Solar Neutrinos: Status and Prospects

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IFIC, Valencia

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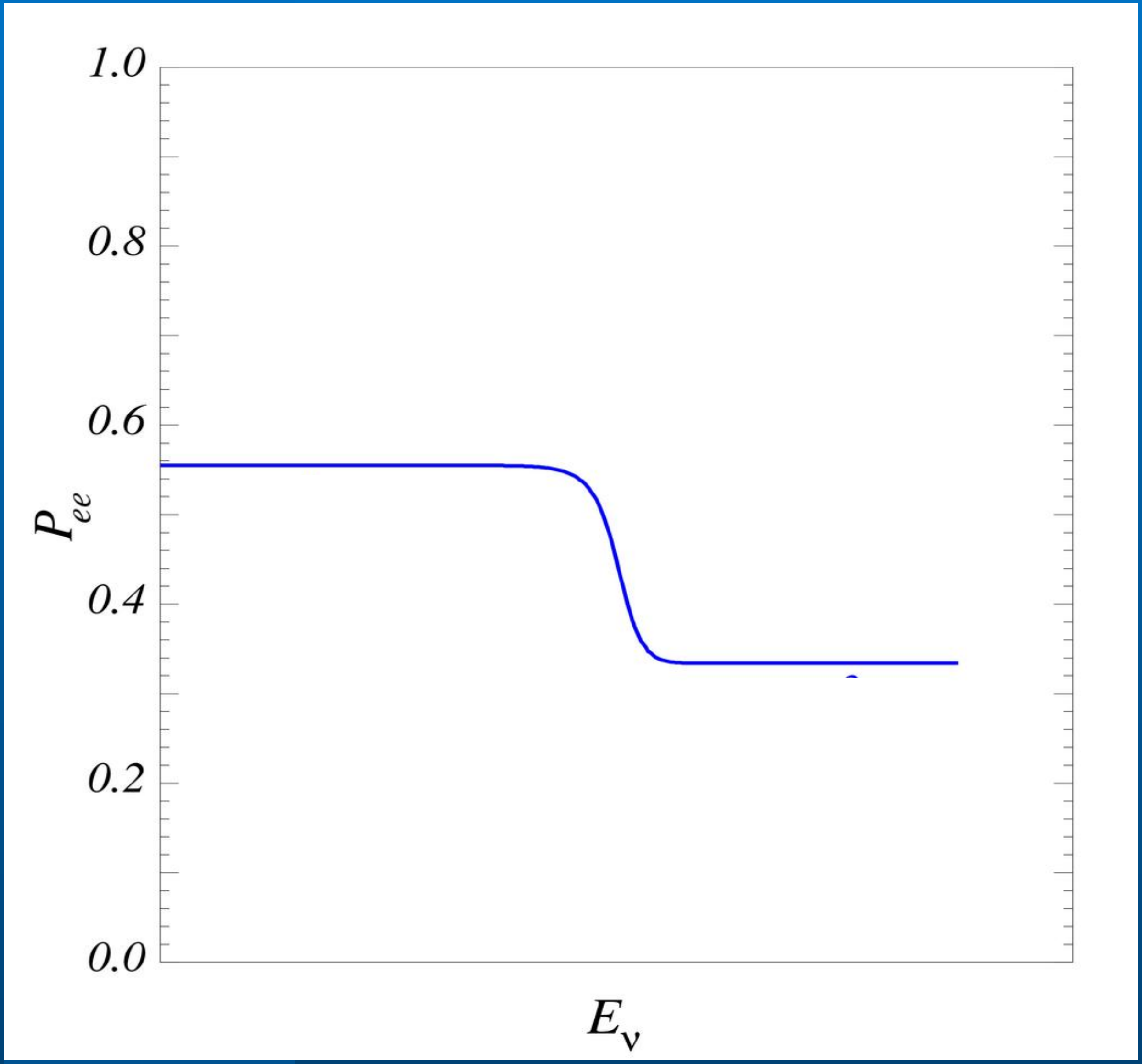
V International Pontecorvo Neutrino Physics School, Alushta

LMA : Vacuum to adiabatic transition

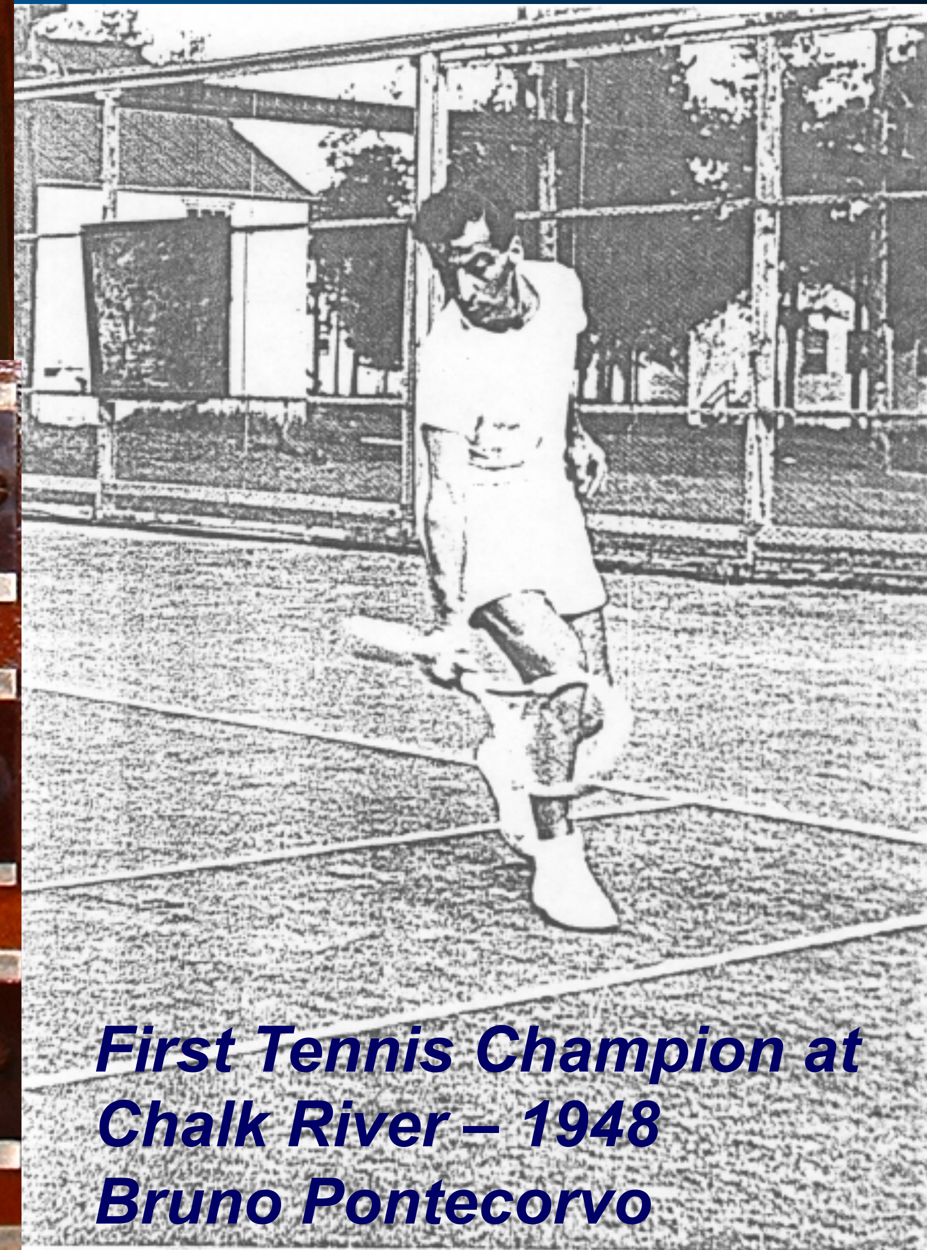


First Part

Short Introduction. Experiments
Flavor conversion
Solar Model

Conception of Neutrino Astrophysics

In 1946 Bruno M. Pontecorvo, then at the Chalk River Nuclear Laboratories in Canada, pointed out that an isotope of chlorine, ^{37}Cl, could capture a neutrino and be transformed into an isotope of the rare gas argon, ^{37}Ar, with the release of an electron. Subsequently the suggestion was discussed in detail by Luis W. Alvarez of the University of California at Berkeley. On the basis of Alvarez' discussion, Davis attempted to observe the argon produced by antineutrinos from the decay of fission products. (with 1,000 and 3000 gallon detector near a nuclear reactor).



First Tennis Champion at Chalk River – 1948
Bruno Pontecorvo

late 1950s: Reconsidering the experiment

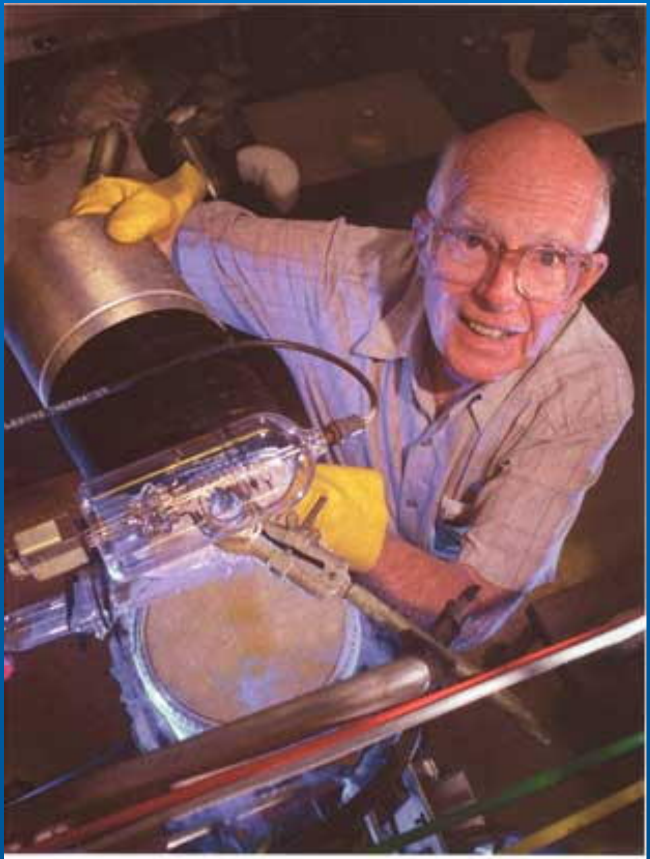


Photo courtesy of Brookhaven National Laboratory

E_{th} = 0.86 MeV

E_ν (pp) < 0.4 MeV

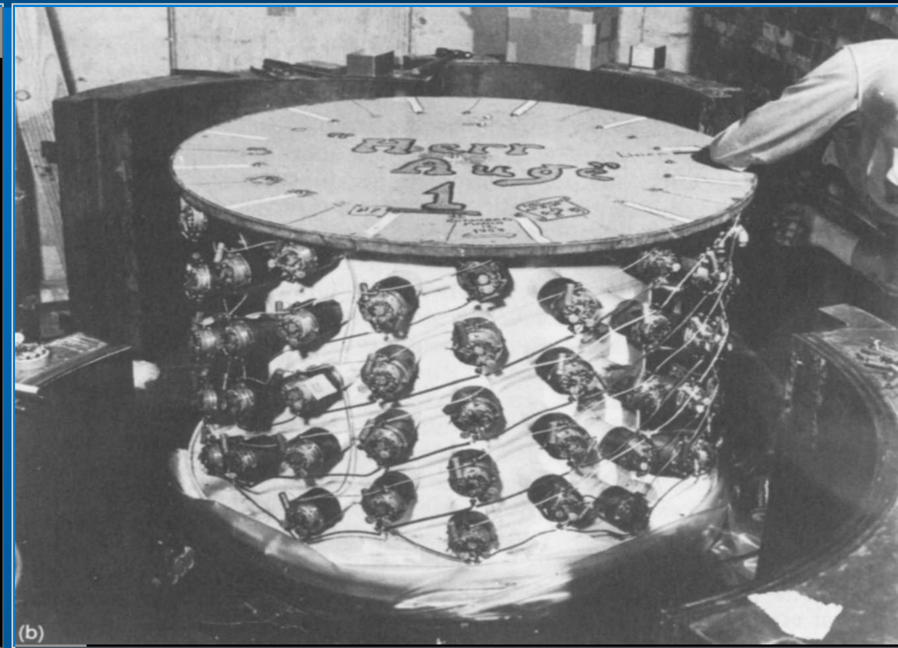
< 10^{14} CNO ν / cm^2 / s
10^6 higher than theoretical prediction

(1955) 1000 gal of C_2Cl_4

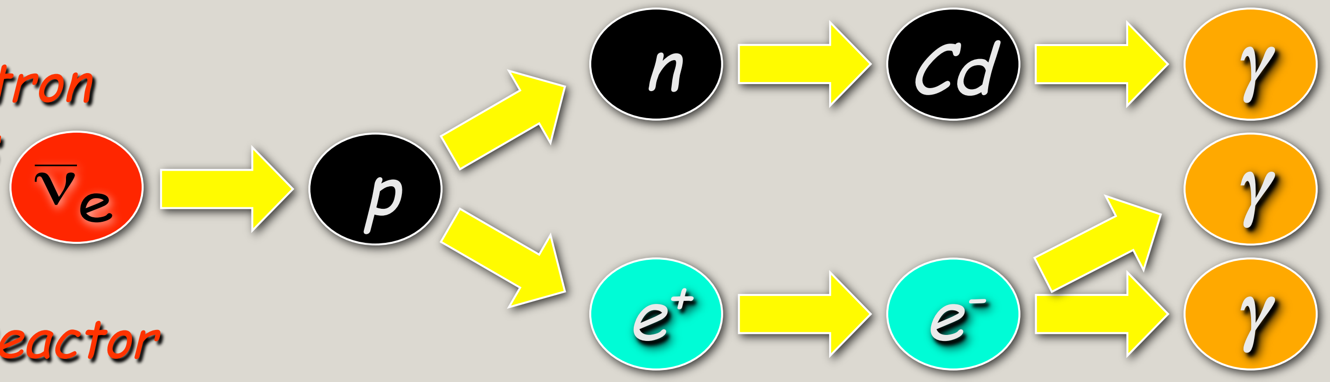
(1958) 3000 gal of C_2Cl_4

In 1957 Bruno M. Pontecorvo, postulates neutrino oscillations

(anti)Neutrinos first observed 1954-56

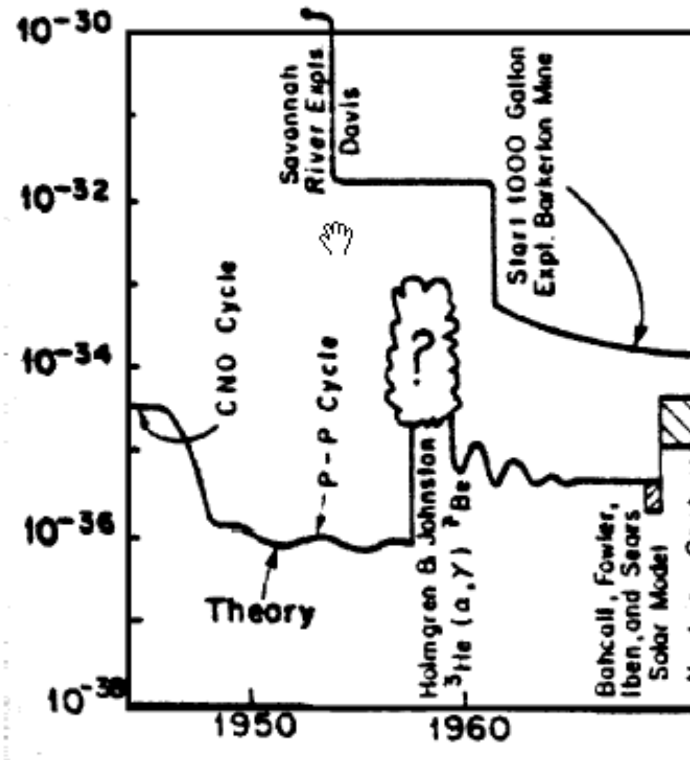


Anti-Electron Neutrinos from Hanford Nuclear Reactor



3 Gammas in Coincidence

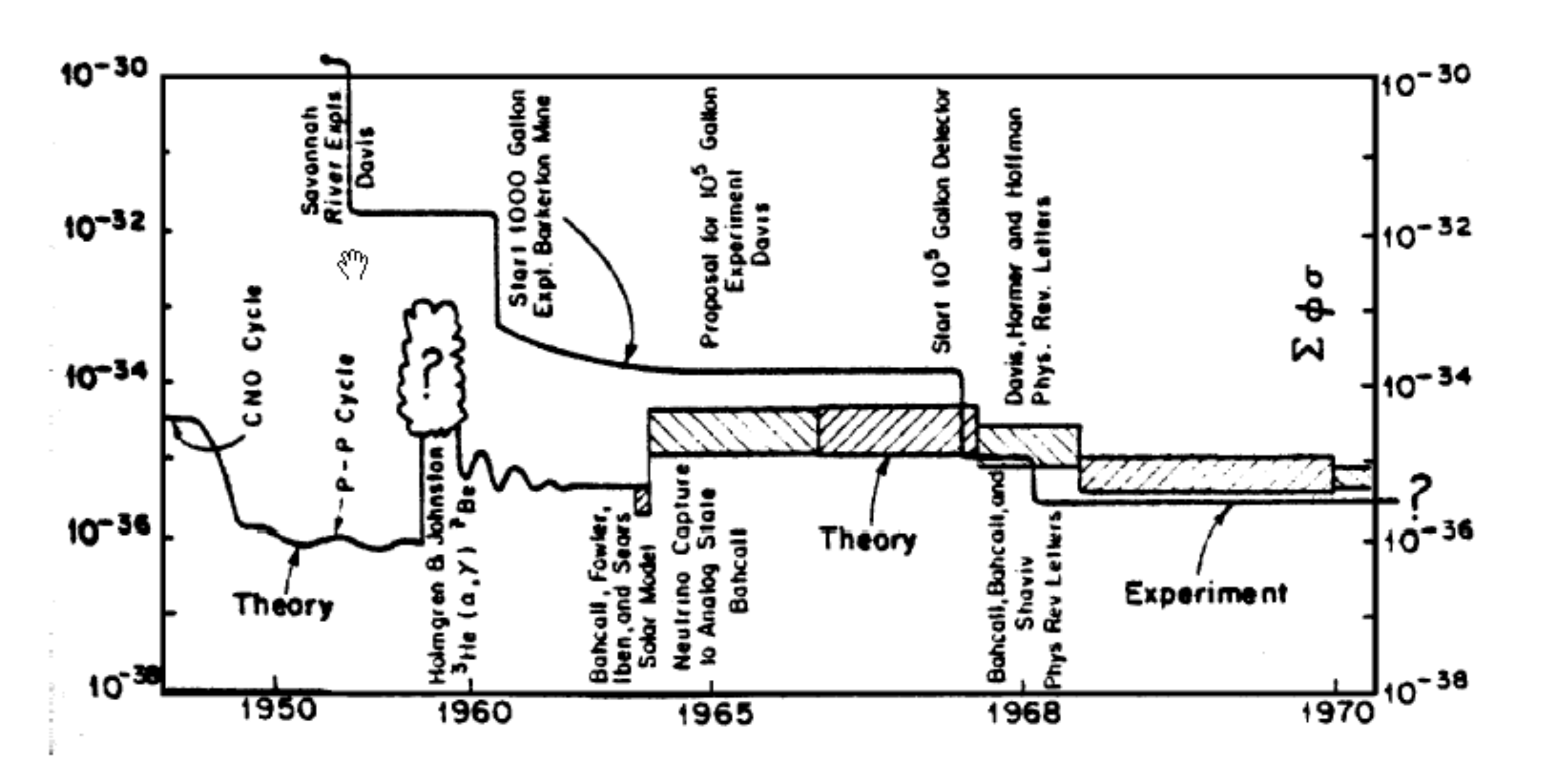
Chlorine rate: Theory vs experiment



Neutrino Astrophysics was born…

"…to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars." Bahcall, Davis, PRL 12 (1964)

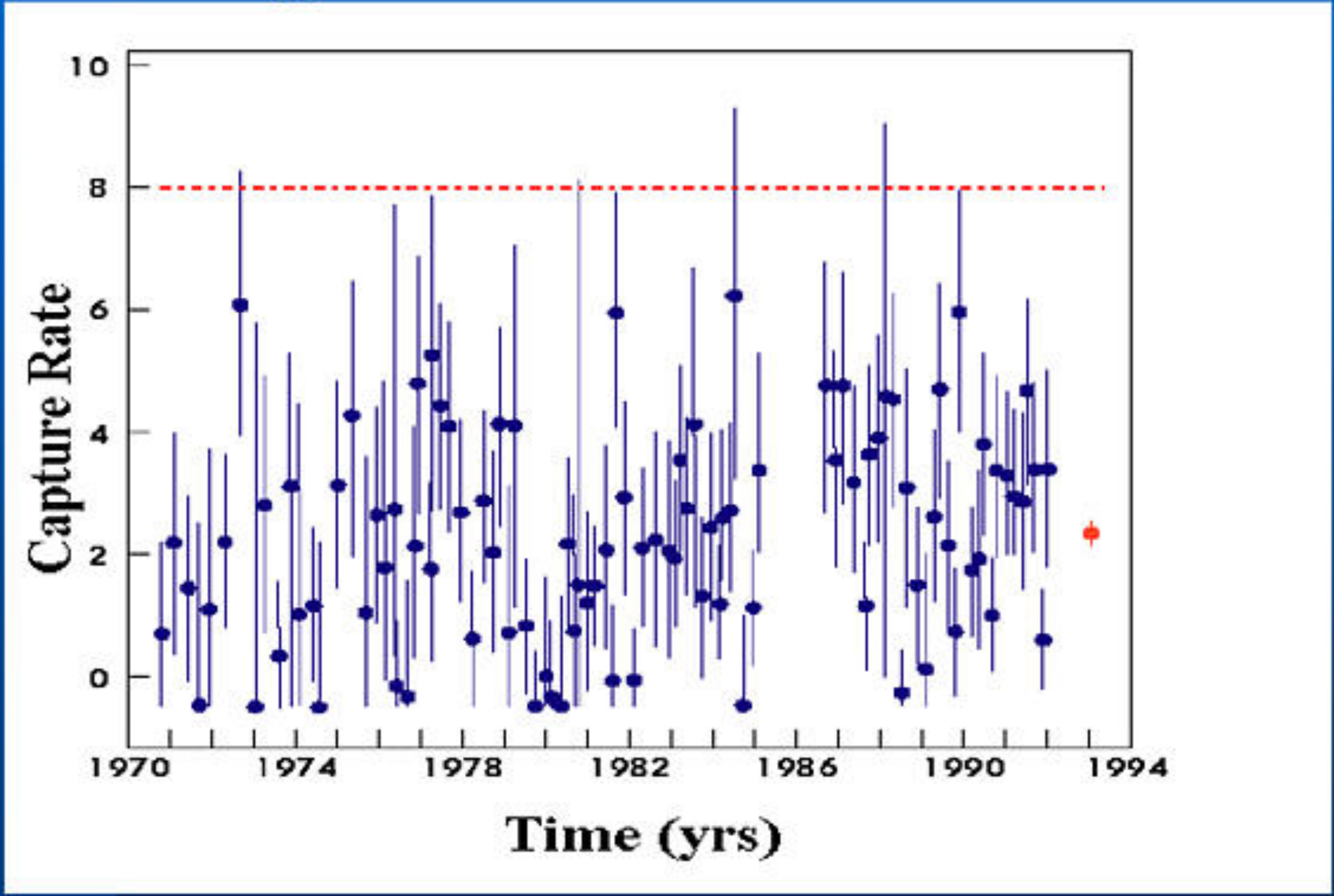
Chlorine rate: Theory vs experiment



In 1968, flux is too low: Davis measurements vs Bahcall calculations. Grivob-Pontecorvo discuss solar neutrino oscillations

Homestake *First Solar Neutrino Problem…*

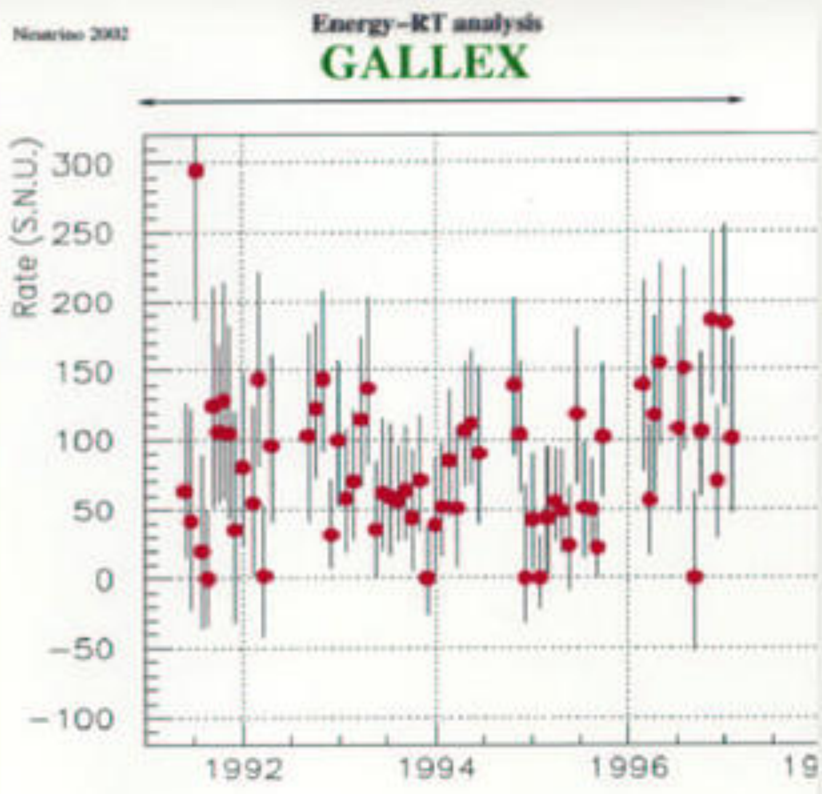
$$N_{CC} = 2.56 \pm 0.23 \;\; \text{SNU}$$



