11 – Neutrino astronomy

11.1 – The standard solar model

As we discussed in "stellar evolution III", to obtain a reliable model for the sun, we need to solve four differential equations (in the absence of convection).

$$\frac{dM(r)}{dr} = 4\pi r^2 \rho(r) \quad (11.1)$$

$$\frac{dP(r)}{dr} = -\frac{GM(r)\rho(r)}{r^2} \quad (11.2)$$

$$\frac{dL(r)}{dr} = 4\pi r^2 \rho(r)\varepsilon(r) \quad (11.3)$$

$$\frac{dT(r)}{dr} = -\frac{3\rho(r)\overline{\kappa}(r)}{16\pi r^2 \sigma T^3(r)} L(r) \quad (11.4)$$

Complemented by

P = P (ρ , T, chemical composition) — **The equation of state**

κ = κ *(ρ , T, chemical composition)* — **Opacity**

ε = ε *(ρ , T, chemical composition)* — **Energy generation**

But we also need to include how the chemical composition changes through nuclear reaction network. For the sun, the pp-chain and the CNO cycle are considered.

General reaction network

When the reaction network proceeds via one-body and two-body reactions, such as the pp-chain. and CNO cycle. But 3-body processes such as the triple-alpha reaction are also possible. A general reaction network can be written as

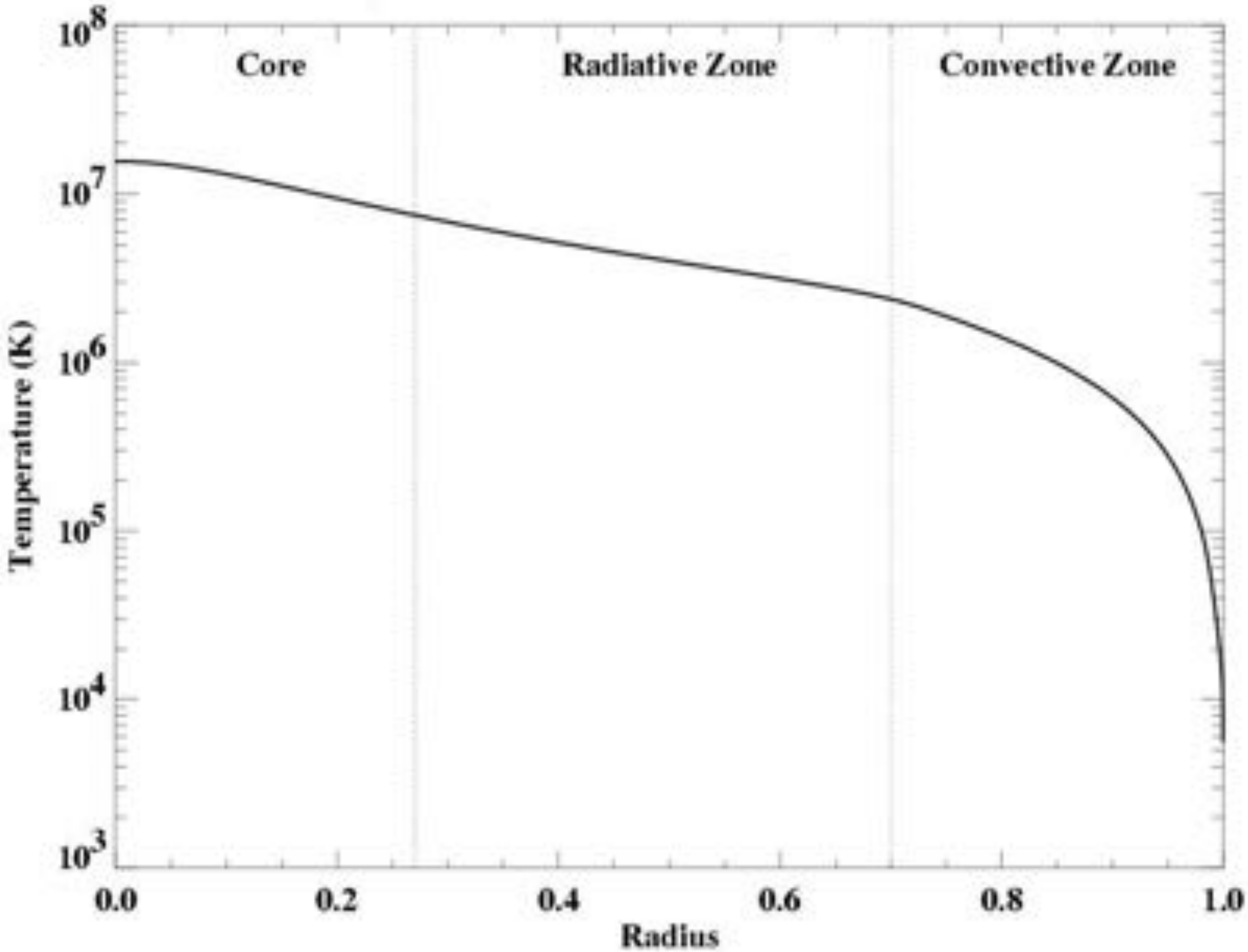
$$\frac{dY_i}{dt} = \sum_j N^i_j \lambda_j Y_j + \sum_{jk} N^i_{jk} \rho N_A < \sigma v > Y_j Y_k + \sum_{jkm} N^i_{jkm} \rho^2 N_A{}^2 < \sigma v > Y_j Y_k Y_m + \cdots \qquad (11.5)$$

where $N^i_{j,k,l,...}$ is the number of particles of nuclear species i created or destroyed by the reaction $j + k + l + \cdot \cdot \cdot \rightarrow i$.

