EXTRACTING OSCILLATION PARAMETERS FROM NEUTRINO DATA

Andrea Donini
Instituto de Física Teórica, Madrid
UAM/CSIC

Outline of the course

Introduction

Lecture I: Solar Neutrinos (θ_{12}, Δm^2_{12})

Lecture II: Atmospheric Neutrinos (θ_{23}, Δm^2_{23})

Lecture III: Bounds on θ_{13} and δ

Lecture IV: Sterile Neutrinos

Introduction

- We need a ν_α neutrino flux, Φ_α
- We need a ν-N cross-section, $\sigma_{\nu N}$
- We need the detector efficiency for a given neutrino (lepton) flavor, ε_α
- We need the relevant oscillation probability: $P(\nu_\alpha \rightarrow \nu_\beta) = P(\theta_{ij},\delta;\Delta m^2_{ij})$
- Eventually, compute $N_\alpha = \int dE\ \Phi_\alpha \times \sigma_{\nu N} \times \varepsilon_\alpha \times P(\theta_{ij},\delta;\Delta m^2_{ij})$

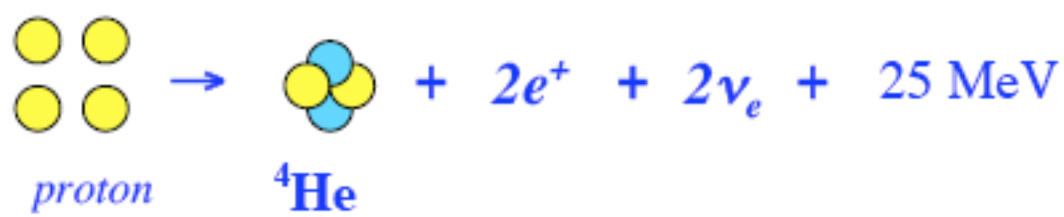
EXTRACTING Θ_{12} AND ΔM^2_{12} FROM SOLAR NEUTRINO DATA

Outline

- The solar neutrino fluxes
- The solar neutrino problem
- Fits to the solar neutrino data

Nuclear reactions in the Sun

Neutrinos are produced in the SUN by the same THERMONUCLEAR reactions that generate the SOLAR ENERGY. The total reaction is given by:



In the total thermonuclear reaction STRONG, EM and EW reactions take place (CHARGE and LEPTON NUMBER are CONSERVED). The main part of the solar energy is irradiated as PHOTON EMISSION (EM RADIATION) and NEUTRINO EMISSION:

$$Q_{RAD} = Q - 2\langle E_\nu \rangle \approx 26 \text{ MeV}$$

$$Q_\nu = 2\langle E_\nu \rangle \approx 0.6 \text{ MeV}$$

- The NUMBER of NEUTRINOS emitted is related to the SOLAR LUMINOSITY:

$$\begin{aligned} \mathcal{L}_{SUN} &\approx 3.8 \times 10^{26}\ \mathrm{W} = 2.4 \times 10^{39}\ \frac{\mathrm{MeV}}{\mathrm{s}} \\ \frac{dN_\nu}{dt} &= 2\frac{dN_{reac}}{dt} = 2\frac{\mathcal{L}_{SUN}}{Q_{RAD}} \approx 1.8 \times 10^{38}\ \mathrm{s}^{-1} \\ \Phi_{SUN}^{\nu_e} &= \frac{2}{4\pi D^2}\frac{\mathcal{L}_{SUN}}{Q_{RAD}} = 2\frac{\Phi_{SUN}^{\gamma}}{Q_{RAD}} \approx 6 \times 10^{10} \frac{\nu}{\mathrm{cm}^2\ \mathrm{s}} \end{aligned}$$

- The SOLAR LUMINOSITY is measured and can be predicted by the Solar Standard Model (SSM) as function of the SOLAR TEMPERATURE T_{SUN}

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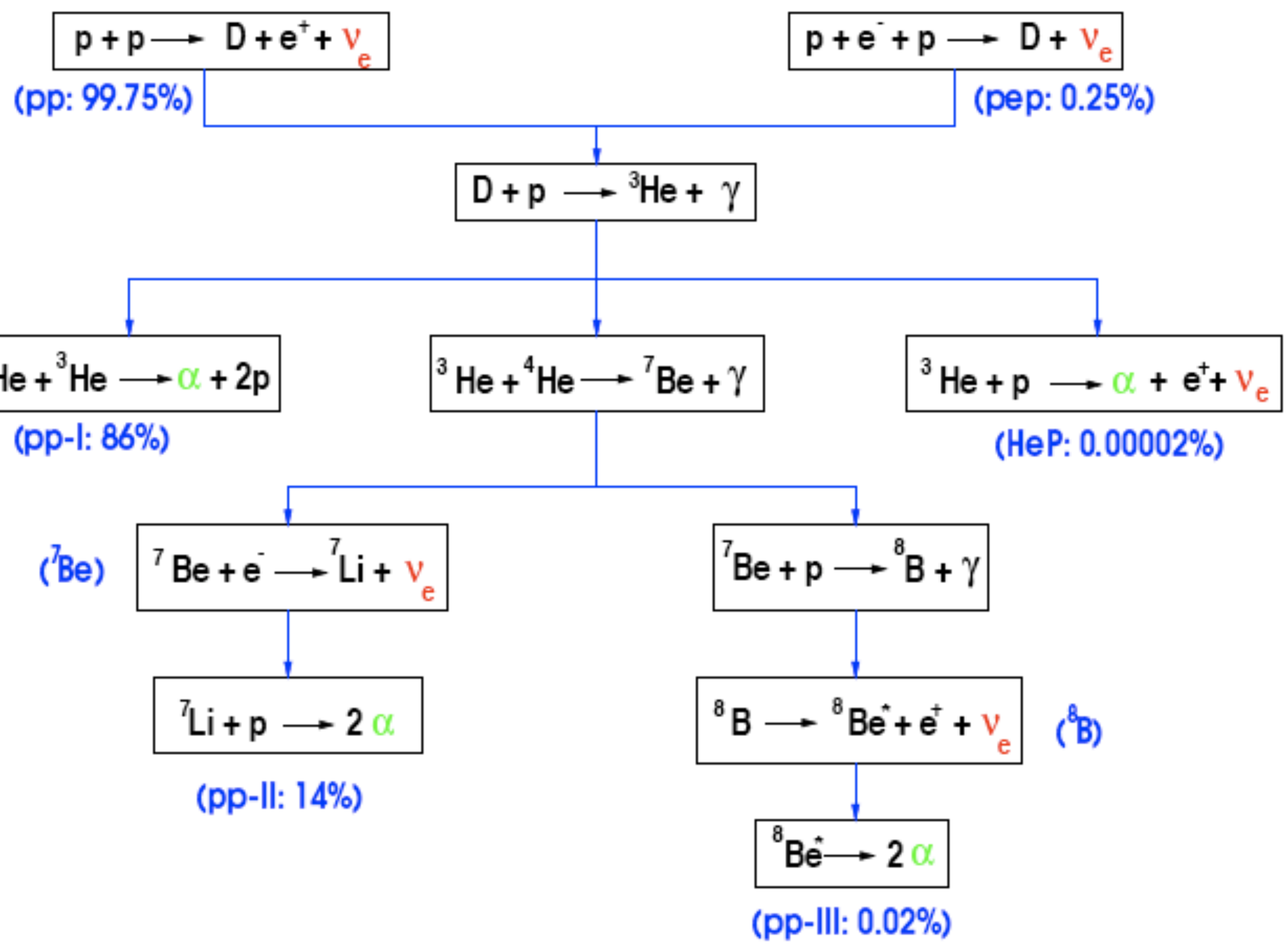
- The SOLAR LUMINOSITY is measured and can be predicted by the Solar Standard Model (SSM) as function of the SOLAR TEMPERATURE T_{SUN}

There are two cycles that produce ENERGY (and NEUTRINOS) in the SUN:

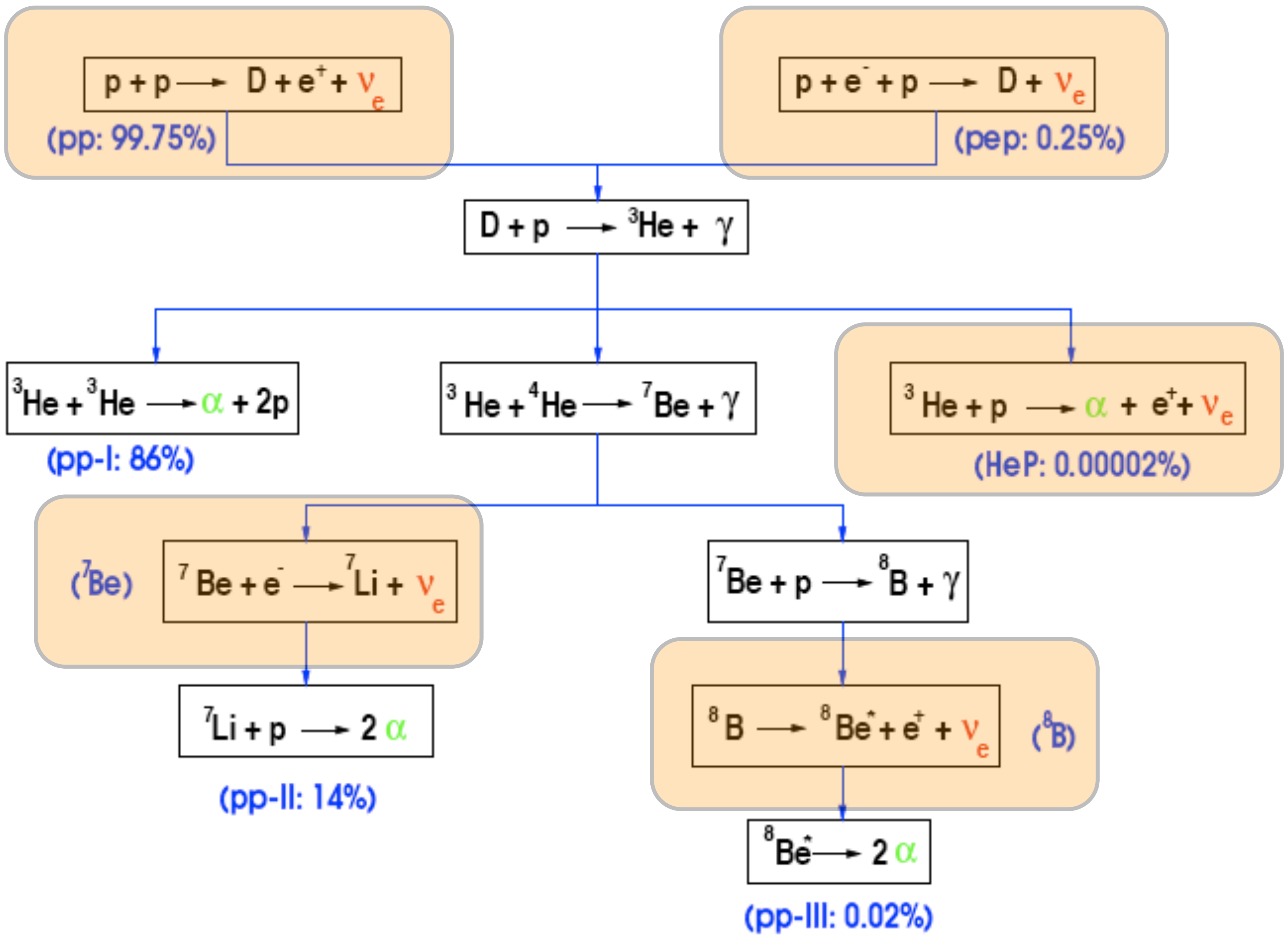
- The pp-CHAIN is the main source (98%) of the solar energy and of the solar neutrino flux.
- The CNO-CHAIN produce only the 2% of the solar energy and so is much less important (both for energy and neutrino production).

