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Solar Neutrinos:

oscillations and magnetic moment

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PLAN

1. How did the question arise: problem or oportunity for Physics?

2. Main solutions: oscillations and magnetic moment

3. Experimental evolution

4. Variability or non variability of $\odot$ ν flux: conversion model for $\nu_{e_L} \to \nu_s$

5. Conclusions

1. Problem or oportunity?

$$pp \rightarrow^2 H + e^+ + \nu_e \quad or \quad pe^- p \rightarrow^2 H + \nu_e$$

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

$$^3He + p \rightarrow^4 He + e^+ + \nu_e$$

Result: $4p \rightarrow^4 He + 2e^+ + 2\nu_e + 26.73MeV$

These are very low energy $\nu' s$, $E_\nu < 0.42MeV$ and are therefore difficult to detect. The process continues

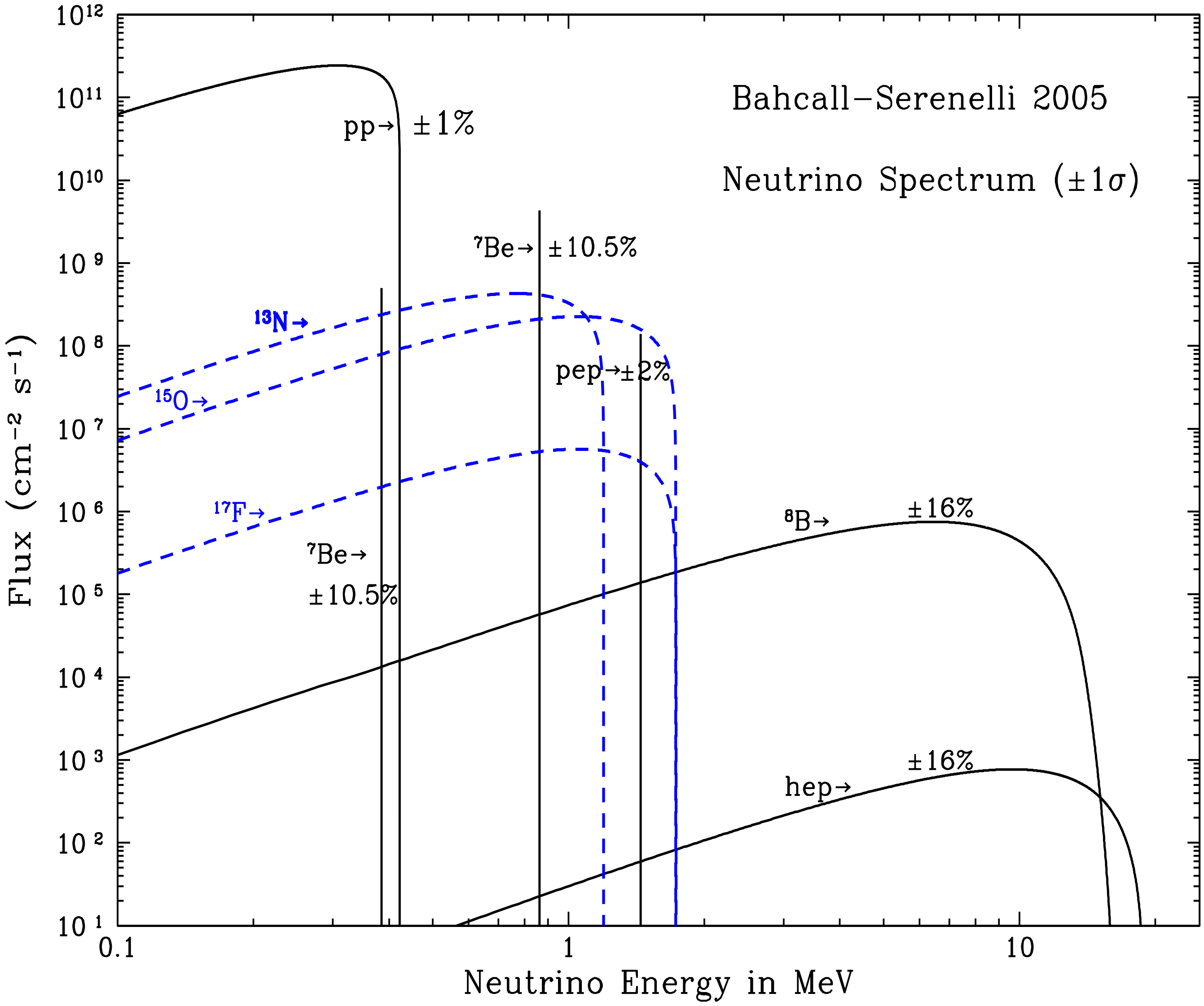
$$^3He +^3 He \rightarrow^4 He + 2p$$

$$^3He +^4 He \rightarrow^7 Be + \gamma$$

$$^7Be + e^- \rightarrow^7 Li + \nu_e$$

$$^7Be + p \rightarrow^8 B + \gamma$$

$$^8B \rightarrow^8 Be + e^+ + \nu_e$$


Bahcall–Serenelli 2005
Neutrino Spectrum (±1σ)
pp→ ±1%
⁷Be→ ±10.5%
¹³N→
¹⁵O→
¹⁷F→
⁷Be→
±10.5%
pep→±2%
⁸B→ ±16%
hep→ ±16%
Flux (cm⁻² s⁻¹)
Neutrino Energy in MeV
10¹²
10¹¹
10¹⁰
10⁹
10⁸
10⁷
10⁶
10⁵
10⁴
10³
10²
10¹
0.1
1
10

It was found (1958) that the reaction

$$^3He +^4 He \rightarrow^7 Be + \gamma$$

is 1000 times stronger than expected $\rightarrow$ hence the high energy $\nu' s$ from reaction

$$^8B \rightarrow^8 Be + e^+ + \nu_e \ \ (0.8 < E_\nu < 15 MeV)$$

are more abundant, and since $\sigma(E) \alpha E^2$ their detection is easier than expected. Moreover it was found that

$$\nu_e +^{37} Cl \rightarrow^{37} Ar + e^- \quad (E_{th} > 0.814 MeV)$$

has a cross section 20 times larger than initially expected (1963).

Cl relatively cheap to obtain $\rightarrow$ first detector is built (Homestake) and with its results (1968) the 'solar neutrino problem': only 1/3 of the expected neutrinos were seen. Hence a new oportunity for Physics.

Or is it the success of $\odot$ $\nu' s$?

2.1.1 Vacuum oscillations (Gribov, Pontecorvo 1969)

$\odot$ produces ν_e which may not have a definite mass but rather be a superposition of mass eigenstates ν_1, ν_2 in which another neutrino is involved, for instance ν_μ, already known since 1962

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \quad (t=0)$$

ν_1, ν_2 propagate as plane waves: at a distance x=t

$$\nu_{1,2} \rightarrow \nu_{1,2}(t) = \nu_{1,2} exp(-iE_{1,2}t)$$

$$\nu_e(t) = \nu_1 exp(-iE_1 t) c_\theta + \nu_2 exp(-iE_2 t) s_\theta$$

$$\nu_\mu(t) = -\nu_1 exp(-iE_1 t) s_\theta + \nu_2 exp(-iE_2 t) c_\theta$$

We use the approximation

$$E_{1,2} = (p^2 + m_{1,2}^2)^{1/2} \simeq p^2 + m_{1,2}^2/2p$$

With $m_1 \neq m_2$ and $\theta \neq 0$ the phases of $\nu_{1,2}$ evolve differently, originating survival and conversion probabilities

$$P(\nu_e \rightarrow \nu_e(t)) = 1 - sin^2 2\theta \; sin^2\left(\frac{\Delta m^2}{4E}t\right)$$

$$P(\nu_e \rightarrow \nu_\mu(t)) = sin^2 2\theta \; sin^2\left(\frac{\Delta m^2}{4E}t\right)$$

Therefore ν_e produced in the Sun becomes a different linear combination of ν_1, ν_2 which contains ν_e and ν_μ, in other words

ν_μ appears where it did not exist: oscillation phenomenon.

