The Standard Solar Model

- 40 years/4 slides
- Uncertainties in predictions
- Challenges and open questions

BP00: astro-ph/0010346

Some highlights in precision theory

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- 1962: Solar model calculation of ν flux

Detailed model; very disappointing

Some highlights in precision theory

- 1962: Solar model calculation of ν flux

- 1962-1968: refined nuclear rates

  Experiment : ^{3}He-^{3}He, p + ^{7}Be

Some highlights in precision theory

- 1962: Solar model calculation of ν flux

- 1962-1968: refined nuclear rates

Theory : σ_{ν}(Superallowed,1964),

$p-p, e^{-}+{}^{7}Be$

Some highlights in precision theory

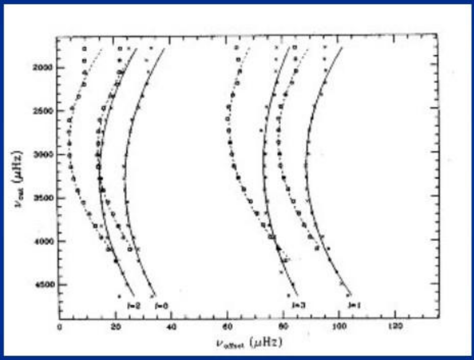
- 1962: Solar model calculation of ν flux
- 1962-1968: refined nuclear rates
- 1968-1988: formalized, reduced errors

1000 solar models; partial derivatives

Highlights: 1988-1995

•1988: helioseismology + ν's: **0.5%**

RMP 60 ('88) with R.K. Ulrich



Highlights: 1988-1995

- **1988: helioseismology + ν's: 0.5%**

- 1990-1994:Radiative opacity, E.O.S.

  LLNL: Rogers and Iglesias

Highlights: 1988-1995

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- 1990-1995: Element Diffusion

jnb, Loeb, Thoul, Pinsonneault

Highlights: 1988-1995

- **1988: helioseismology + ν's: 0.5%**

- 1990-1994:Radiative opacity, E.O.S.

- 1990-1995: Element Diffusion

^{8}B flux: + 35% [RMP 67 (1995)]

Highlights: 1995-1997

- 1995-1997: helioseismological confirmation

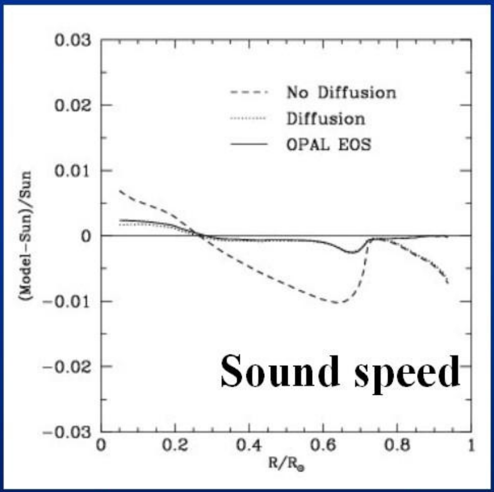
Highlights: 1995-1997

Tomczyk et al. Solar Physics 159,1('95)