The pp-chain



p + p → D + e+ + νe
(pp: 99.75%)
p + e- + p → D + νe
(pep: 0.25%)
D + p → 3He + γ
3He + 3He → α + 2p
(pp-I: 86%)
3He + 4He → 7Be + γ
3He + p → α + e+ + νe
(HeP: 0.00002%)
(7Be)
7Be + e- → 7Li + νe
7Be + p → 8B + γ
7Li + p → 2 α
(pp-II: 14%)
8B → 8Be* + e+ + νe
(8B)
8Be* → 2 α
(pp-III: 0.02%)

The pp-chain



Five reactions produce neutrinos

- In the pp-CHAIN there are FIVE DIFFERENT SOURCES of ν_e , identified by the reaction in which are produced: (1) pp, (2) pep, (3) Be, (4) B, (5) hep:

  ★ pp, B and hep neutrinos are produced in a 3 body reaction and so have a CONTINUOUS SPECTRUM of ENERGY

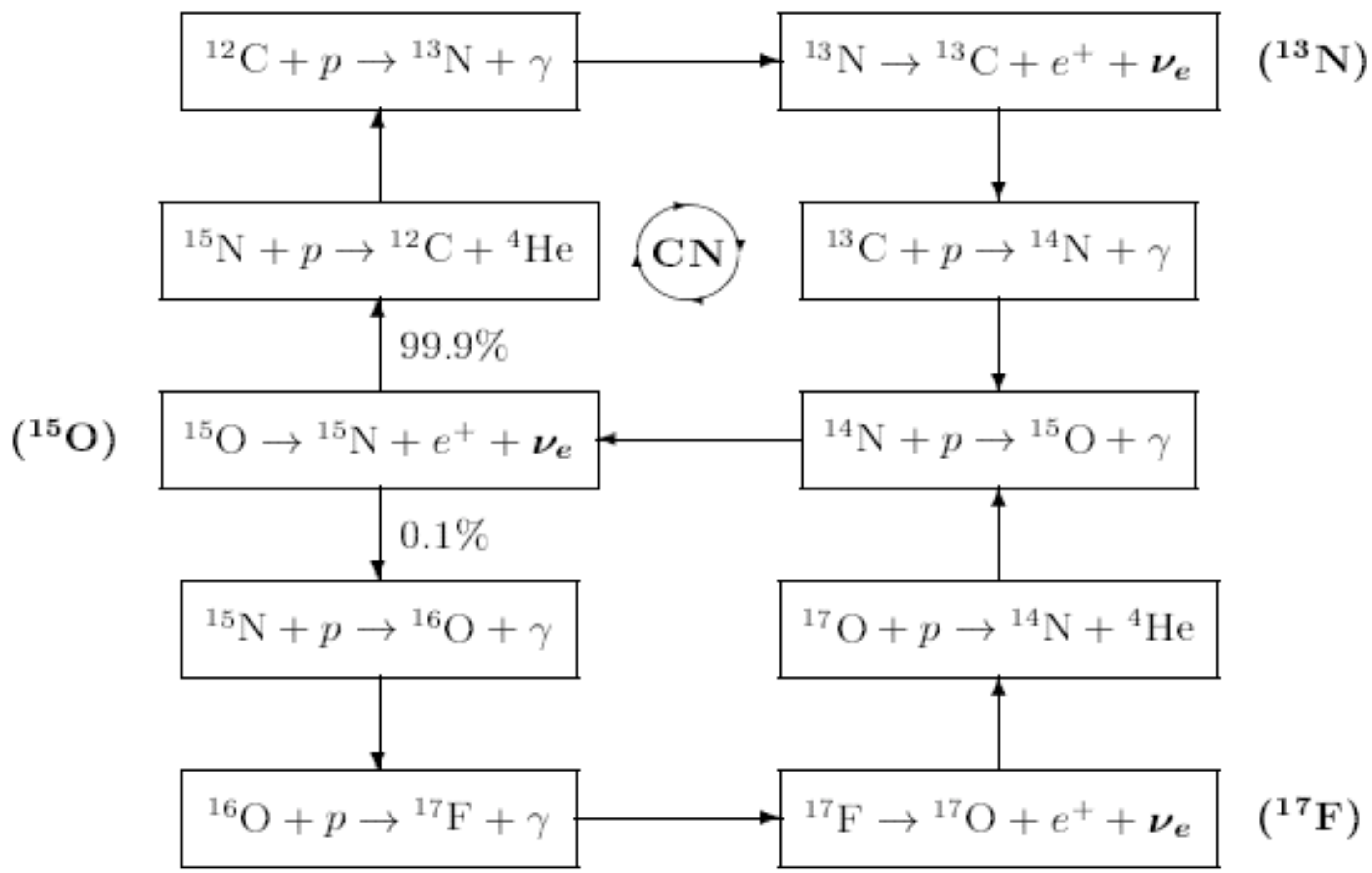
  ★ pep and Be neutrinos are produced in a 2 body reaction and so have a MONO-ENERGETIC SPECTRUM

- As ^{7}Be and ^{8}B are produced only in reactions that burn ^{3}He, that is a by-product coming only from the original pp and pep reactions, the following ν_e flux relation must hold:

$$\Phi_{Be} + \Phi_B \leq \Phi_{pp} + \Phi_{pep}$$

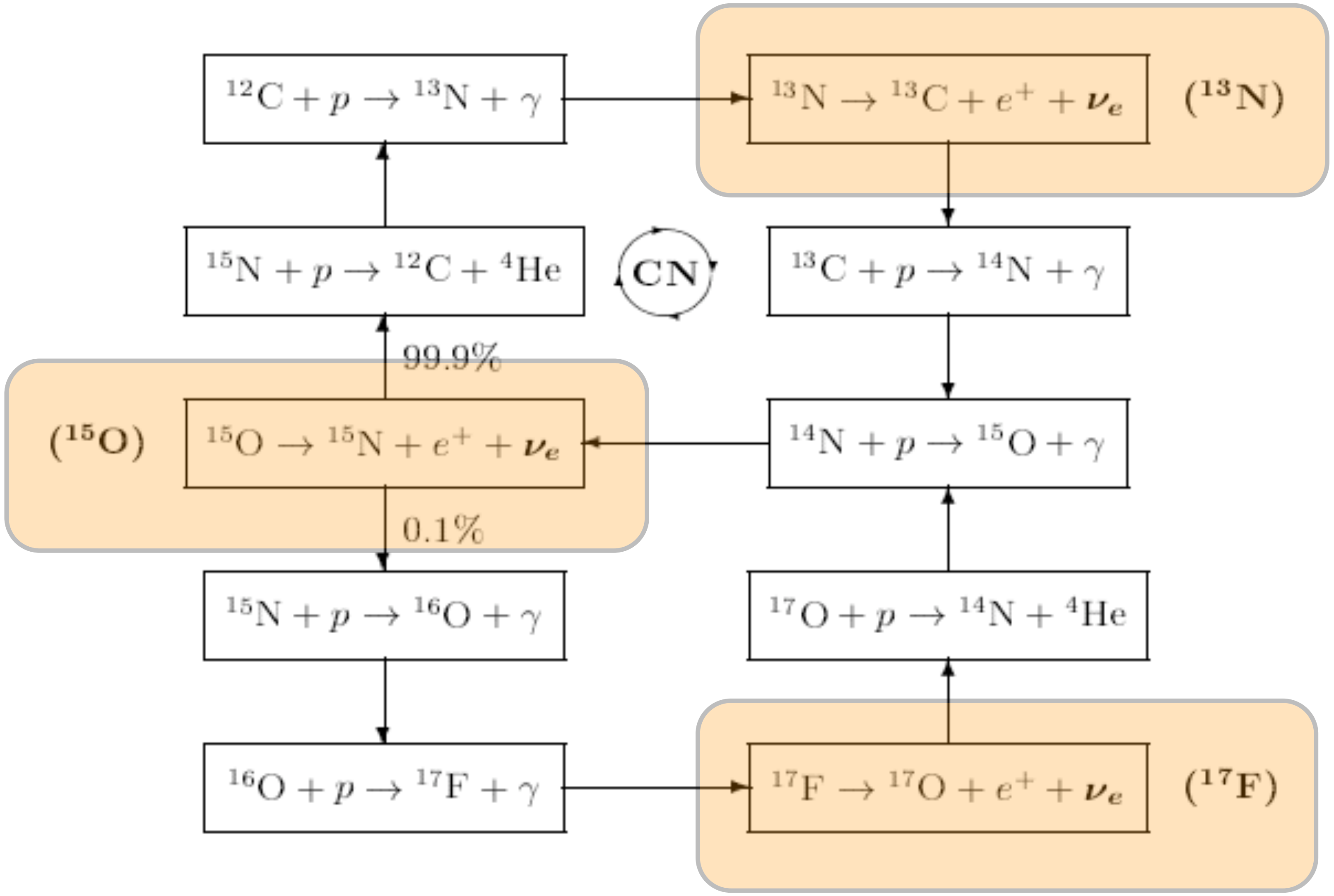
This relation will be useful for constraining the relative observed fluxes.

(a2) CNO - CHAIN



$^{12}C + p \rightarrow {}^{13}N + \gamma$
$^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$
(^{13}N)
$^{15}N + p \rightarrow {}^{12}C + {}^4He$
CN
$^{13}C + p \rightarrow {}^{14}N + \gamma$
99.9%
(^{15}O)
$^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$
$^{14}N + p \rightarrow {}^{15}O + \gamma$
0.1%
$^{15}N + p \rightarrow {}^{16}O + \gamma$
$^{17}O + p \rightarrow {}^{14}N + {}^4He$
$^{16}O + p \rightarrow {}^{17}F + \gamma$
$^{17}F \rightarrow {}^{17}O + e^+ + \nu_e$
(^{17}F)

(a2) CNO - CHAIN



Three reactions produce neutrinos

- There are 3 DIFFERENT SOURCES of ν_e fluxes in the CNO-CHAIN:
  - N-neutrinos produced in the $^{13}N \rightarrow {}^{13}C$ reaction
  - O-neutrinos produced in the $^{15}O \rightarrow {}^{15}N$ reaction
  - F-neutrinos produced in the $^{17}F \rightarrow {}^{17}O$ reaction

All these three sources of ν_e have a continuous spectrum. The combination of low fluxes and low ν_e energies make these fluxes less relevant for the solar neutrinos experiment (even if they are included in the theoretical calculations of the SSM).

$\Downarrow$

The MAIN SOURCE of SOLAR RADIATION and SOLAR NEUTRINOS is the pp-CHAIN

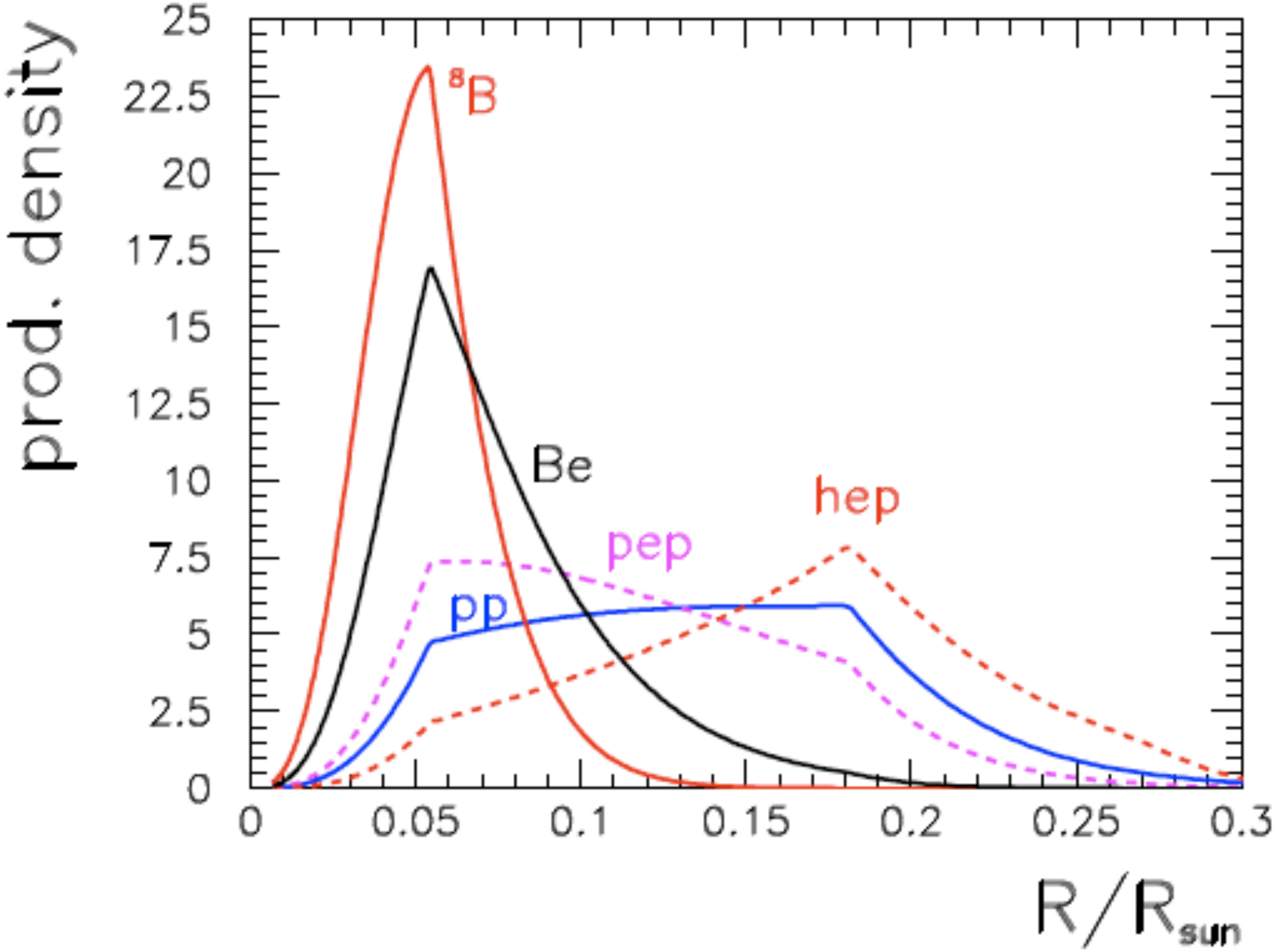
(b) SOLAR NEUTRINOS FLUXES and SOLAR STANDARD MODEL

In order to precisely determine the rates of the different reactions in the two chains which would give the final neutrino fluxes and their energy spectrum a DETAILED KNOWLEDGE of the SUN and its evolution is required. Moreover neutrinos are produced very deeply in the SUN (see Fig. 1) so one has to understand the SOLAR DYNAMICS to very small radius $R \ll R_{SUN}$. The SSM is based on few OBSERVATIONAL PARAMETERS and BASIC ASSUMPTIONS:

- Luminosity, radius, surface and core temperature, mass and approximate age;
- Chemical composition (abundance of H, He and heavier elements);
- Sferical symmetry, hydrostatic equilibrium, opacity;

