PNMS Matrix

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

With $\Delta m_{12} << \Delta m_{23} \sim \Delta m_{13}$ and Θ_{13} small

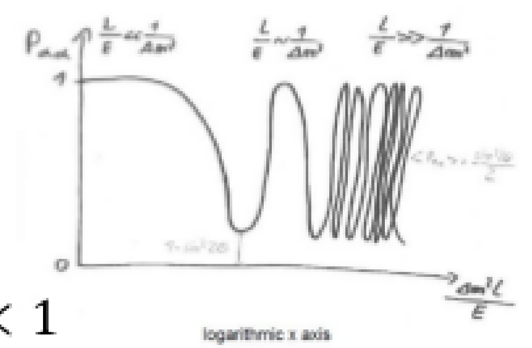
For atmospheric and accelerator neutrions (E large, L medium): $\frac{\Delta m_{12}{}^2 L}{E} \ll 1$

$P(\nu_\mu \rightarrow \nu_\tau) = 1 - \sin^2 2\Theta_{23} \sin^2(\frac{\Delta m_{23}{}^2 L}{4E})$ $\qquad P(\nu_e \rightarrow \nu_e) \sim 1$

For solar neutrinos and very long baseline neutrinos (L large, E small): $\frac{\Delta m_{13}{}^2 L}{E} \gg 1$

(almost like two neutrino system, only one mass difference)

$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\Theta_{12} \sin^2(\frac{\Delta m_{12}{}^2 L}{4E})$



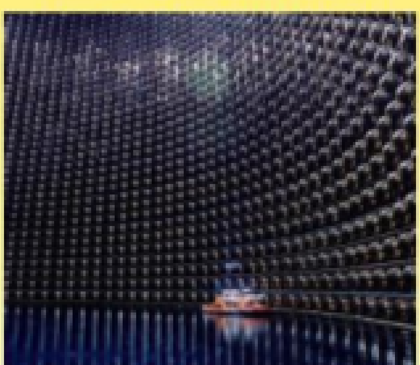
For short baseline reactor neutrinos (E small, L small): $\frac{\Delta m_{12}{}^2 L}{E} \ll 1$

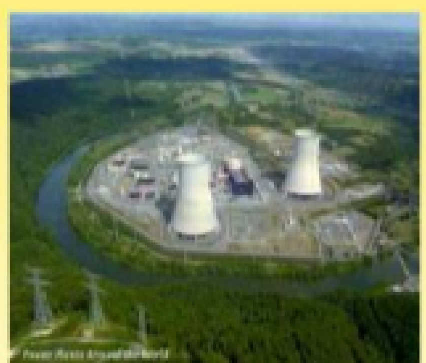
$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\Theta_{13} \sin^2(\frac{\Delta m_{13}{}^2 L}{4E})$

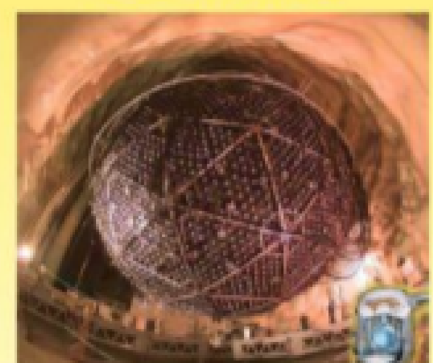
Sensitivity

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

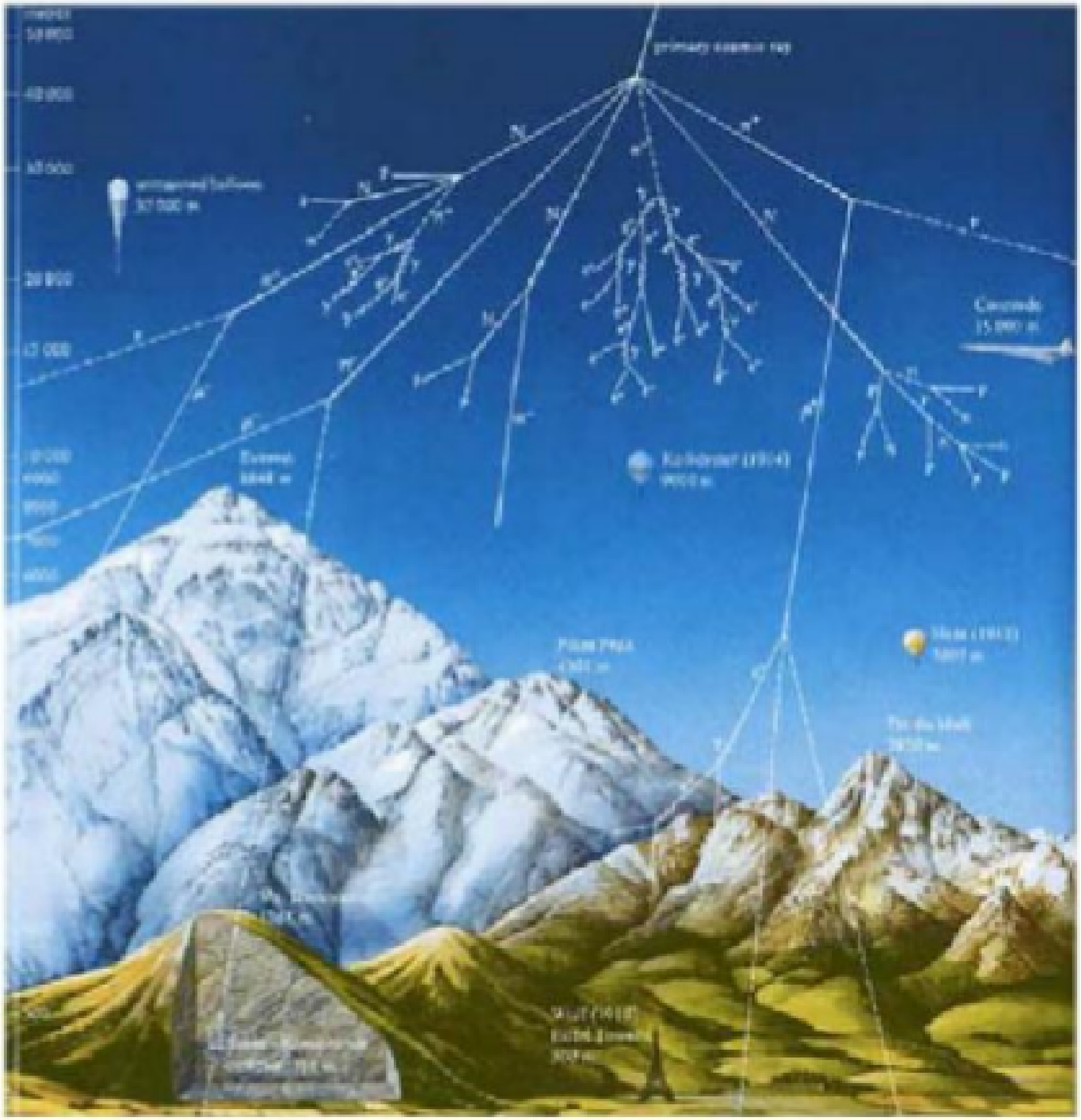
$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric and LBL accelerator}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}\,e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\,e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{SBL reactor}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar and LBL reactor}}$$







Atmospheric Neutrinos



Cosmic radiation: Air shower

$$p + N \rightarrow \pi^{\pm}, K^{\pm}$$

$$\pi^{\pm}, K^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\overline{\nu}_{\mu})$$

$$\mu^{\pm} \rightarrow e^{\pm} + \nu_{e}(\overline{\nu}_{e}) + \overline{\nu}_{\mu}(\nu_{\mu})$$

$$R = \frac{\nu_{\mu} + \overline{\nu}_{\mu}}{\nu_{e} + \overline{\nu}_{e}} = 2$$

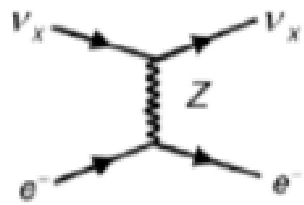
Exact calculation: R=2.1
(E_{ν}<1GeV)

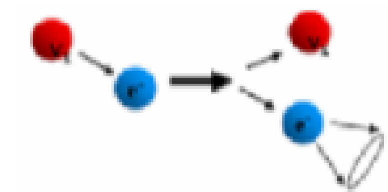
(For larger energies R>2.1)

(Super-)Kamiokande

Water = "active target"

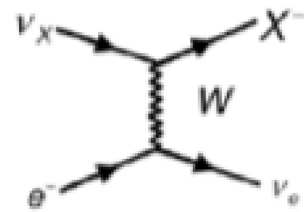
Elastic scattering





Cherenkov Light

Charged current



Detection of Cherenkov photons: Photo multiplier

Experiments:

