最近のSNOデータを巡って

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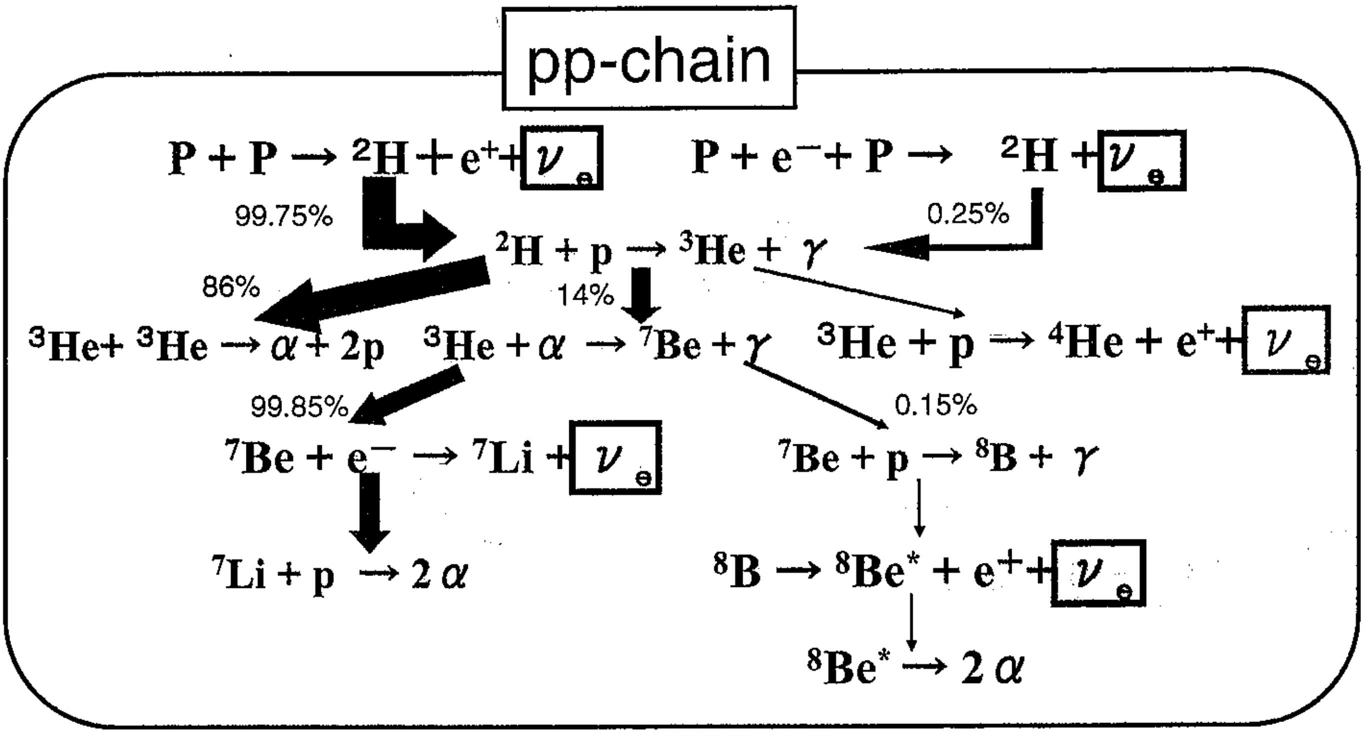
Outline

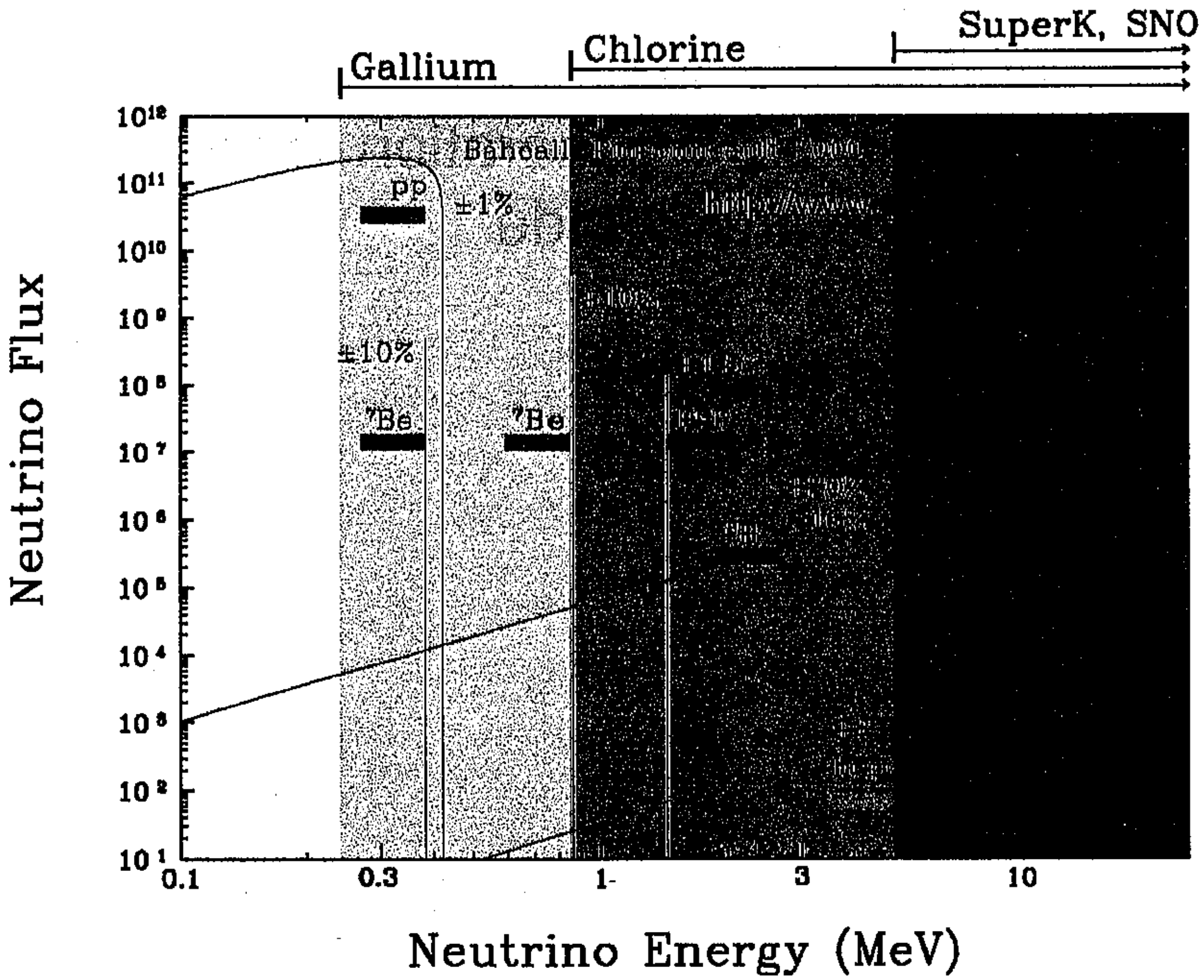
- Solar neutrino
- Solar neutrino flux measurements
- Results from 2nd generation experiments
  - Super-Kamiokande
  - SNO
- Oscillation analysis
- Future experiments
- Summary

Solar neutrino

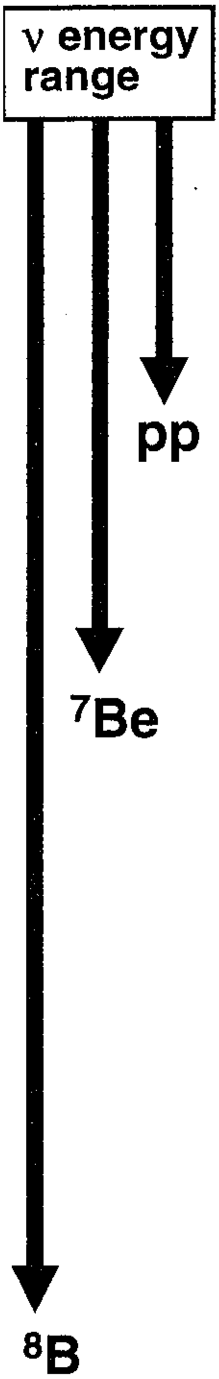
Standard Solar Model (SSM)

Sun burns through: $4p \rightarrow {}^4He + 2e^+ + 2\nu_e + 25MeV$





Solar neutrino flux measurements



SAGE:1990- , GALLEX:1991-1997 , GNO:1998-

SAGE:
(GALLEX:)
GNO:

30～100 tons

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

E_{th}= 235keV

R=0.55 ± 0.05 (SAGE)

R=0.57 ± 0.05 (GALLEX+GNO)

1970-

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

615tons E_{th}= 817keV R=0.33 ± 0.03

Kam-II,III:1987-1995, SK-I:1996-2001

(Kamiokande) :
Super-Kamiokande :

$\nu + e^- \rightarrow \nu + e^-$ (H_2O)

E_{th}(analysis)= 5.0-7.0MeV

4,500 tons R=0.53 ± 0.07 (Kam)

50,000 tons R=0.47 ± 0.02 (SK)

SNO-I:1999-2001, SNO-II(+NaCl) 2001-

SNO (D_2O):

1,000 tons

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

$\nu + d \rightarrow p + n + \nu$ (NC)

$\nu + e^- \rightarrow \nu + e^-$ (ES)

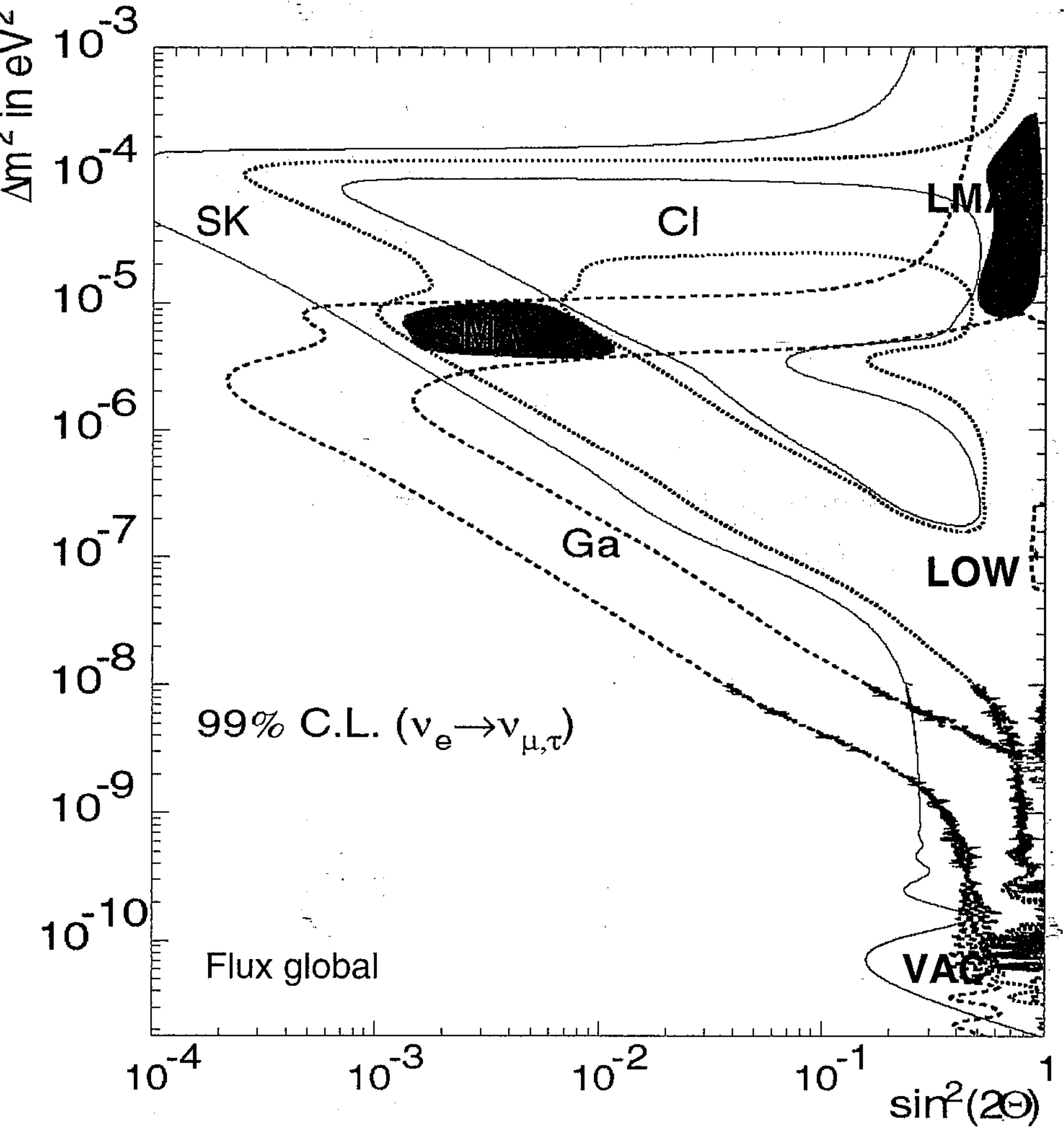
To be explained later

R: Data / SSM(BP2000v2)

Radio chemical experiments: Homestake, SAGE, GNO/GALLEX
CC — Integrated flux above a threshold

Water Cherenkov : Kamiokande, Super-Kamiokande, SNO
Directionality ($\nu_x e \rightarrow \nu_x e$ case)
CC+NC (SK) CC/NC (SNO) — Energy, Event time measurement

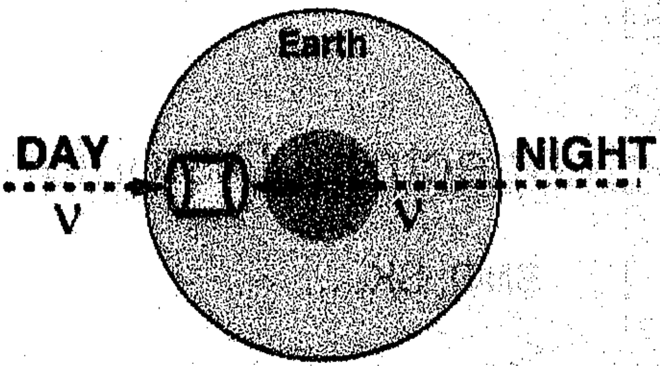
Oscillation parameters based on flux of Homestake, GNO/SAGE and SK



- No unique solution…
- SSM dependent (pp:1% ^{7}Be:10% ^{8}B:+20-16% hep:??)

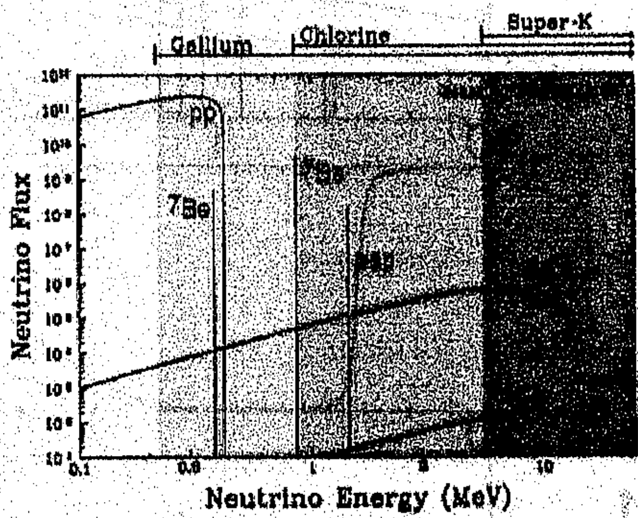
Goal of 2nd generation solar neutrino experiments is to get flux independent evidence of ν oscillation

Matter-effect regeneration



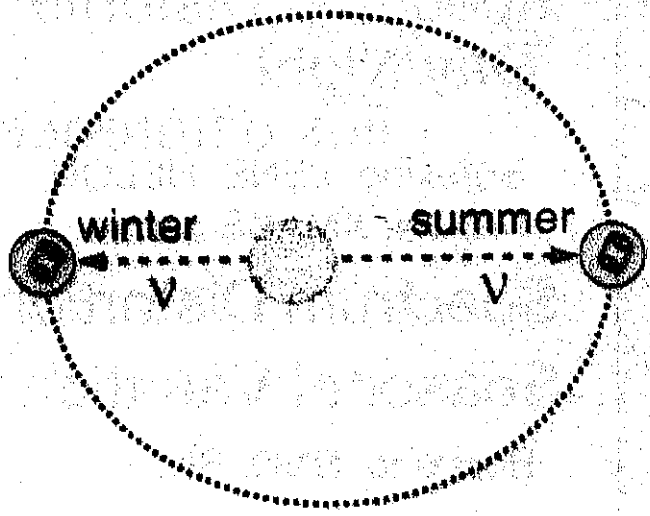
SK, SNO, Borexino, ...

