REAZIONI NUCLEARI DI INTERESSE ASTROFISICO

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Riassunto del corso:

- <u>teoria del momento angolare</u> → costruzione delle funzioni d'onda
- <u>teoria perturbativa dipendente dal tempo</u>: calcolo della sezione d'urto (e fattore astrofisico)
- <u>funzioni d'onda</u>: stati legati (d, ^{3}He, ^{3}H) e stati di scattering (pp, np, Nd) anche con potenziali realistici
- <u>corrente nucleare</u>: termine one-body e meson-exchange currents
- <u>reazioni considerate in dettaglio</u>:

$p + p \rightarrow d + e^+ + \nu_e$ e $n + p \rightarrow d + \gamma$

Campi di applicazione

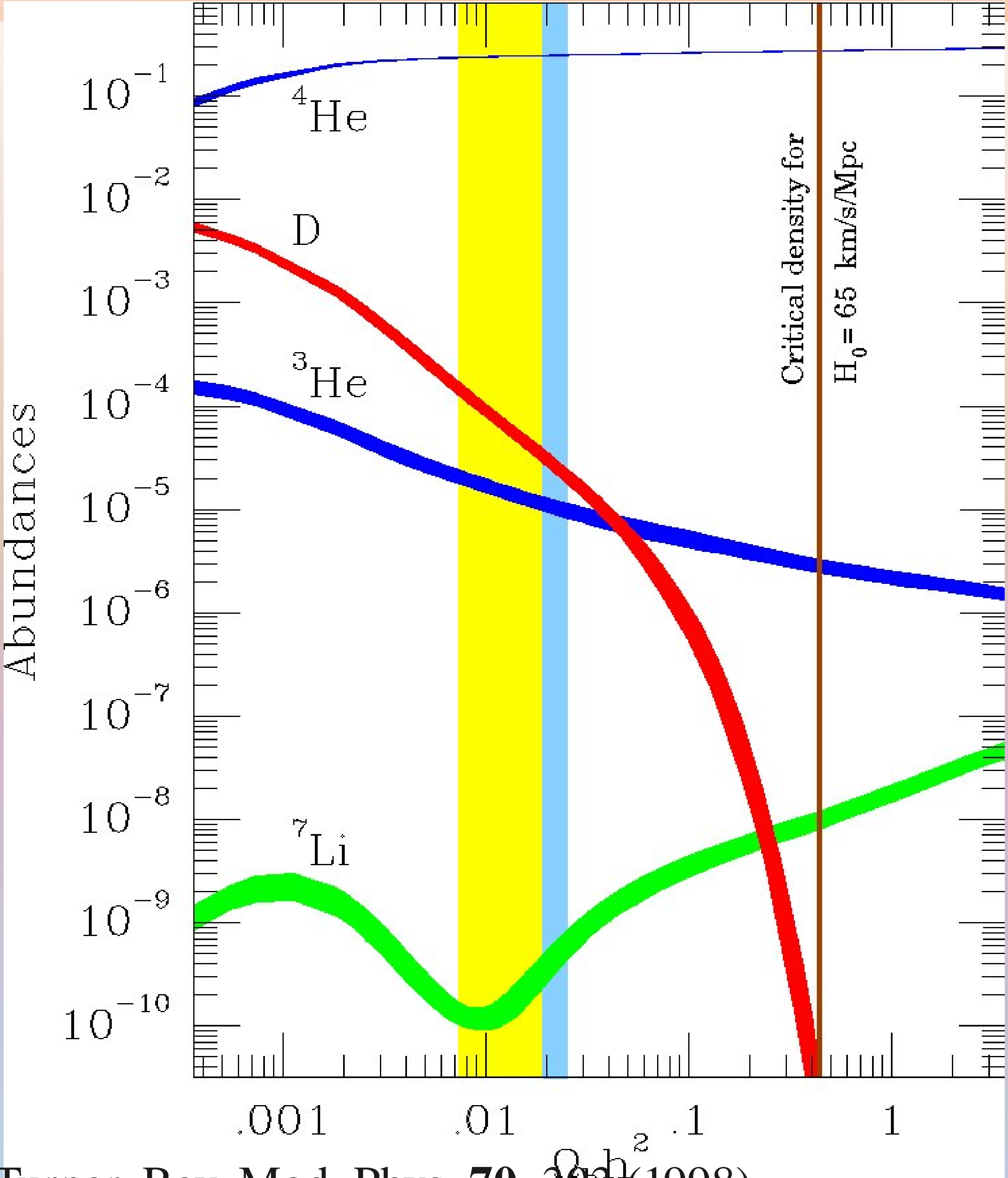
- Big Bang nucleosynthesis (BBN)
- Produzione solare di energia attraverso una catena di reazioni nucleari

Big Bang nucleosynthesis (BBN)
(naive picture)

- Step 1 (kT < few MeV): thermal eq.; *n/p* ~ 1
- Step 2 (kT ~ 0.7 MeV): weak int. freeze-out, *n/p* ~ 1/6 $\rightarrow$ 1/7
- Step 3 (kT ~ 0.5 MeV): nuclear reactions, which form *d*, ^{3}He, ^{4}He, ^{7}Li

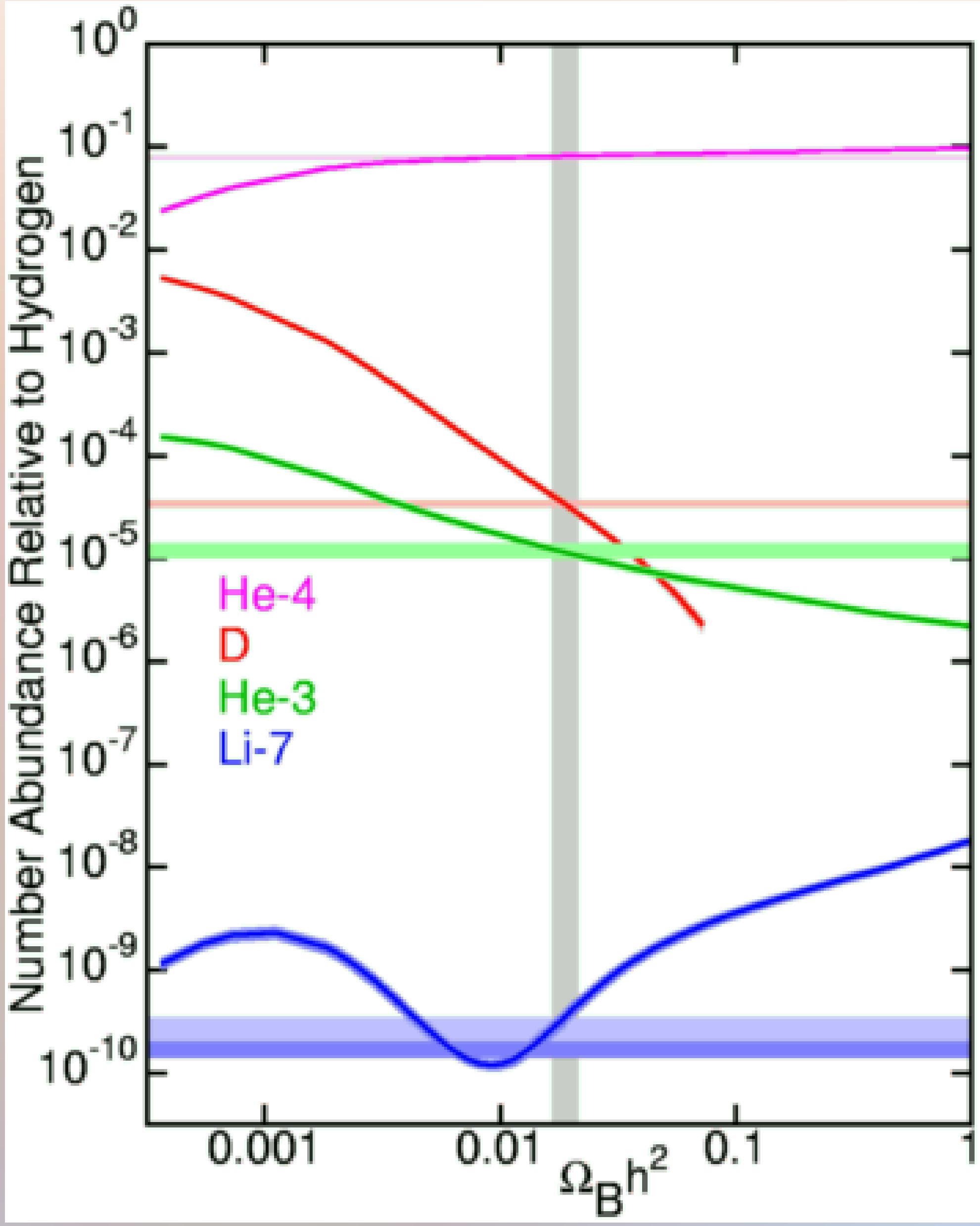
11 key nuclear reactions, among which:

- $n + p \rightarrow d + \gamma$
- $p + d \rightarrow {}^{3}\mathrm{He} + \gamma$
- ${}^{3}\mathrm{H} + \alpha \rightarrow {}^{7}\mathrm{Li} + \gamma$
- ${}^{3}\mathrm{He} + \alpha \rightarrow {}^{7}\mathrm{Be} + \gamma$
- ${}^{7}\mathrm{Be} + n \rightarrow {}^{7}\mathrm{Li} + p$

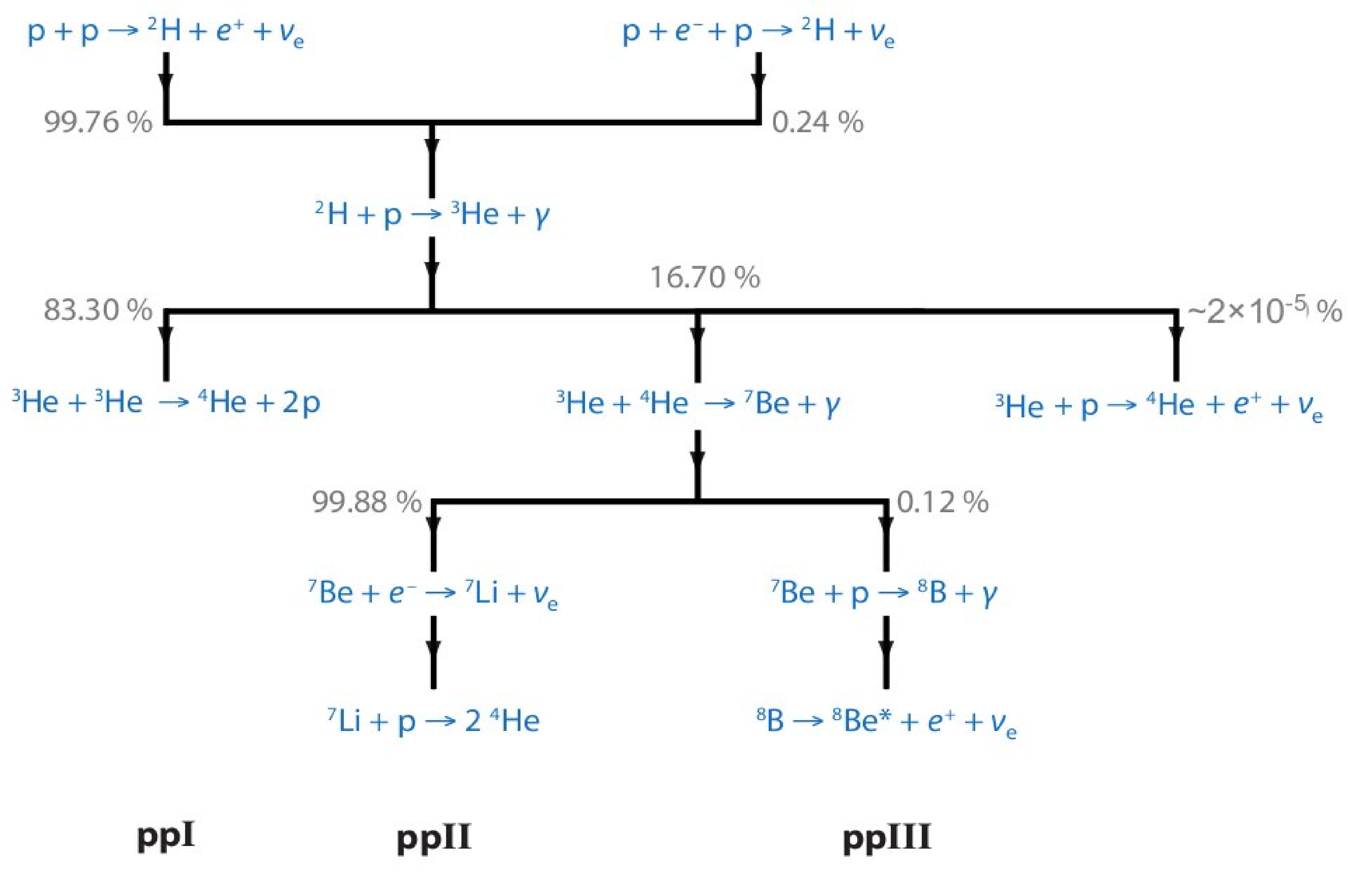


Schramm and Turner, Rev. Mod. Phys. **70**, 303 (1998)

