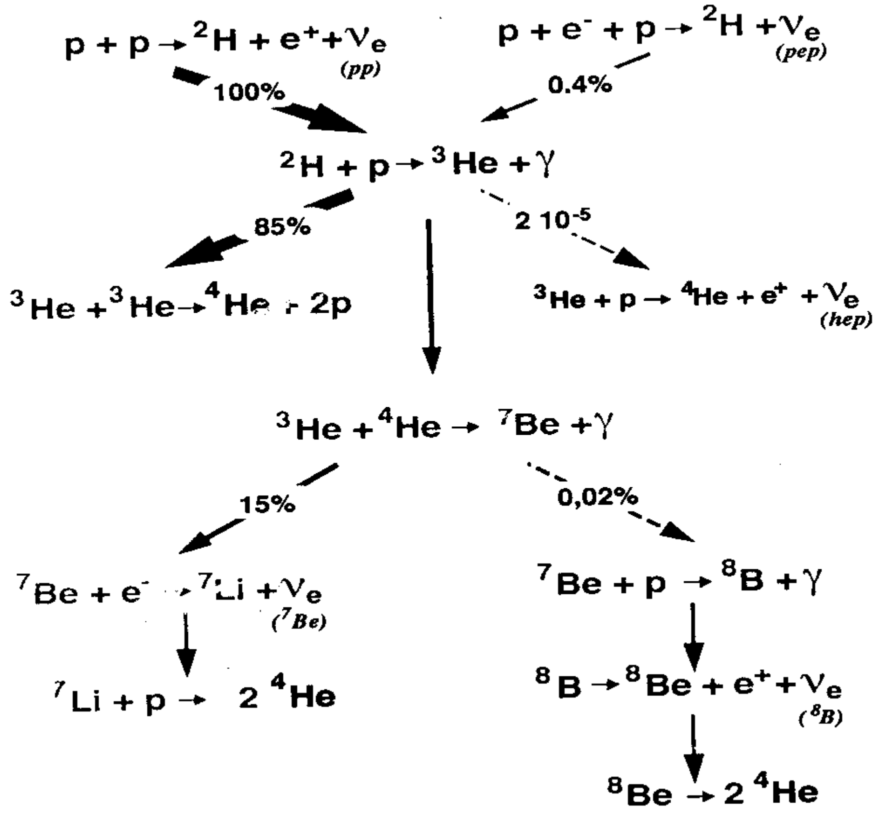
ISAPP 2003 Madonna di Campiglio

2

NEUTRINOS FROM THE SUN

J. BOUCHEZ
APC
CEA/DAPNIA



$p + p \rightarrow {}^2H + e^+ + \nu_e$ *(pp)*

100%

$p + e^- + p \rightarrow {}^2H + \nu_e$ *(pep)*

0.4%

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

85%

2 10^{-5}

${}^3He + {}^3He \rightarrow {}^4He + 2p$

${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$ *(hep)*

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

15%

0,02%

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

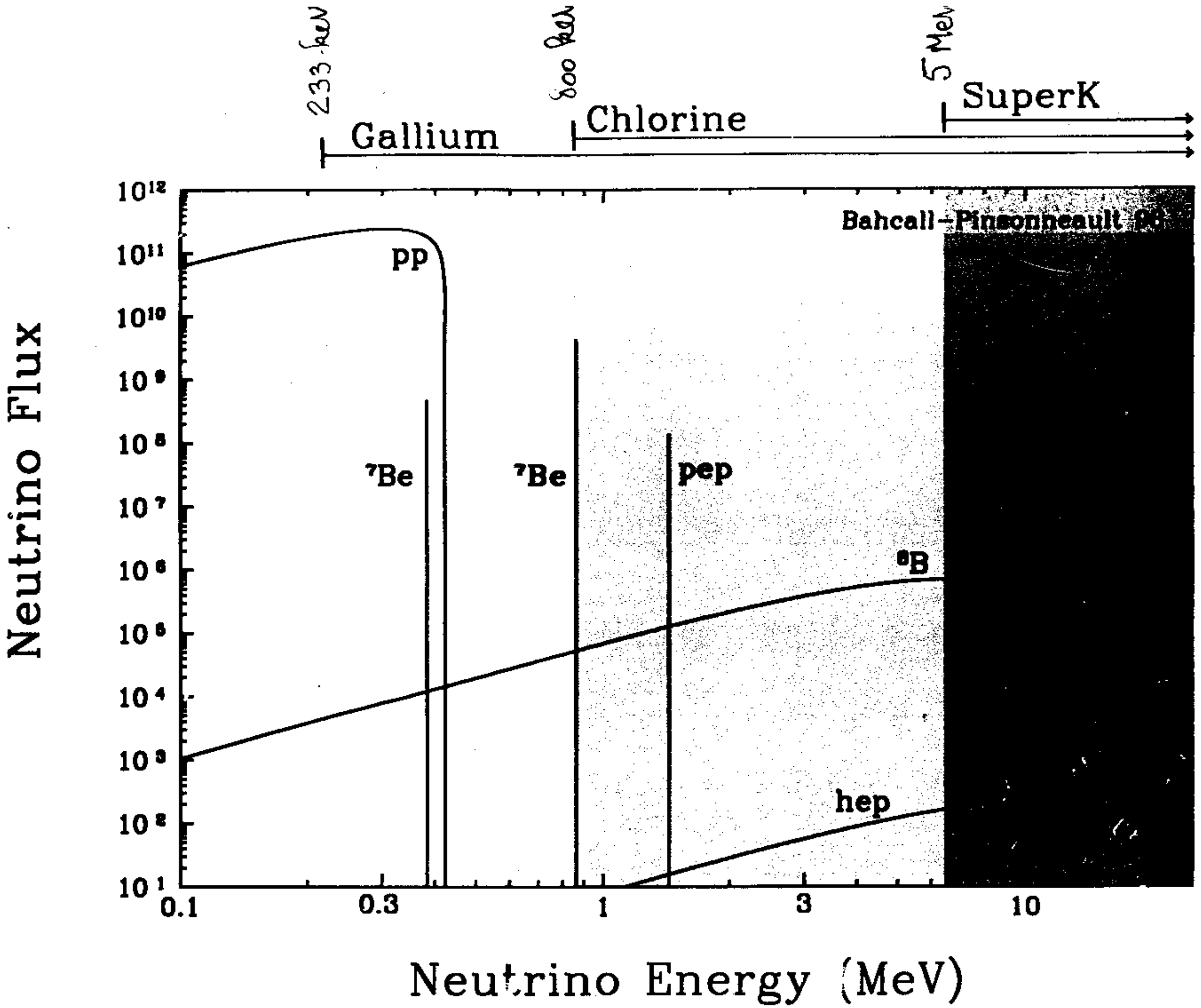
${}^7Li + p \rightarrow 2\,{}^4He$

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

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

${}^8Be \rightarrow 2\,{}^4He$

$$\boxed{4p + 2e^- \rightarrow {}^4He + 2\,\nu_e + 27\ \text{MeV}}$$



Solar neutrino energy spectrum

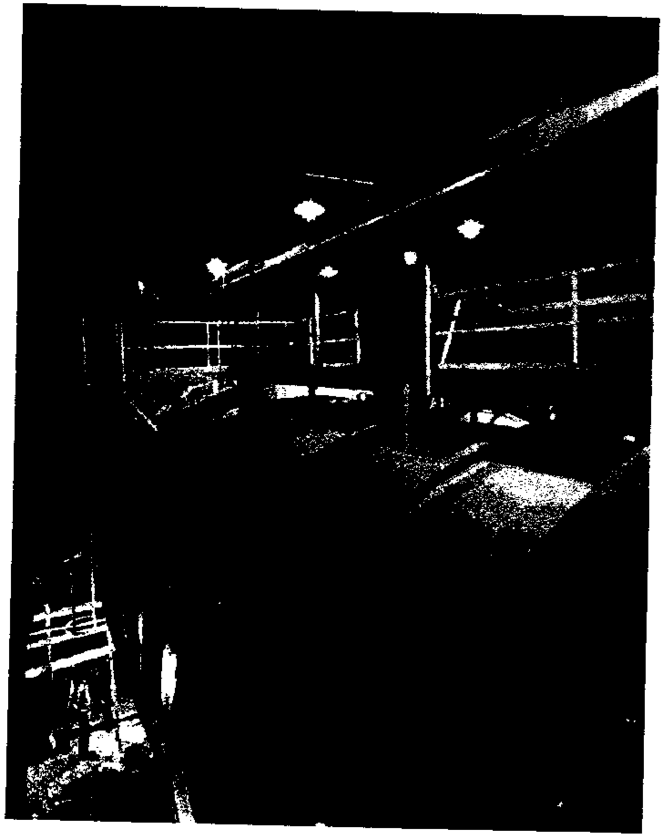
3 main components

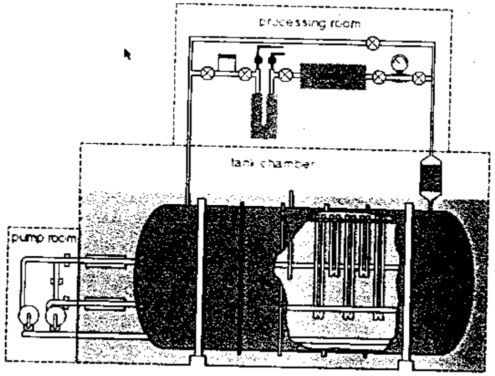
pp, <340 keV

Be^7, monochr.

B^8 up to 15 MeV

The Homestake detector (1968)





$400\ m^3$ of C_2Cl_4

$\nu_{sol} + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

^{37}Ar extracted every 45 days and decays observed in prop. counter

~ 1 atom produced/day!

Volume 20, Number 21 PHYSICAL REVIEW LETTERS 20 May 1968

PRESENT STATUS OF THE THEORETICAL PREDICTIONS FOR THE ^{37}Cl SOLAR-NEUTRINO EXPERIMENT*

John N. Bahcall† and Neta A. Bahcall‡
California Institute of Technology, Pasadena, California

and

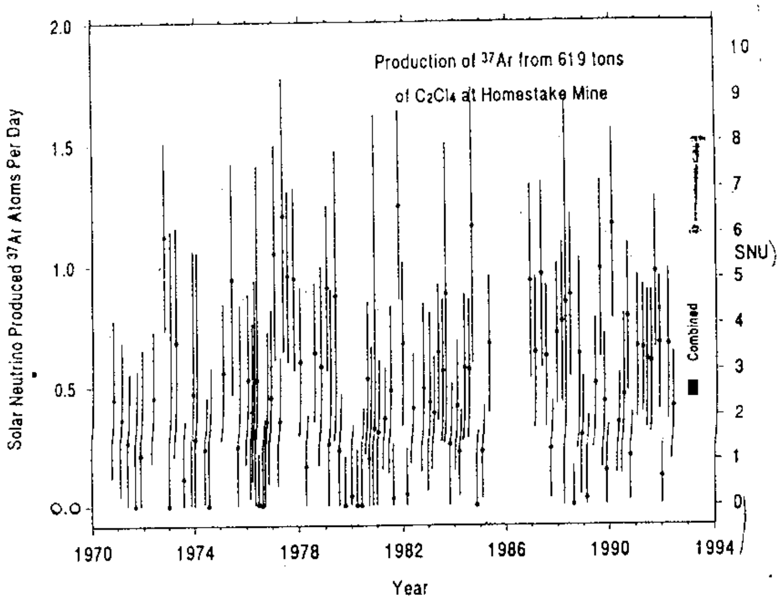
Giora Shaviv§
Cornell University, Ithaca, New York

(Received 8 April 1968)

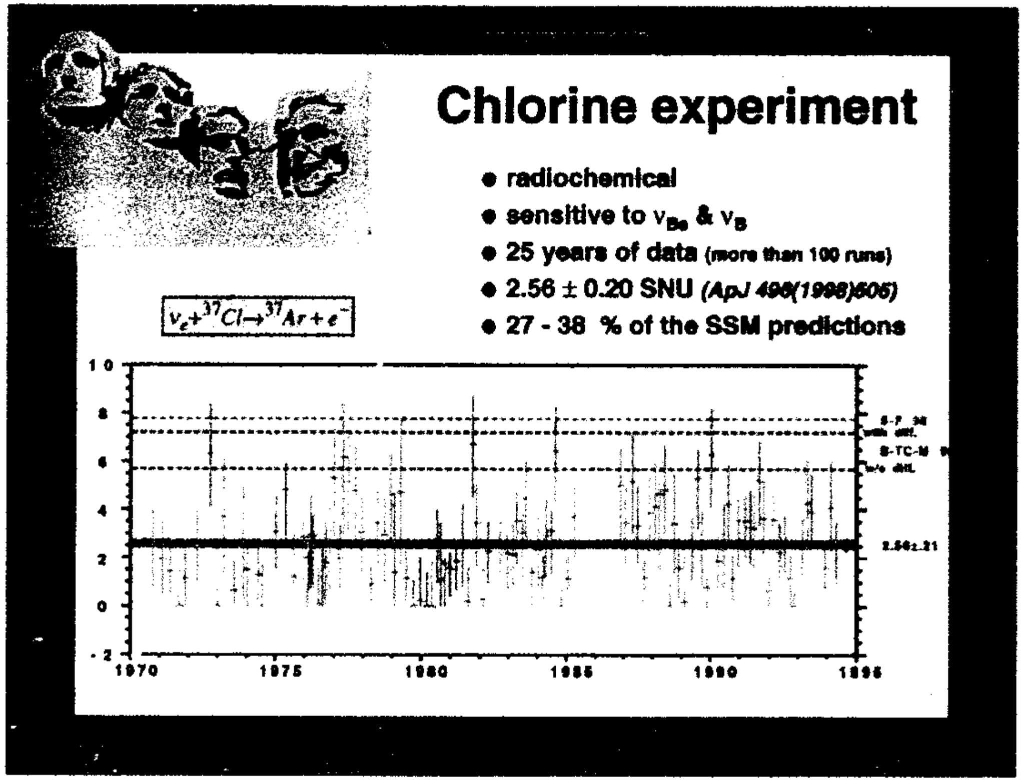
Bahcall Predicted 7.7 SNU [4.4, 11]
Davis (68) Observed < 3 SNU

1 SNU = 10^{-36} interact. per atom and per second

The solar neutrino problem is born...



