Natural neutrino sources and what can we learn from them?

1 Experimental discoveries

- Discovery of neutrinos: Cowan and Reines in 1956 (Nobel prize in 1995)
- No lepton number violating processes $\bar{\nu}_e + n \rightarrow e^- + p$
  for example $\bar{\nu}_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$ observed
  - o Looks like there is difference between $\bar{\nu}_e$ and ν_e.
- Goldhaber experiment (1958): Only left-handed neutrinos observed!
  Remember: $\hat{P}_L|\nu\rangle = |\nu_L\rangle$, $\hat{P}_R|\nu\rangle = |0\rangle$ with $\hat{P}_{L/R} = (1 \pm \gamma_5)$
  - o Difference between $\bar{\nu}_e$ and ν_e could be explained by the V-A structure of weak interaction
- No more than three light neutrino species (LEP)
- Three neutrino species observed:
  ν_e : Cowan and Reines
  ν_μ : Lederman, Schwartz and Steinberger (Brookhaven with 15 GeV proton beam, observation of pion decay, Nobel prize 1985):
  $\pi^+ \rightarrow \mu^+ + \nu_\mu$ $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
  $\nu_\mu + N \rightarrow \mu^- + X$ $\bar{\nu}_\mu + N \rightarrow \mu^+ + X$
  No e^- or e^+ observed!
  ν_τ : DONUT experiment (2001)
- Detection of solar neutrinos (Homestake, Gallex, Superkamiokande, SNO, Borexino, ...)

2 Neutrino Sources

2.1 Cosmic neutrino background

Thermal relic from early universe: freeze-out of neutrinos at temperature ~1 MeV (t~1 s)

$n_\nu = 336\ cm^{-3}$ with $\langle E_\nu \rangle = 5.28 \cdot 10^{-4}\ eV$ corresponding to $T_\nu = 1.946\ K$

The energy of relic neutrinos is so small that it is extremely hard to detect them. Remember, the neutrino elastic scattering cross sections scales linearly with energy → Due to small energy: energy transfer to be measured is tiny & reaction rates are suppressed!

2.2 Solar neutrinos

In the Sun the energy is gained by fusion with energy balance:

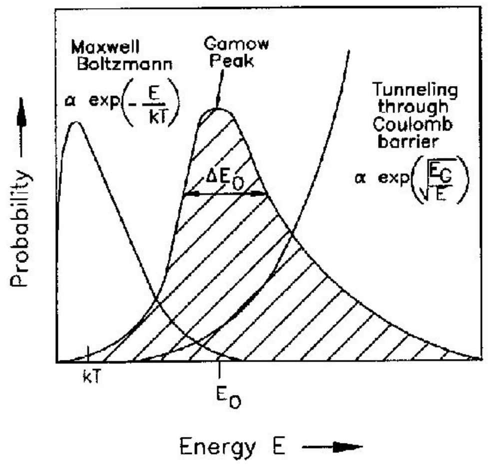
$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e + 26.7\ MeV$$

The typical thermal energy of protons in solar interior is ~keV, while the Coulomb barrier to overcome for fusion is ~MeV

→ Quantum-mechanical tunneling makes fusion possible

→ Stability of stars is based on low tunneling probability at given core temperatures

The probability that a fusion process occurs is given by the convolution of the Maxwell-Boltzmann distribution and the probability of tunneling through the Coulomb barrier → Gamow peak



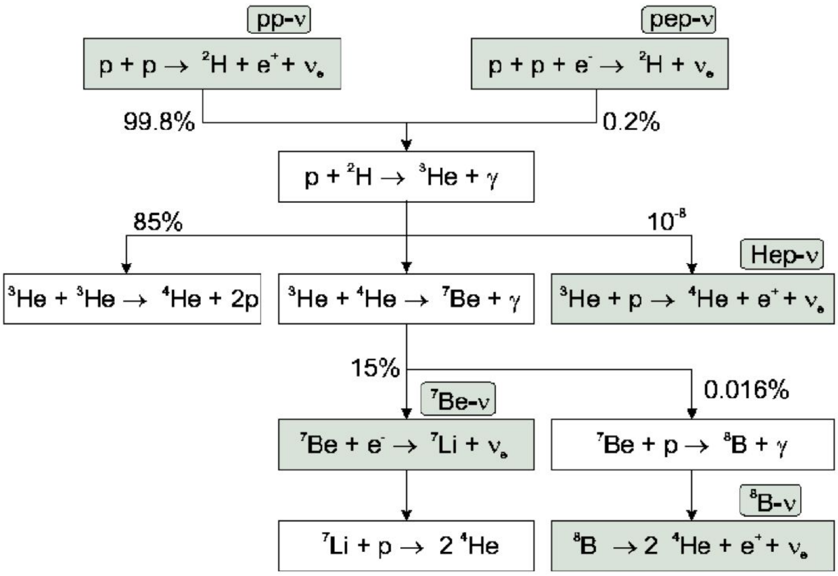
Matter of current research: Measure low energy nuclear reaction cross sections that determine fusion (LUNA at LNGS) using MeV accelerators underground (also relevant for BBN: remember ^{7}Li problem). Example processes:

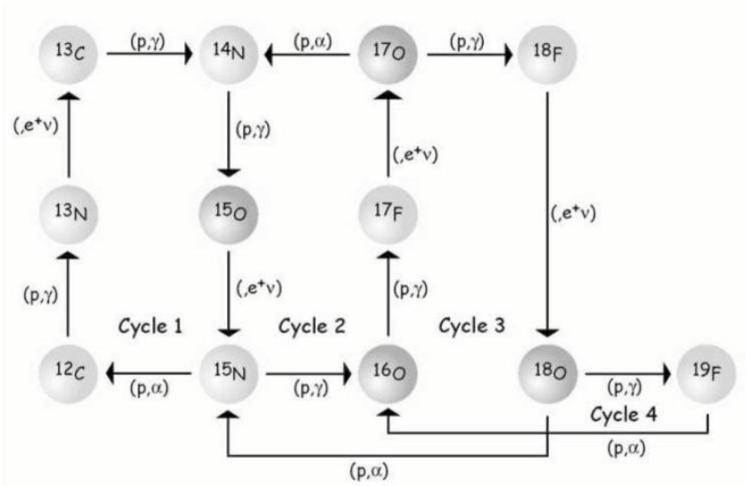
$^3He(^3He,2p)^4He$

$^{14}N(p,\gamma)^{15}O$

$d(p,\gamma)^3He$

Two cycles contribute to the overall energy production of the Sun: the pp and the CNO cycle:





Within the pp cycle neutrinos are produced in the following reactions:

$$p + p \rightarrow {}^{2}H + e^{+} + \nu_e \quad (99.75\%) \quad E_\nu^{pp} \leq 0.42\, MeV$$

$$p + e^{-} + p \rightarrow {}^{2}H + \nu_e \quad (0.25\%) \quad E_\nu^{pep} = 1.44\, MeV$$