(Super)-Kamiokande

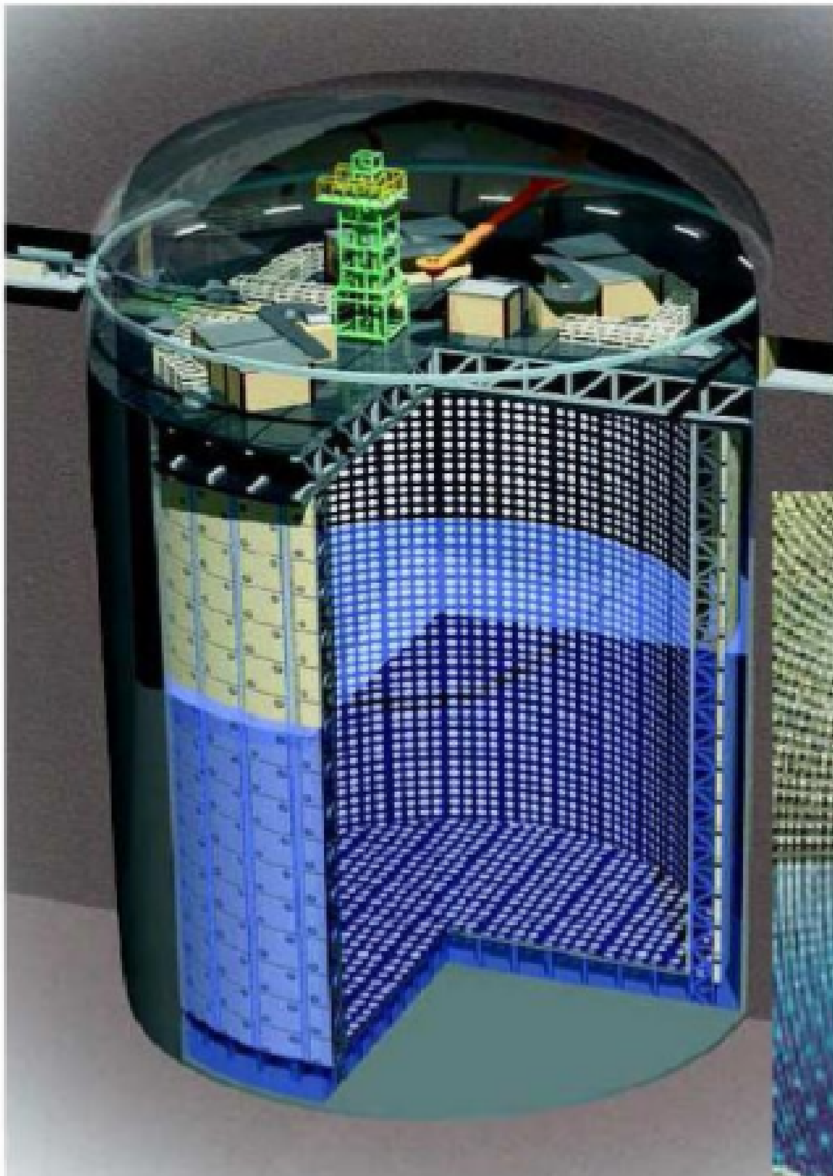
IMB

Soudan-2

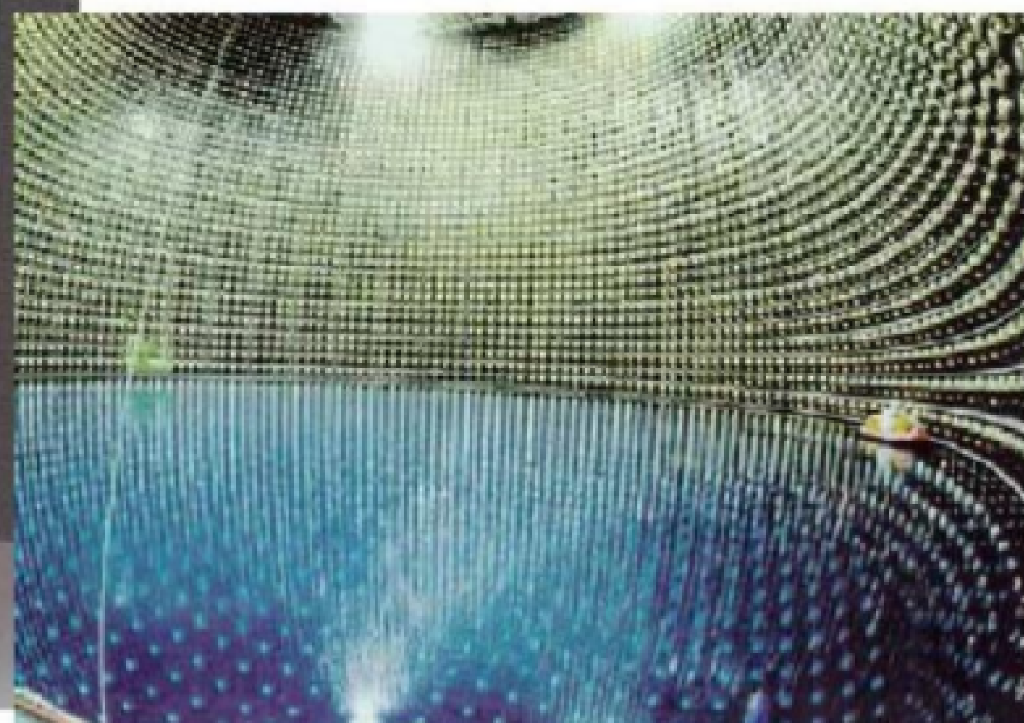
treshold: ~ 5 MeV (to produce sufficiently high energetic electrons to produce Cherenkov light, no issue for atmospheric neutrinos, but for solar neutrinos)

Advantage:
- scattered electron/muons carry direction information
- in-situ detection
- measurement of neutrino energy