Energy spectrum distortion



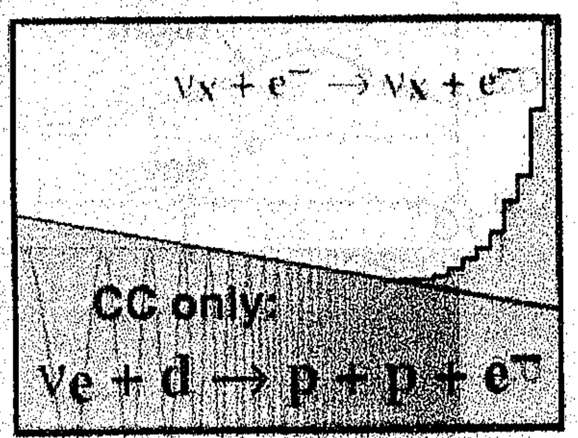
SNO, **SK**, ...

Seasonal flux variation



Borexino, **SK**, GNO, ...

Neutral current / charged current

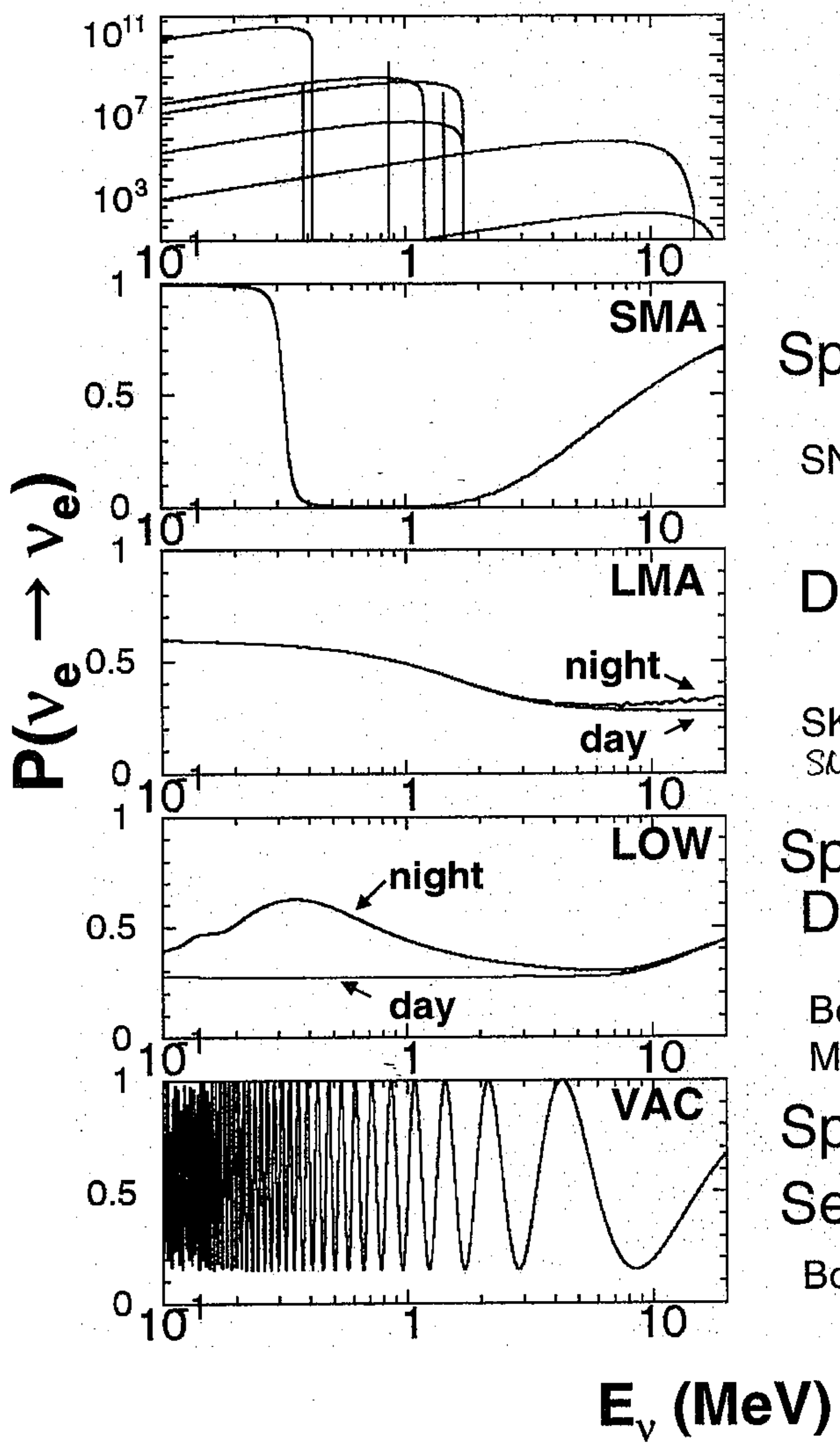


NC: $\nu_x + d \rightarrow \nu_x + p + n$

SNO

Edward T. Kearns
http://ichep2000.hep.sci.osaka-u.ac.jp/scan/0801/pl/kearns/ichep24.jpg

Flux independent analyses



Spectrum Distortion

SNO, SK, ...

Day/Night
flux difference

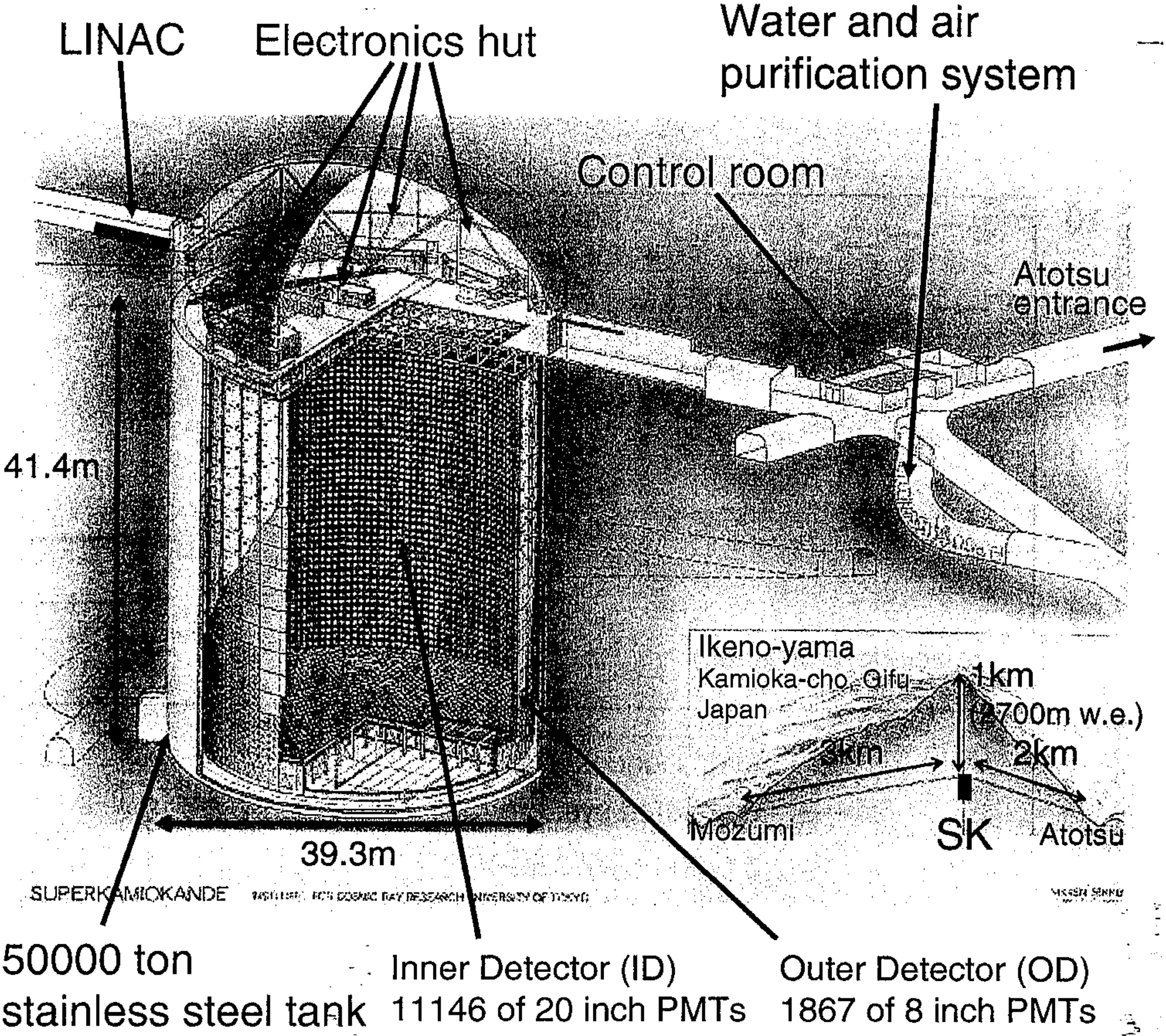
SK, (KamLAND), ...
SNO

Spectrum Distortion
Day/Night
flux difference
Borexino, LENS, HELON, MOON, XMASS ...

Spectrum Distortion
Seasonal Variation
Borexino, SNO, SK, ...

Super-Kamiokande (SK-I)

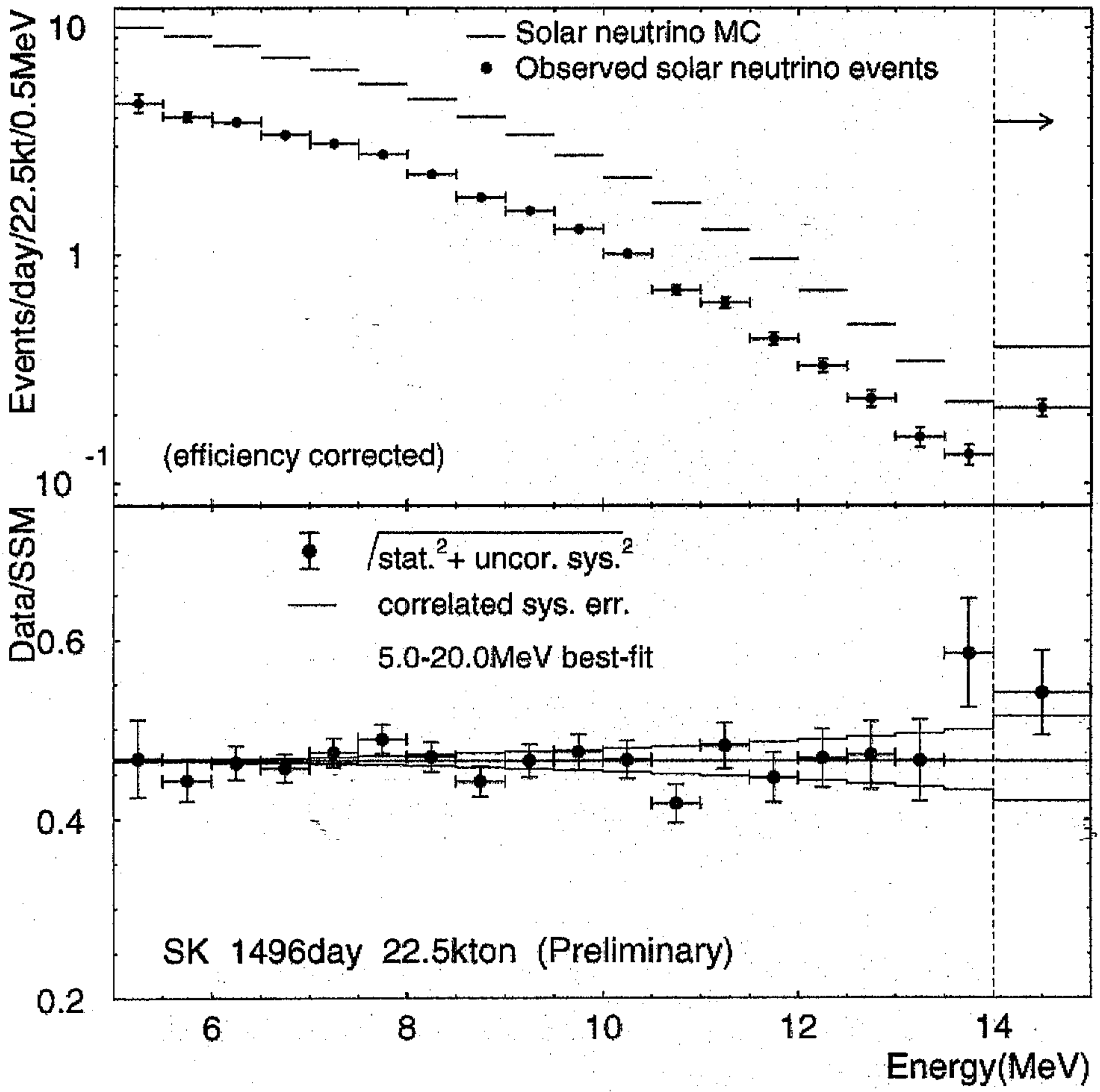
http://www-sk.icrr.u-tokyo.ac.jp/sk/



- photo coverage 40%
- outer detector 2.5m for all surfaces
- fid. vol. for ν_{solar} 22.5kt (2m from ID wall)
- for 10 MeV electron
  - vertex resolution 87cm
  - energy resolution 14%
  - angular resolution 26°

SK-I: Energy spectrum

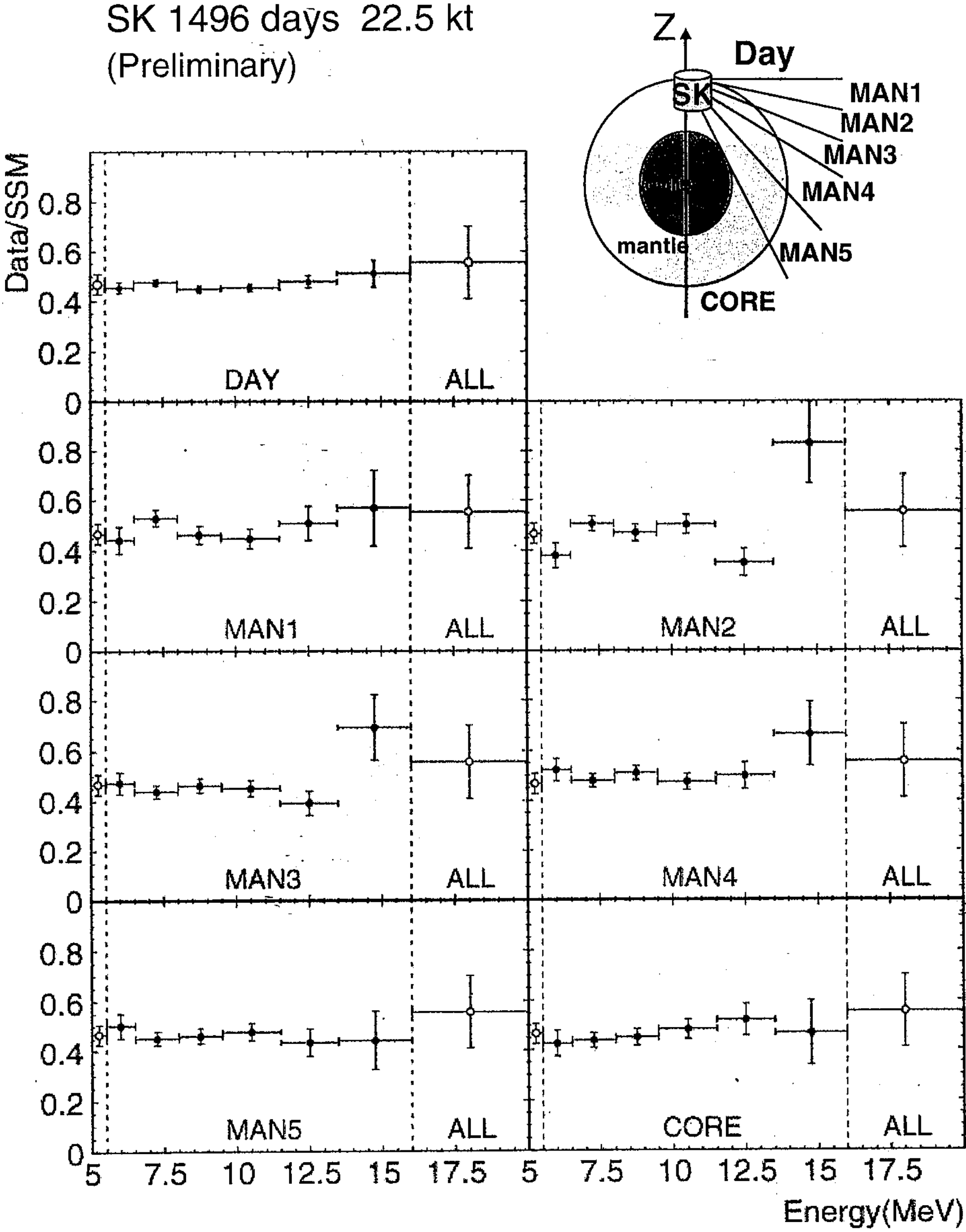
May 31, 1996 – July 15, 2001 1496 days



χ^2 for flat = 17.4 / 18 (d.o.f) 50% C.L.