... and still there in 1994



Chlorine experiment

- radiochemical
- sensitive to ν_{Be} & ν_B
- 25 years of data (more than 100 runs)
- 2.56 ± 0.20 SNU *(ApJ 496(1998)505)*
- 27 - 38 % of the SSM predictions

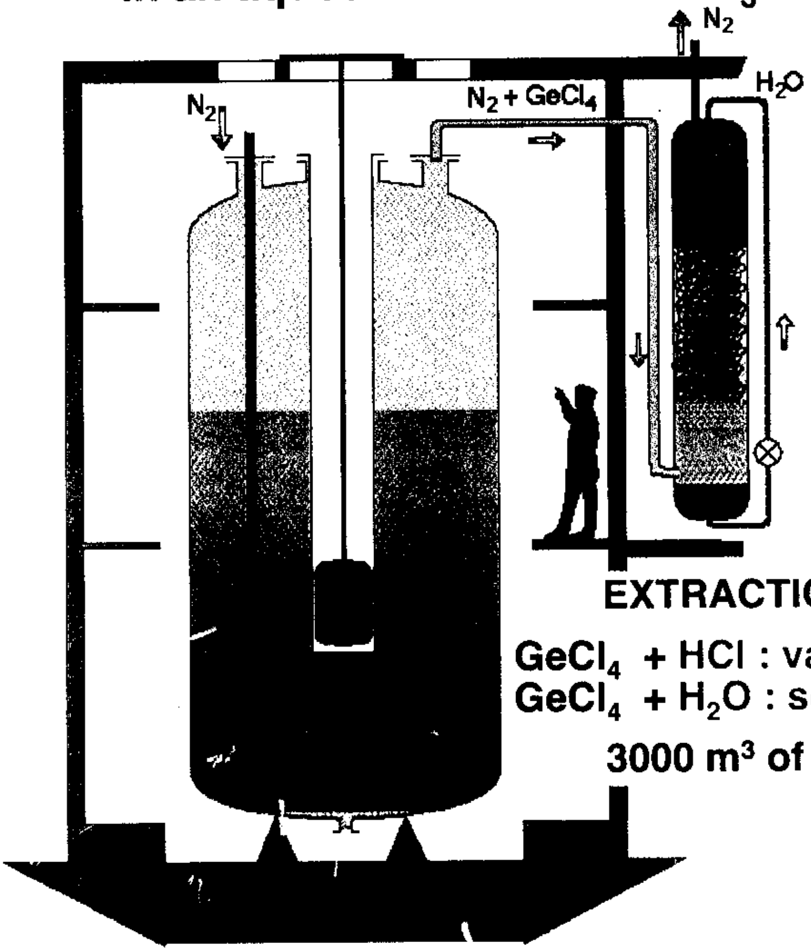
$\boxed{\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-}$

GALLEX

Experimental scheme

$\boxed{\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-}$

30.3 tons of Gallium
in an aqueous solution : $GaCl_3$ + HCl



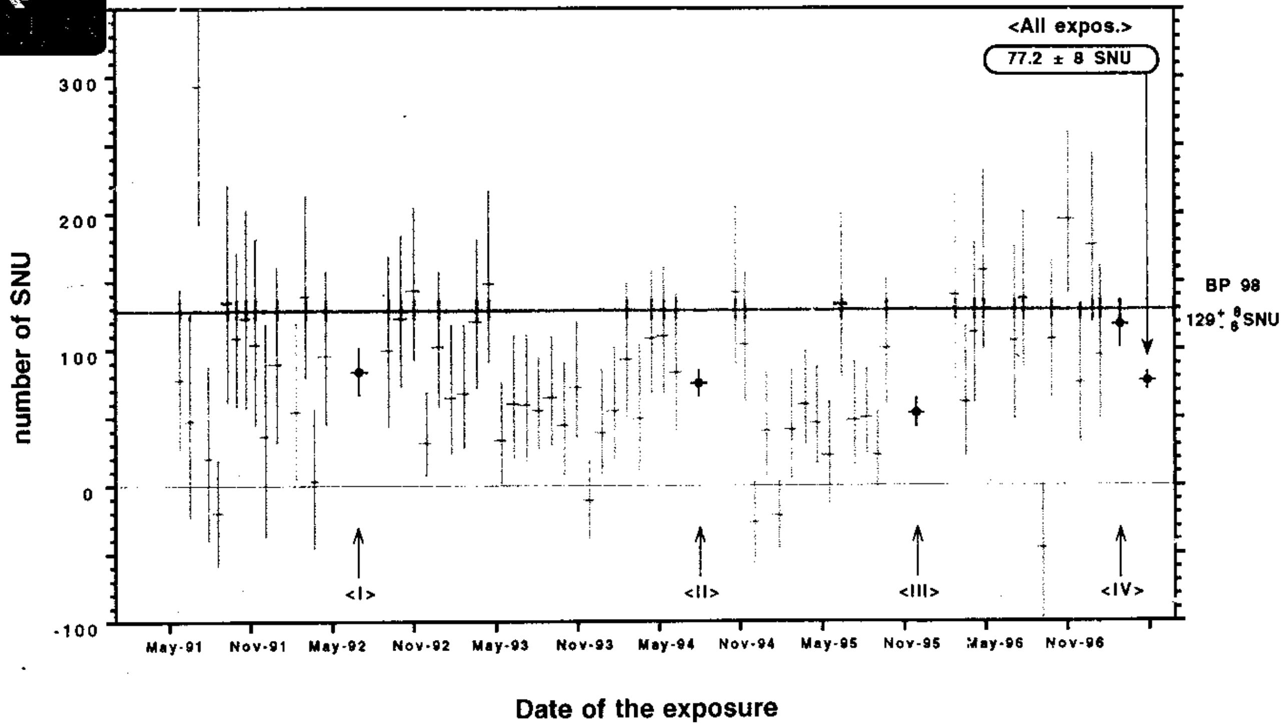
EXTRACTION

$GeCl_4$ + HCl : vapor
$GeCl_4$ + H_2O : solution

3000 m^3 of N_2

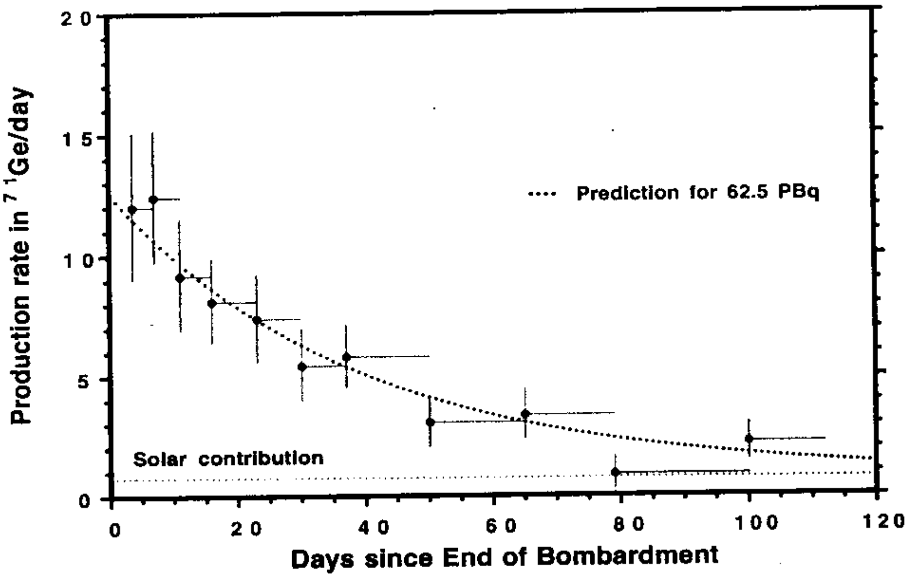
Production rate vs date

Michel Cribier
August 4, 1999



Signal from the ^{51}Cr source

- 11 extractions with the ^{51}Cr



Phys. Lett. B342 (1995) 440

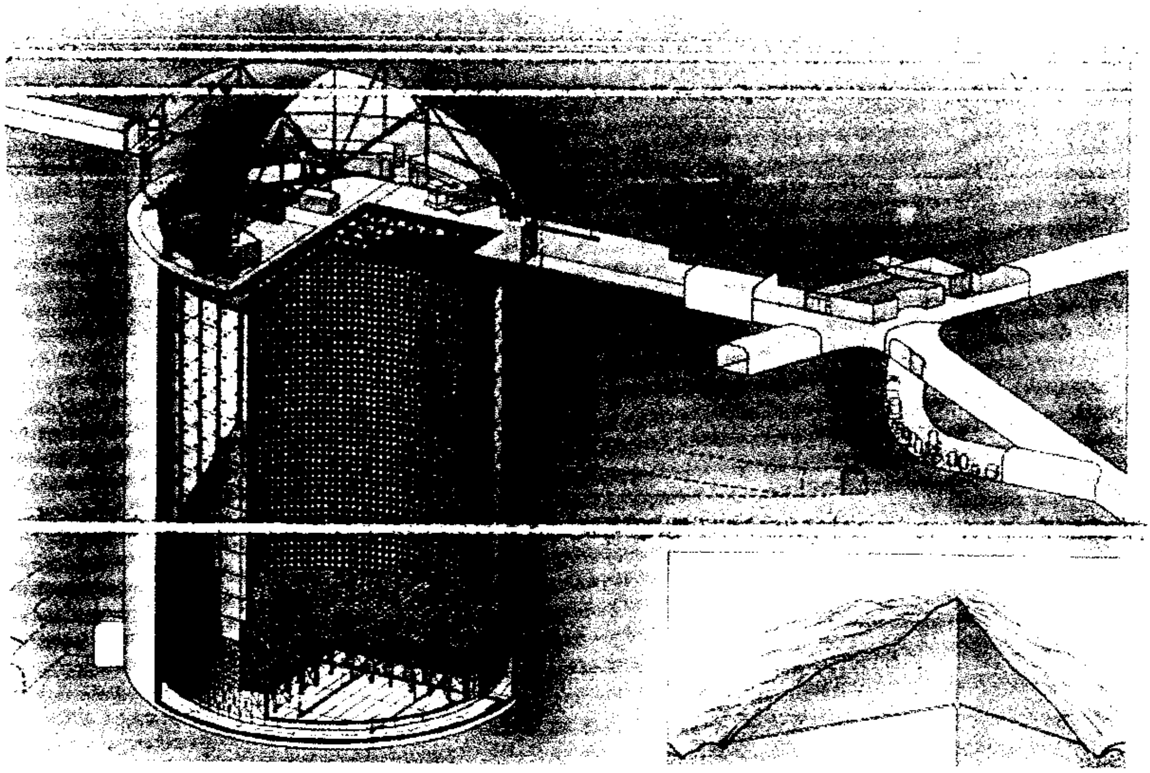
- Follow ^{51}Cr half-life :

$$\boxed{t_{1/2} = 23.8^{+4.2}_{-3.4} \ \textit{days} \quad (27.70)}$$

- Comparison predicted vs measured

$$\boxed{R = \frac{\textit{Activity from } {}^{71}Ge}{\textit{Direct activity}} = 0.97 \pm .11}$$

SUPERKAMIOKA

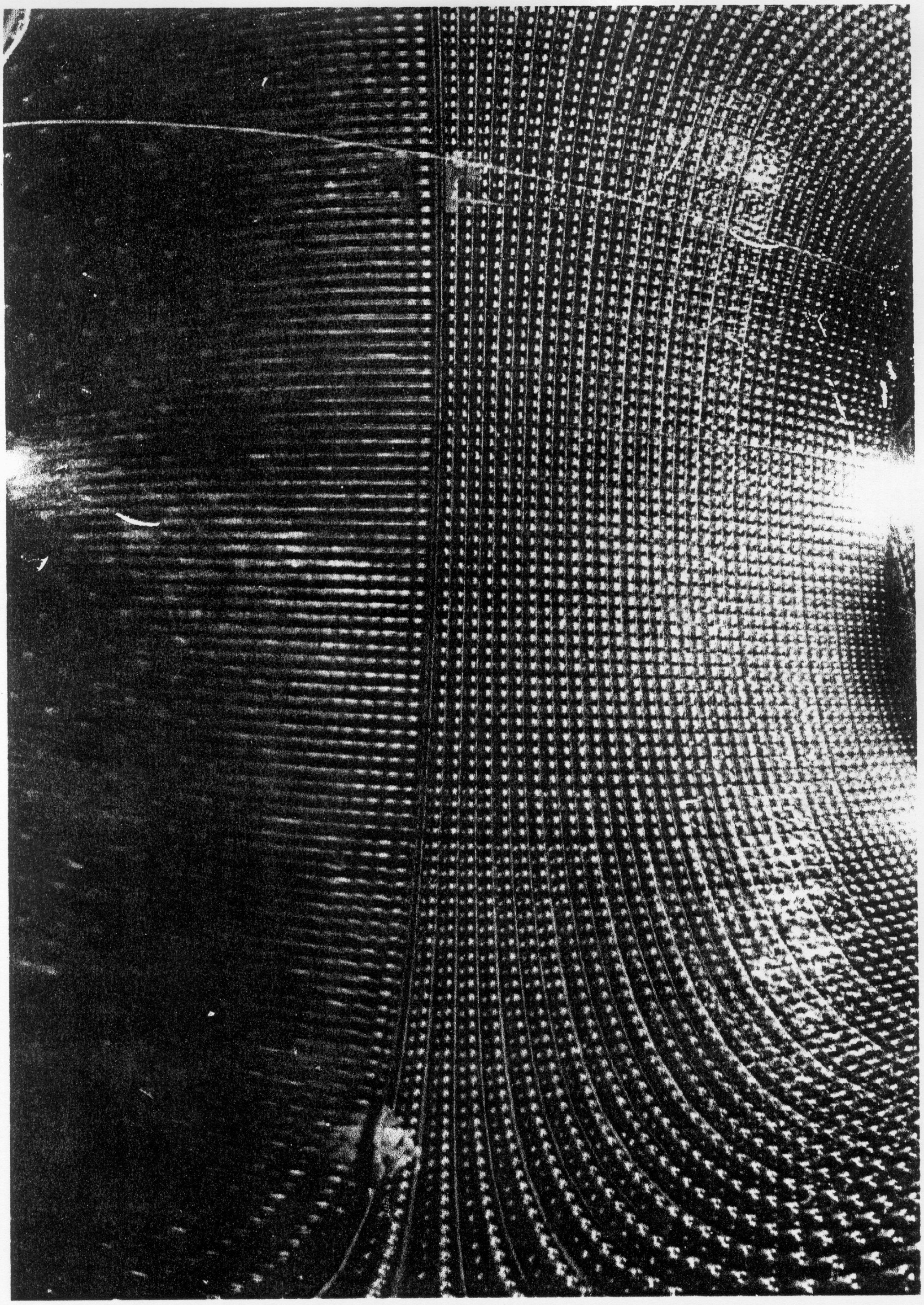


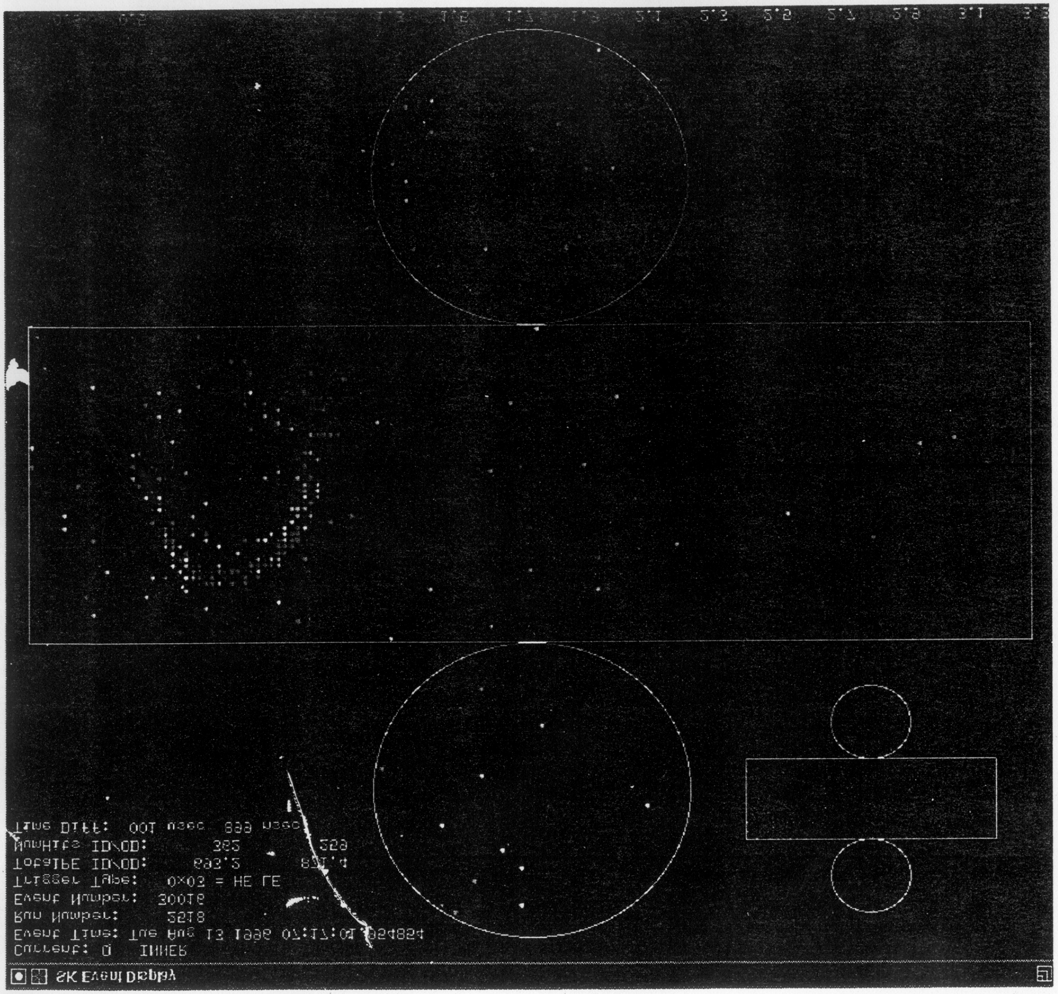
PERKAMIOKANDE INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO

50 kT

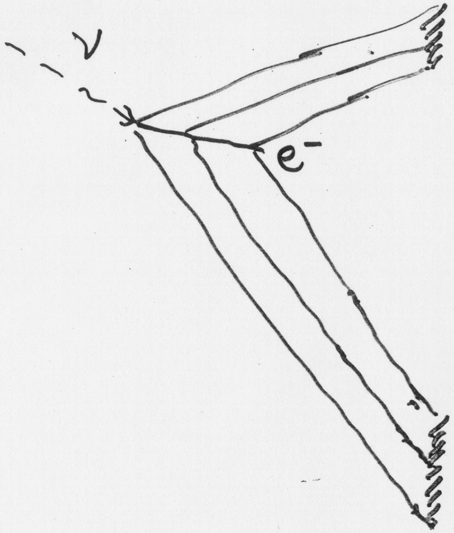
(22 kT utiles)

11 000 PM's





```
Time Diff:  001 usec  999 usec
NumHits ID/OD:        382       356
TotalPE ID/OD:      863.5     831.4
Trigger Type:   0x03 = HE LE
Event Number:  30016
Run Number:        3518
Event Time: Tue Aug 13 1996 07:17:01.854854
Current: 0    INNER
```



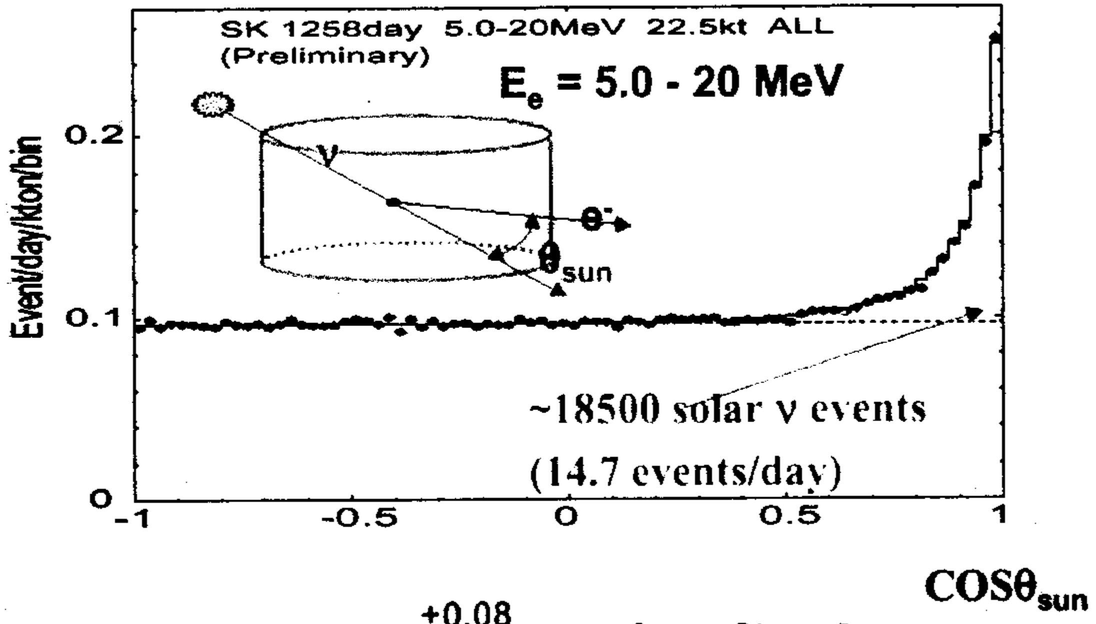
Cerenkov ring
gives e energy
and direction

SuperKamiokande

$\nu_e \to \nu_e$

Direction to the Sun

May 31, 1996 - Oct.6, 2000
1258 days

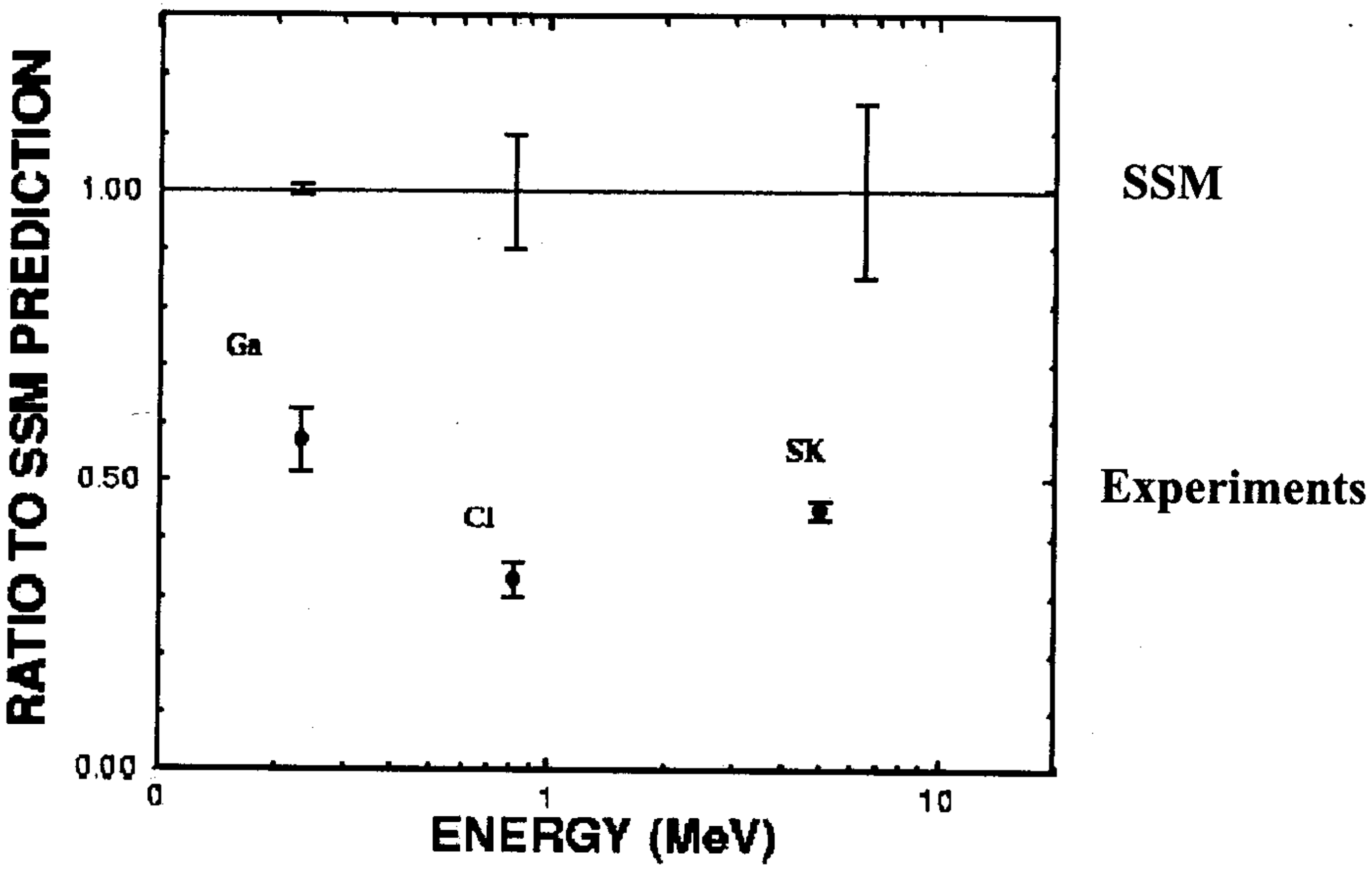


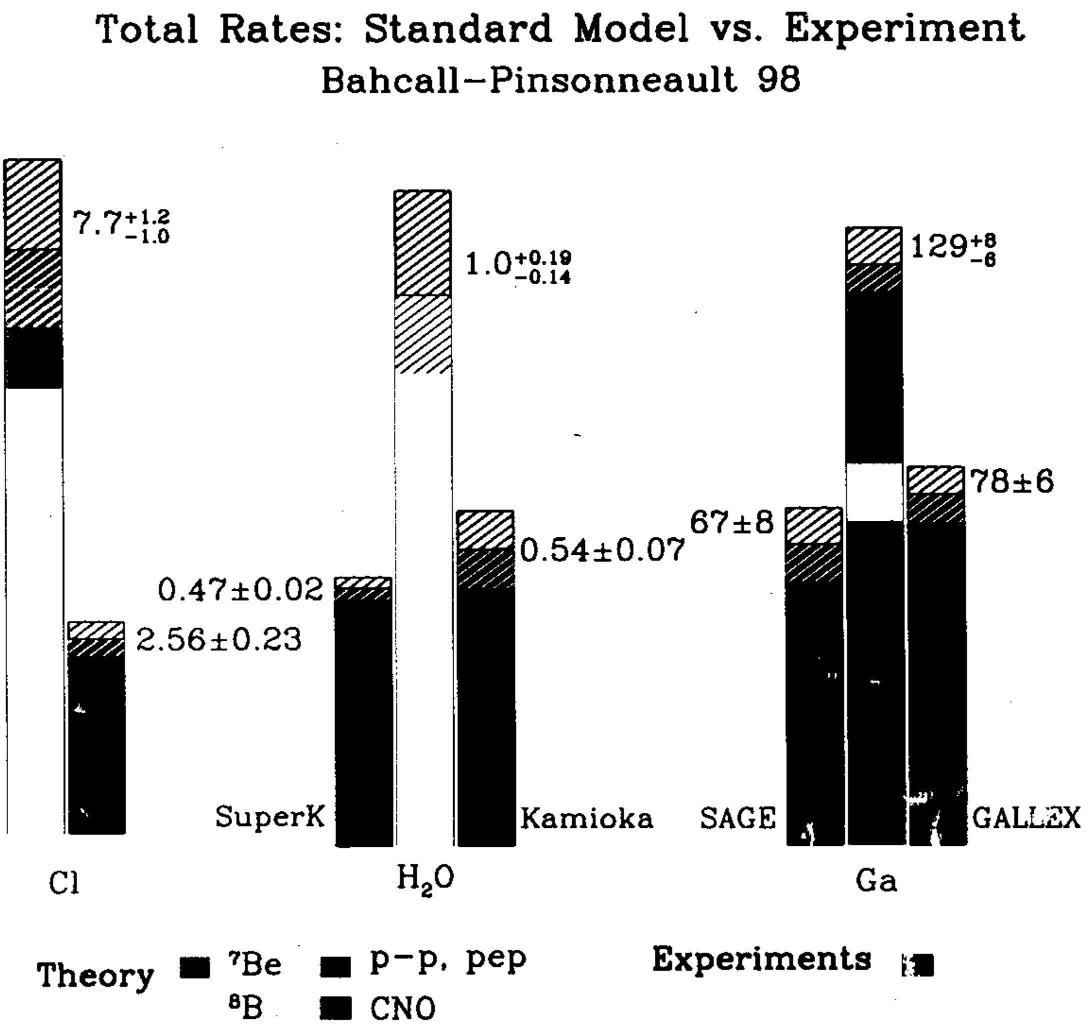
~18500 solar ν events
(14.7 events/day)

^{8}B flux : $2.32 \pm 0.03 \, ^{+0.08}_{-0.07}$ [x 10^6 /cm^2/sec]

$$\frac{\text{Data}}{\text{SSM(BP2000)}} = 0.451 \pm 0.005 \, ^{+0.016}_{-0.013}$$

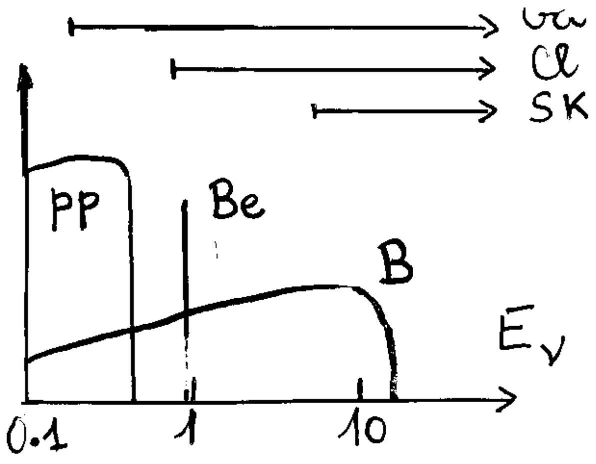
(using Ortiz et al. spectrum shape(nucl-ex/0003006))

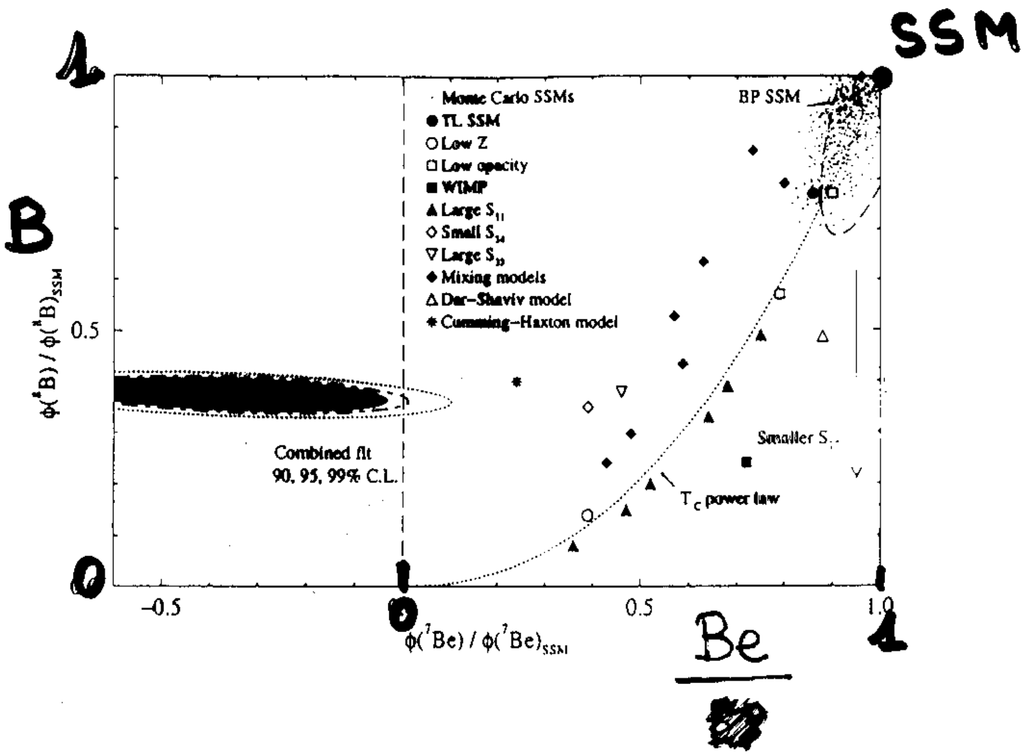

RATIO TO SSM PREDICTION
1.00
0.50
0.00
0
1
10
ENERGY (MeV)
Ga
Cl
SK
SSM
Experiments