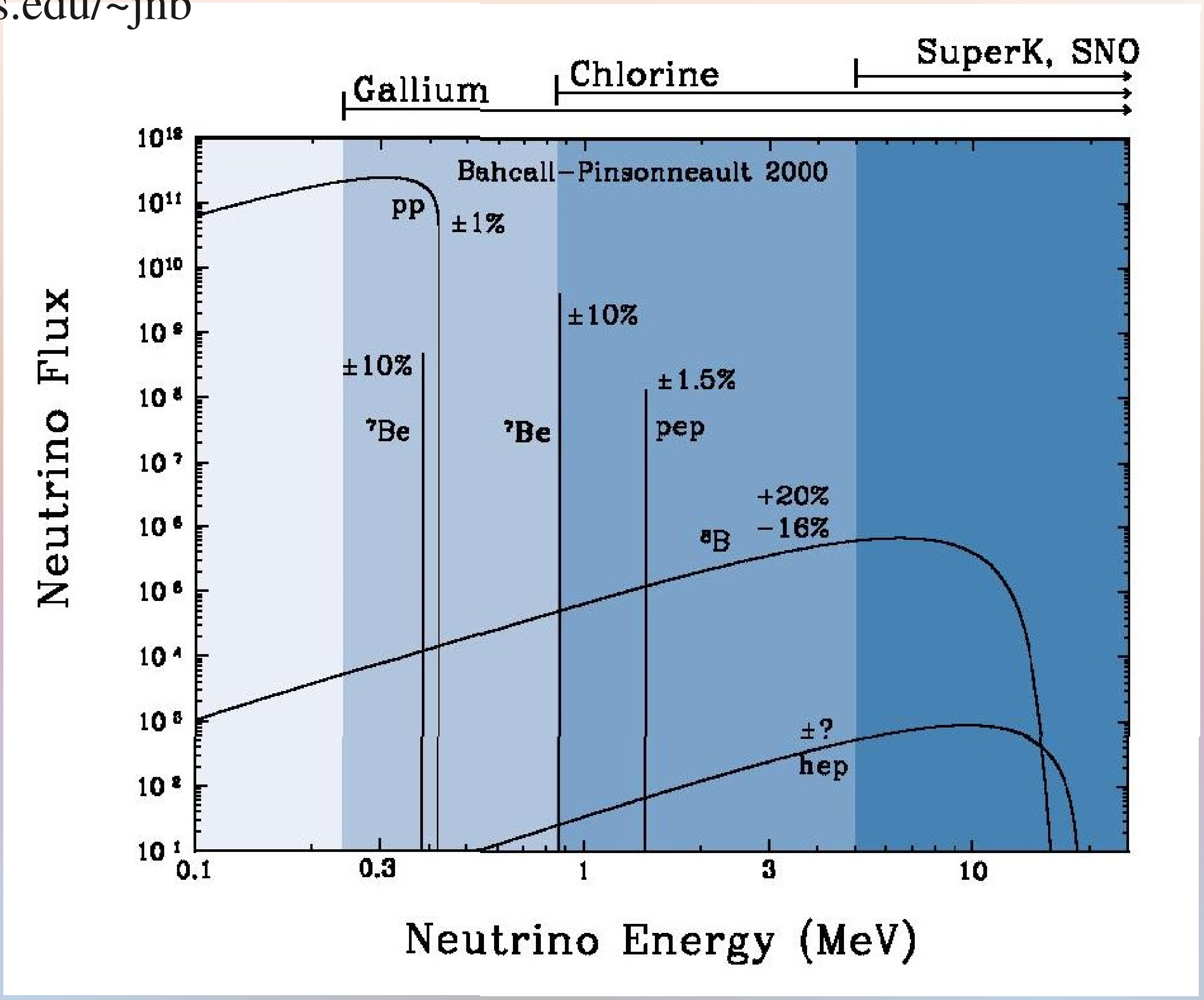
But at present ...



