Solar neutrinos:
form their production to their detection

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Abstract

The reactions that take place in the core of the Sun are nuclear fusion reactions. On our neighborhood star, hydrogen is being fused into helium in the proton-proton chain reaction in which four protons are fused and two of them undergoes a beta decay to become a neutron, releasing positrons and neutrinos.

To test the validity of the solar models, more than 40 years ago, it was suggested to detect solar neutrinos.

The first measurement of the neutrino flux, took place in the Homestake mine in South Dakota in 1968. The experiment detected only one third of the expected value, originating what has been known as the Solar Neutrino Problem. Since then different experiments were built in order to understand the origin of this discrepancy. Now we know that neutrinos undergo oscillation phenomenon changing their nature traveling from the core of the Sun to Earth. Thank to neutrinos detection is possible to infer and to prove how the Sun shine.

"Our" star: the Sun

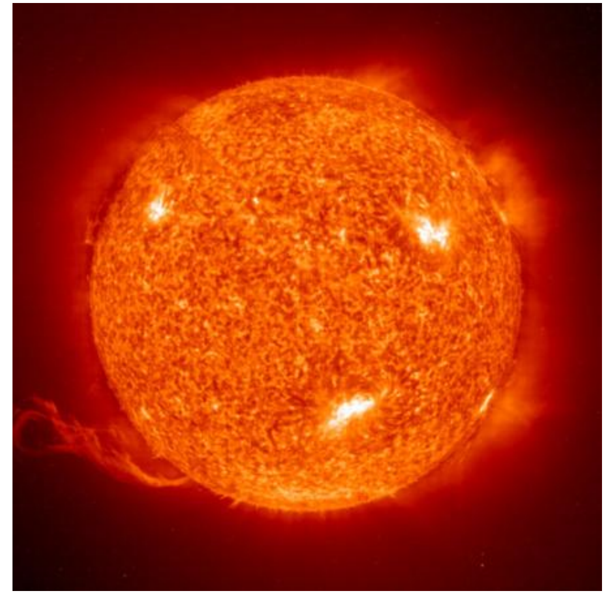
The Sun is a medium-sized star (which lies on the main sequence).

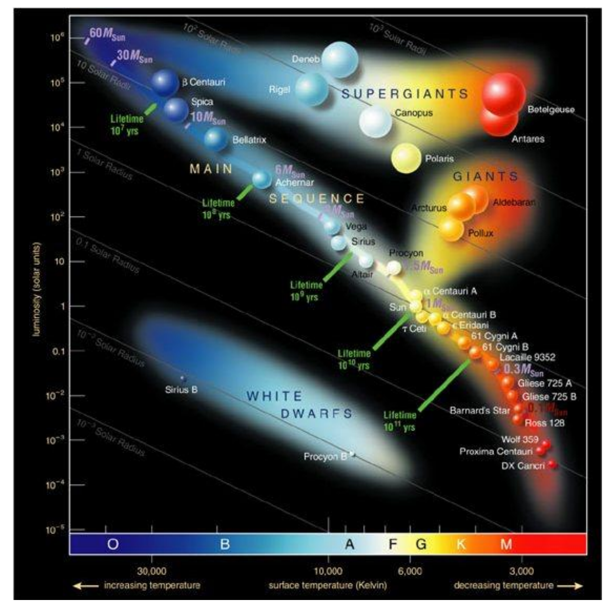
The effective surface **temperature** is 5780 K, (putting it in spectral class G2).

It has a **diameter** of about 1.4 million km (*109 times that of Earth*).

It has a **mass** of about 2×10^{30} kg, (*330,000 times that of Earth*) accounting for about 99.86% of the total mass of the solar system.

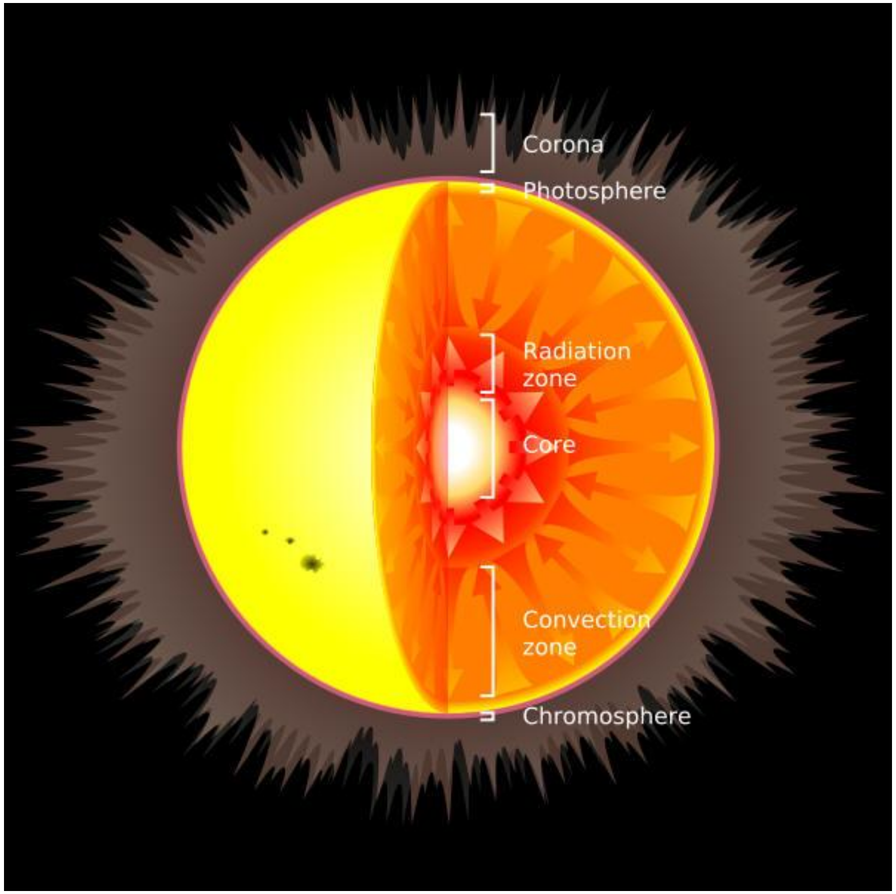
Mass (Earth=1)	332,800
Mean diameter (10^6 m)	1392
Rotation period	26-37 d
Mean distance to Earth, 10^6 km	149
Density	**1.41**
Surface gravity m/s^2	274





About ¾ of the mass of the Sun consists of hydrogen, while the rest is mostly helium.

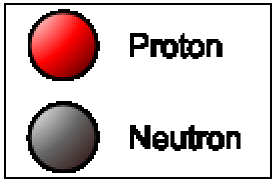
Less than 2% consists of heavier elements, including iron, oxygen, carbon, neon, and others (*In astronomy, any atom heavier than helium is called a ``**metal**'' atom*).



Element	Abundance (% of total number of atoms)	Abundance (% of total mass)
Hydrogen	91.2	71.0
Helium	8.7	27.1
Oxygen	0.078	0.97
Carbon	0.043	0.40
Nitrogen	0.0088	0.096
Silicon	0.0045	0.099
Magnesium	0.0038	0.076
Neon	0.0035	0.058
Iron	0.0030	0.14
Sulfur	0.0015	0.040

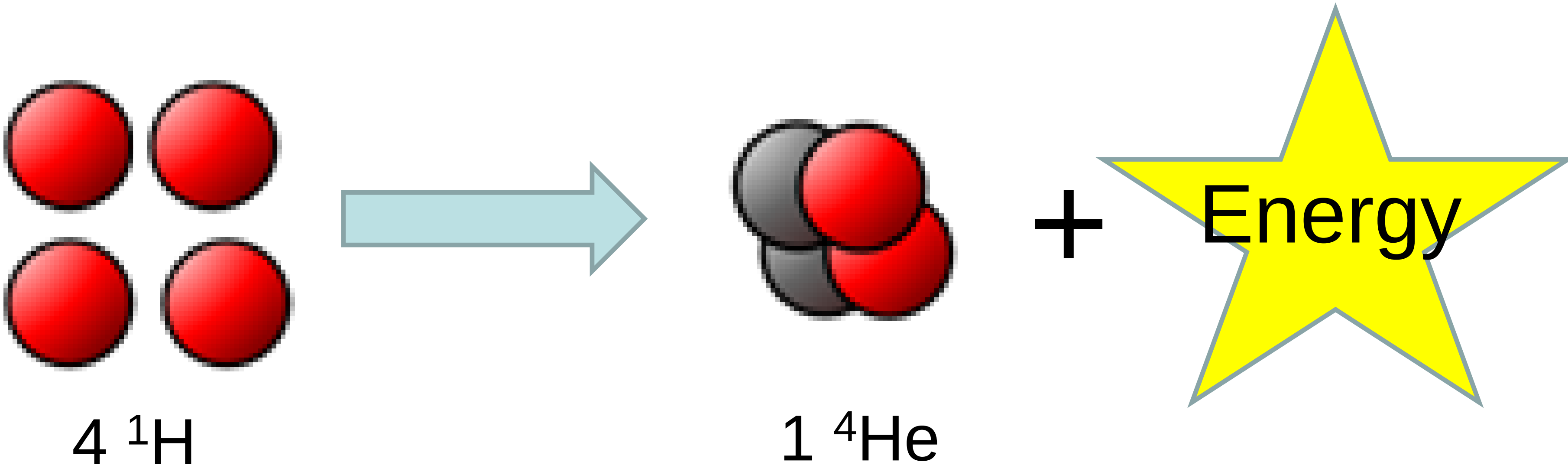
Core density ~ 150 g/cm^3

How the Sun shines



The core of the Sun reaches temperatures of ~ 15.5 million K.

