ν Oscillations in the `Solar Sector' and the Sudbury Neutrino Observatory

Aspen Winter 2005: The Highest ~~Energy~~ velocity Physics

- **Testing the New Neutrino Model**
- **Upcoming Results**
- **Future Physics**
- **SNO Phase III Status**

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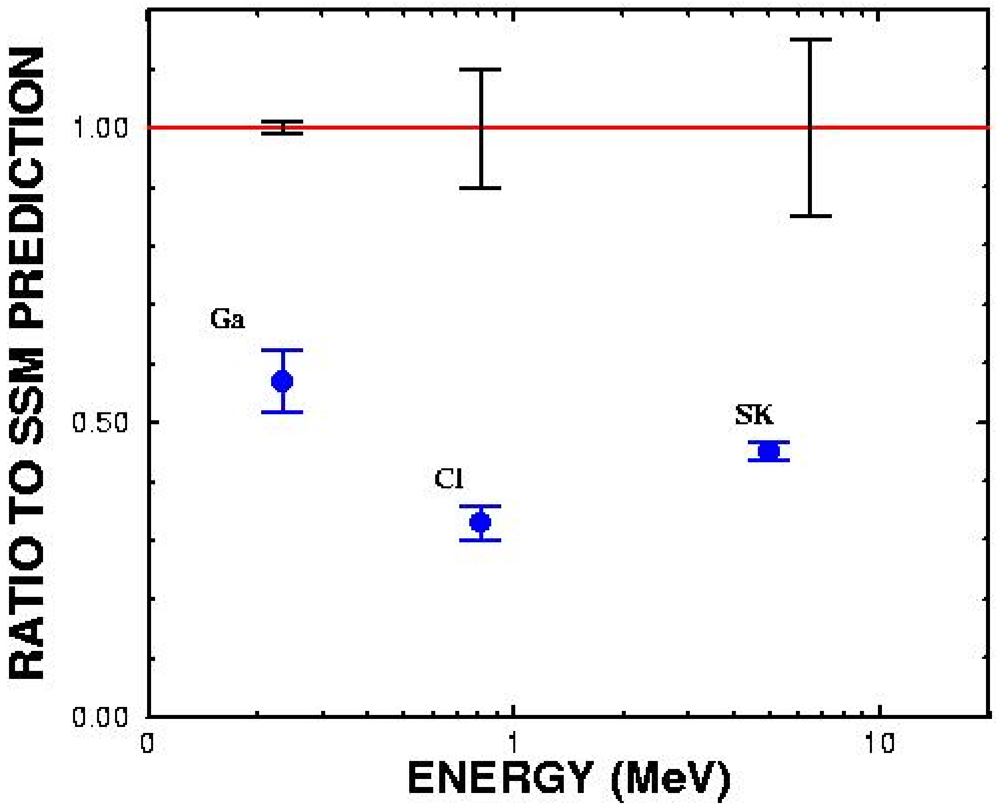
After Six Solar ν Experiments

- 3 Gallium (Radiochemical)
- 1 Chlorine (Radiochemical)
- Kamiokande + Super-Kamiokande (Water Cerenkov)



ν Reactions in SNO

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

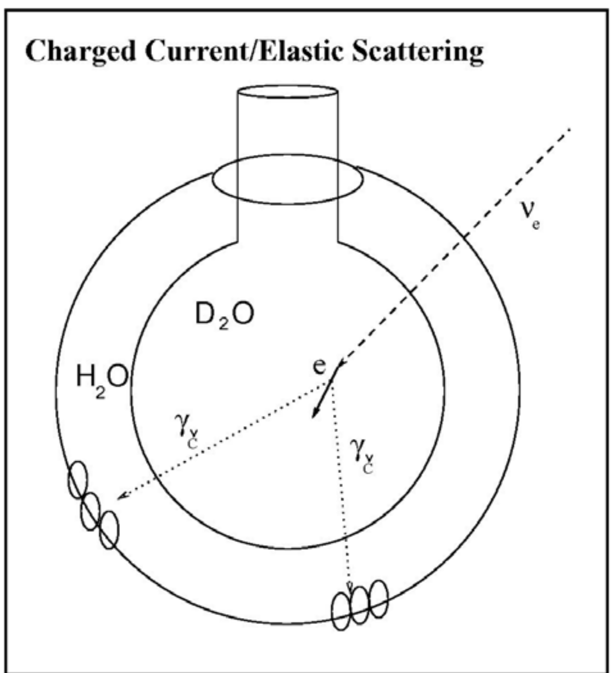
- Good measurement of ν_e energy spectrum
- Weak directional sensitivity $\propto 1-1/3\cos(\theta)$

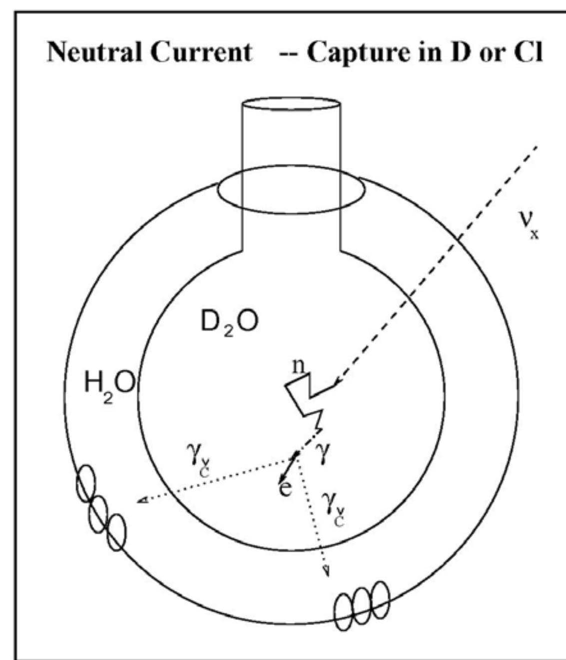
NC $\nu_x + d \Rightarrow p + n + \nu_x$

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

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

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



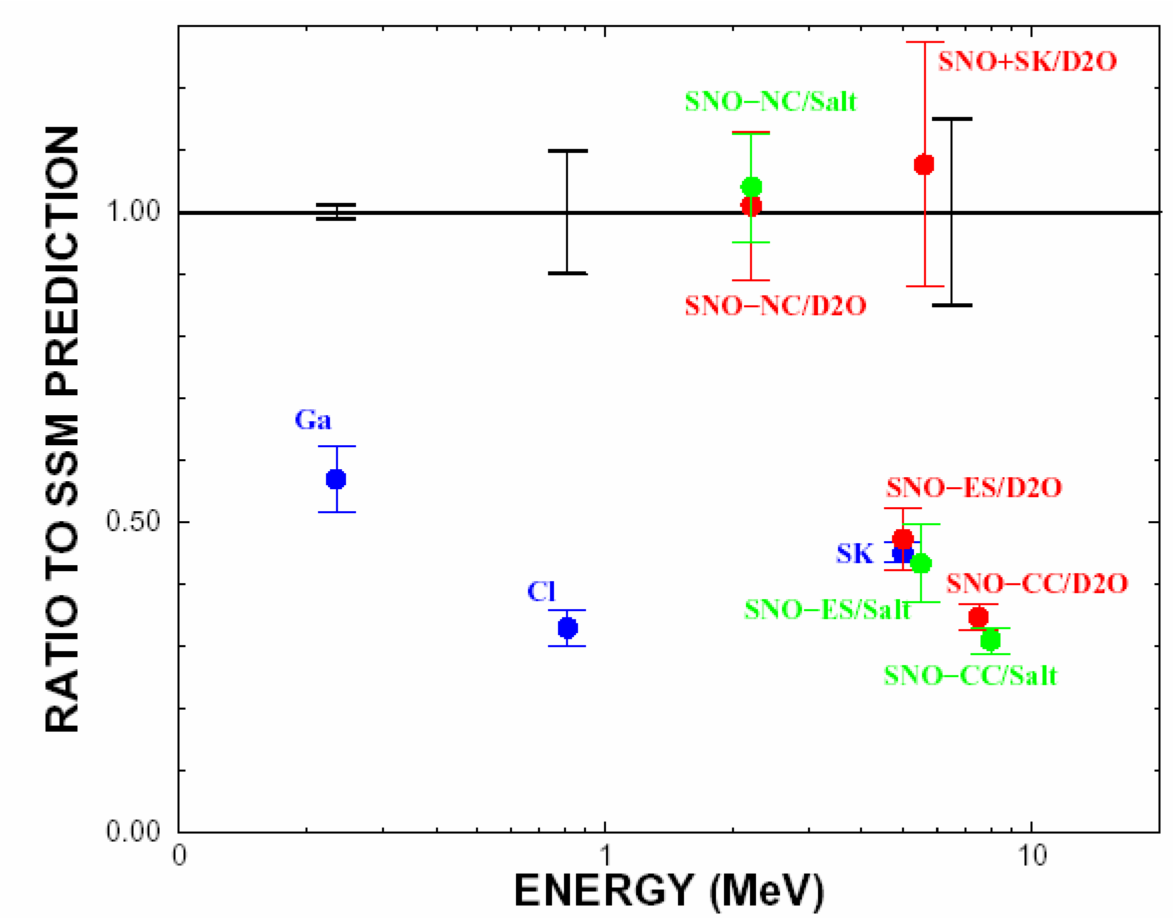


The Three Phases

- **Phase I: Pure D_2O**
  - **Simple detector configuration, clean measurement**
  - **Low neutron sensitivity**
  - **Poor discrimination between neutrons and electrons**
- **Phase II: D_2O + NaCl**
  - **Very good neutron sensitivity**
  - **Better neutron electron separation**
- **Phase III: D_2O + ^3He Proportional Counters**
  - **Good neutron sensitivity**
  - **Great neutron/electron separation**

