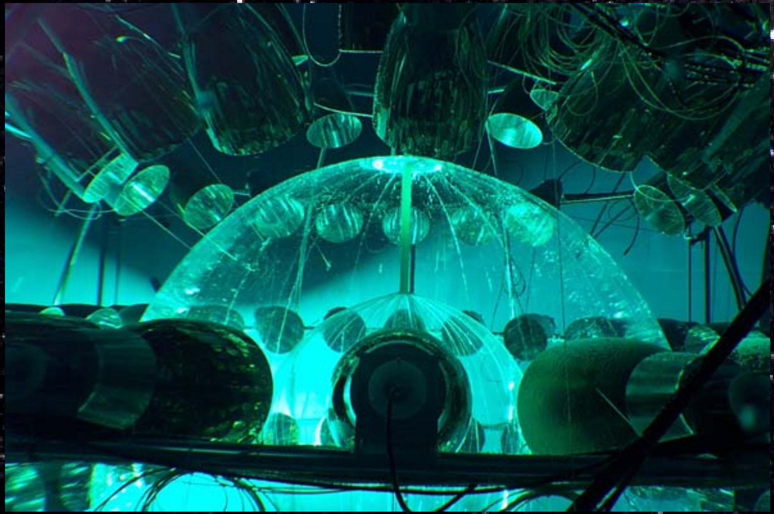
Solar Neutrinos : Puzzle Solved, Book Closed ?

Some Basics on Solar Neutrinos

Solar Neutrino Puzzle, its Evolution & Solution



MPI Informal Seminar, 19 May 2006

2002 - The Year of Neutrinos

Spring: Neutrino Oscillations Established
by Astroparticle Physics Experiments with

Solar Neutrinos
(^{37}Cl, Gallium, Superkamiokande, SNO, ...)

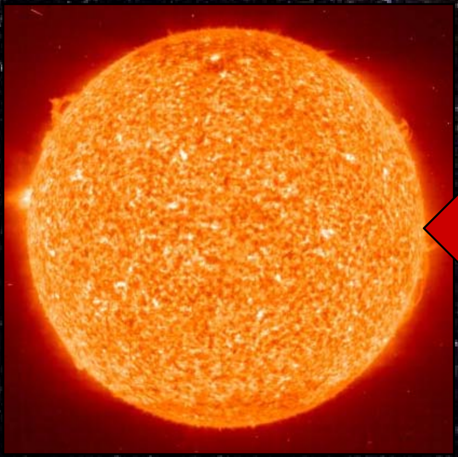
and

Atmospheric Neutrinos
(SuperK, Macro, ...)

October: Nobel Prize
for Davis and Koshiba

December: Neutrino Oscillations
Confirmed by Terrestrial Experiment
(KamLAND)

Sun Glasses for Neutrinos?

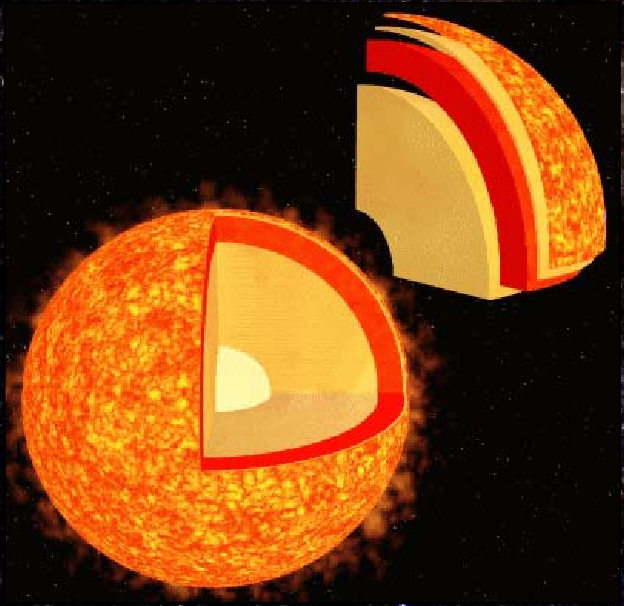


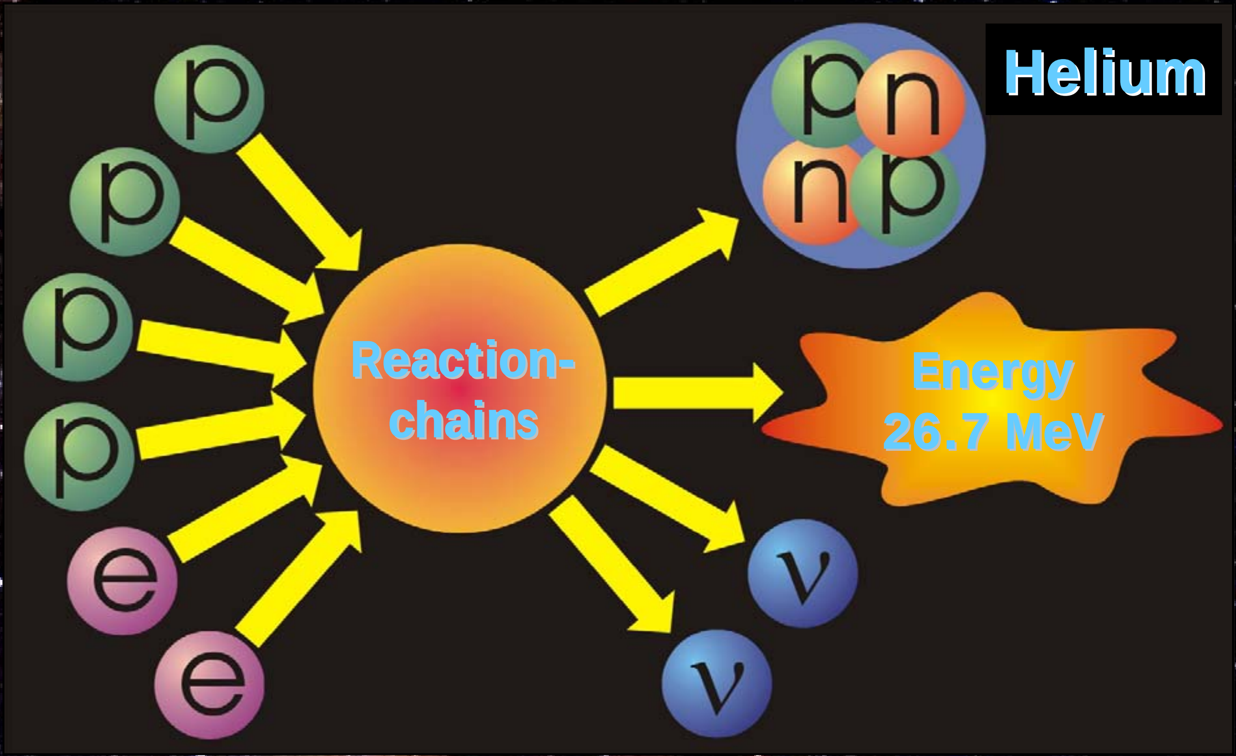
8.3 light minutes

1000 light years of dense matter needed to shield solar neutrinos

<u>Bethe & Peierls 1934:</u>
"… this evidently means that one will never be able to observe a neutrino."

Neutrinos from the Sun





Solar radiation: 98 % light

2 % neutrinos

At Earth 66 billion neutrinos/cm^2 sec

Hans Bethe (born 1906, Nobel prize 1967)
Thermonuclear reaction chains (1938)

Bethe's Classic Paper on Nuclear Reactions in Stars

MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55

Energy Production in Stars*

H. A. Bethe
Cornell University, Ithaca, New York

(Received September 7, 1938)

It is shown that the *most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons*. These reactions form a cycle in which the original nucleus is reproduced, *viz.* $C^{12}+H=N^{13}$, $N^{13}=C^{13}+\epsilon^+$, $C^{13}+H=N^{14}$, $N^{14}+H=O^{15}$, $O^{15}=N^{15}+\epsilon^+$, $N^{15}+H=C^{12}+He^4$. Thus carbon and nitrogen merely serve as catalysts for the combination of four protons (and two electrons) into an α-particle (§7).

The carbon-nitrogen reactions are unique in their cyclical character (§8). For all nuclei lighter than carbon, reaction with protons will lead to the emission of an α-particle so that the original nucleus is permanently destroyed. For all nuclei heavier than fluorine, only radiative capture of the protons occurs, also destroying the original nucleus. Oxygen and fluorine reactions mostly lead back to nitrogen. Besides, these heavier nuclei react much more slowly than C and N and are therefore unimportant for the energy production.

The agreement of the carbon-nitrogen reactions with observational data (§7, 9) is excellent. In order to give the correct energy evolution in the sun, the central temperature of the sun would have to be 18.5 million degrees while integration of the Eddington equations gives 19. For the brilliant star Y Cygni the corresponding figures are 30 and 32. This good agreement holds for all bright stars of the main sequence, but, of course, not for giants.

For fainter stars, with lower central temperatures, the reaction $H+H=D+\epsilon^+$ and the reactions following it, are believed to be mainly responsible for the energy production. (§10)

It is shown further (§5–6) that *no elements heavier than* He^4 *can be built up in ordinary stars*. This is due to the fact, mentioned above, that all elements up to boron are disintegrated by proton bombardment (α-emission!) rather than built up (by radiative capture). The instability of Be^8 reduces the formation of heavier elements still further. The production of neutrons in stars is likewise negligible. The heavier elements found in stars must therefore have existed already when the star was formed.

Finally, the suggested mechanism of energy production is used to draw conclusions about astrophysical problems, such as the mass-luminosity relation (§10), the stability against temperature changes (§11), and stellar evolution (§12).

§1. Introduction

The progress of nuclear physics in the last few years makes it possible to decide rather definitely which processes can and which cannot occur in the interior of stars. Such decisions will be attempted in the present paper, the discussion being restricted primarily to main sequence stars. The results will be at variance with some current hypotheses.

The first main result is that, under present conditions, no elements heavier than helium can be built up to any appreciable extent. Therefore we must assume that the heavier elements were built up *before* the stars reached their present state of temperature and density. No attempt will be made at speculations about this previous state of stellar matter.

The energy production of stars is then due entirely to the combination of four protons and two electrons into an α-particle. This simplifies the discussion of stellar evolution inasmuch as the amount of heavy matter, and therefore the opacity, does not change with time.

