Sudbury Neutrino Observatory

THE SNO COLLABORATION

M. G. Boulay, M. Chen, F. A. Duncan, E. D. Earle, H. C. Evans, G. T. Ewan, R. J. Ford, A. L. Hallin,
P. J. Harvey, J. D. Hepburn, C. Jillings, H. W. Lee, J. R. Leslie, H. B. Mak, A. B. McDonald,
W. McLatchie, B. Moffat, B.C. Robertson, P. Skensved, B. Sur.
Queen's University, Kingston, Ontario K7L 3N6, Canada.

I. Blevis, F. Dalnoki-Veress, W. Davidson, J. Farine, D.R. Grant, C. K. Hargrove, I. Levine, K. McFarlane,
T. Noble, V.M. Novikov, M. O'Neill, M. Shatkay, C. Shewchuk, D. Sinclair
Carleton University, Ottawa, Ontario K1S 5B6, Canada.

T. Anderson, M.C. Chun, P. Jagam, J. Law, I.T. Lawson, R. W. Ollerhead, J. J. Simpson, N. Tagg, J.X. Wang
University of Guelph, Guelph, Ontario N1G 2W1, Canada.

J. Bigu, J.H.M. Cowan, E. D. Hallman, R. U. Haq, J. Hewett, J.G. Hykawy, G. Jonkmans, A. Roberge,
E. Saettler, M.H. Schwendener, H. Seifert, R. Tafirout, C. J. Virtue.
Laurentian University, Sudbury, Ontario P3E 2C6, Canada.

S. Gil, J. Heise, R. Helmer, R.J. Komar, T. Kutter, C.W. Nally, H.S. Ng, R. Schubank,
Y. Tserkovnyak, C.E. Waltham.
University of British Columbia, Vancouver, BC V6T 1Z1, Canada.

E. W. Beier, D. F. Cowen, E. D. Frank, W. Frati, P.T. Keener, J. R. Klein, C. Kyba, D. S. McDonald,
M.S.Neubauer, F. M. Newcomer, V. Rusu, R. Van Berg, R. G. Van de Water, P. Wittich.
University of Pennsylvania, Philadelphia, PA 19104, USA.

T. J. Bowles, S. J. Brice, M. Dragowsky, M. M. Fowler, A. Goldschmidt, A. Hamer,
A. Hime, K. Kirch, J. B. Wilhelmy, J. M. Wouters.
Los Alamos National Laboratory, Los Alamos, NM 87545, USA.

Y. D. Chan, X. Chen, M.C.P. Isaac, K. T. Lesko, A.D. Marino, E.B. Norman, C.E. Okada,
A.W. P. Poon, A. R. Smith, A. Schuelke, R. G. Stokstad.
Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA.

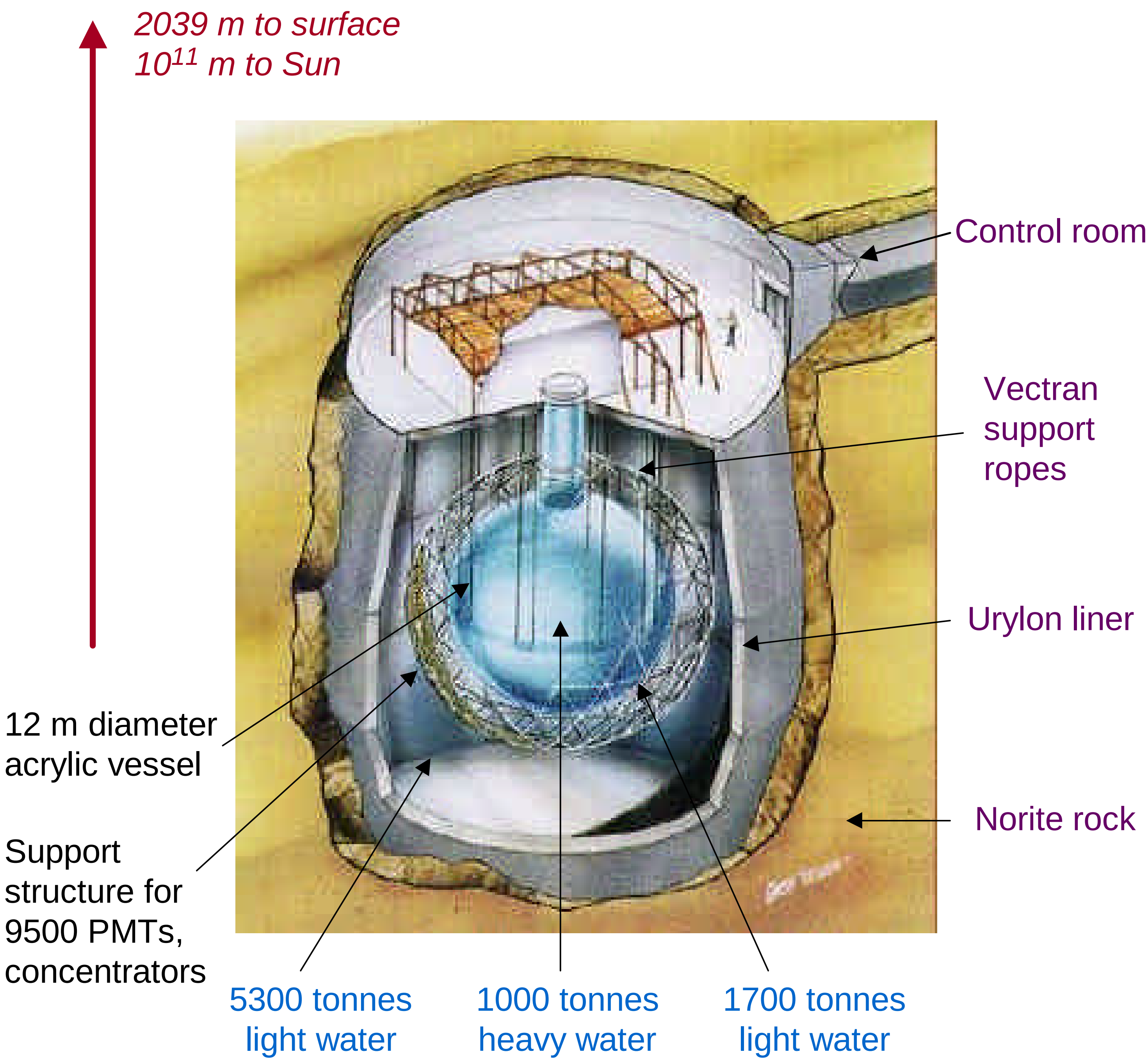
Q. R. Ahmad, M. C. Browne, T.V. Bullard, P. J. Doe, C. A. Duba, S. R. Elliott, R. Fardon, J.V. Germani, A. A. Hamian,
K. M. Heeger, R. Meijer Drees, J. Orrell, R. G. H. Robertson, K. Schaffer, M. W. E. Smith, T. D. Steiger, J. F. Wilkerson.
University of Washington, Seattle, WA 98195, USA.

J. C. Barton, S.Biller, R. Black, R. Boardman, M. Bowler, J. Cameron, B. Cleveland, G. Doucas, Ferraris, H. Fergami,
K.Frame, H. Heron, C. Howard, N. A. Jelley, A. B. Knox, M. Lay,W. Locke, J. Lyon, N. McCaulay, S. Majerus,
G. MacGregor, M. Moorhead, M. Omori, N. W. Tanner, R. Taplin, M. Thorman, P. T. Trent, D. L.Wark, N. West.
University of Oxford, Oxford OX1 3NP, United Kingdom.

J. Boger, R. L Hahn, J.K. Rowley, M. Yeh
Brookhaven National Laboratory, Upton, NY 11973-5000, USA.

R.G. Allen, G. Buhler, H.H. Chen*
University of California, Irvine, CA 92717, USA
* Deceased

The SNO Detector



- **Location:** 6800 ft. level of INCO's Creighton mine near Sudbury, ON, Canada (~70 muons / day)

- **SNO Detector:** 9438_{inward} + $91_{outward}$ Hamamatsu 8" PMTs + concentrators = 64% coverage

SNO Measurements

Charged Current Reaction (D_2O):

CC | n_e **+ d** ® **p + p +** ***e***$^-$ E_{thres}= 1.4 MeV | **(only n_e)**

• ν_e energy spectrum (distortion ⇒ MSW effect)
• Some directional sensitivity (1 - 1/3 cos θ_e)

Neutral Current Reaction (D_2O):

NC | n_x **+ d** ® n_x **+ p +** ***n*** E_{thres} = 2.2 MeV | **(ALL n types)**

• Total solar ^{8}B neutrino flux (active neutrinos)

Ratio = $\frac{CC}{NC}$ = $\frac{(n_e)\ flux}{(n_e + n_m + n_t)\ flux}$

Elastic Scattering Reaction (D_2O,H_2O):

ES | n_x **+ e**$^-$ ® n_x **+** ***e***$^-$ E_{thres} = 0 MeV | **(mostly n_e)**

• Low counting rate
• Directional sensitivity (very forward peaked)

Ratio = $\frac{CC}{ES}$ = $\frac{(n_e)\ flux}{0.86\ n_e + 0.14(n_m + n_t)\ flux}$

SNO Physics Goals

Main Physics Goals:

- **Solar Neutrinos**
  - **Search for Flavour Change (n oscillations):**
  - **Distortion of the ^{8}B Neutrino Energy Spectrum**
  - **Total ^{8}B Neutrino Flux**
  - **Time Dependence**

- **Supernova Neutrinos (See Poster)**

- **Cosmic Ray Muons (See Poster)**

- **Atmospheric Neutrinos (See Poster)**

- **Search for Non-Electron Type Neutrinos from the Sun**

  ® unique signature: anti-$\nu_e + d \rightarrow n + n + e^+$

SNO Experimental Plan

Three Phases (About 1 year Each):

Phase 1: Pure D_2O
- Good sensitivity for CC, lower for ES, NC

Phase 2: Added Salt
- Enhanced sensitivity for NC

Phase 3: ^{3}He detectors in Pure D_2O
- Independent sensitivity for NC

Neutron Detection Methods In 3 Phases:

1. **Neutron capture on deuterium in pure D_2O:**

   n + d ® t + g… ® e^- (E_g= 6.3 MeV)

   -capture efficiency, ε_{D_2O} = 24%

2. **Neutron capture on Cl using Salt in D_2O:**

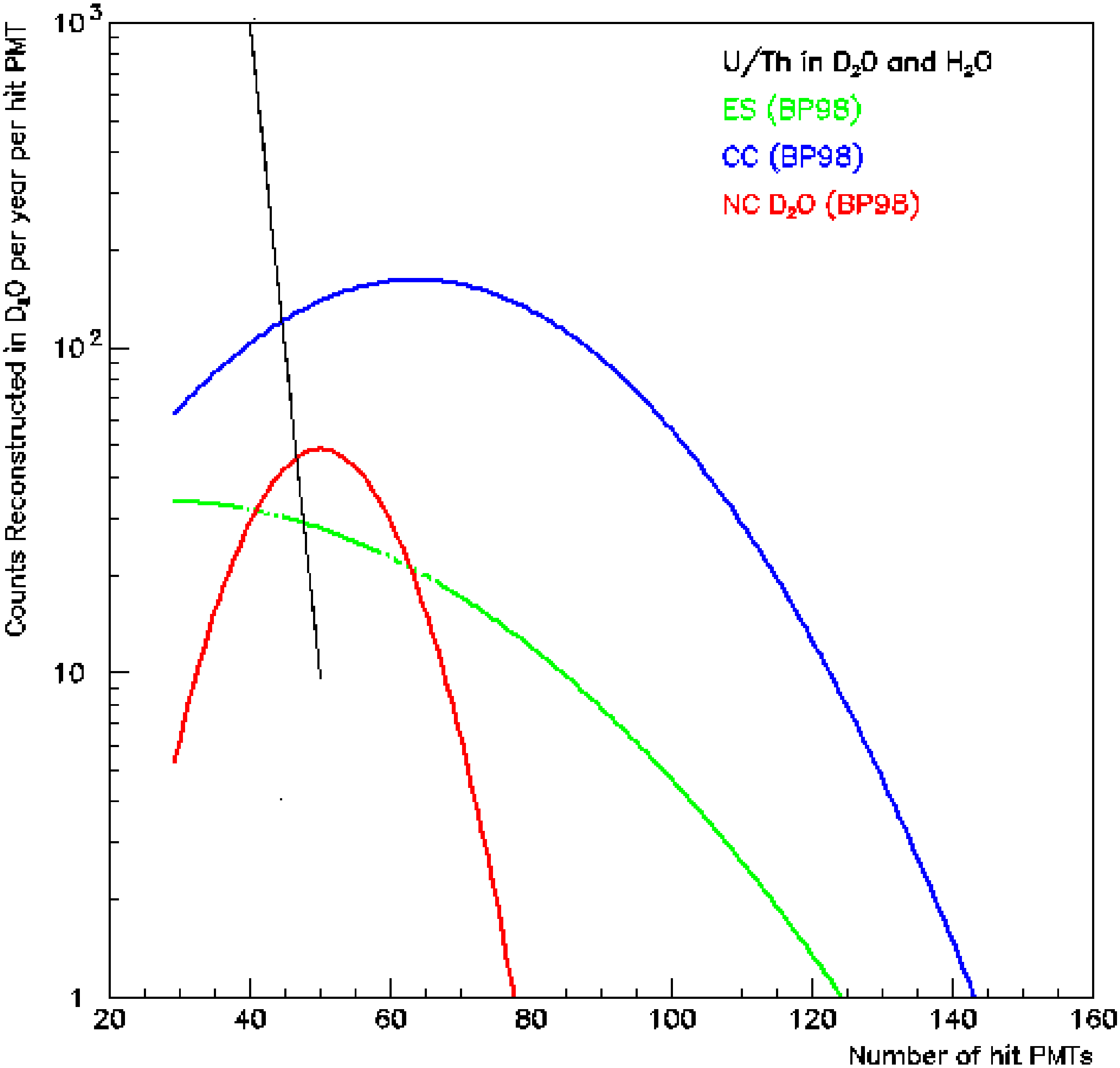
   n + ^{35}Cl ® ^{36}Cl + S g… ® e^- ($E_{S\,g}$= 8.6 MeV)