SK-I: Energy spectrum (day/night-6bin)

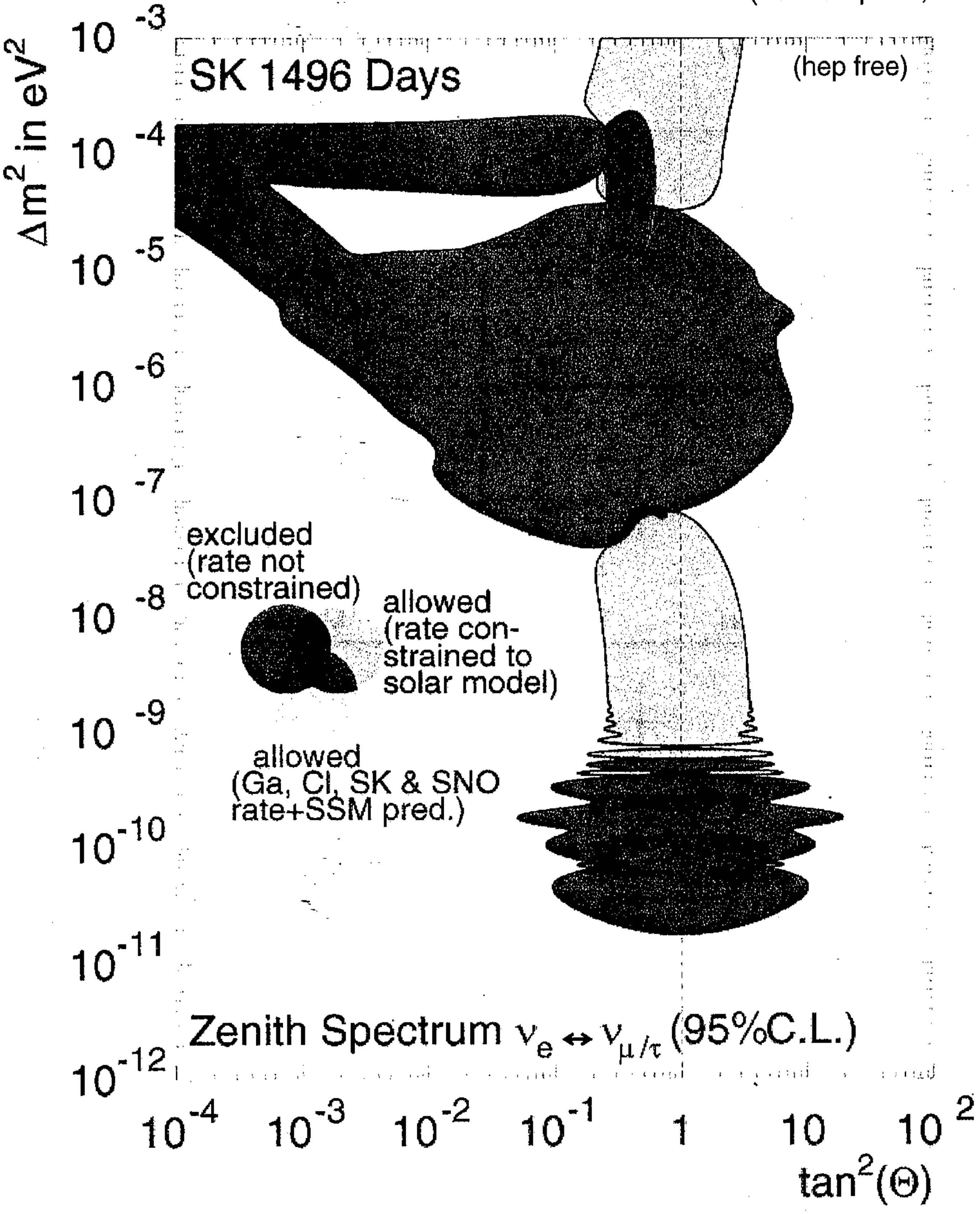
SK 1496 days 22.5 kt
(Preliminary)



Use 44 data points for oscillation analysis

Oscillation analysis (SK vs. global, active)

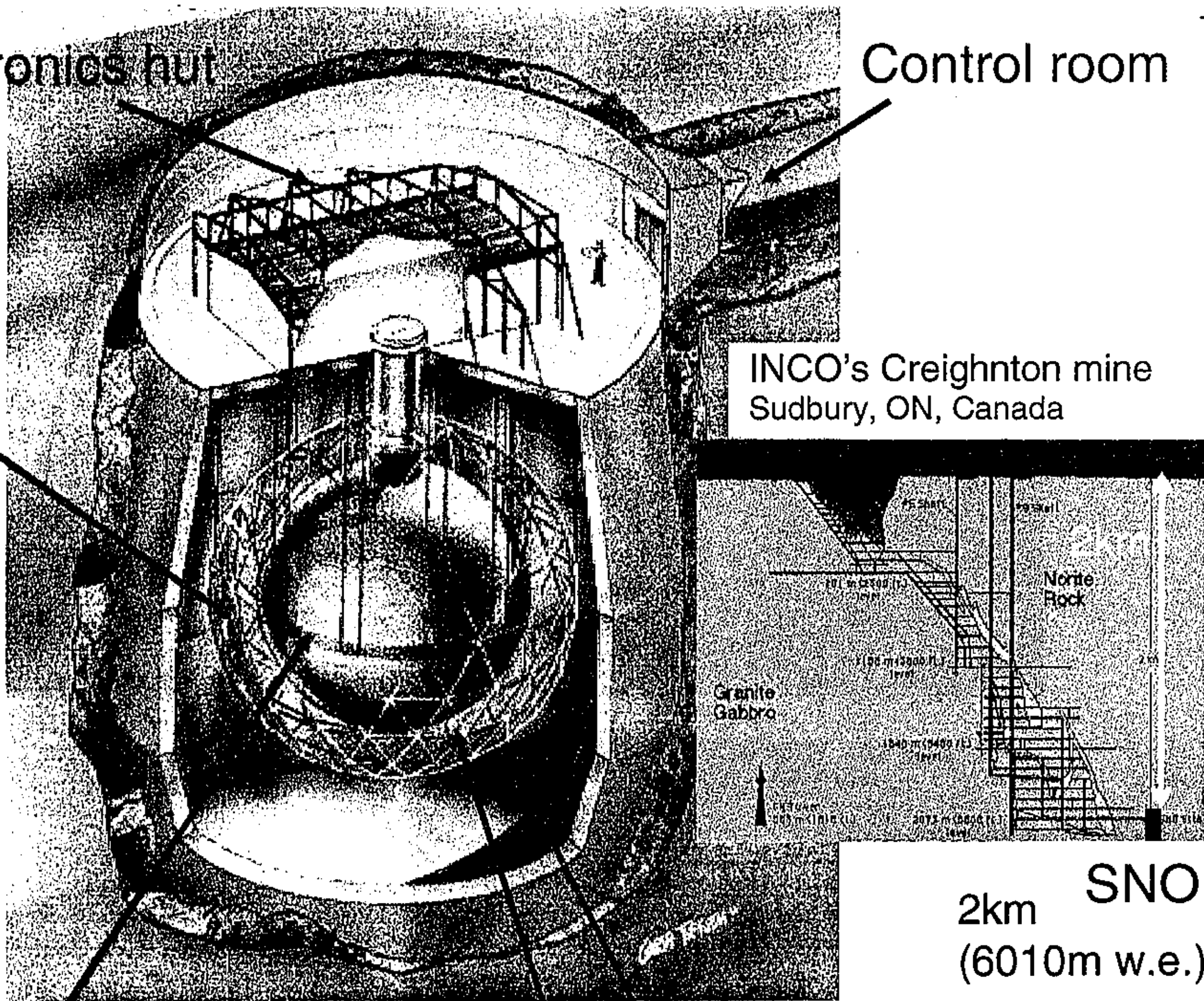
(before Apr 20, 2002)



SK favors large mixing angle regions.

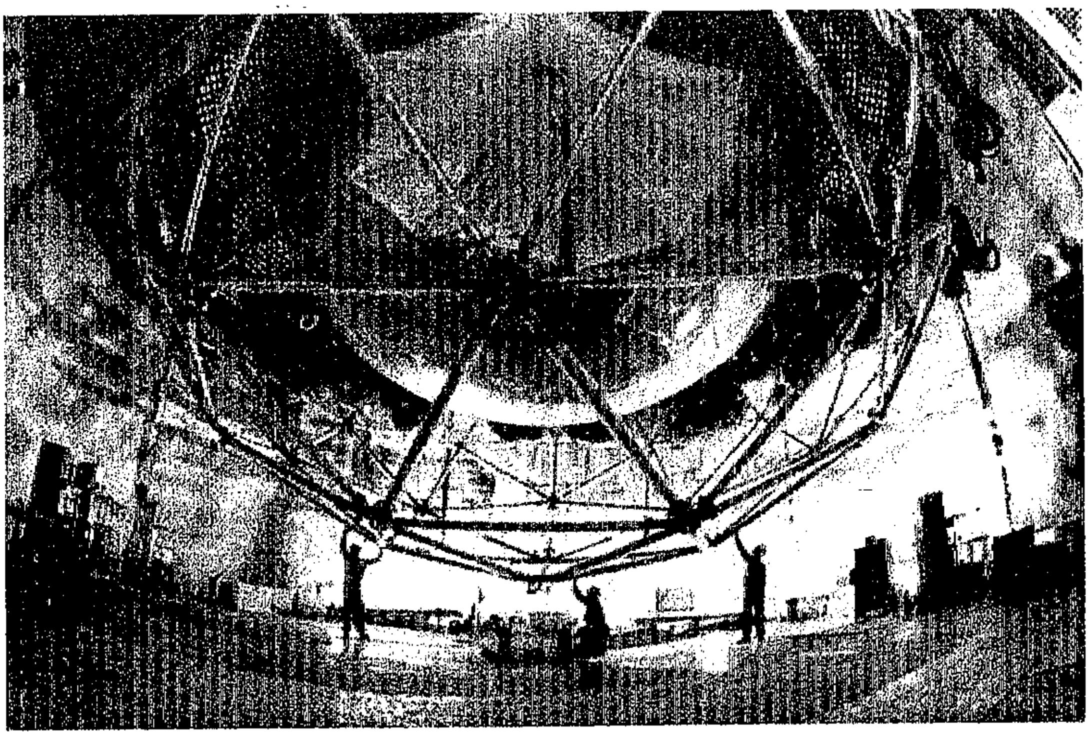
Sudbury Neutrino Observatory (SNO)

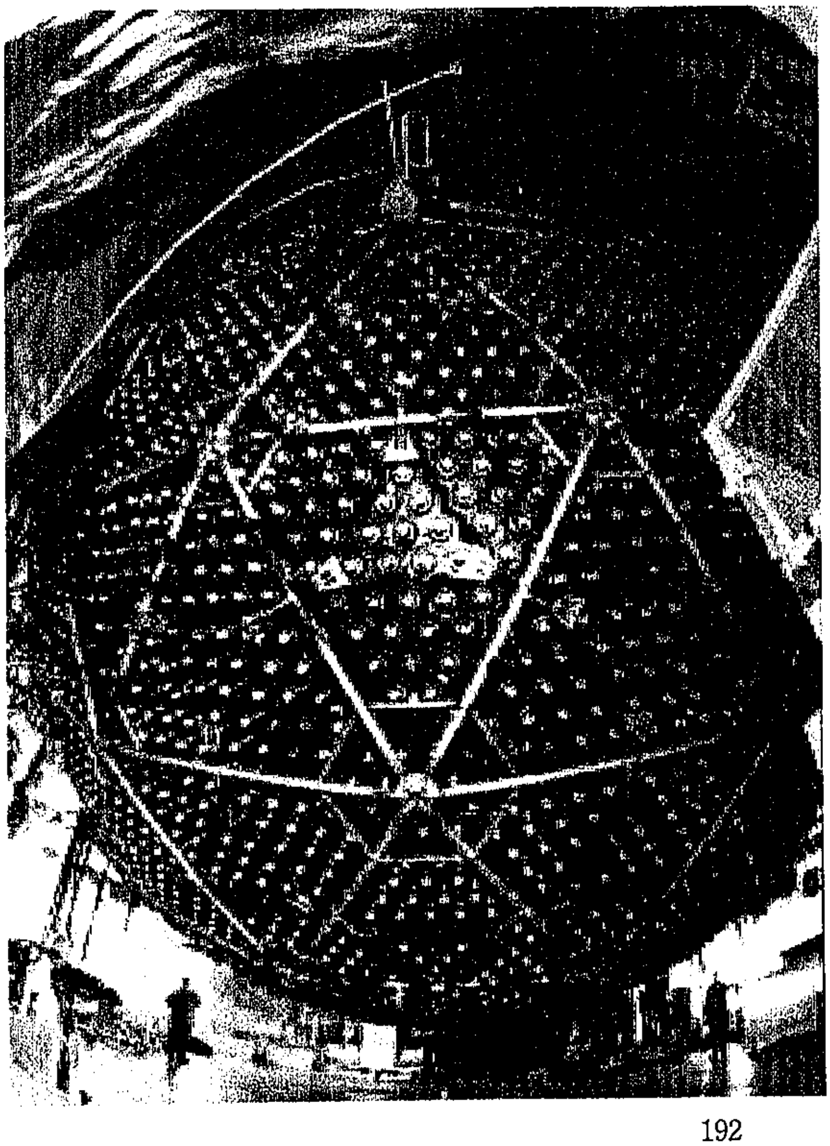
http://www.sno.phy.queensu.ca

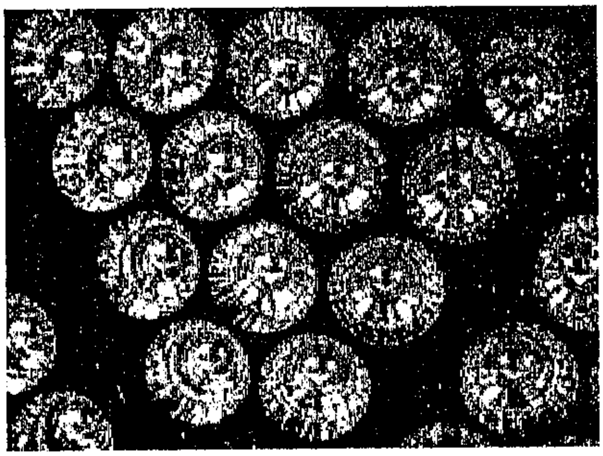


- photo coverage 55% (R<7m)
- cosmic ray muons ~70 events/day
- fiducial volume 0.7kt (R,5.5m)
- Trigger rate (data) 6~8Hz(~2MeV threshold)
- Trigger efficiency 100%@~3MeV
- for compton e^- from ^{16}N source (~5 MeV)
  vertex resolution 16cm
  energy resolution 16%
  angular resolution 27°

SNO detector during construction

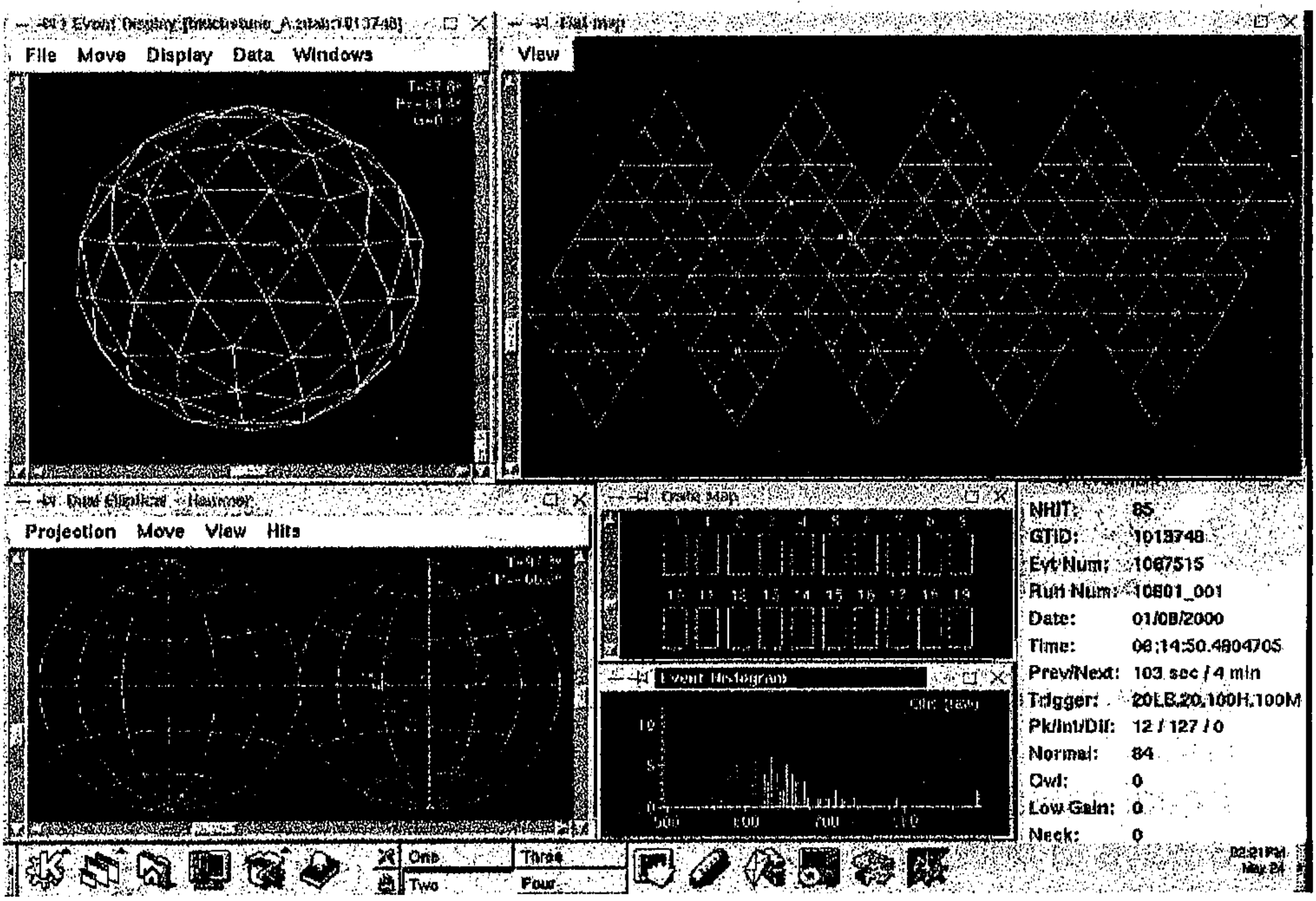






SNO: neutrino event

NHIT=85 (~9MeV)



http://www.sno.phy.queensu.ca/sno/talks/apssno3.ppt

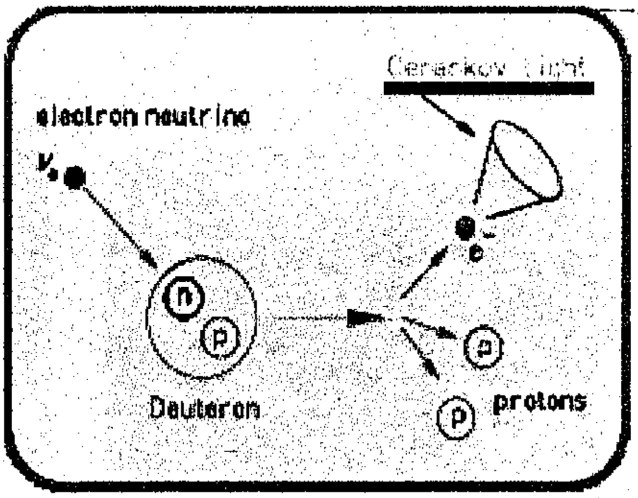
http://ewiserver.npl.washington.edu/sno/UW_Talk.ppt