Solar neutrinos: the *pp* chain



www.sns.ias.edu/~jnb

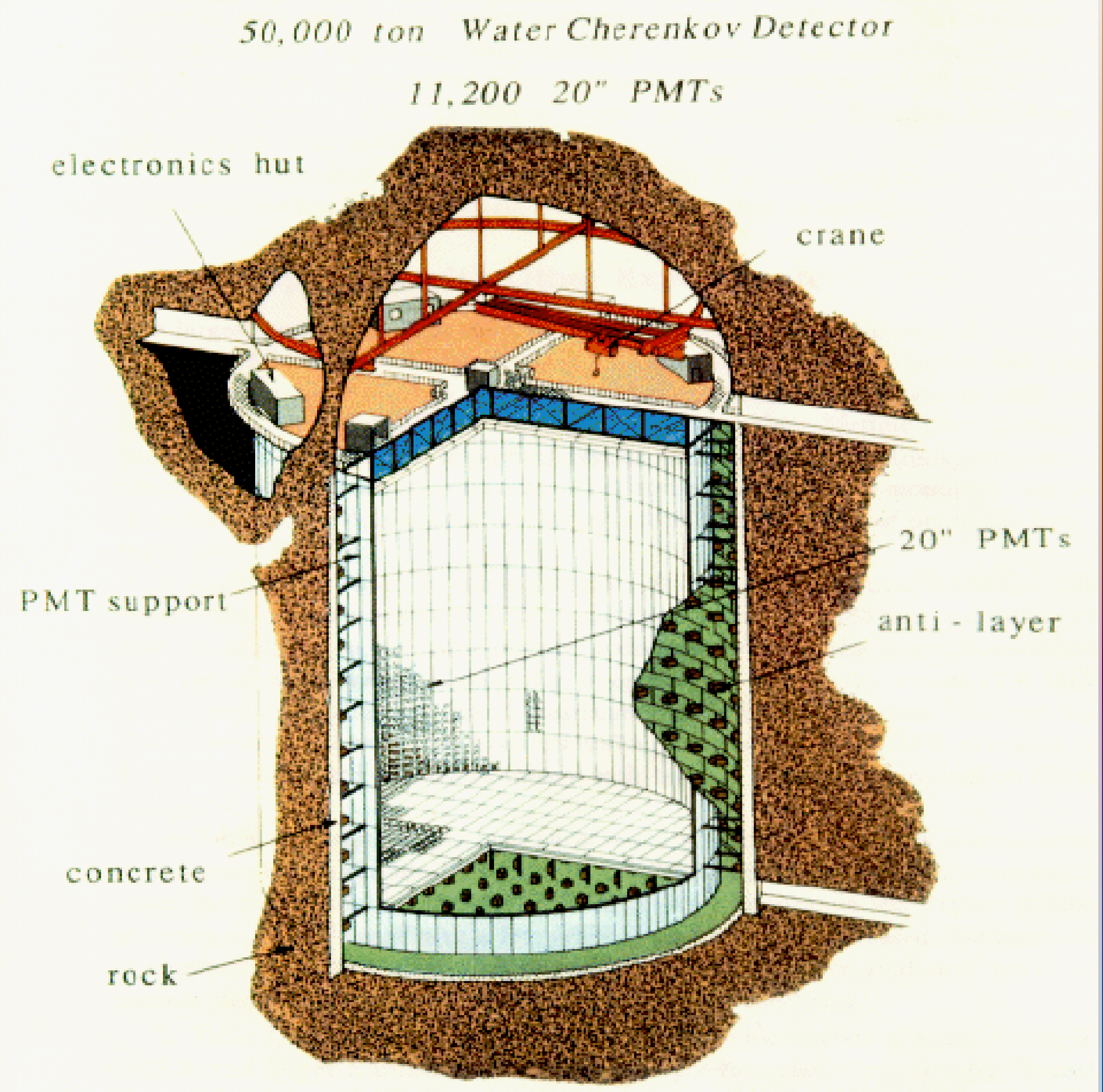


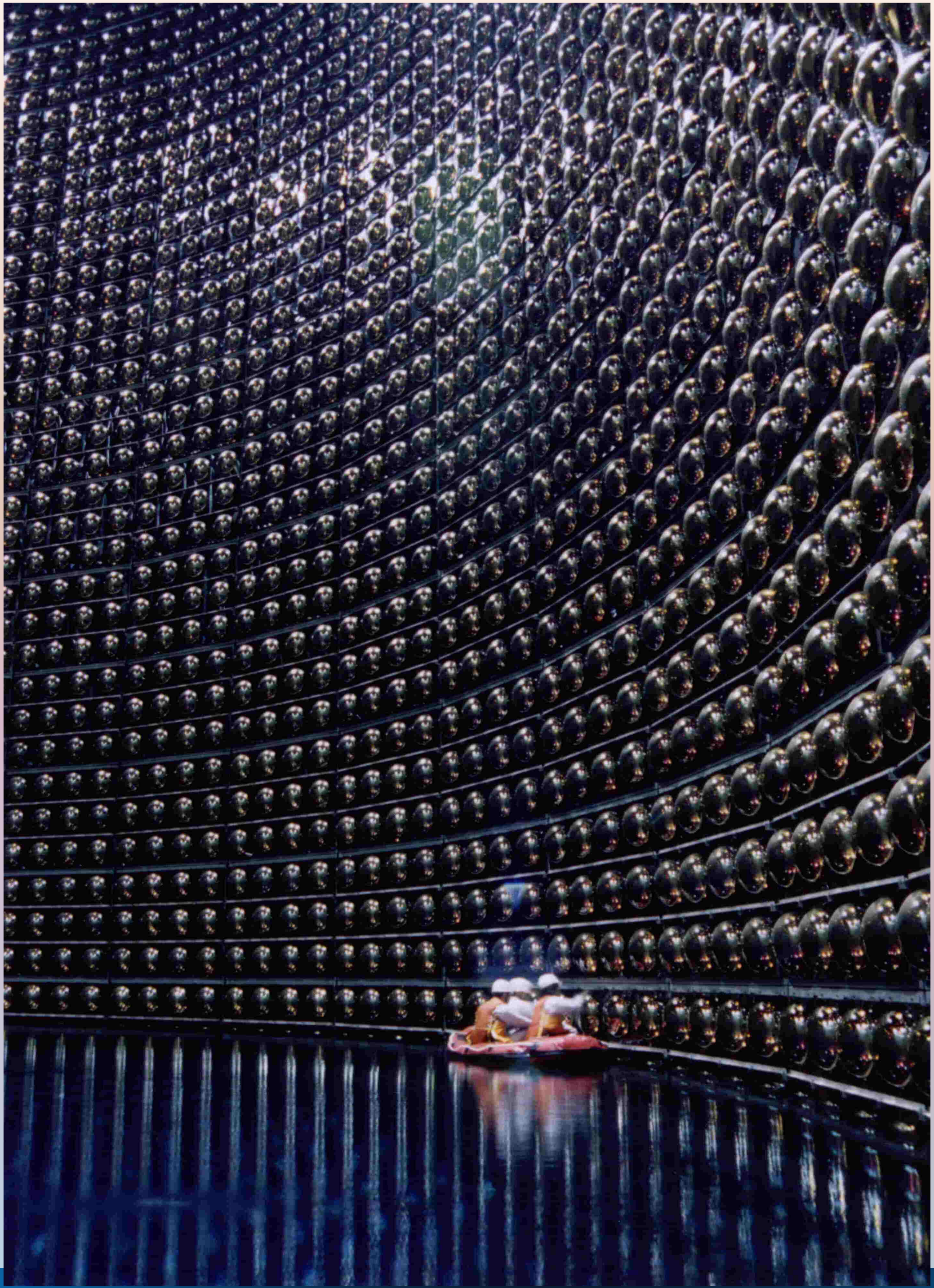
The SuperKamiokande (SK) experiment

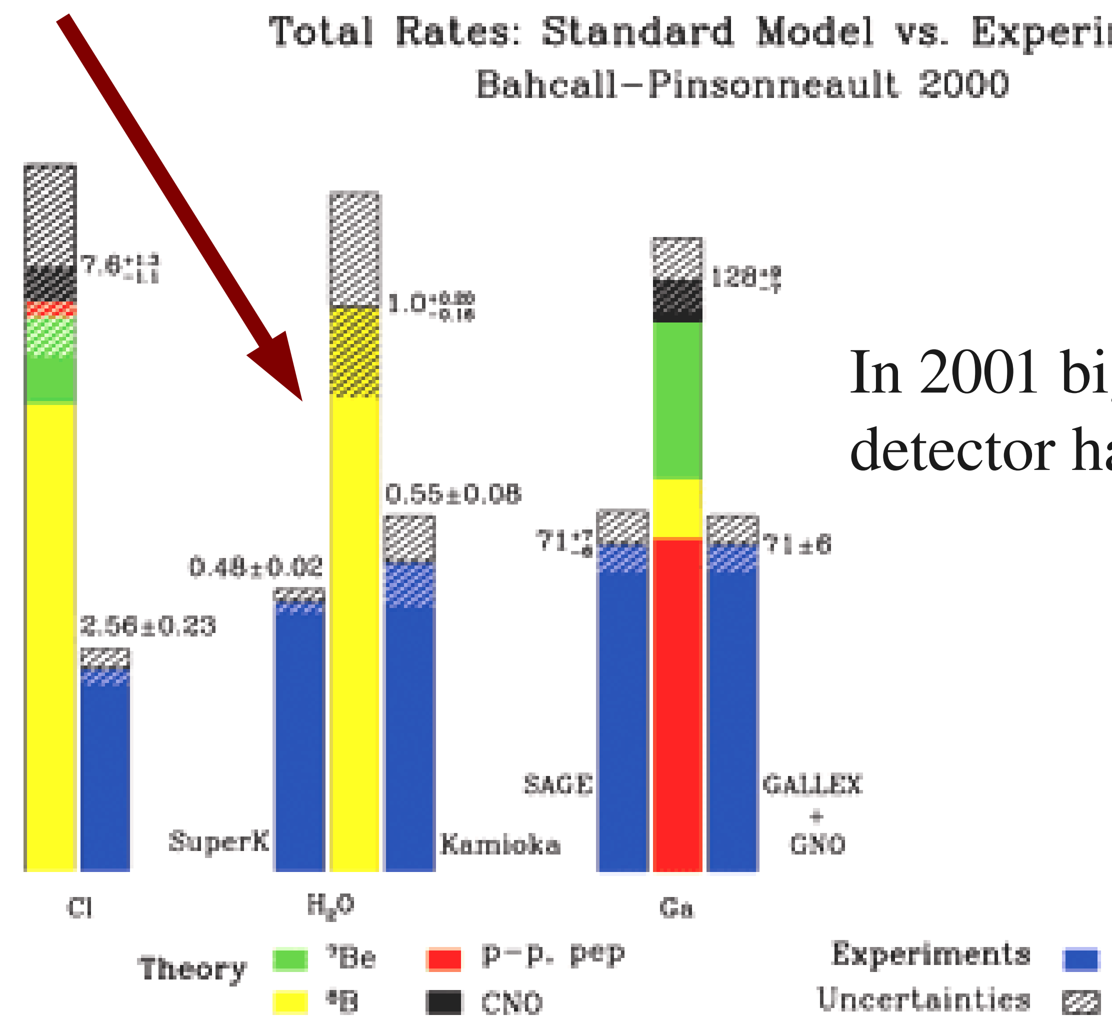
Elastic scattering

$\nu + e \rightarrow \nu + e$

Sensitive to all the ν, but in fact particularly to ν_e

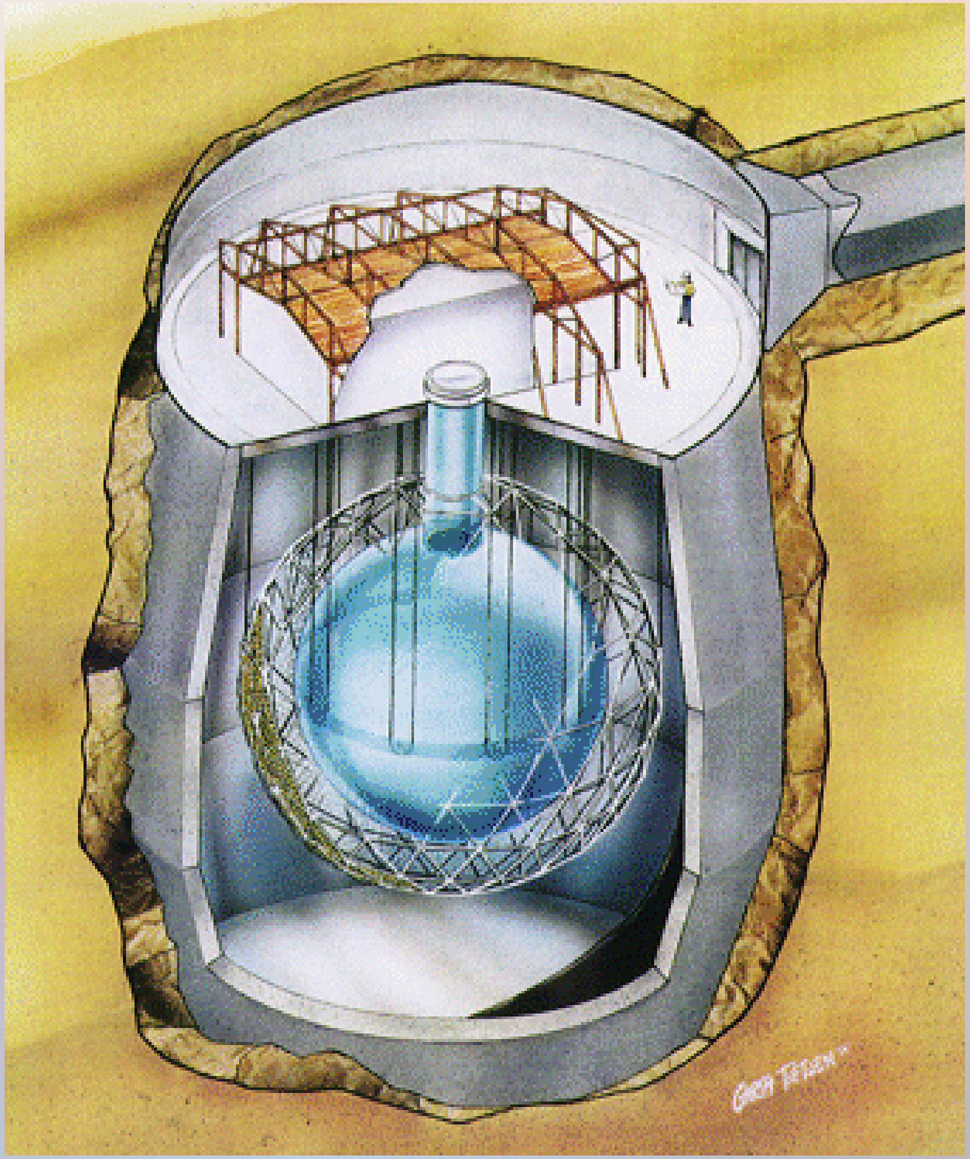


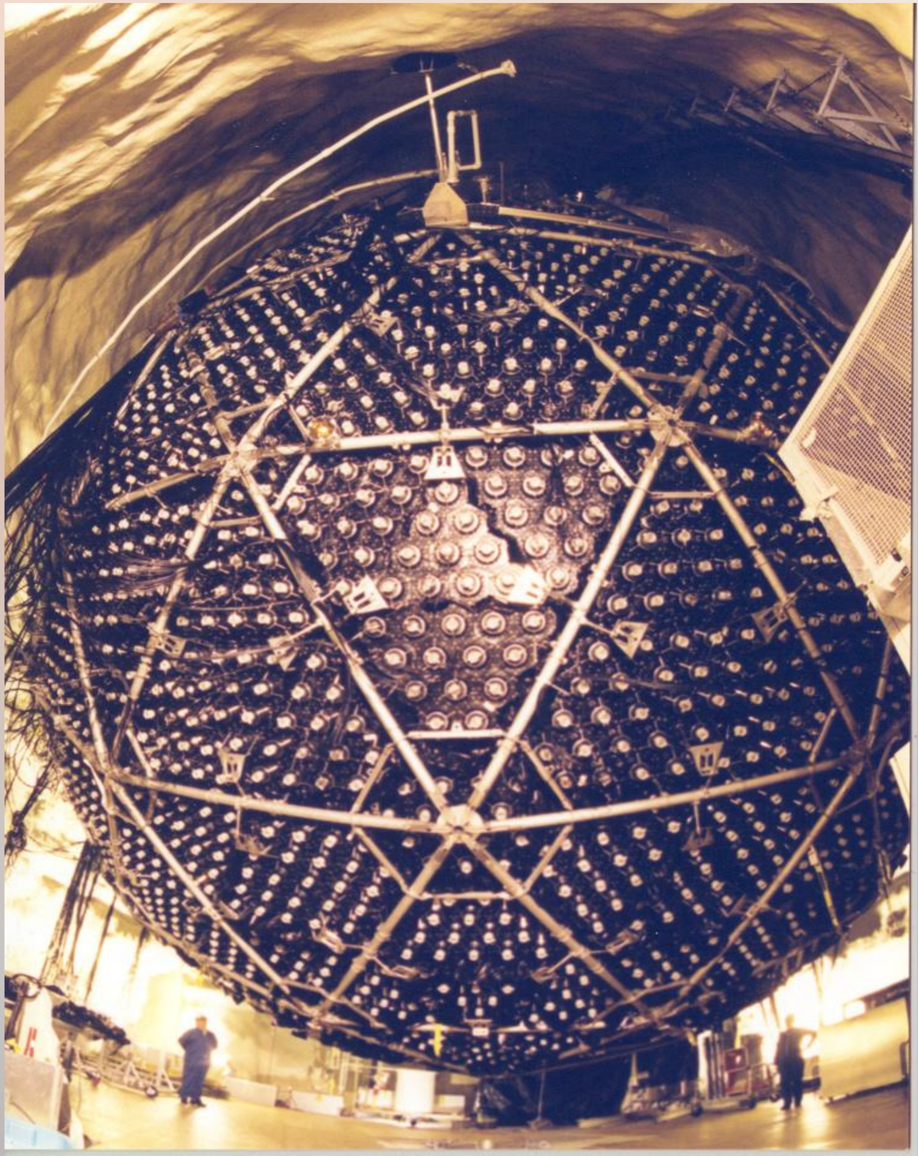




In 2001 big accident: SK detector half-destroyed!