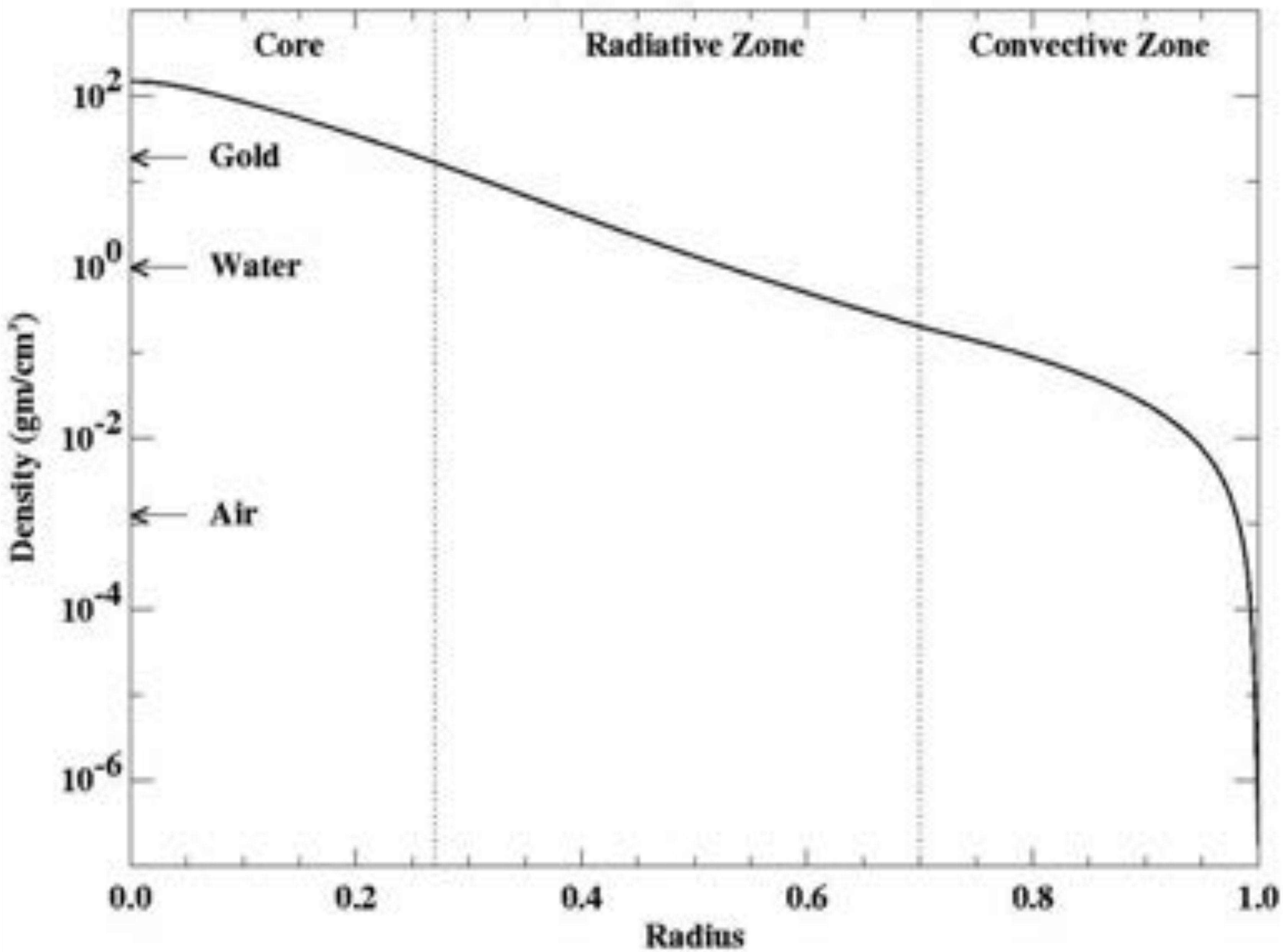
The reactions listed on the right hand side of the equation above belong to three categories of reactions: (1) decays, photodisintegrations, electron and positron captures and neutrino induced reactions ($r_j = \lambda_j n_j$), (2) two-particle reactions ($r_{j,k} = < \sigma v >_{j,k} n_j n_k$), and (3) three-particle reactions ($r_{j,k,l} = < \sigma v >_{j,k,l} n_j n_k n_l$) like the triple-alpha process ($\alpha + \alpha + \alpha \rightarrow {}^{12}C + \gamma$).

Note that by using this definition, the N's can be positive or negative numbers.