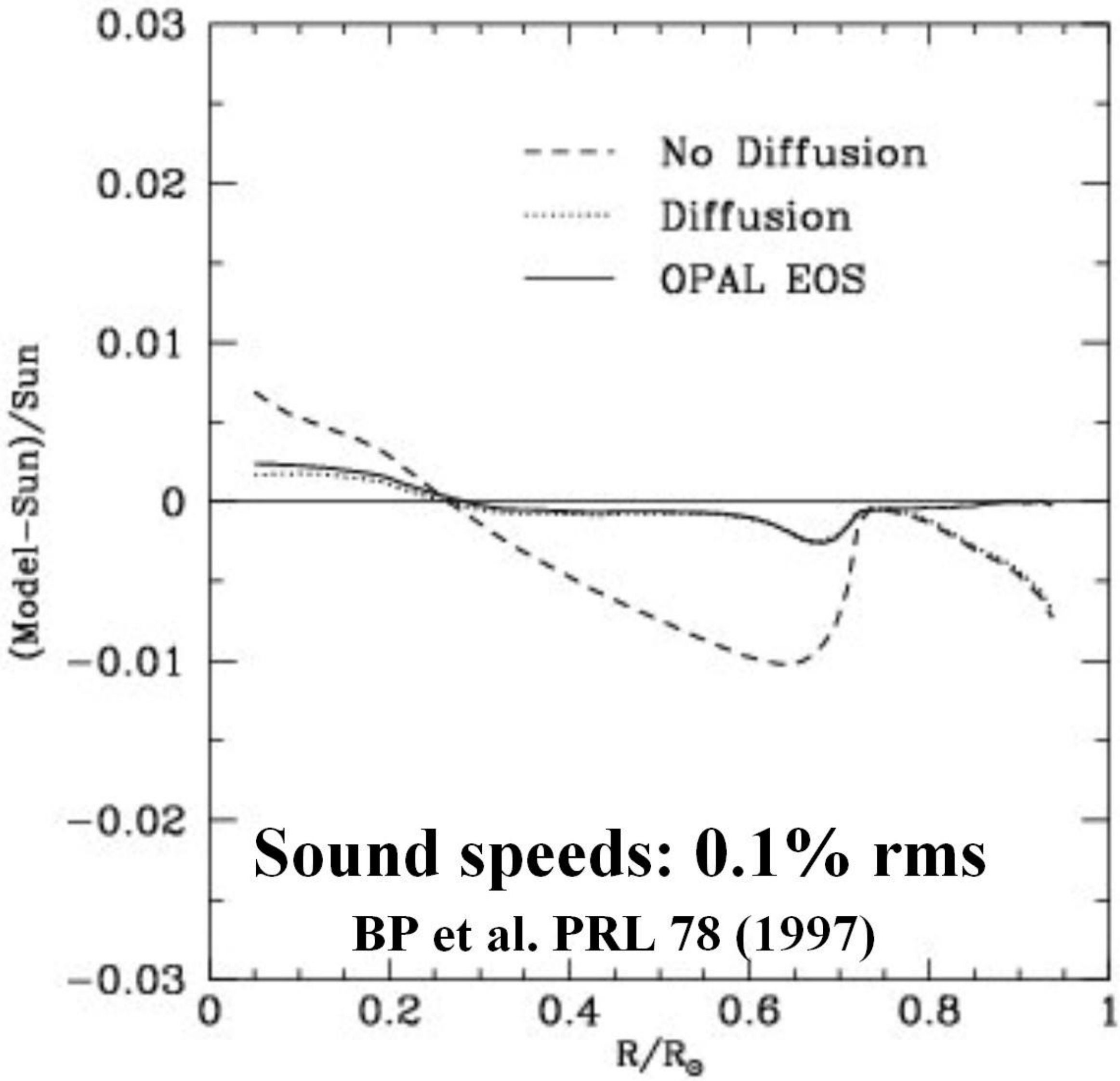
Highlights: 1995-1997

BP et al. PRL 78(1997)

"Standard solar models predict the measured properties of the Sun more accurately than is required for applications involving solar neutrinos."



0.1% rms



No Diffusion
Diffusion
OPAL EOS
(Model–Sun)/Sun
R/R⊙
0.03
0.02
0.01
0
−0.01
−0.02
−0.03
0
0.2
0.4
0.6
0.8
1
Sound speeds: 0.1% rms
BP et al. PRL 78 (1997)

Highlights: 2001-2002

- **2001: First direct ν confirmation**

$$^{8}B(BP00) = 5.05^{+1.0}_{-0.8}\ \ \textbf{(unit : }\mathbf{10^{6}\ cm^{2}s^{-1}}\textbf{)}$$