1 SNU $=10^{-36}$ captures / target atom / s

GALLEX/GNO - SAGE

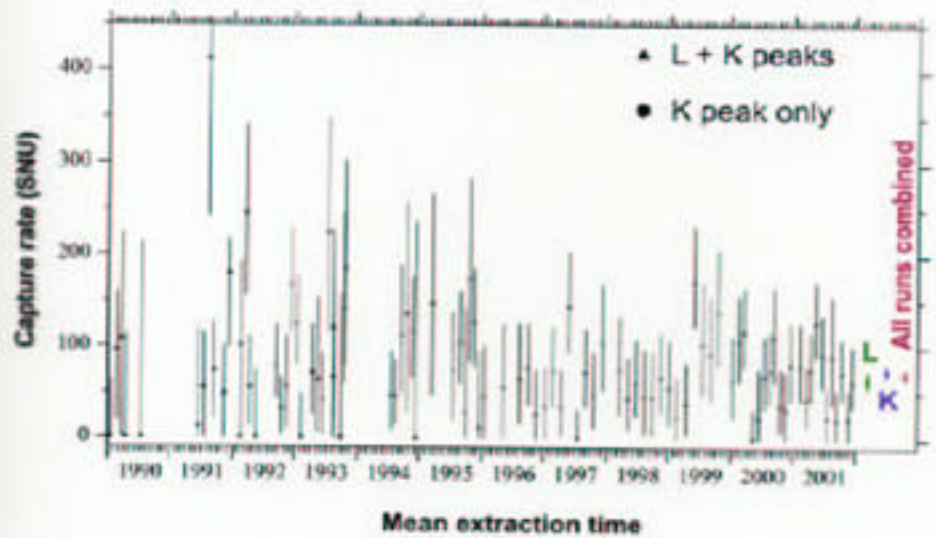
$$N_{CC} = 70.8 \pm 4.4 \ \text{SNU}$$



GALLEX	65 SR	77.5 ·
GNO	43 SR	65.2 ·
GNO+GALLEX	108 SR	70.8

SAGE

January 1990 - December 2001



Combined result:

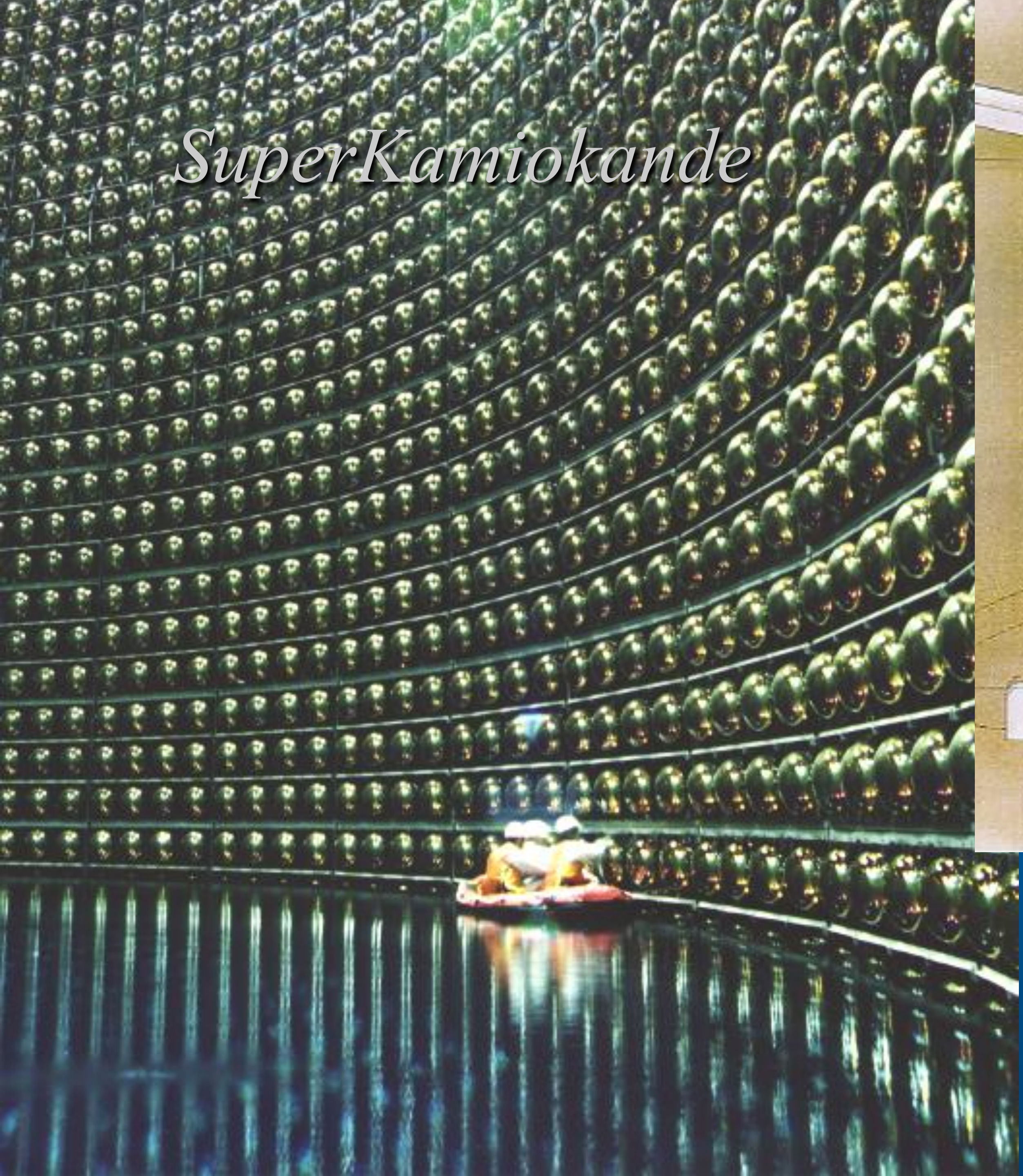
L-peak - 64.8 +8.5/-8.2 SNU

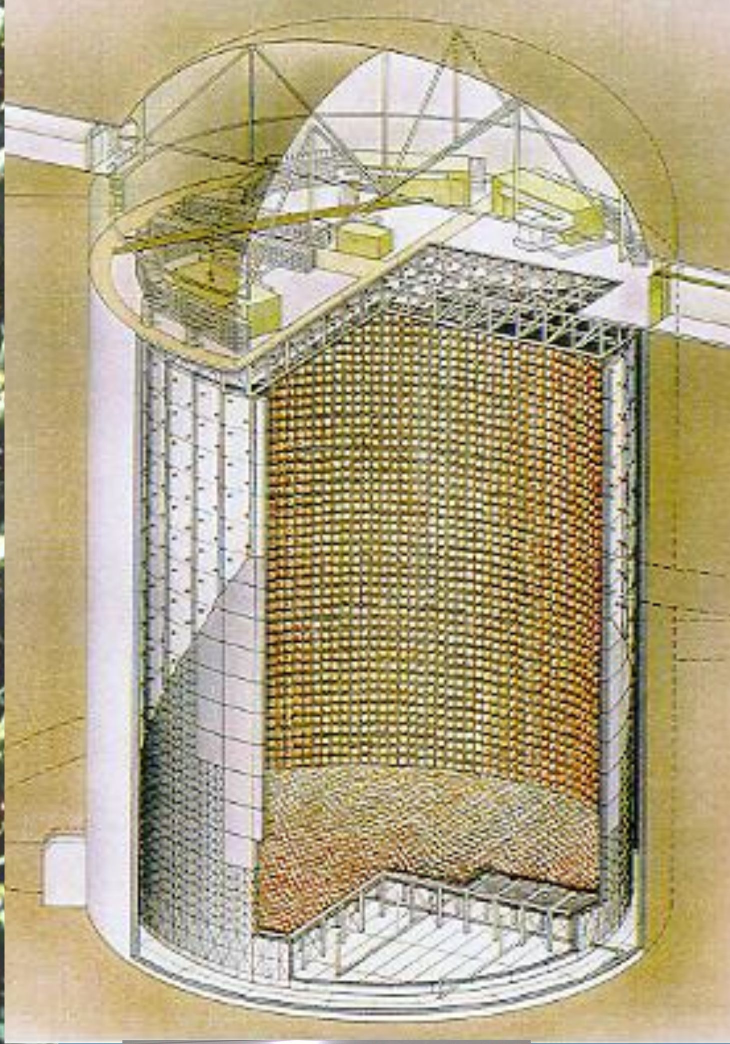
K-peak - 74.4 +6.8/-6.6 SNU

Overall - 70.8 +5.3/-5.2 SNU

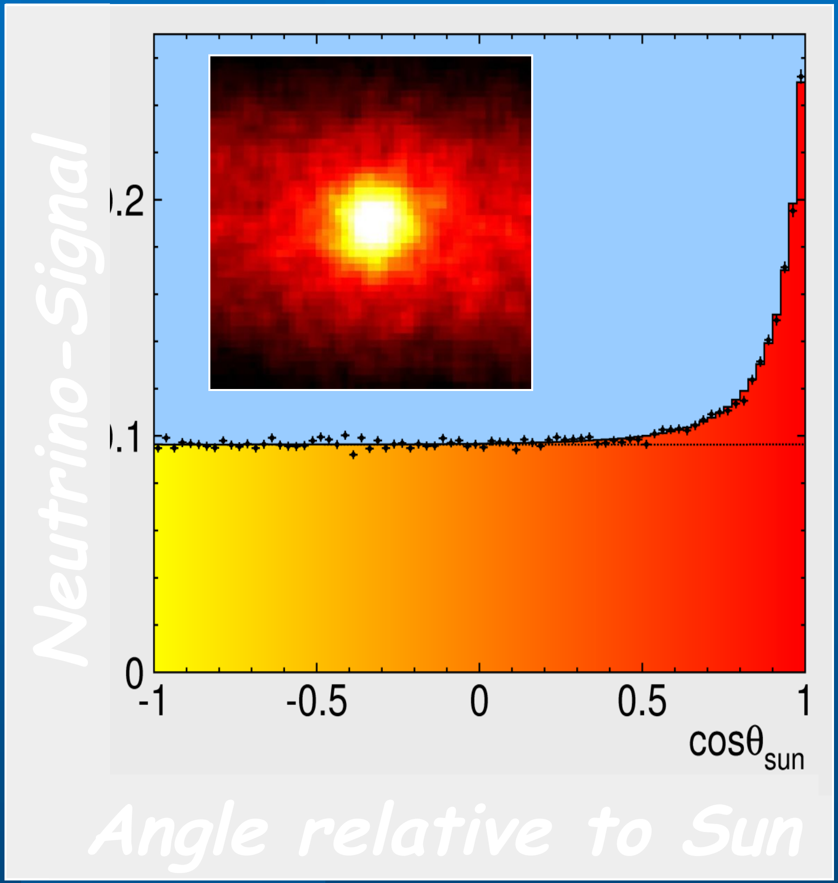
1 SNU = 1 interaction of ν_e /sec in 10^{36} atoms/day