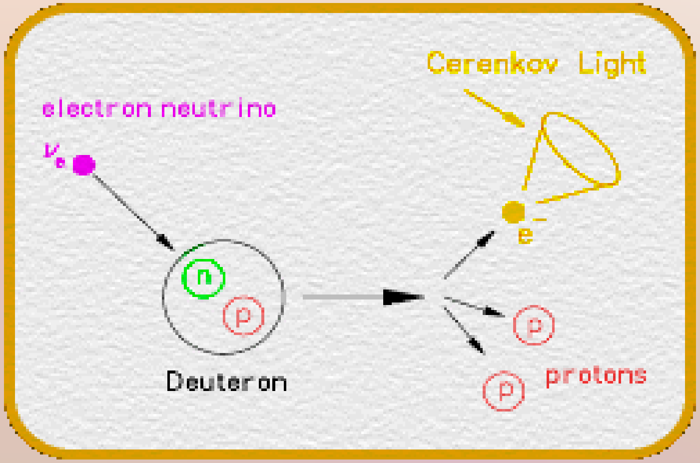
The Sudbury Neutrino Observatory (SNO)



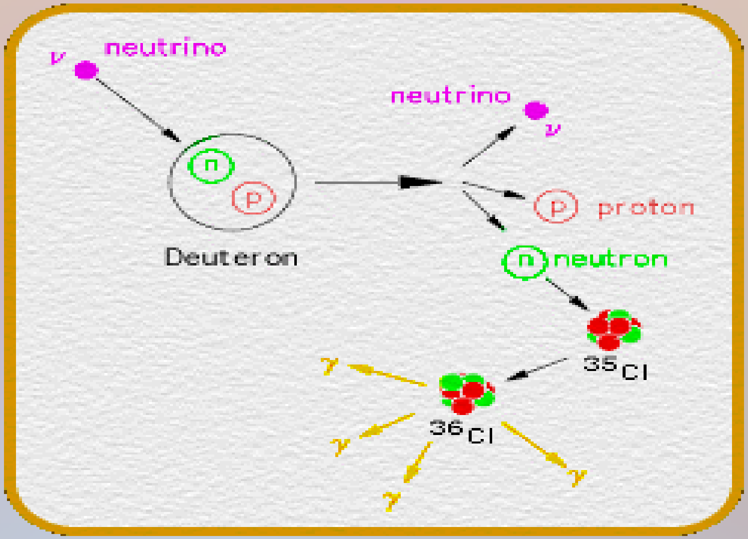


Neutrino interactions in D_2O

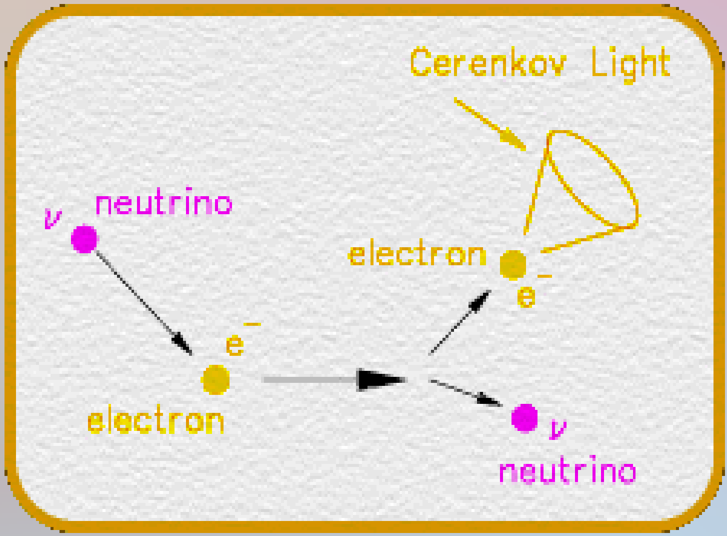
Charged Current Reaction (CC)

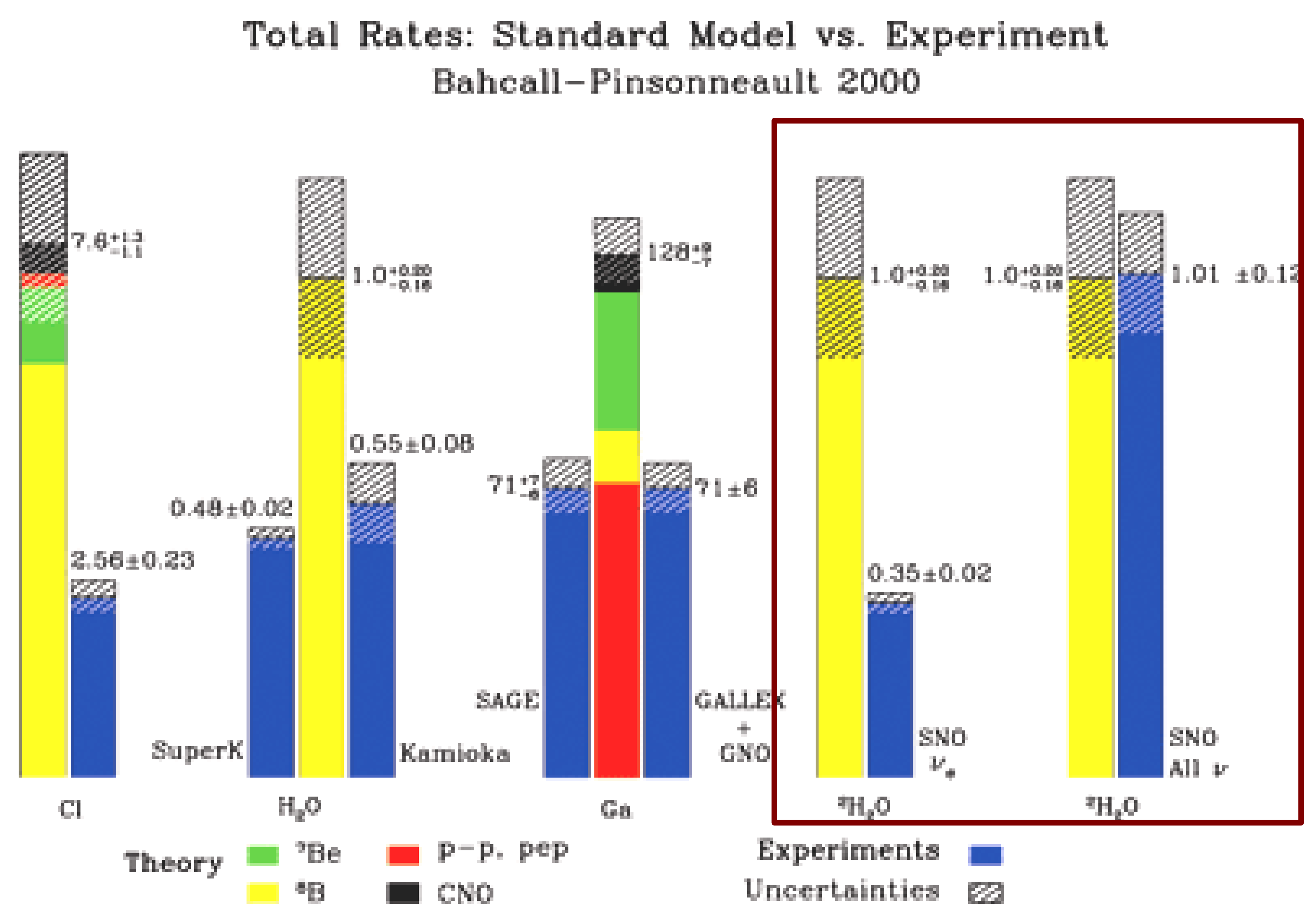


Neutral Current Reaction (NC)



Elastic Scattering (ES)





Total Rates: Standard Model vs. Experiment
Bahcall-Pinsonneault 2000
2.56±0.23
0.48±0.02
0.55±0.08
71±6
0.35±0.02
1.01 ±0.12
SuperK
Kamioka
SAGE
GALLEX + GNO
SNO ν_e
SNO All ν
Cl
H_2O
Ga
^2H_2O
^2H_2O
Theory
^{7}Be
^{8}B
p−p, pep
CNO
Experiments
Uncertainties

Theoretical calculations: state-of-the-art

1) <u>Realistic description of initial and final nuclear bound- and scattering states</u> (*realistic Hamiltonians: two- and three-nucleon interactions)*

2) <u>Realistic description of the electro-weak nuclear current</u> *(one-body and meson-exchange currents)*

For both 1) and 2):

- **high accuracy**
- **widely tested especially in the electromagnetic sector (electron scattering)**

Marcucci *et al*., Nucl. Phys. A **777**, 111 (2006)

Adelberger *et al*., Rev. Mod. Phys. **83**, 195 (2011)

$$n + p \to d + \gamma$$

Total cross section [mb] with the AV18

One-body	304.6
Full	332.7
Expt.	332.6(7)

$$p + p \rightarrow d + e^{+} + \nu_{e}$$

$$S(E) = E\,\sigma(E)\,\exp(2\pi Z_1 Z_2 \alpha / v)$$

$$S(E) \approx \Lambda(E)^2$$

NN model	AV18	CD-Bonn
One-body	6.965	6.985
Full	7.076	7.060

H.A. Bethe and C.L. Critchfield, Phys. Rev. **54**, 248 (1938)

TABLE I. *Numerical results for two values of the radius.*

	$r_0=e^2/mc^2$	$r_0=e^2/2\,mc^2$
x_0	0.645	0.322
V_0 (Mev)	20.9	66.5
D (Mev)	10.3	47.0
μ	2.94	5.45
ν	2.18	4.65
$(rd\log w/dr)$	0.236	0.110
$\Phi(r_0)$	1.050	1.025
$\Theta(r_0)$	0.769	0.854
$(rd\log\Phi/dr)$	0.050	0.025
ζ	0.814	0.915
λ	2.63	4.80
Λ_1	0.689	0.277
Λ_2	1.949	1.547
Λ_3	1.205	1.030
$(1+x_0)(1+\mu^{-2})$	1.835	1.367
Λ	2.84	2.44
Λ^2	8.08	5.93

