Probing the Universe with Neutrinos

ISAPP2008 Valencia
July 2008

Results from Neutrino Oscillation Experiments

Lecture 2

Takaaki Kajita (ICRR and IPMU, U. of Tokyo)

Overall Outline

Lecture 1:
Atmospheric neutrino oscillations
Long baseline neutrino oscillation experiments

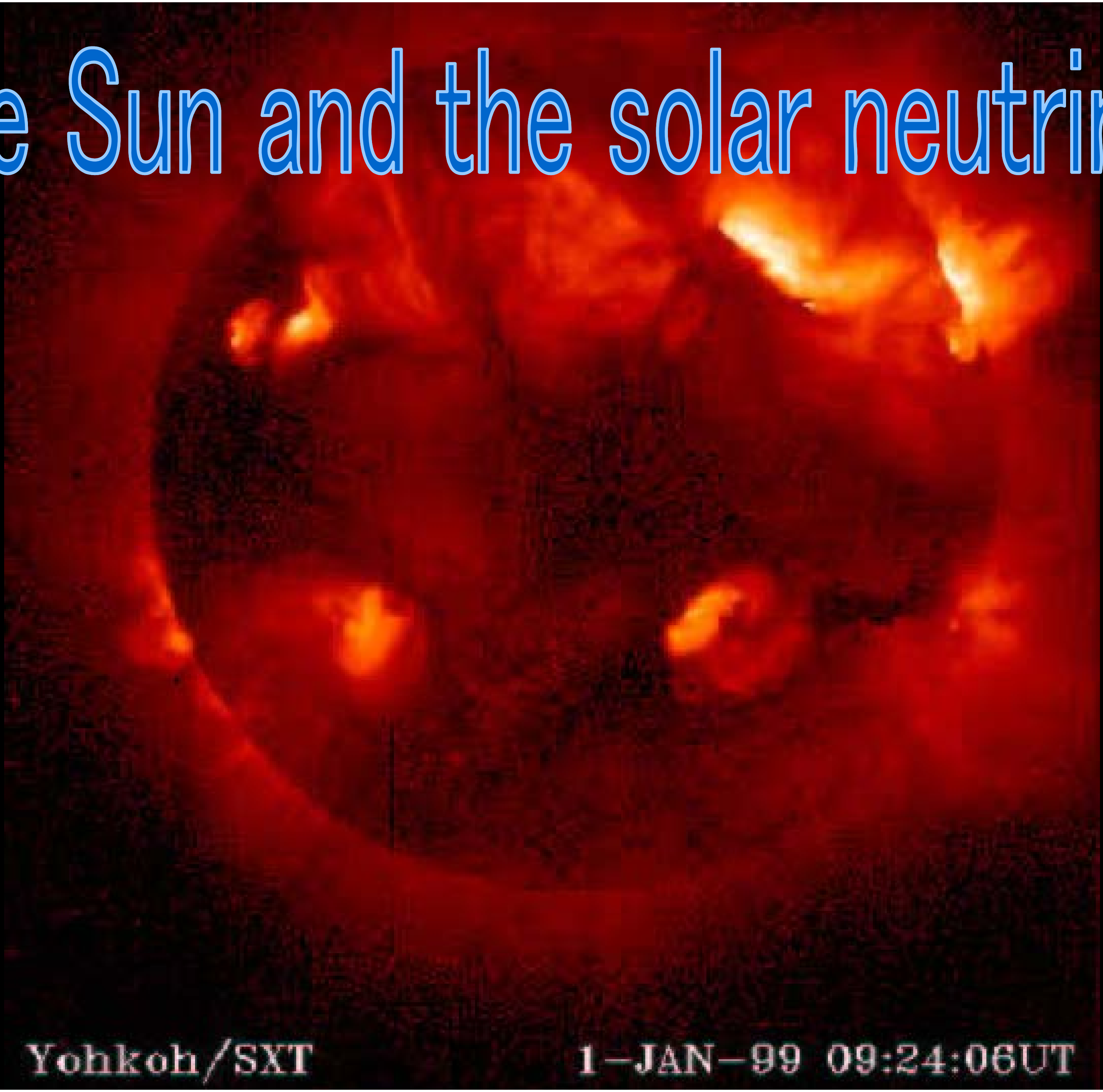
Lecture 2:
Solving the Solar Neutrino Problem with neutrino oscillations

Status of the 3 flavor effects

Outline - Lecture 2 -

- The Sun and the solar neutrinos
- Some early history (solar neutrino problem)
- Solving solar neutrino problem with neutrino oscillations
- Reactor neutrino experiment (KamLAND)
- Next step: Further confirmation of MSW
- Status of the 3 flavor effects (θ_{13})
- Summary of Lecture 2

The Sun and the solar neutrinos



How does the Sun shine?

Quick answer: nuclear fusion reactions

A Helium nucleus is produced by the fusion of 4 Hydrogen nuclei;

$$4p \rightarrow He + 2e^{+} + 2\nu_e$$

This reaction produces about 27 MeV energy.

Then, the total neutrino flux on the Earth is;

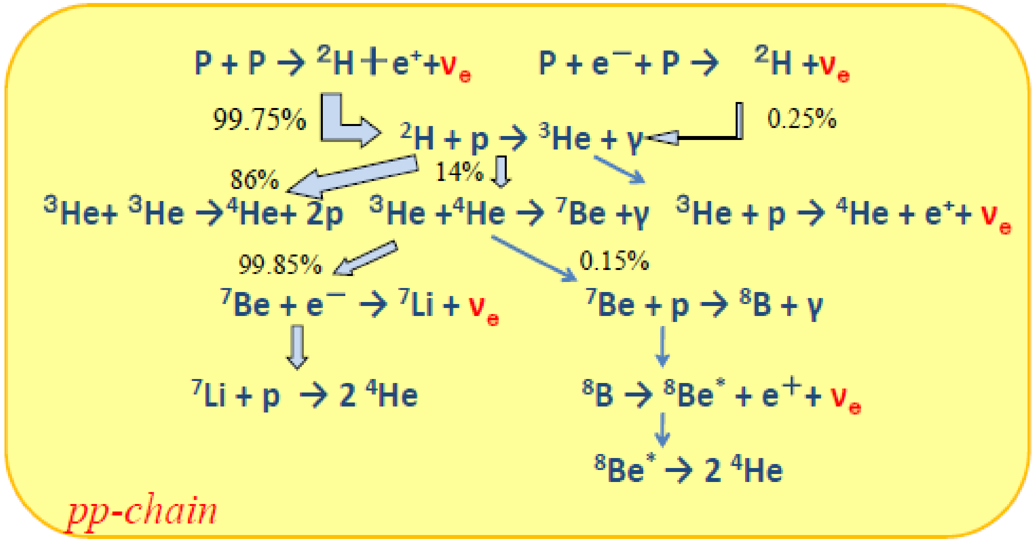
$$flux = \frac{1}{4\pi R^2} \times \frac{L_{sun}}{27 MeV} \times 2\nu_e$$

$$(L_{sun} = 3.86 \times 10^{33} erg / \sec)$$

$$= 6 \times 10^{10} \nu_e / cm^2 / \sec$$

If one observe these neutrinos, it is a proof that the generation of the energy in the Sun is due to nuclear fusion.

Solar neutrino spectrum



$P + P \rightarrow {}^{2}H + e^{+} + \nu_e$ $P + e^{-} + P \rightarrow {}^{2}H + \nu_e$

99.75% 0.25%

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

86% 14%

${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$ ${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$ ${}^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu_e$

99.85% 0.15%

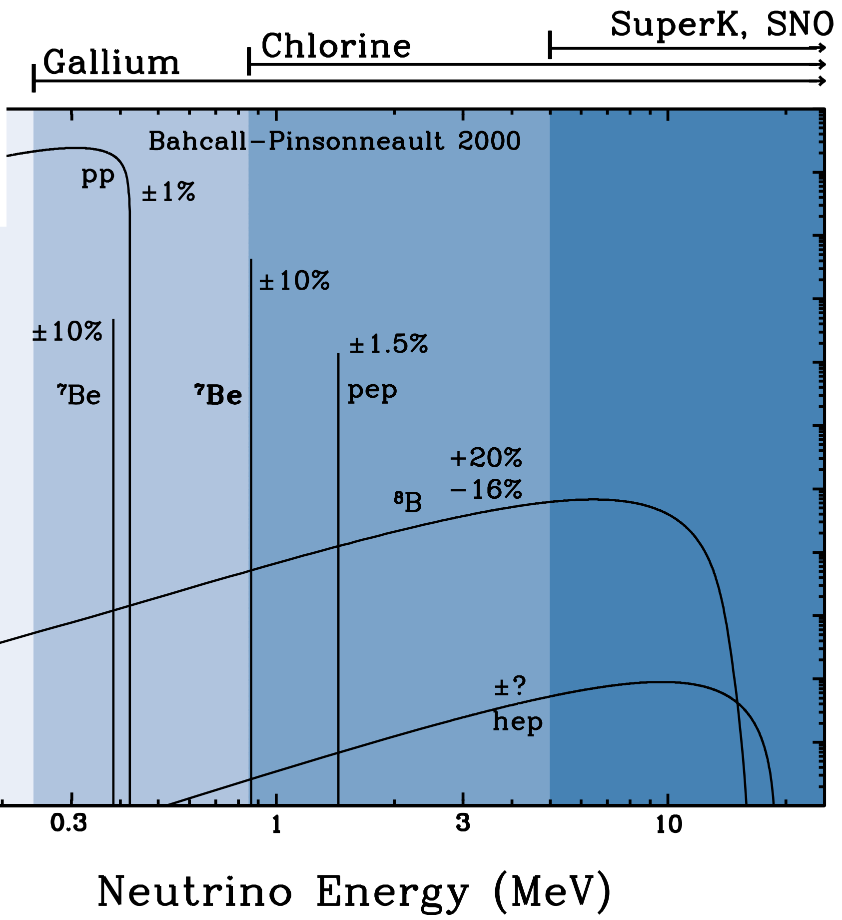
${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e$ ${}^{7}Be + p \rightarrow {}^{8}B + \gamma$

${}^{7}Li + p \rightarrow 2\,{}^{4}He$ ${}^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + \nu_e$

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

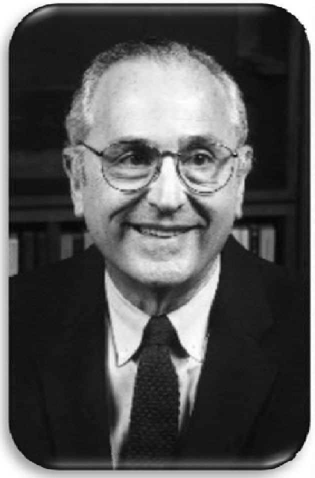
pp-chain

However, in reality, 4 protons cannot make a Helium nucleus at a time…
➔ chain reactions

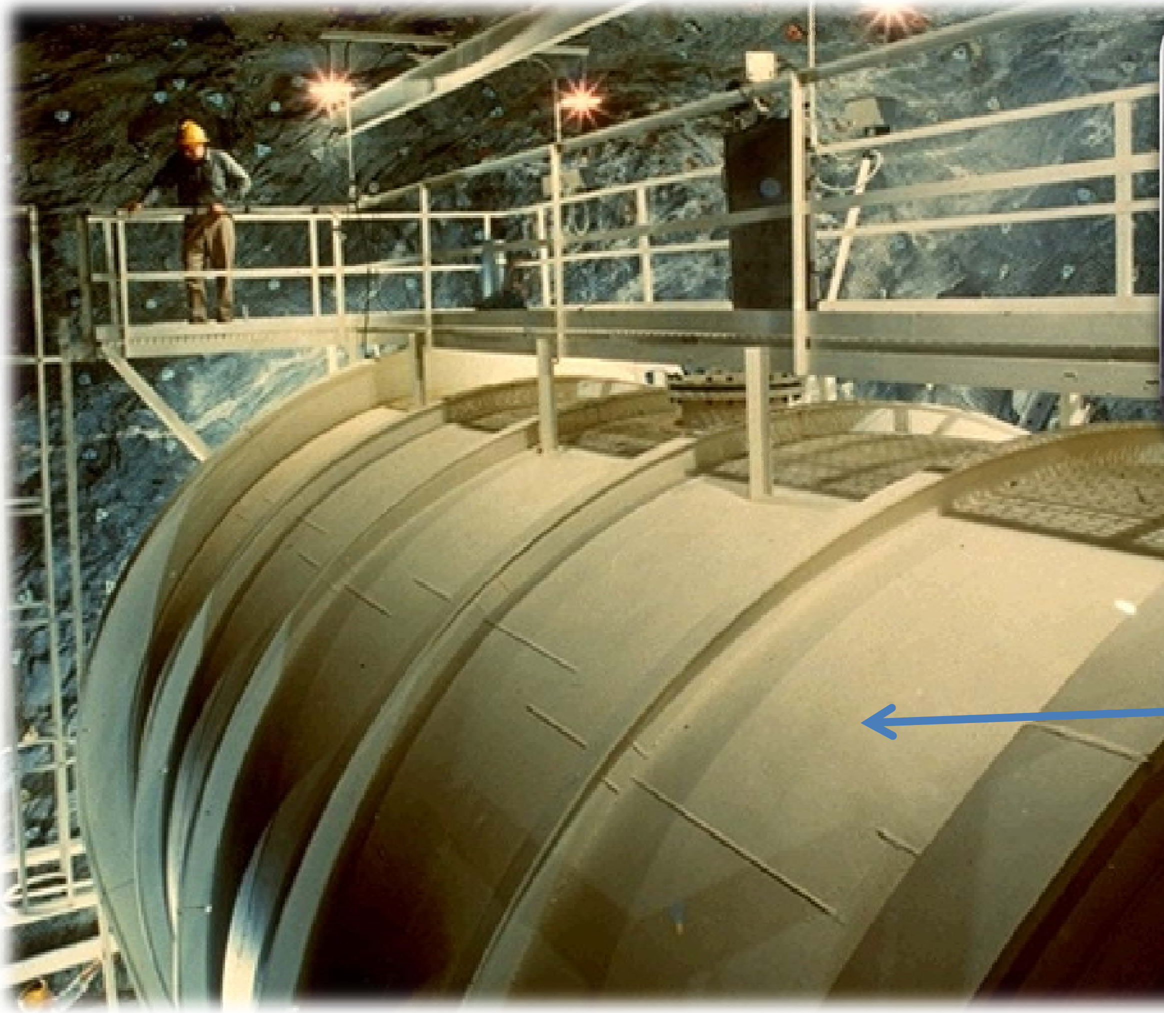


Detecting Solar Neutrinos

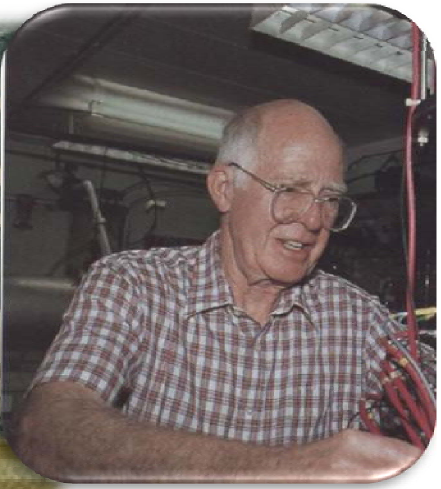
J.N. Bahcall “Solar neutrinos I: Theoretical” P.R.L. 12, 300 (1964)
R. Davis Jr. “Solar neutrinos II: Experimental”, P.R.L.12, 303 (1964)



J. N. Bahcall



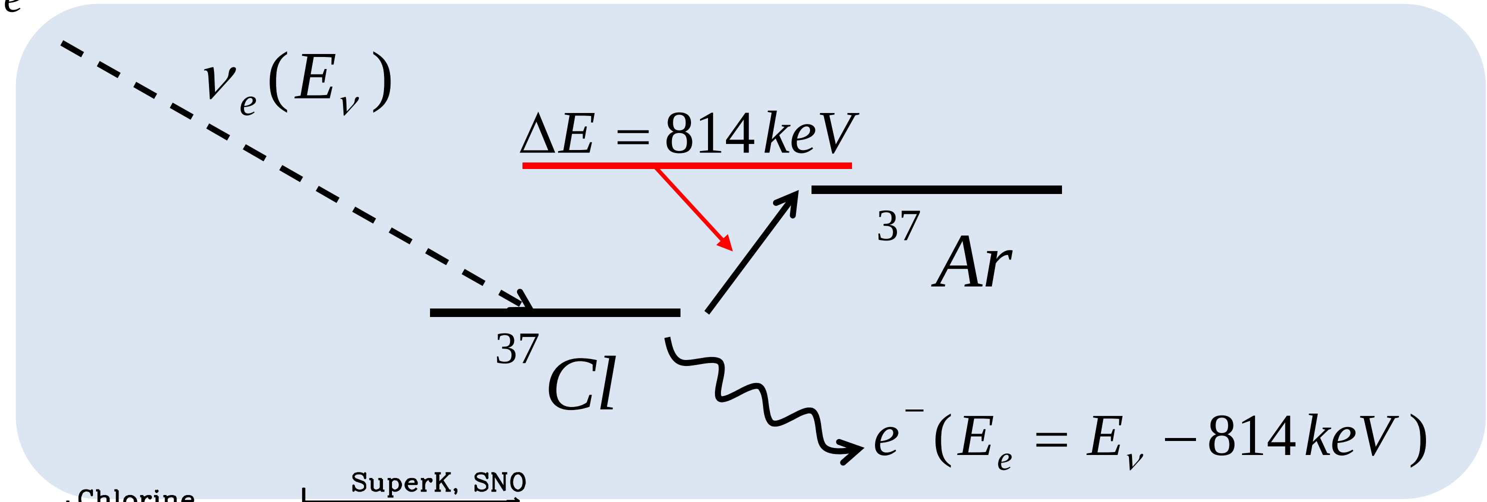
600ton C_2Cl_4

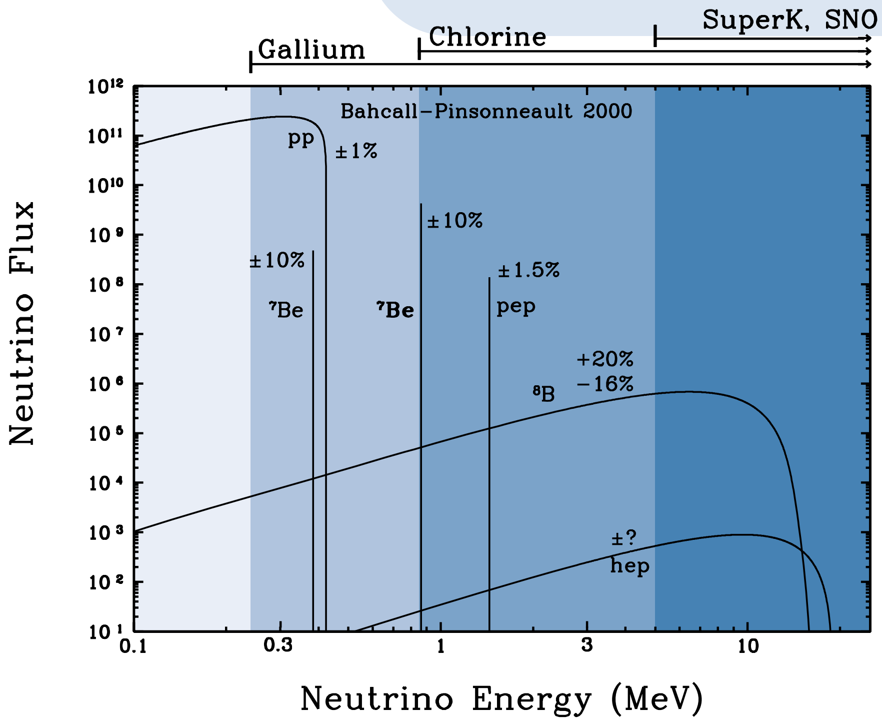


R. Davis Jr.

Interaction of solar neutrinos with ^{37}Cl

$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$ (Threshold = 814keV)





pp: 0

pep: 0.22

^{7}Be: 1.16

^{8}B: 6.32

Others: 0.41

(These numbers are slightly old…)

Total: $8.1^{+1.4}_{-1.1}$ SNU (solar neutrino unit

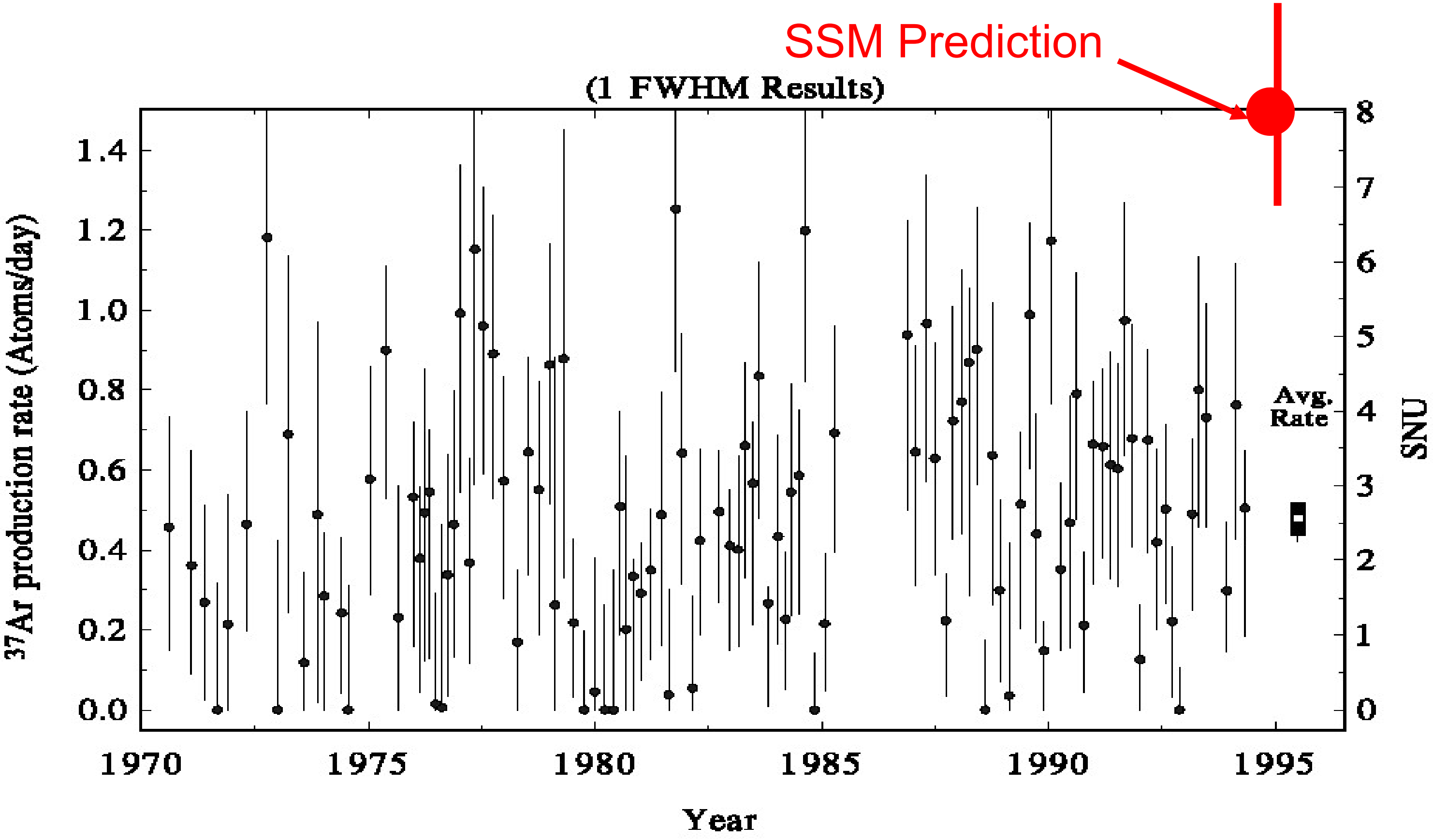
= interactions/10^{36}target/sec)

Solar Neutrino Problem

Search for Neutrinos from the Sun

R. Davis Jr., D.S. Harmer, and K.C. Hoffman, PRL 20, 1205 (1968)

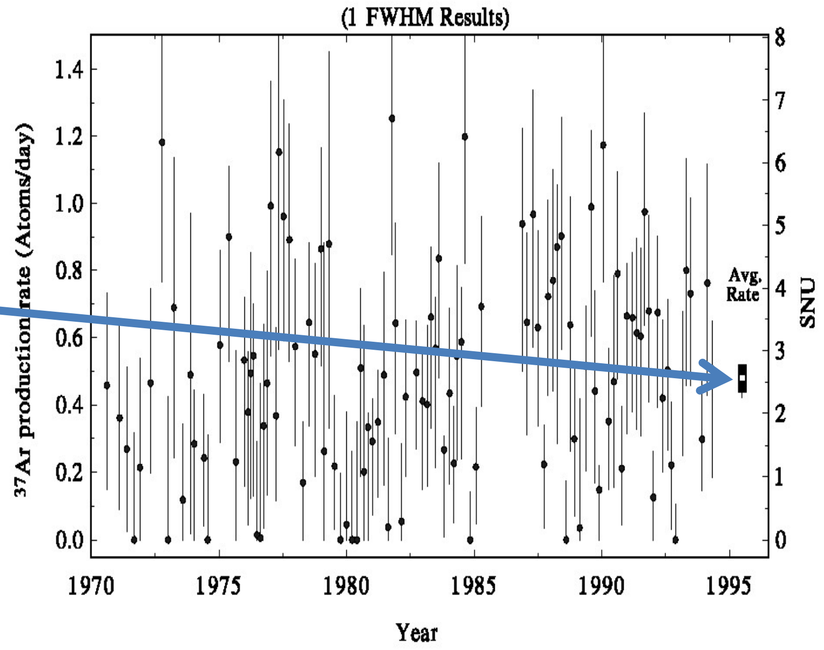
The Ar production rate by $\nu_e{}^{37}Cl \rightarrow e^{-}\,{}^{37}Ar$ was less than 3×10^{-36} sec^{-1} per ^{37}Cl atom (3 SNU), which was substantially smaller than the prediction by the Standard Solar Model.



Solar neutrino experiments are difficult

0.5 ^{37}Ar production per day

600ton C_2Cl_4

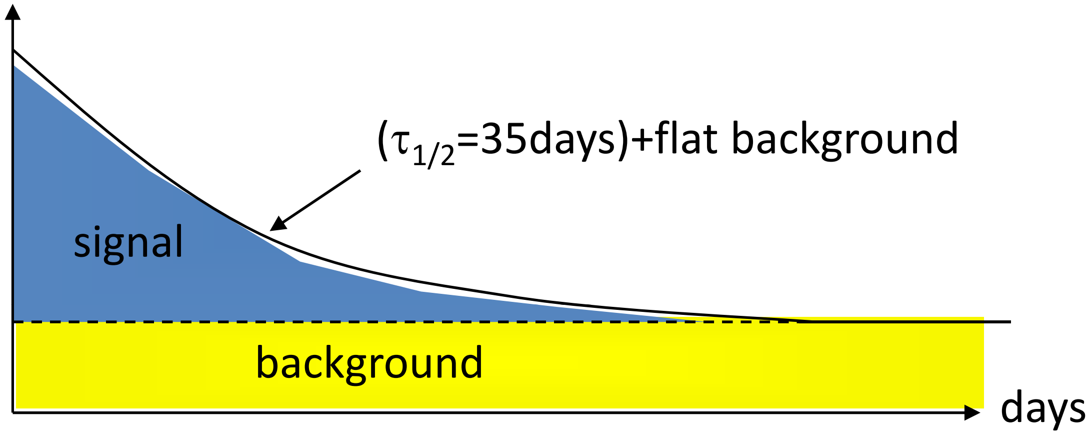


Extract ^{37}Ar from the 600ton tank.

Then,

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

Electrum capture
Detect 2.82keV Auger electrons

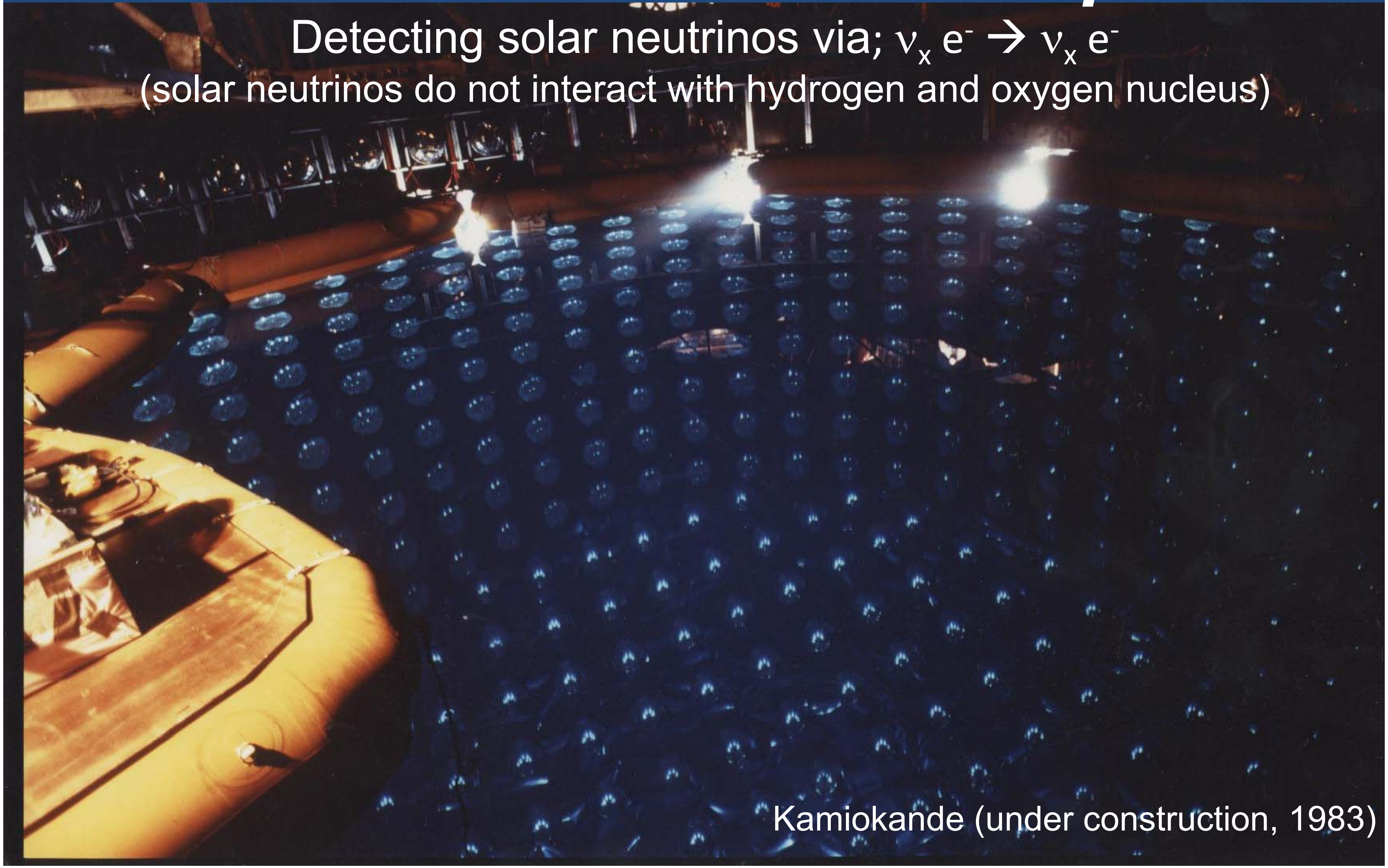


Possible solutions to the solar neutrino problem (before mid. 1980's)

- Experiment might be wrong…
- Theory (SSM) might be wrong….

