NEUTRINO PHYSICS

Neutrino Oscillations

Neutrino Masses and Mixing

Majorana or Dirac Nature of the Neutrino

[Neutrinos as new Messenger from the Universe]

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Fermion Particles in the Standard Model

$\begin{pmatrix} u \\ d' \end{pmatrix}_L$	$\begin{pmatrix} c \\ s' \end{pmatrix}_L$	$\begin{pmatrix} t \\ b' \end{pmatrix}_L$	$Y = -\frac{1}{2}$
d_R	s_R	b_R	$Y = -\frac{1}{3}$
u_R	c_R	t_R	$Y = +\frac{2}{3}$

$$\begin{pmatrix} H^+ \\ H^\circ \end{pmatrix}$$

$$Y = +\frac{1}{2}$$

$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$Y = -\frac{1}{2}$
e_R	μ_R	τ_R	$Y = -1$
$(\nu_e)_R$	$(\nu_\mu)_R$	$(\nu_\tau)_R$	$Y = 0$

Minimal SM

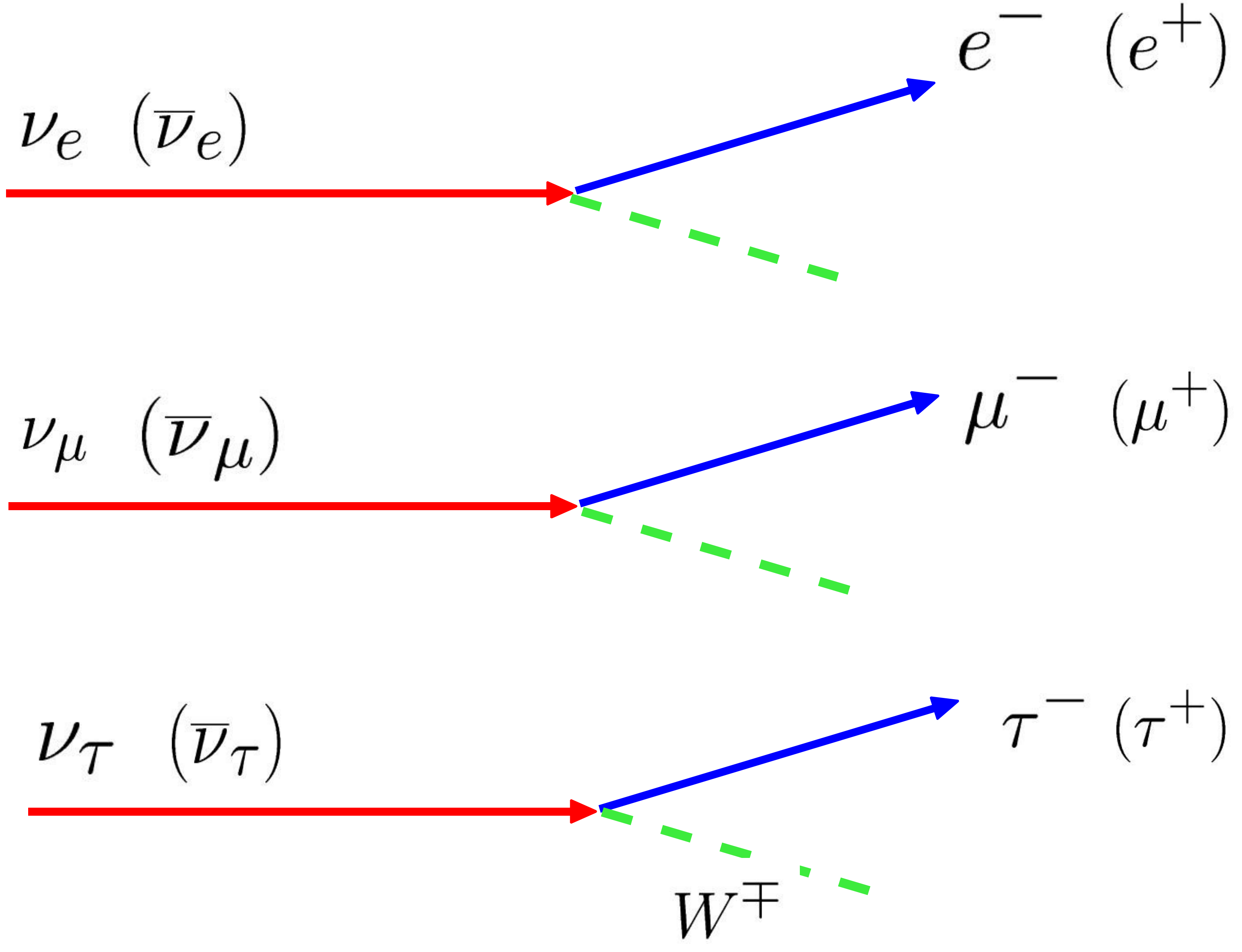
ν_R absent

3 type (FLAVORs) of Neutrinos

$$\nu_e \qquad \nu_\mu \qquad \nu_\tau$$

$$\overline{\nu}_e \qquad \overline{\nu}_\mu \qquad \overline{\nu}_\tau$$

FLAVOR

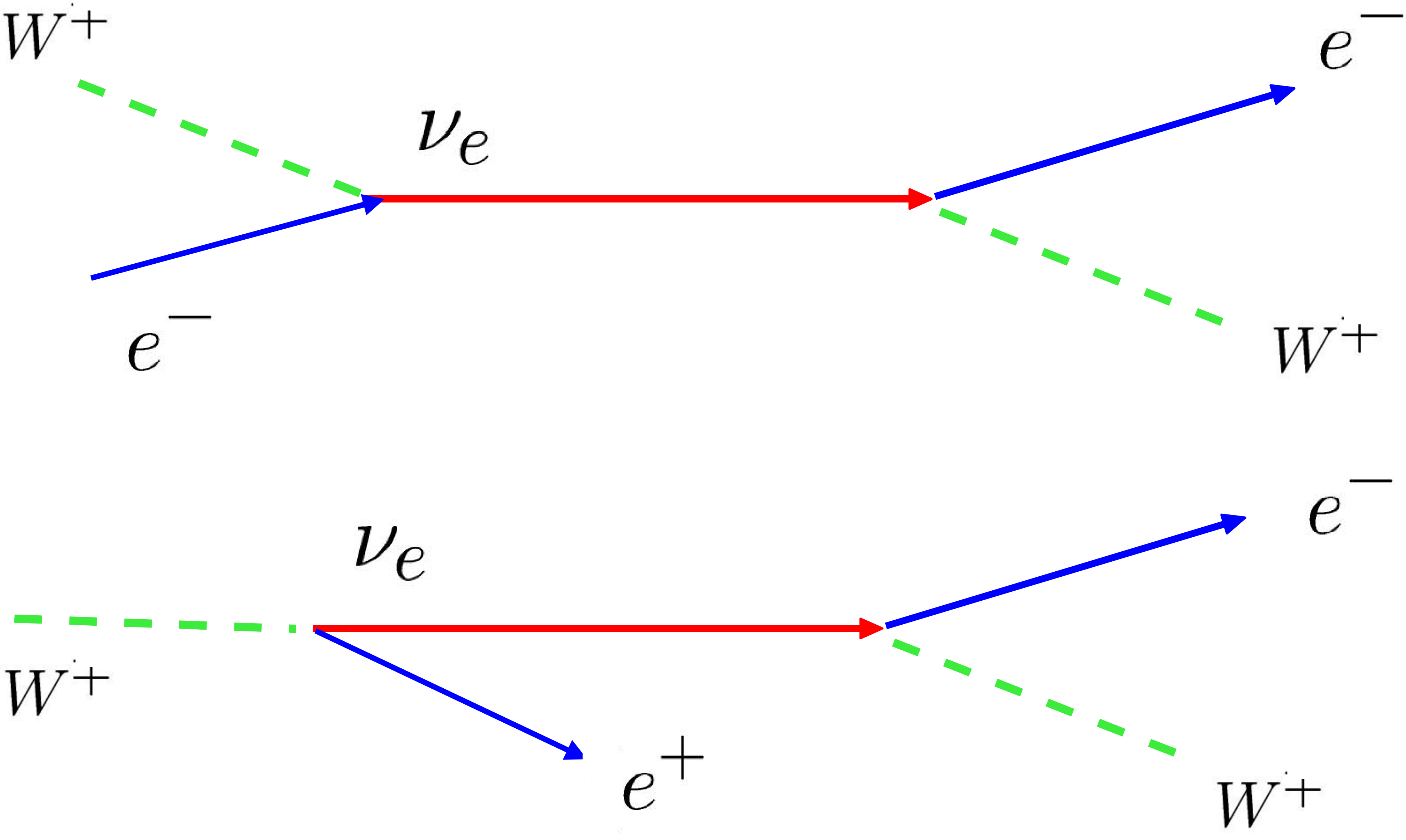


$\nu_e \;\; (\overline{\nu}_e)$
$e^- \;\; (e^+)$
$\nu_\mu \;\; (\overline{\nu}_\mu)$
$\mu^- \;\; (\mu^+)$
$\nu_\tau \;\; (\overline{\nu}_\tau)$
$\tau^- \;\; (\tau^+)$
$W^\mp$

Dirac Particle		Majorana Particle	
e_L^-	e_R^-		
e_L^+	e_R^+		
ν_L	ν_R	ν_L	
$\overline{\nu}_L$	$\overline{\nu}_R$		$\overline{\nu}_R$

FLAVOR

Electron-flavor



How Many Light Neutrinos Exist ?

Answer : **3**

$$Z^0 \rightarrow \nu_\alpha + \overline{\nu}_\alpha$$

$$\Gamma_{\nu\bar{\nu}} = 166.9 \text{ MeV}$$

$$\Gamma_{\text{invisible}} = N_\nu \, \Gamma_{\nu\overline{\nu}}$$

$$\Gamma_{\text{invisible}} = \Gamma_{\text{tot}} - \Gamma_{\text{vis}} = 498 \pm 4.2 \text{ MeV}$$

$$N_\nu = \frac{\Gamma_{\text{inv}}}{\Gamma_{\nu\bar{\nu}}} = 2.994 \pm 0.012$$

3 Neutrinos states: 3 masses m_1, m_2, m_3

States with definite masses
in general do **not** coincide with the "flavor" states

$$\{ |\nu_e\rangle \quad , \quad |\nu_\mu\rangle \quad , \quad |\nu_\tau\rangle \}$$

Flavor basis

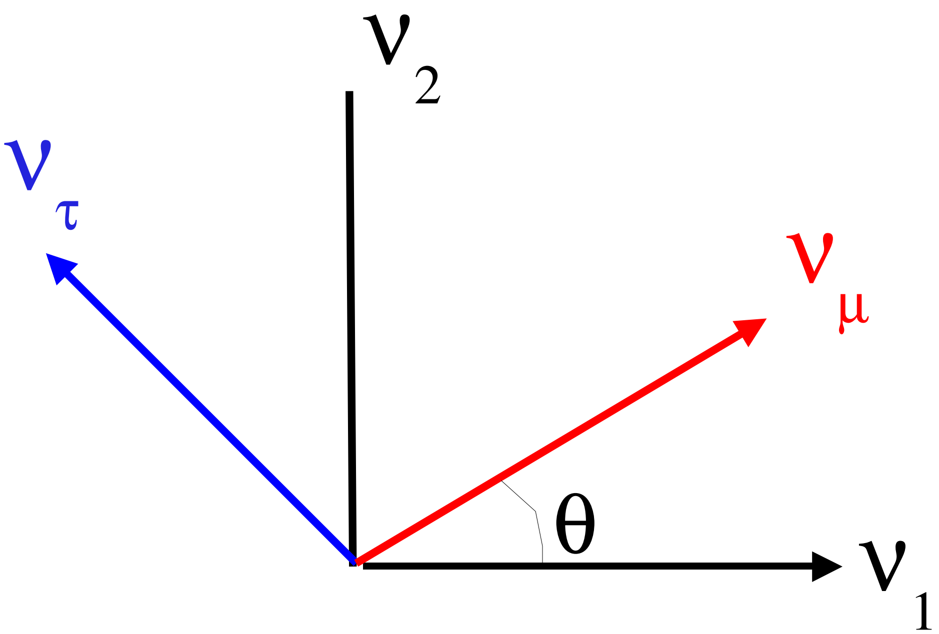
$$\{ |\nu_1\rangle \quad , \quad |\nu_2\rangle \quad , \quad |\nu_3\rangle \}$$

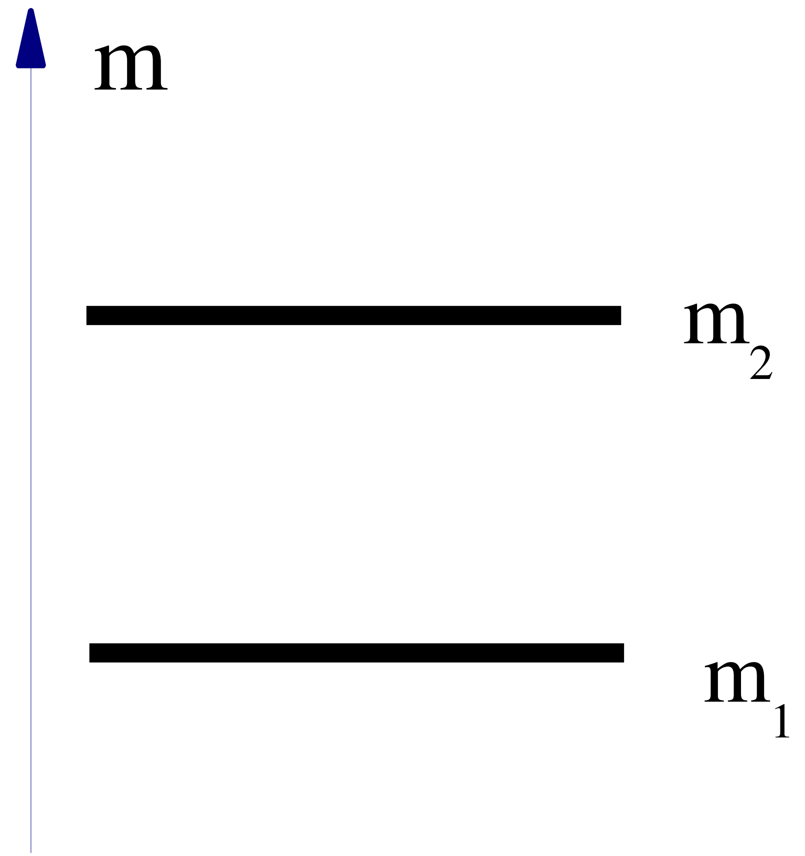
Mass basis

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V^{\mathrm{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U^{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

2 Flavor case





$$|\nu_\mu\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

$$|\nu_\tau\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$

$$\Delta m^2 = m_2^2 - m_1^2$$

Neutrino Propagation

$$|\nu(0)\rangle = |\nu_\mu\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

ν_μ created at t =0
with momentum p

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

Different mass
components
have different energy

$$|\nu(t)\rangle = \cos\theta\, e^{-iE_1 t}|\nu_1\rangle + \sin\theta\, e^{-iE_2 t}|\nu_2\rangle$$

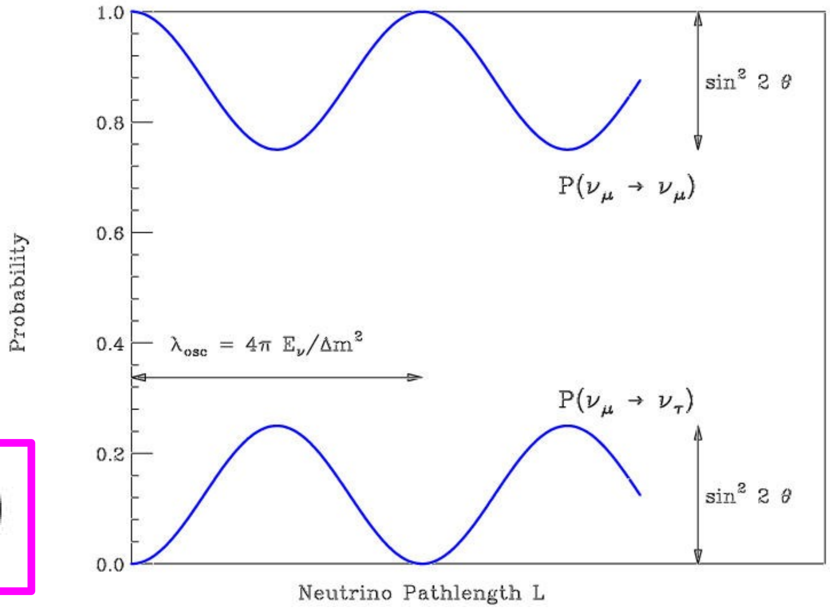
ν state at time t

Oscillation Probability

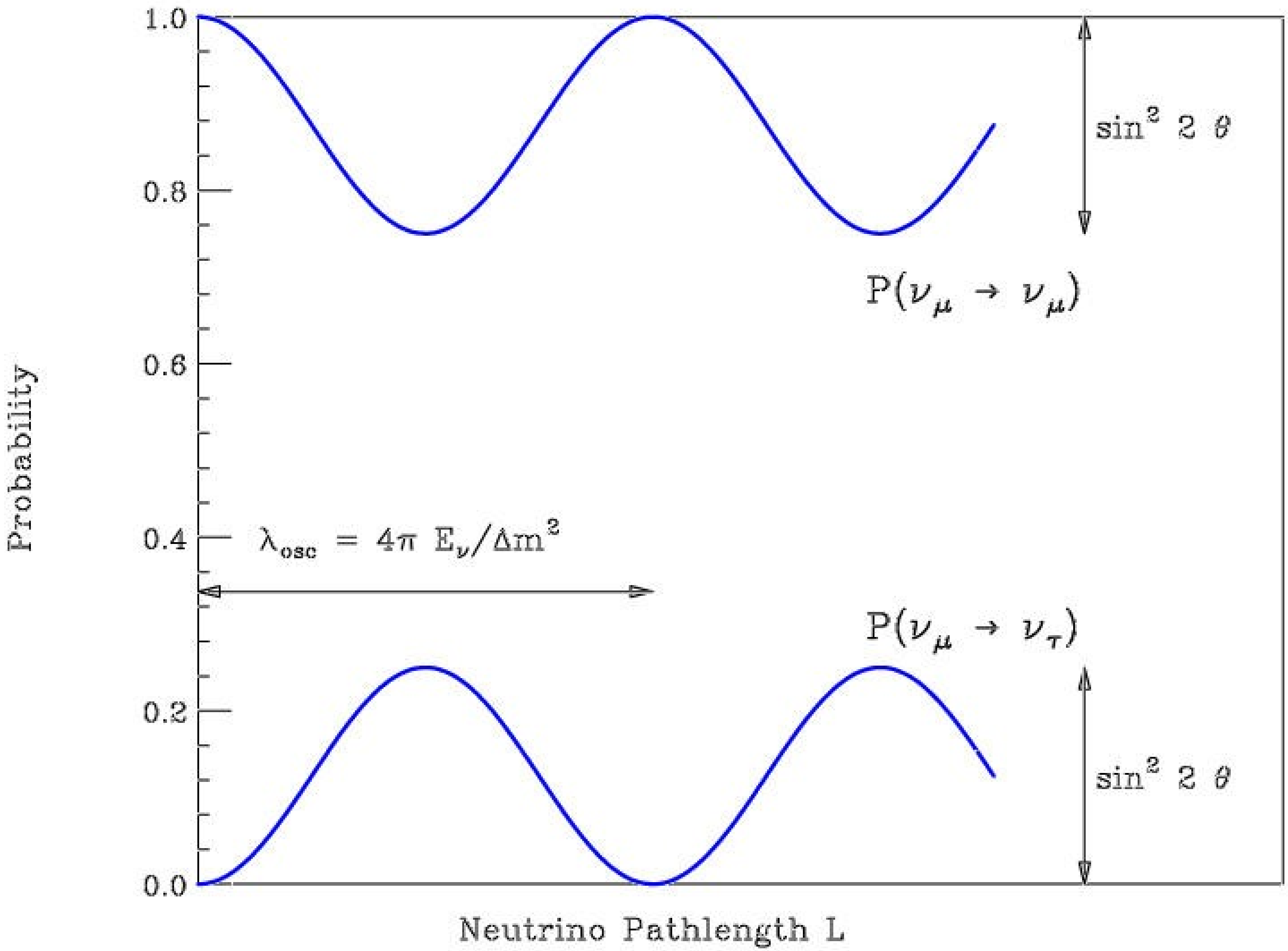
$$P(\nu_\mu \to \nu_\tau;\, t) =$$

$$\begin{aligned}
&= |\langle \nu_\tau | \nu(t) \rangle|^2 \\
&= |\{-\sin\theta\,\langle\nu_1| + \cos\theta\,\langle\nu_2|\}|\{\cos\theta\, e^{-iE_1t}|\nu_1\rangle + \sin\theta\, e^{-iE_2t}|\nu_2\rangle\}|^2 \\
&= \cos^2\theta\,\sin^2\theta\,\left|e^{-iE_2t} - e^{-iE_1t}\right|^2 \\
&= 2\cos^2\theta\,\sin^2\theta\,\{1 - \cos[(E_2 - E_1)t\} \\
&= \sin^2 2\theta\,\sin^2\left[\frac{\Delta m^2}{4E}t\right]
\end{aligned}$$

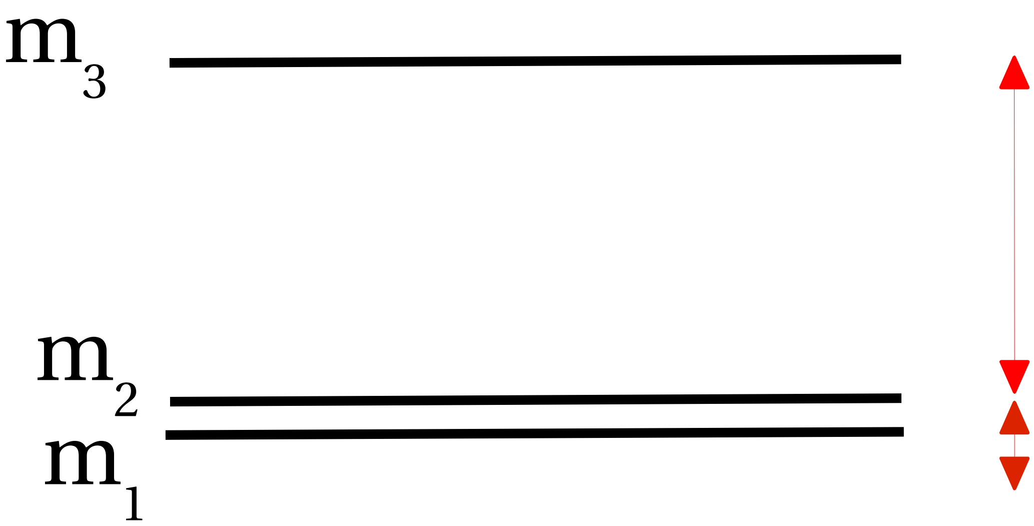
$$P(\nu_\mu \to \nu_\tau;\, t)$$



$$P(\nu_\mu \to \nu_\tau;\, L) = \sin^2 2\theta\, \sin^2\left[1.27\,\Delta m^2(\mathrm{eV}^2)\,\frac{L(\mathrm{Km})}{E(\mathrm{GeV})}\right]$$



3 Flavor Oscillations



$$
\begin{aligned}
|\nu_e\rangle &= U^*_{e1}\,|\nu_1\rangle + U^*_{e2}\,|\nu_2\rangle + U^*_{e3}\,|\nu_3\rangle \\
|\nu_\mu\rangle &= U^*_{\mu 1}\,|\nu_1\rangle + U^*_{\mu 2}\,|\nu_2\rangle + U^*_{\mu 3}\,|\nu_3\rangle \\
|\nu_\tau\rangle &= U^*_{\tau 1}\,|\nu_1\rangle + U^*_{\tau 2}\,|\nu_2\rangle + U^*_{\tau 3}\,|\nu_3\rangle
\end{aligned}
$$

Mixing Matrix: 3 angles, 1 phase

(relevant for neutrino oscillations)

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

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

U* : Mixing Matrix for Antineutrinos

More complex expressions
for the Oscillation Probabilities

3 - Flavor Transitions

$$|\nu(0)\rangle = |\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$$

$$|\nu(t)\rangle = \sum_j U^*_{\alpha j}\, e^{-iE_j t} |\nu_j\rangle$$

$$\begin{aligned}
A(\nu_\alpha \to \nu_\beta;\, t) &= \langle \nu_\beta | \nu(t) \rangle \\
&= \{U_{\beta k} \langle \nu_k |\} \left\{ e^{-iE_j t}\, U^*_{\alpha j} |\nu_j\rangle \right\} \\
&= U_{\beta k}\, U^*_{\alpha j}\, e^{-iE_j t} \langle \nu_k | \nu_j \rangle \\
&= U_{\beta j}\, U^*_{\alpha j}\, e^{-iE_j t}
\end{aligned}$$

Oscillation Probability

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_j U_{\beta j} U^*_{\alpha j} \, e^{-i\, m_j^2 \, \frac{L}{2E_\nu}} \right|^2$$

$$= \sum_{j=1,3} |U_{\beta j}|^4 \; |U_{\alpha j}|^4$$

$$+ \sum_{j<k} 2\,\mathrm{Re}[U_{\beta j} U^*_{\beta k} U^*_{\alpha j} U_{\alpha k}] \; \cos\left(\frac{\Delta m^2_{jk}\, L}{2E}\right)$$

$$+ \sum_{j<k} 2\,\mathrm{Im}[U_{\beta j} U^*_{\beta k} U^*_{\alpha j} U_{\alpha k}] \; \sin\left(\frac{\Delta m^2_{jk}\, L}{2E}\right)$$

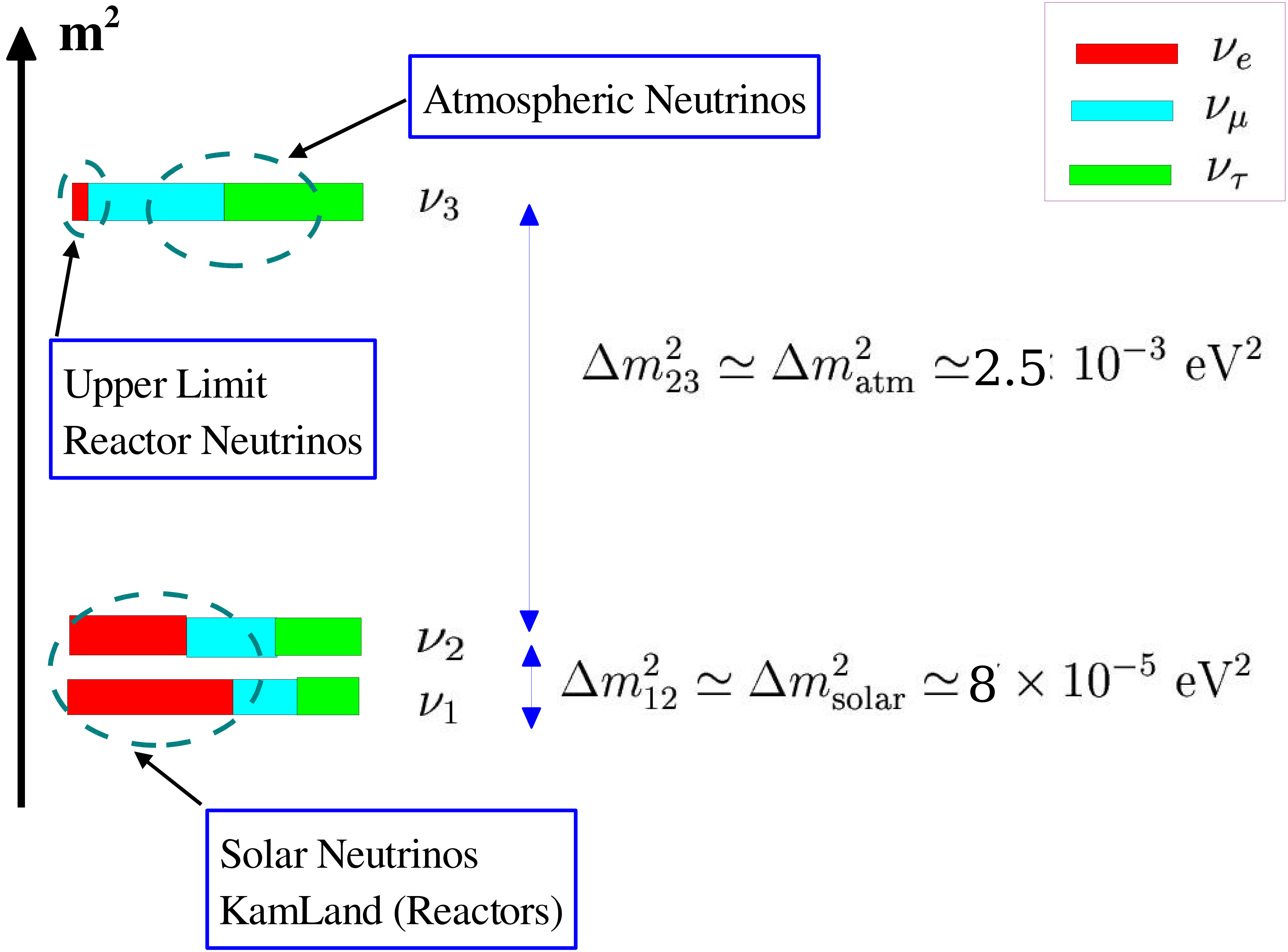
L, E_ν

$$P(\nu_\alpha \to \nu_\beta) \;=\; \left| \sum_j U_{\beta j} U^*_{\alpha j}\, e^{-i\, m_j^2 \frac{L}{2E\nu}} \right|^2$$

$$P(\nu_\alpha \to \nu_\beta) \neq P(\overline{\nu}_\alpha \to \overline{\nu}_\beta)$$ **CP** violated

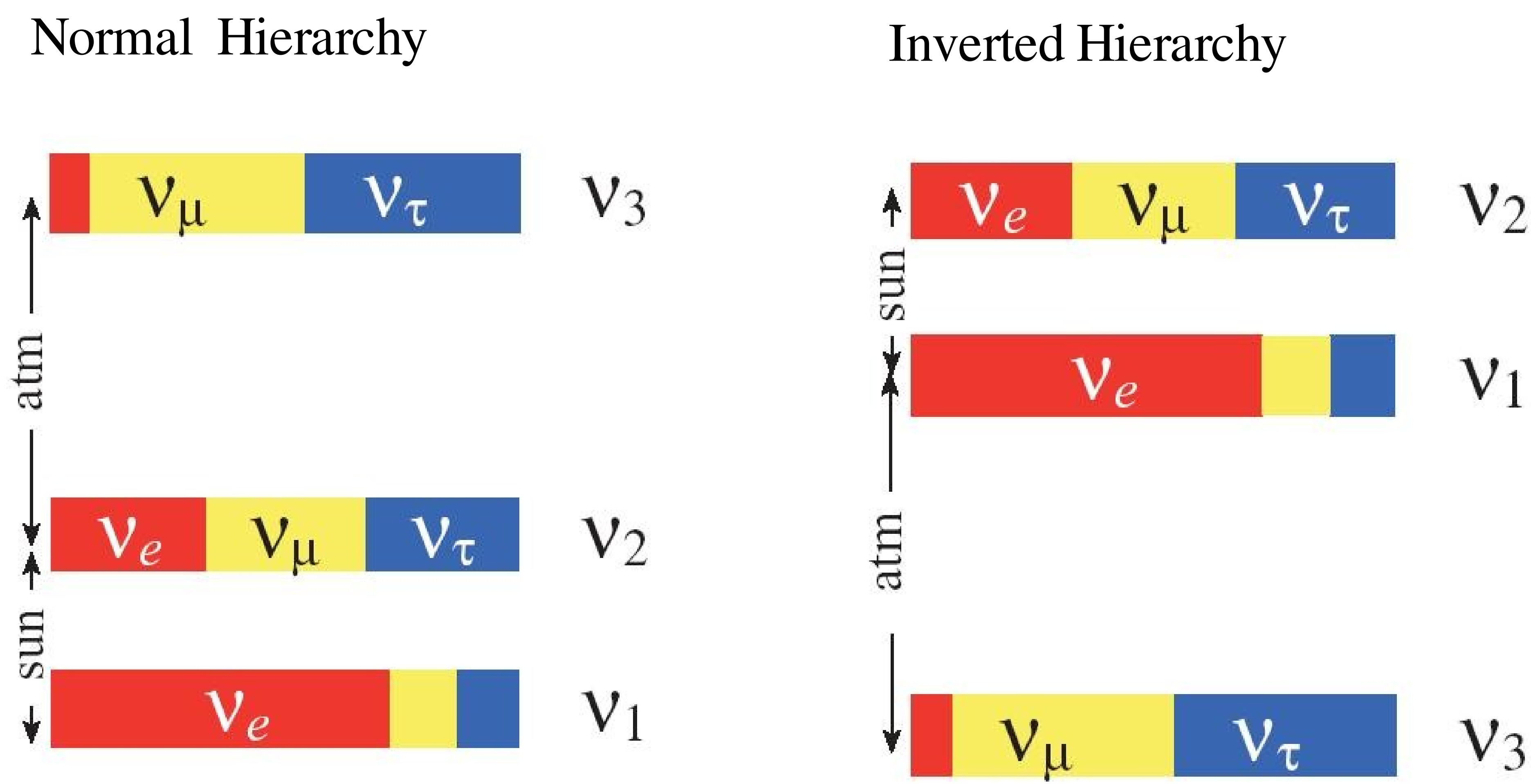
$$P(\nu_\alpha \to \nu_\beta) \neq P(\nu_\beta \to \nu_\alpha)$$ **T** violated

$$P(\nu_\alpha \to \nu_\beta) = P(\overline{\nu}_\beta \to \overline{\nu}_\alpha)$$ **CPT** conserved



m²
Atmospheric Neutrinos
ν₃
Upper Limit
Reactor Neutrinos
$\Delta m^2_{23} \simeq \Delta m^2_{atm} \simeq 2.5 \times 10^{-3}\ eV^2$
ν₂
ν₁
$\Delta m^2_{12} \simeq \Delta m^2_{solar} \simeq 8 \times 10^{-5}\ eV^2$
Solar Neutrinos
KamLand (Reactors)
ν_e
ν_μ
ν_τ

Neutrino MASS Hierarchy



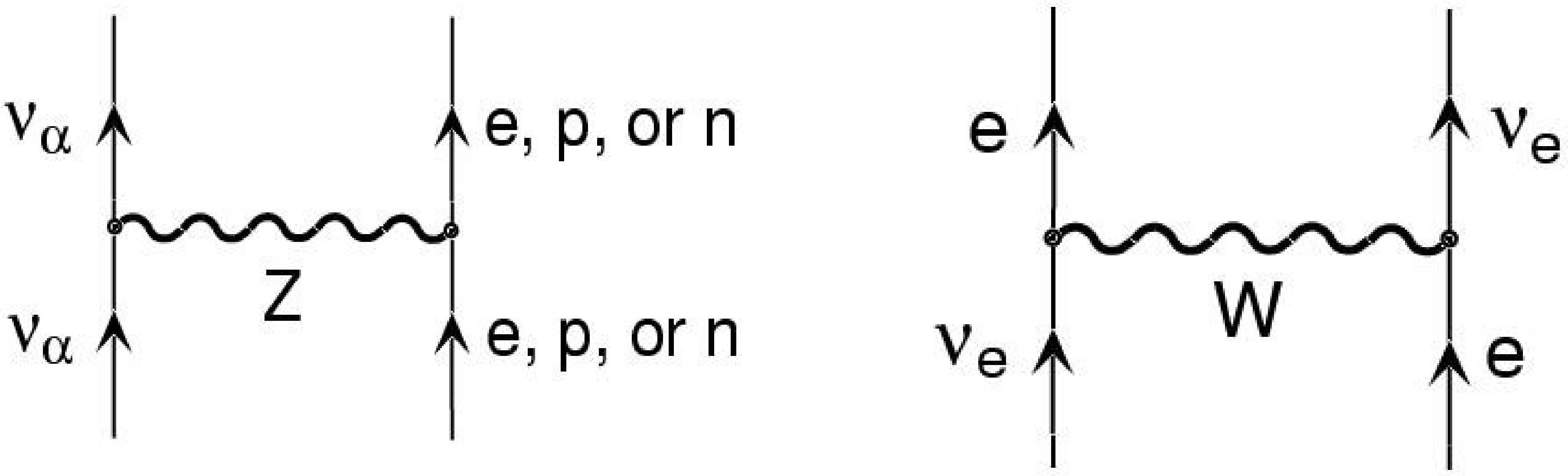
Mass of the lightest Neutrino m_0

Matter Effects

in

Neutrino Oscillations

MATTTER EFFECTS



Neutrino Propagation:

Amplitude =
Amplitude (No-Scattering) + Amplitude (forward Scattering)

EFFECTIVE POTENTIAL

$$V_{\nu_\mu e} = V_{\nu_\tau e} = V^Z_{\nu_e e} = -\frac{\sqrt{2}}{2} G_F N_e$$

$$V_{\nu_\mu p} = V_{\nu_\tau p} = V_{\nu_e p} = +\frac{\sqrt{2}}{2} G_F N_p$$

$$V_{\nu_\mu n} = V_{\nu_\tau n} = V_{\nu_e n} = -\frac{\sqrt{2}}{2} G_F N_n$$

$$V_{\overline{\nu}_\alpha} = -V_{\nu_\alpha}$$

$$V_{\nu_e e} = V^Z_{\nu_e e} + V^W_{\nu_e e} = -\frac{\sqrt{2}}{2} G_F N_e + \sqrt{2} G_F N_e$$

$$V \equiv V_{\nu_e} - V_{\nu_\mu} = V_{\nu_e} - V_{\nu_\tau} = +\sqrt{2} G_F N_e$$

$$3.8 \times 10^{-14} \left(\frac{\rho}{\text{g cm}^{-3}}\right) \left(\frac{Y_e}{0.5}\right) \text{eV}$$

$$E - V = \sqrt{p^2 + m^2} \simeq p + \frac{m^2}{2p}$$

$$m^2 \to m^2 + 2EV$$

$$i\frac{\mathrm{d}}{\mathrm{d}x}\nu_\alpha = \mathcal{H}\,\nu_\alpha$$

$$\mathcal{H}(\nu) = U \begin{bmatrix} E_1 & 0 & 0 \\ 0 & E_2 & 0 \\ 0 & 0 & E_3 \end{bmatrix} U^\dagger + \begin{bmatrix} V_e & 0 & 0 \\ 0 & V_\mu & 0 \\ 0 & 0 & V_\tau \end{bmatrix}$$

NEUTRINO MASSES and MIXING

Fermion Masses :
Yukawa Fermion-Higgs Coupling

$$\lambda_d \;\; (\overline{Q_L} \cdot H) \;\; d_R + \text{h.c.}$$

$$\lambda_u \;\; \left(\overline{Q_L}_a \, \epsilon_{ab} H_b^\dagger\right) \;\; u_R + \text{h.c.}$$

$$\lambda_d \;\; (\overline{u} \quad \overline{d})_L \; \begin{pmatrix} H^+ \\ H_\circ \end{pmatrix} \; d_R + \text{h.c.}$$

$$\lambda_d \;\; (\overline{u} \quad \overline{d})_L \; \begin{pmatrix} H^{\circ *} \\ -H^- \end{pmatrix} \; u_R + \text{h.c.}$$

$$\epsilon_{ab} = i\,(\tau^2)_{ab} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

$$\mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y \to \mathrm{U}(1)_{\mathrm{em}}$$

$$\begin{pmatrix} H^+ \\ H_\circ \end{pmatrix} \to \begin{pmatrix} 0 \\ v \end{pmatrix}$$

→

$$m_u = \lambda_u v$$

$$m_d = \lambda_d v$$

QUARK MIXING

$$\lambda^d_{jk} \quad (\overline{Q_L}_j \cdot H) \quad (d_R)_k \qquad + \text{h.c.}$$

$$Y = -\frac{1}{6} \qquad +\frac{1}{2} \qquad -\frac{1}{3}$$

$$(M_{\text{down}})_{jk} = \lambda^d_{jk} \; v$$

Mass Matrix
for down quarks
{d,s,b}

$$\lambda^u_{jk} \quad (\overline{Q_L}_j \, \epsilon H^\dagger) \quad (u_R)_k + \text{h.c.}$$

$$Y = -\frac{1}{6} \qquad -\frac{1}{2} \qquad +\frac{2}{3}$$

$$(M_{\text{up}})_{jk} = \lambda^u_{jk} \; v$$

Mass Matrix
for up quarks
{u,c,t}

Linear Transformation of the fields

$$u'_L = U_u^{ij}\; u_L^j \qquad\qquad u_L^i = \{u_L, c_L, t_L\}$$

$$d'_L = U_d^{ij}\; d_L^j \qquad\qquad d_L^i = \{d_L, s_L, b_L\}$$

WEAK CURRENT

$$\begin{aligned} J_W^\alpha &= \overline{u_L}^i\, \gamma_\alpha\, d_L^i \\ &= \overline{u_L}'^i\, \gamma_\alpha\, (U_u^\dagger\, U_d)_{ij}\, d_L^j \\ &= \overline{u_L}'^i\, \gamma_\alpha\, \boxed{V_{ij}}\, d_L^j \end{aligned}$$