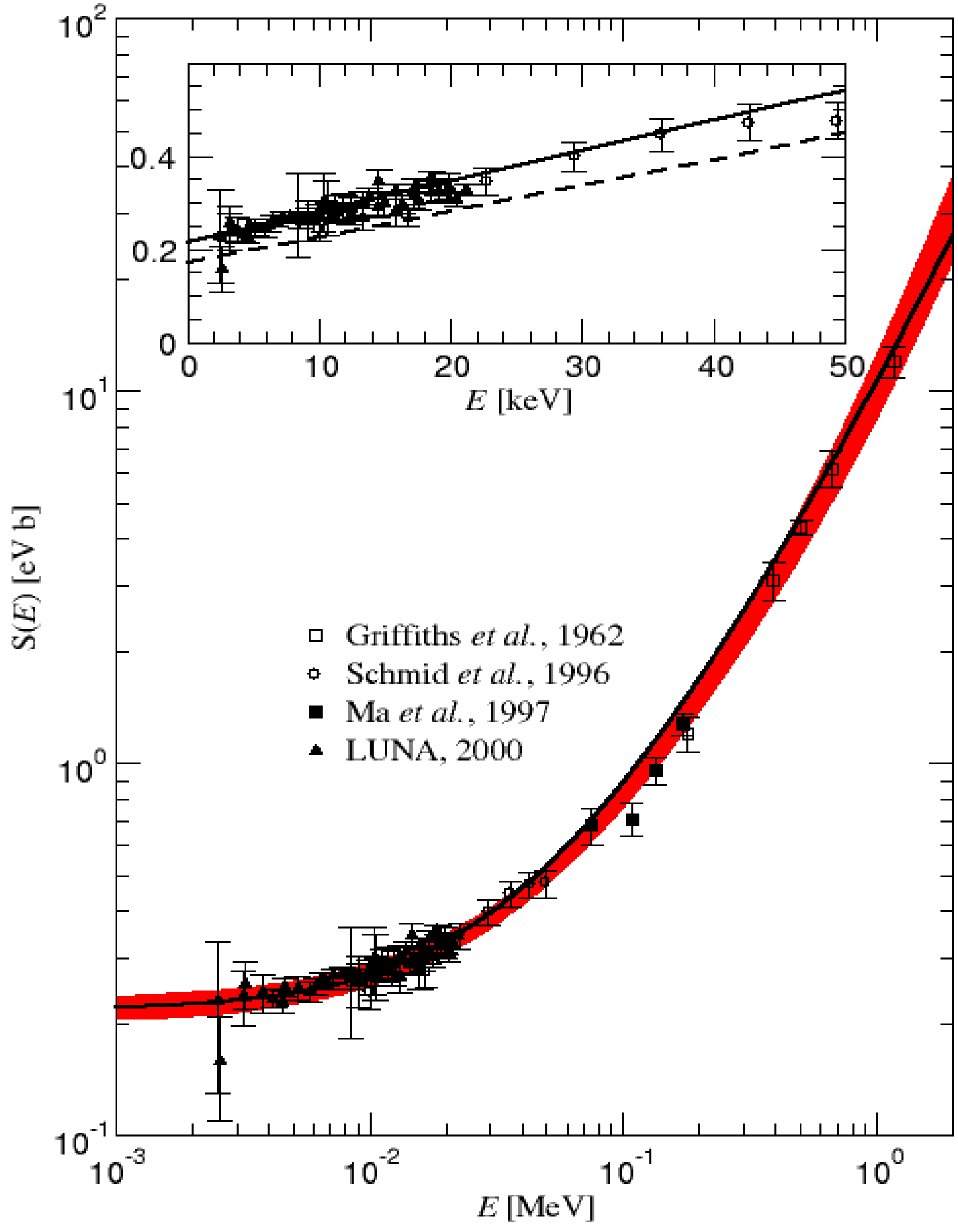
[13] Breit, Condon and Present, Phys. Rev. **50**, 825 (1936).

$$n + d \rightarrow {}^{3}\mathrm{H} + \gamma$$

Total cross section [mb] (AV18/UIX)

One-Body	0.227
Full	0.556
Expt.	0.508(15)

$p + d \rightarrow {}^{3}\mathrm{He} + \gamma$



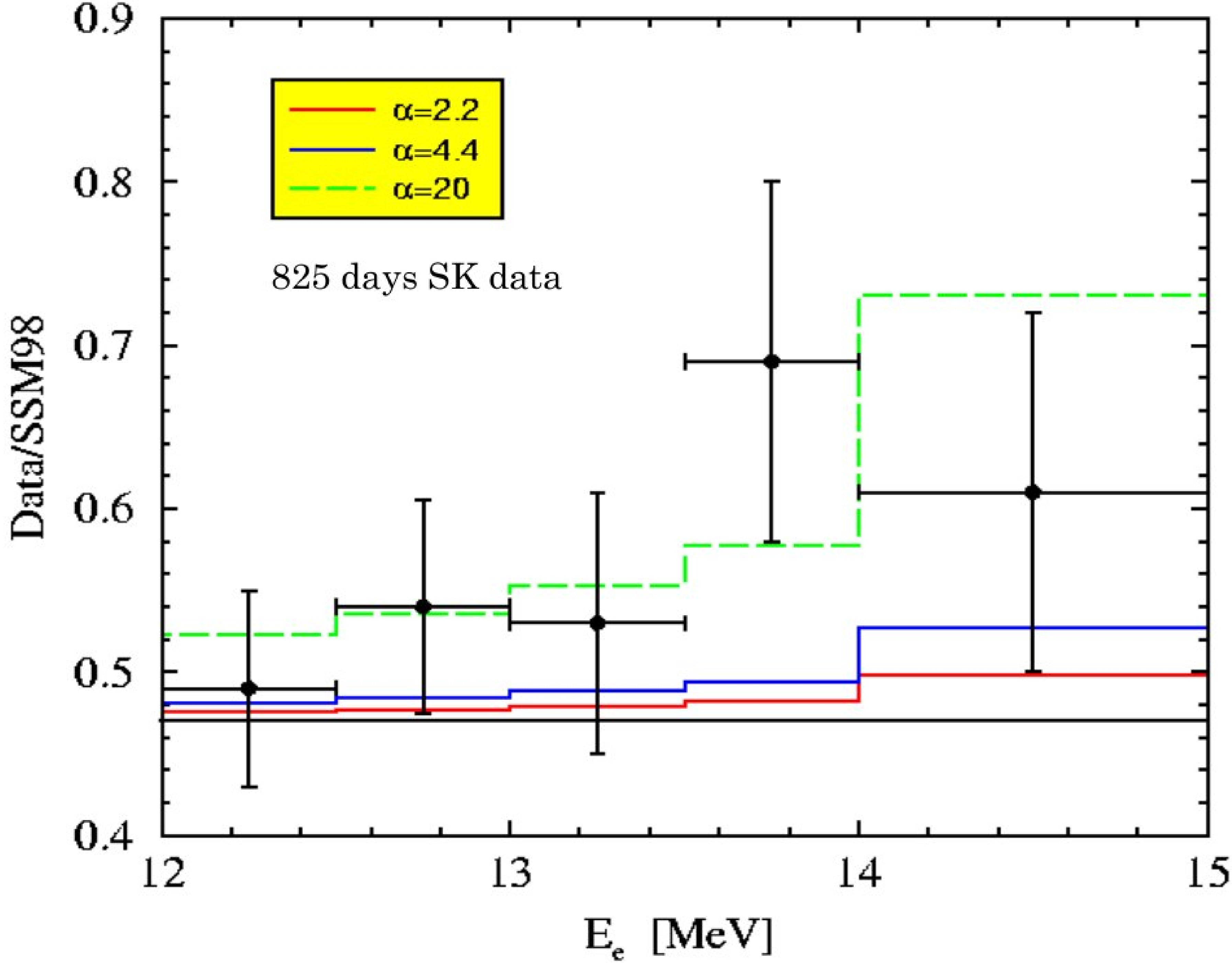
$p+{}^3\text{He} \longrightarrow {}^4\text{He}+e^{+}+\nu_e$: *the hep reaction*

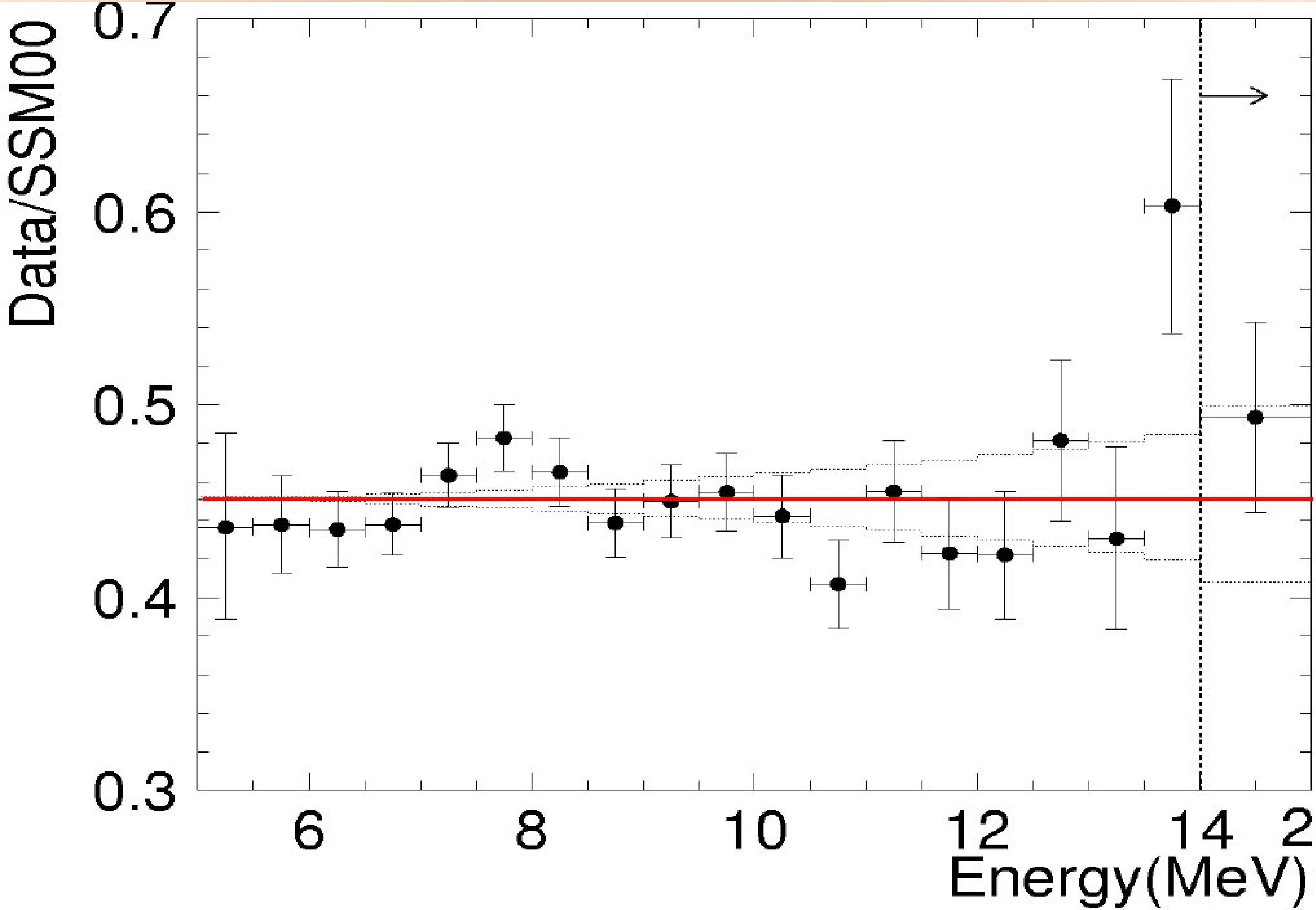
- $S_{\rm SSM98} = 2.3\ \times 10^{-20}$ keV b

- New calculation (Marcucci *et al.*, PRL **84**, 5959 (2000); PRC **63**, 015801 (2001)):

