Matter Effects and CP Violation in ν-Oscillation

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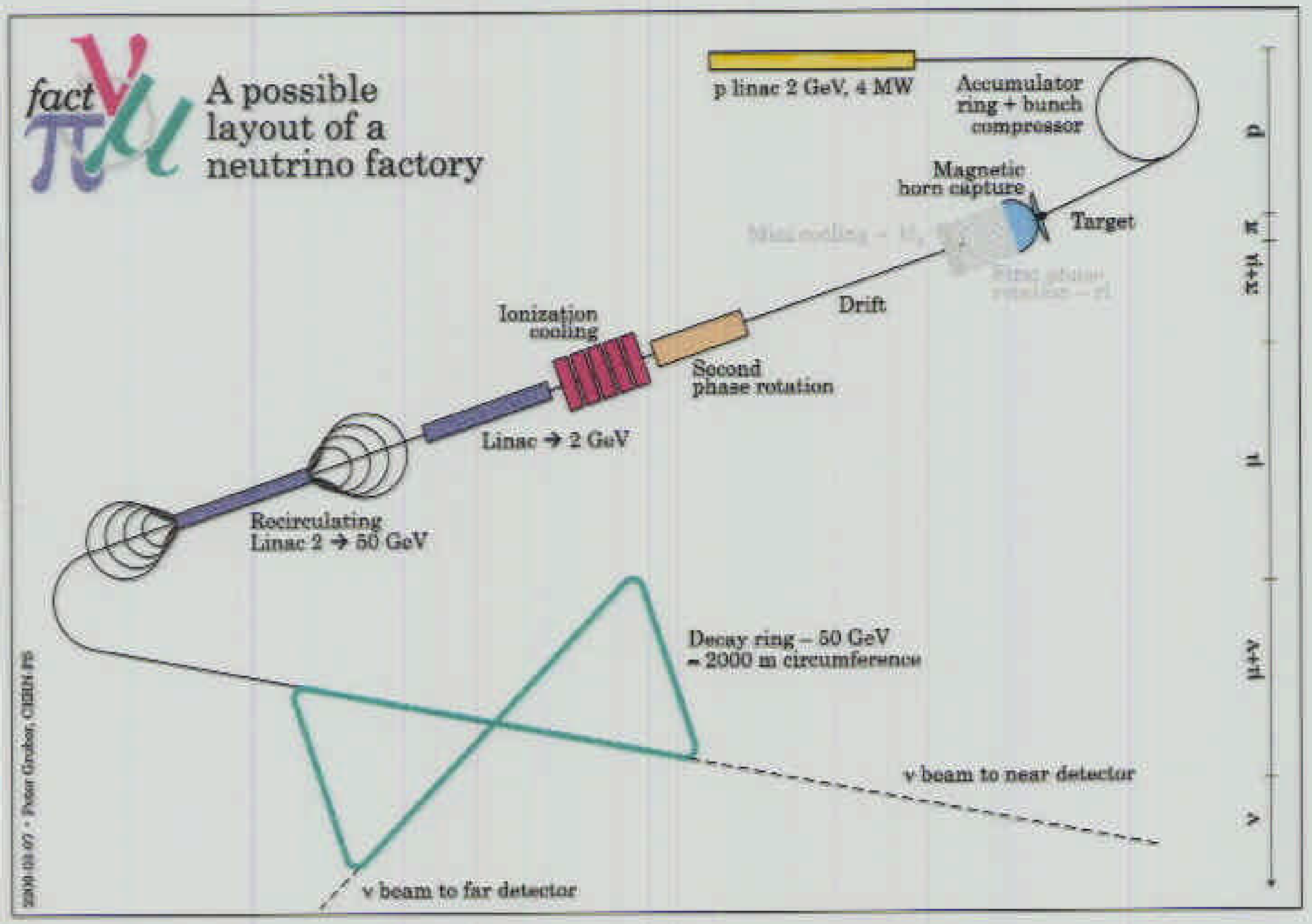
Two Types of Neutrino Beams:

1) Conventional ν-Beams from Beam Dumps

E.g. High energy $p \rightarrow$ target $\rightarrow \pi' s + \ldots \rightarrow \nu -$ beams

2) Neutrino Factories



- Limited target cooling power
- Lower energy muons which are accelerated

$\Rightarrow$ Higher neutrino fluxes: $2 \cdot 10^{20}$ useful μ-decays/year

Possible Signals

Beam $\Rightarrow$ Oscillation $\Rightarrow$ Detector $\Rightarrow$ Muons

$$\boxed{\mu^-} \Longrightarrow \left\{ \begin{array}{l} \overline{\nu}_e \overset{oscillation}{\longrightarrow} \left\{ \begin{array}{lll} \overline{\nu}_e \Rightarrow e^+ & & n_{\mu^-}(e^+) \\ \overline{\nu}_\mu \Rightarrow \boxed{\mu^+} & & n_{\mu^-}(\mu^+) \\ \overline{\nu}_\tau \Rightarrow \tau^+ & & \end{array} \right. \\ \\ \nu_\mu \overset{oscillation}{\longrightarrow} \left\{ \begin{array}{lll} \nu_e \Rightarrow e^- & & \\ \nu_\mu \Rightarrow \boxed{\mu^-} & & n_{\mu^-}(\mu^-) \\ \nu_\tau \Rightarrow \tau^- & & \end{array} \right. \end{array} \right.$$

$$\boxed{\mu^+} \Longrightarrow \left\{ \begin{array}{l} \nu_e \overset{oscillation}{\longrightarrow} \left\{ \begin{array}{lll} \nu_e \Rightarrow e^- & & n_{\mu^+}(e^-) \\ \nu_\mu \Rightarrow \boxed{\mu^-} & & n_{\mu^+}(\mu^-) \\ \nu_\tau \Rightarrow \tau^- & & \end{array} \right. \\ \\ \overline{\nu}_\mu \overset{oscillation}{\longrightarrow} \left\{ \begin{array}{lll} \overline{\nu}_e \Rightarrow e^+ & & \\ \overline{\nu}_\mu \Rightarrow \boxed{\mu^+} & & n_{\mu^+}(\mu^+) \\ \overline{\nu}_\tau \Rightarrow \tau^+ & & \end{array} \right. \end{array} \right.$$

3 Neutrino Oscillation:

Flavour $\mathrm{l} \rightarrow \mathrm{m}$**:** $P(\nu_{e_l} \rightarrow \nu_{e_m}) =$

$$= \quad |\langle \nu_m(t)|\nu_l(t=0)\rangle|^2 = \left|\langle \nu_m | U e^{-iHt} U^\dagger | \nu_l \rangle\right|^2$$

$$= \underbrace{\delta_{lm} - 4\sum_{i>j} \mathrm{Re} J_{ij}^{e_l e_m} \sin^2 \Delta_{ij}}_{P_{CP}} \underbrace{-2\sum_{i>j} \mathrm{Im} J_{ij}^{e_l e_m} \sin 2\Delta_{ij}}_{P_{\not{CP}}}$$