Total Rates: Standard Model vs. Experiment

Bahcall–Pinsonneault 98





IMPOSSIBLE TO RECONCILE DATA
WITH ANY SOLAR MODEL

OSCILLATIONS DE ν

- Dans le vide

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$|\nu_e(t)\rangle = \cos\theta \, e^{-iE_1 t} |\nu_1\rangle + \sin\theta \, e^{-iE_2 t} |\nu_2\rangle$$

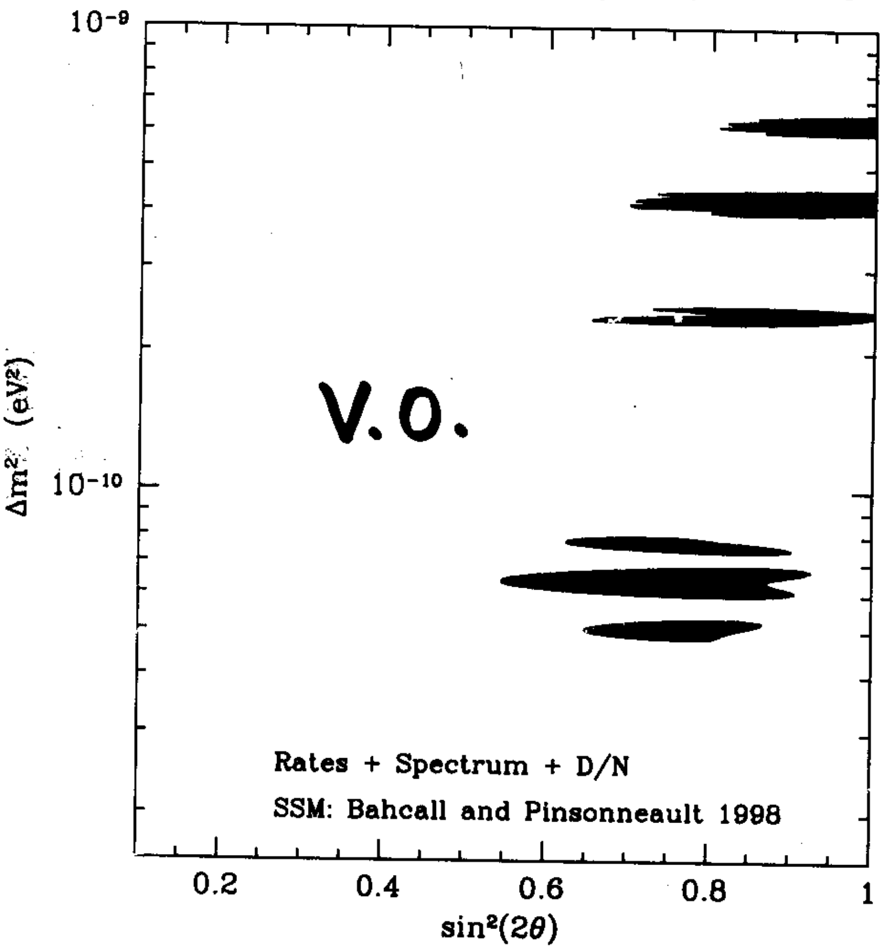
$$|\langle\nu_\mu|\nu_e(t)\rangle|^2 = \sin^2 2\theta \, \sin^2 \frac{\Delta m^2}{4E} t$$

$$\boxed{L_{osc}(m) = 2.5 \, \frac{E_\nu (MeV)}{\Delta m^2 (eV^2)}}$$

$$E_\nu = 12 \text{ MeV} \qquad \Delta m^2 = 10^{-10} \text{ eV}^2$$

$$L_{osc} = 3 \, 10^8 \text{ km} = 2 \times D_{TS}$$

Vacuum oscillations

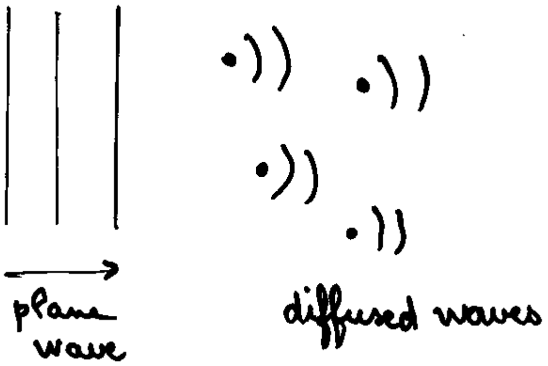


PROPAGATION IN MATTER

- In vacuum

$$\psi(\vec{x},t) = e^{i\vec{p}\vec{x}}\, e^{-iEt} \qquad v_G = \frac{dE}{dp} = \frac{p}{E}$$

- In matter



$$\psi_{tot} = \psi_{inc} + \sum_i \frac{e^{ipr_i}}{r_i} f(\Omega_i)$$

In the forward direction:

$$\psi_{tot}(\ell,t) = e^{inp\ell}\, e^{-iEt}$$

n = refractive index

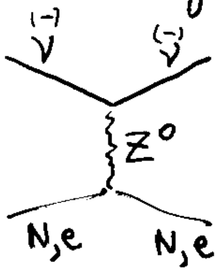
$$n = 1 + 2\pi\rho\,\frac{f(0)}{p^2} \qquad v_G = \frac{1}{n}\frac{p}{E}$$

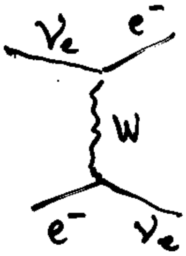
Orders of magnitude for ν's

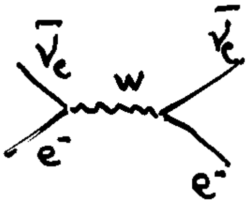
$$f(0) \propto G_F\, p$$

$$\Rightarrow |n-1| \sim 6\,10^{-19}\,\rho\,(g/cm^3)\left(\frac{1\,MeV}{p}\right)$$

But the index of refraction is not the same for ν_e and (ν_μ, ν_τ) :







Common Specific to ν_e Specific to $\bar\nu$

$$\Rightarrow f_{\nu_e}(0) - f_{\nu_{\mu,\tau}}(0) = \frac{\sqrt{2}}{2\pi}\, G_F\, p$$

Matter effects induce a phase shift between ν_e and $\nu_{\mu,\tau}$

The $\bar\nu_e$ phase shift is the opposite ←

$$\varphi_{\nu_e} - \varphi_{\nu_{\mu,\tau}} = \sqrt{2}\, G_F\, \underset{\substack{\uparrow \\ \text{electron number density}}}{\rho_e}\, t$$

which must be taken into account and added to the mass phase shift $E_1 - E_2$ between ν_1 and ν_2

Qualitatively, the effect becomes important if

$$G_F \rho_e \sim \frac{\Delta m^2}{E_\nu}$$

$$\Rightarrow \Delta m^2 \sim 5\, 10^{-8} \left(\frac{Z}{A} \rho_{g/cm^3} \right) E_\nu (MeV)$$

Earth $\rho = 3\ g/cm^3 \quad \frac{Z}{A} = 1/2$

$$\Delta m^2 \sim 10^{-7}\, E_\nu (MeV) \text{ or below}$$

Sun $\rho = 150\ g/cm^3 \quad \frac{Z}{A} = 2/3$

$$\Delta m^2 \sim 5\, 10^{-6}\, E_\nu (MeV) \text{ or below}$$

Analysis for the 2-flavor case

$$|\nu_e\rangle = \cos\theta_v\,|\nu_1\rangle + \sin\theta_v\,|\nu_2\rangle$$

$$|\nu_\mu\rangle - \sin\theta_v\,|\nu_1\rangle + \cos\theta_v\,|\nu_2\rangle$$

$$|\psi\rangle = a\,|\nu_1\rangle + b\,|\nu_2\rangle$$

- Schrödinger equation in vacuum

$$i\frac{d}{dt}\begin{pmatrix} a \\ b \end{pmatrix} = \begin{pmatrix} E_1 & 0 \\ 0 & E_2 \end{pmatrix}\begin{pmatrix} a \\ b \end{pmatrix} \qquad \begin{cases} a(t) = a_0 e^{-iE_1 t} \\ b(t) = b_0 e^{-iE_2 t} \end{cases}$$

- Reexpress in flavor basis

$$|\psi\rangle = a_e|\nu_e\rangle + a_\mu|\nu_\mu\rangle$$

$$i\frac{d}{dt}\begin{pmatrix} a_e \\ a_\mu \end{pmatrix} = \begin{pmatrix} E_1\cos^2\theta_v + E_2\sin^2\theta_v & (E_2-E_1)\cos\theta_v\sin\theta_v \\ (E_2-E_1)\cos\theta_v\sin\theta_v & E_1\sin^2\theta_v + E_2\cos^2\theta_v \end{pmatrix}\begin{pmatrix} a_e \\ a_\mu \end{pmatrix}$$

In this basis, it is easy to add matter effects:
One just adds a diagonal matrix

$$\begin{pmatrix} n_e-1 & 0 \\ 0 & n_\mu-1 \end{pmatrix} = \begin{pmatrix} C + \sqrt{2}G_F\rho_e & 0 \\ 0 & C \end{pmatrix}$$

Note: To simplify formulae, I can always substract a matrix $\begin{pmatrix} K & 0 \\ 0 & K \end{pmatrix}$

It does not change eigenstates
It shifts eigenvalues by K

After substracting $E_1\cos^2\theta_V + E_2\cos^2\theta_V + C$:

$$i\frac{d}{dt}\begin{pmatrix} a_e \\ a_\mu \end{pmatrix} = \begin{pmatrix} \sqrt{2}G_F\rho(t) & \frac{1}{2}(E_2-E_1)\sin 2\theta_V \\ \frac{1}{2}(E_2-E_1)\sin 2\theta_V & (E_2-E_1)\cos 2\theta_V \end{pmatrix}\begin{pmatrix} a_e \\ a_\mu \end{pmatrix}$$

- Difficult to solve when ρ is time dependant
- The propagation instantaneous eigenstates are the eigenvectors of this matrix
- If ρ = cte, we have an equation which is formally identical to the vacuum case

  Propagation eigenstates ν_1 and ν_2 are replaced by ν_{1m} and ν_{2m}

  The mixing angle θ_V is replaced by θ_m

For matter with constant electron density, oscillation frequency and amplitude are modified

The oscillation amplitude can even become maximal ($\sin^2\theta_m = 1 \Rightarrow \theta_m = \pi/4$) for an electron density

$$\rho_R = \frac{(m_2^2 - m_1^2)\cos 2\theta_V}{2\sqrt{2}\,G_F E_\nu}$$

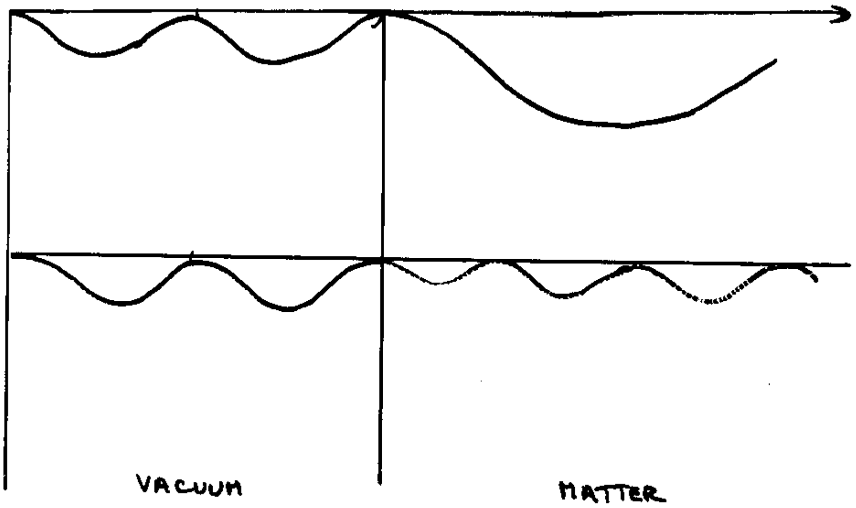
positive for either ν's or $\bar{\nu}$'s

$$R = \frac{\rho}{\rho_R} \qquad \sin^2 2\theta_m = \frac{1}{1+(R-1)^2 \cot g^2 2\theta_v}$$

$$L_m = \frac{L_{vac}}{\sin 2\theta_v \left[1+(R-1)^2 \cot g^2 2\theta_v\right]^{1/2}}$$

$R>0$ $\sin^2 2\theta_m$ and $L_m >$ $\sin 2\theta_v$ and L_v

$R<0$ $\sin^2 2\theta_m$ and $L_m <$ $\sin 2\theta_v$ and L_v



Notice that matter creates a fake CP violation (just because matter is not CP symetric : there are e^- and no e^+)

Enhancement for ν_e : $m_1^2 < m_2^2$

$\bar{\nu}_e$: $m_1^2 > m_2^2$

If $\overset{(-)}{\nu}_e$ is mainly ν_1

More difficult - electron density is not constant.

$$\rho = \rho(t)$$

To solve the equation, it is better to switch to Poincaré representation of 2 level states.

$$|\psi\rangle = \cos\theta\, |1\rangle + \sin\theta\, e^{i\varphi}\, |2\rangle$$

$|\psi\rangle \rightsquigarrow$ Point M on unit sphere, of polar angle 2θ and azimut φ.

North pole is $|1\rangle$

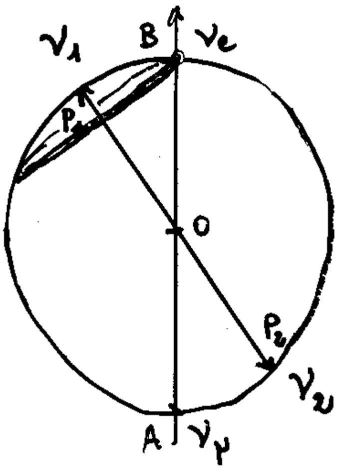
South pole is $|2\rangle$

Important relation:

$$|\langle\psi|\psi'\rangle|^2 = \frac{1}{2}\left(1 + \vec{OM}\cdot\vec{OM'}\right)$$

Usual application:

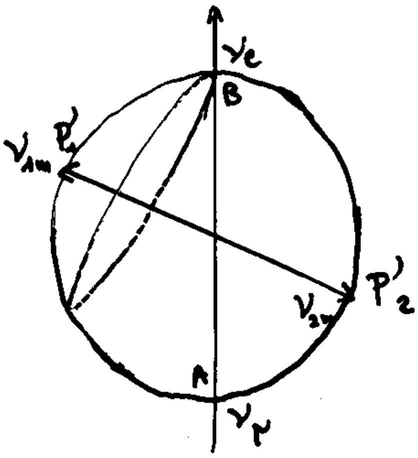
Spin ½ particle - Then $\vec{OM}$ is the direction in space along which the particle is in a spin eigenstate: $\vec{S}$ is along $\vec{OM}$.