SNO: neutrino reactions

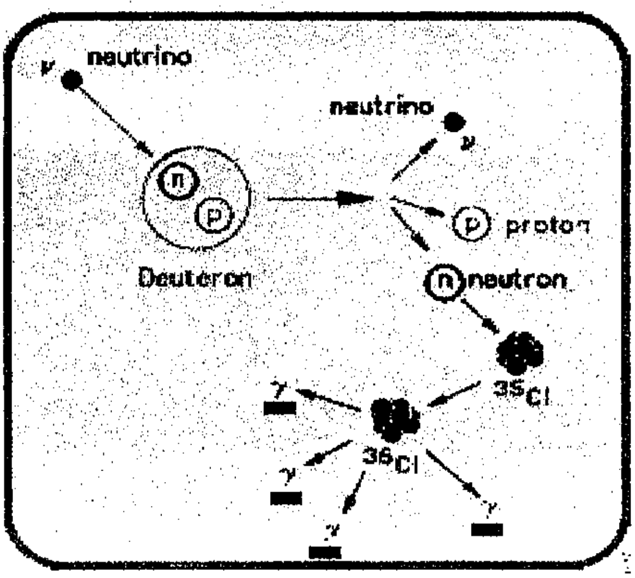
Target = heavy water (D_2O)

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

- Good measurement of ν_e energy spectrum
- Weak directional sensitivity $\propto$ 1-1/3cos(θ)
- ν_e only.

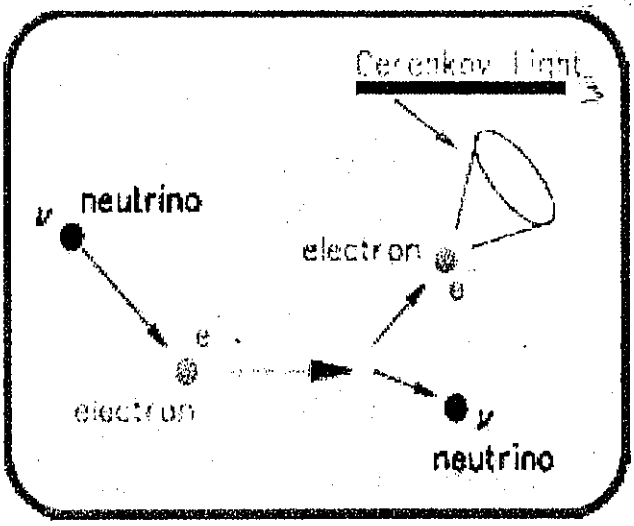


- Measure total ^8B ν flux from the sun.
- Equal cross section for all ν types
- 3 ways to detect neutron



$$\nu_x + e^- \Rightarrow \nu_x + e^-$$

- Low Statistics
- Mainly sensitive to ν_e, some sensitivity to ν_μ and ν_τ
- Strong directional sensitivity



SNO: what's new (April 20, 2002)

Livetime: 306.4 days
(November 2, 1999~May 27, 2001)
Day: 128.5 days Night: 177.9 days

Energy Threshold: 5 MeV Kinetic

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

Flavor change/oscillations

June 2001 $$\frac{\Phi_{cc}}{\Phi_{es}} = \frac{\nu_e}{\nu_e + 0.154(\nu_\mu + \nu_\tau)}$$

new

$$\frac{\Phi_{cc}}{\Phi_{nc}} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau}$$

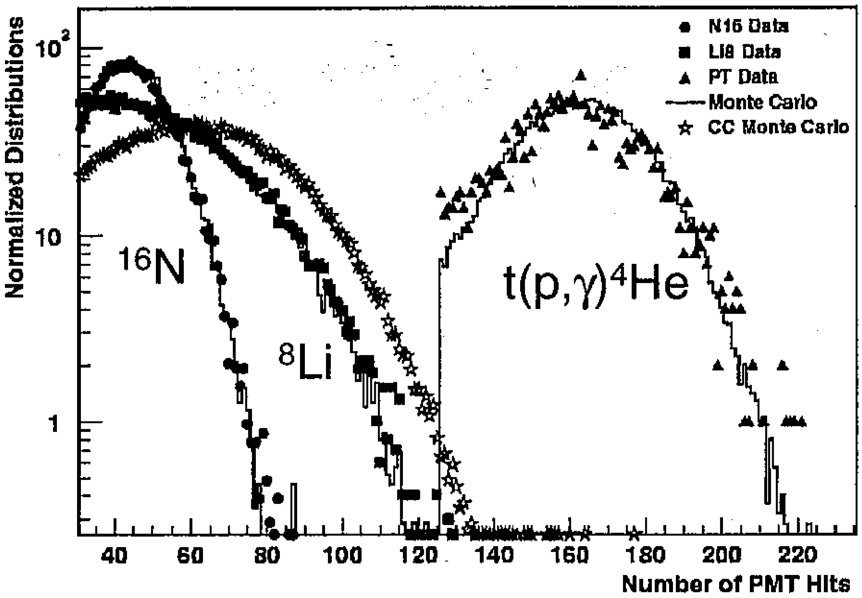
Φ_{day} **vs** Φ_{night}

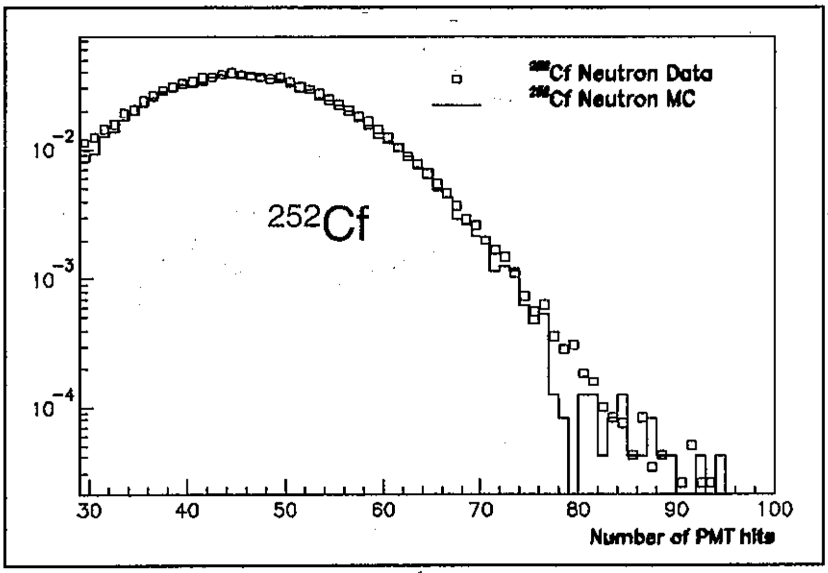
Total ^{8}B Solar Neutrino Flux

June 2001 $$\Phi_x = \Phi_{cc} + (\Phi_{es} - \Phi_{cc}) \times (1/\varepsilon)$$

new $$\Phi_x = \Phi_{nc}$$

SNO: energy calibration

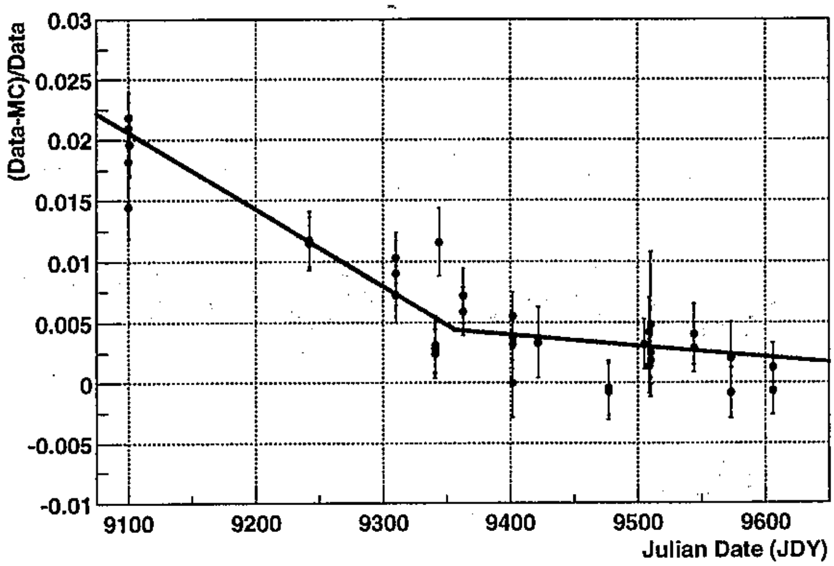




^{16}N	6.13MeV γ
^{8}Li	β (<~14MeV)
t(p,γ)^{4}He	19.8MeV γ
^{252}Cf	n (6.25MeV γ)

● ■ ▲ □ Data

—— MC



- center ^{16}N runs
- ΔE = 1.21 %
  $\Delta\sigma$ = 4.5 %

SNO: neutron BG 1

Source	Events
D_2O photodisintegration	44^{+8}_{-9}
H_2O + AV photodisintegration	27^{+8}_{-8}
Atmospheric ν's and sub-Cherenkov threshold μ's	4 ± 1
Fission	$\ll 1$
$^2H(\alpha,\alpha)pn$	2 ± 0.4
$^{17}O(\alpha,n)$	$\ll 1$
Terrestrial and reactor $\bar{\nu}$'s	1^{+3}_{-1}
External neutrons	$\ll 1$
Total neutron background	78 ± 12

- BG level is ~12% of SSM NC rate

- Dominant BG source is photodisintegration by radioactivity in D_2O, H_2O, and AV

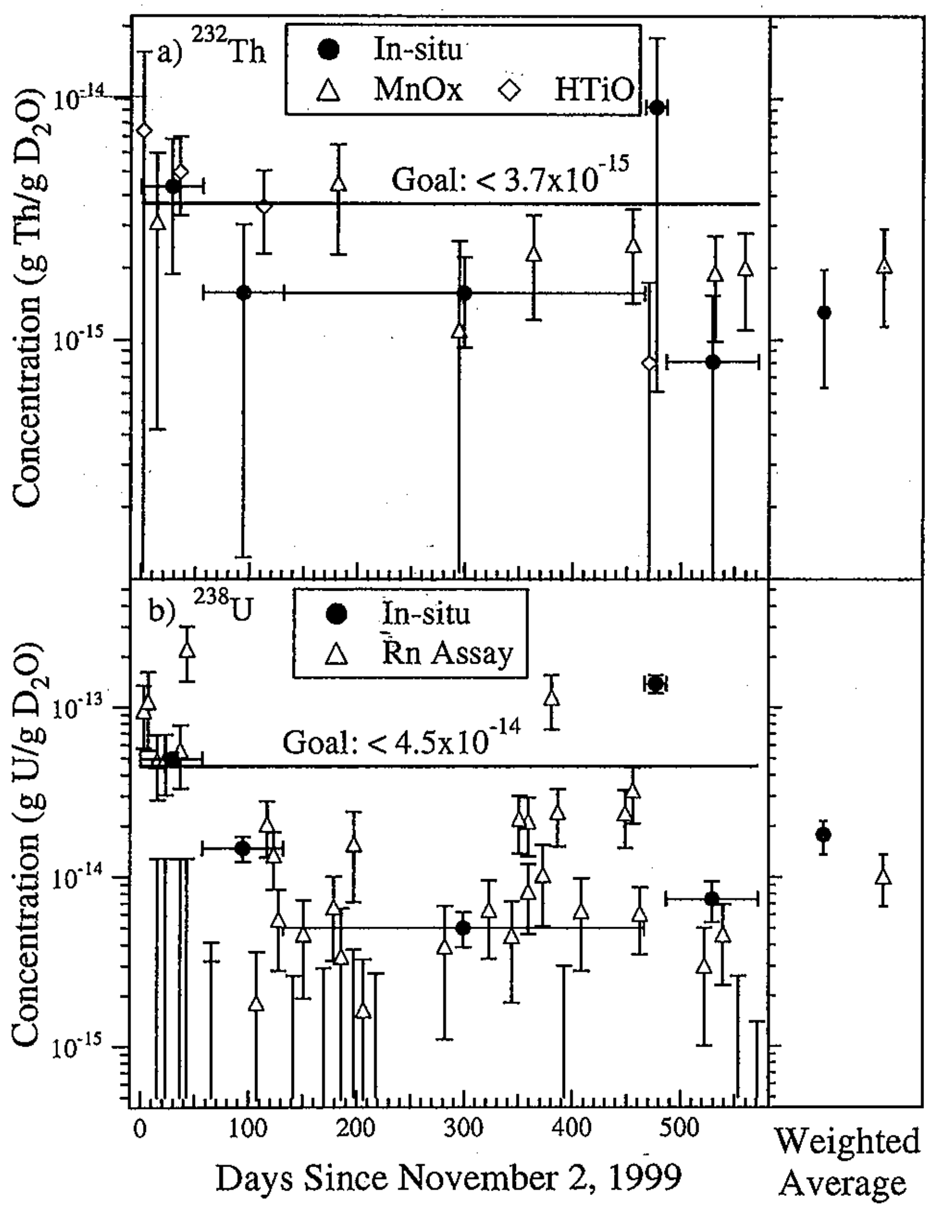
$$\gamma + d \longrightarrow p + n$$

- To estimate U/Th contents is essential

SNO: neutron BG 2 (Estimate U/Th Content)

Ex-situ:
- Extract daughter products in ~400ton of water
  - Ion exchange (^{224}Ra, ^{226}Ra)
  - Membrane Degassing (^{222}Rn)
- Count daughter product decays

In-situ:
- Use low-energy data (4.0-4.5MeV)
- Statistical separation of ^{208}Tl ($\beta+\gamma$) & ^{214}Bi (β)