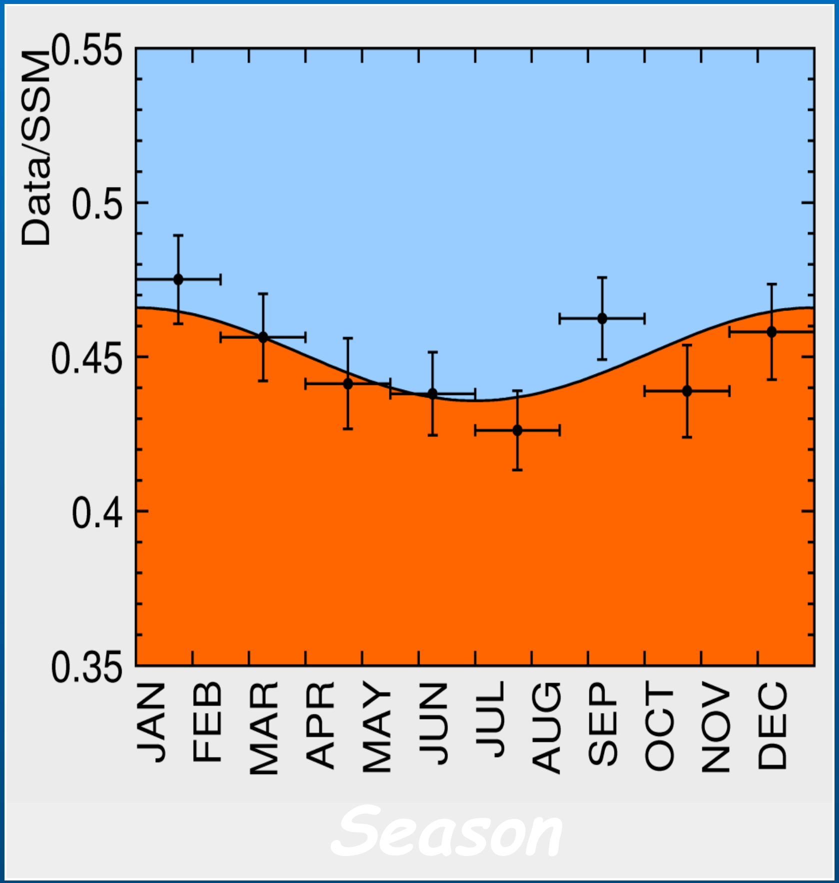
SuperKamiokande



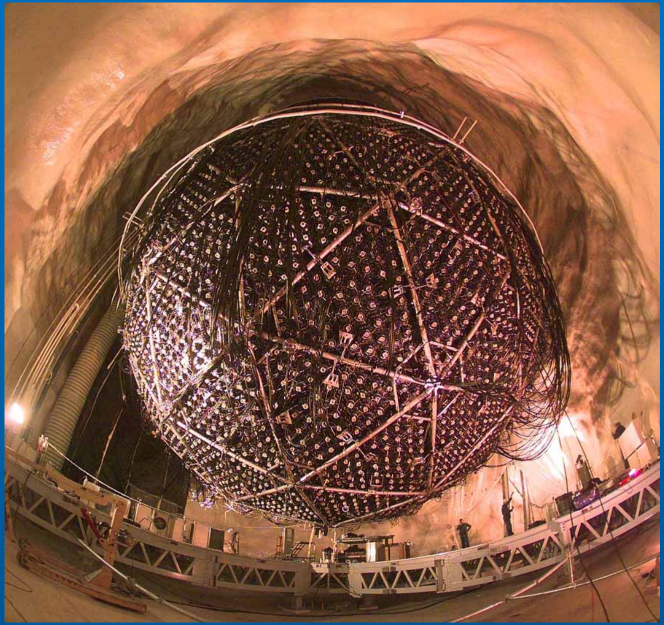


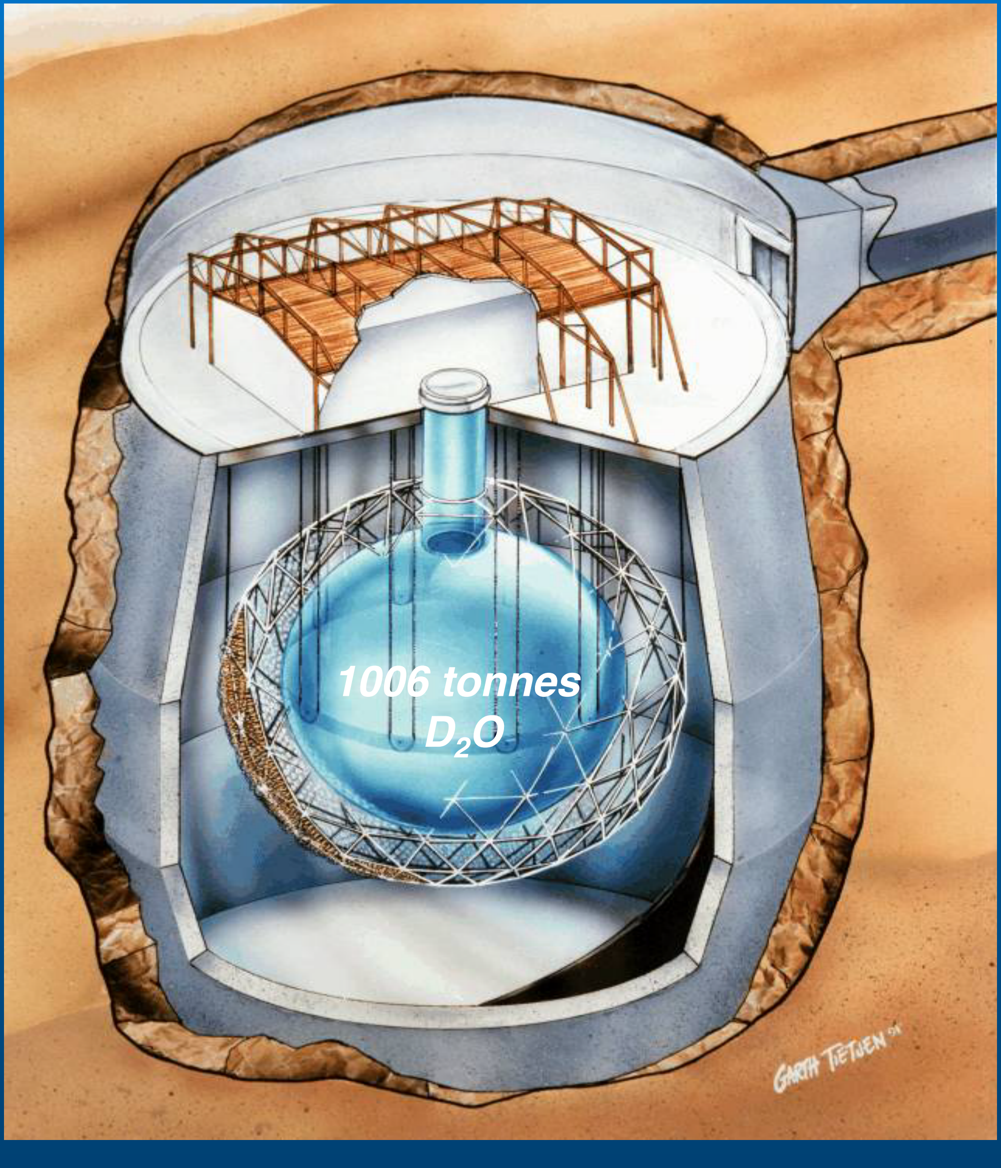
Neutrinos come from the Sun



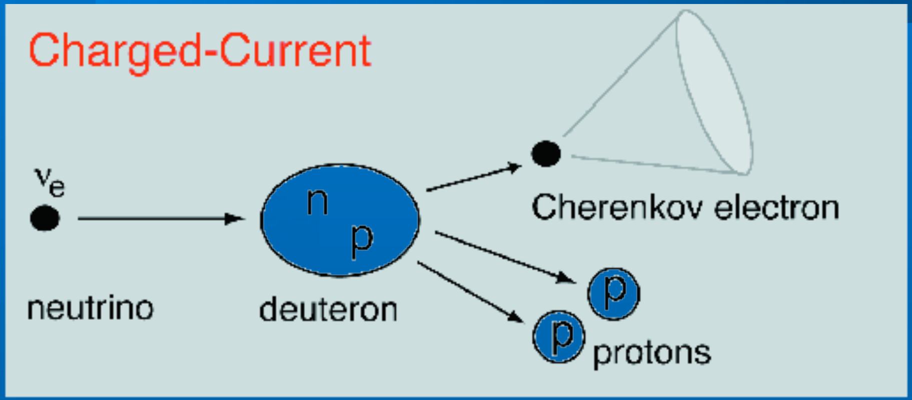


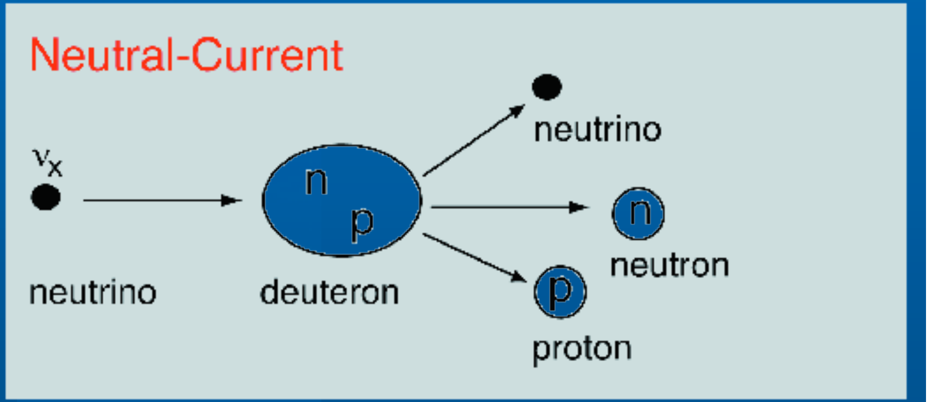
SNO

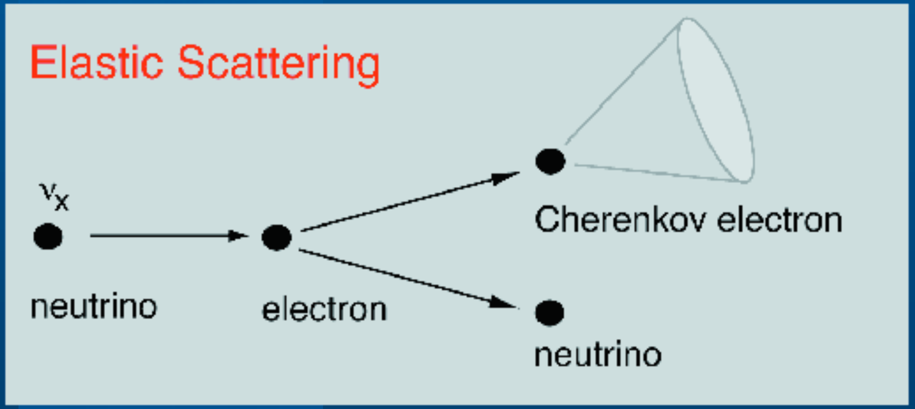


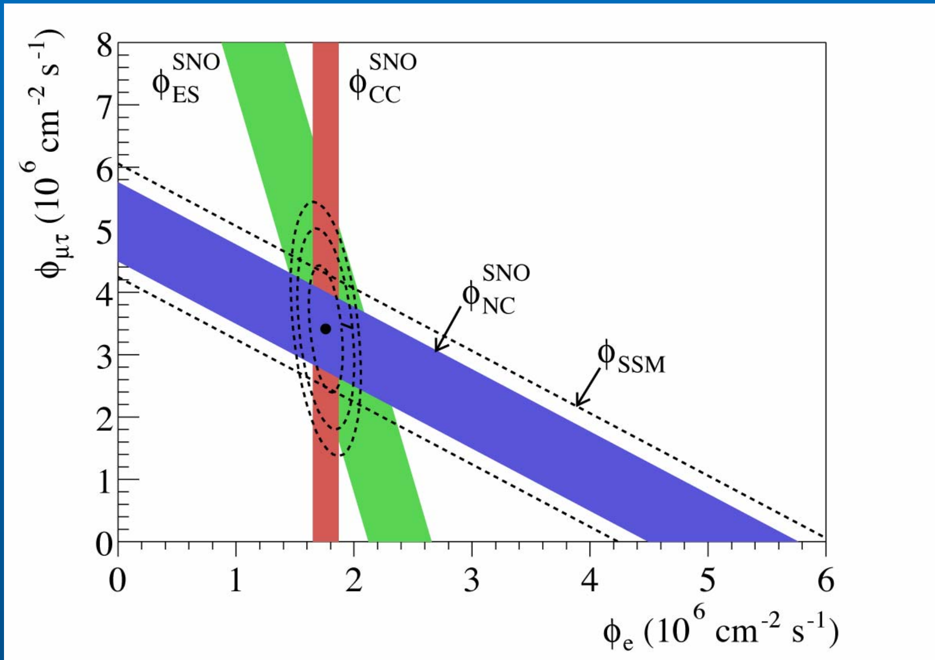


Flavor conversion



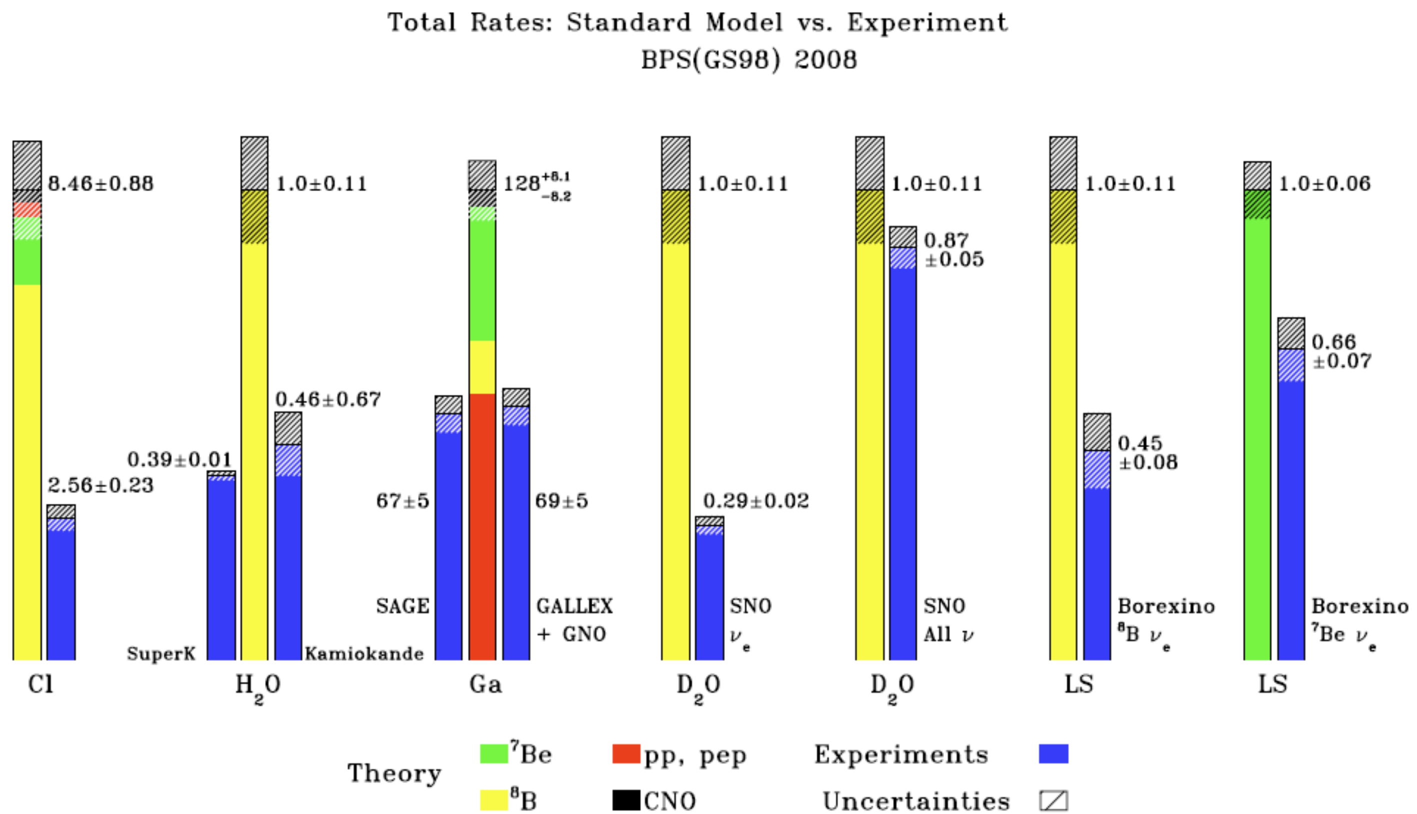




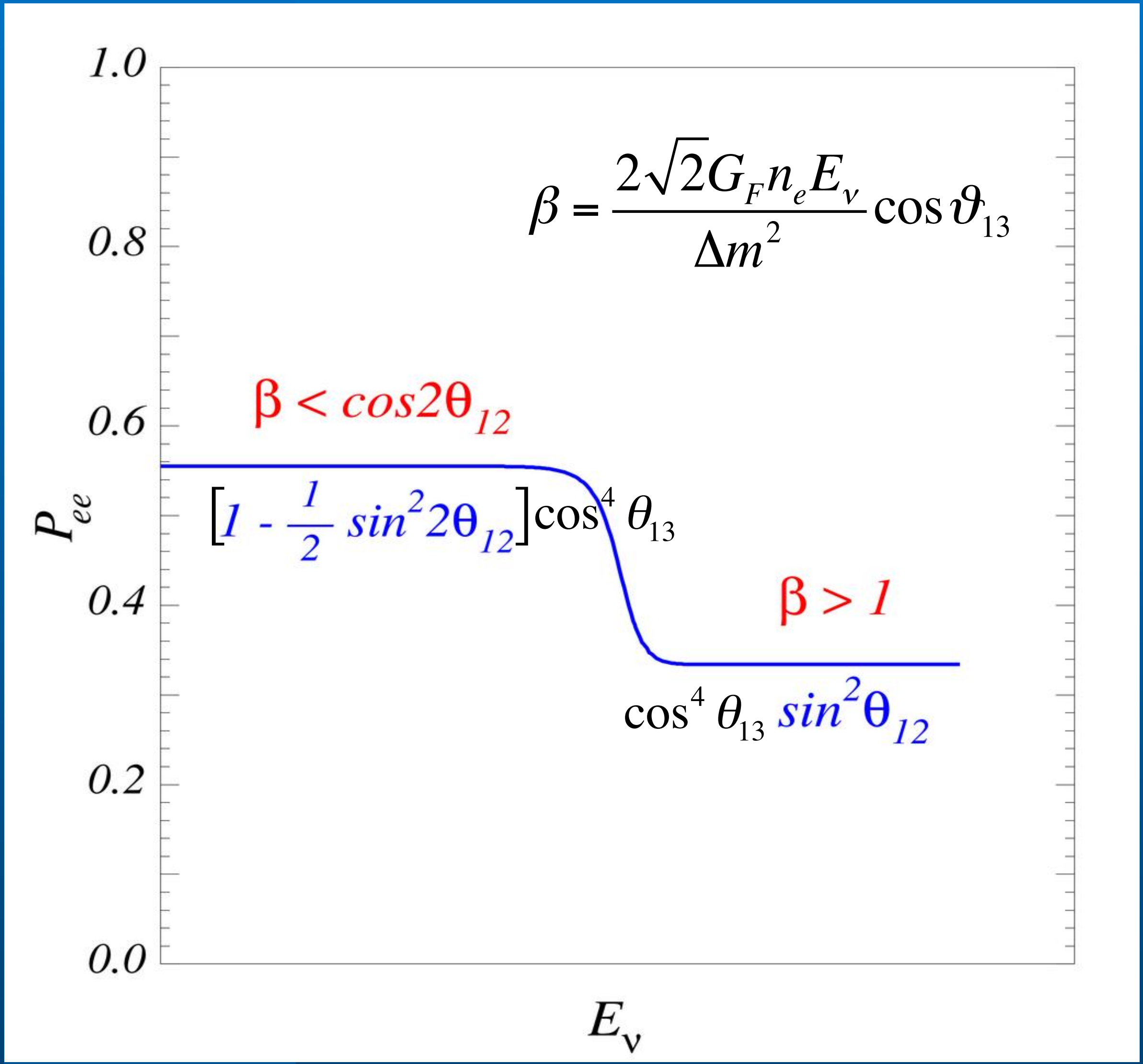


Borexino

BPS08 vs solar ν data



LMA : Vacuum to adiabatic transition



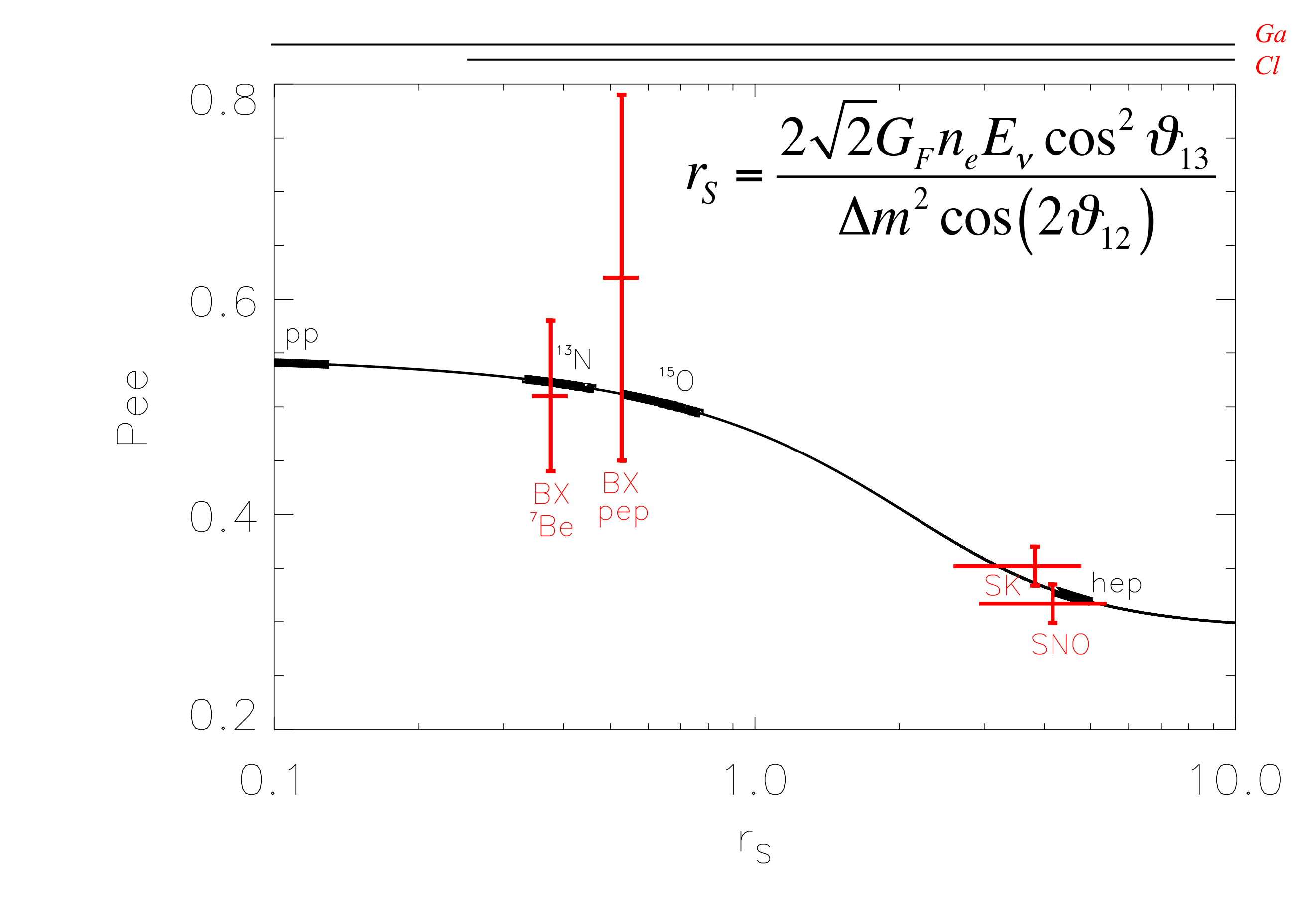
$E_{crit} \; (^8B) = 1.8$ MeV

$E_{crit} \; (^7Be) = 2.2$ MeV

$E_{crit} \; (pep) = 3.2$ MeV

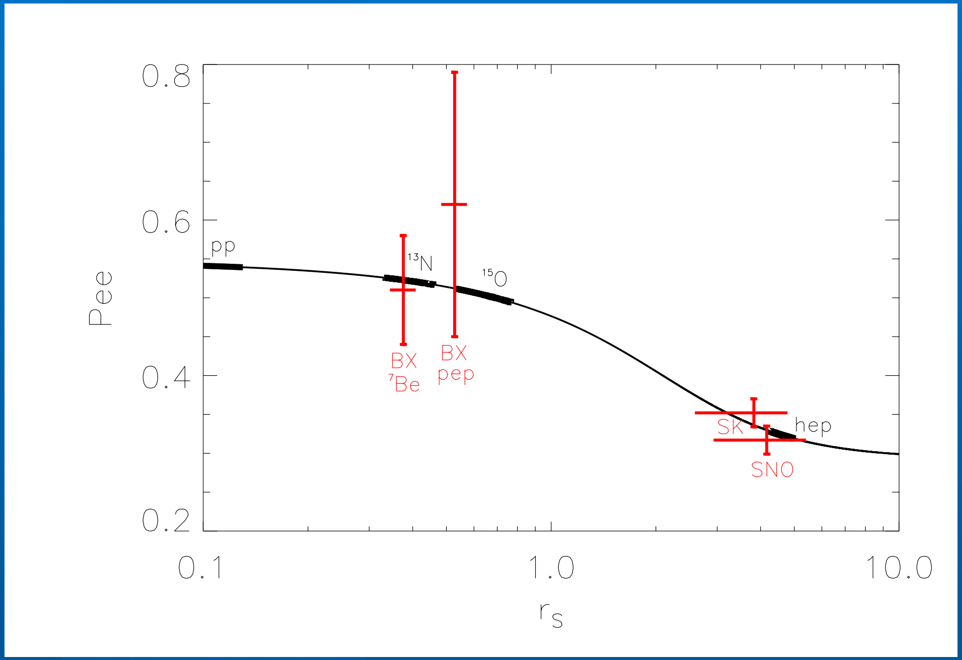
$E_{crit} \; (CNO) = 1.9$ MeV

Flavor Conversion 1-2 in solar and reactor ν

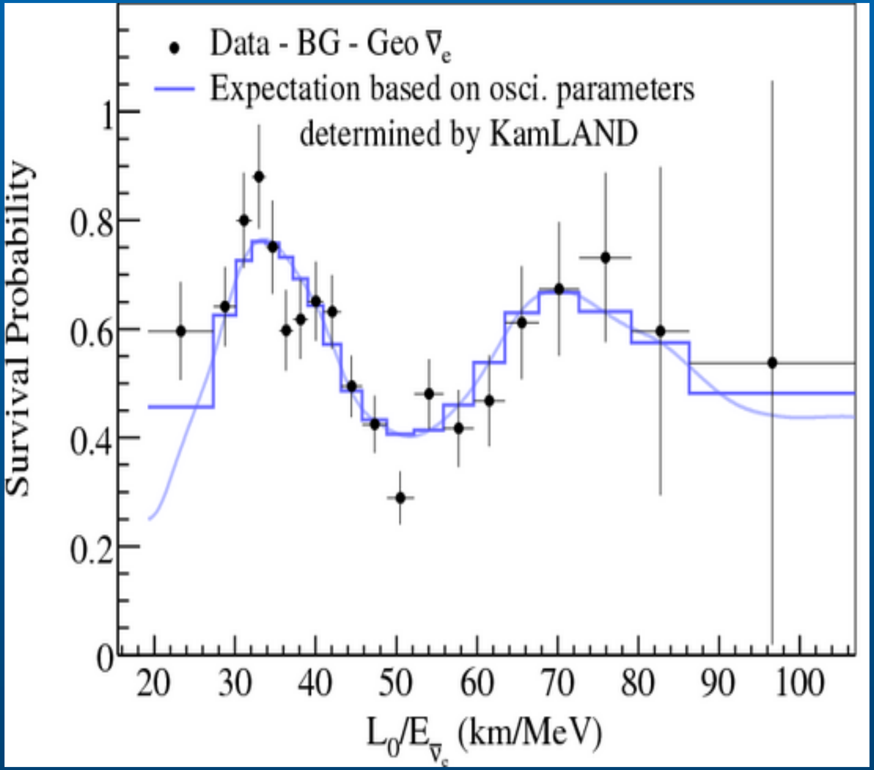


Decoherence of low energy ν and flavor conversion by matter of high energy neutrinos

Flavor Conversion 1-2 in solar and reactor ν



Oscillations of reactor neutrinos



Decoherence of low energy ν and flavor conversion by matter of high energy neutrinos

Neutrino Oscillations *Neutrino interferometry*

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\nu_e = U_{e1} e^{-iE_1 t} \nu_1 + U_{e2} e^{-iE_2 t} \nu_2 + U_{e3} e^{-iE_3 t} \nu_3$$

Parameters :

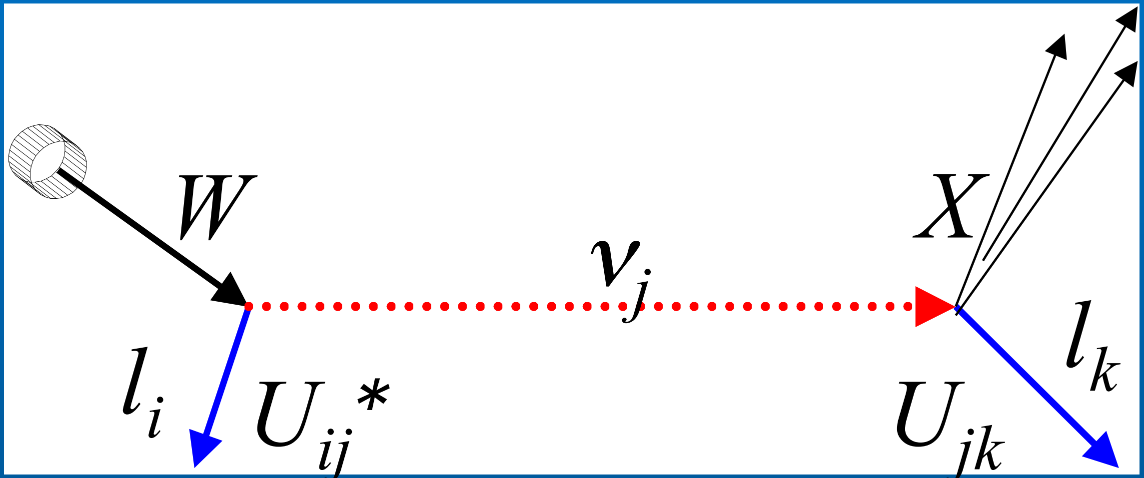
$\mathrm{m_i}$

$$U_{\alpha i} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{+i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Parameters

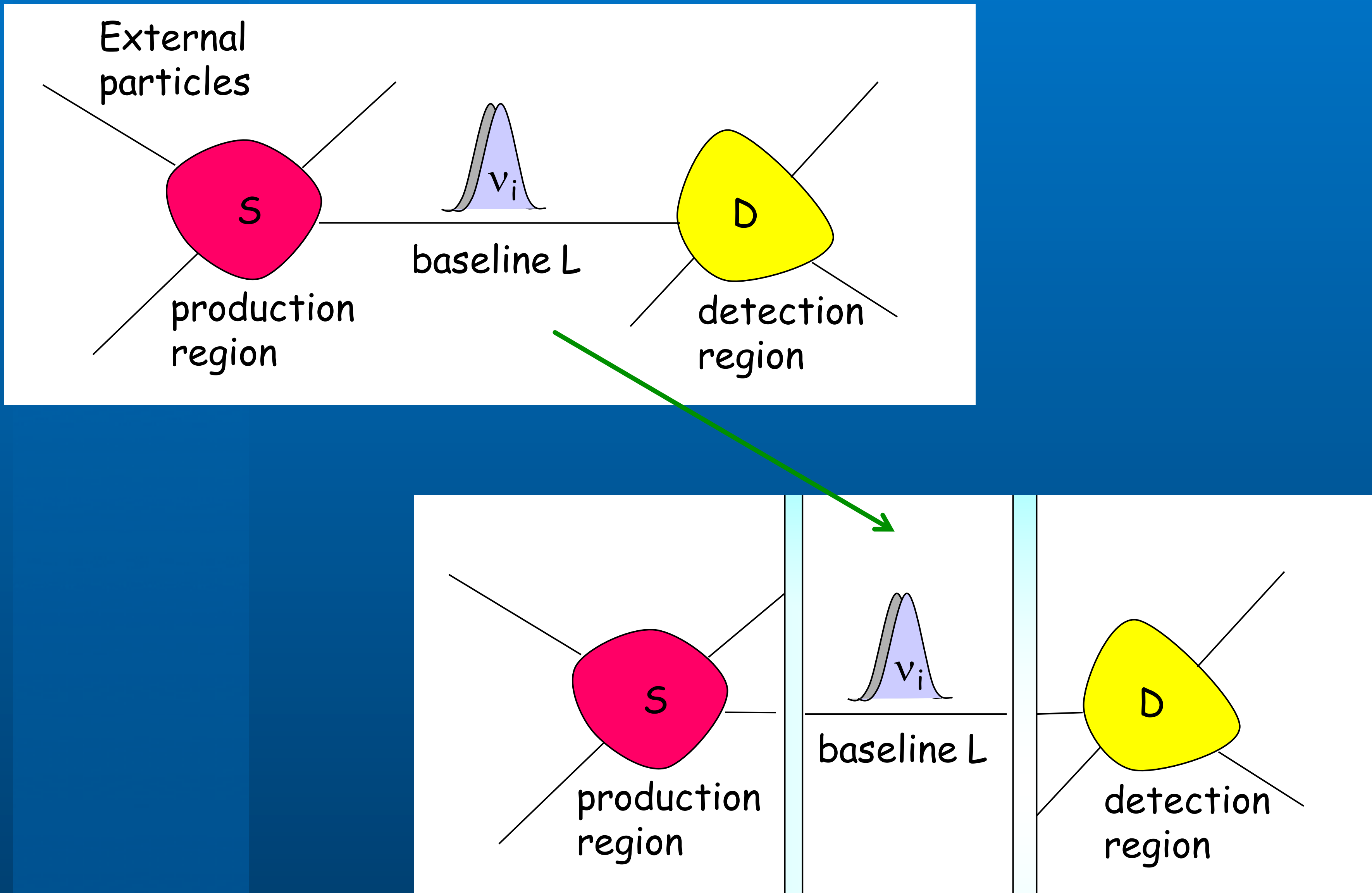
$\sum m$ $\Delta m^2 \geq 0$ $\Delta M^2 \geq 0$ $0 \leq \theta_{ij} \leq \frac{\pi}{2}$ $0 \leq \delta \leq \pi$

Neutrino Oscillations



$$A\left(l_i \rightarrow \nu_j \rightarrow l_k\right) \propto U^*_{ij} U_{jk} e^{-ip_j x - iE_j t}$$

Factorization: converge to mass shell



Neutrino Oscillations in matter

After a plane wave pass through a slab, the phase is shifted : p (x+(n-1)R)

$$e^{ip(x+(n-1)R)} \approx e^{ipx} + 2\pi\, f(0)\, NR \int_{x-R}^{\infty} dr\, e^{ipx}$$

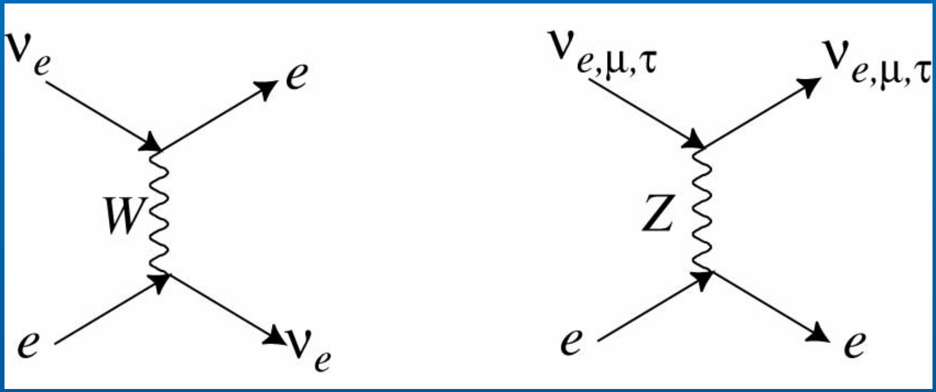
$$= e^{ipx}\left[1 + 1\frac{2\pi\, f(0) NR}{p}\right]$$

Net effect :

$$n - 1 \approx \frac{2\pi\, N\, f(0)}{p^2}$$

Matter effects

Only the difference of potentials is relevant



Net effect on
non relativistic electrons:

$$H_{\text{int}} = \frac{G_F}{\sqrt{2}} \bar{\nu}_e \gamma^\mu (1-\gamma_5) \nu_e \int d^3 p_e \, \mathrm{f(E_e, T)} \, \bar{e} \gamma^\mu (1-\gamma_5) e \Rightarrow \sqrt{2} G_F N_e$$

$$\mathrm{l_{matt}} = \frac{2\pi}{\sqrt{2} G_F N_e}$$

$$< e\gamma^0 e >= N_e$$

$$< e\gamma^i e >= N_e \mathrm{v_i}$$

Wolfenstein '78

Effective Two Neutrino Oscillations in matter

$$i\frac{d}{dt}\begin{pmatrix} \nu_e^{'} \\ \nu_a^{'} \end{pmatrix} = \begin{pmatrix} \frac{\Delta m^2}{4E}\cos(2\theta) - \frac{\sqrt{2}}{2}G_F N_e \cos^2\theta_{13} & \frac{\Delta m^2}{4E}\sin(2\theta) \\ \frac{\Delta m^2}{4E}\sin(2\theta) & -\frac{\Delta m^2}{4E}\cos(2\theta) + \frac{\sqrt{2}}{2}G_F N_e \cos^2\theta_{13} \end{pmatrix}\begin{pmatrix} \nu_e^{'} \\ \nu_a^{'} \end{pmatrix}$$

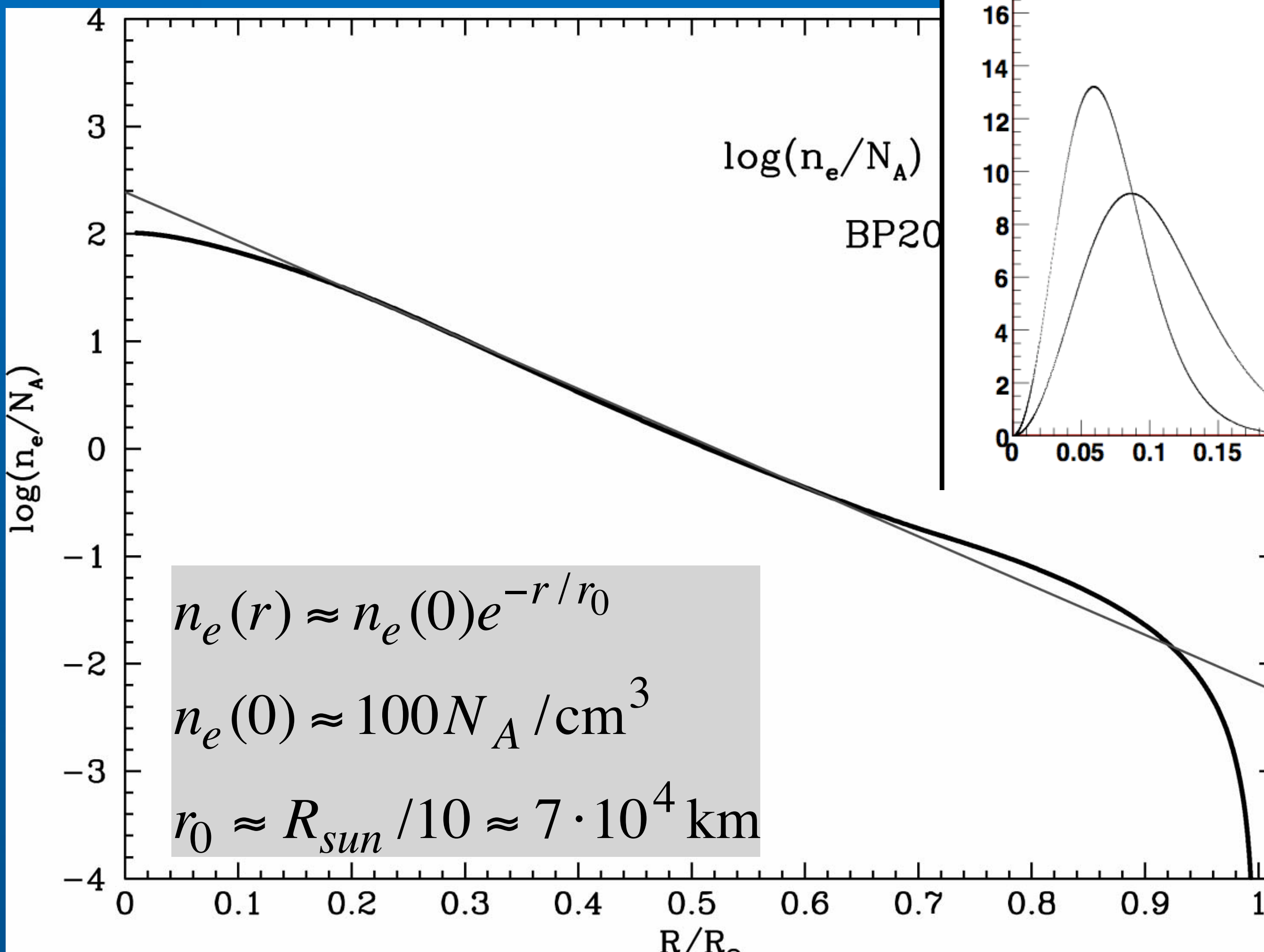
Mixing angle in matter

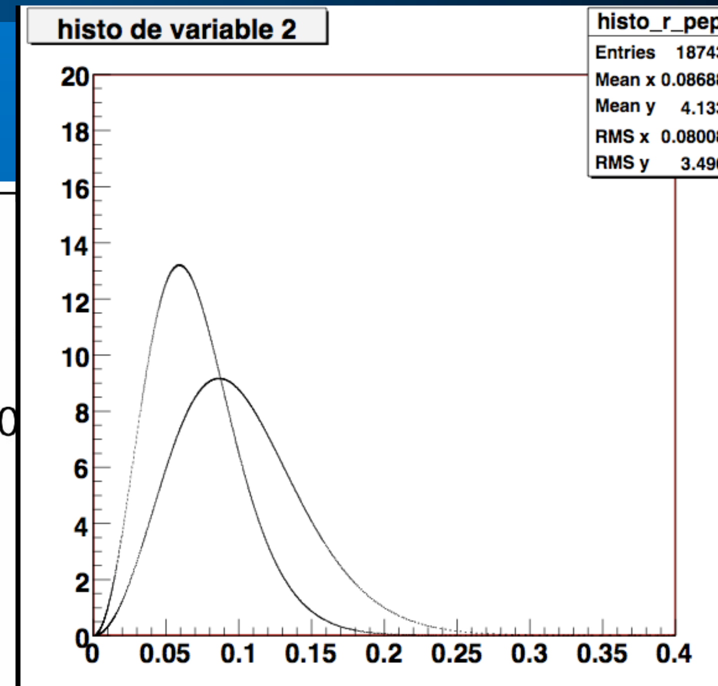
$$\sin^2(2\theta_m) = \frac{\sin^2(2\theta)}{\left(\cos(2\theta) - \frac{2\sqrt{2}}{2\Delta m^2}G_F N_e E \cos^2\theta_{13}\right)^2 + \sin^2(2\theta)}$$