Shrödinger equation in vacuum:

Any state will rotate at constant speed around P1 P2

The instantaneous projection on AB will give the probabilities to interact as a ν_e or a ν_μ



Matter with constant density:

Exactly the same except that $P_1 P_2$ has become $P'_1 P'_2$ and the frequency has changed

Schrödinger equation in this representation

$$\frac{d\vec{OM}}{dt} = \mathcal{M}\,\vec{OM} \quad \text{with } \mathcal{M} = \begin{pmatrix} 0 & \alpha & 0 \\ -\alpha & 0 & -\beta \\ 0 & \beta & 0 \end{pmatrix}$$

$$\alpha = (E_2 - E_1)\cos 2\theta_\nu - \sqrt{2}\, G_F\, \rho$$

$$\beta = (E_2 - E_1)\sin 2\theta_\nu$$

Its eigenvector is OP_1 in vacuum (or OP_2)
OP'_1 in matter (or OP'_2)

and the eigenvalue is 0.

$\Rightarrow \vec{OM} \cdot \frac{d\vec{OM}}{dt} \equiv 0$ (M stays on the sphere)

$\vec{OP} \cdot \frac{d\vec{OM}}{dt} \equiv 0$: M describes the drawn circle

What happens with variable density?

$\vec{OP'}$ varies with time

But if this variation is sufficiently slow compared to the precession speed of $\vec{OM}$ around $\vec{OP'}$ (Larmor frequency / oscillation frequency) then the above results are still valid:

$\vec{OM}$ will rotate around $P'_1P'_2$ and accompany this vector during its slow variation.

This is called the adiabatic approximation

Analogy with the spin of a particle in a magnetic field which varies with time (the equations are formally identical)

The spin precesses around $\vec{B}$

If $\vec{B}$ is varied SLOWLY, the spin continues to rotate around $\vec{B}$

Special case: If $\vec{S}$ is initially aligned with $\vec{B}$, it will stay aligned with $\vec{B}$ at all times:

This is how one rotates the polarization of a polarized target - It is sufficient to change $\vec{B}$ slowly to change $\vec{P}$ in the same way.

Application to solar ν's : MSW effect.

Ⓐ In the center of the Sun, very high electron density - Matter effect dominates over Δm^2
Propagation eigenstates are ν_μ and ν_e
So ν_e is produced as a propagation eigenstate

Ⓑ This neutrino sees the matter density vary very slowly : So it stays at all times a propagation eigenstate (either ν_{1m} or ν_{2m})

At the sun surface, where $\rho = 0$, our neutrino has become a propagation eigenstate in vacuum, either ν_1 or ν_2

<u>Rule</u> If ν_e predominantly coupled to ν_1
then ν_e ends up as a ν_1 if $m_1 > m_2$
as a ν_2 if $m_1 < m_2$.

Dramatic effect in the second case

$$P_{\nu_e}(\text{sun surface}) = \sin^2\theta_V \; !$$

MSW requires statements A and B to be true.

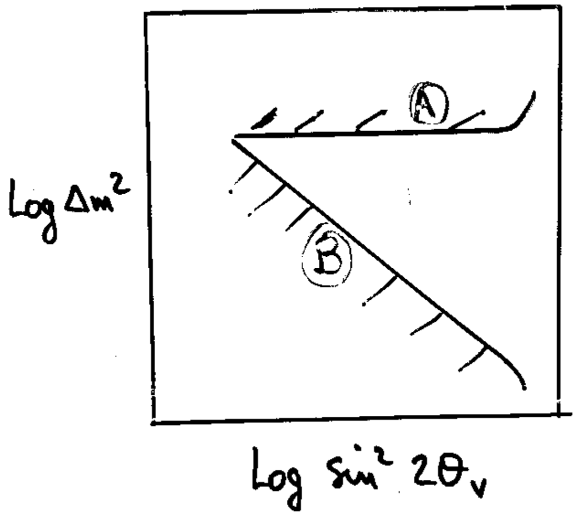
A : $\dfrac{\Delta m^2 \cos 2\theta_\nu}{2\sqrt{2}\, G_F E_\nu} < \rho_e$ (center)

B : $\dfrac{\Delta m^2 \sin^2 2\theta_\nu}{\cos 2\theta_\nu} > 2 K E_\nu$

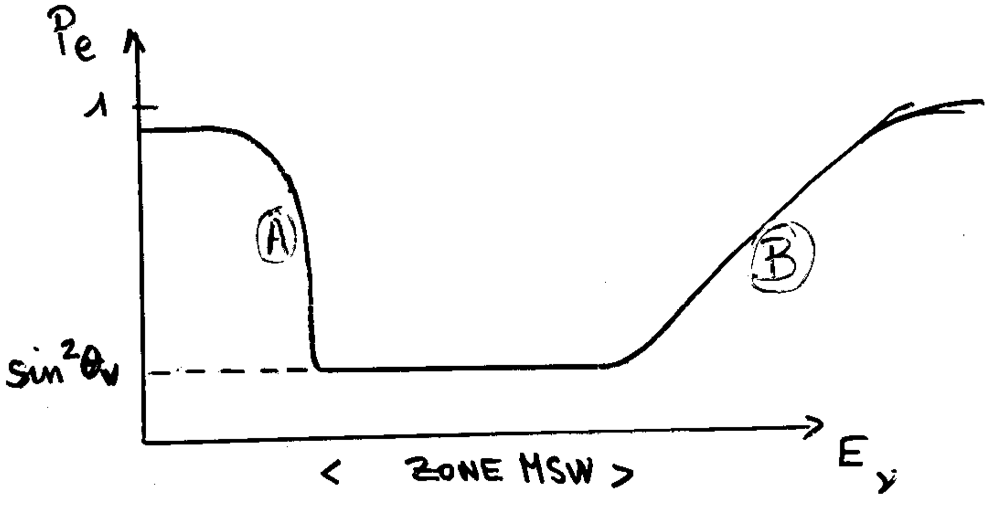
A and B define a triangle in $\log \Delta m^2$, $\log \sin^2 2\theta_\nu$ plane which moves up with energy

When the parameters chosen by nature for Δm^2 and $\sin^2 2\theta_\nu$ are inside this triangle, then the MSW effect is operational.

Note that the MSW effect is not an oscillation, but an (adiabatic) flavor driving from ν_e to ν_2



La position du triangle se déplace avec l'énergie du ν *



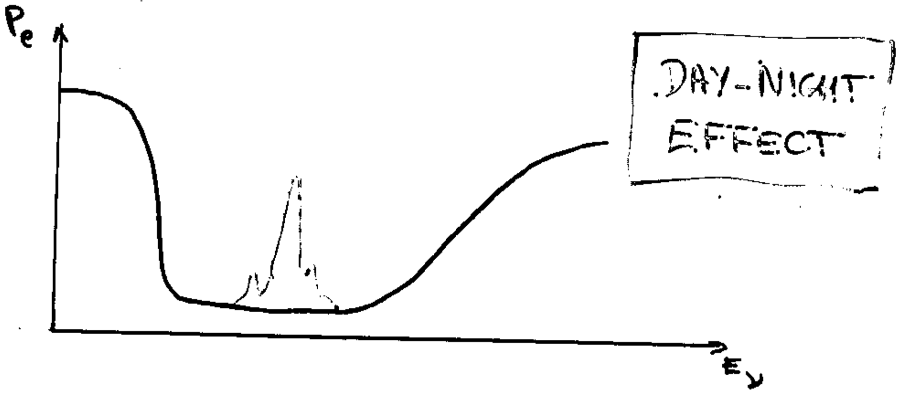
The vertical position of the "adiabatic triangle" depends on E_ν

During the day:

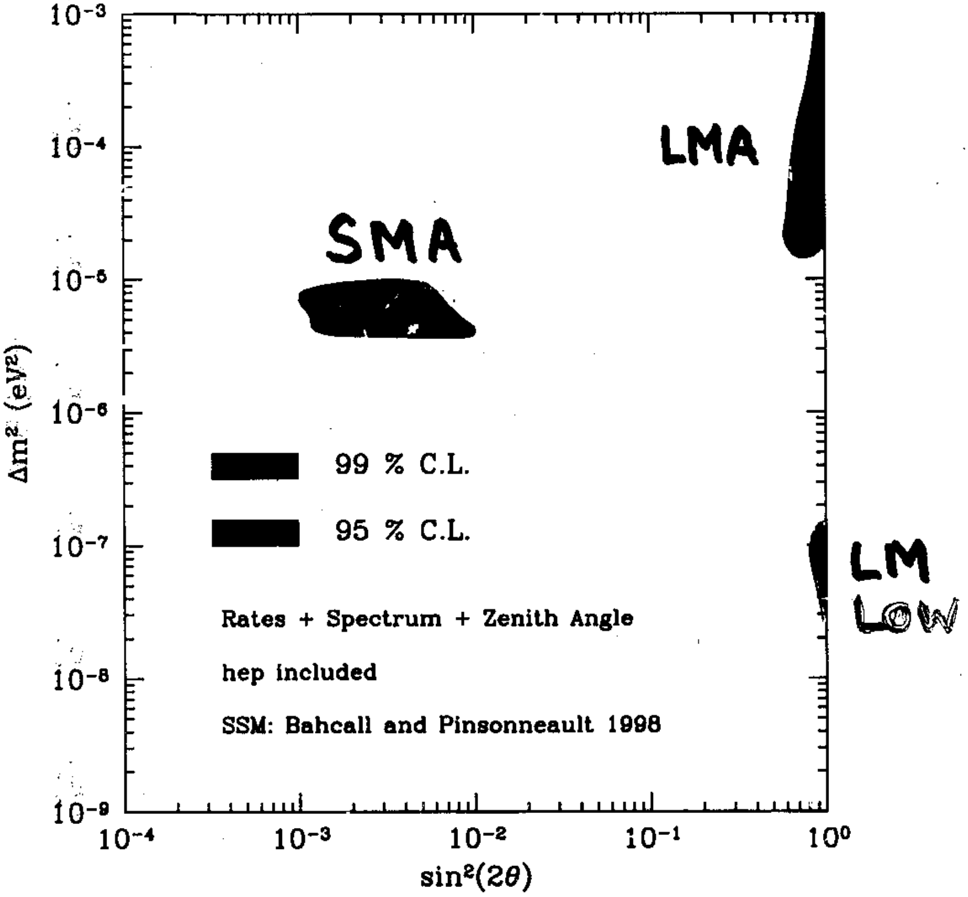
ν's get out of the Sun as ν_2
This is a propagation eigenstate in vacuum
They stay ν_2 from Sun to Earth.

- during day time
  They will interact as ν_e with a probability
  $\sin^2\theta_\nu$

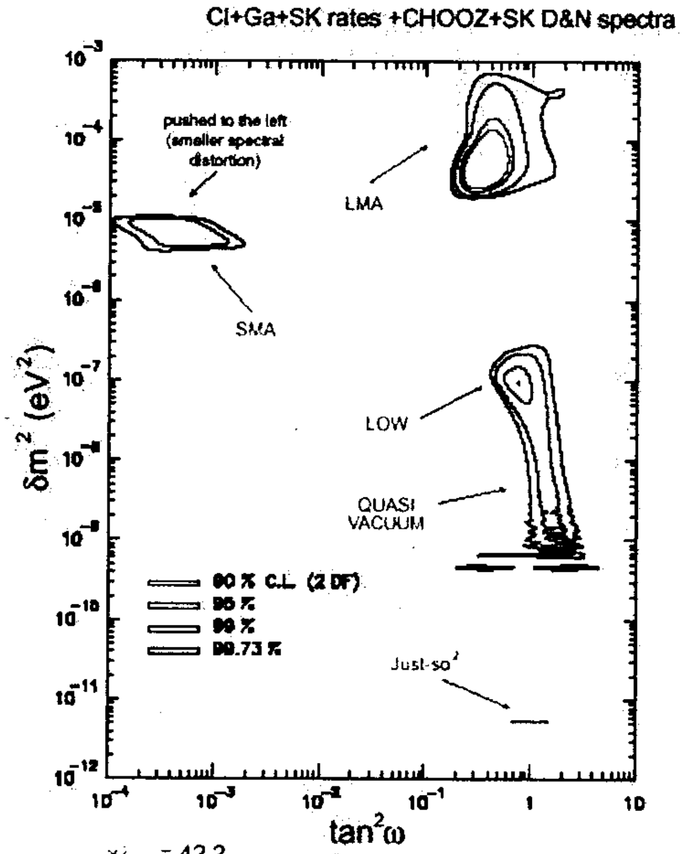
- At night
  ν_2 goes thru the Earth = Due to the presence of electrons, ν_2 is NO LONGER a propagation eigenstate ⇒ It will oscillate
  ⇒ In some cases, this induces a sizeable regeneration of ν_e's at the detector.



MSW solutions



2ν oscillations (φ = 0)

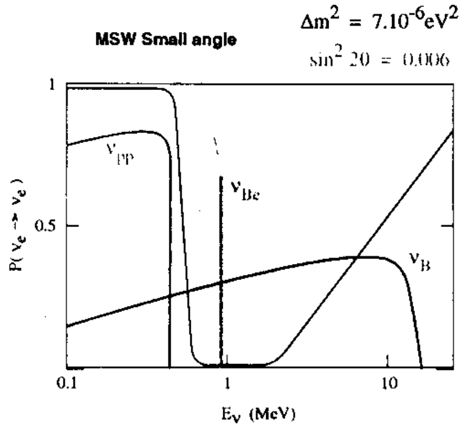


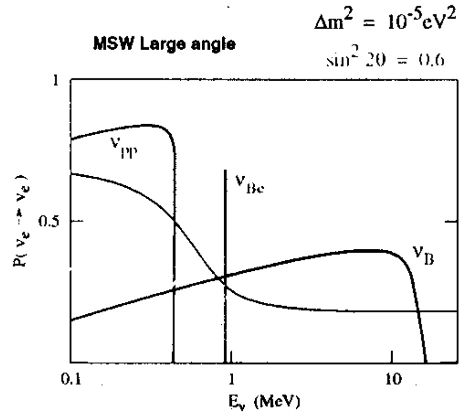
$\chi^2_{LMA} = 42.2$
$\chi^2_{LOW} = 46.8$
$\chi^2_{[illegible]} = 48.1$
$\chi^2_{SMA} = 49.3$