Shorthands: $J_{ij}^{e_l e_m} := U_{li} U_{lj}^* U_{mi}^* U_{mj} \quad \Delta_{ij} := \frac{\Delta m_{ij}^2 L}{4E}$

Two Neutrino Limit: $U = R(\theta), \quad \Delta_{12} = \frac{\Delta m_{12}^2 L}{4E}$

$$P_{CP}(\nu_{e_1} \rightarrow \nu_{e_2}) = \sin^2 2\theta \cdot \sin^2\left(\Delta m_{12}^2 L/4E\right)$$
$$P_{CP}(\nu_{e_i} \rightarrow \nu_{e_i}) = 1 - \sin^2 2\theta \cdot \sin^2\left(\Delta m_{12}^2 L/4E\right)$$
$$P_{\not{CP}}(\nu_{e_1} \rightarrow \nu_{e_2}) = P_{\not{CP}}(\nu_{e_i} \rightarrow \nu_{e_i}) = 0$$

Terminology:

Appearance Experiments: $P(\nu_{e_1} \rightarrow \nu_{e_2})$

Disappearance Experiments: $P(\nu_{e_i} \rightarrow \nu_{e_i})$

Matter Effects and MSW Resonance

1st Generation CC Interaction with Matter:

$\mathcal{L}_{CC} = \pm \sqrt{2} G_F \overline{N}_e^{man} = V$, $\Leftrightarrow$ $\overline{\nu}_e, \nu_e$, e-density $\overline{N}_e^{man}$

NC: $\mathcal{L}_{NC} = V'$ via Z-exchange is flavour universal

Parameter Mapping

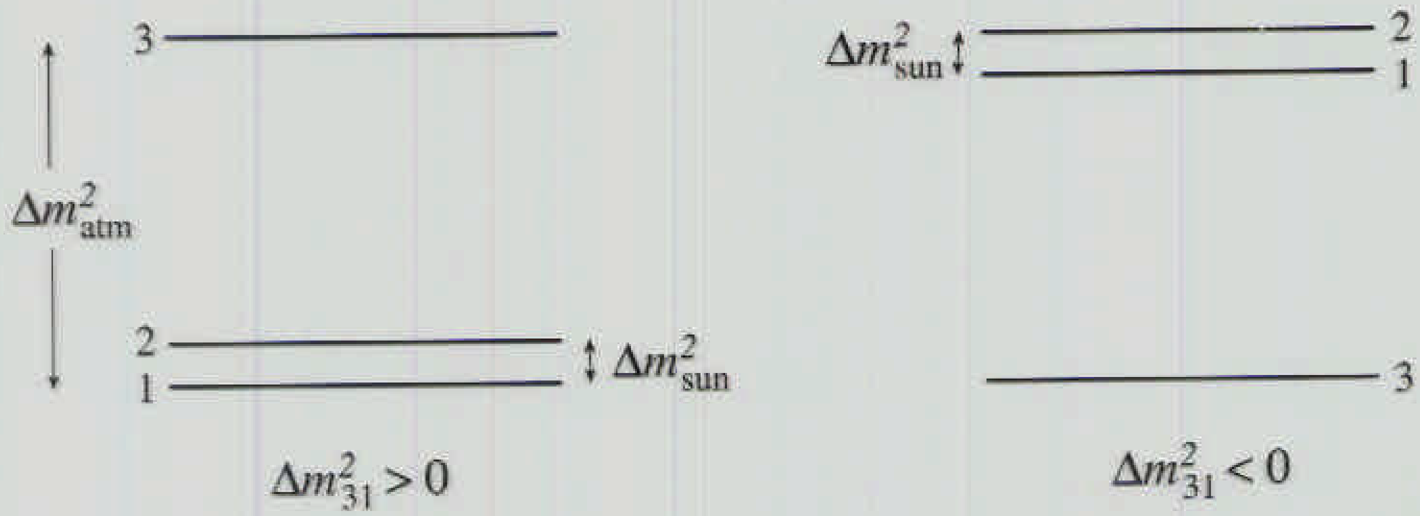
- $\theta_{13} \to \theta_{13,m}$, $m_1^2 \to m_{1,m}^2$, $m_3^2 \to m_{3,m}^2$
- all Δm_{ij}^2 are affected!
- $\theta_{12} \equiv 0$, $\delta \equiv 0$, $\theta_{23} \simeq 1$ unchanged

Different mappings for **neutrinos** and **antineutrinos**

The Sign of Δm^2_{31} via Matter Effects:

Vacuum oscillation insensitive to sign of Δm^2

$\Rightarrow$ **Ambiguities in mass ordering schemes**



$\Rightarrow$ **Sign of Δm^2 via matter effects** $\Leftrightarrow$ $\simeq$ **resonance**

$$\sin^2 2\theta_{13,m} = \frac{\sin^2 2\theta_{13}}{\left(\frac{2EV}{m_3^2 - m_1^2} - \cos 2\theta_{13}\right)^2 + \sin^2 2\theta_{13}}$$

Barger, Geer, Raja and Whisnant: hep-ph/9911524
Freund, Lindner, Petcov and A. Romanino: hep-ph/9912457
Cervera, Donini, Gavela, Gomez Cadenas,
Hernandez, Mena, Rigolin: hep-ph/0002108

Dedicated Test of Matter Effects:

MSW-matter effects are so far experimentally untested

$\Rightarrow$ Analysis of long baseline neutrino beams in earth

Freund, Lindner, Petcov and A. Romanino: hep-ph/9912457
Freund, Huber and Lindner: hep-ph/0004085

Comparison of oscillation with and w/o matter

$\Rightarrow$ optimal sensitivity $\Leftrightarrow$ resonance condition

$$\boxed{2EV = \Delta m^2_{31} \cos 2\theta_{13}}$$

For small θ_{13}:

$$E_{opt} = 15 \text{ GeV} \quad \left(\frac{\Delta m^2_{31}}{3.5\times 10^{-3} \text{ eV}^2}\right) \cdot \left(\frac{2.8 \ g/cm^3}{\rho}\right)$$

Extracting Parameters from Data

⇒ Event Rates including Beam and Detector

$$n_{\mu^\pm}(...) = N_{\mu^\pm} N_{\mathrm{kT}} \frac{10^9 N_A}{m_\mu^2 \pi} \frac{E_\mu^3}{L^2} \int_{E_{\min}}^{E_\mu} f_{...} P_E^{3\nu}(...) \, (dE/E_\mu)$$

where

- $P_E^{3\nu}(...)$ - 3-ν oscillation probabilities in matter
- $N_{\mu^\pm}$ - number of useful muon decays (flux)
- N_{kT} - number of kilotons in the detector (typically 10kt)
- $10^9 N_A$ - nucleons/kiloton

Spectrum, X-section and Detection Efficiency enter via f_i:

$$f_{\nu_e\nu_\mu}(E) = g_{\nu_e}(E/E_\mu)(\sigma_{\nu_\mu}(E)/E_\mu)\epsilon_{\mu^-}(E)$$
$$f_{\overline{\nu}_e\overline{\nu}_\mu}(E) = ...$$
$$f_{\nu_\mu\nu_\mu}(E) = ...$$
$$f_{\overline{\nu}_\mu\overline{\nu}_\mu}(E) = ...$$