CKM Matrix

DIRAC , WEYL and MAJORANA SPINORS

DIRAC SPINOR

$$\psi = \psi_L + \psi_R$$

$$\psi_L = \left(\frac{1-\gamma_5}{2}\right)\psi$$

$$\psi_R = \left(\frac{1+\gamma_5}{2}\right)\psi$$

$$\psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$

Weyl Representation

Charged Conjugation Operator

$$[i\gamma^\alpha\,(\partial_\alpha - ieA^\alpha) - m]\;\psi = 0$$

$$[i\gamma^\alpha\,(\partial_\alpha + ieA^\alpha) - m]\;\psi^c = 0$$

$$\{\quad [i\gamma^\alpha\,(\partial_\alpha - ieA^\alpha) - m]\;\psi = 0 \quad\}^*$$

$$[-i\gamma^{\alpha *}\,(\partial_\alpha + ieA^\alpha) - m]\;\psi^* = 0$$

$$(C\gamma^0)\;\gamma^{\alpha *}\;(C\gamma^0)^{-1} = -\gamma^\alpha$$

Exchange
particle $\Leftrightarrow$ antiparticle

$$\psi^c = C\,\gamma_0\,\psi^*$$

$$C = i\gamma^2\,\gamma^0$$

$$(\psi^c)^c = \psi$$

The conjugate of
the (conjugate field)
goes back to the original field

$$(\psi_L)^c = (\psi^c)_R$$

$$(\psi_R)^c = (\psi^c)_L$$

The conjugate of a Left-field
is a Right-field

(and vice-versa)

$$(1 + \gamma_5)\,\psi = 0$$

$$\begin{aligned}(1 - \gamma_5)\ \psi^c &= (1 - \gamma_5)\,\gamma^2\,\psi^* \\ &= \gamma^2\,(1 + \gamma_5)\,\psi^* = 0\end{aligned}$$

Weyl Representation

$$\psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$

$$\psi^c = C\,\gamma^\circ\,\psi^* = \begin{pmatrix} +i\sigma^2\,\psi_R^* \\ -i\sigma^2\,\psi_L^* \end{pmatrix}$$

Majorana Field

Conjugate of itself

$$\psi = \psi^c$$

$$\psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$

$$\psi_{\mathrm{M}} = \begin{pmatrix} \psi_L \\ -i\sigma^2 \psi_L^* \end{pmatrix} = \begin{pmatrix} \psi_L \\ (\psi_L)^c \end{pmatrix}$$

Mass Terms in the Lagrangian

$$-\mathcal{L}_{\text{mass}}^{\text{Dirac}} = m\,\overline{\psi}\,\psi \qquad = m\,\left(\overline{\psi_R}\,\psi_L + \overline{\psi_L}\,\psi_R\right)$$

$$-\mathcal{L}_{\text{mass}}^{\text{Majorana}} \quad = \quad m\,\left(\overline{(\psi_L)^c}\,\psi_L + \overline{\psi_L}\,(\psi_L)^c\right)$$

Majorana mass term
not invariant
for U(1) transformations

$$\psi \to e^{i\alpha}\,\psi$$
$$\overline{\psi} \to \overline{\psi}\,e^{-i\alpha}$$

Include the 3-Right Neutrino Fields N_j

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \bar{N}_i i \not{D} N_i$$

$$(\lambda_N^{ij} \; N^i L^j H + \frac{M_N^{ij}}{2} N_i N_j + \text{h.c.})$$

Dirac Masses

Majorana Masses

$$\begin{array}{cc} & \begin{array}{cc} \nu_L & \nu_R \end{array} \\ \begin{array}{c} \nu_L \\ \nu_R \end{array} & \begin{pmatrix} 0 & \boldsymbol{\lambda}_N^T v \\ \boldsymbol{\lambda}_N v & \boldsymbol{M}_N \end{pmatrix} \end{array}$$

Terms bilinear in the fields

Only One Family

$$\begin{array}{cc} & \begin{array}{cc} \nu_L & \nu_R \end{array} \\ \begin{array}{c} \nu_L \\ \nu_R \end{array} & \begin{pmatrix} 0 & m \\ m & M \end{pmatrix} \end{array}$$

$$\begin{array}{cc} & \begin{array}{cc} \nu_L & \nu_R \end{array} \\ \begin{array}{c} \nu_L \\ \nu_R \end{array} & \begin{pmatrix} 0 & \lambda v \\ \lambda v & M \end{pmatrix} \end{array}$$

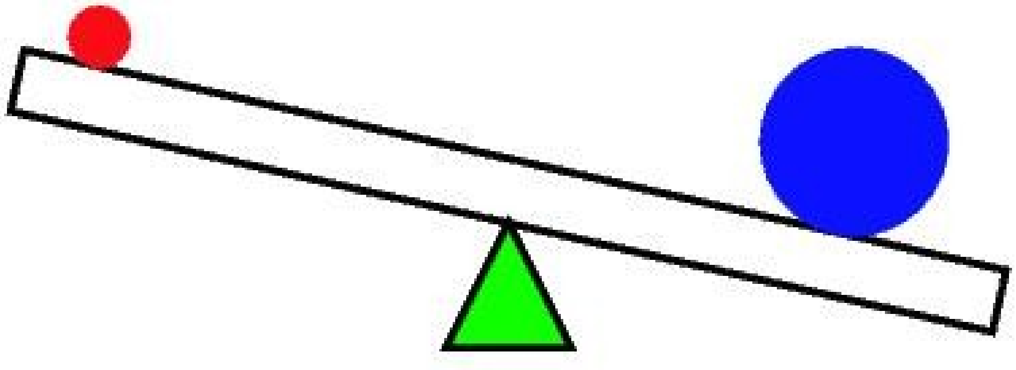
$$\frac{M}{2} \pm \frac{\sqrt{M^2 + 4m^2}}{2}$$

Eigenvalues

$$-\frac{m^2}{M} \qquad \left\{1, -\frac{m}{M}\right\}$$

$$M + \frac{m^2}{M} \qquad \left\{\frac{m}{M}, 1\right\}$$

The SEE-SAW Mechanism



$$m_\nu = m^2/M$$

What High-Mass scale is implied by the neutrino mass determinations ?

$$|\Delta m^2_{\rm atm}| \simeq m_3^2 - m_1^2 \simeq m_3^2 \simeq \left(\frac{m^2_{\rm top}}{M}\right)^2$$

$$M \sim \frac{m^2_{\rm top}}{\sqrt{|\Delta m^2_{\rm atm}|}} \sim 0.6 \times 10^{15}\ {\rm GeV}$$

Additional Phases in the Mixing Matrix (for Majorana neutrinos)

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

Majorana Phases

Non detectable in oscillation experiments

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{\frac{i\,\varphi_2}{2}} & 0 \\ 0 & 0 & e^{\frac{i\,\varphi_3}{2}} \end{pmatrix}$$

DIRAC and Majorana phases

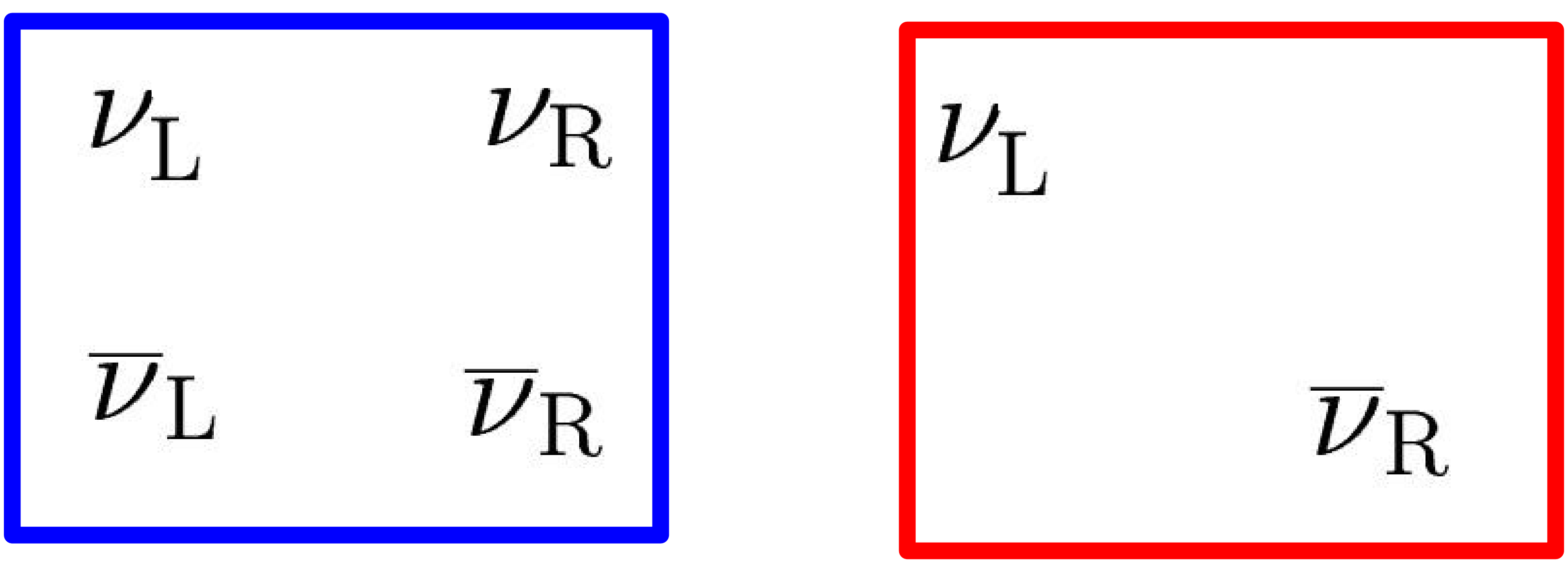
$$N^{\text{Dirac}}_{\text{(physical phases)}} = \frac{n(n+1)}{2} - (2n-1)$$

$(n-1)$ "Majorana" phases

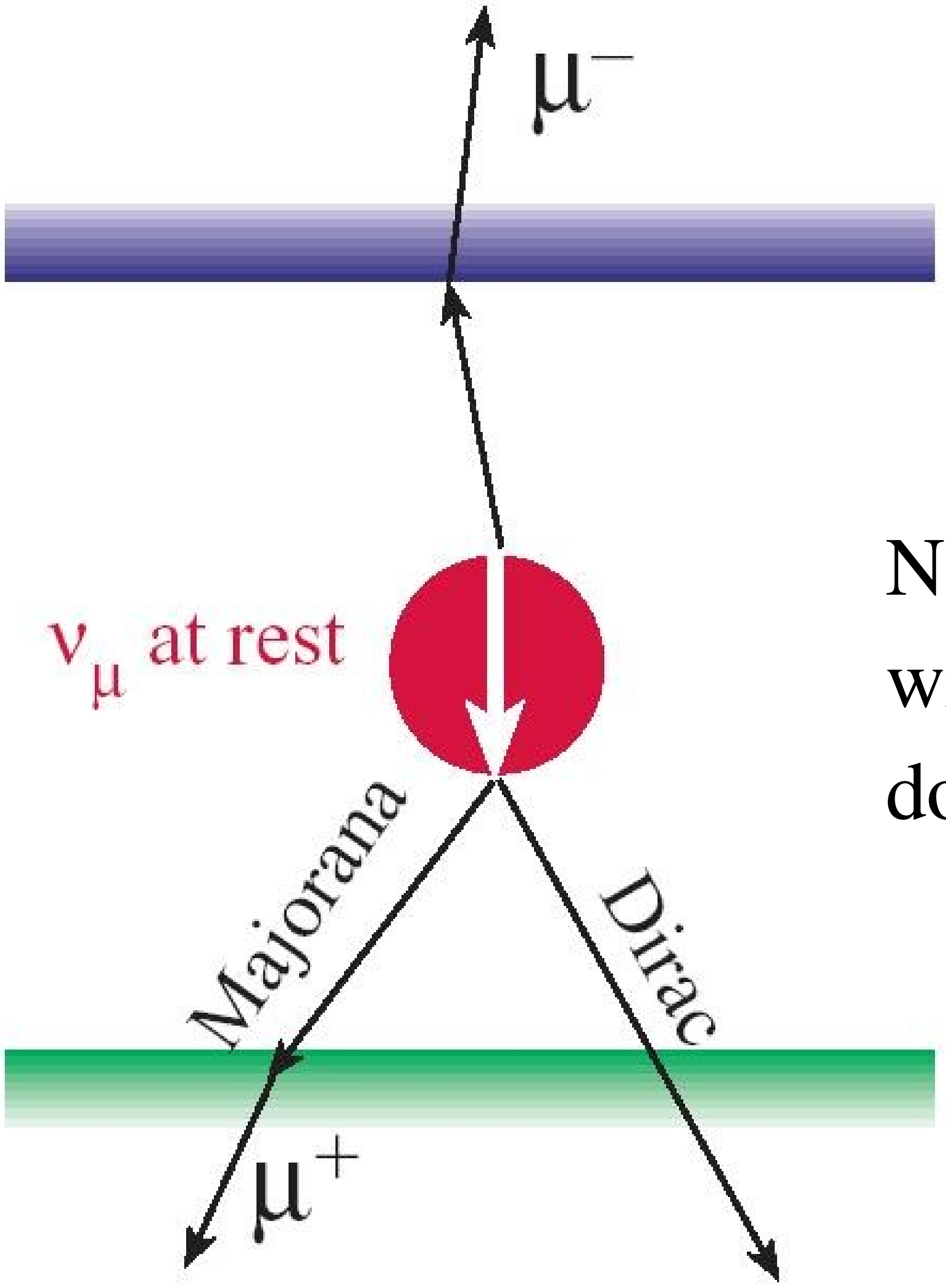
Phases can be eliminated
redefining the fermion fields

$$\lambda^u_{jk} \;\; \left(\overline{Q_L}_j \, \epsilon H^\dagger\right) \;\; (u_R)_k + \text{h.c.}$$

DIRAC or MAJORANA ?



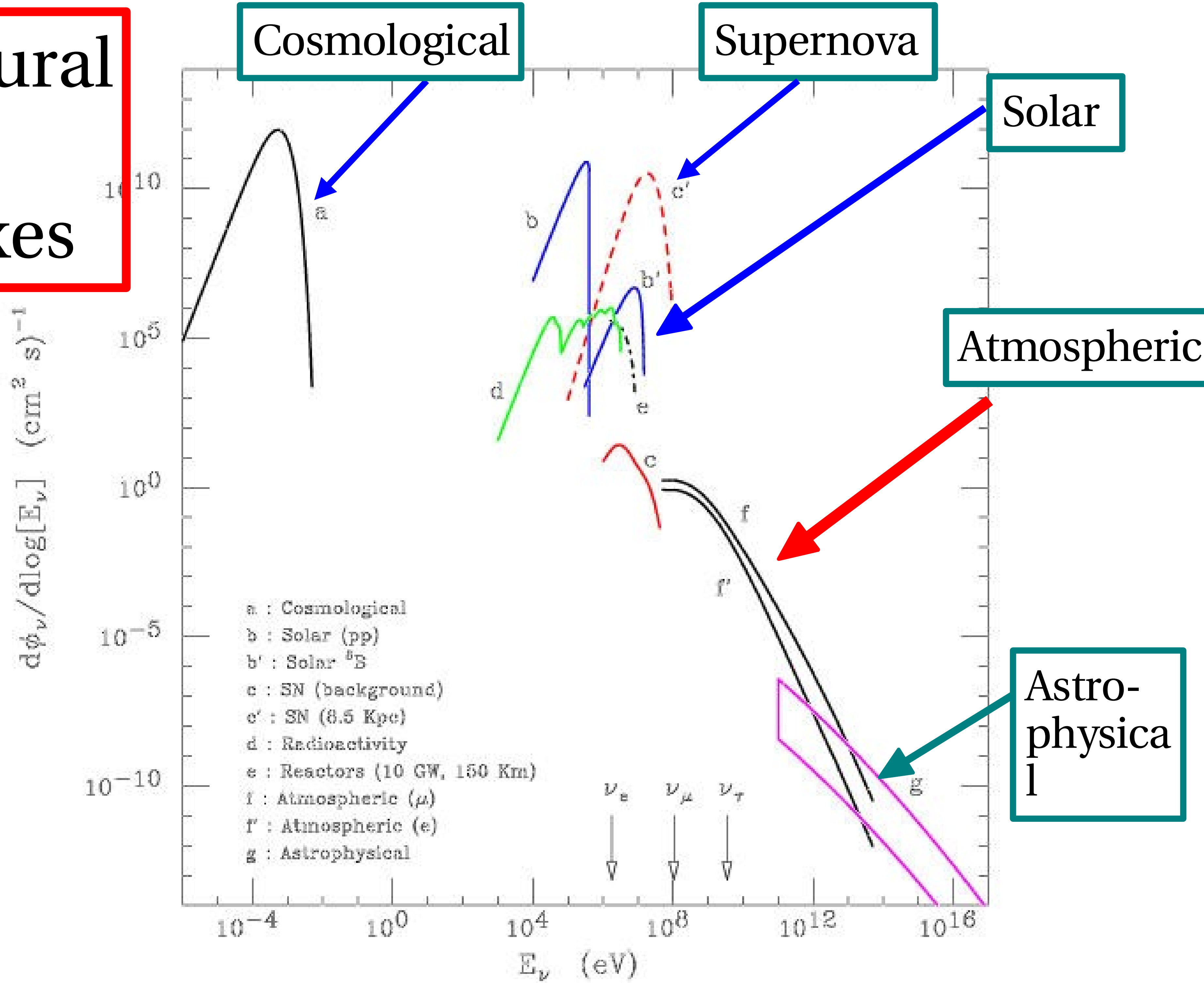
Gedanken Experiment



Neutrino at Rest with spin pointing downward.

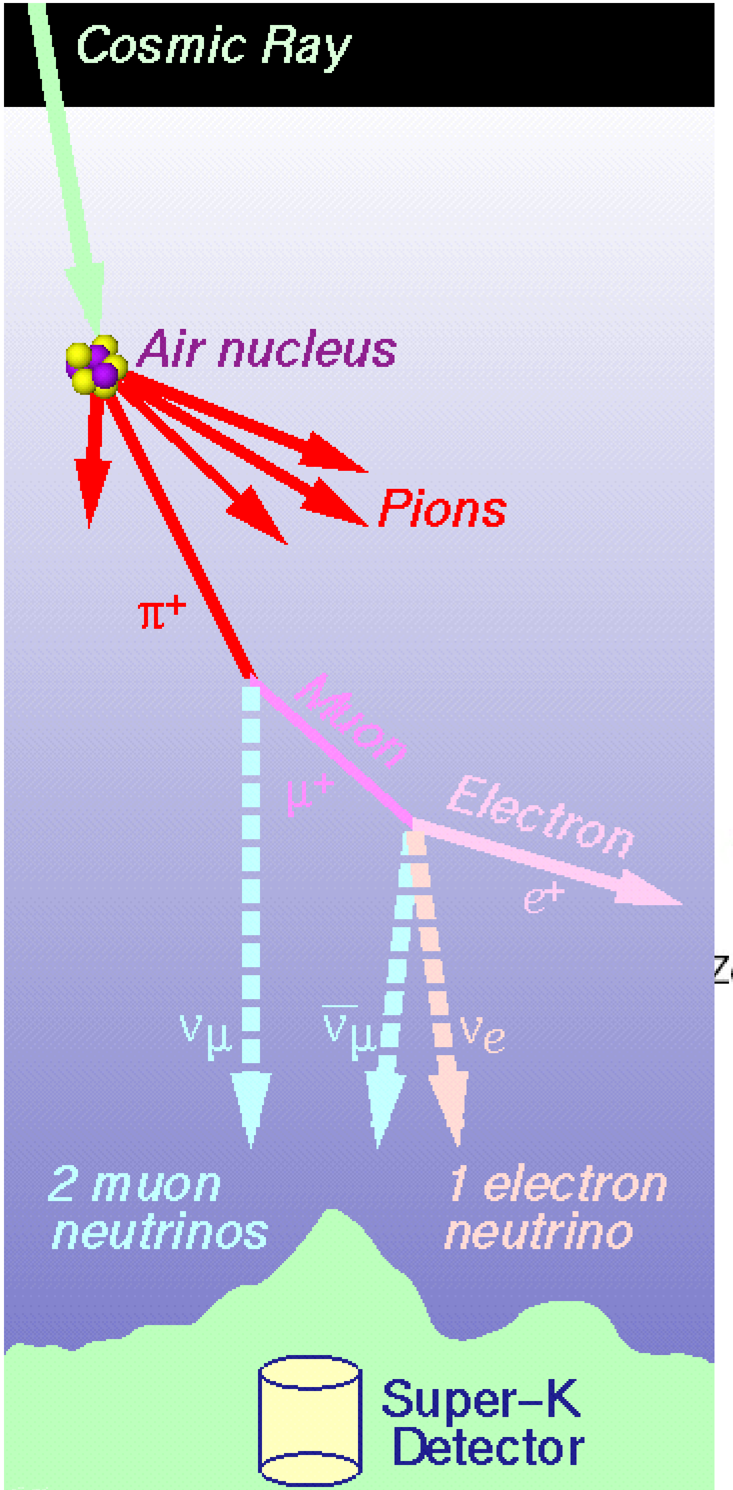
Strumia, Vissani

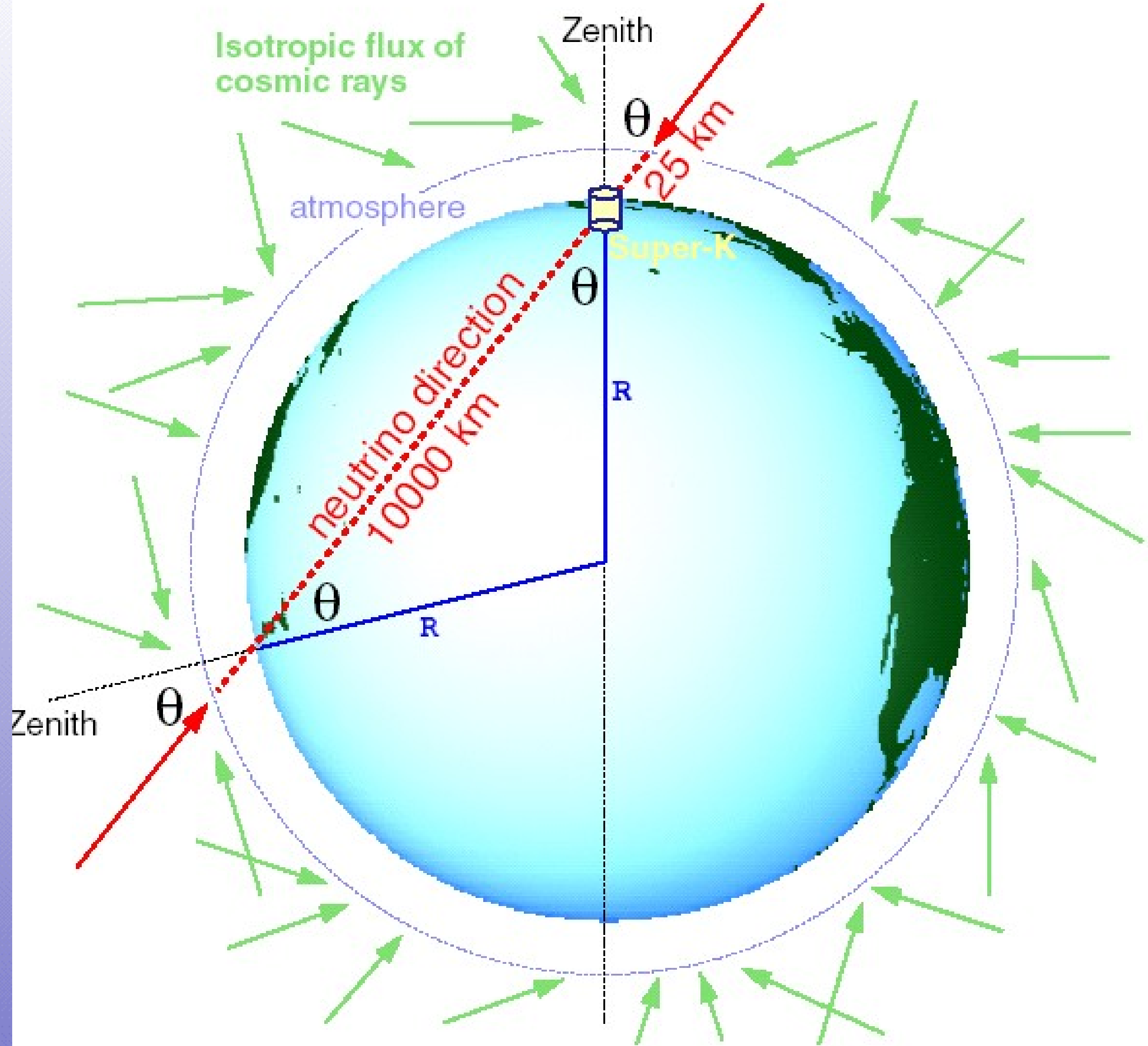
Natural ν Fluxes



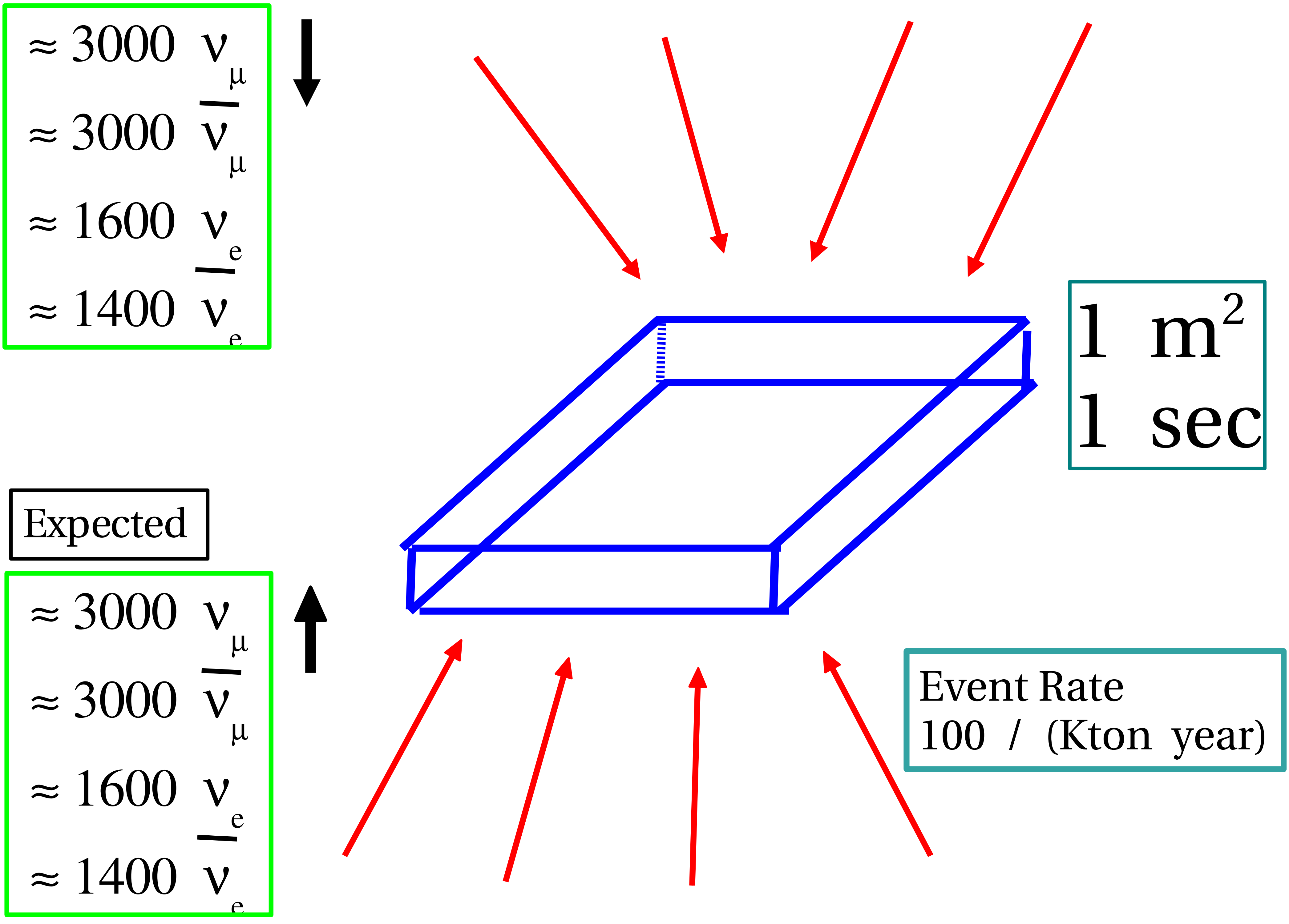
ATMOSPHERIC NEUTRINOS

ATMOSPHERIC NEUTRINOS





Up-Down Symmetric Flux
(for Eν > few GeV)



$\approx 3000\ \nu_\mu$
$\approx 3000\ \bar{\nu}_\mu$
$\approx 1600\ \nu_e$
$\approx 1400\ \bar{\nu}_e$
$1\ m^2$
1 sec
Expected
$\approx 3000\ \nu_\mu$
$\approx 3000\ \bar{\nu}_\mu$
$\approx 1600\ \nu_e$
$\approx 1400\ \bar{\nu}_e$
Event Rate
100 / (Kton year)

Detailed prediction:

Primary Cosmic Rays

Hadronic interactions

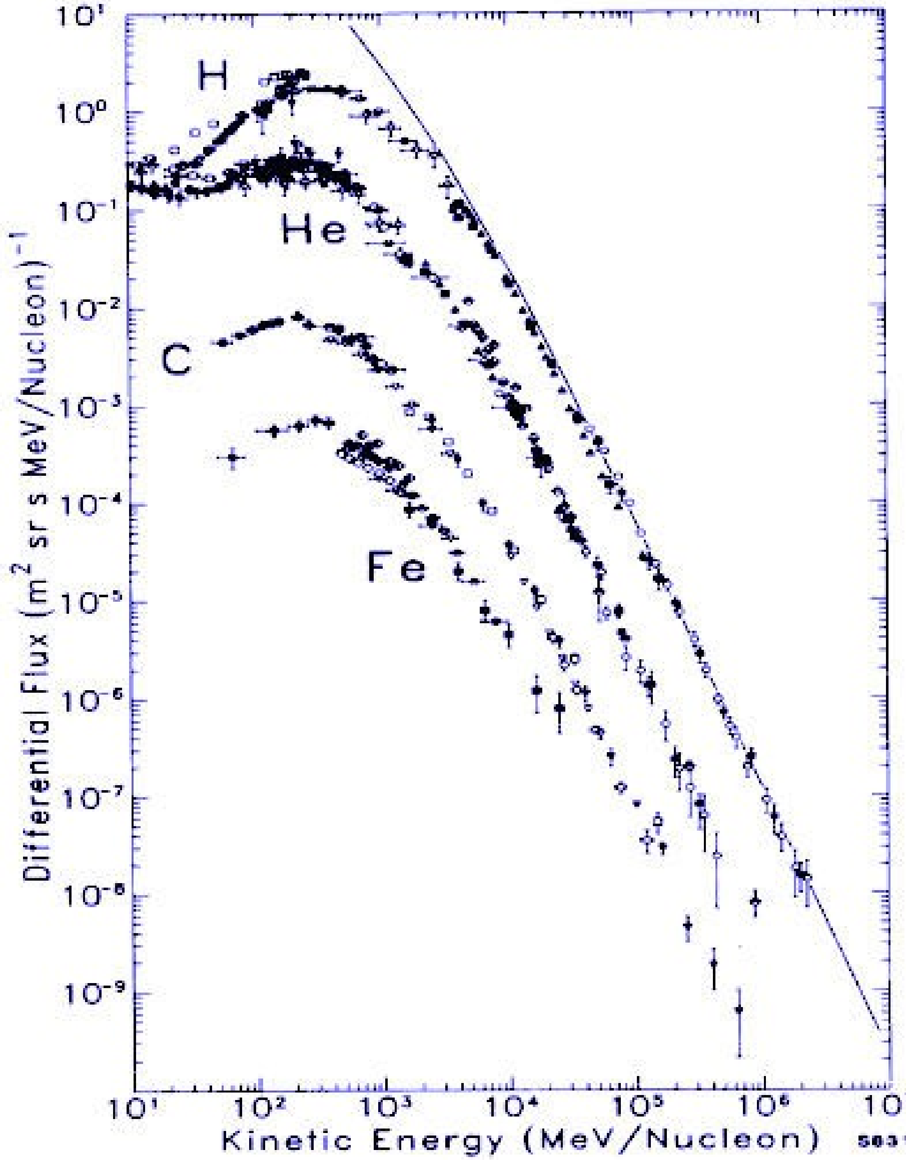
Neutrino Cross section

The Primary Cosmic Ray Fluxes

Interstellar Fluxes

Solar Modulation

Geomagnetic Effects



HADRONIC INTERACTIONS

$$p + A_{\mathrm{Air}} \rightarrow p, n, \ \pi^{\circ}, \ \pi^{\pm}, \ K^{\pm}, K_L \ldots$$

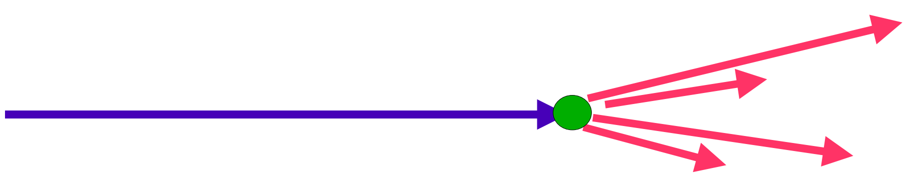
Leading nucleon
50% of energy

$\pi^{o} \rightarrow \gamma\gamma$
Electromagnetic
Shower

Decay

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$
$$\downarrow$$
$$e^{+} + \nu_e + \overline{\nu}_{\mu}$$

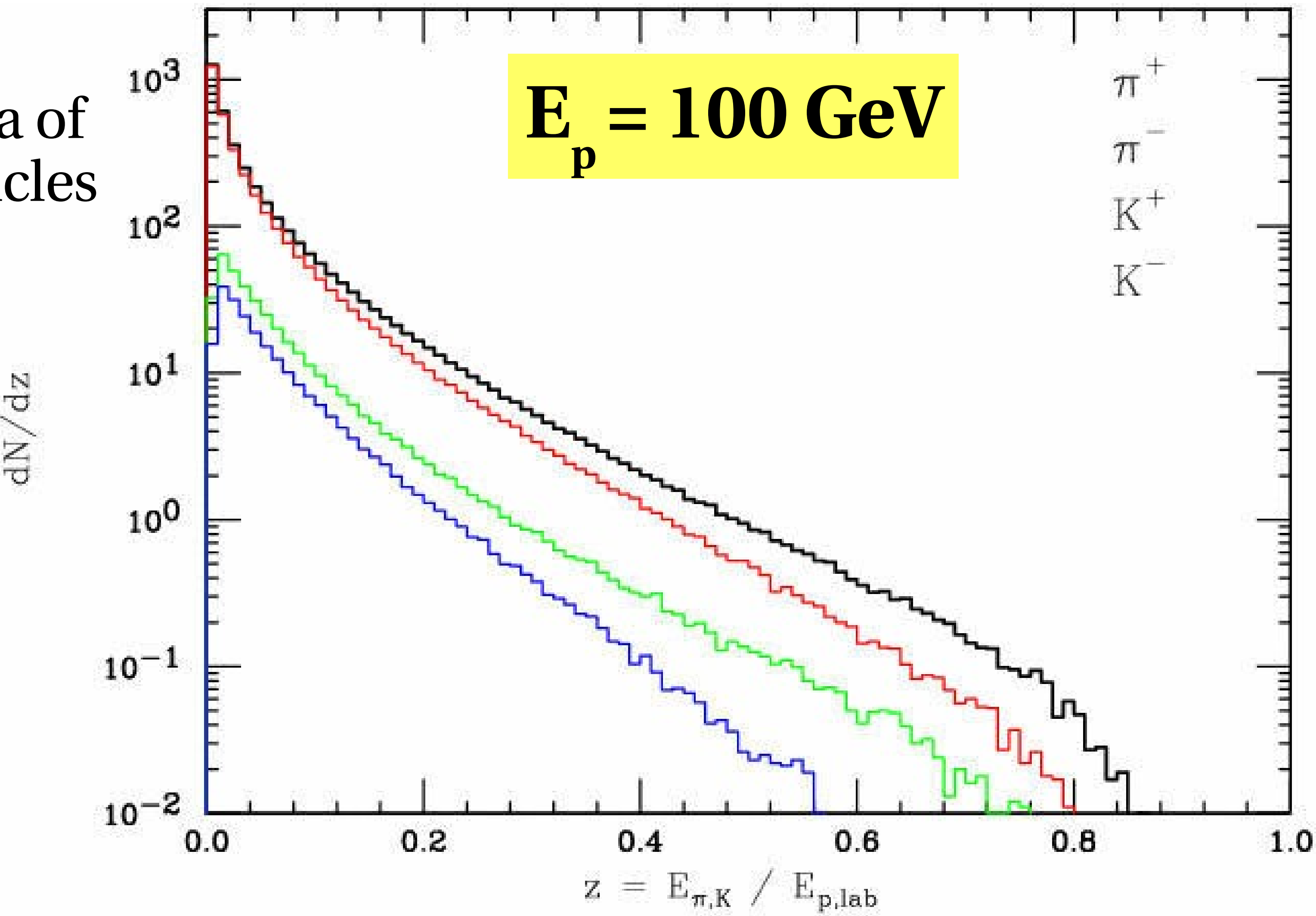
Interaction



HADRONIC INTERACTIONS

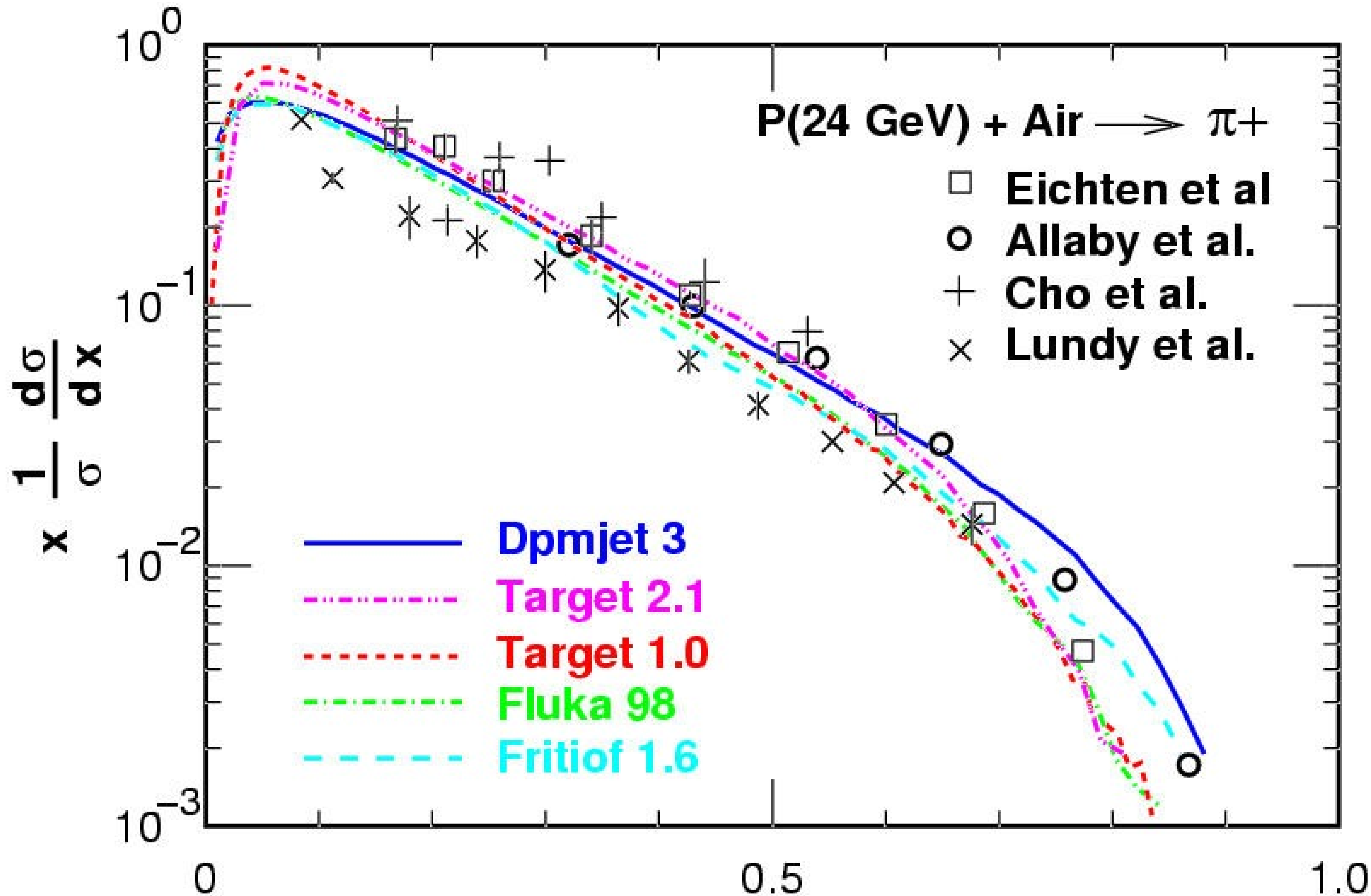
A precise knowledge of hadronic interactions is essential for the calculation of the atmospheric neutrino fluxes.