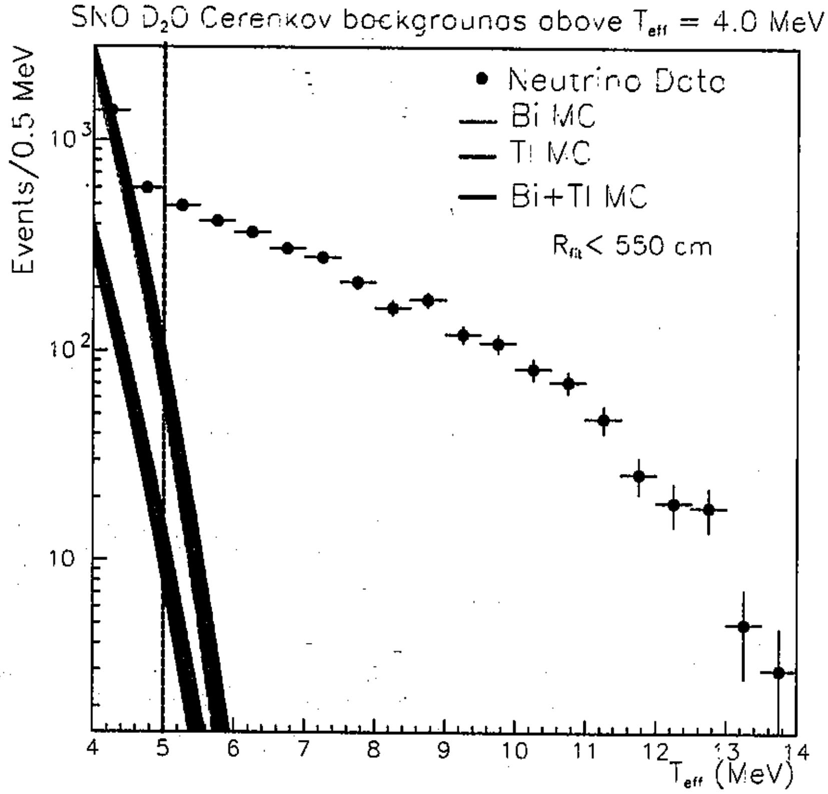


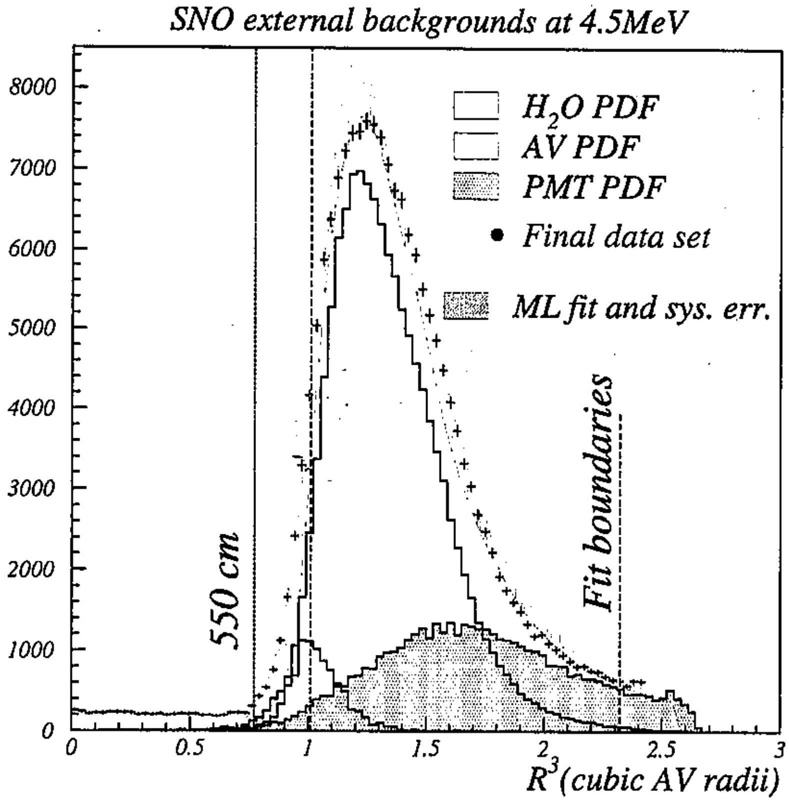
Both methods agrees well

Neutron Events

D_2O	H_2O/AV
44^{+8}_{-9}	27^{+8}_{-8}

SNO: Cherenkov BG

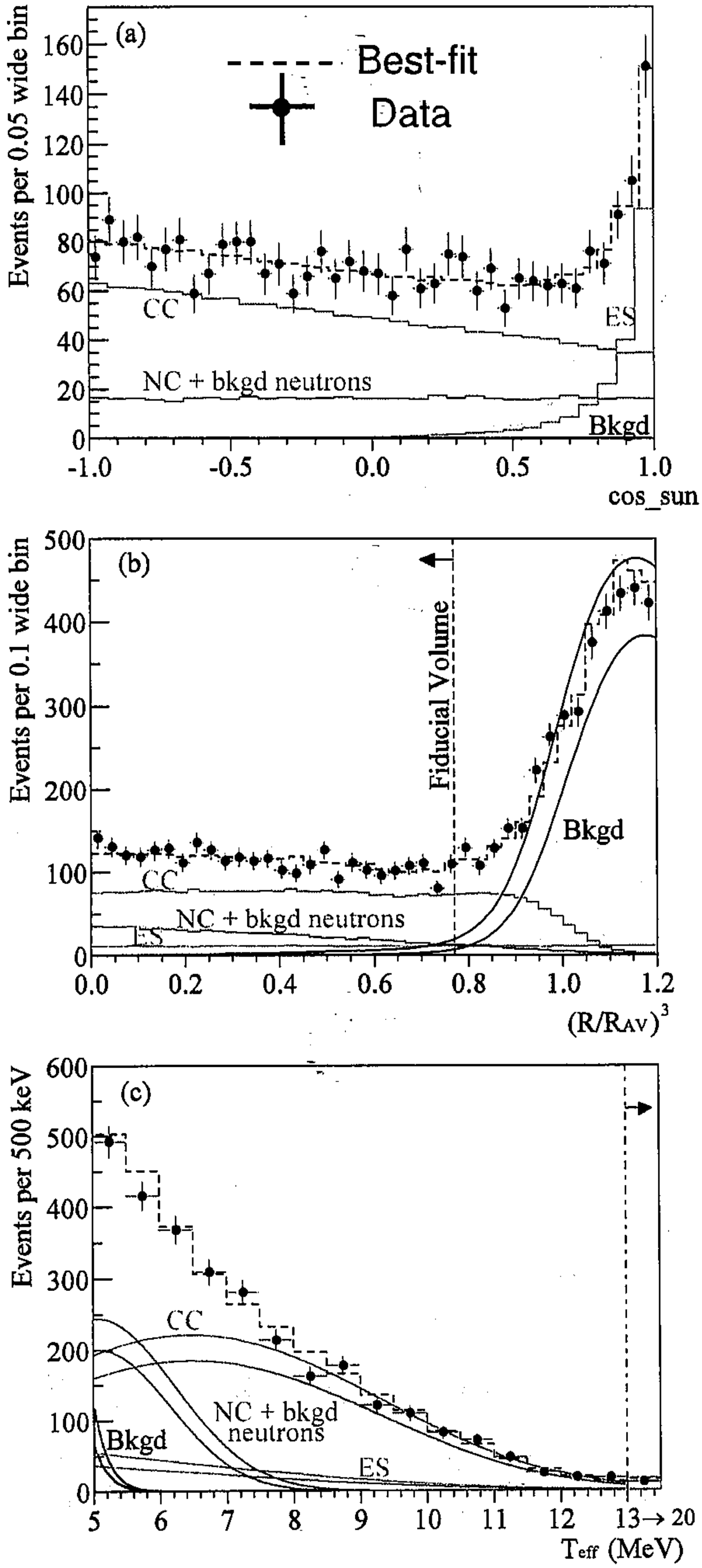




	D_2O	H_2O	Acrylic	PMTs
Cherenkov Events	20^{+13}_{-6}	3^{+4}_{-3}	6^{+3}_{-6}	16^{+11}_{-8}

SNO: Flux 1

hep-ex/0204008



Total: 2928 events
(Te: 5.0-20MeV)

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

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

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

SNO: Flux 2

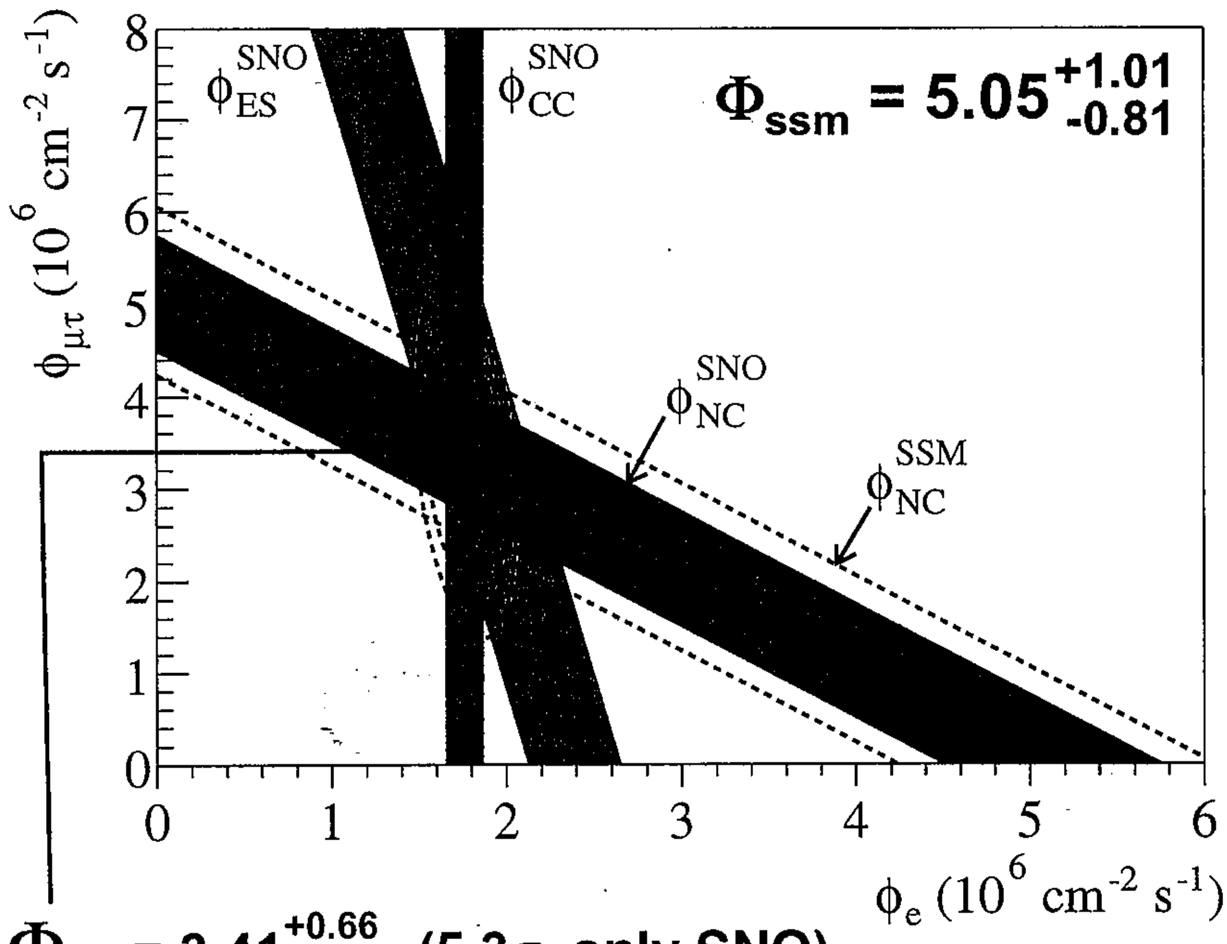
Te > 5 MeV

$$\Phi_{cc}(\nu_e) = 1.76\ ^{+0.06}_{-0.05}(\text{stat.})\ ^{+0.09}_{-0.09}(\text{syst.})\ \text{x}10^6\ \text{cm}^{-2}\text{s}^{-1}$$

$$\Phi_{es}(\nu_x) = 2.39\ ^{+0.24}_{-0.23}(\text{stat.})\ ^{+0.12}_{-0.12}(\text{syst.})\ \text{x}10^6\ \text{cm}^{-2}\text{s}^{-1}$$

$$\Phi_{nc}(\nu_x) = 5.09\ ^{+0.44}_{-0.43}(\text{stat.})\ ^{+0.46}_{-0.43}(\text{syst.})\ \text{x}10^6\ \text{cm}^{-2}\text{s}^{-1}$$

c.f. SK ES FLUX $= 2.32 \pm 0.03(\text{stat.}) \pm ^{0.08}_{0.07}(\text{sys.})$



$\Phi_{\mu\tau} = 3.41^{+0.66}_{-0.64}$ **(5.3σ, only SNO)**

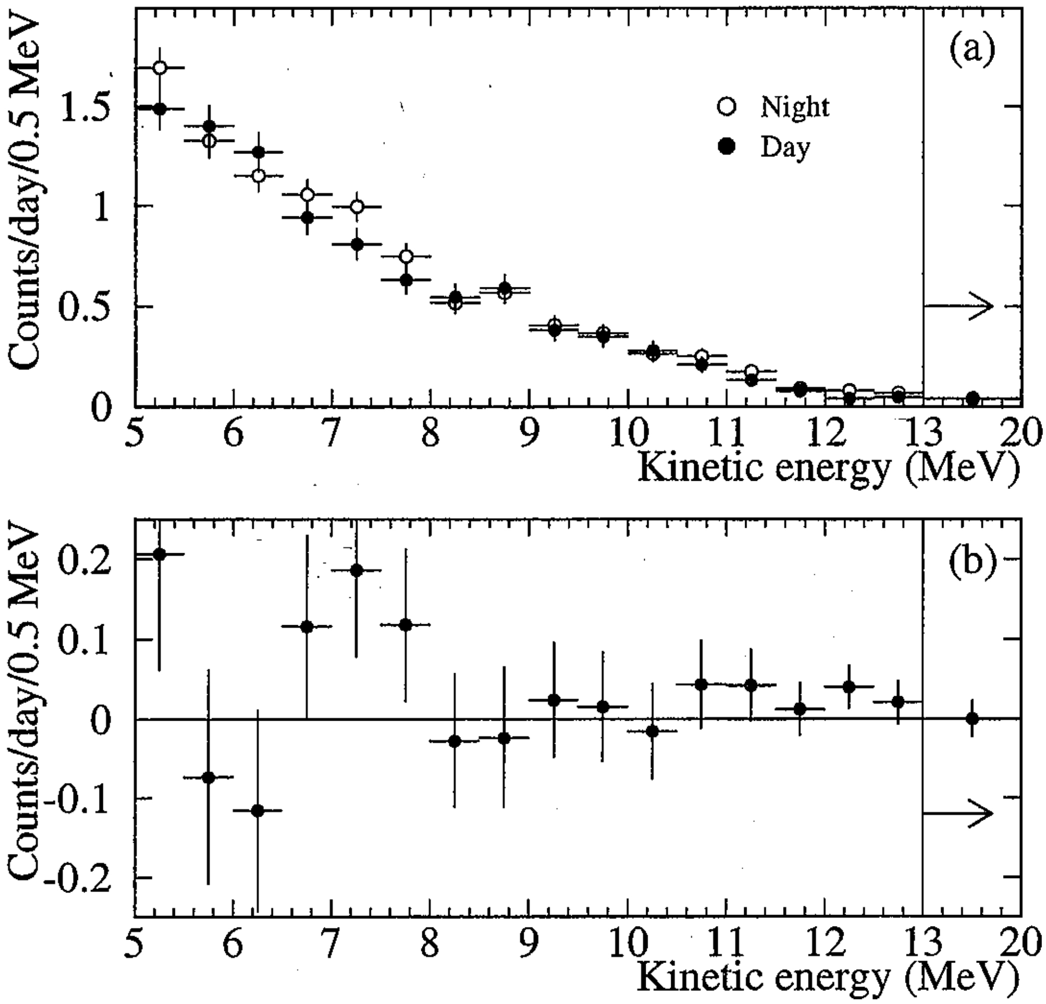
$\Phi_{\mu\tau} = 3.45^{+0.65}_{-0.62}$ **(5.5σ, SNO+SK)**

Previous: SK ES ⟺ SNO CC **3.3σ**

Strong evidence of flavor change

SNO: Day/Night 1

hep-ex/0204009



	Day	Night
Φ_{cc}	$1.62 \pm 0.08 \pm 0.08$	$1.87 \pm 0.07 \pm 0.10$
Φ_{es}	$2.64 \pm 0.37 \pm 0.12$	$2.22 \pm 0.30 \pm 0.12$
Φ_{nc}	$5.69 \pm 0.66 \pm 0.44$	$4.63 \pm 0.57 \pm 0.44$

$\times 10^6\ cm^{-2}s^{-1}$

SNO: Day/Night 2

$$A = 2(\Phi_{night} - \Phi_{day}) / (\Phi_{night} + \Phi_{day})$$

$$A_{CC} = 14.0 \pm 6.3^{+1.5}_{-1.4}$$

$$A_{NC} = -20.4 \pm 16.9^{+2.4}_{-2.5}$$

$$\Phi_{ES} = (1-\varepsilon)\ \Phi_e + \varepsilon\ \Phi_{tot}$$

$$A_e = 12.8 \pm 6.2^{+1.5}_{-1.4}$$

$$A_{tot} = -24.2 \pm 16.1^{+2.4}_{-2.5}$$

$$\Phi_{ES} = (1-\varepsilon)\ \Phi_e + \varepsilon\ \Phi_{tot} \quad A_{tot} = 0$$

$$A_e = 7.0 \pm 4.9^{+1.3}_{-1.2}$$

$\Phi_{ES} = (1-\varepsilon)\ \Phi_e + \varepsilon\ \Phi_{tot} \quad A_{tot} = 0$ SK A_{ES}+SNO Φ_{tot}