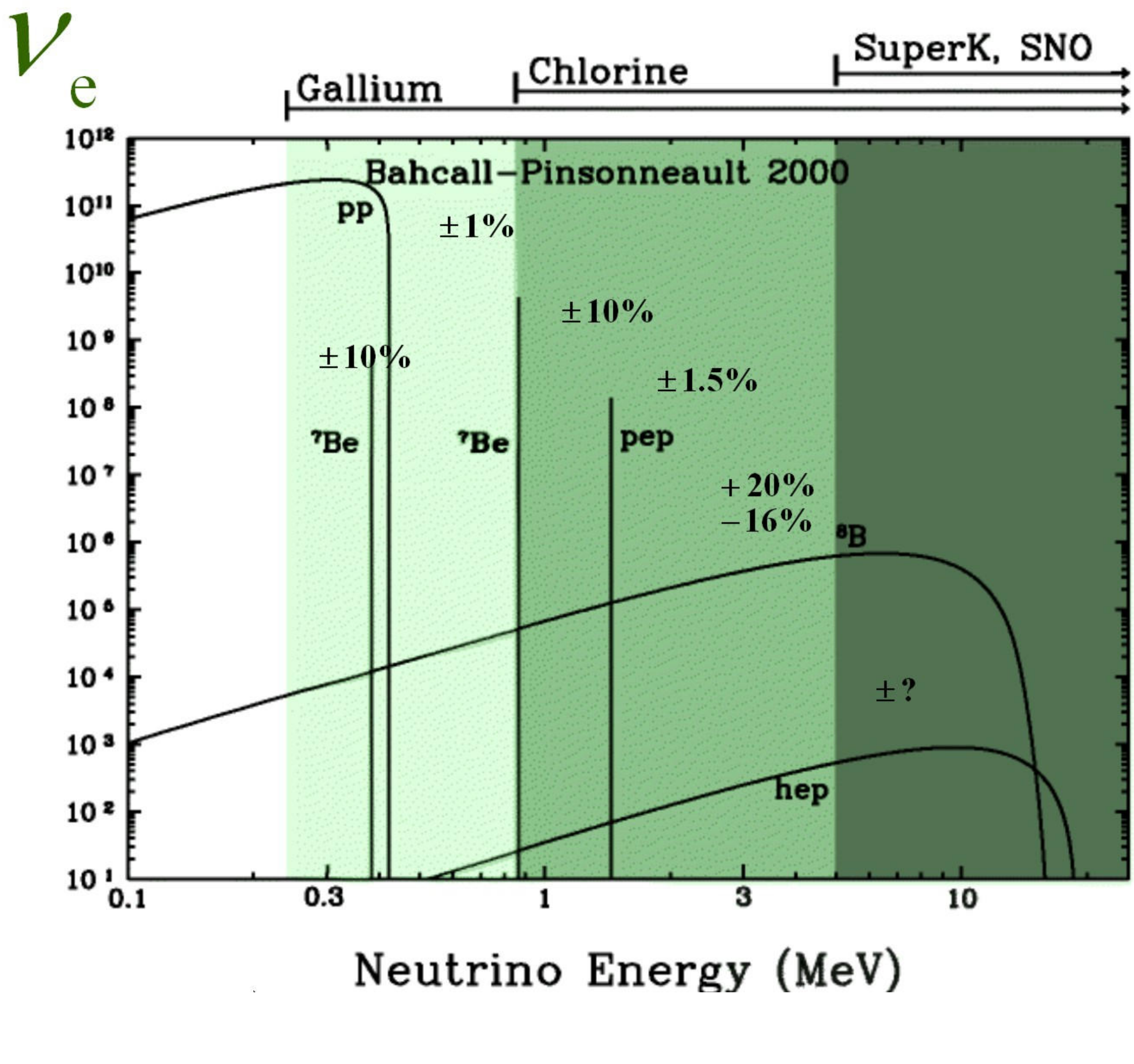
$$^{8}B(SNO + SK) = 5.44 \pm 0.99$$

Agree to 0.3σ

- **2002: SNO NC**

$$\mathbf{^{8}B(SNO\ NC) = 5.09 \pm 0.64\ (undistorted\ spectrum)}$$

Agree to 0.03σ



ν_e
Gallium
Chlorine
SuperK, SNO
Bahcall–Pinsonneault 2000
pp
±1%
±10%
±10%
±1.5%
⁷Be
⁷Be
pep
+20%
−16%
⁸B
±?
hep
Neutrino Flux
Neutrino Energy (MeV)
0.1
0.3
1
3
10

Does the solar luminosity determine the pp flux?

