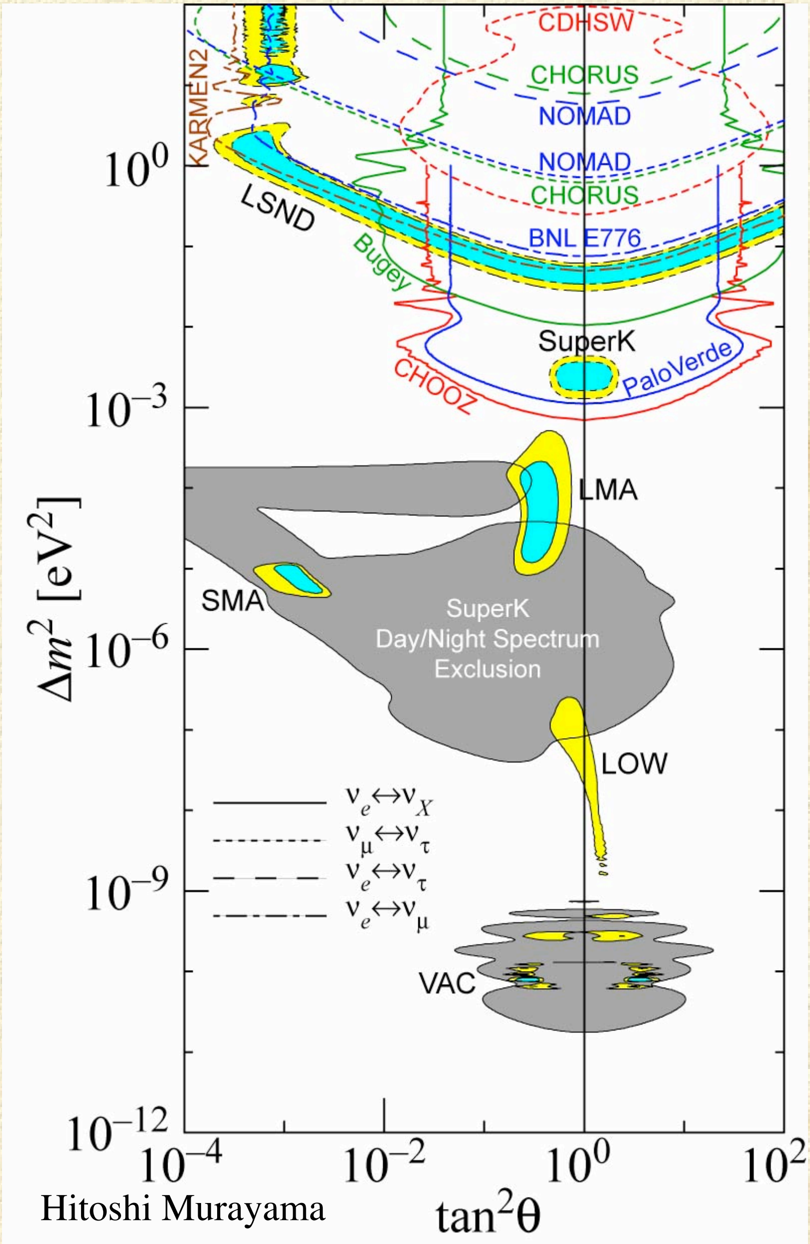
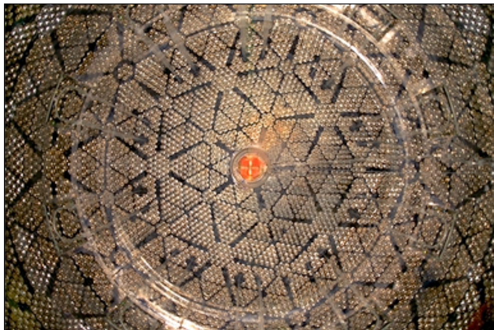
The Sudbury Neutrino Observatory

Kevin T. Lesko
Berkeley Lab
for the SNO Collaboration

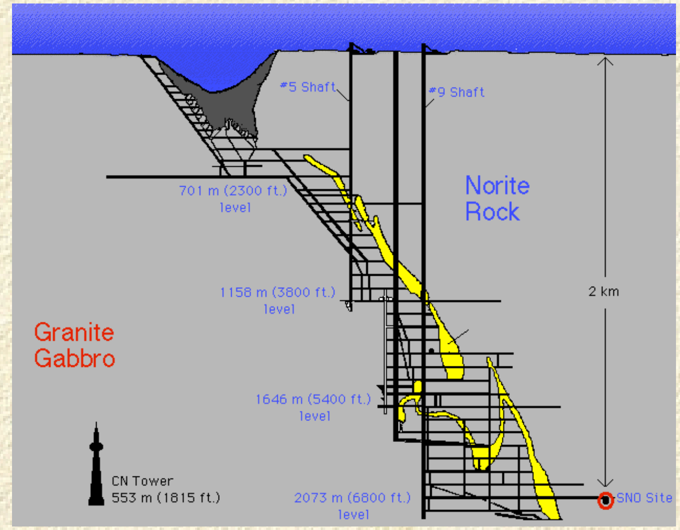
Neutrinos at the time of the last Long Range Plan: ~ 2000

- lots of questions
- many potential answers





Introduction to SNO



- **Charged Current**

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

  $E_{thresh} = 1.4$ MeV

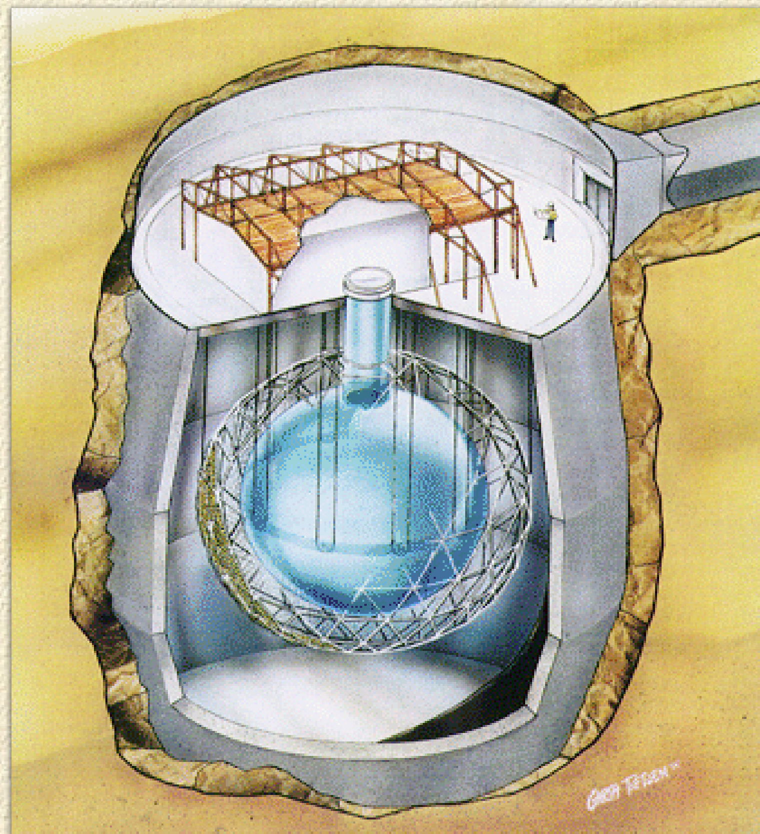
- **Elastic Scattering**

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

- **Neutral Current**

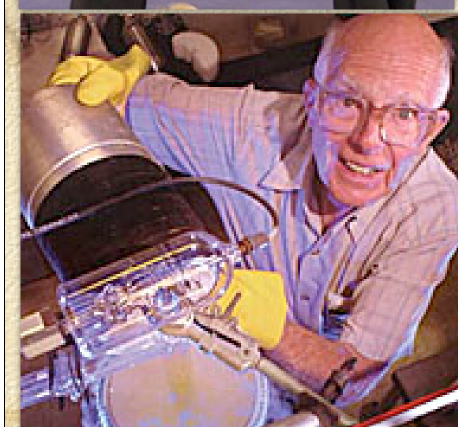
  $\nu_x + d \rightarrow \nu_x + n + p$

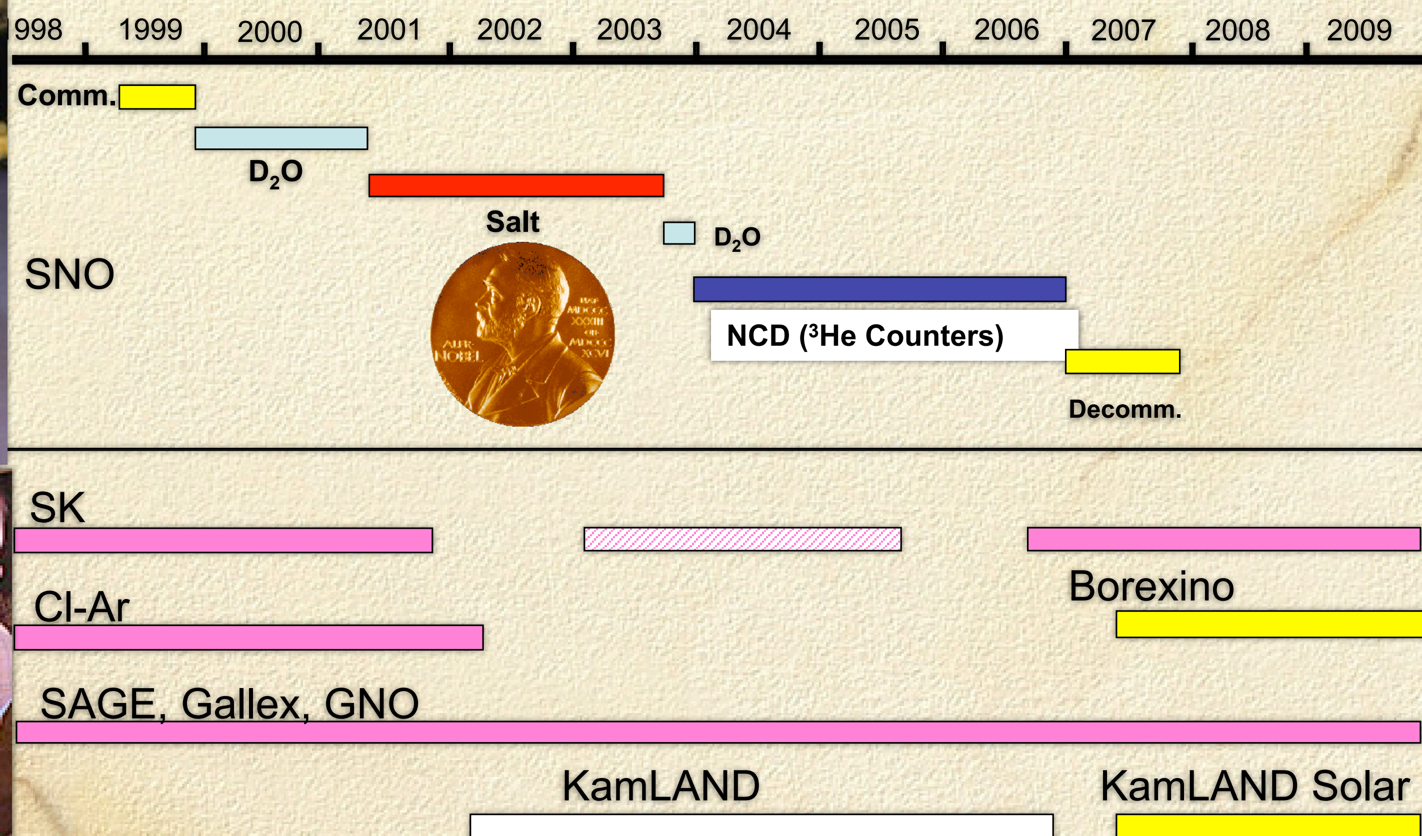
  $E_{thresh} = 2.2$ MeV



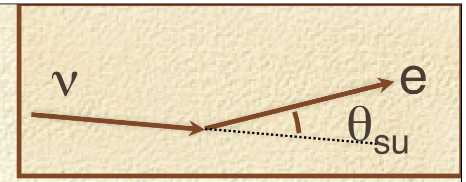
SNO Physics Campaigns

CC: $\nu_e + d \rightarrow p + p + e^-$ NC: $\nu_x + d \rightarrow \nu'_x + p + n$