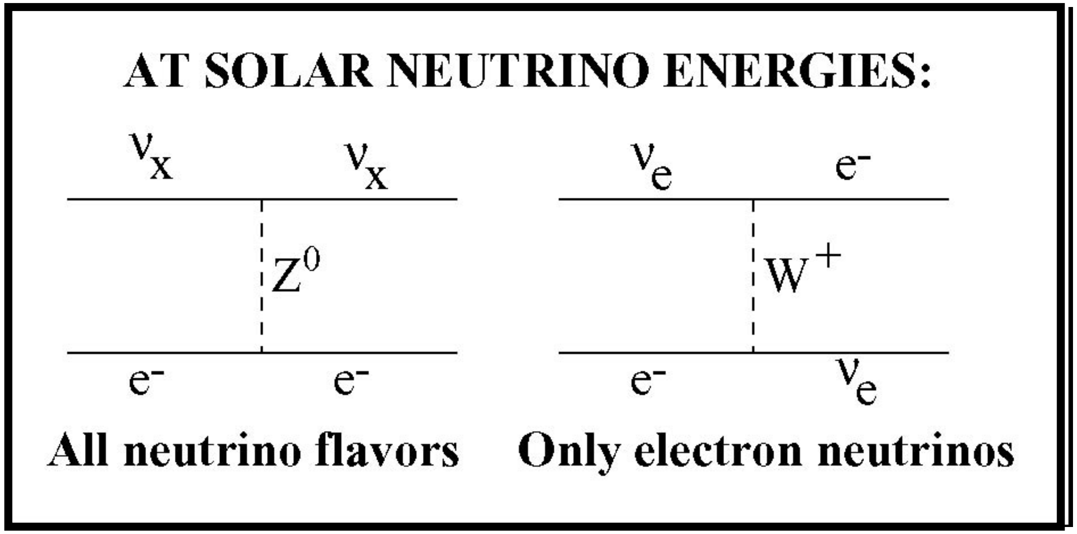
Phase I + First Phase II Results

➢ **SNO Compared to Other Solar Expts.**



But the new neutrino model makes other predictions besides fluxes…

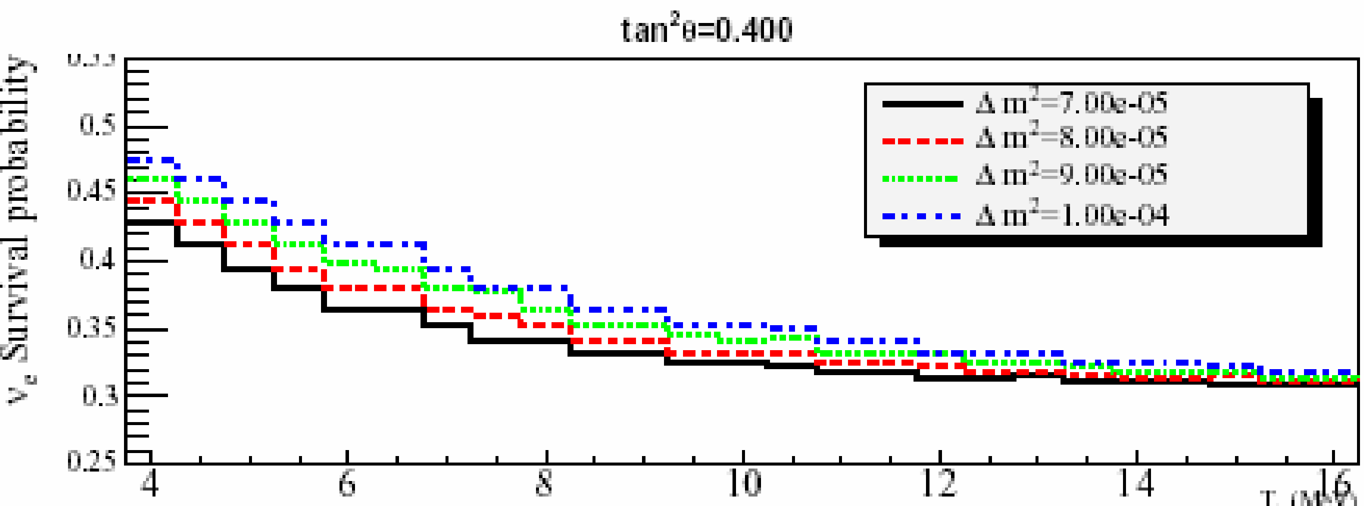
Matter (MSW) Effects



$$\sigma(\nu_{\mu,\tau}) = 0.155\sigma(\nu_e)$$

Day/Night ν_e Asymmetry

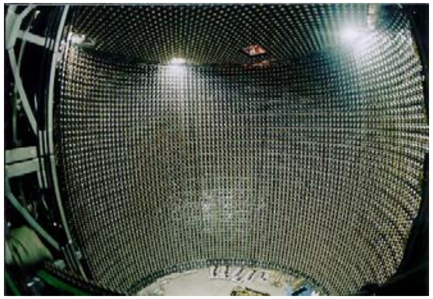
Rise in Survival Probability at low E_ν

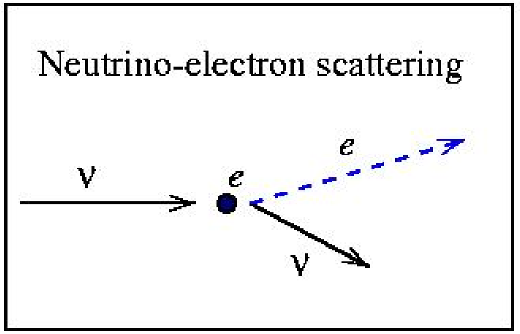


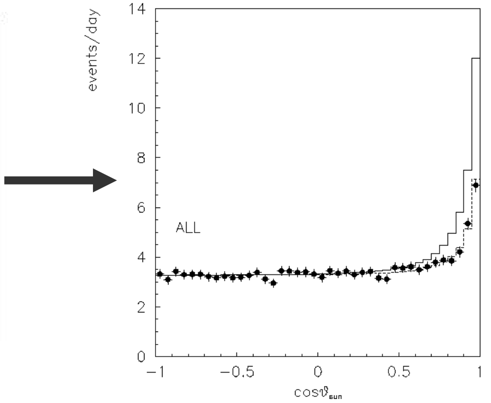
Generally speaking, neutrino oscillations in matter provide a resonant interferometer to detect very small effects.

Spectral Shape/Earth Regeneration

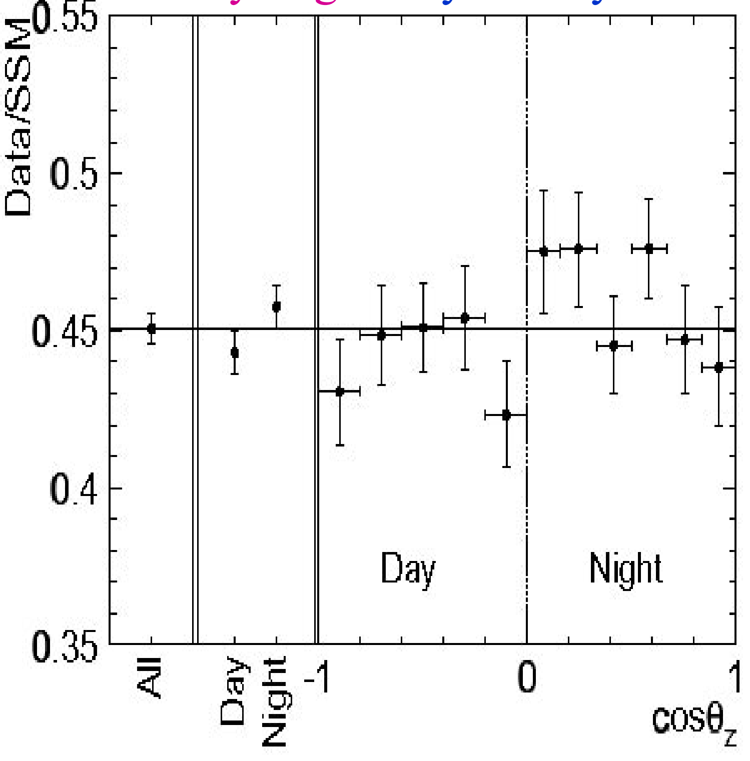
- Super-Kamiokande



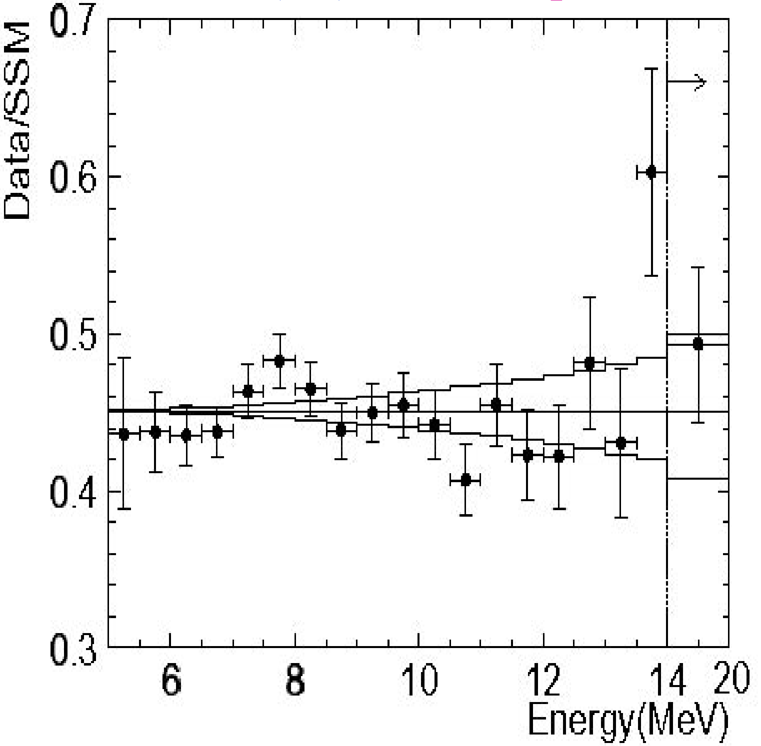




Day/Night Asymmetry:



Recoil (ES) electron spectrum:



Super-Kamiokande Collaboration, Phys. Rev. Lett. ***86***(2001)*5651-5655*

Spectral Shape / Earth Regeneration

➢ SNO

Day/Night Asymmetry? (A_{CC} or A_{NC})?

