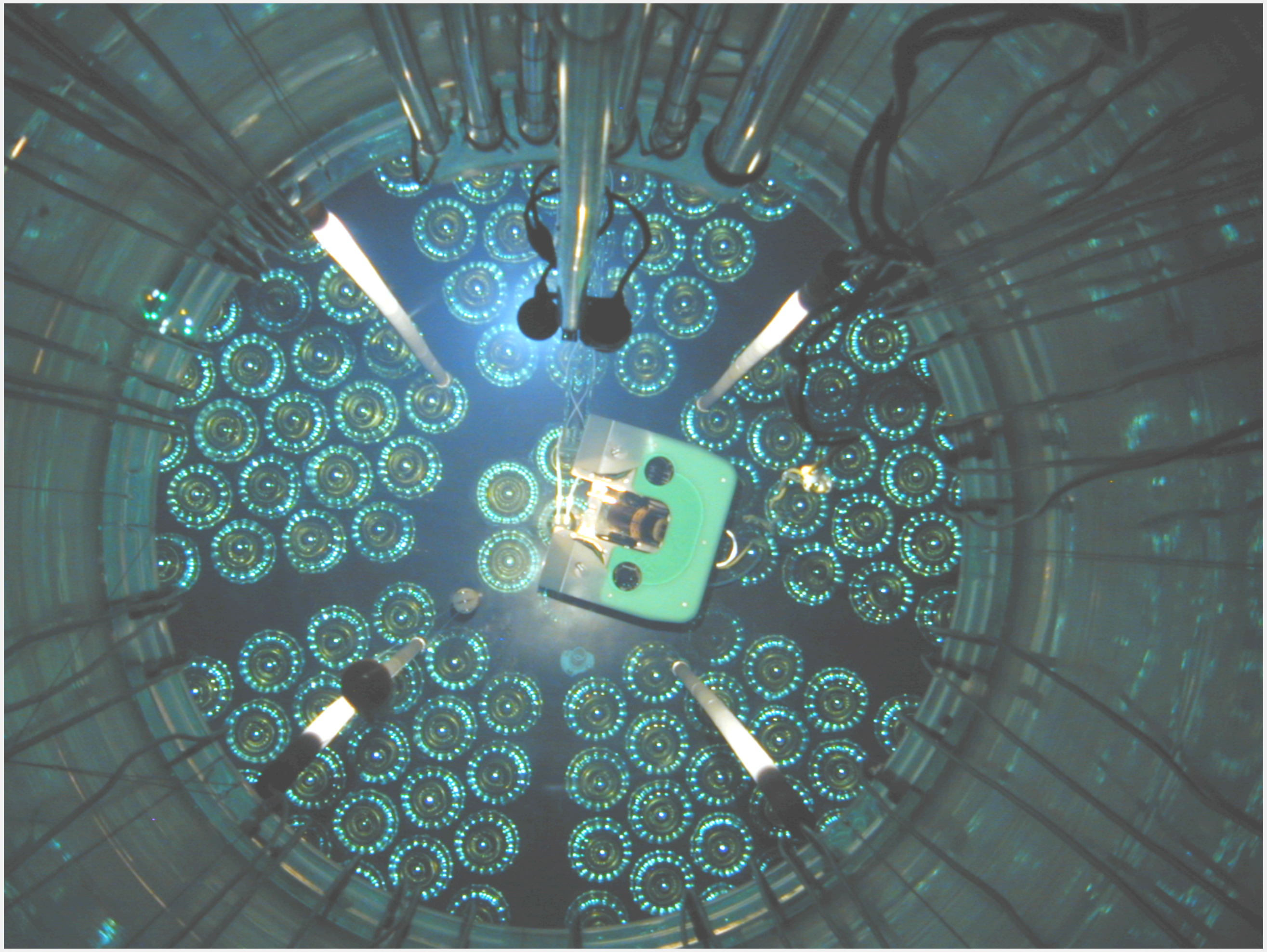
Results from the Sudbury Neutrino Observatory (SNO) Phase III

Gersende Prior (LBNL)

For the SNO Collaboration

NOW 2008,
Conca Specchiulla,
September 8th 2008



BERKELEY LAB

The Sudbury Neutrino Observatory

6000 m.w.e. overburden

1000 tons D_2O

12 m Diameter Acrylic Vessel

1700 tons Inner Shield H_2O

Support Structure 9500 PMTs, 60% coverage

5300 tons Outer Shield H_2O

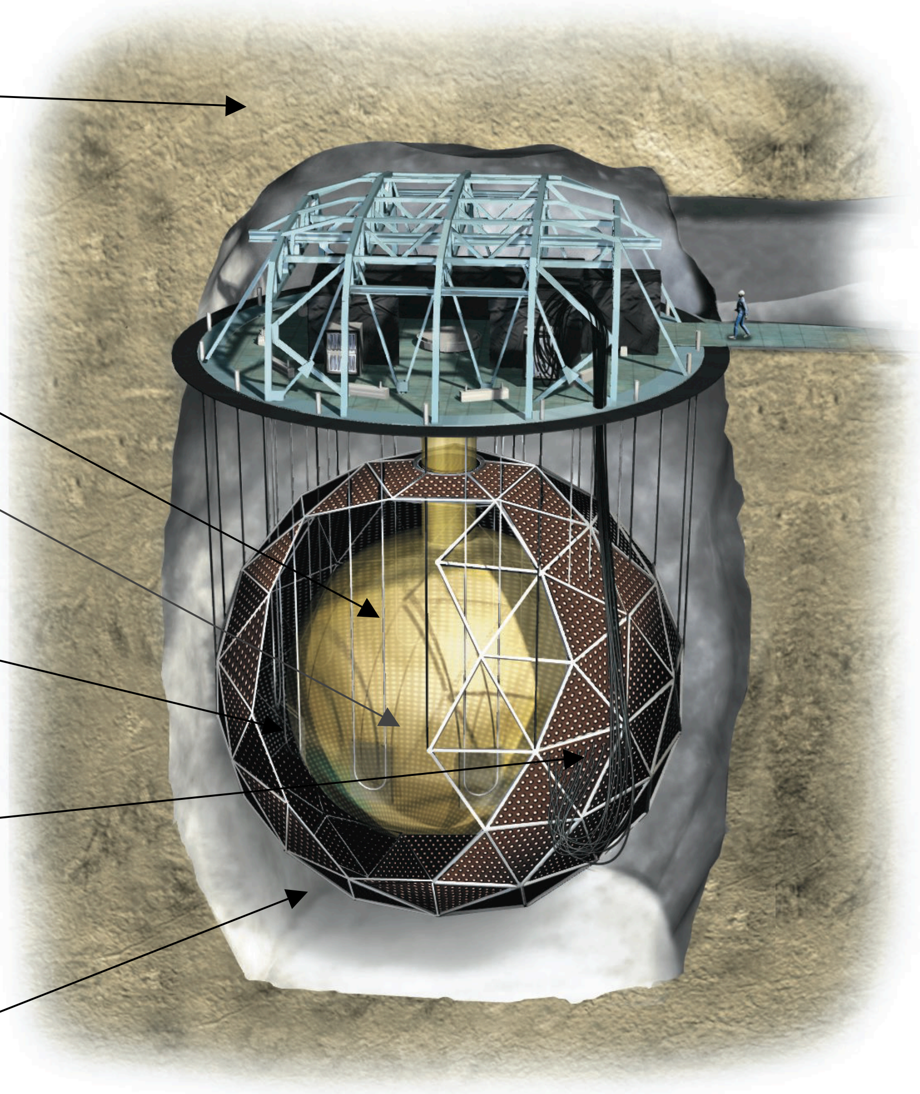
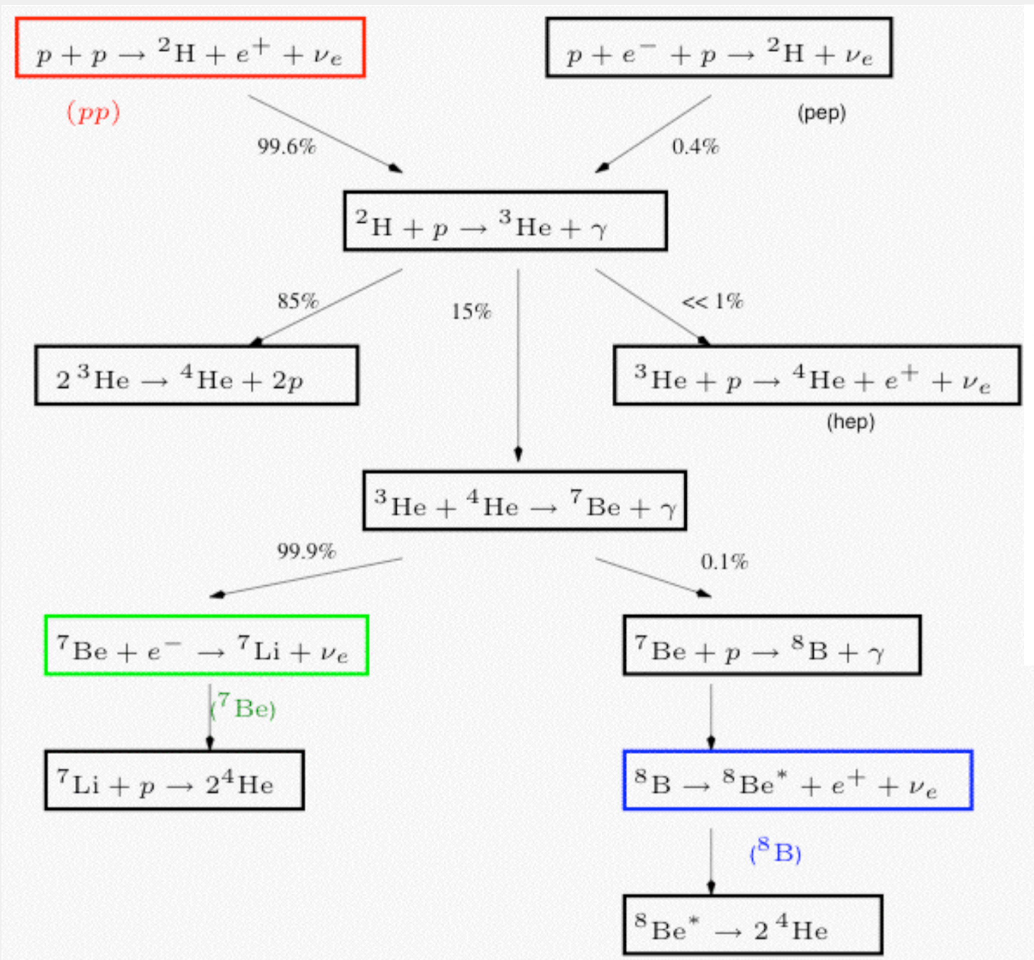


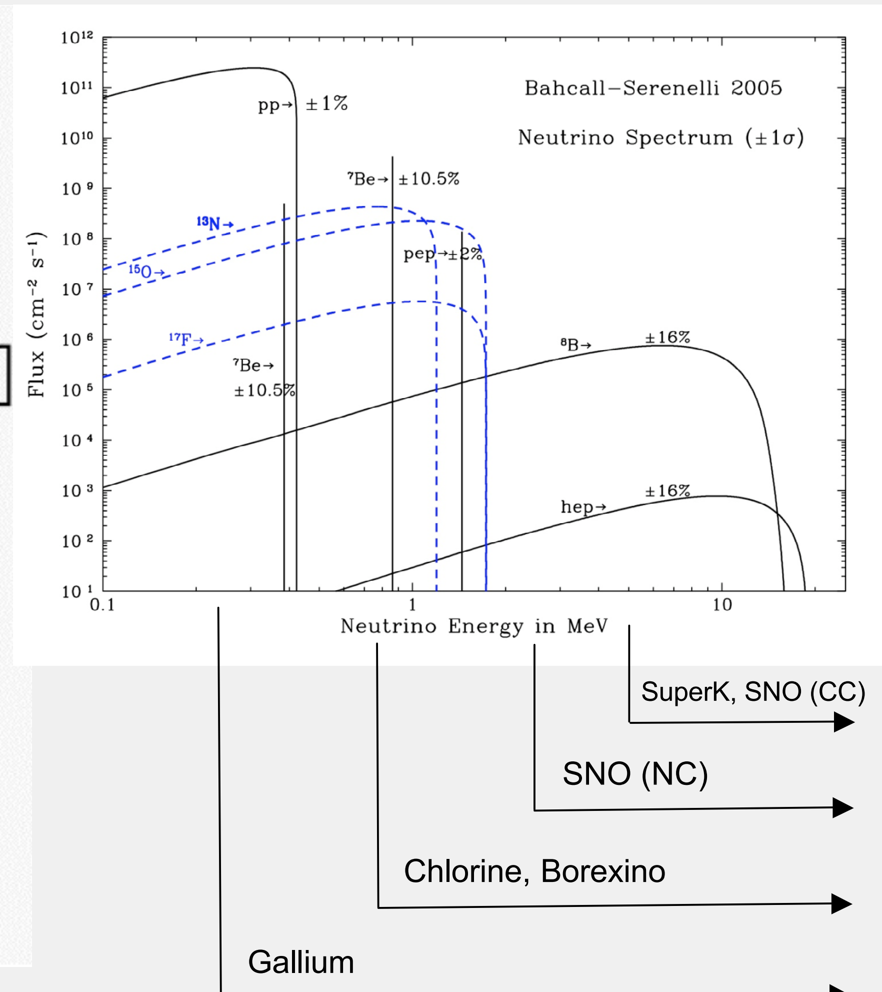
Image courtesy National Geographic

Solar neutrinos

The pp chain reaction:



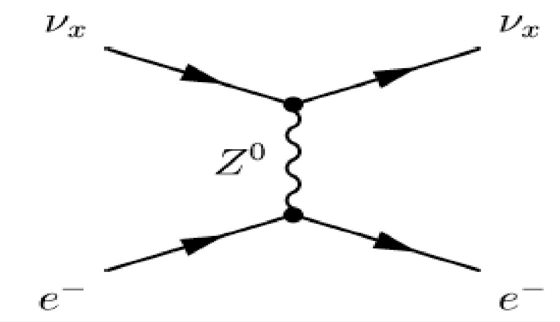
Standard Solar Model (SSM):



SNO interactions

Elastic-scattering (ES):

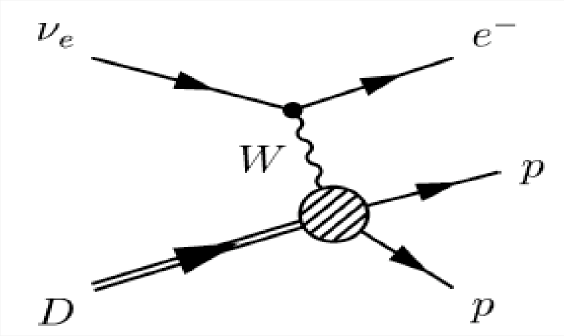
$$\nu_x + e^- \rightarrow \nu_x + e^-$$



ν_e mainly
strong directional sensitivity

Charged-currents (CC):

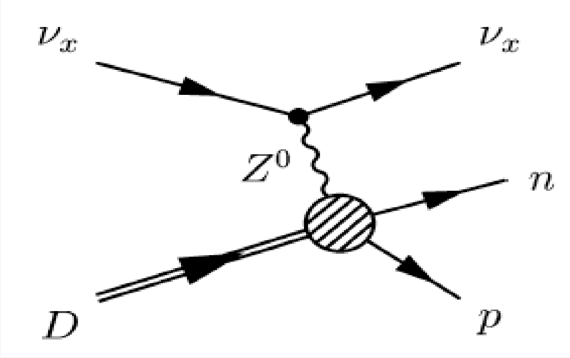
$$\nu_e + d \rightarrow p + p + e^-$$



ν_e only
E_e well correlated with E_ν

Neutral-currents (NC):

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



All flavors equally
Total neutrino flux

The three SNO phases

D_2O phase:

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

σ = 0.0005 b
ε = 14%

Salt phase (D_2O + 2 tons of NaCl):

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

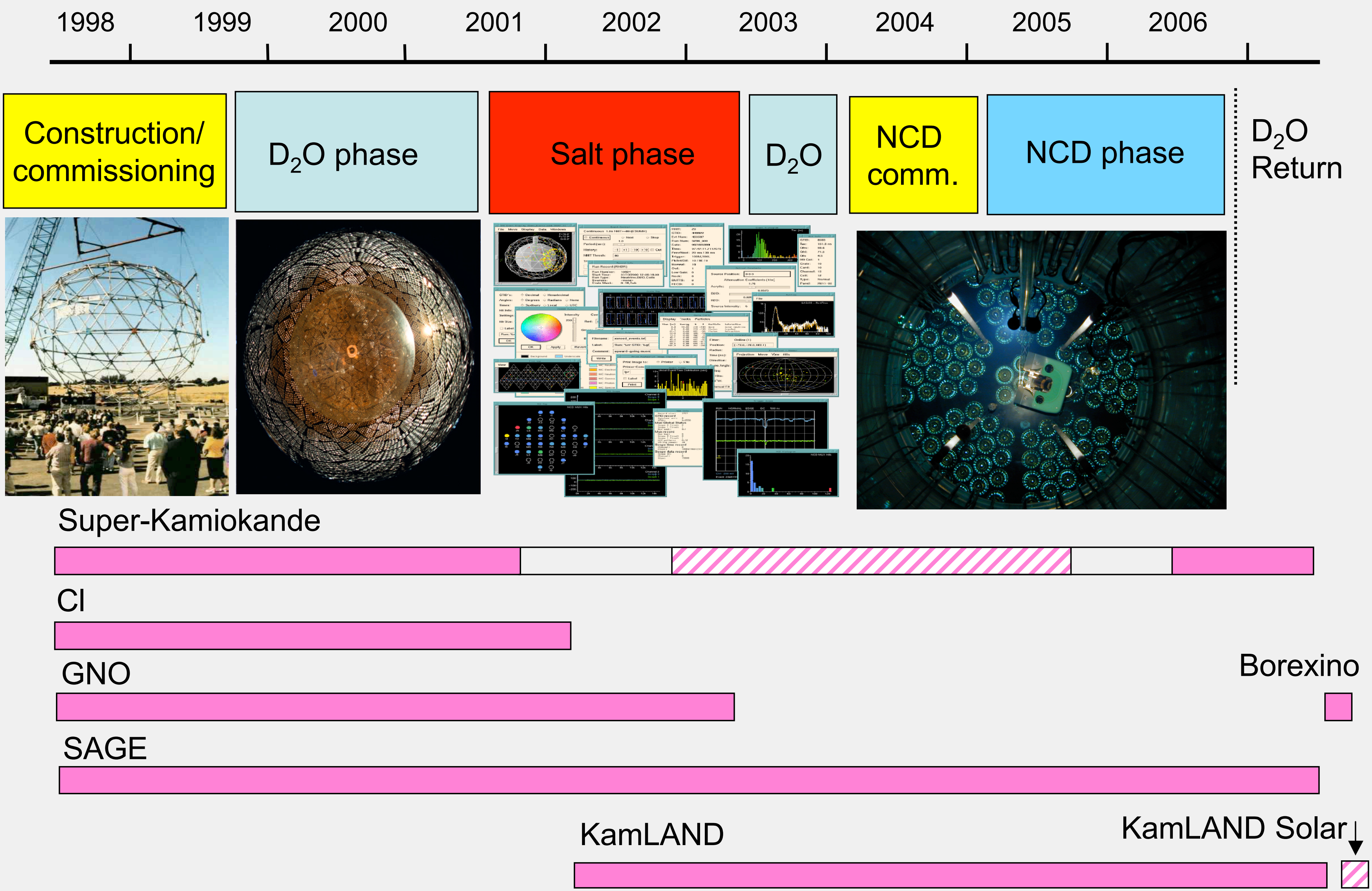
σ = 44 b
ε = 41%

NCD phase (^{3}He proportional counters):

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

σ = 5330 b
ε = 21%

SNO Timeline



Salt phase results

Fluxes and ratio ($10^6\ cm^{-2}\ s^{-1}$):

$$\phi_{CC} = 1.68\ ^{+0.06}_{-0.06}(\text{stat.})^{+0.08}_{-0.09}(\text{syst.})$$

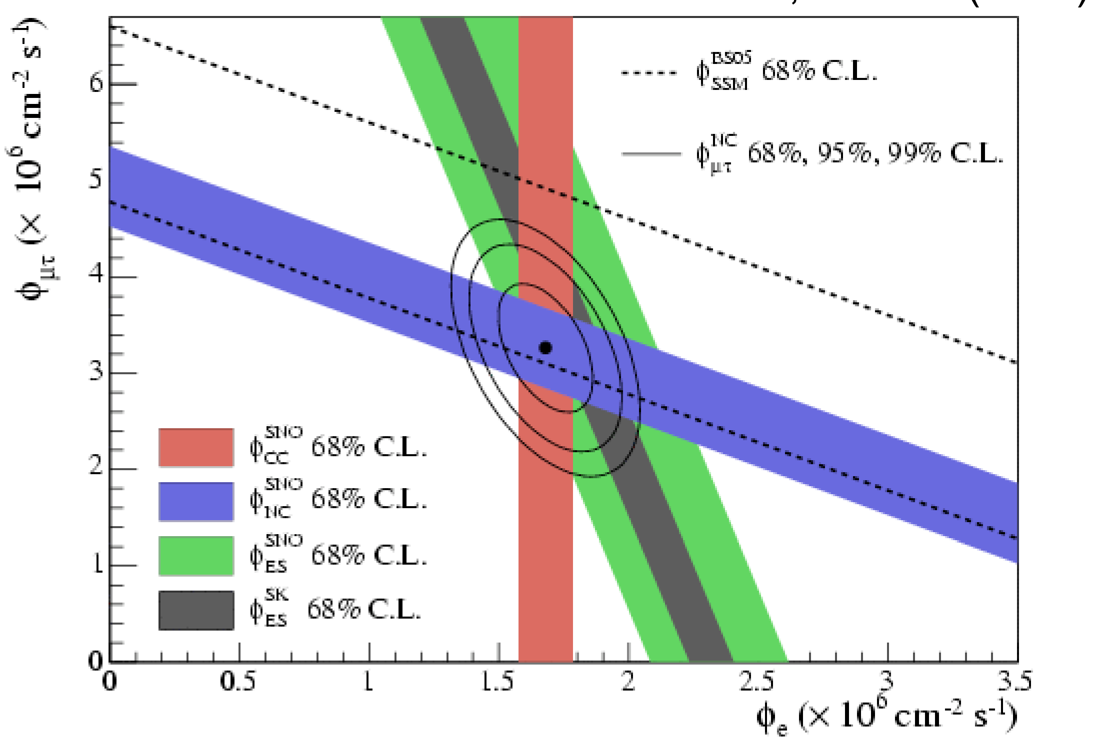
$$\phi_{NC} = 4.94\ ^{+0.21}_{-0.21}(\text{stat.})^{+0.38}_{-0.34}(\text{syst.})$$

$$\phi_{ES} = 2.35\ ^{+0.22}_{-0.22}(\text{stat.})^{+0.15}_{-0.15}(\text{syst.})$$

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.340 \pm 0.023(\text{stat.})^{+0.029}_{-0.031}(\text{syst.})$$

($\phi_{CC}/\phi_{NC} \sim \sin^2\theta_{12}$)

PRC **72**, 055502 (2005)



Mass:

$$\Delta m^2 = 0.8\ ^{+0.6}_{-0.4} \times 10^{-5}\ eV^2$$

Mixing angle:

$$\theta = 33.9\ ^{+2.4}_{-2.2}\ \text{degrees}$$

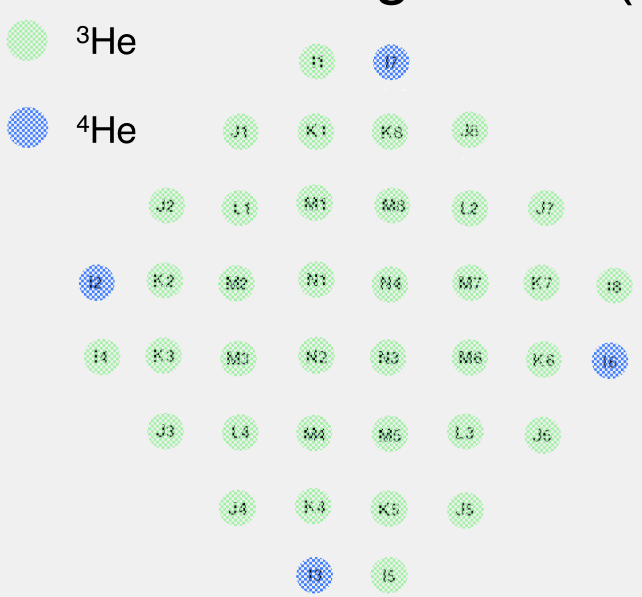
Neutral Current Detectors (NCD)

Why:

- Different systematics compared to previous phases
- Better CC flux measurement
- Correlation between CC and NC signals greatly reduced

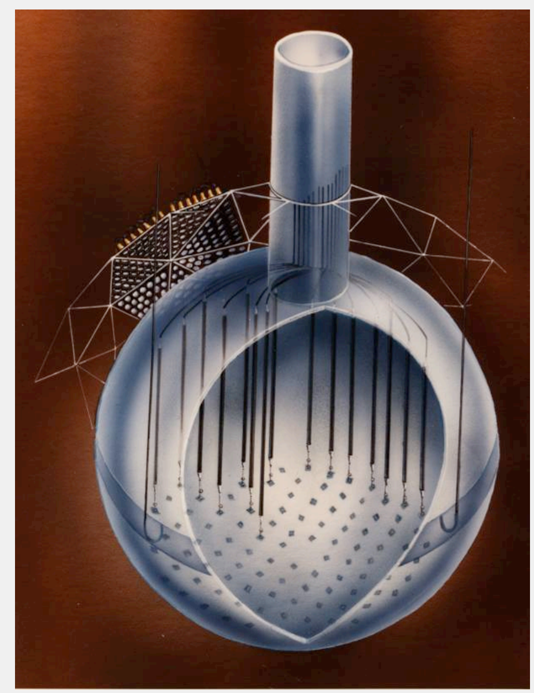
Challenges:

- Low signal rate: ~1000 neutrons/year detected
- Ultra-low background materials needed
- Some light loss (~10%) due to array

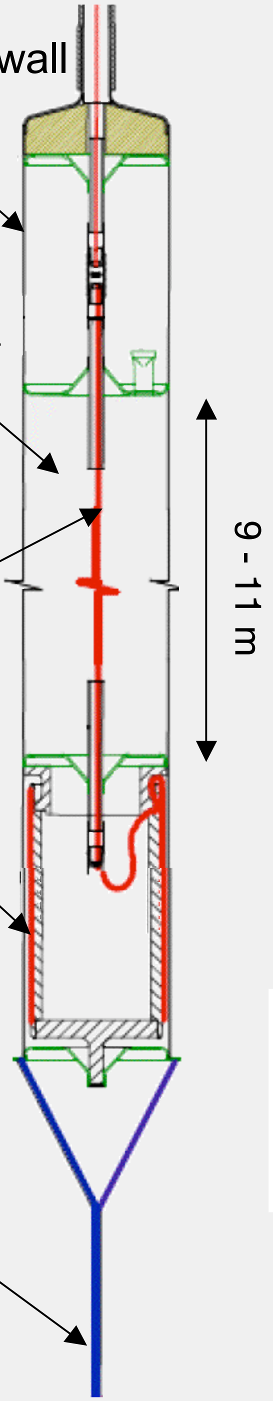


36 ^{3}He strings and 4 ^{4}He strings deployed on a 1x1 m grid.

Total length 398 m.



NCD string

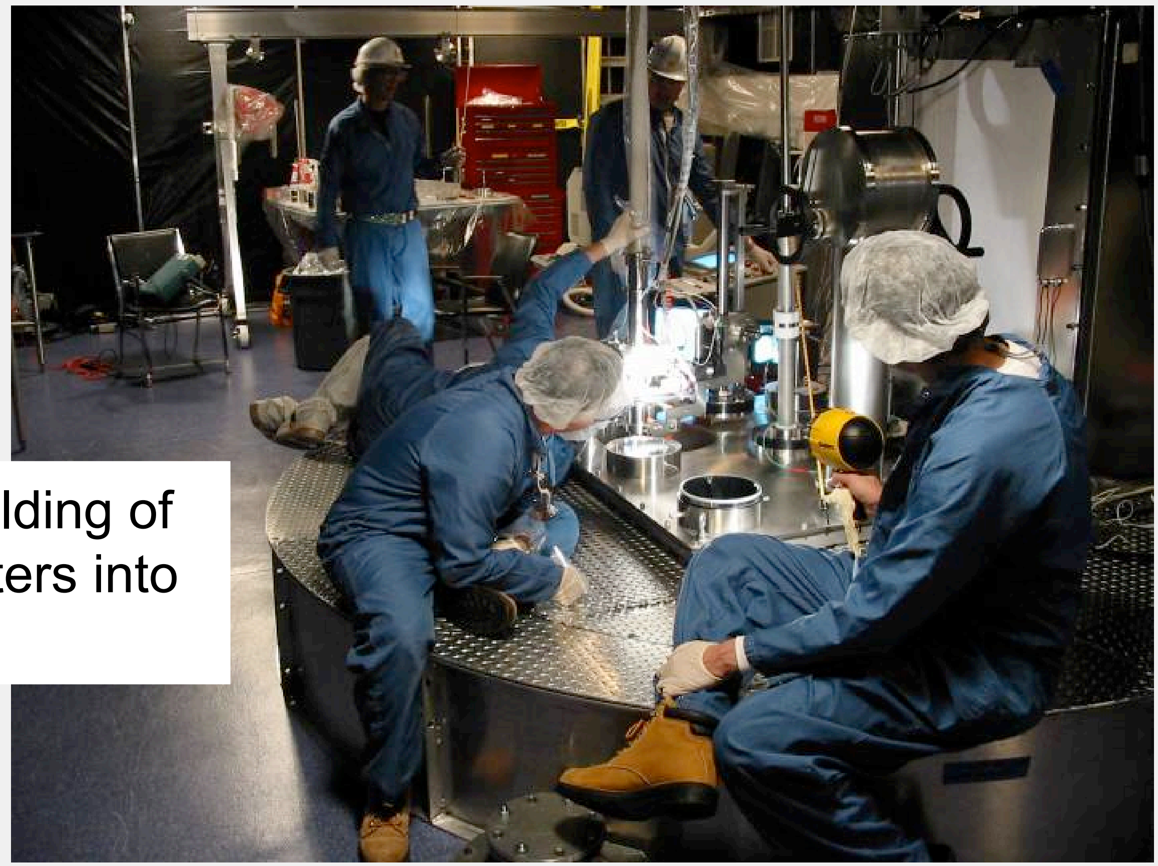


High purity CVD nickel:

$$gTh/gNCD = 3.43\,^{+1.49}_{-2.11} \times 10^{-12}$$

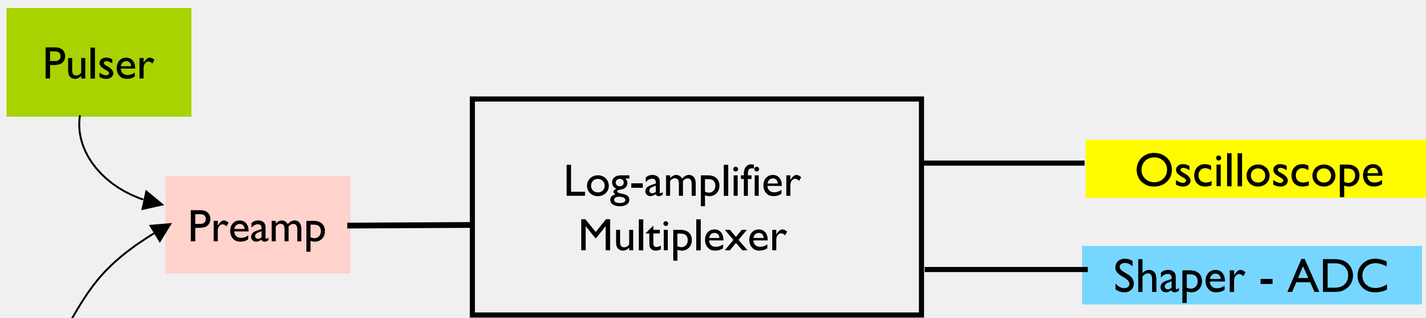
$$gU/gNCD = 1.81\,^{+0.80}_{-1.12} \times 10^{-12}$$

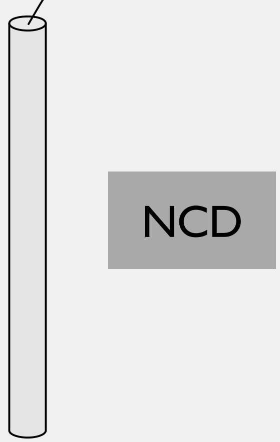
(100 times purer than previous counters)



Laser welding of the counters into strings

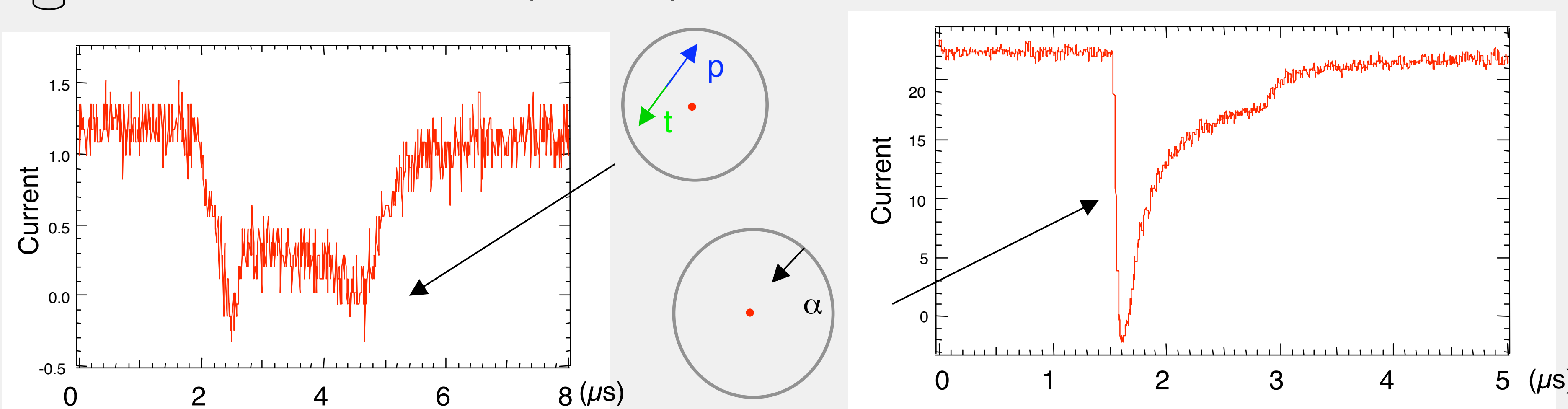
NCD electronics and signal



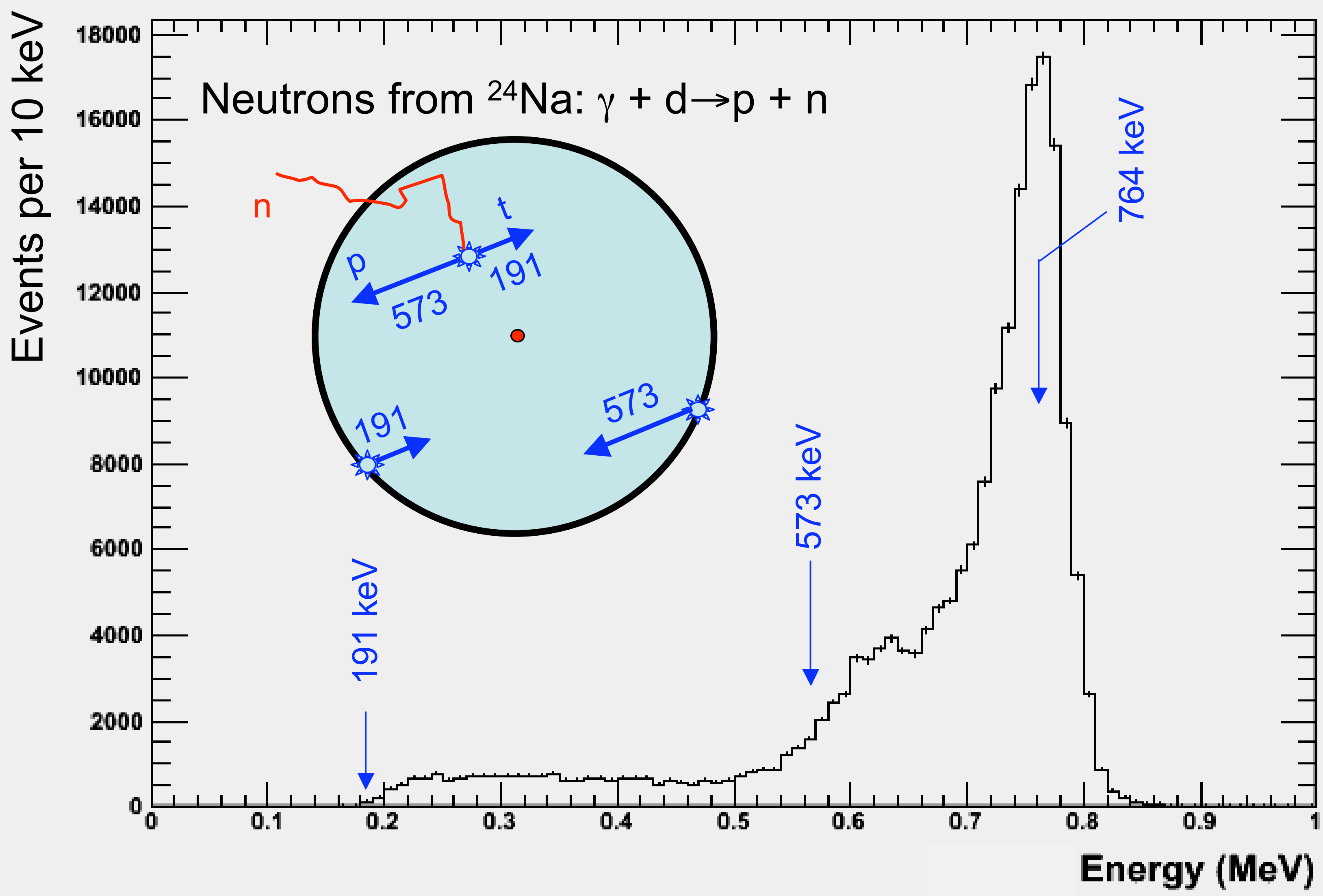


Oscilloscope:
Digitize the pulse, trigger on amplitude, slow readout (^{8}B)