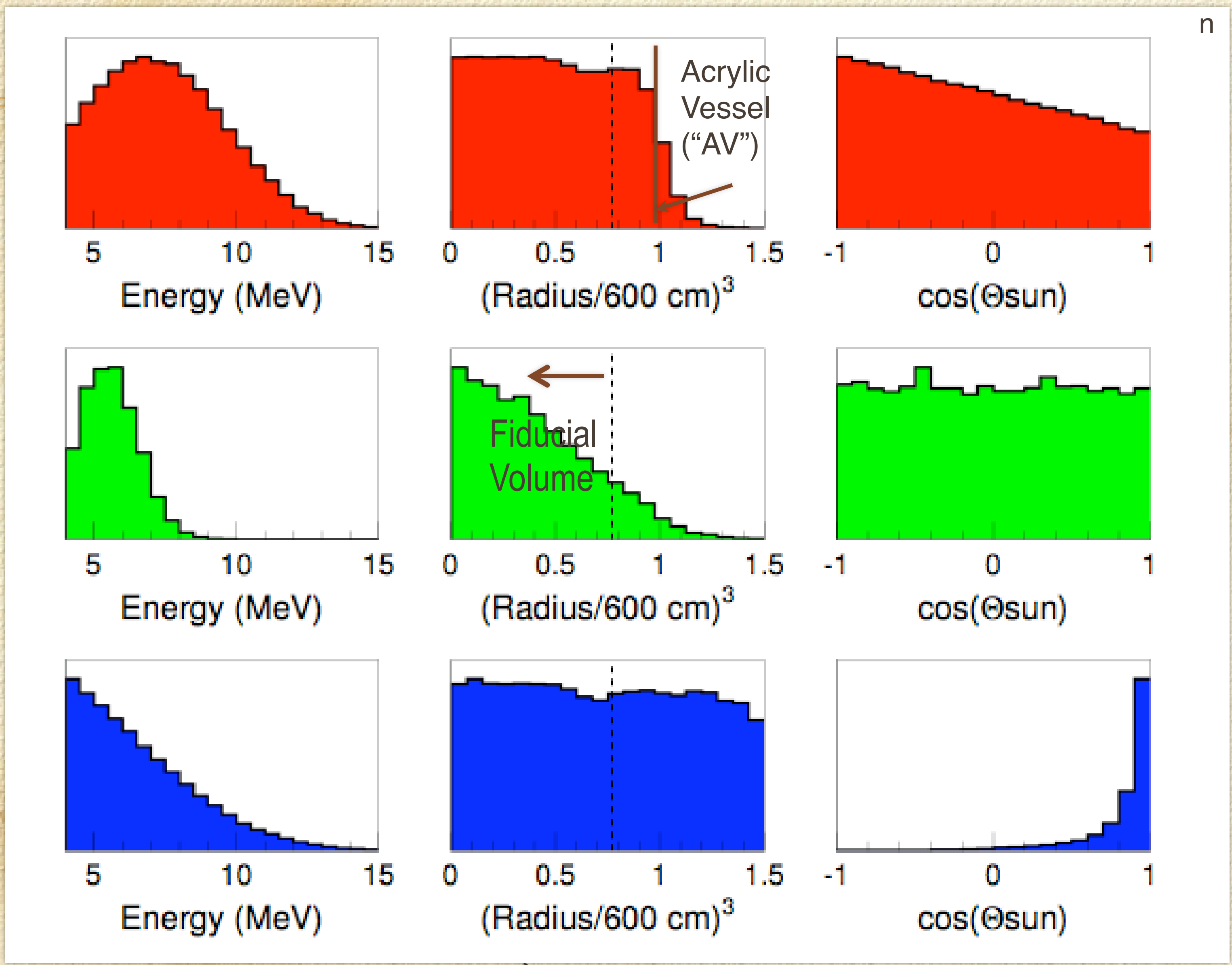
Neutrino Signals in D_2O



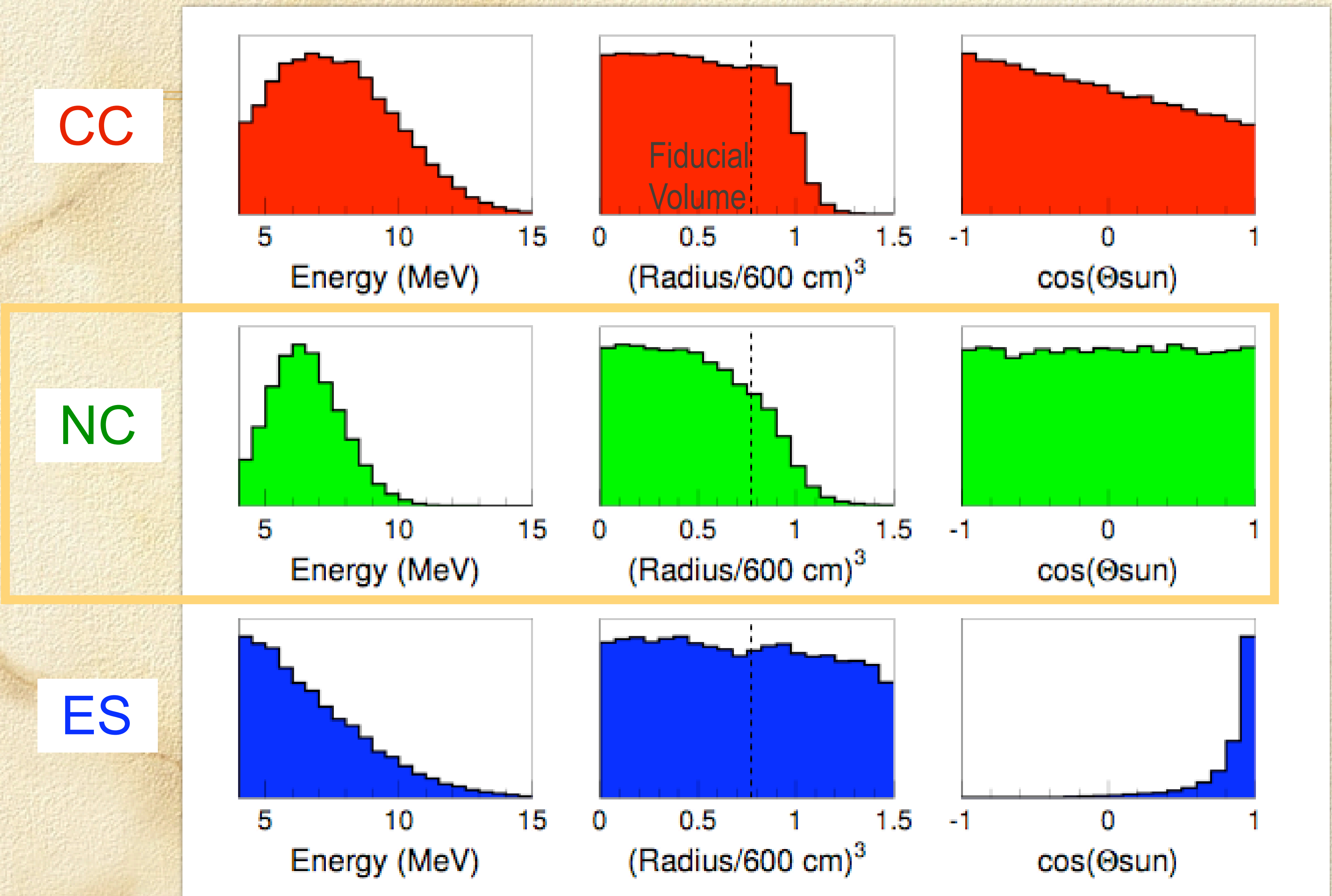
CC

NC

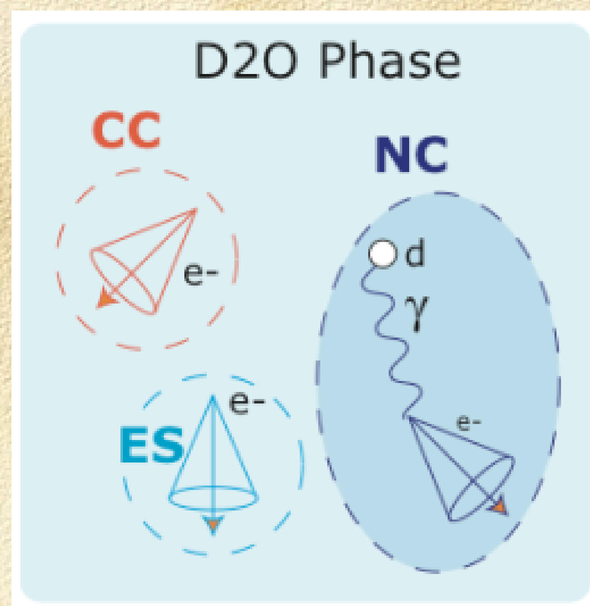
ES

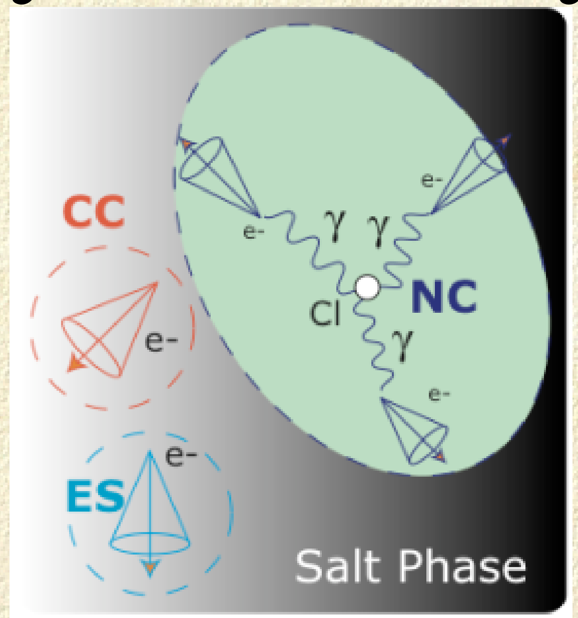


Neutrino Signals in D_2O+NaCl



Using Light Isotropy to Identify NC

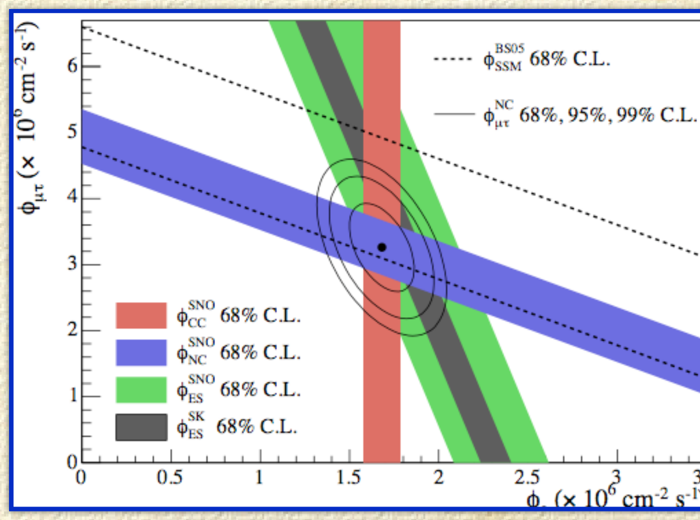




- With salt added, can't rely on radial profiles to distinguish CC / NC
- CC & ES signals yield an electron, producing a single cone of Cherenkov light
- In D_2O phase NC signal yields a single γ ray, while in salt phase there are multiple γ rays
- We can use isotropy to help distinguish CC and NC signals

