Review of Solar- and Geo-neutrinos

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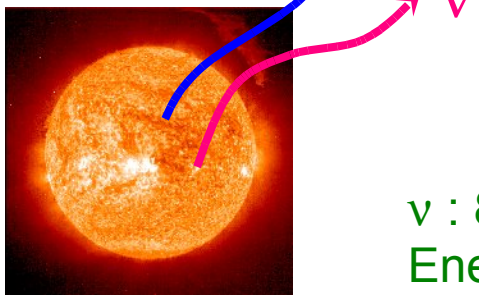
(Research Center for Neutrino Science, Tohoku U.)

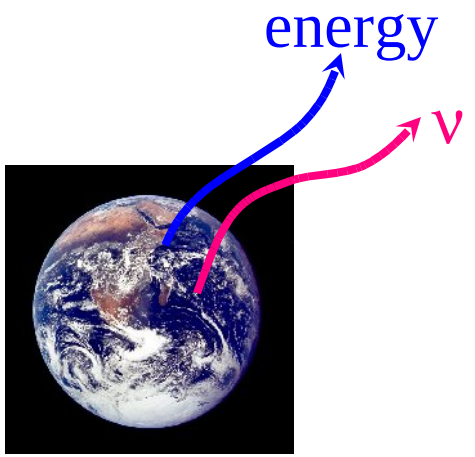
The 4th COE symposium
June 28-30, 2006, Sendai International Center

“Neutrino astronomy”
“Neutrino geophysics”



“No ν
IF the power is from chemical reactions”

ν : 8 min.
Energy: 40,000 years



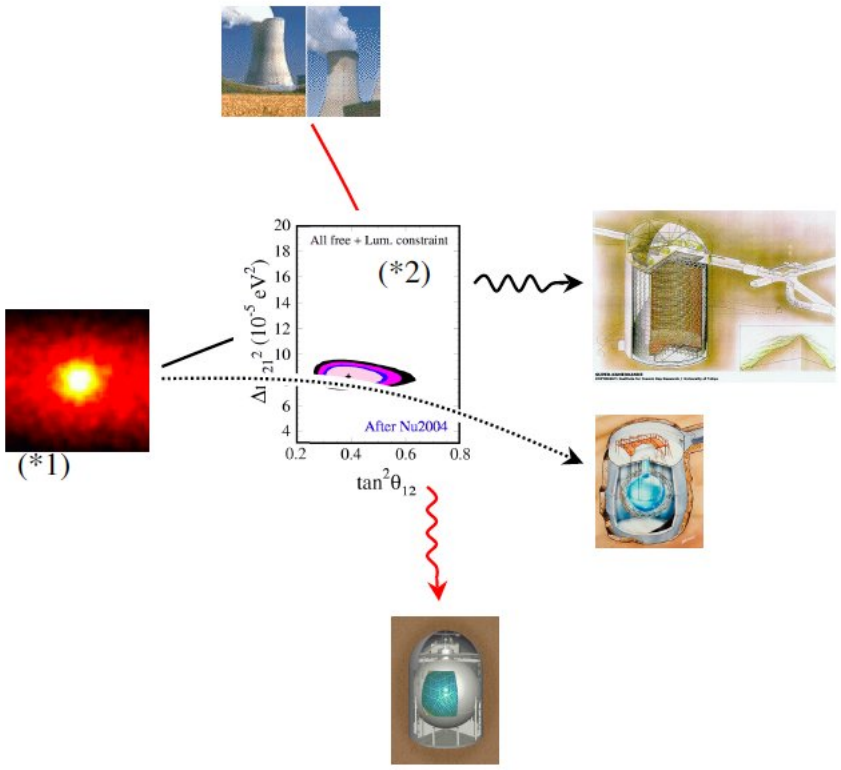
No ν
for the other half of the power (solidification of inner core etc)

- Only 3 objects so far Sun, SN1987, Earth

… but unique information

- Sun: evidence (only direct, and definite) for nuclear fusion … power source of the sun
- Direct and real-time information from the core of the sun
- Earth: (evidence) for radiogenic heat … power source of the Earth

2 unknowns : object and "filter"



(*1) neutrinograph of the sun by Super-K, (*2) hep-ph/0406294

- "Neutrino oscillation":

$\forall$ ν_e (solar ν is pure ν_e)

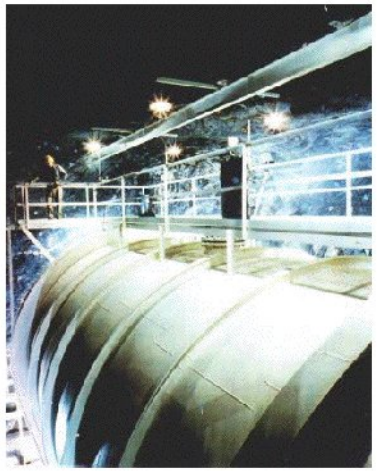
$\rightarrow$ ν_μ, ν_τ

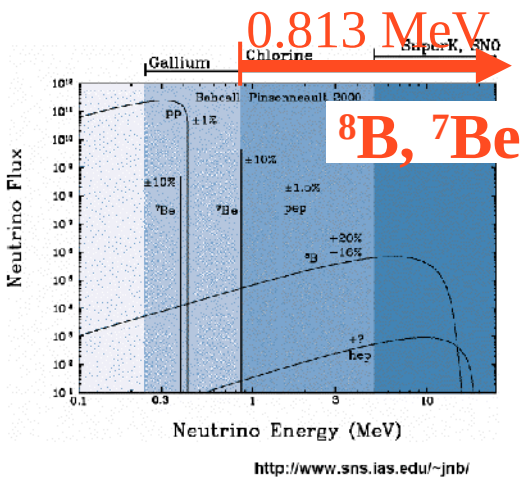
- If the detector is sensitive only to ν_e

$\rightarrow$ deficit, energy spectral distortion (the "filter" is not a ND filter)

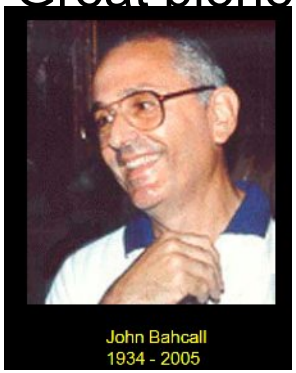
- 2 unknowns: both are important objectives …
- Unique experiments to solve the problem

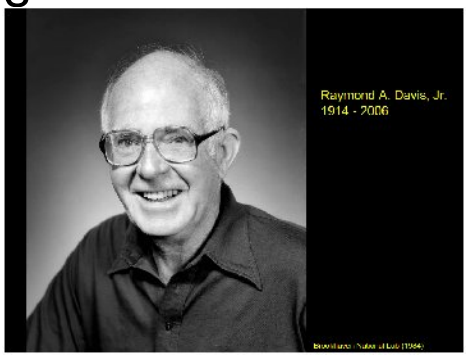
Homestake (1964 ~ 1994)





- First solar neutrino observation
- Established solar neutrino deficit
- 615-ton C_2Cl_4, $\nu_e(^{37}Cl, ^{37}Ar)e^-$
- Final result: 2.56 ± 0.16 ± 0.16 SNU
- SSM (BS05(OP)) expectation:
  8.1 ± 1.2 SNU
- Data/SSM = 0.32 ± 0.02
- Great pioneers





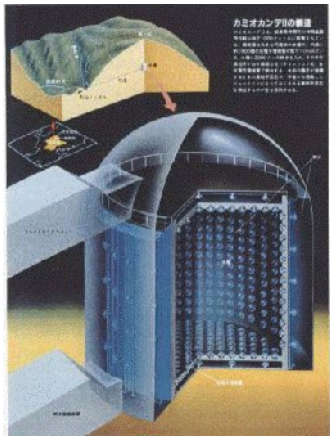
From slides of H. Robertson (neutrino 2006)

http://neutrinosantafe06.com/

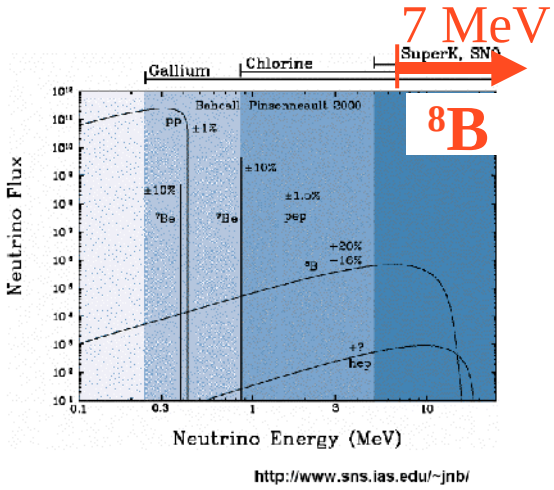
SSM BS05(OP): J.N. Bahcall and Serenelli, 2005

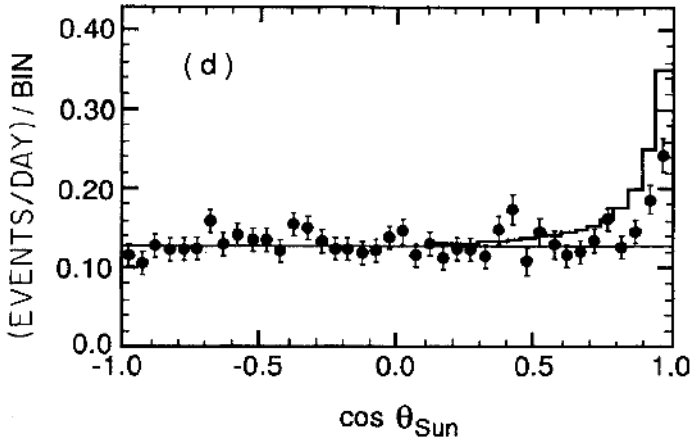
SNU: 1 ν interaction / sec each 10^{36} target atoms

Kamiokande (1987 ~ 1995)



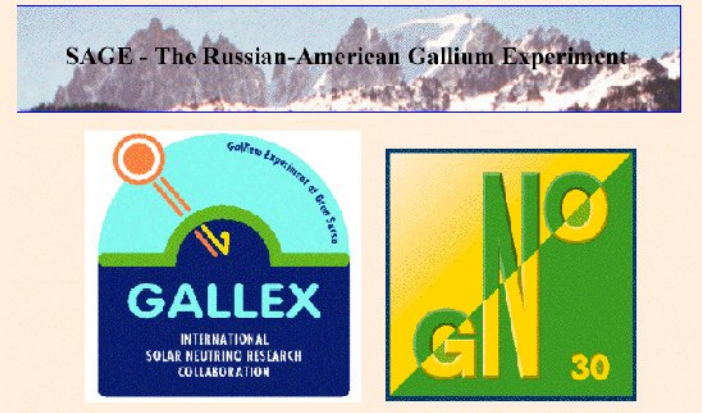
- First measurement of time, direction, energy of solar-ν
- Data/SSM=0.48 ± 0.07
- Upgraded to Super-K

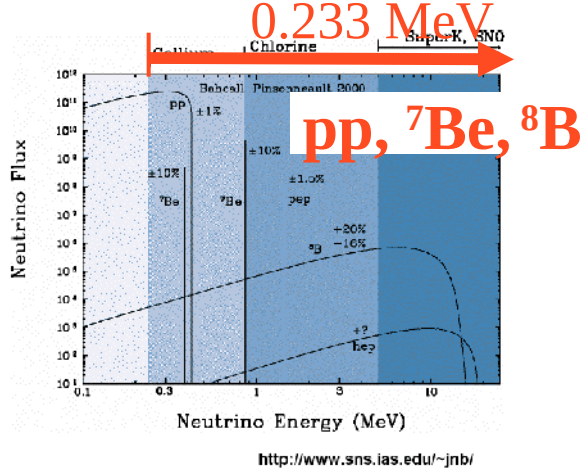




PRD **44** (1991) 2241

Gallium experiments



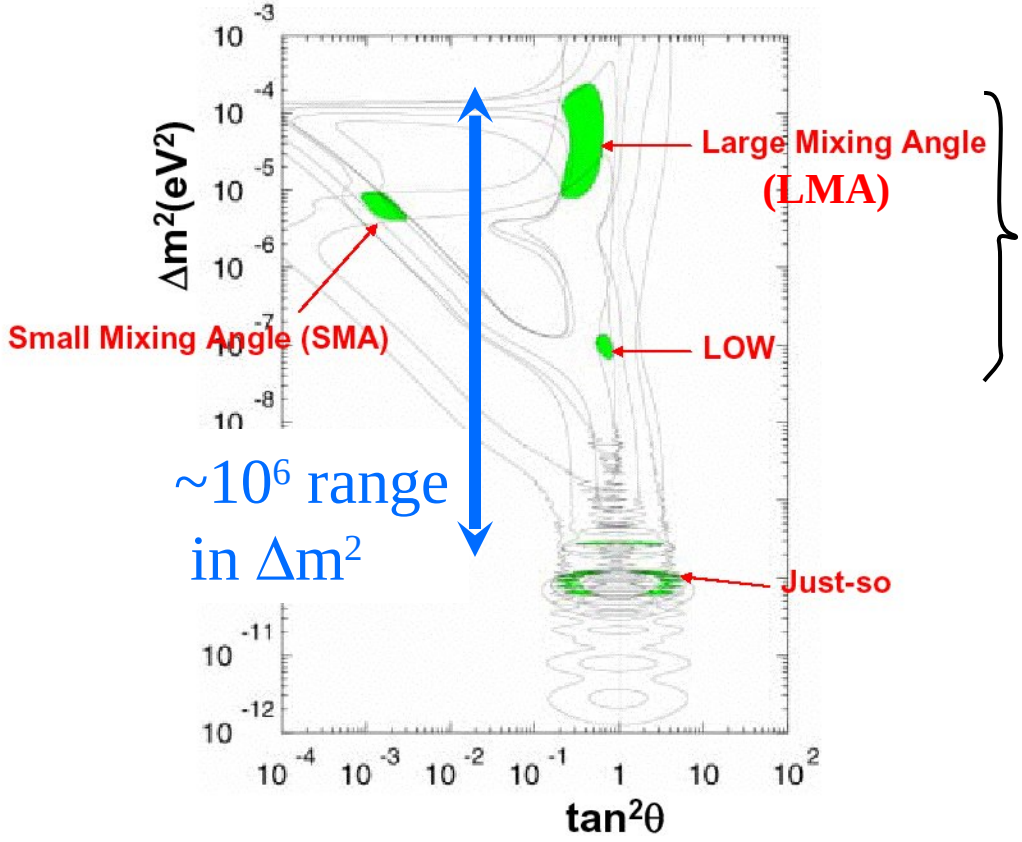


- Sensitive to pp neutrino (main component of solar-ν)
- $\nu_e(^{71}Ga, ^{71}Ge)e^-$
- 67.7 ± 3.6 SNU new results (*1) (GALLEX + GNO + SAGE)
- SSM (BS05(OP)): 126^{+9}_{-7} SNU
- Data / SSM = 0.54 ± 0.03

