Solar Neutrino Opportunity

Can use solar neutrinos for unique physics and astronomy

- Test stellar evolution theory directly
- Search for neutrino masses $\geq 10^{-6}$ eV

STANDARD MODEL

STANDARD ELECTROWEAK THEORY

+

STANDARD SOLAR MODEL

References

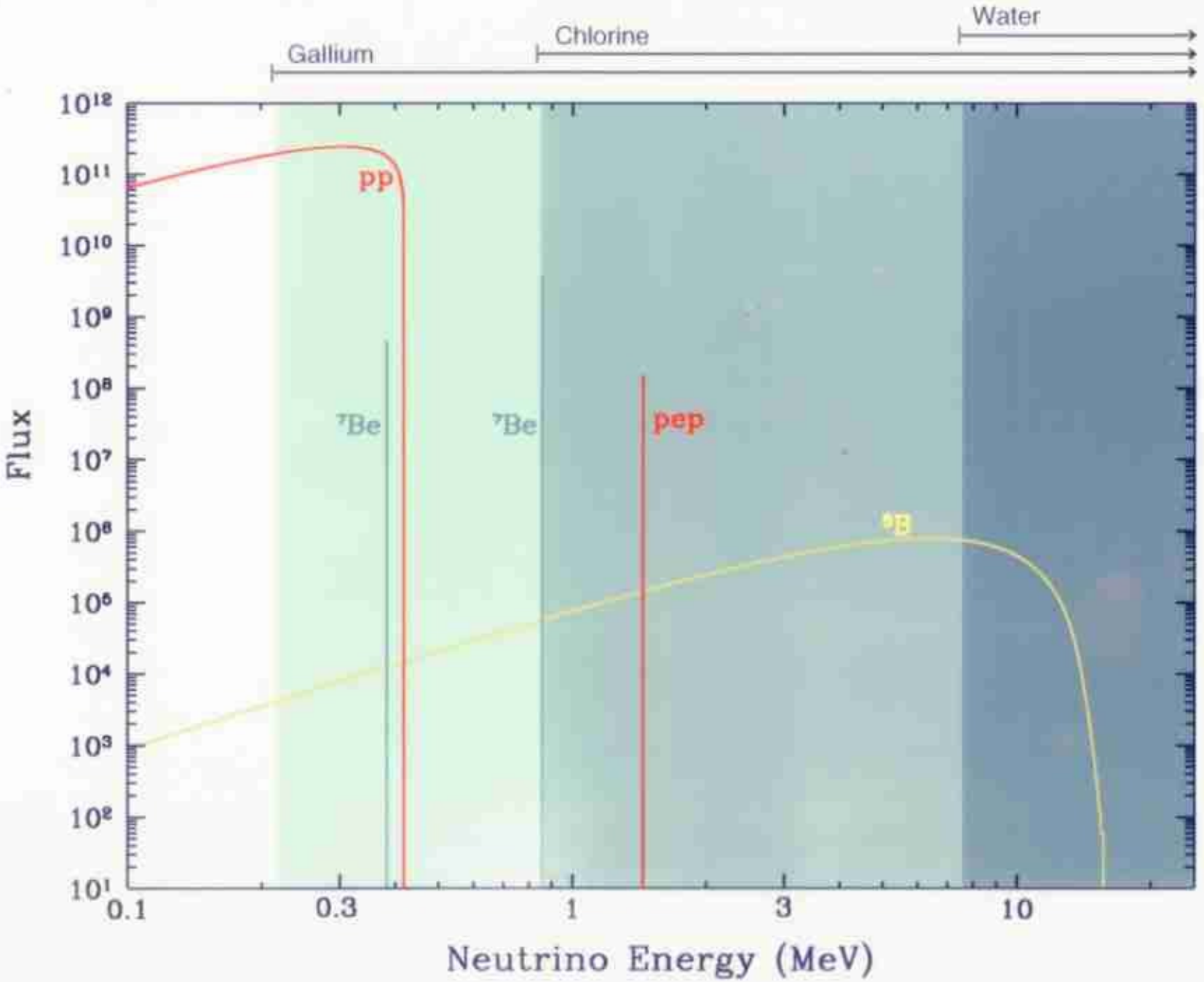
How Uncertain Are Solar Neutrino Predictions?