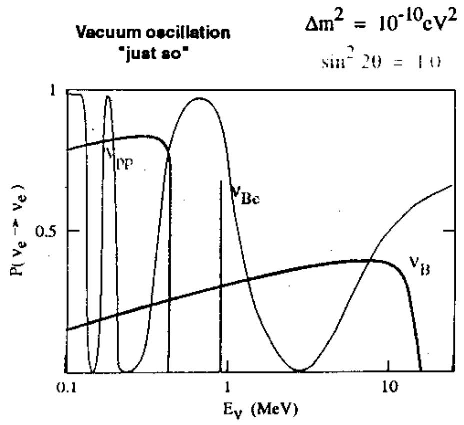
Active Neutrinos

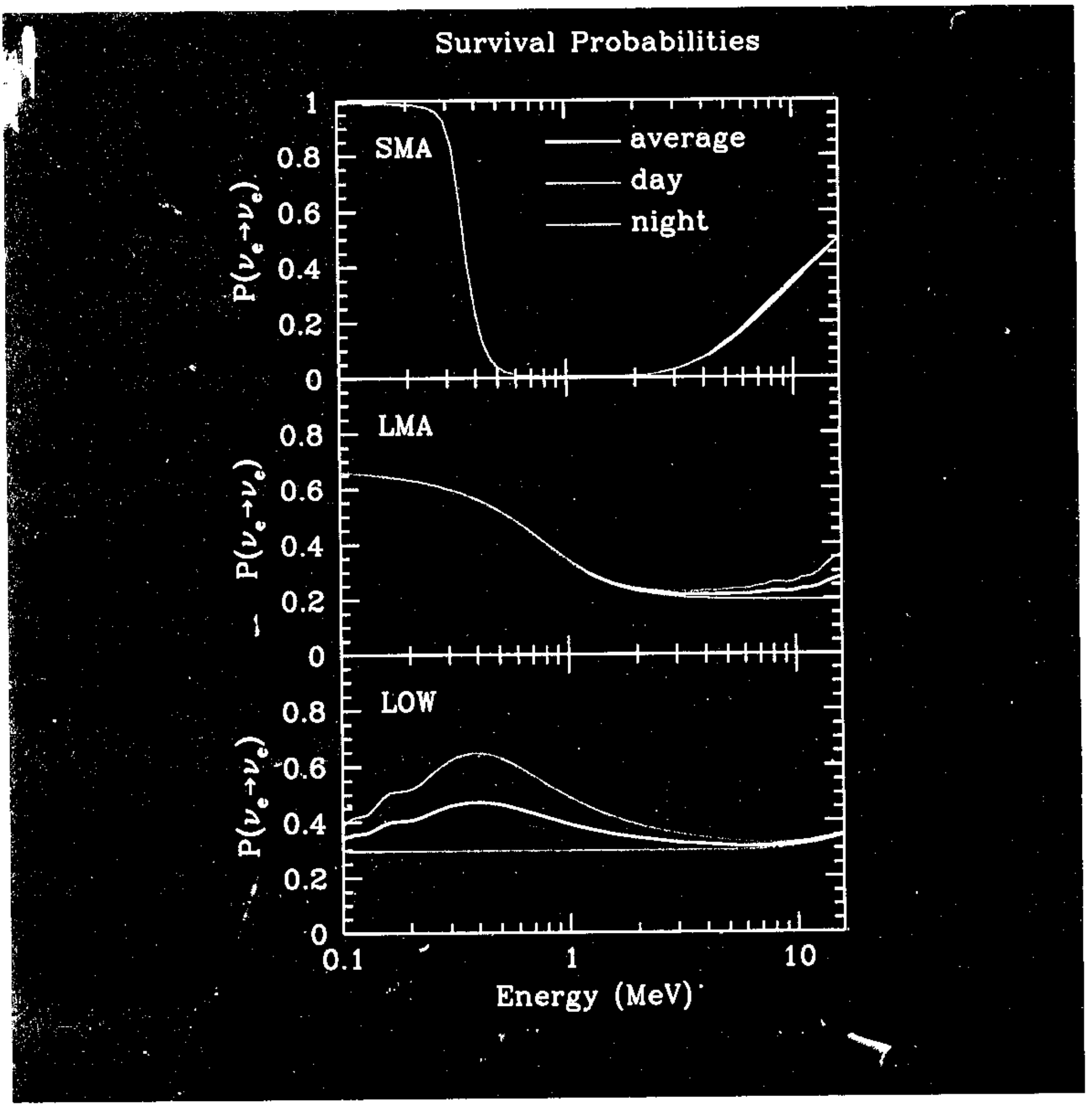
Including SK
Day and Night
Spectra

Fogli et al.
hep-ph/0106247

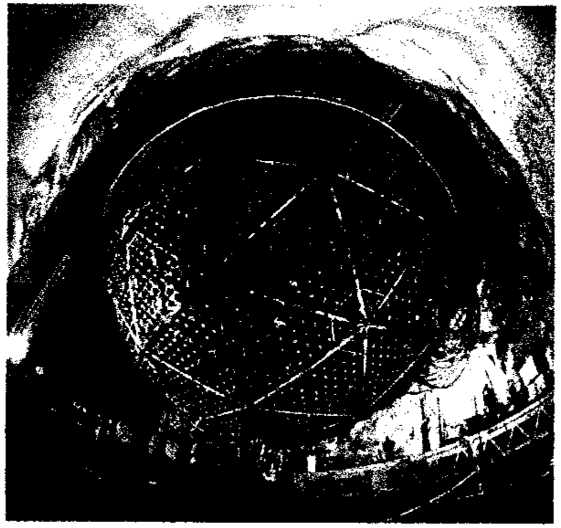

MSW Small angle
$\Delta m^2 = 7.10^{-6} eV^2$
$\sin^2 2\theta = 0.006$
1
0.5
$P(\nu_e \to \nu_e)$
ν_{pp}
ν_{Be}
ν_B
0.1
1
10
E_ν (MeV)

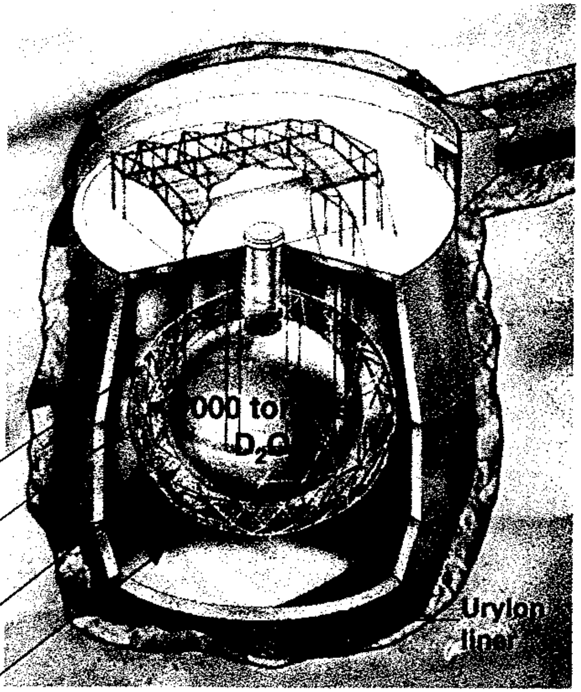

MSW Large angle
$\Delta m^2 = 10^{-5} eV^2$
$\sin^2 2\theta = 0.6$
1
0.5
$P(\nu_e \to \nu_e)$
ν_{pp}
ν_{Be}
ν_B
0.1
1
10
E_ν (MeV)


Vacuum oscillation
"just so"
$\Delta m^2 = 10^{-10} eV^2$
$\sin^2 2\theta = 1.0$
1
0.5
$P(\nu_e \to \nu_e)$
ν_{pp}
ν_{Be}
ν_B
0.1
1
10
E_ν (MeV)


Survival Probabilities
SMA
LMA
LOW
average
day
night
$P(\nu_e \to \nu_e)$
0
0.2
0.4
0.6
0.8
1
0.1
1
10
Energy (MeV)

Sudbury Neutrino Observatory





17.8m dia. PMT Support Structure
9456 PMTs, 56% coverage

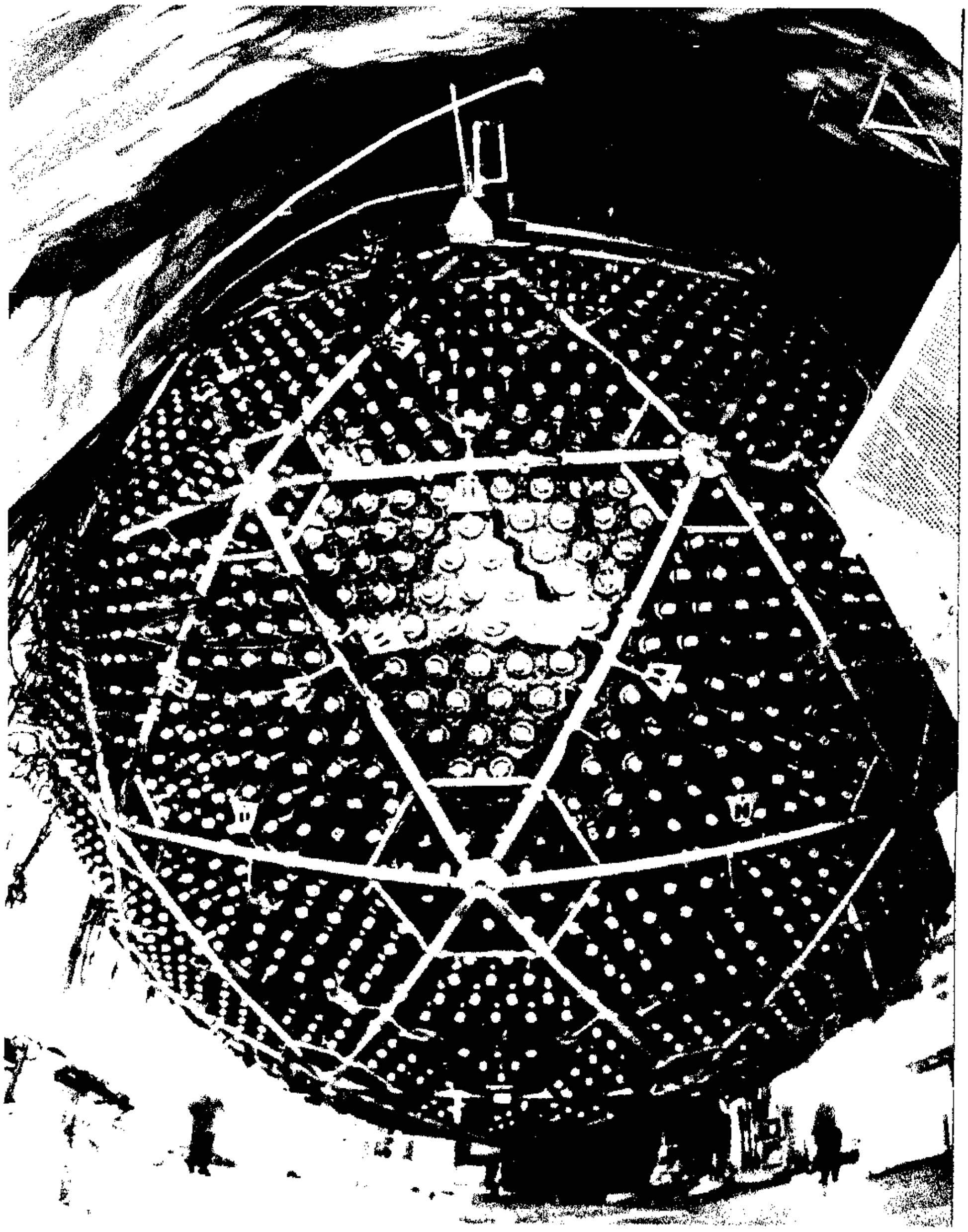
12.01m dia. acrylic vessel

1700 tonnes of inner shielding H_2O

5300 tonnes of outer shielding H_2O

Host: INCO Ltd., Creighton #9 mine
Coordinates: 46°28'30"N 81°12'04"W
Depth: 2092 m (~6010 m.w.e., ~70 μ day^{-1})

SUDBURY NEUTRINO OBSERVATORY

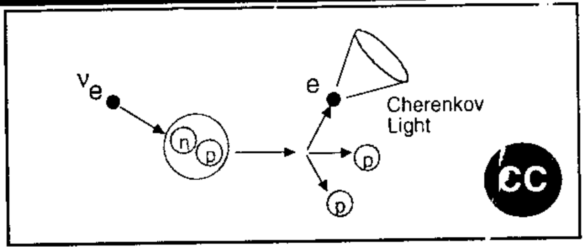


1000 tons of heavy water

ν Reactions in SNO

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

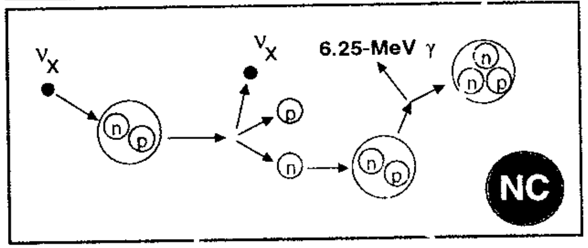
- Measurement of ν_e energy spectrum
- Weak directionality: $1 - 0.340\cos\theta$



ν_e

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

- Measure total ^{8}B ν flux from the sun
- $\sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau)$

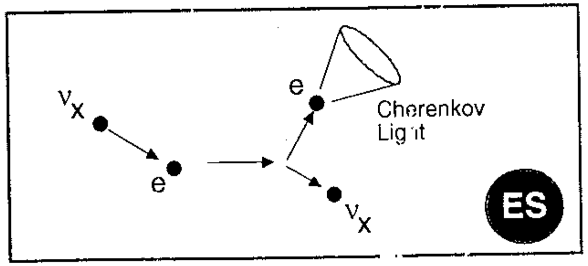


$\nu_e + (\nu_\mu + \nu_\tau$

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

- Low Statistics
- $\Sigma\phi = \phi(\nu_e) + 0.154\,\phi(\nu_\mu + \nu_\tau)$
- Strong directionality:

  $\theta_e \leq 18^\circ$ (T_e = 10 MeV)

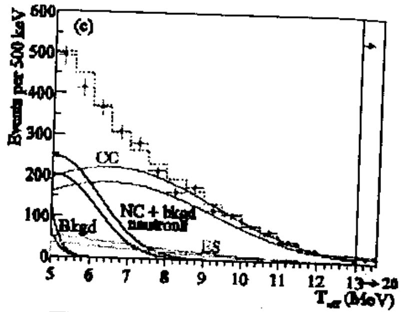


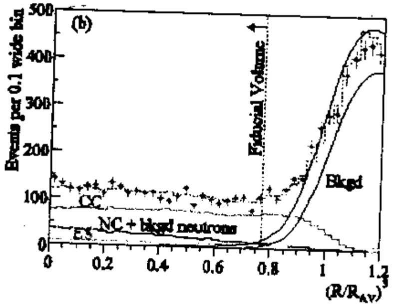
$\nu_e + 0.15(\nu_\mu +$

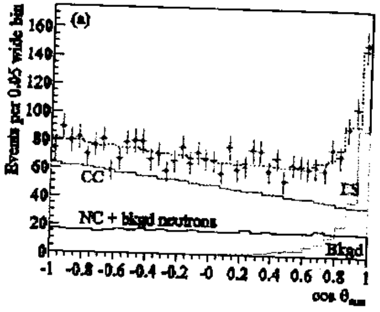
Shape Constrained Signal Extraction Results

#EVENTS

CC	$1967.7^{+61.9}_{+60.9}$
ES	$263.6^{+26.4}_{+25.6}$
NC	$576.5^{+49.5}_{+48.9}$





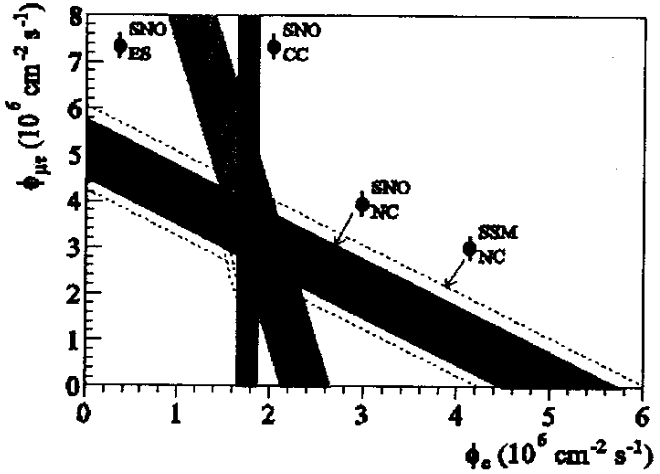


SNC , may 2002

$\Phi_{ssm} = 5.05^{+1.01}_{-0.81}$ $\Phi_{sno} = 5.09^{+0.44+0.46}_{-0.43-0.43}$

$\phi_{\nu_e} = 1.76\ 10^{6}\,cm^{-2}s^{-1}$

$\phi(\nu_\mu+\nu_\tau) = 3.41\ 10^{6}\,cm^{-2}s^{-1}$



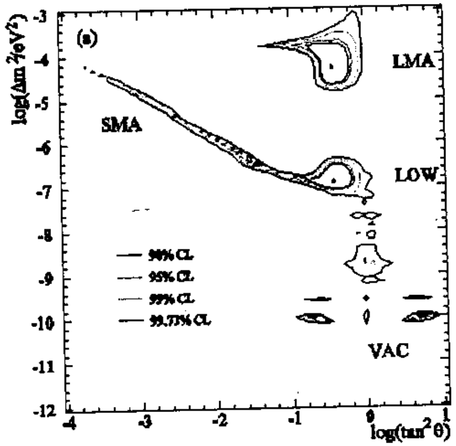
Strong evidence of flavor change

⇒ No deficit on the TOTAL flux

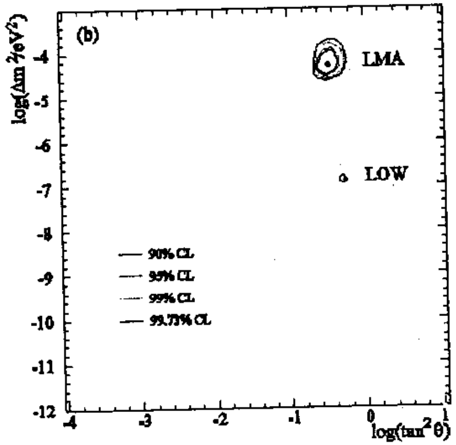
But only 1 ν out of 3 arrives
on Earth as a ν_e !