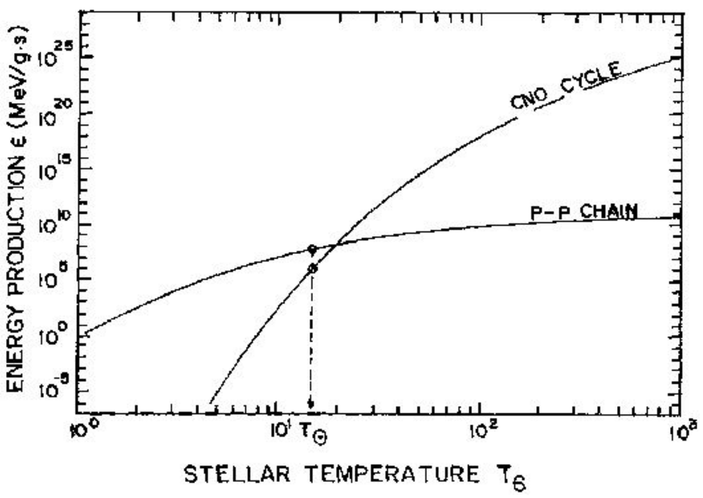
$${}^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu_e \quad \left(2.4 \cdot 10^{-5}\%\right) \quad E_\nu^{hep} \leq 18.77\, MeV$$

$${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e \quad (14\%) \quad E_\nu^{7Be,i} = 0.862\, MeV \quad (90\%), E_\nu^{7Be,ii} = 0.384\, MeV \quad (10\%)$$

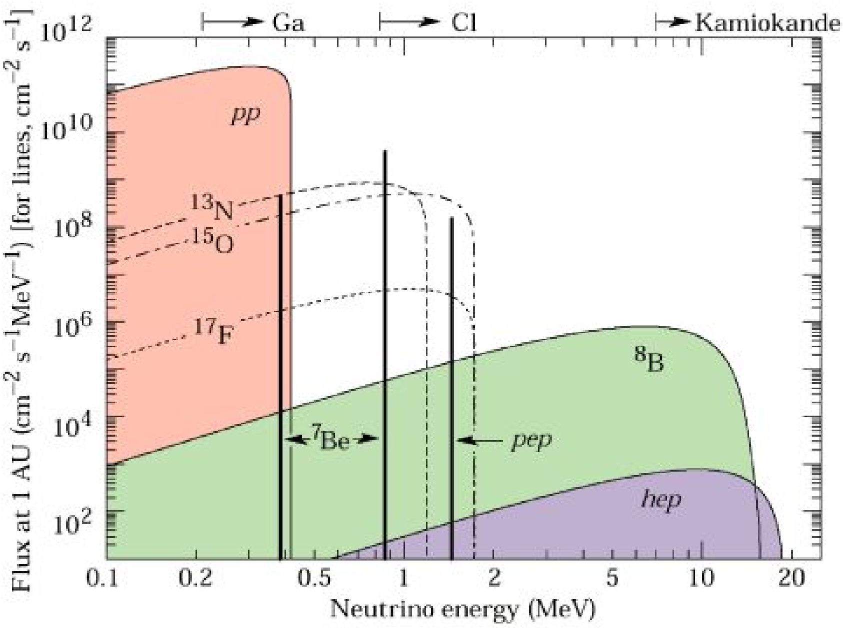
$${}^{8}B \rightarrow {}^{8}Be + e^{+} + \nu_e \quad (0.028\%), \quad E_\nu^{CNO} \leq 14.06\, MeV$$

Alternatively energy can be gained from the CNO cycle. There are no mono energetic neutrino lines from CNO cycle. The energy of CNO neutrinos is $E_\nu^{CNO} > 1.73\, MeV$.

The ratio of energy produced in CNO cycle is heavily dependent on temperature in the core (and on C,N,O abundance, which needs to be at least ~1% for one of the elements).
At $T_\odot$: $E_{pp} > E_{CNO}$.



Energy production rate of pp- and cno- cycles as a function of T



Solar neutrino spectrum as expected from the standard solar model

The total flux on the Earth's surface can be easily calculated from the knowledge of energy production inside the Sun's core and the known energy released in the individual fusion processes.

$$\Phi_\nu^\odot(Earth) = 7\cdot 10^{10}\ cm^{-2}s^{-1}$$

For detection of solar neutrinos it is important to consider maximum and threshold energies of reactions through which neutrinos are detected and the energy thresholds of the detectors!

Stars with a total mass exceeding a critical mass $M_c \sim 8M_\odot$ reach core temperatures of $T \gtrsim 10^8$ K (compare to $T_\odot \sim 10^7$ K). These kind of stars radiate most energy in form of neutrinos! Our Sun: 98% radiation via photons, 2% via neutrinos.

2.3 Atmospheric neutrinos

Cosmic rays consist mainly of hadrons (~99%). Highly energetic hadron impinging on Earth's atmosphere will create an air shower (cascade):

$$p + N \rightarrow \pi^\pm, K^\pm, \ldots$$

$$\pi^+, K^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

$$\pi^-, K^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu$$

→ Expectation of ratio between neutrino flavors:

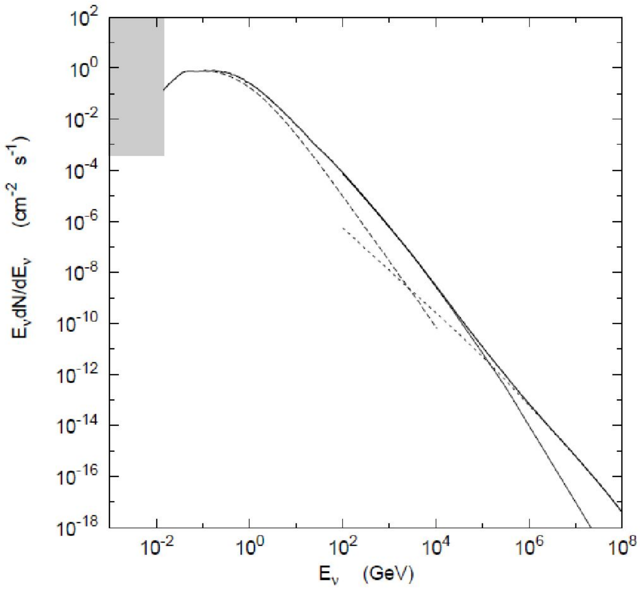
$$R = \frac{\Phi^{atm}_{\nu_\mu} + \Phi^{atm}_{\bar{\nu}_\mu}}{\Phi^{atm}_{\nu_e} + \Phi^{atm}_{\bar{\nu}_e}} \sim 2 \quad \text{while} \quad \frac{\Phi^{atm}_{\nu_\mu}}{\Phi^{atm}_{\bar{\nu}_\mu}}$$

