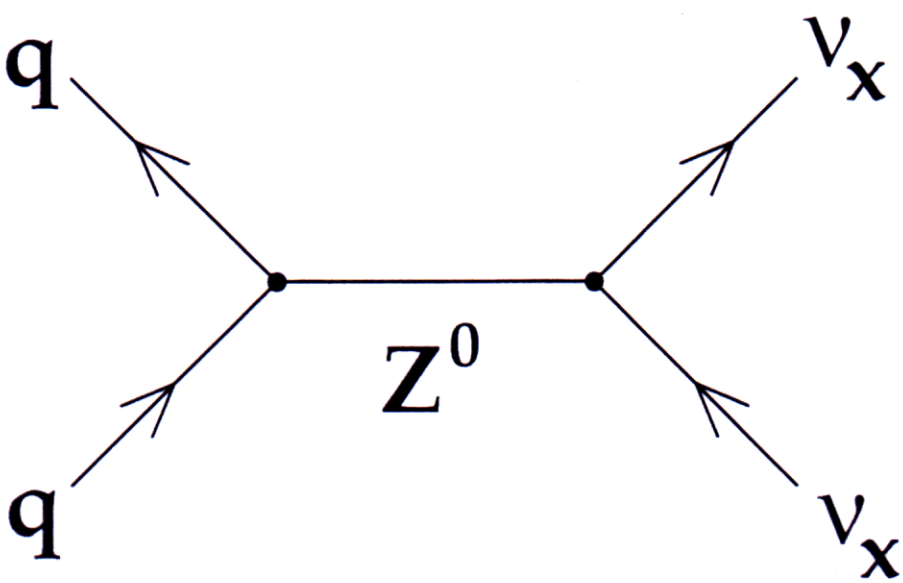
Catching Some Zs:



A Status Report on the Sudbury Neutrino Observatory

Tom Steiger

(on behalf of the SNO Collaboration)

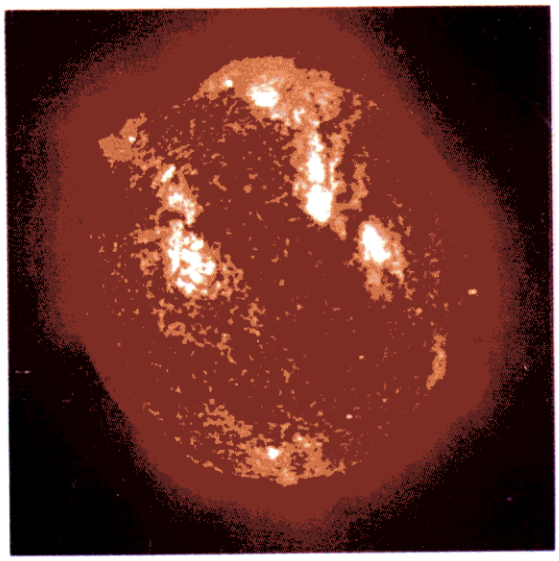
NuFACT '00

May 22-26

Outline

- Overview of the Solar Neutrino Problem
  - MSW Effect
  - A word about sterile neutrinos
- Sudbury Neutrino Observatory (SNO)
  - Overview of design and construction
  - Physics capabilities and goals
  - Neutral-current detection
  - Status report

Why Does the Sun Shine?

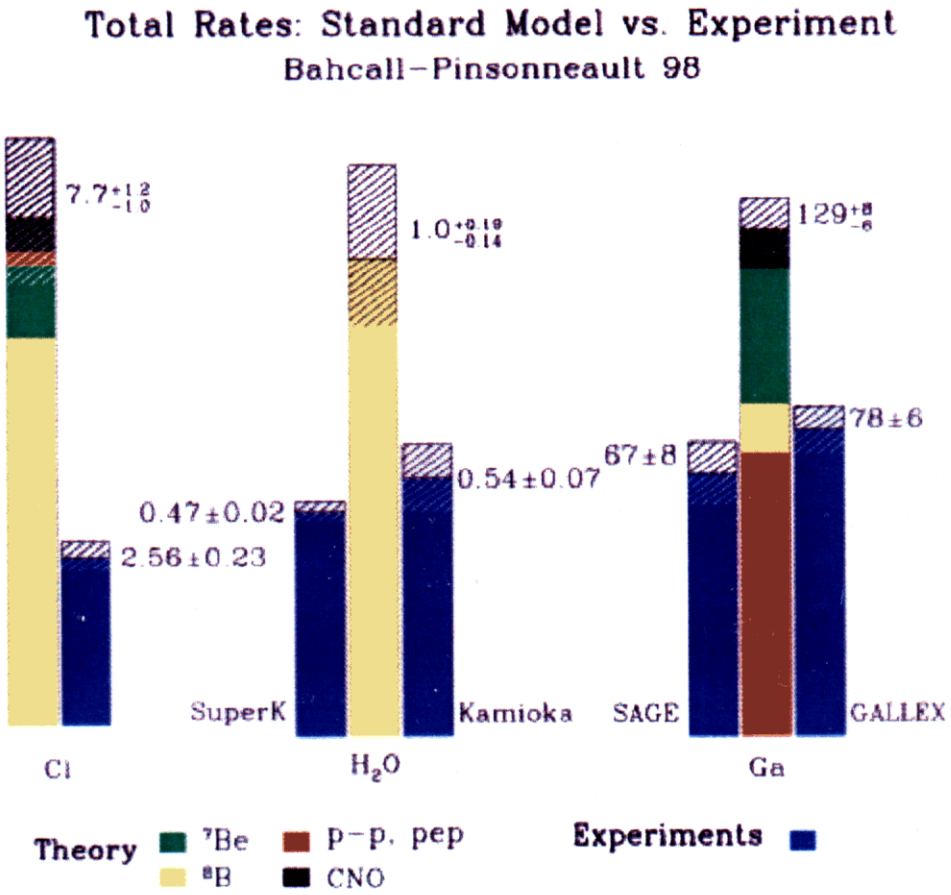


$$4p + 2e^- \longrightarrow {}^4He + 2\nu_e + 26.731\ MeV$$

Solar Constant: 0.14 Wcm^{-2}

$1W = 6.2 \times 10^{12}\ MeVs^{-1}$

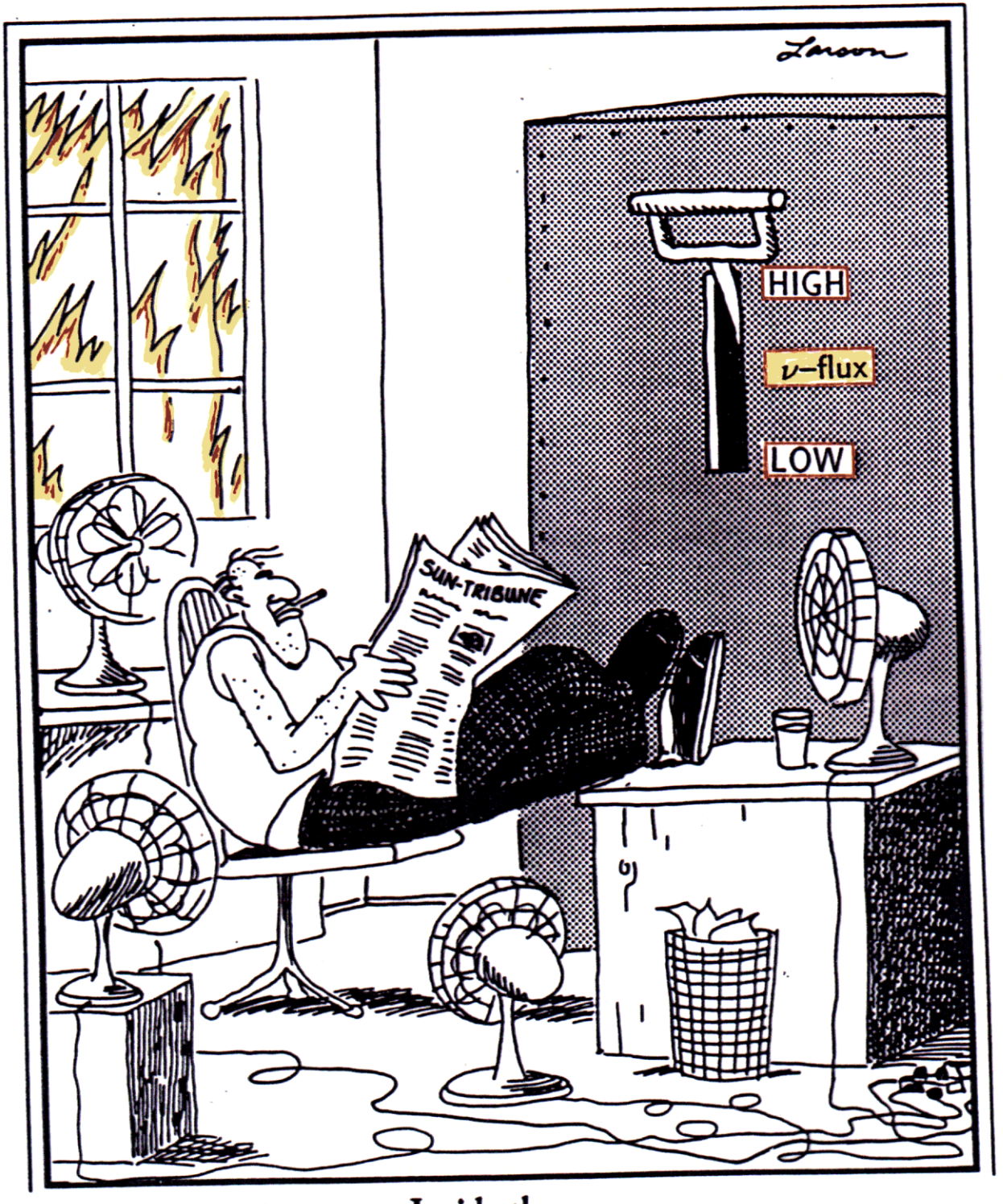
ν_e flux $\sim 6.5 \times 10^{10}\ cm^{-2}\ s^{-1}$