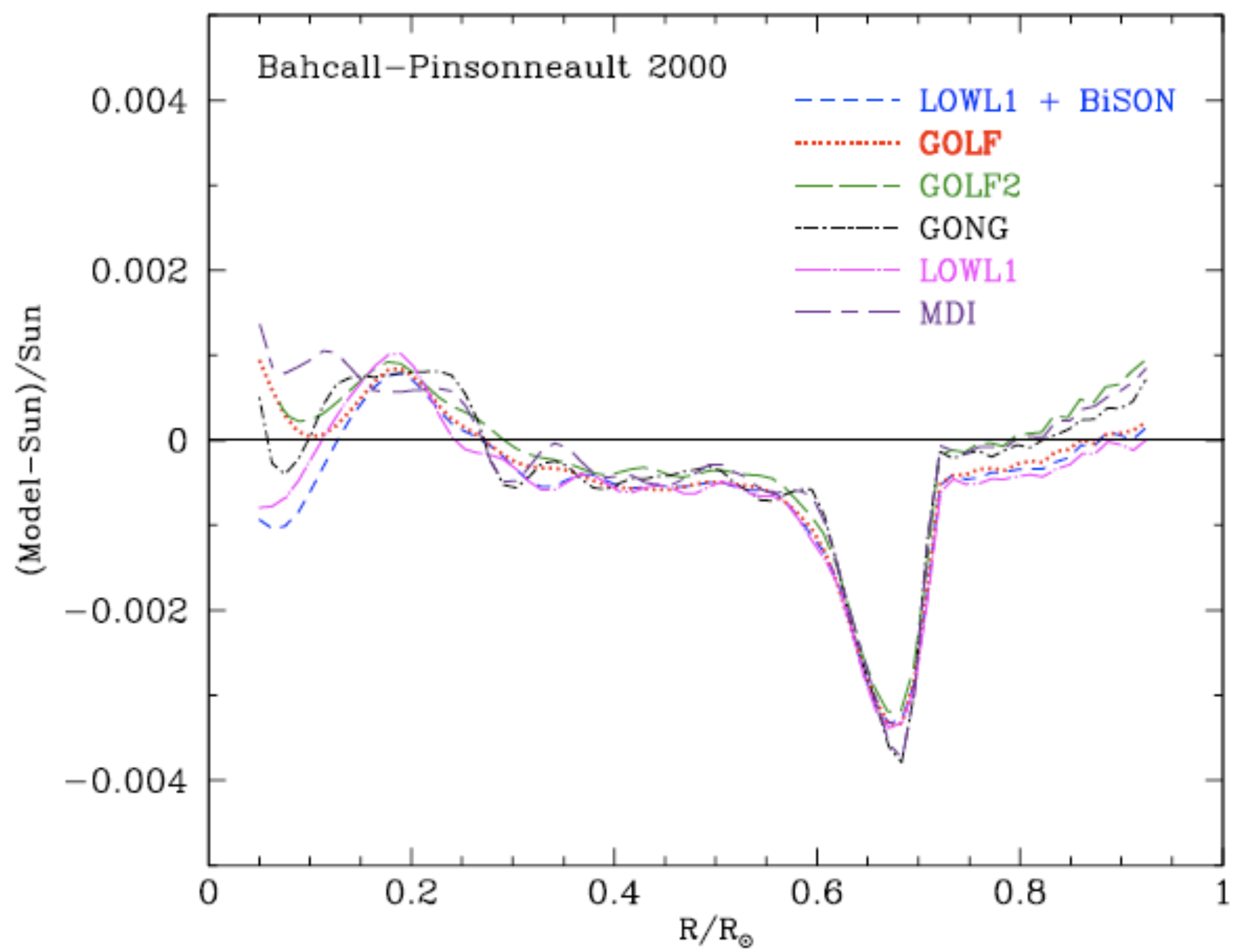
SOLAR NEUTRINO FLUXES
change very little in different
SOLAR MODELS

Solar neutrino fluxes

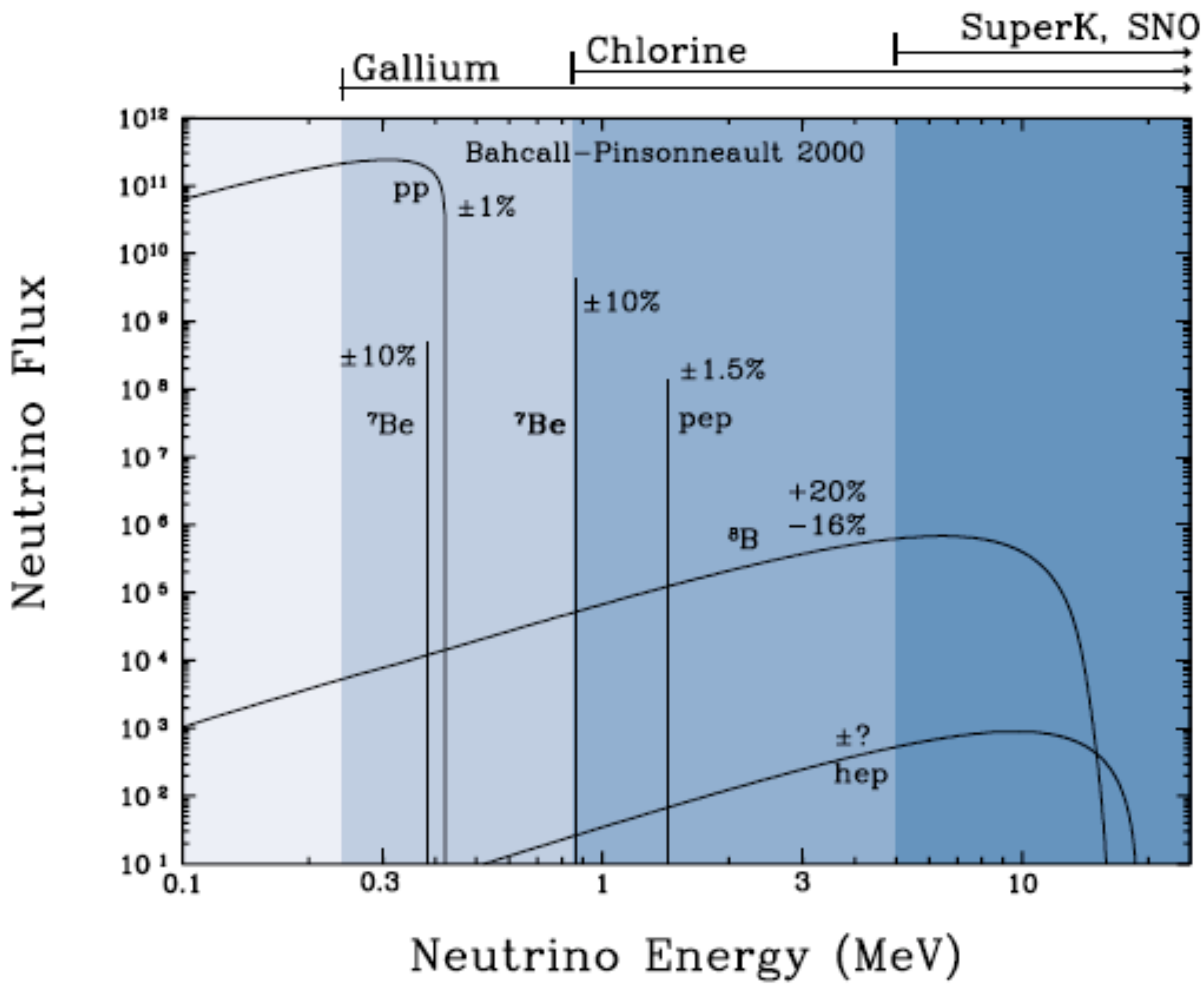


The SSM has also been INDEPENDENTLY TESTED by HELIOSEISMOLOGY

The sun surface undergoes to periodic oscillations with a period of 5-10 minutes. One can decompose this oscillations in a Fourier spectrum measuring more than 3000 p-waves (p=pressure). The frequencies of these waves are correlated with the speed of sound at a certain solar radius. Many of these p-waves excite the deepest part of the sun. The sound speed is related to the physical characteristic of the matter inside the sun (density, temperature, internal rotation rate).



Neutrino spectrum



(1) pp-neutrinos: represent the largest fraction (95%) of the total ν_e flux ($\approx 6 \times 10^{10}$ cm^{-2} s^{-1}). The energy spectrum is CONTINUOUS with $E_{pp}^{max} = 0.426$ MeV and $\langle E_{pp} \rangle = 0.27$ MeV. The pp-flux calculation presents a 1% indetermination.

(2) hep-neutrinos: have a very low flux (10^{-7} respect to pp-neutrino flux). The energy spectrum is CONTINUOUS with $E_{hep}^{max} = 18.8$ MeV and $\langle E_{hep} \rangle = 9.6$ MeV. So they are the most energetic component of the solar ν_e spectrum. This neutrino flux is not known precisely.

(3) Be-neutrinos: represent the second largest fraction of the total ν_e flux (10^{-1} respect to pp-neutrino flux). The energy spectrum presents two MONO ENERGETIC lines with $E_{Be} = 0.38, 0.86$ MeV. The calculation of this flux presents a 10% indetermination.

(4) pep-neutrinos: have a flux that is 10^{-4} respect to pp-neutrino flux. The energy spectrum presents a MONO ENERGETIC with $E_{pep} = 1.445$ MeV. The pep-flux have a small indetermination roughly 1.5%.

(5) B-neutrinos: is the largest component in the high energy part of the spectrum (10^{-4} compared to the pp-neutrino flux). The energy spectrum is continuous with $E_B^{max} = 15$ MeV and $\langle E_B \rangle = 6.7$ MeV. This flux presents 20% indetermination.

Source r	Reaction	$\langle E \rangle_r$ (MeV)	$E_r^{\max}$ (MeV)	α_r (MeV)
pp	$p + p \to d + e^+ + \nu_e$	0.2668	0.423 ± 0.03	13.0987
pep	$p + e^- + p \to d + \nu_e$	1.445	1.445	11.9193
hep	$^3\text{He} + p \to {}^4\text{He} + e^+ + \nu_e$	9.628	18.778	3.7370
^7Be	$e^- + {}^7\text{Be} \to {}^7\text{Li} + \nu_e$	0.3855 0.8631	0.3855 0.8631	12.6008
^8B	$^8\text{B} \to {}^8\text{Be}^* + e^+ + \nu_e$	6.735 ± 0.036	~ 15	6.6305
^{13}N	$^{13}\text{N} \to {}^{13}\text{C} + e^+ + \nu_e$	0.7063	1.1982 ± 0.0003	3.4577
^{15}O	$^{15}\text{O} \to {}^{15}\text{N} + e^+ + \nu_e$	0.9964	1.7317 ± 0.0005	21.5706
^{17}F	$^{17}\text{F} \to {}^{17}\text{O} + e^+ + \nu_e$	0.9977	1.7364 ± 0.0003	2.363

Table 1: Sources of solar neutrinos. For each reaction r, $\langle E \rangle_r$ is the average neutrino energy, $E_r^{\max}$ is the maximum neutrino energy and α_r is the average thermal energy released together with a neutrino from the source r that enters in the luminosity constraint.

Typical neutrino energy: 1-10 MeV

THE SOLAR NEUTRINO PROBLEM

(a) Chlorine: Homestake 1970-1994

CHLORINE Experiment was made in Homestake Mine using a detector of 615 tons of Cl_2Cl_4 (perchloroethylene). It counts the number of ν_e interactions using the ν_e capture reaction:

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

- The energy threshold for the reaction is $E_{th} = 0.814$ MeV and so the chlorine experiment is sensitive only to pep, Be, B and hep neutrinos

(i.e. to all the spectrum)

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(b) Gallium: SAGE (1990-2001) and GALLEX (1991-2000)

Two different Gallium experiments were made: SAGE (Soviet American Gallium Experiment) in Caucasus and GALLEX in Gran Sasso. Both the experiments count the number of ν_e interactions using the ν_e absorption reaction:

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

- The energy threshold for the reaction is $E_{th} = 0.233$ MeV, much smaller then the CHLORINE experiment so the GALLIUM experiments are sensitive to all the components of the solar ν_e flux, in particular to the main flux of pp neutrinos

The radiochemical data are usually reported in unit of SNU (Solar Neutrino Unit = 10^{-36} captures/atom/s), instead of neutrinos fluxes, permitting a simpler interpretation and correlation of experimental data. The results reported by both the radiochemical experiments:

$$\begin{cases} \Phi_{Cl}^{SSM} = 7.7 \pm 1 \; SNU \\ \Phi_{Cl}^{exp} = 2.56 \pm 0.22 \; SNU \end{cases} \rightarrow \left(\frac{EXP}{SSM}\right)_{Cl} = 0.33 \pm 0.05$$

$$\begin{cases} \Phi_{Ga}^{SSM} = 128 \pm 8 \; SNU \\ \Phi_{Ga}^{exp} = 74.4 \pm 4.7 \; SNU \end{cases} \rightarrow \left(\frac{EXP}{SSM}\right)_{Ga} = 0.60 \pm 0.07$$

are in complete disagreement with the prediction of the SSM calculations (see Tab. 1).

- Chlorine experiment sees only 1/3 of the expected ν_e flux
- Gallium experiments see roughly 1/2 of the expected ν_e flux

ENERGY DEPENDENT SUPPRESSION ??