Output of Bahcall's SSM - Solar temperature

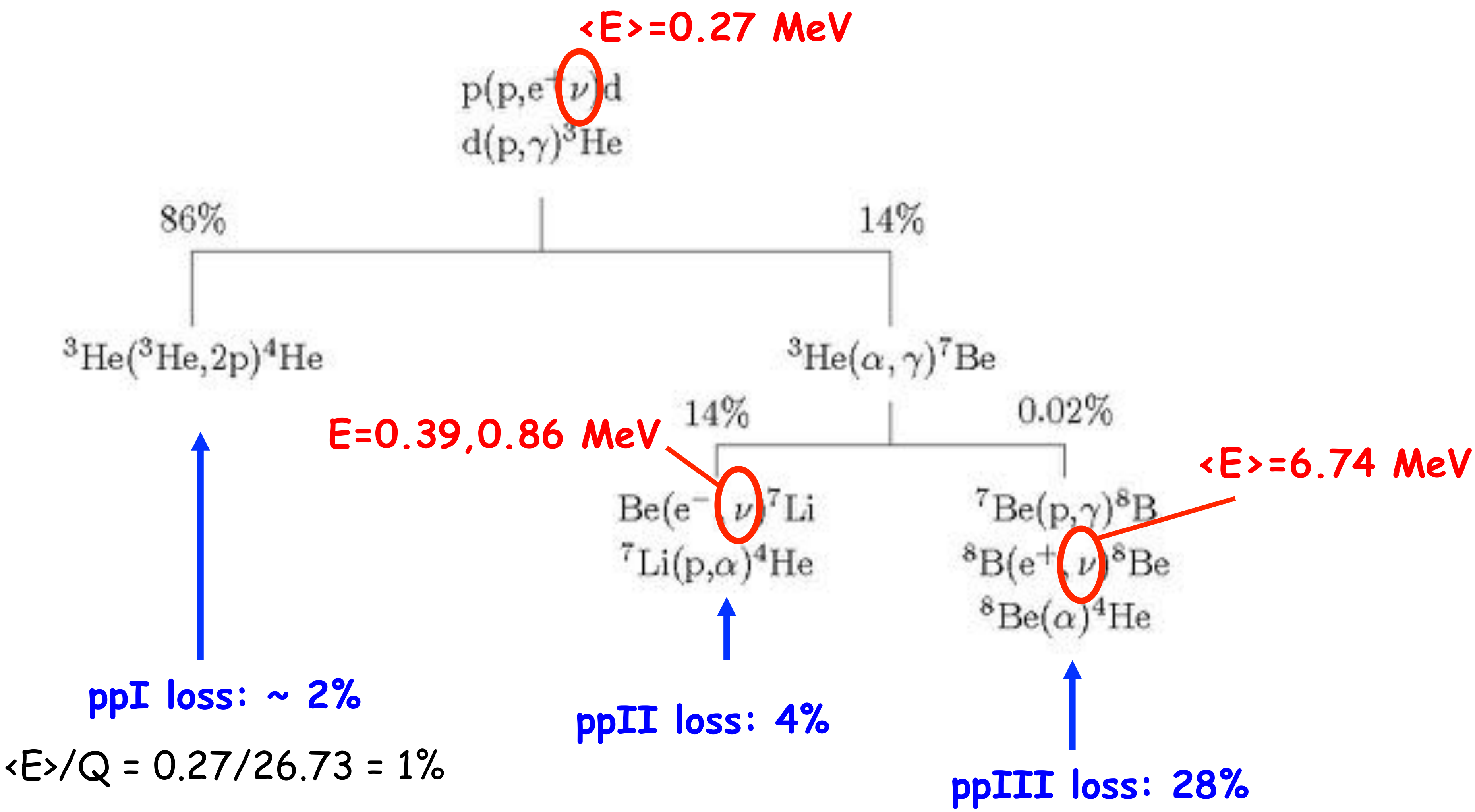


Solar density



The standard solar model

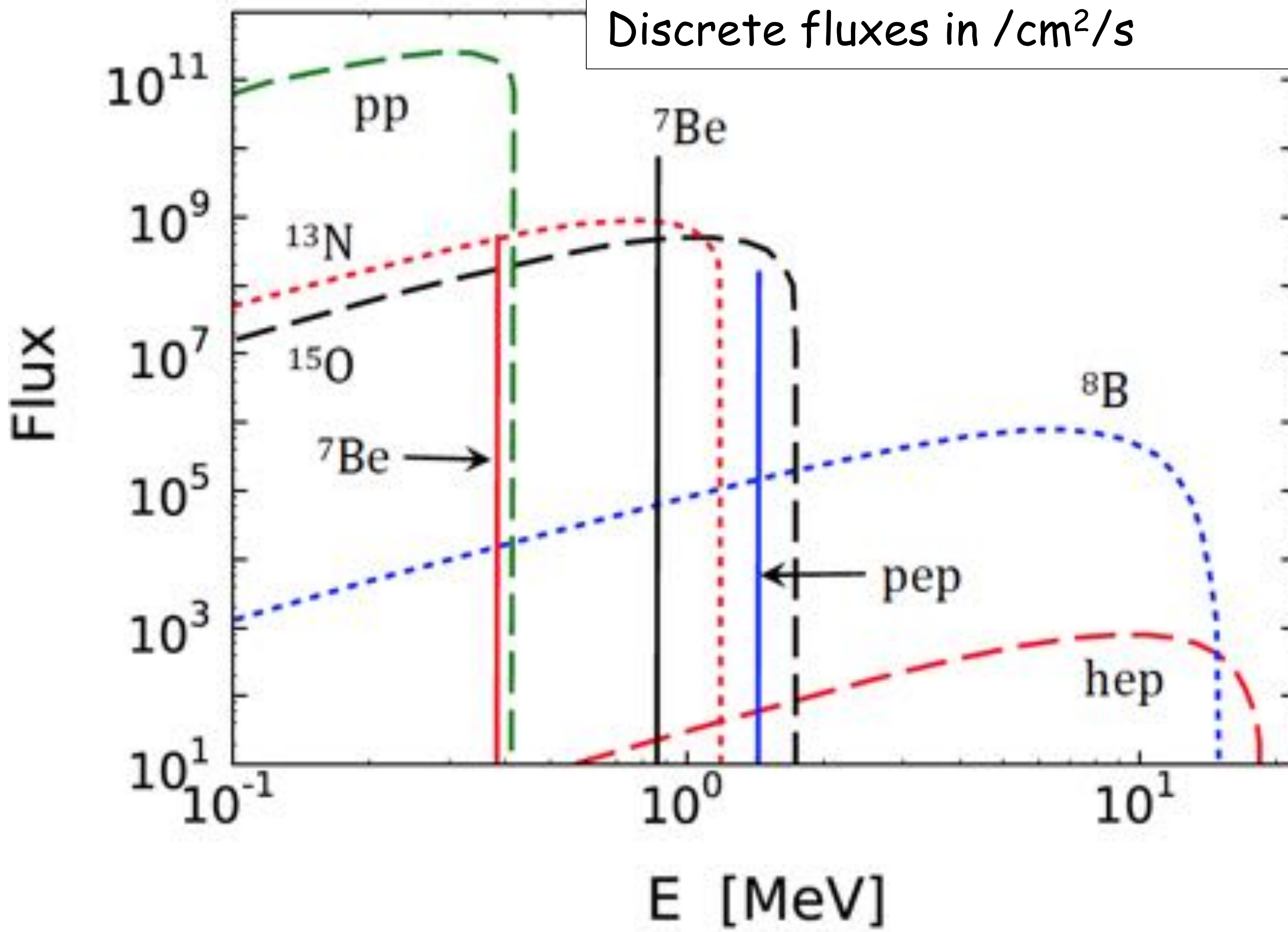
Using Eqs. (11.1-11.5) and the pp-chain and CNO cycle, John Bahcall was able to obtain the major properties of the sun. The model is called the standard solar model. Energy production is lost due to the sun's luminosity. Only a very small amount of energy is lost by neutrino emission. The figure below shows the reactions and energy losses by neutrino emission. The total energy loss by neutrinos is only 2.3%.



Neutrino flux

With the SSM, Bahcall was able to predict the flux of neutrinos from the sun due to the several nuclear processes.

Continuous fluxes in /cm²/s/MeV
Discrete fluxes in /cm²/s



The discrete lines arise because the neutrino energy is fixed by the fact the only the neutrino carries away the decay energy, while in the other processes the neutrino energy is shared with other particles. There are two states in ^{7}Li to where the electron can be captured. Thus, two the discrete lines.

11.2 - Neutrino Astronomy

Light emitted by the sun is not composed of the same photons created by nuclear reactions. The photons are modified by absorption and emission. Transport of heat also proceeds by convection to the surface. The whole process of radiation transport takes a 10 Mio years. But neutrinos can escape freely because they interact very little with matter. They pass through the solar material largely undisturbed. Every second, 10 Bio solar neutrinos pass through your thumbnail. But that makes them also hard to detect.

Neutrinos coming from the decay of ^8B are very energetic (E_ν up to 15 MeV) and should be an excellent probe of the conditions at the core of the sun, the only place where ^8B is found appreciably. The flux, Φ, of ^8B neutrinos are very sensitive to the temperature

$$\Phi_{8B} \sim T^{20} \qquad (11.6)$$

In 1964 John Bahcall and Ray Davis propose the detection of solar neutrinos using the reaction

$$^{37}\mathrm{Cl} + \nu_e \longrightarrow {}^{37}\mathrm{Ar} + e^- \qquad (11.7)$$

Ray builds the Homestake detector. The experiment took place in the Homestake gold mine in Lead, South Dakota.

Neutrino Astronomy

The Homestake experiment:

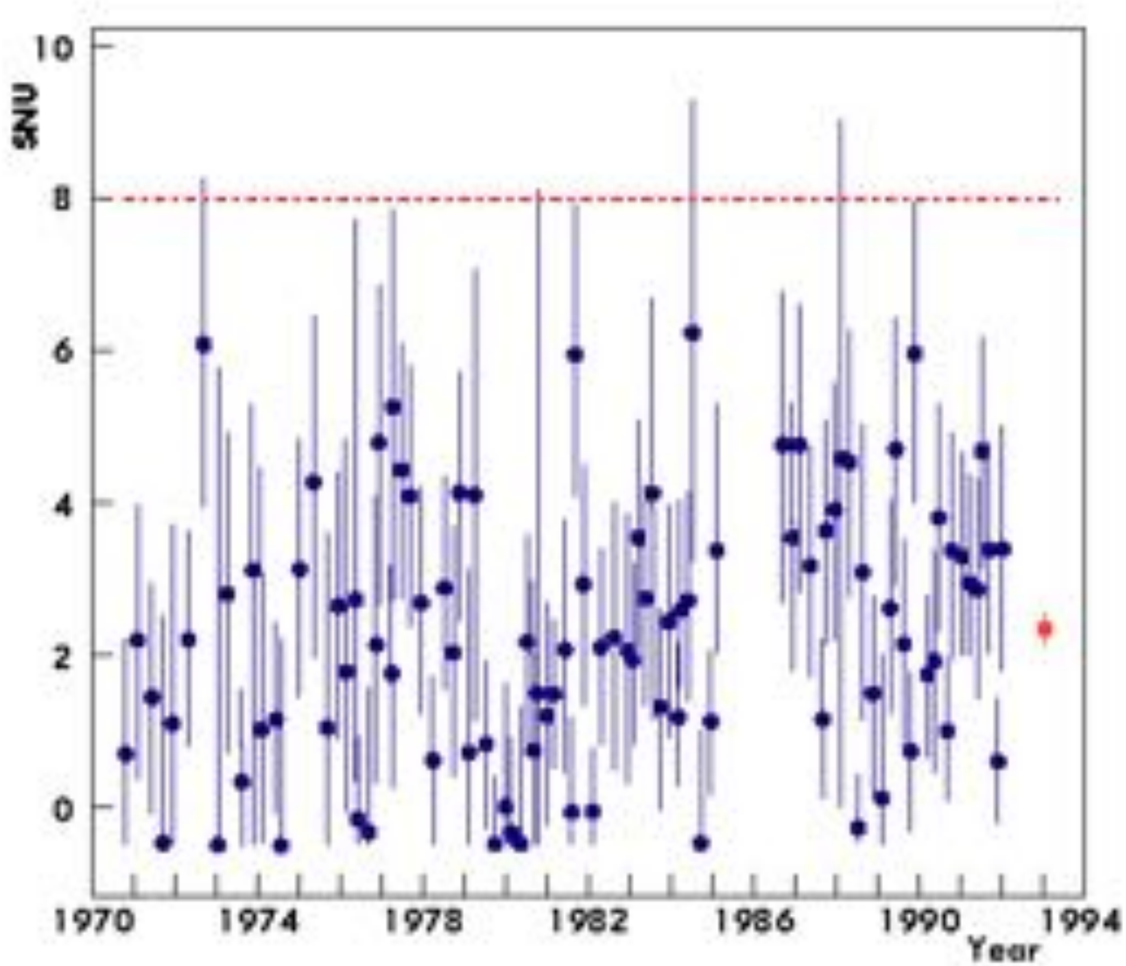
- A tank containing 100,000 gallons of cleaning fluid (full with ^{37}Cl) ~ 1600 meters underground