Theoretical error = 1%

$$4p\ !\ \ {}^{4}He + 2e^{+} + 2÷_{e} + ø\ \ 25\ \ MeV$$

CNO cycle: 0 pp neutrinos

Big ^{7}Be flux : 0.5 max pp flux

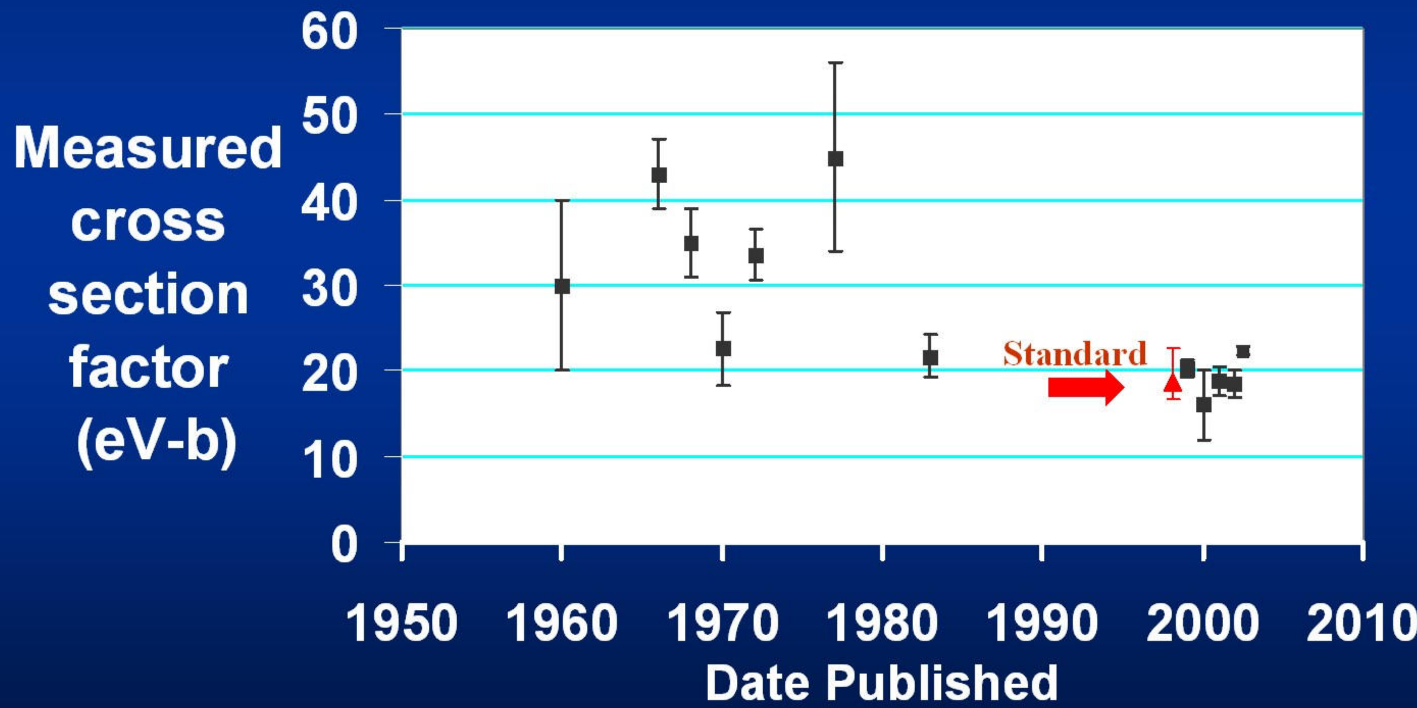
Luminosity determines pp flux: 0 –1.0 max flux