   - capture efficiency, ε_{salt} = 83%

3. **Neutron capture on He using proportional counters:**

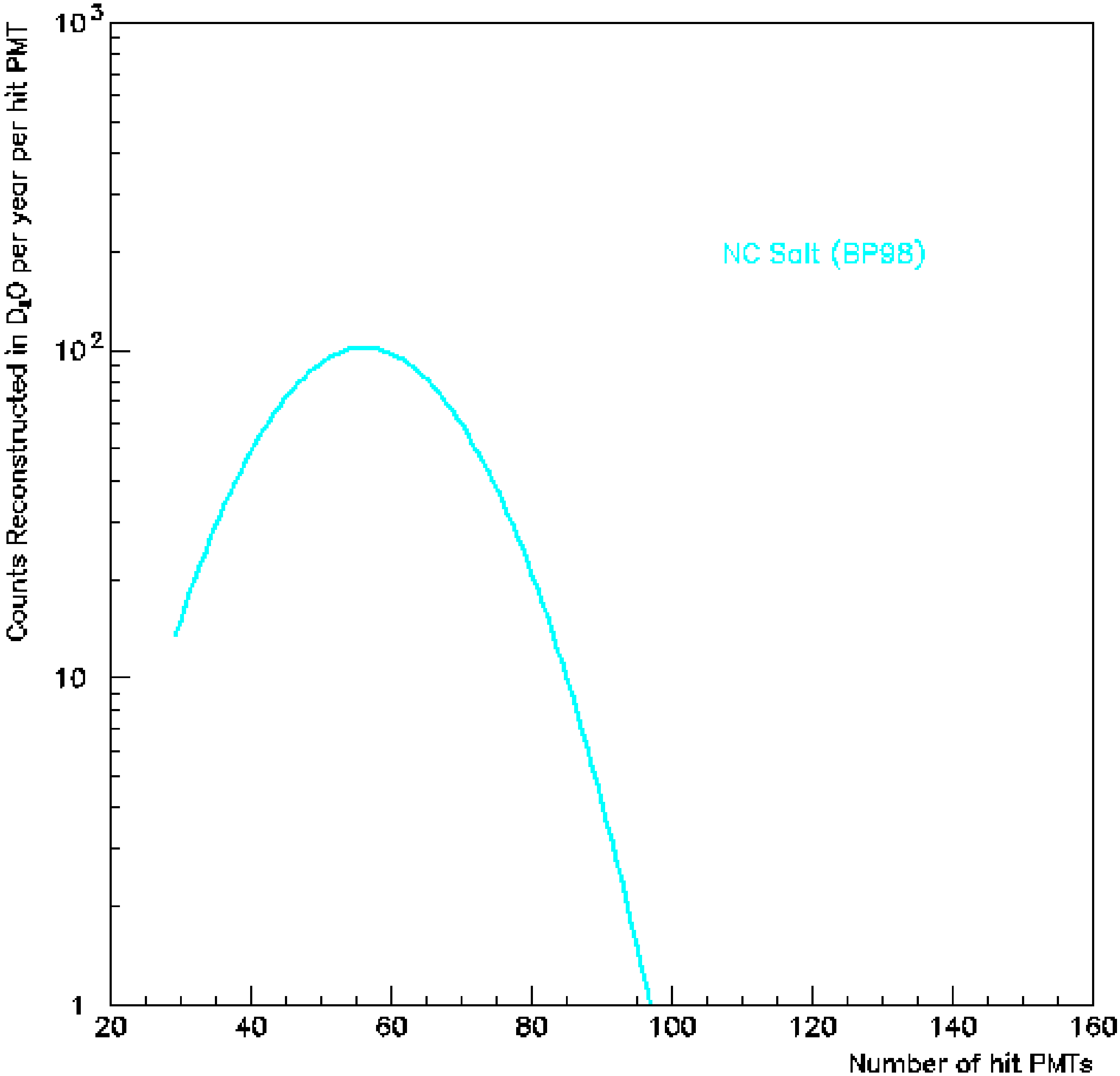
   n + ^{3}He ® p + t

   -capture efficiency, ε_{NCD} = 45%



U/Th in D_2O and H_2O
ES (BP98)
CC (BP98)
NC D_2O (BP98)
Counts Reconstructed in D_2O per year per hit PMT
Number of hit PMTs
10^3
10^2
10
1
20
40
60
80
100
120
140
160

~ 9 NHIT/MeV



Counts Reconstructed in D_2O per year per hit PMT
10^3
10^2
10
1
NC Salt (BP98)
20
40
60
80
100
120
140
160
Number of hit PMTs

Detector Performance

From May to November 1999:

- Improve light sensitivity by 25% and reduce trigger threshold to about 2 MeV.
- Install Neck Phototubes to cut instrumental light.
- Reduce Radon below target levels.

PHASE 1 Begins: November, 1999

- Detector parameters frozen, start of production neutrino data.

Detector Performance Since Nov. 1999

- Average channel thresholds < 0.3 p.e.
- PMT noise rates ~500 Hz; typical noise PMT/event ~2
- Overall trigger rate (all trigger types) ~ 15 Hz
- **>**98.5% of all PMT channels fully operational

CC Analysis For Solar Neutrinos:

Note:

• CC Cross Section Uncertainty ~ 6%. (Also CC/ES).

• CC/NC Cross Section Uncertainty ~ 2%.

Systematic Uncertainties For CC:

Objectives For Systematics in Phase 1:

• Energy Calibration (Objective < 1 %)

(Example: Δ Flux/Flux ~ 3 Δ E/E at E = 7.5 MeV)

• Fiducial volume (<1 % for Δ R/R)

• Background From Instrumental Light (Objective < 1 %)

• Radioactive Background (Objective < 1 %)

SNO Detector Calibrations

Electronics Calibrations (charge slopes,time slopes):

- **Charge pulser:** >600 000 constants; very stable

Optical Calibrations (reflectivity,absorption,timing):

- **Laser source:** photons of 337-700 nm, 0-45 Hz, variable intensity, variable position, into 4π

Energy Calibrations (PMTs/MeV scale, resolution):

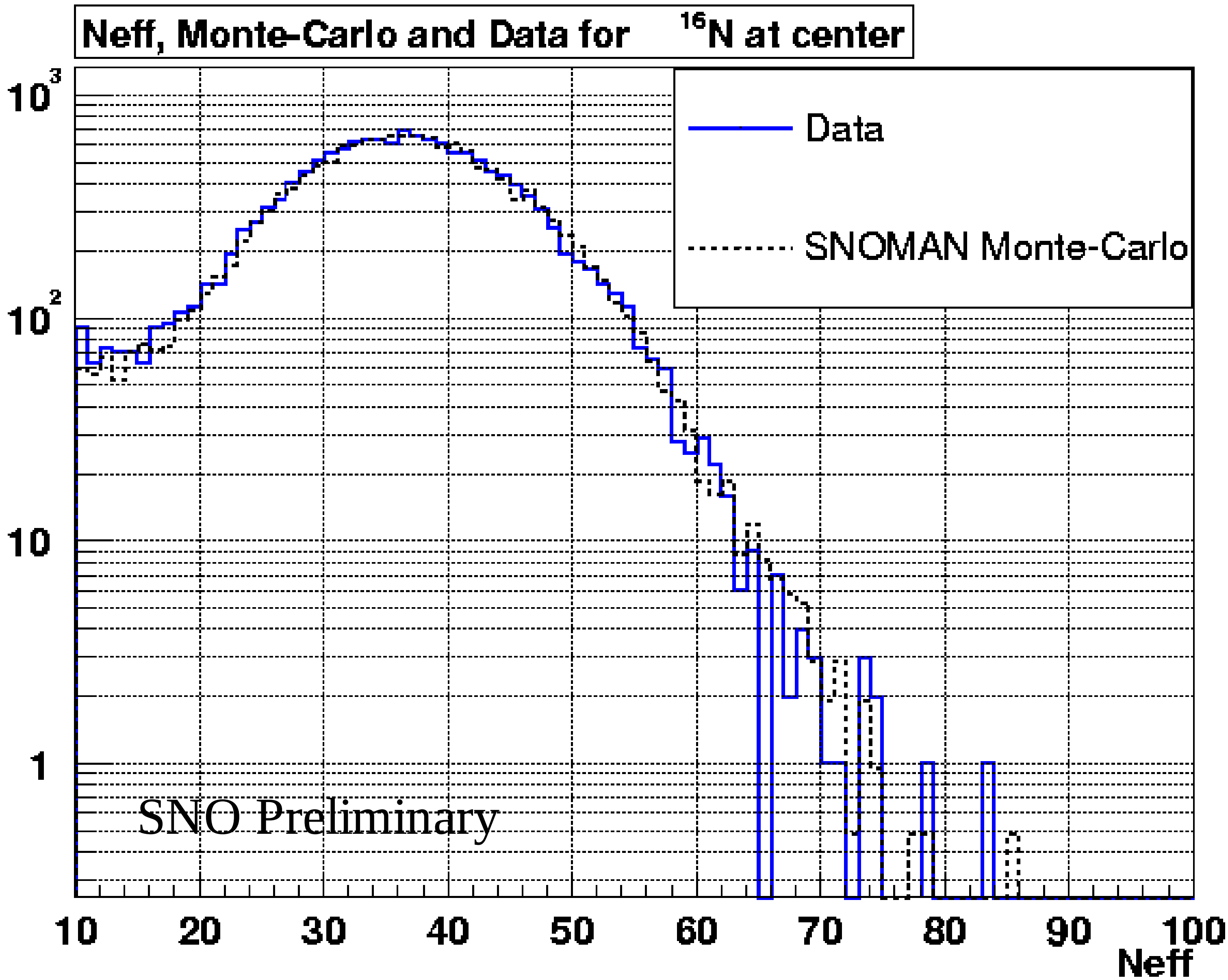
- **^{16}N source:** [$^{16}O(n,p)^{16}N^*$] β-tagged 6.1 MeV gamma source, energy calibration near analysis threshold, gain, angular response

Future:

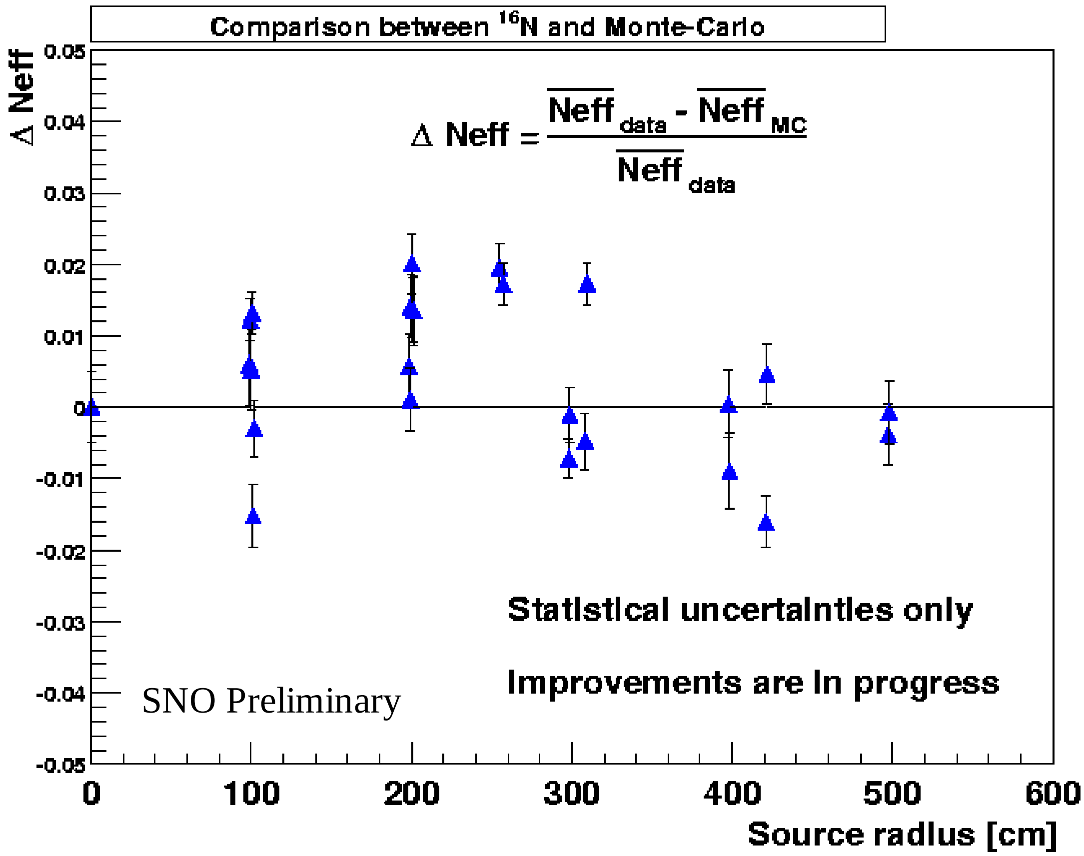
- **pT source:** [$^{3}H(p,\gamma)^{4}He$] 19.8 MeV gamma source, high energy effects (multi-photoelectron, charge response)
- **Triggered U, Th sources:** Low energy gammas (2.6, 2.4 MeV)
- **^{8}Li source:** electron energy spectrum similar to ^{8}B

Neutron Detection Efficiency (NC measurement):

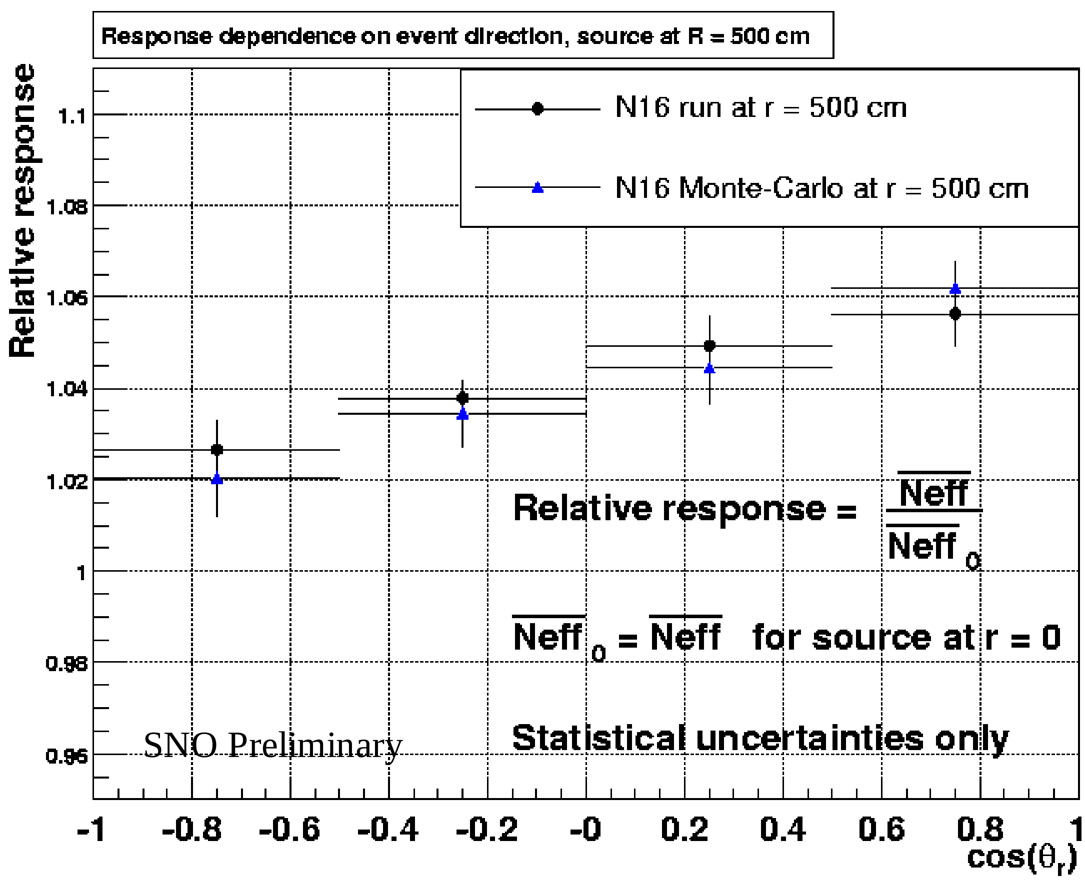
- **^{252}Cf source:** fission neutron source



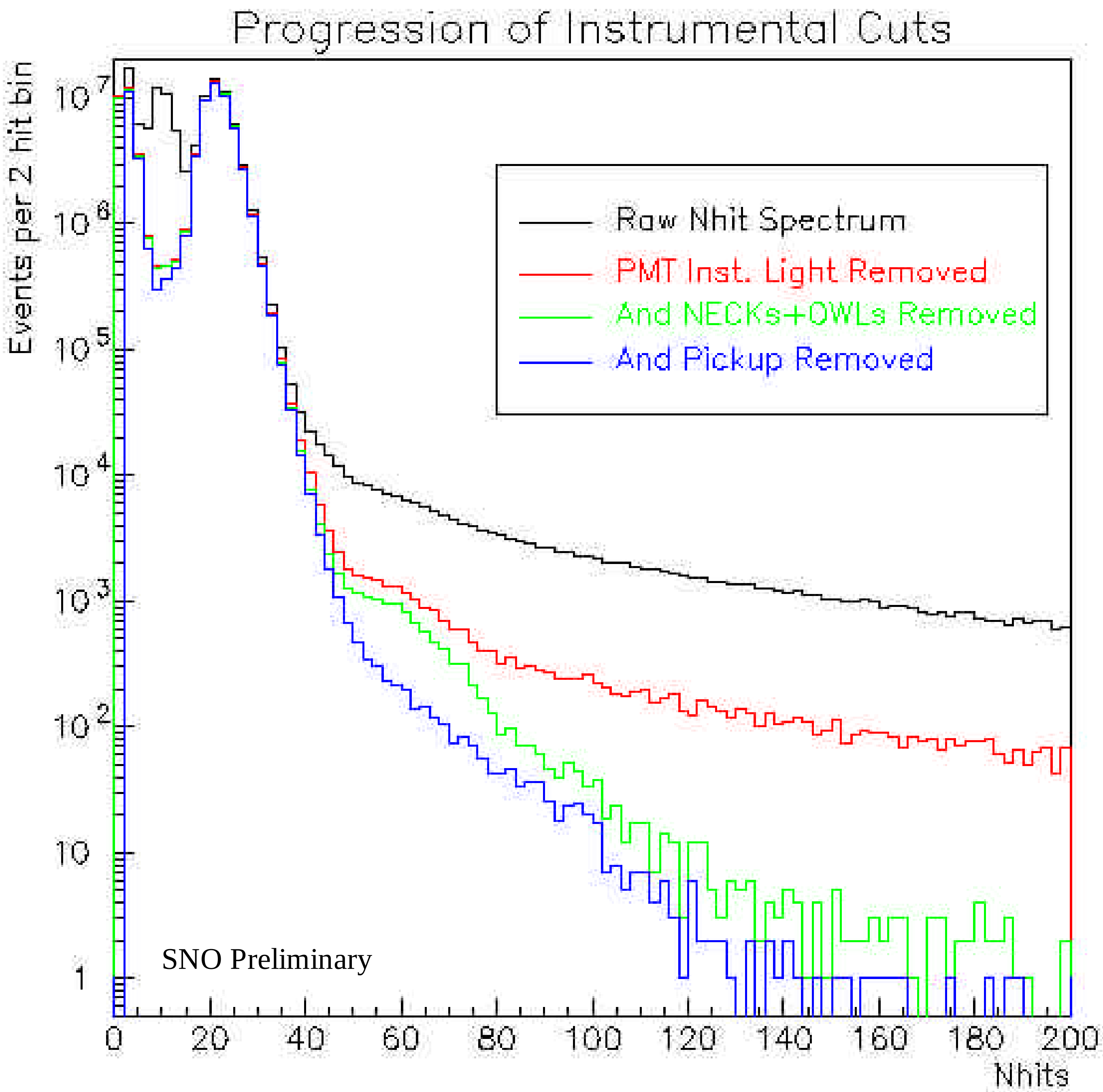
$$N_{eff} = NHIT_{\text{prompt light}} - NHIT_{\text{noise}}$$



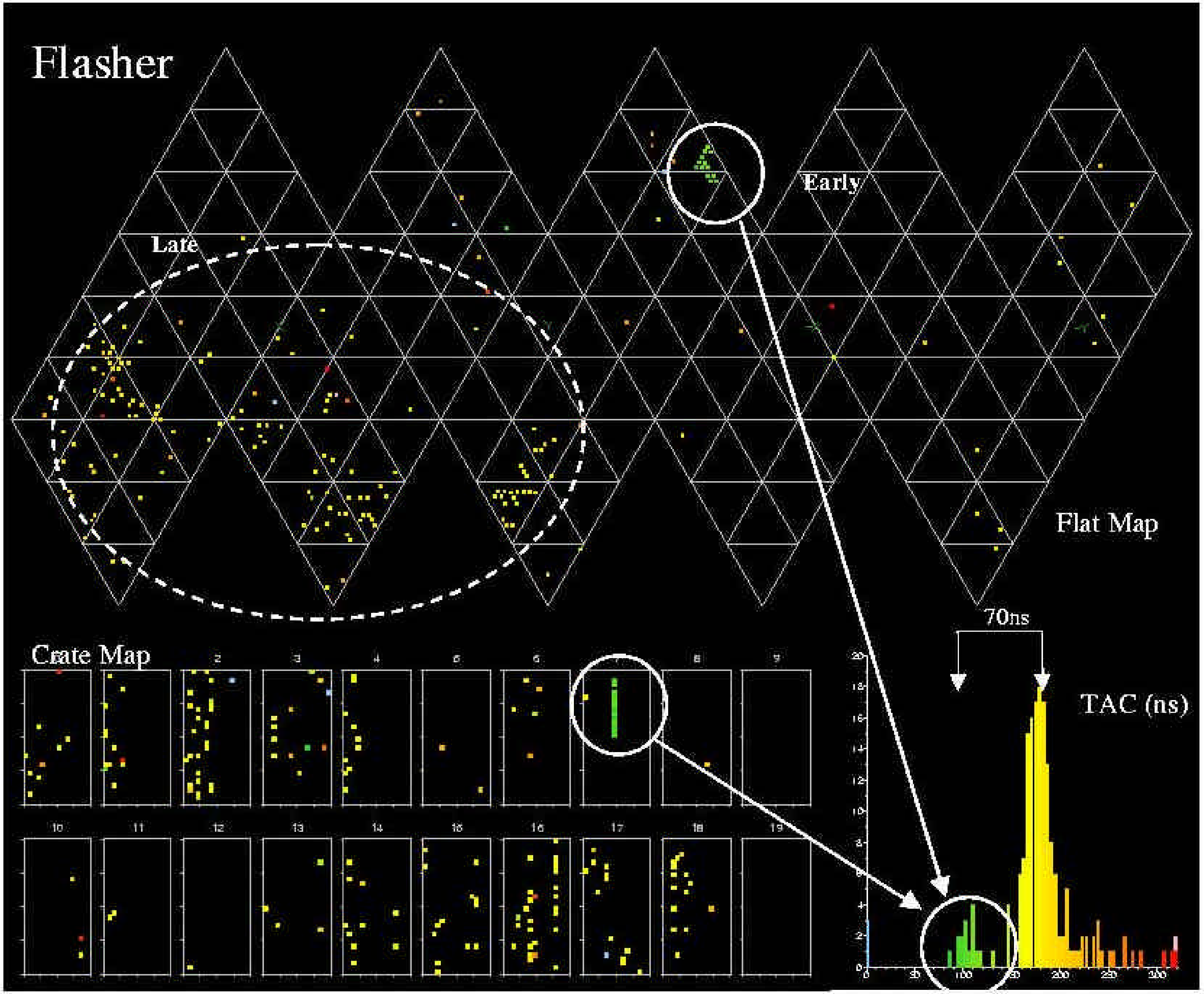
Comparison between ^{16}N and Monte-Carlo
Δ Neff
Δ Neff = $\frac{\overline{Neff}_{data} - \overline{Neff}_{MC}}{\overline{Neff}_{data}}$
Statistical uncertainties only
Improvements are in progress
SNO Preliminary
Source radius [cm]

