X Dinamika okusa II

OSCILACIJE STRANOSTI I DRUGIH OKUSA

- OSCILACIJA I REGENERACIJA STRANOSTI
- OSCILACIJA DRUGIH OKUSA
- MASE I OSCILACIJE NEUTRINA

1. MIJEŠANJE U SUSTAVU NEUTRALNIH MEZONA

1956, $K^0 - \overline{K}^0$: discovery of K_L (proposal of C non-c

1987, $B^0 - \overline{B}^0$: discovery of mixing ($\Rightarrow$ large m_t)

2006, $B_s^0 - \overline{B}_s^0$: measurement of Δm_s

2007, $D^0 - \overline{D}^0$: growing evidence for $\Delta\Gamma = \mathcal{O}(0.01)$

SUSTAV NEUTRALNIH KAONA

The quartet of kaons

- belongs to the pseudoscalar meson octet

I	S			
1/2	-1		K^+	K^0
1	0	π^+	π^0	π^-
0	0		η^0	
1/2	+1		$\bar{K}^0$	K^-

two isodoublets $\begin{pmatrix} K^+ \\ K^0 \end{pmatrix}$ & $\begin{pmatrix} \bar{K}^0 \\ -K^- \end{pmatrix}$

NEUTRALNI KAONI

- forms one of the most intriguing systems in nature

accelerator experiments in 50-ies :

- unknown reasons for the strangeness
- unknown inner machinery of the K^0-$\overline{K^0}$ mixing

Cronin & Fitch 1964

- revealed to us ~~CP~~

- has provided the breakthroughs in our knowledge of fundamental physics

MIJEŠANJE NEUTRALNIH KAONA

Strongly produced $J^P = 0^-$ states $\begin{cases} K^0(\bar{s}d) \\ \bar{K}^0(\bar{d}s) \end{cases}$

e.g. $\pi^- + p \to \Lambda^0 + X$ ← "associated" K^0 or $K^+\pi^-$

◇ strong interaction / strangeness eigenstates

$|K^0\rangle$ $(S=1)$; $|\bar{K}^0\rangle$ $(S=-1)$ convention

$|\bar{K}^0\rangle = -CP|K^0\rangle$ convention

weak decays $2\pi, 3\pi, \pi l \nu_e, \ldots$

CP-conserving Hamilt.

◊ CP eigenstates $|K_{1,2}\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle \mp |\bar{K}^0\rangle\right)$

$CP|K_1\rangle = |K_1\rangle$ (+) , $CP|K_2\rangle = -|K_2\rangle$ (−)

CP-allowed decays

$\downarrow$ 2π (+) $\downarrow$ 3π (−)

suppressed

$\tau_1 \to \tau_{short}$ $\tau_2 = \tau_{Long}$

$0.8926(12)\cdot 10^{-10}\,s$ $5.15(4)\cdot 10^{-8}\,s$

$\Delta m_K = m_L - m_S = 3.4782(176)\cdot 10^{-12}$ MeV ;

$\Delta\Gamma_K = \Gamma_S - \Gamma_L = 7.2823(98)\cdot 10^{-12}$ MeV

the sign measurement involves "regeneration" expt.

observed $K_2 \to \pi^+\pi^-$

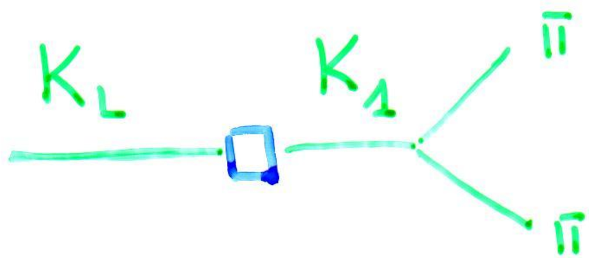
means ~~CP~~ !

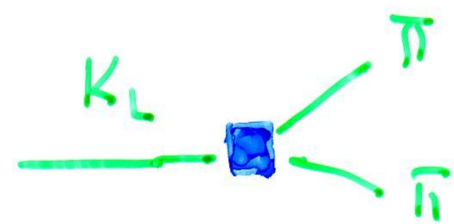
NARUŠENJE CP SIMETRIJE

◇ Physical decay states (CP̸ included)

$$|K_{L,S}\rangle = \frac{1}{\sqrt{1+\varepsilon^2}}\left(|K_{2,1}\rangle + \varepsilon\,|K_{1,2}\rangle\right)$$

lead to CP̸ in $K_L \to \pi\pi$ via two mechanisms





ε — indirect CP̸ (in the mass matrix)

ε' — direct CP̸ (in transition amplitude

- $\Delta S = 2$

$$H = \begin{bmatrix} M - i\,\Gamma/2 & M_{12} - i\,\Gamma_{12}/2 \\ M_{12}^* - i\,\Gamma_{12}^*/2 & M - i\,\Gamma/2 \end{bmatrix}$$

$$\varepsilon = \frac{\mathrm{Im}\,\frac{\Gamma_{12}}{2} + i\,\mathrm{Im}\,M_{12}}{2\mathrm{Re}\,M_{12} - \frac{i}{2}(2\,\mathrm{Re}\,\Gamma_{12})} \simeq \frac{e^{i\pi/4}}{\sqrt{2}}\,\frac{\mathrm{Im}\,M_{12}}{\Delta m_K} \equiv \varepsilon_K$$

- $\Delta S = 1$ CP part $\begin{cases} \text{shifts } \varepsilon_K \to \varepsilon_K + \xi \\ \text{induces } \varepsilon' \end{cases}$

$$\varepsilon' = \frac{\omega}{\sqrt{2}}\, e^{i\left(\frac{\pi}{2} + \delta_2 - \delta_0\right)} \left[\frac{\mathrm{Im}\,A_2}{\mathrm{Re}\,A_2} - \xi \right]$$

$$\omega = \frac{\mathrm{Re}\,A_2}{\mathrm{Re}\,A_0} \simeq \frac{1}{20} \quad ; \quad \xi = \frac{\mathrm{Im}\,A_0}{\mathrm{Re}\,A_0}$$

USPOREDBA MIJEŠANJA NEUTRALNIH K- i B-MEZONA

- USPOREDBA PRODUKCIJE NA REZONANCAMA
- USPOREDBA "OZNAČAVANJA"
- USPOREDBA DULJINE RASPADA

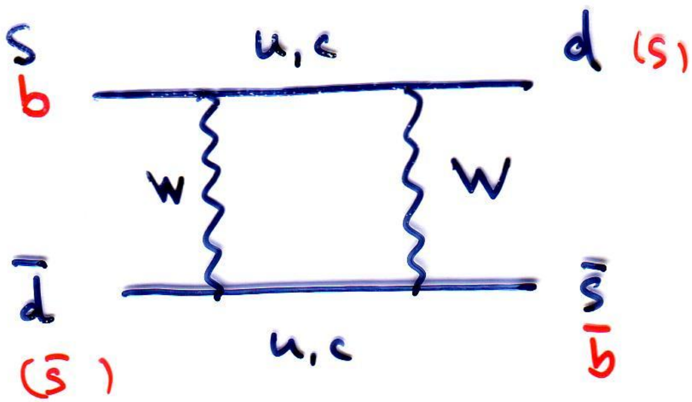
  (asimetrične B-tvornice)

DIJAGRAMI MIJEŠANJA NA KVARKOVSKOJ RAZINI

$$H_{Box} \sim G_F^2 \, (\underset{(\bar{s})}{\bar{d}} \gamma^\mu L \underset{b}{s})^2 \left\{ \eta_1 \lambda_u^2 m_c^2 + \eta_2 \lambda_t^2 m_t^2 - 2 \eta_3 \lambda_u \lambda_t m_c^2 \ln \frac{m_t^2}{m_c^2} \right\}$$