- Some new physics (but less serious ??) …
  - ➔ 3 flavor full mixing oscillation ?
  - ➔ 2 flavor "just-so" oscillation ?
  - ➔ …

Detecting solar neutrinos with the water Cherenkov technique



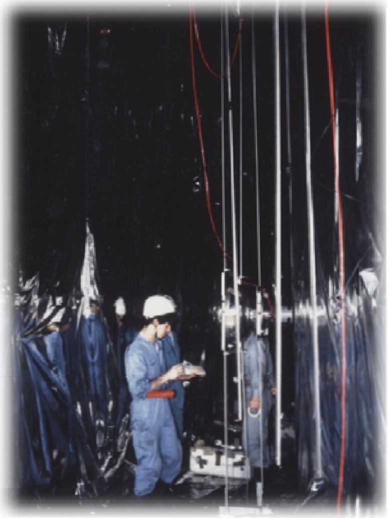
Detecting solar neutrinos via; $\nu_x e^- \rightarrow \nu_x e^-$

(solar neutrinos do not interact with hydrogen and oxygen nucleus)

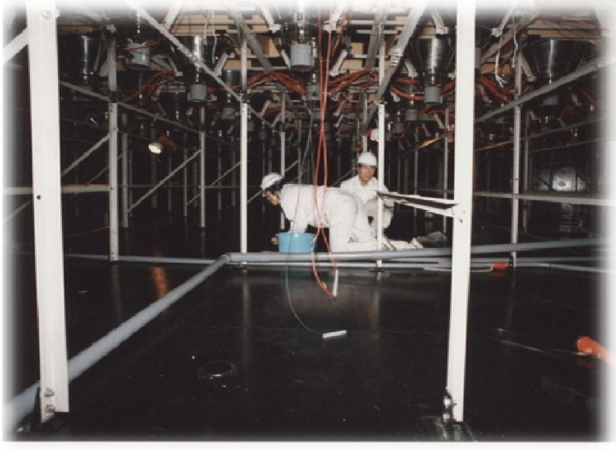
Kamiokande (under construction, 1983)

Toward the observation of solar neutrinos

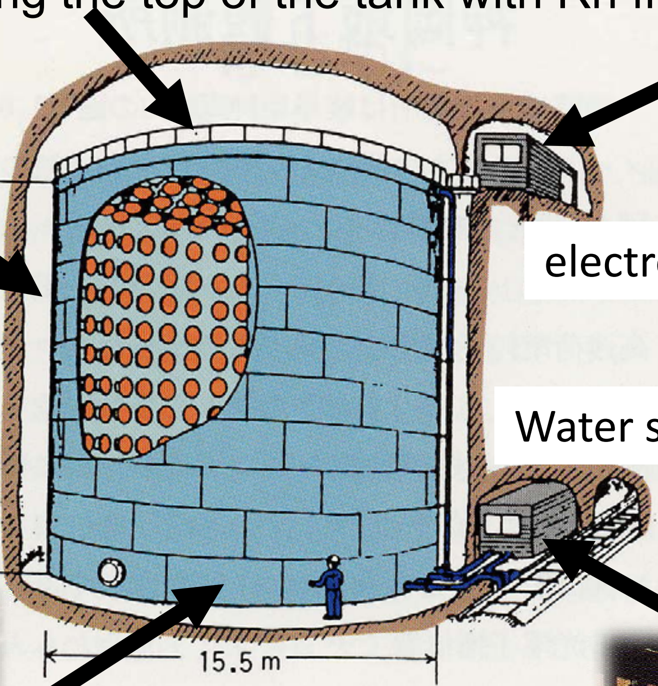
(difficulty: Kamiokande was designed to detect 1GeV (not 10MeV) signal)



Installation of anti-counters

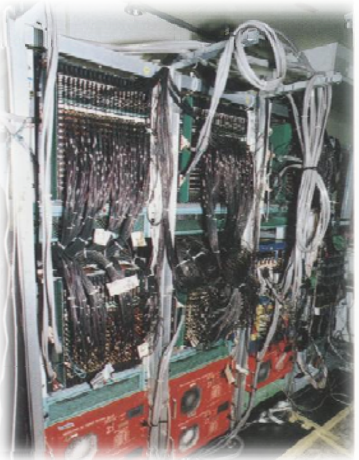


Schilling the top of the tank with Rn free air



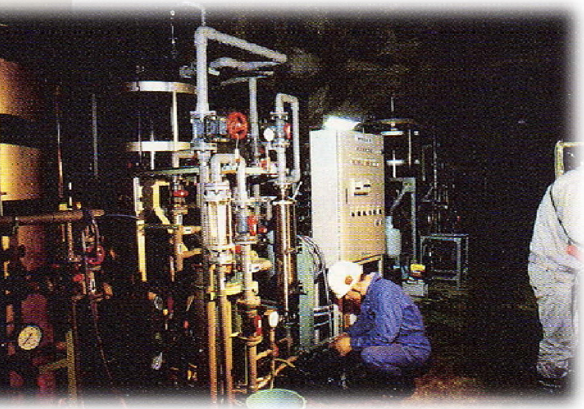
electronics

Water system



Electronics that measure multi-hit T and Q (U. of Penn)

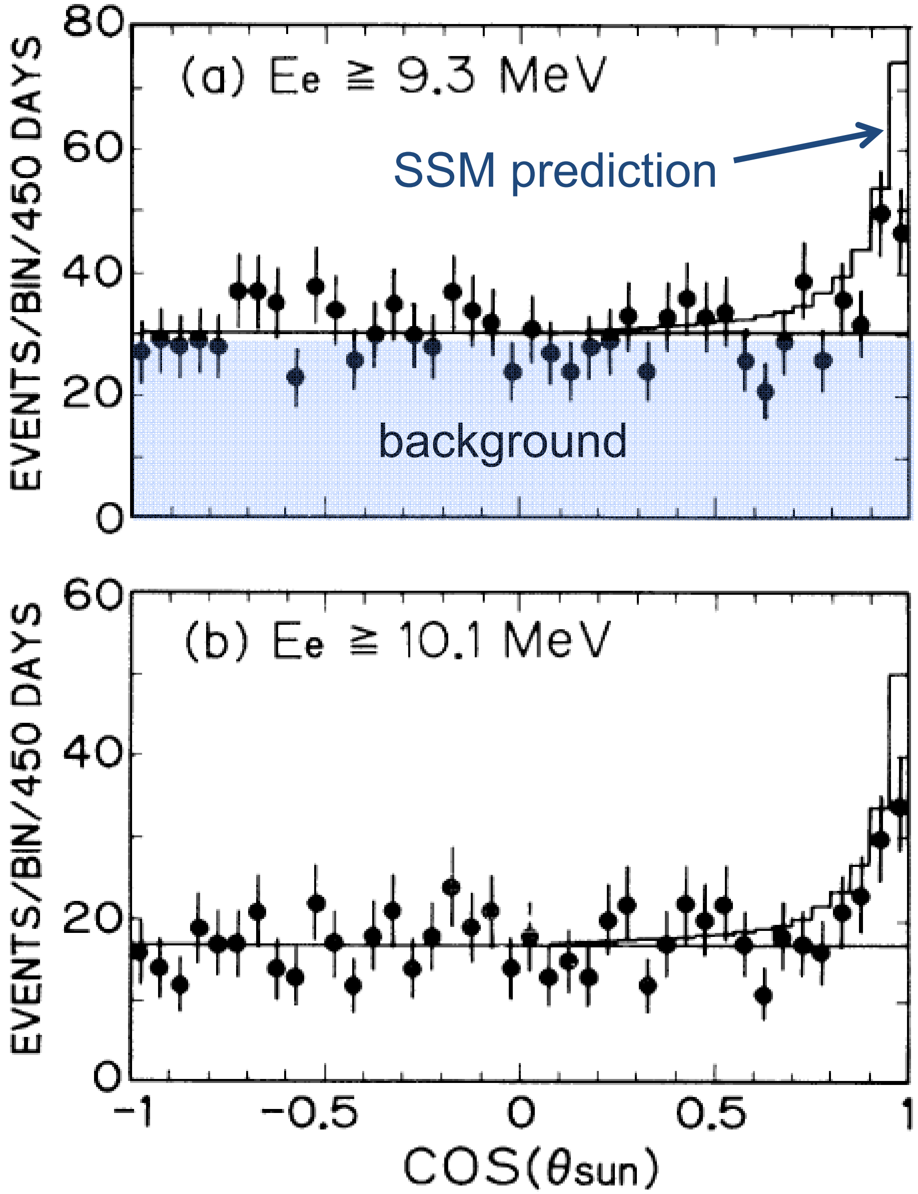
Improving the water purification system



Solar neutrino detection in Kamiokande

Observed flux was;
0.46±0.13(stat)±0.08(syst)
of the SSM prediction.
PRL 63, 16 (1989)

“Experiment wrong”
solution ruled out.



Can we detect neutrinos whose flux is less dependent on SSM ?

Yes, one should observe *pp* neutrinos.
How? ➔ Ga experiments.

$$\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$$ (threshold = 233 keV)

pp: 69.9

pep: 2.9

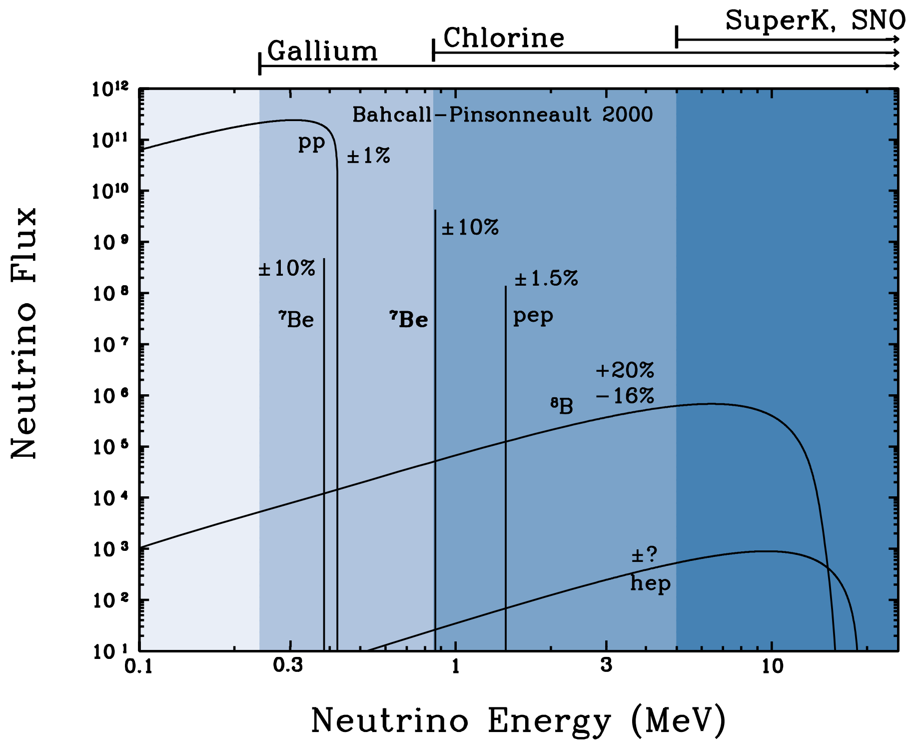
^{7}Be: 34.5

^{8}B: 12.3

others: 9.1

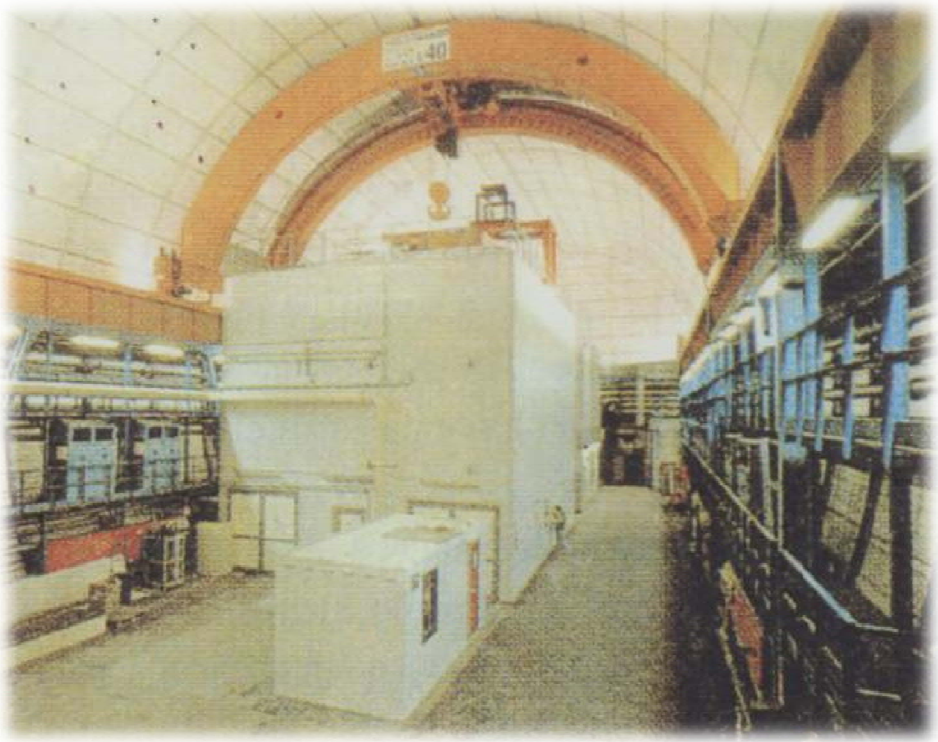
Total: 129^{+9}_{-7} SNU

(These numbers are slightly old…)



Ga experiments

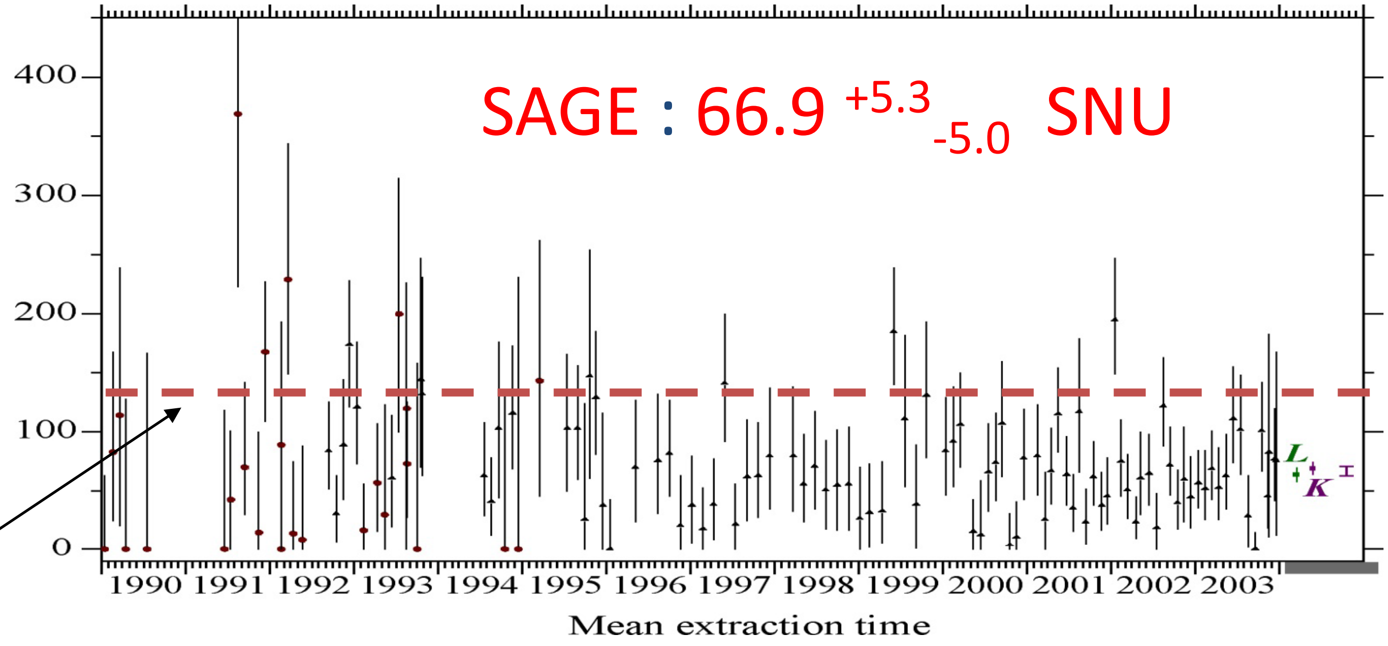
SAGE (Baksan, Russia)



Gallex/GNO (Gran Sasso, Italy)

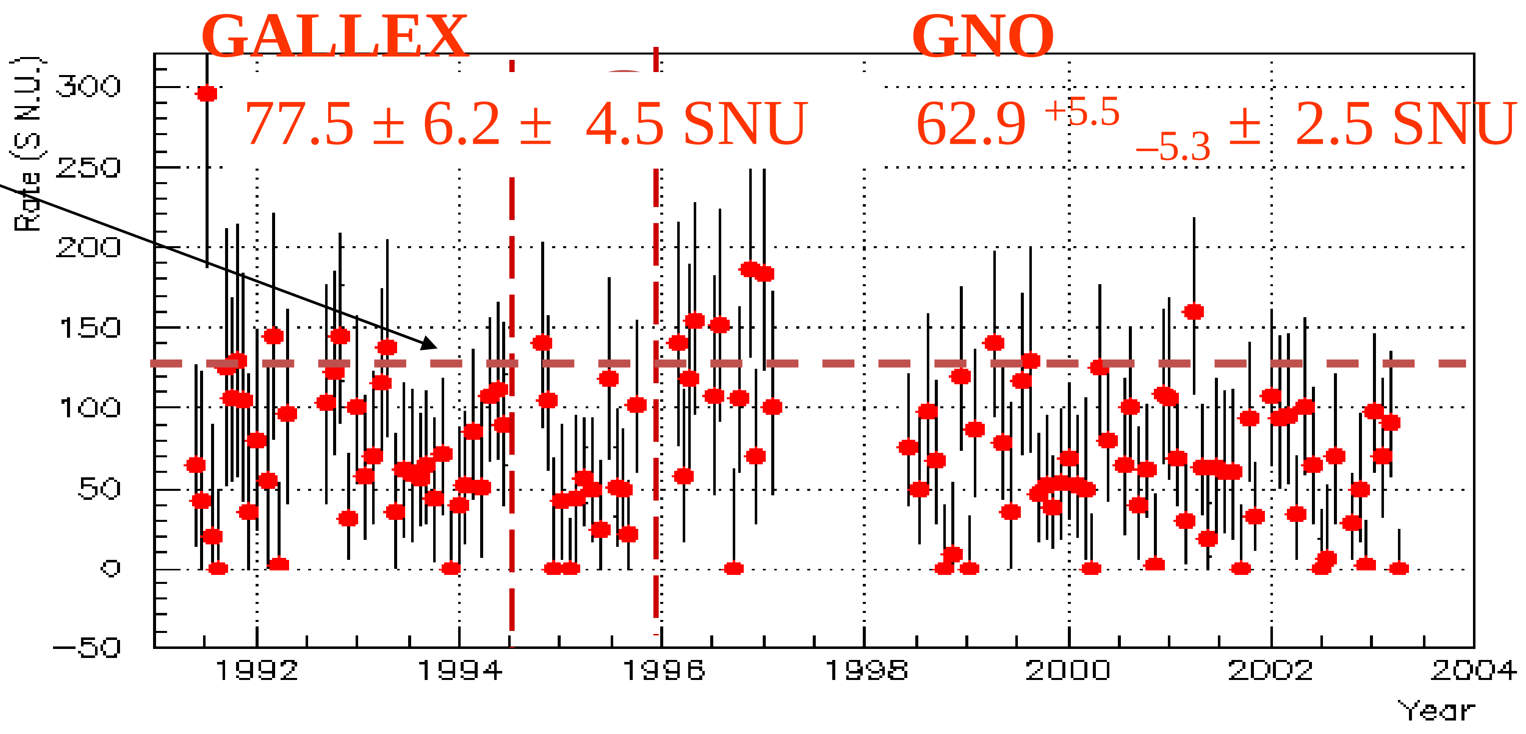
Experimental method: radiochemical technique (similar to the Cl experiment, but more complicated.)

Results from Ga experiments



SAGE : $66.9^{+5.3}_{-5.0}$ SNU

SSM prediction



GALLEX

77.5 ± 6.2 ± 4.5 SNU

GNO

$62.9^{+5.5}_{-5.3}$ ± 2.5 SNU

Conclusions from Ga experiments

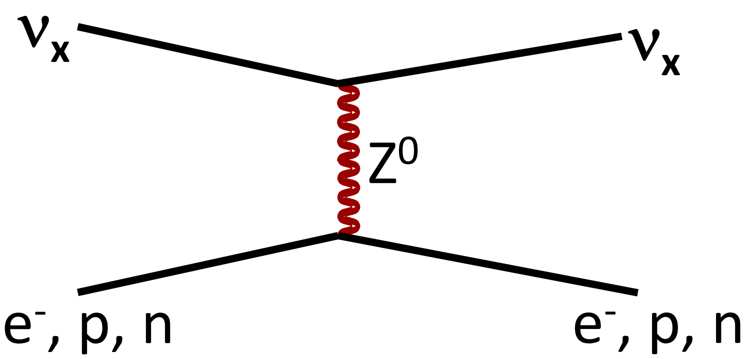
- Ga experiments also observed the solar neutrino deficit.
- The data might suggest neutrino oscillations.
- However, the data might be explained (within a few standard deviations) that the pp neutrinos are detected as expected, while the other neutrinos have much lower flux than calculated by the SSM.

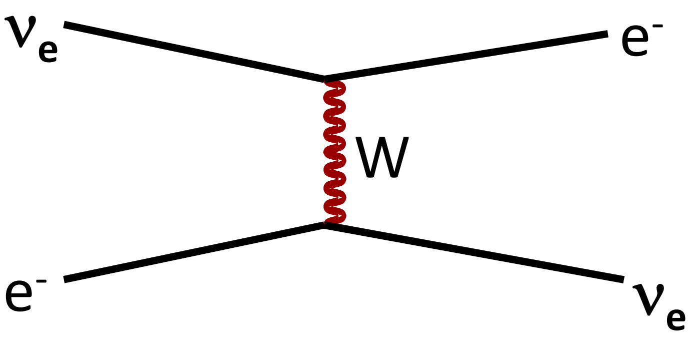
⇩

- Conclusion: It is difficult to conclude…

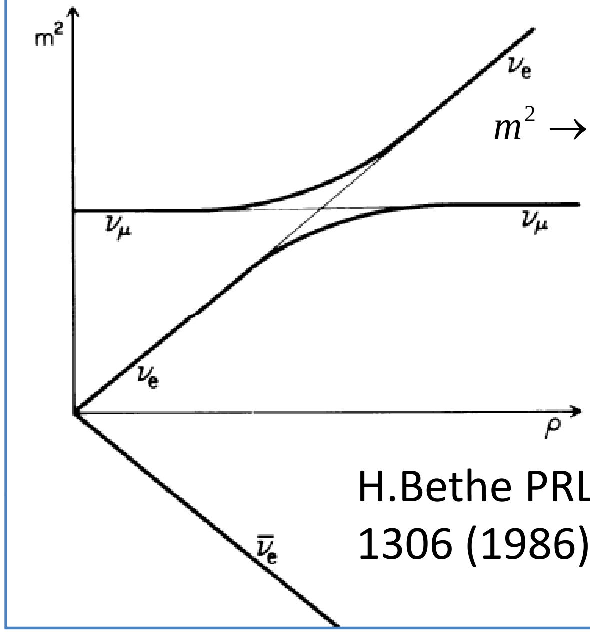
Breakthrough in neutrino oscillation theory: the MSW effect

Neutrino oscillation in matter is different from that in the vacuum due to;





Wolfenstein pointed out the matter effect in neutrino oscillations (1978). Mikheyev and Smirnov pointed out that the large flavor conversion can happen due to the matter effect (1985).

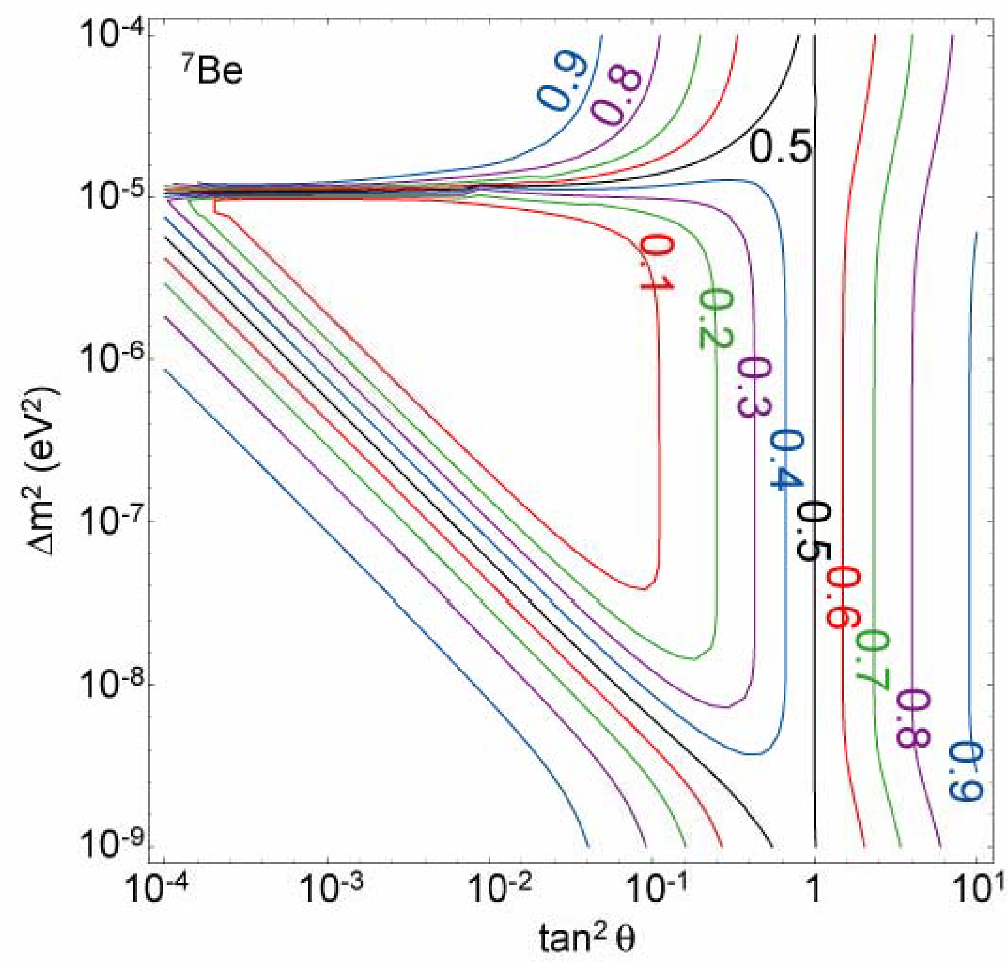


$$m^2 \rightarrow m^2 + 2\sqrt{2}\left(\frac{GY_e}{m_n}\right)\rho E$$

H.Bethe PRL 56, 1306 (1986)

MSW effect and solar neutrino oscillation probabilities

ν_e survival probability for ^{7}Be neutrinos



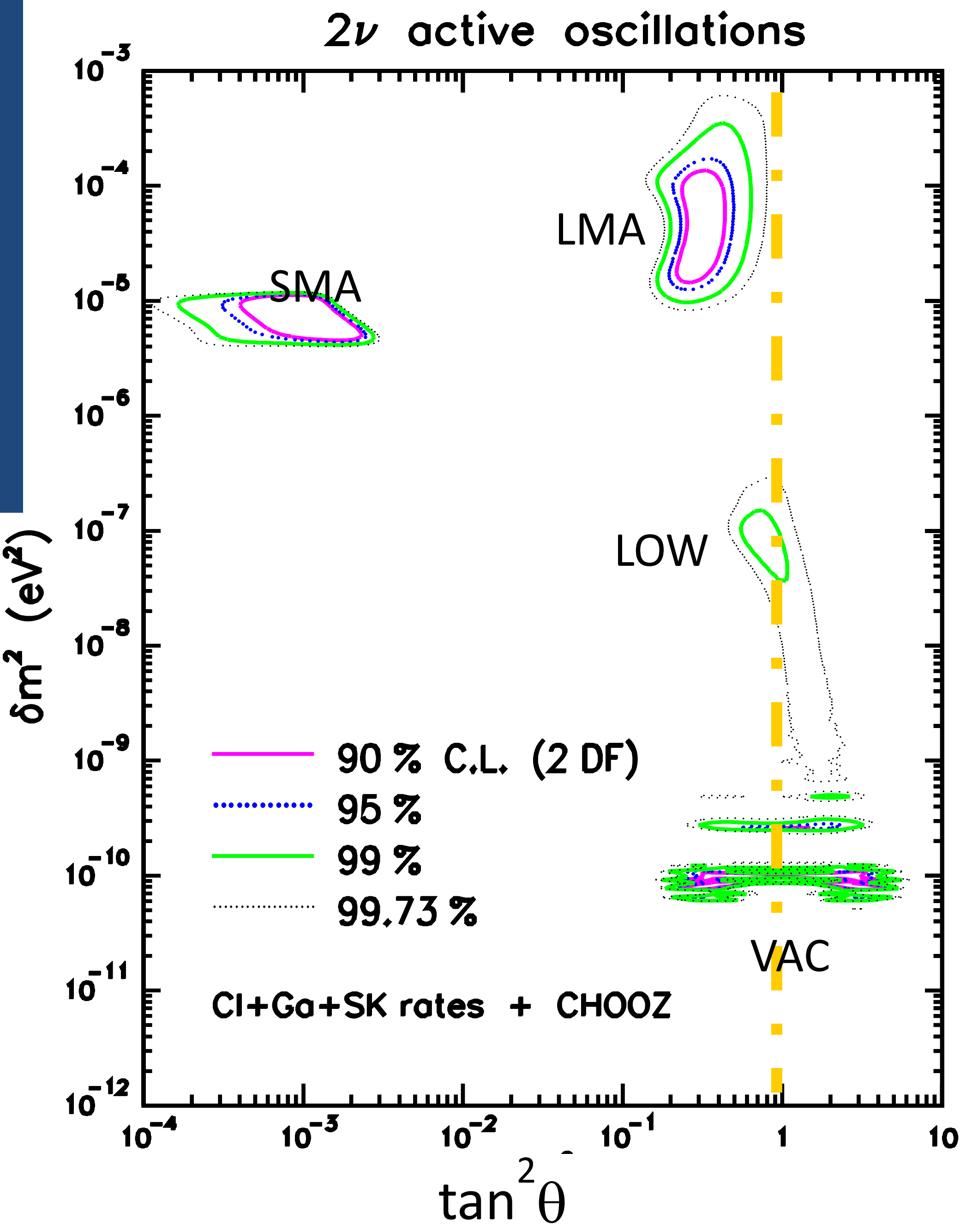
Small mixing angle (θ) (which was generally expected from the quark mixing angles) can generate large solar ν_e deficit !

Neutrino oscillation
➔ A serious possibility !

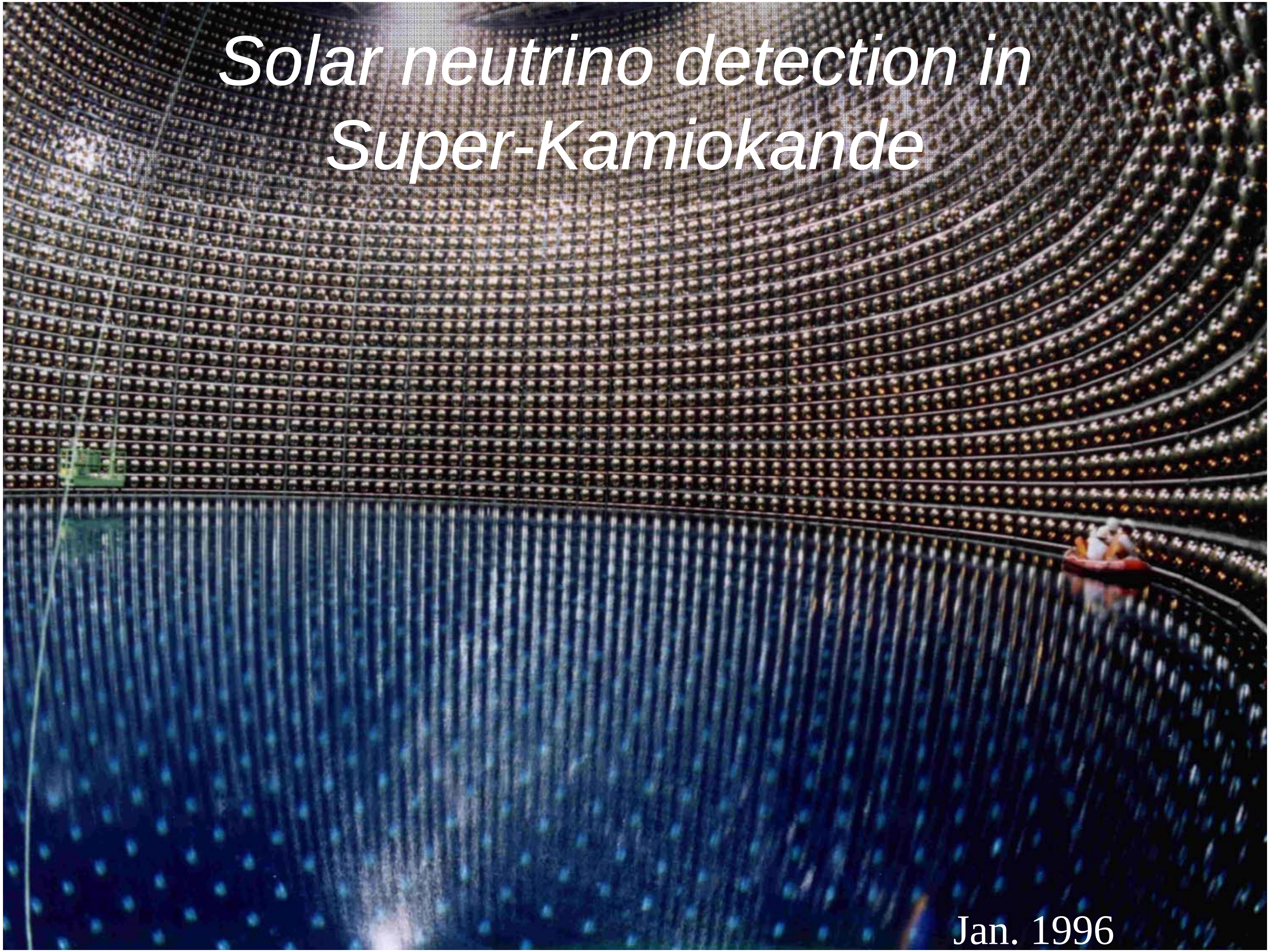
Neutrino oscillation parameters at the end of the last century....