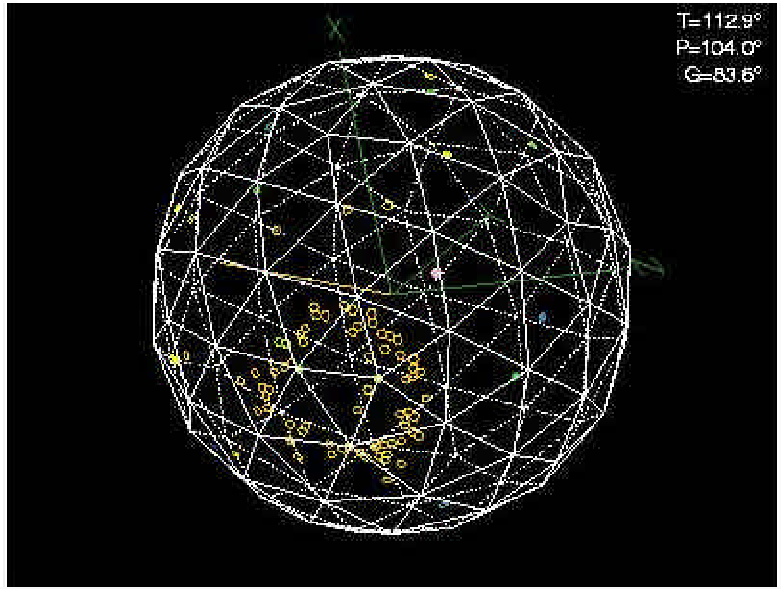


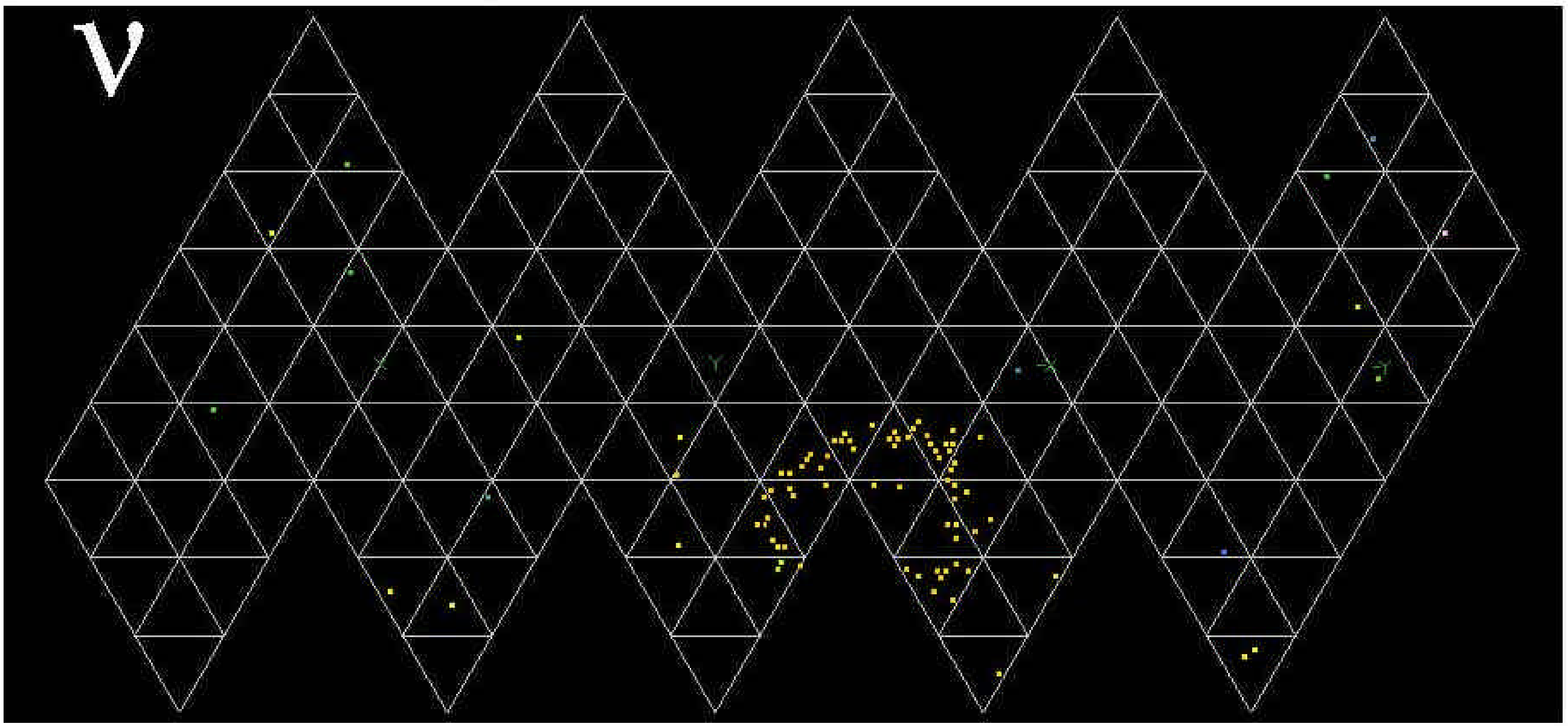
Response dependence on event direction, source at R = 500 cm
Relative response
N16 run at r = 500 cm
N16 Monte-Carlo at r = 500 cm
Relative response = $\frac{\overline{Neff}}{\overline{Neff}_0}$
$\overline{Neff}_0 = \overline{Neff}$ for source at r = 0
Statistical uncertainties only
SNO Preliminary
cos(θ_r)



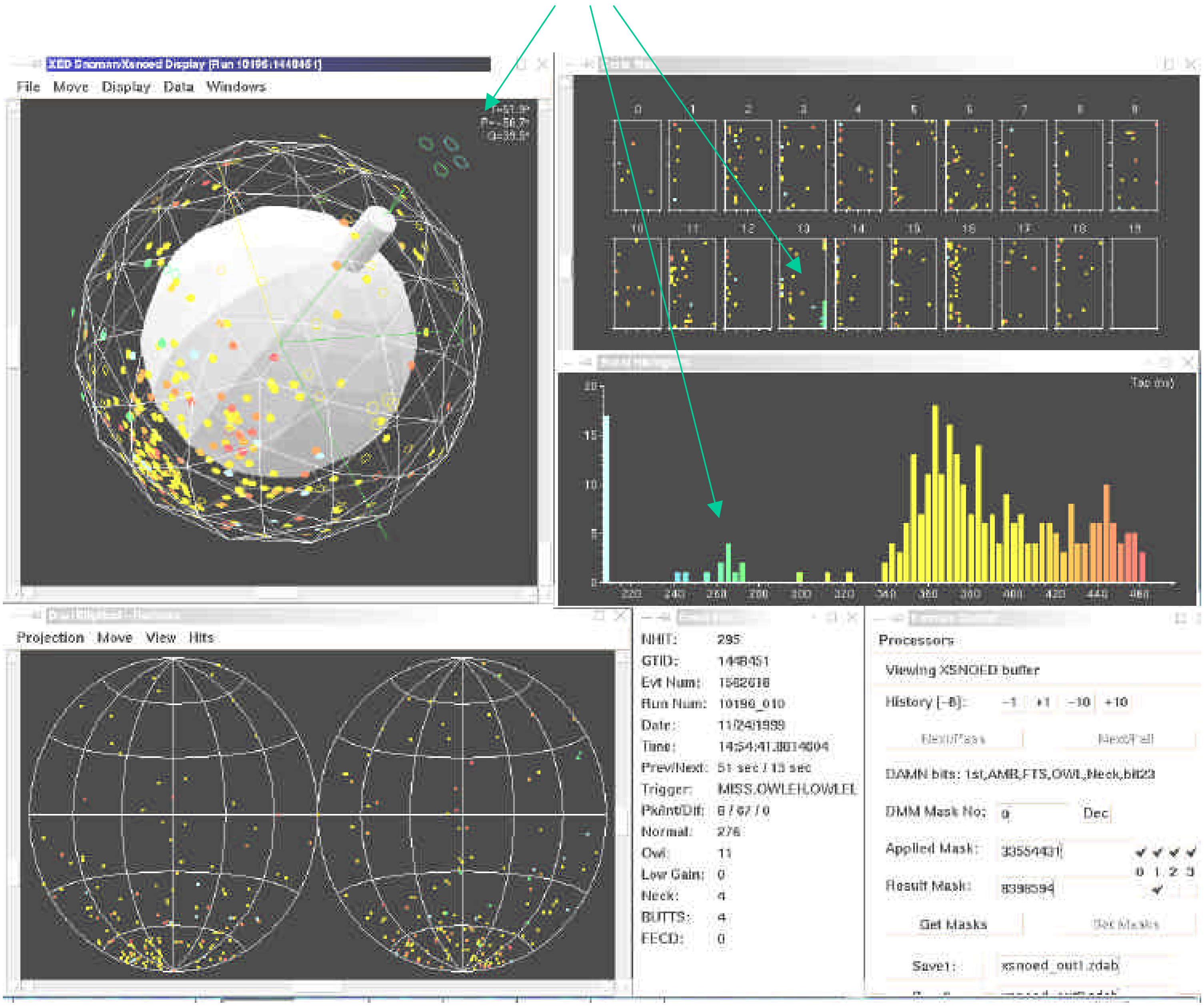
A fraction of the data is being analyzed to study instrumental cuts. The remainder has been retained for a future comparison.


Flasher
Late
Early
Flat Map
Crate Map
70ns
TAC (ns)