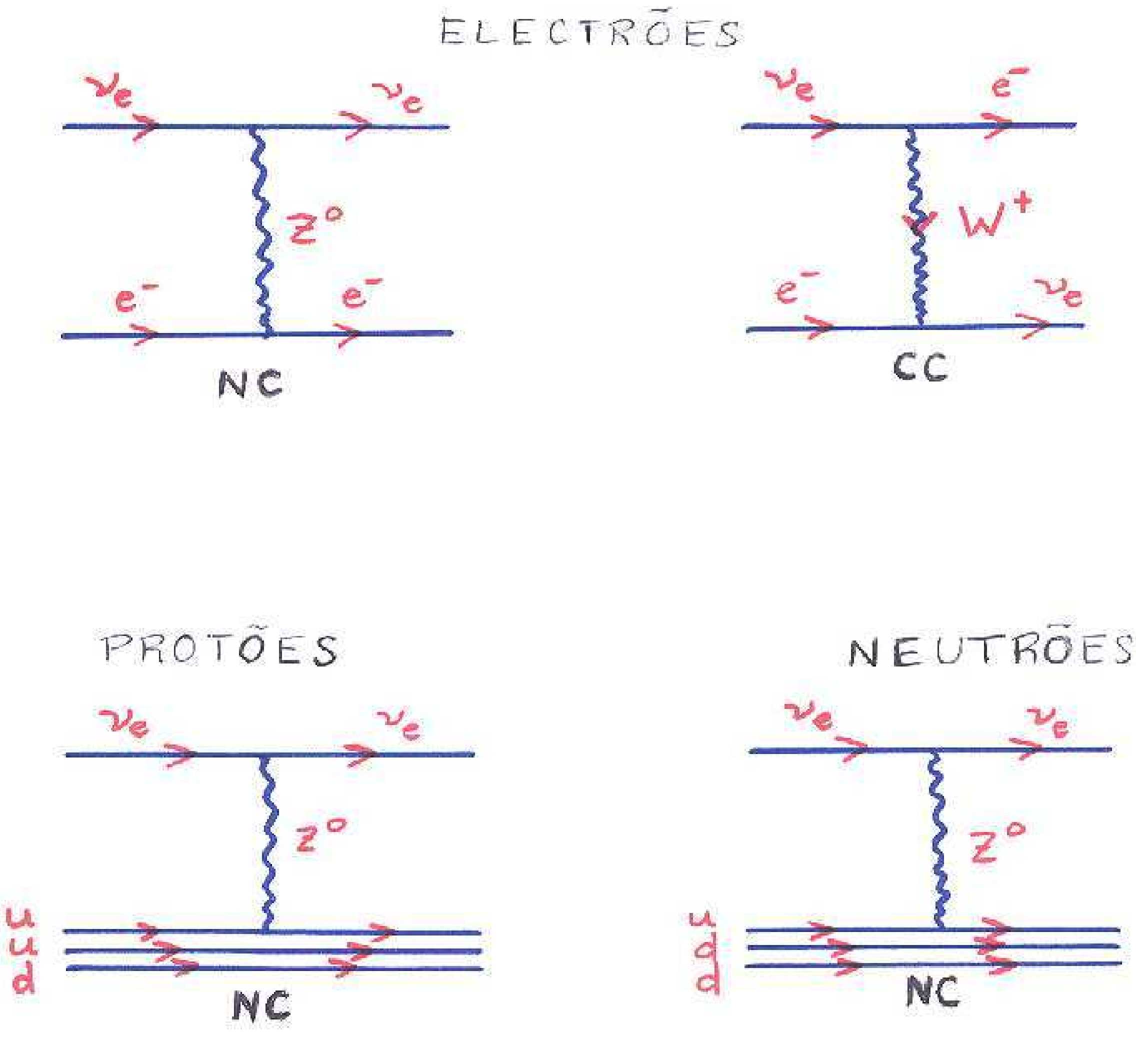
This idea was not appealing as it involved a large mixing angle θ.

Until 1979 the SNP was not taken quite seriously because of possible innacuracies in the SSM: the value of the predicted flux could be wrong. Some even hinted the solar neutrino success since the observations were well within an order of magnitude of the predictions.

2.1.2 Matter oscillations (Wolfenstein 1979)

Refraction indices of ν_e, ν_μ are different:

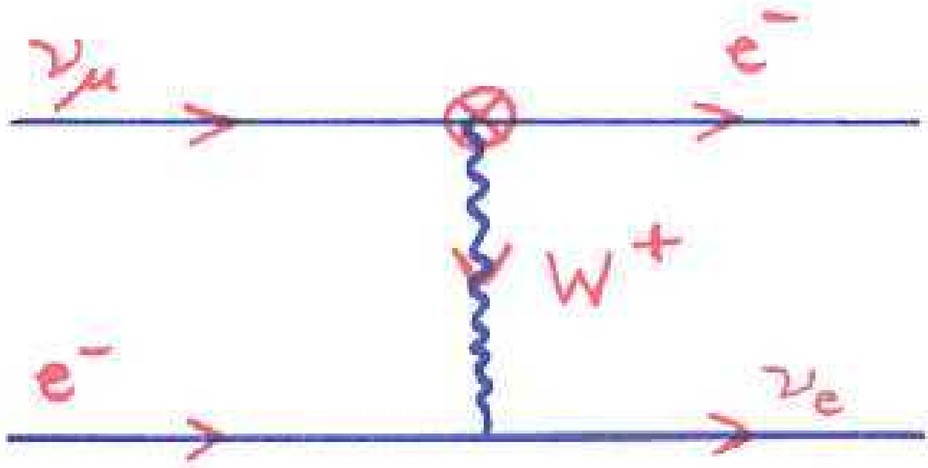
(a) ν_e



adding all contributions $\rightarrow$ the ν_e refraction index in the Sun

$$V_e = G_F/\sqrt{2}[(1+4sin^2\theta_W)N_e+(1-4sin^2\theta_W)N_p-N_n]$$

(b) ν_μ



all diagrams exist for ν_μ except the charged current one because it breaks lepton number ($\otimes$). μ^- cannot be produced (E_ν too low!) hence

ν_μ in the Sun only has neutral current

$$V_\mu = G_F/\sqrt{2}[(-1+4sin^2\theta_W)N_e + (1-4sin^2\theta_W)N_p - N_n]$$

Deriving the Hamiltonian

$$i\frac{d}{dt}\begin{pmatrix}\nu_e(t), \nu_e(0)\\ \nu_\mu(t), \nu_e(0)\end{pmatrix} = [\mathcal{H}]\begin{pmatrix}\nu_e(t), \nu_e(0)\\ \nu_\mu(t), \nu_e(0)\end{pmatrix}$$

$$[\mathcal{H}] = \begin{pmatrix}\frac{\Delta m^2}{2E}s_\theta^2 + V_e & \frac{\Delta m^2}{4E}s_{2\theta}\\ \frac{\Delta m^2}{4E}s_{2\theta} & \frac{\Delta m^2}{2E}c_\theta^2 + V_\mu\end{pmatrix}$$

In the vacuum $V_e = V_\mu = 0$.

