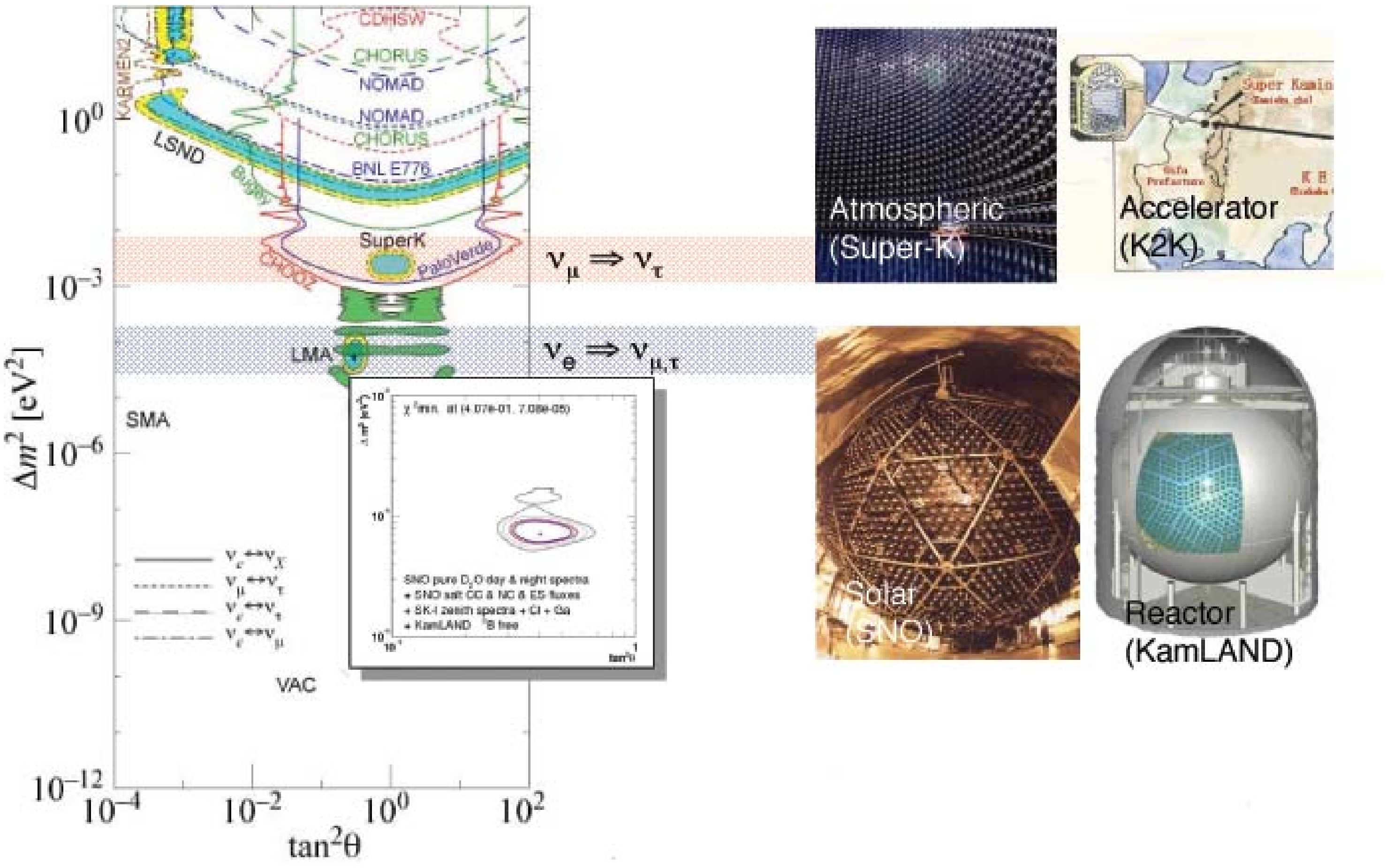
CP violation in neutrino physics

Gabriela Barenboim

DaΦne 2004

We know that neutrinos are massive and oscillate !



