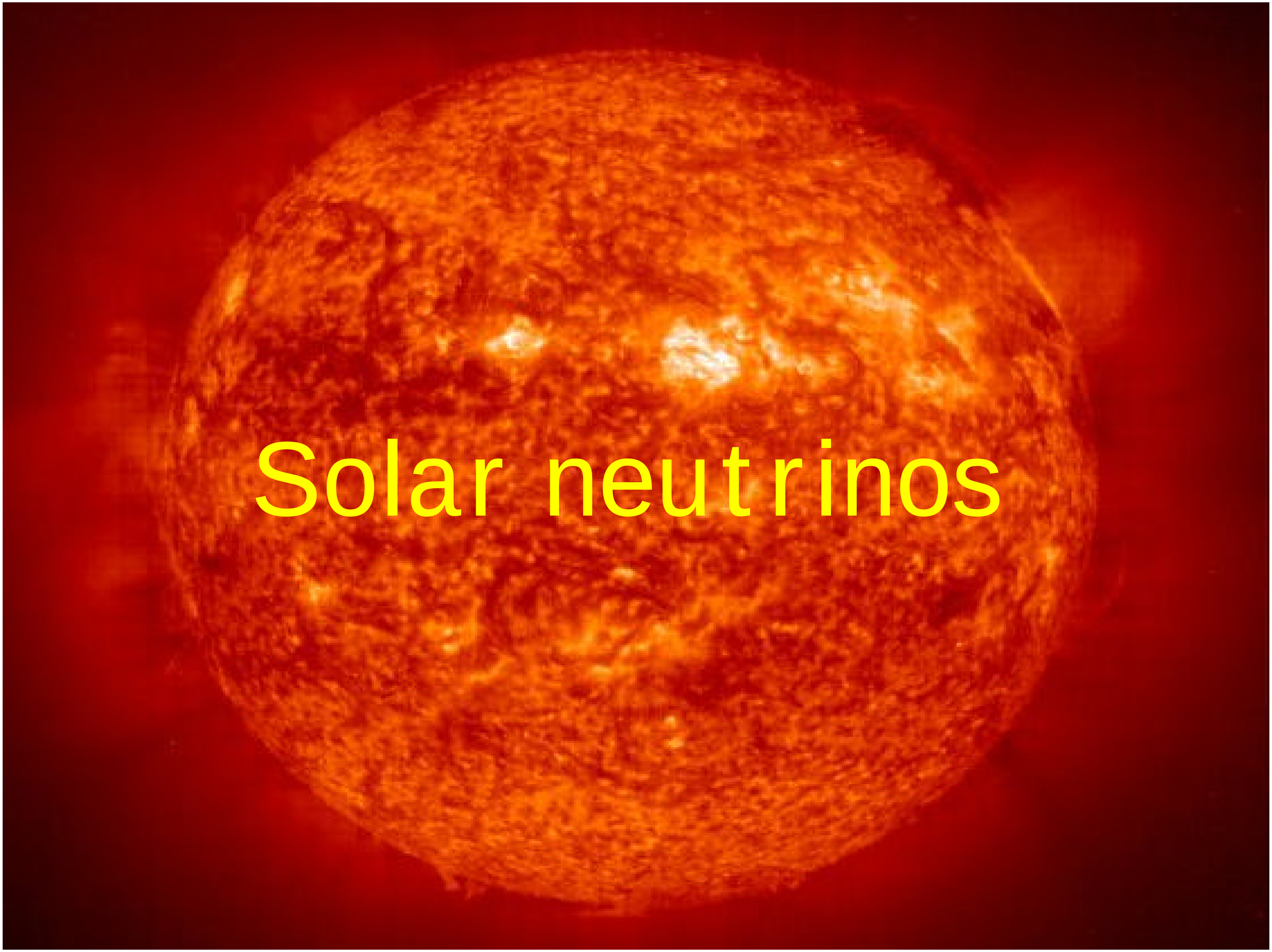
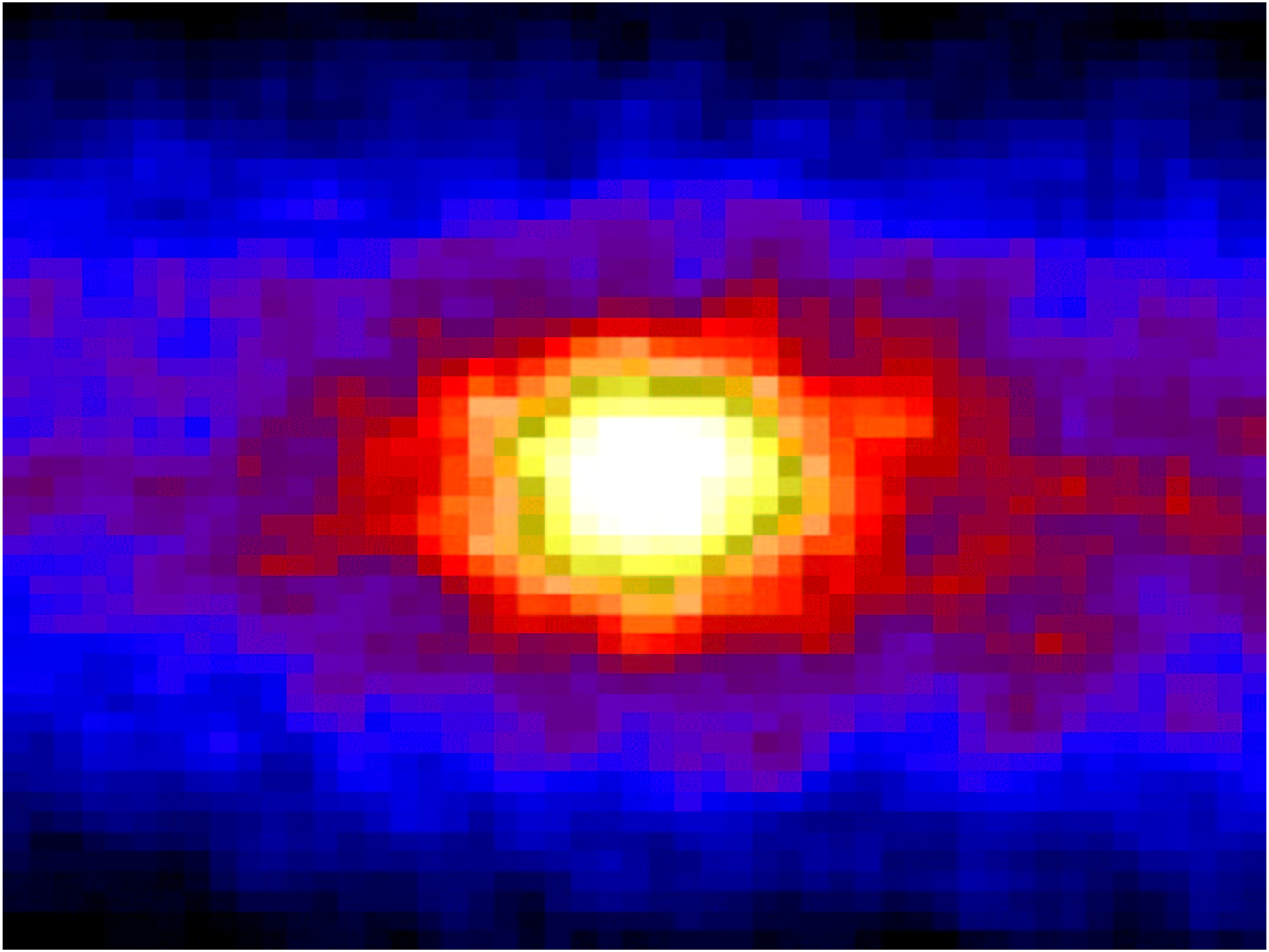
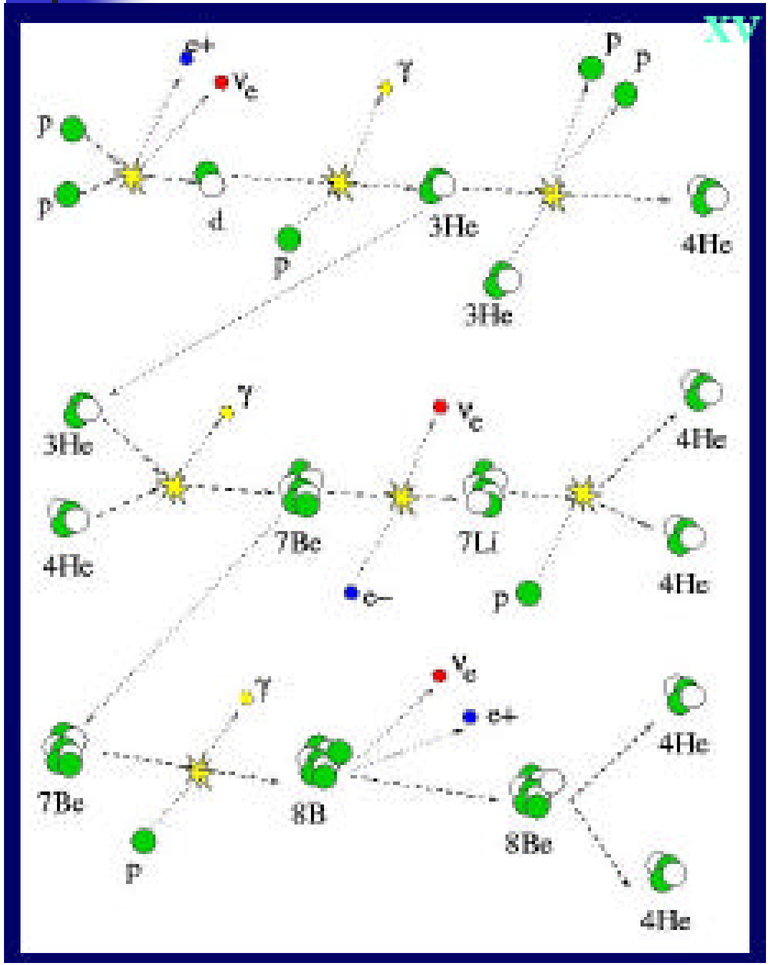
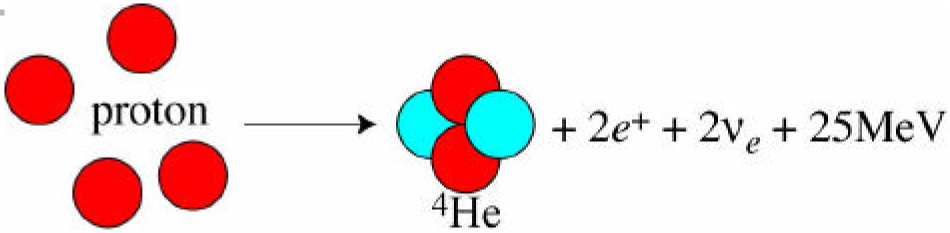
Solar neutrinos

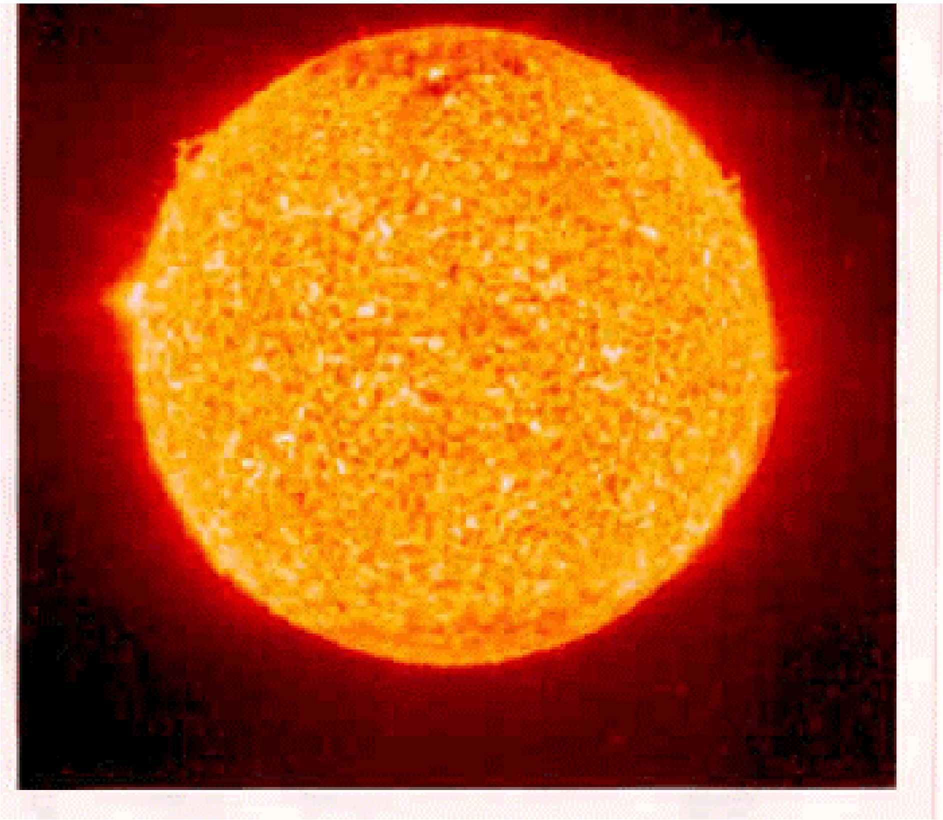




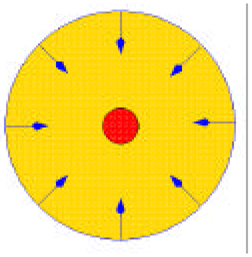
Neutrino production in the SUN







Solar Neutrinos



Birth of a visible star: gravitational contraction of a cloud of primordial gas (mostly ~75% H_2, ~25% He) → increase of density and temperature in the core → ignition of nuclear fusion

Balance between gravity and pressure → hydrostatic equilibrium

Final result from a chain of fusion reactions:

4p ® He^4 + $2e^+$ + 2n_e

Average energy produced in the form of electromagnetic radiation:

$Q = (4M_p - M_{He^4} + 2m_e)c^2 - \langle E(2n_e)\rangle$ » 26.1 MeV

└→ (from $2e^+ + 2e^- \rightarrow 4\gamma$)

($\langle E(2\nu_e)\rangle \approx 0.59$ MeV)

Sun luminosity: $L_\odot = 3.846\text{x}10^{26}$ W = $2.401\text{x}10^{39}$ MeV/s

Neutrino emission rate: $dN(n_e)/dt = 2\,L_\odot/Q$ » $1.84\text{x}10^{38}\ s^{-1}$

Neutrino flux on Earth: $F(n_e)$» $6.4\text{x}10^{10}\ cm^{-2}\ s^{-1}$

(average Sun-Earth distance = $1.496\text{x}10^{11}$ m)

Standard Solar Model (SSM)

Assumptions:

- hydrostatic equilibrium
- energy production by fusion
- thermal equilibrium (energy production rate = luminosity)
- energy transport inside the Sun by radiation

Input:

- cross-sections for fusion processes
- opacity versus distance from Sun centre

Method:

- choose initial parameters
- evolution to present time ($t = 4.6\text{x}10^9$ years)
- compare measured and predicted properties
- modify initial parameters (if needed)

Present Sun properties: **Luminosity $L_\odot = 3.846\text{x}10^{26}$ W**
Radius $R_\odot = 6.96\text{x}10^8$ m
Mass $M_\odot = 1.989\text{x}10^{30}$ kg
Core temperature $T_c = 15.6\text{x}10^6$ K
Surface temperature $T_s = 5773$ K
Hydrogen fraction in core = 34.1% (initially 71%)
Helium fraction in core = 63.9% (initially 27.1%)

} as measured on surface today

pp cycle (98.5% of $L_{\odot}$)

85%

$p + p$ ® $e^{+} + n_{e} + d$ $\quad$ $p + p$ ® $e^{+} + n_{e} + d$ $\quad$ or (0.4%): $p + e^{-} + p$ ® $n_{e} + d$

$p + d$ ® $g + He^{3}$ $\quad$ $p + d$ ® $g + He^{3}$

$He^{3} + He^{3}$ ® $He^{4} + p + p$ $\quad$ or (~$2x10^{-5}$): $He^{3} + p$ ® $He^{4} + e^{+} + n_{e}$

15%

$p + p$ ® $e^{+} + n_{e} + d$

$p + d$ ® $g + He^{3}$

$He^{3} + He^{4}$ ® $g + Be^{7}$

$e^{-} + Be^{7}$ ® $n_{e} + Li^{7}$

$p + Li^{7}$ ® $He^{4} + He^{4}$

or (0.13%)

$p + Be^{7}$ ® $g + B^{8}$

B^{8} ® $Be^{8} + e^{+} + n_{e}$

Be^{8} ® $He^{4} + He^{4}$

CNO cycle (two branches)

$p + N^{15}$ ® $C^{12} + He^{4}$ $\quad$ $p + N^{15}$ ® $g + O^{16}$

$p + C^{12}$ ® $g + N^{13}$ $\quad$ $p + O^{16}$ ® $g + F^{17}$

N^{13} ® $C^{13} + e^{+} + n_{e}$ $\quad$ F^{17} ® $O^{17} + e^{+} + n_{e}$

$p + C^{13}$ ® $g + N^{14}$ $\quad$ $p + O^{17}$ ® $N^{14} + He^{4}$

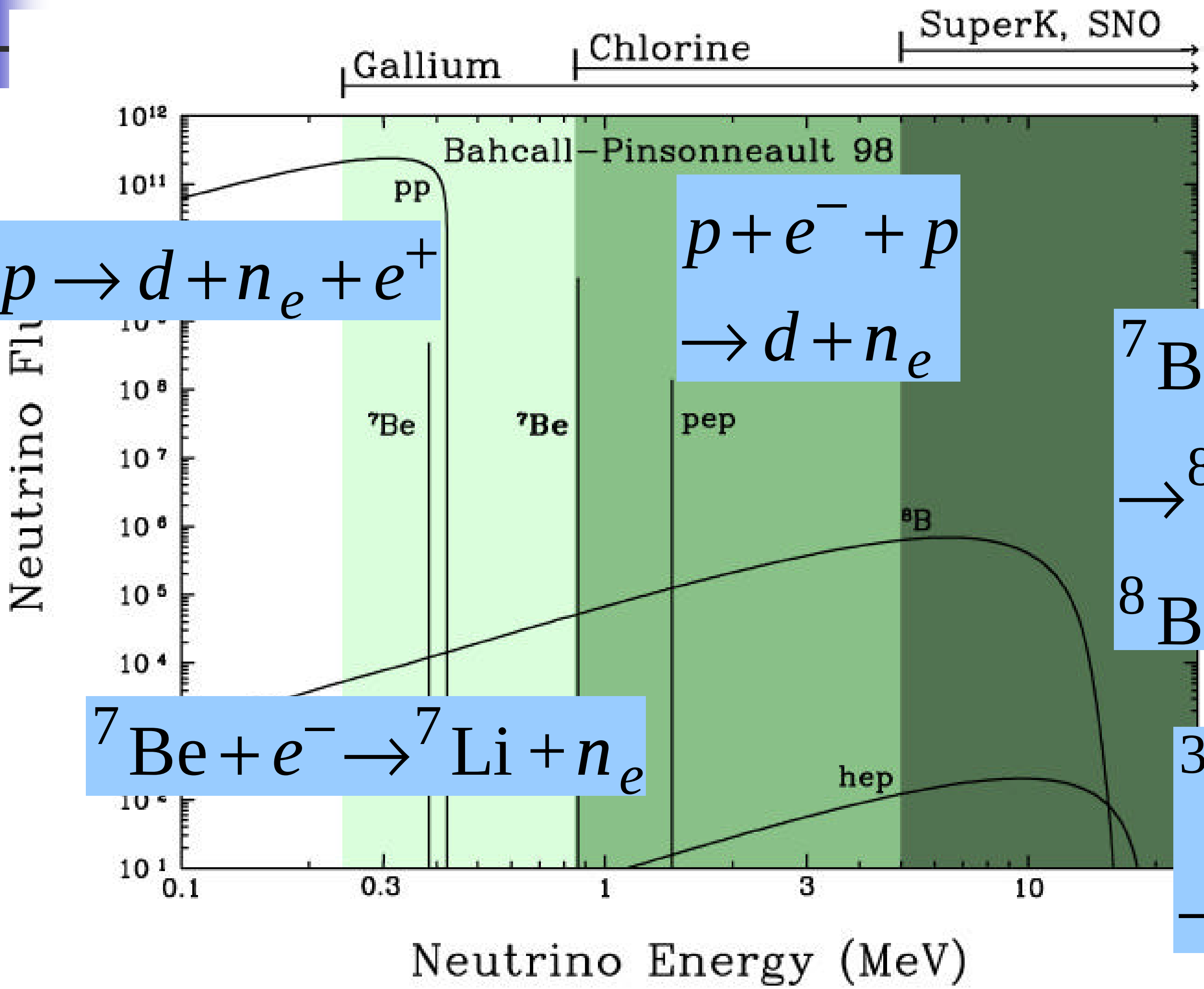
$p + N^{14}$ ® $g + O^{15}$

O^{15} ® $N^{15} + e^{+} + n_{e}$

NOTE #1: in all cycles $4p$ ® $He^{4} + 2e^{+} + 2n_{e}$

NOTE #2: present solar luminosity originates from fusion reactions which occurred ~ 10^{6} years ago. However, the Sun is practically stable over ~ 10^{8} years.

The Solar Neutrino Spectrum



$p+p \rightarrow d+n_e+e^+$

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

$^7\mathrm{Be}+p \rightarrow {}^8\mathrm{B} \rightarrow {}^8\mathrm{Be}+e^++n_e$

$^8\mathrm{Be} \rightarrow 2a$

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

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

The Chlorine experiment

Location: Homestake Gold Mine, South Dakota (USA) 4500 mwe

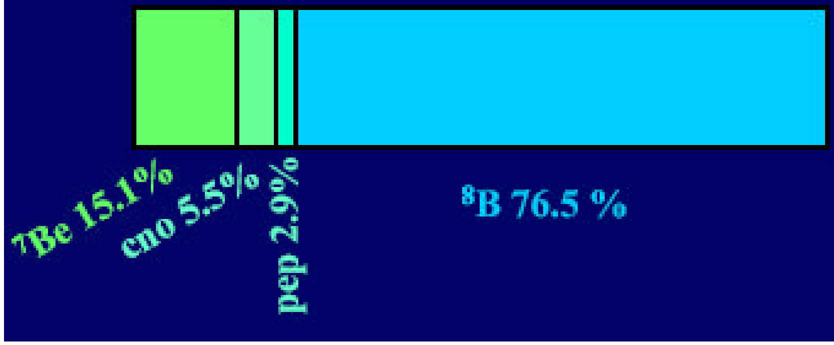
Target: 615 tons of C_2Cl_4

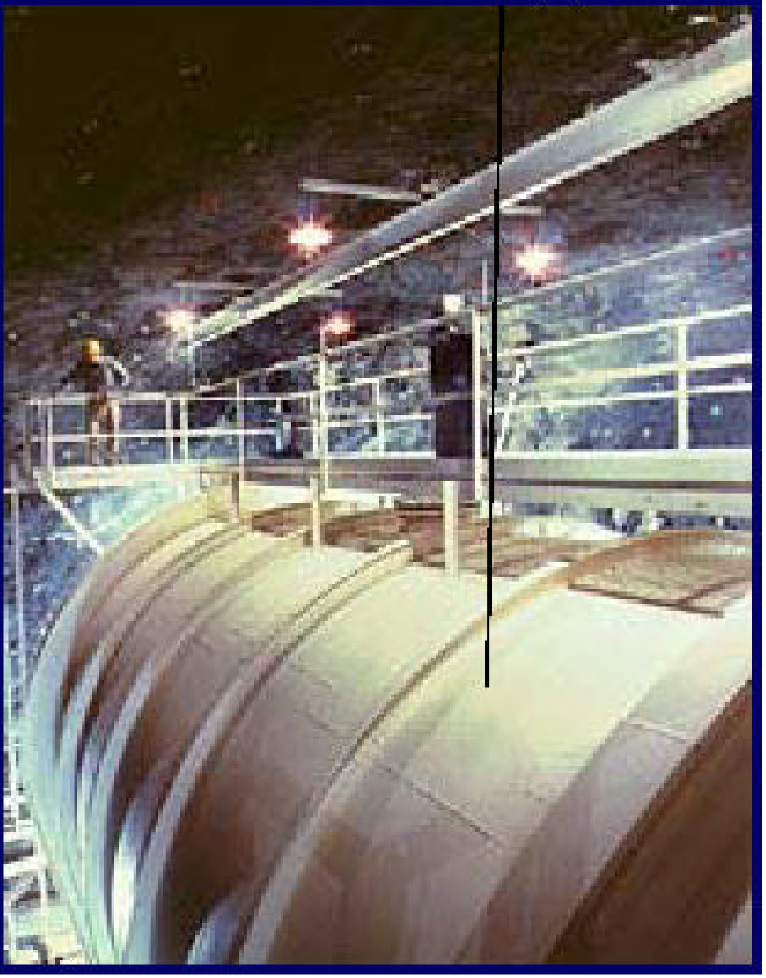
Neutrino interaction: $^{37}Cl\ (\nu_e\ , e)\ ^{37}Ar$
Threshold : 814 keV

Detection Technique: radiochemical

37Ar is extracted from the tank by He purging
every two months, and then counted inside
a gas proportional counter

Signal composition:




The C_2Cl_4 tank

Experimental method

$n_e + Cl^{37}$ ® $e^- + Ar^{37}$ Energy threshold $E(\nu_e) > 0.814$ MeV

<u>Detector</u>: 390 m^3 C_2Cl_4 (perchloroethylene) in a tank installed in the Homestake gold mine (South Dakota, U.S.A.) under 4100 m water equivalent (m w.e.) (fraction of Cl^{37} in natural Chlorine = 24%)

<u>Expected production rate of Ar^{37} atoms</u> ≈ 1.5 per day

<u>Experimental method</u>: every few months extract Ar^{37} by N_2 flow through tank, purify, mix with natural Argon, fill a small proportional counter, detect radioactive decay of Ar^{37}: $e^- + Ar^{37} \rightarrow \nu_e + Cl^{37}$ (half-life $\tau_{1/2}$=34d)

(Final state excited Cl^{37} atom emits Augier electrons and/or X-rays)

Check efficiencies by injecting known quantities of Ar^{37} into tank

<u>Results over more than 20 years of data taking</u>

Data taking: 1970 – 1995 108 solar runs.