(*1) V.N. Gavrin, Neutrino 2006

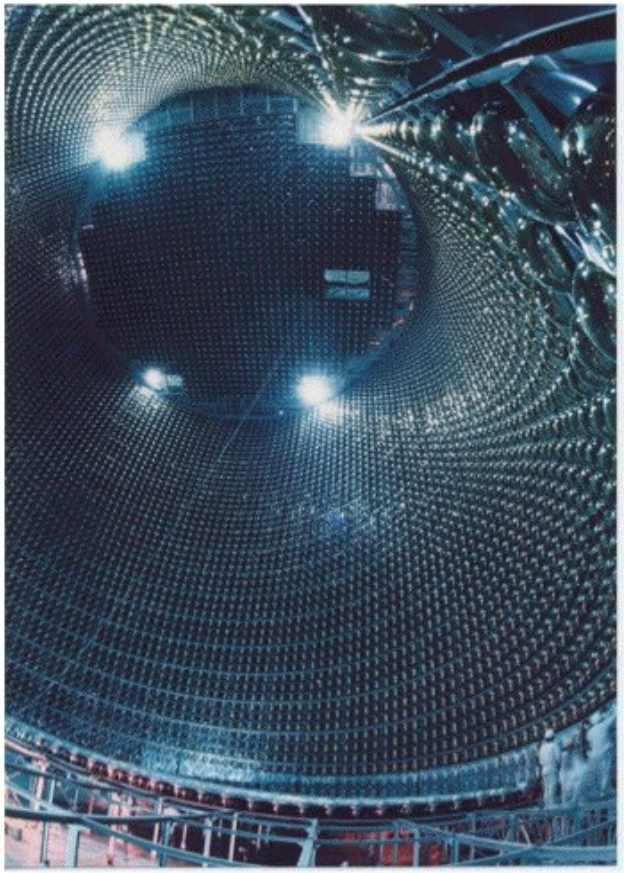
http://neutrinosantafe06.com/

Four solutions that were allowed only with fluxes (Cl, Ga, Kamiokande)

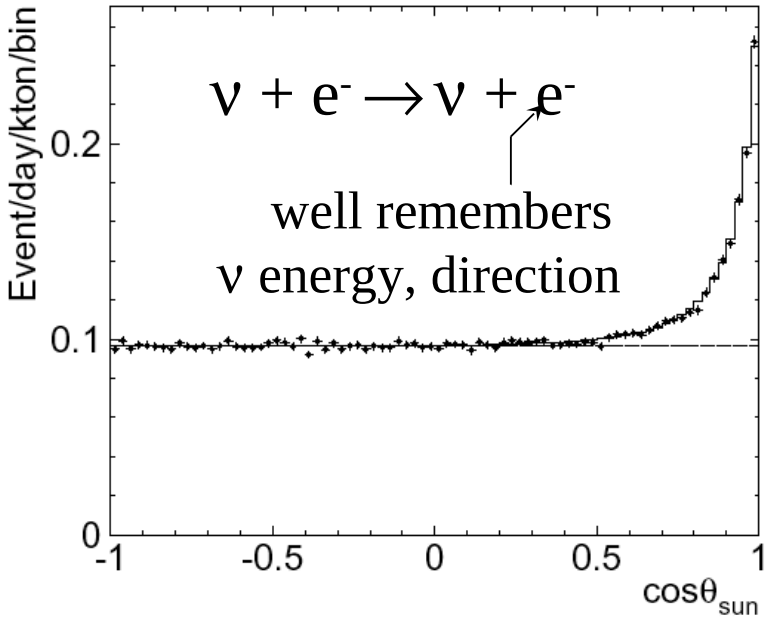


Mikheyev-Smirnov-Wolfenstein (MSW)

Super-Kamiokande (1996 ~)



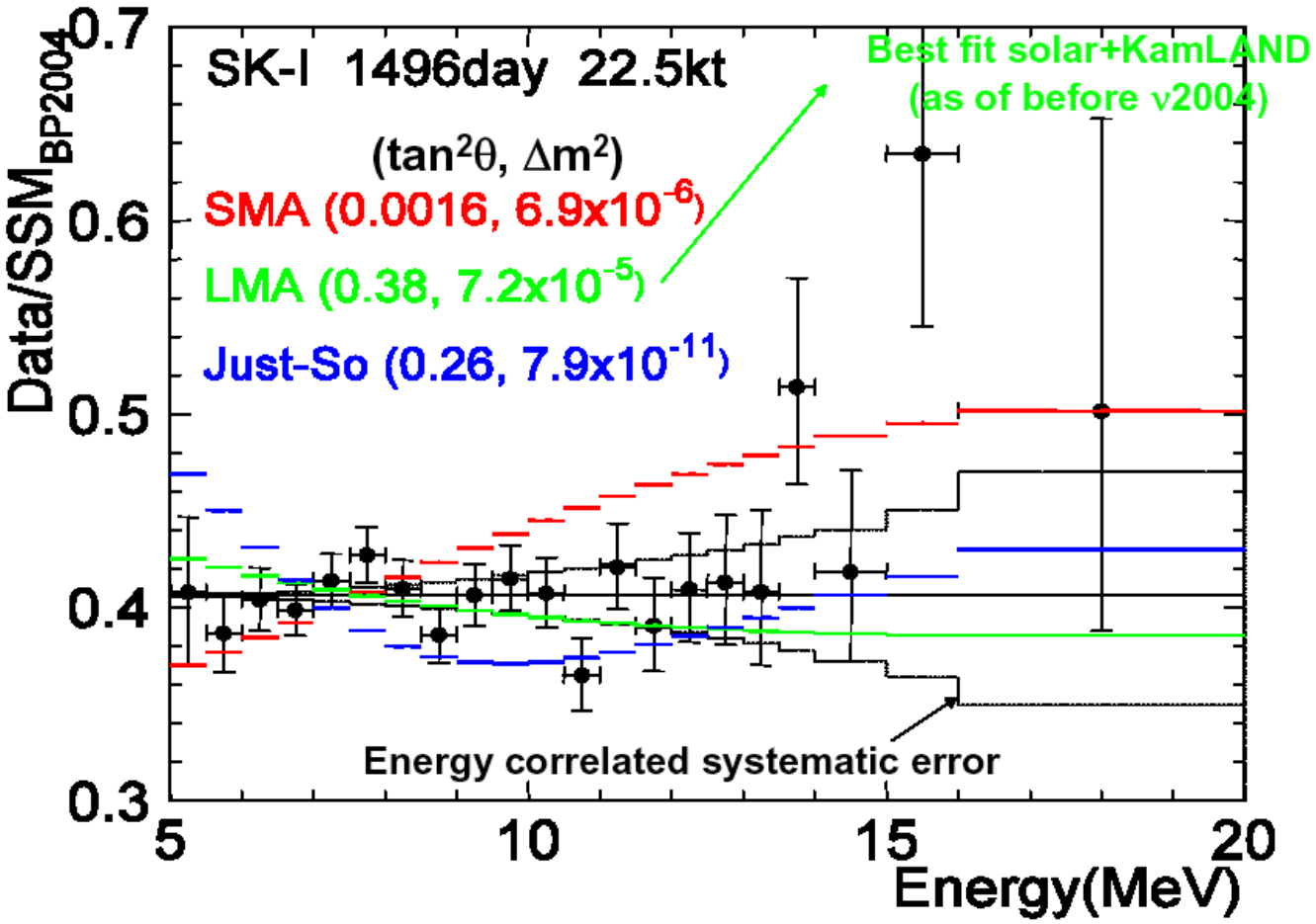
- 50 kton water cherenkov
- 22.5 kton fiducial
- ~ 15 events / day (> 5 MeV)
  (^{8}B, (hep))



Super-Kamiokande-I (1496 days)

May 31, 1996 - July 13, 2001 22400 ± 230 solar ν events

Energy spectrum of SK-I

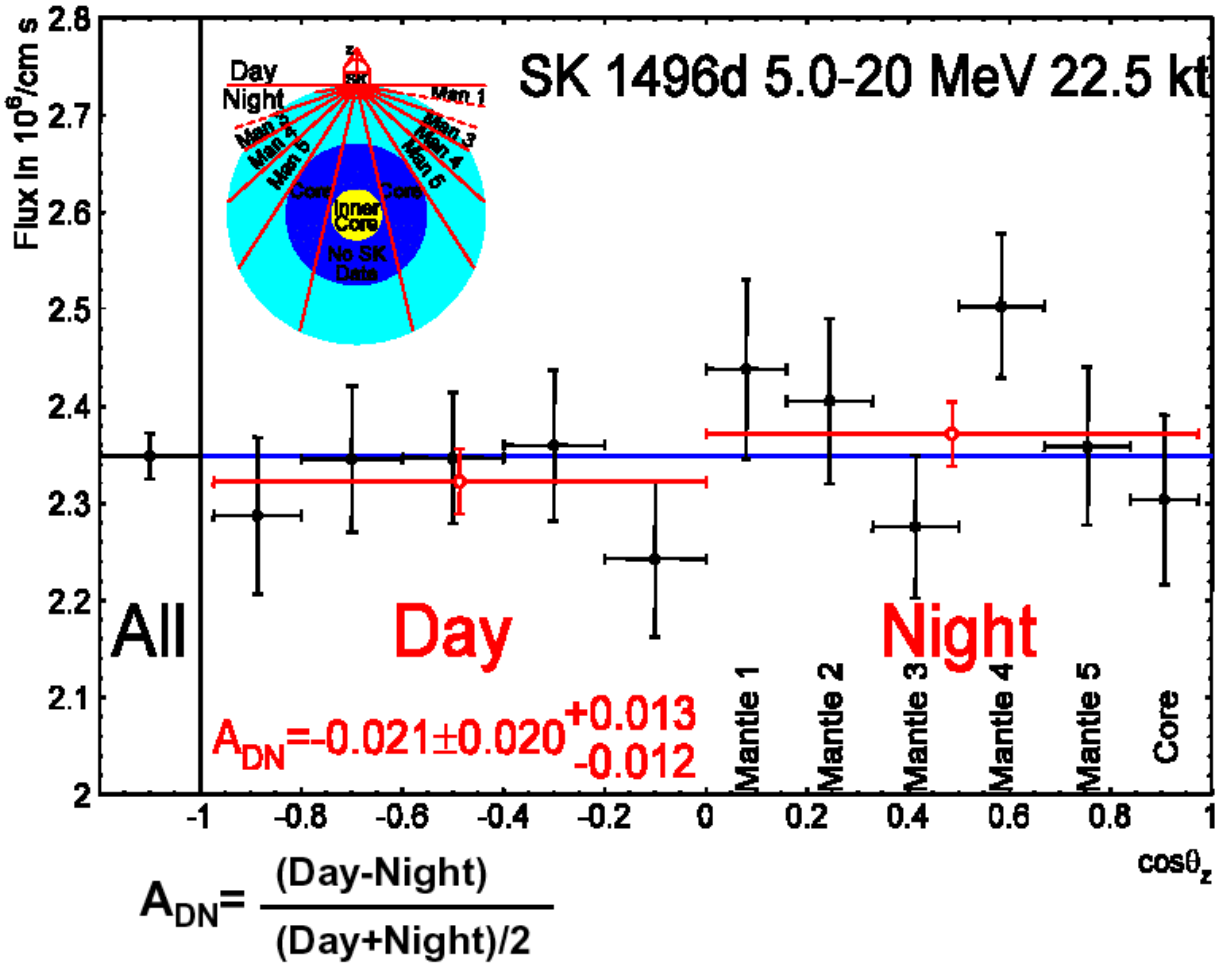


M. Nakahata, Neutrino 2004, PLB **539**, 179

Super-Kamiokande-I (1496 days)