But no smoking gun evidence…

Fogli et al.

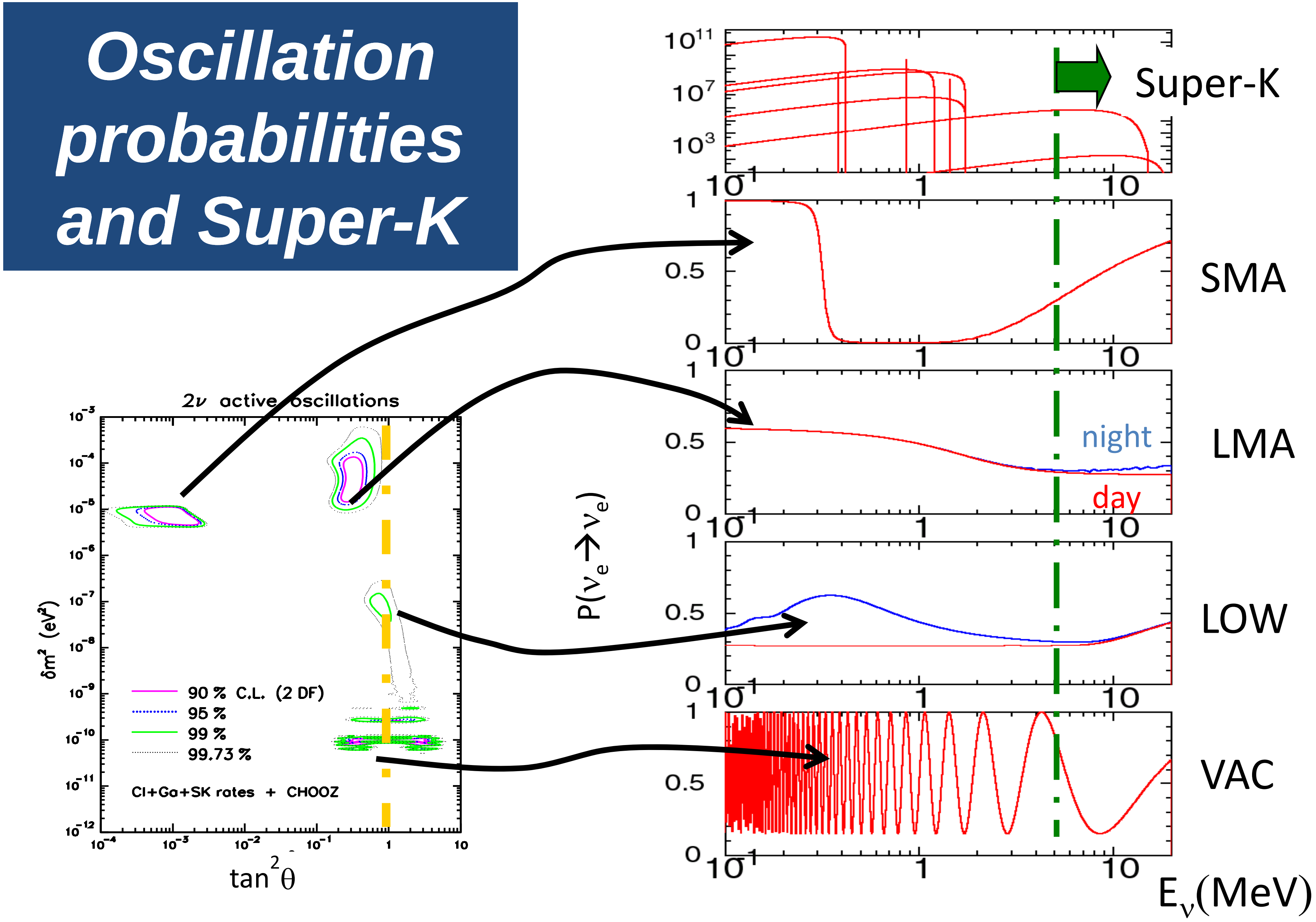


Solar neutrino detection in Super-Kamiokande



Jan. 1996

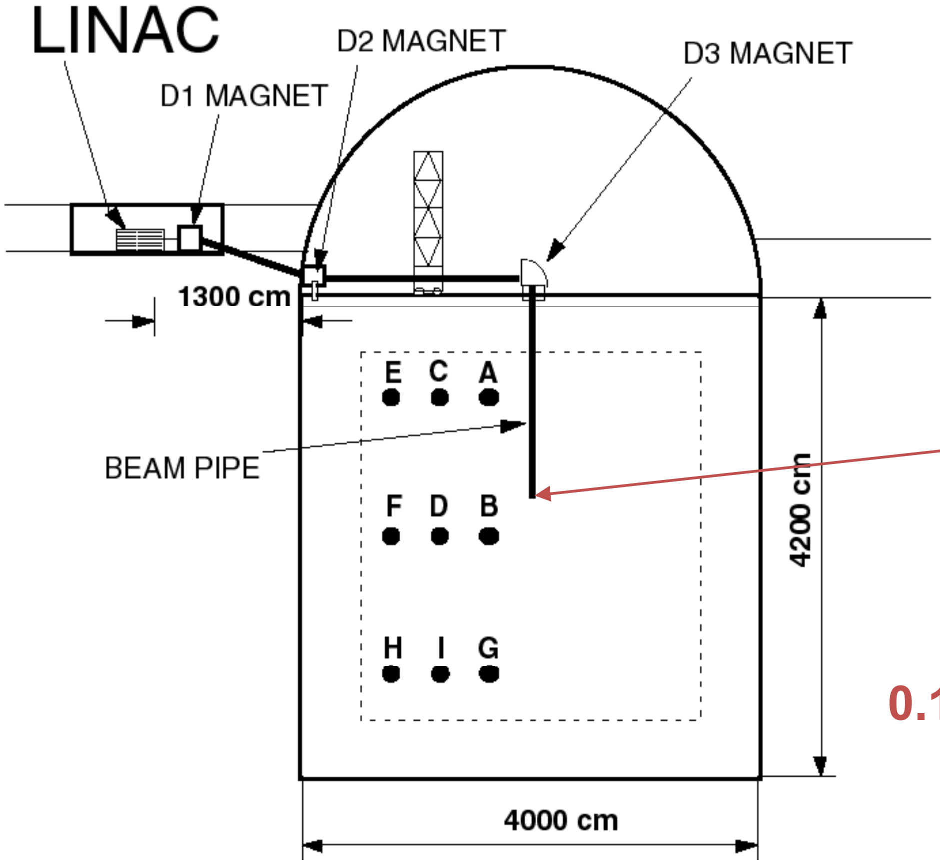
Oscillation probabilities and Super-K

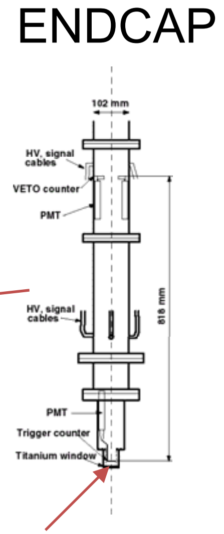


Day-night flux difference, spectrum distortion

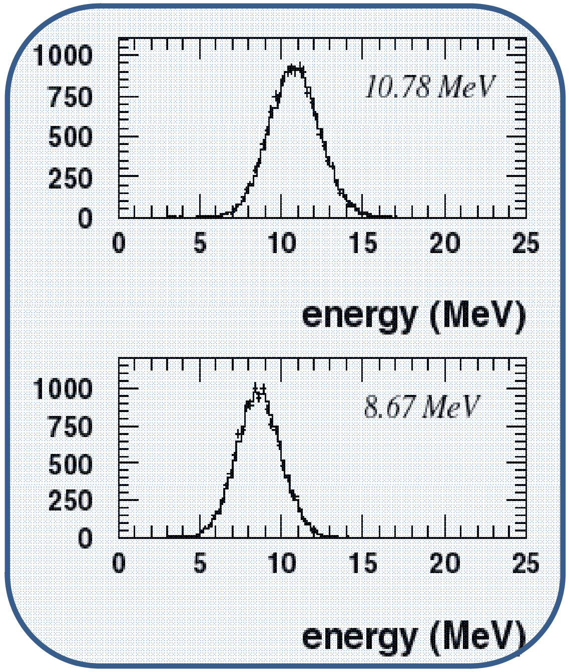
Calibration of Super-K with an electron LINAC

Precise calibration of absolute energy scale, energy resolution, and angular resolution using electron LINAC.





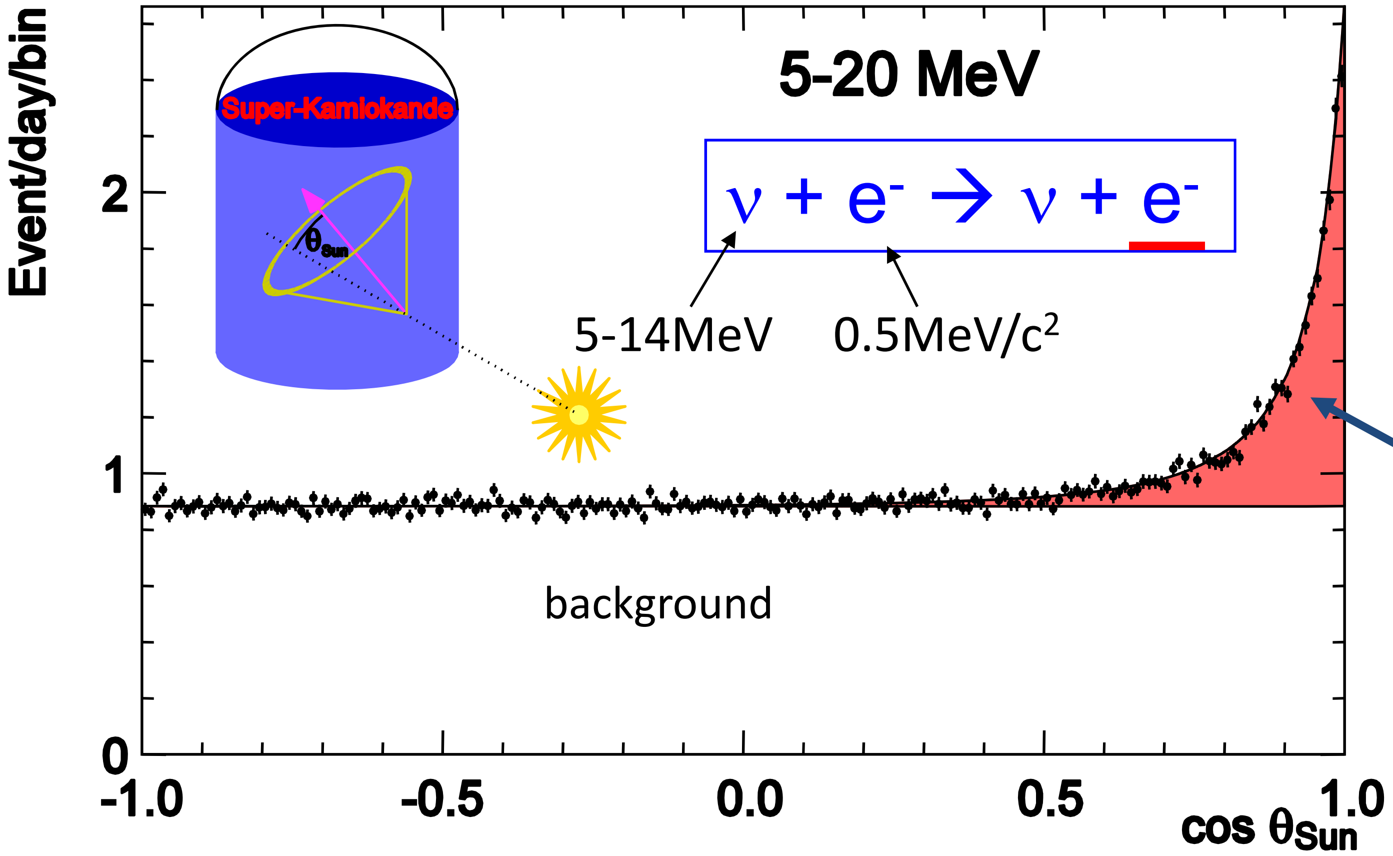
0.1mm thick Ti window



- Beam energy: 5 ~ 16 MeV/c

Systematic error in the absolute energy scale : 0.64 %.

Solar neutrino data from Super-K



$\nu + e^- \rightarrow \nu + \underline{e^-}$

5-14MeV 0.5MeV/c²

May 31, 1996 –
July 13, 2001
(1496 days)

22400±230
solar ν events

(14.5 ev/day)

Assuming ν_e only:

^{8}B flux : 2.35 ± 0.02 ± 0.08 [x 10^6 /cm^2/sec]

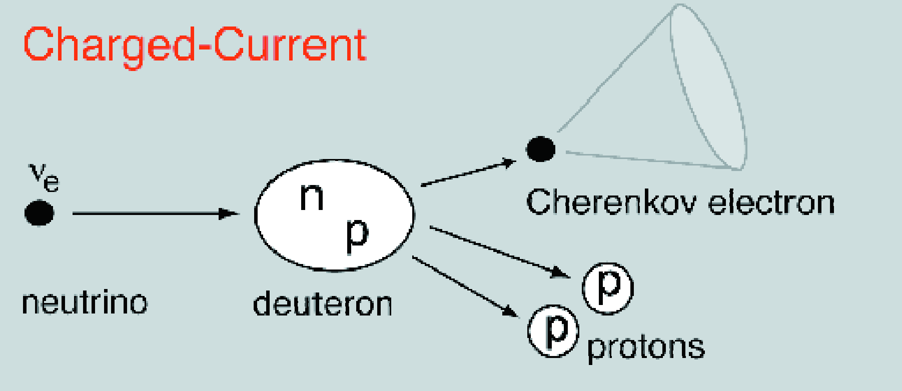
$$\frac{\text{Data}}{\text{SSM(BP2000)}} = 0.465 \pm 0.005 \, {}^{+0.016}_{-0.015}$$

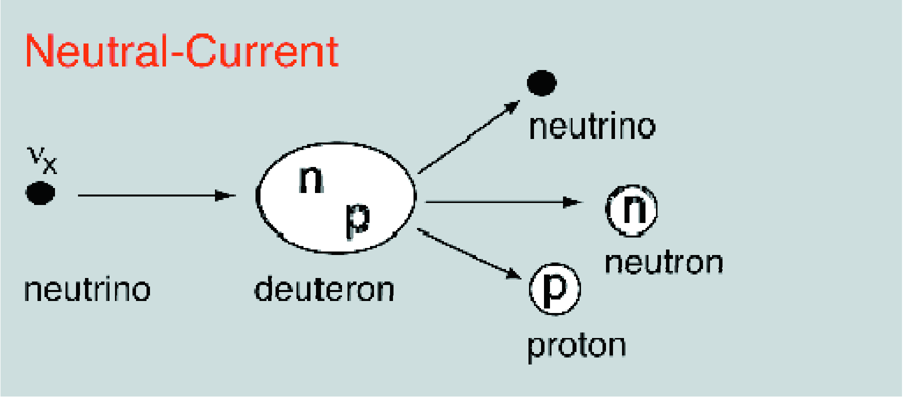
However, no evidence for spectrum distortion nor day-night effect.

Heavy water experiment

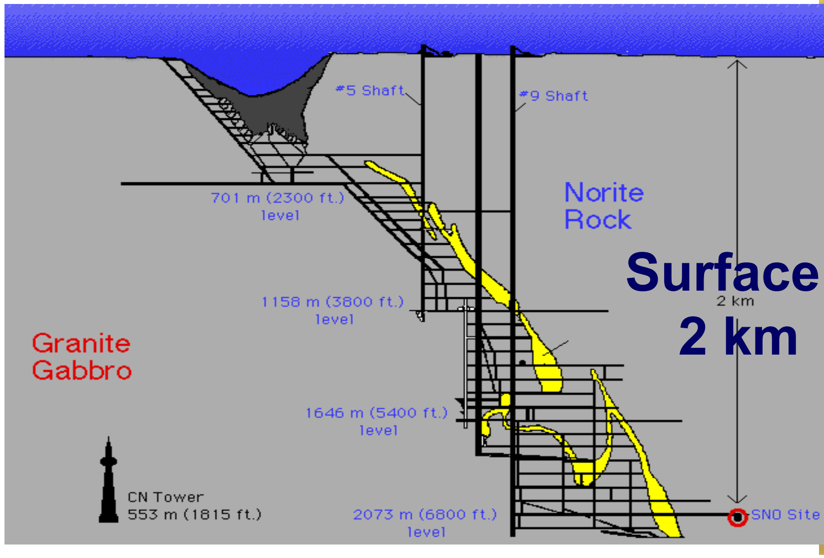
H.Chen PRL 55, 1534 (1985)
“Direct Approach to Resolve the Solar-neutrino Problem”

A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions. Then, the total neutrino flux and the electron-neutrino flux would be separately determined to provide independent tests of the neutrino-oscillation hypothesis and the standard solar model. A large heavy-water Cherenkov detector, sensitive to neutrinos from ^{8}B decay via the neutral-curent reaction $\nu+d\rightarrow\nu+p+n$ and the charged-current reaction $\nu_e+d\rightarrow e^-+p+p$, is suggested for this purpose.

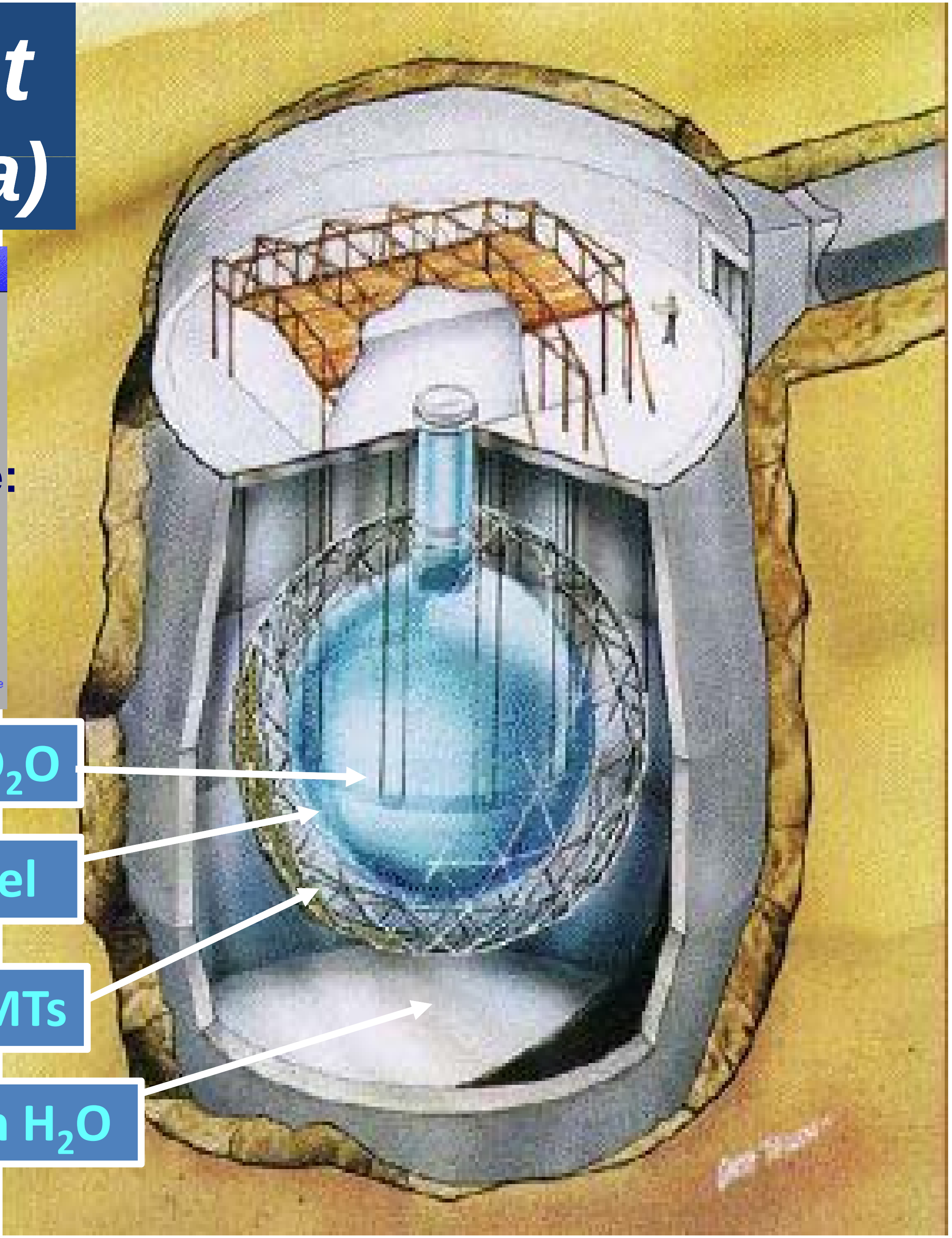




SNO experiment (Sudbury, Canada)



Surface: 2 km



1000 ton D_2O

Acrylic Vessel

9500 8” PMTs

7000 ton H_2O

SNO detector (under construction)

The background: radioactivity

nucl-ex/0204008

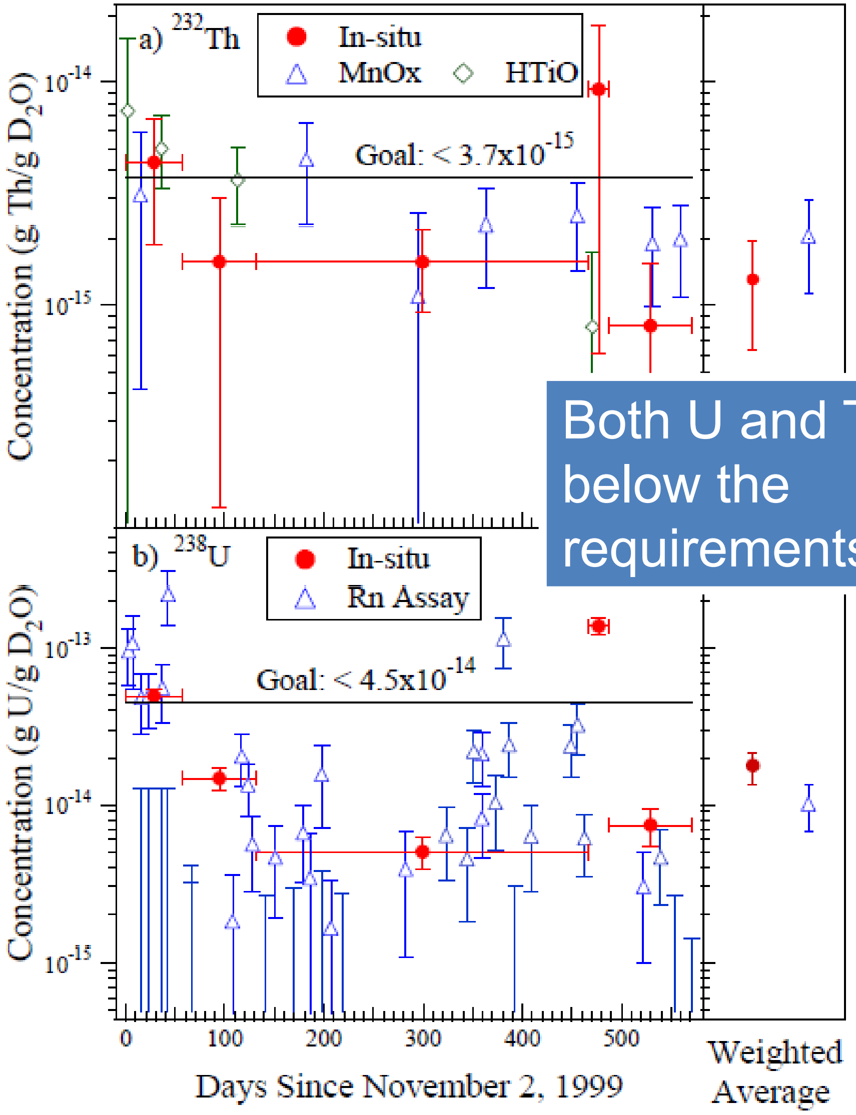
βs and γs from decays in U/Th chains interfere with the signals at low energies

Especially, γs over 2.2 MeV cause $d + \gamma \rightarrow n + p$
(Background for NC)

Requirements:

D_2O $< 4 \times 10^{-15}$ gm/gm Th
D_2O $< 5 \times 10^{-14}$ gm/gm U
H_2O $< 10^{-14}$ gm/gm U/Th
Acrylic $< 10^{-12}$ gm/gm U/Th

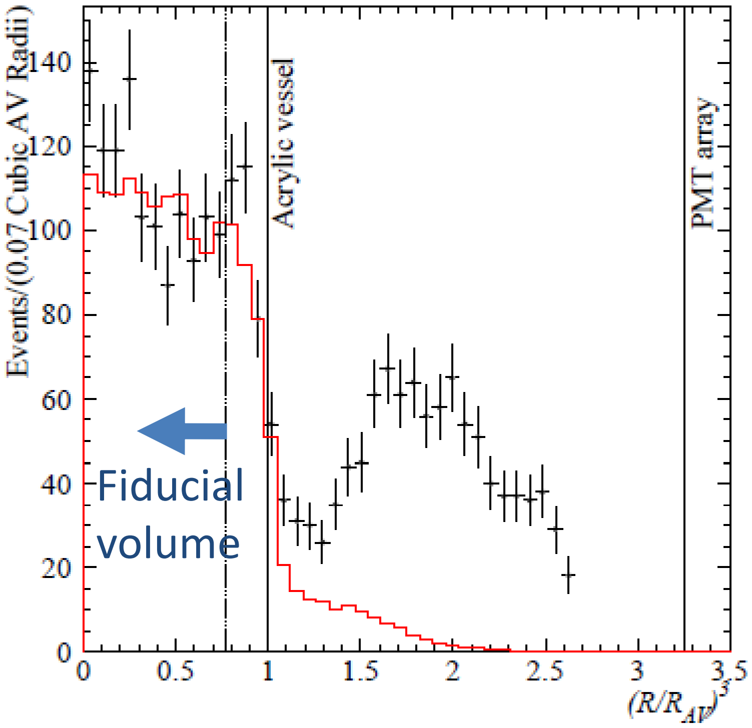
U/Th in D_2O



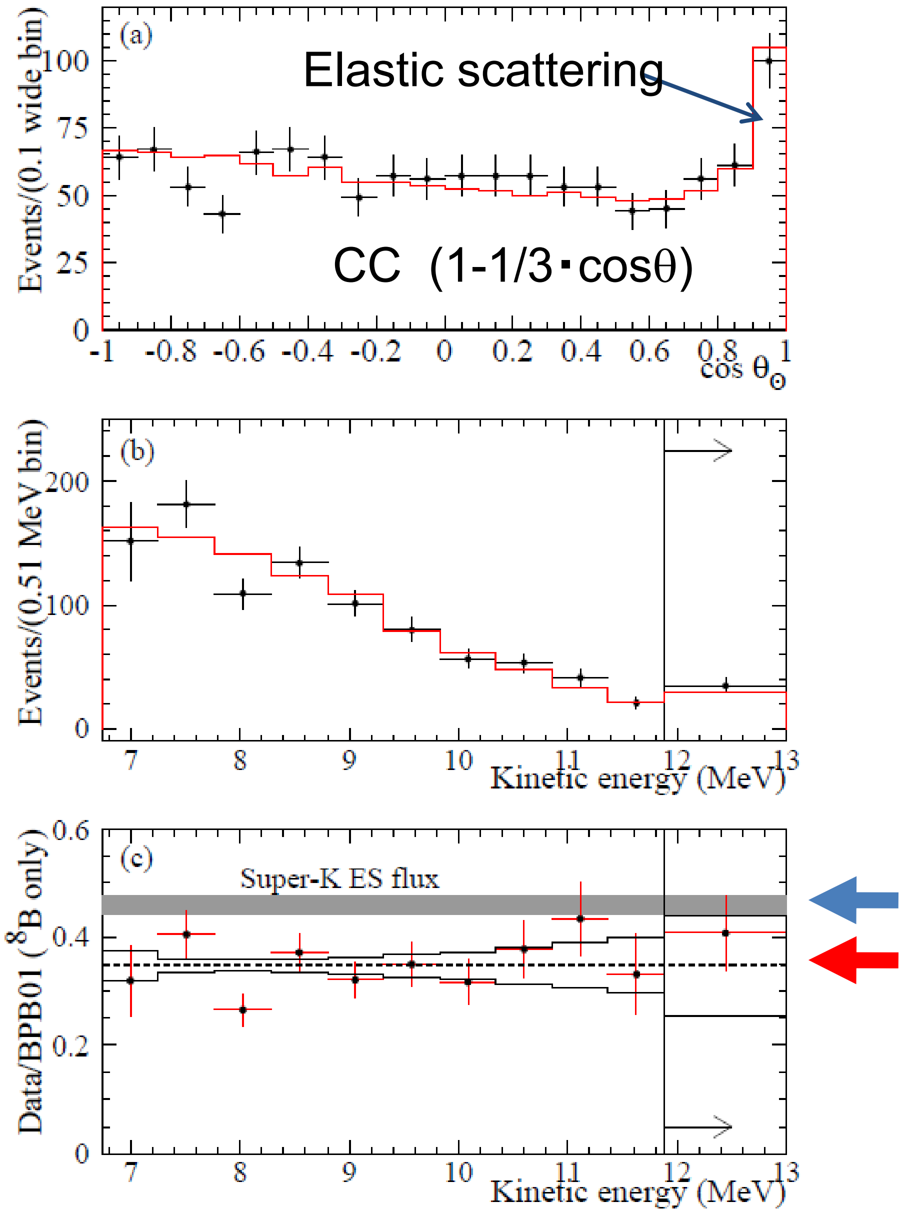
Both U and Th below the requirements

CC measurement

Radial distribution of events with >6.75 MeV



Fiducial volume



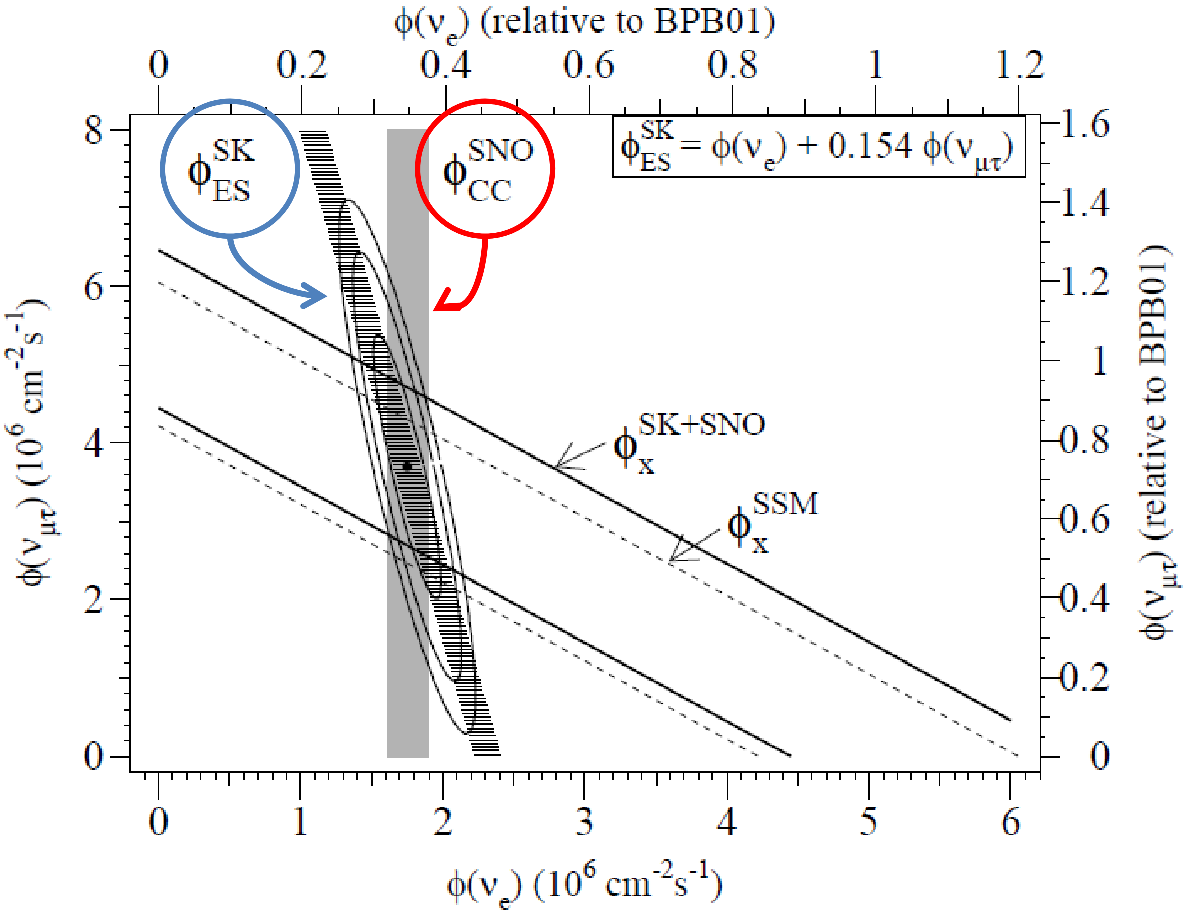
Elastic scattering

CC (1-1/3▪cosθ)