Inclusive spectra of secondary particles



COMPARISON with DATA

π^+



$X = E_\pi$/Eproton

Constraint from **Atmospheric Muon** measurements

Measurements

Ground level

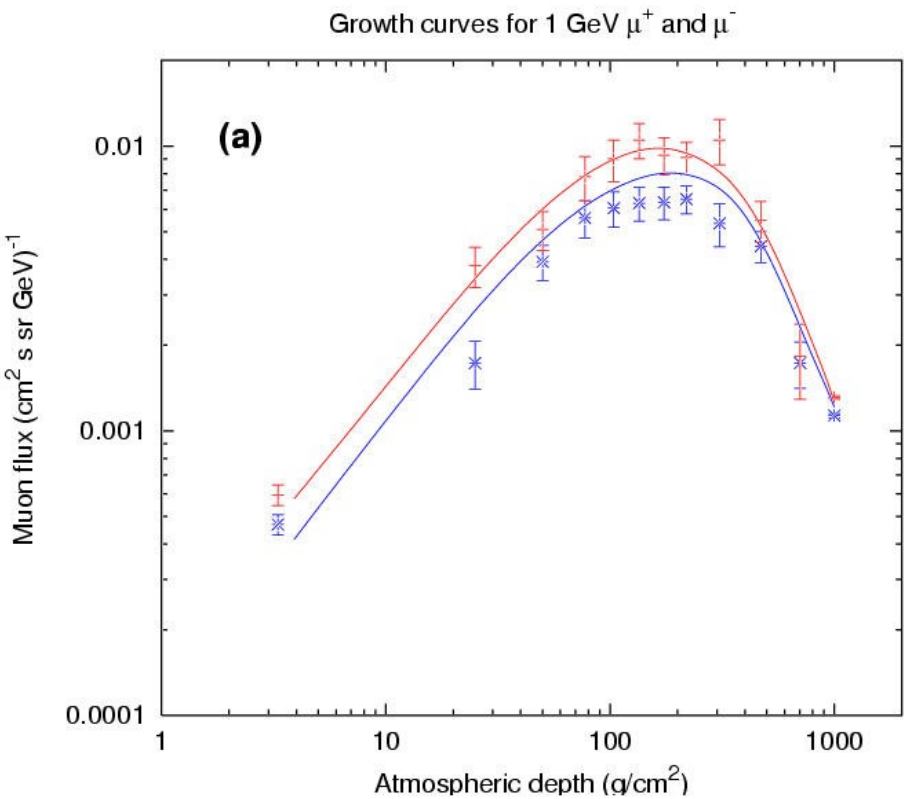
Balloon Float

Balloon Ascent

$$p + A_{\mathrm{Air}} \rightarrow p, n, \pi^{\pm}, \pi^{\circ}, K^{\pm}, \ldots$$

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$

$$\mu^{+} \rightarrow e^{+} + \nu_e + \overline{\nu}_{\mu}$$



Height

2 Very Robust Properties of the Atmospheric Neutrino Fluxes

Strict Relation between the fluxes of different flavor

$$\frac{\nu_\mu + \overline{\nu}_\mu}{\nu_e + \overline{\nu}_e} \simeq 2$$

Up-Down Symmetry of the Fluxes

$$\phi_{\nu_\alpha}(E, \theta) = \phi_{\nu_\alpha}(E, \pi - \theta)$$

$$\pi^+ \to \nu_\mu \, \mu^+ \to \nu_\mu \, \overline{\nu}_\mu \, \nu_e \, e^+$$

$$\pi^- \to \overline{\nu}_\mu \, \mu^- \to \overline{\nu}_\mu \, \nu_\mu \, \overline{\nu}_e \, e^-$$

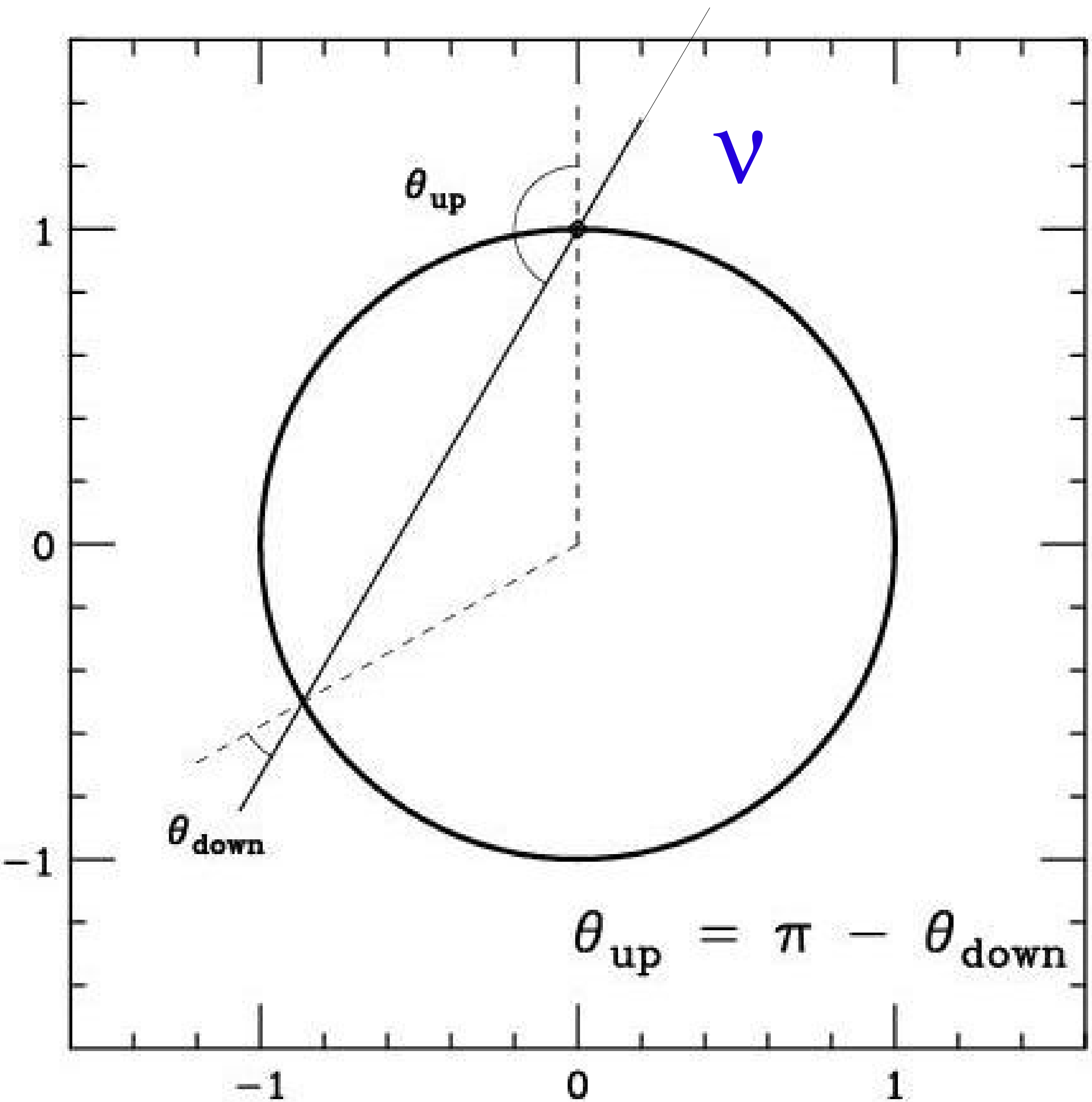
$$\frac{\nu_e}{\overline{\nu}_e} \simeq \frac{\pi^+}{\pi^-} \simeq 1.2 \qquad \frac{\nu_\mu}{\overline{\nu}_\mu} \simeq 1$$

$$\frac{\nu_\mu + \overline{\nu}_\mu}{\nu_e + \overline{\nu}_e} \simeq 2$$

Assume all muons decay
AND
an important kinematical fact.
All 3 neutrinos in decay
have approximately the same
energy

GEOMETRY THEOREM

$$\phi_{\nu_\alpha}(E,\theta) = \phi_{\nu_\alpha}(E,\pi-\theta)$$



If :

the Earth is spherical
Cosmic Rays are Isotropic

Then:

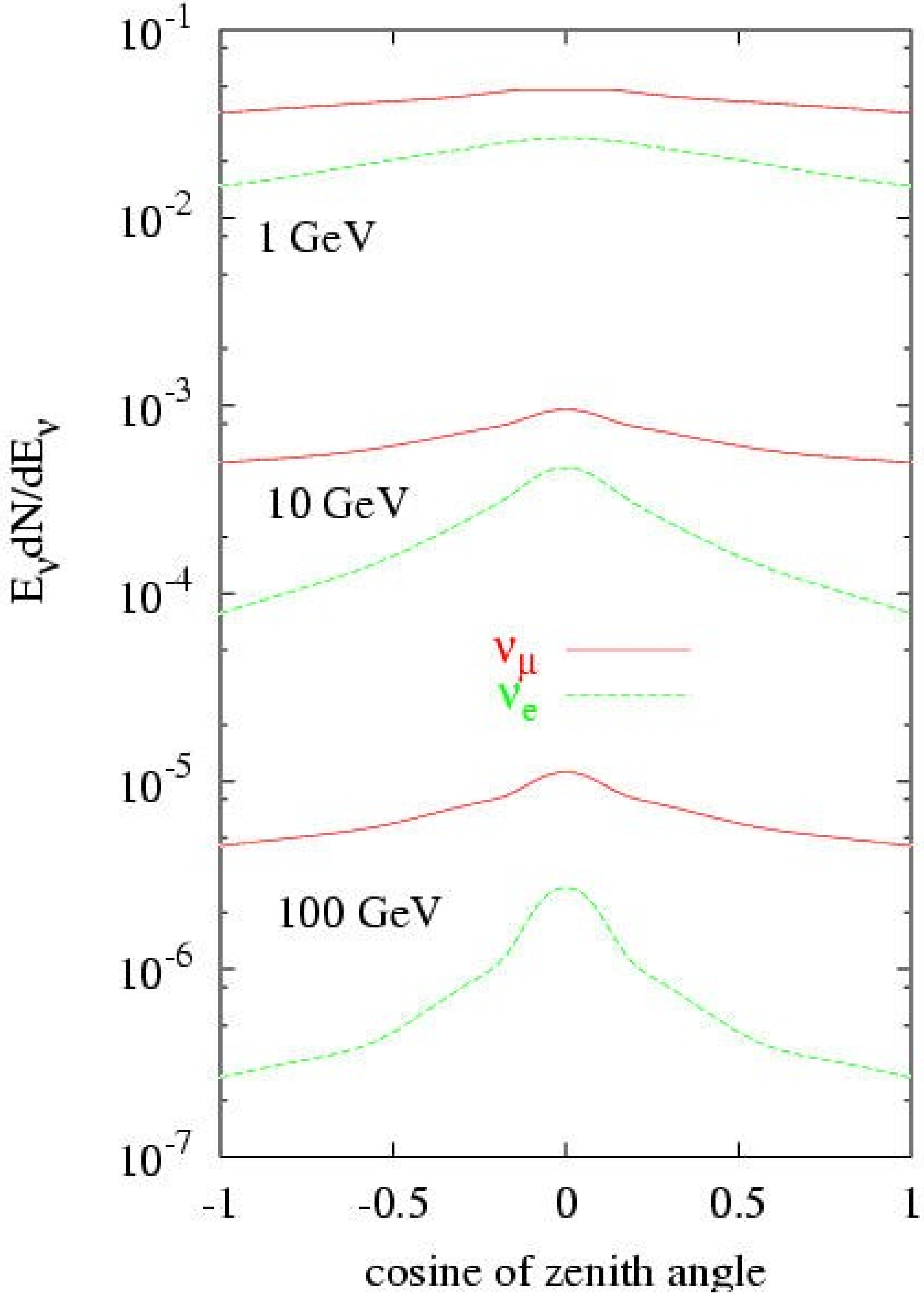
Neutrino Fluxes are
Up-Down Symmetric

Each neutrino
"enters" the Earth as
downgoing

with zenith angle θ_{down}

"exits" the Earth as upgoing
with zenith angle

$\theta_{up} = \pi - \theta_{down}$



Zenith angle distribution
is Up-Down symmetric

Zenith angle distribution
maximum $|\cos\theta| = 0$
minimum $|\cos\theta| = 1$
(μ and π decay effect)

Ratio ν_μ/ν_e
is energy dependent
(grows with increasing energy)

Ratio ν_μ/ν_e
is zenith angle dependent
(grows with $|\cos\theta|$)

The Neutrino Cross section

$$\nu_\ell + \text{Nucleus} \to \ell^- + X$$

Charged Current

$$\nu_\ell + \text{Nucleus} \to \nu_\ell + X$$

Neutral Current

$$\nu_\ell + n \to \ell^- + p$$

$$\overline{\nu}_\ell + p \to \ell^+ + n$$

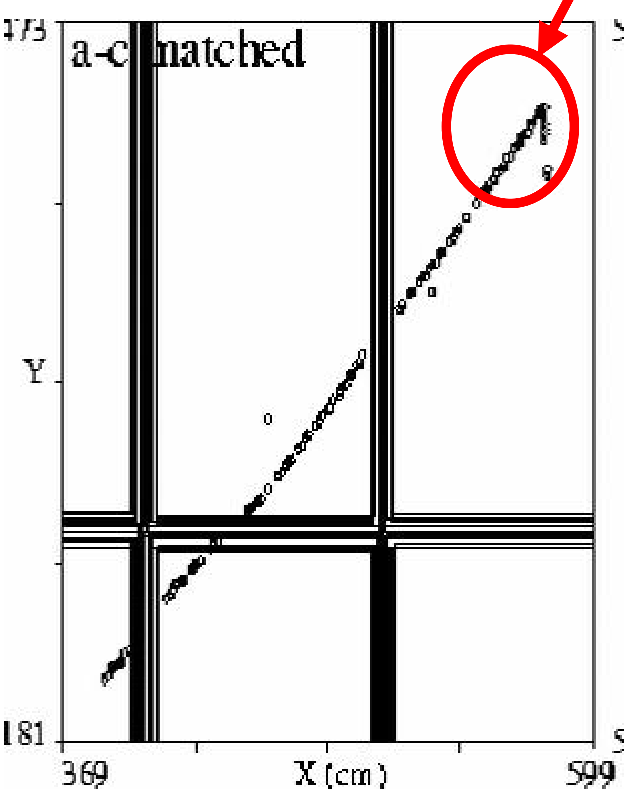
Quasi Elastic Scattering

Atmospheric Neutrino events

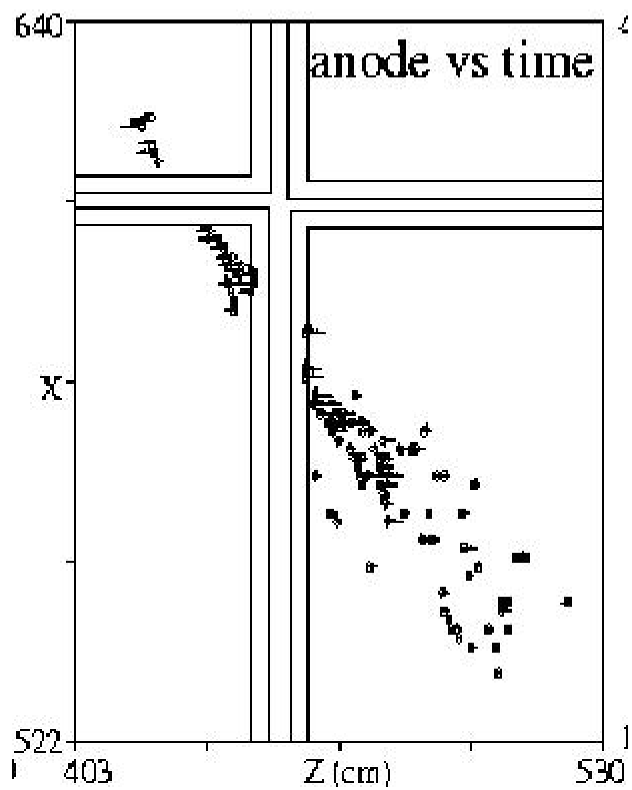
Soudan-2 detector

ν interaction vertex

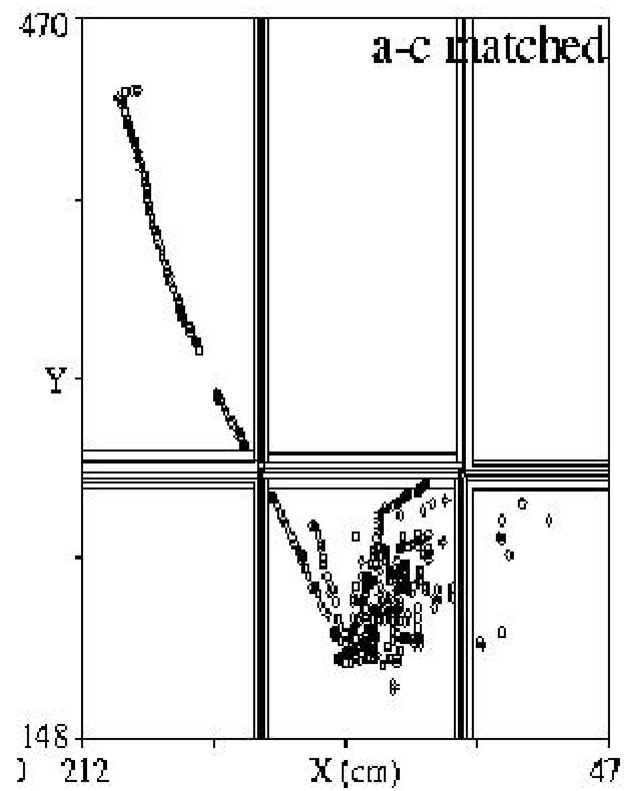
$\nu_\mu + n \rightarrow \mu^- + p$



$\nu_e + N \rightarrow e^\pm + N'$



$\nu_\mu + N \rightarrow \mu^\pm + X$



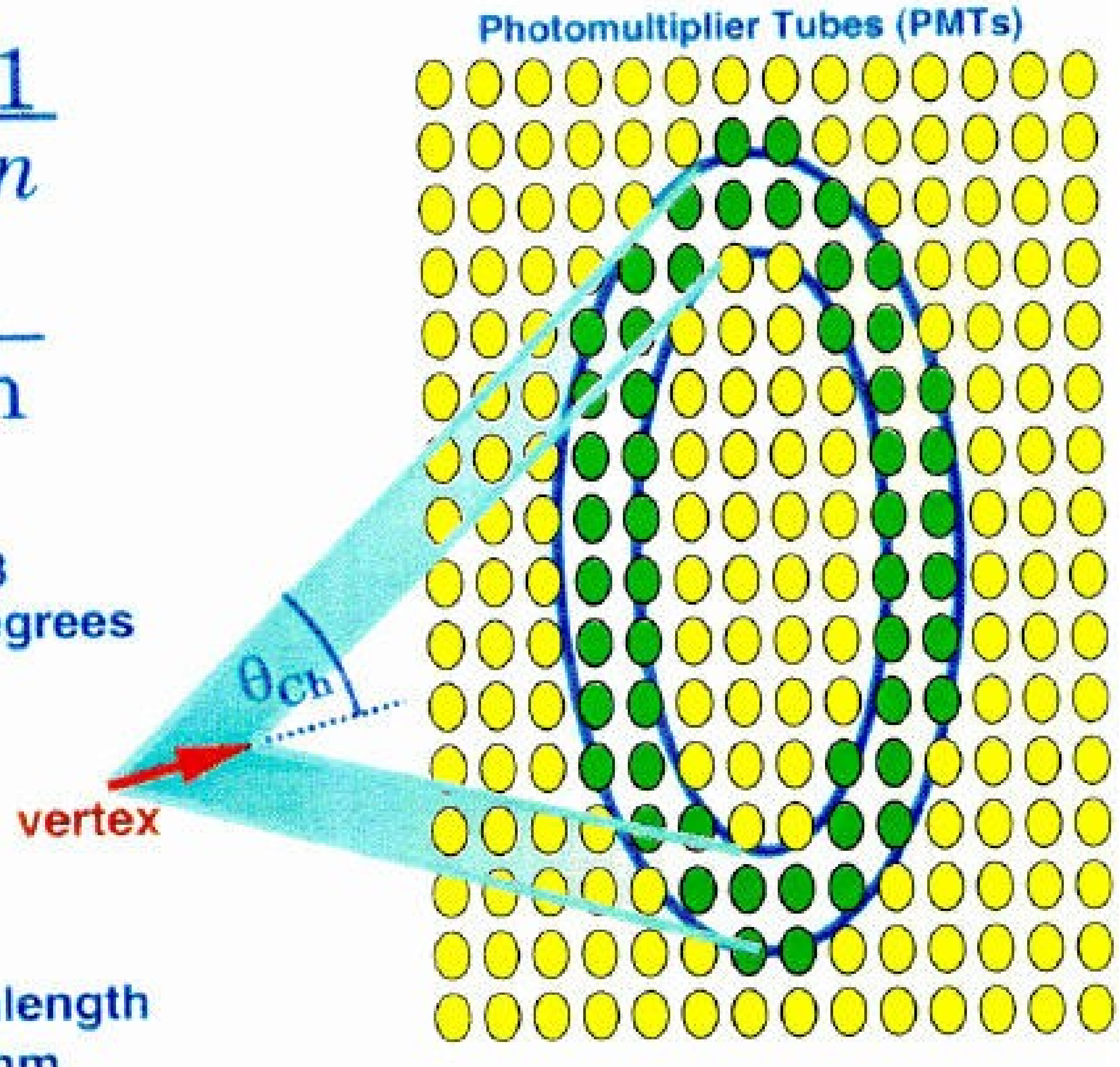

IMB detector

Cherenkov Radiation

$$\beta \left(= \frac{v}{c}\right) > \frac{1}{n}$$

$$\cos\theta_{Ch} = \frac{1}{\beta n}$$

in water, n = 1.33
as $\beta \rightarrow 1$, $\theta_{Ch} \rightarrow 41$ degrees



~340 photons/cm pathlength
300 nm < λ < 600 nm

SuperKamiokande **detector**

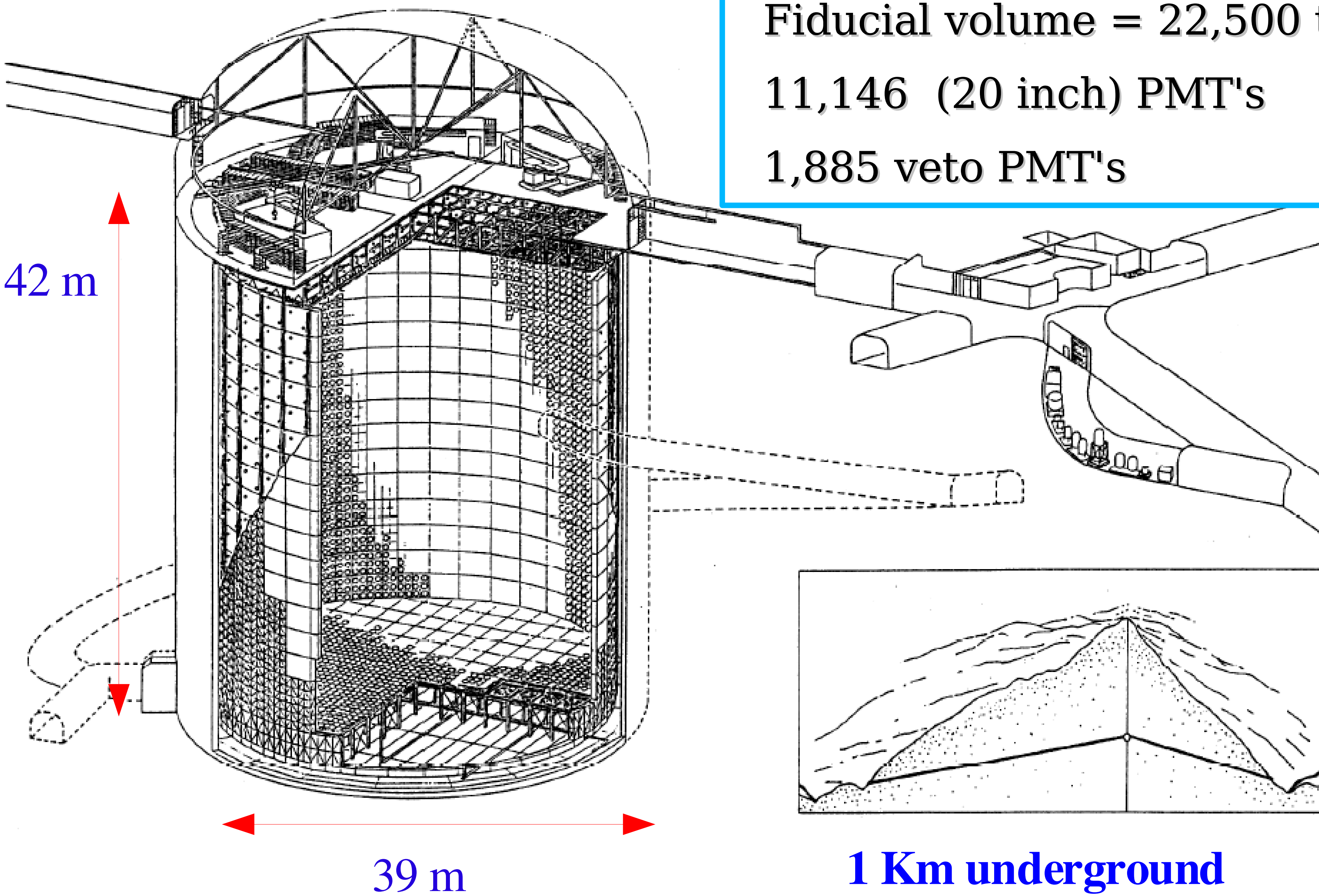
50,000 tons of ultrapure water

2 m of water = veto counter

Fiducial volume = 22,500 tons

11,146 (20 inch) PMT's

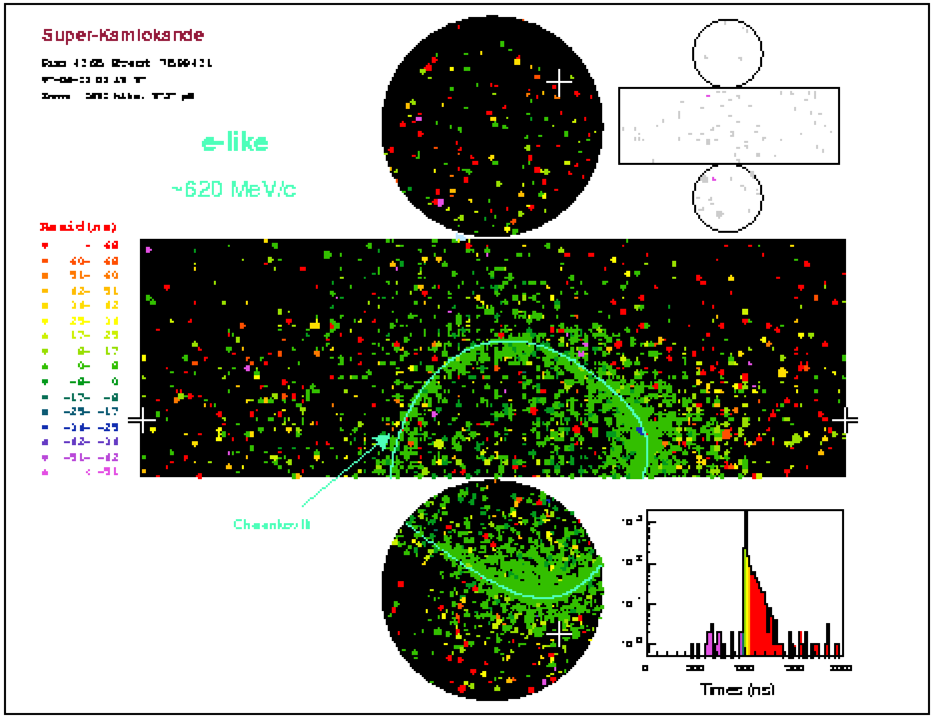
1,885 veto PMT's

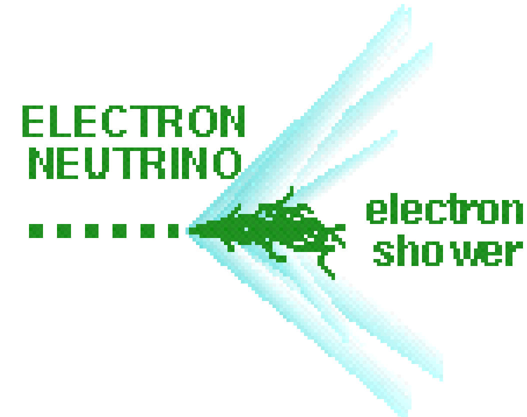


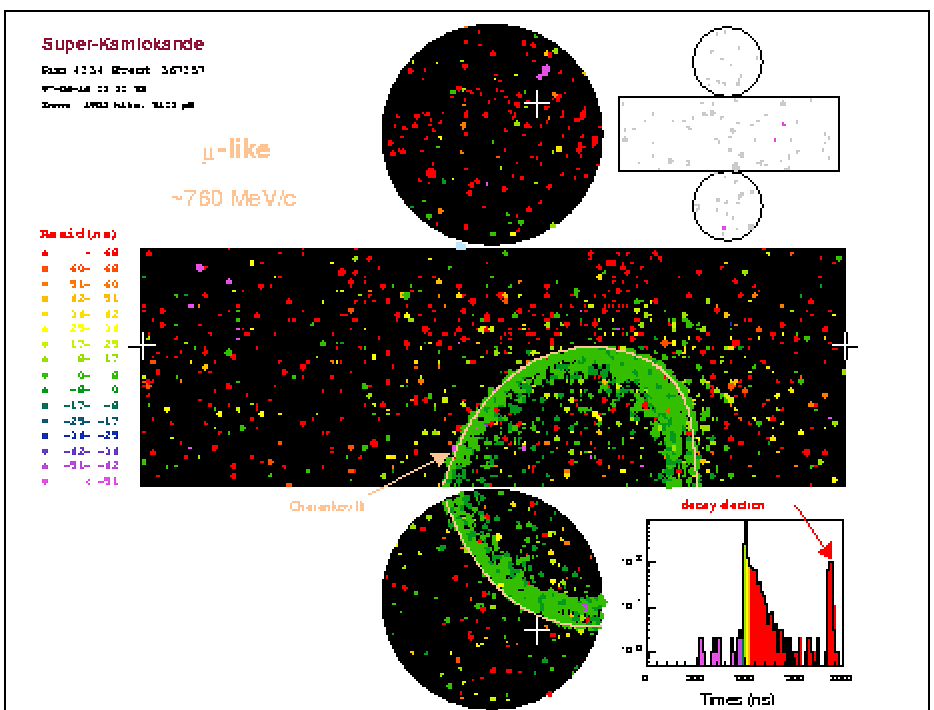
1 Km underground

11,146 20 inch Photomultipliers (PMT's)

(40 % of surface is sensitive)

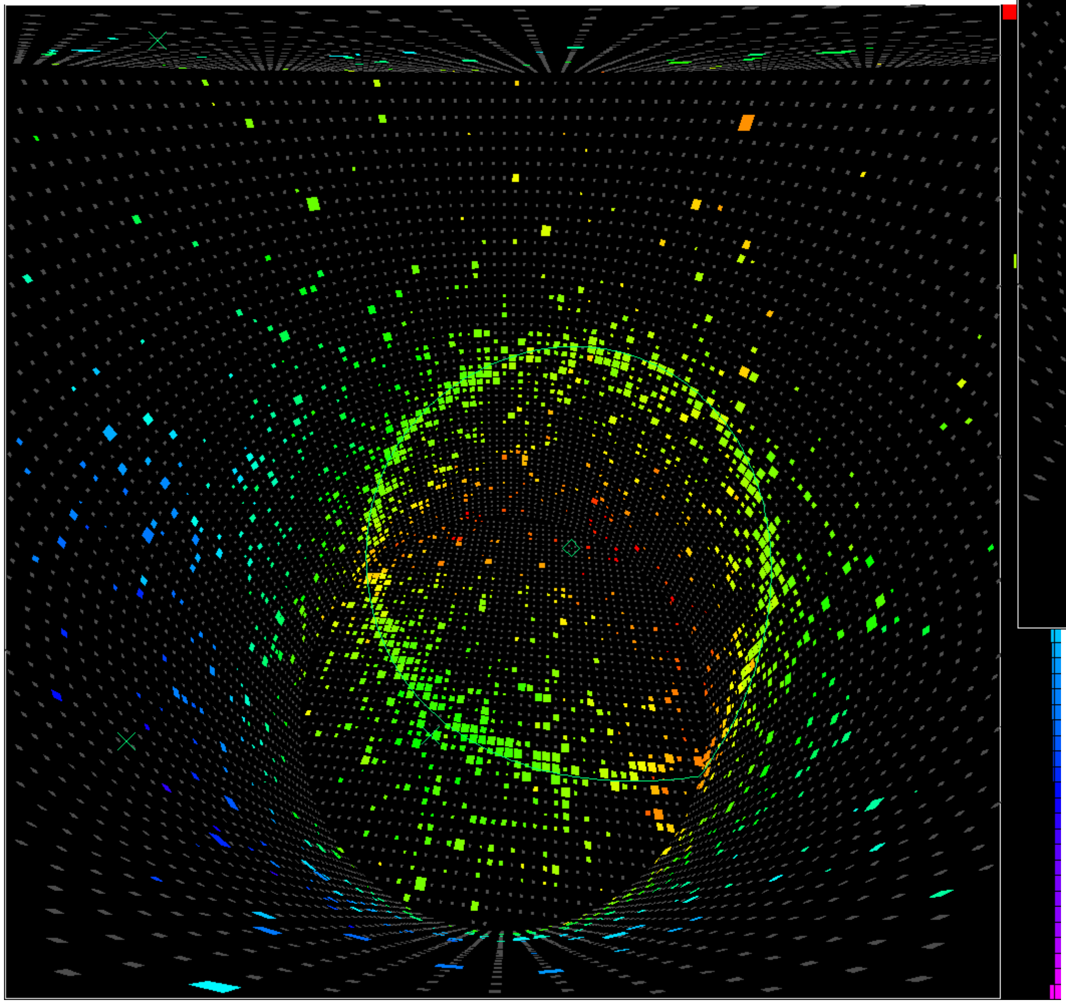

Super-Kamiokande
e-like
~620 MeV/c
Times (ns)

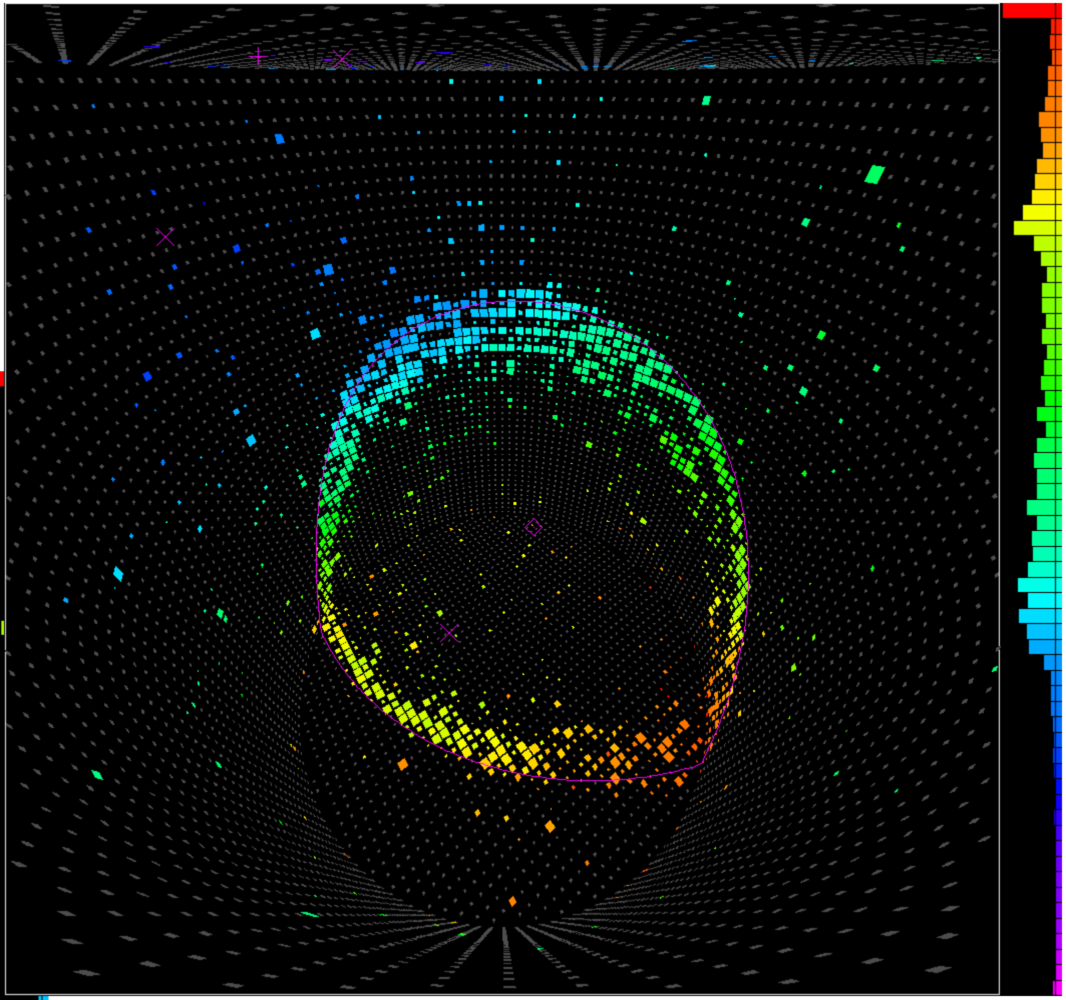

ELECTRON
NEUTRINO
electron
shower


Super-Kamiokande
μ-like
~760 MeV/c
decay electron
Times (ns)


MUON
NEUTRINO
muon

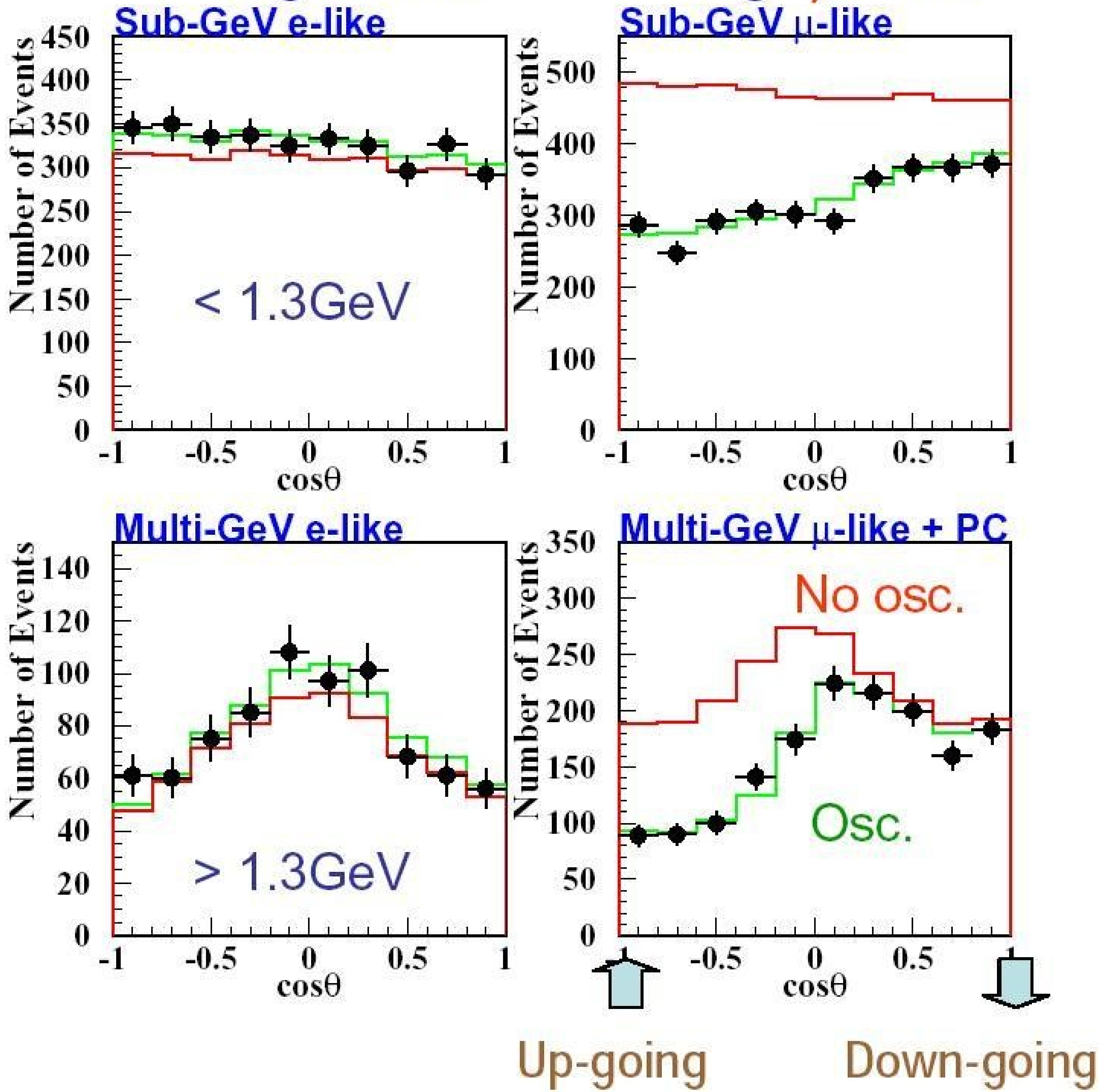
e-like

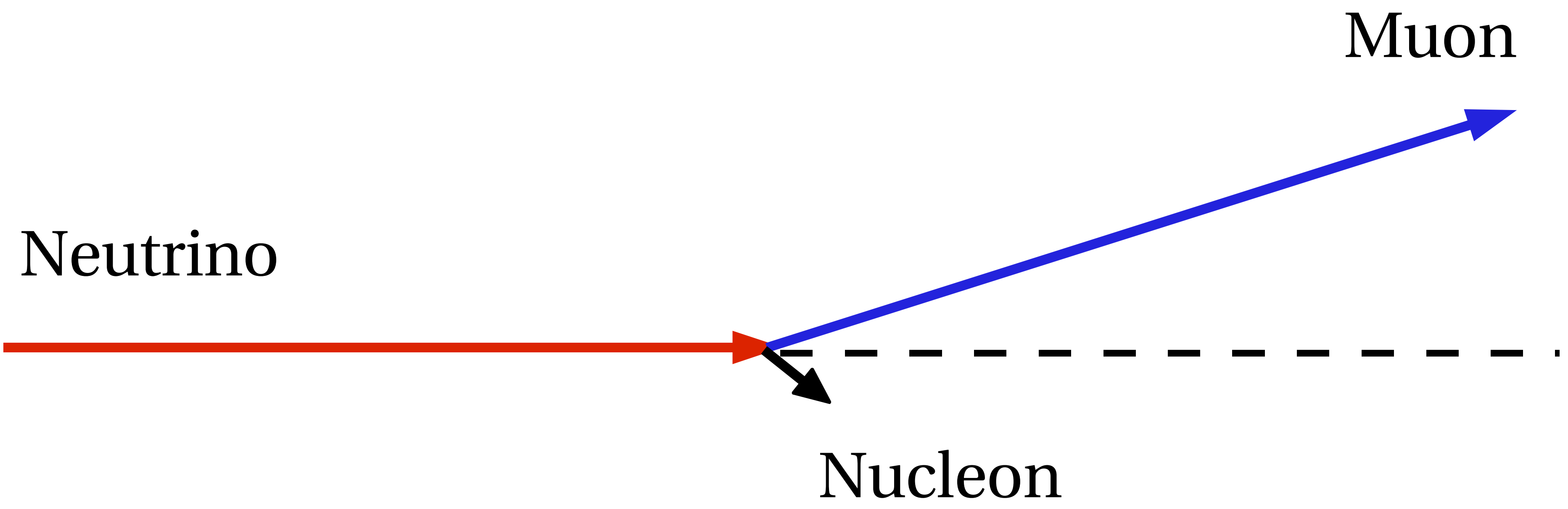




μ-like

1-ring e-like 1-ring μ -like





Angle (Muon-Neutrino)
decreases with the Neutrino Energy

Angle 60 degrees for subGeV
10-15 degrees for multiGeV

Interpretation in terms of:

$\nu_\mu \rightarrow \nu_\tau$ Oscillations

$$P_{\nu_\mu \to \nu_\tau} = \sin^2 2\theta \ \sin^2 \left[\frac{\Delta m^2 \ L}{4 \ E_\nu} \right]$$

$$\begin{aligned} \phi_{\nu_e} \quad & \to \phi_{\nu_e} \\ \phi_{\nu_\mu} \quad & \to [1 - \langle P_{\nu_\mu \to \nu_\tau} \rangle] \ \phi_{\nu_\mu} \\ \phi_{\nu_\tau} \simeq 0 \quad & \to \langle P_{\nu_\mu \to \nu_\tau} \rangle \ \phi_{\nu_\mu} \end{aligned}$$

Disappearance

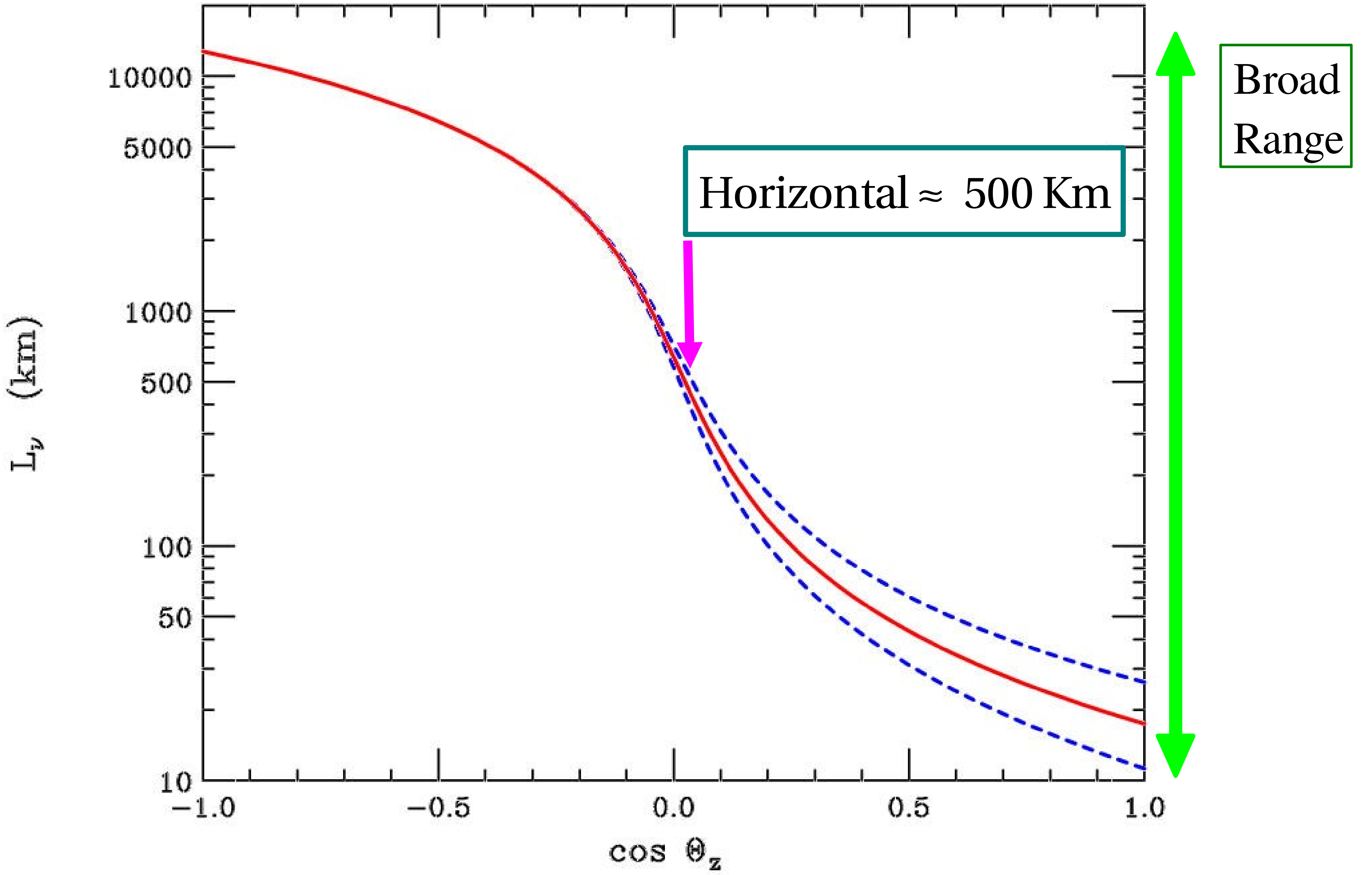
Appearance

Energy Threshold for CC interactions of ν_τ

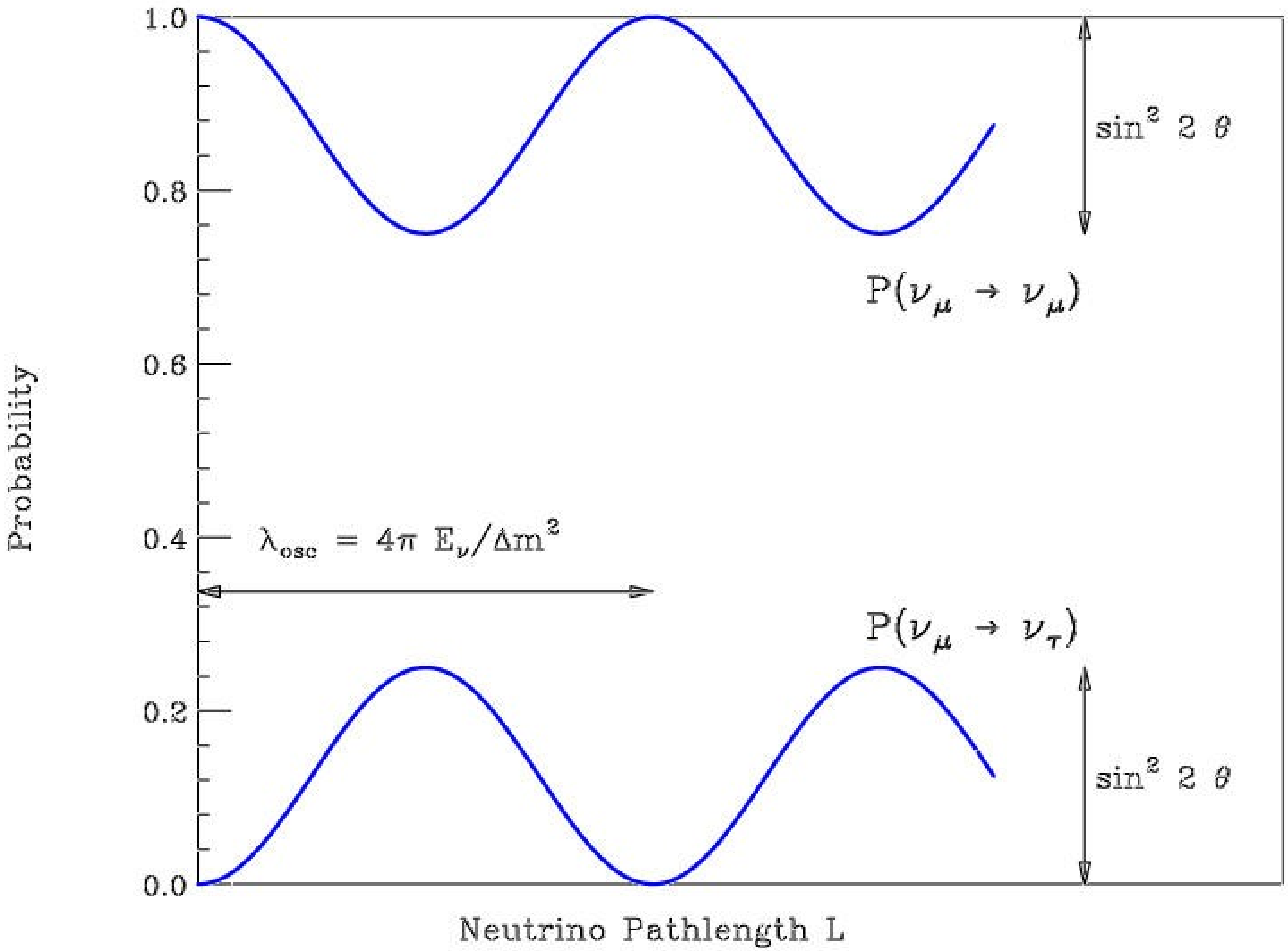
$$E(\nu_\tau) \geq m_\tau + m_\tau^2 / 2m_p \approx 3.5\ \text{GeV}$$

In atmospheric neutrinos most ν_τ are below threshold for CC interactions and therefore simply "disappear".

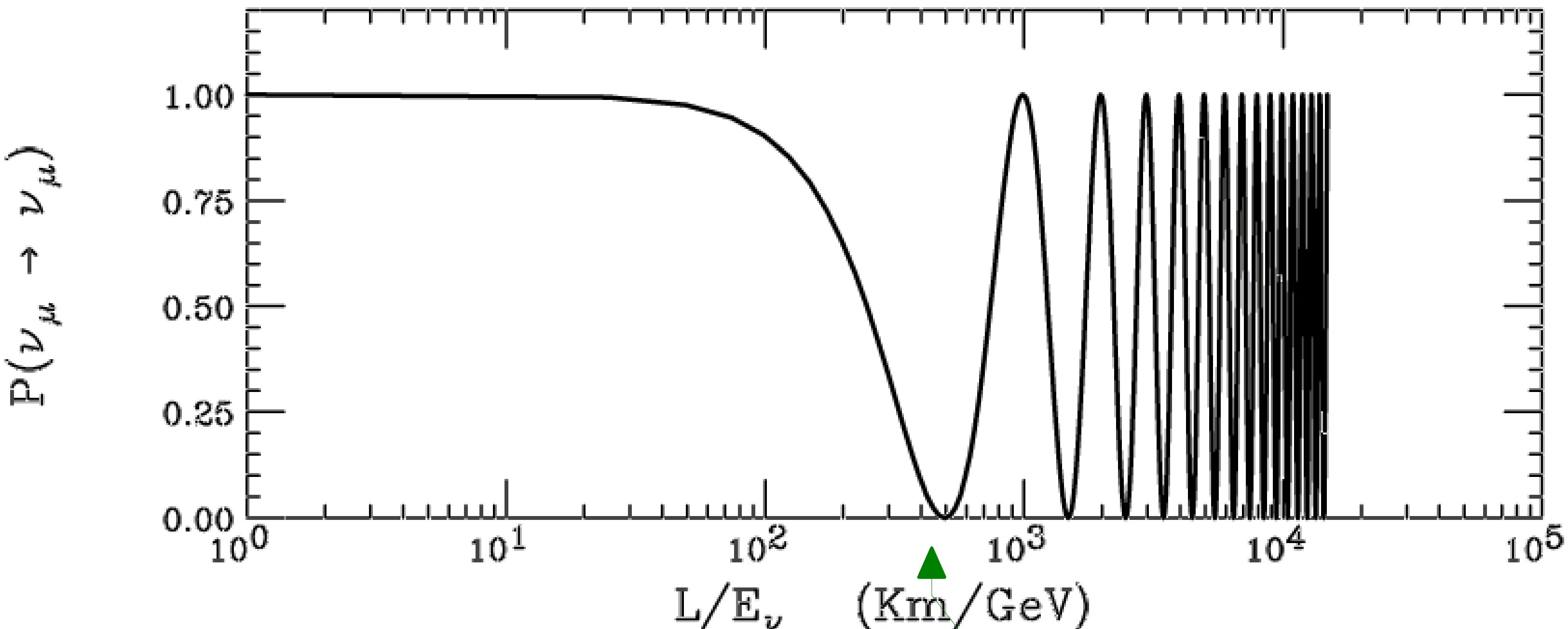
Distance from the Neutrino creation point



$$P(\nu_\mu \to \nu_\tau;\, L) = \sin^2 2\theta \, \sin^2 \left[1.27\, \Delta m^2(\mathrm{eV}^2)\, \frac{L(\mathrm{Km})}{E(\mathrm{GeV})}\right]$$

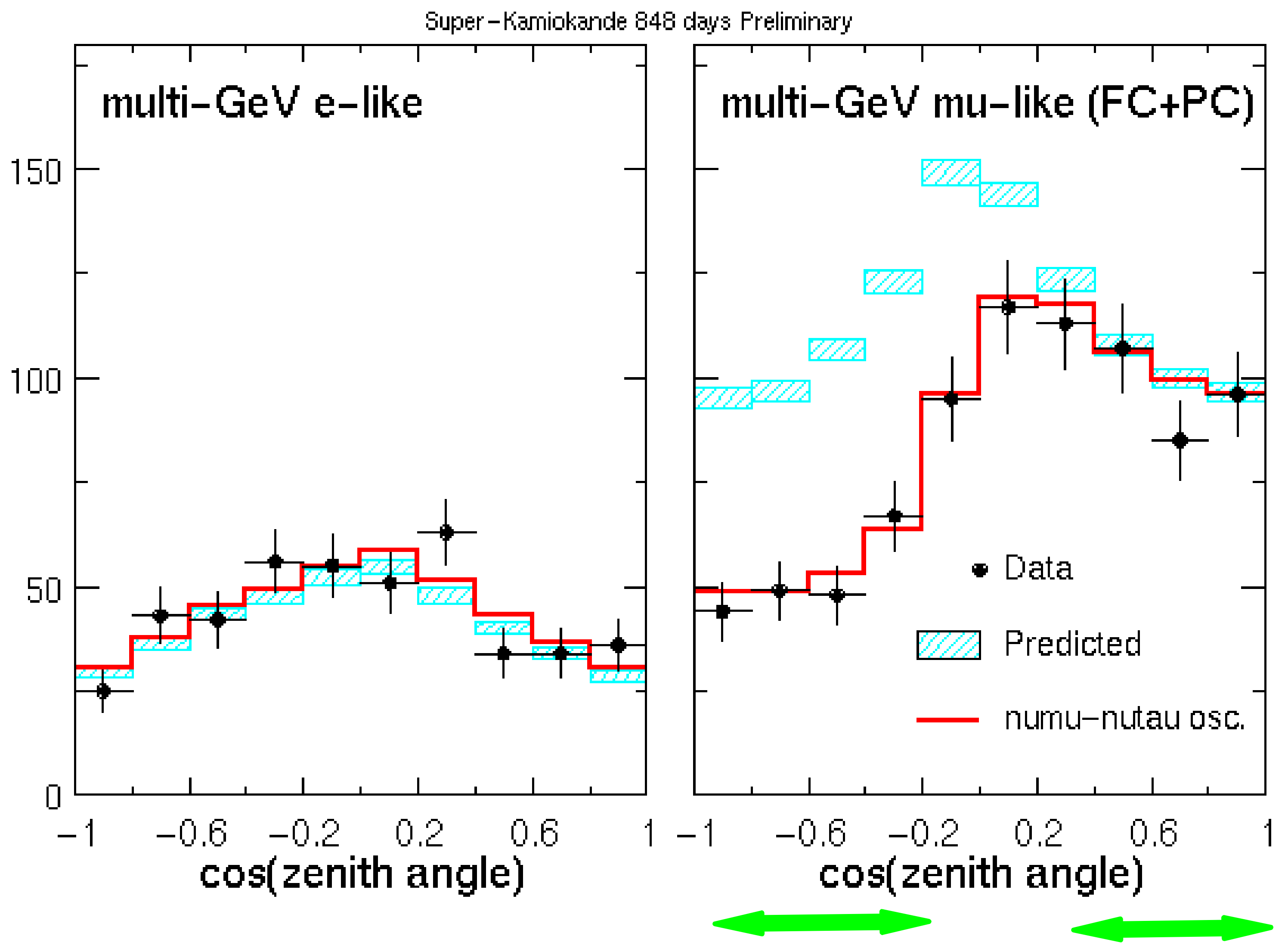


$$P_{\nu_\mu \to \nu_\mu}(L, E_\nu) = 1 - \sin^2 2\theta \ \sin^2\left[\frac{\Delta m^2 L}{4E_\nu}\right]$$



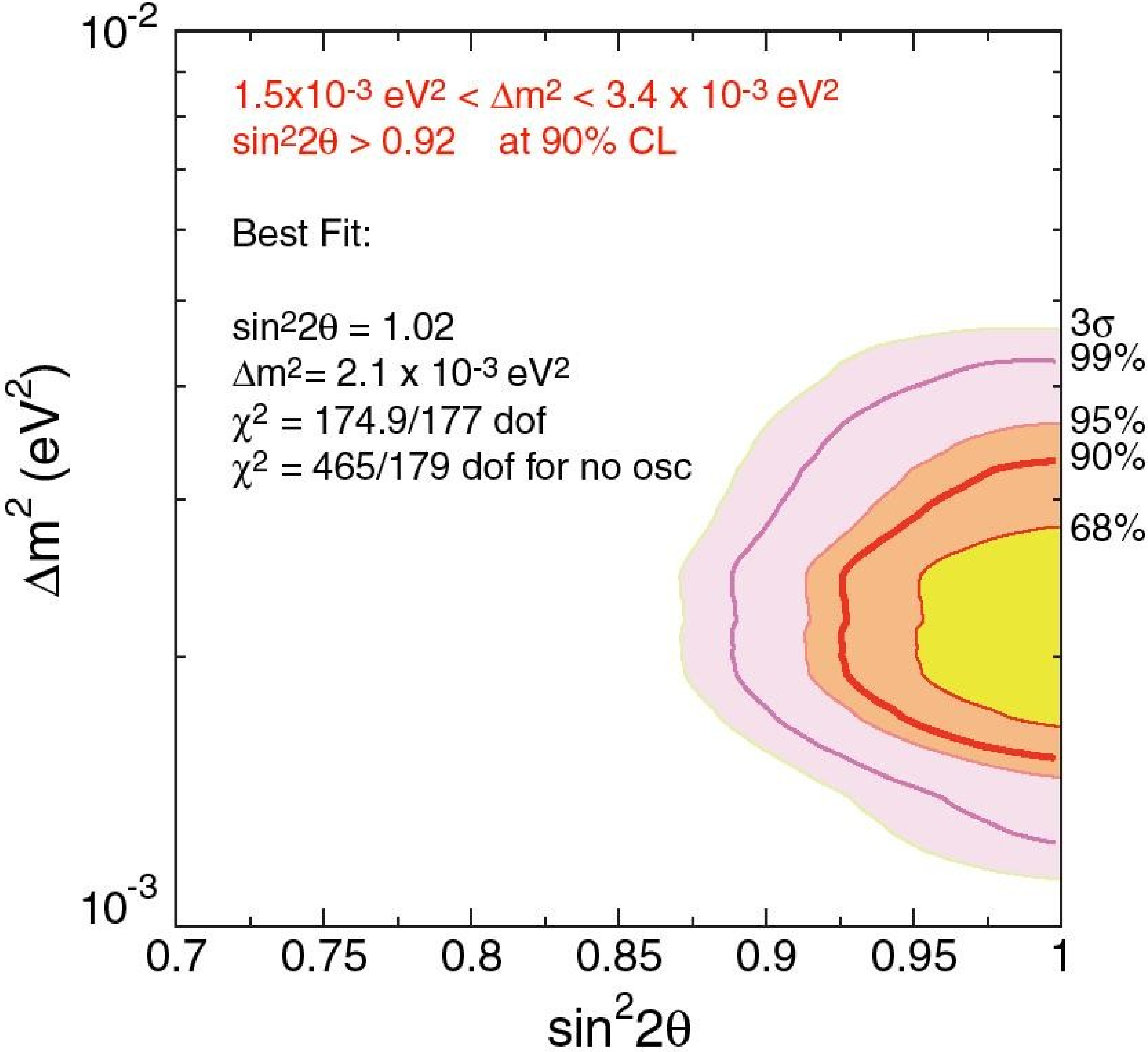
$$P_{\nu_\mu \to \nu_\mu} = \begin{cases} 1 & \text{for } L \text{ small,} \\ 1 - \frac{\sin^2 2\theta}{2} & \text{for } L \text{ large.} \end{cases}$$

$$\simeq \frac{\lambda^*_{\rm osc}}{2} \simeq \frac{2\pi \langle E_\nu \rangle}{|\Delta m^2|}$$



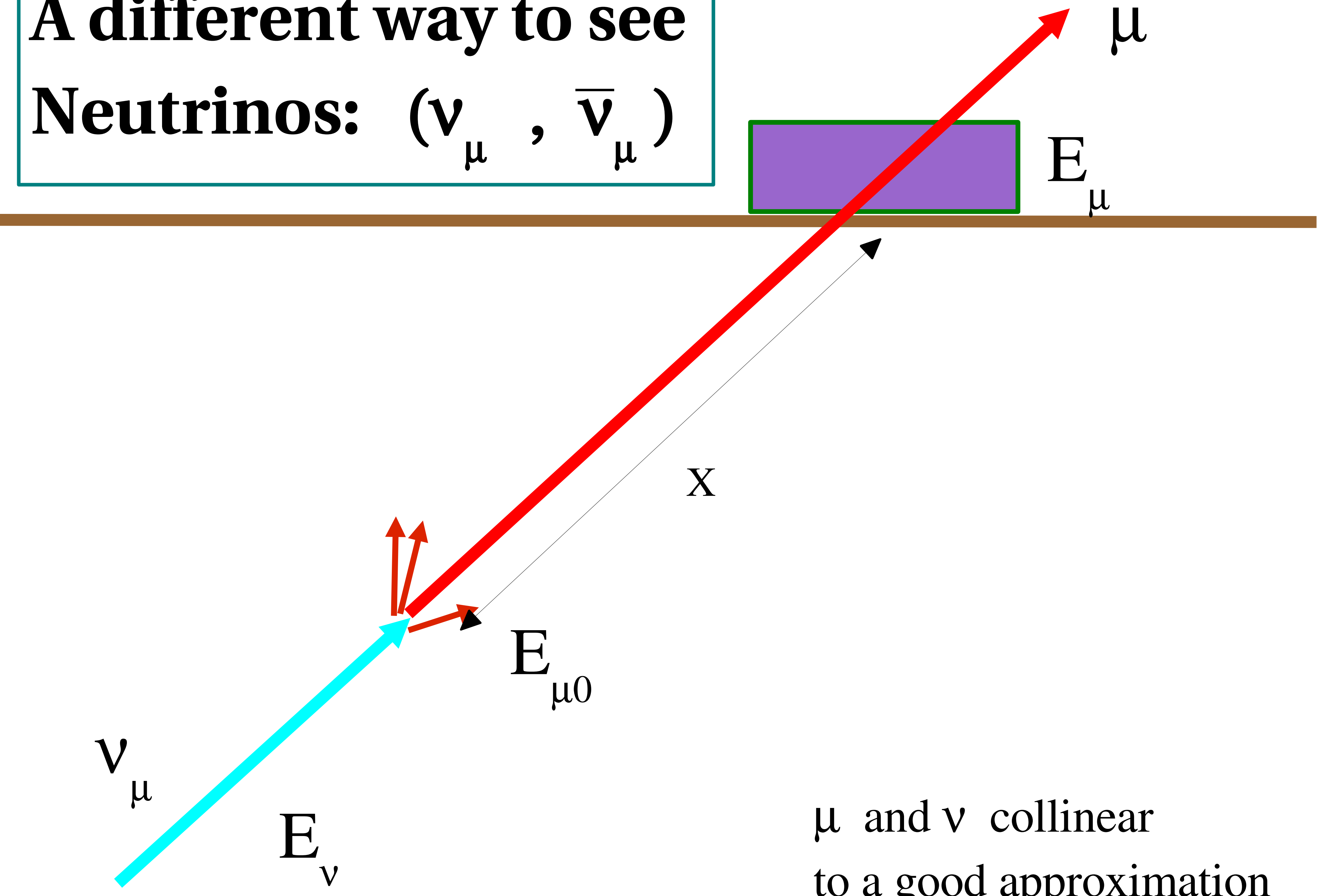
Measurement of $\sin^2 2\theta$

$$\left(\frac{\text{Up}}{\text{Down}}\right)_{\text{multiGeV}} = 0.54 \pm 0.04 \pm 0.01$$



1.5x10-3 eV2 < Δm2 < 3.4 x 10-3 eV2
sin22θ > 0.92 at 90% CL
Best Fit:
sin22θ = 1.02
Δm2= 2.1 x 10-3 eV2
χ2 = 174.9/177 dof
χ2 = 465/179 dof for no osc
3σ
99%
95%
90%
68%
10-2
10-3
0.7
0.75
0.8
0.85
0.9
0.95
1
Δm2 (eV2)
sin22θ

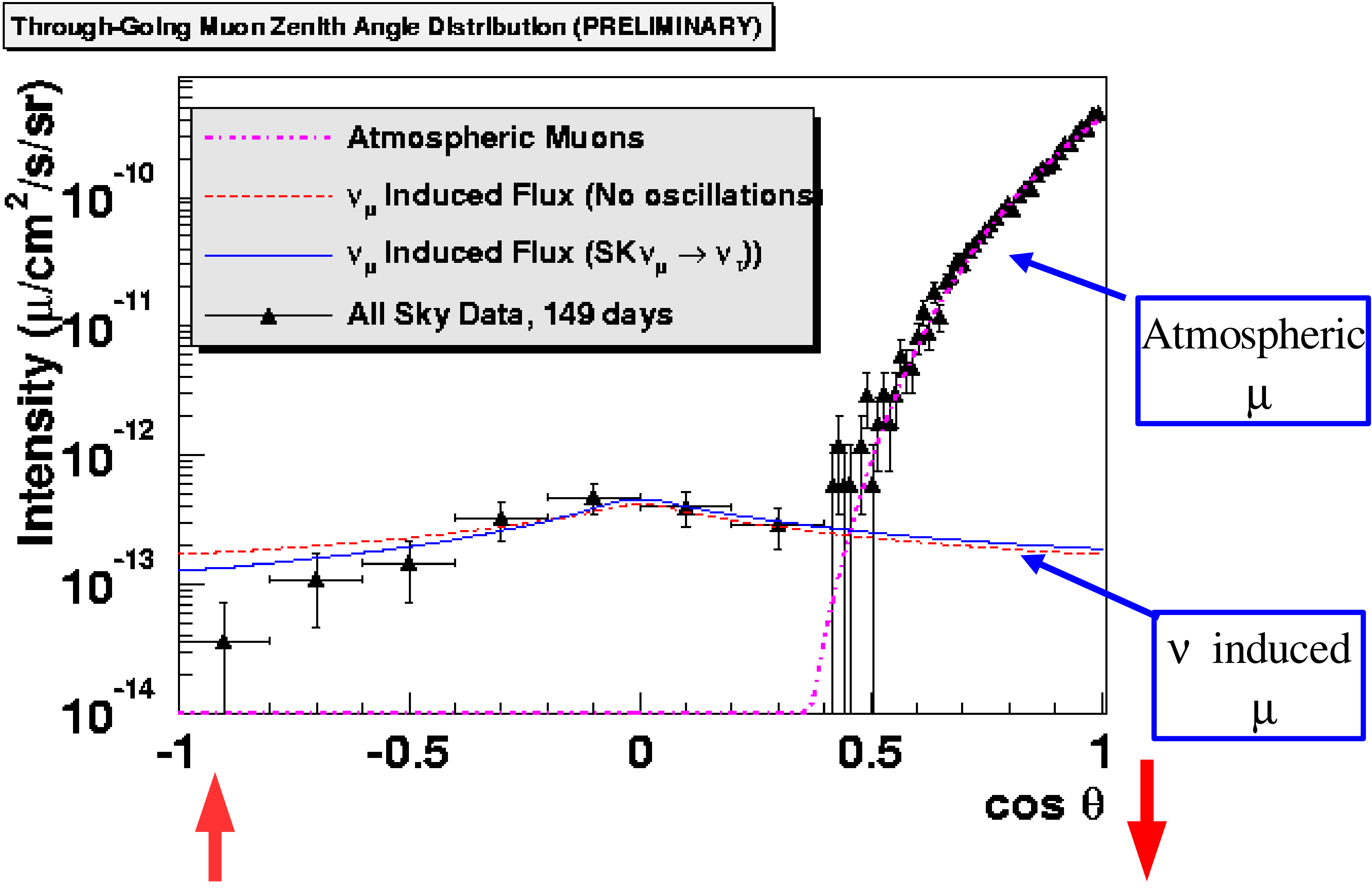
A different way to see Neutrinos: (ν_μ , $\bar{\nu}_\mu$)



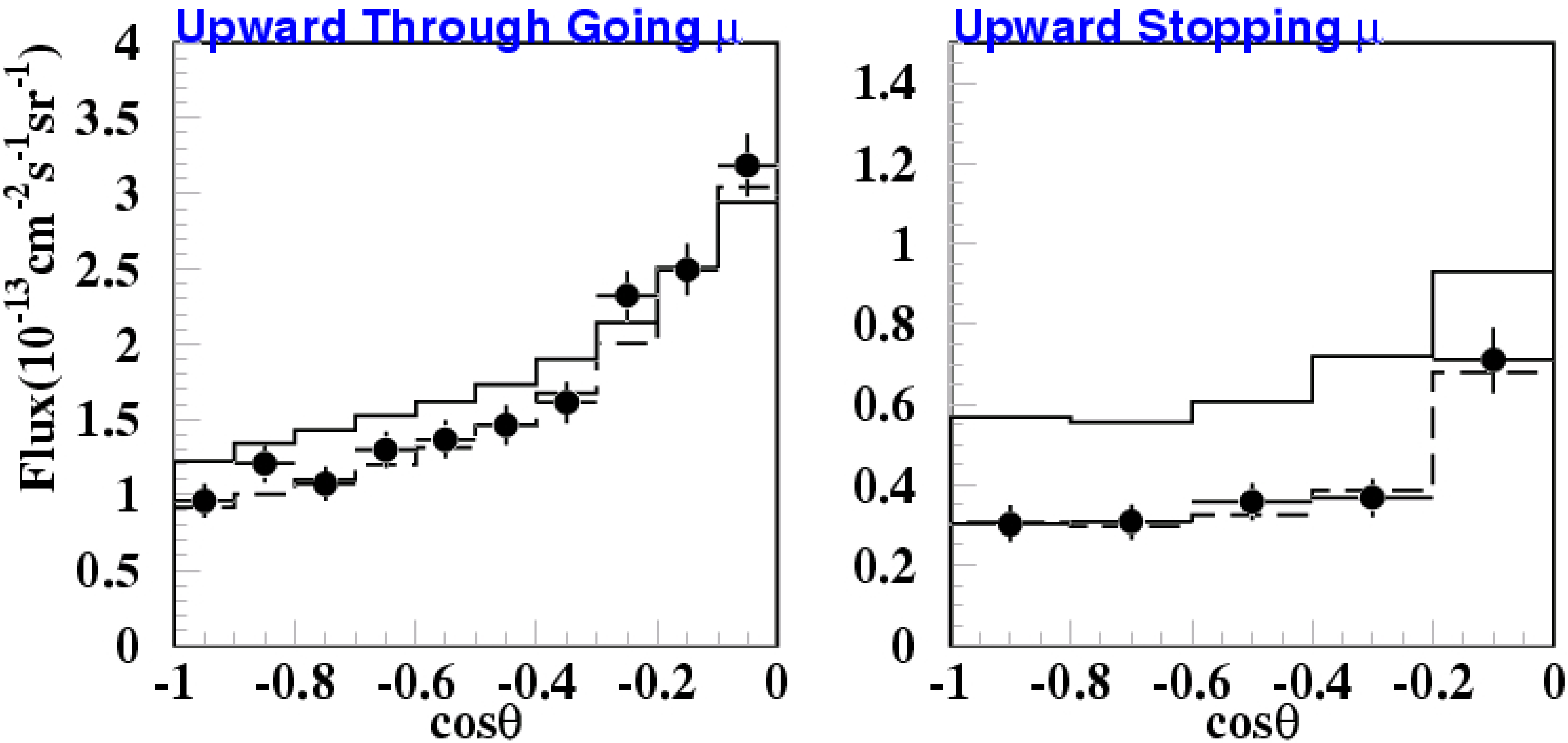
μ and ν collinear
to a good approximation

SNO detector

μ angular distribution

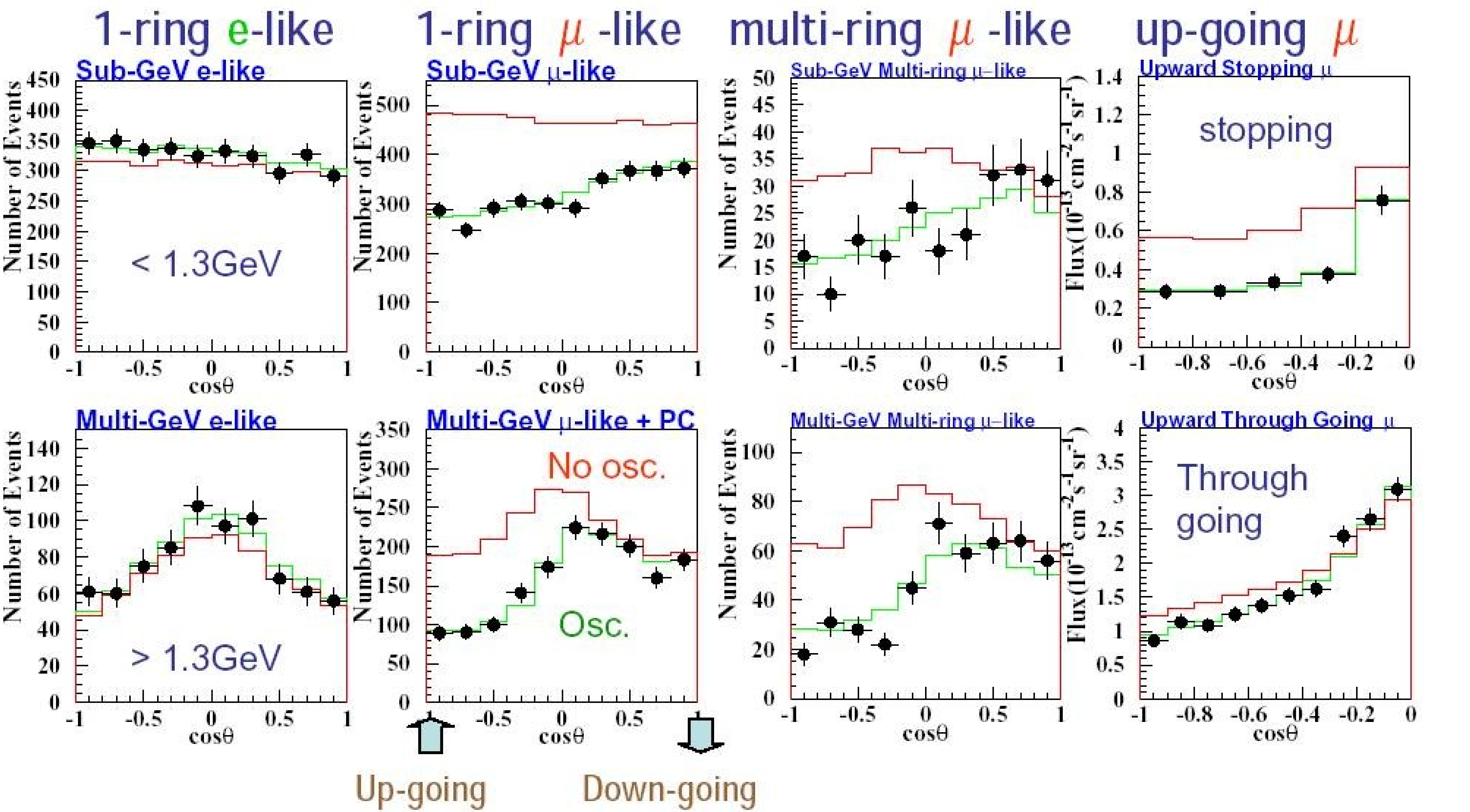


Super-Kamiokande

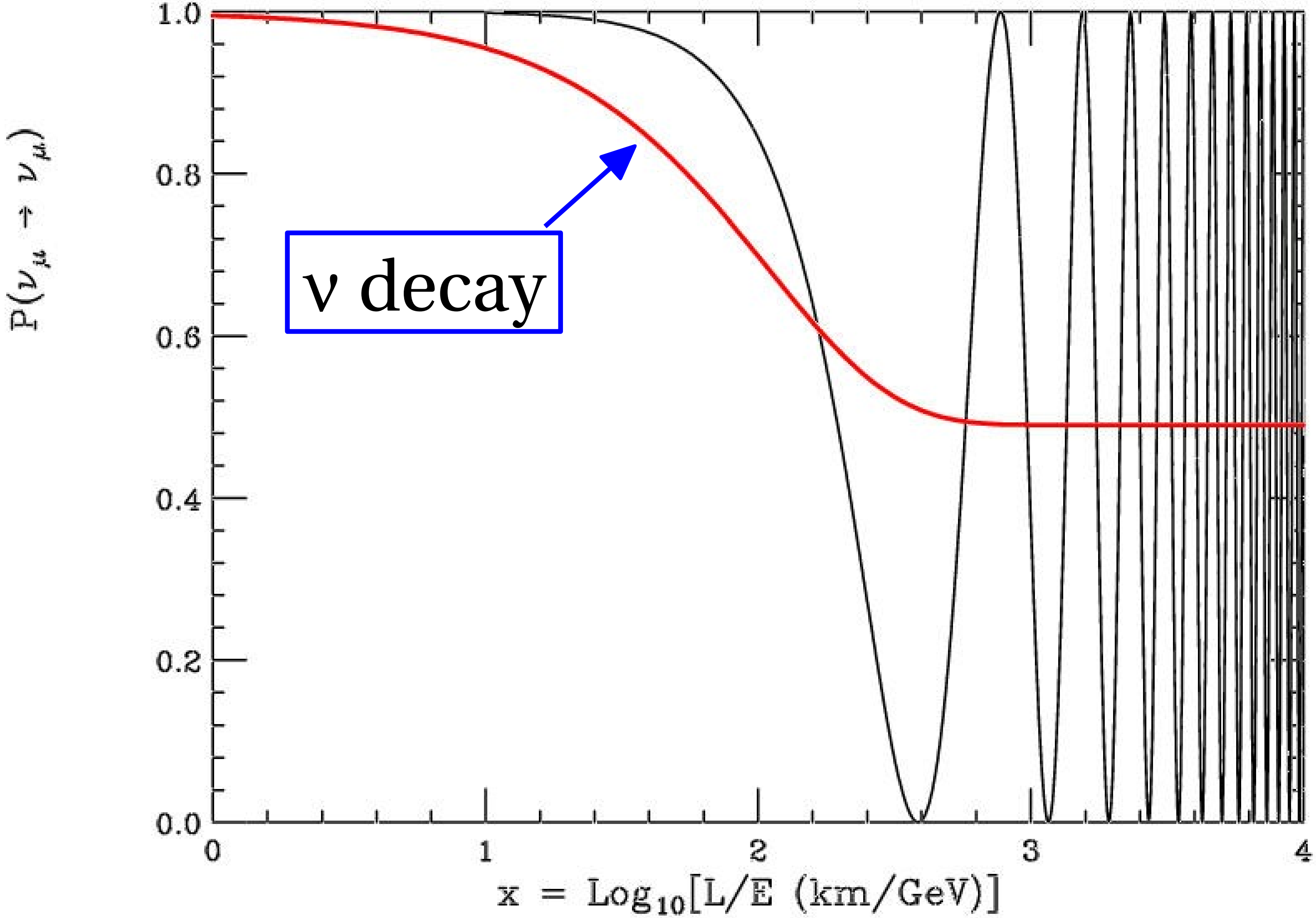


Super-Kamiokande data

1489day FC+PC data + 1678day upward going muon data



Alternative Models for the "disapperance" of ν_τ



$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_{\rm ster} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \nu_2 \\ \nu_3 \\ \nu_1 \end{bmatrix}$$