Physics Interpretation
Neutrino Oscillations

SNO Day and Night
Energy Spectra Alone



Combining All Experimental
and Solar Model information



Present and Fu[illegible]

The Salt Phase

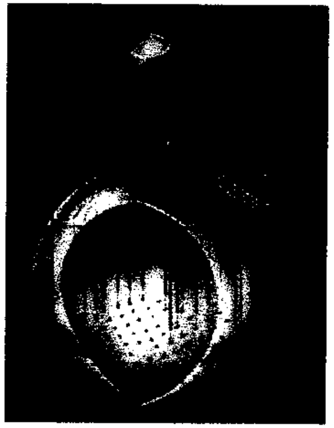
$n + {}^{35}Cl \rightarrow {}^{36}Cl + \Sigma\gamma \ldots \rightarrow e^-$ ($E_{\Sigma\gamma}$ = 8.6 MeV)

- ➢**Higher n-capture efficiency**
- ➢**Higher event light output**
- ➢**Event isotropy differs from e⁻**
- ➢Running since June 2001

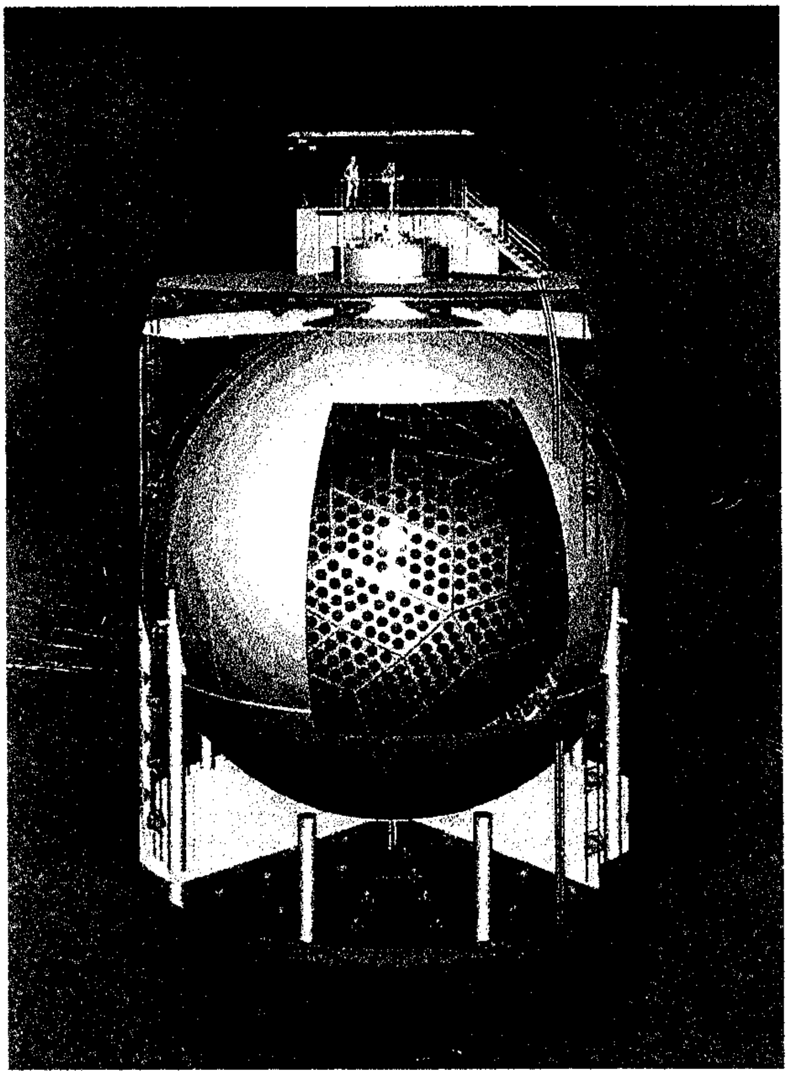
Neutral Current Detectors

$n + {}^{3}He \rightarrow p + t$

- ➢Event by event separation



KAMLAND

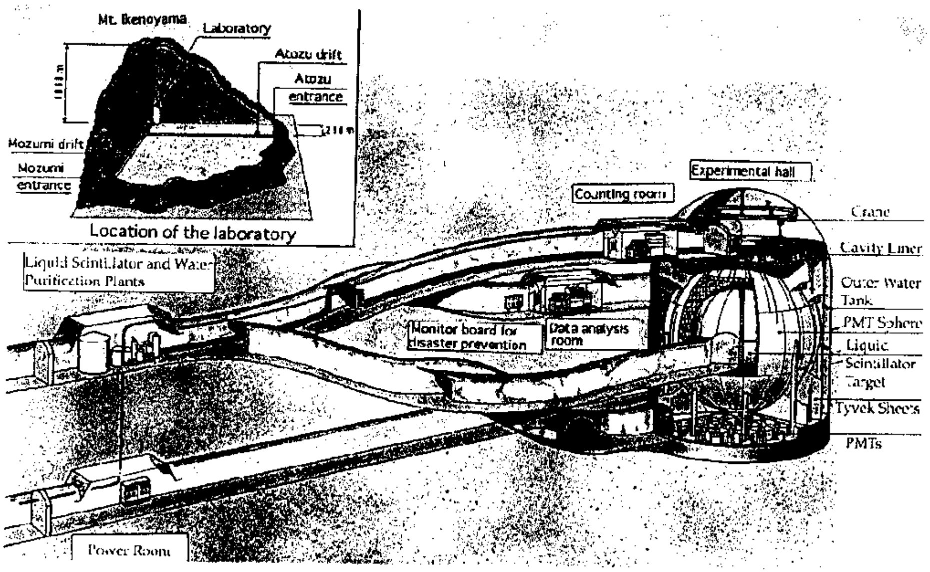


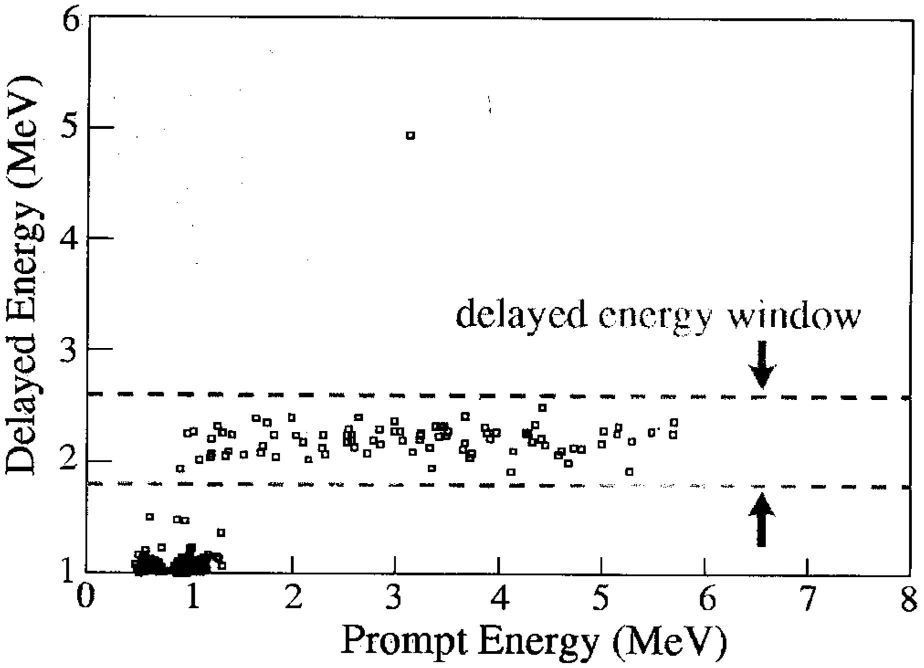
1000 tons of liquid scintillator

$\bar{\nu}_e\, p \to e^+ n$, $n + p \to d + \gamma$ (2.2 MeV)

~ 30 nuclear reactor between 150 - 250 km

~ 1 evt/day is expected (if no osc.)


Mt. Ikenoyama
Laboratory
1000 m
Atozu drift
Atozu entrance
200 m
Mozumi drift
Mozumi entrance
Location of the laboratory
Liquid Scintillator and Water Purification Plants
Counting room
Experimental hall
Crane
Cavity Liner
Outer Water Tank
PMT Sphere
Liquid Scintillator Target
Tyvek Sheets
PMTs
Monitor board for disaster prevention
Data analysis room
Power Room

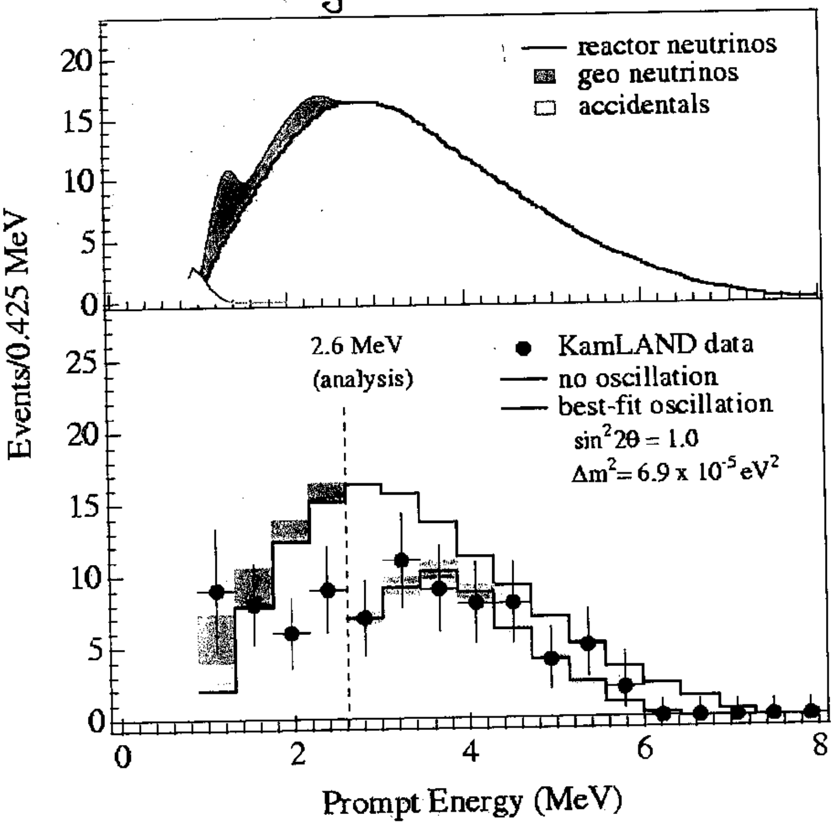


Background free experiment!

(~ 1 evt / year !)

145 days = 162 ton·years

145 jours = 162 tonnes·an



Analysis

$R < 5 \text{ m}$

$0.5\,\mu s < \Delta t < 660\,\mu s$

$\Delta R < 1.6 \text{ m}$

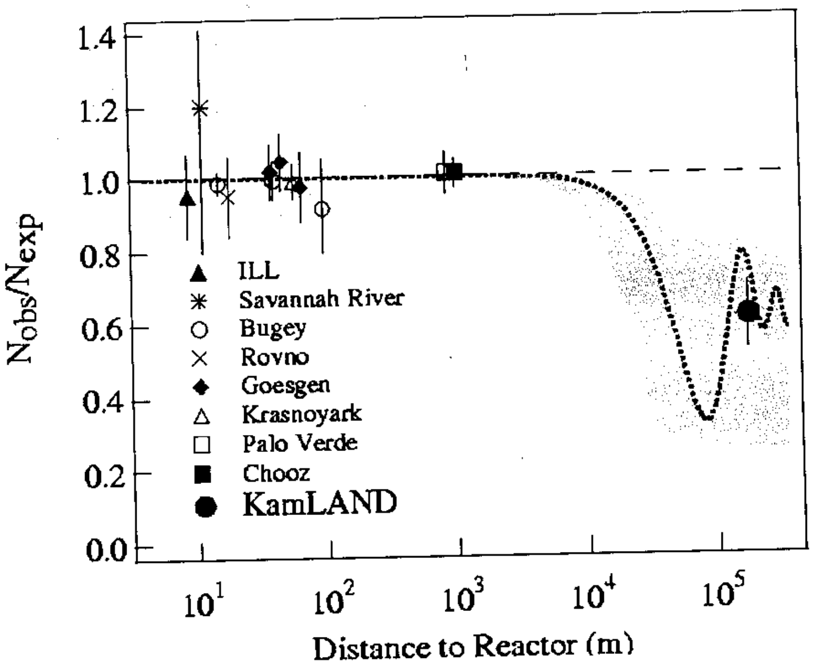
$1.8 \text{ MeV} < E_{capt} < 2.6 \text{ MeV}$

$\left.\right\} \varepsilon \sim 78\%$

$V_{FID}/V_{TOT} = 0.46$

Expected : 86.8 ± 5.6

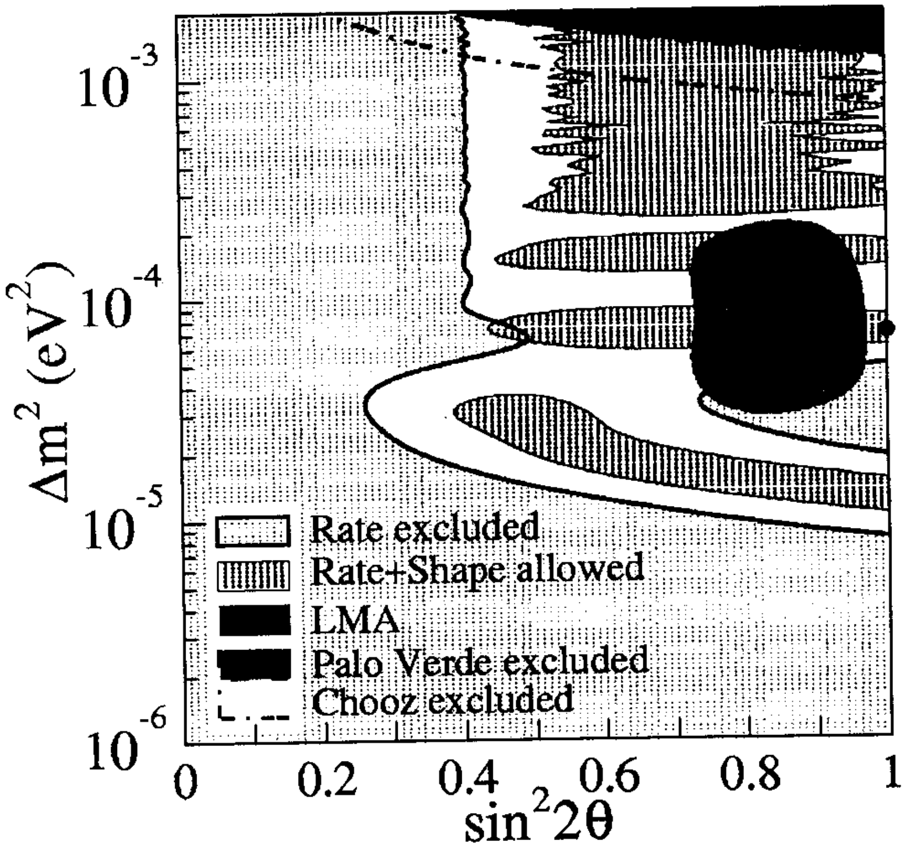
SEEN : 54



The solar neutrino problem
is finally solved !