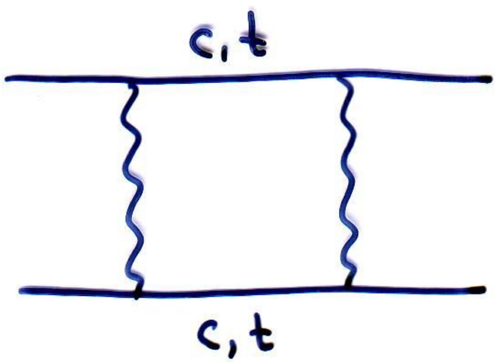
CKM factors $\left\{ \begin{array}{ll} \lambda_q = V_{qd} V_{qs}^* & K^0 - \bar{K}^0 \\ \lambda_q = V_{q\underset{(s)}{d}} V_{qb}^* & B^0_{\underset{(s)}{d}} - \bar{B}^0_{\underset{(s)}{d}} \end{array} \right.$

$$\lambda_u + \lambda_c + \lambda_t = 0$$



$\sim \lambda_u^2 m_c^2$ $\left\{ \begin{array}{lll} \text{CKM favored} & & \Delta M_K \\ \text{CKM suppressed} & & B - \bar{B} \end{array} \right.$

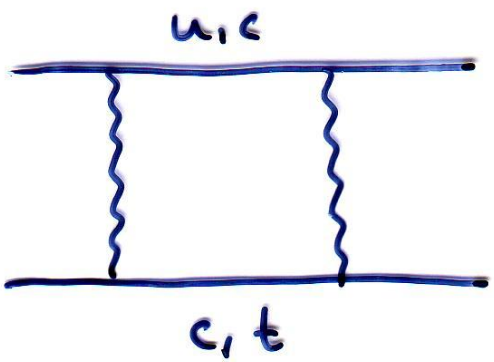
CKM potisnuti dijagrami kaonskog miješanja



$\sim \lambda_t^2 m_t^2$

- CKM suppr. K–$\bar{K}$ ($\not{CP}$ dominant for $m_t \gtrsim M_W$)
- CKM fav. B–$\bar{B}$

