Status of the Standard Solar Model and Predictions for Solar Neutrino Fluxes

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University of Connecticut and Yale University

1. **The Standard Solar Model**
   Helioseismology, Chemical Composition

2. **The Standard Solar Model**
   Nuclear Physics

3. **Future Prospects for New Physics**
   pp Neutrinos

NANP05, Dubna, June 20, 2005

The Laboratory for Nuclear Science
At Avery Point

Бруно Понтекорво

AWARDS

Art McDonald wins 2004 Bruno Pontecorvo Prize for SNO results

The director of the Sudbury Neutrino Observatory (SNO), Arthur McDonald of Queen's University, Kingston, Canada, has been awarded the Bruno Pontecorvo Prize for 2004 by the Joint Institute for Nuclear Research in Dubna. McDonald receives the prize "for the demonstration of solar neutrino oscillations in the SNO experiment".

SNO has observed neutrinos from boron-8 decay in the Sun via two types of neutrino reactions – one sensitive only to electron neutrinos and others sensitive to all active neutrino flavours – and has found clear evidence of neutrino-flavour change. This confirms the hypothesis of Pontecorvo and Vladimir Gribov that the neutrino-flavour change is responsible for the deficit of solar neutrinos observed in other experiments, thereby solving the long-standing "solar-neutrino problem". SNO's measurements combined with other solar experiments and the reactor neutrino measurements of the

SNO Salt Phase Result:

$$\Phi_\nu \;=\; 4.94 \pm 0.21\ (\text{stat})\ {}^{+0.38}_{-0.34}(syst)\ \times 10^6\ cm^{-2}sec^{-1} \qquad [1]$$

$$\frac{\Phi_{SSM}}{\Phi_\nu} = 1.17 \qquad [2]$$

[1] B. Aharmin *et al.*; nucl-ex/0502021.

[2] J.N. Bahcall and M.H. Pinsonneault; Phys. Rev. Lett. **92**(2004)121301.

SOLAR FUSION

$$^1H + {}^1H \rightarrow {}^2D + e^+ + \boxed{\nu_e}$$
$$^2D + {}^1H \rightarrow {}^3He + \gamma$$
$$^3He + {}^3He \rightarrow {}^4He + 2\,{}^1H$$

PPI - 86%

$$^3He + {}^4He \rightarrow {}^7Be + \gamma$$
$$^7Be + e^- \rightarrow {}^7Li + \boxed{\nu_e}$$
$$^7Li + {}^1H \rightarrow 2\,{}^4He$$

PPII - 14%

$$^7Be + {}^1H \rightarrow {}^8B + \gamma$$
$$^8B \rightarrow {}^8Be + e^+ + \boxed{\nu_e}$$
$$^8Be \rightarrow 2\,{}^4He$$

PPIII - 0.01%

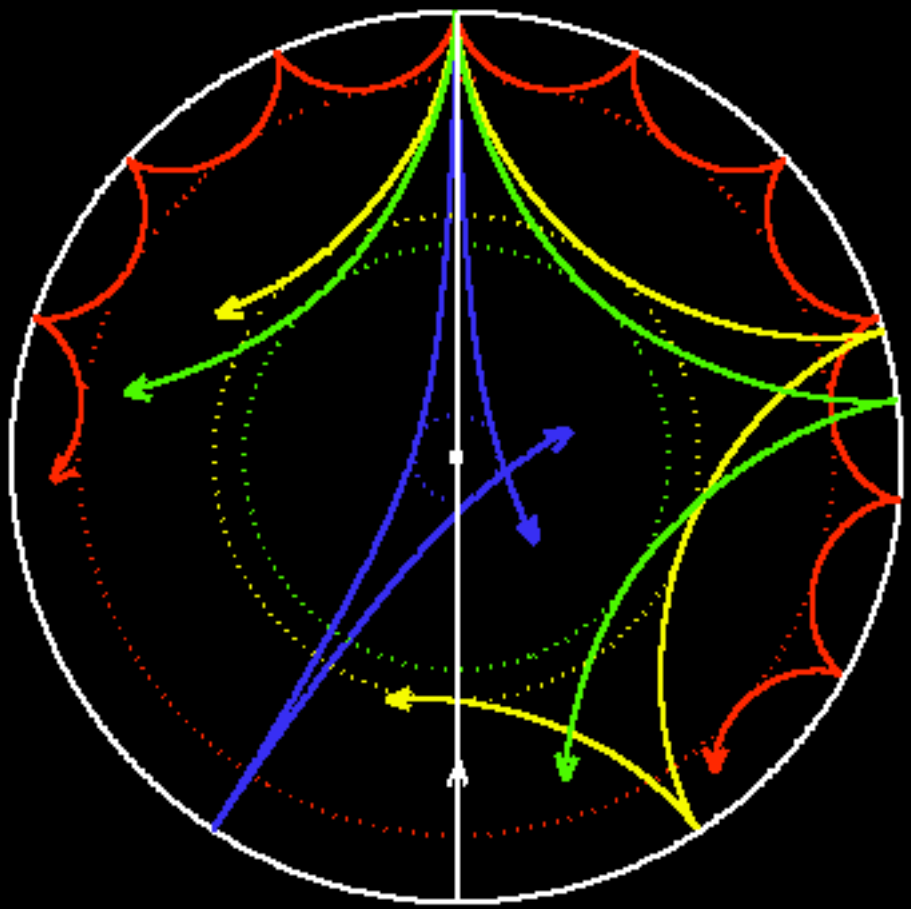
Surface Composition of the Sun:

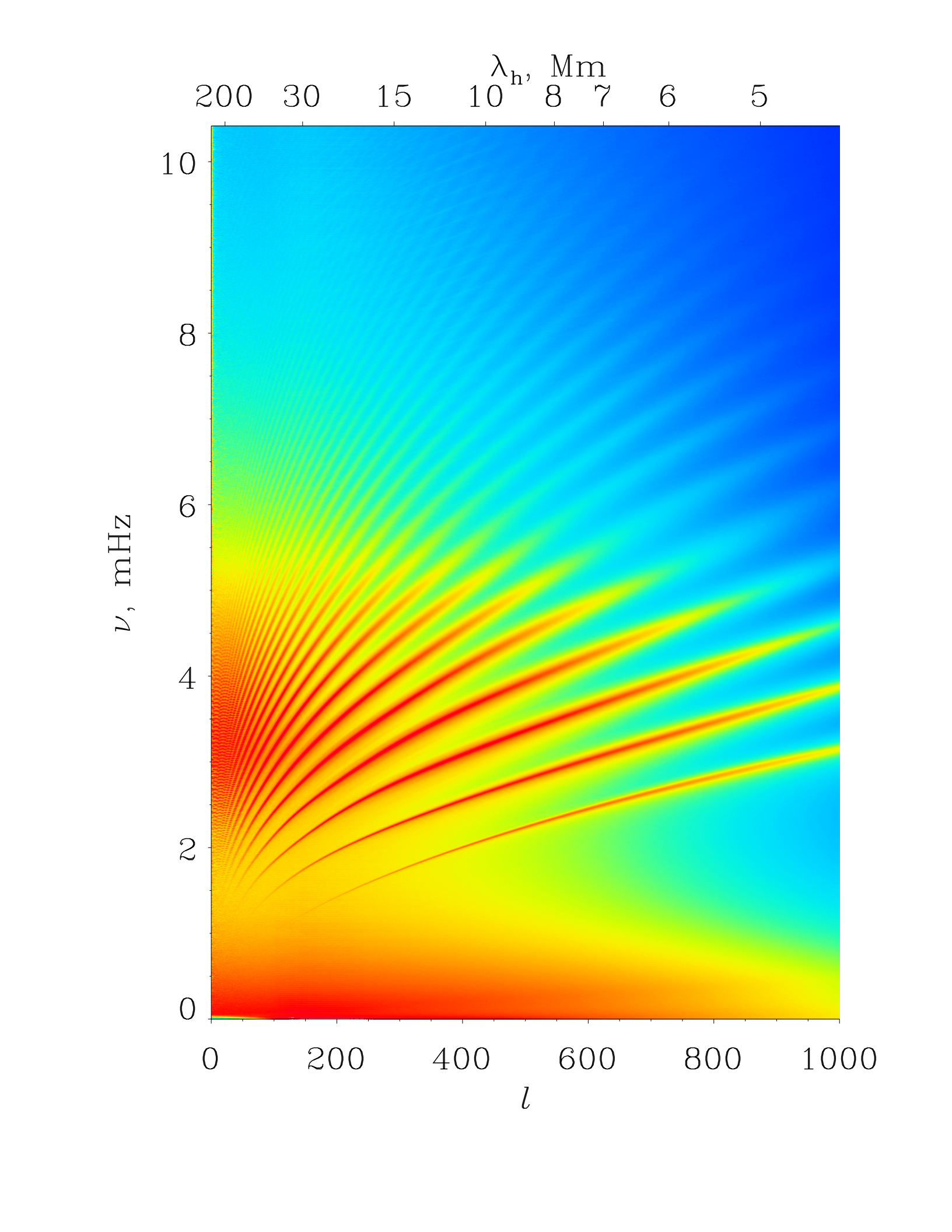
$$X + Y + Z = 1$$

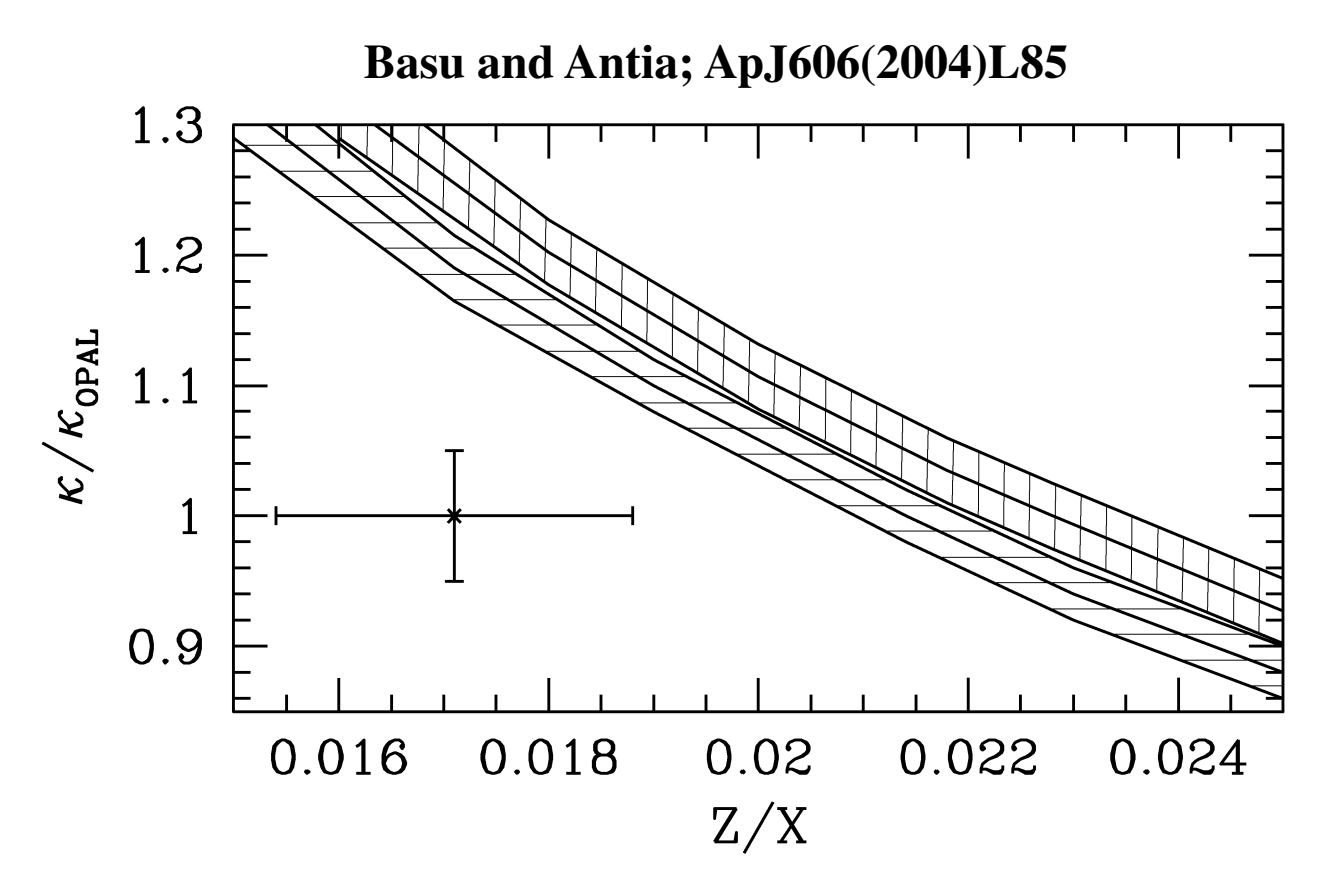
$$P + He + Heavy$$

BS05 Fractional Uncertainties

Source	^{8}B	^{7}Be
p-p	0.01	0.004
$^{3}He + ^{3}He$	0.02	0.02
$^{3}He + ^{4}He$	0.08	0.08
$p + ^{7}Be$	0.04	0.00
Composition	0.12	0.05
Opacity	0.05	0.03
Diffusion	0.04	0.02
Luminosity	0.03	0.01