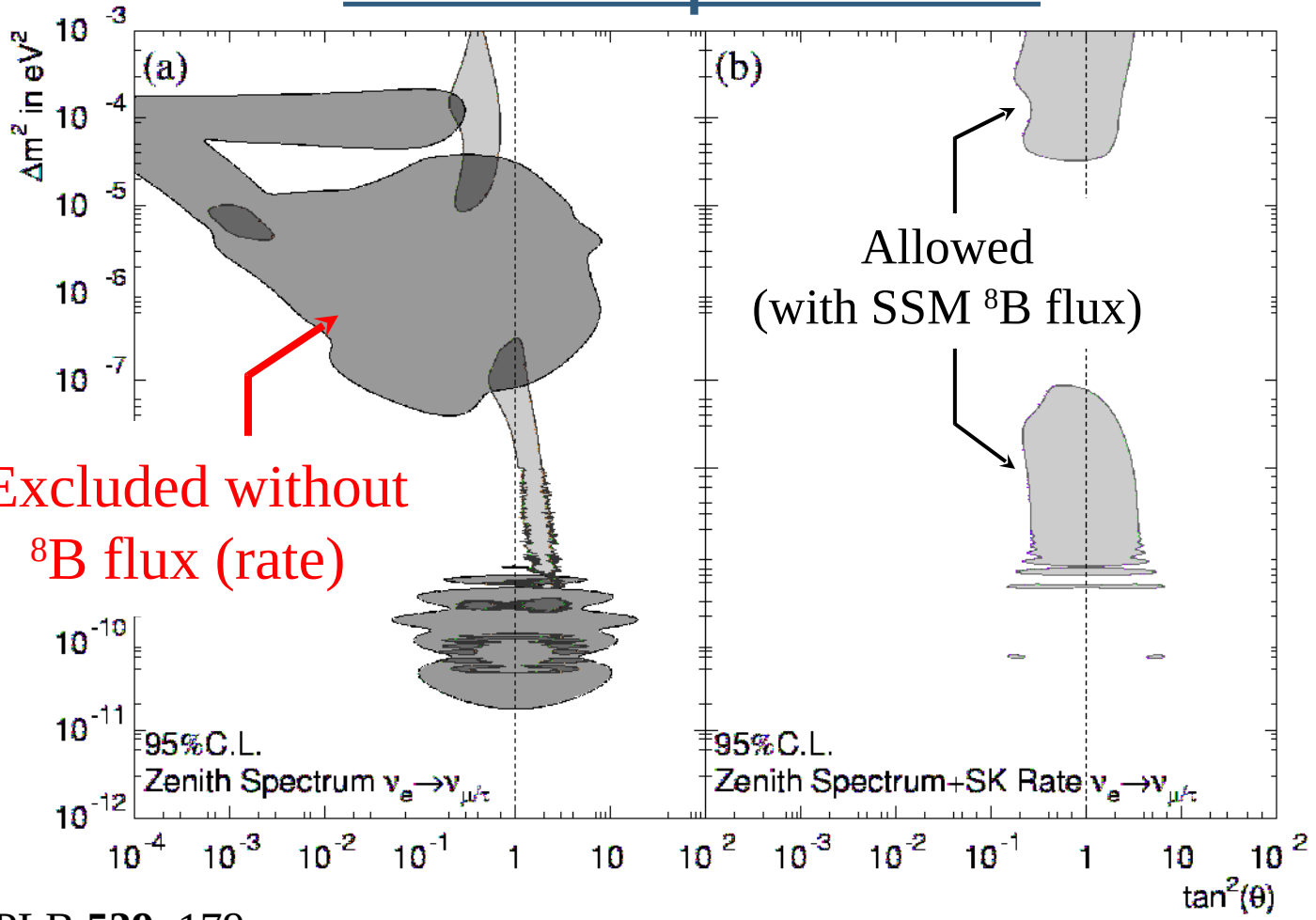
May 31, 1996 - July 13, 2001

SK-I day/night difference



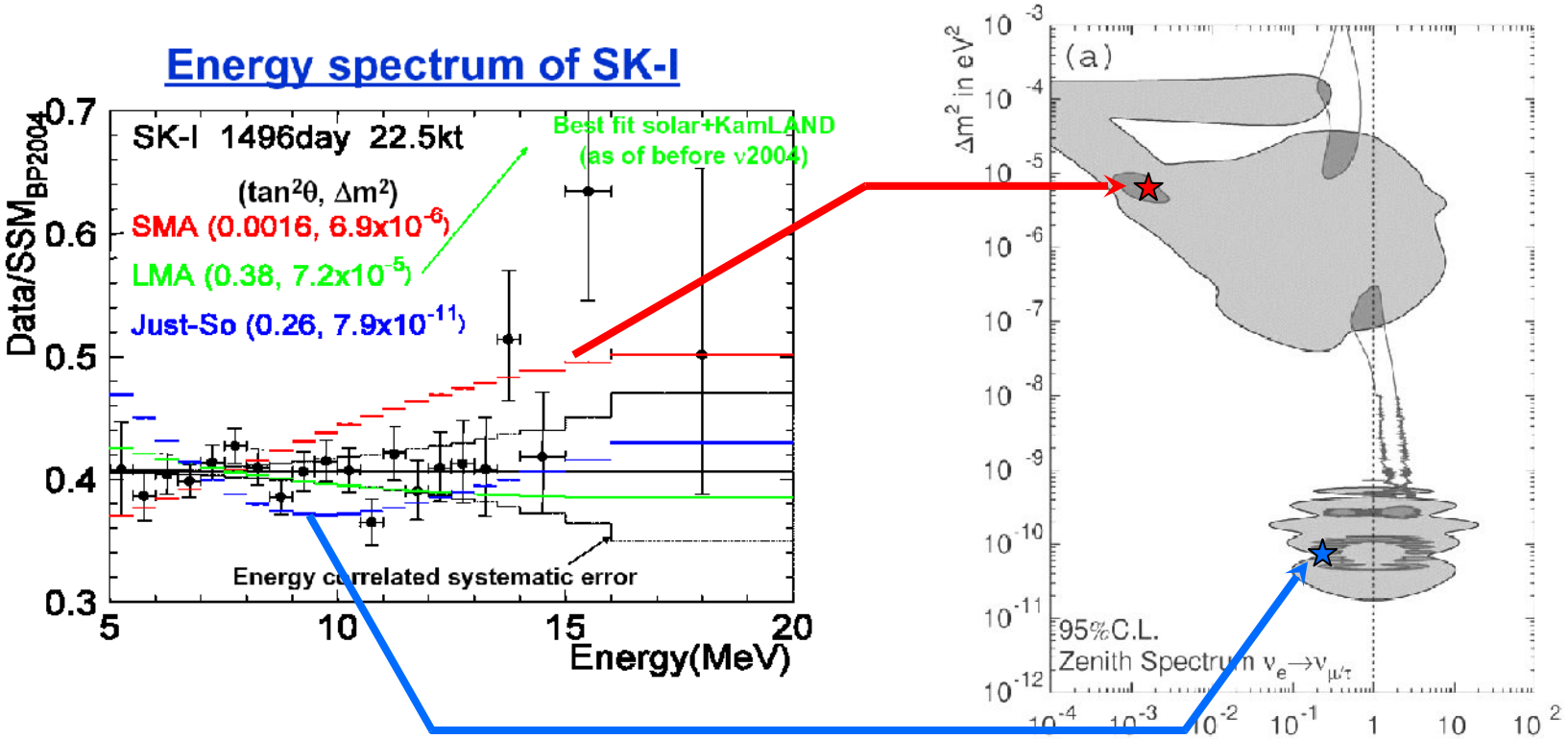
M. Nakahata, Neutrino2004, PLB **539**, 179

SK-I: energy and zenith angle 2-D spectrum "zenith spectrum"



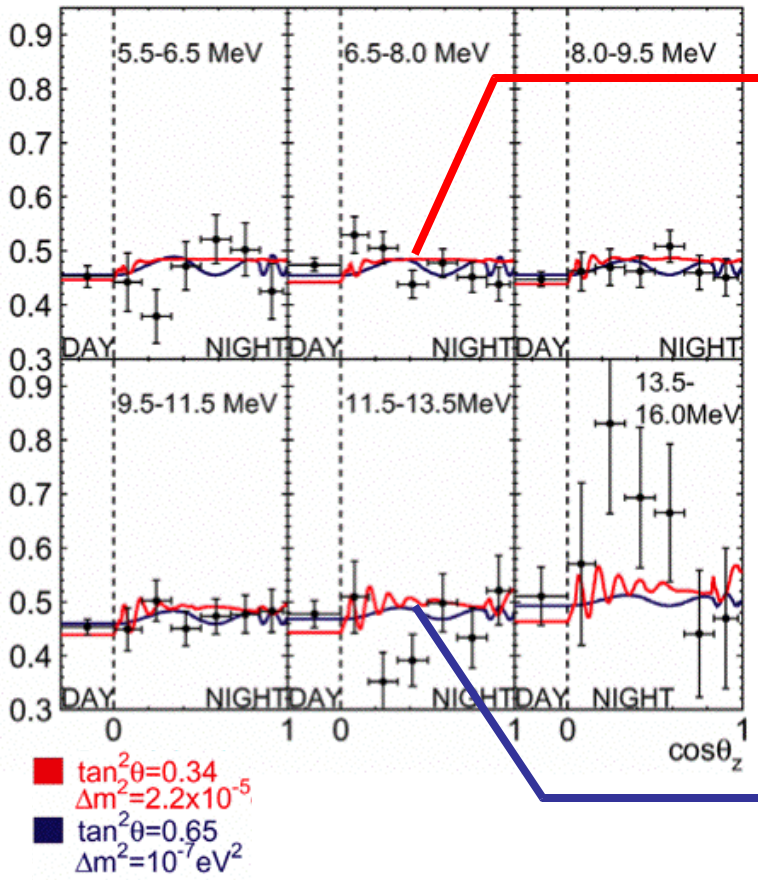
PLB **539**, 179

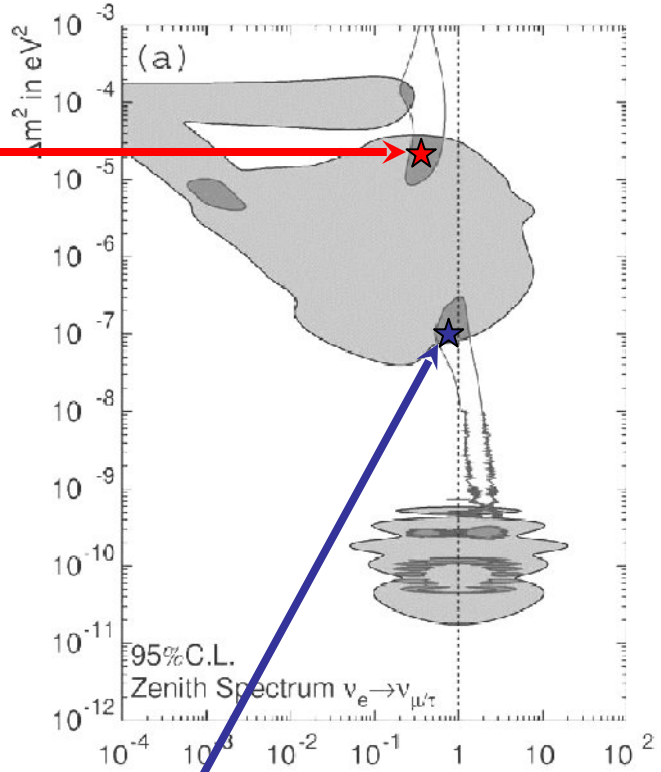
SMA, Just-so: excluded by energy spectrum