The mixing angle is therefore changed by matter, $\theta \rightarrow \tilde{\theta}$

$$tan2\tilde{\theta} = \frac{2H_{12}}{H_{22} - H_{11}} = \frac{\frac{\Delta m^2}{2E}s_{2\theta}}{\frac{\Delta m^2}{2E}c_{2\theta} + V_\mu - V_e}$$

This is the basic message of Wolfenstein: neutrinos oscillate differently in vacuum and in matter. He added (erroneously) that these effects were irrelevant for solar neutrinos.

MSW (1985) - Mikheev & Smirnov proposed the amplification of a small vacuum mixing angle by matter.

$$\frac{\Delta m^2}{2E}c_{2\theta}+V_\mu-V_e=0 \quad \rightarrow tan2\tilde{\theta}=\infty,\ \ \tilde{\theta}=\pi/4$$

Thus a critical density is established which depends on parameters Δm^2 and θ.

1	2
Production	Propagation
$\lvert\nu_e>=c_{\tilde{\theta}_i}\lvert\nu_1>+s_{\tilde{\theta}_i}\lvert\nu_2>$ $c_{\tilde{\theta}_i}\simeq 1,\ \ s_{\tilde{\theta}_i}\simeq 0$	$\lvert\nu_1>,\ \ \lvert\nu_2>$

3	4
Critical density	Propagation
$\lvert\nu_e>=\frac{1}{\sqrt{2}}(\lvert\nu_1>+\lvert\nu_2>)$ $\tilde{\theta}=\pi/4$	$\lvert\nu_1>,\ \lvert\nu_2>$ $\pi/4<\tilde{\theta}<\pi/2$

5
Exit
$\|\nu_e\!> = c_{\tilde{\theta}_f}\|\nu_1\!> + s_{\tilde{\theta}_f}\|\nu_2\!>$ $c_{\tilde{\theta}_f} \simeq 0, \quad s_{\tilde{\theta}_f} \simeq 1$

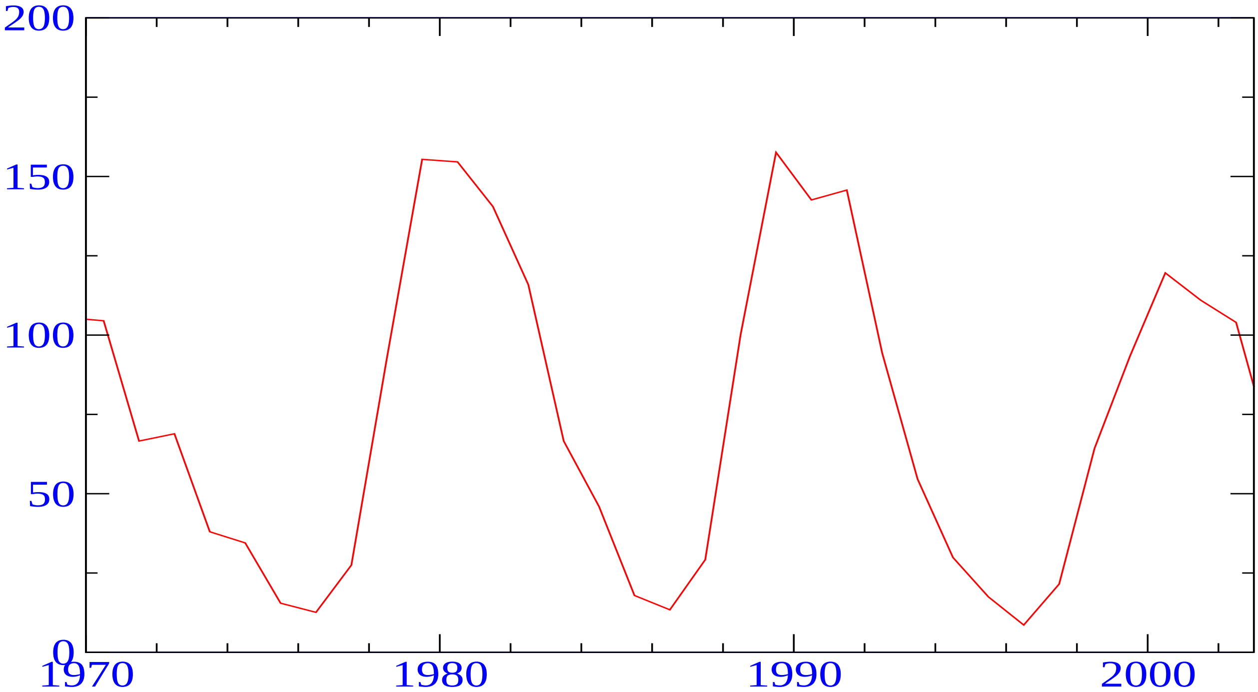
That is: ν_e is produced in the solar centre ($\nu_1 \simeq \nu_e$ with a small percentage of ν_2). Subsequently $\nu_1,\ \nu_2$ evolve, pass through the critical density and on reaching the vacuum $\nu_1 \simeq \nu_\mu$:

This is the resonant amplification of a small mixing angle (SMA) and originates the matter oscillations

The beauty and simplicity of the mechanism lead some physicists to think this might be the solution to the SNP.

2.2 Spin-flavour precession (VVO 1986)

The Homestake collaboration claims (1985) their data show evidence of an event rate time modulation anti-correlated with the sunspot cycle (11-year period).



Theoretical physicists Voloshin, Vysotsky, Okun say: this is a signature of the magnetic moment μ_ν. The more solar activity $\rightarrow$ the more sunspots, the more intense magnetic field ($\vec{B}$, $\vec{H}$).

μ_ν interacts with $\vec{B}$ originating a spin precession in accordance with

$$\frac{d\vec{s}}{dt} = \frac{2\mu_\nu}{h}\vec{s}\,\mathrm{x}\,\vec{H}$$

(maximum precession for a transverse field $\vec{H}$)

Thus ν_{e_R} , sterile for weak interactions (i.e. non-observable), is generated.

More activity, less neutrinos and vice versa!

However no conclusive evidence of this anticorrelation was ever agreed upon in relation with Homestake.

Extension to resonant case (Lim, Marciano, Akhmedov, 1988). Hamiltonian

$$\mathcal{H}_{RSFP} = \begin{pmatrix} V_e & \mu_\nu B \\ \mu_\nu B & \frac{\Delta m^2}{2E} \end{pmatrix} \; acts \; on \; \begin{pmatrix} \nu_{e_L} \\ \nu_{\mu_R} \end{pmatrix} \qquad (1)$$

[$\mathcal{H}_{RSFP}$ Results from

$$\mathcal{H}_{osc} = \begin{pmatrix} \frac{\Delta m^2}{2E} s_\theta^2 + V_e & \frac{\Delta m^2}{4E} s_{2\theta} \\ \frac{\Delta m^2}{4E} s_{2\theta} & \frac{\Delta m^2}{2E} c_\theta^2 + V_\mu \end{pmatrix}$$

