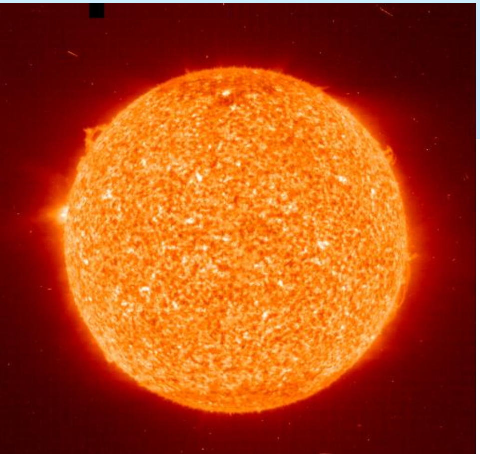
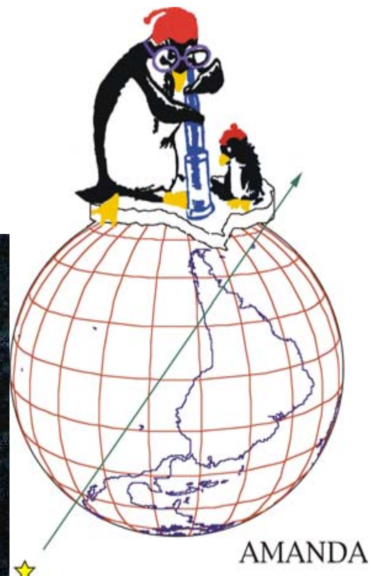
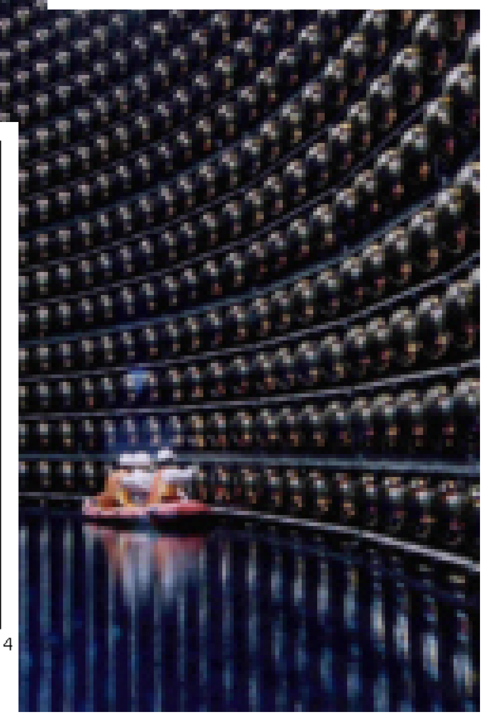
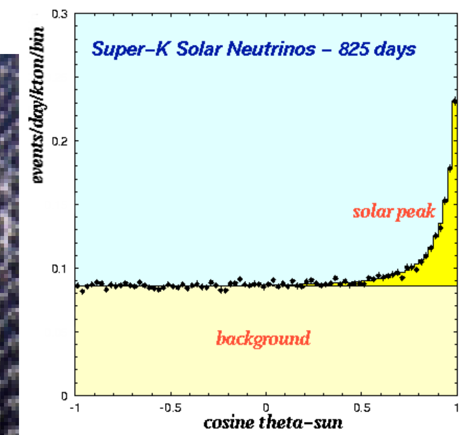
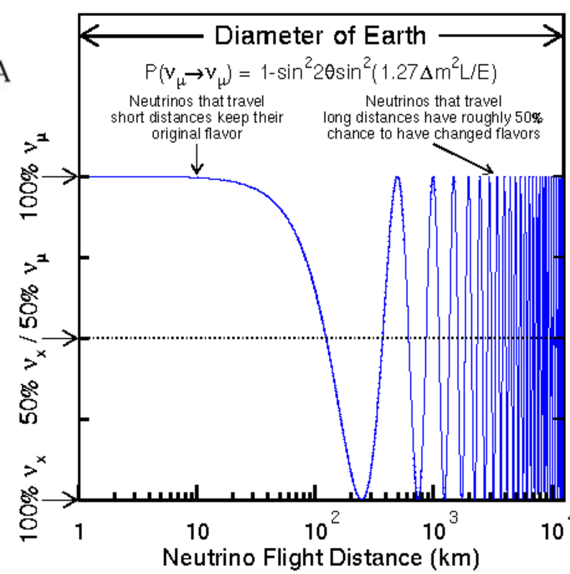
5. Neutrinos



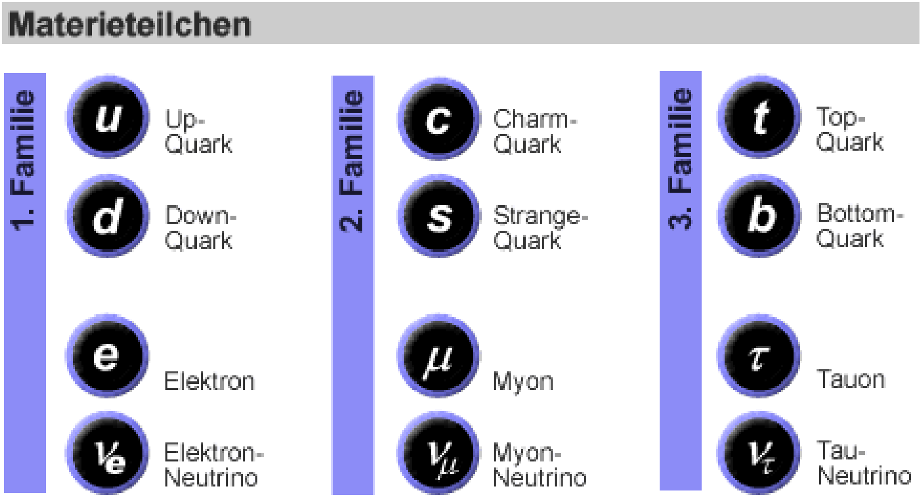

AMANDA




Super-K Solar Neutrinos – 825 days
events/day/kton/bin
solar peak
background
cosine theta-sun
0.3
0.2
0.1
0
-1
-0.5
0
0.5
1


Diameter of Earth
$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$
Neutrinos that travel short distances keep their original flavor
Neutrinos that travel long distances have roughly 50% chance to have changed flavors
$100\%\ \nu_\mu$
$50\%\ \nu_x\ /\ 50\%\ \nu_\mu$
$100\%\ \nu_x$
1
10
10^2
10^3
10^4
Neutrino Flight Distance (km)

Neutrinos: Standard Model and Beyond

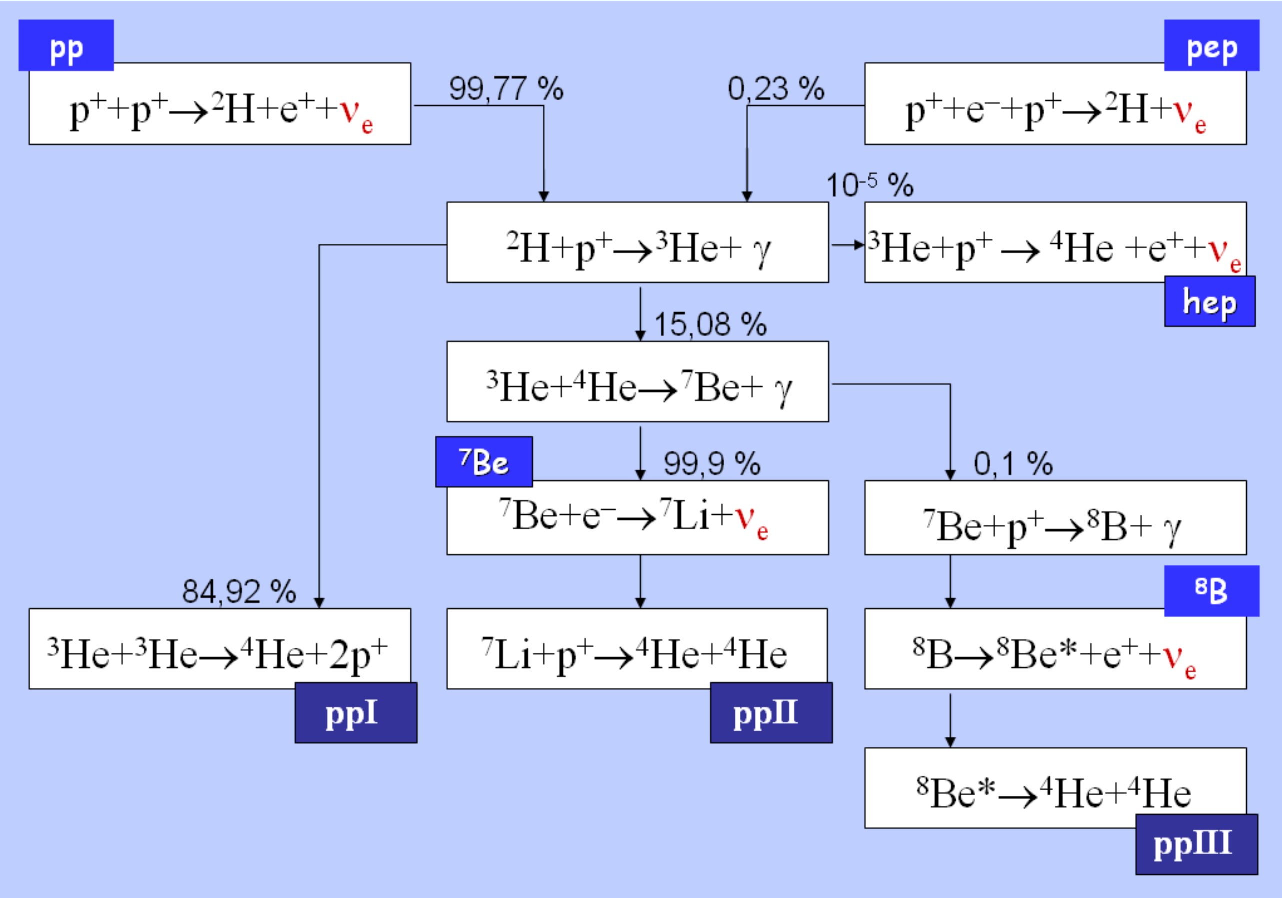


- ν in $SU(2)_L$ dubletts
- Mixing $\Rightarrow$ masses $\Rightarrow$ - flavour eigenstates
  - mass eigenstates
- $\nu = \overline{\nu} \Rightarrow$ double β decay possible