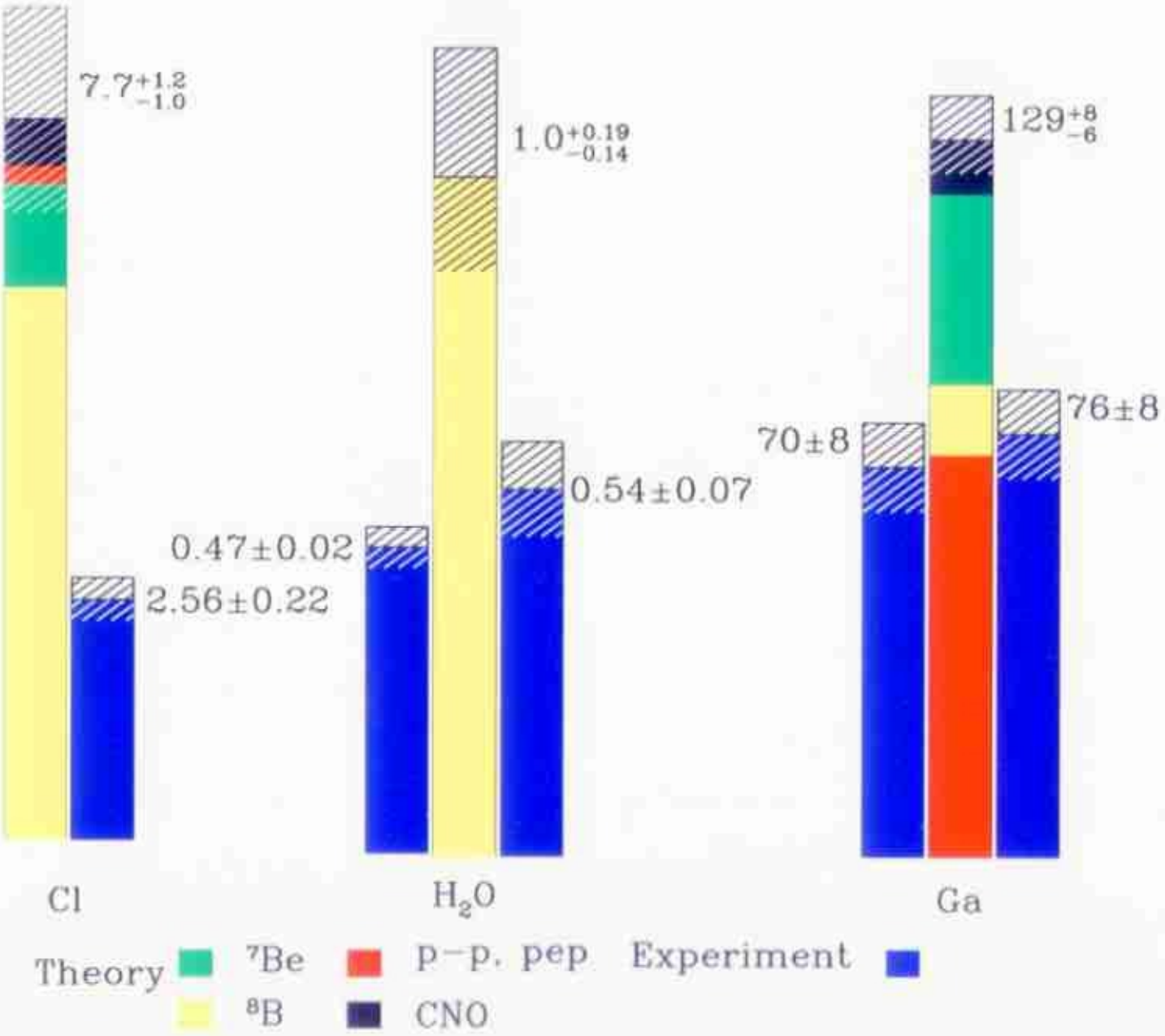
astro-ph/9805135

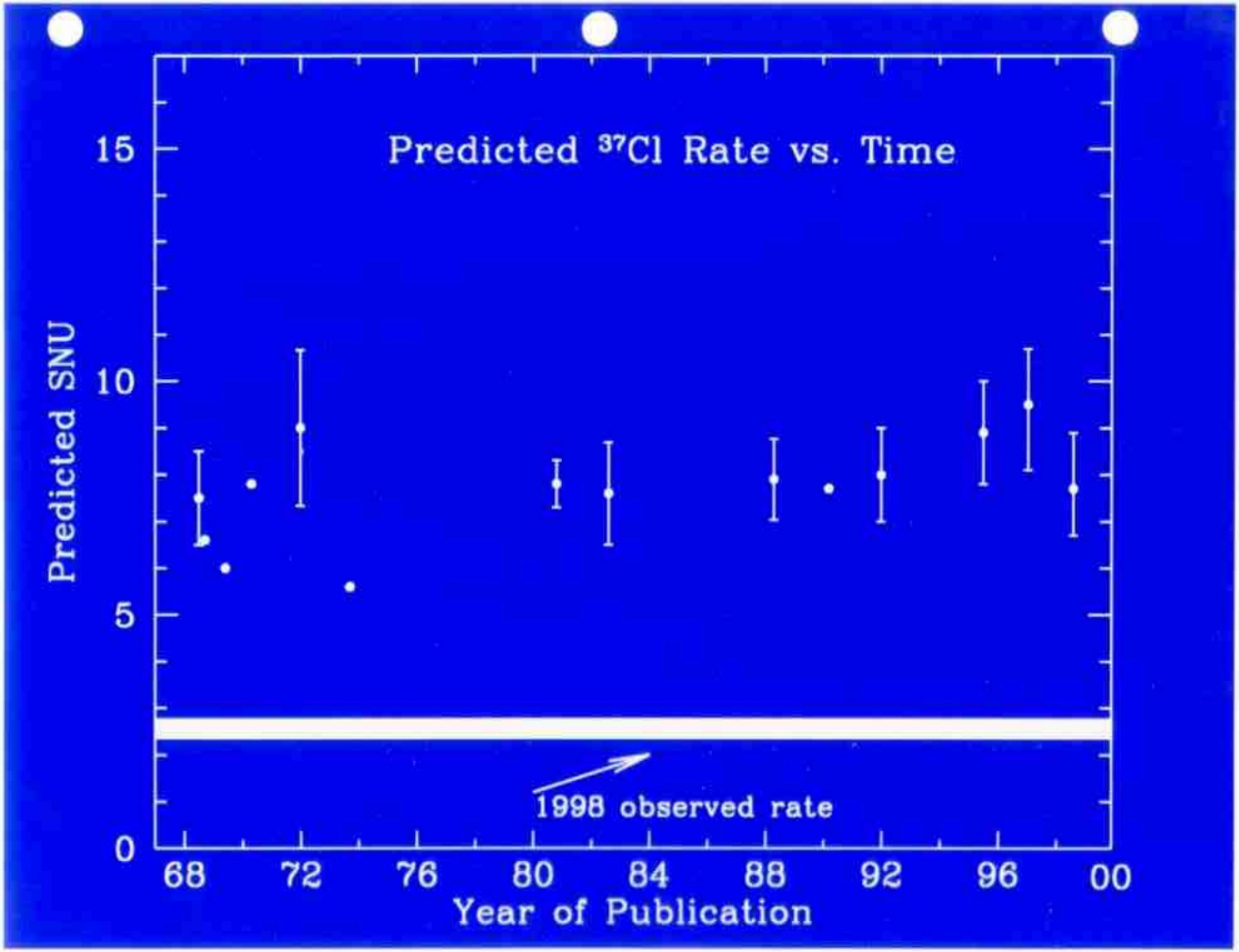
Solar Fusion Cross Sections