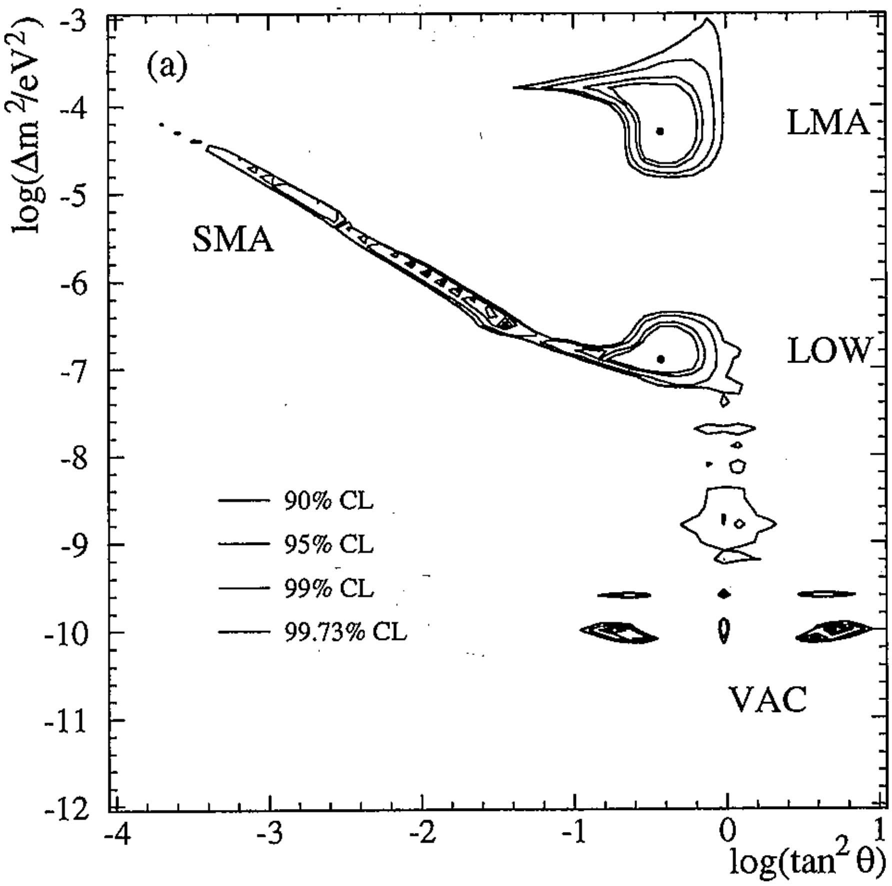
SK $A_e = 5.3 \pm 3.7^{+2.0}_{-1.7}$ (SK1258days)

(SK $A_e \sim 3.2 \pm 3.2$) (SK1496days)

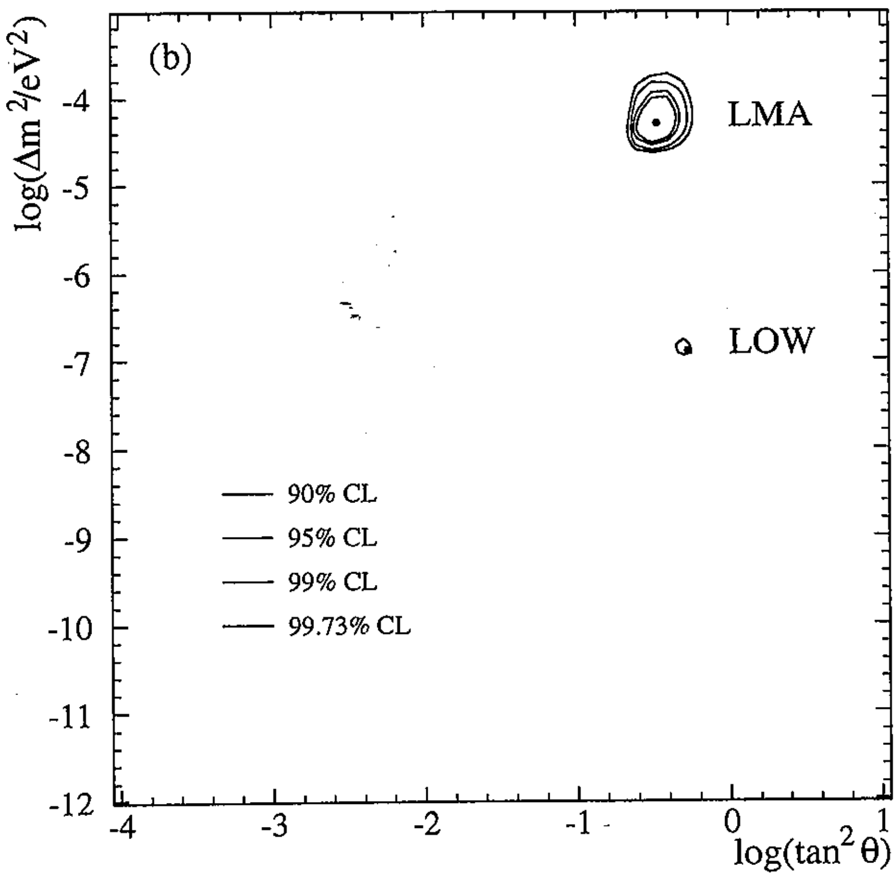
consistent

Oscillation analysis (SNO D/N spectra)

SNO group **hep-ex/0204009**



SNO Day and Night Energy Spectra Alone



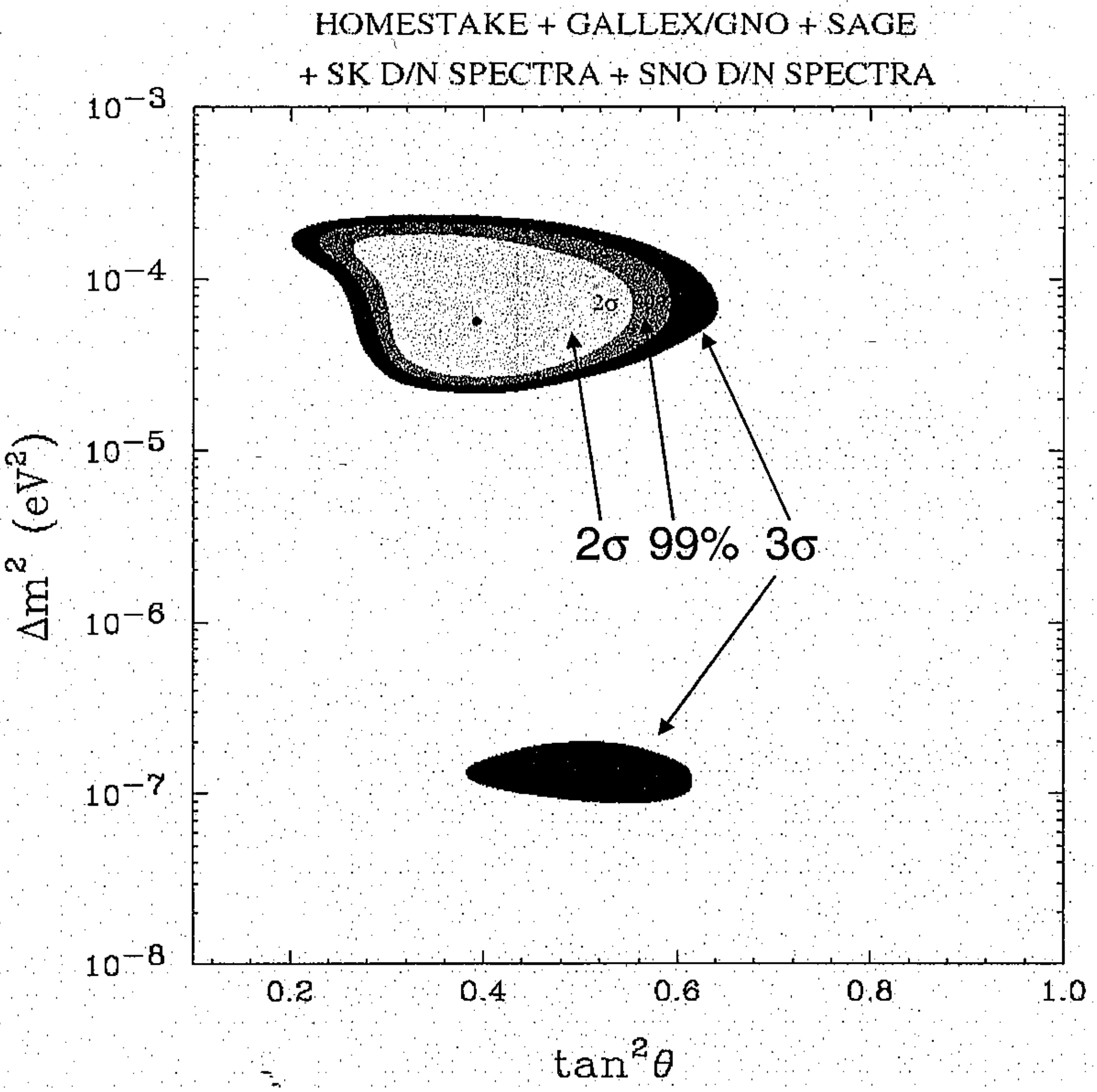
Combining All Experimental and Solar Model information

Best fit:
$(\tan^2\theta, \Delta m^2)=$
$(0.34, 5.0\times10^{-5})$
$\chi^2_{min}=57.0/72$

LOW region:
$(\tan^2\theta, \Delta m^2)=$
$(0.55, 1.3\times10^{-7})$
$\chi^2_{min}=67.7/72$

Oscillation analysis

V.Barger et al. **hep-ex/0204253**

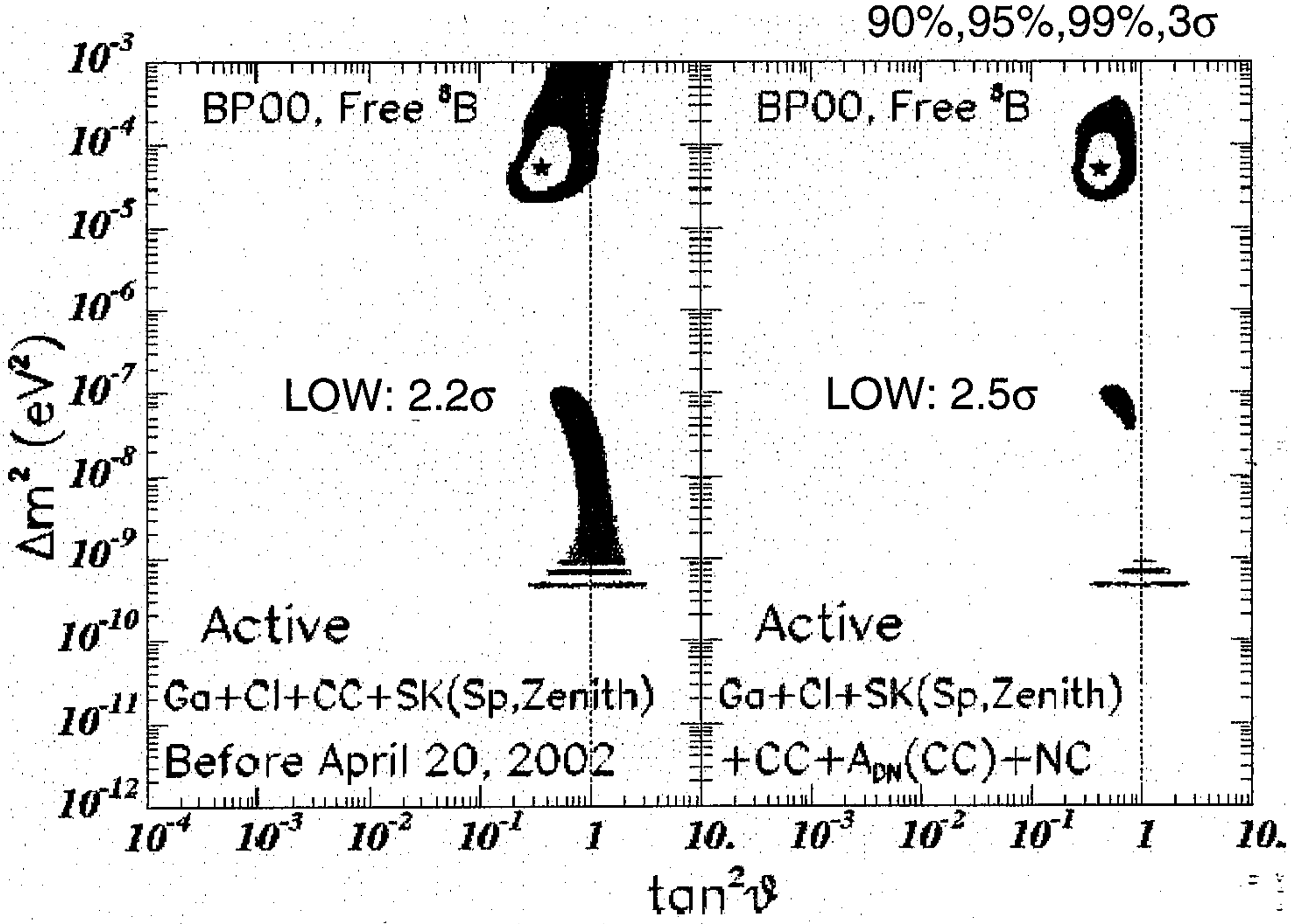


Best fit:
($\tan^2\theta$, Δm^2) = (0.39, 5.6×10^{-5}) χ^2_{min}=50.7/72

LOW region:
($\tan^2\theta$, Δm^2) = (0.46, 1.1×10^{-7}) χ^2_{min}=59.9/72

Oscillation analysis

J.N.Bahcall et al. **hep-ex/0204314**



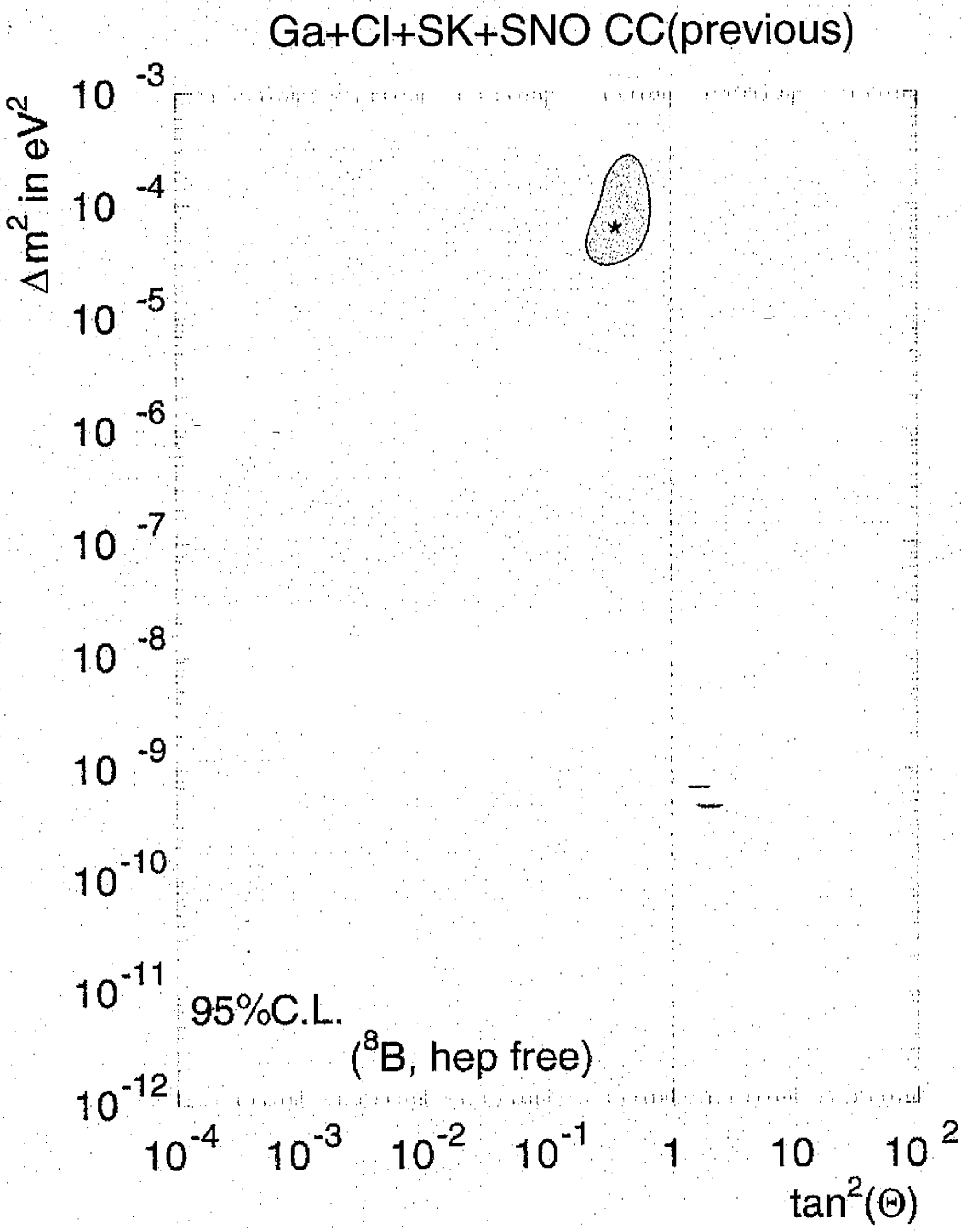
Best fit:
($\tan^2\theta$, Δm^2) = (0.42, 5.0×10^{-5}) χ^2_{min}=45.5/46 98.8%C.L.