Solare Neutrinos

$$4p + 2e^- \rightarrow {}^4_2He + 2\upsilon_e + 26.73MeV$$

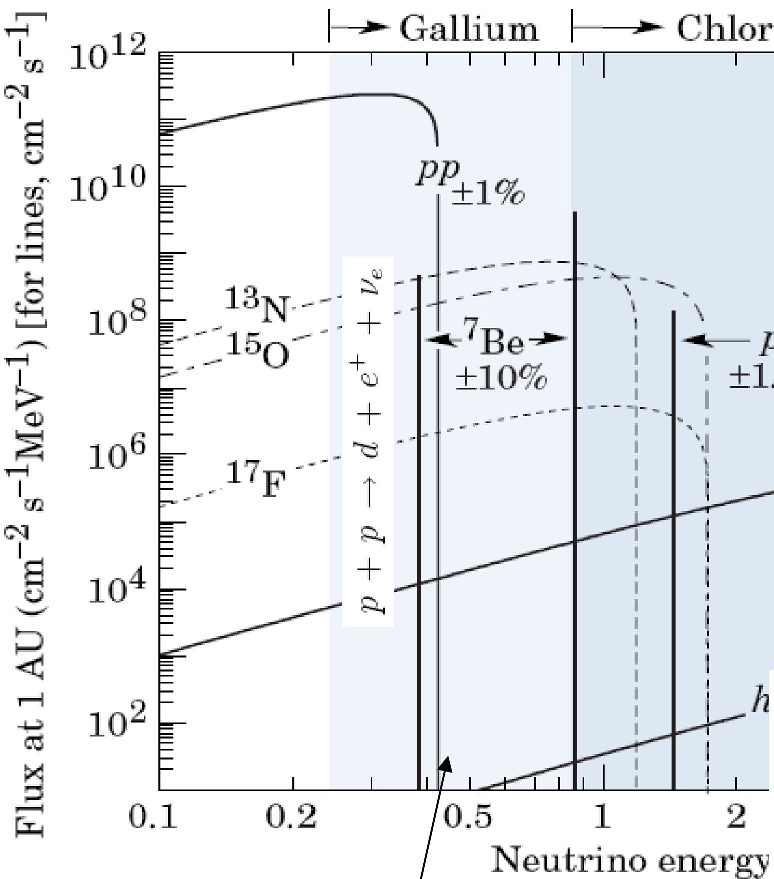
$$\langle E_\nu \rangle = 0.26MeV$$

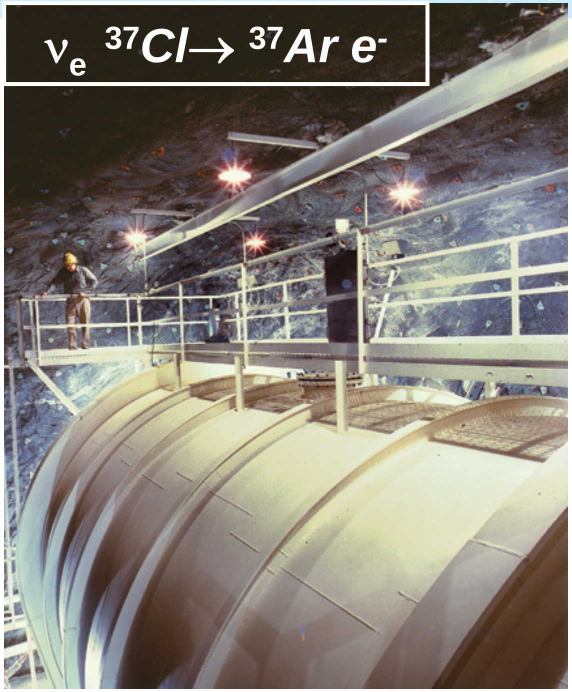


Im Mittel: ~ 13 MeV Sonnenleistung pro pp-Neutrino

Solarkonstante: S = 8.5 x 10^{11} MeV$cm^{-2}s^{-1}$ → Φ_ν = S/<E_ν> ~ 6.5 x 10^{10} $cm^{-2}s^{-1}$

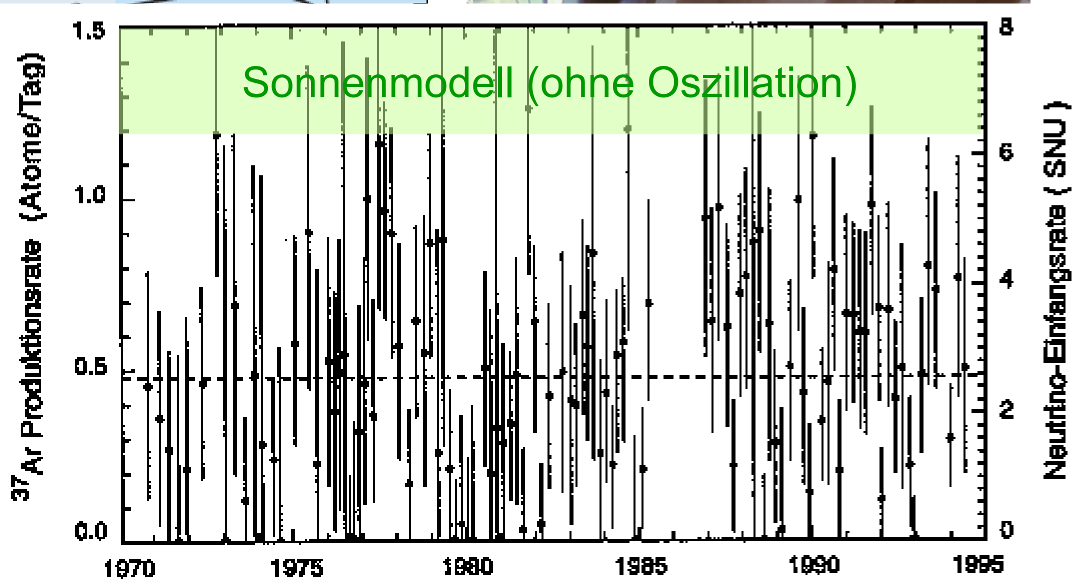
Sonnenneutrino-Defizit



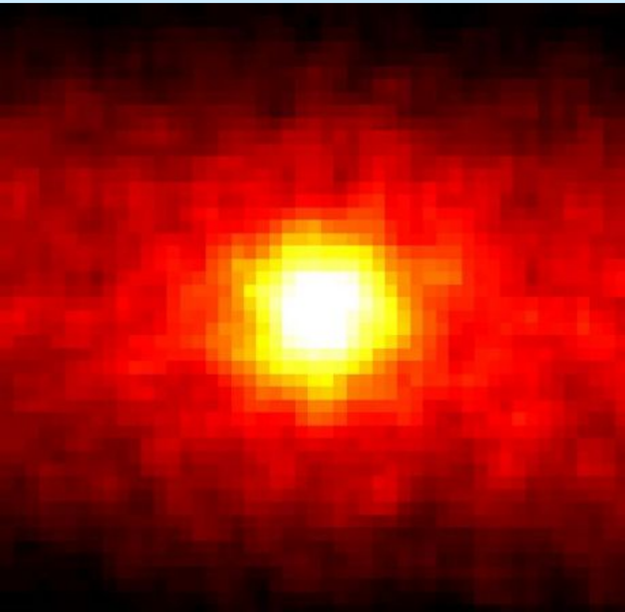


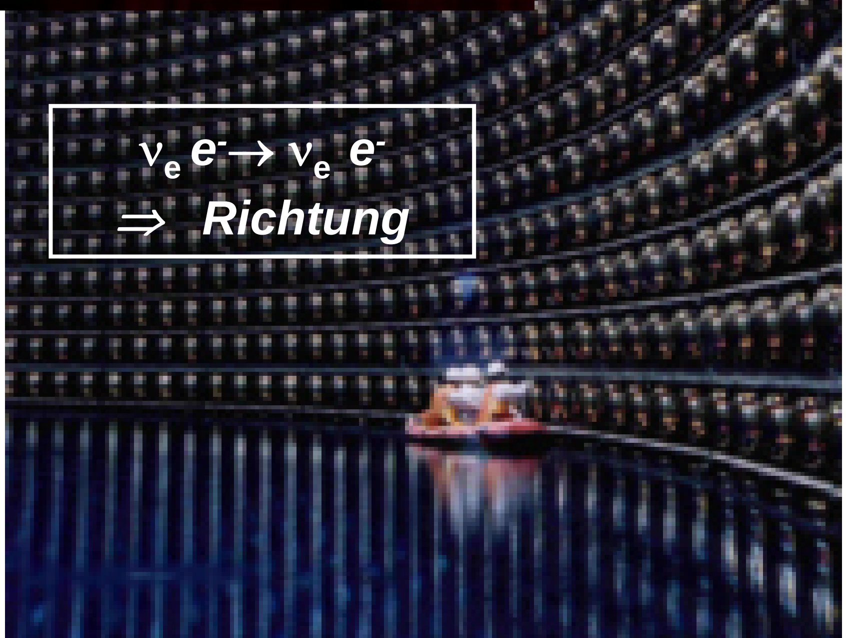
Gallex, Sage

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



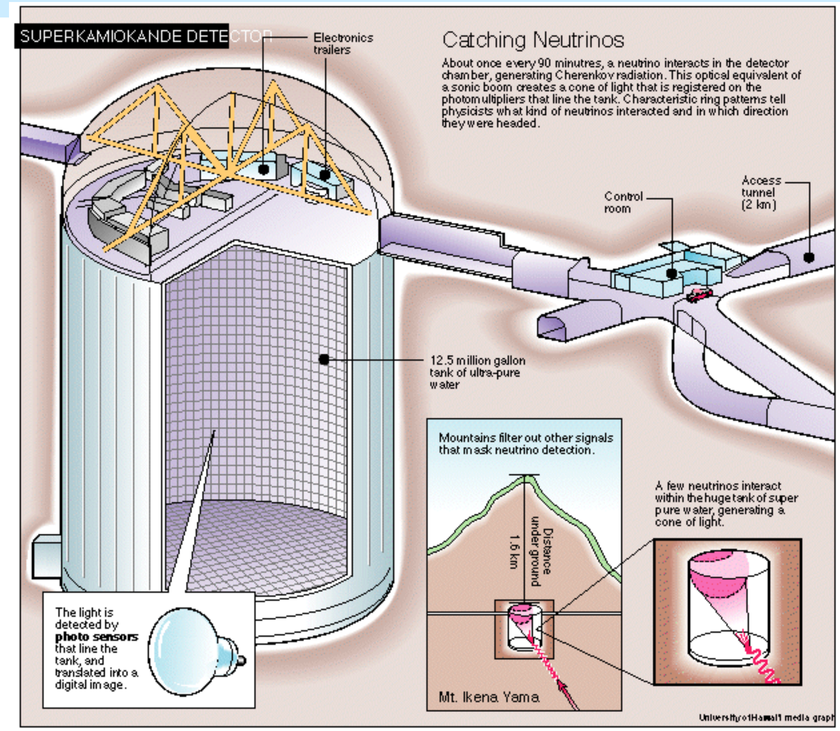
Super-Kamiokande

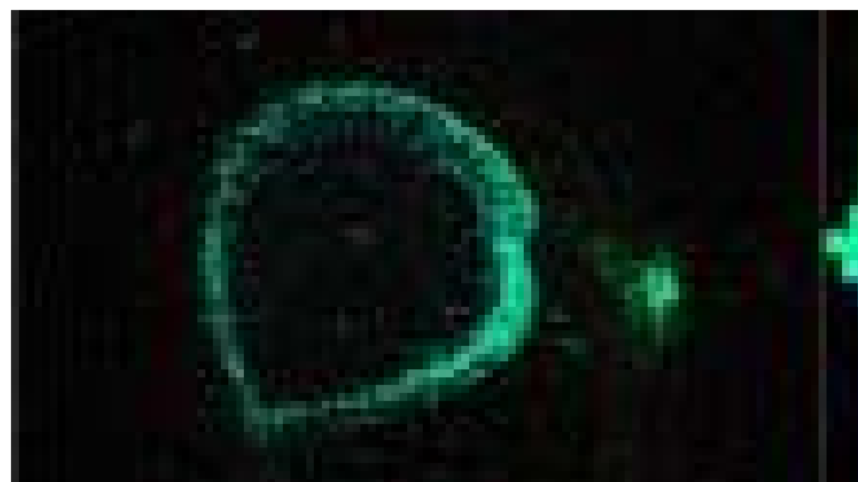




$\nu_e\, e^- \rightarrow \nu_e\, e^-$

$\Rightarrow$ ***Richtung***

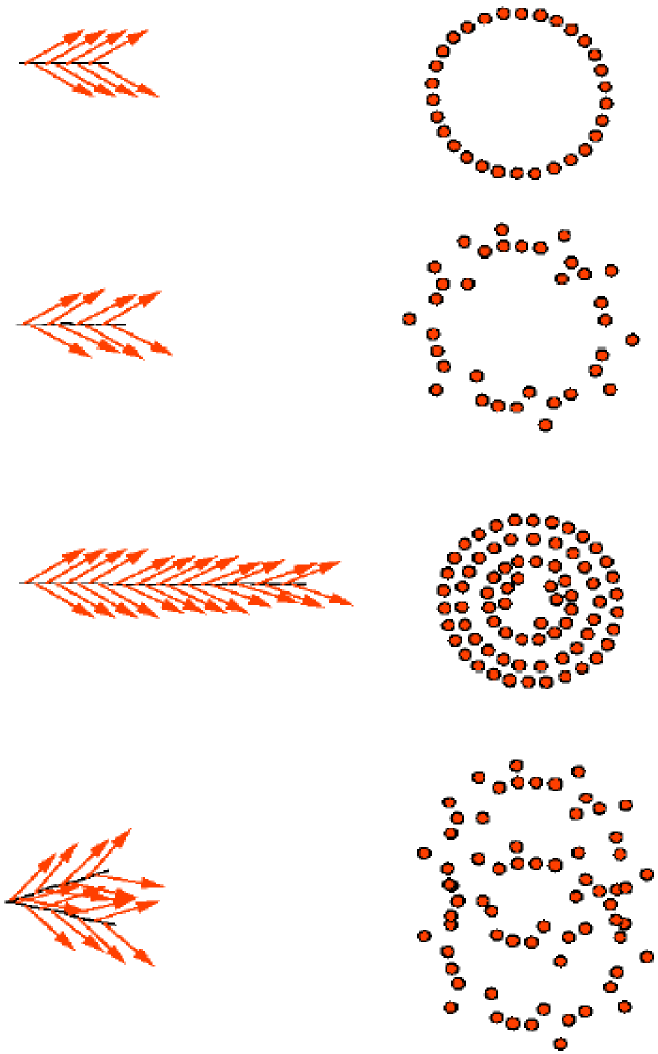




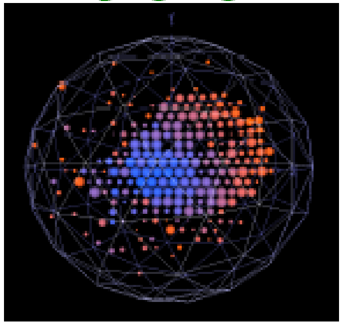
Event Topologies

MiniBooNE

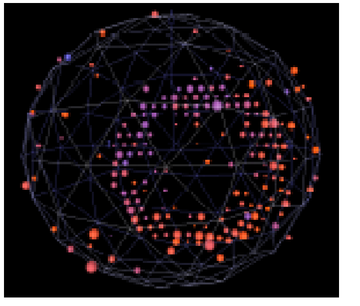
From side		Ring
short track, no multiple scattering		Sharp Ring
electrons: short track, mult. scat., brems.		Fuzzy Ring
muons: long track, slows down		Sharp Outer Ring with Fuzzy Inner Region
neutral pions: 2 electron-like tracks		Two Fuzzy Rings