$$with \; \theta \rightarrow 0 \; , \mu_\nu \neq 0]$$

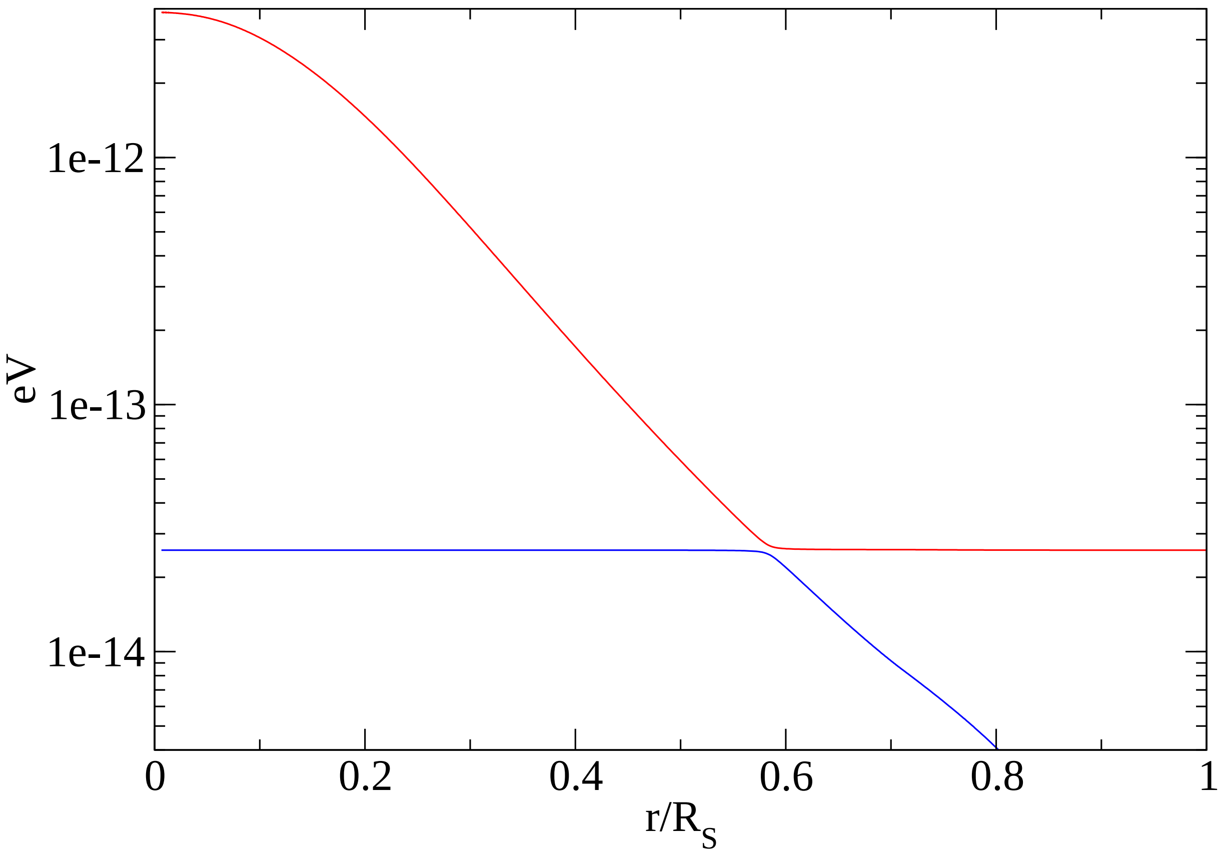
Recall that for $\nu_{e_R, \, \mu_R} \rightarrow V_e = V_\mu = 0$.

The critical density (resonance) corresponds to

$$tan 2\tilde{\theta} = \frac{2H_{12}}{H_{22} - H_{11}} = \frac{2\mu_\nu B}{\frac{\Delta m^2}{2E} c_{2\theta} - V_e} = \infty$$

Besides ν_{μ_R} in the final state, other choices are possible. For instance for $\nu_{e_L} \rightarrow \bar{\nu}_{\mu_R}$ (Maj. $\nu's$) one has

$$H_{22} = \frac{\Delta m^2}{2E} c_\theta^2 - V_\mu.$$



Evolution of mass matter eigenstates $\nu_1,\ \nu_2$

3. Experimental evolution

1986 - A new experiment has started: Kamiokande.

Cerenkov effect in H_2O

$$\nu e^- \to \nu e^- \quad (E_{th_{Kam}} > E_{th_{Cl}})$$

Kamiokande only detects neutrinos from ^8B and observes

$$\Phi(^8B) = (0.40 - 0.50)\Phi(^8B)_{SSM}$$

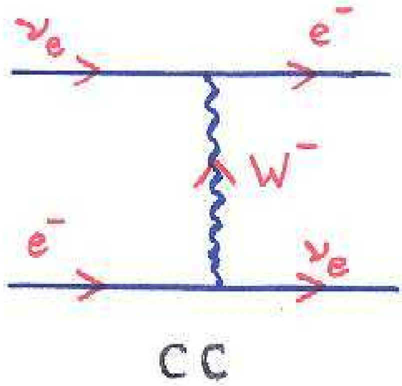
The event rate in Cl experiment has 80% neutrinos from ^8B and 20% intermediate energy ones

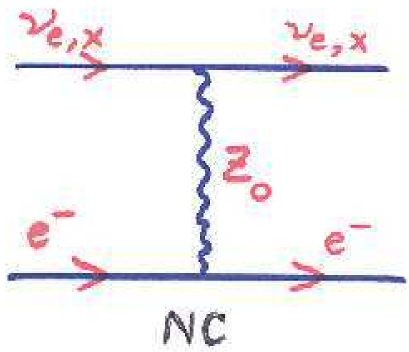
$$R_{Cl} = 1/3 = 0.45 \times 0.80 + x\, 0.20 = 0.36 + x\, 0.20$$

which implies x<0 (using the solar model of that time (1988)).

$\nu' s$ $\odot$, oscillations and magnetic moment

For Kamiokande these two diagrams matter, for Cl only the left one. $(\nu_e +^{37} Cl \rightarrow^{37} Ar + e^-)$





There is a simple and elegant explanation based in oscillations for the $\Phi(^8B)$ deficit in Kamiokande

Cl (Homestake) tells us that 2/3 of $\nu_e' s$ are converted to $\nu_X' s$ $(R_{Cl} = 1/3)$. These (ν_μ or ν_τ) are detected by Kamiokande but only through the neutral current. The Kamiokande *reduced rate*

$$R_{Kam} = \frac{\frac{1}{3}(\sigma_{CC} + \sigma_{NC}) + \frac{2}{3}\sigma_{NC}}{\sigma_{CC} + \sigma_{NC}} \simeq \frac{\frac{1}{3} + 0.18}{1 + 0.18} = 0.44$$

Used $\left(\frac{\sigma_{NC}}{\sigma_{CC}}\right)_{\nu_e} \simeq 0.18$. Correct!

At this stage, from the discrepancy between the two experiments, the community starts to be convinced that something happens to neutrinos between production and detection. The SNP could not be an astrophysics problem, despite the uncertainties in the solar model.

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Y. Totsuka ν '90 (CERN)

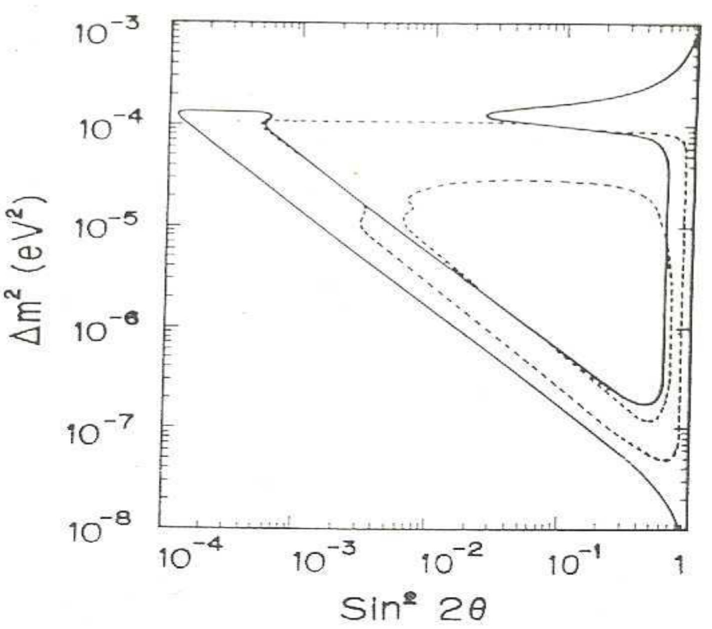


FIGURE 9
90% C.L. allowed regions of the MSW solution for the Kamiokande (solid line) and Homestake (dotted line) results. The theoretical neutrino production rate is taken from Bahcall and Ulrich.