$$\phi(^8B) \sim 0.5\,\phi(^8B)_{SSM}$$

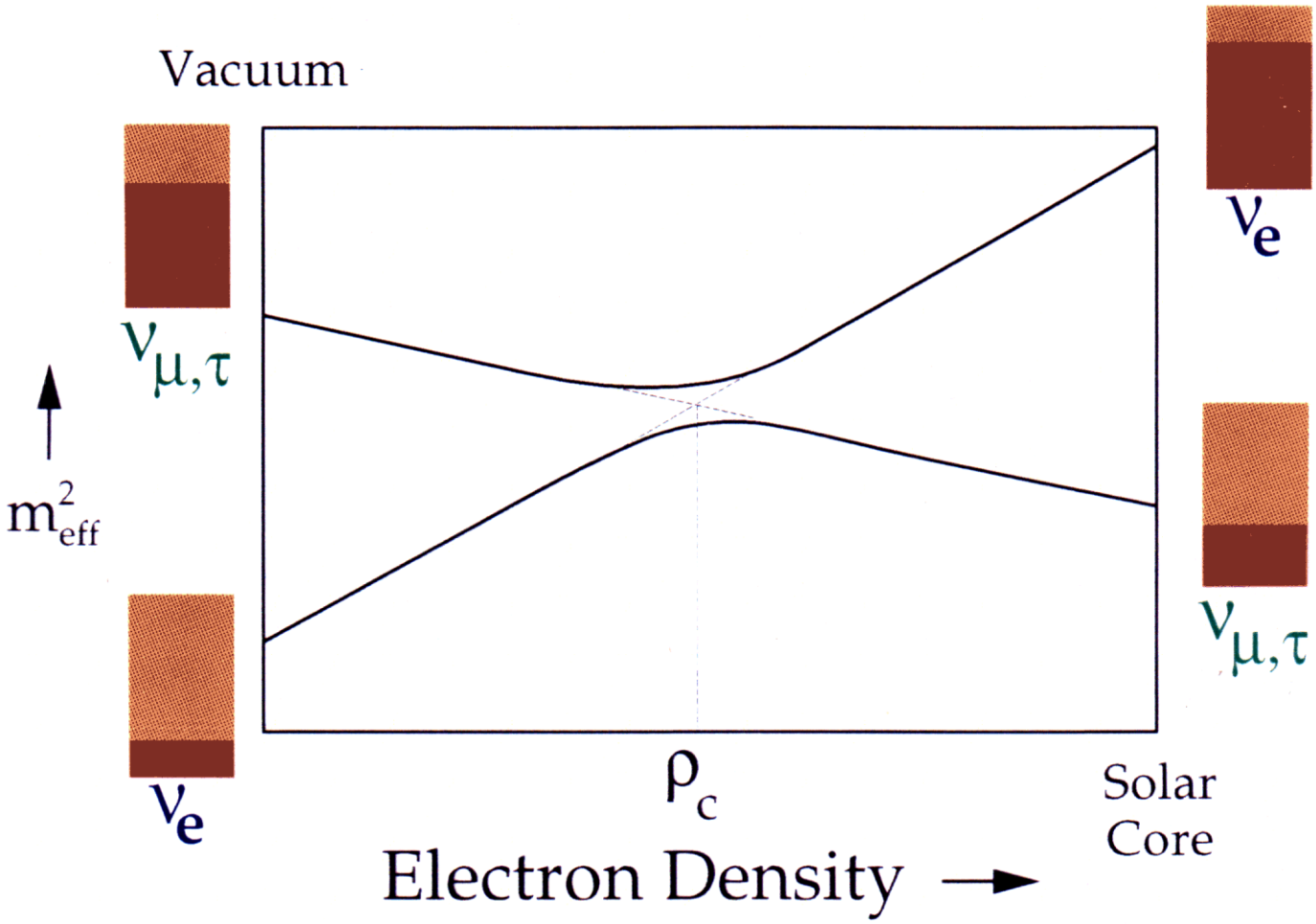
$$\phi(^7Be) \sim 0$$

$$\phi(pp) \sim \phi(pp)_{SSM}$$

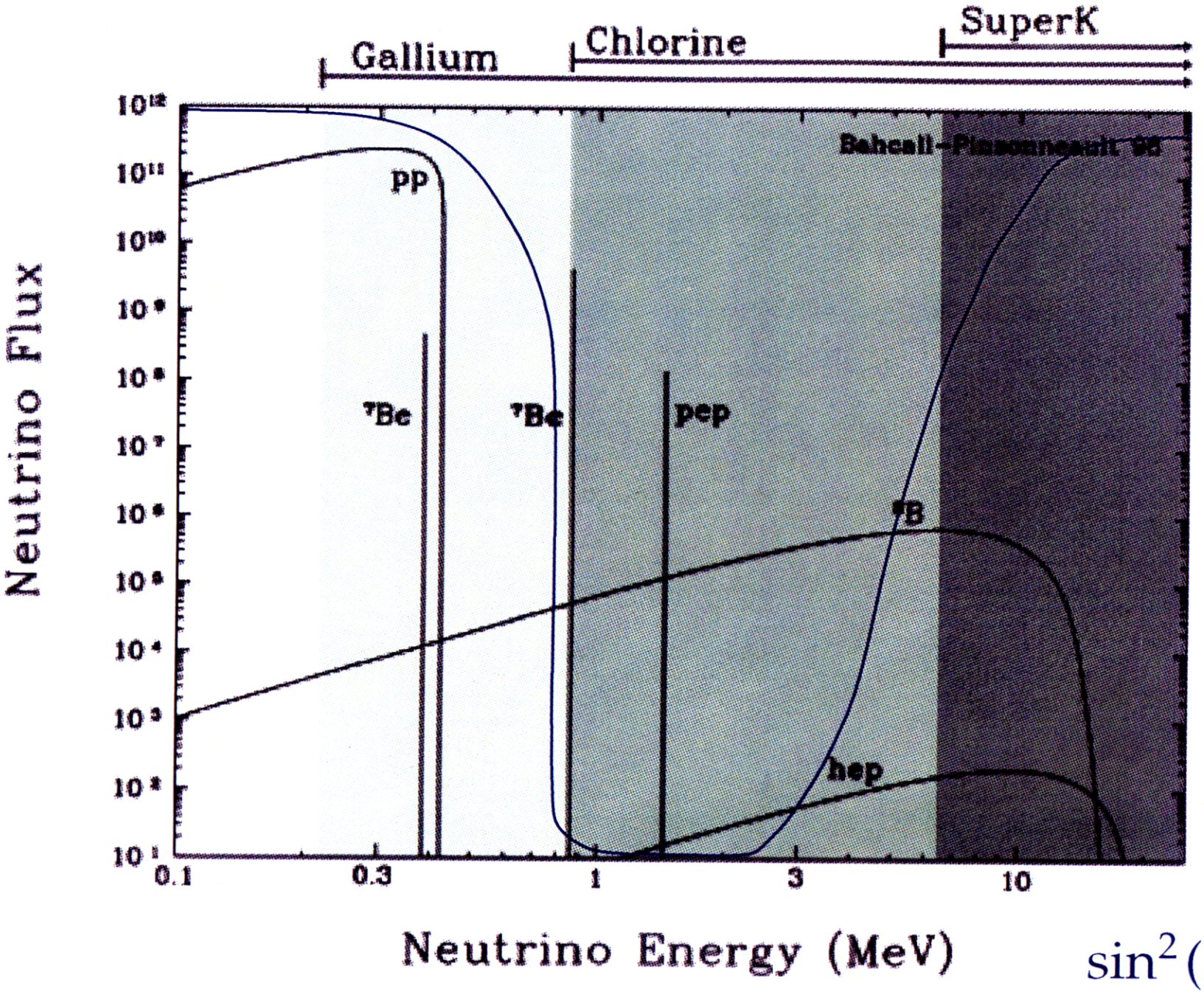


Inside the sun

MSW in the Sun

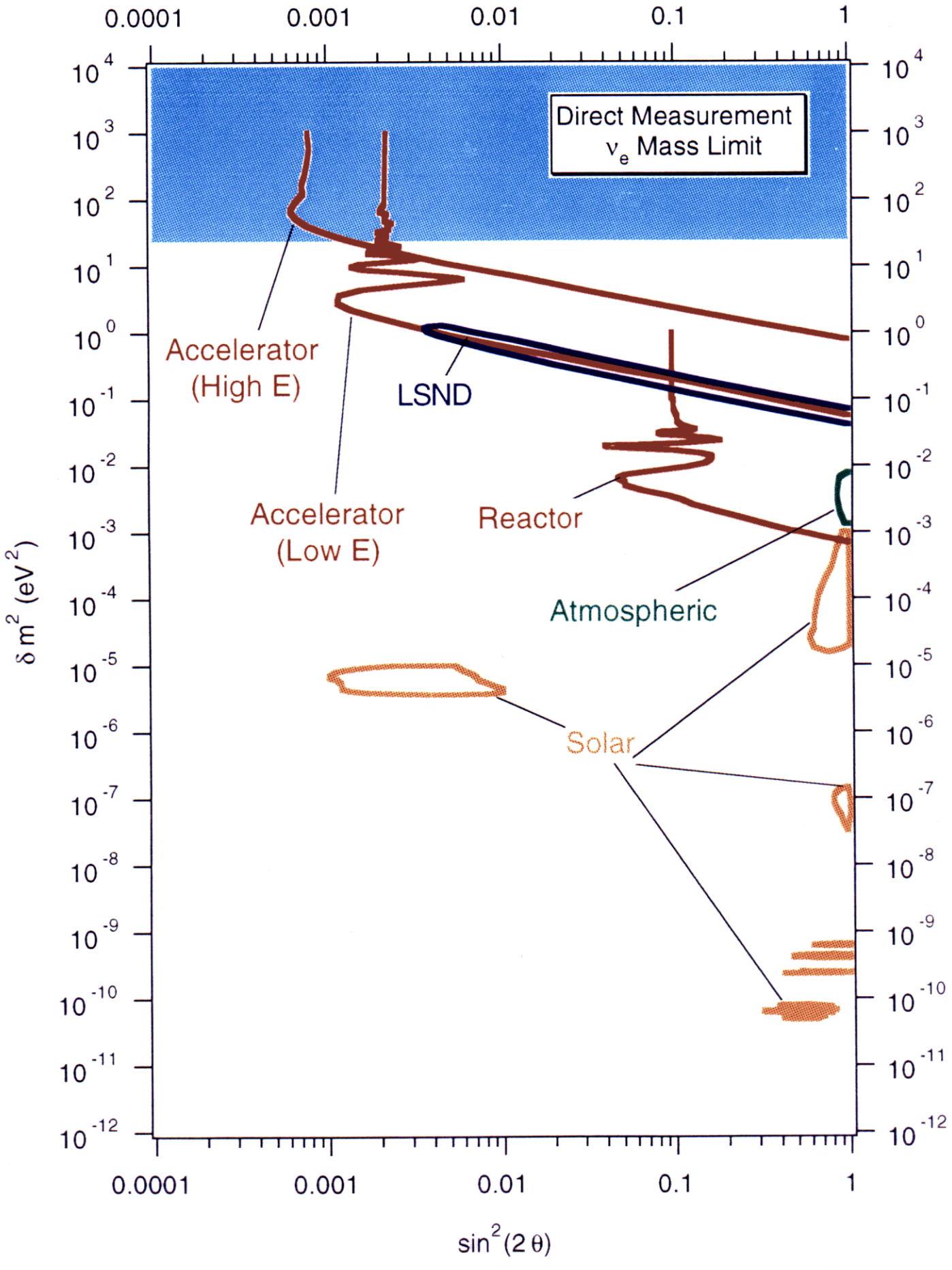


$$\rho_c = \frac{\delta m^2 \cos(2\theta)}{2\sqrt{2}\, G_F E}$$



$P(\nu_e \rightarrow \nu_e)$

$\sin^2(2\theta) = 0.01$

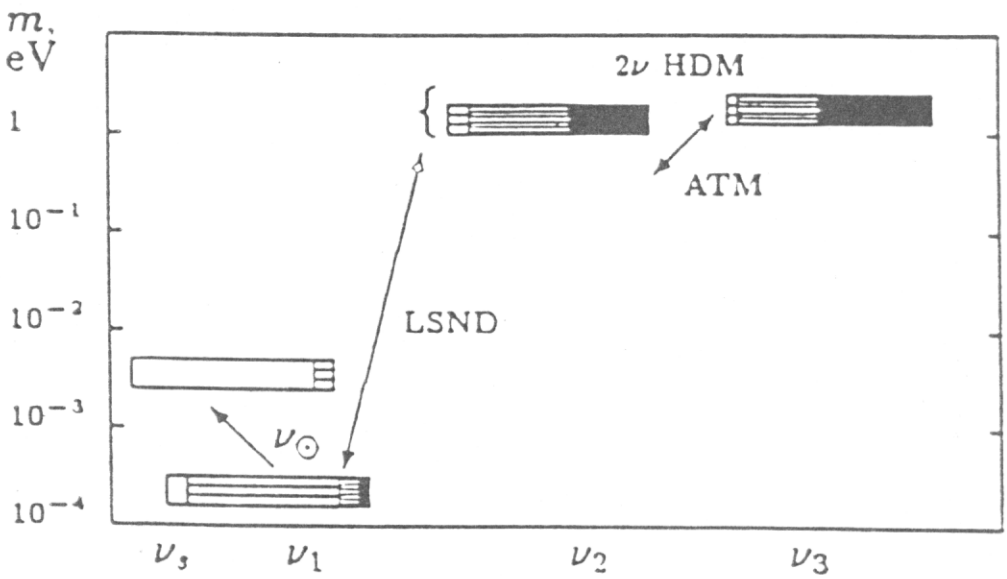

0.0001
0.001
0.01
0.1
1
Direct Measurement
ν_e Mass Limit
Accelerator
(High E)
LSND
Accelerator
(Low E)
Reactor
Atmospheric
Solar
δm^2 (eV^2)
$\sin^2(2\theta)$

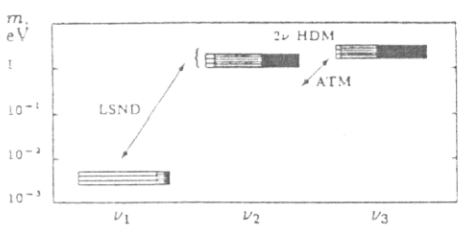
All mixed up

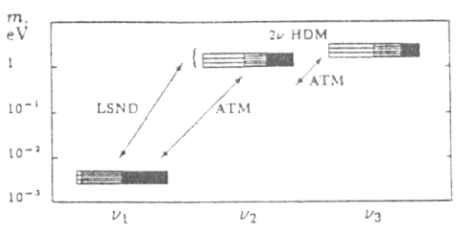
Solar: $\Delta m^2 \sim 10^{-5}$ - 10^{-6}; $10^{-10}\,eV^2$ (small)

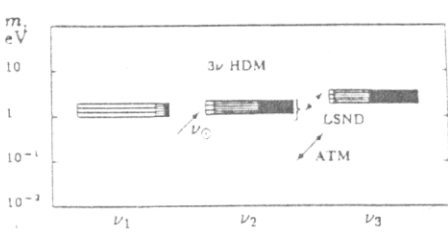
Atmos: $\Delta m^2 \sim 10^{-2}$ - $10^{-3}\,eV^2$ (medium)

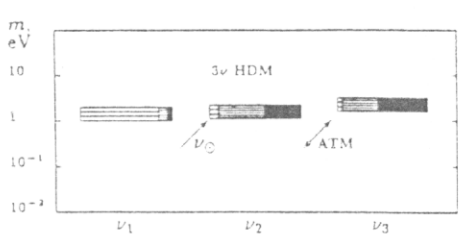
LSND: $\Delta m^2 \sim 1$ - $2\ eV^2$ (large)

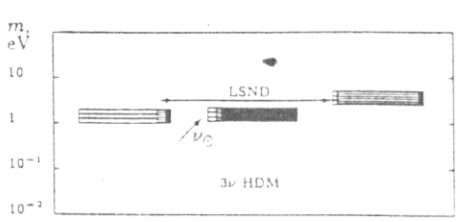


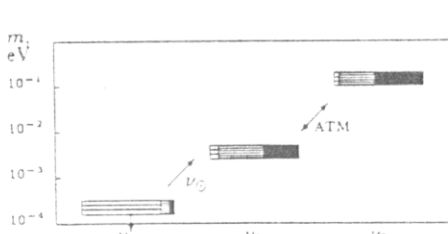


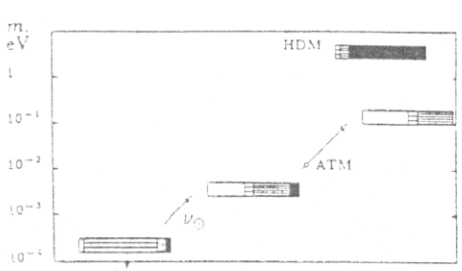


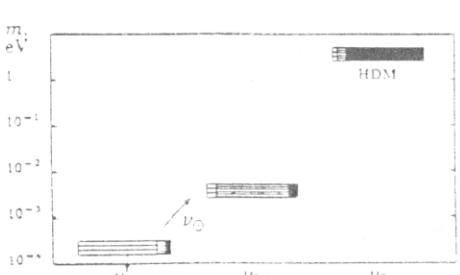












● ● ●

Sterile Neutrinos

"Sterile neutrinos are an ugly idea." - John Bahcall

Are sterile neutrinos *ad hoc*?

