SOLAR NEUTRINOS

Carlos Peña Garay
Canfranc Underground Laboratory

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INSS18, Mainz

PROGRAM: 2 LECTURES

First Lecture

1A) How does the Sun shine? A few stories and heroes (before 1989)

1B) Standard Solar Models (quick tour by A. Serenelli)

1C) Solar Neutrino fluxes at the Earth

Second Lecture

2D) How does the Sun shine? A few stories and heroes I (after 1989)

2E) Solar Neutrino Experiments and Lessons in Neutrino Physics

2F) Roadmap of future solar neutrino research

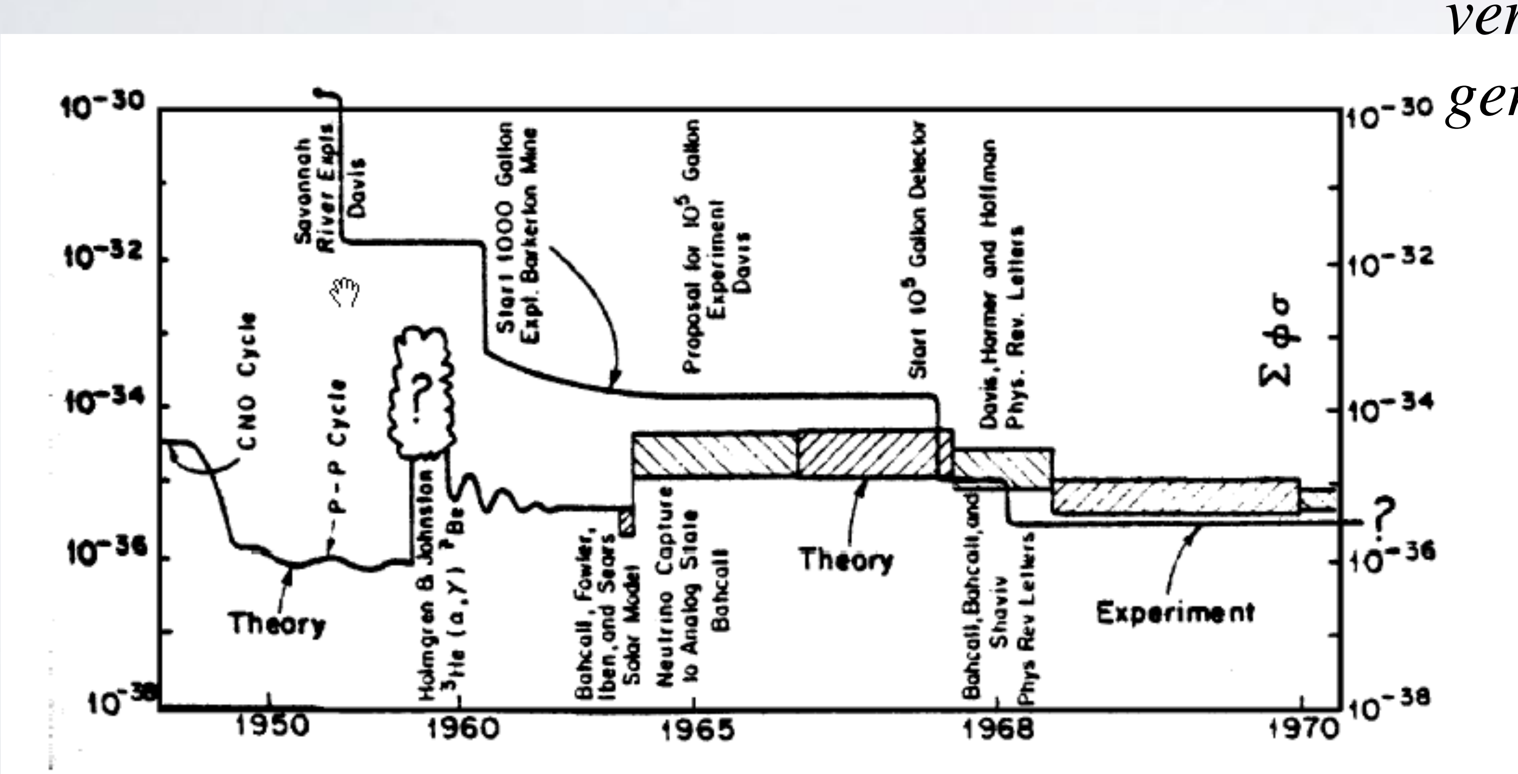
SOLAR NEUTRINO PROBLEM

First solar Model Calculation (1962)
- Ray Davis (1964) Solar Neutrinos: Experimental
- John Bahcall (1964) Solar Neutrinos: Experimental

"proposal to verify that nuclear reactions power the Sun"
- Homestake experiment (since 1968): Fewer neutrinos than predicted

Solar Neutrino Problem identified

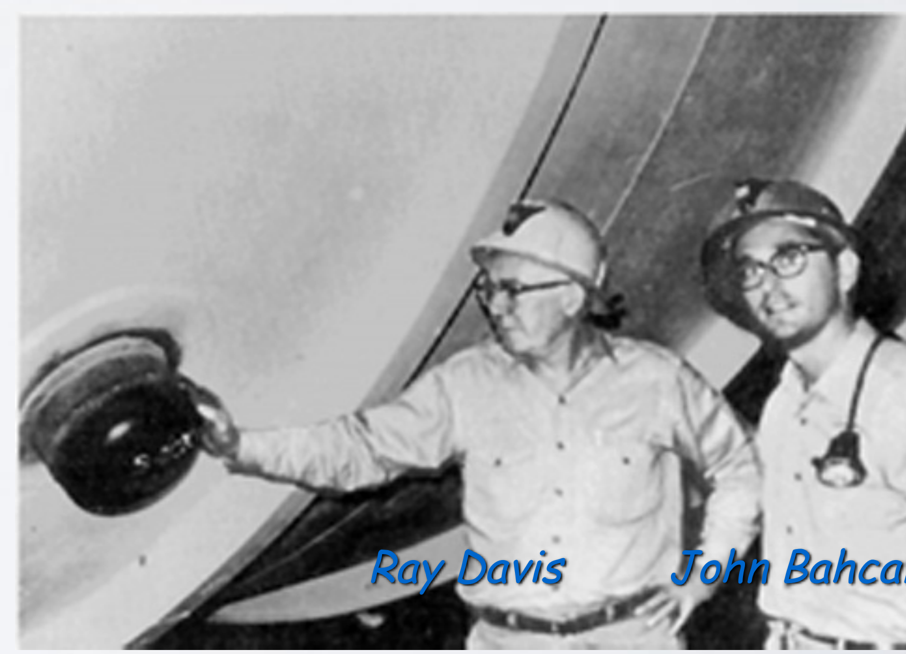
Chlorine rate: Theory vs experiment



Factor 3 missing!

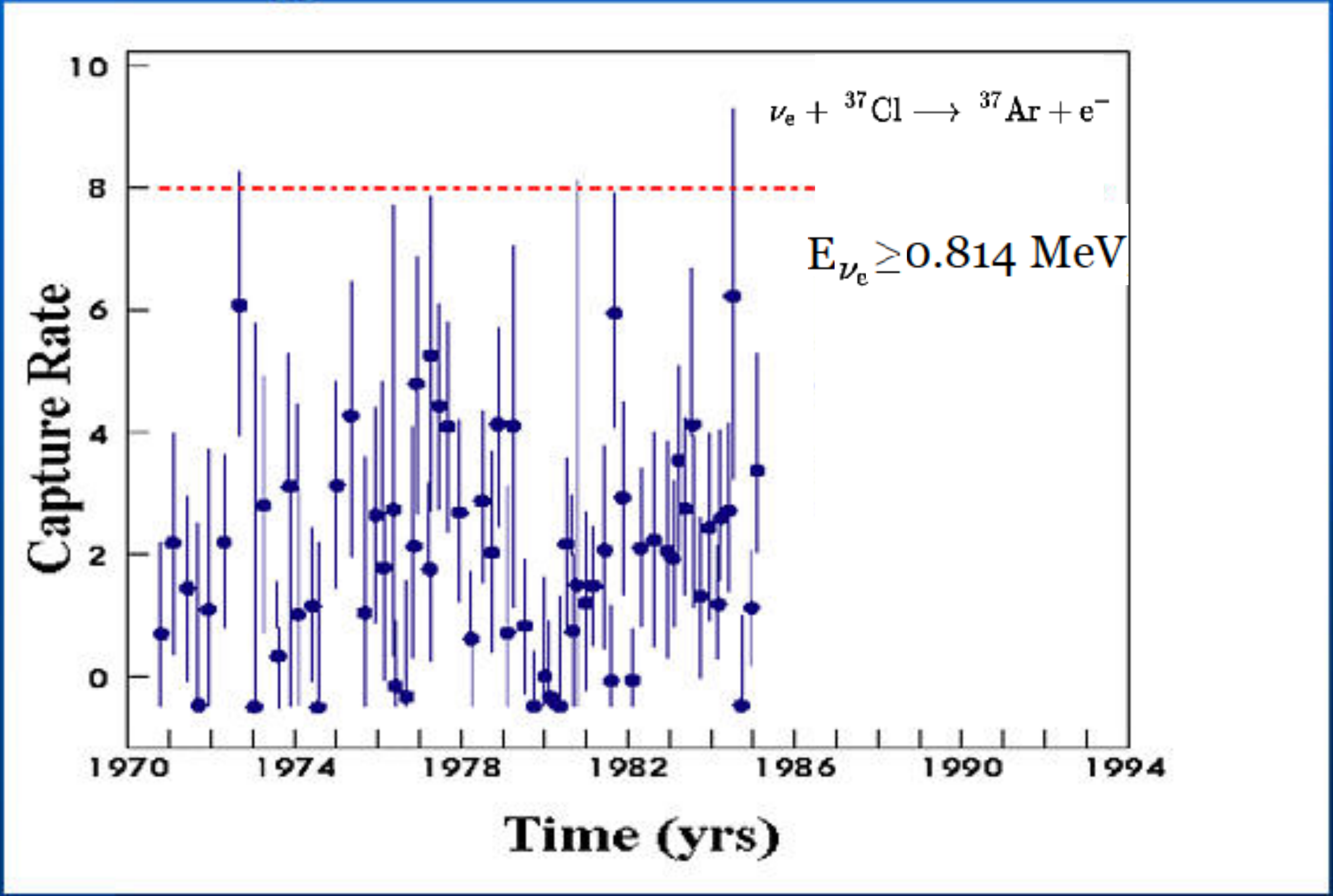
Neutrino Astrophysics was born…

"…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)**



Homestake

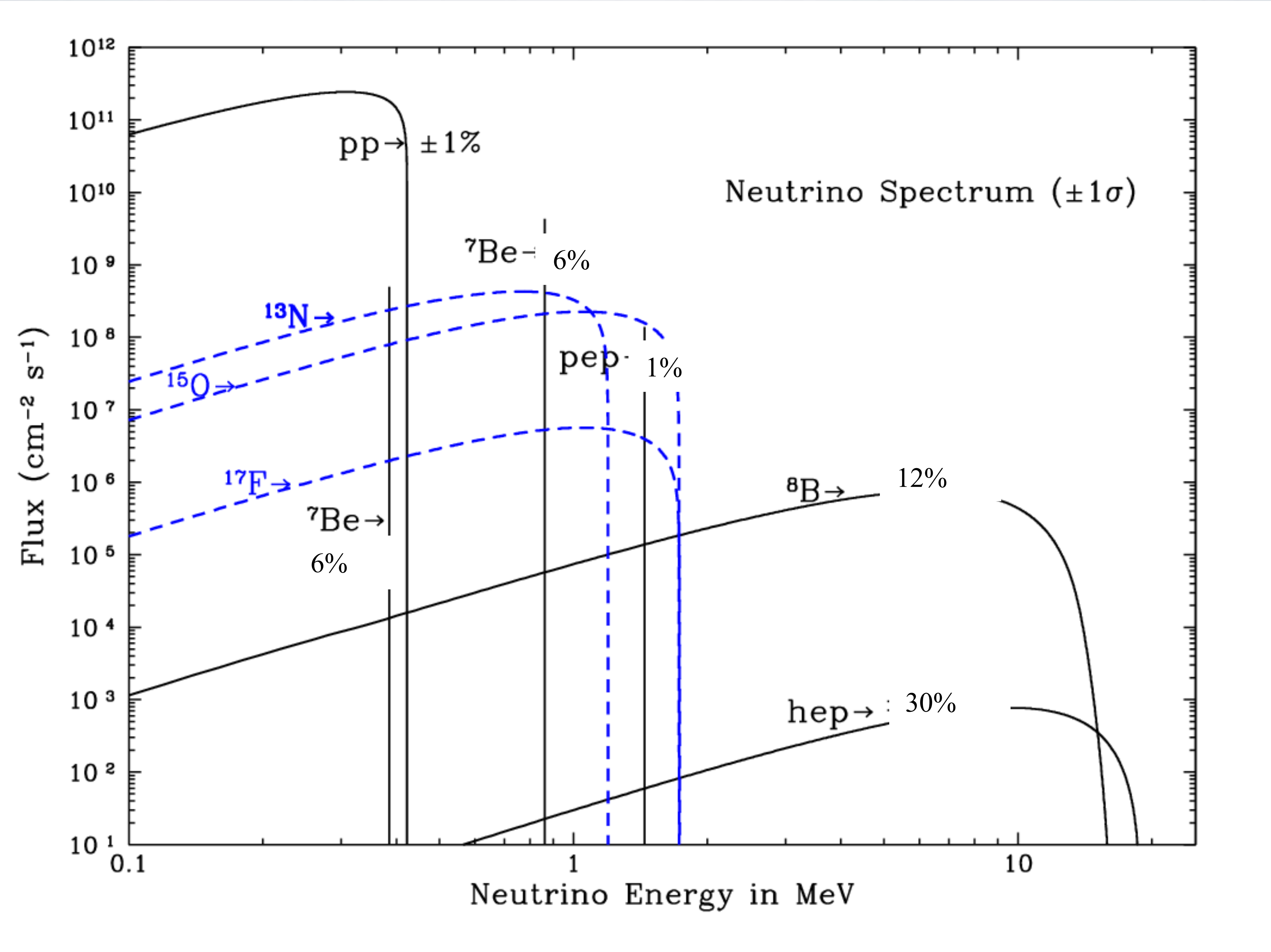
$$N_{cc} = 2.56 \pm 0.23 \text{ SNU}$$



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

Standard Solar Model

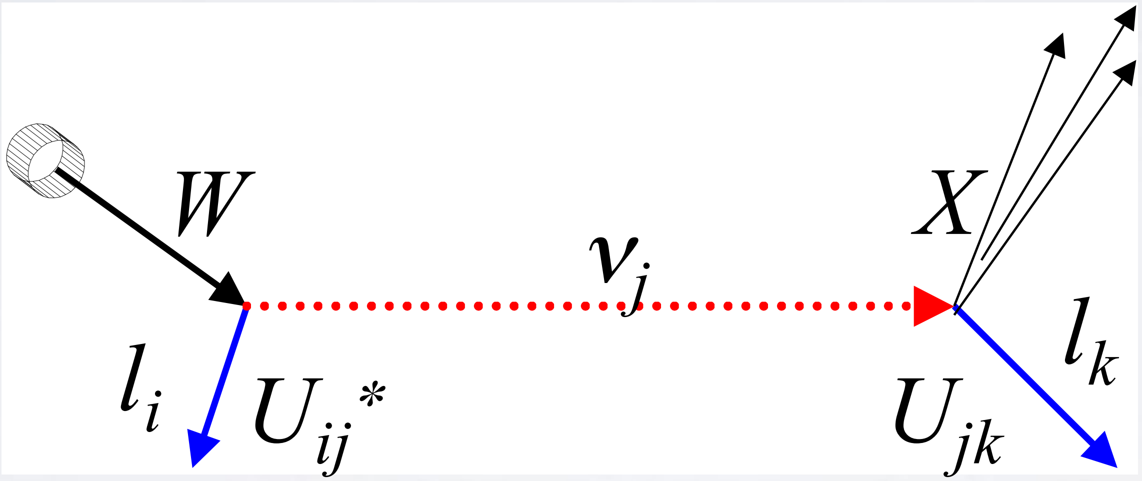
Solar neutrino spectra



SOLAR NEUTRINO PROBLEM

Solar Neutrino Problem solutions proposed
- Pontecorvo (1960s) - Neutrino oscillations

(B. Kaiser's first lecture)



