Neutrino Ocillations and Astroparticle Physics (2)

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- Neutrino Oscillations
  - Solar Neutrinos
  - Atmospheric Neutrinos
  - Reactor and Accelerator data

Experiments

- Super-Kamiokande
- SNO
- LSND/KARMEN
- Opera/ Icarus
- ANTARES

Neutrino Oscillations

Neutrino weak eigenstates ($\nu_e\ \nu_\mu, \nu_\tau$) are mixtures of mass eigenstates ($\nu_1\ \nu_2, \nu_3$)
If masses m_1, m_2, m_3 non-degenerate get mixing
eg. for 2 flavours:

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta_{23} & -\sin\theta_{23} \\ \sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$

where θ_{23} is mixing angle

Time dependence: $|\nu_2(t)\rangle = \exp(-iE_1 t)\ |\nu_2(t)\rangle$

Probability oscillation $\nu_\mu \quad \nu_\tau$

$$|\nu_\mu(t)\rangle^2 = 1 - \sin^2(2\theta)\sin^2(E_2 - E_3)/2\ t$$

$$= 1 - \sin^2(2\theta)\sin^2(\Delta m^2 L/4E)$$

where $\Delta m = (m_2 - m_3)$ is neutrino mass difference
L is distance travelled, ‘oscillation length’
E is average energy

History of Neutrino Oscillations

Theory

1967 Predicted by Pontecorvo

Experiments

1968 -	‘ Solar Neutrino Problem ’
1988 -	‘ Atmospheric Neutrino Anomaly ’
1970 -	Searches at accelerators and nuclear reactors
>2004	‘ Long Baseline Experiment ’
>2010	‘ Neutrino Factories ’

Only in past couple of years
has the situation become clear
and situation understood

Oscillation Length

Oscillation probability:

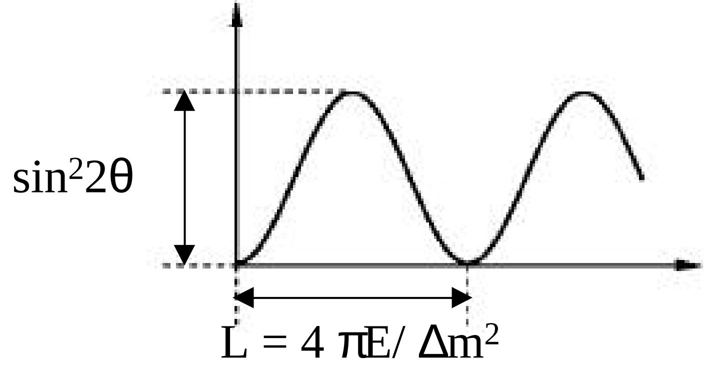
$P(\nu_1 \rightarrow \nu_2) = \sin^2 2\theta \sin^2(1.27\,\Delta m^2 L/E)$,

Δm mass difference,

θ mixing angle

E energy of ν,

L oscillation length



Source	Energy, E	Oscillation Length, L		
		Δm^2=1eV	$\Delta m^2=10^{-3}$ eV	$\Delta m^2=10^{-11}$ eV
Accelerator beam	100 GeV 5 GeV 30 MeV	250 km 13 km 75 m	2.5×10^5 km 1.3×10^4 km 75 km	2.5×10^{13} km 1.3×10^{12} km 7.5×10^9 km
Reactor	4 MeV	10 m	10 km	1.0×10^9 km
Sun	0.2-10 MeV			1.5×10^8 km
Atmosphere	1-10 GeV		1.3×10^4 km	

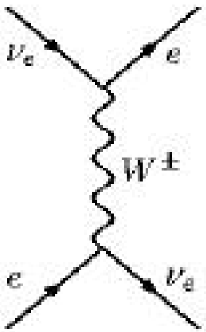
Neutrino Oscillations in Matter
MSW effect

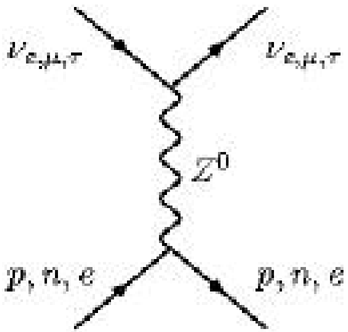
Mikheyev-Smirnov-Wolfenstein: enchancement in matter

Evolution in vacuum:

$$i\frac{d}{dt}\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta_0 & \frac{\Delta m^2}{4E}\sin 2\theta_0 \\ \frac{\Delta m^2}{4E}\sin 2\theta_0 & \frac{\Delta m^2}{4E}\cos 2\theta_0 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

Neutrino interactions in matter:





depends on N_e
electron number density

Evolution in matter:

$$i\frac{d}{dt}\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta_0 + \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta_0 \\ \frac{\Delta m^2}{4E}\sin 2\theta_0 & \frac{\Delta m^2}{4E}\cos 2\theta_0 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

MSW effect for constant N_e

Oscillations in matter: $$P(\nu_e \to \nu_\mu; L) = \sin^2 2\theta \, \sin^2\left(\pi \frac{L}{l_m}\right)$$

Oscillations length scale change:

$$l_m = \frac{2\pi}{E_A - E_B} = \frac{2\pi}{\sqrt{\left(\frac{\Delta m^2}{2E}\cos 2\theta_0 - \sqrt{2}\, G_F\, N_e\right)^2 + \left(\frac{\Delta m^2}{2E}\right)^2 \sin^2 2\theta_0}}$$

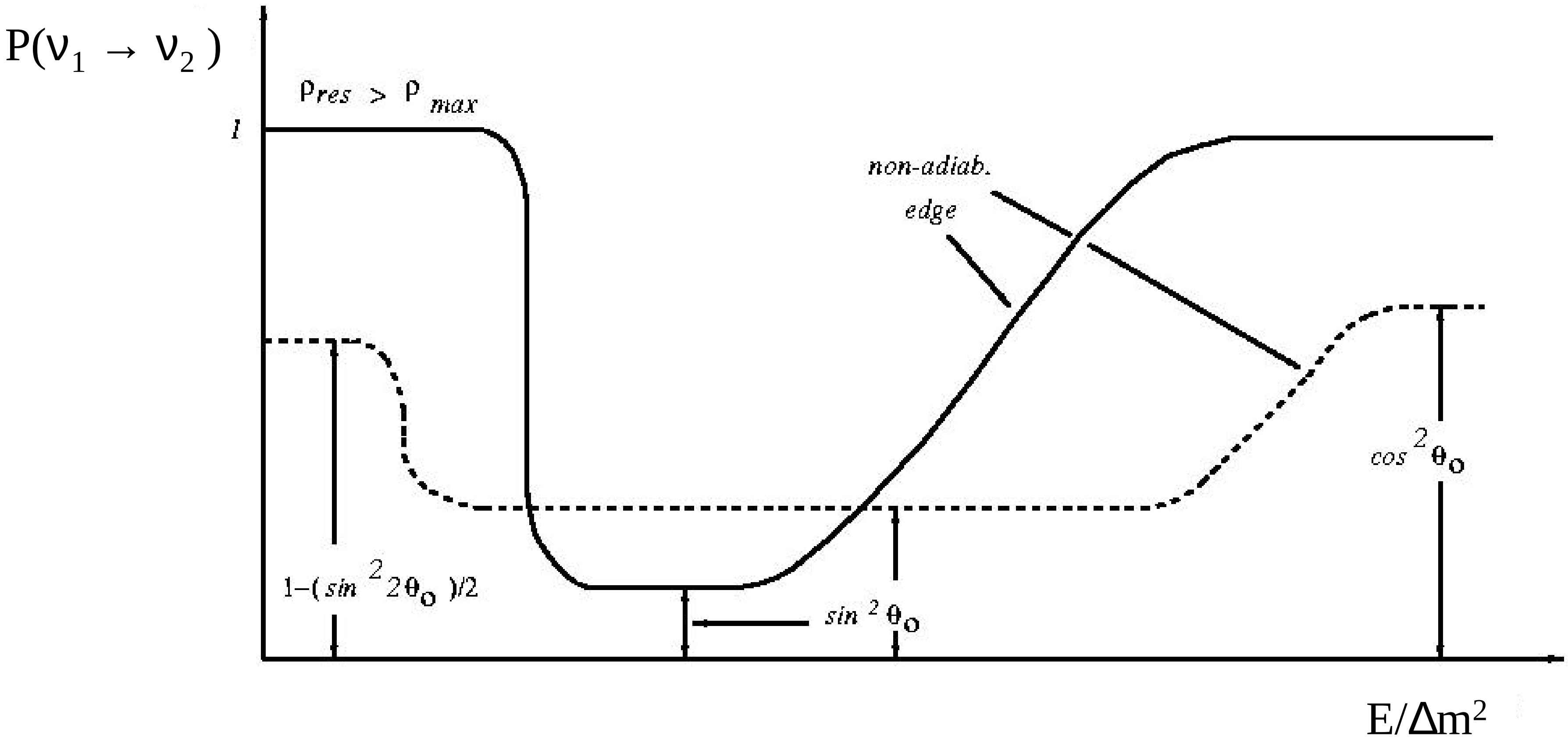
Oscillations amplitude modified:

$$\sin^2 2\theta = \frac{\left(\frac{\Delta m^2}{2E}\right)^2 \sin^2 2\theta_0}{\left(\frac{\Delta m^2}{2E}\cos 2\theta_0 - \sqrt{2}\, G_F\, N_e\right)^2 + \left(\frac{\Delta m^2}{2E}\right)^2 \sin^2 2\theta_0}$$

Resonance condition: $$\sqrt{2}\, G_F\, N_e = \frac{\Delta m^2}{2E}\cos 2\theta_0$$

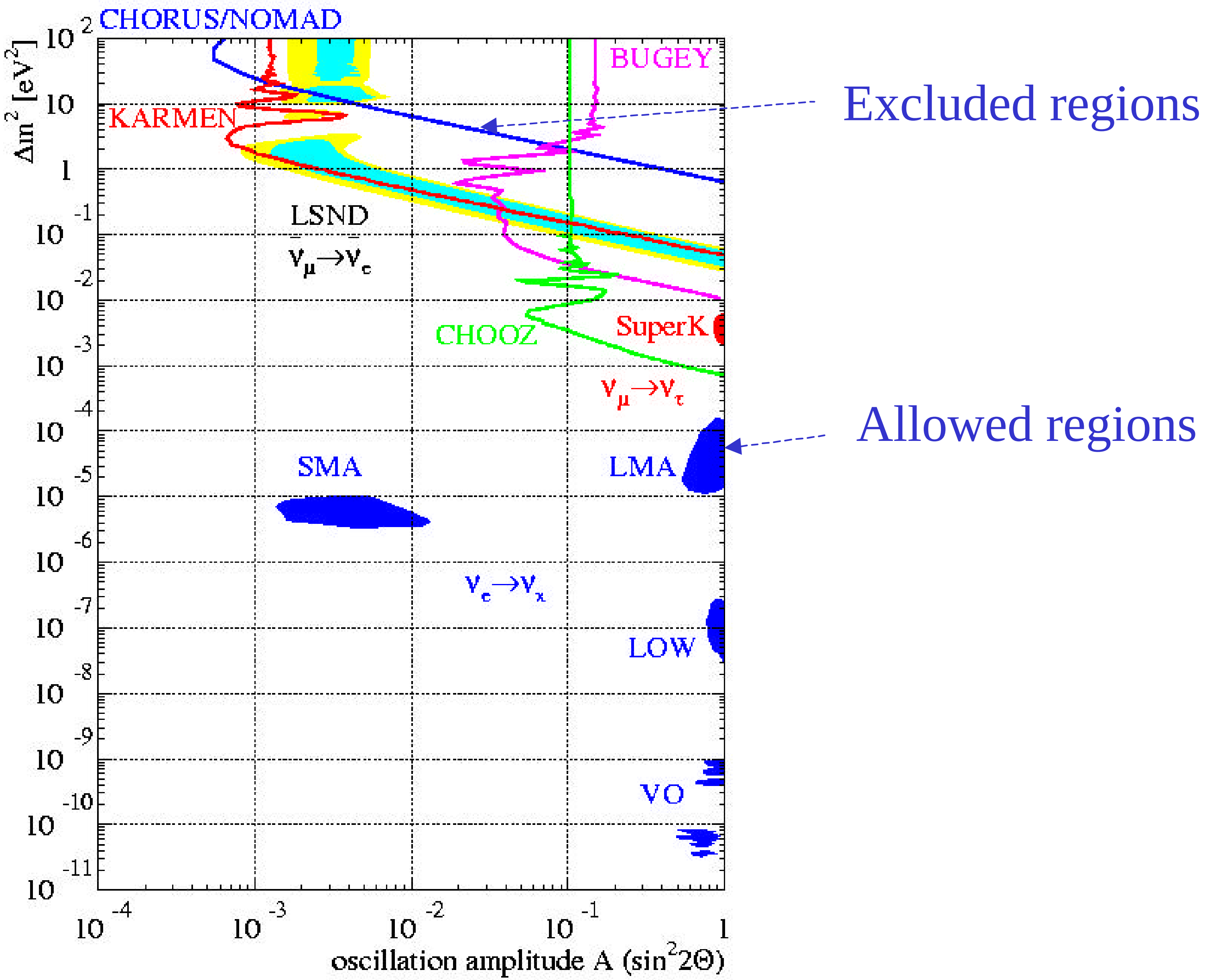
Maximum oscillation amplitude: $\sin^2 2\theta = 1$