SNO CC vs. Super-K elastic scattering

Super-K elastic scattering (ES) flux is higher than the SNO CC flux.
ES is not only sensitive to the ν_e flux but also sensitive to the ν_μ and ν_τ fluxes with the reduced cross section (× (6-7) of that of $\nu_e+e \rightarrow \nu_e+e$) !
The difference can be interpreted as evidence for "$\nu_\mu+\nu_\tau$ flux on the Earth".

nucl-ex/0106015



3.1 σ evidence for non-zero $\nu_\mu+\nu_\tau$ flux (or flavor change)

Three ways to measure the NC events

Neutron Detection Method

(1) Pure D_2O

$$\nu + d \rightarrow \nu + p + \underline{n}$$

$$n + d \rightarrow t + \gamma \quad (E_\gamma = 6.3\ \text{MeV})$$

(γ produces e by Compton scattering)

(2) D_2O with salt

$$n + {}^{35}\text{Cl} \rightarrow {}^{36}\text{Cl} + \gamma\text{'s} \quad (\Sigma(E\gamma) = 8.6\ \text{MeV})$$

(Competing process: n+d → t+γ)

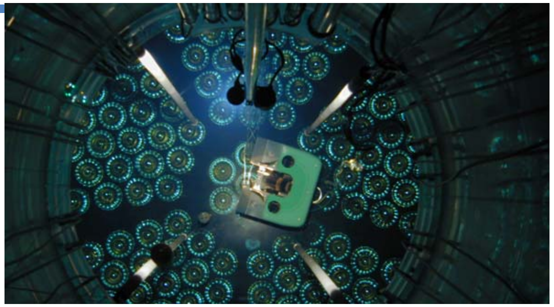
NaCl 2tons

Higher total energy
Higher capture efficiency
Different event pattern compared with the CC events

(3) ^{3}He counters in D_2O

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

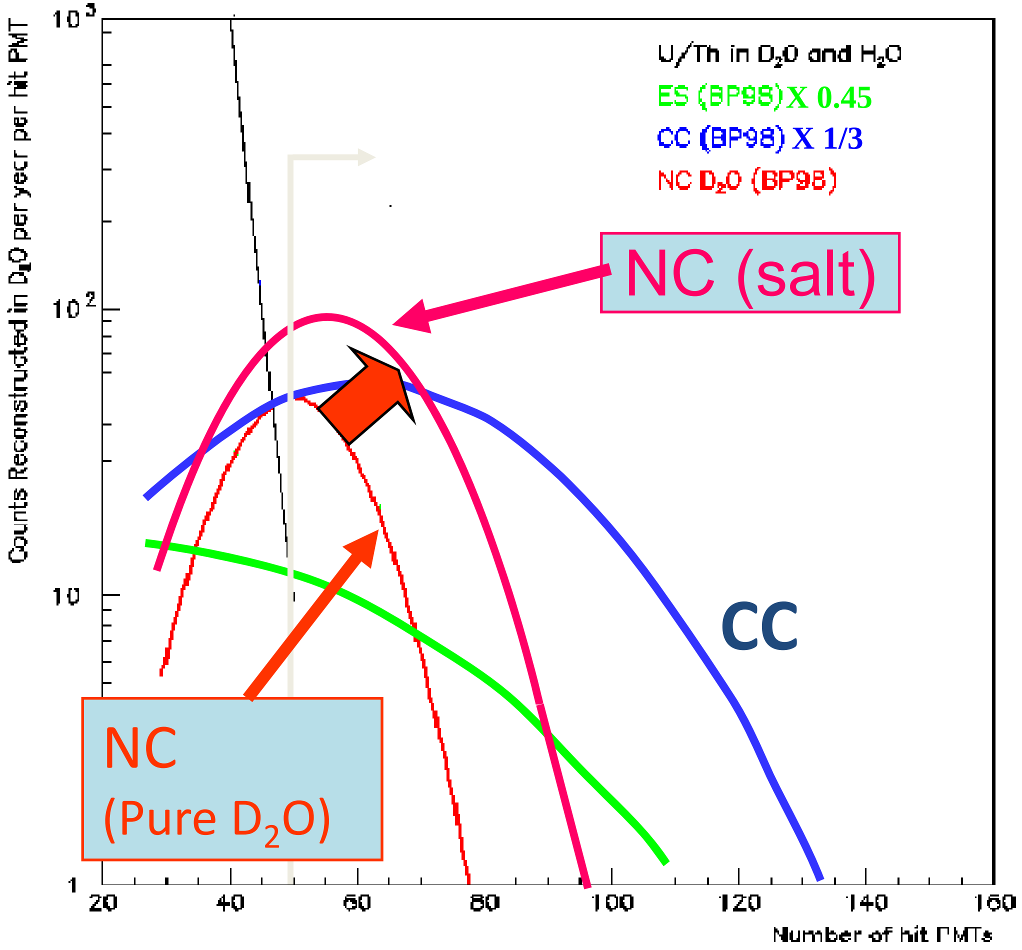
(0.76 MeV)

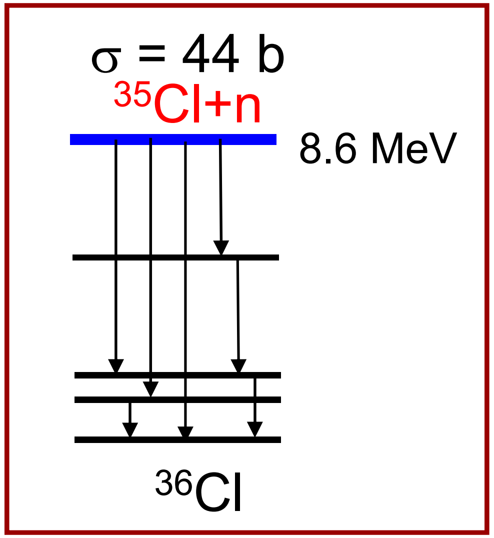


SNO NC: Pure D_2O vs. Salt phase

2 tons of NaCl added into 1000 ton D_2O

(Salt phase: 2001-2003)

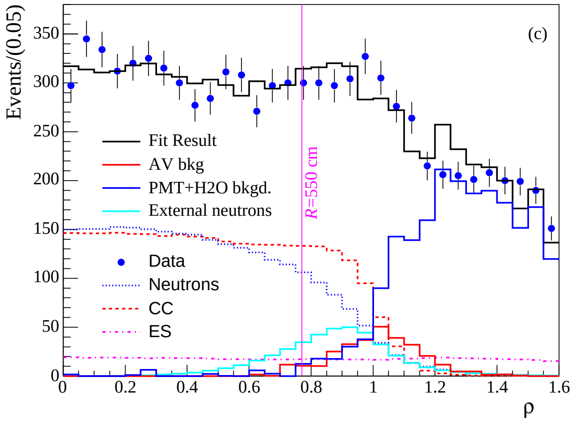




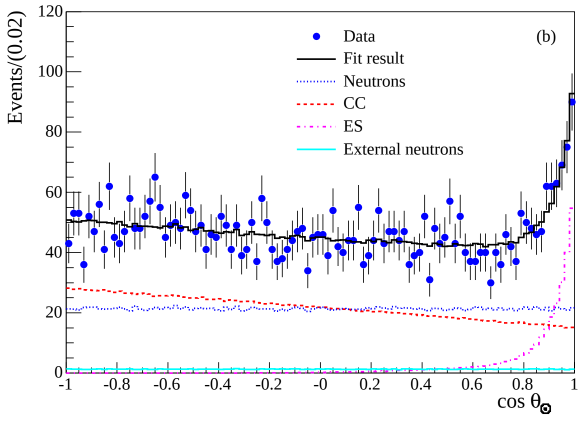
~ 9 NHIT/MEV

391-day salt phase flux measurements

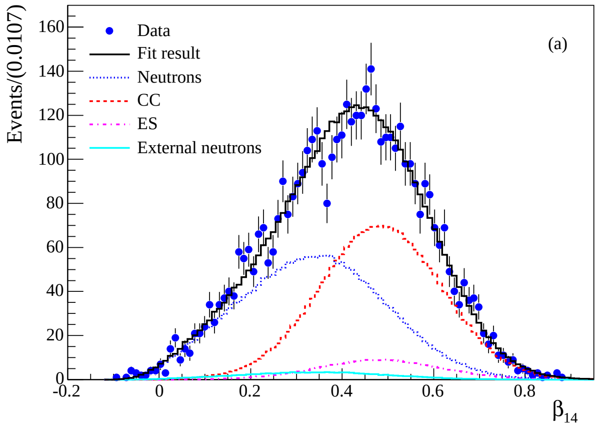
vertex



$\cos\theta_{sun}$



~ isotropy



w/o ^{8}B energy constraint

$$\phi_{CC}(\nu_e) = 1.68\ ^{+0.06}_{-0.06}\ \text{(stat.)}\ ^{+0.08}_{-0.09}\ \text{(syst.)} \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

$$\phi_{ES}(\nu_x) = 2.35\ ^{+0.22}_{-0.22}\ \text{(stat.)}\ ^{+0.15}_{-0.15}\ \text{(syst.)} \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

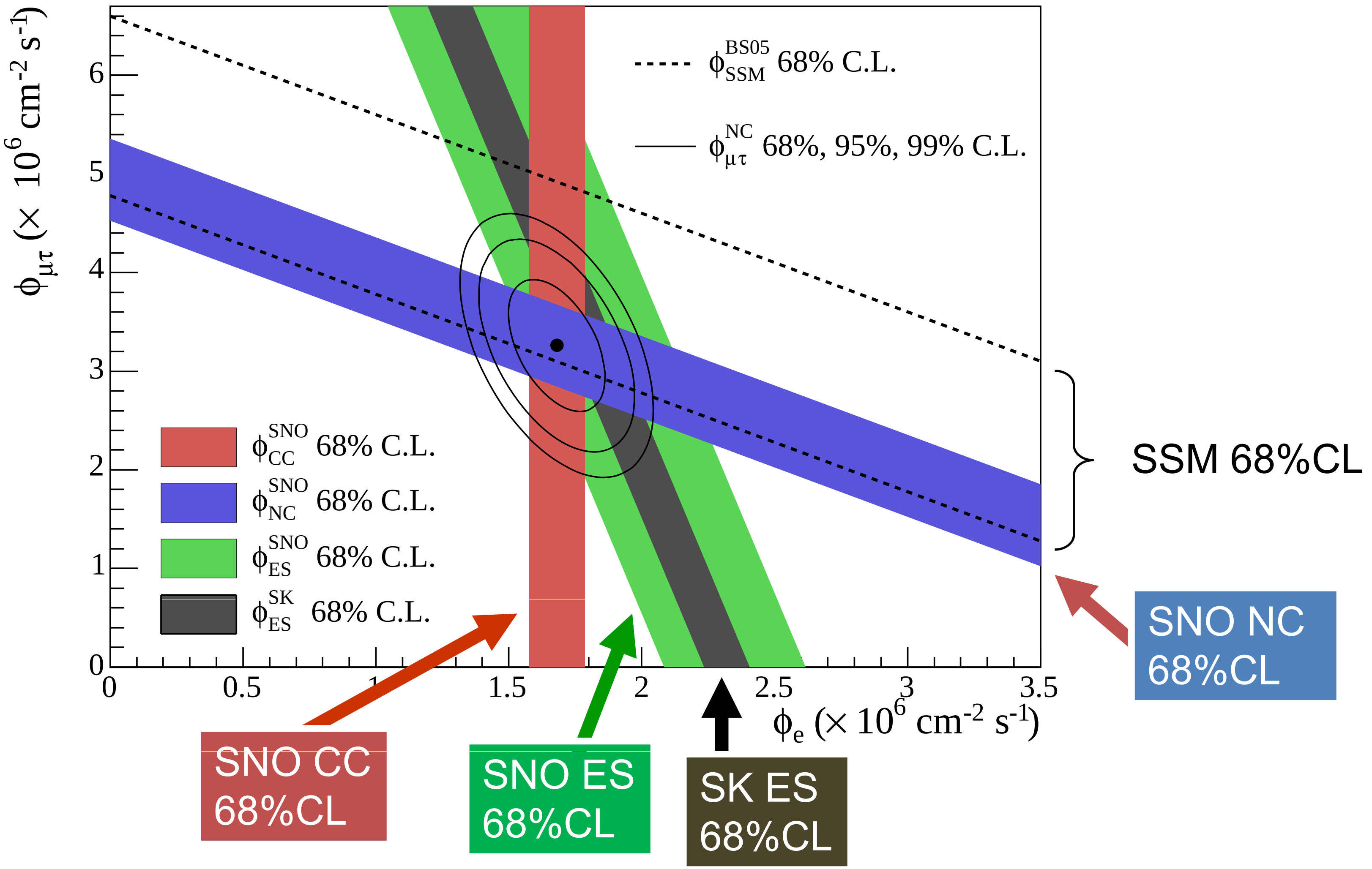
$$\phi_{NC}(\nu_x) = 4.94\ ^{+0.21}_{-0.21}\ \text{(stat.)}\ ^{+0.38}_{-0.34}\ \text{(syst.)} \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

SNO collab.
nucl-ex/
0502012

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.340 \pm 0.023\ ^{+0.029}_{-0.031}$$

Very clear evidence for non-zero $\nu_\mu+\nu_\tau$ flux (flavor change)

ν_e and $(\nu_\mu+\nu_\tau)$ fluxes (Salt phase)



Three (or 4) different measurements intersect at a point (➔non trivial).
All the data are consistently explained within the standard oscillation

New SNO results: Neutron Counter (NCD)

H. Robertson, talk @Nu2008
SNO collab. arXiv: 0806.0989

3 reactions in SNO:

$$\nu_x + e^- \rightarrow \nu_x + e^- \quad \text{(ES)}$$

$$\nu_e + d \rightarrow p + p + e^- \quad \text{(CC)}$$

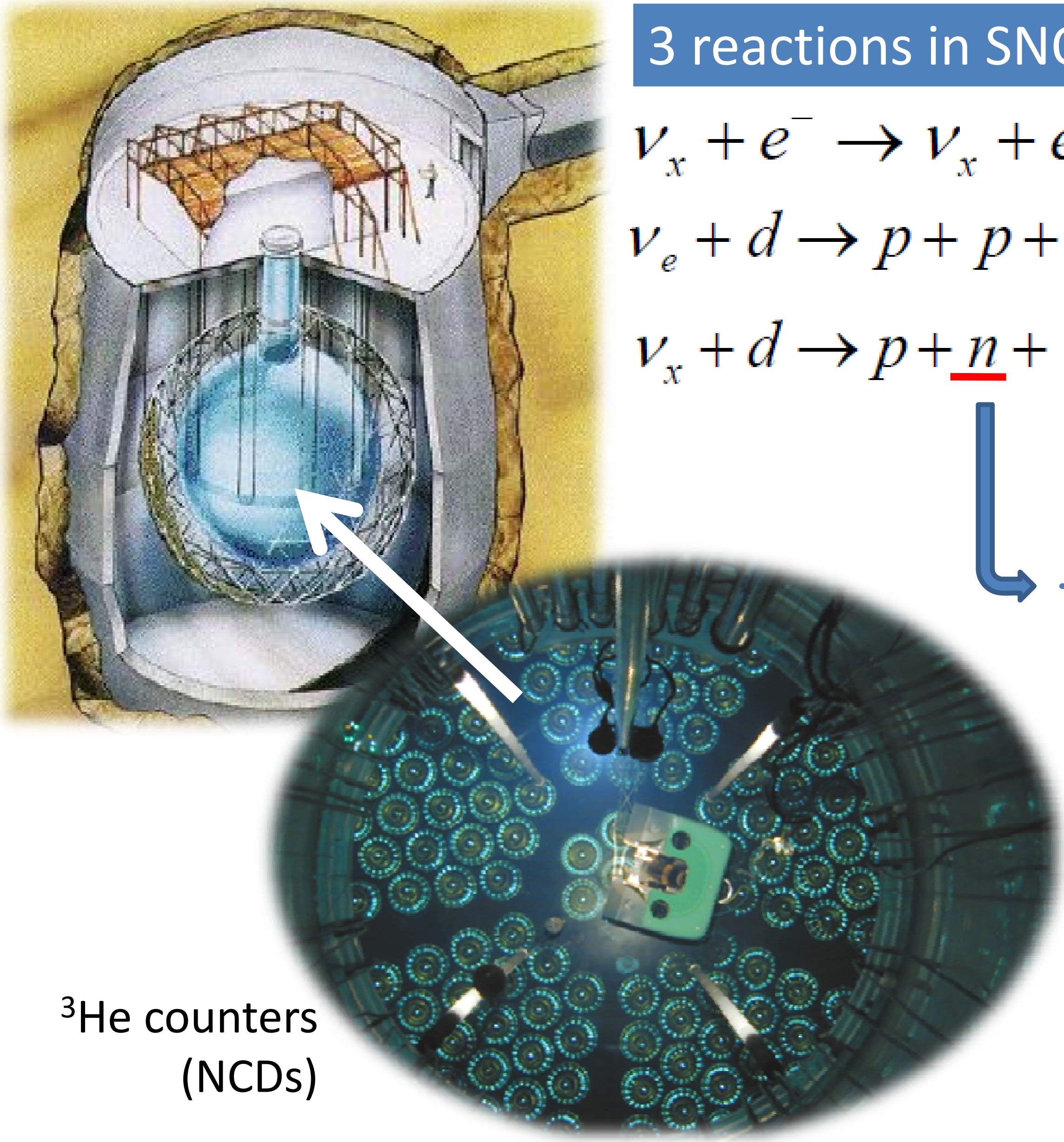
$$\nu_x + d \rightarrow p + \underline{n} + \nu_x \quad \text{(NC)}$$

$$n + d \rightarrow t + \gamma + 6.25 \ \text{MeV}$$

$$n + {}^{35}Cl \rightarrow {}^{36}Cl + \gamma + 8.6 \ \text{MeV}$$

$$\underline{n + {}^{3}He \rightarrow p + t + 0.76 \ \text{MeV}}$$

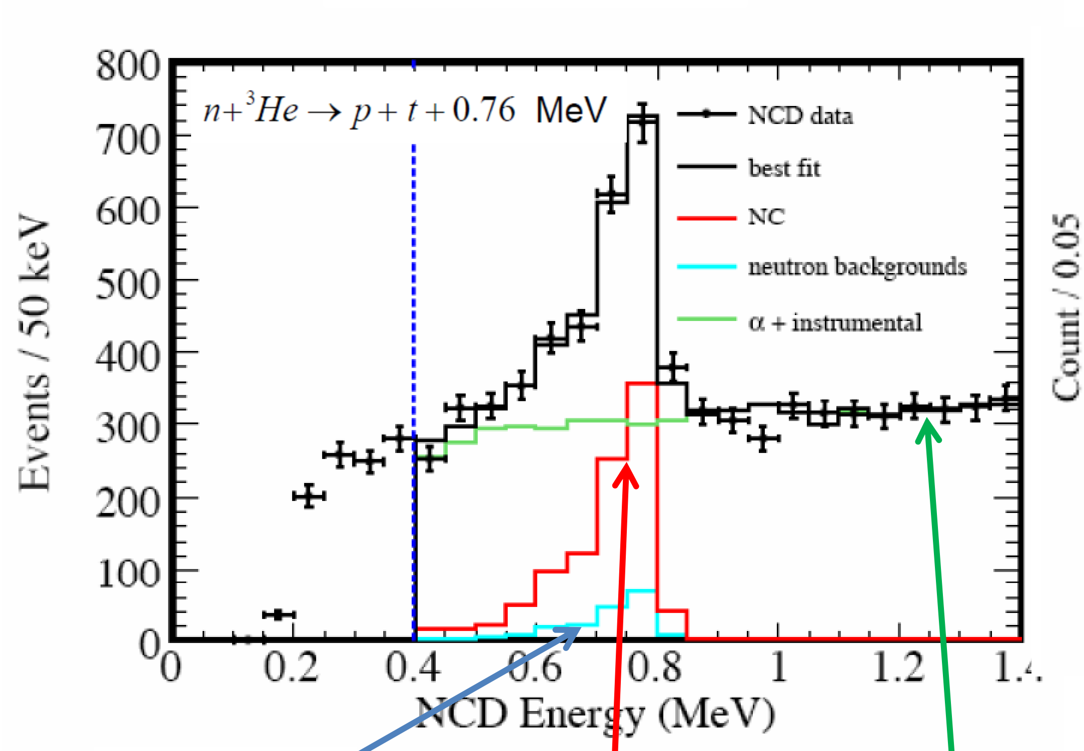
➔Can break the correlation between CC and NC
➔Different systematic errors



^{3}He counters (NCDs)

New SNO results: NCD phase (385 days)

NCD spectrum

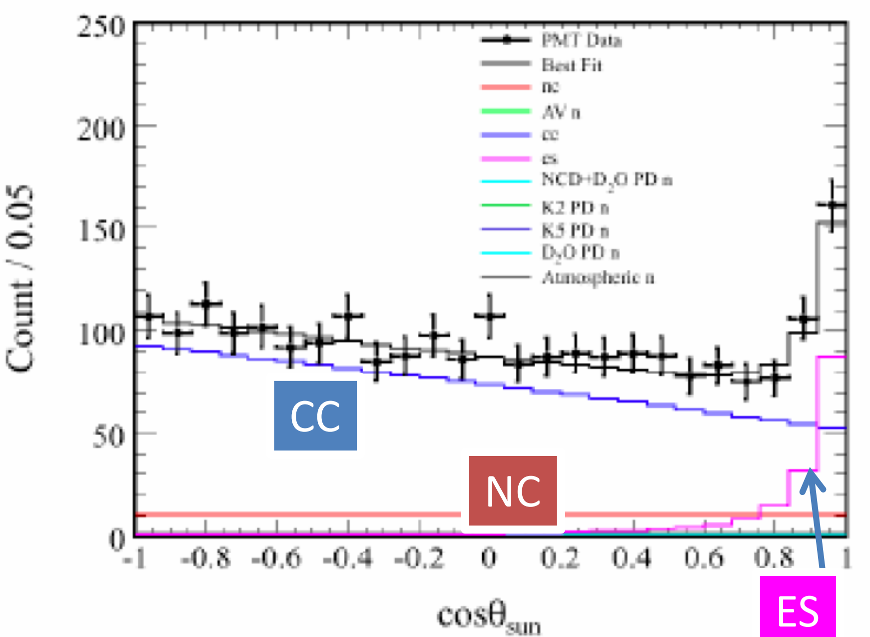


Neutron background:
185±25

NC Signal:
983 ± 77

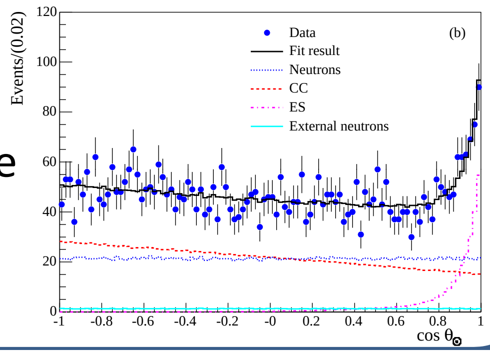
Alphas and Instrumentals:
6126 ± 250
(0.4 to 1.4 MeV)

Cherenkov events



➔ Much smaller NC fraction

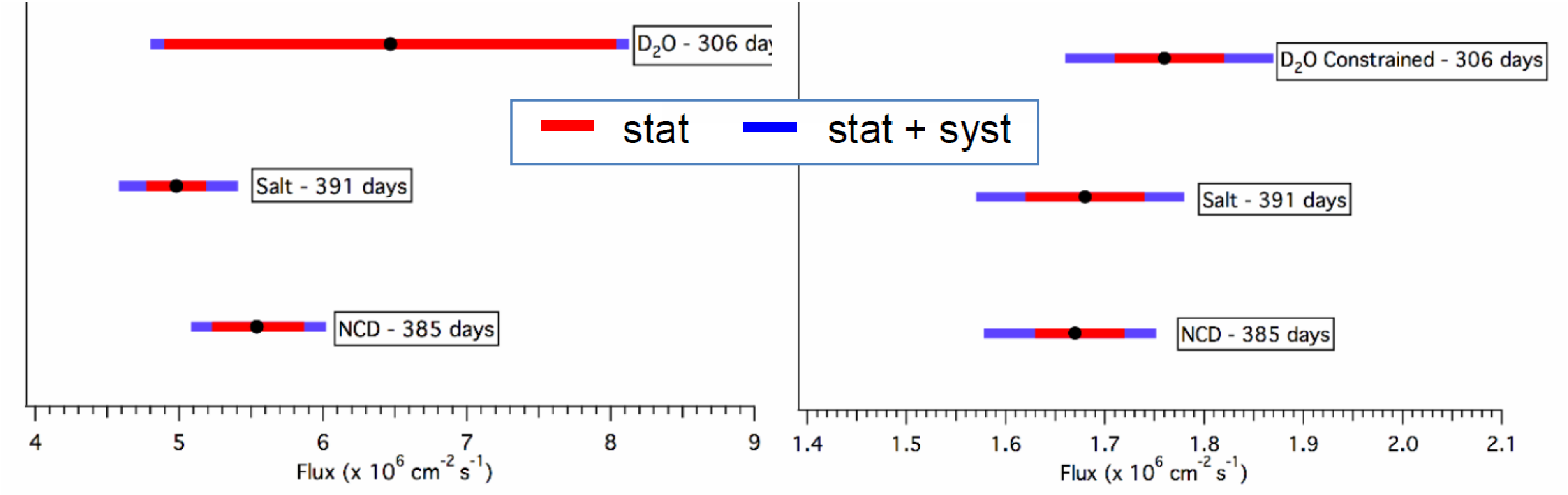
Ref:
Salt phase



New SNO results: NCD phase

Total neutrino flux (NC measurements)

ν_e flux (CC measurements)



We are interested in (CC flux)/(NC flux) since;

$$\frac{\phi_{CC}}{\phi_{NC}} \approx \sin^2 \theta_{12}$$

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.340 \pm 0.023 \,{}^{+0.029}_{-0.031} \text{(Salt phase)}$$

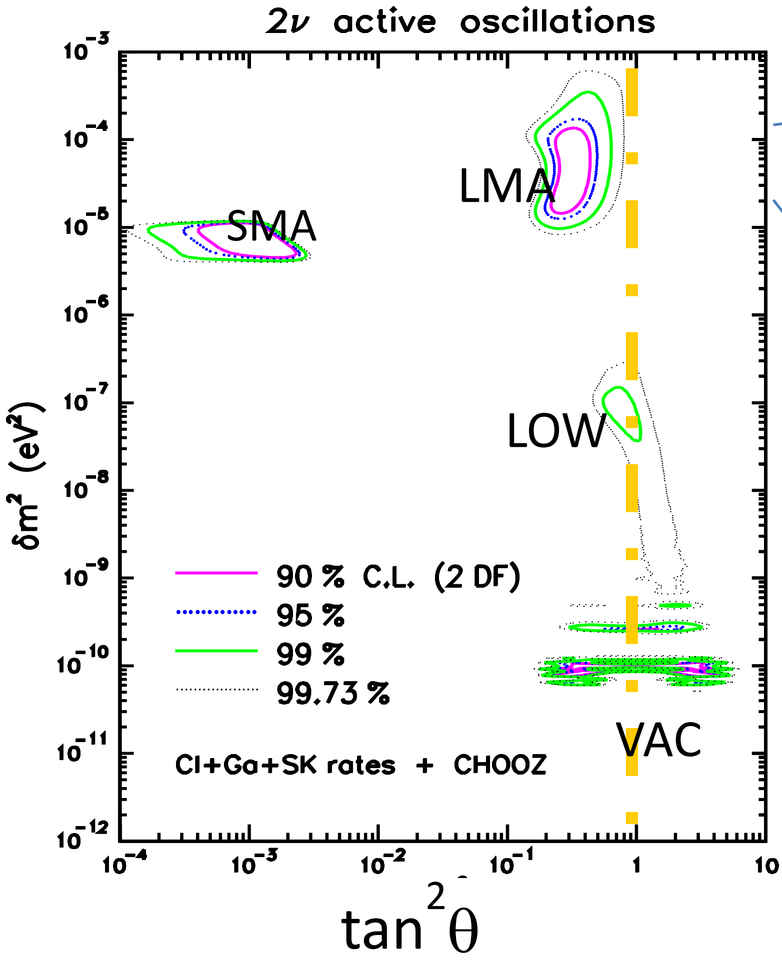
$$\frac{\phi_{CC}}{\phi_{NC}} = 0.301 \pm 0.033 \,(\mathit{total})\ \text{(NCD phase)}$$

Oscillation Analysis with all solar neutrino data

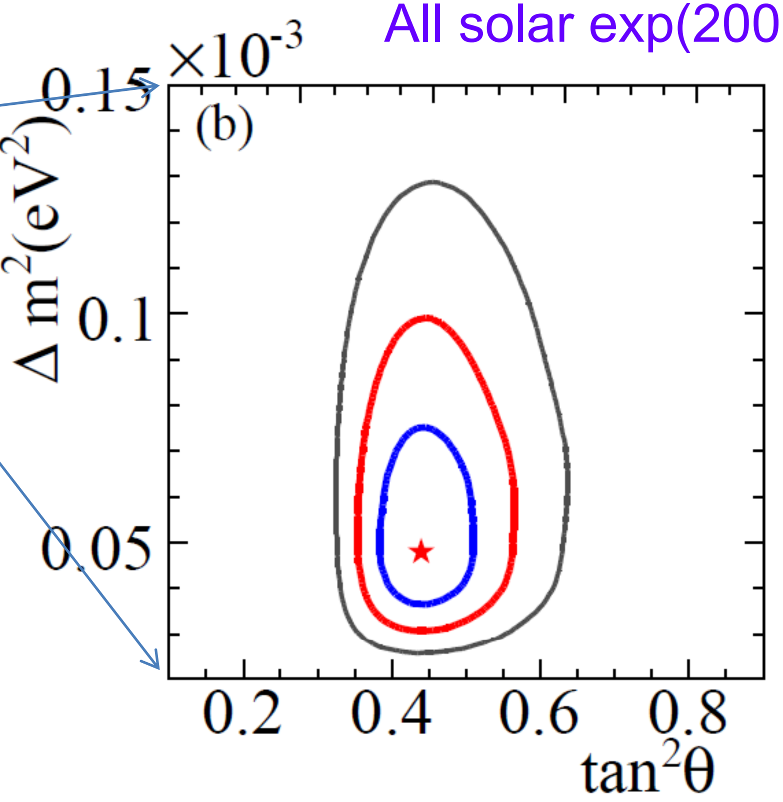
H. Robertson, talk @Nu2008
SNO collab. arXiv: 0806.0989

Earlier in this talk….
(assuming oscillations)

Fogli et al.