LOW, LMA: constrained by day/night

Expected "regeneration" of ν_e during night: too large compared with the data





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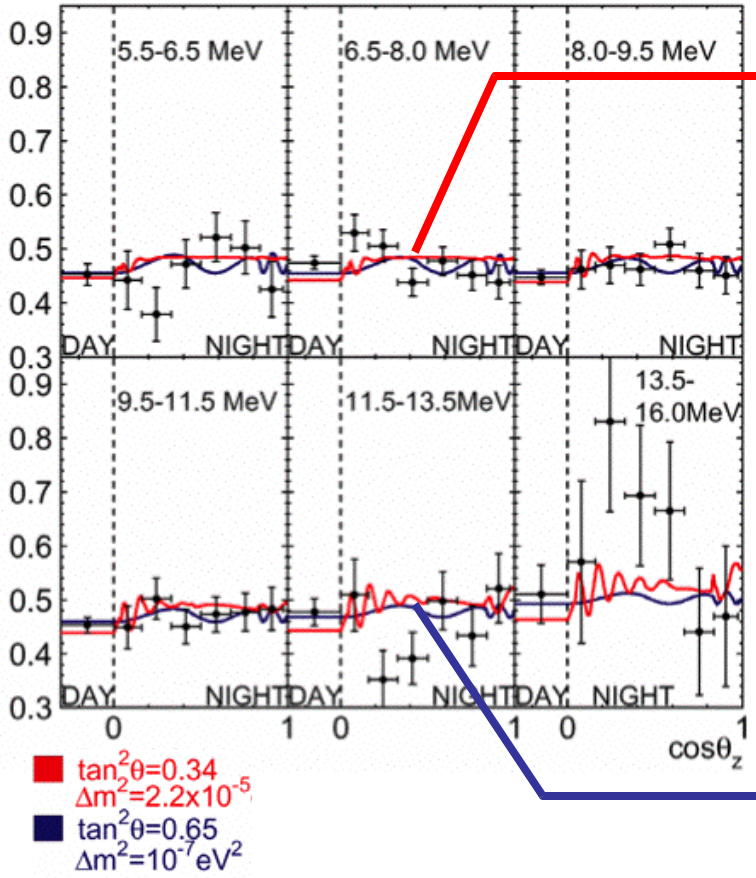
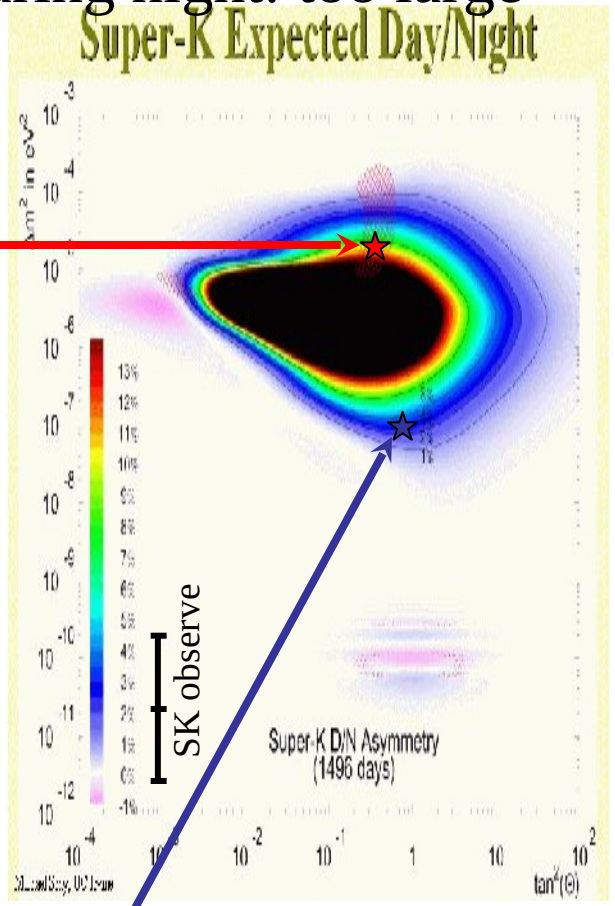
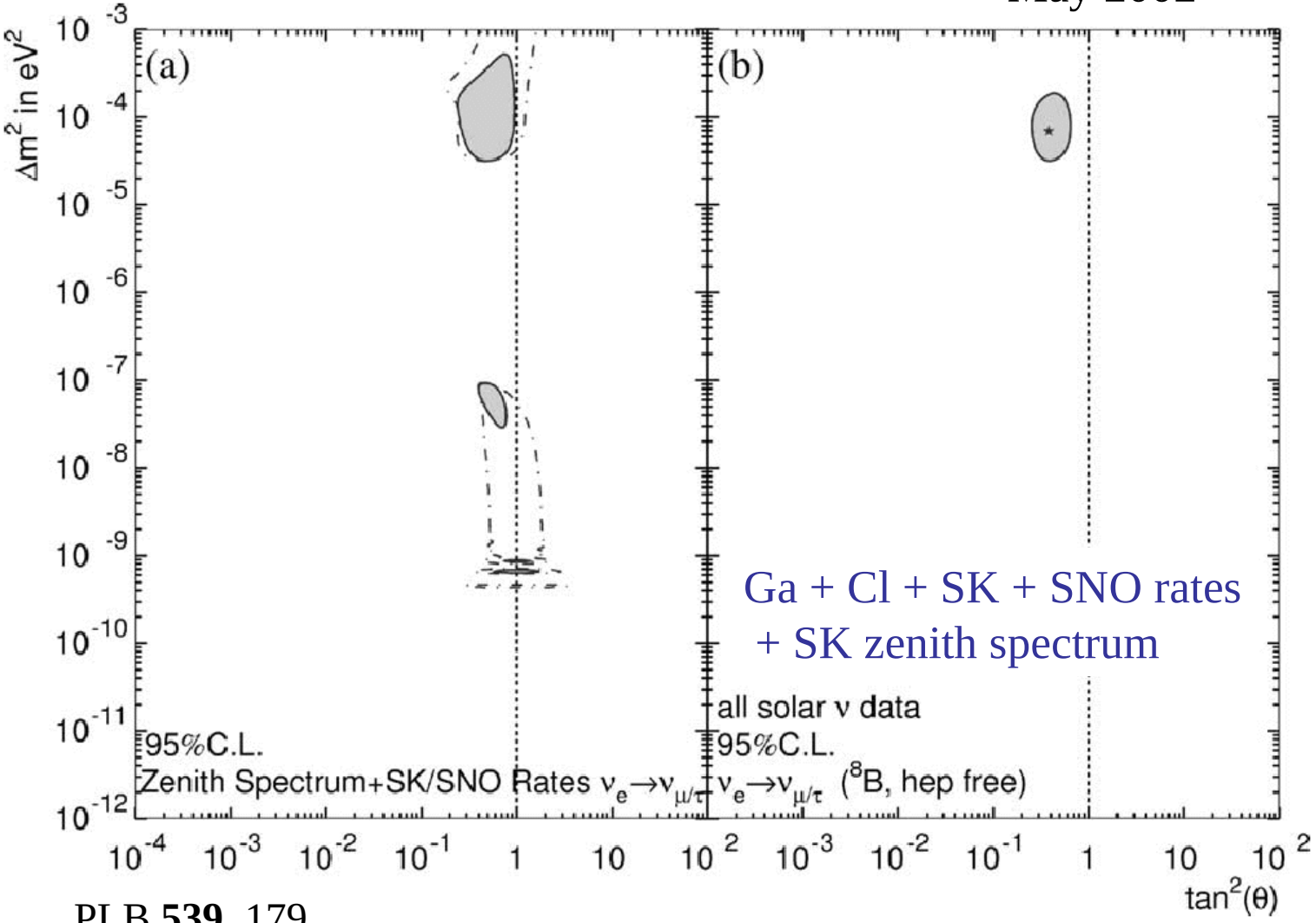




M.B. Smy, Neutrino 2002

Only LMA at 98% C.L.

May 2002

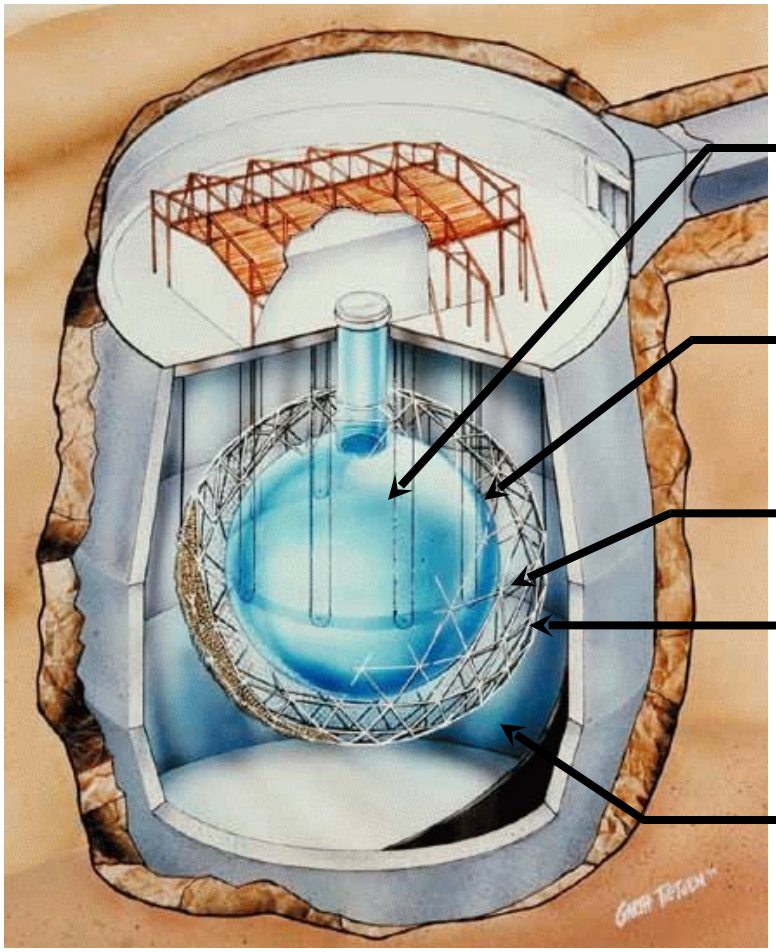


Ga + Cl + SK + SNO rates
+ SK zenith spectrum

PLB **539**, 179

Sudbury Neutrino Observatory (SNO)

1999 ~



1000 ton D_2O

12-m diameter acrylic vessel

1700 ton H_2O

Support structure for 9500 8-inch PMTs

5300 ton outer H_2O

Unique sensitivity to neutrino flavor

CC: charged current

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

energy, (direction)

NC: neutral current

$$\left.\begin{matrix}\nu_e \\ \nu_\mu \\ \nu_\tau\end{matrix}\right\} + d \rightarrow p + n + \nu$$

$n + d \rightarrow {}^3H +$ 6.25-MeV γ (phase I)

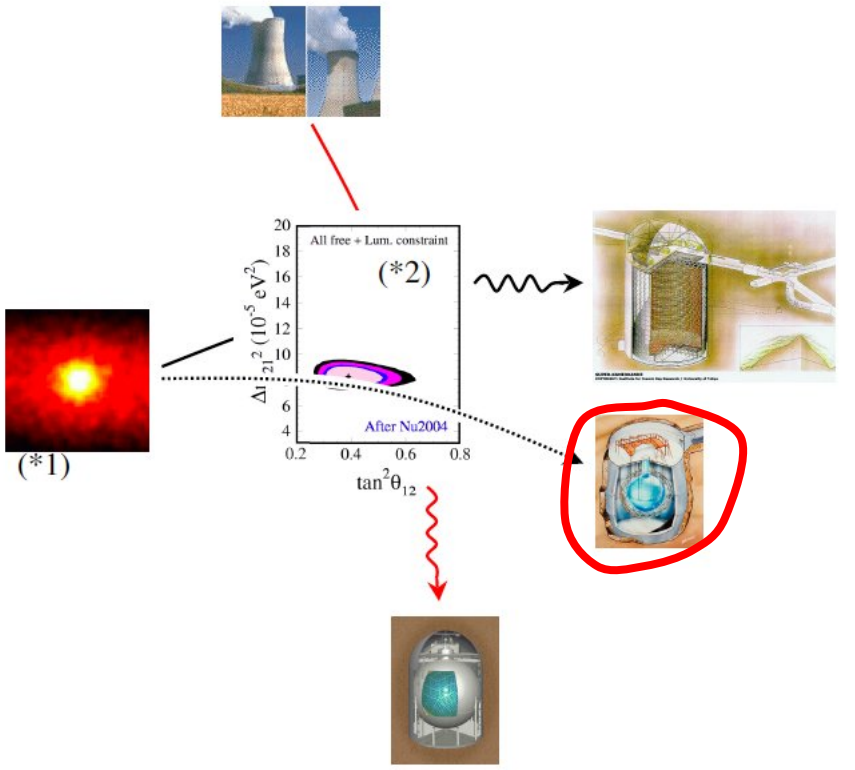
ES: elastic scattering (also SK)

$$\left.\begin{matrix}\nu_e \\ \nu_\mu \\ \nu_\tau\end{matrix}\right\} + e^- \rightarrow \nu_e + e^-$$

energy, direction

- $\phi_{CC} = \phi_e$
- $\phi_{NC} = \phi_e + \phi_\mu + \phi_\tau$
  $= \phi$(all active ν)
- $\phi_{ES} = \phi_e$
  $+ 0.154 \times (\phi_\mu + \phi_\tau)$
- Determine ϕ_e, $\phi_{\mu/\tau}$
  + 1 redundancy

2 unknowns : object and "filter"



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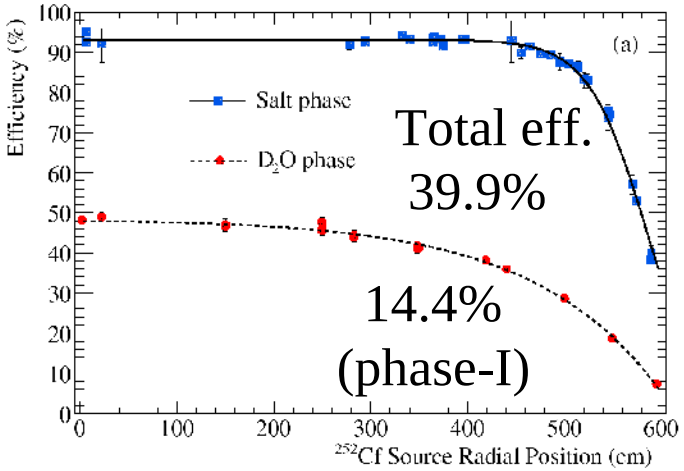
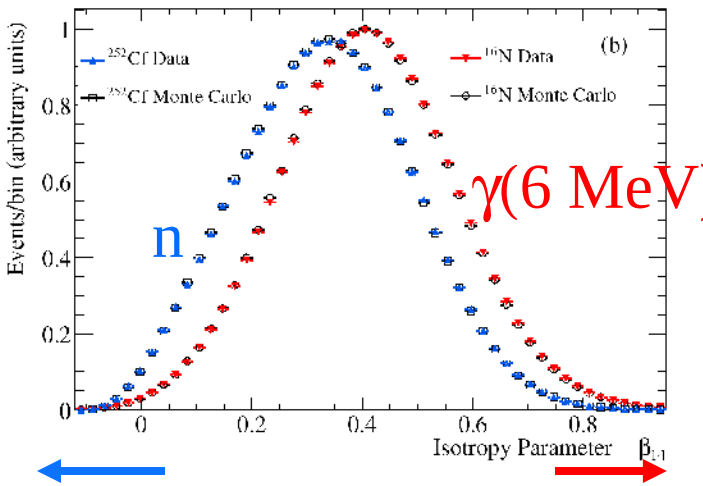
SNO enhanced neutral current (salt) phase