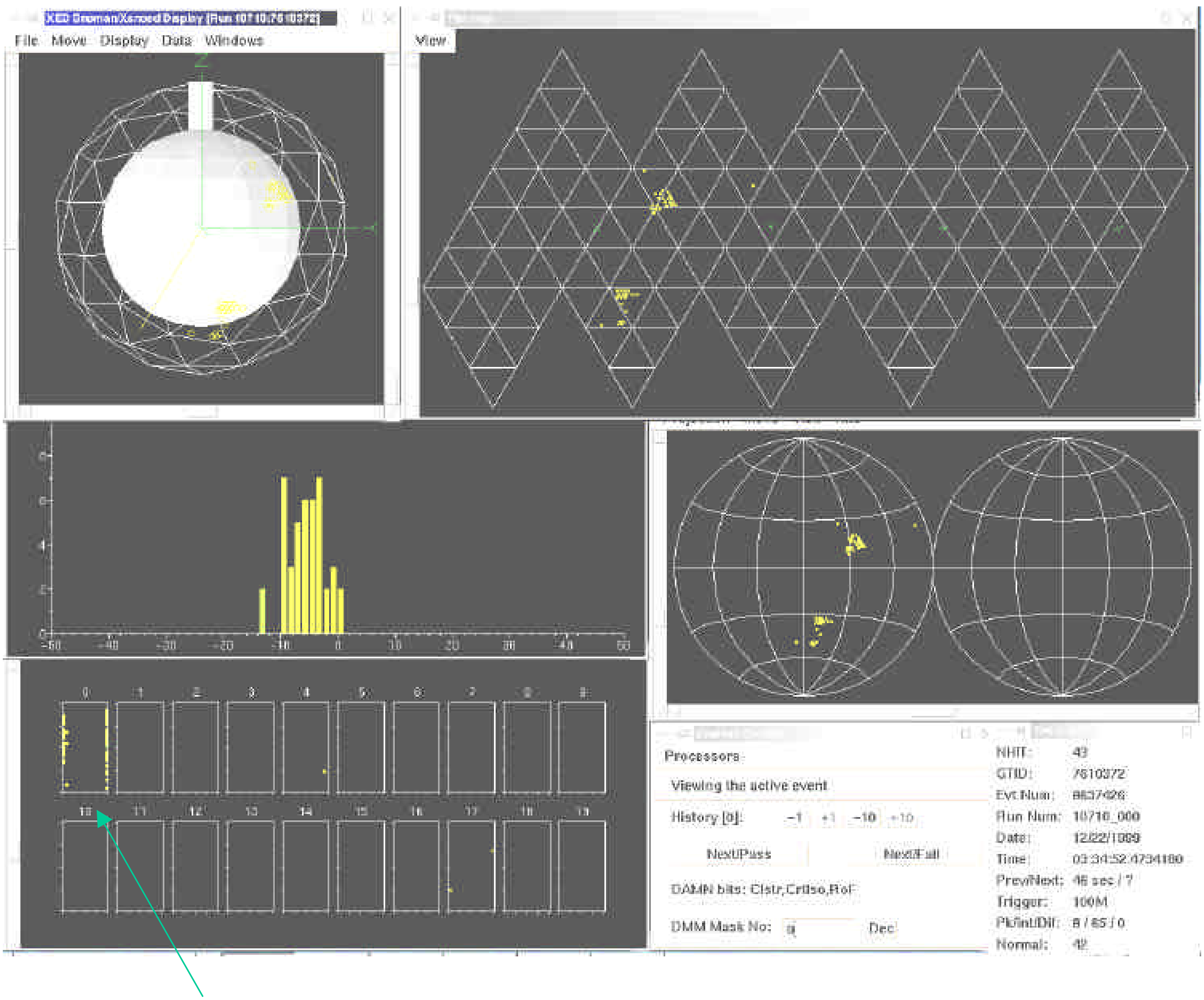

T=112.9°
P=104.0°
G=83.6°


ν

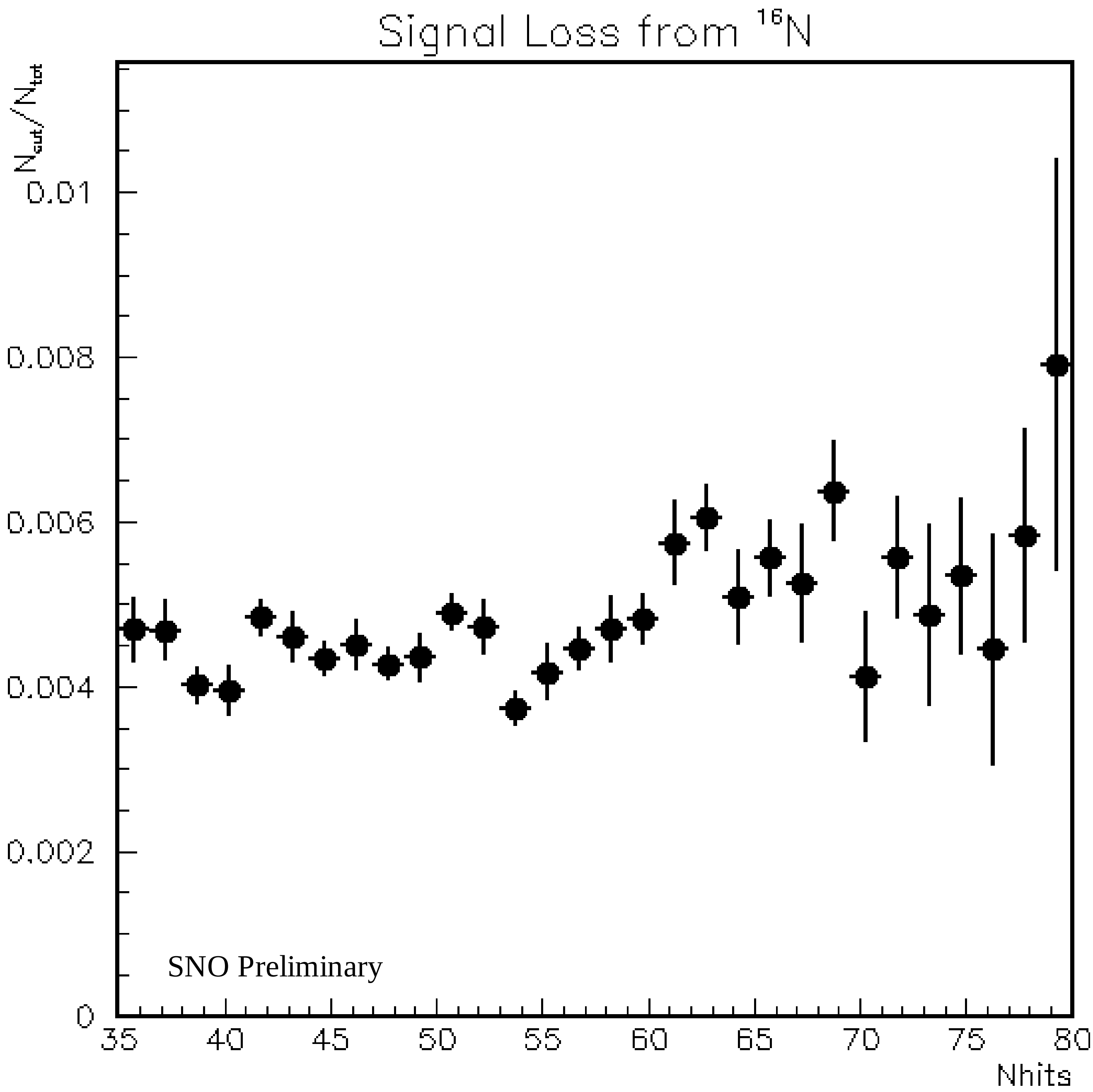
Note Neck Tubes Fired

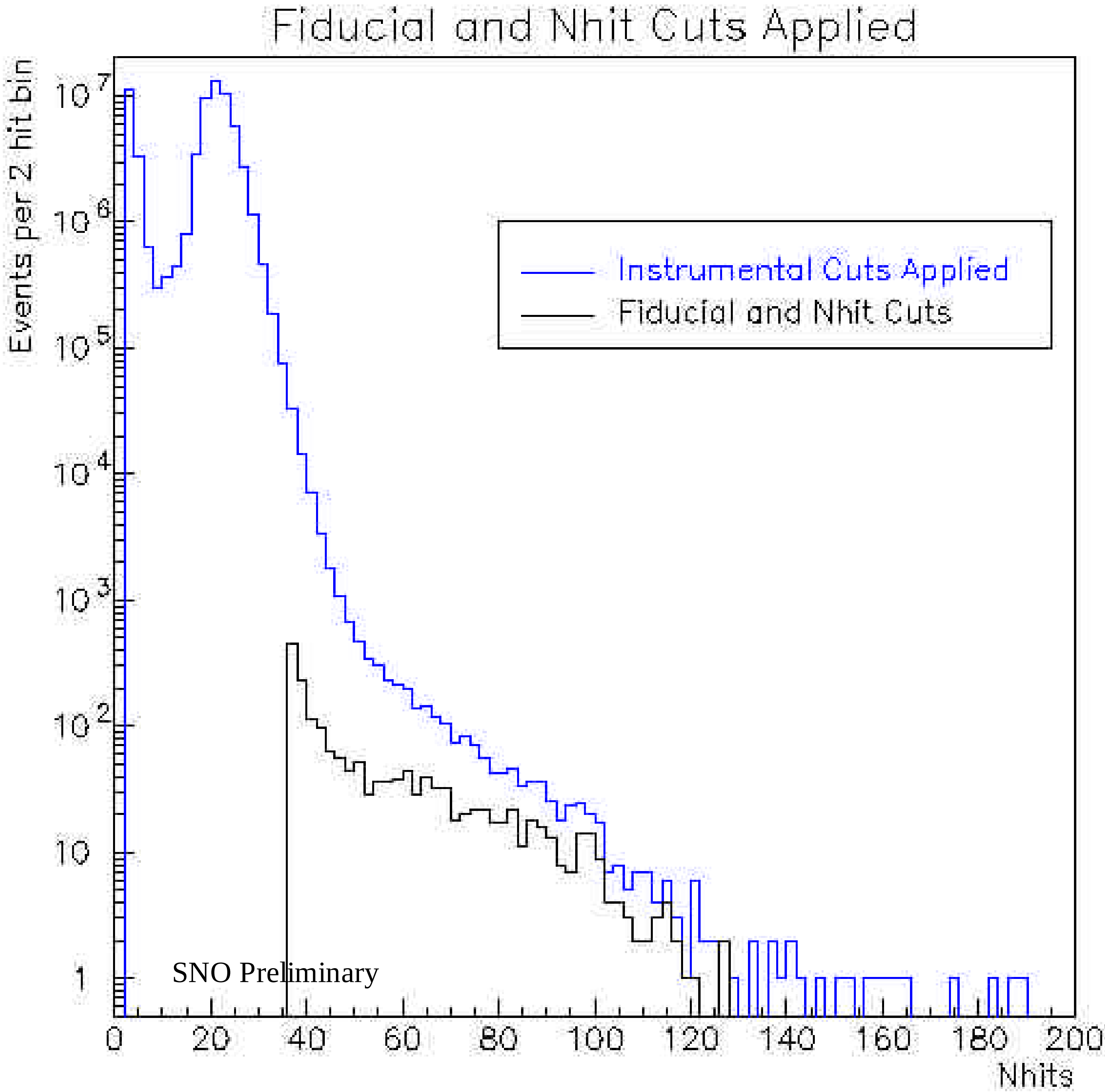


A "Neck" Event

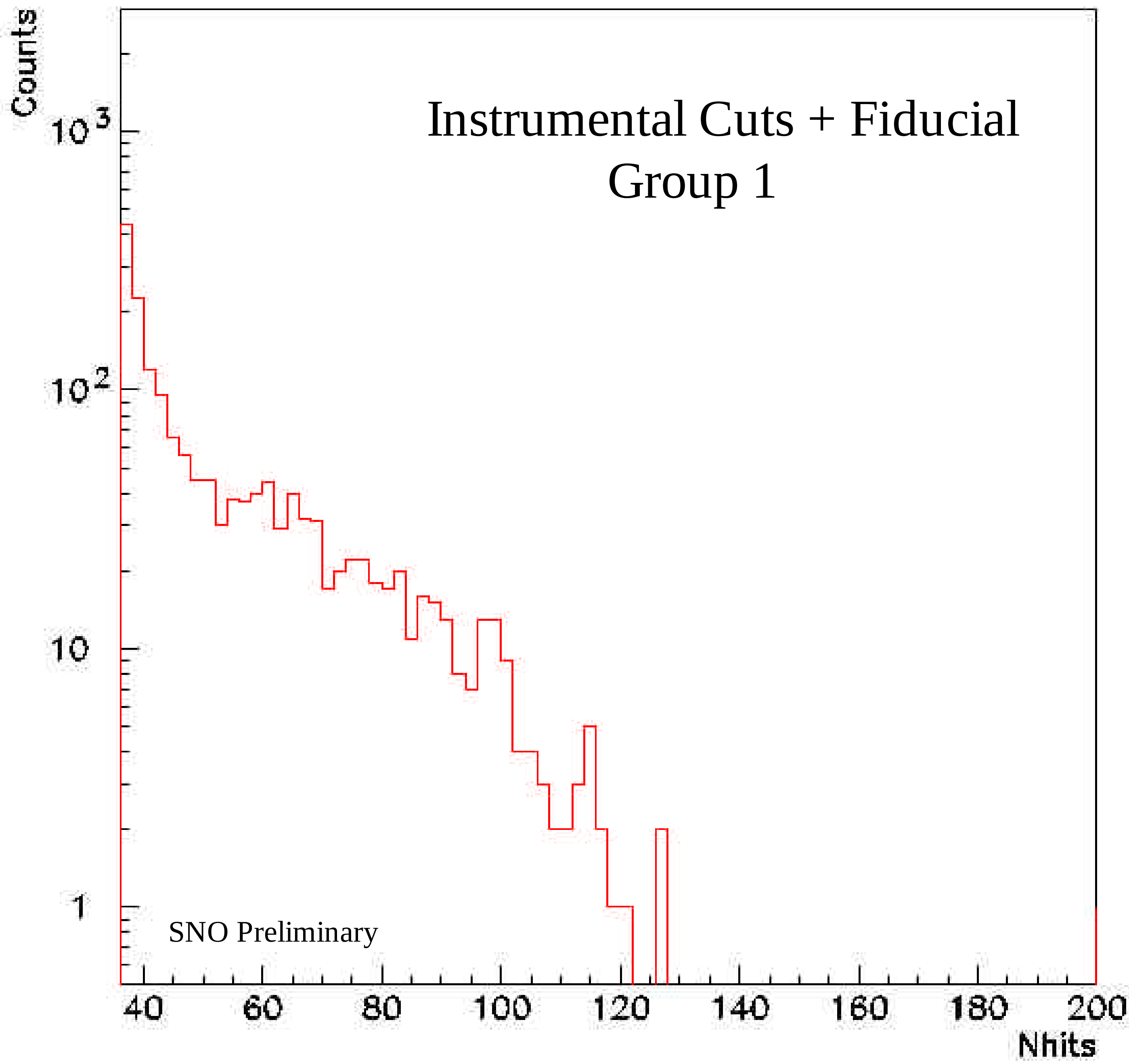


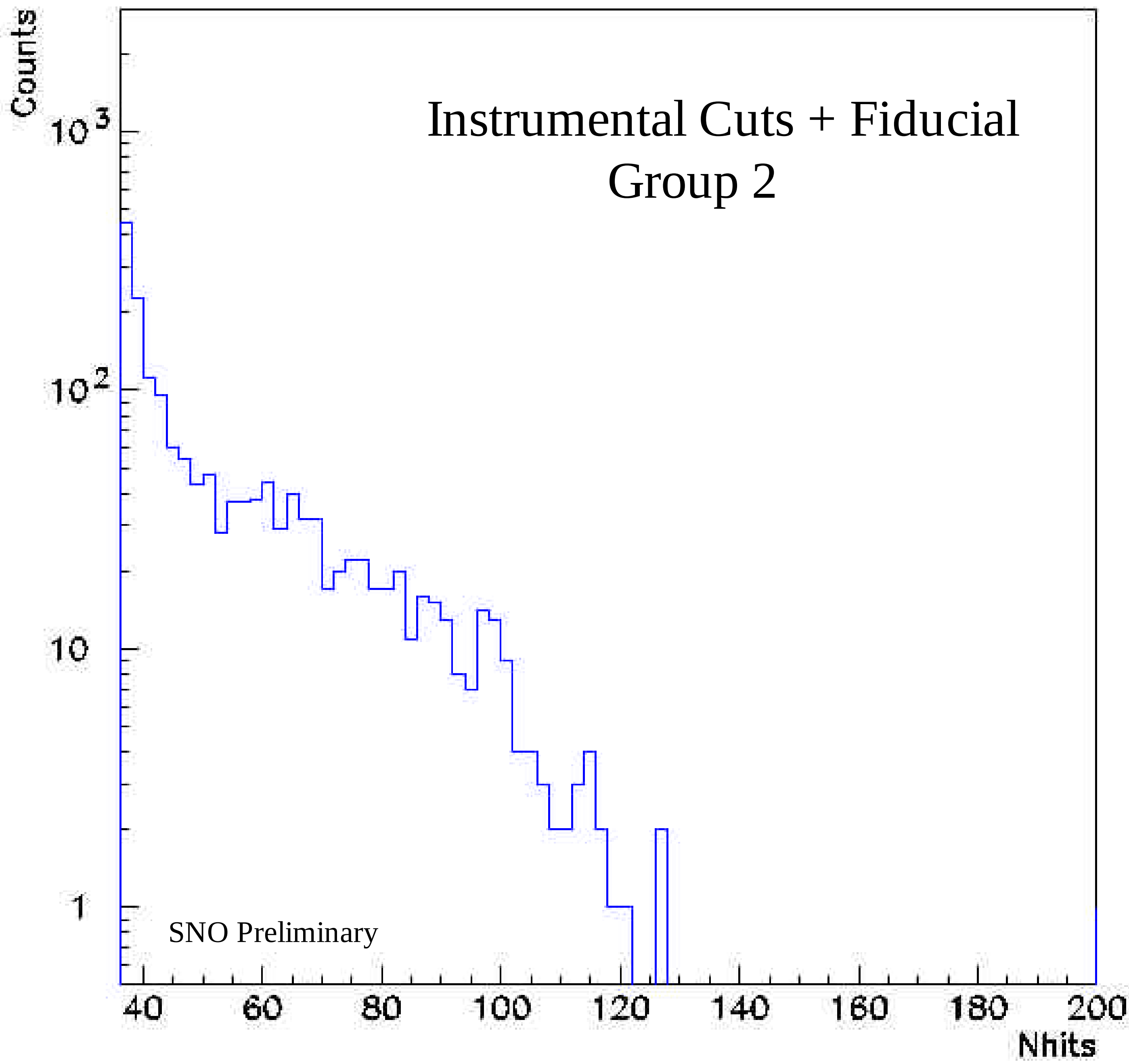
An Electronic Pickup Event