A_{NC} Unconstrained:

$$A_{CC} = 14.0\% \pm 6.3\%^{+1.5}_{-1.4}\%$$

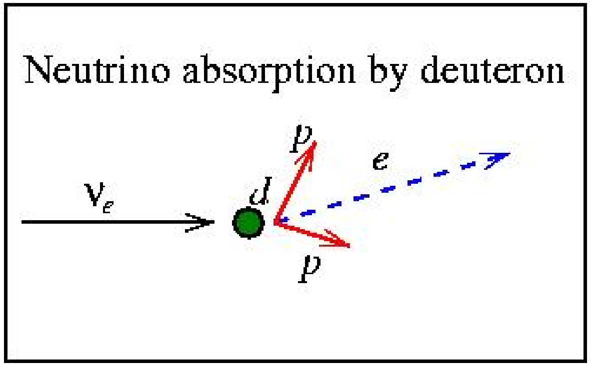
A_{NC} =0:

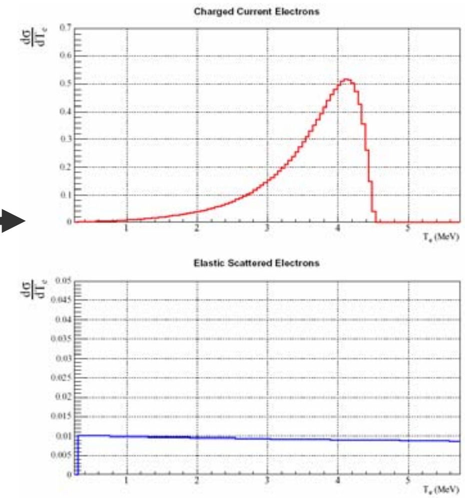
$$A_E = 7.0\% \pm 4.9\%^{+1.3}_{-1.2}\%$$