Difference of the eigenvalues

$$\Delta E = \frac{\Delta m^2}{2E}\sqrt{\left(\cos(2\theta) - \frac{2\sqrt{2}}{2\Delta m^2}G_F N_e E \cos^2\theta_{13}\right)^2 + \sin^2(2\theta)}$$

Solar electron density and neutrino production



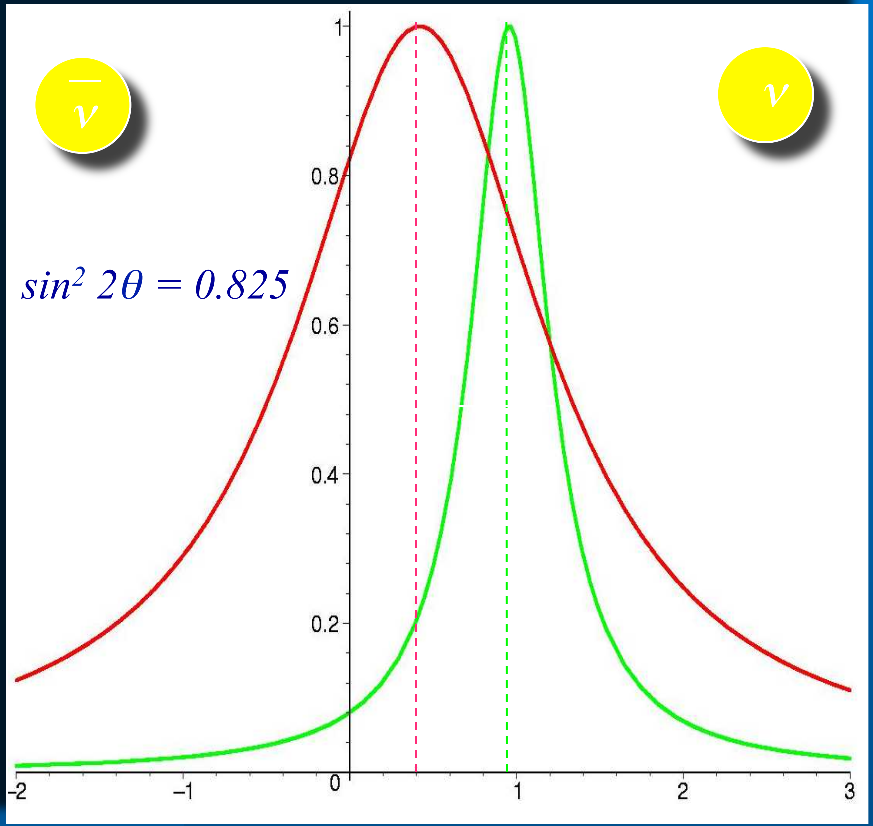


$$n_e(r) \approx n_e(0)e^{-r/r_0}$$

$$n_e(0) \approx 100 N_A/\mathrm{cm}^3$$

$$r_0 \approx R_{sun}/10 \approx 7 \cdot 10^4\,\mathrm{km}$$

MSW Resonance



l_ν / l_0 $\sim n E$

In resonance:

$$\sin^2 2\theta_m = 1$$

Flavor mixing is maximal
Level split is minimal

$$l_\nu = l_m \cos 2\theta$$

Vacuum oscillation length $\approx$ Refraction length

- Resonance width: $\Delta n_R = 2 n_R \tan 2\theta$
- Resonance layer: $n = n_R + \Delta n_R$

Mikheev, Smirnov '85 '86

Survival probability

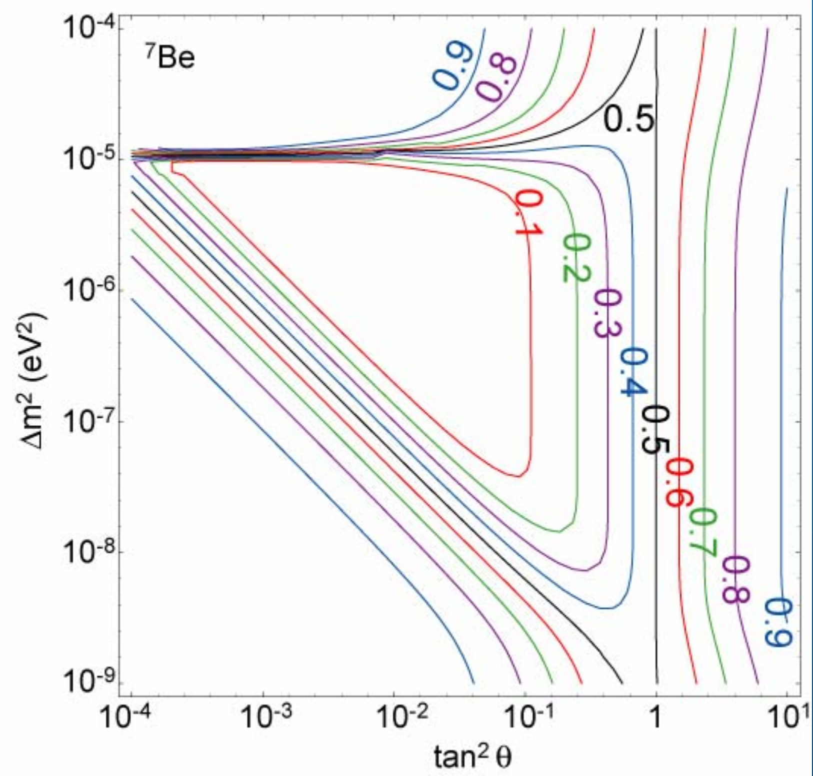
$$\left|\langle \nu_e, \text{Earth} | \nu_e, \text{core} \rangle\right|^2$$

$$= \left[(1-P_c)\cos^2\theta + P_c \sin^2\theta\right]\cos^2\theta_M + \left[P_c\cos^2\theta + (1-P_c)\sin^2\theta\right]\sin^2\theta_M$$

$$-\sqrt{P_c(1-P_c)}\sin 2\theta \cos\left(\frac{\Delta m^2}{2p}L + \delta\right)$$

$$P_c = \frac{e^{-\gamma \sin^2\theta} - e^{-\gamma}}{1-e^{-\gamma}}$$

$$\gamma = 2\pi r_0 \frac{\Delta m^2}{2p} = 1.05 \frac{\Delta m^2}{10^{-9}\,\text{eV}^2}\frac{\text{MeV}}{p}$$



Coherence of wave packets

	$l_{osc} = \frac{4\pi E}{\Delta m^2}$	$l_{coh} = 4\sqrt{2}\sigma_x \frac{E^2}{\Delta m^2}$	$l^e_{matt} = \frac{2\pi}{\sqrt{2}G_F N_e}$
Solar	$10\text{-}10^3$ Km	$10^3 - 10^7$ Km	10^2 Km
Snova	$10^{-11}\text{-}10^{-7}$ Km	$10^{-8} - 10^{-4}$ Km	10^{-10} Km
React	$1, 10^2$ Km	$10^6, 10^8$ Km	10^4 Km
Atmos	$10\text{-}10^5$ Km	$10^{14}\text{-}10^{22}$ Km	$10^3\text{-}10^4$ Km
Accel	$10^2\text{-}10^3$ Km	$10^{16}\text{-}10^{18}$ Km	10^4 Km

Mater does matter *Refraction index*

$$\theta_{12} \rightarrow \theta_{m,12}$$

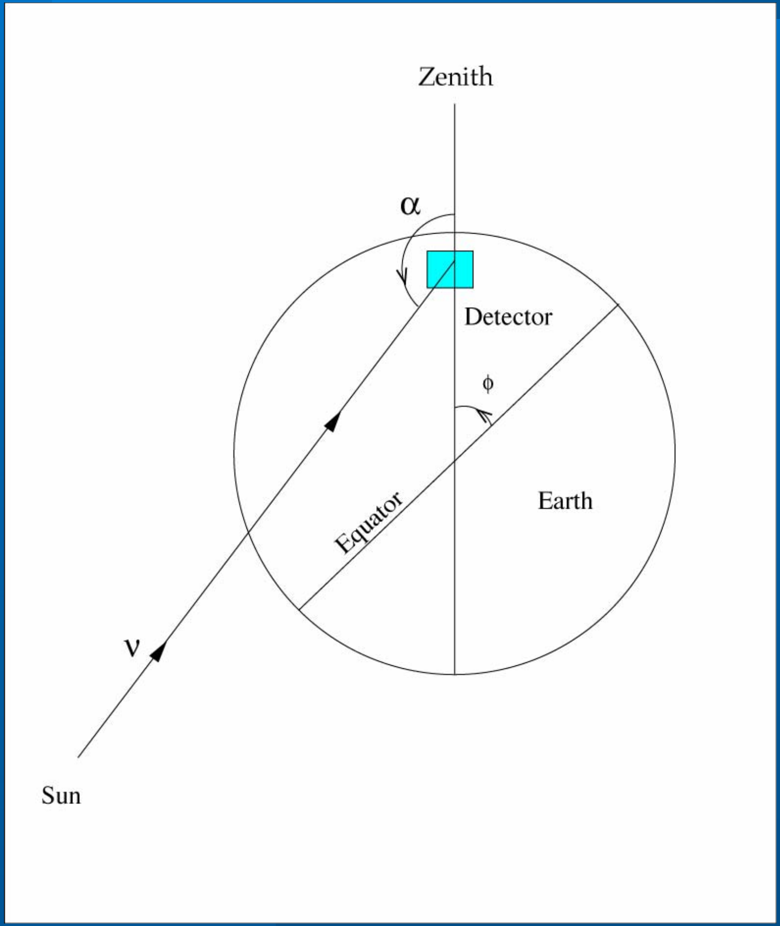
$$\beta = \frac{2\sqrt{2} G_F n_e E_\nu}{\Delta m^2}$$

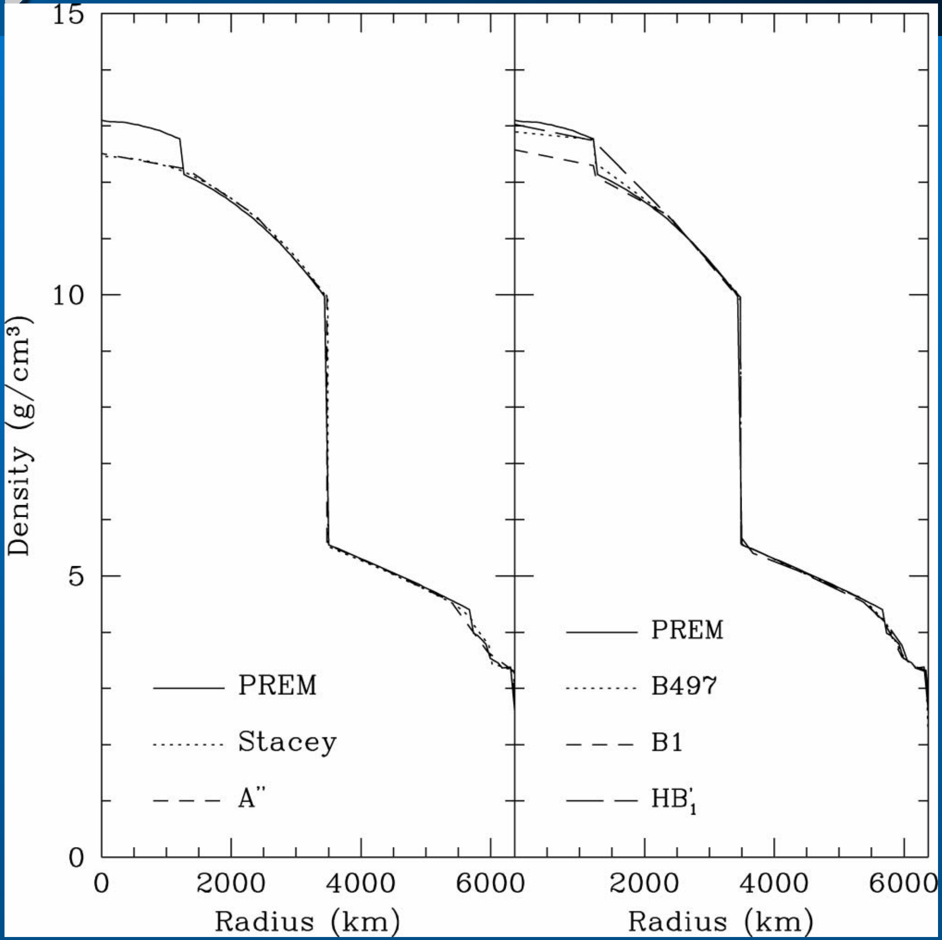
$$P(\nu_e \rightarrow \nu_e) \approx \left(1 - \frac{1}{2}\sin^2(2\theta_{12})\right)\cos^4(\theta_{13}) + \sin^4(\theta_{13})$$

Adiabatic flavor conversion ↓

$$P(\nu_e \rightarrow \nu_e) \approx \left(\cos^2(\theta_{12}) \cdot \cos^2(\theta_{m,12}) + \sin^2(\theta_{12})\sin^2(\theta_{m,12})\right) \cdot$$
$$\cos^4(\theta_{13}) + \sin^4(\theta_{13})$$

Earth matter density





For constant density:

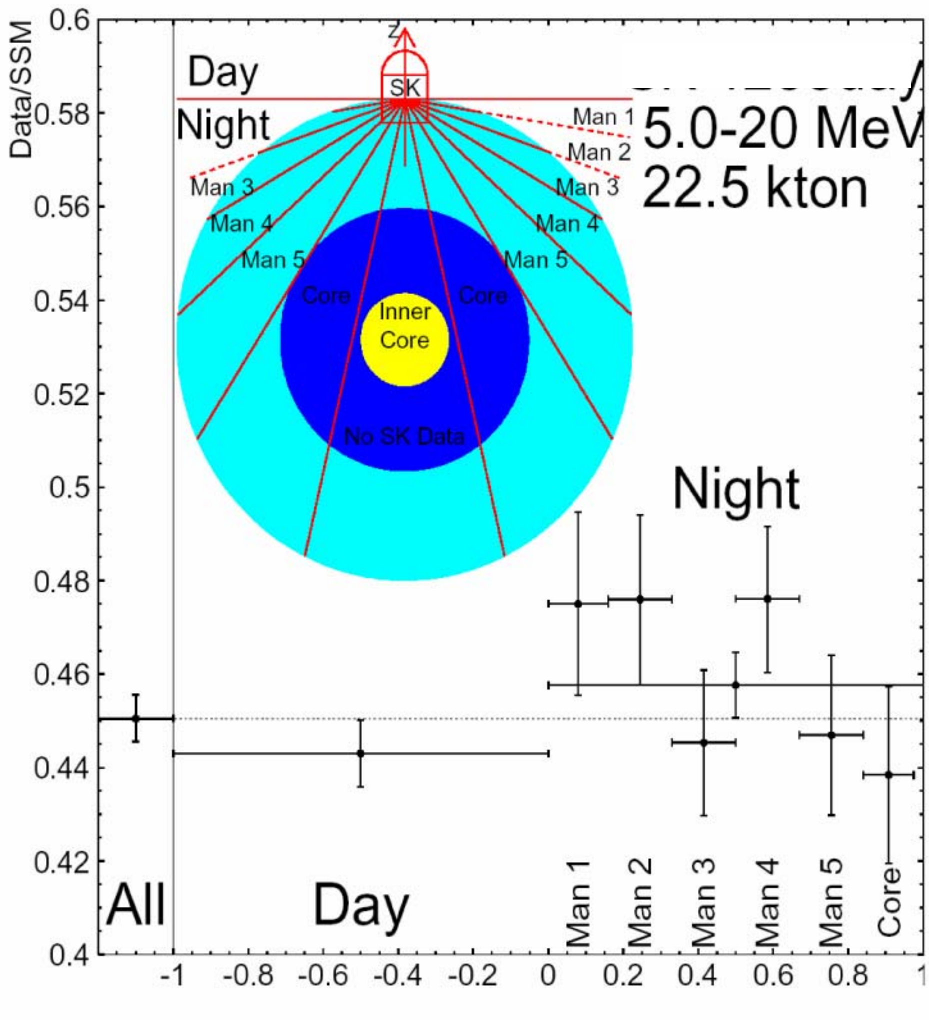
$$\text{freg} \equiv P_{2e} - \sin^2\theta$$

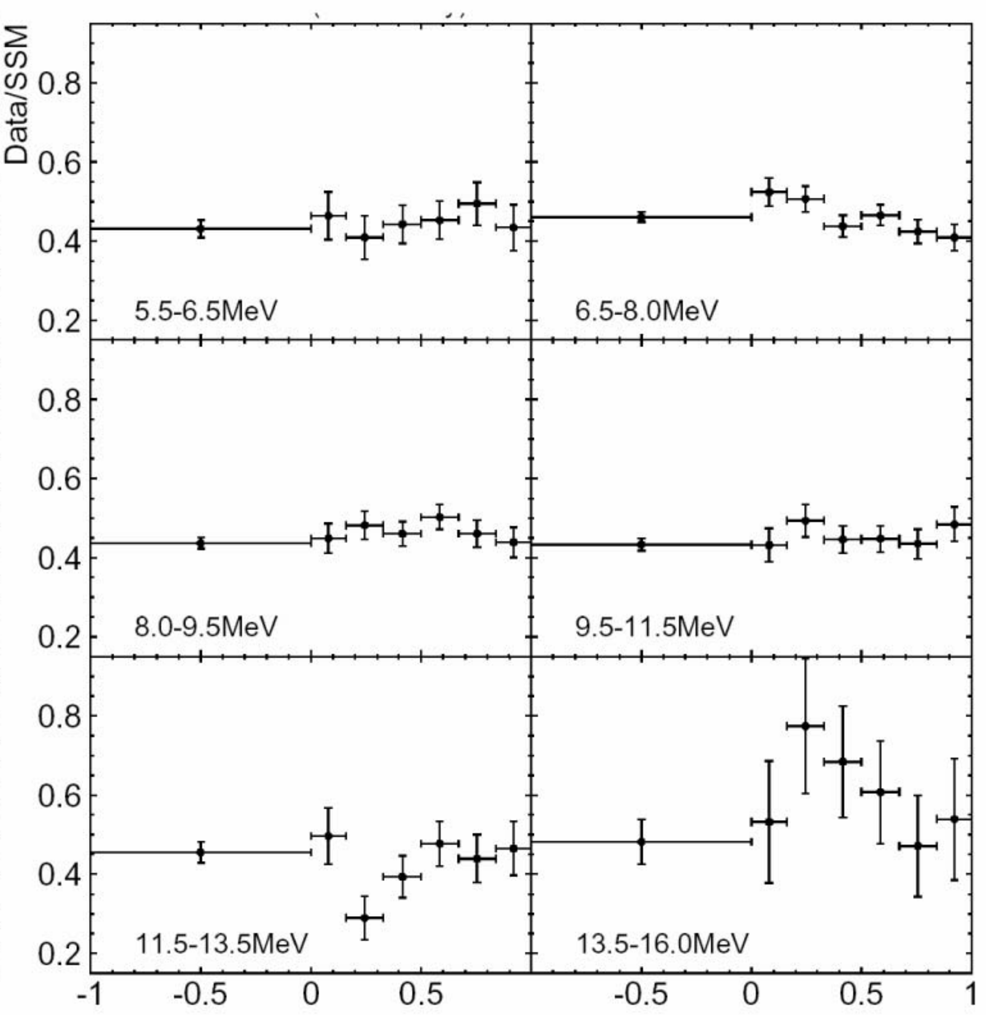
$$\text{freg} = \frac{1}{\eta} \cdot \sin^2 2\theta_m \cdot \sin^2\left(\frac{\pi d}{l_m}\right)$$

$$\eta \equiv \frac{l_0}{l_\nu} = \frac{\sqrt{2} m_N}{G_F \rho Y_e}\frac{\Delta m^2}{E}$$