Shaper:
Energy information only, trigger on integral charge, fast readout (^{8}B, SN)

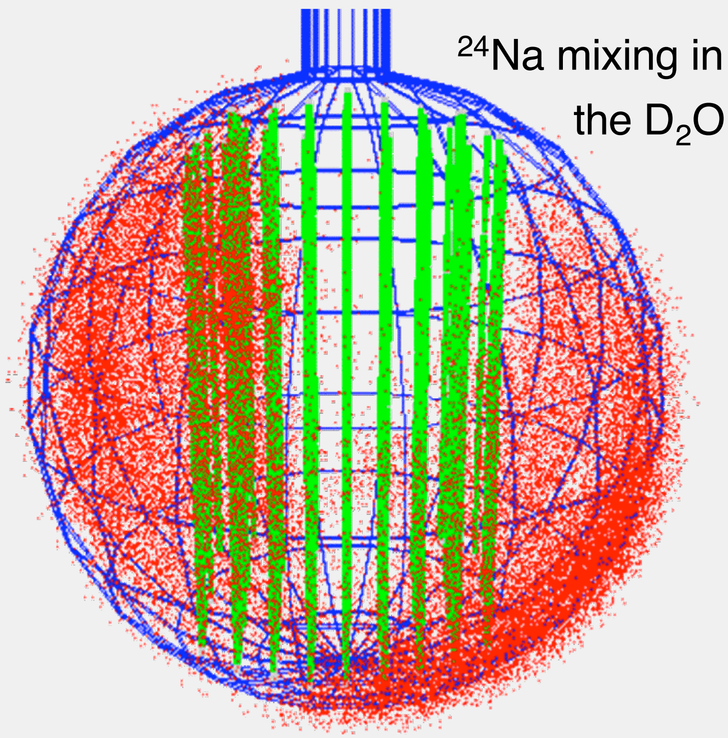


Energy Spectrum from $^3He(n,p)t$



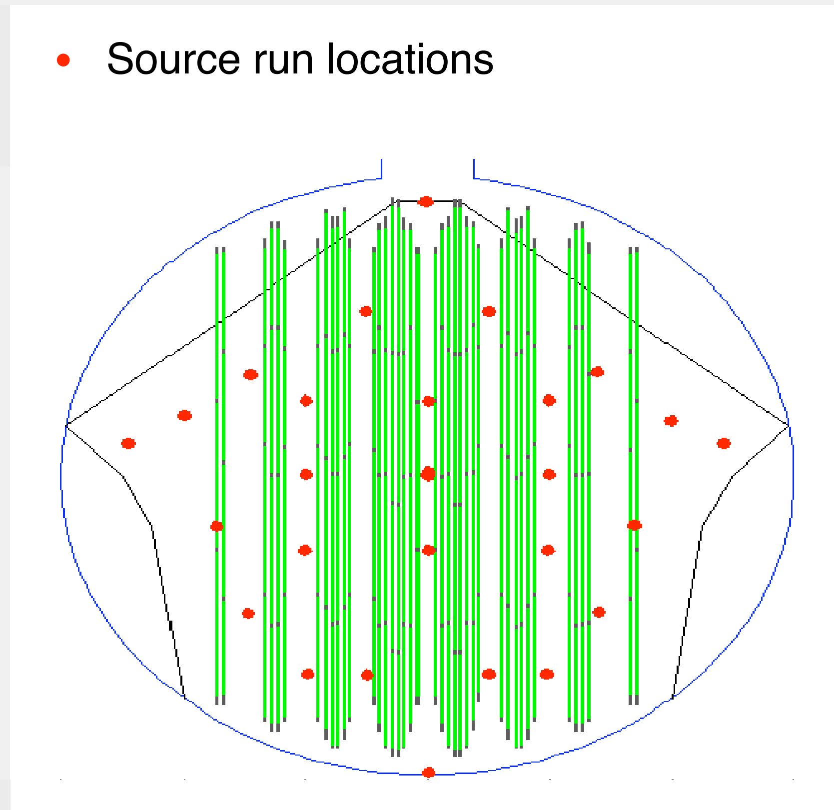
Neutron capture efficiency

1- ^{24}Na method: mimic the signal with mixed ^{24}Na which generates neutrons by: $\gamma + d \rightarrow n + p$.



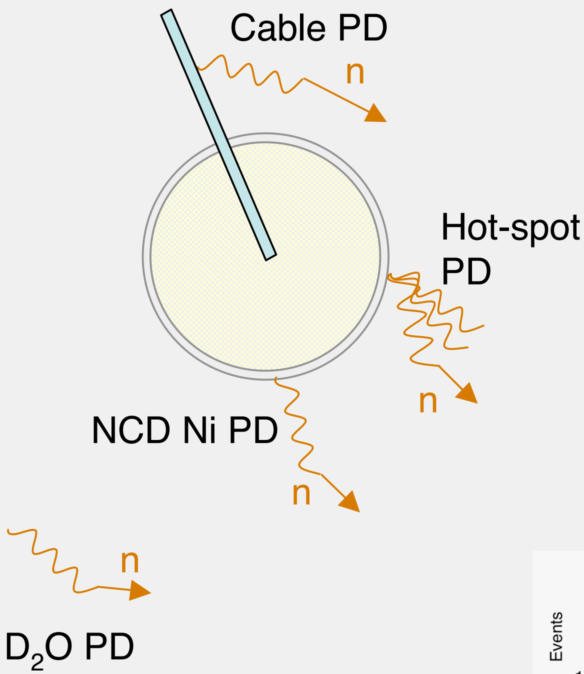
$\varepsilon_n = 0.211 \pm 0.007$

2- Monte Carlo method: calibrate the Monte Carlo with point AmBe and ^{252}Cf sources.



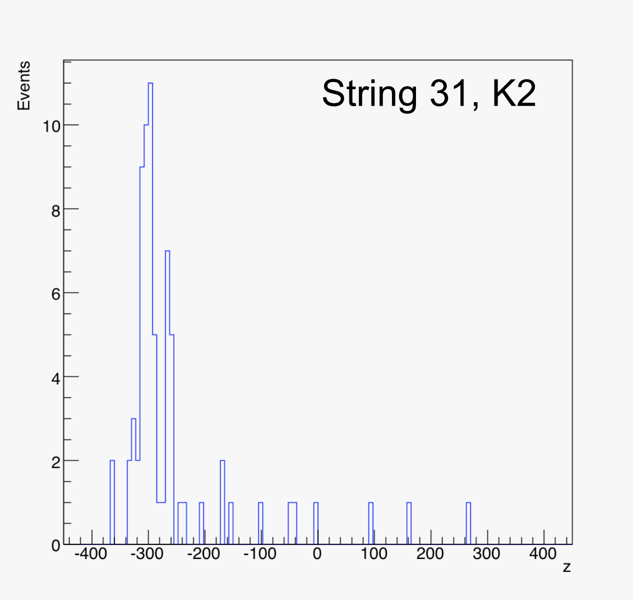
$\varepsilon_n = 0.210 \pm 0.003$

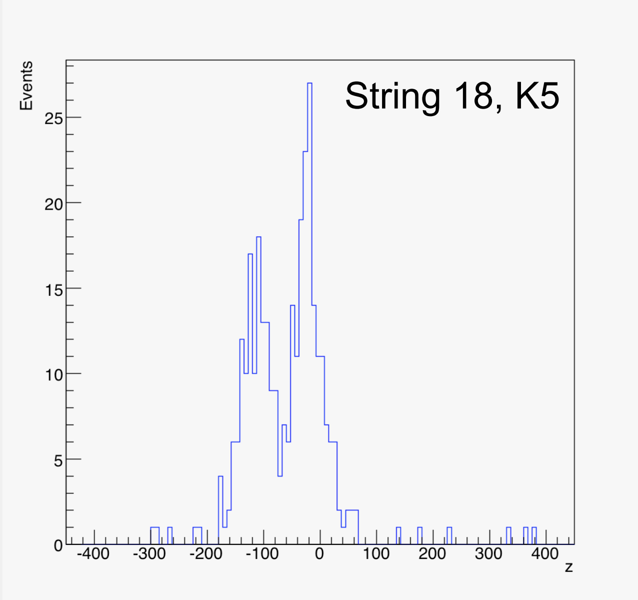
Neutron background



(PD = photodisintegration)

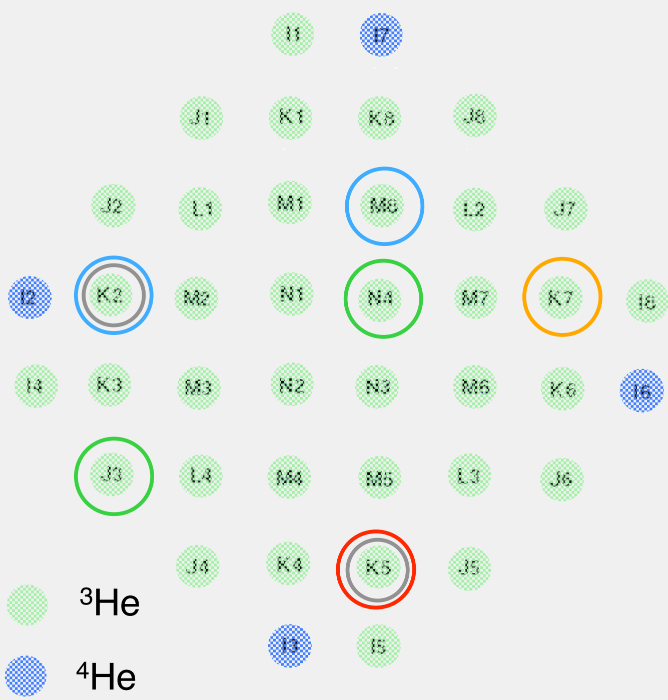
Source	PMT Events	NCD Events
D_2O photodisintegration	7.6 ± 1.2	28.7 ± 4.7
NCD bulk/^{17}O,^{18}O	$4.6^{+2.1}_{-1.6}$	$27.6^{+12.9}_{-10.3}$
Atmospheric ν/^{16}N	24.7 ± 4.6	13.6 ± 2.7
Other backgrounds †	0.7 ± 0.1	2.3 ± 0.3
NCD "hotspots"	17.7 ± 1.8	64.4 ± 6.4
NCD cables	1.1 ± 1.0	8.0 ± 5.2
Total internal neutron background	$56.4^{+5.6}_{-5.4}$	$144.6^{+13.8}_{-14.8}$
External-source neutrons	20.6 ± 10.4	40.9 ± 20.6