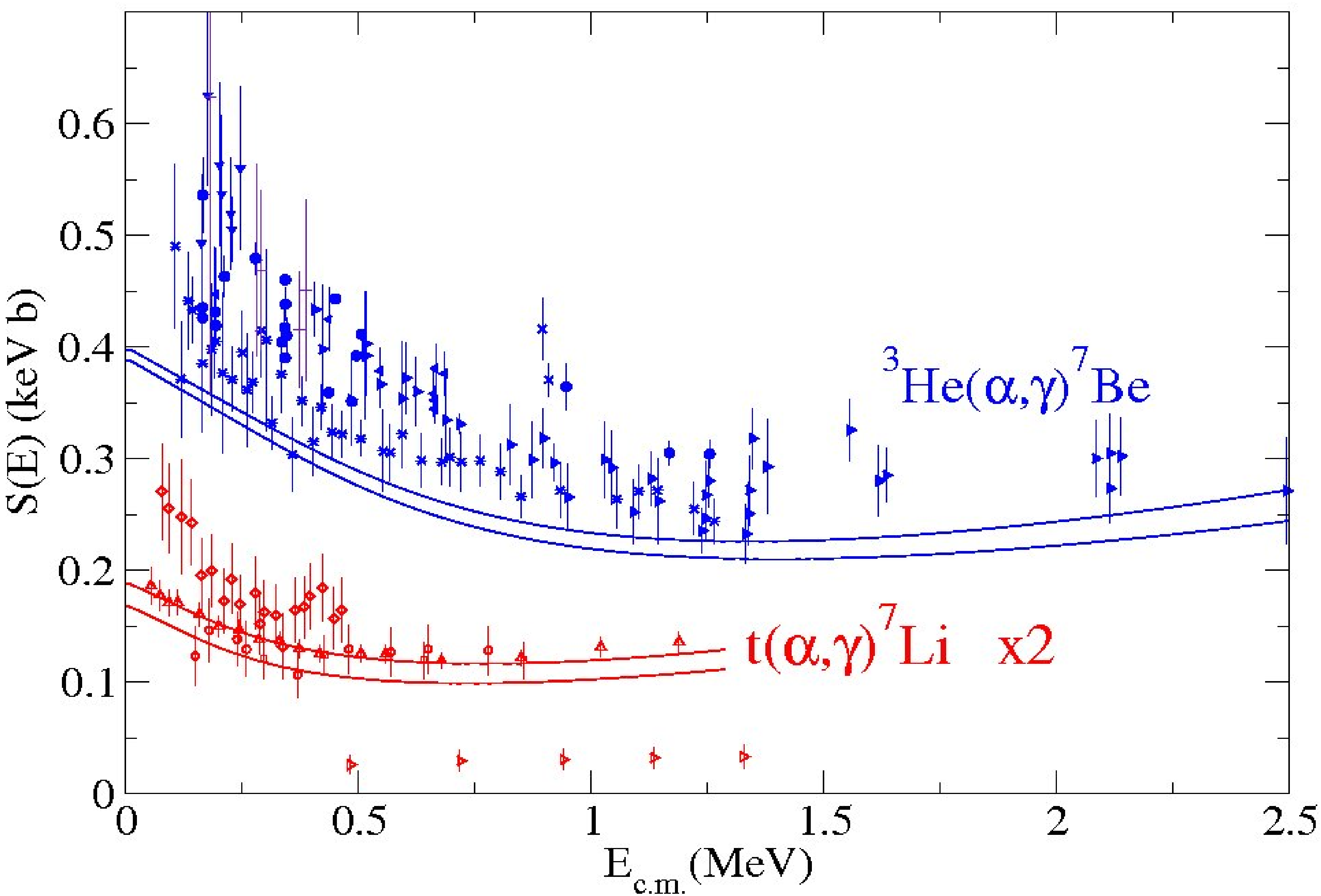
  1. S (10 keV) $= 10.1\ \times 10^{-20}$ keV b
  2. no c.m. energy dependence
  3. no Hamiltonian model dependence (if H reproduces accurately the initial and final state w.f.'s)
  4. importance of the P-waves (40%)
  5. importance of MEC (Δ)

- SSM revisited (Bahcall *et al.*, Astr.J. **555**, 990 (2001)): $S_{\rm SSM00} = 10.1\ \times 10^{-20}$ keV b


α=2.2
α=4.4
α=20
825 days SK data
Data/SSM98
0.9
0.8
0.7
0.6
0.5
0.4
12
13
14
15
E_e [MeV]



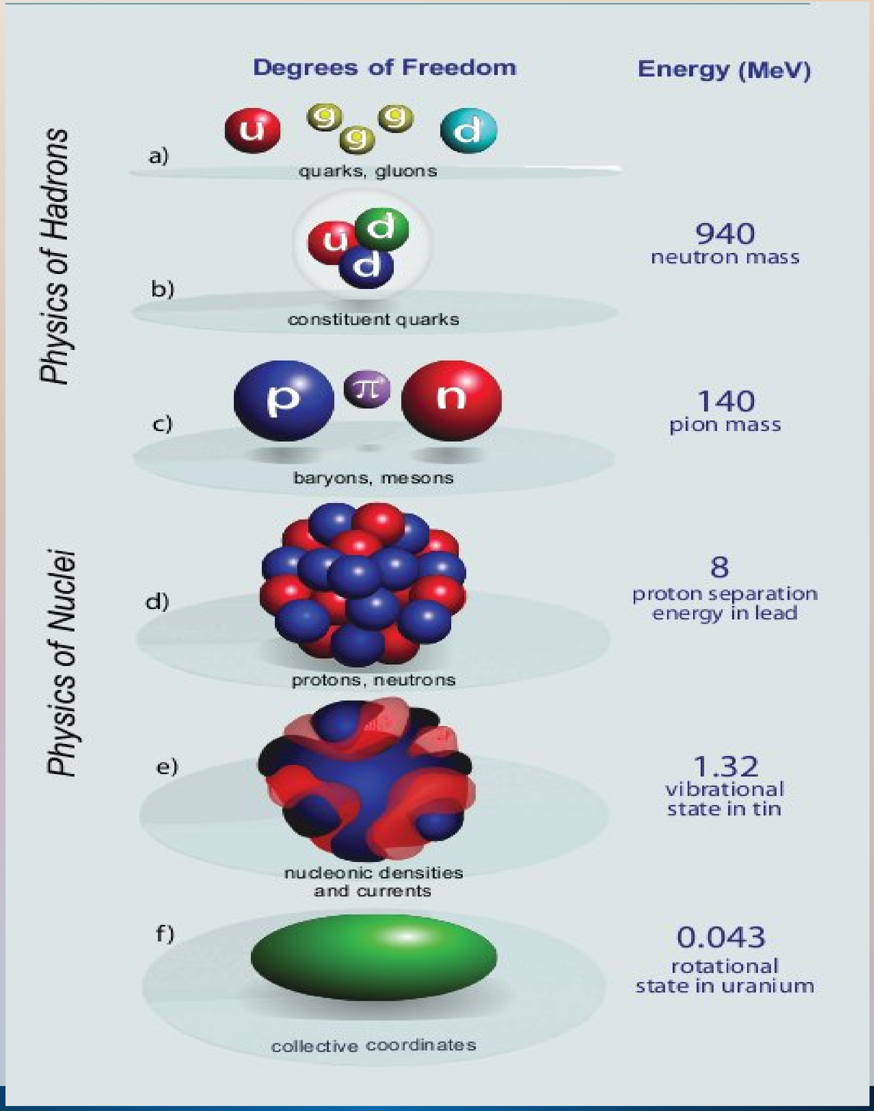
The SK collaboration, PRL **86**, 5651 (2001)



S(E) (keV b)
E c.m. (MeV)
$^3He(\alpha,\gamma)^7Be$
$t(\alpha,\gamma)^7Li$ x2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.5
1
1.5
2
2.5

Limits

- No clear connection with QCD → model-dependence
- No clear determination of theoretical uncertainty



Chiral Effective Field Theory (χEFT)

Chiral Effective Field Theory (χEFT)

- QCD → quark and gluons ("heavy" degrees of freedom)
- Nuclear physics → nucleons and pions ("light" degrees of freedom)
- EFT → processes with $E \sim p \sim m_\pi \ll \Lambda_{QCD} \sim 1$ GeV

► "heavy" d.o.f. integrated out → contact interactions with "light" d.o.f. and low-energy constants (LECs) obtained from experiment

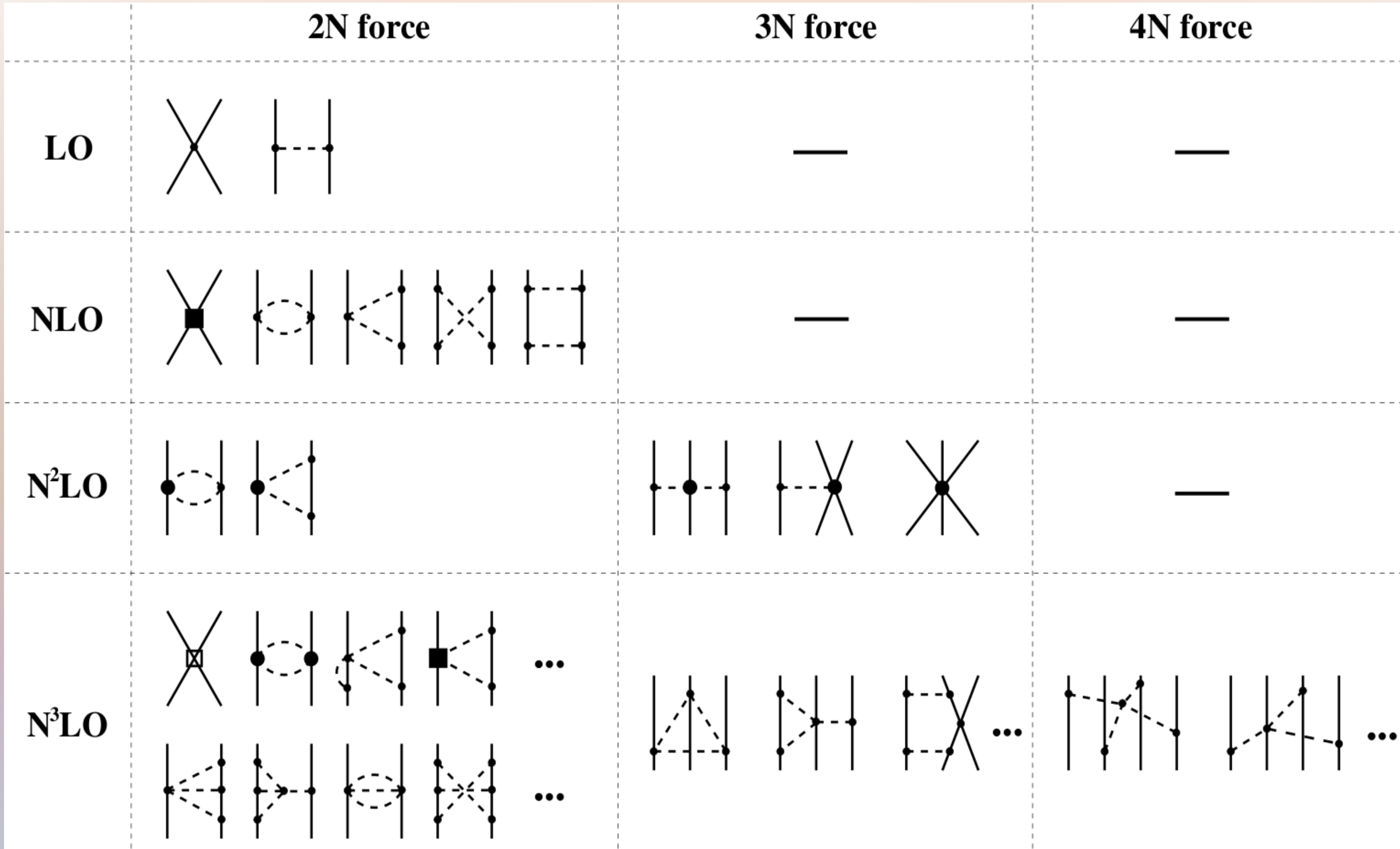
► perturbative theory: matrix elements $\propto O(p/\Lambda_{QCD})^\nu$

χEFT → implement EFT and spontaneous breaking of QCD's chiral symmetry

Advantages: a) "right" treatment of πN interaction
b) nuclear force "hierarchy" → accurate $V_{NN}+V_{NNN}$

Disadvantage: limited to processes occurring at low-energy $E \sim$ 1-2 m_π

Note: renormalization functions → Gaussians with cutoff Λ (~ 500-600 MeV)


2N force
3N force
4N force
LO
NLO
N2LO
N3LO

First steps (~2001): “hybrid” χEFT

- Nuclear wave functions from realistic phenomenological potentials (AV18, etc)
- Nuclear electroweak current from χEFT