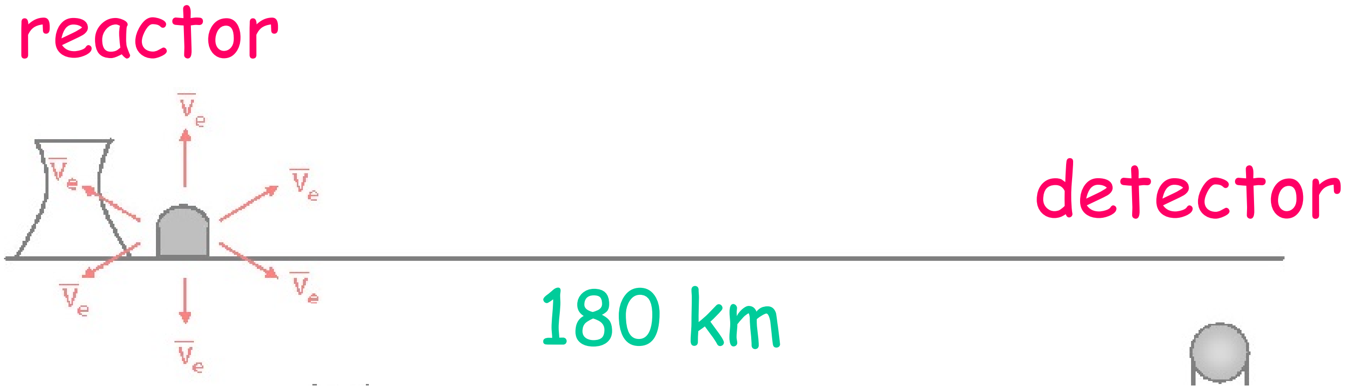
Evidence for flavor change

Solar neutrinos: Compelling evidence

Pure ν_e source

$$\frac{\phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}}{\phi_{\nu_e}} = \frac{1}{3}$$