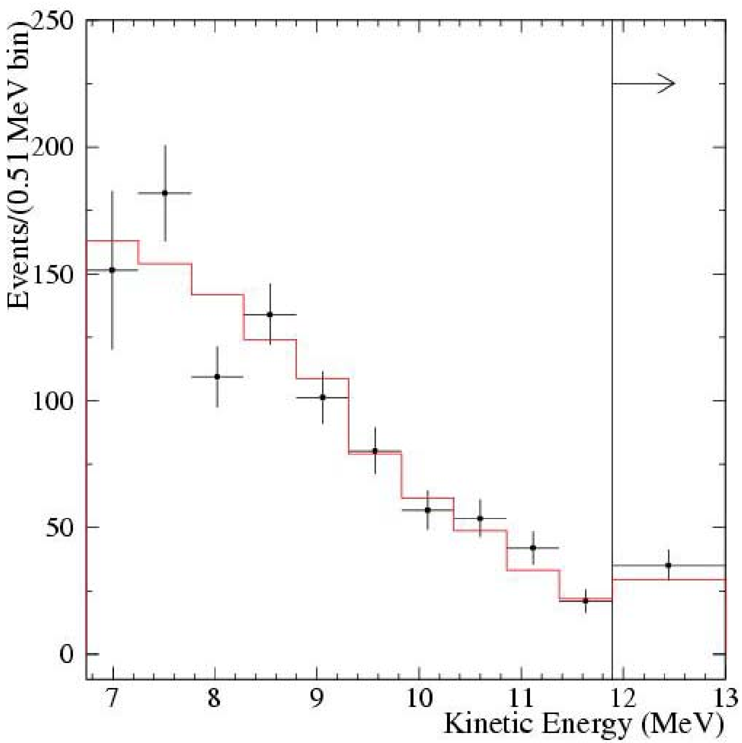
Spectral Shape / Earth Regeneration

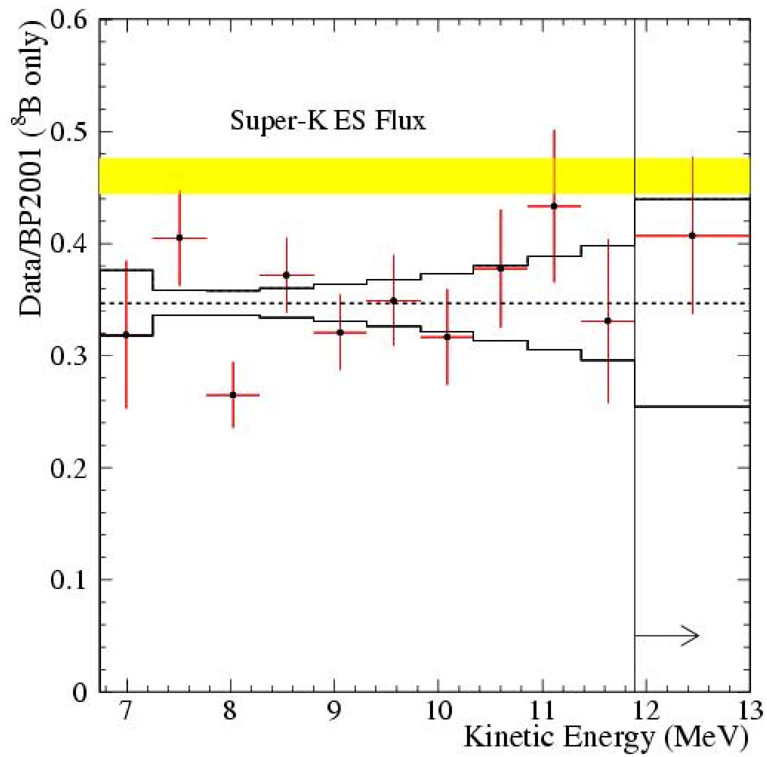
- SNO

CC reaction has good energy response



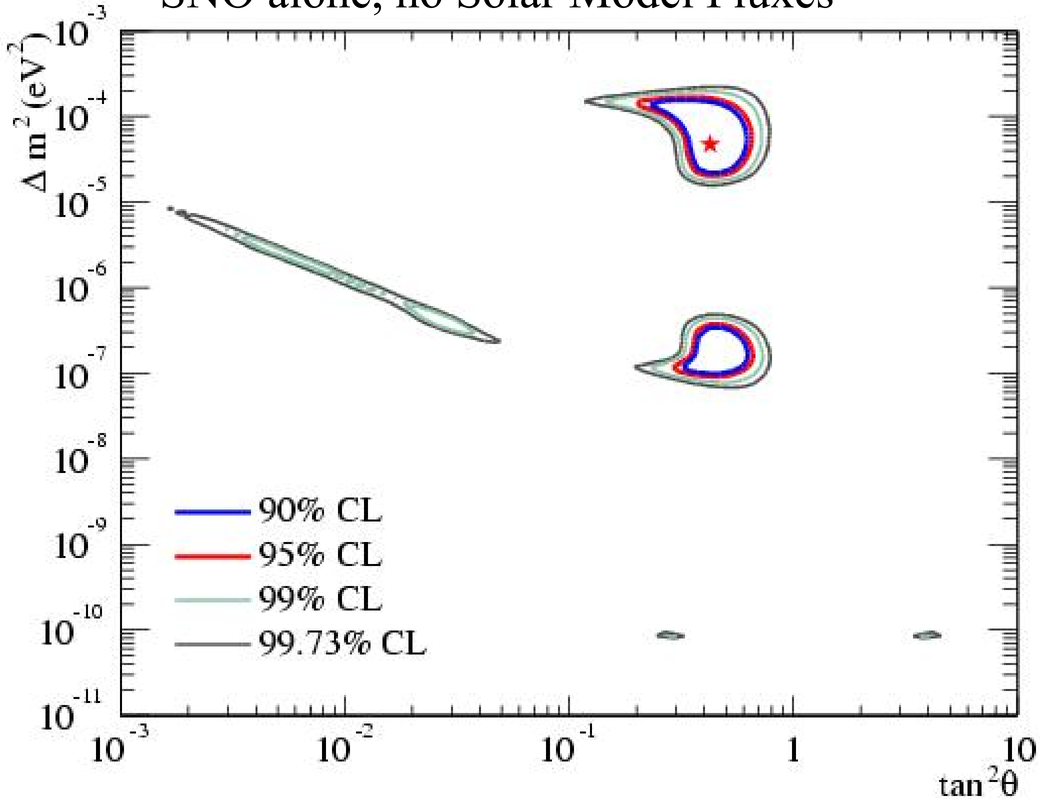




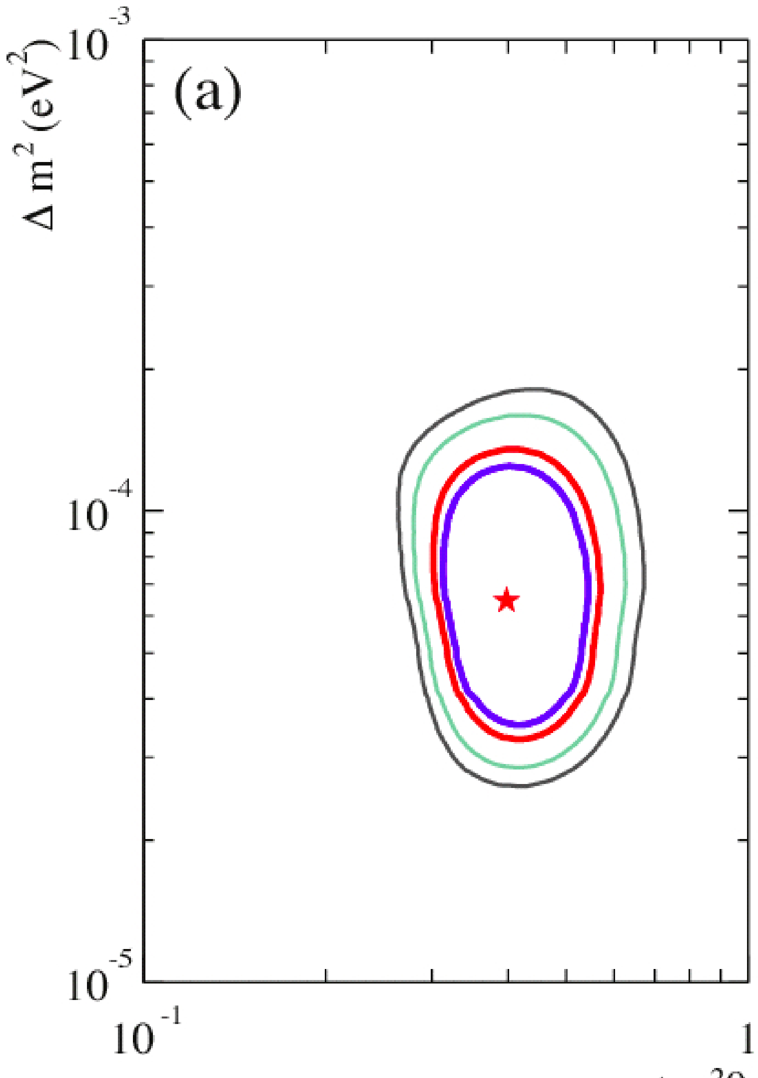


Solar Sector (1,2) Mixing Parameters

SNO alone, no Solar Model Fluxes



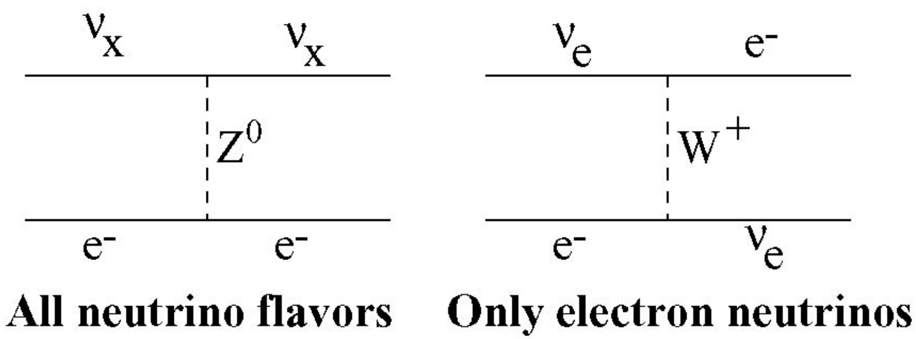
Maximal mixing ruled out at ~ 3 σ



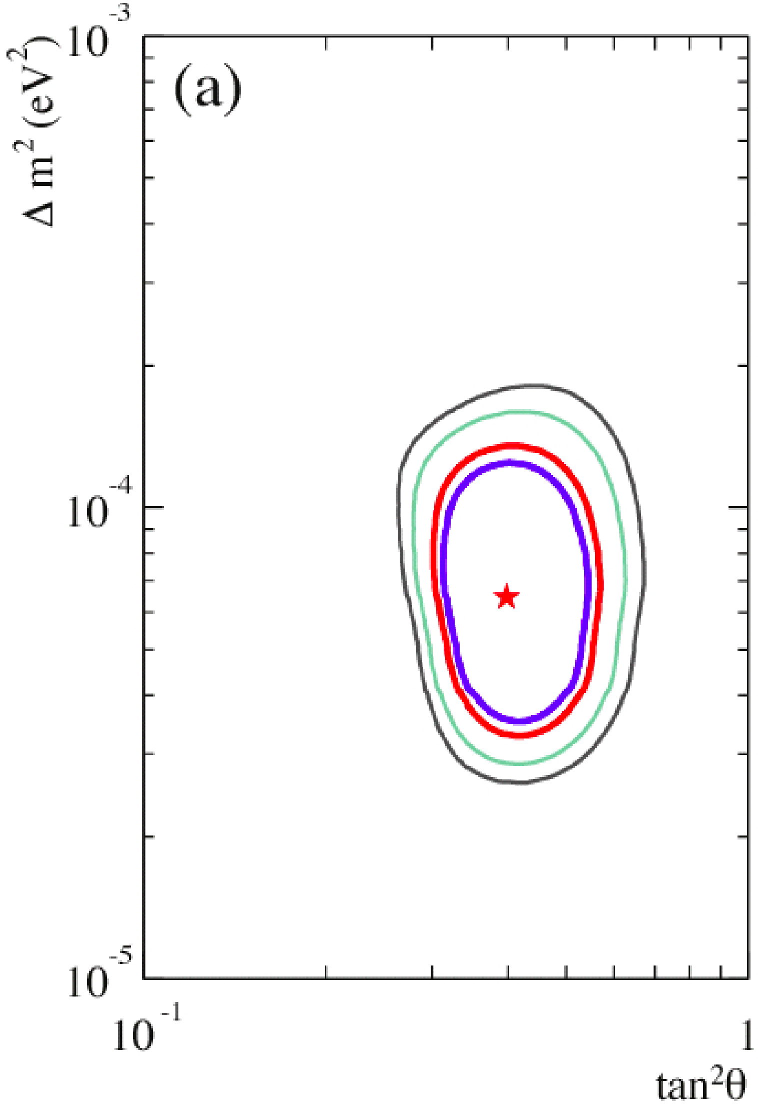
All Solar Experiments+Model Constraints

Notes On `Solar Sector' Parameters ($\Delta m^2_{12}, \sin^2 2\theta_{12}$)

Parameters measured by solar experiments require matter (MSW) effect:



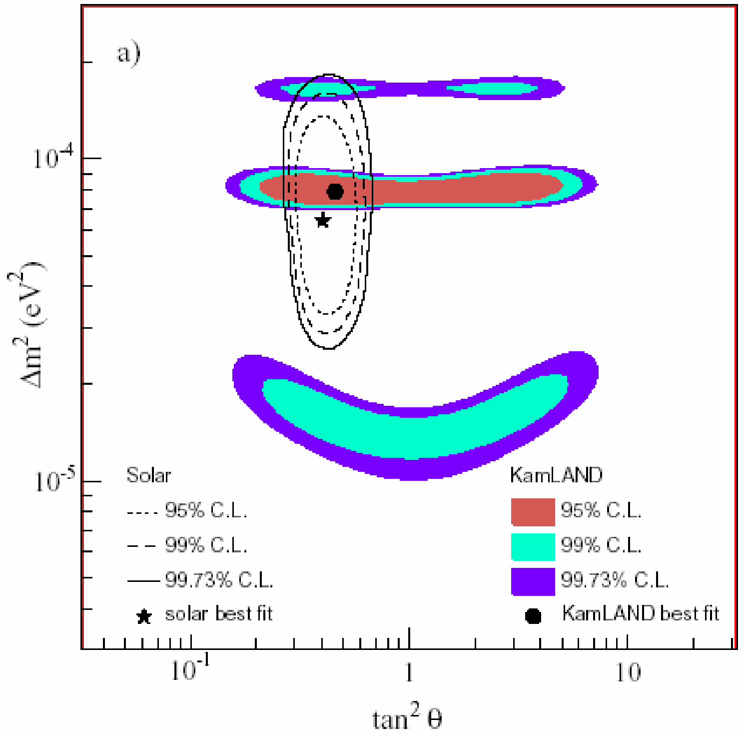
but specific signatures of MSW effect are as yet unobserved (`unlucky' parameters).



Testing the New Neutrino Model

Is our model of neutrino mixing and oscillation complete, or are there other mechanisms at work?