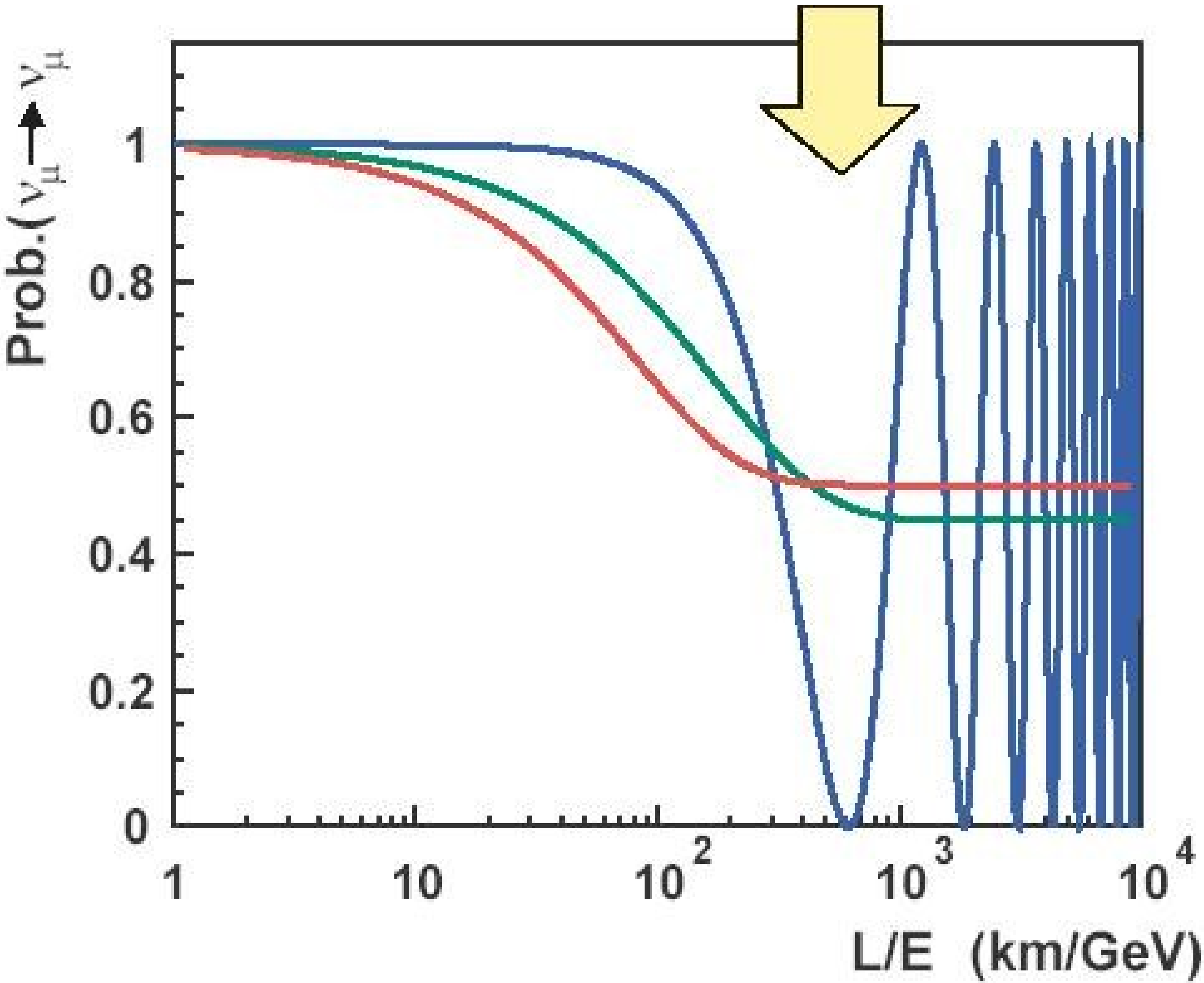
$$\nu_2 \to \overline{\nu}_1 + J$$

Neutrino Decay
(Barger et al)

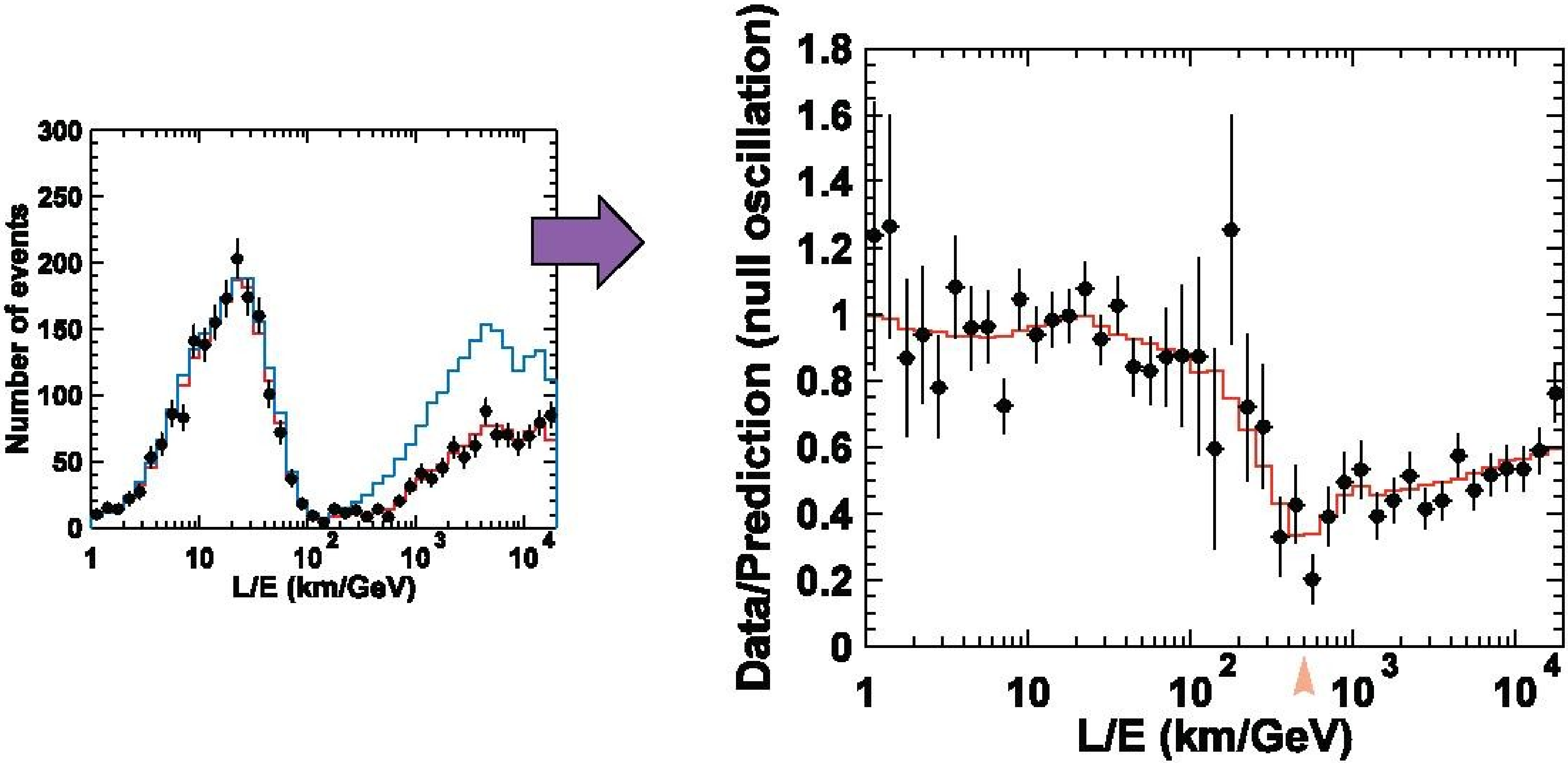
$$P_{\rm decay} = \left\{ \sin^2 2\theta + \cos^2 2\theta \ \exp\left[-\frac{m}{\tau_\nu}\frac{L}{E_\nu} \right] \right\}$$

$$P_{\rm decoherence} = \frac{1}{2}\left[1 + \exp\left(-\beta\,\frac{L}{E_\nu} \right) \right]$$

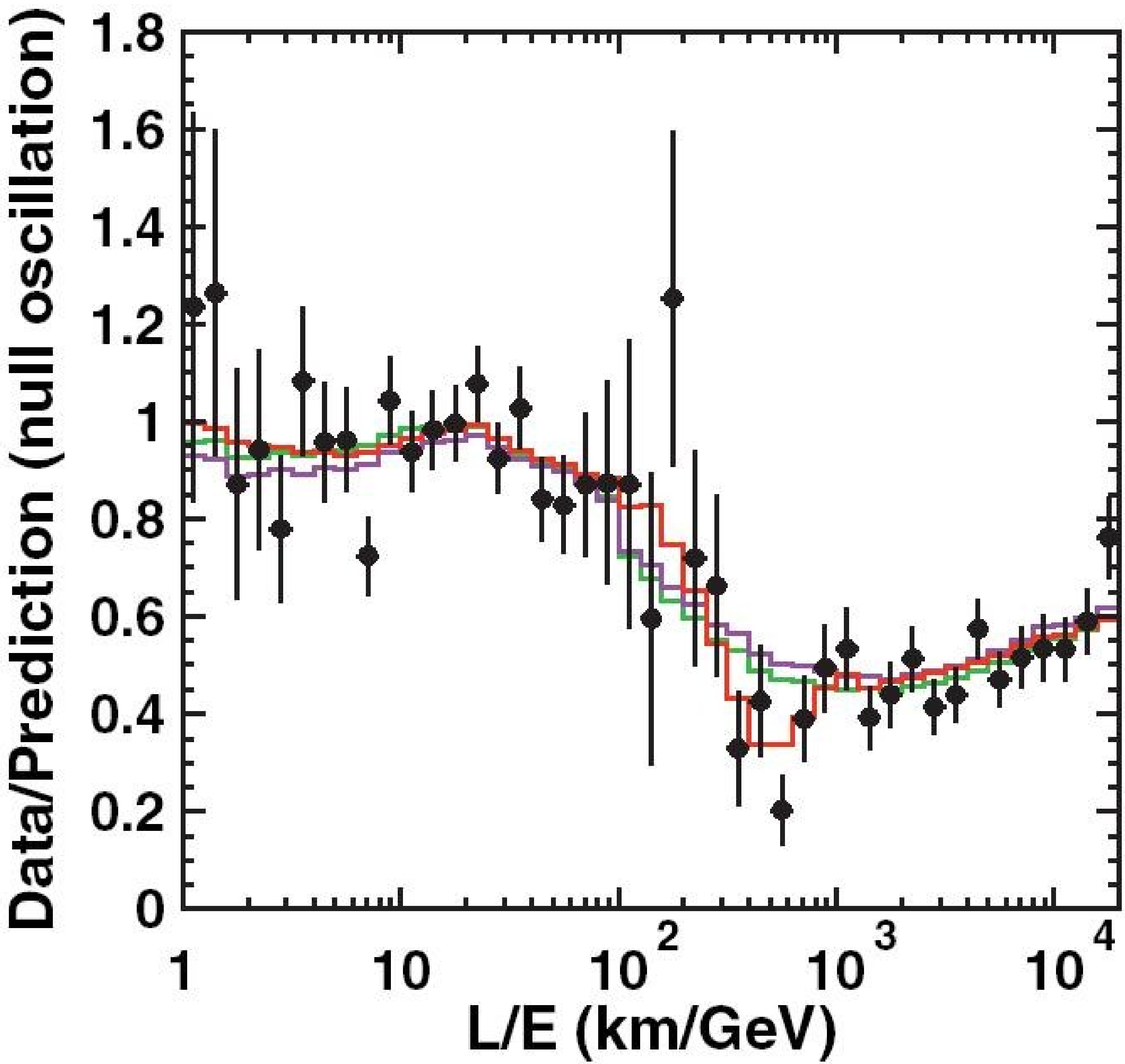
Decoherence : Lisi, Marrone e Montanino



Prob.($\nu_\mu \rightarrow \nu_\mu$)
1
0.8
0.6
0.4
0.2
0
1
10
10^2
10^3
10^4
L/E (km/GeV)



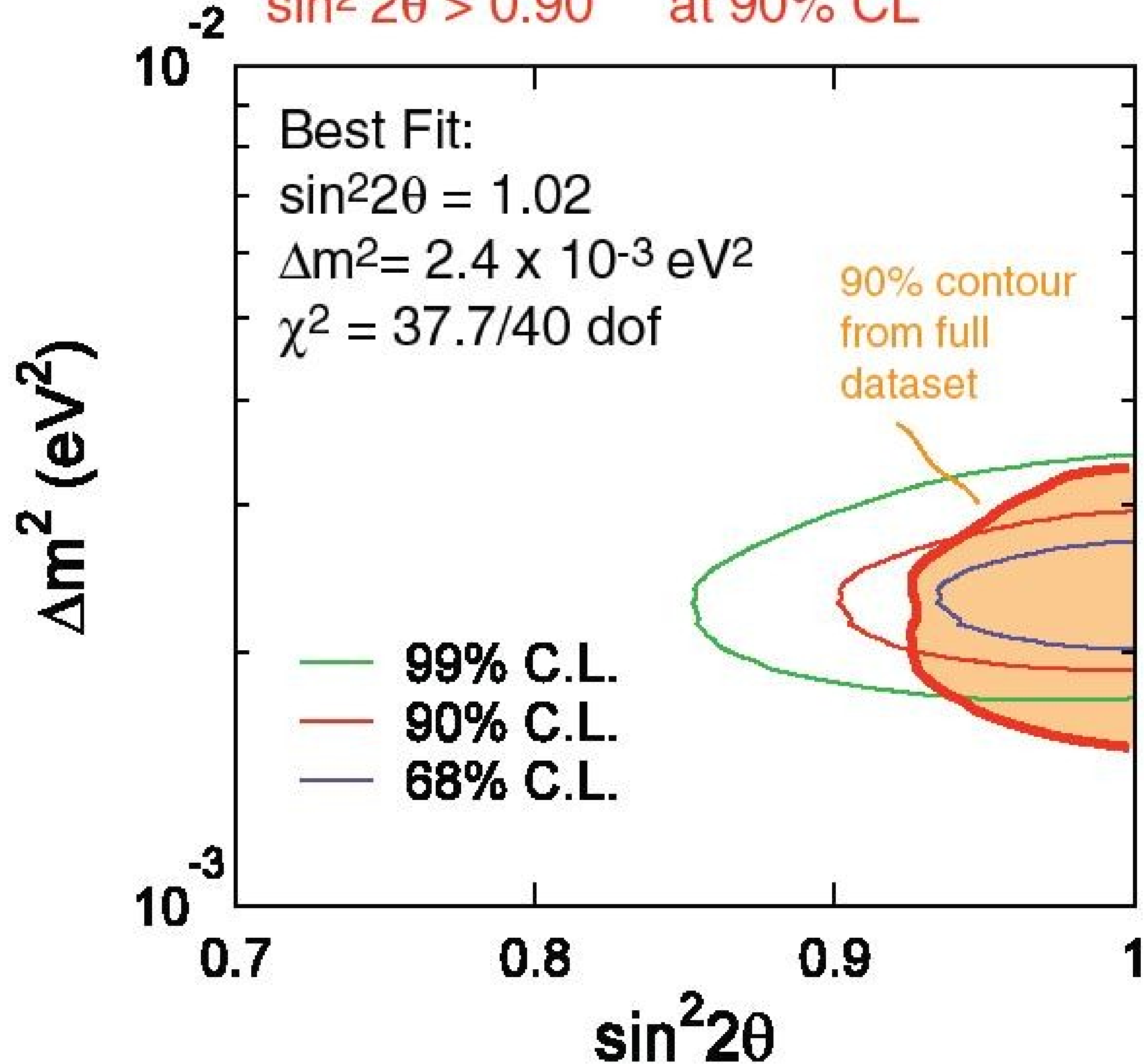
oscillation dip seen at ~500 km/GeV



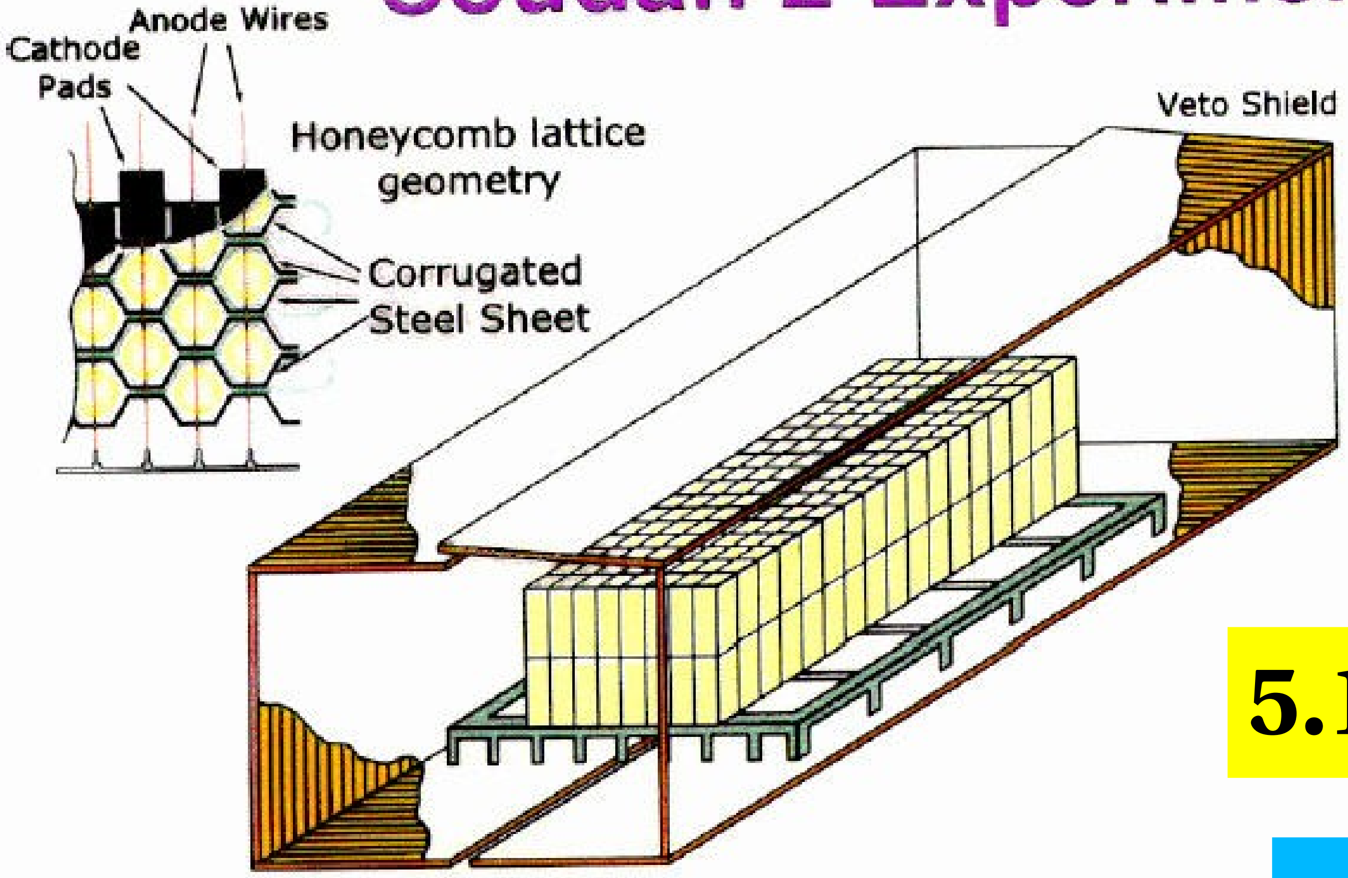
Decay rejected at 3.4σ

Decoherence rejected at 3.8σ

1.9×10^{-3} eV^2 < Δm^2 < 3.0×10^{-3} eV^2
$\sin^2 2\theta > 0.90$ at 90% CL



Soudan 2 Experiment

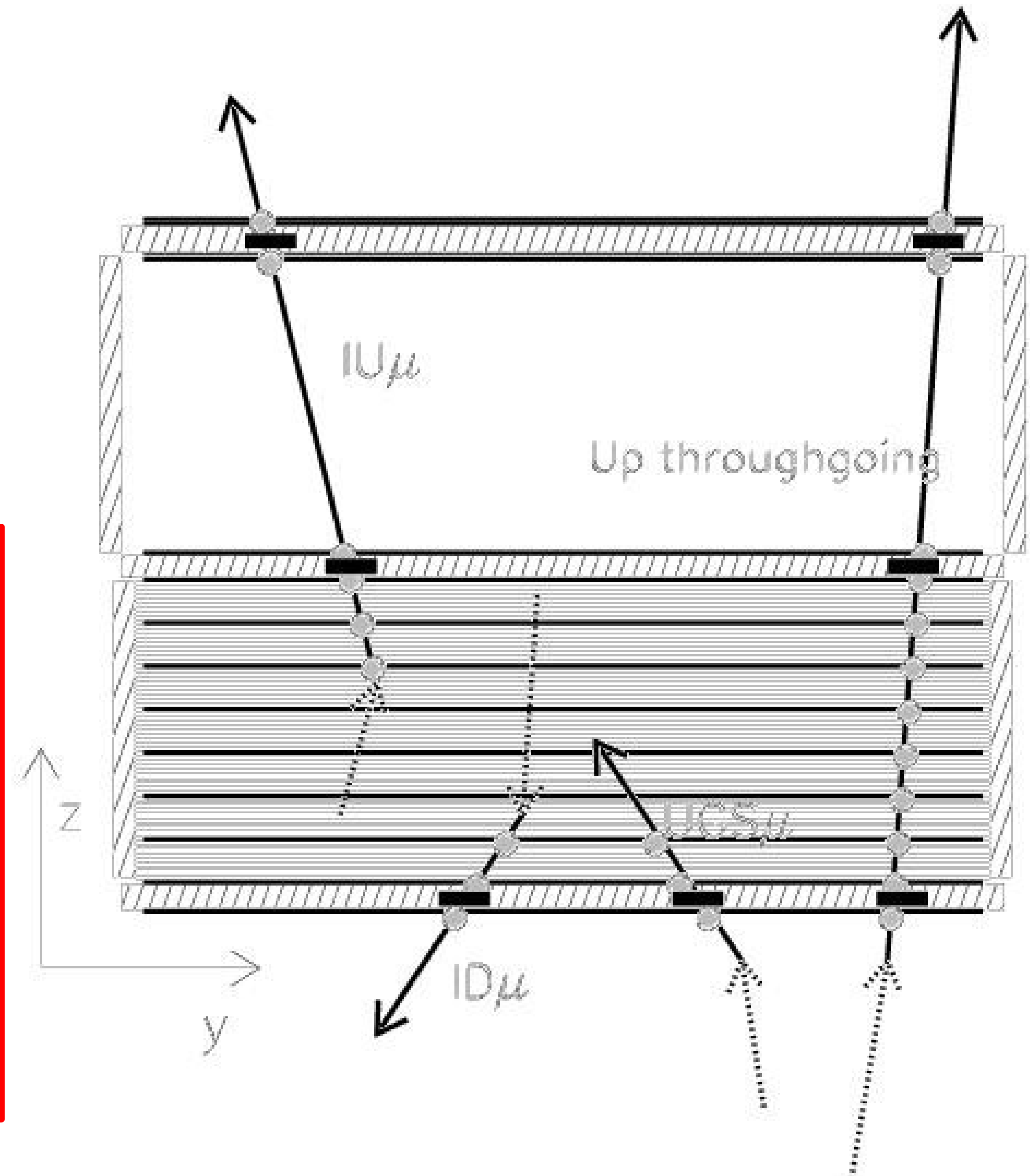


5.1 (Kton yr)

561 ν events

Soudan Mine (Minnesota), 2100 m.w.e.
iron tracking calorimeter
high geomagnetic latitude
5.1 kt-yr, 326 contained interactions
~24% background subtraction using veto events

MACRO detector Gran Sasso laboratory



[a] Through-going muons

[b] Internally produced up-going events

[c] Up-going stopping + Down-going internal interactions

Comparison of :

$$\nu_\mu \leftrightarrow \nu_\tau$$

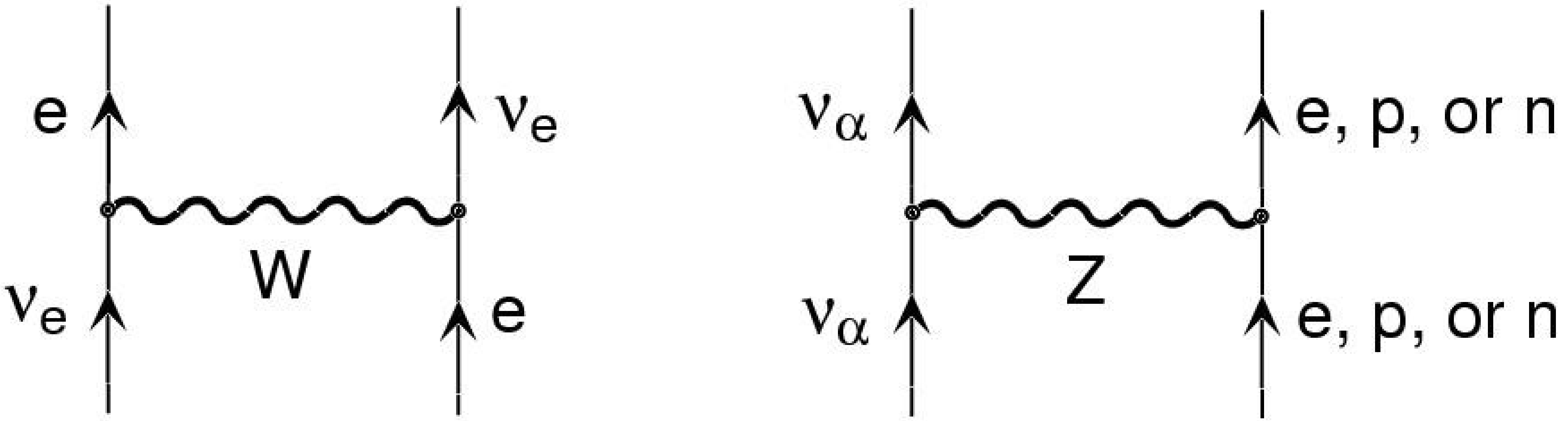
$$\nu_\mu \leftrightarrow \nu_{\mathrm{sterile}}$$

Absence of Neutral Currents

Matter Effects

Tau Appearance events

Effective Potential in Ordinary Matter



$$V_{\mu s} = -\sqrt{2}\,G_F\,\frac{N_n}{2} \simeq -10^{-13}\ \mathrm{eV}\ \left(\frac{\rho}{5\ \mathrm{g\ cm^{-3}}}\right)$$

$$V_{\nu_\mu e} = V_{\nu_\tau e} = \quad V_{\nu_e e}^{Z} = \quad -\frac{\sqrt{2}}{2}\, G_F\, N_e$$

$$V_{\nu_\mu p} = V_{\nu_\tau p} = \quad V_{\nu_e p} = \quad +\frac{\sqrt{2}}{2}\, G_F\, N_p$$

$$V_{\nu_\mu n} = V_{\nu_\tau n} = \quad V_{\nu_e n} = \quad -\frac{\sqrt{2}}{2}\, G_F\, N_n$$

$$V_{\nu_e e} = V_{\nu_e e}^{Z} + V_{\nu_e e}^{W} = -\frac{\sqrt{2}}{2}\, G_F\, N_e + \sqrt{2}\, G_F\, N_e$$

$$V_{\text{sterile}} = 0$$

$$A = \mp \frac{2\sqrt{2}\, G_F\, N_e\, E_\nu}{\Delta m^2}$$

$$\sin^2 2\theta \Longrightarrow \frac{\sin^2 2\theta}{(A - \cos 2\theta)^2 + \sin^2 2\theta}$$

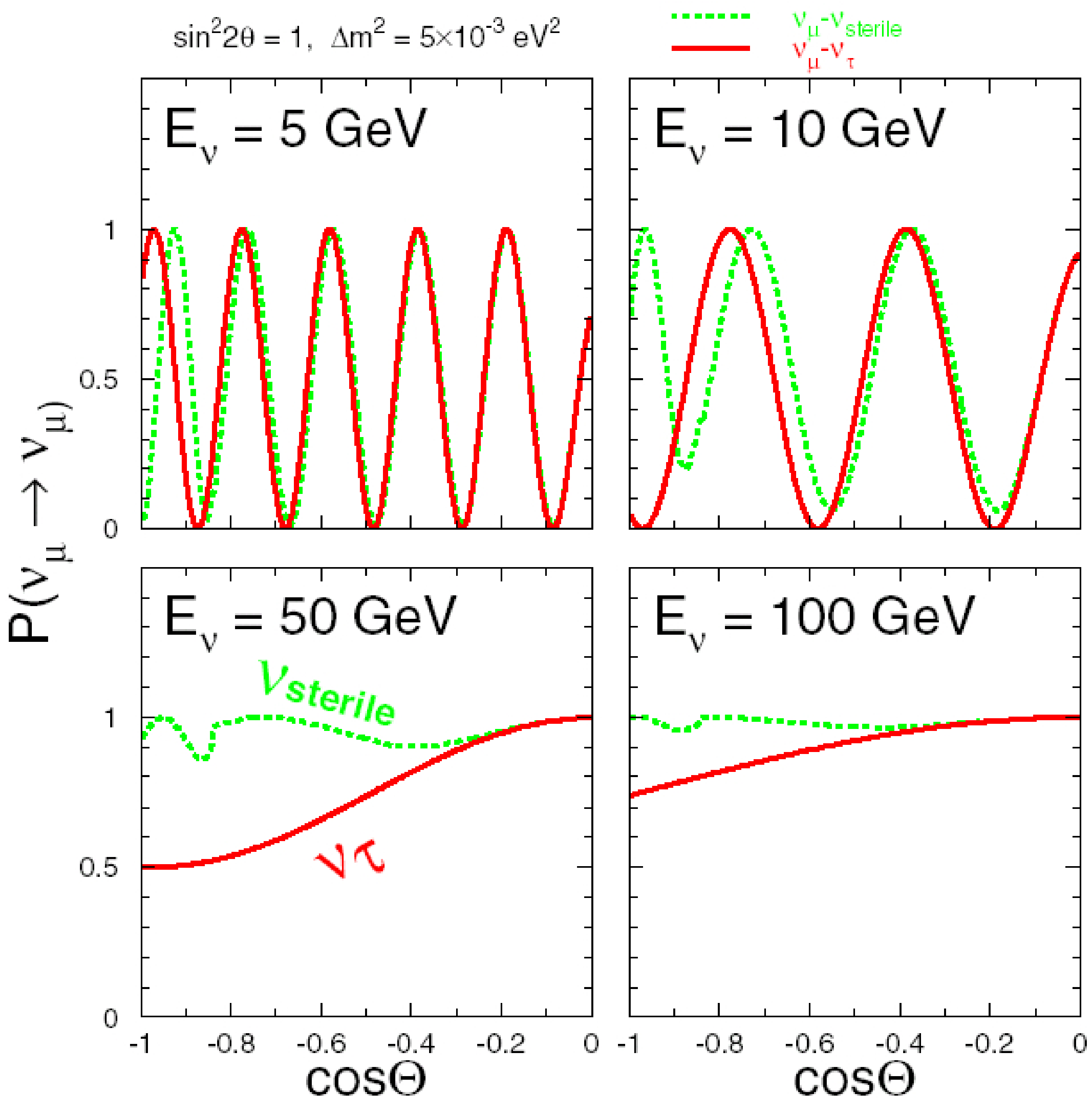
$$\Delta m^2 \Longrightarrow \Delta m^2 \sqrt{(A - \cos 2\theta)^2 + \sin^2 2\theta}$$

small E_ν, $|A| << 1$ no matter effects $\rightarrow$ vacuum oscillation

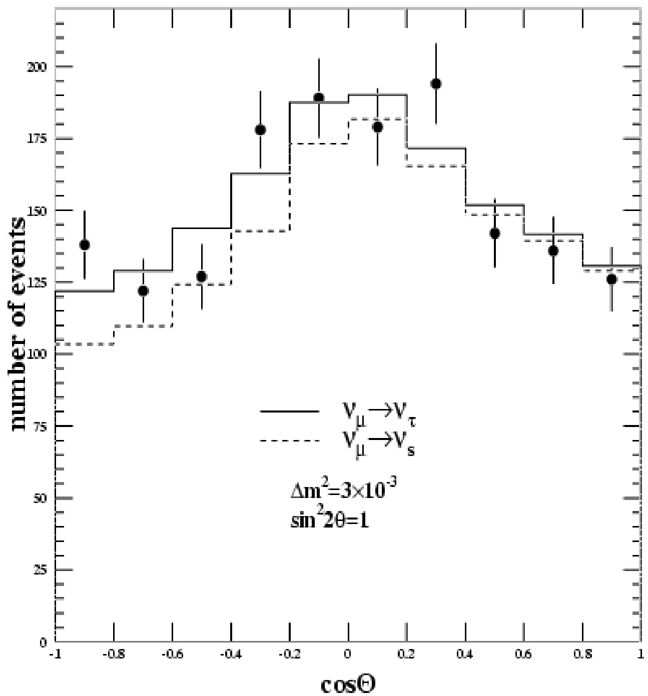
large E_ν, $|A| >> 1$ oscillation is suppressed

$|A| \sim 1$ in earth for $E_\nu = 5$ GeV x $\Delta m^2 (10^{-3}$ eV$^2)$

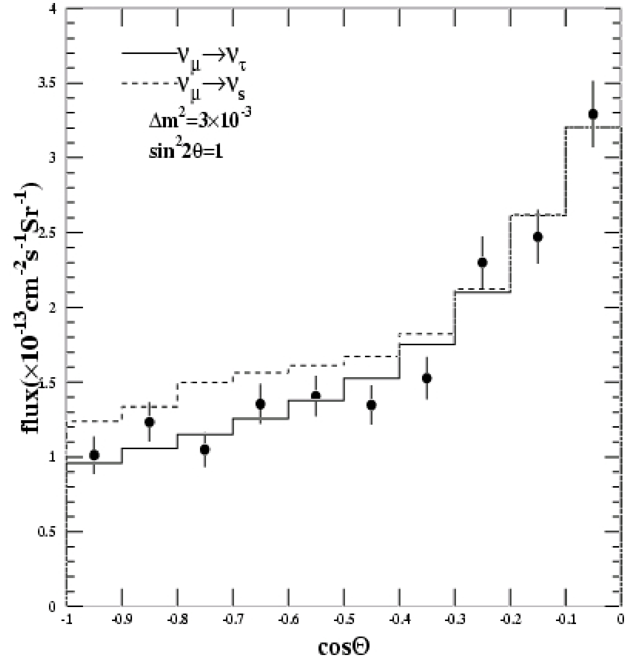
$\nu_\mu - \nu_{sterile}$ Matter Effects



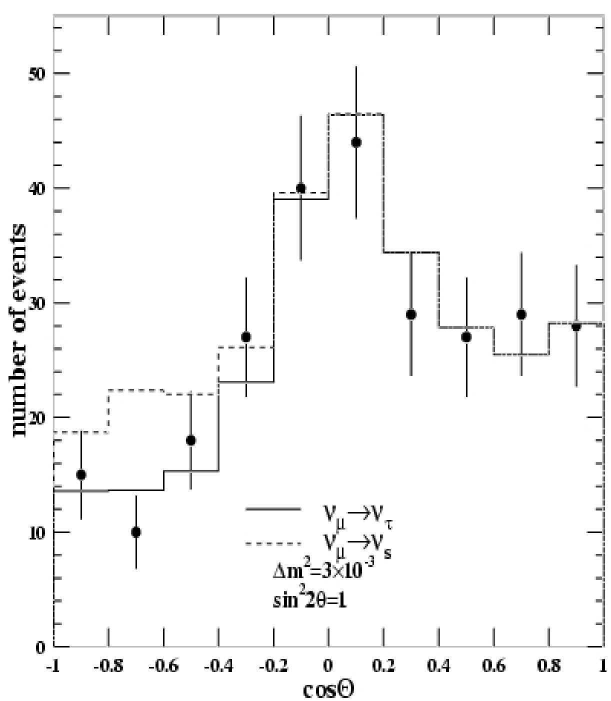
N.C. enriched FC sample (1140days)



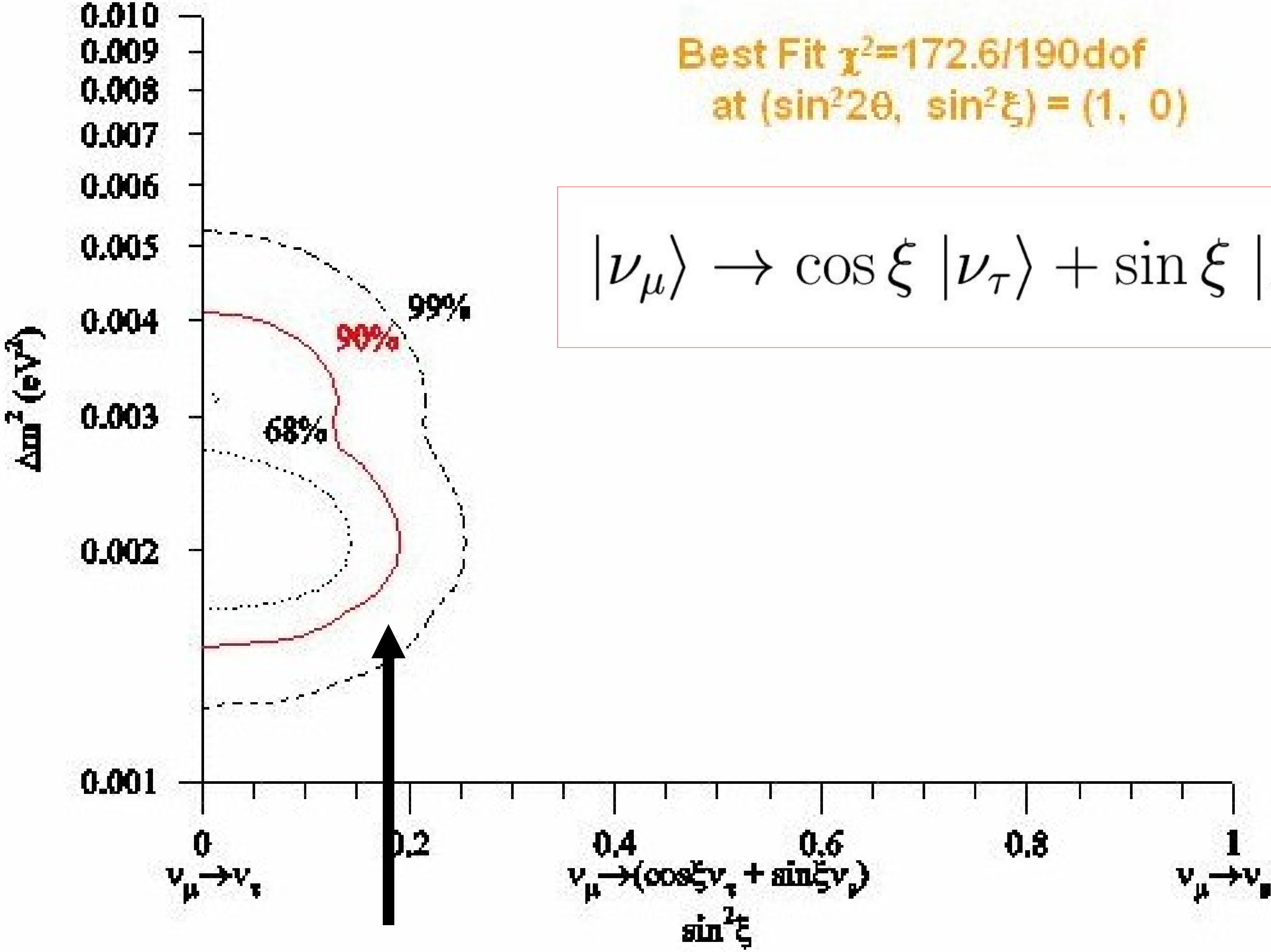
up-through-going muons (1140days)



high-energy PC sample (1140days)



