FLAVOUR OSCILLATION

- IN HEAVY QUARKS

- IN NEUTRINOS

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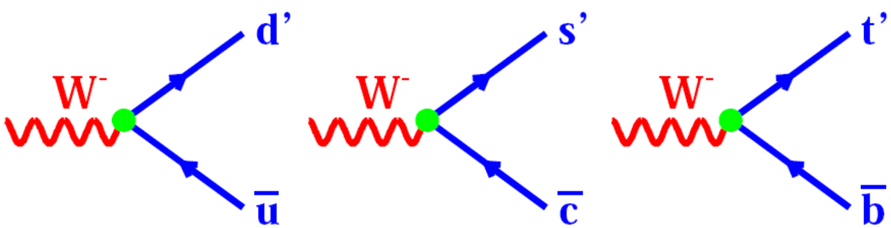
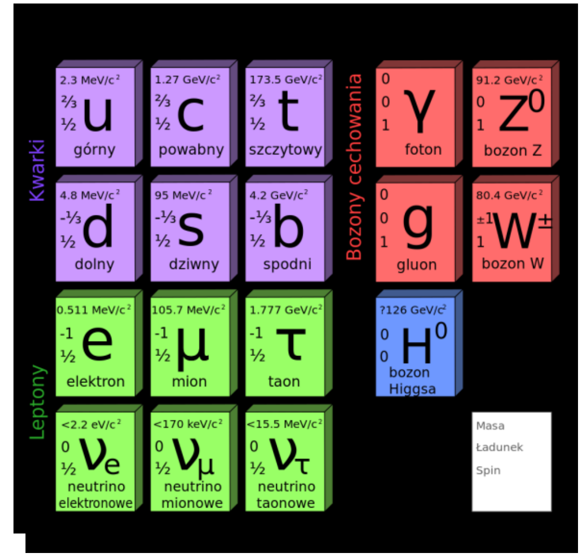
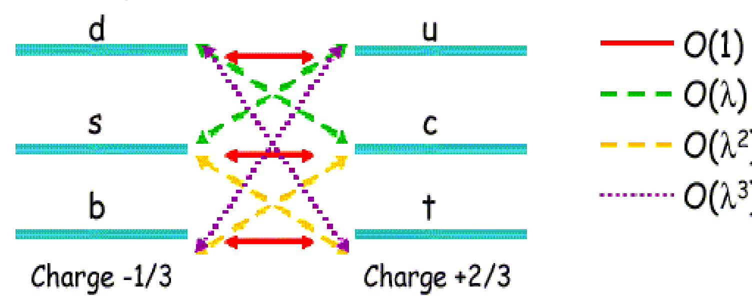
Mass states and weak eigenstates:





$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V_{ckm} \approx \begin{pmatrix} \cos\theta_c & \sin\theta_c & 0.01 \\ -\sin\theta_c & \cos\theta_c & 0.05 \\ 0.01 & -0.05 & 1 \end{pmatrix}$$



Strange kaons

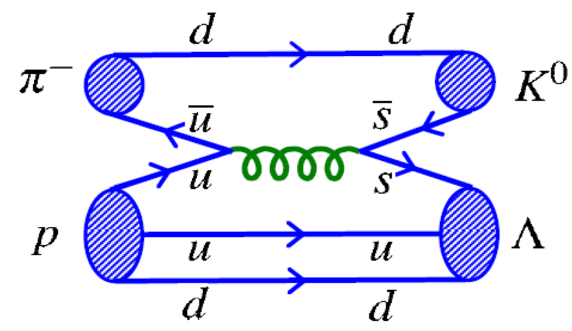
$|K^0\rangle \equiv |\bar{s}d\rangle$ and $|\bar{K}^0\rangle \equiv |\bar{d}s\rangle$

- Kaons are strange mesons produced in strong interactions (pion beam hitting a target):

  $\pi^- + p \to \Lambda^0 + K^0$

  $\pi^+ + p \to K^+ + \bar{K}^0 + p$

  $\pi^- + p \to \bar{\Lambda}^0 + \bar{K}^0 + n + n$



- Neutral kaons are produced in the strong interactions with well defined strangeness, i.e., as eigenstates of the $\mathcal{S}$ operator.

$$\mathcal{S}|K^0\rangle = +1|K^0\rangle, \mathcal{S}|\bar{K}^0\rangle = -1|\bar{K}^0\rangle$$

- Strangeness is conserved in strong interaction (check it!).
- $K^0(\bar{s}d)$ is an antiparticle of $\bar{K}^0(\bar{d}s)$ but they are distinguishable by strong interaction.

  $\bar{K}^0 + p \to \Sigma^+ + \pi^+ + \pi^-$ $\quad$ $K^0 + p \not\to \Sigma^+ + \pi^+ + \pi^-$

  $\bar{K}^0 + p \to \Lambda^0 + \pi^+ + \pi^0$ $\quad$ $K^0 + p \not\to \Lambda^0 + \pi^+ + \pi^0$

- After production by the strong forces the kaons are unstable and decay – we can measure their lifetimes.
  Since they are antiparticles for each other we expect that their **masses** and **lifetimes** are the same!

$J^P = 0^-$

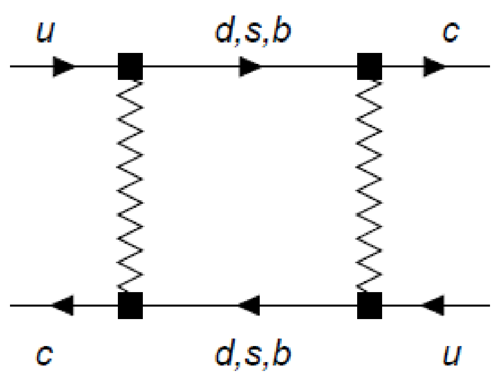
Isospin		
+1	$\overline{K^0}$ $(s\bar{d})$	K^+ $(\bar{s}u)$
-1	K^- $(s\bar{u})$	K^0 $(\bar{s}d)$
	-1	+1 “Strangeness”

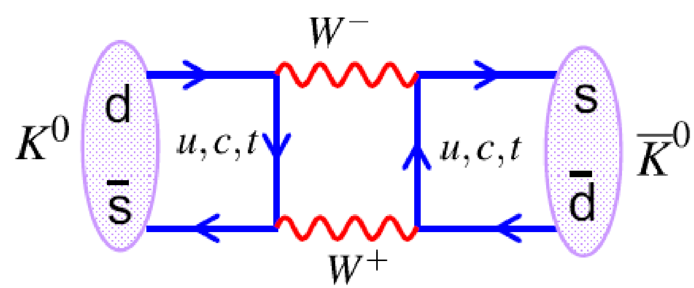
Oscillation of neutral mesons

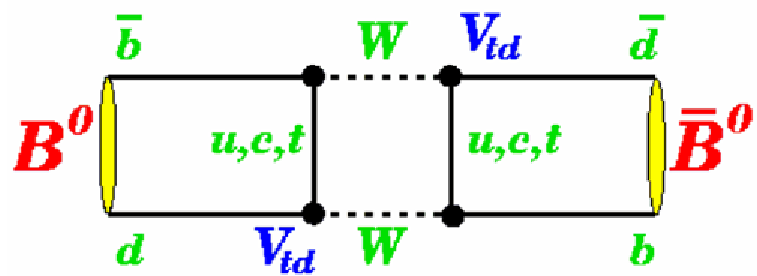
- We can find four P^0 -type mesons and investigate their flavour oscillations: :

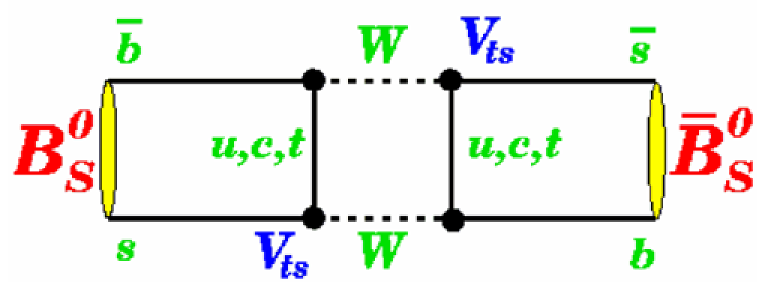
	d	s	b
$\bar{d}$	$\times$	K^0	B^0
$\bar{s}$	$\overline{K^0}$	$\times$	B_s
$\bar{b}$	$\overline{B^0}$	$\overline{B_s}$	$\times$

	u	c	t
$\bar{u}$	$\times$	D^0	$\diamond$
$\bar{c}$	$\overline{D^0}$	$\times$	$\diamond$
$\bar{t}$	$\diamond$	$\diamond$	$\times$









Strange kaons - parity

$|K^0\rangle \equiv |\bar{s}d\rangle$ and $|\bar{K}^0\rangle \equiv |\bar{d}s\rangle$

- Neutral kaons are eigenstate of P but not C nor CP operators:

$$\mathcal{P}|K^0\rangle = -|K^0\rangle \qquad \mathcal{C}|\bar{K}^0\rangle = -|K^0\rangle \qquad \mathcal{CP}|K^0\rangle = -\mathcal{C}|K^0\rangle = -|\bar{K}^0\rangle$$
$$\mathcal{P}|\bar{K}^0\rangle = -|\bar{K}^0\rangle \qquad \mathcal{C}|K^0\rangle = -|\bar{K}^0\rangle \qquad \mathcal{CP}|\bar{K}^0\rangle = -\mathcal{C}|\bar{K}^0\rangle = -|K^0\rangle$$

- But the appropriate linear orthonormal combinations:

$$|K_1^0\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle) \qquad |K_2^0\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle) \qquad \mathcal{CP}(K_1^0) = +1$$

are eigenstates of $\mathcal{CP}$ operator:

$$\mathcal{CP}(K_2^0) = -1$$

$$\mathcal{CP}|K_1^0\rangle = \frac{1}{\sqrt{2}}(\mathcal{CP}|K^0\rangle - \mathcal{CP}|\bar{K}^0\rangle) = \frac{1}{\sqrt{2}}(-|\bar{K}^0\rangle + |K^0\rangle) = \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle) = |K_1^0\rangle$$

- The flavour eigenstates K^0 and $\bar{K}^0$ are not CP eigenstates, but their combination is!
- Does it have any experimental consequences?

The K_1^0 must decay to 2 pions given CP conservation of the weak interactions.

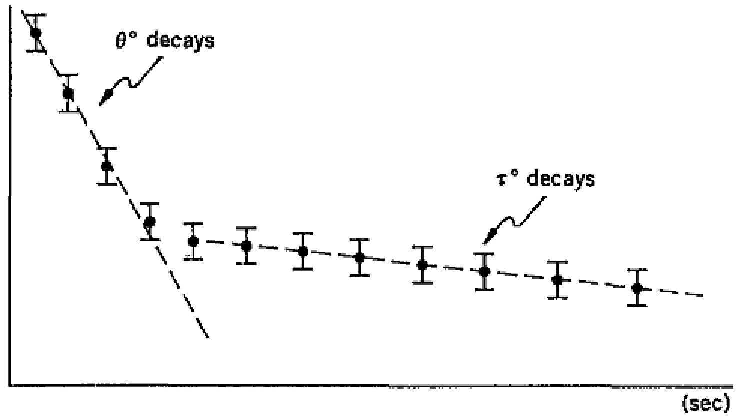
This two pion neutral kaon decay was observed.

K_2^0 must decay to 3 pions if CP is conserved.

$$\mathcal{CP}(\pi^0\pi^0) = [\mathcal{CP}(\pi^0)]^2 = (-1)^2 = +1$$
$$\mathcal{CP}(\pi^0\pi^0\pi^0) = (-1)^3 = -1$$

Strange kaons- the $\theta - \tau$ puzzle

- In 1949 C.F Powell discovered in cosmic rays:
  - pions,
  - two particles θ^0, τ^0 with the same mass and lifetimes but different modes of decay to two and three pions:



$$\theta^0 \to \pi^0 + \pi^0$$

$$\theta^0 \to \pi^+ + \pi^-$$

$$\tau^0 \to \pi^0 + \pi^0 + \pi^0$$

$$\tau^0 \to \pi^+ + \pi^- + \pi^0$$

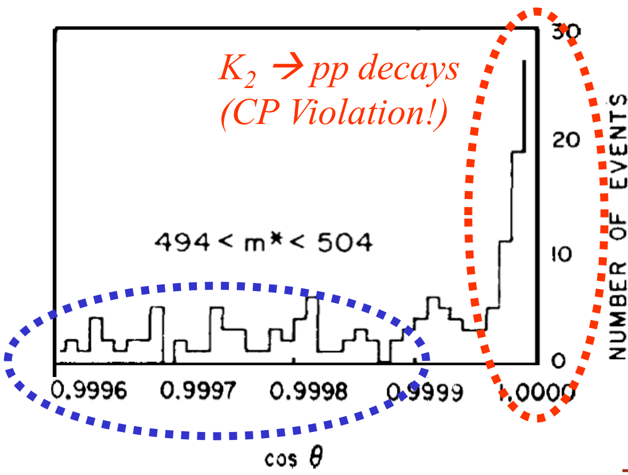
- If this is the same particle than CP is not conserved in weak interaction (confirmed by Wu experiment)
- Together with the info from the previous slide:

$$\theta^0 \to K_1^0 \quad \text{and} \quad \tau^0 \to K_2^0,$$

- CP symmetry is conserved in weak interaction.
- The decay to two particle is more probable, thus K_1^0 should have much shorter time-life,
- In experiment: $\tau_1 \approx 0.9 \times 10^{-10}\ s$ and $\tau_2 \approx 5.0 \times 10^{-8}\ s$.
- So K_1^0 was called K_S^0, K_2^0 is K_L^0 (short and long).