Reactor neutrinos: very strong evidence



reactor

detector

180 km

produced

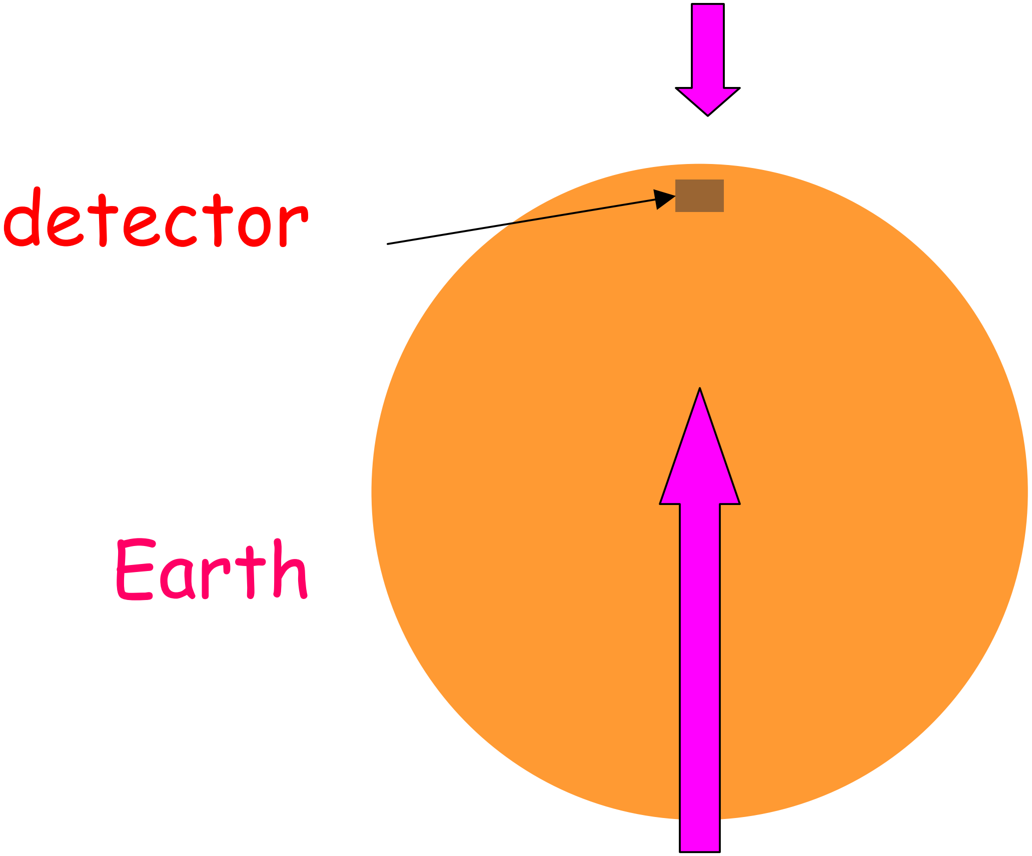
$\phi_{\bar{\nu}_e}$

surviving

$0.6\ \phi_{\bar{\nu}_e}$

One pair of parameters fits both solar and atmospheric data

Atmospheric neutrinos: Compelling evidence



$$\frac{\phi_{\nu_\mu}\,(\text{up})}{\phi_{\nu_\mu}\,(\text{down})} = 2$$

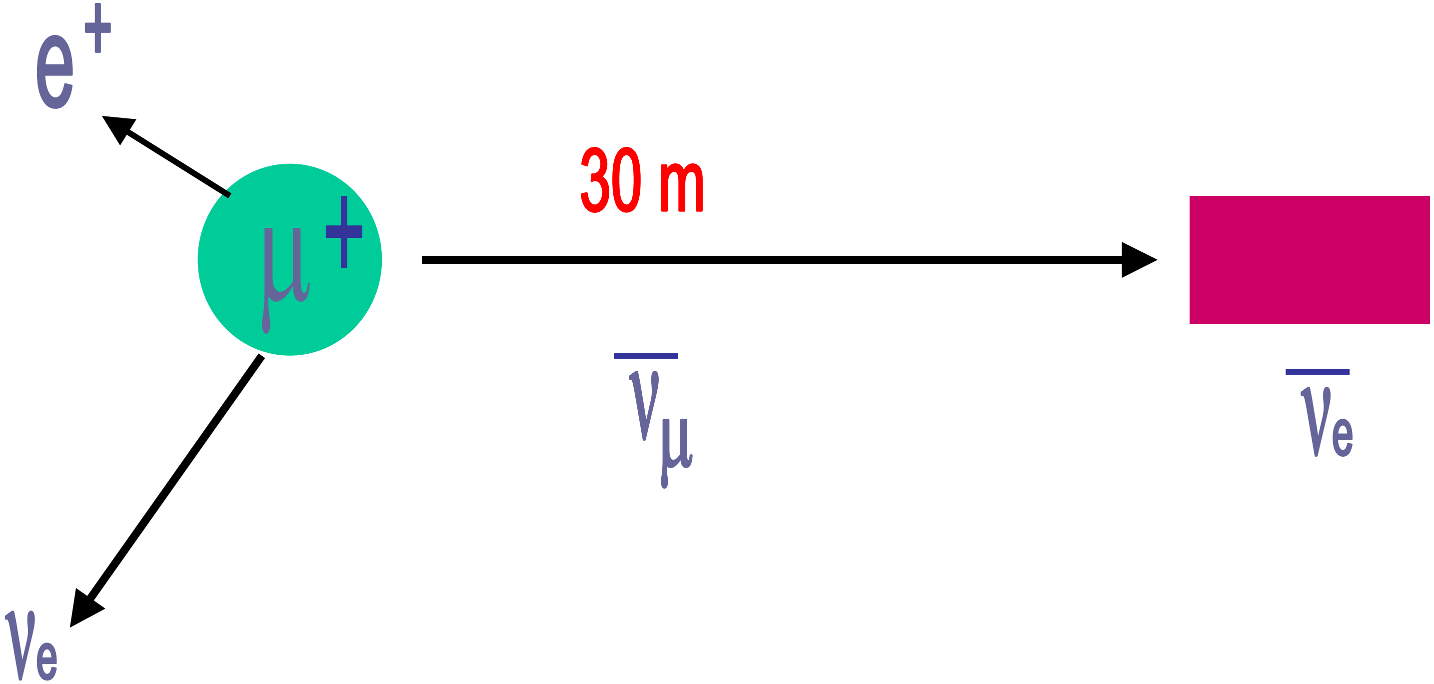
Accelerator neutrinos: interesting evidence

Observe 72 ν_μ events

Expect 106 ν_μ events in far detector

The hypothesis $\nu_\mu \rightarrow \nu_\tau$ with one pair of parameters fits both the atmospheric and accelerator data

LSND: unconfirmed evidence



What have we already learnt ?

We do not know how many neutrino mass eigenstates there are.

Assuming CPT, confirmation of LSND by MiniBooNE
would imply there are more than 3

Neutrinos	Required Δm^2 eV^2
solar - reactor	$10^{-(4-5)}$
atmos.- accelerator	10^{-3}
LSND	1