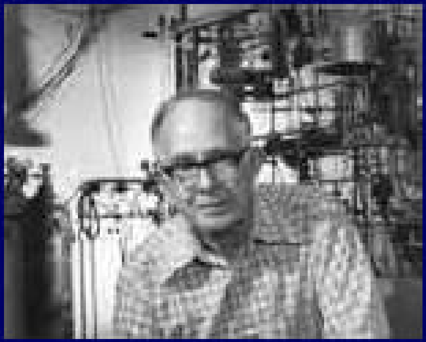
Results:

ν interaction rate on ^{37}Cl: **2.56 +- 0.16 (stat) +- 0.16 (sys) SNU**

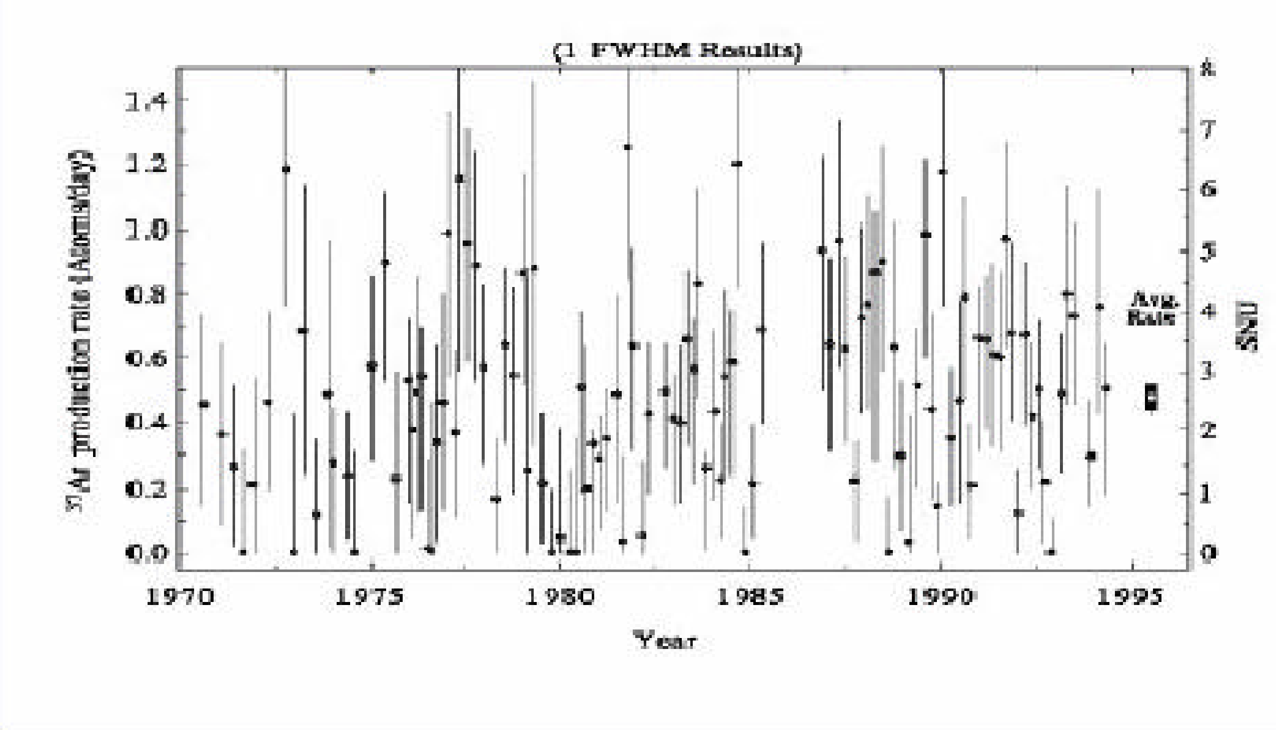
R (exp/SSM) = 0.34 +- 0.03 (exp) +- 0.05 (theo)

FIRST EVIDENCE FOR NEUTRINOS COMING FROM THE SUN
FIRST EVIDENCE FOR DEFICIT IN THE SOLAR NEUTRINO FLUX

R. Davis, Nobel prize 2002



Results from single extractions



THE ASTROPHYSICAL JOURNAL, 496:505-526, 1998 March 20

Real-time experiments using water Cerenkov counters to detect solar neutrinos

Neutrino – electron elastic scattering: $\nu + e^- \rightarrow \nu + e^-$

Detect Cerenkov light emitted by recoil e^- in water (detection threshold ~5 MeV)

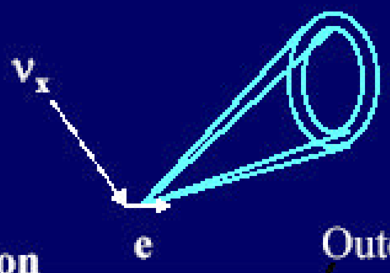
Cross-sections: $$\underset{\uparrow \atop \boxed{\text{W and Z exchange}}}{\sigma(\nu_e)} \approx 6\,\underbrace{\sigma(\nu_\mu) \approx 6\,\sigma(\nu_\tau)}_{\boxed{\text{Only Z exchange}}}$$

(5 MeV electron path
in water ≈ 2 cm)

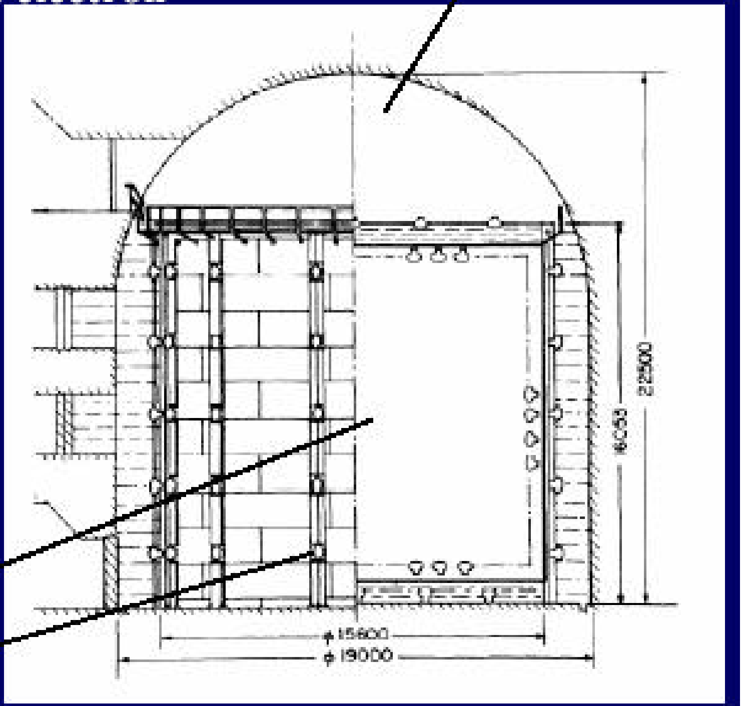
Two experiments: Kamiokande (1987 – 94). Useful volume: 680 m^3
Super-Kamiokande (1996 – 2001). Useful volume: 22500 m^3
installed in the Kamioka mine (Japan) at a depth of 2670 m w.e.

The Kamiokande experiment

- **Location:** **Kamioka mine, Japan,** 2700 mwe depth
- **Target:** **4500 tons of pure water**
  2150 tons (fid. Vol.)
- **Neutrino interaction:** **$e + \nu_x \rightarrow e + \nu_x$ (CC+NC)**
- **Detection Technique:** **Cerenkov light of scattered electron**



- **Signal composition:** **100% from ^8B ν**
  Direction of recoil electron
  Energy spectrum of recoil electron
  Threshold : 7 MeV
- **Data taking:** **1987 → 1995**
  2079 days of live-time.



Outer tank

Inner tank

948 PMTs

Results : 597 ν events observed in 2079 days

$\Phi(^8B) = 2.80 \pm 0.19\ (stat) \pm 0.33\ (sys)\ \ 10^6\ cm^{-2}\ s^{-1}$

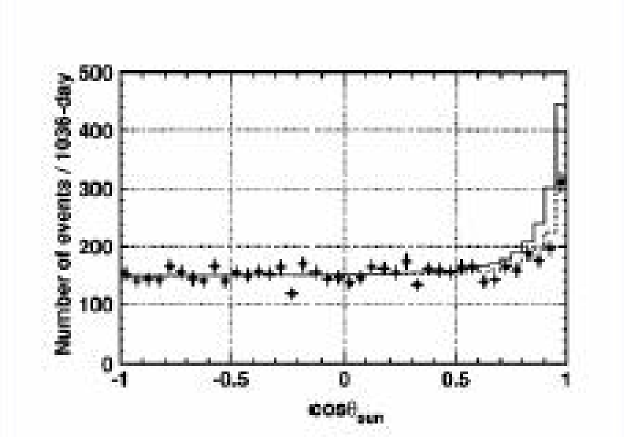
R (exp/SSM) = 0.37

Confirmation of the evidence for a "solar neutrino problem"

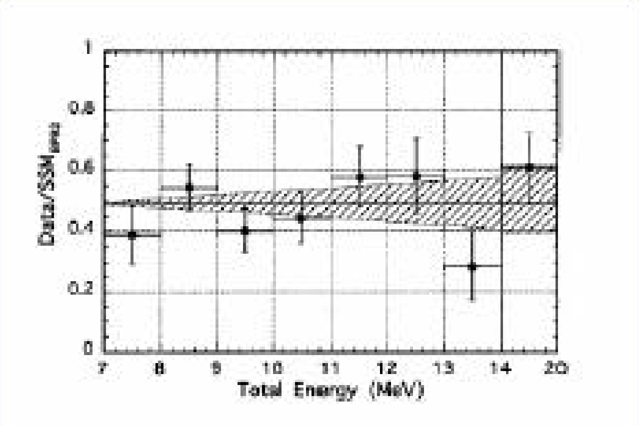
First evidence that neutrino signals are correlated with the Sun direction

First test of the ^{8}B neutrino energy spectrum

First measurement of solar neutrinos in real time

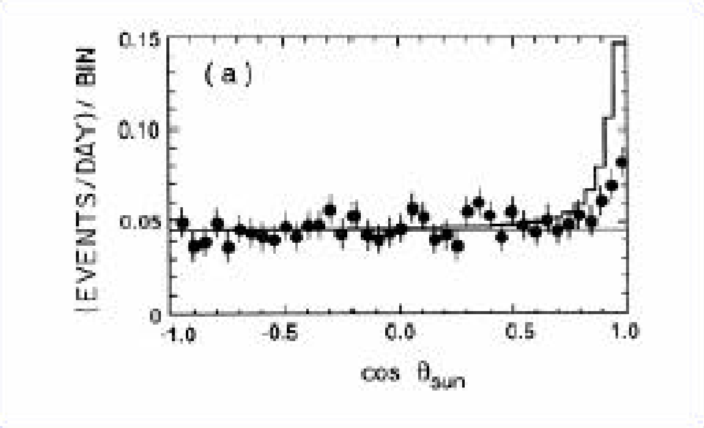


Kamiokande III, direction cos t_{sun}

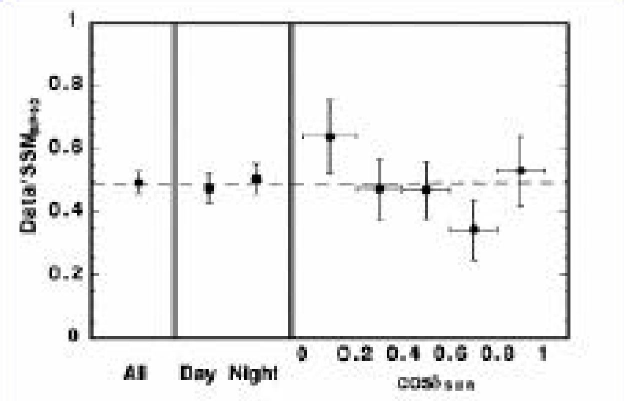


Kamiokande II+III, energy spectrum

M. Koshiba
Nobel prize 2002

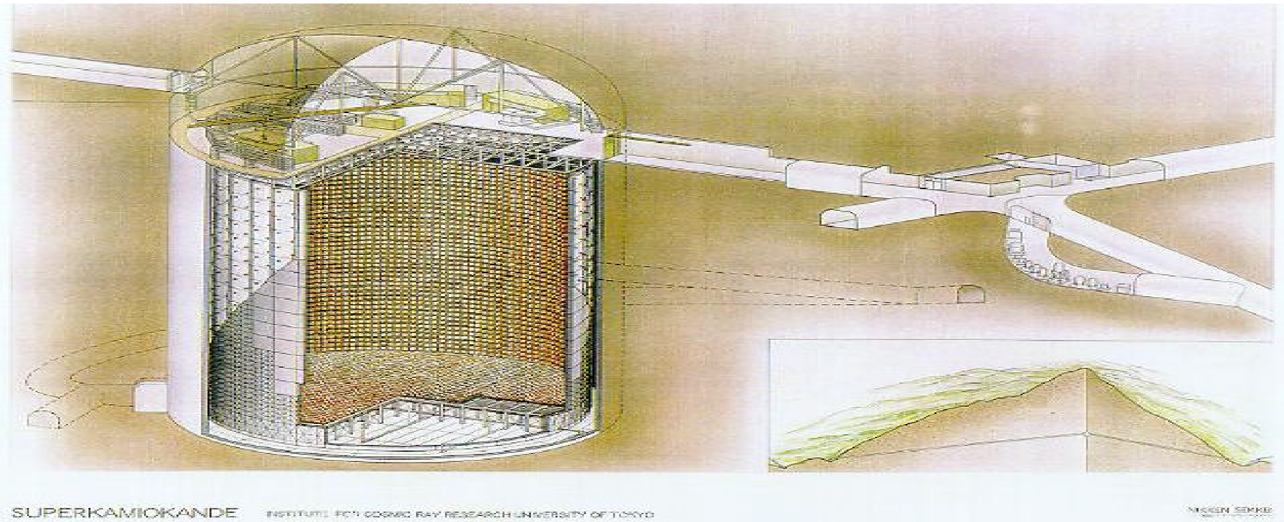


Kamiokande II, direction cos t



Kamiokande II+III, day-night asimmetry

Super-Kamiokande detector



50,000 ton water Cherenkov detector (22.5 kton fiducial volume)

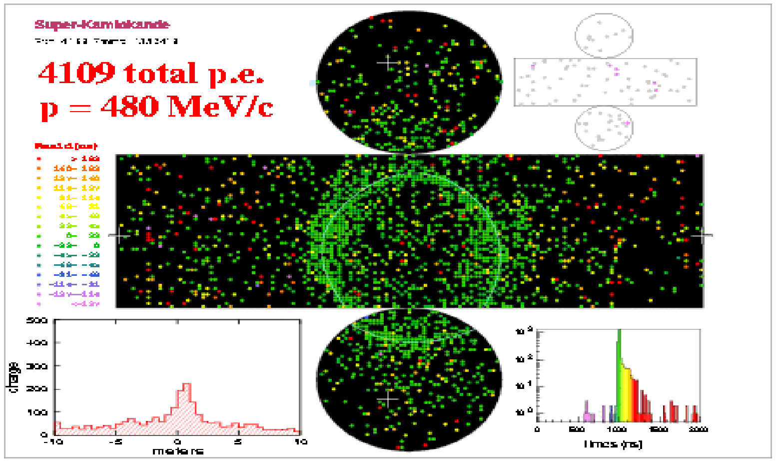
1000m underground (2700 m.w.e.)

11,146 20-inch PMTs for inner detector

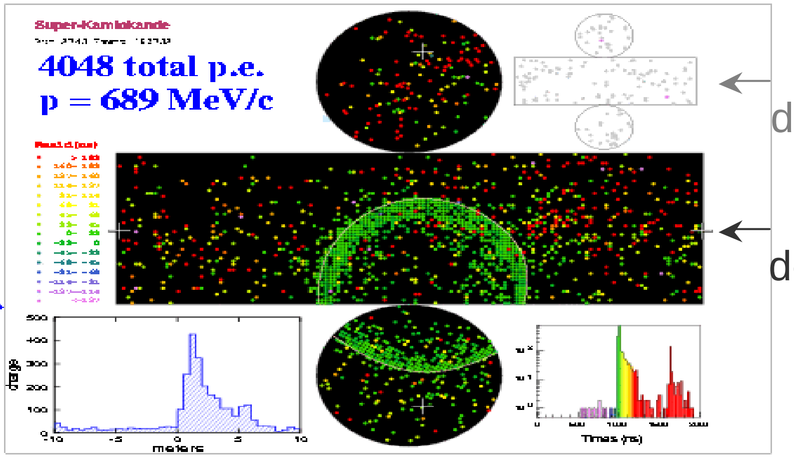
1,885 8-inch PMTs for outer detector

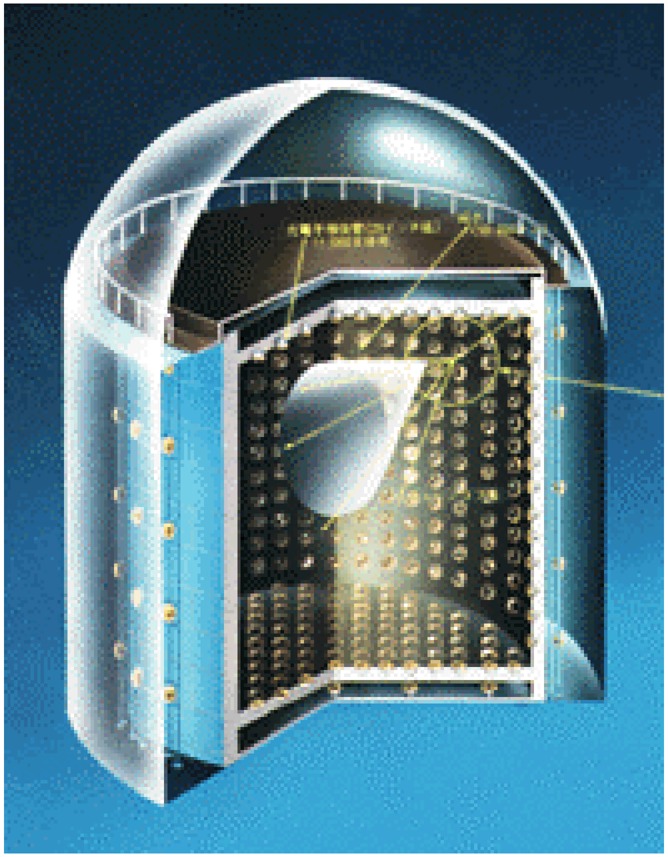
Super-Kamiokande events

e–like



μ–like





Outer detector

Inner detector

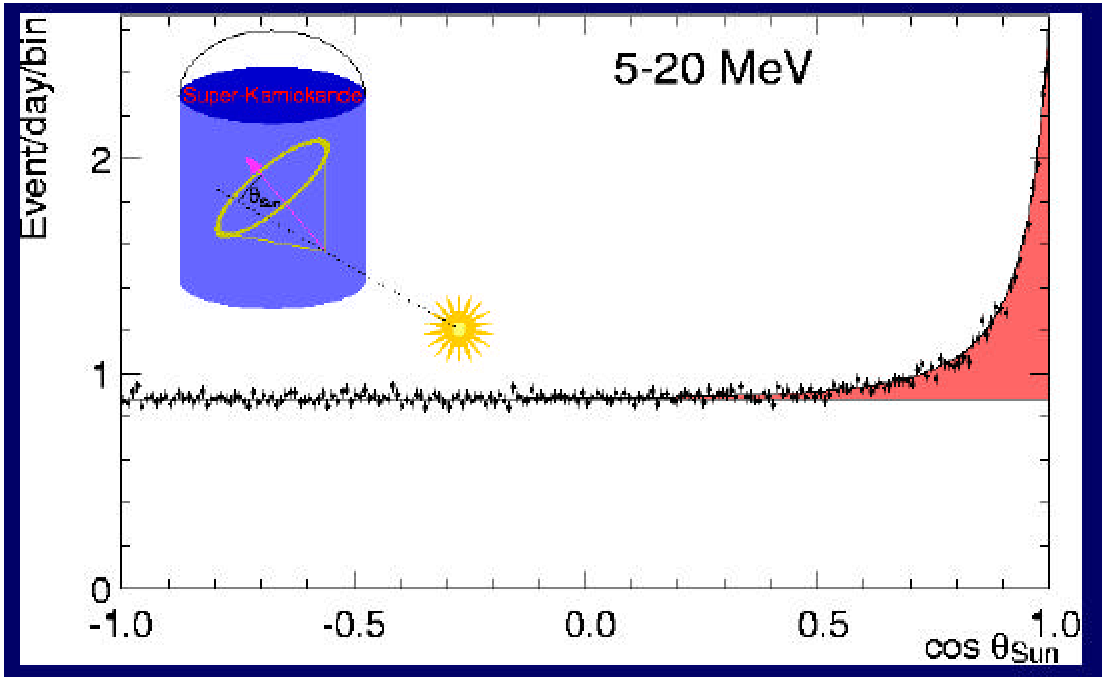
Super-K Elastic Scattering

Results from 22400 events (1496 days of data taking)

Detection principle

$$n + e \rightarrow n + e$$

- Cerenkov light from e is detected
- Good angular and energy correlation between the incoming neutrino and the outgoing electron



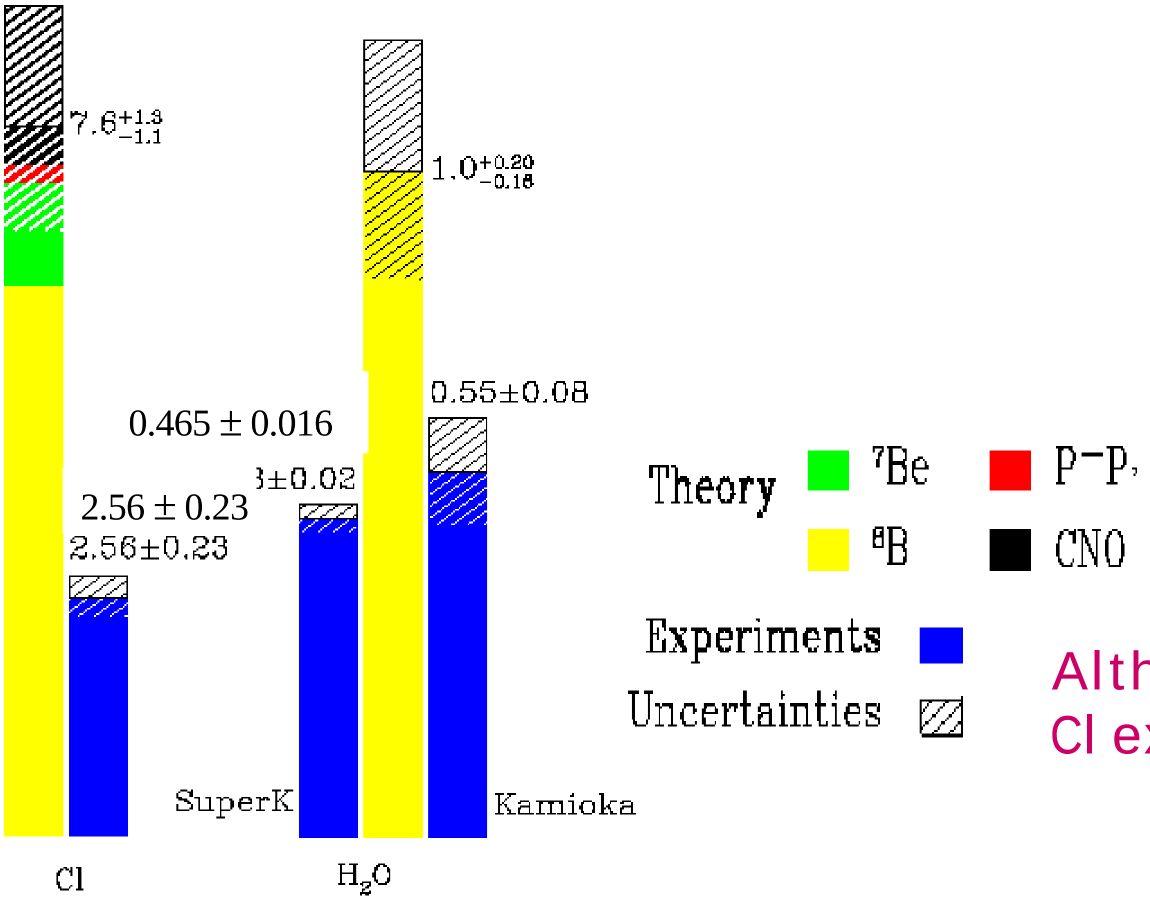
Results from 22400 events (1496 days of data taking)

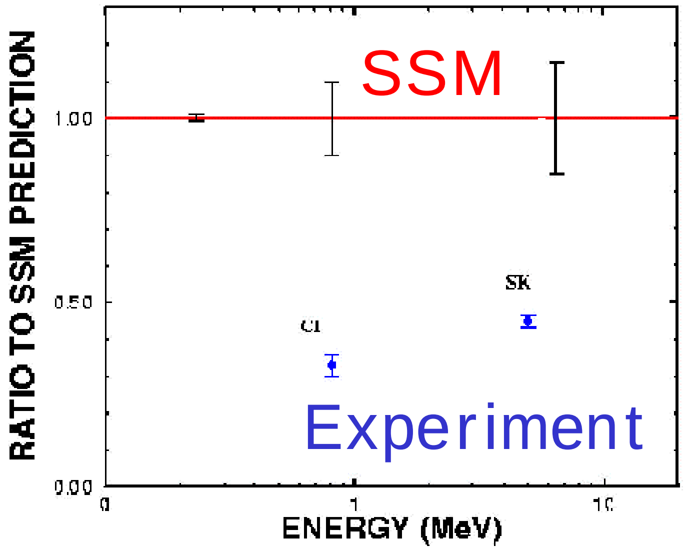
Measured neutrino flux (assuming all n_e): $F(n_e) = (2.35 \underset{(stat)}{\pm 0.02} \underset{(syst)}{\pm 0.08}) \times 10^6 \ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

SSM prediction: $F(n_e) = (5.05)^{+1.01}_{-0.81} \times 10^6 \ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

Data/SSM = $0.465 \pm \underset{(stat)}{0.005}\ {}^{+0.093}_{-0.074}$ (including theoretical error) ← n_e **DEFICIT**

Comparison of Homestake and Kamioka results with SSM predictions





Although with a lower threshold Cl exp sees less ν than K&SK!!!

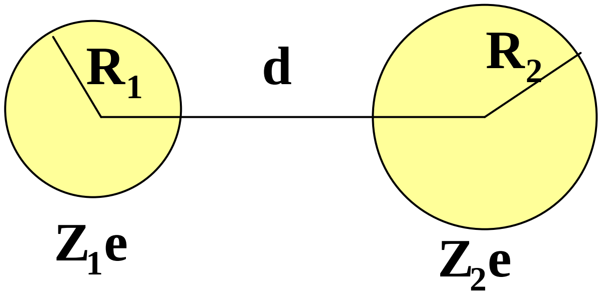
Homestake and Kamioka results were known since the late 1980's.
However, the solar neutrino deficit was not taken seriously at that time.
Why?

The two main solar ν_e sources in the Cl and H_2O exps:

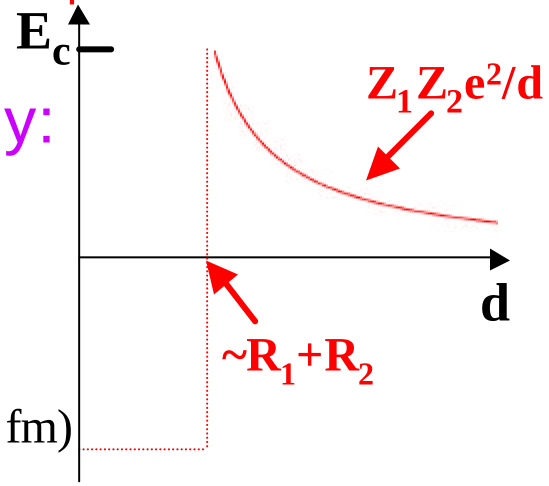
$He^3 + He^4$ ® g + Be^7
p + Be^7 ® g + B^8

$e^- +$ Be^7 ® n$_e$ + Li^7 (Homestake)
B^8 ® $Be^8 + e^+ +$ n$_e$ (Homestake, Kamiokande, Super-K)

Fusion reactions strongly suppressed by Coulomb repulsion



Potential energy:



$$E_c = \frac{Z_1 Z_2 e^2}{R_1 + R_2} = \frac{e^2}{\hbar c}\,\frac{\hbar c Z_1 Z_2}{R_1 + R_2} \approx \frac{197}{137}\,\frac{Z_1 Z_2}{R_1 + R_2}\ \text{MeV}\ (R_1 + R_2 \text{ in fm})$$

E_c » 1.4 MeV for $Z_1Z_2 = 4$, $R_1+R_2 = 4$ fm

Average thermal energy in the Sun core <E> = 1.5 k_BT_c » 0.002 MeV (T_c=15.6 MK)

k_B (Boltzmann constant) = 8.6 x 10^{-5} eV/deg.K

Nuclear fusion in the Sun core occurs by tunnel effect and depends strongly on T_c

Nuclear fusion cross-section at very low energies

$$s\,(E) = \frac{1}{E}\, e^{-2ph}\, S(E) \longleftarrow$$

Nuclear physics term difficult to calculate measured at energies ~0.1– 0.5 MeV and <u>assumed</u> to be energy independent

Tunnel effect: $h = \dfrac{Z_1 Z_2 e^2}{\hbar v}$

v = relative velocity

Predicted dependence of the n$_e$ fluxes on T$_c$:

From e$^-$ + Be^7 ® n$_e$ + Li^7: F(n$_e$) µ $\mathbf{T_c}^{8}$

From B^8 ® Be^8 + e$^+$ + n$_e$: F(n$_e$) µ $\mathbf{T_c}^{18}$

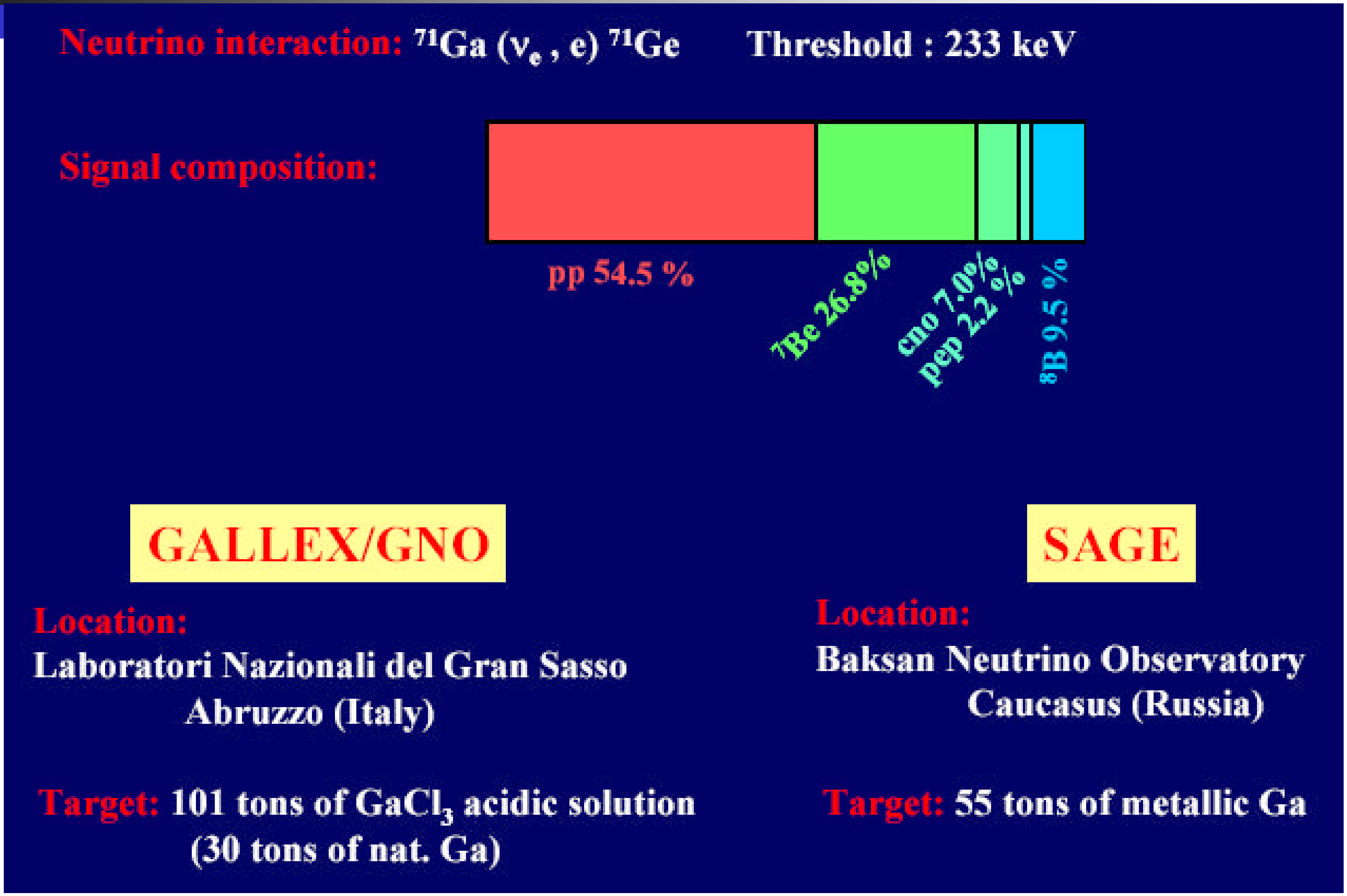
F µ $\mathbf{T_c}^{N}$ ⟶ DF/F = N D$\mathbf{T_c}$/$\mathbf{T_c}$

How precisely do we know the temperature T of the Sun core?