Given KamLAND measurements, model *predicts* solar parameters

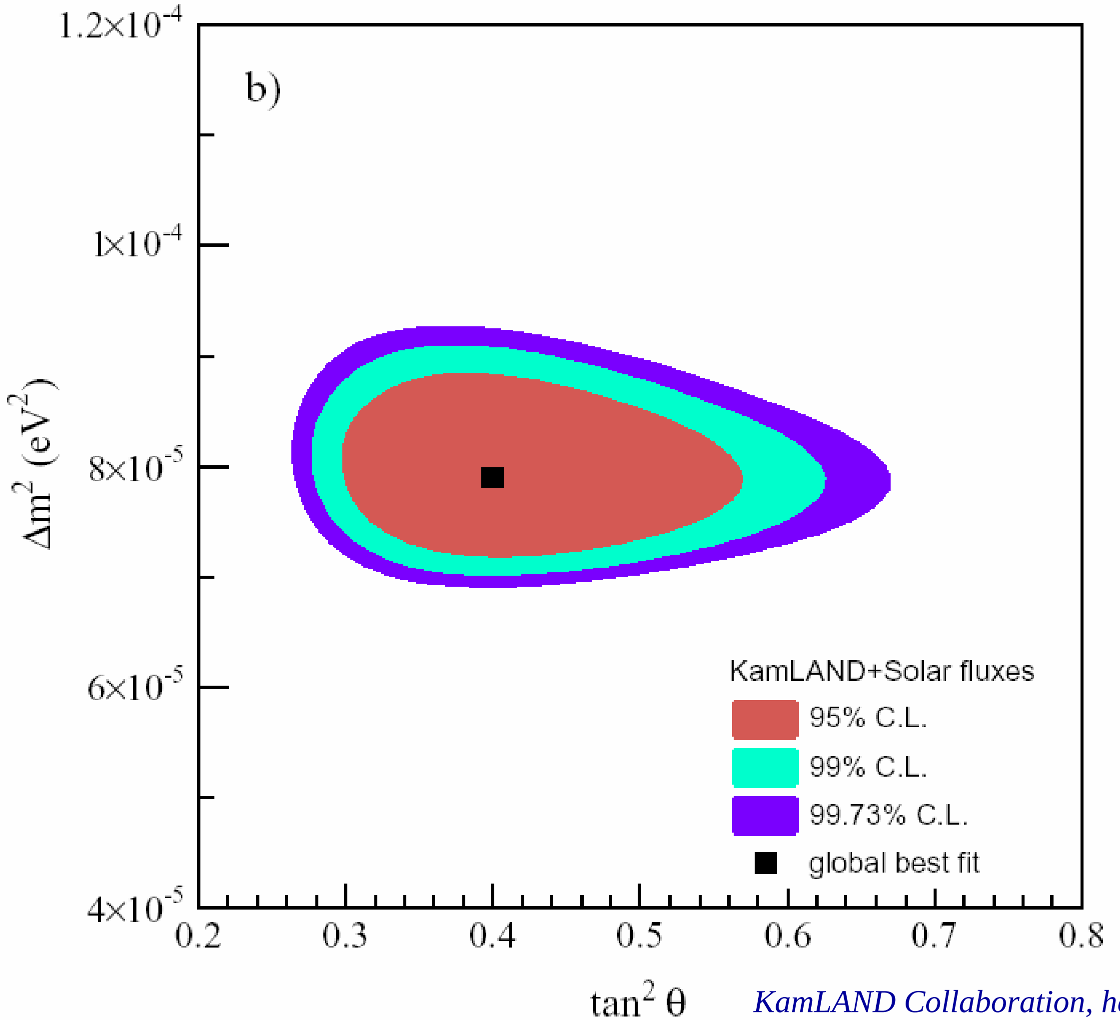


KamLAND Collaboration, hep-ex/0406035, 11/1/2004

	Reactor	Solar
E	2-10 MeV	0.1-15 MeV
L	150 km	1.5 x 10^8 km
MSW	No	Yes
ν	Anti-ν_e	ν_e

Only(?) Standard Model predicts these 2 experimental regimes see the same effect

All Solar Results+KamLAND

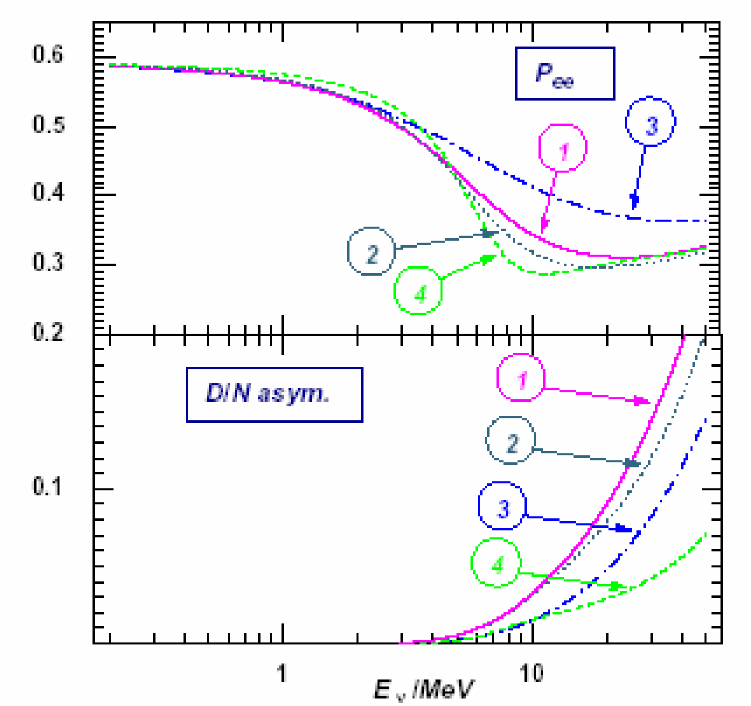


KamLAND Collaboration, hep-ex/0406035, 11/1/2004

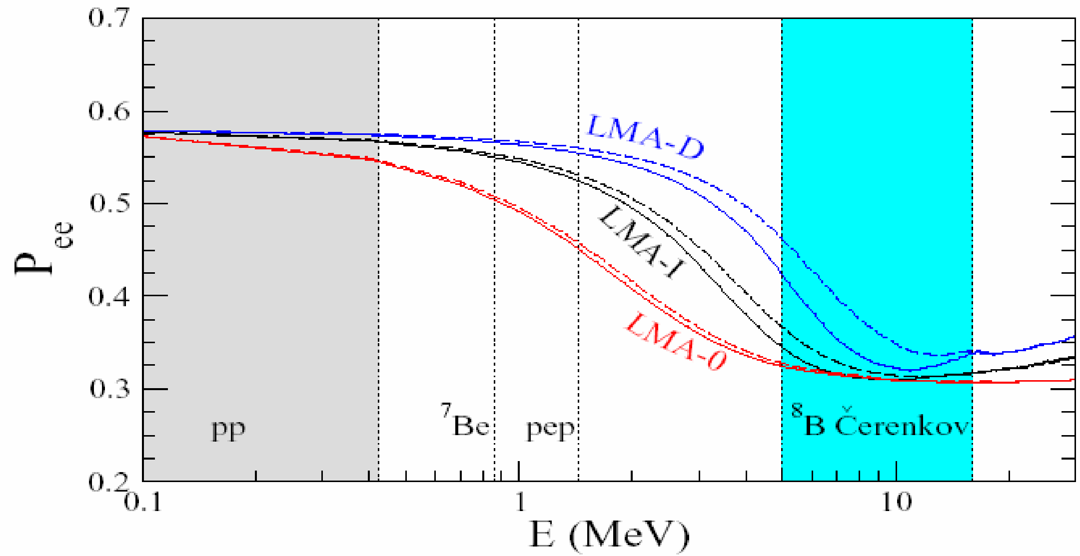
Maximal mixing ruled out at 5.4 σ

Testing the New Neutrino Model

Resonant neutrino `inteferometry' allows us to look for even very small new interactions, which will look like an `MSW'-like effect



Friedland, Lunardini, and Peña-Garay, Phys. Lett.B594:347,2004



Miranda, Tortola, and Valle, hep-ph/0406280v2

Sterile neutrinos will disappear from ν_e spectrum but not reappear in NC rate

So how do we do further tests?

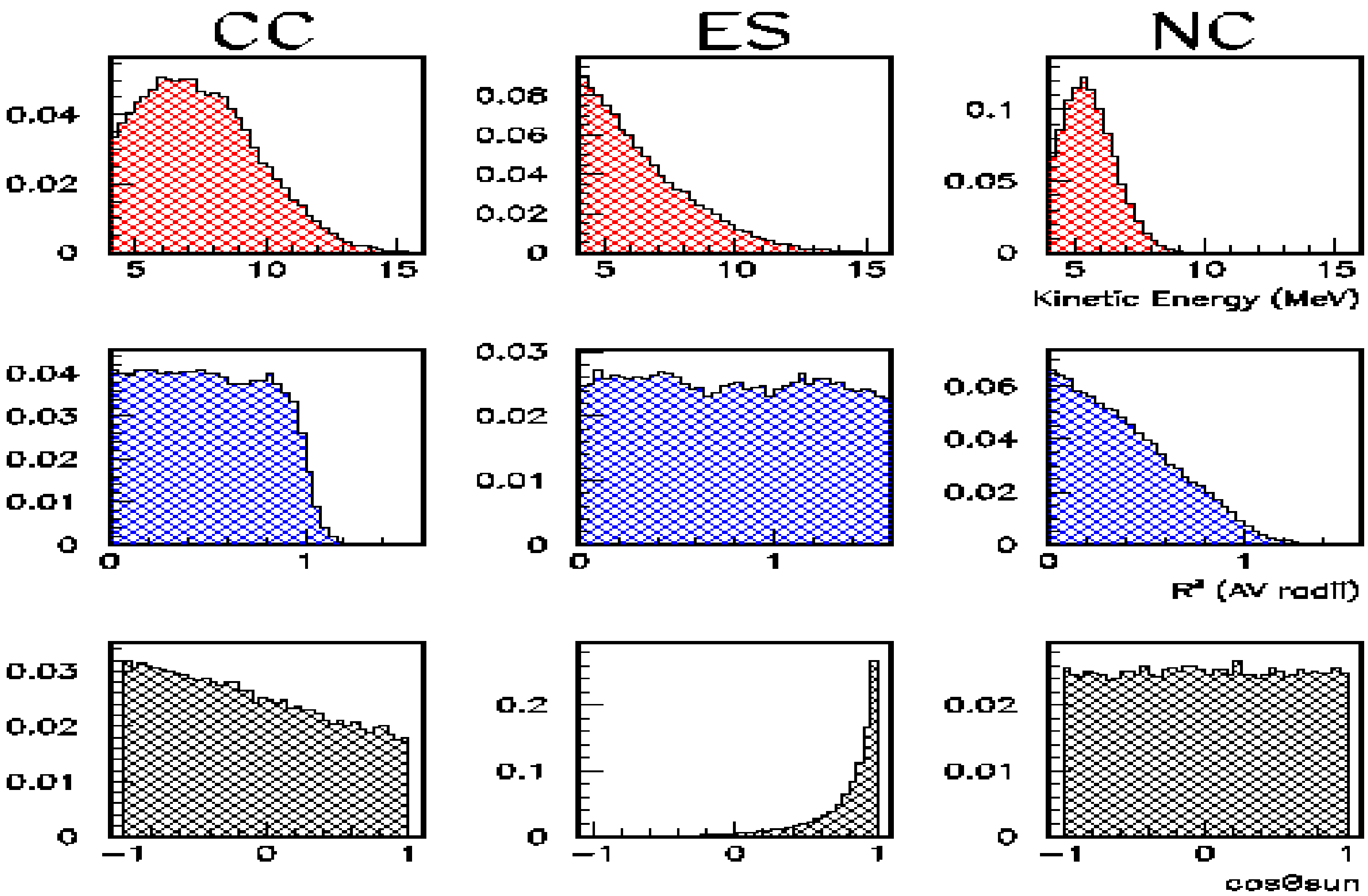
SNO Phase I: Extracting Signals

Can use derived observables (R^3, $\cos\theta_{sun}$, and E) to produce pdfs.