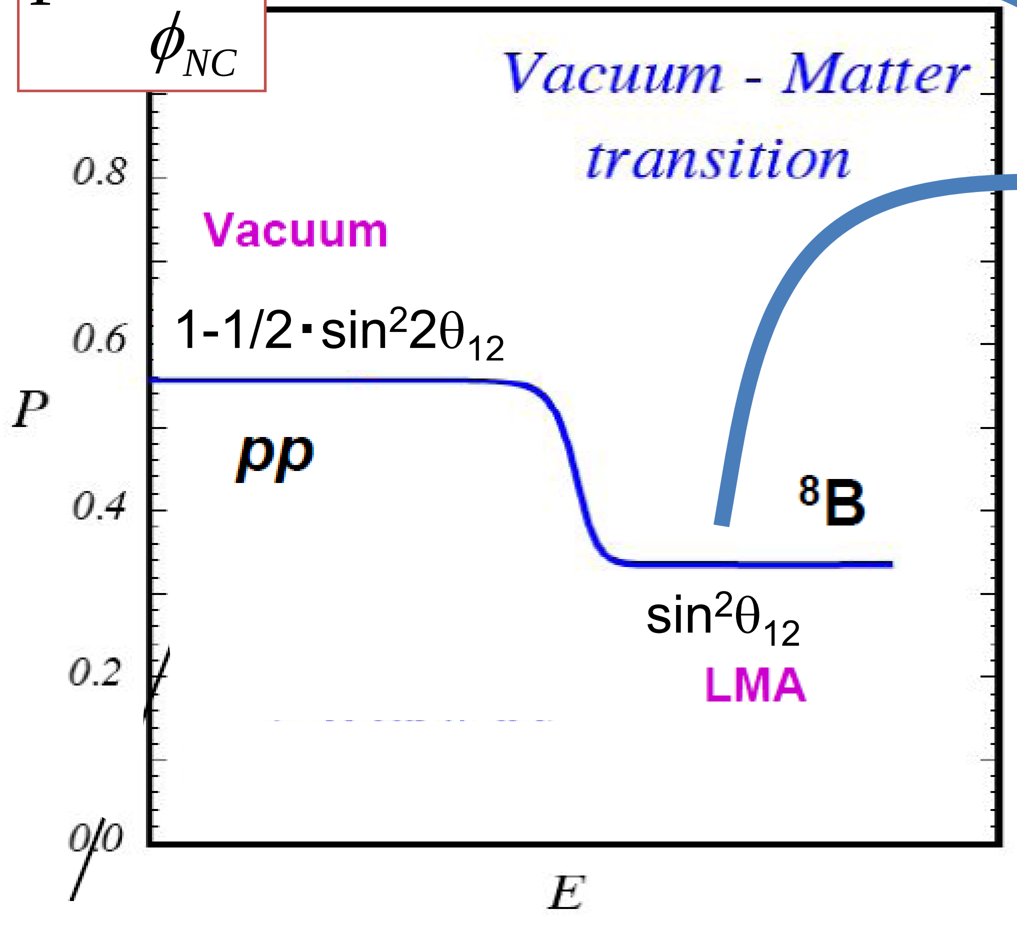
All solar exp(2008)



$$\theta_{12} = 33.8^{+1.4}_{-1.3} \text{ (4\% accuracy)}$$

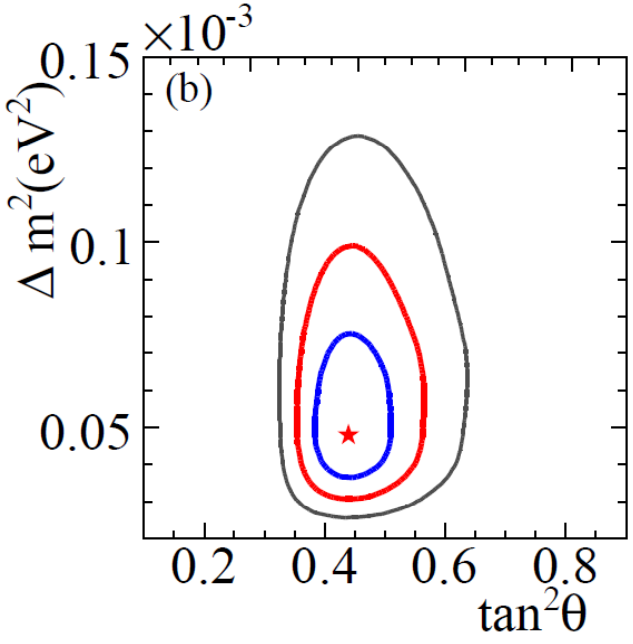
CC/NC and the measurement of θ_{12}

$$P = \frac{\phi_{CC}}{\phi_{NC}}$$



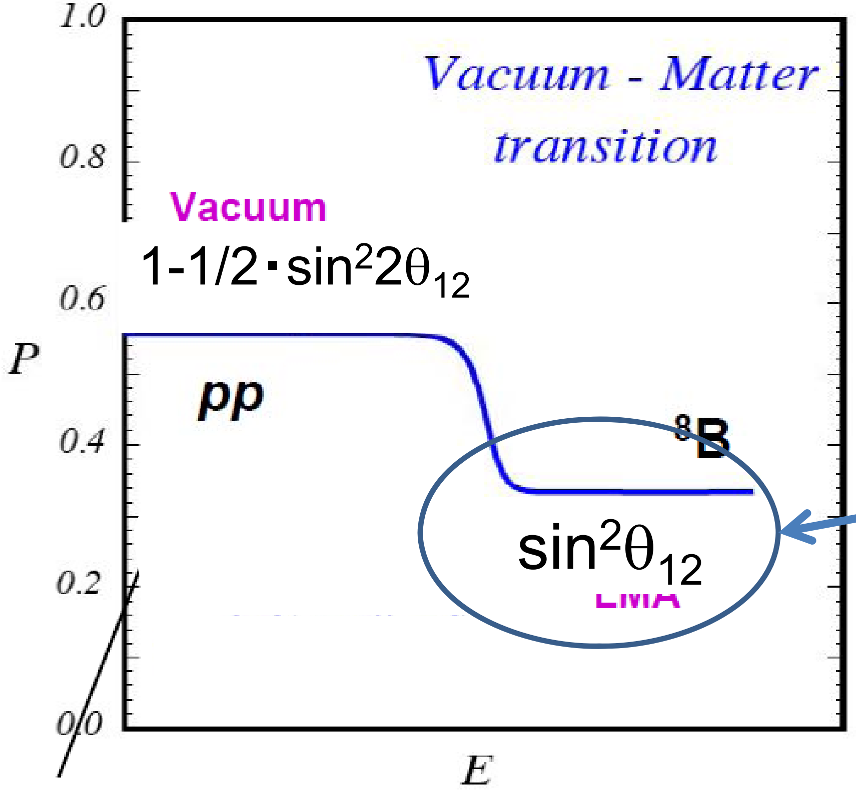
Bahcall & Pena-Garay
hep-ph/0305159

Accurate measurement of $\sin^2\theta_{12}$ is possible by the CC/NC ratio measurement.

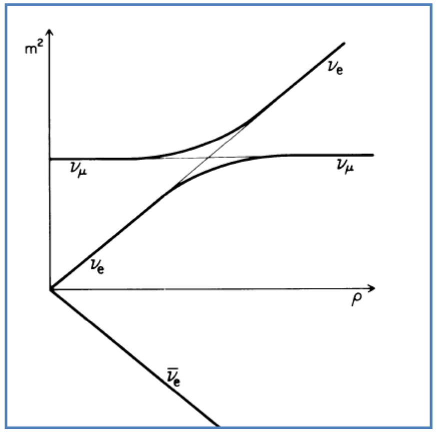


$$\theta_{12} = 33.8^{+1.4}_{-1.3}\ (4\%\ \text{accuracy})$$

CC/NC and the measurement of θ_{12}



Bahcall & Pena-Garay
hep-ph/0305159



This happens only if;

Mass hierarchy between ν_1 and ν_2 determined.

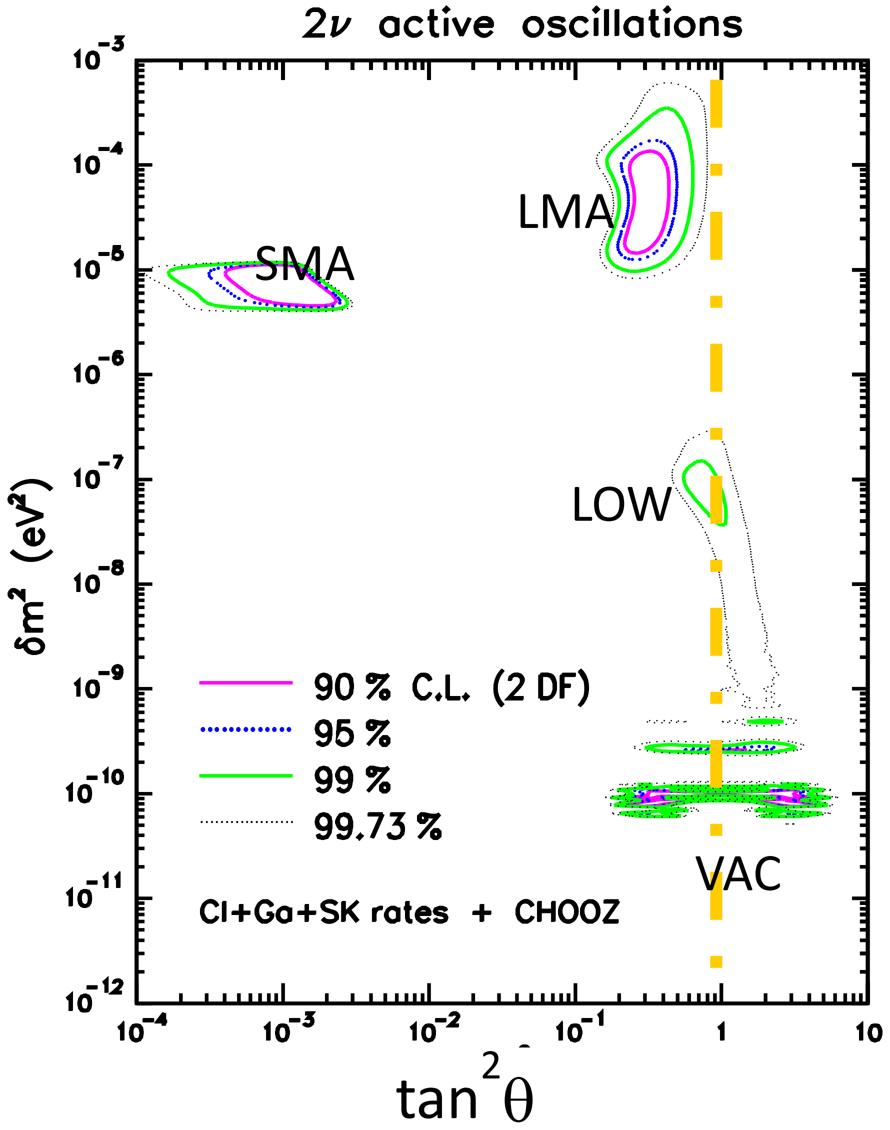
Matter effect is very useful.

KamLAND reactor neutrino oscillation experiments

The idea of KamLAND

Atsuto Suzuki

Fogli et al.



SMA and LMA solutions were equally likely in the 1990's (although many people believed that mixing angles should be small).

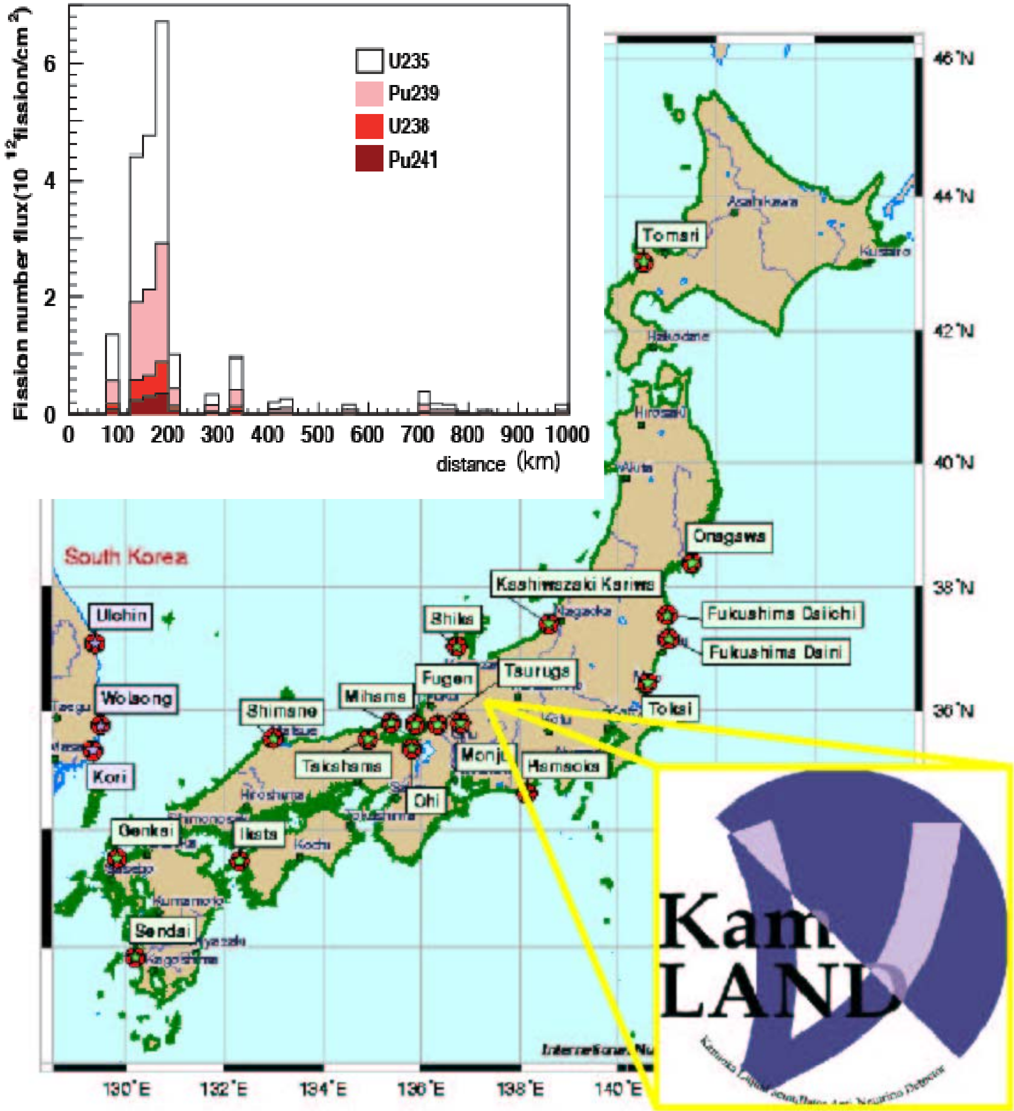
If LMA is the real solution, a reactor long baseline experiment can observe the oscillation.

Even if LMA is not the solution, this experiment can clearly exclude LMA.

➔Found there are many reactors in Japan…

➔ Kamiokande no more used...

Reactors around KamLAND



$$\langle L_\nu \rangle = 180km$$
$$\langle E_\nu \rangle = a\ \ few\ MeV$$

Sensitive to $\Delta m^2 > 10^{-5} eV^2$

However, the cross section is small…. ⇒ need many powerful reactors.

Fortunately,

68GW available

(4% of the world’s manmade power)
(20% of the world’s nuclear power)

with no cost.

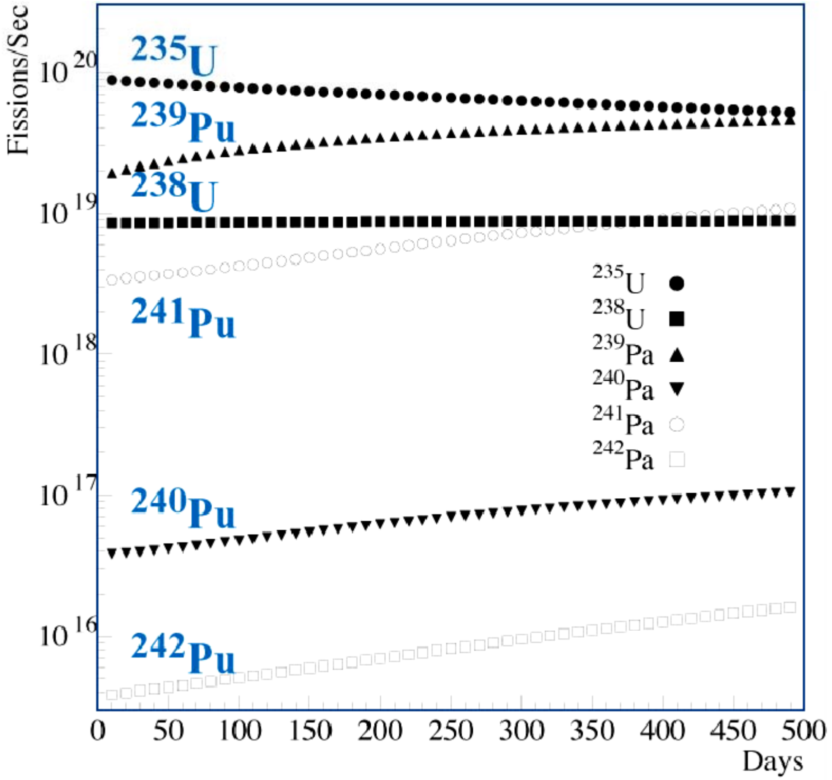
Anti-ν_e production in reactors

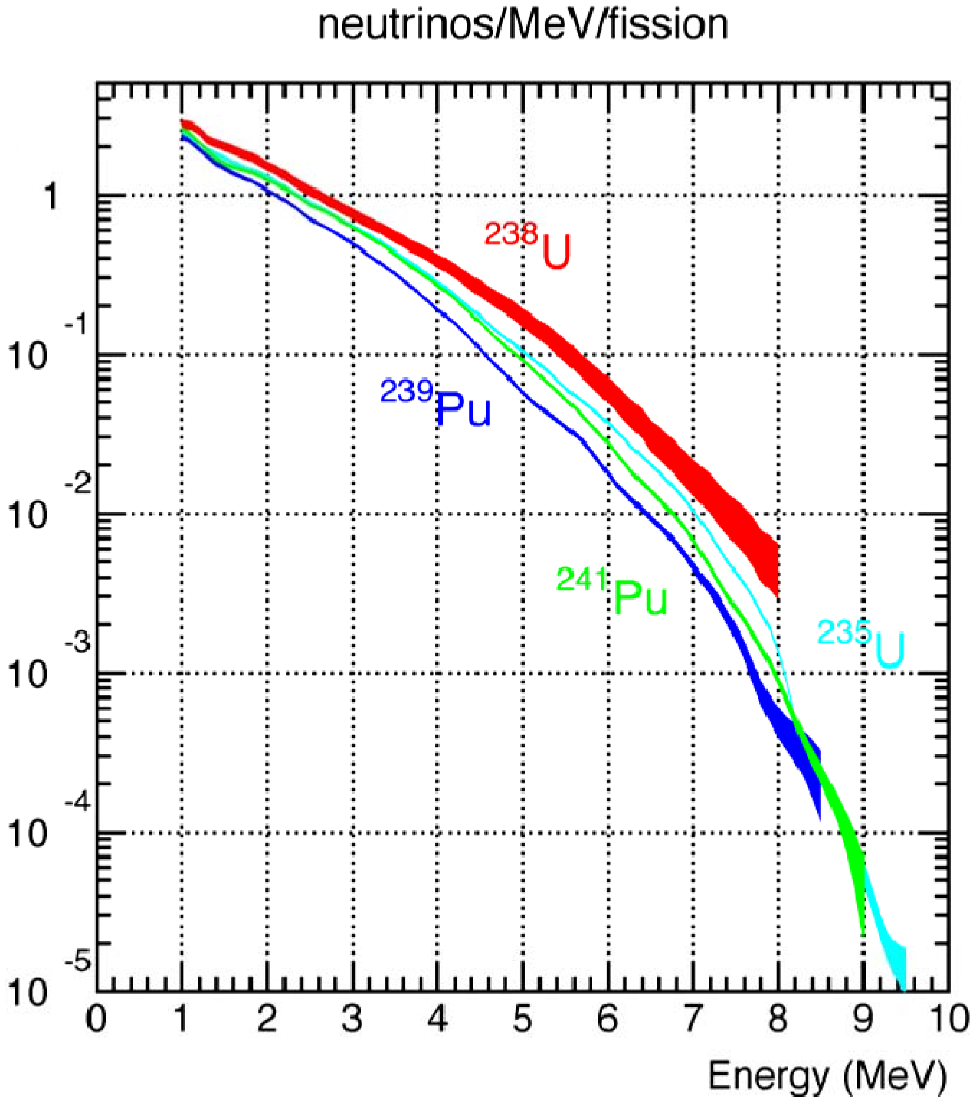
Fission reaction:

$$U + n \rightarrow \underline{X_1} + \underline{X_2} + \ldots.$$

neutron rich

$$X_i \rightarrow Y + e^- + \underline{\bar{\nu}_e}$$





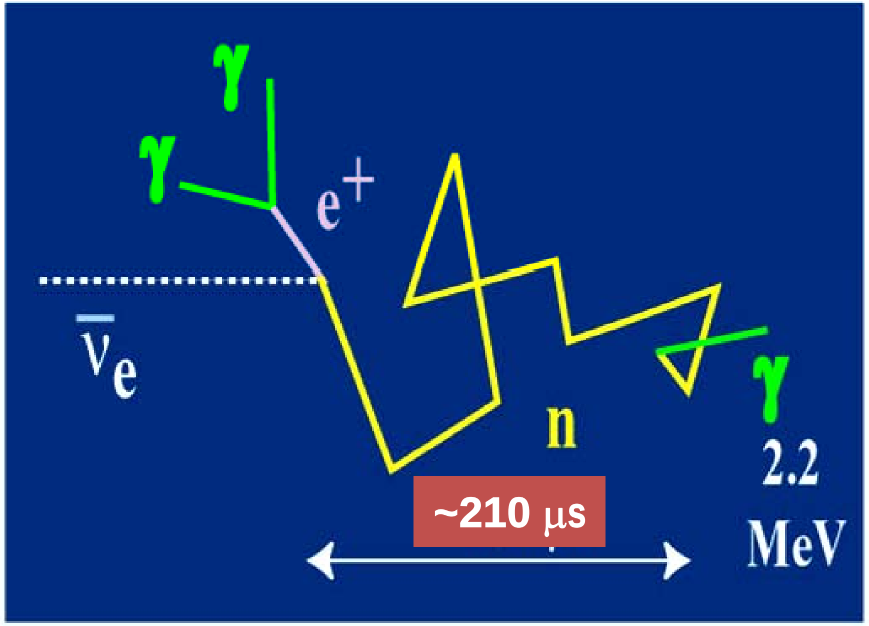
Detecting reactor neutrinos in Liq. scintillators

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

$$\cancel{\bar{\nu}_e + C \rightarrow e^+ + {}^{12}B}$$

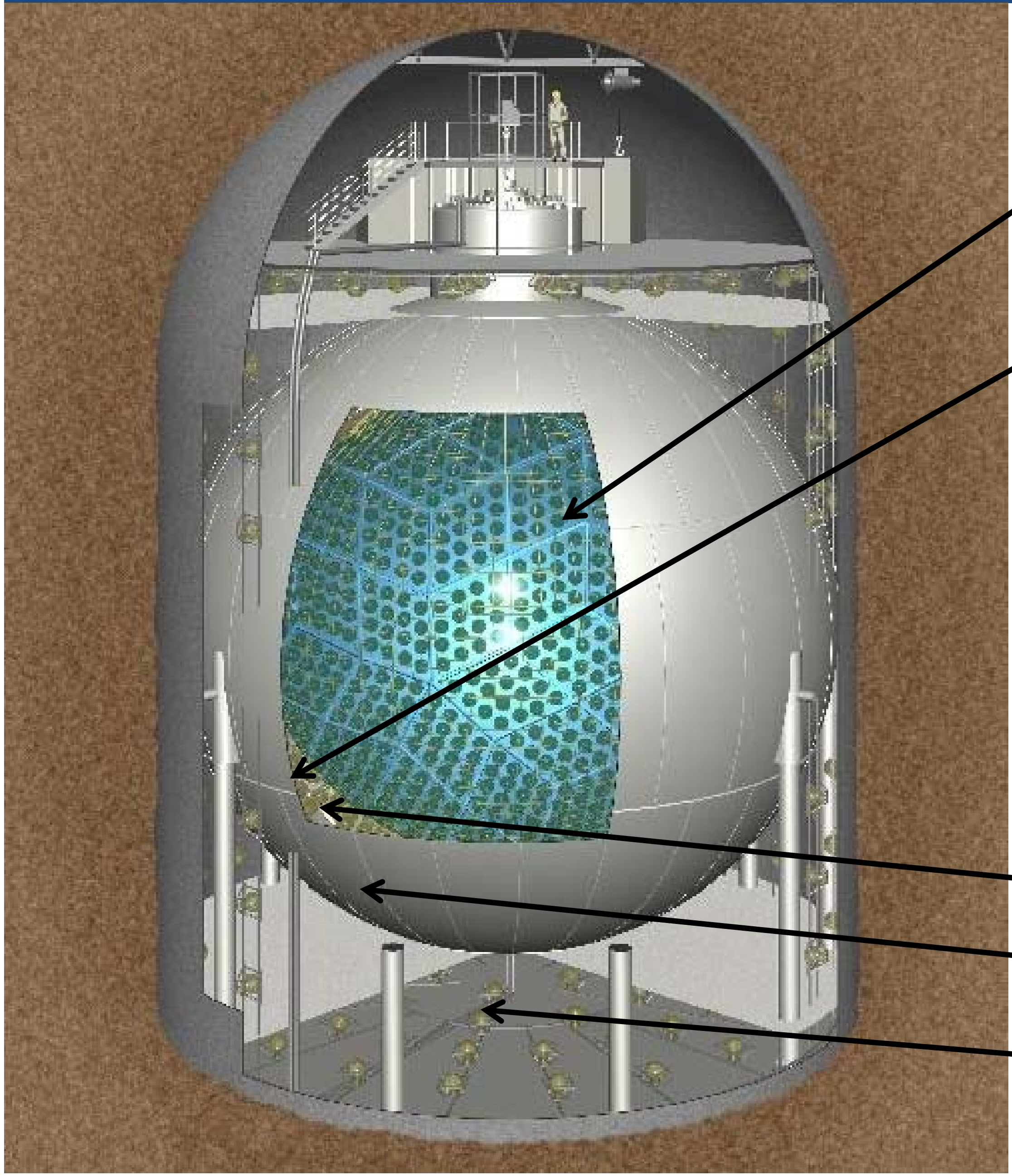
(energy, Eν<8MeV)

$$n + p \rightarrow d + \underline{\gamma(2.2MeV)}$$



Coincidence of e^+ and γ reduces the BG substantially

KamLAND detector (1000 ton Liq. Sci. detector)



1000 ton liquid scintilator contained in a balloon.

17 and 20 inch PMTs.

Light output = 320p.e./MeV

➔About 50 more light than water Cherenkov

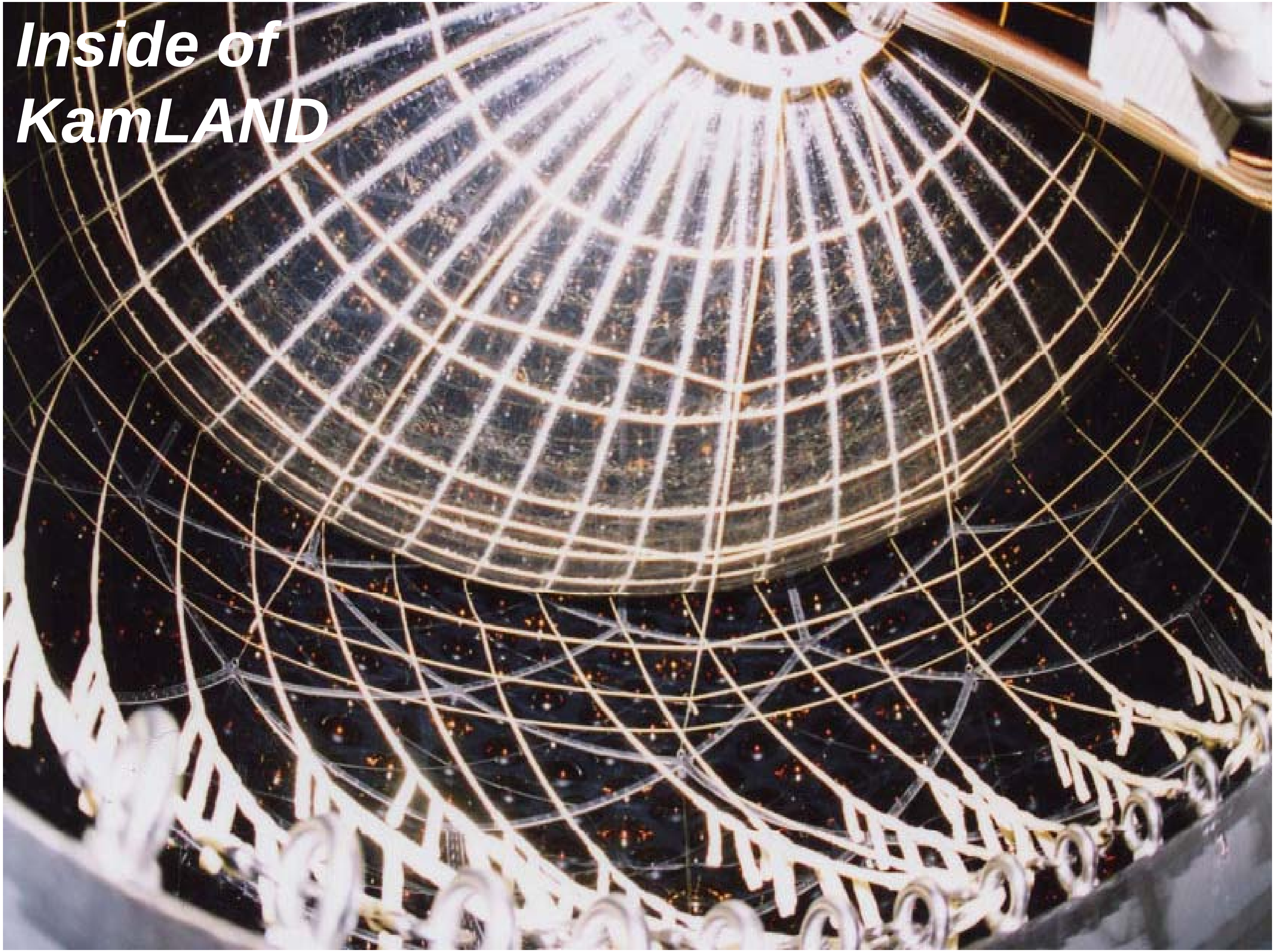
➔But no information on direction

Buffer oil.

Stainless steel tank.

Water Cherenkov anti-counter.