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

Oscillations driven by the relative phase: (two neutrinos)

$$i \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{2E} \cos 2\theta & \frac{\Delta m^2}{4E} \sin 2\theta \\ \frac{\Delta m^2}{4E} \sin 2\theta & 0 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

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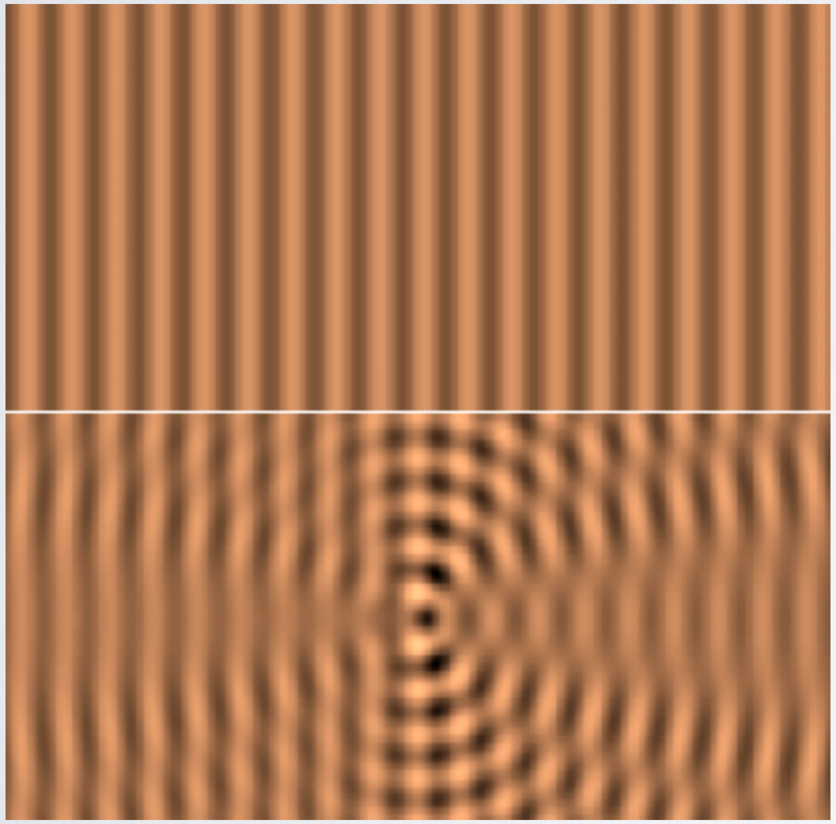
Scattering theory



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

Reminder: $f_{\mathrm{Born}} = -\dfrac{1}{4\pi}\langle\phi_{\mathbf{k}'}|U|\phi_{\mathbf{k}}\rangle = -\int_0^{\infty} r dr \dfrac{\sin(\Delta r)}{\Delta} U(r)$ $\quad \Delta = 2k\sin(\theta/2)$

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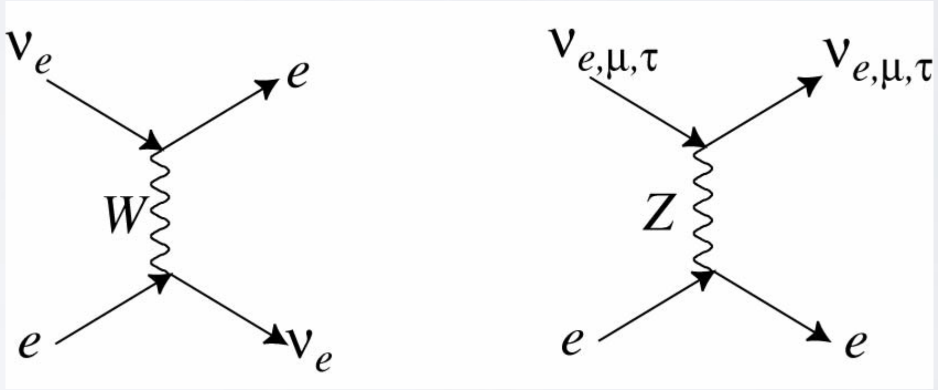
Only the difference of potentials is relevant



Net effect on
non relativistic electrons:

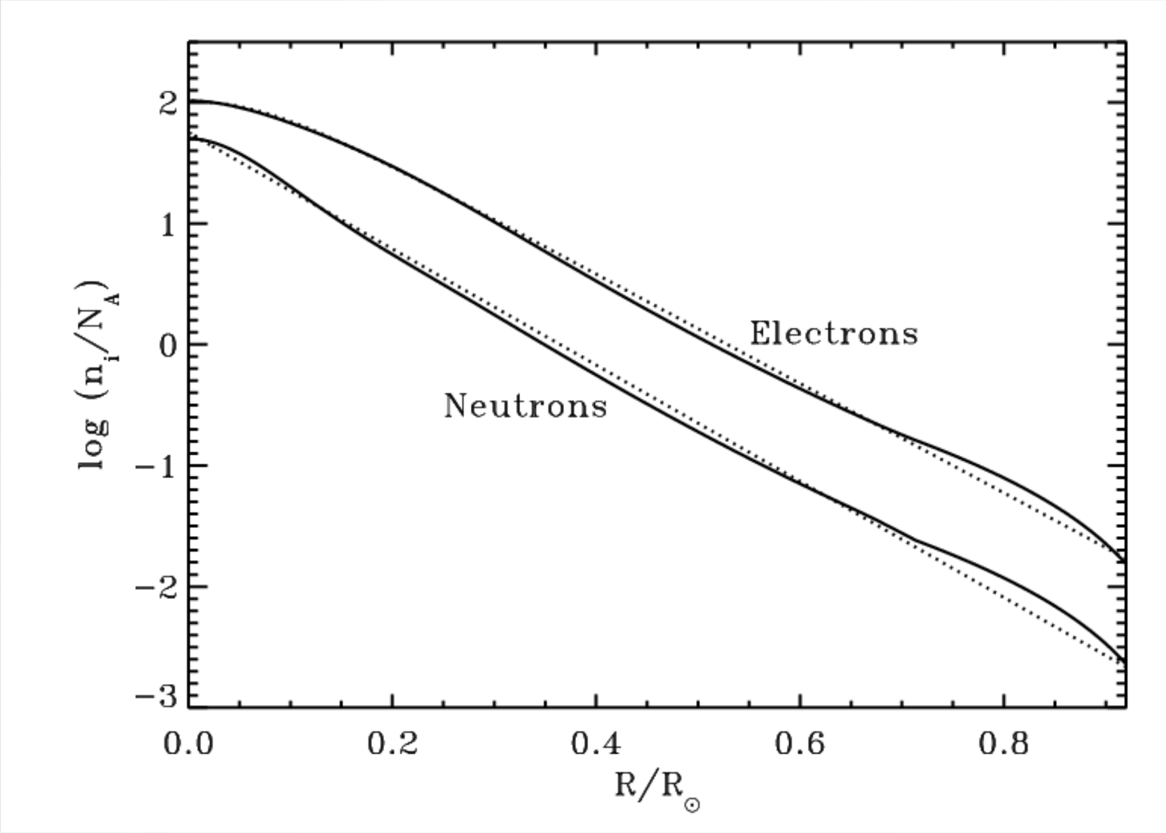
$$H_{\text{int}} = \frac{G_F}{\sqrt{2}} \bar{\nu}_e \gamma^\mu (1-\gamma_5) \nu_e \int d^3 p_e \, \mathrm{f(E_e,T)} \, \bar{e} \gamma^\mu (1-\gamma_5) e \Rightarrow \sqrt{2} G_F N_e$$

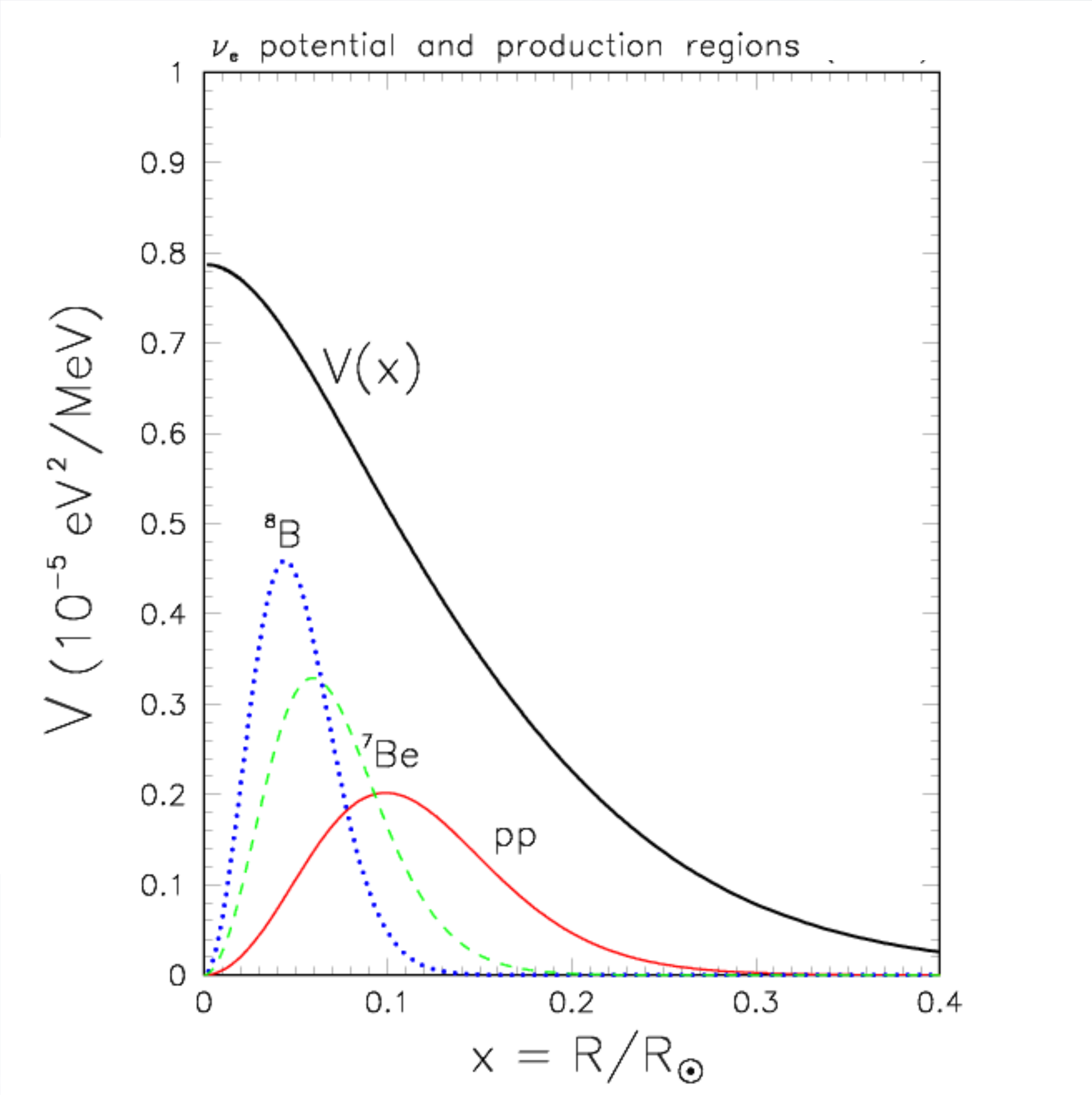
$$\mathrm{l}_{\text{matt}} = \frac{2\pi}{\sqrt{2} G_F N_e}$$

$$< e\gamma^0 e >= N_e$$
$$< e\gamma^i e >= N_e \mathrm{v_i}$$

Standard Solar Model

Solar neutrinos and matter effects





$$V(x) = \sqrt{2} G_F n_e(x)$$

Neutrino fluxes are created in different matter potentials

SOLAR NEUTRINO PROBLEM

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- Lincoln Wolfenstein(1978) Matter effects in neutrino propagation
- Stanislav Mikheiev, Alexei Smirnov (1985) Resonant conversion-MSW effect

$$i\frac{d}{dt}\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{2E}\cos 2\theta + V_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & 0 \end{pmatrix}\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix}$$

Rewrite with:

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

for arbitrary mixing angle, mixing in matter can be large MSW resonance!

Difference of the eigenvalues

$$H_2 - H_1 = \frac{\Delta m^2}{2E}\sqrt{(\cos 2\theta - 2\sqrt{2}G_F n_e E/\Delta m^2)^2 + \sin^2 2\theta}$$

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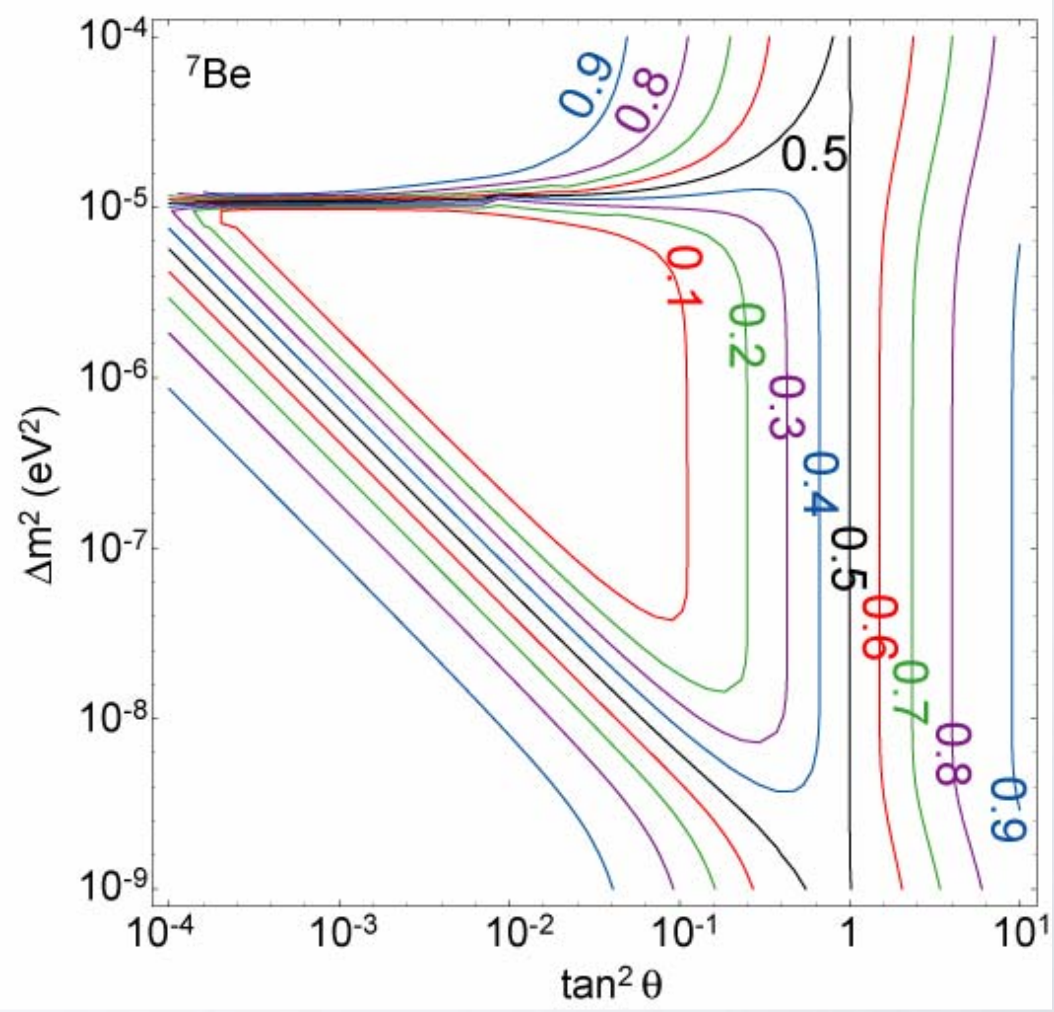
$$\left|\langle \nu_e, \text{Earth} | \nu_e, \text{core} \rangle\right|^2$$
$$= \left[(1-P_c)\cos^2\theta + P_c \sin^2\theta\right]\cos^2\theta_M + \left[P_c\cos^2\theta + (1-P_c)\sin^2\theta\right]\sin^2\theta_M$$
$$-\sqrt{P_c(1-P_c)}\sin 2\theta \cos\left(\frac{\Delta m^2}{2p}L + \delta\right)$$