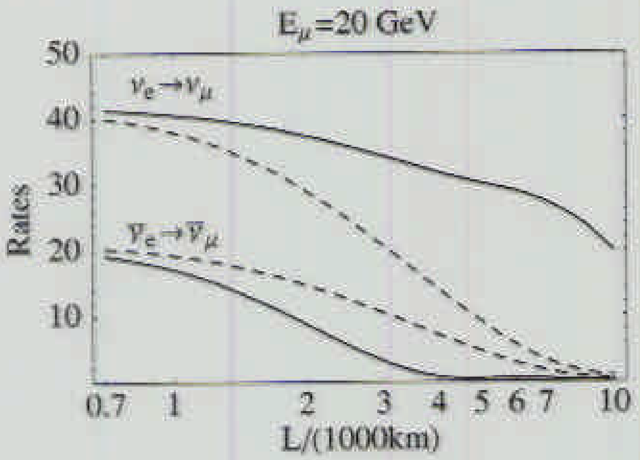
X-sections: $\sigma_{\nu_\mu}(E) = 2 \cdot \sigma_{\overline{\nu}_\mu}(E) = 0.67 \cdot 10^{-38} E \, \mathrm{cm}^2/\mathrm{GeV}$

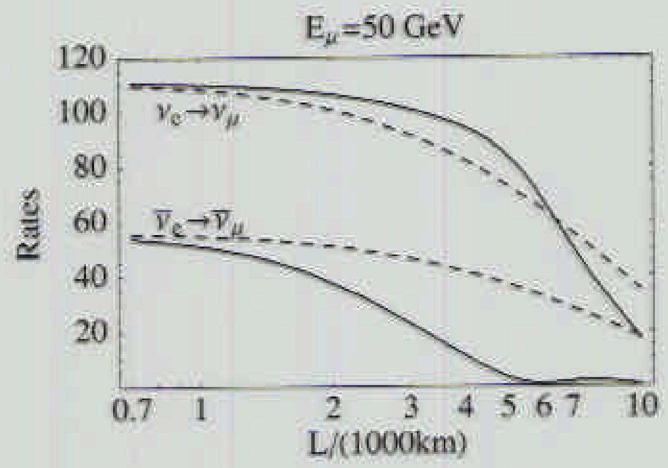
Efficiency: $\epsilon_{\mu^-}(E) = \epsilon_{\mu^+}(E) = 0.5$ for $E > E_{\min} \simeq 4$ GeV

Matter Effects and Baseline

Dashed lines: Oscillation w/o matter. Solid lines: Matter

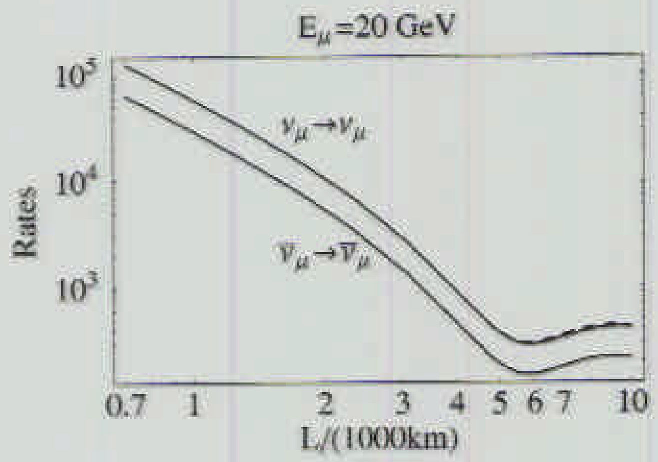
Matter Effects in $\nu_e \to \nu_\mu$ and $\overline{\nu}_e \to \overline{\nu}_\mu$:

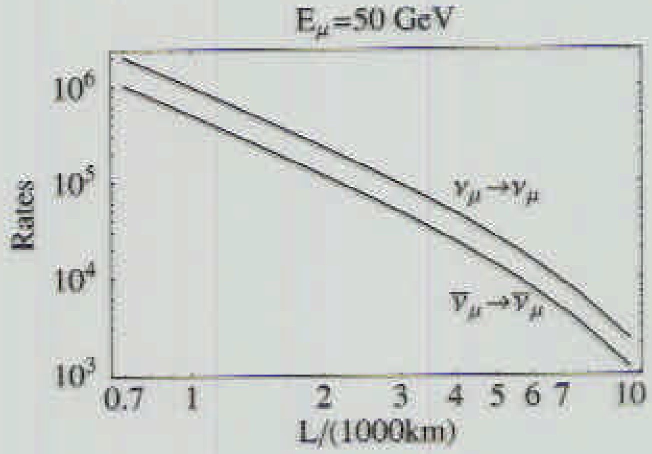




⇒ Sizable asymmetry between neutrinos and anti-neutrinos!

Matter Effects in $\nu_\mu \to \nu_\mu$ and $\overline{\nu}_\mu \to \overline{\nu}_\mu$:

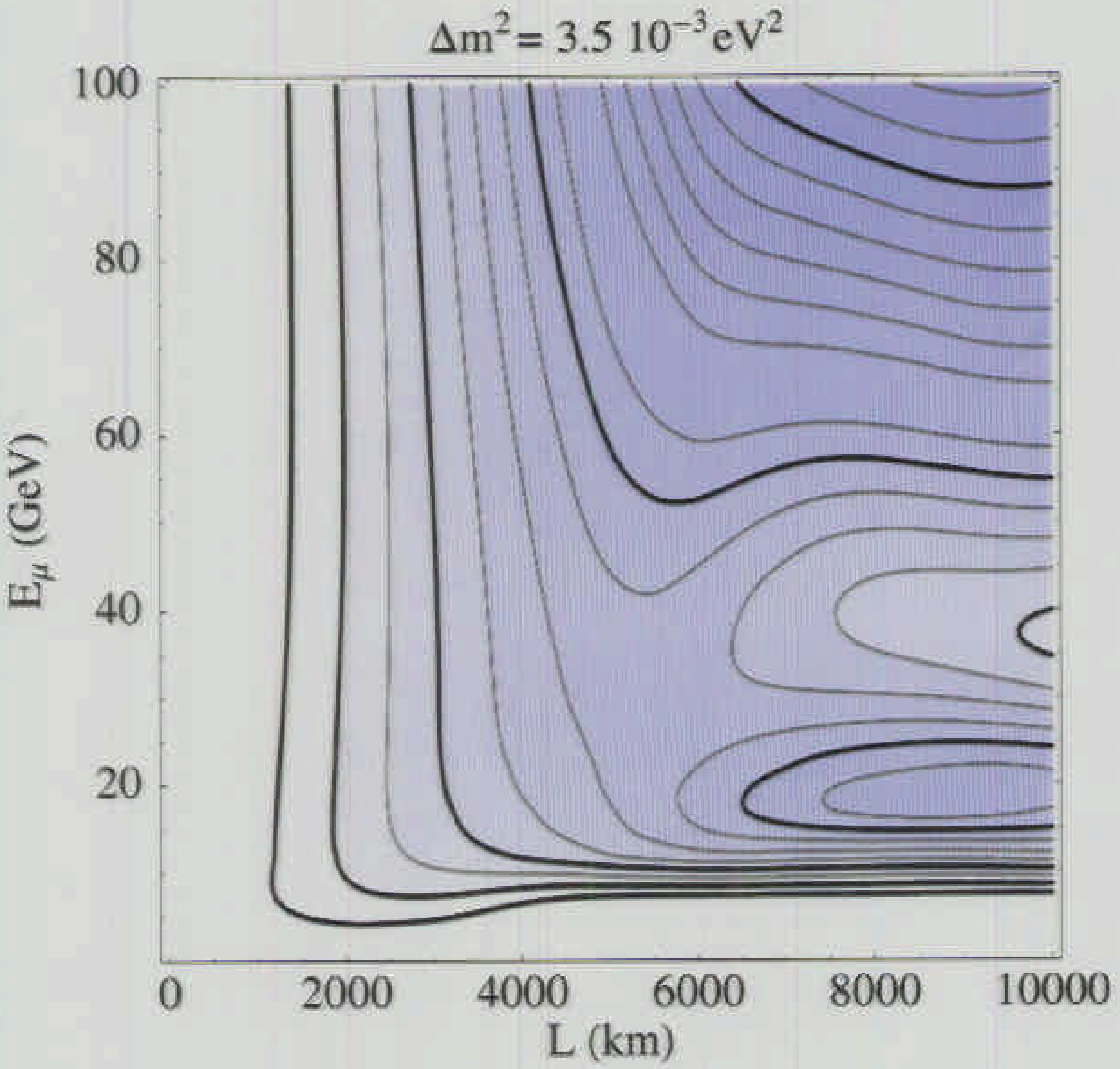




MSW Effect as Deviation from Vacuum:

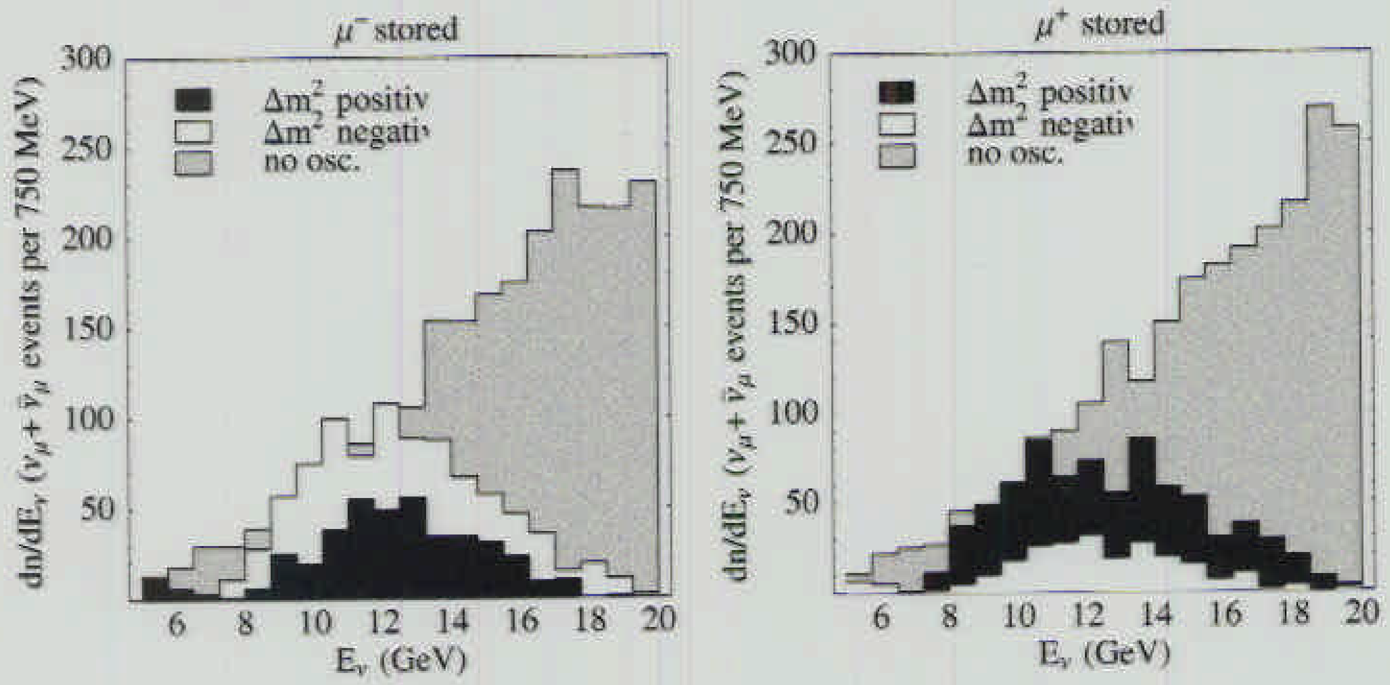
Contour Lines of n_σ Deviations from Vacuum:

Thick solid lines $\Leftrightarrow$ $n_\sigma = 100 \sin^2 2\theta_{13} \cdot \{1, 2, 4, 8, 16\}$
I.e. for $\sin^2 2\theta_{13} = 0.01 \Rightarrow$ 1,2,4,8,16 standard deviations



Used parameters:
Central $\Delta m^2_{31} = 3.5 \cdot 10^3\,\mathrm{eV}^2$
θ_{13} arbitrary $\Leftrightarrow$ scaling
Neutrino factory and detector $N_\mu N_{\mathrm{kT}}\epsilon = 10^{21}$

Differential Event Rates



Two Step Analysis:

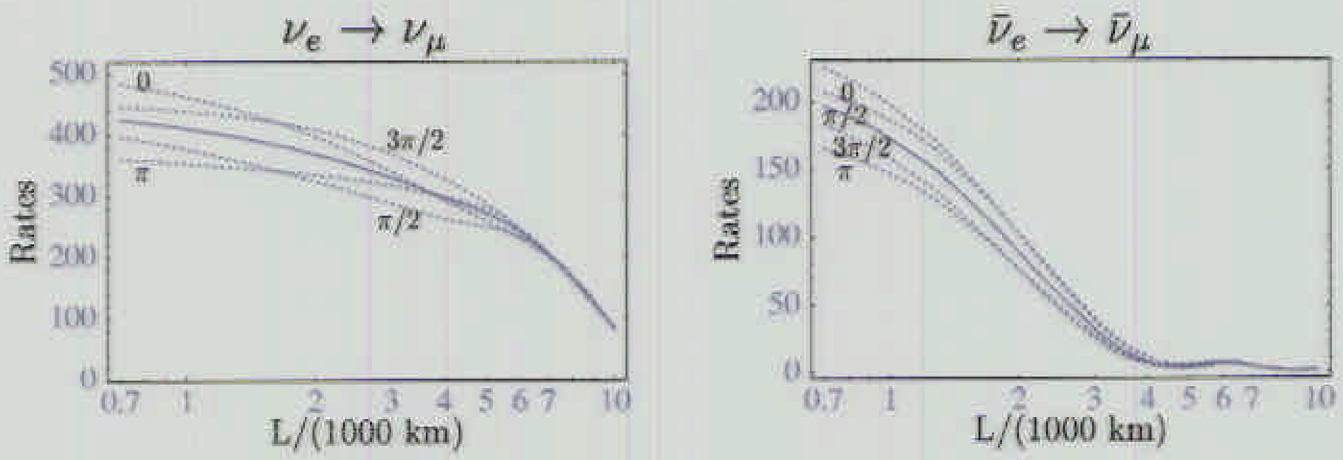
1) Extract the leading parameters $|\Delta m^2_{31}|$ and $\sin^2 2\theta_{23}$ from combined rates where matter effects cancel

