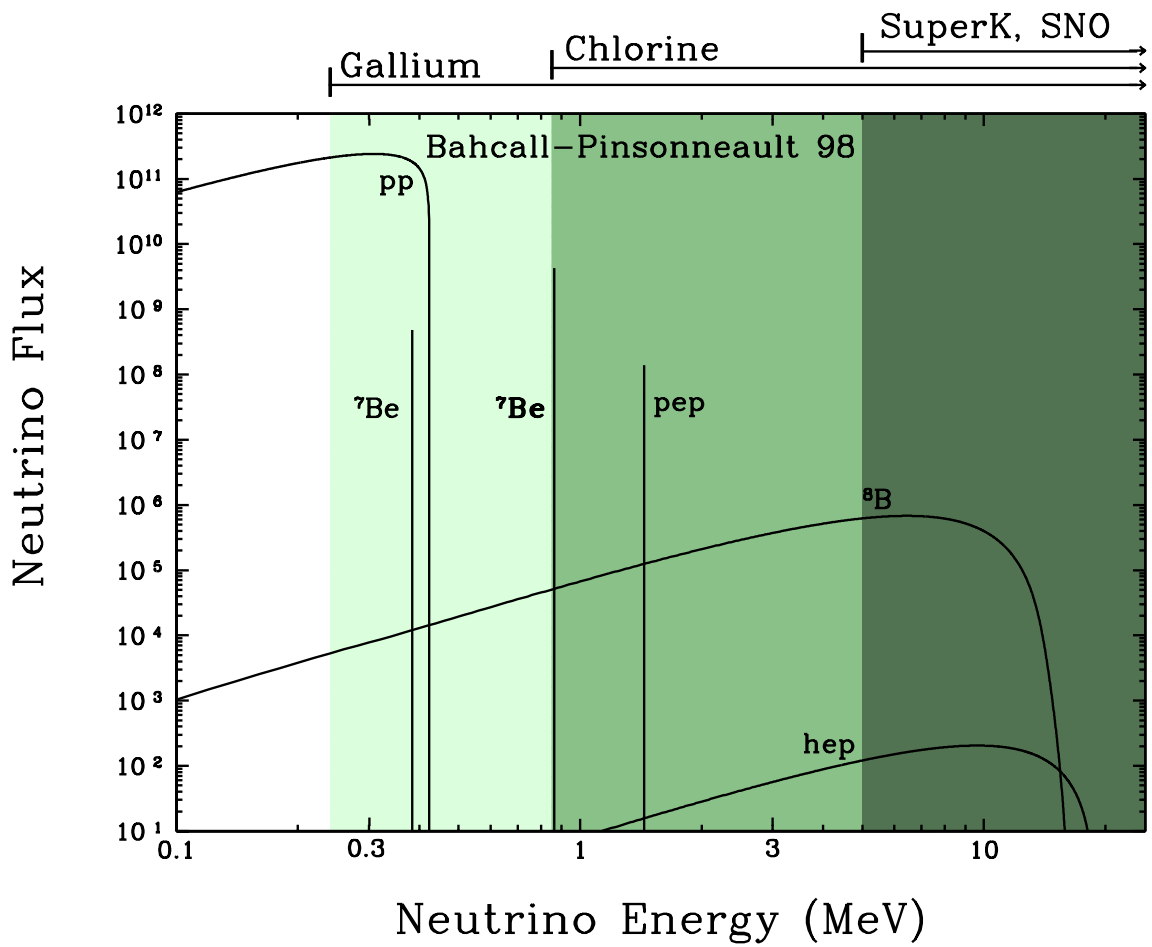
Outline

1. SNO and the Solar Neutrino Problem
2. Neutral Current and Day-Night Results
3. Needs More Salt ...
4. Anti-neutrino Limits (Preliminary)
5. Future Prospects

Solar Neutrinos

The Sun is an intense source of MeV neutrinos!

$$4p + 2e^- \rightarrow {}^4\text{He} + 2\nu_e + 26.731\ \text{MeV}$$



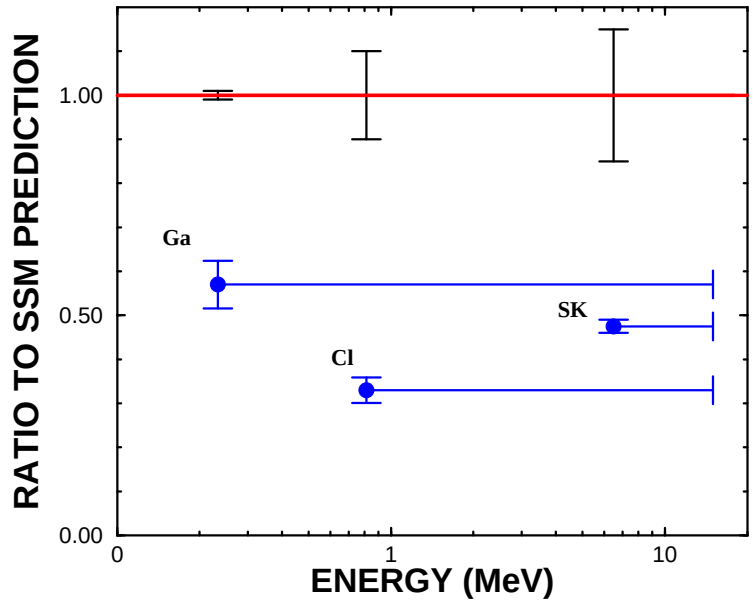
Shape of Spectra Determined By Nuclear Physics.

Solar Models Only Affect Normalization.

Solar Neutrino Flux Measurements

Two Classes of Experiment (so far)

- Radiochemical
  - ν_e interactions convert target nuclei
  - Radioactive products extracted and counted after exposure time
- Water Cerenkov
  - Real-time detection of scattered atomic e^-'s
  - Mixed CC and NC sensitivity



Experiment	Detection Reaction	Threshold	Primary Sources
Homestake	$\nu_e + {}^{37}\text{Cl} \rightarrow e^- + {}^{37}\text{Ar}$	0.8 MeV	${}^7\text{Be}, {}^8\text{B}$
Kamiokande	$\nu_{e,(\mu,\tau)} + e \rightarrow \nu_{e,(\mu,\tau)} + e$	7.3 MeV	${}^8\text{B}$
SAGE, GALLEX/GNO	$\nu_e + {}^{71}\text{Ga} \rightarrow e^+ + {}^{71}\text{Ge}$	0.23 MeV	$pp, {}^7\text{Be}, {}^8\text{B}$
Super-K	$\nu_{e,(\mu,\tau)} + e \rightarrow \nu_{e,(\mu,\tau)} + e$	5 MeV	${}^8\text{B}$

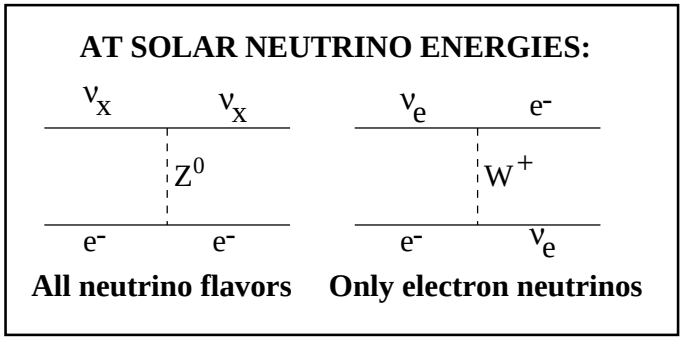
Neutrino Oscillation

Assume mixing between flavor and mass eigenstates, like for quarks:

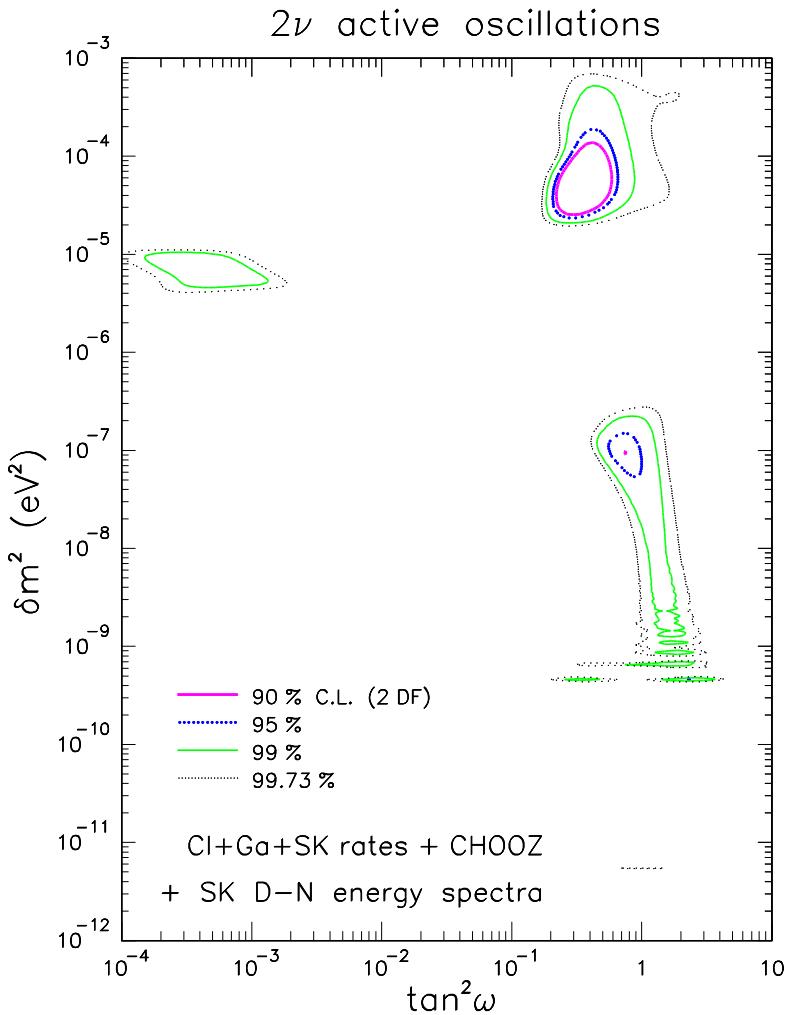
$$
\begin{aligned}
|\nu_e\rangle &= \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle \\
|\nu_\mu\rangle &= -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle
\end{aligned}
$$

Then ν_e's can oscillate to ν_μ's, depending on energy, distance travelled.