→ neutrinos are massive
→ They show flavor oscillations
with a frequency corresponding
to

$$\Delta m^2 \sim 7\ 10^{-5}\ eV^2$$



⇒ The solar LMA solution is confirmed

Sun (ν's) and reactors ($\bar{\nu}$'s) show the same oscillation

No CPT violation

⇒ This result opens up the possibility of observing CP violation (see later)

OTHER SOLAR ν PROJECTS

General idea : Measure the low energy part of the solar spectrum (pp, Be^7) which can discriminate between different scenarios (LMA, SMA, LOW, VAC)

$\Rightarrow$ Funded : BOREXINO at GRAN SASSO (will start when the italian justice will decide so)

$\Rightarrow$ Not yet approved

① $\nu e \to \nu e$ reaction

XMASS : liquid Xenon } scintillation
CLEAN : liquid Neon }

Super MUNU } Huge gas TPC's
HELLAZ }

HERON : Superfluid Helium (scintill. + rotons)

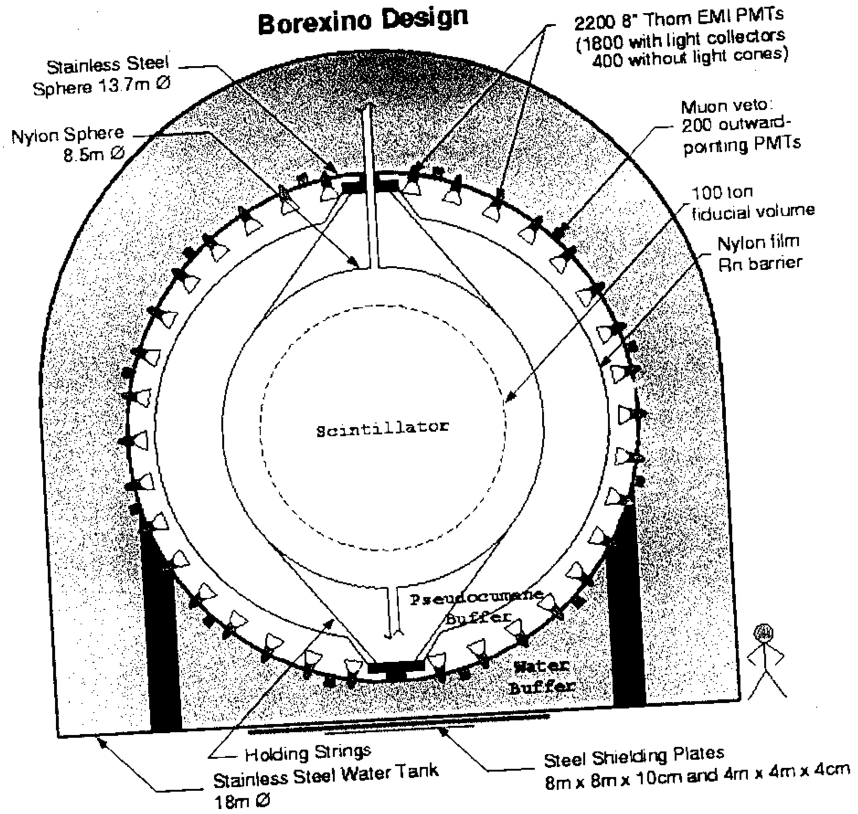
② Charged current on nucleus

LENS : Indium in liquid-loaded scintillator

MOON : liquid scintillator + Molybdenum foils

BOREXINO

(DUE TO START SUMMER 2003)



$\nu e \to \nu e$

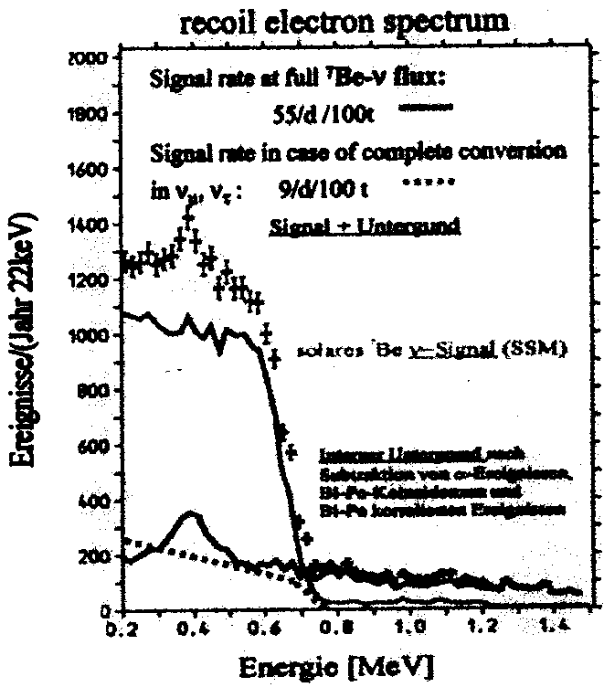
Extreme radiopurity required

$^{14}C / ^{12}C = 10^{-18}$

U, Th : 10^{-16} g/g

A prototype (CTF) has been used to demonstrate the feasibility

BOREXINO: solar ^{7}Be ν-Oscillation Signatures

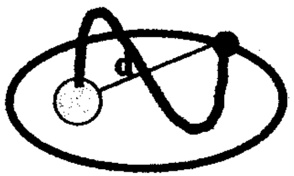


Experimental Challenge:
ultra-purity of detector components ($<10^{-16}$ gU,Th/g), techniques developed in prototype detector (CTF),

MSW-Solutions:

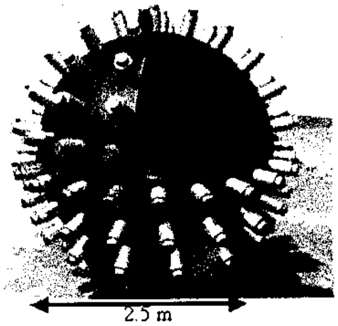
- LMA, SMA: characteristical suppression of the signal rate
- LOW: Day-Night variation of the signal

Vacuum-Solution:



- periodical variation of the signal rate on the time scale of days to months due to the excentricity of the earth´s orbit

XMASS – liquid xenon scintillation detector
Location: Kamioka



- Detection reaction: ES ($\nu + e^- \rightarrow \nu + e^-$)
- 23 t (10 t fid.) detector
- 30cm self-shield (ρ=3.06 g/cm^3)
- 1350 3" PMTs
- 42,000 scintillation photons/MeV
- No inactive buffer (23t volume active)

Background requirements: (<1BG/day)

^{136}Xe 2ν-ββ: $t_{½\,\mathrm{theory}}$=8x 10^{-21} y
⇒ 1000 events/d
⇒ isotope separation factor 10-100 !

Trace contaminations:

^{85}Kr ($t_{1/2}$=10.7y) : < 4x10^{-15} gKr/gXe
^{42}Ar ($t_{1/2}$=33y) : < 4x10^{-11} gAr/gXe
U/Th: < 4x10^{-16}

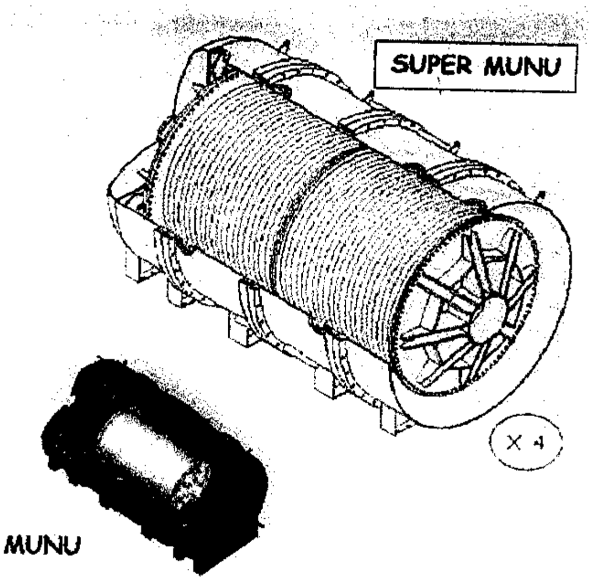
Muon induced:

In-situ spallation: 2/day ??
(assuming 10 mb)

External Background:

Similar to BOREXINO design
Self-shielding ⇒ fiducial volume

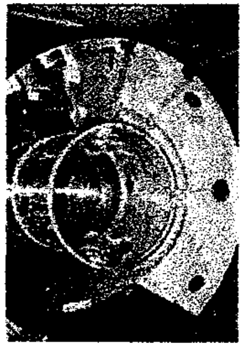
(Y. Suzuki et al.)

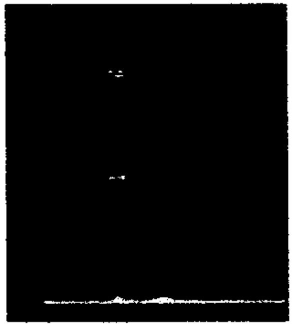


4 x 50 m^3 TPC with Anti-Compton
Neutrino Electron Scattering
CF4 at 2 bars
Measure $(T,\theta)_e$ above 100 keV $\Rightarrow E_\nu$
Rate $\approx$ 2 events / day

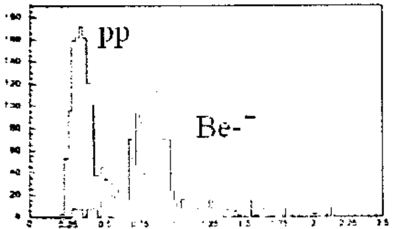
TPC – MUNU: a prototype for solar ν detection

- Low background TPC (1m³) for ν-magnetic moment
- CF_4 @ 3 bar (3.7 g/l @ 1bar)
- angular resolution: 23° @ 300-600 keV
- Sensitivity < 10^{-10} Bohr magnetons
- **Prototype for solar ν-TPC**





Range 14cm
E=190 keV
p=1bar



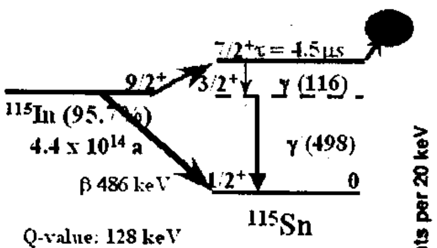
Simulation: 10y 200m³ CF_4-TPC
@ 1bar(=¯t-year)

(Broggini et al.)

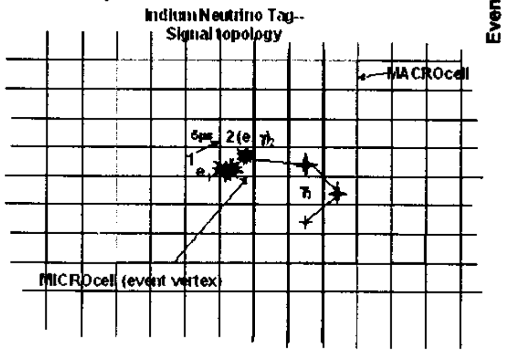
At low energy, the correlation between e^- direction & sun is lost.
Allows for kinematic reconstruction of E_ν from E_e dans θ (e, sun)

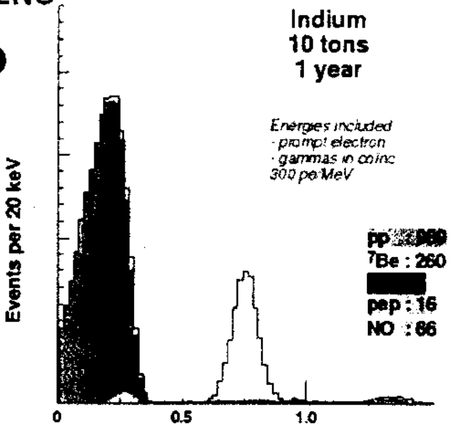
monochromatic ^{7}Be ν appears as a line!

In-LENS

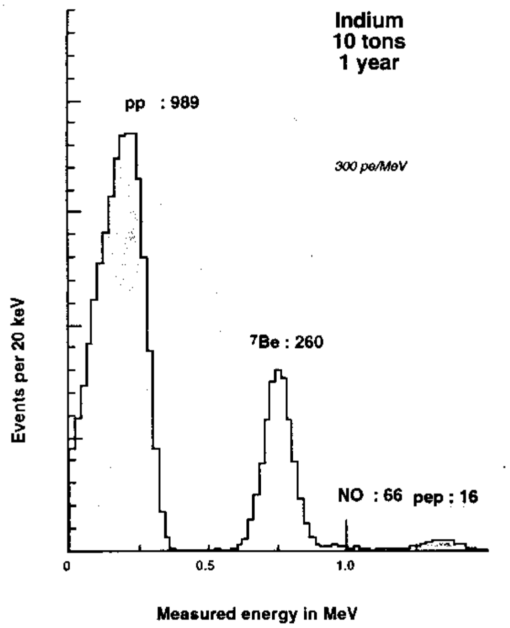


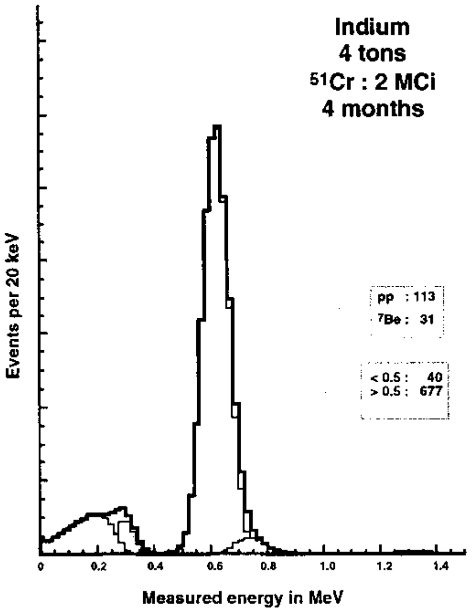
Q-value: 128 keV





Challenge:
Bgd from ^{115}In β-decay 486 keV
& Bremsstrahlung
⇒ ^{7}Be ok!
⇒ pp-ν ???
(MC: ε_ν ~ 11% i.e. 0.1 ev/day 4t In)





LENS with 10t Indium in 1 year