(Gallium measure pp-neutrinos, Chlorine no)

(c) KamiokaNDE (1987-1995) and SuperKamiokaNDE (1996-)

Kamiokande and Super-Kamiokande are REAL-TIME Water Cerenkov detectors (of respectively 4.5 kTon and 50 kTon of water) placed 1 km underground. They measure the flux of ν_e neutrinos using the QE scattering process (dominant in the MeV region):

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

In principle K and SK are sensitive to all the active neutrinos species (through NC QE interaction). But due to the usual suppression of NC respect to CC (QE) interaction one has:

$$\sigma_{ES}(\nu_\mu \, e) \approx 0.16 \, \sigma_{ES}(\nu_e \, e)$$

K and SK measure mainly ν_e solar neutrinos

- The energy threshold in a water Cerenkov detector depends on the background suppression level. For K and SK the threshold was defined at:

$$\begin{cases} E_{th}^{K} &= 6.75 \text{ MeV} \\ E_{th}^{SK} &= 4.75 \text{ MeV} \end{cases}$$

So K and SK experiments are sensitive only to higher energy part of the solar neutrino spectrum: B and hep neutrinos. As the hep neutrino flux is negligible K and SK measure essentially the B neutrino flux. The measured fluxes and the prediction from SSM are:

$$\begin{cases} \Phi_B^{SSM} &= 5.05 \pm 1 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1} & & \\ \Phi_K^{exp} &= 2.82 \pm 0.37 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1} & \rightarrow & \left(\frac{EXP}{SSM}\right)_B = 0.56 \pm 0.15 \\ \Phi_{SK}^{exp} &= 2.348 \pm 0.070 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1} & \rightarrow & \left(\frac{EXP}{SSM}\right)_B = 0.465 \pm 0.094 \end{cases}$$

$\Rightarrow$ **MISSING 1/2 of the B NEUTRINOS !!!**

- Being a REAL-TIME detectors and due to the correlation between the direction of the neutrino and the recoiling lepton both K and SK are able to prove the provenience of the neutrinos. So one can obtain the following additional informations:

1) Confirm that neutrino are coming from the Sun

2) Look for deviations from the SSM

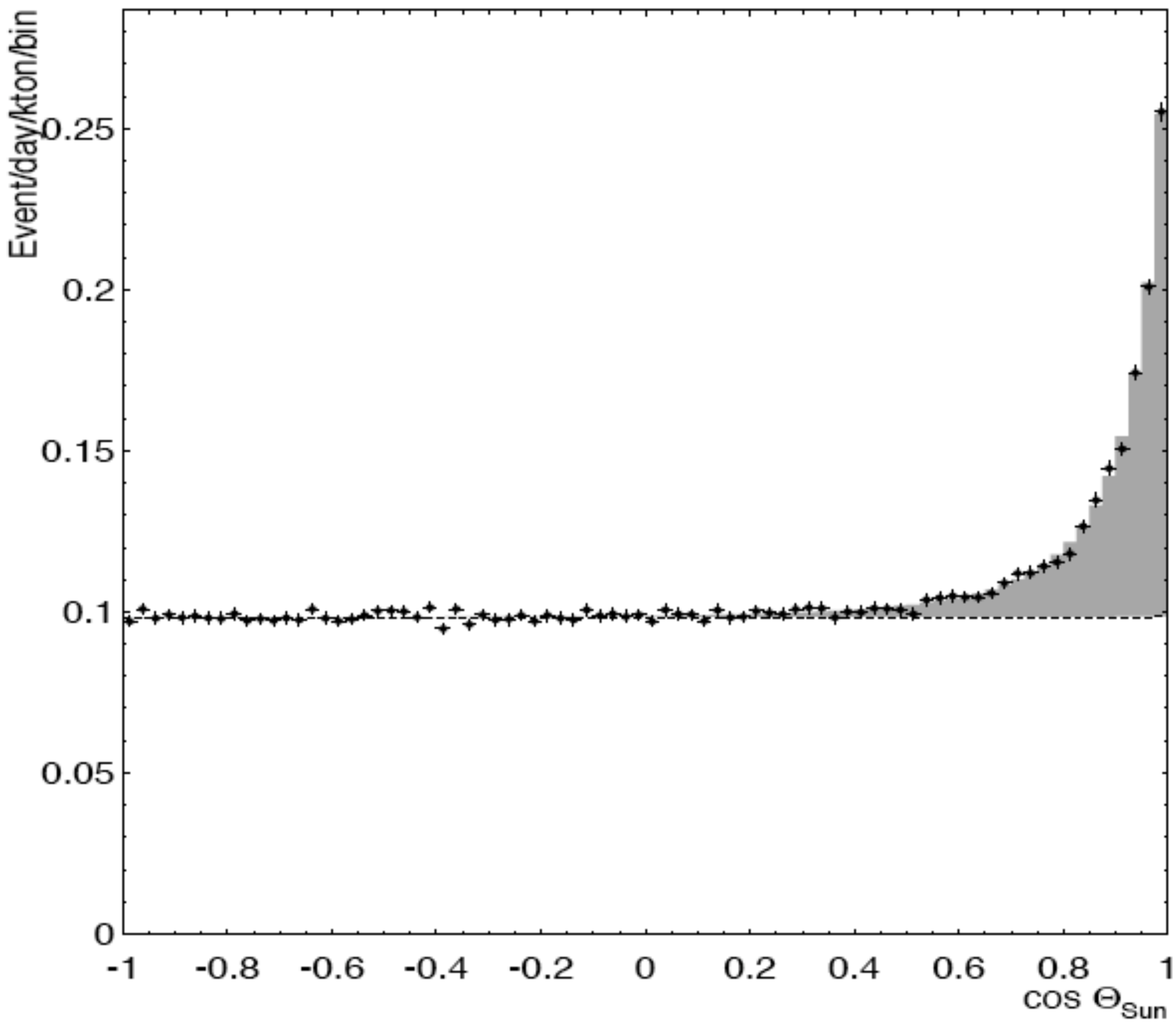
3) Measure the difference between Day and Night fluxes

$$\mathcal{A}_{N-D} = 2\,\frac{N-D}{N+D} = 0.021 \pm 0.020 \pm 0.013$$

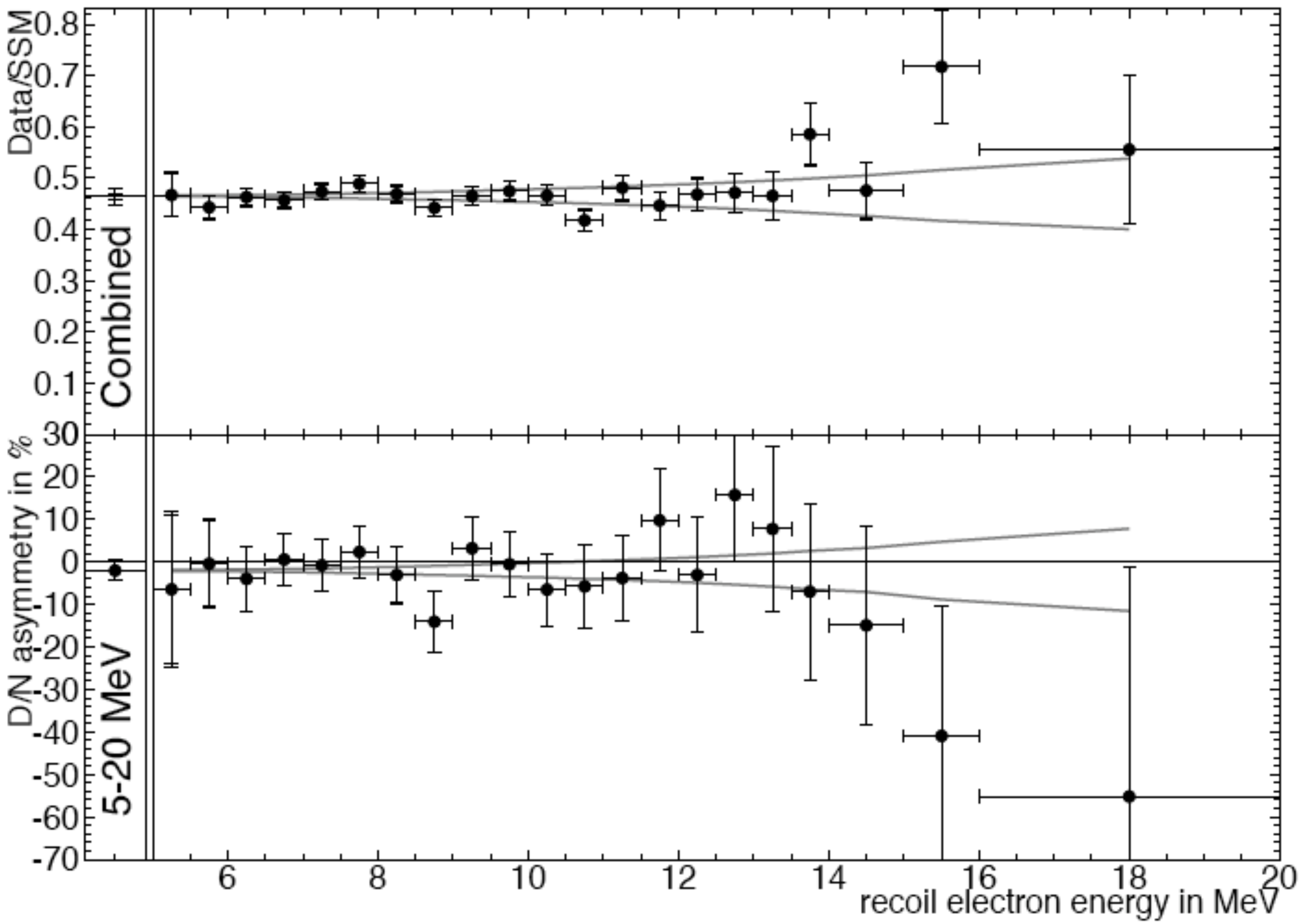
4) Measure seasonal variations of the neutrino fluxes

The last two measurements are important to constrain the oscillation pattern

Directionality



Day-Night asymmetry



(d) Sudbury Neutrino Observatory, SNO (1999-)

A very important piece for solving the solar neutrino puzzle has recently been added by the SNO experiment. SNO detector is a REAL TIME HEAVY WATER (1 kTon of D_2O) tank surrounded by photomultipliers. The SOLAR NEUTRINOS can be detected using 3 different reactions:

(i) CC reaction $\nu_e + d \rightarrow e^- + 2\,p$ with threshold energy $E_{th} = 8.2$ MeV. In the measure of CC interactions SNO is sensitive exclusively to electron neutrinos;

(ii) ES process $\nu_x + e^- \rightarrow \nu_x + e^-$ with threshold energy $E_{th} = 7.0$ MeV. In the measure of ES interactions $\sigma_{ES}(\nu_{\mu,\tau} e) \approx 0.16\ \sigma_{ES}(\nu_e\ e)$ so SNO (as K and SK) is mainly sensitive to electron neutrinos and has low sensitivity to ν_μ and ν_τ fluxes.

(iii) NC reaction $\nu_x + d \rightarrow \nu_x + n + p$ with threshold energy $E_{th} = 2.2$ MeV. In the measure of NC interactions as $\sigma_{NC}(\nu_{\mu,\tau} e) = \sigma_{NC}(\nu_e\ e)$ SNO is equally sensitive to all active neutrinos (enhancing the NC with the addition of $MgCl_2$ and ^{3}He in 2nd and 3rd stages);

Due to the high energy threshold in all the processes also SNO is sensitive only to higher part of the B and hep neutrino flux (as in K and SK where only ES was measured).

★ SNO is SENSITIVE to ALL the ACTIVE NEUTRINO SPECIES ★

In the FIRST PHASE (1999-2001 – heavy water) SNO obtained the following RESULTS:

- The B solar neutrino flux measured by SNO using the ES process:

$$\begin{cases} \Phi_B^{SSM} = 5.05 \pm 1.00 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1} \\ \Phi_{SNO}^{ES} = 2.39 \pm 0.36 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1} \end{cases} \rightarrow \left(\frac{EXP}{SSM}\right)_B = 0.47 \pm 0.15$$

  is CONSISTENT with SuperKamiokande determination and confirm a DEFICIT on the B neutrino flux reaching the earth. Also SNO can measure the electron recoiling spectrum showing (consistently with SK) NO DISTORTION:

⇒ ONLY 1/2 of the EXPECTED B-flux IS OBSERVED

- The solar ν_e flux measured using the CC process:

$$\begin{cases} \Phi^{SSM}_{\nu_e} = 5.05 \pm 1.00 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1} \\ \Phi^{CC}_{SNO} = 1.76 \pm 0.11 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1} \end{cases} \rightarrow \left(\frac{EXP}{SSM}\right)_{\nu_e} = 0.35 \pm 0.07$$

gives exactly the ν_e flux reaching the earth.

$\Rightarrow$ ONLY 1/3 of the EXPECTED ν_e -FLUX IS OBSERVED

- The solar ν_x flux measured using the NC process

$$\begin{cases} \Phi^{SSM}_{\nu_e} = 5.05 \pm 1.00 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1} \\ \Phi^{NC}_{SNO} = 5.09 \pm 0.64 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1} \end{cases} \rightarrow \left(\frac{EXP}{SSM}\right)_{\nu} = 1.01 \pm 0.23$$

gives the total flux of all ACTIVE NEUTRINOS:

$\Rightarrow$ The TOTAL ACTIVE NEUTRINO FLUX is CONSISTENT with the SSM

SNO measurement of CC, NC and ES process **SHOWS EVIDENCE** of ν_e **CONVERSION** into ν_μ and ν_τ . Using NC and CC measurements one can extimate the active non ν_e flux:

$$\Phi_{SNO}(\nu_\mu + \nu_\tau) \approx \Phi_{SNO}^{NC} - \Phi_{SNO}^{CC} = \Phi_{\nu_\mu+\nu_\tau}^{NC} = 3.41 \pm 0.66 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$$

It's 5.3 σ EVIDENCE of NON-ν_e COMPONENTS in the SOLAR FLUX

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It's 5.3 σ EVIDENCE of NON-ν_e COMPONENTS in the SOLAR FLUX

- SNO measures also the DAY-NIGHT asymmetry:

$$\mathcal{A}_{N-D} = 2\frac{N-D}{N+D} = 0.070 \pm 0.051$$

founding a 1.5 σ preference for a SMALL asymmetry compatible with the SuperKamiodande DAY-NIGHT asymmetry.