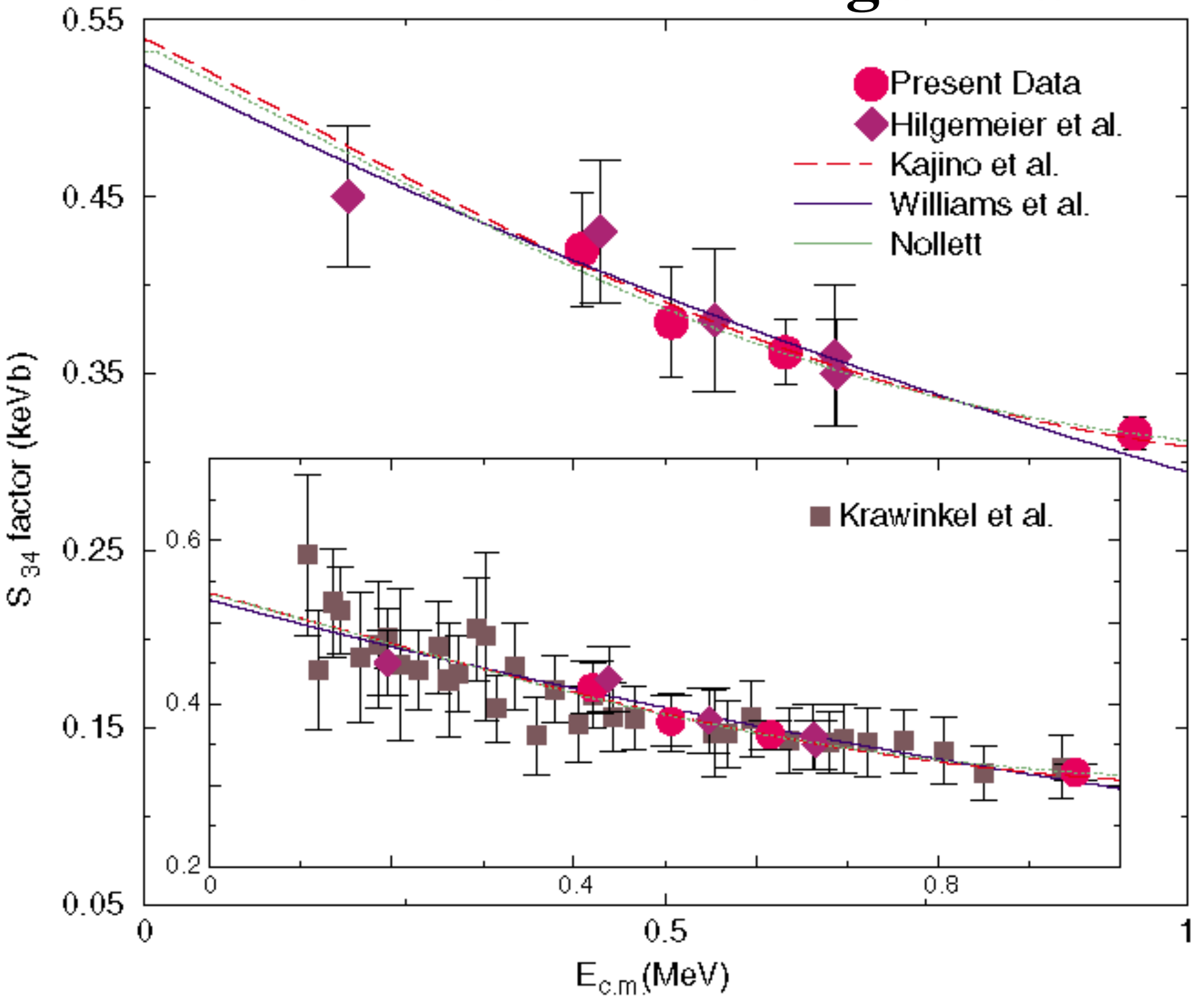


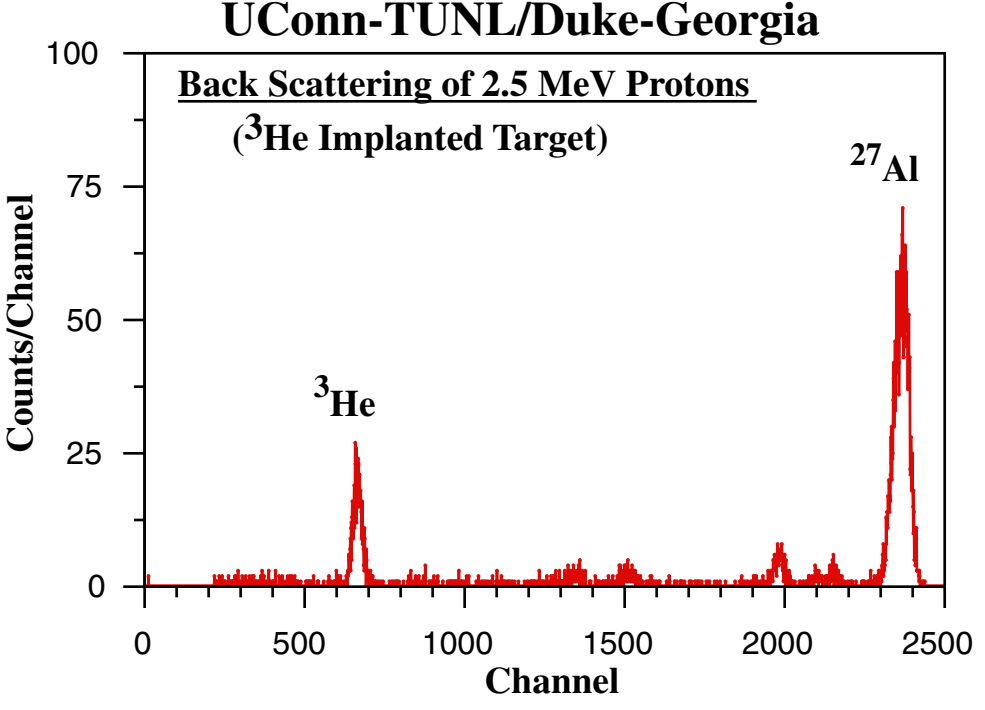

λh, Mm
200
30
15
10
8
7
6
5
10
8
6
4
2
0
ν, mHz
0
200
400
600
800
1000
l


Basu and Antia; ApJ606(2004)L85
1.3
1.2
1.1
1
0.9
κ / κ_{OPAL}
0.016
0.018
0.02
0.022
0.024
Z/X

Weizmann Result, 2004

$^3He + ^4He \longrightarrow ^7Be + gamma$

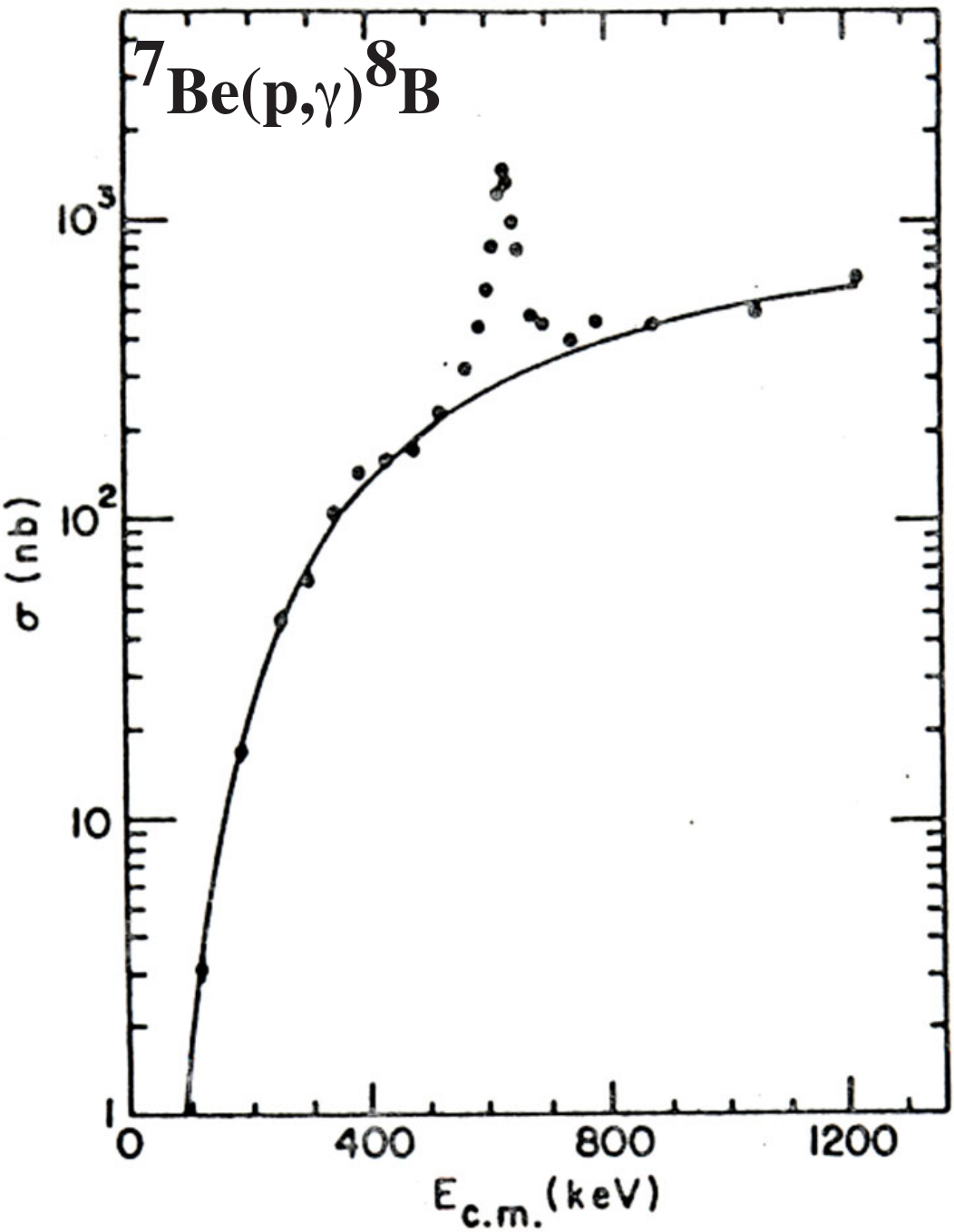



UConn-TUNL/Duke-Georgia
Back Scattering of 2.5 MeV Protons
(3He Implanted Target)
27Al
3He
Counts/Channel
Channel
100
75
50
25
0
0
500
1000
1500
2000
2500

$$\sigma_{17} = S_{17}/E \times e^{-2\pi\eta}$$

$(\eta = Z_1 Z_2 \alpha/\beta)$ $\quad E_{cm} = 18$ keV

Fillipone(1983)



Seattle Result on $^{7}Be + \mathrm{p} \rightarrow {}^{8}B + \gamma$:

$$S_{17}(0) = 21.4 \pm 0.5 \text{ (expt)} \pm 0.6 \text{ (theory)} \text{ eV-b} \qquad [1]$$