Oscillation can be enhanced by matter effects in Sun or Earth:



Can produce day-night asymmetries.



Allowed mixing parameters (pre-SNO)

Fogli *et al.*(hep-ph/0106247)

The SNO Collaboration

Canada

University of British Columbia

Carleton University

University of Guelph

Laurentian University

Queen's University

TRIUMF

United States

Brookhaven National Lab.

Lawrence Berkeley National Lab.

Los Alamos National Lab.

University of Pennsylvania

University of Texas–Austin

University of Washington

U.K.

University of Oxford

RAL/Sussex

Sudbury Neutrino Observatory

2092 m to Surface

18 m Diameter Support Structure for 9500 PMTs, 60% coverage

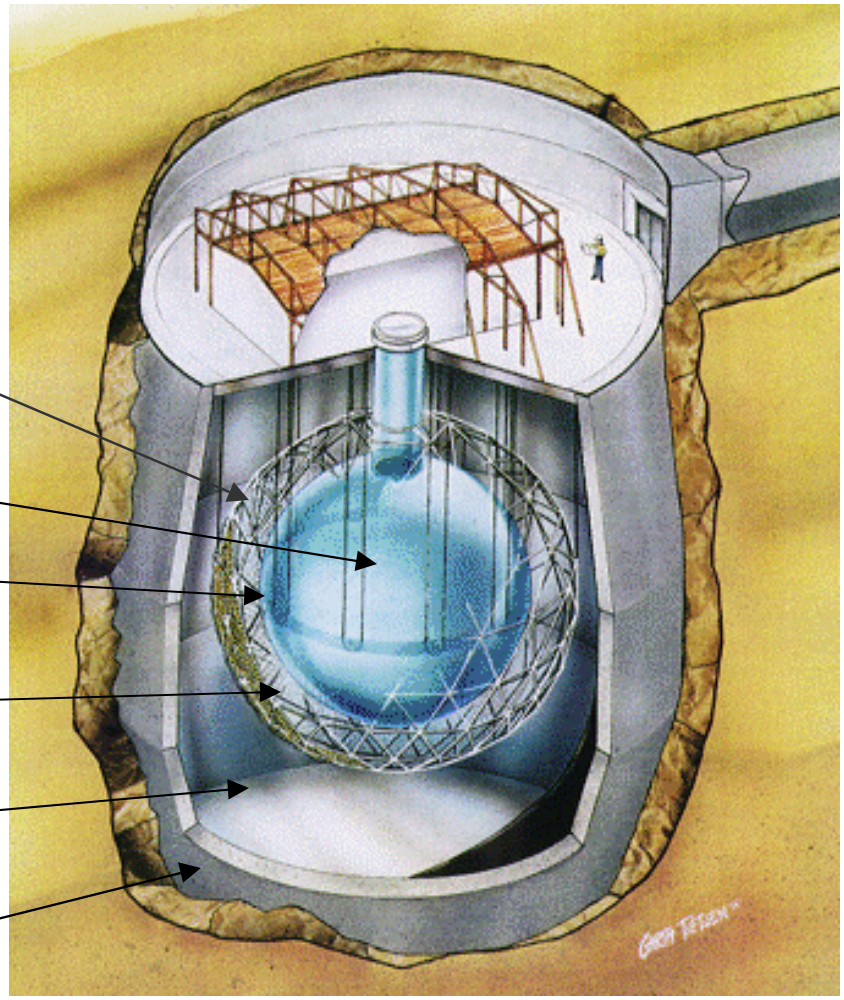
1000 Tonnes D_2O

12 m Diameter Acrylic Vessel

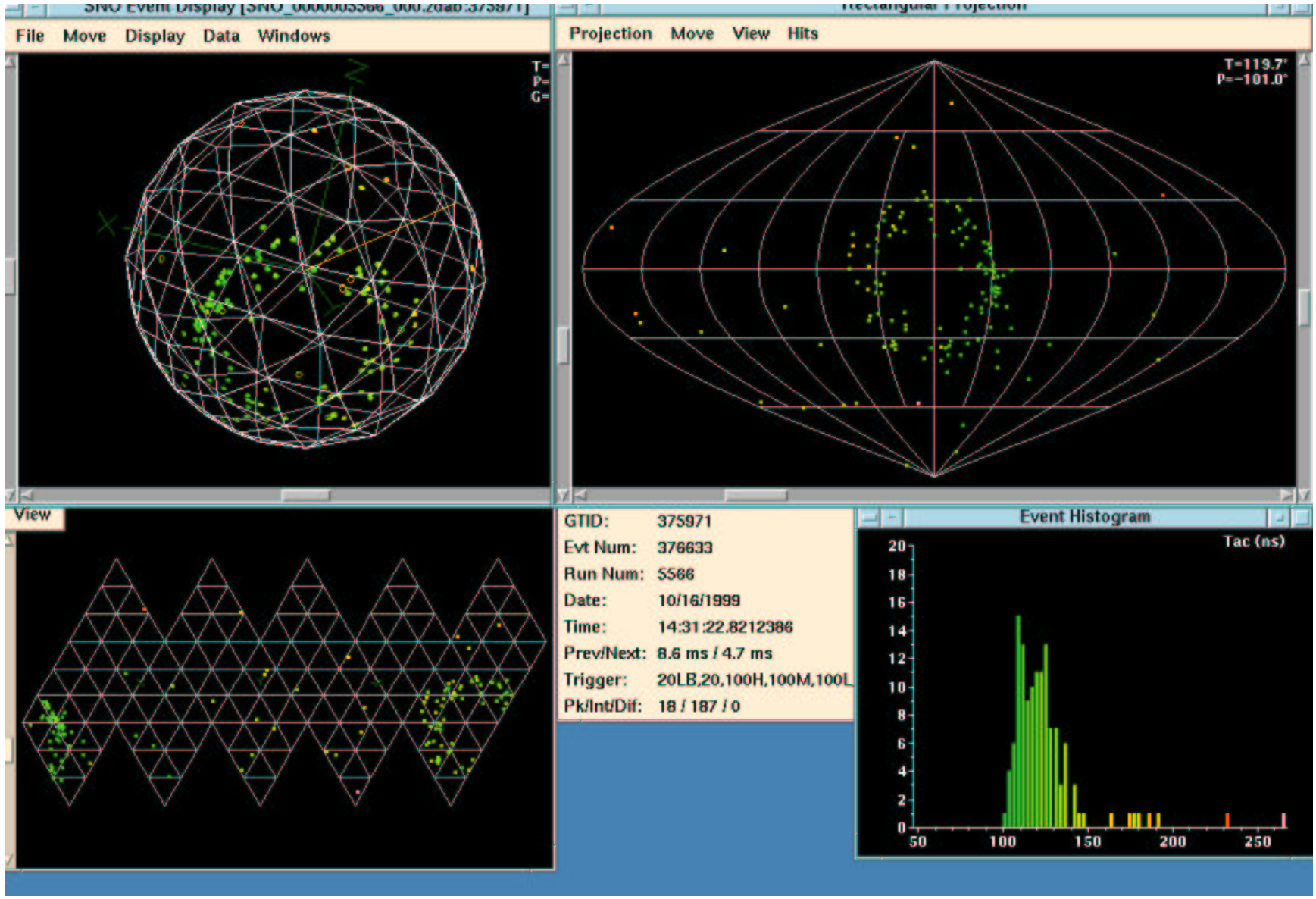
1700 Tonnes Inner Shielding H_2O

5300 Tonnes Outer Shield H_2O

Urylon Liner and Radon Seal



Event Display–Neutrino Event



Solar ν Interactions in SNO

Elastic Scattering (ES) $\boldsymbol{\nu_x + e^- \longrightarrow \nu_x + e^-}$

- Directional sensitivity (e^- forward peaked)
- Cross-section for ν_e is $6.5\times$ larger than for $\nu_{\mu\tau}$