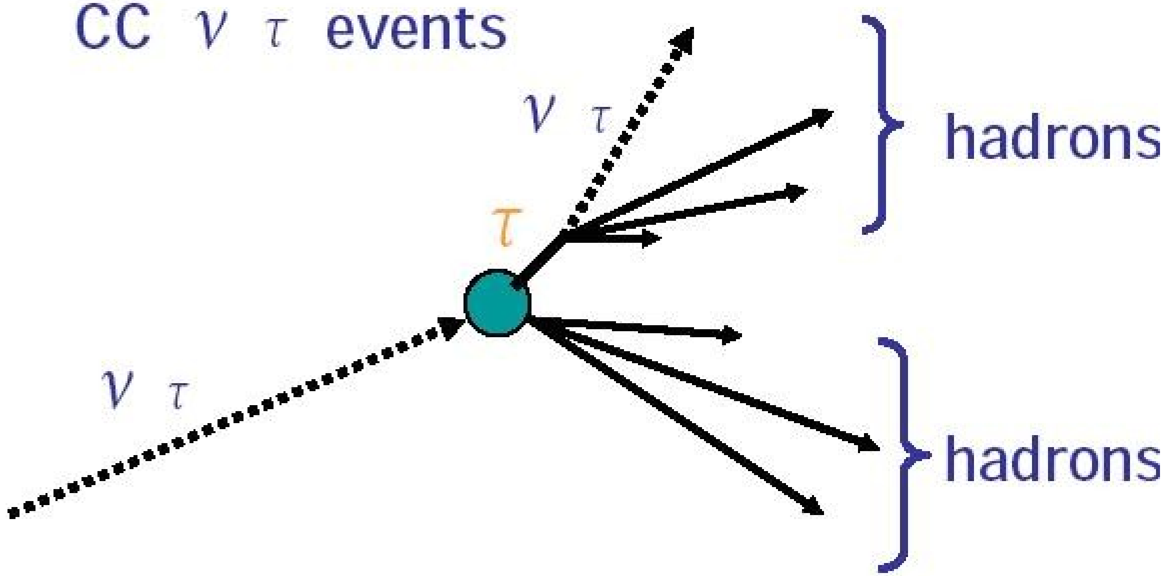
3 samples of data to study the $\nu_\mu \Leftrightarrow \nu_s$ hypothesis



$$|\nu_\mu\rangle \rightarrow \cos\xi\ |\nu_\tau\rangle + \sin\xi\ |\nu_{\mathrm{sterile}}\rangle$$

$$\sin^2\xi < 0.19$$

CC ν_τ events

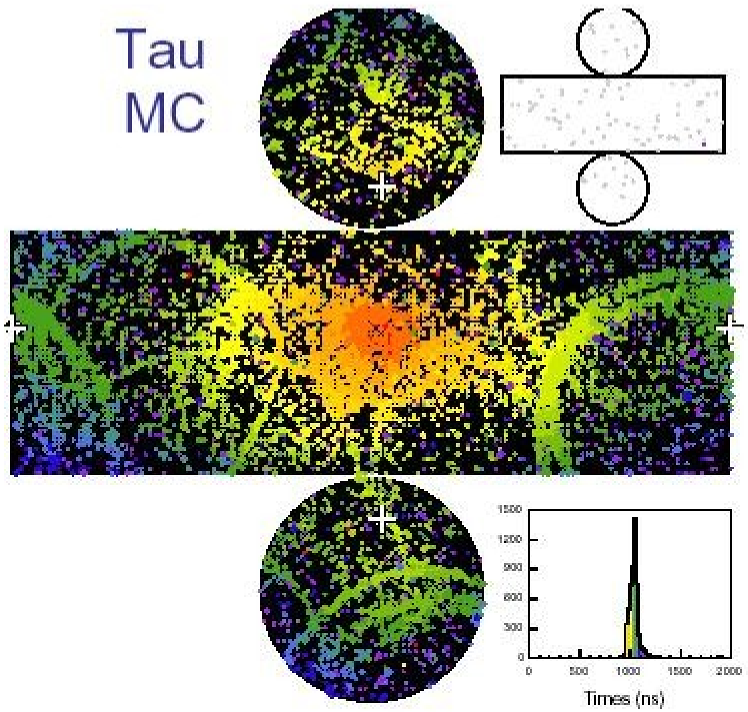


Only ~ 1.0 CC ν_τ FC events/kton •yr

⇕

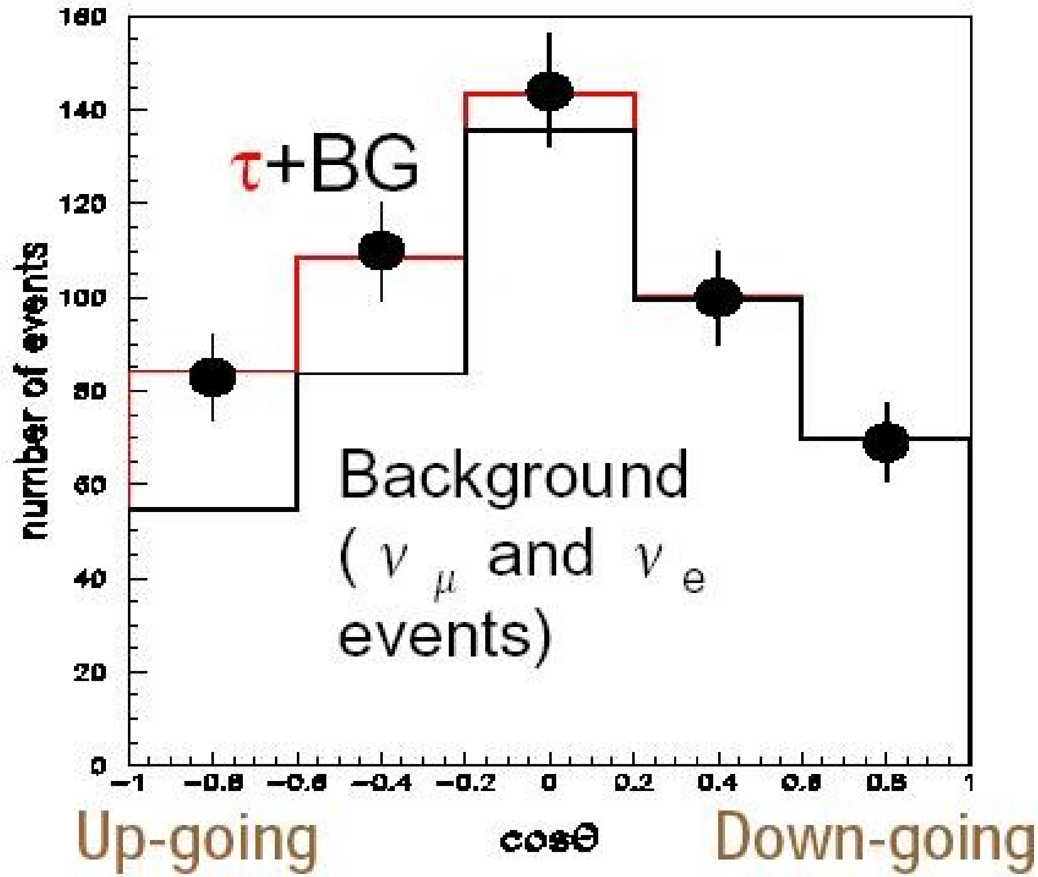
(BG (other ν events) ~ 130 ev./kton •yr)

Tau MC



τ "candidates" Zenith Angle Distribution

Max. likelihood analysis



$N^{FC}_{\tau} = \alpha N^{\tau}_{MC}/(\text{eff.}=0.44$
$= 145 \pm 44 (\text{stat.})$
$+11/-16 (\text{sys.})$

$N_{exp} = 86$

$N_{\tau} = 145 \pm 44^{+11}_{-16}$

Evidence for New Physics in Atmospheric Neutrinos is SOLID

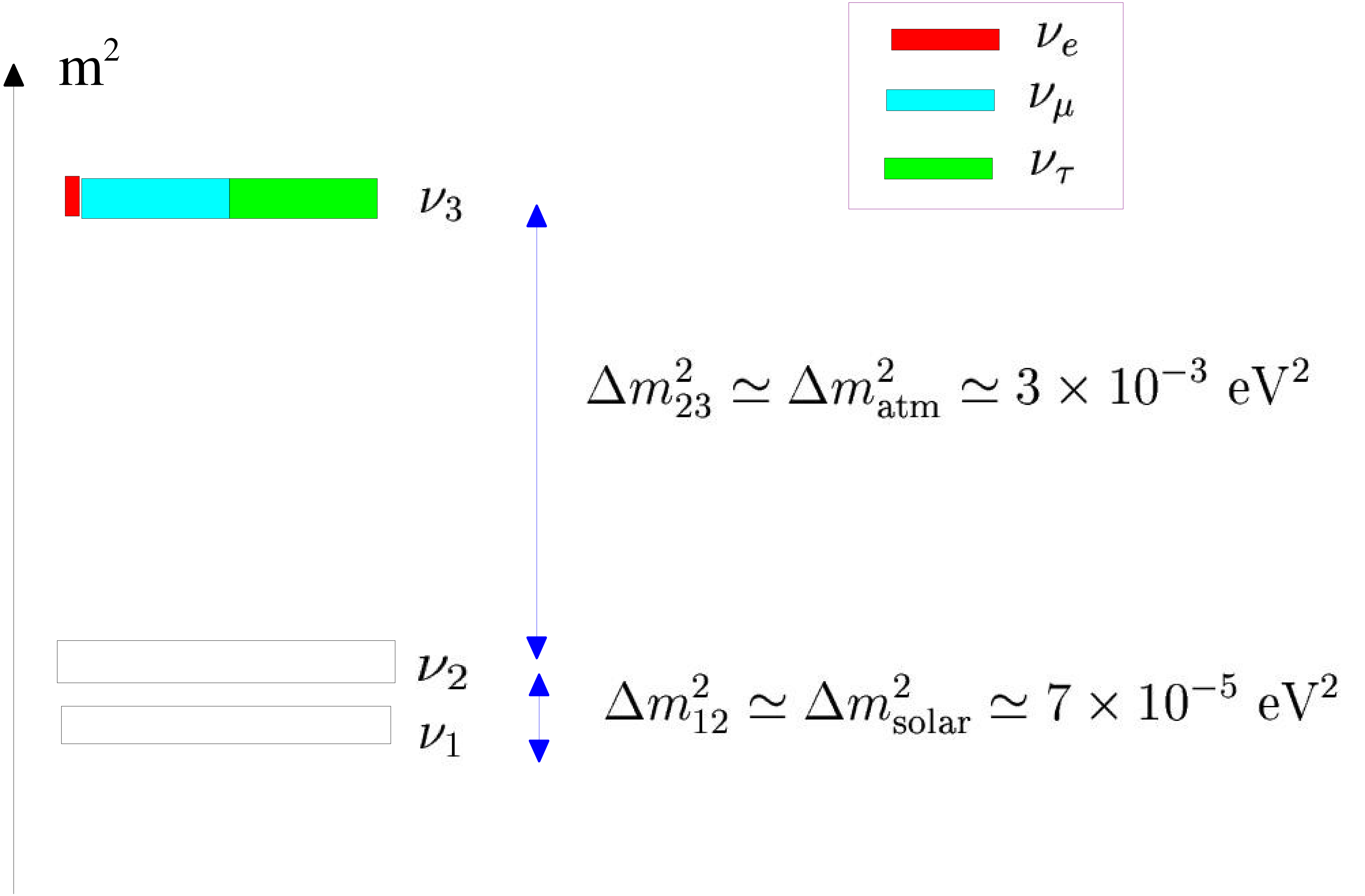
The Oscillation interpretation is very satisfactory

Parameter determination:

$$|\Delta m^2_{23}| = (2.1 \div 3.1)\, 10^{-3}\, \mathrm{eV}^2$$

$$36^\circ < \theta_{23} < 54^\circ$$

90% CL



$$|\nu_j\rangle = U_{ej}\ |\nu_e\rangle + U_{\mu j}\ |\nu_\mu\rangle + U_{\tau j}\ |\nu_\tau\rangle \qquad |U_{ej}|^2 + |U_{\mu j}|^2 + |U_{\tau j}|^2 = 1$$

Confirmation of the Atmospheric Neutrino Results

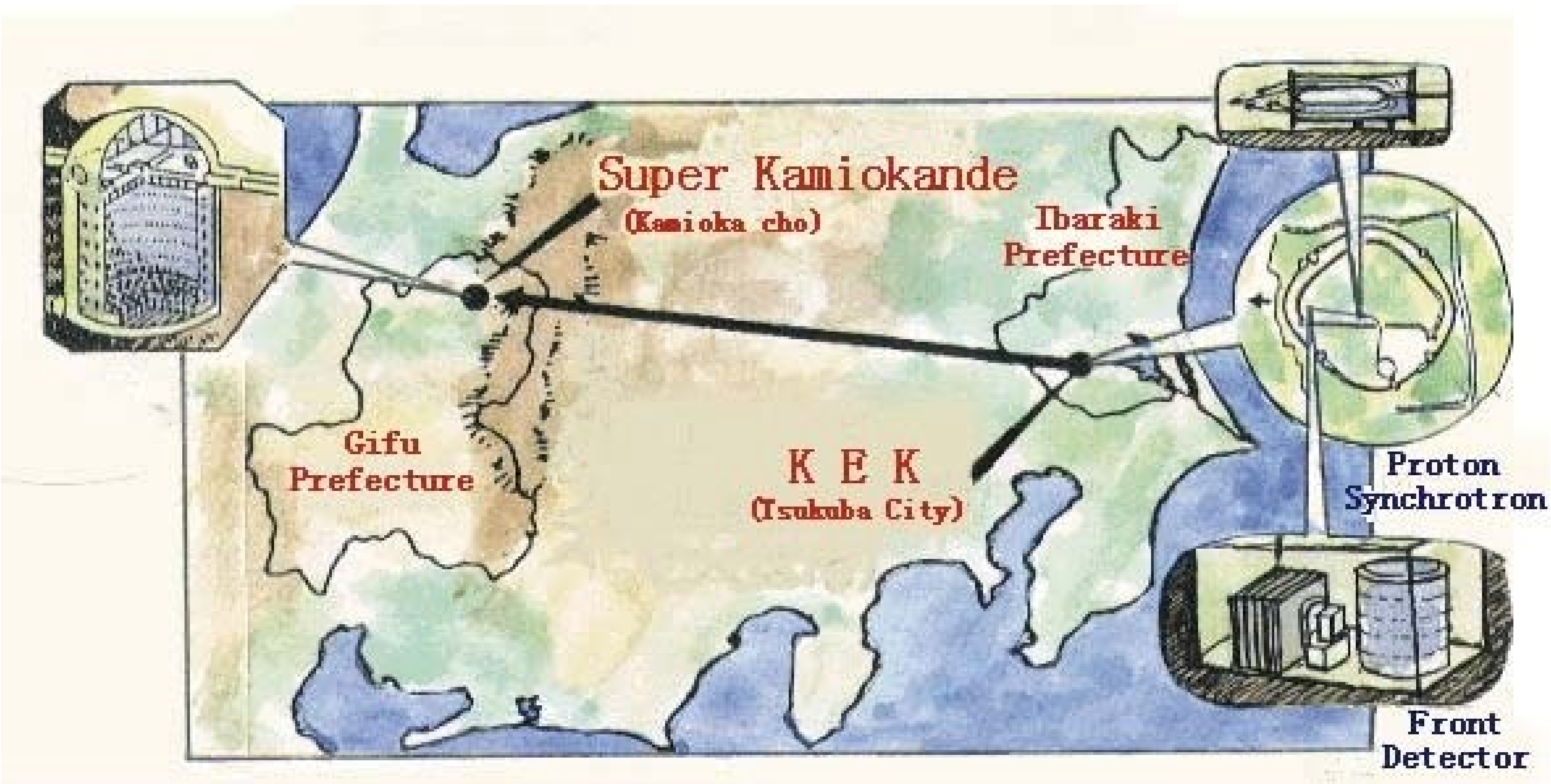
with

ACCELERATOR NEUTRINOS

LONG BASELINE NEUTRINO BEAMS

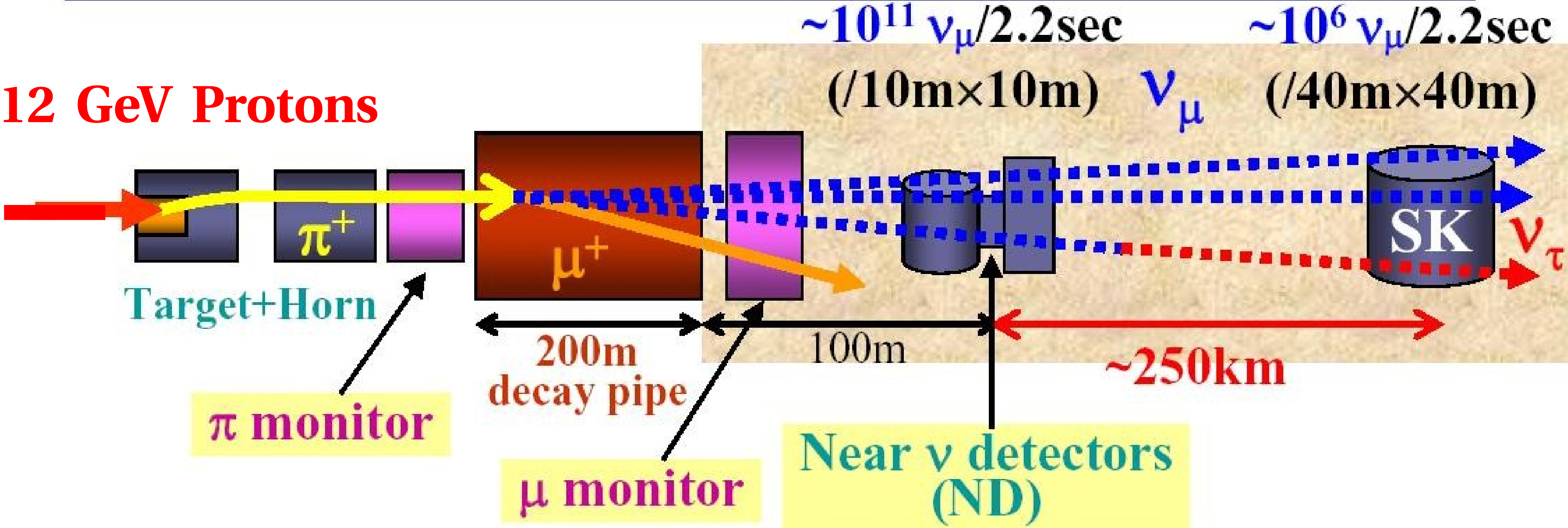
KEK to Kamioka (K2K) project

Fermilab to MINOS
CERN to Gran Sasso

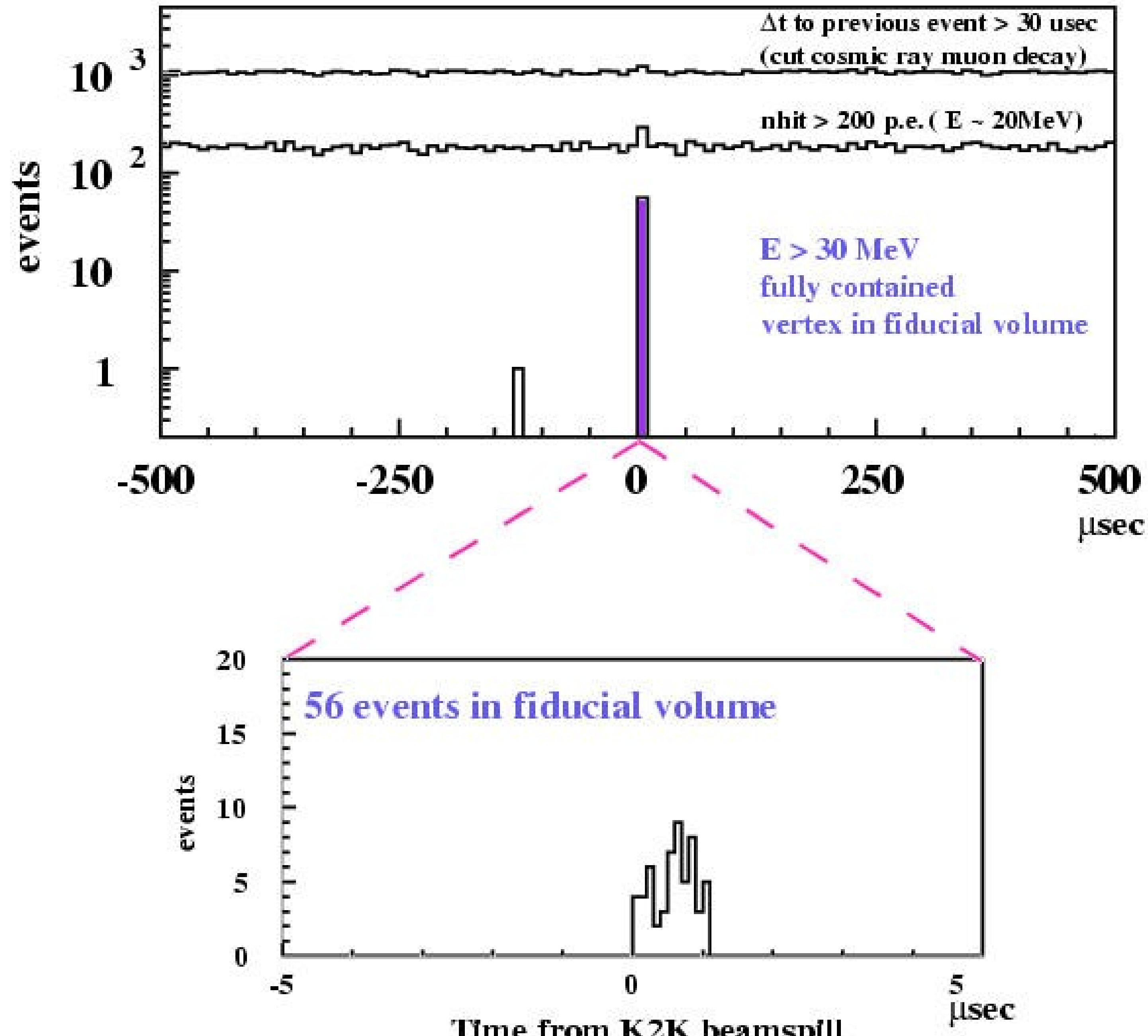


K2K experiment

~1 event/2days



(monitor the beam center)



Δt to previous event > 30 usec
(cut cosmic ray muon decay)
nhit > 200 p.e. (E ~ 20MeV)
E > 30 MeV
fully contained
vertex in fiducial volume
events
10 3
10 2
10
1
-500
-250
0
250
500
μsec
56 events in fiducial volume
20
15
10
5
0
events
-5
0
5
μsec
Time from K2K beamspill

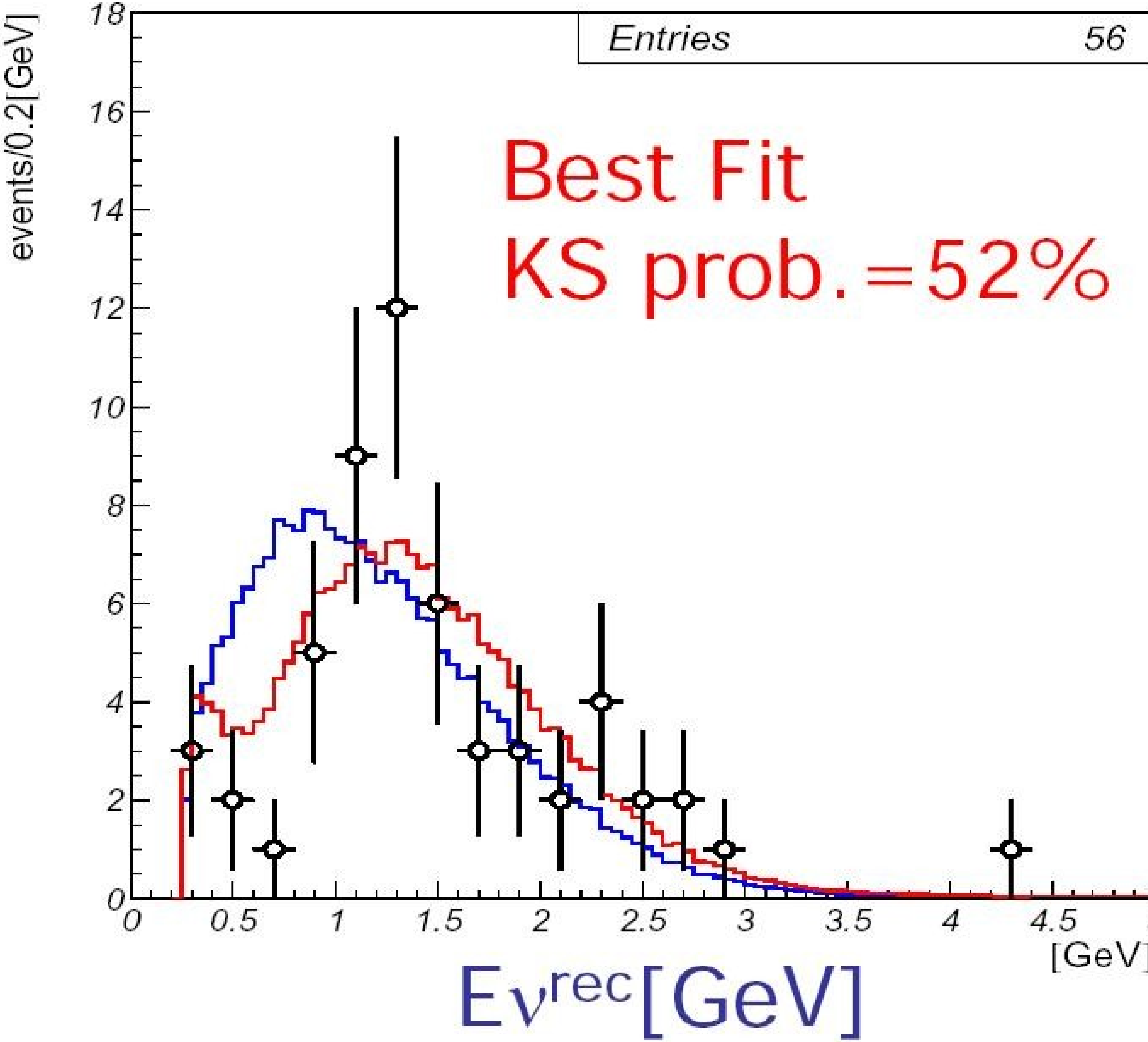
K2K-SK events

preliminary

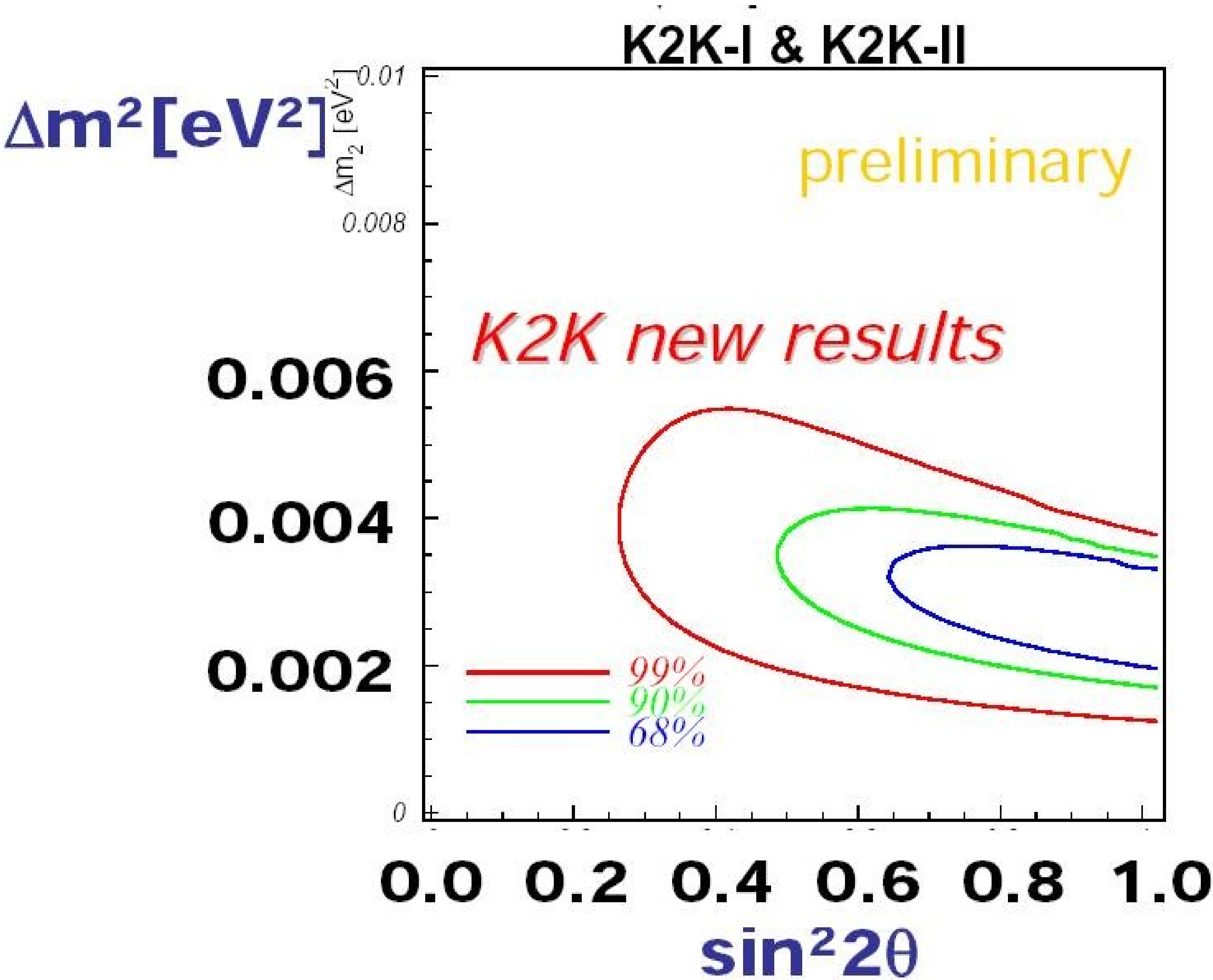
K2K-allI (K2K-I, K2K-II)	DATA (K2K-I, K2K-II)	MC (K2K-I, K2K-II)
FC 22.5kt	**108** (56, 52)	**150.9** (79.1*, 71.8)
1ring	**66** (32, 34)	**93.7** (48.6, 45.1)
μ-like	**57** **(56)** for E_ν^{rec} (30, 27)	**84.8** (44.3, 40.5)
e-like	**9** (2, 7)	**8.8** (4.3, 4.5)
Multi Ring	**42** (24, 18)	**57.2** (30.5, 26.7)

Ref; K2K-I(47.9 × 10^{18}POT), K2K-II(41.2 × 10^{18}POT)

*: The number is changed from the previous one.



events/0.2[GeV]
Entries 56
Best Fit
KS prob.=52%
0
2
4
6
8
10
12
14
16
18
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
[GeV]
Eν^rec[GeV]



K2K-I & K2K-II
Δm²[eV²]
Δm_2 [eV²]
0.01
0.008
0.006
0.004
0.002
0
preliminary
K2K new results
99%
90%
68%
0.0
0.2
0.4
0.6
0.8
1.0
sin²2θ

Neutrinos from NUCLEAR REACTORS

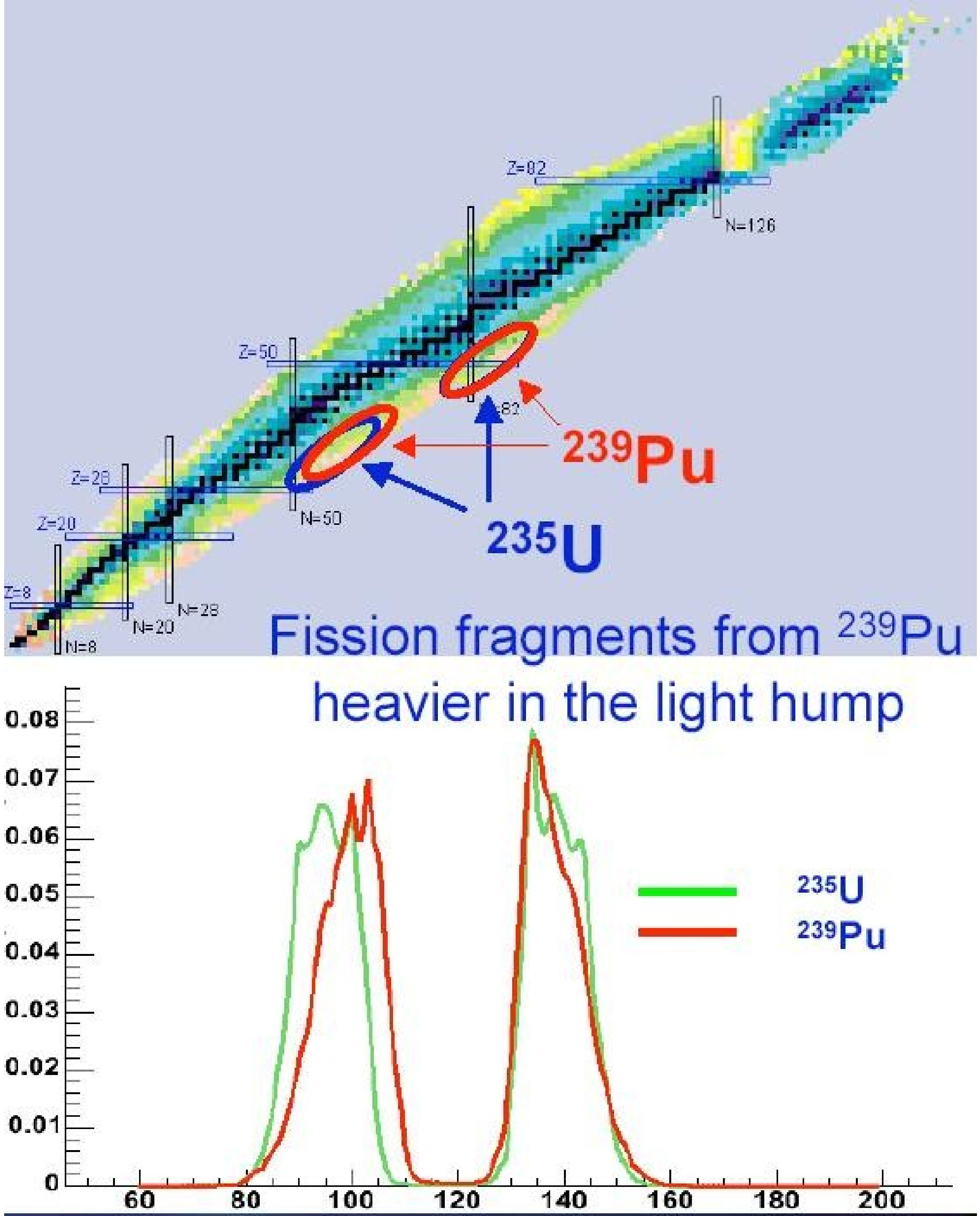
$$n + {}^{235}\mathrm{U} \rightarrow X_1 + X_2 + 2n$$

92 p, 143 n

Neutron Rich Nuclei

Beta decay

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


Z=82
N=126
Z=50
82
239Pu
Z=28
Z=20
N=50
235U
Z=8
N=28
N=20
N=8
Fission fragments from 239Pu
heavier in the light hump
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
60
80
100
120
140
160
180
200
235U
239Pu

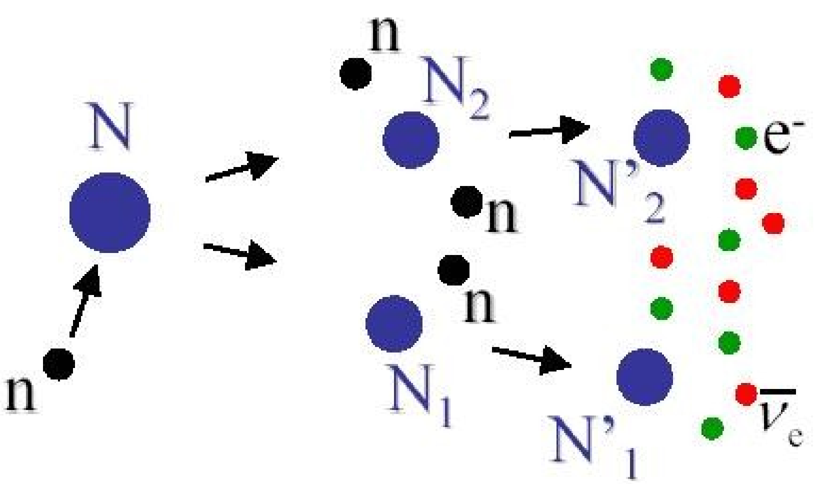
$$\text{Yield} \simeq \frac{6\ \overline{\nu}_e}{200\ \text{MeV}}$$

$$\text{Yield} \simeq \frac{1.8 \times 10^{20}\ \overline{\nu}_e/\text{sec}}{1\ \text{GWatt}}$$

For precision estimate of the flux need to follow the chemical evolution of the nuclear fuel

$$^{238}_{92}\text{U} + \text{n} \rightarrow {}^{239}_{92}\text{U} \xrightarrow{23\ \text{min}} {}^{239}_{93}\text{Np} \xrightarrow{2.3\ \text{d}} {}^{239}_{94}\text{Pu}$$

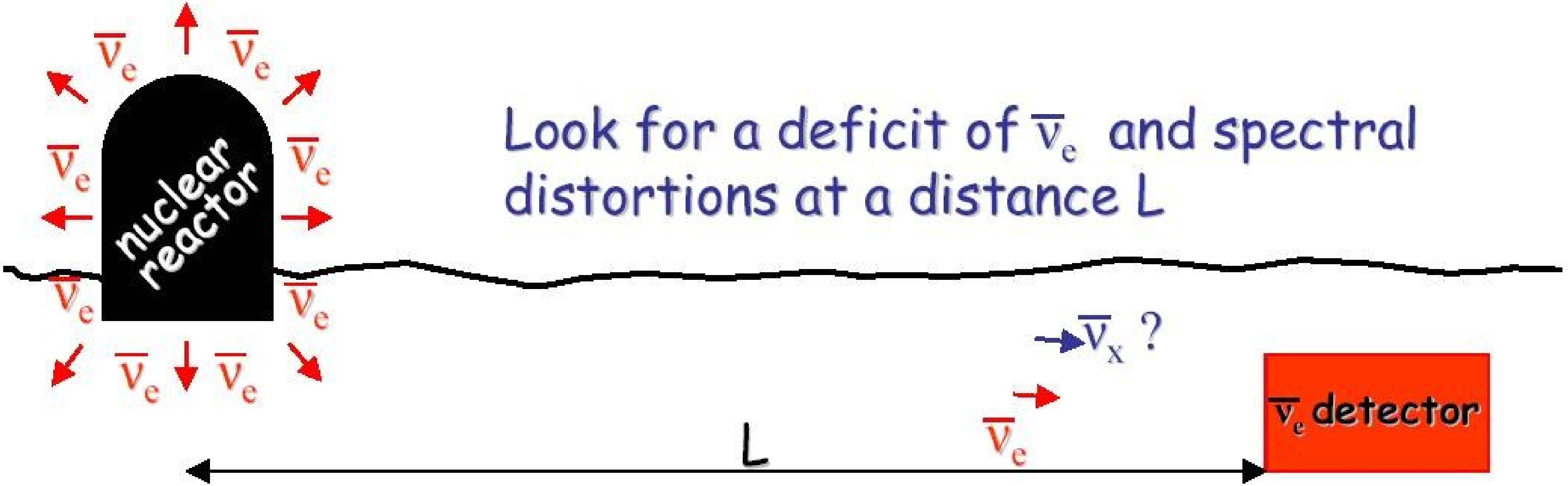
Nuclear reactors are very intense sources of $\overline{\nu}_e$ deriving from beta-decay of the neutron-rich fission fragments



Yield :

$200\,MeV\ /\ fission$

$6\overline{\nu}_e\ /\ fission$



Look for a deficit of $\overline{\nu}_e$ and spectral distortions at a distance L

A specific signature is provided by the inverse-β reaction

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

$\tau \approx 200\ \mu s$

$$p + n \to d + \gamma (2.2\ MeV)$$

Event tagging by coincidence in time, space and energy of the neutron capture

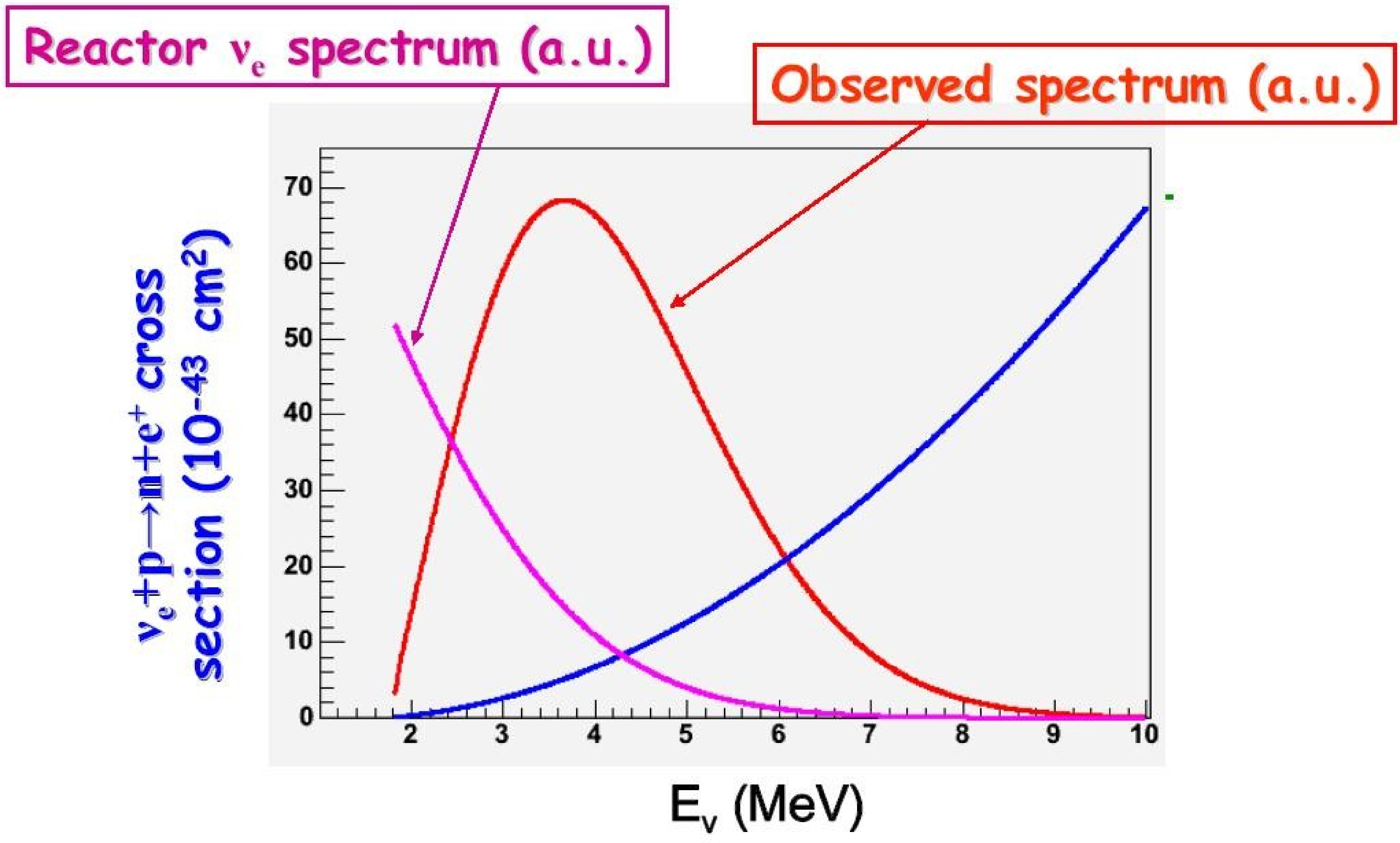
E_ν measurement

$$E_{\overline{\nu}} \cong T_{e^+} + \underbrace{T_n}_{10\text{-}40\ keV} + \underbrace{(M_n - M_p) + m_{e^+}}_{1.8\ MeV}$$