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~~LSND~~	~~1~~

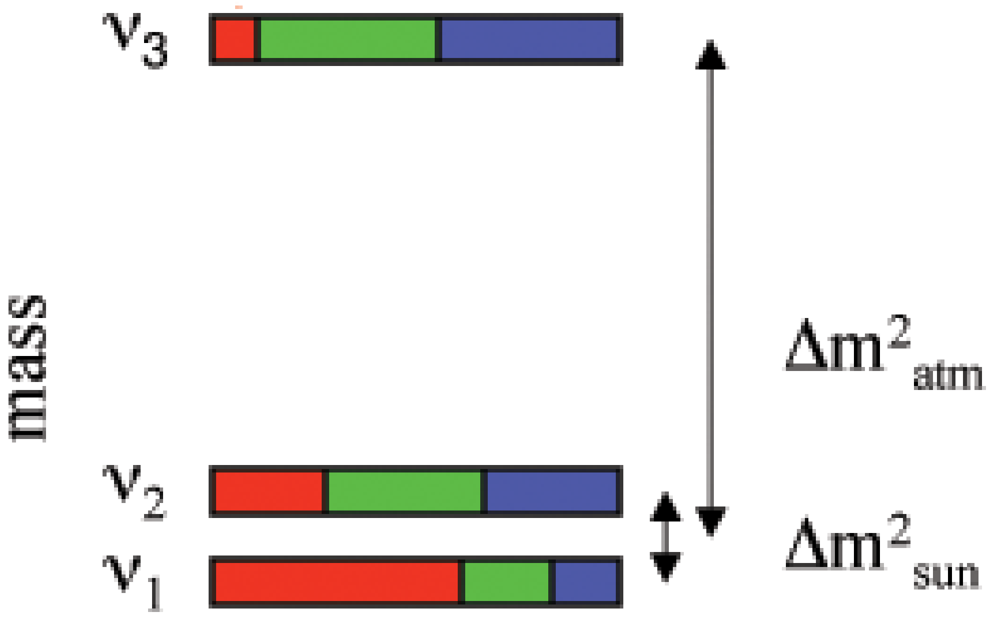
The neutrino mixing matrix

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

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}} \times \underbrace{\overbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}^{\textit{Dirac phase}}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}} \times \underbrace{\overbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}^{\textit{Majorana phases}}}$$

?

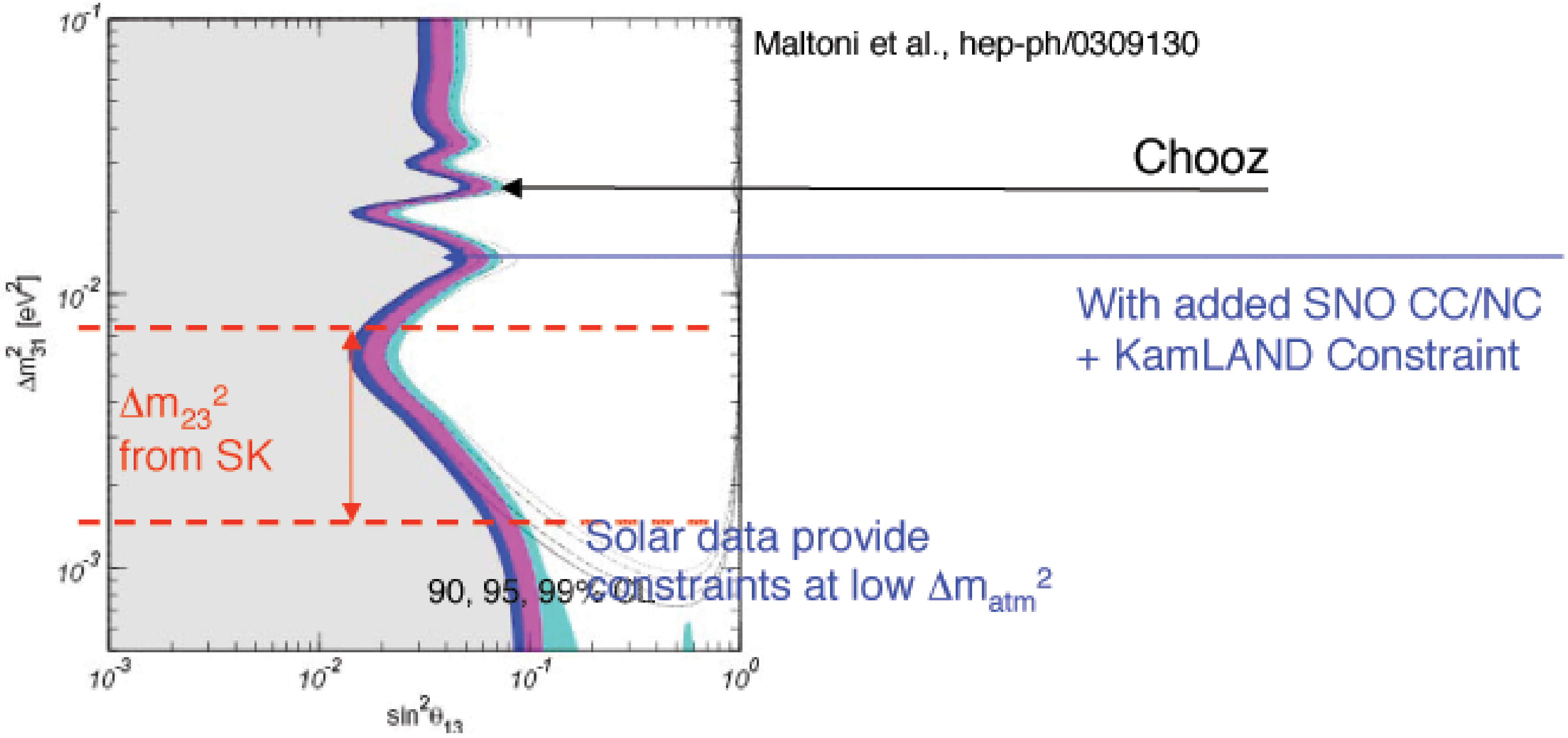
atmospheric, K2K	reactor and accelerator	SNO, solar SK, KamLAND	0νββ
$\theta_{23} = \sim 45°$	$\tan^2\theta_{13} < 0.03$ at 90% CL	$\theta_{12} \sim 32°$	
maximal	*small … at best*	*large*	


ν_3
mass
Δm^2_{atm}
ν_2
Δm^2_{sun}
ν_1

Three unknown oscillation parameters

The three steps

(1) What is the size of $\sin^2(2\theta_{13})$?