Search for ν_e from $p + p \to e^+ + \nu_e + d$ (the main component of the solar neutrino spectrum, constrained by the Sun luminosity)

➡ very little theoretical uncertainties

The gallium experiments



Neutrino interaction: $^{71}Ga\ (\nu_e\ ,\ e)\ ^{71}Ge$ Threshold : 233 keV

Signal composition:

GALLEX/GNO

Location:
Laboratori Nazionali del Gran Sasso
Abruzzo (Italy)

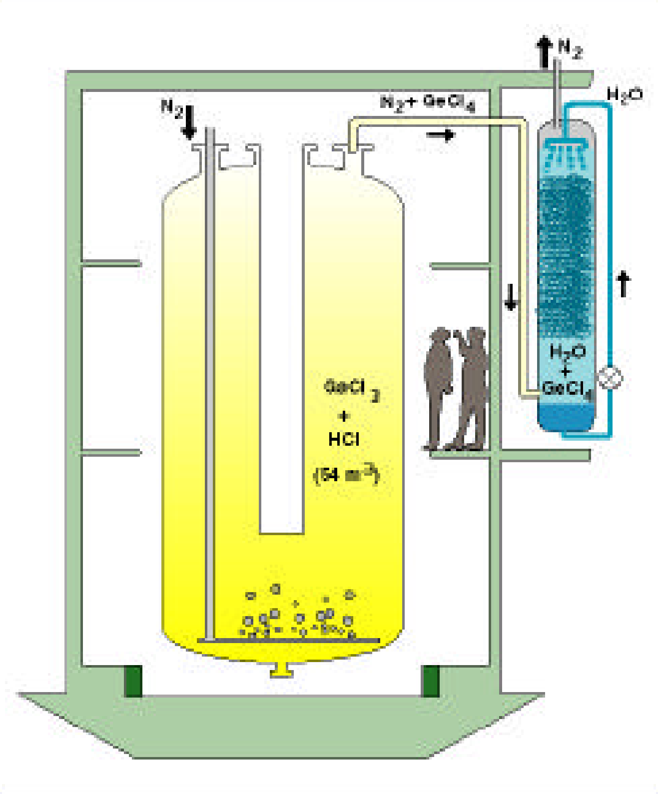
Target: 101 tons of $GaCl_3$ acidic solution
(30 tons of nat. Ga)

SAGE

Location:
Baksan Neutrino Observatory
Caucasus (Russia)

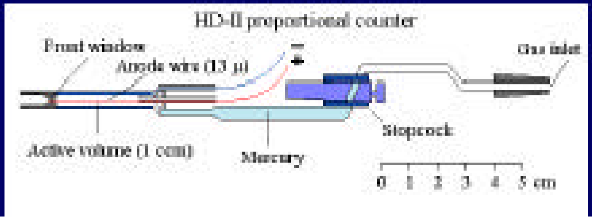
Target: 55 tons of metallic Ga

GALLEX/GNO

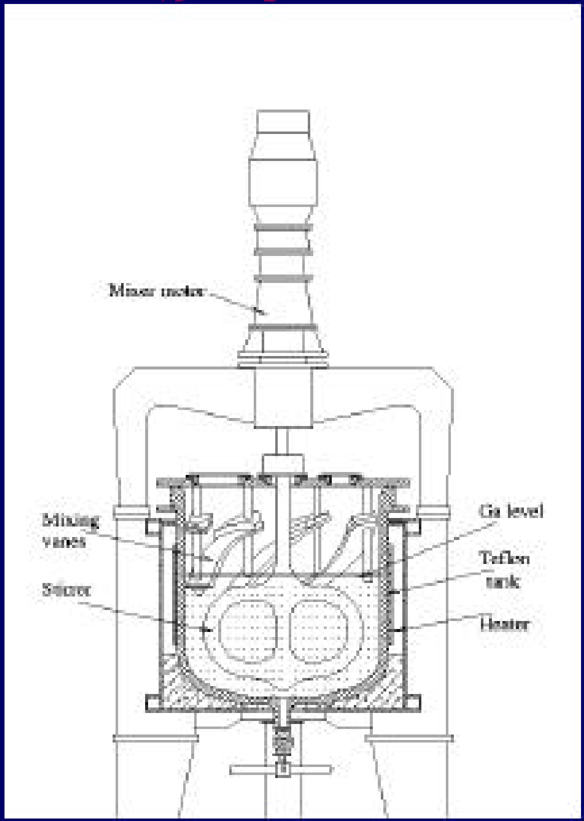


Detection Technique: radiochemical

^{71}Ge is extracted from the solution by N_2 purging every 4 weeks
It is then counted inside gas proportional counters

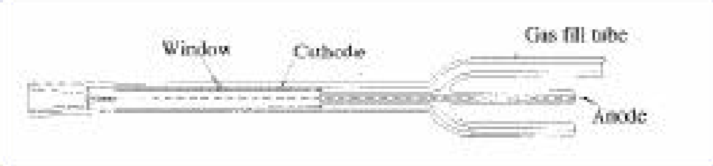


SAGE



Detection Technique: radiochemical

^{71}Ge is extracted from the reactors by a chemical procedure every 4-5 weeks.
It is then counted inside gas proportional counters



Gallium experiments: radiochemical experiments to search for $\nu_e + \mathrm{Ga}^{71} \rightarrow e^- + \mathrm{Ge}^{71}$

Energy threshold $E(\nu_e) > 0.233$ MeV ➡ reaction sensitive to solar neutrinos from $p + p \rightarrow e^+ + \nu_e + d$ (the dominant component)

Three experiments:

- GALLEX (Gallium Experiment, 1991 – 1997)
- GNO (Gallium Neutrino Observatory, 1998 –)

} In the Gran Sasso National Lab
150 km east of Rome
Depth 3740 m w.e.

- SAGE (Soviet-American Gallium Experiment)

In the Baksan Lab (Russia) under the Caucasus. Depth 4640 m w.e.

Target: 30.3 tons of Gallium in HCl solution (GALLEX, GNO)
50 tons of metallic Gallium (liquid at 40°C) (SAGE)

Experimental method: every few weeks extract Ge^{71} in the form of $GeCl_4$ (a highly volatile substance), convert chemically to gas GeH_4, inject gas into a proportional counter, detect radioactive decay of Ge^{71}: $e^- + Ge^{71} \rightarrow \nu_e + Ga^{71}$ (half-life $\tau_{1/2} = 11.43$ d)
(Final state excited Ga^{71} atom emits X-rays: detect K and L atomic transitions)

Check of detection efficiency:

- Introduce a known quantity of As^{71} in the tank (decaying to Ge^{71}: $e^- + Ge^{71} \rightarrow \nu_e + Ga^{71}$)
- Install an intense radioactive source producing mono-energetic ν_e near the tank: $e^- + Cr^{51} \rightarrow \nu_e + V^{51}$ (prepared in a nuclear reactor, initial activity 1.5 MCurie equivalent to 5 times the solar neutrino flux), $E(\nu_e) = 0.750$ MeV, half-life $\tau_{1/2} = 28$ d

GALLEX/GNO

Data taking: 1991 – ongoing

Results: (Runs 1-108) (May 91- Jan 02)

70.8 +- 4.5 (stat) +- 3.8 (sys) SNU

R (exp/SSM) = 0.55 +- 0.05 (exp) +- 0.03 (theo)

SAGE

Data taking: 1991 – ongoing

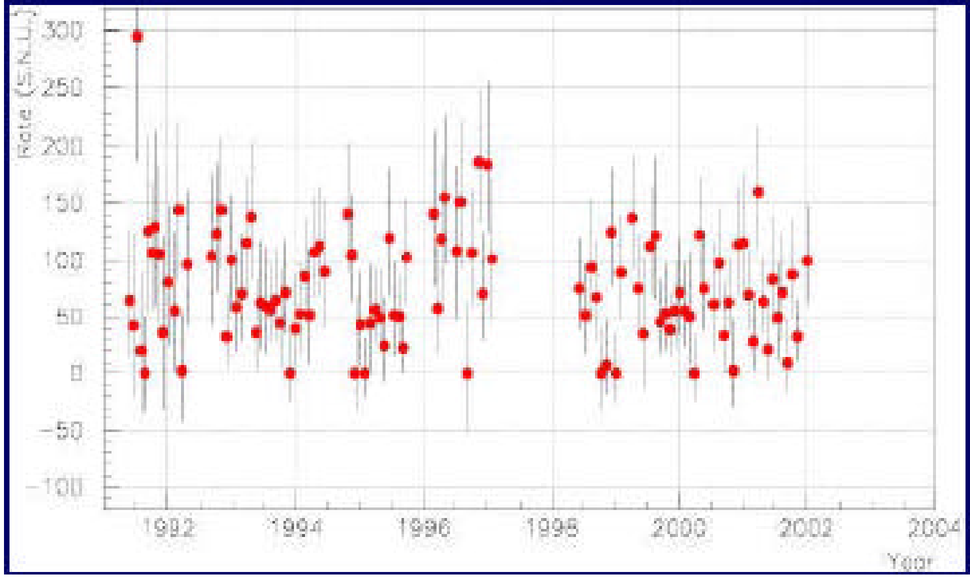
Results: (Runs 1 – 104) (Jan 90 – Jan 03)

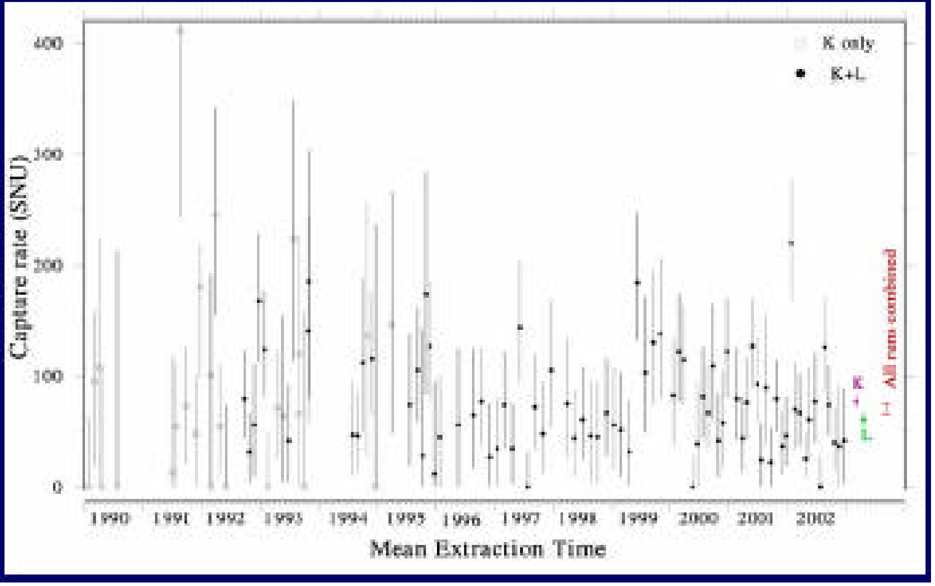
70.5 +- 4.8 (stat) +- 3.5 (sys) SNU

R (exp/SSM) = 0.55 +- 0.05 (exp) +- 0.03 (theo)

FIRST DETECTION OF PP SOLAR NEUTRINOS

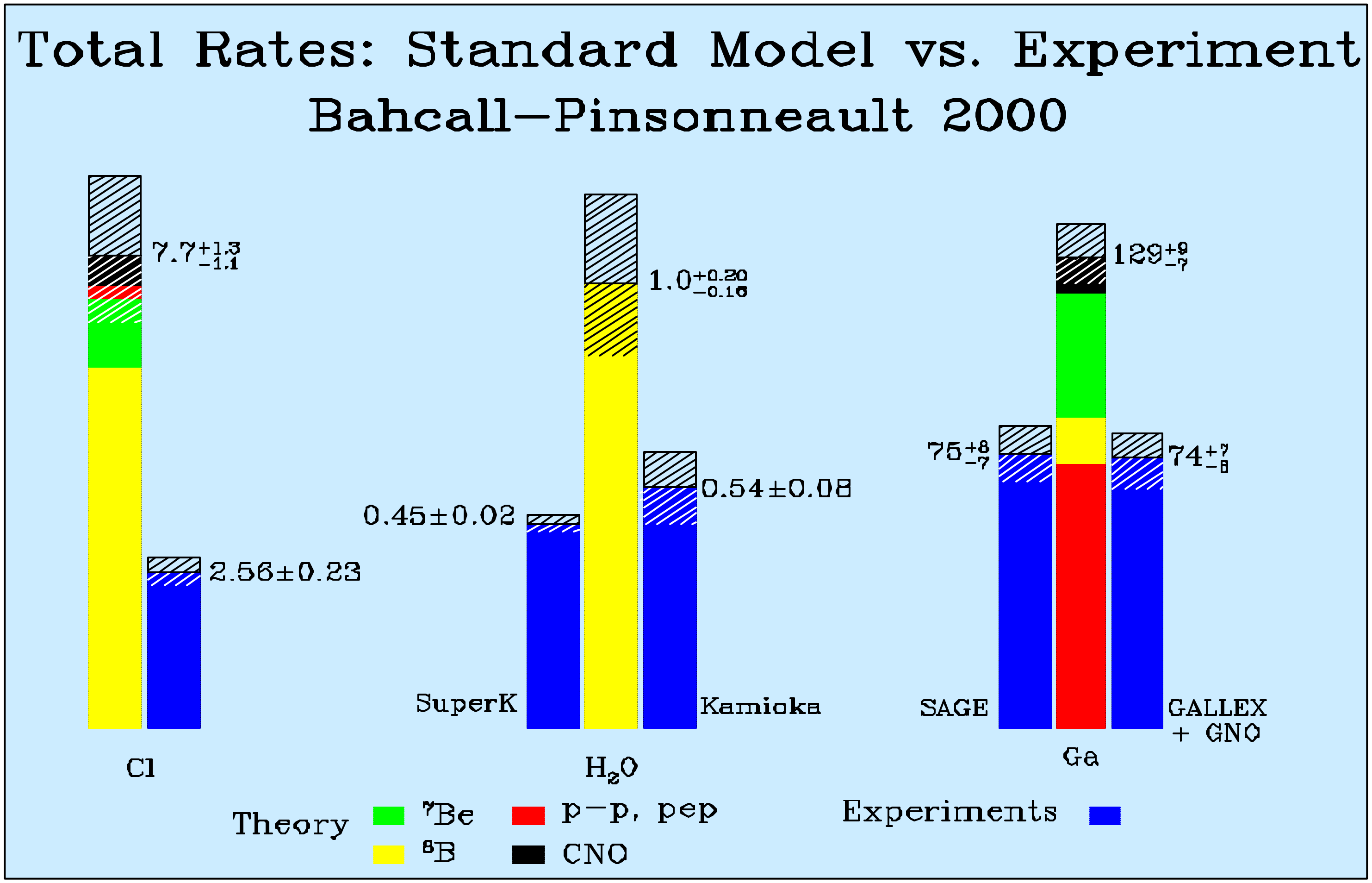
SUPPRESSION OF INTERMEDIATE ENERGY SOLAR NEUTRINO FLUX

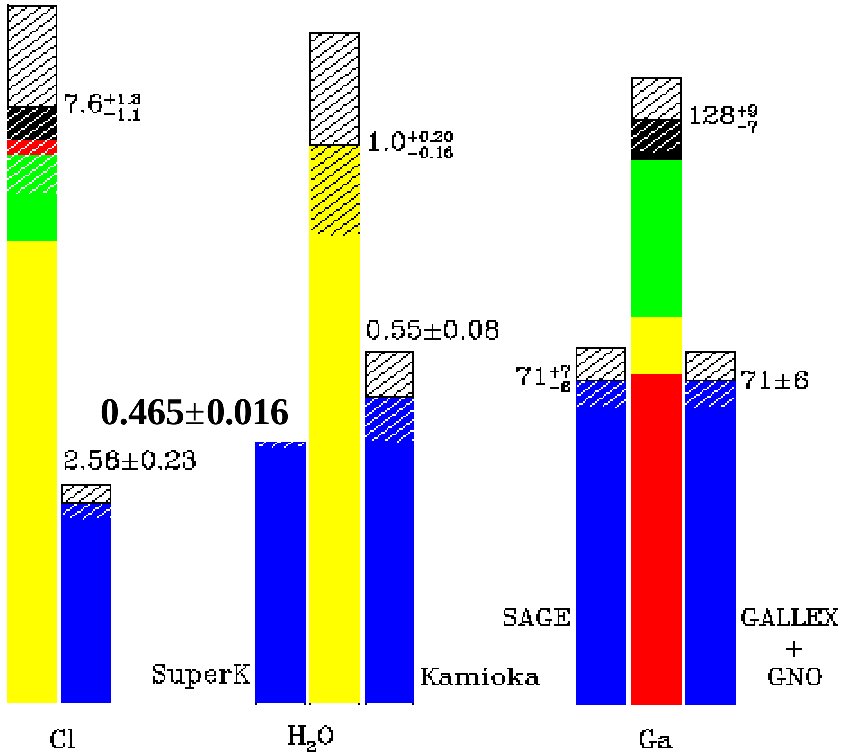




The Solar Neutrino Problem

(we don’t get enough neutrinos)





Data are consistent with:

- Full ν_e flux from $p + p \to e^+ + \nu_e + d$
- ~50% of the ν_e flux from $B^8 \to Be^8 + e^+ + \nu_e$
- Very strong (almost complete) suppression of the ν_e flux from $e^- + Be^7 \to n_e + Li^7$

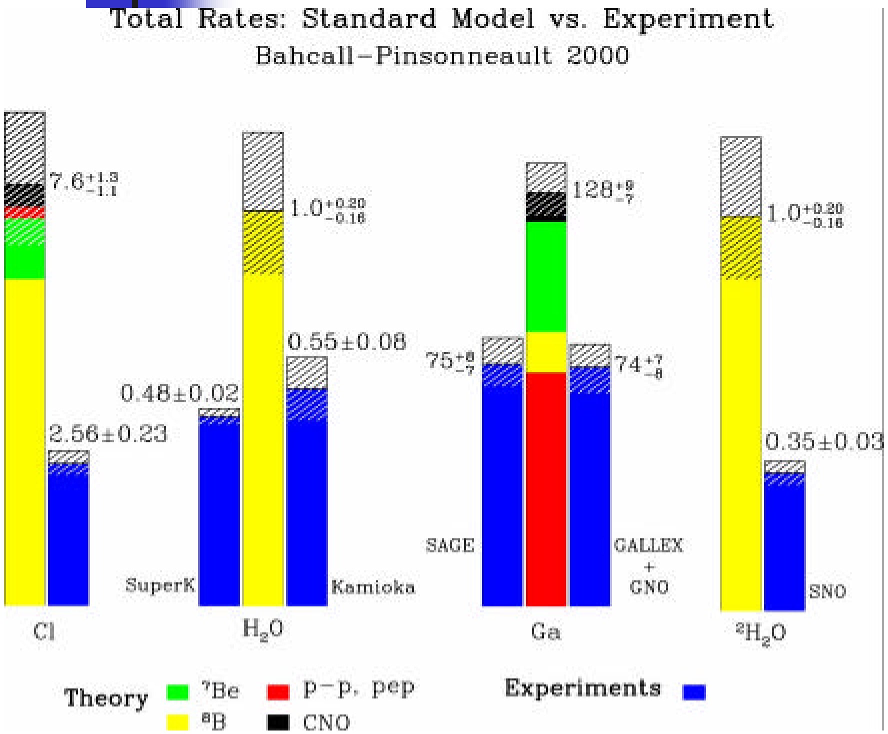
The real solar neutrino puzzle:

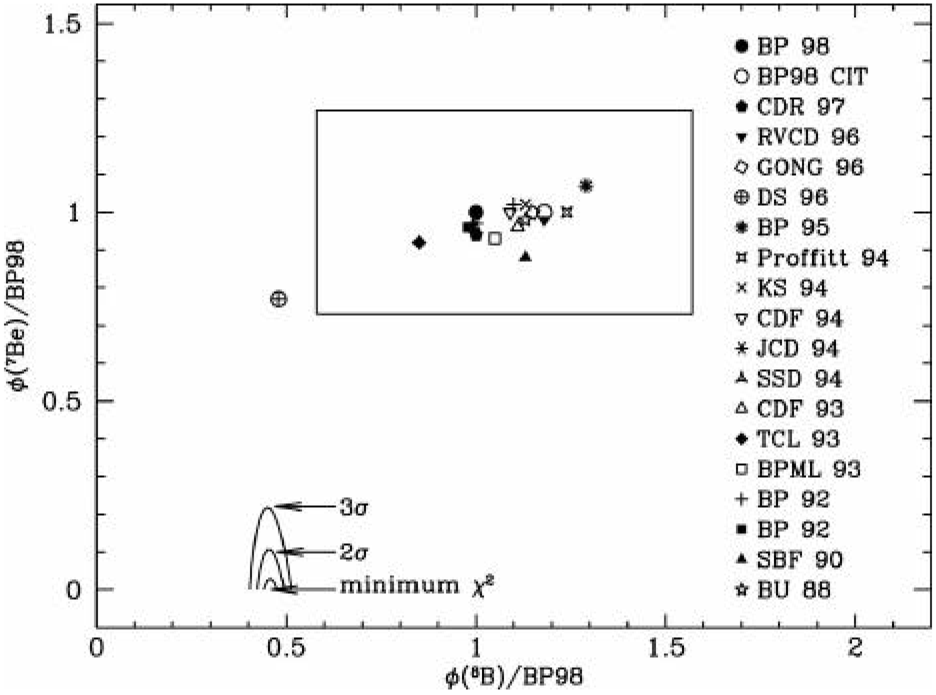
There is evidence for B^8 in the Sun (with deficit 50%), but no evidence for Be^7; yet Be^7 is needed to make B^8 by the fusion reaction $p + Be^7 \to \gamma + B^8$

Possible solutions:

- At least one experiment is wrong
- The SSM is totally wrong
- The ν_e from $e^- + Be^7 \to \nu_e + Li^7$ are no longer ν_e when they reach the Earth and become invisible ➡ ν_e OSCILLATIONS

Astrophysics is wrong?





Fit data with arbitrary ^{7}Be, ^{8}B

Best fit needs negative ^{7}Be

Remember ^{8}B is a product of ^{7}Be!

What is the heliosismology?

Observation of the seismic oscillations of the Sun

Measure the oscillation frequency ⇒ determine the speed of the sound propagation inside the Sun

$$v_s = v(R) \propto \sqrt{\frac{T}{\rho}}$$

R: distance from the center
T: local temperature
ρ local density

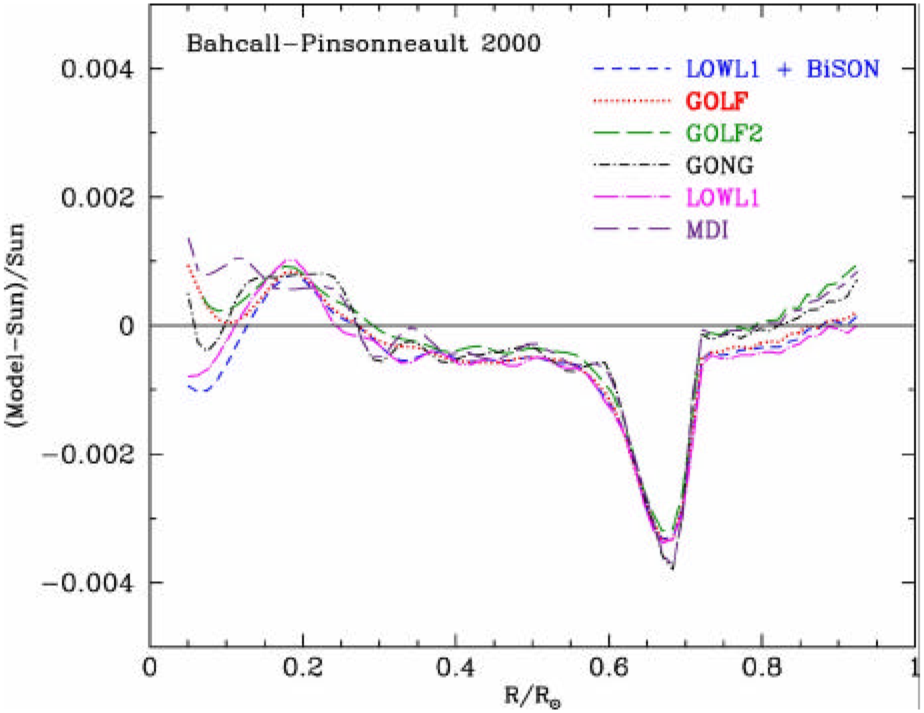
$$\left| \frac{v_s(\mathrm{SSM}) - v_s(\mathrm{mis})}{v_s(\mathrm{mis})} \right| < 2 \times 10^{-3}$$

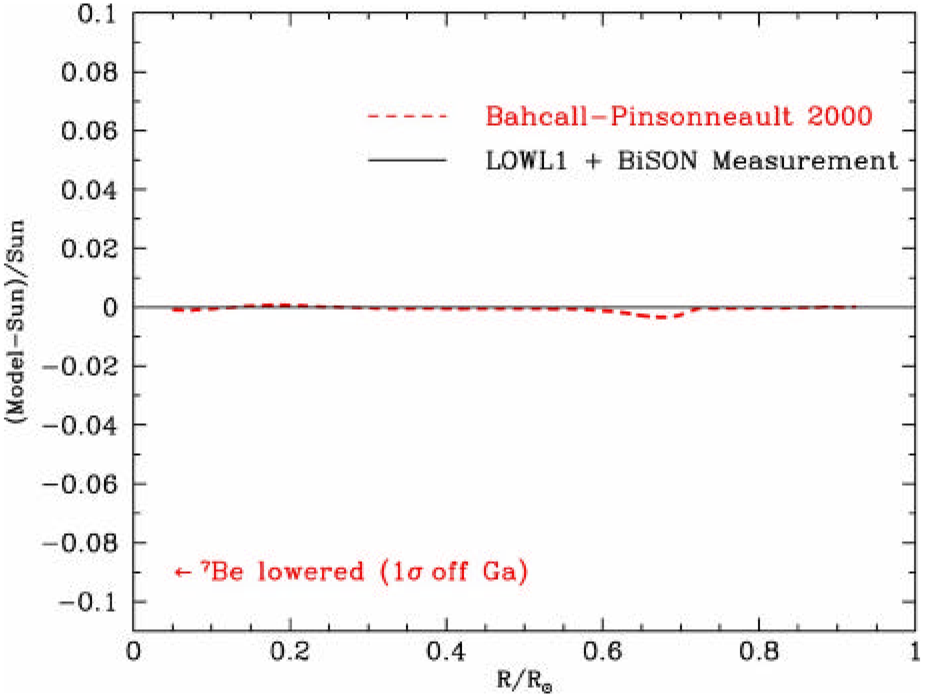
$$\frac{\Delta T}{T} = 2\frac{\Delta v_s}{v_s}$$

Uncertainty on T ≈ 0.4%!!!

Astrophysics is wrong?