The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*

$$H+H=D+\epsilon^+. \quad (1)$$

The deuteron is then transformed into He^4 by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction

$$\begin{aligned} &C^{12}+H=N^{13}+\gamma, && N^{13}=C^{13}+\epsilon^+ \\ &C^{13}+H=N^{14}+\gamma, && \\ &N^{14}+H=O^{15}+\gamma, && O^{15}=N^{15}+\epsilon^+ \\ &N^{15}+H=C^{12}+He^4. && \end{aligned} \quad (2)$$

The catalyst C^{12} is reproduced in all cases except about one in 10,000, therefore the abundance of carbon and nitrogen remains practically unchanged (in comparison with the change of the number of protons). The two reactions (1) and

* Awarded an A. Cressy Morrison Prize in 1938, by the New York Academy of Sciences.

No neutrinos from nuclear reactions in 1938 ...

The combination of four p... and two electrons can occur essentially o... two ways. The first mechanism starts with ...combination of two protons to form a deuter... with positron emission, *viz.*

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Thermonuclear Reactions and Gamow Peak

Coulomb repulsion prevents nuclear reactions, except for Gamow tunneling

Tunneling probability

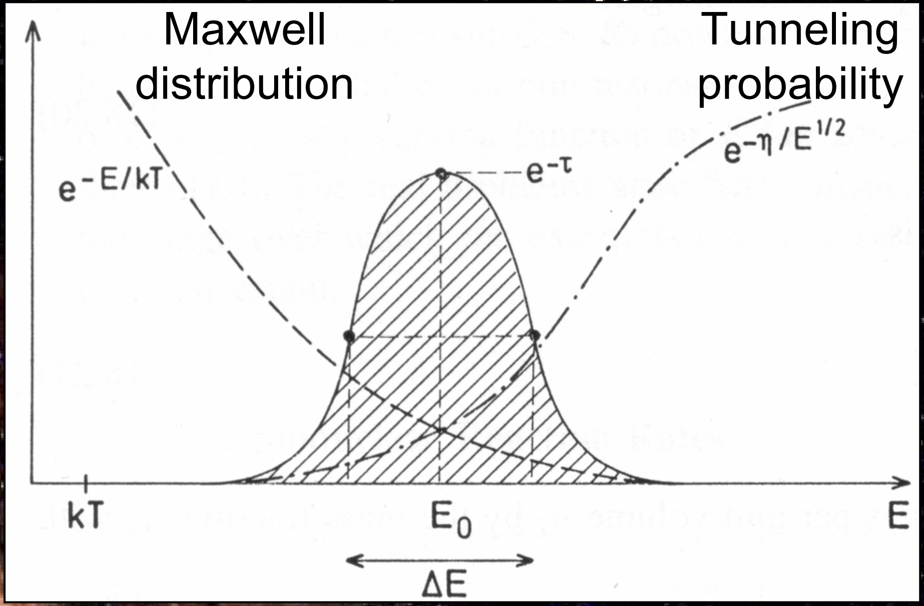
$$p \propto E^{-1/2} e^{-2\pi\eta}$$

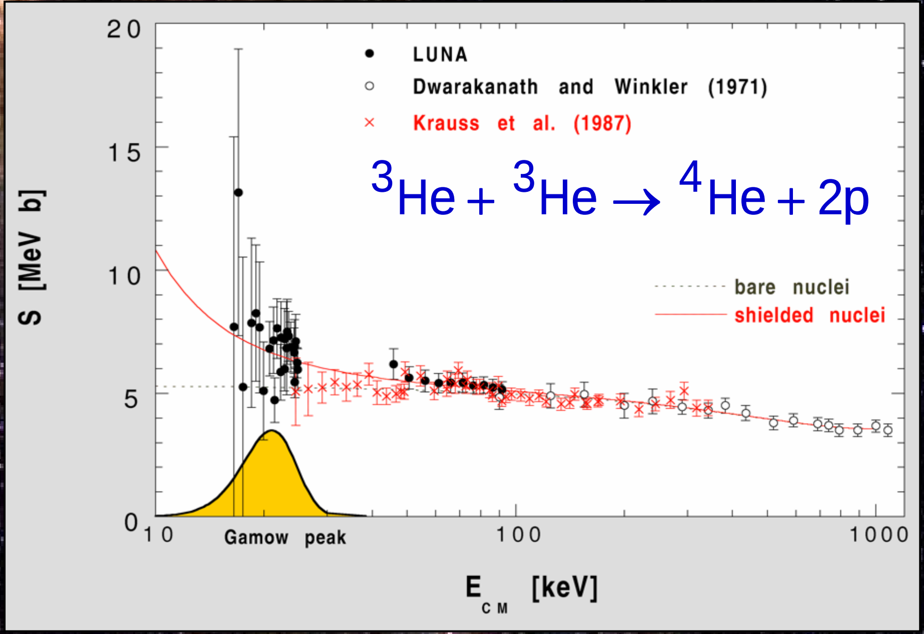
With Sommerfeld parameter

$$\eta = \left(\frac{m}{2E}\right)^{1/2} Z_1 Z_2 e^2$$

Parameterize cross section with astrophysical S-factor

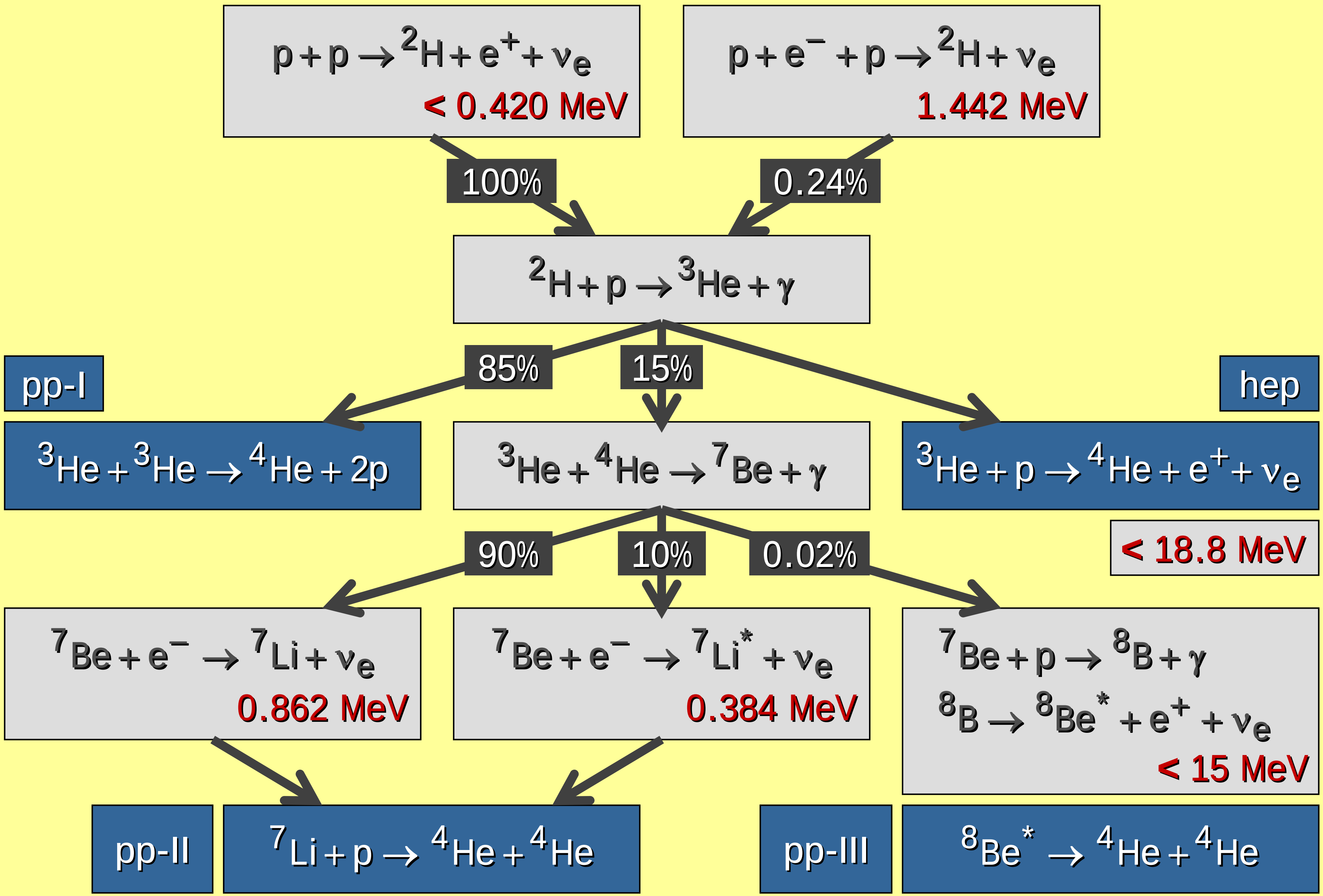
$$S(E) = \sigma(E)\, E\, e^{2\pi\eta(E)}$$