	Left-handed doublet	Right-handed singlet
In the Standard Model:	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$	e^-_R

This can be done because there are no right-handed weak currents. It is a convenient way to prevent νs from acquiring Dirac masses, and it "explains" the observation that νs are much lighter than other fermions. But there is no deep motivation for this convention; it is *ad hoc*.

But neutrinos have mass!

Thus it is "natural" to write $\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_R$ ← THIS is an example of a sterile neutrino!

SUDBURY NEUTRINO OBSERVATORY

CANADA

QUEENS UNIVERSITY
CRPP CARLTON UNIVERSITY
UNIVERSITY OF GUELPH
LAURENTIAN UNIVERSITY
UNIVERSITY OF BRITISH COLUMBIA

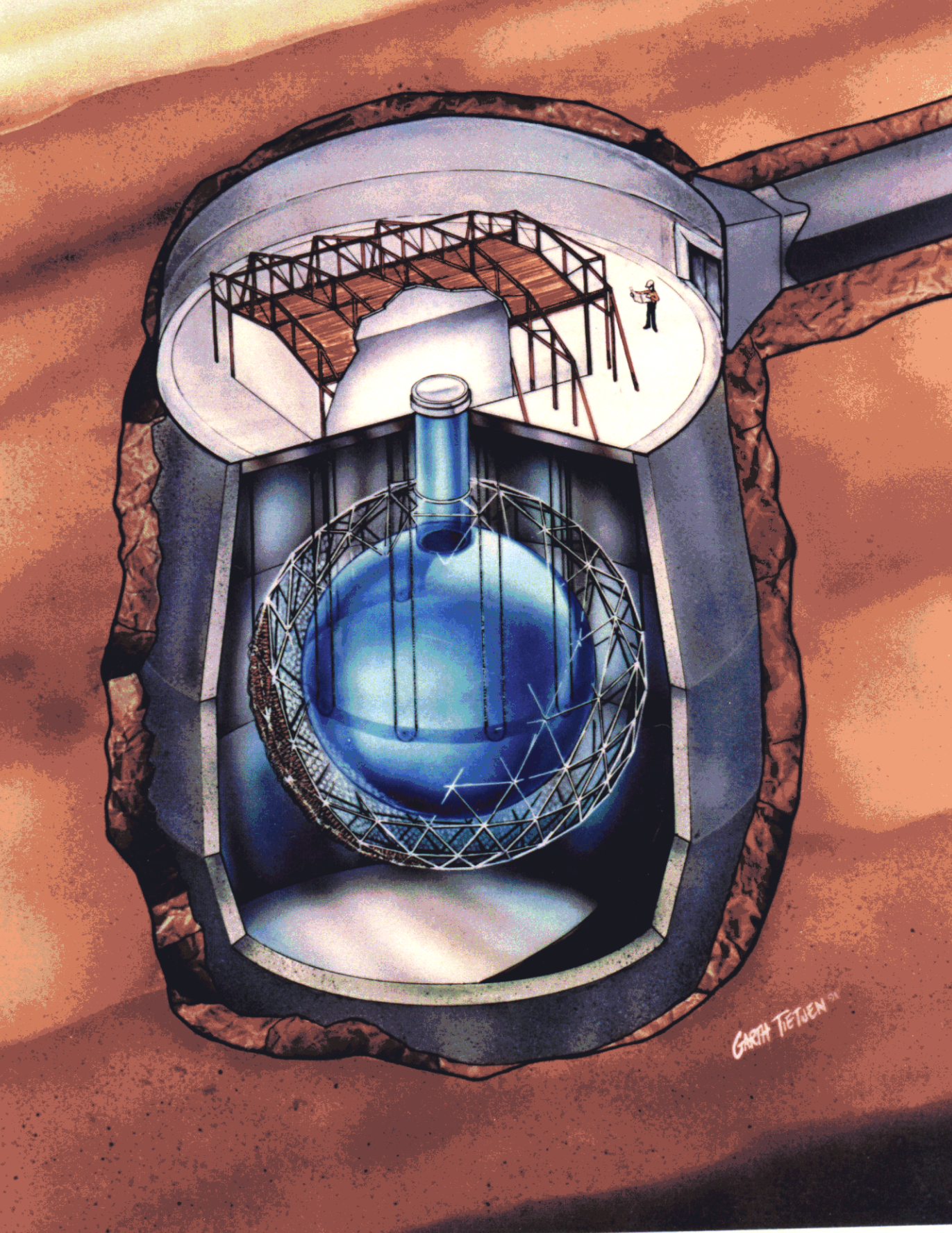
USA

UNIVERSITY OF WASHINGTON
UNIVERSITY OF PENNSYLVANIA
LOS ALAMOS NATIONAL LABORATORY
LAWERENCE BERKELEY NATIONAL LABORATORY
BROOKHAVEN NATIONAL LABORATORY

UK

OXFORD UNIVERSITY

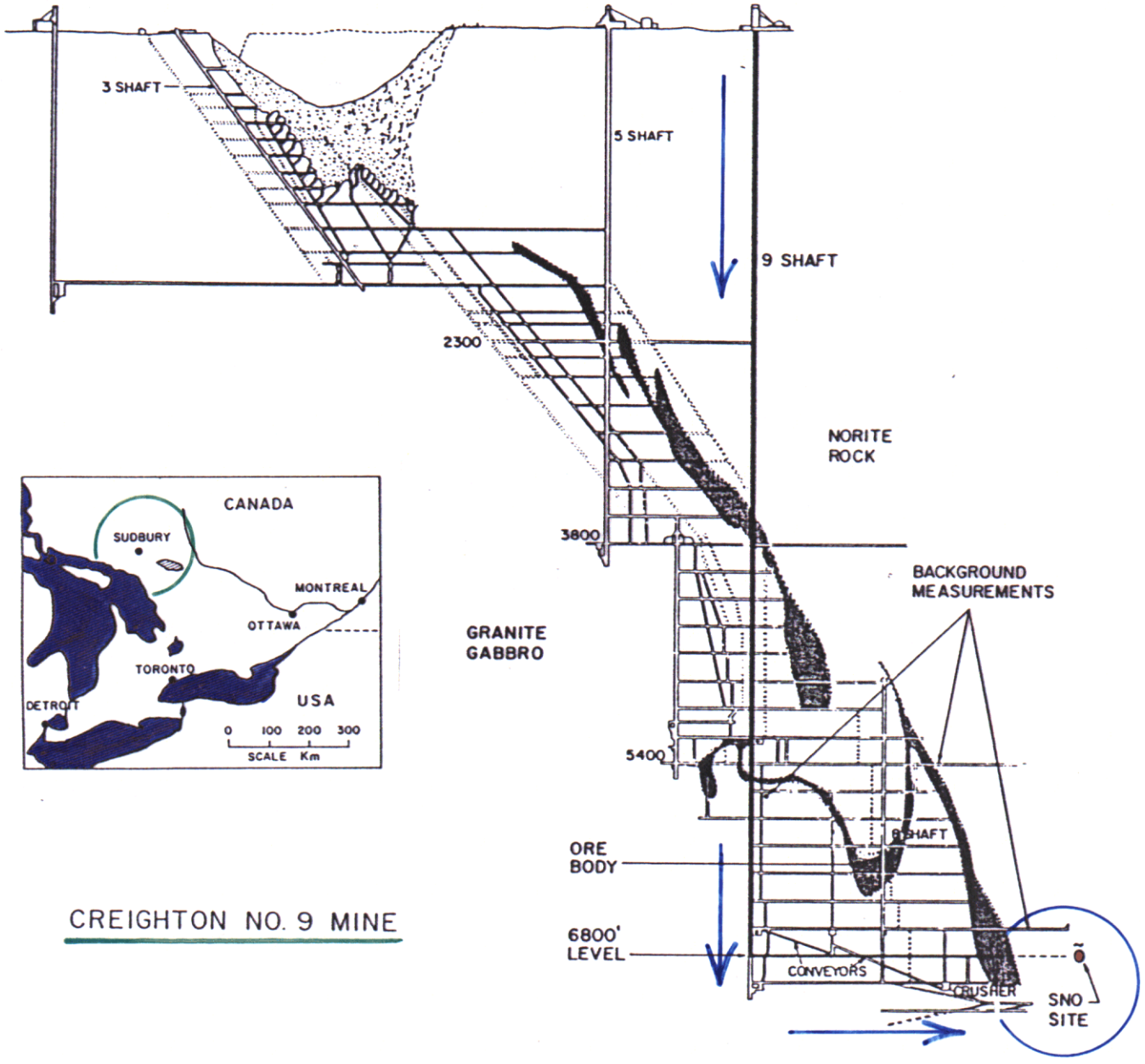
3 COUNTRIES, 11 INSTITUTES, 112 SCIENTISTS


GARTH TIETJEN SN

Civil Engineering View of SNO

Construct a 10-story building 6800 feet underground in an active mine with less than 1/4 ounce of dust allowed.