- ✓ Helioseismology data agree well with the SSM

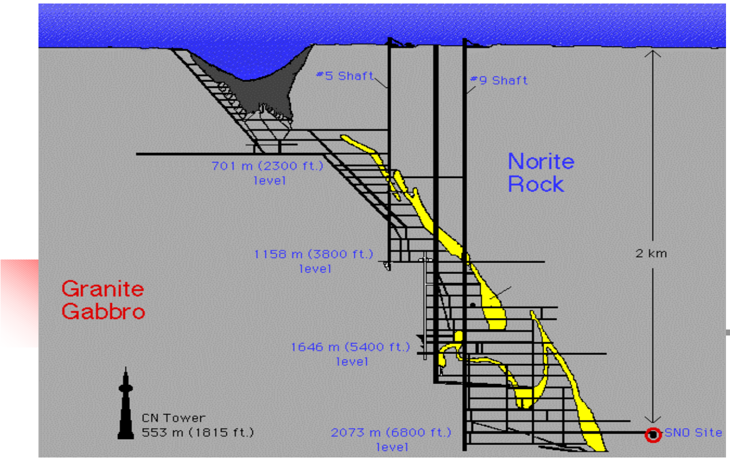


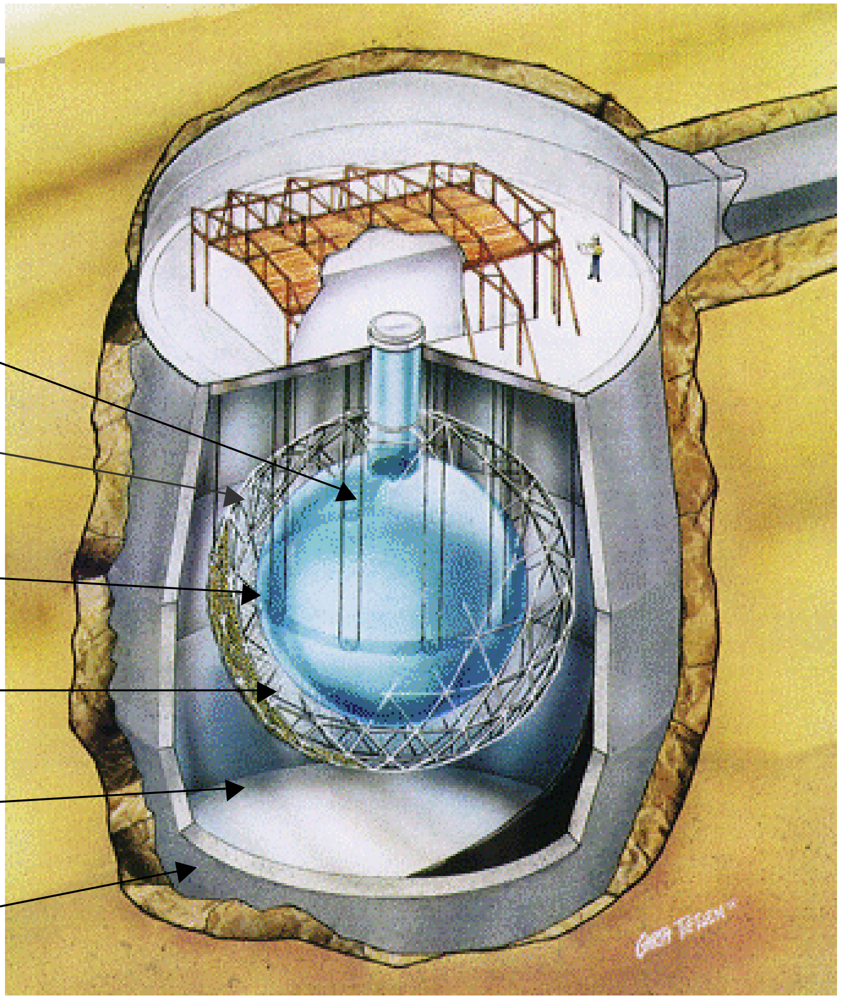


Summary of the solar neutrino problem before SNO

- ✓ The measured flux is smaller than the one predicted by the Standard Solar Model
- ✓ To fit Chlorine, Gallium and SK data one must assume a negative flux from ^{7}Be
- ✓ Astrophysical interpretations are strongly disfavored from heliosismological data
  - Standard Solar Models are in excellent agreement with the heliosismological data
  - All SSM agree to one other with an accuracy better than 10% when the same inputs are used

Sudbury Neutrino Observatory





1000 tonnes D_2O

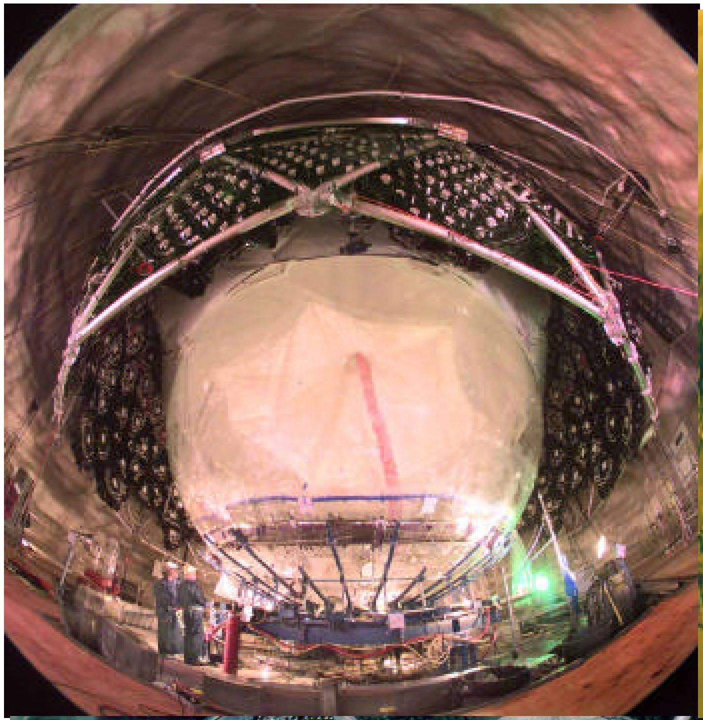
Support Structure for 9500 PMTs, 60% coverage

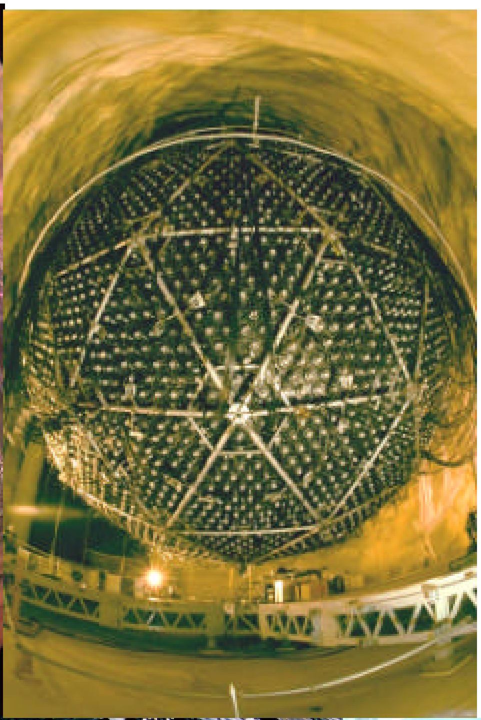
12 m Diameter Acrylic Vessel

1700 tonnes Inner Shielding H_2O

5300 tonnes Outer Shield H_2O

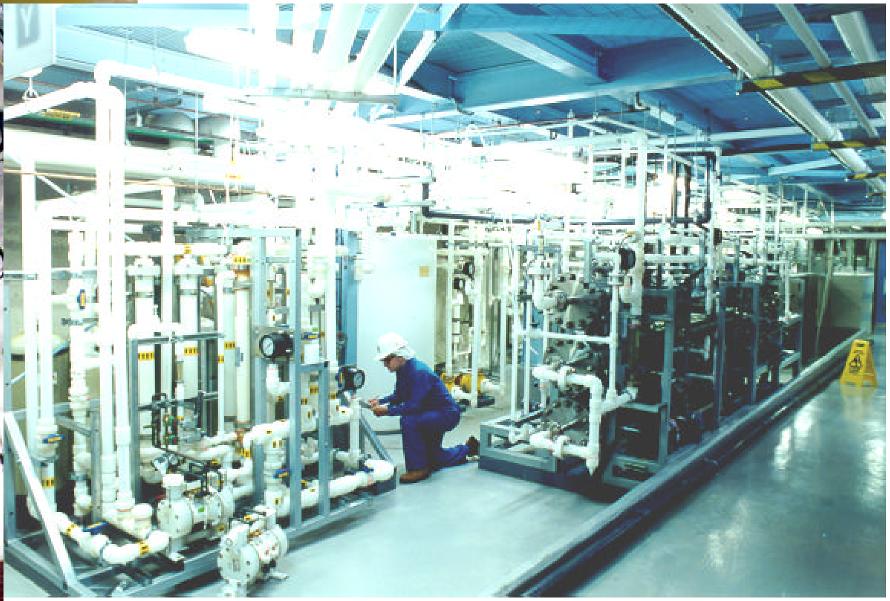
Urylon Liner and Radon Seal





One million pieces transported down in the ~ 10 foot square mine cage and re-assembled under Class 2000 air conditions.

> 60,000 Person-Showers so far



ν reactions in SNO

ES

$$?_x + e^- \Rightarrow ?_x + e^-$$

- Both SK, SNO
- Mainly sensitive to $n_{e,}$, less to n_m and n_t
- Strong directional sensitivity

CC

$$n_e + d \Rightarrow p + p + e^-$$

- Good measurement of n_e energy spectrum
- Weak directional sensitivity μ 1-1/3cos(q)

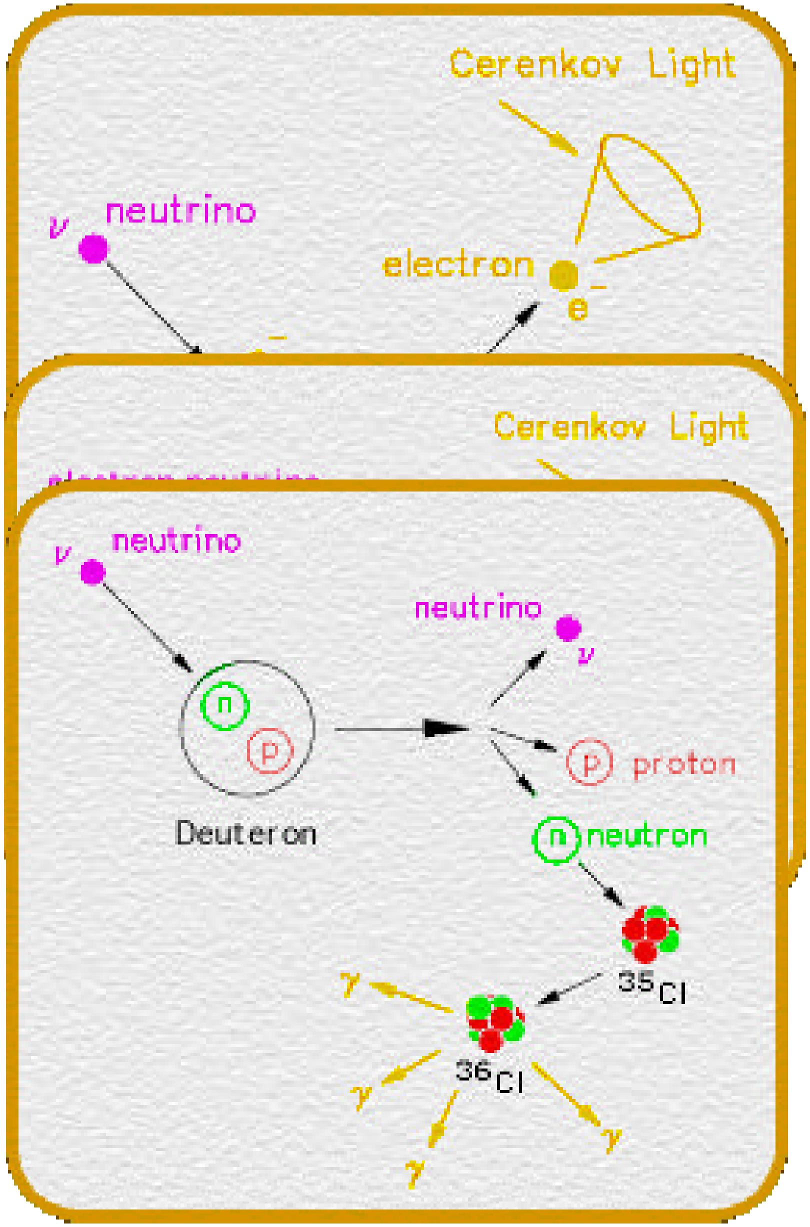
- n_e ONLY

NC

$$n_x + d \Rightarrow p + n + n_x$$

- Measure total ^{8}B n flux from the sun.

- Equal cross section for all n types



Solar Neutrino Physics From SNO

Flavor change/oscillations

June 2001

$$\frac{F_{cc}}{F_{es}} = \frac{n_e}{n_e + 0.154(n_m + n_t)}$$

SNO

SK

April 2002

$$\frac{F_{cc}}{F_{nc}} = \frac{n_e}{n_e + n_m + n_t}$$

SNO

April 2002

$$F_{day} \quad \text{vs} \quad F_{night}$$

Total ⁸B Solar Neutrino Flux

June 2001

$$F_x = F_{cc} + (F_{es} - F_{cc}) \times (1/e)$$

April 2002

$$F_x = F_{nc}$$

Solar neutrino detection at SNO:

(ES) Neutrino – electron elastic scattering: $\mathrm{n} + \mathbf{e}^{-}$ ® $\mathrm{n} + \mathbf{e}^{-}$

Directional, s(n$_{e}$) » 6 s(n$_{m}$) » 6 s(n$_{t}$) (as in Super-K)

(CC) $\mathrm{n}_{\mathbf{e}} + \mathbf{d}$ ® $\mathbf{e}^{-} + \mathbf{p} + \mathbf{p}$

Weakly directional: recoil electron angular distribution µ **1 – (1/3) cos(q$_{\mathbf{sun}}$)**

Good measurement of the n_{e} energy spectrum (because the electron takes most of the ν_{e} energy)

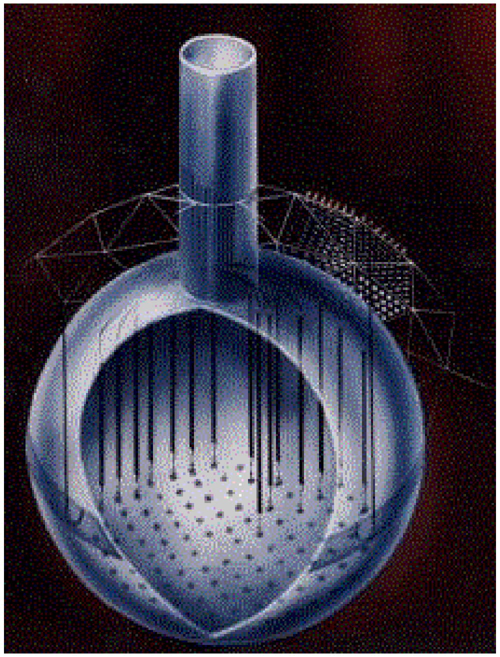
(NC) $\mathrm{n} + \mathbf{d}$ ® $\mathrm{n} + \mathbf{p} + \mathbf{n}$

Equal cross-sections for all three neutrino types

Measure the total solar flux from $\mathbf{B}^{8}$ ® $\mathbf{Be}^{8} + \mathbf{e}^{+} + \mathrm{n}$ in the presence of oscillations by comparing the rates of CC and NC events

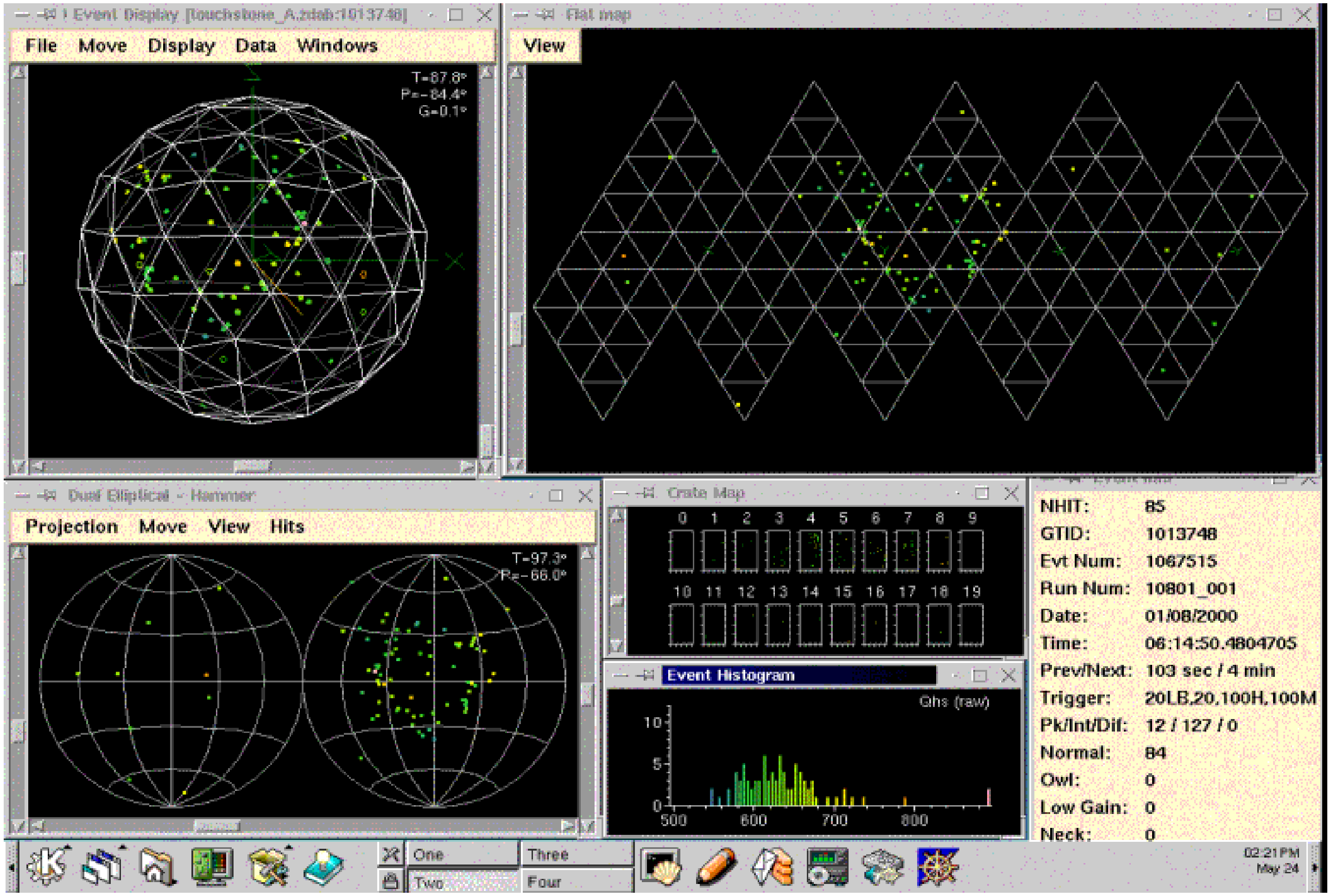
Detection of $\nu + d \rightarrow \nu + p + n$

Detect photons ($\rightarrow$ e+e^{-}) from n capture at thermal energies:



- First phase (November 1999 – May 2001):
  $\mathrm{n} + \mathbf{d}$ ® $\mathbf{H}^{3} + \mathrm{g}$ **(E$_{g}$ = 6.25 MeV)**
- Second phase (in progress): add high purity *NaCl* (2 tons)
  $\mathrm{n} + \mathit{Cl}^{35}$ ® $\mathit{Cl}^{36} + \mathrm{g}$ – ray cascade ($\Sigma E_{\gamma} \approx 8.6$ MeV)
- At a later stage:
  insert He^{3} proportional counters in the detector
  $\mathrm{n} + \mathit{He}^{3}$ ® $\mathit{p} + \mathbf{H}^{3}$ (mono-energetic signal)

A Neutrino Event

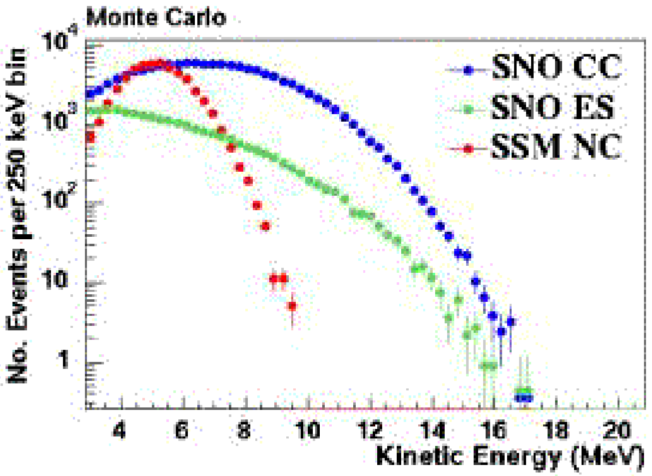


NHIT: 85
GTID: 1013748
Evt Num: 1067515
Run Num: 10801_001
Date: 01/08/2000
Time: 06:14:50.4804705
Prev/Next: 103 sec / 4 min
Trigger: 20LB,20,100H,100M
Pk/Int/Dif: 12 / 127 / 0
Normal: 84
Owl: 0
Low Gain: 0
Neck: 0

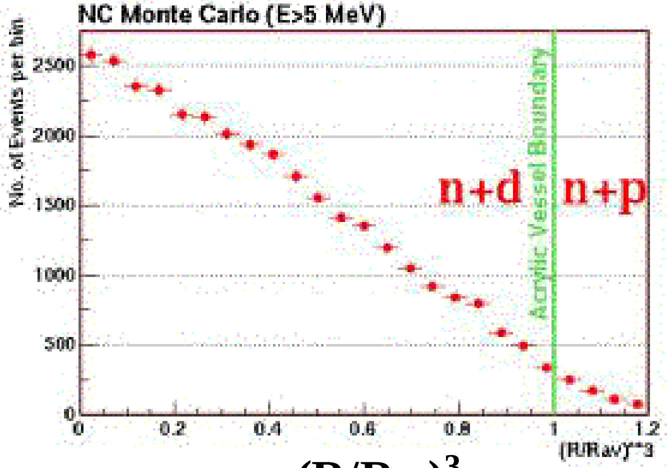
SNO expectations

Use three variables:

- Signal amplitude (MeV)
- $\cos(\theta_{sun})$
- Event distance from centre (R)
  (measured from the PM relative times)

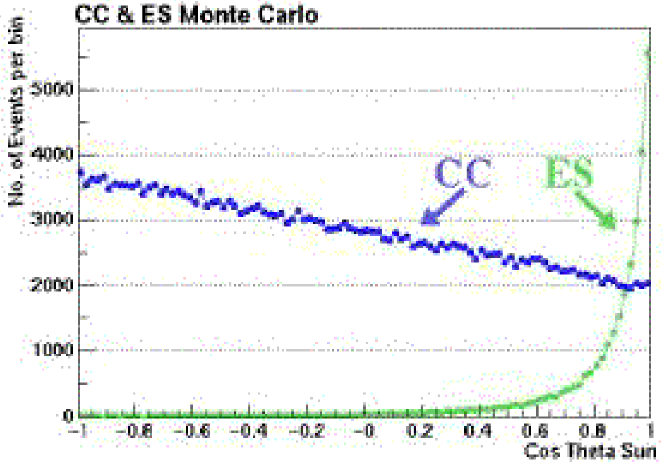


$$n + d \rightarrow t + \gamma \ldots \rightarrow e^- \quad (E_\gamma = 6.25\ \text{MeV})$$



$(R/R_{av})^3$

(proportional to volume)



$\cos(q_{sun})$

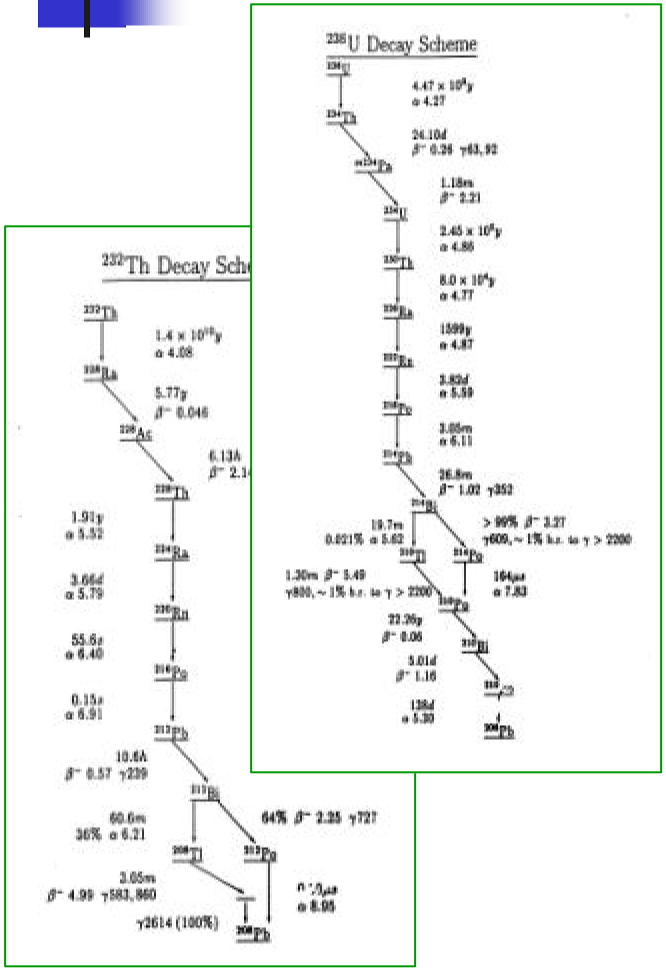
(R_{av} = 6 m = radius of the acrylic sphere)

Use β and γ radioactive sources to calibrate the energy scale

Use Cf^{252} neutron source to measure neutron detection efficiency (14%)

Neutron signal does not depend on $\cos(\theta_{sun})$

The enemy…..



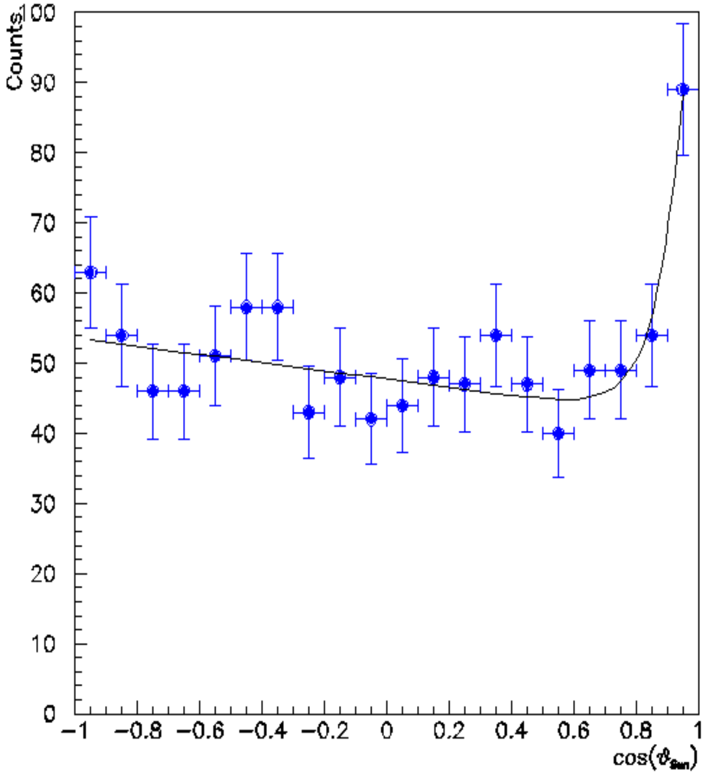
βs and γs from decays in these chains interfere with the signals at low energies

And worse, γs over 2.2 MeV cause $d + \gamma \rightarrow n + p$

Design called for:

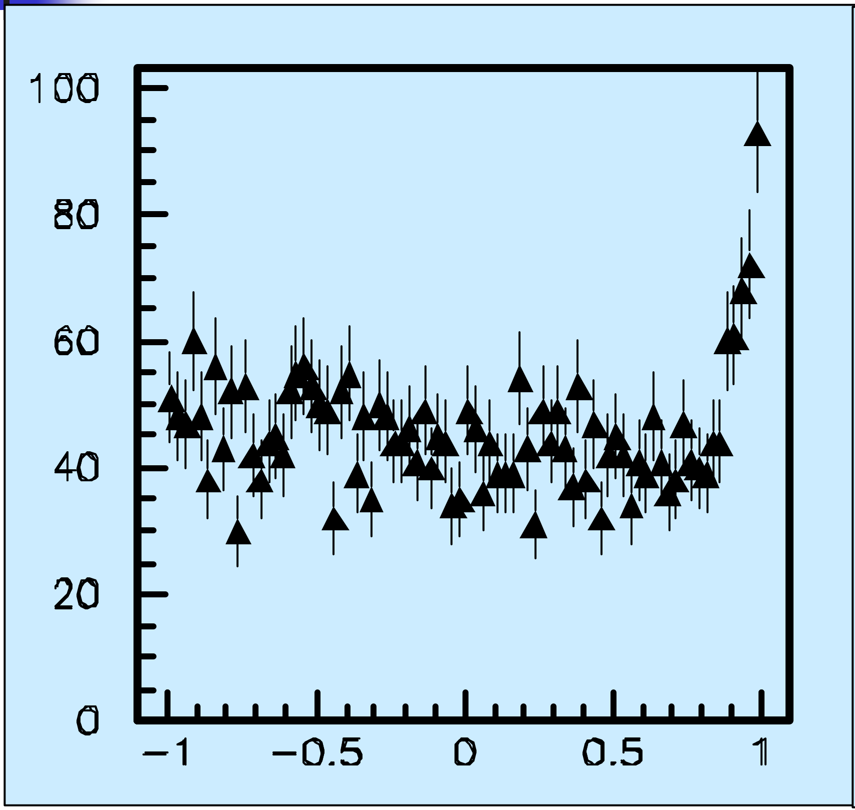
D_2O < 10^{-15} gm/gm U/Th
H_2O < 10^{-14} gm/gm U/Th
Acrylic < 10^{-12} gm/gm U/Th