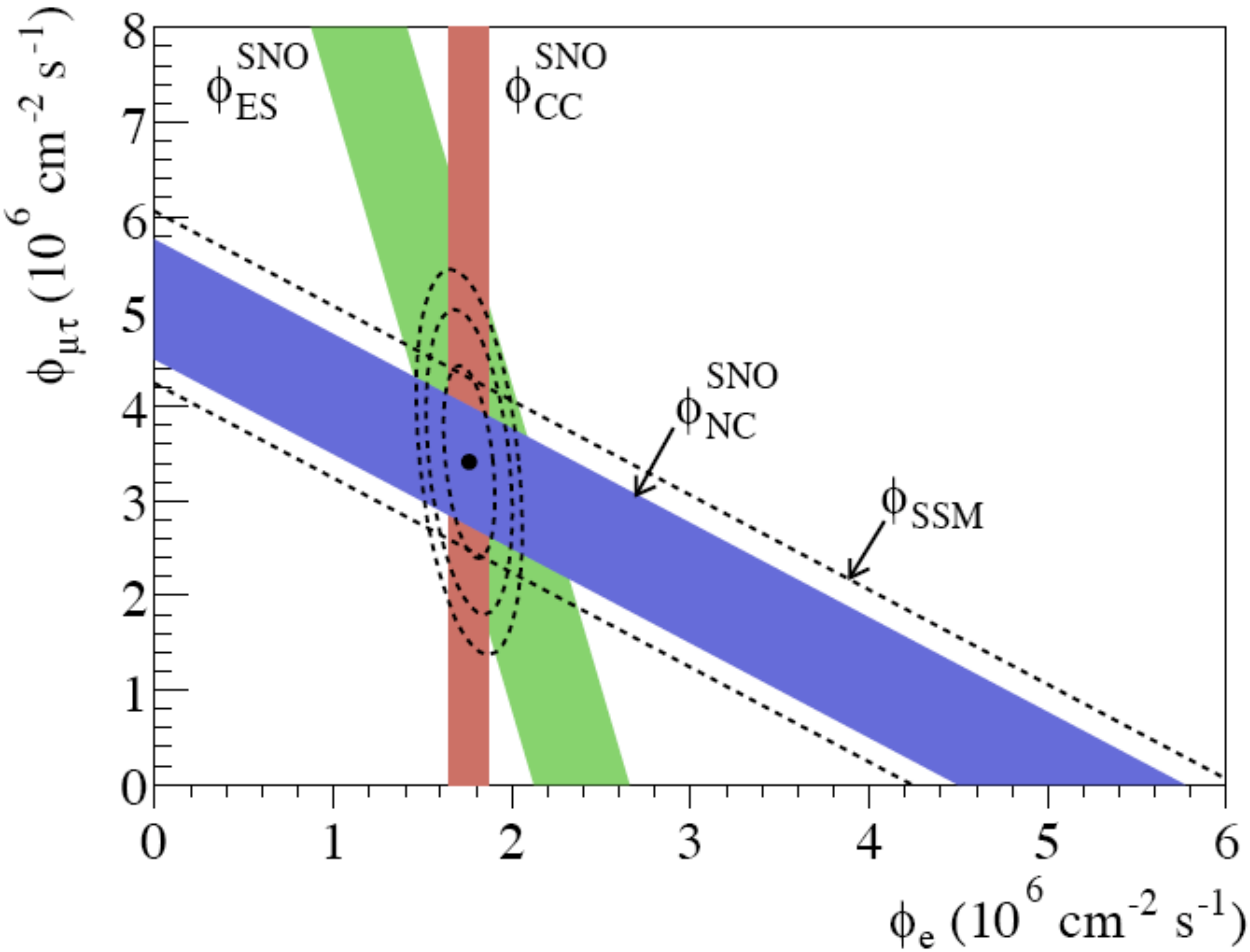

Figure 10: Flux of ν_μ and ν_τ vs flux of ν_e in the ^{8}B energy range deduced from the three neutrino reactions in SNO. The diagonal bands show the total BP2000 ^{8}B flux (dashed lines) and that measured with the NC reaction in SNO (solid band). The intercepts of these bands with the axes represent the $\pm 1\sigma$ errors. The bands intersect at the fit values for $\phi_e \equiv \Phi_{\nu_e}$ and $\phi_{\mu\tau} \equiv \Phi_{\nu_{\mu,\tau}}$.

In the SECOND PHASE or "salt phase" (2002-2003) $MgCl_2$ was added to the heavy water for improving the NC measurement (better efficiencies in neutron capture). In the FIRST PHASE NC were measured observing the photons emitted in neutron-deuteron capture (37% eff):

$$n + d \rightarrow {}^3He + \gamma \quad (E_\gamma = 6.25\text{MeV})$$

The presence of NaCl provides a new neutron capture mechanism (90% eff, 50% total):

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

with better experimental signature and higher cross section. The new measures give:

$$\begin{cases} \Phi_{SNO}^{NC} = 5.21 \pm 0.47 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1} \\ \Phi_{SNO}^{CC} = 1.59 \pm 0.10 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1} \end{cases} \rightarrow \frac{\Phi_{SNO}^{CC}}{\Phi_{SNO}^{NC}} = 0.306 \pm 0.035$$

It's 19σ EVIDENCE of NON-ν_e COMPONENTS in the SOLAR FLUX

To be updated ! Third phase data have been released!

In the THIRD PHASE (2004-) a new detection mechanism will be implemented introducing a discrete array of ^{3}He proportional counters that detect the free neutron through the reaction:

$$n + {}^3He \rightarrow {}^3H + p \qquad (Q = 0.76 \text{ MeV})$$

the final charged particles detected via proportional counters or scintillator detectors.

- Provides a new and independent method for measuring the NC neutrino interactions;
- Expected improvements in the statistics and systematics errors.

Nothing astonishing has been shown...

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Nothing astonishing has been shown...

★ **SNO has FINALLY solved the SOLAR PROBLEM** ★

(e) KamLAND reactor experiment (2002-)

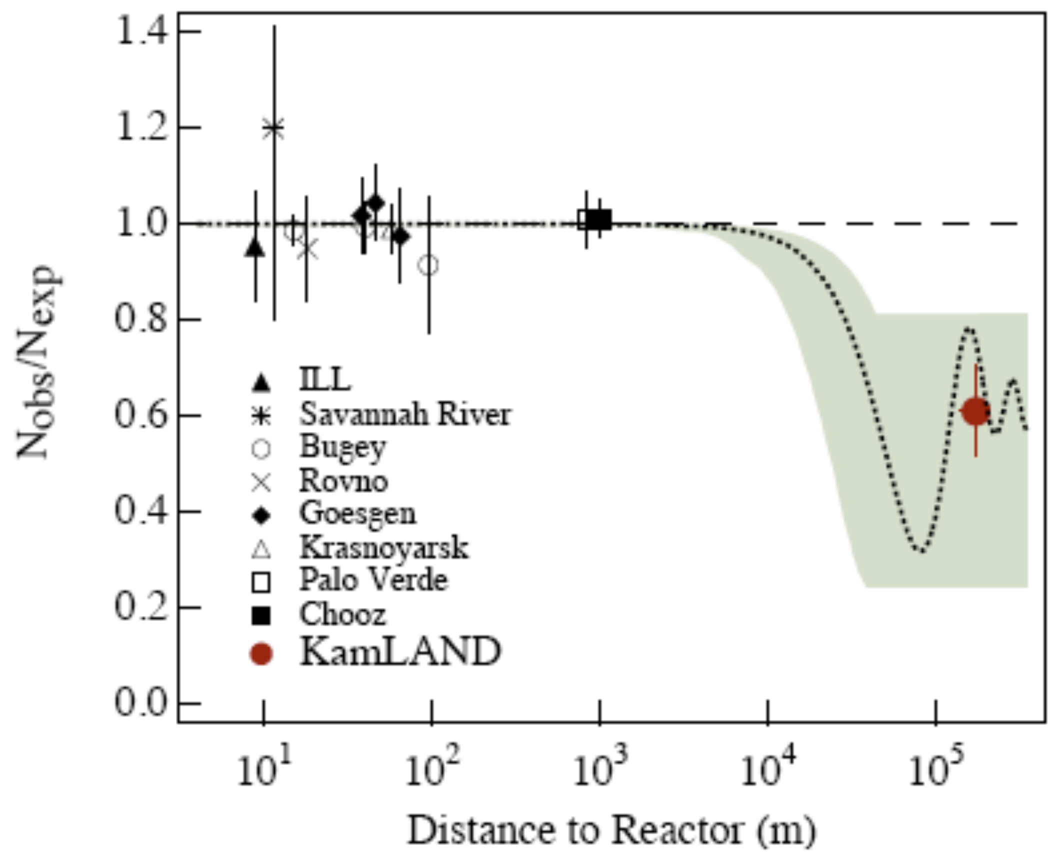
KamLand is a 1-kton liquid scintillator detector based in the Kamioka mine (1000 m underground) and measure the flux on $\bar{\nu}_e$ coming from a bunch of nuclear reactors situated at an average distance of 180 km using the inverse β-decay process:

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

- The energy threshold for the liquid scintillator detector is $E_{th}^{\bar{\nu}_e p} = 1.8$ MeV
- Measuring disappearance of $\bar{\nu}_e$ emitted by nuclear reactors founds (see left plot of Fig. 17):

$$\begin{cases} N_{data} = 54 \\ N_{back} = 0.95 \pm 0.99 \\ N_{theo} = 86.8 \pm 5.6 \end{cases} \rightarrow \quad \frac{N_{data} - N_{back}}{N_{theo}} = 0.611 \pm 0.085 \pm 0.041$$

★ **FIRST EVIDENCE of a terrestrial ν_e PROBLEM** ★



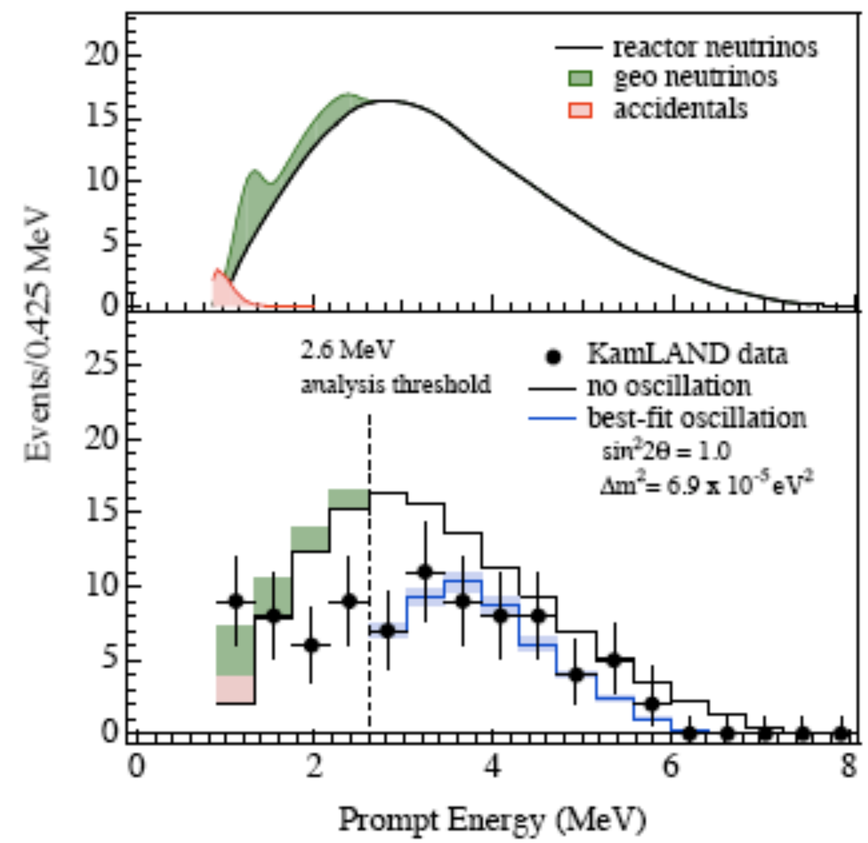


Figure 17: LEFT PLOT: The ratio of measured to expected $\bar{\nu}_e$ flux from reactor experiments. The shaded region indicates the range of flux predictions corresponding to the 95% C.L. LMA region found in a global analysis of the solar neutrino data. The dotted curve corresponds to the best-fit values $\Delta m^2_{\rm sol} = 5.5 \times 10^{-5}\,{\rm eV}^2$ and $\sin^2 2\vartheta_{\rm sol} = 0.83$. RIGHT PLOT: The full line represents the expected reactor $\bar{\nu}_e$ energy spectrum with contributions of $\bar{\nu}_{\rm geo}$ (antineutrinos emitted by ^{238}U and ^{232}Th decays in the earth) and accidental backround. The solid circles with error bars represent the observed events. The blue shaded line is the best fit assuming neutrino oscillations and including systematic errors. The vertical dashed line corresponds to the analysis threshold at 2.6 MeV.

FIT TO “SOLAR” DATA

- SNO has measured the total neutrino flux emitted by the Sun and it is compatible with the SSM.