Ga experiments:

SAGE (1990), Gallex (1991)

Reaction

$$\nu_e +^{71} Ga \rightarrow^{71} Ge + e^- \; (E_{th} = 0.236 MeV)$$

All solar neutrinos (from all sources) are seen. The first result:

$$83 \pm 19 \text{ SNU}$$

As a consequence the parameter range compatible with the data was separated in two regions: SMA and LMA (1992, Dallas Conference)

	$\Delta m^2_{21} eV^2$	$tan^2\theta$
SMA	O $(10^{-5} eV^2)$	O(10^{-4})
LMA	$8 \times 10^{-5} eV^2$	0.37

$\nu's \odot$, oscillations and magnetic moment

D. Vignaud 1099

Dallas Aug. 1992

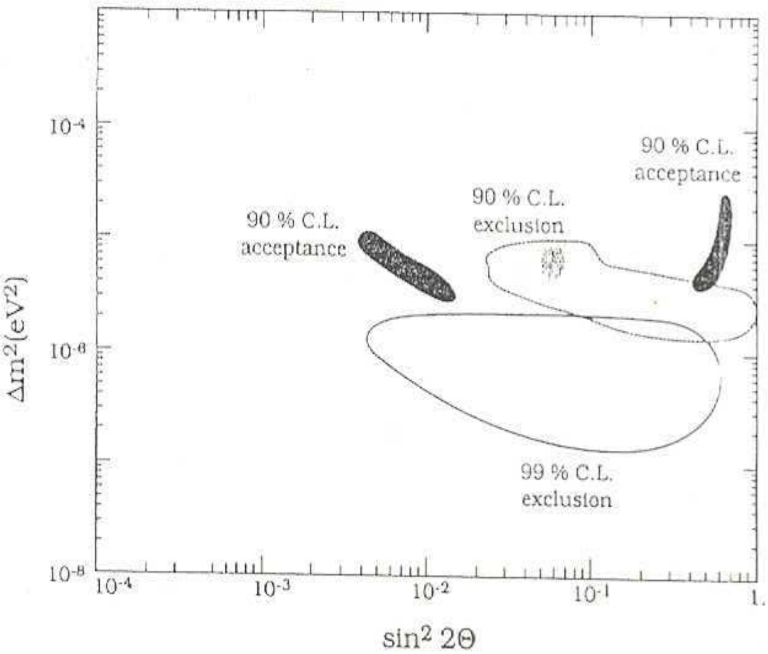


Figure 2. Δm^2 versus $\sin^2 2\theta$ for neutrino oscillation parameters. Within the black areas, the MSW effect successfully (90 % C.L.) reconciles the chlorine, Kamiokande and GALLEX experiments with standard solar models. The area inside the dotted line is excluded at 90 % C.L. by Kamiokande from a study of day-night effects [15]. The area inside the full line is excluded at 99 % C.L. by the GALLEX result.

15a

Other oscillation solutions remained: LOW, VAC, . . . which were however disfavoured by data

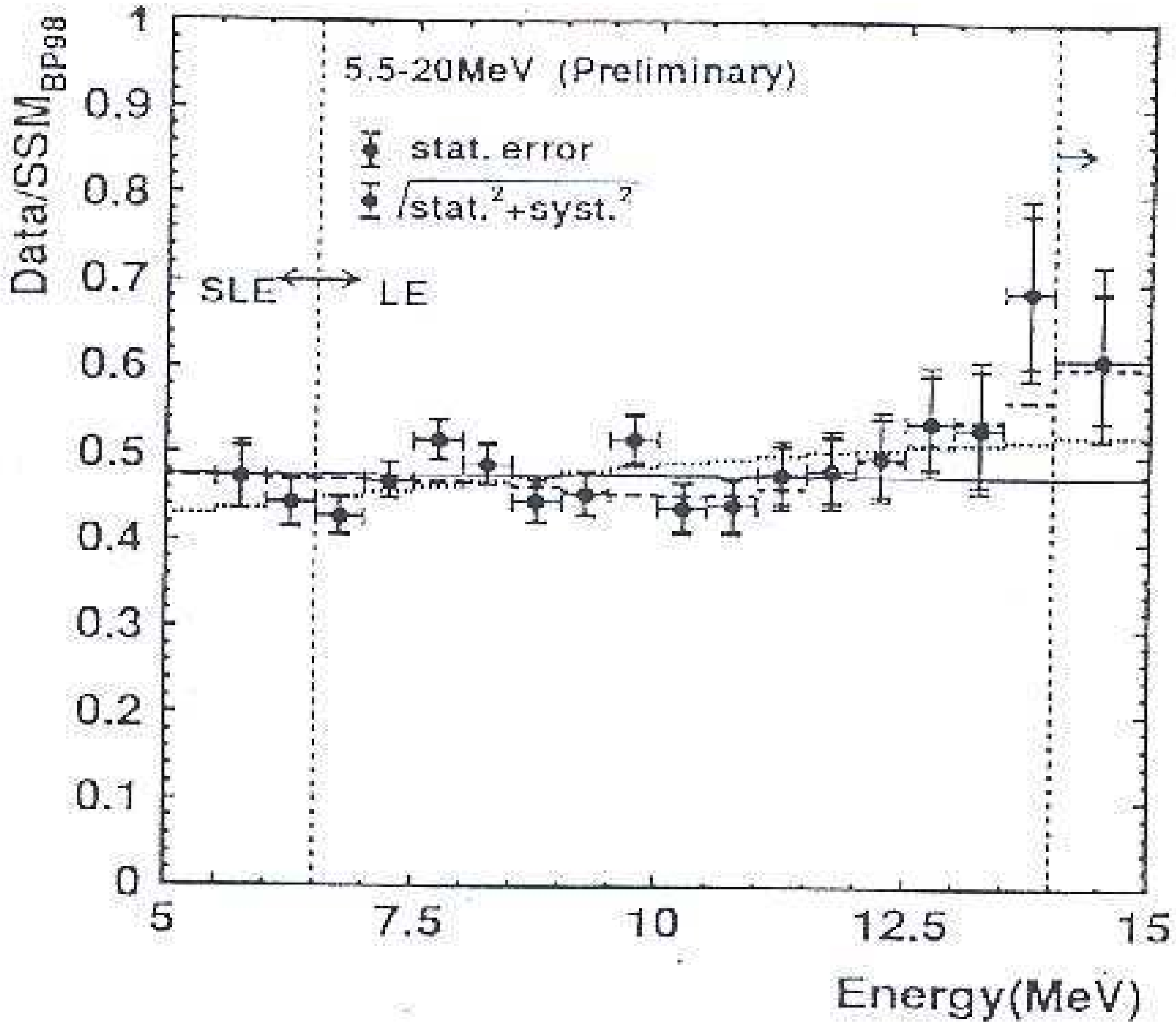
1996 - Kamiokande replaced by a new Cerenkov detector

Kamiokande	SuperKamiokande
4500 ton	50000 ton
948 PMT's	11146 PMT's
0.3 events/day	30 events/day

With such a large event rate (30/day) the e^- energy spectrum (5 - 20 MeV) could be divided in small intervals ('bins') with a sufficiently large number of events (small stat. error) which in Kamiokande had not been possible.

Thus the first spectral data were presented (Dec. 1997).