Energy Distribution

Radial Distribution (R^3, R_{AV}=1)

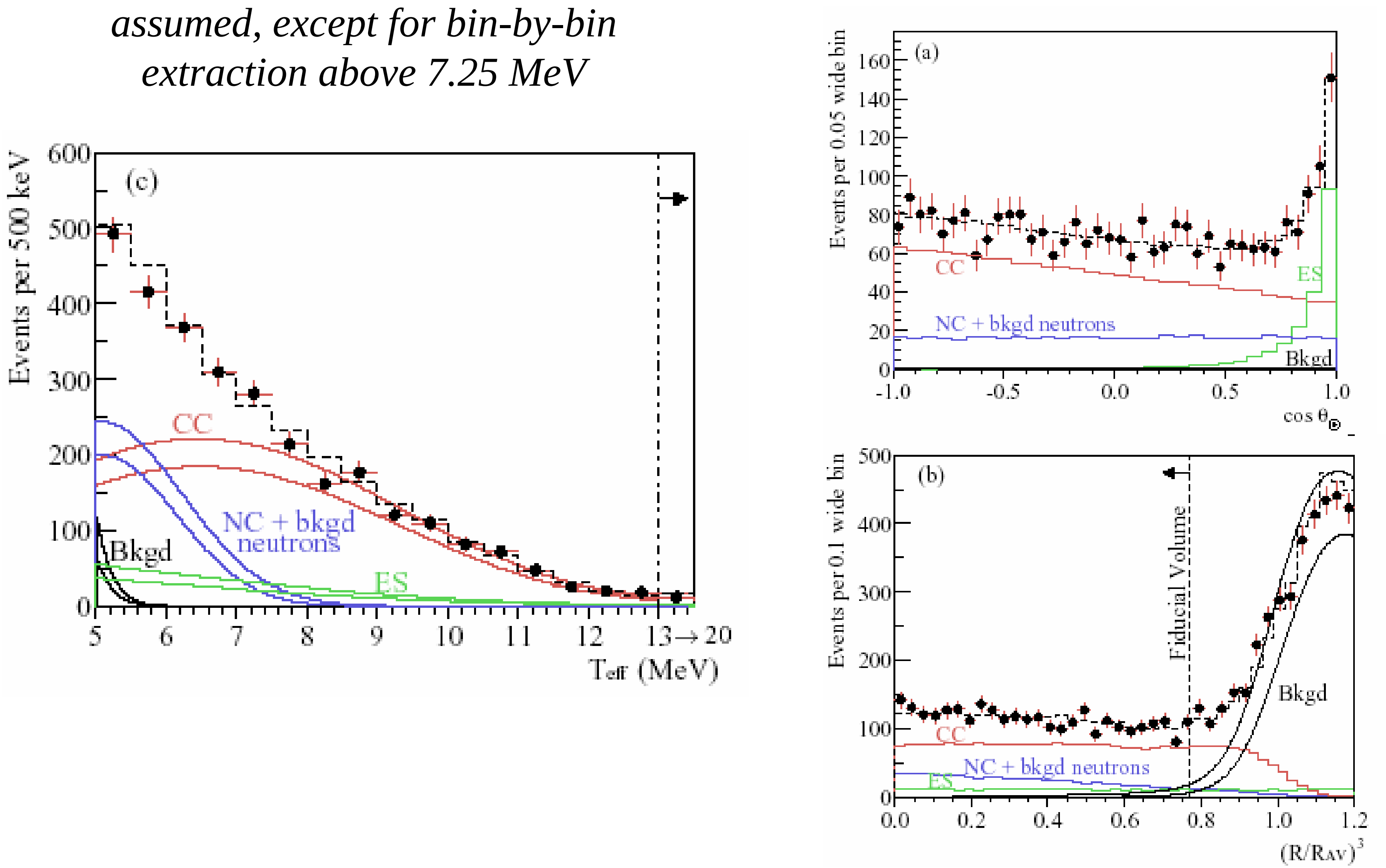
Solar Direction Distribution



Max. Likelihood fit for relative signal amplitudes

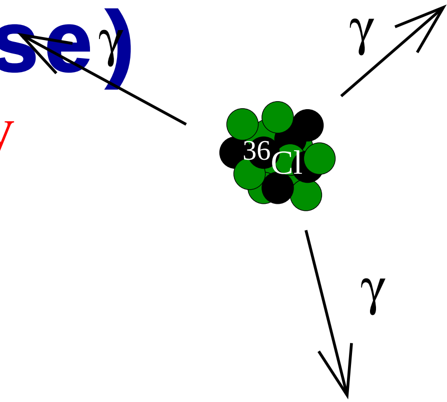
SNO Phase I Signal Fits

Undistorted ^{8}B spectral shape assumed, except for bin-by-bin extraction above 7.25 MeV



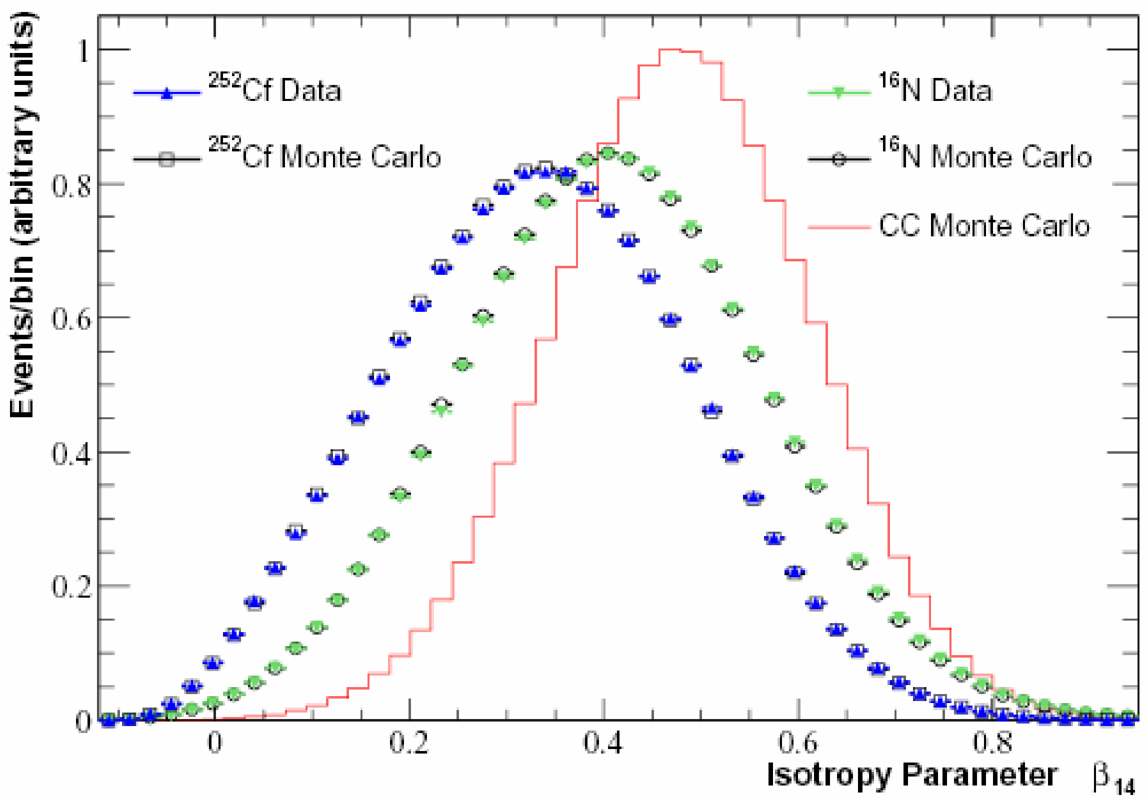
SNO Phase II (Salt Phase)

➢ Advantages of NaCl: Event Isotropy



~2−4 gammas
totalling 8.6 MeV

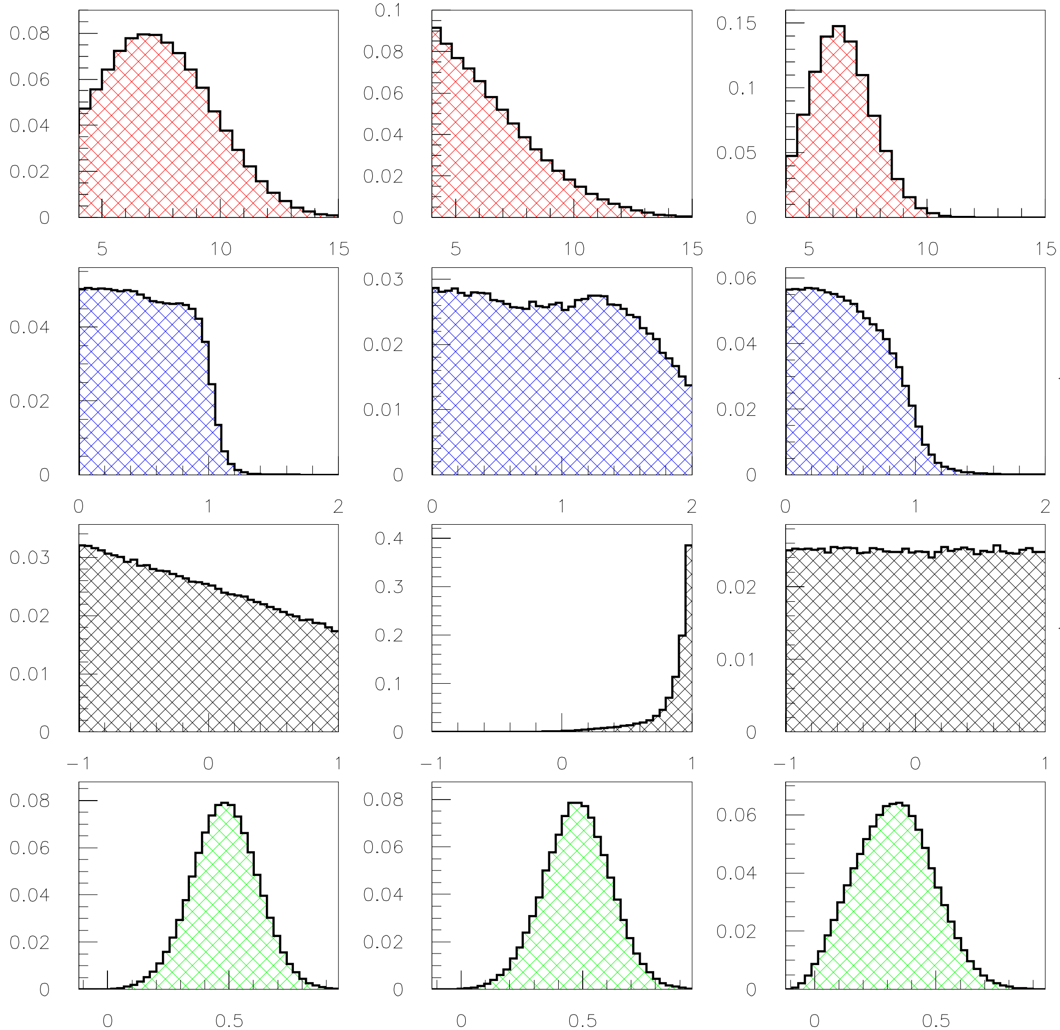
γ multiplicity means PMT hit pattern for neutron events more isotropic than for single Cerenkov electrons