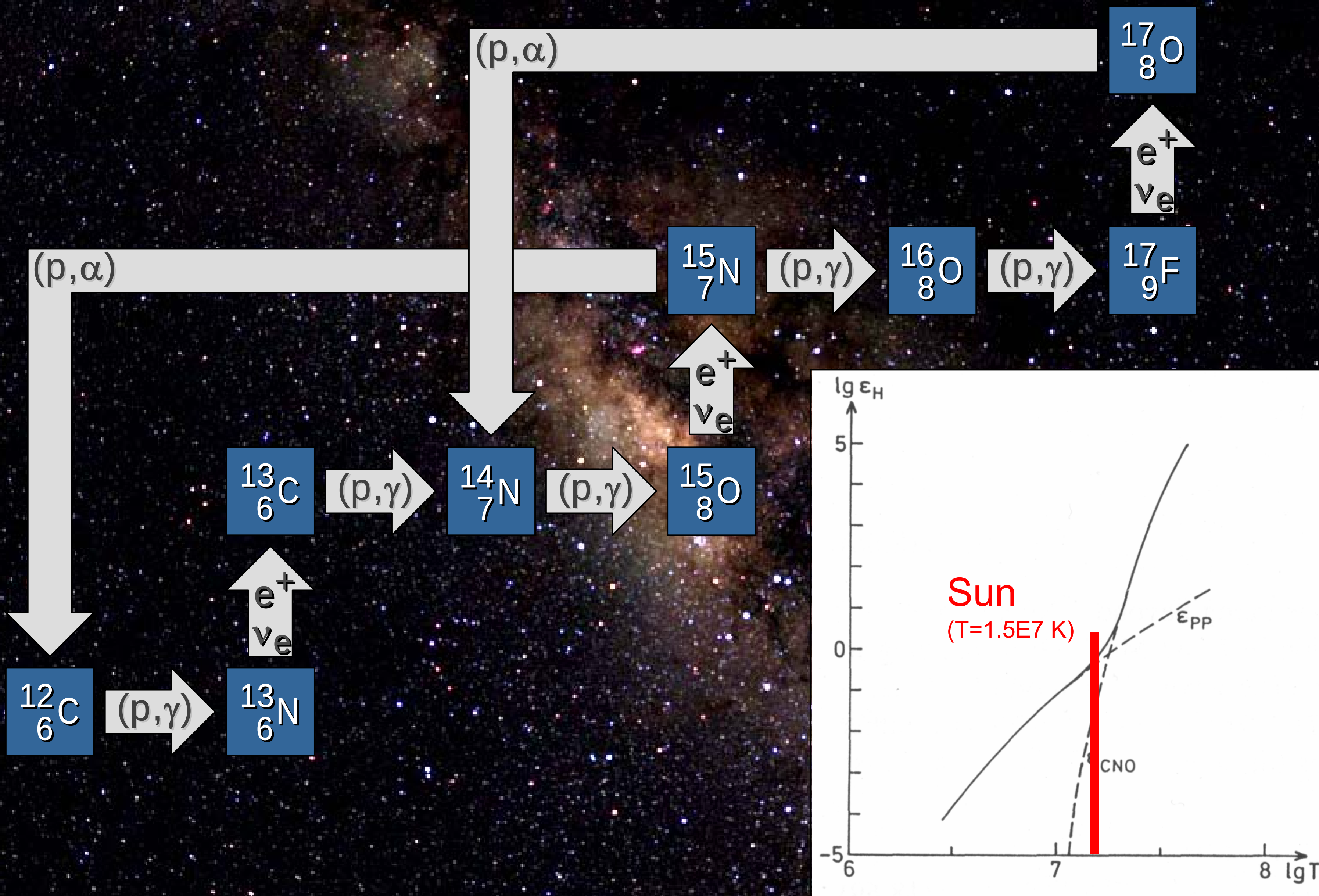


LUNA Collaboration, nucl-ex/9902004

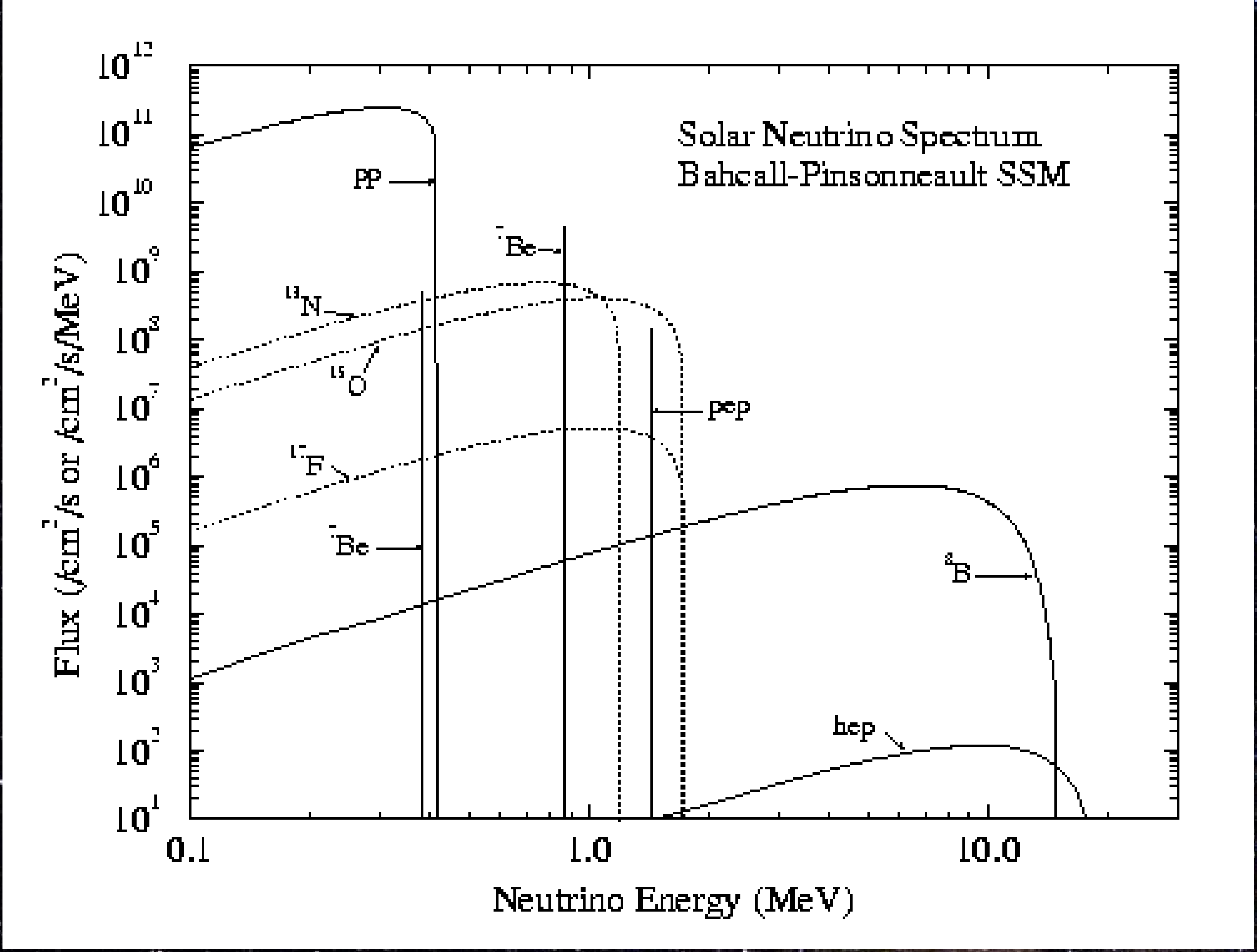
Hydrogen burning: Proton-Proton Chains



Hydrogen Burning: CNO Cycle

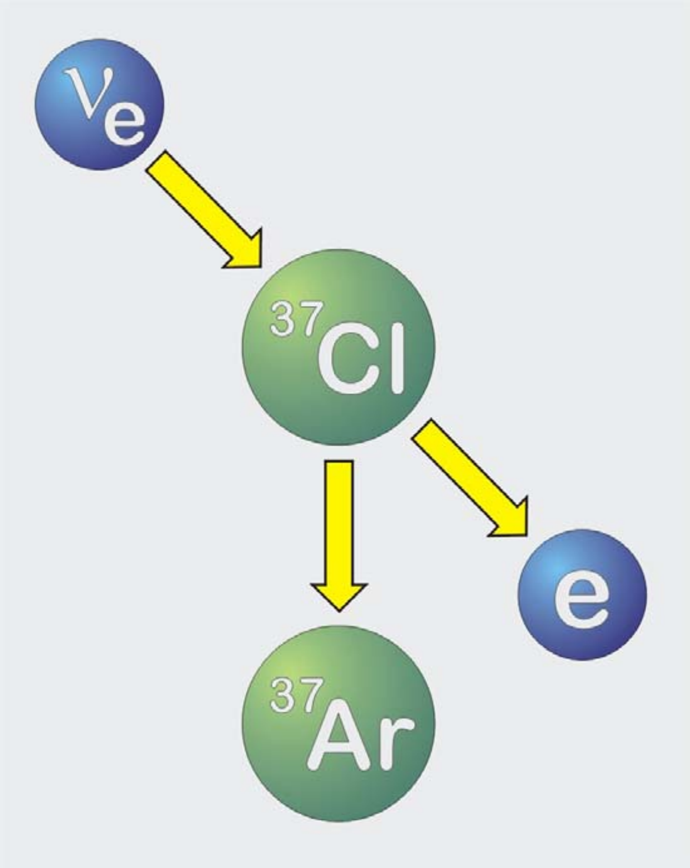