Strange kaons –plan for CP violation

- If we see decays of K_1^0 to three pions decays of K_2^0 to two pions – CP symetry is violated.
- The Cronin & Fitch experiment:



$K_2 \rightarrow ppp$ decays

$$K_2^0 \rightarrow \pi^+ + \pi^- + X$$

$p_{+-} = p_{\pi+} + p_{\pi-}$

θ = angle between p_{K2} and p_{+-}

If $X = 0$, $p_{+-} = p_{K2}$: $\cos\theta = 1$

If $X \neq 0$, $p_{+-} \neq p_{K2}$: $\cos\theta \leq 1$

$$\frac{K_L^0 \rightarrow \pi^+ + \pi^-}{K_L^0 \rightarrow anything} \approx 2.0 \times 10^{-3}$$

Nobel prize 1980:

"The discovery emphasizes, once again, that even almost self evident principles in science cannot be regarded fully valid until they have been critically examined in precise experiments."

- Very tiny effect!
- Weak interactions violate CP at the level of ~0.05%.
- But the P parity was violated almost at 100% - maximal violation of P because absence of right-handed neutrino…

Strange kaons – strangeness oscillation

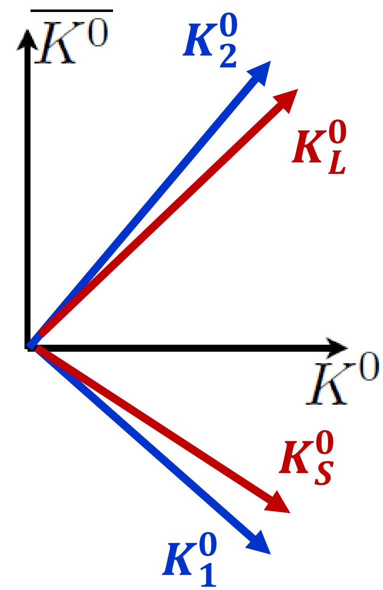
$$|K^0_{1,2}\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle \mp |\bar{K}^0\rangle)$$

- Neutral kaons were produced as flavour state: $K^0, \bar{K}^0$
- They decay via weak interaction.
- If CP is conserved in weak interaction: $(K^0, \bar{K}^0) \rightarrow (K^0_1, K^0_2)$, K^0_1, K^0_2 are CP e-states.
- But precise measurement showed that CP is violated,
- The violation effect is small so this would be a hint that these new states are almost identical to K^0_1, K^0_2:

$$|K^0_S\rangle = \frac{1}{\sqrt{(1+|\epsilon|^2)}}\left(|K^0_1\rangle + \epsilon|K^0_2\rangle\right)$$

$$|K^0_L\rangle = \frac{1}{\sqrt{(1+|\epsilon|^2)}}\left(|K^0_2\rangle + \epsilon|K^0_1\rangle\right)$$

simply K^0_2 has a small admixture of K^0_1…



$|\epsilon| \ll 1$ $\quad$ ϵ represents deviation of K^0_S and K^0_L from true CP e-states (in general this is complex number!)

- Let's find the degree CP is violated:

$$\mathcal{CP}|K^0_S\rangle = \cdots \neq |K^0_S\rangle \qquad \mathcal{CP}|K^0_L\rangle = \cdots \neq |K^0_L\rangle$$

Strange kaons – strangeness oscillation

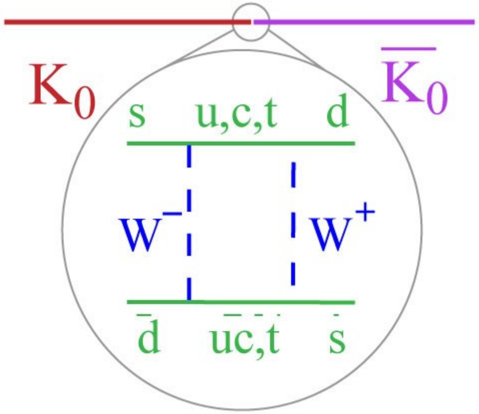
$$|K^0_{1,2}\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle \mp |\bar{K}^0\rangle)$$

- Neutral kaons were produced as flavour state: $K^0, \bar{K}^0$
- They decay via weak interaction.
- But - since $|K^0_2\rangle$ is a mixture of $|K^0\rangle$ and $|\bar{K}^0\rangle$ states, even starting from pure $|K^0\rangle$ (or $|\bar{K}^0\rangle$) state we end up with a mixture of states of different strangeness (this so-called „**flavour oscillations**")

$$|K^0_S\rangle = \frac{1}{\sqrt{(1+|\epsilon|^2)}}\left(|K^0_1\rangle + \epsilon|K^0_2\rangle\right)$$

$$|\epsilon| \ll 1$$

$$|K^0_L\rangle = \frac{1}{\sqrt{(1+|\epsilon|^2)}}\left(|K^0_2\rangle + \epsilon|K^0_1\rangle\right)$$



$$|K^0\rangle = \frac{1}{\sqrt{2}}\left(|K^0_1\rangle + |K^0_2\rangle\right) \qquad |\bar{K}^0\rangle = -\frac{1}{\sqrt{2}}\left(|K^0_1\rangle - |K^0_2\rangle\right)$$

Time evolution of neutral mesons

1. In the absence of mixing, meson $\boldsymbol{K^0}$ can decay into all, allowed by energy-momentum conservation, states.
2. The exponential decay law leads to the time dependence of the wave function:

$$|\boldsymbol{K^0(t)}\rangle = |\boldsymbol{K^0}\rangle\, \underbrace{\boldsymbol{e^{-\frac{\Gamma t}{2}}}}\, \boldsymbol{e^{-imt}}$$

time evolution of a stable state with mass m, $m = E$

total width such that probability of finding an undecayed meson at time t is:

$$|\langle K^0(t)|K^0\rangle|^2 = e^{-\Gamma t}$$

which satisfy the equation:

$$i\frac{\partial}{\partial t}|K^0(t)\rangle = \underbrace{\left(m - \frac{i}{2}\Gamma\right)}_{H}|K^0(t)\rangle$$

3. If $\boldsymbol{K^0}$ can convert into $\overline{\boldsymbol{K^0}}$ through second order mixing diagram, the time evolution of a neutral meson must include both $\boldsymbol{K^0}$ and $\overline{\boldsymbol{K^0}}$:

$$|K^0(t)\rangle = e^{-iHt}|K^0(t=0)\rangle = e^{-iHt}\frac{1}{\sqrt{2}}\left(|K_S^0\rangle + |K_L^0\rangle\right) =$$

$$= \frac{1}{\sqrt{2}}\left[e^{-i\left(m_S - \frac{i\Gamma_S}{2}\right)t}\,|K_S^0\rangle + e^{-i\left(m_L - \frac{i\Gamma_L}{2}\right)t}\,|K_L^0\rangle\right] = \;\ldots = \;\ldots = \;\ldots$$

so let’s be more general: $\boxed{|\boldsymbol{\psi(t)}\rangle = \boldsymbol{a(t)}|\boldsymbol{K^0}\rangle + \boldsymbol{b(t)}|\overline{\boldsymbol{K^0}}\rangle}$

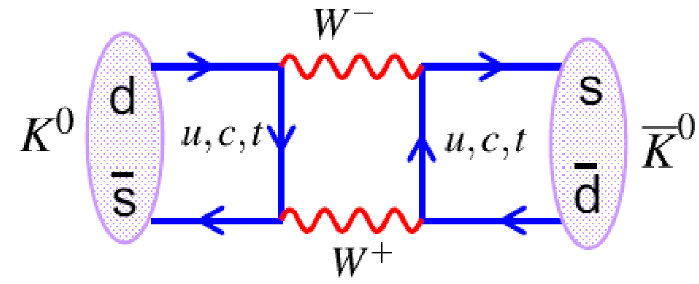
The time evolution of $\boldsymbol{K^0}$: having started the observation with a $\boldsymbol{K^0}$ meson, after some time $\boldsymbol{t}$ we still have $\boldsymbol{K^0}$ or it has oscillated to $\overline{\boldsymbol{K^0}}$

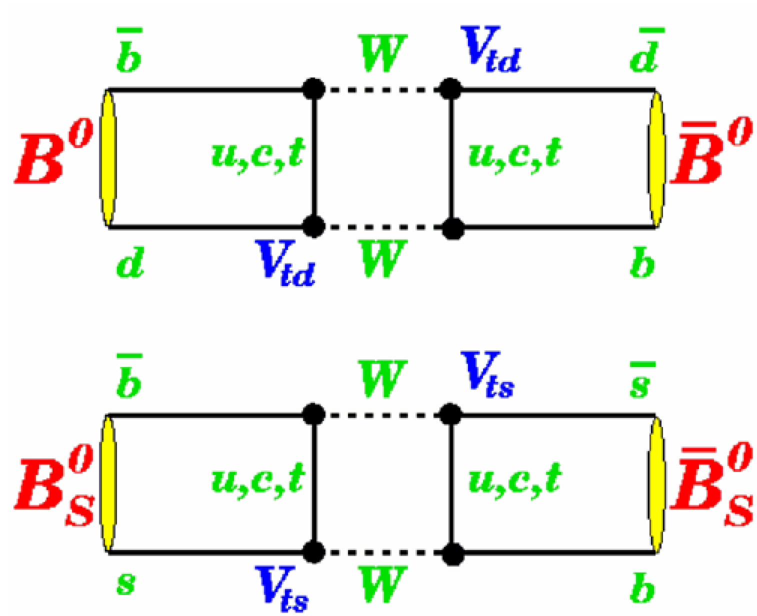
Oscillation of neutral mesons

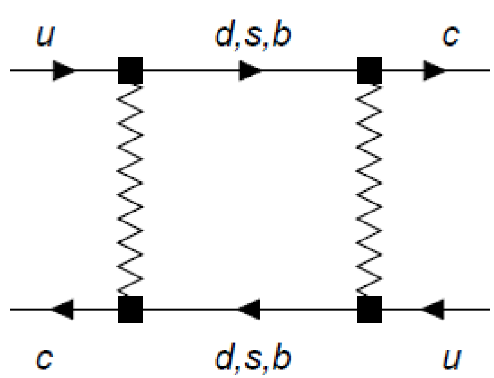
- We can find four P^0 -type mesons and investigate their flavour oscillations: :

	d	s	b
$\bar{d}$	$\times$	K^0	B^0
$\bar{s}$	$\overline{K^0}$	$\times$	B_s
$\bar{b}$	$\overline{B^0}$	$\overline{B_s}$	$\times$

	u	c	t
$\bar{u}$	$\times$	D^0	$\diamond$
$\bar{c}$	$\overline{D^0}$	$\times$	$\diamond$
$\bar{t}$	$\diamond$	$\diamond$	$\times$







- What next? Is there any connection between the flavour oscillation and CP violation?

CPV in weak interaction
Flavour oscillation
→ Matter - antimatter differences seen through weak interaction

Sakharov conditions for matter-antimatter asymmetry of the universe (1967):

1. **There must be a process that violates baryon number conservation.**

   Proton – the lightest baryon should decay, so far this is unobserved, the lifetimes of proton is greater than 10^{35} years.

2. **Both C and CP symmetries should be violated.**

$$\boldsymbol{p \neq \overline{p}}$$

3. **These two conditions must occur in a phase when there was no thermal equilibrium.**

Otherwise $N_{baryons} = N_{\overline{baryons}}$

How to find CP violation?

- Observed One of the simplest way to discover $\mathcal{CP}V$ is to compare the decay rates $\Gamma(P \to f)$ with $\Gamma(\overline{P}) \to \overline{f}$
- This is a method for direct $\mathcal{CP}V$ in decay amplitudes, when two amplitudes with different phases interfere.
- If we define the asymmetry between $\mathcal{CP}$ conjugated decays, for charged and neutral mesons:

$$A_{CP,dir} = \frac{\Gamma\{P \to f\} - \Gamma\{\overline{P} \to \overline{f}\}}{\Gamma\{P \to f\} + \Gamma\{\overline{P} \to \overline{f}\}}$$

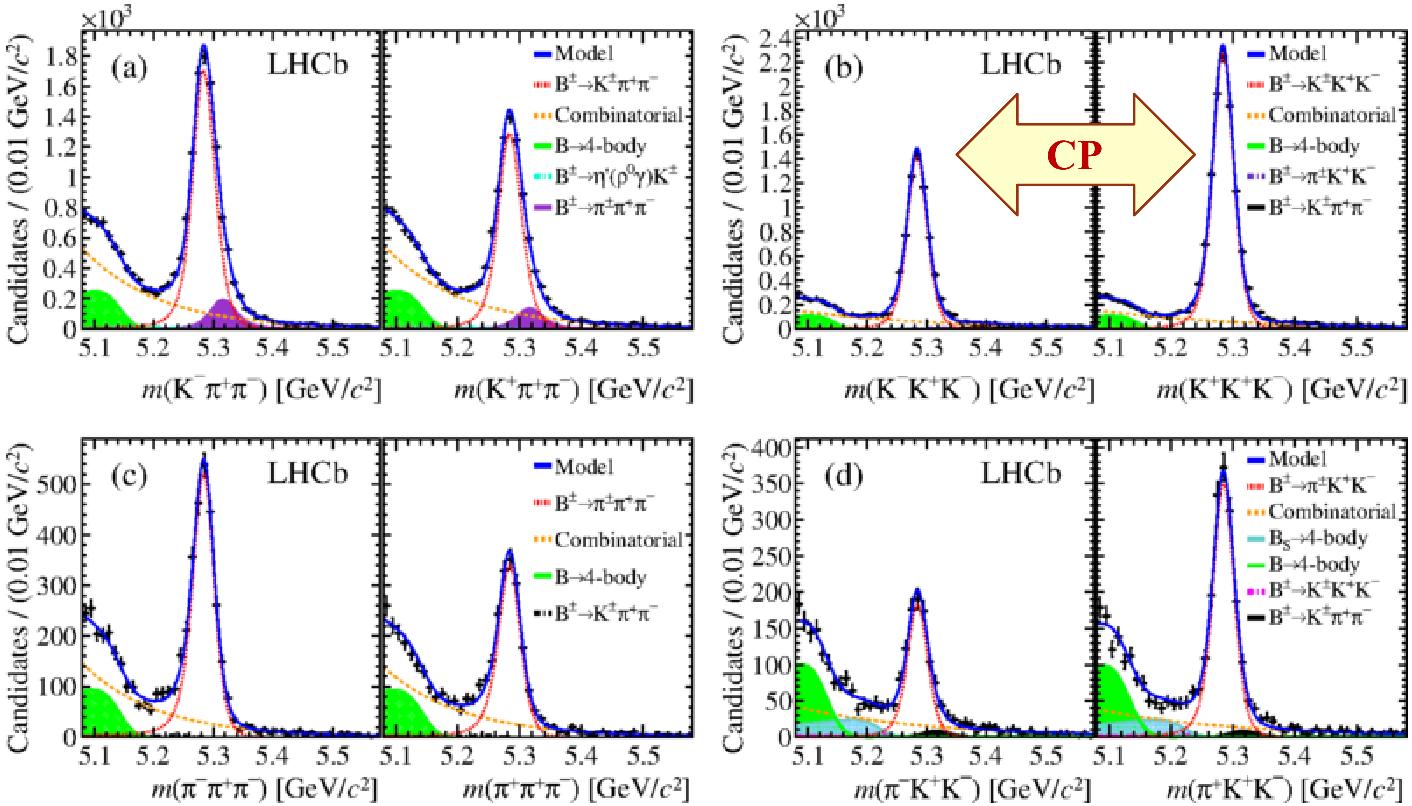
where: $\Gamma(P \to f) \propto |A_f|^2$

- Amplitude A_f is defined as a matrix element that describes the transition between state P and f, such that $P \to f$ depends on: $A_f = \langle f|H|P\rangle$ and $\overline{P} \to f$ on: $\overline{A_f} = \langle f|H|\overline{P}\rangle$

Where we can find CP violation?