And the SMA solution started to become disfavoured



The accumulation of more data showed that the e^- spectrum is flat. SMA on the contrary predicted that it would rise strongly approaching unity with increasing E_e.

Eventually SMA was set aside by more experimental data: it predicted a brighter Sun at night from possible neutrino regeneration inside the Earth which was not the case. There remained LMA and SFP.

SNO experiment (2001)

Heavy water detector (D_2O). 3 processes are observed (only ^8B neutrinos are detected)

1. $\nu_e D \rightarrow ppe^-$ (charged current, CC)

2. $\nu_X D \rightarrow \nu_X pn$ (deuteron fission, only neutral current, NC: $X = \mu, \tau$)

3. $\nu_X e^- \rightarrow \nu_X e^-$ (CC+NC if $X = e$, NC if $X = \mu, \tau$)

First results (CC only) - June 2001

$$\frac{\#\, events\ measured\ in\ \nu_e D \rightarrow ppe^-}{\#\, events\ expected\ in\ \nu_e D \rightarrow ppe^-} = 0.347$$

later corrected to 0.340. This number is very similar to $R_{Cl} = 0.33$ and indicates that only 1/3 of ^8B neutrinos survive in the ν_e mode.

New result (NC) - April 2002

ν flux in process $\nu D \rightarrow \nu pn$ is consistent with the SSM prediction.

WHAT DOES THIS RESULT MEAN?

Together with the previous one (CC) it is confirmed that 1/3 of ν_{e_L} produced in the sun remain as ν_{e_L}. The remainder are converted into other neutrino species that only have neutral currents (NC). They either oscillated or have undergone spin flavour precession ($\nu_e \rightarrow \bar{\nu}_\mu$) through a Majorana magnetic moment μ_ν. It is not proven that solar neutrinos oscillated: only that they changed their flavour.

KamLAND experiment: situation is clarified

Several nuclear reactors (powerful antineutrino emitters) and one detector - a liquid cintilator replacing previous Kamiokande water detector, $n > n_{H_2O}$. This allows for a lower energy threshold.

If neutrinos have a vacuum mixing angle they oscillate according to

$$P[\nu_e \rightarrow \nu_e(L)] = 1 - sin^2 2\theta sin^2 \left(\frac{\Delta m^2}{4E} L \right)$$

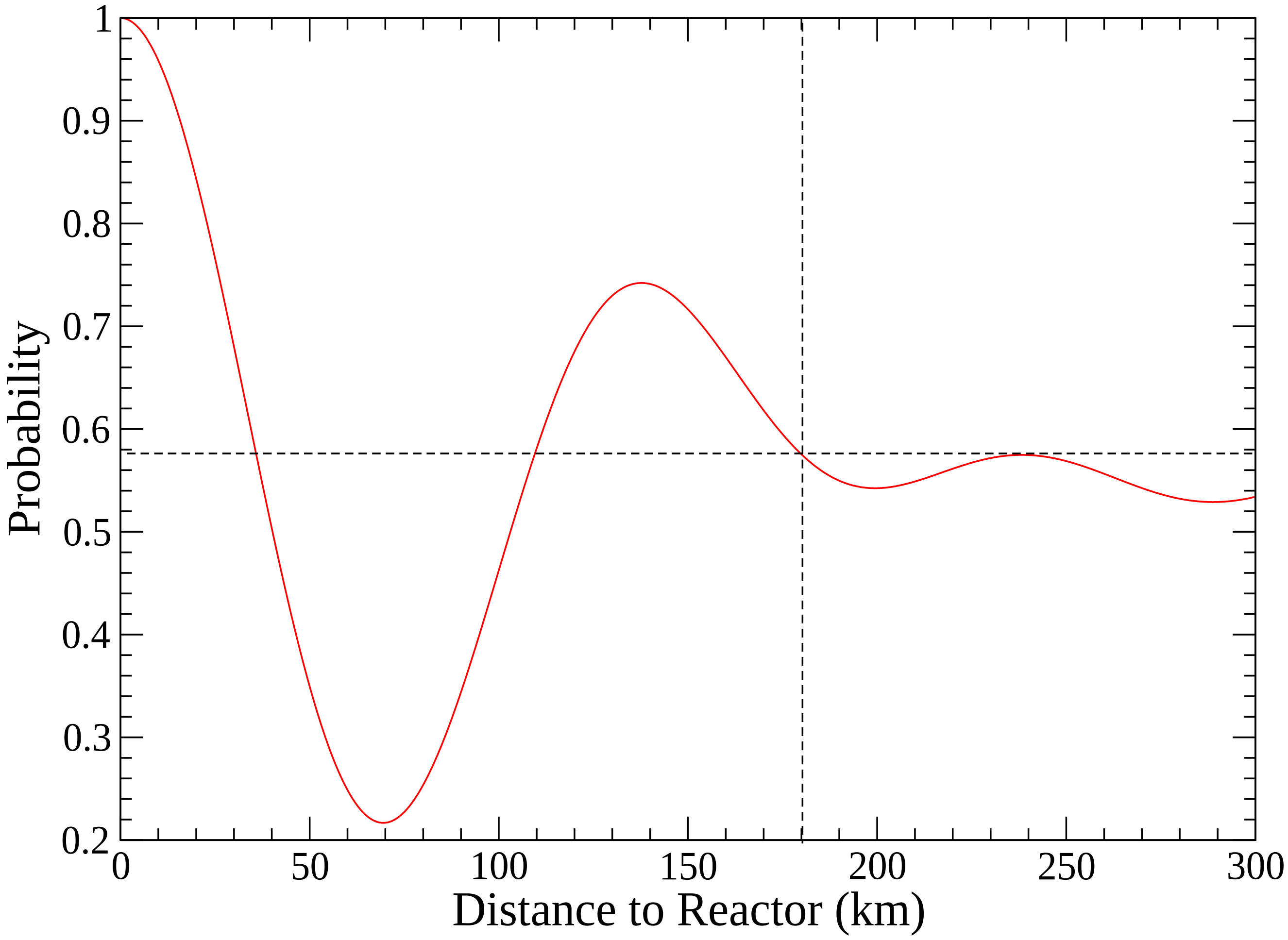
also valid for $\bar{\nu}_e$ (CPT invariance).

On their way from the reactors to the detector, neutrinos oscillate in vacuum.

Inserting:

Average distance $L = 180 km$

LMA parameters, $\theta = 34^o$, $\Delta m^2 = 7.9 \times 10^{-5} eV^2$



LMA is confirmed: $R_{KamLAND} = P_{LMA}[\nu_e \rightarrow \nu_e]$

$$P_{LMA} = 0.576, \quad P_{exp} = 0.658 \pm 0.064$$

4. Variability or not

Incontroversial: the event rate in the two Ga experiments has always been decreasing. This could be the effect of a long term periodicity. Discrepancy of 2.4σ

Period	1991-97	1998-03
SAGE+Ga/GNO	77.8 ± 5.0	63.3 ± 3.6
Ga/GNO	77.5 ± 7.7	62.9 ± 6.0
SAGE	79.2 ± 8.6	63.9 ± 5.0
no. of sunspots	52	100

Possible anticorrelation with 11 year solar cycle.

Cl experiment did not provide any results on variability. But Ga experiments may provide.

They are the only ones with a significant contribution of low energy neutrinos, pp, ^7Be.

pp, ^7Be contribute $\simeq 80\%$ of events and they constitute $> 99\%$ of $\nu' s \odot$ total flux. Therefore the time dependence of these fluxes becomes an open possibility.

We proposed an alternative to the conventional LMA scenario:

Do not average over time. One would obtain

$$68.3 \pm 2.9 \, SNU$$

but rather find out the neutrino parameters consistent with the two previous sets and with all other $\odot$ ν experiments (Cl, SuperK, . . .).