- ^{37}Ar extracted chemically every few months. ^{37}Ar has a half-life of 35 days. The decay of ^{37}Ar emits a low-energy electron from the argon atom, and this electron can be detected by counters.

- The number of detected neutrino events were very low. This process was able to identify ~ 1 neutrino capture per day on ^{37}Cl.

Neutrino Astronomy

The figure below shows the results of the Homestake experiment. The flux is measured in Solar Neutrino Units (SNU). 1 SNU is only 1 capture per six days. The experiment is very difficult, error bars are large. But one observed a systematically smaller value of SNUs compared to Bahcall's SSM prediction of 8 SNU. With time error bars decreased and it was evident that either the SSM was wrong (not possible, according to Bahcall), there was something wrong with the experiment (later), or **something wrong with neutrinos**!



This led to a new era in astronomy: the era of **neutrino astronomy**. Other neutrino detectors were constructed to solve this neutrino experiment puzzle, often called the "**solar neutrino problem**".

The solar neutrino problem

By the mid 90s the solar neutrino puzzle was such a popular scientific problem that many popular articles and public discussions were commonly published about it, such as the interesting and lively article published below in Science, November 1994.

RESEARCH NEWS

Electronic Battle Over Solar Neutrinos

An elusive measurement of a key solar reaction has prompted a fierce dispute, with attacks and counter-attacks circulating electronically well before the measurement was published

One of the problems facing physics in these days of electronic communication is keeping up with the back-and-forth, as results and theories are kicked around even before they are formally published. Witness the 14 November issue of *Physical Review Letters*, which includes a new and unique experimental determination of what has been called by astrophysicists "the most important nuclear measurement there is"—the rate at which beryllium-7 in the sun will fuse with a proton to become boron-8, which will later emit a high-energy neutrino.

The experiment that produced these results was done at Japan's Institute of Physical and Chemical Research (RIKEN) by a group

the 1960s, was erected in the Homestake gold mine in South Dakota by Ray Davis, who was then at Brookhaven National Laboratory on Long Island. That detector has spotted only a third of the solar neutrinos it was predicted to find. The Kamiokande detector in Japan, which came on line in 1987, has detected only half the predicted flux. The two newest detectors, both using gallium as the target for the neutrinos, recently reported seeing only two thirds of the expected number of neutrinos.

The most exciting explanation proposed so far for the discrepancy between experiment and theory is that neutrinos "oscillate" into a neutrino species that the experiments

the two gallium experiments can also see the much more plentiful low-energy neutrinos from the fusion of protons into deuterium.)

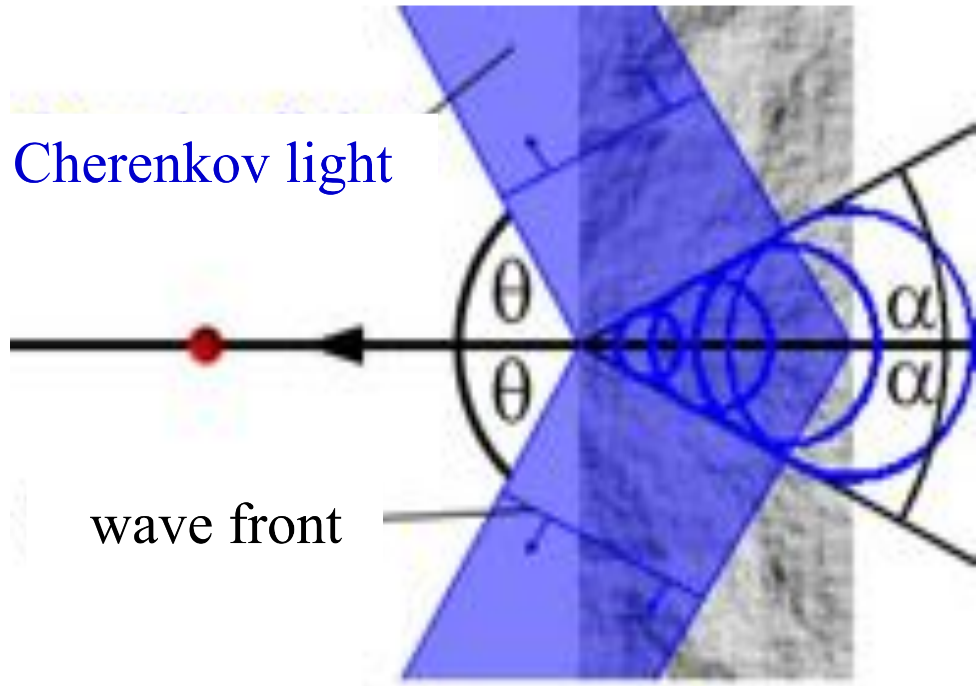
A handful of attempts have been made to measure this reaction rate in the laboratory by bombarding a target of ^{7}Be with a beam of protons. The two best measurements have come from physicists now at the California Institute of Technology—Ralph Kavanagh in 1969 and Brad Filippone in 1983—but Filippone's experiment came up with a reaction rate 25% lower than Kavanagh's. "John Bahcall has been beating on people's heads for 20 years to get a better measurement of [the reaction rate]," says Yale University nuclear physicist Peter Parker.

Neutrino Astronomy

The Kamiokande detector was build much later than Homestake (1983) and used a different concept to detect neutrinos. The neutrinos are detected by their scattering off electrons in a large water reservoir.

$$\nu + e^- \longrightarrow \nu + e^- \qquad (11.8)$$

The neutrino has high energy compared to the electron rest mass and gives the electron a very high kinetic recoil energy (relativistic). The recoiled electron produces **Cerenkov radiation** when traveling in water. This radiation is like a sonic wave front made by fast jets. Only that in this case it is light and not sound that is emitted.