2) Fit the subleading, matter enhanced parameters Δm^2_{31} and $\sin^2 2\theta_{13}$ to individual channels

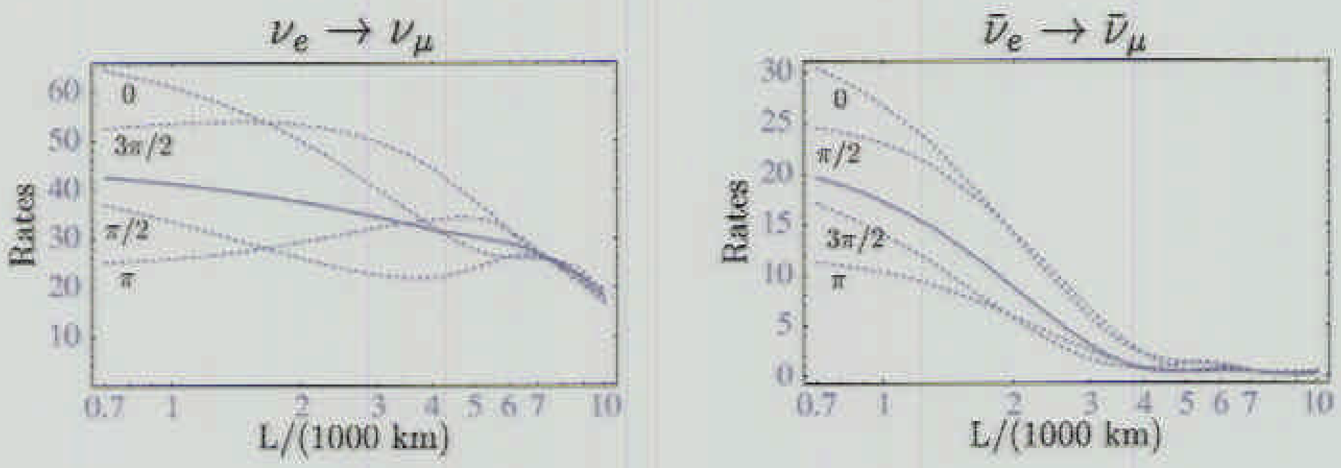
$\not{C}\not{P}$– Effects for the LMA-MSW Solution

⇒ Δm^2_{21} and δ can no longer be ignored

Effects for $\sin^2 2\theta_{13} = 0.1$ for different δ



Effects for $\sin^2 2\theta_{13} = 0.01$ for different δ



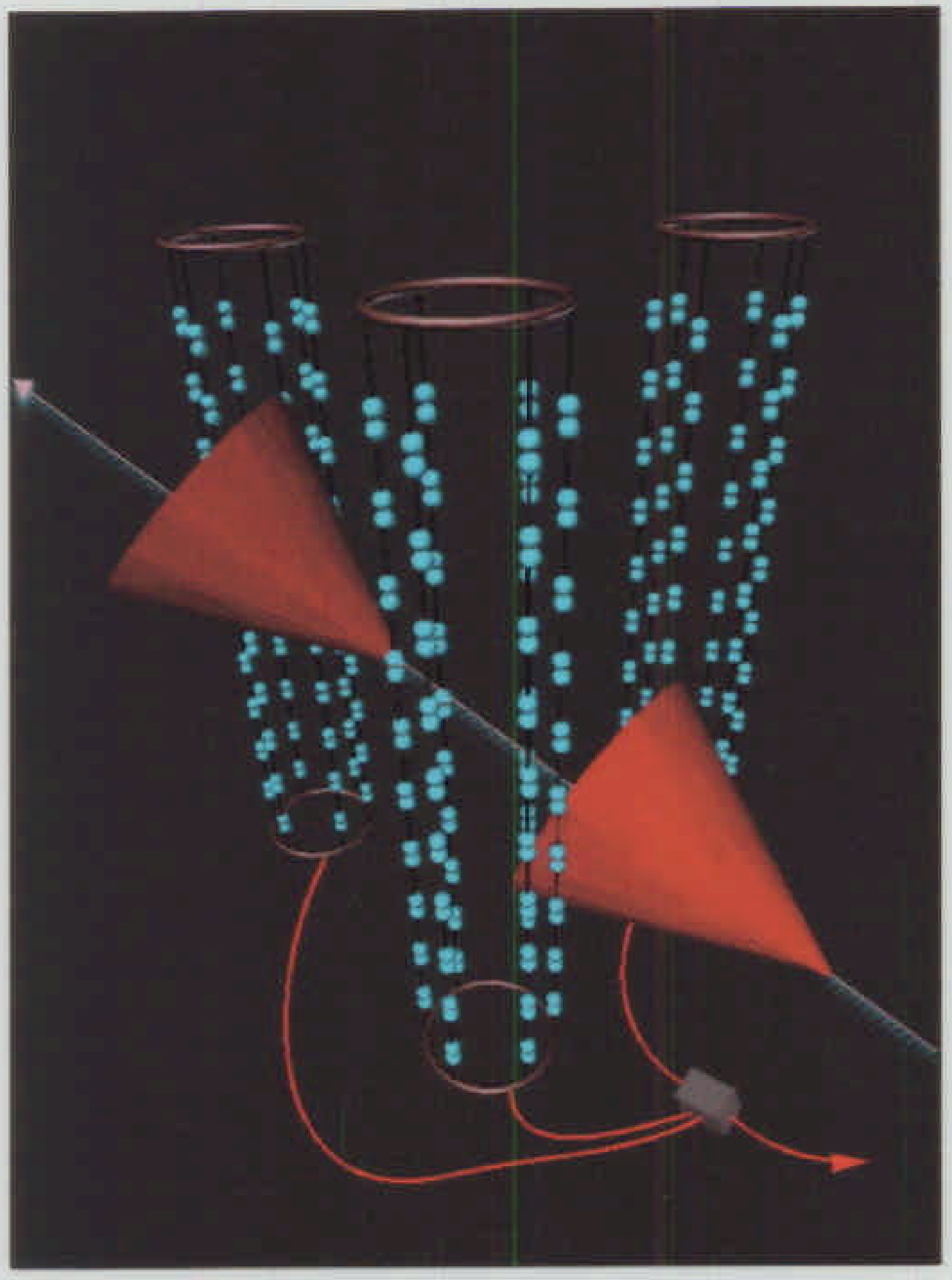
- smaller CP-violating effects for $L = 7332$ km