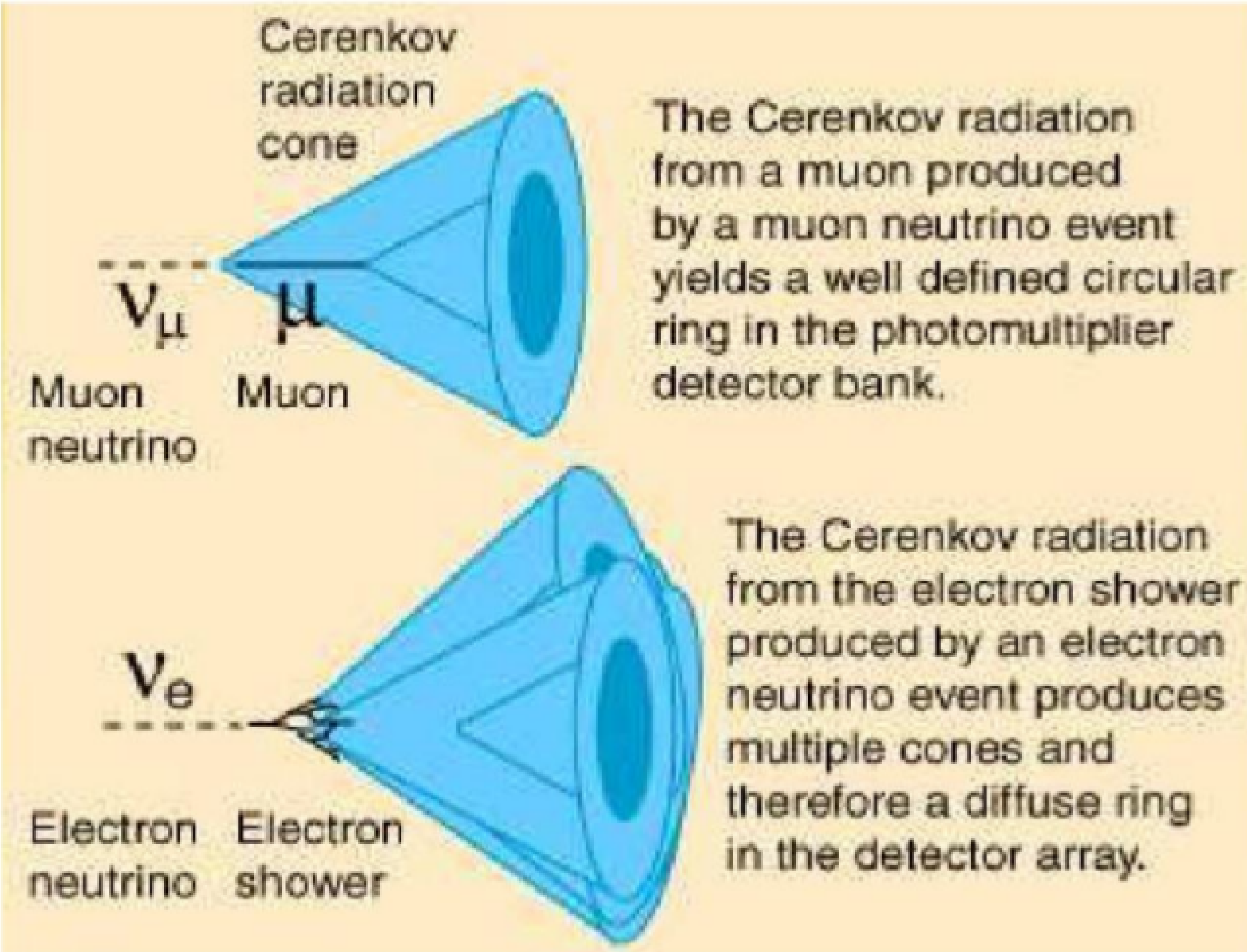
(Super-)Kamiokande



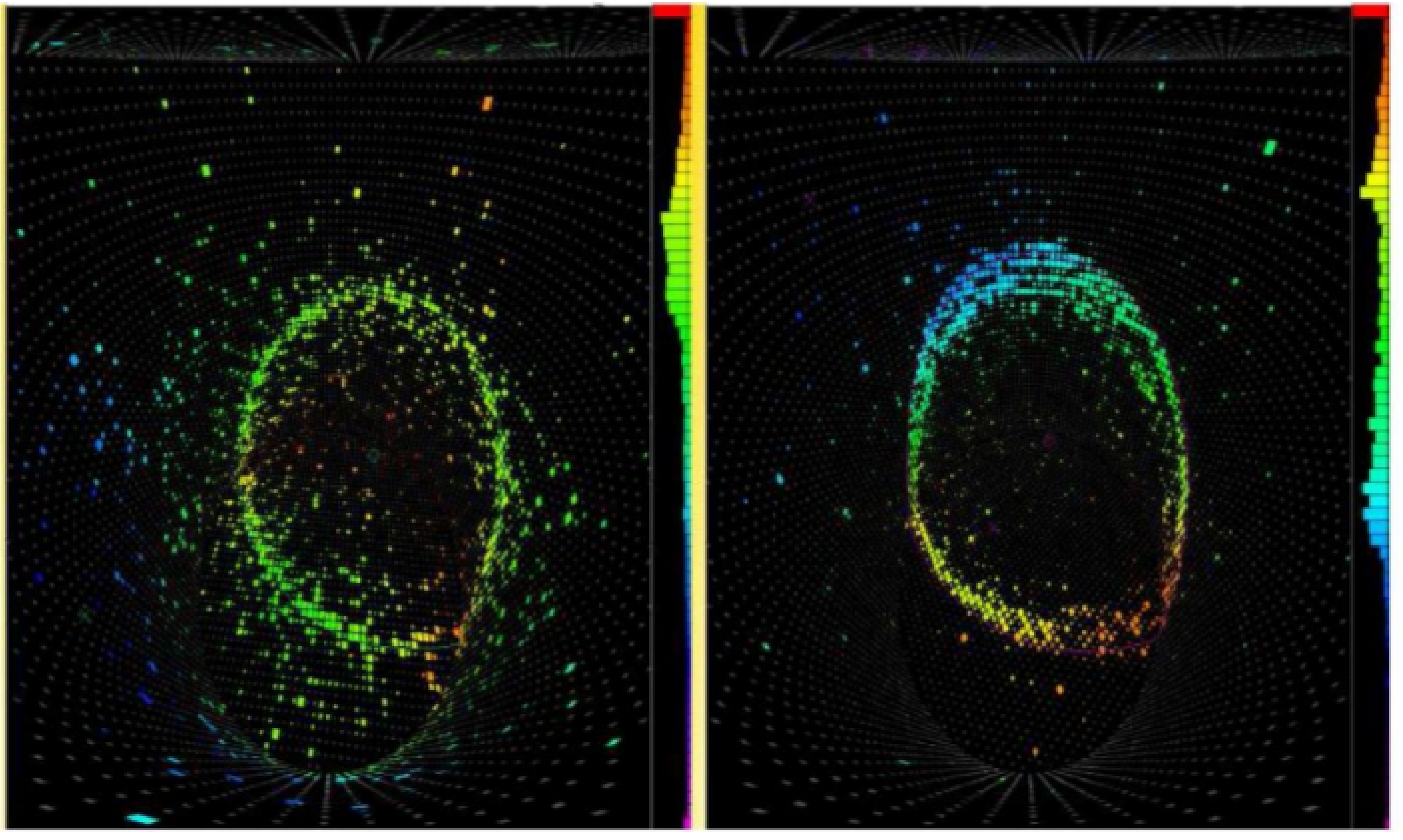
- Largest artificial water detector (50 kt)
- Until the 2001 accident:
  11000 PMTs (50 cm tubes!): 40% of surface covered with photo-cathode
- Back in operation since 2003



Detection of Cherenkov-Light



$\nu_e \leftrightarrow \nu_\mu$



Energy measurement:

Thickness of ring is related to travel distance of electron/muon in the detector. This is related to the energy of the electron/muon thus (with some uncertainties) to the original neutrino energy.

Ratio of Muon to Electron Neutrinos

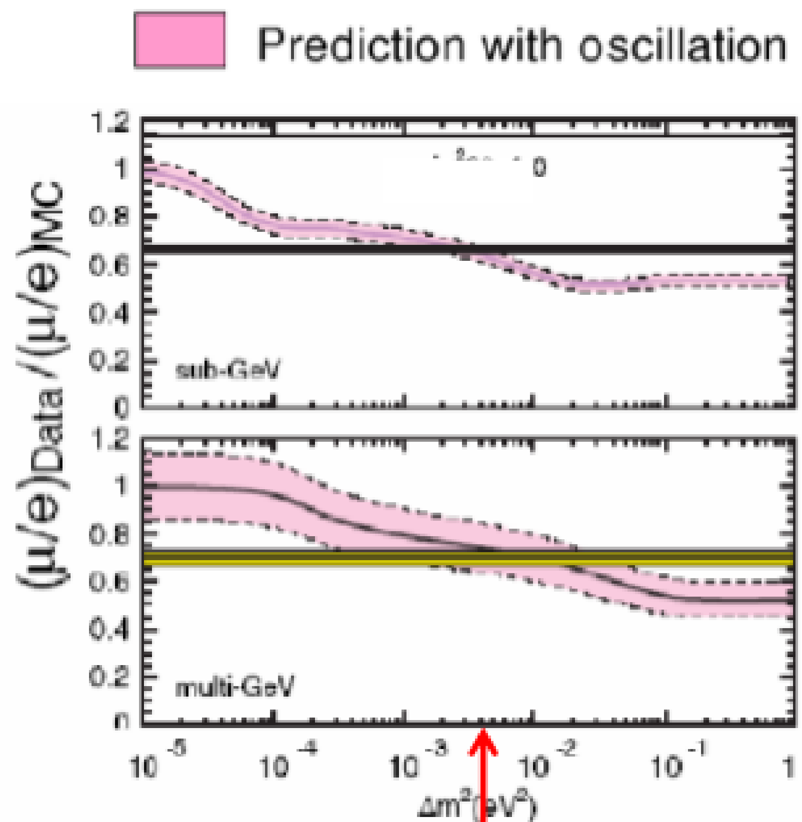
oscillation depend on E, thus split up
sample in high and low momentum neutrinos

$$R_{sub-GeV} = 0.658 \pm 0.016(stat) \pm 0.032(sys)$$

$$R = \frac{(\mu/e)_{DATA}}{(\mu/e)_{M.C.}}$$

$$R_{multi-GeV} = 0.702^{+0.032}_{-0.030}(stat) \pm 0.099(sys)$$

assuming no oscillation
in simulation



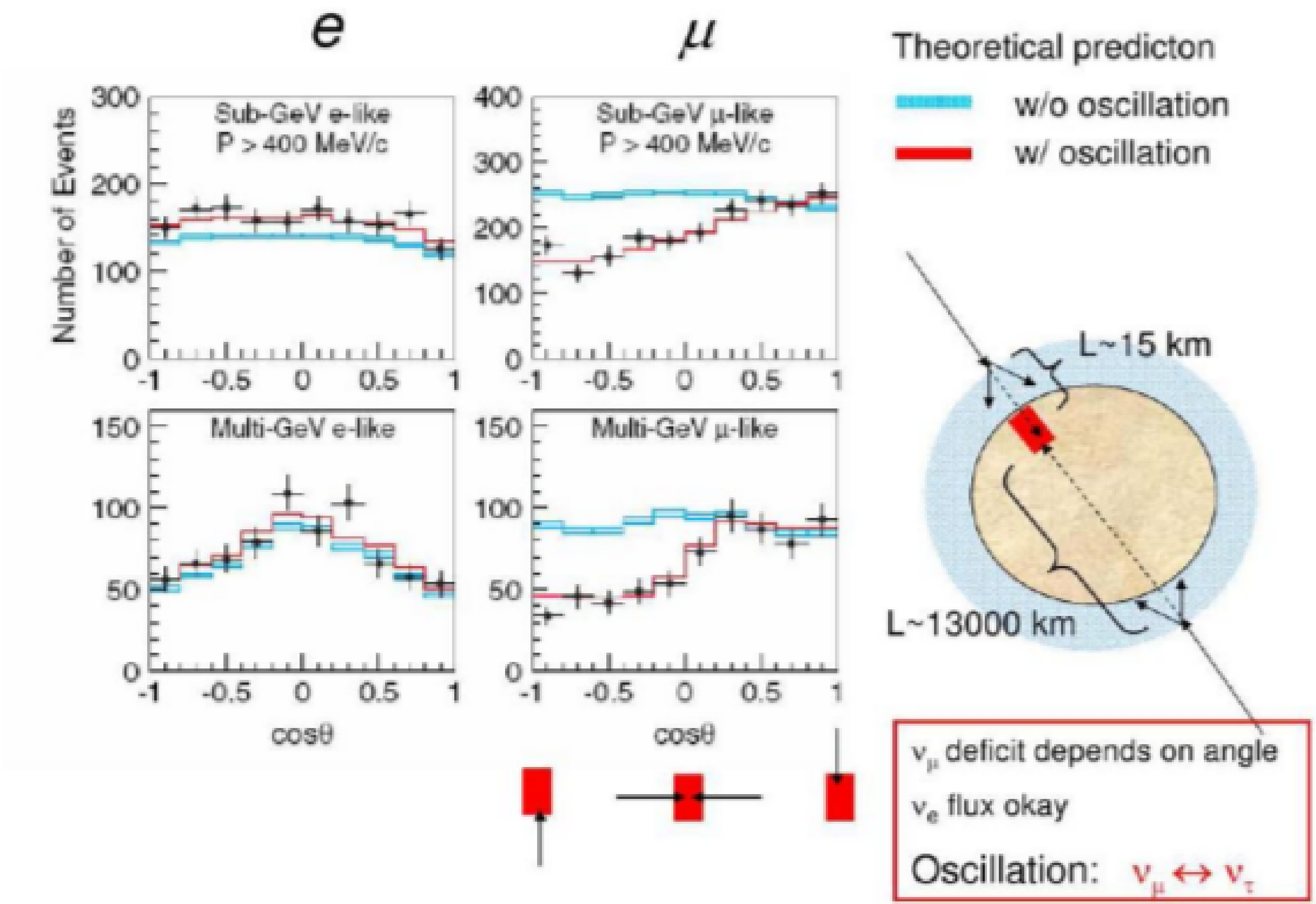
Δm^2(atmospheric) ~ 2-5 10^{-3}

To few muon neutrinos observed → can be explained by oscillation!