MSW effect: Variable Ne

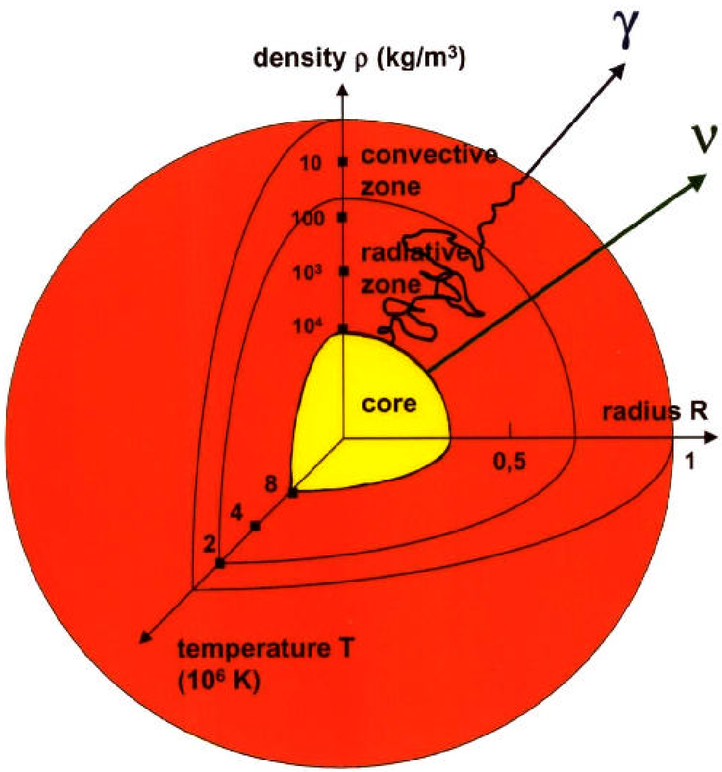


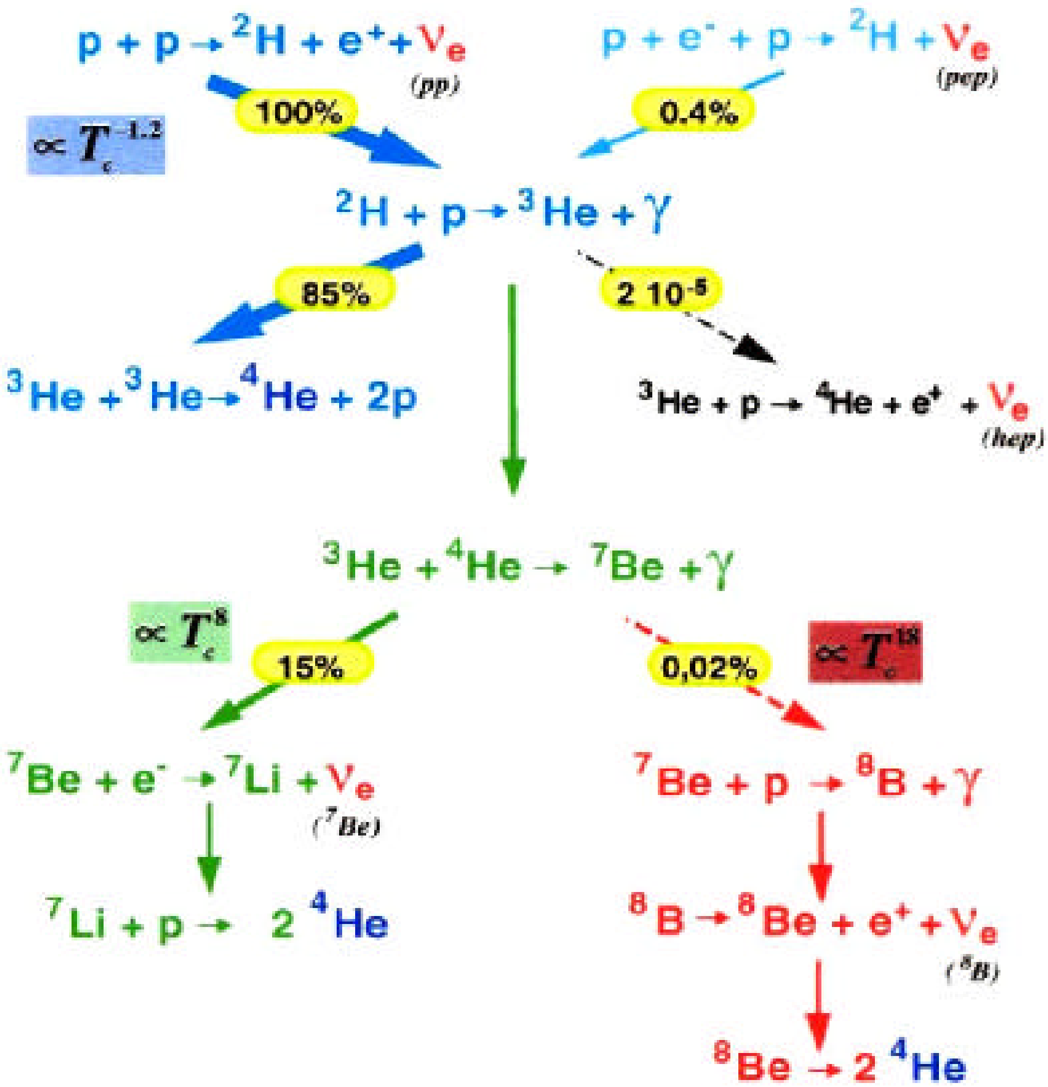
Modifications different for different energies

Present Situation (Last Year !)

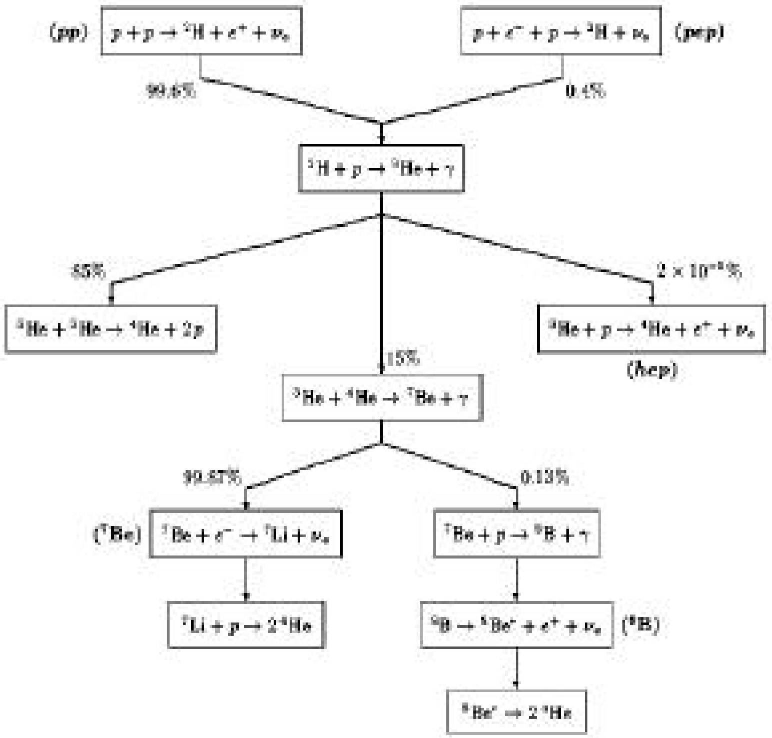


Solar Neutrinos



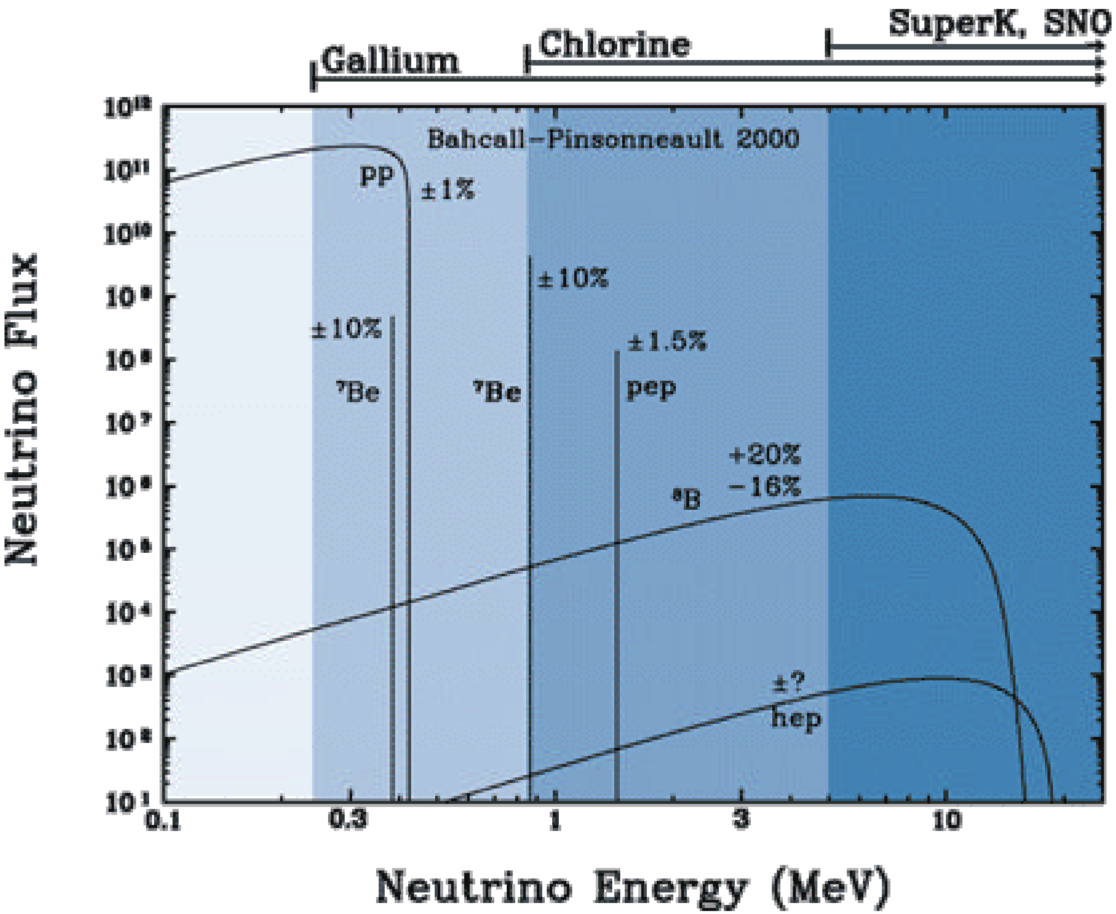


Solar Neutrino Reactions



Name	Reaction	$\langle E_\nu \rangle$ [MeV]	$E_\nu^{\max}$ [MeV]	Fractional solar flux
pp	$p + p \rightarrow D + e^+ + \nu_e$	0.26	0.42	0.909
pep	$p + e^- + p \rightarrow D + \nu_e$	1.44	—	2×10^{-3}
hep	${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$	9.62	18.77	2×10^{-8}
^{7}Be	${}^7Be + e^- \rightarrow {}^7Li + \nu_e$	(90%) 0.86	—	0.074
		(10%) 0.38	—	
^{8}B	${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$	6.71	≈ 15	8.6×10^{-5}