Charged Current (CC) $\boldsymbol{\nu_e + d \longrightarrow p + p + e^-}$

- Some directional information ($1 - \frac{1}{3}\cos\theta_{e\nu}$)
- good E_ν sensitivity (ν_e spectrum)

Neutral Current (NC) $\boldsymbol{\nu_x + d \longrightarrow n + p + \nu_x}$

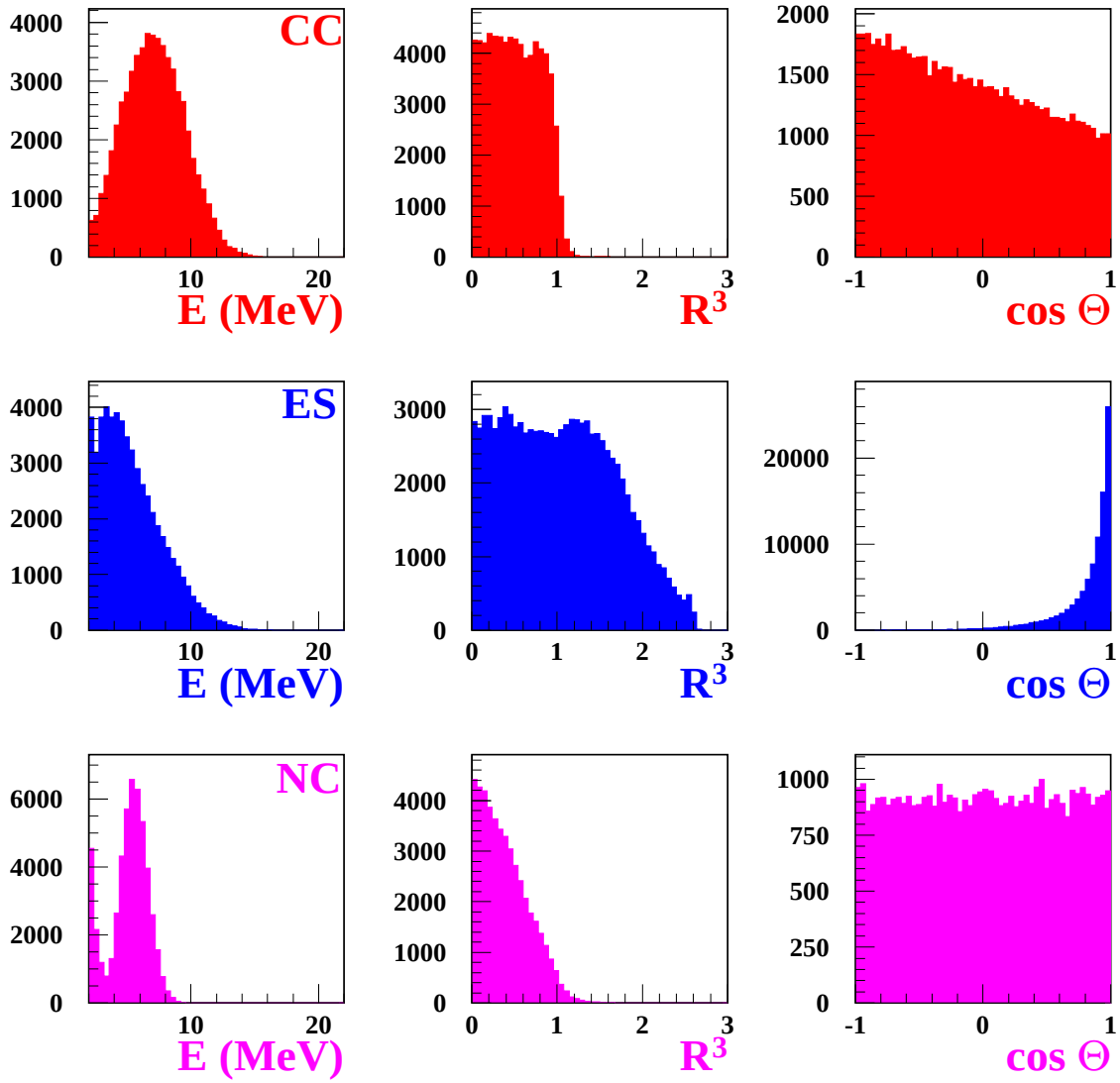
- Total flux of active neutrinos above 2.2 MeV
- Detect neutrons by $n + d \longrightarrow t + 6.25$ MeV γ

Signal Probability Distributions

CC PDF

ES PDF

NC PDF



Each signal has characteristic energy, radial, and angular distributions.

Deriving Flavor Content from Reaction Rates

$$\boldsymbol{CC} = \boldsymbol{\nu_e}$$

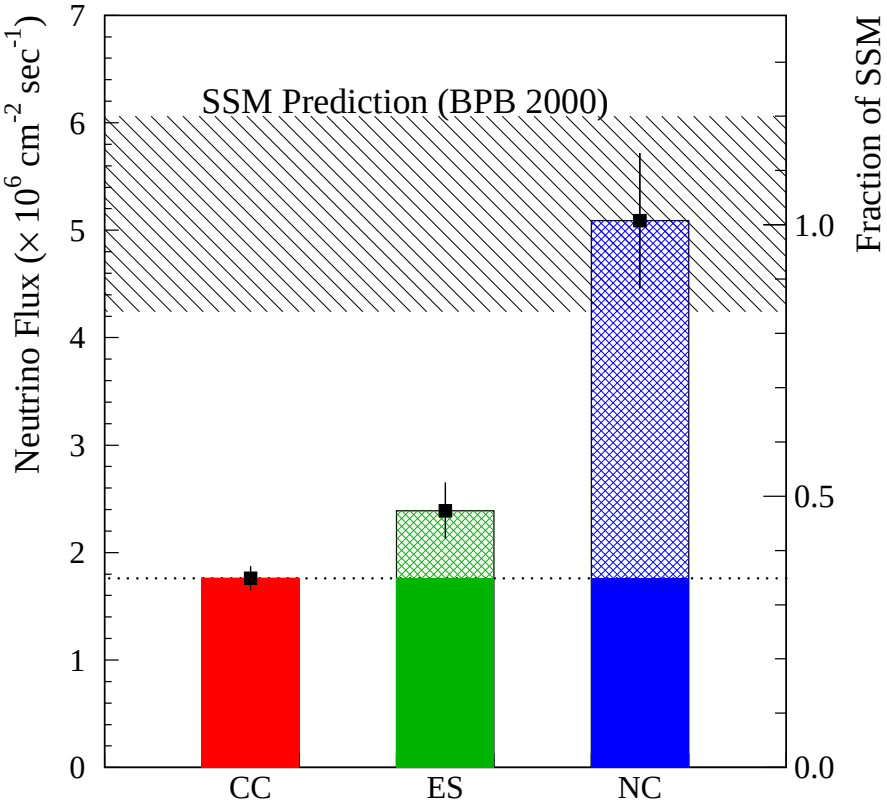
$$\boldsymbol{ES} = \boldsymbol{\nu_e} + \mathbf{0.154}\,\boldsymbol{\nu_{\mu\tau}}$$

$$\boldsymbol{NC} = \boldsymbol{\nu_e} + \boldsymbol{\nu_{\mu\tau}}$$

Measuring 2 out of 3 determines flavor content.

Measuring all three gives consistency check.

Measured SNO Fluxes



Assuming ^{8}B energy spectrum ...

Fluxes ($\times 10^6$ cm^{-2} sec^{-1})

$$\phi_{CC} = 1.76 \pm^{0.06}_{0.05} \text{ (stat.)} \pm 0.09 \text{ (sys.)}$$

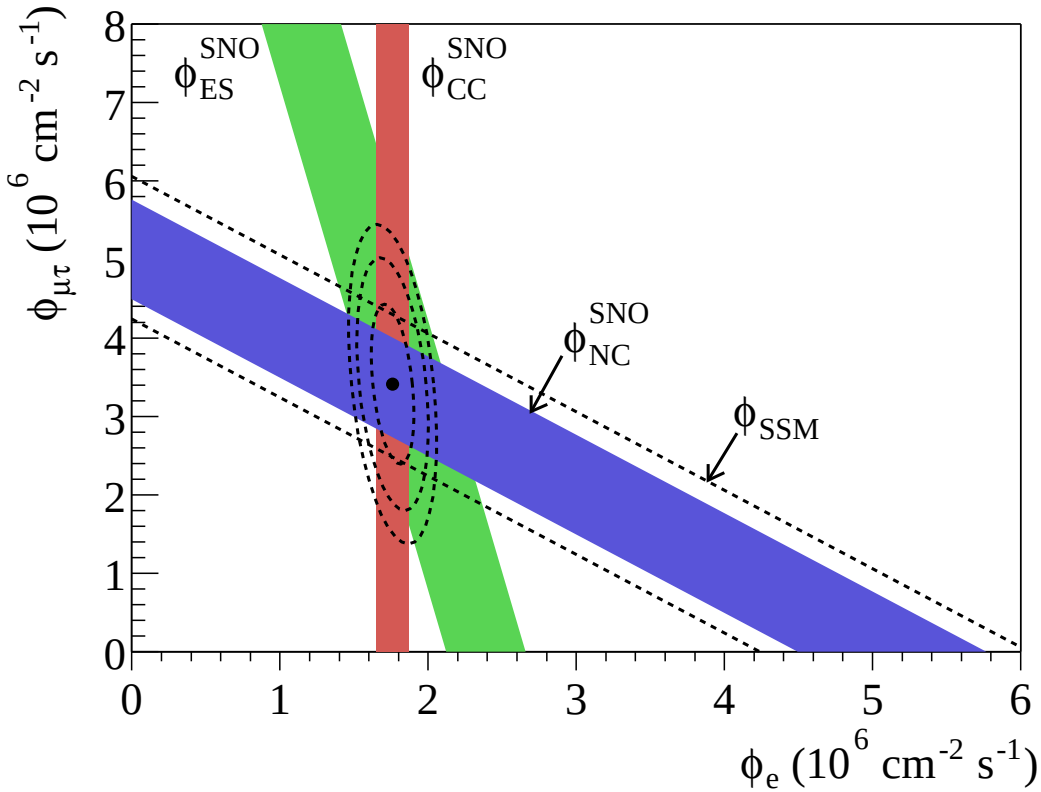
$$\phi_{ES} = 2.39 \pm^{0.24}_{0.23} \text{ (stat.)} \pm 0.12 \text{ (sys.)}$$

