The Solar Neutrino Problem

effective solar fusion reaction

$4p \rightarrow {}^4He + 2e^+ \; 2\nu_e + 25$ MeV

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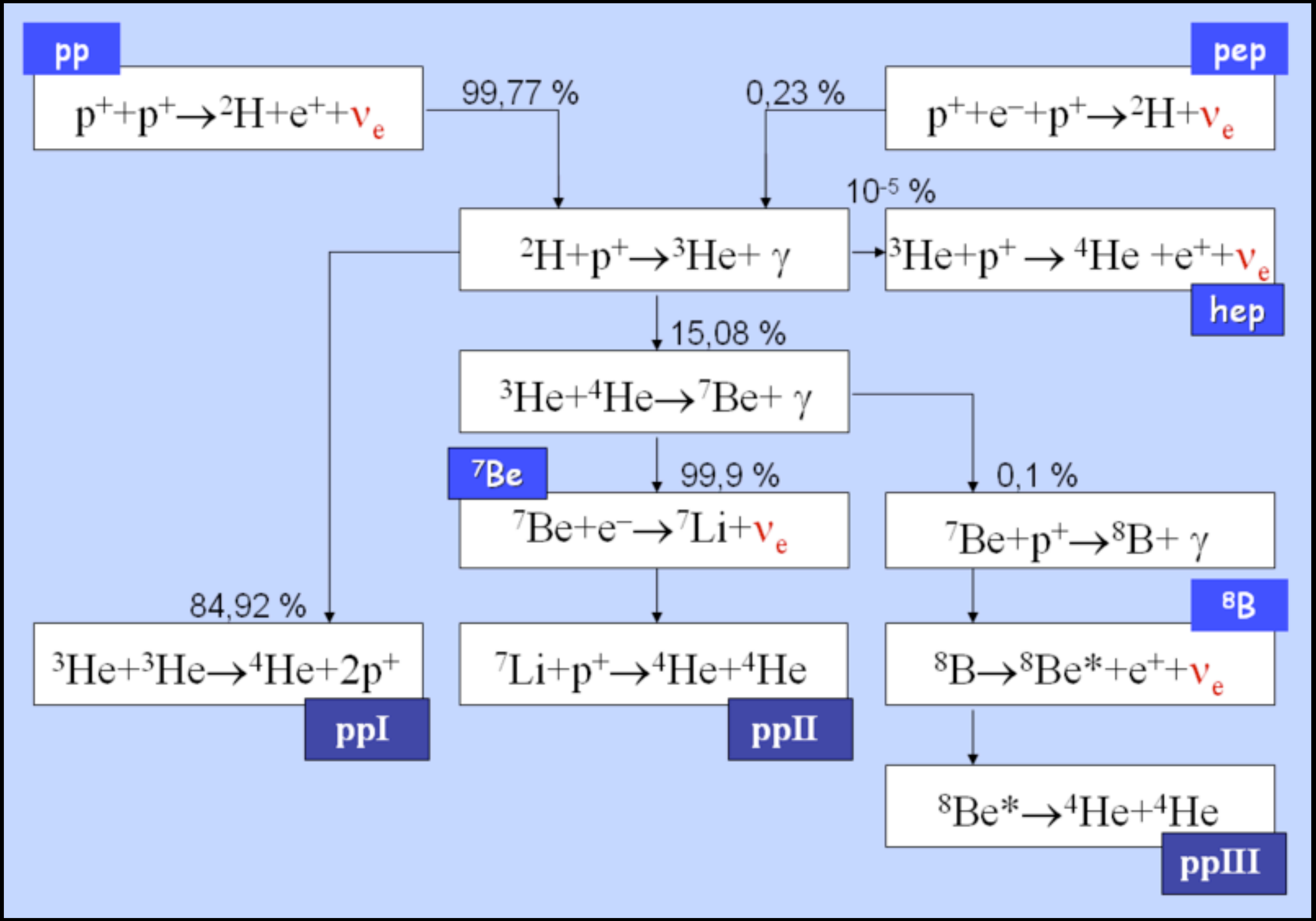
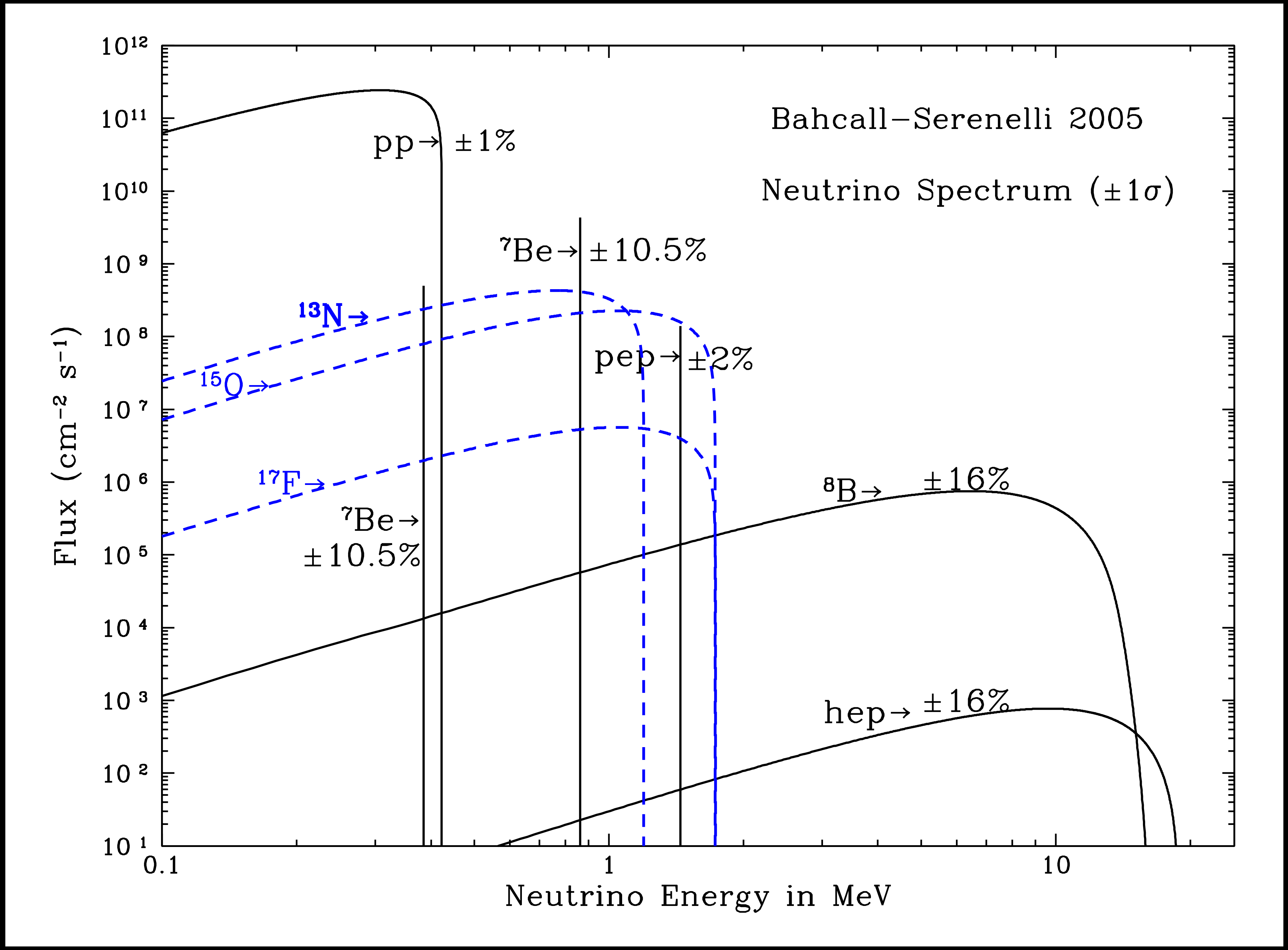