"top-meter" $\Delta m \sim m_t^2 \, |V_{td(s)} V_{tb}^*|^2$

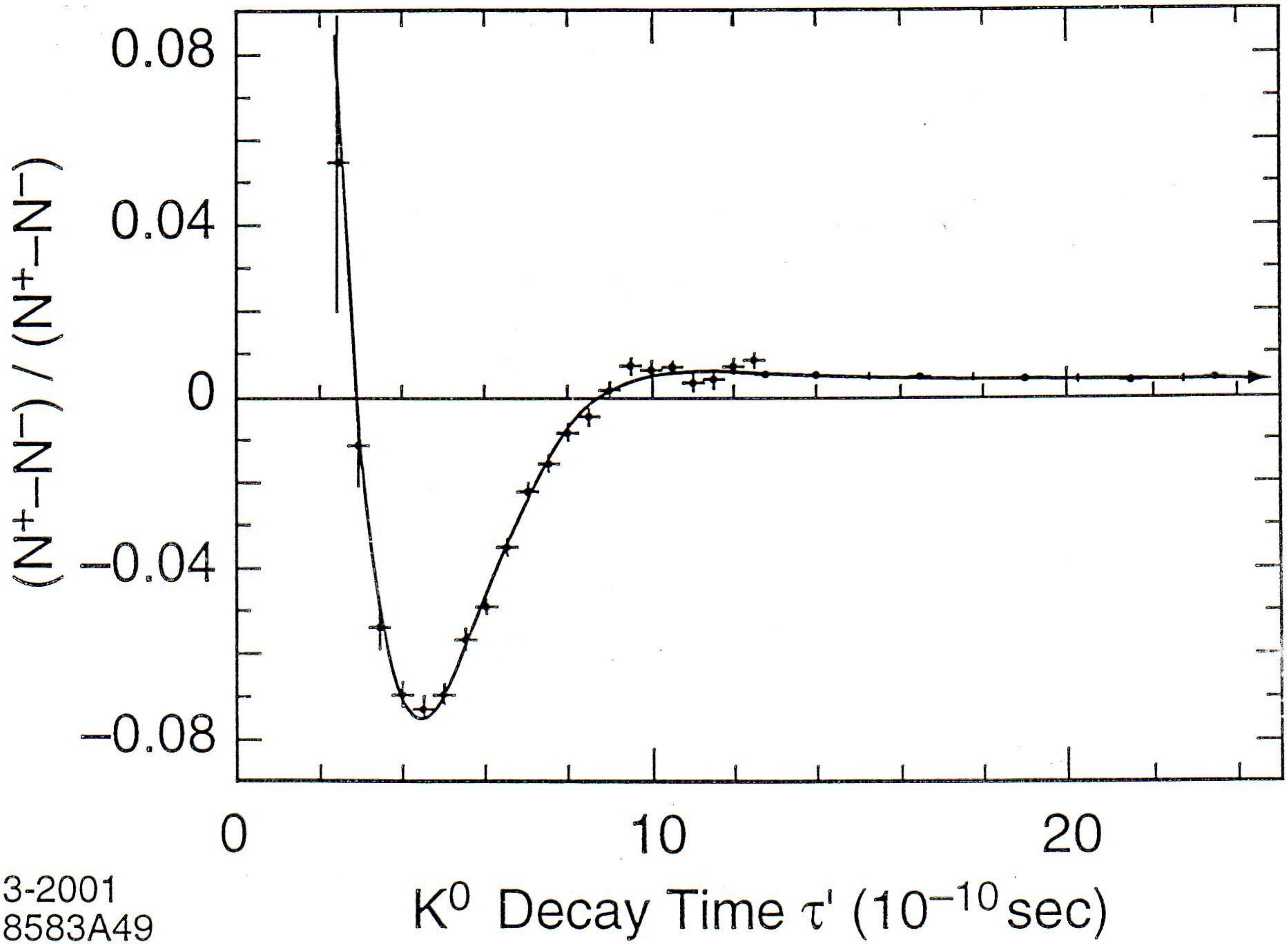


$\sim \lambda_u \lambda_t m_c^2 \ln \frac{m_t^2}{m_c^2}$

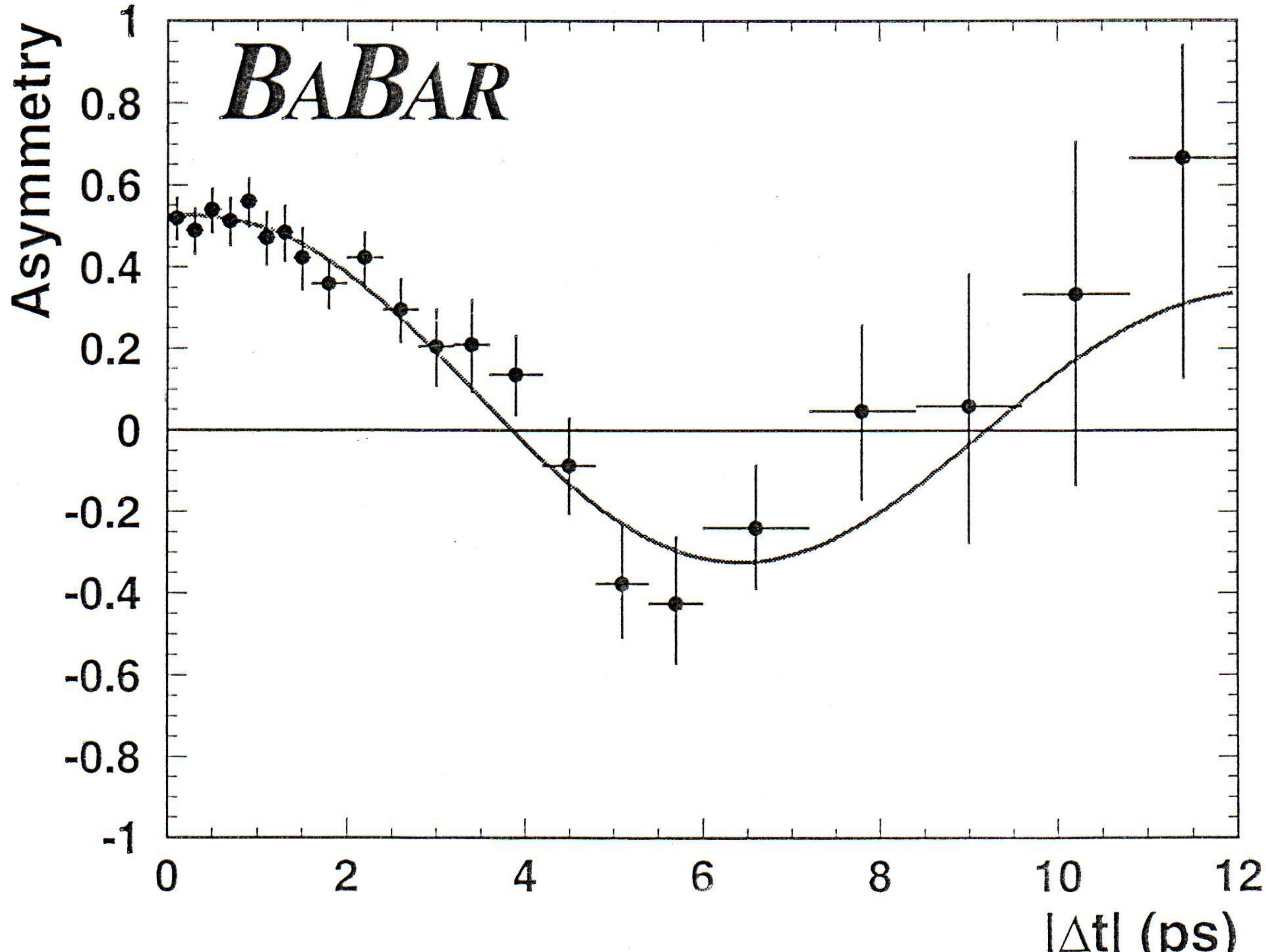
– CKM suppr. "interference term"
($\not{CP}$ dominant K–$\bar{K}$ for $m_t^2 \ll M_W^2$)

$K^0/\bar{K}^0$

Charge Asymmetry in the Decays $K^0 \longrightarrow \pi^{\mp} e^{\pm} \nu$



◊ $B/\bar{B}$



The asymmetry in # of K^0 (B_d) mesons w.r.t. $\bar{K}^0$ ($\bar{B}_d$) as a function of time

Oscilacije i mase neutrina

BRANIMIR RADOVČIĆ

Sveučilište u Zagrebu

Prirodoslovno-matematički fakultet

Fizički odsjek

NOBELOVA NAGRADA IZ FIZIKE 2015

Takaaki Kajita

Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan

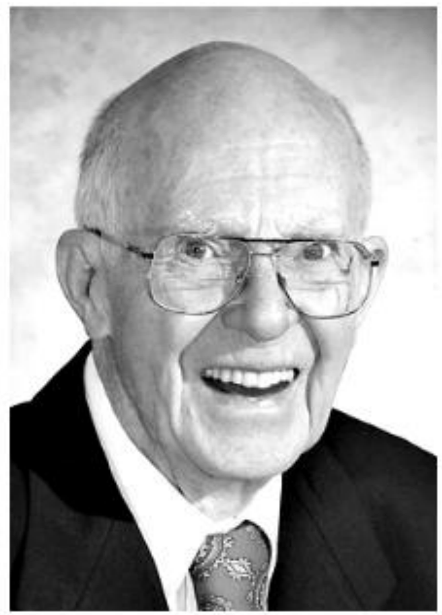
Arthur B. McDonald

SNO Collaboration
Queen’s University, Kingston, Canada

“ for the discovery of neutrino oscillations,
which shows that neutrinos have mass”

HOMESTAKE EKSPERIMENT

Raymond Davis Jr. - Facts



Raymond Davis Jr.

Born: 14 October 1914, Washington, DC, USA

Died: 31 May 2006, Blue Point, NY, USA

Affiliation at the time of the award: University of Pennsylvania, Philadelphia, PA, USA

Prize motivation: "for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

Field: neutrino astrophysics

Prize share: 1/4

PROBLEM SOLARNIH NEUTRINA

	$^{37}Cl \rightarrow ^{37}Ar$ (SNU)	$^{71}Ga \rightarrow ^{71}Ge$ (SNU)
Homestake [6]	$2.56 \pm 0.16 \pm 0.16$	–
GALLEX [10]	–	$77.5 \pm 6.2^{+4.3}_{-4.7}$
GALLEX-Reanalysis [109]	–	$73.4^{+6.1+3.7}_{-6.0-4.1}$
GNO [11]	–	$62.9^{+5.5}_{-5.3} \pm 2.5$
GNO+GALLEX [11]	–	$69.3 \pm 4.1 \pm 3.6$
GNO+GALLEX-Reanalysis [109]	–	$67.6^{+4.0+3.2}_{-4.0-3.2}$
SAGE [8]	–	$65.4^{+3.1+2.6}_{-3.0-2.8}$
SSM [BPS08(GS)] [104]	$8.46^{+0.87}_{-0.88}$	$127.9^{+8.1}_{-8.2}$

MASE NEUTRINA

$$\mathcal{L}_{\text{mass}} \sim \begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \end{pmatrix} \begin{pmatrix} m_{ee} & m_{e\mu} & m_{e\tau} \\ m_{\mu e} & m_{\mu\mu} & m_{\mu\tau} \\ m_{\tau e} & m_{\tau\mu} & m_{\tau\tau} \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

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

$$\nu_\alpha = \sum_{k=1}^{3} U_{\alpha k} \nu_k \qquad (\alpha = e, \mu, \tau)$$

$$\mathcal{L}_{\text{mass}} \sim \begin{pmatrix} \nu_1 & \nu_2 & \nu_3 \end{pmatrix} \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \sum_{k=1}^{3} m_k \nu_k \nu_k$$

MIJEŠANJE NEUTRINA

$$\begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix}$$

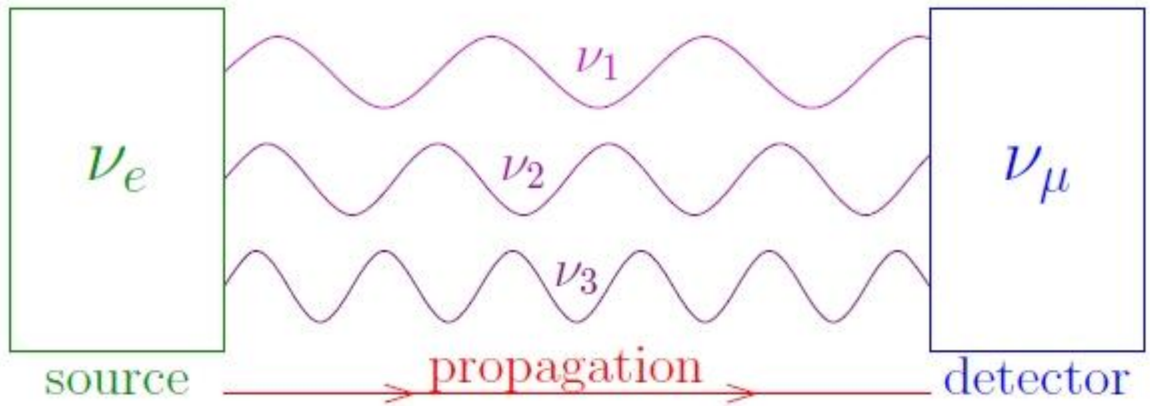
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta_{13}} \\ -s_{12} c_{23} - c_{12} s_{23} s_{13} e^{i\delta_{13}} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i\delta_{13}} & s_{23} c_{13} \\ s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta_{13}} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i\delta_{13}} & c_{23} c_{13} \end{pmatrix}$$

$$c_{ab} \equiv \cos \vartheta_{ab} \qquad s_{ab} \equiv \sin \vartheta_{ab} \qquad 0 \leq \vartheta_{ab} \leq \frac{\pi}{2} \qquad 0 \leq \delta_{13} < 2\pi$$