$$\phi_{NC} = 5.09 \pm^{0.44}_{0.43} \text{ (stat.)} \pm^{0.46}_{0.43} \text{ (sys.)}$$

$$\phi_{CC} < \phi_{ES} < \phi_{NC}$$

NC flux in agreement with SSM prediction!

Flavor Content



$$\phi_e = 1.76 \pm 0.06 \pm 0.09 \quad \times 10^6 \text{ cm}^{-2} \text{ sec}^{-1}$$

$$\phi_{\mu\tau} = 3.41 \pm 0.45^{+0.48}_{-0.45} \quad \times 10^6 \text{ cm}^{-2} \text{ sec}^{-1}$$

$\phi_{\mu\tau} > 0$ at 5.3σ level!

Day-Night Asymmetries

Day-night rate asymmetry is signature of matter effects:

$$A = \frac{N - D}{\frac{1}{2}(N + D)}$$

Measure both A_e and A_{tot}:

- MSW matter effect: $0 < A_e < 20\%$
- If only active ν's, $A_{tot} = 0$

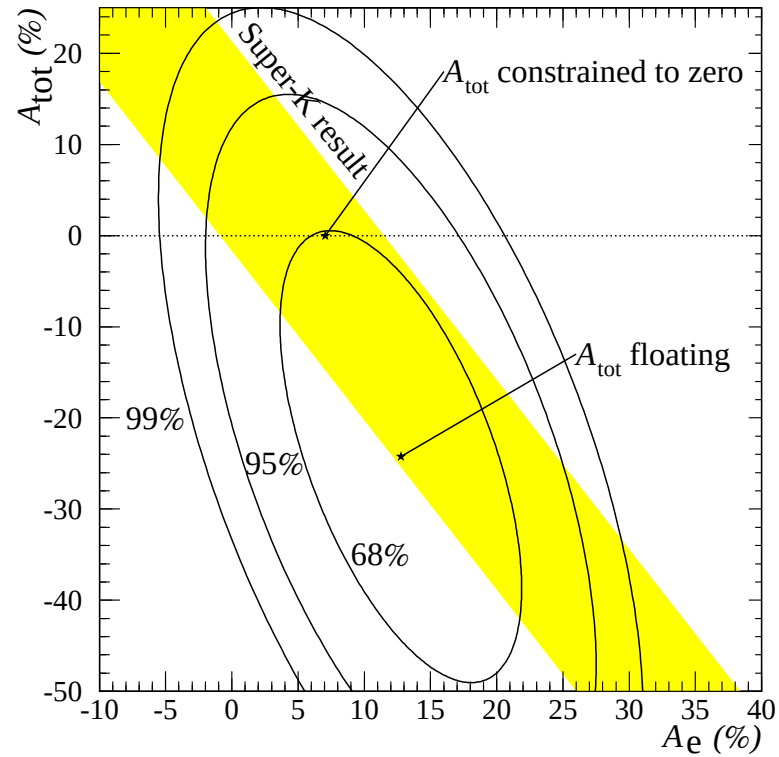
Letting A_{tot} float:

$$A_e = +12.8\% \pm 6.2\% \pm^{1.5}_{1.4} \%$$

$$A_{tot} = -24.2\% \pm 16.1\% \pm^{2.4}_{2.5} \%$$

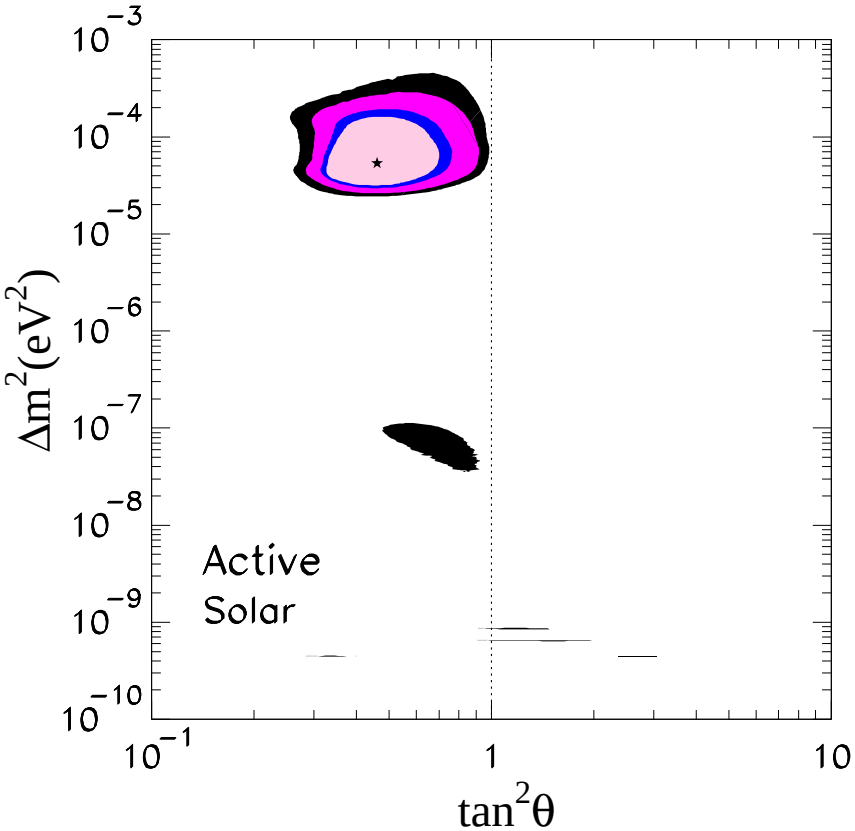
Demanding $A_{tot} \equiv 0$:

$$A_e = +7.0\% \pm 4.9\% \pm^{1.3}_{1.2} \%$$



All results assume undistorted ^{8}B spectrum.

Global Solar Neutrino Analysis Results



Bahcall, Gonzalez-Garcia, & Peña-Garay hep-ph/0212147 v3

Fit to all solar ν data strongly favors LMA solution

LOW, vacuum oscillations ruled out at $\sim 99\%$ C.L.

For LMA, maximal mixing excluded at 3σ level

- Equivalent to $m(\nu_1) < m(\nu_2)$
- Indirect evidence for matter effects

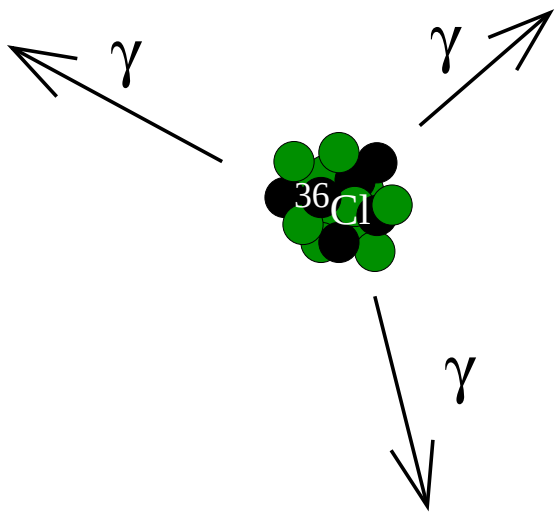
Limitations of the SNO Results

- Assumes ^{8}B spectral shape in signal extraction
  - Required to separate CC/NC effectively
  - OK for null hypothesis test, but couples oscillation parameters and flux measurements
  - Need to break CC/NC covariances in bin-by-bin manner
- Significant CC/NC correlations (statistical *and* systematic)
- Cannot distinguish $\nu_{\mu\tau}$ from $\overline{\nu}_{\mu\tau}$
- Statistics-limited for many physics topics
  - day-night, spectrum, seasonal variations ...