pp
$p^+ + p^+ \rightarrow {}^2H + e^+ + \nu_e$
99,77 %
0,23 %
pep
$p^+ + e^- + p^+ \rightarrow {}^2H + \nu_e$
10^{-5} %
${}^2H + p^+ \rightarrow {}^3He + \gamma$
${}^3He + p^+ \rightarrow {}^4He + e^+ + \nu_e$
hep
15,08 %
${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
7Be
99,9 %
0,1 %
${}^7Be + e^- \rightarrow {}^7Li + \nu_e$
${}^7Be + p^+ \rightarrow {}^8B + \gamma$
84,92 %
8B
${}^3He + {}^3He \rightarrow {}^4He + 2p^+$
${}^7Li + p^+ \rightarrow {}^4He + {}^4He$
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$
ppI
ppII
${}^8Be^* \rightarrow {}^4He + {}^4He$
ppIII

SNU = 10^{-36} events/atom/s



The predicted solar neutrino energy spectrum. The figure shows the energy spectrum of solar neutrinos predicted by the BP04 solar model. For continuum sources, the neutrino fluxes are given in number of neutrinos $cm^{-2}s^{-1}$ MeV^{-1} at the Earth's surface. For line sources, the units are number of neutrinos $cm^{-2}s^{-1}$. Total theoretical uncertainties are shown for each source. To avoid complication in the figure, we have omitted the difficult-to-detect CNO neutrino fluxes.