Maltoni et al., hep-ph/0309130

Chooz

With added SNO CC/NC
+ KamLAND Constraint

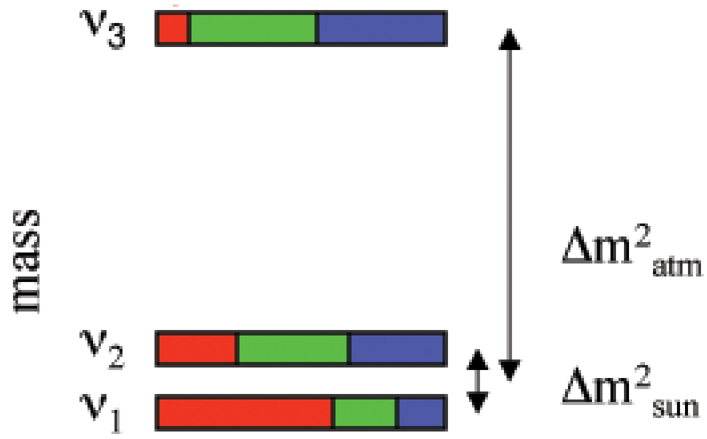
Δm_{23}^2
from SK

Solar data provide
constraints at low Δm_{atm}^2

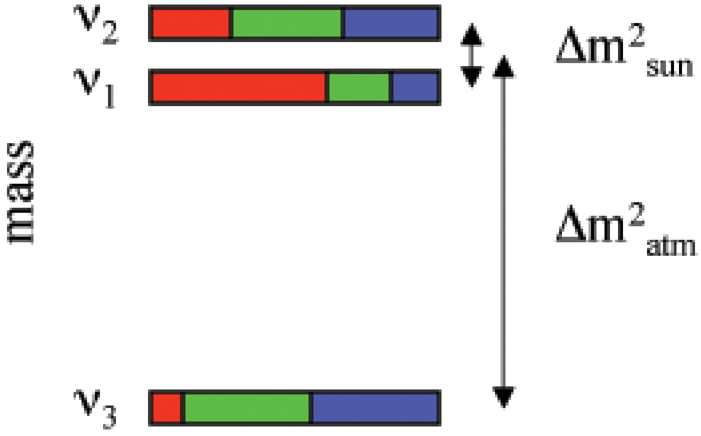
90, 95, 99% CL

(2) What is the mass hierarchy ?

What is the sign of Δm^2_{13} ?



Normal mass hierarchy



Inverted mass hierarchy

We determined that $m(K_L) > m(K_S)$ by

- Passing kaons through matter (regenerator)
- Beating the unknown sign$[m(K_L) - m(K_S)]$ against the known sign[reg. ampl.]

We determined that $m(K_L) > m(K_S)$ by

- Passing kaons through matter (regenerator)
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We will determine the sign(Δm^2_{13}) by

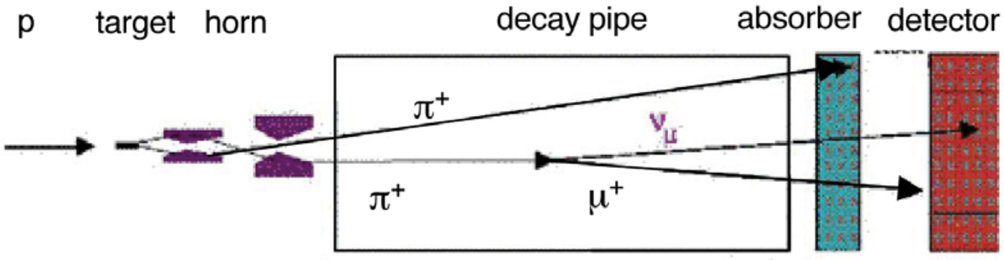
- Passing neutrinos through matter (Earth)
- Beating the unknown sign(Δm^2_{13}) against the known sign[forward $\nu_e e \longrightarrow \nu_e e$ ampl]

(3) Is there CP violation ?
Measure δ

$$J_{\mathrm{lepton}} \sim \underbrace{\cos^2(\theta_{13})}_{\sim 1}\underbrace{\sin(2\theta_{12})}_{\sim 0.9}\underbrace{\sin(2\theta_{23})}_{\sim 1}\sin(2\theta_{13})\sin(\delta_{CP})$$

How we are going to do it ?