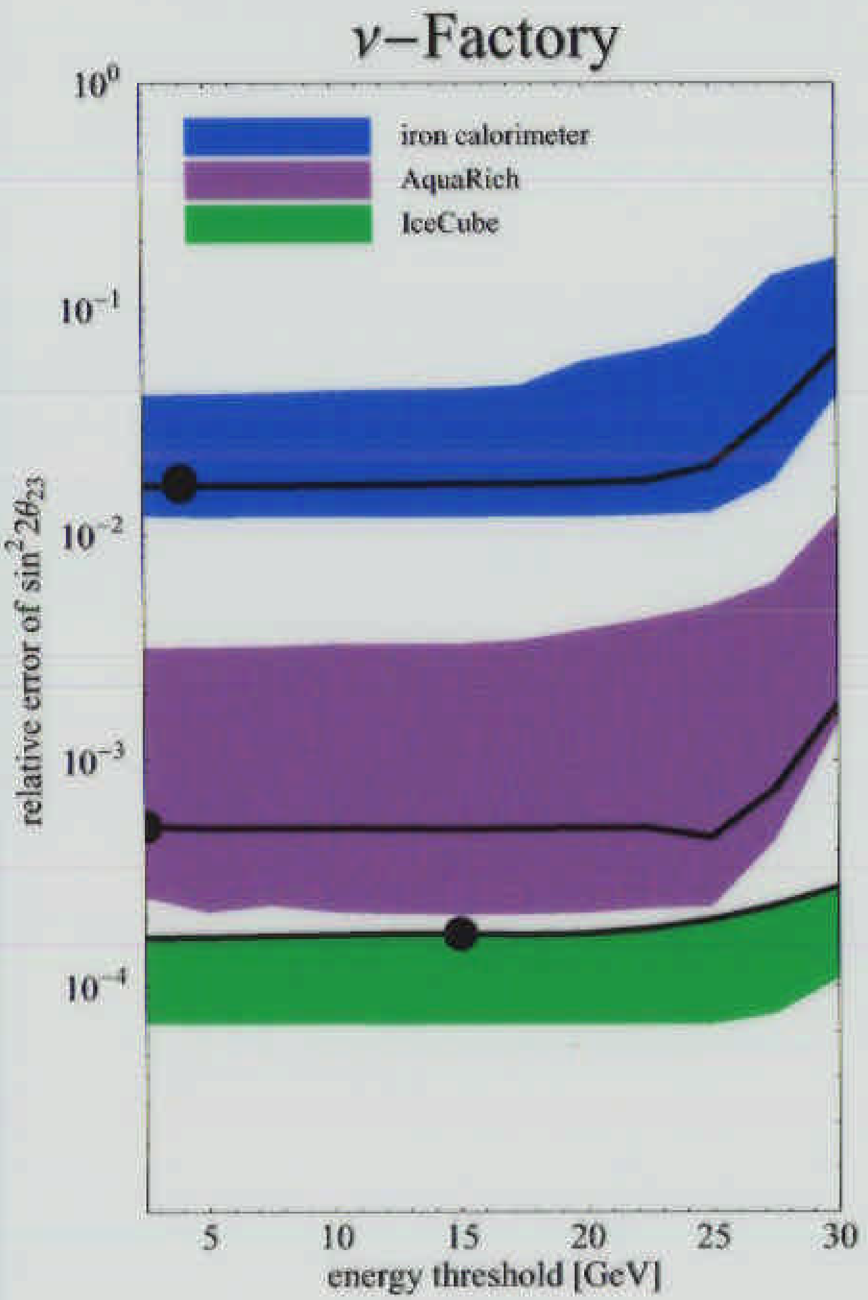
⇒ LMA-MSW: 2 baselines to separate matter and CP effects

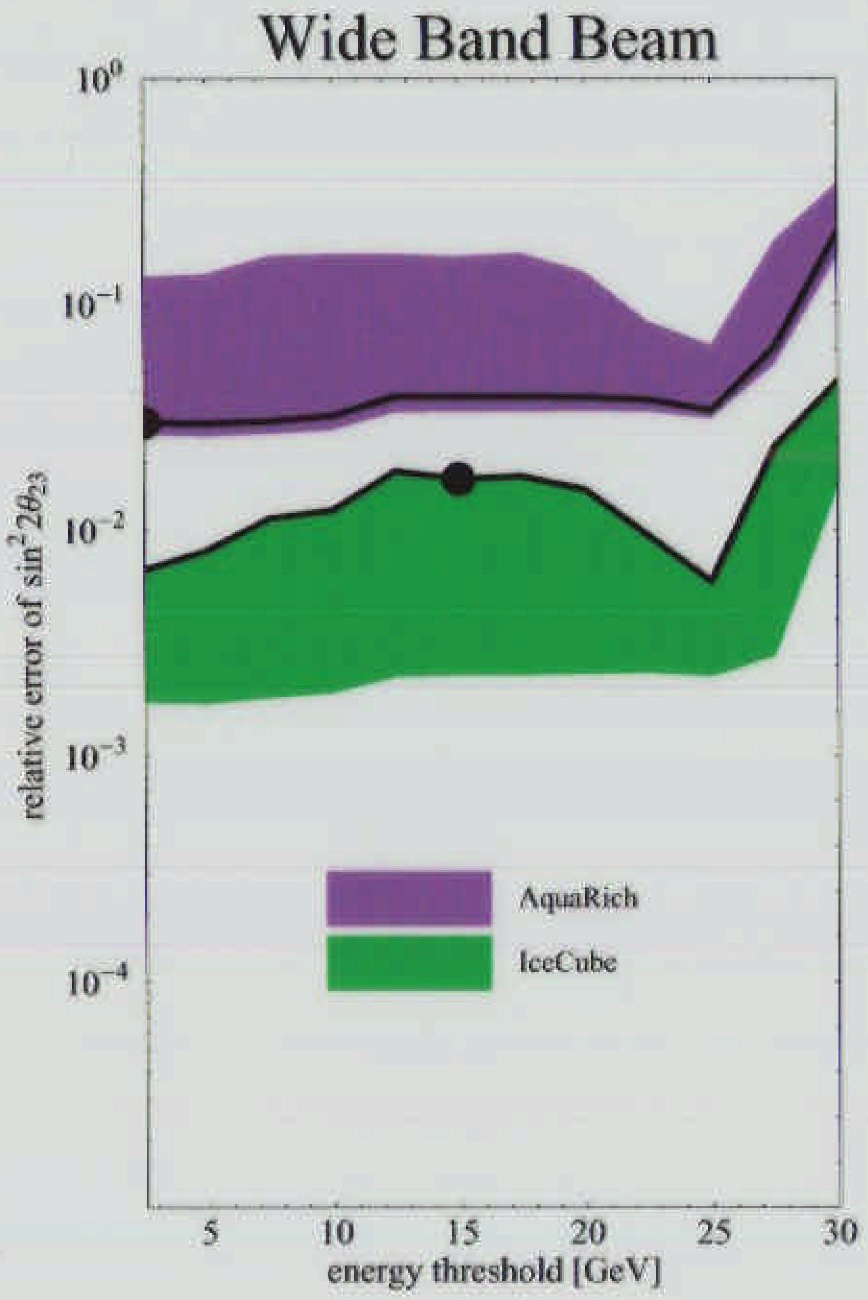
- Would become less relevant if Δm^2_{atm} is larger (K2K)