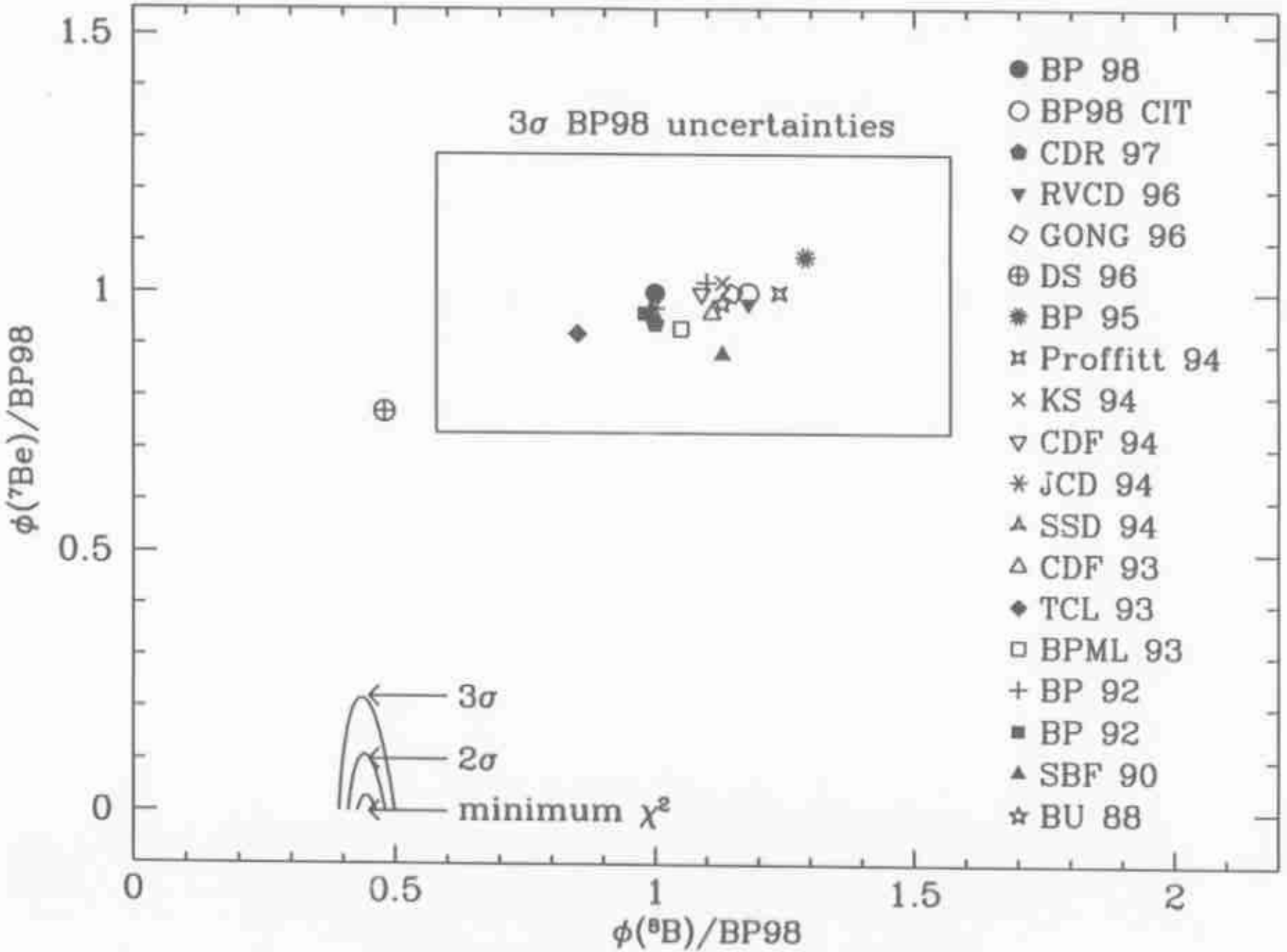
astro-ph/9805121

www.sns.ias.edu/~jnb


Water
Chlorine
Gallium
Flux
pp
7Be
7Be
pep
8B
10^12
10^11
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
0.1
0.3
1
3
10
Neutrino Energy (MeV)