Method 1: accelerator experiments

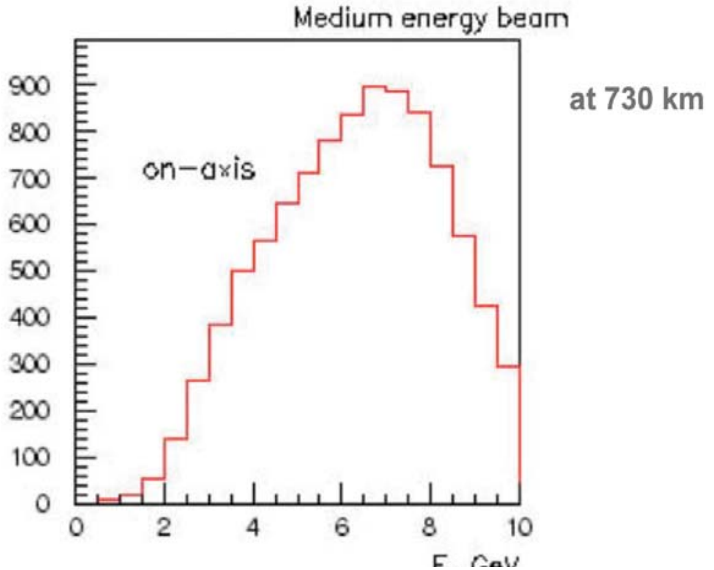


$$P_{\mu e} \approx \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{31}{}^2 L}{4E_\nu} + \ldots$$

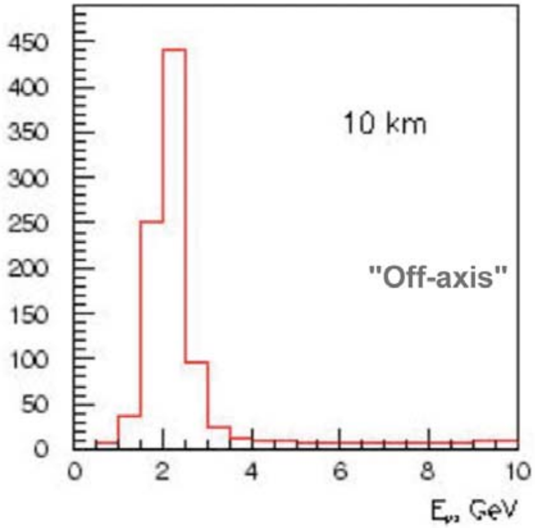
- Appearance experiment $\nu_\mu \rightarrow \nu_e$
- Measurement of $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ yields θ_{13} and δ
- Matter effects present, baselines of O(100-1000 km)

The off axis idea

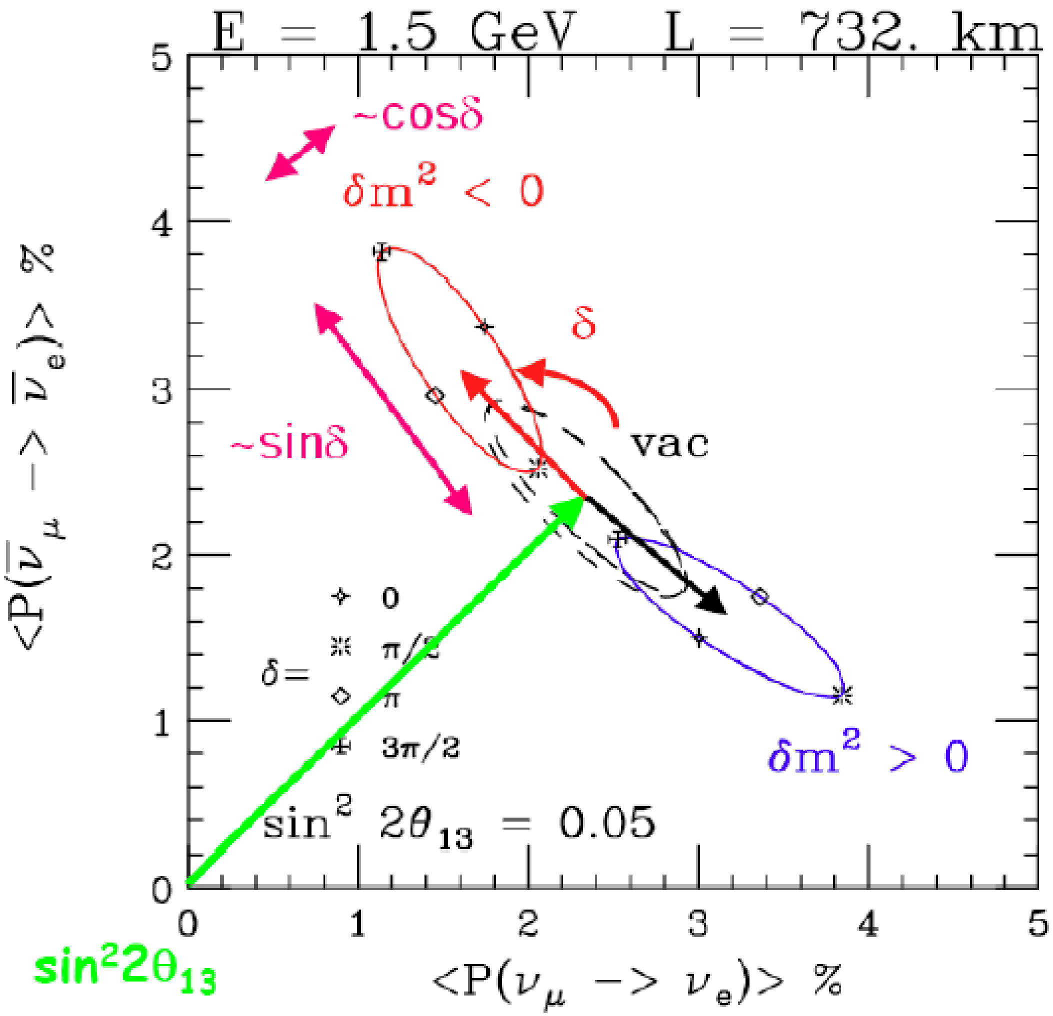
By going off axis, the beam energy is reduced and the spectrum becomes very sharp.