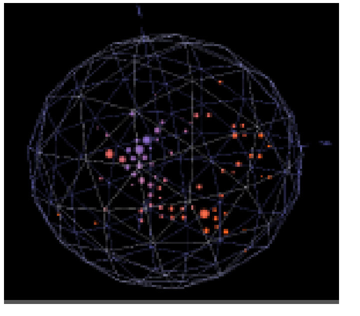
Through-going Muon



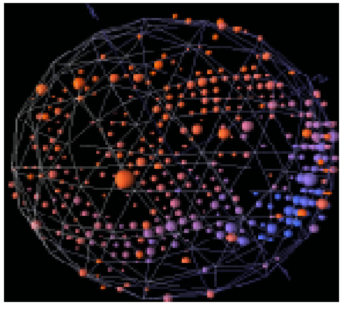
Stopping Muon



Electron



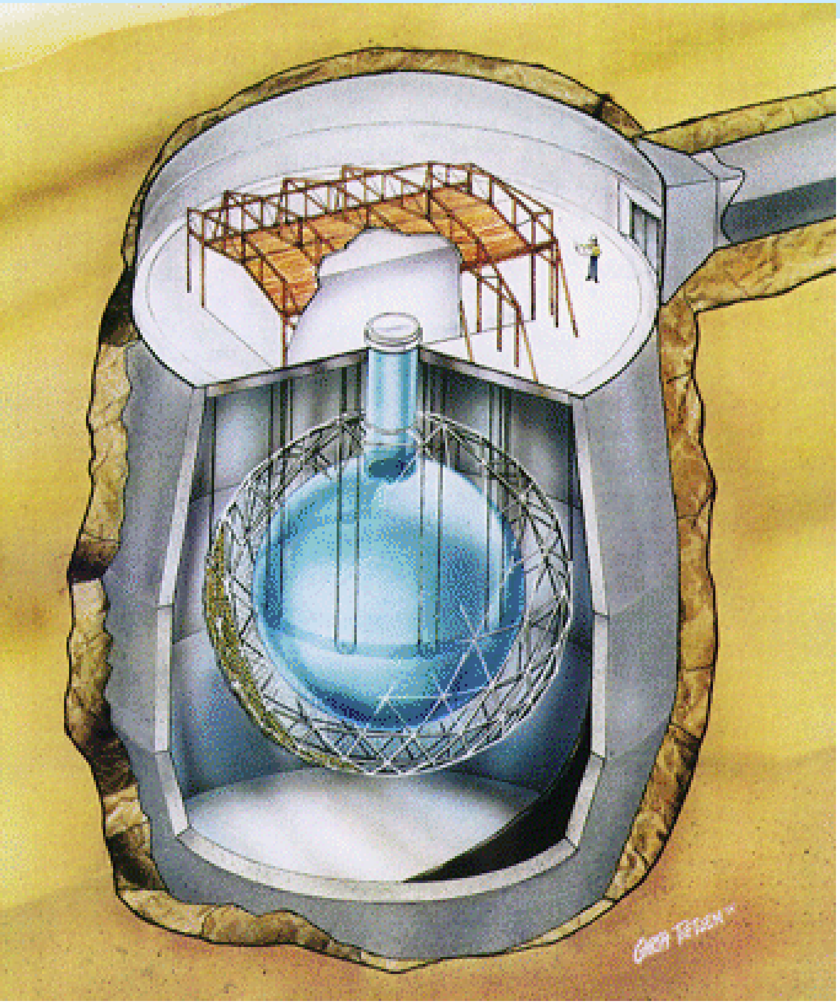
Neutral Pion



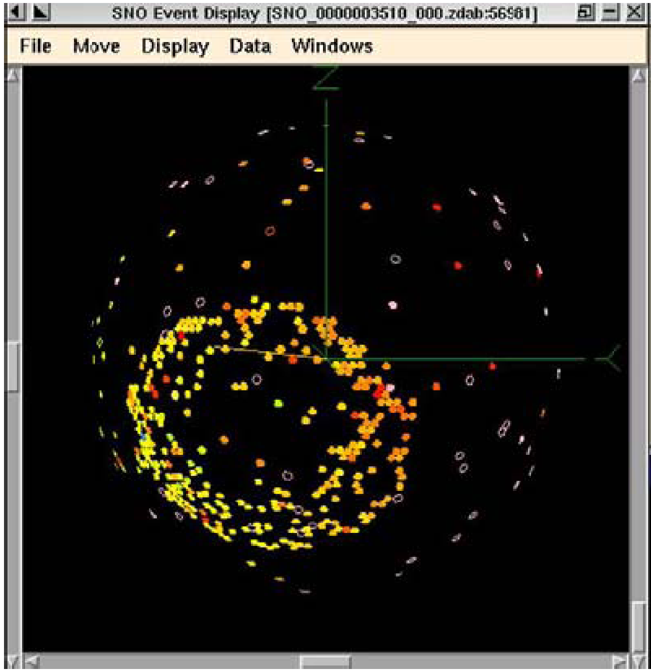
ν_e-Defizit von der Sonne

	Homestake	Kamiokande	Super-Kamiokande	Gallex	Sage
Schwelle [MeV]	0.814	7.5	7.0	0.233	0.233
Laufzeit	1970 - 1994	1987 - 1995	1996 - 1998	1991 - 1997	1990 - 1997
Vorhersage	$7.7^{+1.2}_{-1.0}$U	$5.15^{+0.98}_{-0.72}$	$5.15^{+0.98}_{-0.72}$	129^{+8}_{-6}	129^{+8}_{-6}
Experiment	2.56 ± 0.22	2.82 ± 0.38	2.42 ± 0.08	77.5 ± 8	66.6 ± 8
S_{th}/S_{exp}	3.0	1.8	2.1	1.7	1.9

SNO: totaler ν-Fluss von der Sonne



Sudbury Neutrino Observatory

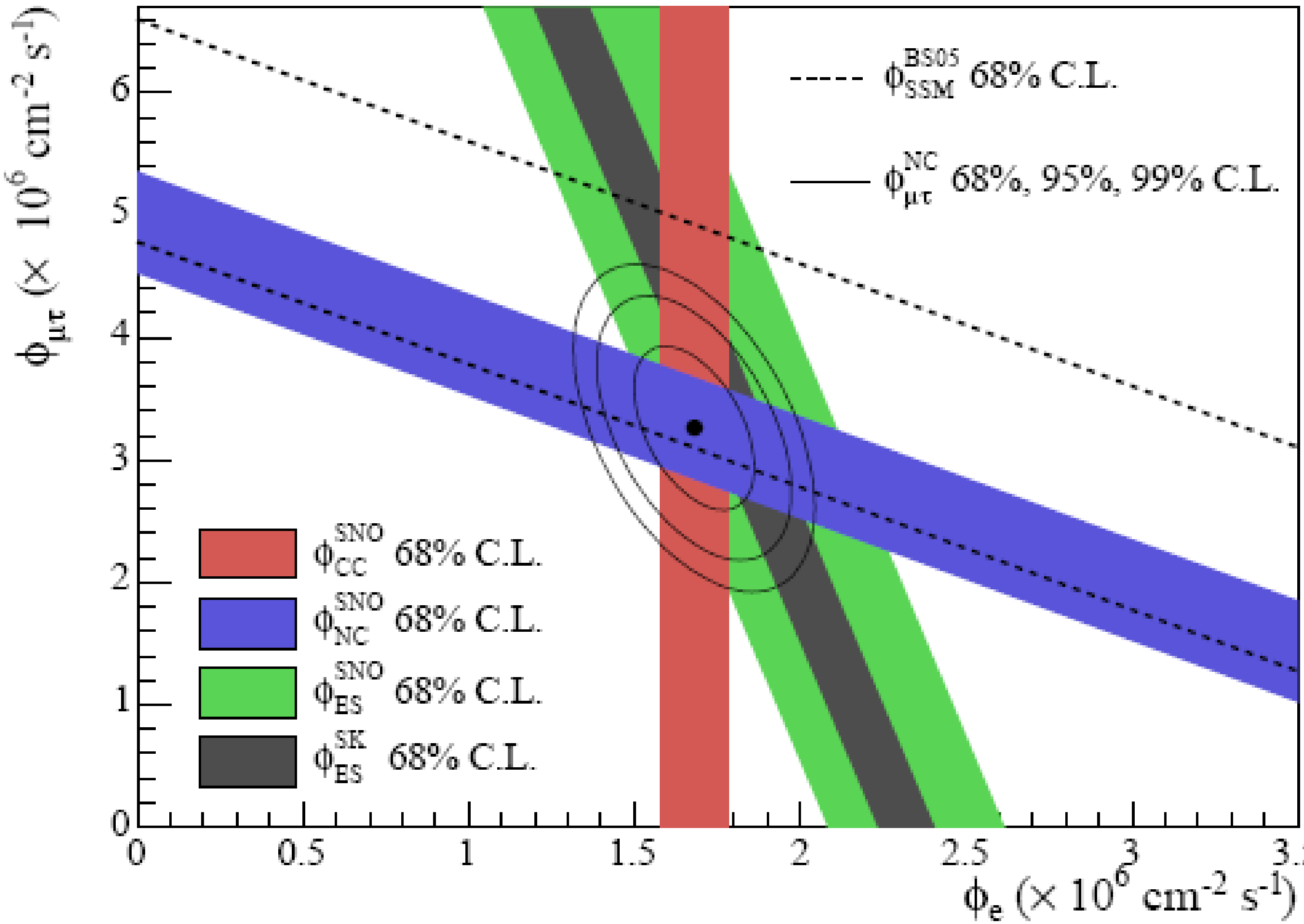


Messe ^{8}B-ν's in D_2O
CC und NC
(had.& lept.)

$$
\begin{array}{llll}
\nu_e + d & \rightarrow & e^- + p + p & \text{(CC)} \\
\nu_l + d & \rightarrow & \nu_l + p + n & \text{(NC)} \\
\nu_l + e^- & \rightarrow & \nu_l + e^- & \text{(ES)}
\end{array}
$$

$$
\frac{\phi(\nu_e)}{\phi(\nu_e) + \phi(\nu_{\mu,\tau})} = 0.340 \pm 0.023 \pm 0.030
$$