Threshold: $E_{\overline{\nu}} > 1.8 MeV$

$\to$ only ~1.5 antineutrinos/fission can be detected

The $\overline{\nu}_e$ energy spectrum

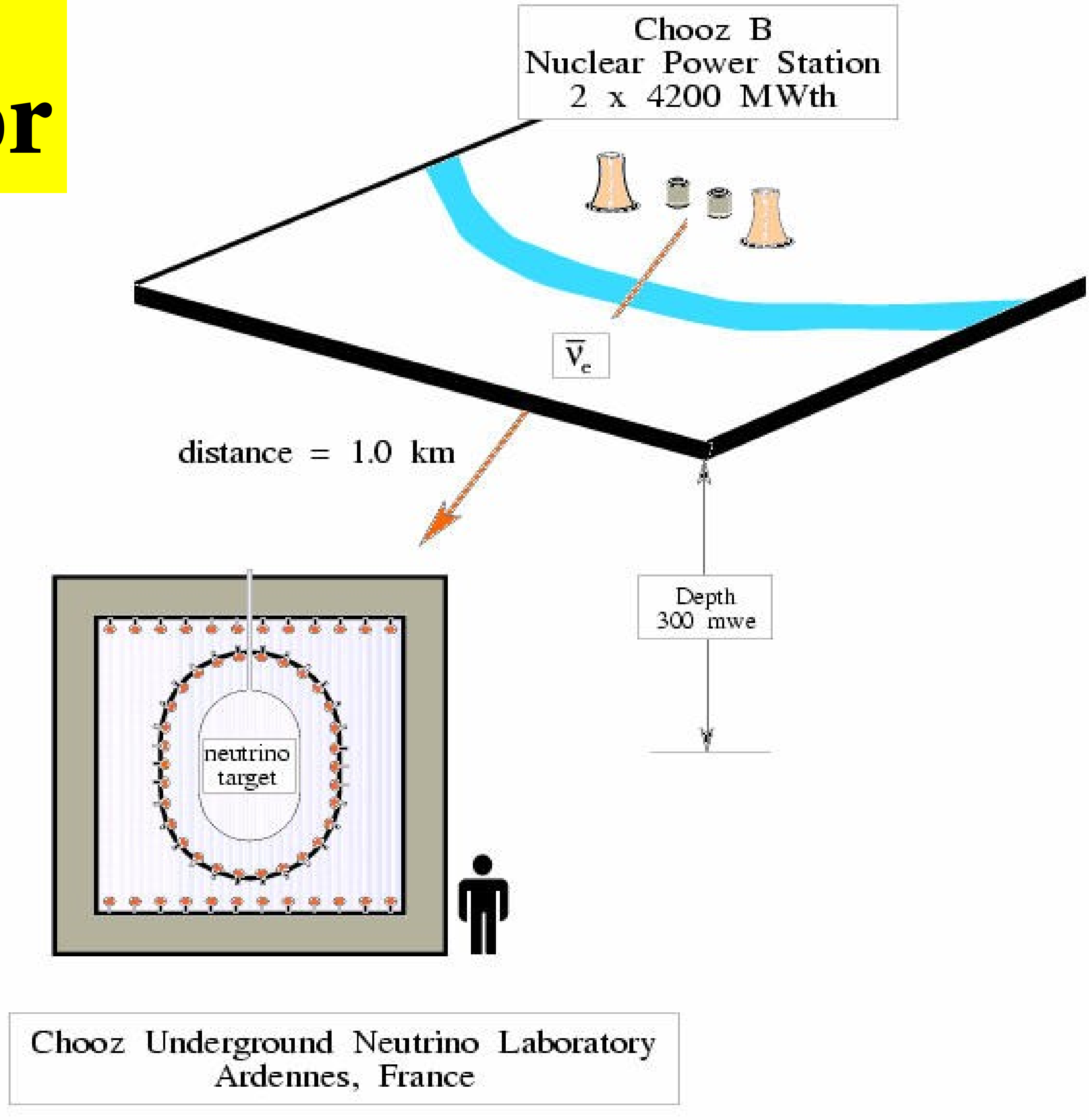


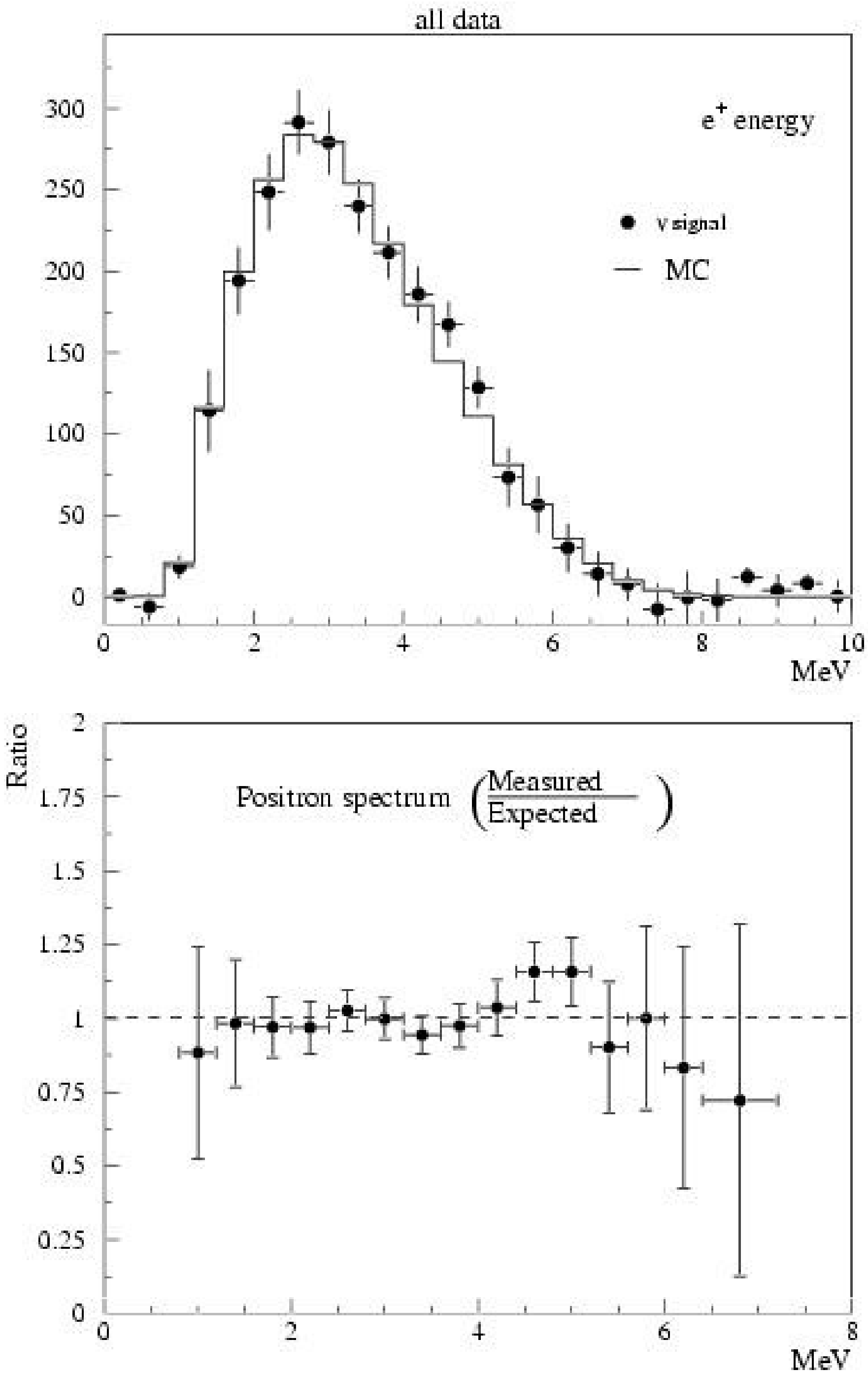
Study of $\nu_e \to \nu_\mu$ $\nu_e \to \nu_\tau$ Transitions

Chooz Experiment (L = 1 Km)
(Palo Verde)

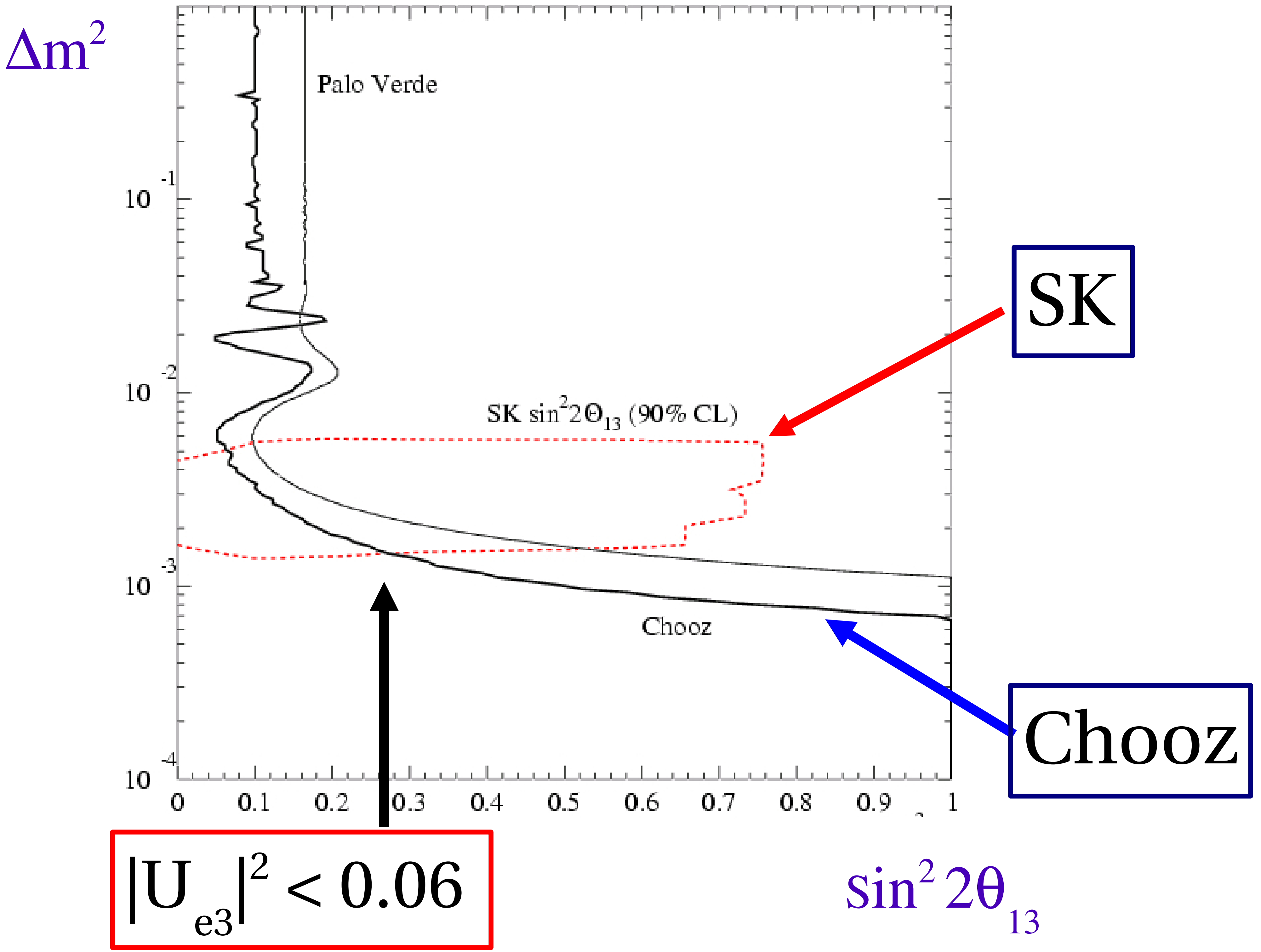
KamLand Experiment (L 150 Km)

Chooz Detector

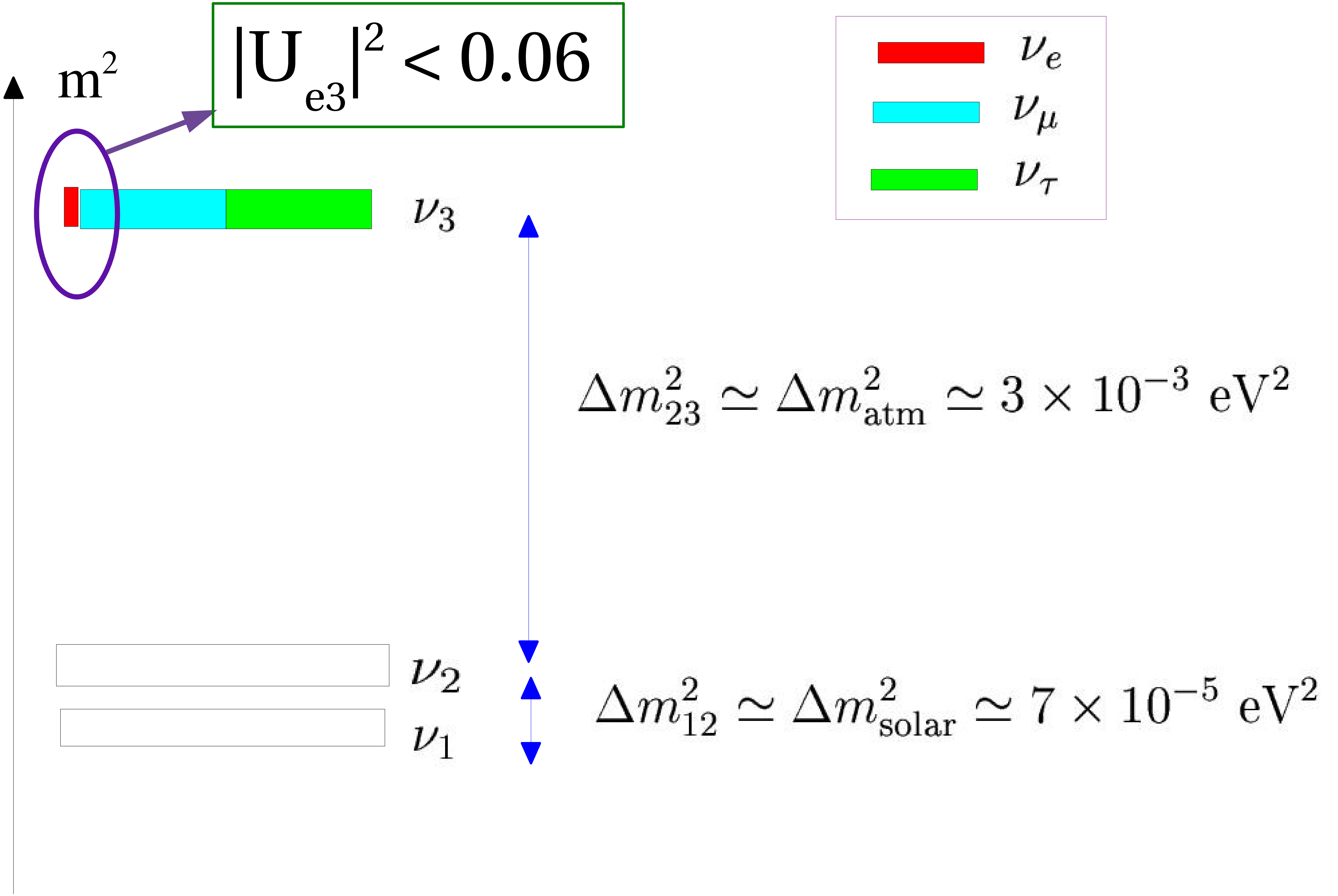




Data/Prediction =
1.01 ± 2.8% (stat) ± 2.7% (sys)



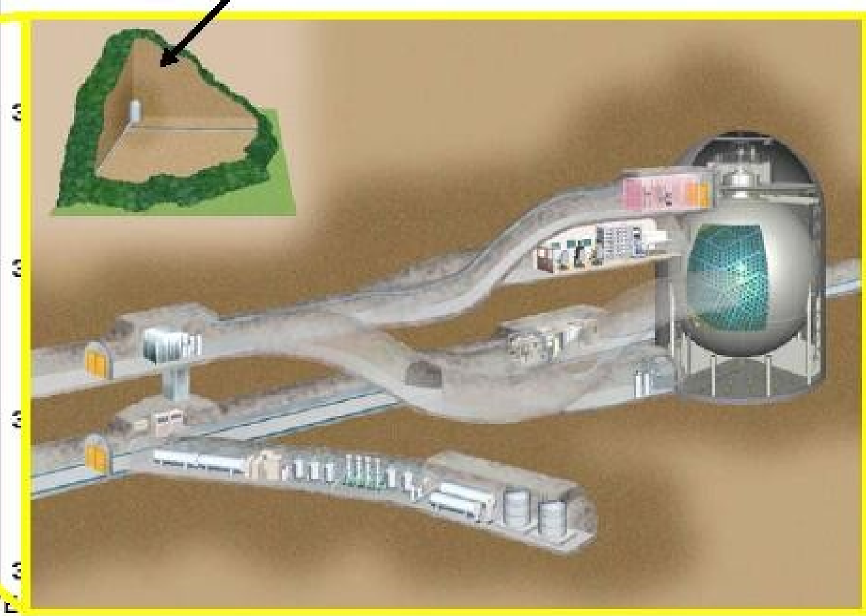
Δm²
Palo Verde
SK sin²2Θ13 (90% CL)
Chooz
SK
Chooz
10⁻¹
10⁻²
10⁻³
10⁻⁴
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
|Ue3|² < 0.06
Sin² 2θ13



$$|\nu_j\rangle = U_{ej}\ |\nu_e\rangle + U_{\mu j}\ |\nu_\mu\rangle + U_{\tau j}\ |\nu_\tau\rangle \qquad |U_{ej}|^2 + U_{\mu j}|^2 + U_{\tau j}|^2 = 1$$

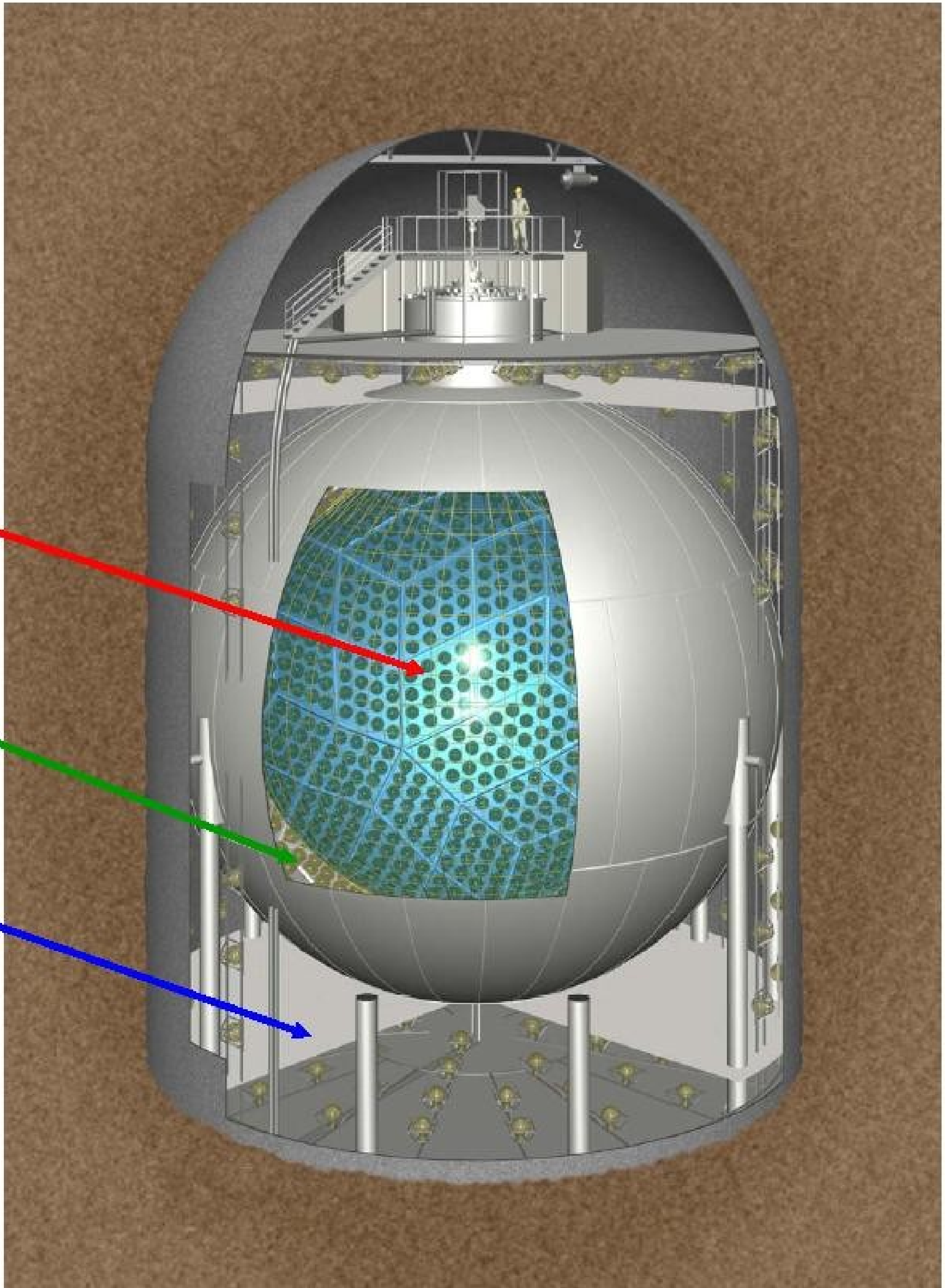
KAMLAND Experiment

~1 km high
Mt Ikenoyama



KamLAND:
Kamioka Liquid scintillator AntiNeutrino Detector

- 1 kton liq. Scint. Detector in the Kamiokande cavern
- 1325 17" fast PMTs
- 554 20" large area PMTs
- 34% photocathode coverage
- H_2O Cerenkov veto counter



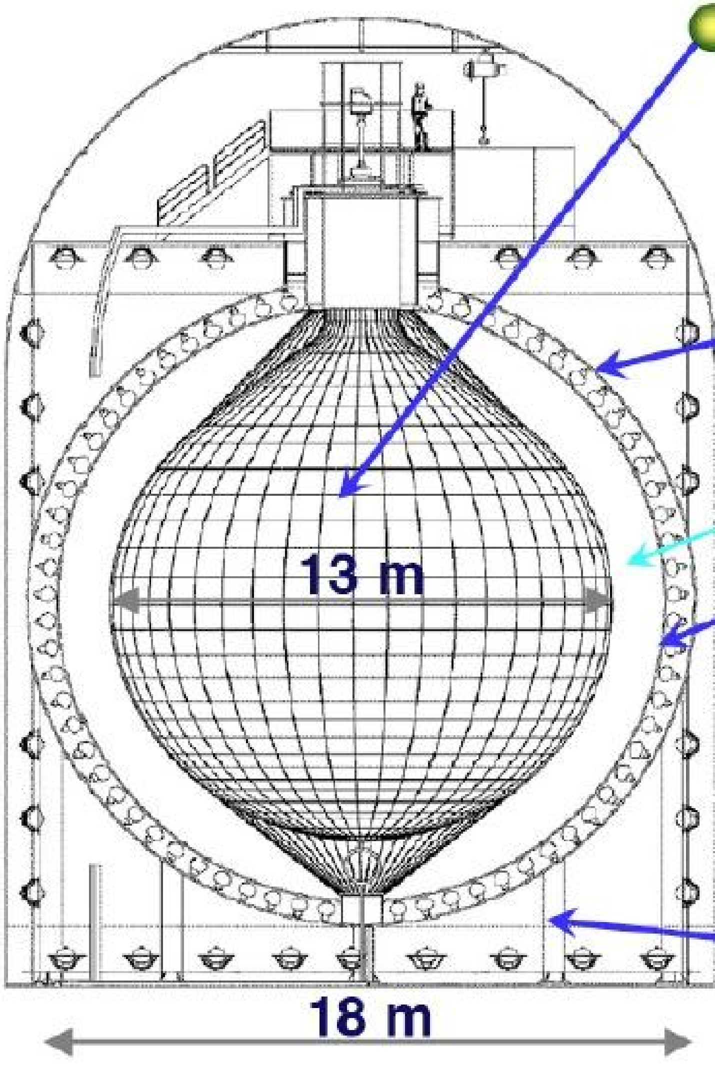
KamLAND Detector

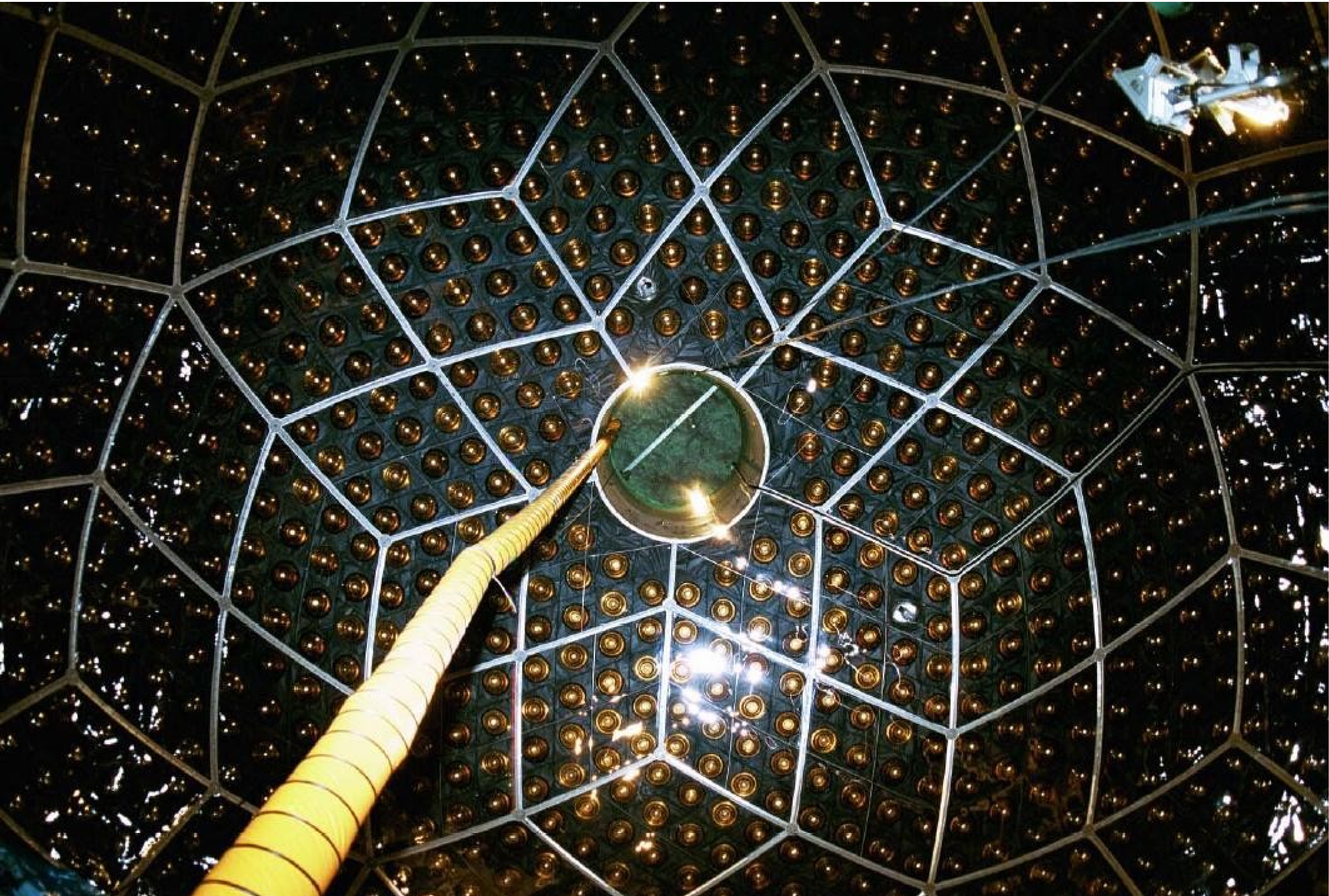
- detector location: old Kamiokande site
  : 2700 m.w.e.
- 1000 ton liquid scintillator
  : 80% (dodecane) + 20% (pseudocumene)
  + 1.52 *g/l* PPO
  : housed in spherical plastic balloon
- 3000 m^3 stainless steel vessel
  : filled with a mixture of paraffin oil
  and dodecane ($\Delta\rho$ = 0.04%)
- 1325 17-inch + 554 20-inch PMT's

commissioned in February, 2003

photocathode coverage : 22% → 34%
energy resolution at 1 MeV : 7.3% → 6.3%

- water Cerenkov outer detector





Many reactors contribute to the antineutrino flux at KamLAND

	Site	Dist (km)	Cores (#)	P_{therm} (GW)	Flux ($cm^{-2}\ s^{-1}$)	Rate noosc* ($yr^{-1}\ kt^{-1}$)
Japan	Kashiwazaki	160	7	24.3	$4.1 \cdot 10^5$	254.0
	Ohi	179	4	13.7	$1.9 \cdot 10^5$	114.3
	Takahama	191	4	10.2	$1.2 \cdot 10^5$	74.3
	Tsuruga	138	2	4.5	$1.0 \cdot 10^5$	62.5
	Hamaoka	214	4	10.6	$1.0 \cdot 10^5$	62.0
	Mihama	146	3	4.9	$1.0 \cdot 10^5$	62.0
	Sika	88	1	1.6	$9.0 \cdot 10^4$	55.2
	Fukushima1	349	6	14.2	$5.1 \cdot 10^4$	31.1
	Fukushima2	345	4	13.2	$4.8 \cdot 10^4$	29.5
	Tokai2	295	1	3.3	$1.6 \cdot 10^4$	10.1
	Onagawa	431	3	6.5	$1.5 \cdot 10^4$	9.3
	Simane	401	2	3.8	$1.0 \cdot 10^4$	6.3
	Ikata	561	3	6.0	$8.3 \cdot 10^3$	5.1
	Genkai	755	4	10.1	$7.8 \cdot 10^3$	4.8
	Sendai	830	2	5.3	$3.4 \cdot 10^3$	2.1
	Tomari	783	2	3.3	$2.3 \cdot 10^3$	1.4
South Korea	Ulchin	712	4	11.5	$9.9 \cdot 10^3$	6.1
	Yonggwang	986	6	17.4	$7.8 \cdot 10^3$	4.8
	Kori	735	4	9.2	$7.5 \cdot 10^3$	4.6
	Wolsong	709	4	8.2	$7.1 \cdot 10^3$	4.3
Total Nominal		**-**	**70**	**181.7**	**$1.3 \cdot 10^6$**	**803.8**

*$E_\nu > 3.4$MeV ($E_{prompt} > 2.6$MeV)

Japan: Detailed power and fuel Composition calculation used

South Korea: From electrical power Japanese average fuel used

Results

(766.3 ton·yr, ~4.7× the statistics of the first paper)

Observed events	258
No osc. expected	365±24(syst)
Background	7.5±1.3

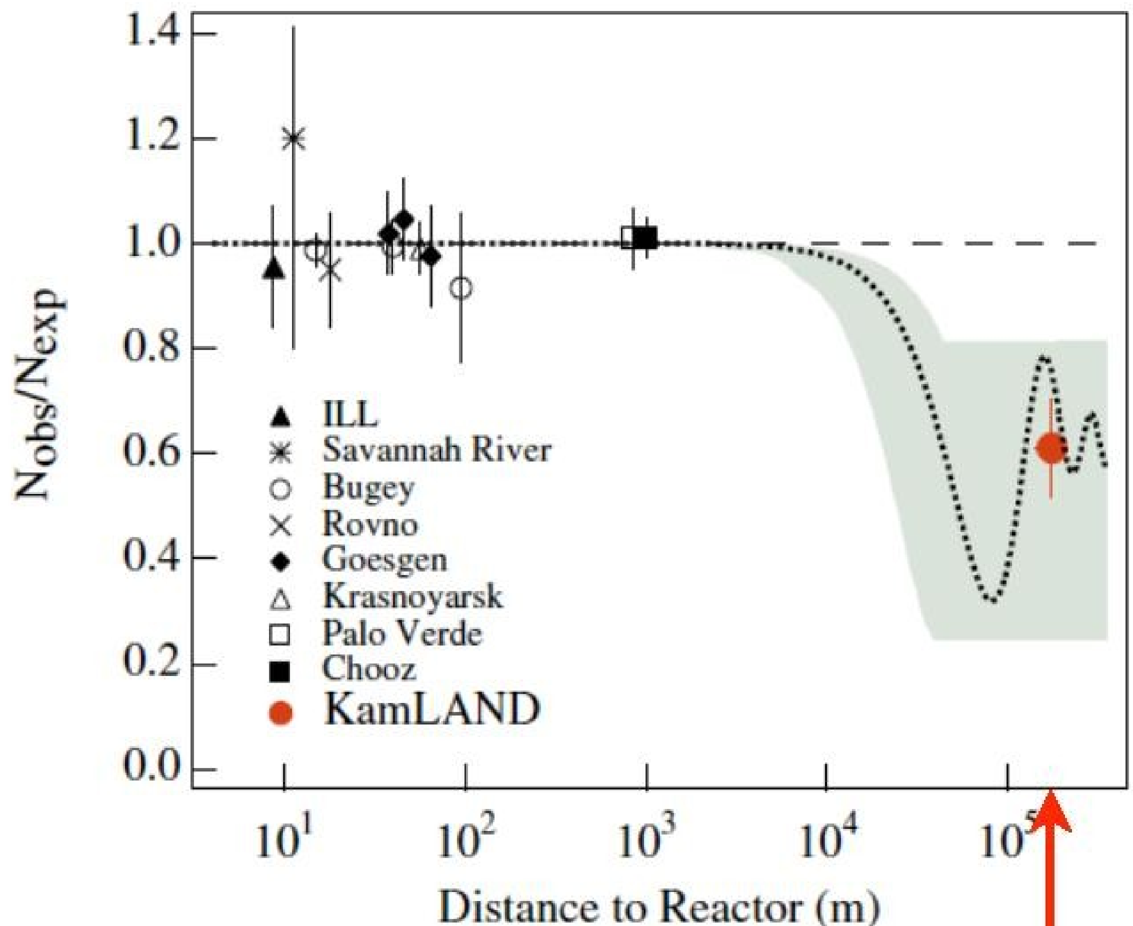
Background	Events
Accidentals	2.69±0.02
$^{8}He/^{9}Li$	4.8±0.9
μ-induced n	<0.89
Total	7.5±1.3

Inconsistent with simple $1/R^2$ propagation at 99.995% CL

(Observed-Background)/Expected = 0.686±0.044(stat)±0.045(syst)

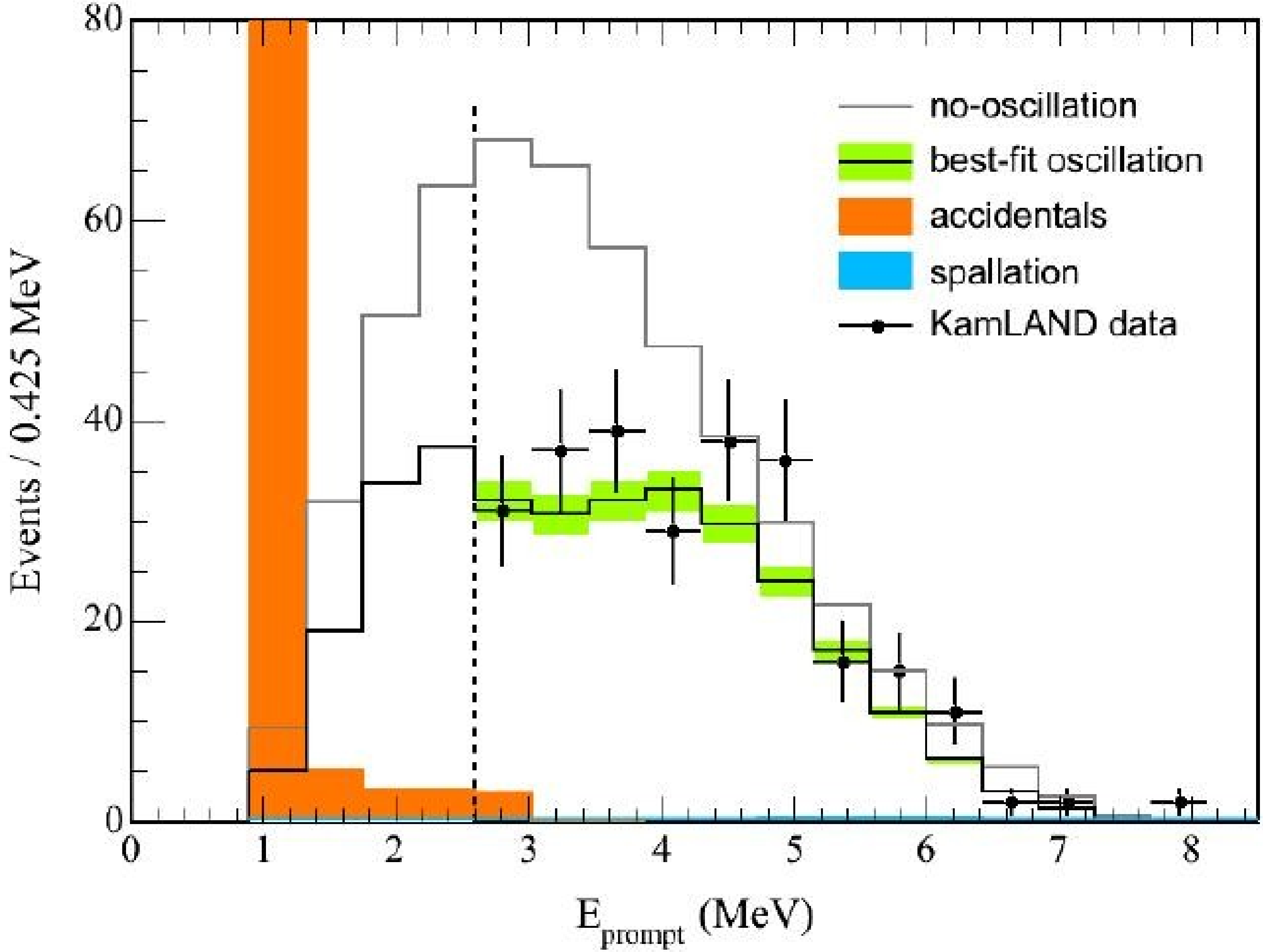
Caveat: this specific number does not have an absolute meaning in KamLAND, since, with oscillations, it depends on which reactors are on/off