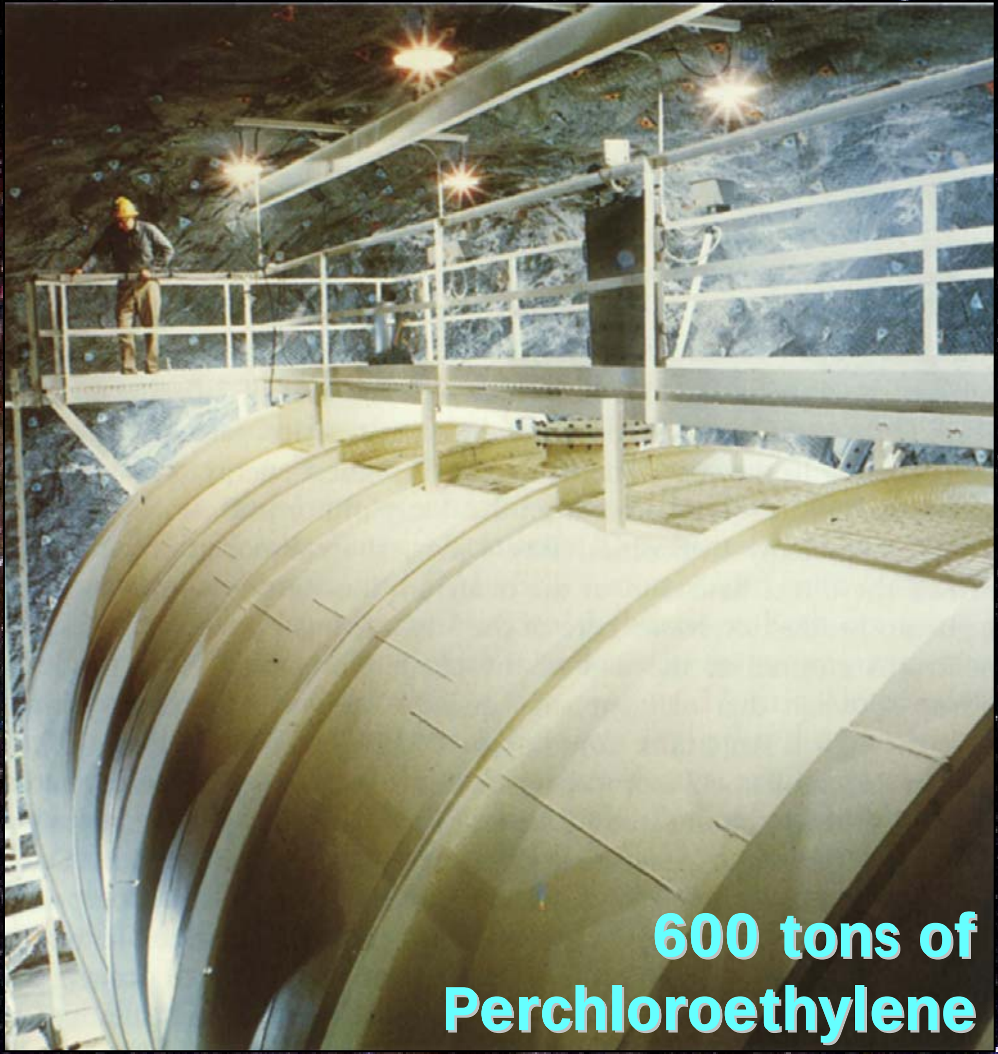
Solar Neutrino Spectrum



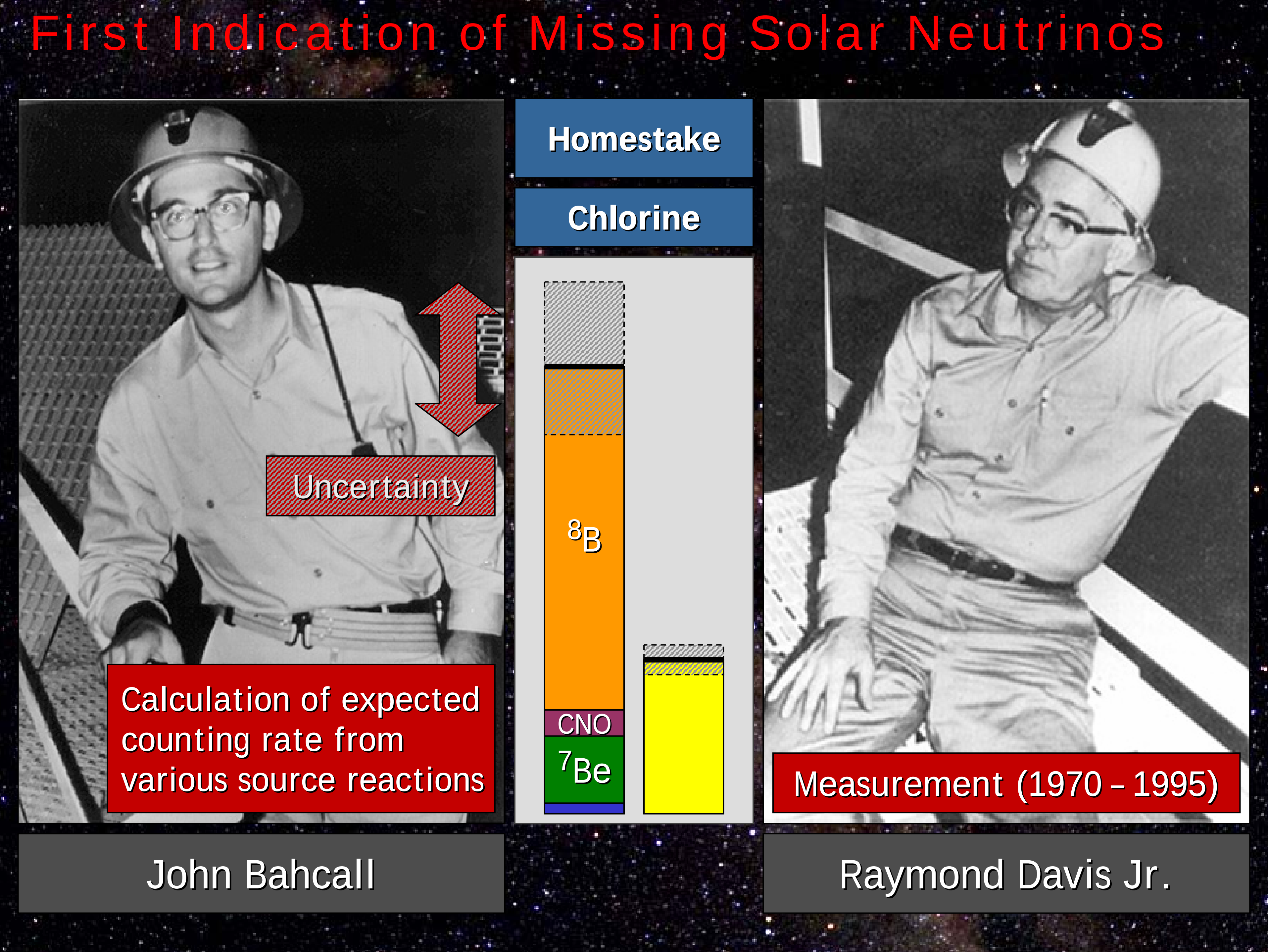
First Measurement of Solar Neutrinos

Inverse beta decay of chlorine



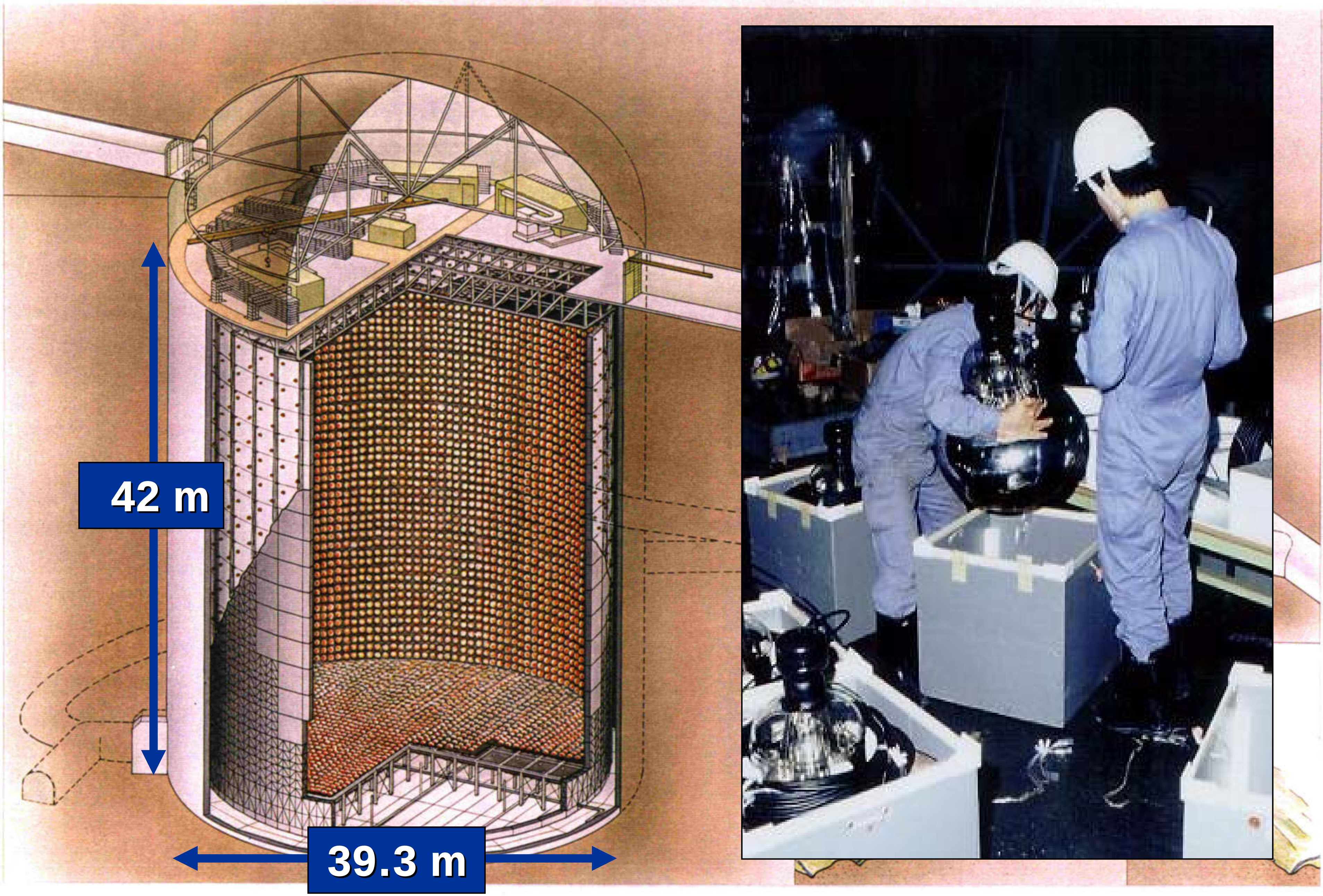


Homestake solar neutrino observatory (1967–2002)