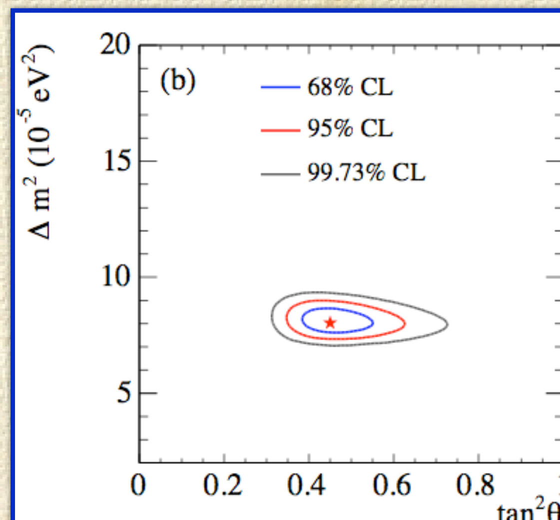
SNO Scientific Accomplishments

- Direct evidence for $\nu_e \rightarrow \nu_x$ flavor transformation
  - Null hypothesis of no transformation rejected at > 7σ
  - First SNO CC paper [PRL 87:071301 (2001)]:
    - 1200+ Spires citation
  - First SNO NC paper [PRL 89:011301 (2002)]:
    - 1200+ Spires citation



- Measurement of total active solar ν flux and verification of solar model predictions
- Neutrino mixing parameters (with other solar ν experiments and KamLAND):
  - LMA-I strongly favored: $(\Delta m_{\odot}^2, \theta_{\odot}) = (8.0\ 10^{-5}\ eV^2, 33.9)$
  - Mass hierarchy: $m_2 > m_1$
  - Beginning to constrain θ_{13}
  - Null hypothesis of no MSW effect rejected at > 5.6 σ

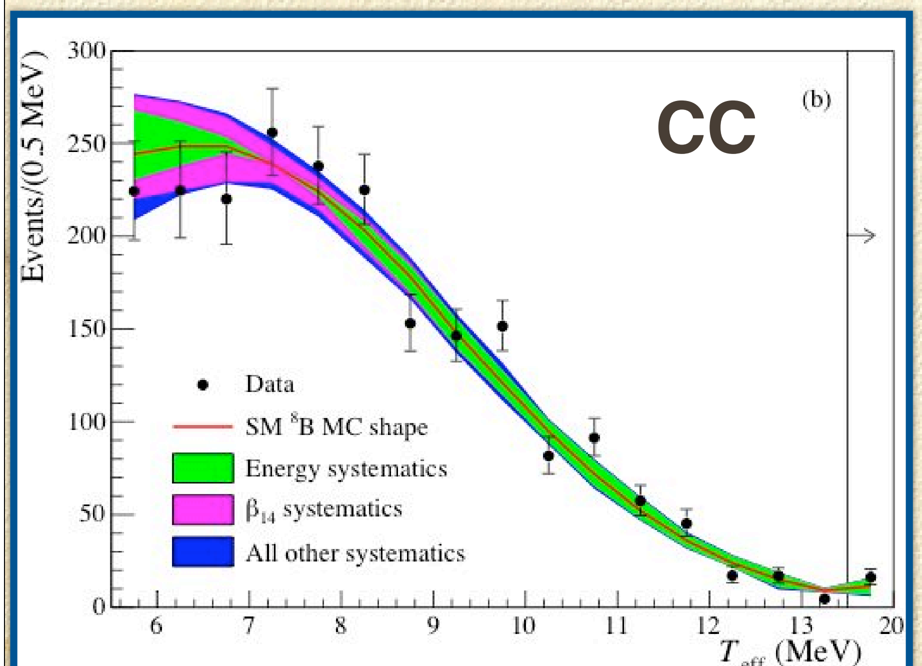
[Fogli *et al.*, Phys.Lett. B583:149-156,2004]

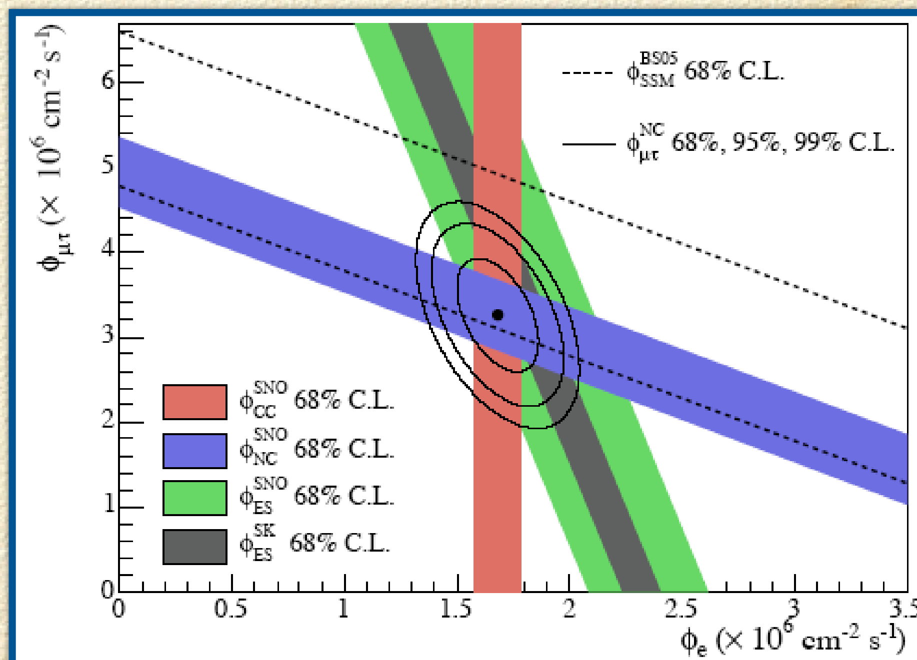


Recent SNO Publications

The "Next Salt Paper" (NSP)

- Expanded Data Set (391 live days with D_2O + NaCl)
    - CC, NC, ES integral flux
    - CC, ES spectra
    - Day-Night asymmetry in flux
- Phys. Rev. C72 (2005) 055502
- Comprehensive presentation of analysis techniques





hep & DSNB analyses

- Submitted ApJ, hep-ex/0607010
- D_2O data set
  14.3 MeV < E_ν < 20 MeV
  see 2 events, expect 3.1 background events
- Results improves limit on *hep* flux:
  - < 2.3 x 10^4 $cm^{-2}s^{-1}$ (90%CL)
    SSM: 7.97±1.24 x 10^3 10^4 $cm^{-2}s^{-1}$
  - 6.5 improvement over previous limits
- Diffuse Supernovae Background
  - 21 MeV < E_ν < 35 MeV
    see 0 events
  - < 70 $cm^{-2}s^{-1}$ (90%CL)
  - 100x improvement for ν_e

p-p Chain

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

${}^2H + p \quad {}^3He + \gamma$

85% $\quad$ 15%

${}^3He + {}^3He \rightarrow {}^4He + 2p$ $\quad$ ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

${}^7Be + p \rightarrow {}^8B + \gamma$

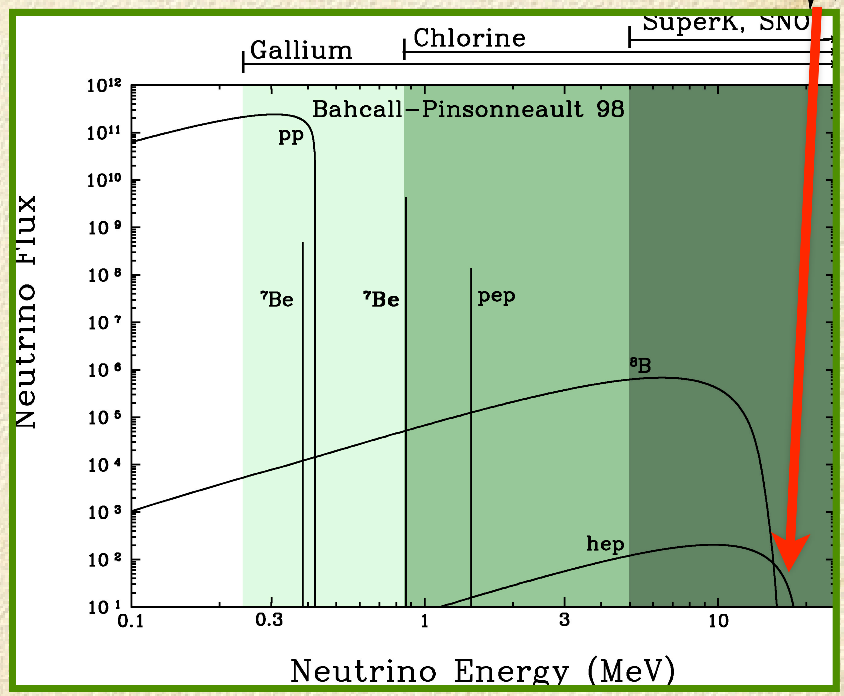
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

${}^8Be^* \rightarrow {}^4He + {}^4He$

${}^7Be + e^- \rightarrow {}^7Li + \nu_e$

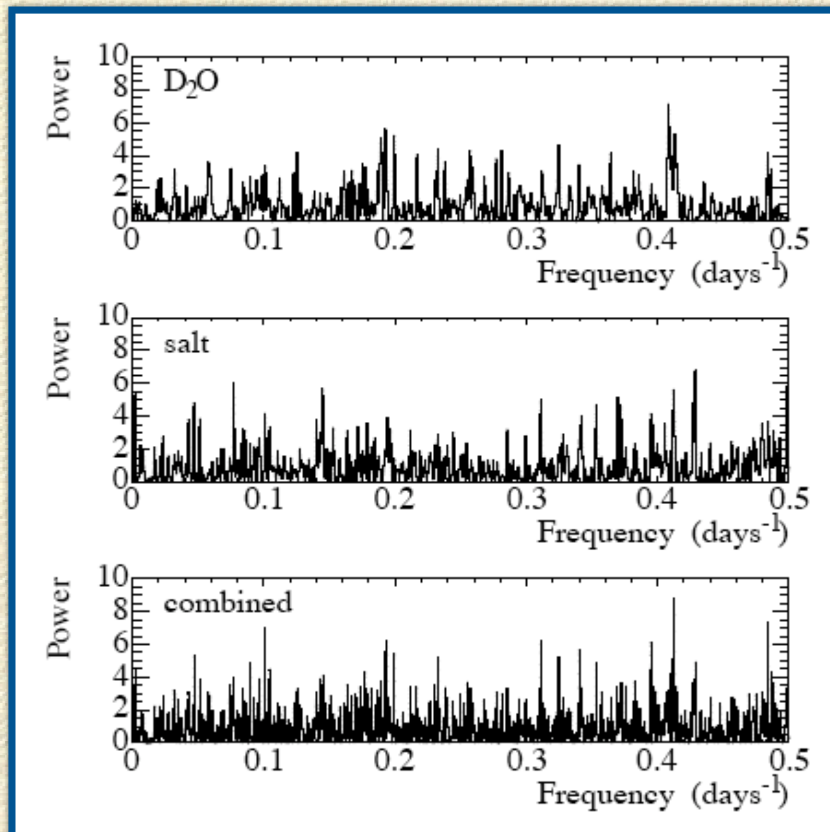
${}^7Li + p \rightarrow {}^4He + {}^4He$