180 km

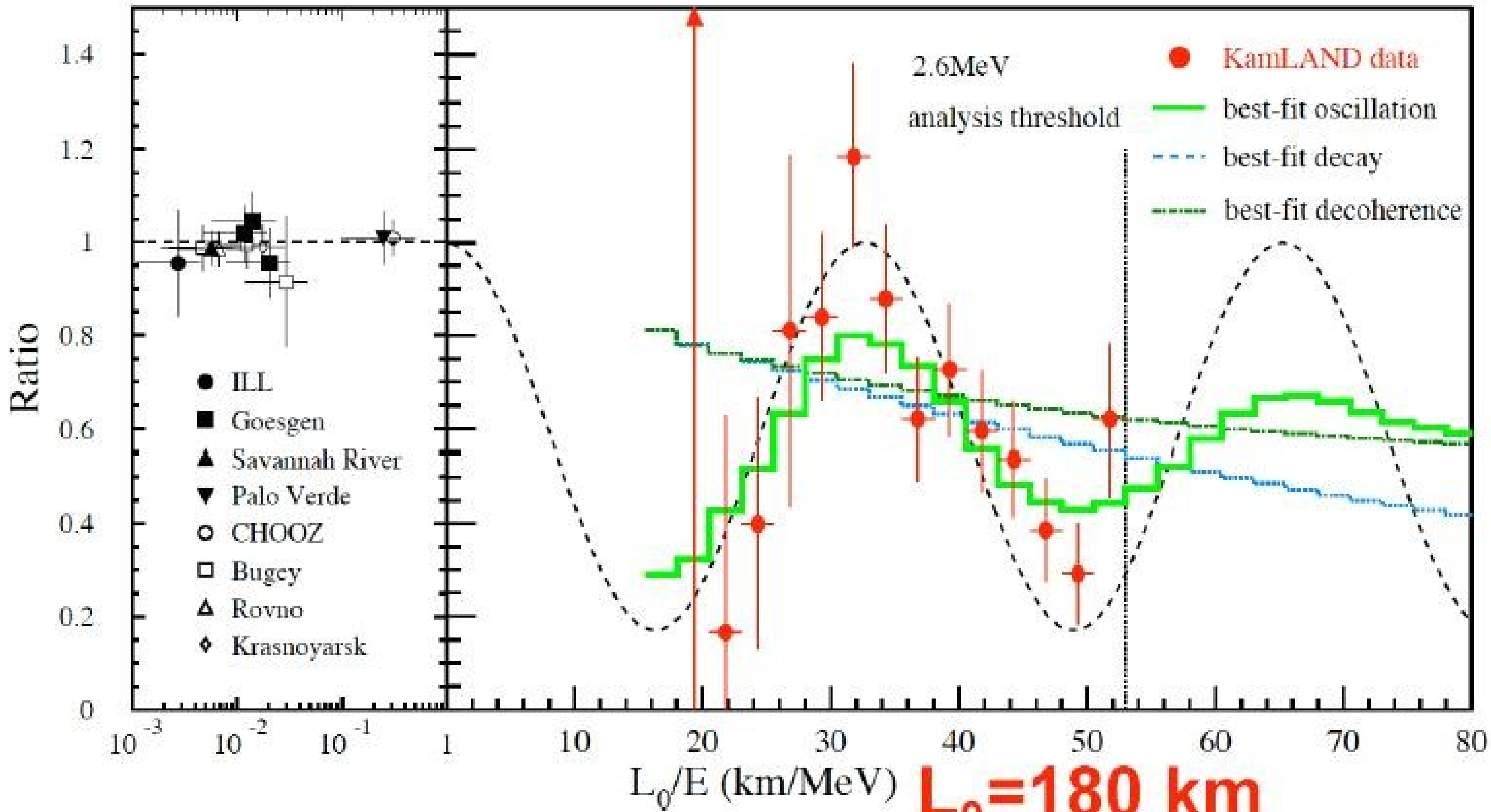


180 km

$$\frac{N_{obs} - N_{BG}}{N_{expected}} = 0.611 \pm 0.085(\mathrm{stat}) \pm 0.041(\mathrm{syst})$$

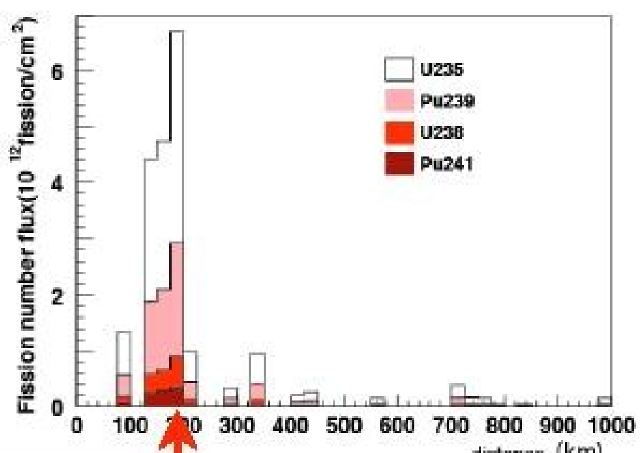

no-oscillation
best-fit oscillation
accidentals
spallation
KamLAND data
Events / 0.425 MeV
E_{prompt} (MeV)
0
20
40
60
80
0
1
2
3
4
5
6
7
8

Phys. Rev. Lett. 94 (2005) 081801



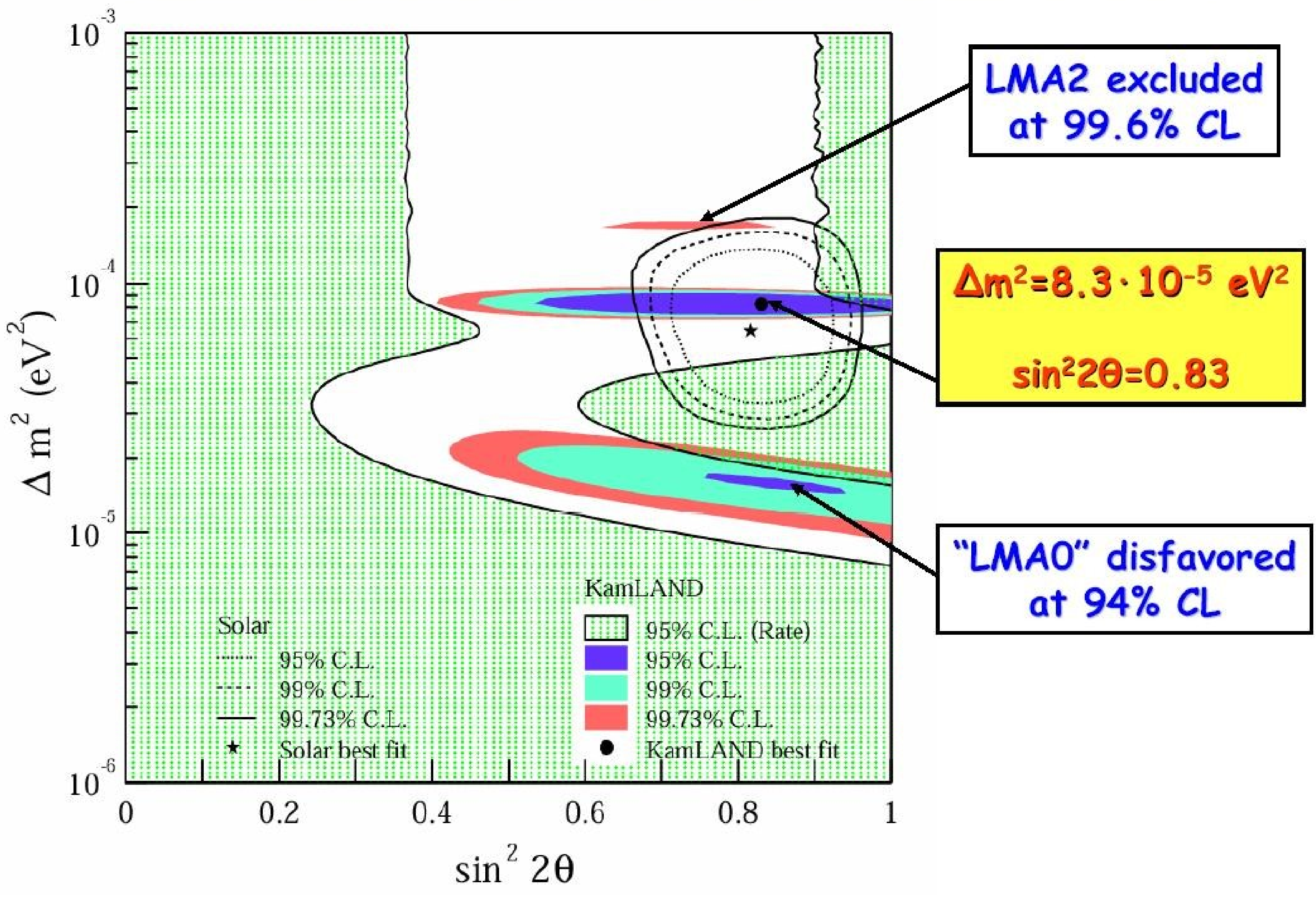
L_0=180 km

L_0

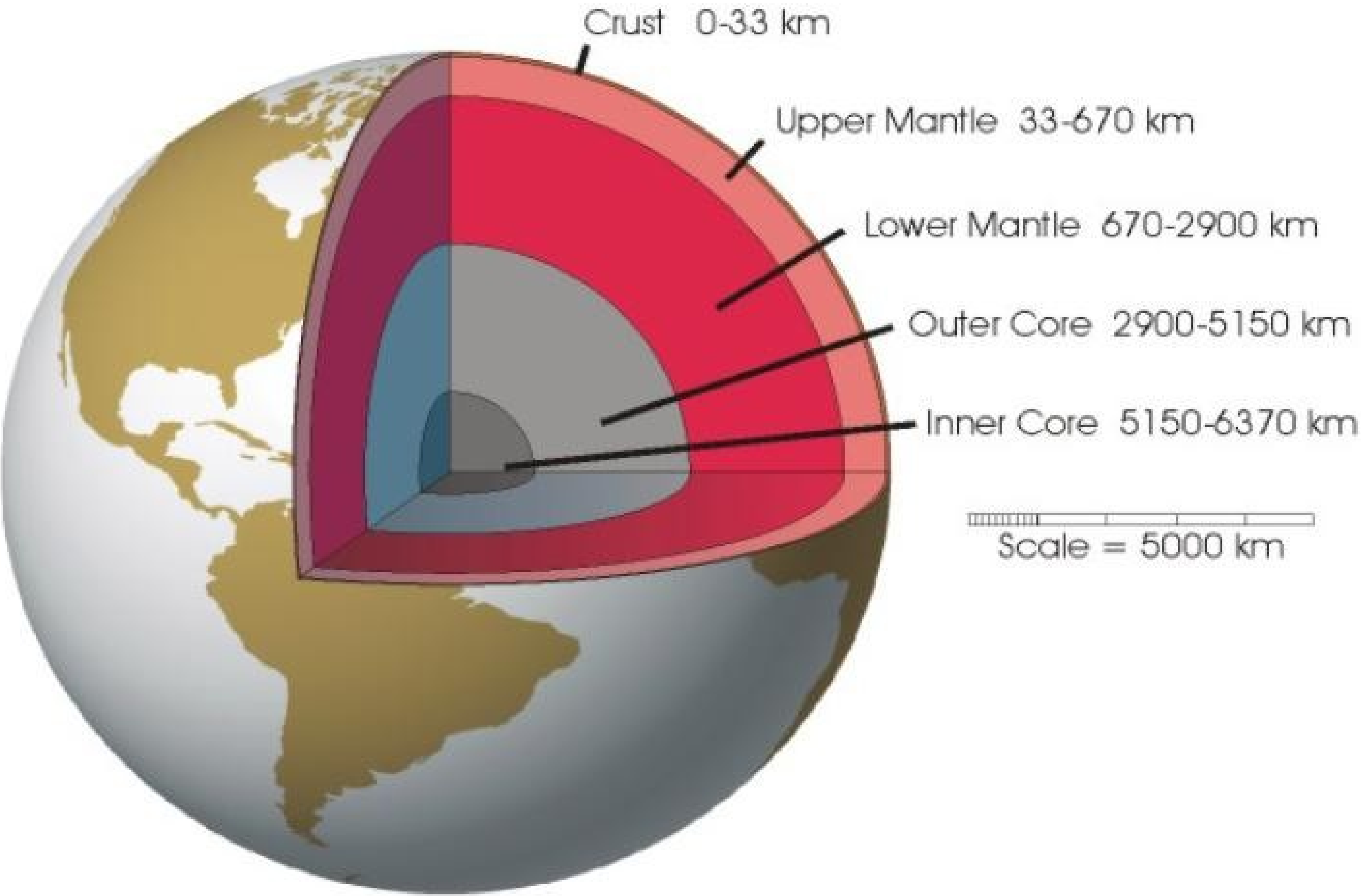


L_0

Un-binned likelihood fit to 2-flavor oscillations



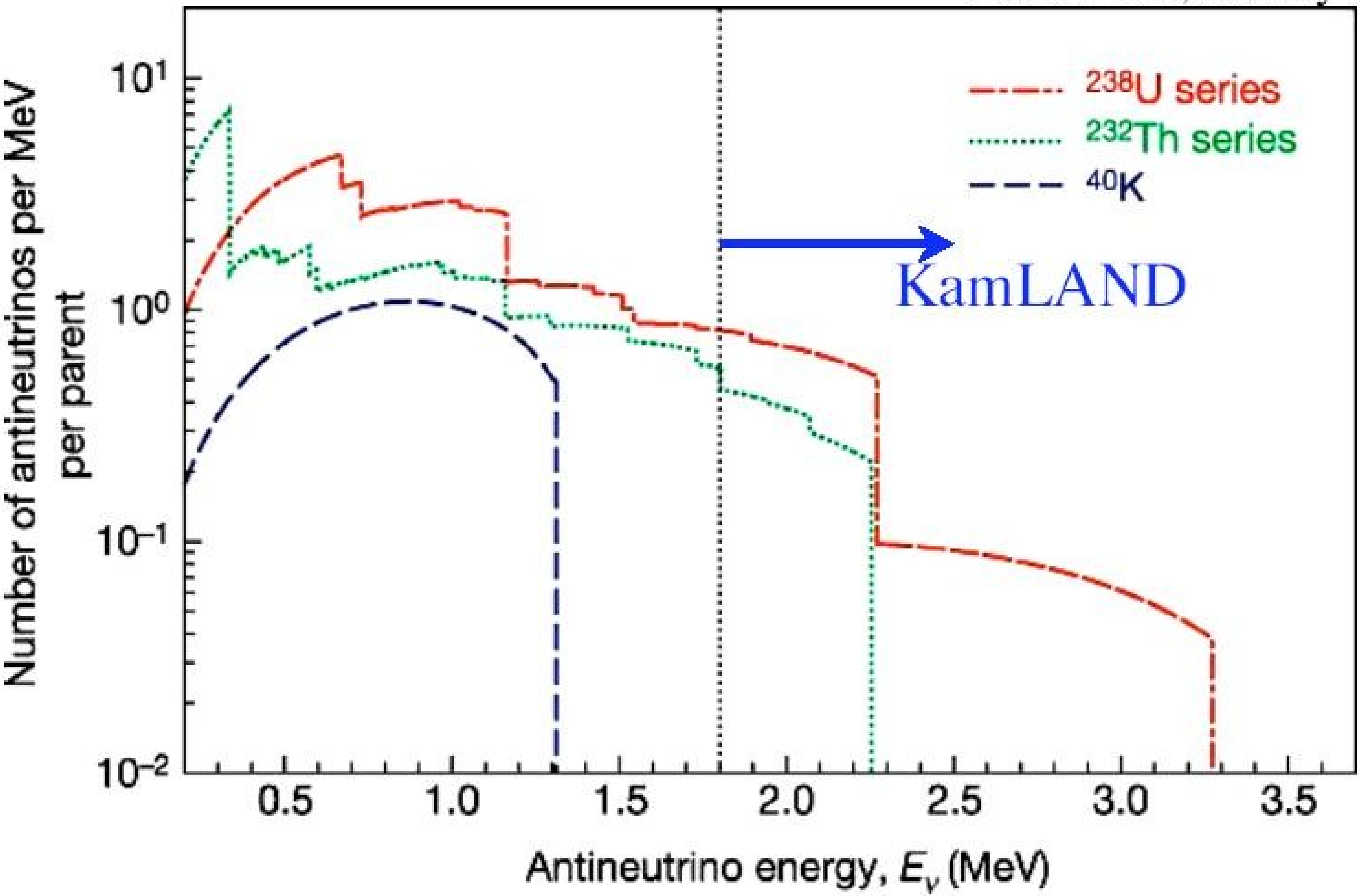
Geophysical Neutrinos



Geophysical Neutrinos

Decay	Q [MeV]	$\tau_{1/2}$ [10^9 yr]	E_{max} [MeV]	ε_H [W/kg]	$\varepsilon_{\bar{\nu}}$ [$kg^{-1}s^{-1}$]
$^{238}U \rightarrow {}^{206}Pb + 8\,{}^4He + 6e + 6\bar{\nu}$	51.7	4.47	3.26	$0.95 \cdot 10^{-4}$	$7.41 \cdot 10^7$
$^{232}Th \rightarrow {}^{208}Pb + 6\,{}^4He + 4e + 4\bar{\nu}$	42.8	14.0	2.25	$0.27 \cdot 10^{-4}$	$1.63 \cdot 10^7$
$^{40}K \rightarrow {}^{40}Ca + e + \bar{\nu}$	1.32	1.28	1.31	$0.36 \cdot 10^{-8}$	$2.69 \cdot 10^4$

Nature 436, 28 July 2005

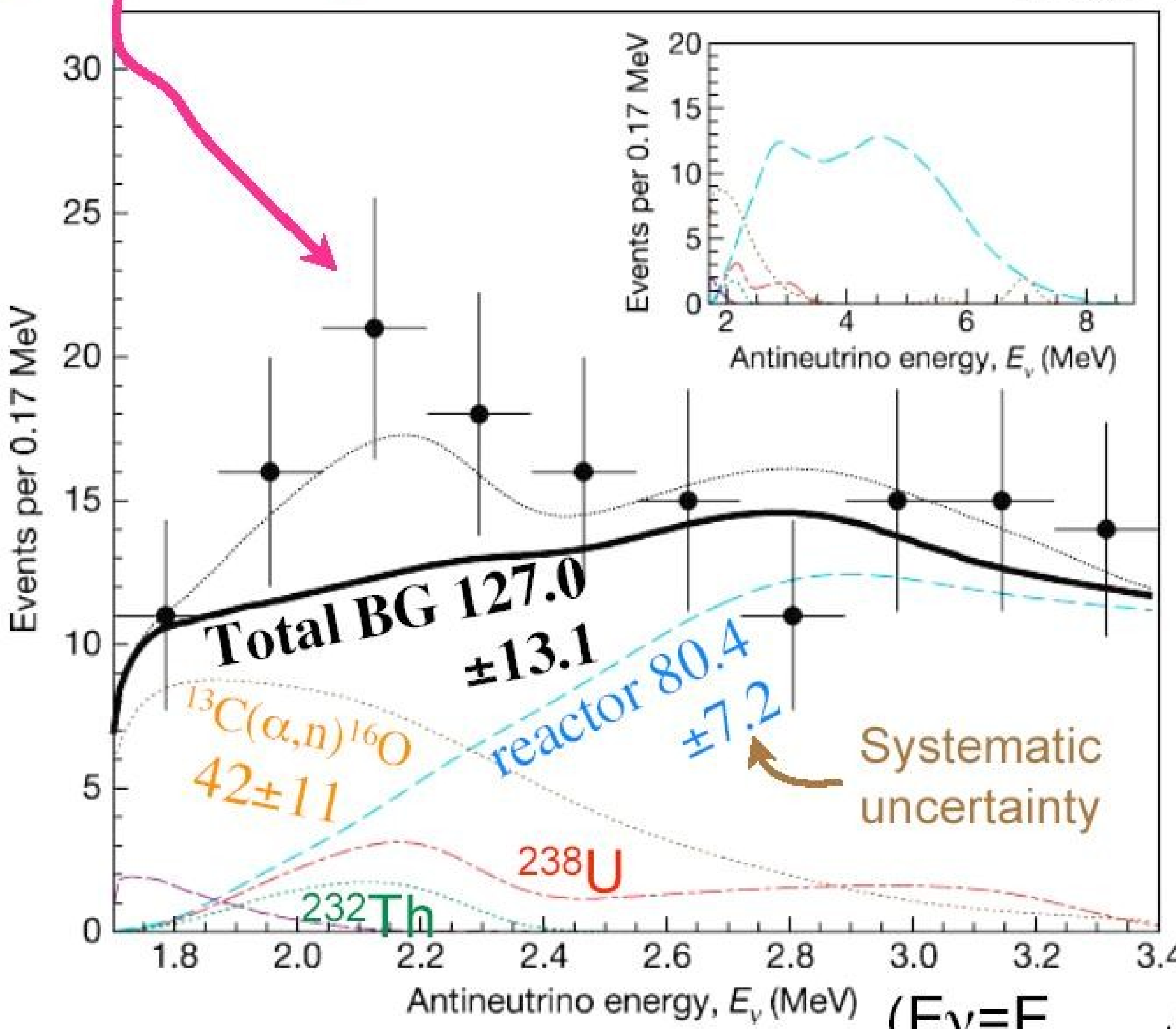


The expected ^{238}U, ^{232}Th, and ^{40}K decay chain electron anti-neutino energy distribution. KamLAND can only detect electron antineutrinos to the right of the vertical dotted black line; hence it is insensitive to ^{40}K electron antineutrinos.

152 events observed
"signal" 25^{+19}_{-18}

Geoneutrino results

Nature 436, 28 July 2005



Data-set:
749.1 days
(Mar. 9, 2002
-Oct. 30, 2004)

Fiducial:
5 m radius

($E\nu = E_{prompt} + 0.8MeV$)

Geoneutrino future: $^{13}C(\alpha,n)^{16}O$ reduction

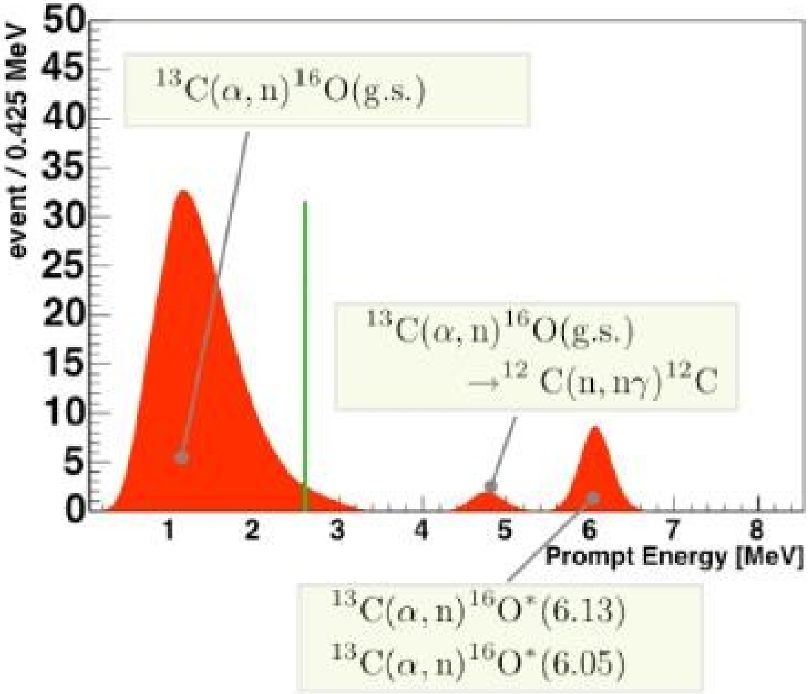
$T_{1/2}$ = 22.3y　　5.013d　　138.4d

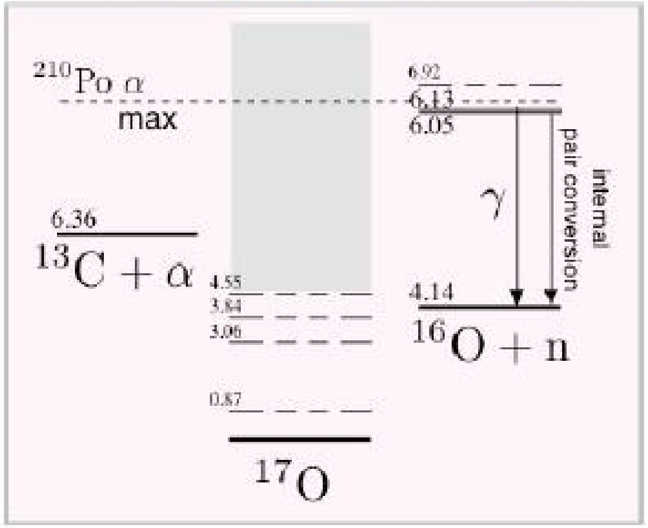
$^{210}Pb \rightarrow {}^{210}Bi \rightarrow {}^{210}Po \rightarrow {}^{206}Pb$

α

5.3 MeV

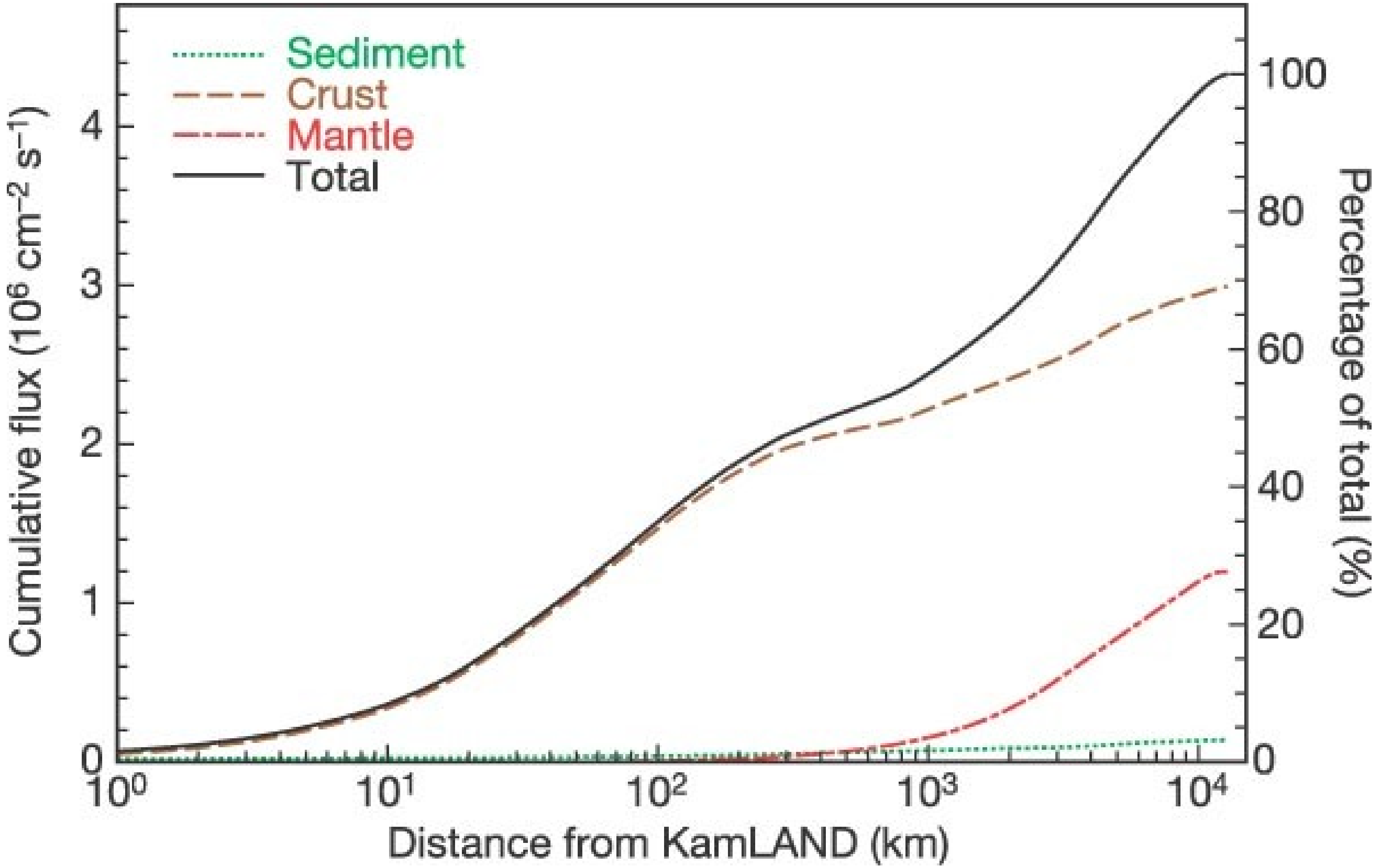
$^{13}C\ (\alpha,\ n)\ ^{16}O$





- Reduction of systematic error: currently going on
- Reduction of ^{210}Pb: near future (see "solar neutrino future" next)

Where are the Geo-neutrinos coming from ?



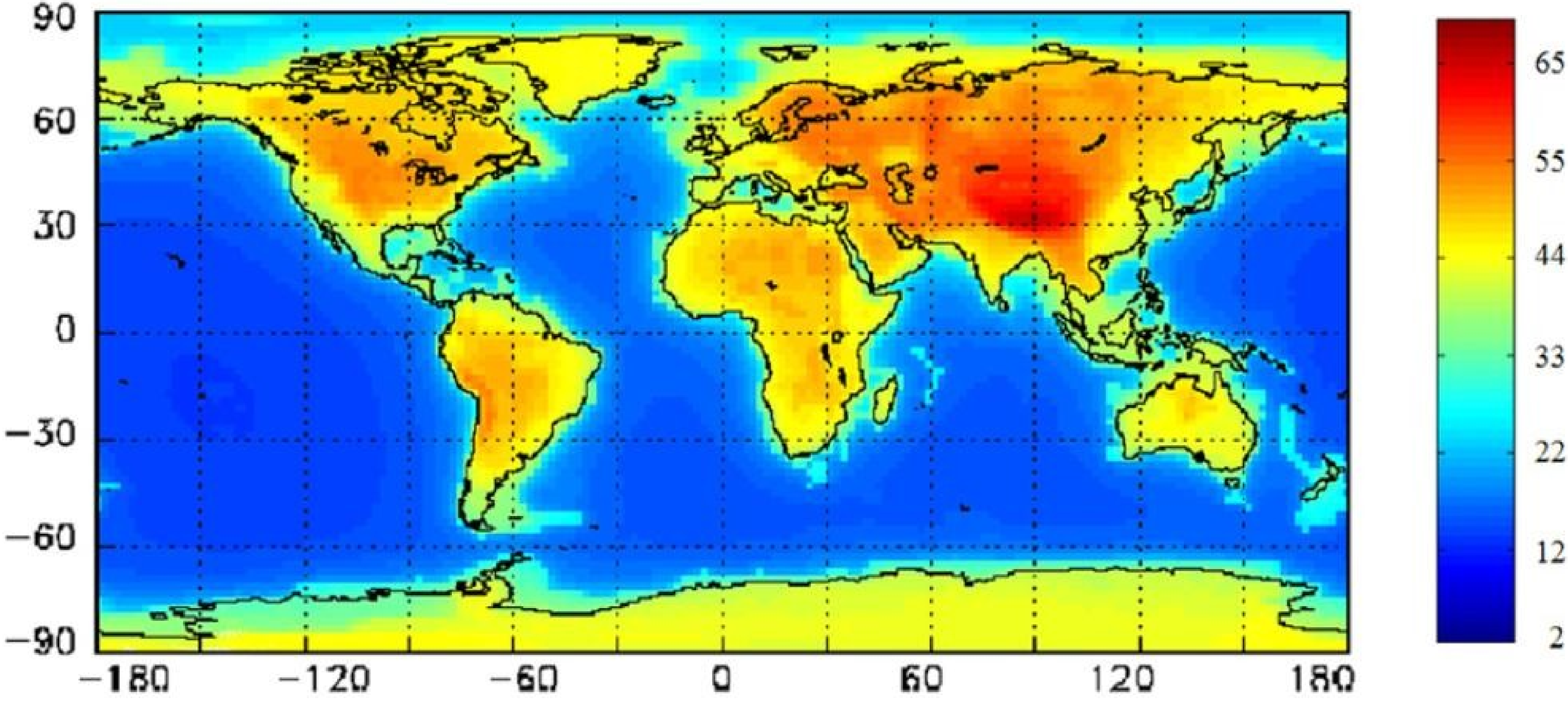
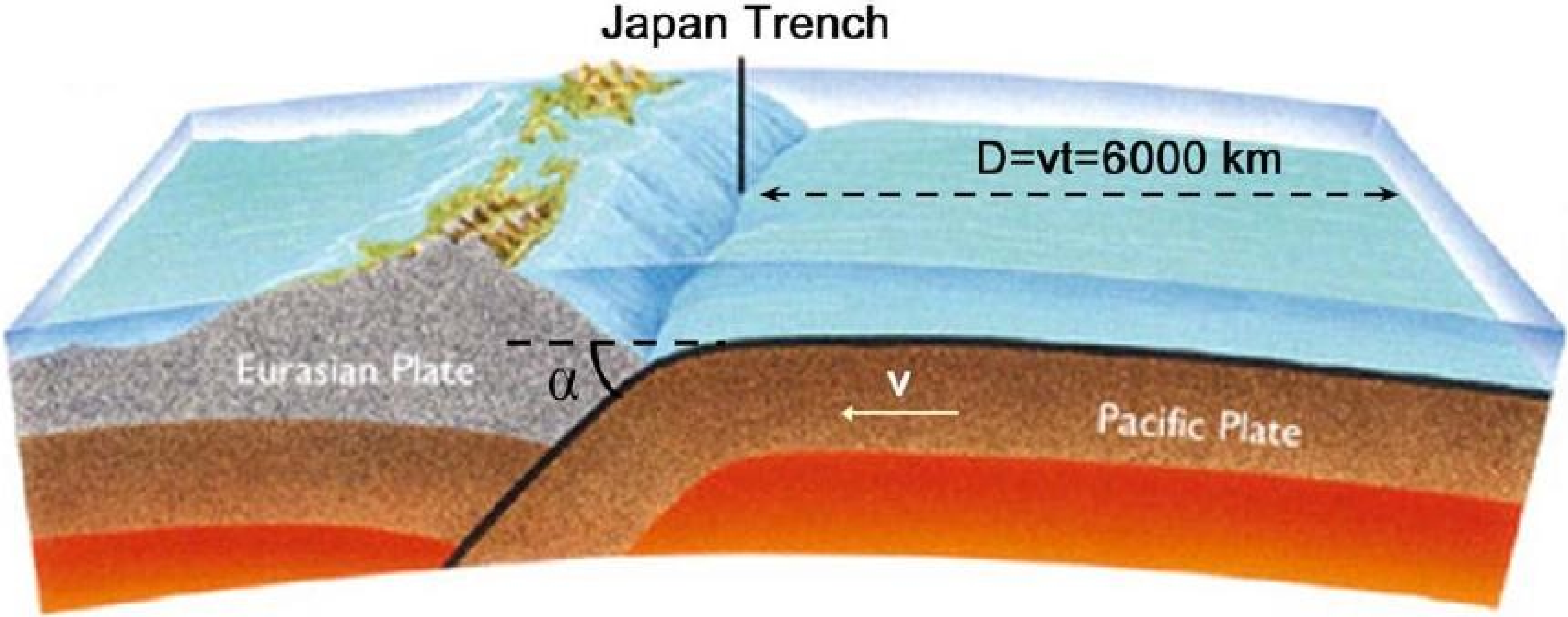
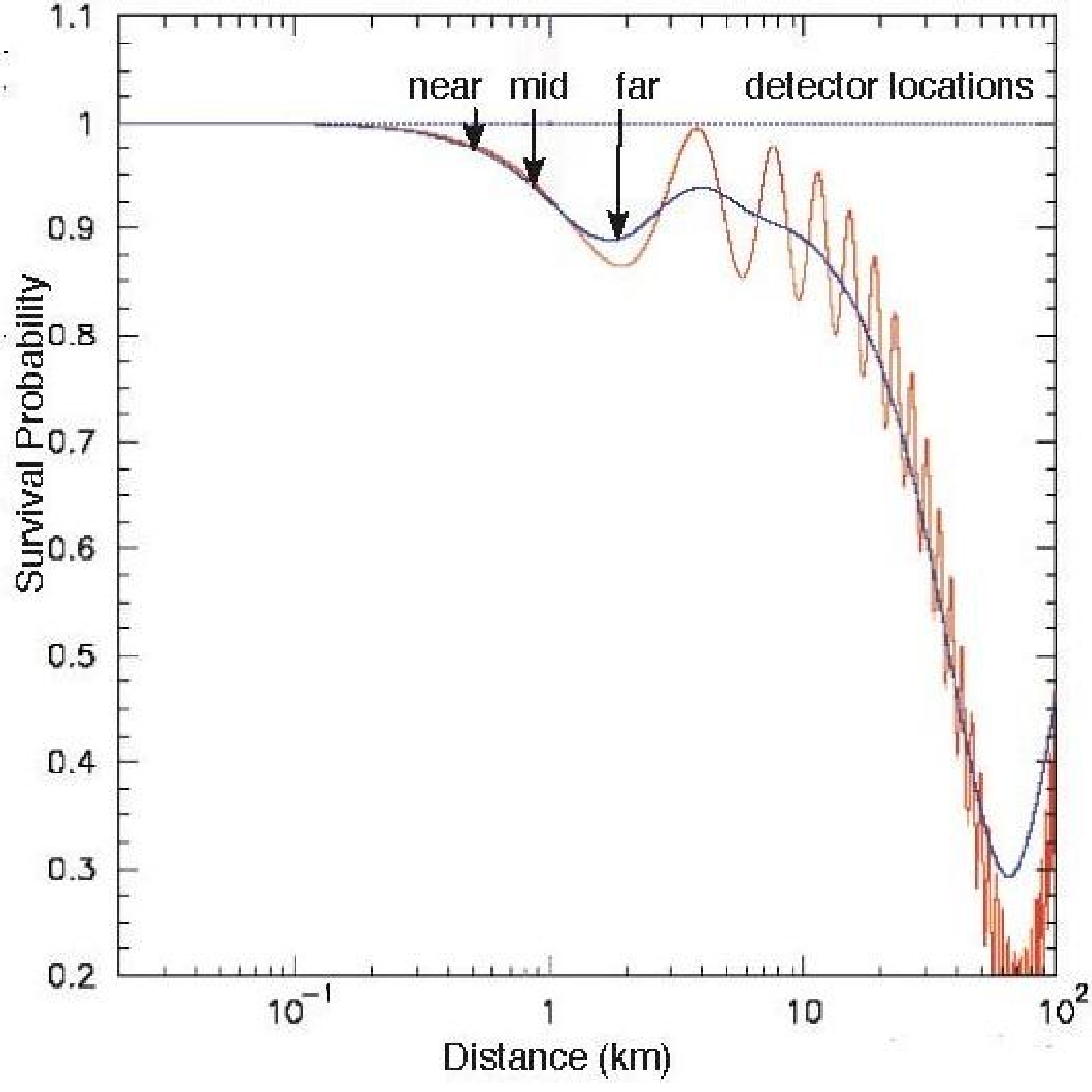


Fig. 2. Predicted geo-neutrino events from Uranium and Thorium decay chains, normalized to 10^{32} protons yr and 100% efficiency.



From FIORENTINI

Measurement of θ_{13}



Within

Gravelines
Penly
Paluel
Flamanville
Chooz
Cattenom
Nogent
Fessenheim
St-Laurent
Dampierre
Belleville
Chinon
Bugey
Civaux
Creys-Malville
St-Alban
Blayais
Cruas
Golfech
Tricastin
> 500 $\overline{\nu}_e$ /d
280 m
1051 m
2 x 4270 MWth

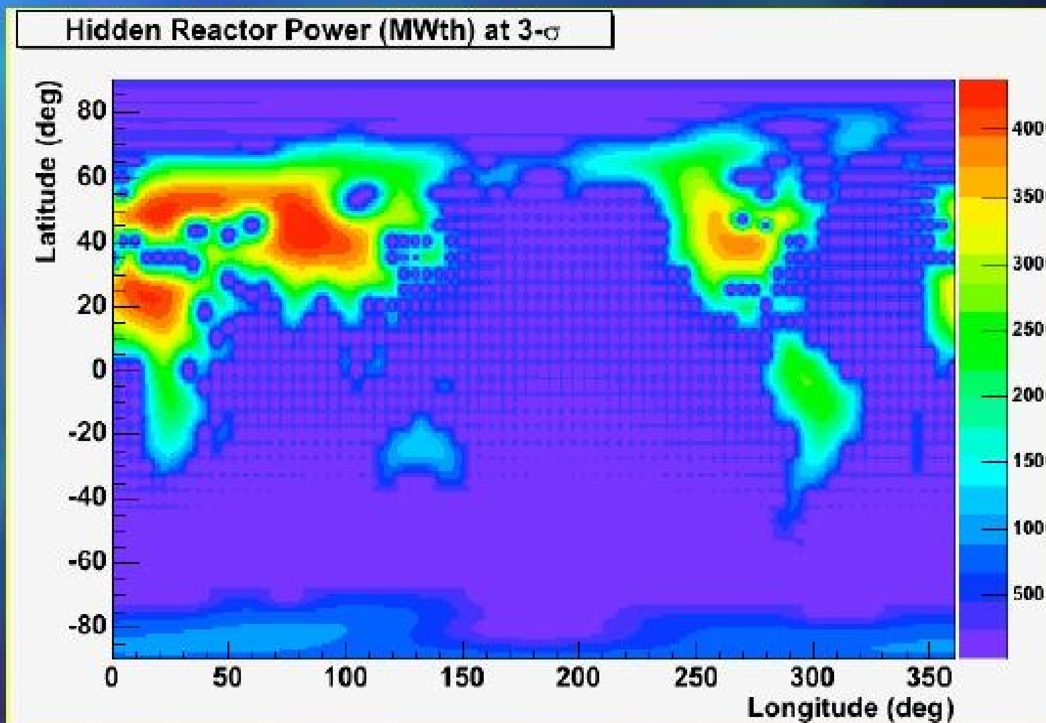
Systematic Errors

		Chooz	Double Chooz	
Reactor-induced	ν flux and σ	1.9 %	<0.1 %	Two "identical" detectors, Low bkg
	Reactor power	0.7 %	<0.1 %	
	Energy per fission	0.6 %	<0.1 %	
Detector - induced	Solid angle	0.3 %	<0.1 %	Distance measured @ 10 cm + monitor core barycenter
	Volume	0.3 %	0.2 %	Same weight sensor for both det.
	Density	0.3 %	<0.1 %	Accurate T control (near/far)
	H/C ratio & Gd concentration	1.2 %	<0.1 %	Same scintillator batch + Stability
	Spatial effects	1.0 %	<0.1 %	"identical" Target geometry & LS
	Live time	few %	0.25 %	Measured with several methods
Analysis	From 7 to 3 cuts	1.5 %	0.2 - 0.3 %	
	Total	**2.7 %**	**< 0.6 %**	


Chooz, France
Krasnoyasrk, Russia
Braidwood, USA
Kashiwazaki, Japan
RENO, Korea
Diablo Canyon, USA
Daya Bay, China
Angra, Brazil

Remote survey

- Movable submarine "KamLAND"
  - only 2 - 5 bigger
- Count at 3 positions :
  - Signal ≈ (P_{th} ???)/ R^2
  - Triangulation
- Detection of underground clandestine reactor



- Global survey
  - 10 Mtons units
  - ≈ 1000 units in ocean
  - *J. Learned at Neutrino'04*