$7.7^{+1.2}_{-1.0}$
2.56±0.22
$1.0^{+0.19}_{-0.14}$
0.47±0.02
0.54±0.07
129^{+8}_{-6}
70±8
76±8
Cl
H_2O
Ga
Theory
^{7}Be
^{8}B
p−p, pep
CNO
Experiment


Predicted ^{37}Cl Rate vs. Time
Predicted SNU
15
10
5
0
1998 observed rate
68
72
76
80
84
88
92
96
00
Year of Publication


1.5
1
0.5
0
0
0.5
1
1.5
2
$\phi(^7Be)/BP98$
$\phi(^8B)/BP98$
3σ BP98 uncertainties
3σ
2σ
minimum χ²
BP 98
BP98 CIT
CDR 97
RVCD 96
GONG 96
DS 96
BP 95
Proffitt 94
KS 94
CDF 94
JCD 94
SSD 94
CDF 93
TCL 93
BPML 93
BP 92
BP 92
SBF 90
BU 88

Fits to Experiments

- SSM: $\chi^2_{\rm min} = 63$ (3 D.O.F.)
- No Model except BP98 CNO: $\chi^2_{\rm min} = 24$ (1 D.O.F.)
- No Model (CNO = 0): $\chi^2_{\rm min} = 6.5$ (1 D.O.F.)

BP 98 Predictions

Source	Flux (10^{10} cm^{-2}s^{-1})	Cl (SNU)	Ga (SNU)
pp	$5.94\left(1.00^{+0.01}_{-0.01}\right)$	0.0	69.6
pep	$1.39 \times 10^{-2}\left(1.00^{+0.01}_{-0.01}\right)$	0.2	2.8
hep	2.10×10^{-7}	0.0	0.0
^{7}Be	$4.80 \times 10^{-1}\left(1.00^{+0.09}_{-0.09}\right)$	1.15	34.4
^{8}B	$5.15 \times 10^{-4}\left(1.00^{+0.19}_{-0.14}\right)$	5.9	12.4
^{13}N	$6.05 \times 10^{-2}\left(1.00^{+0.19}_{-0.13}\right)$	0.1	3.7
^{15}O	$5.32 \times 10^{-2}\left(1.00^{+0.22}_{-0.15}\right)$	0.4	6.0
^{17}F	$6.33 \times 10^{-4}\left(1.00^{+0.12}_{-0.11}\right)$	0.0	0.1
Total		$7.7^{+1.2}_{-1.0}$	129^{+8}_{-6}

$\phi\left(^{8}\mathrm{B};\ \mathrm{CIT}\right) = 6.1^{+1.1}_{-0.9} \times 10^{-4}$ cm^{-2}s^{-1}; Cl (CIT) $= 8.8^{+1.4}_{-1.1}$ SNU;