At these temperatures, nuclear fusion can occur transforming 4 Hydrogen nuclei into 1 Helium nucleus



1 Helium nucleus has a mass that is smaller than the combined mass of the 4 Hydrogen nuclei.

That “missing mass” is converted to energy to power the Sun.

Net reaction: $4\ ^1H \rightarrow 1\ ^4He$ + energy

Mass of 4 ^{1}H	**6.6943**	**10^{-27}**	**kg**	
Mass of 1 ^{4}He	**6.6466**	**10^{-27}**	**kg**	
	0.0477	**10^{-27}**	**kg**	**(0.7%)**

Using $E=mc^2$ each fusion releases

$0.0477 \cdot 10^{-27}$ kg $\cdot (3 \cdot 10^8$ m/s$)^2 = 4.3 \cdot 10^{-12}$ J $\rightarrow$ (**26.7 MeV)**

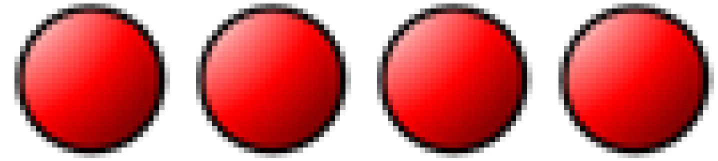
1 eV ~ $1.6 \cdot 10^{-19}$ J

Each second about 600 million tons of Hydrogen is converted into about 596 million tons of Helium-4.

The remaining 4 million tons (actually 4.26 million tons) are converted into energy.

The current luminosity of the Sun is **$3.846 \cdot 10^{26}$ Watts**

What about neutrinos?

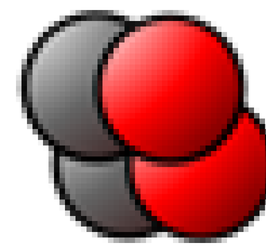


We start from 4 protons and we end with 1 He nucleus which is composed of 2 protons and 2 neutrons.

This means that we have to transform 2 protons into 2 neutrons:

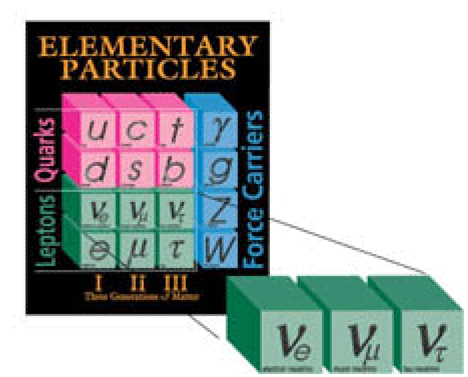
$$p \rightarrow n + e^{+} + \nu_e$$

(inverse β-decay)

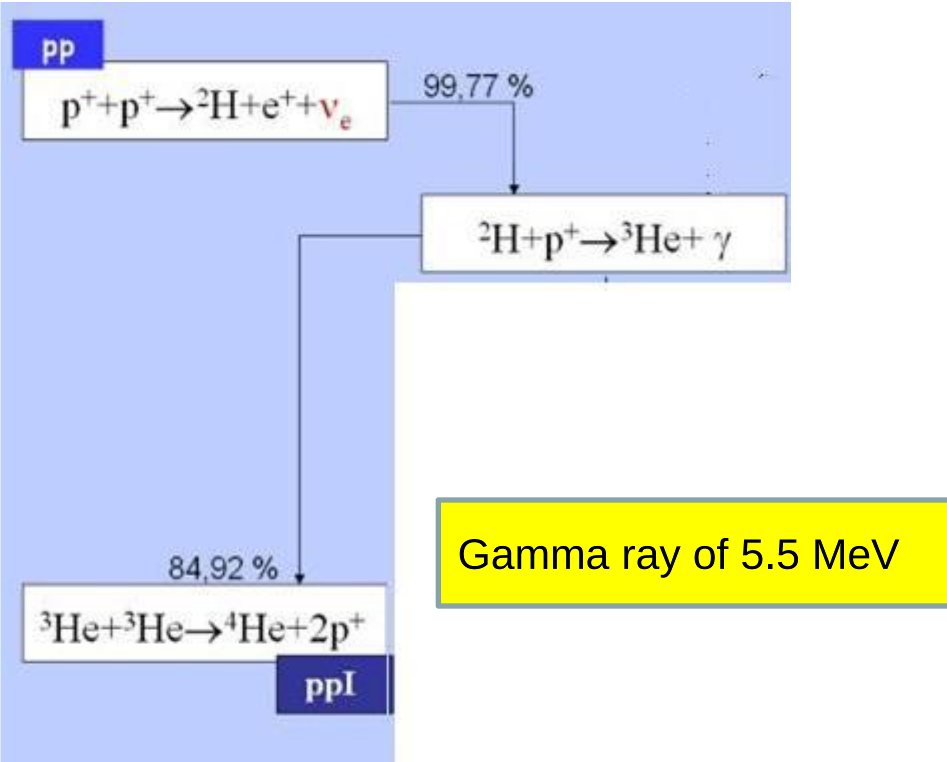


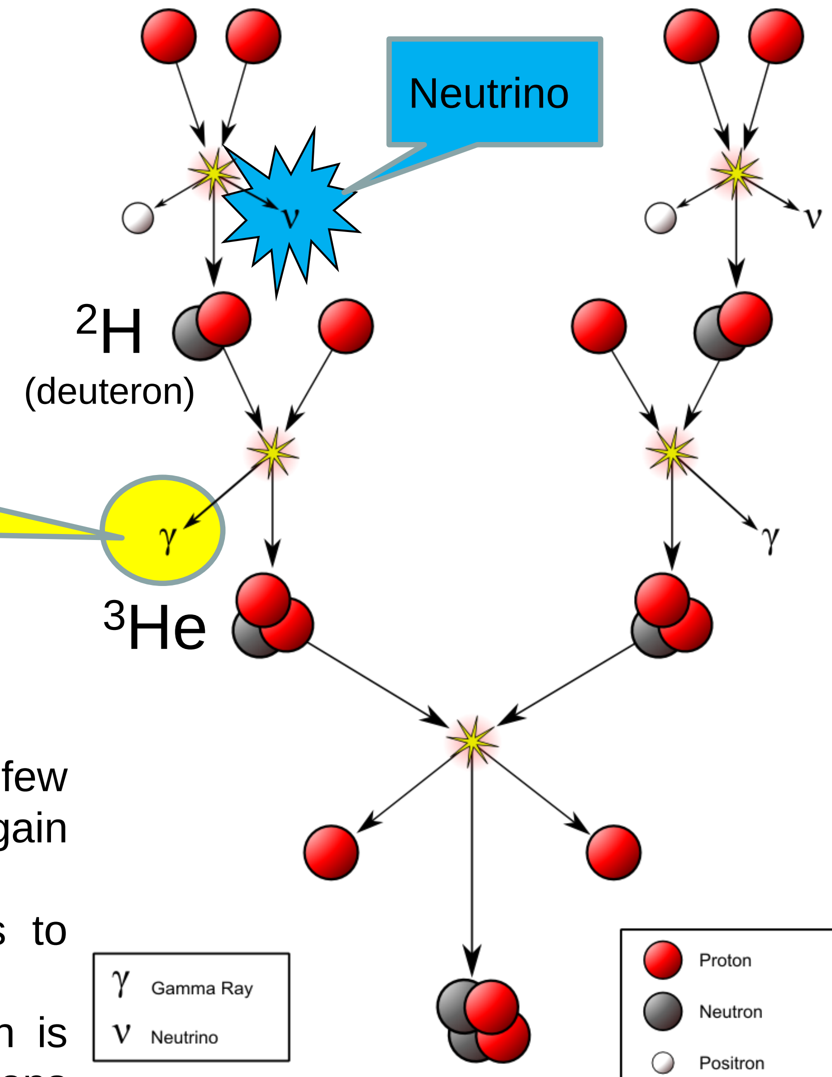
In the inverse beta decay a proton becomes a neutron emitting a **positron** and an **electron neutrino ν_e**