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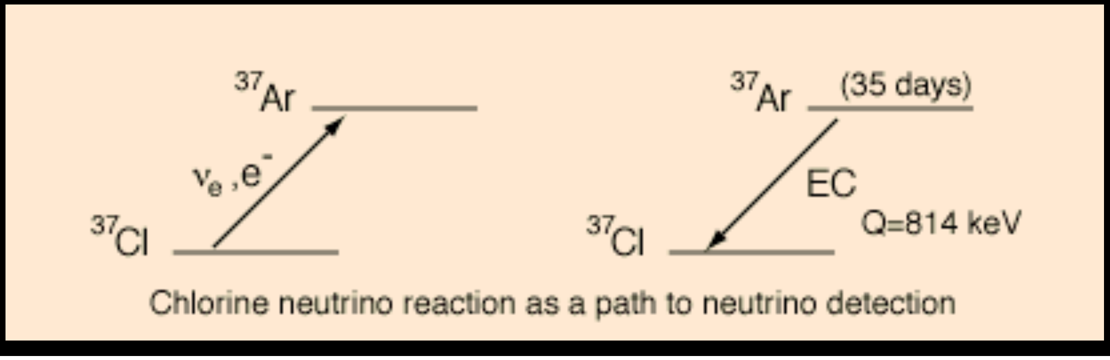