OSCILACIJE NEUTRINA

$$|\nu(t=0)\rangle = |\nu_e\rangle = U_{e1}\,|\nu_1\rangle + U_{e2}\,|\nu_2\rangle + U_{e3}\,|\nu_3\rangle$$



$$|\nu(t>0)\rangle = U_{e1}\,e^{-iE_1 t}\,|\nu_1\rangle + U_{e2}\,e^{-iE_2 t}\,|\nu_2\rangle + U_{e3}\,e^{-iE_3 t}\,|\nu_3\rangle \neq |\nu_e\rangle$$

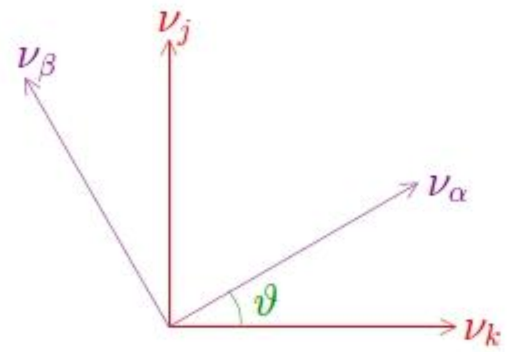
PRAG DETEKCIJE NEUTRINA

$$\nu + A \to B + C$$
$$\Downarrow$$
$$s = 2Em_A + m_A^2 \geq (m_B + m_C)^2$$
$$\Downarrow$$
$$E_{\rm th} = \frac{(m_B + m_C)^2}{2m_A} - \frac{m_A}{2}$$

$\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-$	$E_{\rm th} = 0.233\,\mathrm{MeV}$
$\nu_e + {}^{37}\mathrm{Cl} \to {}^{37}\mathrm{Ar} + e^-$	$E_{\rm th} = 0.81\,\mathrm{MeV}$
$\bar{\nu}_e + p \to n + e^+$	$E_{\rm th} = 1.8\,\mathrm{MeV}$
$\nu_\mu + n \to p + \mu^-$	$E_{\rm th} = 110\,\mathrm{MeV}$
$\nu_\mu + e^- \to \nu_e + \mu^-$	$E_{\rm th} \simeq \frac{m_\mu^2}{2m_e} = 10.9\,\mathrm{GeV}$

OSCILACIJE NEUTRINA

$$|\nu_\alpha\rangle = \cos\vartheta\,|\nu_k\rangle + \sin\vartheta\,|\nu_j\rangle$$
$$|\nu_\beta\rangle = -\sin\vartheta\,|\nu_k\rangle + \cos\vartheta\,|\nu_j\rangle$$



$$U = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix}$$

$$\Delta m^2 \equiv \Delta m^2_{kj} \equiv m^2_k - m^2_j$$

Transition Probability: $$P_{\nu_\alpha\to\nu_\beta} = P_{\nu_\beta\to\nu_\alpha} = \sin^2 2\vartheta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Survival Probabilities: $$P_{\nu_\alpha\to\nu_\alpha} = P_{\nu_\beta\to\nu_\beta} = 1 - P_{\nu_\alpha\to\nu_\beta}$$

OSCILACIJE NEUTRINA

Fields $\overline{\nu_{\alpha L}} = \sum_k U^*_{\alpha k} \overline{\nu_{kL}} \implies |\nu_\alpha\rangle = \sum_k U^*_{\alpha k} |\nu_k\rangle$ States

$$\mathcal{H}|\nu_k\rangle = E_k|\nu_k\rangle \Rightarrow |\nu_k(t)\rangle = e^{-iE_k t}|\nu_k\rangle \Rightarrow |\nu_\alpha(t)\rangle = \sum_k U^*_{\alpha k} e^{-iE_k t}|\nu_k\rangle$$

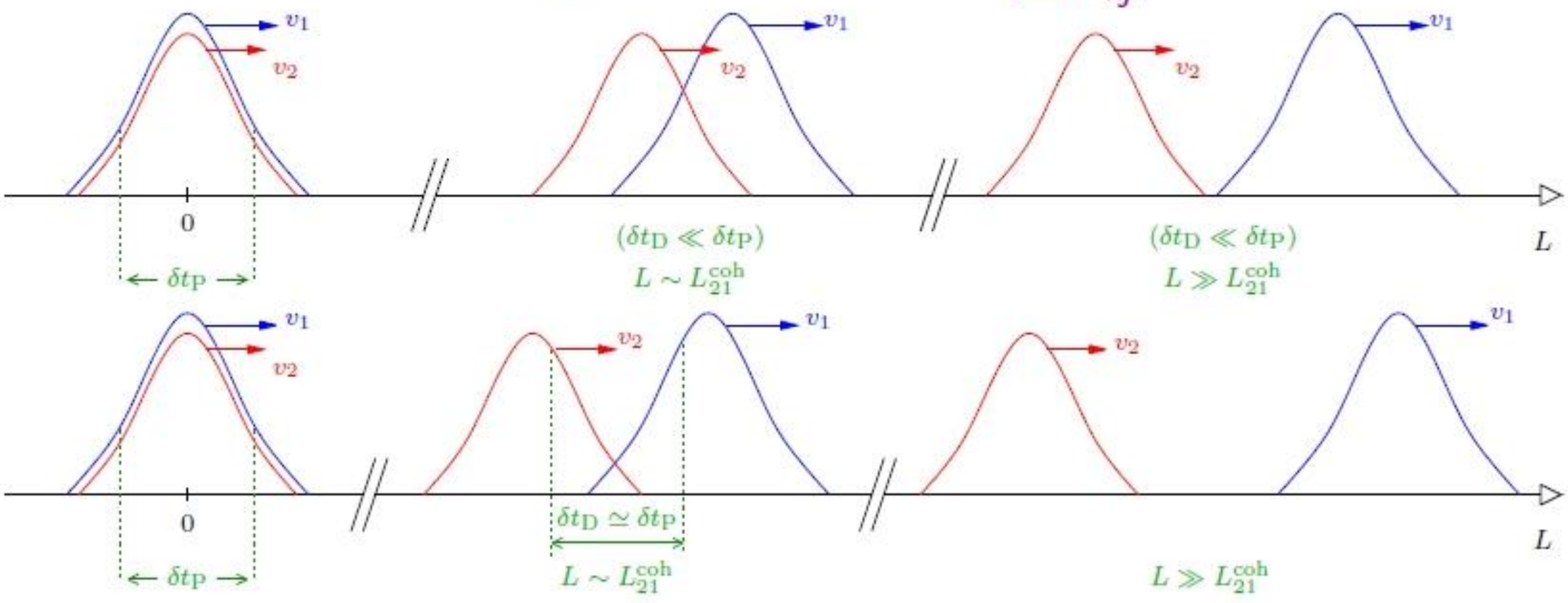
$$|\nu_k\rangle = \sum_{\beta=e,\mu,\tau} U_{\beta k}|\nu_\beta\rangle \Rightarrow |\nu_\alpha(t)\rangle = \sum_{\beta=e,\mu,\tau} \underbrace{\left(\sum_k U^*_{\alpha k} e^{-iE_k t} U_{\beta k}\right)}_{\mathcal{A}_{\nu_\alpha \to \nu_\beta}(t)} |\nu_\beta\rangle$$