For atmospheric and accelerator neutrions (E large, L medium): $\frac{\Delta m_{12}^2 L}{E} \ll 1$

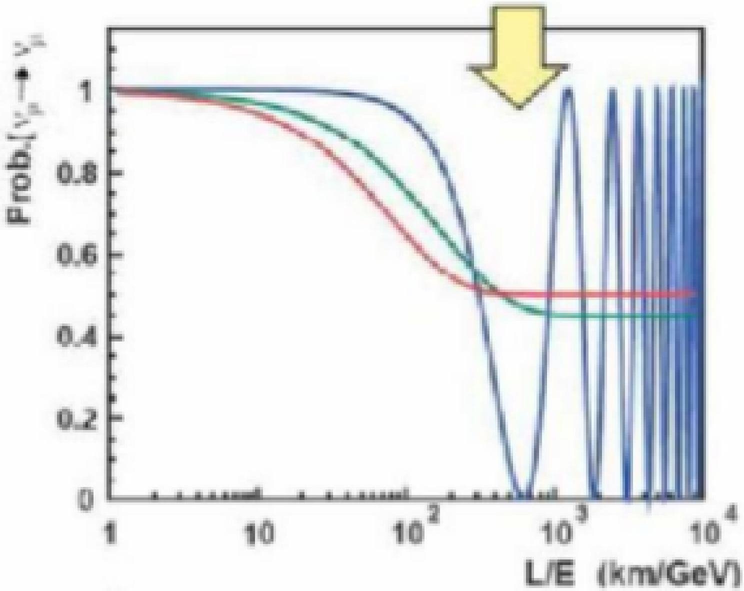
$P(\nu_\mu \to \nu_\tau) = 1 - \sin^2 2\Theta_{23} \sin^2(\frac{\Delta m_{23}^2 L}{4E})$ $\quad$ $P(\nu_e \to \nu_e) \sim 1$

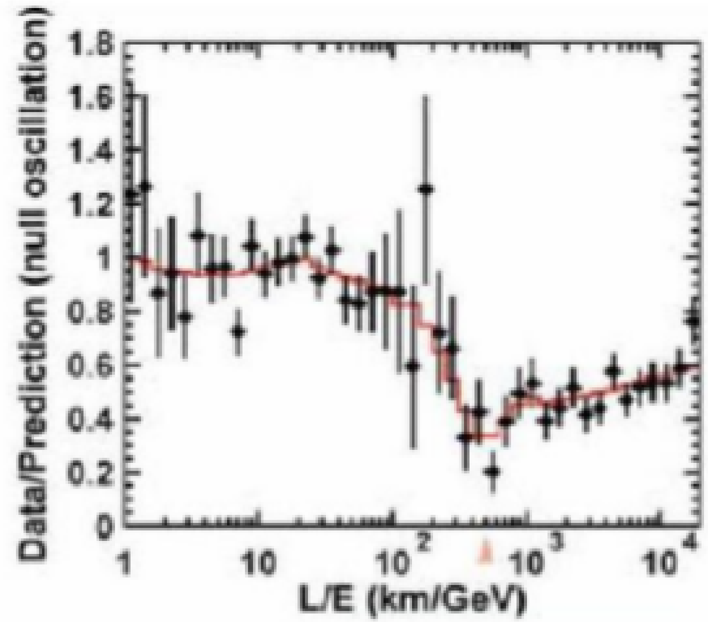
Zenith Angle Dependence of Neutrino Flux



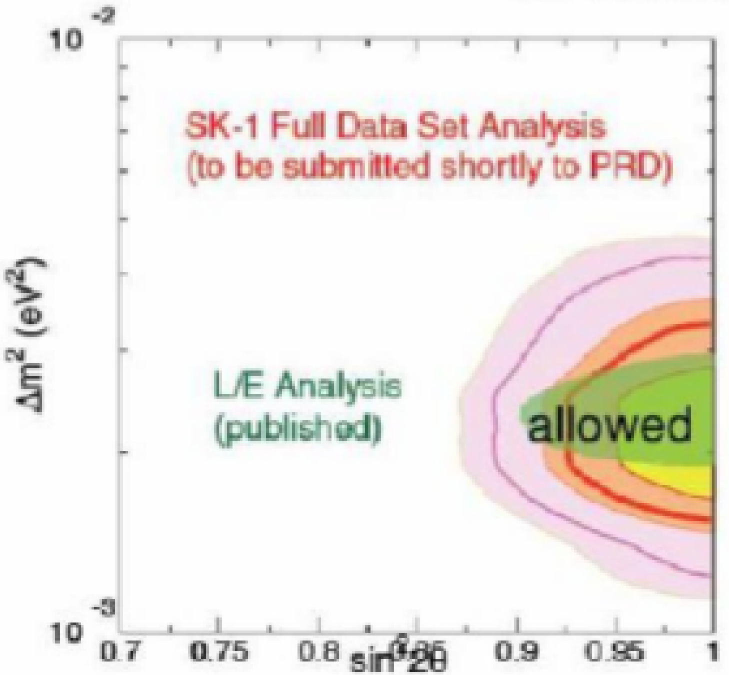
Electron neutrion seem to consist mainly of matter
eigenstate, which has a significant longer oscillation distance both compared to
Distance atmosphere earth and to diameter of the earth.

Oscillating Pattern of Atmospheric Neutrinos





oscillation dip seen at ~500 km/GeV



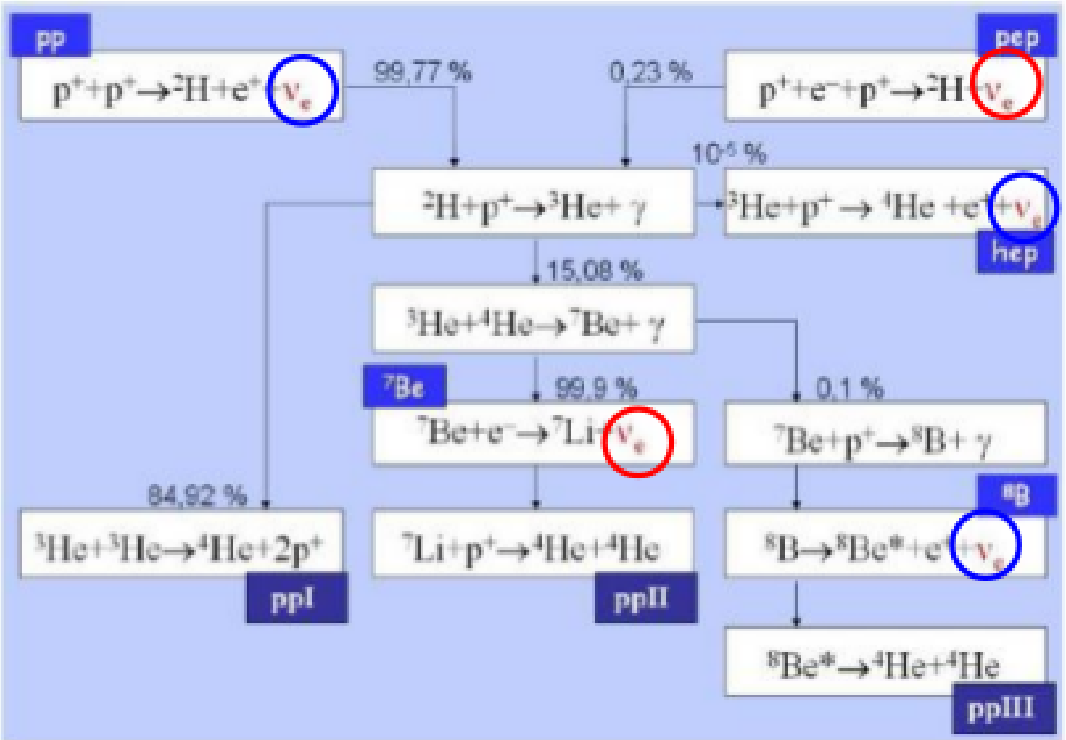
$\nu_\mu \leftrightarrow \nu_\tau$ mixing of atmos. neutrinos

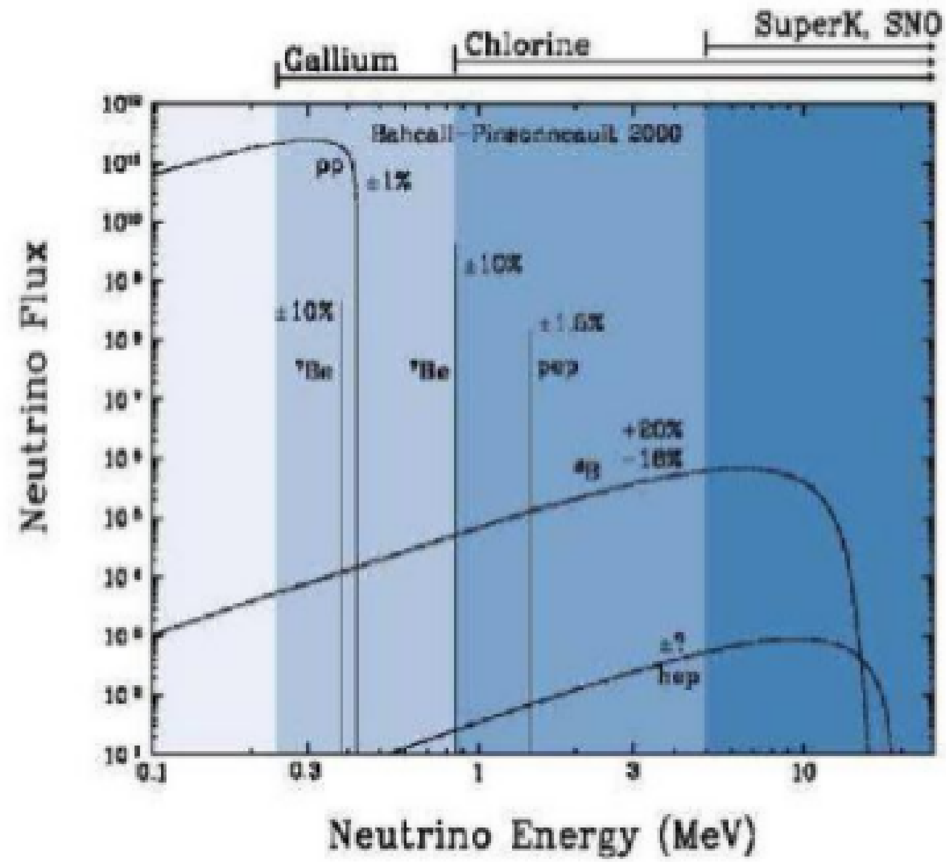
$$\Delta m^2 = (2.4 \pm 0.4) \times 10^{-3}\,\mathrm{eV}$$

$$\sin^2 2\theta > 0.92\ @\ 90\%\ C.L.$$

Slide taken from Neutrino 2004 conference

Solar Neutrinos





5 sources of solar neutrinos:

fixed energy from 2 body decay, continious spectrum from multi-body decay

measured flux depends strongly on detection treashold

Homestake Experiment

Pioneering experiment, started in 1970:

Raymond Davids Jr. (NP 2002)

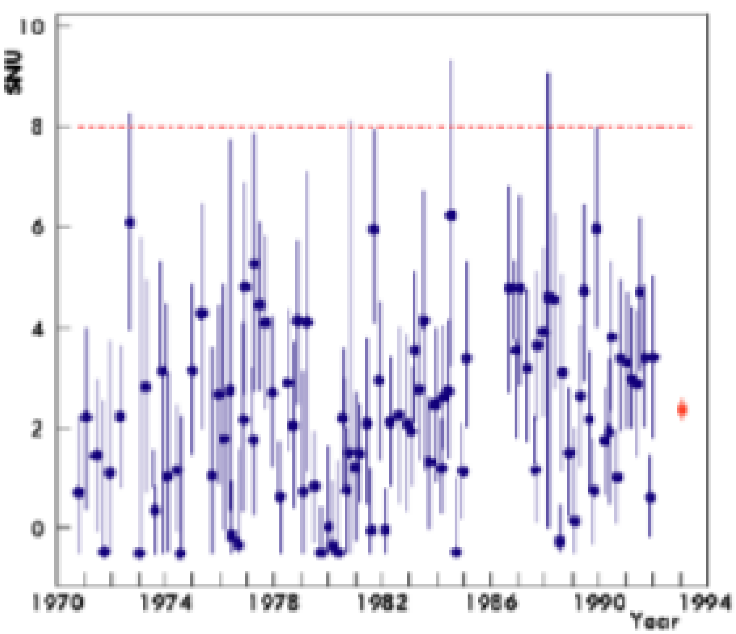
Homestake mine, 1400 m underground

615 t of $C_2CL_4 \sim 2.2 \times 10^{30}$ atoms of ^{37}Cl

Detection via: $\nu_e +^{37} Cl \rightarrow^{37} Ar + e$, treshold (0.8 MeV)

Homestake Experiment

- after 60-70 days ^{37}Ar is extracted by blowing helium gas over a thin layer of ^{37}Cl (^{37}Ar mean decay time: 35 days)
- measured ^{37}Ar decays in helium gas in proportional counters
- no "in-situ" measurement
- average count: one neutrino event every 2 days
- expected number of neutrino events: 1.6 per day



First indication of solar neutrino problem

→ initially results were ignored
„maybe" a mistake in the measurement method

Further Solar Neutrino Experiment

- GALLEX/GNO/SAGE, radiochemic experiments:

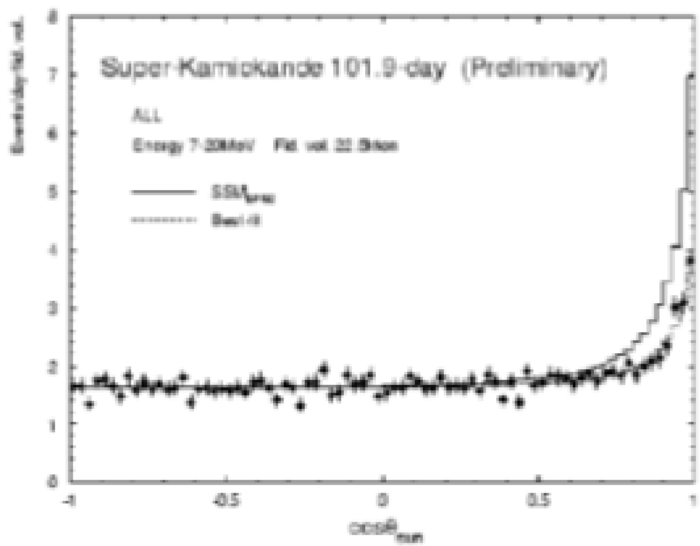
  $\nu_e +^{71} Ga \rightarrow^{71} Ge + e^-$, threshold: 0.2 MeV

  - delayed read out

  - no information on neutrino energy

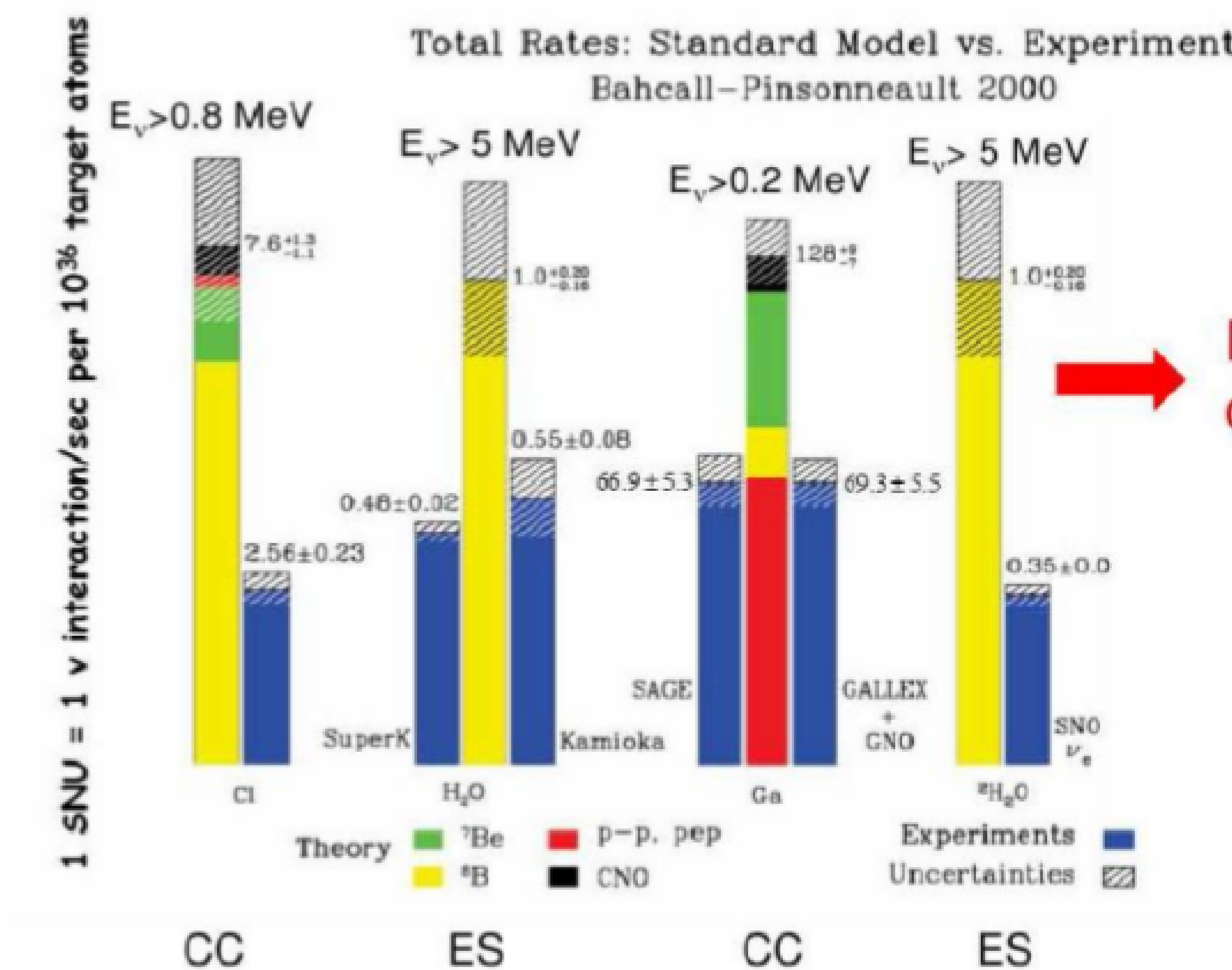
  - no direction information

- (Super)Kammiokande: $\nu_e + e^- \rightarrow \nu_e + e^-$



elastic scattering: direction of electron related to direction of initial neutrino, thus usefull to separate background from neutrinos from the sun.

Solar Neutrino Problem



Neutrino disappearance

CC: Charge current IA
ES: elastic scattering

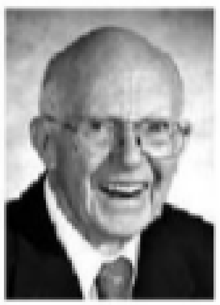
To establish neutrino mixing, need to measure additionally appearance effects!