Previous Compilation:

$$S_{17}(0) = 19 \text{ +4 -2 eV-b} \qquad [2]$$

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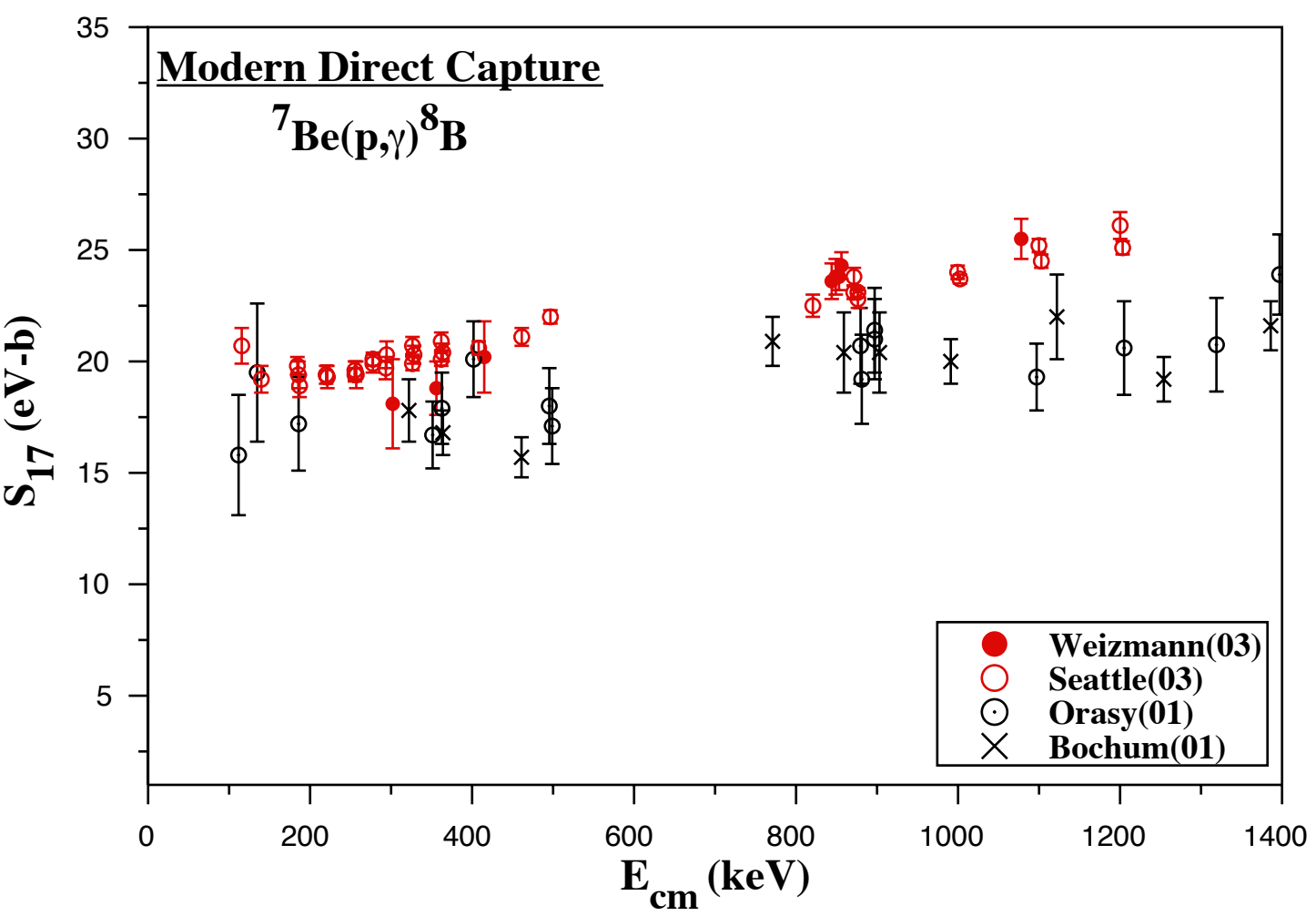
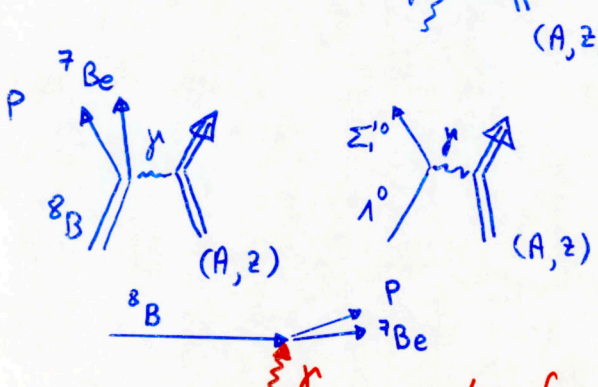
[1] A.R. Junghans *et al.*; Phys. Rev. **C68**(2003)065803.

[2] E.G. Adelberger *et al.*; rev. Mod. Phys. **70**(1998)1265.


Modern Direct Capture
$^{7}Be(p,\gamma)^{8}B$
S_{17} (eV-b)
E_{cm} (keV)
35
30
25
20
15
10
5
0
200
400
600
800
1000
1200
1400
Weizmann(03)
Seattle(03)
Orasy(01)
Bochum(01)

CAPTURE REACTION: $^7Be + p \rightleftarrows {}^8B + \gamma$

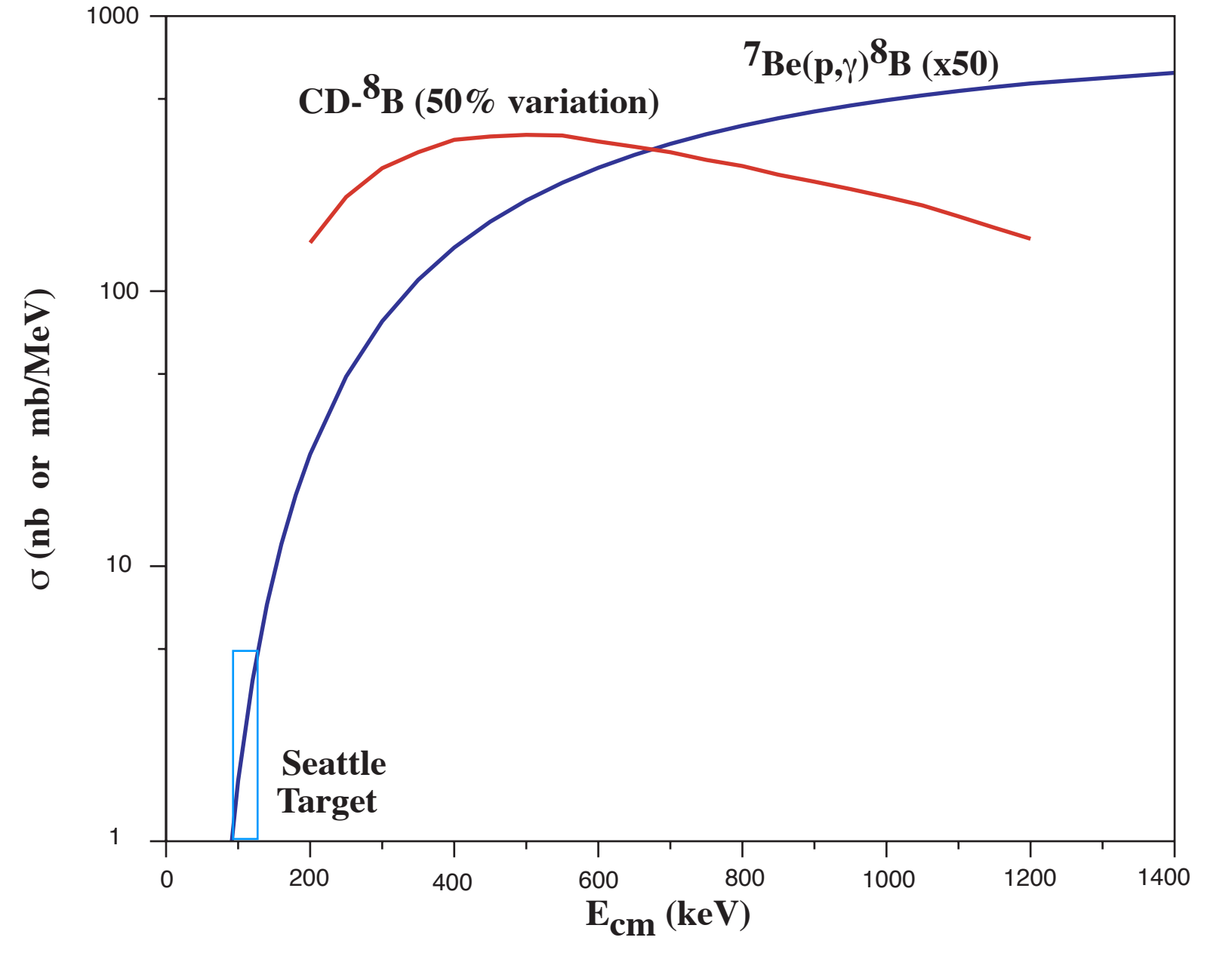
PRIMAKOFF (1951):