Allows an experiments to pick an energy for the maximum oscillation length.

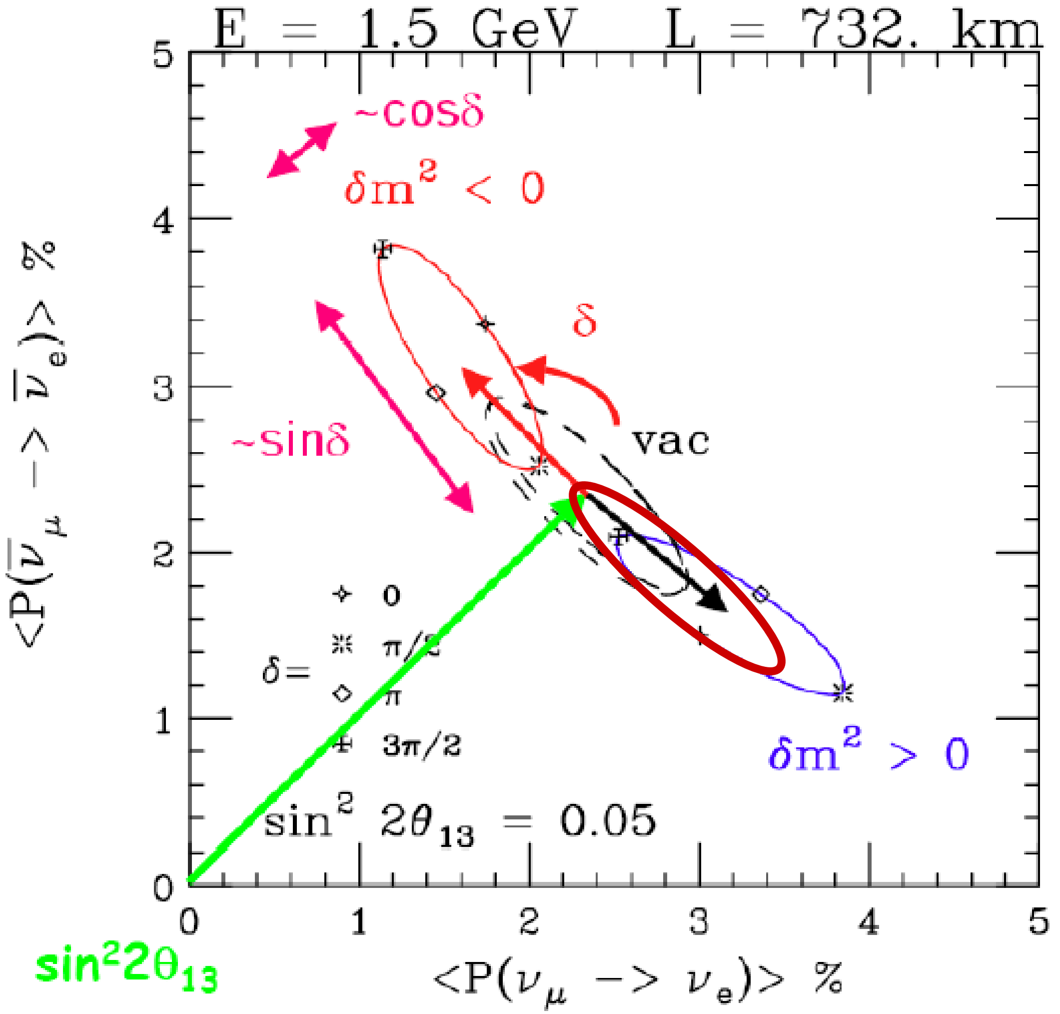


What will we get ?