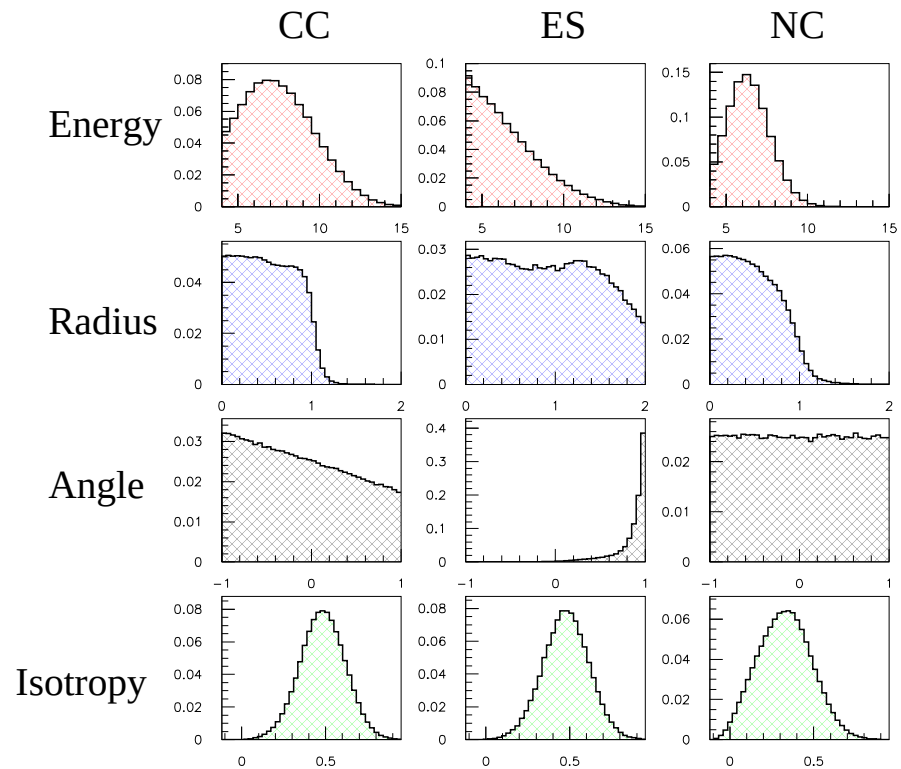
Next Phase: Salt

In June 2001 added 0.2% NaCl to D_2O to increase neutron capture (on ^{35}Cl)

Capture efficiency increased by $\times 2.6$



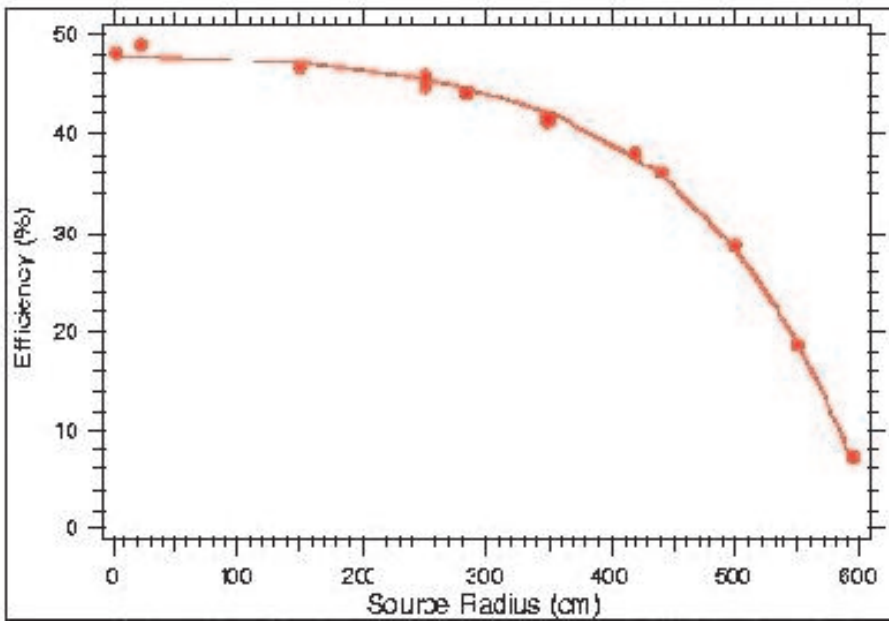
~2−4 gammas
totalling 8.6 MeV

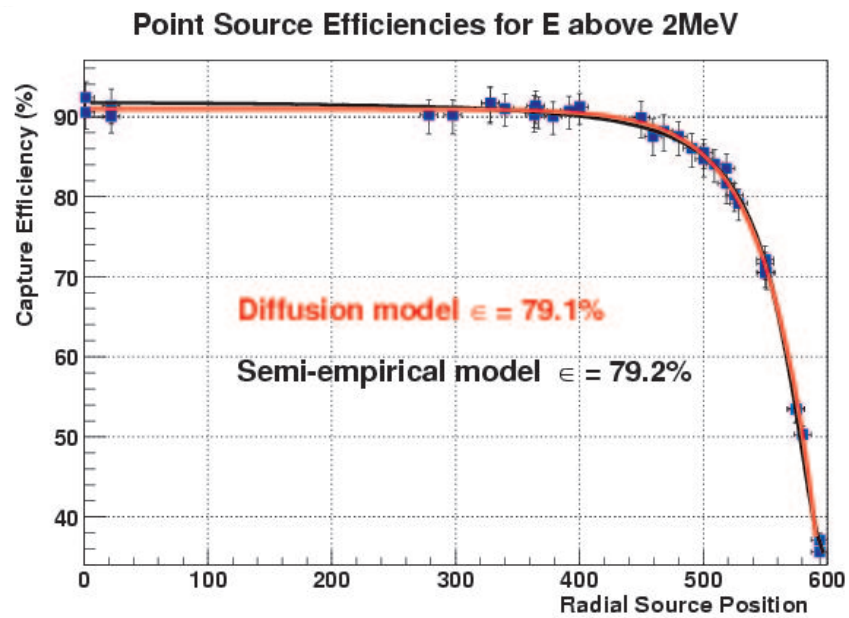


Emitted radiation increases from 6.25 MeV to 8.6 MeV

Multiple γ's emitted—separate CC, NC events using event topology, isotropy

Neutron Capture in Salt and D_2O

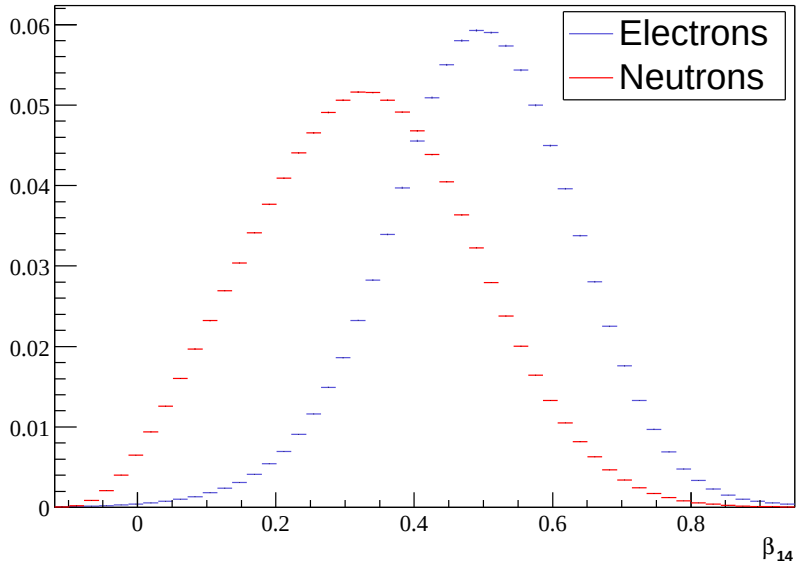


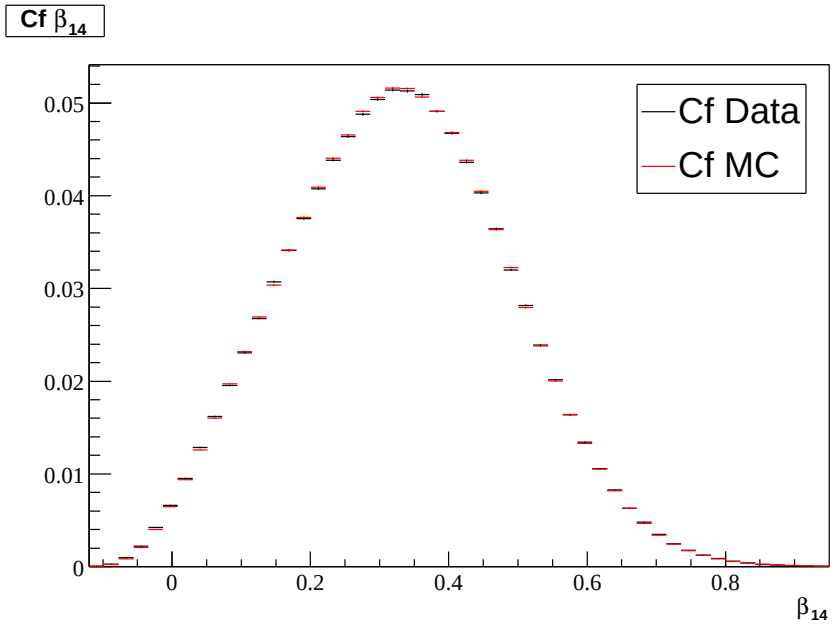


Notable change in neutron capture radial profile.