Standard Solar Model



Experiments have different E_ν thresholds

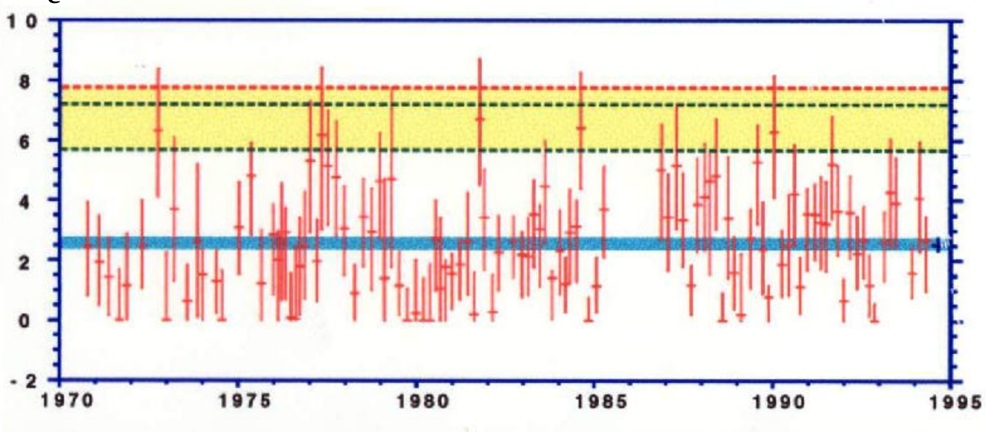
⬇

Sensitive to ν from different reactions

‘ Solar Neutrino Problem’

HOMESTAKE

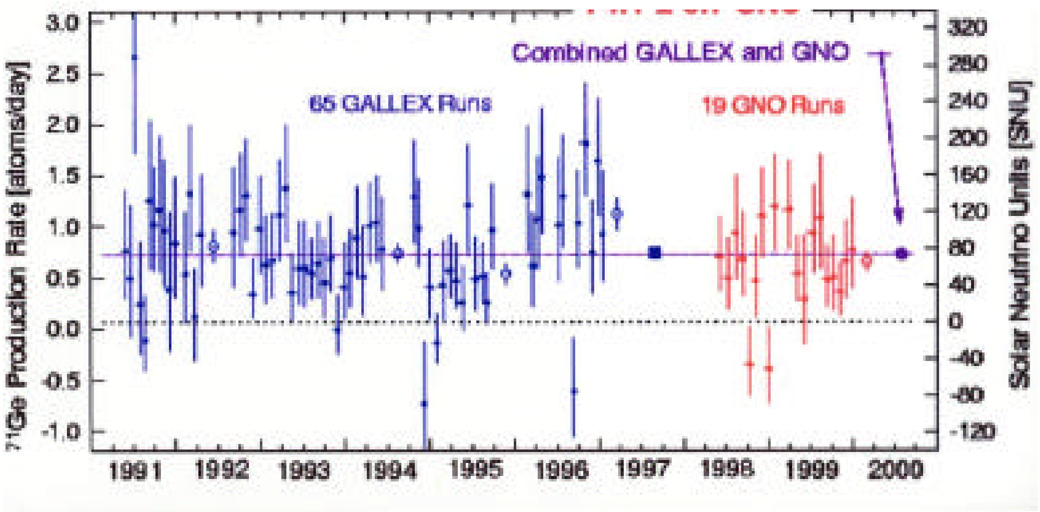
$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$: threshold 0.8 MeV, sensitive to Be and B solar neutrinos



0.3 of Standard Solar Model

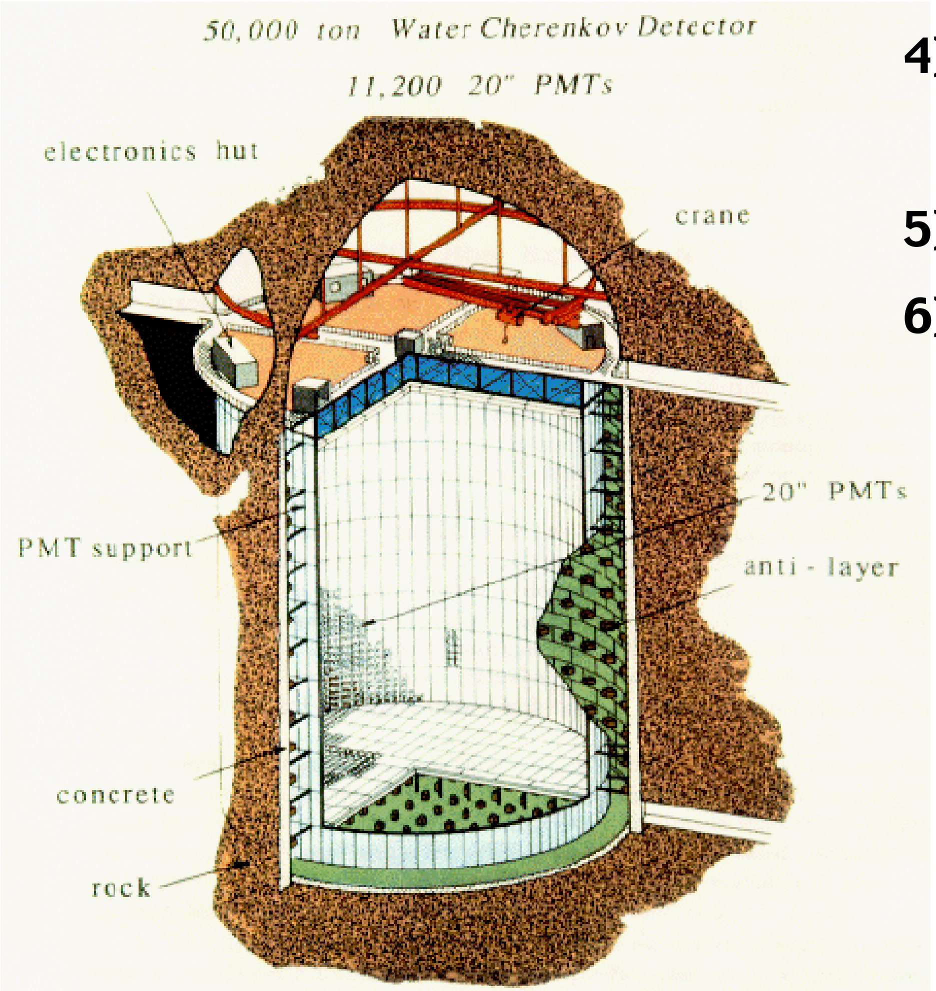
GALLEX

$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$: threshold 0.2 MeV, sensitive to pp solar neutrinos



0.6 of Standard Solar Model

Super-Kamiokande



1) Size: Cylinder of 41.4m (h) x 39.3m (d)

2) Mass: 50,000 tons of pure water

3) Light Sensitivity: 11,200 photomultiplier

4) Energy Resolution :

2.5% (at 1 GeV) at 16% (at 10 MeV)

5) Energy Threshold: 5 MeV

6) Location: Kamioka-cho, Yoshiki-gun, Gi

(1,000m underground at the Mozumi mi

of the Kamioka Mining and Smelting Co

Super-Kamiokande: Solar Neutrinos

$\nu_x + e^- \rightarrow \nu_x + e^-$: threshold 5 MeV, sensitive to B solar neutrinos