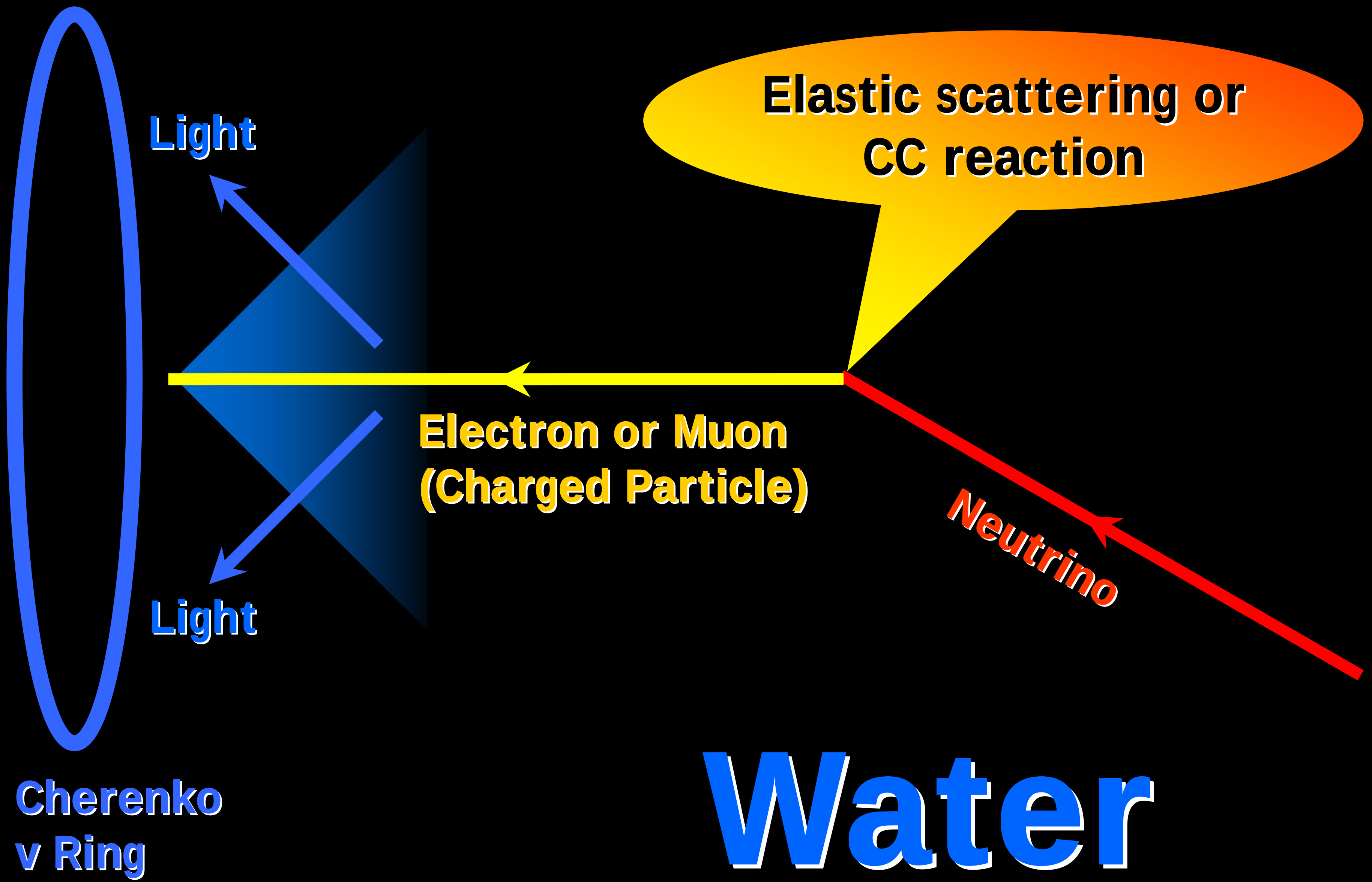


First Indication of Missing Solar Neutrinos
Homestake
Chlorine
Uncertainty
8B
CNO
7Be
Calculation of expected counting rate from various source reactions
Measurement (1970 – 1995)
John Bahcall
Raymond Davis Jr.

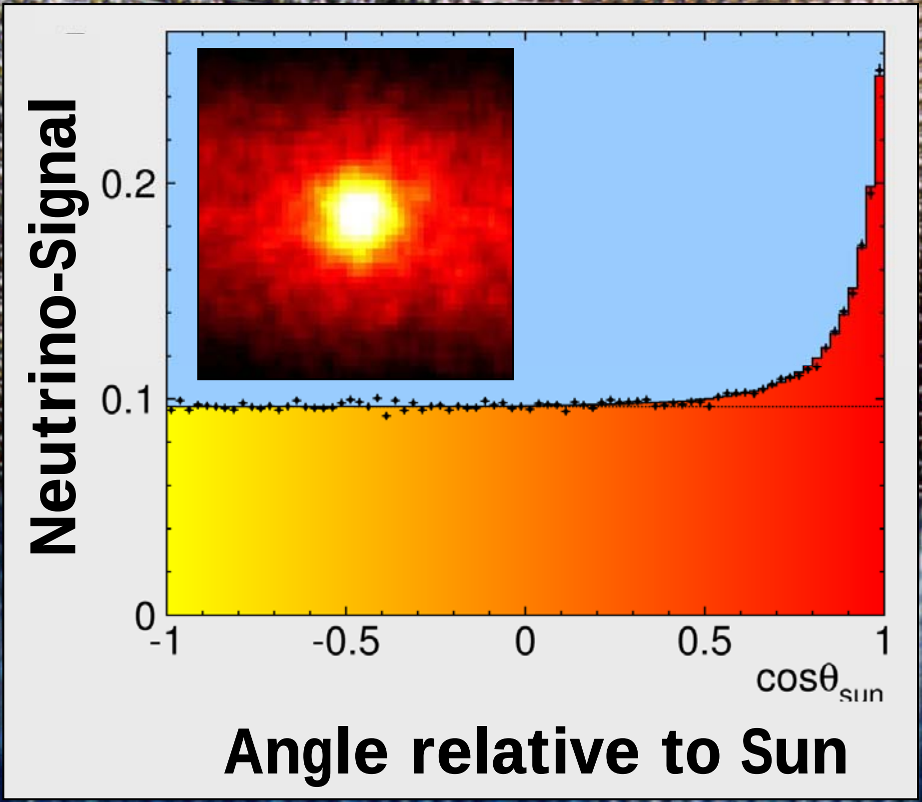
Super-Kamiokande Neutrino Detector

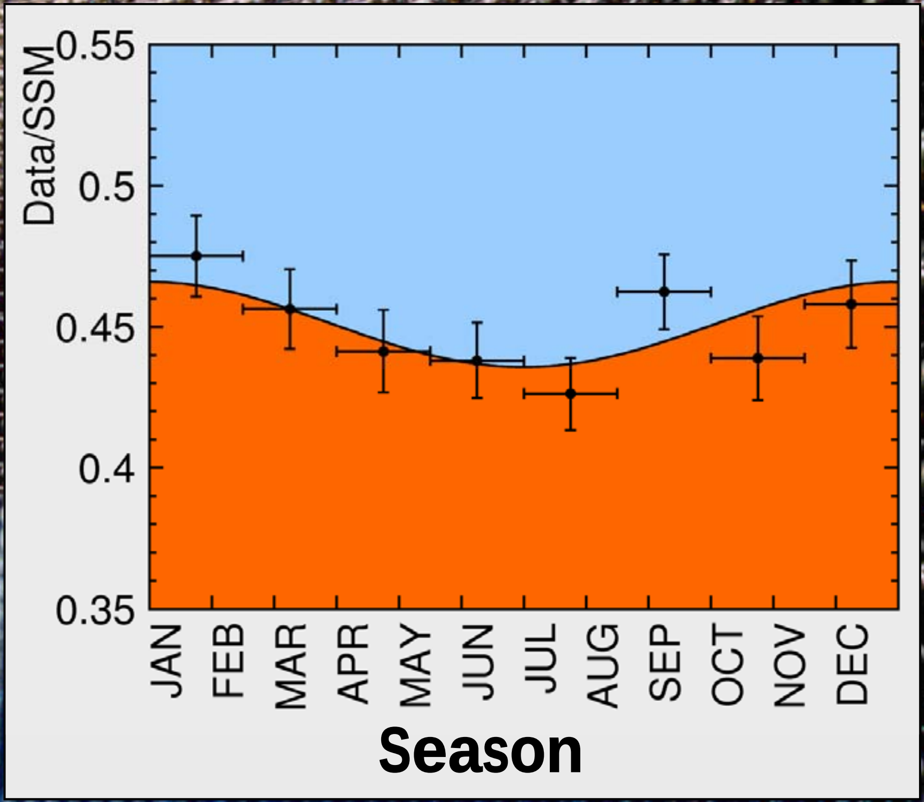


Cherenkov Effect



Superkamiokande: Our Sun in the Light of Neutrinos





Third Measurement of Solar Neutrinos

Inverse beta decay of gallium

$$\text{Ga-71} + \nu_e \rightarrow \text{Ge-71} + e^-$$

Sensitive to neutrinos from the primary pp-reaction

100 tons of Gallium tetrachloride (30 tons of Ga)

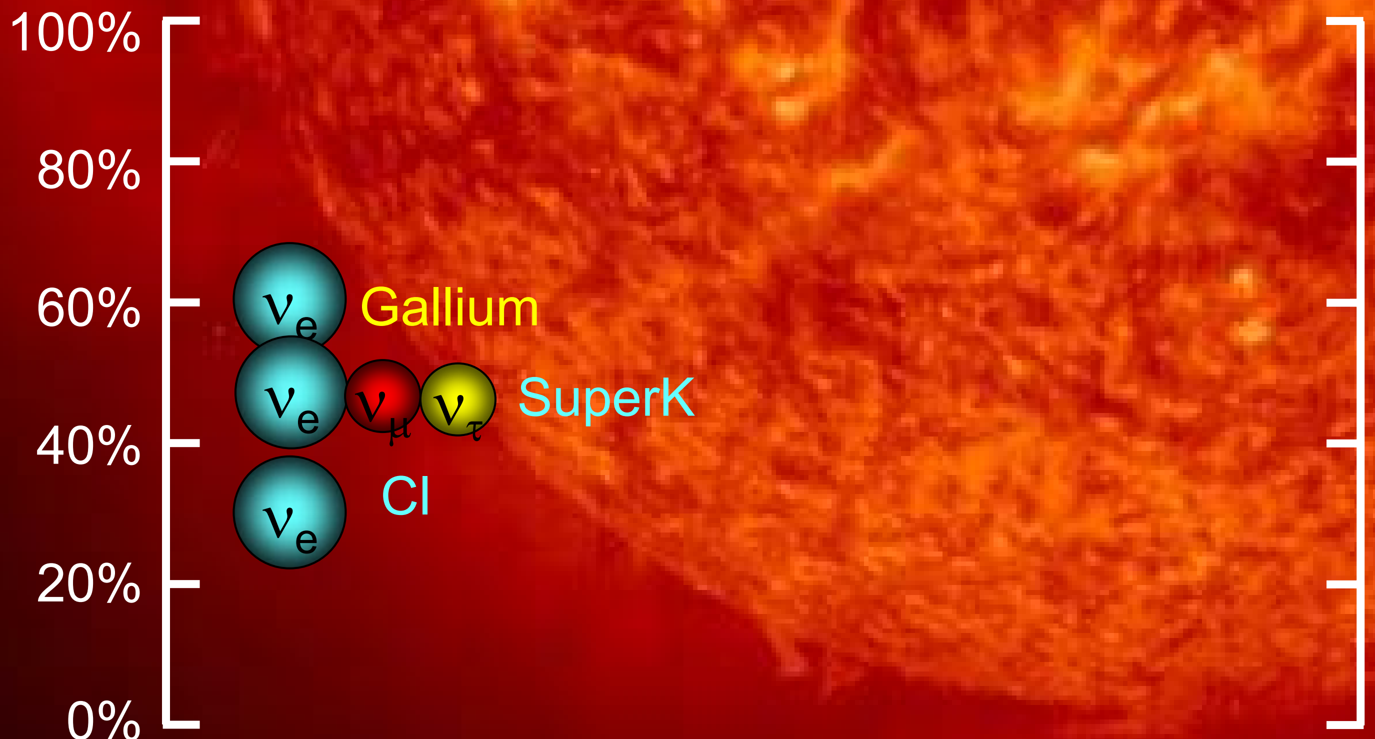
GALLEX / GNO solar neutrino observatory (1990–2004)