$B^+ \to K^- K^+ K^+$

$B^- \to K^- K^+ K^-$



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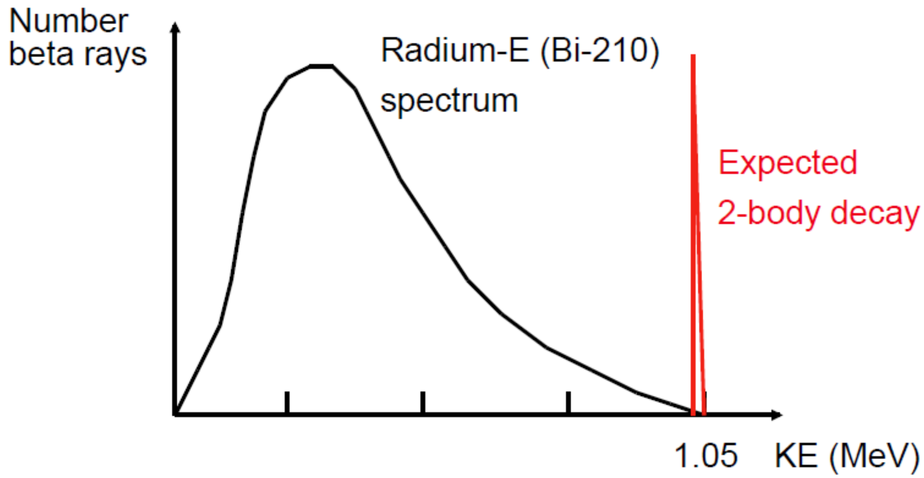
CP violation cont.

- If you are more interested in CP violation in heavy quarks – we have a course of CPV at AGH
- NOW…..

PUZZELS of NEUTRINOS

Puzzles of neutrino

- 1914: discovery of continuous energy spectrum in β decay (Chadwick)



$$n \to p + e^- + \bar{\nu}, \text{ or } \nu + n \to p + e^-$$
$$p \to n + e^+ + \nu, \text{ or } \bar{\nu} + p \to n + e^+$$

- 1930: Pauli proposes the existence of „neutron", particle with half spin and less than 1% of proton mass

"Dear radioactive ladies and gentlemen,
I have hit upon a desperate remedy to save the laws of energy conservation. This is the possibility of the existence in the nucleus of neutral particles…which I will call neutrons…"

Neutrino cross-section

- Cross section calculations (from Fermi theory): $\sigma \approx 10^{-44}\ cm^2$ for $E(\nu) = 2\ MeV$.
- Mean free path in water: $\lambda = \frac{1}{n\sigma} \approx 1.5 \times 10^{21} cm \approx 1600$ light years.

$$n = \frac{N\ of\ prot}{volume} \approx \frac{2N_A}{A}\rho$$

$$\text{in water: } n = \frac{2\times 6\times 10^{23}}{18} = 6.7 \times 10^{22} cm^{-3}$$

- Probabilty of interaction:

$$P = 1 - exp\left(-\frac{L}{\lambda}\right) \cong \frac{L}{\lambda} = 6.7 \times 10^{-20}\ m^{-1}$$

- Only very strong sources of neutrino can be directly detected

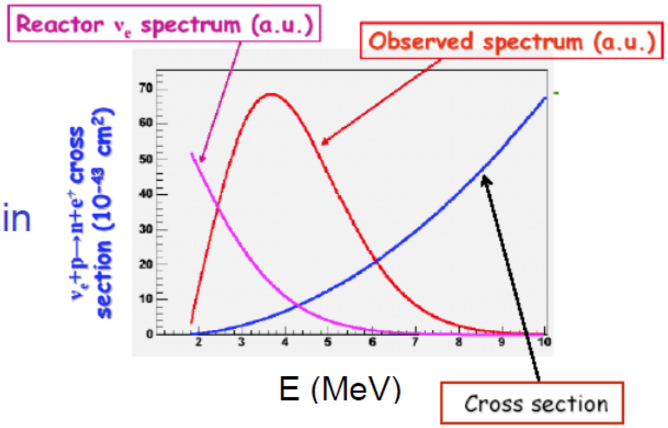
Nuclear reactors: fission of ${}_{92}U^{235}$ produces chain of beta reactions

$$(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}_e \rightarrow (A,Z+2) + e^- + \bar{\nu}_e \rightarrow \ldots$$

On average 6 antineutrinos/fission, 200 MeV average energy per chain

$$N_{\bar{\nu}} = \frac{6P_{th}}{1.6\times 10^{-19} \times 10^{6} \times 200 MeV} \approx 1.9\times 10^{11} P_{th}\ \bar{\nu}/s$$

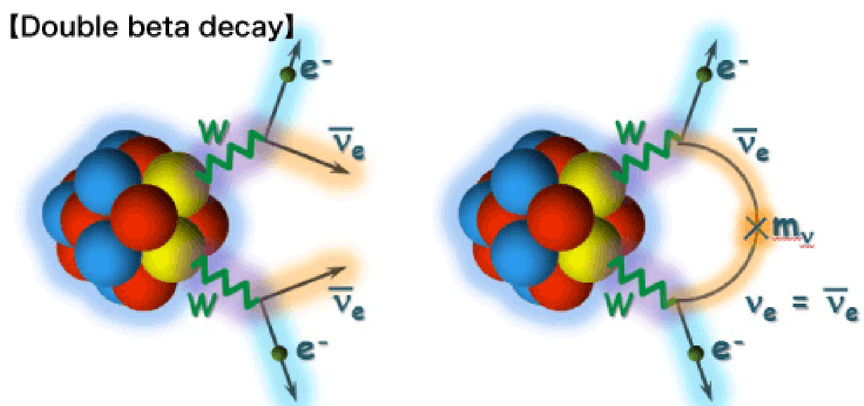
$$P_{th} \approx 3\times 10^{9}\ Watt \Rightarrow N_{\bar{\nu}} \approx 5.6\times 10^{20}\ s^{-1}\ in\ 4\pi$$



Puzzels of neutrino (1)– neutrino mass

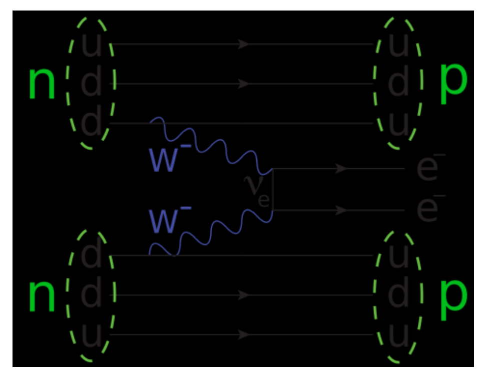
- In the Standard Model, neutrino are assumed to be massless particles described by Dirac equation.
- Dirac neutrinos ($L = 1$): ν_L, ν_R, should have distinct antineutrinos ($L = -1$): $\bar{\nu}_L, \bar{\nu}_R$.
- It is also possible that neutrinos have no distinct antiparticles, so only two states ν_L, ν_R exist with no lepton number (Majorana neutrinos). Majorana neutrinos are completely neutral (no charge, no lepton number) spin 1/2 particles, which are identical to their antiparticles.
- If neutrino has no mass two options cannot be experimentally distinguished and Dirac and Majorana equations are the same.
- If neutrinos are not massless:

  - Majorana neutrinos might be observed in LFV processes,



Double beta decay which emits anti-neutrinos

Neutrinoless double beta decay



The only emitted products in this process are two electrons, which can occur if the neutrino and antineutrino are the same particle

https://wwwkm.phys.sci.osaka-u.ac.jp/en/research/r01.html

Puzzels of neutrino (1)– neutrino mass

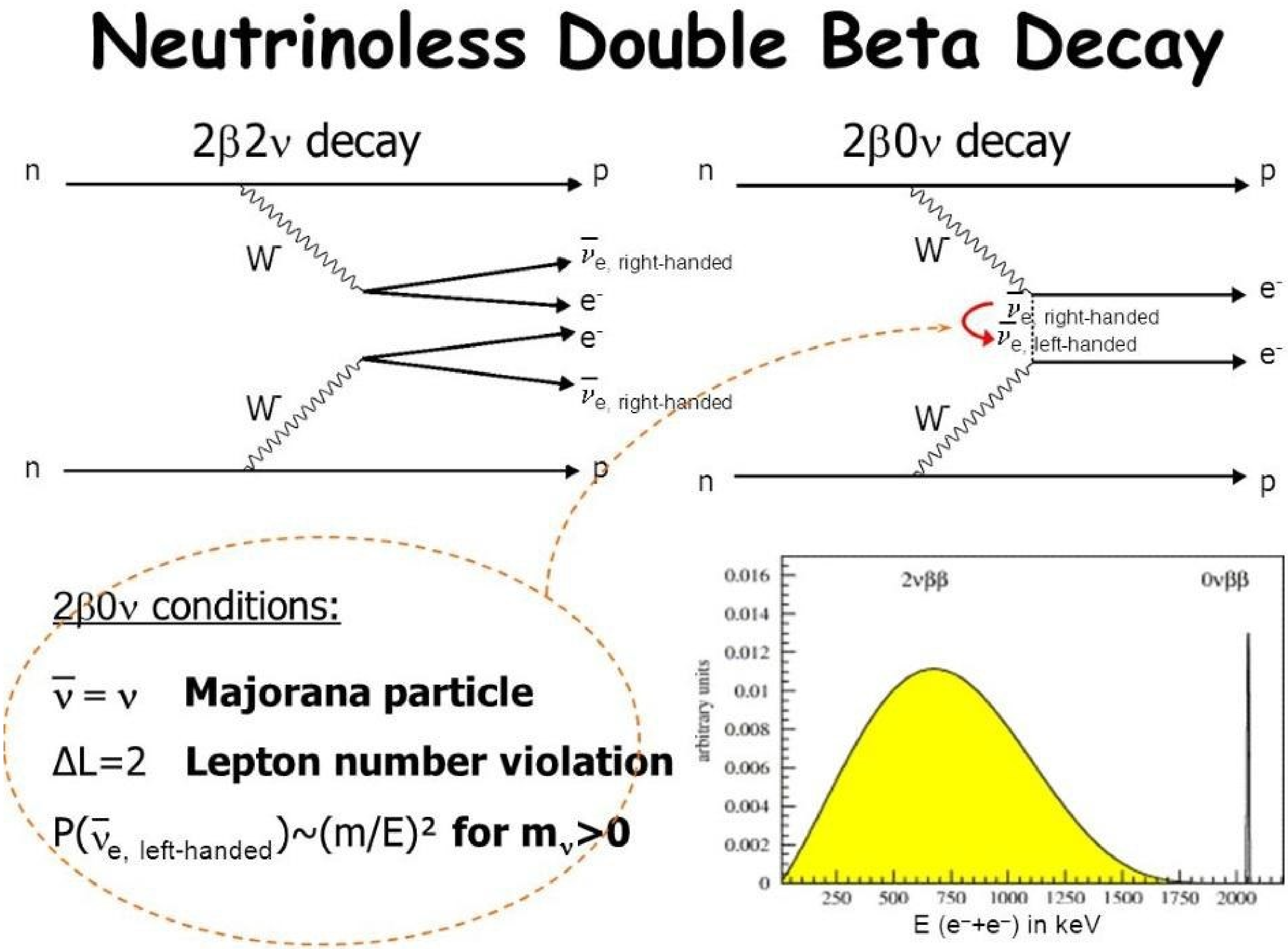


Image credit: Ludwig Niedermeier, Universitat Tubingen / GERDA.