Excellent angular resolution

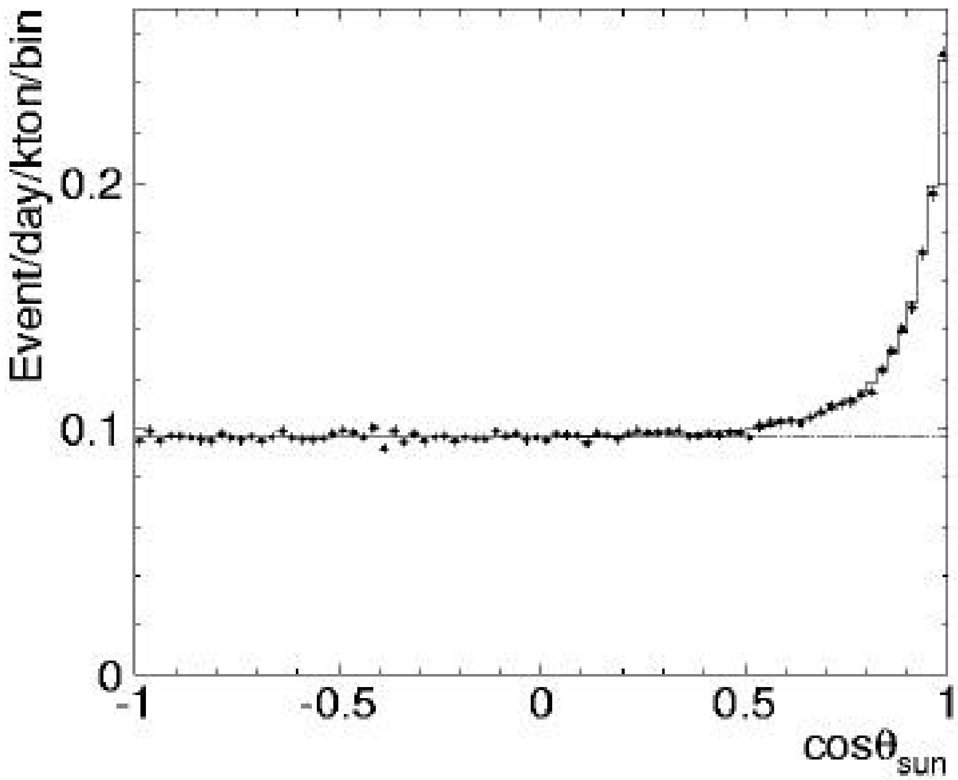
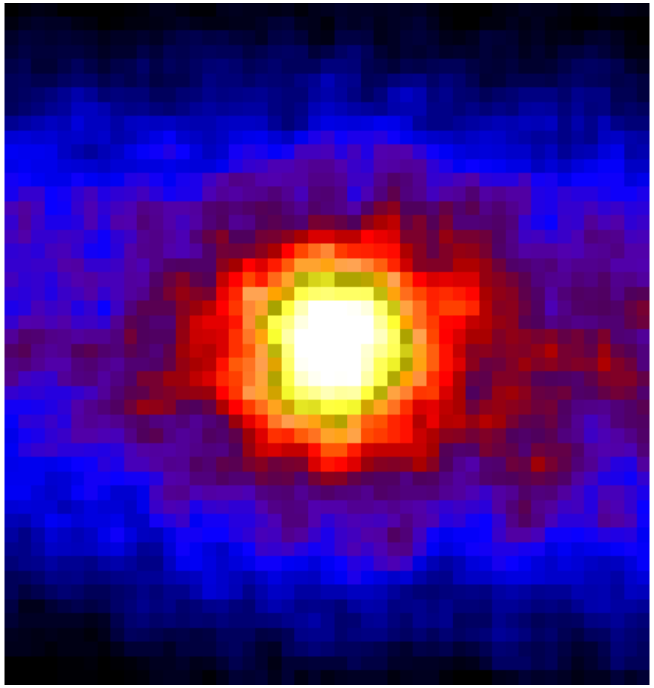
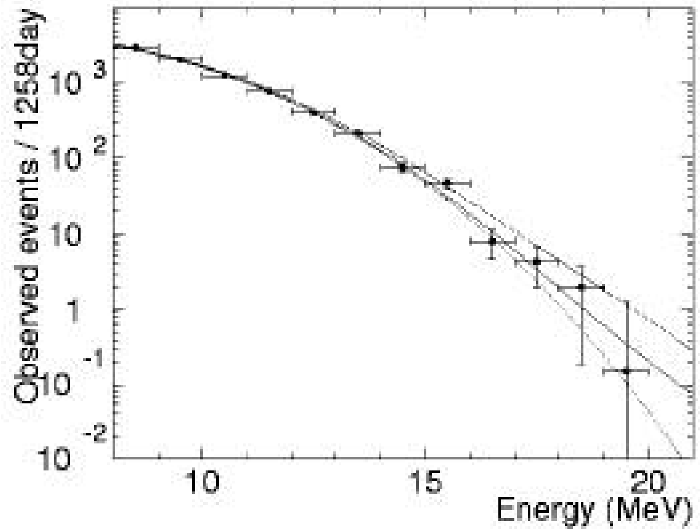


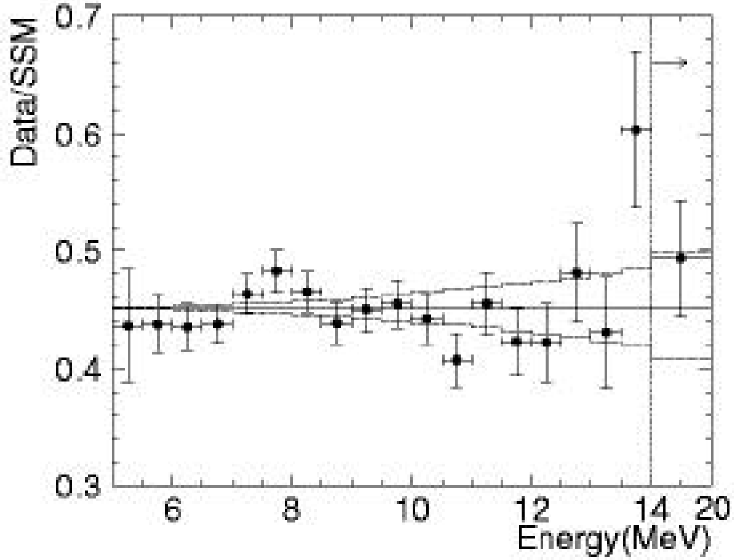
Image of sun with neutrinos

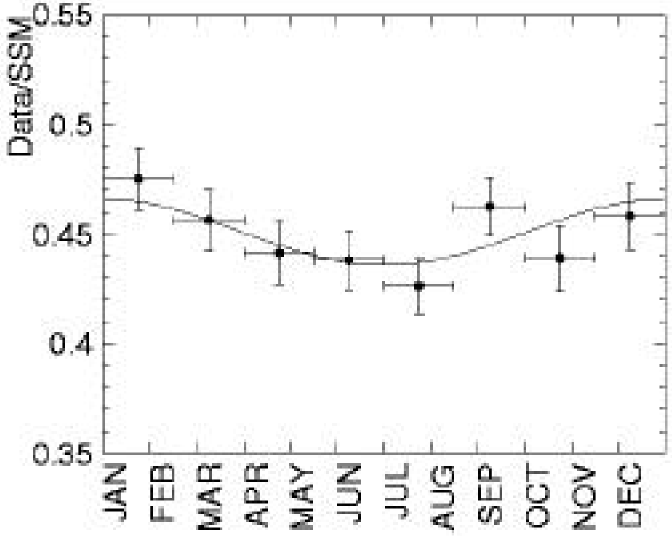


Super-Kamiokande: Solar Neutrinos

$\nu_x + e^- \rightarrow \nu_x + e^-$: threshold 5 MeV, sensitive to B solar neutrinos