SNO Phase II (Salt Phase)

➢ Advantages of NaCl: Signal Extraction

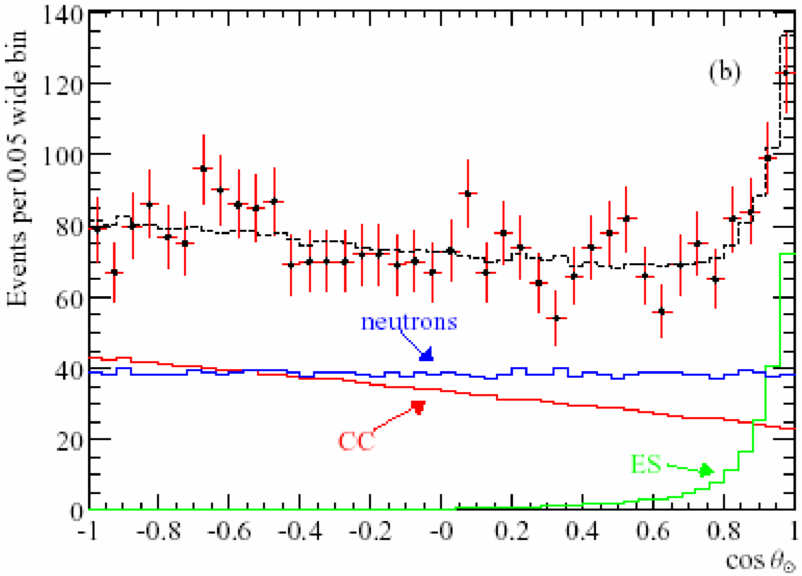
	CC	ES	NC	
Energy Distribution				← NC Shifted
Radial Distribution (R^3, $R_{AV}=1$)				← NC Changed
Solar Direction Distribution				← Unchanged
Isotropy Distribution				← All New



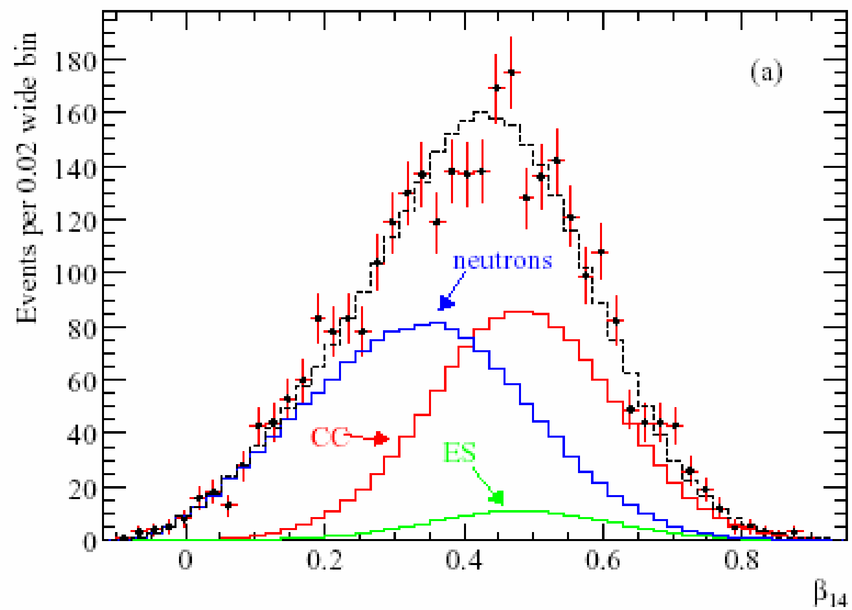
Covariances between Isotropy and Energy actually require 2D PDFs

SNO Phase II Signal Fits

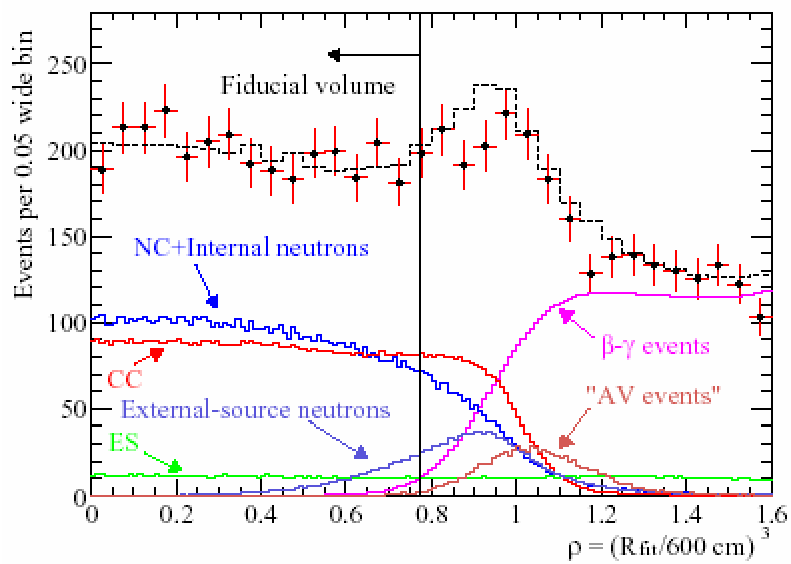
Solar Direction



Isotropy



Now entire analysis can be done bin-by-bin.



Radius (R^3)

First Phase II Results

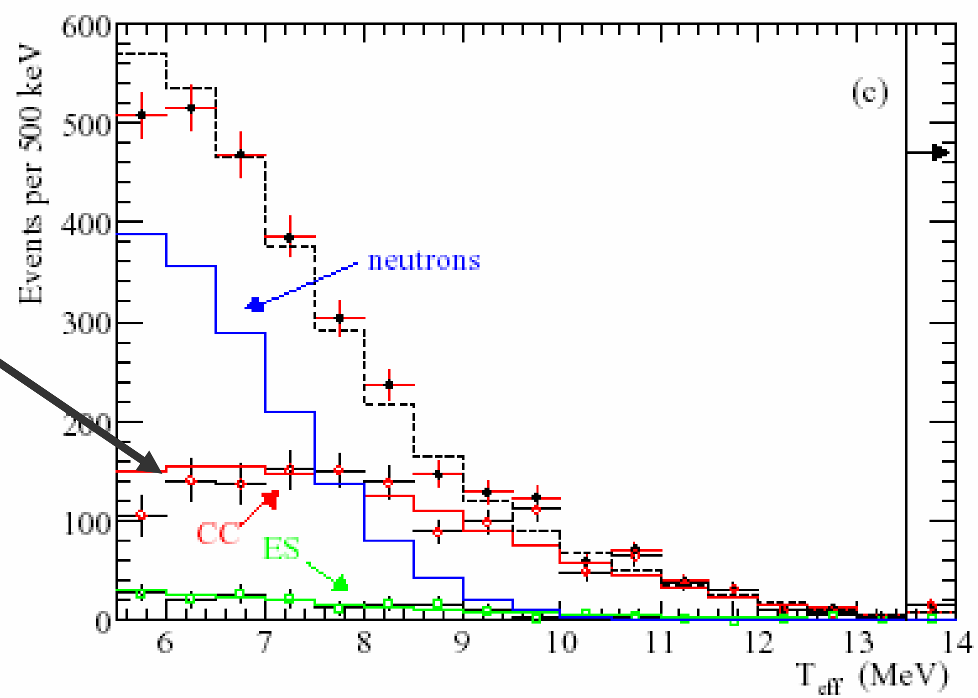
➢ Flux Measurements (units 10^6 cm^{-2} s^{-1})

$$\phi_{CC}^{SNO} = 1.59^{+0.08}_{-0.07}(\text{stat})^{+0.06}_{-0.08}(\text{syst})$$