Transition Probability

$$P_{\nu_\alpha \to \nu_\beta}(t) = |\langle \nu_\beta | \nu_\alpha(t)\rangle|^2 = |\mathcal{A}_{\nu_\alpha \to \nu_\beta}(t)|^2 = \left|\sum_k U^*_{\alpha k} e^{-iE_k t} U_{\beta k}\right|^2$$

VALNI PAKETI

$$|\delta t_{kj}| \simeq |v_k - v_j|\, T \simeq \frac{|\Delta m^2_{kj}|}{2E^2} L \quad \Longrightarrow \quad L^{\mathrm{coh}}_{kj} \sim \frac{2E^2}{|\Delta m^2_{kj}|} \sqrt{(\delta t_{\mathrm{P}})^2 + (\delta t_{\mathrm{D}})^2}$$



VALNI PAKETI

$$|\nu_\alpha\rangle = \sum_k U^*_{\alpha k} \int \mathrm{d}p\, \psi^P_k(p)\, |\nu_k(p)\rangle \qquad |\nu_\beta\rangle = \sum_k U^*_{\beta k} \int \mathrm{d}p\, \psi^D_k(p)\, |\nu_k(p)\rangle$$

$$\begin{aligned} \mathcal{A}_{\alpha\beta}(x,t) &= \langle \nu_\beta |\, e^{-i\widehat{E}t + i\widehat{P}x}\, |\nu_\alpha\rangle \\ &= \sum_k U^*_{\alpha k}\, U_{\beta k} \int \mathrm{d}p\, \psi^P_k(p)\, \psi^{D*}_k(p)\, e^{-iE_k(p)t + ipx} \end{aligned}$$

Gaussian Approximation of Wave Packets

$$\psi^P_k(p) = \left(2\pi\sigma^2_{pP}\right)^{-1/4} \exp\left[-\frac{(p-p_k)^2}{4\sigma^2_{pP}}\right]$$

$$\psi^D_k(p) = \left(2\pi\sigma^2_{pD}\right)^{-1/4} \exp\left[-\frac{(p-p_k)^2}{4\sigma^2_{pD}}\right]$$

$$\mathcal{A}_{\alpha\beta}(x,t) \propto \sum_k U^*_{\alpha k}\, U_{\beta k} \exp\left[-iE_k t + ip_k x \underbrace{-\frac{(x - v_k t)^2}{4\sigma^2_x}}\right]$$

OSCILACIJE NEUTRINA

$$P_{\alpha\beta}(L) = \sum_{k,j} U^*_{\alpha k}\, U_{\beta k}\, U_{\alpha j}\, U^*_{\beta j}\, \exp\left[-i\,\frac{\Delta m^2_{kj} L}{2E}\right]$$
$$\times \exp\left[-\left(\frac{\Delta m^2_{kj} L}{4\sqrt{2} E^2 \sigma_x}\right)^2 - 2\xi^2 \left(\frac{\Delta m^2_{kj} \sigma_x}{4E}\right)^2\right]$$

Oscillation Lengths

$$L^{\text{osc}}_{kj} = \frac{4\pi E}{\Delta m^2_{kj}}$$

Coherence Lengths

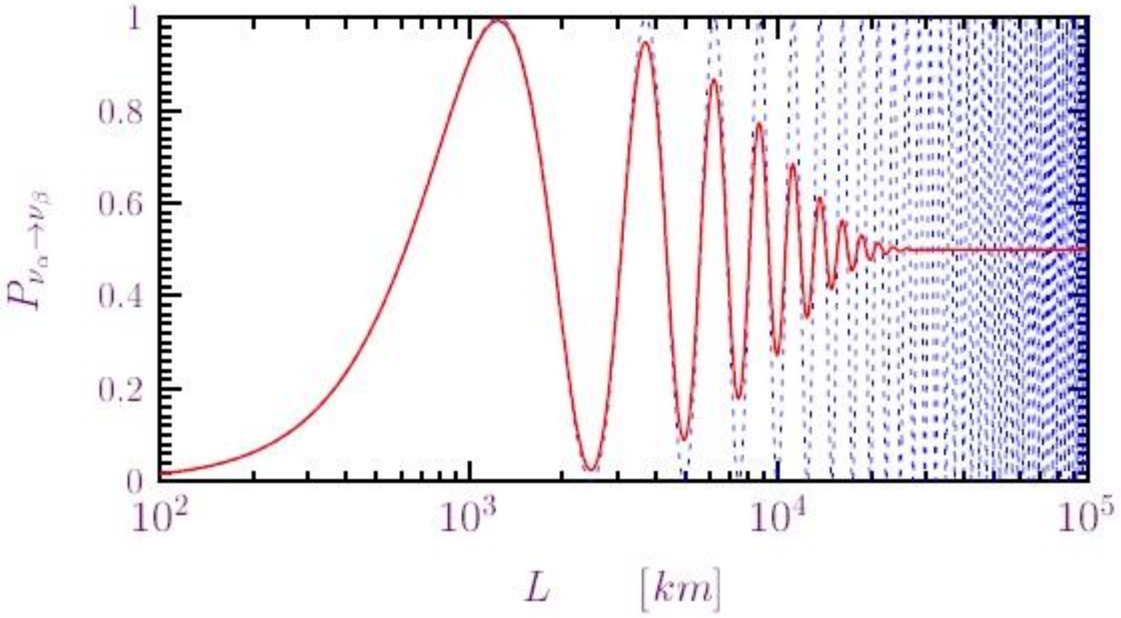
$$L^{\text{coh}}_{kj} = \frac{4\sqrt{2} E^2}{|\Delta m^2_{kj}|}\, \sigma_x$$

$$P_{\alpha\beta}(L) = \sum_{k,j} U^*_{\alpha k}\, U_{\beta k}\, U_{\alpha j}\, U^*_{\beta j}\, \exp\left[-2\pi i\,\frac{L}{L^{\text{osc}}_{kj}}\right]$$
$$\times \exp\left[-\left(\frac{L}{L^{\text{coh}}_{kj}}\right)^2 - 2\pi^2 \xi^2 \left(\frac{\sigma_x}{L^{\text{osc}}_{kj}}\right)^2\right]$$

OSCILACIJE NEUTRINA

$\Delta m^2 = 10^{-3}\,\mathrm{eV}^2 \qquad \sin^2 2\vartheta = 1 \qquad E = 1\,\mathrm{GeV} \qquad \sigma_p = 50\,\mathrm{MeV}$

$$L^{\mathrm{osc}} = \frac{4\pi E}{\Delta m^2} = 2480\,\mathrm{km} \qquad L^{\mathrm{coh}} = \frac{4\sqrt{2}E^2}{|\Delta m^2|}\sigma_x = 11163\,\mathrm{km}$$