LOW region:
($\tan^2\theta$, Δm^2) = (0.61, 7.9×10^{-8}) χ^2_{min}=54.3/46 2.5σ

SMA: 3.7σ
Pure sterile: 5.4σ

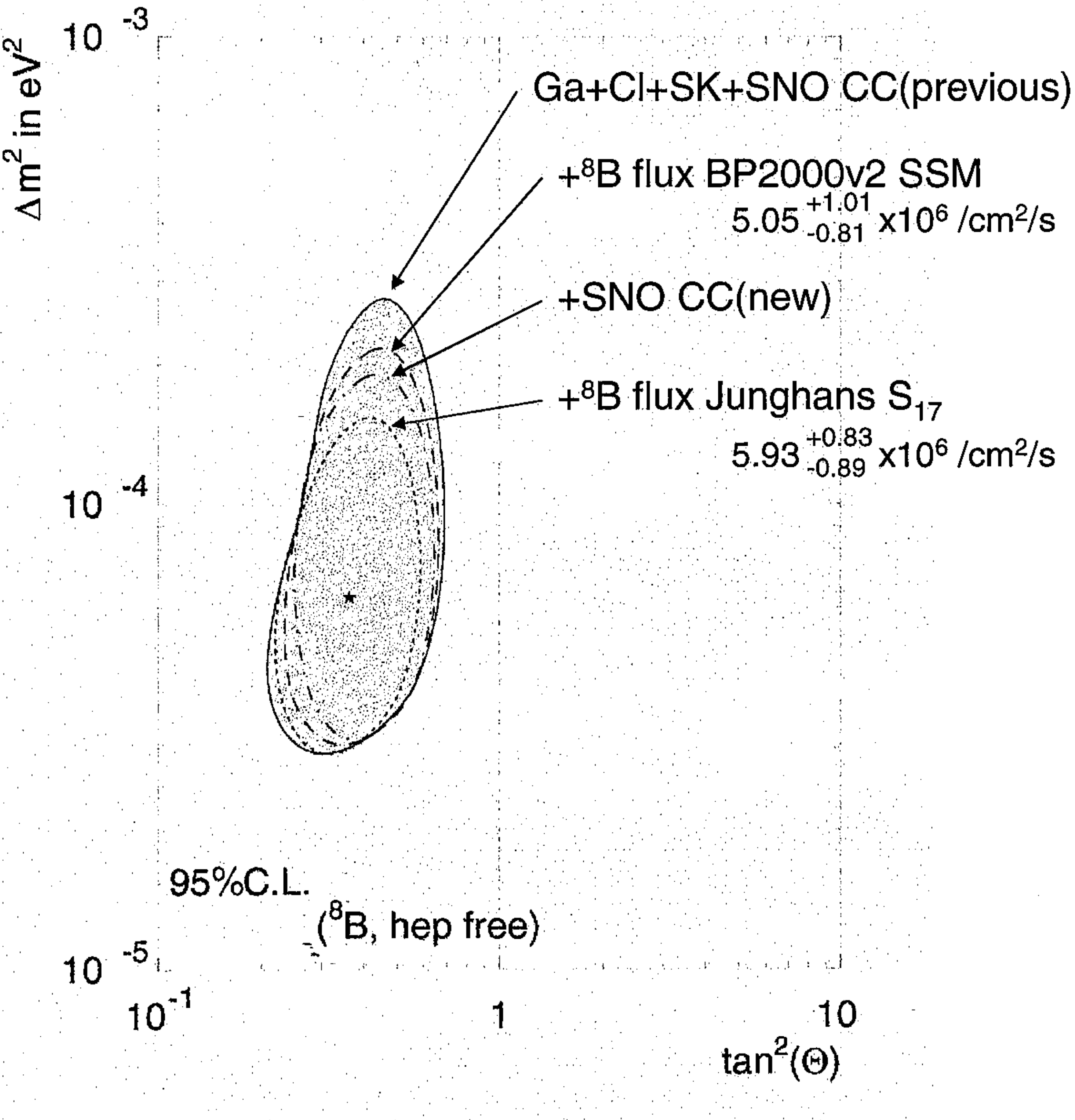
Oscillation analysis

SK group (preliminary)



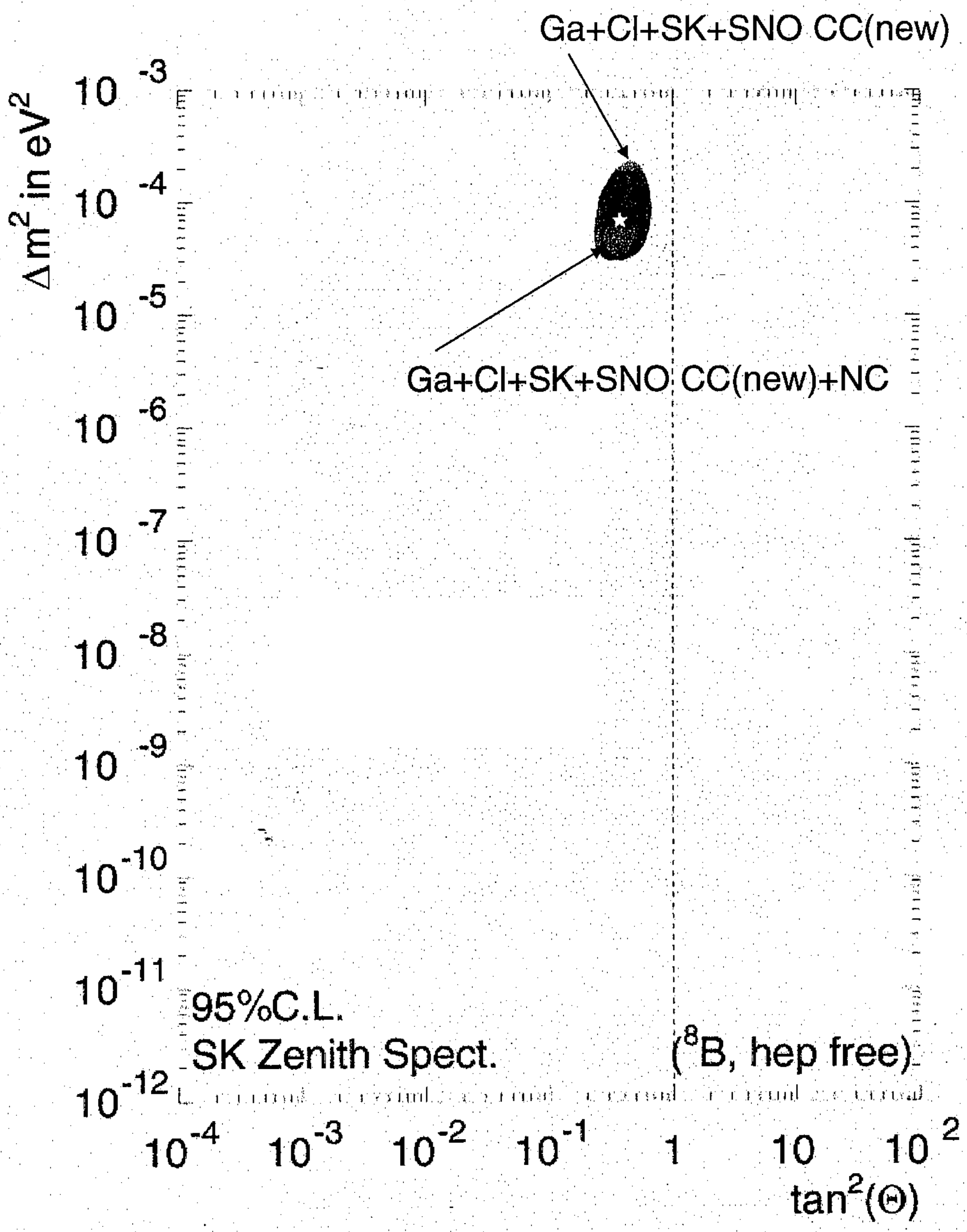
Oscillation analysis

SK group (preliminary)

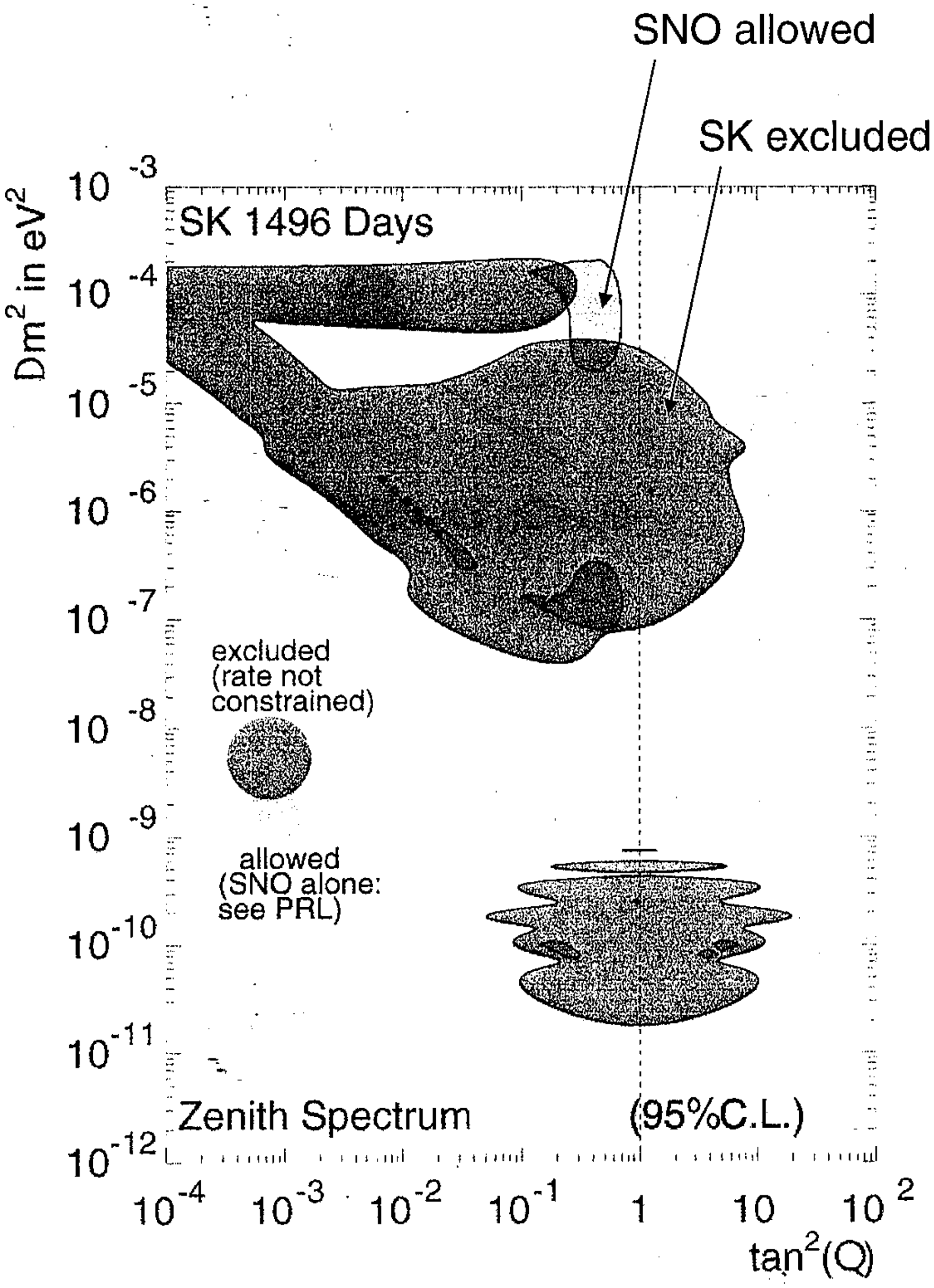


Oscillation analysis

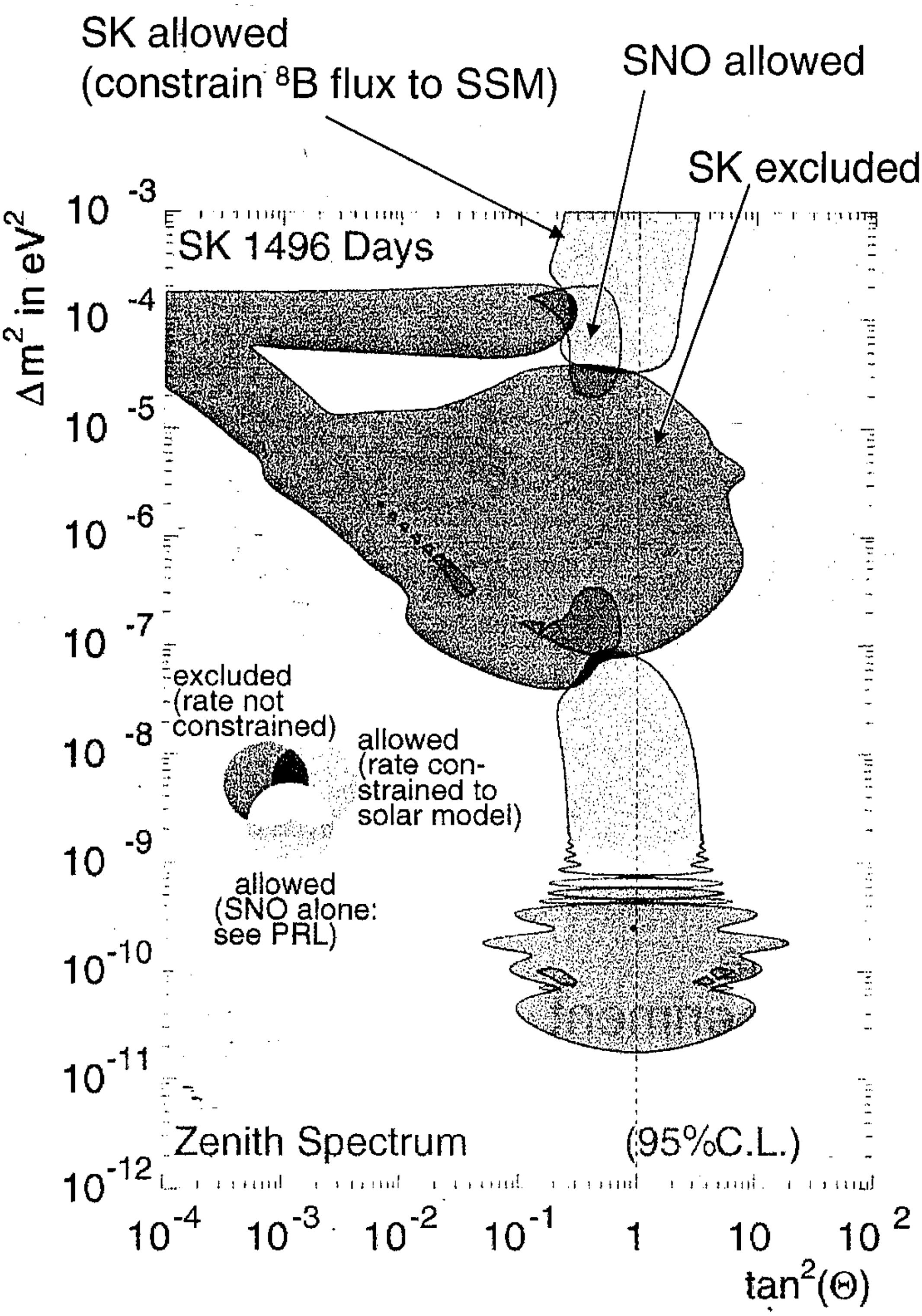
SK group (preliminary)