MODEL

Introduce sterile neutrinos. In vacuum they do not mix with active ones

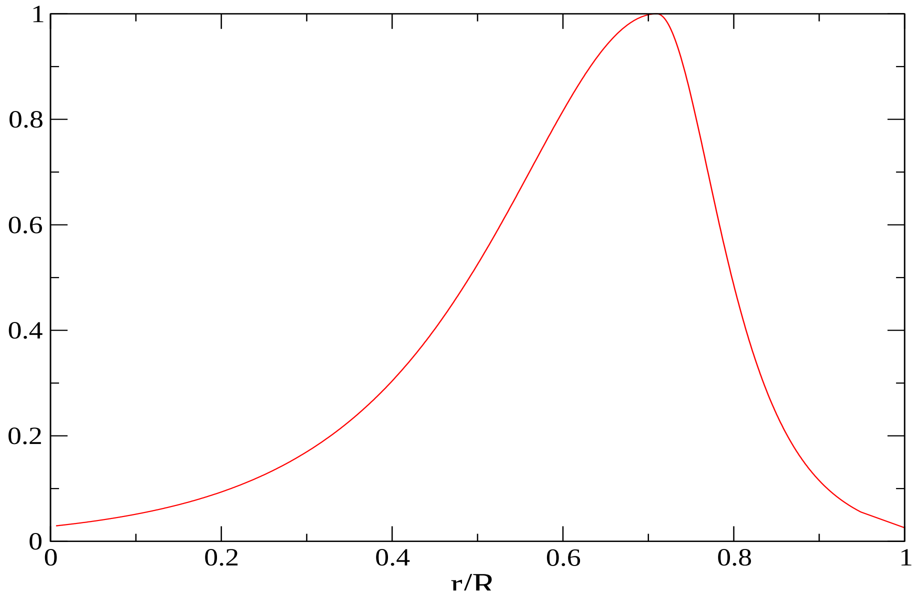
$$\begin{pmatrix} \nu_s \\ \nu_e \\ \nu_x \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_\theta & s_\theta \\ 0 & -s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} \nu_0 \\ \nu_1 \\ \nu_2 \end{pmatrix} \quad (2)$$

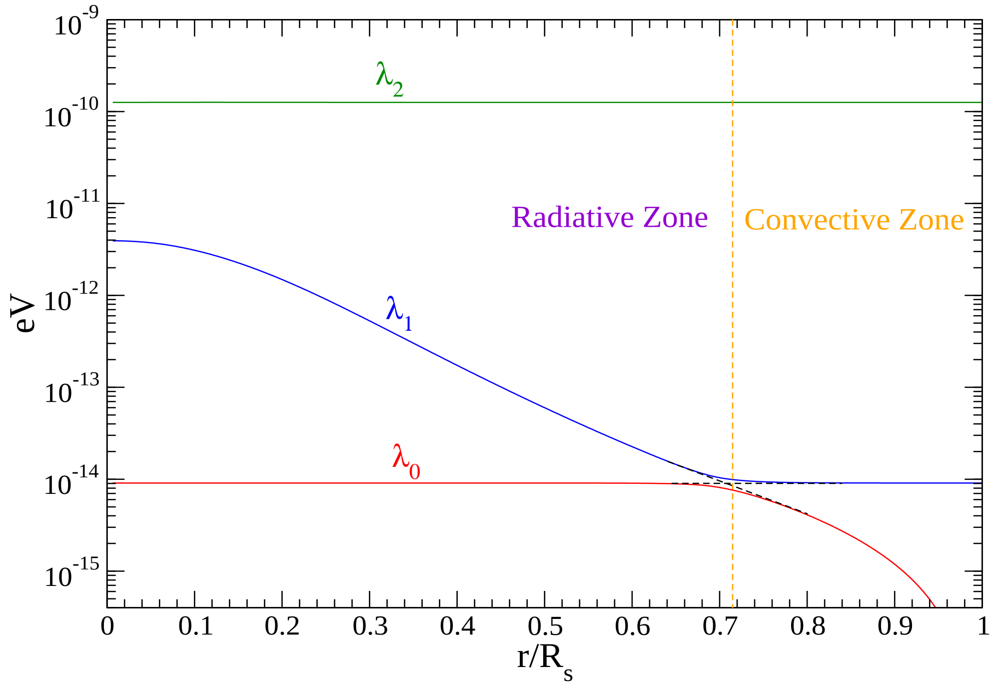
and in matter they communicate with active ones through magnetic moment only (simplest version)

$$\mathcal{H}_{\rm M} = \begin{pmatrix} \frac{-\Delta m^2_{10}}{2E} & \mu_\nu B & 0 \\ \mu_\nu B & \frac{\Delta m^2_{21}}{2E} s^2_\theta + V_e & \frac{\Delta m^2_{21}}{4E} s_{2\theta} \\ 0 & \frac{\Delta m^2_{21}}{4E} s_{2\theta} & \frac{\Delta m^2_{21}}{2E} c^2_\theta + V_x \end{pmatrix} \quad (3)$$

$\Delta m^2_{10} = m^2_1 - m^2_0$ fixes the resonance location of active $\rightarrow$ sterile.

$\Delta m^2_{21} = m^2_2 - m^2_1$ fixes the location of the LMA resonance.





At times of greater solar activity expect

$$B_0 = 200 - 300 kG$$

at the base of the convection zone ($r/R_S = 0.713$)

$\Delta m^2_{10} = O(10^{-8} eV^2) \rightarrow$ resonances of pp, ^7Be neutrinos are located near the peak field B_0.

Significant neutrino conversion requires strong B at the resonance range. Otherwise the resonance is not adiabatic $\rightarrow$ little or no conversion! If B is time-varying in that zone (possibly in relation with solar activity), it implies modulation of the low energy ν flux:

$$mainly\ \ pp\ \ ,\ \ ^7Be$$

Thus we obtain

	Ga	Cl	K (SK)	$\mathrm{SNO_{NC}}$	$\mathrm{SNO_{CC}}$	$\mathrm{SNO_{ES}}$
Set (I)	73.8	2.66	2.29			
Set (II)	60.3		2.28	5.65	1.59	2.25
LMA	64.8	2.74	2.30	5.10	1.75	2.28

All within 1σ except SNO_{NC} (1.5σ).