M.Altmann et al., Phys. Lett. B 616 (2005) 174

Solar Neutrinos – Experimental Status I

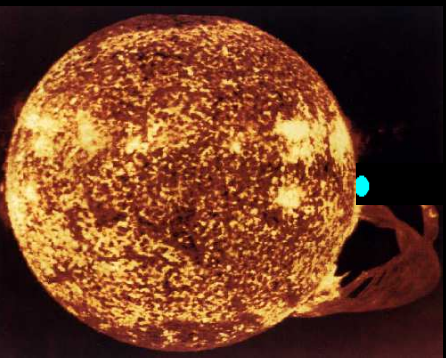
Energy dependent
electron neutrino deficit
(flavour conversion)

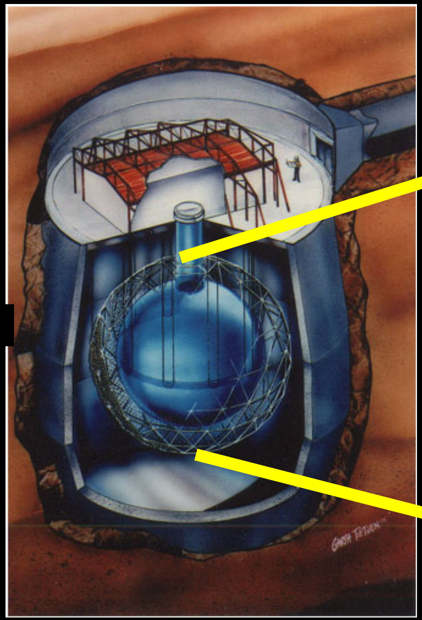
Solar Neutrino Flux at Earth

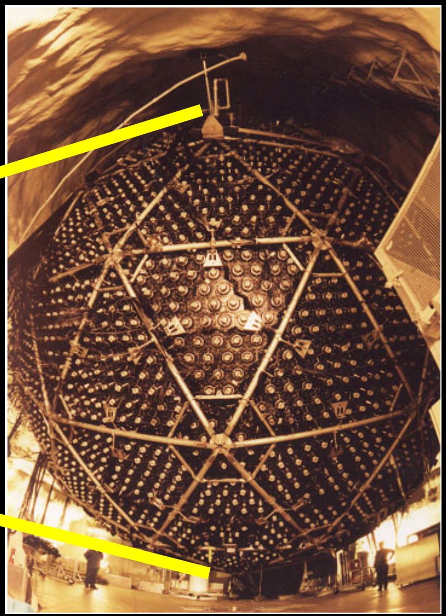


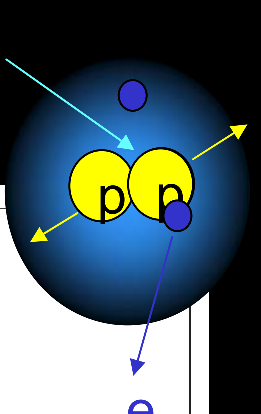
The Sudbury Neutrino Observatory SNO

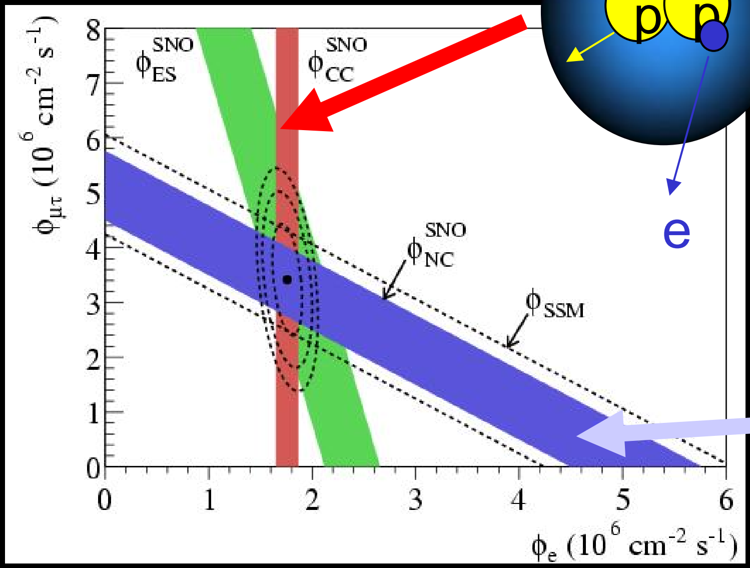
A 1 kilo-ton heavy water detector
with photomultiplier-readout



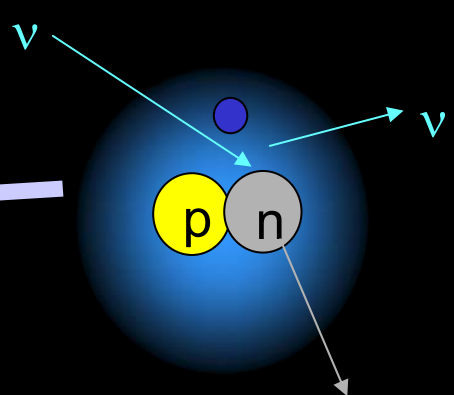








Charged Current Reaction (CC) on deuterium
➔ works for ν_e only



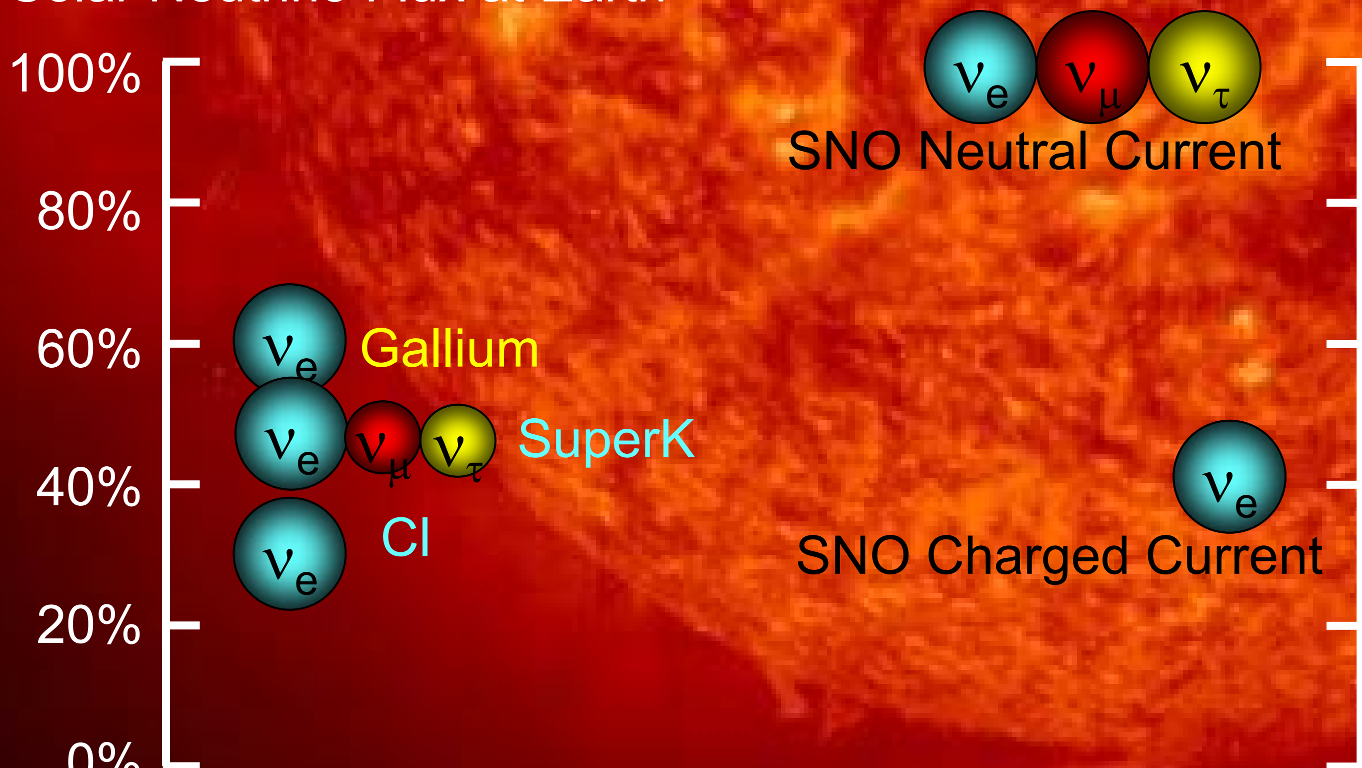
Neutral Current
Reaction (NC)
➔ works for all
active ν flavours