- All experiments testing the Sun neutrino flux observe a deficit in the number of ν_e neutrinos reaching the detector

- KamLAND has observed a similar deficit for ν_e neutrinos produced in nuclear reactors

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta_{sol} \sin^2 (\Delta m^2_{sol}\, L / E)$$

- As solar neutrinos have a typical energy of 1-10 MeV and travel an average distance $L_{SUN} = 1.5 \times 10^7$ km one expect to be sensitive to a mass difference of the order:

$$\Delta m^2_{SUN}\ (\mathrm{eV}^2) \approx \frac{E_{SUN}\ (\mathrm{GeV})}{L_{SUN}\ (\mathrm{km})} = 10^{-10}\ \mathrm{eV}^2$$

If mass difference much larger than the probabilty averages to $P(\nu_e \to \nu_e) = 1 - \frac{1}{2}\sin^2 2\theta_{sol}$

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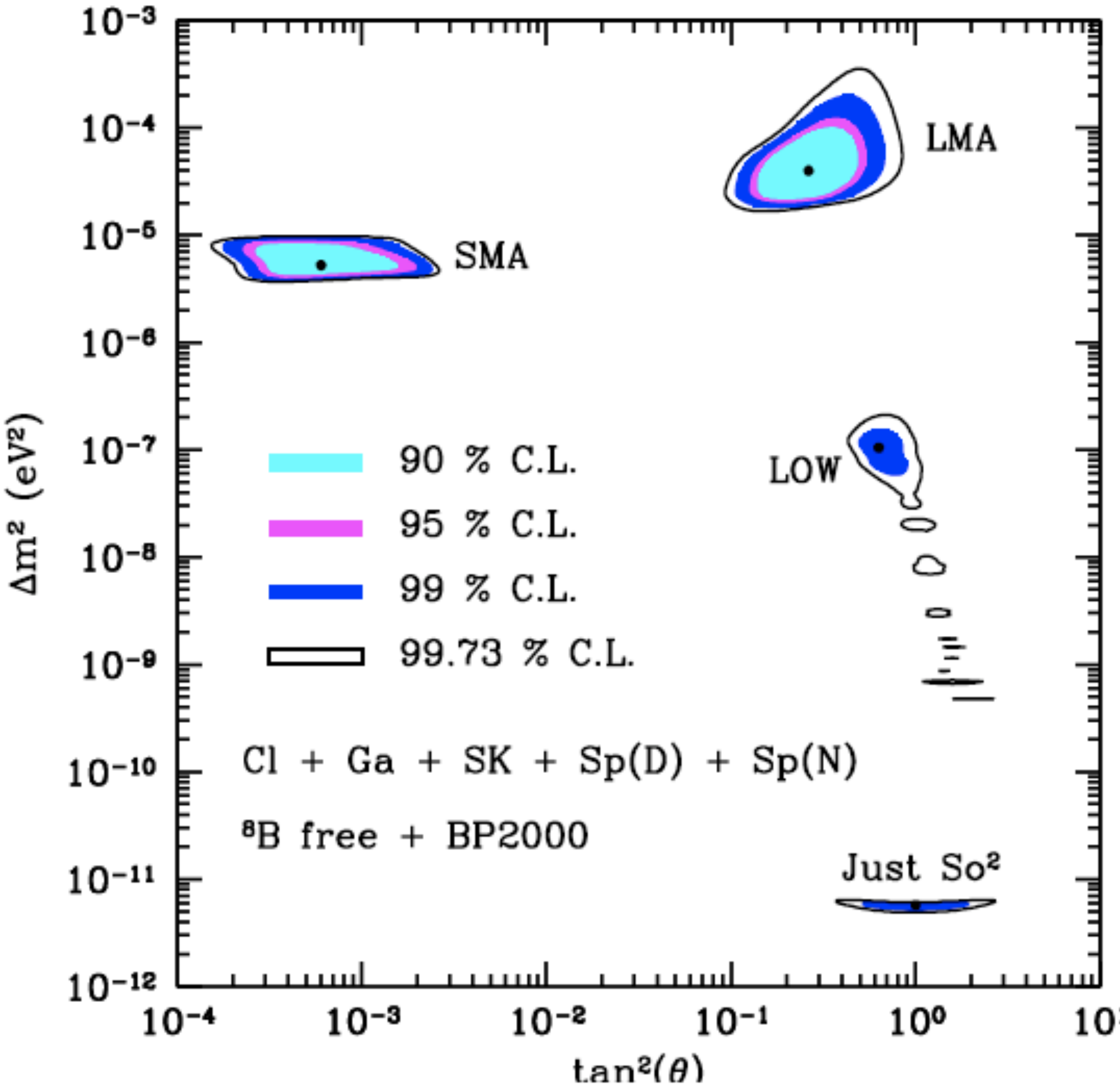
If mass difference much larger than the probabilty averages to $P(\nu_e \to \nu_e) = 1 - \frac{1}{2}\sin^2 2\theta_{sol}$

- Unfortunately things are not so easy as neutrino can interact with the matter inside the sun (as they are produced in the sun's core) and/or the earth. So generally there are more possible allowed region in the $(\Delta m^2_{SUN}, \sin^2 2\theta_{SUN})$ oscillation plane depending if the dominant mechanism for oscillations is VACUUM OSCILLATION, MSW ENHANCED OSCILLATION (in the sun or in the earth) or a combination.

Four possible oscillation solutions to the SNP

- **VACUUM OSCILLATION** (VO) region characterized by very small mass difference ($\Delta m^2 \approx 10^{-10}$ eV^2) and maximal mixing angle ($\sin^2 2\theta \approx 1$). Just pure vacuum oscillations between sun and earth;
- **LOW** region characterized by small mass difference ($\Delta m^2 \approx 10^{-6} - 10^{-8}$ eV^2) and maximal mixing angle ($\sin^2 2\theta \approx 1$). MSW resonance inside sun and earth;
- **LARGE MIXING ANGLE** (LMA) region characterized by a mass difference ($\Delta m^2 \approx 10^{-4} - 10^{-5}$ eV^2 and large mixing angle ($\sin^2 2\theta \lesssim 1$) even if probably not maximal. MSW resonance inside the sun;
- **SMALL MIXING ANGLE** (SMA) region characterized by a mass difference ($\Delta m^2 \approx 10^{-5}$ eV^2 and small mixing angle ($\sin^2 2\theta \approx 10^{-3}$). MSW resonance inside the sun;



10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
Δm^2 (eV^2)
LMA
SMA
LOW
Just So^2
90 % C.L.
95 % C.L.
99 % C.L.
99.73 % C.L.
Cl + Ga + SK + Sp(D) + Sp(N)
^{8}B free + BP2000
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
$\tan^2(\theta)$

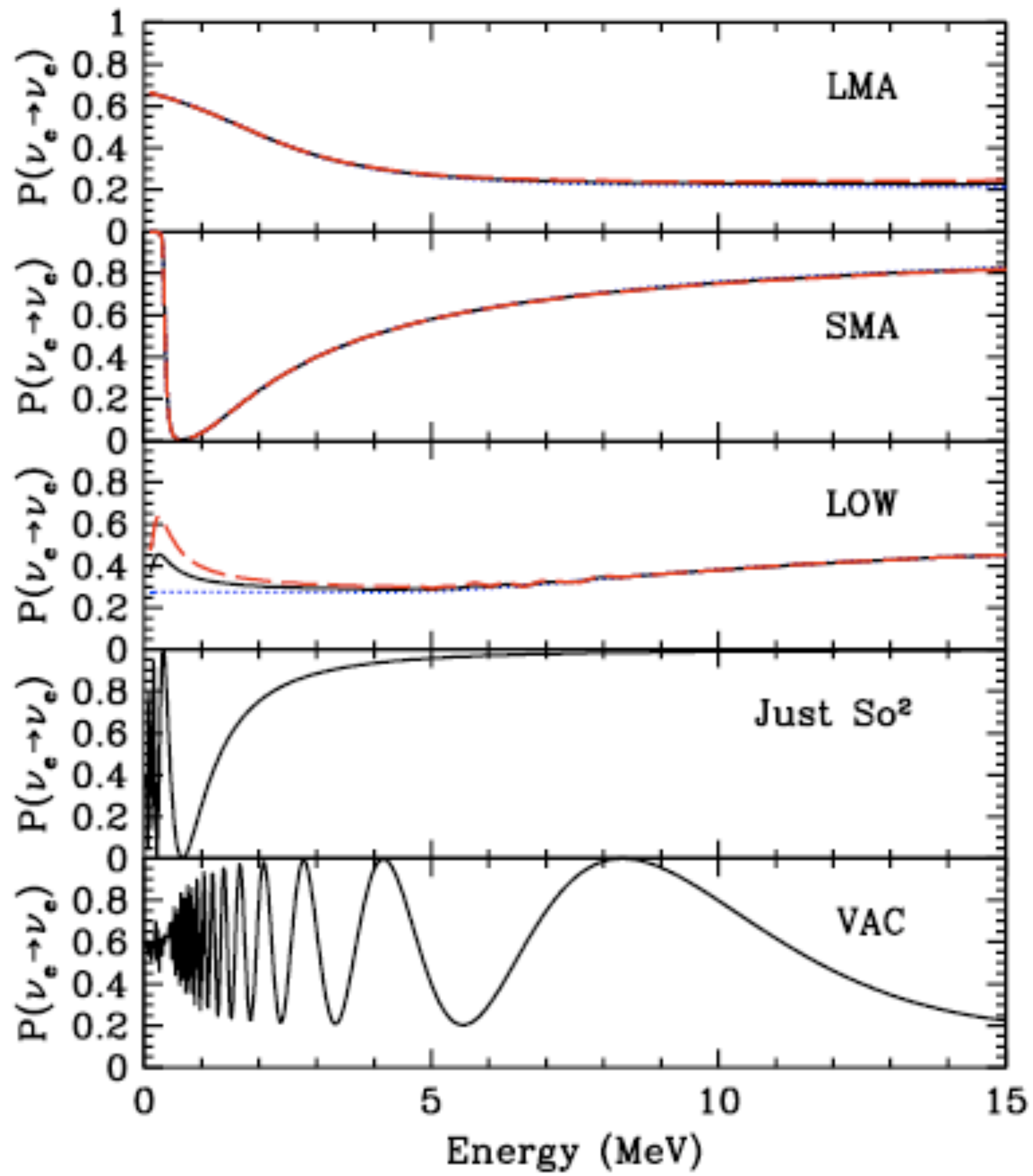
★ Different solutions have different experimental signatures that can help in disantangle the correct region in the parameter space:

- ENERGY SPECTRUM: the neutrino energy spectrum can be distorted (SUPPRESSED or ENHANCED) by MATTER EFFECTS in the Sun or in the Earth.

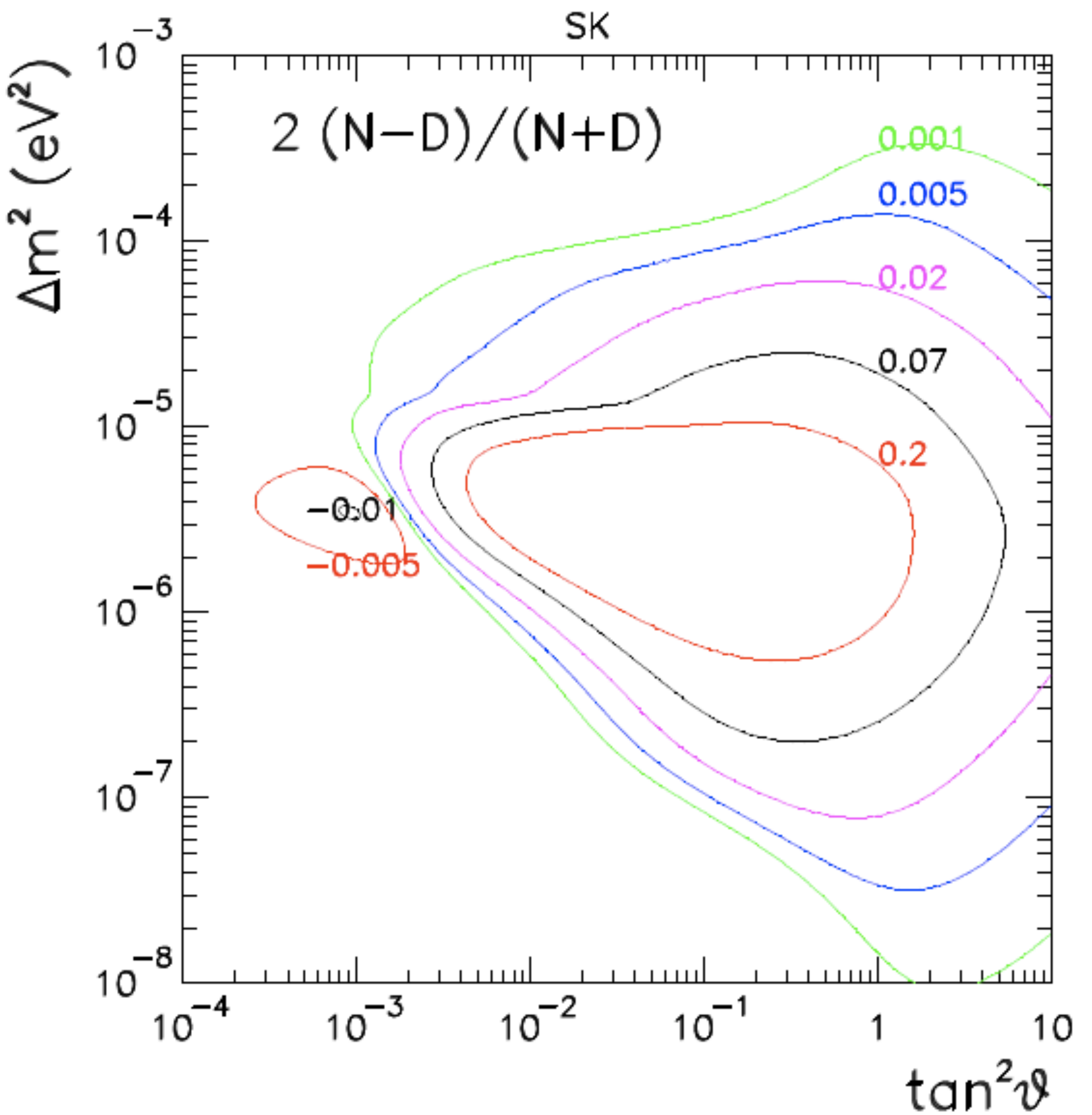
- DAY-NIGHT ASYMMETRY: the appearance (or not) of a D-N asymmetry would indicate (or not) sensitivity to matter effects in the Earth, selecting particular regions in the $(\Delta m^2, \sin^2 2\theta)$ space. For example SMA has large DN asymmetry and so it is disfavoured by small DN asymmetry