Inside of KamLAND



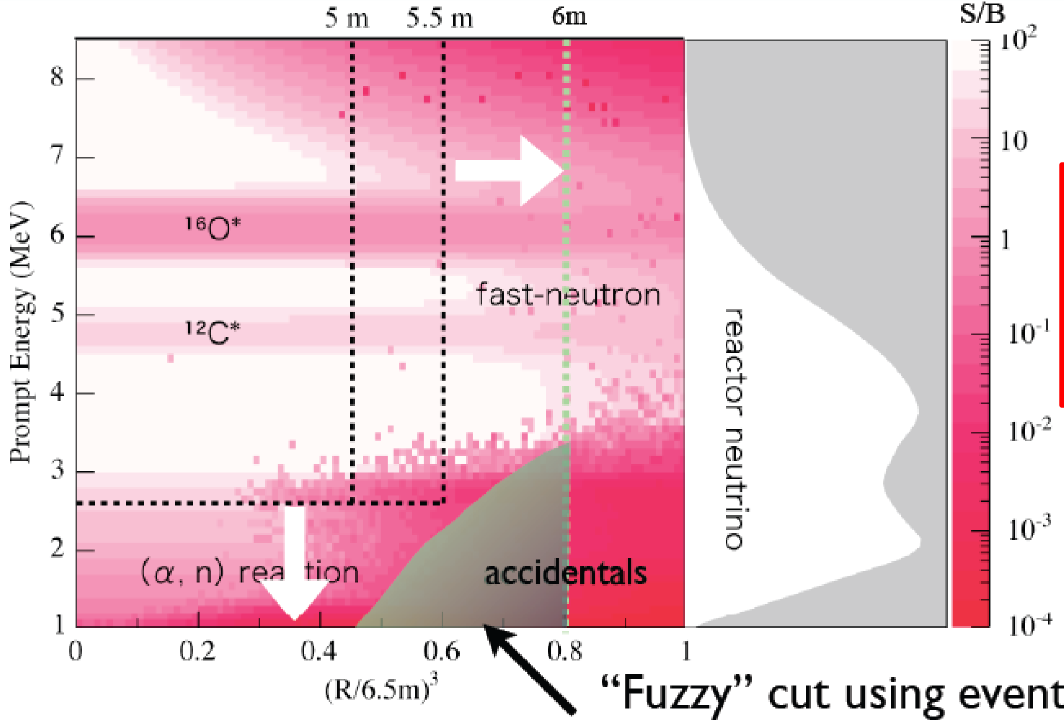
KamLAND improvements

P. Decowski, talk @Nu2008

	Radius (m)	Live time (days)	Ton･year
2002	5	145	162
2004	5.5	515	766
2008	6	1491	2881

× 18

Significant improvements in the event statistics.

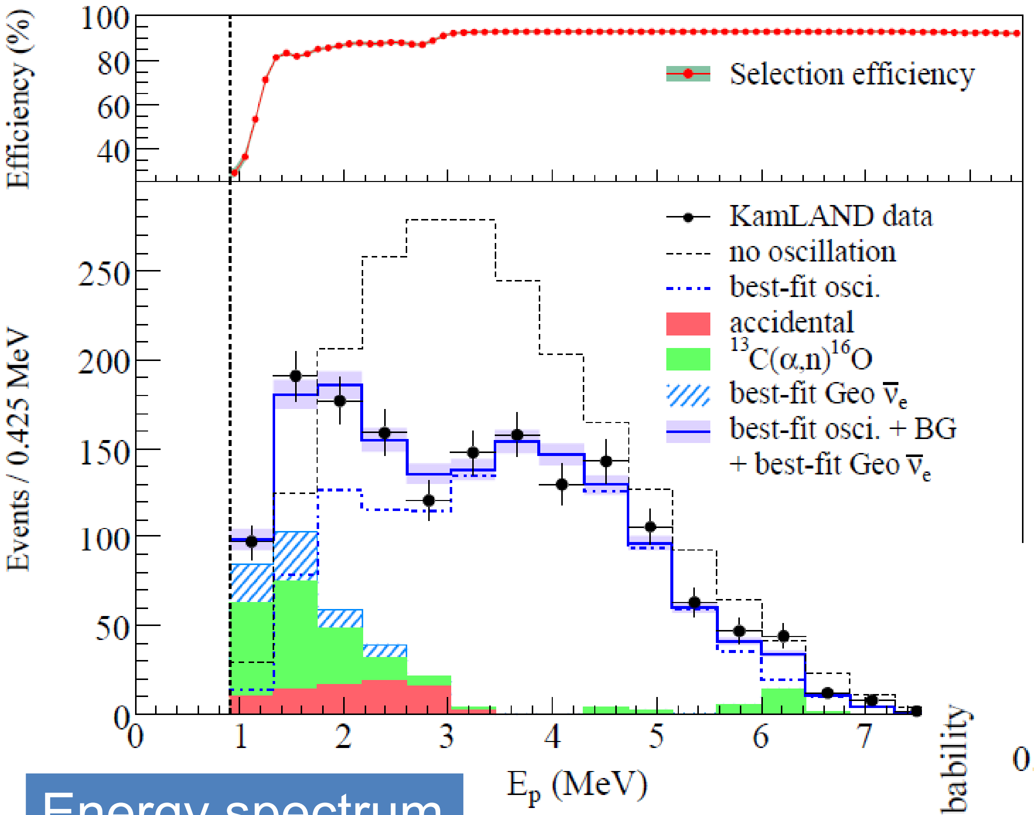


Energy threshold from 2.6MeV → 1.0MeV (Inverse Beta Decay threshold)

"Fuzzy" cut using event characteristics to distinguish signal from accidentals

KamLAND reactor data 2008

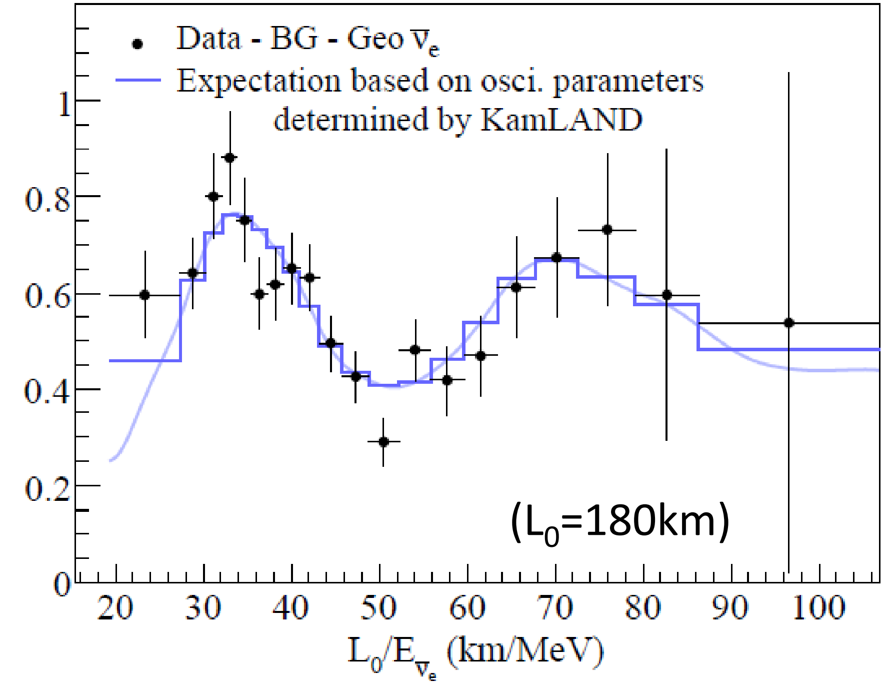
P. Decowski, talk @Nu2008
kamLAND collab. arXiv0801.4589



Energy spectrum

OR …

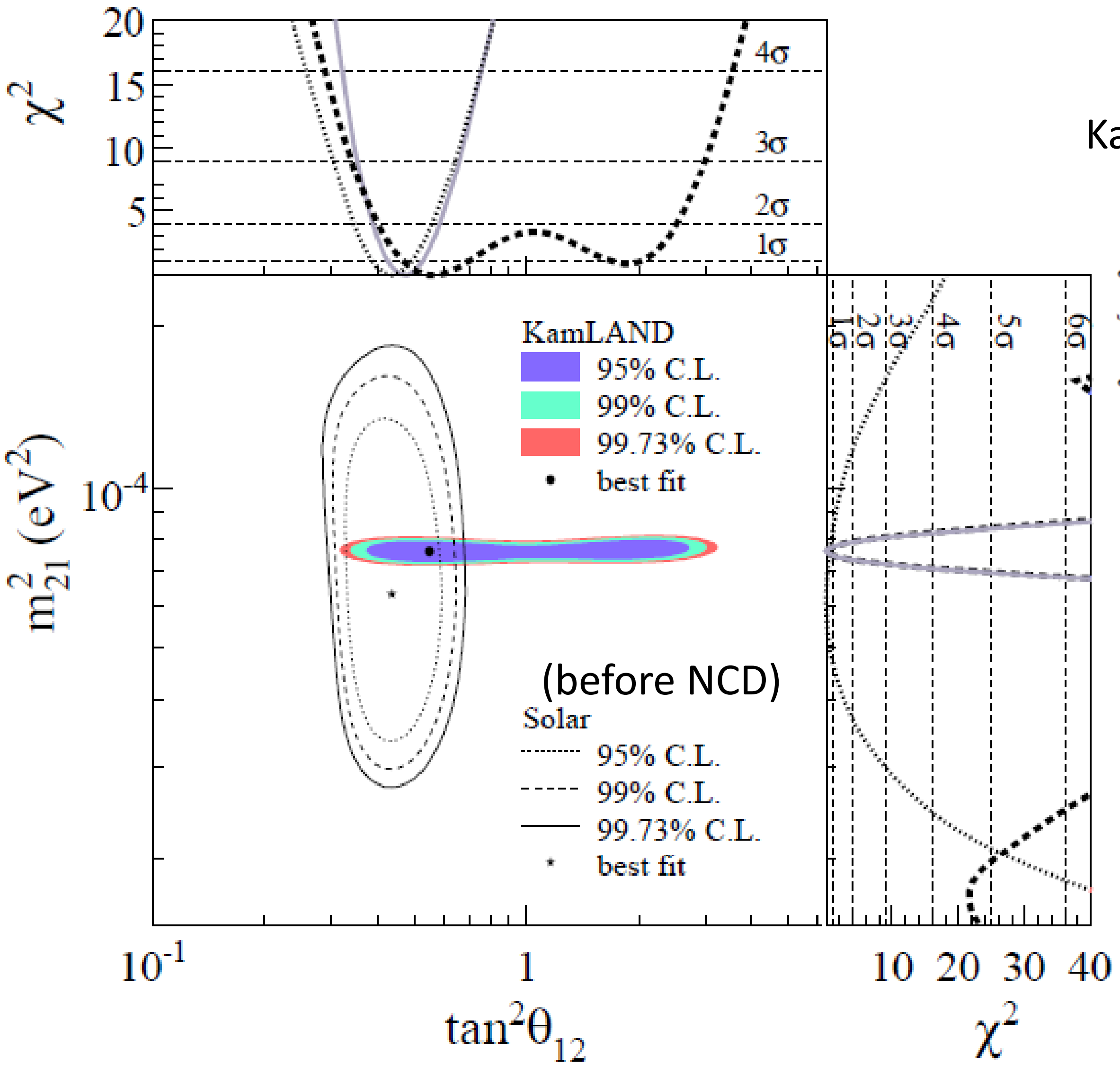
L/E plot



Really, really oscillation !!

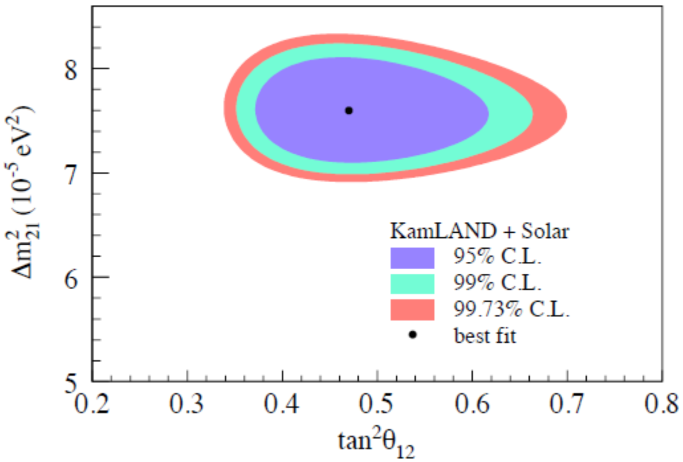
Oscillation parameters

P. Decowski, talk @Nu2008
KamLAND arXiv:0801.4589



(before NCD)

KamLAND + solar (before SNO-NCD)



KamLAND data favor slightly larger mixing angle.

Very interesting to know the allowed region with the SNO NCD results.

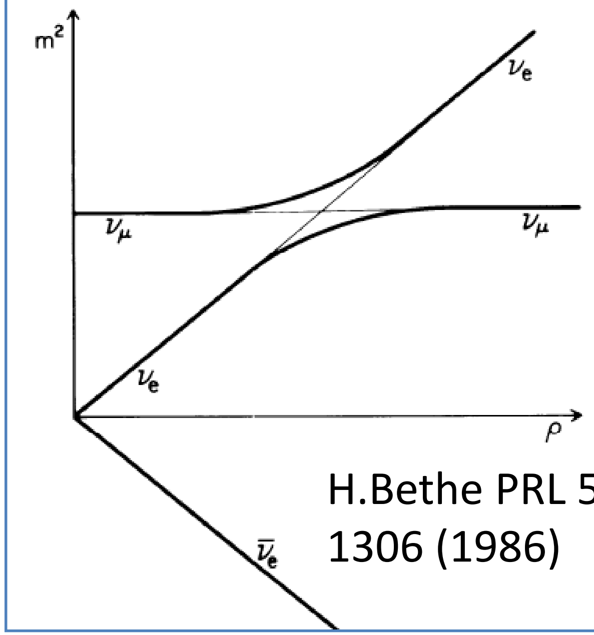
$$\Delta m^2_{21} = 7.58^{+0.14}_{-0.13}(\text{stat})^{+0.15}_{-0.15}(\text{syst}) \times 10^{-5}\,\text{eV}^2$$ (2.7% accuracy)

Next step: Further confirmation of MSW

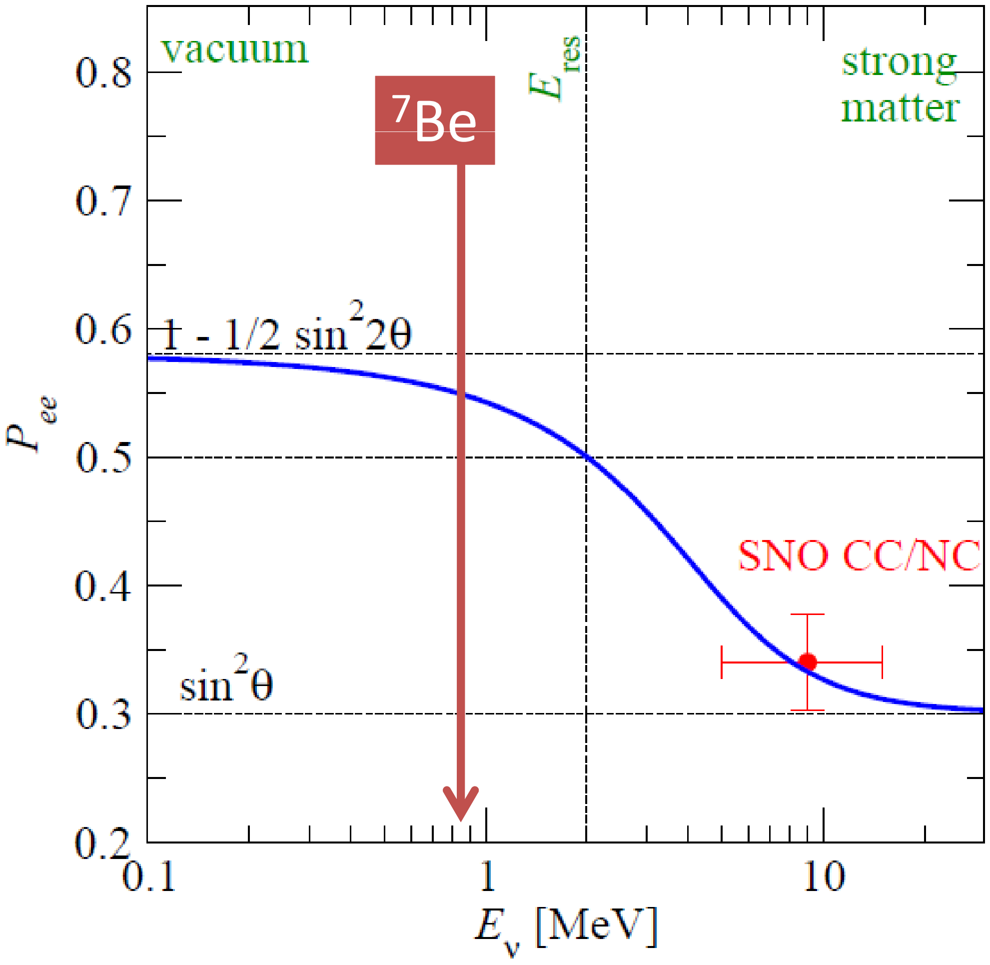
Further confirmation of MSW

T.Schwetz, WHEPP-X, 2008, Chennai

$$m^2 \rightarrow m^2 + 2\sqrt{2}\left(\frac{GY_e}{m_n}\right)\rho E$$



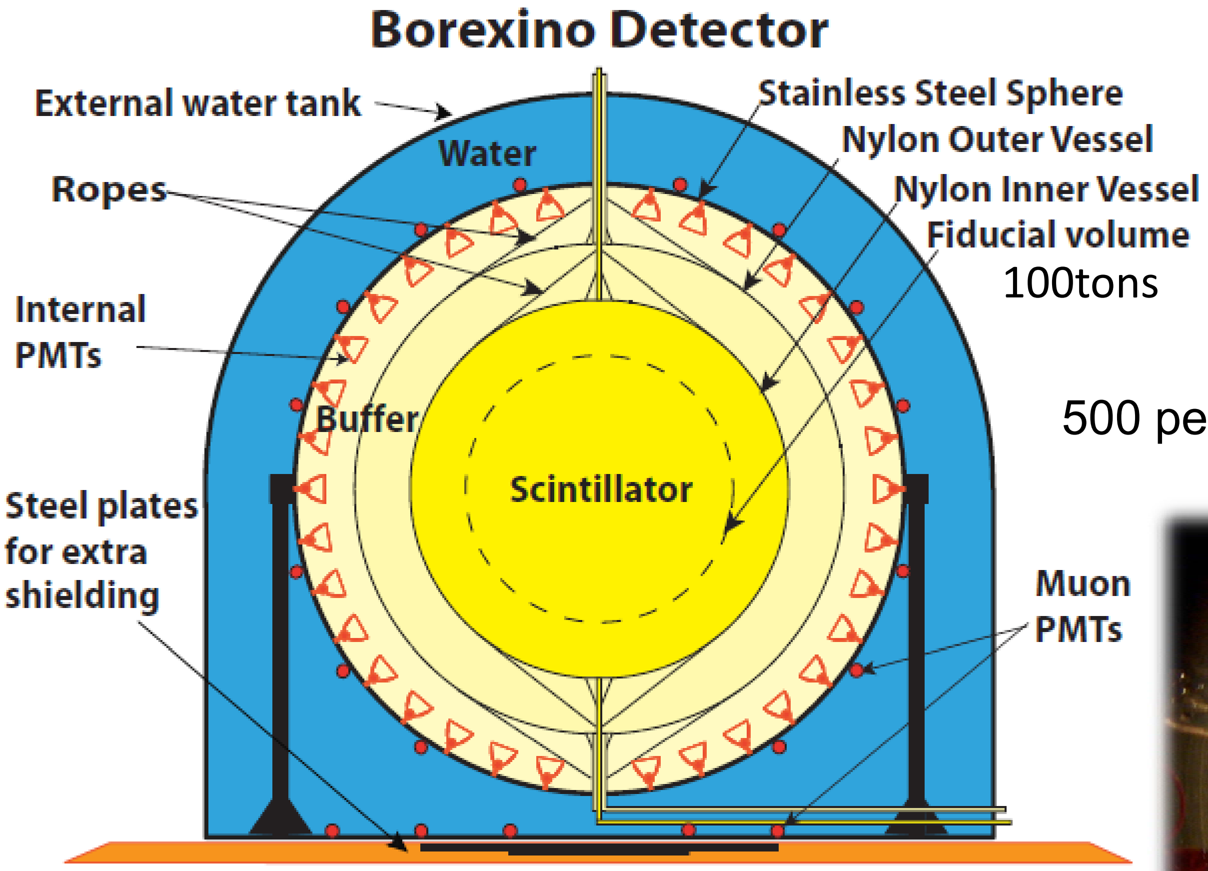
H.Bethe PRL 56, 1306 (1986)



➔Sub-MeV (^{7}Be) solar neutrino experiments

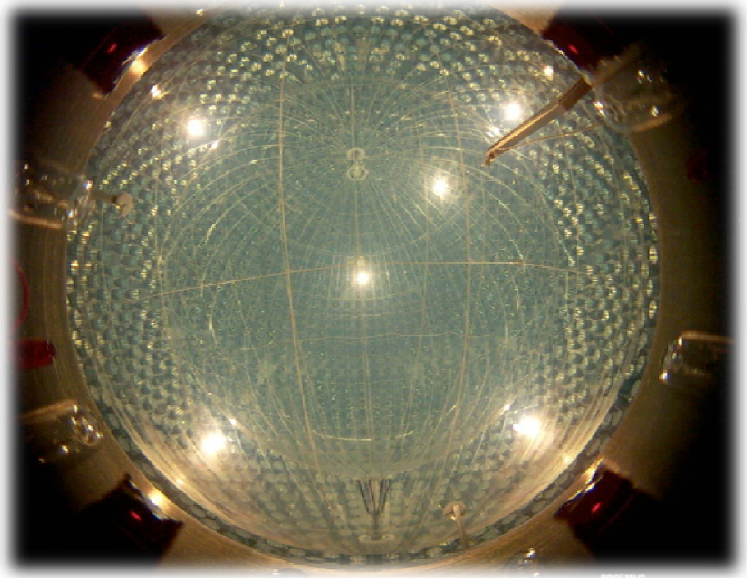
Borexino experiment

Solar neutrino experiment designed to measure neutrinos below 1-2 MeV by neutrino–electron scattering.
The first target is the ^{7}Be solar neutrinos (862keV).



500 pe/MeV

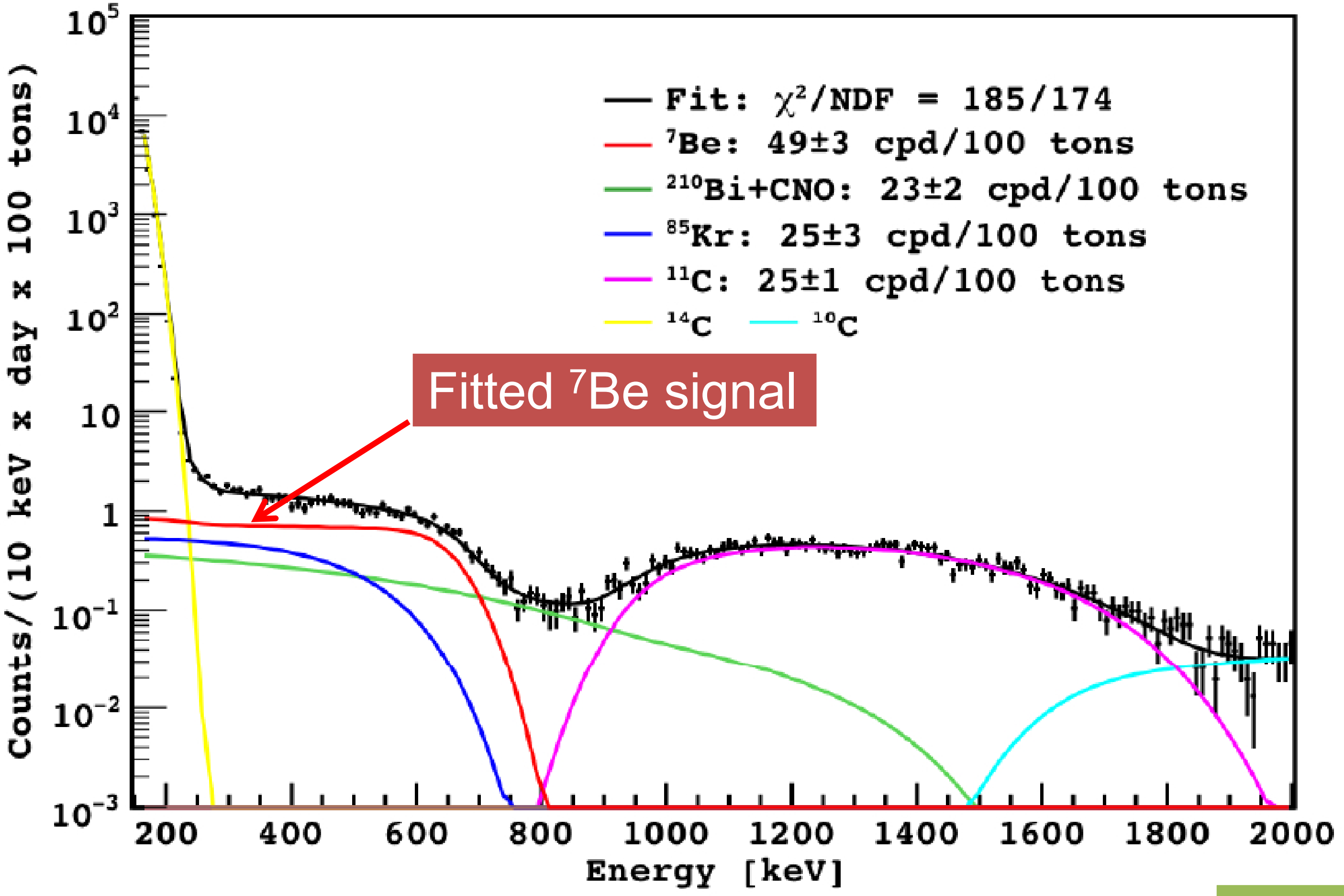
Started data taking in May 2007.



Borexino detector after filling

Energy spectrum

C. Galbiati, talk
@Nu2008
Borexino collab.
arXiv:0805.3843



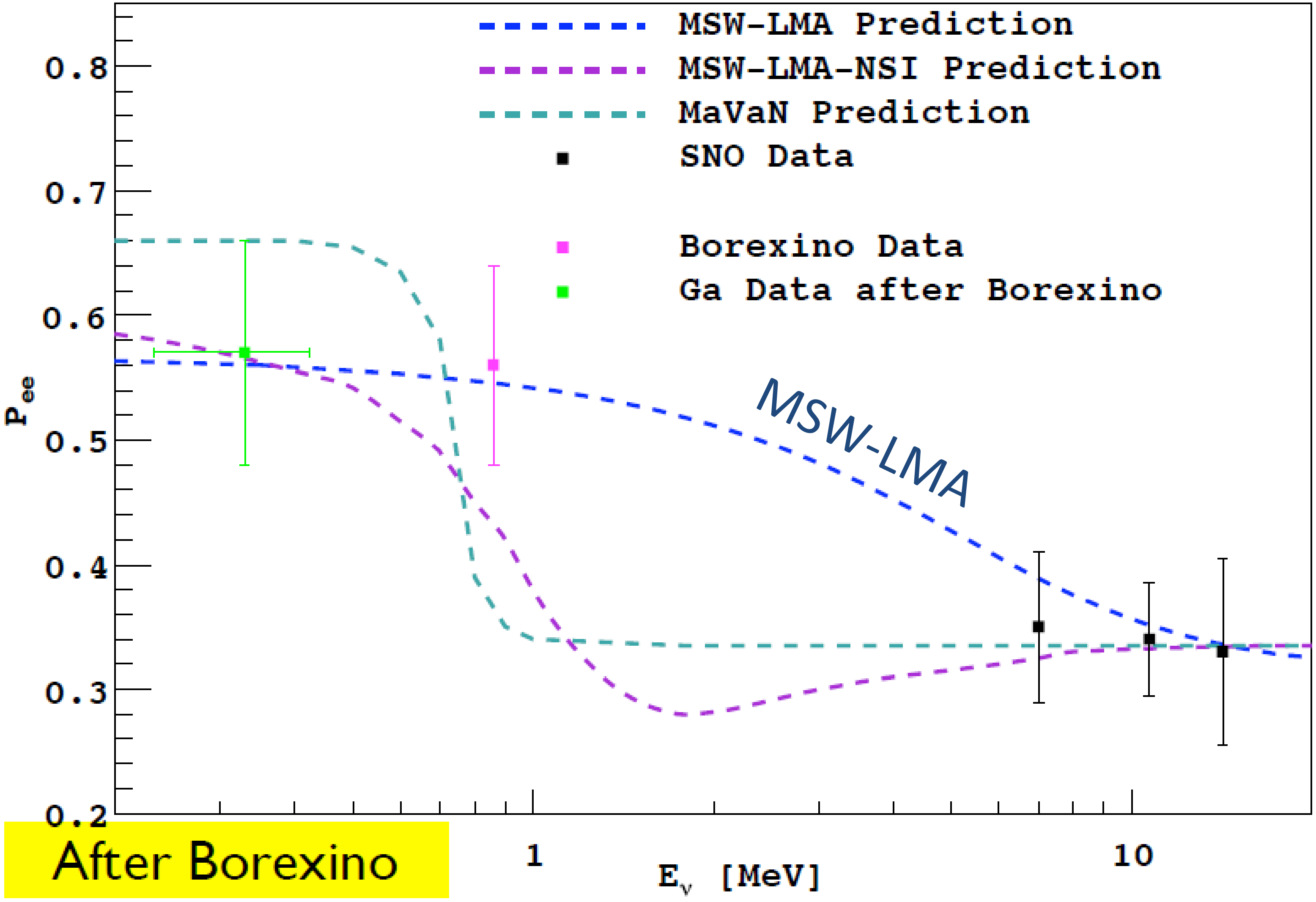
Fitted ^{7}Be signal

Data = 49±3(stat)±4(syst) counts/day/100tons

No oscillation:
75±4
MSW-LMA:
48±4

Main syst. error sources:
Fiducial volume, and detector response function

Solar neutrino survival probability



After Borexino

Borexino further confirmed the MSW-LMA solution!

Status of the 3 flavor effects (θ_{13})

3 flavor framework

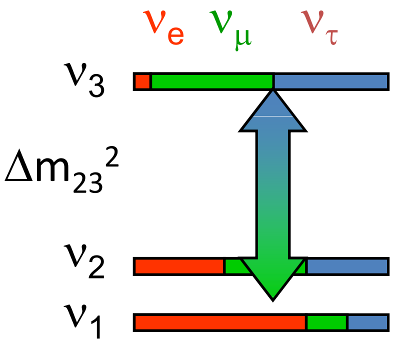
All the data are explained within the
3-flavor neutrino oscillation framework !

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U\cdot\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Various experiments

From now on (2nd lecture)

$$U=\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\times\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\times\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

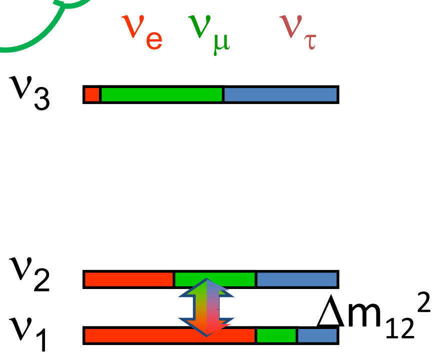


Atmospheric
LBL

(1st lecture)

Solar
KamLAND

(2nd lecture so far)



Searches for non-zero θ_{13}

θ_{13} with reactor experiments

- $<E_\nu>$ ~ a few MeV ➔ only disappearance experiments
- $P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta_{13} \cdot \sin^2(1.27\Delta m^2_{31} L/E)$ + (small solar effect)

➔ Almost pure measurement of θ_{13} with negligible matter effect.

θ_{13} with acclerator experiments

- $<E_\nu>$ ~ O(GeV) ➔ appearance experiments
- $P(\nu_\mu \rightarrow \nu_e) = 1 - \sin^2\theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2(1.27\Delta m^2_{31} L/E)$ + many terms

➔ Appearance measurement of θ_{13}.