Ga (CIT) $= 131^{+2}_{-7}$ SNU

Dominant Neutrino Uncertainties

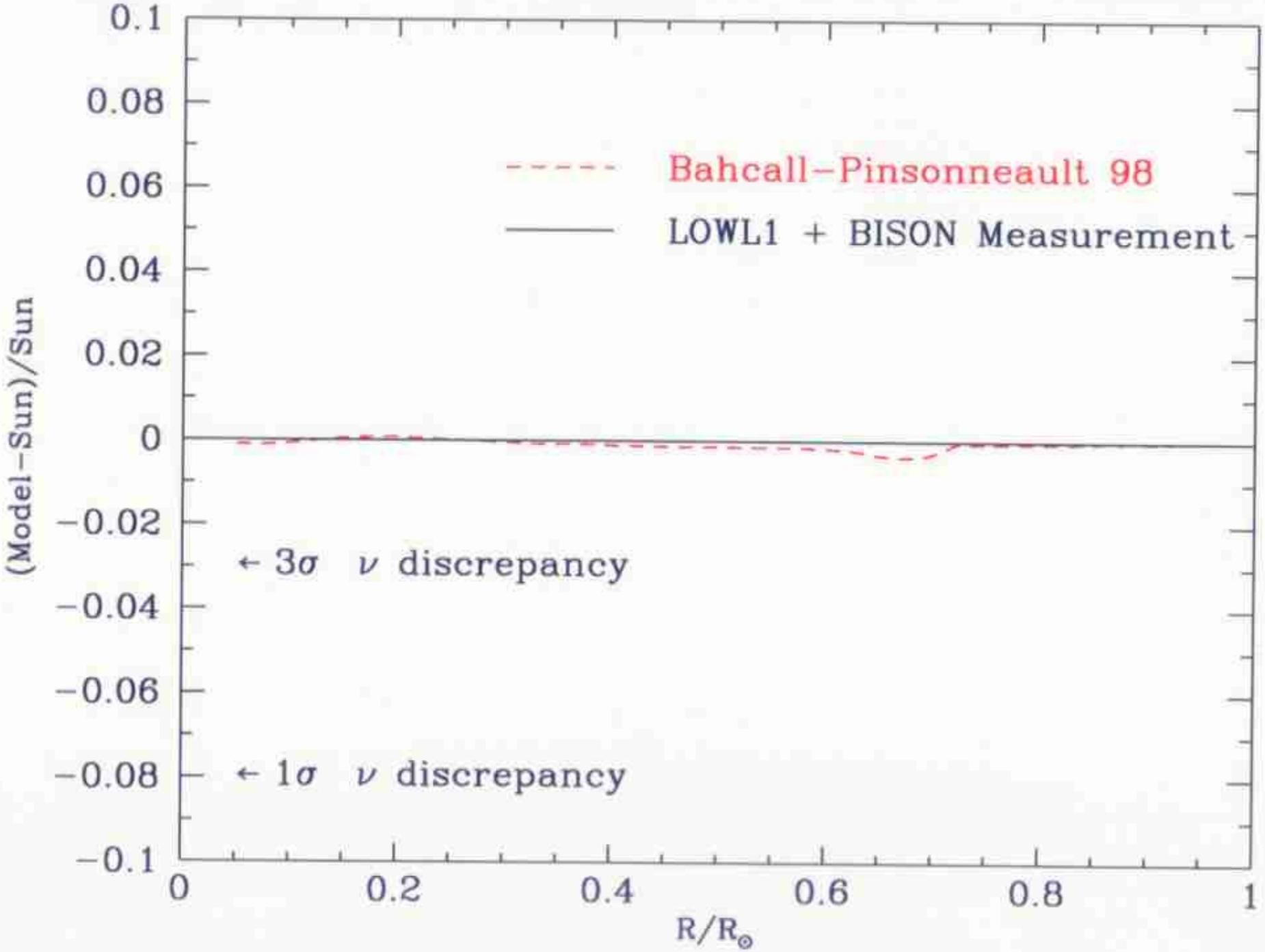
$^7\mathrm{Be}(\mathrm{p},\gamma)^8\mathrm{B}$