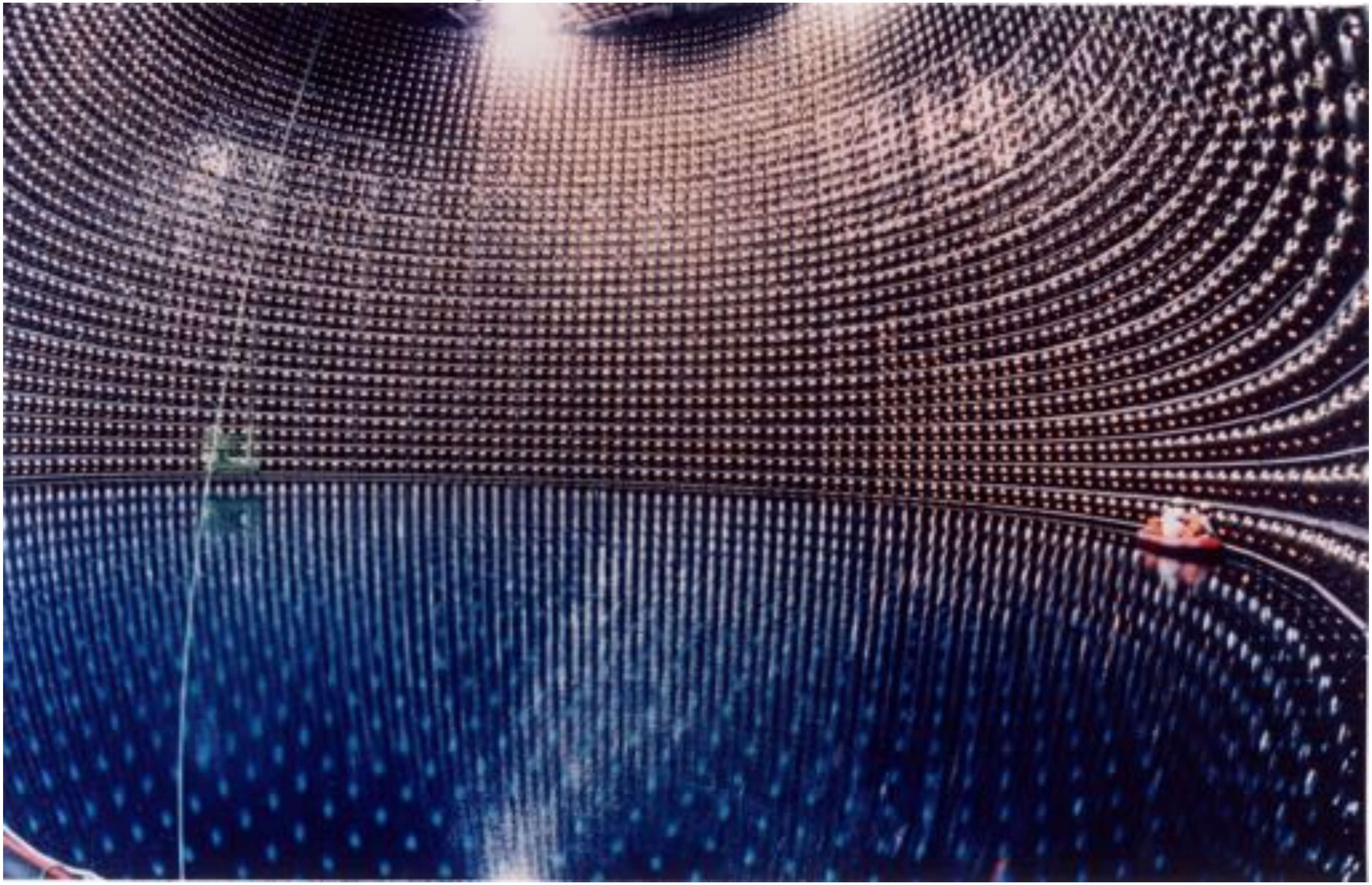


The direction to which light is emitted is basically the same as the direction of motion of the neutrinos. Thus, this sort of detection technique allows to see the direction from which neutrinos are coming.

$$\sin\alpha = \frac{c}{v} = \frac{c_0}{n}\frac{1}{v}$$

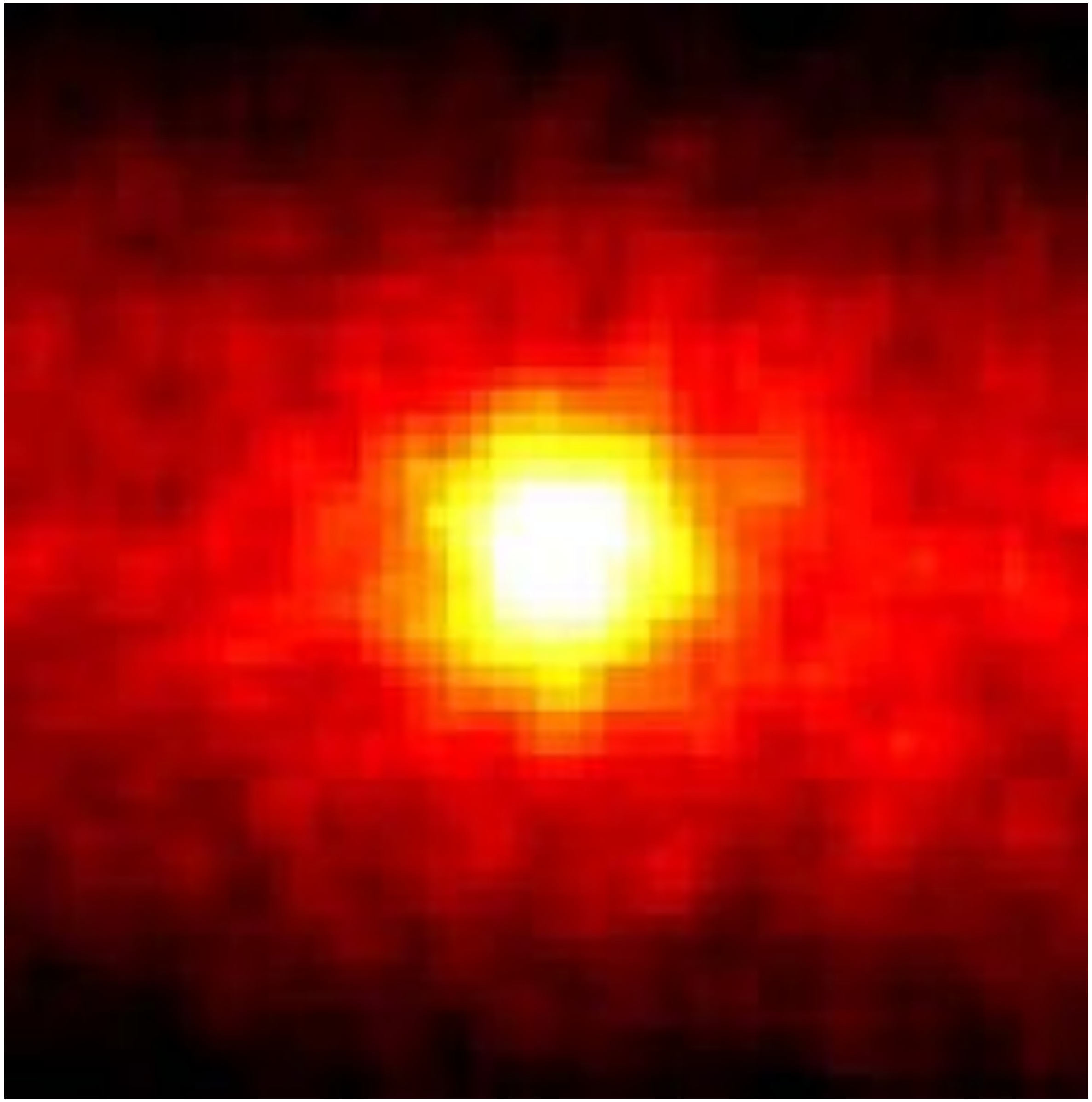
c_0 = speed of light in vacuum

Neutrino Astronomy



The **Super-Kamiokande detector** was an improvement of the Kamiokande detector and started operating in 1996. It holds 5,000 tons of ultra-pure water and 6,000 photomultiplier detectors. The figure shows technicians in a boat, inspecting the photomultipliers.