Solar Neutrinos – Experimental Status II

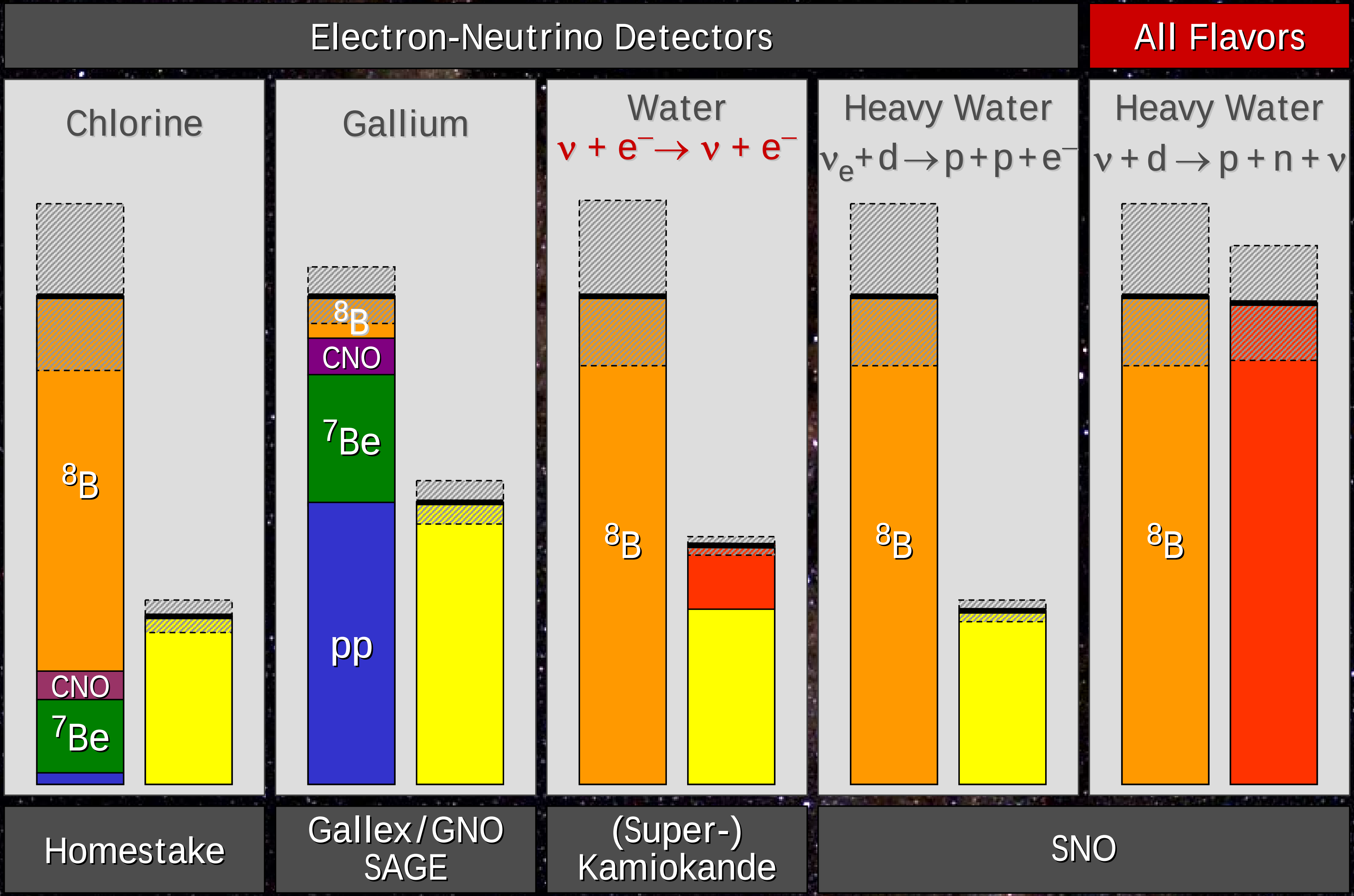
Energy dependent electron neutrino deficit (flavour conversion)

Direct measurement of neutrino flavour conversion

Solar Neutrino Flux at Earth



Solar Neutrino Results: The Full Picture



How to Understand This ?

Neutrino-Masses and Neutrino-Mixing

Three massive ν_1, ν_2, ν_3 of masses $m_1<m_2<m_3$

Flavour States ≠ Mass Eigenstates

If

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix} \qquad \begin{pmatrix} \nu_1 \\ e^- \end{pmatrix} \begin{pmatrix} \nu_2 \\ \mu^- \end{pmatrix} \begin{pmatrix} \nu_3 \\ \tau^- \end{pmatrix}$$

Neutrino Mixing

then

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

occurs

The same, written a little differently …

For 3 massive neutrinos we have
3 mixing angles and
(at least) 1 CP-violating phase

θ_{13}, δ θ_{sol}

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

θ_{atm}

Neutrino oscillations are a direct consequence …

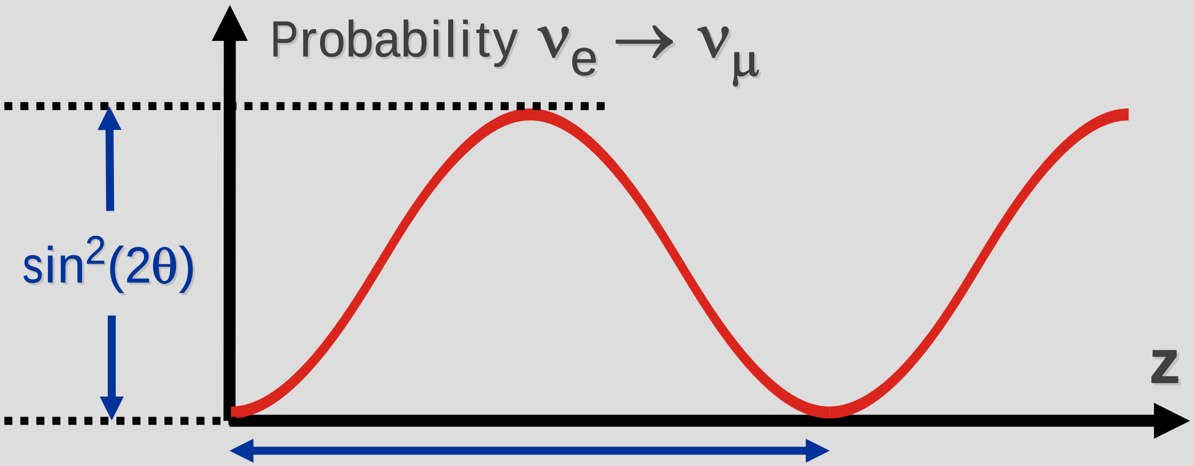
Neutrino Flavor Oscillations

Two-flavor mixing $\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$

Each mass eigenstate propagates as e^{ipz}

with $p = \sqrt{E^2 - m^2} \approx E - \frac{m^2}{2E}$

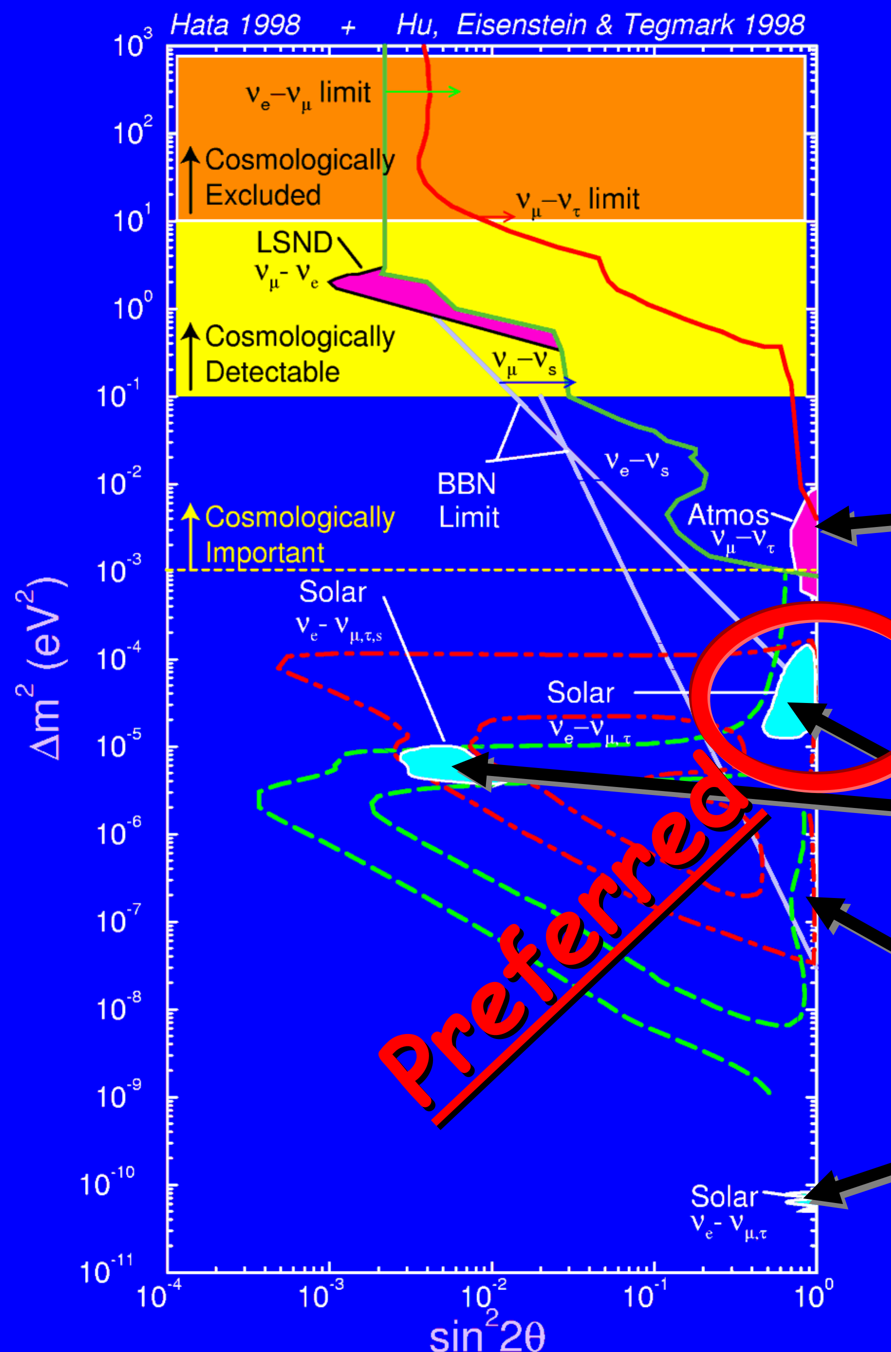
Phase difference $\frac{\delta m^2}{2E} z$ implies flavor oscillations



Oscillation Length $\frac{4\pi E}{\delta m^2} = 2.5\,\mathrm{m} \left(\frac{E}{\mathrm{MeV}}\right)\left(\frac{\mathrm{eV}^2}{\delta m^2}\right)$

Bruno Pontecorvo
(1913 – 1993)
Invented nu oscillations

Neutrino Oscillations: The Global Picture



Atmospheric Neutrino Anomaly

Solar Neutrinos:

MSW Solutions

(Matter effects important)