Nobel Prize in 2002

Homestake experiment

The Nobel Prize in Physics 2002

spokesperson Kamiokande



Raymond Davis Jr.	Masatoshi Koshiba	Riccardo Giaconi

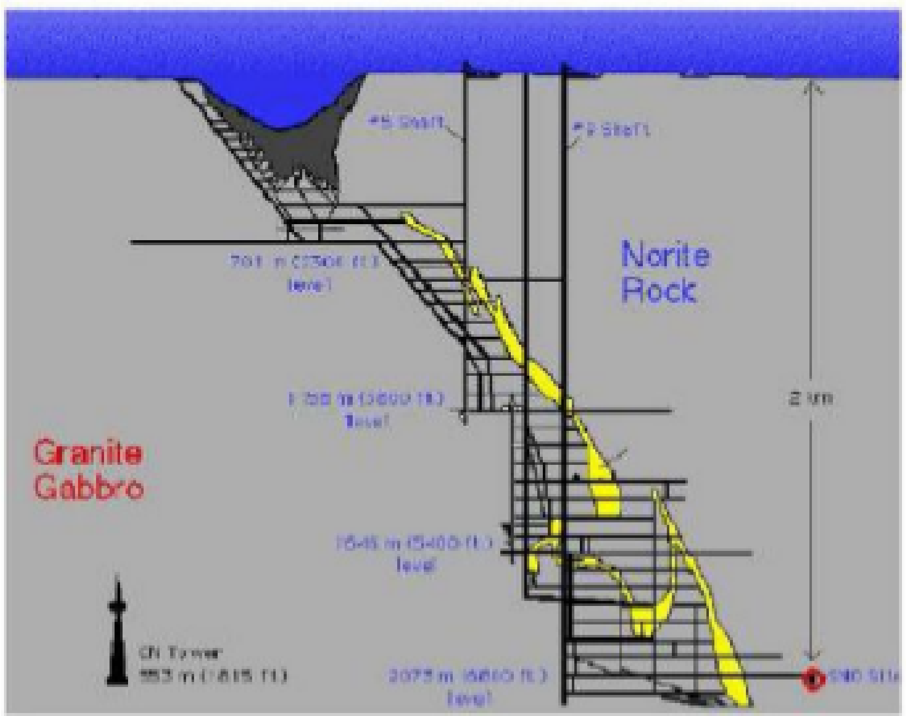
"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

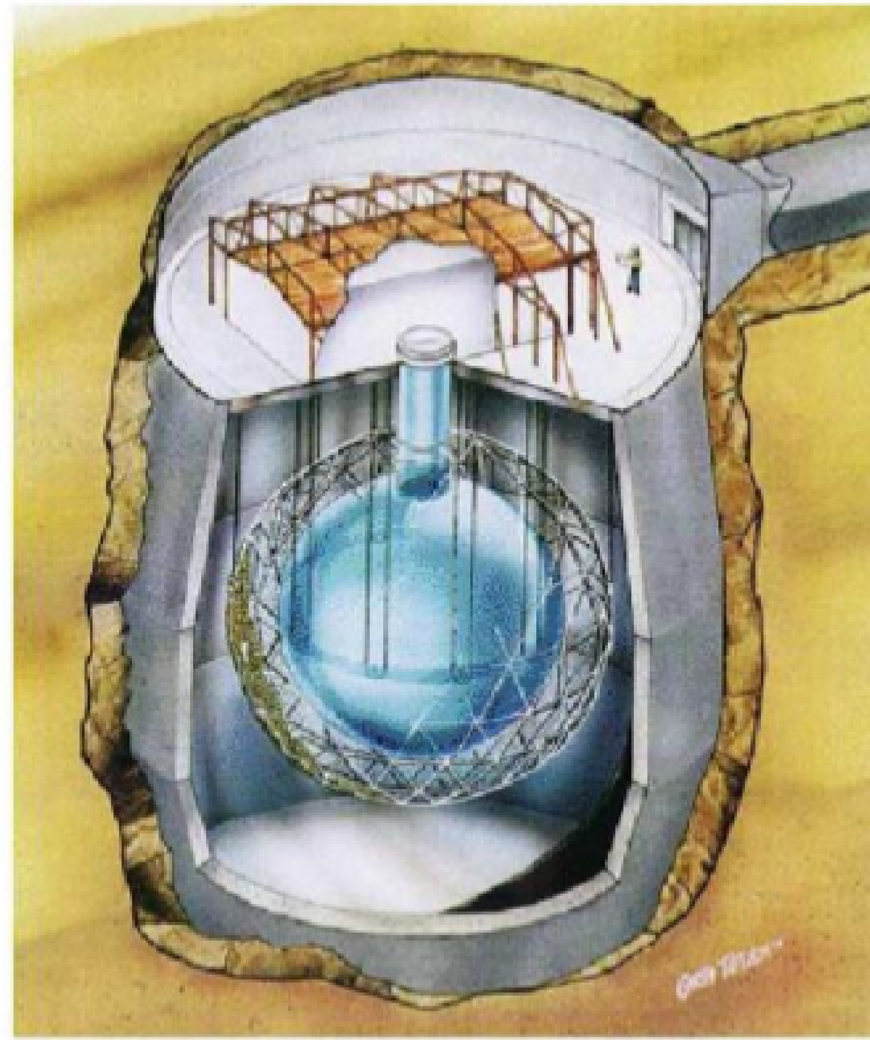
"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"

SNO Experiment

Sudbury Neutrino Observatory:

- 6 m radius transparent acrylic vessel
- 1000 t of heavy water (D_2O)
- 9456 inward looking photo multipliers
- Add 2 t of NaCl to detect neutrons



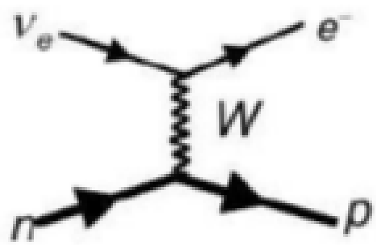


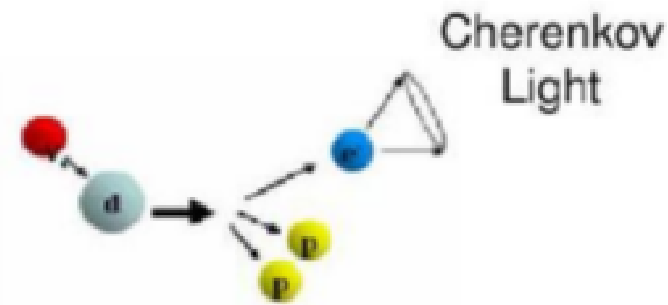
SNO Experiment

Charged current

$$\sigma(\nu_\mu) = \sigma(\nu_\tau) = 0$$

$$\phi_\nu = \phi_{\nu_e}$$

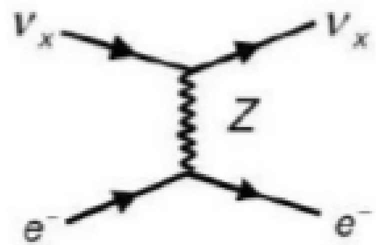


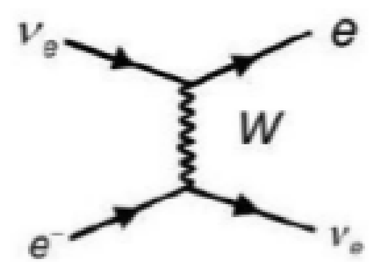


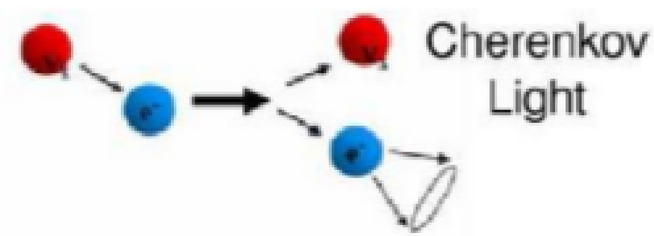
Elastic scattering

$$0.154 \cdot \sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau)$$

$$\phi_\nu = \phi_{\nu_e} + (\phi_{\nu_\mu} + \phi_{\nu_\tau})/6$$



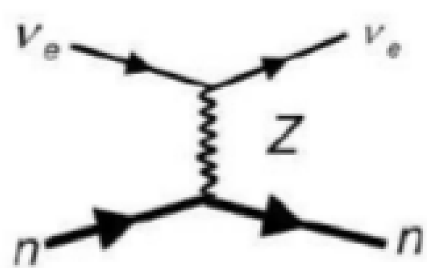


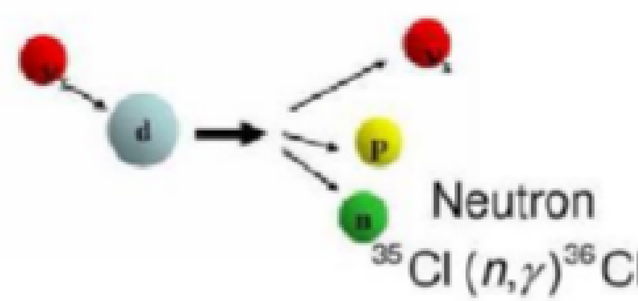


Neutral current

$$\sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau)$$

$$\phi_\nu = \phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}$$



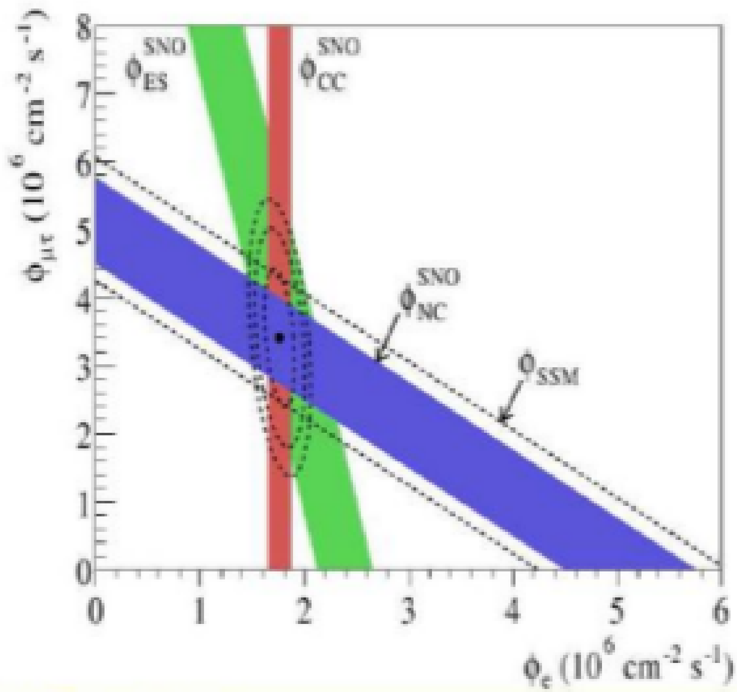


SNO Experiment

$\phi_{CC} < \phi_{ES} < \phi_{NC}$!