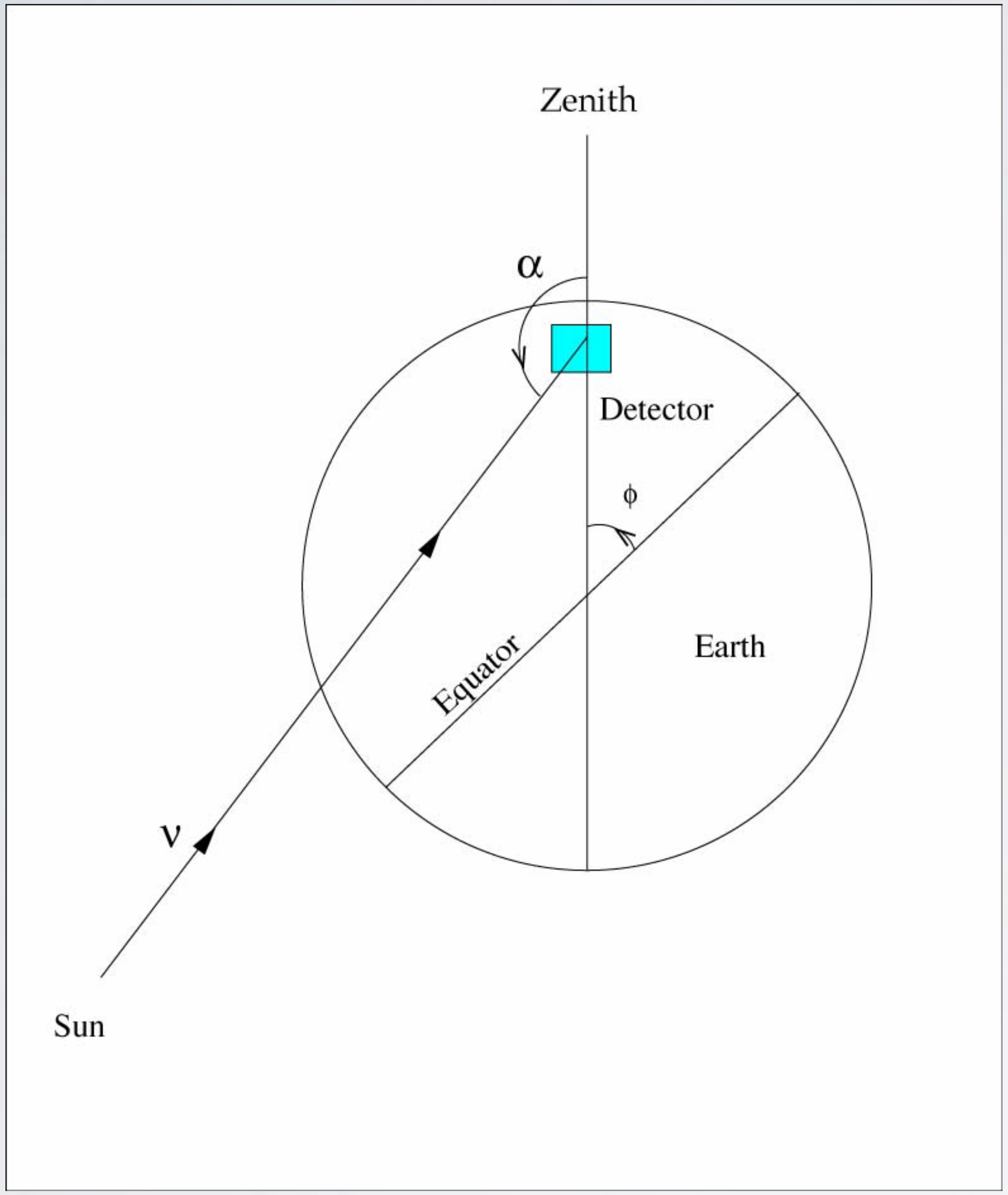
$$P_c = \frac{e^{-\gamma \sin^2\theta} - e^{-\gamma}}{1-e^{-\gamma}}$$

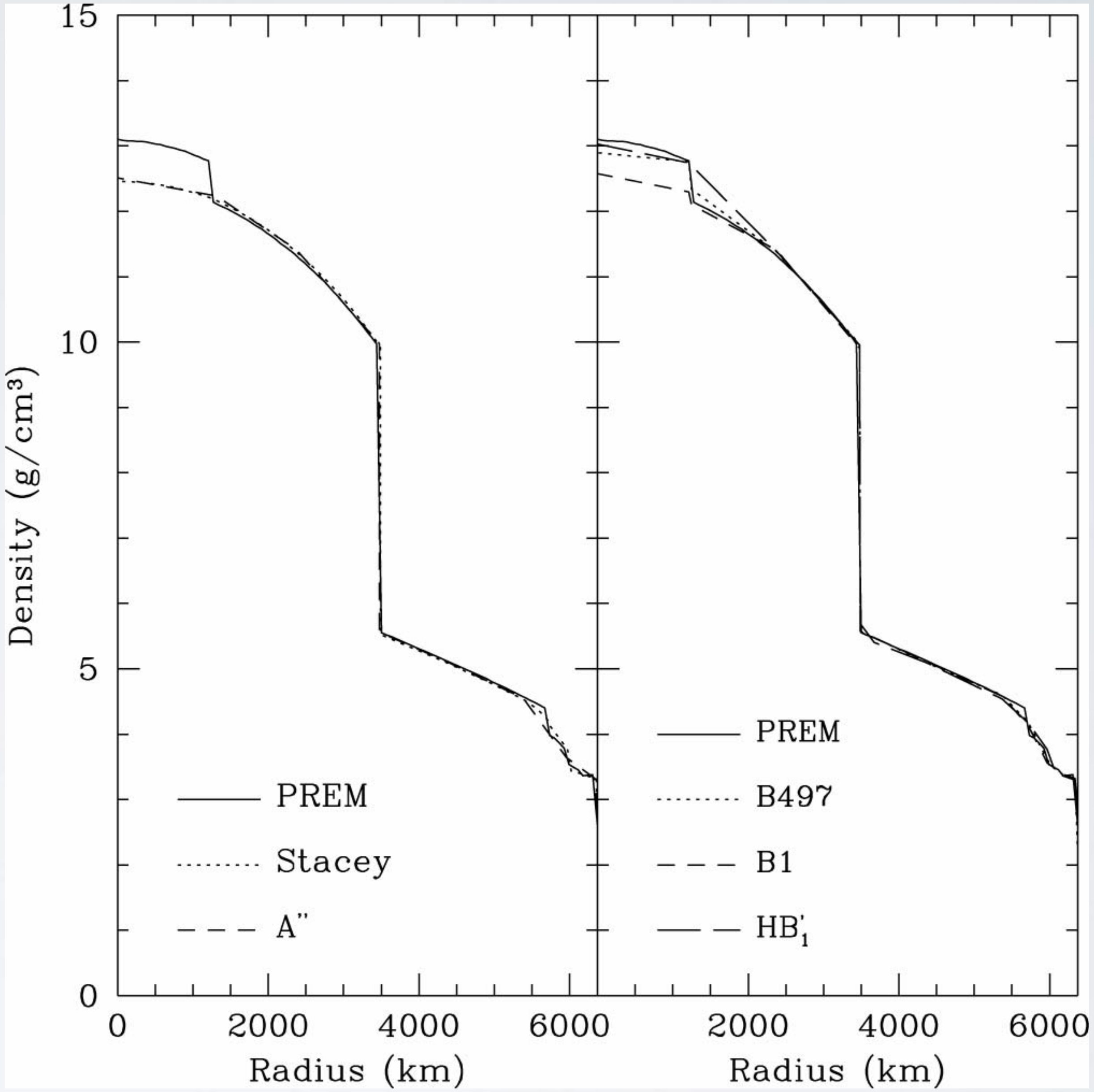
$$\gamma = 2\pi r_0 \frac{\Delta m^2}{2p} = 1.05 \frac{\Delta m^2}{10^{-9}\,\text{eV}^2}\frac{\text{MeV}}{p}$$



Family of solutions with large or small angles, with larger or smaller mass squared spplitings

INCLUDE EARTH MATTER EFFECTS AT NIGHT!





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

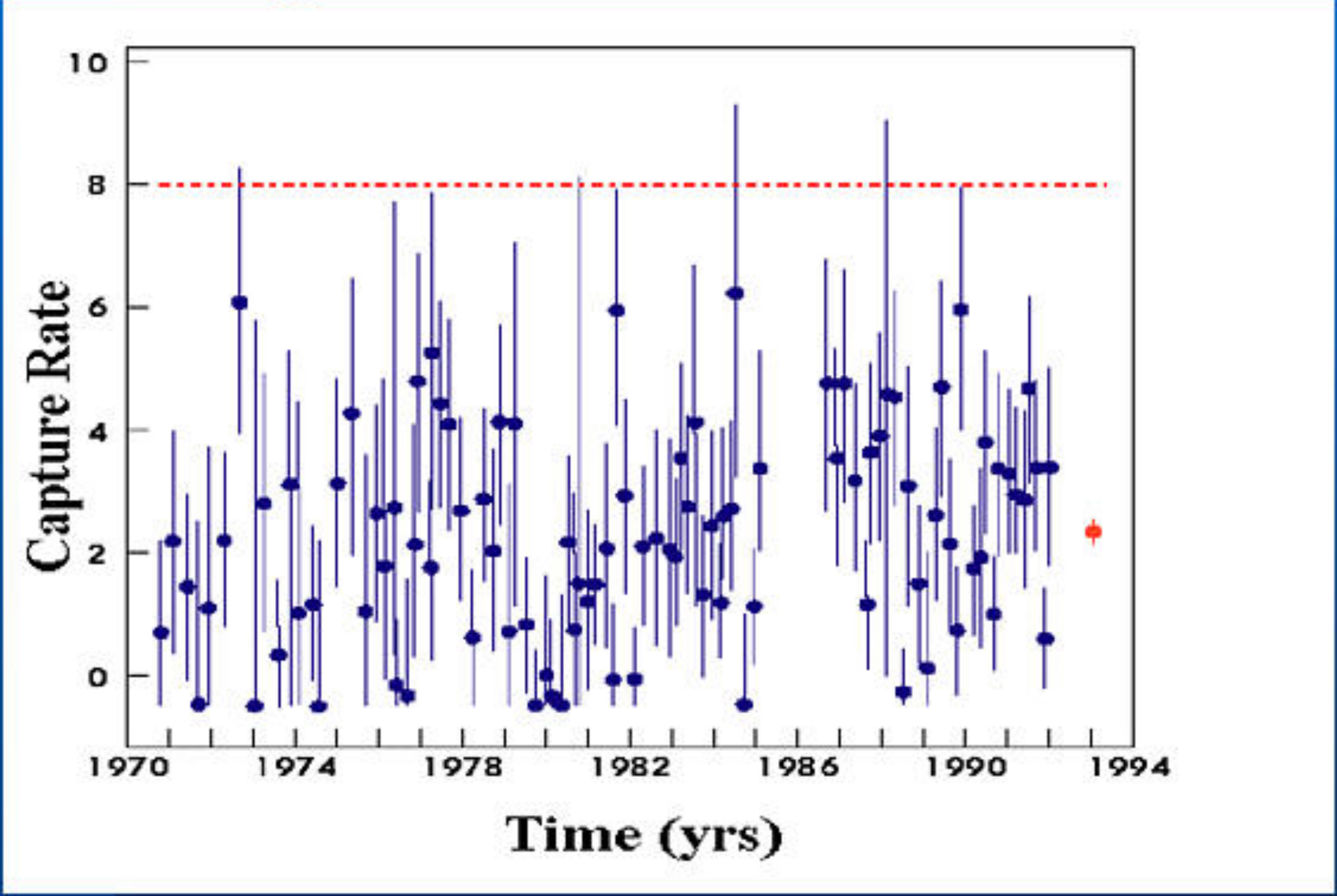
$$freg = \frac{1}{\eta} \cdot \sin^2 2\theta_m \cdot \sin^2\left(\frac{\pi d}{l_m}\right)$$

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

The Sun is brighter at night in neutrinos !

Homestake

$$N_{cc} = 2.56 \pm 0.23 \ \text{SNU}$$



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- Stanislav Mikheiev, Alexei Smirnov (1985) Resonant conversion-MSW effect
- Masatoshi Koshiba, Kamiokande experiment (since 1986): Fewer neutrinos
- 1989 "Neutrino Astrophysics" book by John Bahcall
- Since 1990s: Helioseismology and new neutrino experiments

GALLEX/GNO - SAGE

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

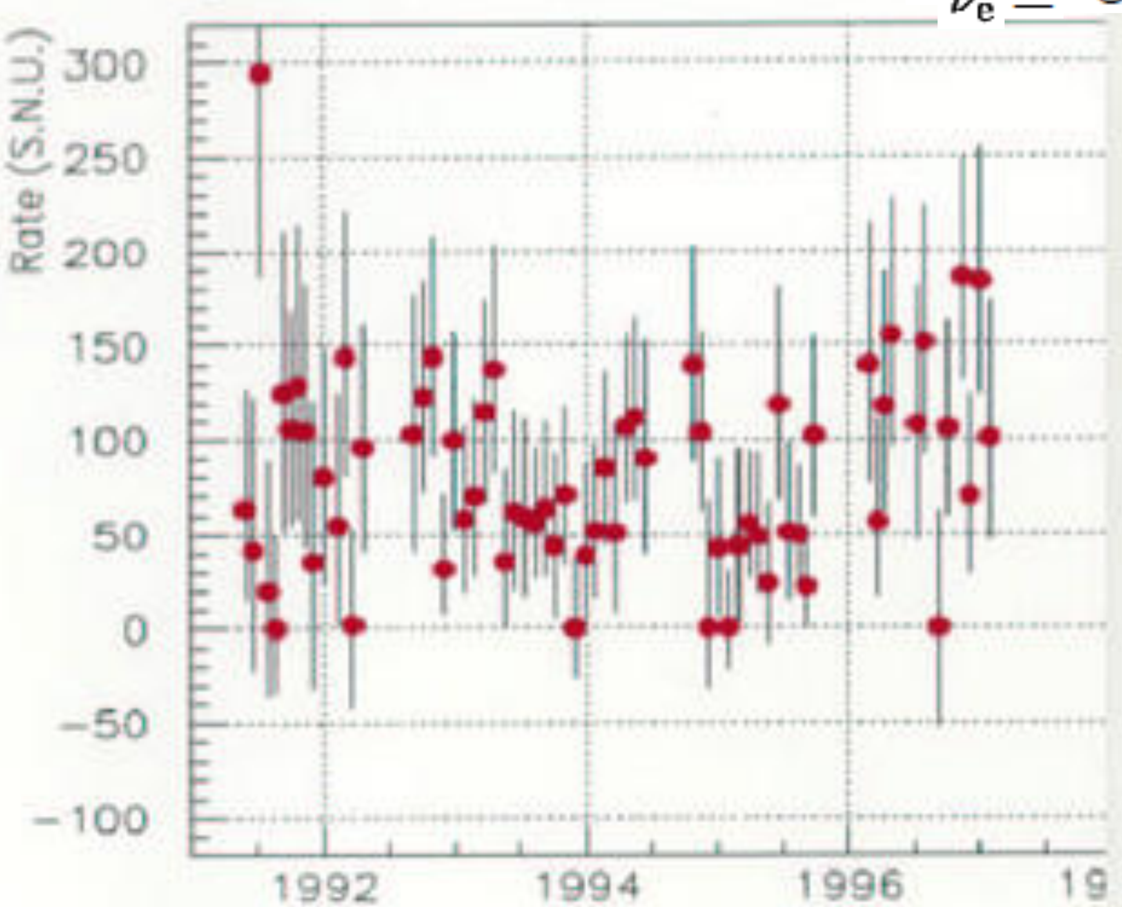
$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$