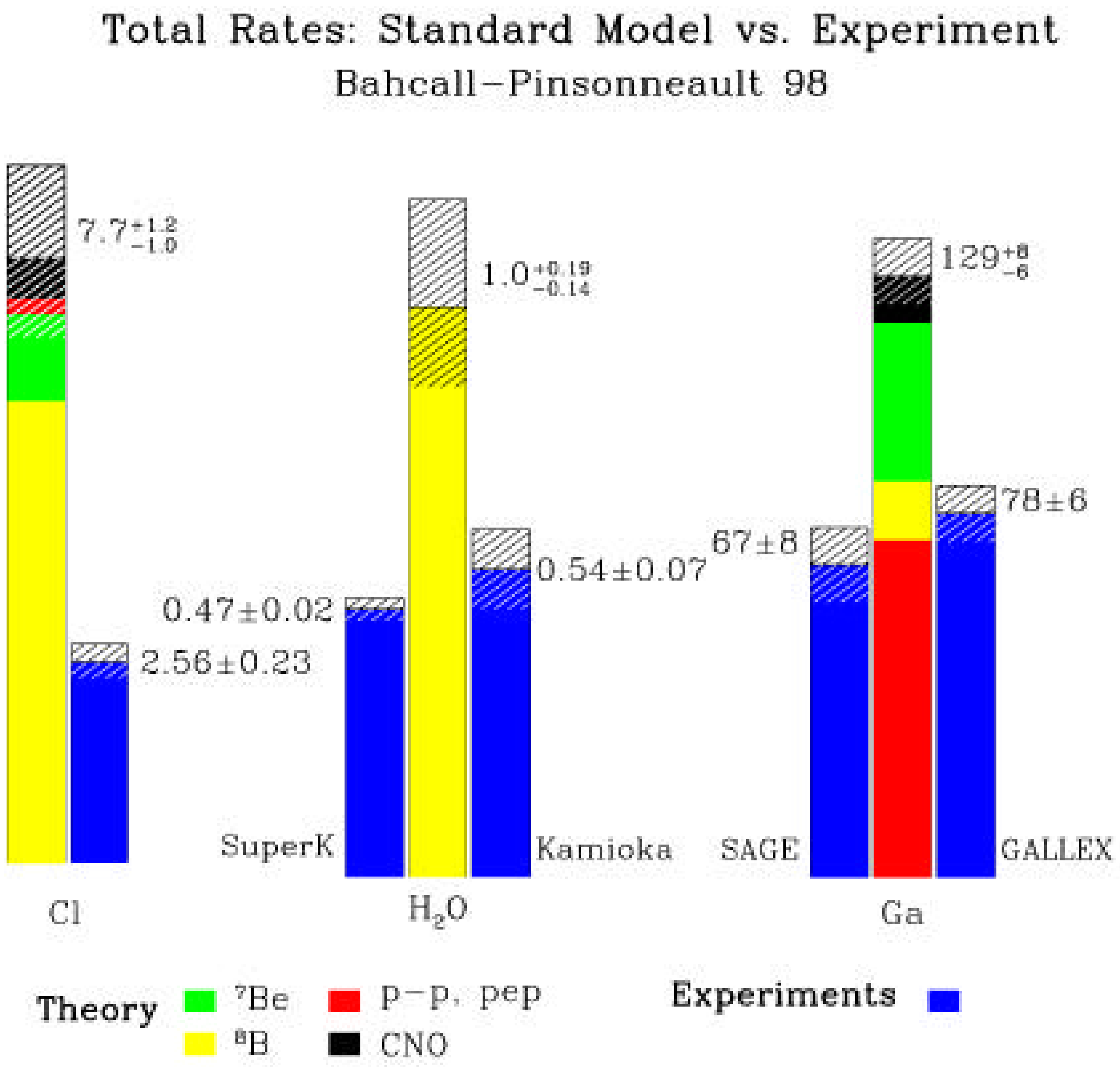




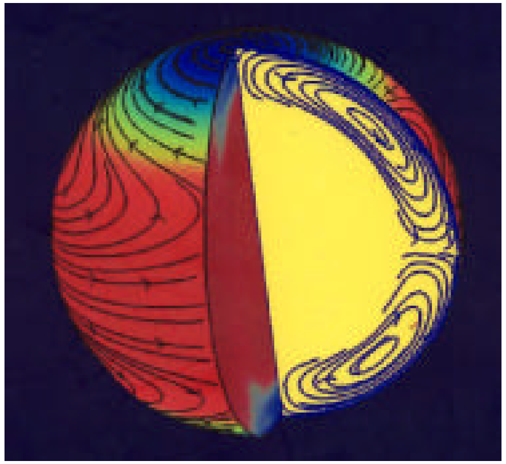


0.5 of Standard Solar Model

Summary of Solar Neutrinos



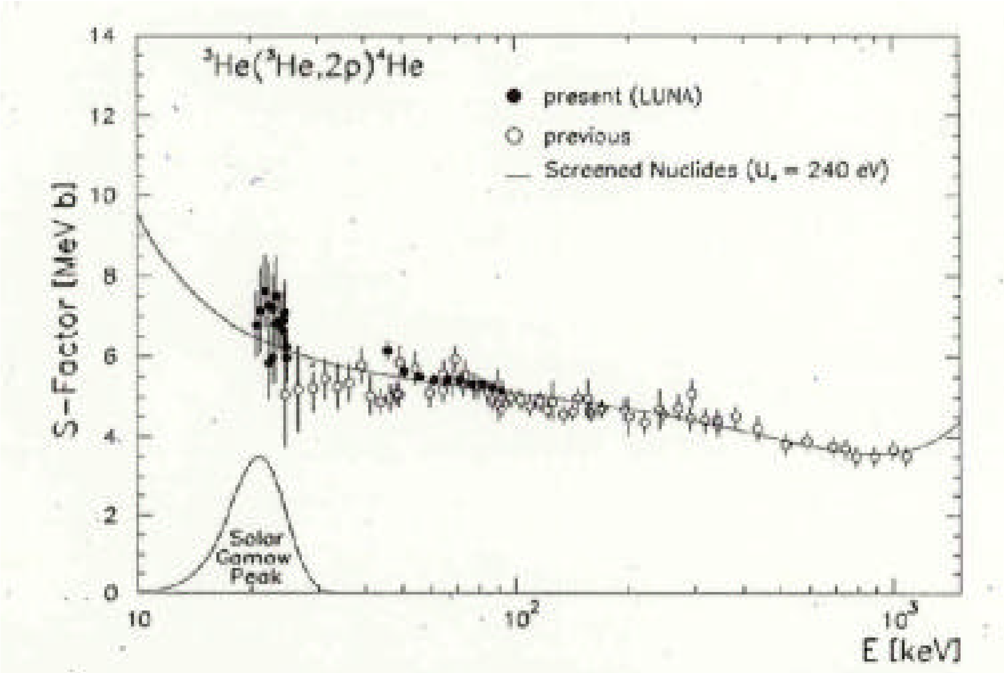
Believe SSM ?