SNO cos(q)$_{\text{sun}}$ distribution

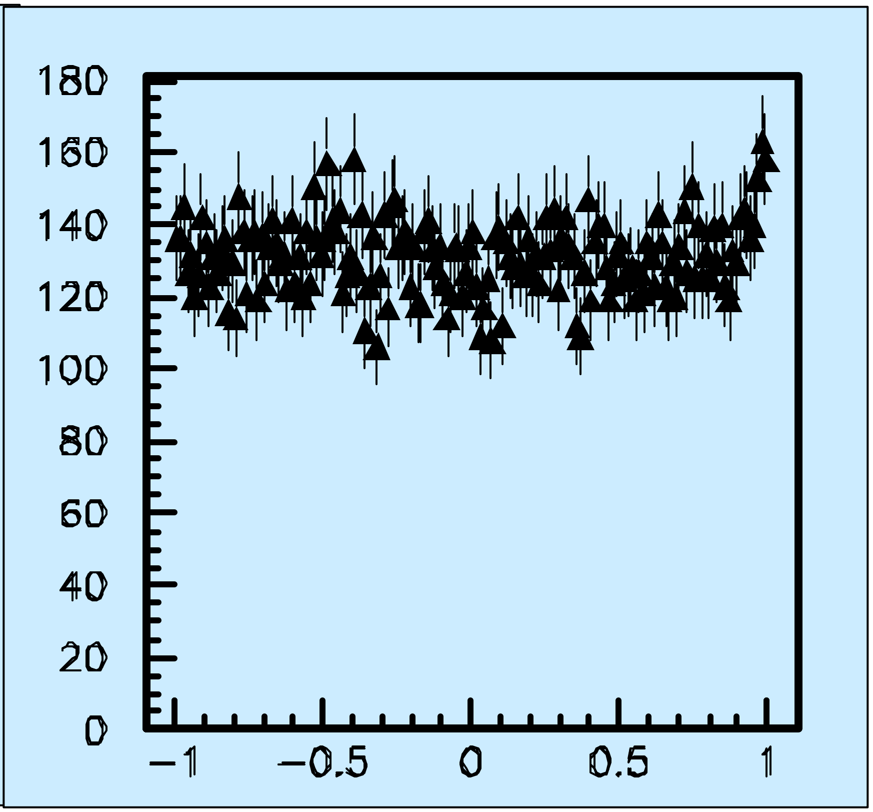


Electron Angle with respect to the direction from the Sun

Low threshold cos(q)$_{\text{sun}}$



E_{thresh} ~ 4.5 MeV



E_{thresh} ~ 3.5 MeV

From 306.4 days of data taking:

Number of events with kinetic energy $T_{eff} > 5$ MeV and $R < 550$ cm: 2928

Neutron background: 78 ± 12 events. Background electrons 45^{+18}_{-12} events

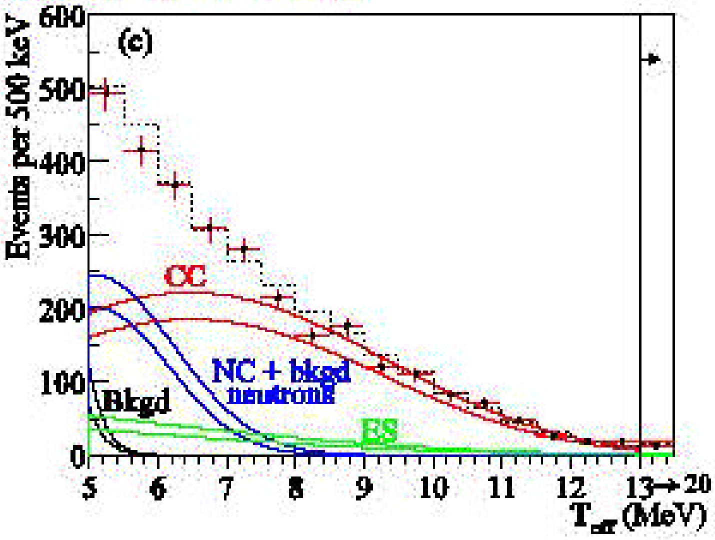
Use likelihood method and the expected distributions to extract the three signals

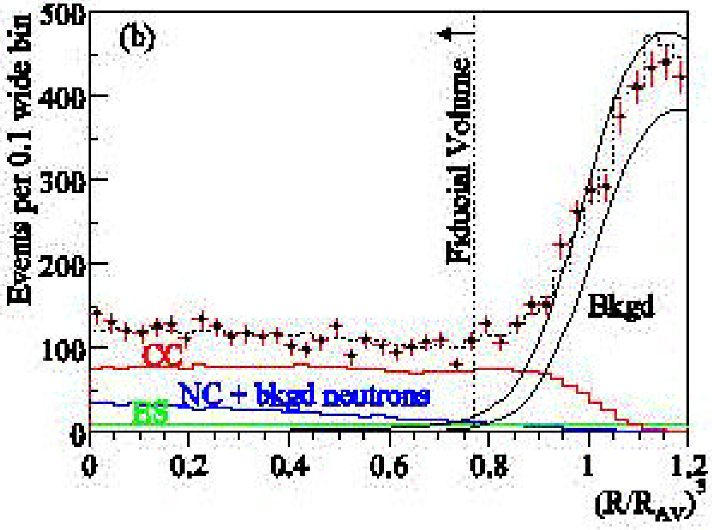
#EVENTS

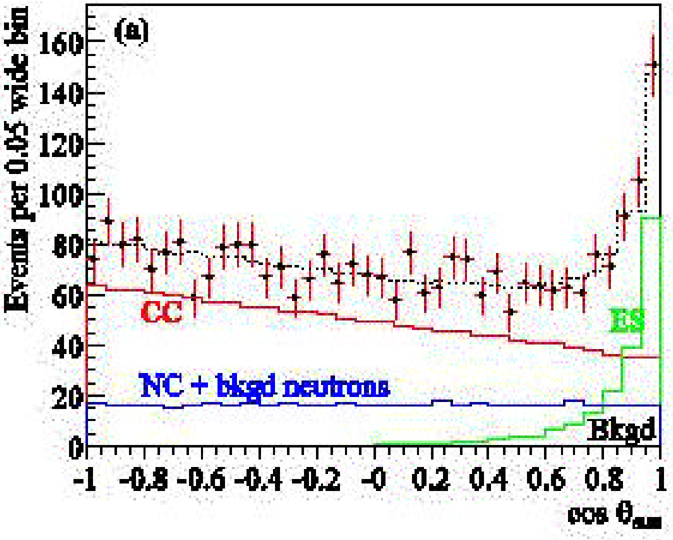
CC $1967.7^{+61.9}_{+60.9}$

ES $263.6^{+26.4}_{+25.6}$

NC $576.5^{+49.5}_{+48.9}$







Solar neutrino fluxes, as measured separately from the three signals:

$F_{CC}(n_e) = 1.76 \,{}^{+0.06}_{-0.05}\,{}^{+0.09}_{-0.09}$ x 10^6 cm^{-2}s^{-1}

Note: $F_{CC}(n_e)$ ° $F(n_e)$

$F_{ES}(n) = 2.39 \,{}^{+0.24}_{-0.23}\,{}^{+0.12}_{-0.12}$ x 10^6 cm^{-2}s^{-1}

Calculated under the assumption that all incident neutrinos are ν_e

$F_{NC}(n) = 5.09 \,{}^{+0.44}_{-0.43}\,{}^{+0.46}_{-0.43}$ x 10^6 cm^{-2}s^{-1}

stat. syst.

$F_{SSM}(n) = 5.05 \,{}^{+1.01}_{-0.81}$ x 10^6 cm^{-2}s^{-1}

$\Phi_{NC}(\nu) - \Phi_{CC}(\nu_e) = \Phi(\nu_{\mu\tau}) = 3.33 \pm 0.64$ x 10^6 cm^{-2} s^{-1} { stat. and syst. errors combined

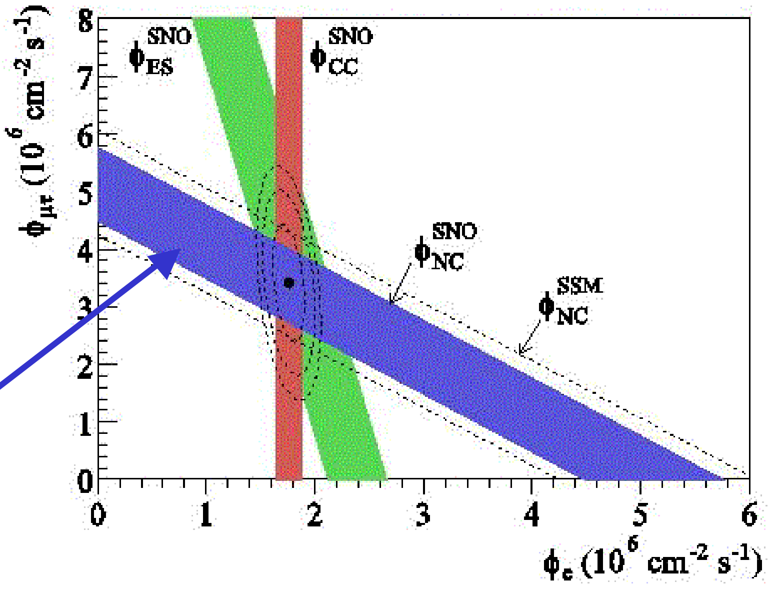
5.2 standard deviations from zero → evidence that solar neutrino flux on Earth contains sizeable ν_μ or ν_τ component (in any combination)

Write $\Phi_{ES}(\nu)$ as a function of $\Phi(\nu_e)$ and $\Phi(\nu_{\mu\tau})$:

$$\Phi_{ES}(n) \approx \Phi(n_e) + \frac{1}{6}\Phi(n_{mt})$$

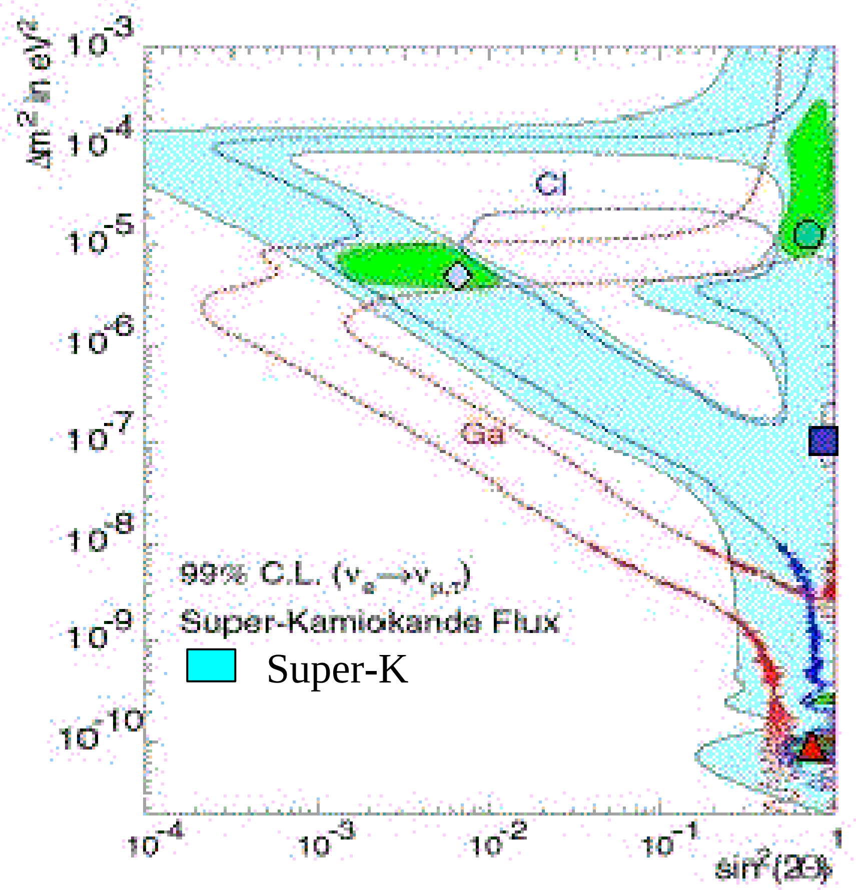
(because $s_{ES}(n_{mt}) \approx \frac{1}{6} s_{ES}(n_e)$)

$\Phi(\nu) = \Phi(\nu_e) + \Phi(\nu_{\mu\tau})$



Regions of the (Δm^2 , $\sin^2 2\theta$) plane allowed by the solar neutrino flux measurements in the Homestake, Super-K and Gallium experiments
(using only data available before the end of the year 2000)

Different energy thresholds → different regions of the (Δm^2 , $\sin^2 2\theta$) plane



The regions common to the three measurements contain the allowed oscillation parameters

Smoking guns from solar ν?

- ✓ The appearance of the wrong-flavour neutrinos in the "beam" has been seen ⇒ ν_e changes into active ν (μ or τ)
- ✓ The relevant question is: what kind of oscillations?
  - Oscillations in vacuum?
  - Oscillations in matter?
- ✓ In the following we focus on the so-called "smoking guns" typical of each scenario

Interpretation of the solar neutrino data using the two-neutrino mixing hypothesis

Vacuum oscillations

ν_e spectrum on Earth $\Phi(\nu_e) = P_{ee}\,\Phi_0(\nu_e)$ ($\Phi_0(\nu_e) \equiv$ spectrum at production)

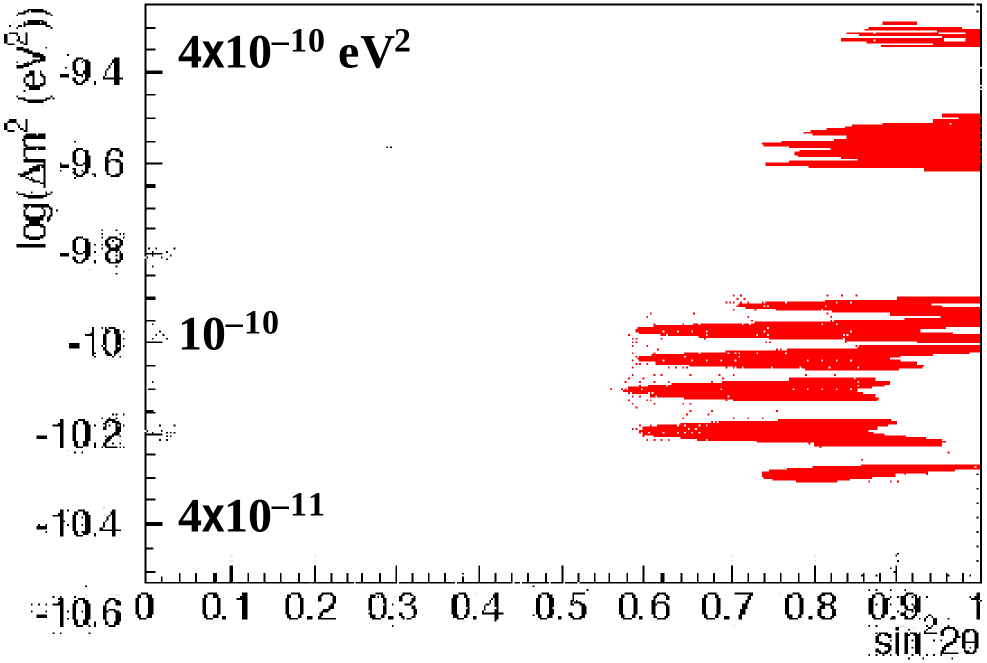
ν_e disappearance probability $P_{ee} = 1 - \sin^2(2\theta)\sin^2(1.267\Delta m^2 \frac{L}{E})$

L [m]
E [MeV]
Δm^2 [eV^2]

$L = 1.496 \times 10^{11}$ m (average Sun – Earth distance with 3.3% yearly variation from eccentricity of Earth orbit)

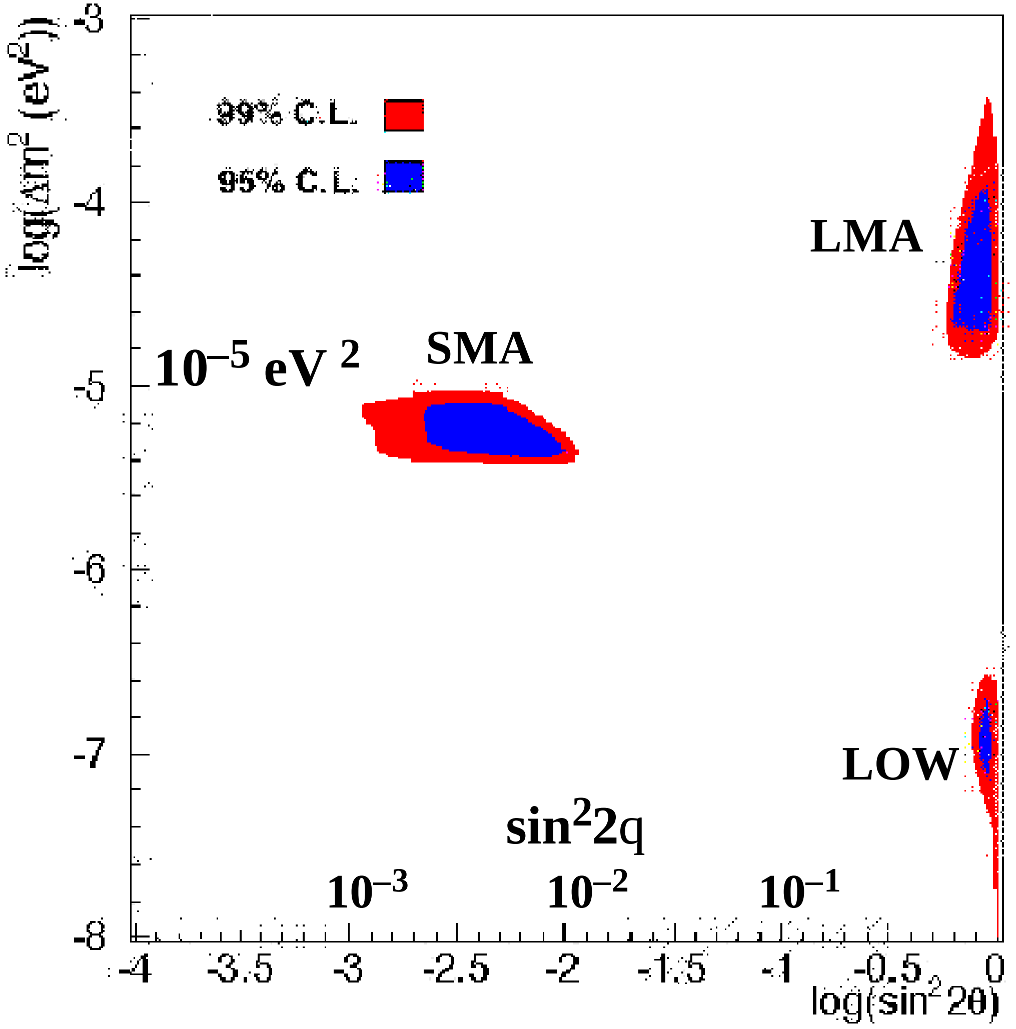
Fit predicted ν_e spectrum to data using θ, Δm^2 as adjustable parameters

Regions of oscillation parameters consistent with solar neutrino data available before the end of the year 2000



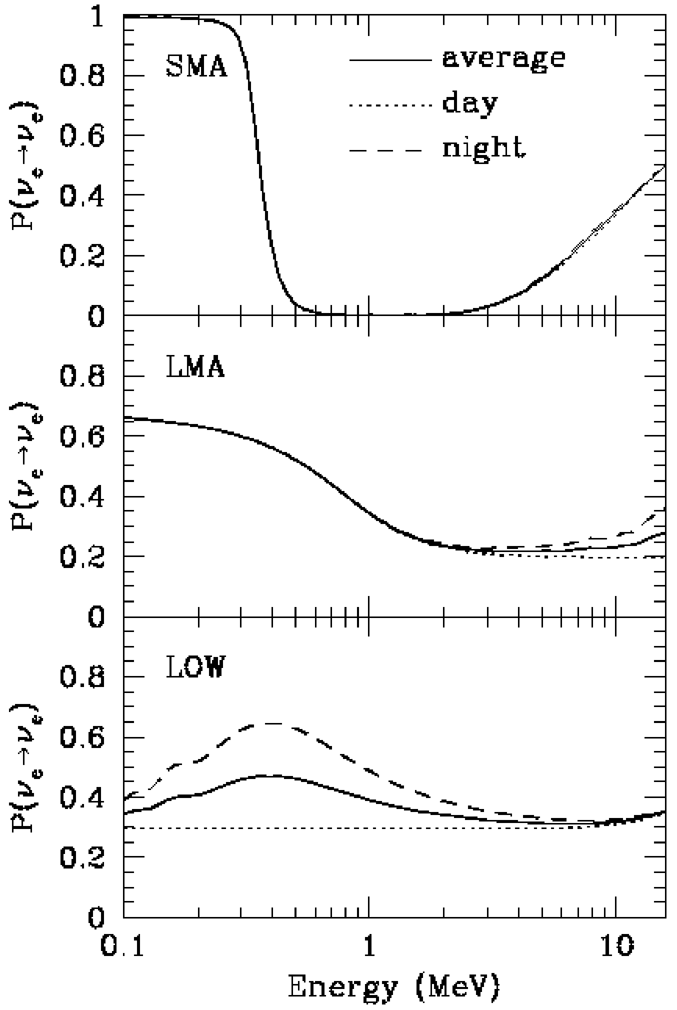
Matter-enhanced solar neutrino oscillations ("MSW solutions")

(using only data available before the end of the year 2000)



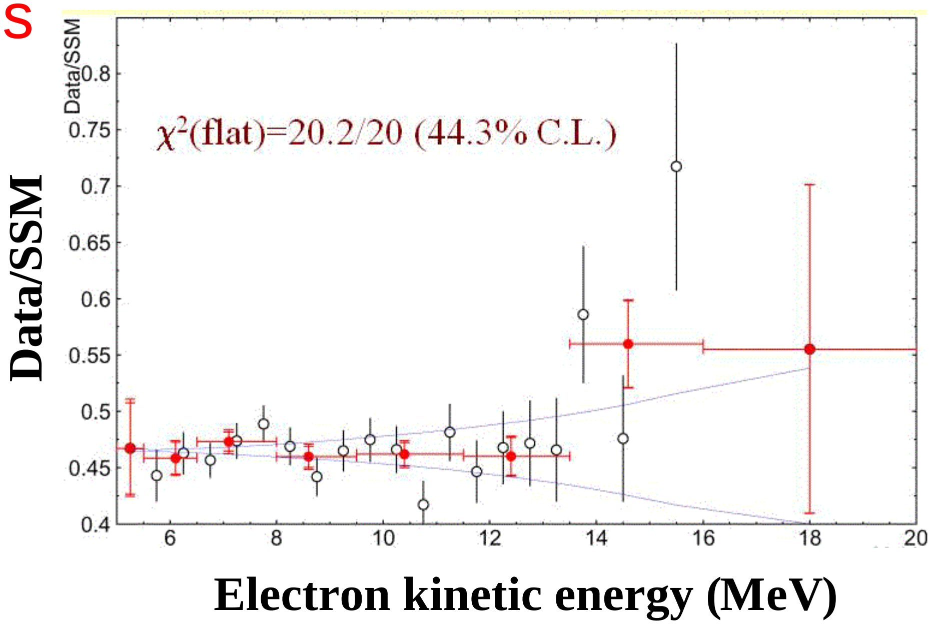
LMA: Large Mixing Angle
SMA: Small Mixing Angle

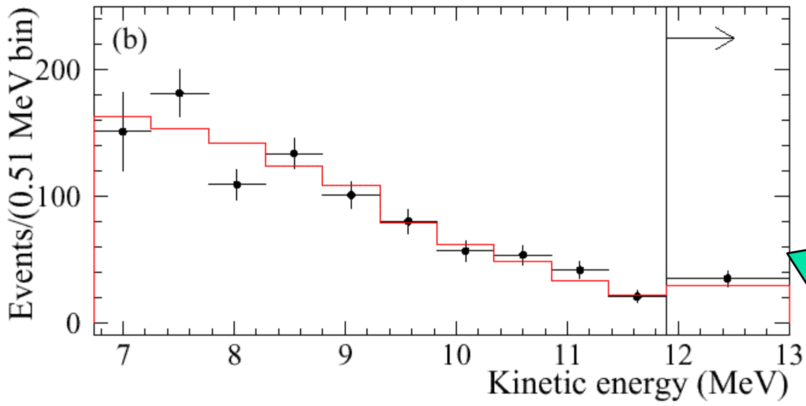
Survival probability
versus neutrino energy



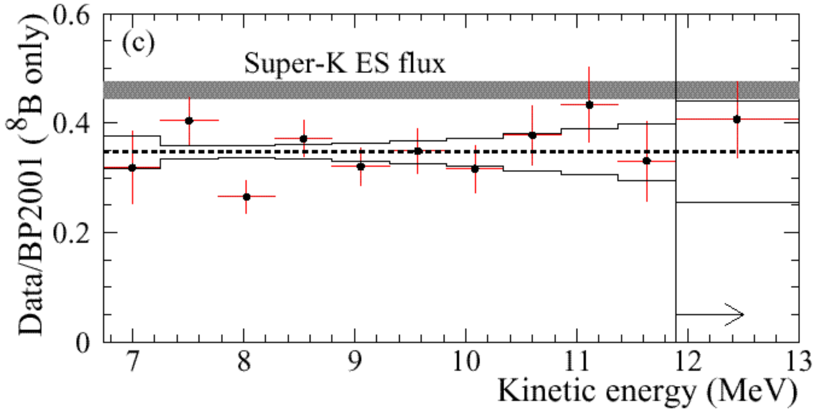
Additional experimental information: Energy spectrum distortions

Super-K 2002





SNO recoil electron spectrum from n$_e$ + d ® e$^-$ + p + p

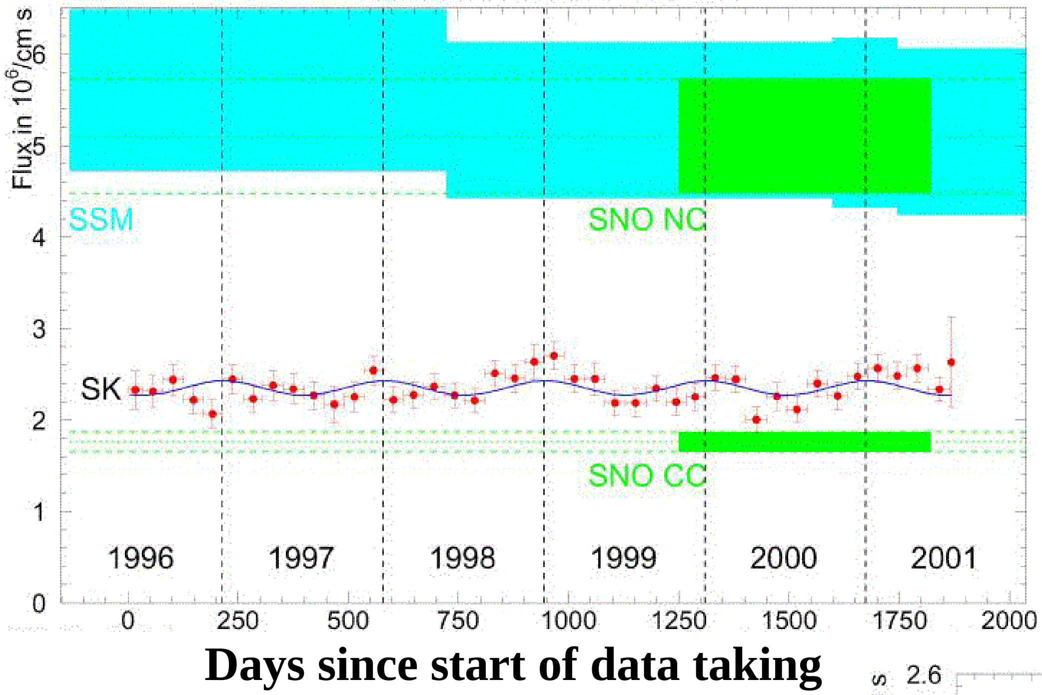


SNO data/SSM prediction

ν_e deficit is energy independent within errors (no distortions)

SMA disfavoured!