➔ $P(\nu_\mu \rightarrow \nu_e) = F(\theta_{13}$, CP δ, mass hierarchy, $\theta_{23})$

θ_{13} with atmospheric ν experiments

- $<E_\nu>$ ~ O(5-10 GeV) ➔ appearance experiments (matter resonance)
- Other features similar to accelerator experiments

Status of θ_{13}

Reactor neutrinos

Long baseline Experiments

Atmospheric neutrinos

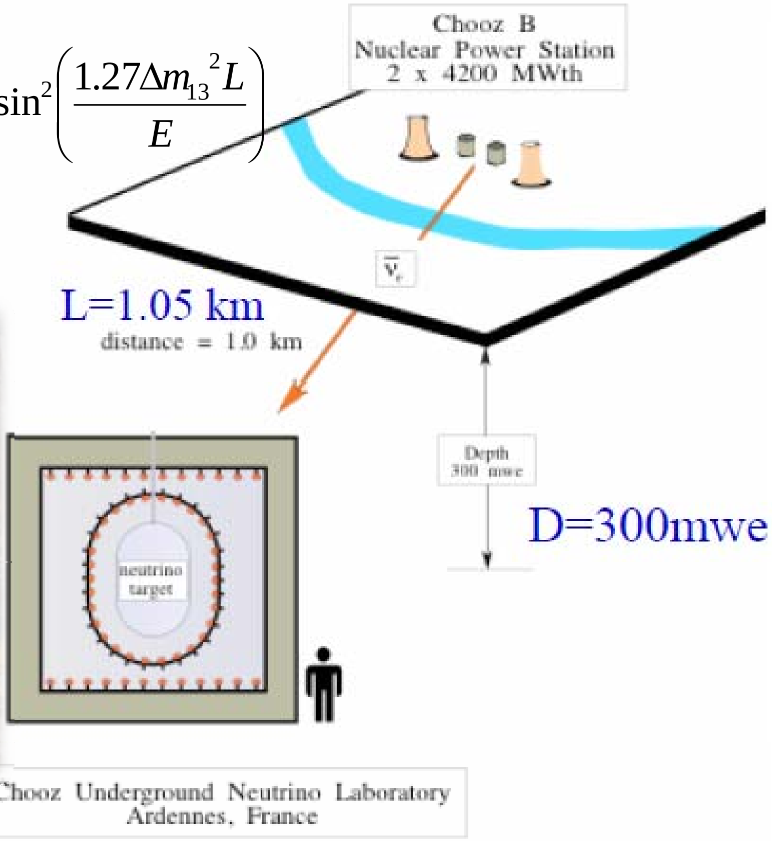
Solar neutrinos

Most sensitive experiment so far: CHOOZ

hep-ex/9907037
hep-ex/0301017

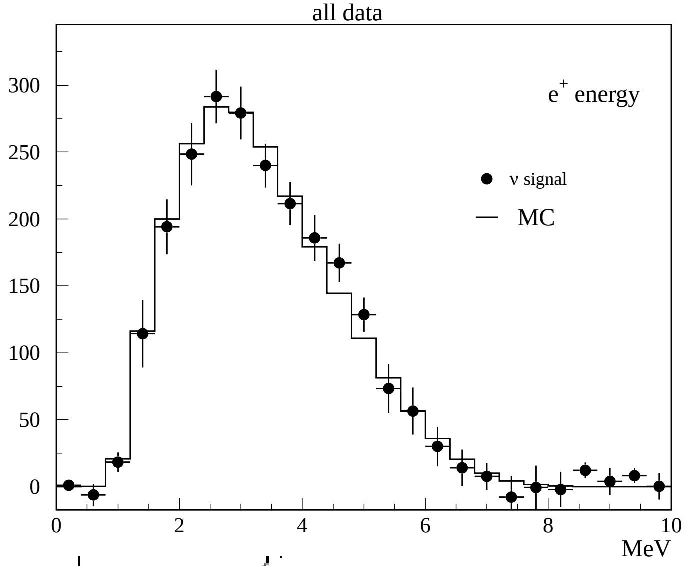
P=8.4 GW_{th}

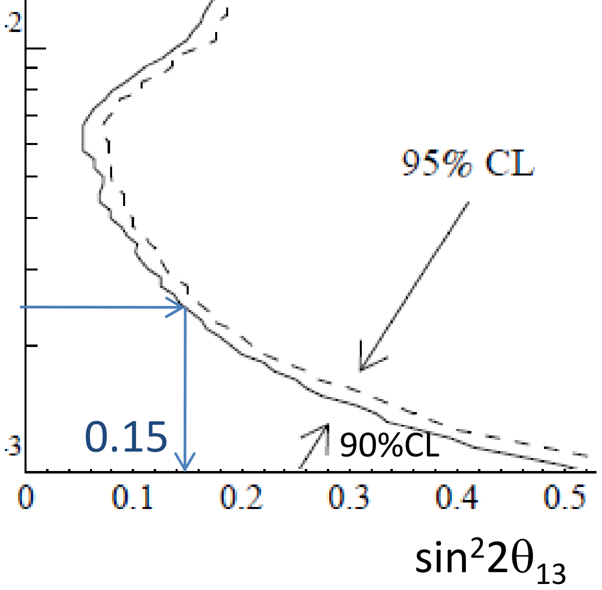
$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{1.27\Delta m_{13}^2 L}{E}\right)$$



L=1.05 km

D=300mwe





m = 5 tons, Gd-loaded liquid scintillator

Data/Expectation = 1.01±0.028(stat)±0.027(syst)

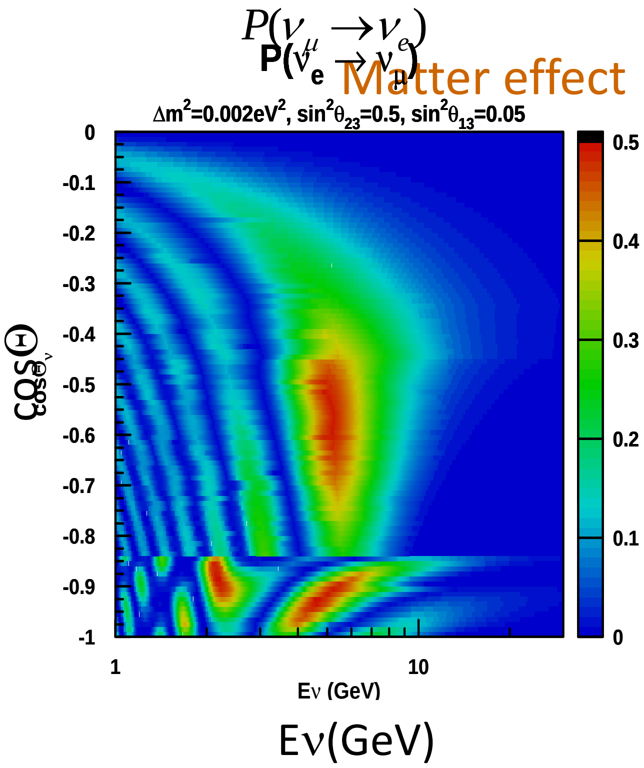
Search for θ_{13} in atmospheric neutrino exp.

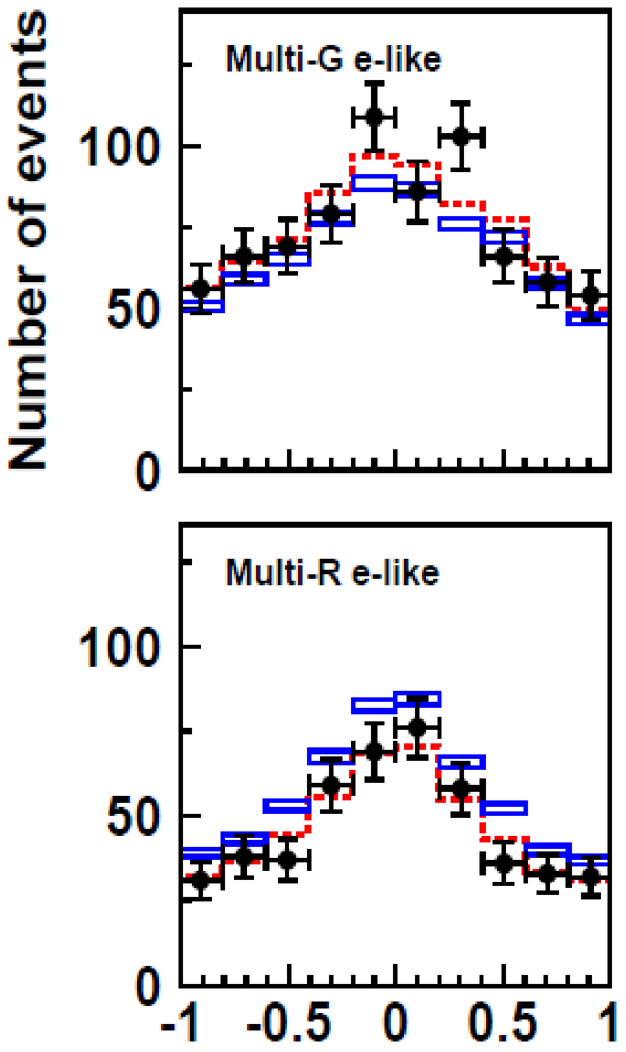
SK atmospheric

hep-ex
/0604011

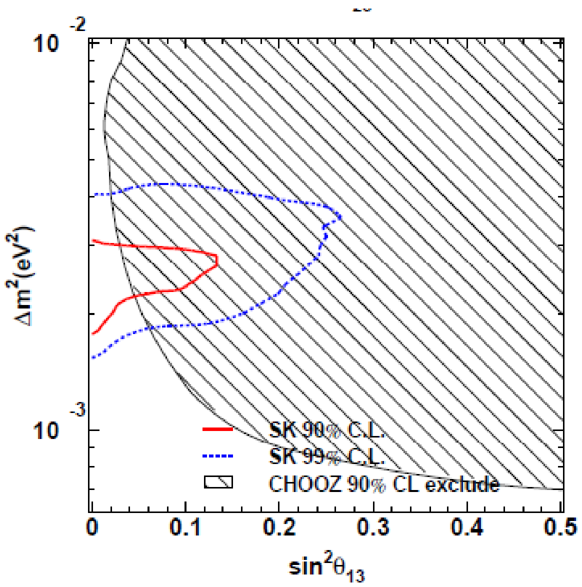
$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{1.27\Delta m_{13}^2 L}{E}\right)$$

(assuming $\Delta m_{12}^2=0$, vacuum)





Matter resonance effect
➔ No evidence for excess of multi-GeV up-going electrons



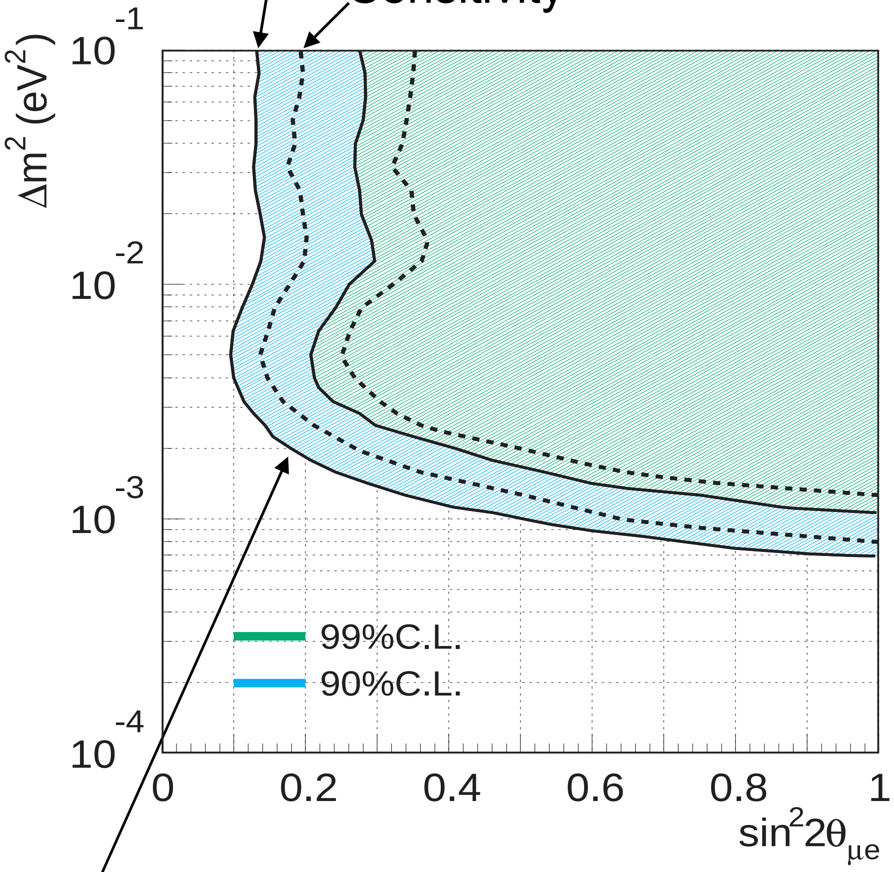
Search for θ_{13} (electron appearance) in K2K

K2K hep-ex/0603004

K2K-I + II	data	MC
FC 22.5kt	112	158.1
e-like	8	6.7

Tight e-selection cuts

data	MC
1	1.63
	($1.25\ \nu_\mu + 0.38\ \nu_e$)



Limit

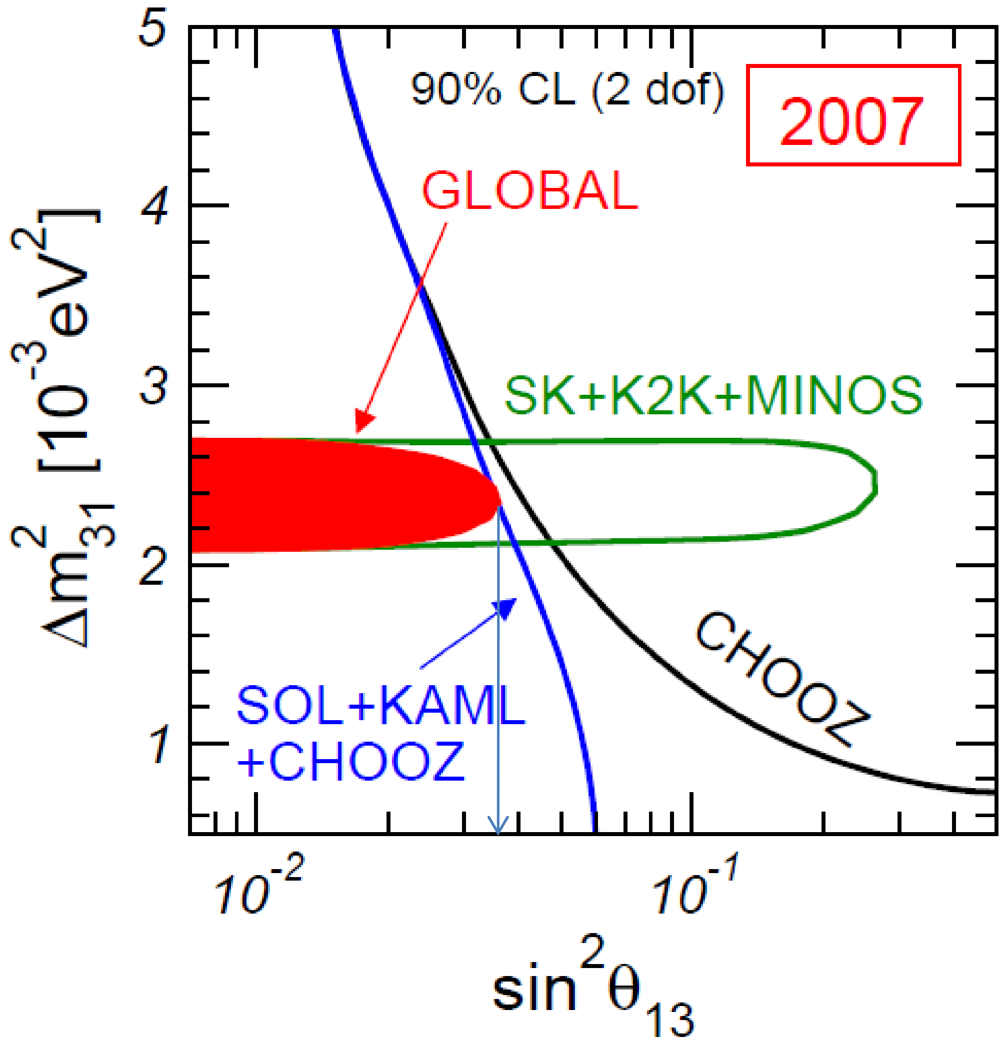
Sensitivity

About factor 2
to the Chooz limit

$=\sin^2\theta_{23}\cdot\sin^2 2\theta_{13}$

2007 θ_{13} global fit

hep-ph/0405172v6 (Sep.2007 version)



➔CHOOZ: dominant contribution.

➔Other experiments improves the limit slightly.

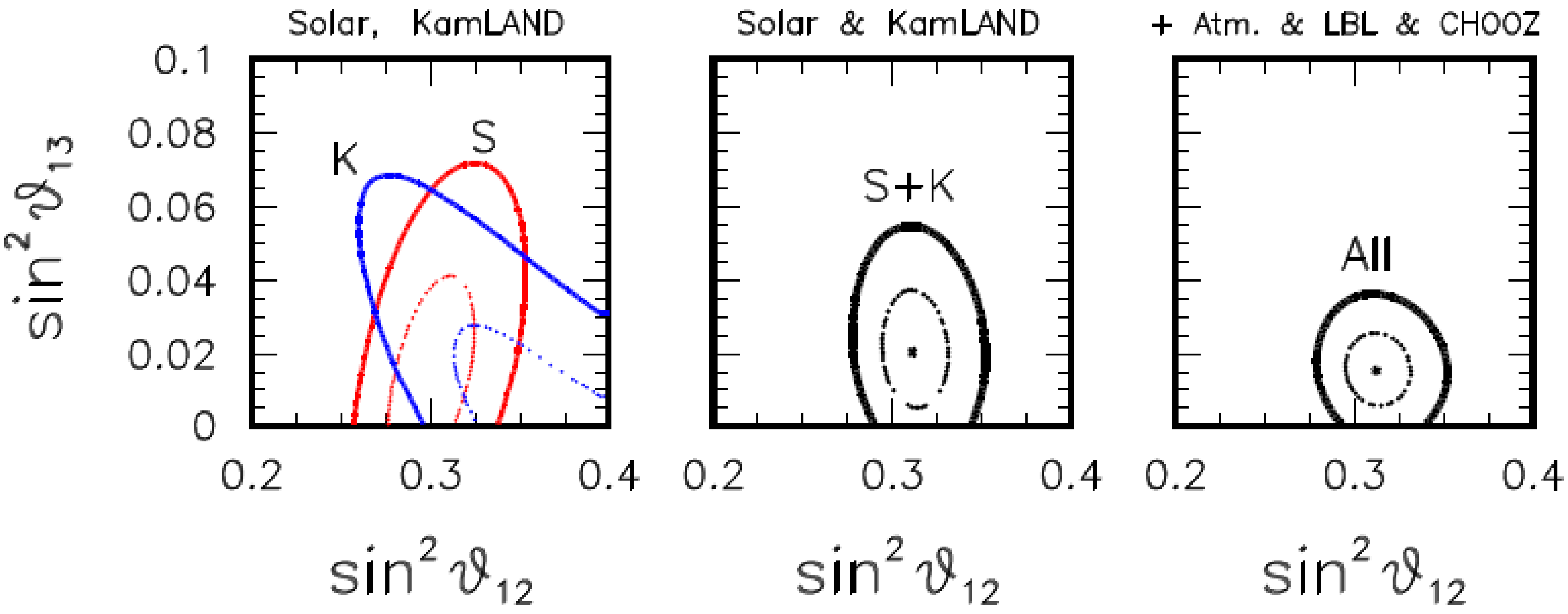
➔ However, due to the lower best fit Δm^2, the limit on $\sin^2 2\theta_{13}$ is still about 0.14 - 0.15…

Much higher sensitivity experiments required.

Global analysis and a hint of non-zero θ_{13}?

G.L. Fogli et al arxiv:0806.2649 [hep-ph]

Hint in the atmospheric neutrino data with an analysis with the Δm_{12}^2 term.
Hint in the possible tension between solar and kamLAND data on $\sin^2\theta_{12}$.



Much higher sensitivity experiments required.

Summary of Lecture-2

- Nearly 40 years ago, the first solar neutrino experiment (Homestake ^{37}Cl experiment) was carried out to study the energy generation in the Sun. This experiment found "The missing solar neutrino problem".
- The problem was clearly solved by the SNO D_2O experiment, with an important contribution from the Super-K data.
- KamLAND reactor experiment observed the oscillation pattern, and determined the Δm_{12}^2 parameter accurately.
- Recent Borexino data further confirmed the MSW-LMA solution.
- No clear evidence for non-zero θ_{13} yet. Much sensitive experiments are necessary.

Summary

- Search for proton decay
  ➔ Discovery of $\nu_\mu \rightarrow \nu_\tau$ oscillation, large mixing
- Study of energy generation in the Sun
  ➔ Discovery of $\nu_e \rightarrow \nu_{(\mu, \tau)}$ oscillation
- Trying to measure, θ_{13}, CP violation, mass hierarchy, double beta decay …

  ➔ ? ? ?

- Neutrino physics is probably related to "big questions" in nature.

We are in an extremely interesting era!

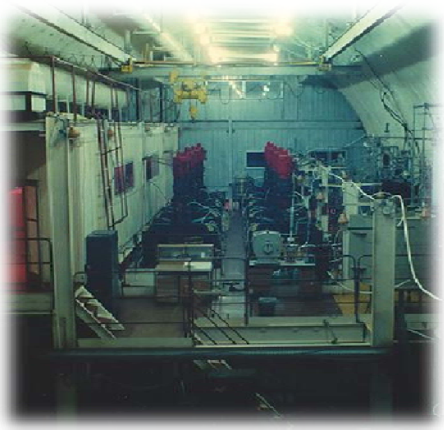
Let's enjoy neutrino physics!

End

Summary of solar neutrino experiments before the present generation exp’s.

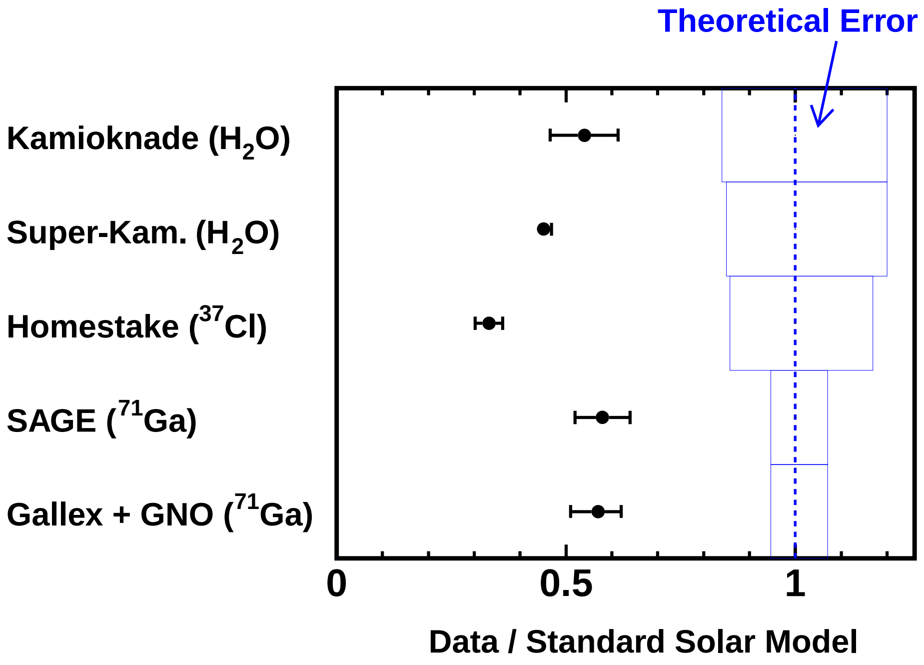
Homestake (Cl)

Kamiokande (H_2O)



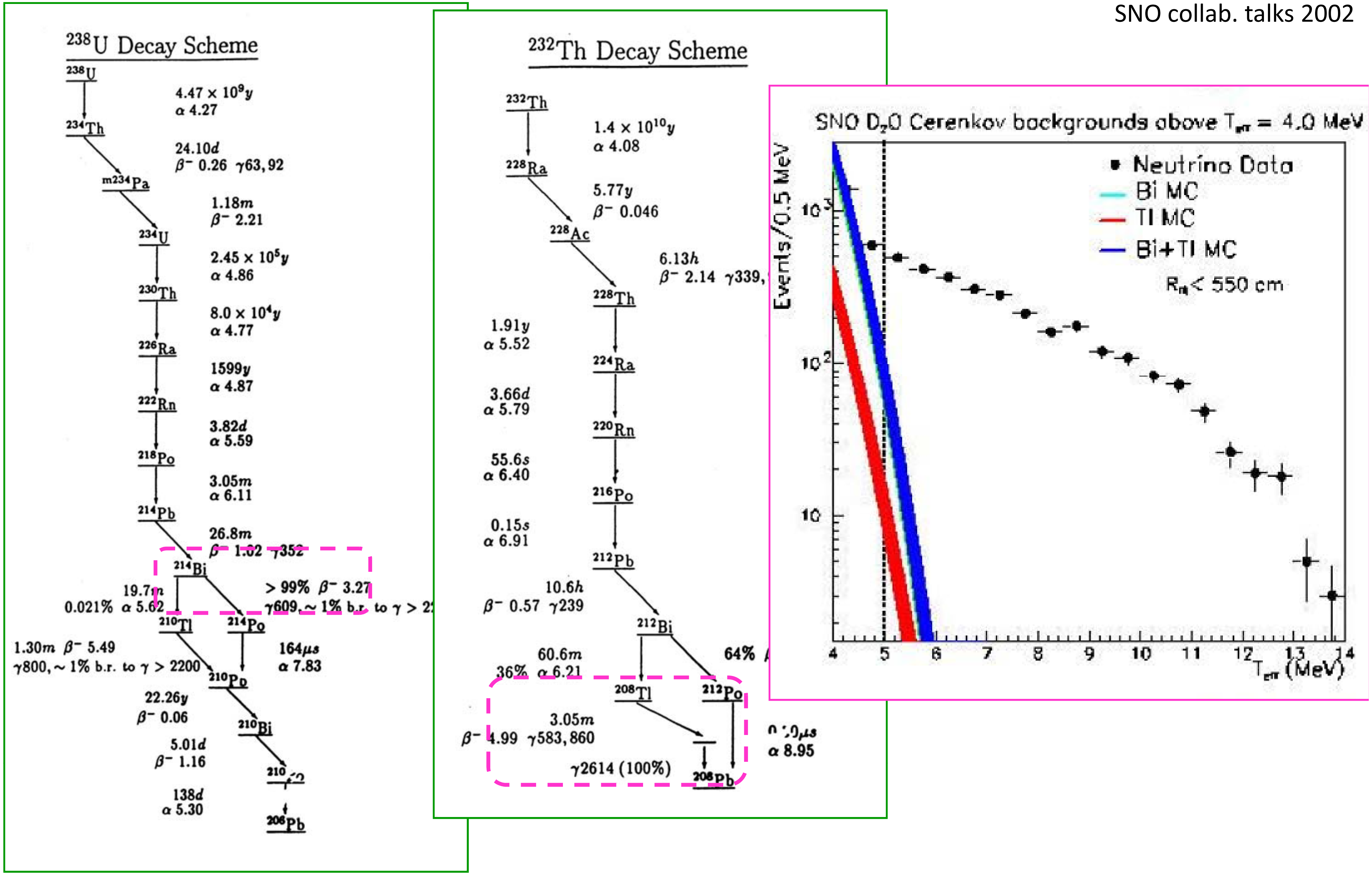
SAGE (Ga)

Gallex/GNO (Ga)

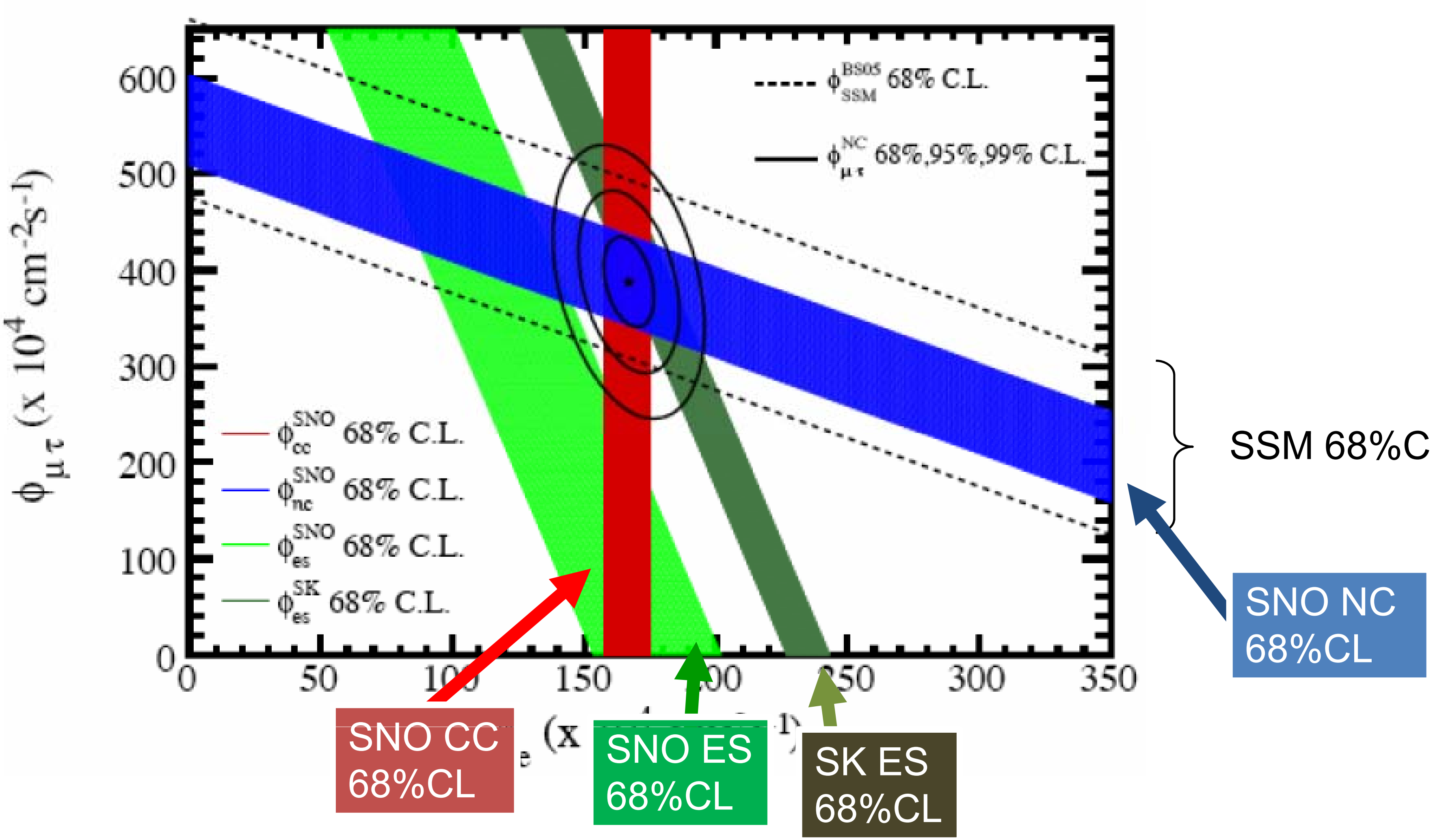


In-situ BG measurement in SNO

SNO collab. talks 2002



ν_e and $(\nu_\mu+\nu_\tau)$ fluxes (NCD phase)



SSM 68%CL

SNO NC
68%CL

SNO CC
68%CL

SNO ES
68%CL

SK ES
68%CL

Three different measurements intersect at a point.

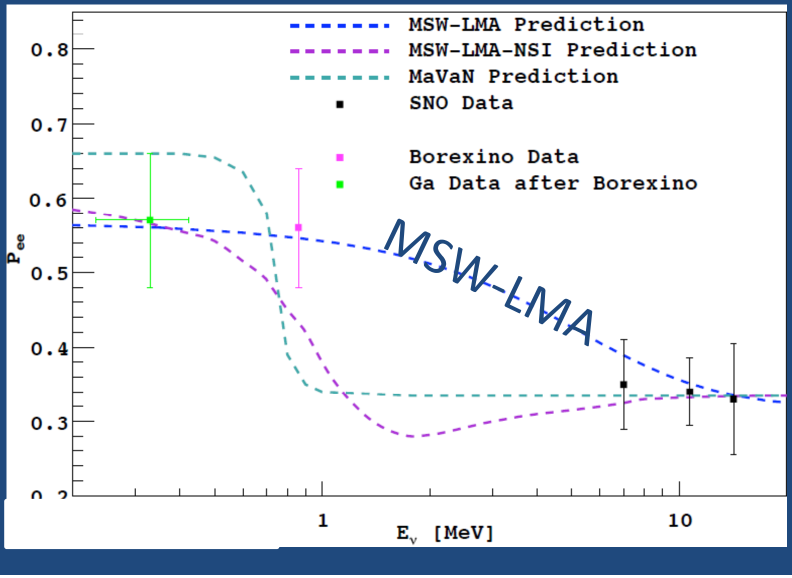
Prospects for solar neutrino experiments

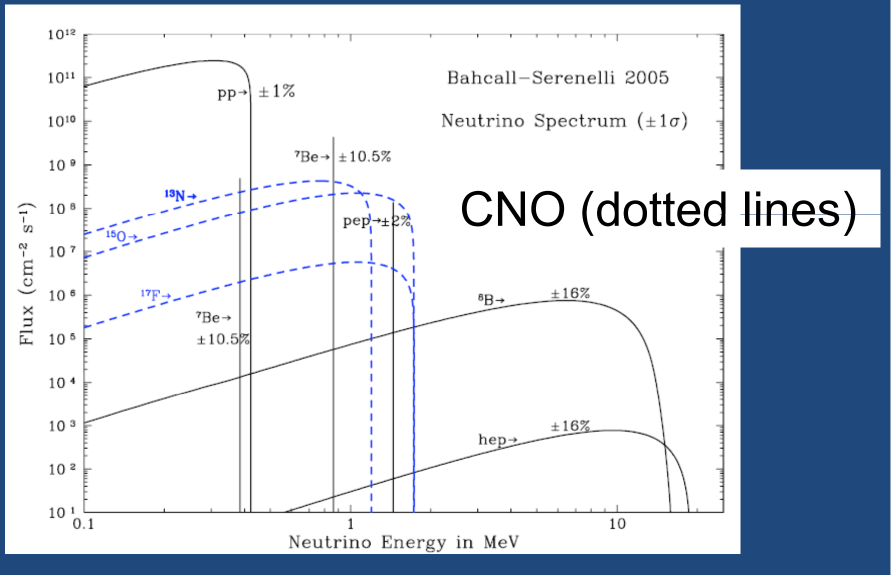
Future goals?:

➔Understanding the SUN better (CNO neutrinos)

➔ Further confirming the MSW mechanism

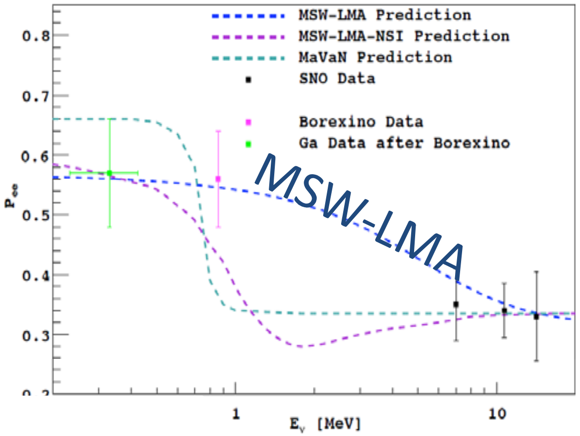
➔ Searching for physics beyond the standard MSW-LMA solution.





CNO (dotted lines)

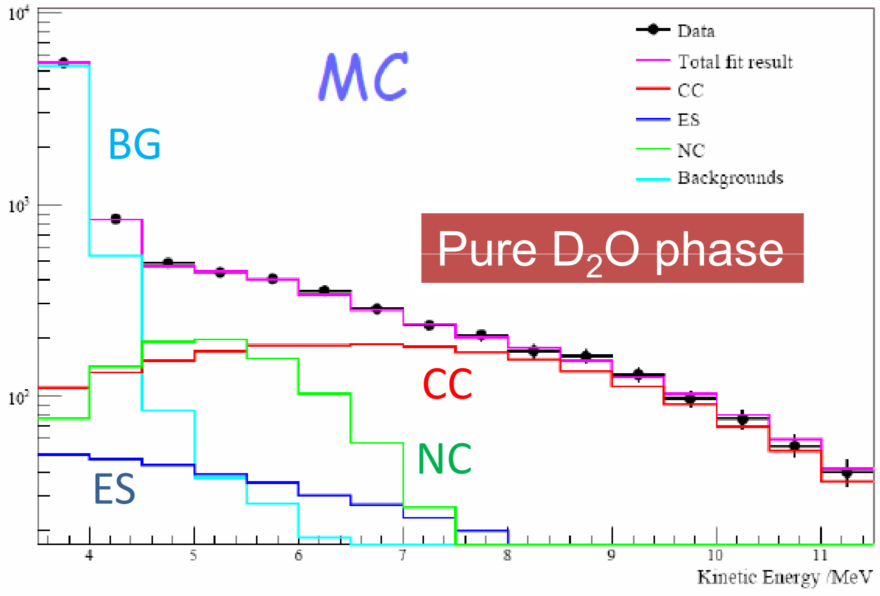
Future ^{8}B solar neutrino data



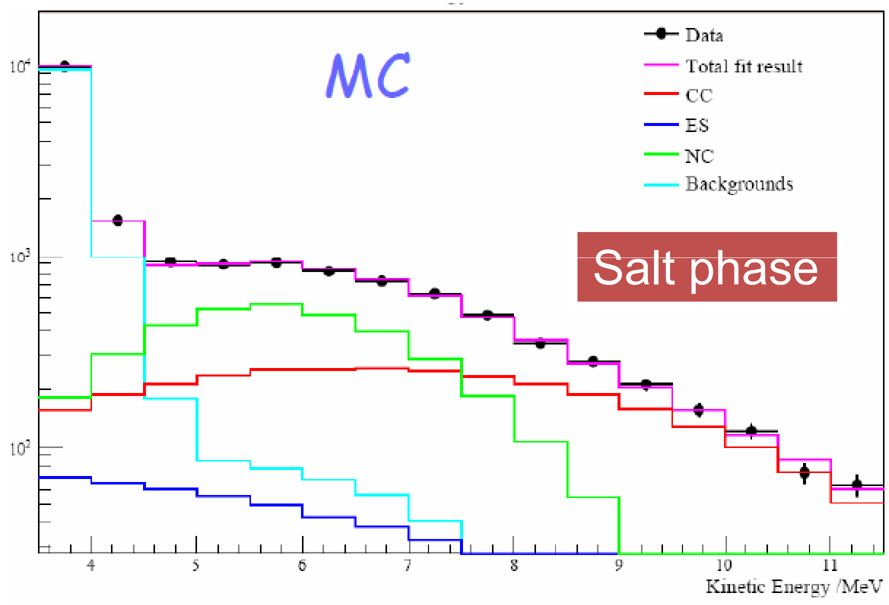
Up-turn of Pee should be observed in ^{8}B solar neutrino experiments!

SNO

J. Klein, talk @Nu2008



Pure D_2O phase



Salt phase

Lowering the threshold down to ～4 MeV seems to be possible.
(Very good understanding of the background is required.)

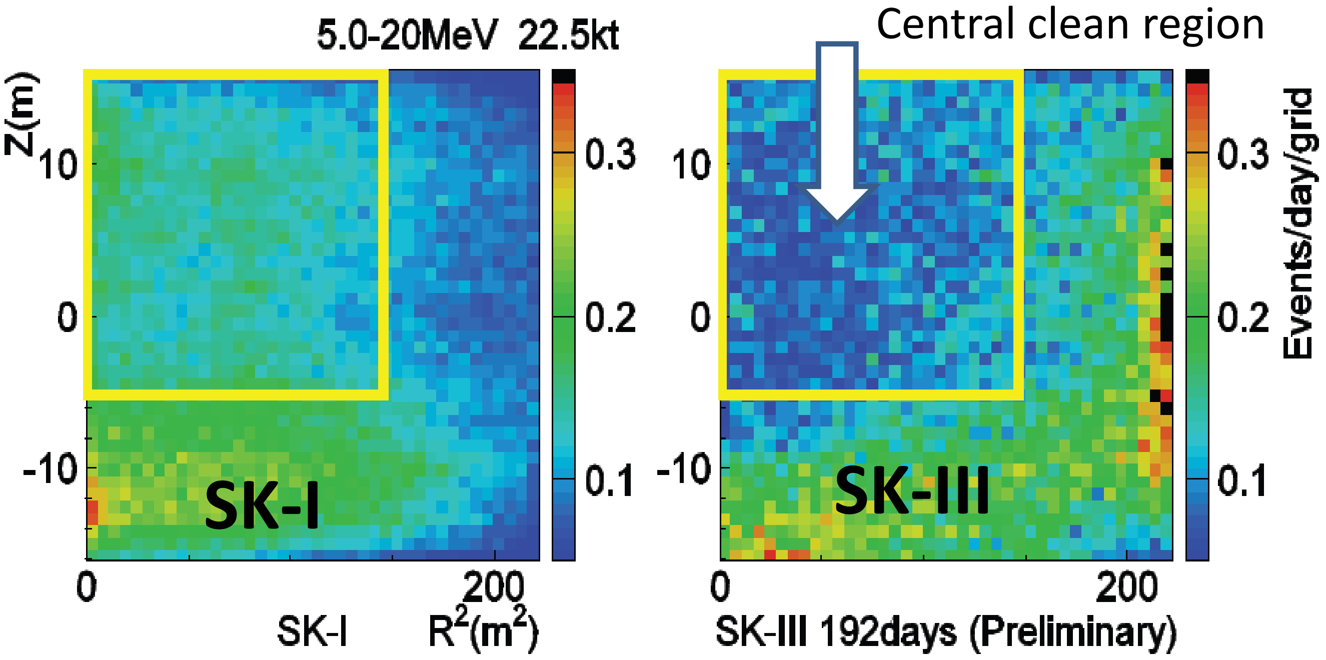
Future ^{8}B solar neutrino data

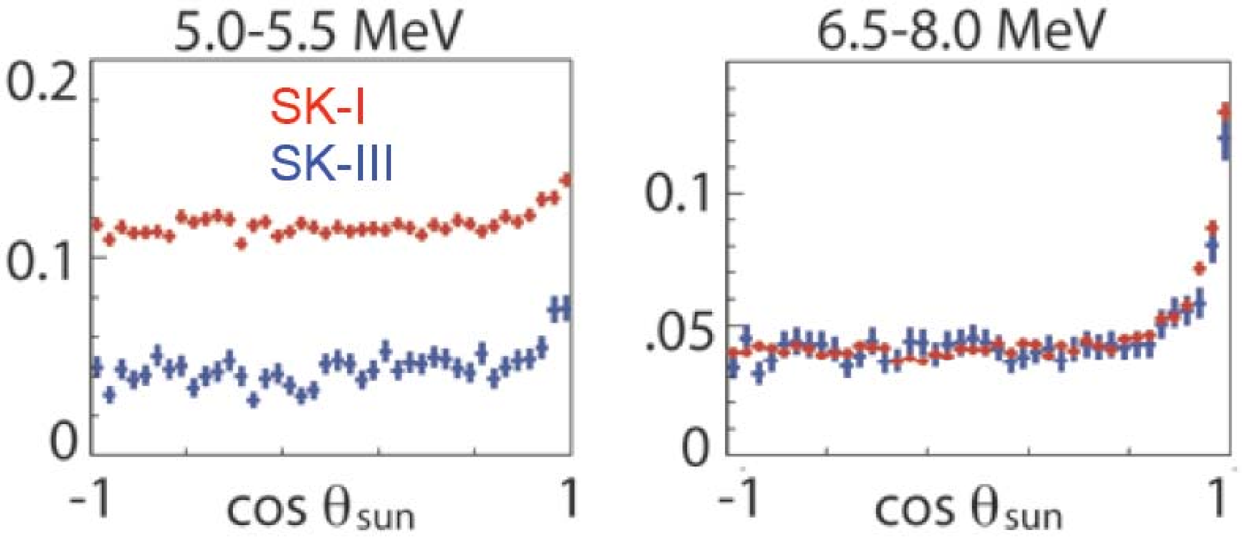
Super-K-III

In a part of the central region, the BG rate has been reduced due to the improvements in the water system.

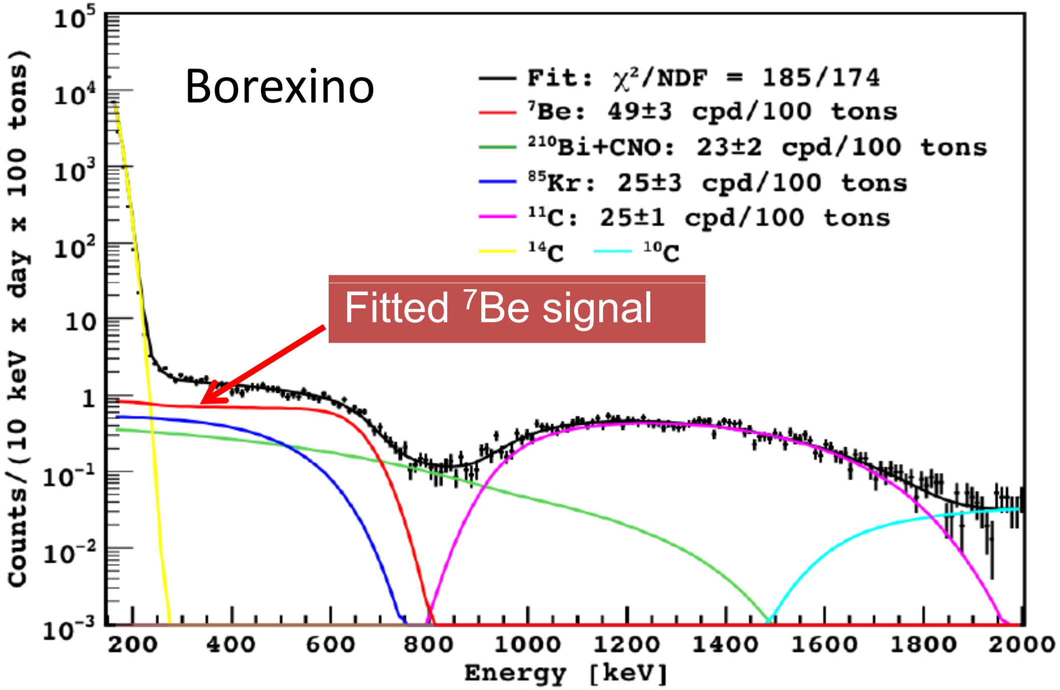
Threshold below 5MeV.

Upturn in several years(?)

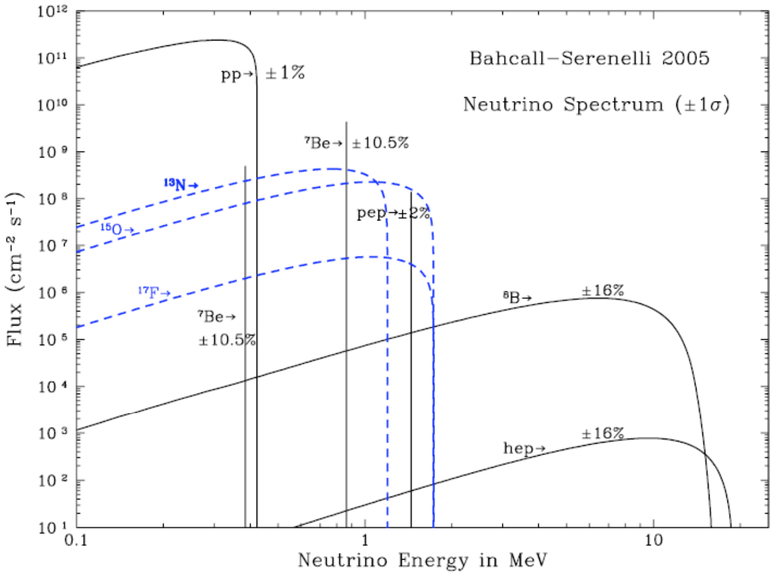




Future sub-MeV solar neutrino experiments



Fitted ^{7}Be signal



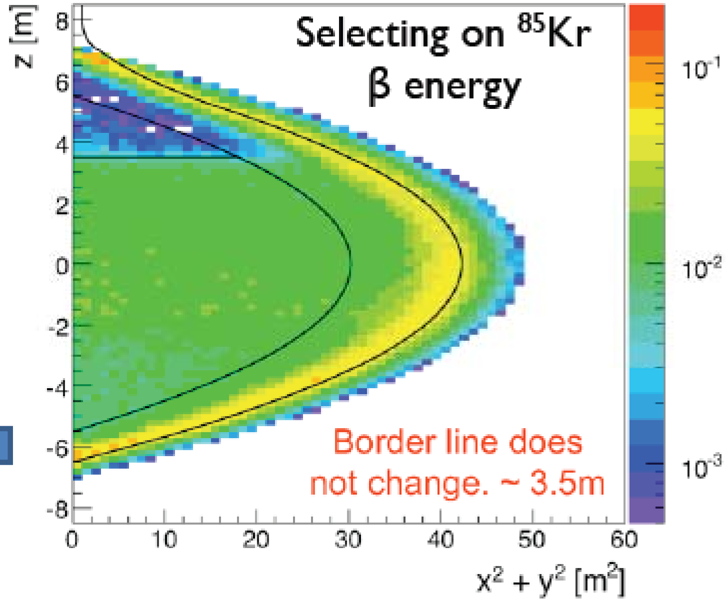
The next major goals:

- ● Detection of the pep and CNO neutrinos.
- ● Precise measurement of 7Be neutrinos.

Borexino
SNO+
KamLAND

KamLAND solar neutrino experiment

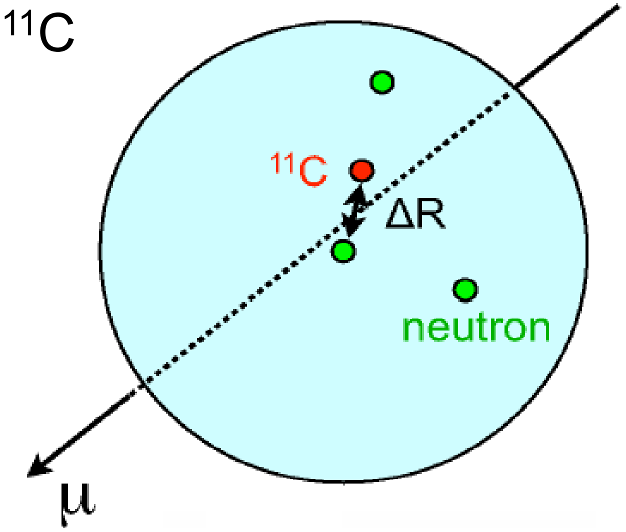
5 orders of magnitude BG (^{85}Kr, ^{210}Bi, …) reduction required.
First purification in 2007. (Substantial BG reduction in a small volume.)
Purification in 2008 started.



Selecting on ^{85}Kr β energy

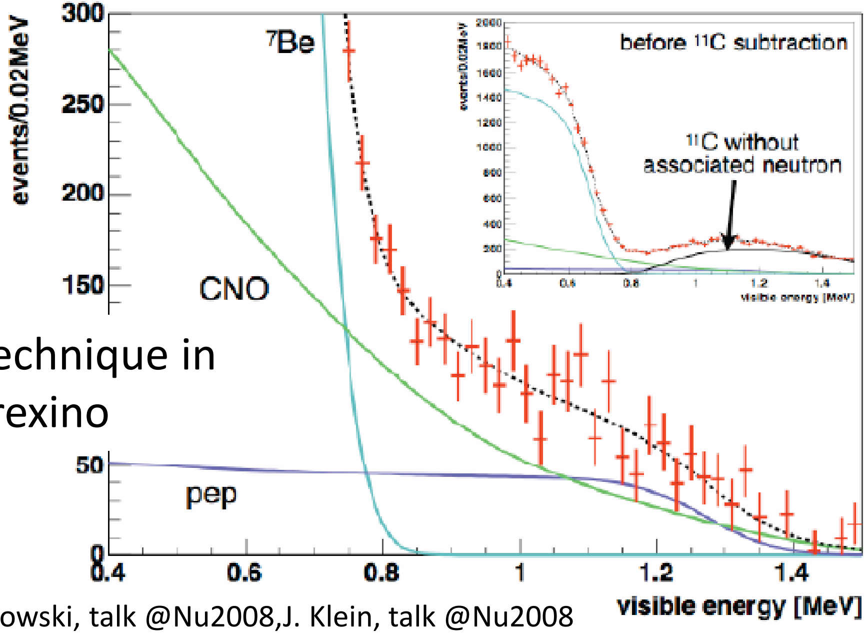
Border line does not change. ~ 3.5m

Potential difficulty:
^{11}C



- prompt muon
- γ from n capture after ~210 μs
- ^{11}C decay after ~30 min

Similar technique in Borexino



before ^{11}C subtraction

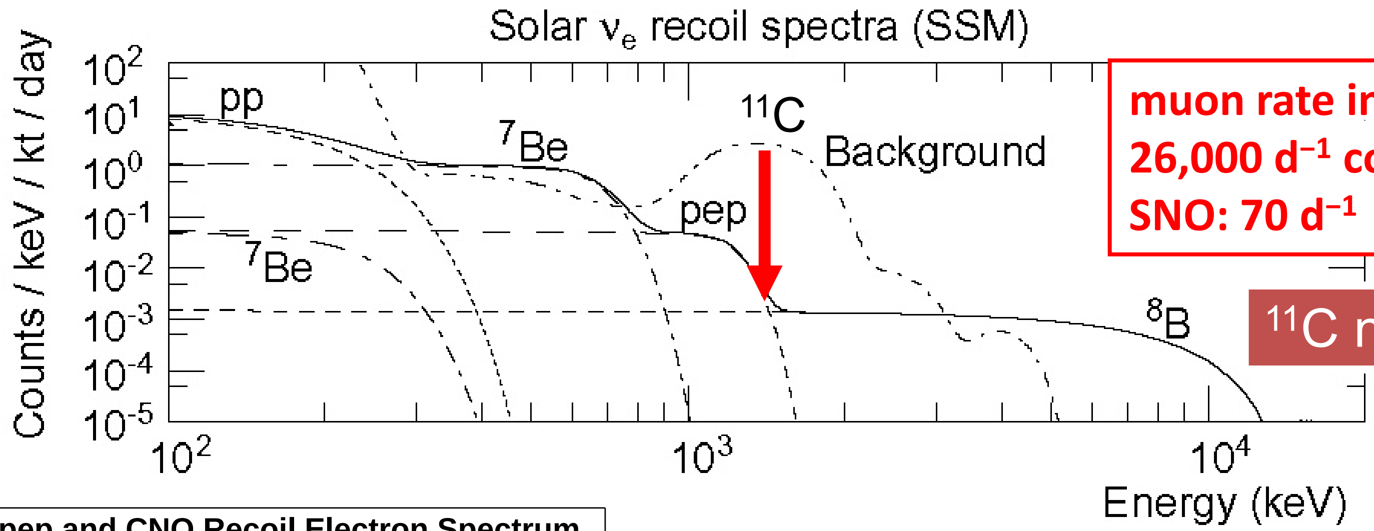
^{11}C without associated neutron

P. Decowski, talk @Nu2008,J. Klein, talk @Nu2008

SNO+

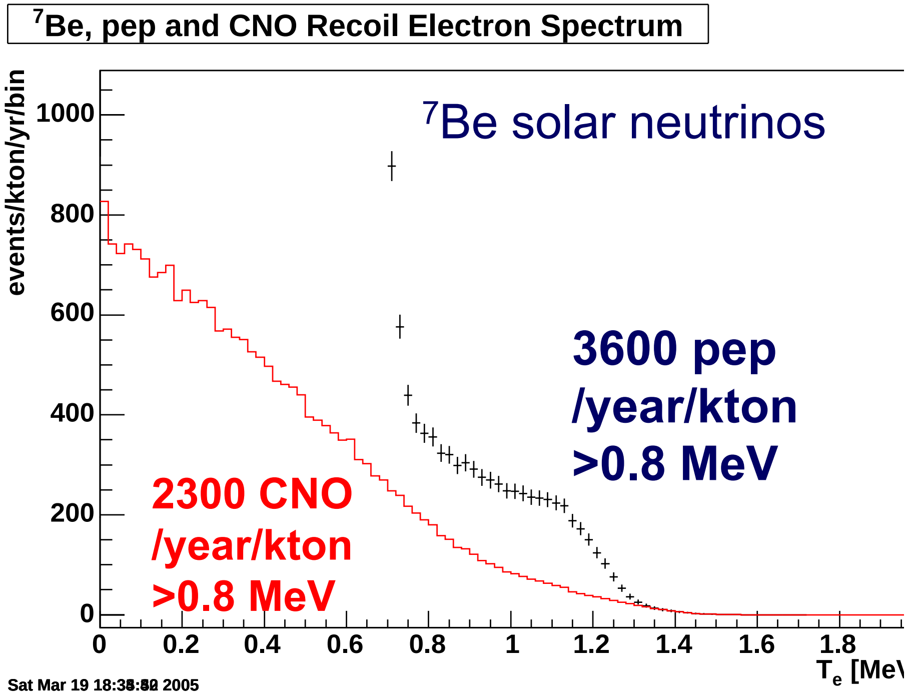
Fill the existing SNO detector with very pure liquid scintillator.

J. Klein, talk @Nu2008



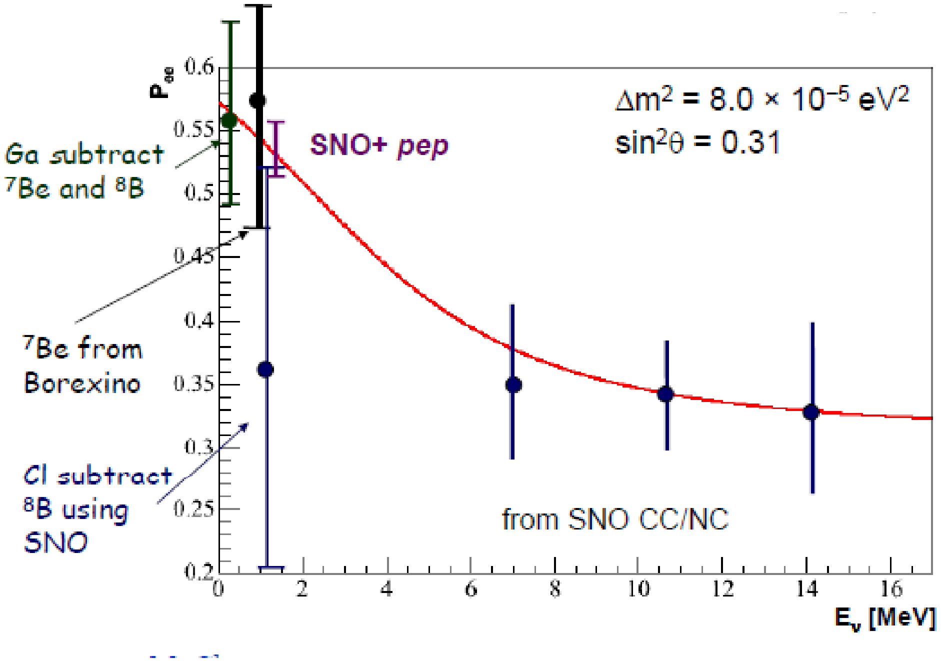
muon rate in KamLAND: 26,000 d^{-1} compared with SNO: 70 d^{-1}

^{11}C not a problem



3600 pep /year/kton >0.8 MeV

2300 CNO /year/kton >0.8 MeV

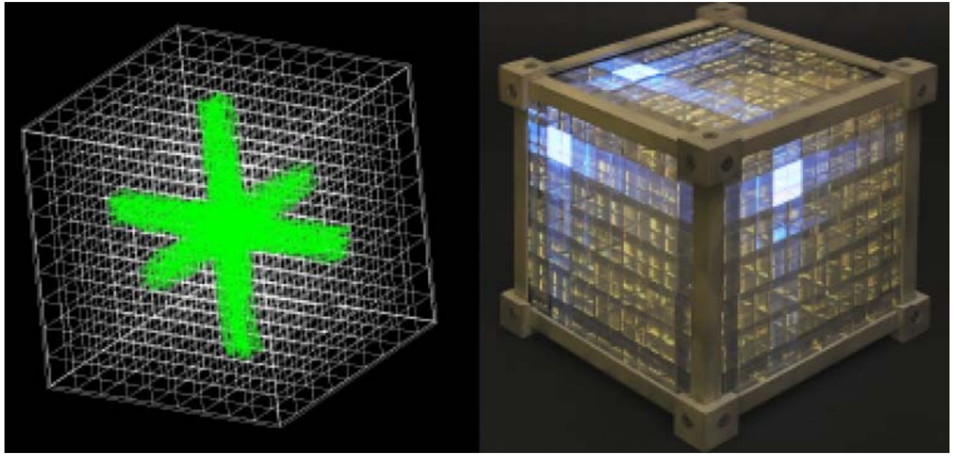


Many R&D's for future pp solar ν experiments

J. Klein, talk @Nu2008

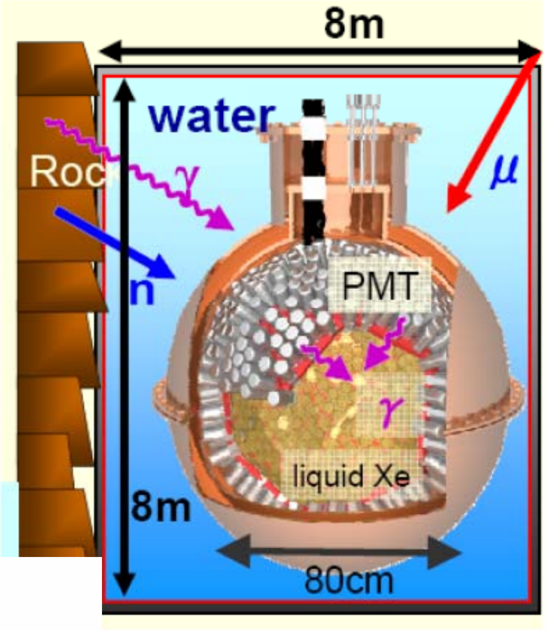
LENS

$\nu_e + {}^{115}\mathrm{In} \rightarrow e^- + {}^{115}\mathrm{Sn} + 2\gamma$ (CC int.)



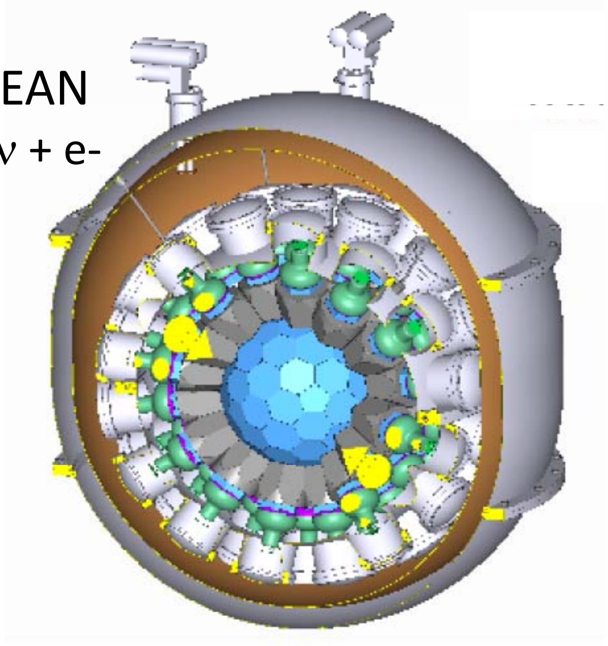
XMASS

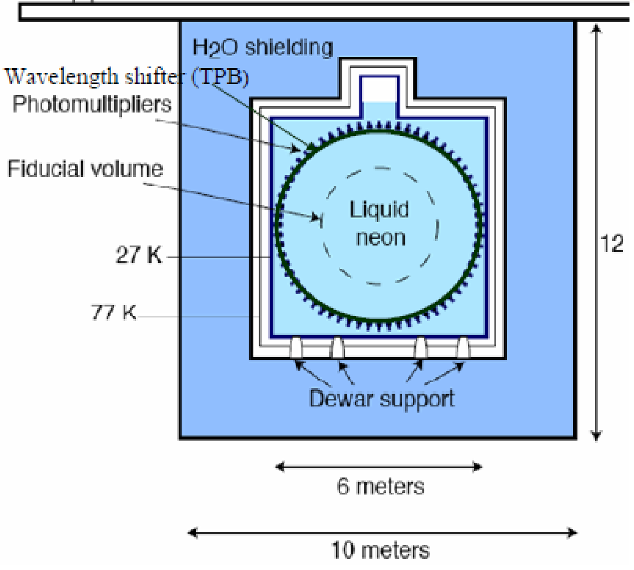
$\nu + e^- \rightarrow \nu + e^-$



DEAP/CLEAN

$\nu + e^- \rightarrow \nu + e^-$





+ MORE