PROBLEM SOLARNIH NEUTRINA

	Reaction	$^8B\ \nu$ flux ($10^6 cm^{-2} s^{-1}$)
Kamiokande [7]	νe	$2.80 \pm 0.19 \pm 0.33$
Super-K I [114,116]	νe	$2.38 \pm 0.02 \pm 0.08$
Super-K II [115,116]	νe	$2.41 \pm 0.05^{+0.16}_{-0.15}$
Super-K III [116]	νe	$2.32 \pm 0.04 \pm 0.05$
SNO Phase I [14]	CC	$1.76^{+0.06}_{-0.05} \pm 0.09$
(pure $D_2 0$)	νe	$2.39^{+0.24}_{-0.23} \pm 0.12$
	NC	$5.09^{+0.44+0.46}_{-0.43-0.43}$
SNO Phase II [118]	CC	$1.68 \pm 0.06^{+0.08}_{-0.09}$
(NaCl in D_2O)	νe	$2.35 \pm 0.22 \pm 0.15$
	NC	$4.94 \pm 0.21^{+0.38}_{-0.34}$
SNO Phase III [119]	CC	$1.67^{+0.05+0.07}_{-0.04-0.08}$
(^3He counters)	νe	$1.77^{+0.24+0.09}_{-0.21-0.10}$
	NC	$5.54^{+0.33+0.36}_{-0.31-0.34}$
SNO Phase I+II [120]	NC	$5.140^{+0.160+0.132}_{-0.158-0.117}$
	Φ_B from fit to all reactions	$5.046^{+0.159+0.107}_{-0.152-0.123}$
SNO Phase I+II+III [121]	Φ_B from fit to all reactions	$5.25 \pm 0.16^{+0.11}_{-0.13}$
Borexino [126]	νe	$2.4 \pm 0.4 \pm 0.1$
SSM [BPS08(GS)] [104]	–	$5.94(1 \pm 0.11)$
SSM [SHP11(GS)] [106]	–	$5.58(1 \pm 0.14)$

OSCILACIJE NEUTRINA

Source	Type of ν	$\overline{E}$[MeV]	L[km]	min(Δm^2)[eV^2]
Reactor	$\overline{\nu}_e$	~ 1	1	$\sim 10^{-3}$
Reactor	$\overline{\nu}_e$	~ 1	100	$\sim 10^{-5}$
Accelerator	$\nu_\mu, \overline{\nu}_\mu$	$\sim 10^3$	1	~ 1
Accelerator	$\nu_\mu, \overline{\nu}_\mu$	$\sim 10^3$	1000	$\sim 10^{-3}$
Atmospheric ν's	$\nu_{\mu,e}, \overline{\nu}_{\mu,e}$	$\sim 10^3$	10^4	$\sim 10^{-4}$
Sun	ν_e	~ 1	1.5×10^8	$\sim 10^{-11}$

OSCILACIJE NEUTRINA

Solar
$\nu_e \to \nu_\mu, \nu_\tau$
(SNO, BOREXino; Super-Kamiokande; GALLEX/GNO, SAGE; Homestake, Kamiokande)

VLBL Reactor
$\bar{\nu}_e$ disappearance
(KamLAND)

$\to$ $\Delta m^2_{\text{S}} \simeq 7.6 \times 10^{-5}\,\text{eV}^2$, $\sin^2\vartheta_{\text{S}} \simeq 0.30$

Atmospheric
$\nu_\mu \to \nu_\tau$
(Super-Kamiokande; Kamiokande, IMB; MACRO, Soudan-2)

LBL Accelerator
ν_μ disappearance
(K2K, MINOS, T2K)

LBL Accelerator
$\nu_\mu \to \nu_\tau$
(Opera)

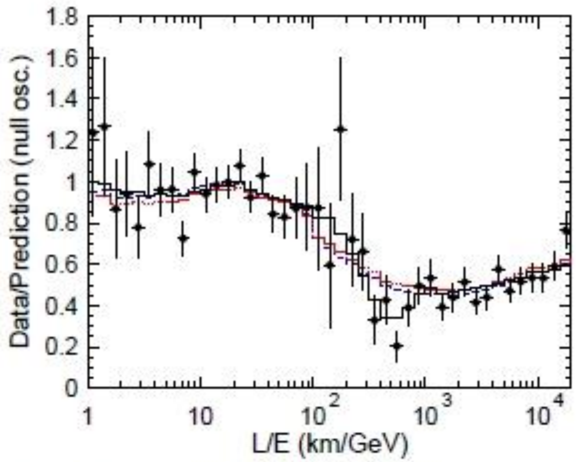
$\to$ $\Delta m^2_{\text{A}} \simeq 2.4 \times 10^{-3}\,\text{eV}^2$, $\sin^2\vartheta_{\text{A}} \simeq 0.50$

LBL Accelerator
$\nu_\mu \to \nu_e$
(T2K, MINOS)

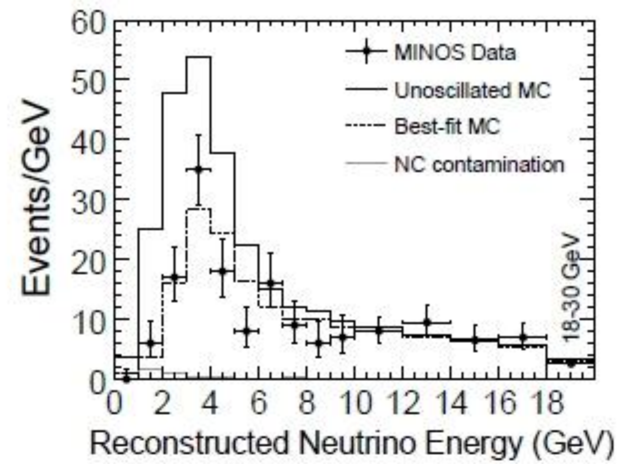
LBL Reactor
$\bar{\nu}_e$ disappearance
(Daya Bay, RENO; Double Chooz)

$\to$ Δm^2_{A}, $\sin^2\vartheta_{13} \simeq 0.023$

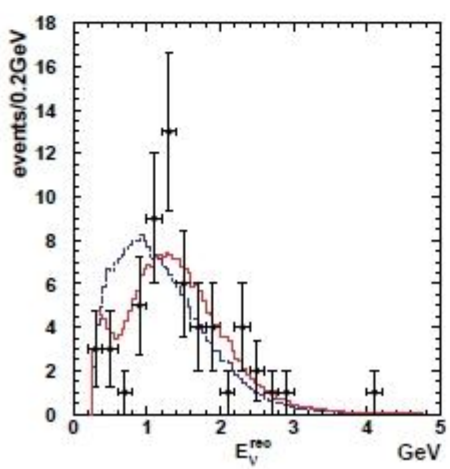
OSCILACIJE NEUTRINA



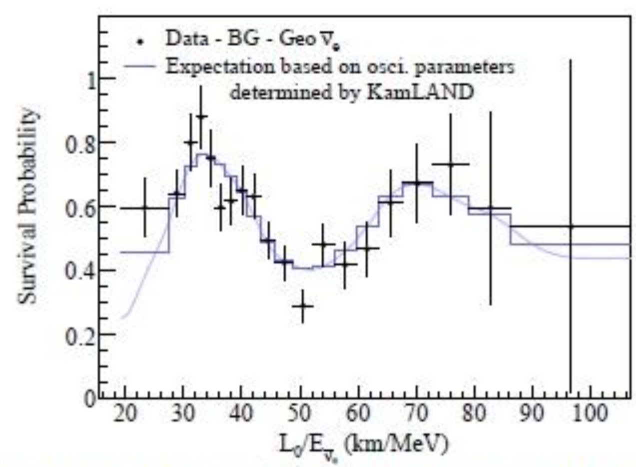
[Super-Kamiokande, PRL 93 (2004) 101801, hep-ex/0404034]



[MINOS, PRD 77 (2008) 072002, arXiv:0711.0769]

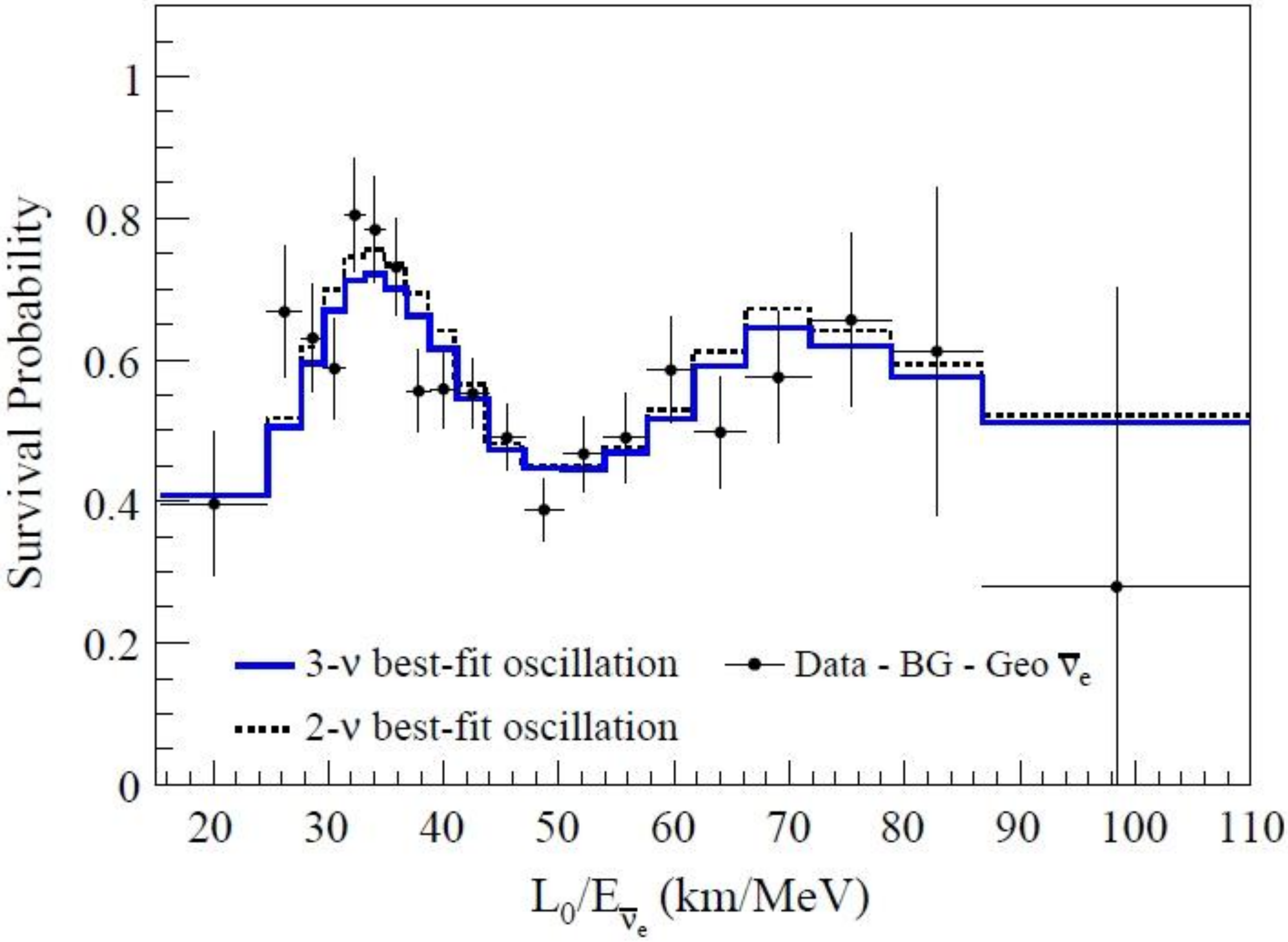


[K2K, PRD 74 (2006) 072003, hep-ex/0606032v3]



[KamLAND, PRL 100 (2008) 221803, arXiv:0801.4589]

KAMLAND



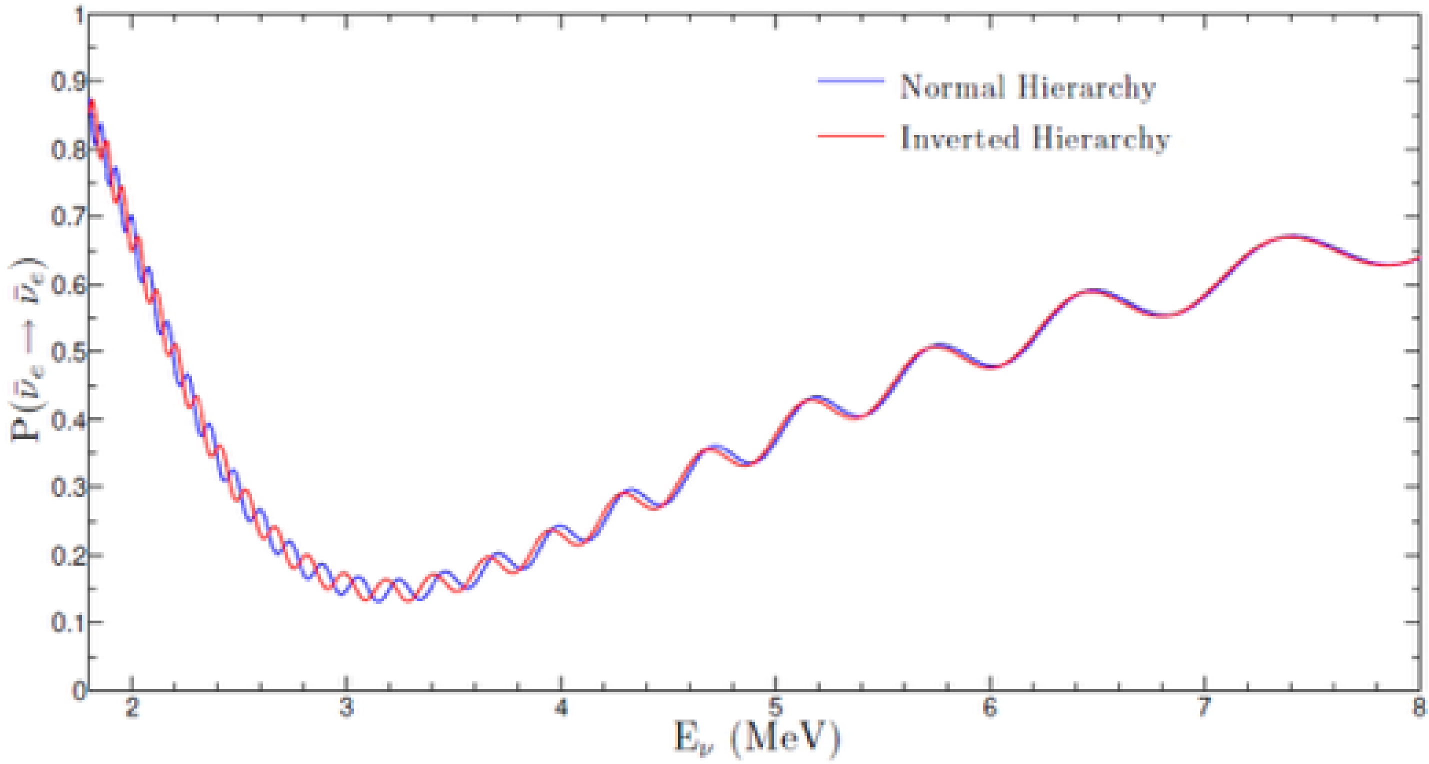
Survival Probability
0
0.2
0.4
0.6
0.8
1
20
30
40
50
60
70
80
90
100
110
$L_0/E_{\overline{\nu}_e}$ (km/MeV)
3-ν best-fit oscillation
2-ν best-fit oscillation
Data - BG - Geo $\overline{\nu}_e$