Seasonal variation of measured neutrino flux in Super-K

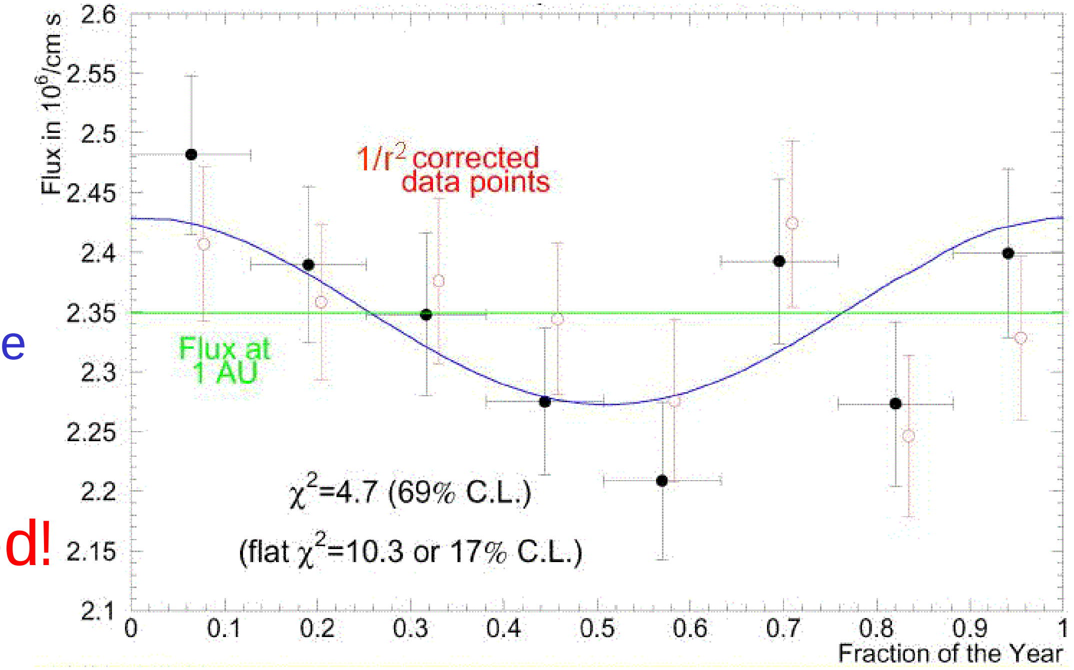


Yearly variation of the Sun-Earth distance: 3.3% ⇒ seasonal variation of the solar neutrino flux for some vacuum oscillation solutions

<u>Note</u>: expected seasonal variation from change of solid angle ≈ 6.6%

The observed effect is consistent with the variation of solid angle alone

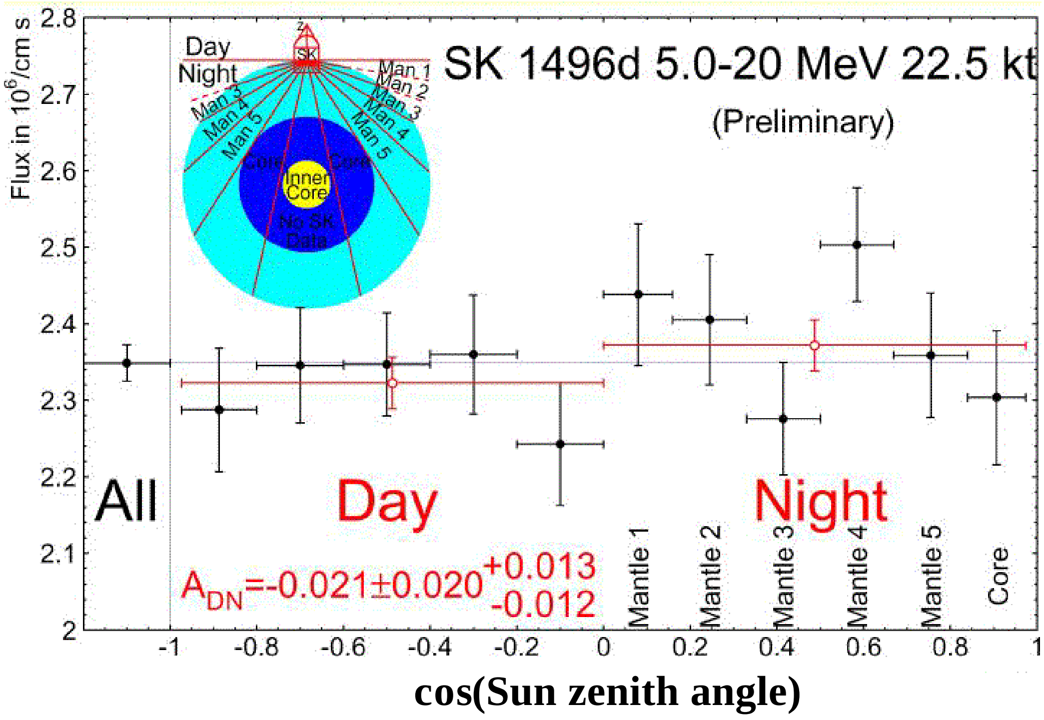
➡ vacuum disfavoured!

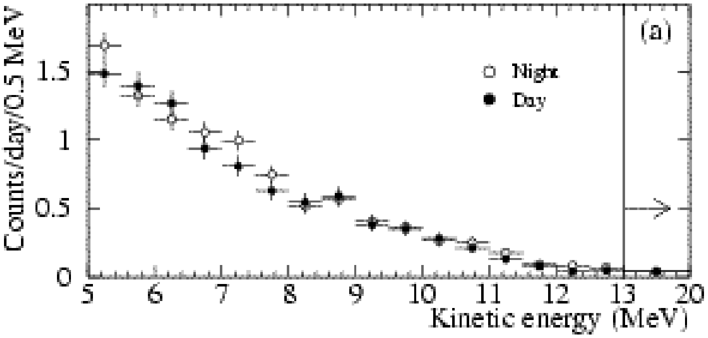


Day-night effects (expected for some MSW solutions from matter-enhanced oscillations when neutrinos traverse the Earth at night → increase of ν_e flux at night)

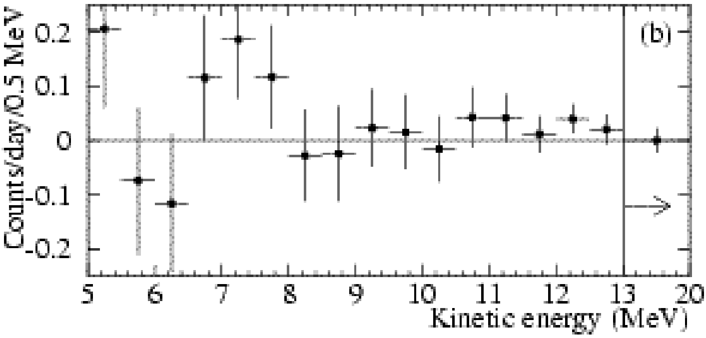
Subdivide night spectrum into bins of Sun zenith angle to study dependence on path length inside Earth and density

$$A_{DN} = \frac{D-N}{0.5(D+N)}$$





SNO Day and Night Energy Spectra (CC + ES + NC events)



Difference Night – Day

→ LOW disfavoured!

SK data: comparison with oscillations

🟨 **Vacuum oscillation**

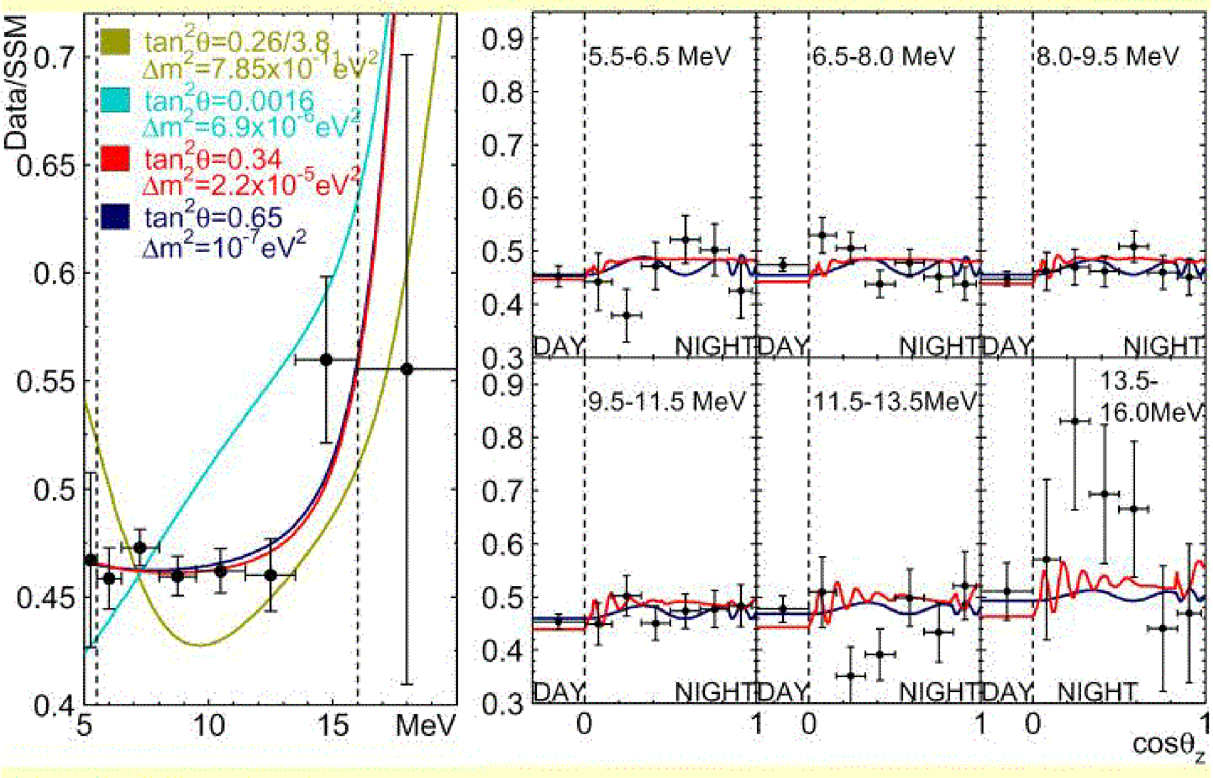
🟦 **SMA**

🟥 **LMA**

⬛ **LOW**

Electron energy distribution

Sun zenith angle distributions for different electron energy bins



- Vacuum oscillation and SMA solution disagree with electron energy distribution
- LMA and LOW solutions describe reasonably well the zenith angle distributions
- No dependence on zenith angle within errors

Global fits to all existing solar neutrino data

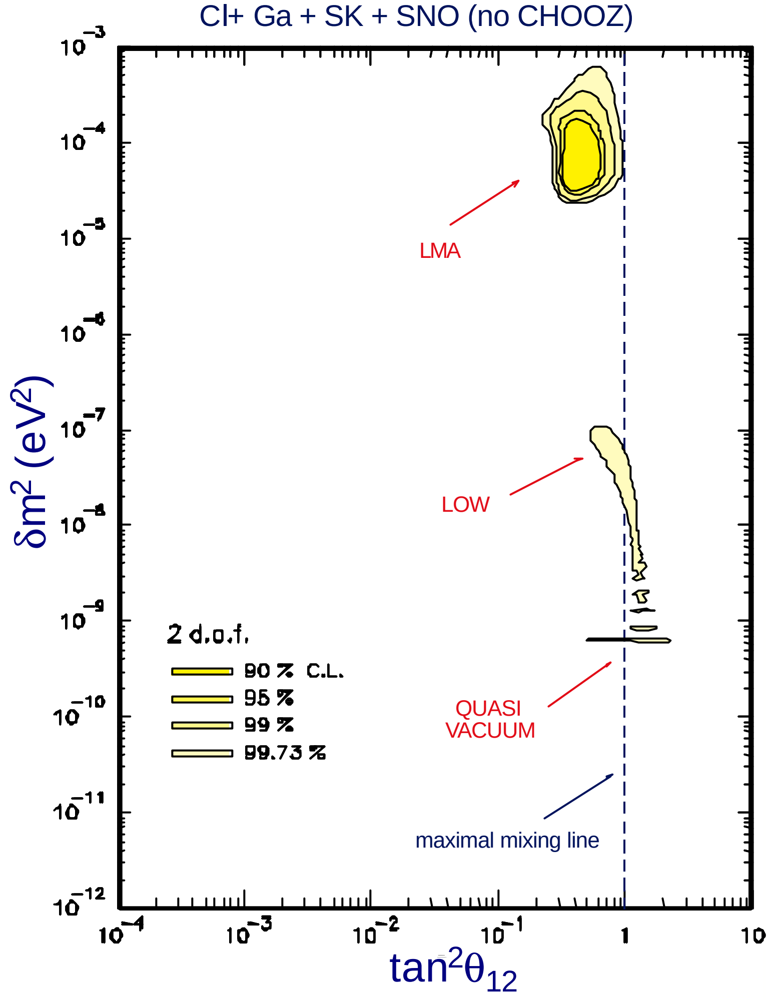
48 data points, two free parameters (mixing angle θ_{12}, Δm^2) ⇒ 46 d.o.f.

<u>LMA solution</u>: c^2 = 43.5; Dm^2 = 6.9x10^{-5} eV^2; q = 31.7° (BEST FIT)

<u>LOW solution</u>: c^2 = 52.5; Dm^2 = 7.2x10^{-8} eV^2; q = 39.1°

Dc^2 = 9; Prob(Dc^2 ³ 9) = 1.1% (marginally acceptable)

The present interpretation of all solar neutrino data using three-neutrino mixing



<u>Note</u>: variable $\tan^2\theta_{12}$ is preferred to $\sin^2 2\theta_{12}$ because $\sin^2 2\theta_{12}$ is symmetric around θ_{12} = 45° and MSW solutions are possible only if θ_{12} < 45°

Conclusions solar neutrinos

- ✓ The “solar neutrino problem” has been studied by using different experimental technique
  - the measured flux is smaller than expected from SSM
- ✓ The SSM seems to work well
- ✓ The recent SNO data give a strong evidence for ν_e oscillations into active neutrinos
- ✓ The SMA solution is strongly disfavoured
- ✓ What next?

The link between Solar and Reactor neutrinos

While atmospheric (SK) and K2K bounds on (Δm^2_{23}, θ_{23}) can be studied well in the 2ν approximation, a 3ν analysis is mandatory for reactor experiments:

$P_{ee}^{Reactor} = P_{ee}^{Reactor}(\Delta m^2_{12}, \theta_{12}, \theta_{13}, \Delta m^2_{23})$ survival ν_e probability

In practice, Δm^2_{23} is marginalized away in the χ^2 construction, by adding the "atmospheric + K2K" likelihood

Therefore, "solar and reactor" data are linked through the parameters

$$(\Delta m^2_{12}, \theta_{12}, \theta_{13})$$

Caveat

From the Sun we get neutrinos

From reactors we get anti-neutrinos

↓

There is a link only if CPT is true

Verification of the LMA solution using antineutrinos from nuclear reactors

Nuclear reactors: intense, isotropic sources of $\bar{n}_e$ from b decay of neutron-rich fission fragments

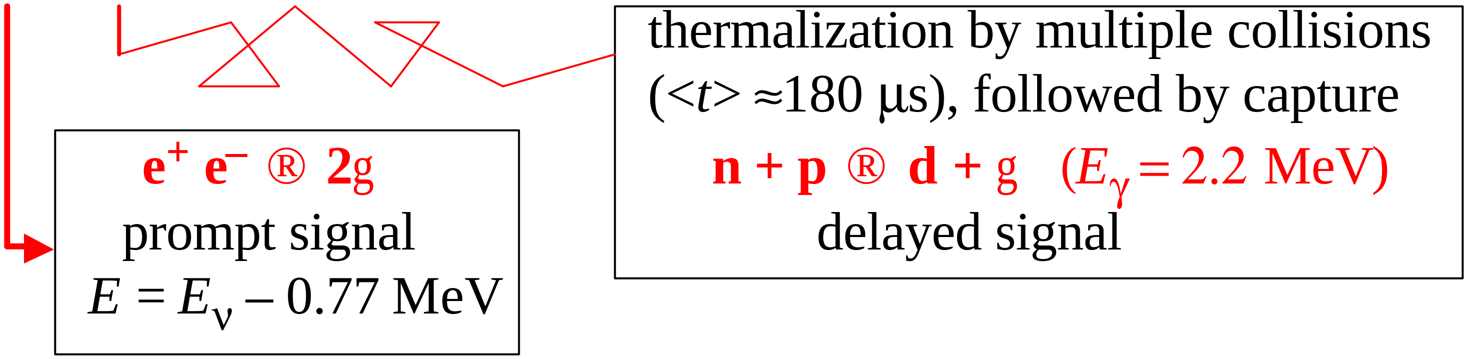
$\bar{n}_e$ production rate: $1.9\text{x}10^{20}$ P_{th} s^{-1} (P$_{th}$ [GW]: reactor thermal power)

Broad energy spectrum extending to 10 MeV, <E> » 3 MeV

Uncertainty on the expected $\bar{n}_e$ flux: ±2.7 %

Detection:

$\bar{n}_e$ + p ® e^+ + n (on the free protons of hydrogen – rich liquid scintillator)

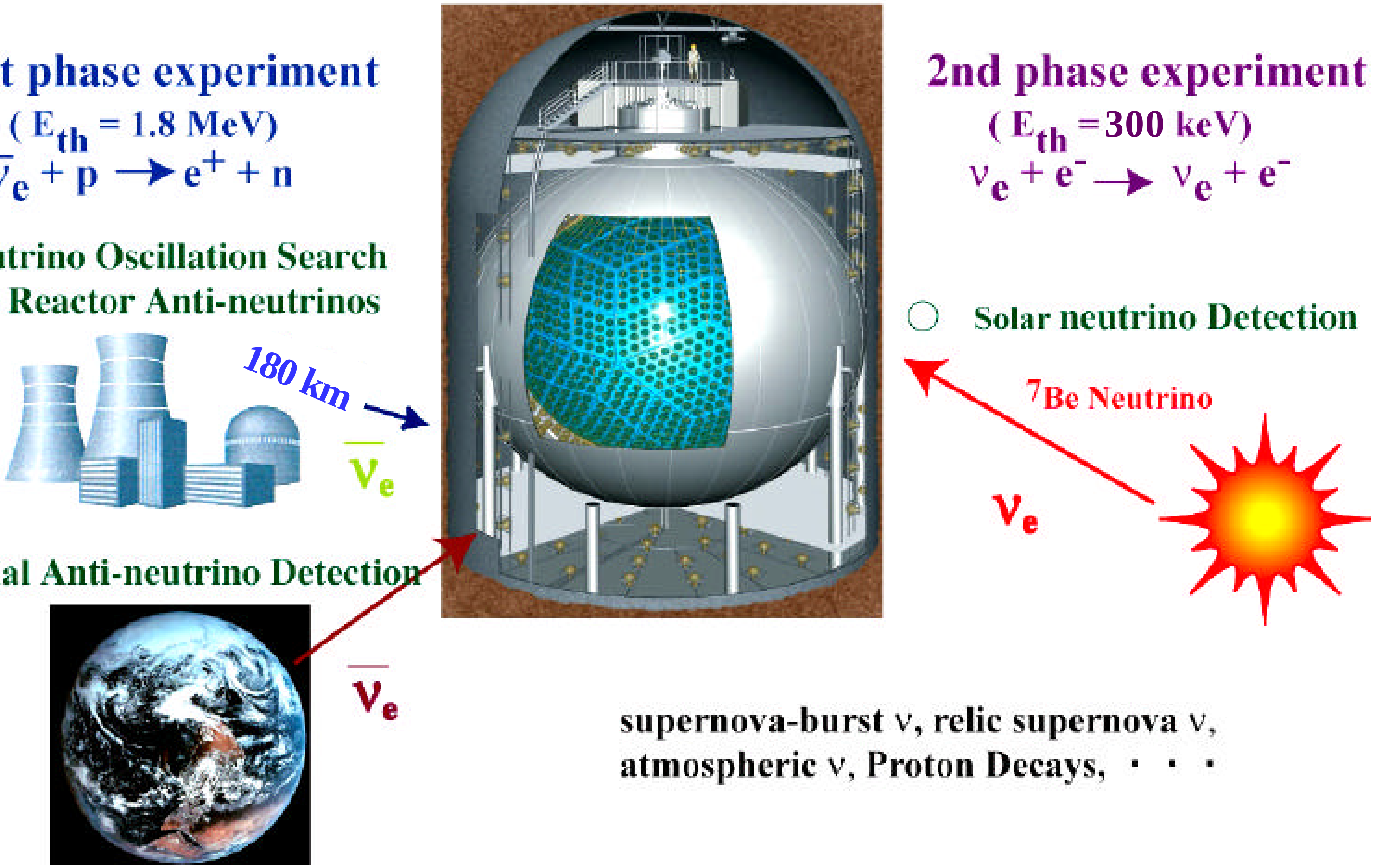


e^+ e^- ® 2g
prompt signal
$E = E_\nu - 0.77$ MeV

thermalization by multiple collisions (<t> ≈180 µs), followed by capture
n + p ® d + g ($E_\gamma = 2.2$ MeV)
delayed signal

The KamLand experiment

1,000 ton liquid scintillator neutrino detector



1st phase experiment

(E_{th} = 1.8 MeV)

$\bar{\nu}_e + p \rightarrow e^+ + n$

○ Neutrino Oscillation Search by Reactor Anti-neutrinos

○ Terrestrial Anti-neutrino Detection

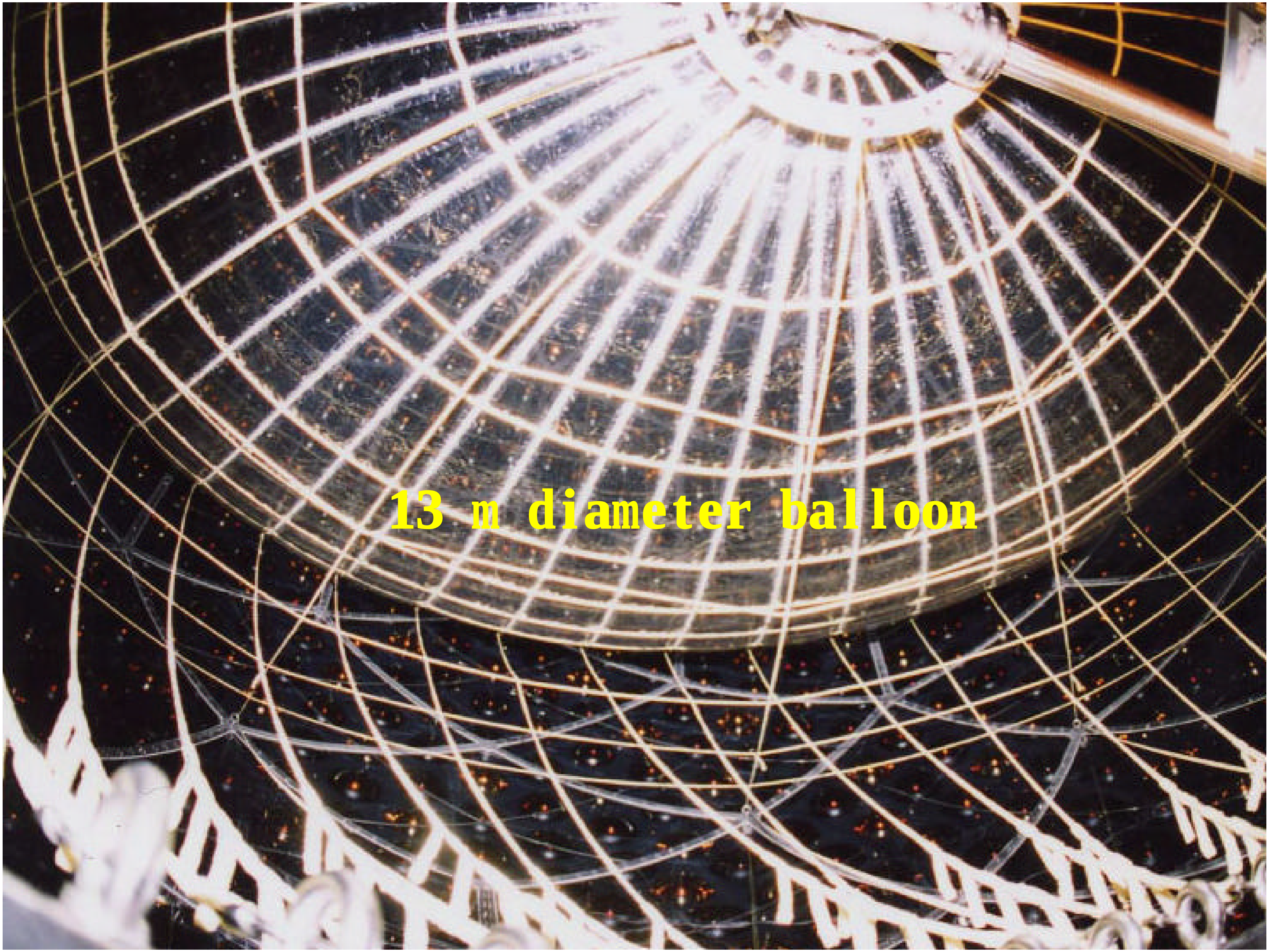
2nd phase experiment

(E_{th} =300 keV)

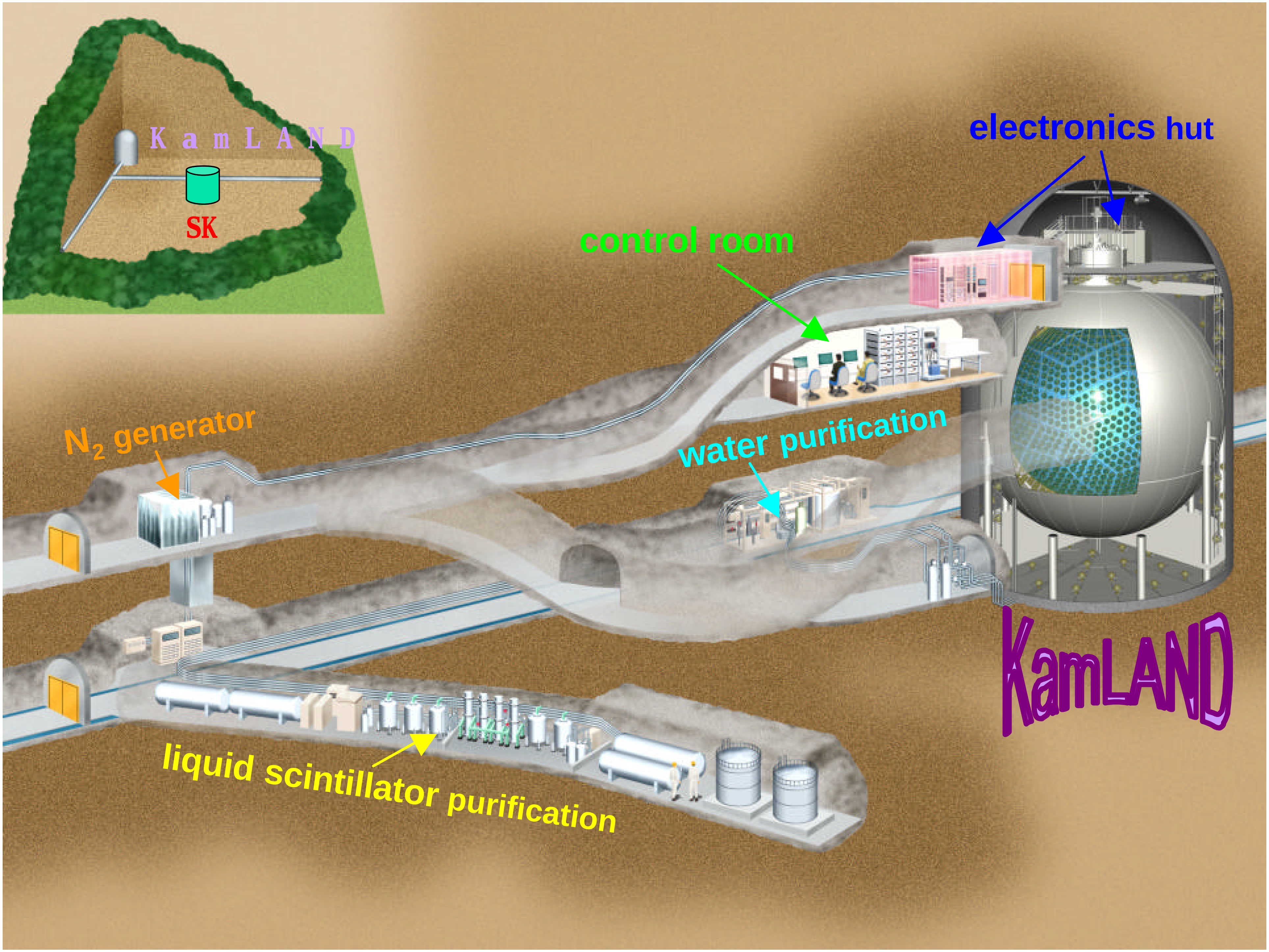
$\nu_e + e^- \rightarrow \nu_e + e^-$

○ Solar neutrino Detection

supernova-burst ν, relic supernova ν,
atmospheric ν, Proton Decays, · · ·

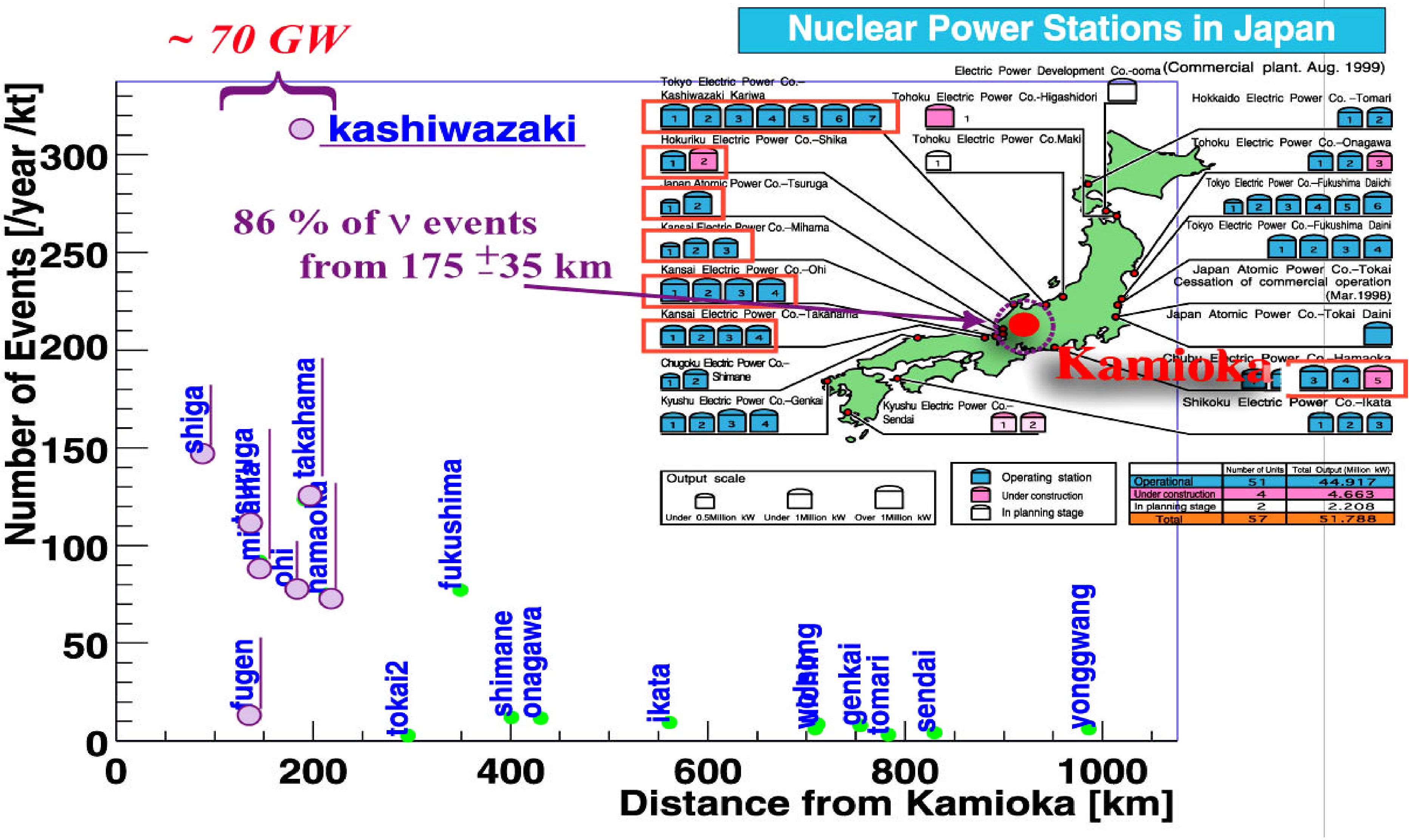


13 m diameter balloon


KamLAND
SK
electronics hut
control room
N_2 generator
water purification
liquid scintillator purification
KamLAND

20 % of world nuclear power

~ 70 GW



	Number of Units	Total Output (Million kW)
Operational	51	44.917
Under construction	4	4.663
In planning stage	2	2.208
Total	57	51.788

86 % of ν events from 175 ± 35 km

Geoneutrinos

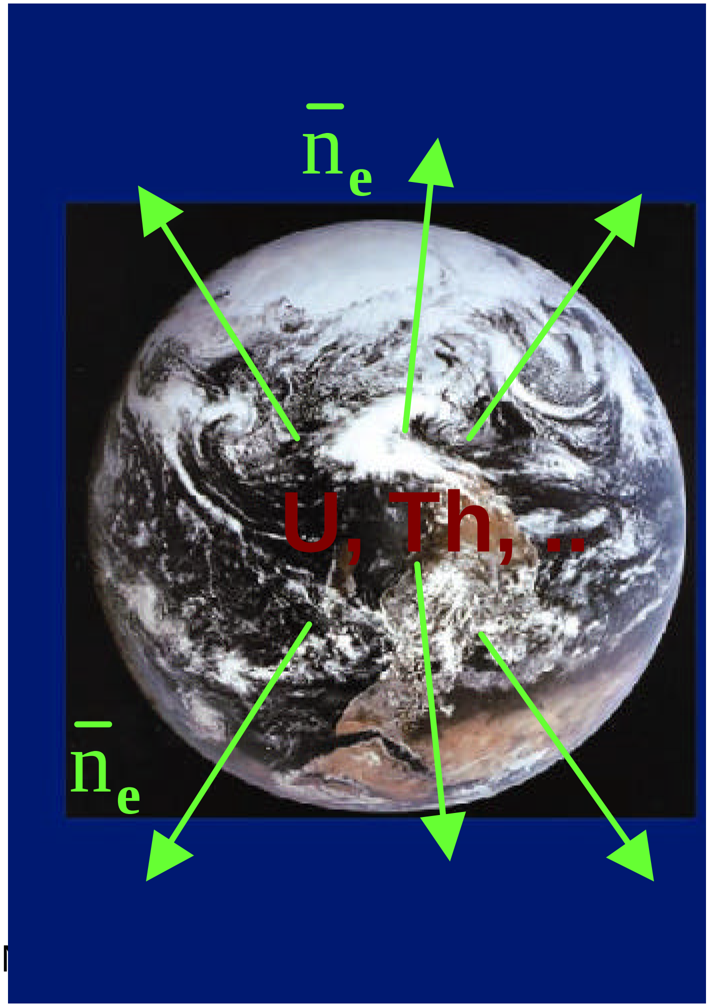
Earth is Anti-Neutrino Star

? ?