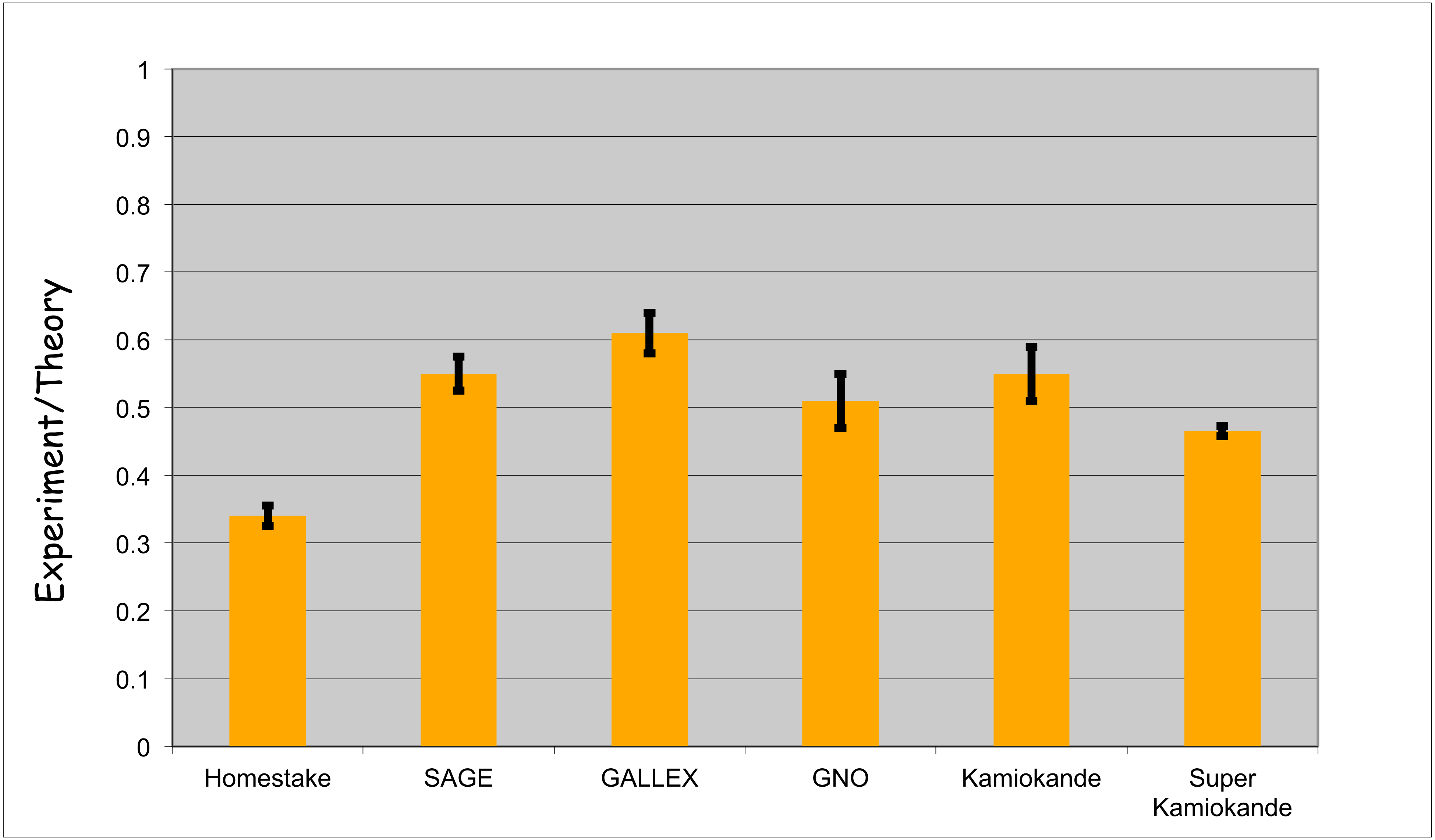
Neutrino Astronomy



Neutrino image of the sun by Super-Kamiokande – Astronomy Picture of the Day, June 5, 1998

Neutrino Astronomy

Many more experiments were carried out over the years with very different energy thresholds. Experiments such as GALLEX, SAGE, SNO, etc.



All these experiments showed a deficit of the detected neutrinos compared to the predictions of the SSM.

11.3 – Neutrinos have mass → neutrino oscillations/mixing

Assume for simplicity that there are only 2 types of neutrinos and both neutrinos are stable ($\tau_1 = \tau_2 = \infty$). At t = 0 we have an electron (ν_e) and muon (ν_μ) neutrino which are both mixtures of ν_1 and ν_2 (mass eigenstates). The electron neutrino wavefunction at t = 0 is given by

$$\nu_e(t=0) \equiv \nu_e = a\nu_1 + b\nu_2 \qquad (11.9)$$

Since the wavefunction is normalized to one, then $a^2 + b^2 = 1$. Thus, we might equally well use $a = \cos\vartheta$ and $b = \sin\vartheta$.

$$\nu_e(t=0) \equiv \nu_e = \nu_1\cos\vartheta + \nu_2\sin\vartheta, \qquad \nu_\mu(t=0) \equiv \nu_\mu = \nu_1\sin\vartheta + \nu_2\cos\vartheta \qquad (11.10)$$

Since we don't know (beforehand) how "mixed" the neutrinos are we use ϑ to describe the mixture.

The mass eigenstates (ν_1 and ν_2) propagate through space with energy E_1 and E_2 according to:

$$\left|\nu_e(t)\right\rangle = \left|\nu_1\right\rangle e^{-iE_1t/\hbar}\cos\vartheta + \left|\nu_2\right\rangle e^{-iE_2t/\hbar}\sin\vartheta \qquad (11.11)$$

$$\left|\nu_\mu(t)\right\rangle = -\left|\nu_1\right\rangle e^{-iE_1t/\ell}\sin\vartheta + \left|\nu_2\right\rangle e^{-iE_2t/\hbar}\cos\vartheta \qquad (11.12)$$

Neutrino oscillations/mixing

We are interested in the case where the neutrinos are relativistic ($E \gg mc^2$) and therefore

$$E = \sqrt{p^2c^2 + m^2c^4} \cong pc + \frac{m^2c^3}{2p} \qquad (11.13)$$

Assuming the same energy (and E ~ pc) for both neutrino components we can write:

$$\left|\nu_e(t)\right\rangle = e^{-i(pc+m_1^2c^4/2E_\nu)t/\hbar}\left(\left|\nu_1\right\rangle\cos\vartheta + \left|\nu_2\right\rangle e^{-it\Delta m^2c^4/2\hbar E_\nu}\sin\vartheta\right)$$

$$\text{with } \Delta m^2 \equiv m_2^2 - m_1^2 \qquad (11.14)$$

The probability of observing a ν_μ at x (=ct) given that a ν_e was produced at t = 0 is

$$P\left(\nu_e \to \nu_\mu\right) = \left|\left\langle \nu_\mu | \nu_e(t)\right\rangle\right|^2 \qquad (11.15)$$

and we will use $\left\langle \nu_1 | \nu_1 \right\rangle = 1, \quad \left\langle \nu_2 | \nu_2 \right\rangle = 1, \quad \left\langle \nu_1 | \nu_2 \right\rangle = 0$.