$E_{\nu_e} \geq 233.2$ keV

Neutrino 2002

Energy–RT analysis

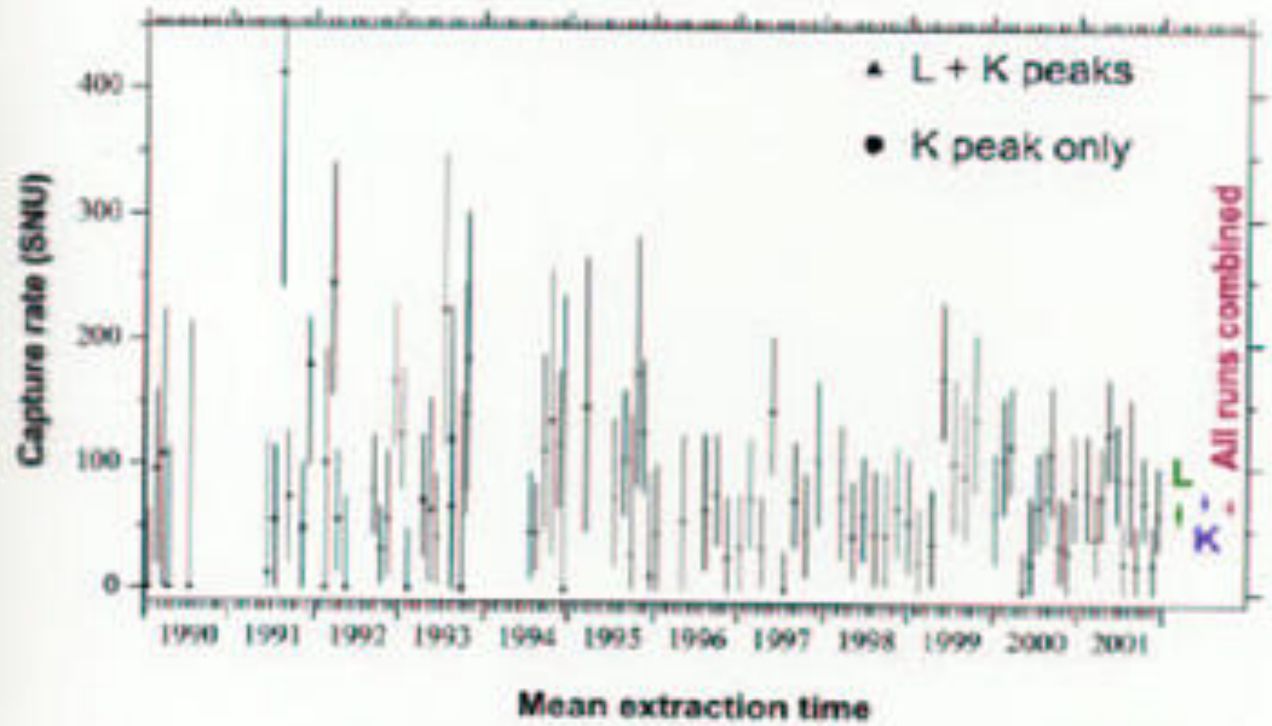
GALLEX



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

SAGE

January 1990 - December 2001



Combined result:

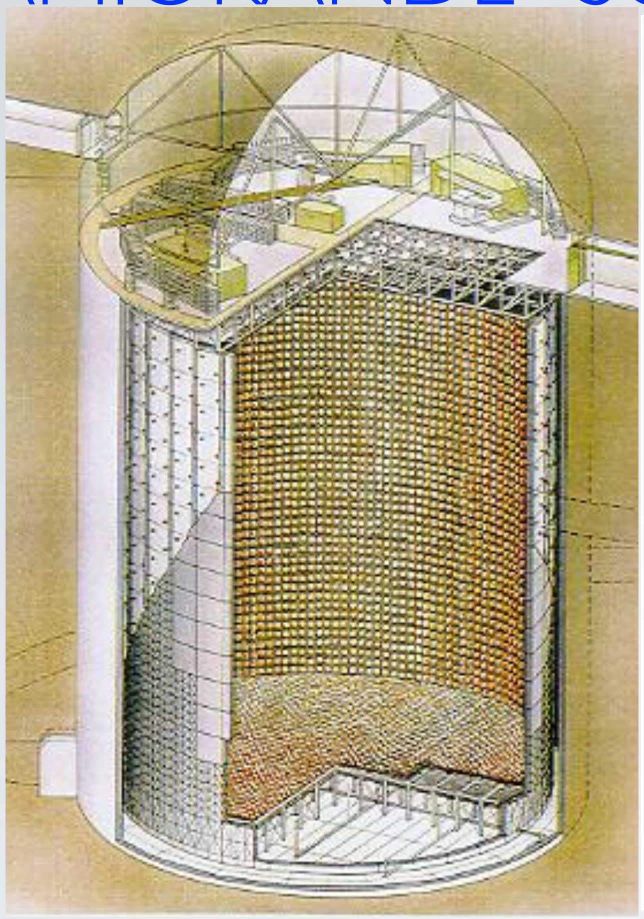
L-peak - 64.8 +8.5/-8.2 SNU

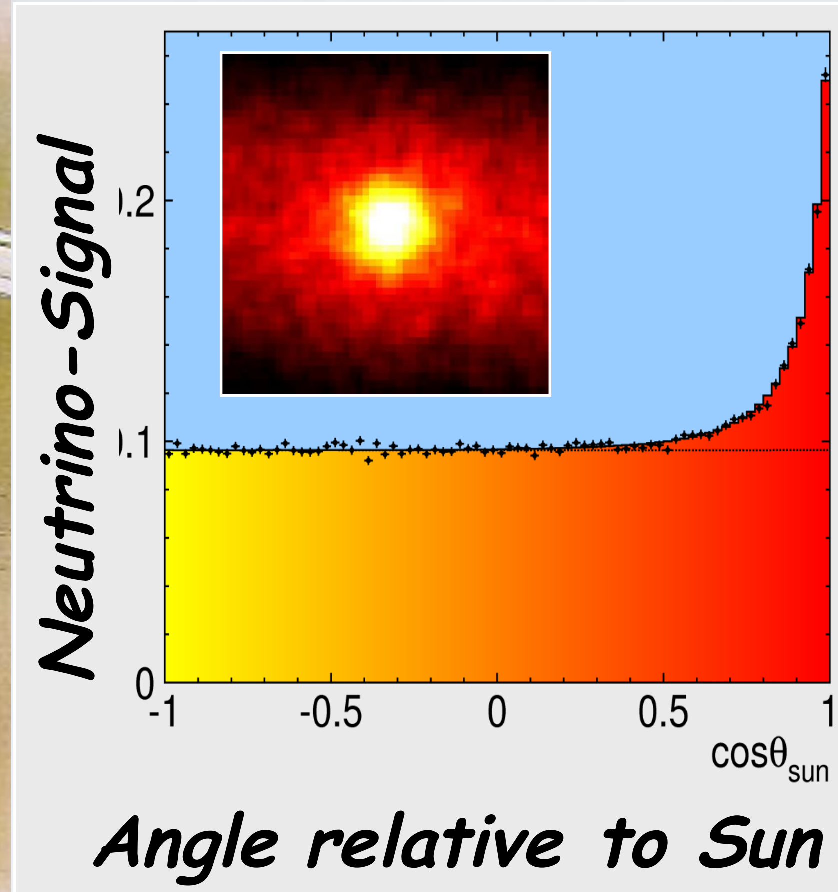
K-peak - 74.4 +6.8/-6.6 SNU

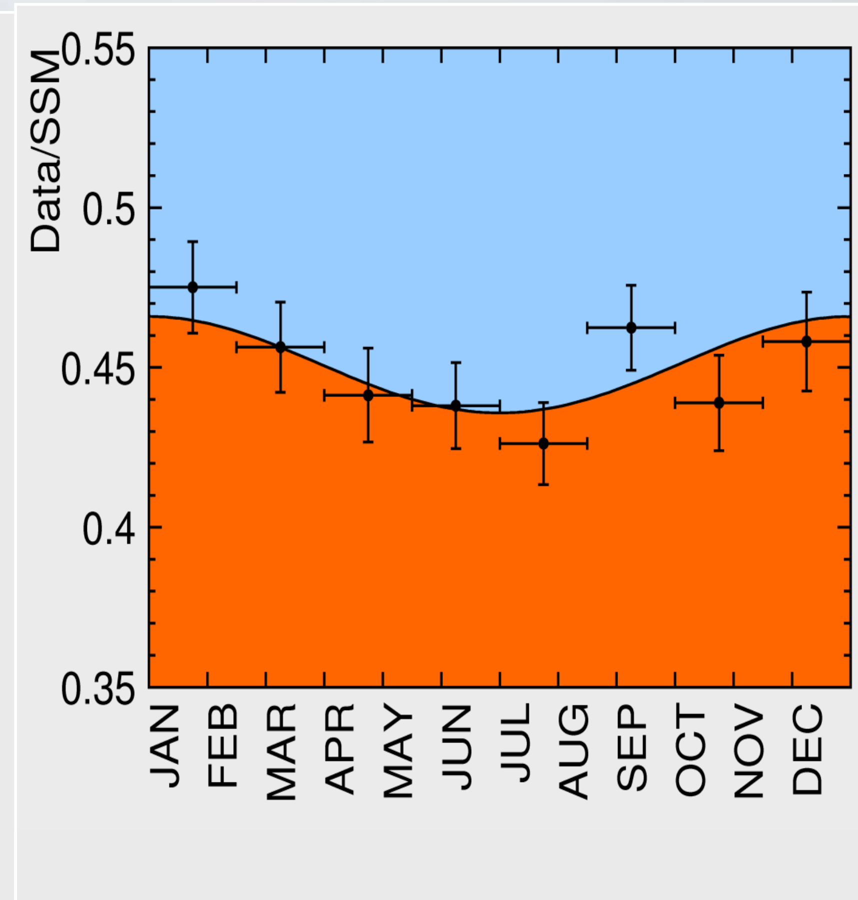
Overall - 70.8 +5.3/-5.2 SNU

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

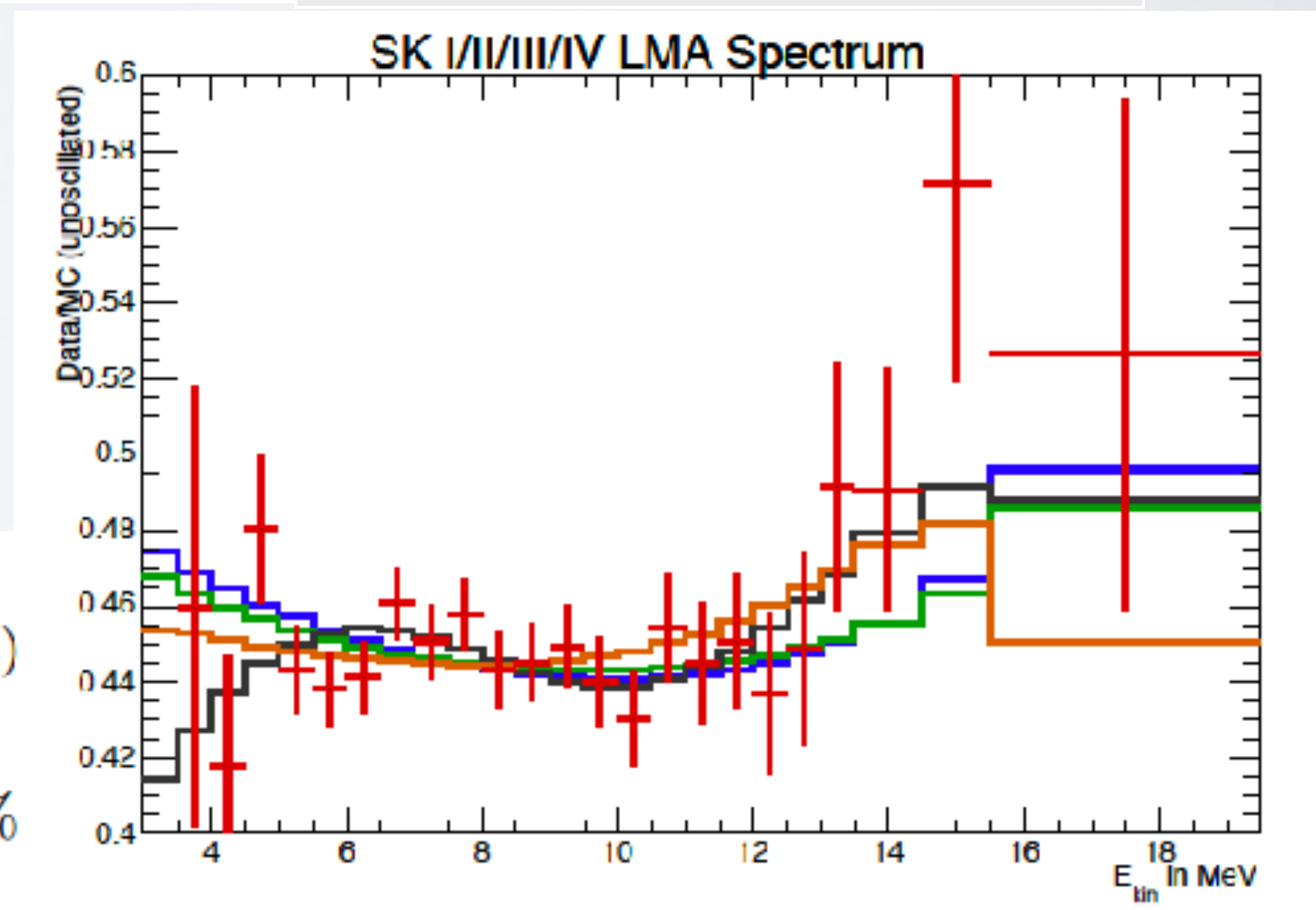
KAMIOKANDE- SUPERKAMIOKANDE







Elastic scattering on electrons (in water)
Cherenkov electrons keep information on the energy and direction
Neutrinos come from the Sun!
Deficit persists!
Hint to Earth regeneration.

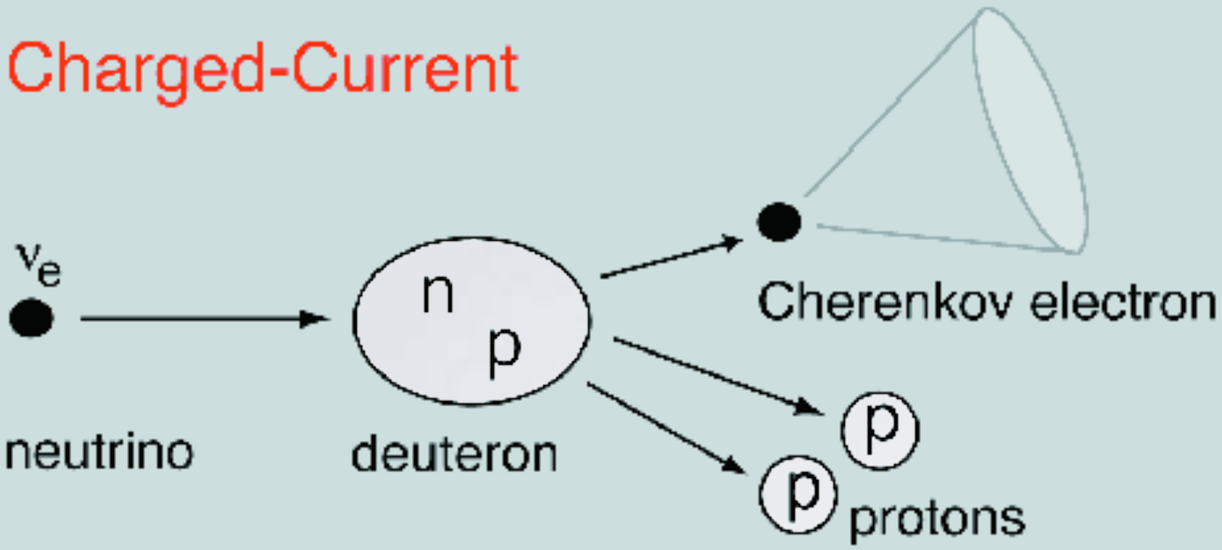


$$\Phi_{^8B}(SK) = (2.345 \pm 0.014(\text{stat.}) \pm 0.036(\text{syst.})) \times 10^6/(\text{cm}^2\text{sec})$$

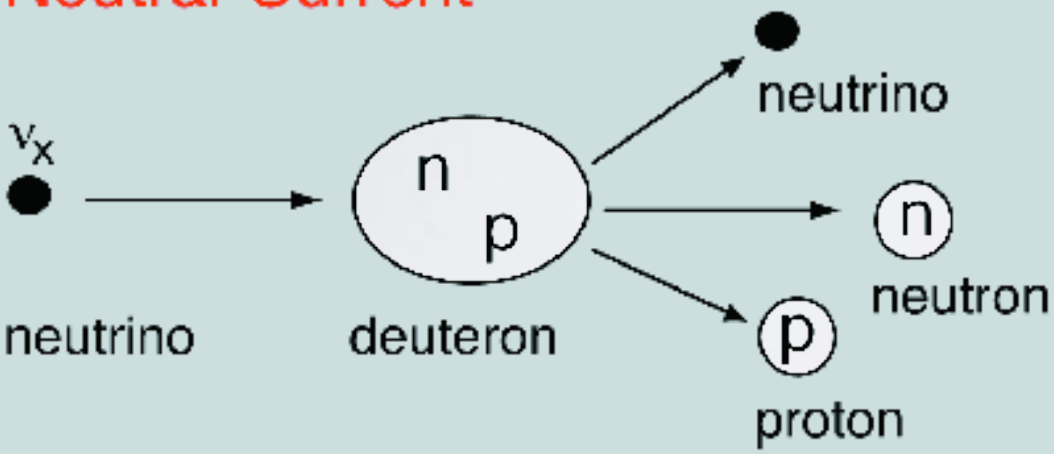
$$A_{DN}^{\text{fit, SK}} = (-3.3 \pm 1.0(\text{stat.}) \pm 0.5(\text{syst.}))\%$$

SNO: FLAVOR CONVERSION!