Oscillation analysis



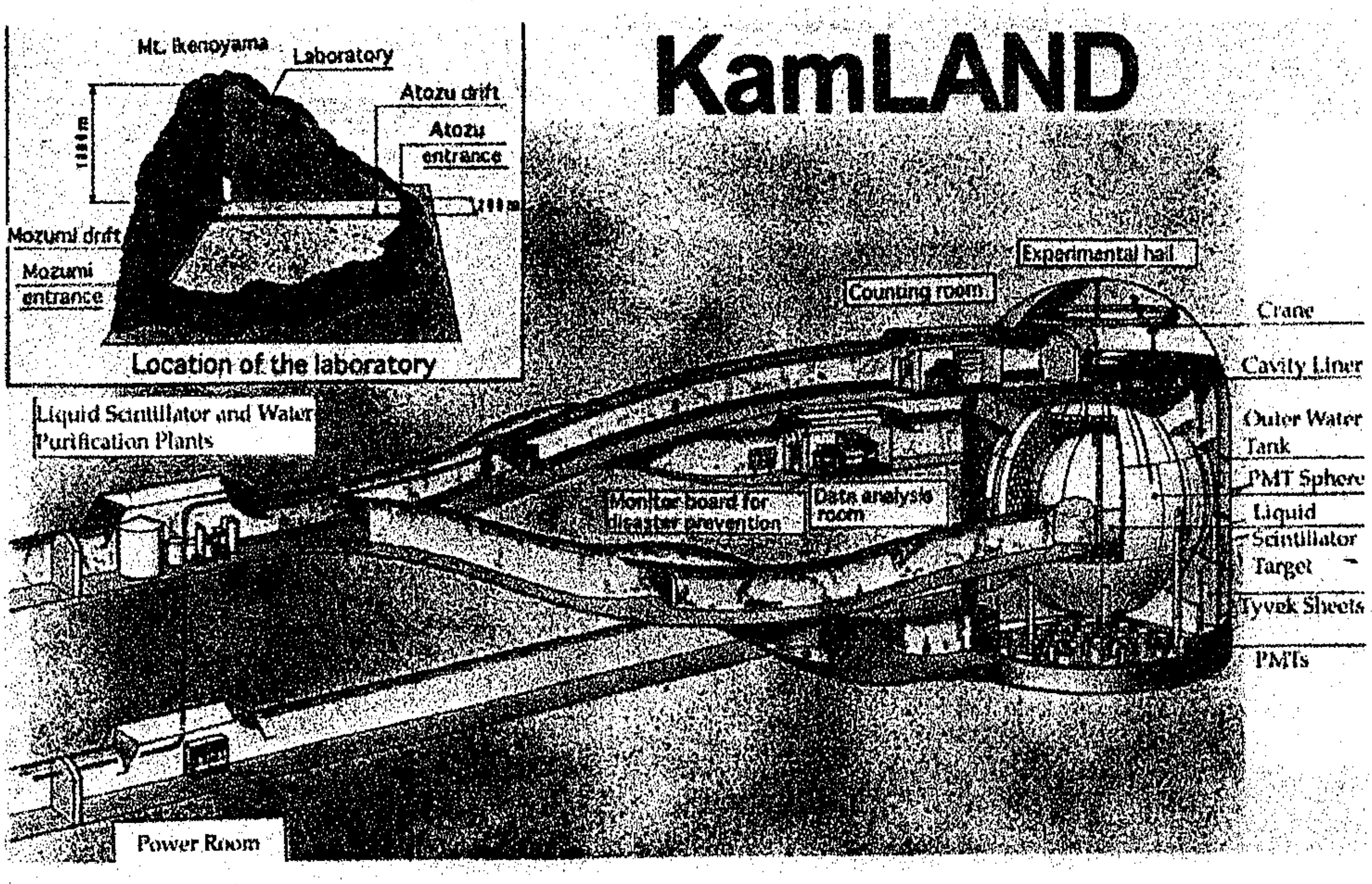
Oscillation analysis



KamLAND

http://www.awa.tohoku.ac.jp/KamLAND

Kamioka Liquid scintillator Anti-Neutrino Detector



long baseline
reactor experiment

converted from
KAMIOKANDE

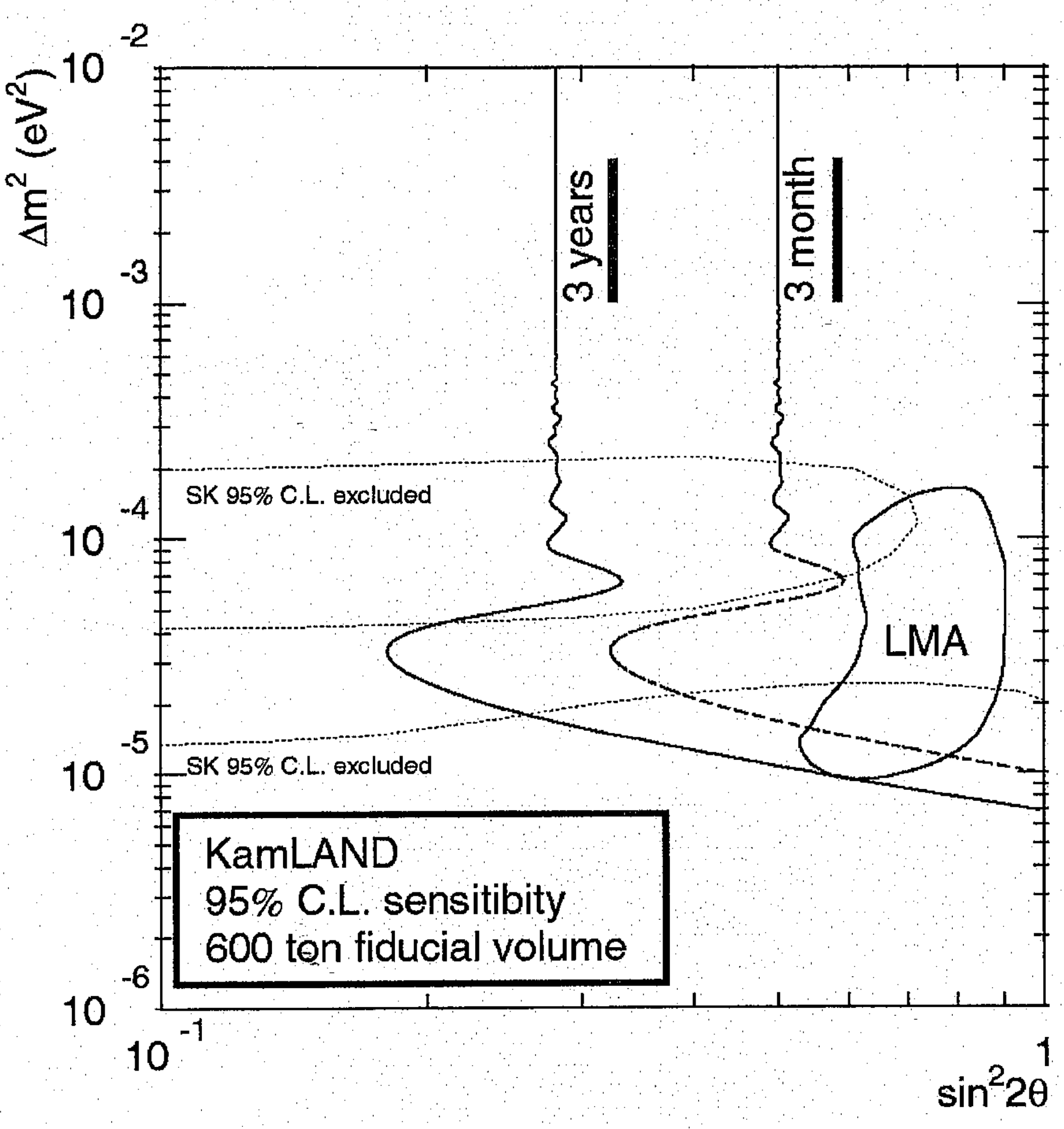
hosted by
Tohoku University

Filling: Apr. 2001~
Observation: Oct. 2001~

1,000 m^3 liq. scint.
1,300 17-inch PMTs
+600 20-inch PMTs
22+14% coverage
anti: 3,000m^3 water
reactor L~170km
700 events/kt/year

$\overline{\nu}_e + p \rightarrow e^+ + n$
(E_{th} = 1.8MeV)

KamLAND: sensitivity

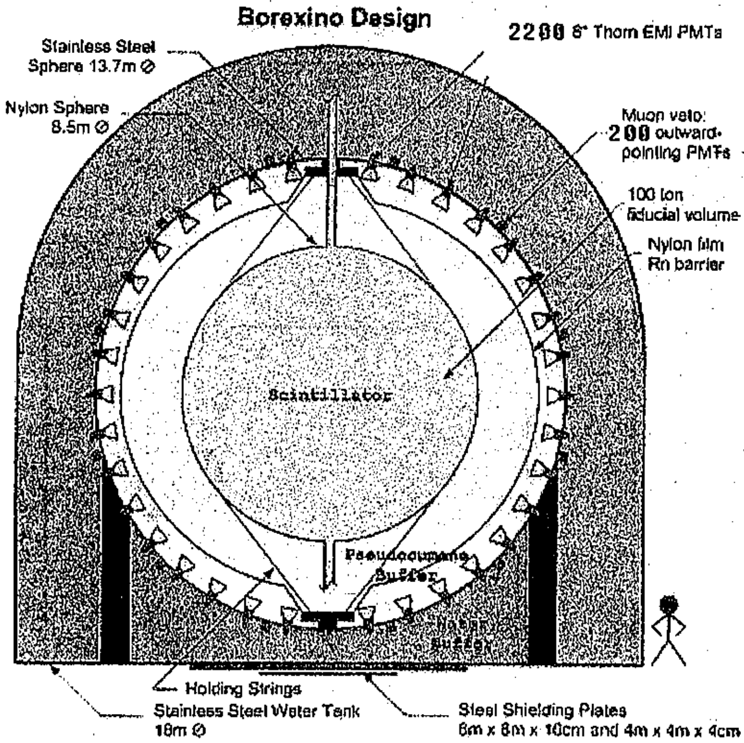


From K.Inoue (Tohoku Univ.)

Borexino

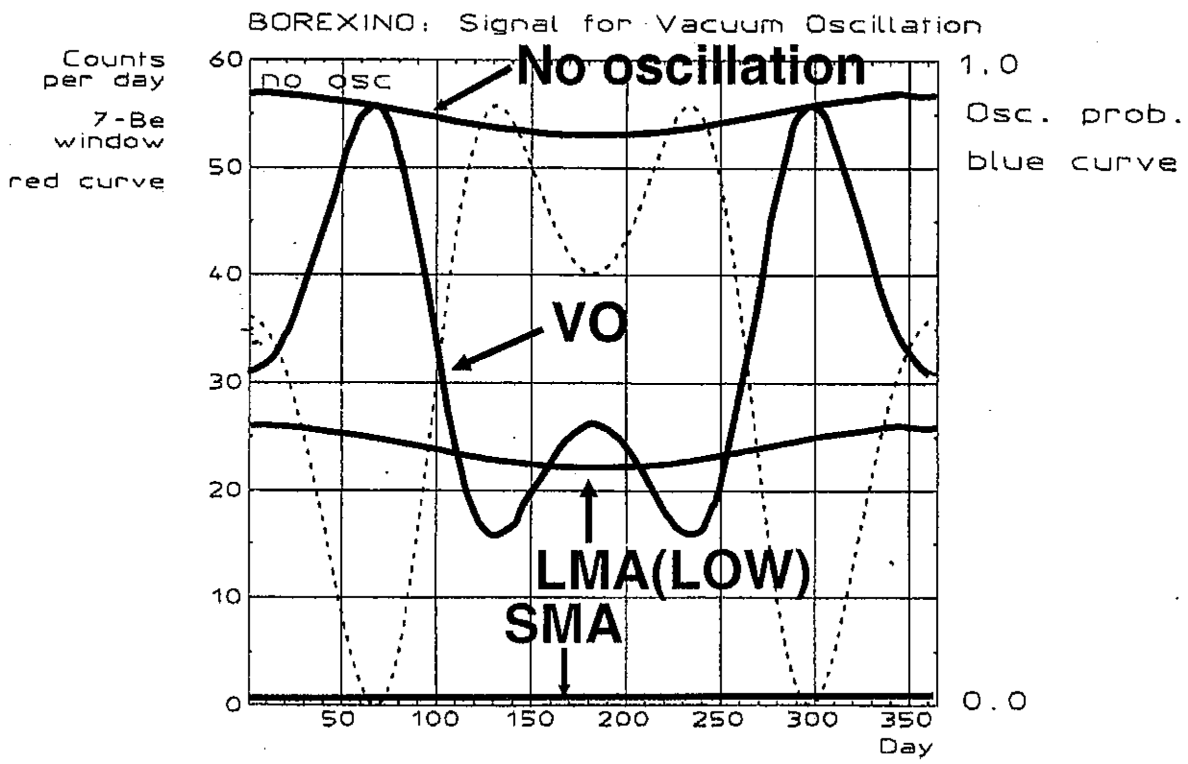
http://almine.mi.infn.it/

detection of $^{7}Be\ \nu$
(edge 660 keV)



300 tons liq. scint.
(fid. vol. 100 tons)
2,200 8-inch PMTs
Ee > 250keV?
55ev/day for SSM
$\nu_x + e^- \rightarrow \nu_x + e^-$

SMA ➡ ~ full suppression
LMA ➡ ~ half suppression
V.O. ➡ seasonal variation

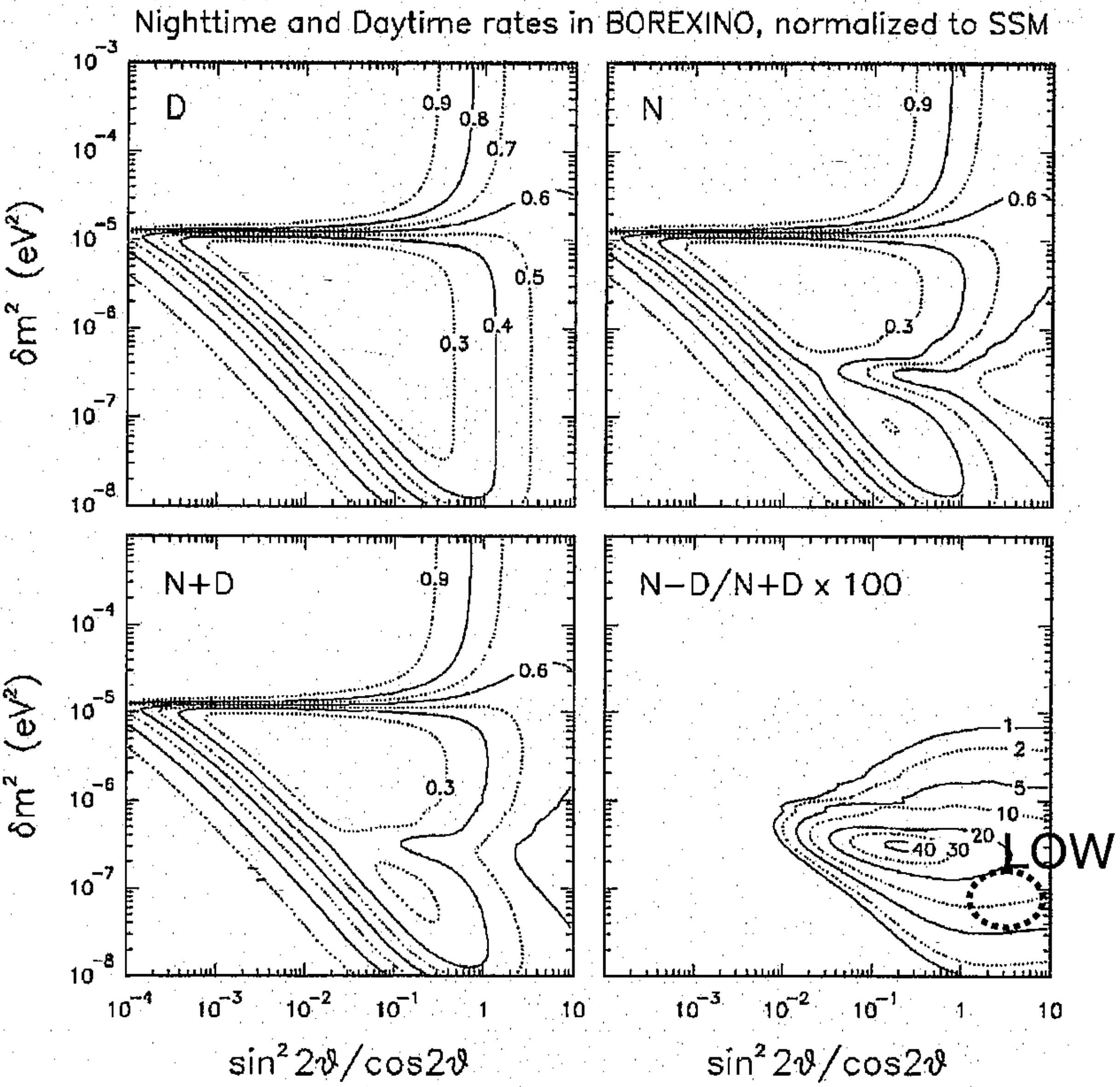


Starting Mar 2002

Borexino: Day/Night sensitivity

G.L.Fogli et al PRD61(2000)073009

LOW region ⟷ 10~20% effect



Summary

- **New information from SNO**

FLUX

306.4days, 5.0-20.0MeV

SNO $\phi_{CC} = 1.76 ^{+0.06}_{-0.05} {}^{+0.09}_{-0.09}$ [x10^6/cm^2/s]

SNO $\phi_{ES} = 2.39 ^{+0.24}_{-0.23} {}^{+0.12}_{-0.12}$ [x10^6/cm^2/s]

SNO $\phi_{NC} = 5.09 ^{+0.44}_{-0.43} {}^{+0.46}_{-0.43}$ [x10^6/cm^2/s]

SK $\phi_{ES} = 2.32 \pm 0.09$ [x10^6/cm^2/s]

BP2001 $\phi_{SSM} = 5.05 ^{+1.01}_{-0.81}$ [x10^6/cm^2/s]

Day/Night

SNO $A_e = 7.0 \pm 4.9 ^{+1.3}_{-1.2}$ $\Phi_{ES} = (1-\varepsilon)\,\Phi_e + \varepsilon\,\Phi_{tot}$ $A_{tot} = 0$

SK $A_e = 5.3 \pm 3.7 ^{+2.0}_{-1.7}$ SK A_{ES}+SNO Φ_{tot}

$A_e \sim 3.2 \pm 3.2$ SK 1496days

- **Oscillation analysis**

MSW LMA solution is favored

MSW LOW solution: 2.5~3σ