Radiogenic Heat (40-60 % of 40 TW) from U/Th (Crust, Mantle) Decays

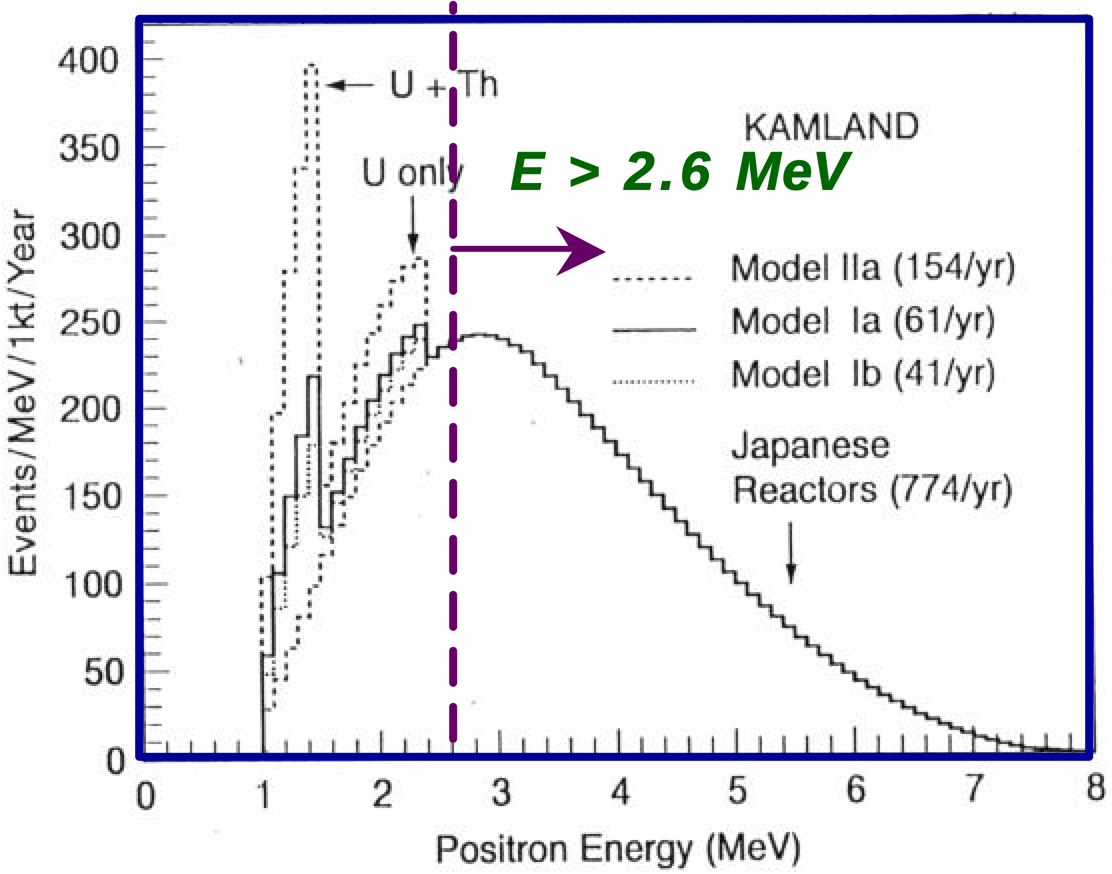
Basic Factor in Interior Dynamics and History of the Present Earth

$\bar{\nu}_e$ detection : new telescope



Geoneutrino Energy Spectra

PRL **80** (1998)635



Radioactivity inside Liquid Scintillator

$$^{238}\mathrm{U} : {}^{214}\mathrm{Bi} \xrightarrow[\beta+\gamma]{} {}^{214}\mathrm{Po} \xrightarrow[\alpha]{} {}^{210}\mathrm{Pb}$$

$E = 3.27\ MeV$ $\quad$ $E = 7.69\ MeV$

$\tau = 28.7\ min.$ $\quad$ $\tau = 237\ \mu s$

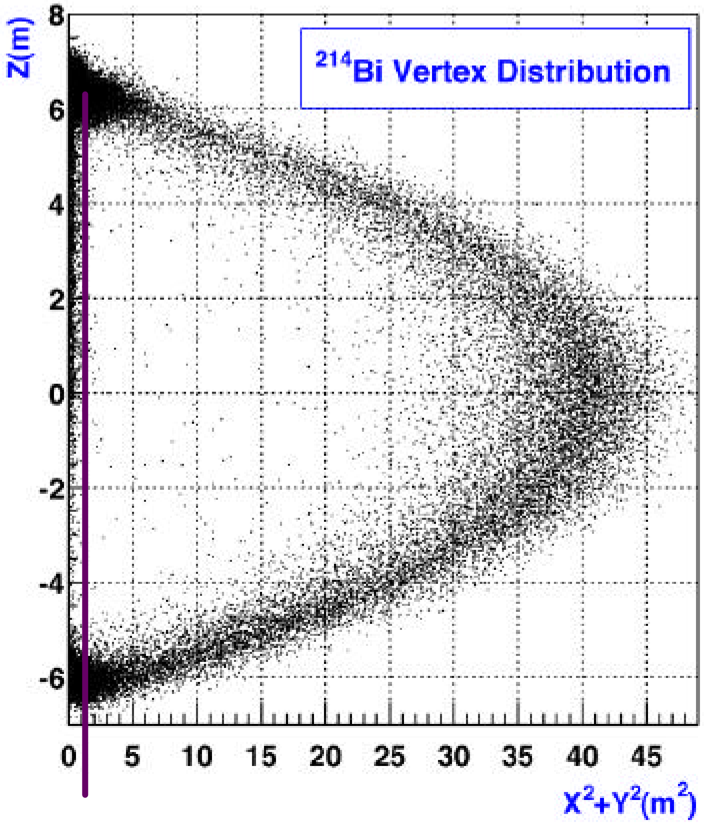
event selection

$\Delta R < 100\ cm$

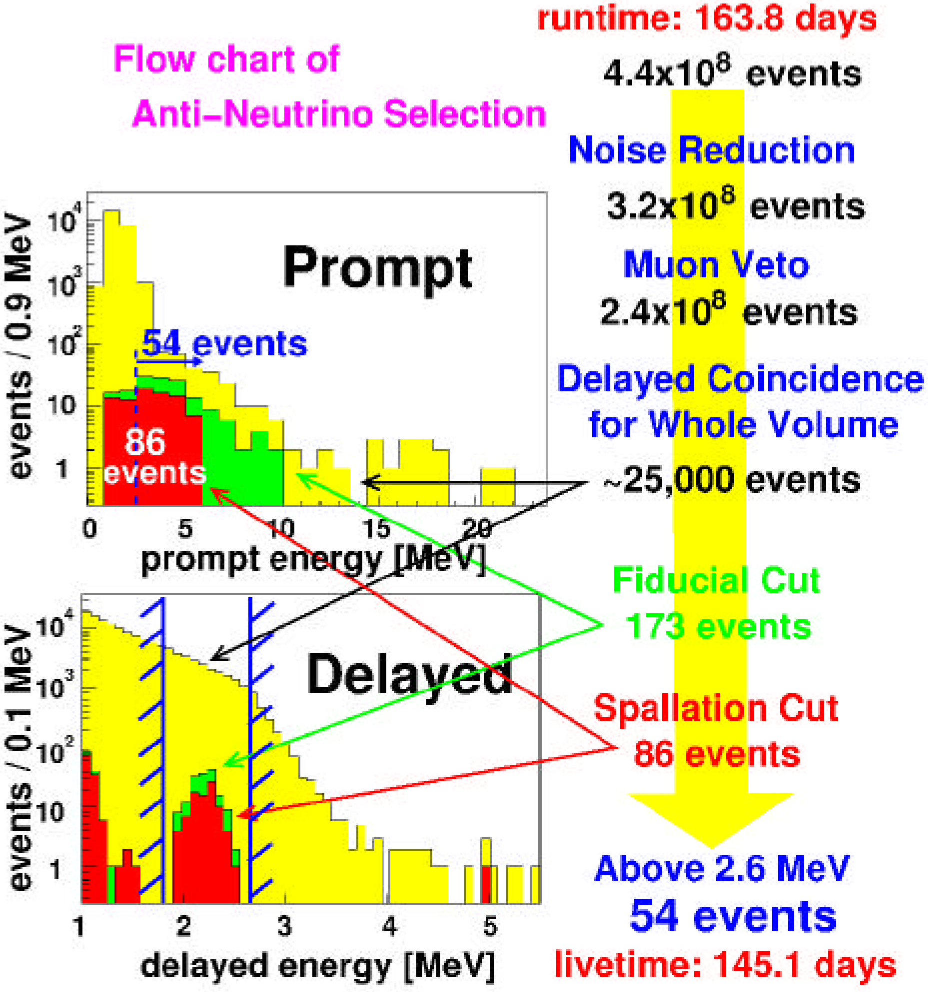
$5\ \mu s < \Delta t < 1000\ \mu s$

$E_{prompt} > 1.3\ MeV$

$0.3 < E_{delayed} < 1\ MeV$



Neutrino Event selection



runtime: 163.8 days

4.4×10^8 events

Noise Reduction

3.2×10^8 events

Muon Veto

2.4×10^8 events

Delayed Coincidence for Whole Volume

~25,000 events

Fiducial Cut

173 events

Spallation Cut

86 events

Above 2.6 MeV

54 events

livetime: 145.1 days

Details

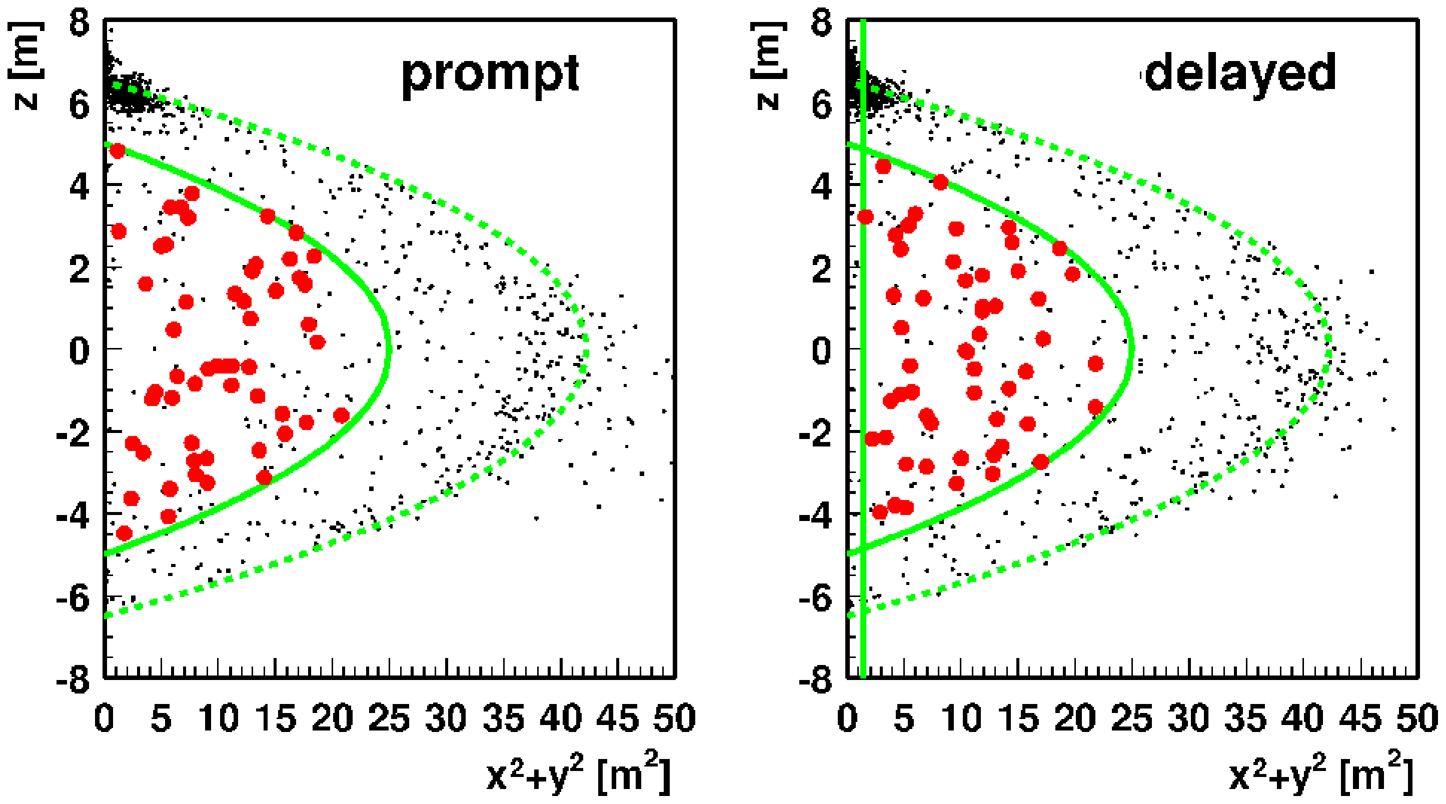
- **Timing correlation in PMTs**
- **no μ veto signals**
- **$0.5 < \Delta T < 660$ μsec**
- **$1.8 < E_{delayed} < 2.6$ MeV**

- **R < 5 m : 409 ton, 3.46×10^{31} free protons**
- **$\Delta R < 1.6$ m, $R_d > 1.2$ m**

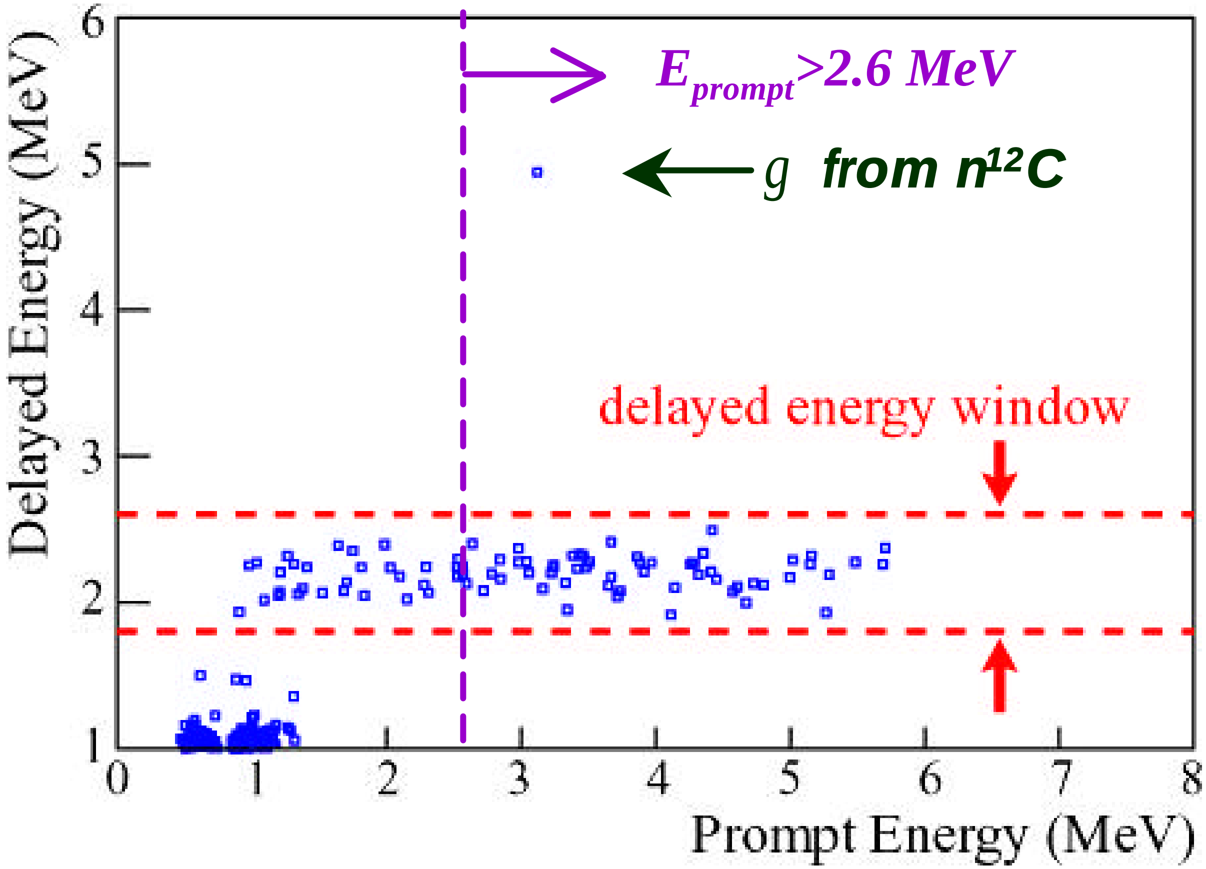
- **Veto for 2msec. after muons.**
- **Veto for 2sec. after muons ($E>10^6$p.e.) (0.02Hz)**
- **Cylindrical (R=3m) 2sec veto around muons ($E<10^6$p.e.)**

⇒ **tagging efficiency 78.3%**

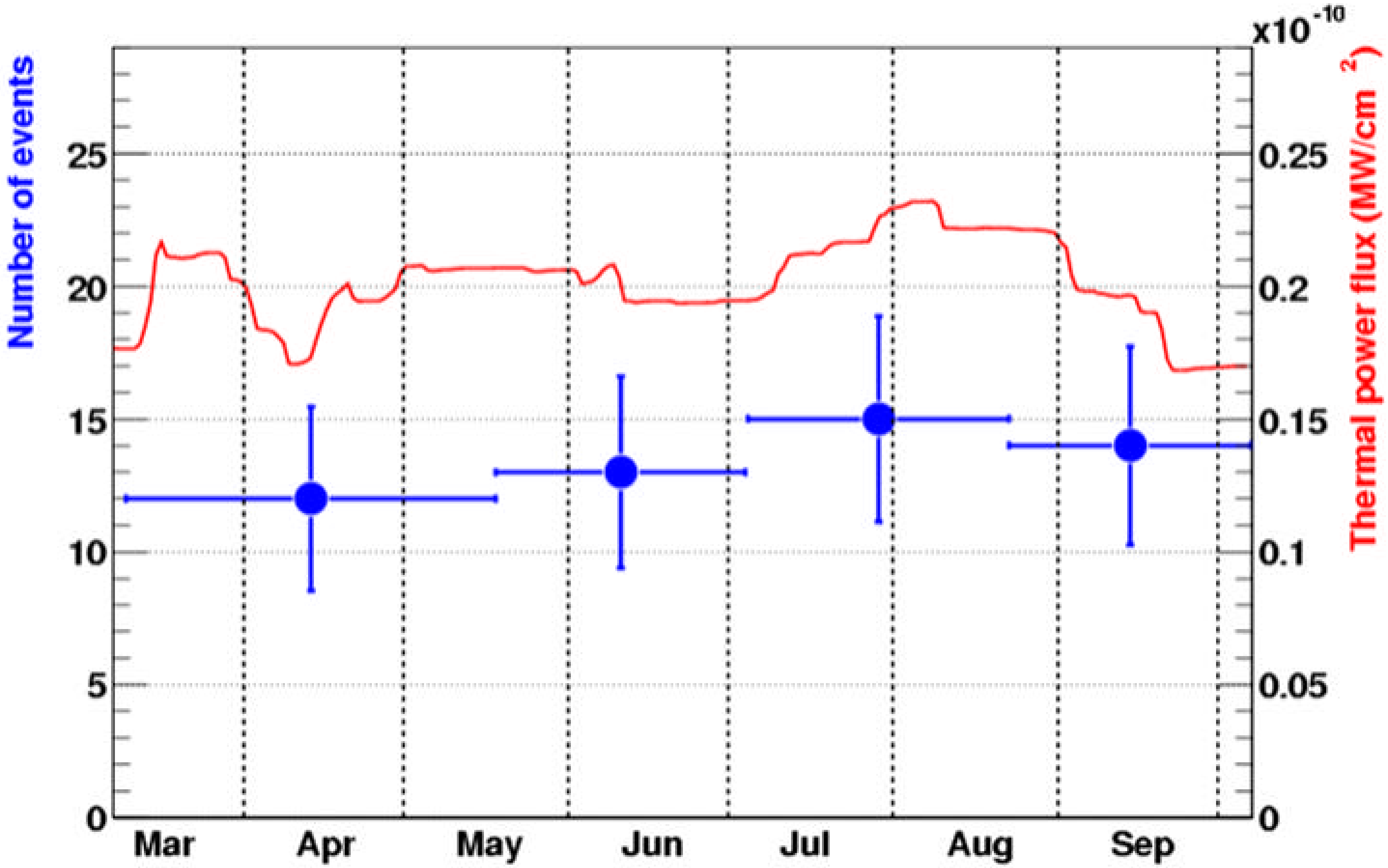
Vertex position after delayed coincidence



Scatter Plot of Prompt and Delayed Energies



Time Variations of Reactor Power and Signals



2002

Observed Event Rates

Final sample

162 ton•yr, $E_{prompt} > 2.6$ **MeV**

54 ev

Expected **86.8 ± 5.6 eV**

Background **0.95 ± 0.99 ev**

accidental	0.0086 ± 0.0005
^{9}Li/^{8}He (b, n)	0.94 ± 0.85
fast neutron	0 ± 0.5

Evidence for Reactor $\bar{n}_e$ Disappearance

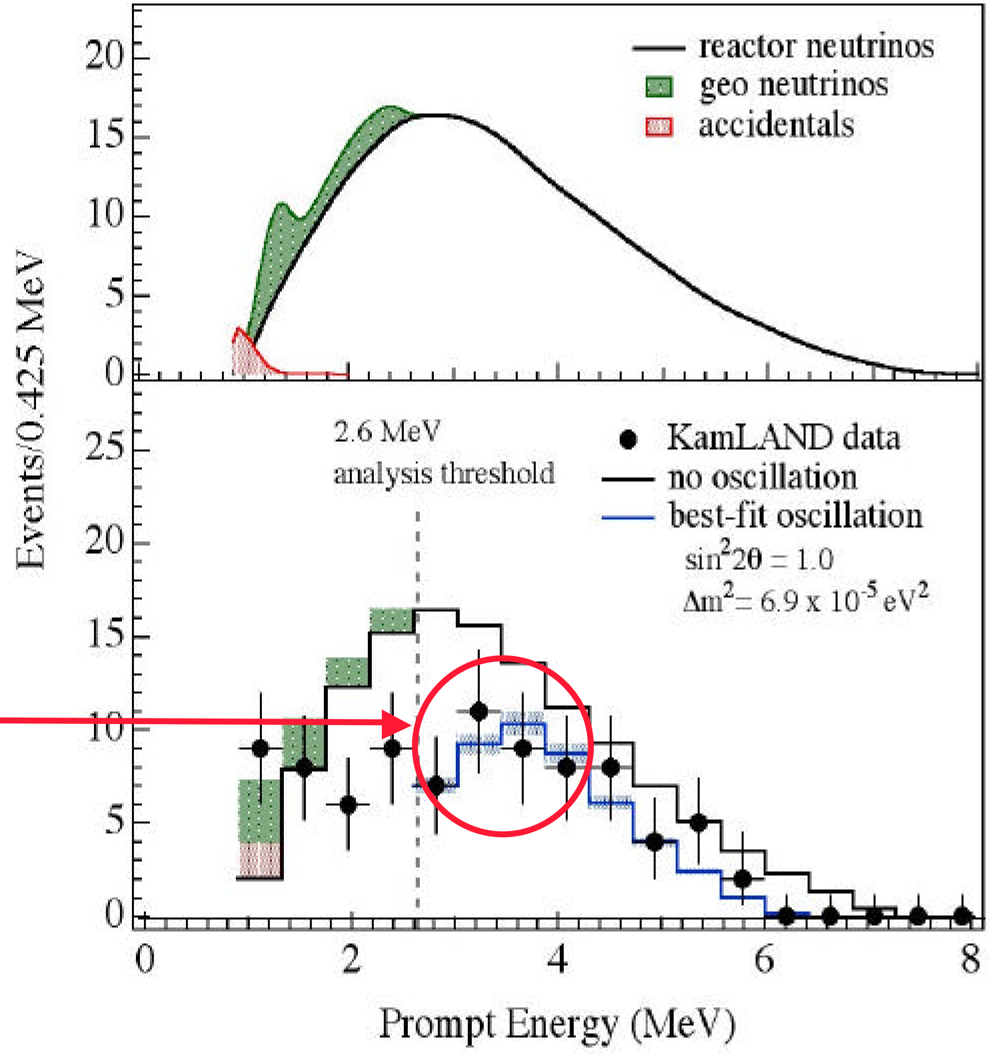
$$\frac{N_{obs} - N_{BG}}{N_{expected}} = 0.611 \pm 0.085\ (\mathrm{stat}) \pm 0.041\ (\mathrm{syst})$$

99.95 % C.L.