PRL **92**, 181301

Sept. 2003





Isotropic event

Single cherenkov ring

NC: neutral current

Phase-I (Nov. 99 - May 01)

$\nu_e, \nu_\mu, \nu_\tau + d \rightarrow p + n + \nu$

$n + d \rightarrow {}^3H +$ 6.25-MeV γ

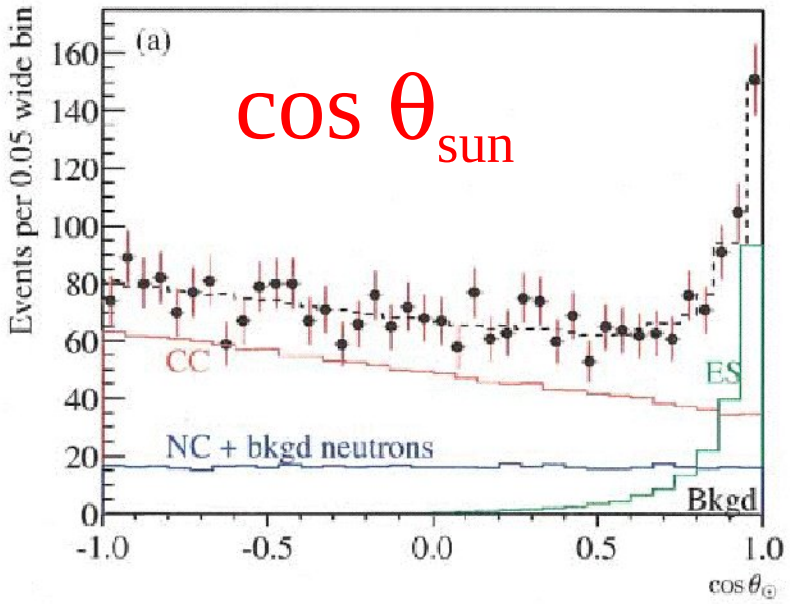
2 ton NaCl dissolved

Phase-II (July 01 - Sep 03)

$\nu_e, \nu_\mu, \nu_\tau + d \rightarrow p + n + \nu$

$n + {}^{35}Cl \rightarrow {}^{36}Cl +$ 8.6-MeV γ's

Results: extraction of 3 reactions



PRL **89**, 011301, results from 306.4 days

CC: $1967.7^{+61.9}$ events

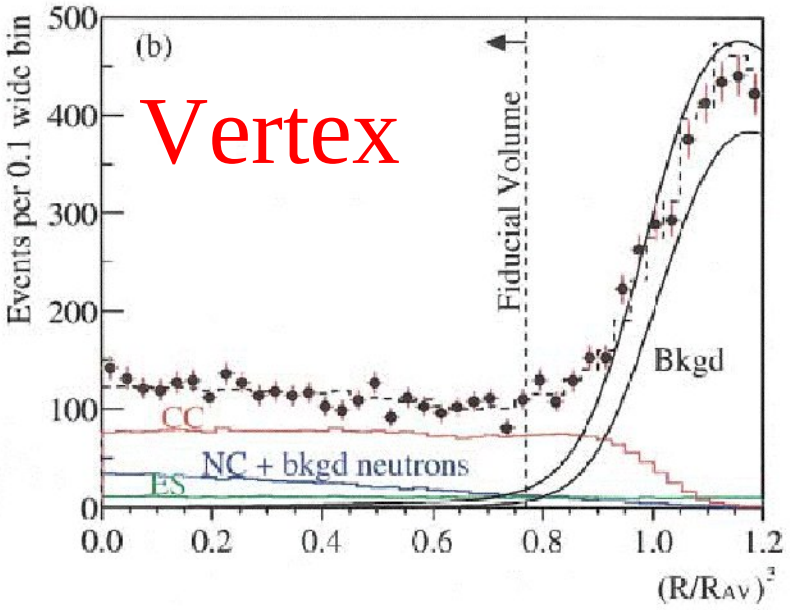
NC: $576.5^{+49.5}$ events

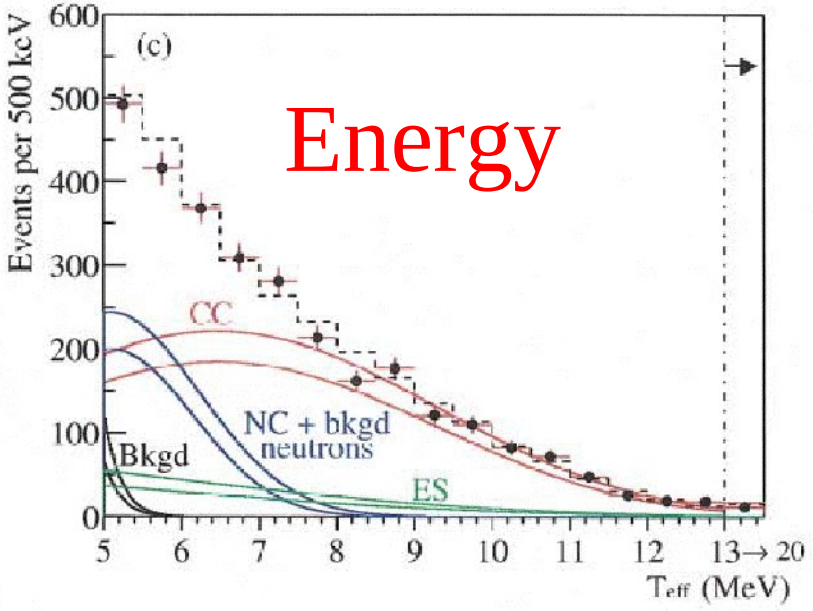
ES: $263.6^{+26.4}$ events

- 60.9

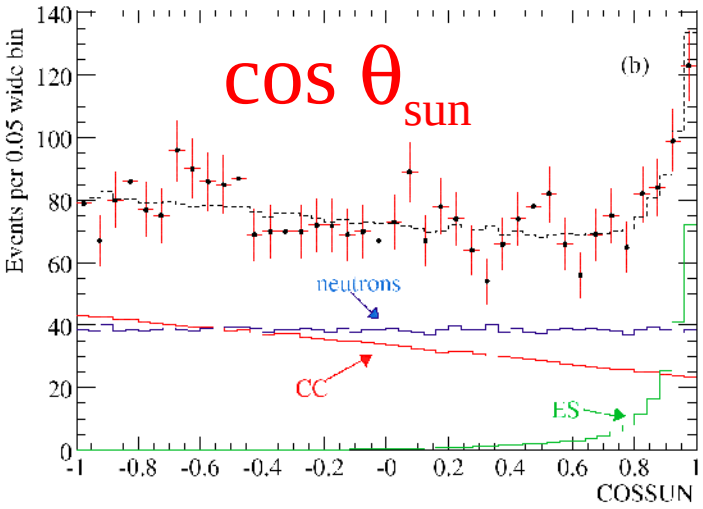
- 48.9

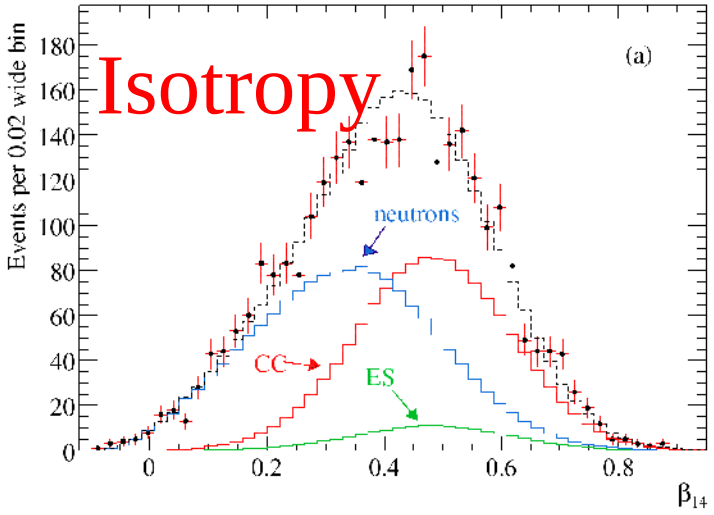
- 25.6

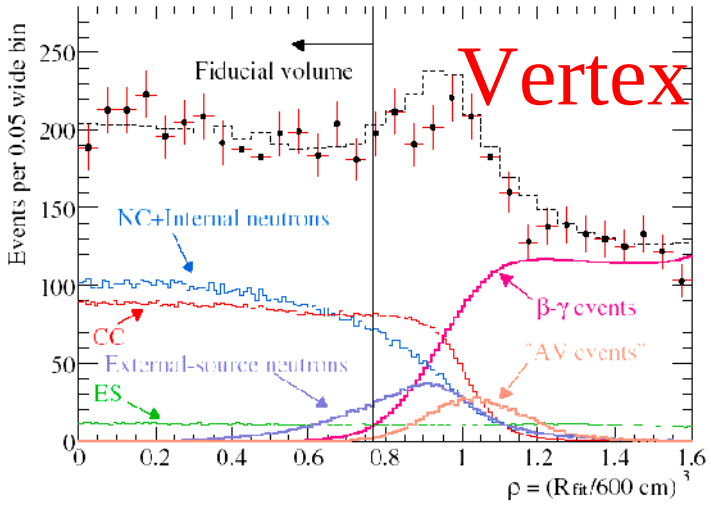


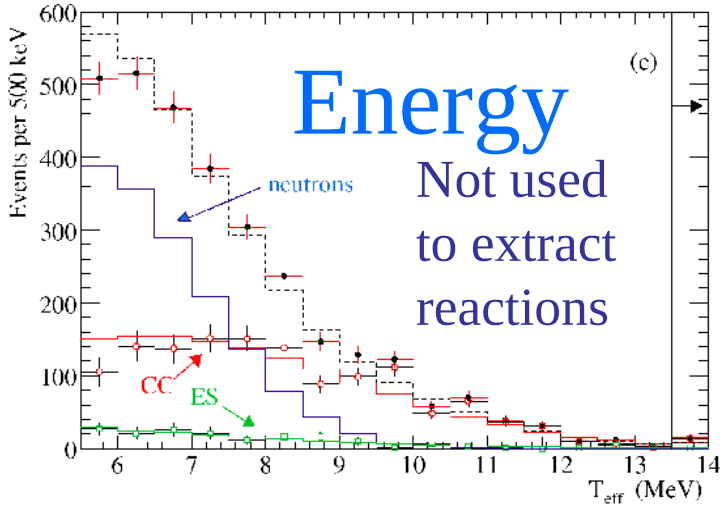


Energy spectra: not assumed but measured

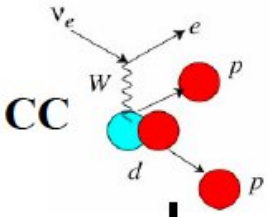


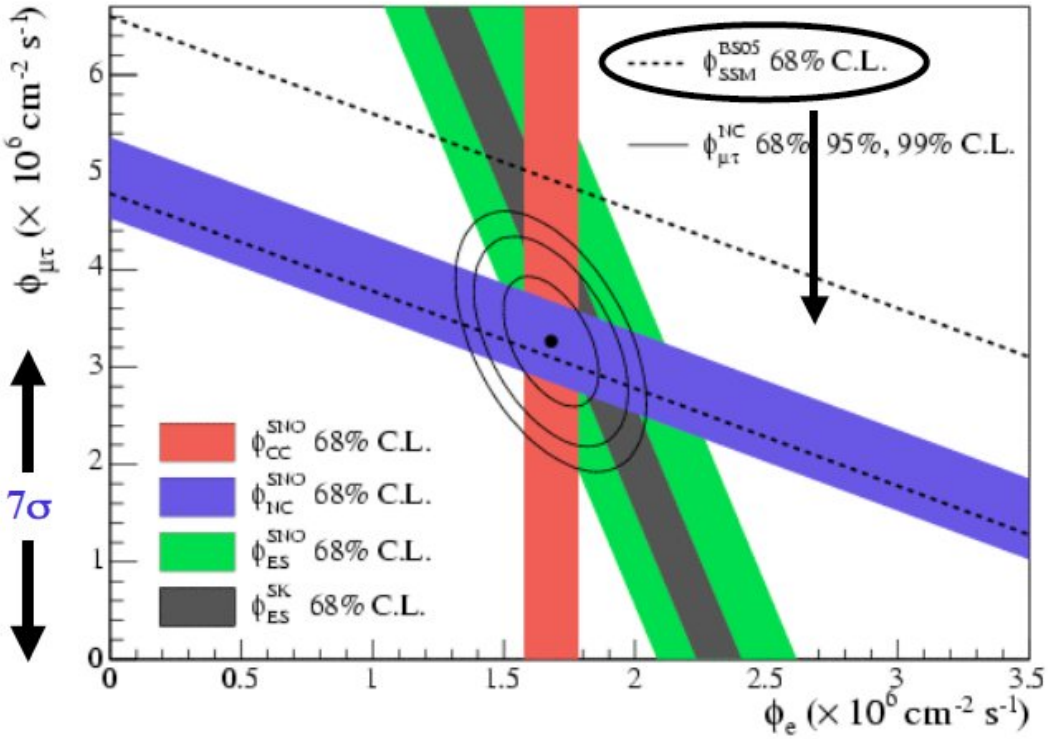




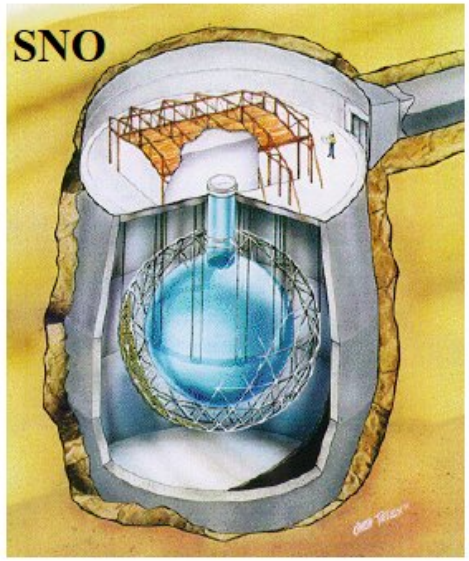


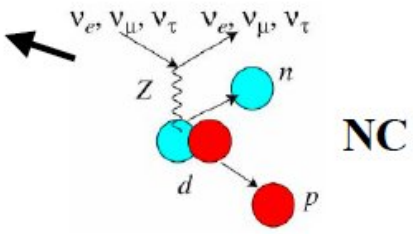
SNO Collaboration, PRC **72**, 055502 (2005)
391 Days of Dissolved Salt Data