LOW solution

Vacuum Solution

Confirmation by a terrestrial experiment

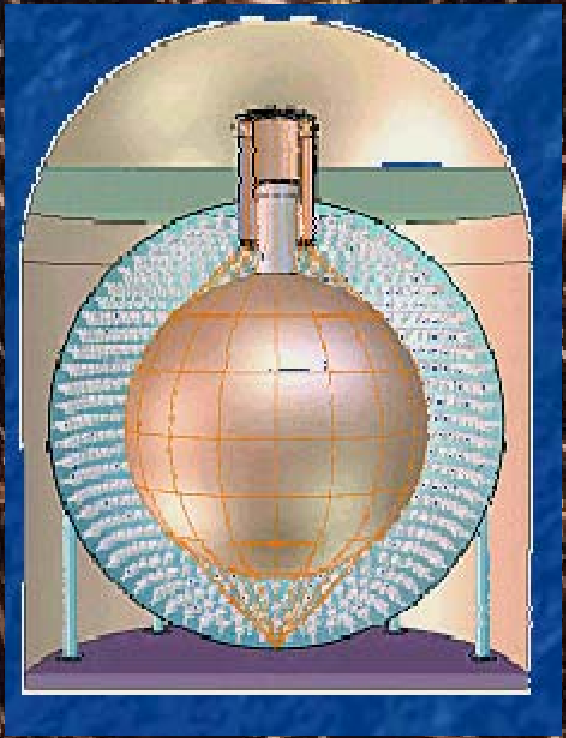
KamLAND

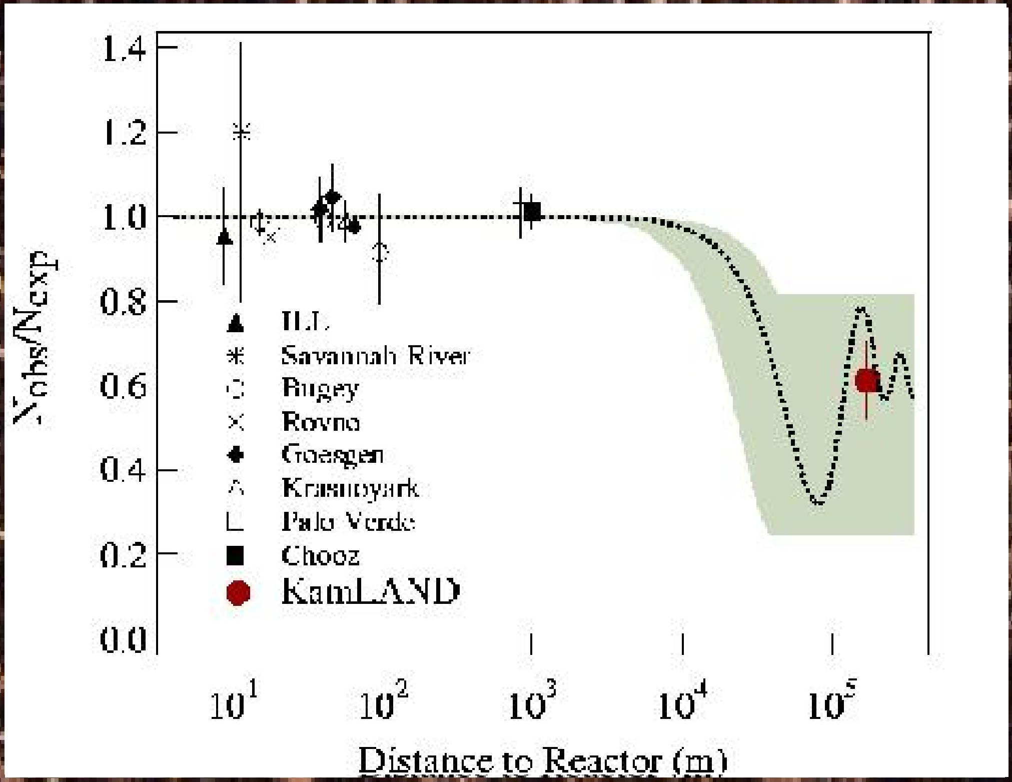
Electron Antineutrinos from Nuclear Reactors

Detected in SuperK by inverse beta-decay on p

Baseline: some 100 km, Energy: some MeV

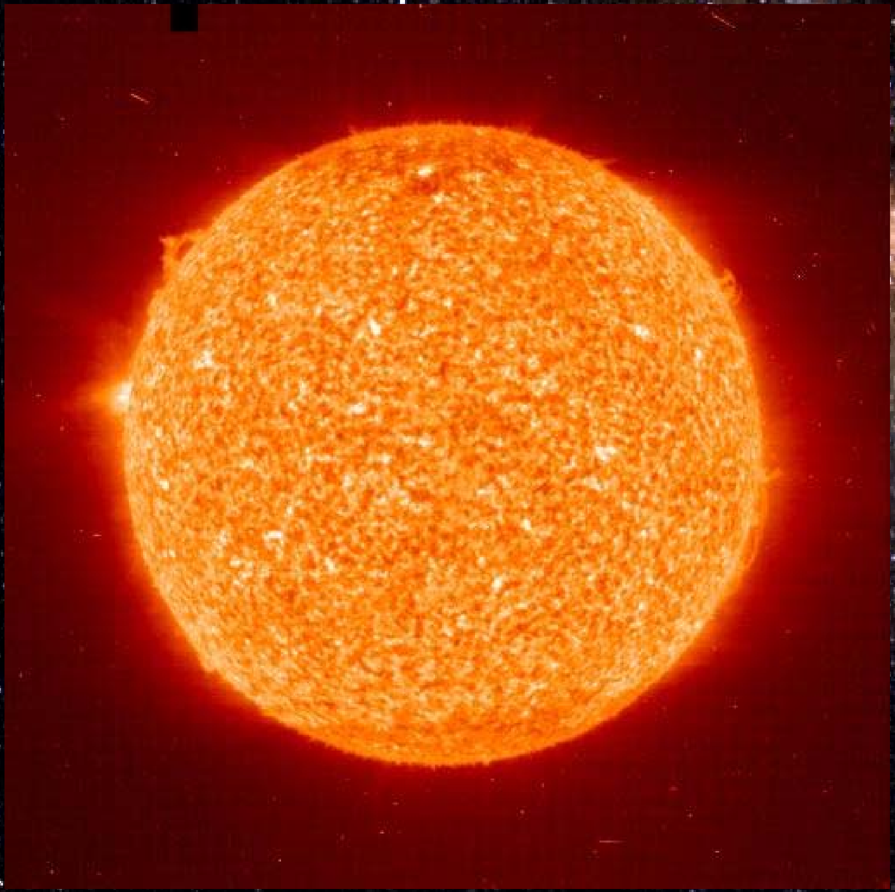
→ Sensitivity Δm^2 - range of ~ 10^{-5} eV^2





Conclusions and Outlook

Solar Neutrino Experiments (Cl, Ga, SuperK, SNO) have proven nuclear burning reactions to fuel stars and neutrinos to be massive particles exhibiting flavour mixing



Thermal plasma reactions
E ~ 1 eV - 30 keV
No apparent way to measure

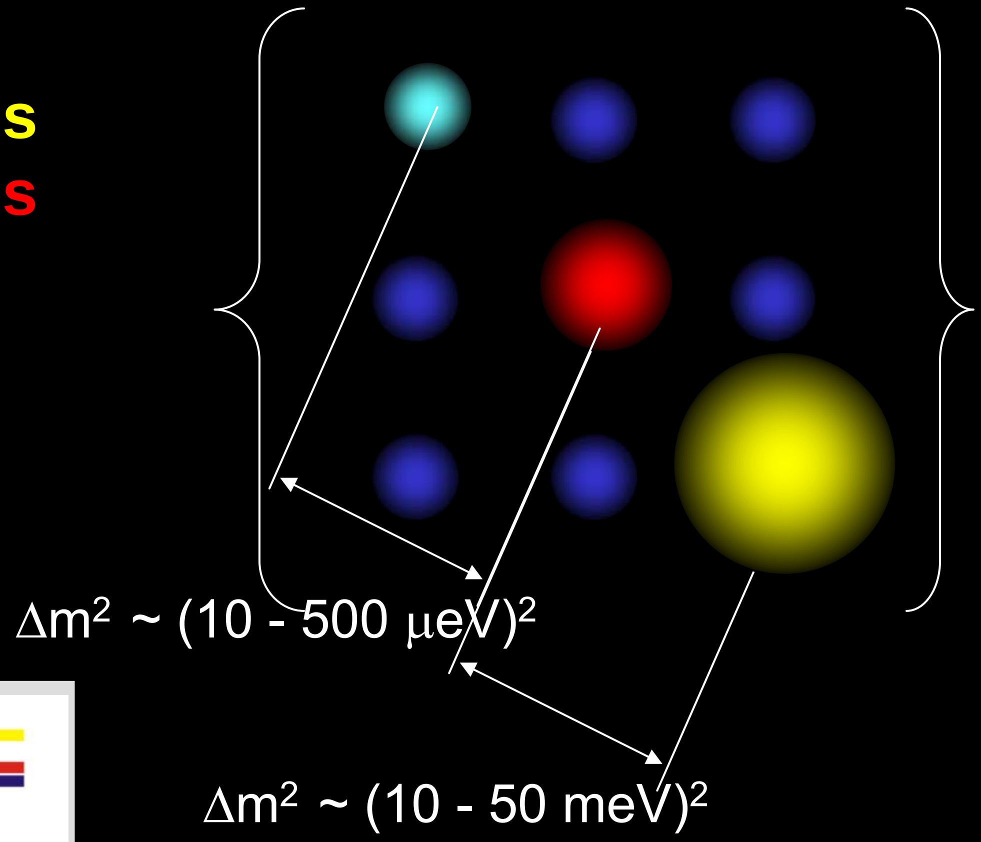
Nuclear burning reactions
E ~ 0.1 - 15 MeV
Routine detailed measurements

Cosmic-ray interactions in the Sun
E ~ 10 - 10^9 GeV
Future high-E neutrino telescopes (?)

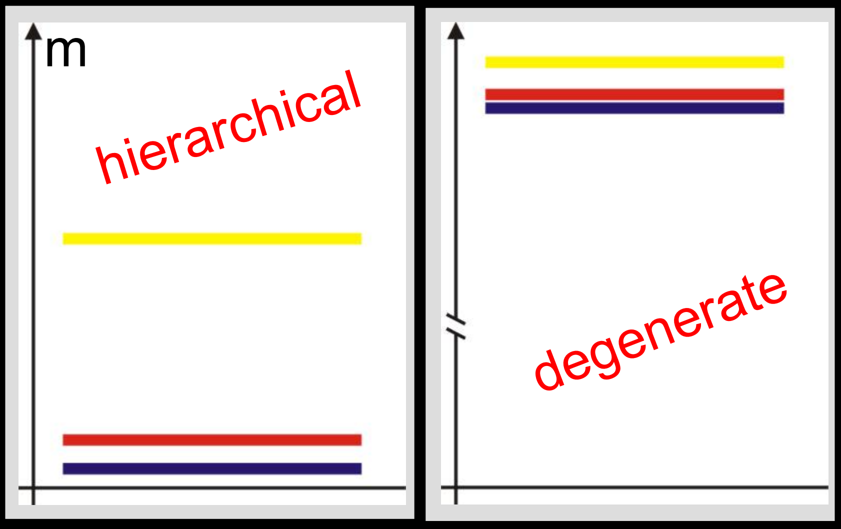
Dark matter annihilation in the Sun
E ~ GeV - TeV (?)
Future high-E neutrino telescopes (?)

Wanted: Absolute Values for the Masses

Oscillations only tell us
Mass Differences



What is the absolute mass scale ??



How to find out ??