There are 3 types of neutrinos but this reaction is possible only with electron neutrinos



From protons to helium nucleus : The ppI chain





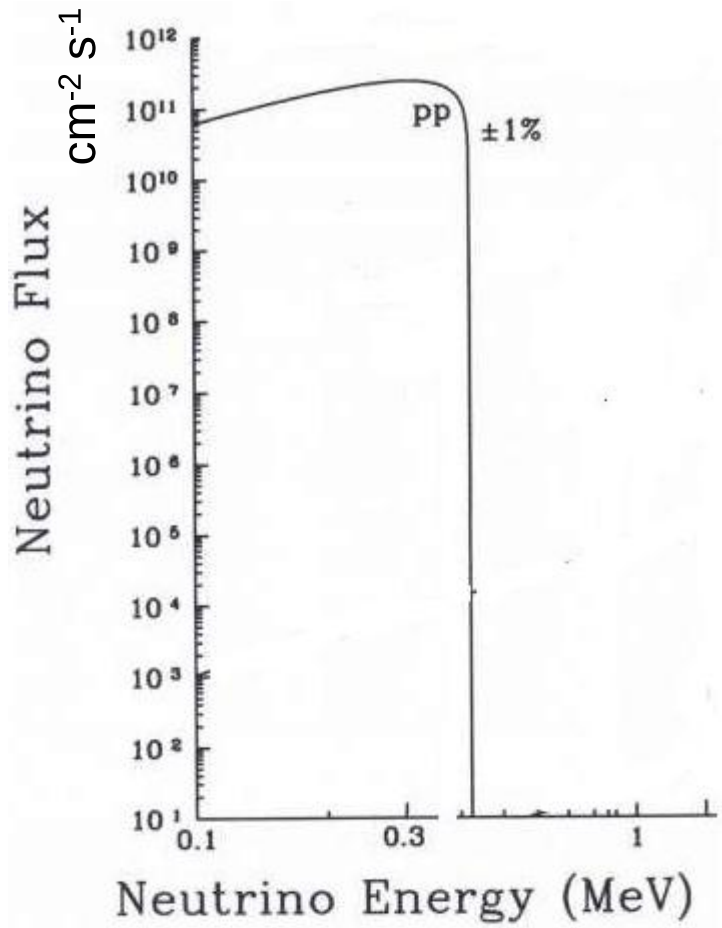
The 5.5 MeV gamma rays are absorbed in only a few millimeters of solar plasma and then re-emitted again in random direction (and at slightly lower energy)

The gamma rays take 10,000 to 170,000 years to reach the surface of the Sun.

Each gamma ray created in the core of the Sun is converted into several million of visible light photons (**some eV**) before escaping into space. The photons escape as visible light.

Since **neutrinos** only interact with matter via the **weak force**, neutrinos generated by solar fusion pass immediately out of the core and into space.

The study of solar neutrinos was conceived as a way *to test* the nuclear fusion reactions at the core of the Sun.

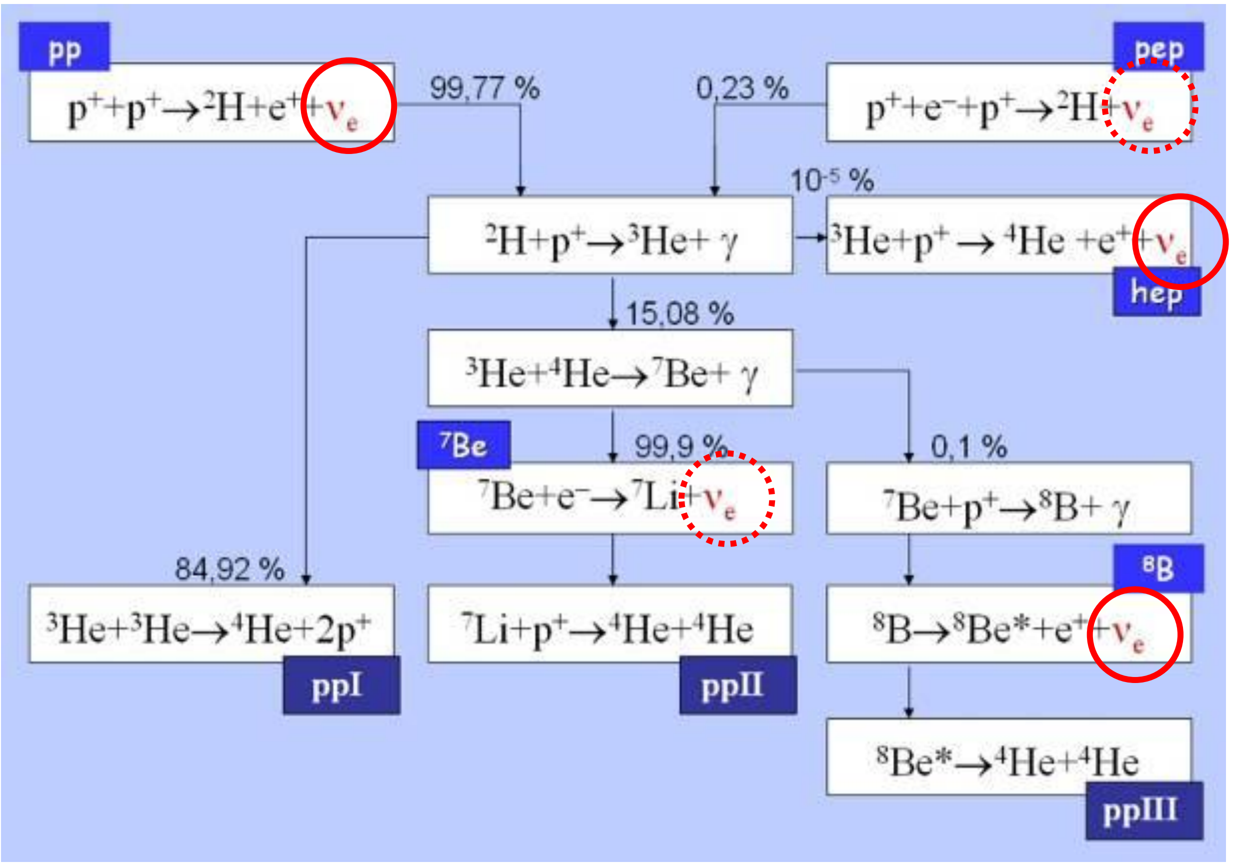


$$p + p \rightarrow {}^{2}H + e^{+} + \nu_e$$

We have 3 bodies in the final state; this means that the emitted neutrino (like the electron) has a **continuous spectrum** extending from 0 to 0.42 MeV.

The pp chain

There are different steps in which energy (and neutrinos) are produced



ν from:

pp

pep

^{7}Be

^{8}B

hep

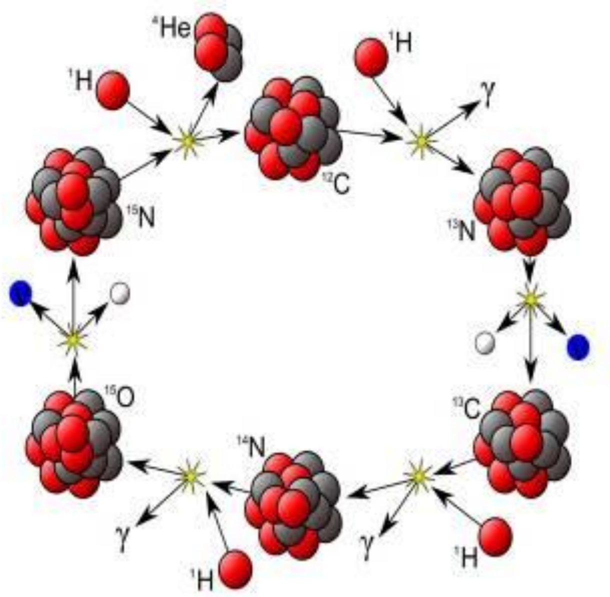
Monocrhomatic ν's
(2 bodies in the final state)

…. But pp chain is not the only reaction that transform protons into helium …..