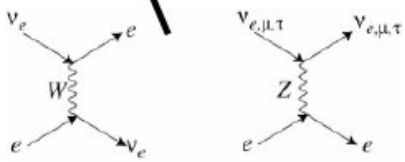


7σ





ES

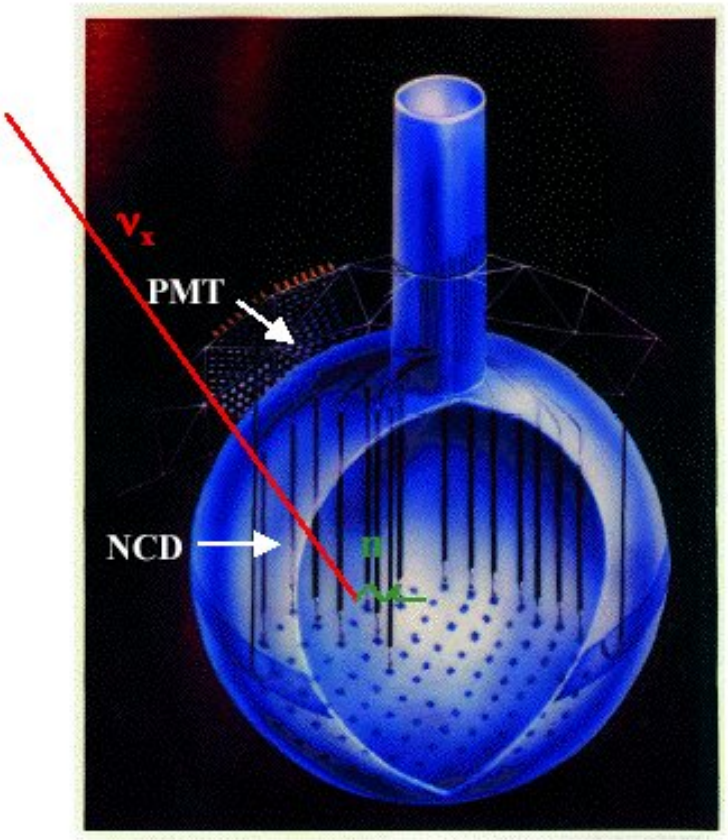


Slide by A. Hime (neutrino 2006)

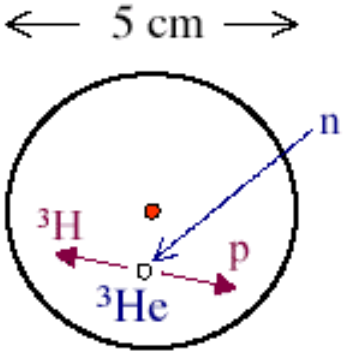
http://neutrinosantafe06.com/

SNO ^{3}He phase

J.F. Wilkerson, Neutrino 2004



- ^{3}He proportional counter: to detect n from NC
- Event-by-event separation
- Better CC energy spectrum



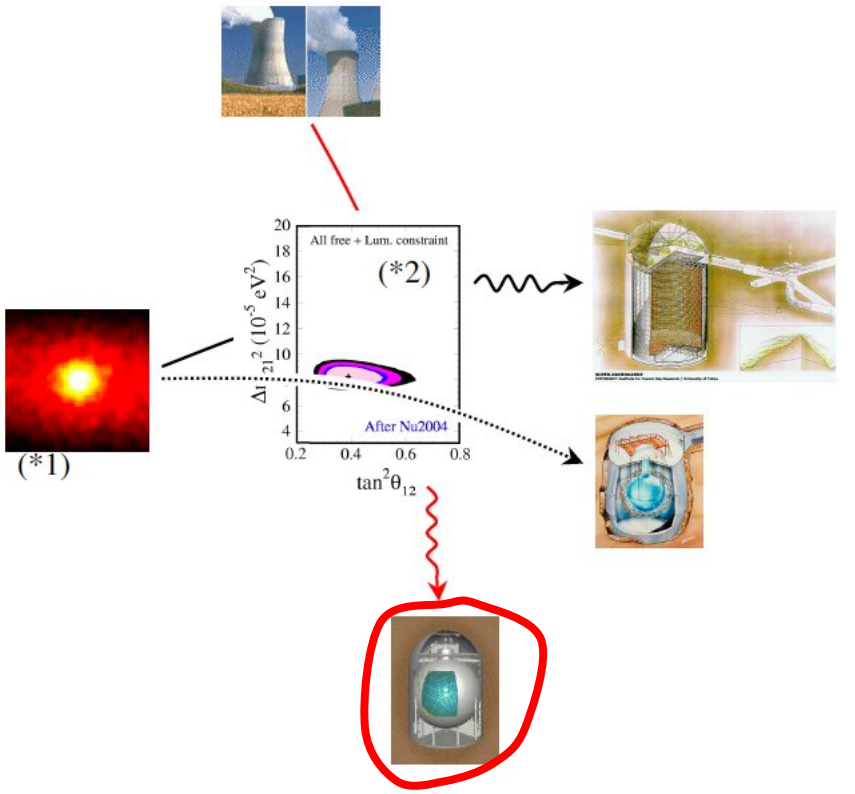
$n + {}^3He \rightarrow p + {}^3H$

SNO ^{3}He phase

J.F. Wilkerson, Neutrino 2004

- All 40 ^{3}He strings installed (April, 2004)
- run for 2.5 years $\rightarrow \times 2$ precision of present SNO result

2 unknowns : object and “filter”



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Determination of solar neutrino solution
Precise measurement of Δm_{12}^2

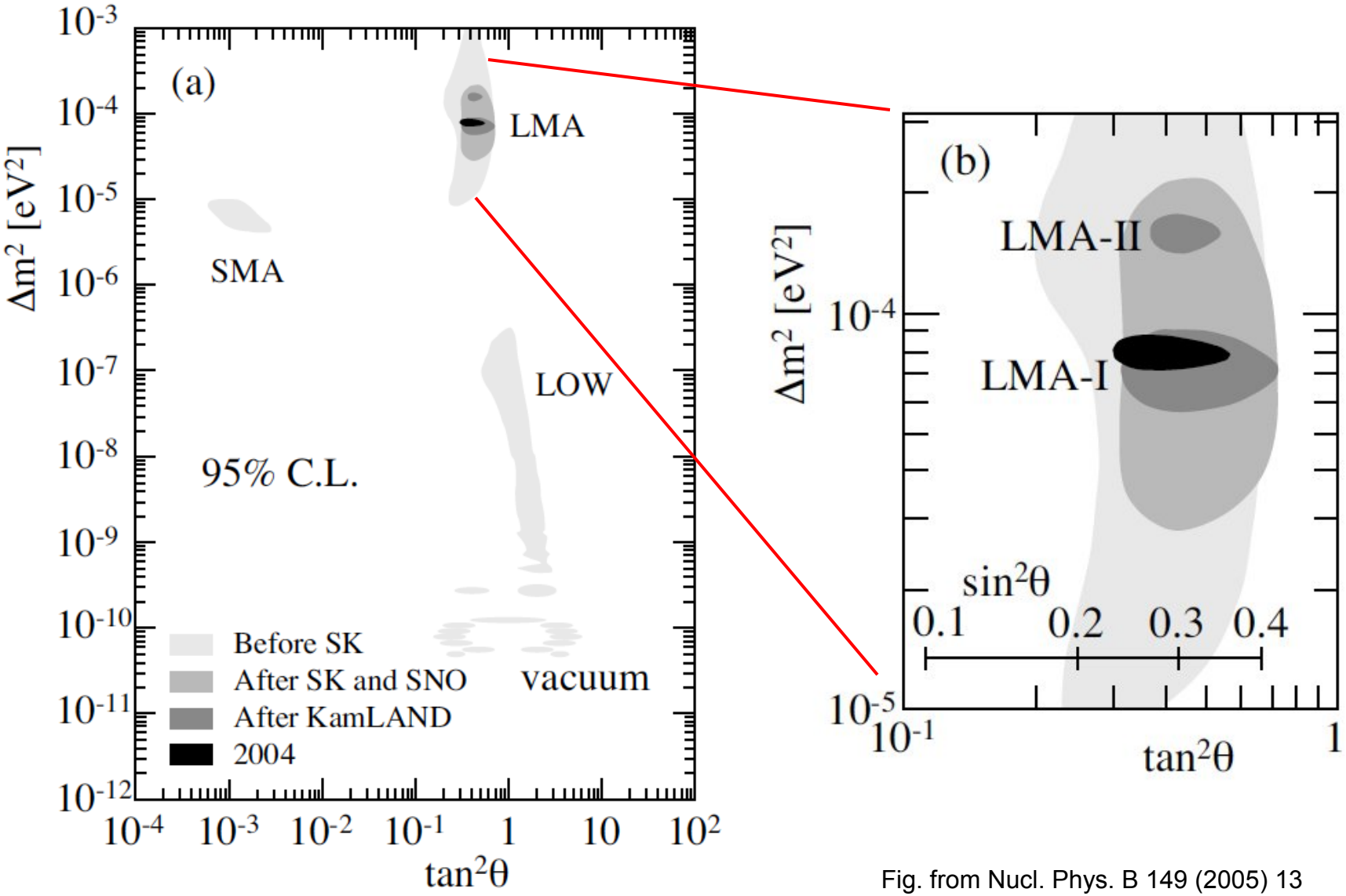
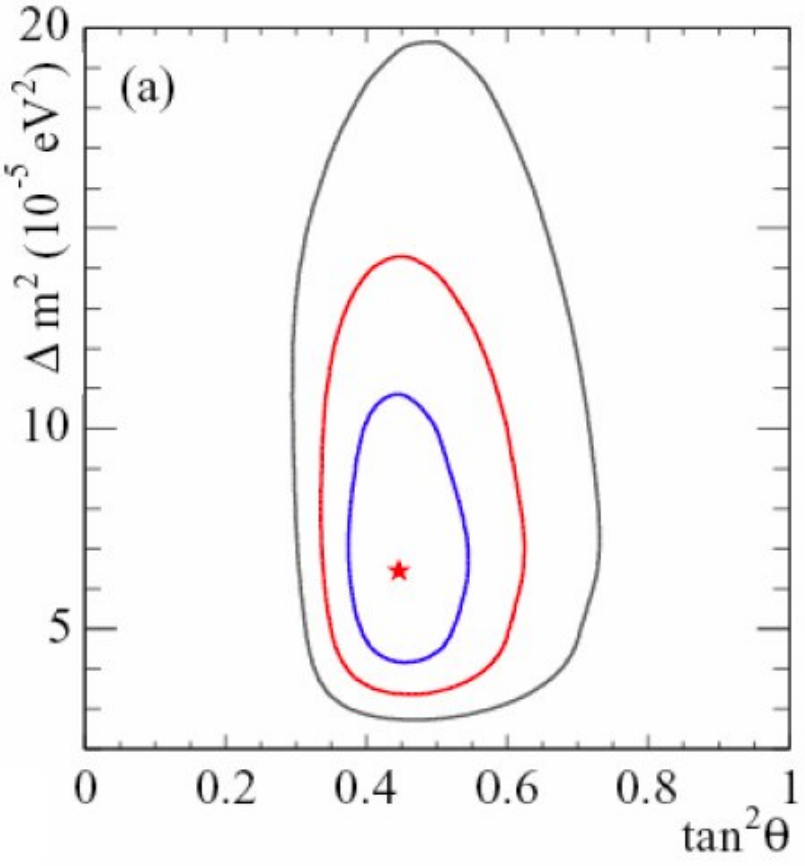
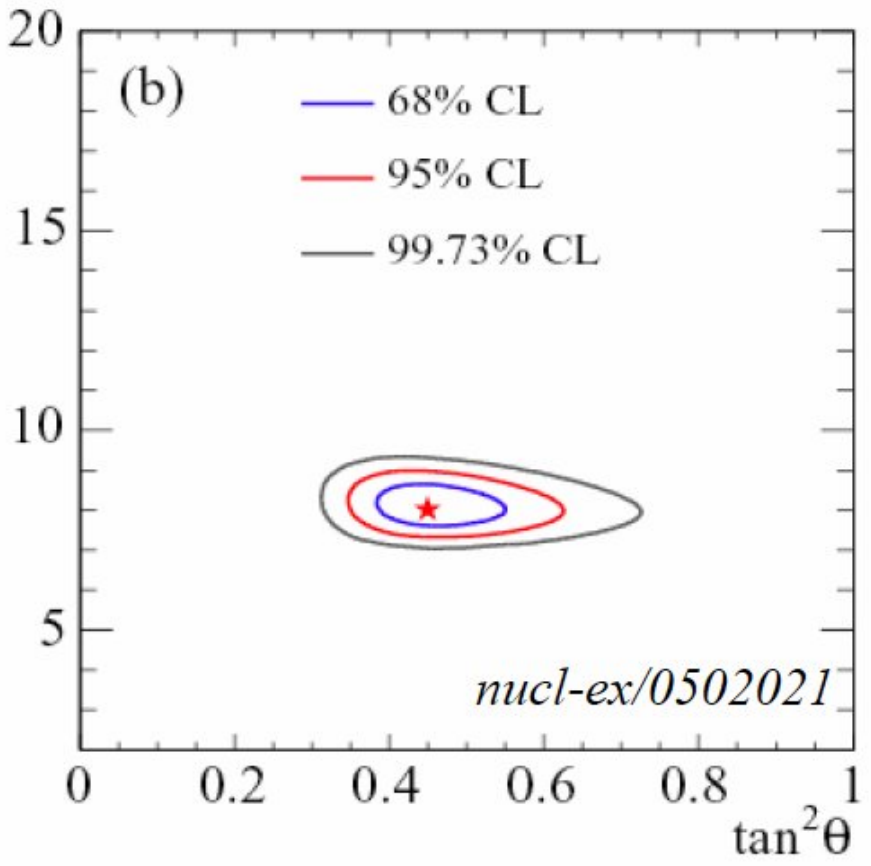