Better sensitivity to neutrons produced near AV.

Particle ID with Event Isotropy





Neutrons produce multi-particle decay $\longrightarrow$ more isotropic

Electrons produce single Cherenkov rings

Comparison of isotropy for calibration neutron data and MC.

Isotropy can provide statistical separation of neutrons and electrons, and reduce dependence on energy spectra.

Can produce “model-independent” NC flux

Projected Statistical Uncertainties

D_2O results used energy spectrum to separate CC from NC events.

For salt results, add in isotropy as additional separation parameter.

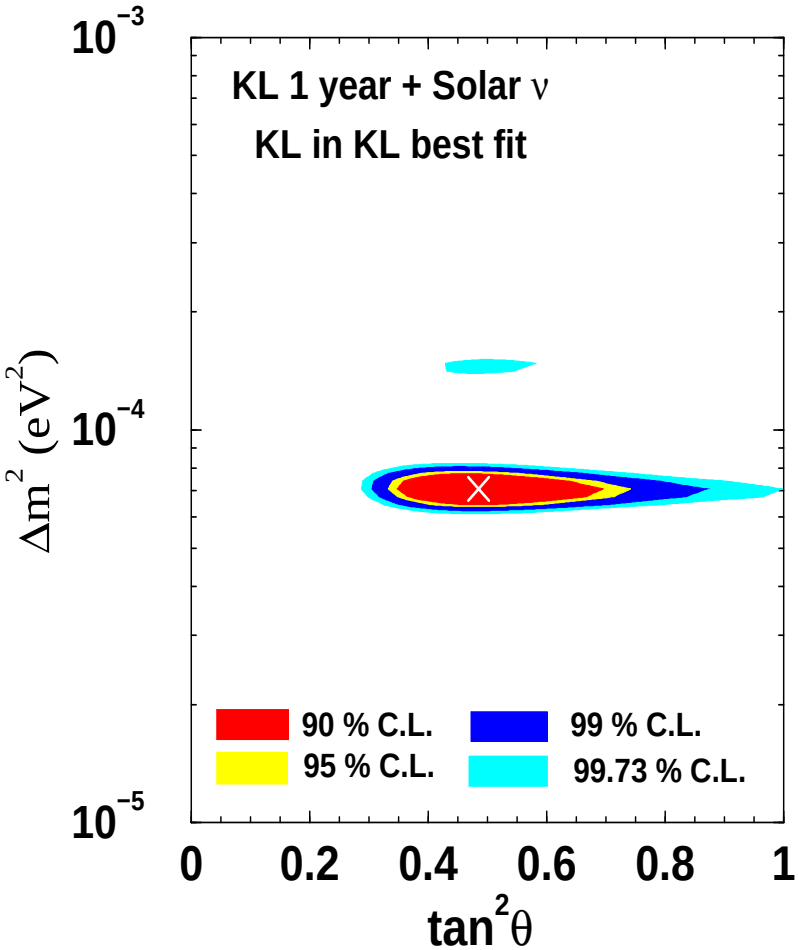
Two ways to do analysis:

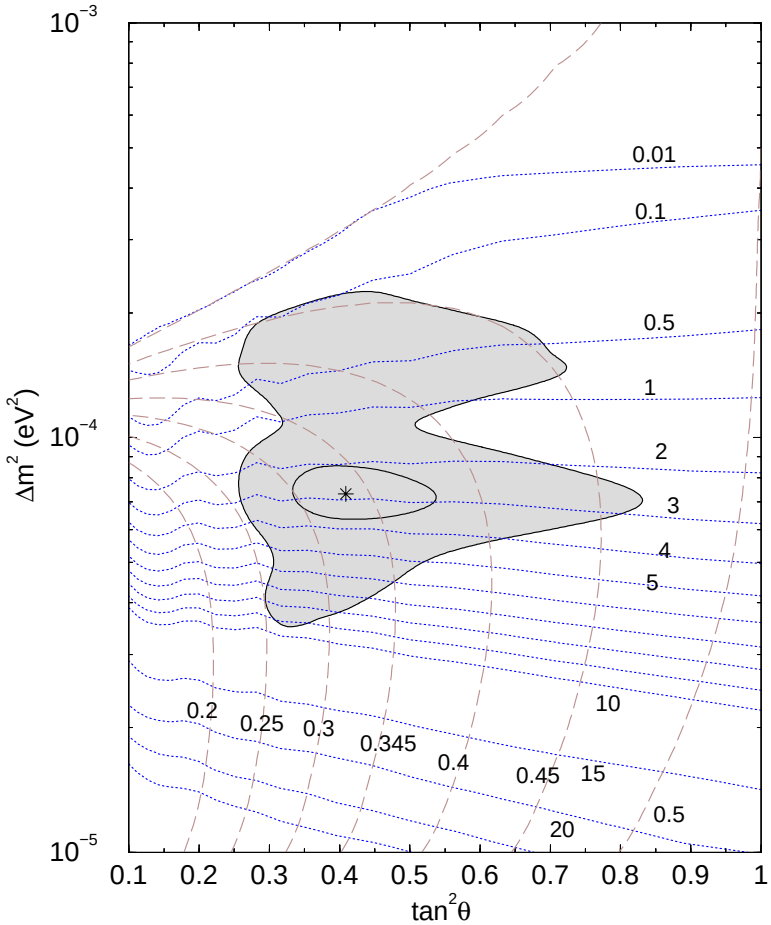
- Assume ^{8}B spectral shape (best statistical separation)
- Assume nothing about shape (least model dependence)

All salt results are Monte Carlo

Analysis Method	CC	ES	NC
D_2O (published) $(E, r, \theta_\odot)$	3.4%	10%	8.6%
Salt (MC) $(E, r, \theta_\odot)$	4.2%	10%	6.3%
Salt (MC) $(E, r, \theta_\odot, \beta_{14})$	3.3%	10%	4.6%
Salt (MC) $(r, \theta_\odot, \beta_{14})$	3.8%	10%	5.4%

Precision Mixing Parameter Estimation





KamLAND will provide precision Δm^2 measurement, but weak θ_{12} constraint

(Plot from Nunokawa, Teves, Funchal, hep-ph/0212202)

Precision solar measurements, especially SNO CC/NC ratio and day-night, constrain Δm^2 but especially θ_{12}

(de Holanda & Smirnov, hep-ph/0212270)

Electron Antineutrino Search

- Solar oscillations believed for theoretical reasons to be $\nu_e \longrightarrow \nu_{\mu\tau}$
- However, $\nu_e \longrightarrow \overline{\nu}_{\mu\tau}$ is not ruled out
- What about $\nu_e \longrightarrow \overline{\nu}_e$?

Spin Flavor Precession

1. Give ν's small magnetic moment ($< 10^{-10}\mu_B$)
2. Coupling of μ_ν with strong solar B field produces

$$\nu_e \longrightarrow \overline{\nu}_{\mu\tau}$$

3. Standard neutrino oscillations (with or without MSW) can then produce:

$$\overline{\nu}_{\mu\tau} \longrightarrow \overline{\nu}_e$$

Does the Sun put out any $\overline{\nu}_e$'s?

Searching for $\overline{\nu}_e$'s at SNO

SNO has a unique triple-coincidence signal for $\overline{\nu}_e$'s:

$$\overline{\nu}_e + d \rightarrow e^+ + n + n$$

Three detection channels:

		Detection Effiency$(prelim.)$
$3-\text{fold}$	$e^+ + n + n$	$(1.1 \pm 0.02 \pm^{0.05}_{0.12})\%$
$2-\text{fold}$	$e^+ + n$	$(10.27 \pm 0.05 \pm^{0.37}_{0.94})\%$
$2-\text{fold}$	$n + n$	$(1.1 \pm 0.02 \pm^{0.05}_{0.10})\%$

Coincidence signal provides almost background-free measurement.