appearance of μ/τ neutrinos detected!

$$\phi_{CC}^{SNO} = 1.76^{+0.06}_{-0.05}(stat)^{+0.09}_{0.09}(syst)$$
$$\phi_{ES}^{SNO} = 2.39^{+0.24}_{-0.23}(stat)^{+0.12}_{0.12}(syst)$$
$$\phi_{NC}^{SNO} = 5.09^{+0.44}_{-0.43}(stat)^{+0.46}_{0.43}(syst)$$

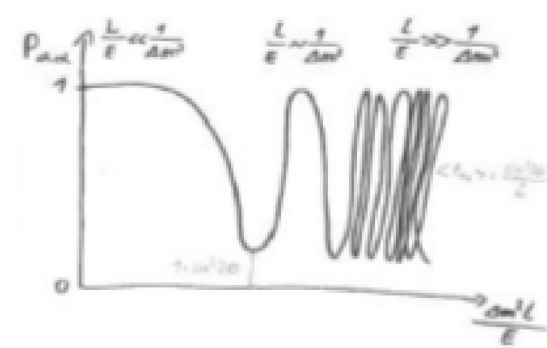


Electron neutrino flux is too low: $P_{\nu_e \to \nu_e} = (35 \pm 2)\%$

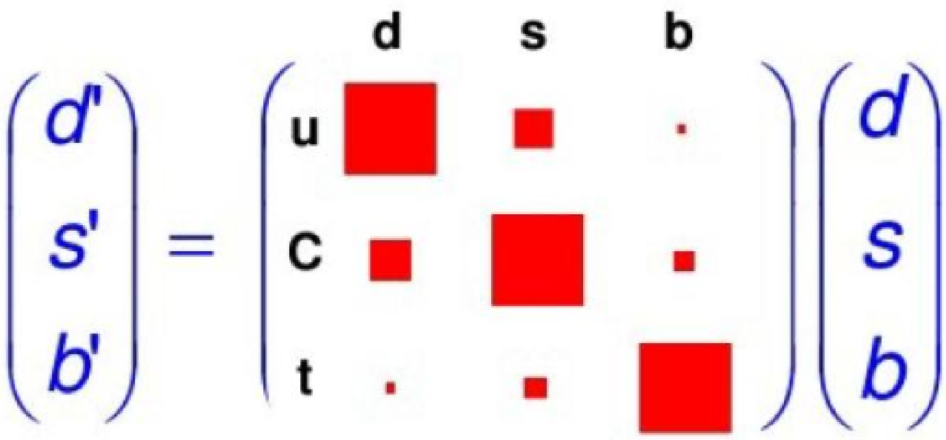
Total flux of neutrinos is correct $\longrightarrow$ Interpreted as $\nu_e \leftrightarrow \nu_\mu$ or $\nu_e \leftrightarrow \nu_\tau$ oscillation

But in case of simple "vacuum oszillation":

$$P_{\nu_e \to \nu_e} = 1 - \frac{1}{2}\sin^2 2\theta = 50\%$$



V-A Coupling for Quarks



Most preferred transitions with in the same quark family.

$$|V_{CKM}| = \begin{pmatrix} 0.975 & 0.225 & 0.00364 \\ 0.225 & 0.975 & 0.0405 \\ 0.00820 & 0.0405 & 1 \end{pmatrix}$$

In first order only V_{td} and V_{ub} are complex numbers.
CKM matrix and their complex elements important for meson mixing and CP violation

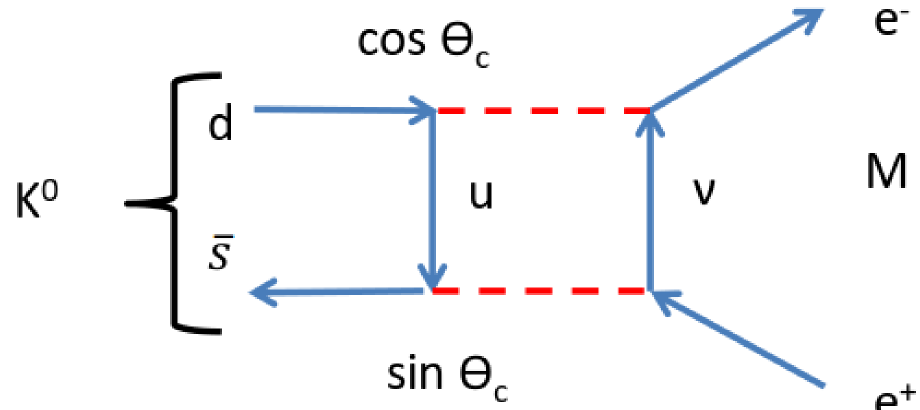
Missing FCNC GIM mechanism

In early 70s only 3 quarks where known (u,d,s)

$$\binom{u}{d'} = \binom{u}{\cos\Theta_c\, d + \sin\Theta_c\, s}$$

$$\binom{d'}{s'} = \begin{pmatrix} \cos\Theta_c & \sin\Theta_c \\ -\sin\Theta_c & \cos\Theta_c \end{pmatrix} \binom{d}{s}$$

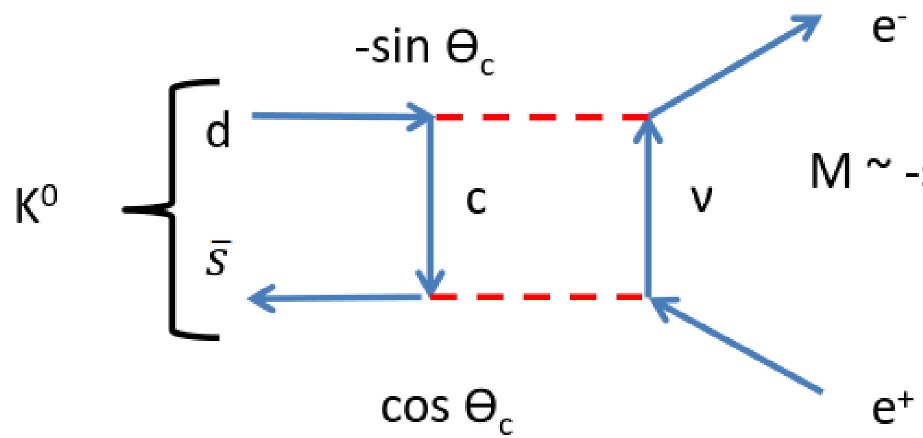
$$\frac{BR(K\to\mu\mu)}{BR(K\to all)} = 7.2 \pm 0.5\ 10^{-9}$$



M ~ $\sin\Theta_c \cos\Theta_c$

Proposal by Glashow, Ilianopoulus, Miani (GIM) 1970:

➡ There is a fourth quark which build together with the s quar a second doublet



M ~ $-\sin\Theta_c \cos\Theta_c$

$$\binom{c}{s'} = \binom{c}{-\sin\Theta_c\, d + \cos\Theta_c\, s}$$

➡ Prediction of a fourth quark!

Discovery of J/Ψ Resonance

- SLAC-Mark-I experiment (see tau discovery)
  group leader Burton Richter

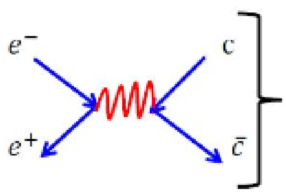
$e^+ + e^- \rightarrow \Psi$

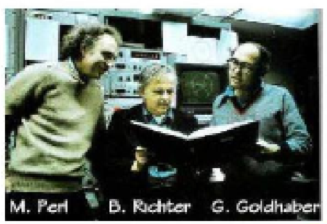
↳ multi hadrons

↳ e^+e^-

↳ $\mu^+\mu^- + K^+K^- + \pi^+\pi^-$

$m(\psi) = 3.105 \pm 0.003$ GeV, $\Gamma(\psi) < 1.3$ MeV





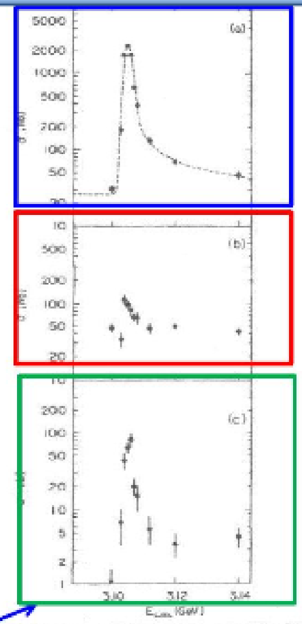


FIG. 1. Cross section versus energy for (a) multi-hadron final states, (b) e^+e^- final states, and (c) $\mu^+\mu^-$, $\pi^+\pi^-$, and K^+K^- final states. The curve in (a) is the ...

performed scan of $E_{CMS}(e^+ + e^-)$

- BNL (Berkly National Laboratory): proton beam on fix target (Berilium)
  group leader Samuel Ting

$p\ (28\ \text{GeV}) + Be \rightarrow J + X$

↳ e^+e^-

$m(J) = 3.1$ GeV

Γ: consistent with detector resolution (20 MeV)