Puzzels of neutrino (2)– neutrino mixing

- if neutrina have mass, they should mix similarly to quarks.
- mixing matrix: PMNS (Pontecorvo, Maki, Nakagawa, Sakata)

❑ Weak eigenstates do not have to coincide with mass eigenstates

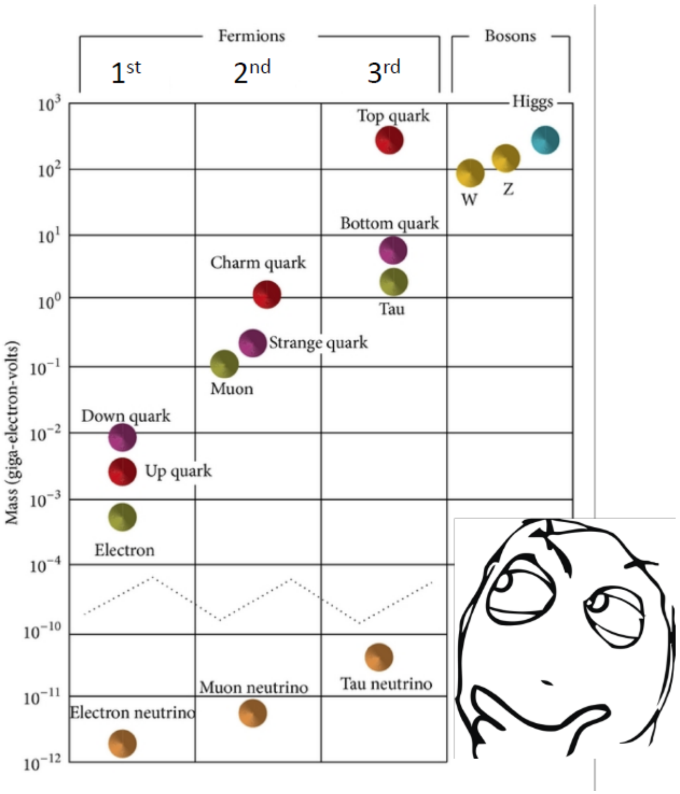
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \Rightarrow U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23}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

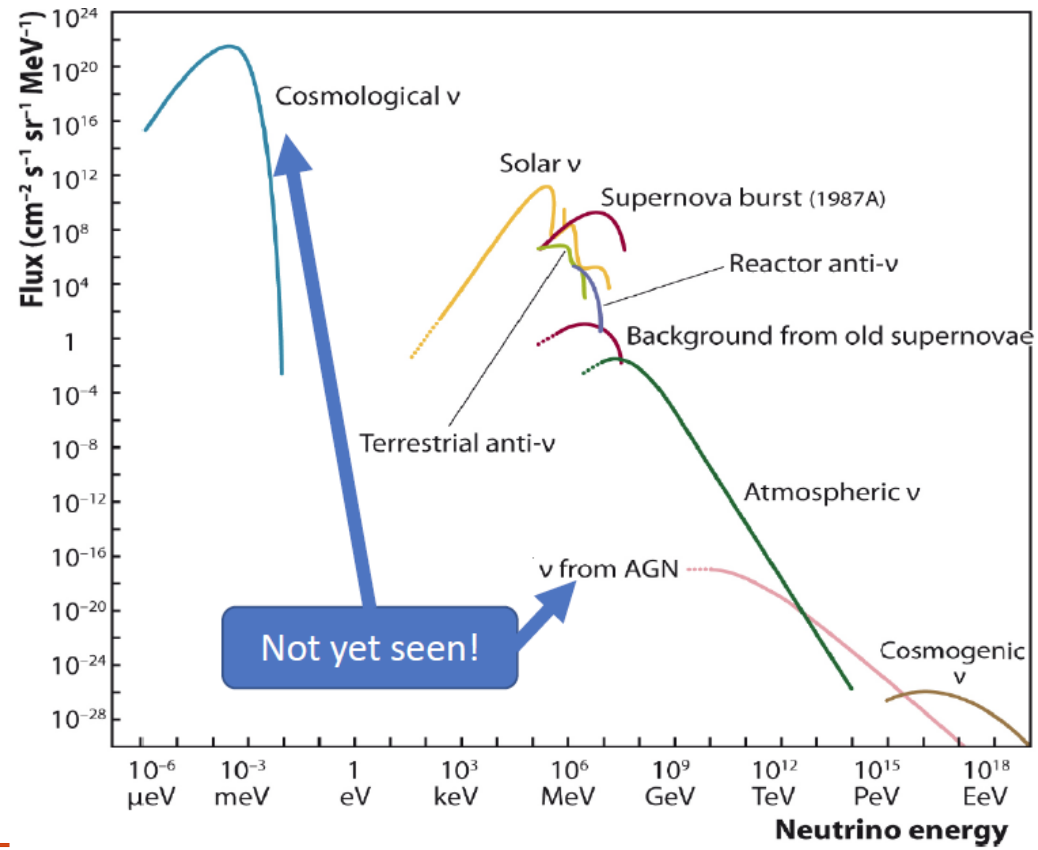
$$where\ c_{ij} = \cos\theta_{ij},\ and\ s_{ij} = \sin\theta_{ij}$$

change of the neutrino flavour is possible if mass is non-zero!

Sources of neutrinos

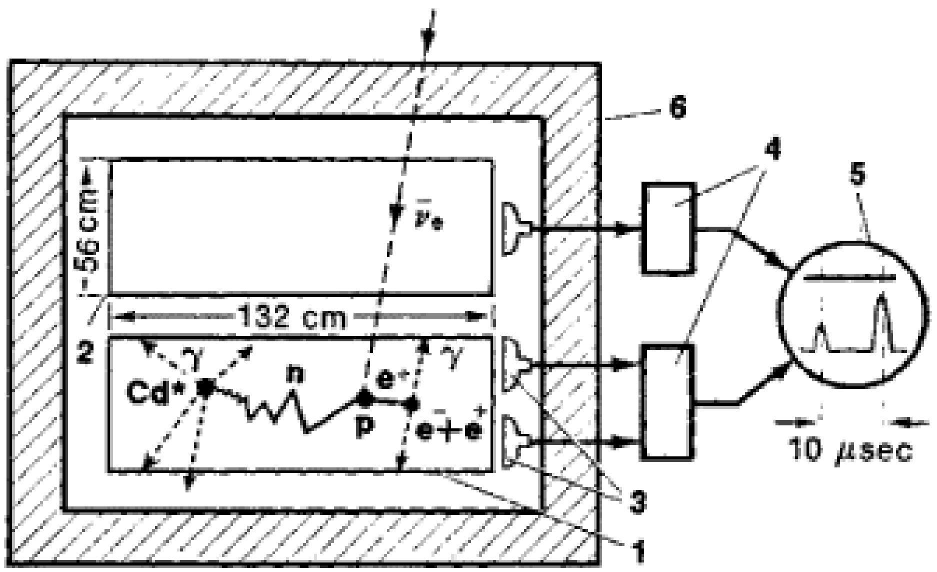
- Natural:
  - Big Bang,
  - stars (Sun),
  - interaction in atmosphere,
  - Erth's crust,
- Human made:
  - nuclear reactors,
  - HEP experiments,

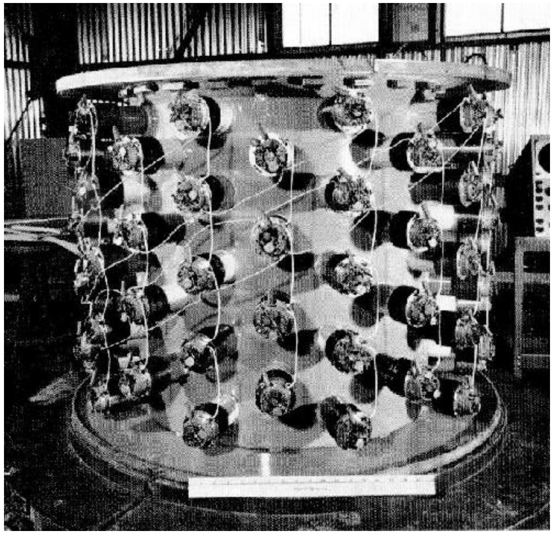




Neutrino discovery 1956

- Neutrino scattering: $\bar{\nu}_e + p \rightarrow n + e^+$ is regarded as neutrino discovery (1953)
- Reines and Cowan experiment:
  - detection of two back-to-back promt γs from $e^+e^- \rightarrow \gamma\gamma$
  - neutron capture in Cd and emission of late photons





In 1995, Frederick Reines was honored with the Nobel Prize for his work on neutrino physics

Muon Neutrino discovery

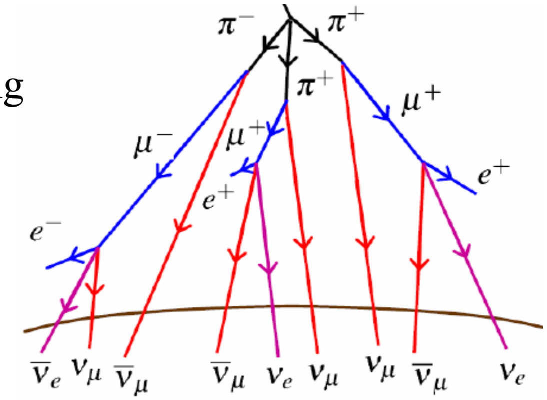
$$\pi^+ \rightarrow \mu^+ + \mu_\nu$$

- Are neutrinos in pion decays the same neutrino as the beta decay neutrinos?
- If yes, then $\mu \rightarrow e\,\gamma$ should be observable
- Lederman, Schwartz, Steinberger: muon neutrinos only are produced in muon processes.
- We have two neutrino flavours!

Steinberger Schwartz Lederman
Nobel Prize 1988

Atmospheric neutrino

- Atmospheric neutrinos are produced from cosmic rays in atmosphere. Protons produce cascades of particles, including pions that decay giving (on average) 2 muon neutrinos for each electron neutrino.



$$\pi^+ \to \mu^+ + \nu_\mu \qquad \tau_\pi = 26\ ns$$

$$\llcorner\ e^+ + \nu_e + \bar{\nu}_\mu \qquad \tau_\mu = 2.2\ \mu s$$

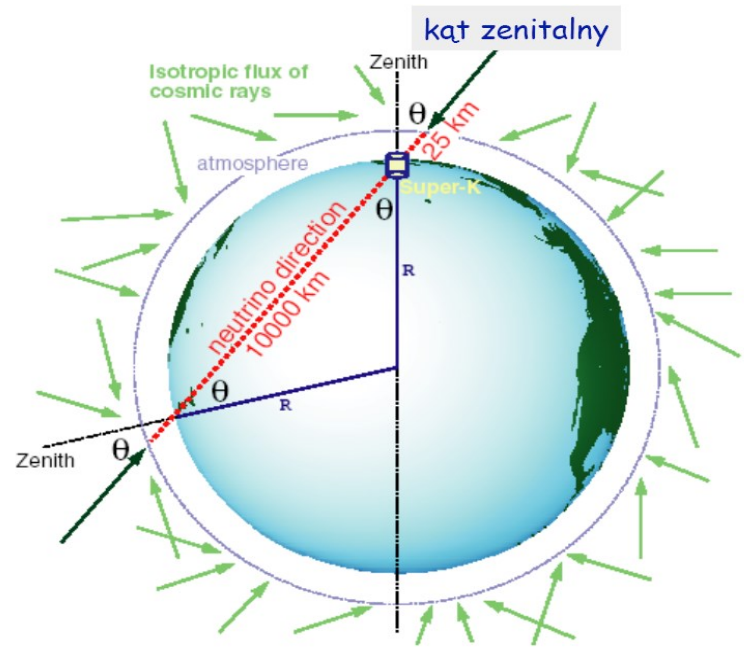
$$\pi^- \to \mu^- + \bar{\nu}_\mu$$

$$\llcorner\ e^- + \bar{\nu}_e + \nu_\mu$$

pions decay,
low E muons decay,
if E_μ~5-6 GeV, they can reach the Earth

$$\boxed{\frac{N(\nu_\mu+\bar{\nu}_\mu)}{N(\nu_e+\bar{\nu}_e)} \approx 2}$$

$$2\ \nu_\mu, 2\overline{\nu_\mu}, 1\nu_e, 1\ \overline{\nu_e}$$



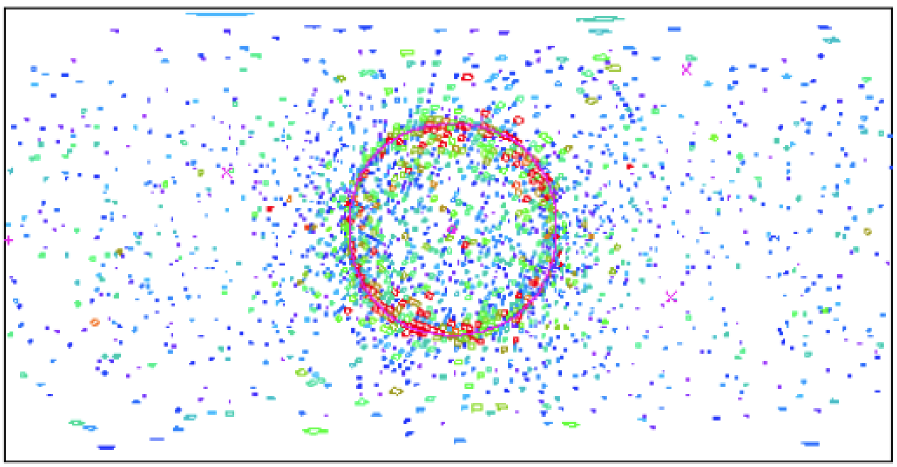
- Cosmic rays should be isotropic: the neutrino flux from the top of planet and bottom should be the same

- Super-Kamiokande detects faint flashes of Cherenkov radiation inside huge tank with 50 000 tons of super clean water.
- Electron neutrino produces electron, muon neutrino – muon in quasi-elastic interactions:

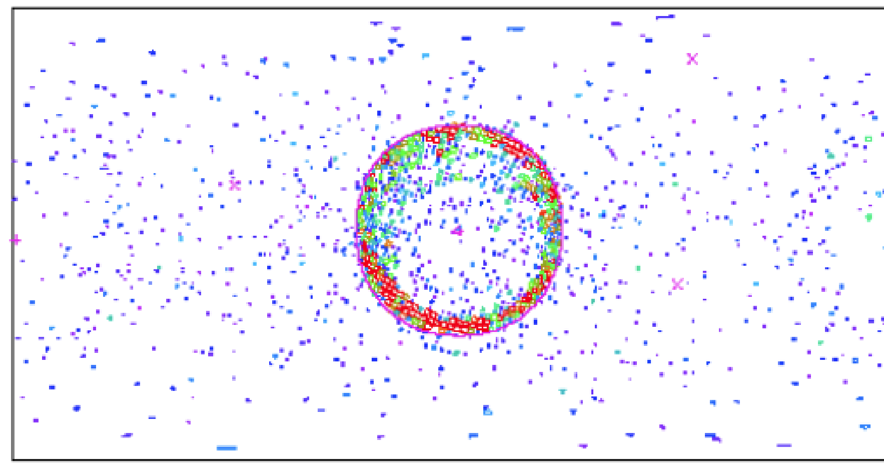
$$\nu_\mu(\nu_e) + n \rightarrow \mu^-(e^-) + p \qquad \bar{\nu}_\mu(\bar{\nu}_e) + p \rightarrow \mu^+(e^+) + n$$

- Electron rings looks different than muon rings (clean edges).