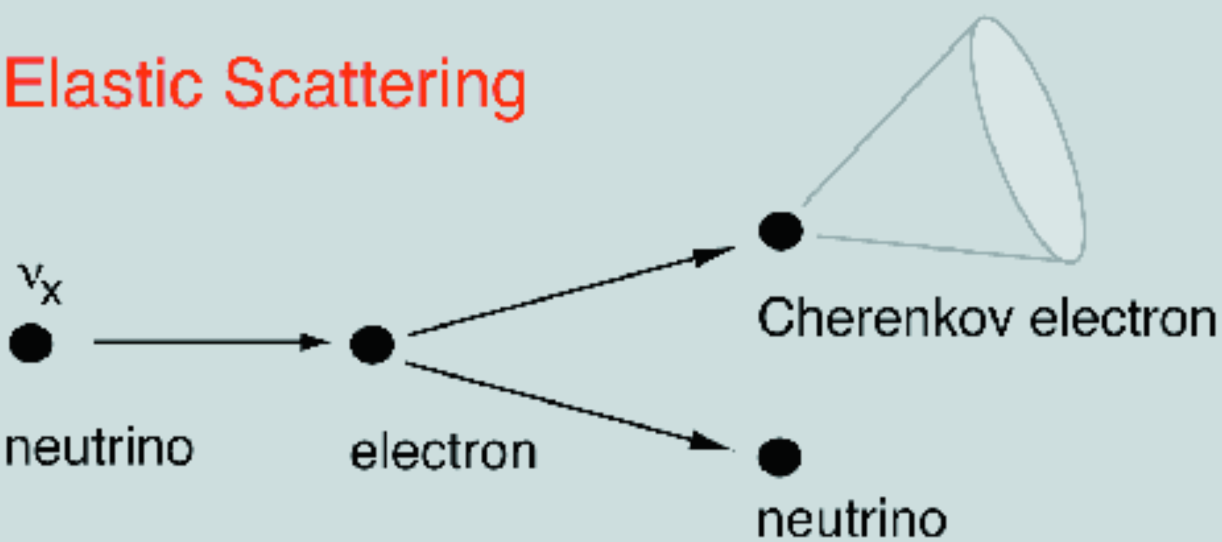
Charged-Current

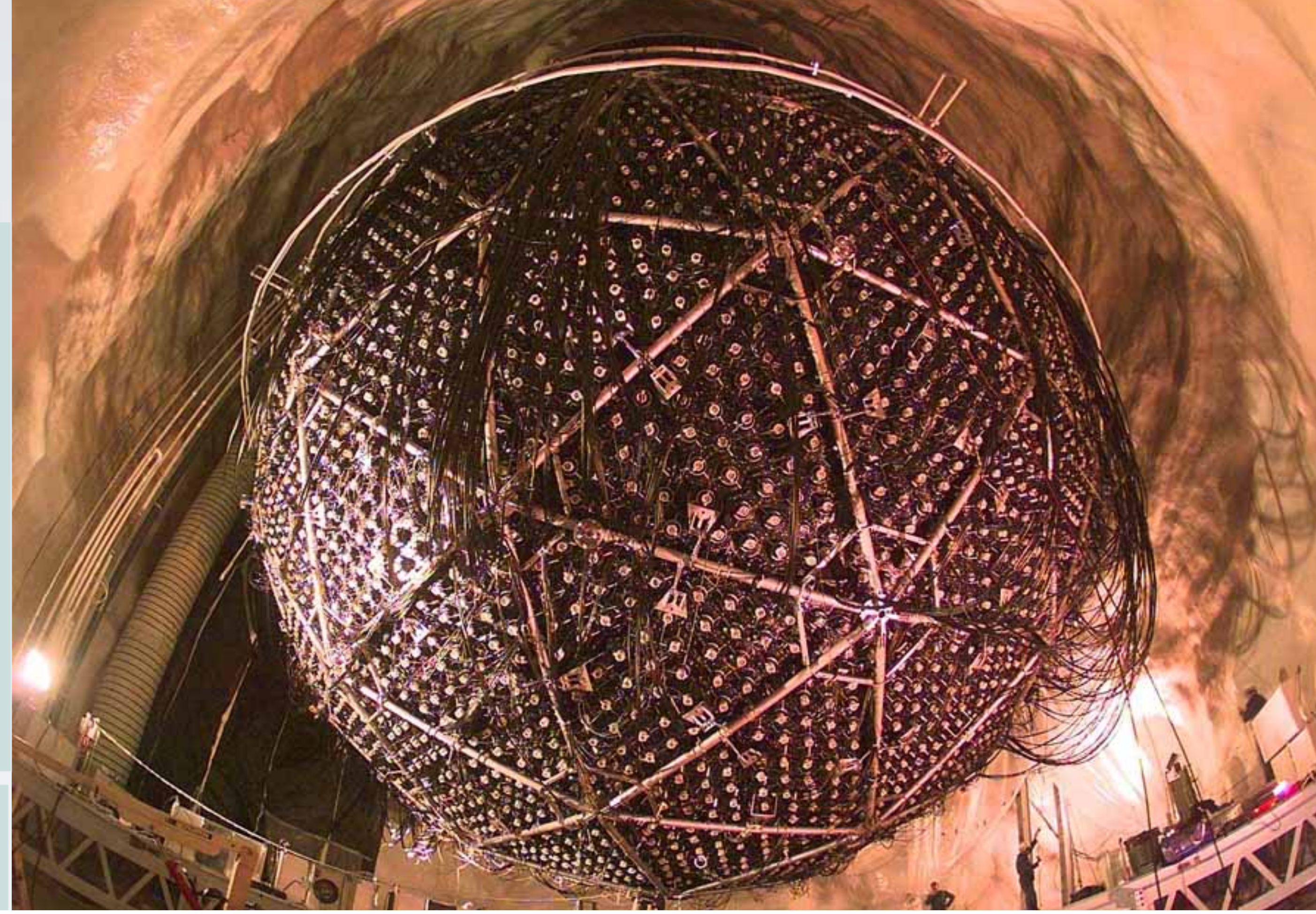


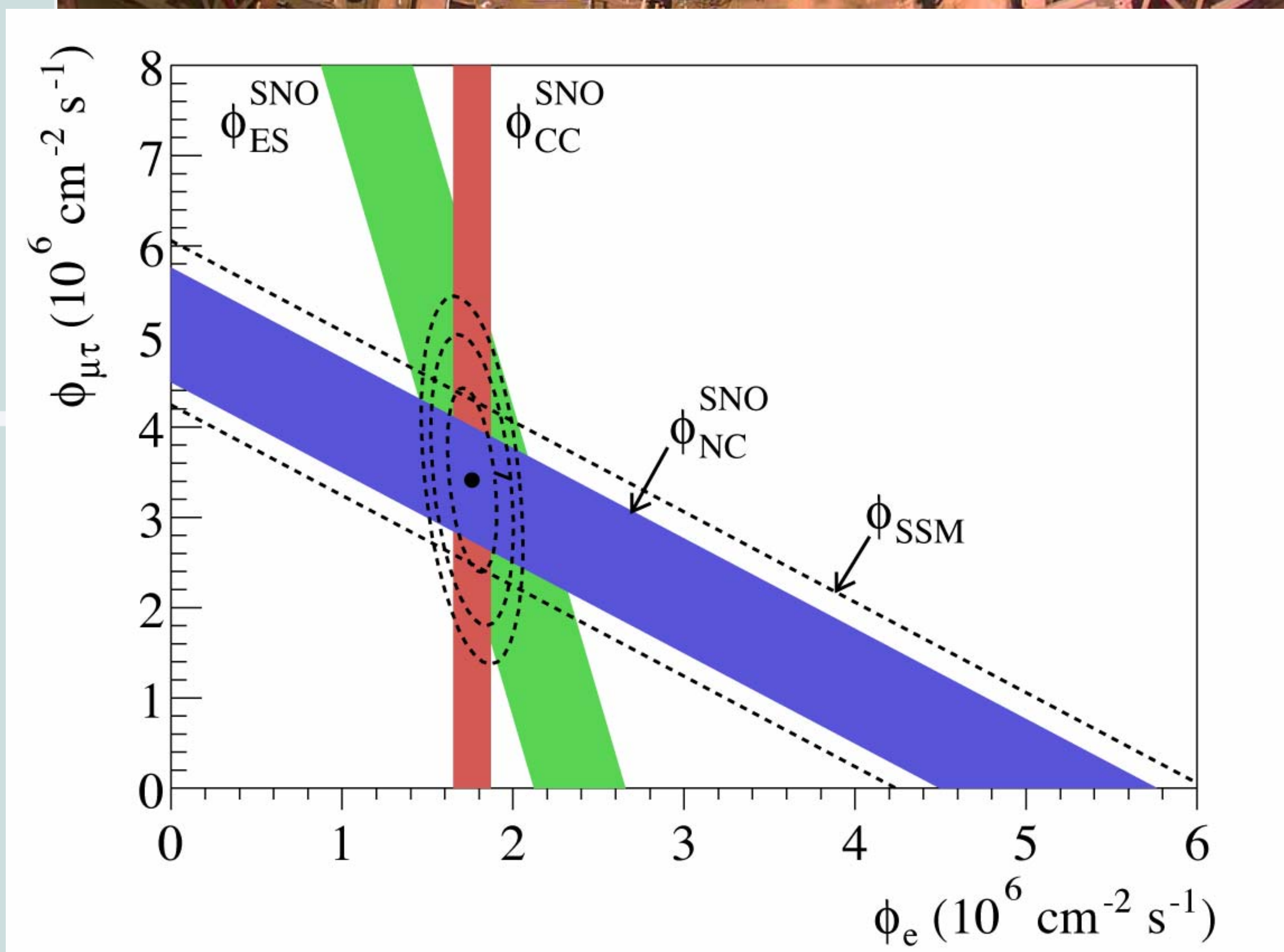
Neutral-Current



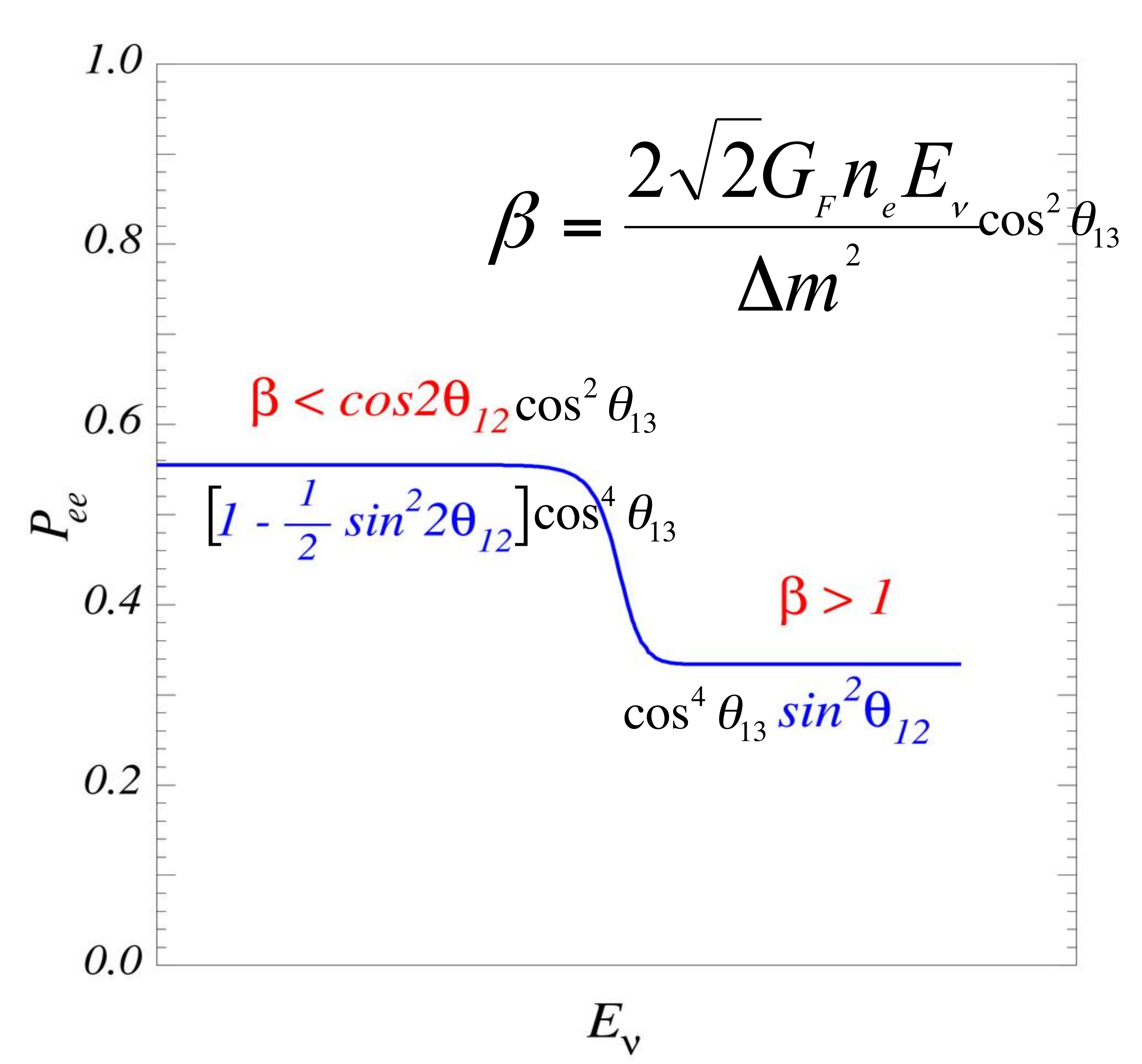
Elastic Scattering







LMA : Vacuum to adiabatic transition



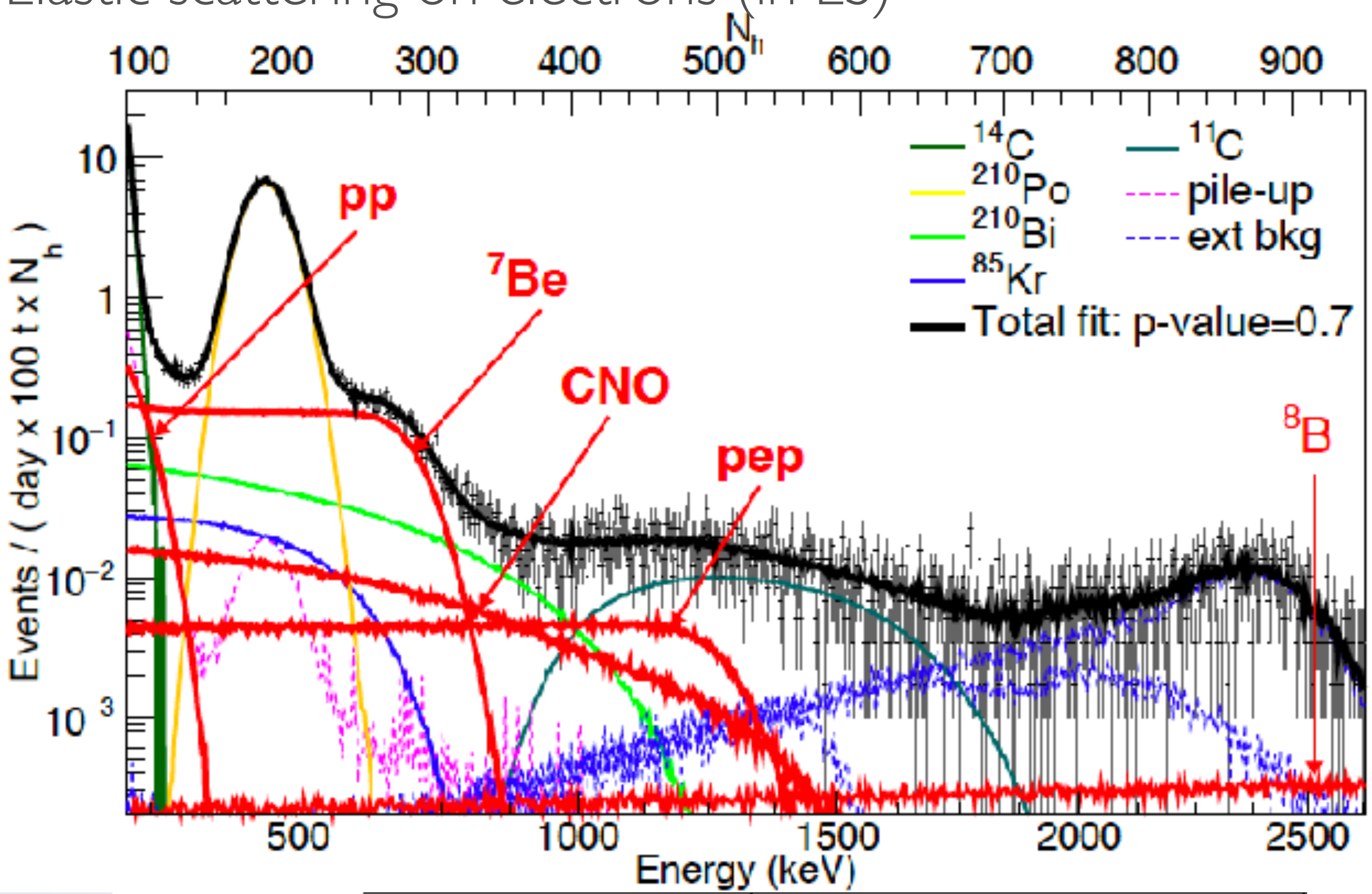
$E_{crit}\,(^8\mathrm{B}) = 1.8\ \mathrm{MeV}$