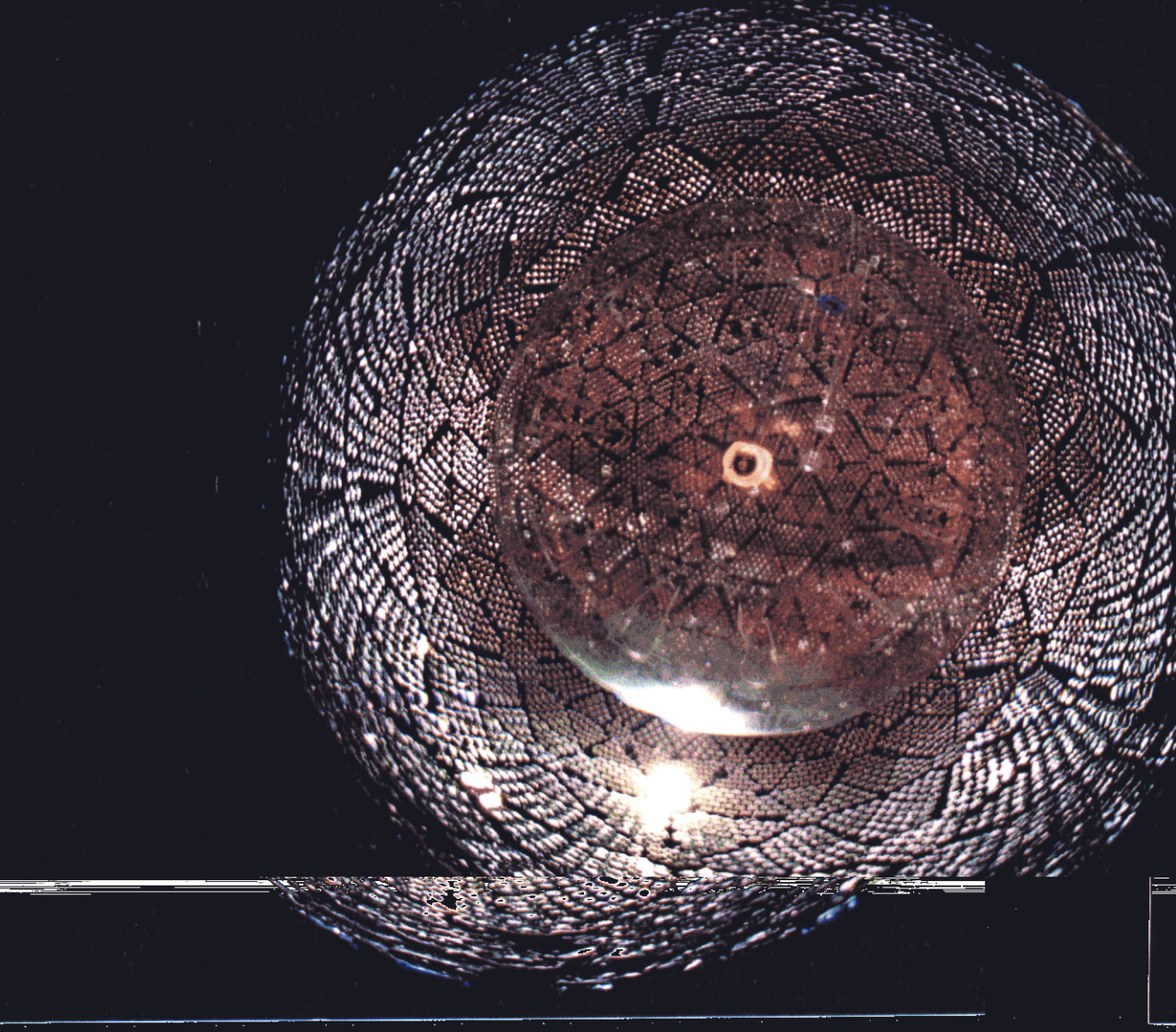
LANL preprint:
nucl-ex/9910016

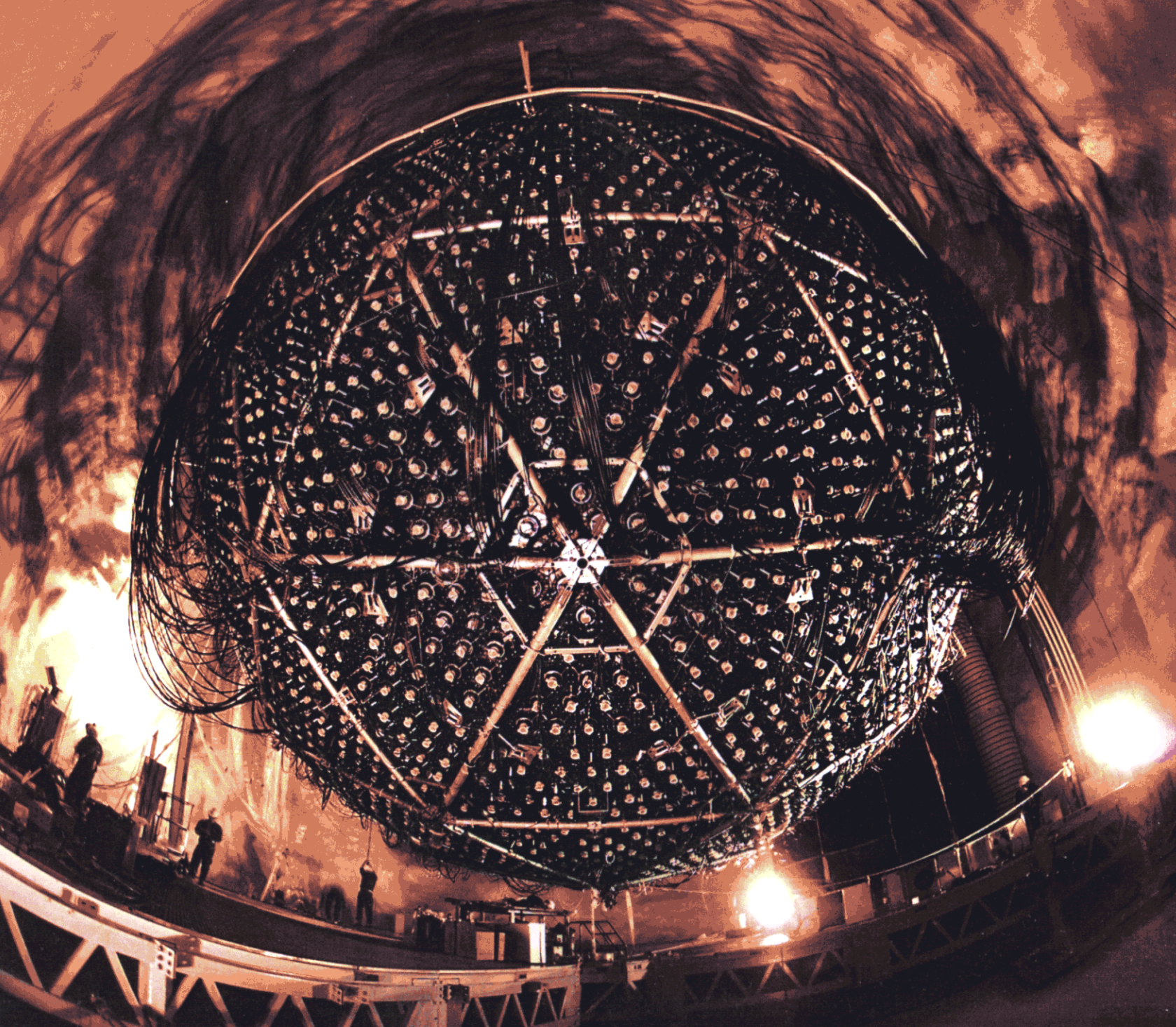


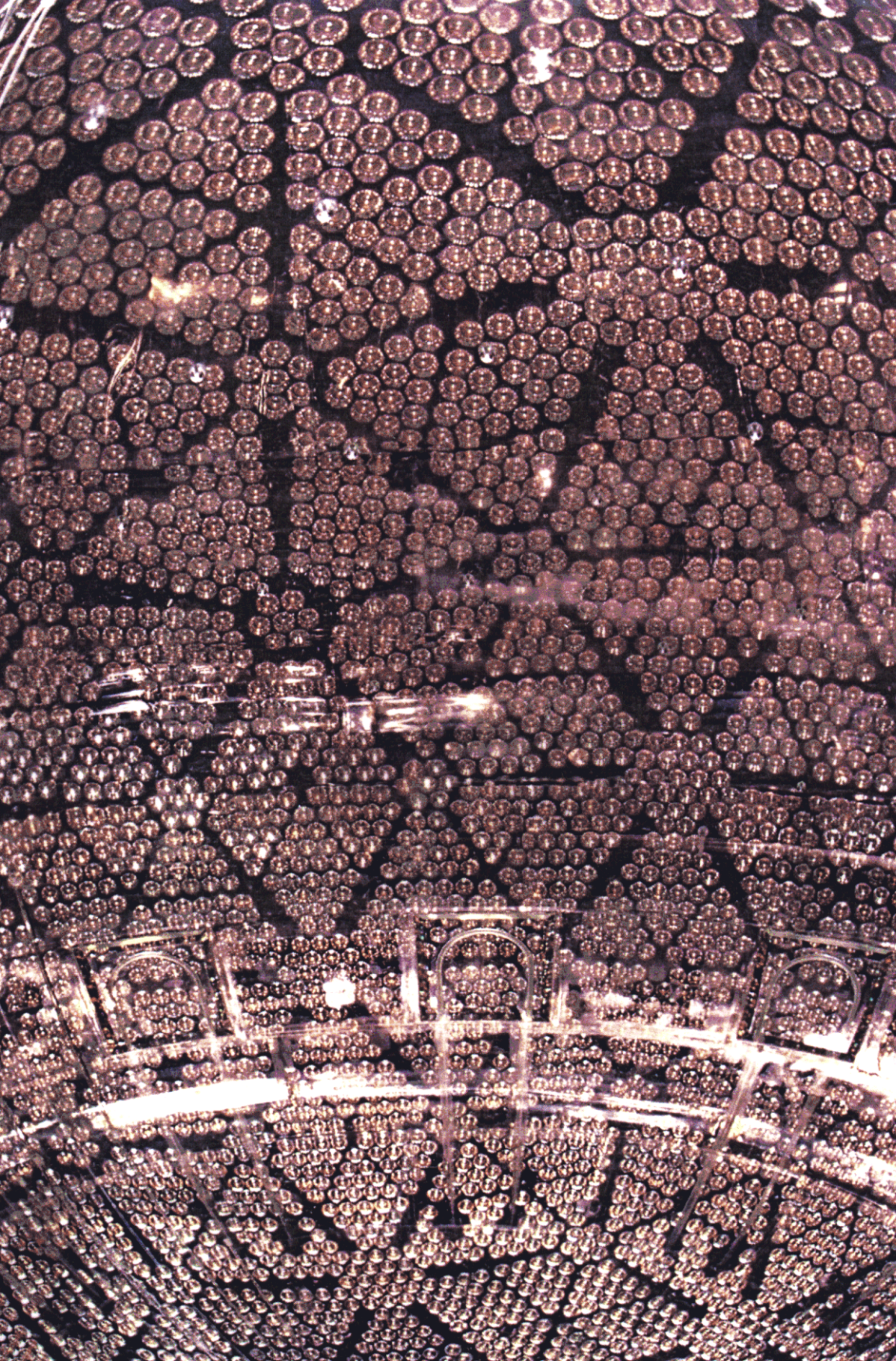
CREIGHTON NO. 9 MINE

SNO

Creighton Mine - Inco - 2050 m level

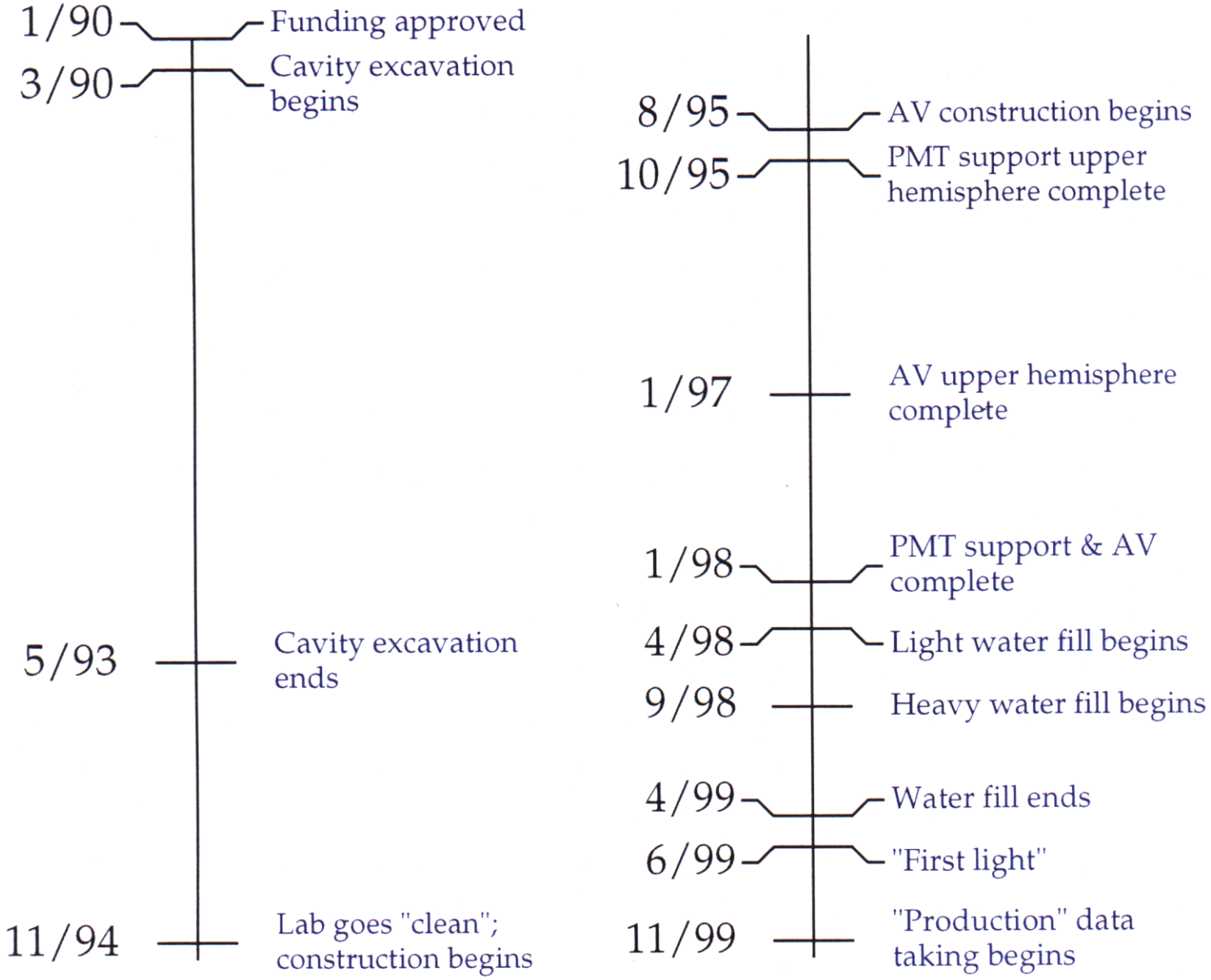






A SNO Timeline

11/84 : Herb Chen visits INCO to discuss the possibility of SNO



SOLAR NEUTRINO REACTIONS IN SNO

1.CHARGED CURRENT INVERSE BETA REACTION:

$$\nu_e + d \rightarrow p + p + e^- \qquad \text{1.44 MeV threshold}$$

- ONLY ν_e CAN PARTICIPATE
- GOOD SPECTRAL INFORMATION
- SOME DIRECTIONAL INFORMATION
- 12.7 EVENTS/DAY (SSM/2)

2. NEUTRAL CURRENT REACTION:

$$\nu_x + d \rightarrow \nu_x + p + n \qquad \text{2.22 MeV threshold}$$

- ALL NEUTRINO'S PARTICIPATE (TOTAL FLUX)
- MUST DETECT FREE NEUTRINO (DIFFICULT)
- 25.5 EVENTS/DAY (SSM)