Fig. from Nucl. Phys. B 149 (2005) 13



Solar data: Δm_{12}^2, θ

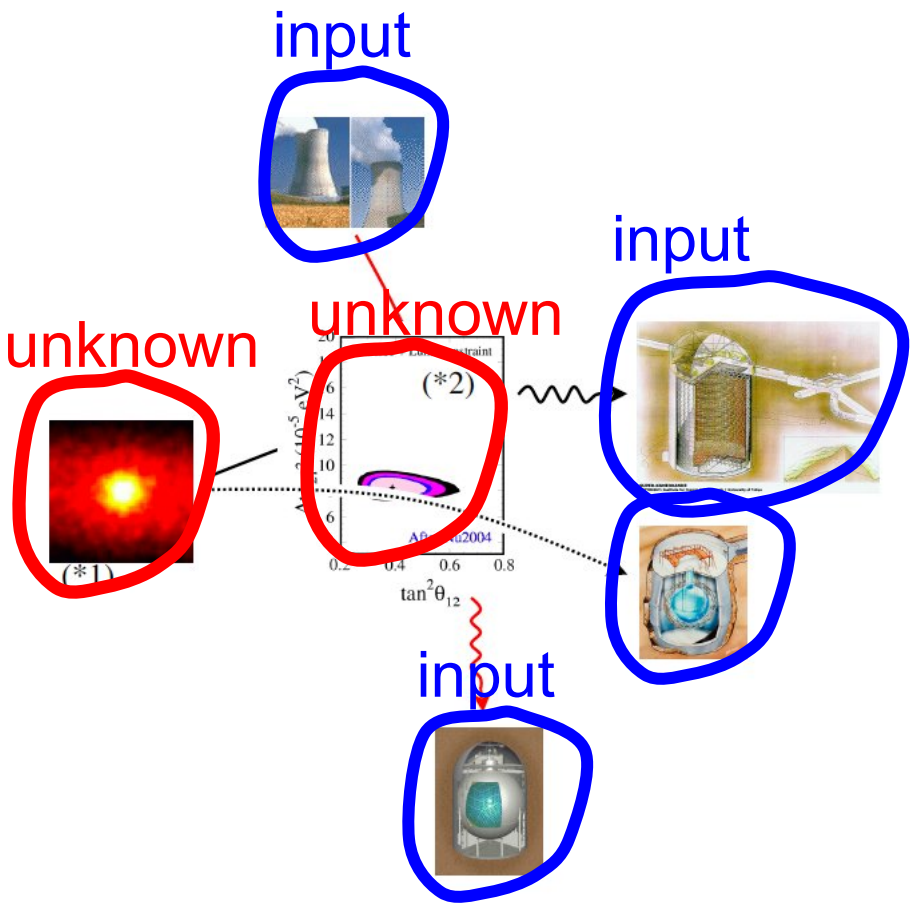


add anti-neutrinos (KamLAND)
(assumes CPT): Δm_{12}^2, θ

Slide by B. Vogelaar (neutrino 2006)

http://neutrinosantafe06.com/

2 unknowns : object and "filter"



(*1) neutrinograph of the sun by Super-K, (*2) hep-ph/0406294

- "Neutrino oscillation":

∀ ν_e (solar ν is pure ν_e)

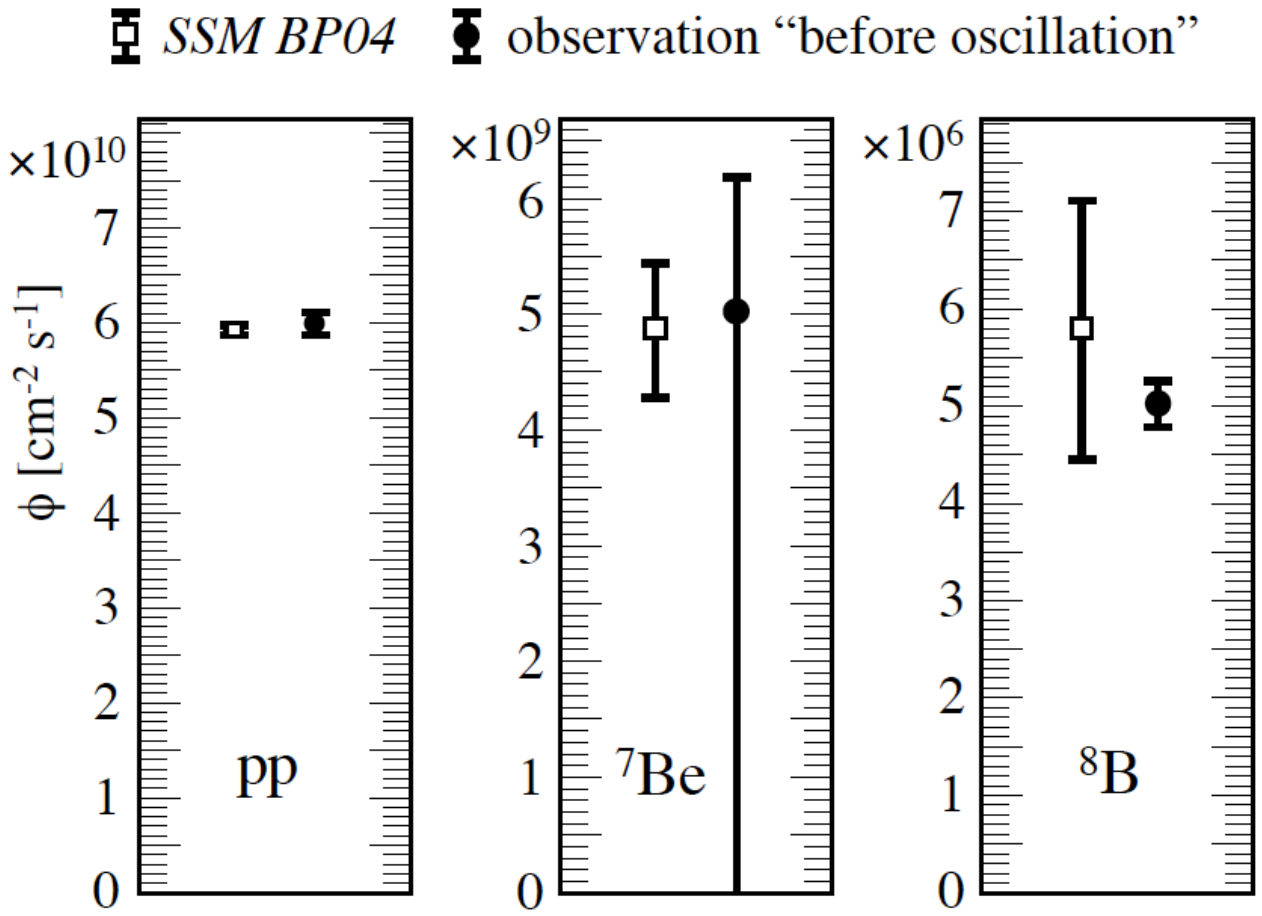
$\rightarrow \nu_\mu, \nu_\tau$

- If the detector is sensitive only to ν_e

$\rightarrow$ deficit, energy spectral distortion (the "filter" is not a ND filter)

- 2 unknowns: both are important objectives …
- Unique experiments to solve the problem

Solar neutrino with correction of "filter effect"

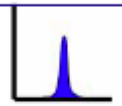
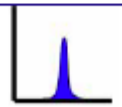
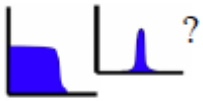


All flux free
Luminosity
constraint

J.N. Bahcall, M.C. Gonzalez-Garcia, and C. Pena-Garay, J. High Energy Phys. 0408 (2004) 016,hep-ph/0406294.

Fig. from Nucl. Phys. B 149 (2005) 13

- ^{8}B: precisely measured
- pp: constrained by luminosity
- ^{7}Be: key to understand total pp-chain

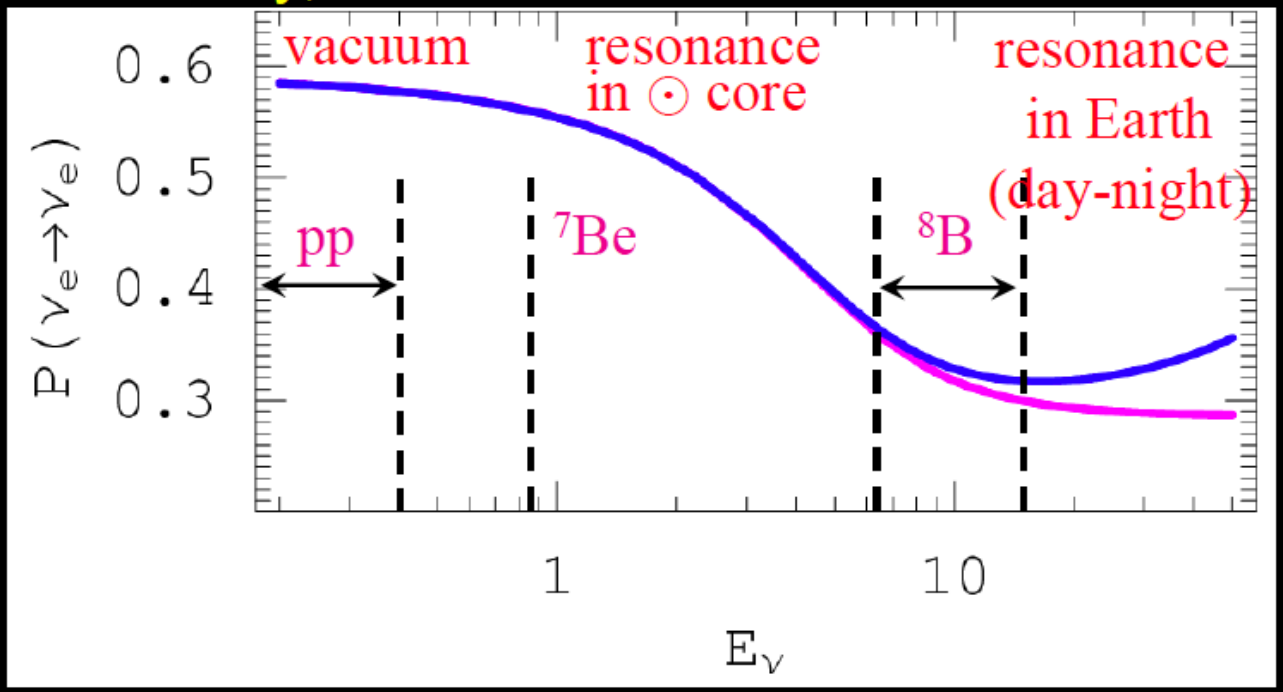
Experiment	mono-energetic ν response	Solar ν Sensitivity	%pp 5 yr	%^{7}Be 5 yr	Status
Borexino		^{7}Be, pep?		5	results in a few years
KamLAND		^{7}Be, CNO?		5	results in a few years
LENS		pp ⇔ CNO	3	5	ready to prototype
MOON		pp ⇔ CNO			r&d only (for now)
CLEAN		pp ⇔ ^{7}Be	1	< 3	ready to prototype
HERON		pp ⇔ ^{7}Be	1.5	5	r&d only (for now)
TPC		pp ⇔ ^{7}Be			r&d
XMass		pp, ^{7}Be			100 kg prototype
SNO+		^{7}Be, pep	1.5(pep)		TDR Fall 06, construct 07