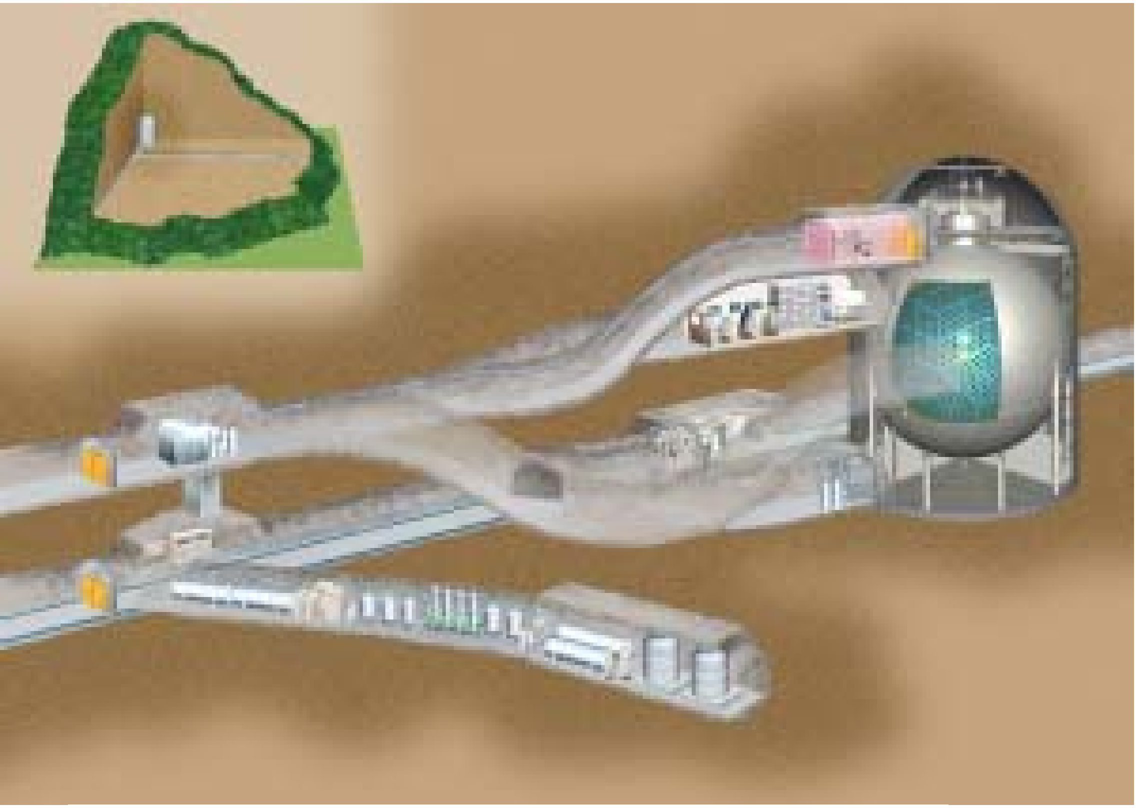
SSM verglichen mit $\Phi_{\mu\tau} - \Phi_e$



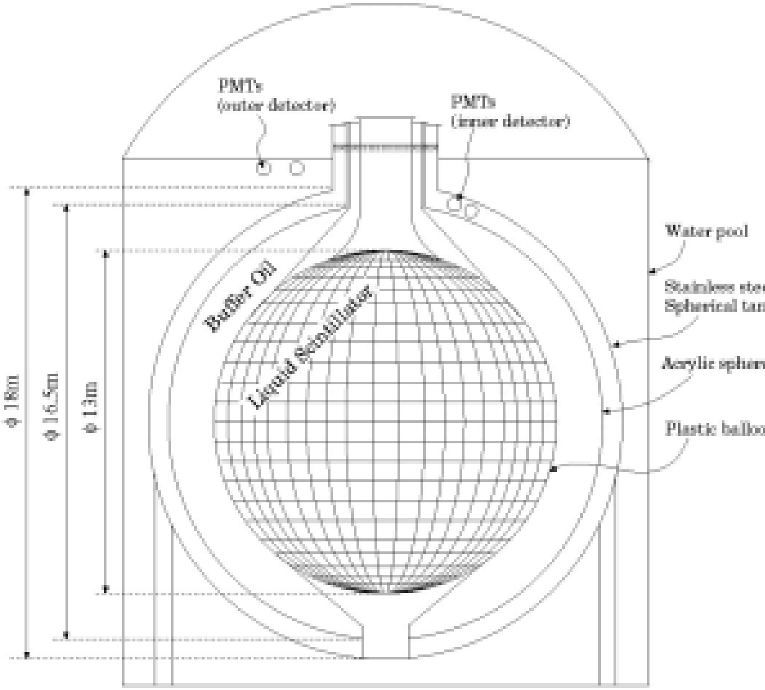
SSM
= Standard-
sonnen-
modell

Reaktor-Antineutrinos: KamLand

Notwendige Information zur Interpretation der Sonnenneutrinos



KamLAND is surrounded by 53 Japanese power reactor units



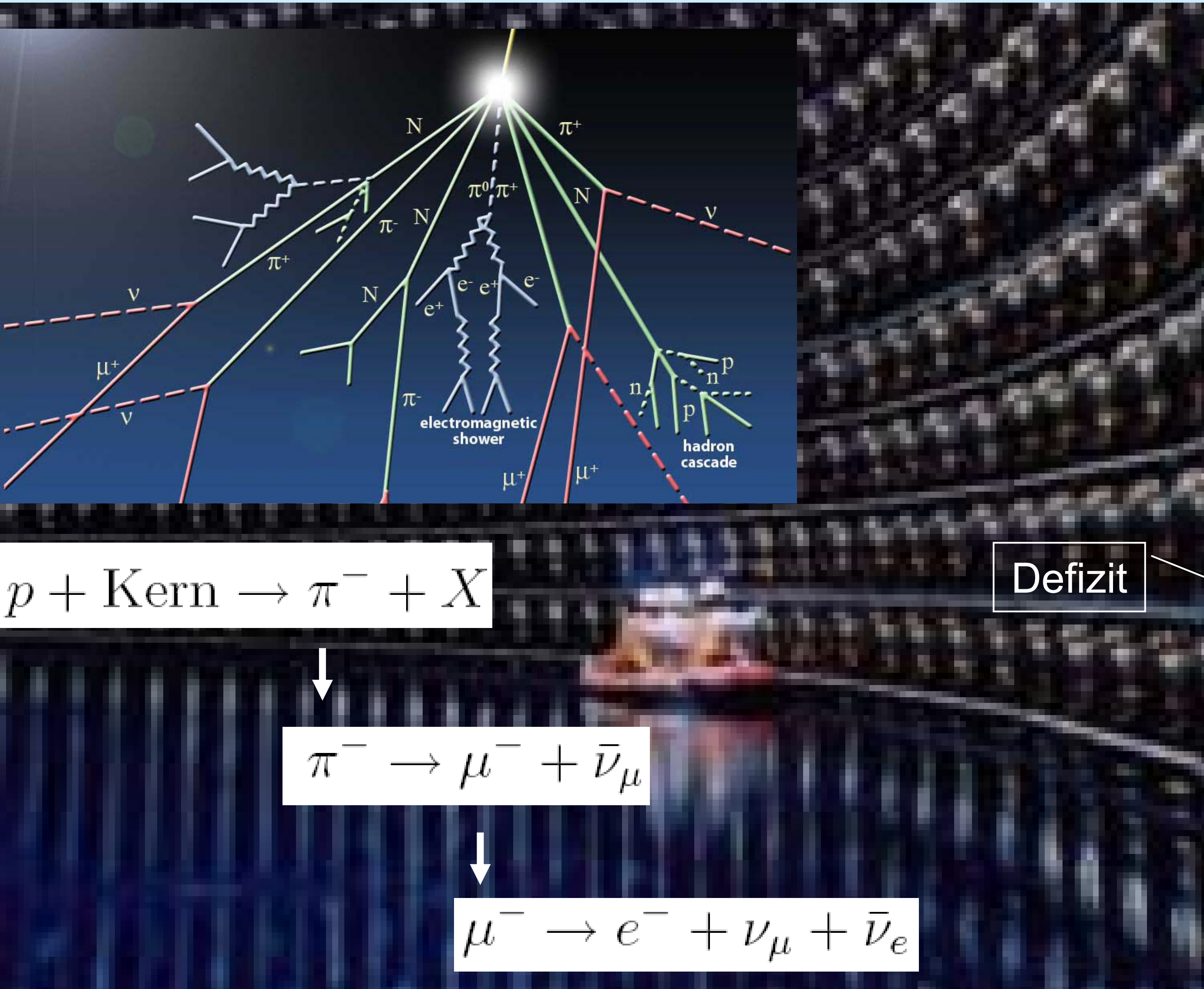
$$\overline{\nu}_e + p \rightarrow e^+ + n$$

when CPT holds

$$P(\overline{\nu}_\alpha \rightarrow \overline{\nu}_\beta; U) = P(\nu_\alpha \rightarrow \nu_\beta; U^*)$$

Erwartet:	365.2 ±23.7 Ereignisse
Beobachtet:	258 Ereignisse

Atmosphärische Neutrinos



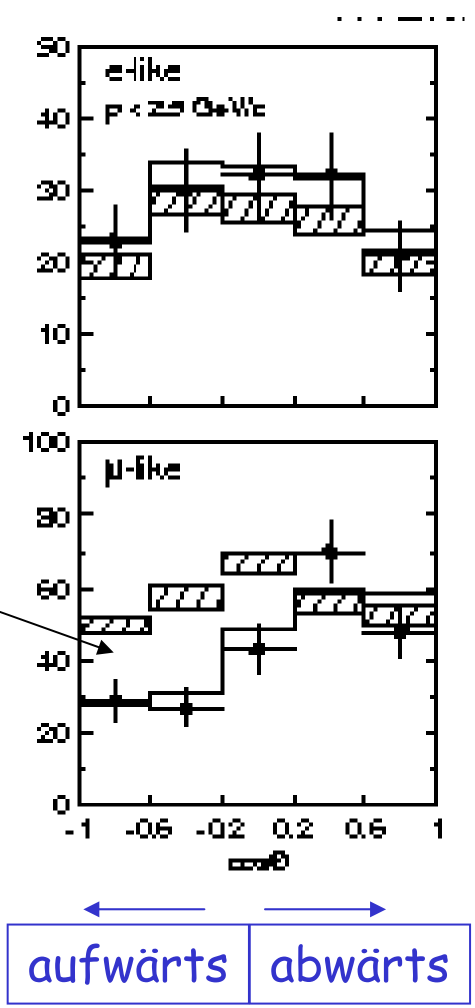
$$p + \mathrm{Kern} \rightarrow \pi^- + X$$