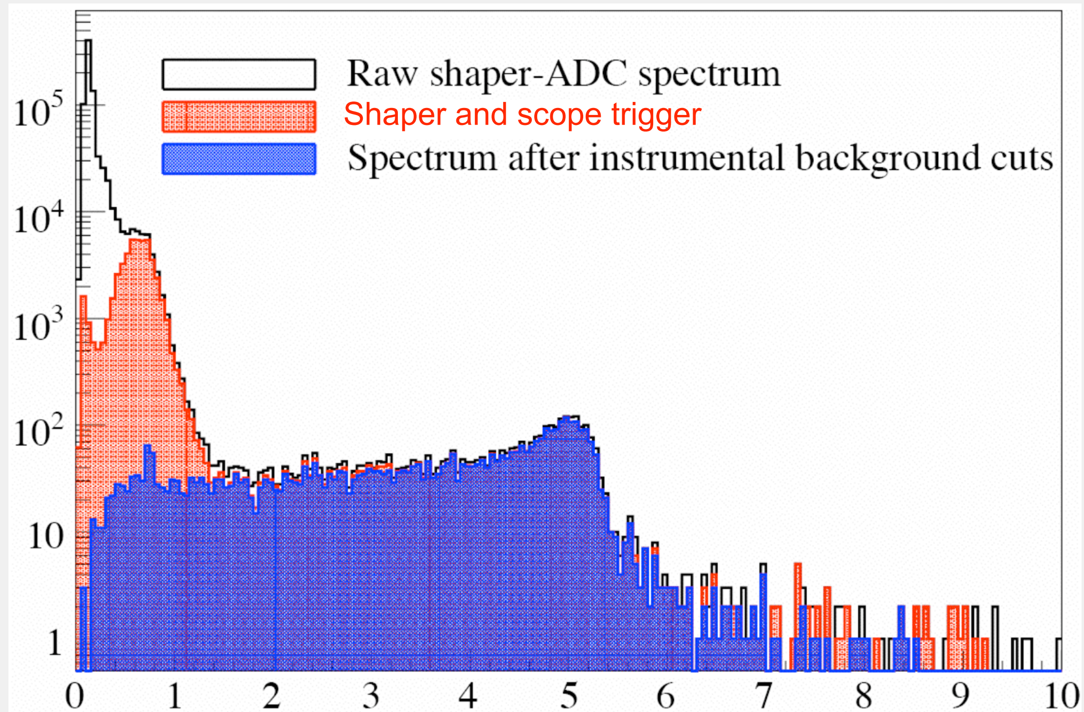




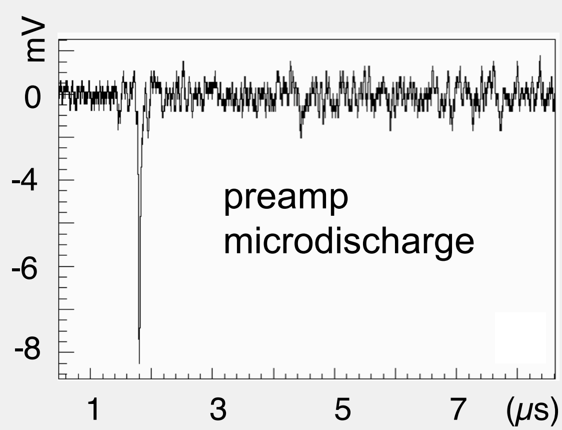
Instrumental background

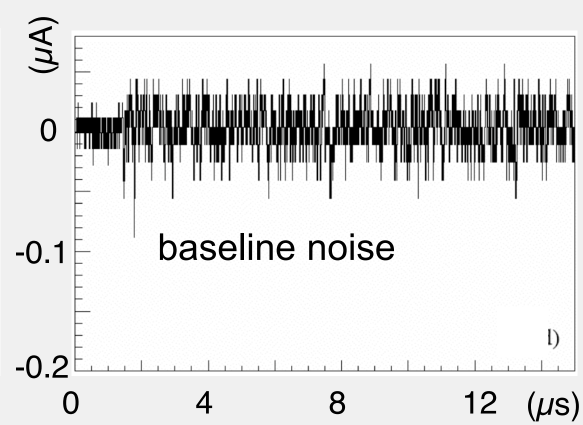
- Hot spot
- Gas leak into counter inter-space
- Electrical disconnect
- Electrical micro-discharge
- Gain instability



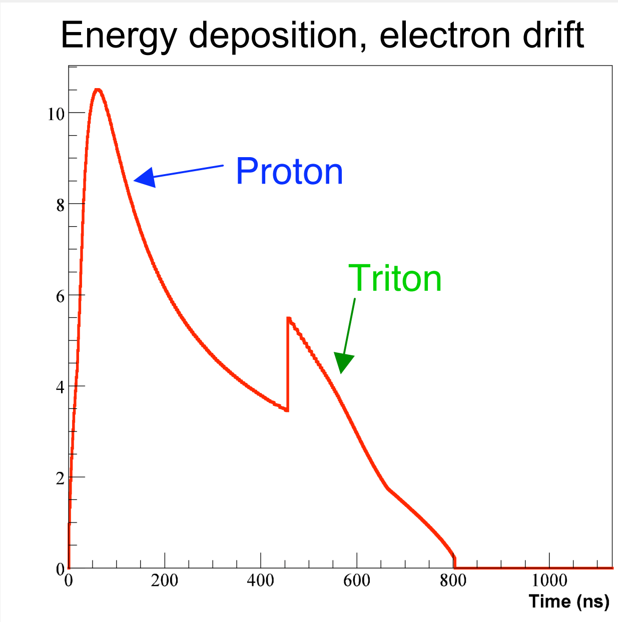


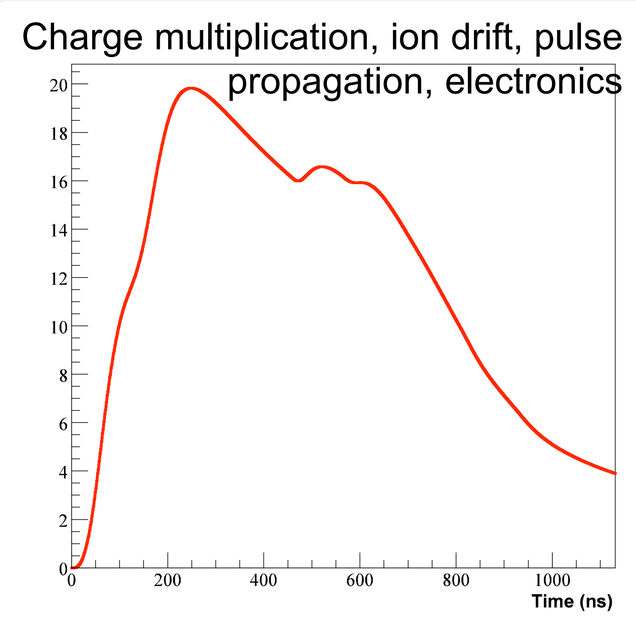
Energy spectrum before and after cuts

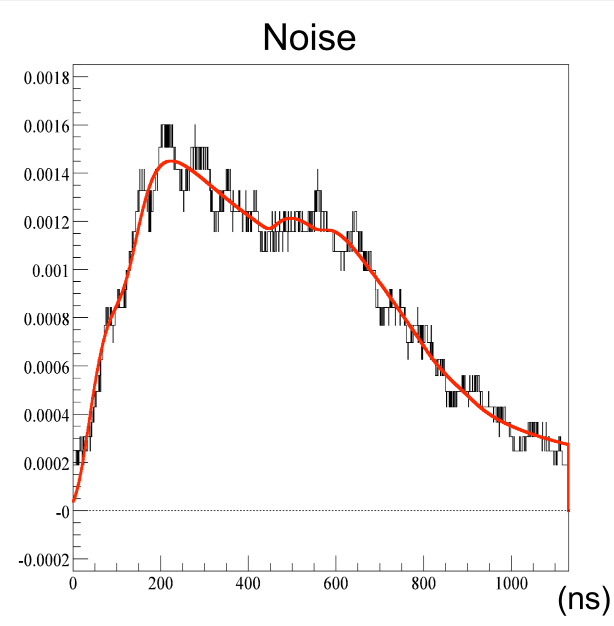


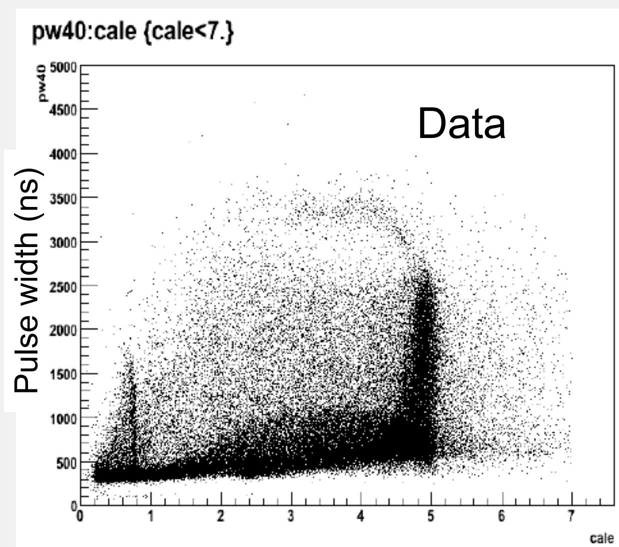


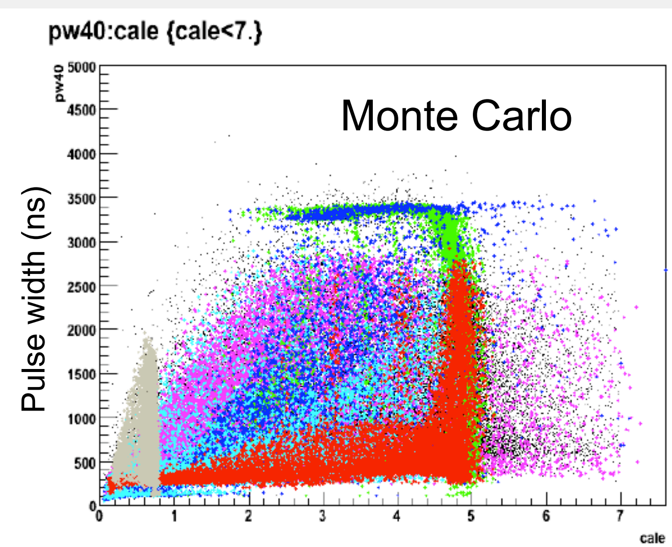
NCD pulse simulation











neutrons

alphas background:

- **wall Po alphas**
- **wire Po alphas**
- **wire U/Th alphas**
- **endcap Po alphas**
- **wall U/Th alphas**

Blindness scheme and observables

First month of neutrino data open

1- Subtract an unknown fraction of neutrino candidates

2- Add an unknown amount of muon follower neutrons

Log-likelihood fit $L = L_{PMT} + L_{NCD}$:

$$L_{PMT} = -\sum_{d=1}^{N_d} \log\left(\sum_{s=1}^{N_s} n_s f_s(\bar{x_d})\right) + \sum_{s=1}^{N_s} n_s - \frac{1}{2}\sum_{p=1}^{N_p}\left(\frac{\lambda_p - \bar{\lambda_p}}{\bar{\sigma_p}}\right)^2$$

$$L_{NCD} = -\sum_{d=1}^{N'_d} \log\left(\sum_{s=1}^{N'_s} n'_s f'_s(\bar{x_d})\right) + \sum_{s=1}^{N'_s} n'_s - \frac{1}{2}\sum_{p=1}^{N'_p}\left(\frac{\lambda'_p - \bar{\lambda'_p}}{\bar{\sigma'_p}}\right)^2$$

Signal:
$f(T, \cos\theta_{sun}, \rho)$
$f(E_{ACD})$

Background:
$f(T) \times f(\cos\theta_{sun}) \times f(\rho)$
$f(E_{ACD})$

Box Opened May 2, 2008:

- ~10% difference in NC flux uncertainties between the 3 signal extraction codes: after correction of the input energy resolution systematic constraint the errors agree, no effect on the central fit values.

- Parametrization failure of the algorithm (for one extraction code) used to fit the peak value from each ES bin 's distribution: more robust fit method implemented, ES fluxes agree.

Markov Chain Monte Carlo

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.