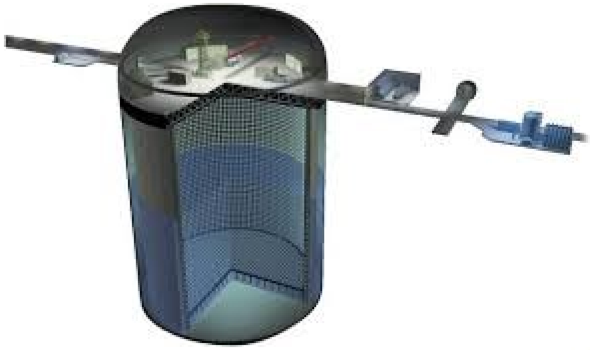
Electron-like

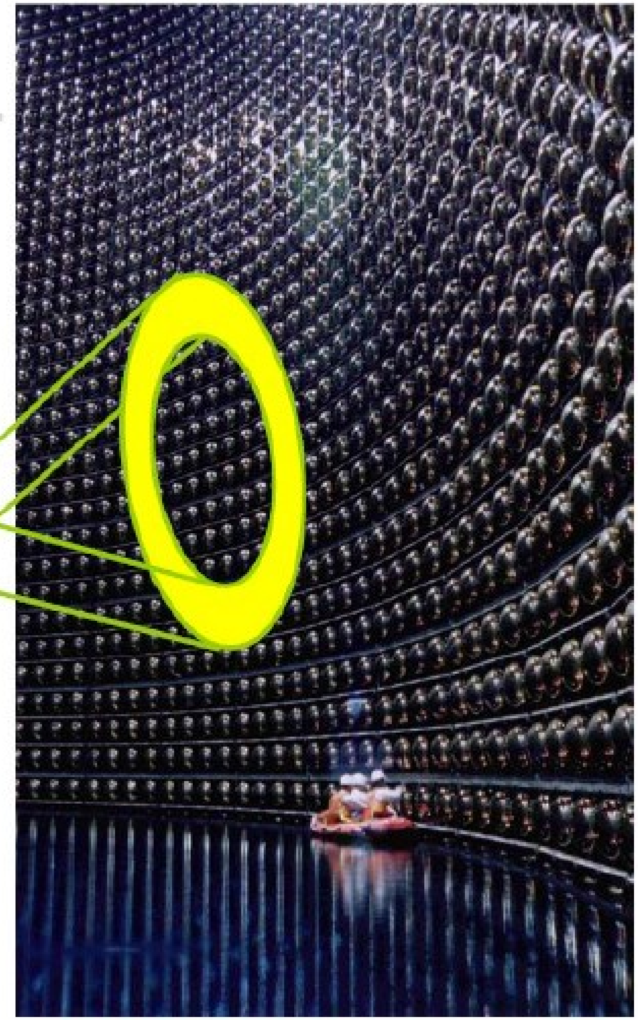


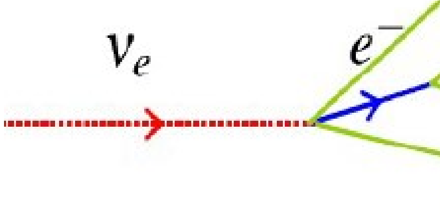
Muon-like

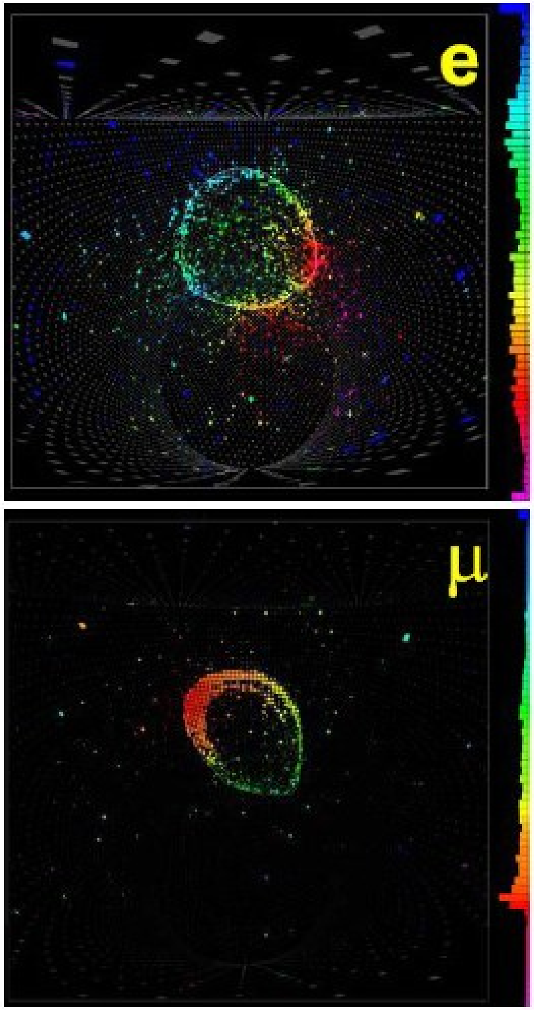


Super-Kamiokande









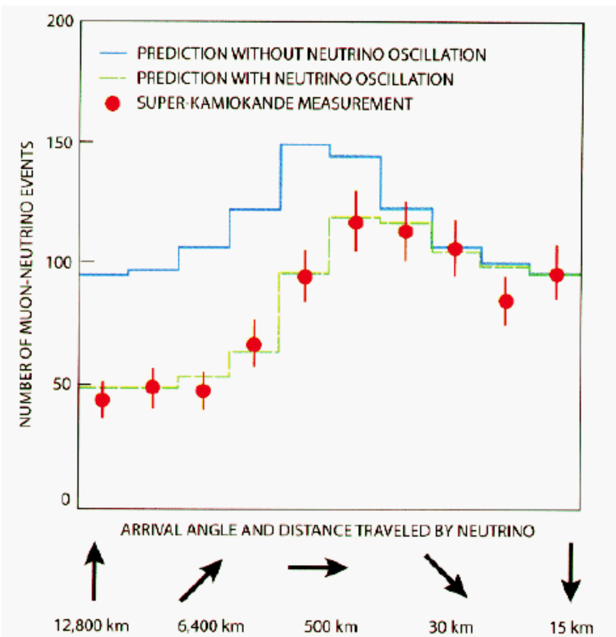
Atmospheric neutrino

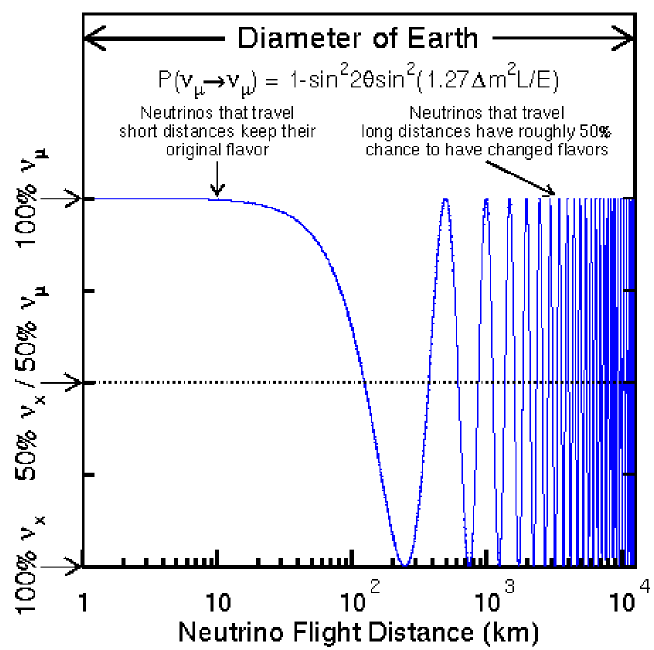
- Ratio of muon-type neutrinos versus electron-type neutrinos is less than expected:

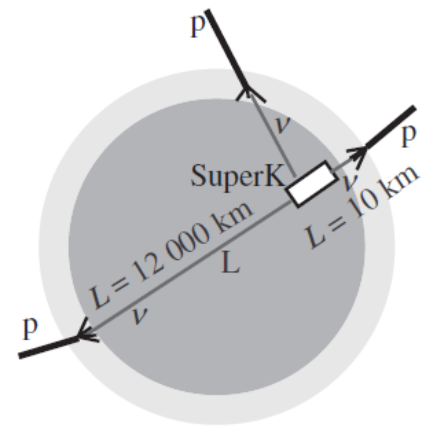
$$R = \frac{(\nu_\mu/\nu_e)\ measured}{(\nu_\mu/\nu_e)\ predicted}$$

$R=0.668^{+0.024}_{-0.023}$ +-0.052

- But, proof of oscillations came from zenith-angle distribution in Super-Kamiokande due to having less muons in the upward direction than in the downward direction.



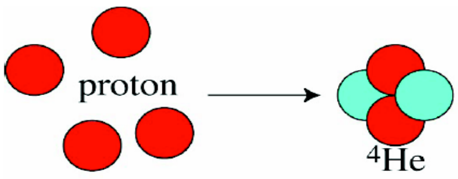




Lack of upward going neutrinos, while upward-going electron neutrinos slightly higher than expected: proof of neutrino oscillations!

Solar neutrinos

- Solar energy from thermonuclear reaction:



$$+2e^{+} + 2\nu_e + 25\ MeV$$

only electron neutrinos!
energy about 0.5 MeV

$$\Phi_\nu = 2 \cdot 10^{38}/s$$

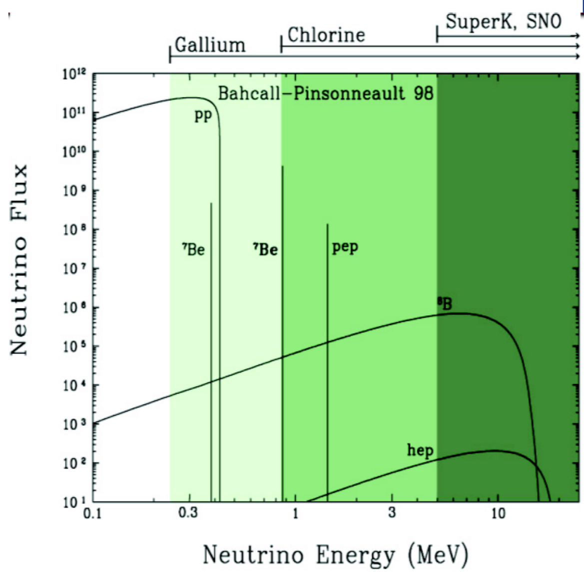
REACTION	TERM. (%)	ν ENERGY (MeV)
$p+p \rightarrow {}^2H+e^{+}+\nu_e$	(99.96)	≤ 0.423
or		
$p+e^{-}+p \rightarrow {}^2H+\nu_e$	(0.44)	1.445
${}^2H+p \rightarrow {}^3He+\gamma$	(100)	
${}^3He+{}^3He \rightarrow \alpha+2p$	(85)	
or		
${}^3He+{}^4He \rightarrow {}^7Be+\gamma$	(15)	
${}^7Be+e^{-} \rightarrow {}^7Li+\nu_e$	(15)	0.863 90% 0.385 10%
${}^7Li+p \rightarrow 2\alpha$		
or		
${}^7Be+p \rightarrow {}^8B+\gamma$	(0.02)	
${}^8B \rightarrow {}^8Be^{*}+e^{+}+\nu_e$		< 15
${}^8Be^{*} \rightarrow 2\alpha$		
or		
${}^3He+p \rightarrow {}^4He+e^{+}+\nu_e$	(0.00003)	< 18.8

Neutrino terminations from BP2000 solar model. Neutrino energies include solar corrections: J. Bahcall, Phys. Rev. C, 56, 3391 (1997).

- Detection in radiochemic reactions

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

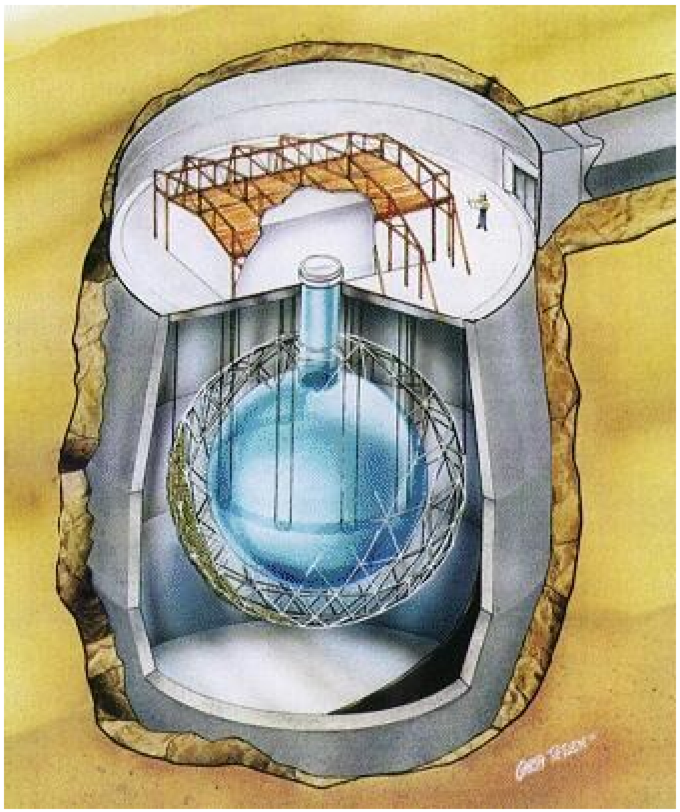
$$\nu_e + {}^{71}Ga \rightarrow e^{-} + {}^{71}Ge$$

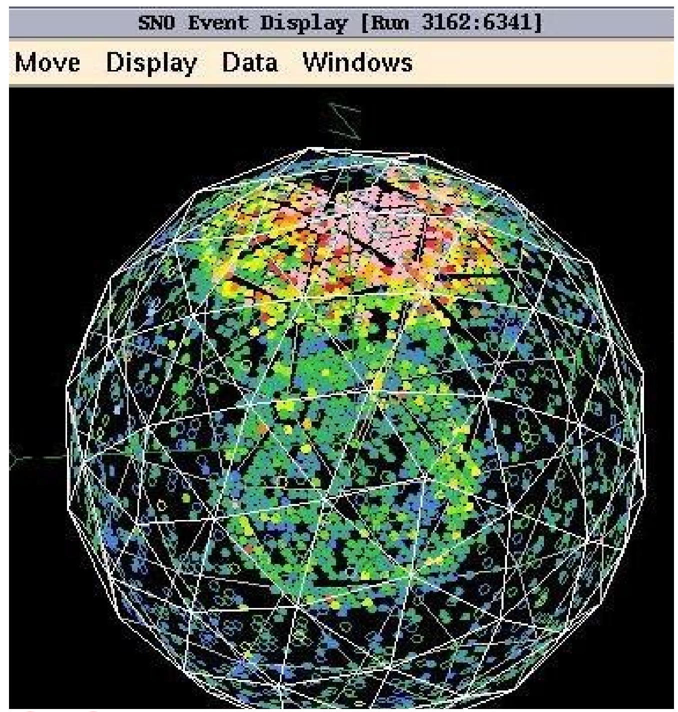


Solar neutrinos

- Detection in radiochemical reactions (isotopes are removed and counted),
- Prediction: 1.7 neutrinos per day
- Measured: 0.48
- No information about time and direction of the neutrino arrival.

The Sudbury Neutrino Observatory (SNO)





SNO Results:

$$\phi(\nu_e) = (1.8 \pm 0.1) \times 10^{-6}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

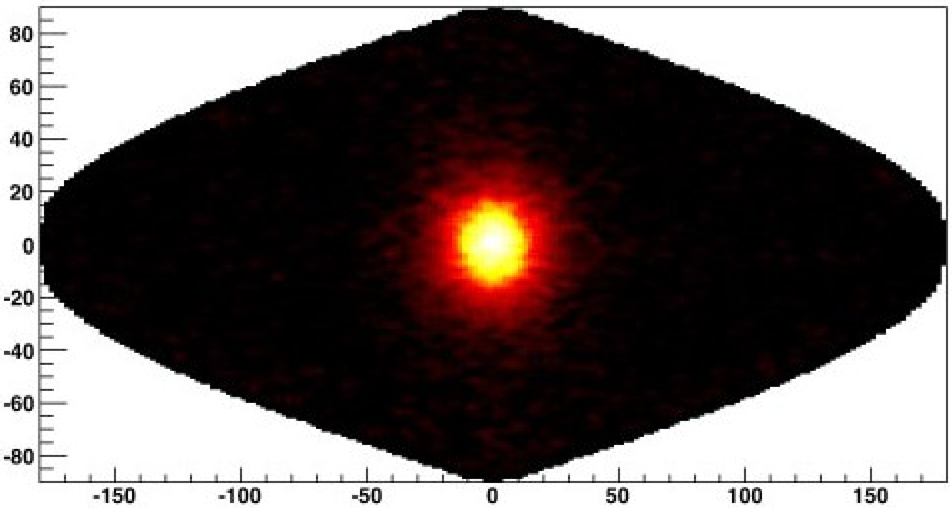
$$\phi(\nu_\mu) + \phi(\nu_\tau) = (3.4 \pm 0.6) \times 10^{-6}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

SSM Prediction:

$$\phi(\nu_e) = 5.1 \times 10^{-6}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

Super-Kamiokande and solar neutrinos

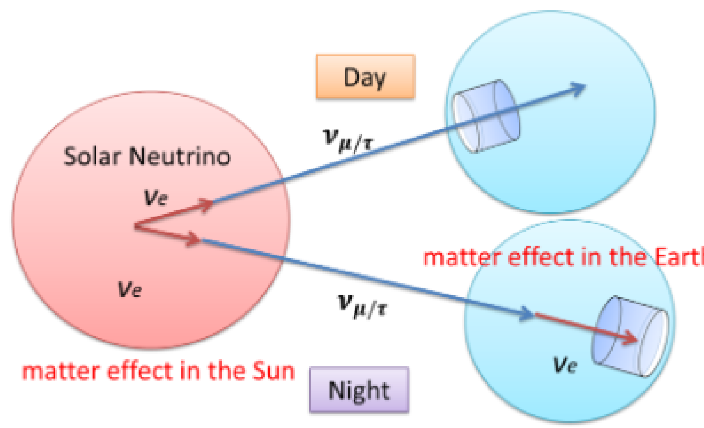
The Sun seen with neutrinos in SK



It will take about 100,000 years to appear the heat, generated by the fusion reaction in the center of the Sun, on the solar surface. On the other hand, solar neutrinos, born in the center of the Sun, will arrive in approximately 8 minutes to Earth, since neutrinos are very hard to interact. In other words, we see 10 million years ago solar activity in the light, but in the neutrino we are able to observe the current activities of the center of the Sun.

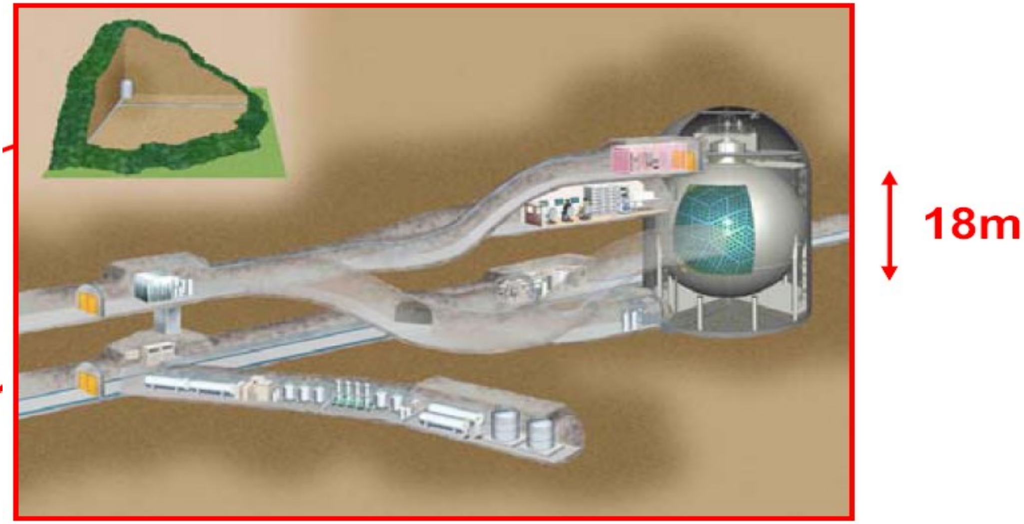
R. Davis during 30 years of research: the observed production rate was about 1/3 of the expected value from Standard Solar Model (SSM).

In June 2000, Super-Kamiokande has reported the observation result of the solar neutrino flux with a highest accuracy than ever before. As a result, the observed solar neutrino flux was about 45% of the expected flux in SSM with more than 99.9% confidence level, suggesting the solar neutrino problem was caused by a neutrino oscillation.



$$A_{\mathrm{DN}} = \frac{\Psi_{\mathrm{day}} - \Psi_{\mathrm{night}}}{(\Psi_{\mathrm{day}} + \Psi_{\mathrm{night}})/2}$$

Reactor neutrino

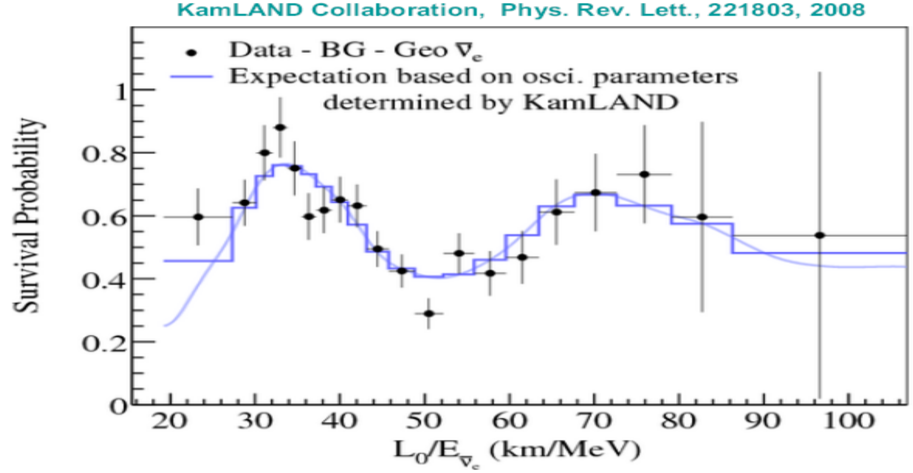


KamLAND RESULTS:

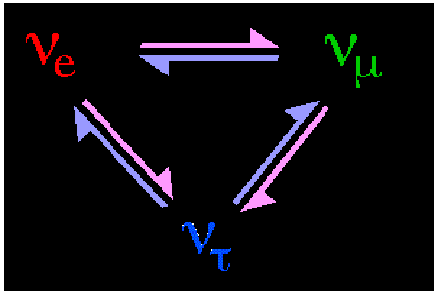
Observe: 1609 events

Expect: 2179±89 events (if no oscillations)

KamLAND Collaboration, Phys. Rev. Lett., 221803, 2008



Neutrinos – the interpetation



- Flux of electron and muon neutrinos created in the atmosphere: ν_e, ν_μ
- Underground experiments observe:

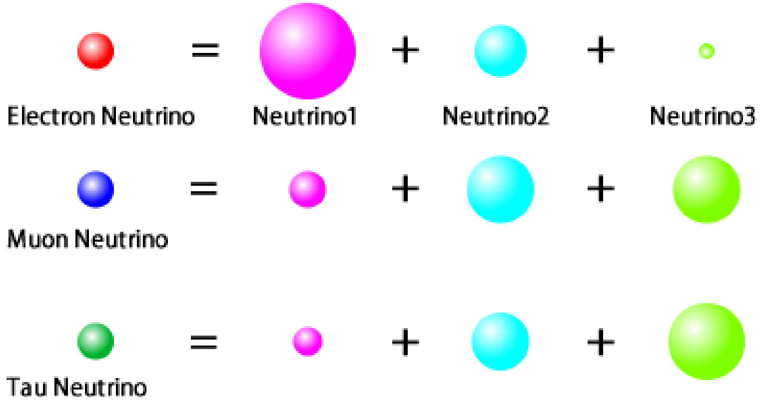
  ν_e: in agreement with expectation,

  ν_μ: too low,

  ν_τ ??
- Neutrino changed flavour during flight on large distances or while interaction with matter.
- Lepton flavour violation (LPV).
- Discovery of the neutrino oscillation (1998).
- Flux of solar ν_e observed as: ν_e, ν_μ, ν_τ $\boxed{\nu_e \rightarrow \quad a\nu_\mu + b\nu_\tau}$

All puzzles of neutrinos can be explained if we introduce neutrino mixing:

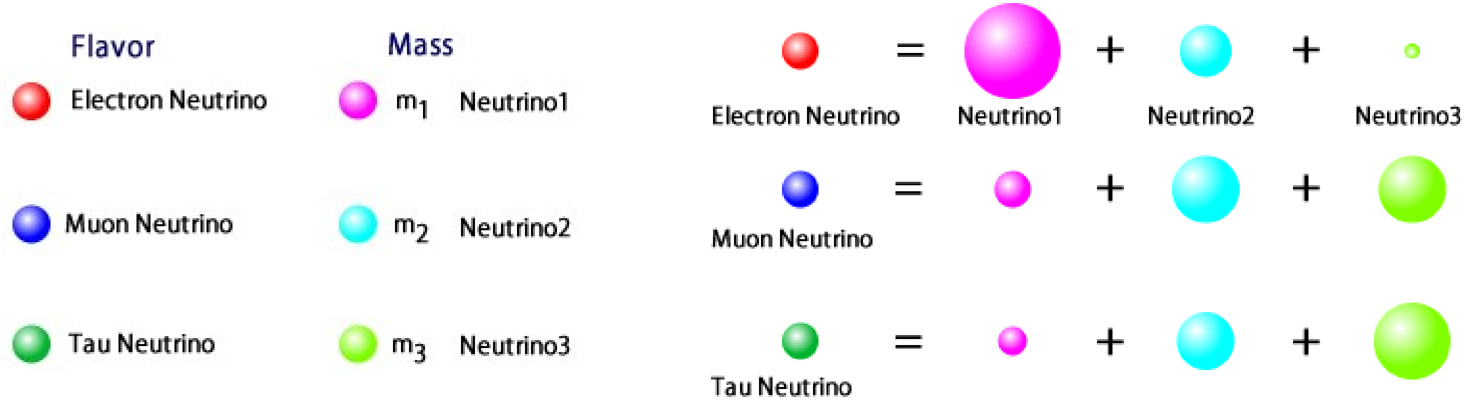
$$\begin{bmatrix} \nu_e & \nu_\mu & \nu_\tau \end{bmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$



Neutrinos – the interpetation of mixing

Mixing is not possible for massless particles.
Mixing may occur then mass states are diffrent than the flavour states:

$\nu_e \quad m_1$
$\nu_\mu \quad m_2$
$\nu_\tau \quad m_3$



Neutrinos are produced in weak interaction (flavour states) but propagate as mass eigenstates.
Flavour states are mix of mass states.

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

Neutrinos oscillation

$$m_1(t) = m_1(0)e^{-iE_1 t}$$
$$m_2(t) = m_2(0)e^{-iE_2 t}$$

- The relations m_1/m_2 changes during flight:

$$\nu(t,x) = m_1(t,x)\cos\theta + m_2(t,x)\sin\theta$$

- Probability of transition ν_1 to ν_2:

$$P(\nu_1 \rightarrow \nu_2) = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2 L}{E_\nu}\right)$$

  neutrino flavour is an oscillation function of time and flight distance.

- Parameters: mass difference $\Delta m^2 = m_1^2 - m_2^2[eV^2]$ and mixing angle θ.

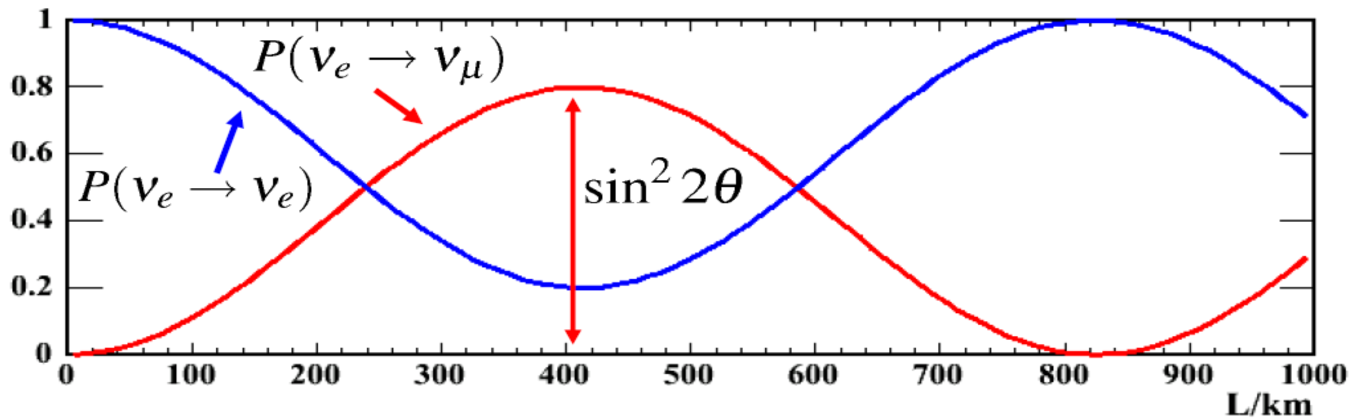
- Oscillation is possible if:

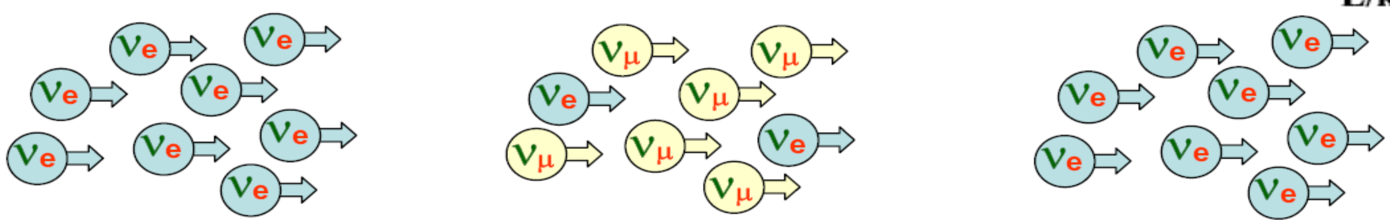
  at least one state has non zero mass,

  all states have diffrent masses,

  factor: $1.27\ \Delta m^2 L/E_\nu$ is about one. It means that if Δm is small, we need to have huge distances to make observations.

Neutrinos – mixing





$$\boxed{P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)}$$

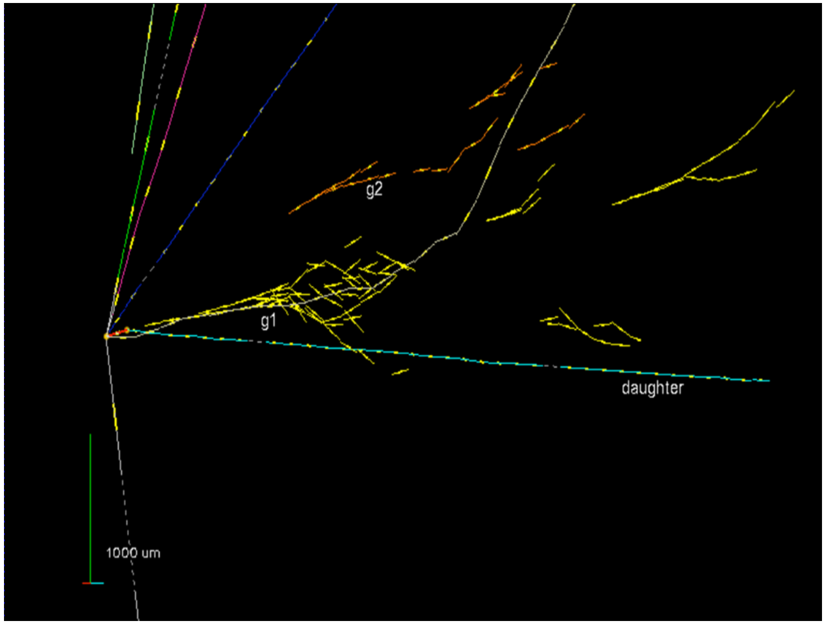
$$\boxed{P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)}$$

$$\Delta m^2_{\text{solar}} \approx 8 \times 10^{-5}\,\text{eV}^2,\ \sin^2 2\theta_{\text{solar}} \approx 0.85$$

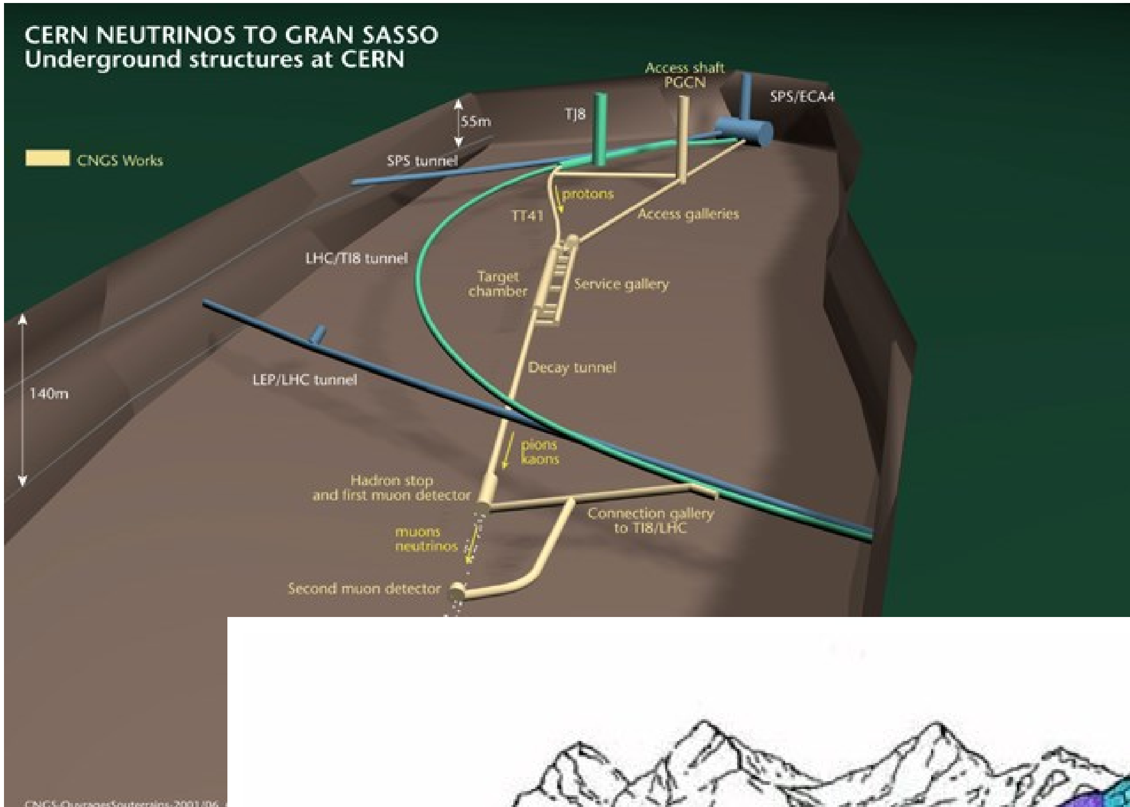
$$\Delta m^2_{\text{atmos}} \approx 2.5 \times 10^{-3}\,\text{eV}^2,\ \sin^2 2\theta_{\text{atmos}} > 0.92$$

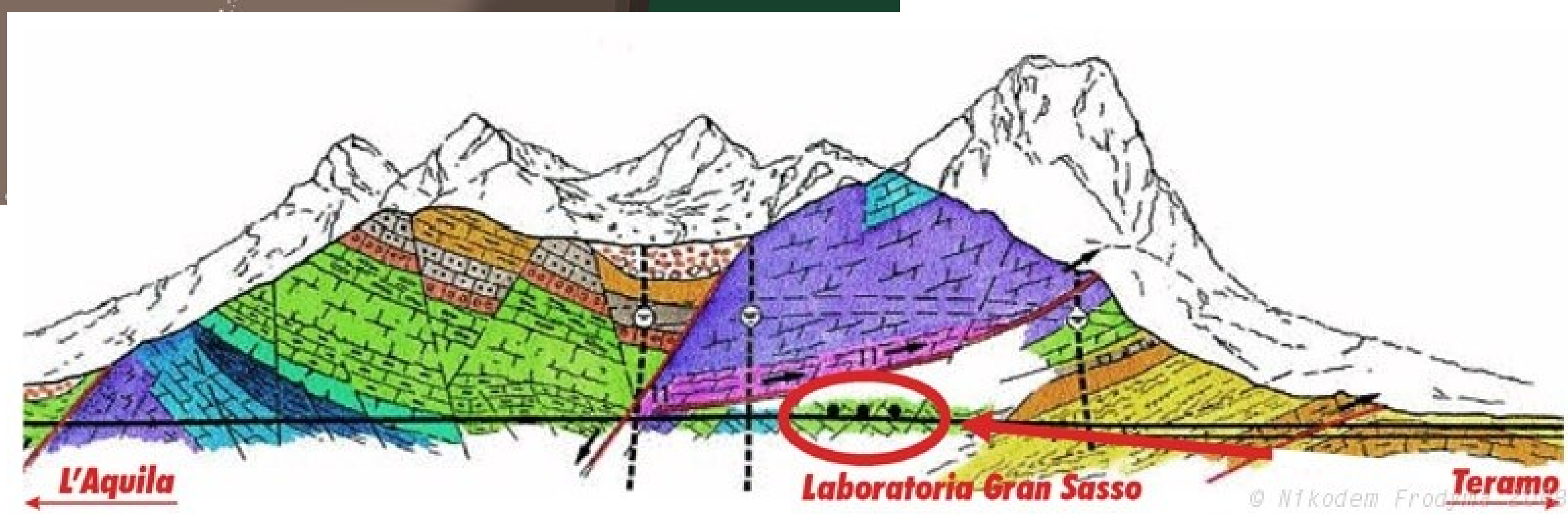
Tau Neutrinos – the discovery

- 31 maja 2010 w detektorze OPERA ogłoszono, że znaleziono neutrino taonowe w wiązce neutrin mionowych.
- Detektor OPERA znajduje się w podziemnym Laboratorium Gran Sasso. W jego stronę wysyłane są neutrina mionowe produkowane w CERN (w odległości 732 km).
- W wyniku oscylacji neutrin w wiązce tej mogą pojawić się neutrina innych zapachów, podobnie jak przy oscylacjach neutrin atmosferycznych.
- Neutrina atmosferyczne mają zbyt niską energię, by w oddziaływaniu wytworzyć taon (znacznie cięższego "kuzyna" elektronu), którego pojawienie się świadczy o obecności neutrin taonowych. Wiązka neutrin z CERN ma natomiast dostatecznie dużą energię.
- Ponieważ taon bardzo szybko się rozpada, do zobaczenia jego śladu potrzebny jest detektor o bardzo dobrej przestrzennej zdolności rozdzielczej. W OPERZE wykorzystano w tym celu emulsje jądrowe - specjalne rodzaj "klisz"