Neutrino Oscillations/Mixing

$$P(\nu_e \to \nu_\mu) = \left|\sin\vartheta\cos\vartheta(1 - e^{-it\Delta m^2 c^4/2\hbar E_\nu})\right|^2 \qquad (11.16)$$

If we measure mass in eV, x in meters, and E in MeV we can write the above as

$$P(\nu_e \to \nu_\mu) = \sin^2 2\vartheta \sin^2\left(\frac{1.27x\Delta m^2}{E_\nu}\right) = \sin^2 2\vartheta \sin^2\left(\frac{\pi x}{\lambda}\right) \qquad (11.17)$$

where

$$\lambda = \frac{\pi E_\nu}{1.27\Delta m^2} \qquad (11.18)$$

The probability of observing a ν_e at x given that a ν_e was produced at t = 0 is

$$P\left(\nu_e \to \nu_e\right) = \left|\left\langle \nu_e | \nu_e(t)\right\rangle\right|^2 \qquad (11.19)$$

or

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\vartheta \sin^2\left(\frac{1.27x\Delta m^2}{E_\nu}\right) \qquad (11.20)$$

Neutrino Oscillations/Mixing

Hence, in order to have neutrino oscillations, neutrinos must have mass and their ground-state energy (mass) states must mix. The oscillation depends on Δm^2 the mass of the neutrinos. The neutrino oscillation mechanism described in the previous slides is observed as an apparent disappearance of electron neutrinos on their wave from the interior of the sun to the earth.

Neutrino oscillations have been proven: with the SNO (Sudbury Neutrino Observatory) detector.

This detector uses three reactions in heavy water

CC $\quad \nu_e + d \longrightarrow p + p + e^-$ $\quad$ (Cerenkov) – mostly sensitive to ν_e

ES $\quad \nu + e^- \longrightarrow \nu + e^-$ $\quad$ (Cerenkov) – only sensitive to ν_e

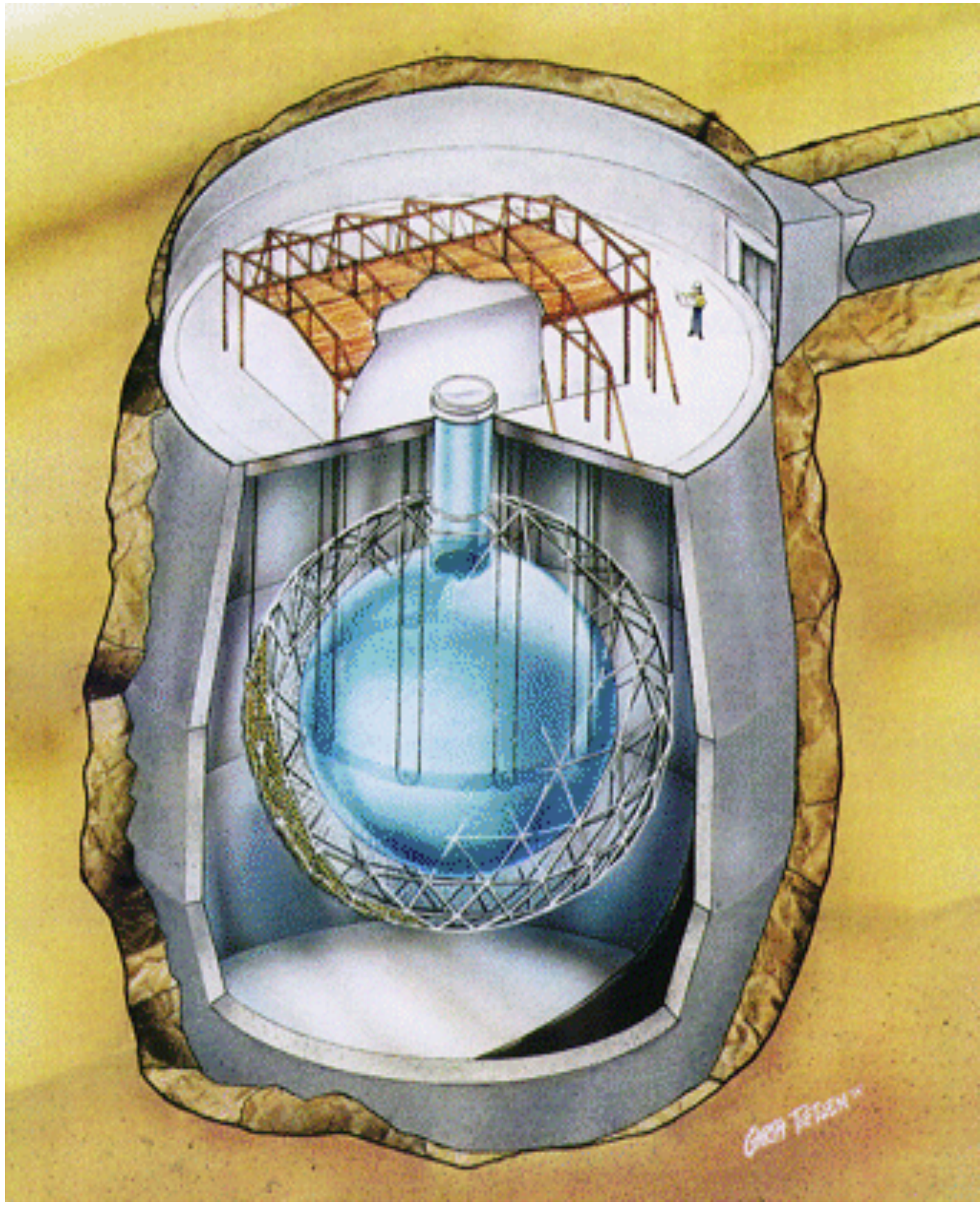
NC $\quad \nu + d \longrightarrow p + n + \nu$ $\quad$ (n-capture by ^{35}Cl - γ scatter - Cerenkov)

The NC capture reaction does not dependent of flavor (i.e., if ν_e or ν_μ). Hence, it should always be equal to the SSM predictions if the oscillations explain the solar neutrino problem.

The difference between CC and ES should also indicate if additional flavors are present (we know, e.g., that the ν_τ – tau neutrino – exists).