- Experiment: $19(1 + {}^{+0.21}_{-0.11})$ eV b
- Required Accuracy: $\pm 5\%$

$^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$

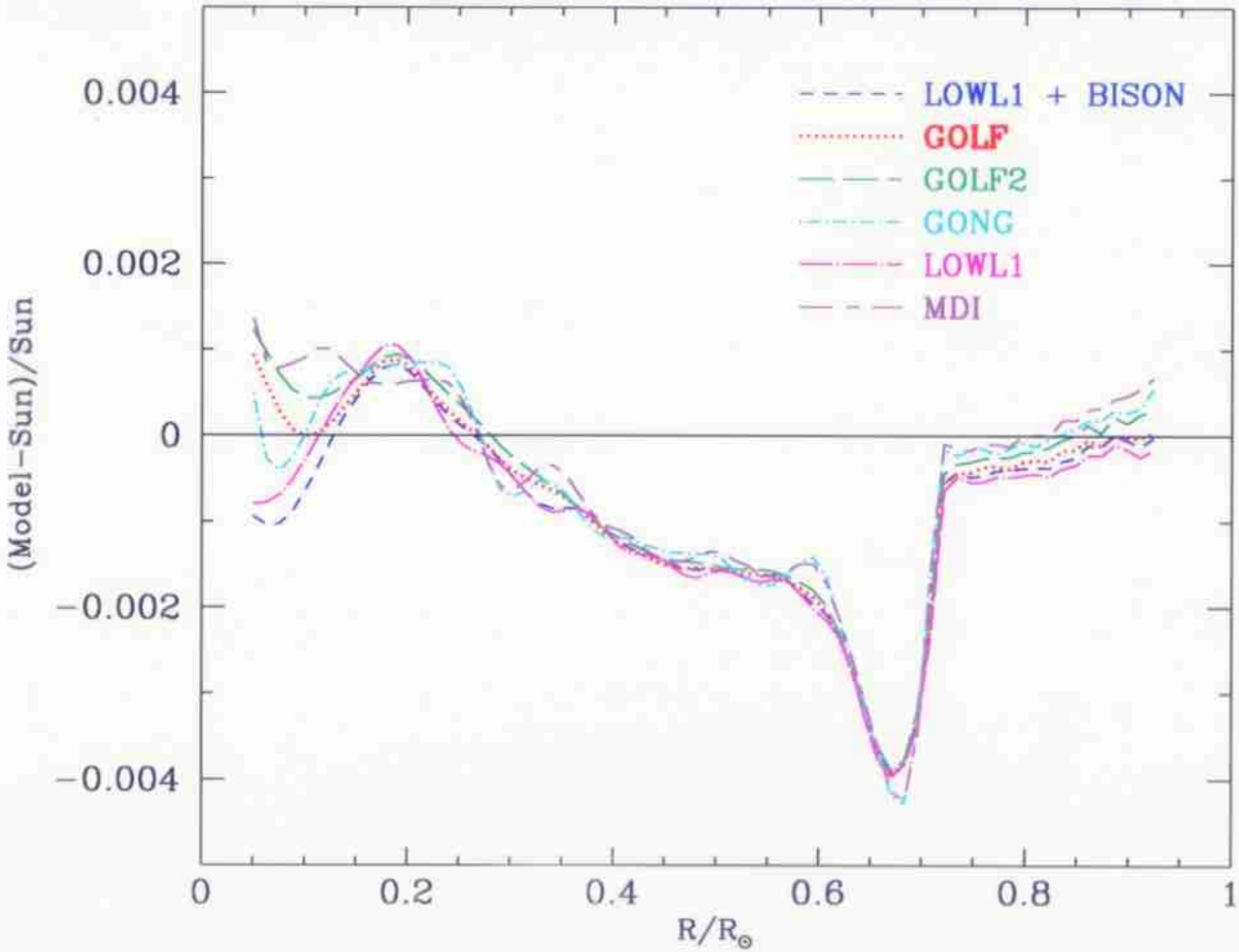
- Prompt γ's: $507(1 + \pm 0.03)$ eV b
- ^{7}Be Activity: $579(1 + \pm 0.04)$ eV b

Differ: 14%; Required accuracy: 3.5%


0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
−0.1
(Model−Sun)/Sun
Bahcall−Pinsonneault 98
LOWL1 + BISON Measurement
← 3σ ν discrepancy
← 1σ ν discrepancy
0
0.2
0.4
0.6
0.8
1
R/R⊙

Model Versus Helioseismology

- No free parameters
- No input from helioseismology
- Agreement in sound speeds: 0.1% rms


LOWL1 + BISON
GOLF
GOLF2
GONC
LOWL1
MDI
0.004
0.002
0
−0.002
−0.004
(Model−Sun)/Sun
0
0.2
0.4
0.6
0.8
1
R/R⊙

The Age of the Sun

(SSM: 4.6×10^9 yr)

- C. Darwin and geologists: $> 3 \times 10^8$ yr (1859-)
- Kelvin-Helmholtz: $t_\odot < GM_\odot^2/(R_\odot L_\odot) = 3 \times 10^7$ yr (1856-1889)
- H. Bethe: CNO cycle (p-p chain) (1939)
- R. Davis: solar neutrino experiment (1968)
- Kamiokande,GALLEX,SAGE,SuperK,SNO, BOREXINO: **new physics? (1989-?)**