- SEASONAL VARIATIONS: the appeareance of seasonal effects would indicate sensitivity to the Sun-Earth DISTANCE (for example it should happen in the case of VO but not for LMA or SMA solutions). NOTE that "normal" seasonal flux variation due to lager-smaller sun-earth distance should be subtracted

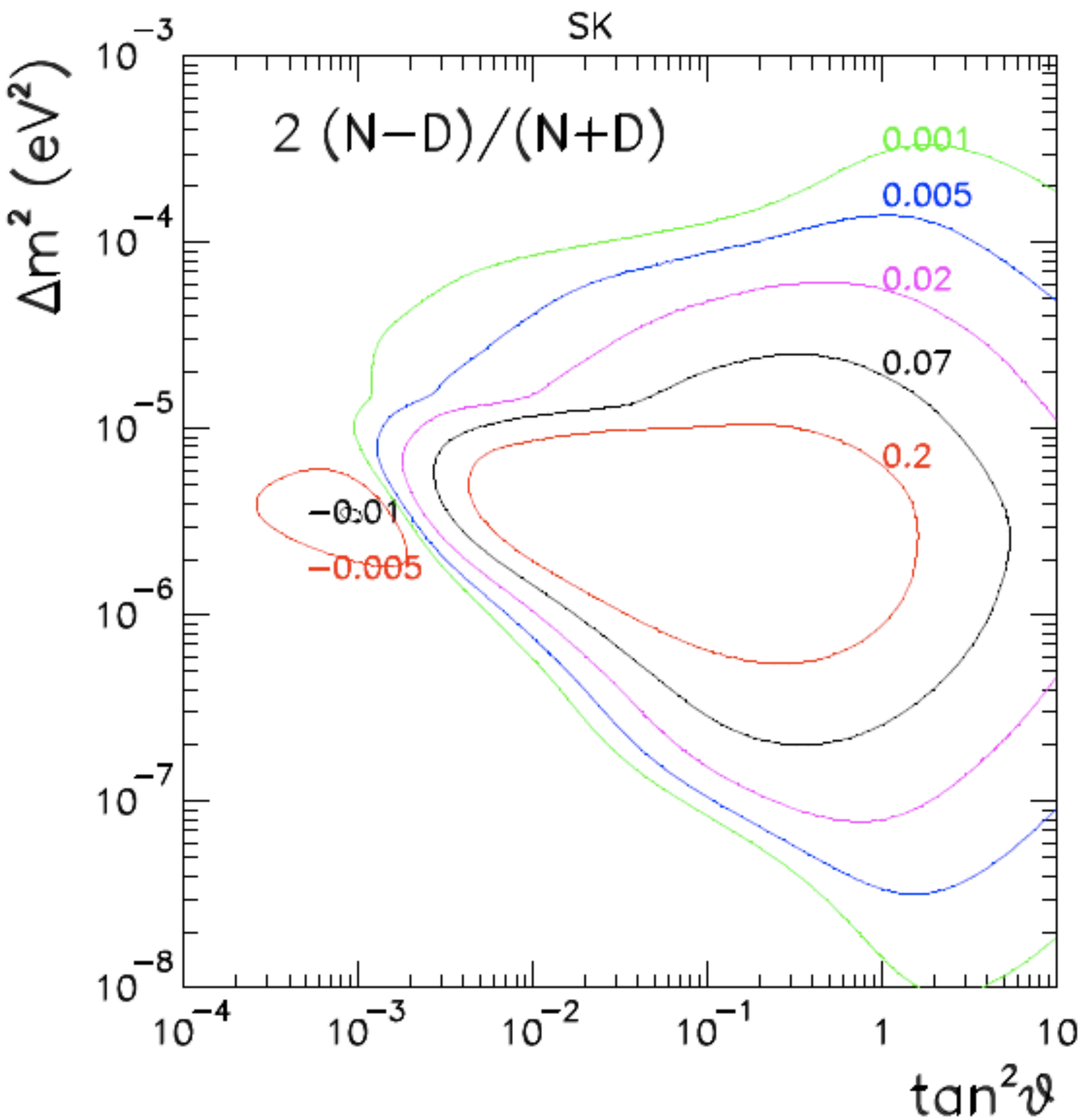
Solar ν_e survival probability as a function of the energy