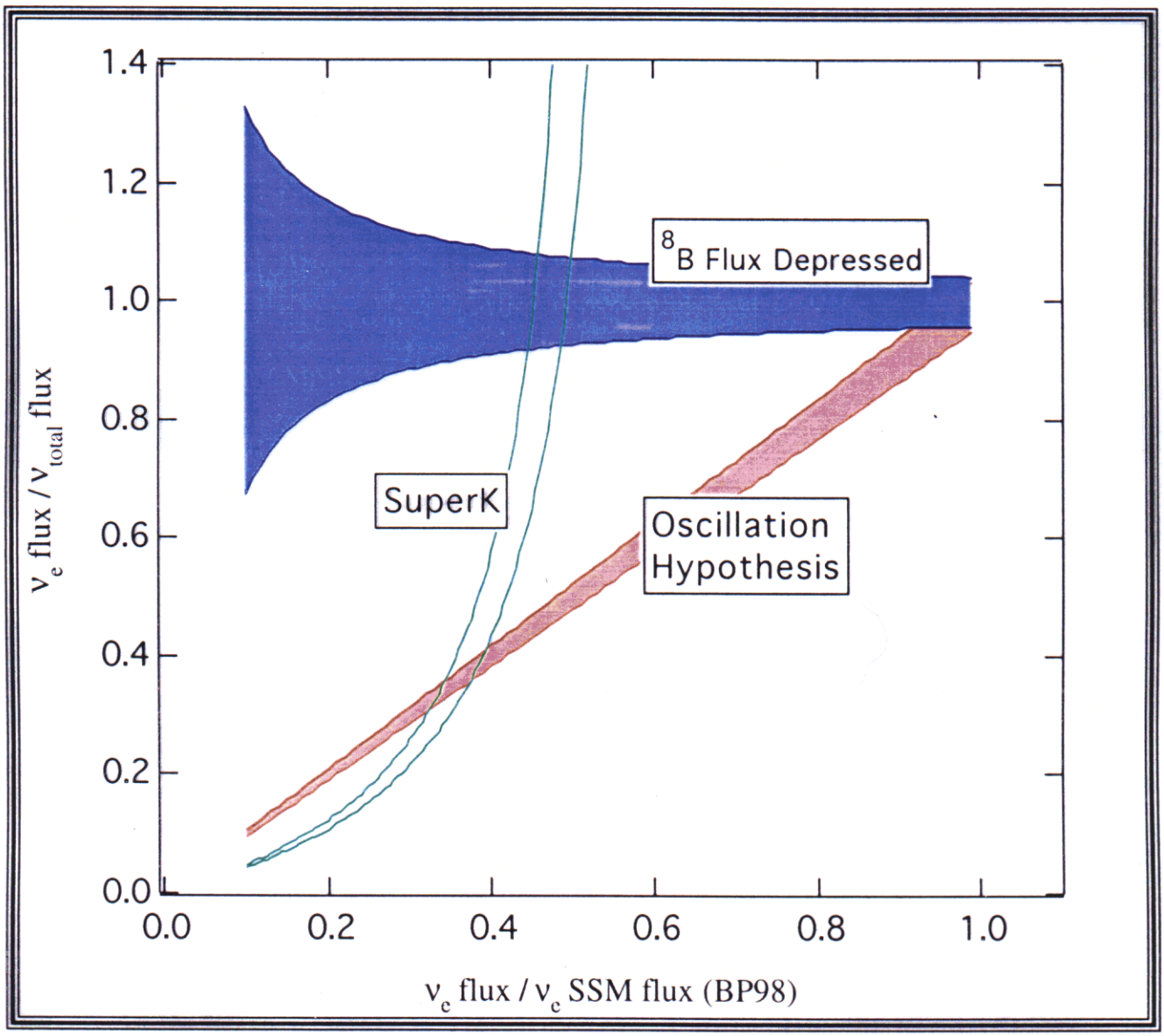
3. NEUTRINO-ELECTRON ELASTIC SCATTERING:

$$\nu_x + e \rightarrow \nu_x + e$$

- ALL NEUTRINOS PARTICIPATE
- GOOD DIRECTIONAL INFORMATION
- POOR SPECTRAL INFORMATION
- 1.4 EVENTS/DAY (SSM/2)

NOTE: RATES ASSUME ^{8}B FLUX OF 6 x 10^6 cm^{-2} sec^{-1}
PLUS NEUTRINO OSCILLATIONS

CC/NC Ratio
1 Year

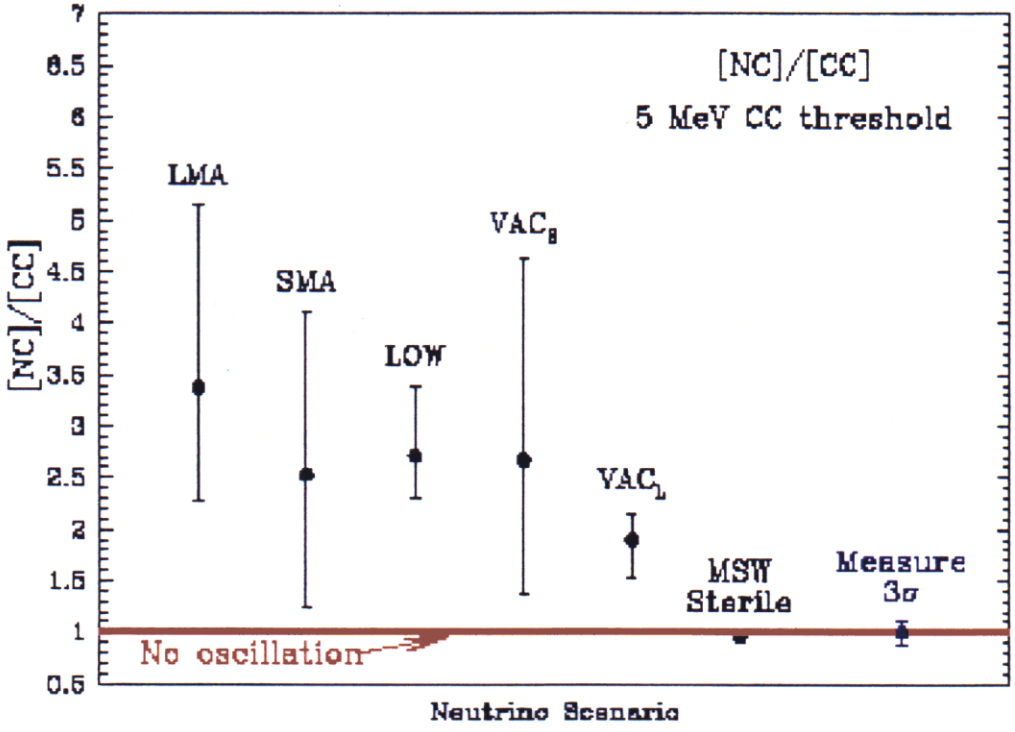


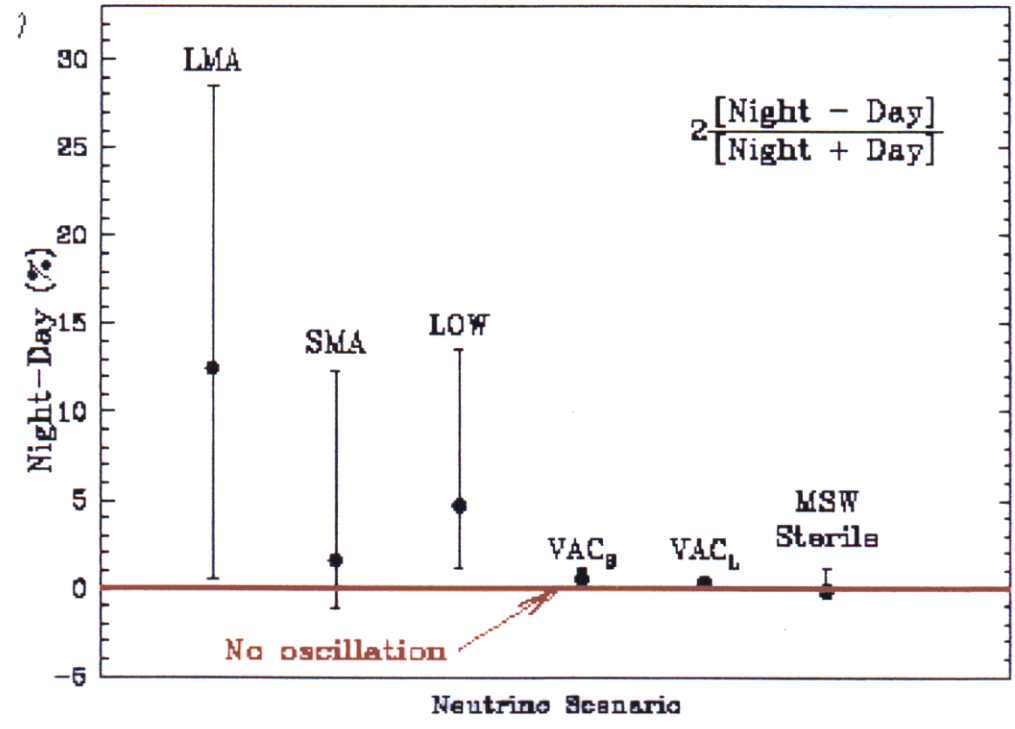
photodisintegration neutrons: 900/year
CC efficiency: 0.61
NC efficiency: 0.45