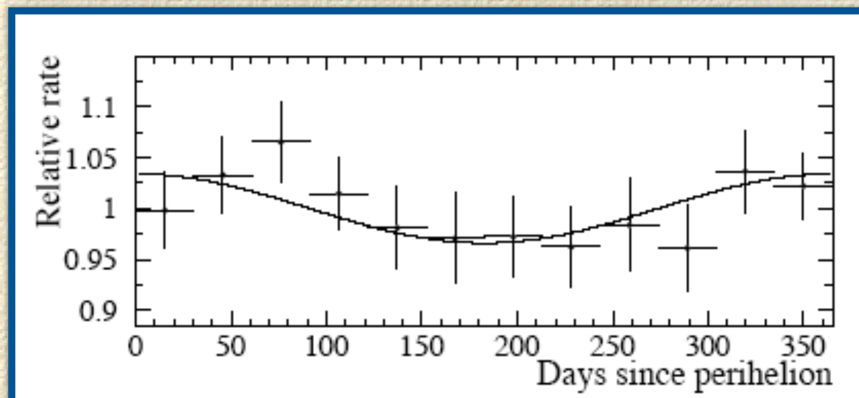
${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$



^{8}B ν-Periodicity Paper

- Phys. Rev. D 72, 052010 (2005)
- Independent analyses:
  - Lomb-Scargle periodogram
  - Unbinned max. likelihood
- Our amplitude fit disagrees with the claim of a 7% amplitude periodicity in the ^{8}B ν flux at 9.43 y^{-1} (Sturrock *et al.*) by 3.6σ.
- Run start and stop times + 1-day binned data released to the public: http://owl.phy.queensu.ca/sno/periodicity/
- Rayleigh power test + flavor periodicity to be released in a future paper

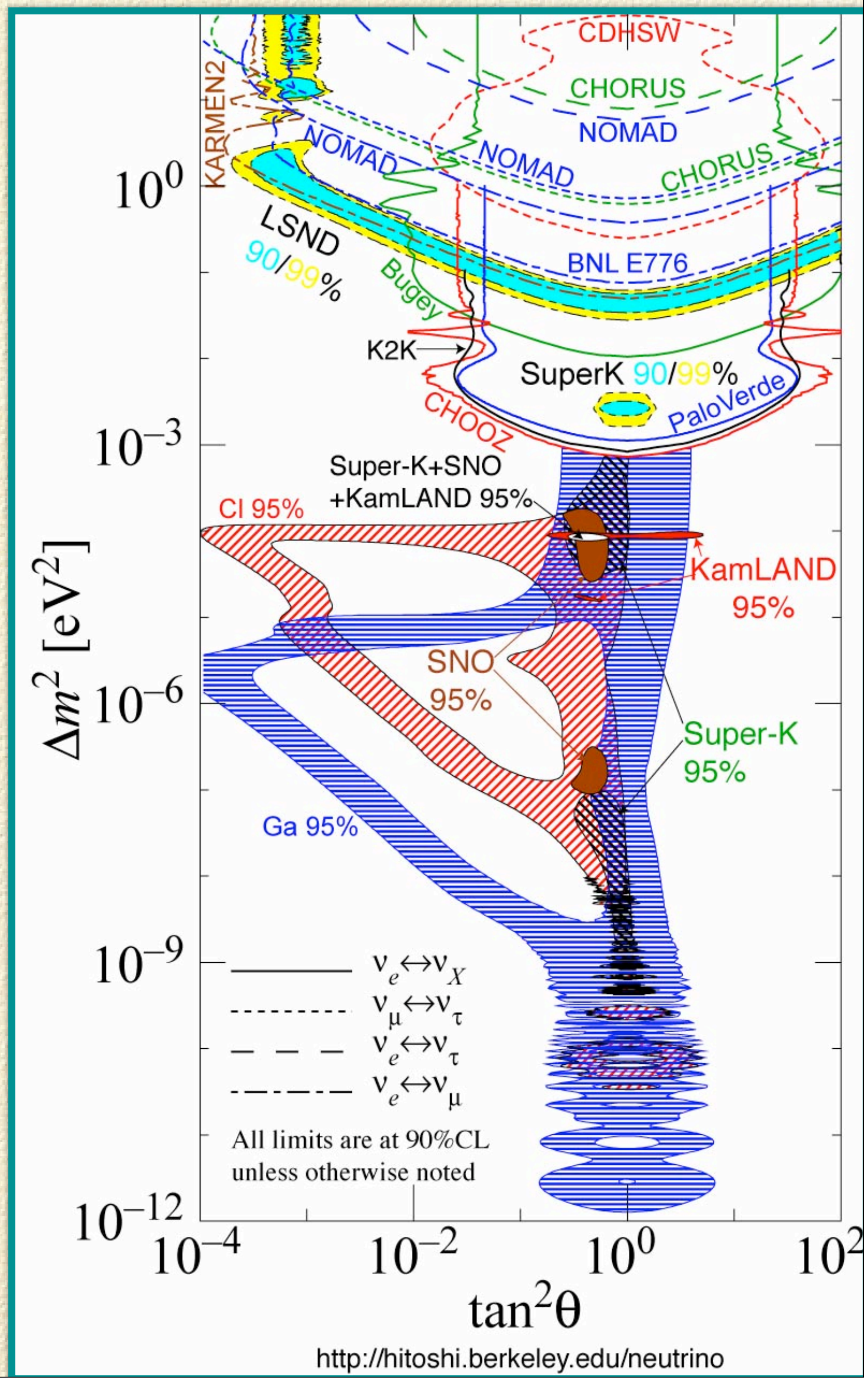




Neutrinos at the time of <u>this</u> Long Range Plan:

- Minos reporting,
- T2K reporting,
- miniBooNE reporting soon,
- KamLAND ➙ solar,
- Borexino coming on line,
- SNO NCDs reporting soon

...



Upcoming SNO Physics Program

- Precision measurements of total solar ν flux and ν_e flux
  - ⇒ improving constrains on $\Delta m_\odot^2$, $\theta_\odot$, θ_{13}, $\phi_{sterile}$
  - ⇒ NCD phase
- Search for MSW signatures:
  - Day-night asymmetry of ν flux
  - Distortion of ν_e energy spectrum
- Other ancillary physics:
  - hep ν flux ✓(1st paper)
  - atmospheric μ and ν
  - periodicity of ν signals ✓ (1st paper)
  - relic supernova ν_e flux ✓ (1st paper)
  - galactic supernova watch
  - exotic processes

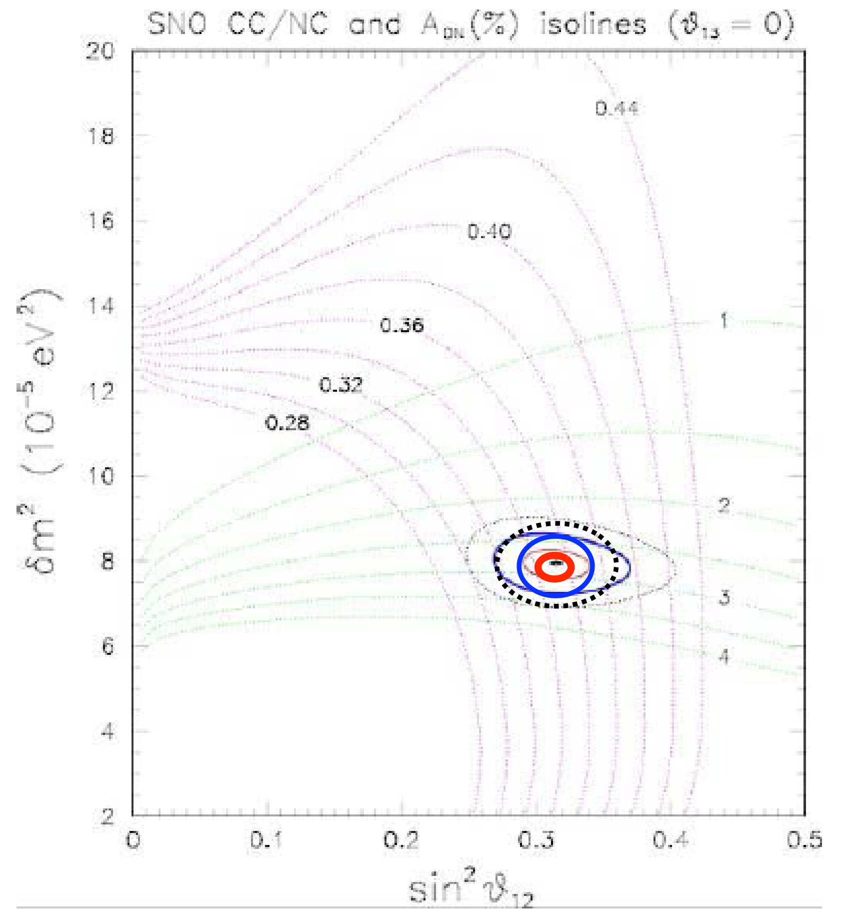
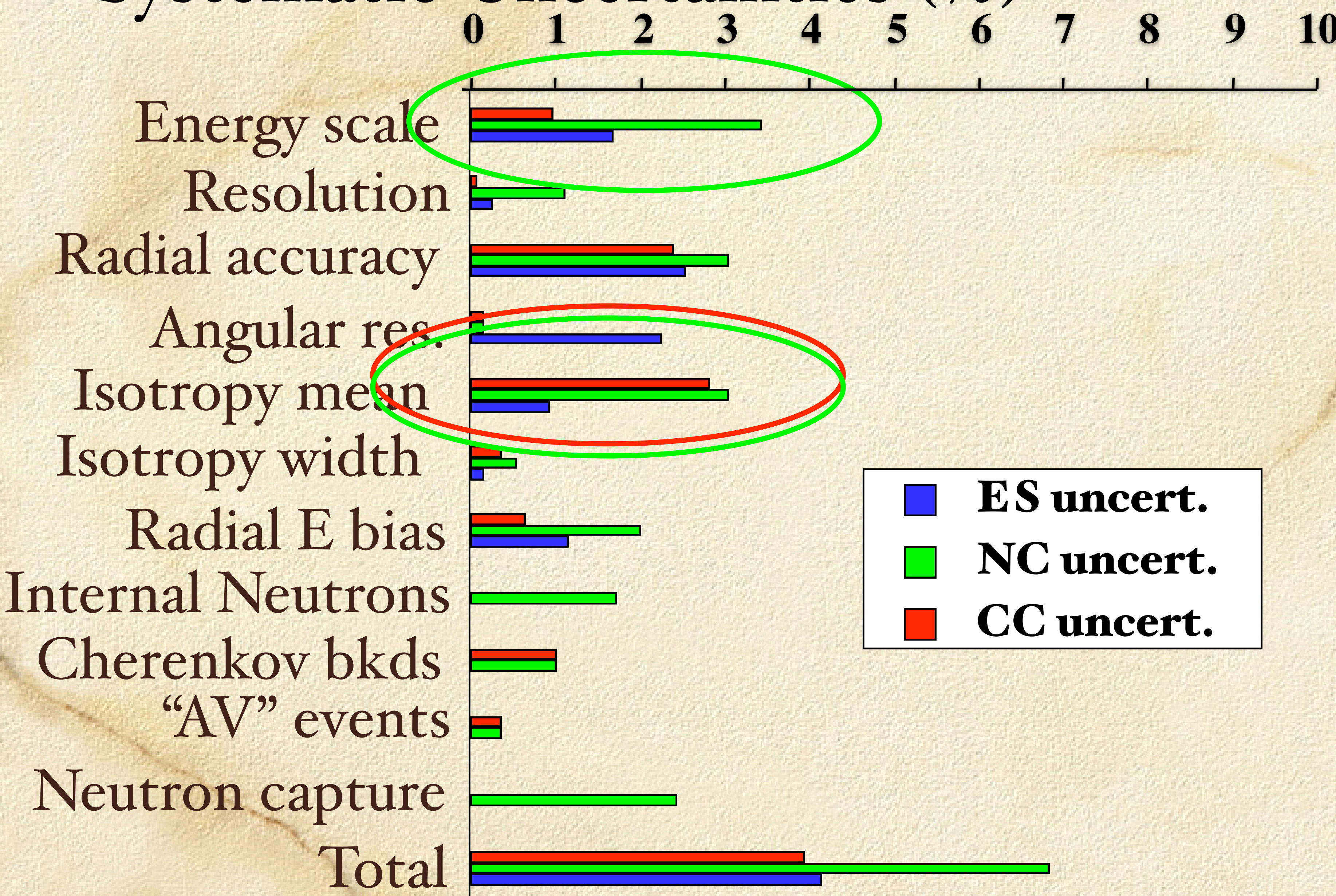


Figure 6: Isolines of the charged-to-neutral current flux ratio and of the day-night asymmetry in SNO, superposed to the global (solar+KamLAND) LMA allowed region.