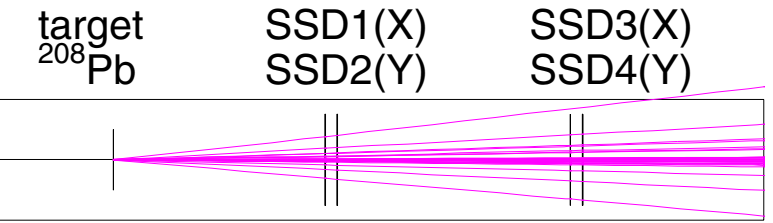
ENHANCEMENT: (I) $\pi/k^2 \approx 1,000$

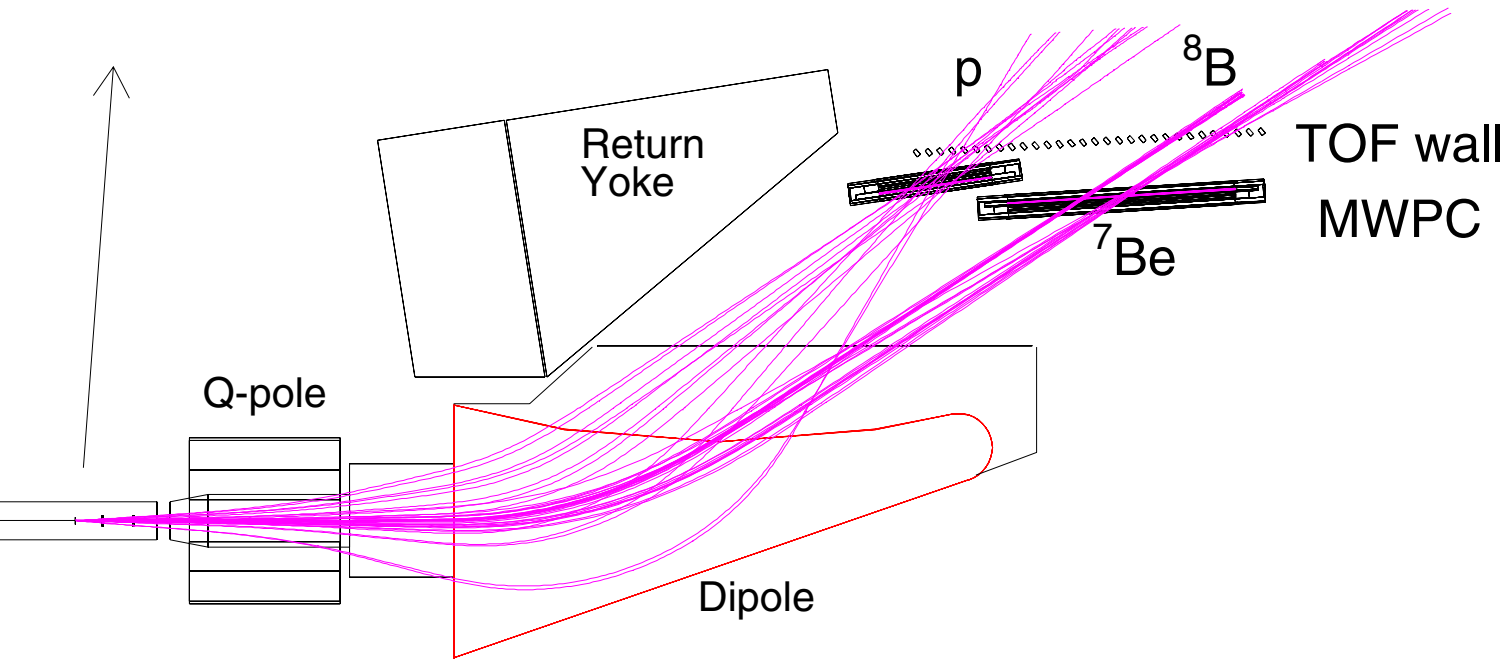
(II) $n_\gamma(E1) \approx 1000$

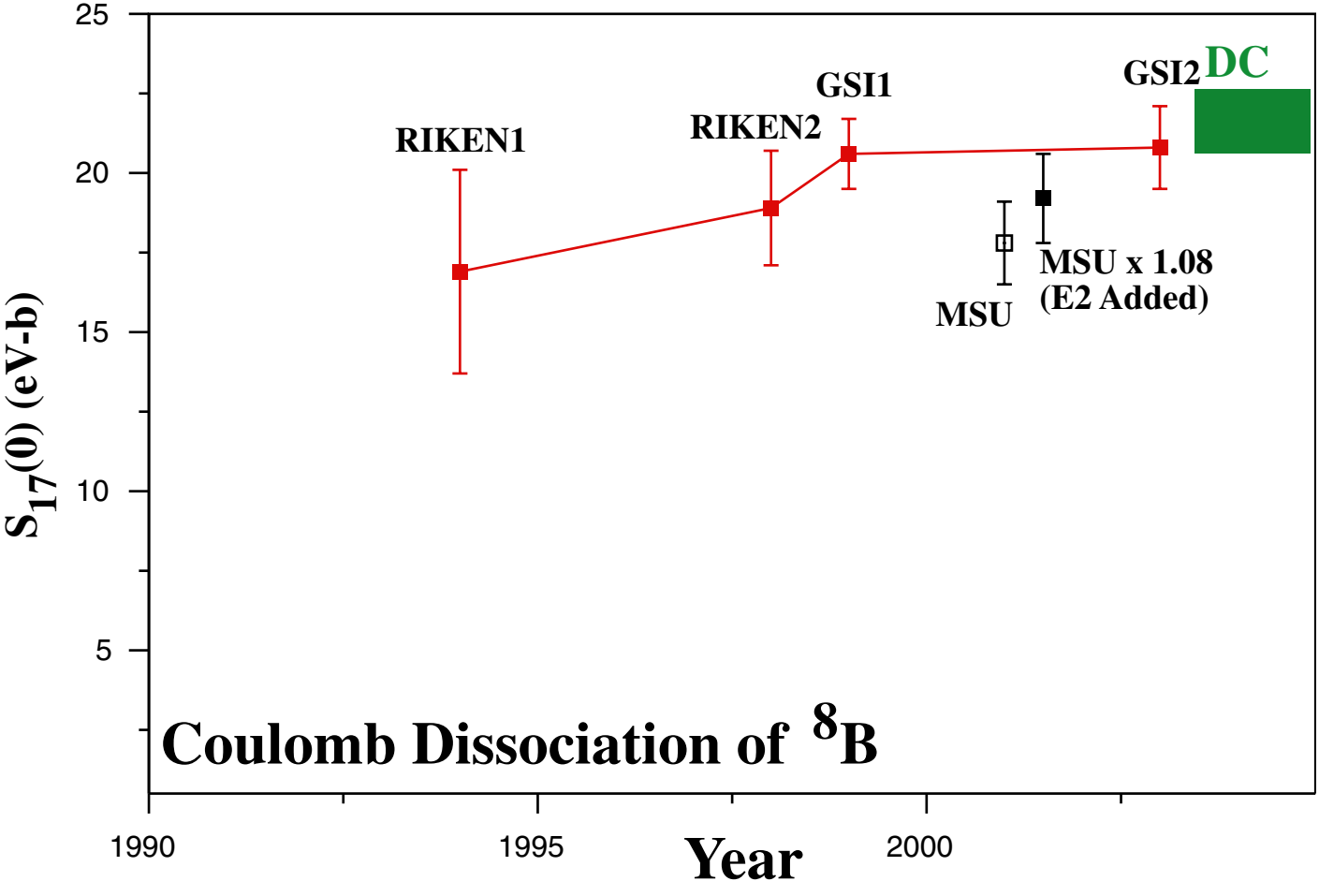
BAUR, BERTULANI, REBEL - 1986

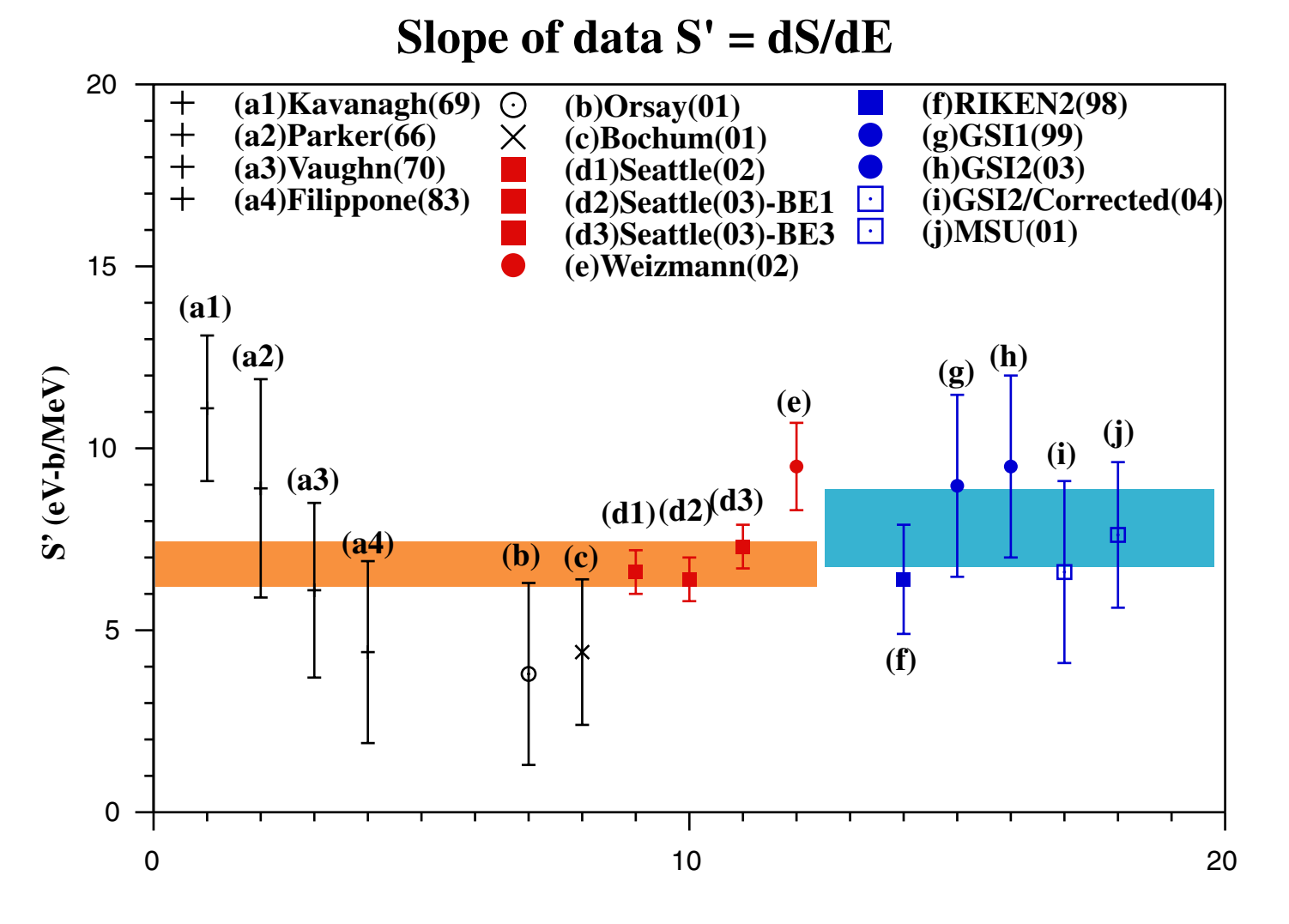

1000
100
10
1
σ (nb or mb/MeV)
0
200
400
600
800
1000
1200
1400
E_cm (keV)
7Be(p,γ)8B (x50)
CD-8B (50% variation)
Seattle
Target

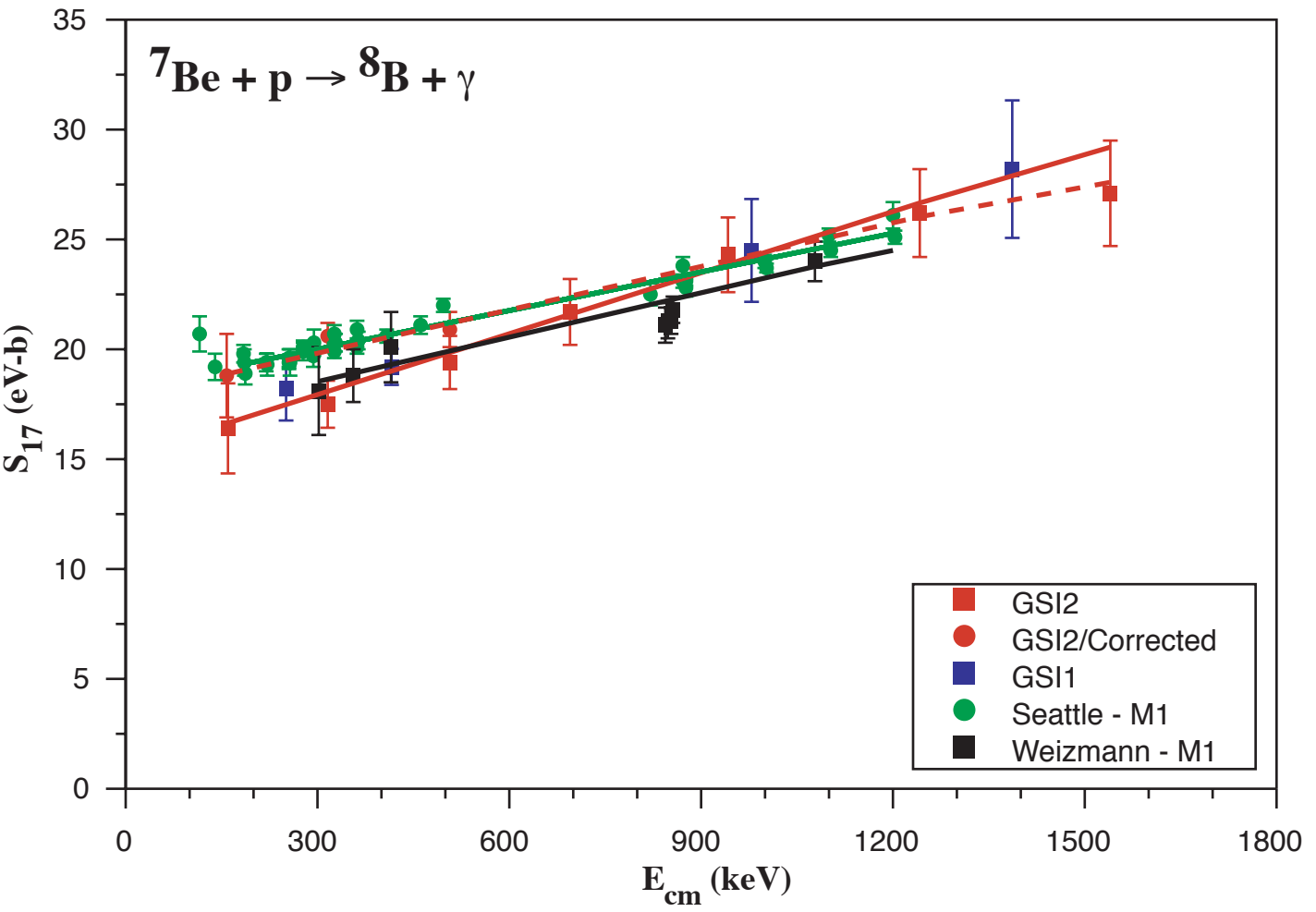
KAOS @ GSI

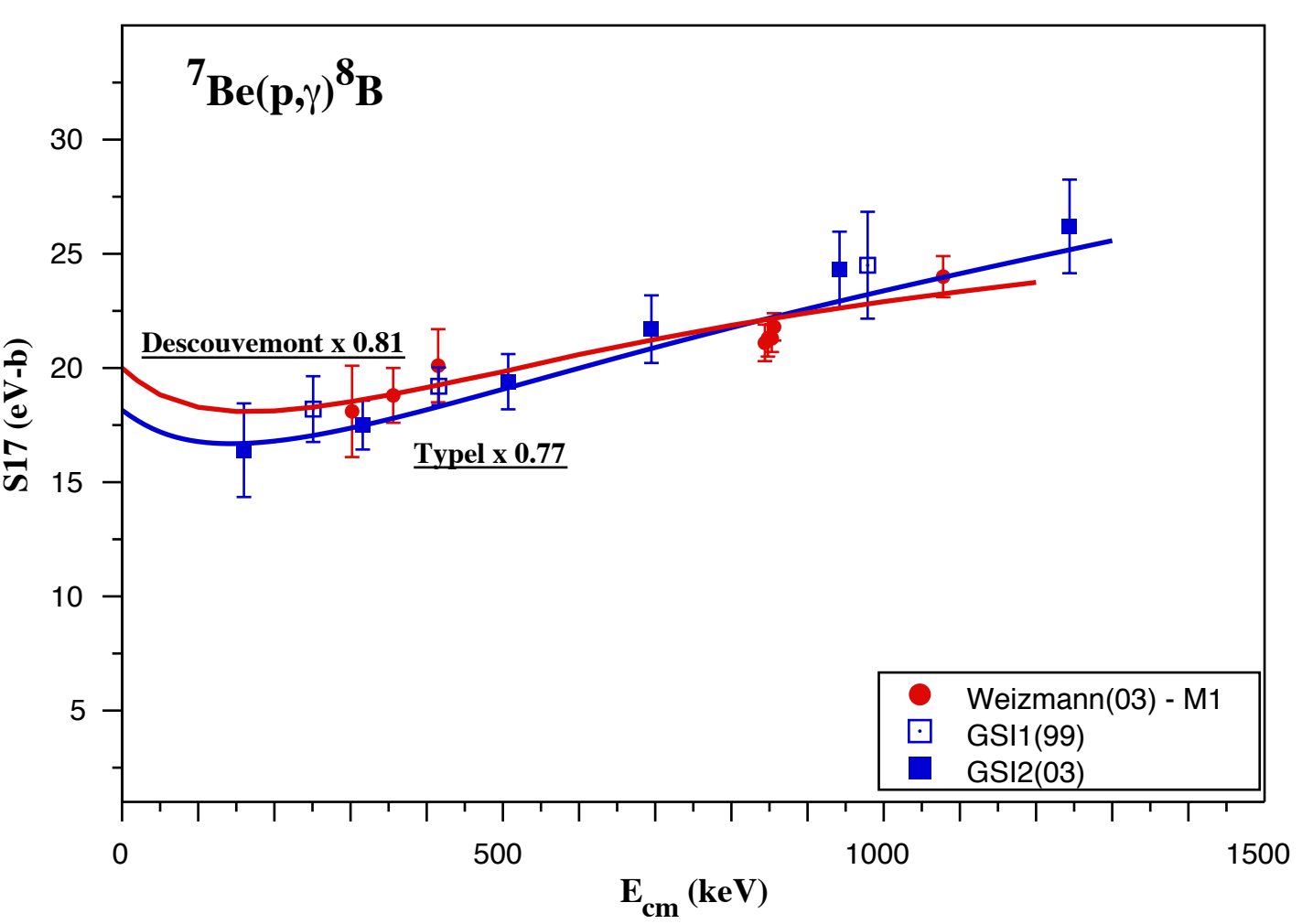

target
^{208}Pb
SSD1(X)
SSD2(Y)
SSD3(X)
SSD4(Y)


p
^{8}B
TOF wall
MWPC
Return
Yoke
^{7}Be
Q-pole
Dipole


25
20
15
10
5
$S_{17}(0)$ (eV-b)
RIKEN1
RIKEN2
GSI1
GSI2
DC
MSU
MSU x 1.08
(E2 Added)
Coulomb Dissociation of ^{8}B
1990
1995
2000
Year


Slope of data S' = dS/dE
(a1)Kavanagh(69)
(a2)Parker(66)
(a3)Vaughn(70)
(a4)Filippone(83)
(b)Orsay(01)
(c)Bochum(01)
(d1)Seattle(02)
(d2)Seattle(03)-BE1
(d3)Seattle(03)-BE3
(e)Weizmann(02)
(f)RIKEN2(98)
(g)GSI1(99)
(h)GSI2(03)
(i)GSI2/Corrected(04)
(j)MSU(01)
S' (eV-b/MeV)
0
5
10
15
20
0
10