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

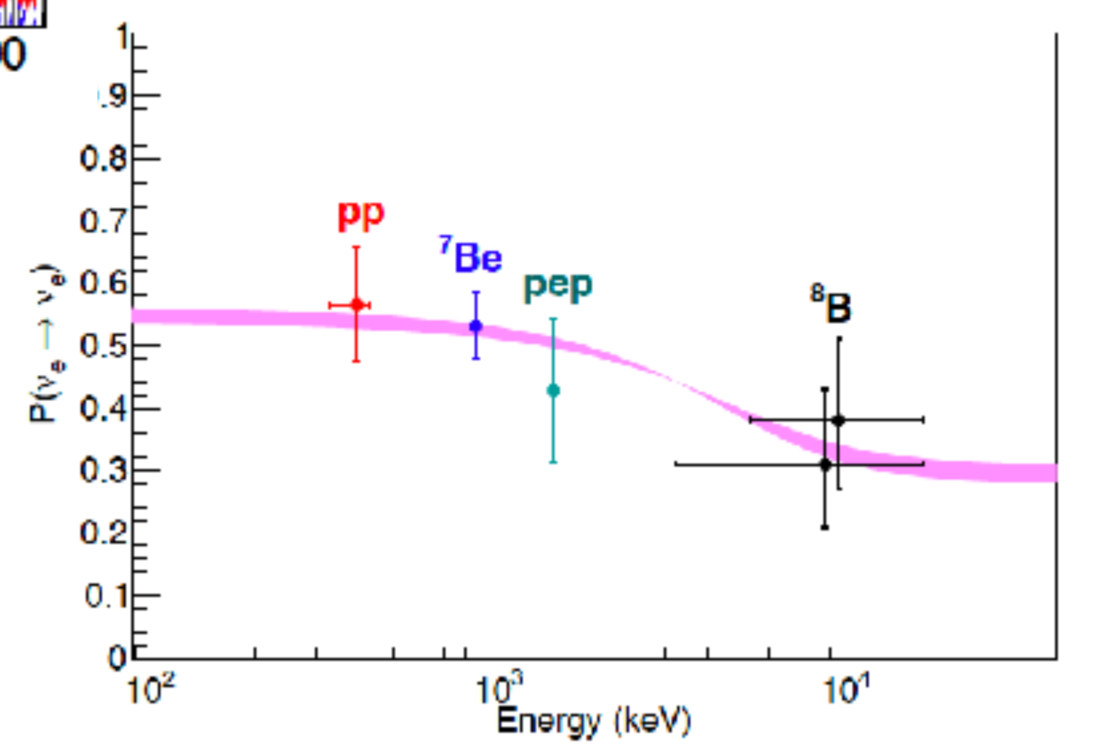
$E_{crit}\,(\mathrm{pp}) = 3.3\ \mathrm{MeV}$

BOREXINO: NEUTRINO SPECTROSCOPY

Elastic scattering on electrons (in LS)



Solar ν	Rate [cpd/100 t]	Flux $[cm^{-2}s^{-1}]$
pp	$134 \pm 10 ^{+6}_{-10}$	$(6.1 \pm 0.5 ^{+0.3}_{-0.5}) \times 10^{10}$
^{7}Be	$48.3 \pm 1.1 ^{+0.4}_{-0.7}$	$(4.99 \pm 0.11 ^{+0.06}_{-0.08}) \times 10^9$
pep (HZ)	$2.43 \pm 0.36 ^{+0.15}_{-0.22}$	$(1.27 \pm 0.19 ^{+0.08}_{-0.12}) \times 10^8$
pep (LZ)	$2.65 \pm 0.36 ^{+0.15}_{-0.24}$	$(1.39 \pm 0.19 ^{+0.08}_{-0.13}) \times 10^8$
CNO	< 8.1 (95% C.L.)	$< 7.9 \times 10^8$ (95% C.L.)



SUMMARY: NEUTRINO PARAMETERS INVOLVED

Mostly from Solar Data

$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$
$\theta_{12}/^\circ$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$

Mostly from KamLAND

$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$

Mostly from Data Bay (with other reactor and accelerador data)

$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.01934 \to 0.02392$
$\theta_{13}/^\circ$	$8.46^{+0.15}_{0.15}$	$7.99 \to 8.90$

COHERENCE OF WAVE PACKETS: COMPARE SCALES

$$\int^{L_{coh}} dx \Delta v_m = \delta_\nu \qquad L_{coh} = \delta_\nu \frac{2E^2}{\Delta m^2}$$

^{8}B neutrinos:

$$L_{coh} \sim (4-8) R_\odot \left(\frac{E}{10\mathrm{MeV}}\right)^2$$

^{7}Be neutrinos:

$$L_{coh}(Be) \sim 0.01 R_\odot$$

pp neutrinos:

$$L_{coh}(pp) \sim 0.002 R_\odot \left(\frac{E}{0.4\mathrm{MeV}}\right)^2$$

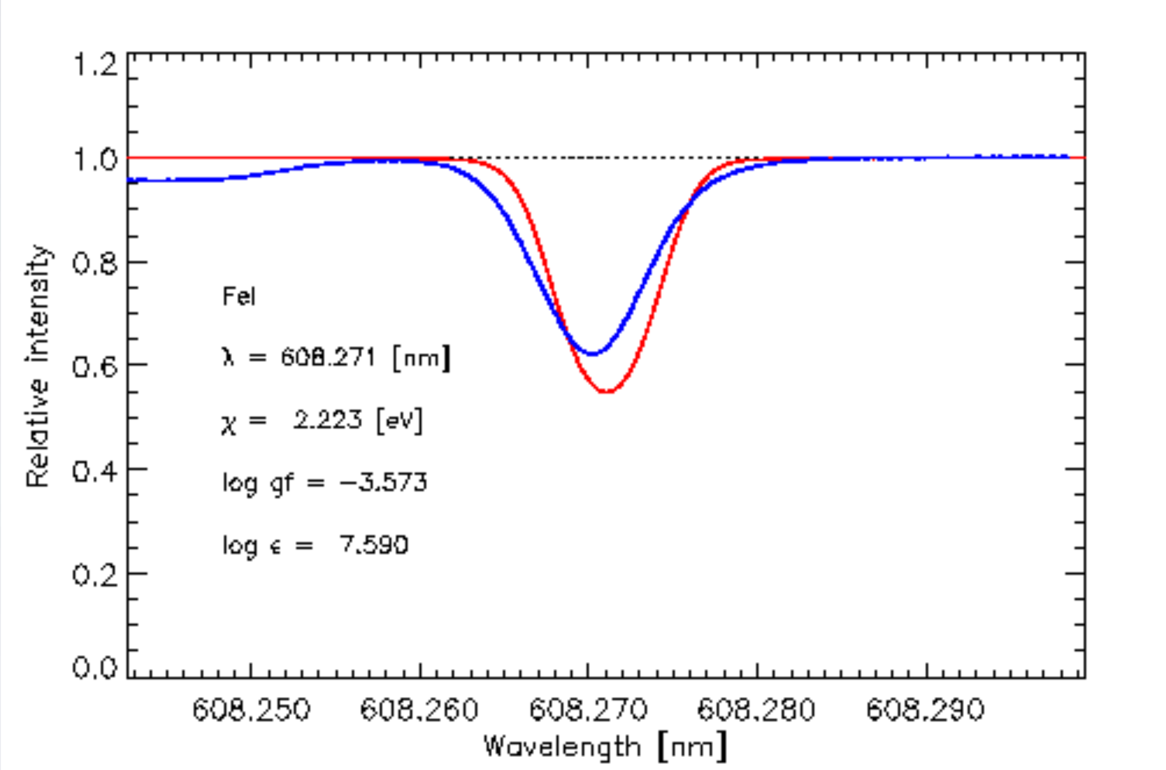
Compare with oscillation length (10-1000 Km) and refraction length (100 Km):

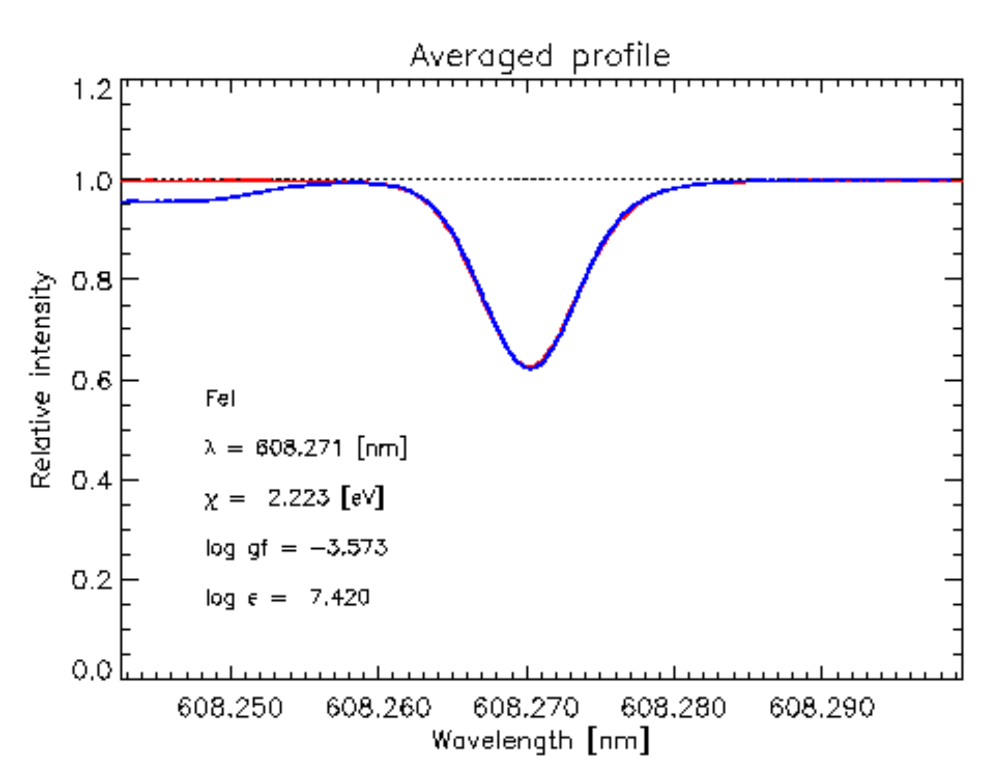
$$L_{osc} = \frac{4\pi\bar{p}}{\Delta m^2} \qquad l_0 \equiv \frac{2\pi}{V_e - V_a} = \frac{\sqrt{2}\pi}{G_F n_e}$$

ROADMAP OF SOLAR NEUTRINOS: SOLAR ABUNDANCES

Metal volatile abundances
1D vs 3D

Which are the right inputs?





Lines	MARCS	Holweger-	3D
[C I]	8.40	8.45	8.39
C I	8.35+/-0.03	8.39+/-0.03	8.36+/-0.03
CH,	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,	8.46+/-0.03	8.53+/-0.03	8.44+/-0.03
CO,	8.55+/-0.02	8.60+/-0.01	8.40+/-0.01
CO,	8.58+/-0.02	8.69+/-0.02	8.37+/-0.01

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

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

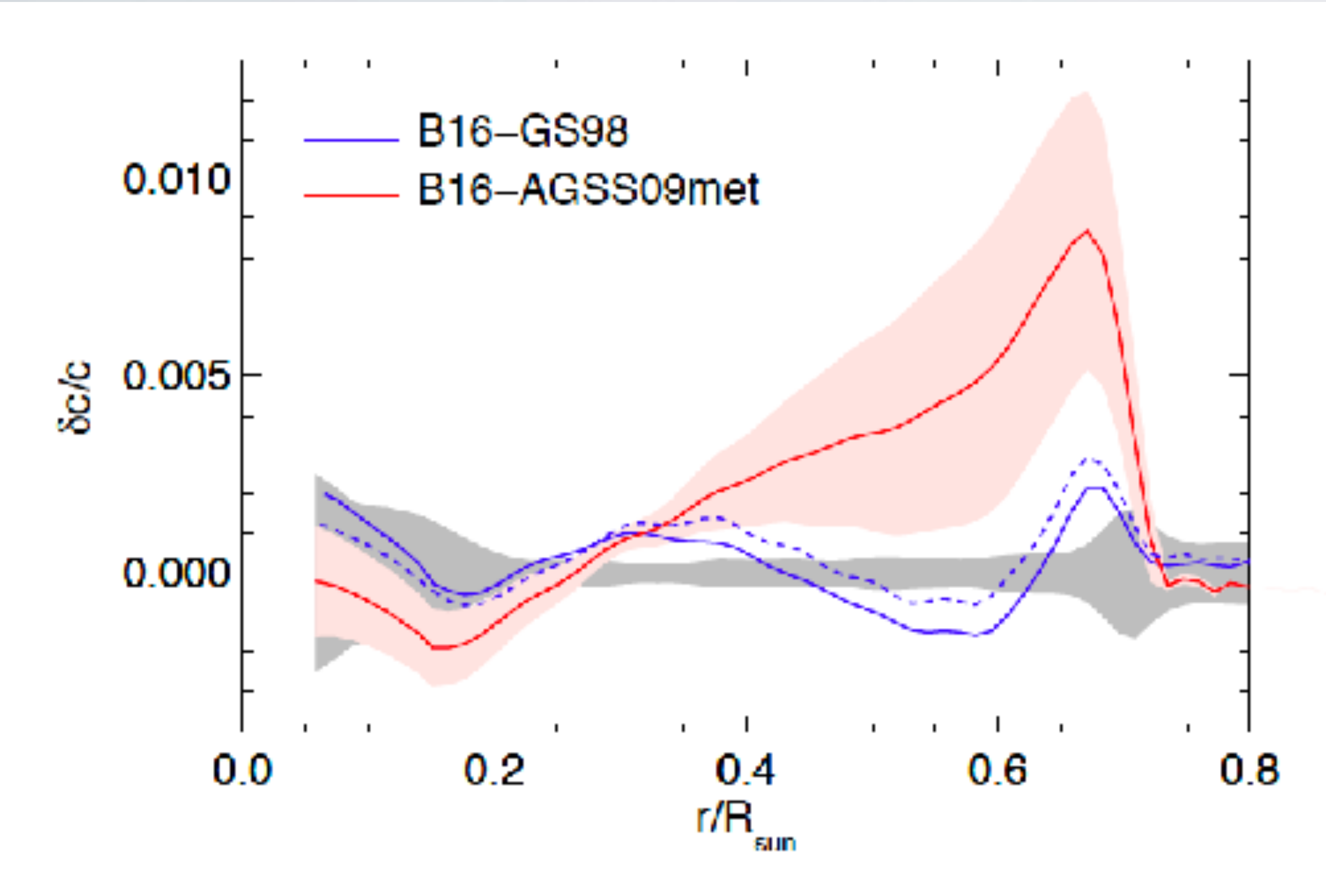
Neutrino fluxes

CNO fluxes depend ~ linearly; affects pp and pep indirectly

lower opacity → lower T in core

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

Standard Solar Model
Helioseismology



Solar Abundances Problem

Best determinations of solar abundances lead so a wrong beating solar model

	B16-GS98	B16-AGSS09met	Solar
Y_S	0.2426 ± 0.0059	0.2317 ± 0.0059	0.2485 ± 0.0035
$R_{CZ}/R_\odot$	0.7116 ± 0.0048	0.7223 ± 0.0053	0.713 ± 0.001
$\langle \delta c/c \rangle$	$0.0005^{+0.0006}_{-0.0002}$	0.0021 ± 0.001	0^a
α_{MLT}	2.18 ± 0.05	2.11 ± 0.05	-
Y_{ini}	0.2718 ± 0.0056	0.2613 ± 0.0055	-
Z_{ini}	0.0187 ± 0.0013	0.0149 ± 0.0009	-
Z_S	0.0170 ± 0.0012	0.0134 ± 0.0008	-
Y_C	0.6328 ± 0.0053	0.6217 ± 0.0062	-
Z_C	0.0200 ± 0.0014	0.0159 ± 0.0010	-