Neutrino Telescopes as Large Mass Detectors

Dick, Freund, Huber, Lindner: hep-ph/000690 and 0007xxx




ν–Factory
iron calorimeter
AquaRich
IceCube
relative error of $\sin^2 2\theta_{23}$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
5
10
15
20
25
30
energy threshold [GeV]


Wide Band Beam
AquaRich
IceCube
relative error of $\sin^2 2\theta_{23}$
10^0
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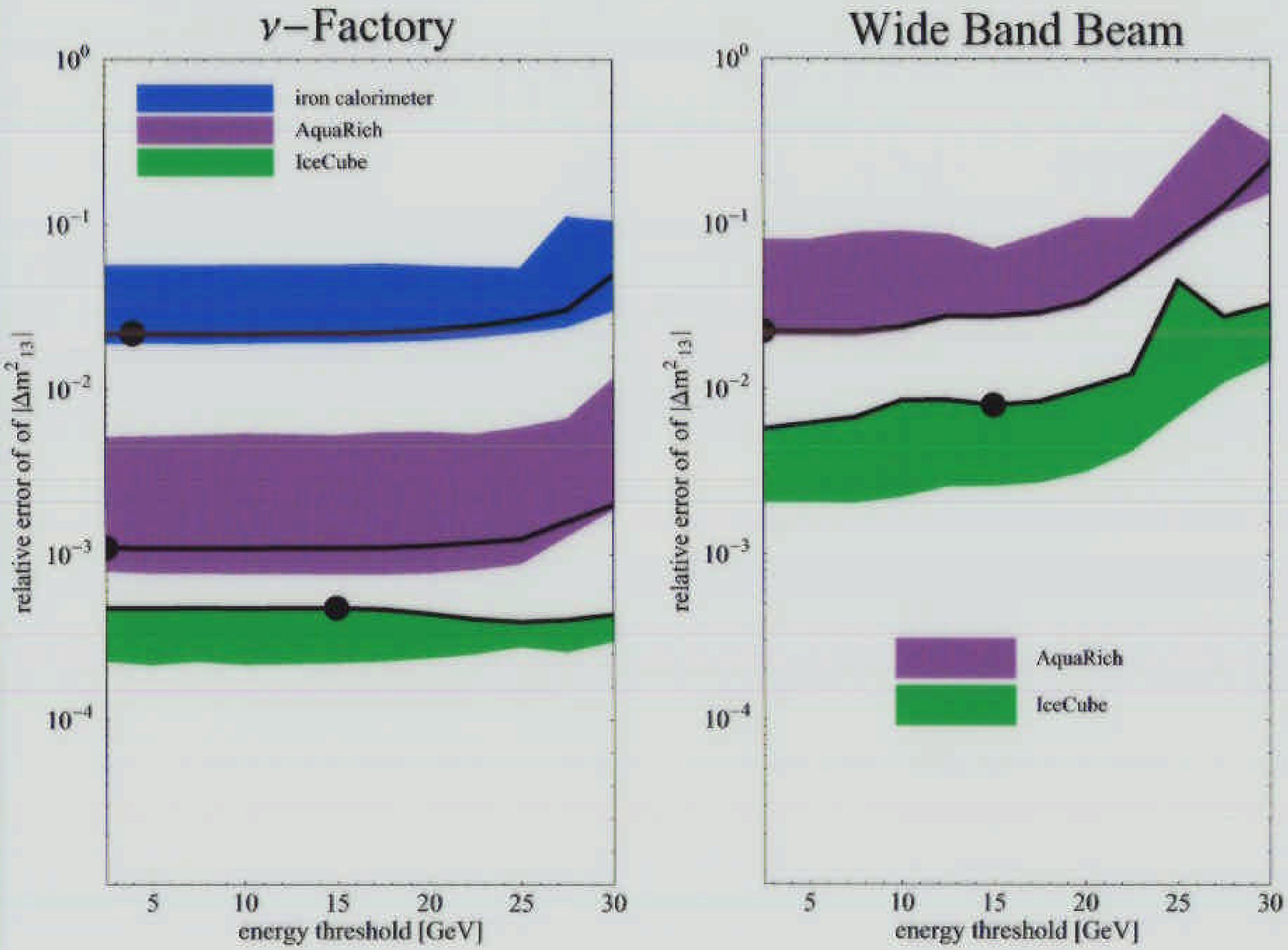
ν–Factory
relative error of of |Δm$^2_{13}$|
iron calorimeter
AquaRich
IceCube
energy threshold [GeV]
Wide Band Beam
relative error of of |Δm$^2_{13}$|
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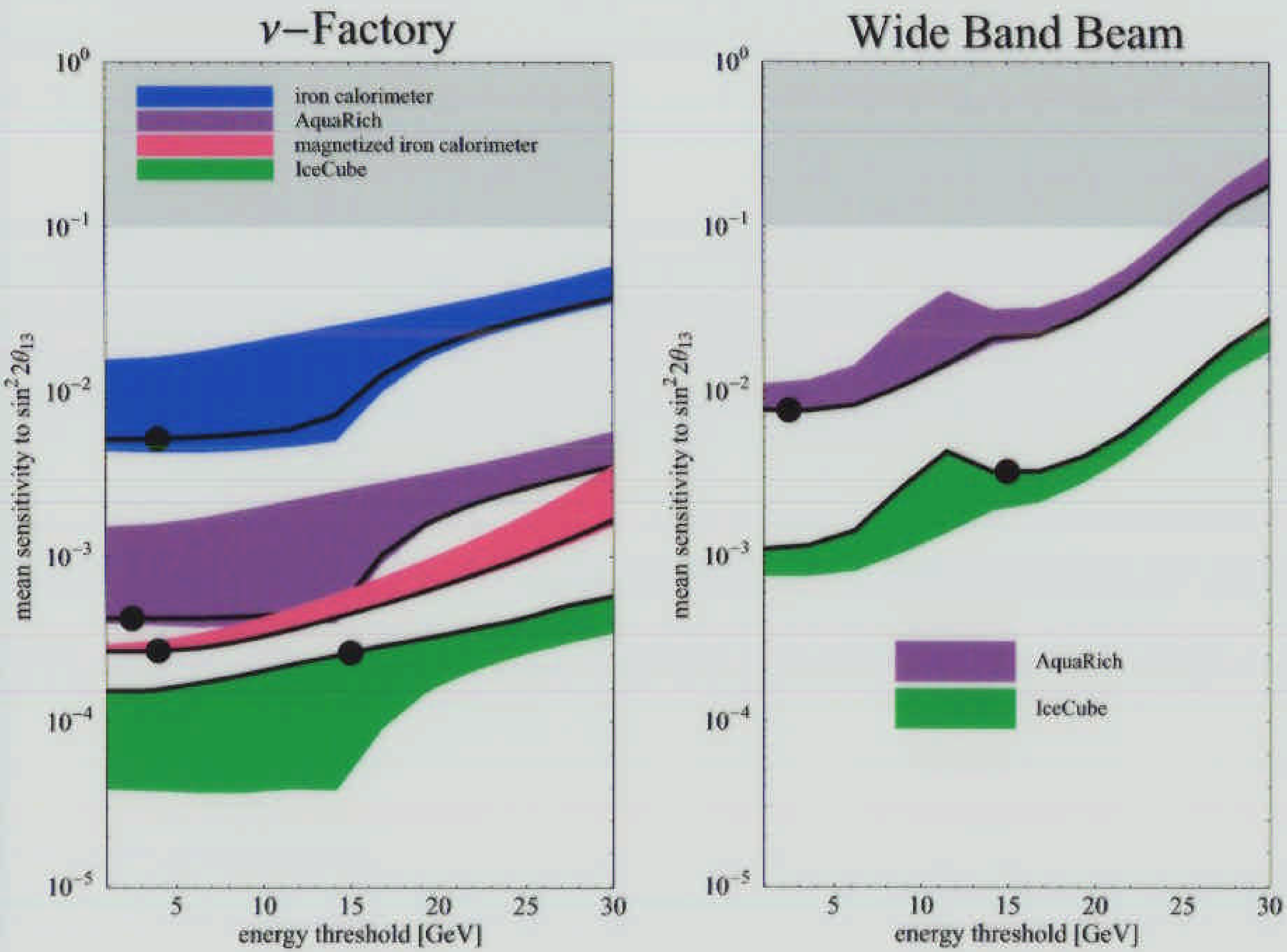
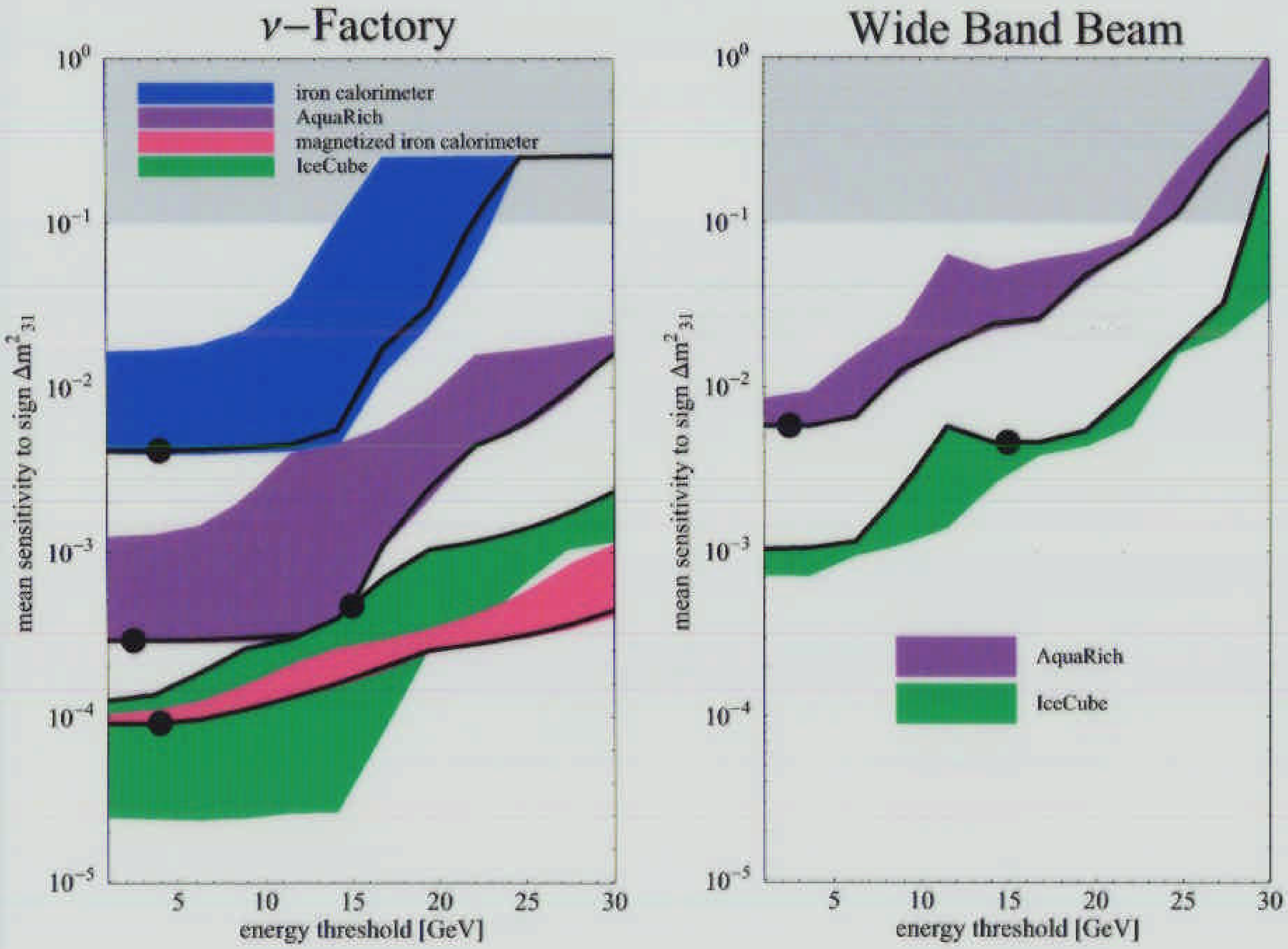

ν–Factory
Wide Band Beam
iron calorimeter
AquaRich
magnetized iron calorimeter
IceCube
mean sensitivity to $\sin^2 2\theta_{13}$
energy threshold [GeV]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
5
10
15
20
25
30


ν–Factory
iron calorimeter
AquaRich
magnetized iron calorimeter
IceCube
mean sensitivity to sign Δm²₃₁
energy threshold [GeV]
Wide Band Beam
AquaRich
IceCube
mean sensitivity to sign Δm²₃₁
energy threshold [GeV]

Conclusion: Parameters in the Future

Leading Oscillation – Precision Measurements

$$\sin^2 2\theta_{23} \simeq \pm 1\% \quad |\Delta m^2_{31}| \simeq \pm 1\%$$

ν–factory → magnetized iron detector
Wide band beam → ICECUBE

Subleading Oscillation – MSW–Effect

$$\sin^2 2\theta_{13} < 10^{-4} \quad \text{sgn}\ \Delta m^2_{31} = \text{yes}$$

ν–factory → magnetized iron detector
Wide band beam → ICECUBE for $\sin^2 2\theta_{13} > 10^{-3}$

Small Δm^2–Effects – CP-Violation

in case of LMA–solution and maximal mixing

$$\delta \simeq \pm 20\%$$

ν–factory → magnetized iron detector

Very promising future for neutrino physics