20


$^7Be + p \rightarrow {}^8B + \gamma$
S_{17} (eV-b)
E_{cm} (keV)
0
5
10
15
20
25
30
35
0
300
600
900
1200
1500
1800
GSI2
GSI2/Corrected
GSI1
Seattle - M1
Weizmann - M1


$^{7}Be(p,\gamma)^{8}B$
Descouvemont x 0.81
Typel x 0.77
Weizmann(03) - M1
GSI1(99)
GSI2(03)
S17 (eV-b)
E_{cm} (keV)
30
25
20
15
10
5
0
500
1000
1500

Seattle Result on $^7Be + \mathrm{p} \rightarrow {}^8B + \gamma$:

$$S_{17}(0) = 21.4 \pm 0.5 \text{ (expt)} \pm 0.6 \text{ (theory) eV-b} \quad [1]$$

Previous Compilation:

$$S_{17}(0) = 19 \ {}^{+4}_{-2} \text{ eV-b} \quad [2]$$

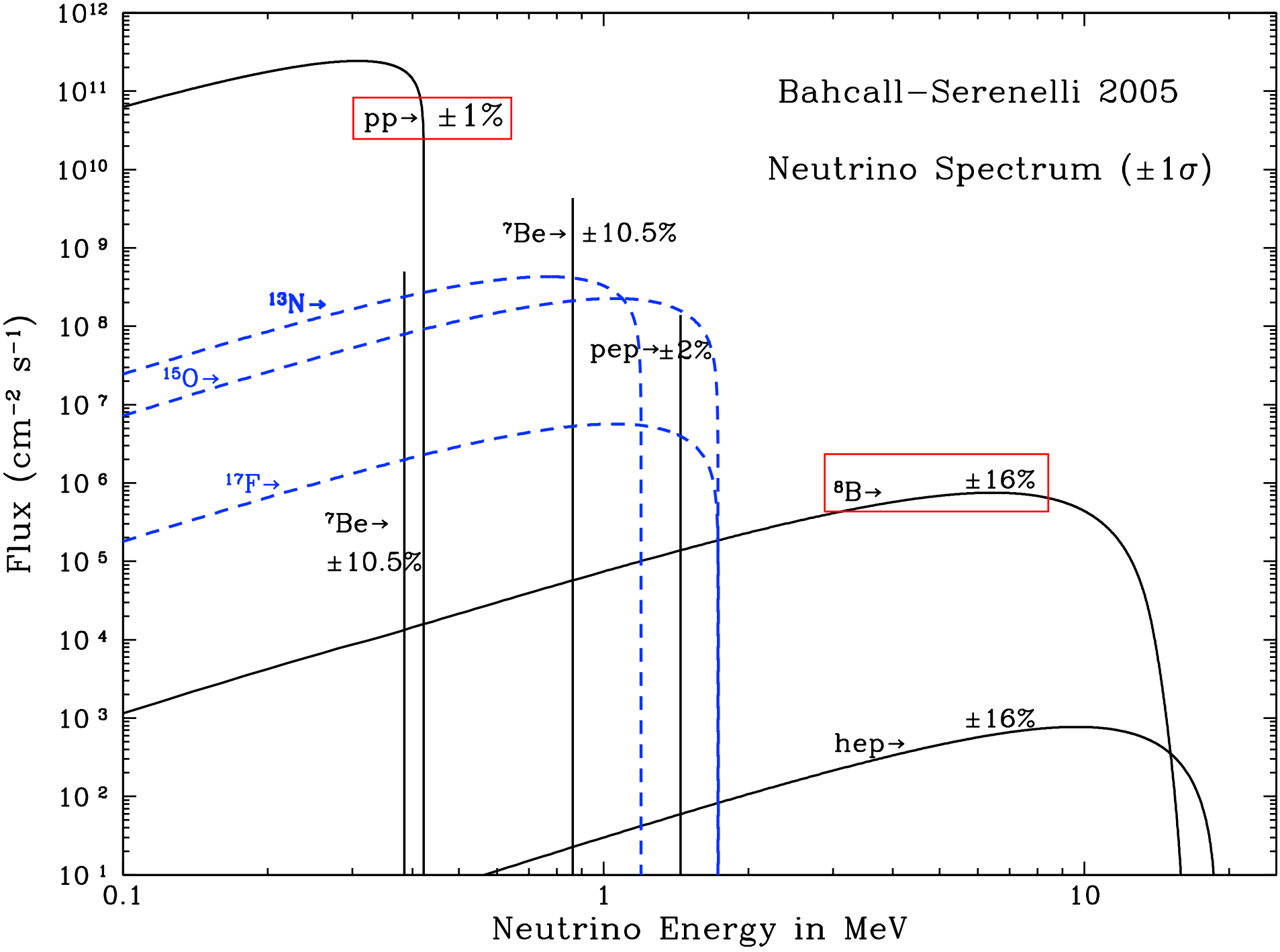
Reasonable Conservative Estimate:

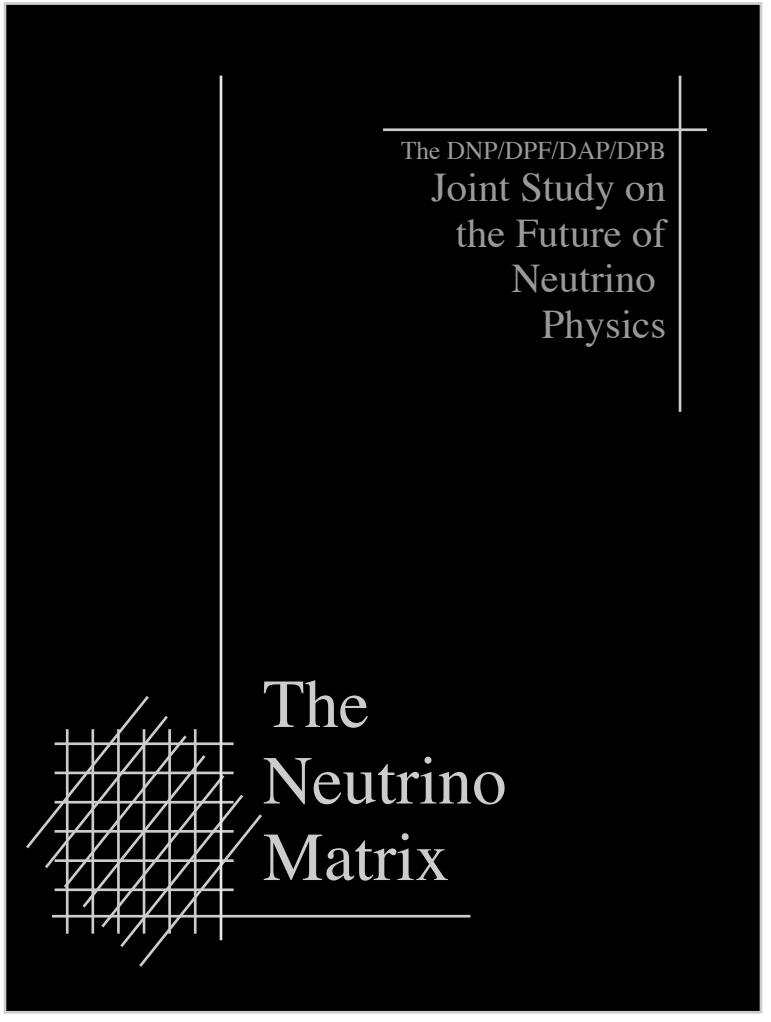
$$S_{17}(0) = 21.4 \pm 0.8 \text{ (expt)} \ {}^{+0.0}_{-3.0} \text{ (extrap) eV-b} \quad [3]$$

[1] A.R. Junghans *et al.*; Phys. Rev. **C68**(2003)065803.

[2] E.G. Adelberger *et al.*; rev. Mod. Phys. **70**(1998)1265.

[3] M. Gai; nucl-ex/0312003.


Bahcall–Serenelli 2005
Neutrino Spectrum (±1σ)
pp→ ±1%
⁷Be→ ±10.5%
¹³N→
¹⁵O→
¹⁷F→
pep→±2%
⁷Be→
±10.5%
⁸B→ ±16%
hep→ ±16%
Flux (cm⁻² s⁻¹)
Neutrino Energy in MeV
10¹²
10¹¹
10¹⁰
10⁹
10⁸
10⁷
10⁶
10⁵
10⁴
10³
10²
10¹
0.1
1
10



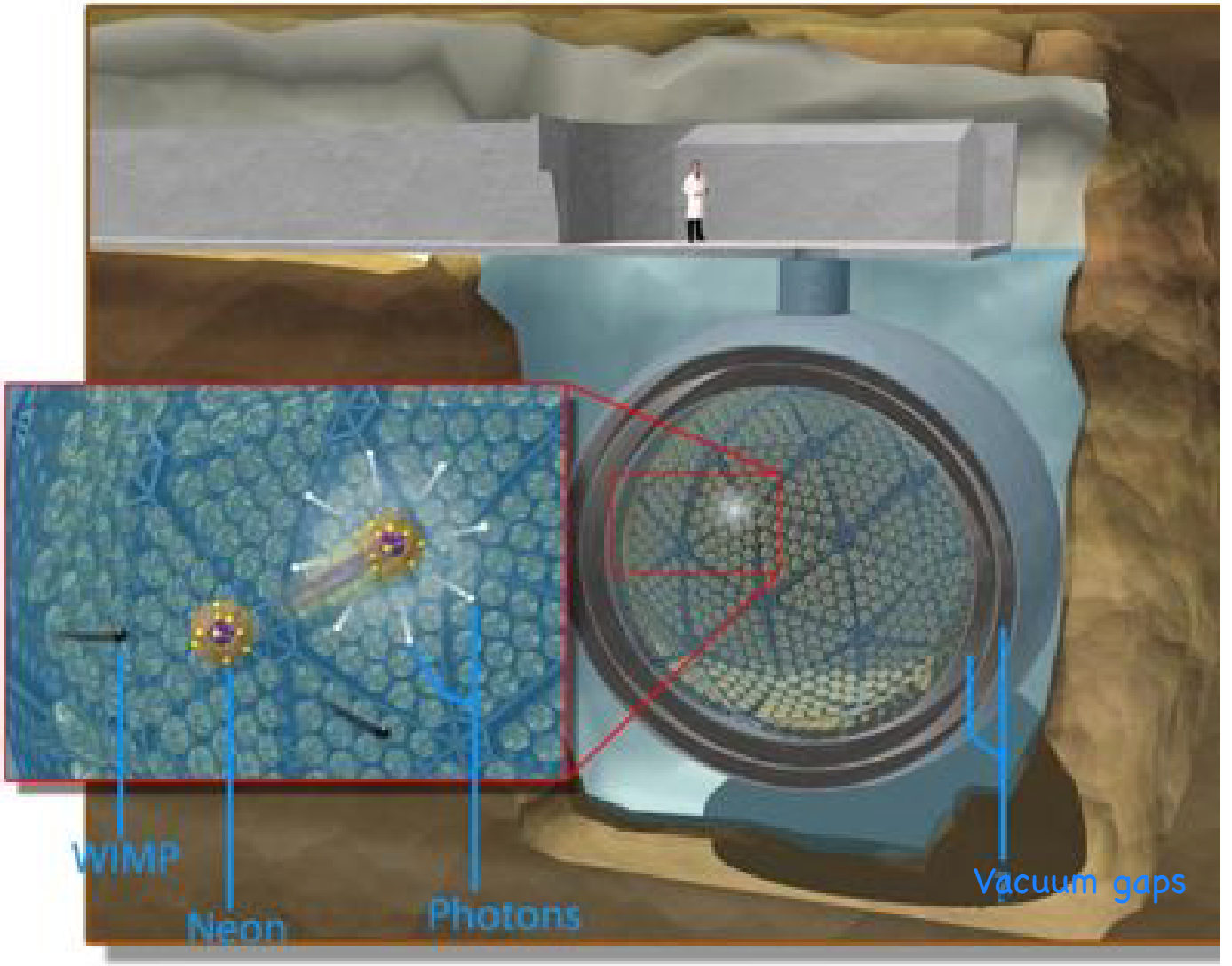
The Neutrino Matrix:

- We recommend, as a high priority, that a phased program of sensitive searches for neutrinoless nuclear double beta decay be initiated as soon as possible.

- We recommend, as a high priority, a comprehensive U.S. program to complete our understanding of neutrino mixing, to determine the character of the neutrino mass spectrum, and to search for CP violation among neutrinos.

- We recommend the development of a spectroscopic solar neutrino experiment capable of measuring the energy spectrum of neutrinos from the primary pp fusion process in the sun.

Artist's Rendition of CLEAN



Solar Composition:

^{8}B Flux error down from 20% to 12%
Confrontation with SSM
Must be resolved

^{8}B Solar Neutrino Flux:

S_{34} soon will be known (<5%)
S_{17} Seattle result must be checked
Extrapolation must be checked

Is SSM/Flux = 1.17 significant?

pp Solar Neutrino Flux:

Most Exciting Frontier (CLEAN)