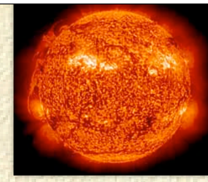
Fogli et al., hep-ph/0506083

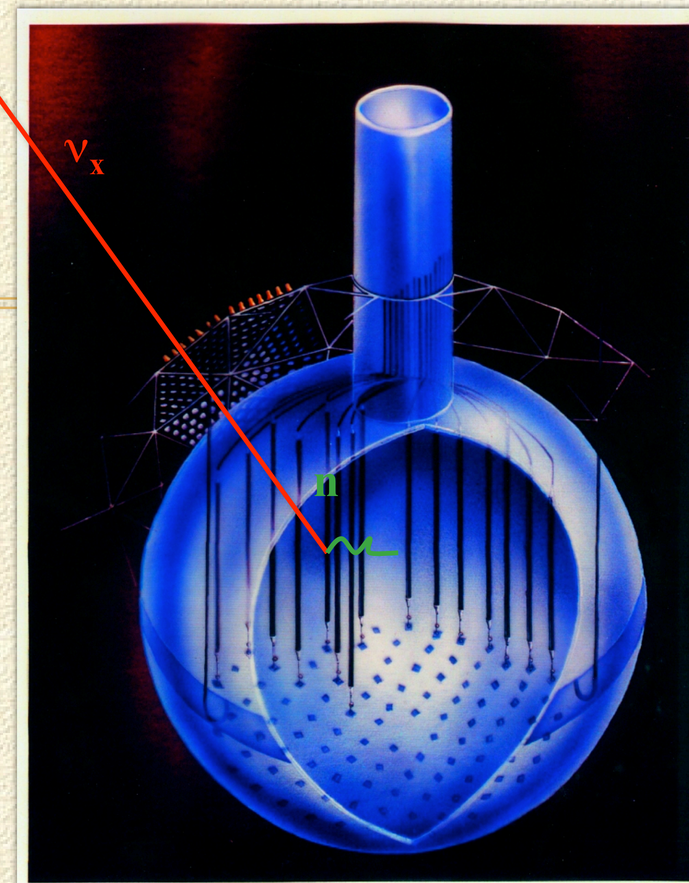
Systematic Uncertainties (%)



Cross Section Uncertainties: NC 1.1%, CC 1.2 %, ES 0.5%

Phase III NCDs



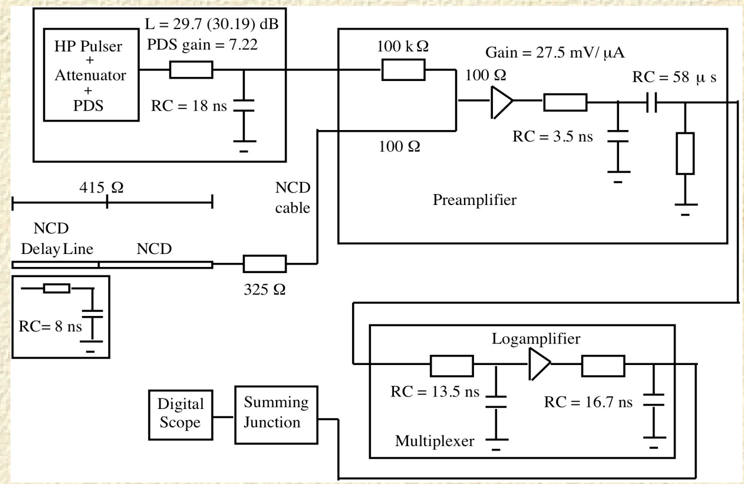


- Neutral Current Detectors installed and commissioned
  - ➡ 36 ^3He and 4 ^4He proportional counter strings
- Production data taking:
  - ➡ Nov 2004 - Dec 2006
- Analysis program to be completed in 2008
- Improvements:
  - ➡ Improve statistical precision by breaking CC and NC covariance in physics extraction
  - ➡ Reduction in systematic uncertainties

NCD Analysis Development

Two critical issues for NCD Analysis

- Understanding the calibration of the NCD electronic chain (“ECA”)
- Distinguishing neutron events from instrumental and radioactive backgrounds



☑ NCD ECA

- Special calibration campaigns + bench measurements + analysis
- Robust electronic model + calibration established

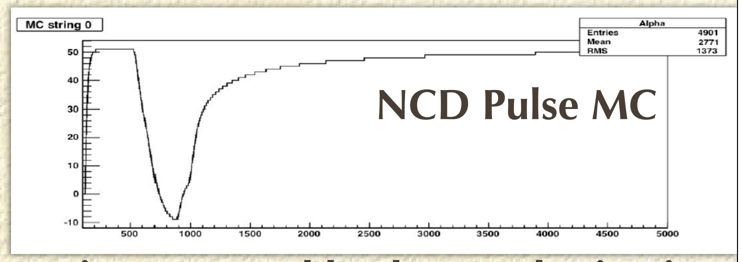
☑ Removal of instrumental backgrounds

- Two independent sets of *cuts* (time domain and frequency domain)

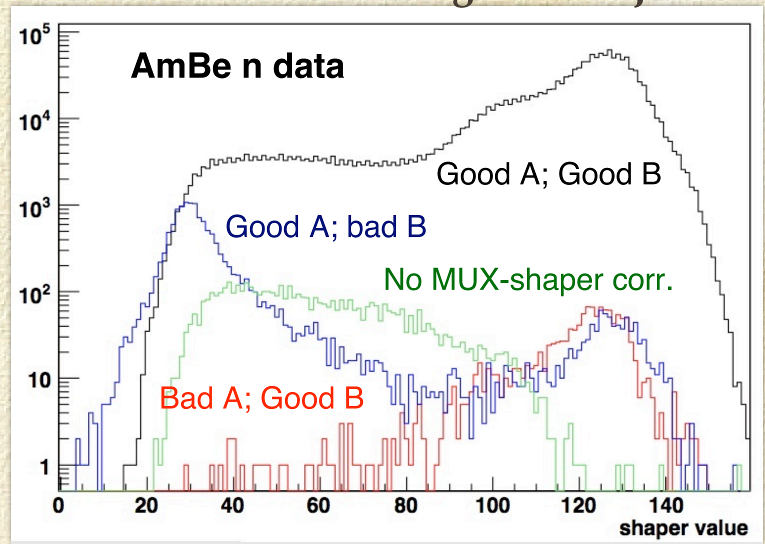
Pulse Shape Analysis

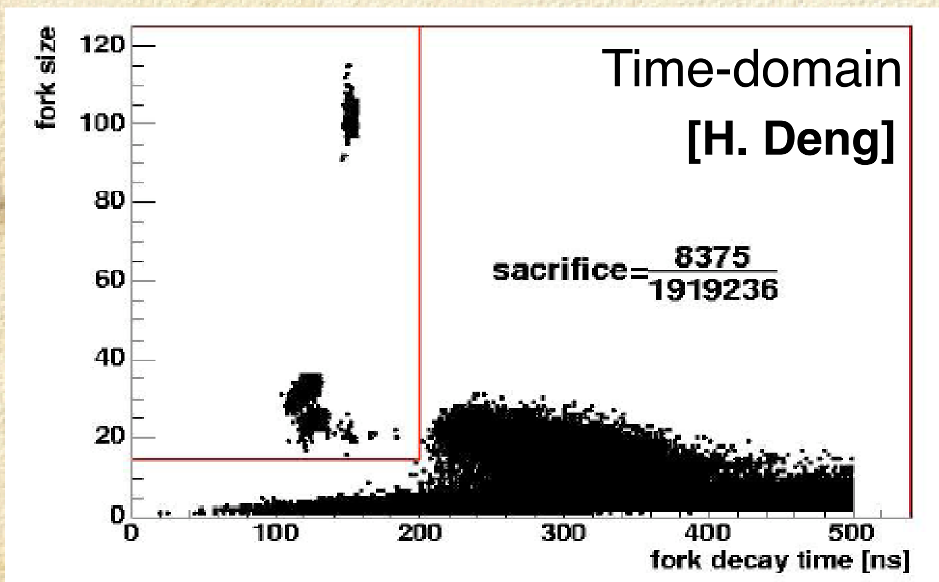
- n and α pulse fitting and discrimination

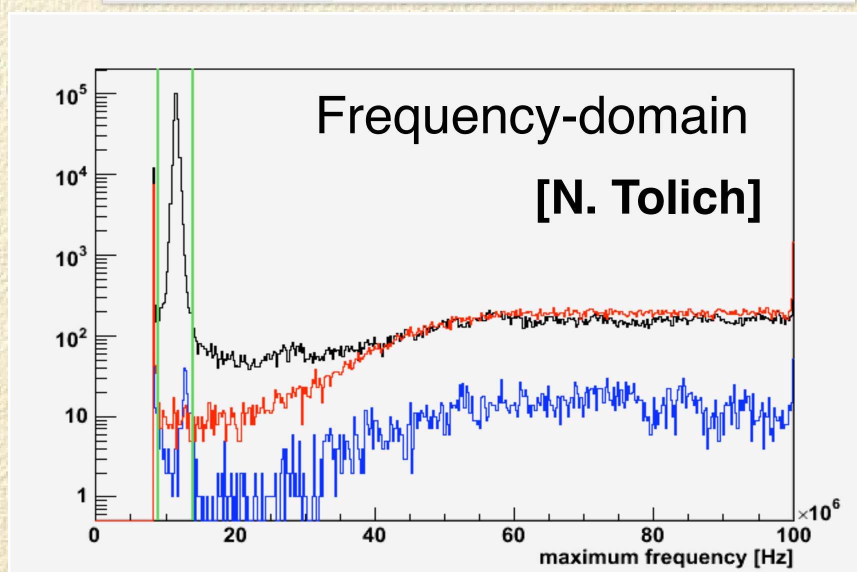
NCD Background Identification & Rejection