丁肇中簡介

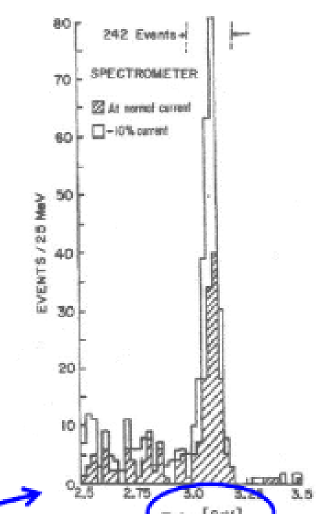


FIG. 2. Mass spectrum showing the existence of J. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

reconstructed invariant mass of final state particles

Direct discovery of charm quark 5 years later than indirect prediction

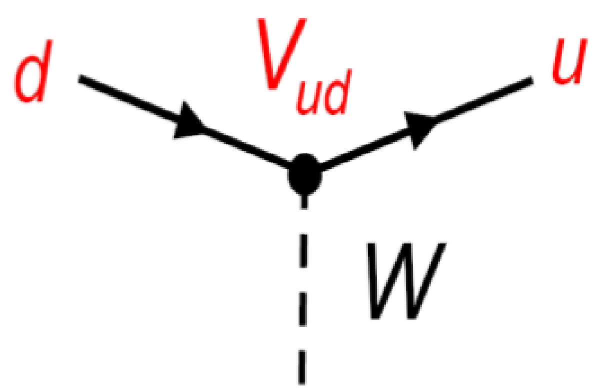
CKM Matrix

CKM matrix is consequence of introduction of Yukawa term to Lagrangian:

Charged currents: $J^{+}_{\mu} \propto \left(\bar{u}, \bar{c}, \bar{t}\right) \left(1 - \gamma_5\right) \gamma_\mu V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$

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

flavour CKM matrix mass



18 parameters (9 complex elements)

-5 relative quark phases (unobservable)

-9 unitarity conditions

________________-

= 4 independent parameters 3 Euler angles and 1 Phase

Phase is only source of CPV in SM, requires third quark family (Nobel Prize 2008)

5 relative phases

Charged currents: $J^+_\mu \propto \left(\bar{u}, \bar{c}, \bar{t}\right)\left(1-\gamma_5\right)\gamma_\mu V_{CKM}\begin{pmatrix} d \\ s \\ b \end{pmatrix}$

Lagrangian insensitive to phases of left-handed fields, possible redefinition:

$$u_L \to e^{i\phi_u} u_L \quad c_L \to e^{i\phi_c} c_L \quad t_L \to e^{i\phi_t} t_L$$
$$d_L \to e^{i\phi_d} d_L \quad s_L \to e^{i\phi_s} s_L \quad b_L \to e^{i\phi_b} b_L$$

$$V_{CKM} \to \begin{pmatrix} e^{i\phi_u} & 0 & 0 \\ 0 & e^{i\phi_c} & 0 \\ 0 & 0 & e^{\phi_t} \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} e^{-i\phi_d} & 0 & 0 \\ 0 & e^{-i\phi_s} & 0 \\ 0 & 0 & e^{-i\phi_b} \end{pmatrix}$$

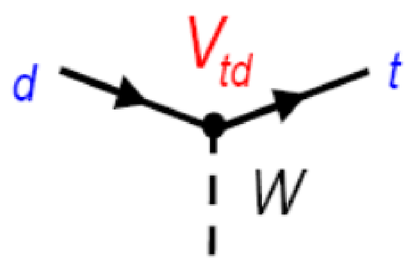
or $V_{\alpha\beta} \to e^{\phi_\beta - \phi_\alpha} V_{\alpha\beta}$

5 unobservable phase differences $\phi_\beta - \phi_\alpha$.

CKM under CP Transformation

Quarks

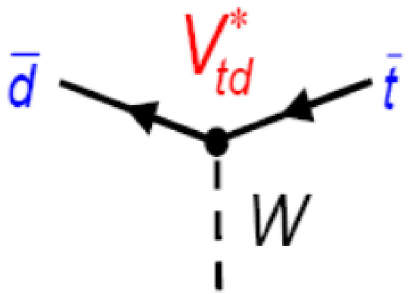
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



----- CP -----

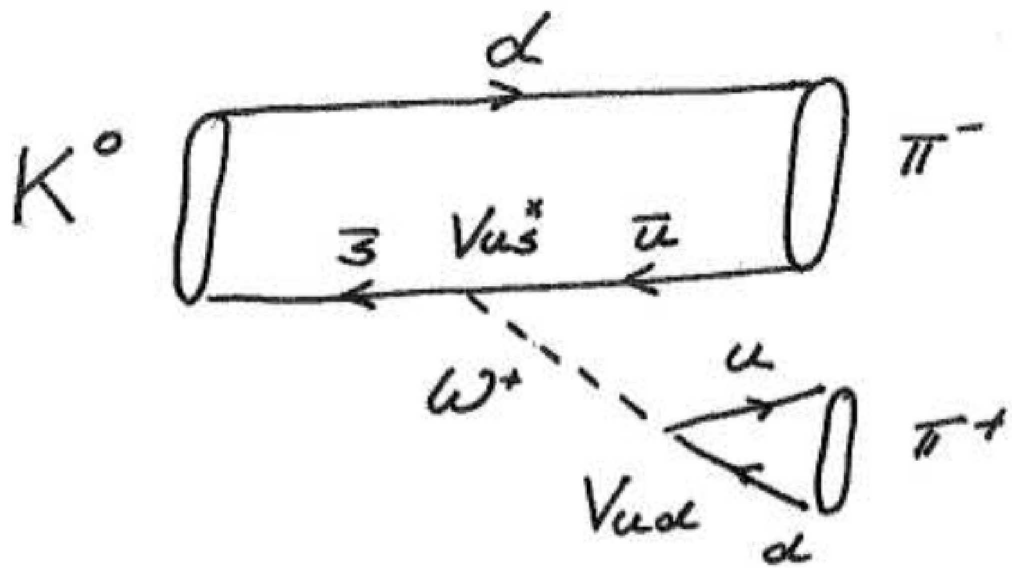
Anti-quarks:

$$\begin{pmatrix} \bar{d}' \\ \bar{s}' \\ \bar{b}' \end{pmatrix} = \begin{pmatrix} V^*_{ud} & V^*_{us} & V^*_{ub} \\ V^*_{cd} & V^*_{cs} & V^*_{cb} \\ V^*_{td} & V^*_{ts} & V^*_{tb} \end{pmatrix} \begin{pmatrix} \bar{d} \\ \bar{s} \\ \bar{b} \end{pmatrix}$$



Weak (CKM) phases change sign under CP transformation!

Weak and Strong Phases



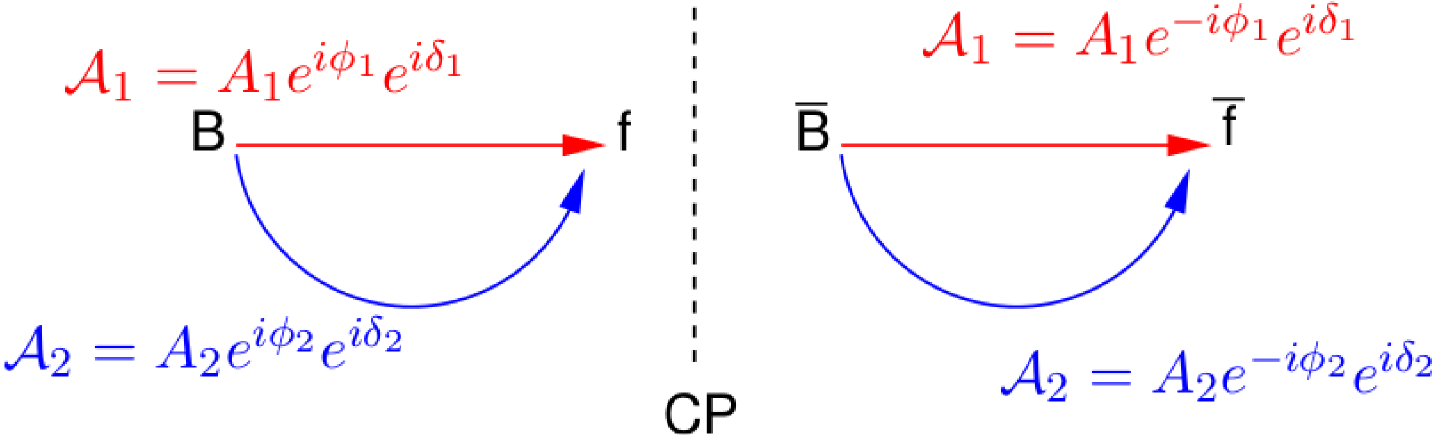
Weak phases are related to involved CKM elements: $\phi_{weak} = arg(V^*_{us}V_{ud})$

Strong phases δ comes often (but not always) from the hadronisation.

Definition of strong phase:

phase which doesn't change sign under CP transformation.

CP Violation



$$|\mathcal{A}|^2 =$$
$$A_1^2 + A_2^2 + 2A_1A_2\cos(\Delta\phi + \Delta\delta)$$

$$|\mathcal{A}|^2 =$$
$$A_1^2 + A_2^2 + 2A_1A_2\cos(-\Delta\phi + \Delta\delta)$$

$\mathcal{A}_1$ and $\mathcal{A}_2$ need to have different weak phases ϕ and different strong phases δ.

For sizable (measurable) effects both amplitudes should have about same size,

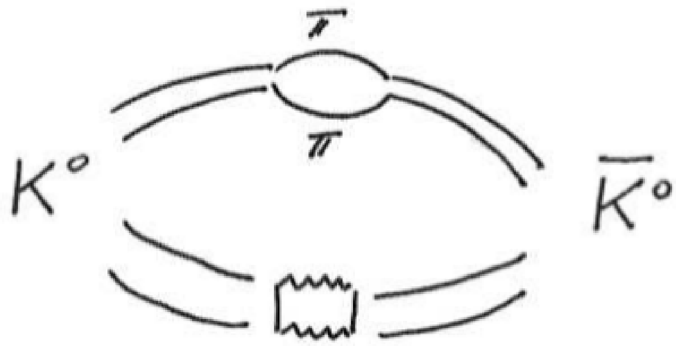
and both phase differences have to be sizable.

To conclude on weak phases, strong phases need to be known/measured.

CPV in Kaon System

Interfering amplitudes which cause CPV in mixing:

long range contribution $\Delta\Gamma$



short range contribution Δm

Interfering amplitudes which cause CPV in decay: