The International Neutrino Summer School
INSS2013
August 6-16, 2013, Beijing, China

Solar, Reactor and Atmospheric Neutrinos

Lecture 2

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Overall Outline

Lecture 1:

Δm_{23}^2 and θ_{23}:

Atmospheric neutrino experiments

Lecture 2:

Δm_{12}^2 and θ_{12}:

Solar neutrino and reactor experiments

Lecture 3:

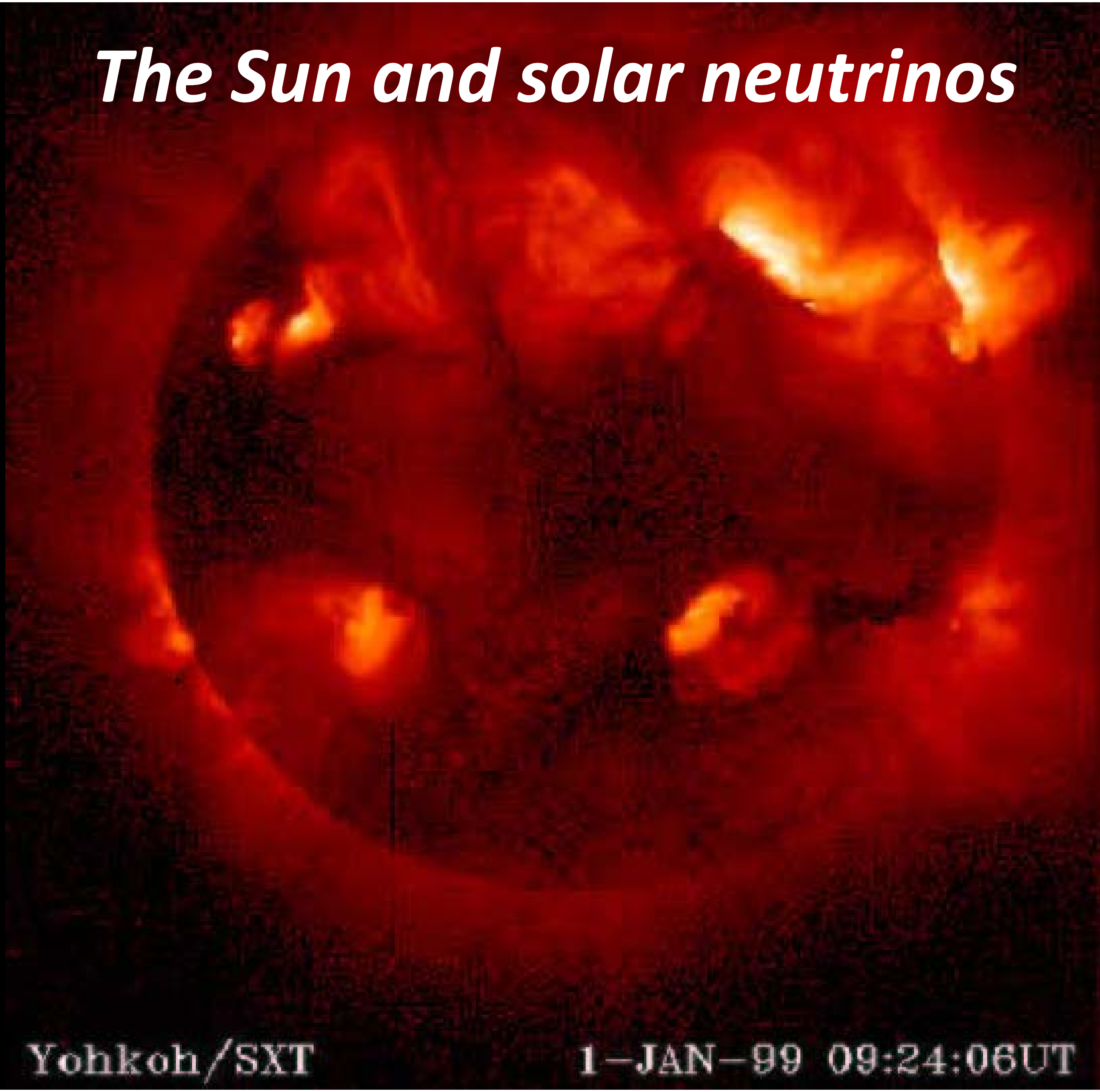
θ_{13} and beyond:

Reactor and atmospheric neutrino exps

Outline - Lecture 2 -

- The Sun and the solar neutrinos
- Some early history (solar neutrino problem)
- Solving solar neutrino problem with neutrino oscillations
- KamLAND reactor neutrino oscillation experiment
- Next steps: further confirmation of MSW
- Summary of Lecture 2

The Sun and 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;

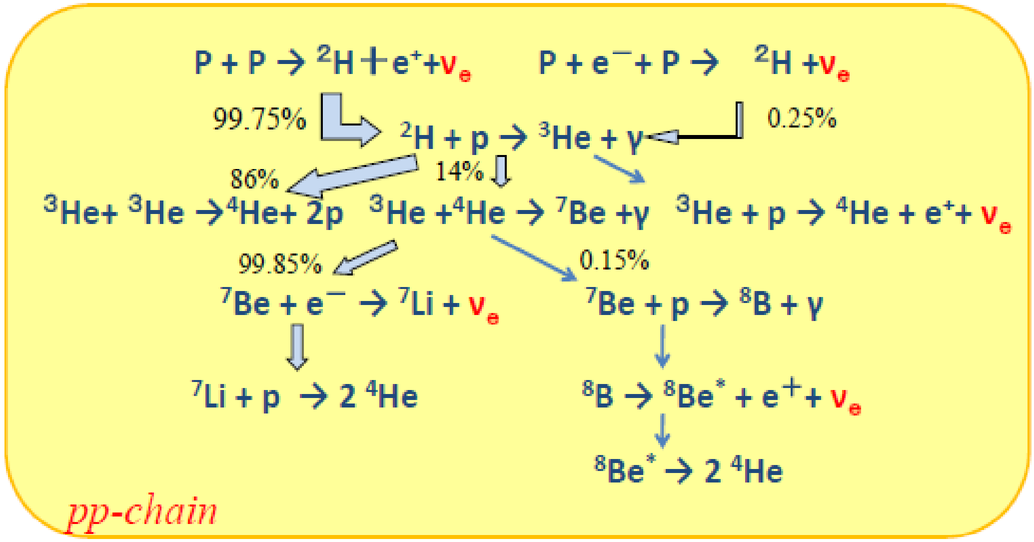
$$flux = \frac{1}{4\pi R^2} \times \frac{L_{sun}}{27MeV} \times 2\nu_e$$

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

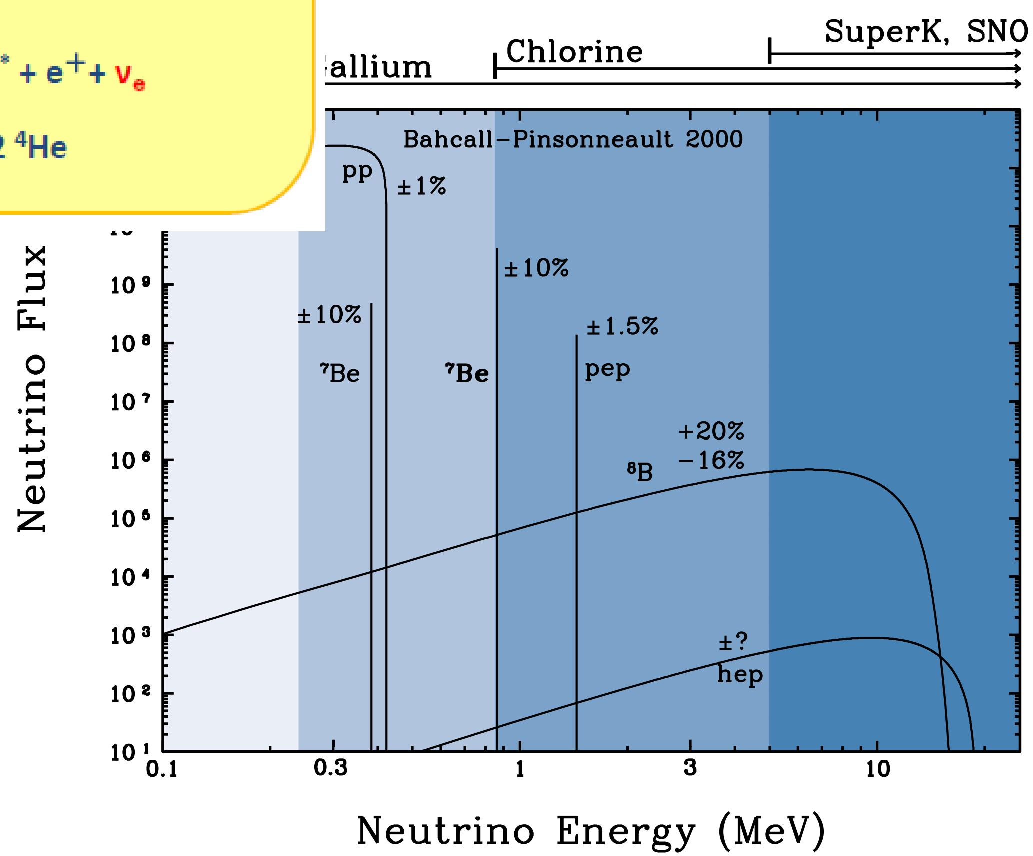
$$= 6 \times 10^{10} \nu_e / cm^2 / \mathrm{sec}$$

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

Solar neutrino spectrum



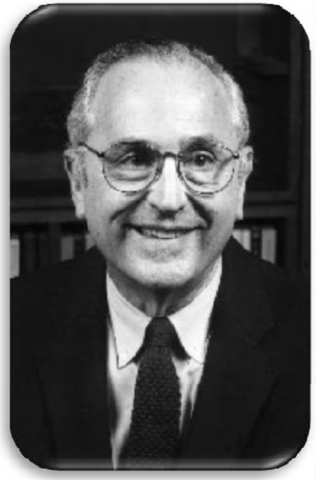
However, in reality, 4 protons cannot make a Helium nucleus at a time…
➔ chain reactions



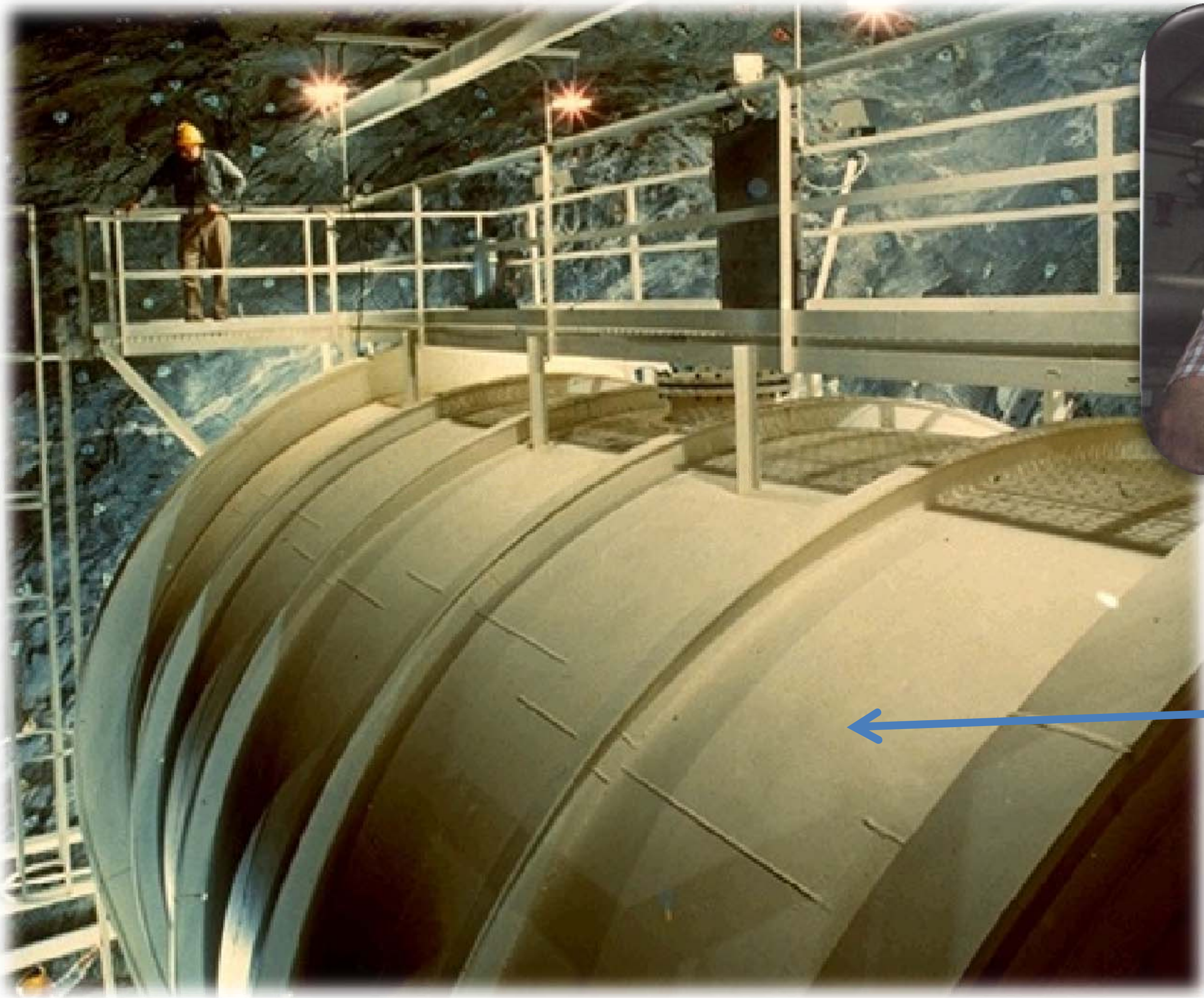
Some early history (solar neutrino problem)

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

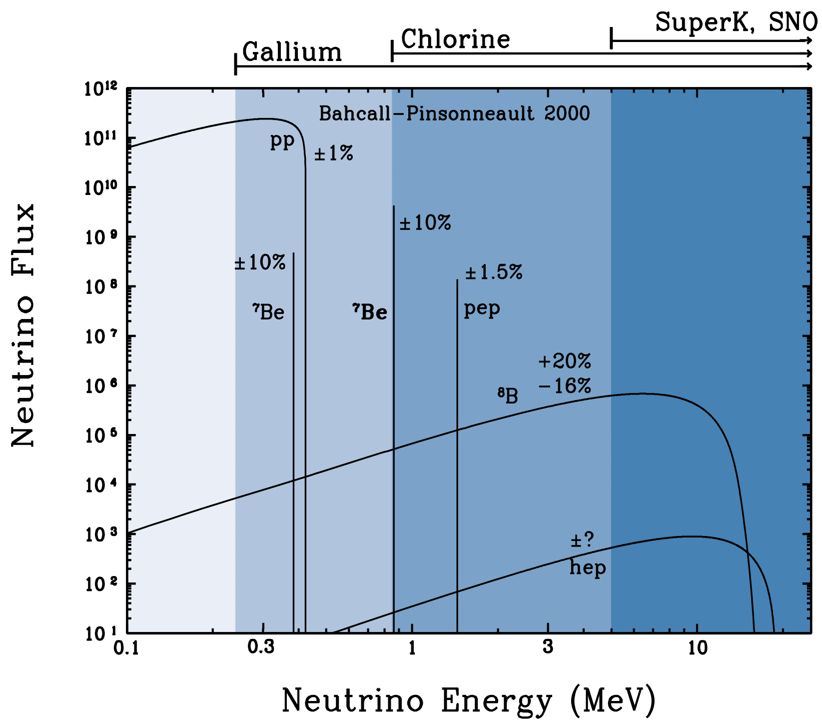


R. Davis Jr.

600ton C_2Cl_4

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

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

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

(These numbers are slightly old...)

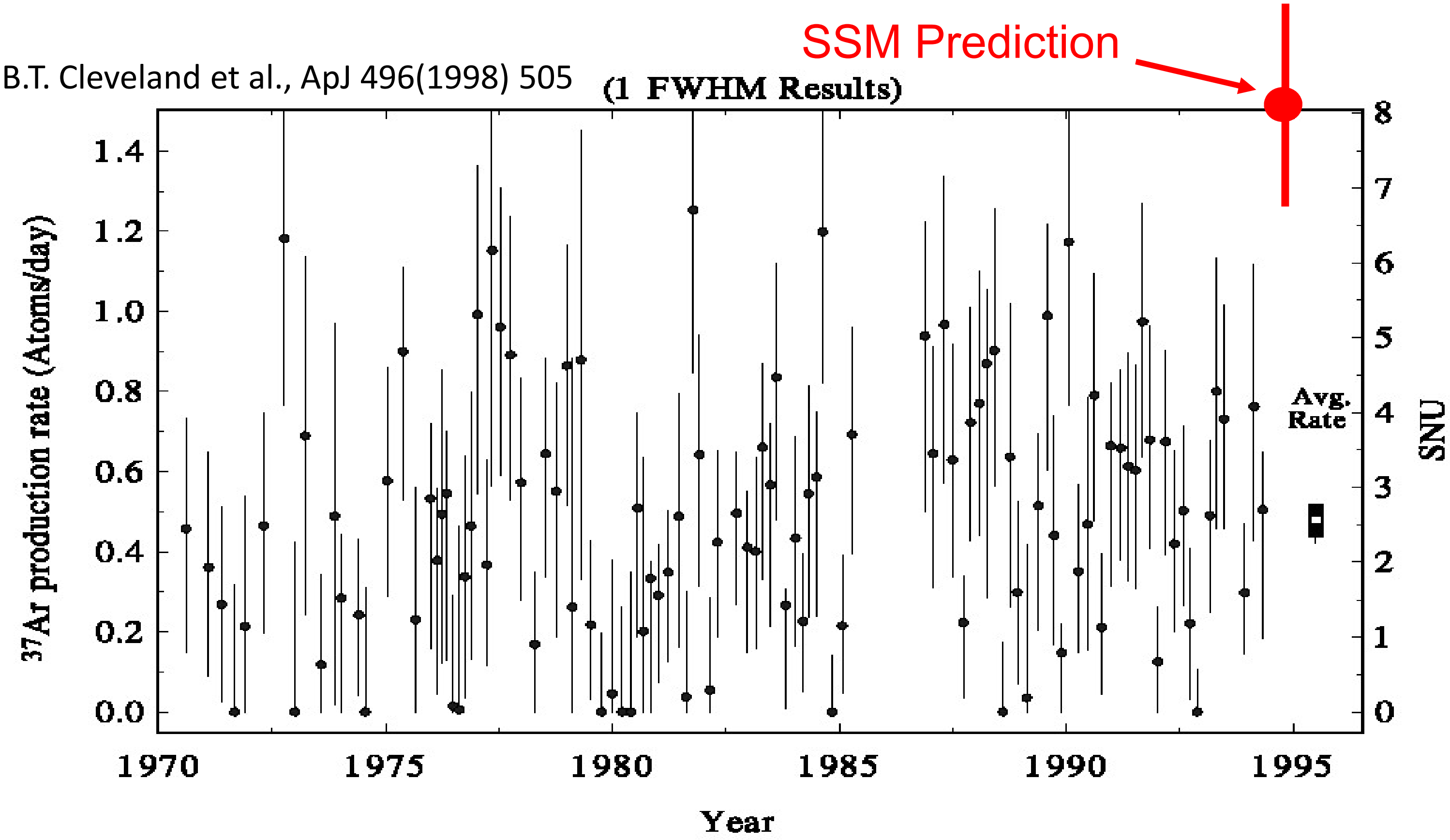
Solar Neutrino Problem

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, which was substantially smaller than the prediction by the Standard Solar Model.

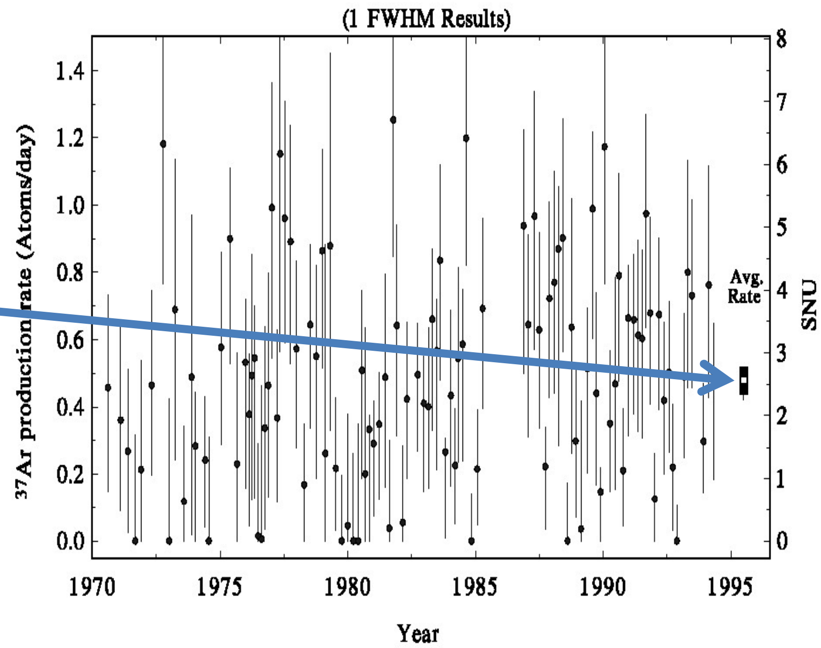
B.T. Cleveland et al., ApJ 496(1998) 505



Solar neutrino experiments are difficult

0.5 ^{37}Ar production per day

600ton C_2Cl_4



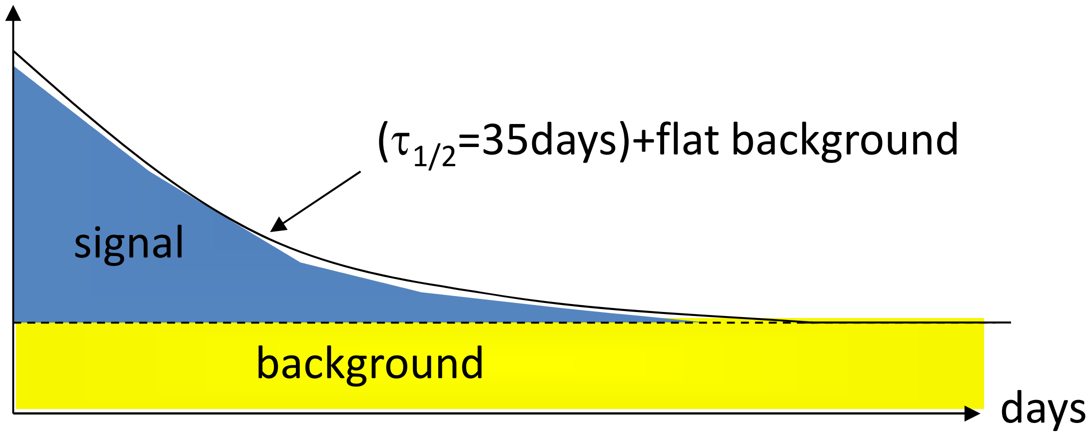
Extract ^{37}Ar from the 600ton tank.

Then,

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

(Electrum capture)

→ Detecting 2.82keV Auger electrons



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

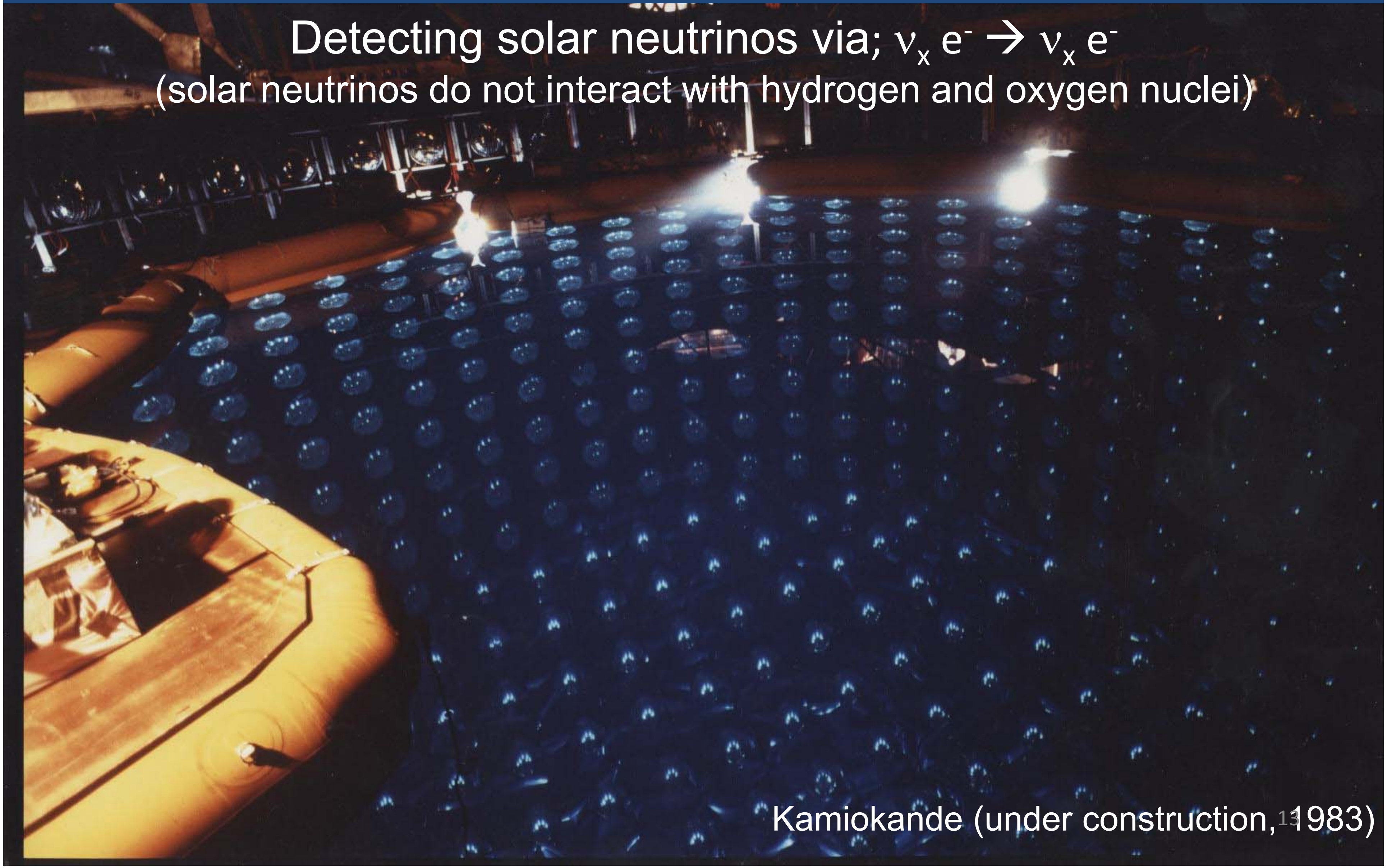
- Experiment might be wrong…
- Theory (SSM) might be wrong….

- 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 nuclei)



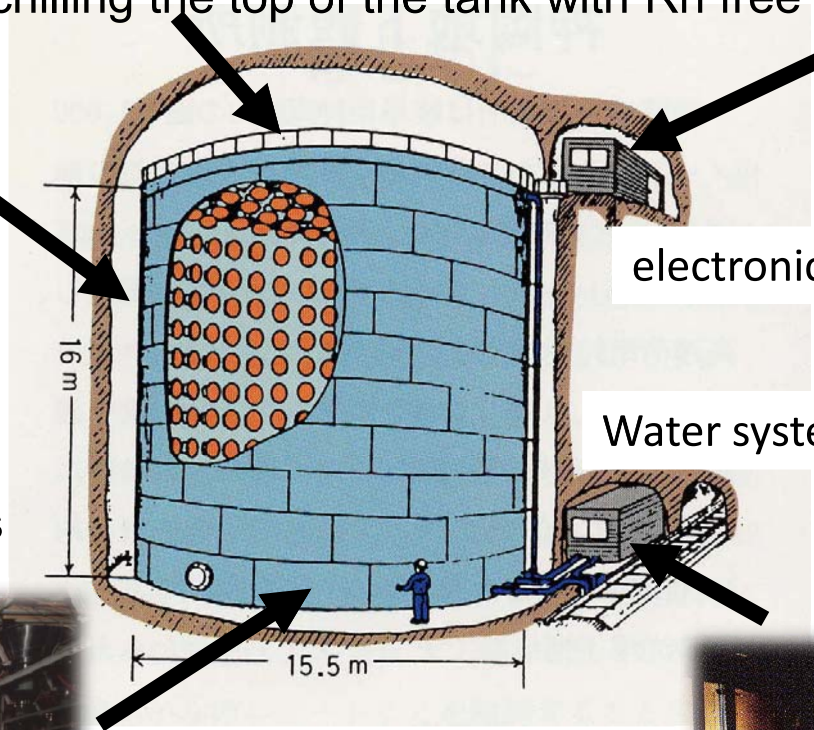
Kamiokande (under construction, 1983)

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

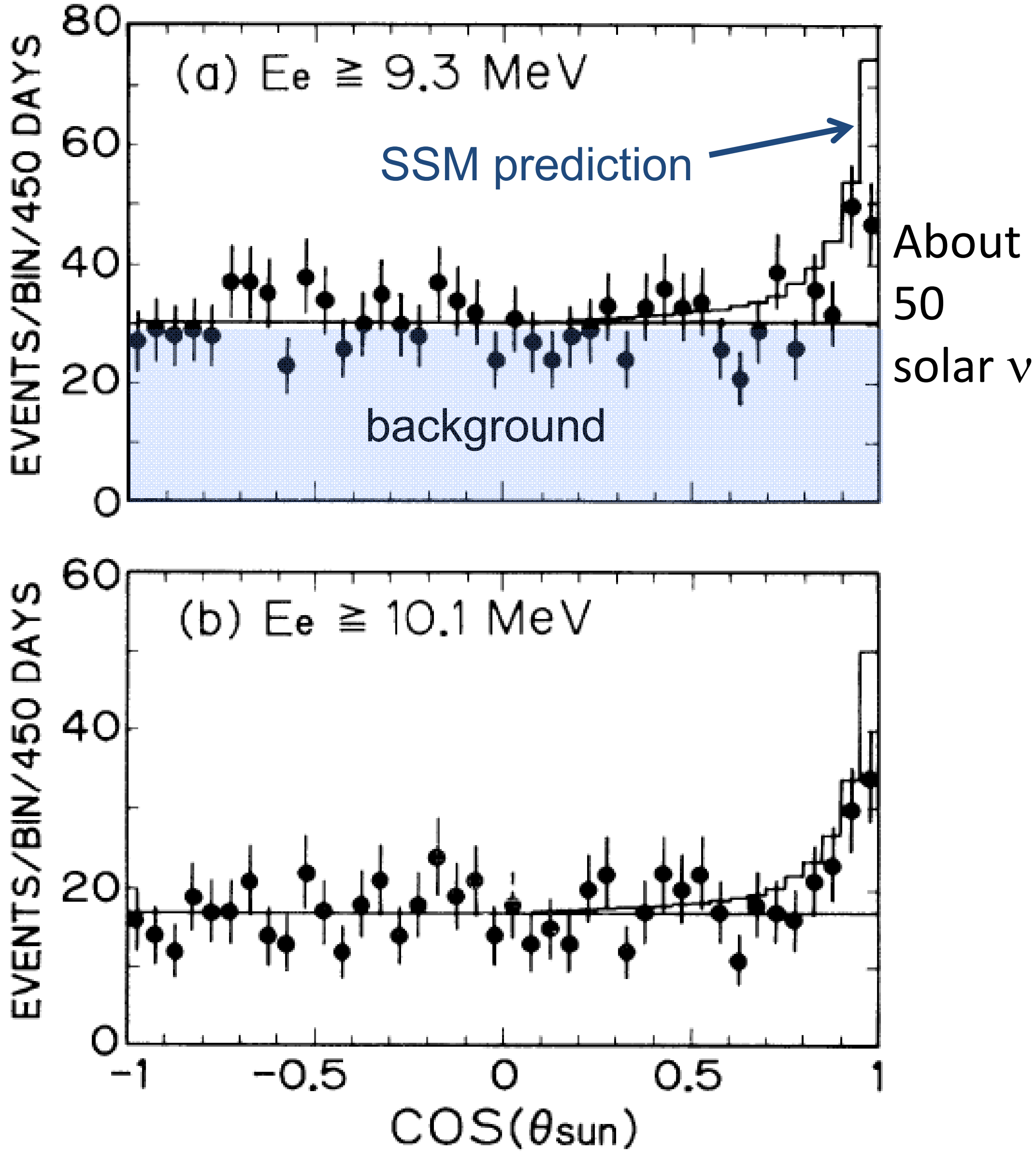
Improving the water purification system

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

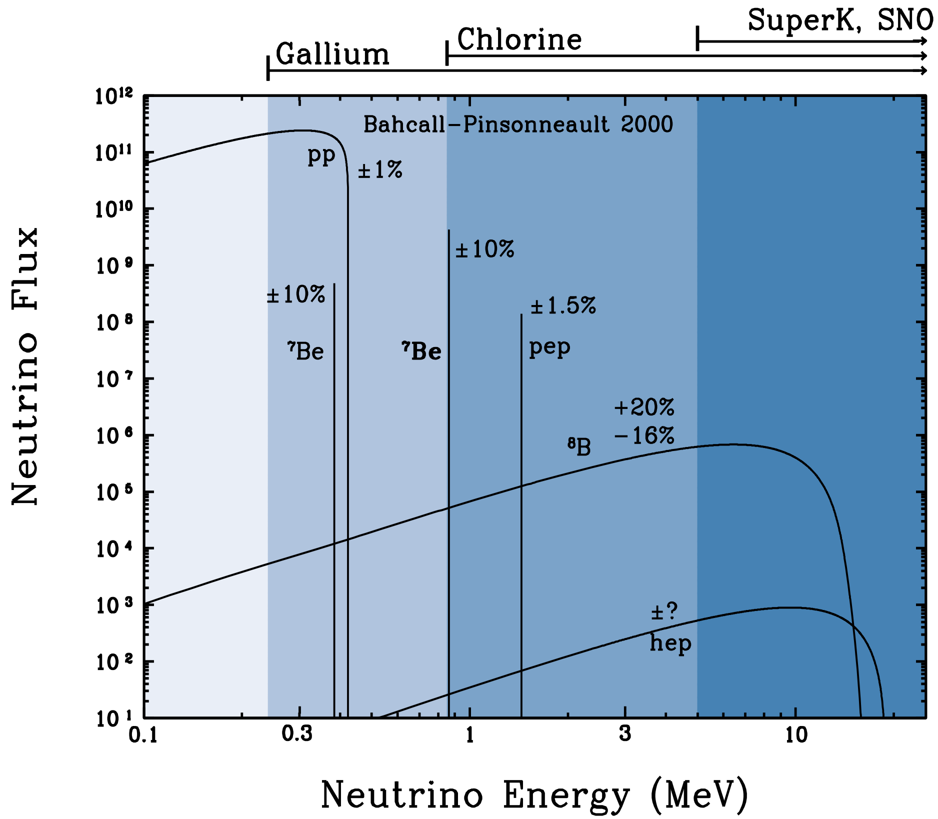
^{7}Be: 34.5

^{8}B: 12.3

others: 9.1

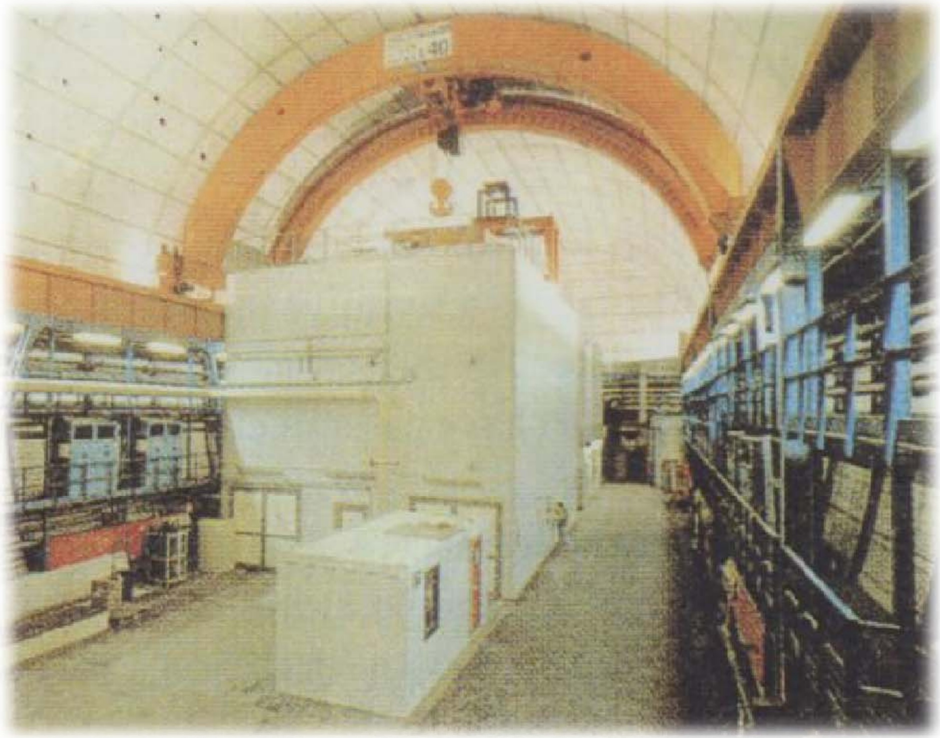
Total: 129^{+9}_{-7} SNU

(These numbers are slightly old…)



Ga experiments

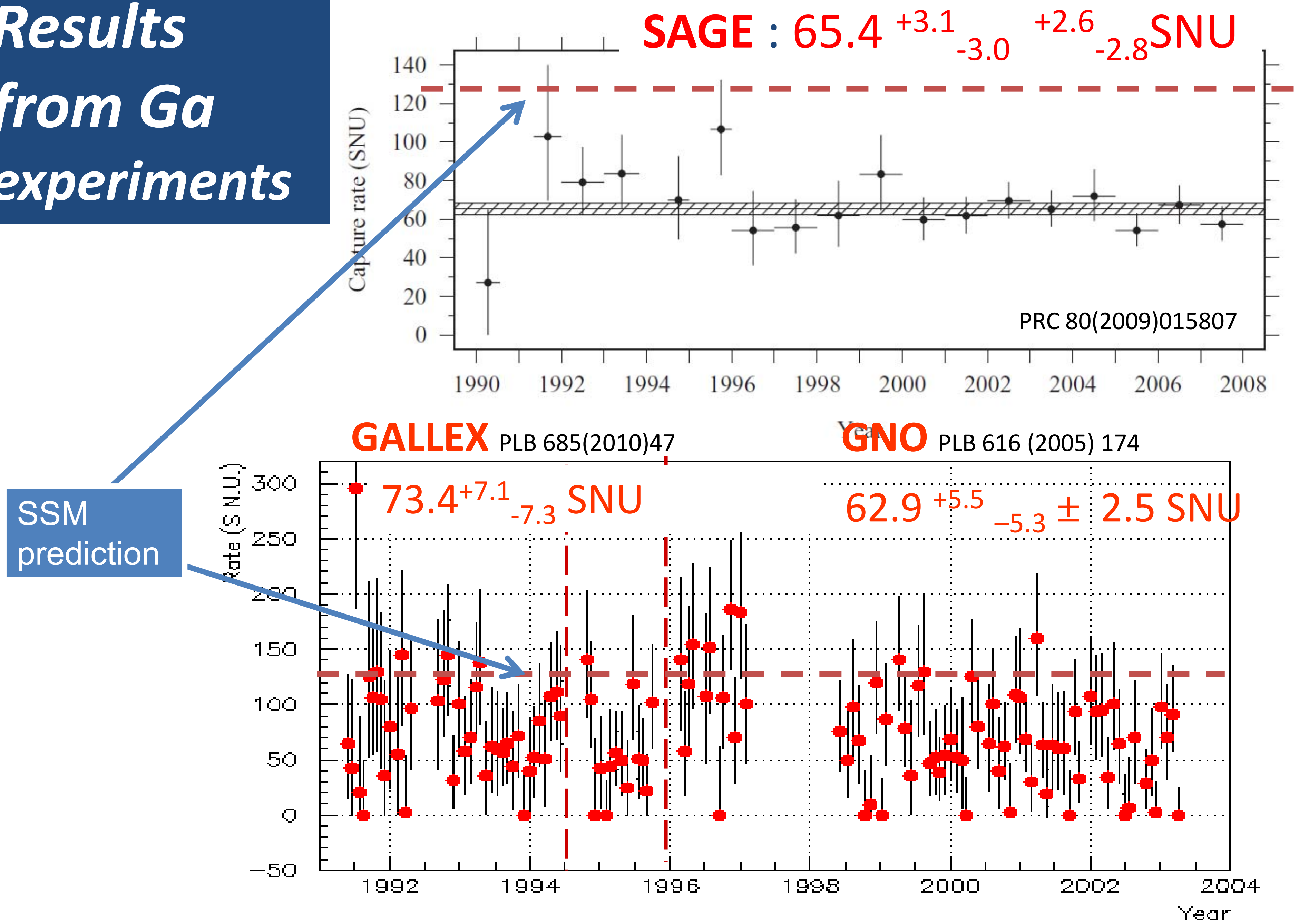
SAGE (Baksan, Russia)



Gallex/GNO (Gran Sasso, Italy)

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

Results from Ga experiments



Early conclusions from Ga experiments

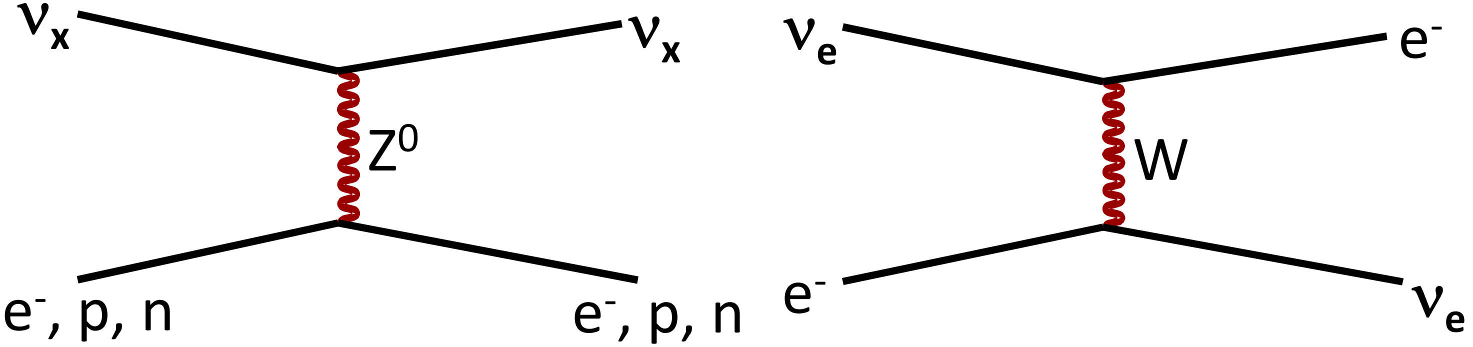
- Ga experiments also observed the solar neutrino deficit.
- The data might suggest neutrino oscillations.
- However, the data might be explained (within a few standard deviations) that the pp neutrinos are detected as expected, while the other neutrinos have much lower flux than calculated by the SSM,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

⇩

- Conclusion: It is difficult to conclude…

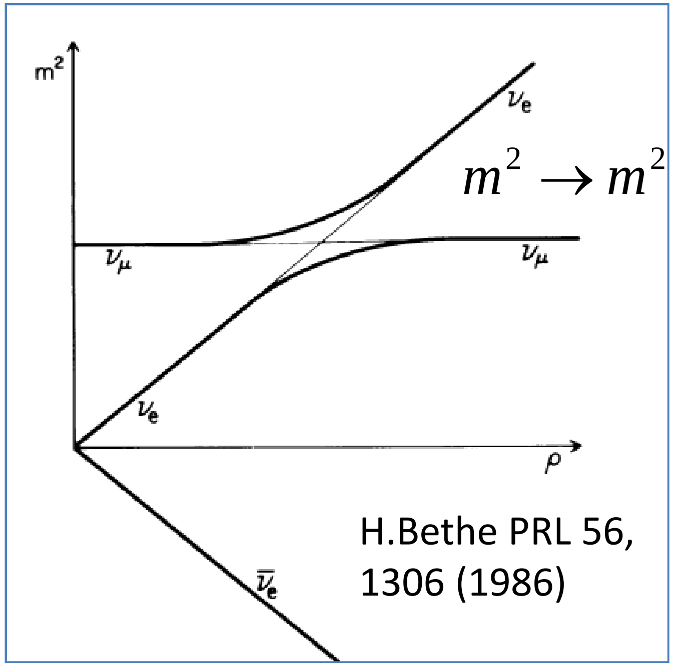
Breakthrough in neutrino oscillation: the MSW effect

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).

L. Worfenstein PRD 17, 2369 (1978)
Mikheev , Smirnov Sov.J.Nucl.Phys. 42, 913 (1985)

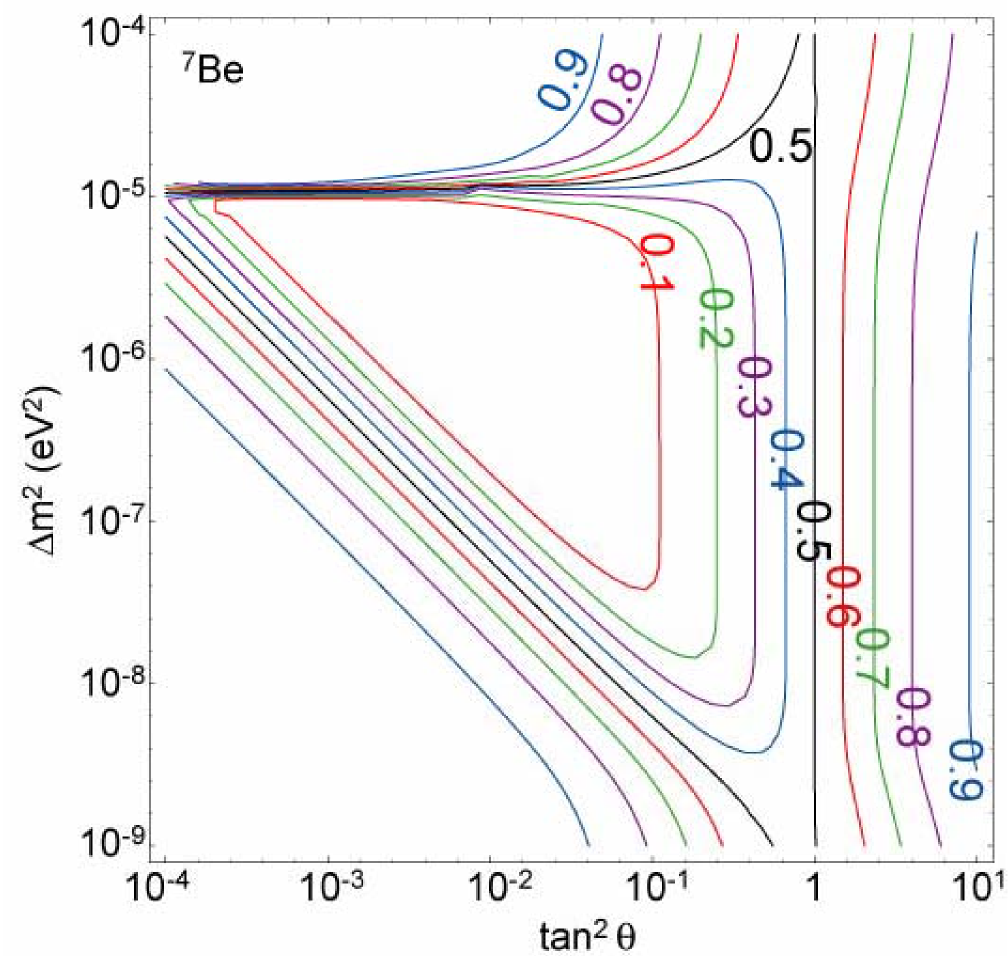


H.Bethe PRL 56, 1306 (1986)

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

MSW effect and solar neutrino oscillation probabilities

ν_e survival probability for ^7Be neutrinos



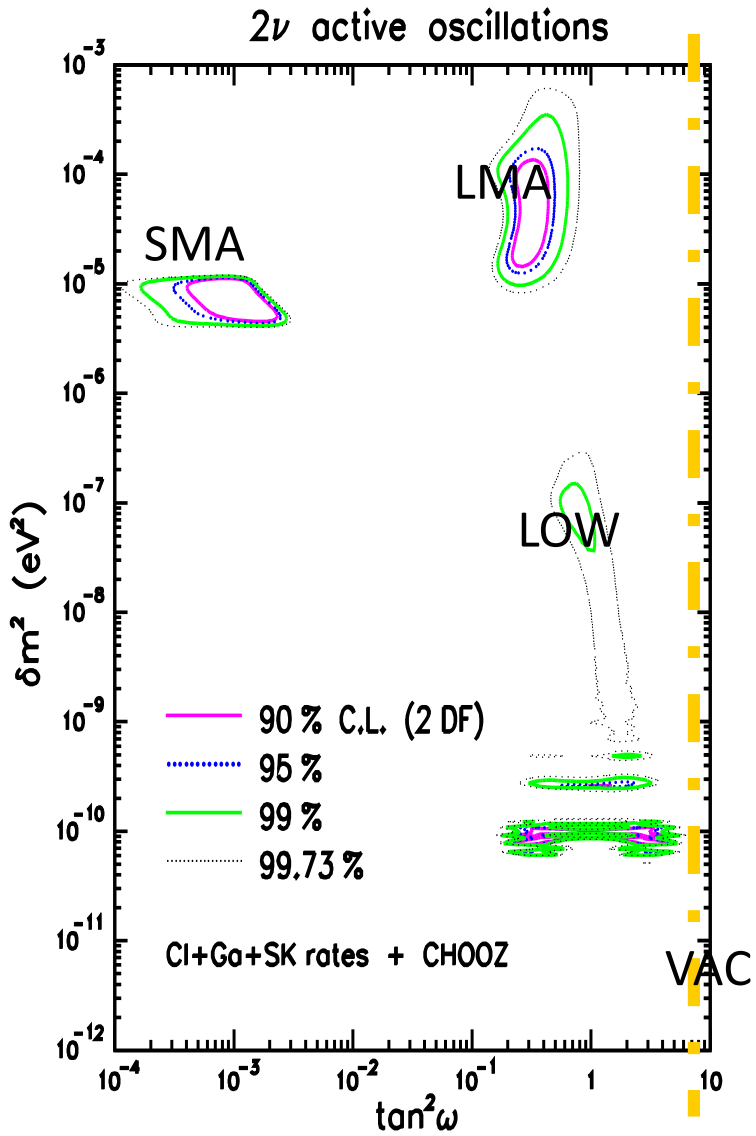
Small mixing angle (θ) (which was generally expected from the quark mixing angles) can generate large solar ν_e deficit !

Neutrino oscillation
➔ A serious possibility !

Neutrino oscillation parameter estimate at the end of the last century….

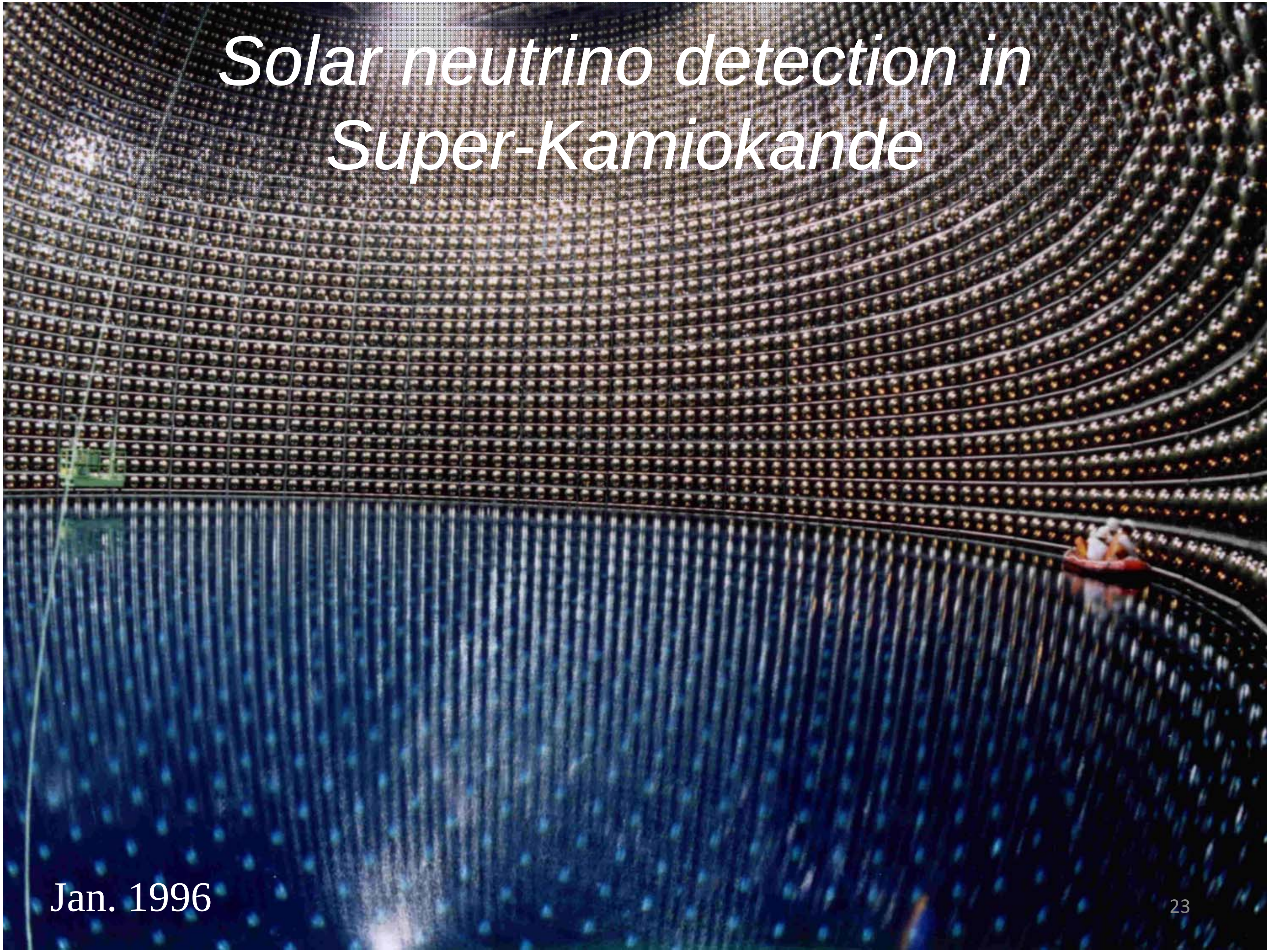
But no smoking gun evidence…

Fogli et al.



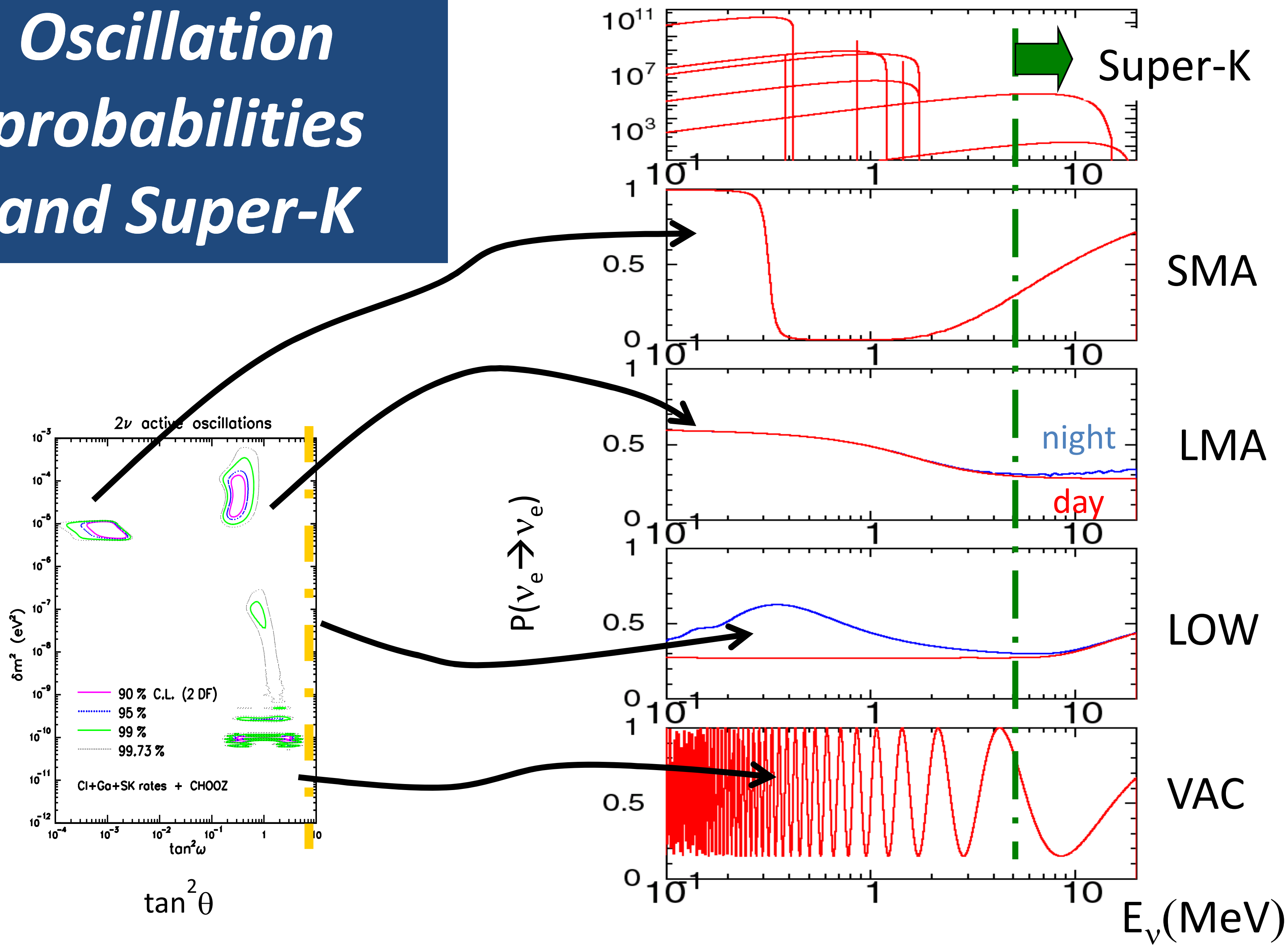
$\tan^2\theta$

Solar neutrino detection in Super-Kamiokande



Jan. 1996

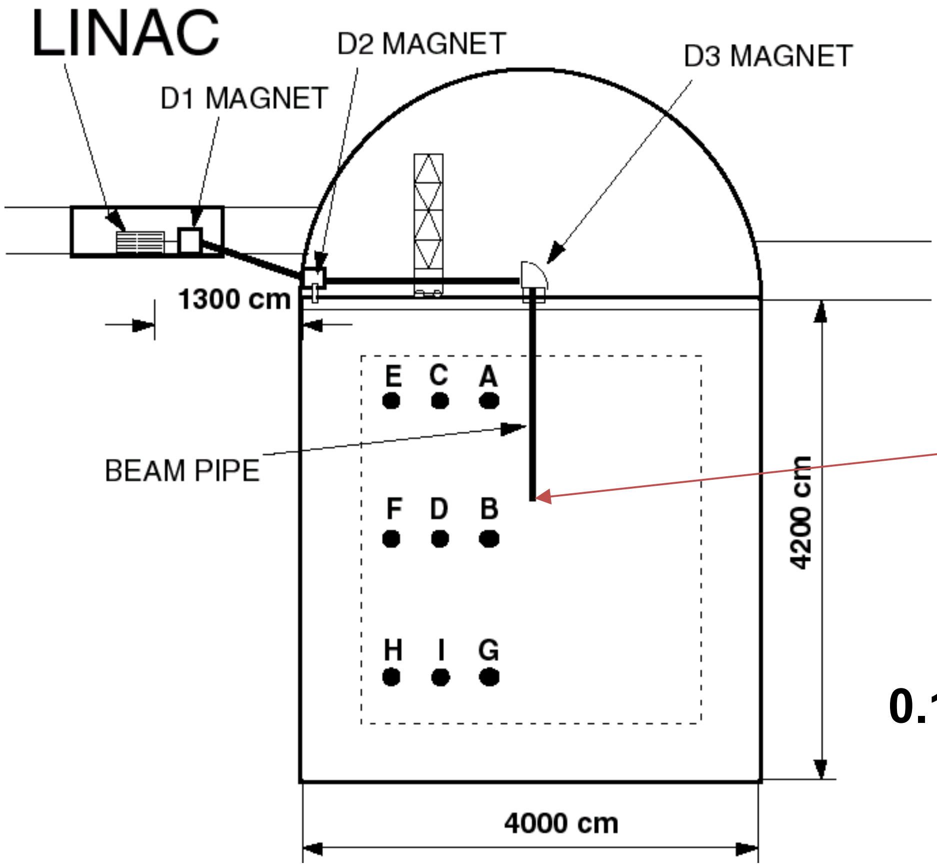
Oscillation probabilities and Super-K



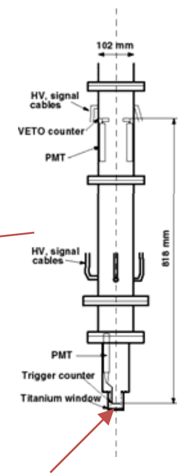
Day-night flux difference, spectrum distortion

Calibration of Super-K with an electron LINAC

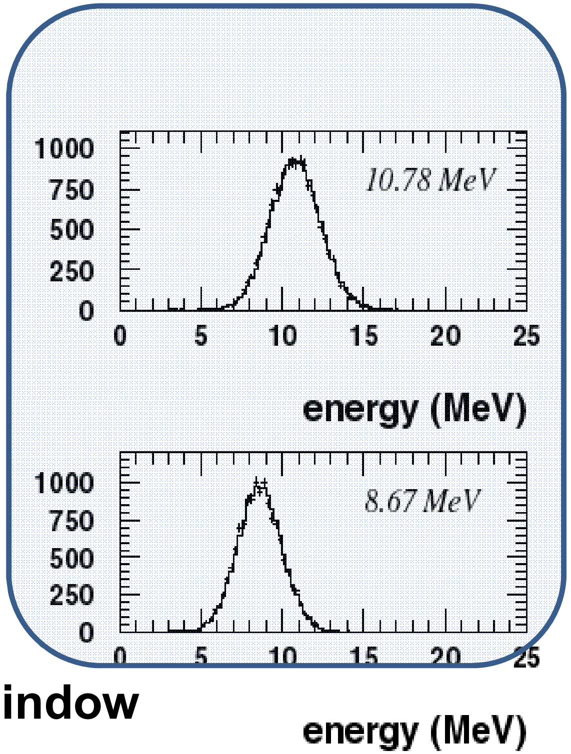
Precise calibration of absolute energy scale, energy resolution, and angular resolution using electron LINAC.



ENDCAP



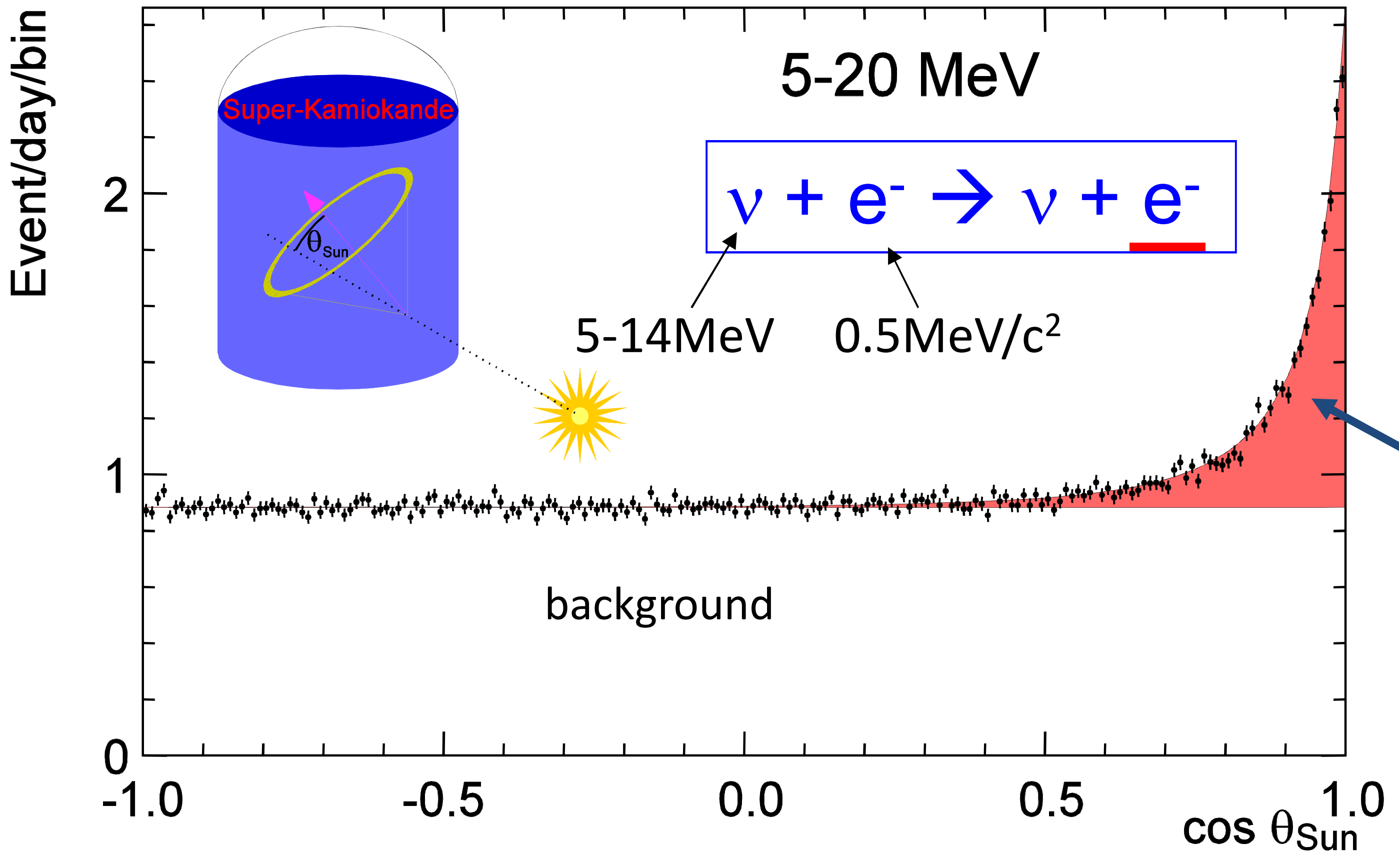
0.1mm thick Ti window



- Beam energy: 5 ~ 16 MeV/c

Systematic error in the absolute energy scale : 0.64 % (SK-I).

Solar neutrino data from SK-I



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

22400±230 solar ν events

(14.5 ev/day)

Assuming ν_e only:

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

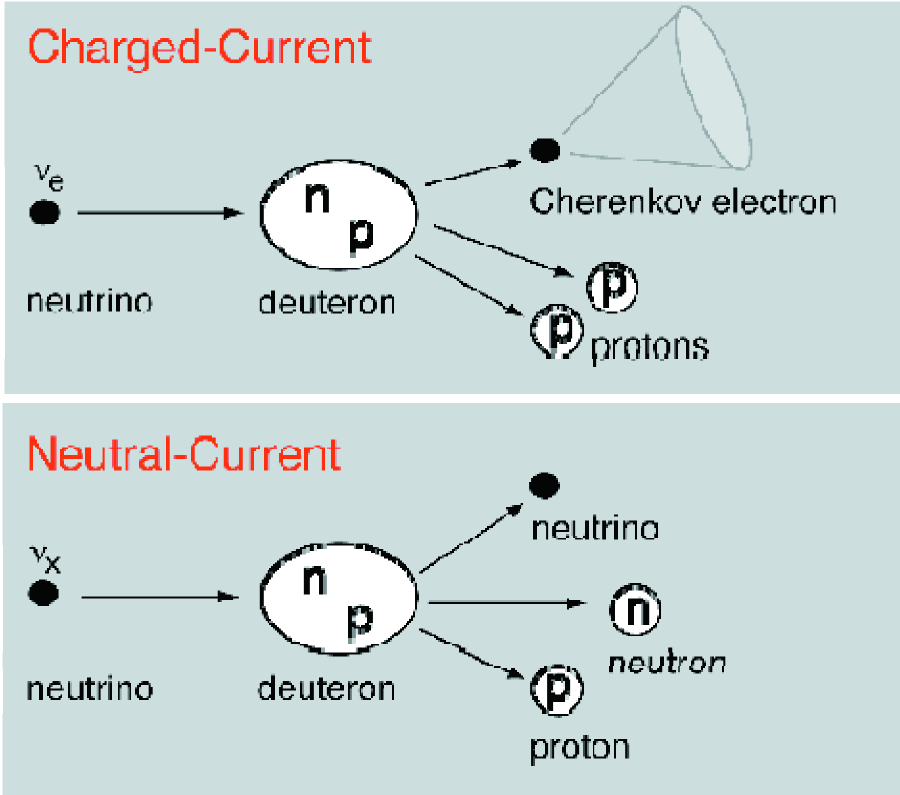
However, no clear evidence for spectrum distortion nor day-night effect.

Solving solar neutrino problem with neutrino oscillations

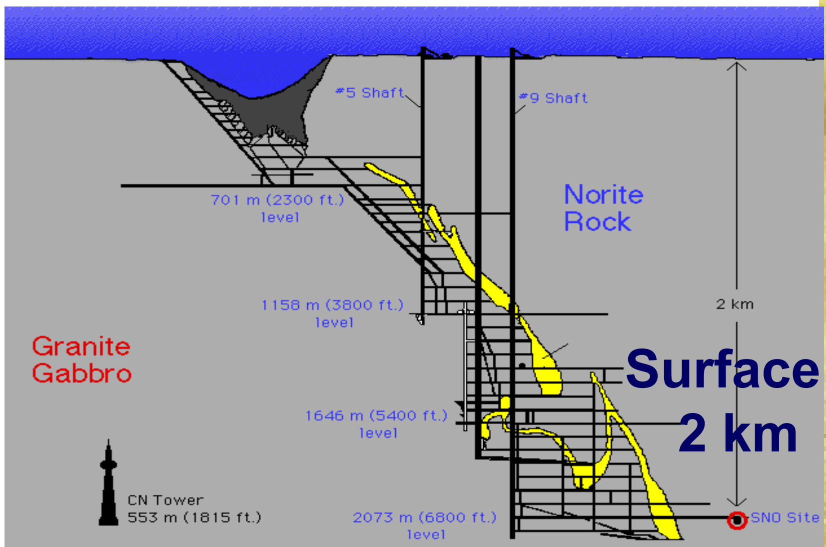
Heavy water experiment

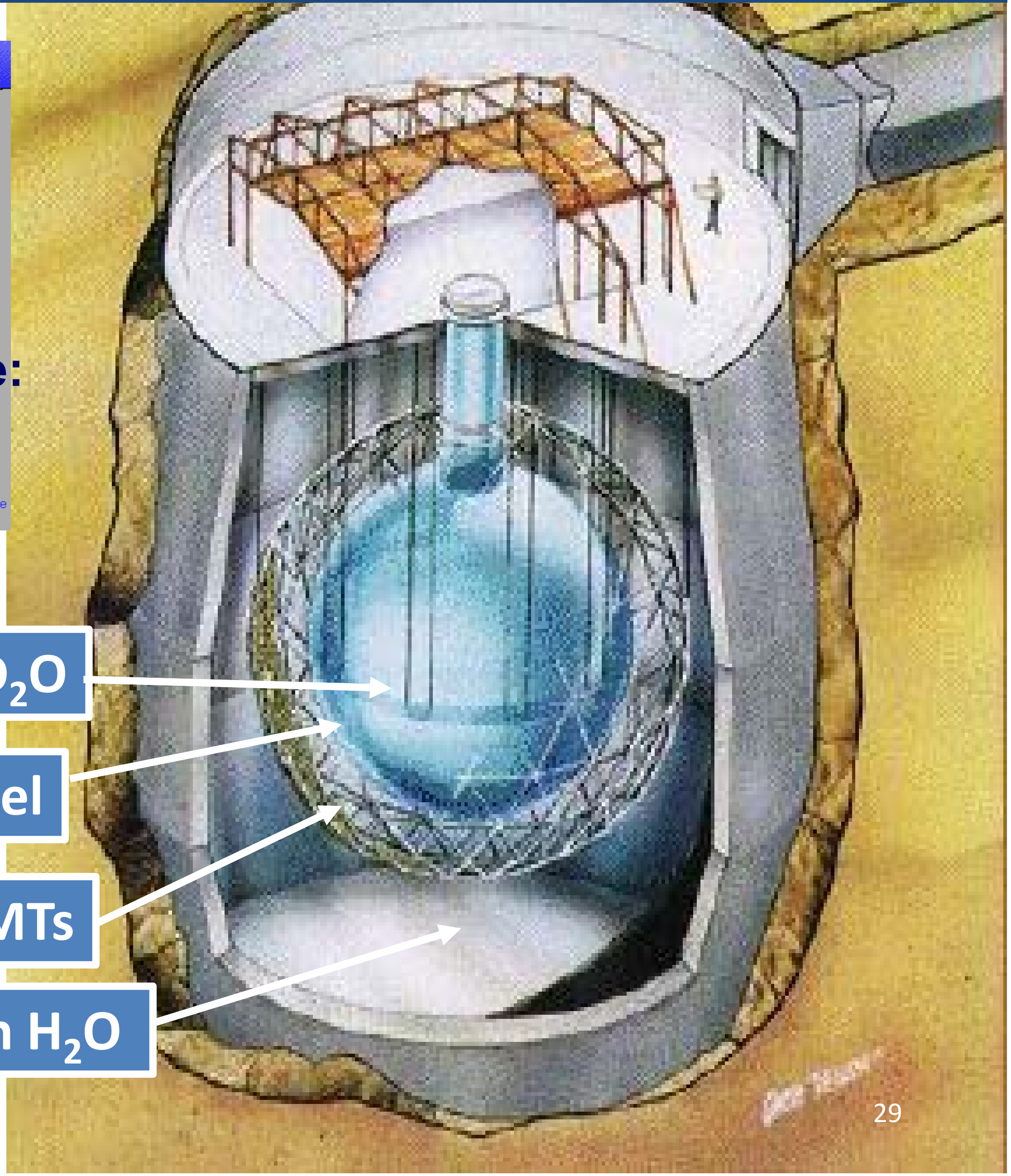
Herbert Chen PRL 55, 1534 (1985)
"Direct Approach to Resolve the Solar-neutrino Problem"

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 ^8B 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)





SNO detector construction

The background: radioactivity

SNO PRL 89 (2002)011301

U/Th in D_2O

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

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

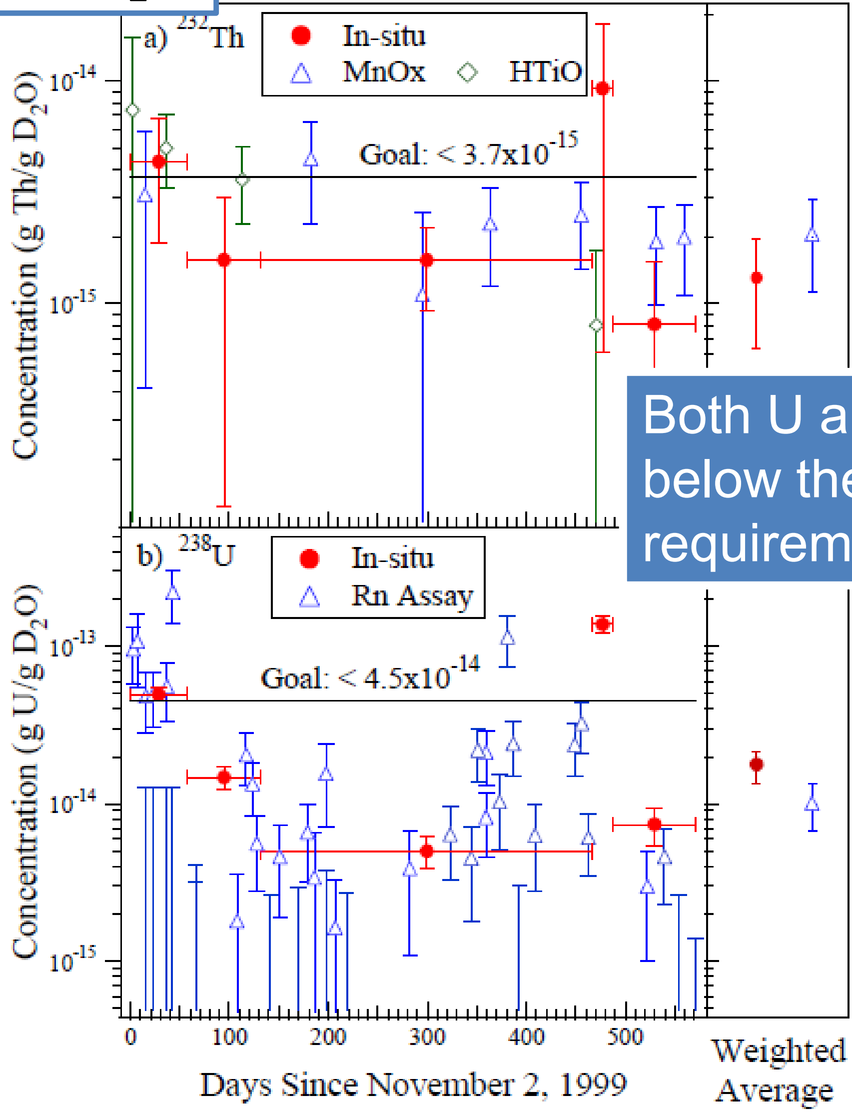
Requirements:

D_2O < 4×10^{-15} gm/gm (Th)

D_2O < 5×10^{-14} gm/gm (U)

H_2O < 10^{-14} gm/gm (U/Th)

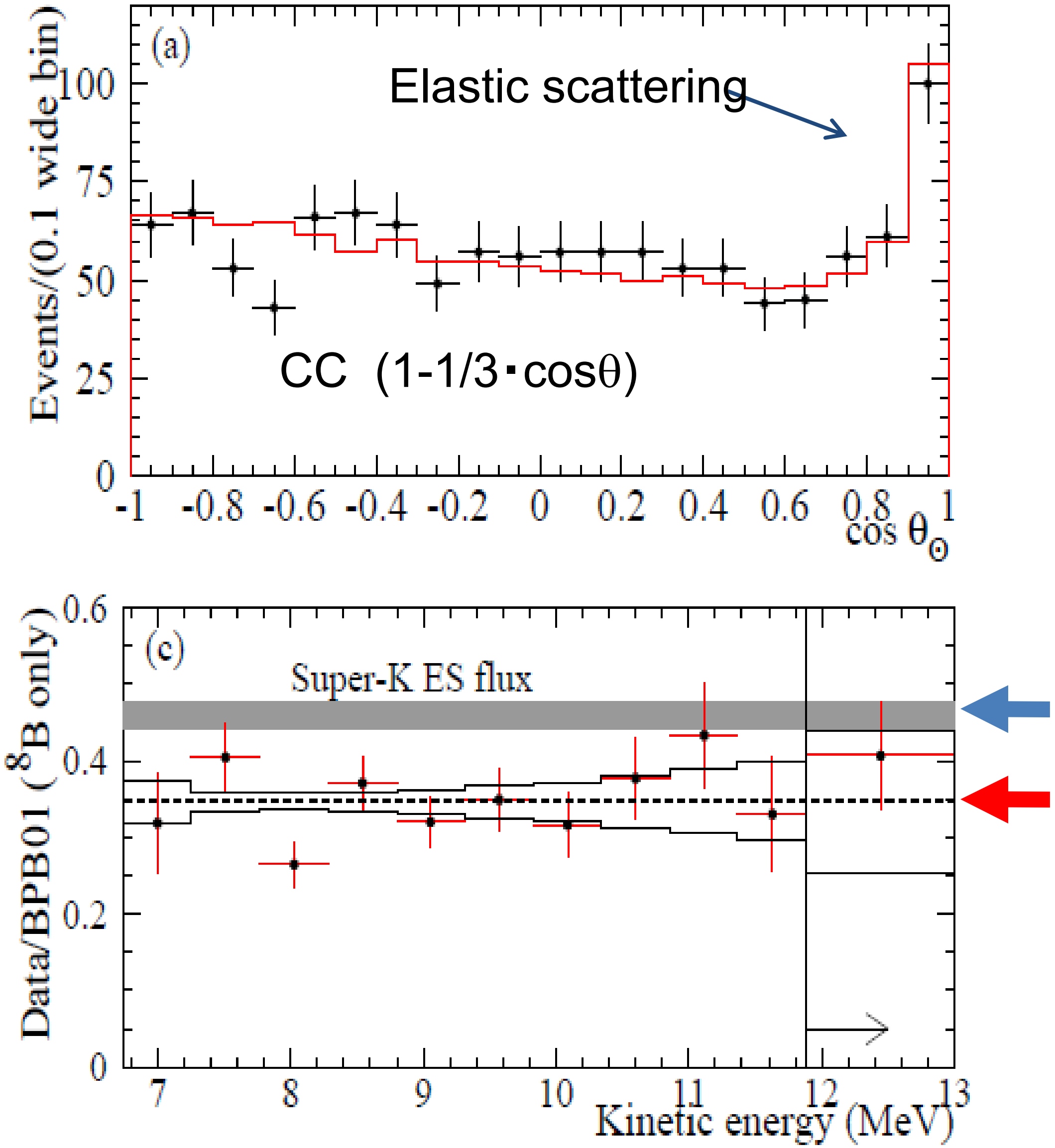
Acrylic < 10^{-12} gm/gm (U/Th)



Both U and Th below the requirements

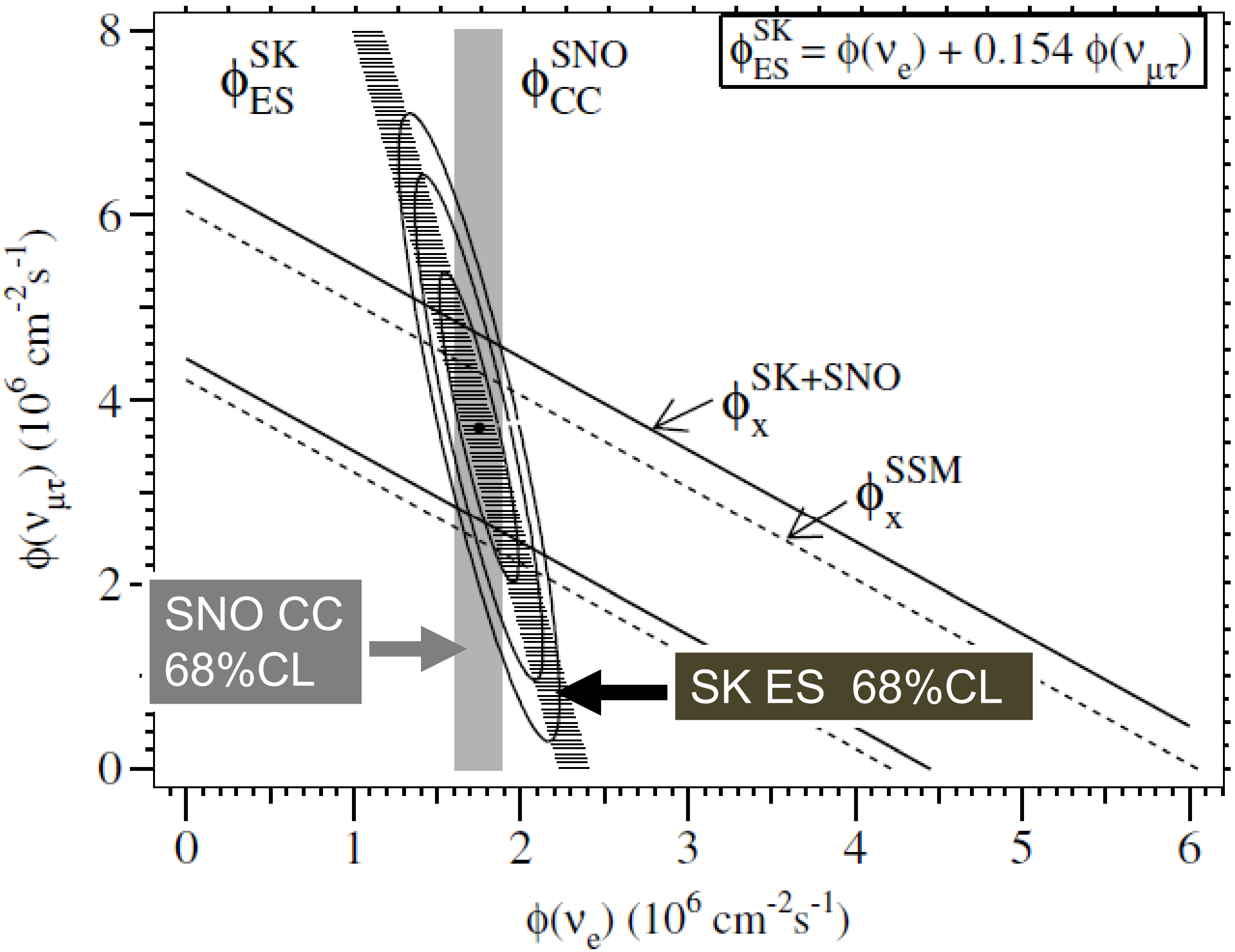
CC measurement

SNO PRL 87 (2001)071301



SK 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 (×1/(6-7) of that of $\nu_e+e \rightarrow \nu_e+e$)
The difference can be interpreted as (3.1 σ) evidence for "$\nu_\mu+\nu_\tau$ flux on the Earth".

ν_e and $(\nu_\mu+\nu_\tau)$ fluxes (2001)



>3 σ evidence for non-zero $\phi(\nu_\mu+\nu_\tau)$.

Stronger evidence possible?

Three ways to measure the NC events

(1) Pure D_2O

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

$n + d \rightarrow t + \gamma$ (E_γ = 6.3 MeV)

(γ produces e by Compton scattering)

(2) D_2O with salt

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

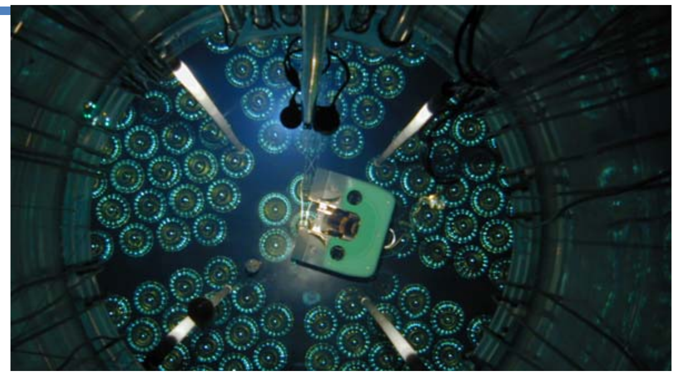
(Competing process: $n+d \rightarrow t+\gamma$)

NaCl 2tons

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

(3) ${}^{3}He$ counters in D_2O

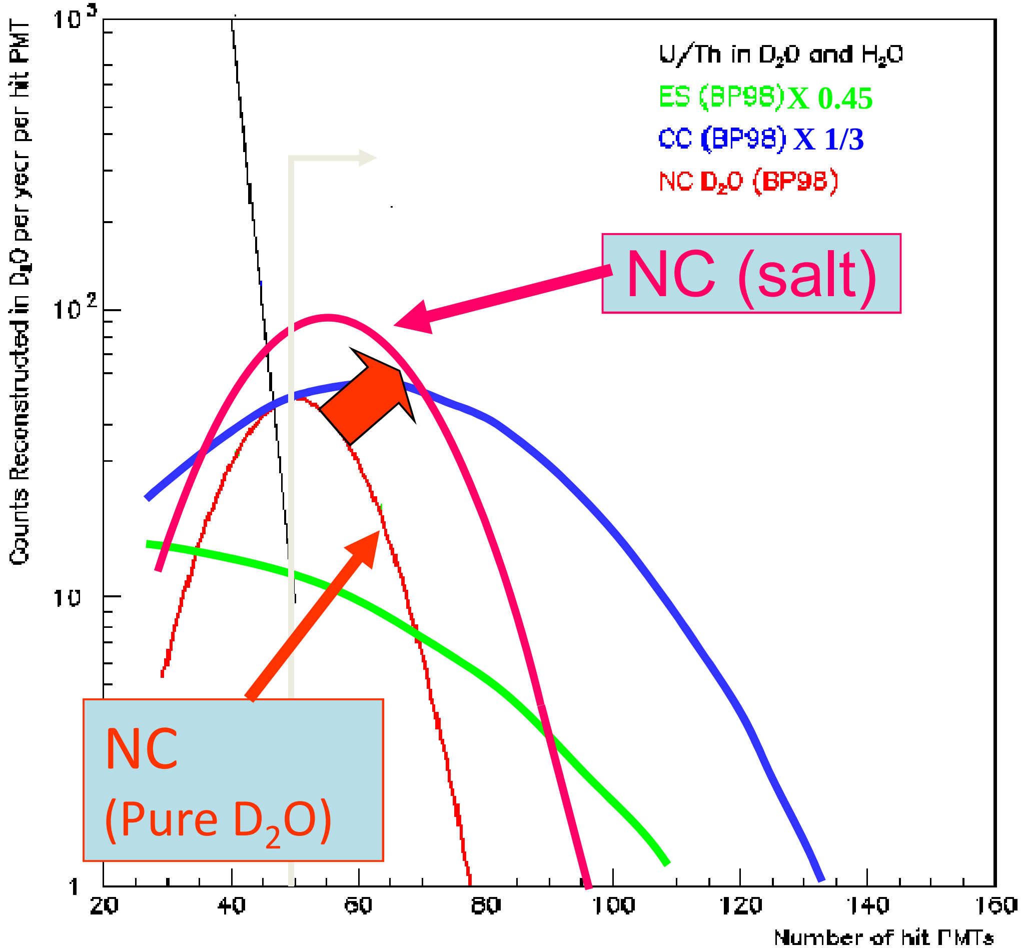
$n + {}^{3}He \rightarrow p + t$

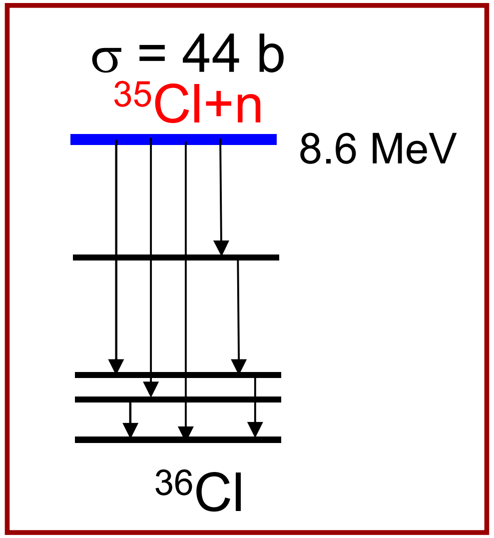


SNO NC: Pure D_2O vs. Salt phase

2 tons of NaCl added into 1000 ton D_2O

(Salt phase: 2001-2003)

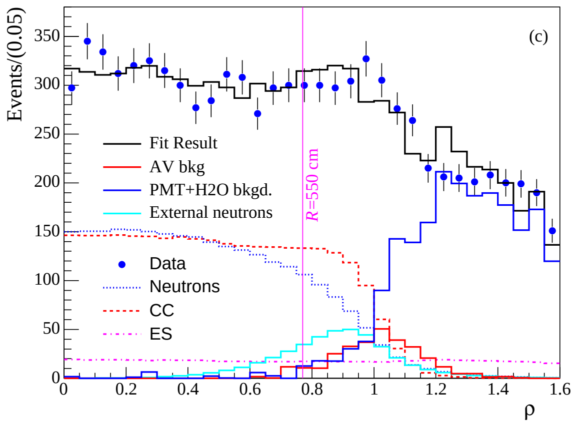




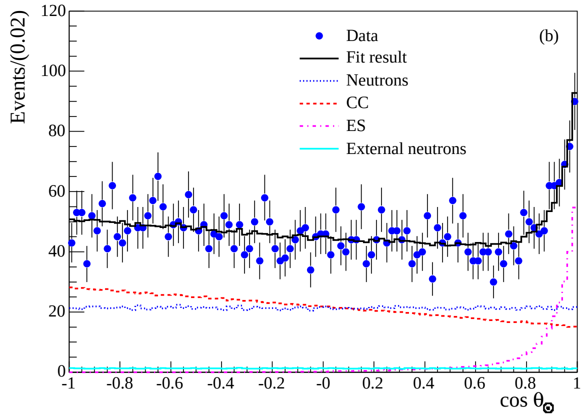
~ 9 NHIT/MEV

Salt phase flux measurements

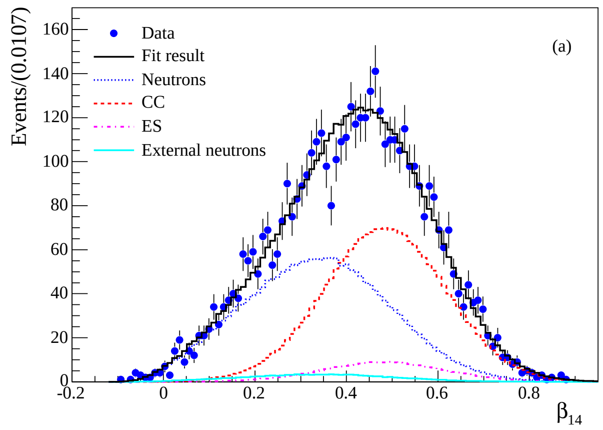
vertex



$\cos\theta_{sun}$



~ isotropy



w/o ^{8}B energy spectrum constraint

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

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

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

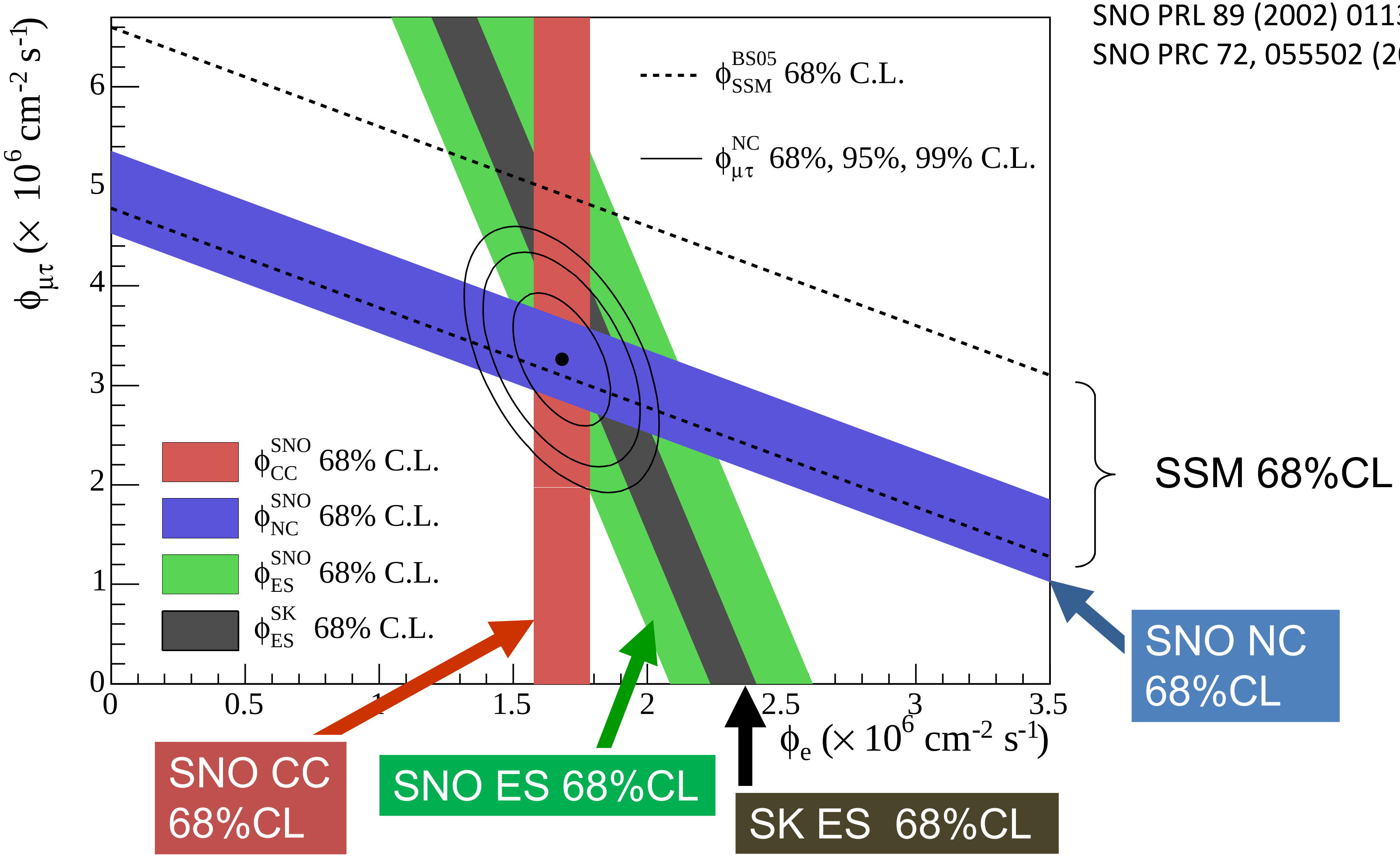
SNO PRC 72, 055502 (2005)

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

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

ν_e and $(\nu_\mu+\nu_\tau)$ fluxes

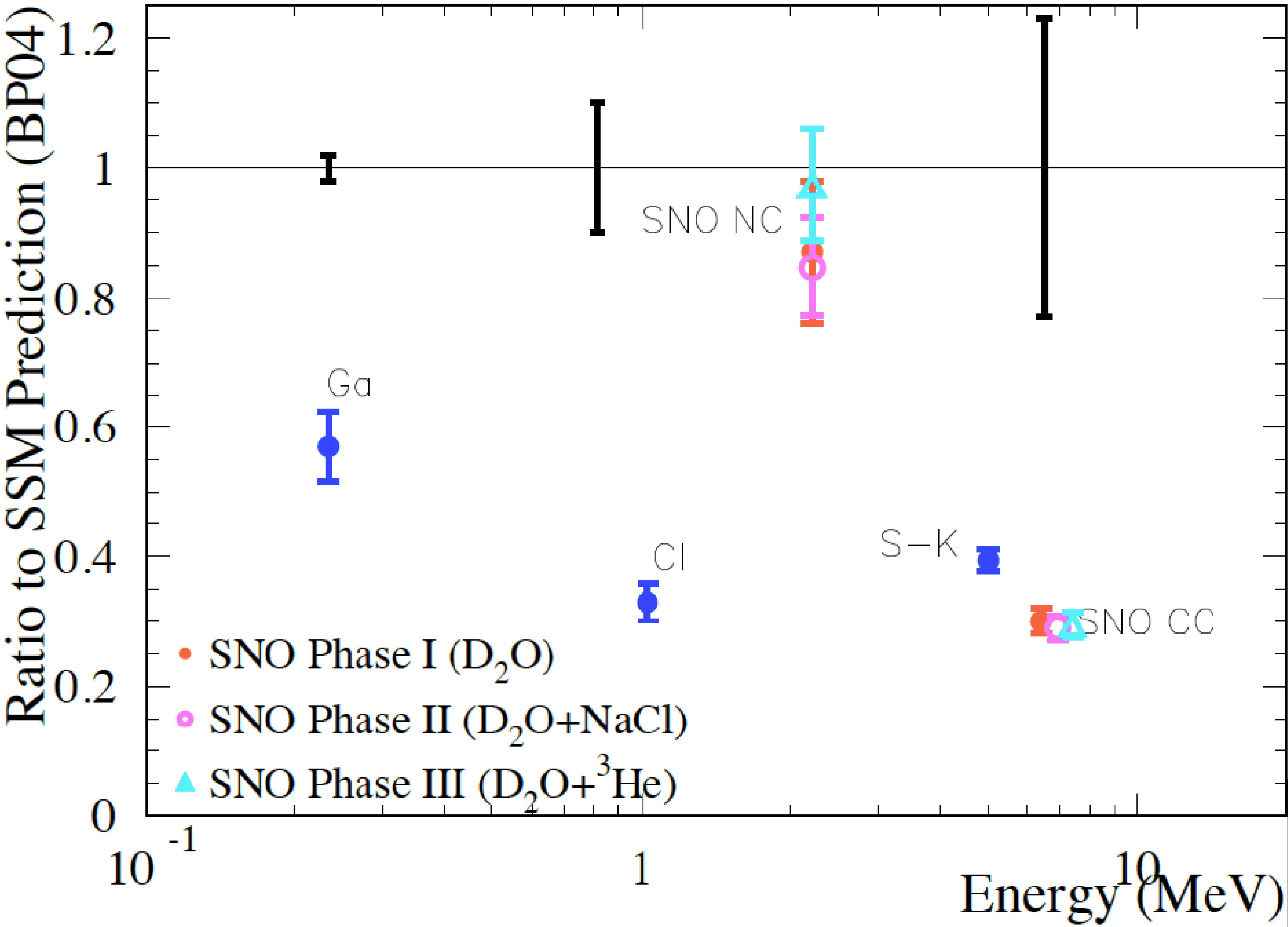
SNO PRL 89 (2002) 011301
SNO PRC 72, 055502 (2005)



Three (or 4) different measurements intersect at a point (→non trivial).
All the data are consistently explained within the existence of $(\nu_\mu+\nu_\tau)$

SNO measurements: summary

A. McDonald nu2012



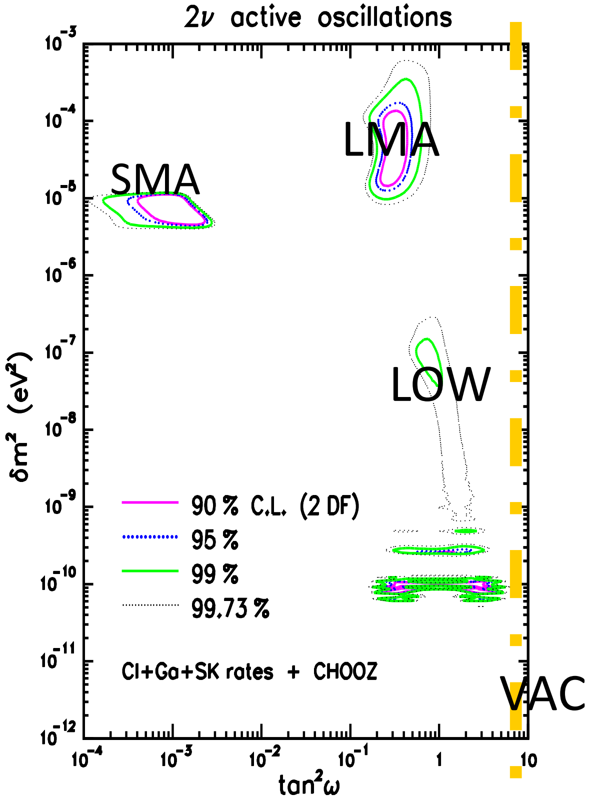
Oscillation Analysis with all solar neutrino data

Let us assume standard neutrino oscillation…

N. Barros (for SNO) NPB (proc suppl) 237-238(2013) 107
Also many other analyses

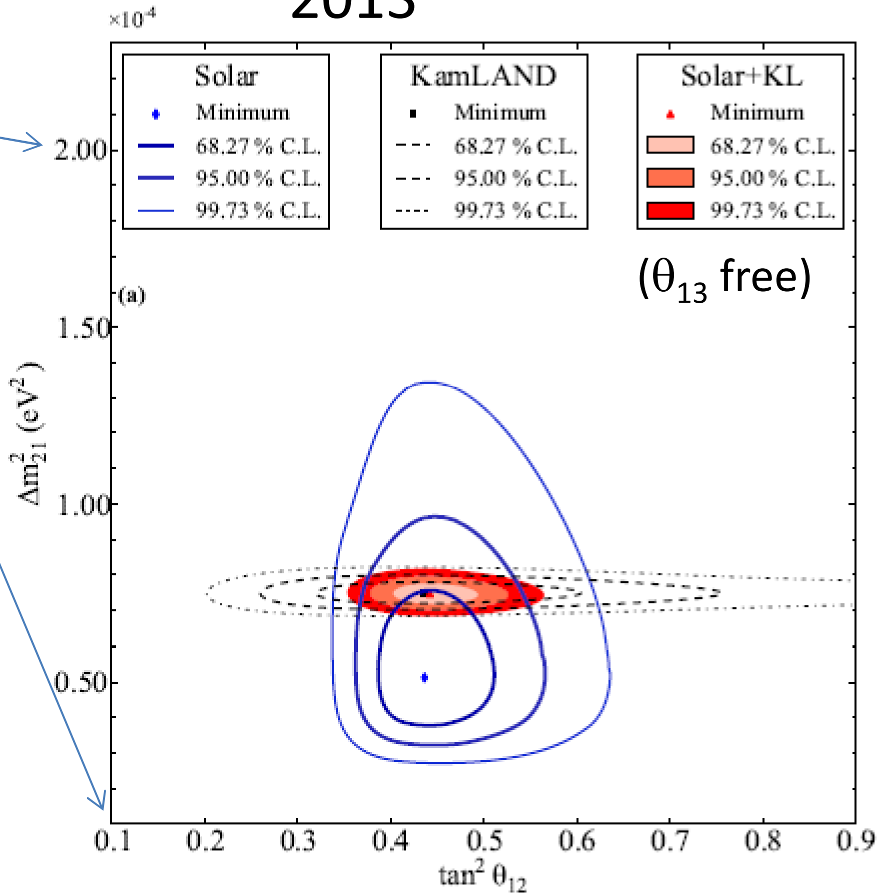
Earlier in this talk….
(assuming oscillations)

Fogli et al.



$\tan^2\theta$

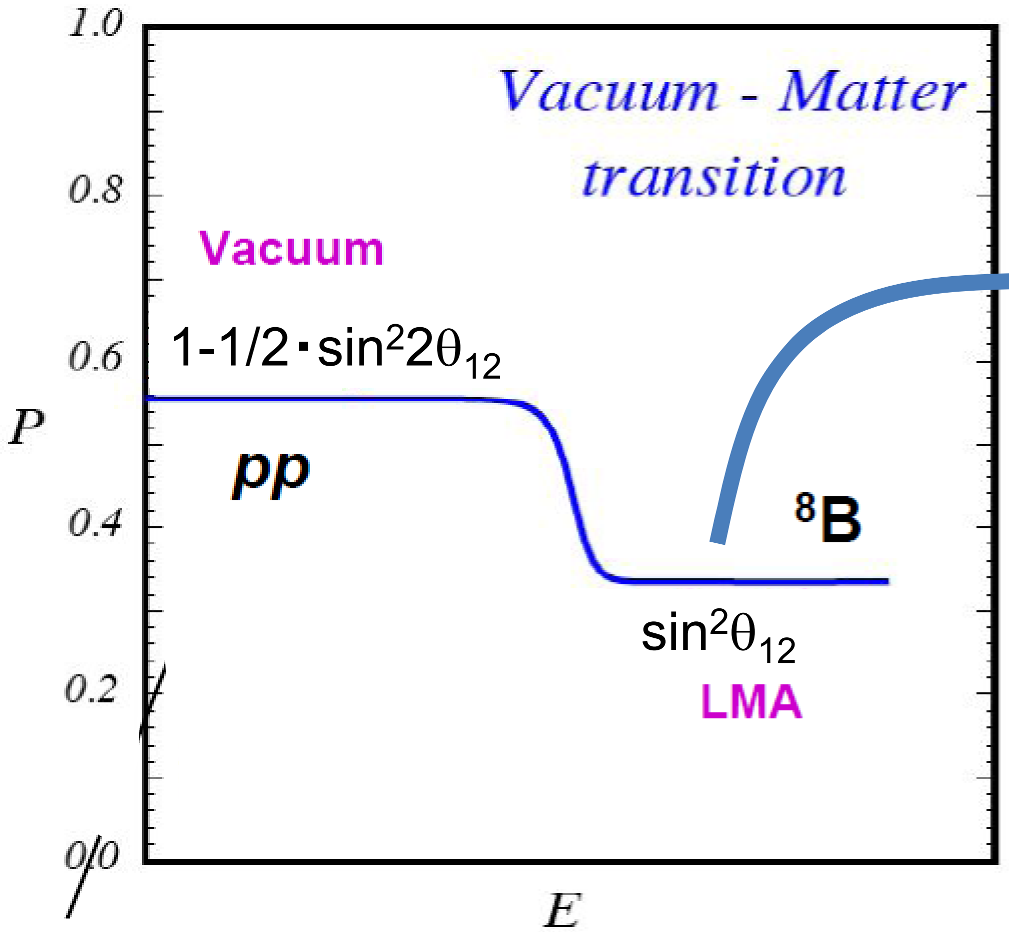
2013



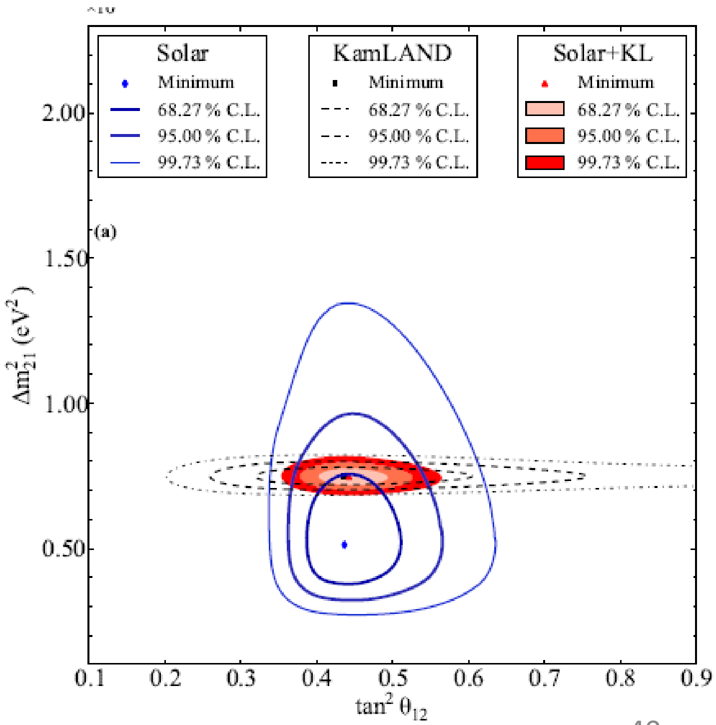
CC/NC and the measurement of θ_{12}

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

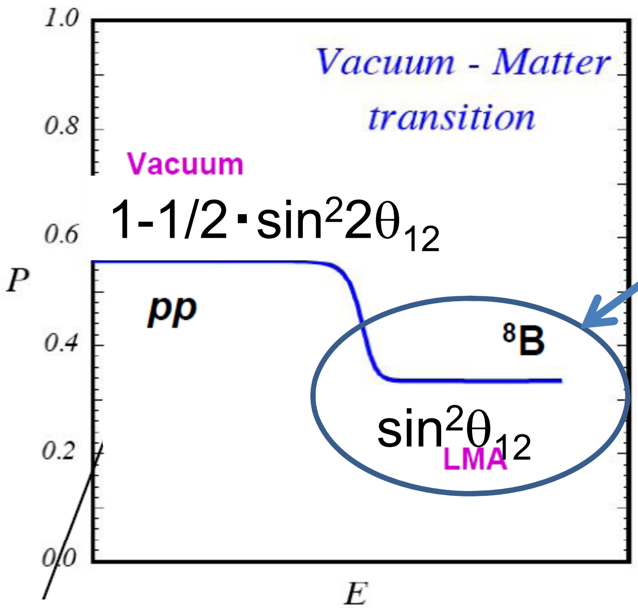
Accurate measurement of $\sin^2\theta_{12}$ is possible by the CC/NC ratio measurement.



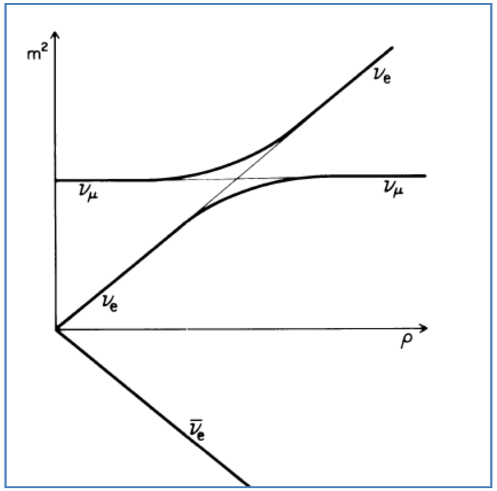
Bahcall & Pena-Garay
hep-ph/0305159



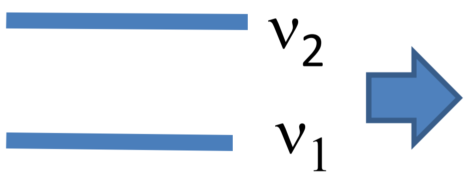
CC/NC and the measurement of θ_{12}



Bahcall & Pena-Garay
hep-ph/0305159



This happens only if;



Mass hierarchy between ν_1 and ν_2 determined.

Furthermore,

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

Is less than 0.5.

➔ θ_{12} < 45 degree. (about 34 deg.).

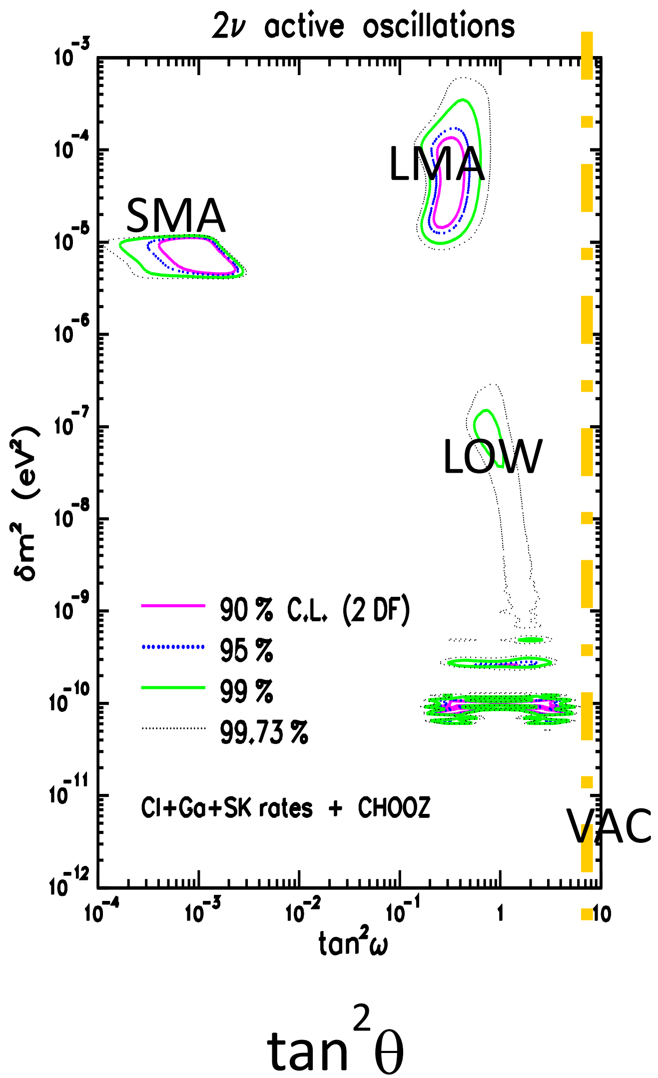
Octant ambiguity of θ_{12} resolved.

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).

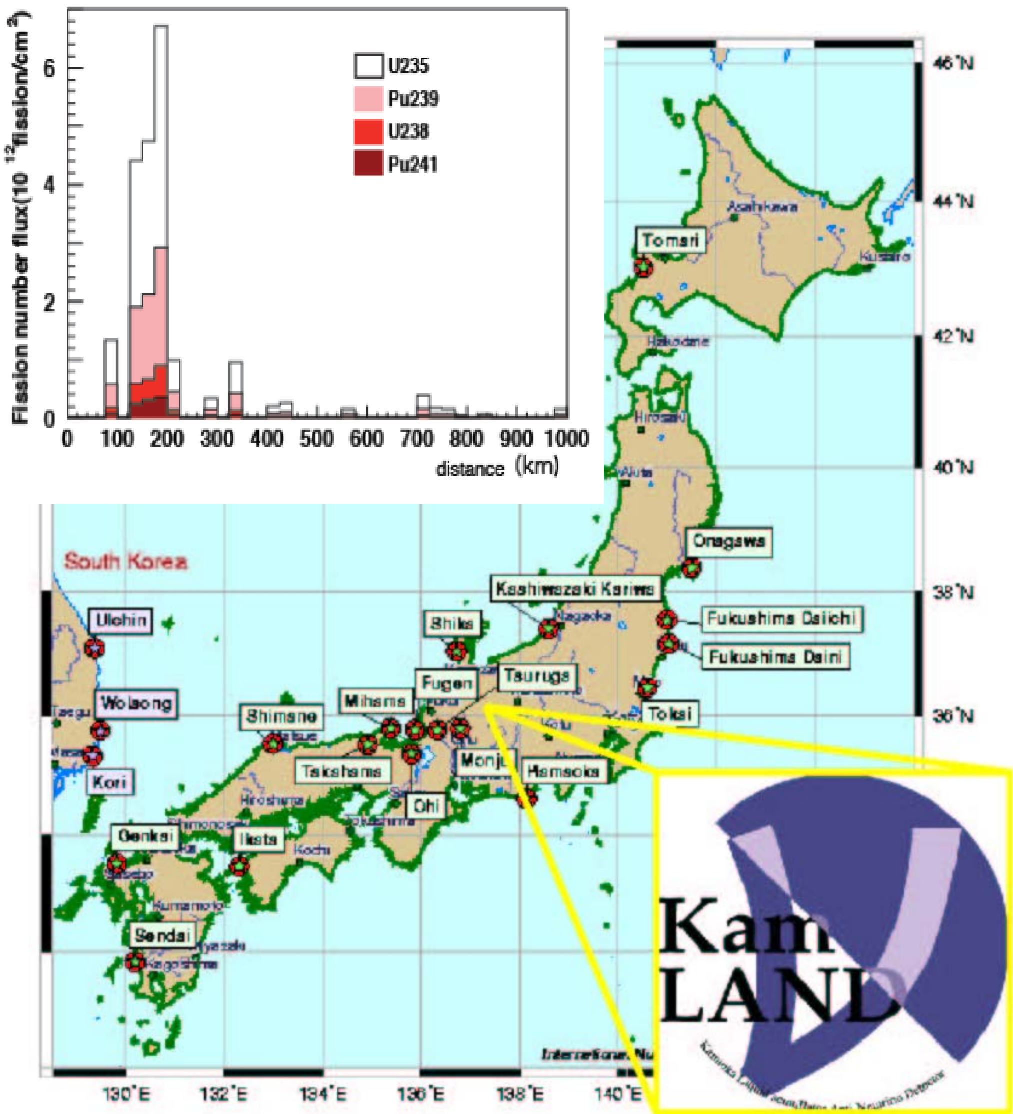
If LMA is the real solution, a reactor long baseline experiment can observe the oscillation.

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

➔Found there were 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 a lot of powerful reactors.

Fortunately,

68GW used to be available

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

with no cost.

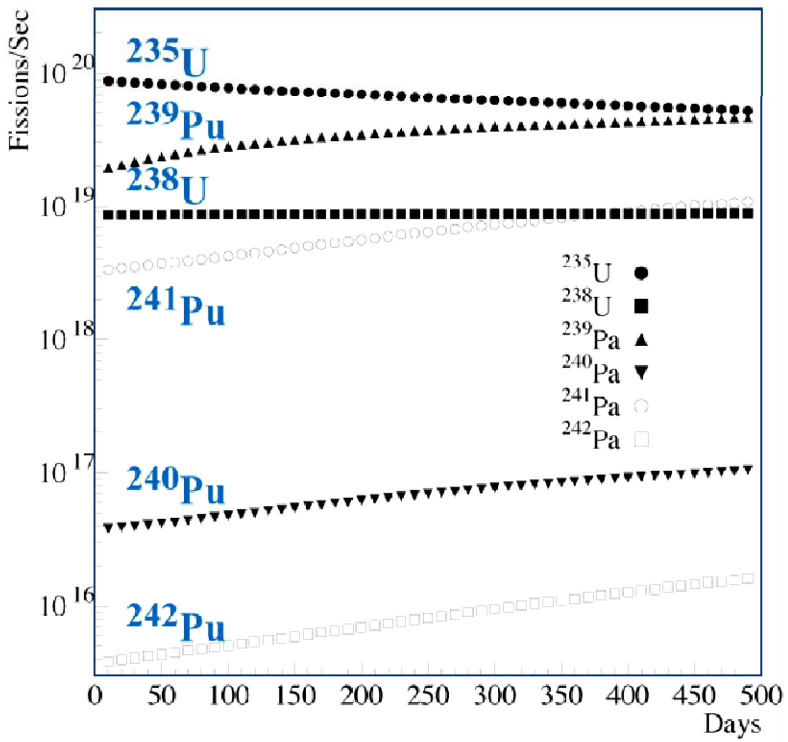
Anti-ν_e production in reactors

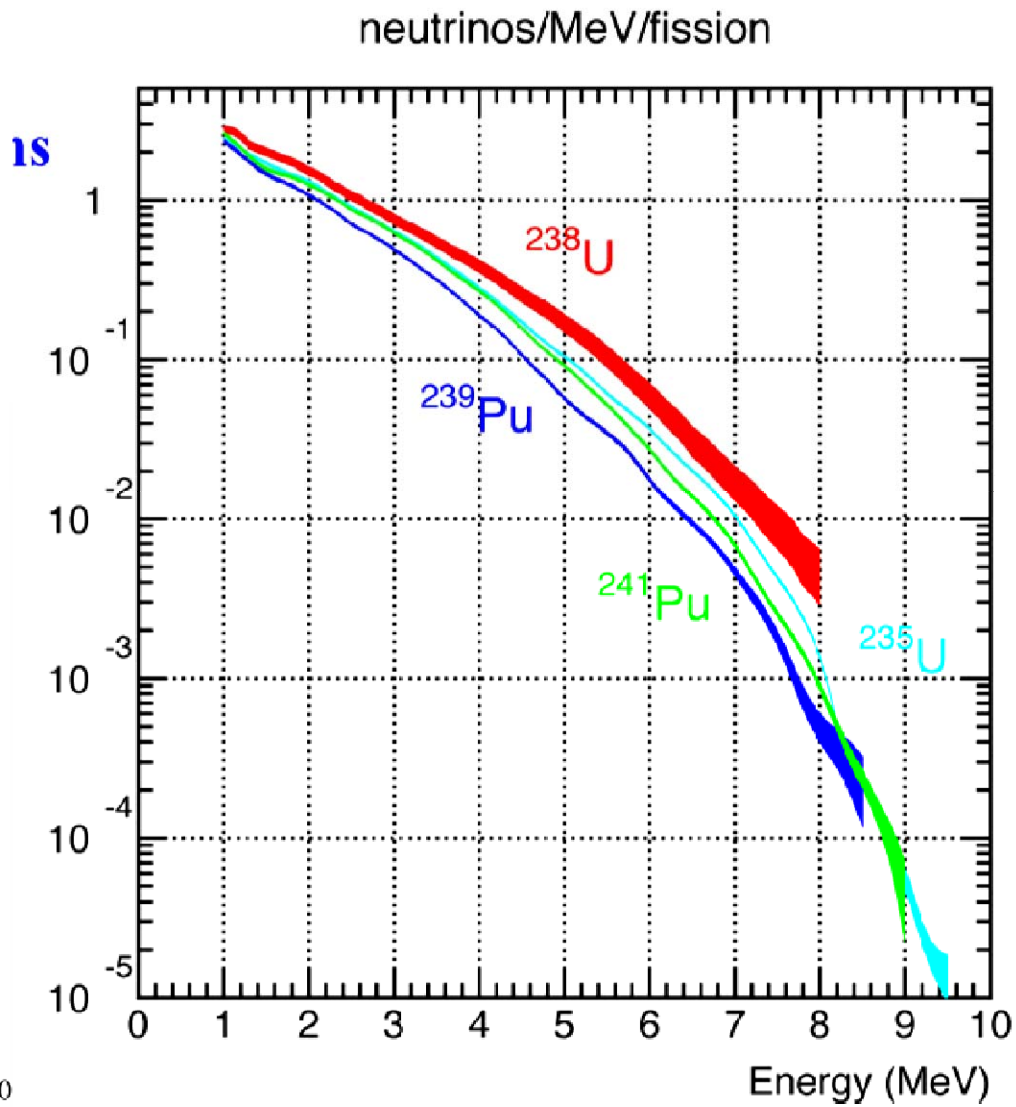
Fission reaction:

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

neutron rich

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



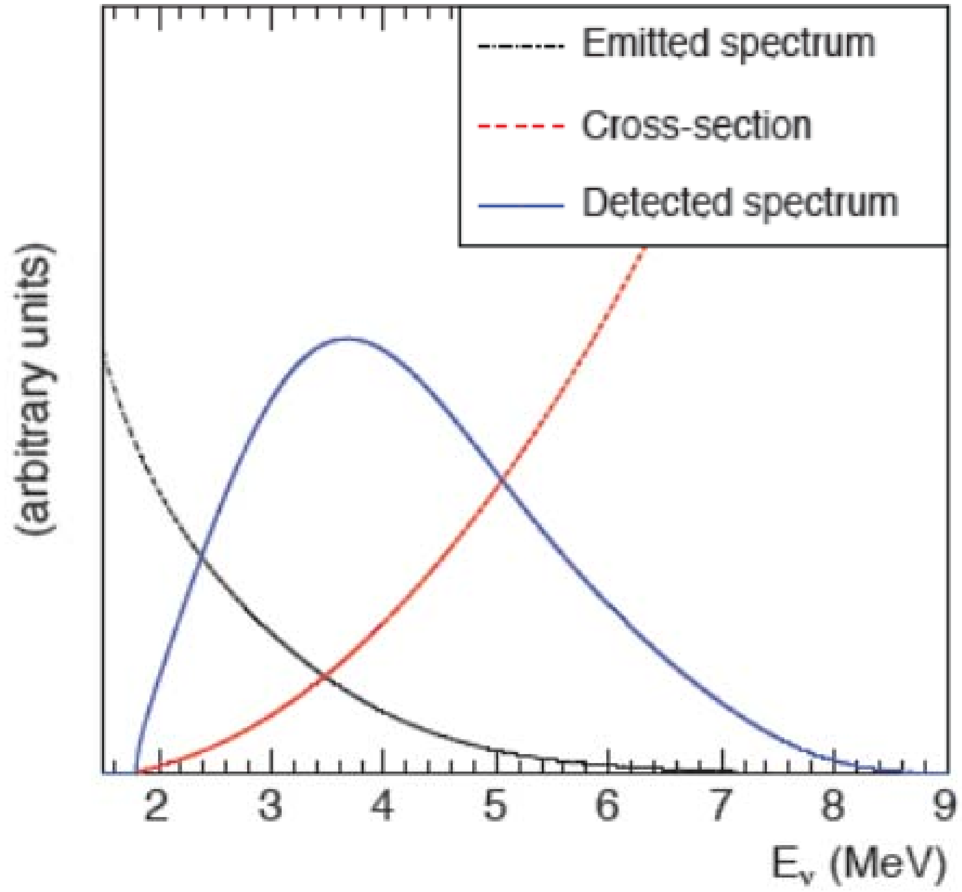


Anti-ν_e detection

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

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

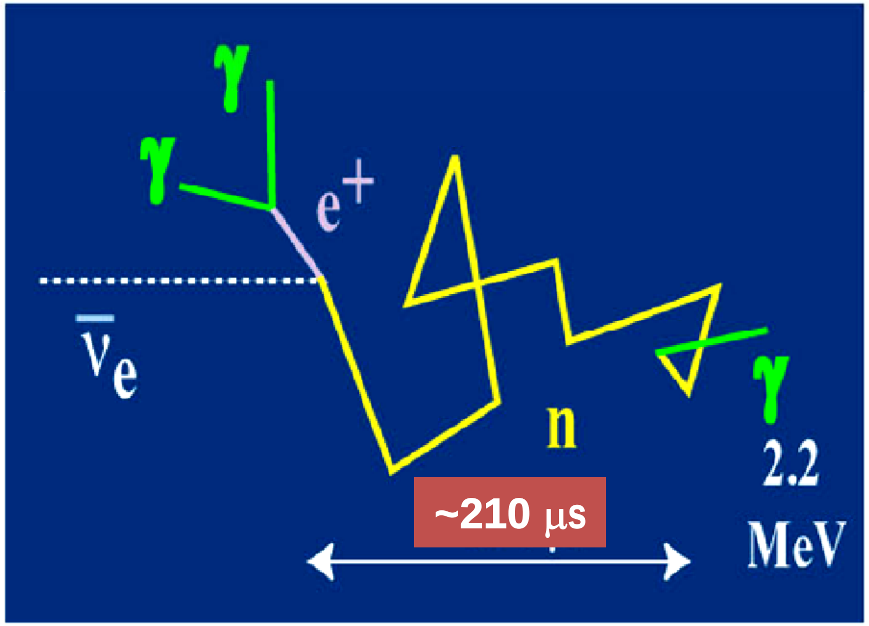
(energy, E_ν<8MeV)



Detecting reactor neutrinos in Liq. scintillators

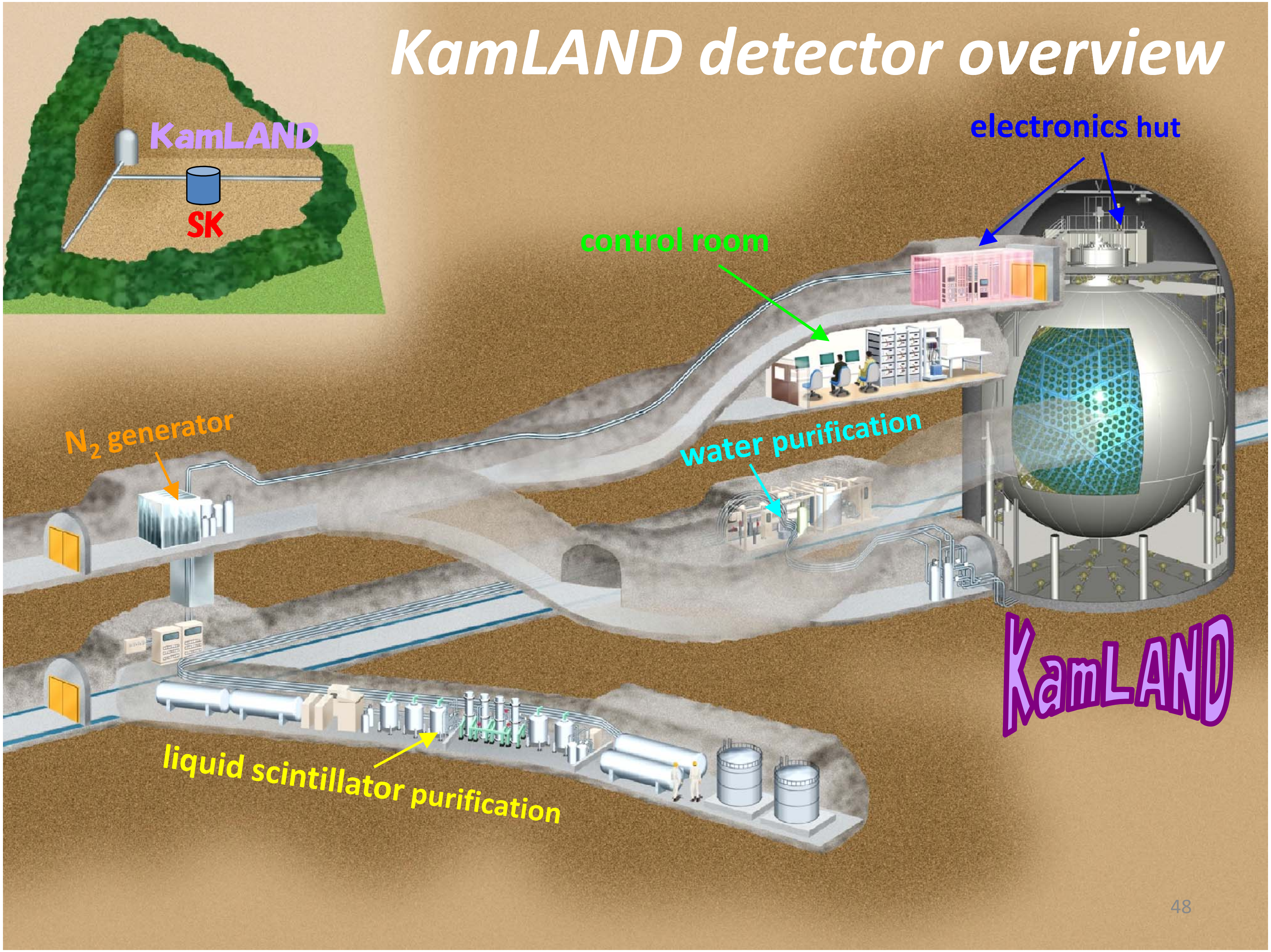
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

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

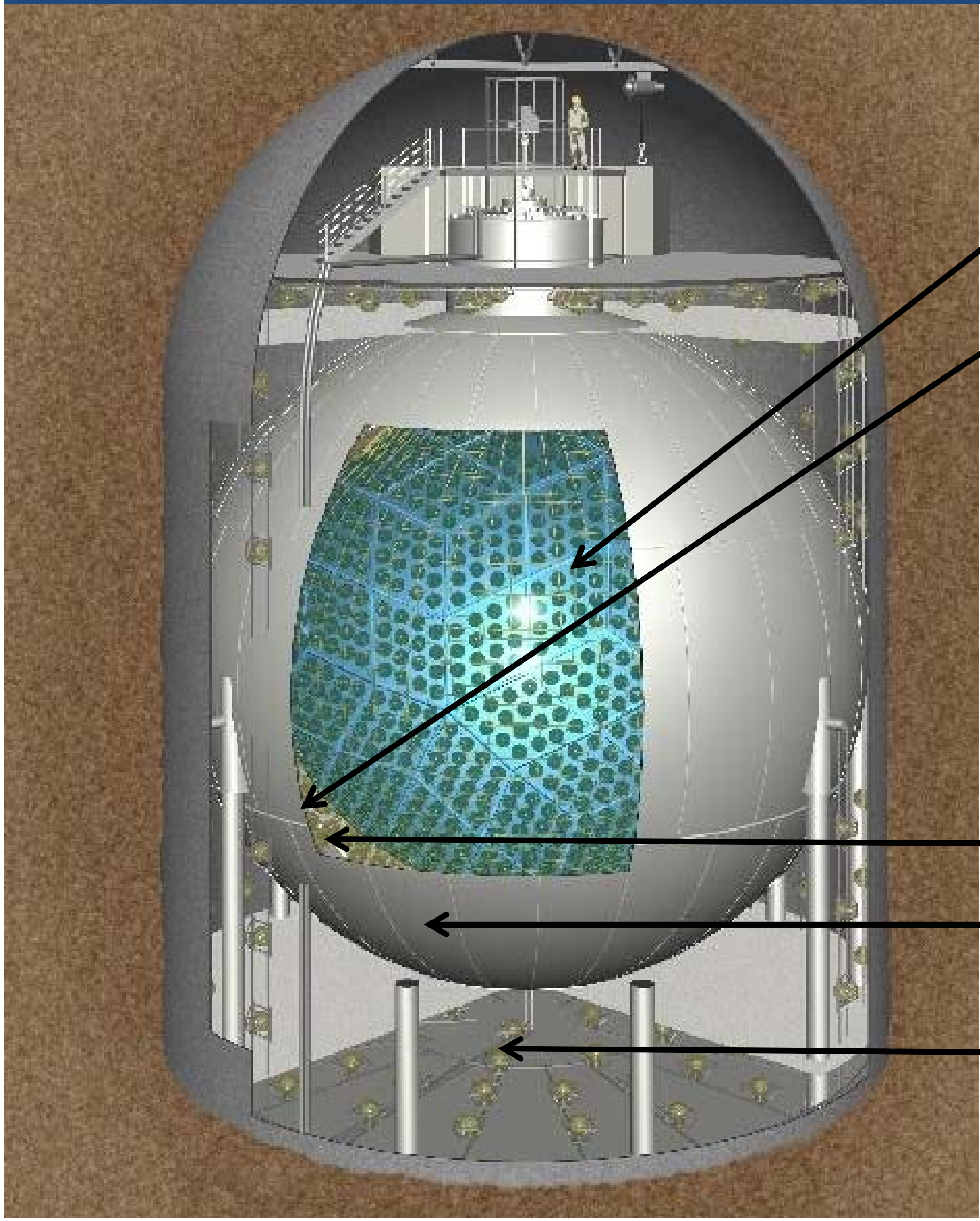


Coincidence of e^+ and γ reduces the BG substantially

KamLAND detector overview



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

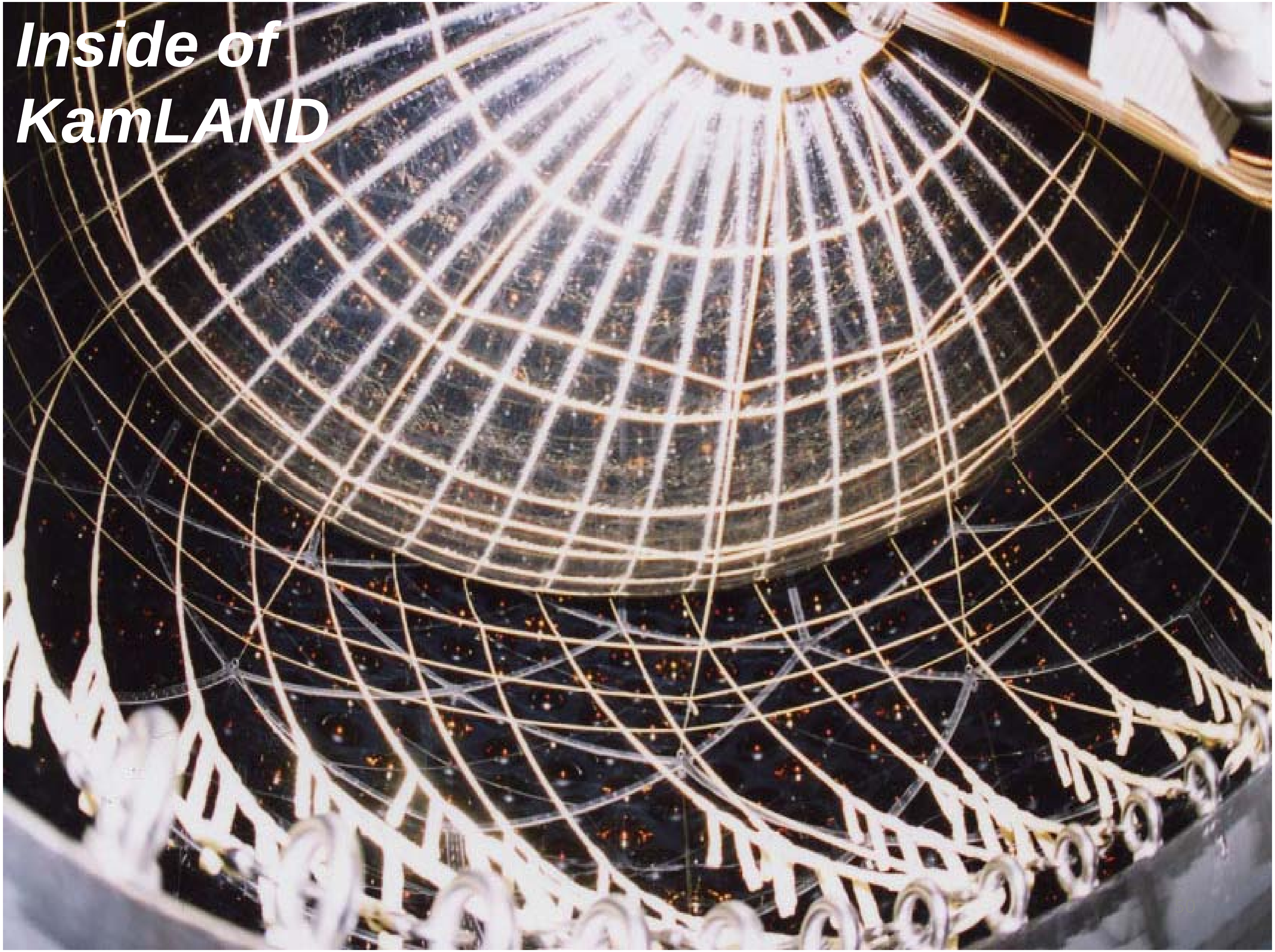
➔About 50 more light than water Cherenkov

➔But no information on direction

Buffer oil.

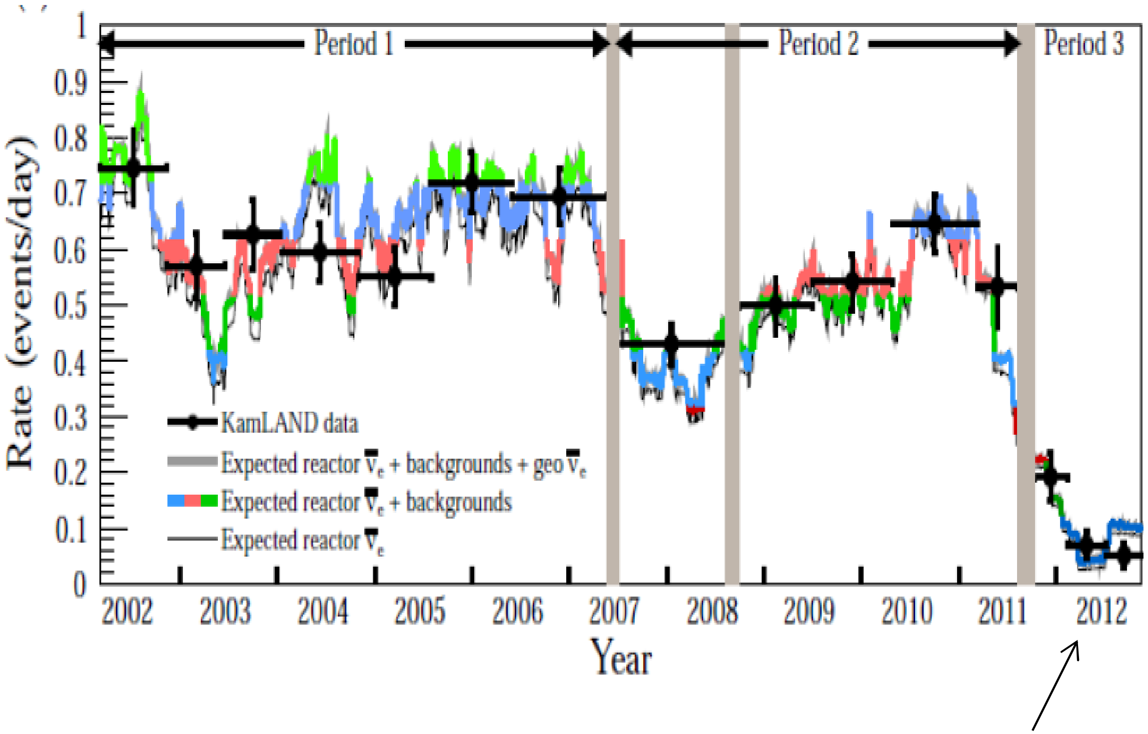
Stainless steel tank.

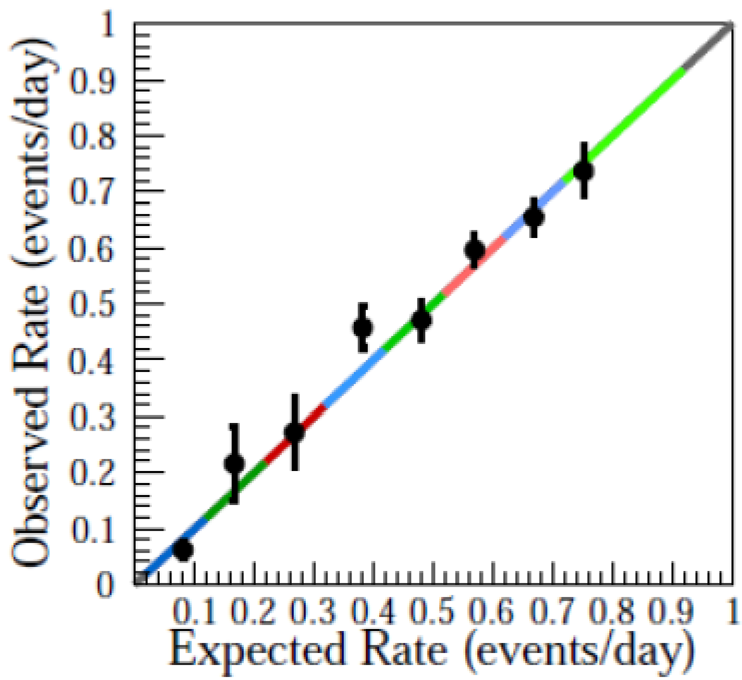
Water Cherenkov anti-counter.


Inside of
KamLAND

KamLAND event rate

KamLAND: 10 years of event rate



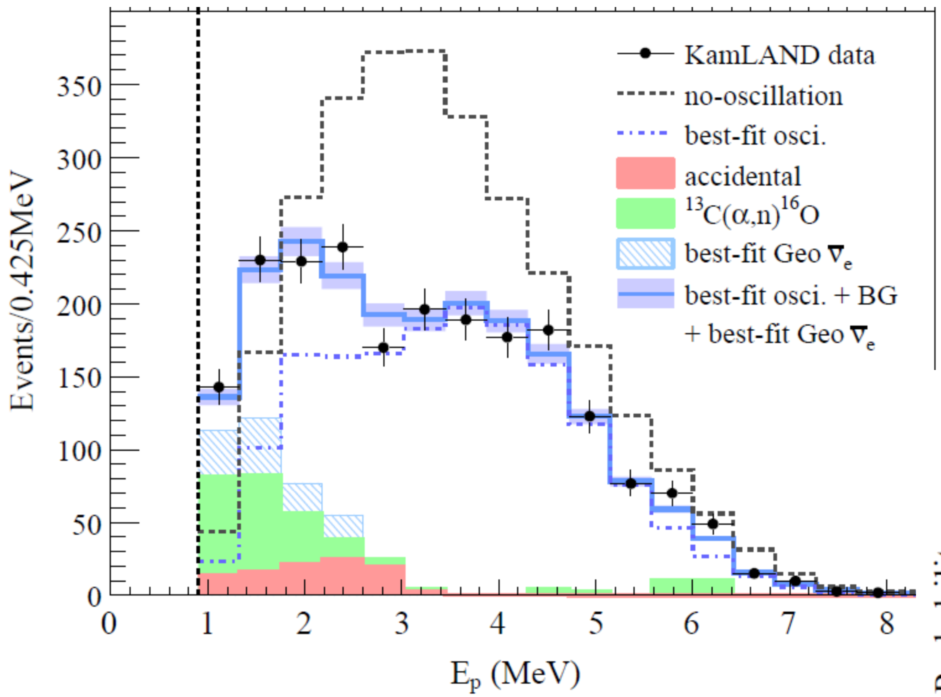


BG (reactor neutrino) free geo-neutrino flux measurement

Clear proof that the events are mostly reactor neutrinos.

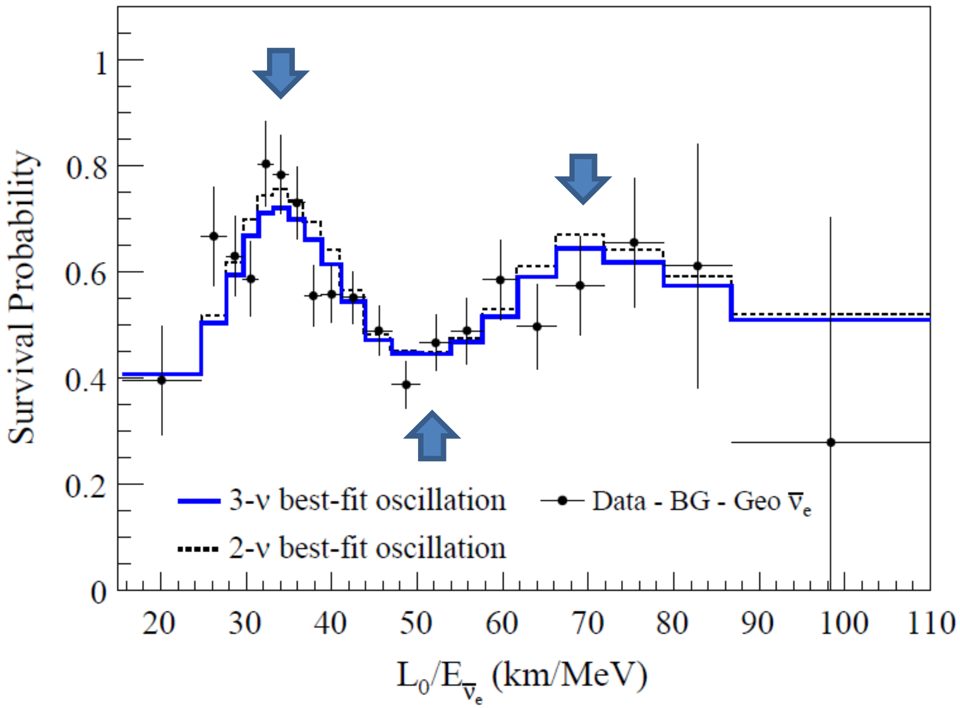
KamLAND results on reactor neutrinos

KamLAND collab. PRD 83, 052002 (2011)



OR

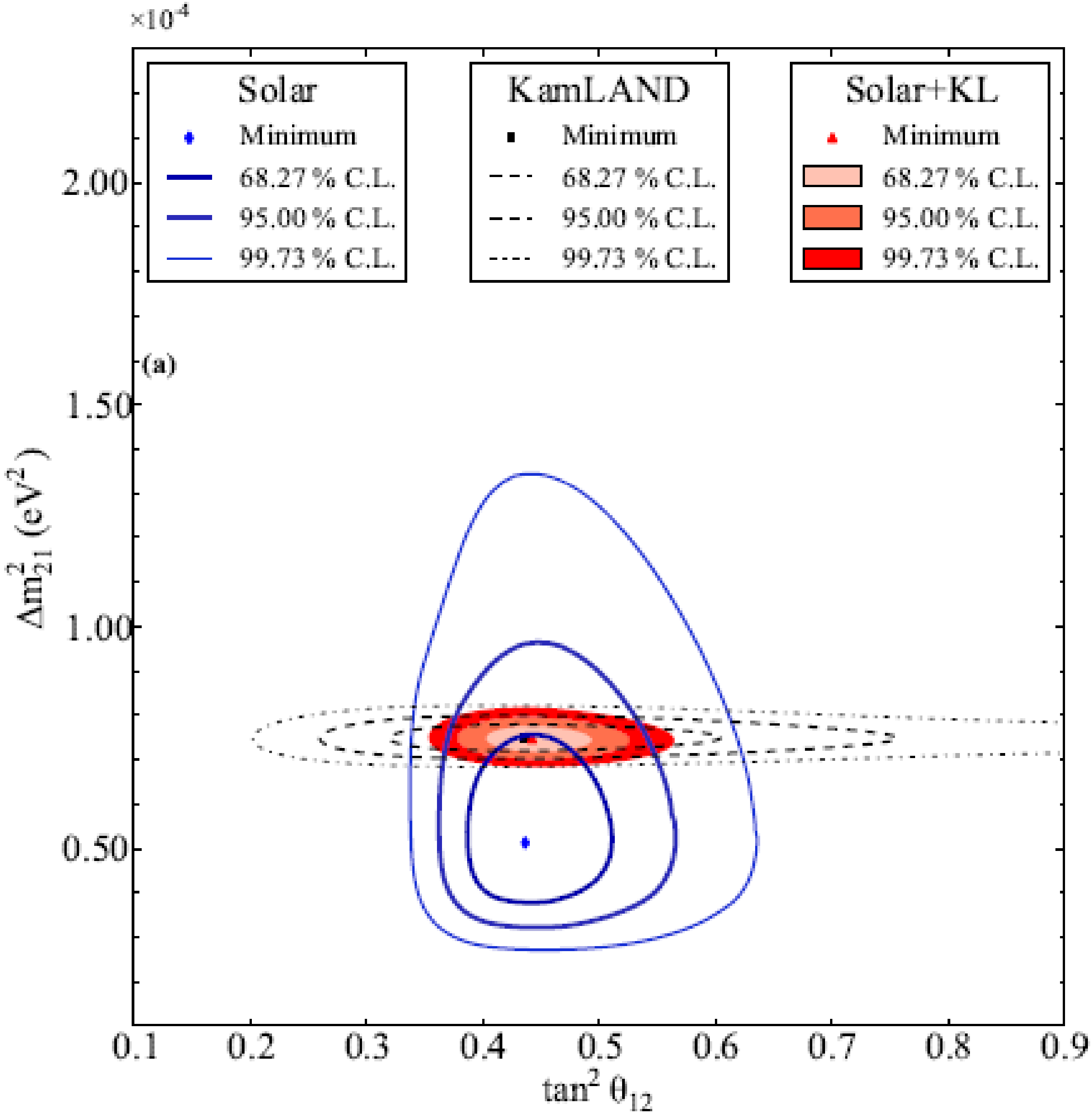
Really, really neutrino oscillation!



Multiple measurement of oscillation minimum and maximum allows a precise measurement of Δm_{12}^2

Measured (Δm_{12}^2, $\sin^2\theta_{12}$) values

N. Barros (for SNO) NPB (proc suppl) 237-238(2013) 107
Also many other analyses
kamLAND PRD 83, 052002 (2011)



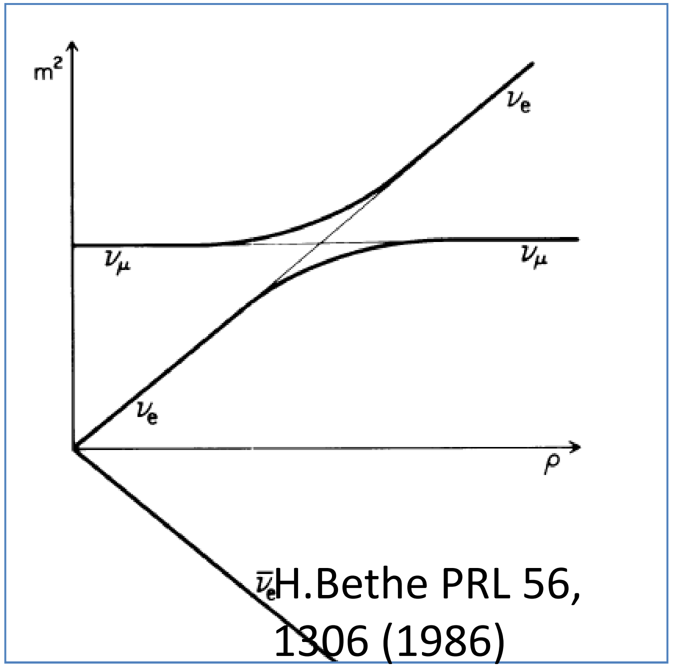
✓KamLAND measured Δm_{12}^2 most precisely.
✓Solar neutrino experiments measured $\sin^2\theta_{12}$ most precisely. (KamLAND $\sin^2\theta_{12}$ measurement is almost as precise as that by solar neutrino exp.)

Next steps: Further confirmation of MSW

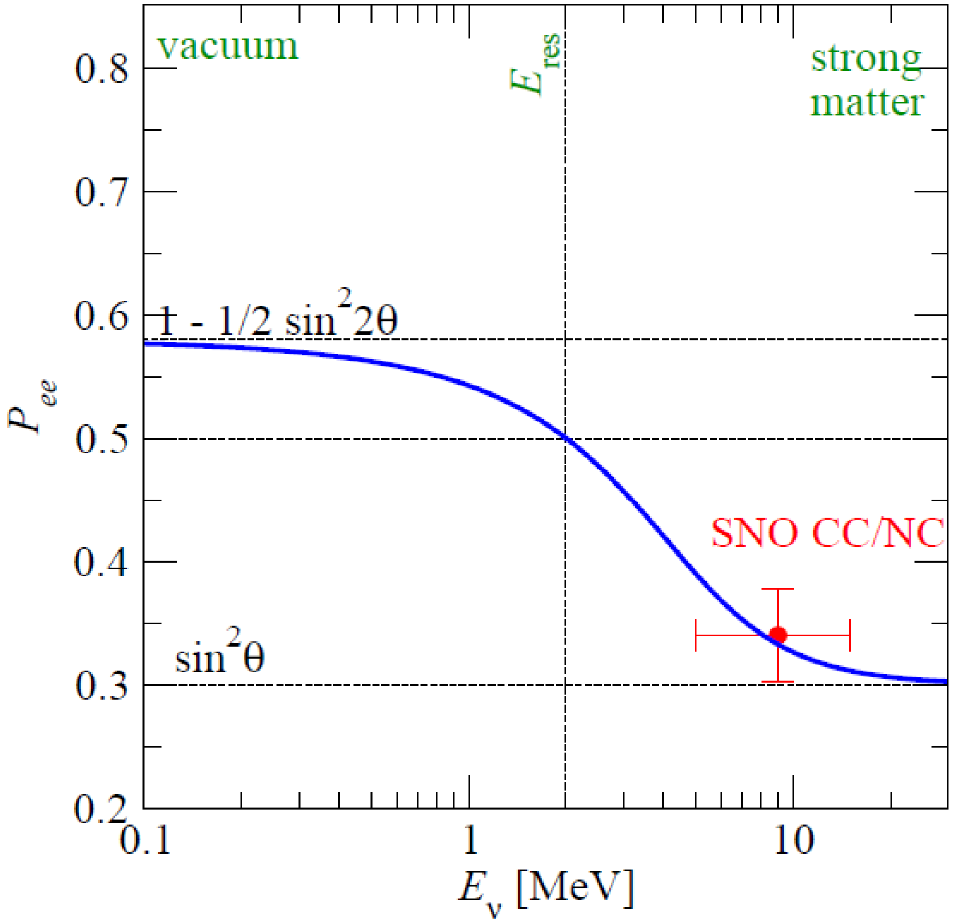
Upturn

T.Schwetz, WHEPP-X, 2008, Chennai

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



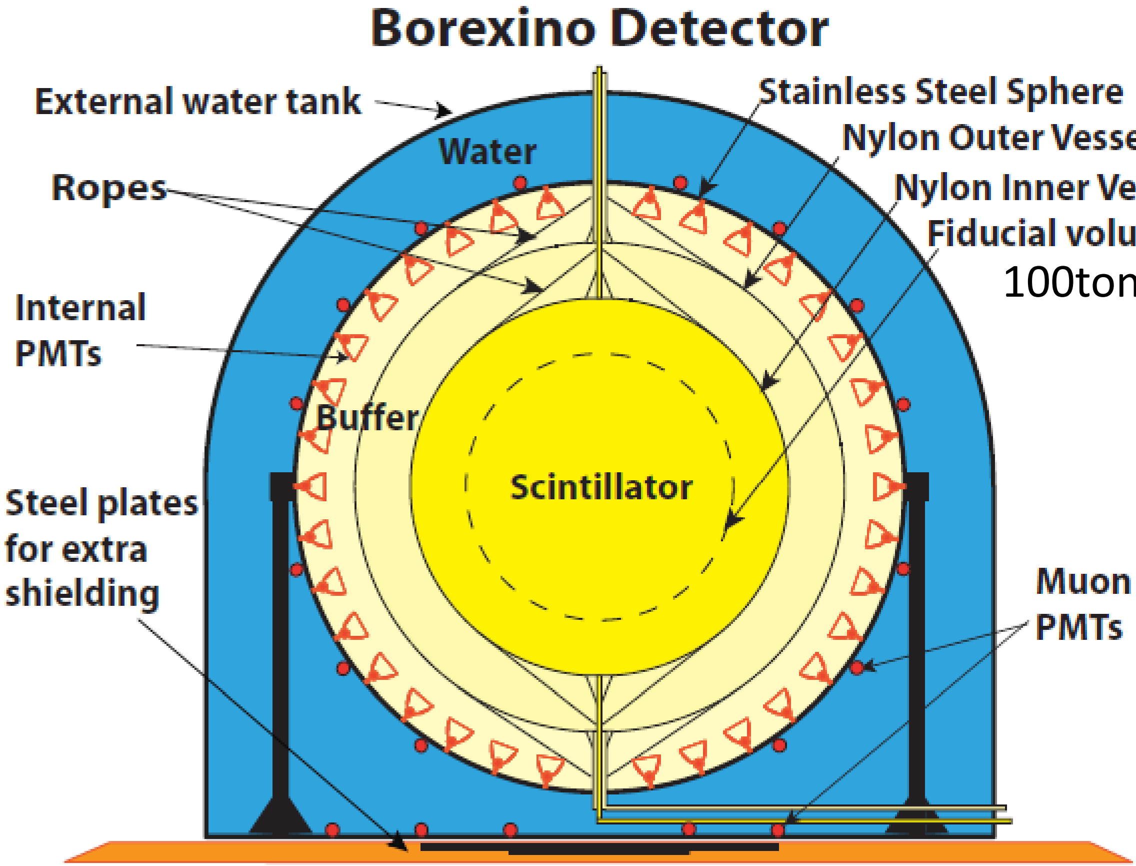
H.Bethe PRL 56, 1306 (1986)



➔Sub-MeV solar neutrino experiments,

➔Precise measurements of the ^{8}B spectrum.

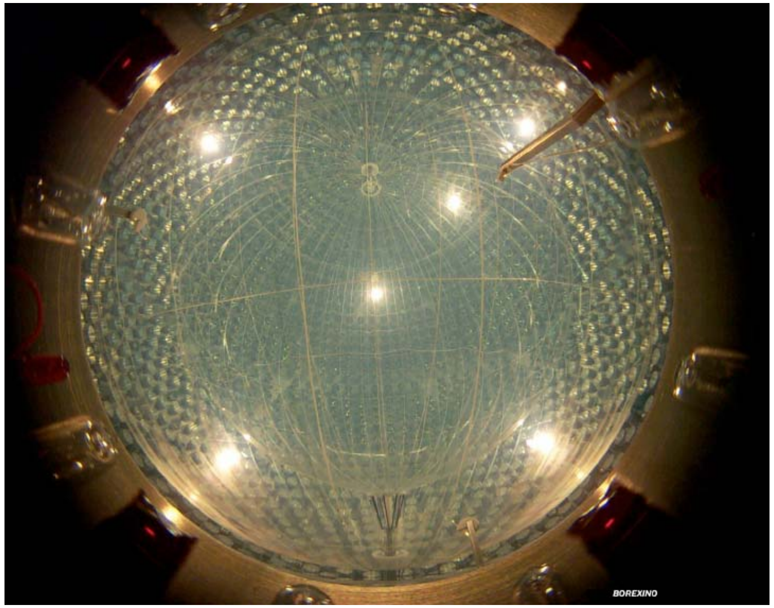
Borexino experiment



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).

Started data taking in May 2007.

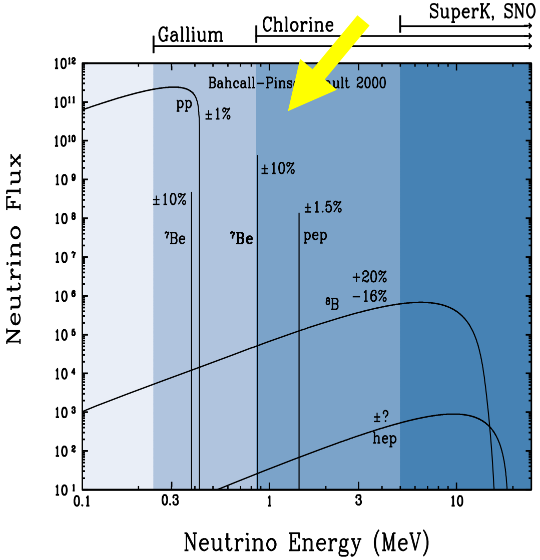
Borexino detector after filling

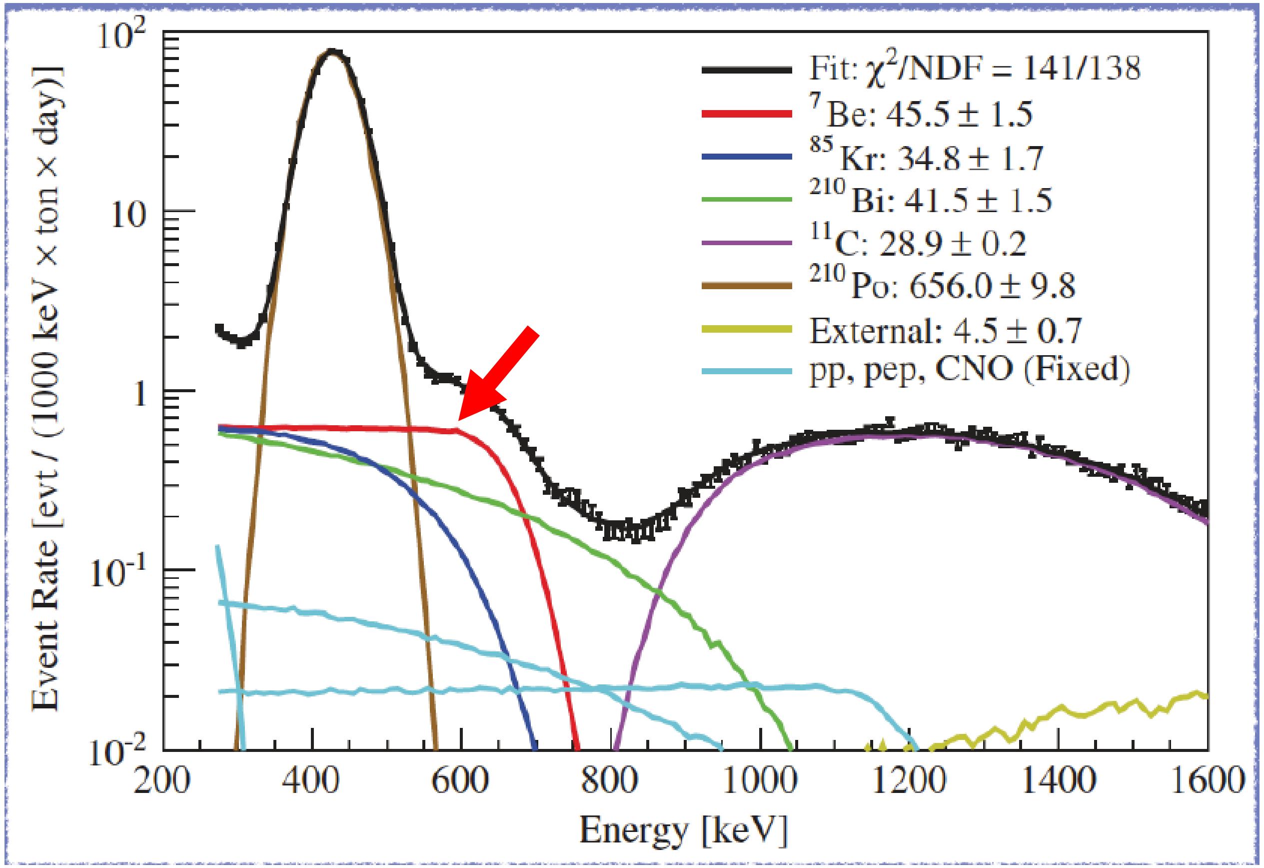


Results from Borexino (1): ^{7}Be

Energy spectrum from one of the 2 analyses. (no ^{210}Po peak subtraction version)

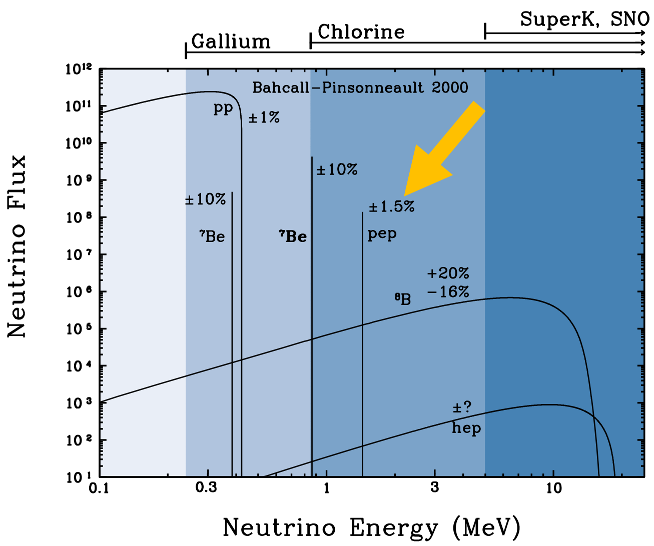
M. Pallavicini nu2012
Borexino, PRL 107, 141302 (2012)



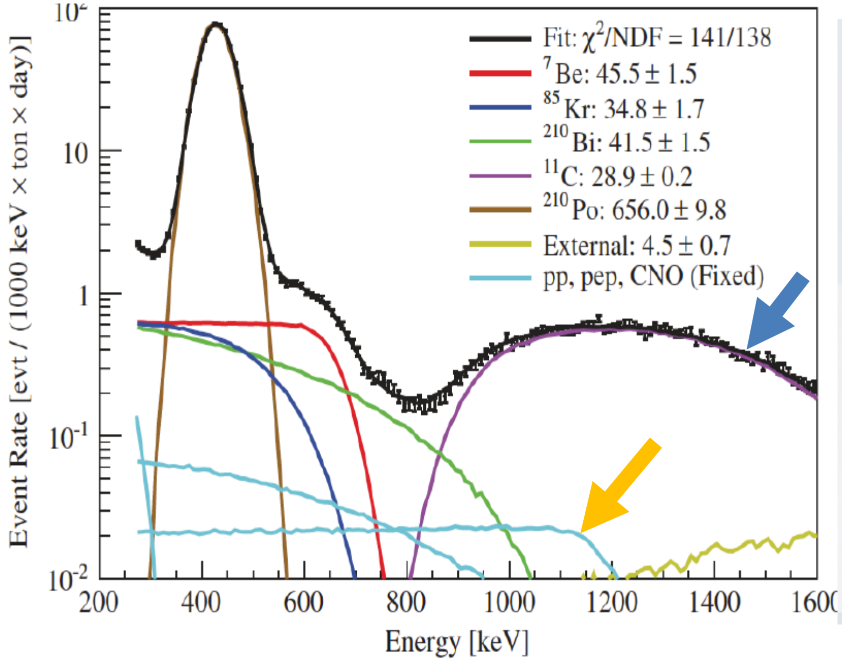


46.0±1.5(stat)±1.5(syst) events /(day･100ton)

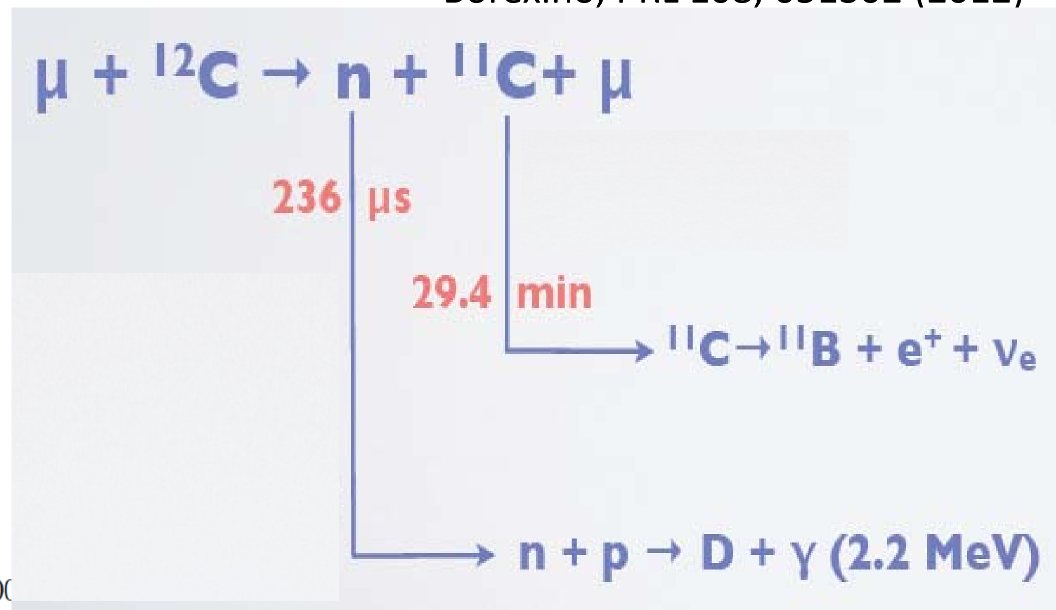
Results from Borexino (2): pep



pep neutrinos have mono-energetic spectrum at 1.44MeV. (the MSW transition energy range). The flux is precisely (1.2%) predicted.
➔ very good for the precise study of MSW.

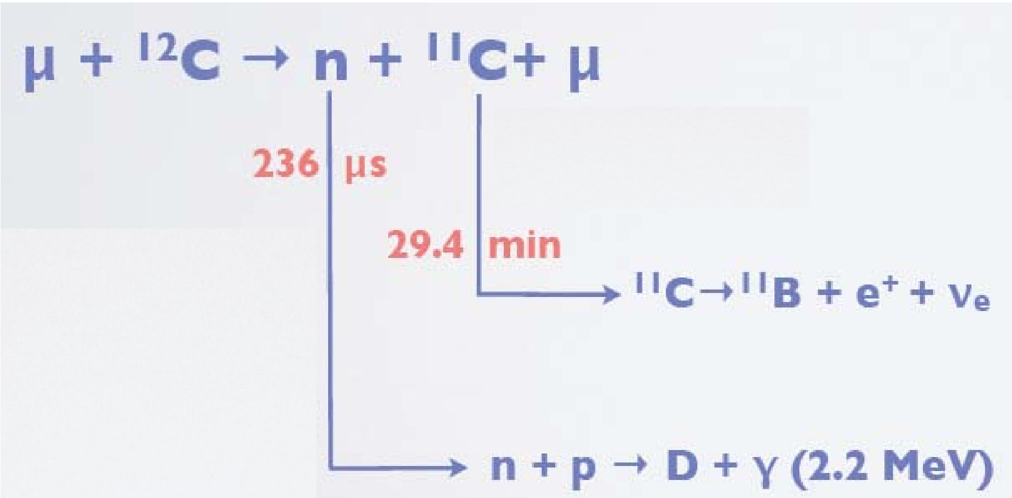


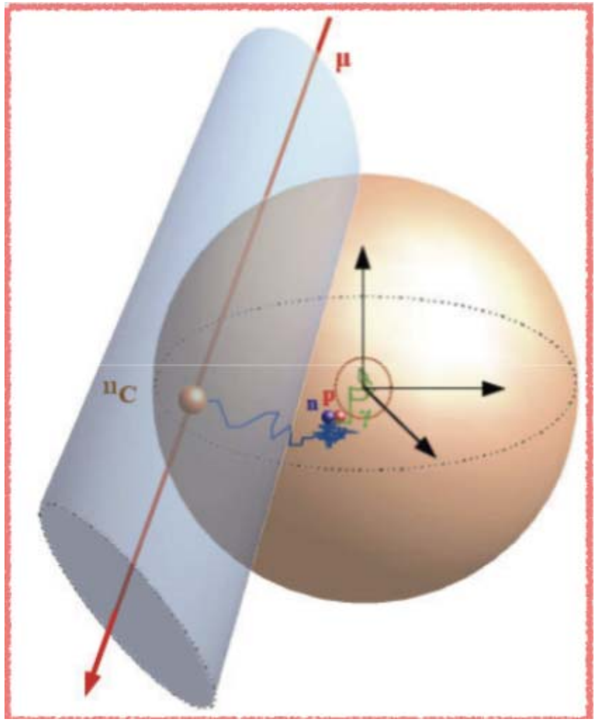
M. Pallavicini nu2012
Borexino, PRL 108, 051302 (2012)



Results from Borexino (2): pep

M. Pallavicini nu2012
Borexino, PRL 108, 051302 (2012)





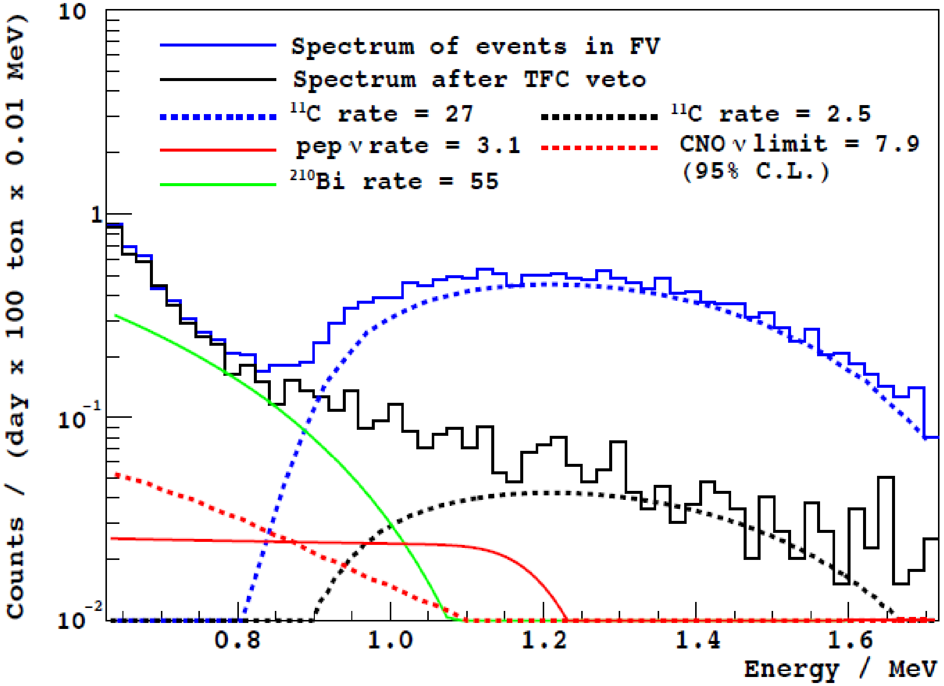
<u>^{11}C backgrounds are eliminated by;</u>
1) 3-fold coincidence of μ, neutron, and ^{11}C.
2) with the constraint of the distance between μ and the delayed events.

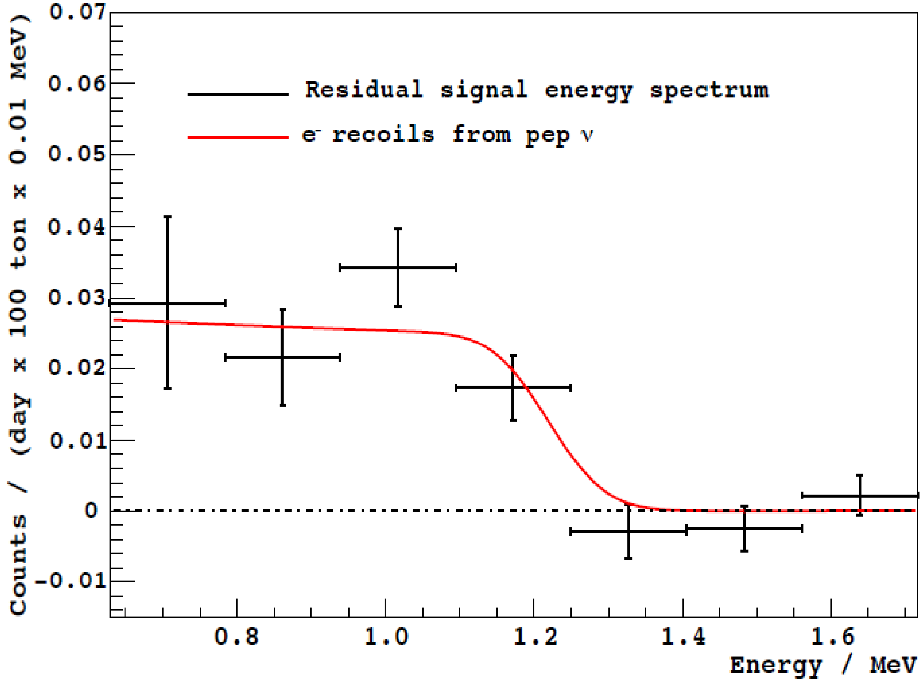
➔ 91% rejection of ^{11}C, and 51.5% signal eff.

Still the ^{11}C BG is serious. ➔ ^{11}C decay produces e^+, while the signal is e^-. e^+ signal has slightly different signal timing distribution due to the finite lifetime of positoronium (which produces annihilation gamma-rays). ➔ This feature is used to statistically estimate the e^+ fraction.

Results from Borexino (2): pep

M. Pallavicini nu2012
Borexino, PRL 108, 051302 (2012)

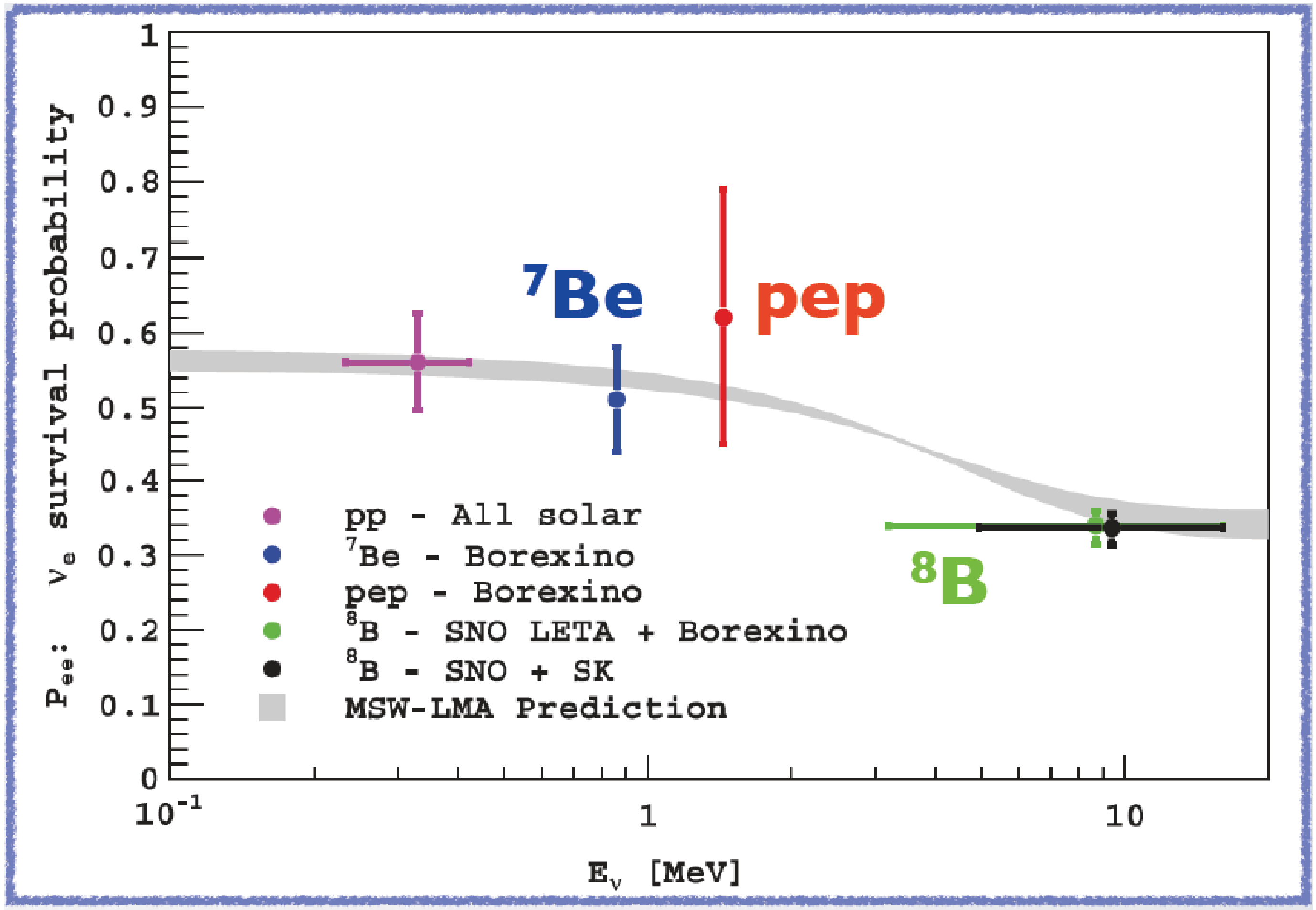




pep even rate	3.1±0.6(stat)±0.3(syst)
Data / SSM (LMA)	1.1±0.2

Results from Borexino (2): pep

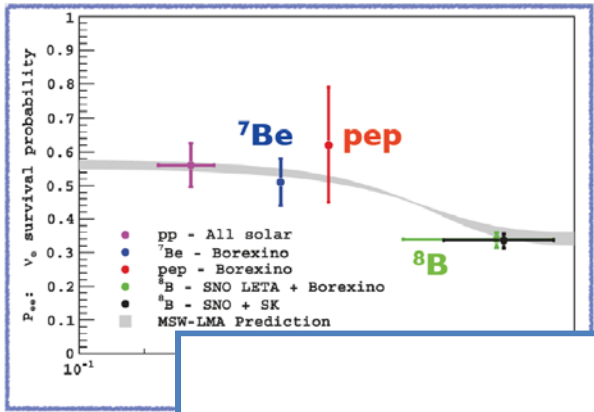
M. Pallavicini nu2012
Borexino, PRL 108, 051302 (2012)



LMA-MSW explains the data very well !

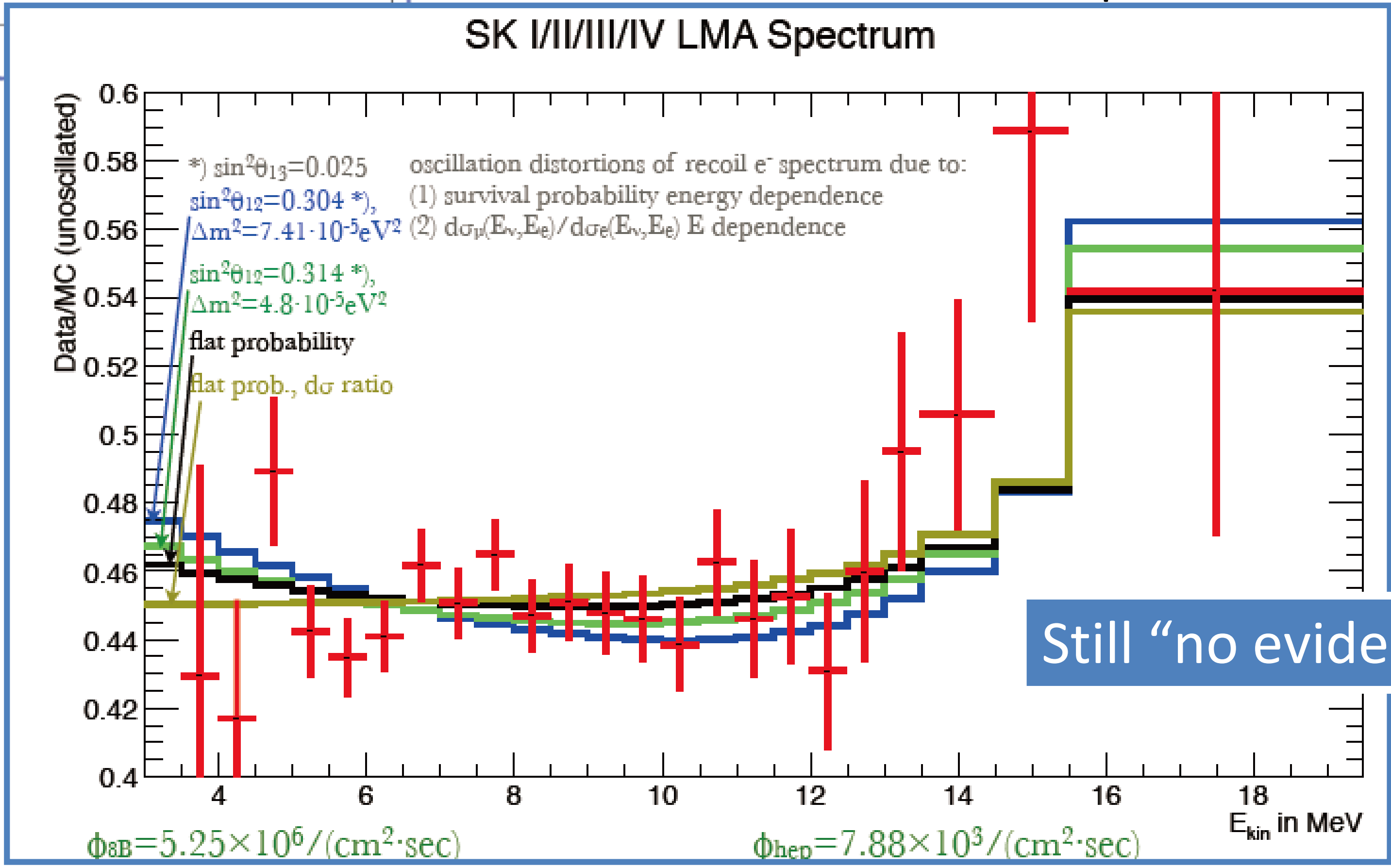
Super-K: energy spectrum

M. Smy (Super-K) nu2012



Super-K is trying to observe the upturn of the ^{8}B energy spectrum as predicted by LMA-MSW.

Fit results with several assumptions

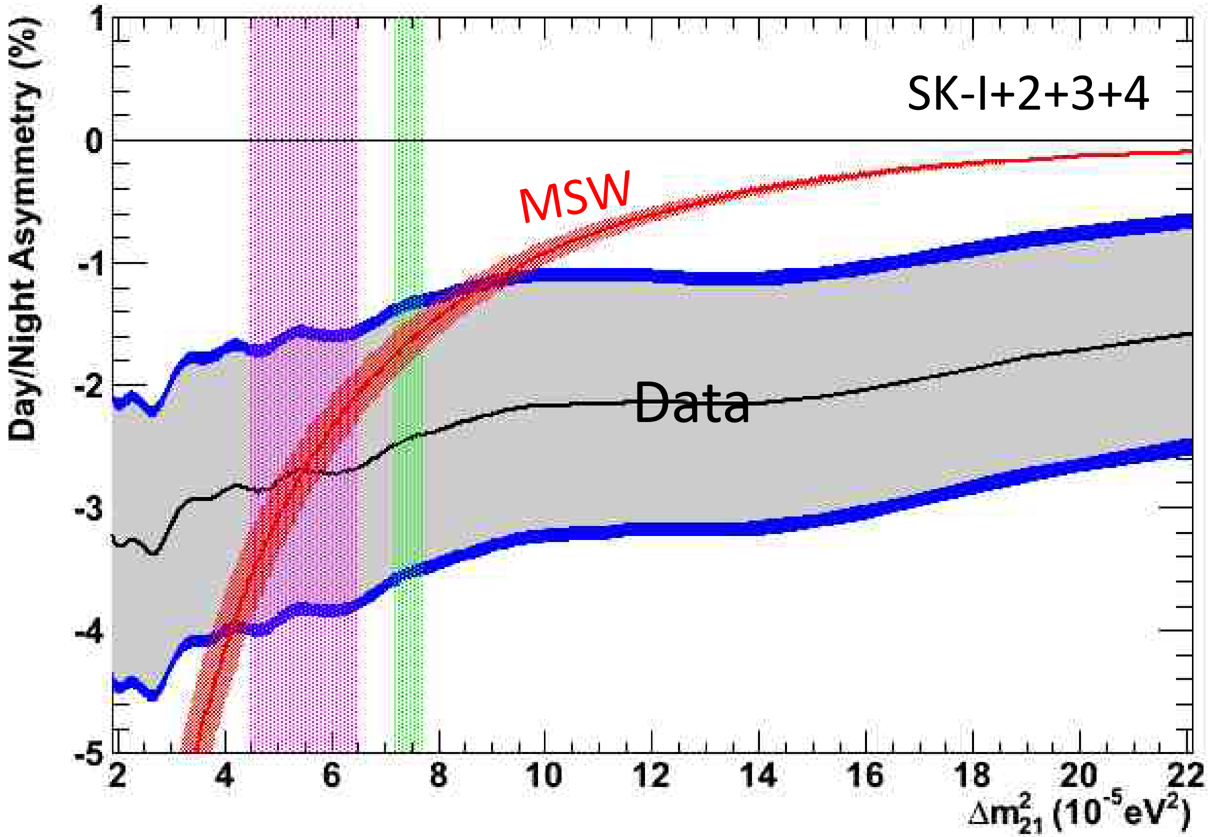


Still "no evidence" …

Super-K: day-night asymmetry

M. Smy (Super-K) nu2012

~2% day-night asymmetry in the flux is expected due to the Earth matter effect for LMA-MSW.



✓Data are consistent with LMA-MSW.

✓Asymmetry is more than 2σ...

SK-1-4 = -2.5% ± 1.0%(Stat) ± 0.5%(Syst)

(for $\Delta m_{12}^2 = 7.58 \times 10^{-5}$eV^2)

Summary of Lecture-2

- Nearly half a century 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 deficit was confirmed by many subsequent experiments.
- The problem was clearly solved by the SNO D_2O experiment, with an important contribution from Super-K.
- KamLAND reactor experiment observed the oscillation pattern, and determined the Δm_{12} parameter accurately.
- Measurement of sub-MeV solar neutrinos and studies of day-night effect and up-turn of the spectrum will still contribute to our better understanding of neutrinos.