BP00 %Uncertainties

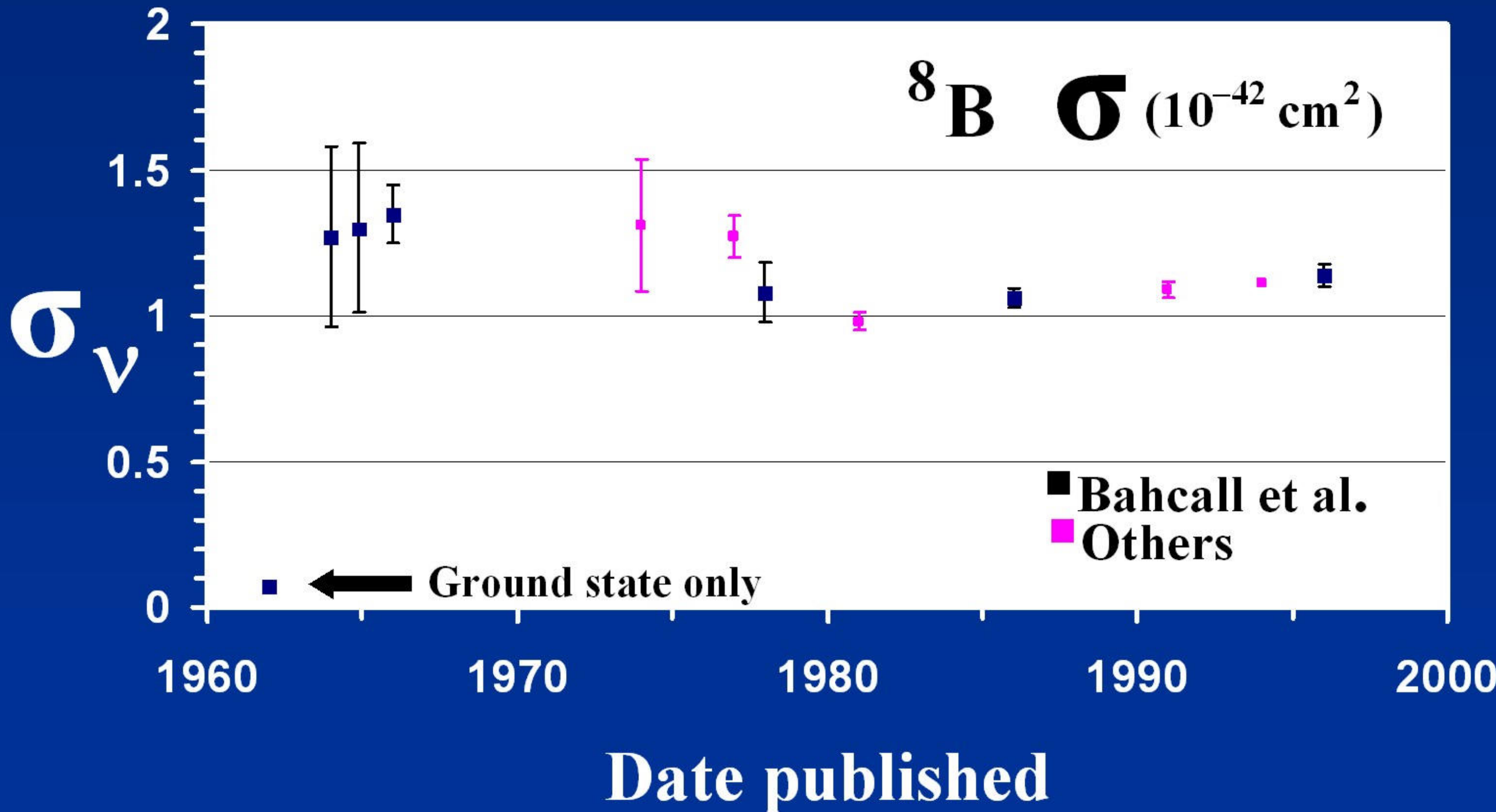
Source	^{8}B	^{7}Be
p-p	0.04	0.02
$^{3}He + ^{3}He$	0.02	0.02
$^{3}He + ^{4}He$	0.08	0.08
$p + ^{7}Be$	$^{+0.14}_{-0.07}$	0.00
Composition	0.08	0.03
Opacity	0.05	0.03
Diffusion	0.04	0.02
Luminosity	0.03	0.01

Cross section: $^{7}Be(p,\gamma)^{8}B$

$\varphi(^{8}B) \propto$ Cross Section Factor



$^{37}Cl(\nu_e,e)^{37}Ar$ vs. date published



Why did it take so long?

- **Unfamiliar accelerator and beam**

"Most likely, the solar neutrino problem has nothing to do with particle particle physics. It is a great triumph that astrophysicists are able to predict the number of ^{8}B neutrinos to within a factor of 2 or 3"….

H. Georgi and M. Luke, Nucl. Phys. B347, 1(1990)

Why did it take so long?

- **Unfamiliar accelerator and beam**
- ^{8}B neutrino flux $\propto$ (Temperature)^{25}
- **Large mixing angles (ironic)**

SSM: Additional fundamental tests

- 99.99% of predicted flux is below 5 MeV.

- Stellar evolution theory predicts:

$$\frac{\langle {}^3He + {}^4He \rangle}{\langle {}^3He + {}^3He \rangle} = \frac{2\varphi({}^7Be)}{\varphi(pp) - \varphi({}^7Be)} = 0.174$$

  pp fusion formula: summarizes competition between different fusion chains.

- CNO neutrinos represent 1.5% of luminosity.