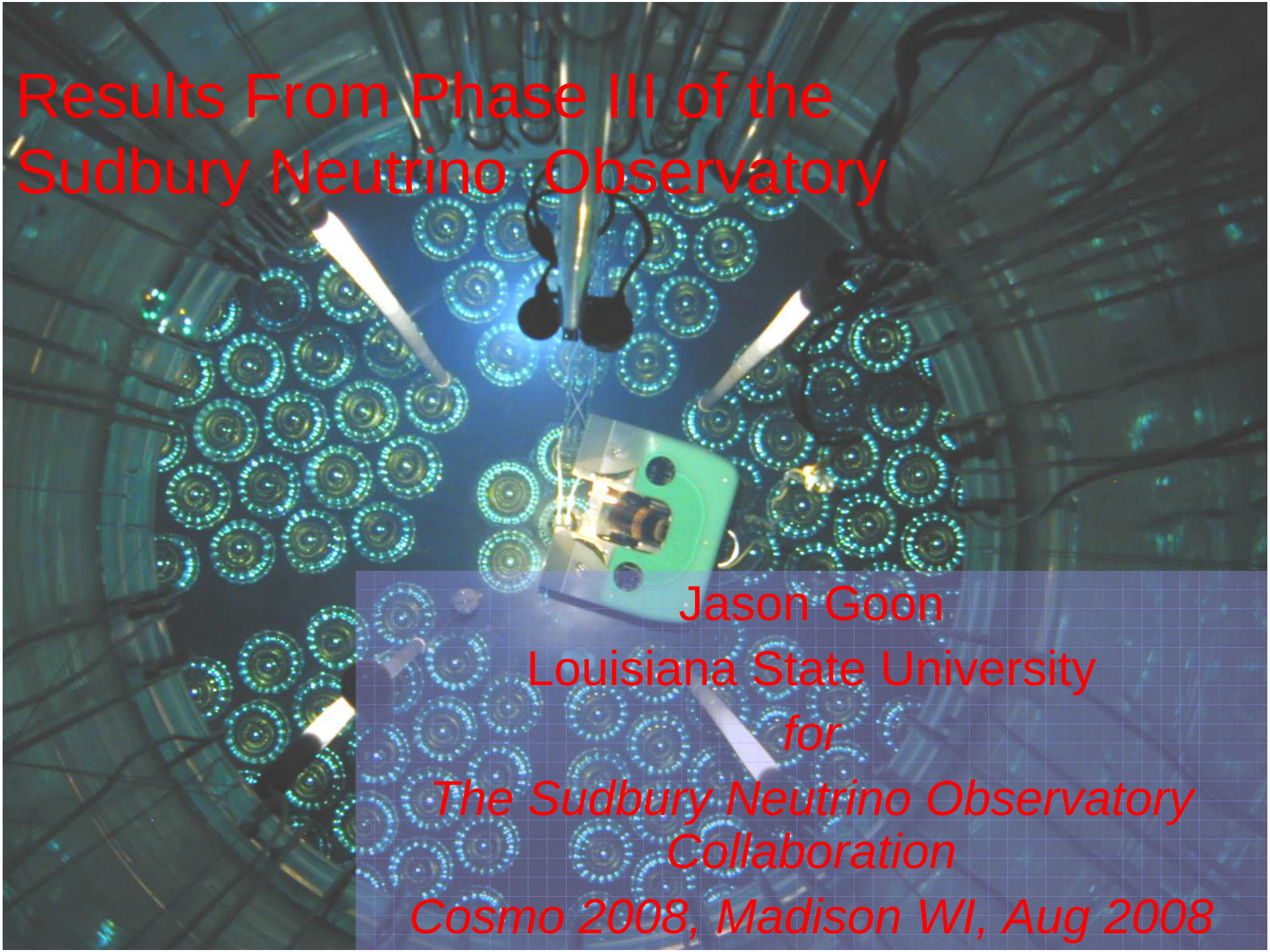


Results From Phase III of the Sudbury Neutrino Observatory

Jason Goon

Louisiana State University

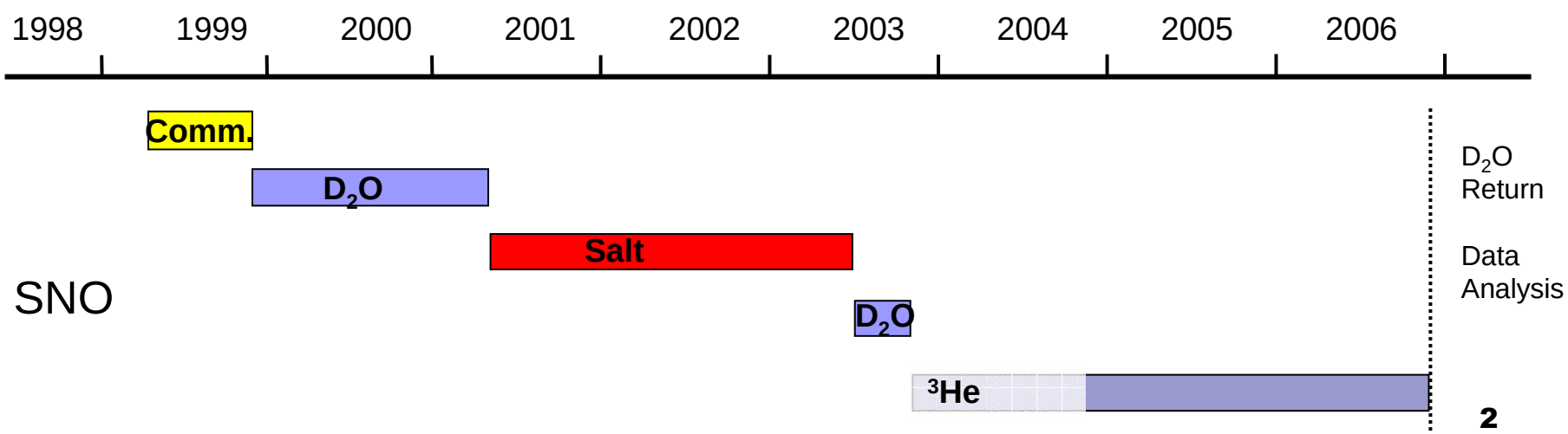
for

The Sudbury Neutrino Observatory Collaboration

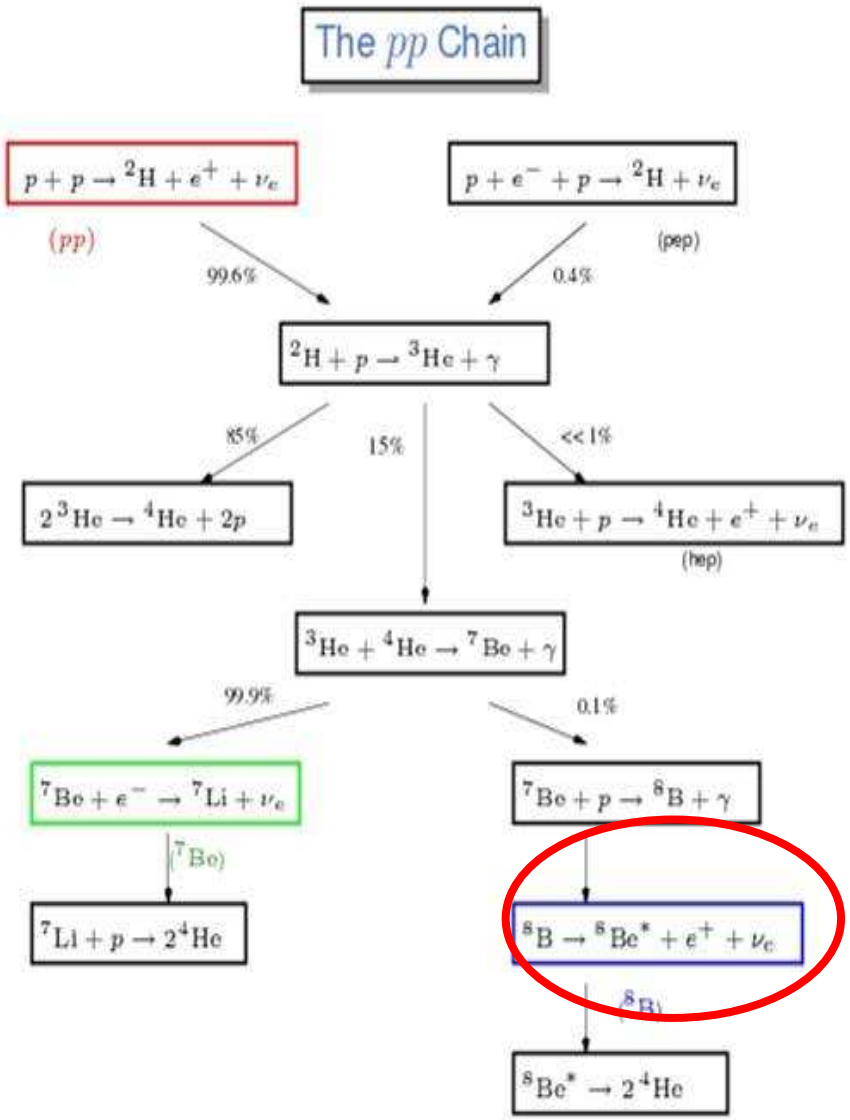
Cosmo 2008, Madison WI, Aug 2008

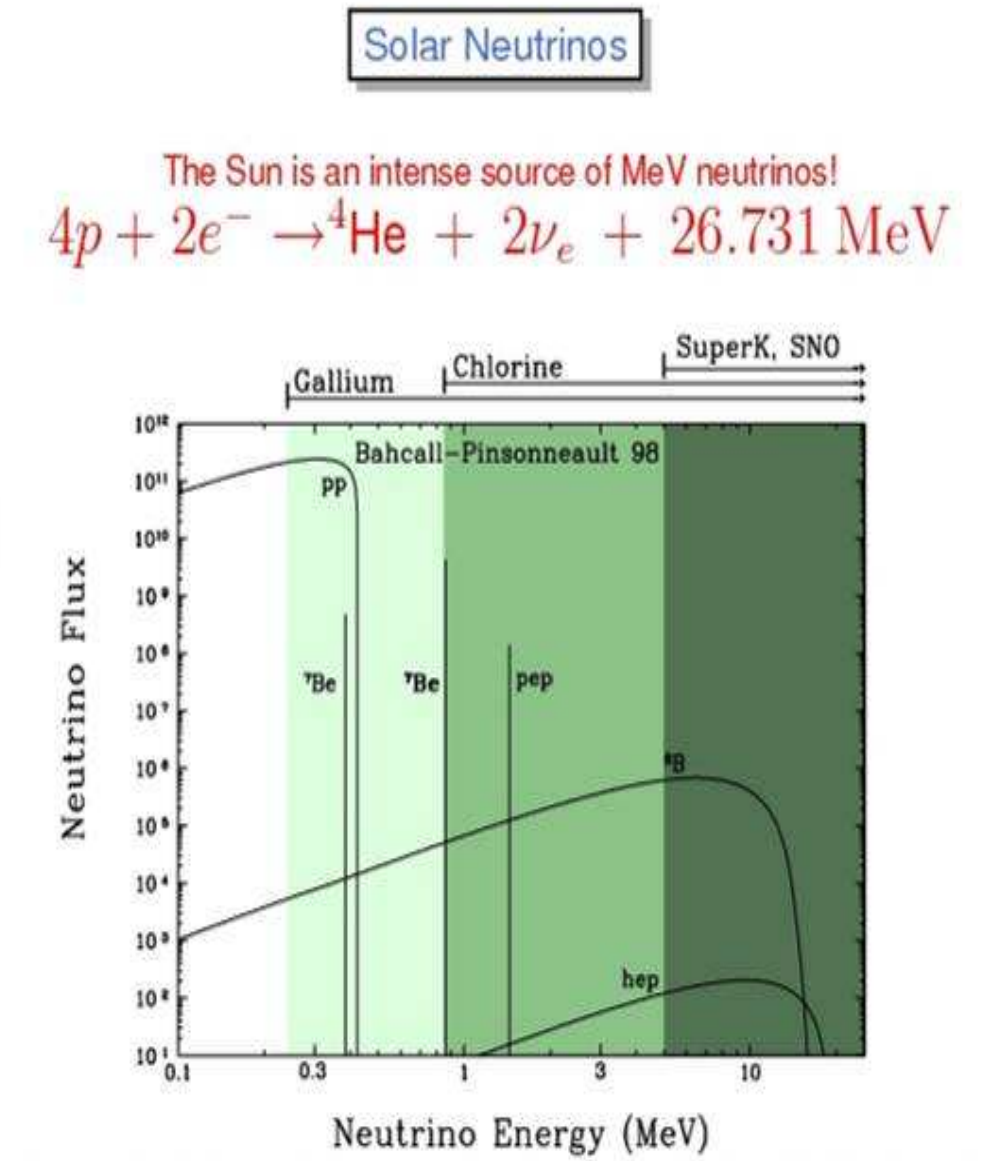
Outline

- Physics and Reactions
- Motivation
- Detectors and Detections
- Signal Extraction and Analysis
- Summary



Solar reactions and spectra





olar models let us predict the rates of each neutrino-producing reactio

SNO

6000 mwe overburden

1000 tonnes D_2O

12 m Diameter Acrylic Vessel

1700 tonnes Inner Shield H_2O

Support Structure for 9500 PMTs, 60% coverage

5300 tonnes Outer Shield H_2O

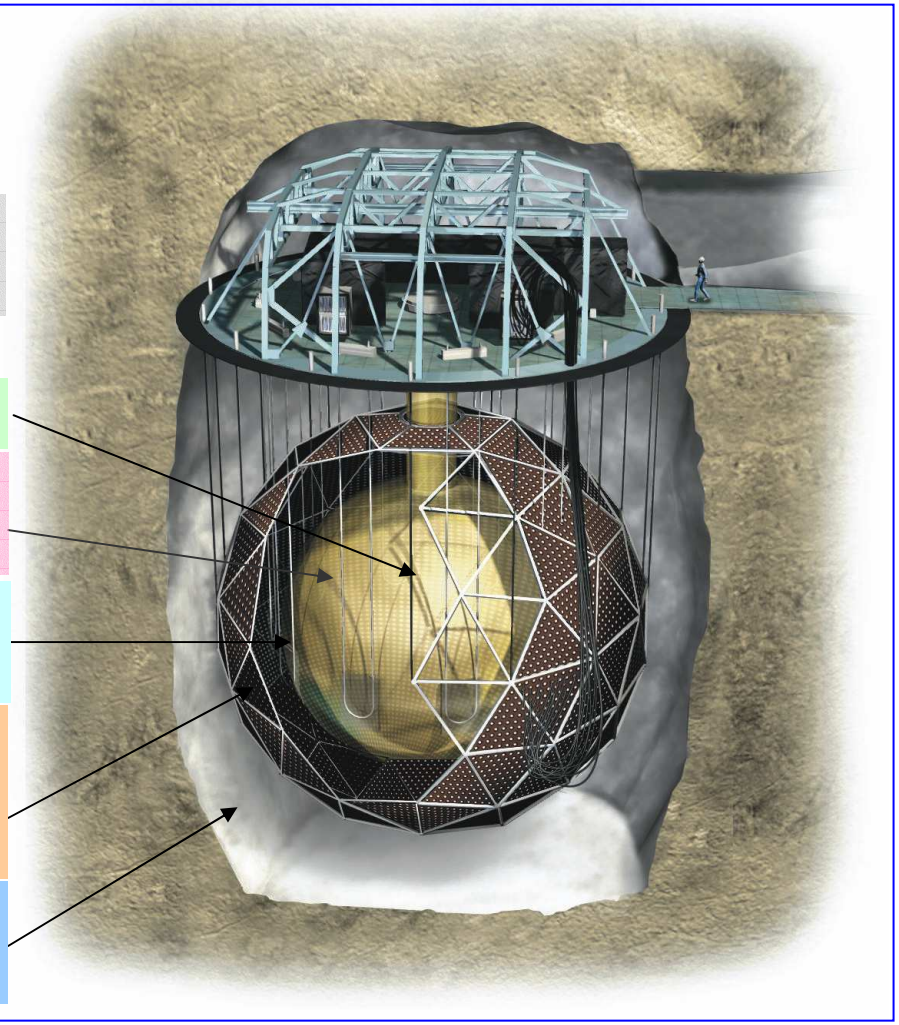


Image courtesy National Geographic

3 Reactions:

$$\nu_x + e^- \rightarrow \nu_x + e^- \quad \text{ES}$$

$$\nu_e + d \rightarrow p + p + e^- \quad \text{CC}$$

$$\nu_x + d \rightarrow p + n + \nu_x \quad \text{NC}$$

3 neutron detection methods:

$$n + d \rightarrow t + \gamma + 6.25 \text{ MeV}$$

$$n + {}^{35}Cl \rightarrow {}^{36}Cl + \gamma + 8.6 \text{ MeV}$$

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

3 Phases:

- Just D_2O
- D_2O + 2 tonnes NaCl
- D_2O + ^{3}He Proportional Counters (“NCDs”)

Motivation

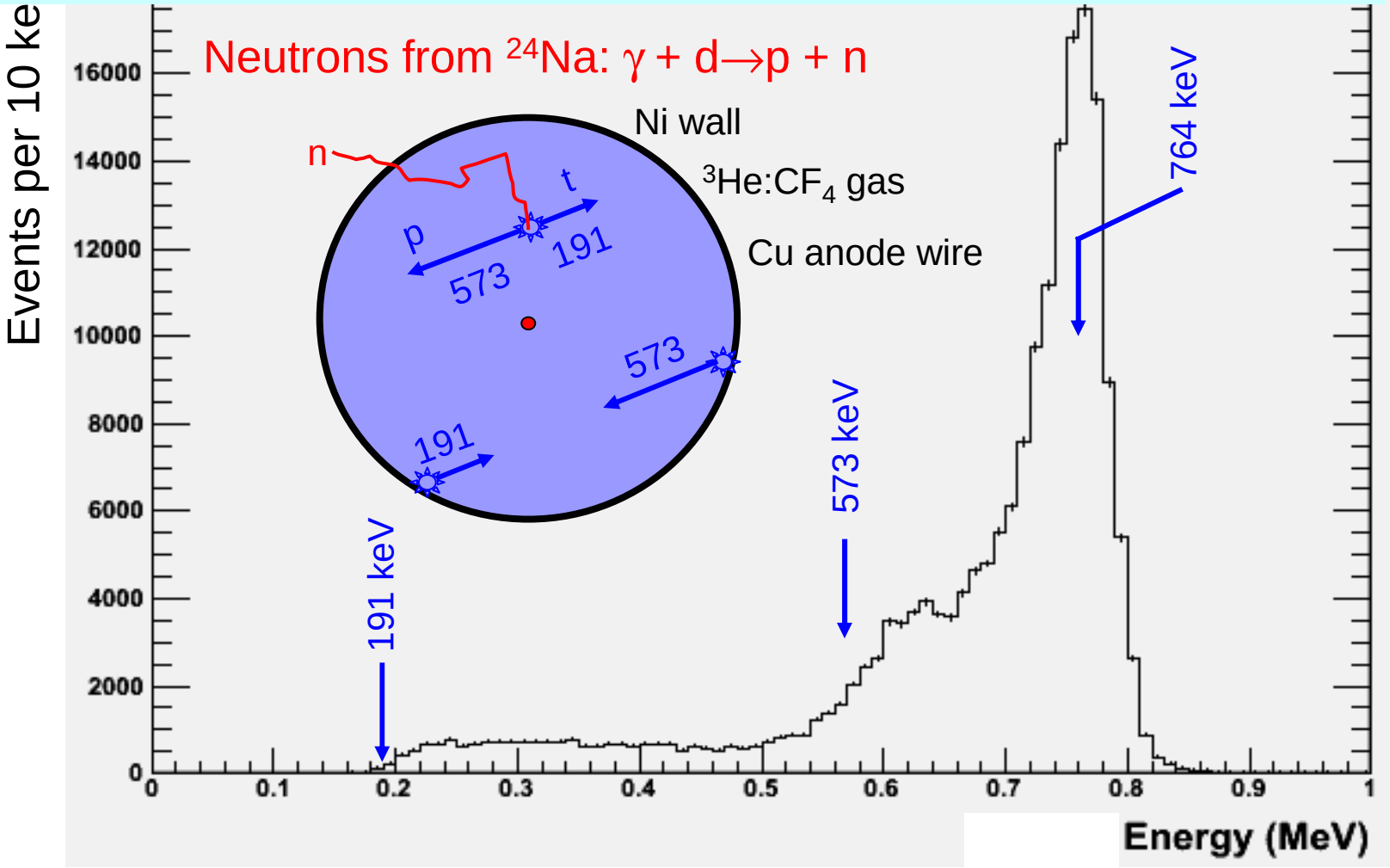
- Separate CC and NC signal paths: neutron capture no longer competes with CC events in Cherenkov light.

  (CC spectrum contamination by 6.25-MeV capture gammas reduced by capture in NCD array, and determined independently)
- Break correlation between CC and NC signals
- Signal extraction of CC, ES, NC analysis employs “Floating systematics”

NCD

Counters 2 - 3m long laser-welded together and deployed by a submersible vehicle.
36 strings of ^{3}He, 4 strings of ^{4}He on a 1 x 1 m grid.

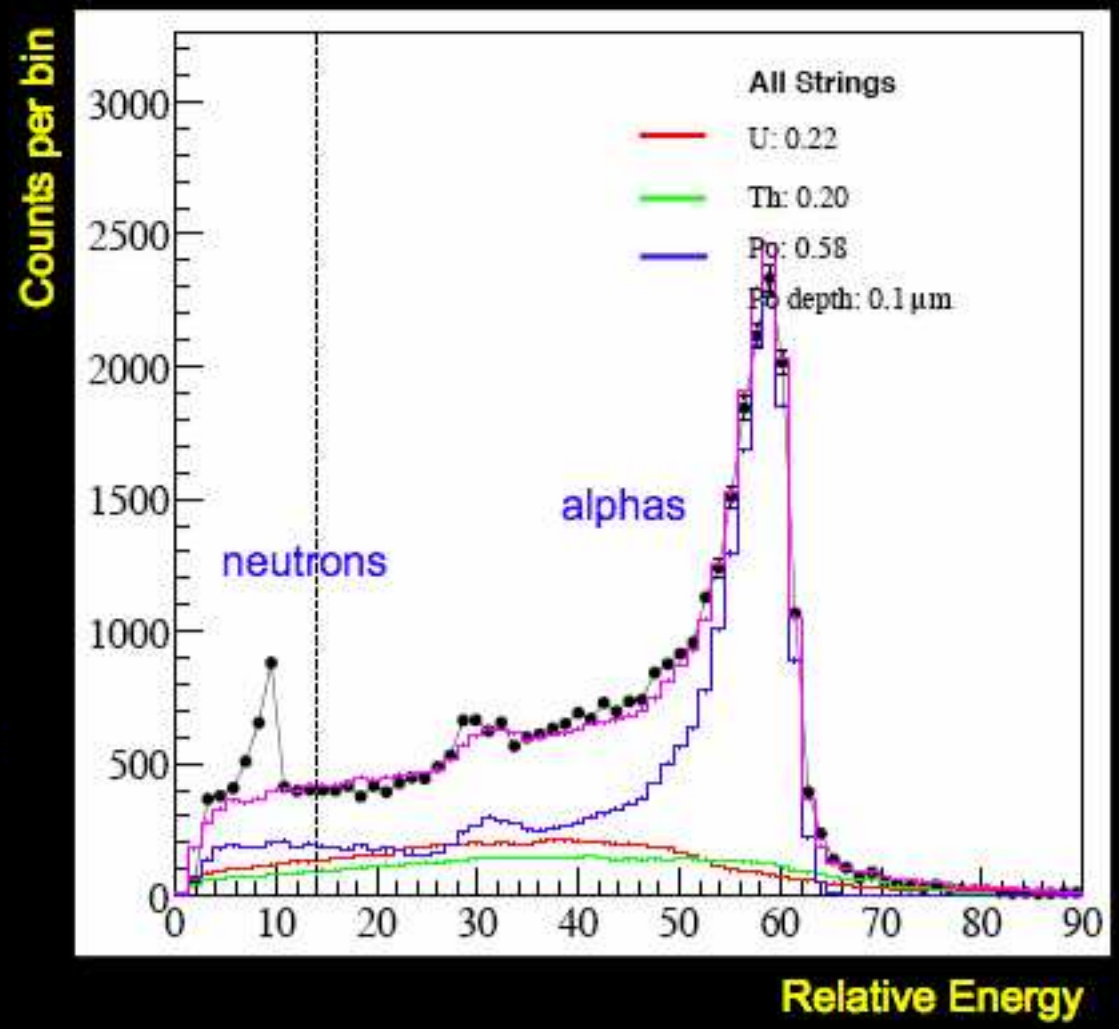
Neutron spectrum is obtained from ^{24}Na calibration source



NCD Simulation Physics:

model:
alpha energy loss
alpha energy straggling
alpha multiple scattering
electron-ion pair generation
electron drift, diffusion
electron multiple scattering
ion mobility
electron avalanche
space charge
signal generation
propagation through electronics

extract from calibration data:
Po/bulk ratio
energy scale
energy resolution
alpha depth
contributions from different parts of the NCD



Sigex Extraction

- Joint-fits: 2 data streams (PMT and NCD)
- PMT-NC signal constrained to NCD-NC signal
- Performed at PMT e^- kinetic thres. > 6 MeV.
- Energy spectral shape is unconstrained.
- 3 different and independent sigex codes
- All 3 sigex codes used likelihood functions

$$-logL = \sum_{i}^{M^{PMT}} f_i^{PMT} \phi_i - \sum_{j}^{N^{PMT}} \log \sum_{i}^{M^{PMT}} f_i^{PMT} \phi_i g_i(p_j; p_j^0, p_j^{true}, d, s, r) + logL_{NCD} + logL_{constr}$$

The physics parameters ("fluxes") are fitted allowing nuisance parameters (calibration constants, etc.) to vary weighted by their external uncertainties. The likelihood is maximized via randomized search steps

Blind and Box Analysis

Blind

- First month of open dataset (26.7days) and 359.5 days of blind dataset which consist of hidden fraction of neutrons that follow muons, AND Omit an unknown fraction of candidate events
- Analyze with 3 different sigex codes and blind comparison

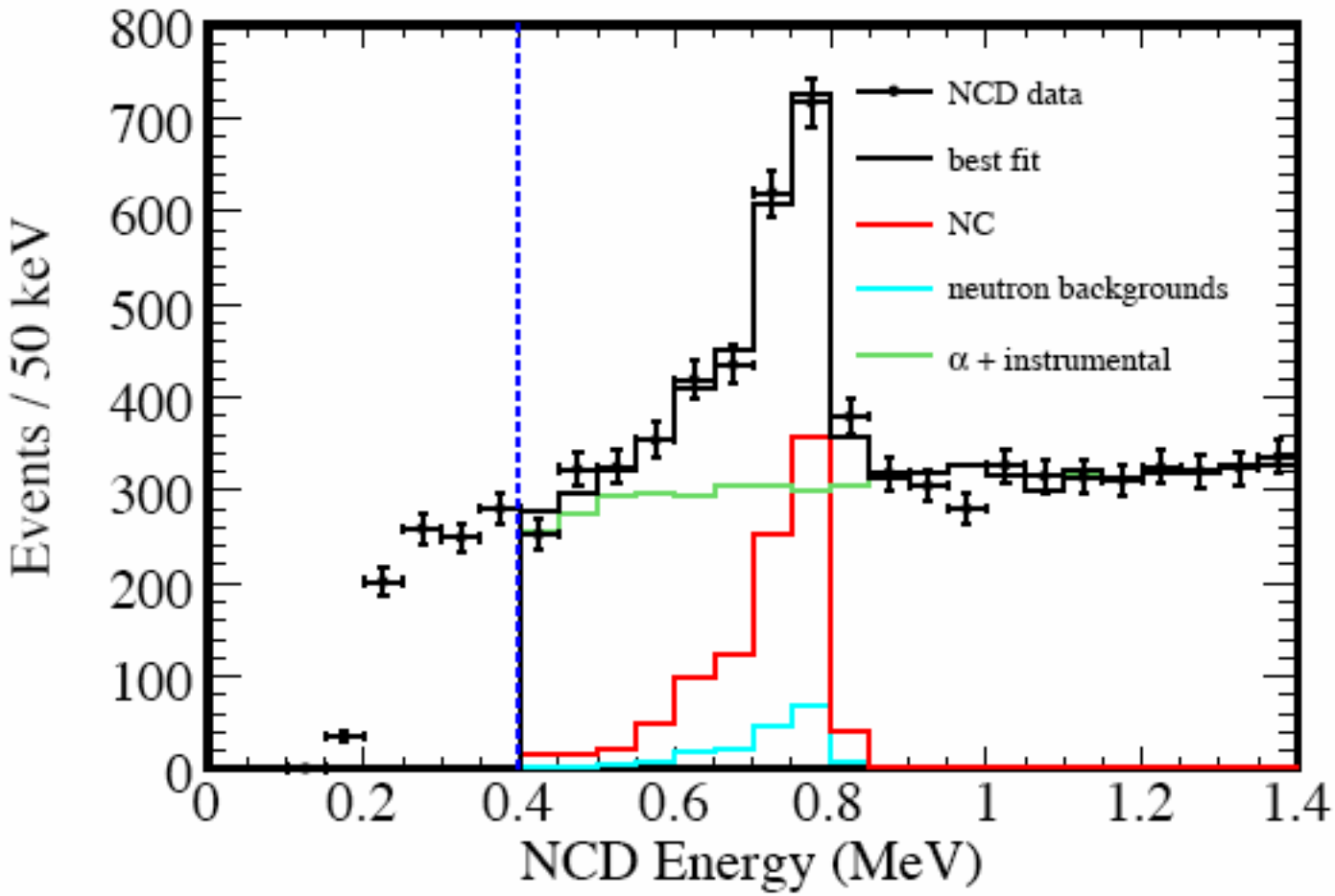
Box open on 2nd of May 2008

- Results presented are as found, except…
- Difference between uncertainties from 3 signal-extraction codes: “Pilot errors” corrected, no change in central values, uncertainties agree.
- An incorrect algorithm in fitting the peak of the ES posterior distributions replaced

Backgrounds

Source	PMT Events (neutrons)	NCD Events (neutrons)
D_2O Radioactivity	7.6 ± 1.2	28.7 ± 4.7
Atmospheric ν, ^{16}N	24.7 ± 4.6	13.6 ± 2.7
Other backgrounds	0.7 ± 0.1	2.3 ± 0.3
NCD Bulk PD, $^{17,18}O(\alpha,n)$	$4.6^{+2.1}_{-1.6}$	$27.6^{+12.9}_{-10.3}$
NCD hotspots	17.7 ± 1.8	64.4 ± 6.4
NCD cables	1.1 ± 1.0	8.0 ± 5.2
External-source neutrons	20.6 ± 10.4	40.9 ± 20.6
TOTAL	77^{+12}_{-10}	185^{+25}_{-22}

NCD neutrons from solar neutrino interactions

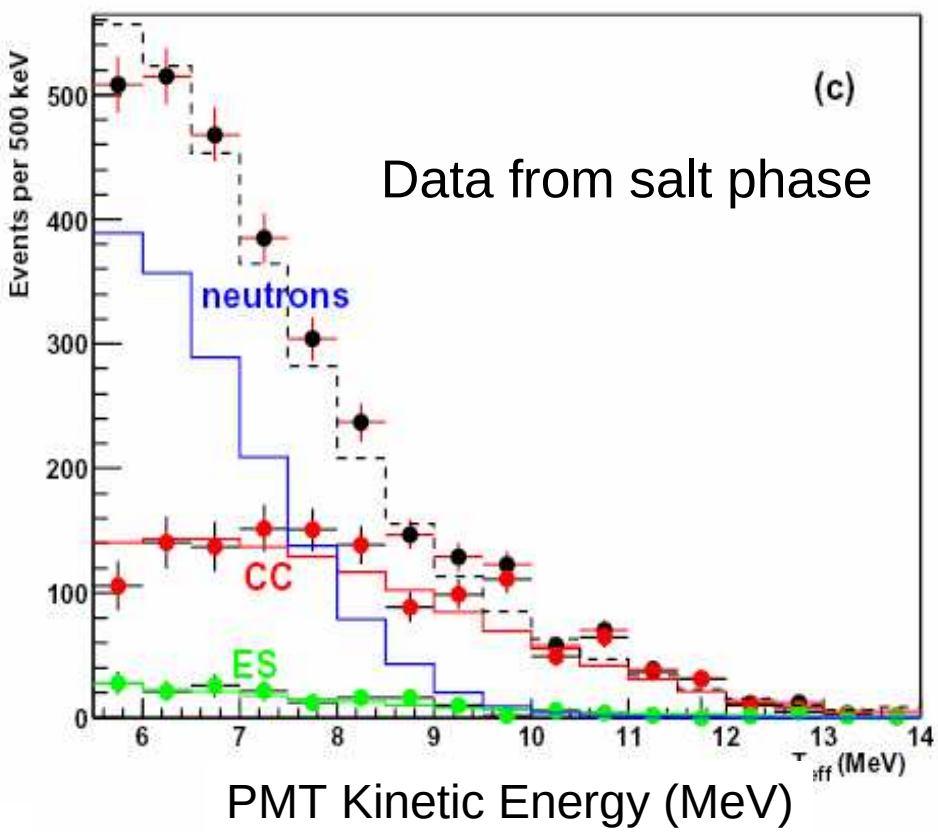


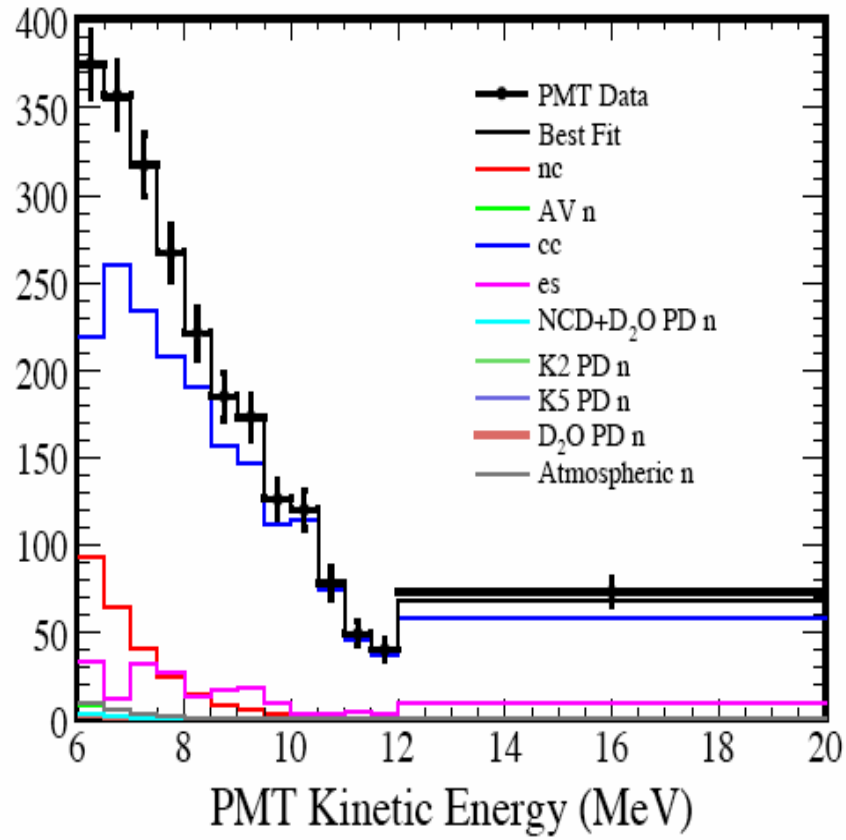
NC Signal:
983 ± 77

Neutron background:
185 ± 25

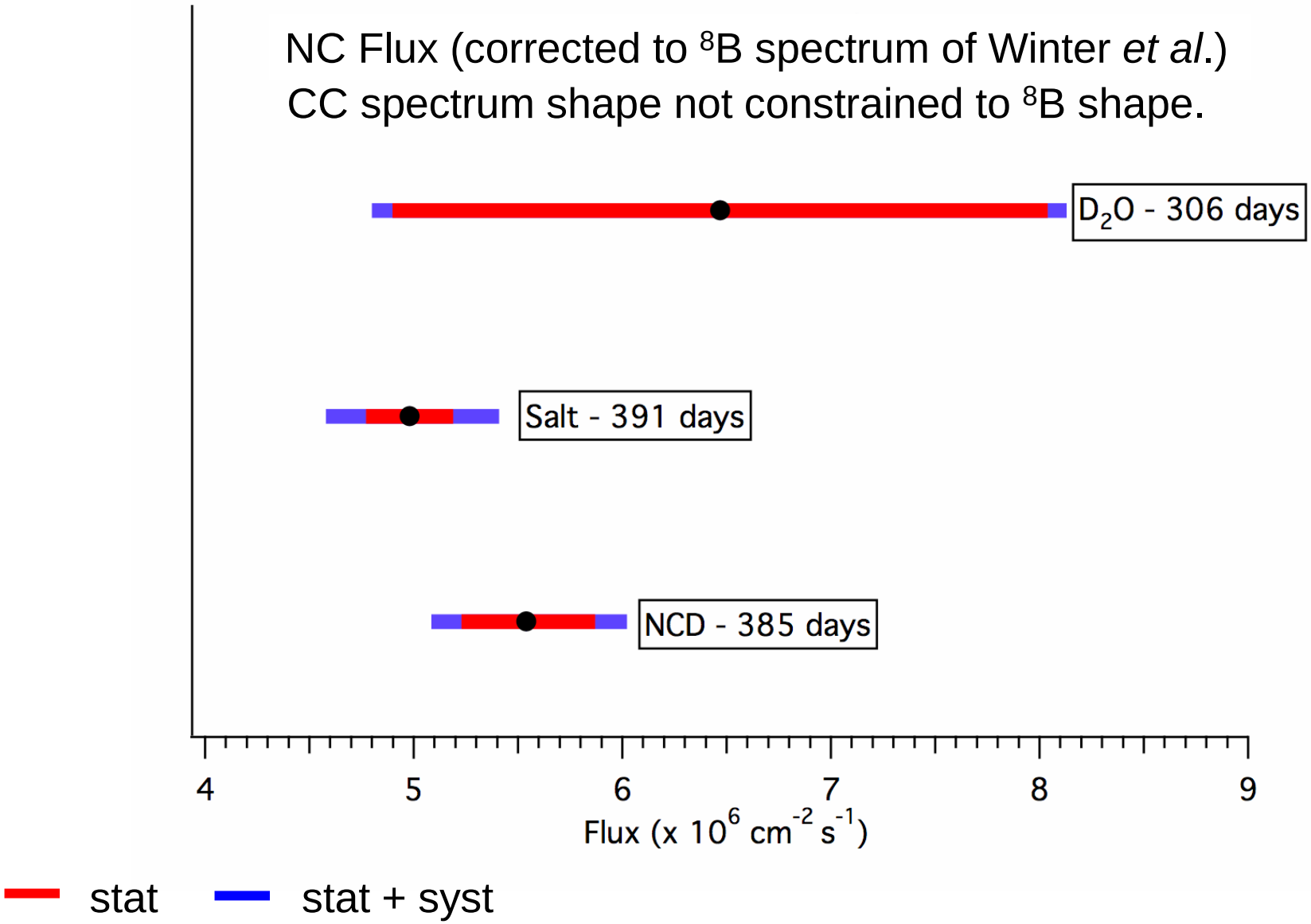
Alphas and Instrumentals:
6126 ± 250
(0.4 to 1.4 MeV)

PMT Distributions - $\cos(\theta_{sun})$, Energy

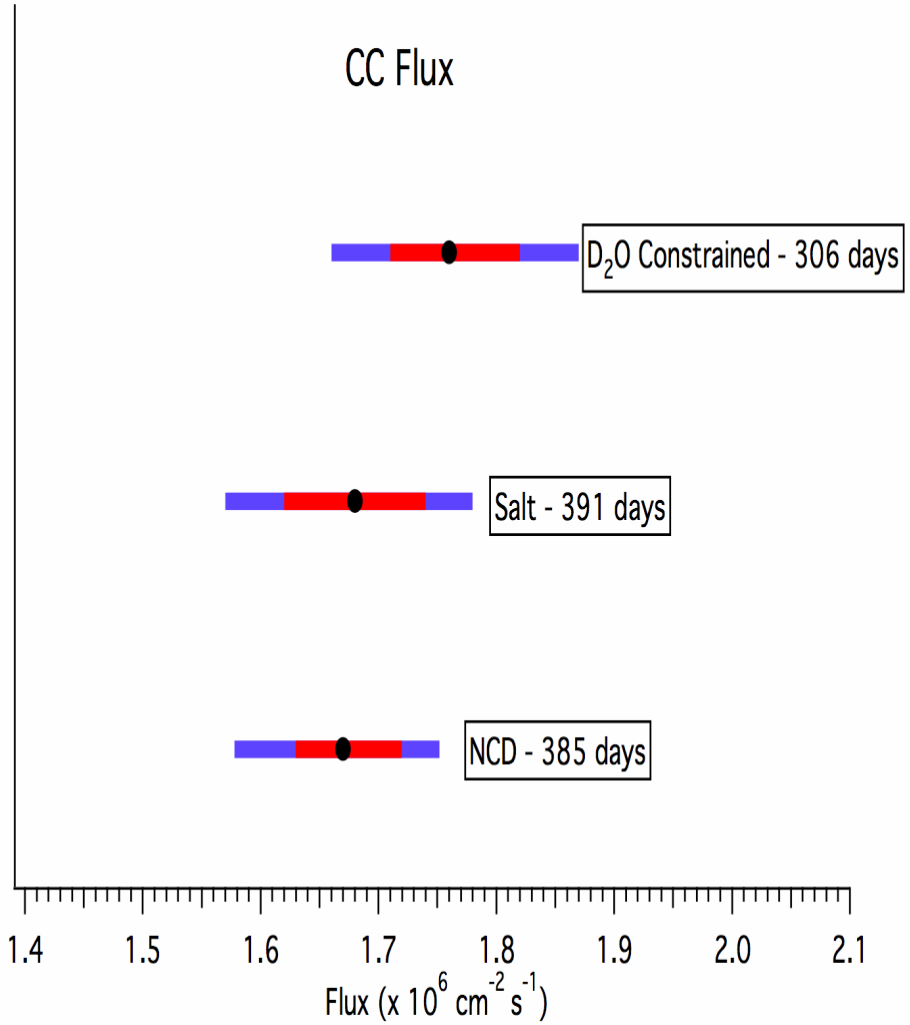


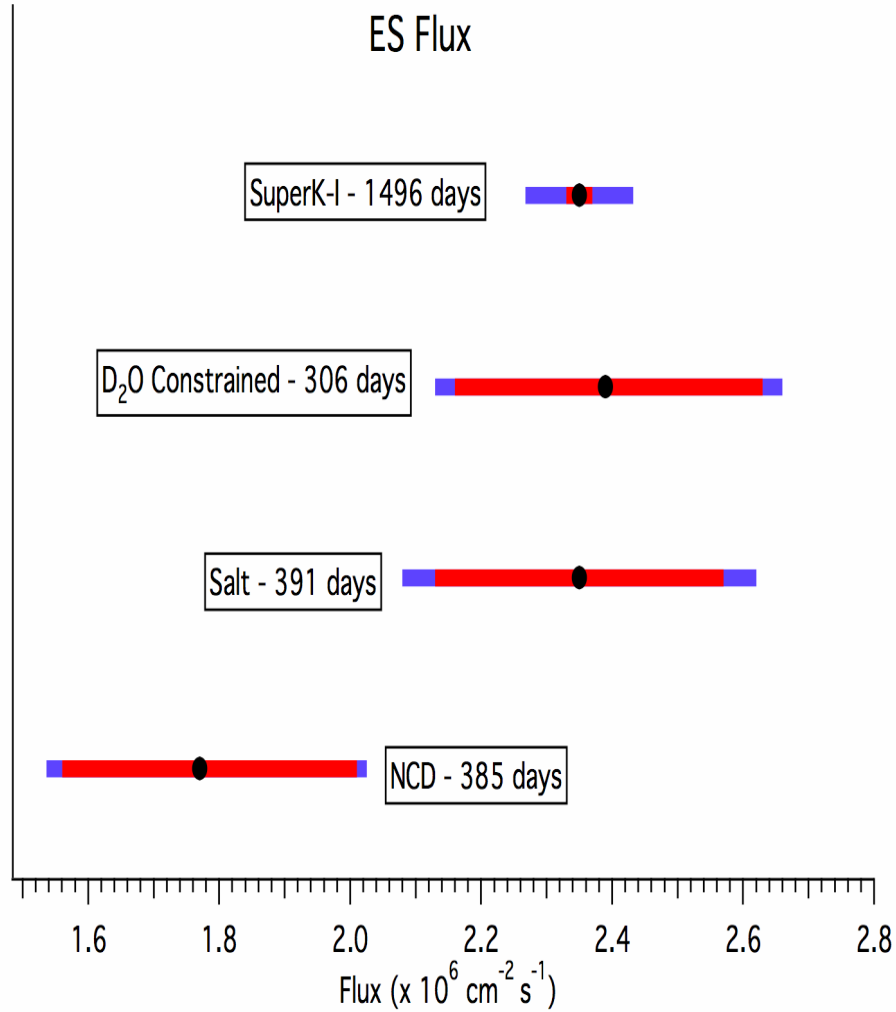


SNO NC Flux: 3 Phases



SNO CC and ES Fluxes: 3 Phases



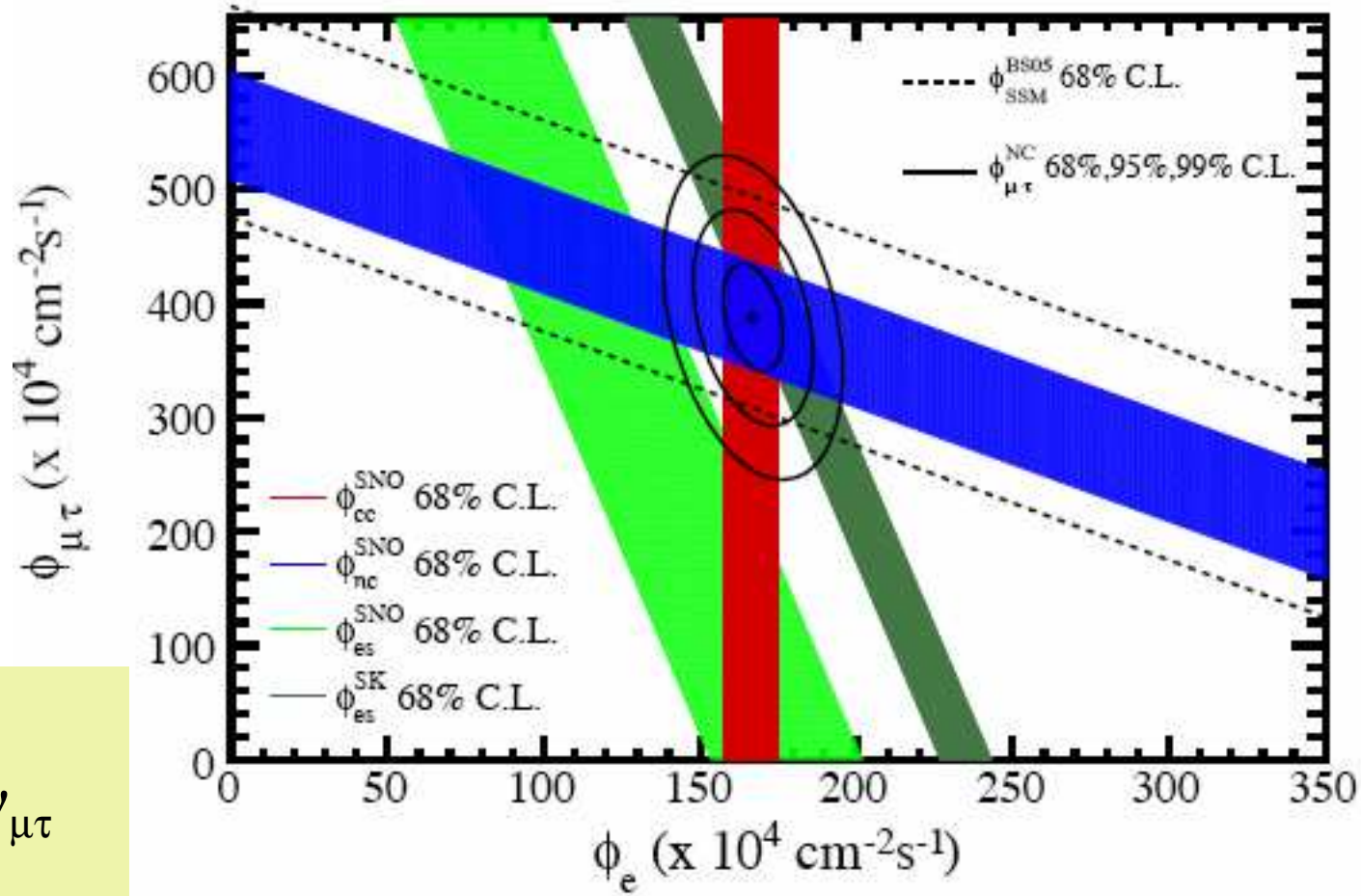


Results from SNO NCD Phase & Super-K

Fluxes

(10^6 cm^{-2} s^{-1})

ν_e:	1.67(9)
ν_{ES}:	1.77(26)
ν_{total}:	5.54(48)
ν_{SSM}:	5.69(91)

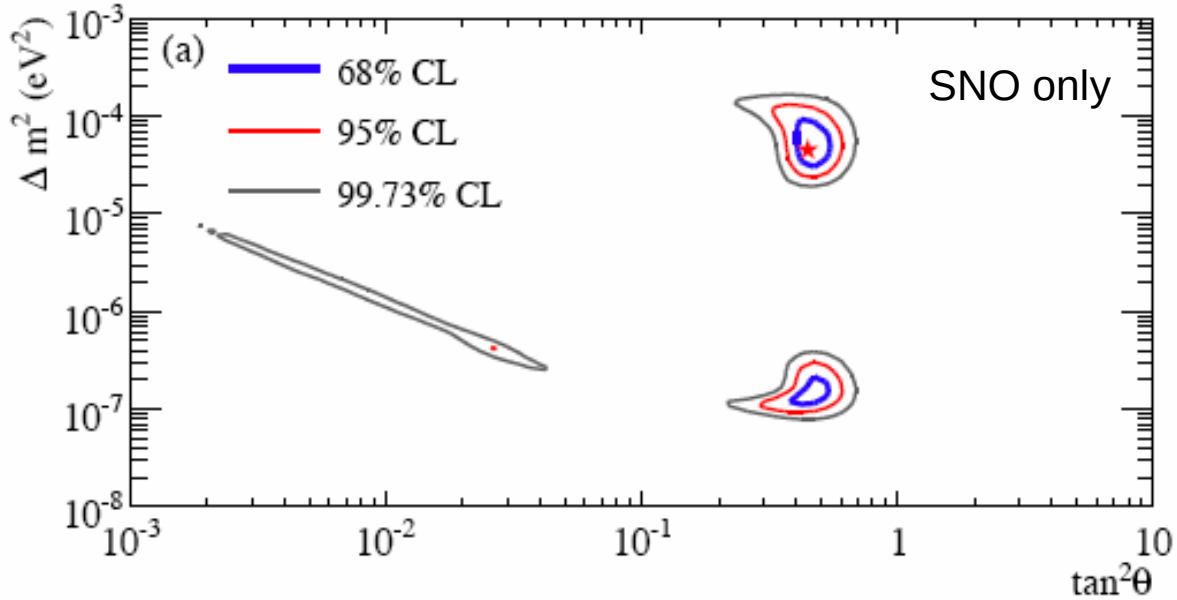


$$\phi_{CC} = \nu_e$$
$$\phi_{ES} = \nu_e + 0.154\nu_{\mu\tau}$$
$$\phi_{NC} = \nu_e + \nu_{\mu\tau}$$

ϕ_{SSM} = 5.69(1±0.16) x 10^6 cm^{-2} s^{-1} (BSB05-OP: Bahcall, Serenelli, Basu Ap. J. 621, L85, 2005).
Super-K: PRD 73, 112001, 2006

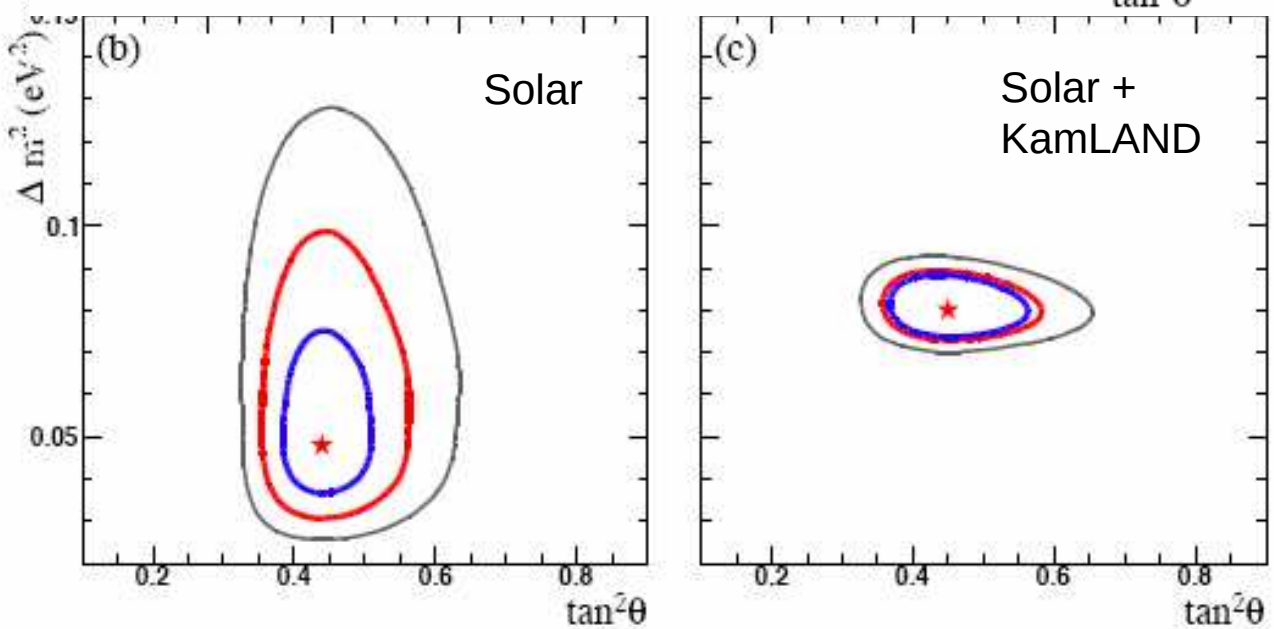
2-Neutrino Oscillation Contours

$$\frac{\phi_{CC}^{SNO}}{\phi_{NC}^{SNO}} = 0.301 \pm 0.033 \text{ (total)}.$$



Cl-Ar
Super-K
SAGE
Gallex
GNO
SNO
Borexino

766 t-y KamLAND



Summary

- Good agreement between NCD and previous SNO phase results and with theory
- Minimal NC and CC correlation
- New precision on θ

Solar + KamLAND fit results

$\sin^2\theta_{12} \sim \Phi_{CC}/\Phi_{NC} = 0.301 \pm 0.033$ (*tot*)

$\Delta m^2 = 7.94^{+0.42}_{-0.26} \times 10^{-5}$ eV^2 $\tan^2\theta = 0.447^{+0.047}_{-0.043}$

$\theta = 33.8^{+1.4}_{-1.3}$ degrees $\phi_{8B} = 0.873(1 \pm x)\phi_{8B(BSB05-OP)}$

2-neutrino mixing model. Marginalized 1-σ uncertainties. All SNO phases. KamLAND: PRL 94, 081801 (2005). x to be published later.

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