↓

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

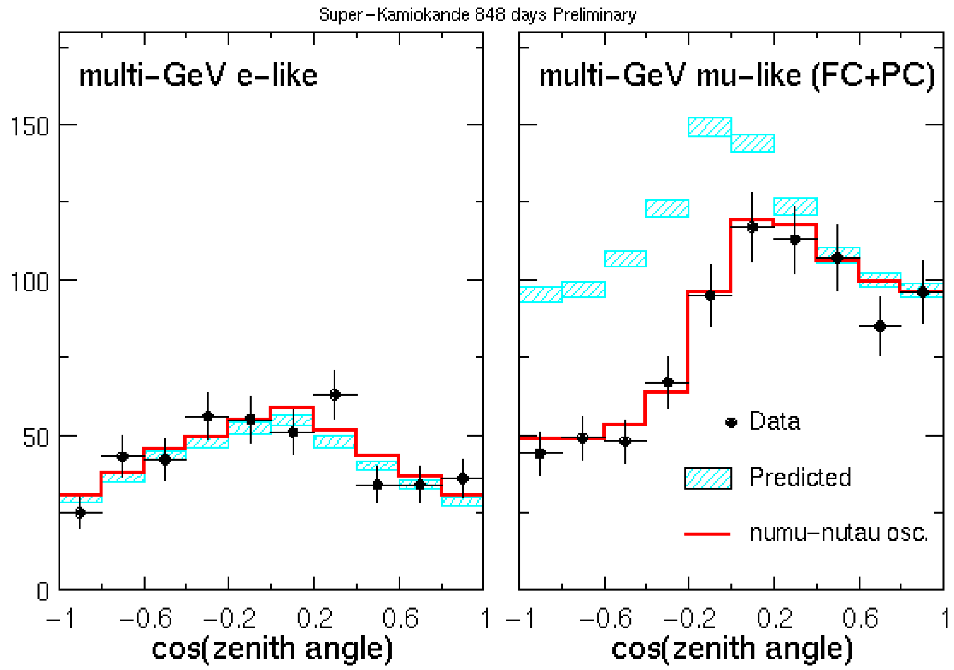
↓

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

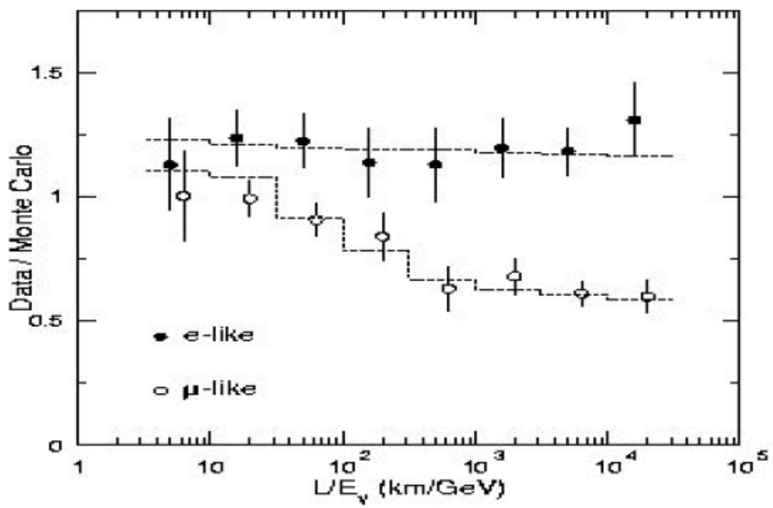


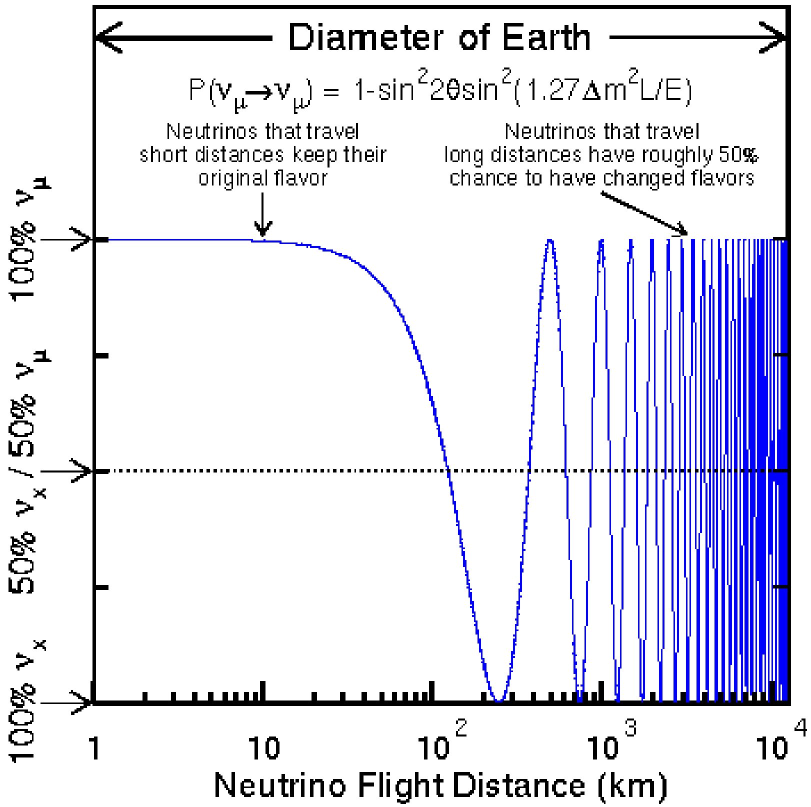
http://ale.physics.sunysb.edu/~jimhill/Winter2001Talk/node6.html

Atmosphärische Neutrinos



$\nu_\mu \rightarrow \nu_x, \quad \nu_x \neq \nu_e$!!





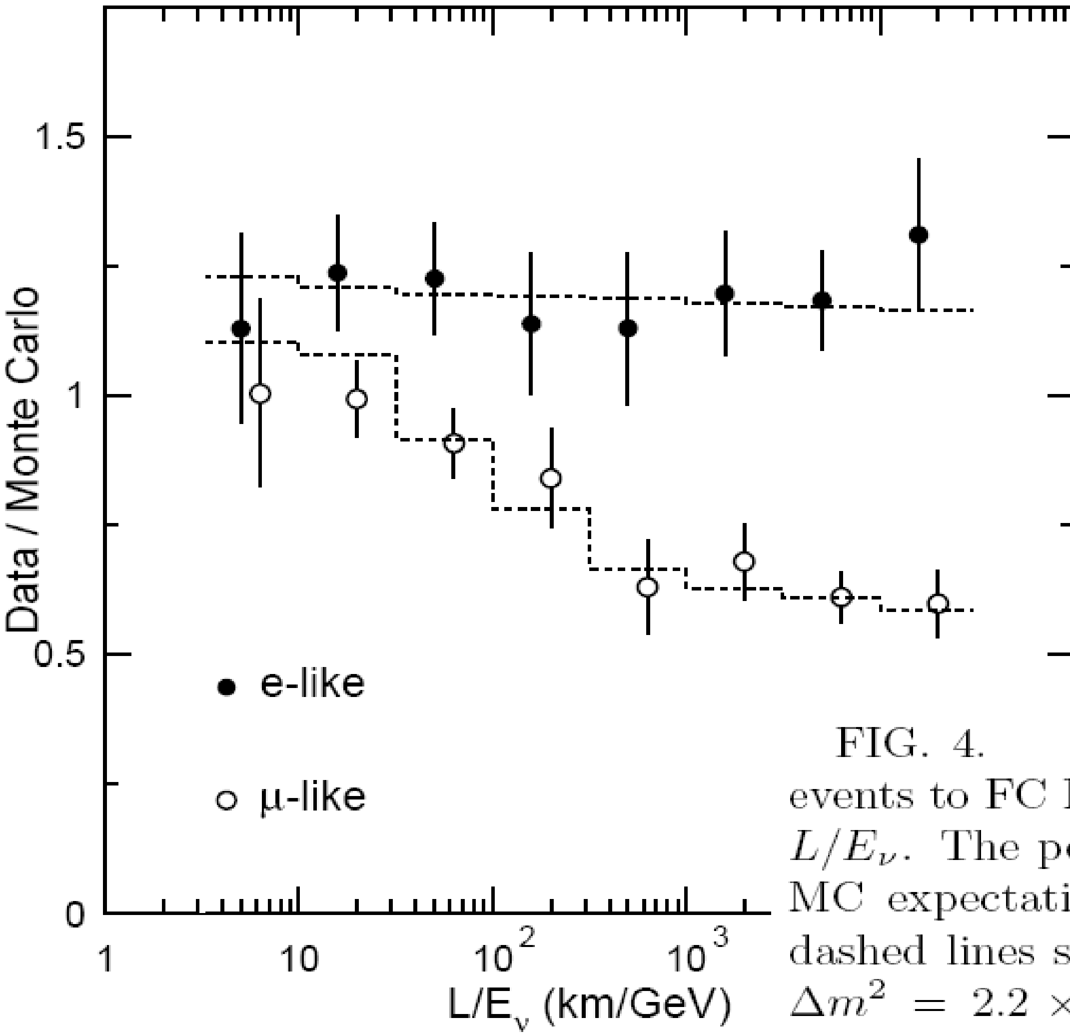


FIG. 4. The ratio of the number of FC data events to FC Monte Carlo events versus reconstructed L/E_ν. The points show the ratio of observed data to MC expectation in the absence of oscillations. The dashed lines show the expected shape for $\nu_\mu \leftrightarrow \nu_\tau$ at $\Delta m^2 = 2.2 \times 10^{-3}\mathrm{eV}^2$ and $\sin^2 2\theta = 1$. The slight L/E_ν dependence for e-like events is due to contamination (2-7%) of ν_μ CC interactions.

Neutrino-Oszillationen (Formalismus)

Favour-EZ
(def. durch CC-Kopplung an $l_\alpha^{\pm}$) → $\nu_\alpha = \sum_{i=1}^{3} U^*_{\alpha i}\, \nu_i$ ← **Massen-EZ**

zeitl. Entwicklung der Massen-EZ:

$$\nu_i(x) = e^{-i(\frac{m_i^2}{2p_i})x}\, \nu_i(0)$$

zeitl. Entwicklung der Flavour-EZ:

$$\nu_\alpha(x), = \sum_{i=1}^{3} U^*_{\alpha i}\, e^{-i(\frac{m_i^2}{2E})x}\, \nu_i(0)$$

Flavour-Oszillationen:

$$\nu_\alpha(x), = \sum_{\beta=1}^{3} \sum_{i=1}^{3} U^*_{\alpha i}\, e^{-i(\frac{m_i^2}{2E})x}\, U_{\beta i}\, \nu_\beta$$

$$P(\nu_\alpha \rightarrow \nu_\beta;\, x) = |\langle \nu_\beta(0) | \nu_\alpha(x) \rangle|^2$$

$$P(\nu_\alpha \rightarrow \nu_\beta;\, x) = \delta_{\alpha\beta} \quad -4 \sum_{i>j} Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j} \sin^2 \frac{\Delta m_{ij}^2}{4E} x$$
$$+2 \sum_{i>j} Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j} \sin \frac{\Delta m_{ij}^2}{2E} x$$

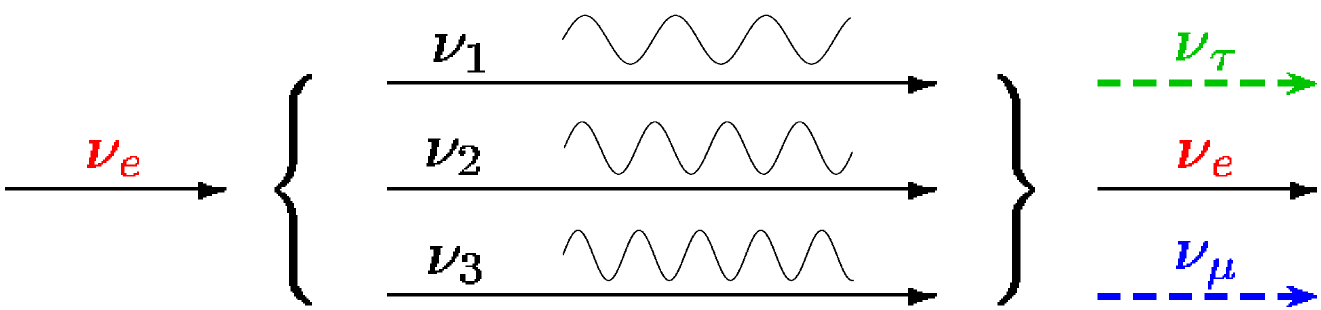
3-Generation-Neutrinomischung

PMNS Mischungsmatrix (ohne Majorana Phasen)