$$\phi_{ES}^{SNO} = 2.21^{+0.31}_{-0.26}(\text{stat}) \pm 0.10\,(\text{syst})$$

$$\phi_{NC}^{SNO} = 5.21 \pm 0.27\,(\text{stat}) \pm 0.38\,(\text{syst})$$

Still not really a spectrum



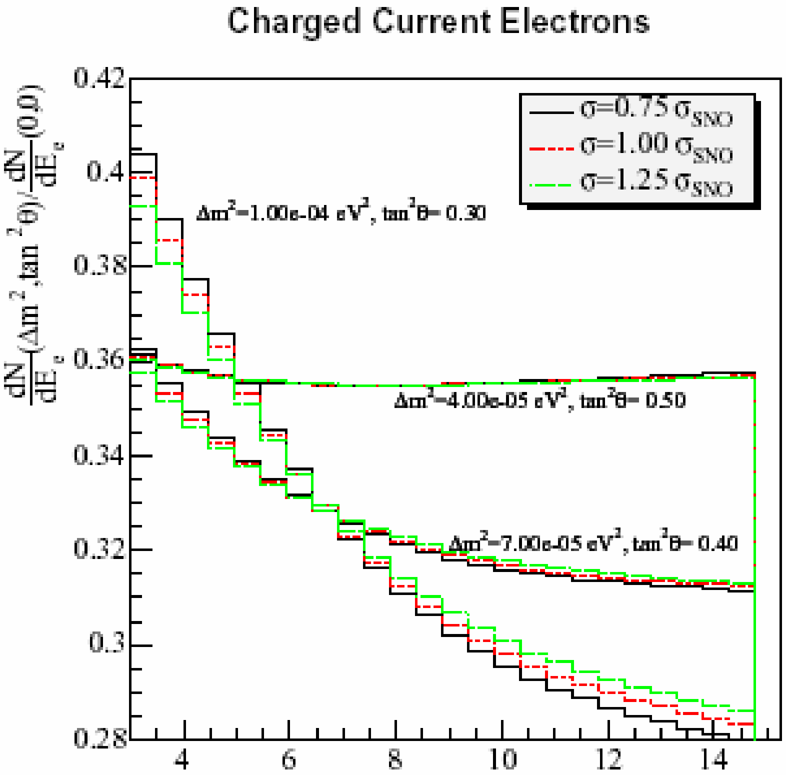
Upcoming Phase II Results

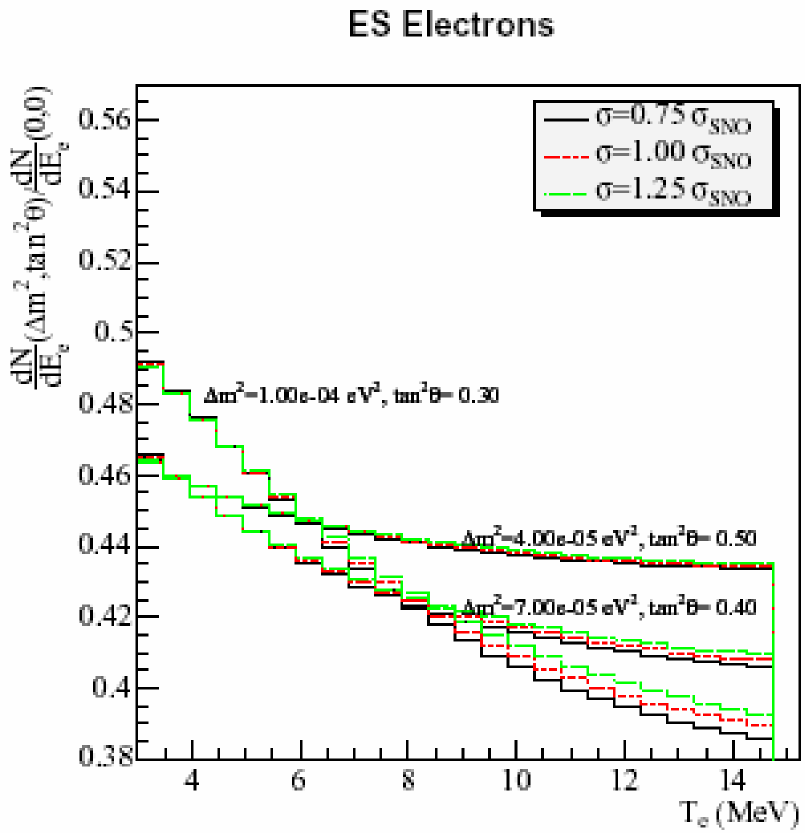
- Roughly 50% more data (391 live-days)
- First spectrum with all differential sys. uncertainties
- New Day/Night asymmetry result
- `Full' details (~40 pp)
- (`Long' paper detailing Phase I results starting internal editing and review process ~70 pp)

SNO Low Threshold Analysis

Work underway to push threshold on Phase I+II data to T > 4 MeV

Predictions for SNO response for various MSW solns:





SNO Phase III (NCD Phase)

➤ ^{3}He Proportional Counters

Array of ^{3}He counters

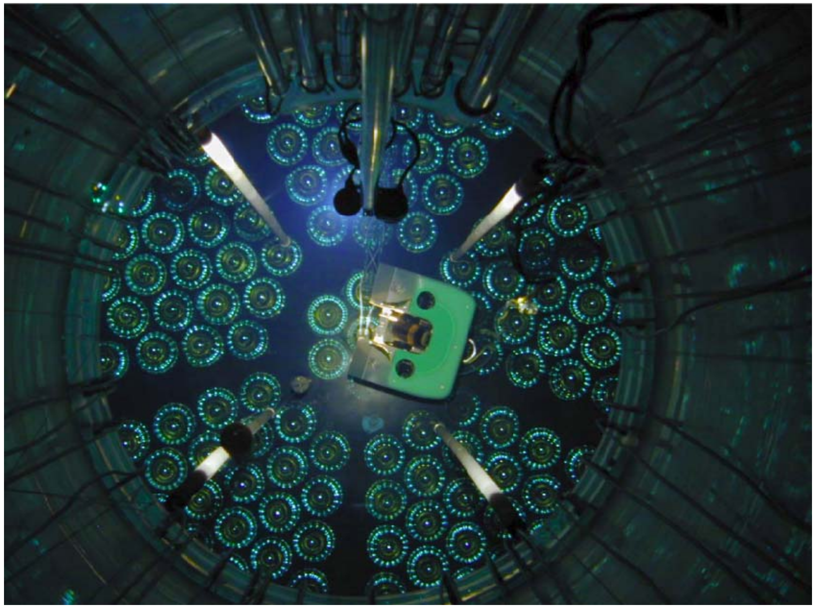
40 Strings on 1-m grid

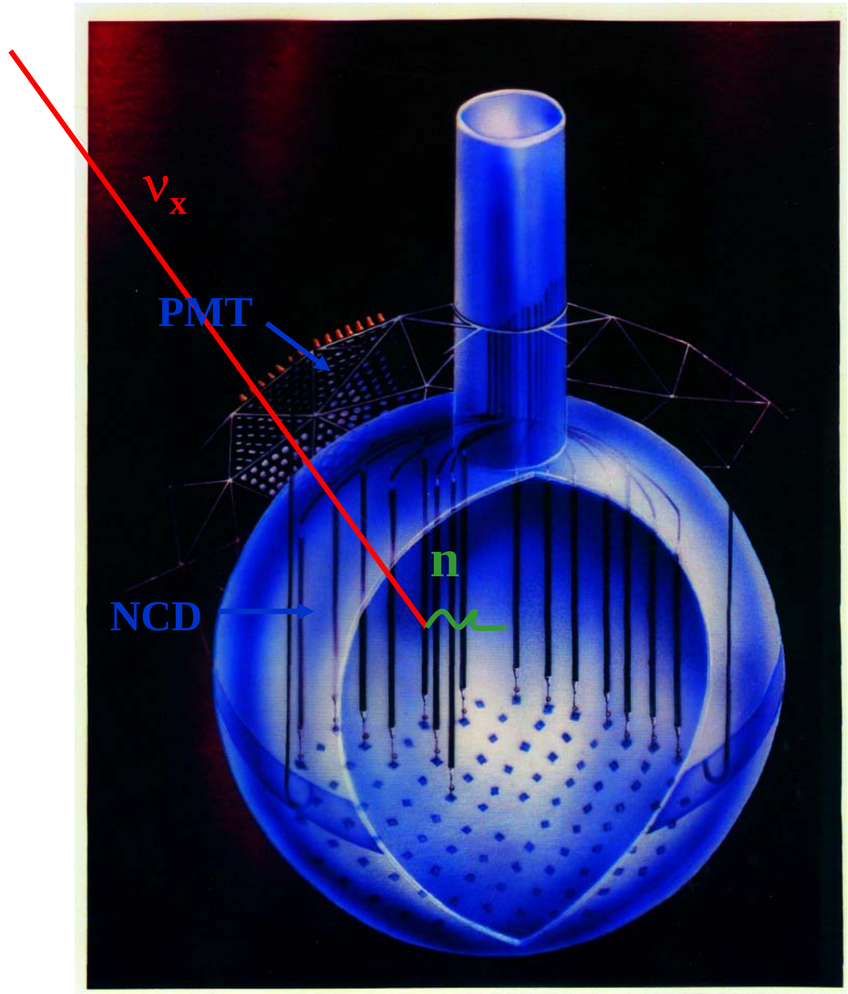
440 m total active length

Detection Principle

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

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





Production data taking began Dec 2004

SNO Phase III (NCD Phase)

➢ Physics Motivation---Energy Spectrum

- **CC and NC separation in pure D2O had big covariances (>90% correlations)**

- **Salt phase broke covariance with isotropy, but additional neutrons dilute CC signal**

	Correlation Coefficient		
	D_2O	Salt	^3He
CC,NC	-0.950	-0.521	~0
NC,ES	-0.297	-0.064	~0
CC,ES	-0.208	-0.156	~ -0.2

- **Third phase has best of both worlds**
  - **^{3}He (\`NCD') counters absorb neutrons**
  - **Independently constrain remainder**
  - **And can be applied retroactively**

Conclusions

- Starting to look at `precision' tests of the new neutrino model
  - KamLAND + SNO + Super-K + BOREXINO +???

- Upcoming SNO results will contain first `precision' SNO spectrum and new Day/Night asymmetry results

- Further work to lower SNO energy threshold, test model further

- SNO Phase III likely to highest precision low threshold ^{8}B measurement