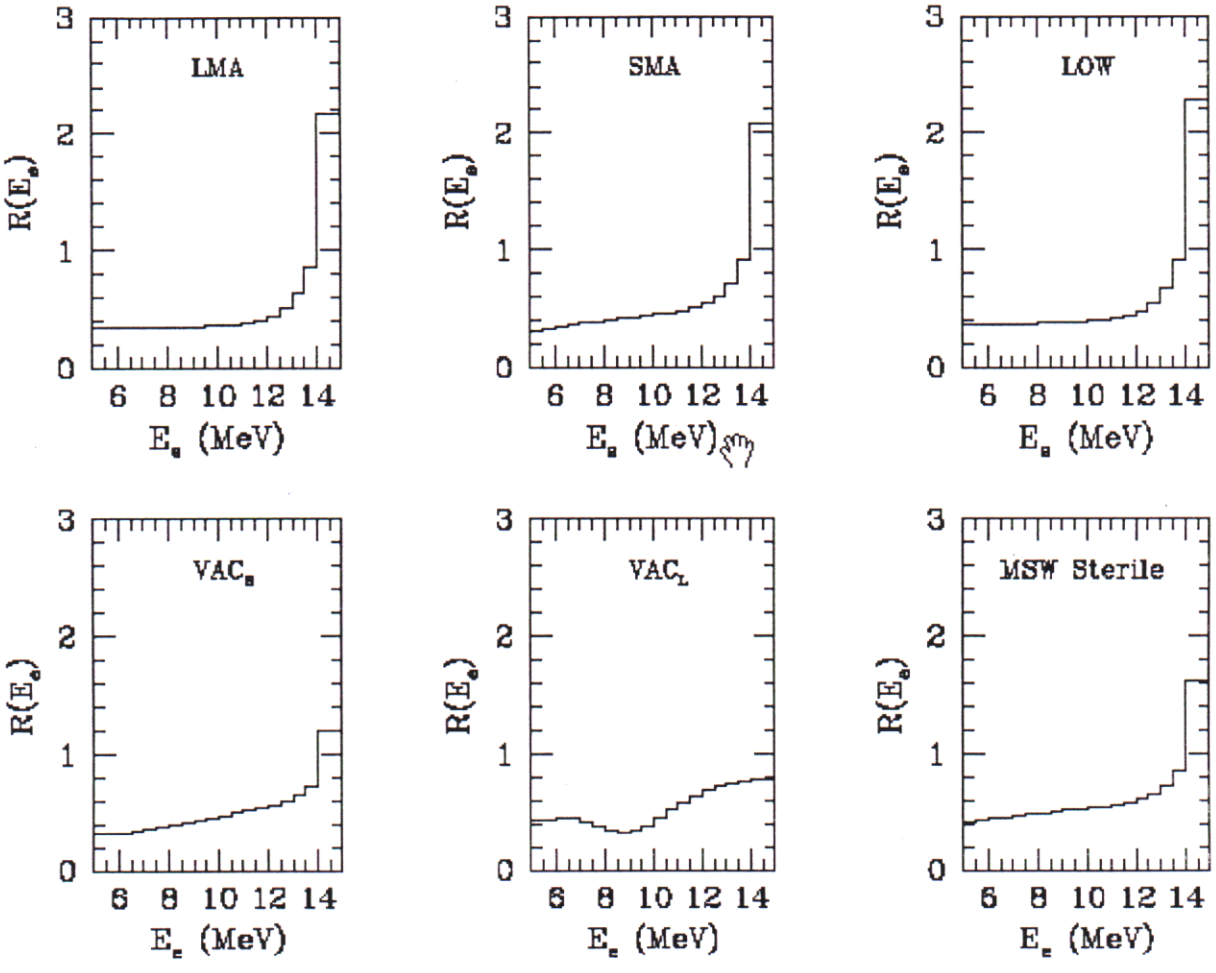
Elliott

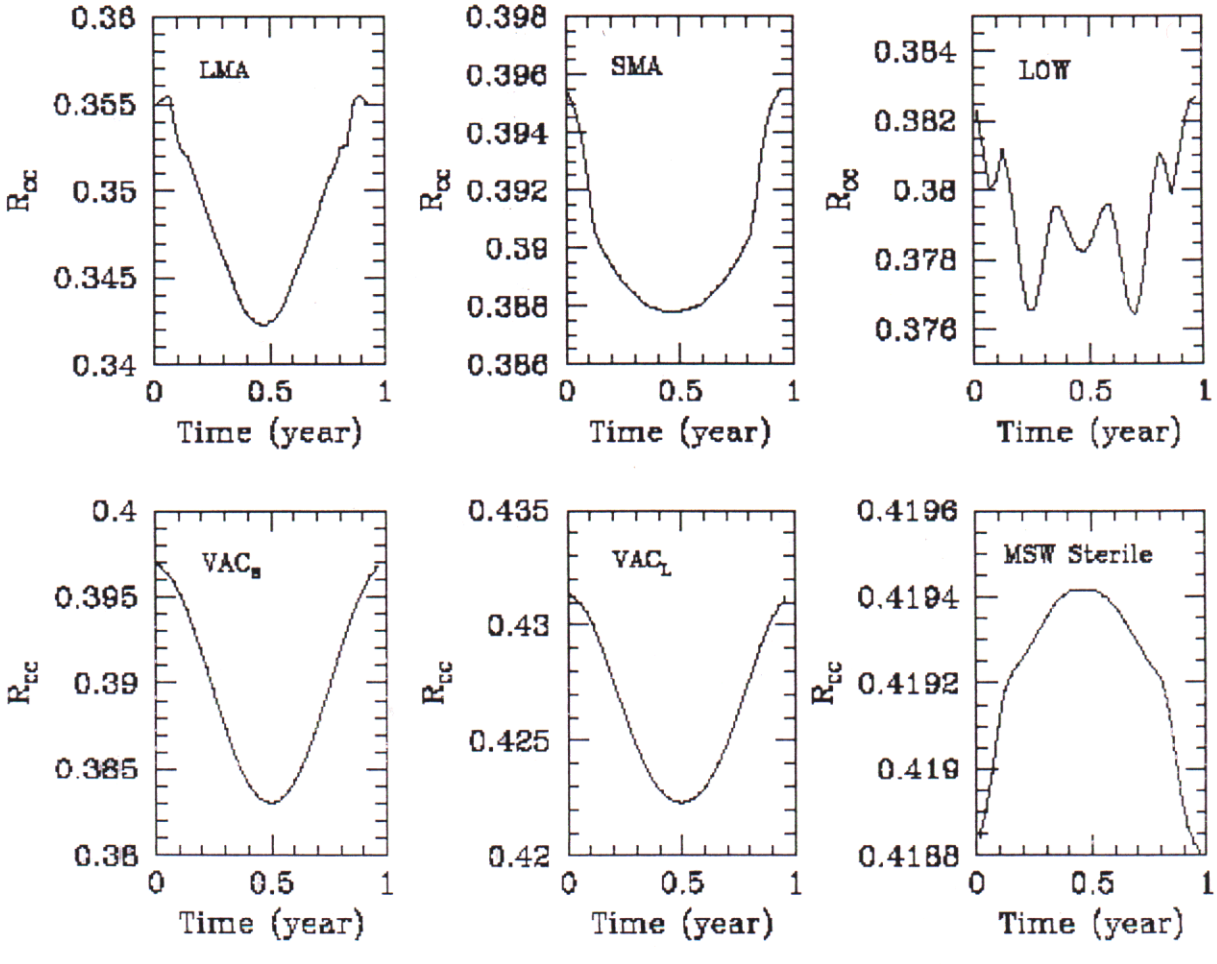
Observable	LMA	SMA	LOW	VAC	Sterile
NC/CC	HI	HI	HI	HI	LO
DAY-NIGHT	HI	MED	MED	LO	LO
SEASONAL	LO	LO	LO	LO	HI
e^- σ	LO	LO	LO	HI	LO
e^- ΔT	LO	HI	LO	HI	HI
e^- DISTORT.	LO	LO	LO	HI	LO

Bahcall, Krastev, & Smirnov
hep-ph/0002293


[NC]/[CC]
5 MeV CC threshold
LMA
SMA
LOW
VAC$_S$
VAC$_L$
MSW Sterile
Measure 3σ
No oscillation
[NC]/[CC]
Neutrino Scenario


LMA
SMA
LOW
VAC$_S$
VAC$_L$
MSW Sterile
No oscillation
$2\frac{[\text{Night} - \text{Day}]}{[\text{Night} + \text{Day}]}$
Night−Day (%)
Neutrino Scenario


LMA
SMA
LOW
VAC$_s$
VAC$_L$
MSW Sterile
R(E$_e$)
E$_e$ (MeV)


LMA
SMA
LOW
VAC$_s$
VAC$_L$
MSW Sterile
R$_{cc}$
Time (year)

Standard deviation of electron recoil energy spectrum

Scenario	$(\Delta\sigma)_{\rm b.f.}$ keV 5 MeV	$(\Delta\sigma)_{\rm min}$ keV 5 MeV	$(\Delta\sigma)_{\rm max}$ keV 5 MeV	$(\Delta\sigma)_{\rm b.f.}$ keV 8 MeV	$(\Delta\sigma)_{\rm min}$ keV 8 MeV	$(\Delta\sigma)_{\rm max}$ keV 8 MeV
LMA	3	−19	9	4	−13	11
SMA	23	1	38	23	3	34
LOW	3	−3	13	2	−3	10
$\rm VAC_S$	70	11	136	44	9	76
$\rm VAC_L$	127	−29	199	160	−40	212
Sterile	19	2	32	14	−4	36

Centroid shift of electron recoil energy spectrum

Scenario	$(\Delta T)_{\rm b.f.}$ keV 5 MeV	$(\Delta T)_{\rm min}$ keV 5 MeV	$(\Delta T)_{\rm max}$ keV 5 MeV	$(\Delta T)_{\rm b.f.}$ keV 8 MeV	$(\Delta T)_{\rm min}$ keV 8 MeV	$(\Delta T)_{\rm max}$ keV 8 MeV
LMA	8	−115	34	4	−35	15
SMA	218	50	341	66	15	105
LOW	12	−17	63	7	−5	25
$\rm VAC_S$	283	−80	576	122	40	227
$\rm VAC_L$	21	−152	214	236	−54	358
Sterile	164	41	265	51	13	83

Options for NC Detection

Additives

- **MgCl salt** $^{35}Cl(n,\gamma)^{36}Cl$
  - ~84% capture efficiency

PROS:

- Technologically (relatively) simple
- High efficiency
- 8.6 MeV γ well above threshold

CONS:

- Radial dependence lost
- No event-by-event discrimination of NC & CC
- Not systematically independent from CC

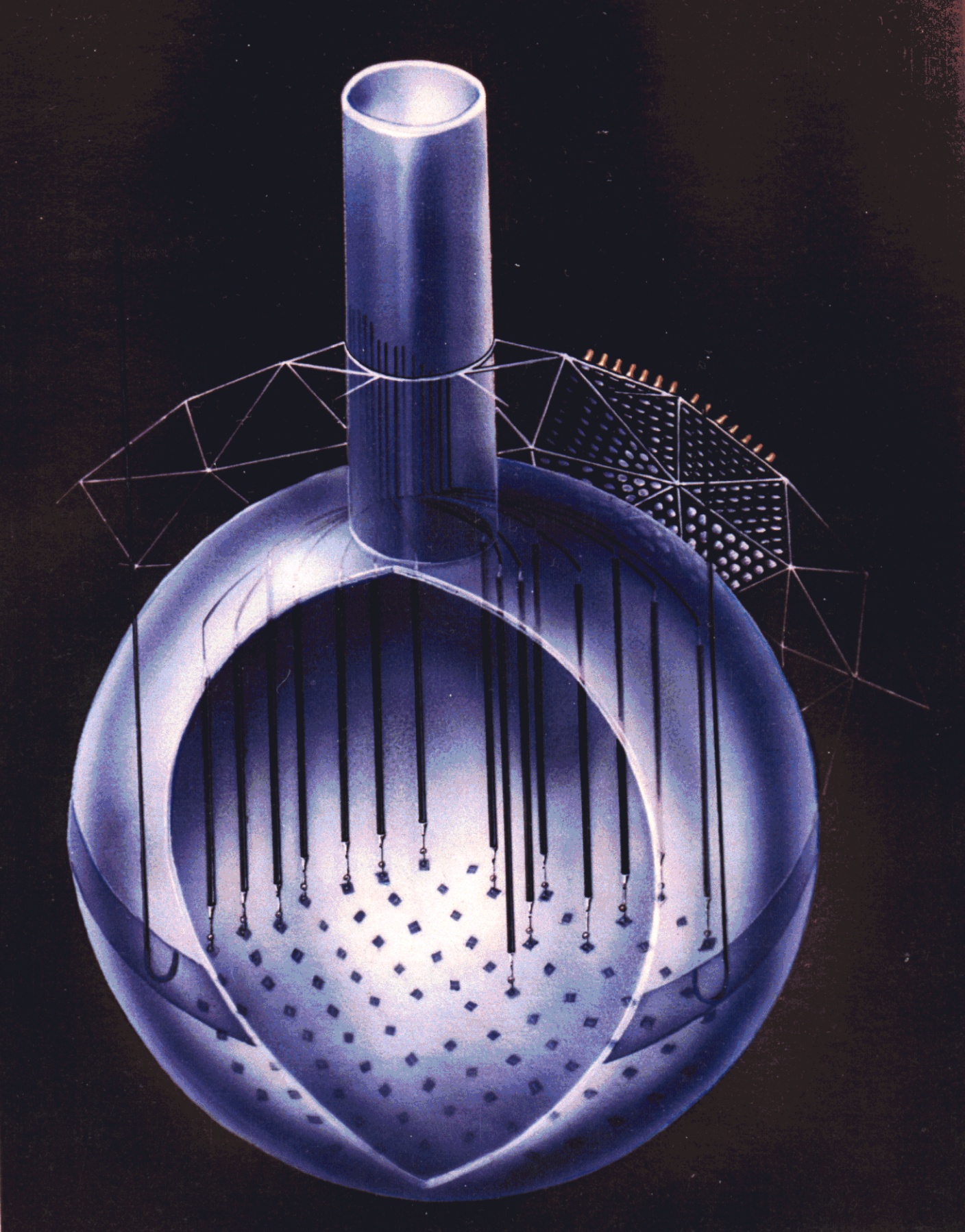
- **NCDs** $^{3}He(n,p)^{3}H$
  - ~45% capture efficiency

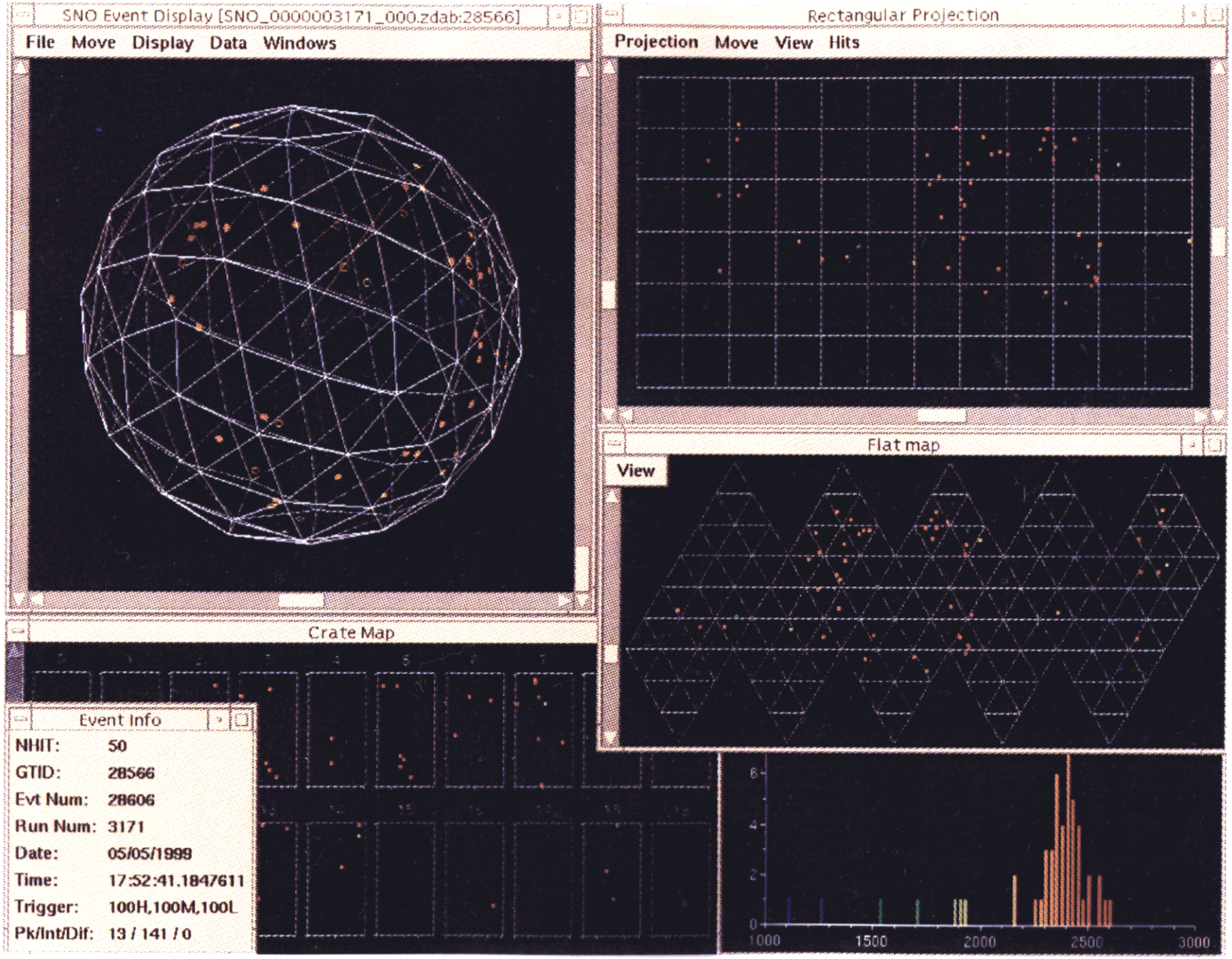
PROS:

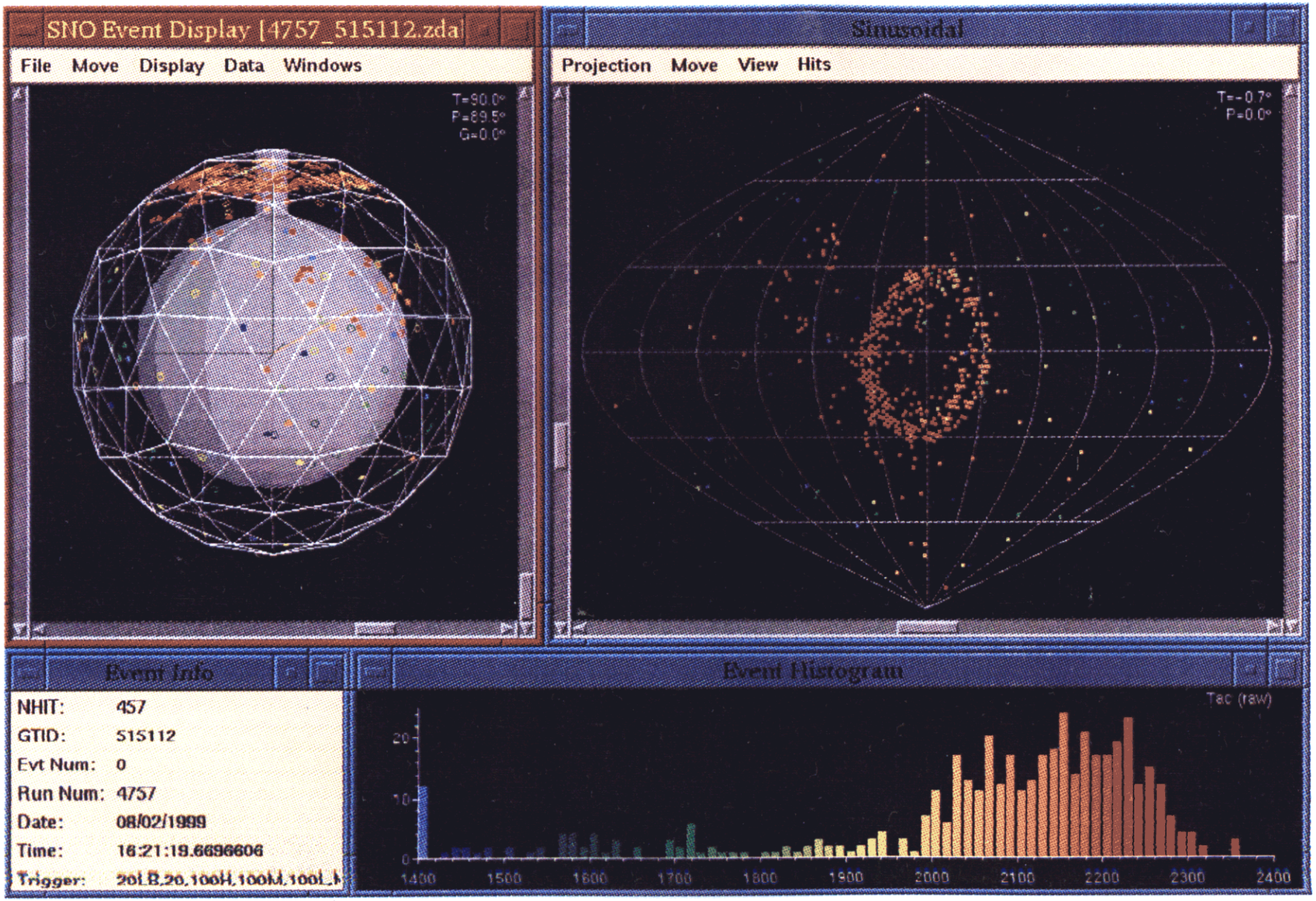
- Event-by-event discrimination of NC & CC
- Systematically independent from CC

CONS:

- Technologically complicated
- Occlude ~15% CC light
- Must shut detector down for ~1 month to install

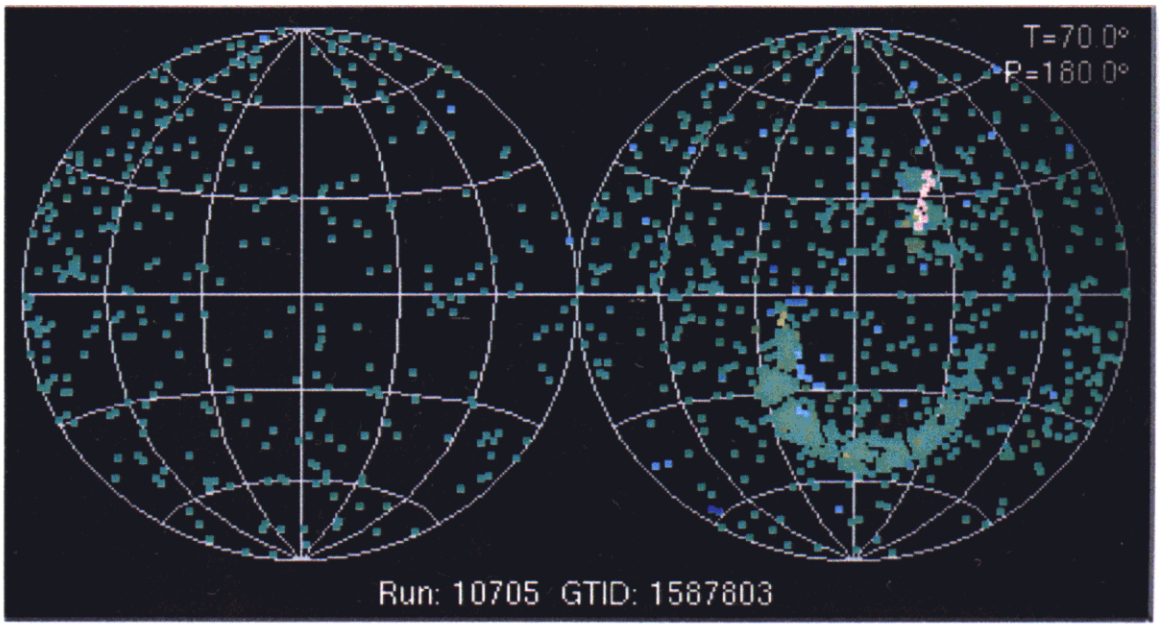



SNO Event Display [SNO_0000003171_000.zdab:28566]
File Move Display Data Windows
Rectangular Projection
Projection Move View Hits
Flat map
View
Crate Map
Event Info
NHIT: 50
GTID: 28566
Evt Num: 28606
Run Num: 3171
Date: 05/05/1999
Time: 17:52:41.1847611
Trigger: 100H,100M,100L
Pk/Int/Dif: 13 / 141 / 0
0
2
4
6
1000
1500
2000
2500
3000

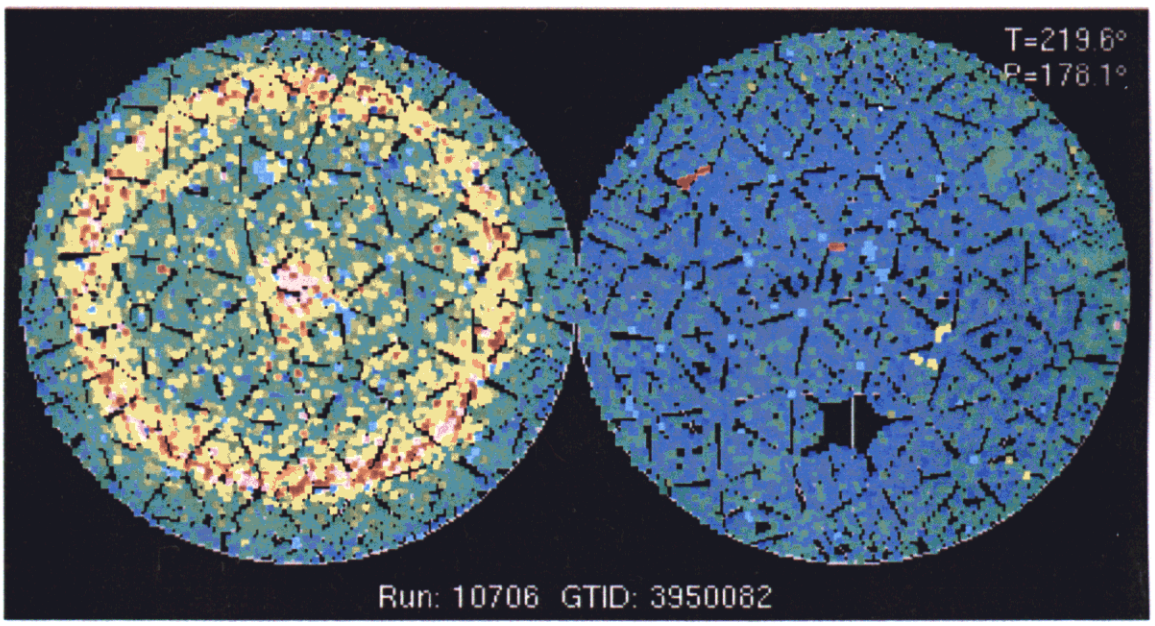

SNO Event Display [4757_515112.zda]
File Move Display Data Windows
T=90.0°
P=89.5°
G=0.0°
Sinusoidal
Projection Move View Hits
T=-0.7°
P=0.0°
Event Info
NHIT: 457
GTID: 515112
Evt Num: 0
Run Num: 4757
Date: 08/02/1999
Time: 16:21:19.6696606
Trigger: 20LB,20,100H,100M,100L,N
Event Histogram
Tac (raw)
20
10
0
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400

Muon Events

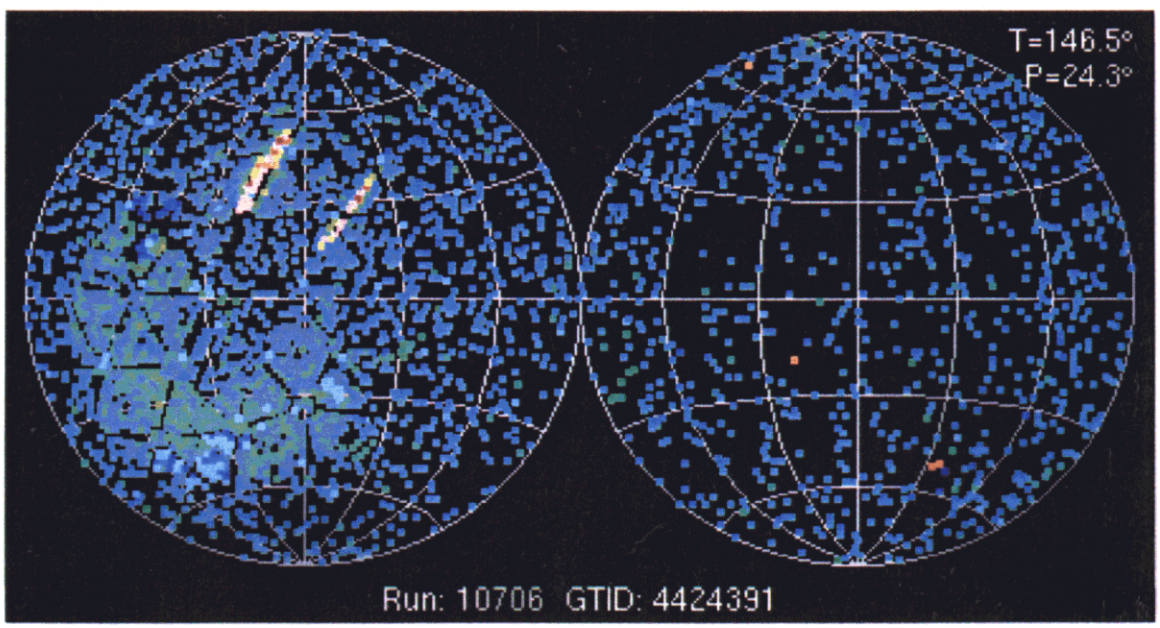
Clipper



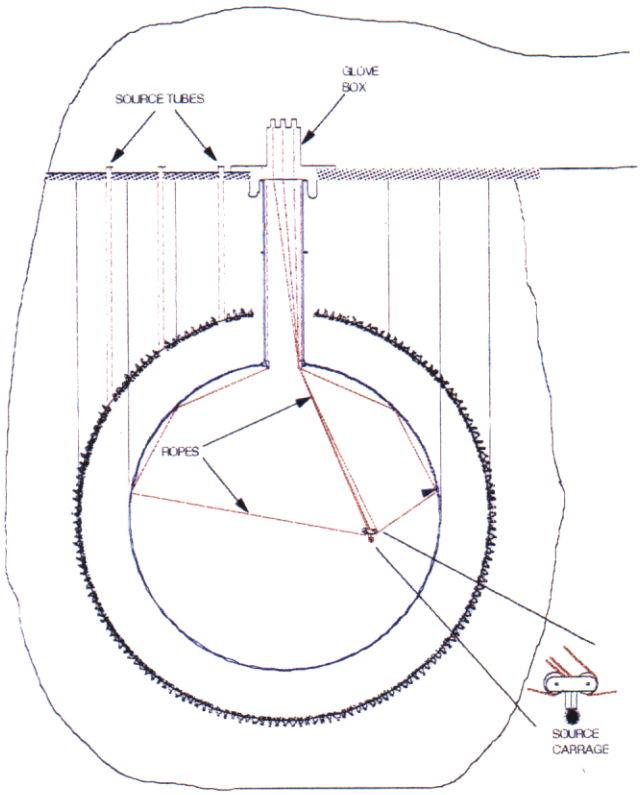
Through-going



Dual Clippers



CALIBRATIONS



Source Insertion

D_2O
Manipulator
± 5cm in 2 planes

H_2O
6 Insertion tubes

Optical:

: **Laser** photons, 337 - 700 nm, 0 - 45 Hz

: **Sonoluminescent** 200ps timing pulse

Energy:

: **^{16}N source** ß tagged 6.1 MeV gamma

pT source 19.8 MeV gamma

^{8}Li source electron spectrum ≈ ^{8}B

Neutron:

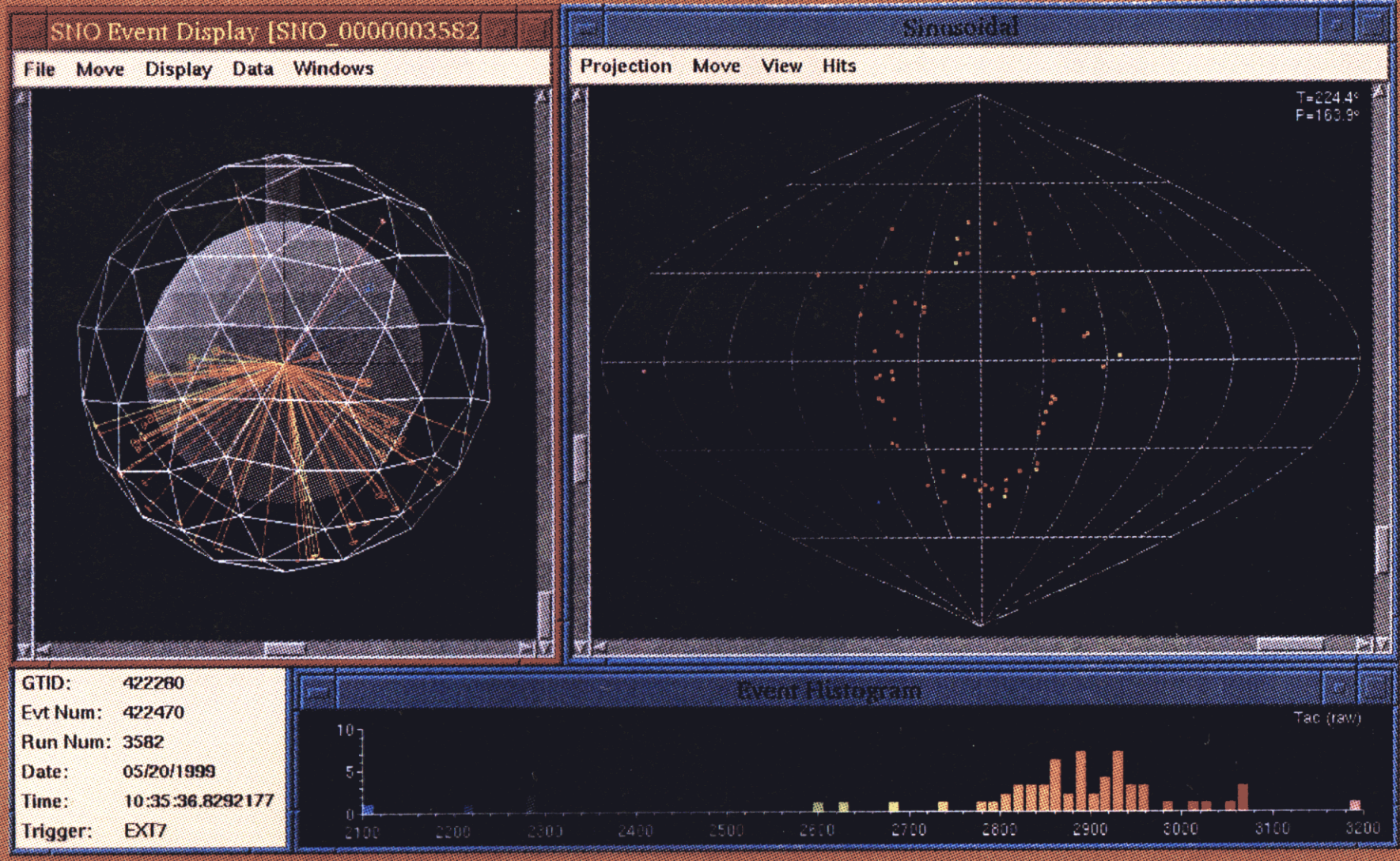
^{252} Cf Fission neutron source

^{17}N Triggered neutron source

Electronics:

: **Charge pulser**

^{16}N Source Event



DETECTOR PERFORMANCE

February 2000

CALIBRATIONS:

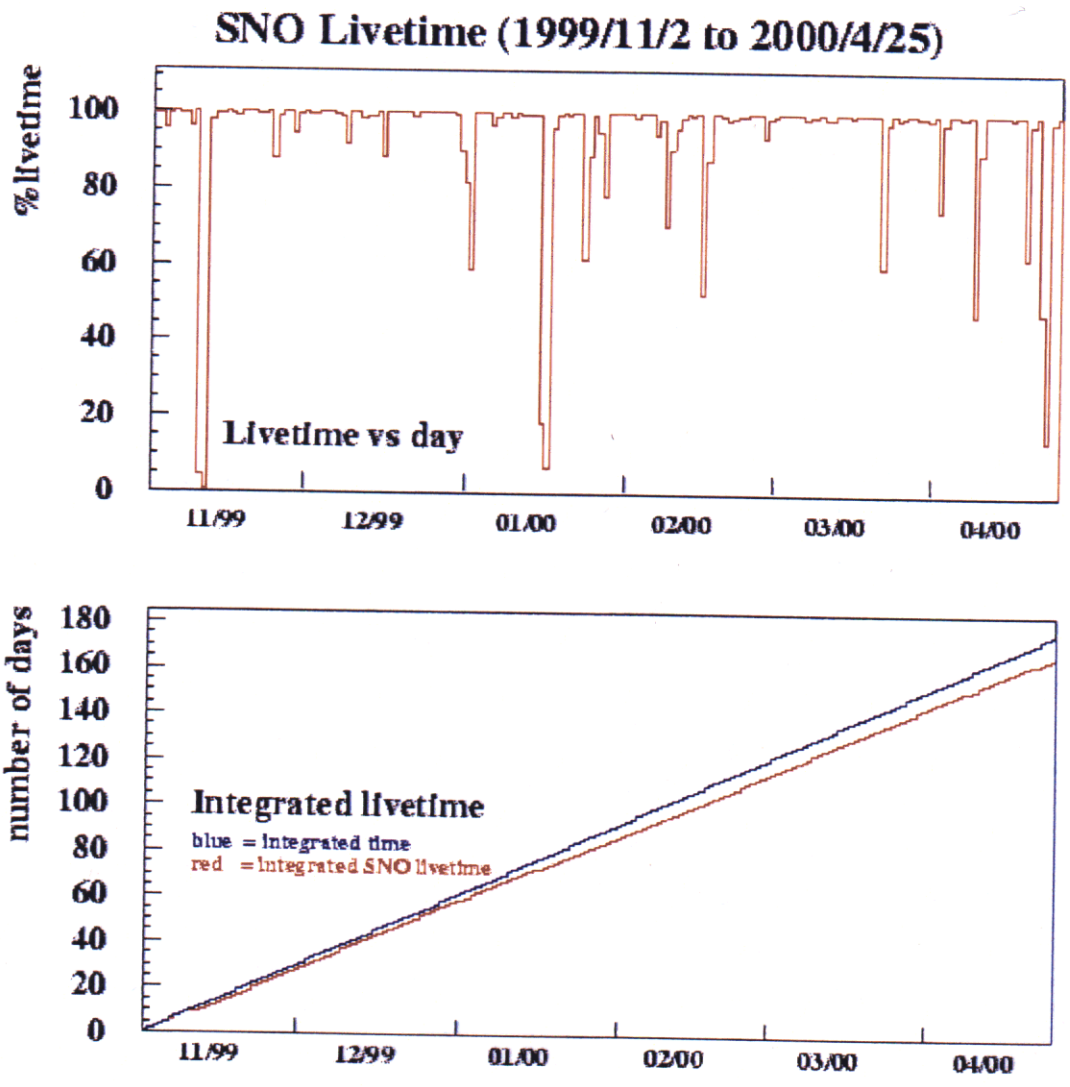
- Detector efficiency increased 9% by increasing PMT gain (Oct. '99)
- Production optical and energy calibration taken
- Monte Carlo NHIT/MeV ≈ 8hits/MeV
- Electronic calibrations (pedestals + slopes) very stable
- PMT timing resolution near goal of 1.7 ns

PMT's:

- Number of dead PMT's/Channels roughly 175
- Death rate (all causes) about 0.5%/year
- Flasher rate approximately 1/minute
  - Varies by factor of 2
  - Correlated to seismic events
  - Easy to identify/eliminate
- No significant connector breakdown

ELECTRONICS:

- > 98.5% of 9598 PMT channels fully working
- Reduced channel threshold (Oct. '99)
- Average channel threshold 0.25pe
- Average tube noise @ 0.25pe ≈500Hz
- Typical noise tubes in 420ns window ≈2


SNO Livetime (1999/11/2 to 2000/4/25)
% livetime
100
80
60
40
20
0
Livetime vs day
11/99
12/99
01/00
02/00
03/00
04/00
number of days
180
160
140
120
100
80
60
40
20
0
Integrated livetime
blue = integrated time
red = integrated SNO livetime
11/99
12/99
01/00
02/00
03/00
04/00

DETECTOR PERFORMANCE

February 2000

TRIGGER RATES/THRESHOLDS/LIVETIMES:

- Overall Rate ≈ 15 Hz

TRIGGER TYPE	HARDWARE THRESHOLD	RATE (HZ)
Pulsed Trigger	Zero bias	5 Hz
100 ns coincidence	18 PMT's	5 Hz
20 ns coincidence	18 PMT's	2-3 Hz
Energy sum	≈ 150 pe	≈ 1 Hz
Prescaled (1:10000)	12 PMT's	≈ 1 Hz

- Trigger threshold (HARD WARE) ≈ 2 MeV
- Livetimes:

  solar neutrinos ≈ 85%

  Supernova ≈ >95%

SUMMARY OF SNO STATUS

FEBRUARY 2000

CURRENT:

- Started "production: " data November 1999
- Currently running in pure D_2O mode
  - ^8B Flux
  - Spectral shape
- Detector is very "quiet", running "smoothly"
- Livetime (neutrino) $\geq 85\%$
- Radioactive backgrounds close to (or better than) design specifications

FUTURE:

- Improve livetime
- Reduce backgrounds, improve assay
- Streamline analysis
- Enhance NC detection
- Preliminary running plan:
  - ~1 Year pure D_2O
  - ~1 year ^{35}Cl
  - Install ^3He Array

Summary

- **Solar Neutrino Problem:** $\phi(^8B) \sim 0.5\, \phi(^8B)_{SSM}$, $\phi(^7Be) \sim 0$, $\phi(pp) \sim \phi(pp)_{SSM}$
- **No sol'ns from nuclear or astro**
- **If all exps correct → sterile neutrinos**
- **Matter-enhanced ν osc. look promising**
- **SNO can measure NC/CC: model indep.**
- **SNO running well; 1st results later this year**