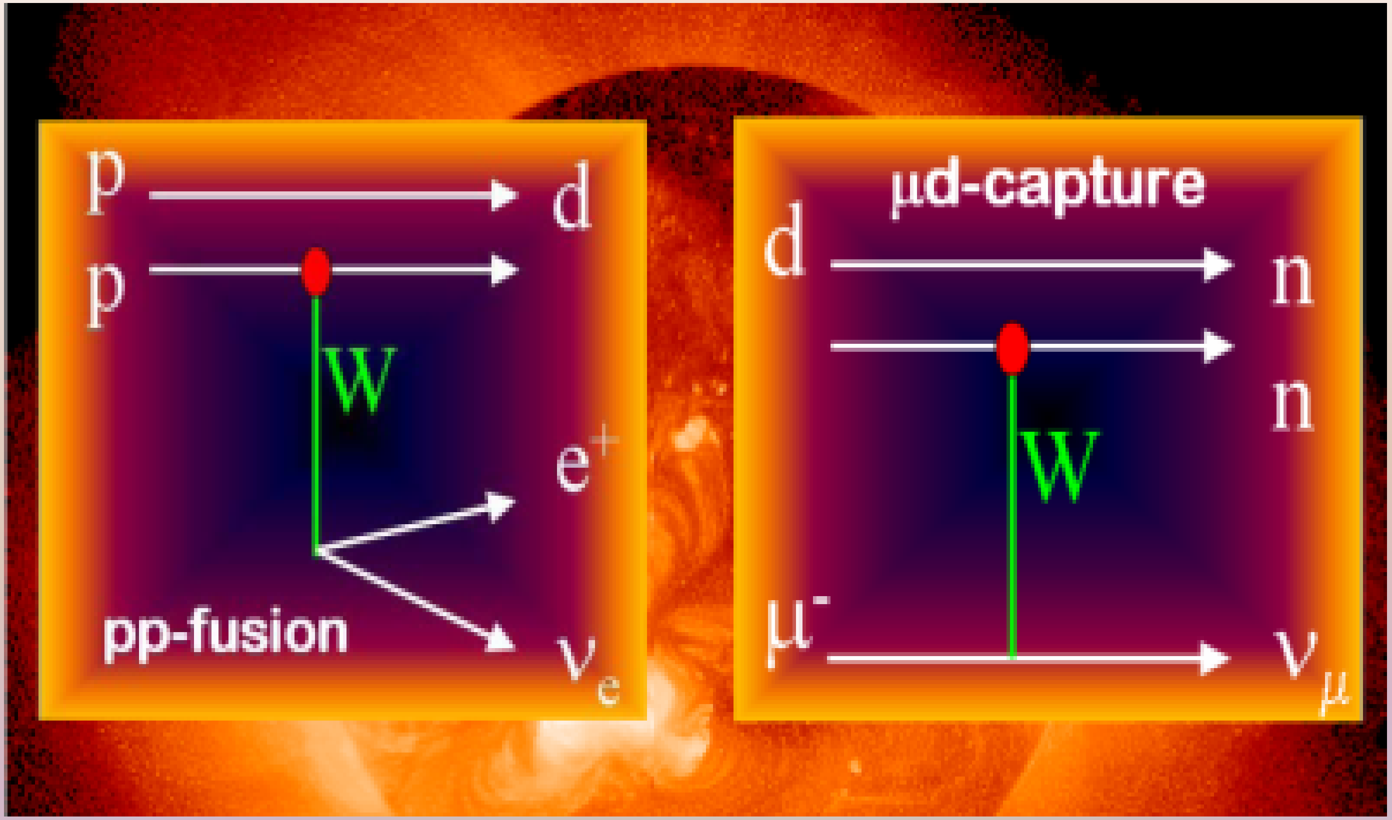
Study of the *pp* and *hep* reactions in agreement with “old” phenomenological ones

T.S. Park *et al*., Phys. Rev. C **67**, 055206 (2003)

On-going work toward a fully consistent χEFT calculation

Fully consistent χEFT calculation

- Nuclear interactions and currents in χEFT at N3LO (three-nucleon interaction at N2LO)
- First χEFT calculation for $\mu^- + d \rightarrow n + n + \nu_\mu$ and $\mu^- + {}^3\mathrm{He} \rightarrow {}^3\mathrm{H} + \nu_\mu$ → test of the framework
- First χEFT calculation for $p + p \rightarrow d + e^+ + \nu_e$
- Future work for
  - $p + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + e^+ + \nu_e$
  - $p + d \rightarrow {}^3\mathrm{He} + \gamma$ (on-going)



Muon-captures: weak processes experimentally accessible

Results (with RC)

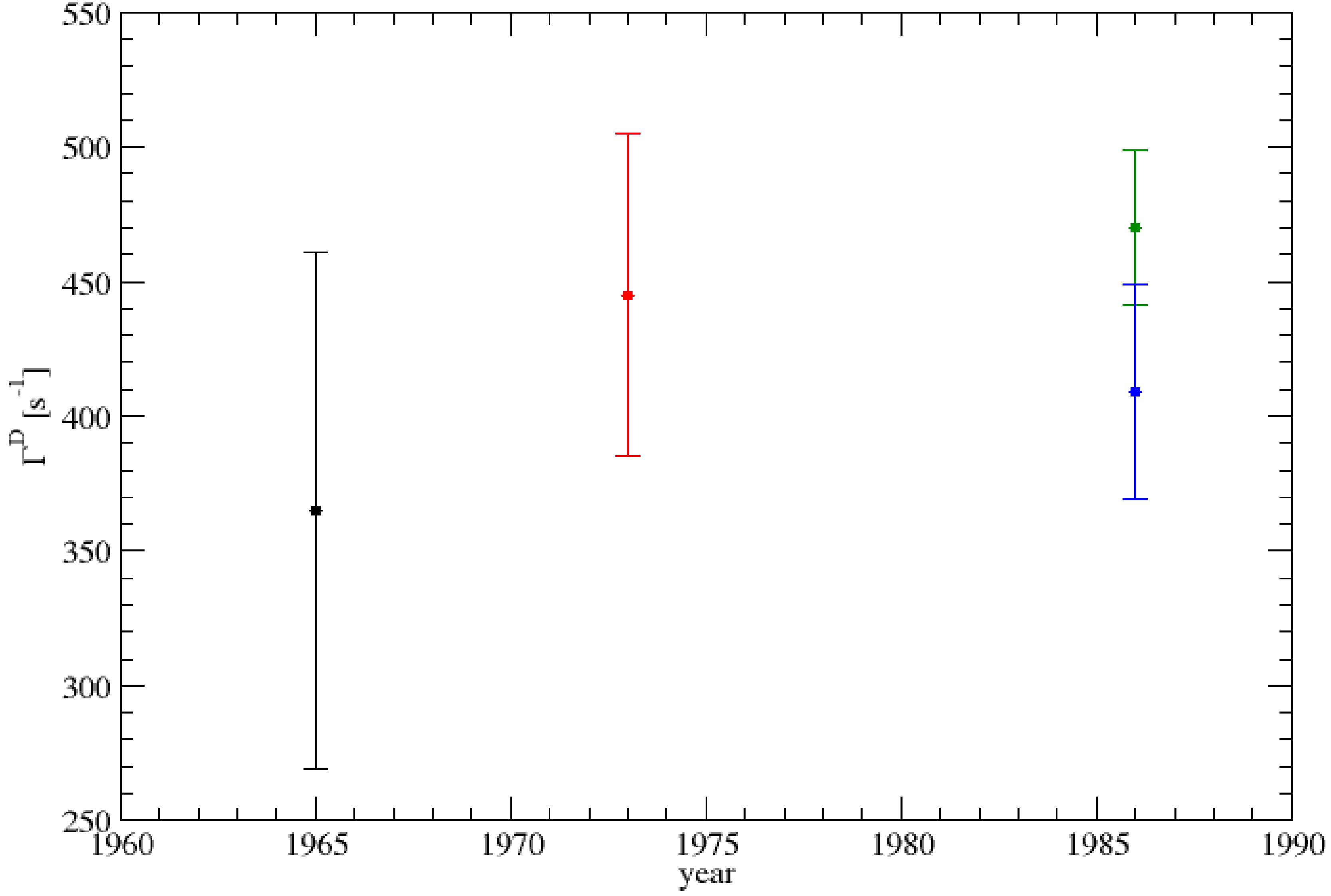
	$^1S_0$	$^3P_0$	$^3P_1$	$^3P_2$	Γ^D	Γ_0
IA – $\Lambda = 500$ MeV	238.8	21.1	44.0	72.4	381.7	1362
IA – $\Lambda = 600$ MeV	238.7	20.9	43.8	72.0	380.8	1360
FULL – $\Lambda = 500$ MeV	254.4(9)	20.5	46.8	72.1	399.2(9)	1488(9)
FULL – $\Lambda = 600$ MeV	255(1)	20.3	46.6	71.6	399(1)	1499(9)
χEFT* – $\Lambda = 500$ MeV	251.5(7)	20.0	46.6	71.8	395.1(7)	1489(9)

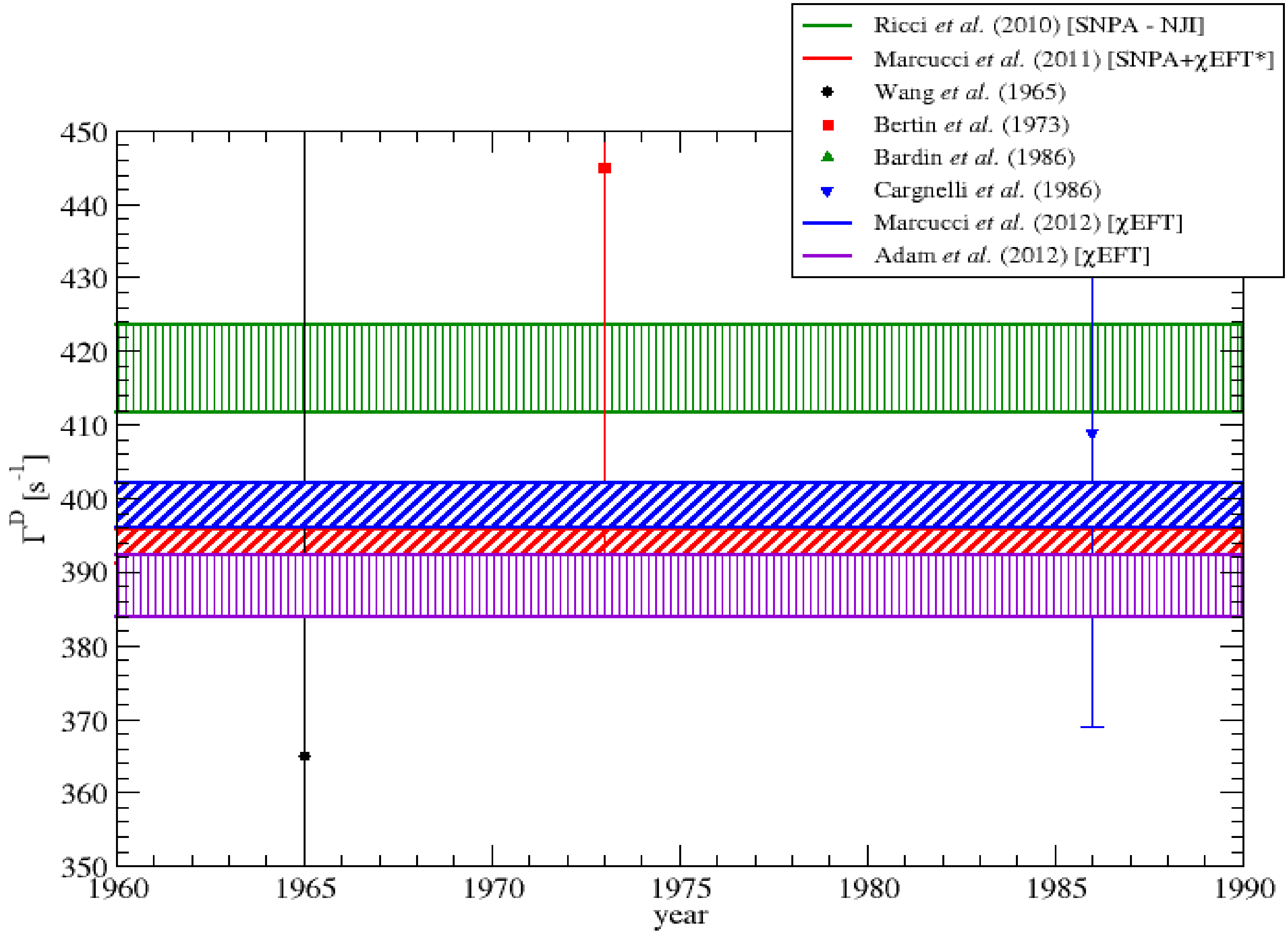
$\boxed{\Gamma^D = \mathbf{399(3)\ s^{-1}}\ \&\ \Gamma_0 = \mathbf{1494(21)\ s^{-1}}}$