- 3 Mischungswinkel: θ_{12}, θ_{23}, θ_{13}
- 1 CP-verletzende Dirac-Phase: δ

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

θ_{atm} θ_{13}, δ θ_{sol}



3-Flavour-Mischungsmatrix

wie bei CKM-Matrix: 3 Winkel + 1 Phase

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

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

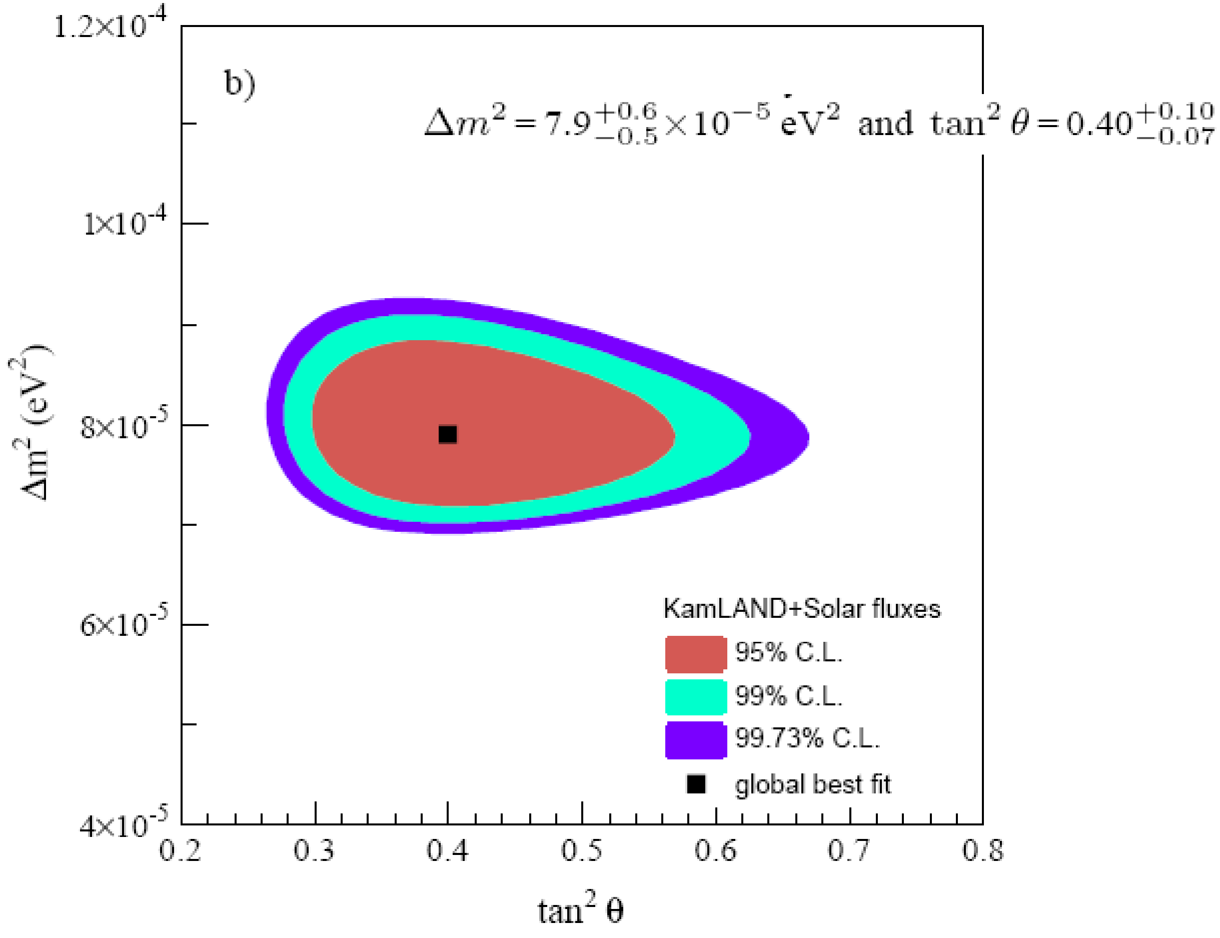
Ergebnisse $\sin^2\theta_{12} \approx 0.31, \quad \sin^2\theta_{23} \approx 0.50, \quad \sin^2\theta_{13} \approx 0$

$$\theta_{12} \approx 33.8^\circ, \quad \theta_{23} \approx 45.0^\circ, \quad \theta_{13} \approx 0^\circ$$

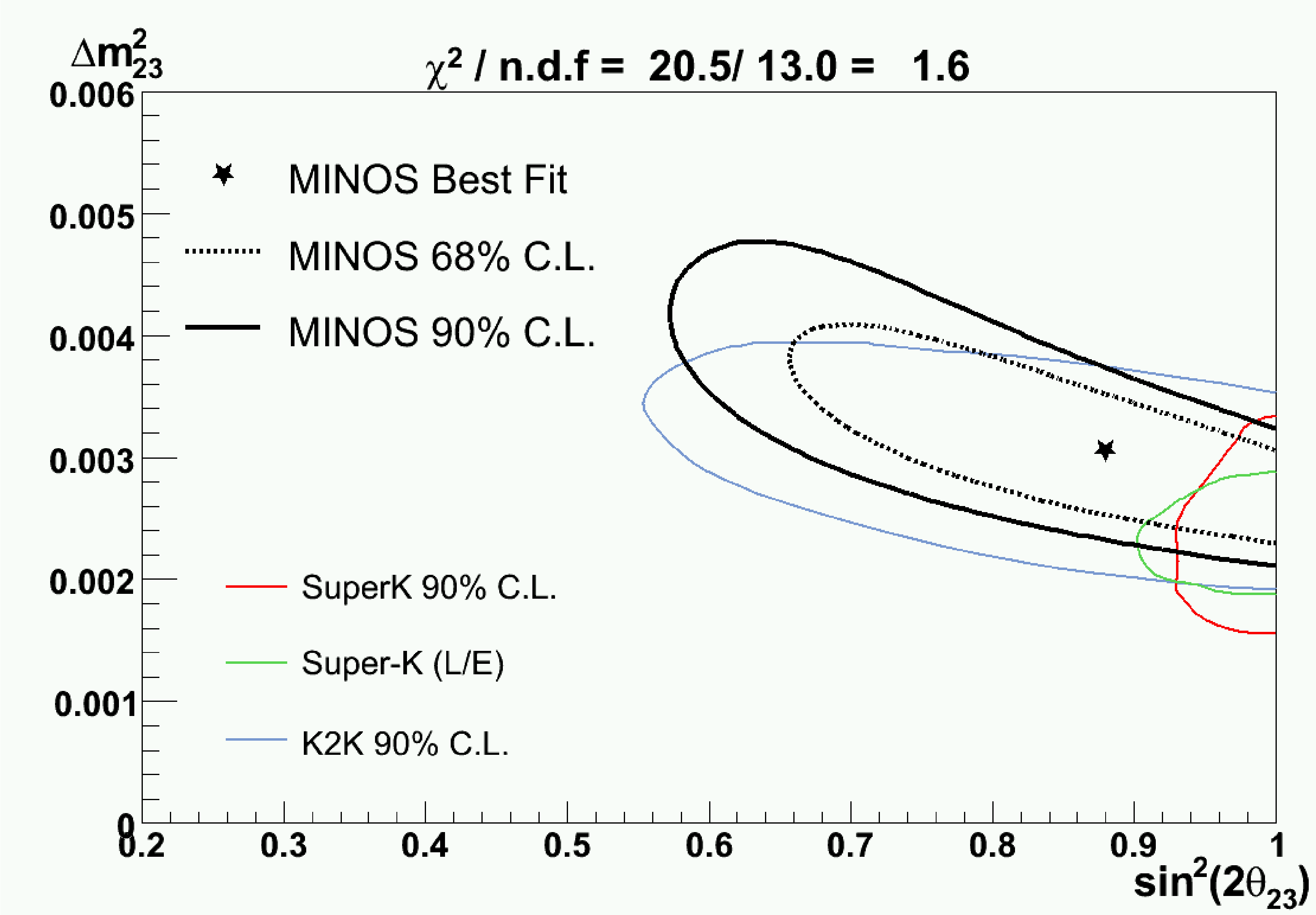
$\Rightarrow$ ganz andere Situation als bei Quarkmischung:
2 große, 1 kleiner Winkel (oder =0)

$\Rightarrow$ Wolfenstein-Parametrisierung nicht möglich

Reaktor- und Sonnenneutrinos



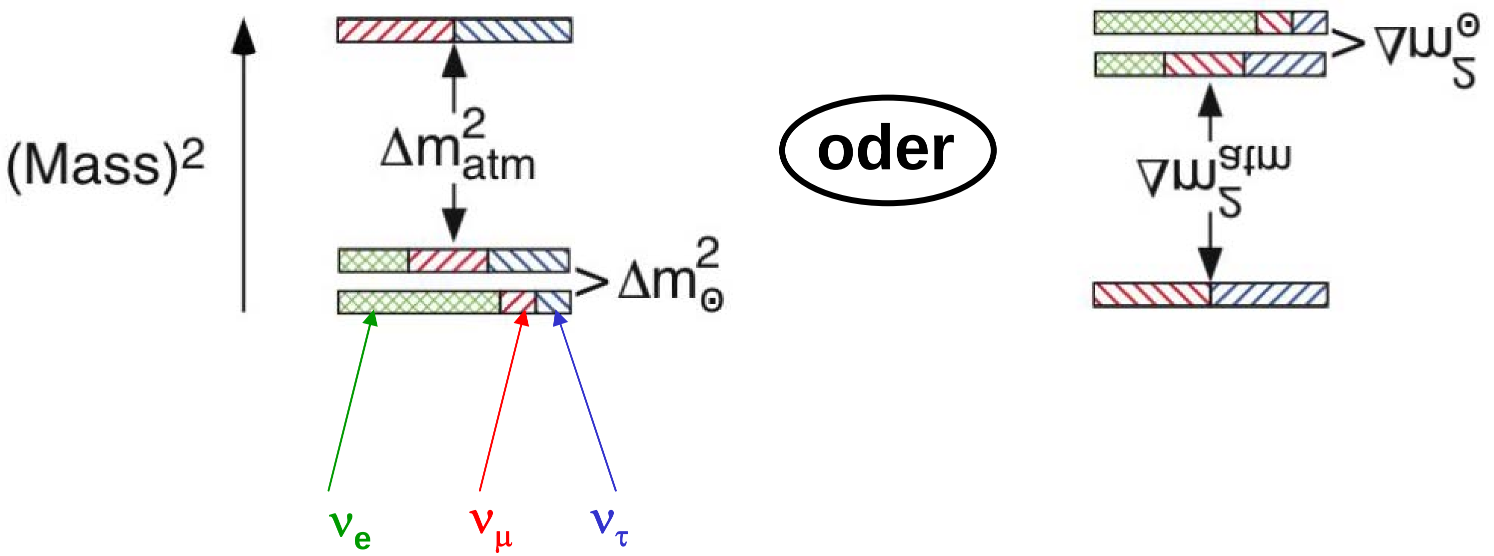
Atmosphärische und Beschleuniger- Neutrinos



Massenhierarchie

$$\Delta m^2_{12} = m_2^2 - m_1^2 \approx 7.9 \cdot 10^{-5}\,\mathrm{eV}^2 \qquad (>0,\ \text{festgelegt})$$

$$\Delta m^2_{(12)3} = \left| m_3^2 - \frac{m_2^2 - m_1^2}{2} \right| \approx 2.4 \cdot 10^{-3}\,\mathrm{eV}^2$$



$\Delta m^2_{atm} >> \Delta m^2_{\odot}$ & $\theta_{13} \approx 0$ $\Rightarrow$ Aufspaltung in effektiv 2-kompon. Mischung für jeweils solare und atm. Neutrinos

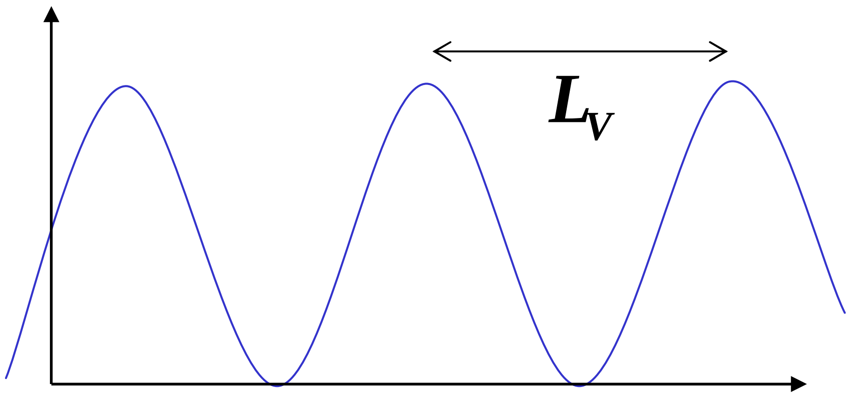
2-Komponenten-Mischung

Vakuum-Lösung: $$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_V & \sin\theta_V \\ -\sin\theta_V & \cos\theta_V \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$P(\nu_e \to \nu_e;\, x) = |<\nu_e(x)|\nu_e(0)>|^2 = 1 - \sin^2 2\theta_V \underbrace{\sin^2 \frac{\Delta m^2}{4E} x}_{\sin^2 \frac{\pi}{L_V} x}$$

$$L_V = \frac{4\pi E \hbar}{\Delta m^2 c^3} = 2.48\,\mathrm{m} \left(\frac{E}{\mathrm{MeV}}\right)\left(\frac{\mathrm{eV}^2}{\Delta m^2}\right)$$

$$\frac{\pi}{\boldsymbol{L_V}} = 1.27 \frac{1}{\mathrm{m}} \cdot \left(\frac{\boldsymbol{\Delta m}^2}{\mathrm{eV}^2}\right) \cdot \left(\frac{\mathrm{MeV}}{\boldsymbol{E}}\right)$$