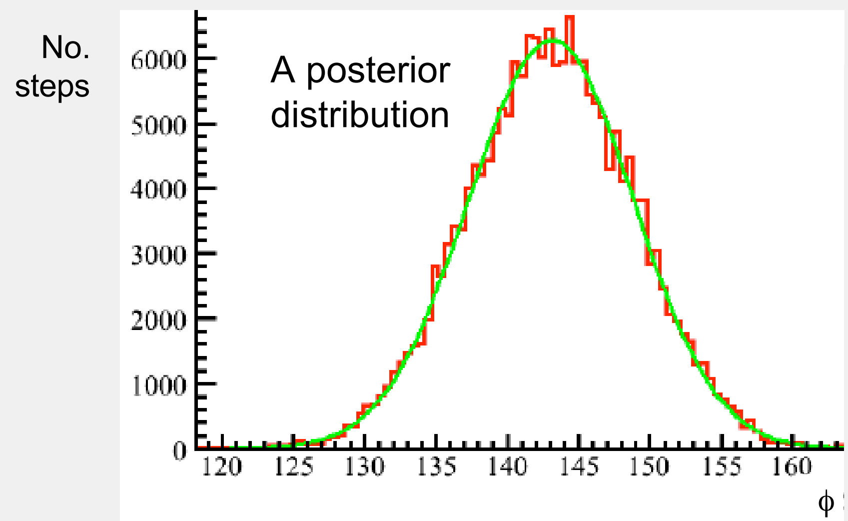
Algorithm:

Initial step i
- parameter guesses p_i
- calculate likelihood L_i

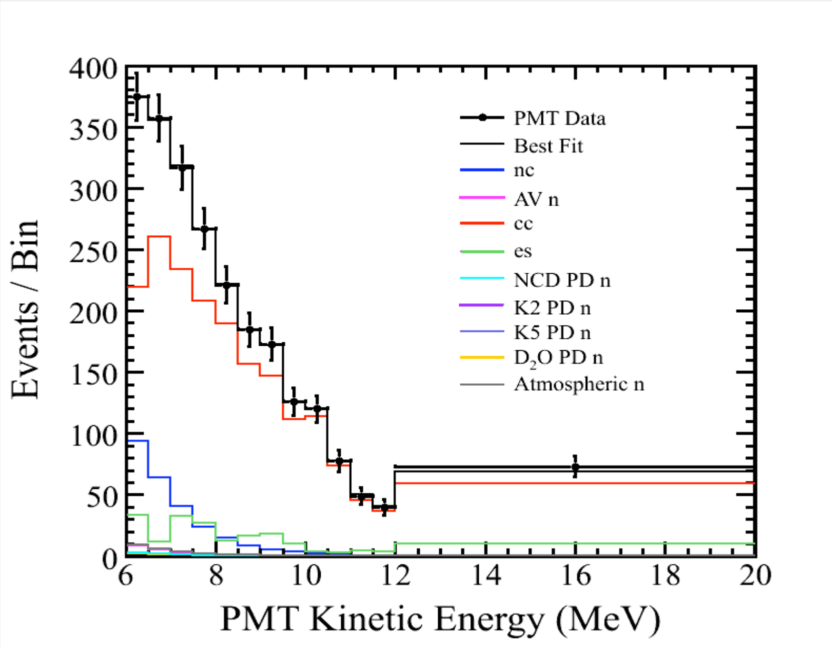
Add random amounts to all parameters
- $p_{i+1} = p_i + \mathrm{Norm}(0,\sigma_i)$
- calculate likelihood L_{i+1}

Keep p_i or p_{i+1} :
- $p_{keep} = \max(1, L_{i+1} / L_i)$

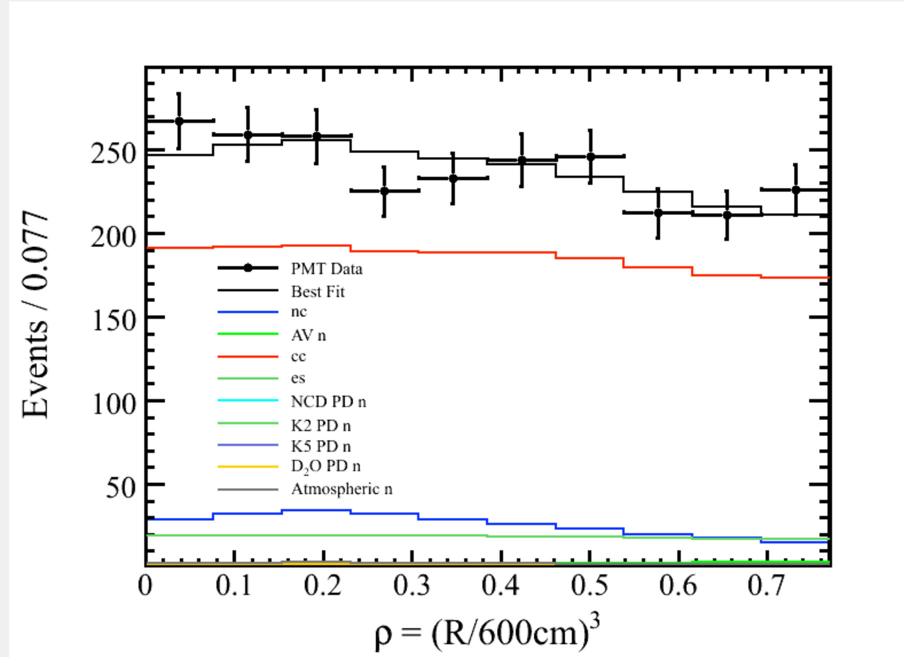
62-parameter likelihood function
- 13 CC flux energy bins
- 13 ES flux energy bins
- NC flux
- 35 systematic parameters



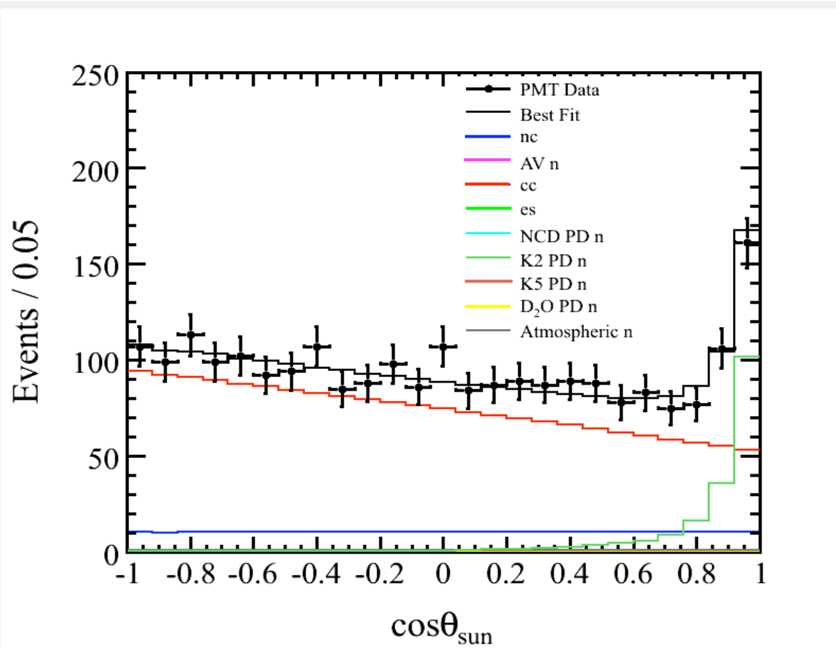
Results



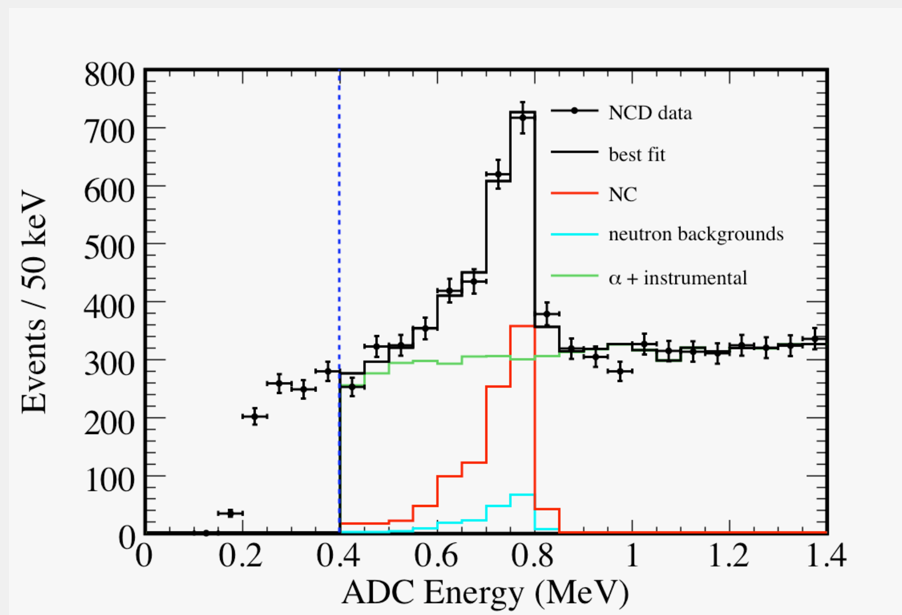
Events / Bin
PMT Kinetic Energy (MeV)
PMT Data
Best Fit
nc
AV n
cc
es
NCD PD n
K2 PD n
K5 PD n
D_2O PD n
Atmospheric n



Events / 0.077
$\rho = (R/600cm)^3$
PMT Data
Best Fit
nc
AV n
cc
es
NCD PD n
K2 PD n
K5 PD n
D_2O PD n
Atmospheric n



Events / 0.05
$\cos\theta_{sun}$
PMT Data
Best Fit
nc
AV n
cc
es
NCD PD n
K2 PD n
K5 PD n
D_2O PD n
Atmospheric n



Events / 50 keV
ADC Energy (MeV)
NCD data
best fit
NC
neutron backgrounds
α + instrumental

Fluxes and number of events

Fluxes (in unit of 10^6 cm^{-2} s^{-1}):

CC $1.67\,^{+0.05}_{-0.04}\,(stat)\,^{+0.07}_{-0.08}\,(sys)$

ES $1.77\,^{+0.24}_{-0.21}\,(stat)\,^{+0.09}_{-0.10}\,(sys)$

NC $5.54\,^{+0.33}_{-0.31}\,(stat)\,^{+0.36}_{-0.34}\,(sys)$

PMT events:

CC $1867\,^{+91}_{-101}$

ES $171\,^{+24}_{-22}$

NC $267\,^{+24}_{-22}$

Background $77\,^{+12}_{-10}$

Correlation Matrix for the Salt phase:

	CC	ES	NC
CC	1.00		
ES	-0.16	1.00	
NC	-0.52	-0.06	1.00

Correlation matrix for the NCD phase:

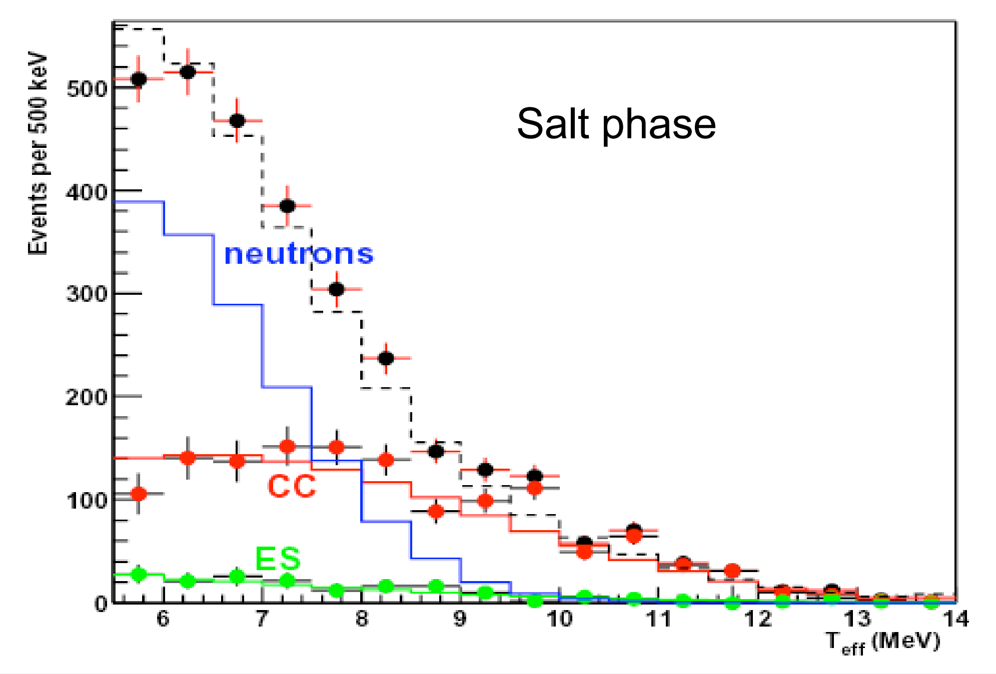
	CC	ES	NC
CC	1.00		
ES	0.24	1.00	
NC	-0.19	0.02	1.00

NCD events:

NC $983\,^{+77}_{-76}$

Background $185\,^{+25}_{-22}$

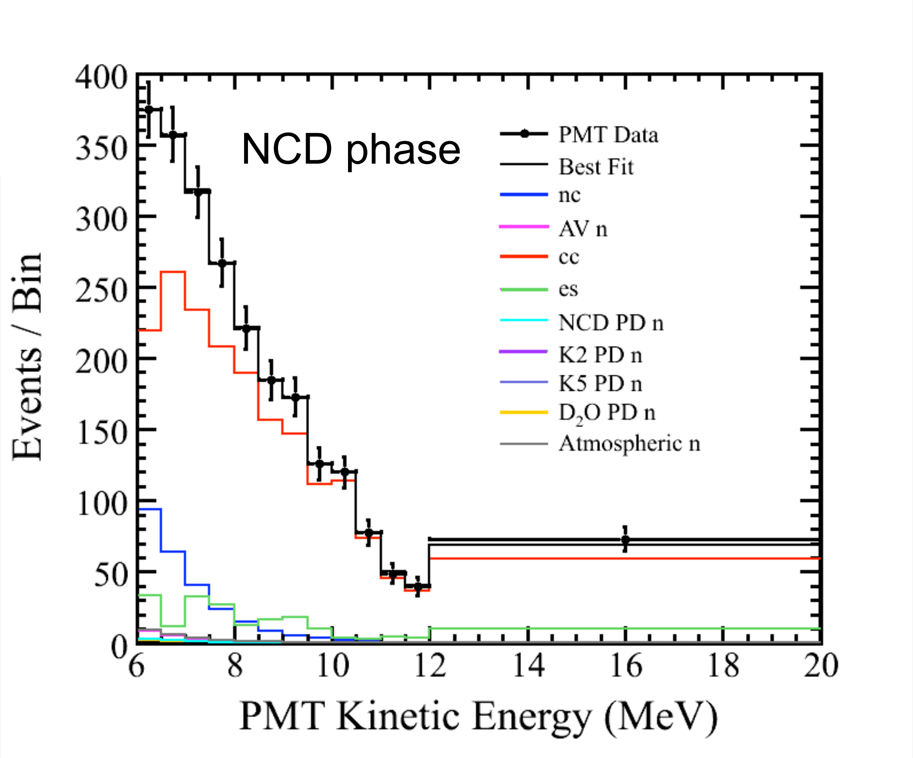
Salt and NCD phases comparison



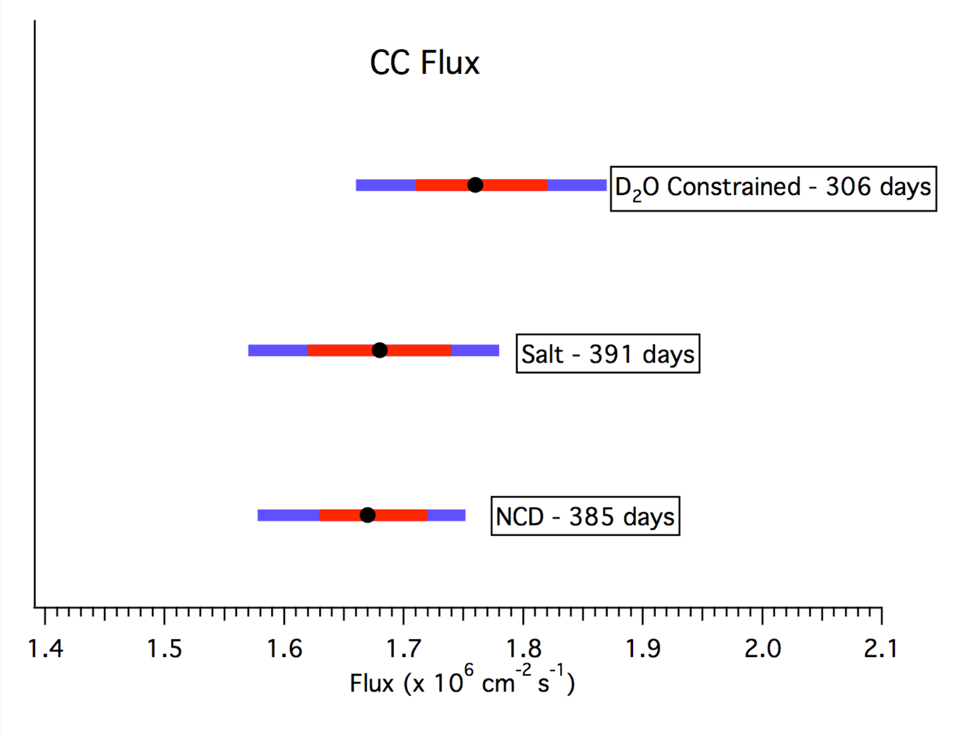
Better measurement of the CC flux.

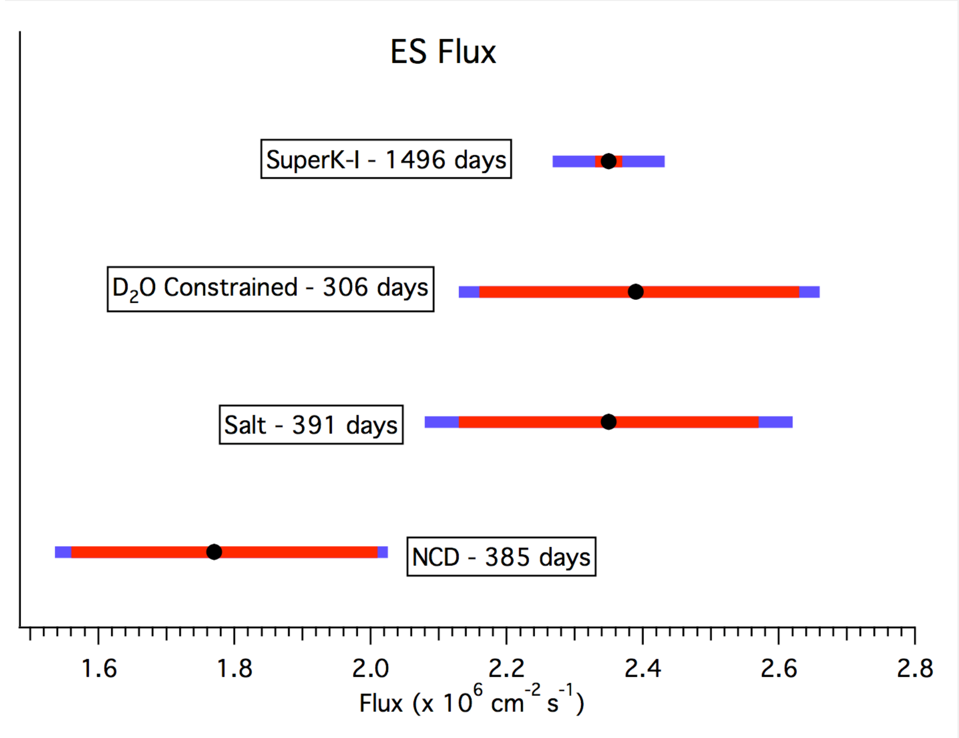
Lower ES flux.

ES results deviation from prior results due to a statistical fluctuation.



Comparisons

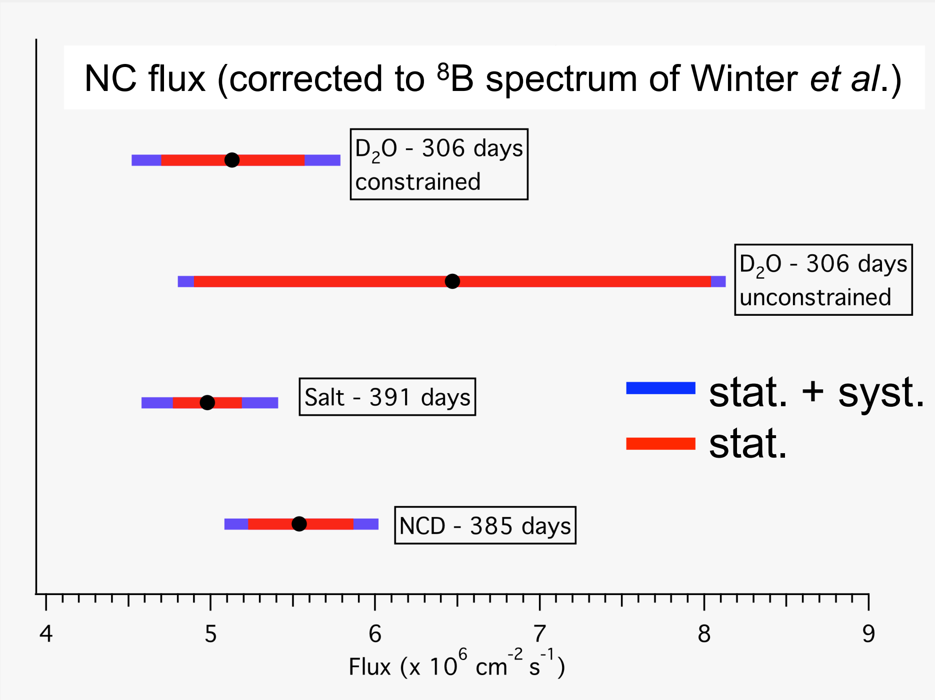




stat. + syst.

stat.

Comparisons



Fluxes (in unit of 10^4 cm^{-2} s^{-1})

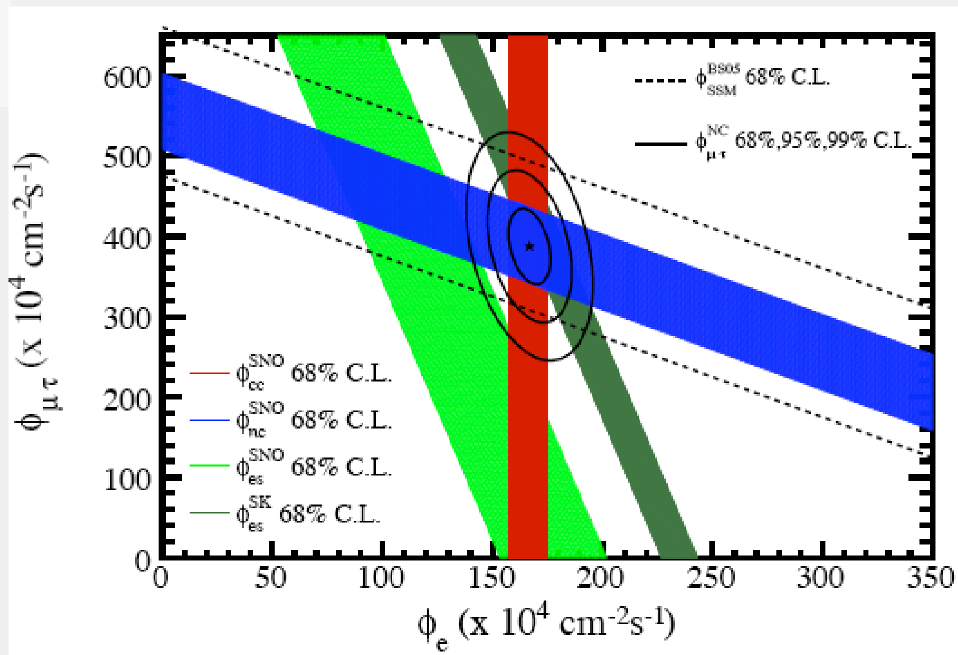
CC: 167(9)

ES: 177(26)

NC: 554(49)

SSM: 569(91) [BSB05-OP: Ap. J. 621, L85, 2005]

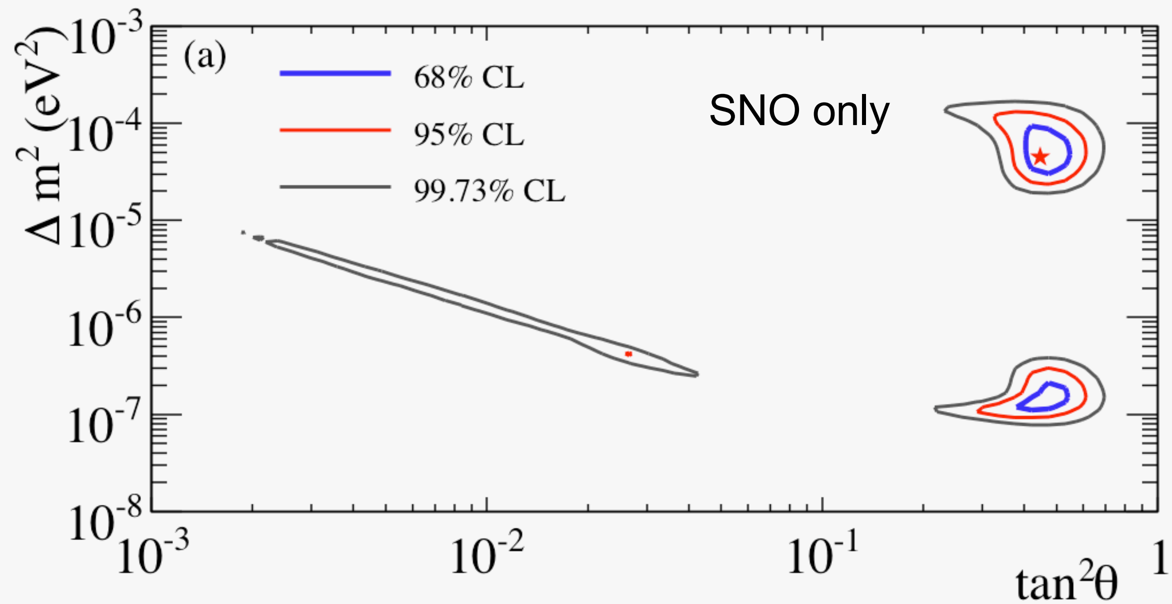
Super-K: 235(8) [PRD 73, 112001, 2006]