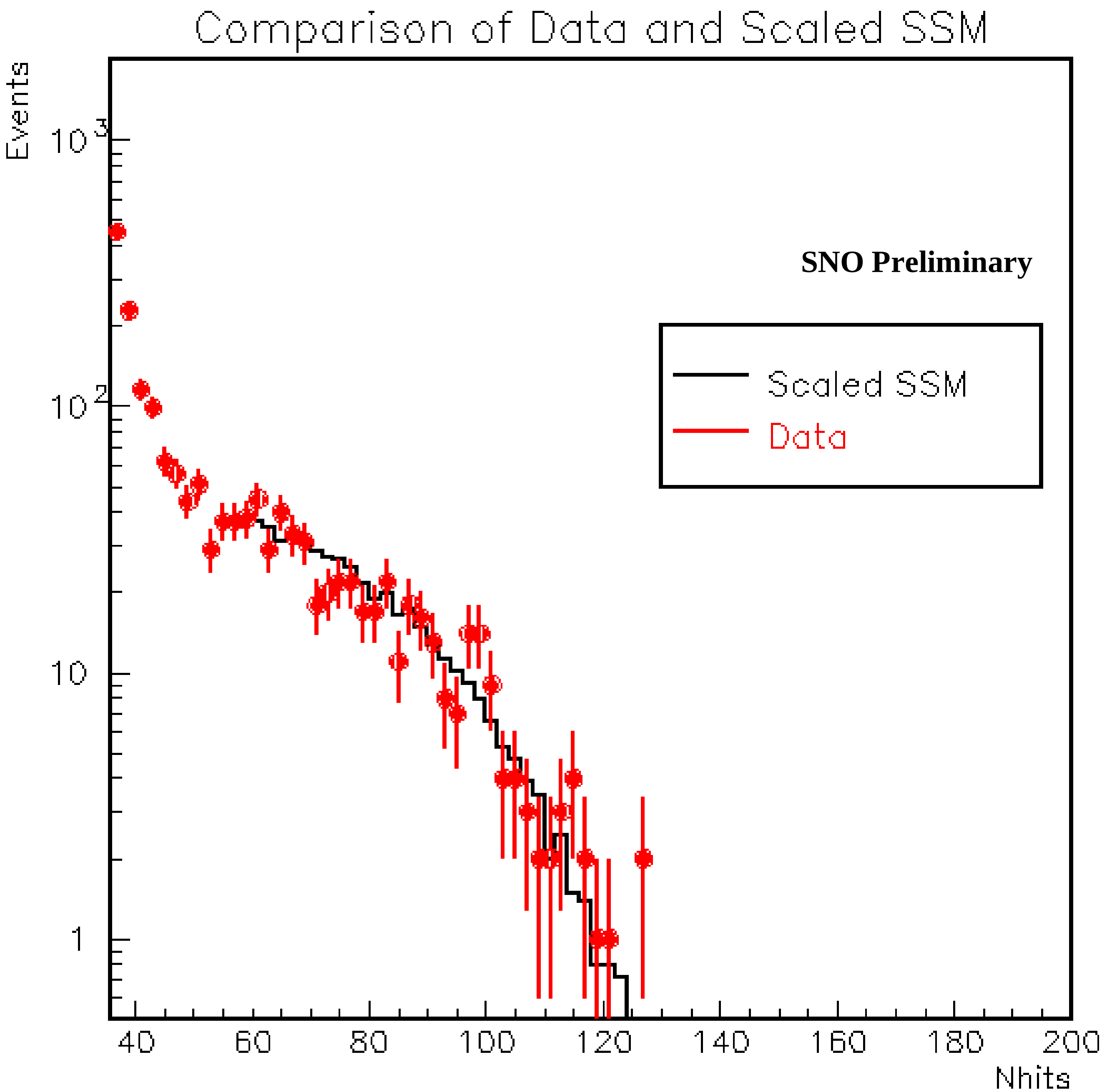

Signal Loss from 16N
Ncut/Ntot
0.01
0.008
0.006
0.004
0.002
0
35
40
45
50
55
60
65
70
75
80
Nhits
SNO Preliminary

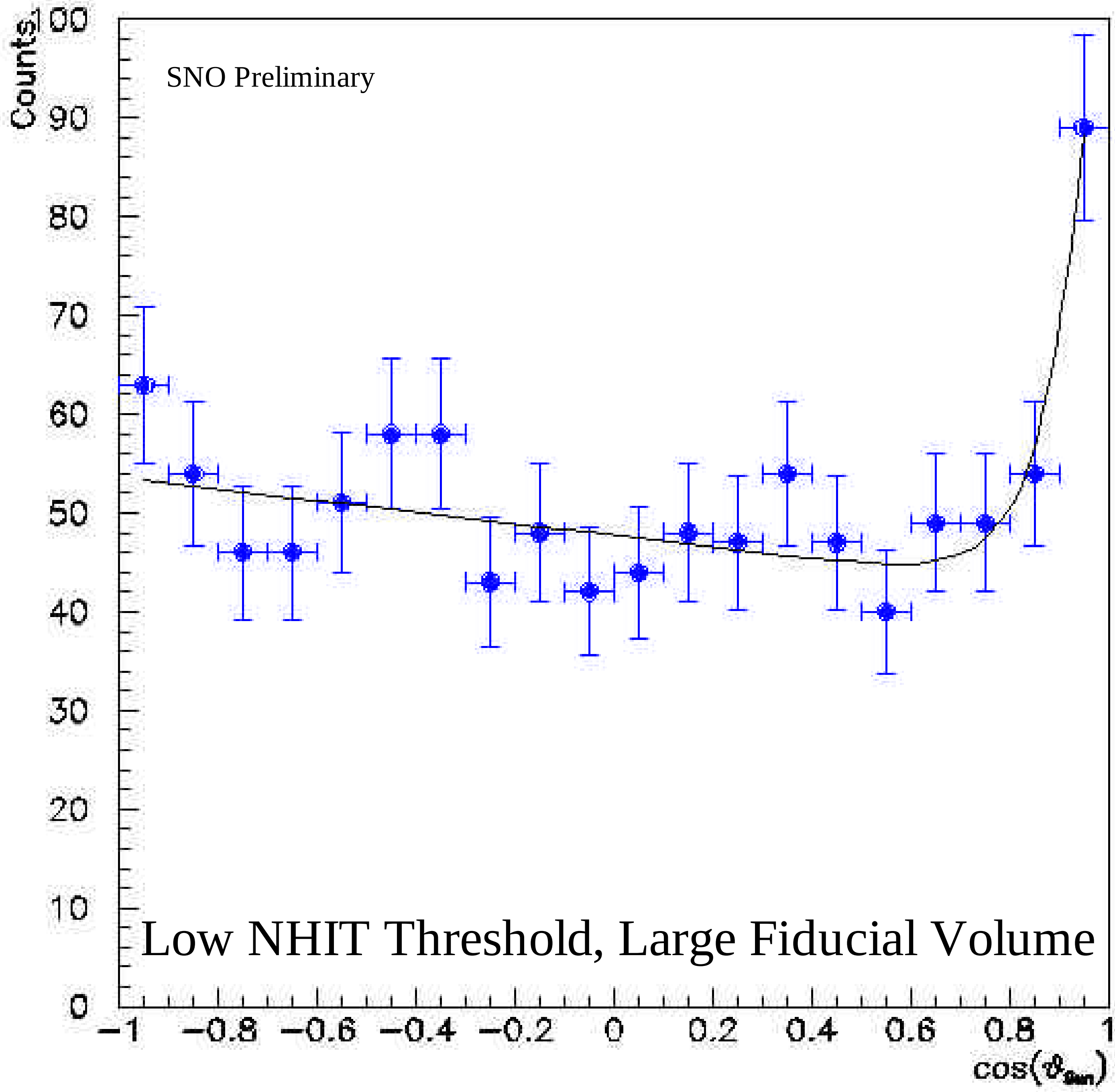


Fiducial and Nhit Cuts Applied
Events per 2 hit bin
Instrumental Cuts Applied
Fiducial and Nhit Cuts
SNO Preliminary
Nhits

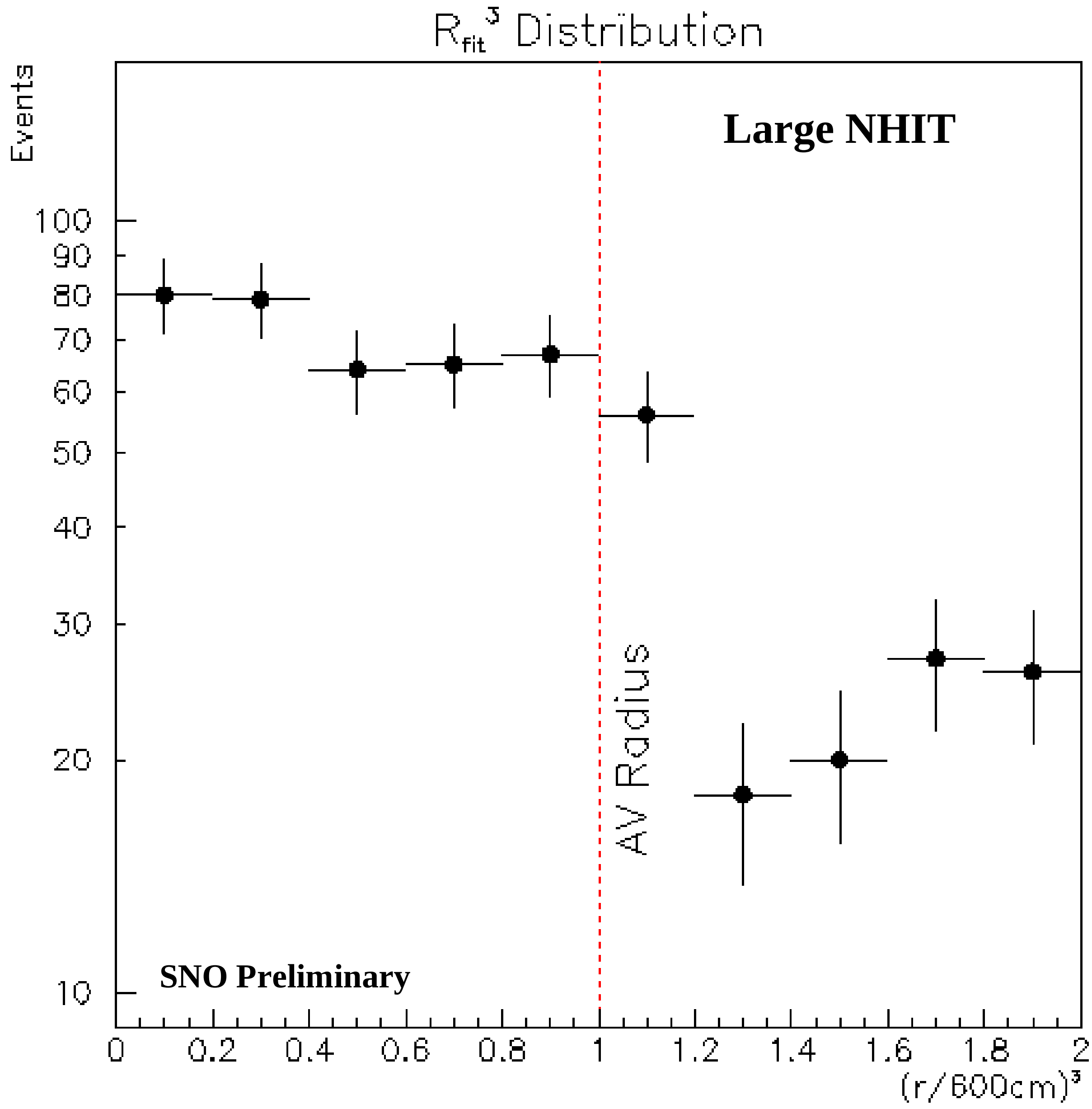

Instrumental Cuts + Fiducial
Group 1
Counts
10^3
10^2
10
1
SNO Preliminary
40
60
80
100
120
140
160
180
200
Nhits


Instrumental Cuts + Fiducial
Group 2
Counts
10^3
10^2
10
1
SNO Preliminary
40
60
80
100
120
140
160
180
200
Nhits

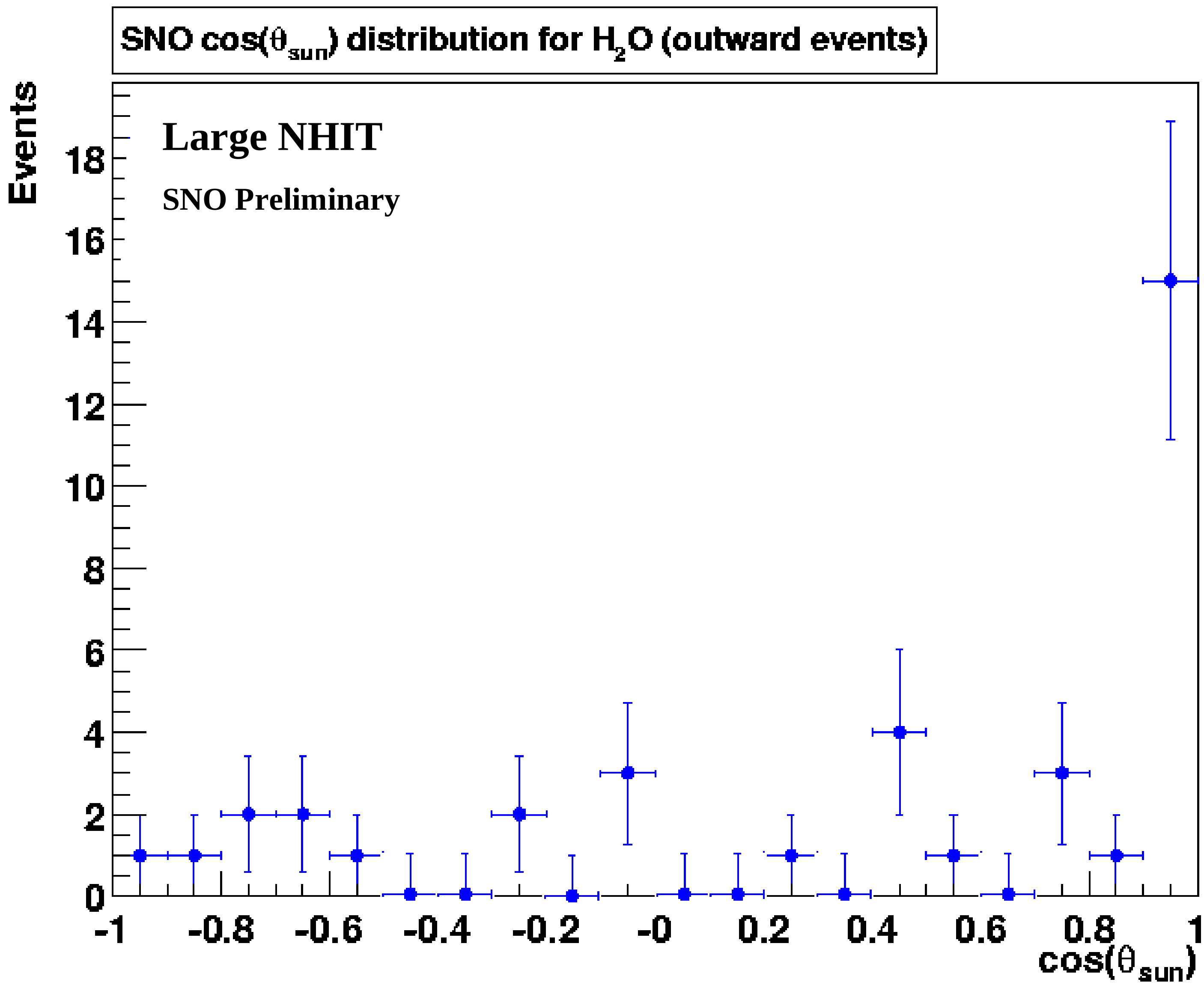

Comparison of Data and Scaled SSM
Events
10^3
10^2
10
1
40
60
80
100
120
140
160
180
200
Nhits
SNO Preliminary
Scaled SSM
Data



SNO Preliminary
Low NHIT Threshold, Large Fiducial Volume
Counts
cos(ϑ_Sun)



R_{fit}^3 Distribution
Events
Large NHIT
AV Radius
SNO Preliminary
100
90
80
70
60
50
40
30
20
10
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
$(r/600cm)^3$


SNO cos(θ_{sun}) distribution for H_2O (outward events)
Large NHIT
SNO Preliminary
Events
18
16
14
12
10
8
6
4
2
0
-1
-0.8
-0.6
-0.4
-0.2
-0
0.2
0.4
0.6
0.8
1
cos(θ_{sun})

CONCLUSIONS

The SNO Detector is Meeting Stringent Objectives For:

- Energy Calibration and Resolution.
- Stability
- Instrumental Backgrounds
- Radioactive Backgrounds

- **Preliminary Analysis of Data:**

- Based on Energy, Direction and Location, the data in the region of interest appear to be dominated by ^{8}B solar neutrinos detected via the CC and ES reactions, with very little background.

- **This implies that:**

- Phase 1 measurements will provide an accurate measurement of the electron neutrino flux via the Charged Current reaction, after completion of the planned measurements of experimental systematic effects

RADIOACTIVE BACKGROUNDS

Contributions To Cerenkov Light

- Low Energy Gammas, Betas (Mainly U, Th Chains)
  - Radioassay (Rn gas, Ra absorbers)
  - Assay by Cerenkov Light (< 5 MeV)
    - Pattern recognition discriminates U, Th
    - Rates consistent with radioassays

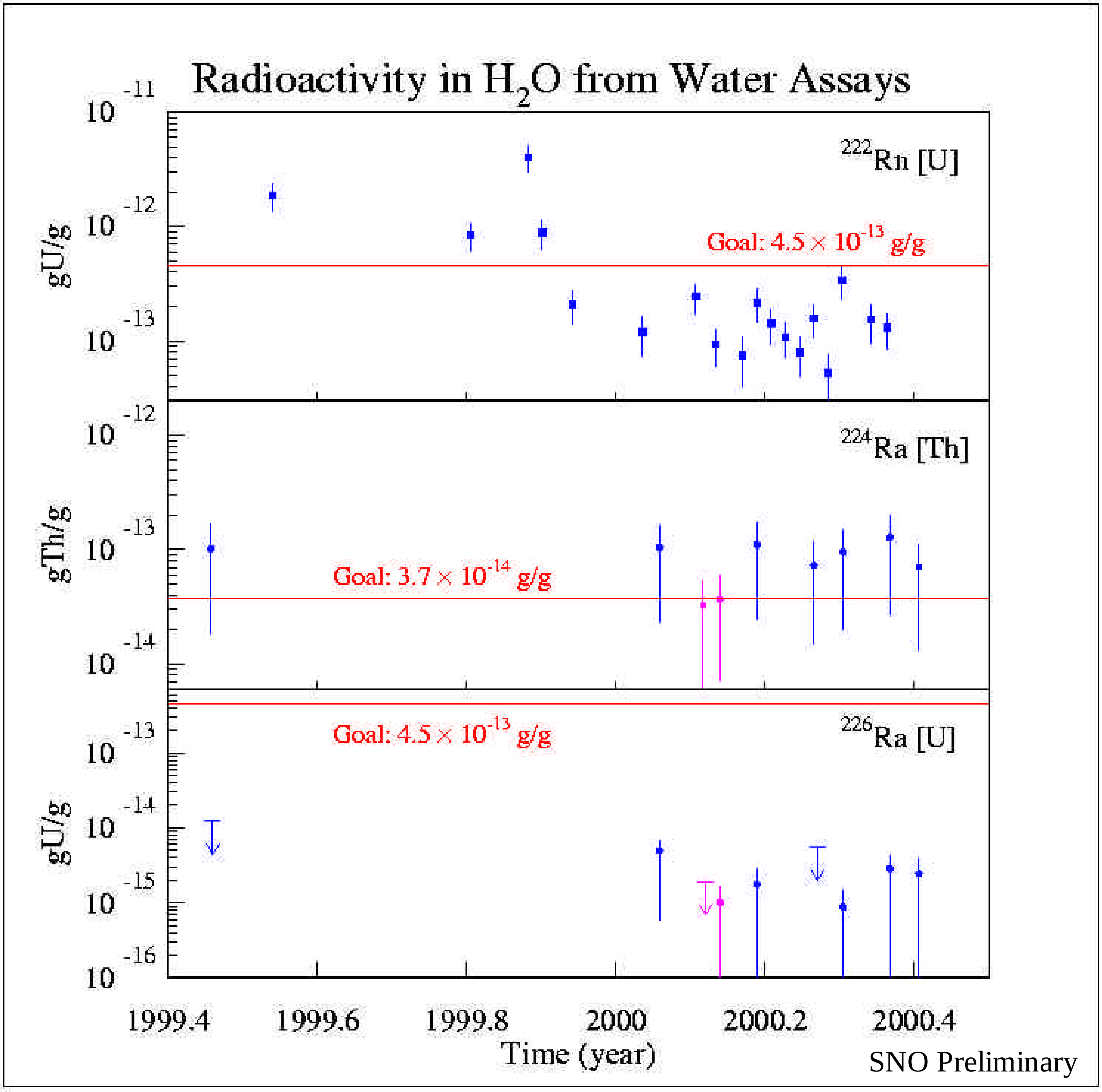
Large uncertainties at present. Future:Triggered sources

- External High Energy Gammas
  - Extrapolate from rates in light water

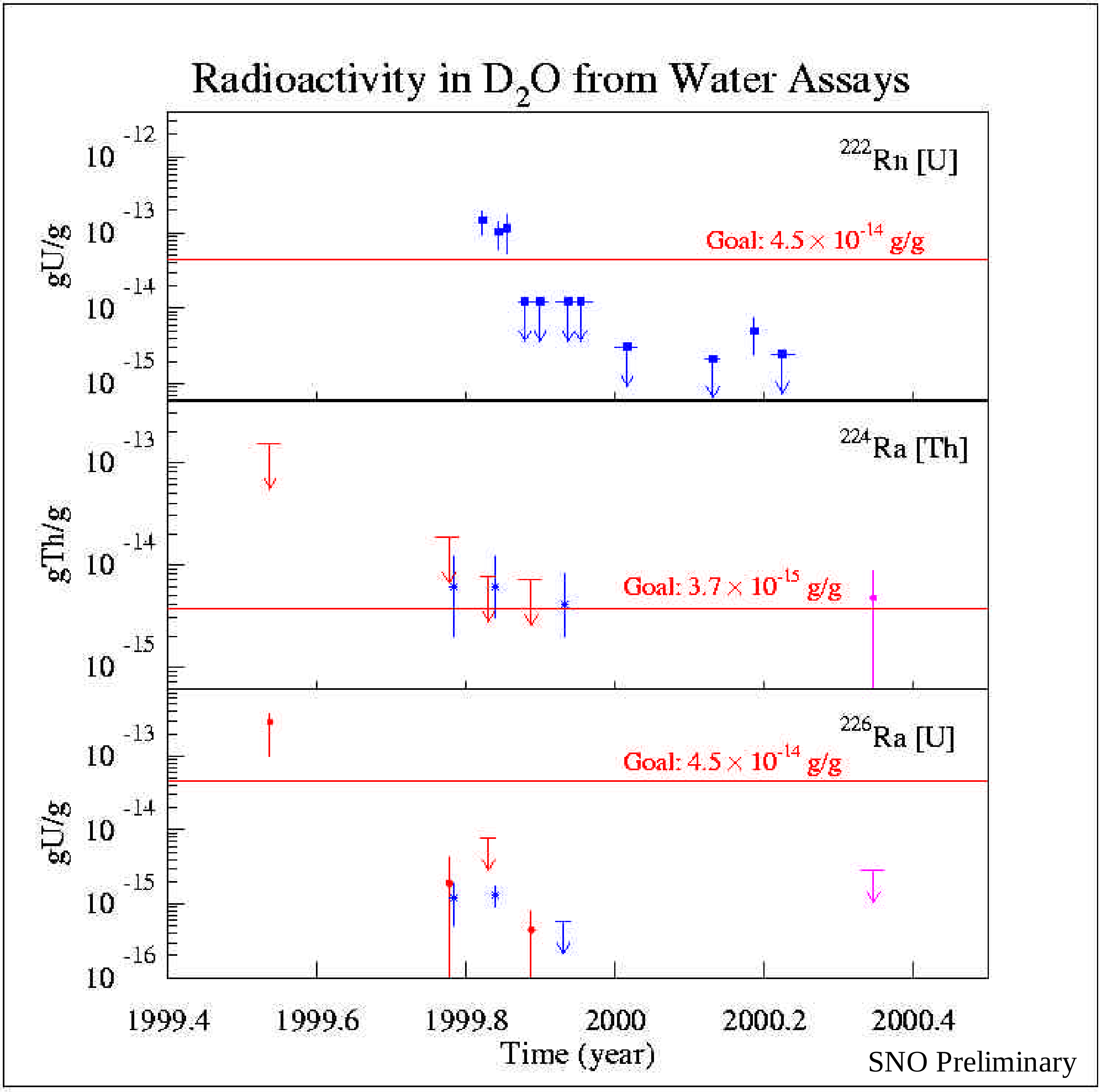
Preliminary < few percent of CC in heavy water.

Contributions to NC Background (Neutrons)

- Photodisintegration of Deuteron (Threshold 2.2 MeV)
  - Gammas: Th Chain (2.6 MeV), U Chain (2.4 MeV)



Radioactivity in H_2O from Water Assays
^{222}Rn [U]
Goal: 4.5×10^{-13} g/g
^{224}Ra [Th]
Goal: 3.7×10^{-14} g/g
^{226}Ra [U]
Goal: 4.5×10^{-13} g/g
gU/g
gTh/g
gU/g
10^{-11}
10^{-12}
10^{-13}
10^{-12}
10^{-13}
10^{-14}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
1999.4
1999.6
1999.8
2000
2000.2
2000.4
Time (year)
SNO Preliminary

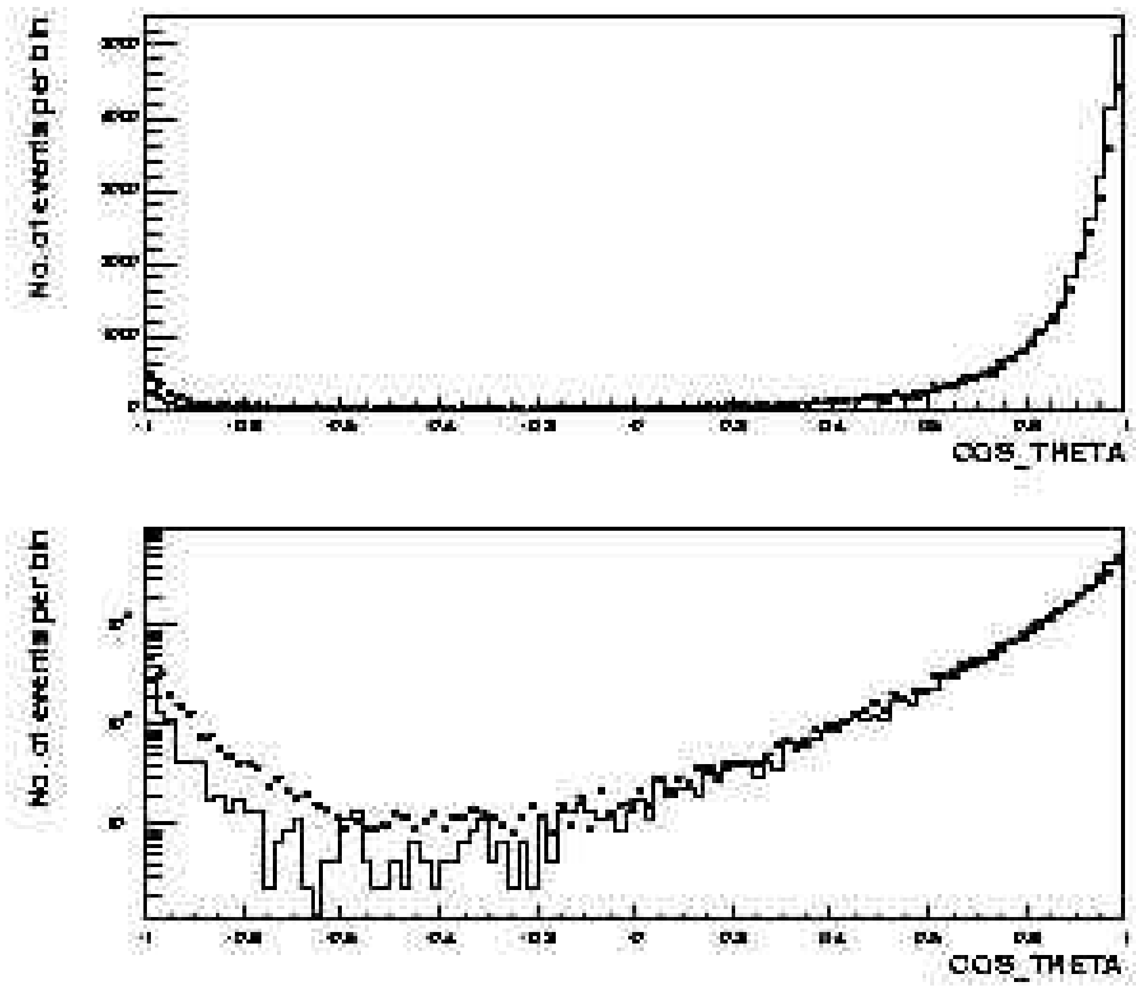


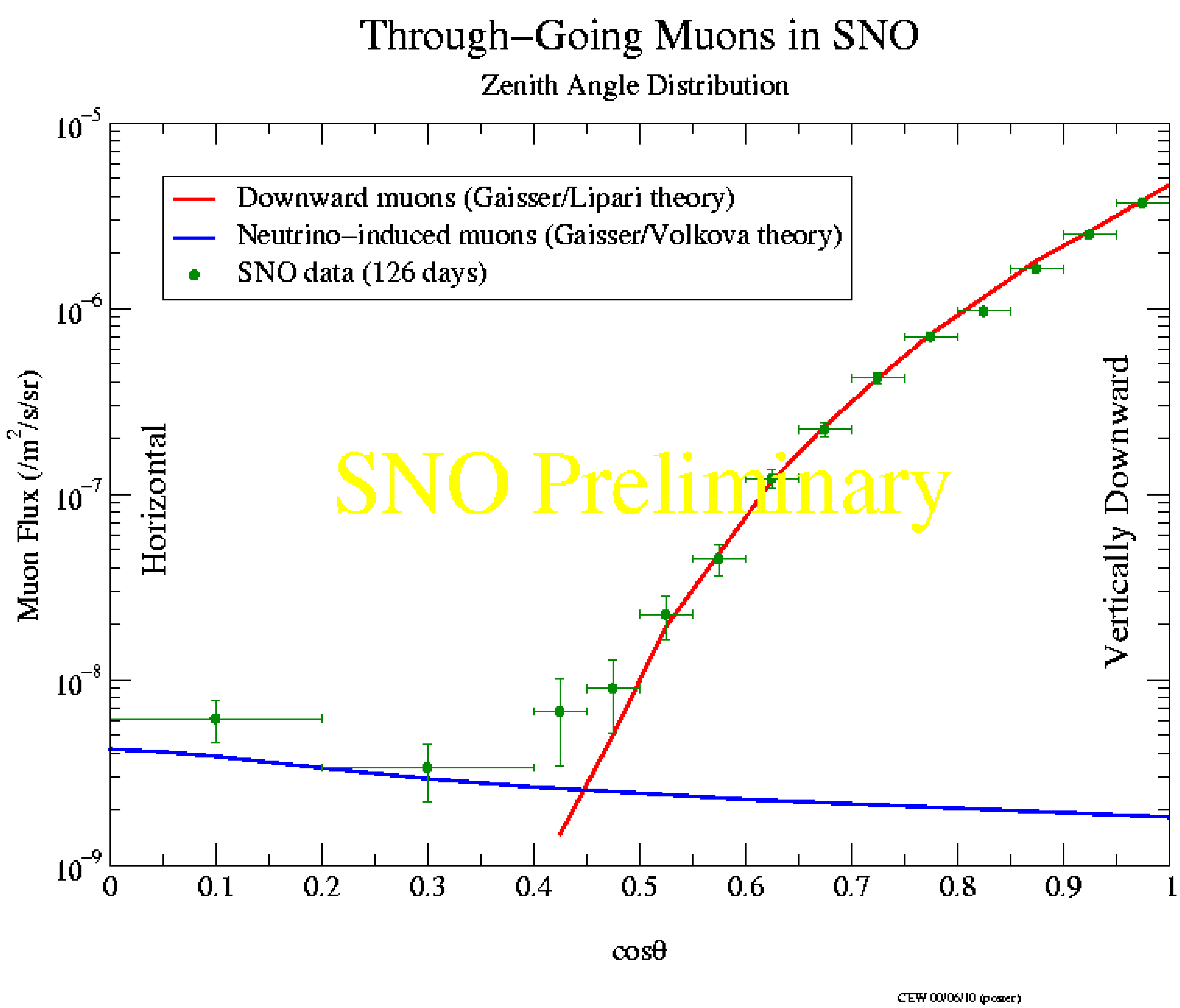
Goal Limits: Photodisintegration < 5% of SSM NC Signal

Conclusion: Radioactive Backgrounds are low enough to permit an accurate measurement of the total flux of active neutrinos via the NC reaction in future phases.

Angular Resolution Tested with ^{16}N Source

Points = Data, Line = Monte Carlo




Through–Going Muons in SNO
Zenith Angle Distribution
Downward muons (Gaisser/Lipari theory)
Neutrino–induced muons (Gaisser/Volkova theory)
SNO data (126 days)
Muon Flux (/m^2/s/sr)
Horizontal
Vertically Downward
SNO Preliminary
cosθ
CEW 00/06/10 (poster)