Solar Model Parameters and Direct Measurement of Solar Neutrino Fluxes

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OUTLINE

- **Standard Solar Model and its parameters**
- **Motivations for using neutrinos as probes to SSM parameters**
- **Neutrino flux – present knowledge and future measurements**
- **Techniques to determine SSM parameters using neutrino flux measurements**
- **Results**
- **Summary**

Standard Solar Model & its parameters

- Homogeneous cloud of H, He, small fraction of heavier elements
- Mass = M_{sun}
- Evolved throughout a time $t = t_{sun}$
- To get present day value of L_{sun} and R_{sun}

- Hydrostatic equilibrium
- Energy transport primarily by photon diffusion
- Energy generations by nuclear reactions
- Abundance changes caused by nuclear reactions

SSM & its parameters (contd..)

Low E Cross Sections

$$S_{11} :: {}^{1}H + {}^{1}H \rightarrow {}^{2}He + e^{+} + \nu_{e}$$

$$S_{33} :: {}^{3}He + {}^{3}He \rightarrow \alpha + 2\mathrm{p}$$

$$S_{34} :: {}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$$

$$S_{1,14} :: {}^{14}N + p \rightarrow {}^{15}O + \gamma$$

$$S_{17} :: {}^{7}Be + p \rightarrow {}^{8}B + \gamma$$

$$S_{e-7} :: {}^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_{e}$$

Astronomical parameters

- **Solar Age**
- **Solar Luminosity**
- **Initial heavy element abundance: Z / X**
- **Diffusion**
- **Opacity**

Solar Neutrino Flux – present knowledge and future measurements $({}^8B)$

- **SSM Prediction:** $\phi_B = 5.79(1 \pm 0.23) \times 10^6 cm^{-2} s^{-1}$
- **SNO NC:** $\phi_B = 4.94(1 \pm 0.088) \times 10^6 cm^{-2} s^{-1}$
- **Global analysis of Solar+KamLAND data:** $\phi_B = 4.88(1 \pm 0.036) \times 10^6 cm^{-2} s^{-1}$

Data Set	$\frac{\Delta \phi_B}{\phi_B}$
Solar	4.4%
+ KamLAND	3.6%
+ SNO-III	3.2%
+ pp	2.5%
+ SPMIN	1.7%

Solar Neutrino Flux – present knowledge and future measurements $(^{7}Be, pp)$

$\phi_{7Be}/(10^{9}\,cm^{-2}\,s^{-1})$

SSM : 4.16(1 +- 0.12)

$\frac{\Delta\phi_{Be}}{\phi_{Be}}$

Solar+KL: worse

+Borexino(10%): 10%

(+Borexino(5%)): 5.5%

$\phi_{pp}/(10^{10}\,cm^{-2}\,s^{-1})$

SSM : 5.94(1 + - 0.01)

$\frac{\Delta\phi_{pp}}{\phi_{pp}}$

Solar+KL: worse

+ Lum Constraint: 2%

+Borexino(5%): 0.5%

Dependence of Neutrino flux on SSM parameters [BP04] http://www.sns.ias.edu/~bahcall

$$\phi_B = Const \times S_{11}^{-2.59} S_{33}^{-0.40} S_{34}^{+0.81} S_{1,14}^{+0.01} S_{17}^{1.0} S_{e-7}^{-1.0} L^{+6.76} \tau^{+1.28} Opac^{-2.93} D^{-2.2} (Z/X)^{+1.36}$$

$$\phi_{Be} = Const \times S_{11}^{-0.97} S_{33}^{-0.43} S_{34}^{+0.86} L^{+3.40} \tau^{+0.69} Opac^{-1.49} D^{-0.96} (Z/X)^{0.62}$$

$$\phi_{pp} = Const \times S_{11}^{+0.14} S_{33}^{+0.03} S_{34}^{-0.06} S_{1,14}^{-0.02} L^{+0.73} \tau^{-0.07} Opac^{+0.14} D^{+0.13} (Z/X)^{-0.08}$$

$$\phi_i = C_i \Pi_{all\, j} x_j^{\alpha_{ij}} \qquad \alpha_{ij} = \frac{\partial \ln \phi_i}{\partial \ln x_j}$$