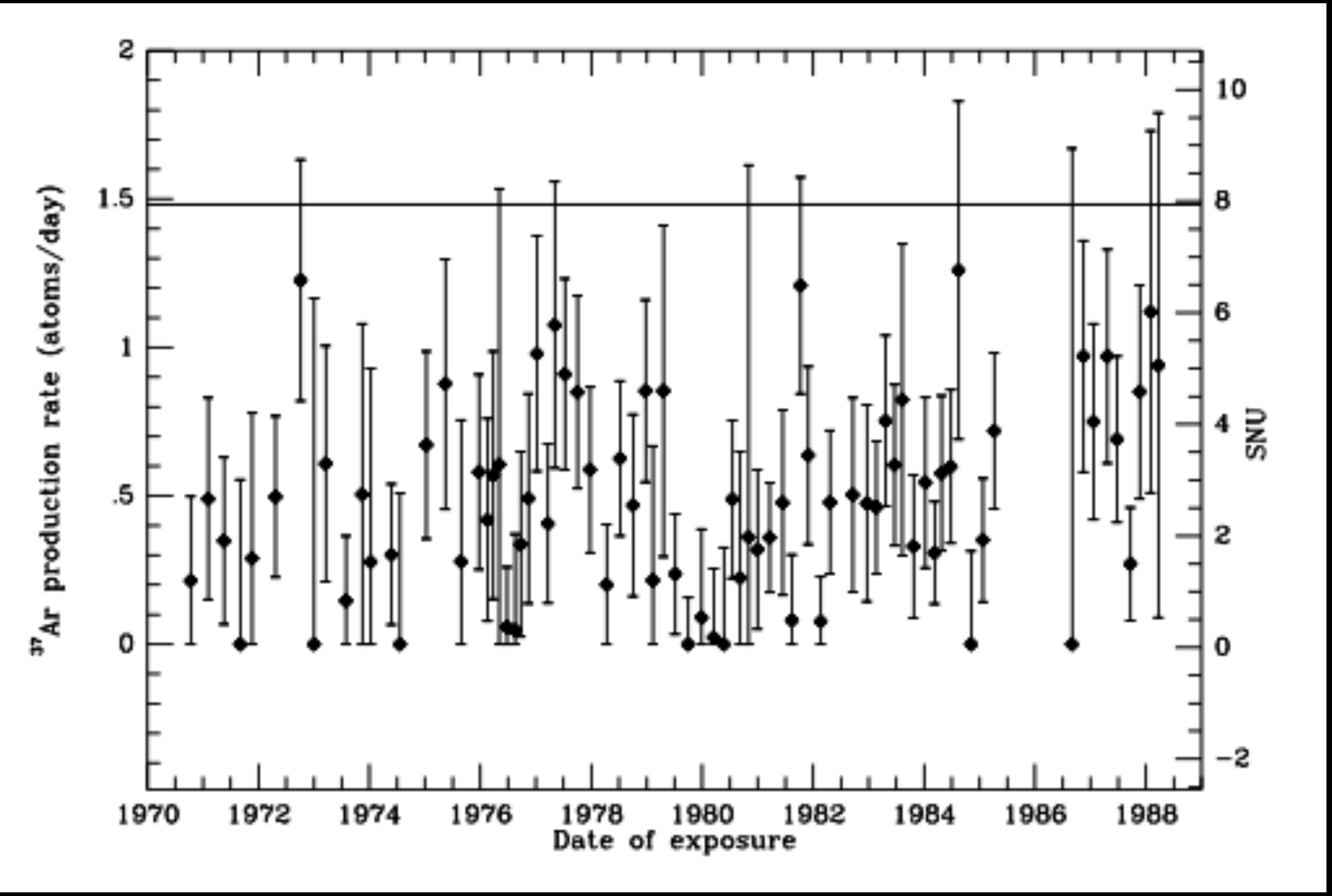
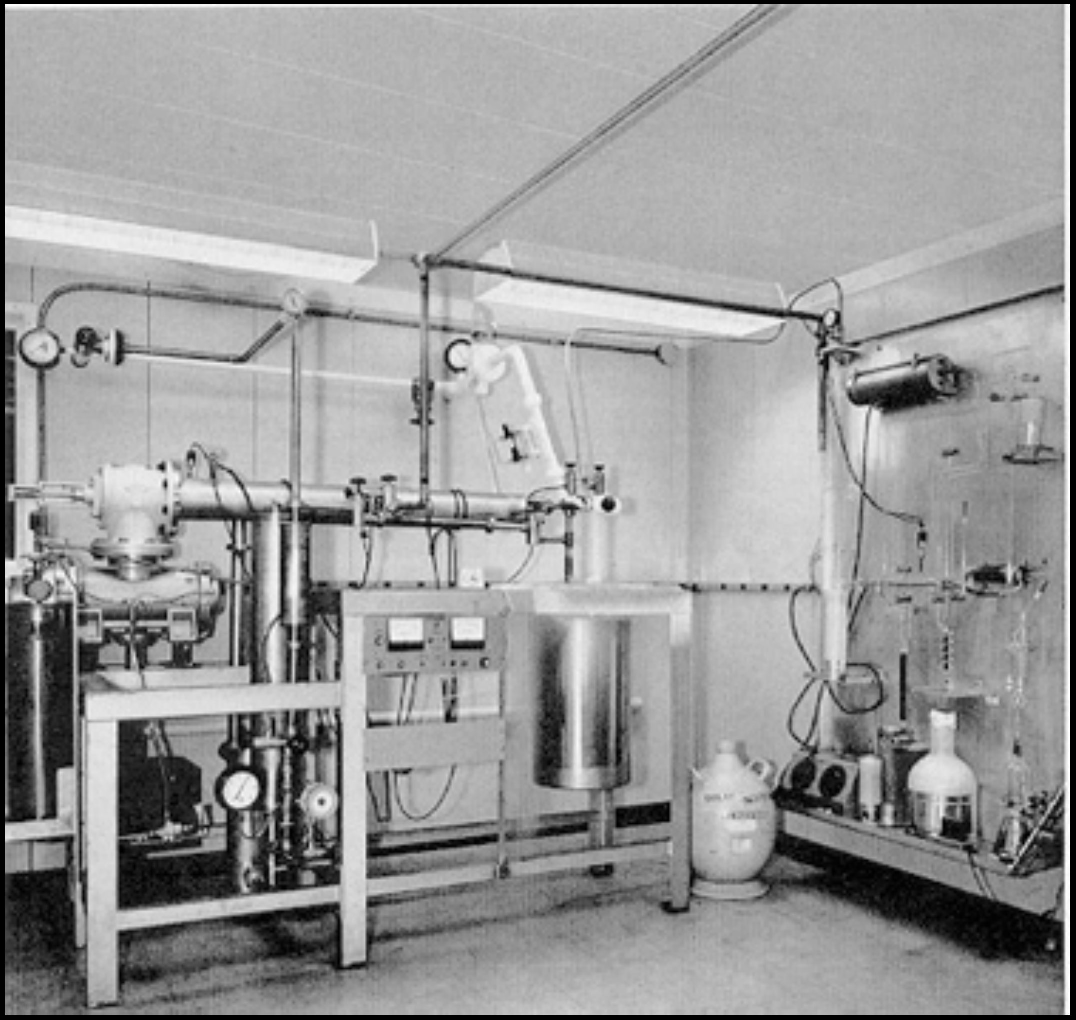
1964