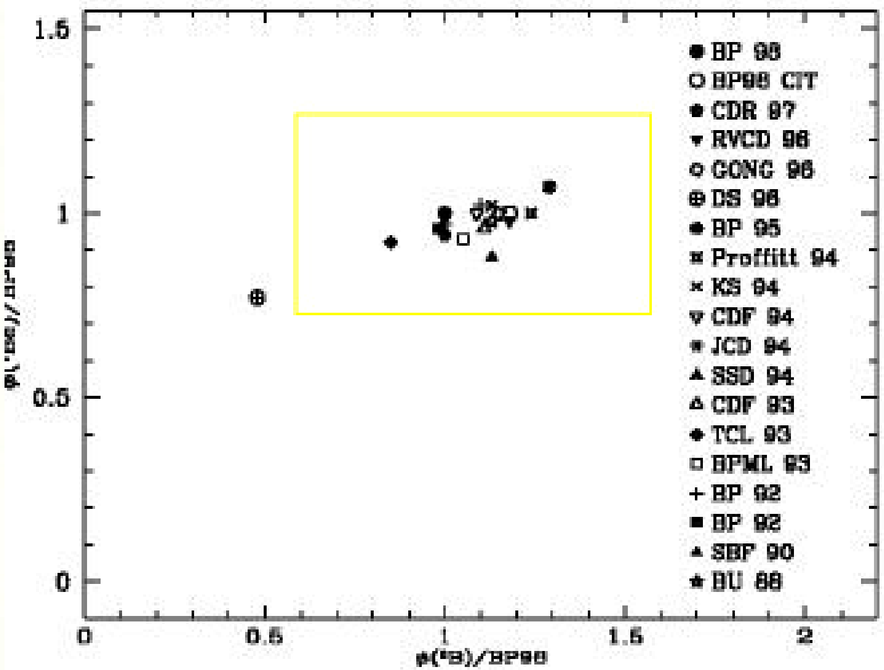


Structure of sun ?
- helioseimology data precise
- experts convinced OK

Nuclear Cross-Sections
- not all well known
- new experiments in prgress

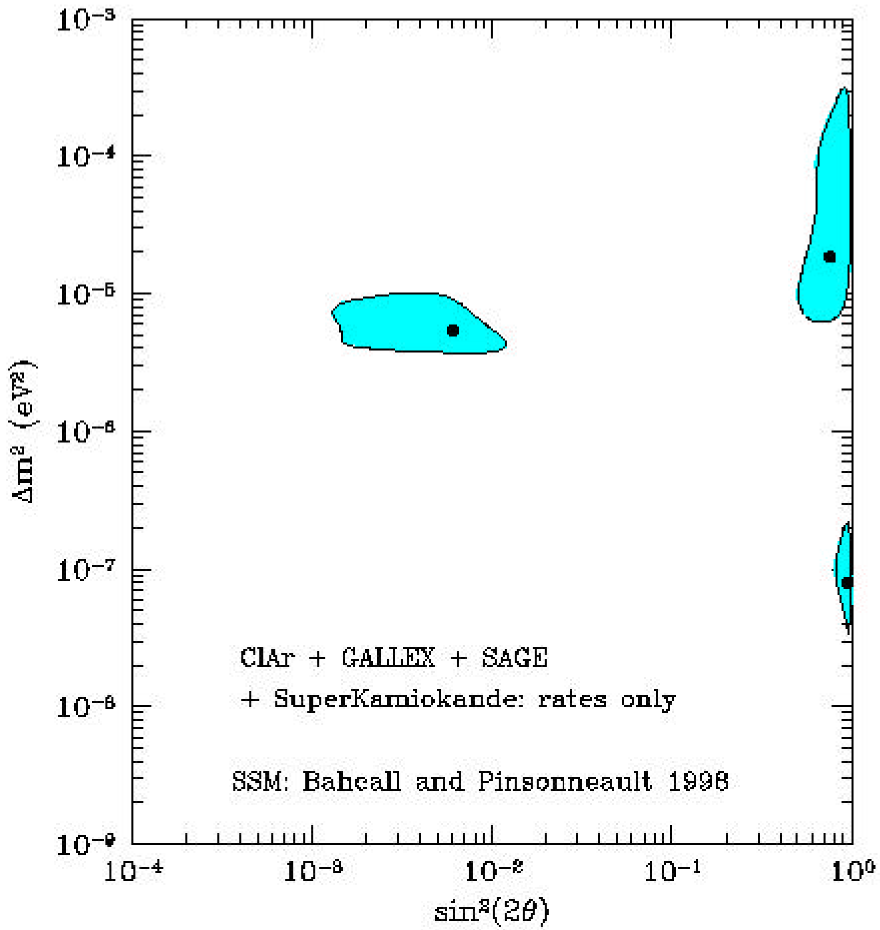
Many Calculations Agree



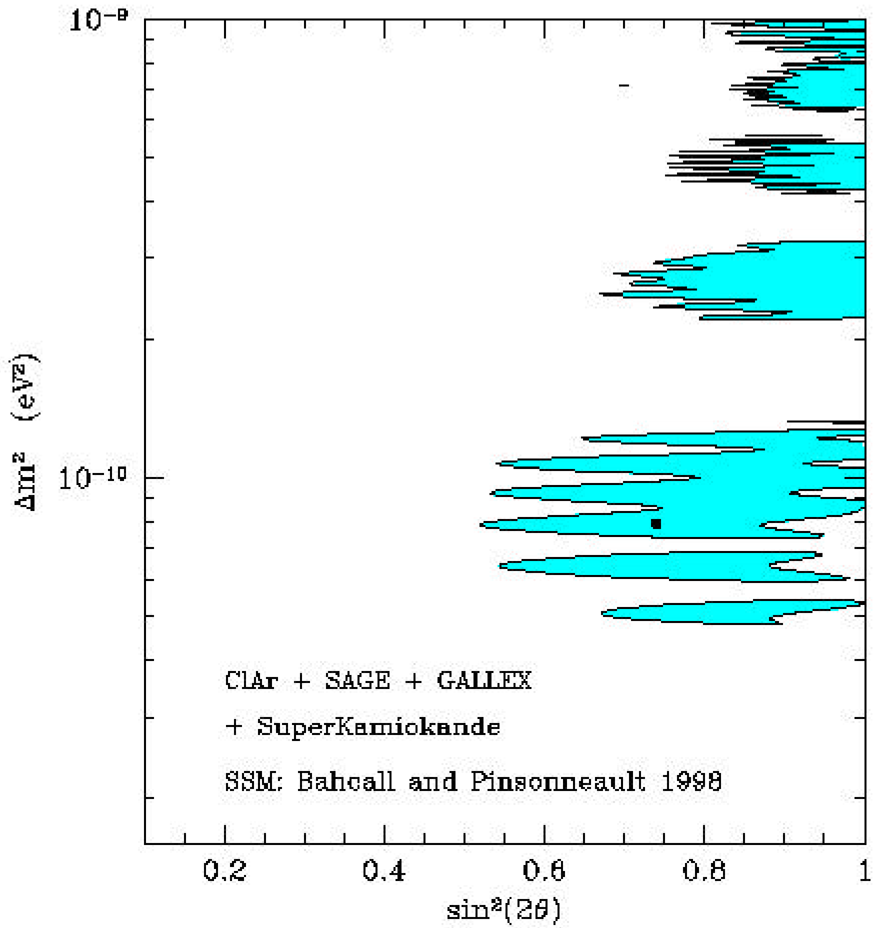


Solar Neutrino Oscillation Summary
(1 year ago)

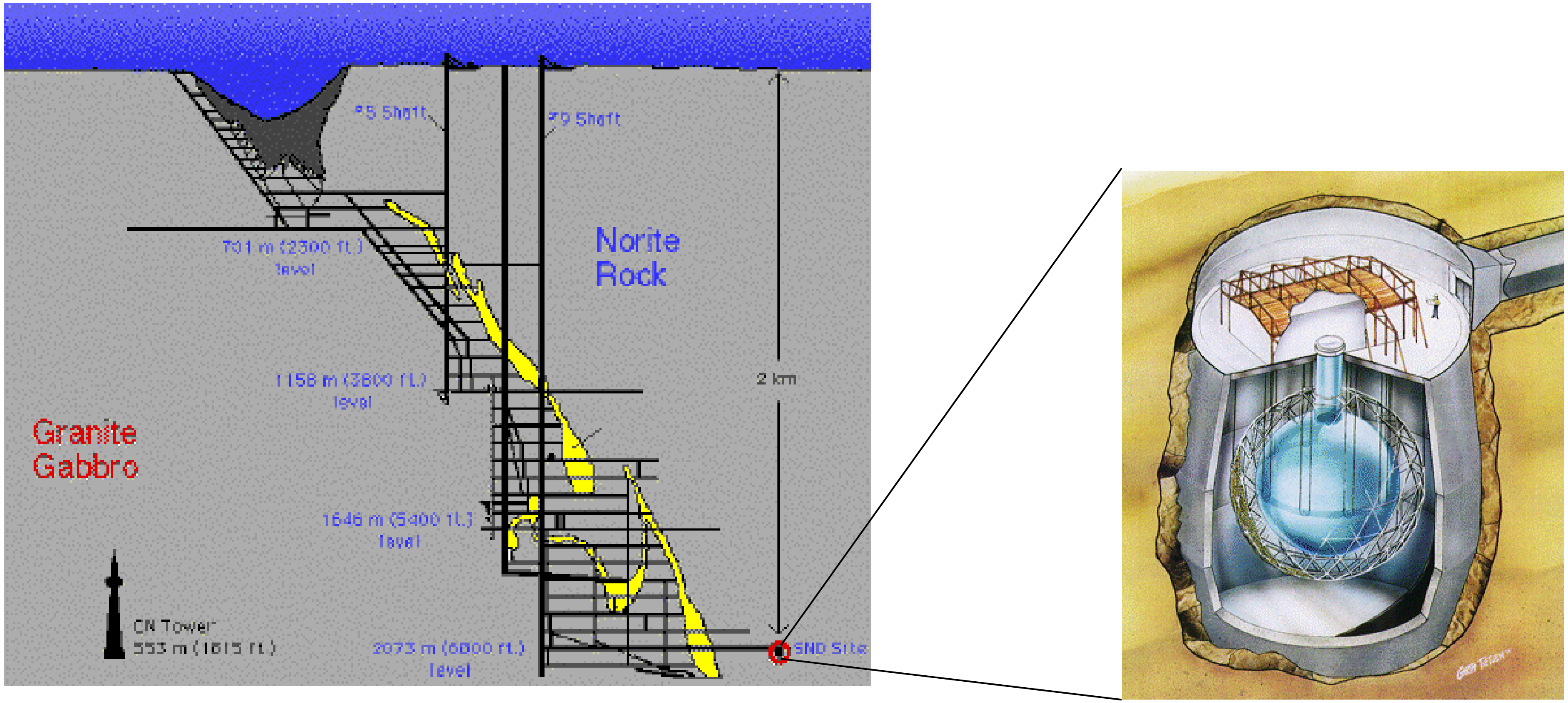
MSW Solutions



Vacuum Solutions



Sudbury Neutrino Observatory
First results 2001,
New results April 2002



Sudbury Neutrino Observatory

2092 m to Surface (6010 m w.e.)