Determination of SSM parameters using measured neutrino flux

$$\phi_i = C_i \Pi_{all\ j} x_j^{\alpha_{ij}}$$

i=pp, pep, hep, B, Be, N, O, F

K = # of known fluxes   N = total # of input parameters

Use the set of K eqns. to solve for any K input parameters (x), taking rest (N-K) parameters from their laboratory measurements.

$$(\Delta \ln x_j)^2 = \Sigma_{i=1,k} P_{ir}^2 (\Delta \ln \phi_i)^2 + \Sigma_{j \neq 1,K} Q_{jr}^2 (\Delta \ln x_j)^2$$

$$\Delta \ln x_r = \ln\left(1 + \frac{\Delta x_r}{x_r}\right)$$

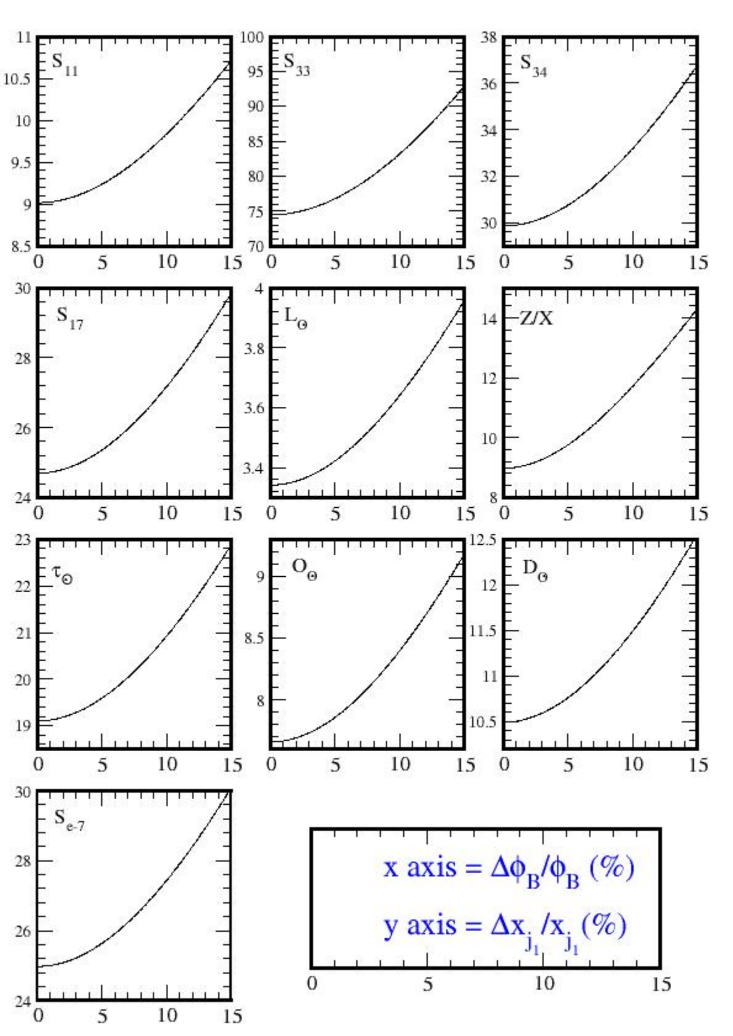
Results (Measured flux = B)