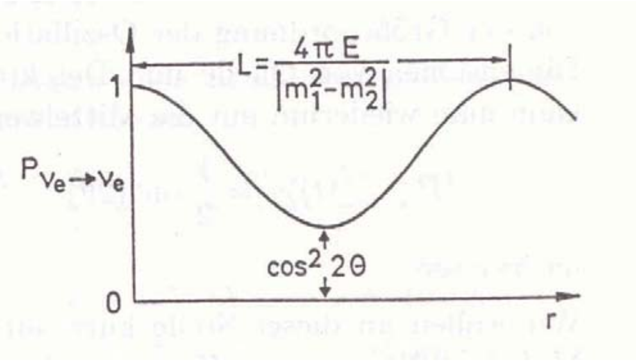


$$\Delta m^2_{ij}(L/4E) \simeq 1.27\, \Delta m^2_{ij}(\mathrm{eV}^2) \frac{L(\mathrm{km})}{E(\mathrm{GeV})}$$

Pendel-Neutrino-Korrespondenzen

Pendel	Neutrinos
Lineare Schwingung	Kreisbewegung des „Phasenzeigers"
Feste Moden	Massezustände
Mischung wegen Kopplung => $\Delta\omega^2 \sim k/M$	Flavor Mischungsmatrix => Δm^2
Oszillationsfrequenz der Pendel $\sim \Delta\omega^2$ der festen Moden	Oszillationsfrequenz der Neutrinos $\sim \Delta m^2$ der Massezustände
Amplitude^2 jedes Pendels	Wahrscheinlichkeit, Neutrino zu finden

Anmerkung:
nicht-maximale Neutrino Mischung
entspräche Pendel mit $\ell_I \neq \ell_{II}$



$L_{12} = 30\,km \times E(MeV)$ Derzeitige Werte $L_{23} = 1\,km \times E(MeV)$

$\Delta m^2_{23} = 2.4 \times 10^{-3}\, eV^2$	$\Delta m^2_{13} = 2.5 \times 10^{-3}\, eV^2$	$\Delta m^2_{12} = 0.08 \times 10^{-3}\, eV^2$
„schnelle“ Oszillation		„langsame“ Oszillation
$L_{23} = 1$ km × E/MeV		$L_{12} = 30$ km × E/MeV
$\theta_{23} = 45°$	$\theta_{13} < 10°$	$\theta_{12} = 32^{+3}_{-2}\,°$

- konsistent mit tri/bi-maximaler Mischung

$$U_{PMNS} \approx \begin{pmatrix} \frac{2}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

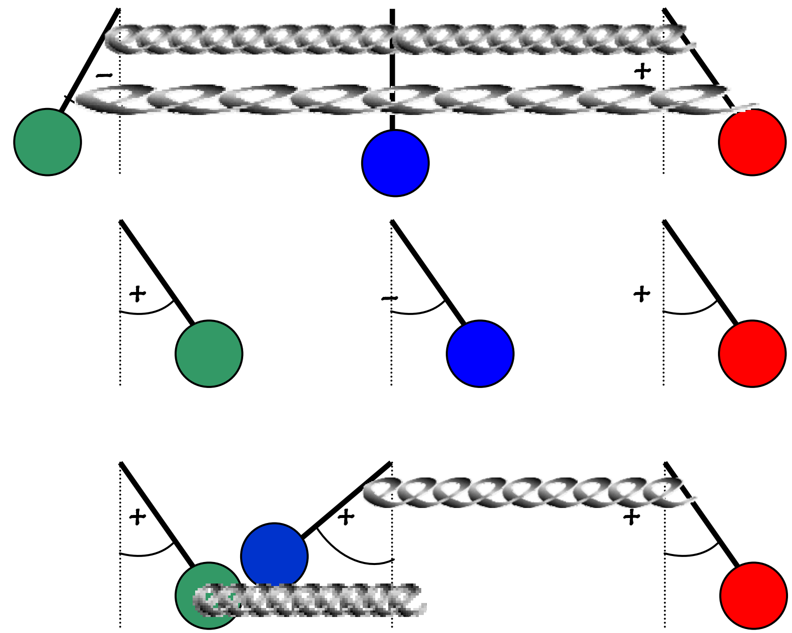
Harrison, Perkins, Scott '99,'02
Z.Xing,'02, He, Zee, '03, Koide '03
Chang, Kang, Kim '04, Kang '04

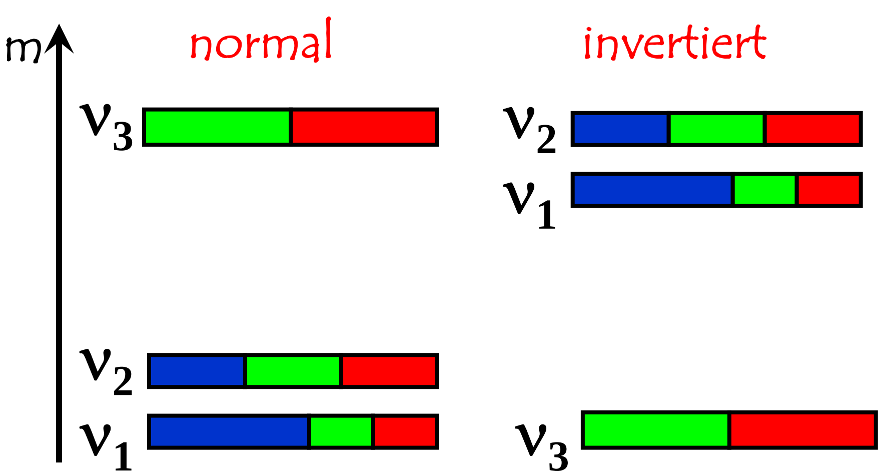
Realisation als gekoppelte Pendel

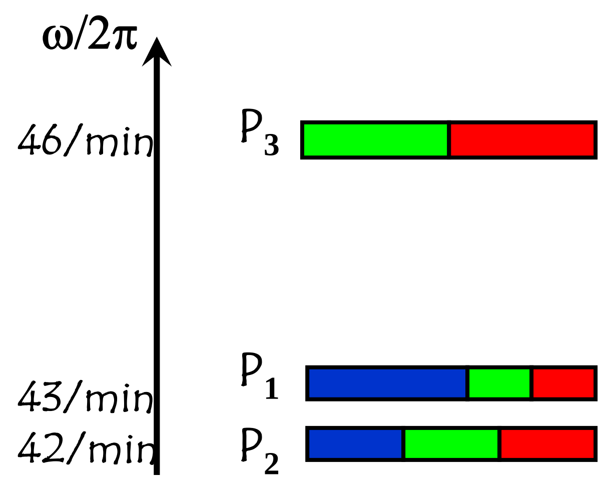
$$\nu_3 = (\quad - \nu_\mu + \nu_\tau)/\sqrt{2}$$

$$\nu_2 = (-\nu_e + \nu_\mu + \nu_\tau)/\sqrt{3}$$

$$\nu_1 = (2\nu_e + \nu_\mu + \nu_\tau)/\sqrt{6}$$

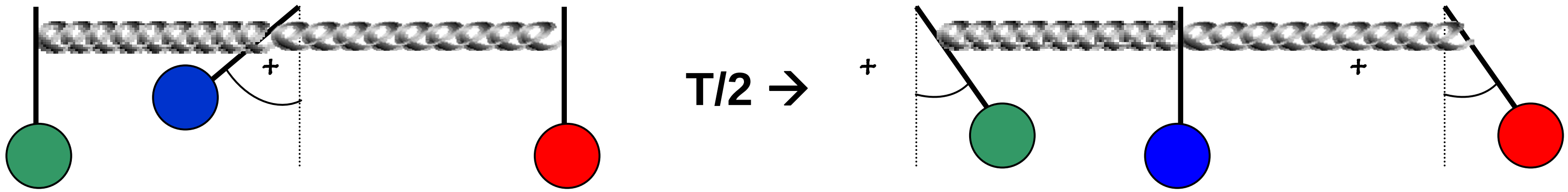






Solare Neutrinos

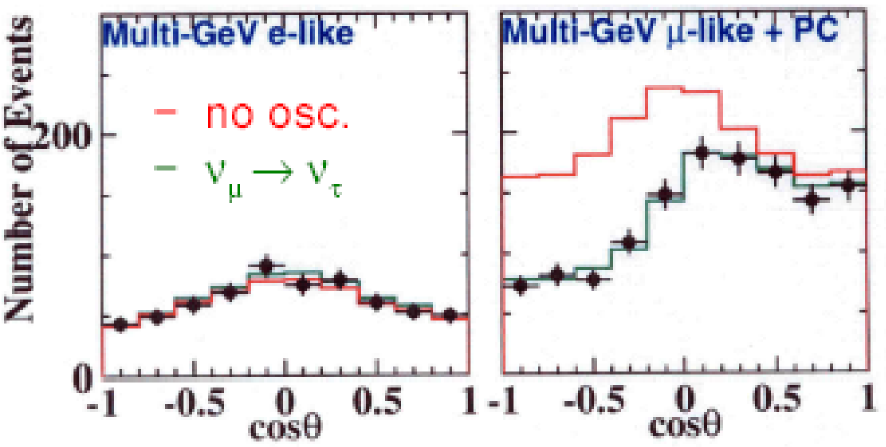
- nukleare Fusion: (ohne MSW Effekt: Produziere 100% ν_e)
  4p → ^{4}He + 2e$^+$ + $2\nu_e$ + 27 MeV
- Vakuum: langsame Oszillation mit θ_{12}, Pendel: schwache Federn

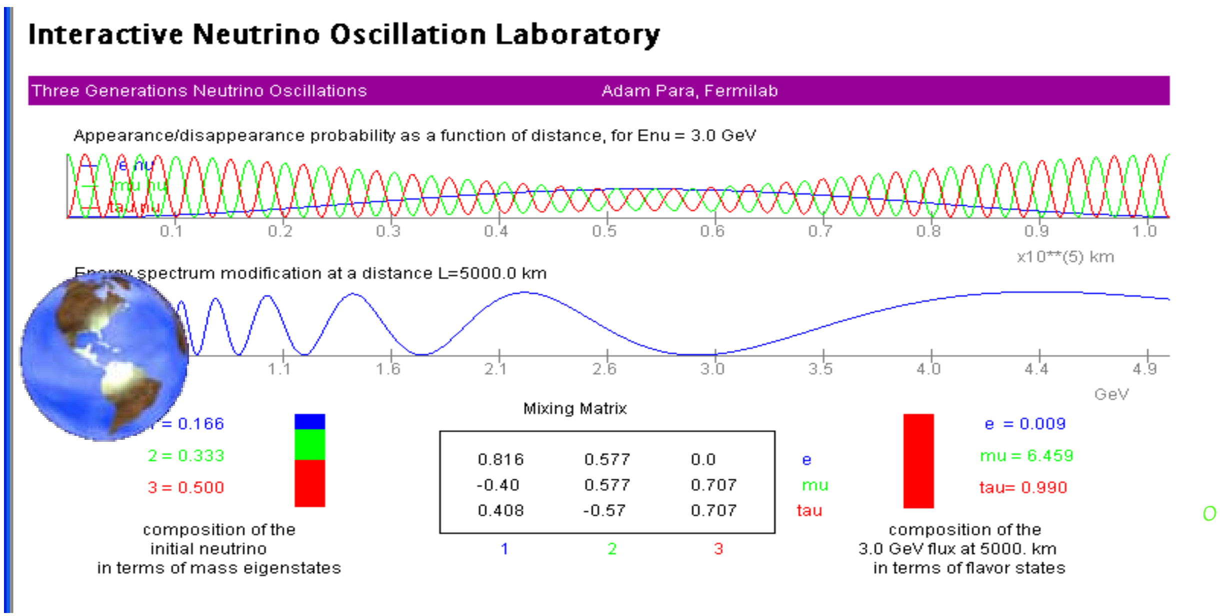


- Anregung von $(\nu_\tau - \nu_\mu)/\sqrt{2}$ nicht möglich, weil ν_e nicht in ν_3
- Oszillation nur zu $(\nu_\tau + \nu_\mu)/\sqrt{2}$
- $P(\nu_e \rightarrow \nu_e) > 50\%$ da nur ν_1 und ν_2 beteiligt