Parameters used

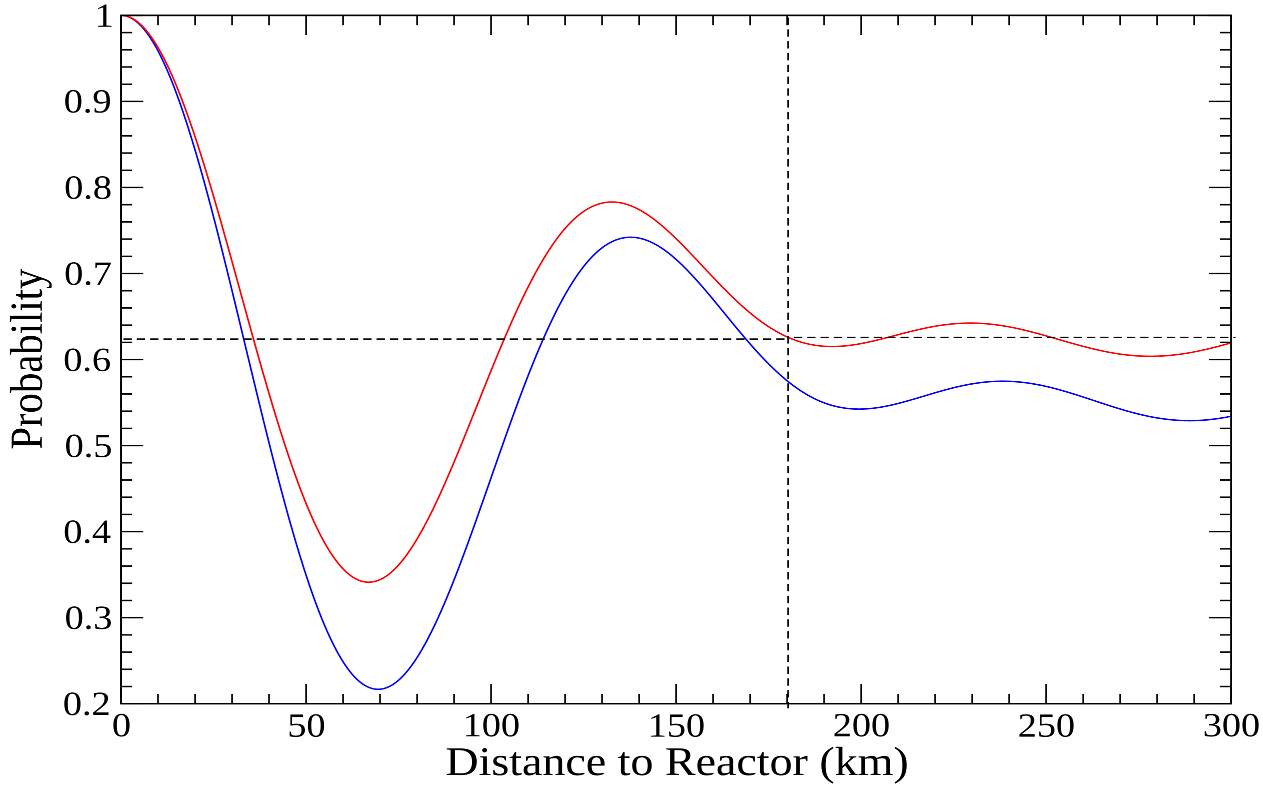
$$\Delta m^2_{21} = 8.2 \times 10^{-5} eV^2,\ tan^2\theta = 0.31$$

$$\Delta m^2_{10} = -1.7 \times 10^{-8} eV$$

LMA parameters (KamLAND only)

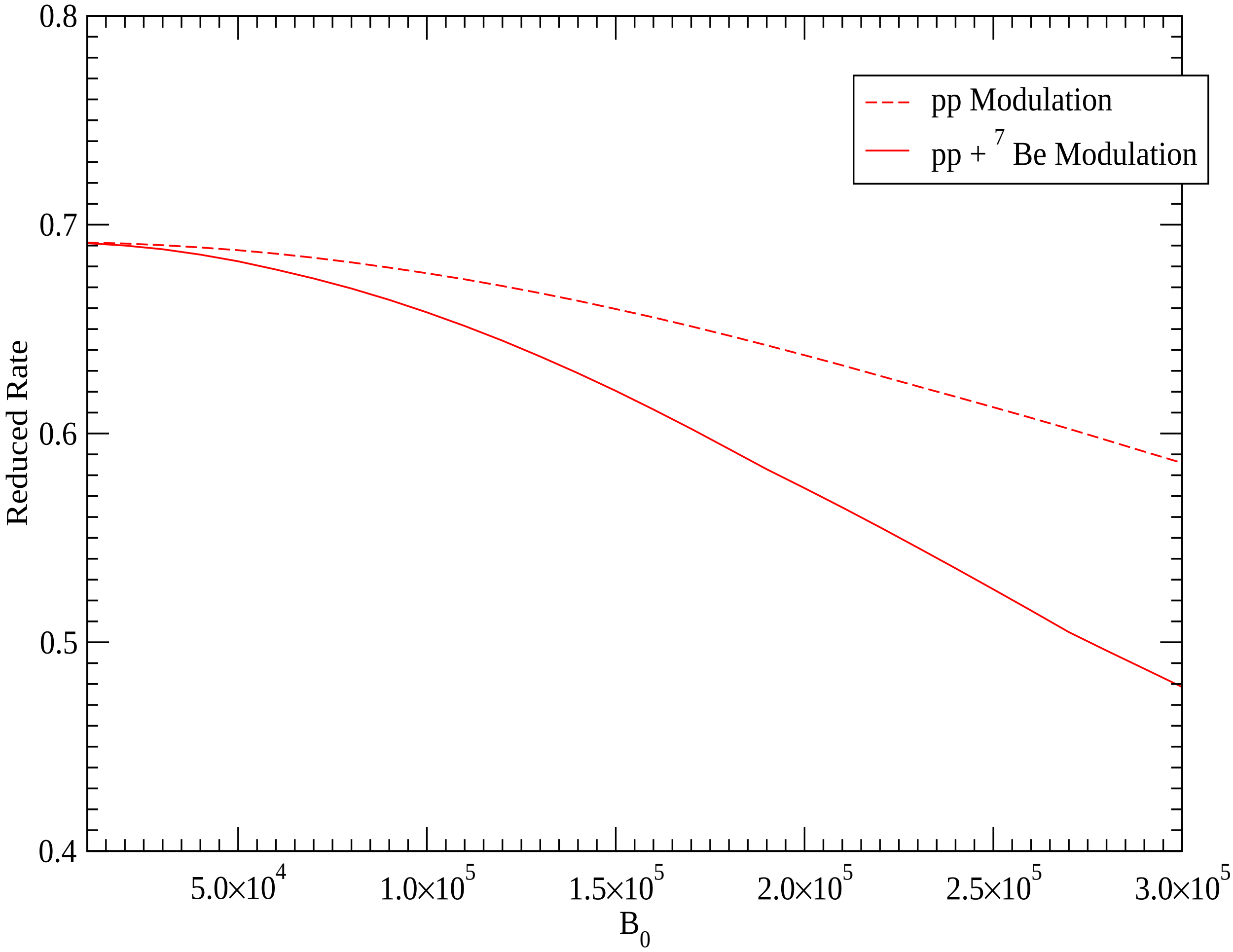
$$\Delta m^2_{21} = 7.9 \pm^{0.6}_{0.5} \times 10^{-5} eV^2,\ tan^2\theta = 0.46 \pm^{4.5}_{0.25} (2\sigma)$$

We therefore used the uncertainty in θ from the KamLAND analysis (θ is largely uncertain, conventional solar fit removes it partially but in the present work this fit is ignored).



$$P_{LMA} = 0.576,\ \ P_{SFP} = 0.623, P_{exp} = 0.658 \pm 0.064$$

Borexino



Reduced Borexino rate

$$\frac{\int_{T_m}^{T_M} dT \int_{E_m}^{E_M} dE \phi(E) [P_{ee}(E) \frac{d\sigma_{\nu_e}}{dT} + (1 - P_{ee}(E)) \frac{d\sigma_{\nu_x}}{dT}]}{\int_{T_m}^{T_M} dT \int_{E_m}^{E_M} dE \phi(E) \frac{d\sigma_{\nu_e}}{dT}}$$

5. Conclusions

SNP is one of the most beautiful in recent Physics: experiment contradicted existing theory. New ideas were created to understand results, implying new Physics. New experiments were developed confirming them. Merit goes to John Bahcall (1934-2005) mostly . . .

And the magnetic moment? Does it play any role? May be: its signature will be the possible variability of the active neutrino flux. Thus the distinction between 'conventional' LMA and LMA+SFP:

(a) KamLAND - new reactors - the two curves for P can be distinguished for $d_{eff} < (110 - 120)km$.

(b) Borexino will initiate shortly, SNO+ within the next 2-3 years and both will be directed to LE $\nu's$.

The main challenge is to ascertain whether there is variability or not. That will imply new Physics.