The KamLAND data

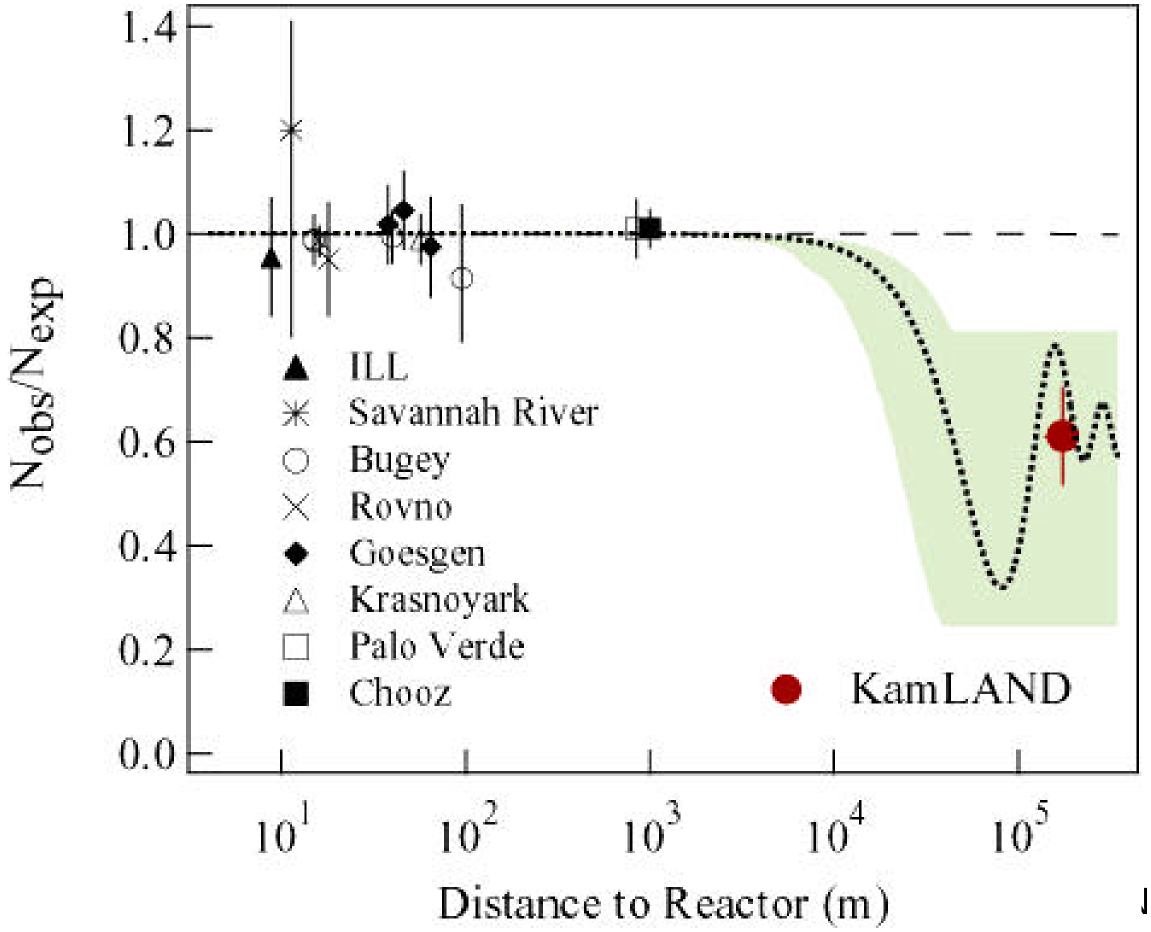
- The KamLAND total rate singles LMA out
- The KamLAND spectrum fixes the LMA sub-structure:

Above the analysis threshold (2.6 MeV) the “bulk” of the spectrum (first 4 bins above threshold) seems more suppressed than the “tail”



Ratio of Measured to Expected ν_e Flux from Reactor Neutrino Experiments

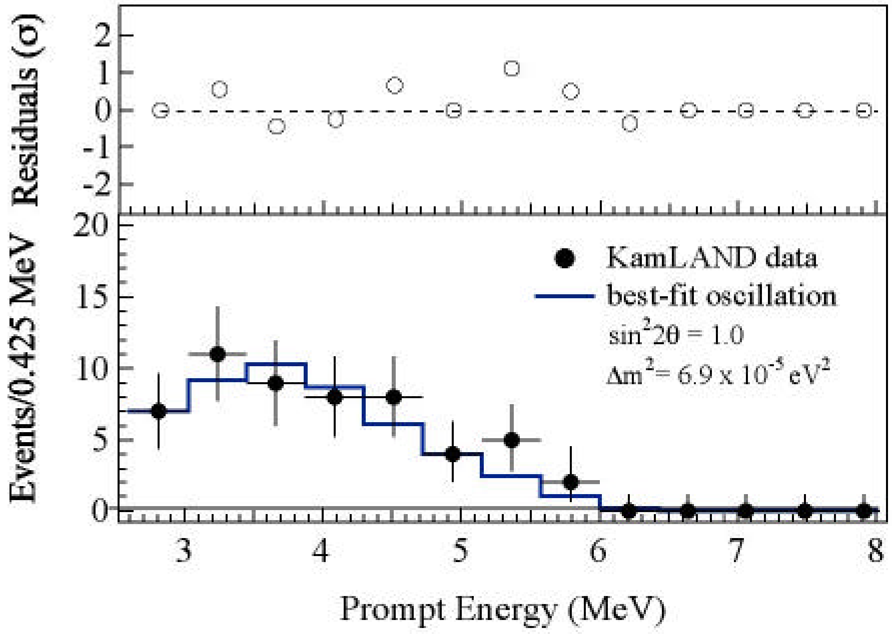
Continuous line is the expected value for $\Delta m^2 = 5.5\text{x}10^{-5}\text{eV}^2$ $\sin^2 2\theta_{12}=0.833$



G.Fogli et al.,
PR D66, 010001-406, (2002)

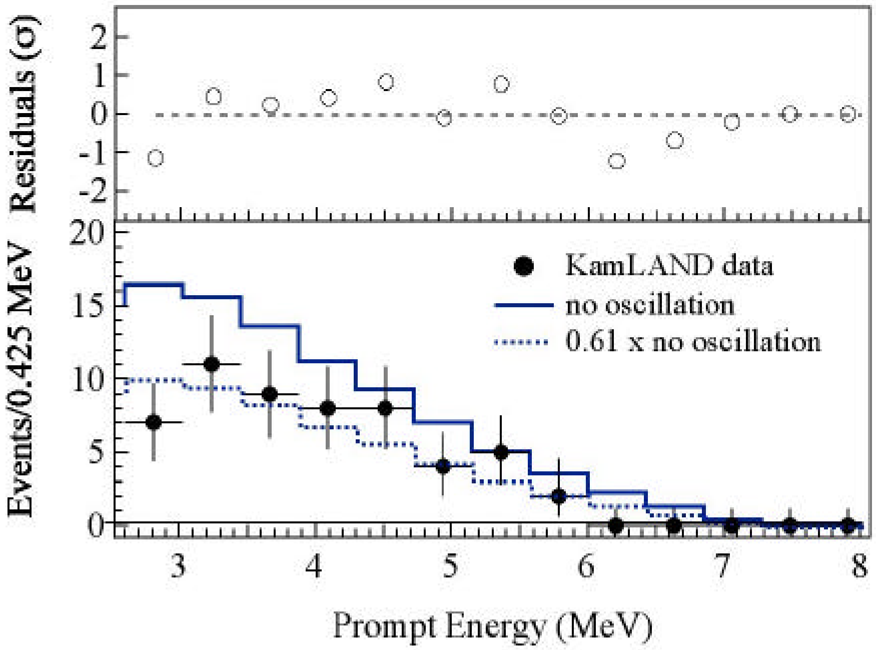
Spectral Distortion?

2-ν oscillation: best-fit



Data and best oscillation fit consistent at 93% C.L.

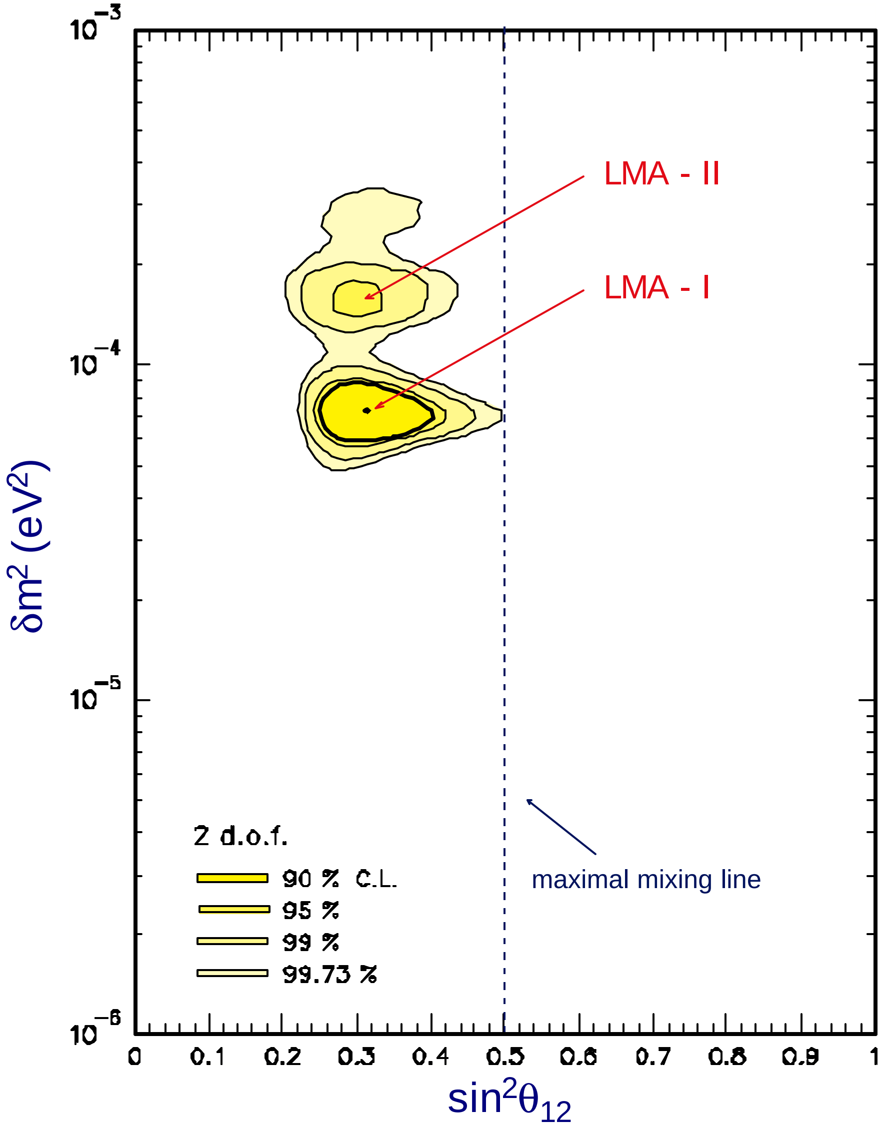
No oscillation, flux suppression



Data and scaled no-oscillation shape consistent at 53% C.L

Need more reactor neutrino and calibration data

Impact of solar and reactor neutrinos



Taking LMA-I as the reference solution, we can extract the following ±1σ estimate for the relevant solar 3ν parameters:

LMA-I solution (~1σ)

$$\begin{cases} \delta m^2 \approx (7.3 \pm 0.8) \text{x } 10^{-5}\ \text{eV}^2 \\ \sin^2 \theta_{12} \approx 0.315 \pm 0.035 \\ \sin^2 \theta_{13} \leq 0.017 \end{cases}$$

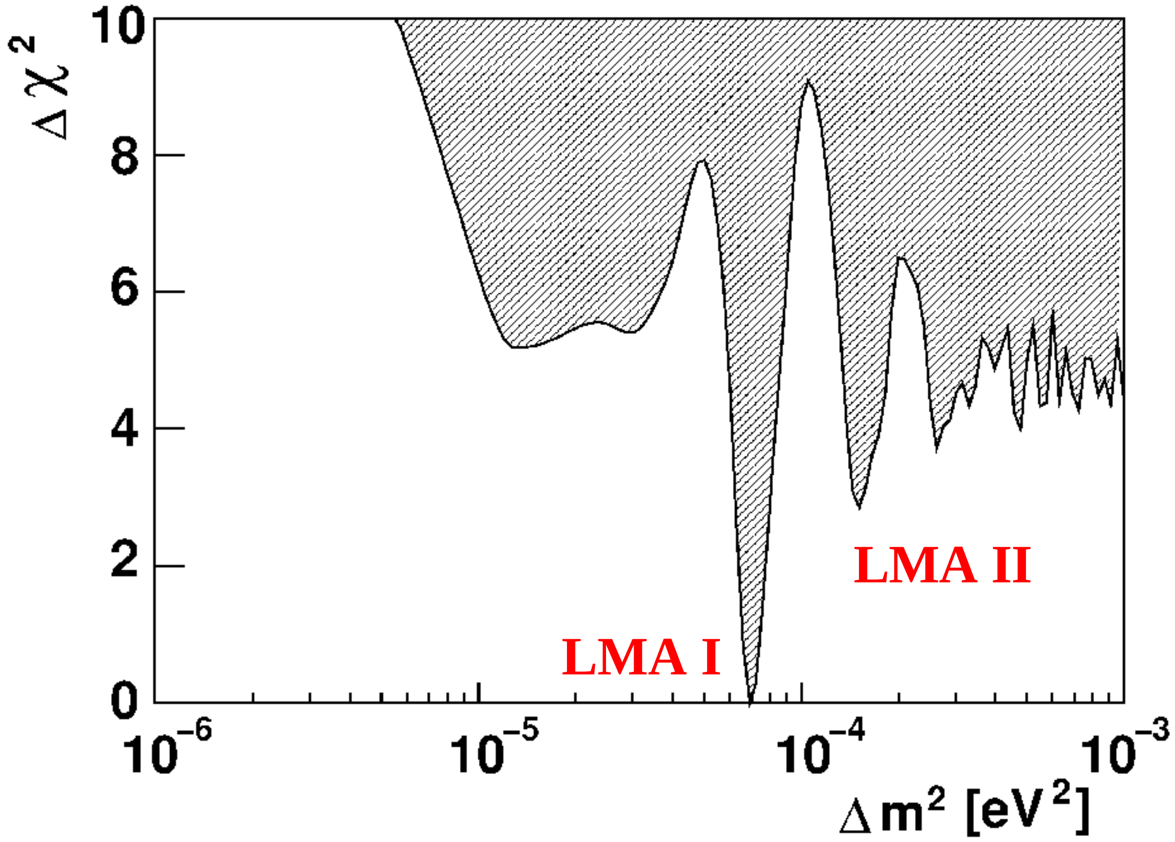
This is one of the conditions to fulfilled to make CP detectable in the leptonic sector

KamLAND Prospects

- ✓ Neutrino Oscillation? Precision measurements
  - Energy Spectrum distortion?
  - Current reactor power in Japan ~50%.
  - A new reactor is coming.
  - LMA 1 or LMA2

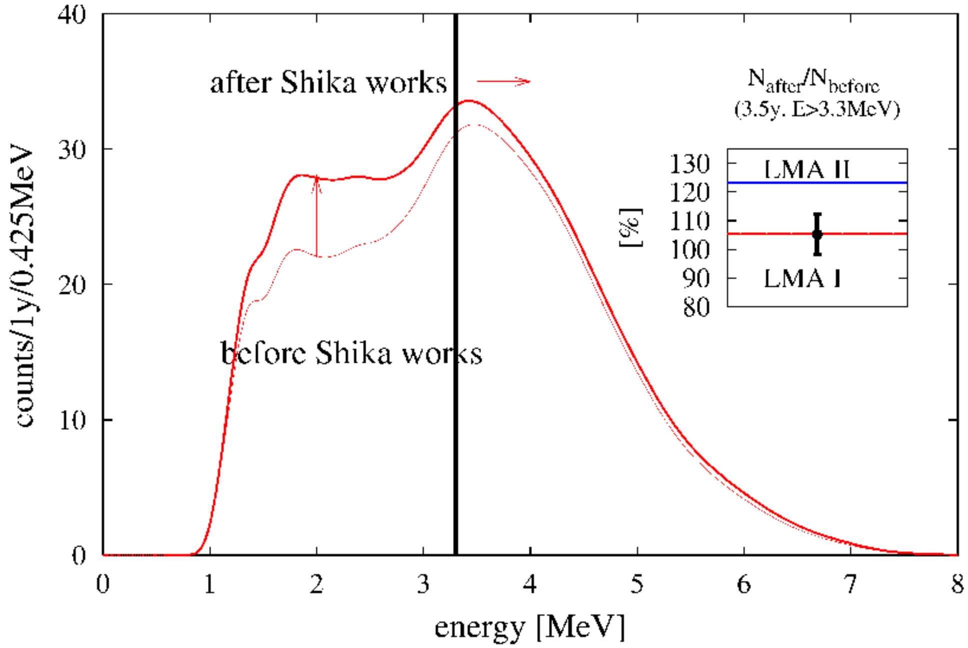
- ✓ ^{7}Be
  - Purification system improvement

χ^2 projection

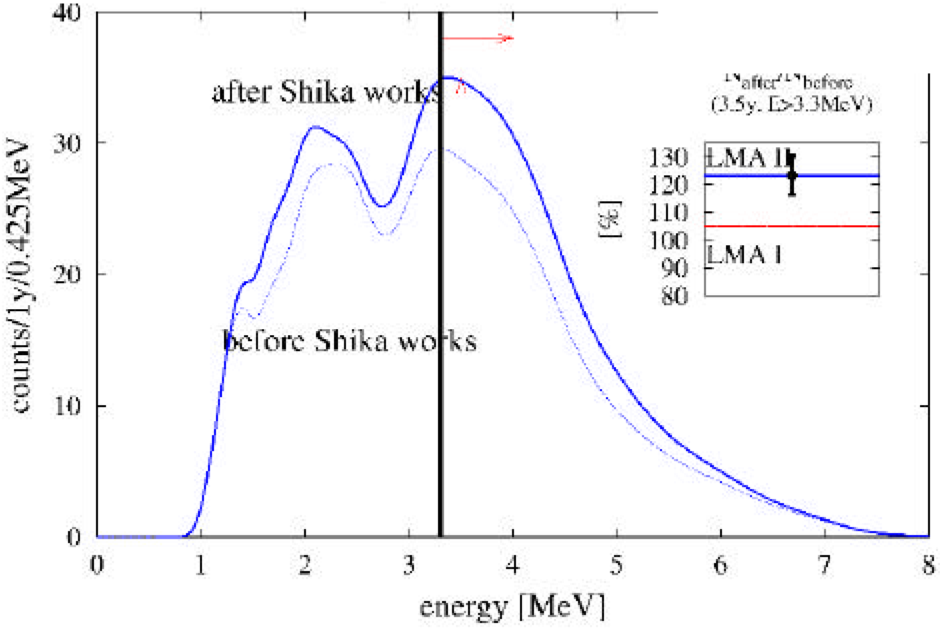


Before and After Shika

LMA I $(\sin^2 2\theta=0.84,\ \Delta m^2=7.0\text{x}10^{-5}[eV^2])$



LMA II $(\sin^2 2\theta=0.84,\ \Delta m^2=1.4\text{x}1$



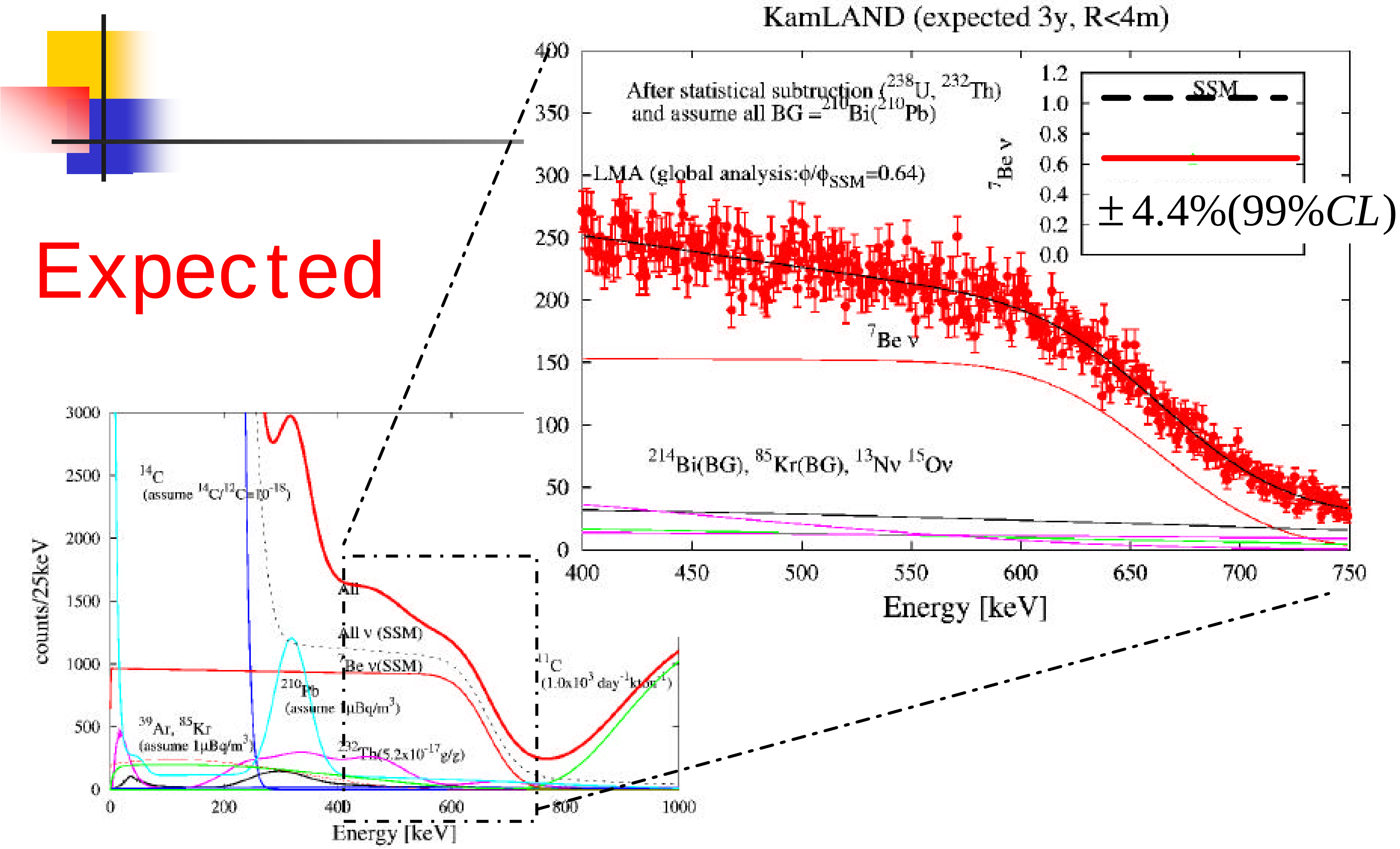
Solar ν @ KamLAND

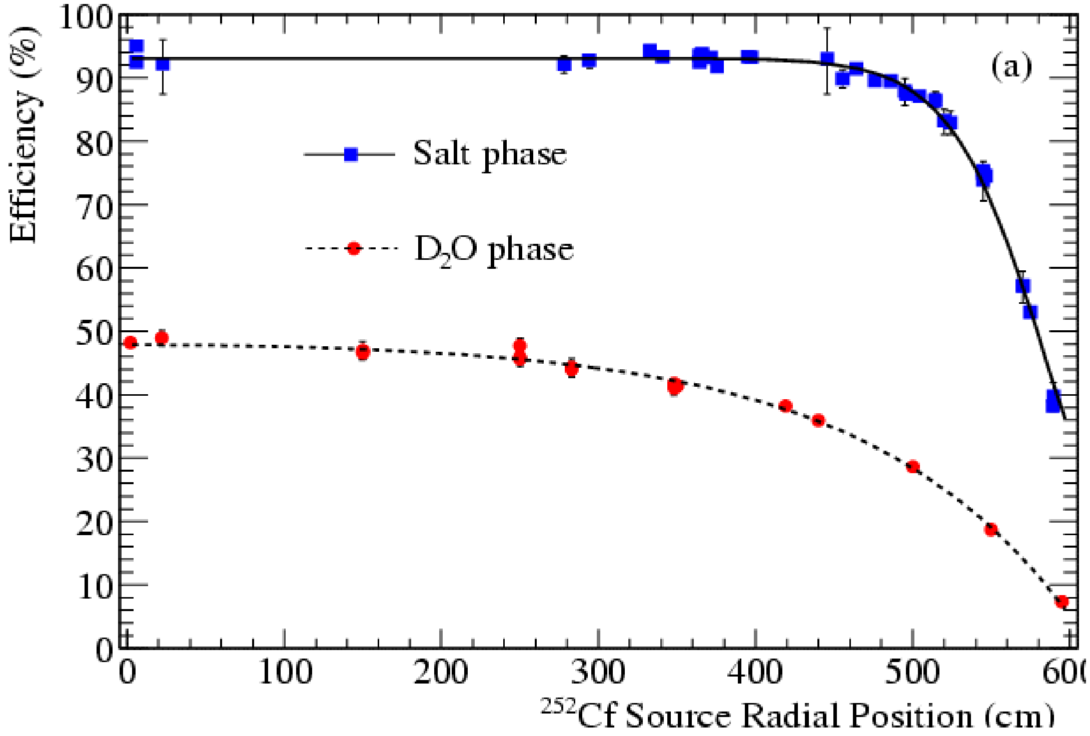
- No direct observation of ^{7}Be ν.

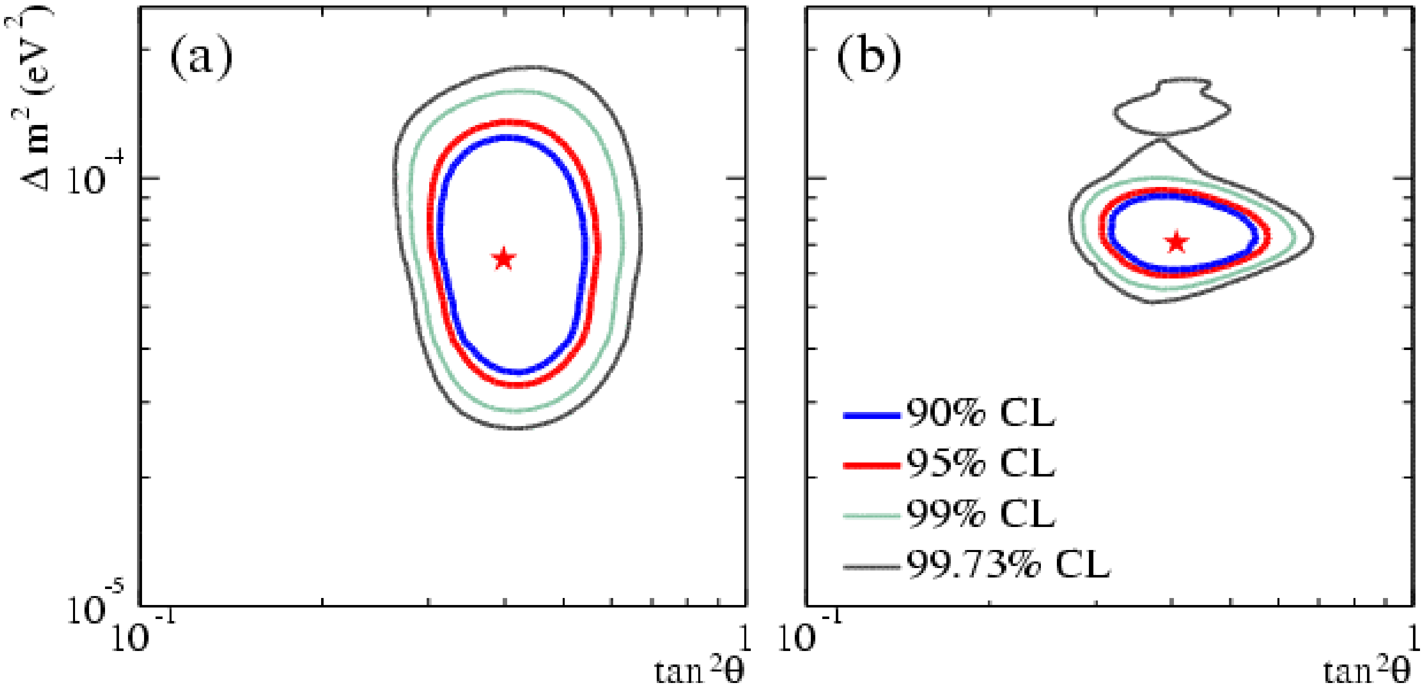
- Improve KamLAND purification system.
- ^{210}Pb; 10^{-20} g/g → 10^{-25} g/g (Water extraction)

- Air tight valve housings.
- Testing the water extraction.

Expected


KamLAND (expected 3y, R<4m)
After statistical subtruction (^{238}U, ^{232}Th)
and assume all BG = ^{210}Bi(^{210}Pb)
LMA (global analysis:φ/φ$_{SSM}$=0.64)
^{7}Be ν
^{214}Bi(BG), ^{85}Kr(BG), ^{13}Nν ^{15}Oν
Energy [keV]
400
450
500
550
600
650
700
750
0
50
100
150
200
250
300
350
400
^{7}Be ν
SSM
1.2
1.0
0.8
0.6
0.4
0.2
0.0
$\pm 4.4\%(99\%CL)$
counts/25keV
3000
2500
2000
1500
1000
500
0
0
200
400
600
800
1000
Energy [keV]
^{14}C
(assume ^{14}C/^{12}C=10^{-18})
All
All ν (SSM)
^{7}Be ν(SSM)
^{210}Pb
(assume 1μBq/m^3)
^{39}Ar, ^{85}Kr
(assume 1μBq/m^3)
^{232}Th(5.2x10^{-17}g/g)
^{11}C
(1.0x10^3 day^{-1}kton^{-1})


(a)
Efficiency (%)
0
10
20
30
40
50
60
70
80
90
100
Salt phase
D_2O phase
0
100
200
300
400
500
60
^{252}Cf Source Radial Position (cm)


(a)
(b)
$\Delta m^2 (eV^2)$
10^{-4}
10^{-5}
10^{-1}
1
$\tan^2\theta$
10^{-1}
1
$\tan^2\theta$
90% CL
95% CL
99% CL
99.73% CL