- Good precision of S_{11}, Z/X, L, Opacity
- Uncertainty in Z/X is smaller than its currently elstimated uncertainty in SSM
- Poor precision of S_{33} and $S_{1,14}$

x_j	$\frac{\Delta x_{j1}}{x_{j1}}$ (%) $\frac{\Delta\phi_B}{\phi_B} = 2\%$	$\frac{\Delta\phi_B}{\phi_B} = 3\%$	$\frac{\Delta\phi_B}{\phi_B} = 4\%$	$\frac{\Delta x^0_{j1}}{x^0_{j1}}$ (%)	$\frac{x_{j1}}{x^0_{j1}}$
S_{11}	9.05	9.10	9.16	0.4	1.07
S_{34}	30.01	30.19	30.44	9.4	0.81
S_{17}	24.80	24.94	25.12	3.8	0.84
$L_\odot$	3.35	3.37	3.39	0.4	0.97
Z/X	9.11	9.27	9.48	15.0	0.88
Age	19.18	19.28	19.42	0.4	0.87
$O_\odot$	7.69	7.73	7.79	2.0	1.06
$D_\odot$	10.54	10.59	10.66	2.0	1.08
$S_{e\text{-}7}$	25.08	25.22	25.40	2.0	1.19

Results (Measured flux = B)

- Model payrameter uncerts depends strongly on 8B flux uncert if 8B flux uncert> 5%
- Model parameter uncert are stable below 4% of 8B uncert.



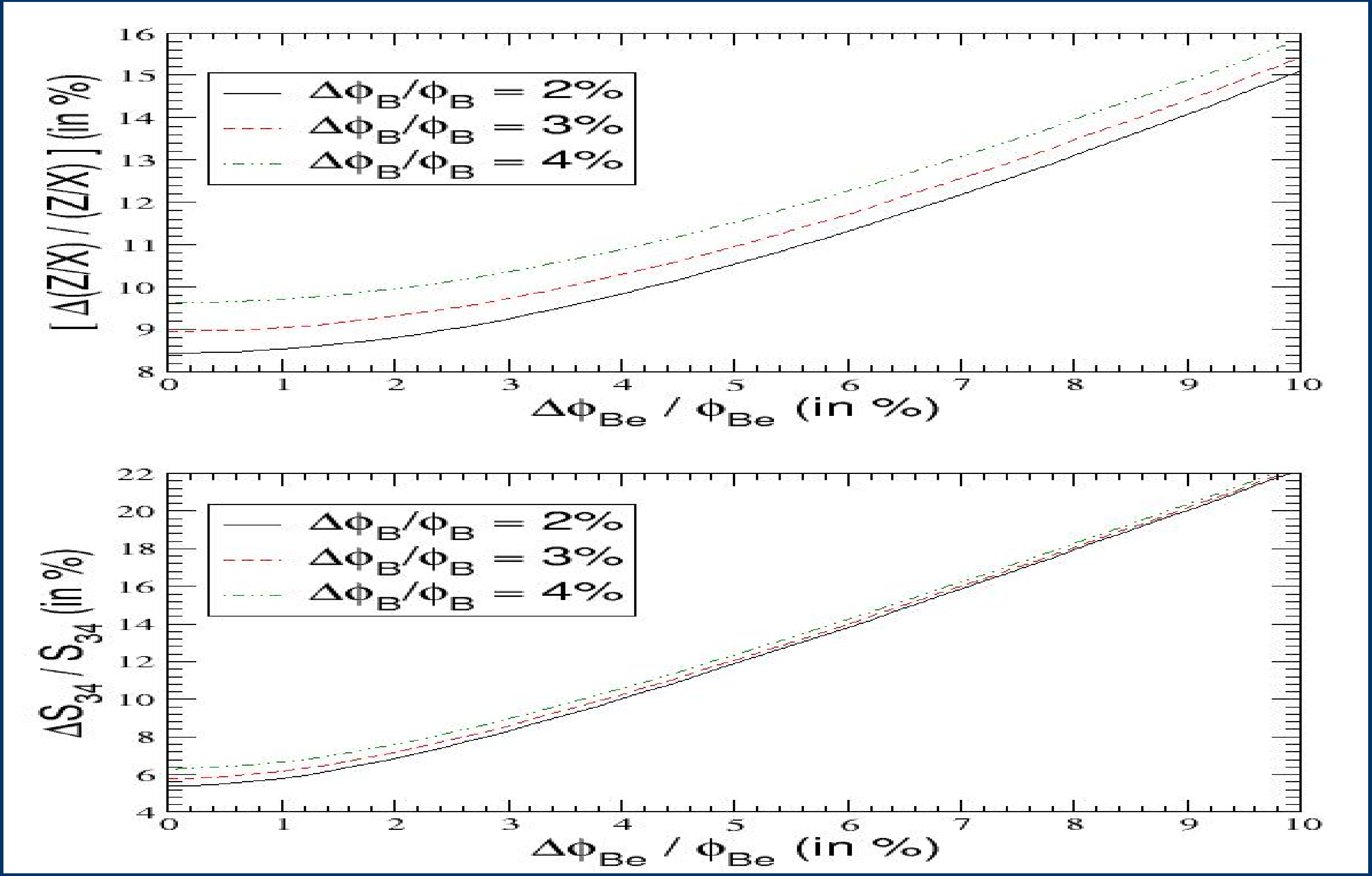
Results (Measured flux = B, Be)