Neutrino Oscillations/Mixing

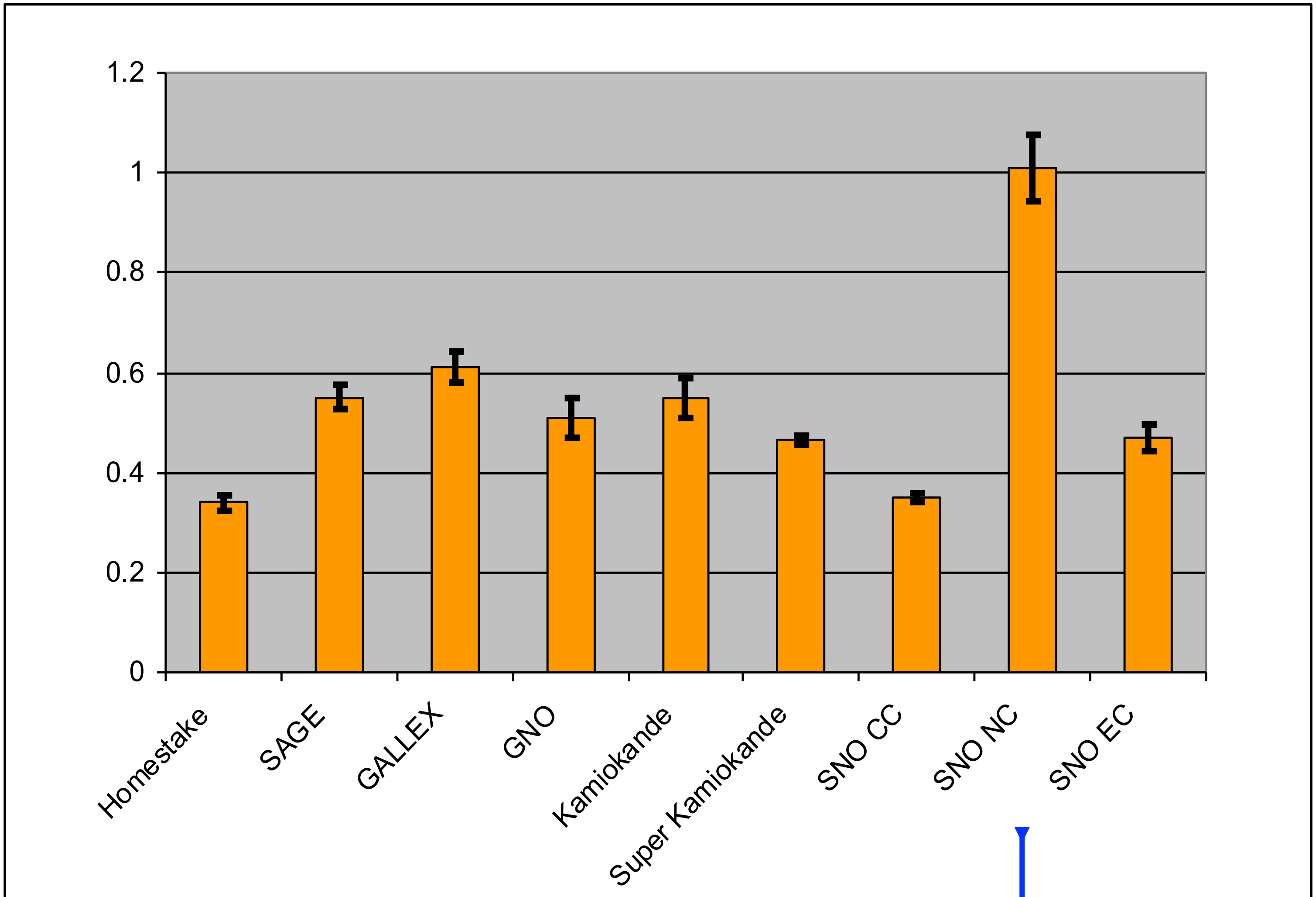
The Sudbury Neutrino Observatory (SNO) was located 2 km underground in the Creighton Mine in Sudbury, Ontario, Canada.
It contains a large tank of heavy water and photon detectors. The detector was functioning from1999 to 2006.



Sudbury Neutrino Observatory

Neutrino Oscillations/Mixing

The results of the SNO were conclusive



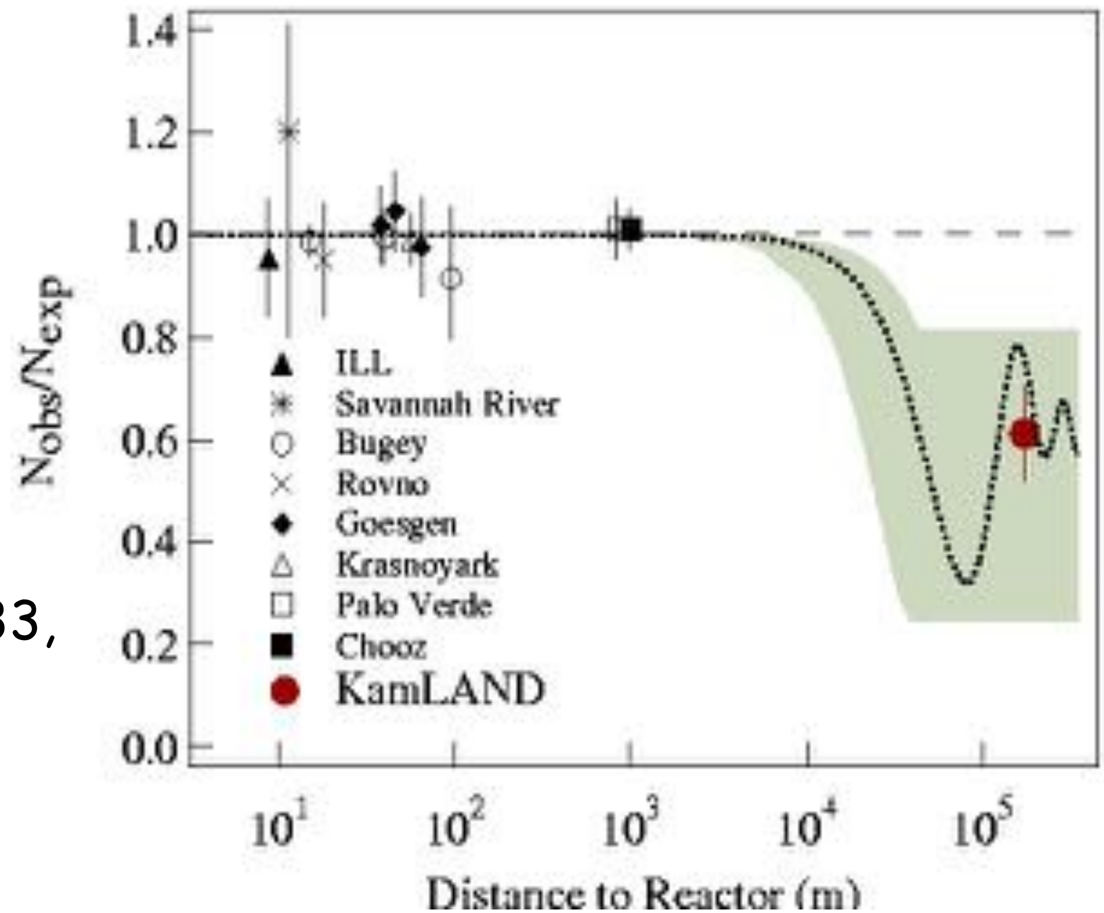
The solar neutrino problem is due to the neutrino oscillations: electron neutrinos change to muon neutrinos on their way to earth. That is why they were not seen by the Homestake experiment.

Solar neutrino puzzle solved …

Other proofs of neutrino oscillations

Two other experiments proved that neutrino oscillations exist

- In 1998 the Super Kamiokande reported evidence for ν_μ --> ν_τ oscillations for neutrinos created by cosmic ray interaction with the atmosphere
- In 2003 the KamLAND experiments reported evidence for disappearance of electron anti-neutrinos from reactors. The KamLAND reactor produced anti-ν_e from beta decay of radioactive material in its core. These were detected in a liquid scintillator in the Kamiokande mine 180 km away. It was a check whether neutrinos disappear.



In the figure (2003), the dashed curve is a best fit with $\sin^2 2\vartheta = 0.833$, $\Delta m^2 = 5.5 \times 10^{-5}$ eV^2.

The shaded area shows the overlap with solar neutrino data.

Neutrinos

FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

- There are 3 flavors of neutrinos. Together with their anti- particles, there are six of them.
- Neutrinos have mass
- **But, there is not enough neutrino mass to account for the Dark Matter.**
- The 2002 Nobel prize went for research with neutrino astronomy to Ray Davis (BNL), Masatoshi Koshiba (Tokyo – Kamiokande), and Riccardo Giacconi (Washington). Bahcall was left out. He passed away in 2005, Ray in 2006.