In a star like the Sun ~ 98% of the energy is created in pp chain

Beside pp chain there is also the CNO cycle that become the dominant source of energy in stars heavier than the Sun

(in the Sun the CNO cycle represents only 1-2 %)



Neutrinos are also produced in the CNO cycle

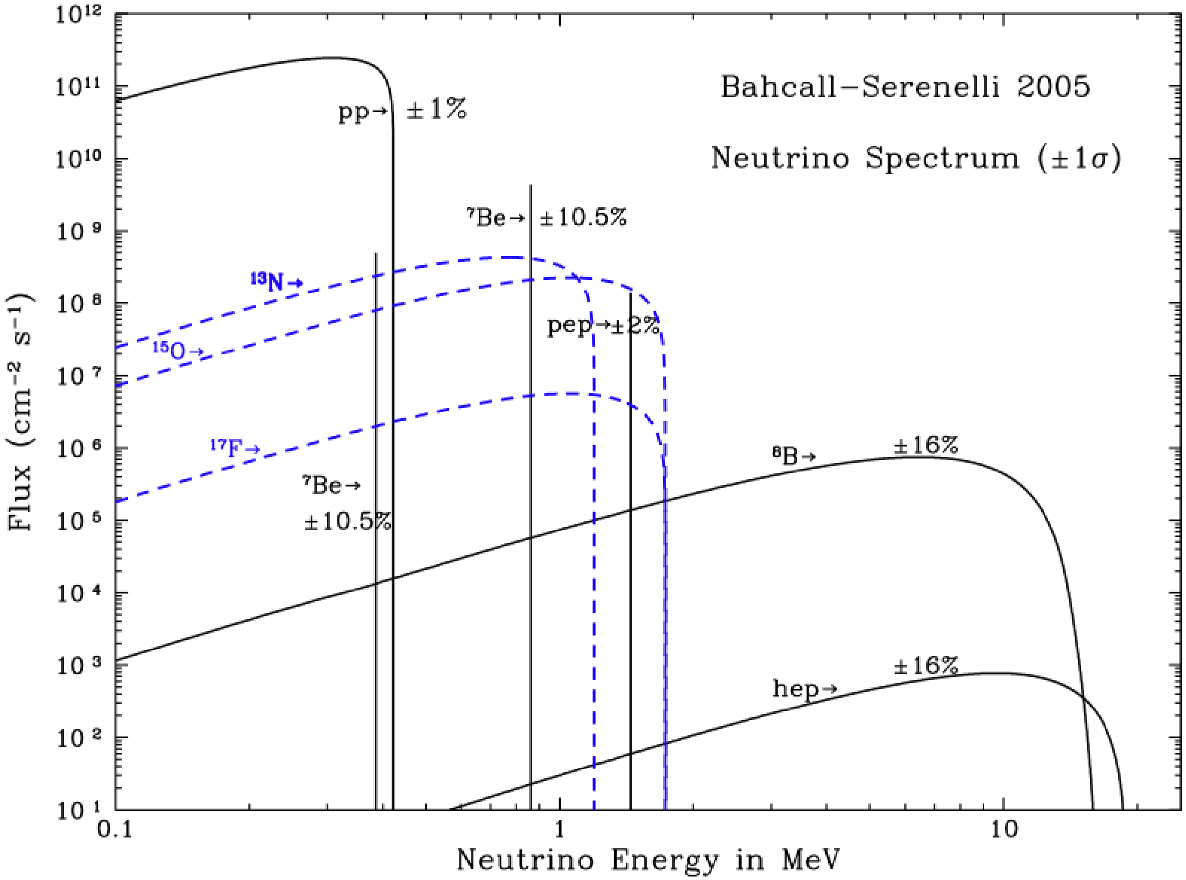
ν from:

^{13}N

^{15}O

^{17}F

Neutrino energy spectrum as predicted by the **Solar Standard Model (SSM)**



ν from:

pp

pep

^{7}Be

^{8}B

hep

ν from:

^{13}N

^{15}O

^{17}F

^{7}Be:

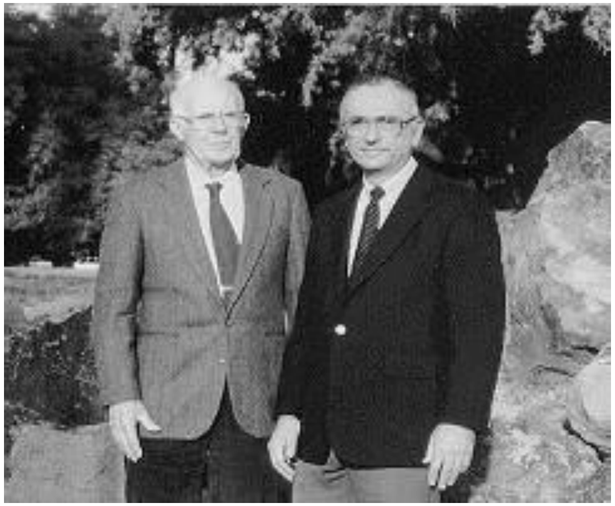
384 keV (10%)

862 keV (90%)

pep:

1.44 MeV

"…..to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars."



Davis and Bahcall

Phys. Rev. Lett. 12, 300–302 (1964)
Solar Neutrinos. I. Theoretical
John N. Bahcall *California Institute of Technology, Pasadena, California*

Phys. Rev. Lett. 12, 303–305 (1964)
Solar Neutrinos. II. Experimental
Raymond Davis, Jr.
Chemistry Department, Brookhaven National Laboratory, Upton, New York

The first experiment built to detect solar neutrinos was performed by Raymond Davis, Jr. and John N. Bahcall in the late 1960's in the Homestake mine in South Dakota

How to detect Solar Neutrinos?

There are 2 possible ways to detect solar neutrinos:

- radiochemical experiments
- real time experiments.

In radiochemical experiments people uses isotopes which, once interacted with an electron neutrino, produce radioactive isotopes.

$$\nu_e + {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^-$$

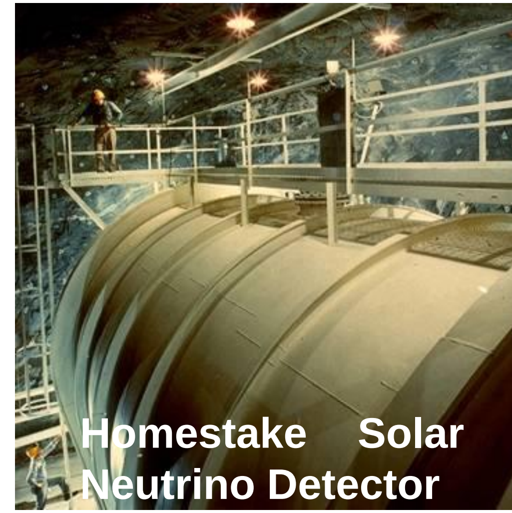
The production rate of the daughter nucleus is given by

$$R = N \int \Phi(E)\sigma(E)dE$$

where
•Φ is the solar neutrino flux
•σ is the cross section
•*N* is the number of target atoms.

With a typical **neutrino flux of 10^{10} ν cm^{-2} s^{-1}** and a **cross section of about 10^{-45} cm^{2}** we need about 10^{30} target atoms (that correspond to ktons of matter) to produce one event per day.

Homestake: *The first solar neutrino detector*



Large tank of 615 tons of liquid containing ^{37}Cl.

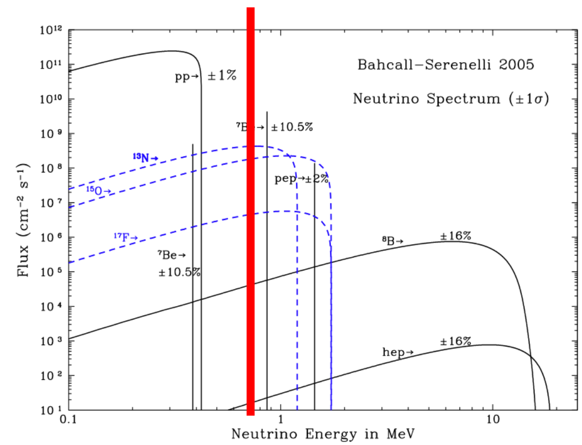
Neutrinos are detected via the reaction:

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$$

^{37}Ar is radioactive and decay by EC with a $\tau_{1/2}$ of 35 days into $^{37}Cl^*$

$$^{37}\mathrm{Ar} + e^- \rightarrow {}^{37}\mathrm{Cl}^* + \nu_e$$

Once a month, bubbling helium through the tank, the ^{37}Ar atoms were extracted and counted *(only ≈ 5 atoms of ^{37}Ar per month in 615 tons C_2Cl_4).*

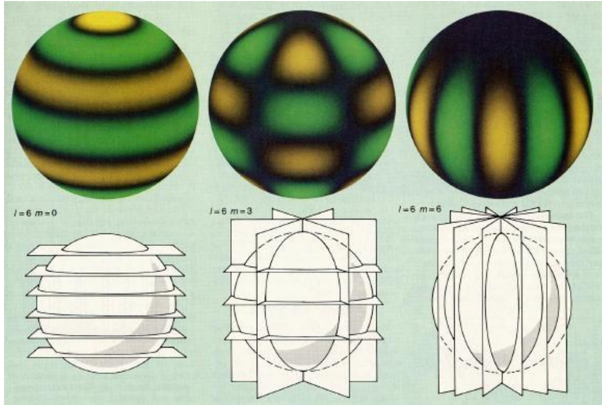


***E*$_{th}$ = 814 keV**

The number of detected neutrino was about **1/3** lower than the number of expected neutrino → **Solar Neutrino Problem (SNP)**

Possible Explanations to the SNP

❑ Standard Solar Model is not correct



..but Solar models have been tested independently by **helioseismology** *(that is the science that studies the interior of the Sun by looking at its vibration modes),* and the standard solar model has so far passed all the tests.

beside ..... Non-standard solar models seem very unlikely.

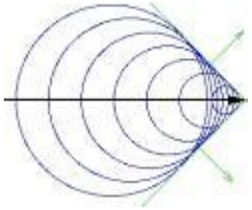
❑ Homestake is wrong

❑ Something happens to ν's travelling from the core of the Sun to the Earth

Kamiokande & SuperKamiokande: *Real time detection*

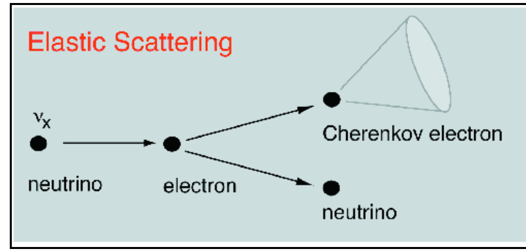
In 1982-83 was built in Japan the first real time detector. It consisted in a Large water Cherenkov Detector

Electrons are accelerated to speeds $v > c/n$ "faster than light".



In real time experiments people looks for the light produced by the electrons scattered by an impinging neutrino

$$\nu_x + e^- \rightarrow \nu_x + e^-$$



Kamiokande

- 3000 tons of pure water
- 1000 PMTs

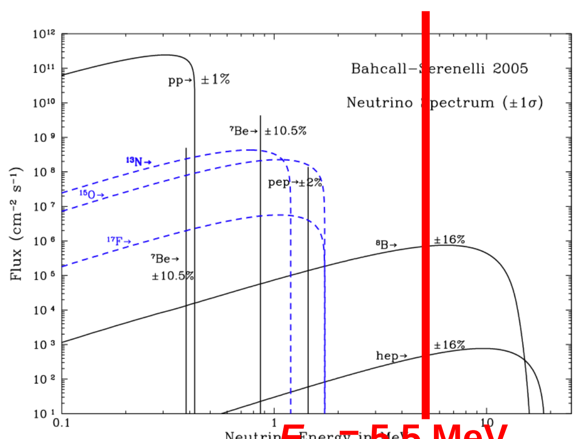
SuperKamiokande

- 50000 tons of pure water
- 11200 PMTs

E_{th} = 7.5 MeV (for Kamiokande)

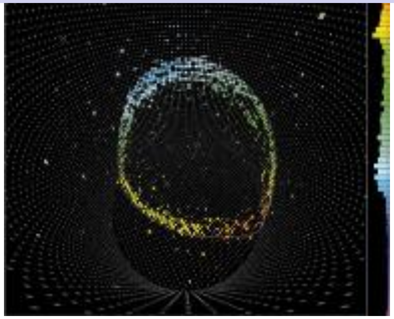
E_{th} = 5.5 MeV (for SKamiokande)

only ^{8}B neutrinos (and hep)



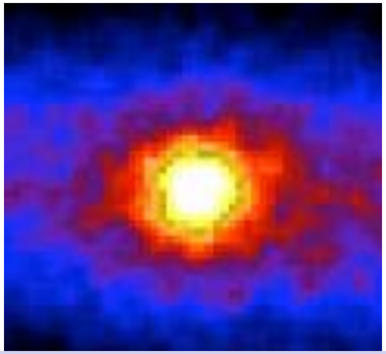
E_{th} = 5.5 MeV

Ring of Cherenkov light



Radiochemical experiments integrate in time and in energy.

Unlike in radiochemical experiments, in real time experiments it is possible to obtain a **spectrum energy** and hence to distinguish the different neutrino contribution.



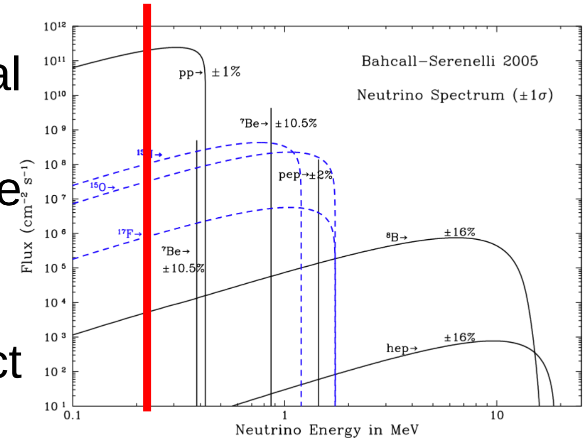
Picture of the center of the Sun the made with neutrinos

Furthermore, thank to the fact that the scattered electron conserves the **direction** of the impinging neutrino, it is possible to infer the direction of the origin of the incoming neutrino and hence to point at the source. **Neutrinos come from the Sun!**

The number of detected neutrino was about **1/2** lower than the number of expected neutrino confirming the Solar Neutrino Problem.

…looking for pp neutrinos …

Until the year 1990 there was no observation of the initial reaction in the nuclear fusion chain (i.e. pp neutrinos).
pp neutrinos are **less model-depended** and hence more robust to prove the validity of the SSM.



E_{th} = 233 keV

Two radiochemical experiments were built in order to detect solar *pp* neutrinos; both employing the reaction:

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

Gallex & SAGE

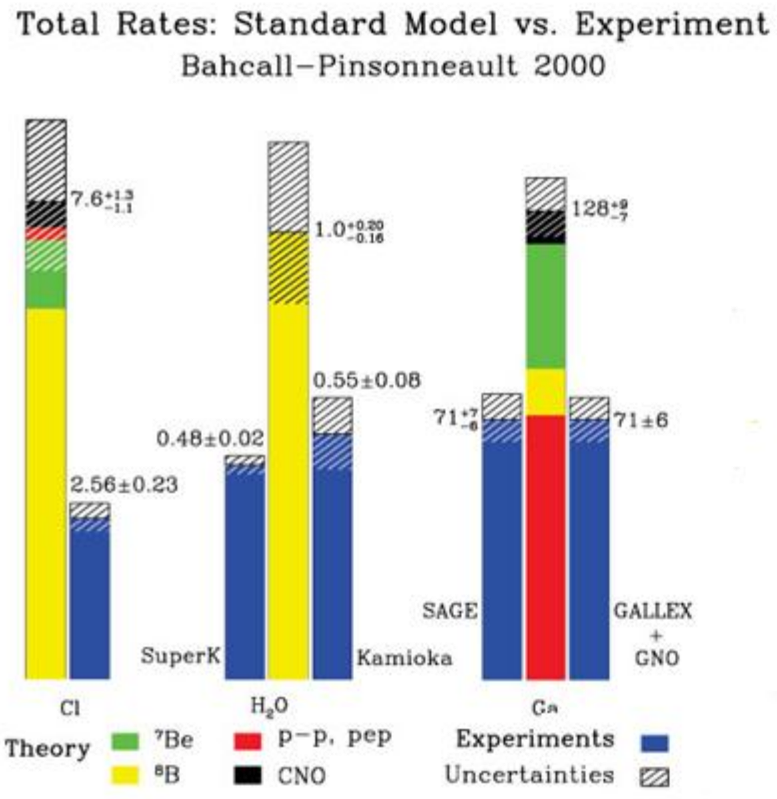
30 tonnes of natural gallium
(at LNGS Italy)

50 tons of metallic gallium
(at Baksan Russia)

Calibration tests with an artificial neutrino source (^{51}Cr) confirmed the efficiencies of the detectors.

Once again the measured neutrino signal was smaller than the one predicted by the standard solar model (**~ 60%).**

All experiments detect less neutrino than expected from the SSM !



Rate measurement	Reaction	Obs / Theory
Homestake	$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$	0.34 ± 0.03
Super-K	$\nu_x + e^- \rightarrow \nu_x + e^-$	0.46 ± 0.02
SAGE	$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$	0.59 ± 0.06
Gallex+GNO	$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$	0.58 ± 0.05

1 SNU (Solar Neutrino Unit) = 1 capture/sec/10^{36} atoms

…… something happens to neutrinos!

Neutrinos have the peculiar property that their flavour eigenstates do not coincide with their mass eigenstates.

Flavour eigenstates ν_e, ν_μ, ν_τ

$\neq$

Mass eigenstates ν_1, ν_2, ν_3

Flavour states can be expressed in the mass eigenstate system and vice versa.

The neutrino **flavour states** ν_e , ν_μ , ν_τ are related to the **mass states** ν_1 , ν_2 , ν_3 by the linear combinations

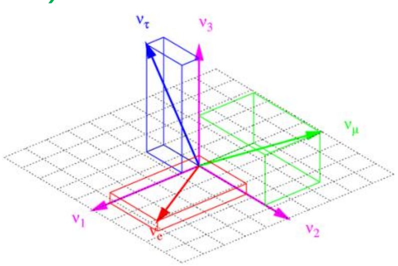
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

U is the Pontecorvo-Maki-Nakagawa-Sakata matrix

(the analog of the CKM matrix in the hadronic sector of the Standard Model).

Consequently, for a given energy the mass states propagate at different velocities and the flavour states change with time.

This effect is known as **neutrino oscillations**.



3 mixing angles:
$\theta_{12}, \theta_{13}, \theta_{23}$

Because one of the three mixing angles in very small (i.e. θ_{13}), and because two of the mass states are very close in mass compared to the third, for solar neutrinos we can restrict to **2 neutrinos case** and consider the **oscillation between** $\nu_e \leftrightarrow \nu_{\mu,\tau}$

$$P(\nu_e \rightarrow \nu_{\mu,\tau}) = \sin^2 2\theta \sin^2 \frac{\Delta m^2}{4E} L$$

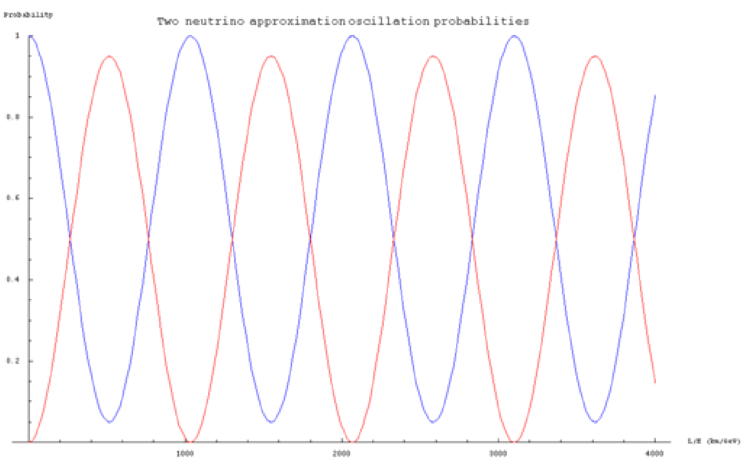
Probability of an electron neutrino produced at t=0 to be detected as a muon or tau neutrino

...Depends Upon Two Experimental Parameters:

- L – The distance from the ν source to detector (km)
- E – The energy of the neutrinos (GeV)

...And Two Fundamental Parameters:

- $\Delta m^2 = m_1^2 - m_2^2 \quad (eV^2)$
- $\sin^2 2\theta$



L/E (km/GeV)

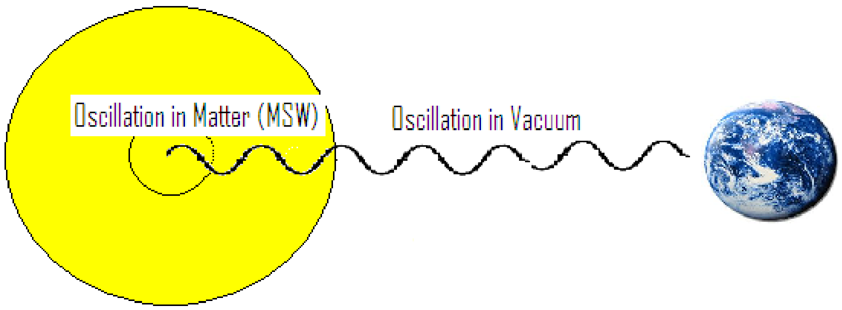
So, for a given energy E and a detector at distance L it is possible to determine θ and Δm^2.

The blue curve shows the probability of the original neutrino retaining its identity. The red curve shows the probability of conversion to the other neutrino.

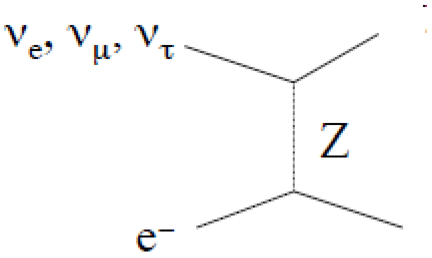
The Mikheyev Smirnov Wolfenstein Effect (**MSW**) … or Matter Effect

Neutrino oscillations can be enhanced by traveling through matter

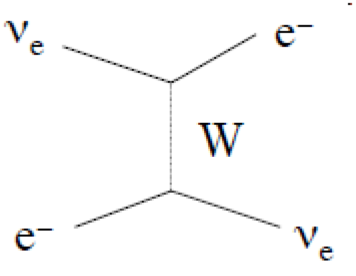
The core of the Sun has a density of about 150 g/cm^3



The Sun is made of up/down quarks and electrons



ν_e, ν_μ, ν_τ. <u>All neutrinos</u> can interact through NC equally.



ν_e, <u>Only electron neutrino</u> can interact through CC scattering:

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

The interaction of ν_e is different from ν_μ and ν_τ .

…… detecting all ν types

Sudbury Neutrino Observatory (SNO)

1000 tonnes D_2O (Heavy Water)

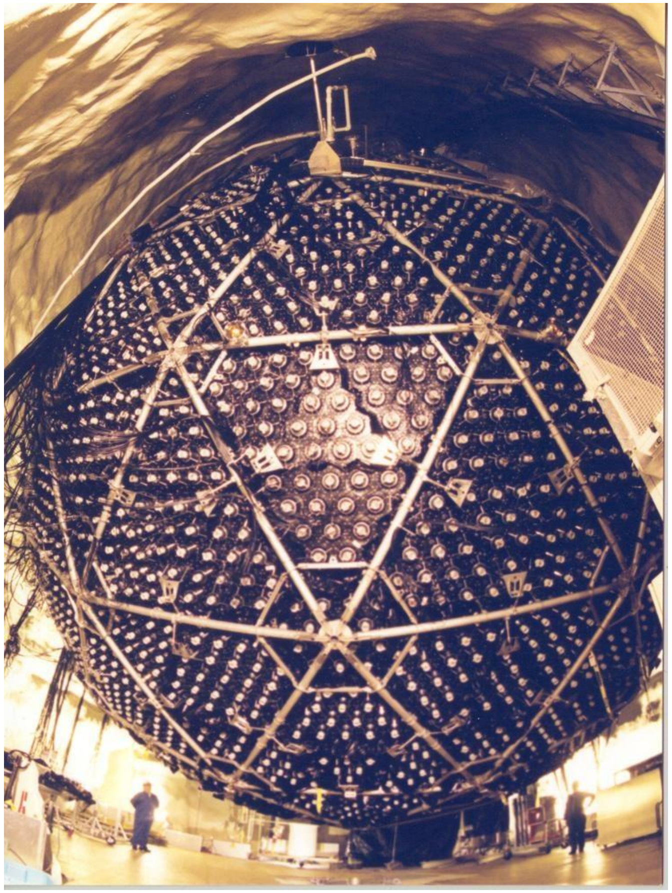
12 m diameter Acrylic Vessel

9500 PMTs

1700 tonnes inner shielding H_2O

5300 tonnes outer shielding H_2O

At Sudbury Ontario Canada (since 1999)

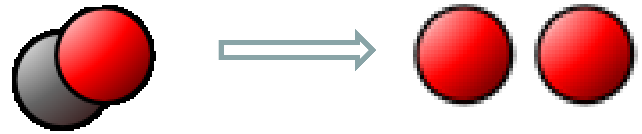


Neutrino reactions in SNO

CC, NC FLUXES MEASURED INDEPENDENTLY

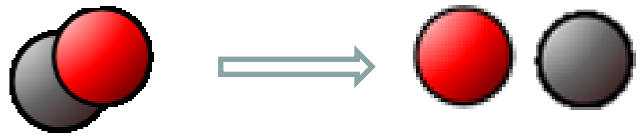
CC $\nu_e + d \rightarrow p + p + e^-$

Possible only for electron ν



NC $\nu_x + d \rightarrow p + n + \nu_x$

Equal cross section for all ν flavors

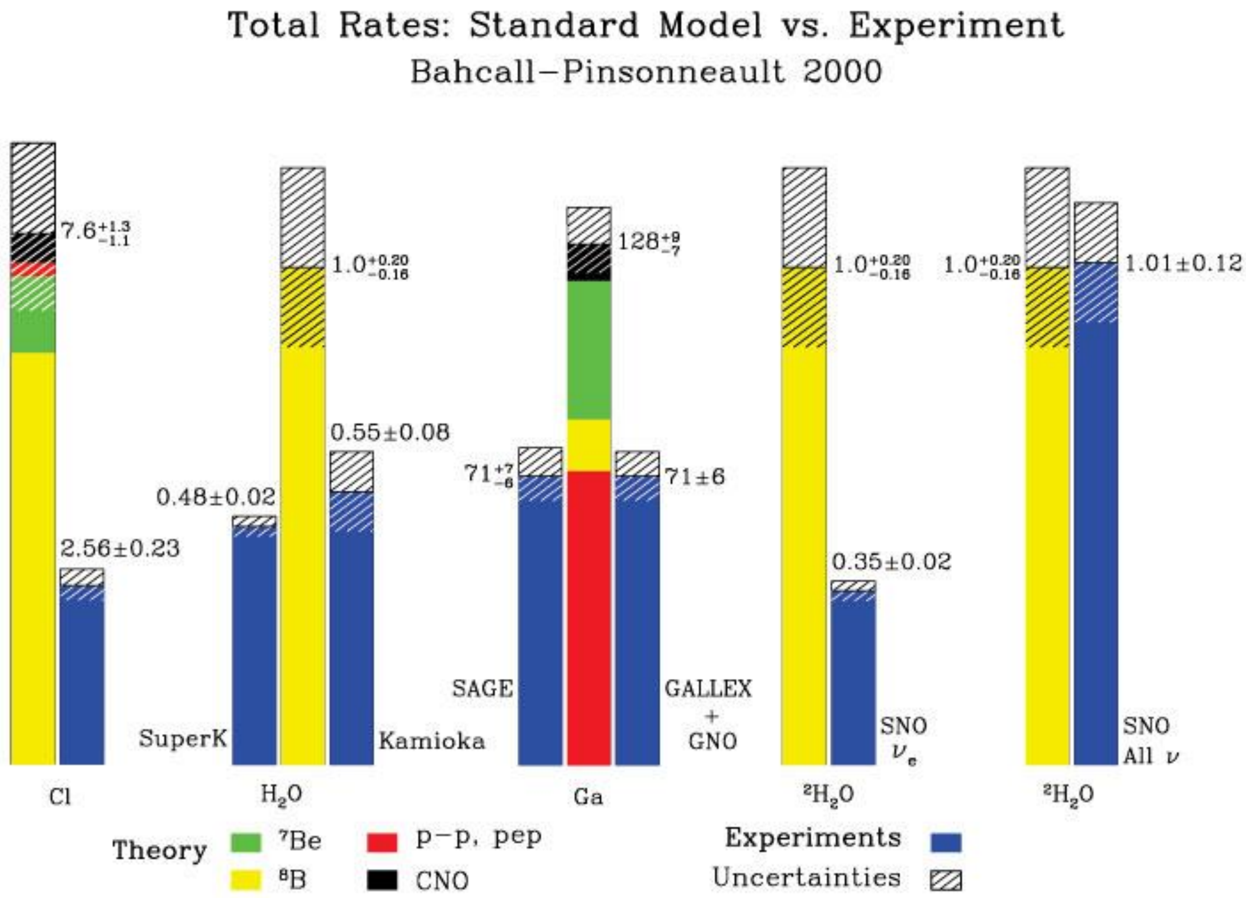


$$\begin{cases} \phi_{CC} = \phi_{\nu_e} \\ \phi_{NC} = \phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau} \end{cases}$$

Experiment	Theory
$\phi_{CC} = 1.68\ ^{+0.06}_{-0.06}(\text{stat.})^{+0.08}_{-0.09}(\text{syst.}) \cdot 10^6\ cm^{-2}s^{-1}$ $\phi_{NC} = 4.94\ ^{+0.21}_{-0.21}(\text{stat.})^{+0.38}_{-0.34}(\text{syst.}) \cdot 10^6\ cm^{-2}s^{-1}$	The total flux calculated with the solar standard model is (*BPS07*) $(4.7 \pm 0.5) \cdot 10^6\ cm^{-2}s^{-1}$

$$\frac{\phi_{CC}}{\phi_{NC}} = \frac{1.68}{4.94} \sim \frac{1}{3}$$

Summary of all Solar neutrino experiments before Borexino



All experiments "see" less neutrinos than expected by SSM ……..

……. (but SNO in case of Neutral Currents!)

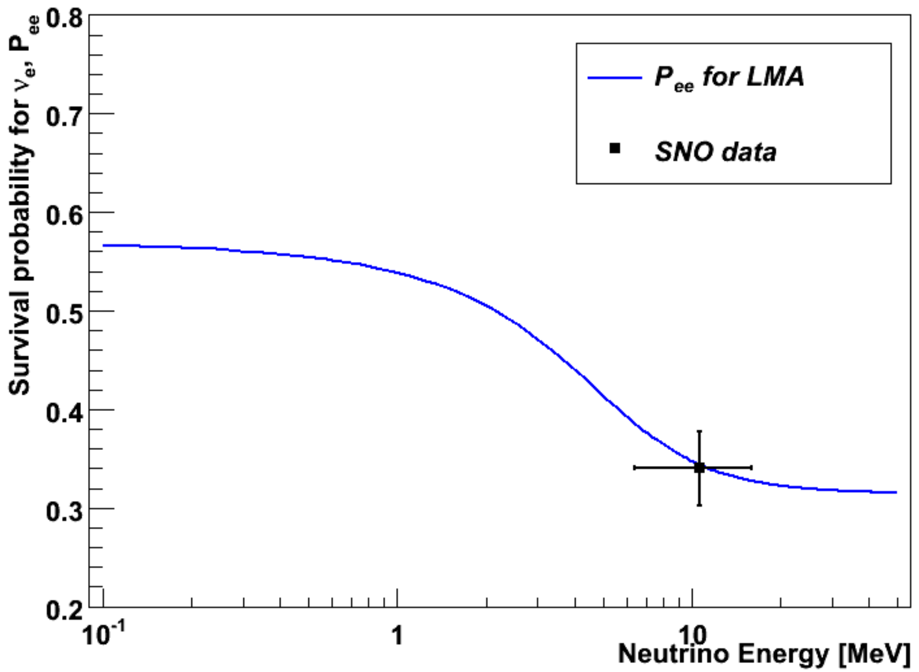
electron neutrinos (ν_e) oscillate into non-electron neutrino (ν_μ, ν_τ) with these parameters:

$$\Delta m^2_{12} = 7.6 \cdot 10^{-5} eV^2$$
$$\sin^2 2\vartheta_{12} = 0.87$$

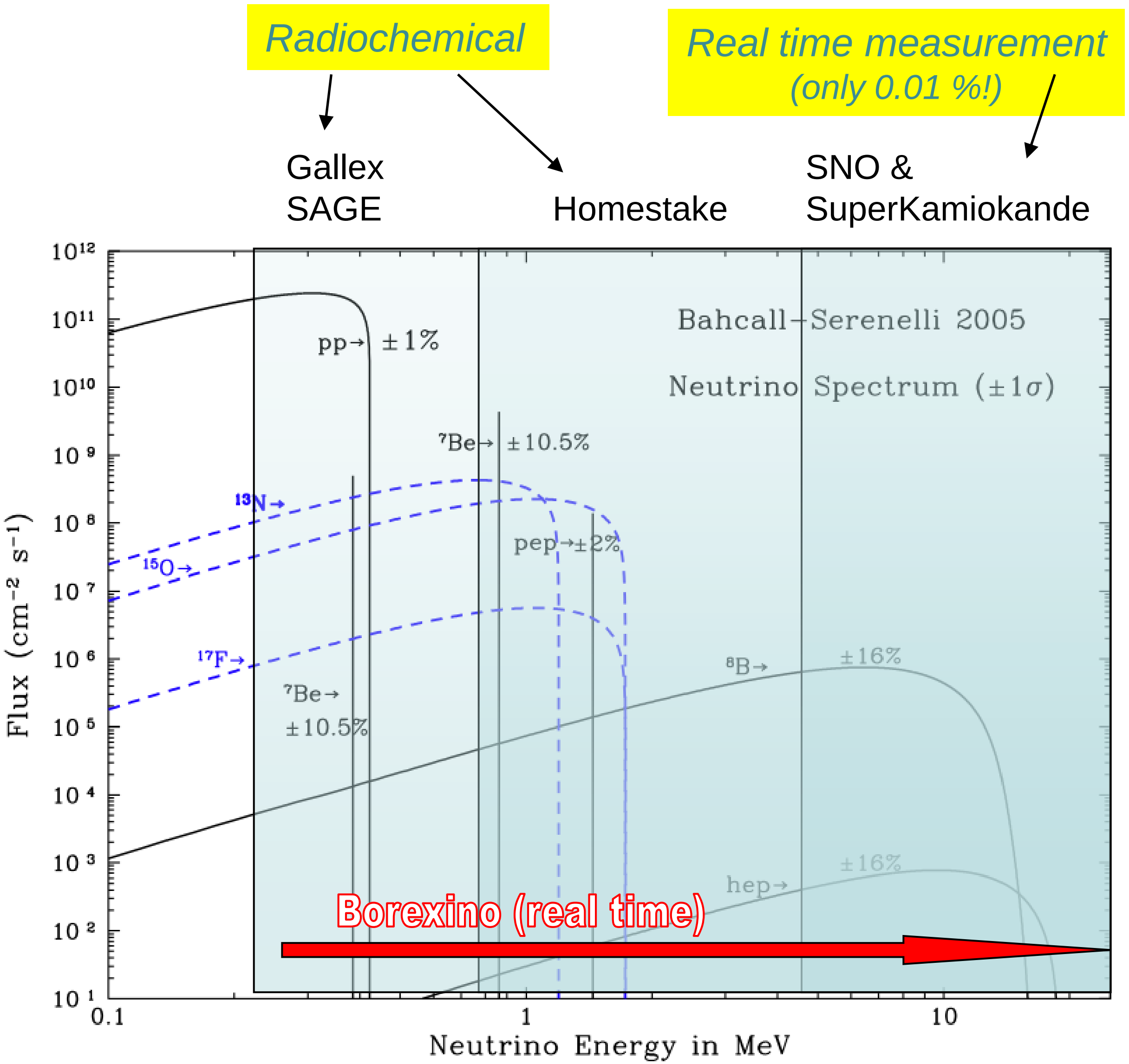
from KamLAND Collab. arXiv:0803.4312v1

Corresponding to the Large mixing Angle (LMA) Region: MSW

Survival probability vs energy



To measure in real time below 1 MeV



Borexino

$E_{th} \sim 200$ keV

Borexino is able to measure neutrino coming from the Sun in real time with low energy (~ 200 keV) and high statistic.

It is possible to distinguish the different neutrino contributions.

First real time detection of ^{7}Be solar neutrinos by Borexino
Physics Letters B *Volume 658, Jan 2008,*

Detection principles and neutrino signature

elastic scattering (ES) on electrons in very high purity liquid scintillator (100 tons)

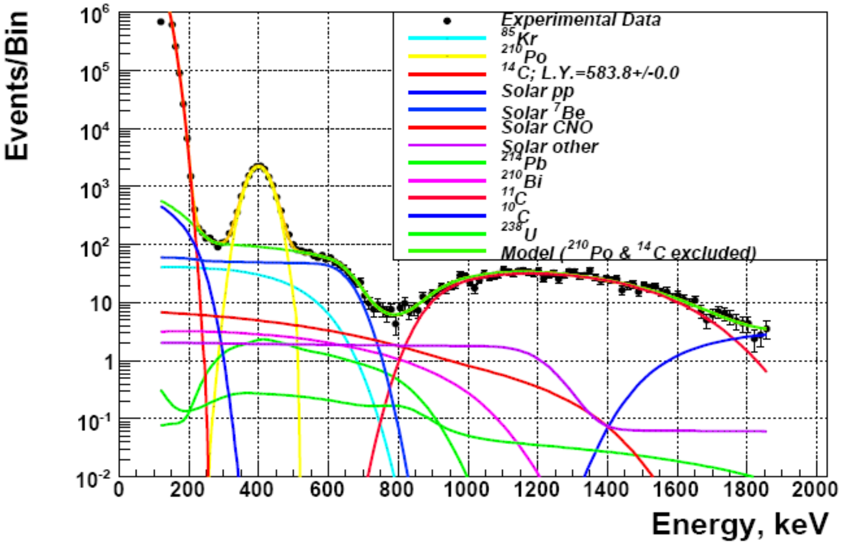
$$\nu_x + e^- \rightarrow \nu_x + e^-$$

The ν induced events can't be distinguished from other γ/β events due to **natural radioactivity**.

The neutrino signal is on the order of **some tens of events/day/100 tons** above threshold.

In order to have a signal to noise ratio on the order of 1 the **^{238}U** and **^{232}Th** intrinsic contamination can't exceed **10^{-16} g/g**! (this means 9-10 orders of magnitude less radioactive then anything on Earth)

The measured energy spectrum (May 2007 – Oct 2008)

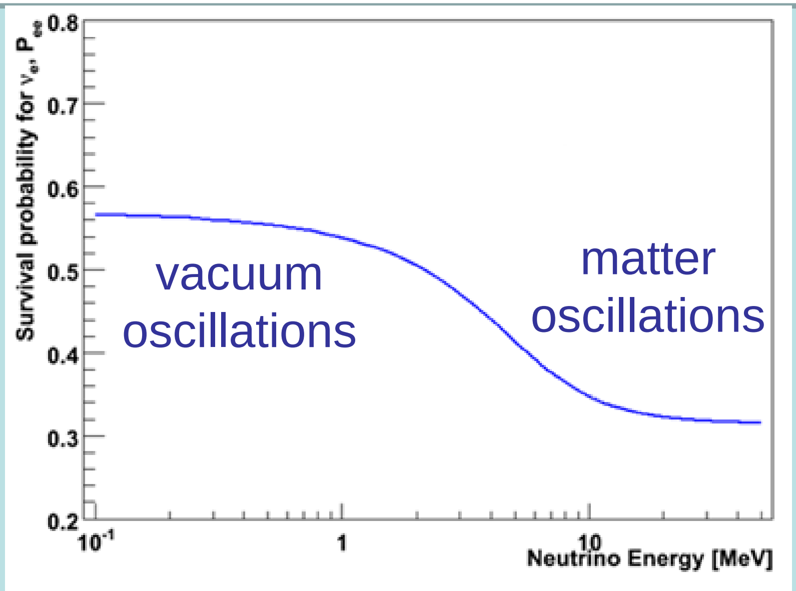


Neutrino survival probability

For **high energy** neutrinos flavor change is dominated by matter oscillations

For **low energy** neutrinos flavor change is dominated by vacuum oscillations

Regime transition expected between **1-2 MeV**



Borexino is able to measure both low energy and high energy neutrinos

Solar Model Chemical Controversy

$$\nu_{CNO}$$

One fundamental input of the Standard Solar Model is the **metallicity** (abundance of all elements above Helium) of the Sun

A lower metallicity implies a variation in the neutrino flux (reduction of ~ 40% for CNO neutrino flux) → A **direct measurement of the CNO neutrinos** rate could help to solve this controversy giving a direct indication of metallicity in the core of the Sun