The correct values depend on the details of air showers and deviate slightly from the first order approximation. The total integrated atmospheric neutrino flux is about

$$\Phi_{\nu_{tot}}^{atm} \sim 10\ cm^{-2}s^{-1}$$

Relevant energy range of atmospheric neutrinos:

$$E_{\nu}^{atm} \sim 10^{2}\ MeV - 10^{4}\ GeV$$



Vertical flux of $\bar{\nu}_\mu + \nu_\mu$ (solid line); $\bar{\nu}_e + \nu_e$ (dashed line); prompt neutrinos (dotted line); $\bar{\nu}_\mu + \nu_\mu$ from pions and kaons (thin solid line at high energy). The shaded region is dominated by solar neutrinos. Fig. taken from Ann. Rev. Nucl. Part. Sci. 52 (2002) 153

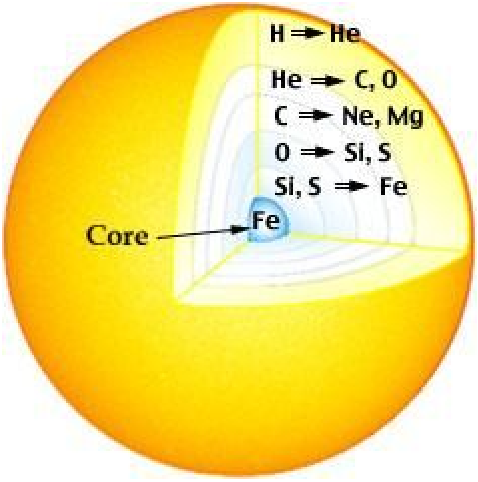
2.4 Supernova neutrinos (diffuse supernova neutrino background)

Supernovae of type II are triggered by gravitational collapse at the end of the fusion process (no fuel available). Gravitational energy is transformed into an explosion. Only stars with mass to bring up sufficient gravitational energy can trigger a SN explosion: $M_C \sim 8\ M_\odot$.

Process leading to SN explosion for star with $M \sim 20\ M_\odot$:

- Once hydrogen in the stellar core is depleted and is dominated by Helium: gravitational pressure will be higher than radiation power.
- Star contracts, temperature increases, H-shell is pushed outward (can still undergo fusion in spherical shell)
- Fusion from helium to carbon and oxygen starts
- Once helium is depleted, the fusion rate reduces, gravitational pressure exceeds radiation pressure, temperature increases
- Fusion from carbon and oxygen to neon, manganese, silicon and sulphur starts
- In the last step silicon is fused to iron

→ Onion shell structure



Durations of different burning cycles vary greatly:

Hydrogen	Helium	Carbon	Oxygen	Neon	Silicon
10^6	$5{\cdot}10^5$	600	0.5	1	0.004

For less massive stars, the evolution is similar but constrained by the gravitational pressure and, hence, by the core temperature. If temperature is not high enough, next burning cycle cannot be ignited.

In core collapse SN → once silicon is depleted:

- No further thermonuclear reactions
- No more radiation pressure to counteract gravitational pressure
- Gravitational collapse
- Core mass exceeds Chandrasekhar mass limit $M_{Cha} \sim 1.4 M_{\odot}$
- Core becomes unstable and implodes
- Electrons are captured by protons: $p + e^- \to n + \nu_e$
- Emission of $\sim 10^{57}$ neutrinos within $\sim 0.1\ s$!
- Transport of $\sim 10^{57} \cdot 10\ MeV\ =\ 10^{58} MeV$ in the form of neutrinos away from core
- Compression of core to density $\rho \sim 2.5 \cdot 10^{14}\ g\ cm^{-3}$ and temperature $T \sim 10^{11} K$
- Collision of outer core onto central dense region
- Rebound shock wave with speed $v \sim \frac{1}{3} c$
- Rebound shock wave and neutrinos collide with outer shells of the star and ignite explosion

	Core density	Core radius:
Core before implosion:	$\rho_i \sim 10^{11}\ g\ cm^{-3}$	$\sim 10^3\ km$
Before reaching M_{Cha}		$\sim 10^2\ km$
After collapse:	$\rho_{ii} \sim 2.5 \cdot 10^{14}\ g\ cm^{-3}$	$\sim 20\ km$

Now consider the mean free path of neutrinos in supernovae:

$l(\rho) = \frac{M_{core}}{\rho \cdot \sigma}$

$\sigma(\nu - Fe\ at\ 10\ MeV) \sim 10^{-40} cm^2$

$\langle l(\rho_{i)}\rangle \sim 20\ km$ and $\langle l(\rho_{ii})\rangle \sim 10\ m$

$\rightarrow\ l \ll R_{core}$

Neutrinos can undergo the following reactions with the material of the in-falling shell:

$$\nu + A \rightarrow \nu + A \qquad \bar{\nu} + A \rightarrow \bar{\nu} + A$$
$$\nu + e^- \rightarrow \nu + e^- \qquad \bar{\nu} + e^+ \rightarrow \bar{\nu} + e^+$$
$$\bar{\nu} + \nu \rightarrow e^- + e^+$$
$$\nu_e + n \rightarrow e^- + p \qquad \bar{\nu}_e + p \rightarrow n + e^+$$

ν_e can do CC + NC, while ν_μ and ν_τ only undergo NC → Opacity higher for ν_e !
Only a fraction of neutrinos released in the core will actually be directly radiated away.

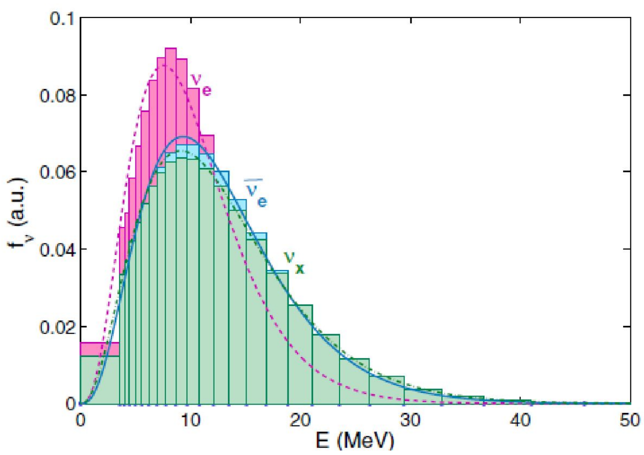
The energy range for SN-neutrinos is between $1 - 10\ MeV$.

Length of neutrino signal is given by diffusion of neutrinos to the "neutrino sphere", the radius at which the shell becomes transparent to neutrinos:

- Few seconds
- Exact distribution depends on neutrino physics
- Tool to gain information on neutrino parameters by studying time distribution of SN neutrinos!