Slide by B. Vogelaar (neutrino 2006)

http://neutrinosantafe06.com/

Designing LMA

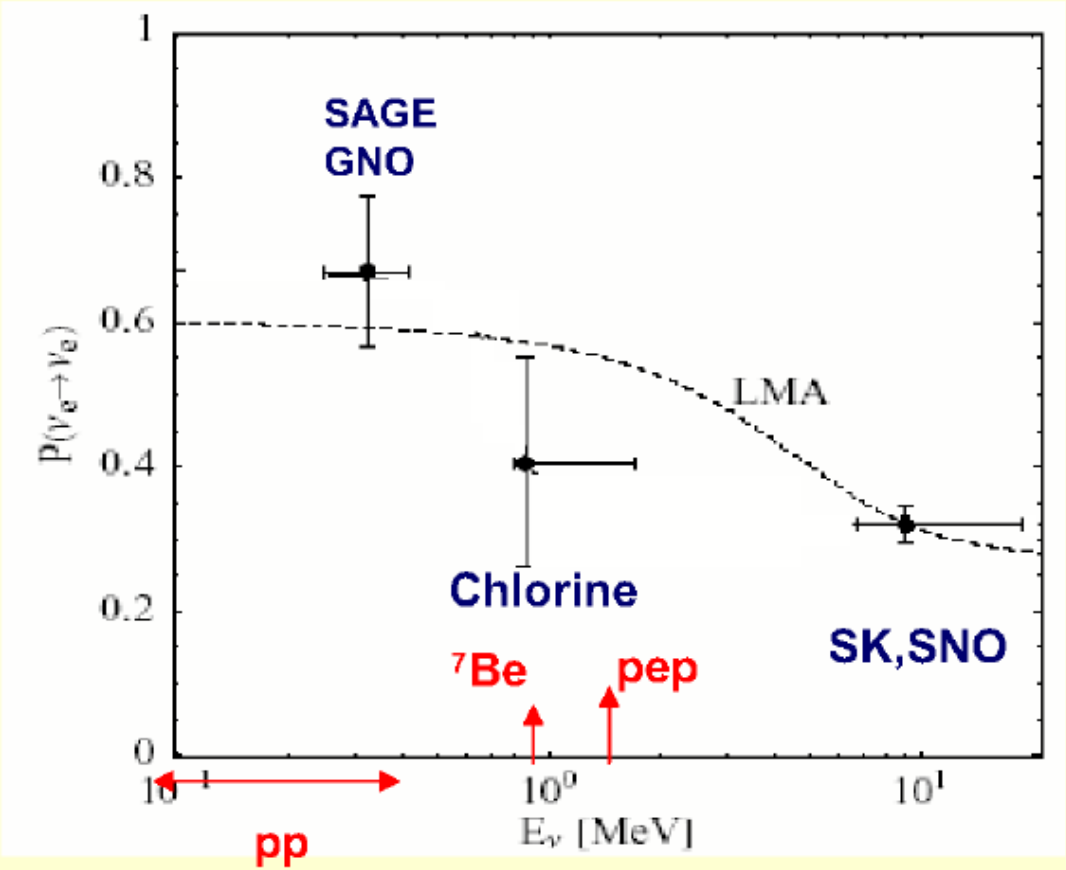
- Fine-tune Δm^2 such that the transition between the regimes occurs at the intermediate solar energies
  $\Delta m^2 \sim G_F N_\odot$ (10^6eV) $\sim$ a few $\times$ 10^{-5} eV^2
- Remarkably, checks with KamLAND reactor ν osc.!



Slide by A. Friedland (neutrino 2006) http://neutrinosantafe06.com/

Matter Interaction Effect:LMA

Current Data for ν_e Survival



From Slide by E. Akhmedov (neutrino 2006) http://neutrinosantafe06.com/

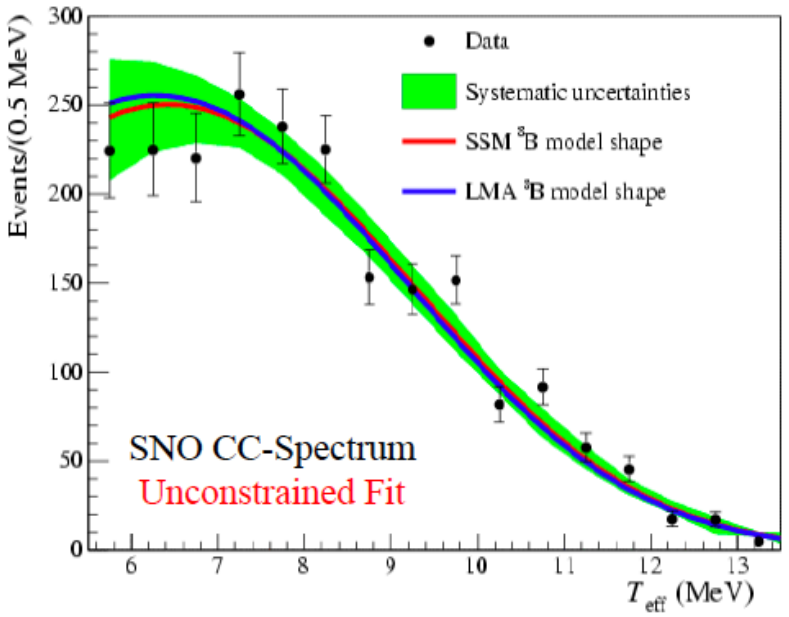
SNO Collaboration, PRC **72**, 055502 (2005)
391 Days of Dissolved Salt Data

$$\phi_{CC} = 1.68\ ^{+0.06}_{-0.06}(\text{stat.})^{+0.08}_{-0.09}(\text{syst.})$$

$$\phi_{NC} = 4.94\ ^{+0.21}_{-0.21}(\text{stat.})^{+0.38}_{-0.34}(\text{syst.})$$

$$\phi_{ES} = 2.35\ ^{+0.22}_{-0.22}(\text{stat.})^{+0.15}_{-0.15}(\text{syst.})$$

x 10^6 cm^{-2} s^{-1}



$$A_{DN} = \frac{\text{(Night-Day)}}{\text{(Day+Night)/2}}$$

$$A_{\text{salt + D}_2\text{O}} = 0.037 \pm 0.040$$

(assuming $A_{NC} = 0$)

Statistical Limitation for Observing "Small" Day-Night Asymmetry

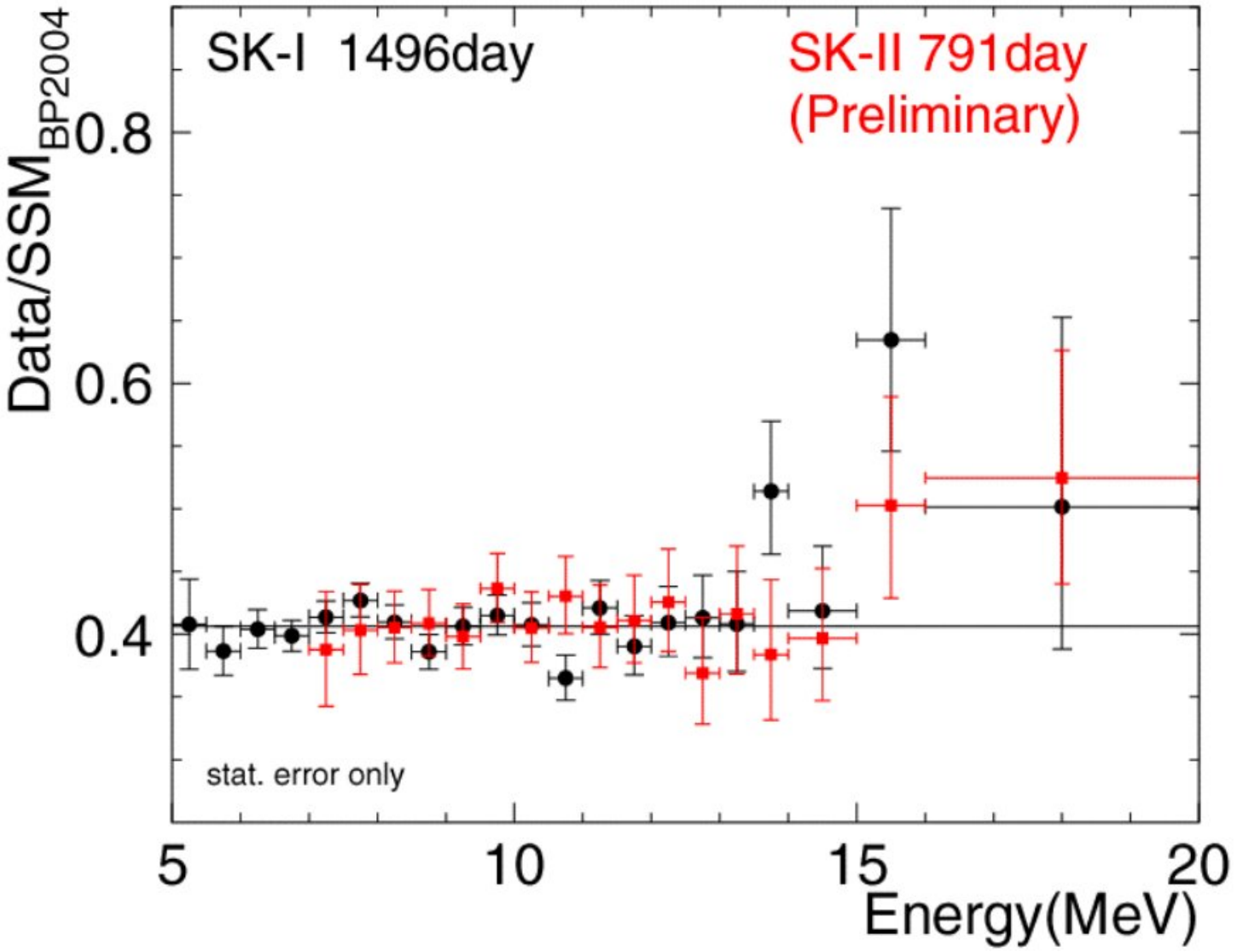
➔ Combined "Low-Energy Threshold" Analysis of D2O & Salt-Phase Data Sets

➔ Break CC-NC Correlation with Neutral-Current-Detectors (NCDs)

➔ Ultimately Combine Data from all Phases

Slide by A. Hime (neutrino 2006) http://neutrinosantafe06.com/

SK ES-Spectrum

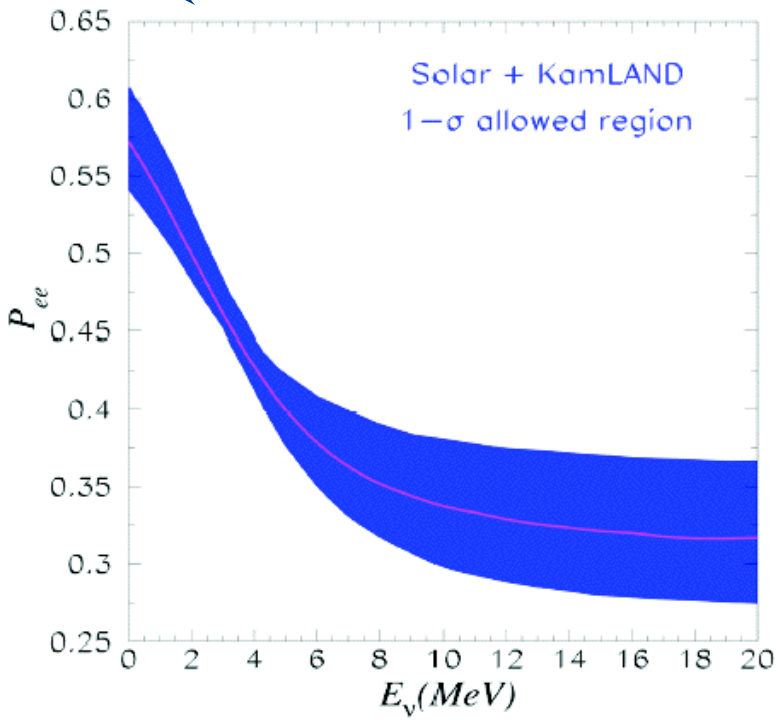


Slide by A. Hime (neutrino 2006) http://neutrinosantafe06.com/

Low-energy ^{8}B neutrino–MSW distortion

- If ^{208}Tl ($\beta + \gamma$, Q = 5 MeV) reduced enough
- $\rightarrow$ ^{232}Th reduction needed (distillation works?)

KamLAND: low-energy frontier



from Pena-Garay

"Geoneutrinos"

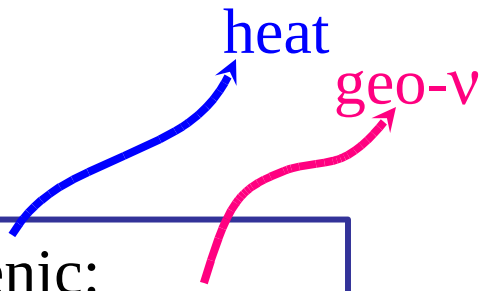
- Electron antineutrinos produced in the Earth's interior (crust and mantle) by decays of ^{238}U, ^{232}Th, and ^{40}K
- Decays of ^{238}U, ^{232}Th, and ^{40}K :

  ~40% of Earth's power

- Earth's power: $\rightarrow$ plate tectonics, earthquakes, volcanoes, geomagnetism, …
- Origin and history of the Earth
- Pointed out since ν discovered

  (1950's, G. Gamow, …)

Heat balance of the Earth



Heat flow measurement:

44 TW? (Pollack H.N. et al, Rev. Geophys 31, 267)

31 TW? (Hofmeister, A.M et al. Tectonophysics 395)

=

(?)

Radiogenic:

19 TW(McDonough et a. Chem. Geol. 120, 223)

+

Cooling of core, solidification of outer core, … (originates from initial gravitational energy)

Summary

- see talks S. Enomoto and I. Shimizu