Raymond Davis of Brookhaven National Laboratory constructed a neutrino detector 1.6 km underground in the Homestake Gold Mine in Lead, South Dakota. The detector consists of a 378,000 liter tank of perchloroethylene, which is further isolated by being submerged in water. Theoretical expections were about one neutrino-chlorine interaction per day, but the measured solar neutrino events were about a third of that, raising serious questions about the abundance of solar neutrinos





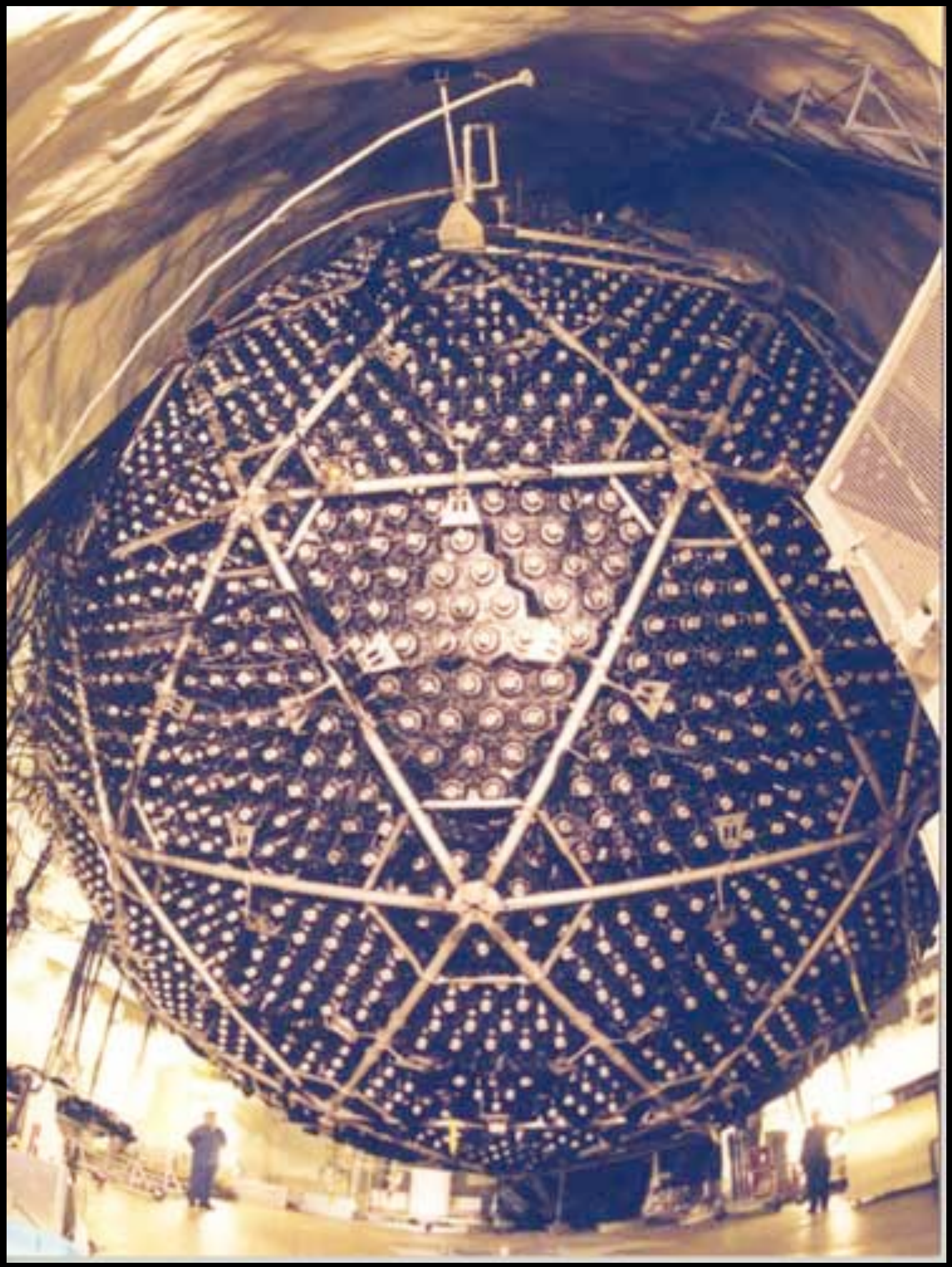


$$\nu_e \rightarrow W^+ + e^-$$

$$\nu_\mu \rightarrow W^+ + \mu^-$$

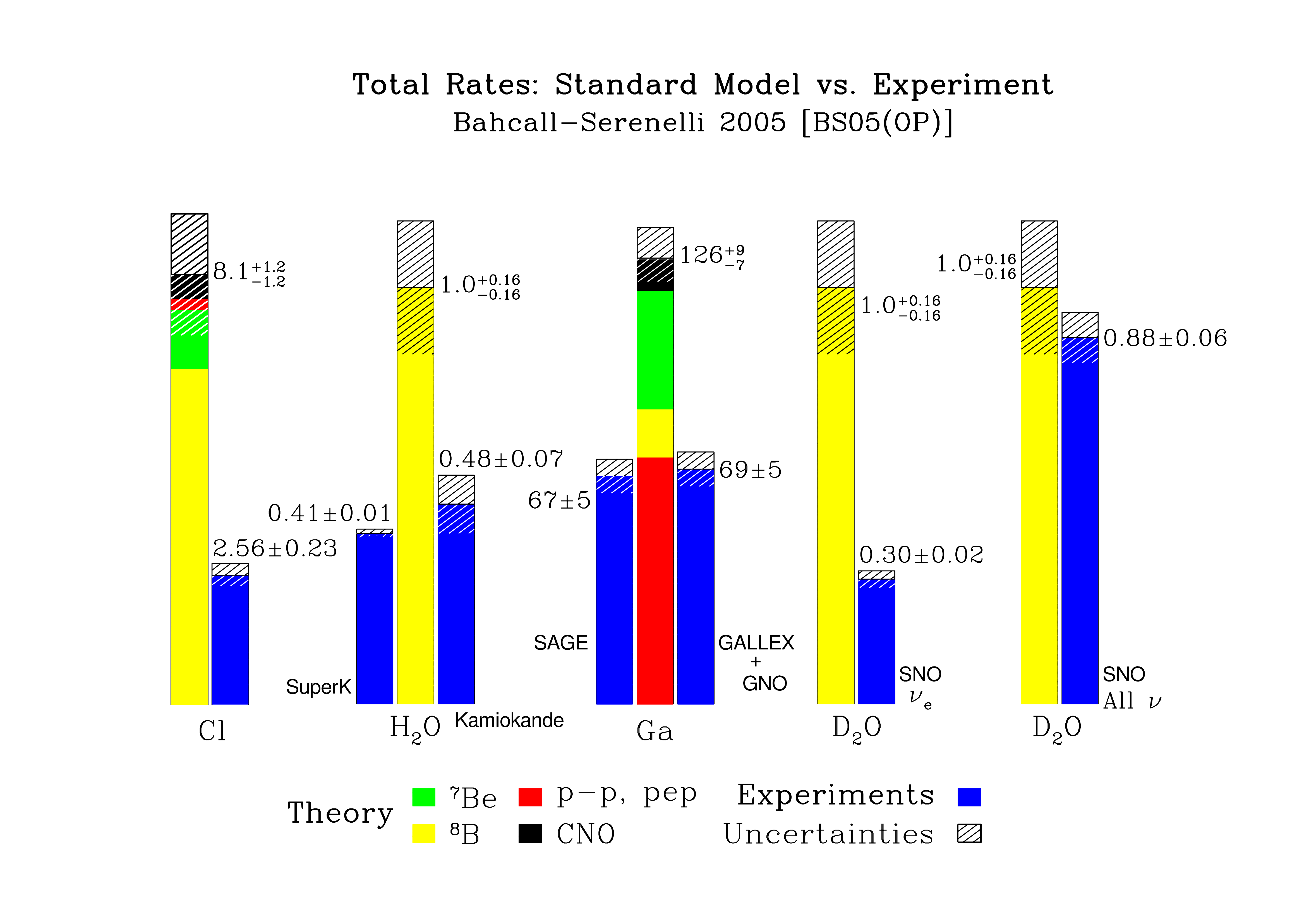
$$\nu_\tau \rightarrow W^+ + \tau^-$$

$$\nu \rightarrow Z + \nu$$



Sudbury Neutrino Observatory, a 12-meter sphere filled with heavy water surrounded by light detectors located two thousand meters below the ground in Sudbury, Ontario, Canada.