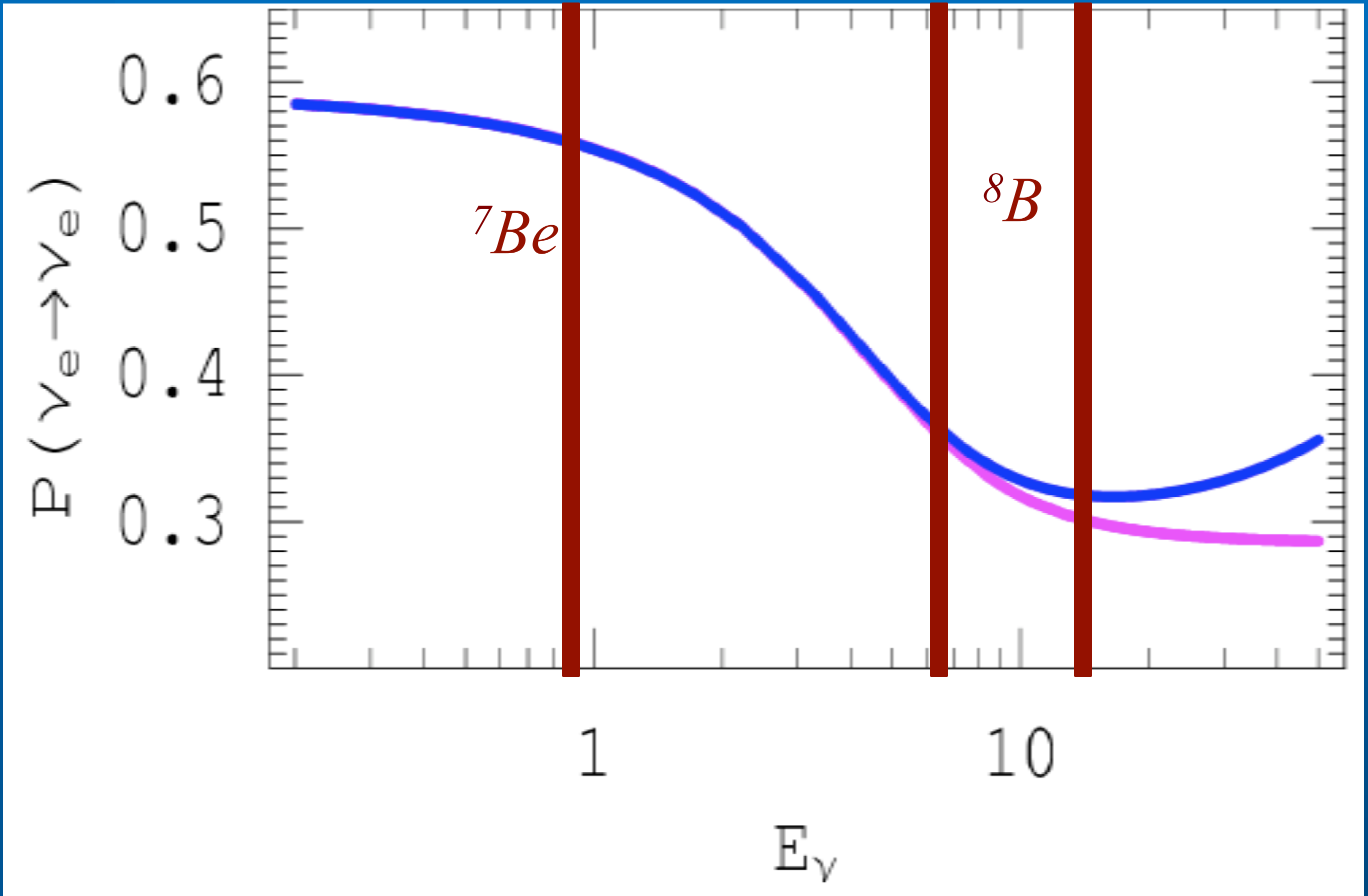
Earth Matter effects

$$A_{DN} = 2\frac{N-D}{N+D} = 0.028 \pm 0.011 \pm 0.005$$

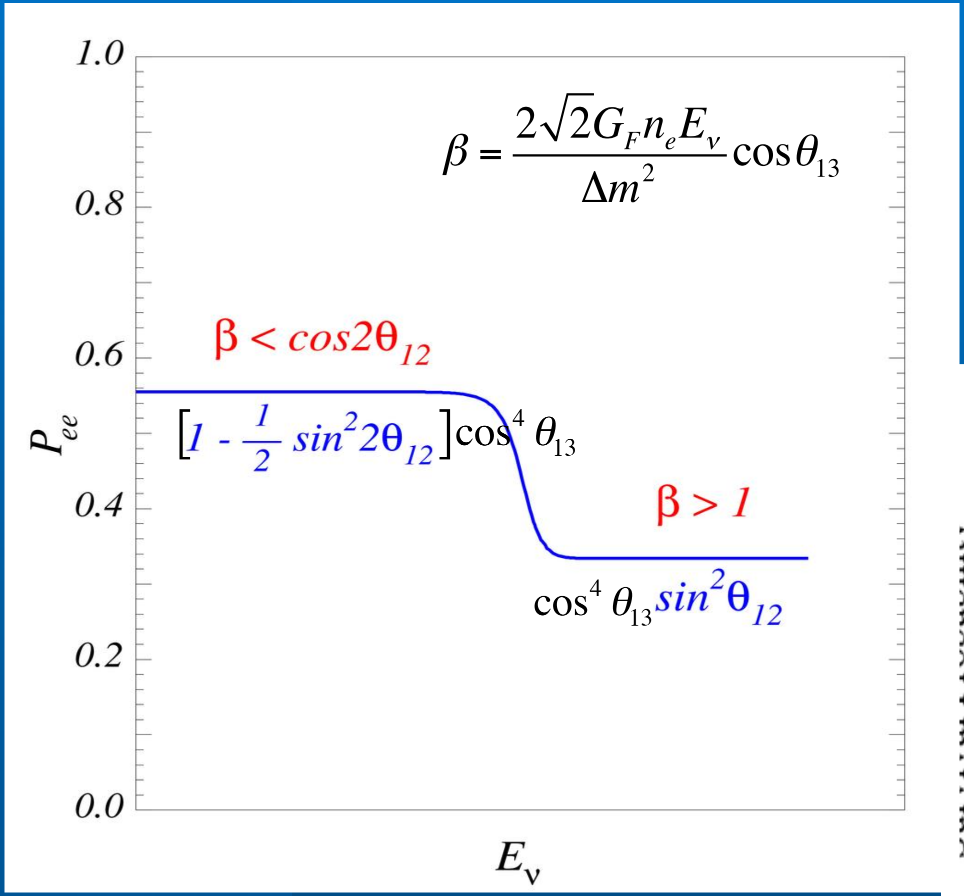


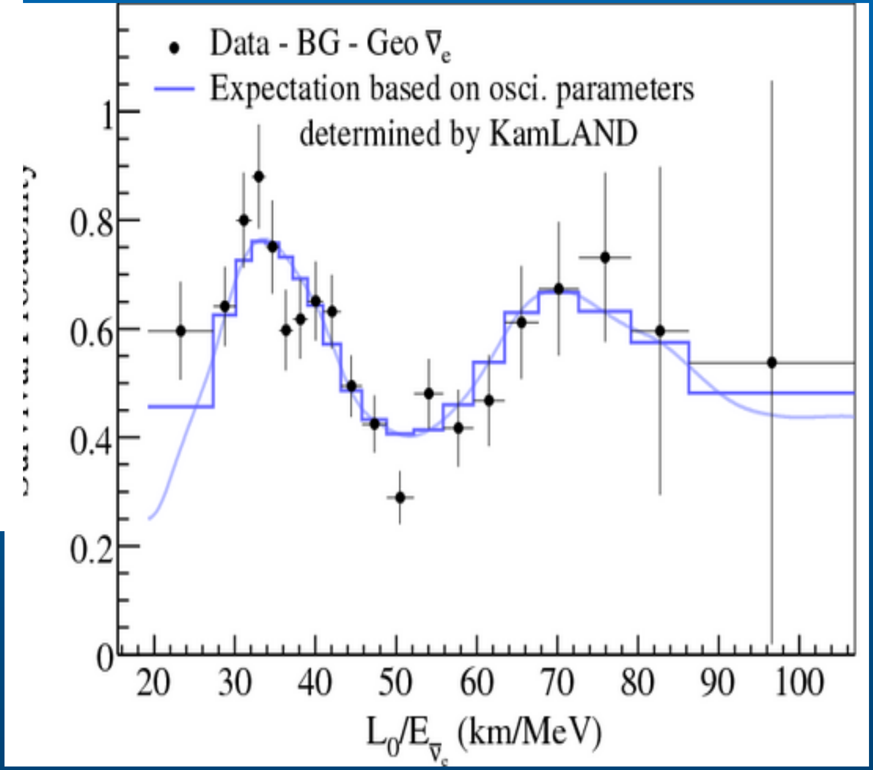


LMA solution



Solar & KamLAND flavor conversion





Implications of Solar and Reactor ν experiments

$$\Delta m^2_{21} = (7.6 \pm 0.2)\cdot 10^{-5}\,\mathrm{eV}^2$$

$$|U_{ei}|^2 = \begin{pmatrix} 0.665^{+0.017}_{-0.020} & 0.311^{+0.020}_{-0.017} & 0.024 \pm 0.003 \end{pmatrix}$$

Error corr: $(\rho_{12} = -0.98,\ \rho_{13} = -0.13,\ \rho_{23} = -0.05)$

Flavor conversion:

$$P_{ee} = (|U_{e1}|^2 |U_{1e,m}|^2 + |U_{e2}|^2 |U_{2e,m}|^2)(1 - |U_{e3}|^2)^2 + |U_{e3}|^4$$

$$P^{vac}_{ee} = |U_{e1}|^4 + |U_{e2}|^4 + |U_{e3}|^4 = 0.540 \pm 0.012$$

$$P^{matt,dom}_{ee} = |U_{e2}|^2 (1 - |U_{e3}|^2)^2 + |U_{e3}|^4 = 0.304 \pm 0.016$$

Unitarity test (heavier states):

$$|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 = 1.00 \pm 0.05$$

Standard Solar Models

The Sun burns in hydrostatic equilibrium, maintaining a local balance between the gravitation force and pressure gradient. To implement this condition, we need to use an equation of state. An ideal gas equation of state is used, with corrections for incomplete ionization of metals, radiation pressure, and screening.

The mechanisms for energy transport are radiation and convection. To describe radiative transport the opacity must be known as a function of temperature, density, and composition. Thomson scattering off electrons, inverse bremmstrahlung off fully ionized hydrogen and helium, bound-free scattering off metals contribute to opacity. In the Sun's outer envelope, convection dominates the energy transport, modeled through mixing length theory, in which volume elements are transported radially over a characteristic distance determined empirically in the model, but typically on the order of the pressure scale height.

Stellar evolution: Complete set of equations

$$\frac{\partial P}{\partial m} = -\frac{Gm}{4\pi r^4}$$

Euler eq. with Hydrostatic equilibrium

$$\frac{\partial r}{\partial m} = \frac{1}{4\pi r^2 \rho}$$

Mass conservation

$$\frac{\partial L_m}{\partial m} = \varepsilon_n - \varepsilon_\nu - T\frac{ds}{dt}$$

Energy equation

$$\frac{\partial T}{\partial m} = -\frac{GmT}{4\pi r^4 P}\begin{cases}\nabla_{rad} \\ \nabla\end{cases}$$

Energy transport

$$\frac{dn_i}{dt} = \left.\frac{\partial n_i}{\partial t}\right|_{nuc} + \left.\frac{\partial n_i}{\partial t}\right|_{conv} + \left.\frac{\partial n_i}{\partial t}\right|_{diff} \quad ; i = 1, \ldots, N$$

Composition changes

Microscopic physics: equation of state, radiative opacities, nuclear cross sections

Standard Solar Models: Howto 1

Solve Euler, mass, energy and composition eqs. with good microphysics, starting from a Zero Age Main Sequence (chem. homogeneous) to present solar age

Fixed quantities		
Solar mass	$M_\odot=1.989\times10^{33}$g 0.1%	Kepler's 3rd law
Solar age	$t_\odot=4.57\times10^{9}$yrs 0.5%	Meteorites

Quantities to match		
Solar luminosity	$L_\odot=3.842\times10^{33}$erg s^{-1} 0.4%	Solar constant
Solar radius	$R_\odot=6.9598\times10^{10}$cm 0.1%	Angular diameter
Solar metals/hydrogen ratio	$(Z/X)_\odot= 0.0229$	Photosphere and meteorites

Standard Solar Models: Howto 2

3 free parameters:

- *Convection theory has 1 free parameter:* α_{MLT} *determines the temperature stratification where convection is not adiabatic (upper layers of solar envelope)*
- *2 of the 3 quantities determining the initial composition:* $X_{ini}, Y_{ini}, Z_{ini}$ *(linked by* $X_{ini}+Y_{ini}+Z_{ini}=1$*). Individual elements grouped in* Z_{ini} *have relative abundances given by solar abundance measurements (e.g. GS98, AGS05)*

Construct a $1M_\odot$ *initial model with* X_{ini}, Z_{ini}, $(Y_{ini}=1- X_{ini}-Z_{ini})$ *and* α_{MLT}, *evolve it during* $t_\odot$ *and match* $(Z/X)_\odot$, $L_\odot$ *and* $R_\odot$ *to better than one part in* 10^{-5}

Hydrogen burning: pp chain

$$\begin{cases} p+p \rightarrow {}^2H + e^+ + \nu_e + \gamma \\ p+p+e^- \rightarrow {}^2H + \nu_e \end{cases}$$

Q=1.44 MeV, <Q$_\nu$>=0.265 — *pp neutrinos*

Q=Q$_\nu$=1.44 — *pep neutrinos*

$${}^2H + p \rightarrow {}^3He + \gamma$$ *Q=5.49*

$$\underbrace{{}^3He + {}^3He \rightarrow {}^4He + 2p + \gamma}$$ *Q=12.86*

ppI
88-89%

Q=1.59 $${}^3He + {}^4He \rightarrow {}^7Be + \gamma$$

Q=Q$_\nu$=0.86 (90%)-0.38 (10%) $${}^7Be + e^- \rightarrow {}^7Li + \nu_e$$

^{7}Be neutrinos

Q=17.35 $$\underbrace{{}^7Li + p \rightarrow {}^4He + {}^4He + \gamma}$$

ppII
10%

Q=0.137 $${}^7Be + p \rightarrow {}^8B + \gamma$$

^{8}B neutrinos *Q=17.98, <Q$_\nu$>=6.71* $${}^8B \rightarrow {}^8Be + e^+ + \nu_e + \gamma$$

$$\underbrace{{}^8Be \rightarrow {}^4He + {}^4He}$$

ppIII
1%

Marginal reaction:

$${}^3He + p \rightarrow {}^4He + e^+ + \nu_e + \gamma$$

Q=19.795, <Q$_\nu$>=9.625 *hep neutrinos*

Hydrogen burning: CNO cycle

CN-cycle

$$^{12}C + p \rightarrow {}^{13}N + \gamma \qquad Q=1.94$$

$$^{13}N \rightarrow {}^{13}C + e^{+} + \nu_e + \gamma \qquad Q=2.22,\ \langle Q_\nu \rangle = 0.707 \qquad {}^{13}N\ \text{neutrinos}$$

$$^{13}C + p \rightarrow {}^{14}N + \gamma \qquad Q=7.55$$

$$^{14}N + p \rightarrow {}^{15}O + \gamma \qquad Q=7.30$$

$$^{15}O \rightarrow {}^{15}N + e^{+} + \nu_e + \gamma \qquad Q=2.75,\ \langle Q_\nu \rangle = 0.996 \qquad {}^{15}O\ \text{neutrinos}$$

$$^{15}N + p \rightarrow {}^{12}C + {}^{4}He + \gamma \qquad Q=4.97$$

NO-cycle

$$^{15}N + p \rightarrow {}^{16}O + \gamma \qquad Q=12.13$$

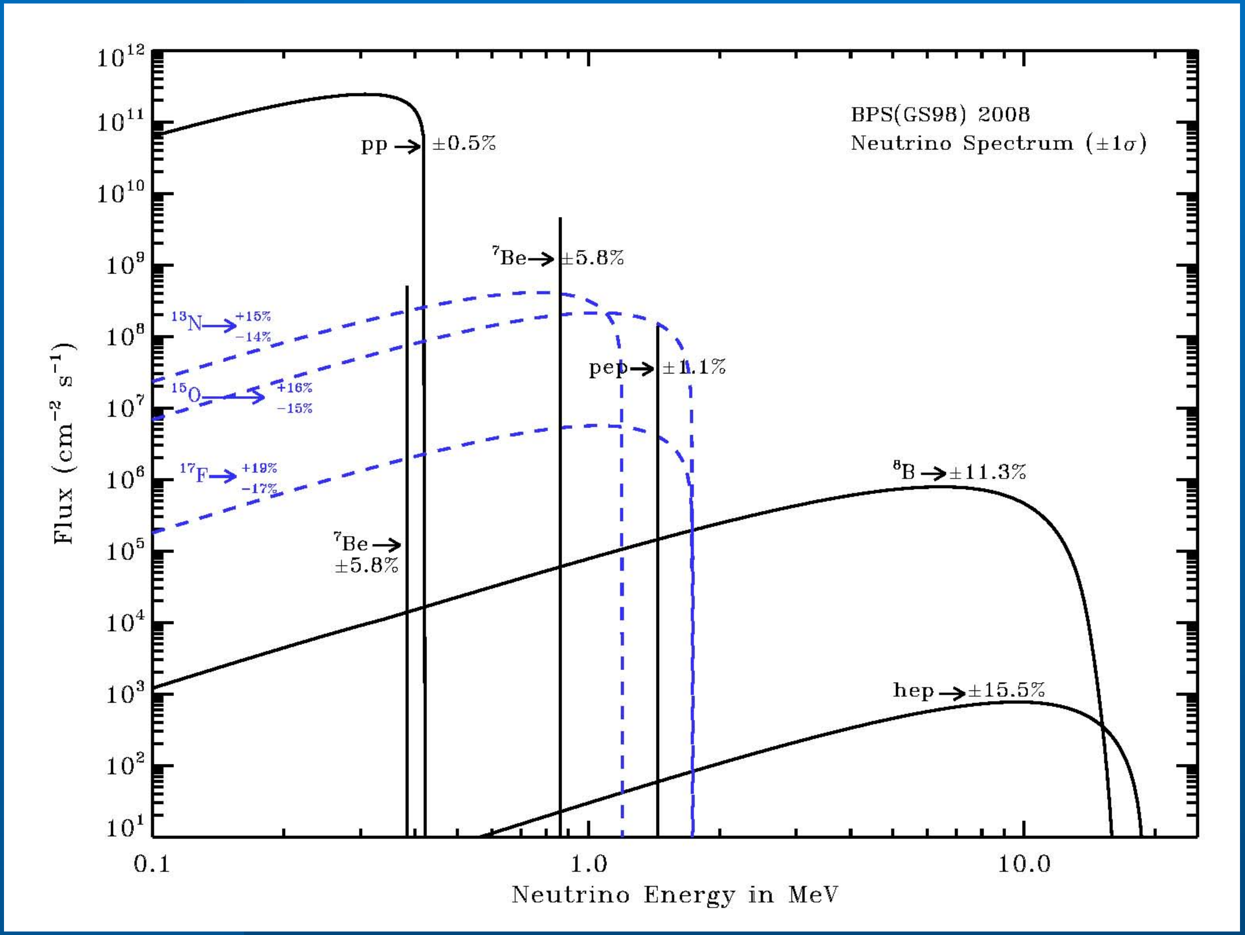
$$^{16}O + p \rightarrow {}^{17}F + \gamma \qquad Q=0.600$$

$$^{17}F \rightarrow {}^{17}O + e^{+} + \nu_e + \gamma \qquad Q=2.76,\ \langle Q_\nu \rangle = 0.999 \qquad {}^{17}F\ \text{neut.}$$

$$^{17}O + p \rightarrow {}^{14}N + {}^{4}He + \gamma \qquad Q=1.19$$

CNO cycle is regulated by ^{14}N+p reation (slowest)

SSM: BPS08(GS)



Input physics:
- Nuclear cross sections
- Radiative opacities
- Equation of state

Input parameters:
R, M, L, t, Z_i/X

Free parameters:
- Fix the composition
- Entropy jump in CZ

Solar Neutrinos: SSM vs Experiments

pp chain	GS	AGSS	DATA
pp (10^{10} cm^{-2} s^{-1})	5.98 (0.04)	6.03 (0.04)	
pep (10^{8} cm^{-2} s^{-1})	1.44 (0.02)	1.47 (0.02)	1.6 (0.3)
^{7}Be (10^{9} cm^{-2} s^{-1})	5.0 (0.3)	4.6 (0.3)	4.9 (0.2)
^{8}B (10^{6} cm^{-2} s^{-1})	5.6 (0.6)	4.6 (0.5)	5.1 (0.2)
hep (10^{3} cm^{-2} s^{-1})	8.0 (2.4)	8.3 (2.5)	
CNO cycle			
^{13}N (10^{8} cm^{-2} s^{-1})	3.0 (0.4)	2.2 (0.3)	
^{15}O (10^{8} cm^{-2} s^{-1})	2.2 (0.3)	1.6 (0.2)	
^{17}F (10^{6} cm^{-2} s^{-1})	5.5 (0.9)	3.4 (0.5)	

Serenelli, Haxton, PG, AJ743 (2011)

Uncertainties: Partial contributions

Source	No composition % (S_{33}, S_{34}, S_{17}, S_{114}, Op, Diff)	Composition %
^{7}Be	5 (2.5,2.8,0.0,0.0,3.2,2.0)	2
^{8}B	10 (2.6,2.7,3.8,0.0,6.8,4.2)	5
^{13}N	8 (0.2,0.2,0.0,6.0,3.6,5.1)	13
^{15}O	11 (0.2,0.2,0.0,8.3,5.2,5.9)	12

Recommendations:
- Reduce $S_{1,14}$ uncertainty to be below 5%
- Reduce uncertainty in Fe (to 0.02 dex)
- Reduce uncertaintiy in C (to 0.02 dex)

Uncertainties: where to improve

Source	S_{11}	S_{33}	S_{34}	S_{17}	S_{hep}	$S_{1,14}$	$S_{7Be,e}$	$L_\odot$	Age	Diff	Opac	C	N	O	Ne	Mg	Si	S	Ar	Fe
pp	0.090	0.029	-0.059	0.000	0.000	-0.004	0.000	0.808	-0.067	-0.011	-0.099	-0.005	-0.001	-0.005	-0.004	-0.004	-0.009	-0.006	-0.001	-0.016
pep	-0.236	0.043	-0.086	0.000	0.000	-0.007	0.000	1.041	0.017	-0.016	-0.300	-0.009	-0.002	-0.006	-0.003	-0.002	-0.012	-0.014	-0.003	-0.054
hep	-0.112	-0.459	-0.072	0.000	1.000	-0.004	0.000	0.174	-0.118	-0.037	-0.398	-0.007	-0.002	-0.020	-0.014	-0.017	-0.036	-0.028	-0.005	-0.064
^7Be	-1.07	-0.441	0.878	0.000	0.000	-0.001	1.000	3.558	0.786	0.136	1.267	0.004	0.002	0.053	0.044	0.057	0.116	0.083	0.014	0.217
^8B	-2.73	-0.427	0.846	1.000	0.000	0.005	0.000	7.130	1.380	0.280	2.702	0.025	0.007	0.111	0.083	0.106	0.211	0.151	0.027	0.510
^{13}N	-2.09	0.025	-0.053	0.000	0.000	0.711	0.000	4.400	0.855	0.340	1.433	0.861	0.148	0.047	0.035	0.051	0.109	0.083	0.015	0.262
^{15}O	-2.95	0.018	-0.041	0.000	0.000	1.000	0.000	6.005	1.338	0.394	2.060	0.810	0.207	0.075	0.055	0.076	0.158	0.117	0.021	0.386
^{17}F	-3.14	0.015	-0.037	0.000	0.000	0.005	0.000	6.510	1.451	0.417	2.270	0.024	0.005	1.083	0.061	0.084	0.174	0.128	0.023	0.428
R_{CZ}	-0.061	0.002	-0.003	0.000	0.000	0.000	0.000	-0.016	-0.081	-0.018	-0.012	-0.006	-0.005	-0.028	-0.012	-0.005	0.002	0.004	0.001	-0.009
Y_S	0.134	-0.005	0.009	0.000	0.000	0.001	0.000	0.373	-0.110	-0.073	0.646	-0.009	-0.001	0.023	0.033	0.037	0.070	0.048	0.009	0.089

Logarithmic partial derivatives of neutrino fluxes with respect to solar inputs times uncertainties show leading sources of uncertainty

Characterize correlations

PG & Serenelli 08

Luminosity eq: Energy conservation

If nuclear fusion reactions among light elements are responsible for solar energy generation and using that D and ^3He are in local kinetic equilibrium

$$\frac{L_{SUN}}{4\pi(\mathrm{A.U.})^2} = \sum_i \alpha_i \Phi_i$$

Spiro, Vignaud, PLB (1990)

α_i ***determined from nuclear masses and neutrino energies independent of details of solar model at 1:10^4***

Bahcall, PRC (2002)

$$1 = 0.918 f_{pp} + 0.069 f_{Be} + 0.013 f_{CNO}$$

New neutrino data: LC correct within 20%

Standard Solar Models

ν flux	E_ν^{max} (MeV)	GS98-SFII	AGSS09-SFII	Solar	units
$p+p \to {}^2H+e^++\nu$	0.42	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.006)$	$6.05(1^{+0.003}_{-0.011})$	$10^{10}/cm^2s$
$p+e^-+p \to {}^2H+\nu$	1.44	$1.44(1 \pm 0.012)$	$1.47(1 \pm 0.012)$	$1.46(1^{+0.010}_{-0.014})$	$10^8/cm^2s$
${}^7Be+e^- \to {}^7Li+\nu$	0.86 (90%)	$5.00(1 \pm 0.07)$	$4.56(1 \pm 0.07)$	$4.82(1^{+0.05}_{-0.04})$	$10^9/cm^2s$
	0.38 (10%)				
${}^8B \to {}^8Be+e^++\nu$	~ 15	$5.58(1 \pm 0.14)$	$4.59(1 \pm 0.14)$	$5.00(1 \pm 0.03)$	$10^6/cm^2s$
${}^3He+p \to {}^4He+e^++\nu$	18.77	$8.04(1 \pm 0.30)$	$8.31(1 \pm 0.30)$	—	$10^3/cm^2s$
${}^{13}N \to {}^{13}C+e^++\nu$	1.20	$2.96(1 \pm 0.14)$	$2.17(1 \pm 0.14)$	≤ 6.7	$10^8/cm^2s$
${}^{15}O \to {}^{15}N+e^++\nu$	1.73	$2.23(1 \pm 0.15)$	$1.56(1 \pm 0.15)$	≤ 3.2	$10^8/cm^2s$
${}^{17}F \to {}^{17}0+e^++\nu$	1.74	$5.52(1 \pm 0.17)$	$3.40(1 \pm 0.16)$	$\leq 59.$	$10^6/cm^2s$
χ^2/P^{agr}		3.5/90%	3.4/90%		

Neutrino fluxes: correlations

Flux	pp	pep	hep	^{7}Be	^{8}B	^{13}N	^{15}O	^{17}F
pp	1.000	0.967	-0.012	-0.796	-0.642	-0.127	-0.132	-0.111
pep	0.967	1.000	0.001	-0.793	-0.667	-0.162	-0.171	-0.137
hep	-0.012	0.001	1.000	0.022	0.021	-0.005	-0.008	-0.014
^{7}Be	-0.796	-0.793	0.022	1.000	0.878	0.125	0.155	0.237
^{8}B	-0.642	-0.667	0.021	0.878	1.000	0.257	0.296	0.412
^{13}N	-0.127	-0.162	-0.005	0.125	0.257	1.000	0.984	0.299
^{15}O	-0.132	-0.171	-0.008	0.155	0.296	0.984	1.000	0.338
^{17}F	-0.111	-0.137	-0.014	0.237	0.412	0.299	0.338	1.000

Large correlation of fluxes (^{8}B - ^{7}Be, ^{13}N - ^{15}O) may help to discriminate predicted fluxes

How to extract solar physics: ^{8}B and ^{7}Be

Minimize impact of astrophysical errors: Test nuclear astrophysics

$$f_{Be} \propto s_{33}^{-0.441} s_{34}^{0.878} d^{0.136} o^{1.267} x_C^{0.004} x_N^{0.002} x_O^{0.053} x_{Ne}^{0.044} x_{Si}^{0.116} x_{Fe}^{0.217}$$

$$f_{B} \propto s_{33}^{-0.427} s_{34}^{0.846} s_{17}^{1.0} d^{0.280} o^{2.702} x_C^{0.025} x_N^{0.007} x_O^{0.111} x_{Ne}^{0.083} x_{Si}^{0.211} x_{Fe}^{0.510}$$

$$\frac{f_B}{f_{Be}^2} \propto s_{33}^{0.455} s_{34}^{-0.91} s_{17}^{1.0} d^{0.008} o^{0.168} x_C^{0.017} x_N^{0.003} x_O^{0.005} x_{Ne}^{-0.005} x_{Si}^{-0.013} x_{Fe}^{0.076}$$

$$\frac{f_B}{f_{Be}^2} = \left[1 + 1\%(astro) + 6.7\%(nuclear)\right] s_{17}$$

$S_{17}/S_{17,SFII} = 1.02\ (1 \pm 0.12)$

Haxton, Serenelli, PG, 2012

$$\frac{f_B}{f_{Be}^2} = \left[1 + 1\%(astro) + < 1\%(nuclear)\right] s_{17}\ s_{33}^{0.455} s_{34}^{-0.91} s_{11}^{-0.59} s_{e7}^{-2}$$

$[S_{11}^{0.238}\ S_{33}^{-0.236}\ S_{34}^{0.473}\ S_{17}^{-0.479}\ S_{e7}^{0.479}\ S_{114}^{-0.003}] = 1.02\ (1 \pm 0.05)$

Second Part

Standard Solar Models failure

More on Neutrino Flavor conversion

Next experimental goals: CNO neutrinos

Solar system abundances

Meteorites

Mass spectroscopy

Very high accuracy

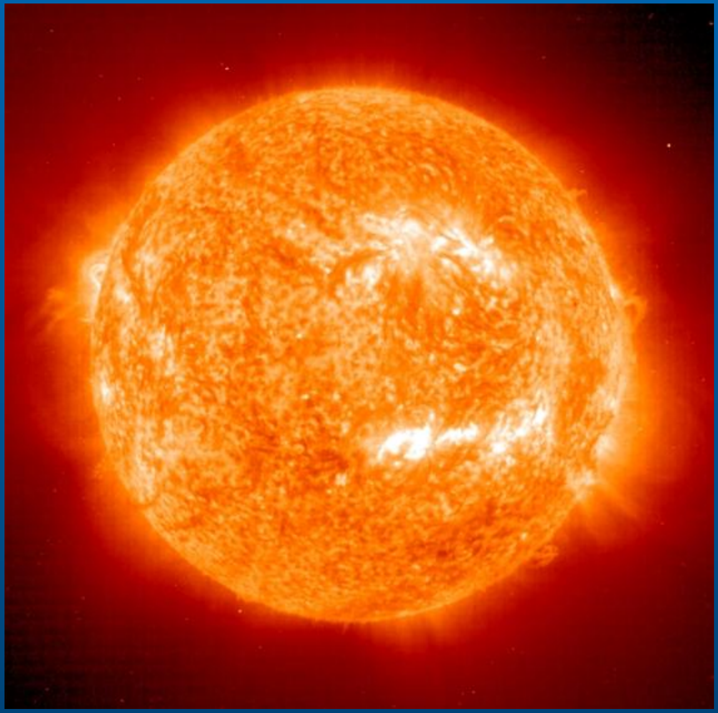
Element depletion

Solar atmosphere

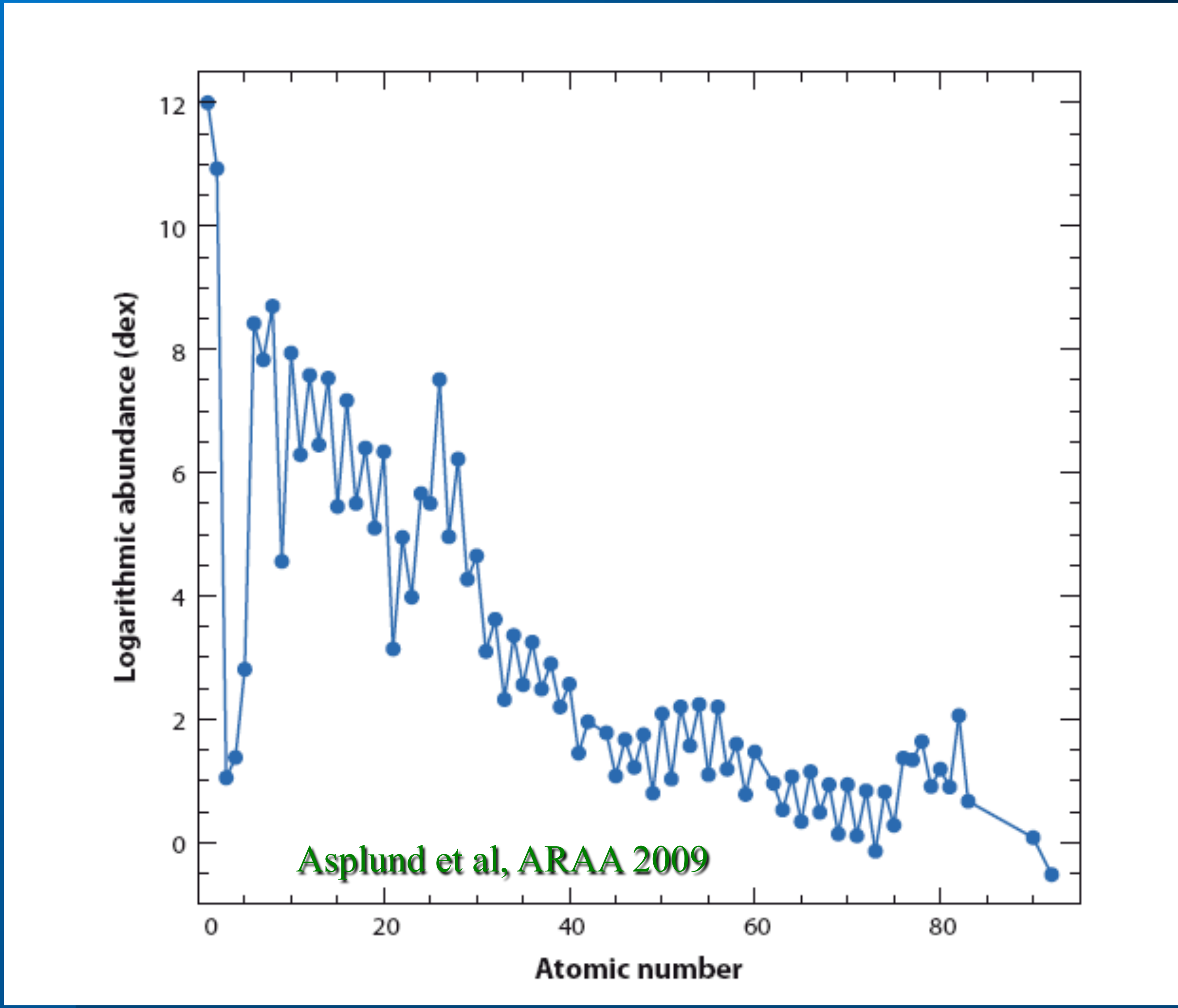
Solar spectroscopy

Modelling-dependent

Very little depletion



Solar system abundances

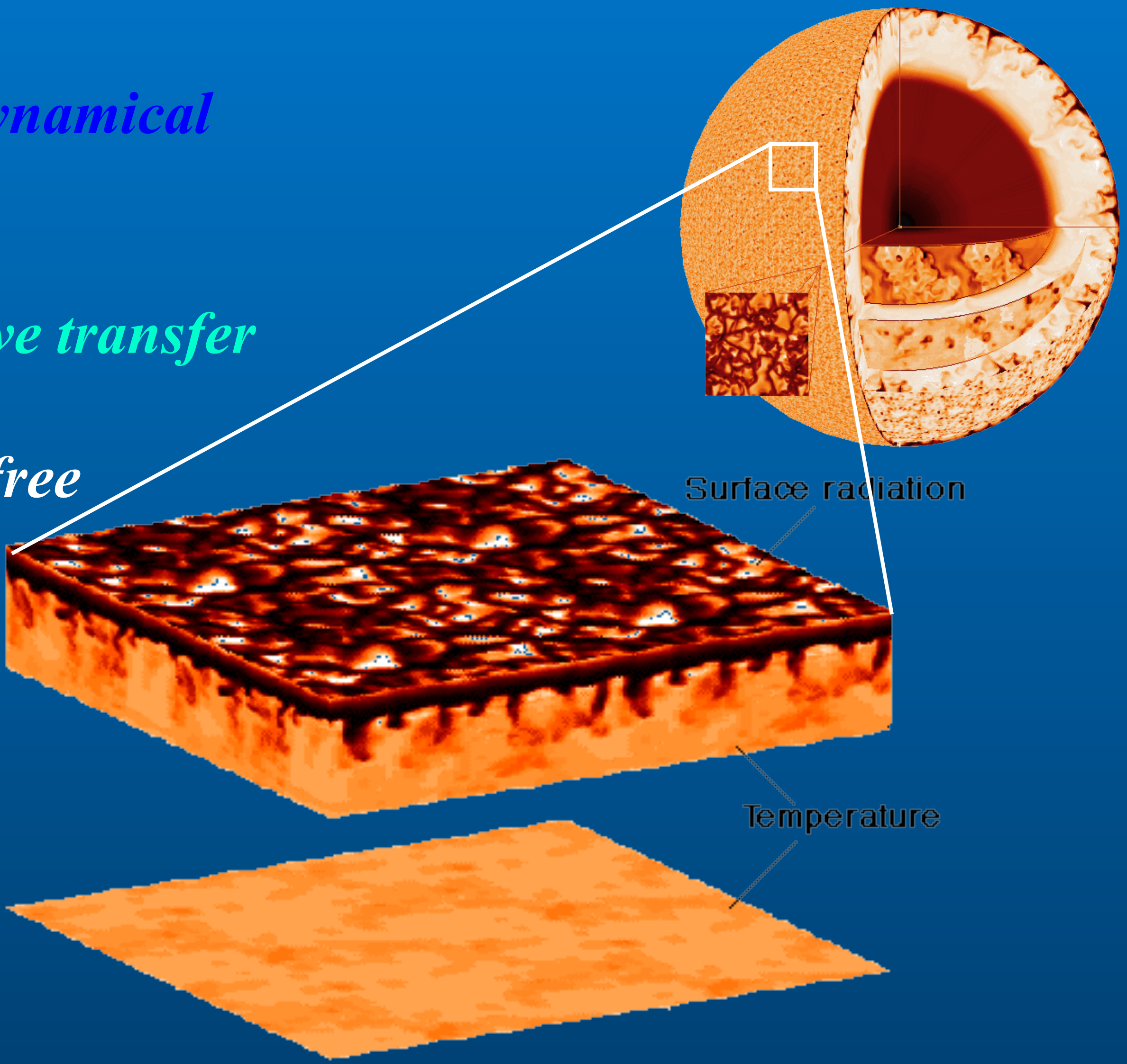


3D solar atmosphere models

Ingredients:

- *Radiative-hydrodynamical*
- *Time-dependent*
- *3-dimensional*
- *Simplified radiative transfer*
- *LTE*

Essentially parameter free



Improved abundances: GS vs AGS

Different total metallicity

$Z/X = 0.0229$ (GS98)

$Z/X = 0.0165$ (AGS05)

GS98		AGS05		
8.52	0.06	8.39	0.05	C
7.92	0.06	7.78	0.06	N
8.83	0.06	8.66	0.05	O
8.08	0.06	7.84	0.06	Ne
7.58	0.03	7.53	0.03	Mg
7.56	0.02	7.51	0.02	Si
7.20	0.04	7.16	0.04	S
6.40	0.06	6.18	0.08	Ar
7.50	0.03	7.45	0.03	Fe

$\text{Abd} = \log n_X/n_H + 12$

Helioseismology

lower opacity below CZ → R_{CZ} and c_s profile

lower core opacity → higher hydrogen to keep $L_\odot$ → lower helium

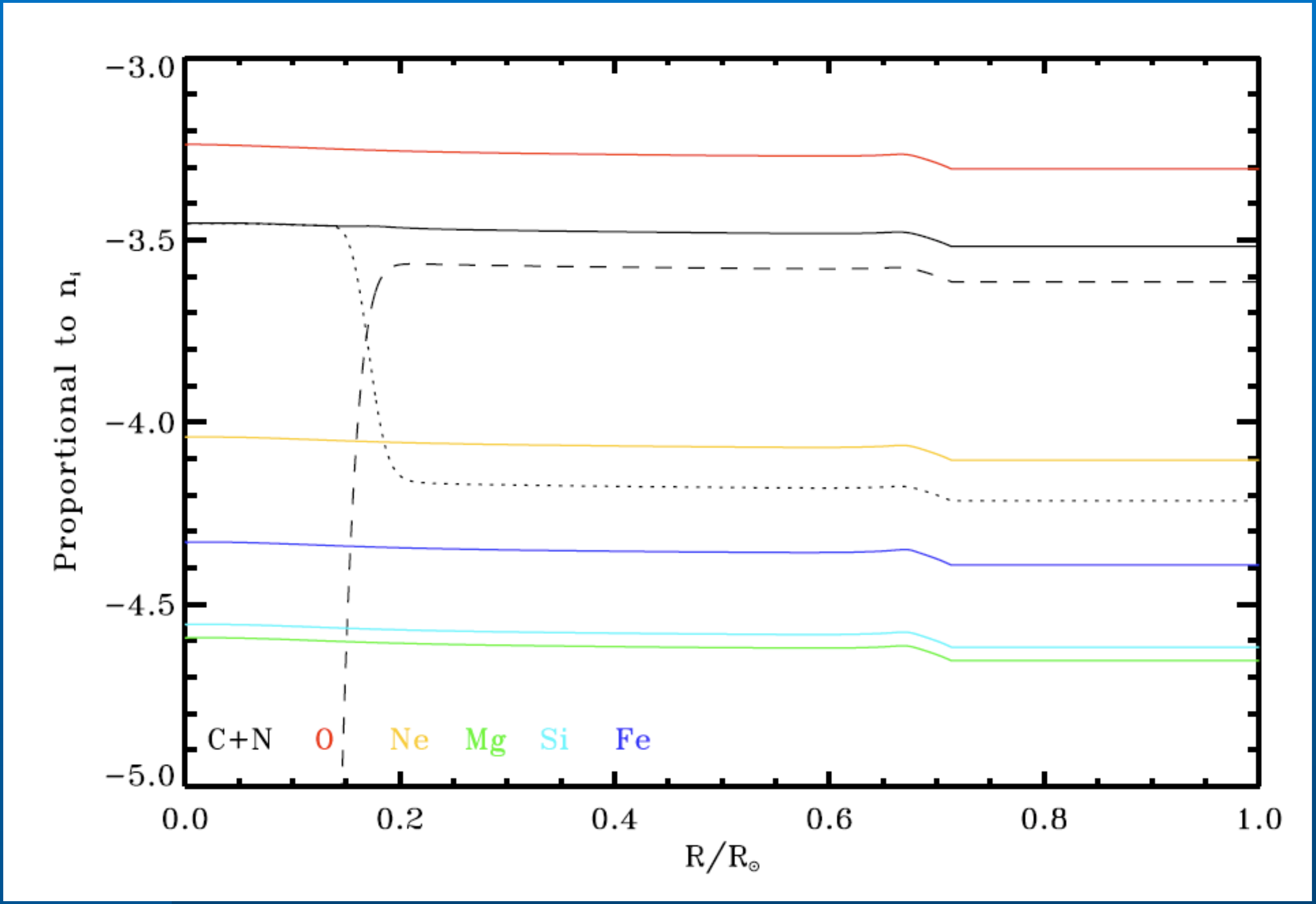
Neutrino fluxes

CNO fluxes depend ~ linearly; affects pp and pep indirectly

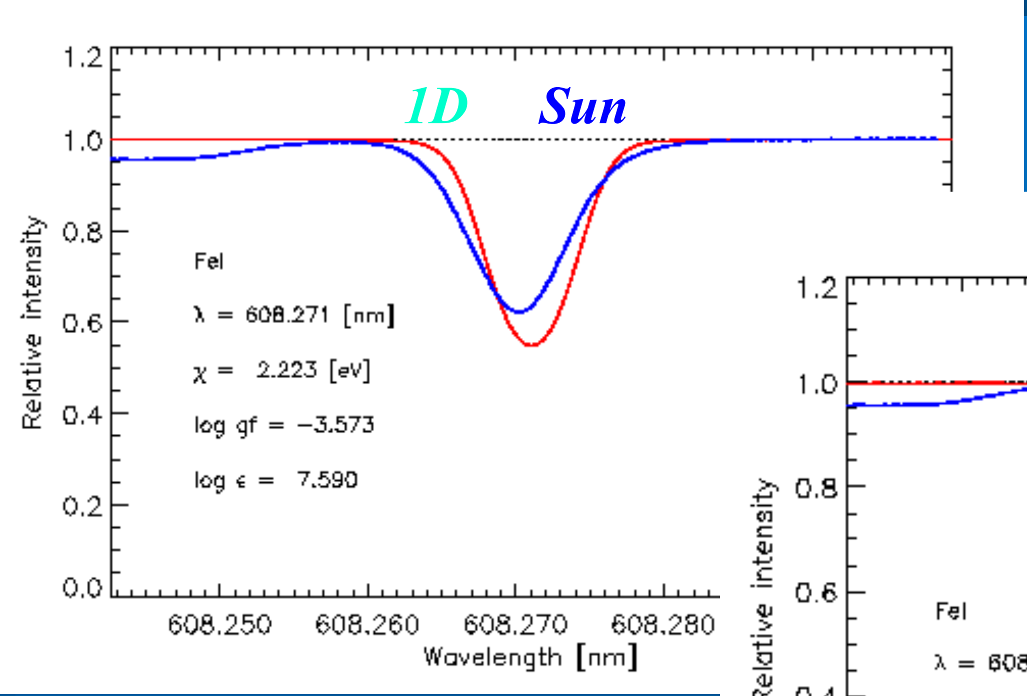
lower opacity → lower T in core

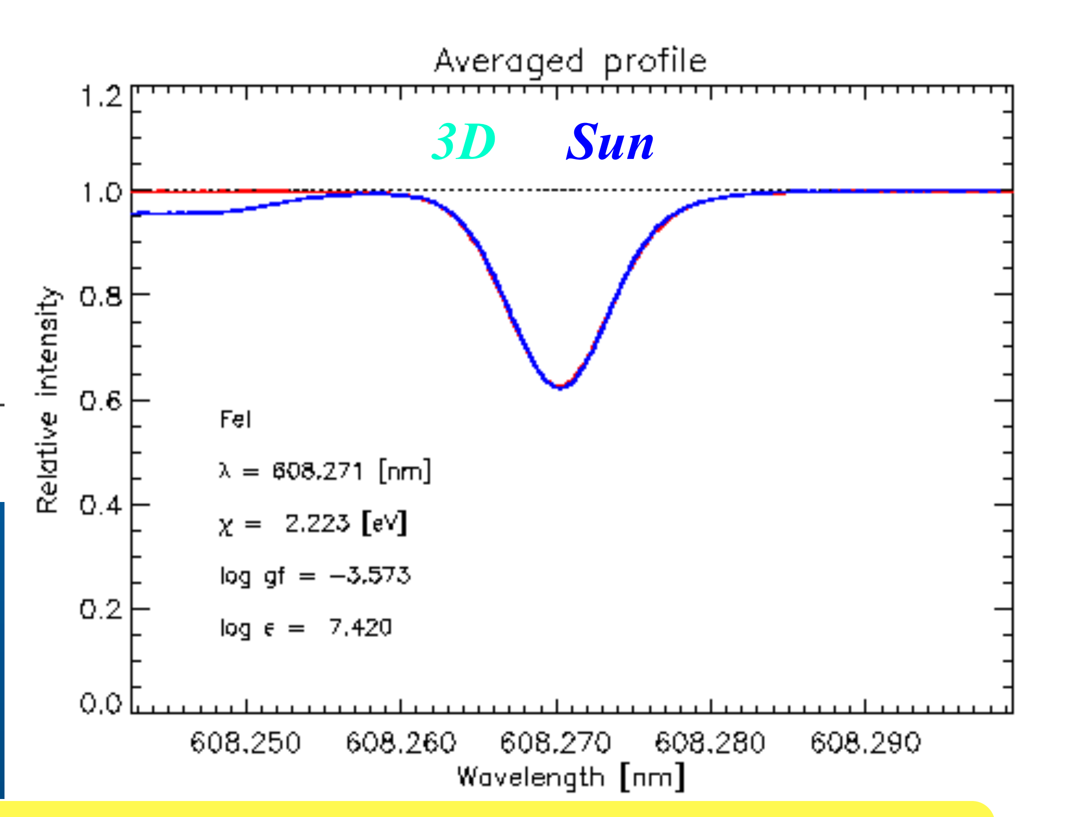
lower opacity → largest individual contribution to lower ^{7}Be and ^{8}B

Metal difusion



Averaged line profiles AGS vs GS





Asplund et al

No micro- and macroturbulence needed in 3D!

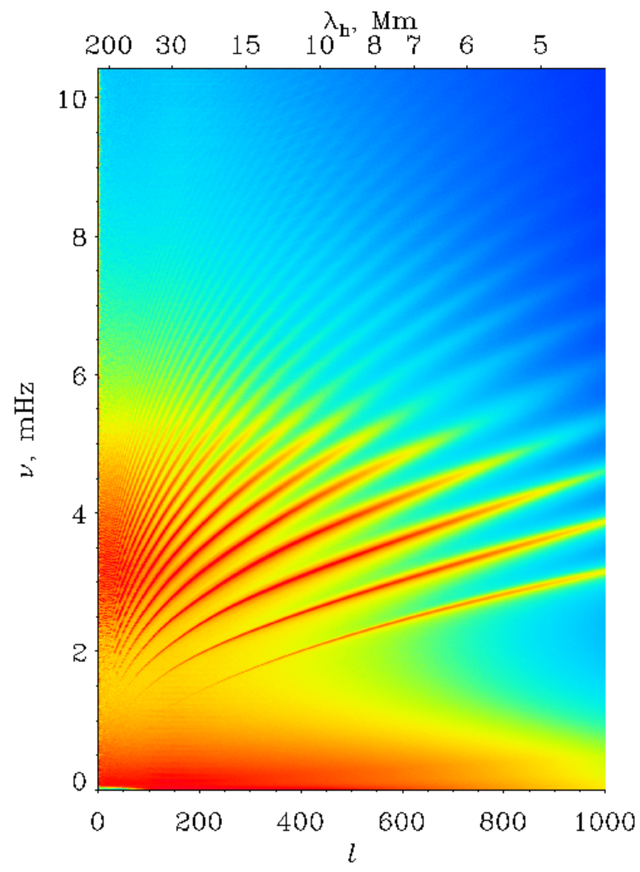
Carbon diagnostics

- *Discordant results in 1D: log C~8.4-8.7*
- *Excellent agreement in 3D: log C=8.39+/-0.05*

Lines	MARCS	Holweger-Mueller	3D
[C I]	8.40	8.45	8.39
C I	8.35+/-0.03	8.39+/-0.03	8.36+/-0.03
CH, dv=1	8.42+/-0.04	8.53+/-0.04	8.38+/-0.04
CH, A-X	8.44+/-0.04	8.59+/-0.04	8.45+/-0.03
C_2, Swan	8.46+/-0.03	8.53+/-0.03	8.44+/-0.03
CO, dv=1	8.55+/-0.02	8.60+/-0.01	8.40+/-0.01
CO, dv=2	8.58+/-0.02	8.69+/-0.02	8.37+/-0.01

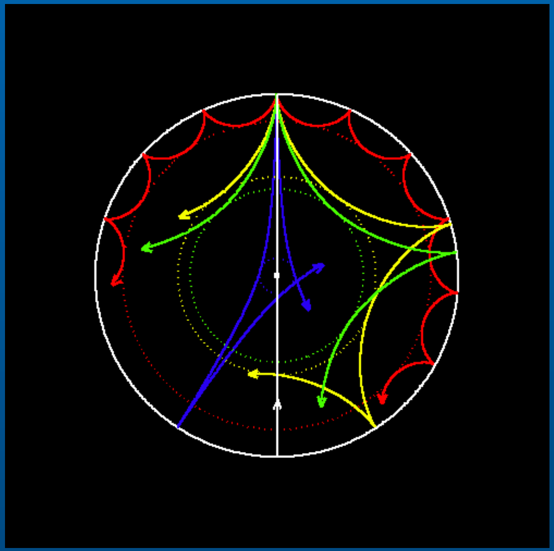
Asplund et al

The pulsating Sun: Helioseismology



Doppler observation of spectral lines:

- *velocities ~ cm/s*
- *long observations needed*
- *Accuracy in frequencies ~10^{-5}*



Physics: Acoustic waves, pressure-modes, stochastically excited by convection

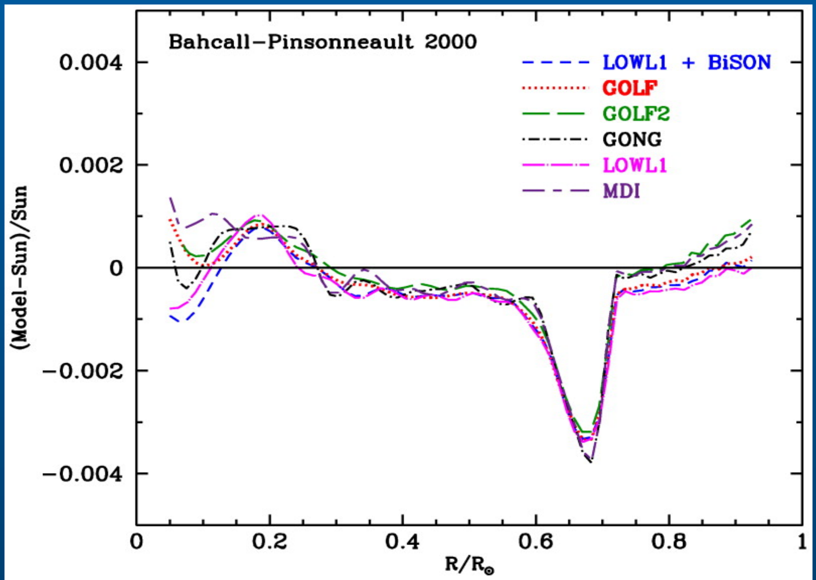
Helioseismology

- *Oscillation frequencies depend on ρ, P, g, c*
- *Inversion problem: use measured frequencies and a reference solar model to determine the solar structure*

$$\frac{\delta\omega_i}{\omega_i} = \int K^i_{c^2,\rho}(r)\frac{\delta c^2}{c^2}(r)dr + \int K^i_{\rho,c^2}(r)\frac{\delta\rho}{\rho}(r)dr + F_{surf}(\omega_i)$$