GLOBALNA PRILAGODBA

	Normal Ordering ($\Delta\chi^2 = 0.97$)		Inverted Ordering (best fit)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.270 \to 0.344$
$\theta_{12}/^\circ$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$31.29 \to 35.91$
$\sin^2\theta_{23}$	$0.452^{+0.052}_{-0.028}$	$0.382 \to 0.643$	$0.579^{+0.025}_{-0.037}$	$0.389 \to 0.644$	$0.385 \to 0.644$
$\theta_{23}/^\circ$	$42.3^{+3.0}_{-1.6}$	$38.2 \to 53.3$	$49.5^{+1.5}_{-2.2}$	$38.6 \to 53.3$	$38.3 \to 53.3$
$\sin^2\theta_{13}$	$0.0218^{+0.0010}_{-0.0010}$	$0.0186 \to 0.0250$	$0.0219^{+0.0011}_{-0.0010}$	$0.0188 \to 0.0251$	$0.0188 \to 0.0251$
$\theta_{13}/^\circ$	$8.50^{+0.20}_{-0.21}$	$7.85 \to 9.10$	$8.51^{+0.20}_{-0.21}$	$7.87 \to 9.11$	$7.87 \to 9.11$
$\delta_{CP}/^\circ$	306^{+39}_{-70}	$0 \to 360$	254^{+63}_{-62}	$0 \to 360$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.02 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.457^{+0.047}_{-0.047}$	$+2.317 \to +2.607$	$-2.449^{+0.048}_{-0.047}$	$-2.590 \to -2.307$	$\begin{bmatrix} +2.325 \to +2.599 \\ -2.590 \to -2.307 \end{bmatrix}$

Gonzalez-Garcia, Maltoni, Schwetz arXiv:1409.5439

OSCILACIJE NEUTRINA



OSCILACIJE U MATERIJI

$$i\frac{d}{dt}\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

MASE NEUTRINA

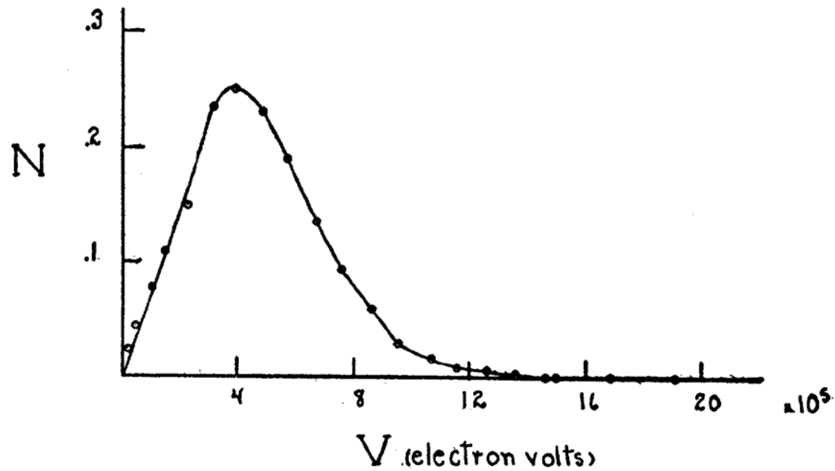


FIG. 5. Energy distribution curve of the beta-rays.

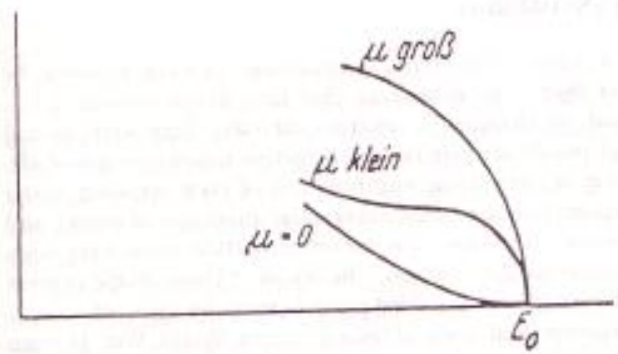
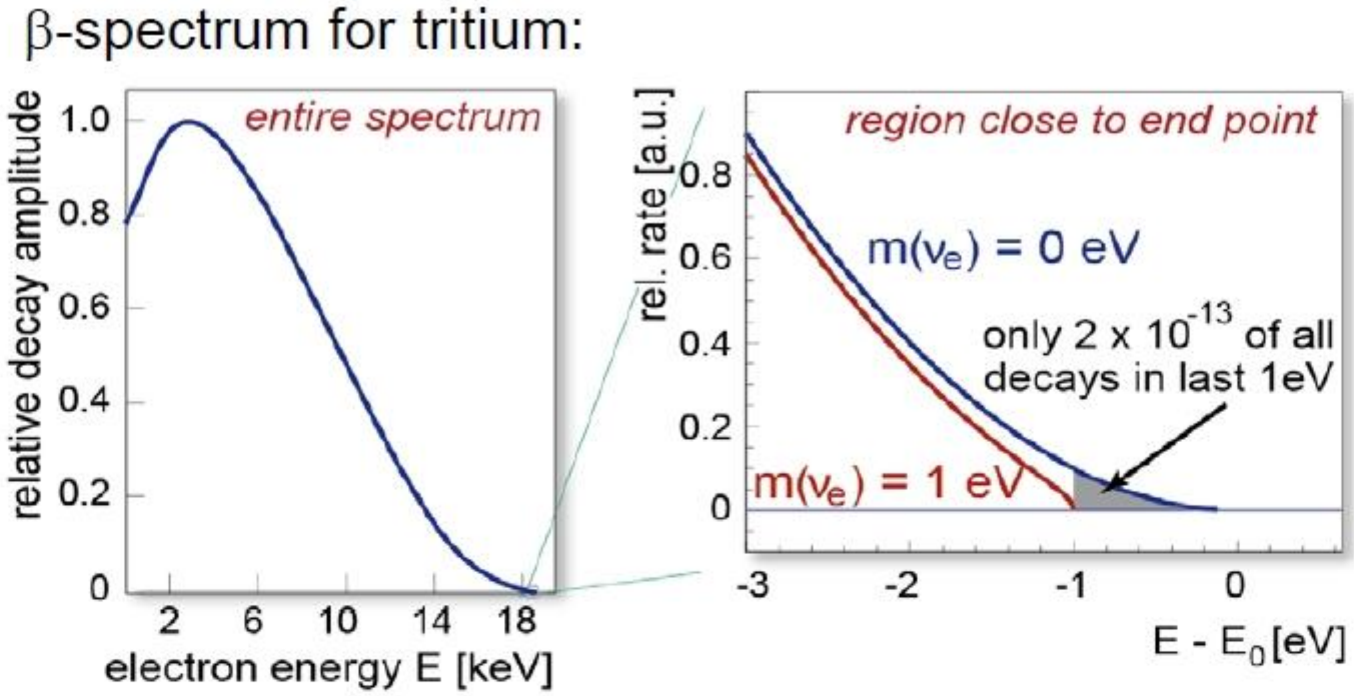


Fig. 1.2. Graph from Fermi's famous paper on the theory of beta decay, showing how the shape of the emitted electron's energy spectrum varies with neutrino mass

KATRIN – MASE NEUTRINA

KATRIN – MASE NEUTRINA



SAŽETAK

- Promjene okusa neutrina prilikom propagacije (oscilacije neutrina) potvrđene u nizu eksperimenata
- Oscilacije neutrina vode na masivne neutrine
- $P(\nu_e \to \nu_\mu) = \sin^2(2\theta) \sin^2(\Delta m^2 L / 4E)$
- Zašto su mase neutrina tako male?