ROADMAP OF SOLAR NEUTRINOS: CNO NEUTRINOS

hydrogen burning – CNO cycle

CN-cycle

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

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

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

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

$$^{15}O \rightarrow {}^{15}N + e^+ + \nu_e + \gamma \qquad Q=2.75,\ \langle Q_\nu \rangle=0.996$$ ^{13}N neutrinos

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

NO-cycle

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

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

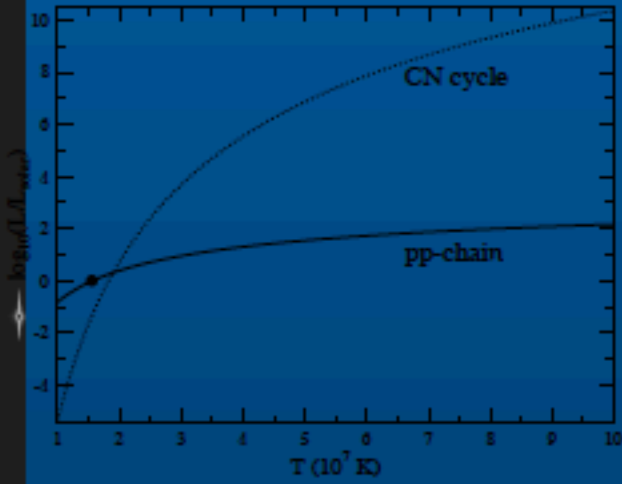
$$^{17}F \rightarrow {}^{17}O + e^+ + \nu_e + \gamma \qquad Q=2.76,\ \langle Q_\nu \rangle=0.999$$ ^{17}F neut.

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

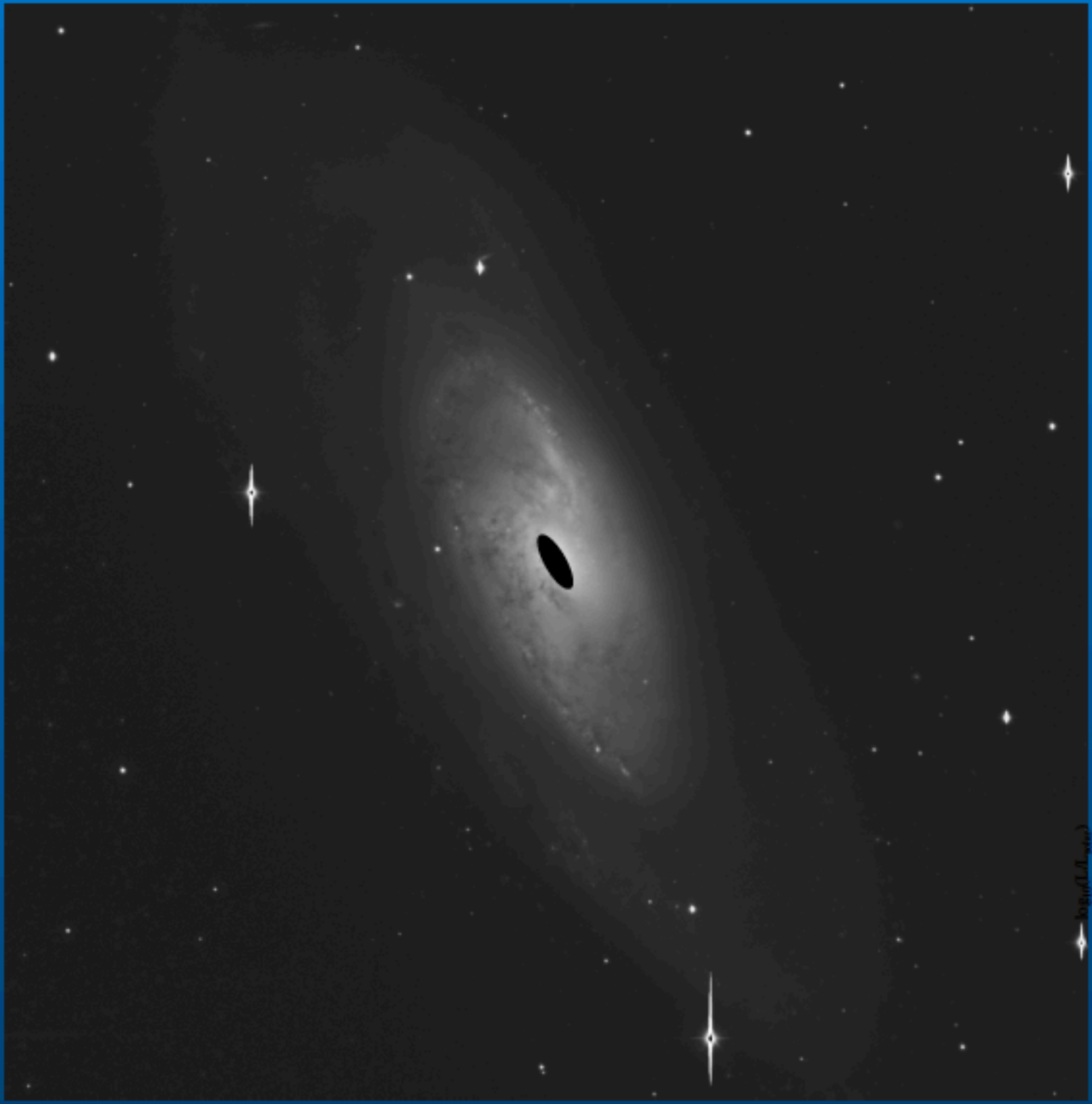
CNO cycle is regulated by ^{14}N+p reation (slowest)

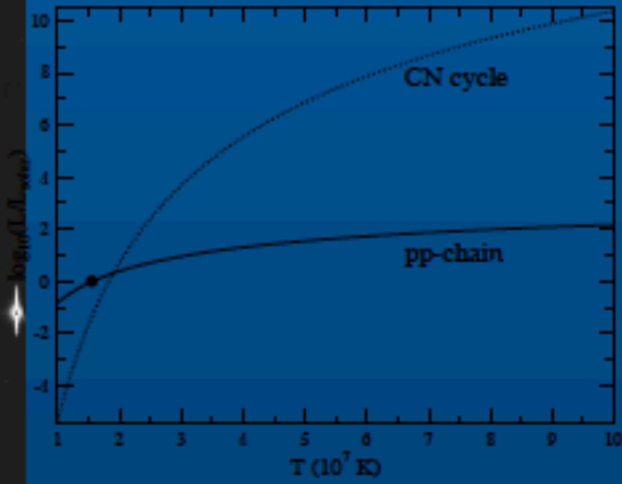
M106 (R filter-Hα)