Atmosphärische Neutrinos

- Kamiokande 2000:
  beschrieben als $\nu_\mu \rightarrow \nu_\tau$
- Pendel:
  ν_e : schwache Feder zu ν_μ, ν_τ
  ν_μ: schwache Feder zu ν_e
  starke Feder zu ν_τ





http://minos.phy.bnl.gov/nu-osc-lab/Superposition1.html

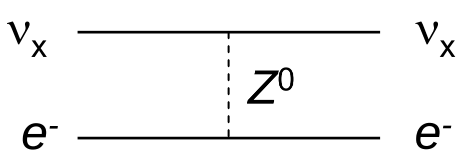
MSW-Effekt

Vakuum:

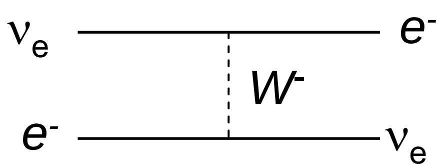
$$i\frac{\partial}{\partial x}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix} = \frac{1}{2p}\begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix} = H_0\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$ Massen-EZ

$$i\frac{\partial}{\partial x}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \frac{\Delta m_{12}^2}{4p}\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = H_V\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$ Flavour-EZ

NC (x= e, μ, τ):



CC:



CC-Wechselwirkung der ν_e in der Sonne ~ N_e

$$V(x) = \sqrt{2}G_F N_e(x)$$

$N_e \approx 6 \cdot 10^{25}\,\mathrm{cm}^{-3}$ bei $r = 0$

$$i\frac{\partial}{\partial x}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \left[\frac{\Delta m_{12}^2}{4p}\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta\end{pmatrix} + \frac{V(x)}{2}\begin{pmatrix} 1 & 0 \\ 0 & -1\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

MSW-Effekt: adiabatische Lösung

$$i\frac{\partial}{\partial x}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \left[\frac{\Delta m_{12}^2}{4p}\begin{pmatrix}-\cos 2\theta & \sin 2\theta\\ \sin 2\theta & \cos 2\theta\end{pmatrix} + \frac{V(x)}{2}\begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

$$V(x) = \sqrt{2}G_F N_e(x) \qquad\qquad N_e \approx 6\cdot 10^{25}\ \mathrm{cm}^{-3}$$

Falls *H* im Sonneninneren quasi-diagonal (*V(x)* gross) $\Rightarrow \approx$ Massen-EZ = ν_{2m}

bei **adiabatischer Entwicklung** $V(x) \rightarrow 0$ am Sonnenrand

$\Rightarrow$

$$\nu_2 = \sin\theta\,\nu_e + \cos\theta\,\nu_\mu$$

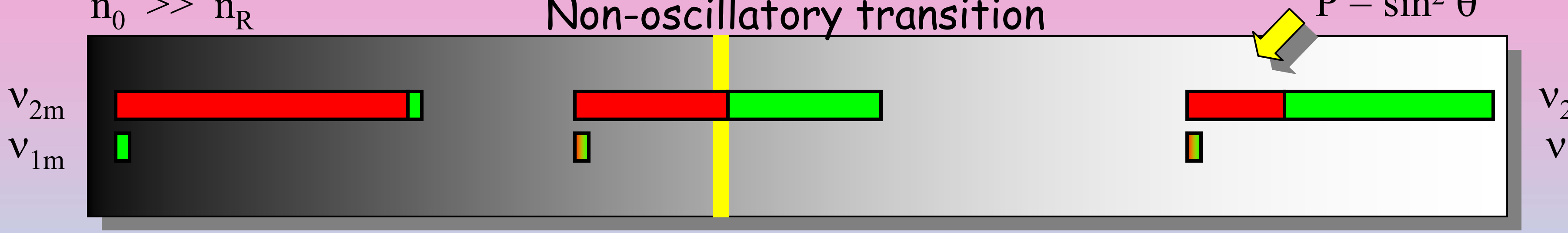
$\Rightarrow$

$$P(\nu_e) = \sin^2\theta, \qquad P(\nu_\mu) = \cos^2\theta.$$

Adiabatic conversion

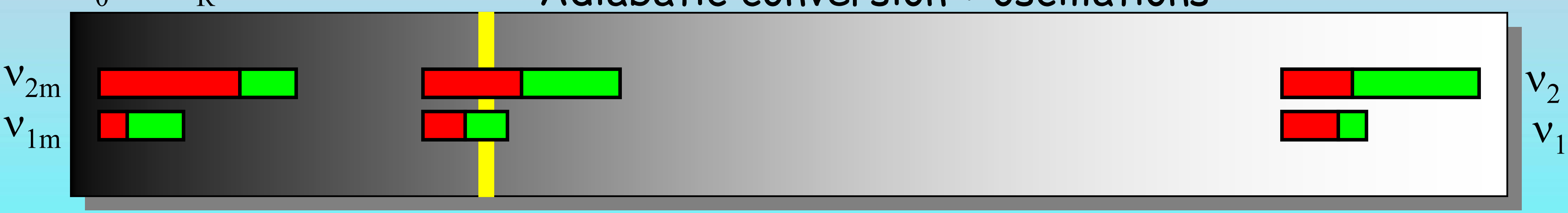
ν_{1m} <-/-> ν_{2m}

$n_0 >> n_R$ Non-oscillatory transition $P = \sin^2\theta$

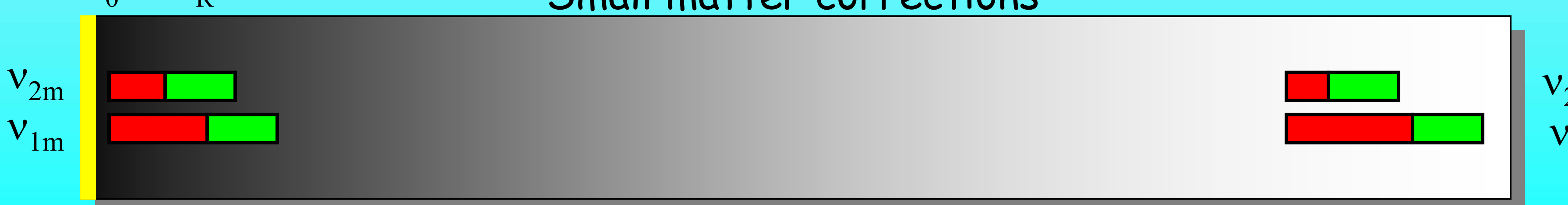


Mixing suppressed Resonance interference suppressed

$n_0 > n_R$ Adiabatic conversion + oscillations



$n_0 < n_R$ Small matter corrections



n_e

A. Yu. Smirnov

Solar Neutrinos

$4p + 2e^- \Rightarrow {}^4He + 2\nu_e + 26.73$ MeV

electron neutrinos are produced

Adiabatic conversion
in matter of the Sun

$F = 6\ 10^{10}\ cm^{-2}\ c^{-1}$

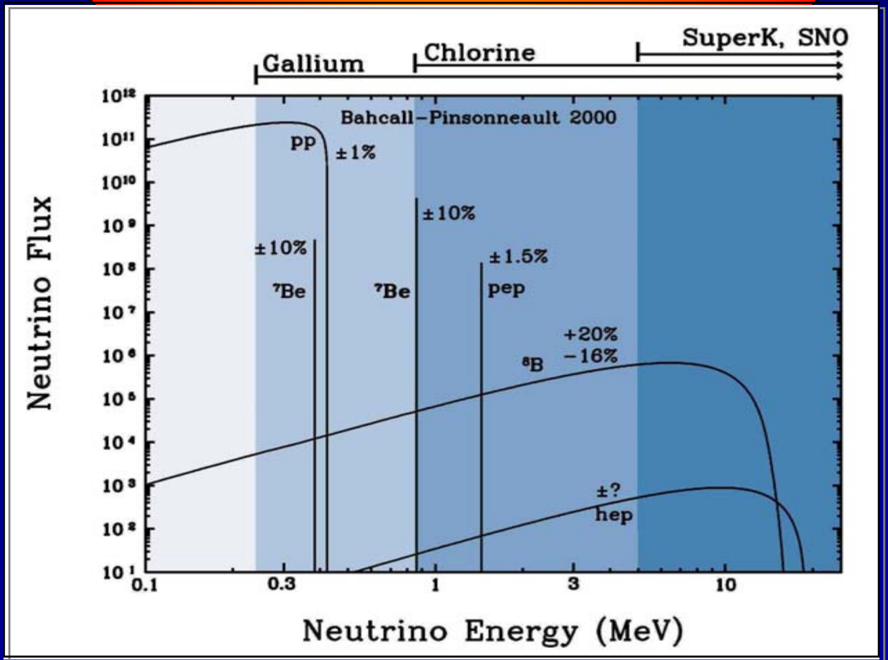
total flux at the Earth

ρ : (150 $\Rightarrow$ 0) g/cc

Oscillations
in vacuum

ν

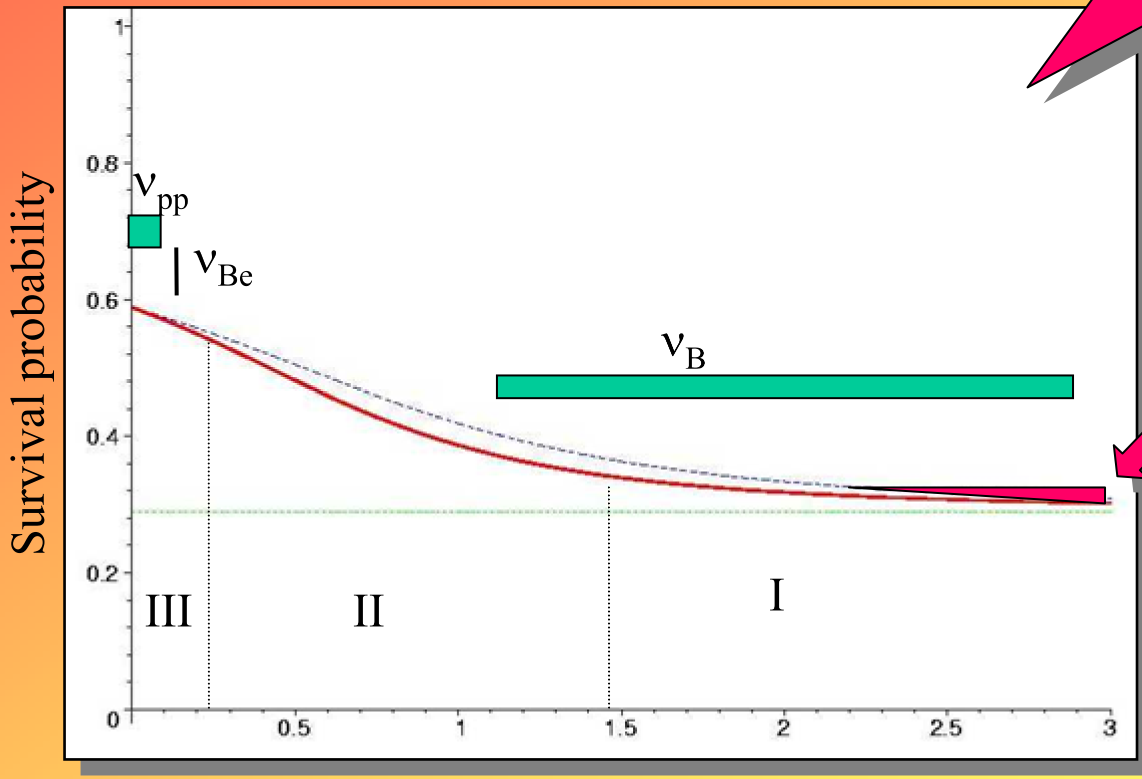
Oscillations
in matter
of the Earth



J.N. Bahcall

Profile of the effect

Adiabatic solution



Earth matter effect

$\sin^2\theta$

$l_\nu / l_0 \sim E$

Oscillations with small matter effect

Conversion + oscillations

Conversion with small oscillation effect

Non-oscillatory transition