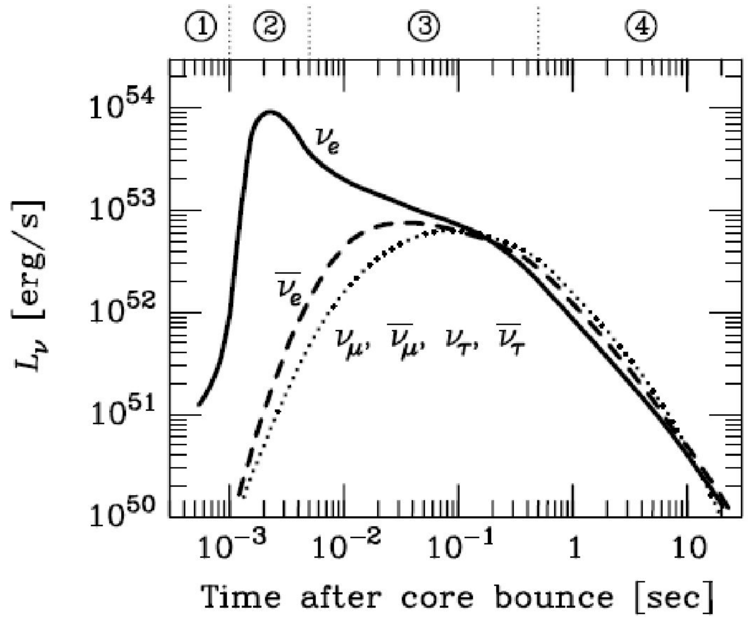
The light signal of the SN is expected few hours after the core collapse happened!

Neutrinos carry away $\sim 99\%$ of the energy → cooling of the SN happens through neutrinos (Kelvin-Helmholtz-Neutrino Cooling).



Neutrino spectra expected for SN modelled for a $15M_\odot$ progenitor star at $\sim 1s$ after the core collapse (ν_x denotes any single kind of the neutrino species $\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$).

Fig taken from Phys. Rev. D 86 (2012) 120531



Schematic light curve for different neutrino flavors. Fig. taken from G. G. Raffelt, "Stars as laboratories for fundamental physics" (University of ChicagoPress, 1996).

Expected mean SN rate in our galaxy: ~1 per 30 years!

Last confirmed observation of SN in our galaxy: "Kepler SN" from 1604!
Since then only in Large Magellanic Cloud: SN1987A.

From this: Difference in propagation time for light and neutrinos can be used to set limits on neutrino mass. For example from observation of neutrinos from SN1987A:

$$m_{\nu_e} < 31\ eV\,.$$

2.5 Astrophysical / High-energy neutrinos

Produced in hadronic interaction at cosmic-ray sources. We can learn about the origin and nature of cosmic rays.

Their spectrum is expected to follow the same power-law as the cosmic ray spectrum.

They are produced with a flavor ratio of 1:2:0 → arriving 1:1:1 due to oscillations.

IceCube is the main experiment measuring high-energy neutrinos at the south pole:
track-like ν_μ and cascade-like ν_τ events.

The surprisingly high level of the neutrino flux observed by IceCube implies that a significant fraction, possibly all, of the energy in the non-thermal universe is generated in hadronic accelerators. The non-thermal universe contains collapsed objects such as black holes or neutron stars. High-energy neutrinos, which are unique fingerprints of hadron acceleration, represent therefore a discovery potential for either revealing new sources or unveiling new insight on the energy generation in known sources.

IceCube detected the first likely source of high-energy neutrinos, a blazar that was also observed with gamma rays and lower energy photons. This observation of neutrino and gamma-ray emission from TXS0506+06 is the first evidence that blazars, and possibly other sources of gamma rays, are the sources of both gamma-ray and neutrino emission at the highest energies.

2.6 Reactor neutrinos

Nuclear power reactors use fission of the isotopes $^{235}U,\ ^{238}U,\ ^{239}Pu,\ ^{241}Pu$ to produce energy. Fission produces neutron rich fission fragments / isotopes, which mostly decay via β^- decay. Emission of $\sim 6\,\overline{\nu}_e$ per fission with typical energies around $10\ MeV$ are expected. The spectrum is described by the composition of the spectra from different isotopes (Watt spectra).

It is easy to estimate the number of neutrinos emitted isotropically from the reactor ε and hence the flux at a distance $L,\ \Phi_\nu^{reac}(L)$:

$$\varepsilon = 1.9 \cdot 10^{20} \tfrac{P}{GW} s^{-1} = 4\pi L^2\ \Phi_\nu^{reac}(L)$$

For a typical reactor core with $P = 1.5\ GW$ power (like for one core of the Chooze reactor):

$$\varepsilon_{Chooze\ B1} = 2.85 \cdot 10^{20} s^{-1}$$

Exact calculation of energy spectrum is non-trivial, as it depends on the composition of fission material and isotope ratios change with time. → The energy spectrum of reactor neutrinos is changing as a function of time! → Systematic uncertainties!

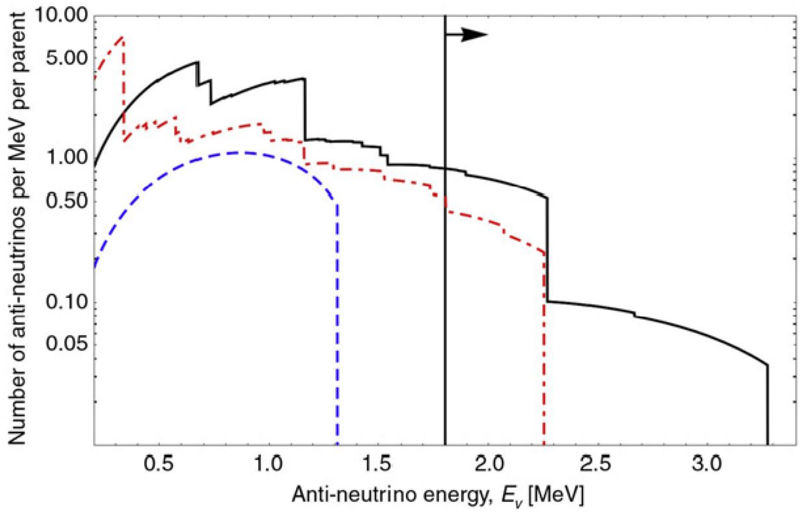
2.7 Geoneutrinos

Earth's crust contains long lived radioactive isotopes in non-negligible amounts (heating of Earth's core?). Neutrinos from their decay (chains) lead to emission of $\overline{\nu}_e$ s:

$$^{238}U \rightarrow\ ^{206}Pb + 8\alpha + 8e^- + 6\overline{\nu}_e + 51.7\ MeV$$
$$^{232}Th \rightarrow\ ^{208}Pb + 6\alpha + 4e^- + 4\overline{\nu}_e + 42.7\ MeV$$
$$^{40}K \rightarrow\ ^{40}Ca + \overline{\nu}_e + 1.31\ MeV$$

The ratio of radiogenic heat and neutrino flux is well defined → In principle it is possible to determine the overall radiogenic heat of Earth by measuring the geoneutrino flux.
Expected flux at the surface from measured content of crust with $^{238}U,\ ^{232}Th$ and ^{40}K :

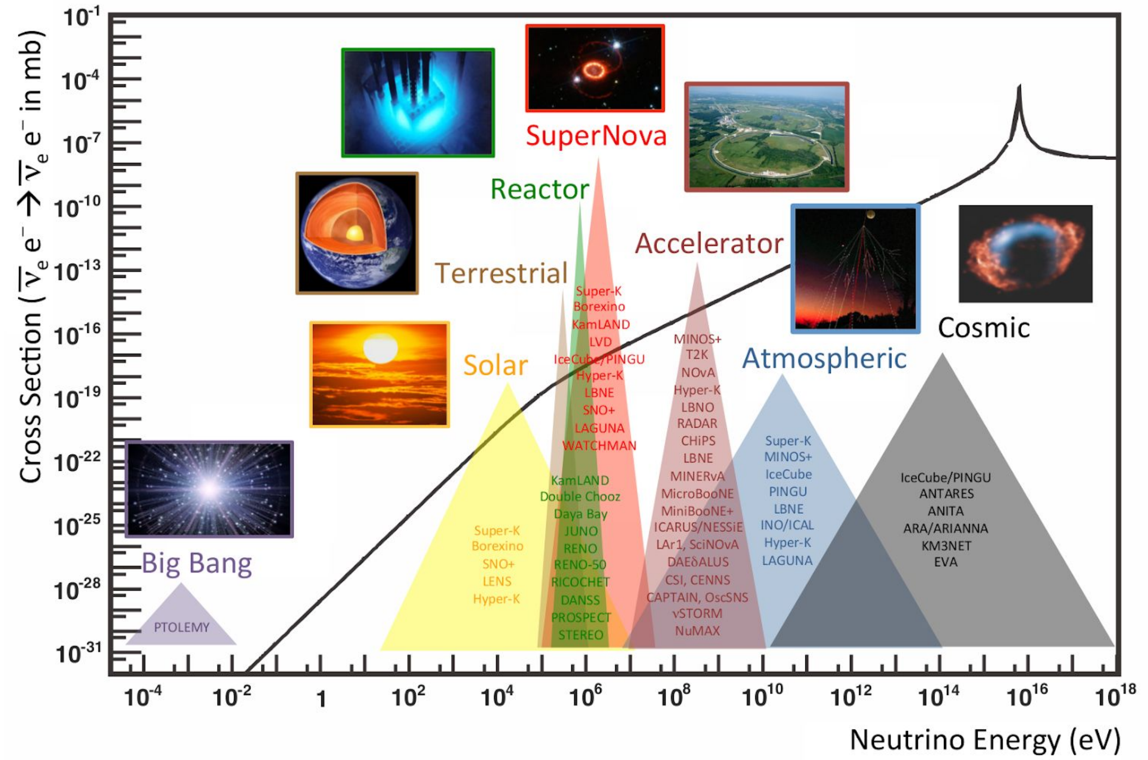
$$\Phi_{\overline{\nu}_e}^{geo}\ \sim\ 10^6\ cm^{-2}s^{-1}$$



Neutrino spectra expected from the ^{238}U chain (solid black line), ^{232}Th chain (dashed–dotted red line) and ^{40}K (dashed blue line). The vertical line shows the threshold for inverse beta decay reaction $\bar{\nu}_e + p \rightarrow e^+ + n$. Fig. taken from Prog. Part. Nucl. Phys. 73 (2013) 1

Summary of neutrino sources

Fig. taken from arXiv:1401.6077



3 Neutrino Oscillations

For Yukawa coupling (standard model mass generation) the mass terms contain both right- and left-handed neutrinos. However, the SM does not contain right handed neutrinos → in the SM neutrino mass is set to 0! If nevertheless right handed neutrinos exist: Must be very heavy → cannot be SM mass generation!

Massive neutrinos can in principle oscillate between flavor eigenstates

$$\nu_\alpha \leftrightarrow \nu_\beta \qquad (\alpha, \beta = e, \mu, \tau)$$

This can only happen if

1. The three corresponding mass eigenstates are not degenerate
2. Lepton-flavor conservation is slightly broken
3. Flavor eigenstates of the weak interaction are not identical with the mass eigenstates of neutrinos

→ Analogy to quark-sector

Flavor and mass eigenstates are connected by mixing matrix (PMNS)

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle \text{ with } U^\dagger U = 1$$

If lepton number is not a good quantum number (violated) then mass and flavor eigenstates do not have to correspond to each other.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -c_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{c13} & 0 & e^{-i\delta_{cp}} s_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{cp}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\beta_1} & 0 \\ 0 & 0 & e^{-i\beta_2} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

where $s_{ij} = sin\vartheta_{ij}$, $c_{ij} = cos\vartheta_{ij}$, δ_{cp} complex a Dirac phase and β_1, β_2 two complex Majorana phases.

3.1 Two neutrino mixing

For understanding oscillations it is easier to look at the two neutrino mixing case, neglecting the third flavor:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} \\ -s_{12} & c_{12} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Time evolution of a neutrino in pure state $|\nu_e\rangle$ is then given by:

$$|\nu_e(t)\rangle = cos\,\vartheta_{12}\; e^{(-iE_1 t)} |\nu_1\rangle + sin\,\vartheta_{12}\; e^{(-iE_2 t)} |\nu_2\rangle$$

→ Probability to observe same flavor after time t:

$$P(\nu_e \rightarrow \nu_e, t) = |\langle \nu_e(t) | \nu_e(0) \rangle|^2 = 1 - sin^2 2\vartheta_{12}\, sin^2\left(\tfrac{1}{2}(E_1 - E_2)\, t\right)$$

Assuming that both mass eigenvalues have same momentum:

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

$$\rightarrow (E_1 - E_2)\, t = \frac{m_2^2 - m_1^2}{2E} t = \frac{\Delta m_{12}^2}{2E} t = \frac{\Delta m_{12}^2}{2E} L$$

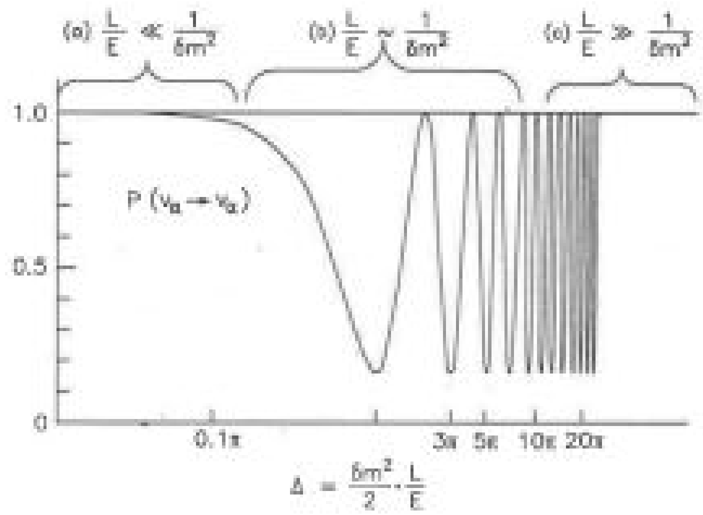
with the energy of the neutrino $E \cong p$ and $L = ct = t$ the distance the neutrino propagated. Introducing the oscillation length for a complete oscillation cycle $\nu_e \rightarrow \nu_\mu \rightarrow \nu_e$

$$L_{12} = \frac{4\pi E \hbar c}{\Delta m_{12}^2} = 2.48 \left(\frac{E}{MeV}\right)\left(\frac{eV^2}{\Delta m_{12}^2}\right) m$$

One obtains:

$$P(\nu_e \rightarrow \nu_e) = 1 - sin^2 2\vartheta_{12}\, sin^2\left(\frac{\pi R}{L_{12}}\right) = 1 - sin^2 2\vartheta_{12}\, sin^2\left(\frac{L}{E}\,\frac{\Delta m_{12}^2}{4\hbar c}\right)$$

And for the system $P(\nu_e \rightarrow \nu_\mu) = 1 - P(\nu_e \rightarrow \nu_e) = sin^2 2\vartheta_{12}\, sin^2\left(\pi \frac{L}{L_{12}}\right)$



3.2 The MSW effect (Mikheev-Smirnov-Wolfenstein)

Matter influences propagation of neutrinos: while ν_μ and ν_τ interact with electrons in matter only via neutral current (Z_0 exchange), ν_e can also react via charged current interaction:

→ coherent elastic forward scattering

→ additional potential acting on ν_e from additional CC term

$$V = \langle \nu_e e \left| L_{CC}^{eff} \right| \nu_e e \rangle = \sqrt{2} G_F N_e$$

where G_F : Fermi constant, N_e : electron density

→ change of energy momentum relation $(E \gg V)$:

$$p^2 + m_{ee}^2 = (E - V)^2 \cong E^2 - 2EV = E^2 - 2\sqrt{2}\left(\frac{G_F y_e}{m_n}\right)\rho E = E^2 - A$$

where y_e : number of electrons per nucleon, m_n : nucleon mass, ρ : matter density

→ ν_e s thus acquire effective mass: $m_{eem}^2 = m_{ee}^2 + A$

→ leading to two new mass eigenstates m_{1m} and m_{1m}

$$m_{1m,2m}^2 = \frac{1}{2}\left(m_1^2 + m_2^2 + A\right) \mp \sqrt{\left(A - \Delta m^2 cos2\vartheta - A\right)^2 + \left(\Delta m^2\right)^2 sin^2 2\vartheta}$$

For the mass difference one obtains

$$m_{2m}^2 - m_{1m}^2 = \Delta m^2 \sqrt{\left(\frac{A}{\Delta m^2} - cos2\vartheta\right)^2 + sin^2 2\vartheta}.$$

The relation between mass eigenstates and flavor eigenstates are then given by

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = U_m \begin{pmatrix} \nu_{1m} \\ \nu_{2m} \end{pmatrix} = \begin{pmatrix} cos\vartheta_m & sin\vartheta_m \\ -sin\vartheta_m & cos\vartheta_m \end{pmatrix} \begin{pmatrix} \nu_{1m} \\ \nu_{2m} \end{pmatrix}$$

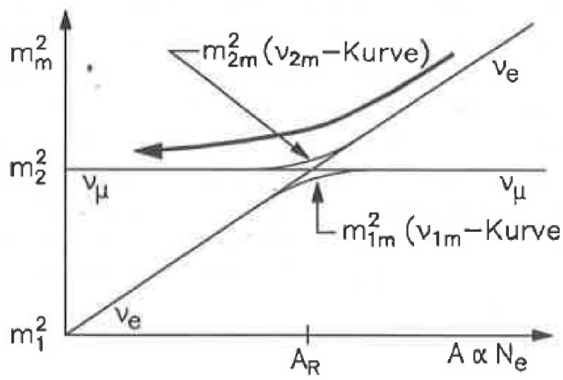
with

$$sin2\vartheta_m = \frac{sin2\vartheta}{\sqrt{\left(\frac{A}{\Delta m^2} - cos2\vartheta\right)^2 + sin^2 2\vartheta}}.$$

For $\frac{A}{\Delta m^2} = cos2\vartheta \rightarrow A = \Delta m^2 cos2\vartheta$ this becomes unity:

$$P\left(\nu_e \rightarrow \nu_\mu, A = \Delta m^2 cos2\vartheta\right) = 1.$$

This corresponds to resonant conversion.



Neutrinos ν_e propagating outwards from the core of the Sun cross the resonance point inside the solar radius and are converted to ν_μ .

3.3 Measurement of neutrino oscillations

In order to measure neutrino oscillations, neutrino fluxes have to be measured as a function of $\frac{L}{E}$ → different type of detectors are needed.

3.3.1 Radio Chemical experiments

Use neutrino capture reaction

$$\nu_e + N(Z) \rightarrow e^- + N(Z+1)$$

Example: Homestake experiment Ray Davis Jr. (Nobel prize 2002):

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

Threshold energy for reaction: $814\ keV$

→ only capture of neutrinos with $E > 814\ keV$

→ mainly ${}^{8}B$ neutrinos

Using 615 tons of the solvant perchlorideethylene the expected rate of ${}^{37}Ar$ production is

$$R \sim 1.32 \cdot 10^{-5} s^{-1} \sim 1 \text{ per day}$$

Quote results in Solar Neutrino Units:

$$1\ SNU = 10^{-36}\ s^{-1}\ \nu_e \text{ captures per target nucleus}$$

${}^{37}Ar$ is a noble gas with $T_{1/2}\left({}^{37}Ar\right) = 35.04$ days → EC reaction

One can detect and count ${}^{37}Ar$ atoms after extracting from the fluid.

Measured production rate: $(0.482 \pm 0.042)\, d^{-1}\ {}^{37}Ar$ nuclei ⍰ $(2.56 \pm 0.22)\ SNU$
Expected production rate: $(1.51 \pm 0.57)\, d^{-1}\ {}^{37}Ar$ nuclei⍰ $(8.0 \pm 3.0)\ SNU$

→ Solar neutrino deficit

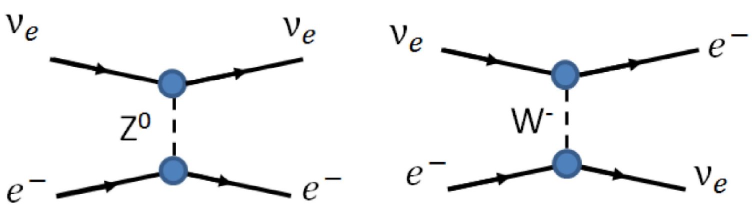
Measurement was confirmed by GALLEX and SaGe experiments via the reaction

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

with threshold energy for reaction $233\ keV$ → first detection of solar pp neutrinos

3.3.2 Water Čerenkov detectors

Interaction of neutrinos can create charged particles, for example ν_e:



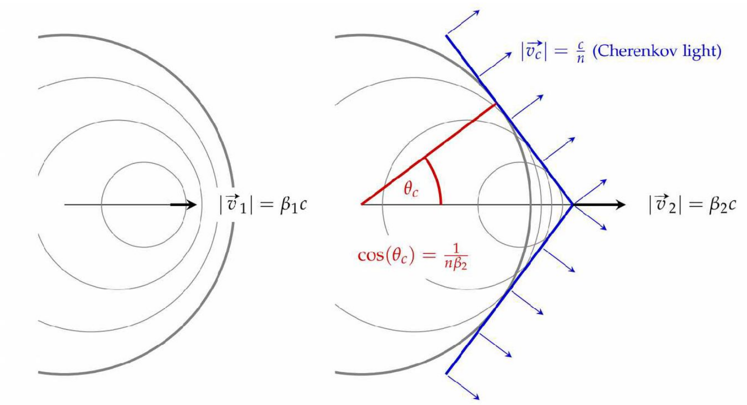
For solar neutrinos: $E_{\nu_e} \lesssim 15\ MeV \rightarrow E_{e^-} < 15\ MeV$.

Charged particles propagating in medium with refractive index n with speed

$$v > \frac{c}{n} \quad \text{or} \quad \beta > \frac{1}{n}$$

emit detectable Čerenkov light. Light is emitted at angle θ_c with respect to trajectory of charged particle, where

$$cos\ \theta_c = \frac{c}{vn} = \frac{1}{\beta n} .$$

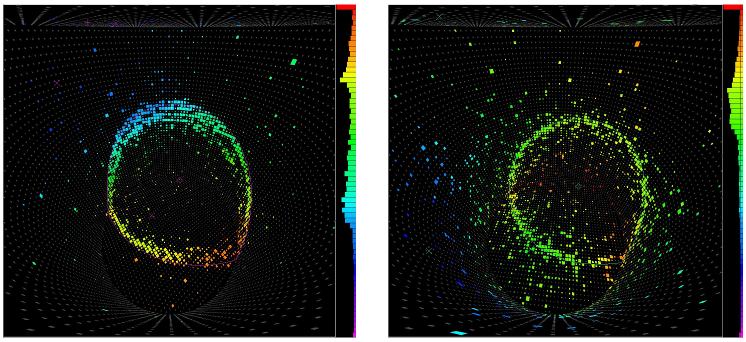


Distinction between ν_e and ν_μ via difference in interaction of e^- and μ^- with (mostly electrons of) medium: energy transfer from electron to electron higher than from muon to electron

→ shorter mean free path

→ more EM showers by e^+e^- pair creation

→ e^- induced Čerenkov rings are more diffuse than μ^- induced ones

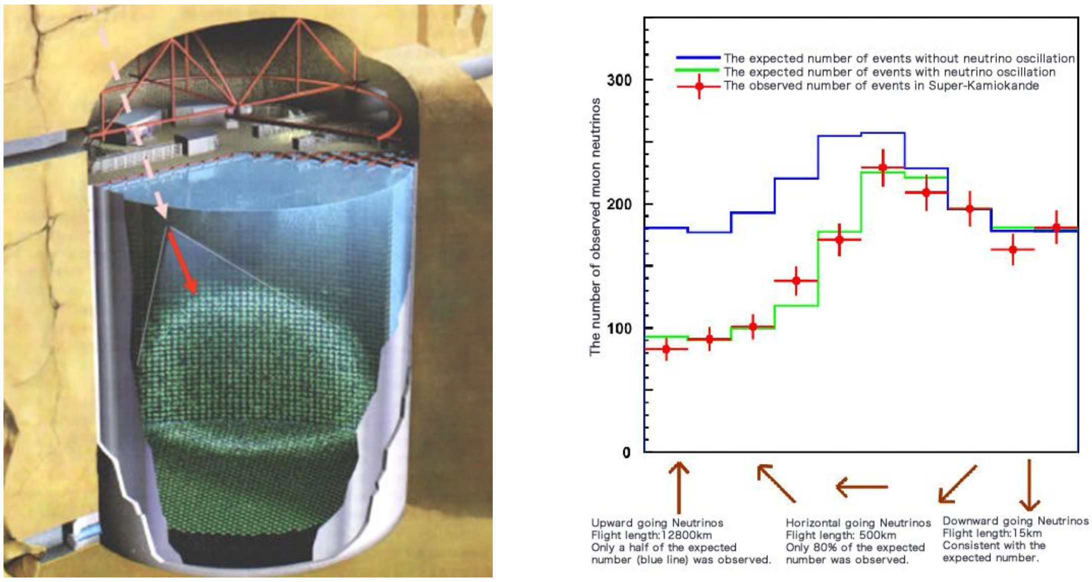


Superkamiokande events: 603 MeV muon event (left) and 492 MeV electron event (right)

Measurement of number of emitted photons, Čerenkov ring opening angle, Čerenkov ring thickness and vertex of interaction gives information on the type, on the energy and the incident direction of the particle.

Super-Kamiokande

Welded stainless steel tank with diameter 39 m and 50 kt water capacity. The tank is equipped with 11 146 PMTs pointing inwards and 1885 PMTs pointing outwards.