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

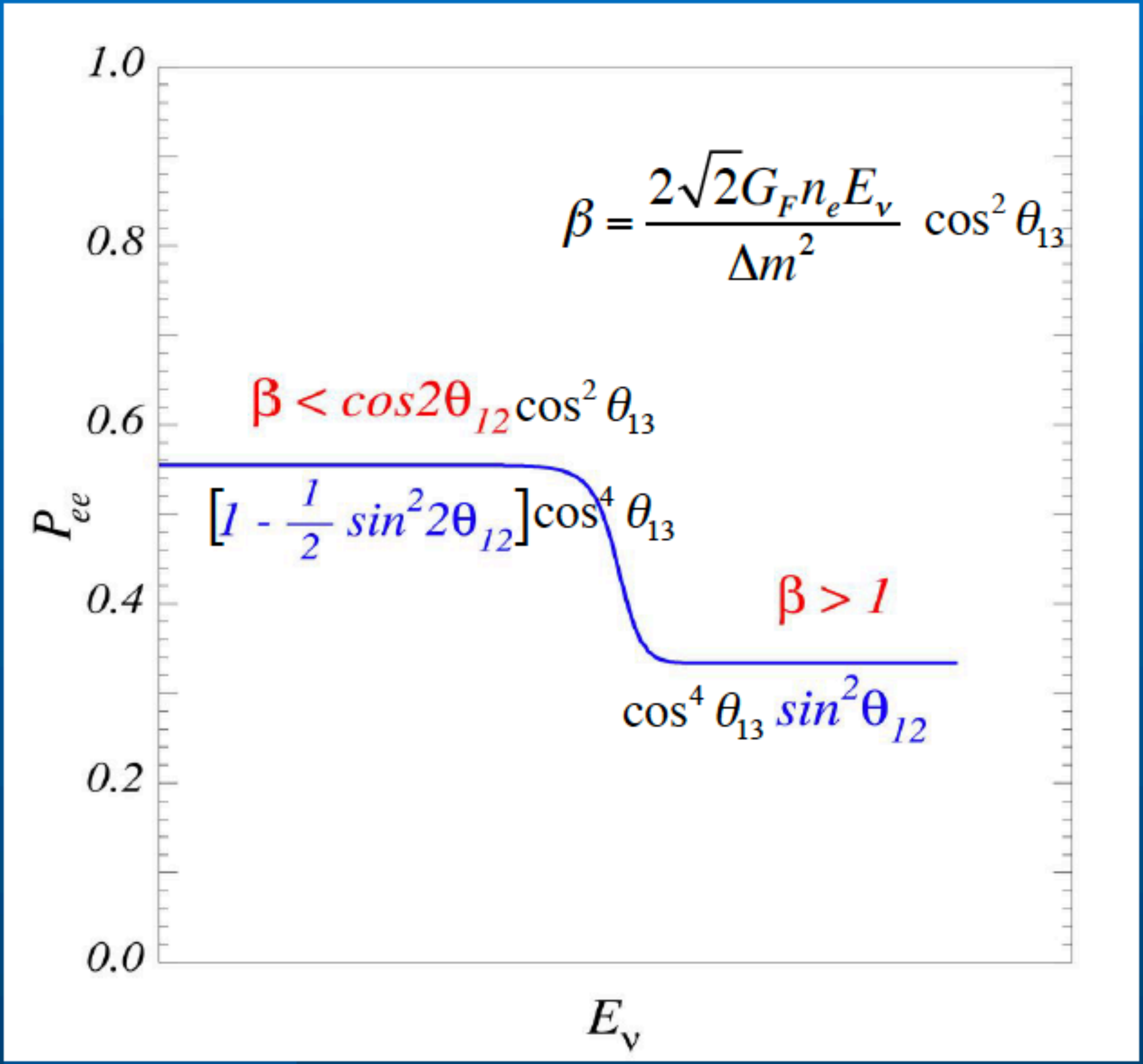


M106 (R filter-Hα): : Luminosity by CNO cycle





LMA : Vacuum to adiabatic transition



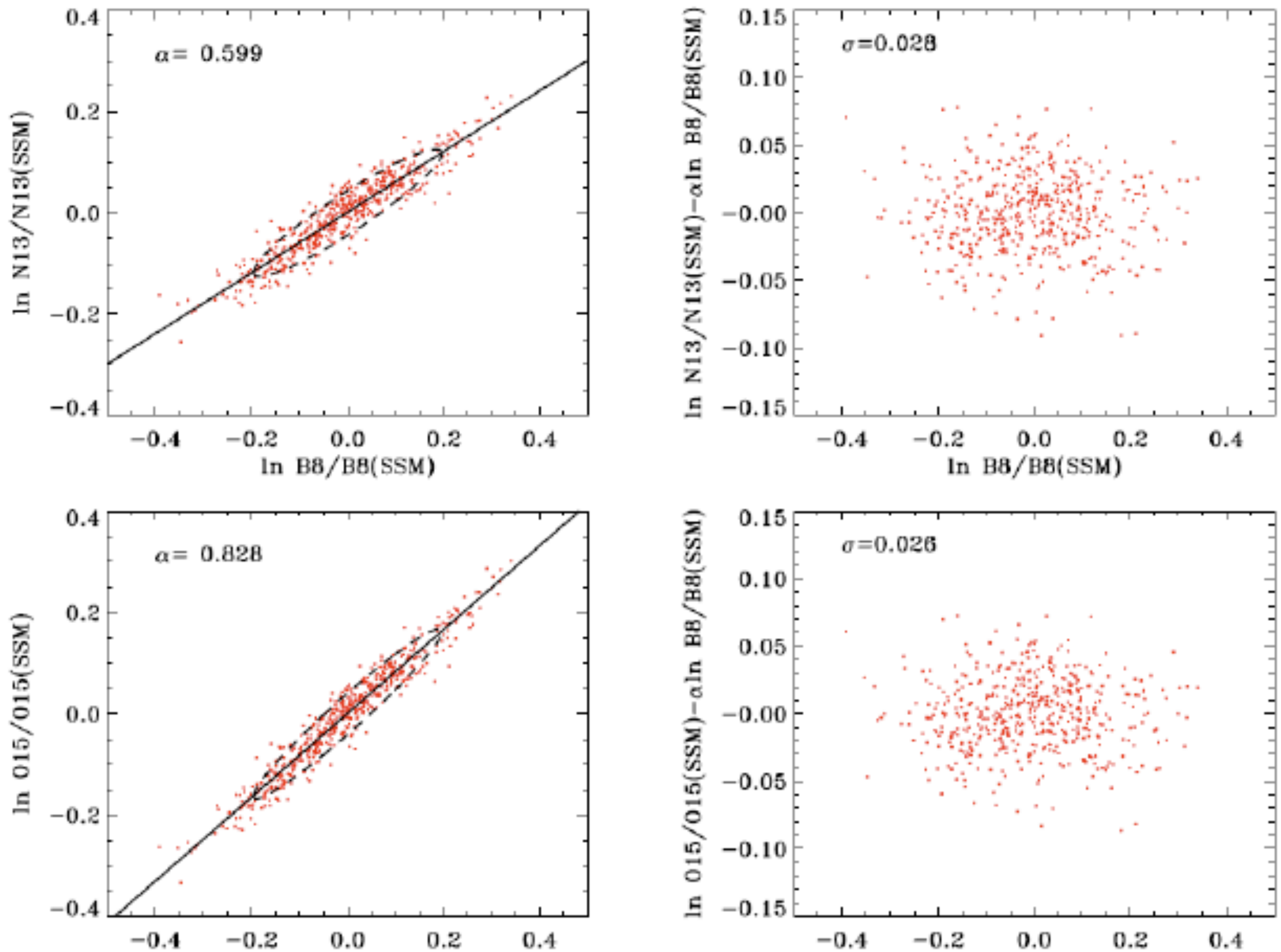
$E_{crit}\ (^8B) = 1.8$ MeV

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

E_{crit} (pep) = 3.2 MeV

E_{crit} (CNO) = 1.9 MeV

How to extract core metallicities



Haxton & Serenelli 08

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

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

Linear dependence with C+N

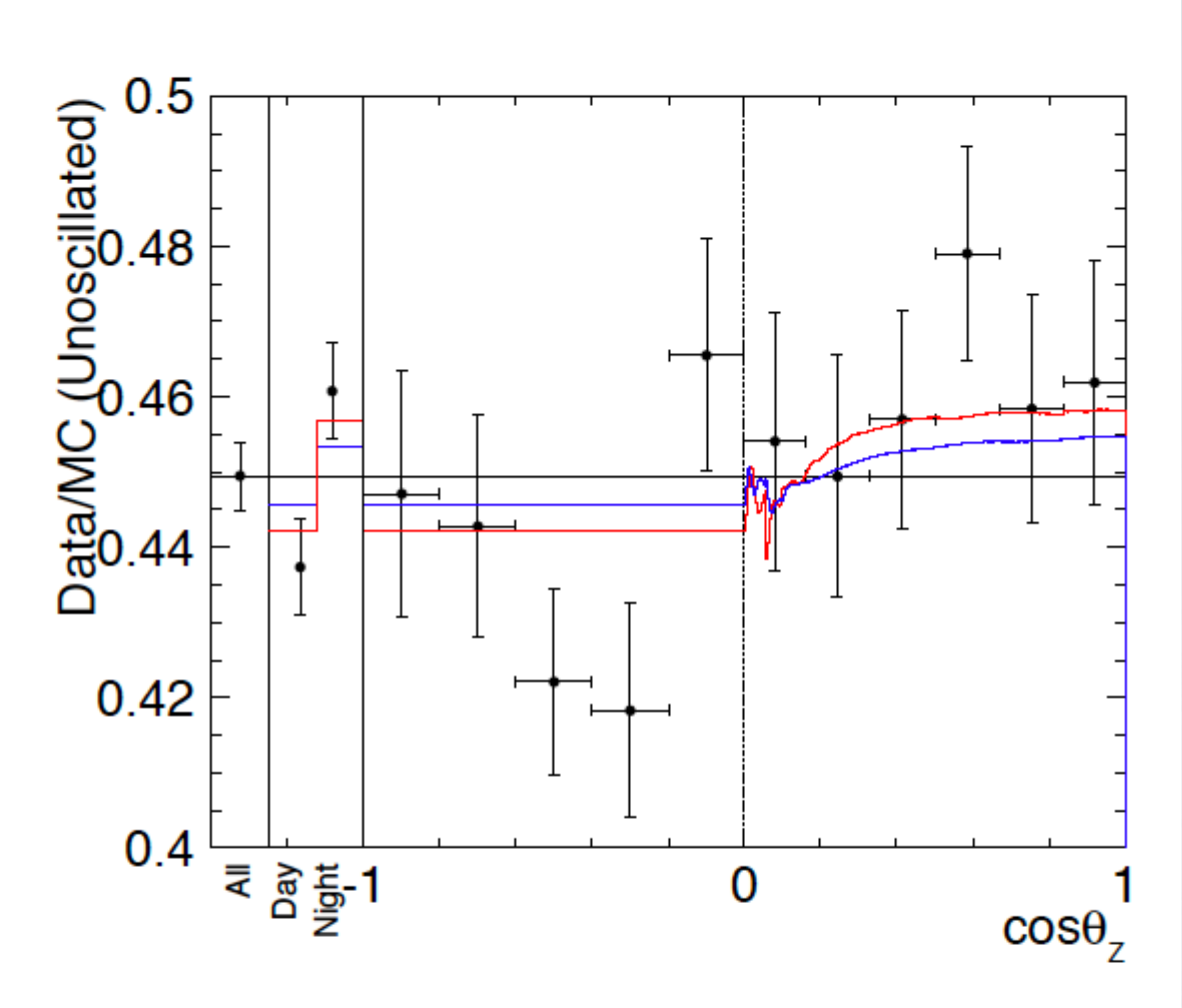
$$x_C^{0.791} x_N^{0.202} \Rightarrow \left[\frac{N_{^{12}\mathrm{C}} + N_{^{14}\mathrm{N}}}{N_{^{12}\mathrm{C}}^{\mathrm{SSM}} + N_{^{14}\mathrm{N}}^{\mathrm{SSM}}}\right]$$

ROADMAP OF SOLAR NEUTRINOS: LUMINOSITY TEST

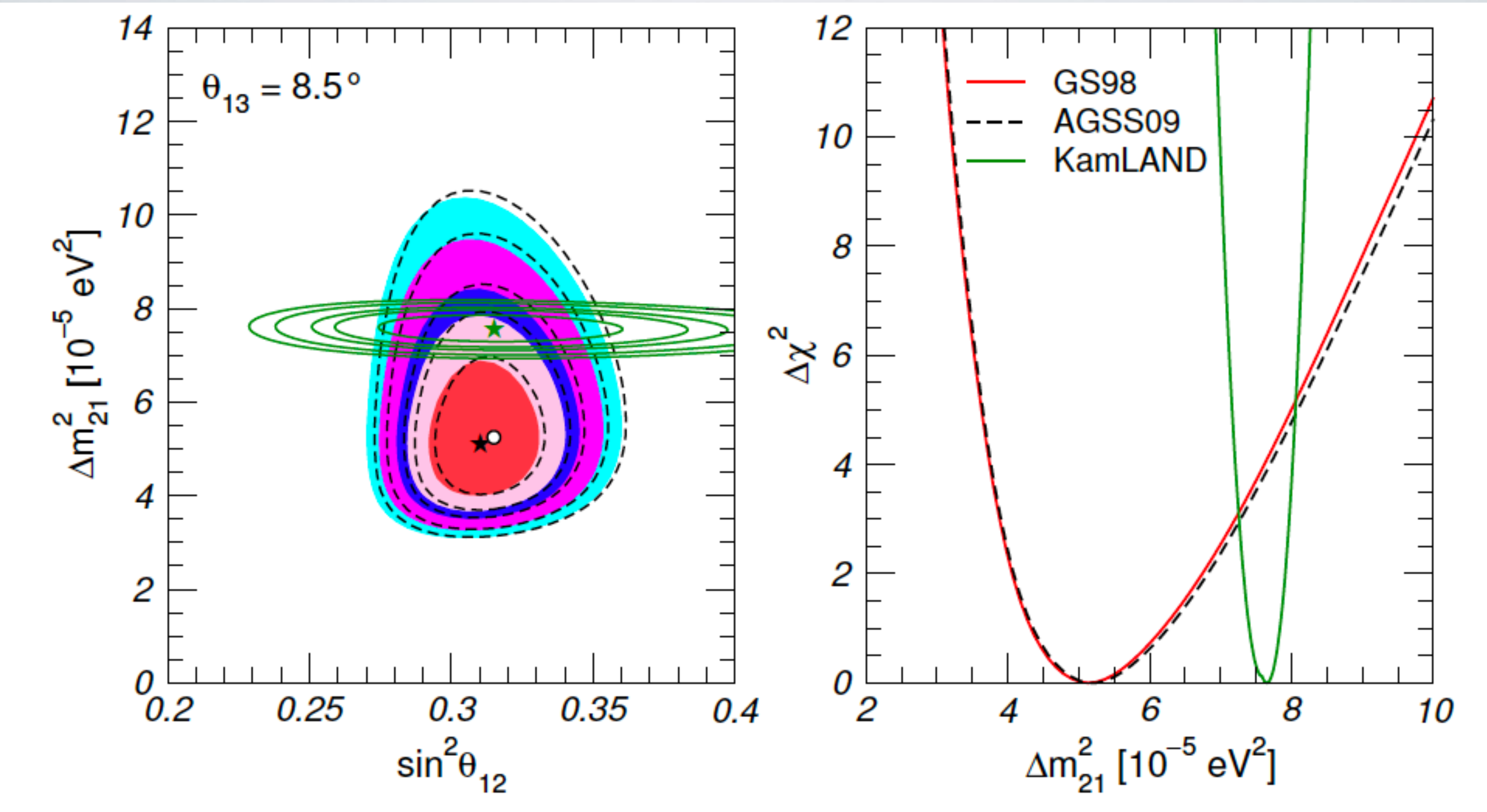
Flux	B16-GS98	B16-AGSS09met	Solar^a
$\Phi(pp)$	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$	$5.971^{(1+0.006)}_{(1-0.005)}$
$\Phi(pep)$	$1.44(1 \pm 0.01)$	$1.46(1 \pm 0.009)$	$1.448(1 \pm 0.009)$
$\Phi(hep)$	$7.98(1 \pm 0.30)$	$8.25(1 \pm 0.30)$	$19^{(1+0.63)}_{(1-0.47)}$
$\Phi(^7Be)$	$4.93(1 \pm 0.06)$	$4.50(1 \pm 0.06)$	$4.80^{(1+0.050)}_{(1-0.046)}$
$\Phi(^8B)$	$5.46(1 \pm 0.12)$	$4.50(1 \pm 0.12)$	$5.16^{(1+0.025)}_{(1-0.017)}$
$\Phi(^{13}N)$	$2.78(1 \pm 0.15)$	$2.04(1 \pm 0.14)$	≤ 13.7
$\Phi(^{15}O)$	$2.05(1 \pm 0.17)$	$1.44(1 \pm 0.16)$	≤ 2.8
$\Phi(^{17}F)$	$5.29(1 \pm 0.20)$	$3.26(1 \pm 0.18)$	≤ 85

Table 6. Model and solar neutrino fluxes. Units are: 10^{10} (pp), 10^9 (^{7}Be), 10^8 (pep, ^{13}N, ^{15}O), 10^6 (^{8}B, ^{17}F) and 10^3 (hep) cm^{-2}s^{-1}. ^{a}Solar values from Bergström et al. (2016).

ROADMAP OF SOLAR NEUTRINOS: D/N



ROADMAP OF SOLAR NEUTRINOS: VERIFY CONSISTENCY

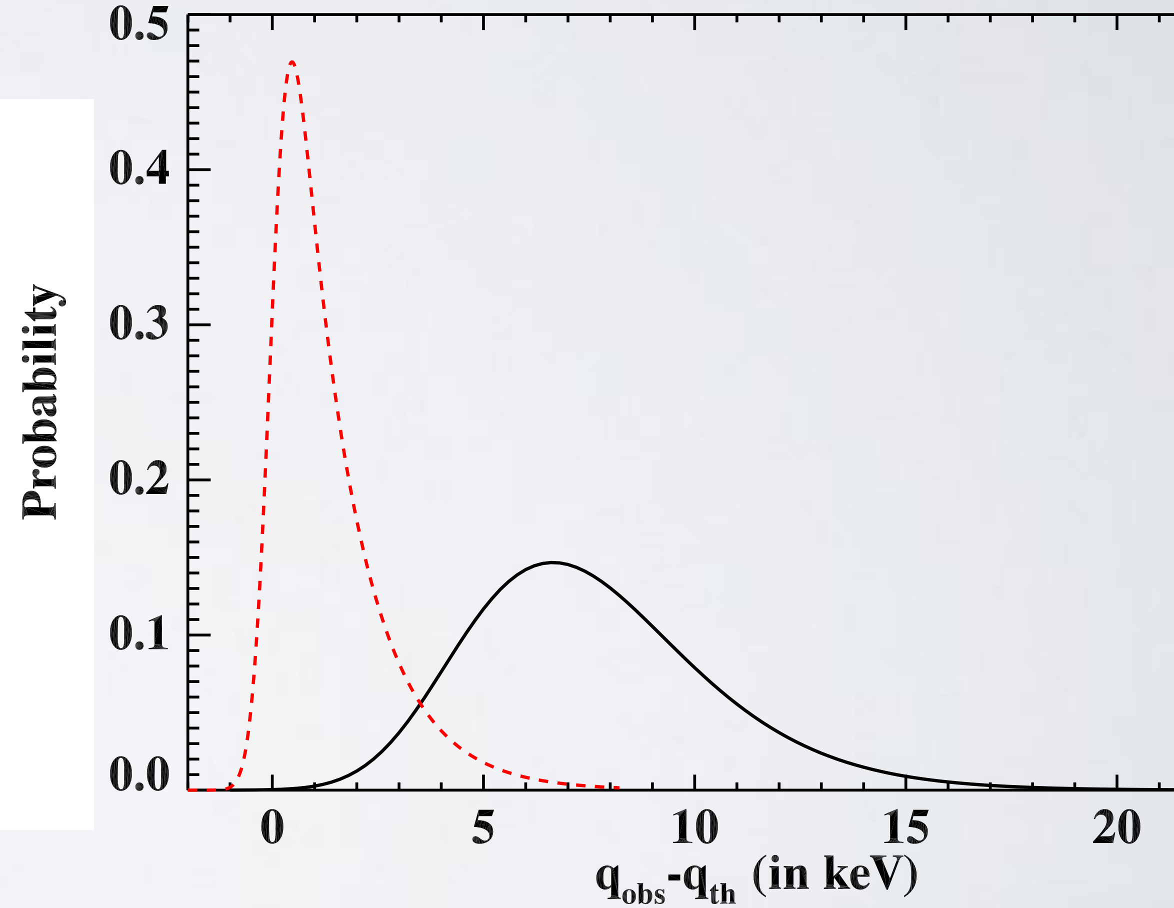


ROADMAP OF SOLAR NEUTRINOS: VERIFY CONSISTENCY

Measure the central temperature of the Sun via neutrino lines.

Influence of Doppler effect on shift and width of the lines
Comparison ^{7}Be vs pep lines

	^7Be (Bahcall, 1994)	^7Be	pep
(N_R, N_x, N_K)	-	$(256, 512, 512)$	$(128, 128, 128, 128)$
dx	0.1	0.02	0.2
q_{lab}	861.84	861.84	1442
$q_{peak} - q_{lab}$	0.43	0.46	6.6
Δ	1.29	1.30	7.59
FWHM	1.63	1.72	6.29
W^-	0.56	0.59	2.71
W^+	1.07	1.13	3.58



PROGRAM: 2 LECTURES

First Lecture

1A) How does the Sun shine? A few stories and heroes (before 1989)

1B) Standard Solar Models (quick tour by A. Serenelli)

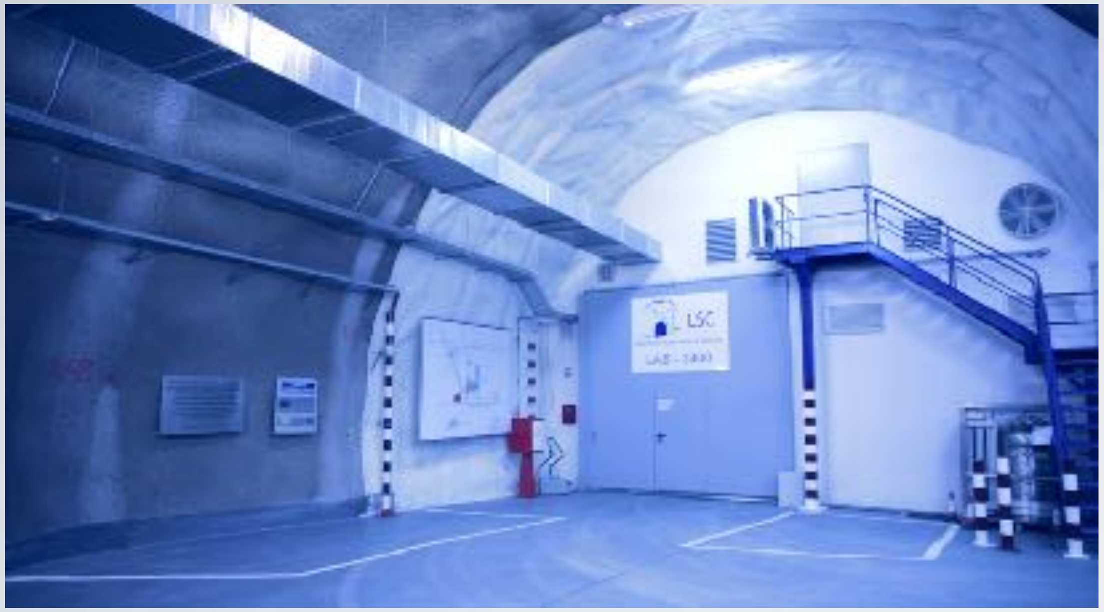
1C) Solar Neutrino fluxes at the Earth

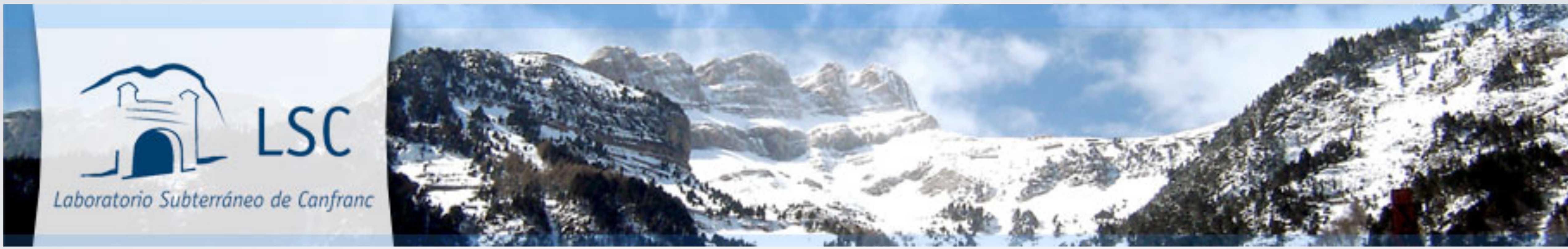
Second Lecture

2D) How does the Sun shine? A few stories and heroes I (after 1989)

2E) Solar Neutrino Experiments and Lessons in Neutrino Physics

2F) Roadmap of future solar neutrino research


LSC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