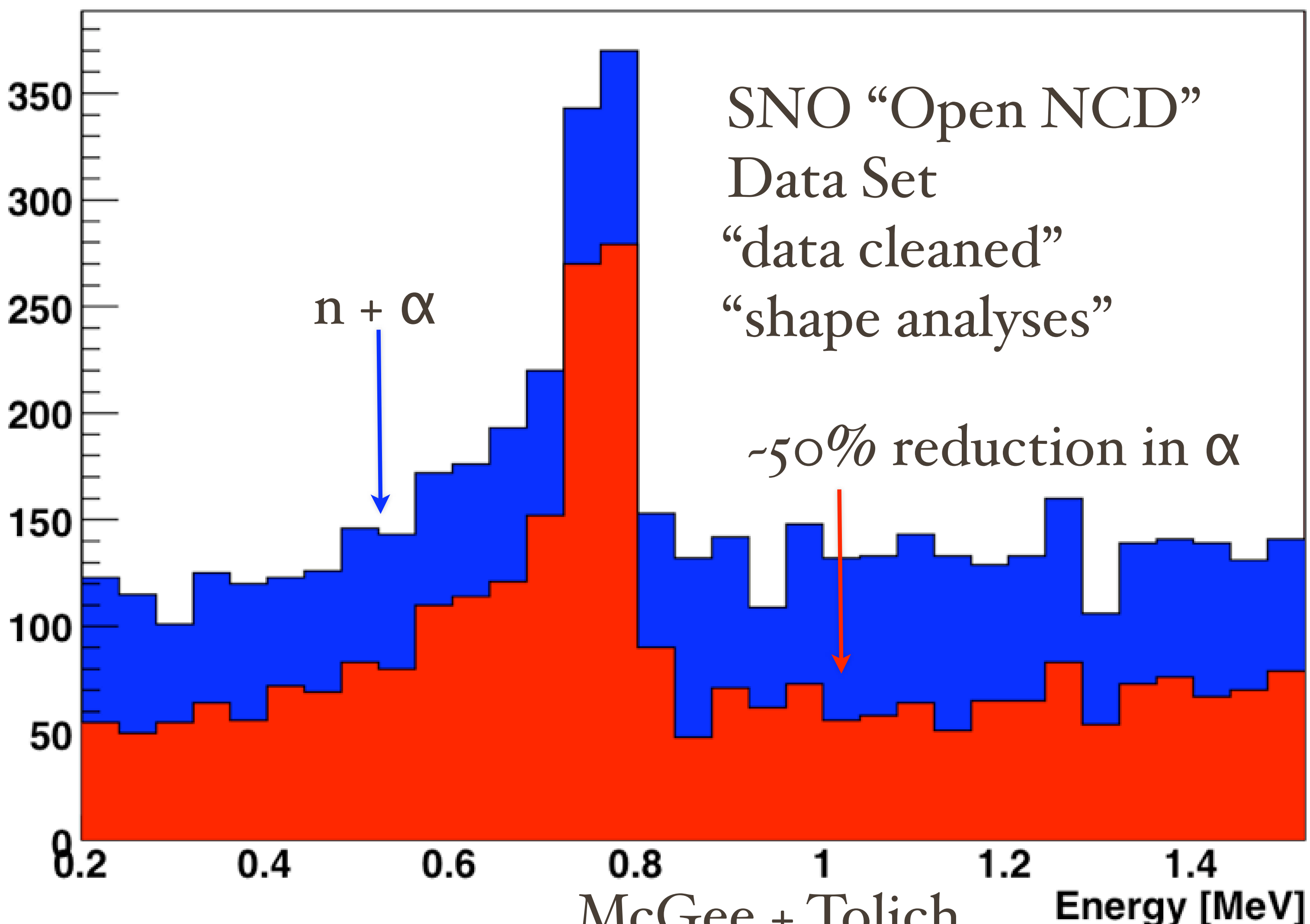
NCD instrumental background rejection







NCD Pulse Shape Analysis



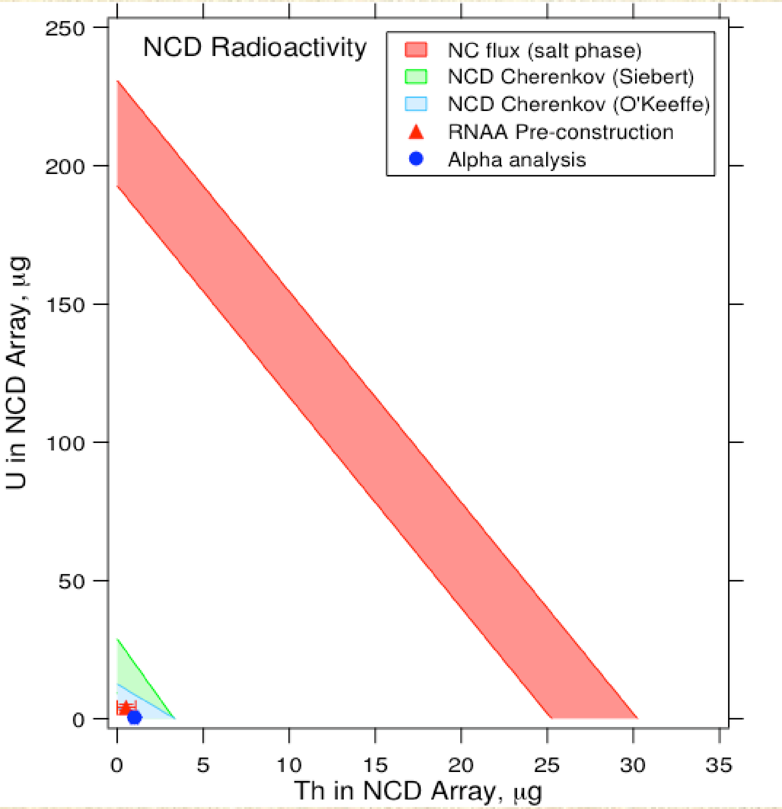
McGee + Tolich

NCD Neutrino Physics Analysis

Main activity is to understand the alpha background

Multi-prong approach:

- ^{4}He counters in detector
- Spare ^{4}He counters
- Bench test of “bulk” alphas
- Beam test @ Yale WNSL



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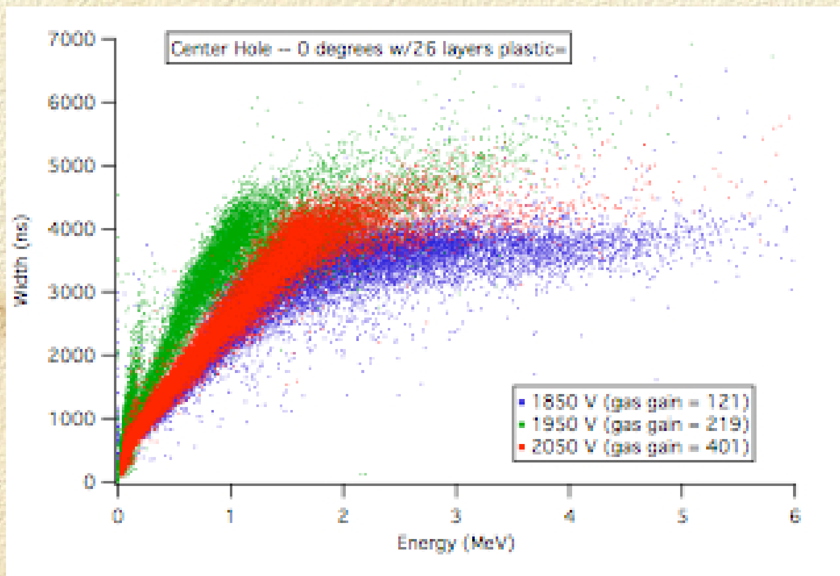
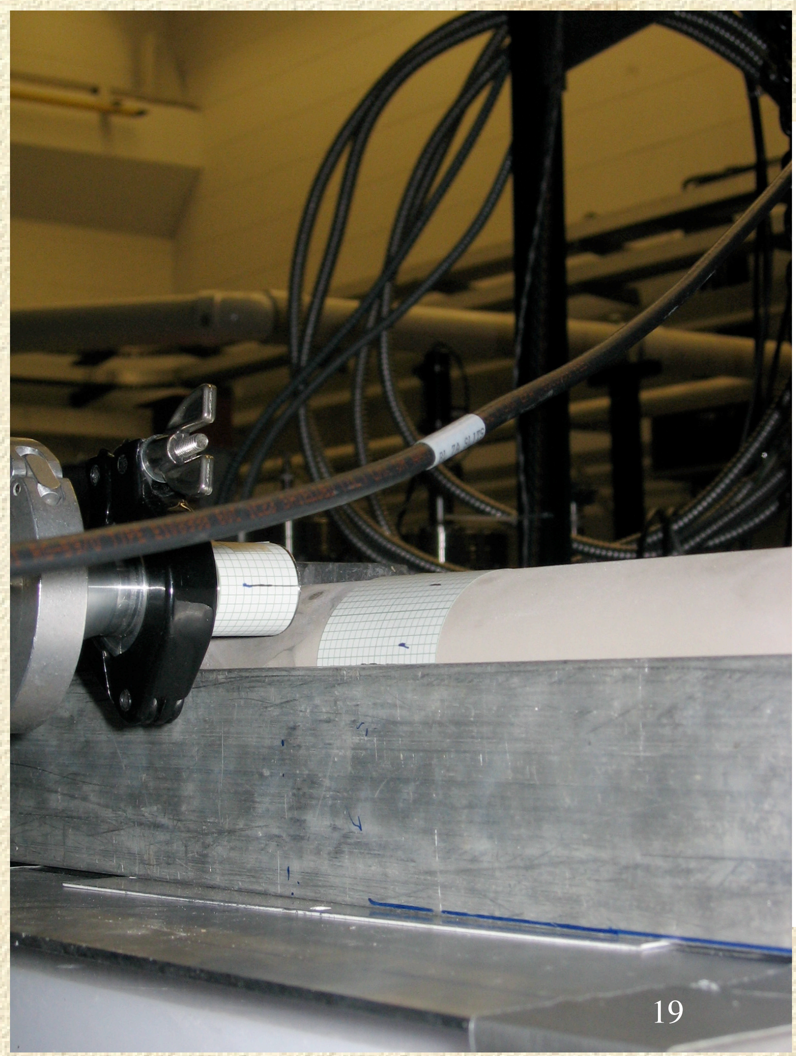
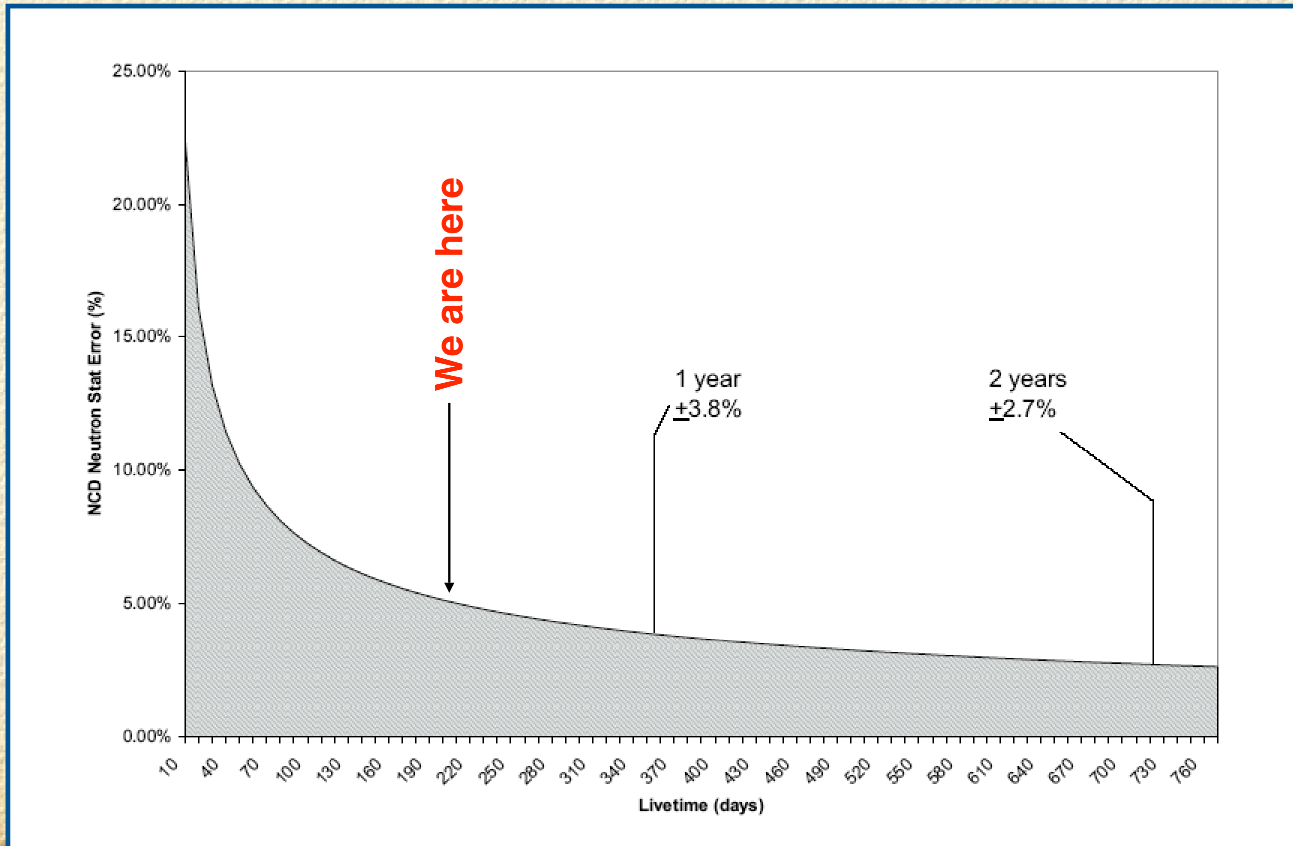




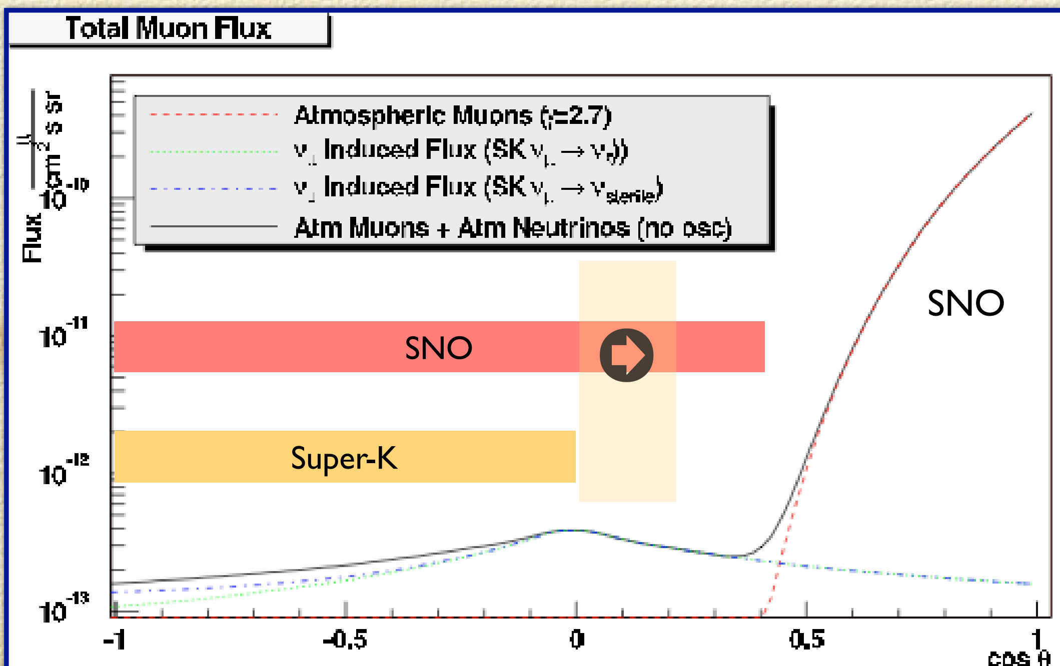
Initial NCD Physics Plans

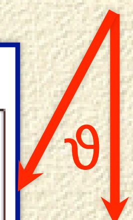
- Scope: NC measurement + CC and ES flux, similar to the first salt PRL
- Data set: data cutoff day is the end of Feb. 2006 if better than 6% statistical
- Actively working 1st NCD analysis and publication: low level analysis in good shape and significant progress on high-level components



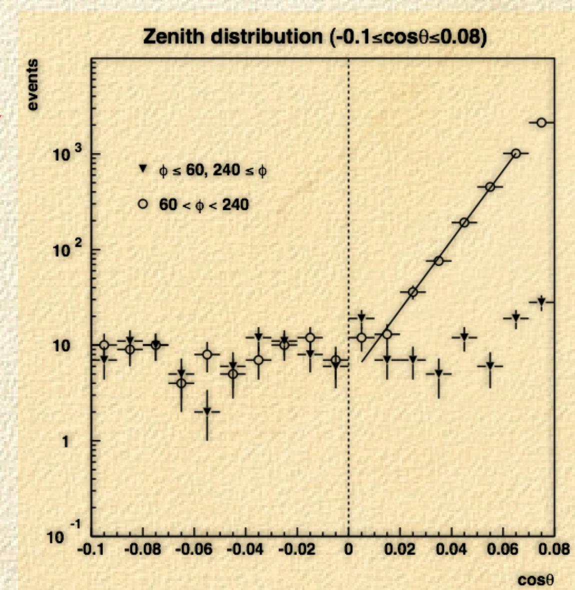
Atmospheric neutrinos in SNO

- SNO is of modest size ➪ cannot perform contained events analysis e-like/μ-like ➪ zenith distribution of muons (up vs down)
- For zenith angles θ<66° (cosθ>0.4), muons from cosmic rays
- For θ>66° ➪ muons generated in neutrino interactions in the rock





[Takahata thesis, SK]

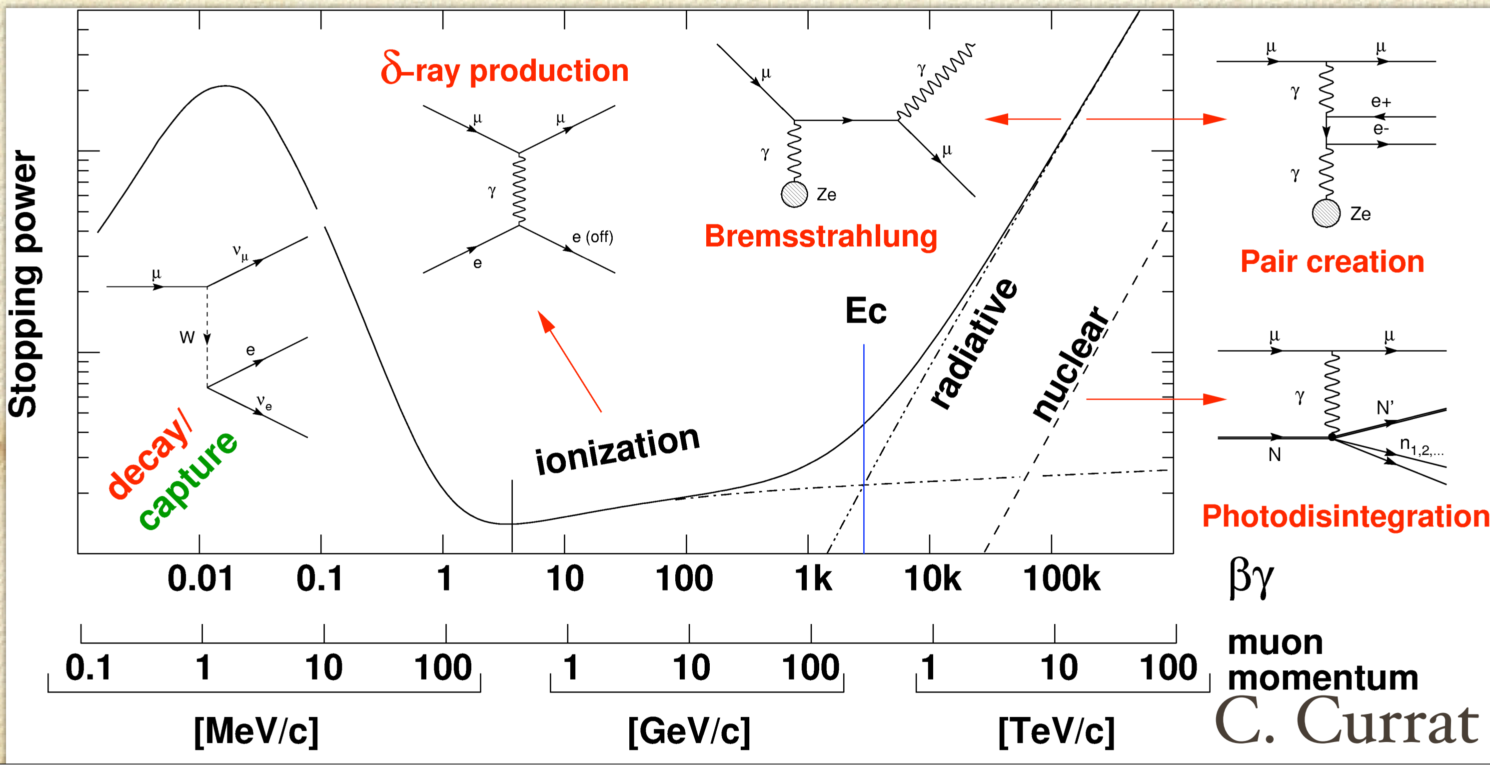


SNO's Simulations of Neutrinos

Muon simulations in SNO Monte Carlo: from O(10 TeV) down to explicit thermalization of spallation products (neutron @ 1/40 eV) the same data structure accommodates {~14 orders of magnitude} in energy!

=> year-long group-wide effort, now completed

=> fine tuning and performance/physics benchmark tests

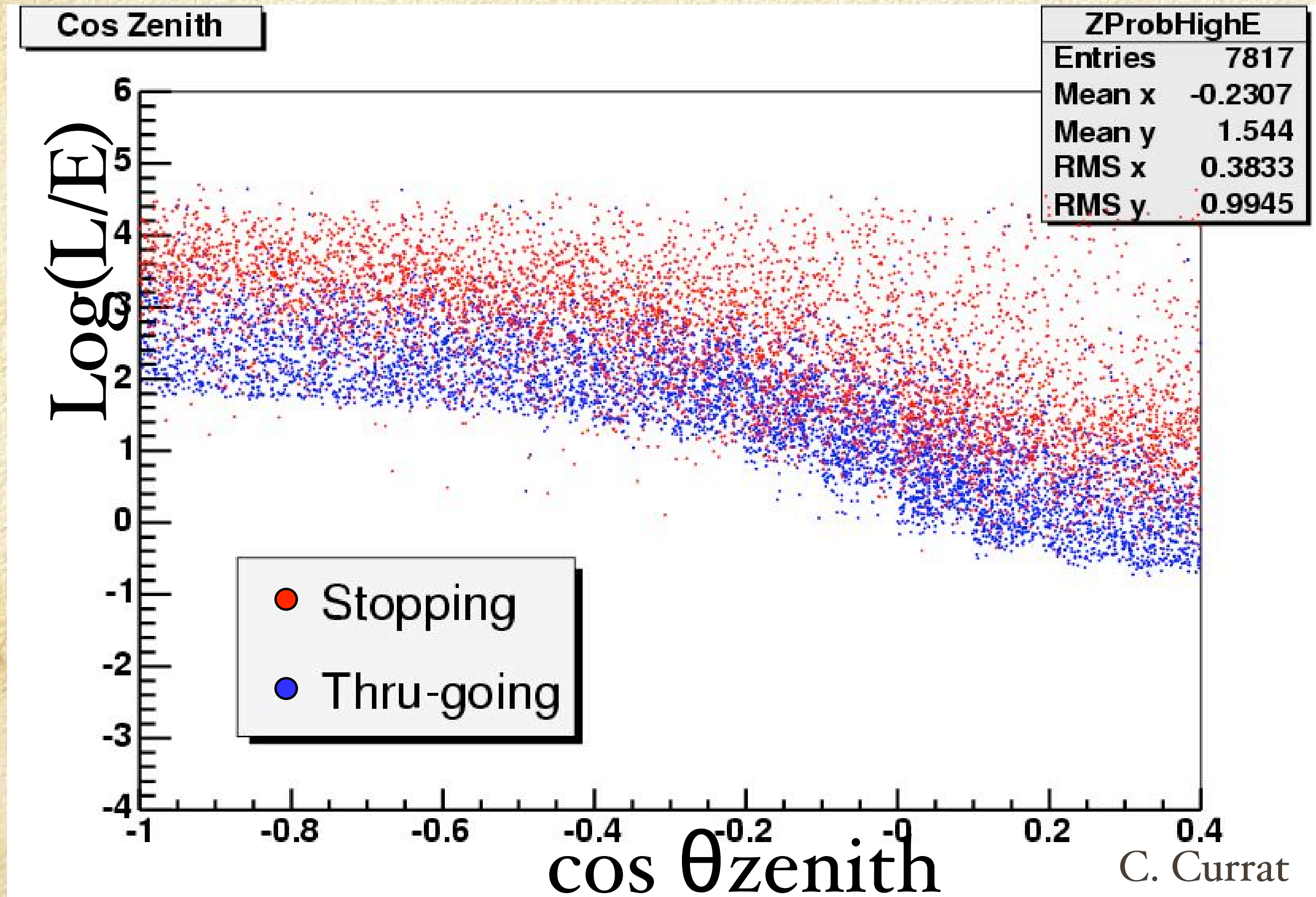


C. Currat

Muon Analysis

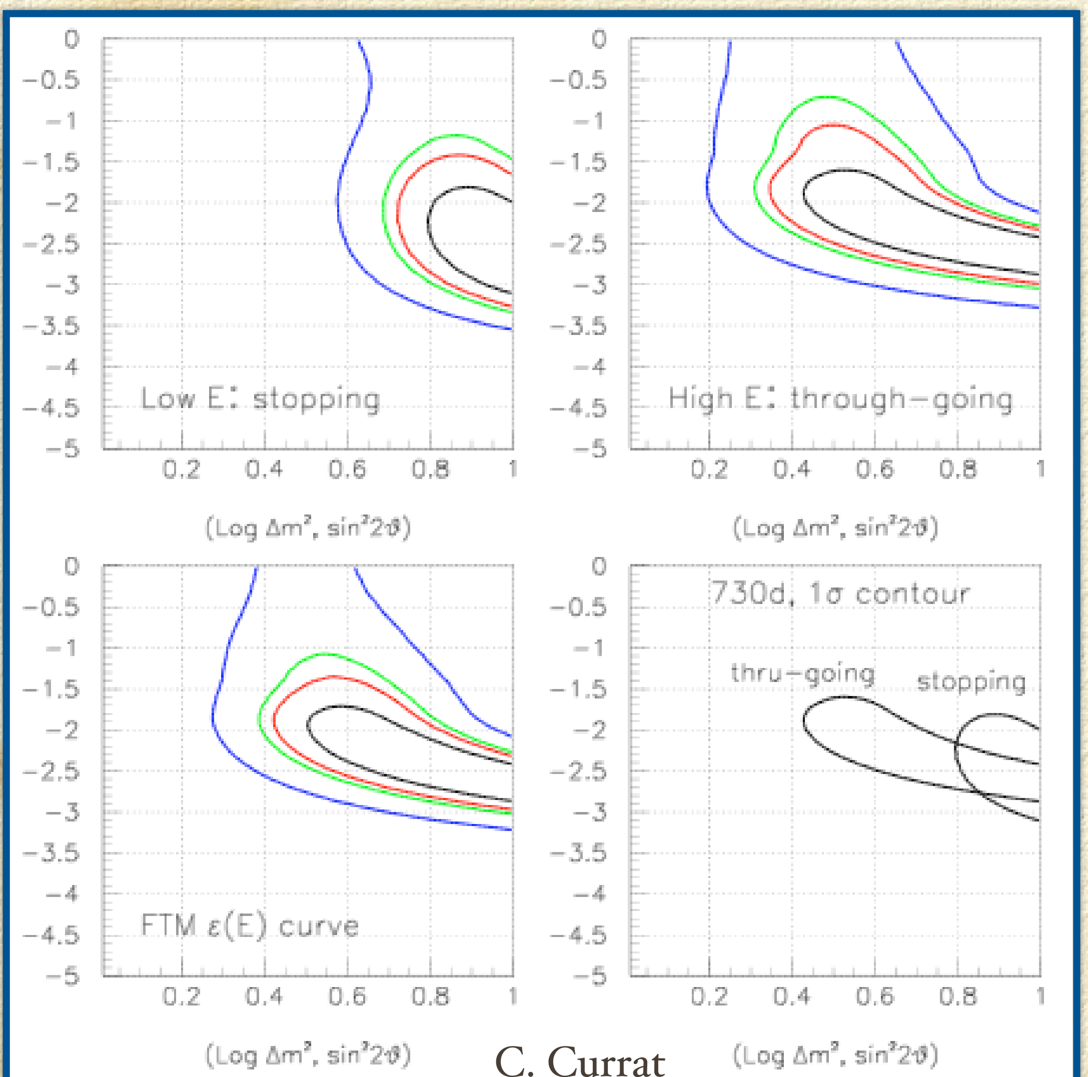
Low energy muons that stop in the detector probing a different parameter region

$$P_{ee} = 1 - \sin^2 2\theta^* \sin^2(1.27 * \Delta m^2 \, L\,[\mathrm{km}]/E\,[\mathrm{GeV}])$$

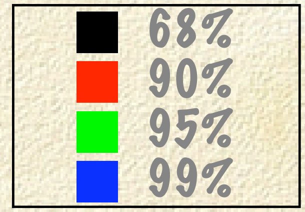


Sensitivity to oscillation parameters

MC only
no systematics

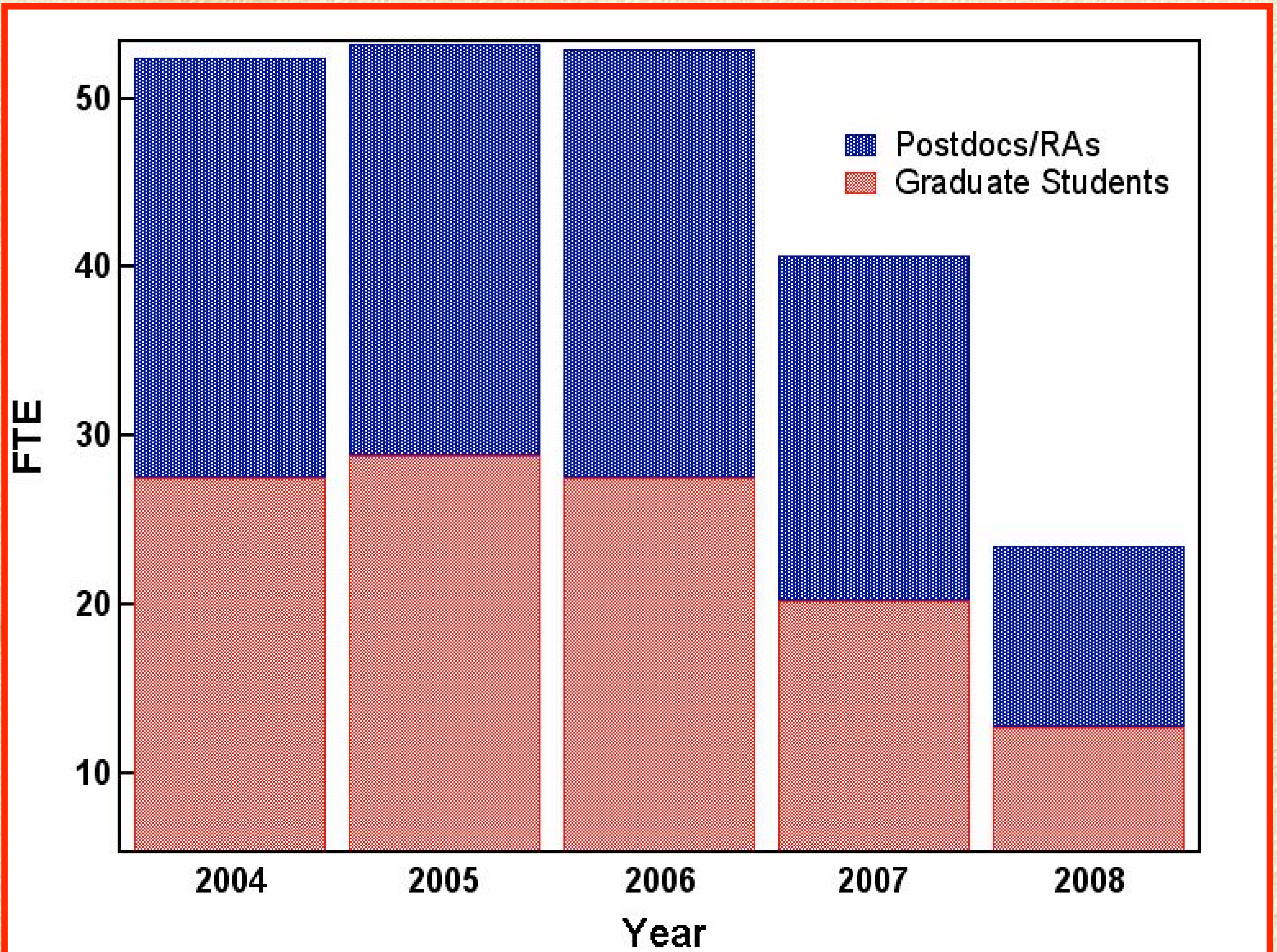


C. Currat



- Assuming parameters (Δm^2, $\sin^2 2\vartheta$)=(2.3×10^{-3},1)
- 730 days livetime in D_2O+salt solar datasets
- Final dataset will be ~900 days (extended dataset + some calibration runs)

Graduate & Postgraduate Training



Graduate & Postgraduate Training

- Dr. Alysia Marino - UCB - Lesko
  - 2006 APS Tanaka Dissertation Award - DPF
  - "For her contributions to the measurement of neutrino fluxes which conclusively support the hypothesis of flavor oscillation of neutrinos produced in the sun as they travel toward the earth. The results further suggest the most likely cause of the flavor change to be matter-induced oscillation."

- Dr. Karsten Heeger - U. W. - Robertson
  - 2003 DNP Dissertation Award
  - " For his role in the generation and analysis of the data from the Sudbury Neutrino Observatory, and the resulting resolution of the solar neutrino problem."

SNO's Physics Goals 2006-2008

- Three main areas:
  - Solar Neutrinos
    - Integral flux measurements, day-night flux asymmetry, θ_{12} and θ_{13}
    - Search for direct evidence of MSW effect and other new physics with ^{8}B solar neutrino spectrum (shape distortion, day-night, ...)
    - *hep* neutrinos update
  - High Energy Neutrinos
    - Atmospheric neutrinos
    - Spallation neutron productions
  - Other physics
    - Neutron-antineutron oscillation
    - Time correlation analyses, abnormal event rate and exotics
    - ...

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TRIUMF
R.L. Helmer

Remaining Questions for Neutrinos

- Absolute mass of a neutrino?
- How many neutrinos are there? 3 or more?
  - Sterile neutrinos?
- Are neutrinos their own anti-particle or not?
  - Neutrinoless double beta decay?
  - Understanding the full mixing of neutrinos?
- Precision Measurements of parameters
  - θ_{13} of particular interest
- CP violation in Leptons?
- Extend the Standard Model
- Hints for new symmetries and origins of mass?