The Super-Kamiokande detector and the discovery of atmospheric neutrino oscillations

Measurement of the ratio of ν_e to ν_μ $\rightarrow$ Δm_{23} and θ_{23} [Phys. Rev. D 71 (2005) 112005]:

$$sin^2\vartheta_{23} > 0.092 \text{ and } 1.5 \cdot 10^{-3} eV^2 < \Delta {m_{23}}^2 < 3.4 \cdot 10^{-3} eV^2$$

SNO (Sudbury Neutrino Observatory)

1000 tonnes of heavy water

Deuterium as target for simultaneous measurement of $\Phi^{\odot}_{\nu_e}$ and $\Phi^{\odot}_{\nu_e+\nu_\mu+\nu_\tau}$

CC: $D + \nu_e \rightarrow p + p + e^-$

NC: $D + \nu_x \rightarrow p + n + \nu_x$

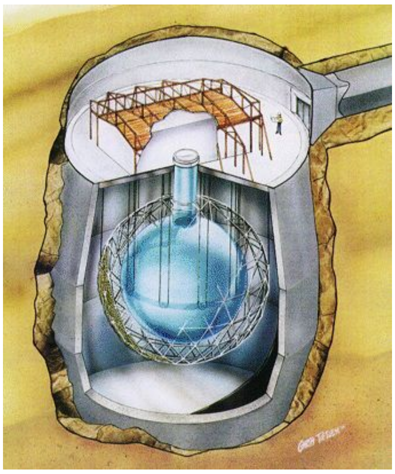
ES: $\nu_x + e^- \rightarrow \nu_x + e^-$

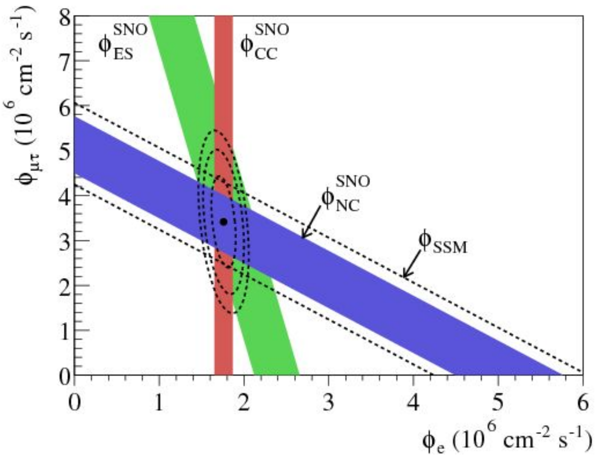
Detect Čerenkov light for different processes → unambiguous evidence for solar neutrino oscillations

$$\phi_{CC} = 1.76^{+0.06}_{-0.05}\,(\text{stat.})^{+0.09}_{-0.09}\,(\text{syst.}),$$

$$\phi_{ES} = 2.39^{+0.24}_{-0.23}\,(\text{stat.})^{+0.12}_{-0.12}\,(\text{syst.}), \quad \text{and}$$

$$\phi_{NC} = 5.09^{+0.44}_{-0.43}\,(\text{stat.})^{+0.46}_{-0.43}\,(\text{syst.}).$$

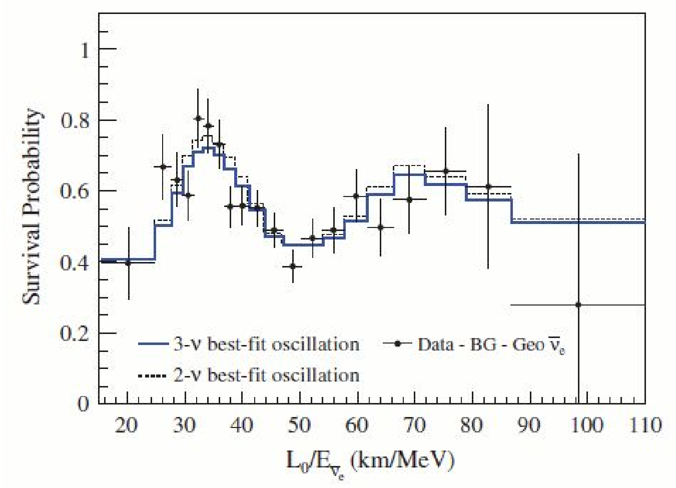




3.3.3 Liquid scintillator detectors

KamLAND

Liquid scintillator reactor neutrino experiment making use of many reactors in Japan with different distances → scan L/E



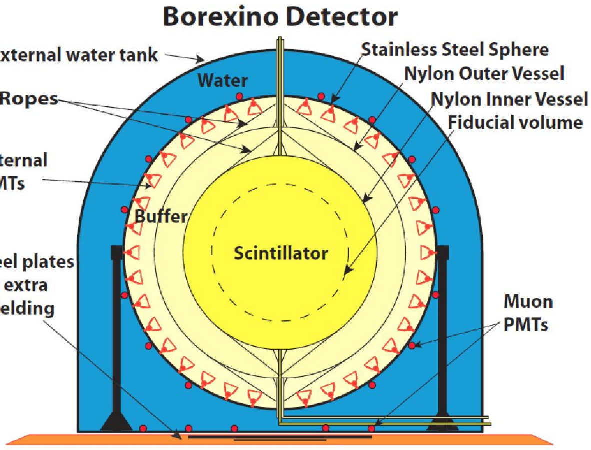
Oscillation in the KamLAND reactor neutrino experiment: Variation of the survival probability as a function of L/E. The points are the data (with known background subtracted); the lines are the prediction from oscillation models. From Phys. Rev. D83 (2011) 052002.

Double Chooze, Daya Bay, RENO

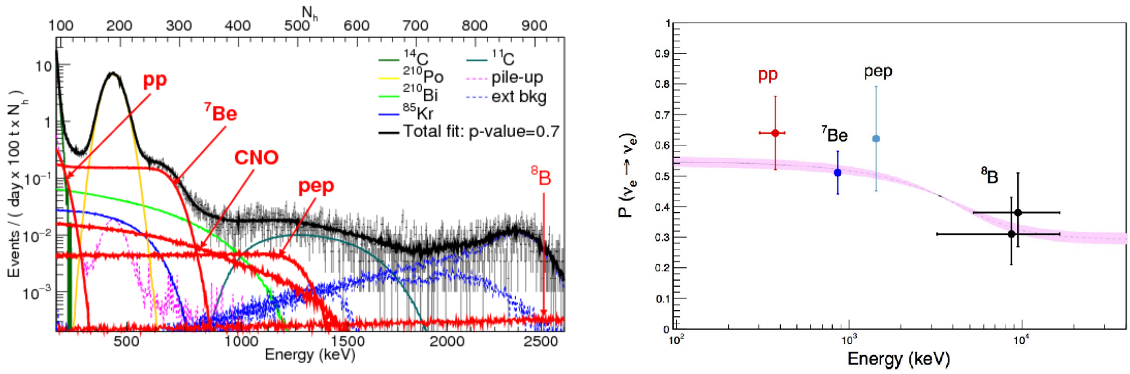
Reactor neutrino experiments based on liquid scintillator detectors measuring ϑ_{13}

Borexino

Liquid scintillator experiment: solar neutrinos (real time measurement of pp neutrinos, ^{7}Be neutrinos) and geoneutrinos



The Borexino detector from Nature 512 (2014) 385



Left: Fit of the neutrino energy spectrum measured by Borexino. Right: Survival probability of electron-neutrinos produced by the different nuclear reactions in the Sun as measured by Borexino. From Nature 512 (2014) 385