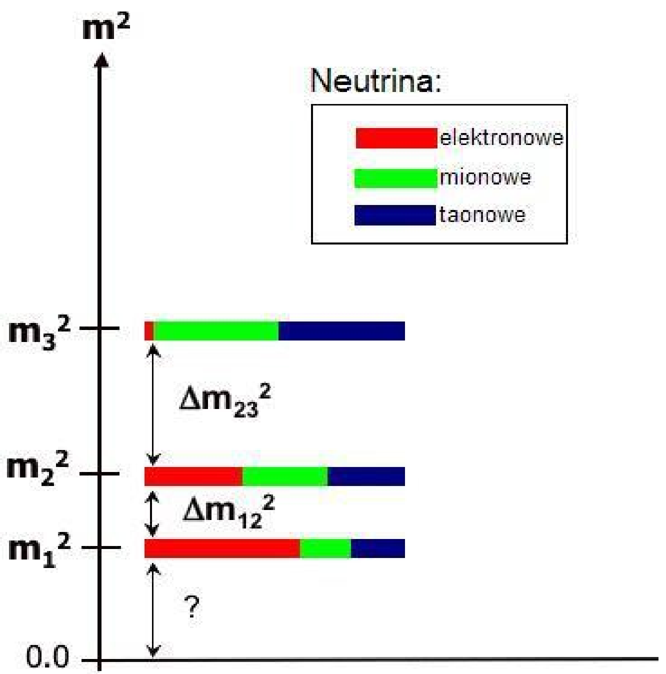


CERN Neutrinos





Neutrinos - summary



SOLAR Neutrinos/KamLAND

KamLAND + Solar: $|\Delta m^2_{21}| \approx (7.6 \pm 0.2) \times 10^{-5}\,\mathrm{eV}^2$

SNO + KamLAND + Solar: $\tan^2\theta_{12} \approx 0.47 \pm 0.05$

$\rightarrow$ $\boxed{\sin\theta_{12} \approx 0.56; \qquad \cos\theta_{12} \approx 0.82}$

Atmospheric Neutrinos/Long Baseline experiments

MINOS: $|\Delta m^2_{32}| \approx (2.4 \pm 0.1) \times 10^{-3}\,\mathrm{eV}^2$

Super Kamiokande: $\sin^2 2\theta_{23} > 0.92$

$$\boxed{\cos\theta_{23} \approx \sin\theta_{23} \approx \frac{1}{\sqrt{2}}}$$

CHOOZ + (atmospheric)

$$\boxed{\sin^2\theta_{13} < 0.06}$$

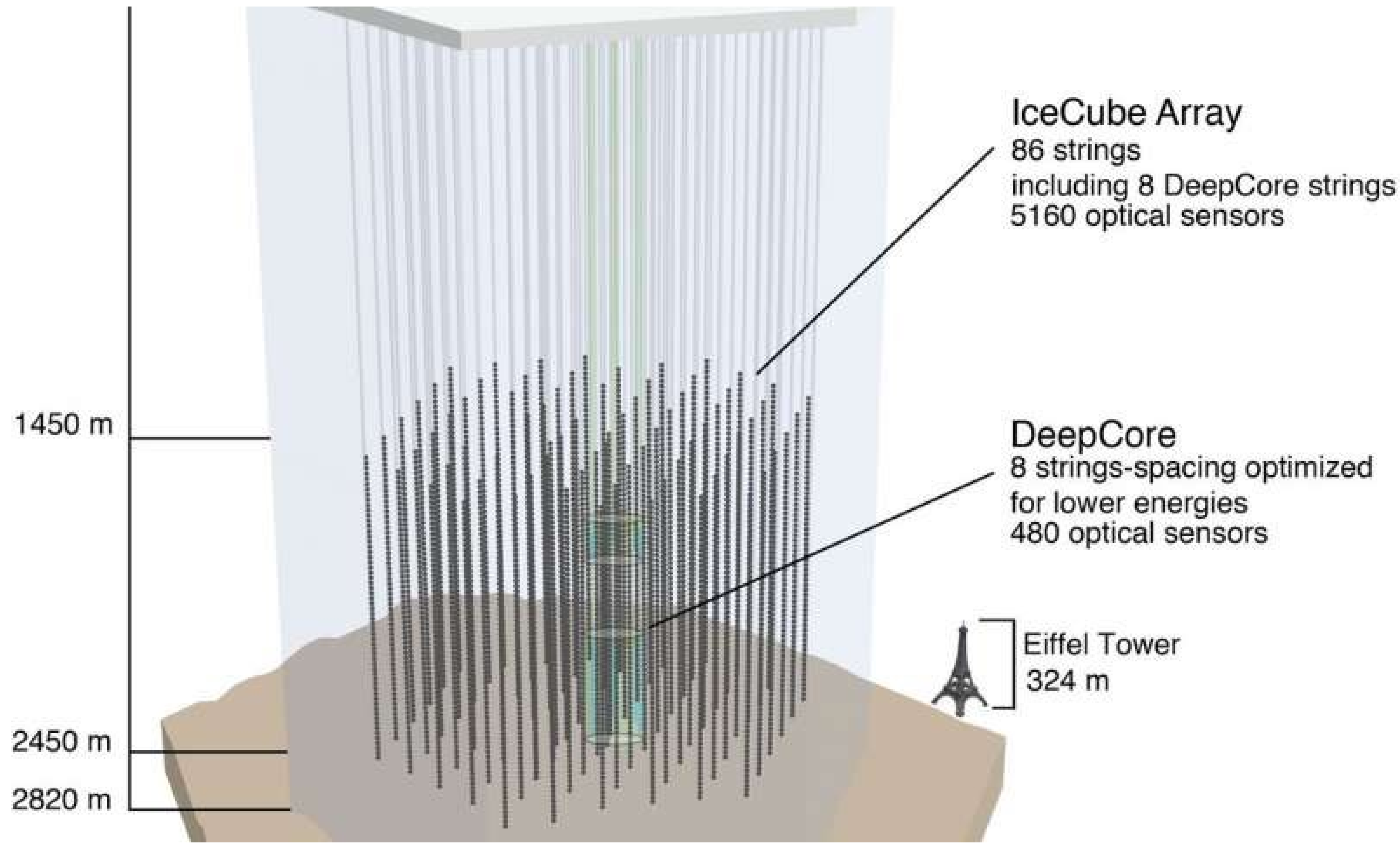
$$|\nu_3\rangle \approx \frac{1}{\sqrt{2}}(|\nu_\mu\rangle + |\nu_\tau\rangle)$$

$$|\nu_2\rangle \approx 0.53|\nu_e\rangle + 0.60(|\nu_\mu\rangle - |\nu_\tau\rangle)$$

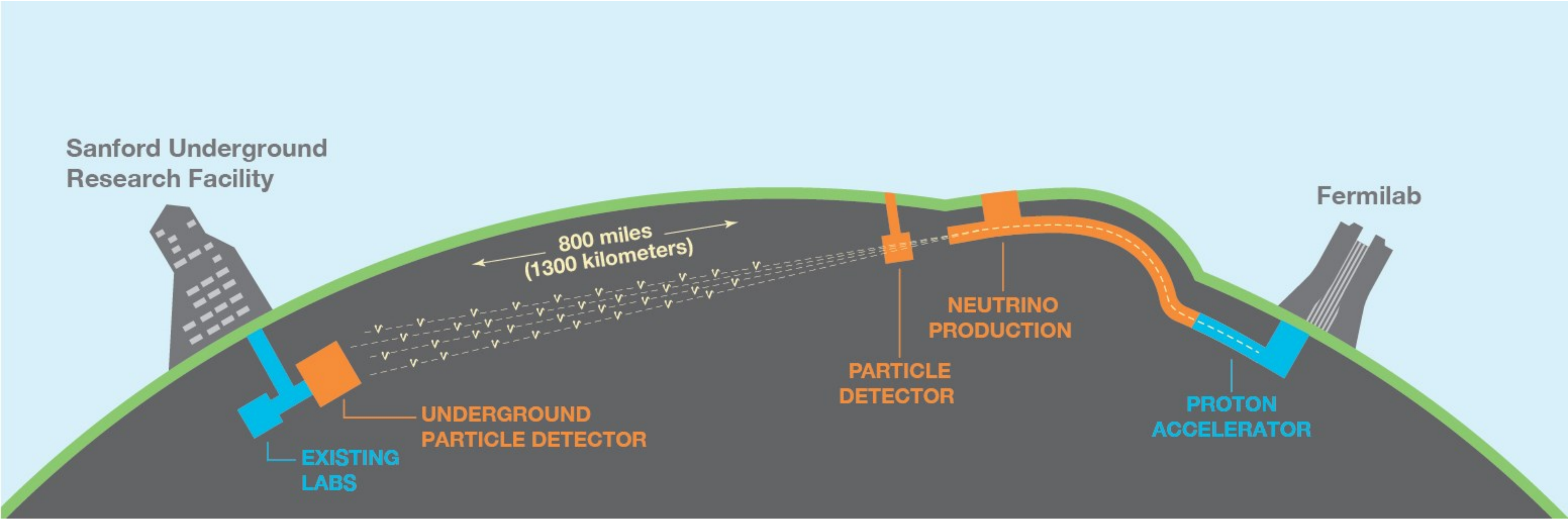
$$|\nu_1\rangle \approx 0.85|\nu_e\rangle - 0.37(|\nu_\mu\rangle - |\nu_\tau\rangle)$$

Fizyka neutrin to obecnie bardzo „modny” kierunek.
W ciągu 10 lat pokazano, że neutrina mają masę i mogą oscylować.
Wciąż wiele niepewności.
Niektóre parametry Modelu Standardowego muszą się zmienić.

The IceCube Neutrino Observatory in Antarctica is about to get a significant upgrade. This huge detector consists of 5,160 sensors embedded in a 1x1x1 km volume of glacial ice deep beneath the geographic South Pole.

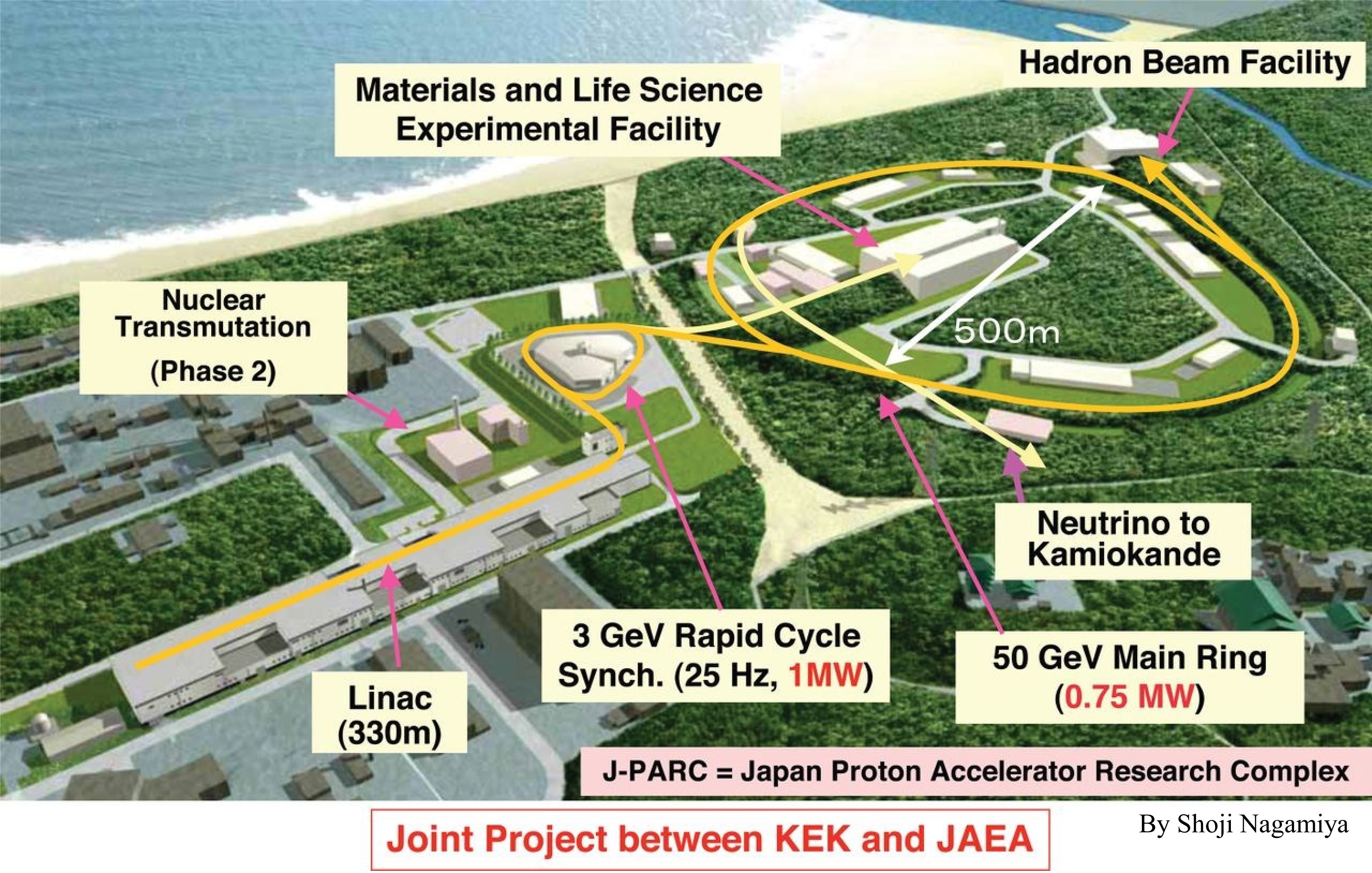


Deep Underground Neutrino Experiment (DUNE)



DUNE will consist of two neutrino detectors placed in the world's most intense neutrino beam. One detector will record particle interactions near the source of the beam, at the Fermi National Accelerator Laboratory in Batavia, Illinois. A second, much larger, detector will be installed more than a kilometer underground at the Sanford Underground Research Laboratory in Lead, South Dakota — 1,300 kilometers downstream of the source. These detectors will enable scientists to search for new subatomic phenomena and potentially transform our understanding of neutrinos and their role in the universe.
Two prototype far detectors are at the European research center CERN. The first started taking data in September 2018 and the second is under construction.

https://www.dunescience.org/



By Shoji Nagamiya

J-PARC uses high intensity proton beams to create high intensity secondary beams of neutrons, hadrons, and neutrinos