4% Uncert of B flux
6% Uncert of Be flux

- Good precision of S34 when attempted to measure with S11 or Z/X or D
- L is measured with good accuracy when attempted to measure with S17, S34, Se-7

combinations		$\frac{\Delta x_{j1}}{x_{j2}}$ (%)	$\frac{\Delta x_{j2}}{x_{j2}}$ (%)
j_1	j_2		
S_{34}	S_{11}	12.71	8.81
S_{34}	Z/X	14.25	12.26
S_{34}	$D_{\odot}$	13.79	11.35

Results (Measured flux = B, Be)



Results (Measured flux =B, Be, pp)

Uncerts in fluxes:

B -> 3%

Be -> 4%

pp -> 1%

Some Most effective combinations:

{S_{34}, L, S_{e-7}} -> S_{34} (6.3%)
(present~9.4%)

{S_{17}, L, Z/X} ->Z/X (6.65%)
(present~15%)

combinations			$\frac{\Delta x_{j_1}}{x_{j_2}}$ (%)	$\frac{\Delta x_{j_2}}{x_{j_2}}$ (%)	$\frac{\Delta x_{j_3}}{x_{j_3}}$ (%)
x_{j_1}	x_{j_2}	x_{j_3}			
S_{11}	S_{34}	$L_\odot$	6.16	7.98	1.62
S_{11}	$L_\odot$	$O_\odot$	13.67	1.72	12.25
S_{34}	$L_\odot$	Z/X	8.87	1.00	8.63
S_{34}	$L_\odot$	$O_\odot$	10.45	1.69	5.31
S_{34}	$L_\odot$	$D_\odot$	9.03	1.57	5.77
S_{34}	$L_\odot$	$\tau_\odot$	11.40	1.66	12.86
S_{11}	S_{17}	$L_\odot$	4.73	11.05	1.73
S_{11}	$L_\odot$	S_{e-7}	4.53	1.73	11.05
S_{33}	S_{17}	$L_\odot$	12.40	8.47	1.95
S_{33}	$L_\odot$	S_{e-7}	13.43	1.95	8.47
S_{34}	S_{17}	$L_\odot$	8.61	8.98	1.86
S_{34}	$L_\odot$	S_{e-7}	6.33	1.85	8.98
S_{17}	$L_\odot$	Z/X	9.26	1.21	6.65
S_{17}	$L_\odot$	$\tau_\odot$	9.05	1.85	7.34
S_{17}	$L_\odot$	$O_\odot$	9.21	1.84	3.40
S_{17}	$L_\odot$	$D_\odot$	9.74	1.74	4.68
$L_\odot$	Z/X	S_{e-7}	1.21	6.65	9.88
$L_\odot$	$\tau_\odot$	S_{e-7}	1.85	7.42	9.29
$L_\odot$	$O_\odot$	S_{e-7}	1.84	3.40	9.48
$L_\odot$	$D_\odot$	S_{e-7}	1.73	4.68	10.12