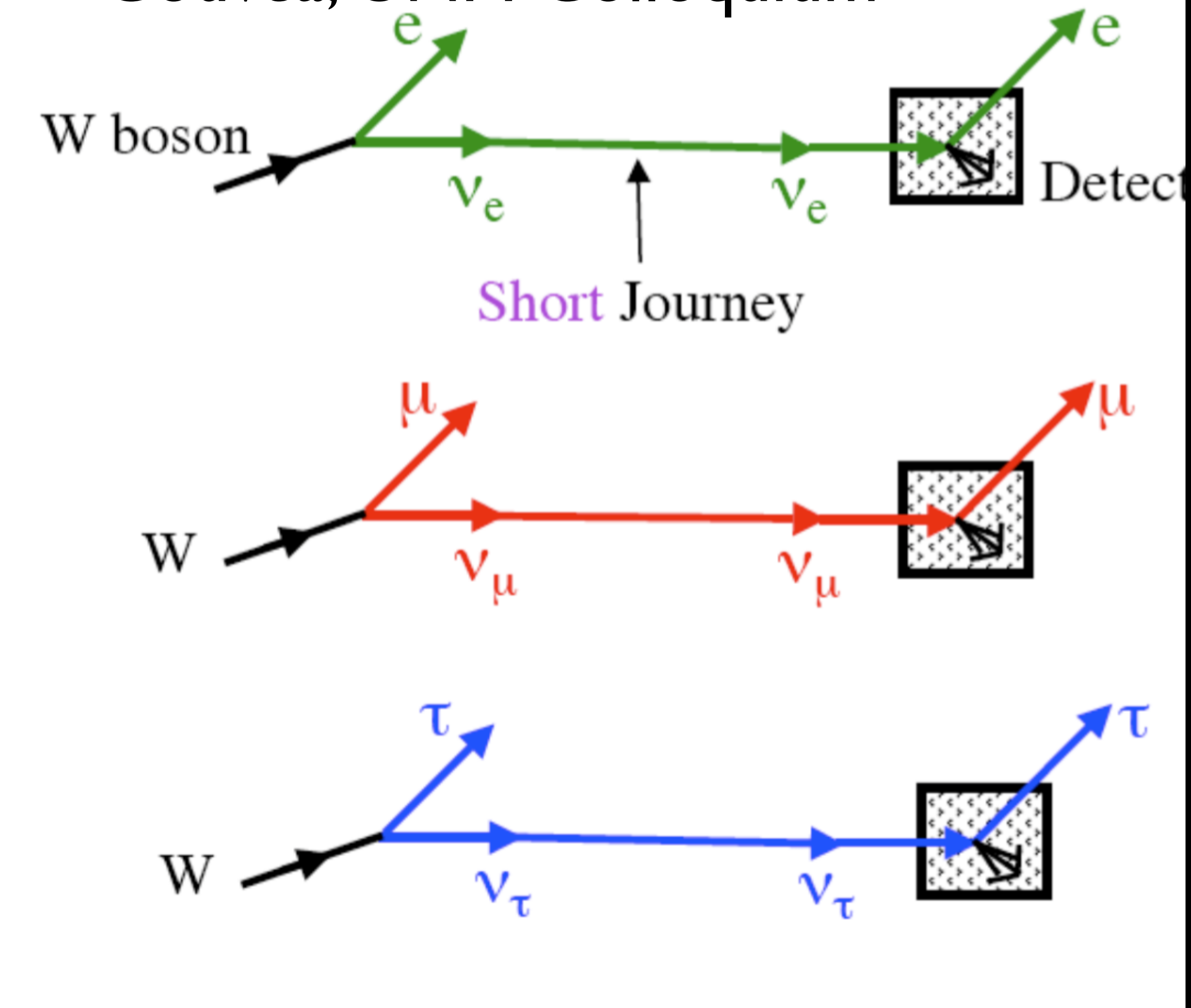
$$d + \nu \rightarrow p + n + \nu$$



Total Rates: Standard Model vs. Experiment
Bahcall−Serenelli 2005 [BS05(OP)]
8.1 +1.2 −1.2
2.56±0.23
Cl
1.0 +0.16 −0.16
0.41±0.01
0.48±0.07
SuperK
H2O
Kamiokande
126 +9 −7
67±5
69±5
SAGE
GALLEX + GNO
Ga
1.0 +0.16 −0.16
0.30±0.02
SNO νe
D2O
1.0 +0.16 −0.16
0.88±0.06
SNO All ν
D2O
Theory
7Be
8B
p−p, pep
CNO
Experiments
Uncertainties

Neutrino Mixing implies neutrino mass

Gouvea, UNM Colloquium



Neutrino Mixing

For simplicity, 2 massive neutrino states
masses m_1, m_2.

$$\begin{pmatrix} \chi_e \\ \chi_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix}$$

orthogonal $\chi_i^+ \chi_j = \delta_{ij}$

at $t=0$, produce ν_e flavor

$$\Psi_e(0) = \cos\theta\, \chi_1 + \sin\theta\, \chi_2$$

Propagate as

$$e^{-iE_i t/\hbar}$$

ultra-relativistic

$$E_i = \sqrt{p^2 + m_i^2} \cong p + \frac{m_i^2}{2p}$$

Then there is a phase difference

$$\Psi_e(t) = \underbrace{e^{-ipt/\hbar}\, e^{-im_1^2 t/\hbar}}_{\text{overall phase can be ignored}} \left[\cos\theta\, \chi_1 + e^{-i\phi_{21} t} \sin\theta\, \chi_2\right]$$

$$\phi_{21} = \frac{m_2^2 - m_1^2}{2p\hbar}$$

Probability to detect ν_μ flavor

$$P(e \to \mu) = \left|\chi_\mu^+ \Psi_e(t)\right|^2$$

Neutrino mixing:

then

$$\chi_\mu^+ = -\sin\theta\ \chi_1^+ + \cos\theta\ \chi_2$$

using orthogonality

$$\chi_\mu^+ \psi_e(t) = -\sin\theta\cos\theta + \sin\theta\cos\theta\ e^{-i\phi_{21}t}$$

$$= -\underbrace{\sin\theta\cos\theta}_{\frac{1}{2}\sin\left(\frac{\theta}{2}\right)}\ e^{-i\phi_{21}t/2}\Big[\underbrace{e^{i\phi_{21}t/2} - e^{-i\phi_{21}t/2}}_{2i\sin\left(\frac{\phi_{21}t}{2}\right)}\Big]$$

$$P(e\to\mu) = \left|\chi_\mu^+ \psi_e(t)\right|^2$$

$$= \sin^2\left(\frac{\theta}{2}\right)\sin^2\left(\frac{\phi_{21}t}{2}\right)$$

with $L = ct$, $cp \simeq E$

$$\boxed{P(e\to\mu) = \sin^2\left(\frac{\theta}{2}\right)\sin^2\left(\frac{\Delta m^2 L}{4E\hbar c}\right)}$$

depends on square mass difference

$$\Delta m^2 = m_2^2 - m_1^2$$

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