Agreement with previous measurements (estimated p-value = 0.328)

Agreement with standard solar models

2-neutrinos oscillation contours



a) SNO only:
D_2O & Salt day and night spectra, NCD phase fluxes.

b) Solar Global:
SNO, Super-K, Cl, Ga, Borexino

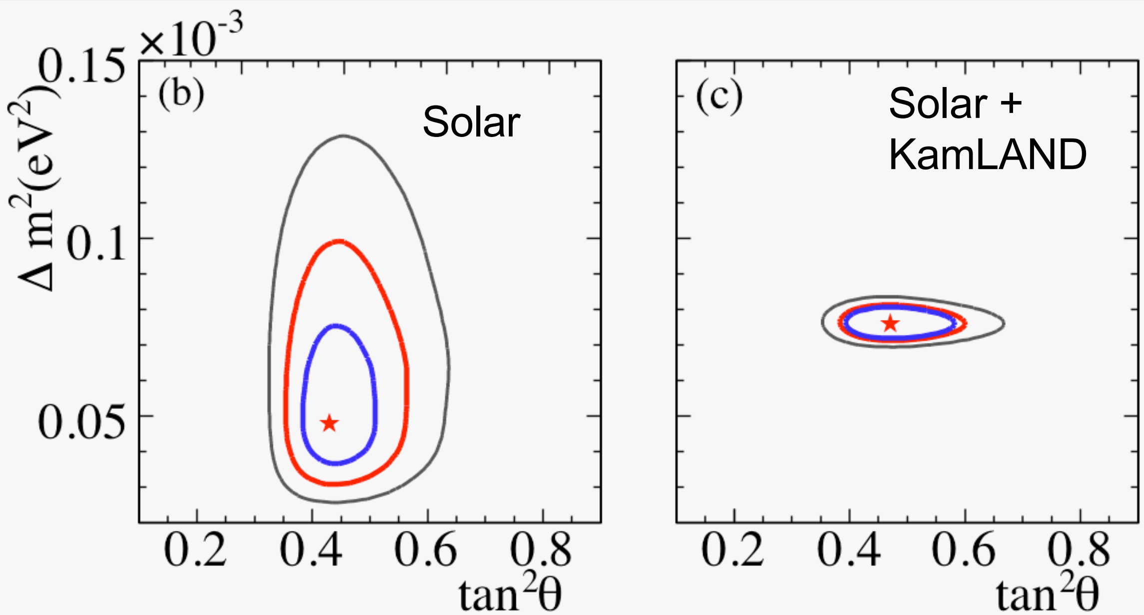
c) Solar Global + KamLAND

Solar+KamLAND best fit:

$\Delta m^2_{12} = 7.59 ^{+0.19}_{-0.21} \times 10^{-5}\ eV^2$

$\theta_{12} = 34.4 ^{+1.3}_{-1.2}$ degrees

$\tan^2\theta_{12} = 0.468 ^{+0.048}_{-0.040}$



Conclusion

Results from the NCD phase:

Independent measurement of the ^{8}B flux.

NCD results agree well with previous SNO phases.

Reduced correlations between CC and NC.

Different systematics.

New precision on θ_{12}, 40% improvement on our previous result.

More from SNO:

LETA (Low Energy Threshold Analysis)

Three phase analysis

Three neutrino analysis

hep flux

Day-night, other variations

Muons, atmospheric ν

Phase III results available online in PRL September 9th.

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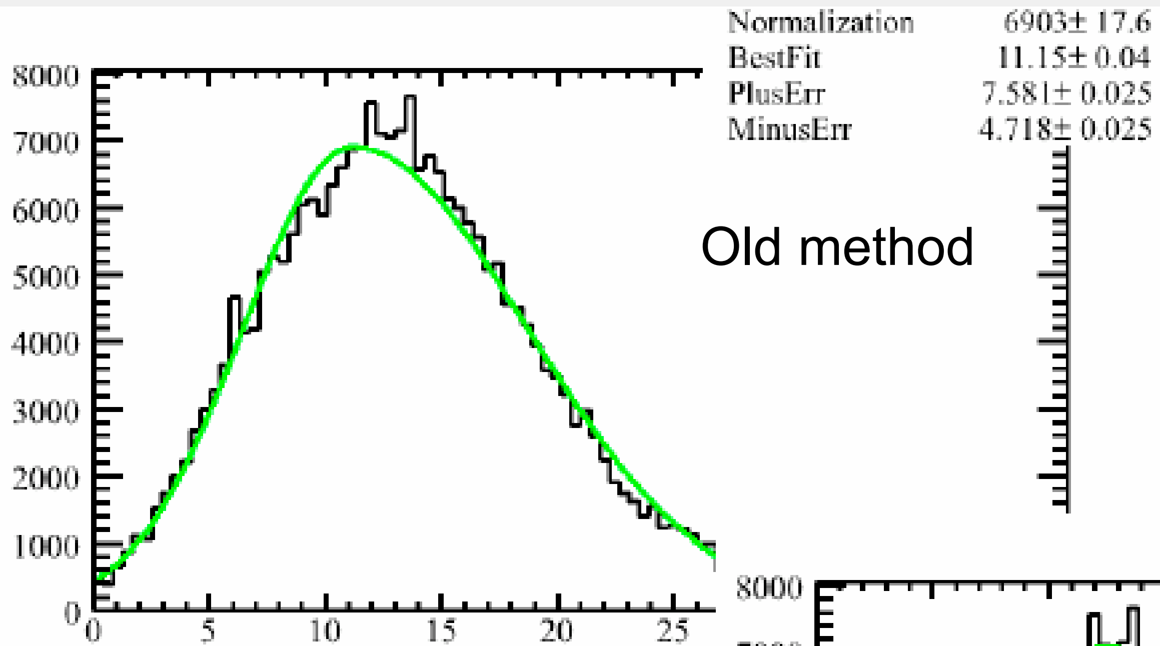
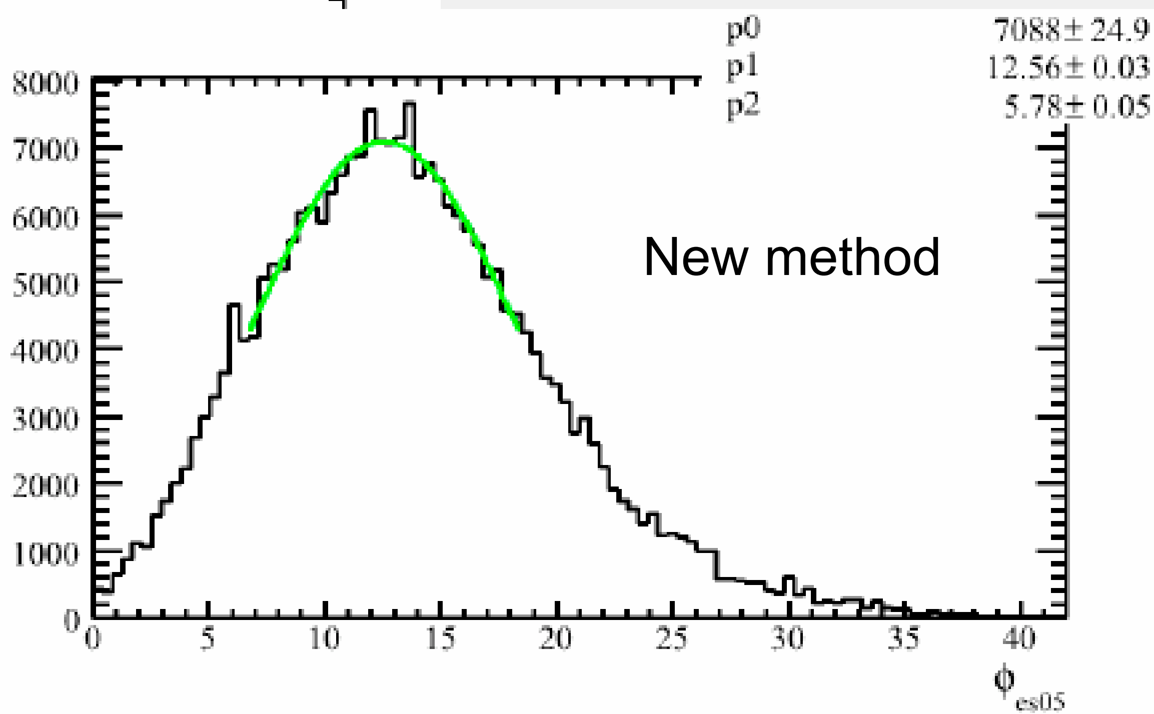
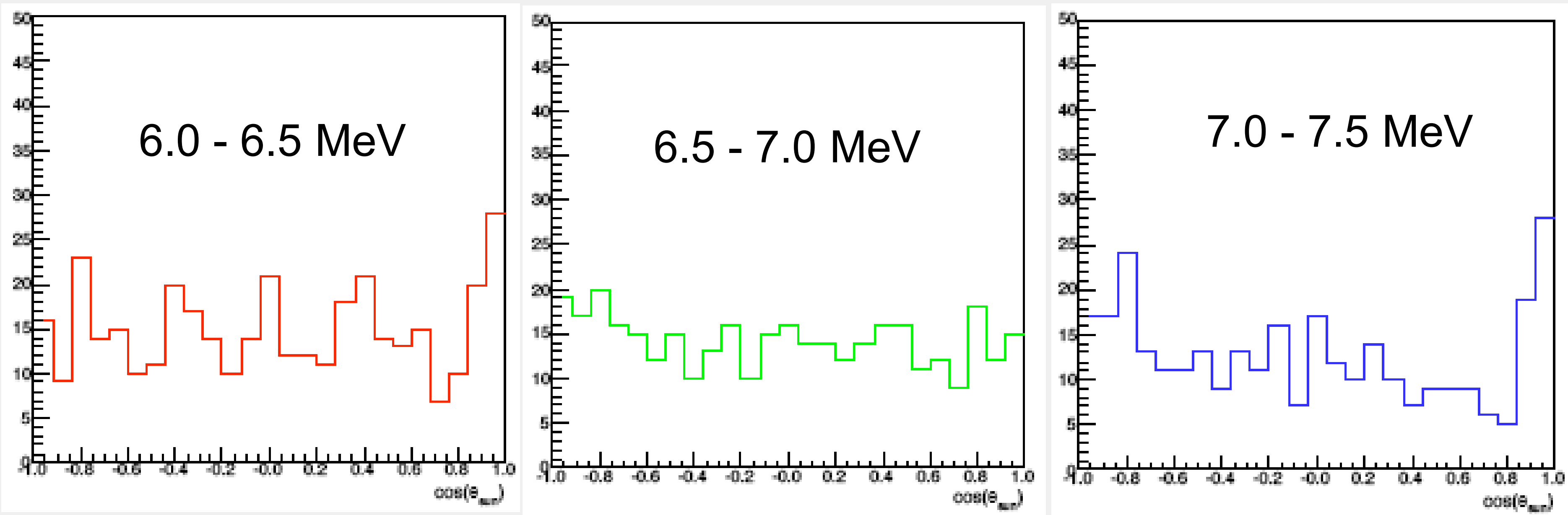
Change in parameterization for ES fit

ES 5th energy bin posterior





Angular distributions for ES



Distribution for the energy bin 6.5-7.0 MeV: no peak at $\cos(\theta_{sun})= 1$ as expected.
Statistical fluctuation (1.3% probable to obtain such a low number in this bin assessed by a MC of 10000 trials).

χ^2 map (SNO collaboration)