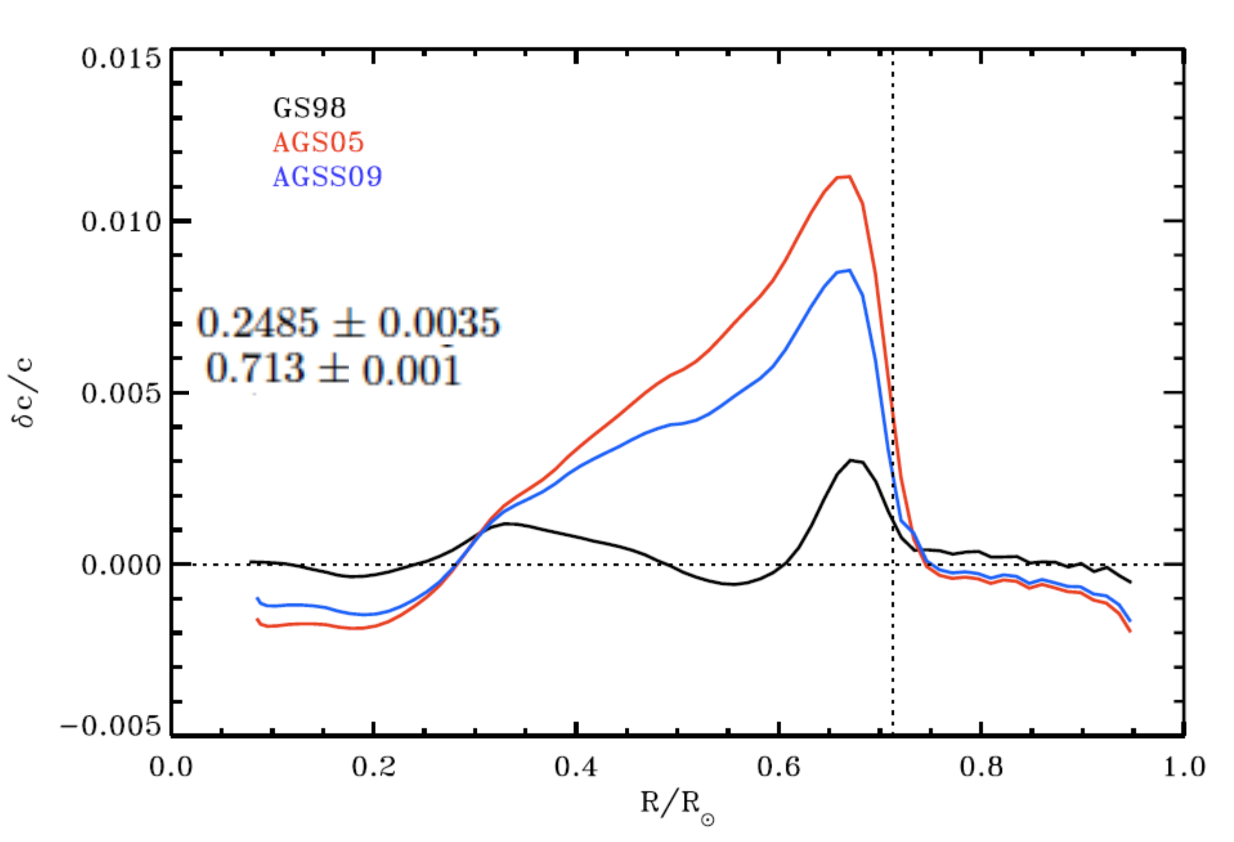
Output of inversion procedure: $\delta c^2(r)$, $\delta\rho(r)$, R_{CZ}, Y_{SURF}

Relative difference of c between Sun and BP00



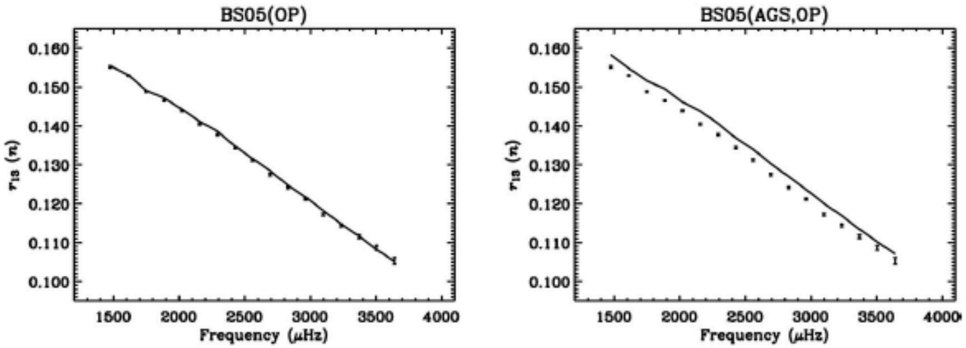
The Solar Abundances Problem

	GS98	AGSS09
$(Z/X)_S$	0.0229	0.0178
Z_S	0.0170	0.0134
Y_S	0.2429	0.2319
$R_{CZ}/R_\odot$	0.7124	0.7231
$\langle\delta c/c\rangle$	0.0009	0.0037
Z_c	0.0200	0.0159
Y_c	0.6333	0.6222
Z_{ini}	0.0187	0.0149
Y_{ini}	0.2724	0.2620



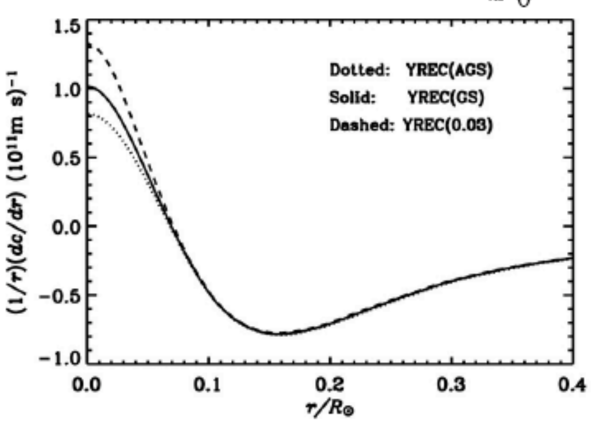
Low abundances: non-local solution needed

Solar core: Helioseismology with low-l modes



Effect of metalicity arise in the core

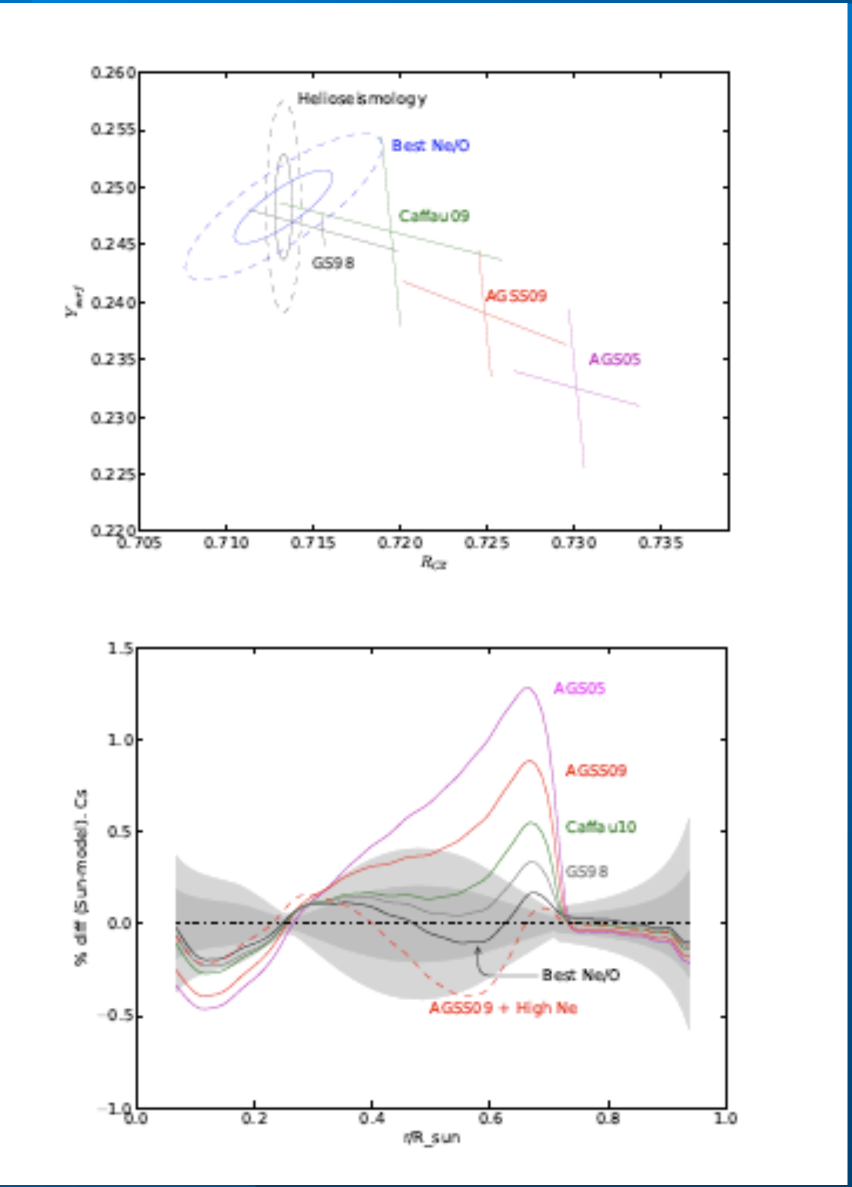
$$\delta_{nl} \equiv \nu_{nl} - \nu_{n-1\,l+2} \simeq -(4l+6)\frac{\Delta\nu}{4\pi^2\nu_{nl}}\int_0^R \frac{dc}{dr}\frac{dr}{r}$$



Low l-modes BiSON data
Chaplin et al (2007)

- Low-Z models not compatible with low-l frequencies
- Conservative abundances: too conservative → assume smaller uncertainties for SSM

Solution 1: increase Ne ?

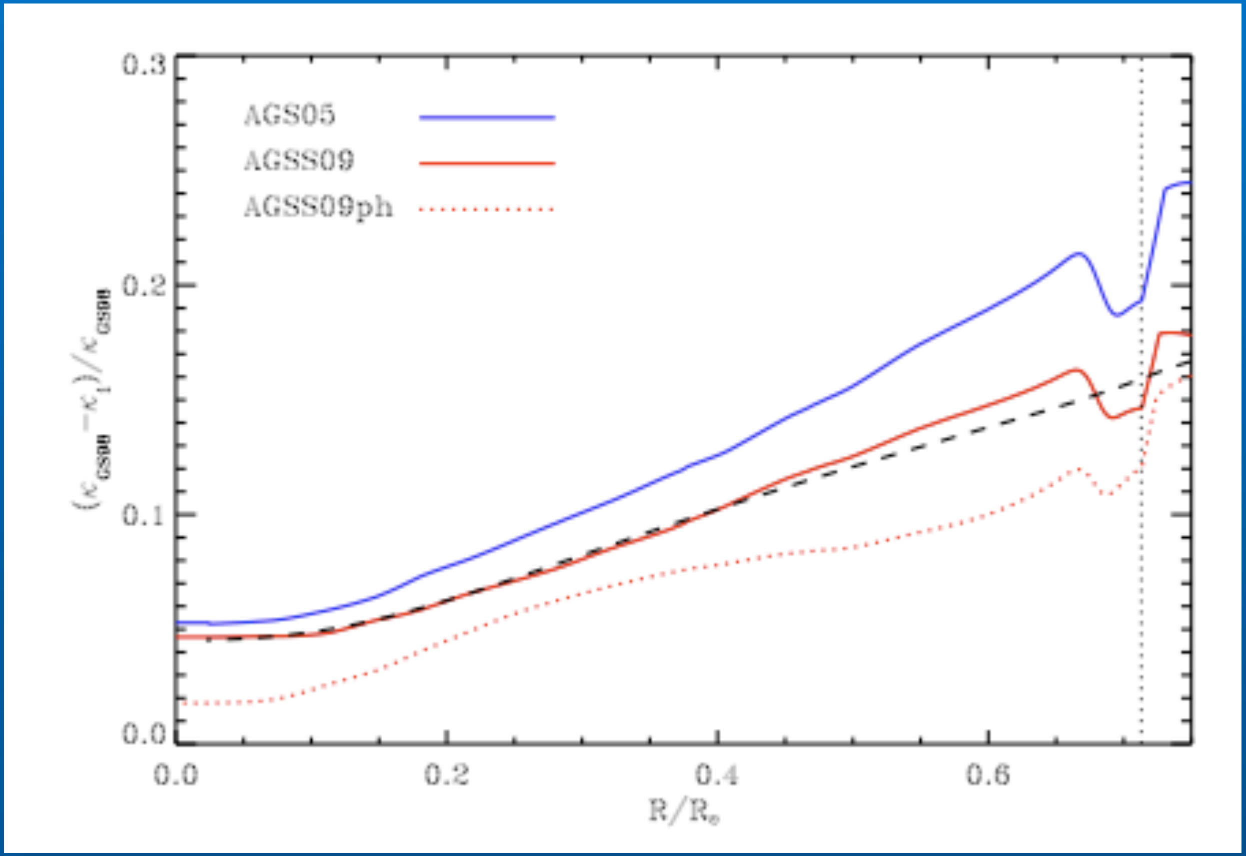


Ne/O inferred from helioseismology

agrees well with adopted Ne

Delahaye et al (2010)

Solution 2: Increase opacities?

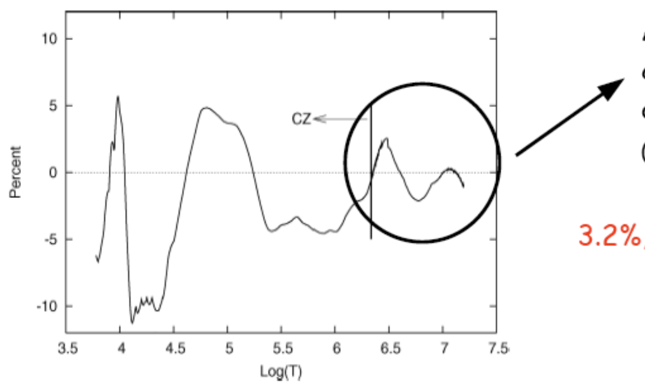


Non standard :

- Higher metallicity in the core: Astrophysics
- Higher metallicity in the core: Particle physics
- Other tests to opacities at MK temperatures?

Solution 2: Increase opacities?

Effects of Opacity



Adopted uncertainty: 2.5% characteristic of OP - OPAL difference in radiative core (Badnell et al. 2005)

3.2%, 7%, 4%, 5%, 6% (^{7}Be, ^{8}B, CNO)

Difference oscillates. If 1-σ defined as difference SSM(OP) - SSM(OPAL), uncertainties are reduced: 1%, 2.4%, 1.3%, 2.1%, 2.2% (^{7}Be, ^{8}B, CNO)

First approach a bit more conservative

- ***Global or inner radiative zone opacity change does not make fit the helioseismology data*** *Villante (2010)*
- ***15% increase (much larger than adopted uncertainty) is needed in the outer part of the radiative zone***

Solution 3: Accretion Histories

Proposal of metal-poor matter accretion and mixing in the convective envelope after MS. Ad hoc models with low Z/X convective envelope and with a radiative interior retaining a higher Z/X. Guzik & Mussack (2010), …

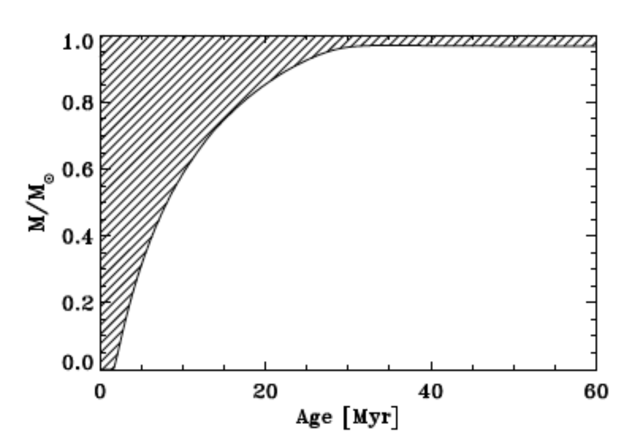
Plan: Consider large range of accretion histories

$0 < M_{ac} < 20000\ M_{Earth}$

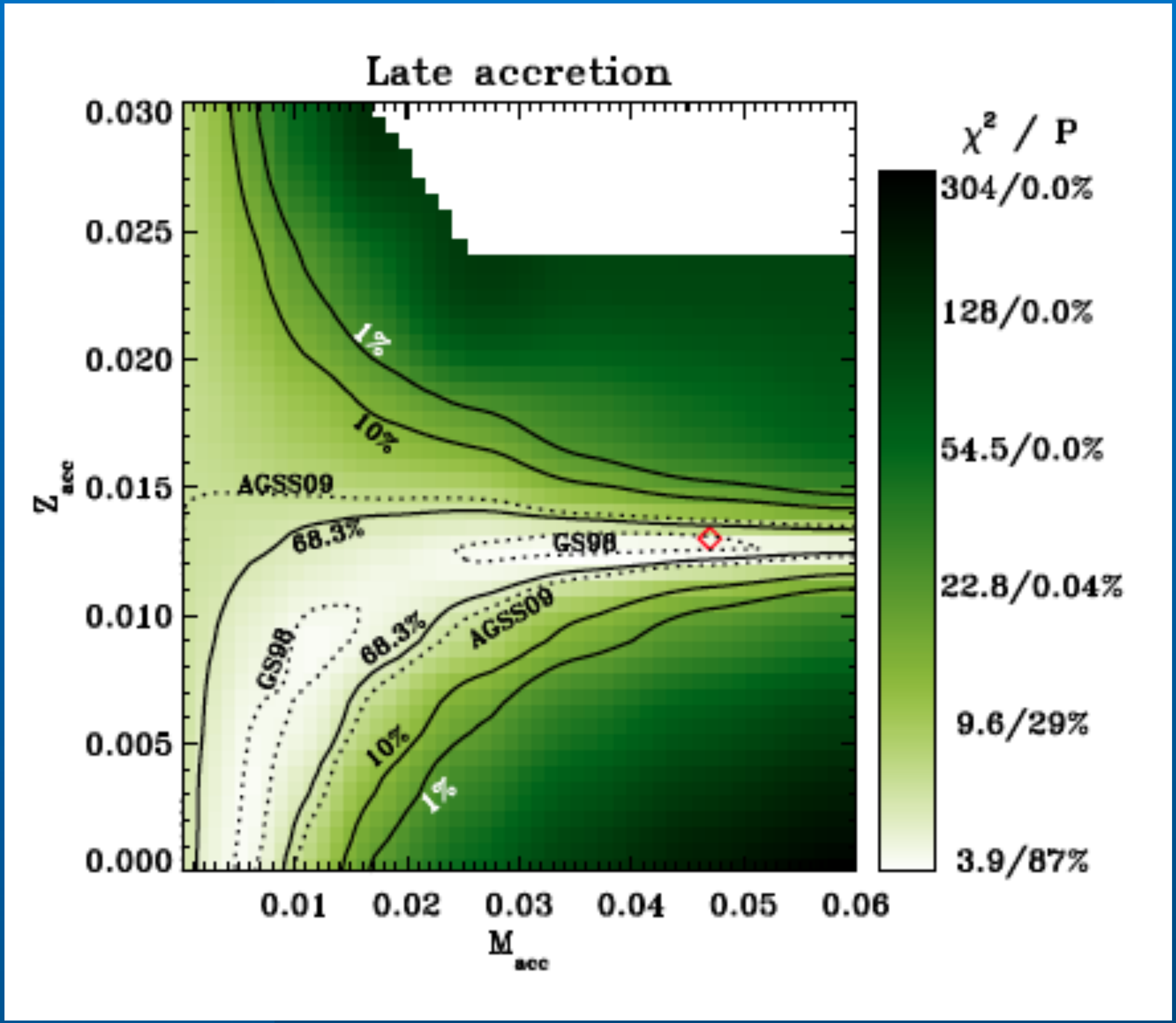
$0 < Z_{ac} < 600\ M_{Earth}$

$t_{ac,i} = 5, 15, 30$ Myr ; $t_{ac,f} = t_{ac,i} + 10$ Myr

and test model predictions with observed neutrino fluxes and helioseismology data.



Late Accretion: Neutrino Fluxes



Early accretion:
Improvement in R_{CZ}
Worsening in Y_S
Metal-rich larger accretion
Disfavored

Late accretion
Improvement in R_{CZ}
Worsening in Y_S
Large accretion excluded
(metal-rich and metal-poor)

Large accretion excluded by data !

pep/pp neutrinos

Precise pep neutrinos (Borexino, SNO+):
Best measurement of solar mixing angle because solar flux of pep neutrinos is known very precisely and also can be determined by neutrino data and energy conservation. Future measurements should improve ~ 5% error on $\sin^2\theta_{12}$

pep/pp ratio is predicted with error better than 1%:
Best test of non standard neutrino physics in the ~ 1 MeV region

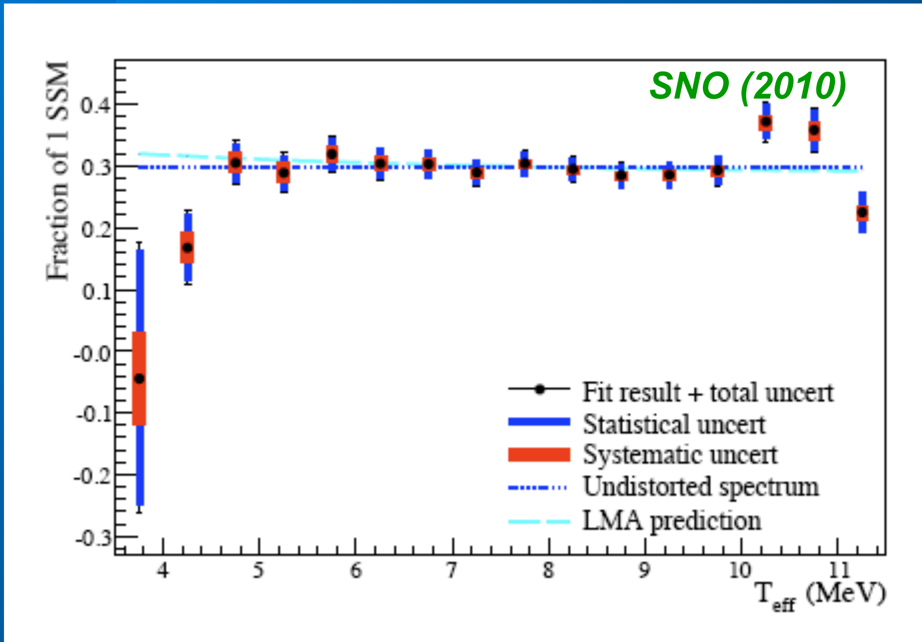
8B neutrinos

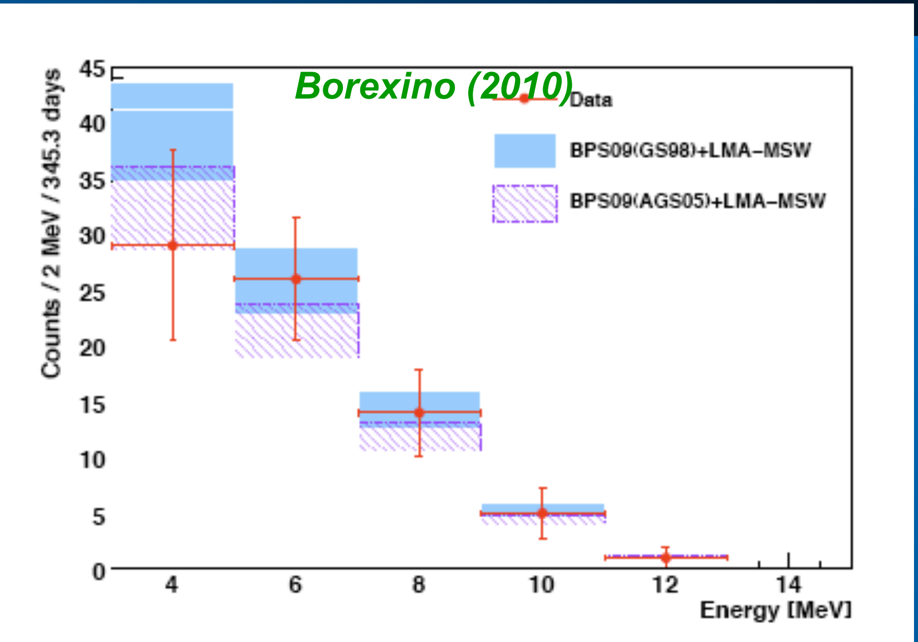
Check Standard Model prediction of matter effects
More precise test of agreement between KamLAND and Solar neutrino parameters:

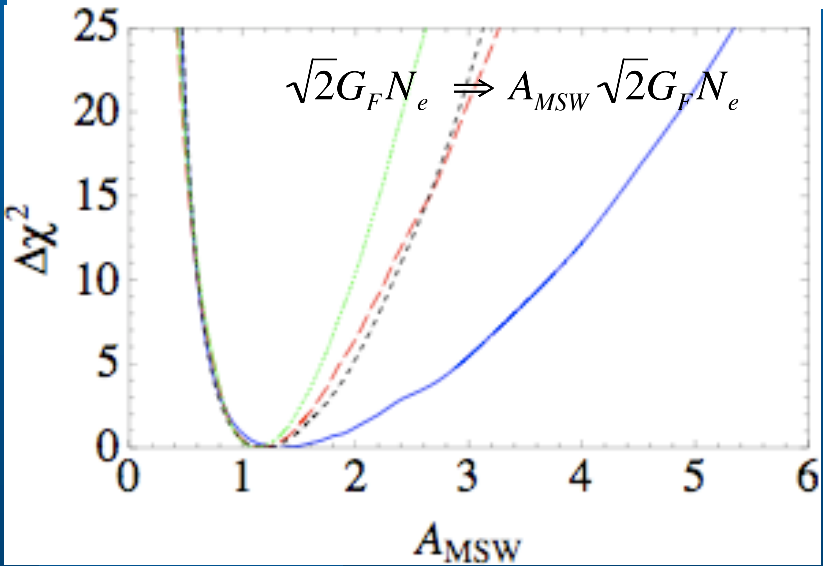
Measurement of the upturn in the spectrum

Measurement of the daynight effect

Amplitude of matter effects







Loose upper bound.
Improved by 3σ upturn, pep, 2σ DN
Probe matter potential for different matter compositions:
Sun (dominantly protons)
and Earth (even protons, neutrons)

Minakata , PG (2010,2012)

BSM ν-interactions at low energies

$$\mathcal{L}_{eff}^{NSI} = -\varepsilon_{\alpha\beta}^{fP} 2\sqrt{2} G_F (\bar{\nu}_\alpha \gamma_\rho L \nu_\beta)(\bar{f} \gamma^\rho P f)$$

We assume new neutral currents and no new physics in the charged sector at tree level. Sensitivity to new couplings at :

- ***neutrino production***

- ***neutrino detection***

- ***matter effects: sensitive to the vector coupling (L+R)***

Evolution in matter (SM and BSM)

$$H_{\text{matter}} = V \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \longrightarrow V \left[\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^{*} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^{*} & \varepsilon_{\mu\tau}^{*} & \varepsilon_{\tau\tau} \end{pmatrix} \right]$$

$$\varepsilon_{\alpha\beta} = \sum_{f,P} \varepsilon_{\alpha\beta}^{fP} \frac{n_f}{n_e}$$