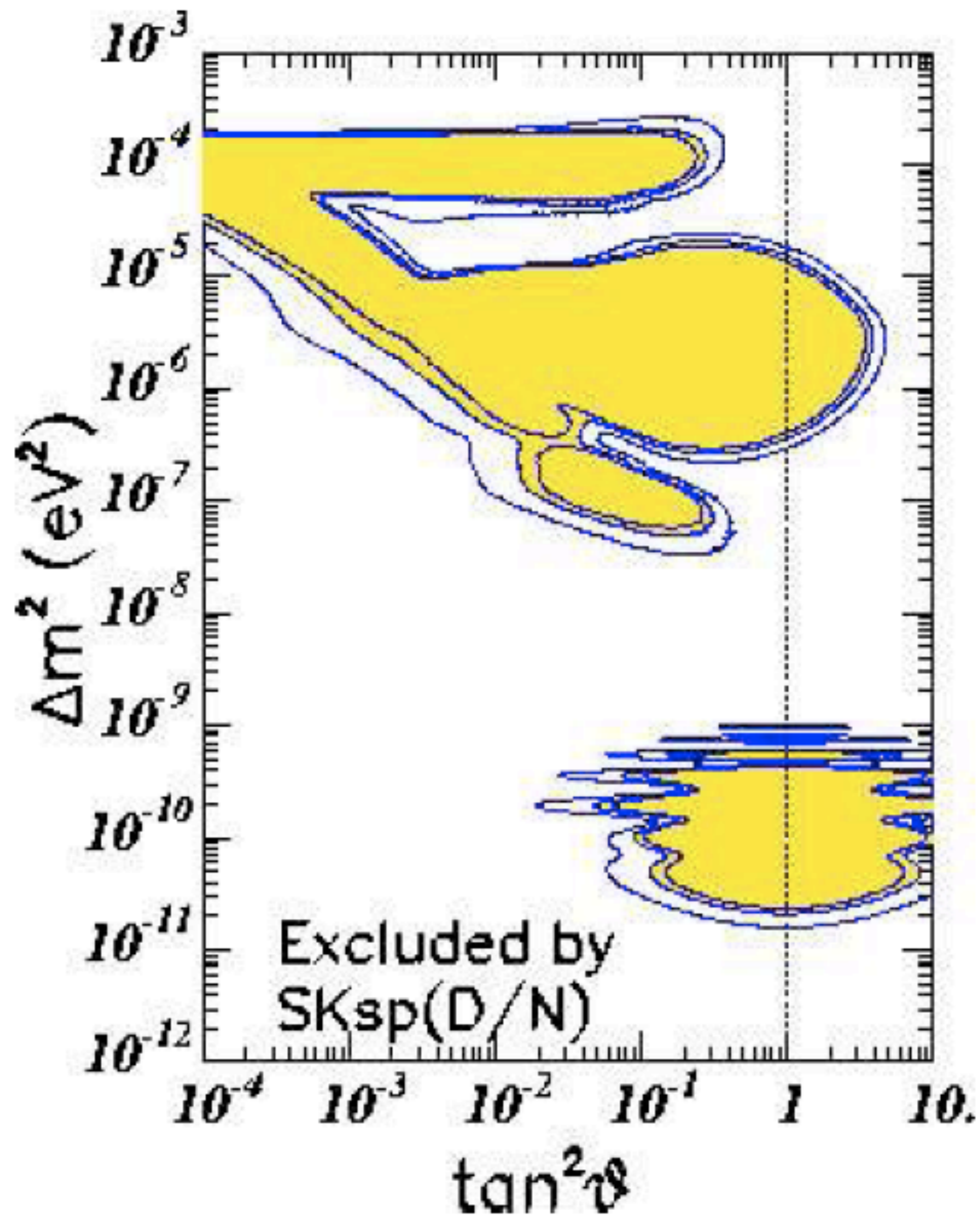


Day-night asymmetry at SuperKamiokaNDE

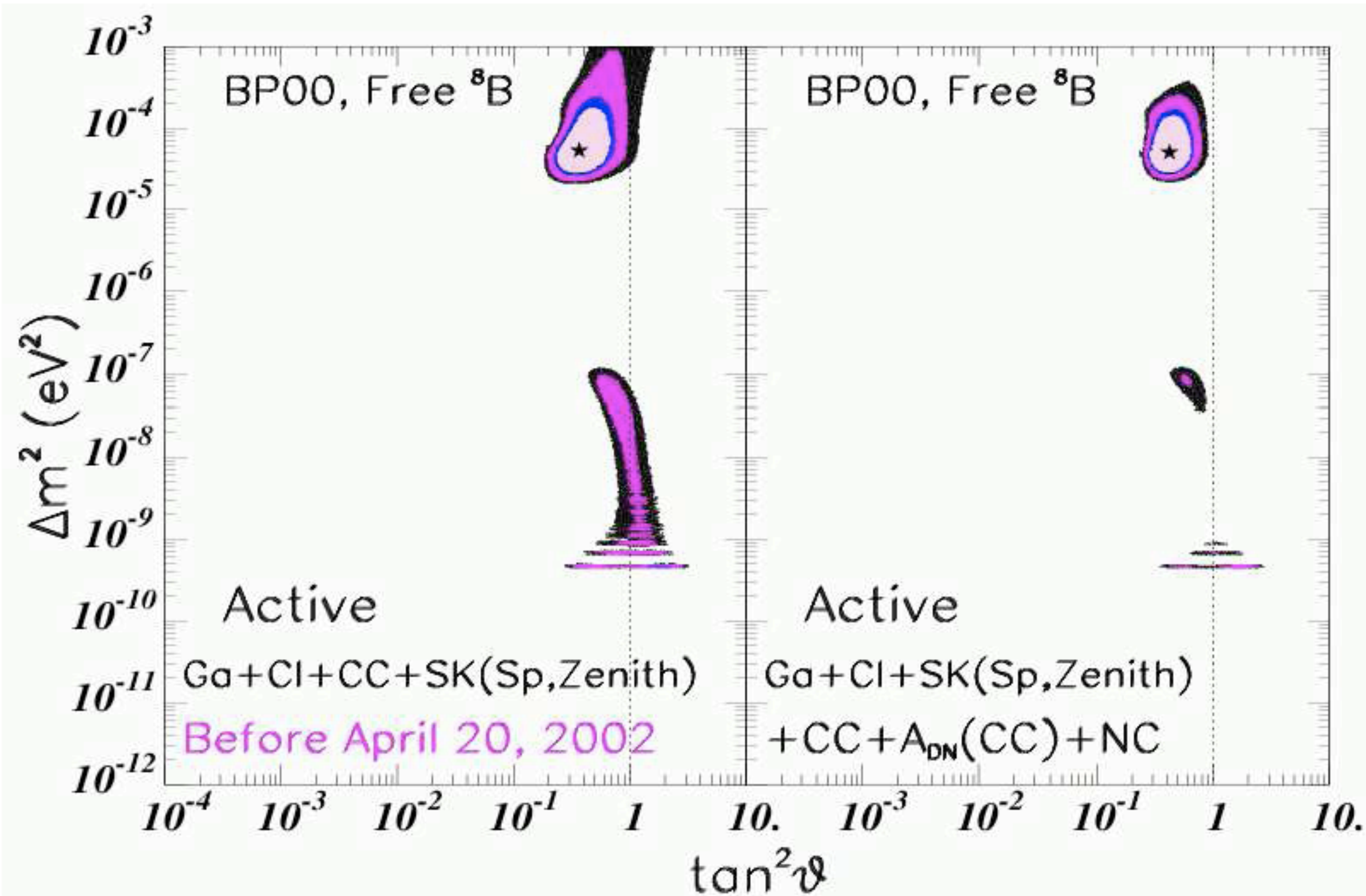


Day-night asymmetry at SuperKamiokaNDE

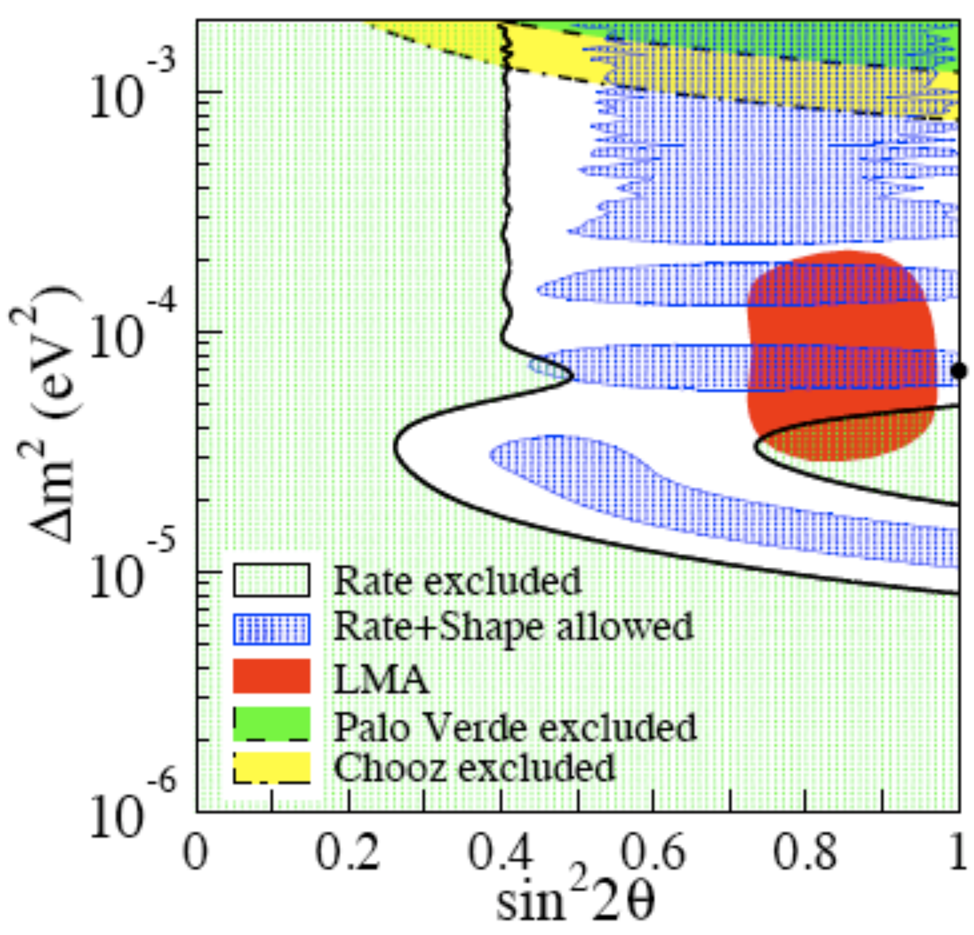


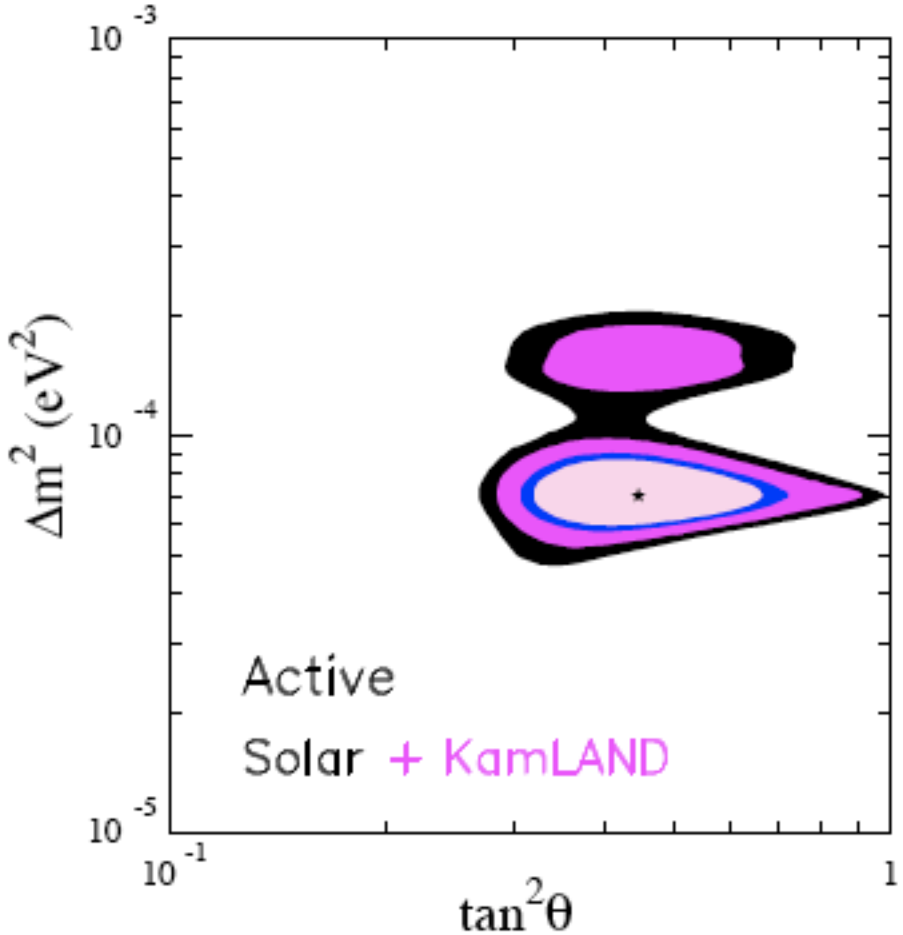


Allowed regions in 2002 with SK and SNO data



SNO and KamLAND





CONCLUSIONS

- The solar neutrino flux is extremely complicated: it took 40 years to be convinced that the SSM works, and that particle physics must be changed.

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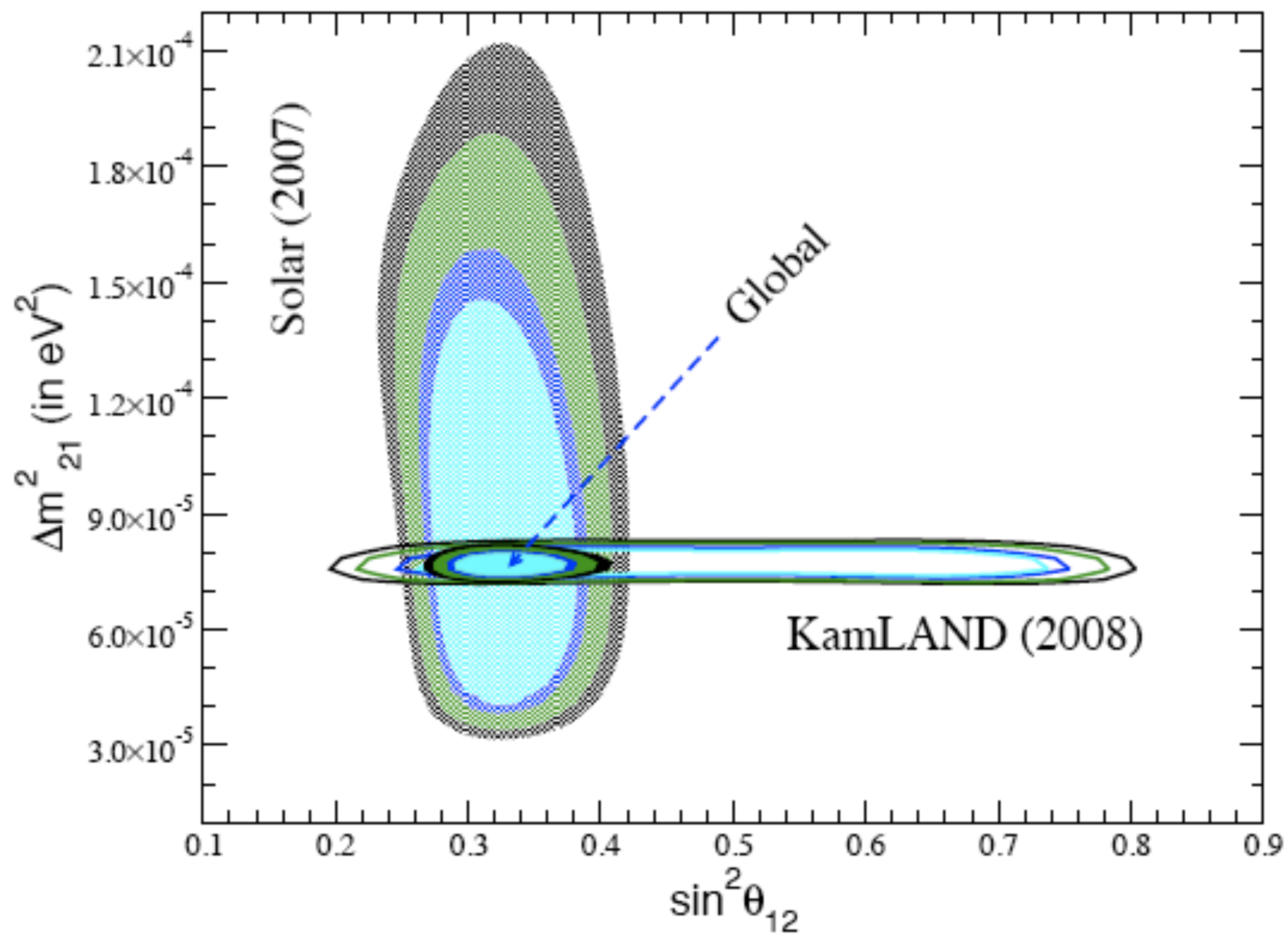
- The most recent data give:

$$\Delta m^2_{21} = 7.67\,^{+0.22}_{-0.21}\,\left(^{+0.67}_{-0.61}\right) \times 10^{-5}\ \mathrm{eV}^2$$

$$\theta_{12} = 34.5 \pm 1.4\,\left(^{+4.8}_{-4.0}\right)$$

Gonzalez-García and Maltoni, 2008



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TUTORIAL

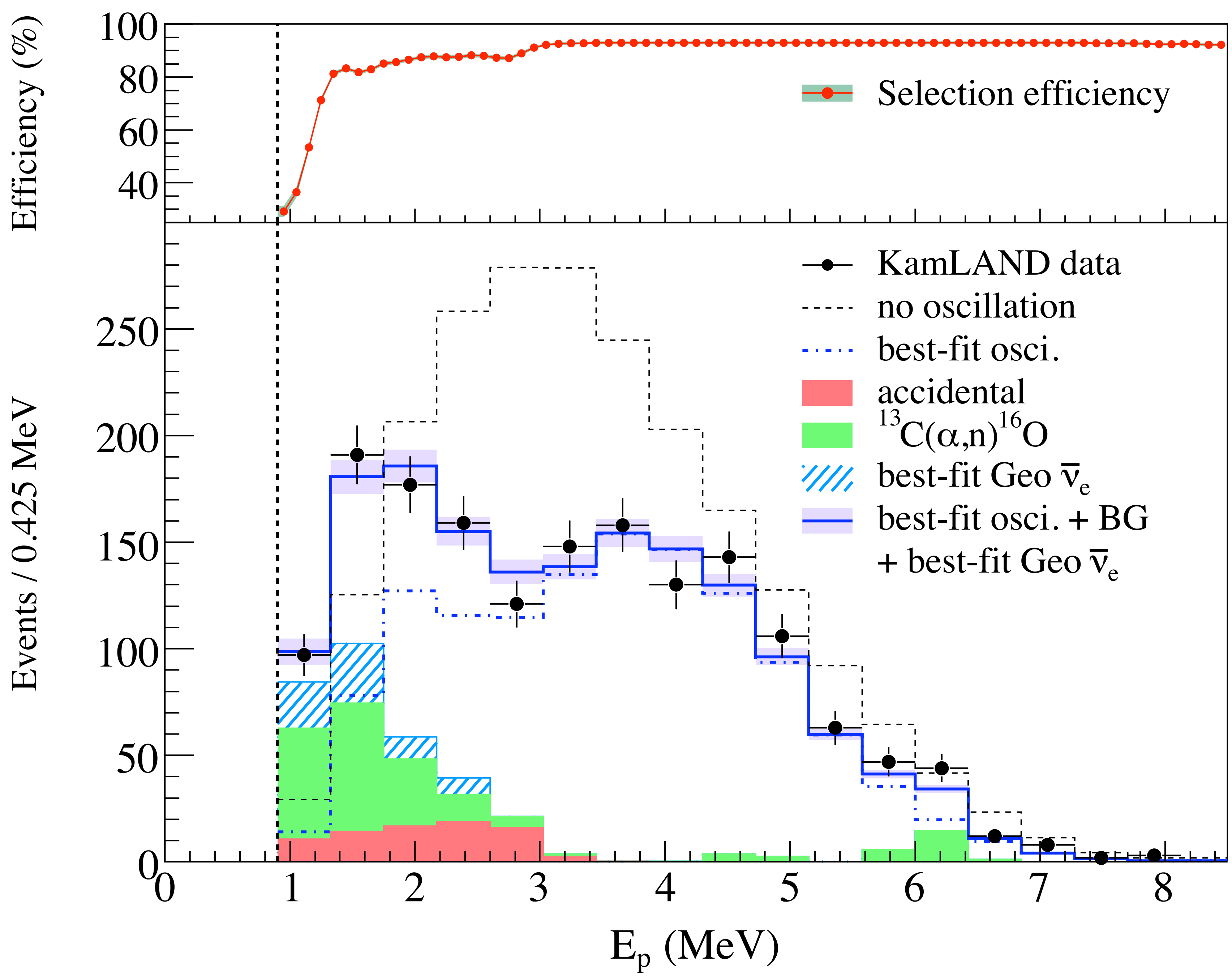
- Write a code to compute numerically 2x2 oscillation probabilities in matter, $P(\theta_{12};\Delta m^2_{12})$. Check the result with the analytic formulae.

- Consider the new KamLAND data from arXiv:0801.4589v2. From non-oscillated events, we have $N_\alpha(\text{bin})=\int dE\ \Phi_\alpha \times \sigma_{\nu N} \times \varepsilon_\alpha$

- $N_{theo}\ (\text{bin}) = N_\alpha(\text{bin}) \times P(\text{bin};\ \theta_{12};\Delta m^2_{12})$

- Fit: $\chi^2 = [N_{theo}\ (\text{bin}) - N_{exp}\ (\text{bin})]^2 / \sigma^2$

KamLAND data, 2008



- Repeat the exercise for the MINOS data from arXiv:hep-ex/0607088v2

- Notice: if some of you have access to the fluxes of KamLAND (painful) or MINOS we could compute much better this: $N_\alpha(\text{bin})=\int dE\ \Phi_\alpha \times \sigma_{\nu N} \times \varepsilon_\alpha$

- Notice: we have not included ANY systematics. We are not considering backgrounds. We are not doing three-family probabilities.

MINOS data, 2006