"Two-neutron" channel sensitive down to $E_\nu = 4.03$ MeV

Searching for $\overline{\nu}_e$'s

Selection Cuts:

- $T_{eff} > 5$ MeV
- $R < 550$ cm
- Coincidence window: 150 msec (neutron capture time: 42 msec)
- Spallation cuts:
  - Events following muons
  - Events with NHIT$>$150 and anything within 0.5 sec afterwards (removes most atmospheric ν's)

Livetime: 305.9 days

Candidate events (preliminary):

- 1 three-fold coincidence
- 2 two-fold coincidences

But if we lower energy to 4.5 MeV:

- Two-folds become 1 three-fold and 1 four-fold
- Four-fold rejected because P(4-fold from $\overline{\nu}_e$) $\ll$ P(4-fold from inelastic NC)

No further coincidences seen at 4.0 MeV

Backgrounds for $\overline{\nu}_e$'s (Preliminary)

Direct $\overline{\nu}_e$ Backgrounds (prelim.):

atmospheric	≤ 0.072
reactor	≤ 0.15
terrestrial radio-isotopes	0
relic supernovae	$\leq 5.2 \times 10^{-3}$
Total	≤ 0.23

Non-$\overline{\nu}_e$ Coincidence Backgrounds (prelim.):

inelastic NC from atmos. ν's	≤ 1
spallation neutrons	≤ 0.23
accidentals	0.10
intrinsic	
^{214}Bi $\beta - \gamma$	7.6×10^{-5}
^{210}Tl $\beta - \gamma$	10^{-8}
^{208}Tl $\beta - \gamma$	8.7×10^{-4}
^{238}U spontaneous fission	0.14
$\gamma \longrightarrow$ scattered $e^- +$ new n	$< 8 \times 10^{-4}$
n cap. $\longrightarrow$ multiple $\gamma \longrightarrow n$'s	< 0.05
fast $n \longrightarrow (n, 2n)$	$< 1 \times 10^{-4}$
^{13}C$(\alpha, n\, e^+\, e^-)^{16}$O	$< 1.7 \times 10^{-3}$
instrumental contam.	< 0.027
Total	< 1.57

Total background < 1.8 events

Solar $\overline{\nu}_e$ Limit (Preliminary)

Kamiokande (1991)	$< 3.03 \times 10^5$ cm^{-2} sec^{-1}	99% CL
LSD (1996)	$< 1 \times 10^{-5}$ cm^{2} sec^{-1}	90% CL
Super-Kamiokande (2000)	$< 1.8 \times 10^5$ cm^{-2} sec^{-1}	95% CL
Super-Kamiokande (2002)	$< 4.04 \times 10^4$ cm^{-2} sec^{-1}	90% CL
SNO (2003, preliminary)	$< 5.15 \times 10^4$ cm^{-2} sec^{-1}	90% CL

Preliminary SNO limit is $< 1.0\%$ of SSM ^{8}B flux

SNO limit is comparable to SK limit, but uses different, independent technique.

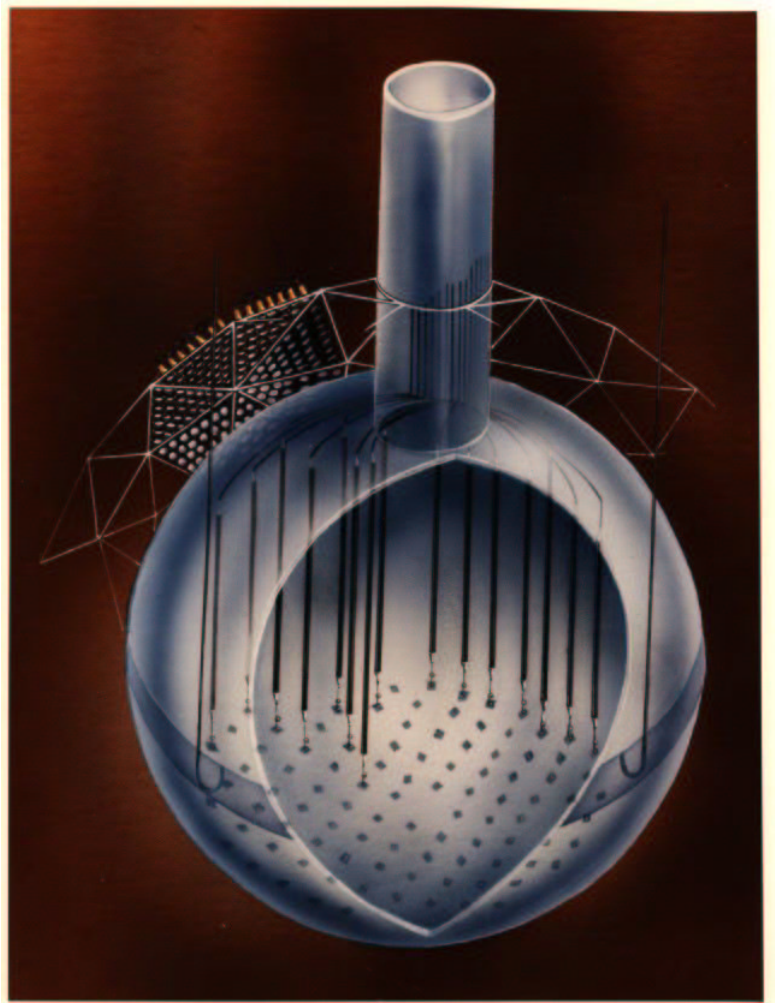
Salt data will provide $\times 3$ gain in sensitivity.

Neutron Capture Detectors

In Fall 2003 SNO will begin installation of ^{3}He proportional counters

Measures NC rate by independent method

Event-by-event neutron ID breaks charged current, neutral current covariances



Conclusions

- Direct evidence for neutrino flavor transformation at the 5.3σ level.
- Solar ν data strongly favors LMA solution — see KamLAND talk
- Salt data will improve statistics, reduce model dependence
- Preliminary solar antineutrino limit: $< 1\% \times$ SSM
- Plethora of other topics: anti-ν's, supernovae, atmospheric ν's, baryon decay

Calibrating Neutron Response

Need to measure neutron capture efficiency as function of radius

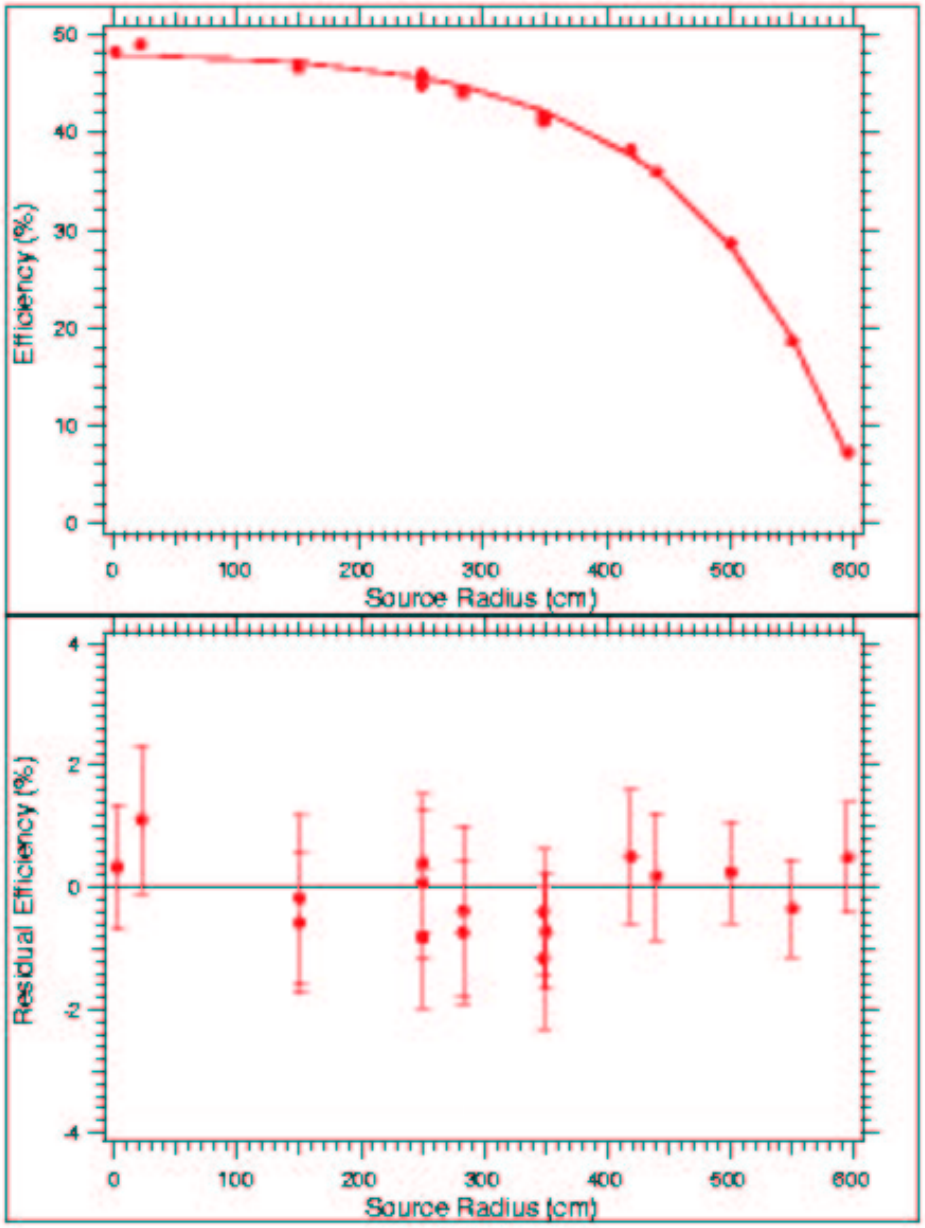
^{252}Cf source produces thermal neutrons through fission (average multiplicity of 3.8)

Three techniques for determining response:

- Analytic calculation using cross sections, isotopic abundances
- Directly count neutron captures from absolutely calibrated source
- Use multiplicity distribution, Poisson statistics to get capture efficiency

Average capture efficiency for NC events:

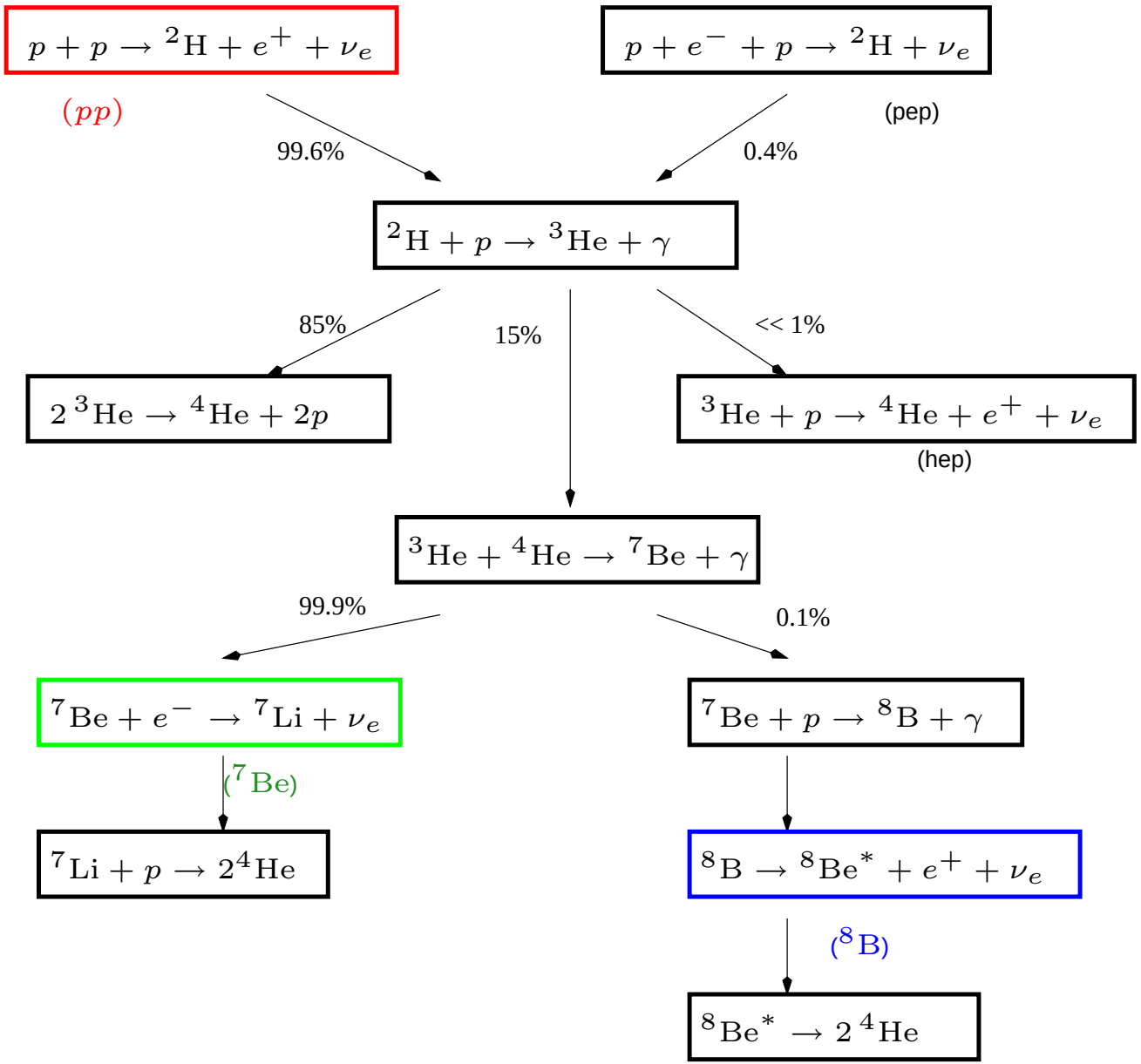
$$29.9\% \pm 1.1\%$$



Dominant Systematic Errors

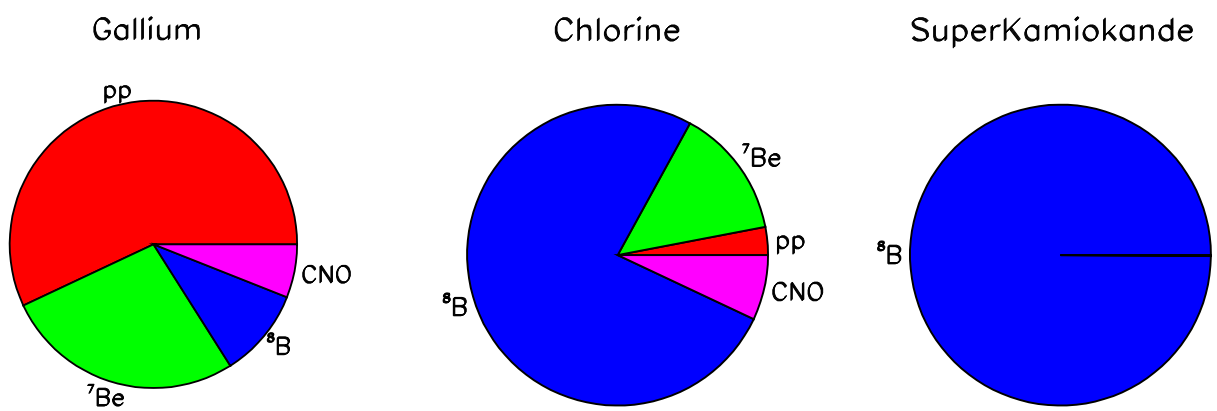
Source	CC Uncert. (percent)	NC Uncert. (percent)	$\phi_{\mu\tau}$ Uncert. (percent)
Energy scale †	-4.2,+4.3	-6.2,+6.1	-10.4,+10.3
Energy resolution †	-0.9,+0.0	-0.0,+4.4	-0.0,+6.8
Vertex accuracy	-2.8,+2.9	± 1.8	± 1.4
Angular resolution	-0.2,+0.2	-0.3,+0.3	-0.3,+0.3
Internal source pd †	± 0.0	-1.5,+1.6	-2.0,+2.2
External source pd	± 0.1	-1.0,+1.0	± 1.4
D_2O Cherenkov †	-0.1,+0.2	-2.6,+1.2	-3.7,+1.7
AV Cherenkov	± 0.0	-0.2,+0.2	-0.3,+0.3
PMT Cherenkov †	± 0.1	-2.1,+1.6	-3.0,+2.2
Neutron capture	± 0.0	-4.0,+3.6	-5.8,+5.2
Experimental uncertainty	-5.2,+5.2	-8.5,+9.1	-13.2,+14.1
Cross section	± 1.8	± 1.3	± 1.4

The pp Chain

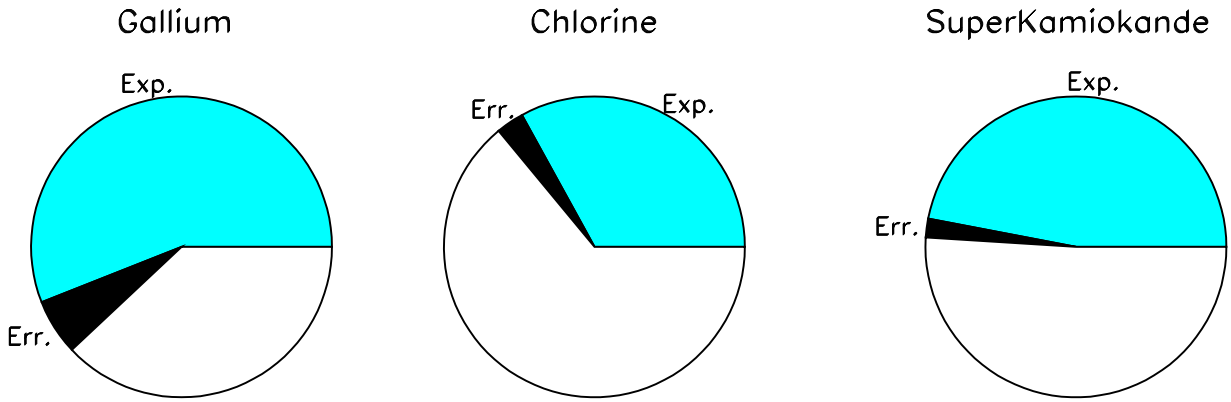

$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$
(pp)
99.6%
$p + e^- + p \rightarrow {}^2\mathrm{H} + \nu_e$
(pep)
0.4%
${}^2\mathrm{H} + p \rightarrow {}^3\mathrm{He} + \gamma$
85%
15%
<< 1%
$2\,{}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p$
${}^3\mathrm{He} + p \rightarrow {}^4\mathrm{He} + e^+ + \nu_e$
(hep)
${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$
99.9%
0.1%
${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$
${}^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} + \gamma$
(^{7}Be)
${}^7\mathrm{Li} + p \rightarrow 2\,{}^4\mathrm{He}$
${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be}^* + e^+ + \nu_e$
(^{8}B)
${}^8\mathrm{Be}^* \rightarrow 2\,{}^4\mathrm{He}$

The Solar Neutrino Problem

- BAD: All experiments show a flux deficit of 30-60%.
- WORSE: Flux suppression is energy dependent.
  - Standard Solar Model Predictions:



  - Measurements:



$\longrightarrow$ Looks like complete absence of $^7\mathrm{Be}$ neutrinos.