Summary of bounds

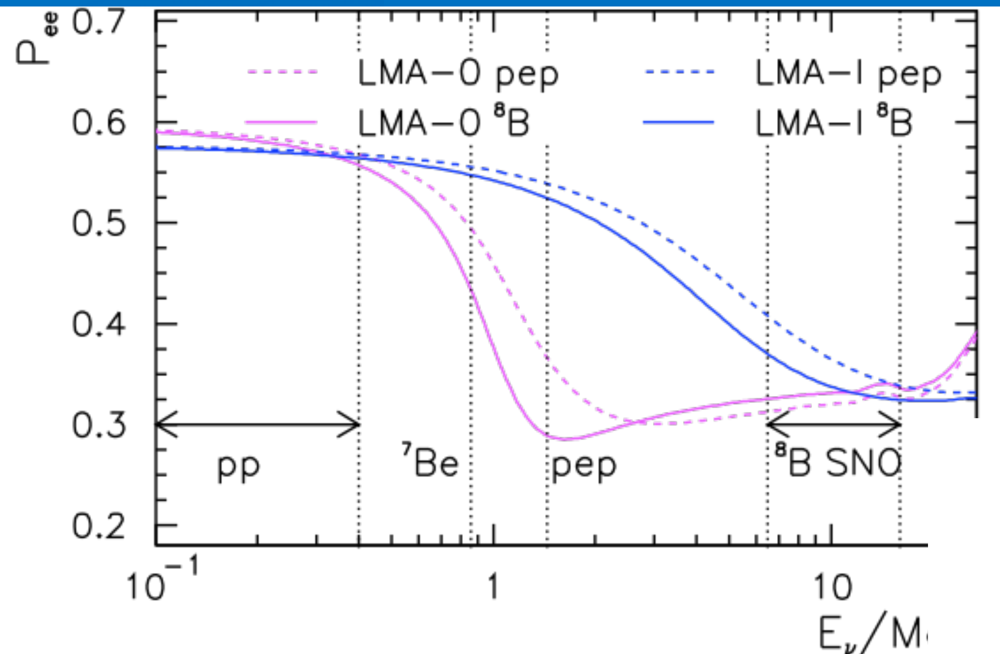
$$|\varepsilon^e_{\alpha\beta}| < \begin{pmatrix} \begin{matrix}0.06\\0.14\end{matrix} & 0.10 & \begin{matrix}0.4\\0.27\end{matrix} \\ 0.10 & 0.03 & 0.10 \\ \begin{matrix}0.4\\0.27\end{matrix} & 0.10 & \begin{matrix}0.16\\0.4\end{matrix} \end{pmatrix}$$

$$|\varepsilon^u_{\alpha\beta}| < \begin{pmatrix} \begin{matrix}1.0\\0.7\end{matrix} & 0.05 & 0.5 \\ 0.05 & \begin{matrix}0.003\\0.008\end{matrix} & 0.05 \\ 0.5 & 0.05 & \begin{matrix}1.4\\3\end{matrix} \end{pmatrix}$$

$$|\varepsilon^d_{\alpha\beta}| < \begin{pmatrix} \begin{matrix}0.3\\0.6\end{matrix} & 0.05 & 0.5 \\ 0.05 & \begin{matrix}0.003\\0.015\end{matrix} & 0.05 \\ 0.5 & 0.05 & \begin{matrix}1.1\\6\end{matrix} \end{pmatrix}$$

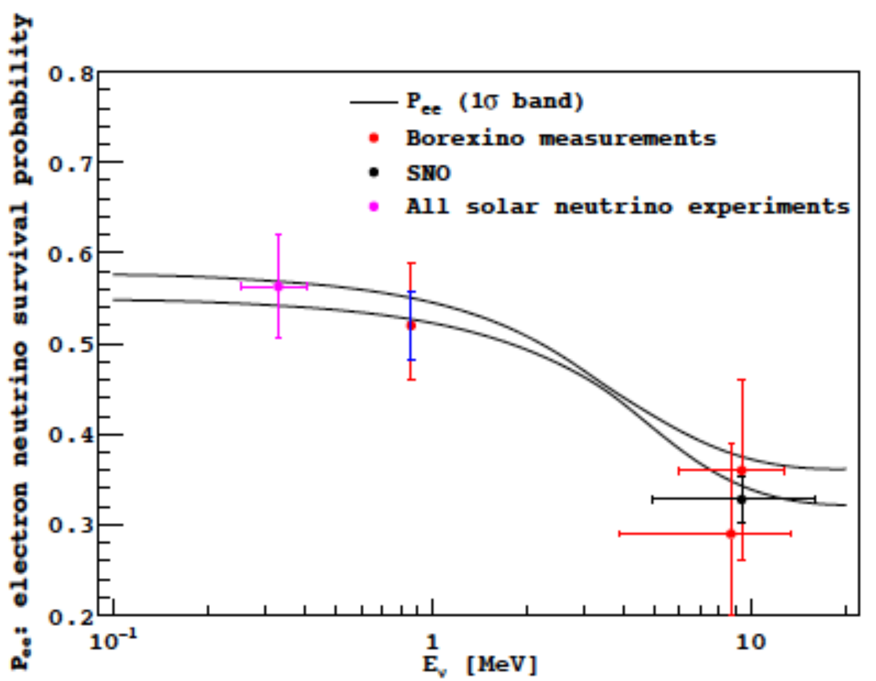
Davidson et al, hep-ph/0302093; Biggio et al, 0907.0097

Solar: Test Matter-Vacuum transition



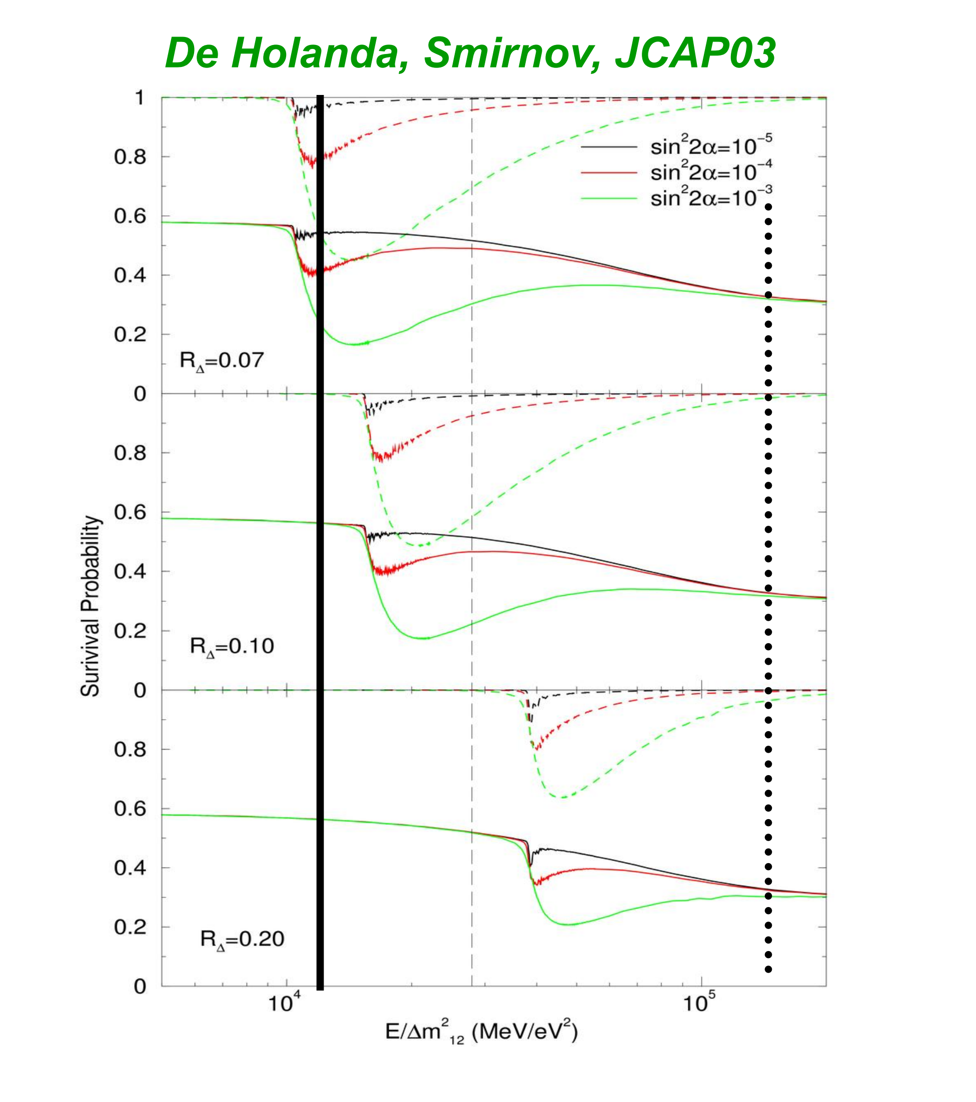
Friedland et al, hep-ph/0402266

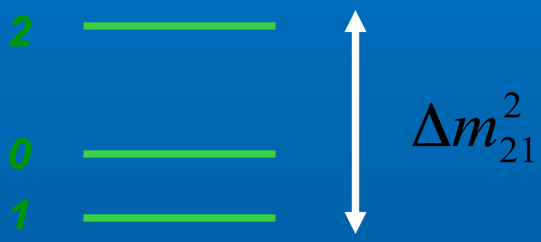
Blue: Standard ν oscillations
Red: Non-standard interactions tuned to agree with experiments.



Borexino col., 1104.1816

Sterile neutrino with small splitting





Berezinsky et al (2003)

Small sterile admixture :

No sensitivity in KamLAND reactor

Sensitivity in low energy solar neutrino experiments (Borexino/KamLAND sol)

Why CNO Neutrinos?

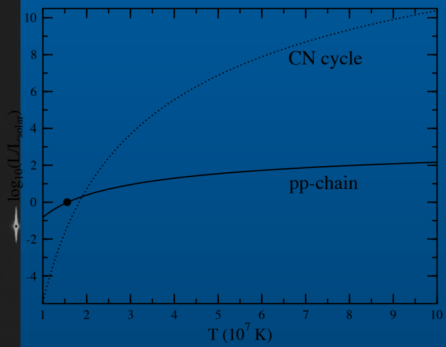
Verify how hot stars shine

1. Most sensitive to matter effects
2. Most sensitive to the Solar Abundances Problem
3. Most sensitive to the Solar Core Composition

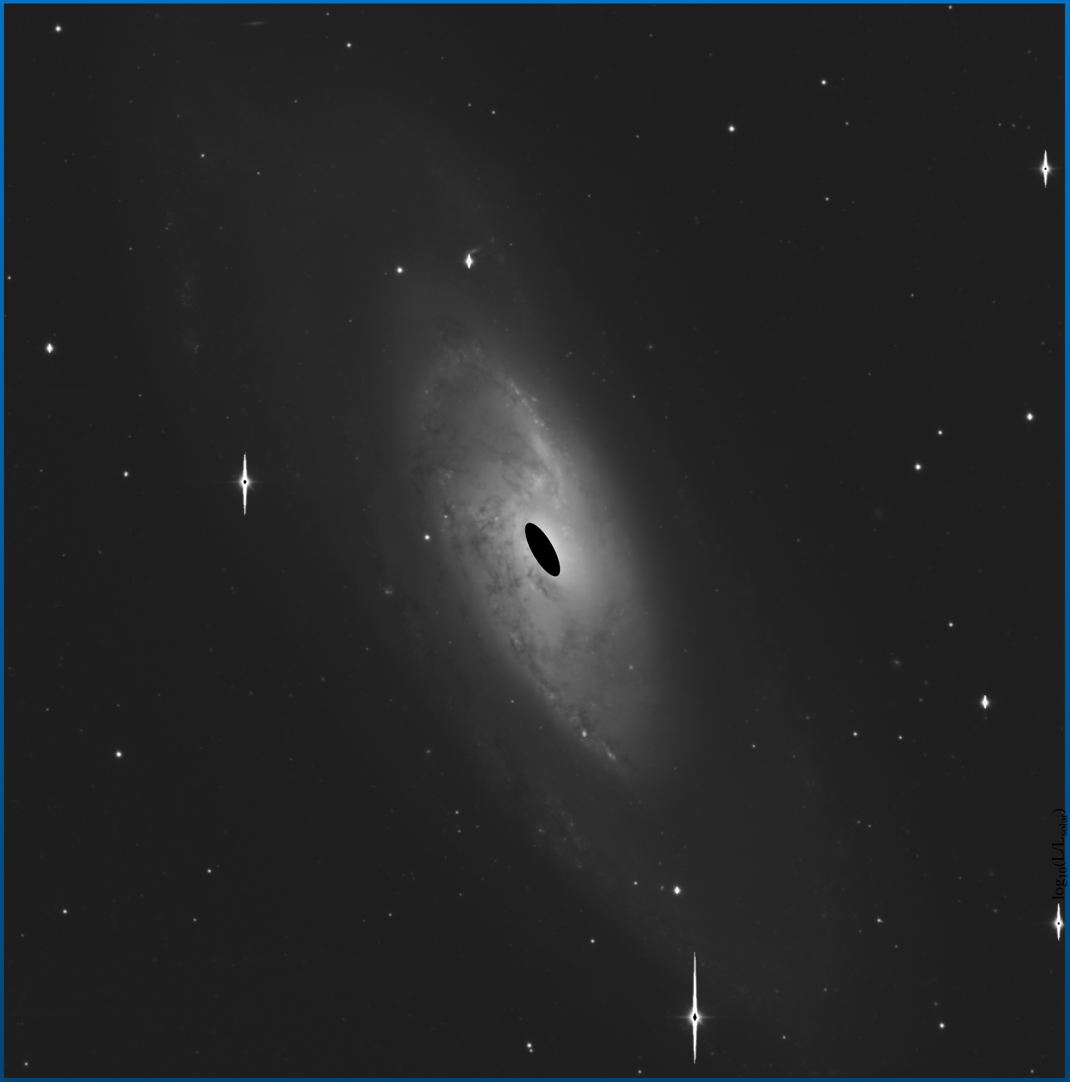
M106 (R filter)

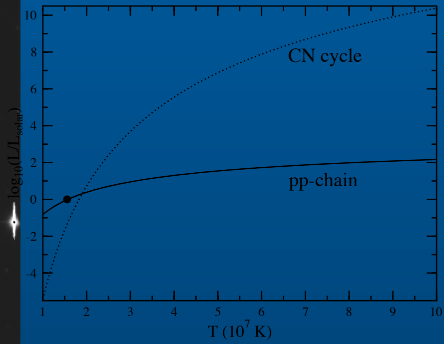
M106 (R filter-Hα)

M106 (R filter-Hα): Luminosity by pp chain



M106 (R filter-Hα): : Luminosity by CNO cycle





Limits on CNO: Energy conservation

If nuclear fusion reactions among light elements are responsible for solar energy generation and using that D and ^{3}He are in local kinetic equilibrium

$$\frac{L_{SUN}}{4\pi(\mathrm{A.U.})^2} = \sum_i \alpha_i \Phi_i$$

Spiro, Vignaud, PLB (1990)

α_i *determined from nuclear masses and neutrino energies independent of details of solar model at 1:10^4*

Bahcall, PRC (2002)

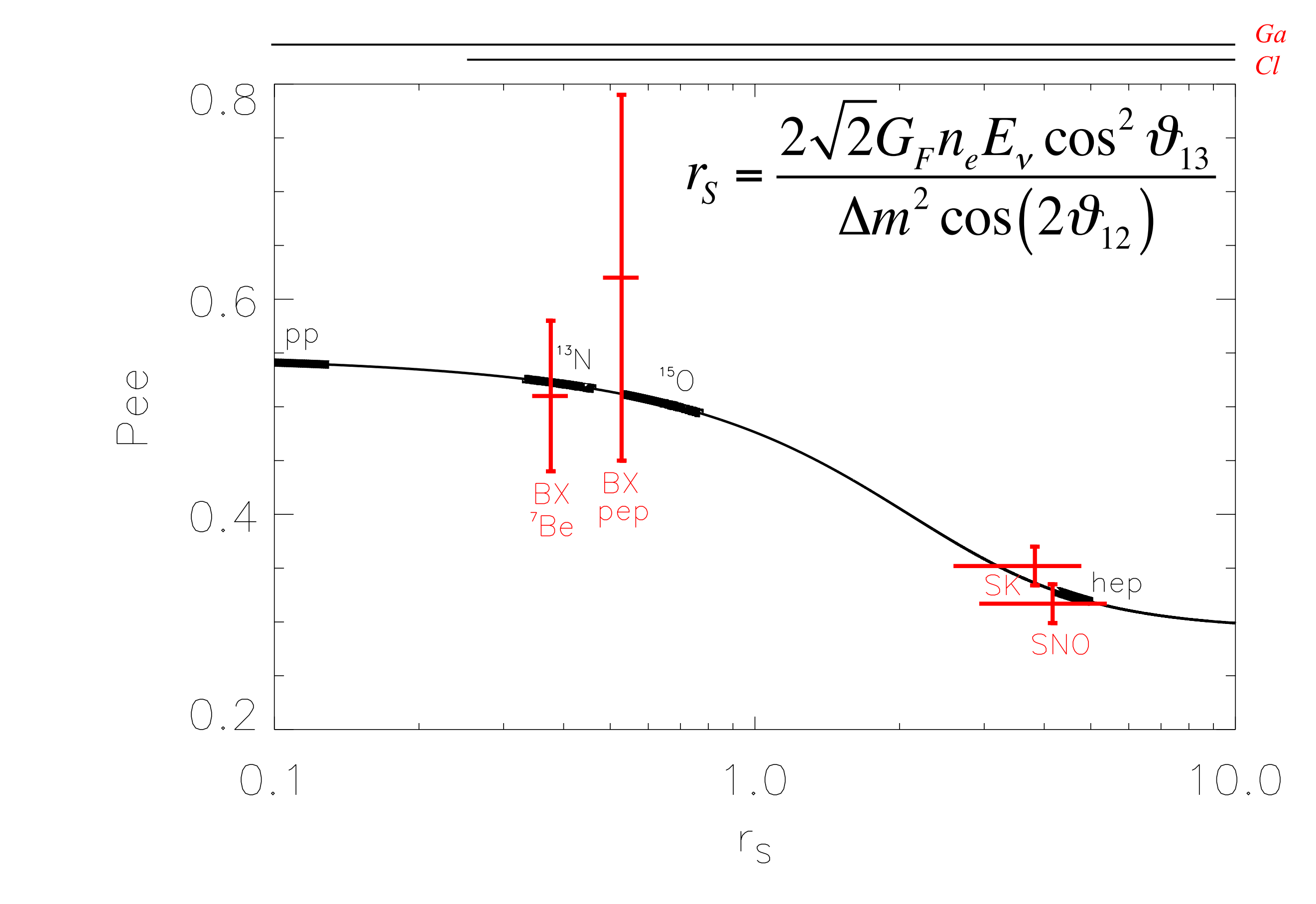
$$1 = 0.918 f_{pp} + 0.069 f_{Be} + 0.013 f_{CNO}$$

New neutrino data: LC correct within 20%

Standard Solar Models

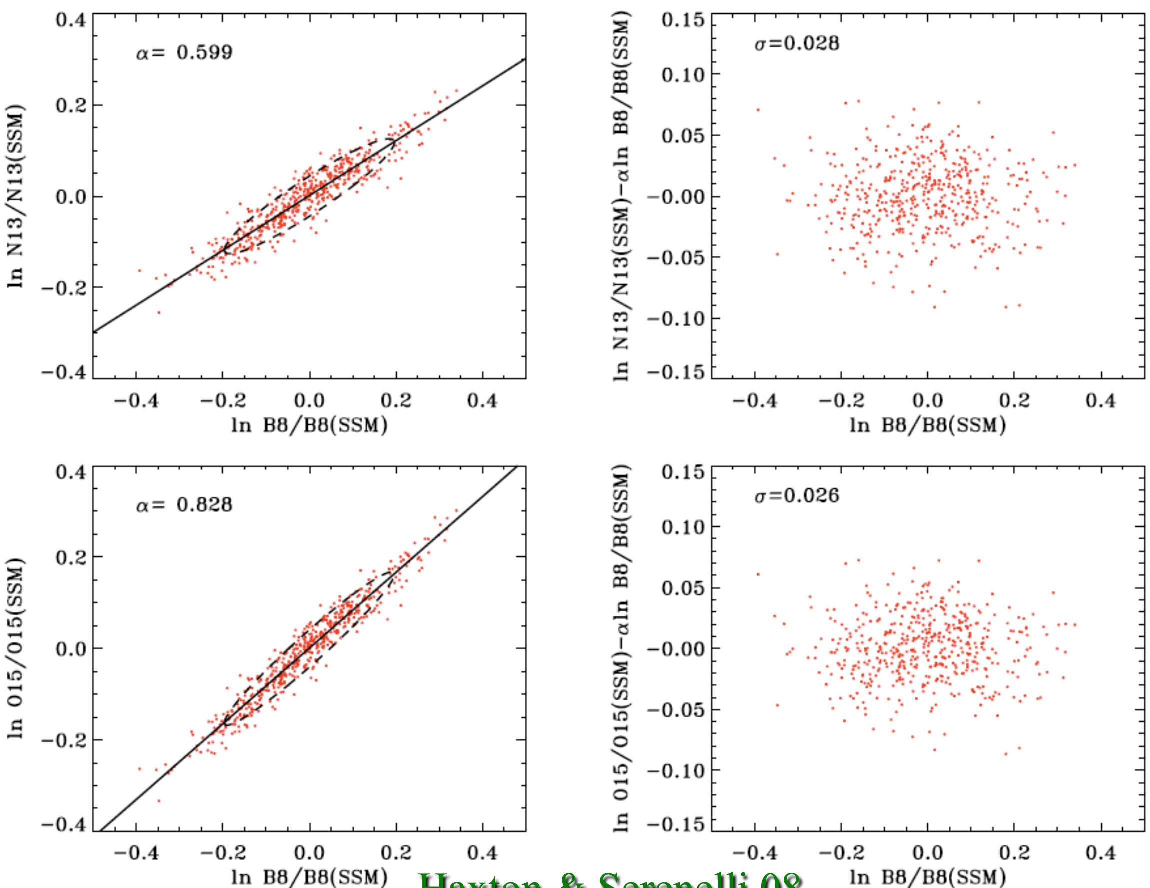
ν flux	E_ν^{max} (MeV)	GS98-SFII	AGSS09-SFII	Solar	units
$p+p \to {}^2H+e^+ + \nu$	0.42	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.006)$	$6.05(1^{+0.003}_{-0.011})$	$10^{10}/cm^2s$
$p+e^- + p \to {}^2H+\nu$	1.44	$1.44(1 \pm 0.012)$	$1.47(1 \pm 0.012)$	$1.46(1^{+0.010}_{-0.014})$	$10^{8}/cm^2s$
${}^7Be+e^- \to {}^7Li+\nu$	0.86 (90%)	$5.00(1 \pm 0.07)$	$4.56(1 \pm 0.07)$	$4.82(1^{+0.05}_{-0.04})$	$10^{9}/cm^2s$
	0.38 (10%)				
${}^8B \to {}^8Be+e^+ + \nu$	~ 15	$5.58(1 \pm 0.14)$	$4.59(1 \pm 0.14)$	$5.00(1 \pm 0.03)$	$10^{6}/cm^2s$
${}^3He+p \to {}^4He+e^+ + \nu$	18.77	$8.04(1 \pm 0.30)$	$8.31(1 \pm 0.30)$	—	$10^{3}/cm^2s$
${}^{13}N \to {}^{13}C+e^+ + \nu$	1.20	$2.96(1 \pm 0.14)$	$2.17(1 \pm 0.14)$	≤ 6.7	$10^{8}/cm^2s$
${}^{15}O \to {}^{15}N+e^+ + \nu$	1.73	$2.23(1 \pm 0.15)$	$1.56(1 \pm 0.15)$	≤ 3.2	$10^{8}/cm^2s$
${}^{17}F \to {}^{17}0+e^+ + \nu$	1.74	$5.52(1 \pm 0.17)$	$3.40(1 \pm 0.16)$	$\leq 59.$	$10^{6}/cm^2s$
χ^2/P^{agr}		3.5/90%	3.4/90%		

Flavor Conversion 1-2 in solar and reactor ν



Decoherence of low energy ν and flavor conversion by matter of high energy neutrinos

How to extract core metallicities



Haxton & Serenelli 08

$$\frac{\phi(^{13}\mathrm{N})}{\phi^{SSM}(^{13}\mathrm{N})} = \left[\frac{\phi^{SNO}(^{8}\mathrm{B})}{\phi^{SSM}(^{8}\mathrm{B})}\right]^{0.599} [1 \pm 2.8\%(\text{resid. environ.}) \pm 5.0\%)(\text{nuclear})] \left(\frac{X(^{12}\mathrm{C})}{X(^{12}\mathrm{C})_{SSM}}\right)^{0.858} \left(\frac{X(^{14}\mathrm{N})}{X(^{14}\mathrm{N})_{SSM}}\right)^{0.141}.$$

$$\frac{\phi(^{15}\mathrm{O})}{\phi^{SSM}(^{15}\mathrm{O})} = \left[\frac{\phi^{SNO}(^{8}\mathrm{B})}{\phi^{SSM}(^{8}\mathrm{B})}\right]^{0.828} [1 \pm 2.6\%(\text{resid. environ.}) \pm 7.1\%(\text{nuclear})] \left(\frac{X(^{12}\mathrm{C})}{X(^{12}\mathrm{C})_{SSM}}\right)^{0.805} \left(\frac{X(^{14}\mathrm{N})}{X(^{14}\mathrm{N})_{SSM}}\right)^{0.199}$$

Linear dependence with C+N

$$x_C^{0.791} x_N^{0.202} \Rightarrow \left[\frac{N_{^{12}\mathrm{C}} + N_{^{14}\mathrm{N}}}{N_{^{12}\mathrm{C}}^{\mathrm{SSM}} + N_{^{14}\mathrm{N}}^{\mathrm{SSM}}}\right]$$

Summary

Status:

Solar neutrinos undergo flavor conversion:

- Partially averaged vacuum oscillations with decoherence of low energy neutrinos (<1.5 MeV)
- Adiabatic flavor conversion at high energies (> 4 MeV)
- Standard Solar Models fail to explain helioseismology with best abundances

Prospects:

Measure more precisely mixing angle

Test matter effects: upturn, daynight

Measure CNO neutrinos and test solar models with different metallicities