17.8 m Diameter Support Structure for
9456 20 cm PMTs
~55% coverage within 7 m

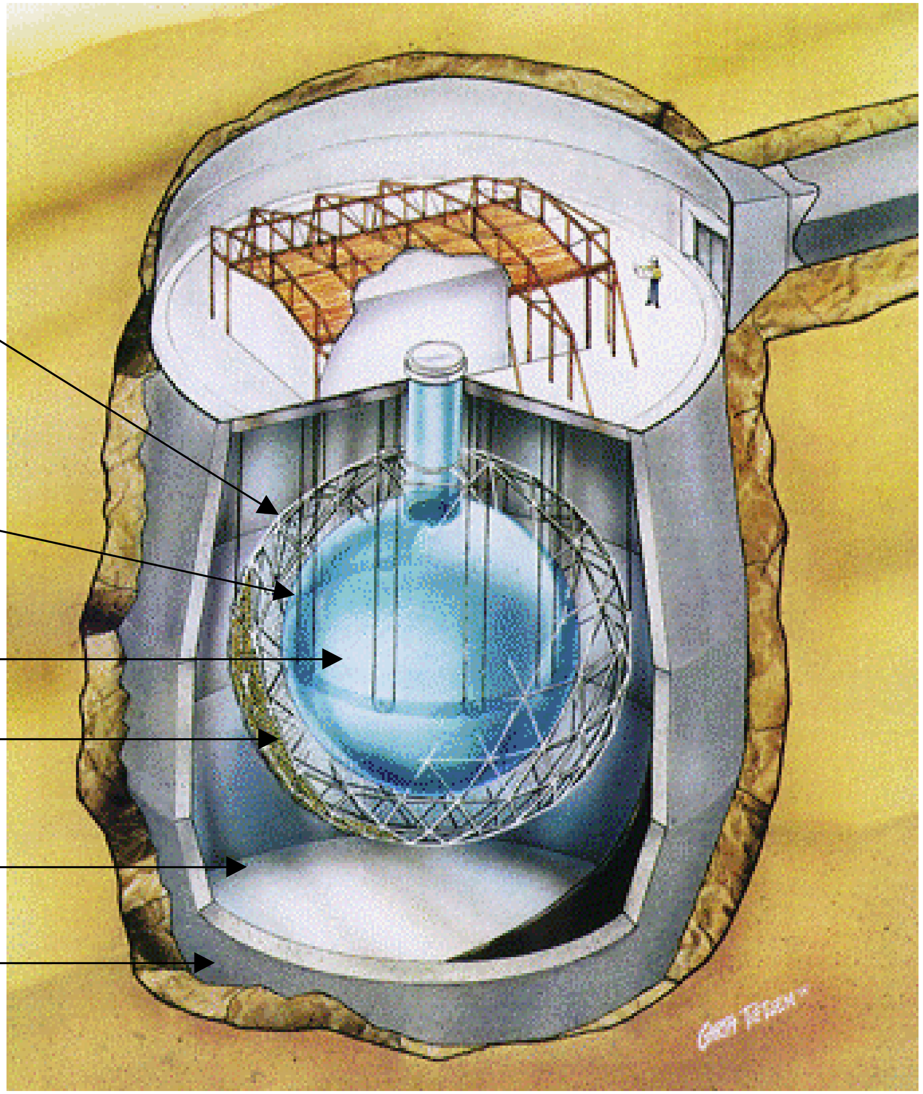
12 m Diameter Acrylic Vessel

1000 Tonnes D_2O

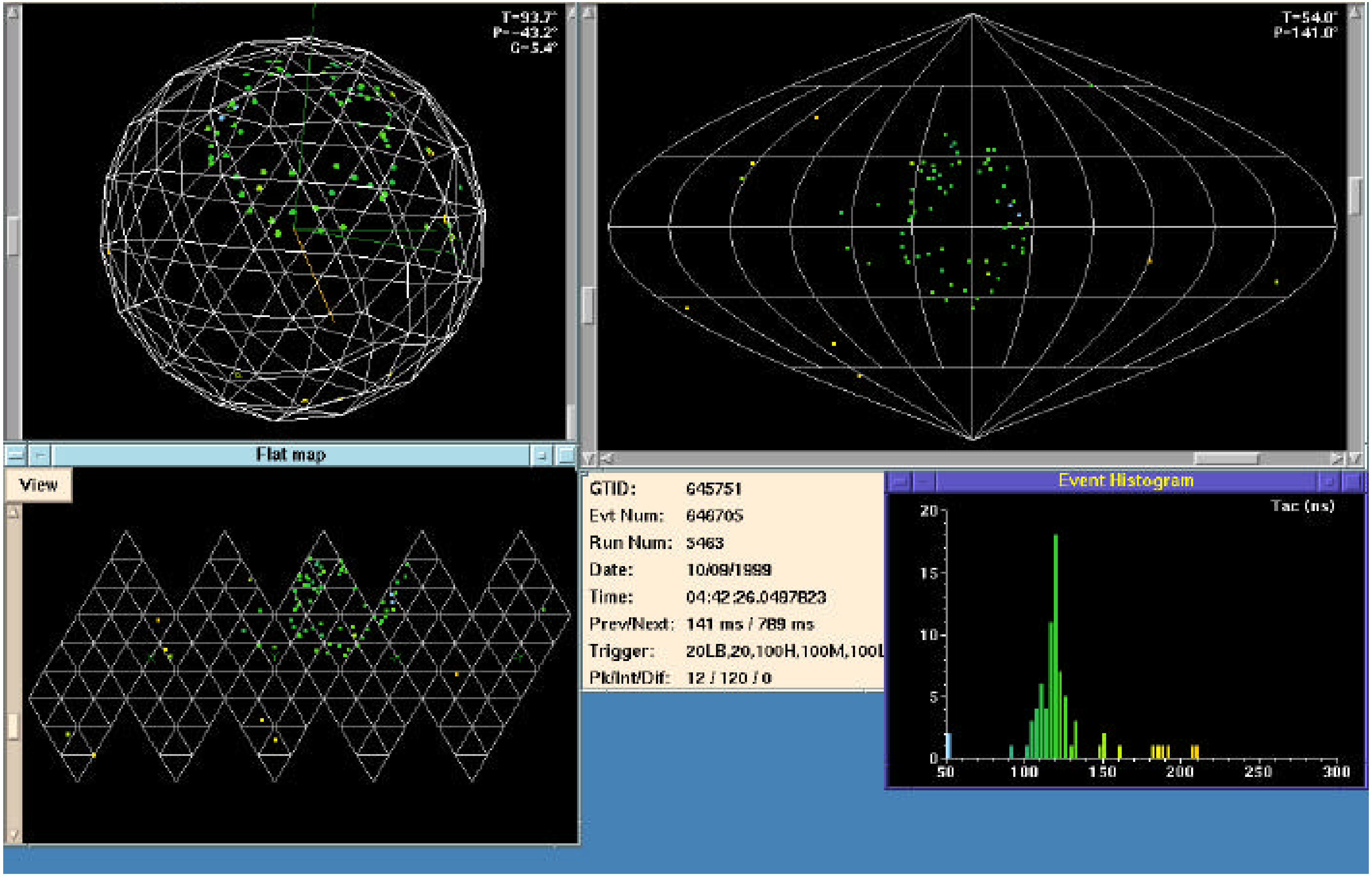
1700 Tonnes Inner
Shielding H_2O

5300 Tonnes Outer Shield H_2O

Urylon Liner and Radon Seal



Typical SNO event



D_2O Backgrounds

Target Level
- Equivalent of 7% SSM neutrons

Measurement Techniques
- Radiochemical assays
- In-situ Cerenkov measures

Status

at or below target level