Marcucci *et al.*, PRL **108**, 052502 (2012)

$\Gamma_0(\text{exp}) = 1496(4)\ s^{-1}$

$\Gamma^D(\mathrm{exp})$




Ricci et al. (2010) [SNPA - NJI]
Marcucci et al. (2011) [SNPA+χEFT*]
Wang et al. (1965)
Bertin et al. (1973)
Bardin et al. (1986)
Cargnelli et al. (1986)
Marcucci et al. (2012) [χEFT]
Adam et al. (2012) [χEFT]
450
440
430
420
410
400
390
380
370
360
350
Γ^D [s^{-1}]
1960
1965
1970
1975
1980
1985
1990
year

$$p + p \rightarrow d + e^{+} + \nu_{e}$$

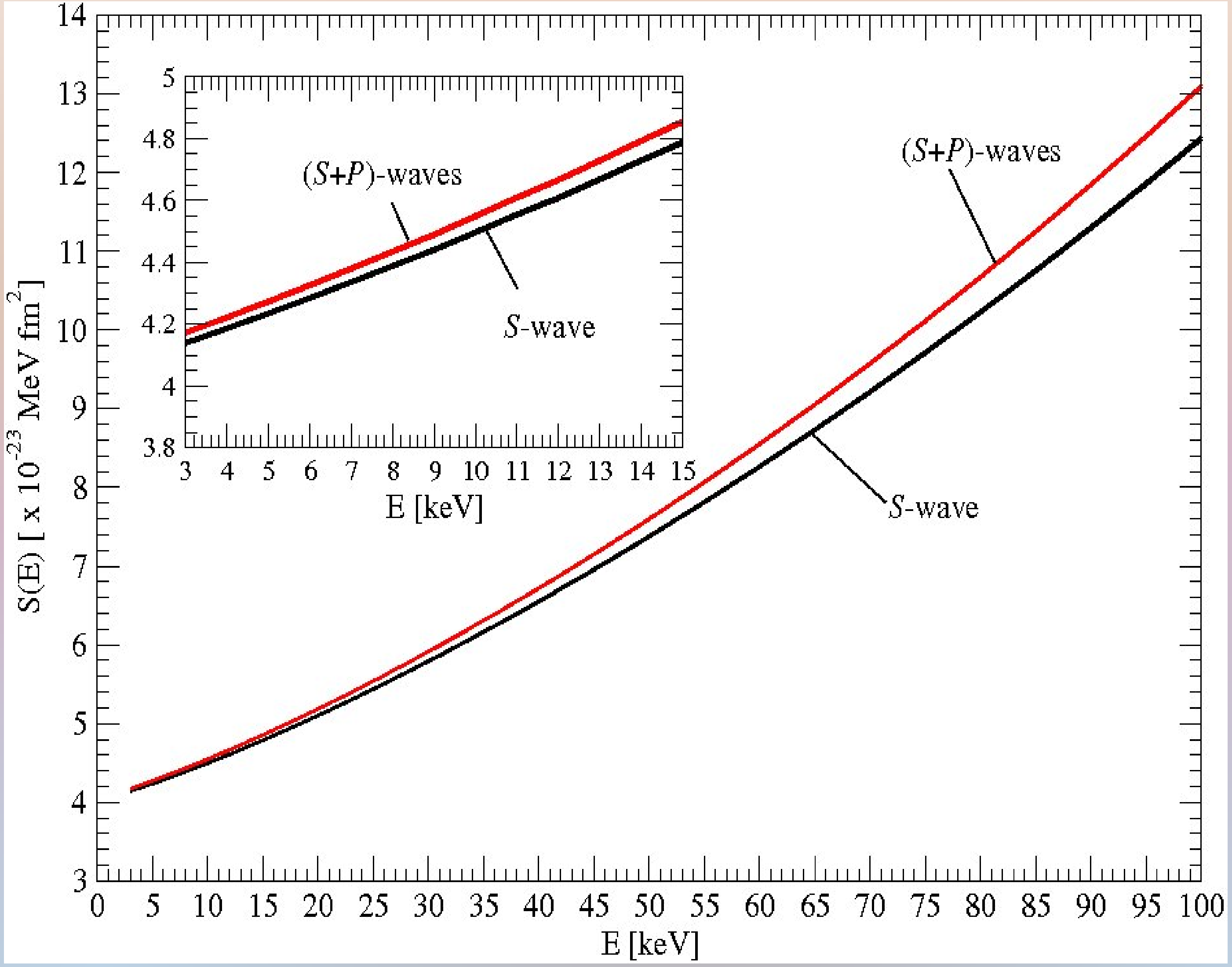
- χEFT calculation between 0-100 keV (Gamow peak: Sun E~6 keV; medium-mass stars E~15 keV)
- *S*- and *P*-waves included
- "Old" values [Adelberger *et al*., Rev. Mod. Phys. **83**, 195 (2011)]:

$$S(0)=(4.01\pm0.01)\times10^{-23}\ \text{MeV b}$$

$$S'(0)/S(0)=(11.2\pm0.1)\ \text{MeV}^{-1}$$

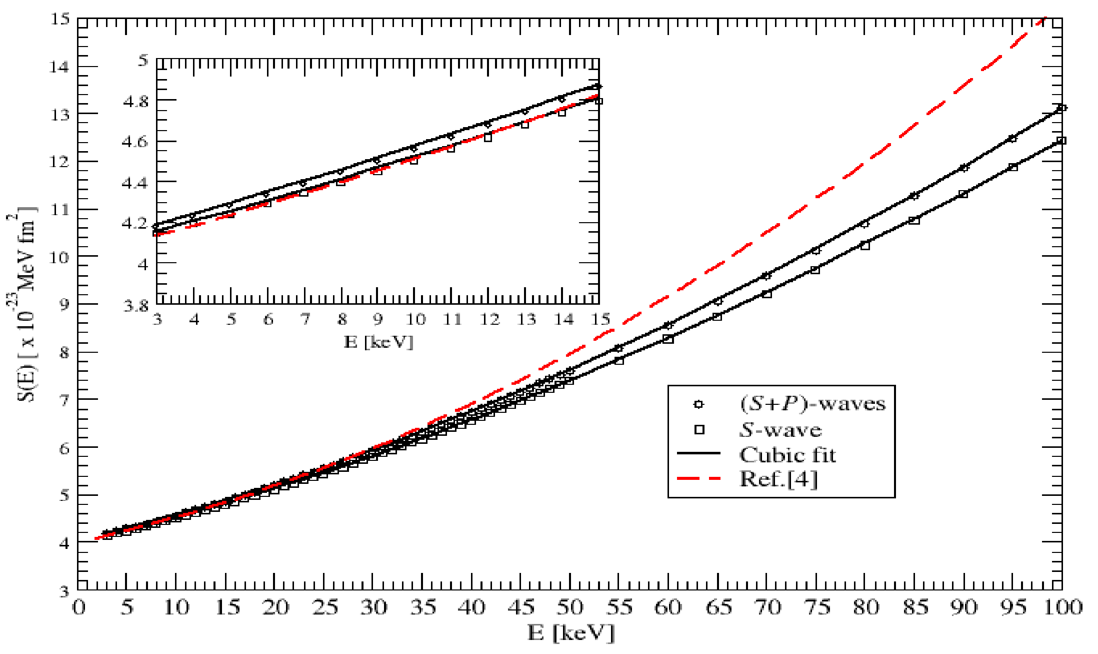
$$S''(0)/S(0) \sim\ 1\%\ \text{effect}$$

	$^1S_0$	$^3P_0$	$^3P_1$	$^3P_2$
Λ=500 MeV	4.008(5)	4.011(5)	4.020(5)	4.030(5)
Λ=600 MeV	4.008(5)	4.010(5)	4.019(5)	4.029(5)

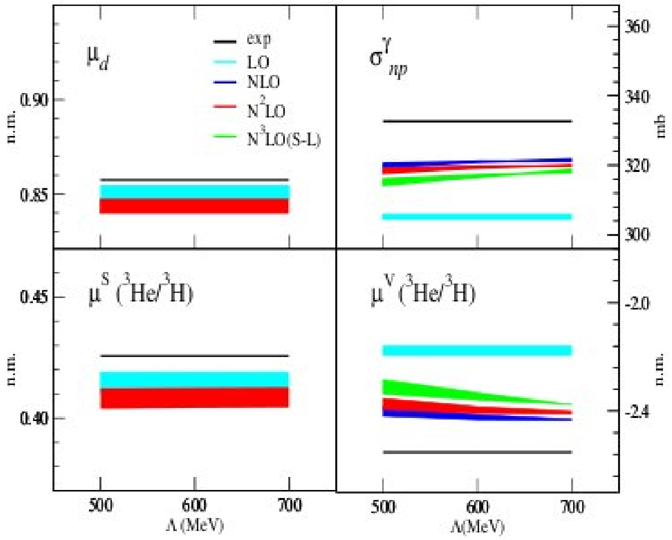


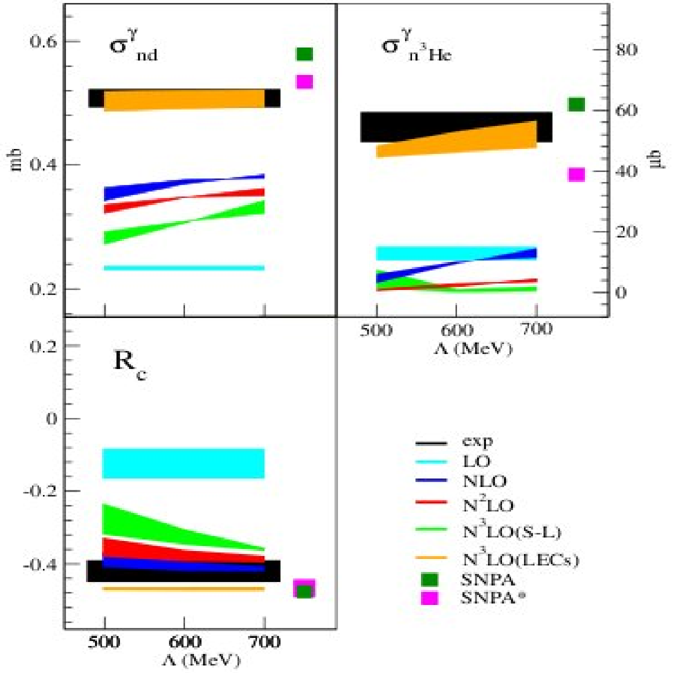
$S^n(0)/S(0)$ in MeV^{-n}

n	1	2	3	4	χ^2
Fit 1	12.59(1)	199.3(1)			8.8×10^{-4}
Fit 2	11.94(1)	248.8(2)	-1183(8)		1.9×10^{-4}
Fit 3	11.34(1)	327.1(5)	-5592(12)	99×10^3	2.0×10^{-5}
S-wave / old values	11.3(1)	170(2)			3.4×10^{-1}



$n + d \rightarrow {}^3\mathrm{H} + \gamma$ & $n + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + \gamma$ (χ**EFT***)





Girlanda *et al.*, Phys. Rev. Lett. **105**, 232502 (2010)