Minakata and Nunokawa

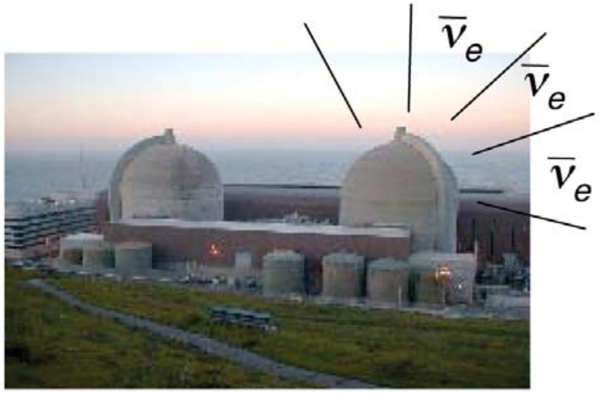
What will we get ?



Minakata and Nunokawa

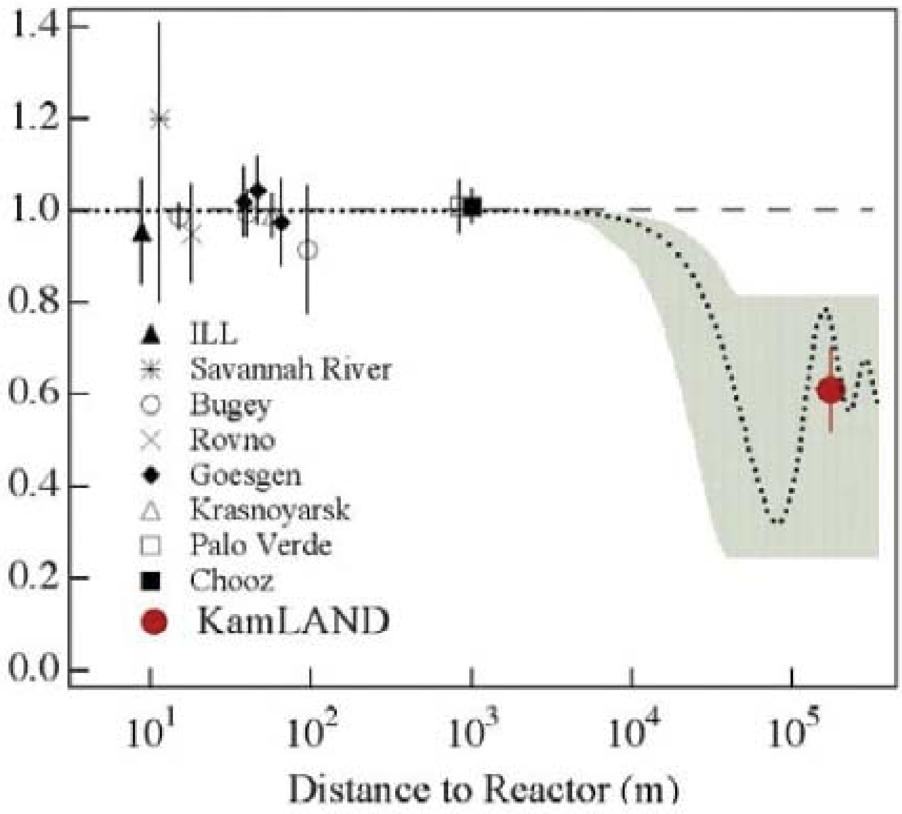
Method 2: reactor experiments

$$P_{ee} \approx 1 - \left(\sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}{}^2 L}{4E_\nu} + \left(\frac{\Delta m_{21}{}^2 L}{4E_\nu} \right) \cos^4 \theta_{13} \sin^2 2\theta_{13} \right)$$

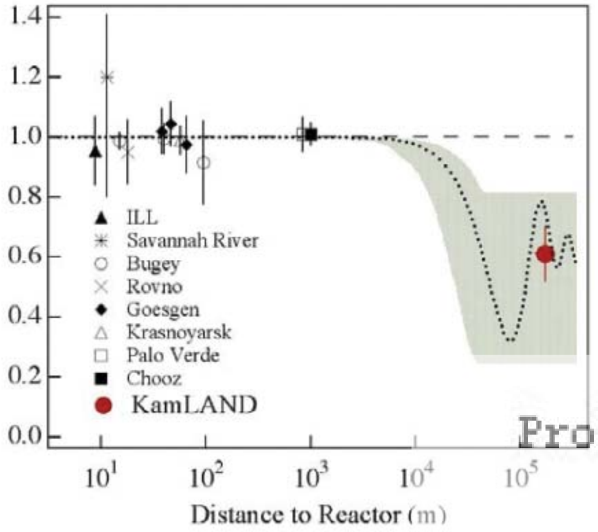


- Disappearance experiment $\bar{\nu}_e \rightarrow \bar{\nu}_x$
- Clean measurement of θ_{13}
- No matter effects, baselines O(1 km)

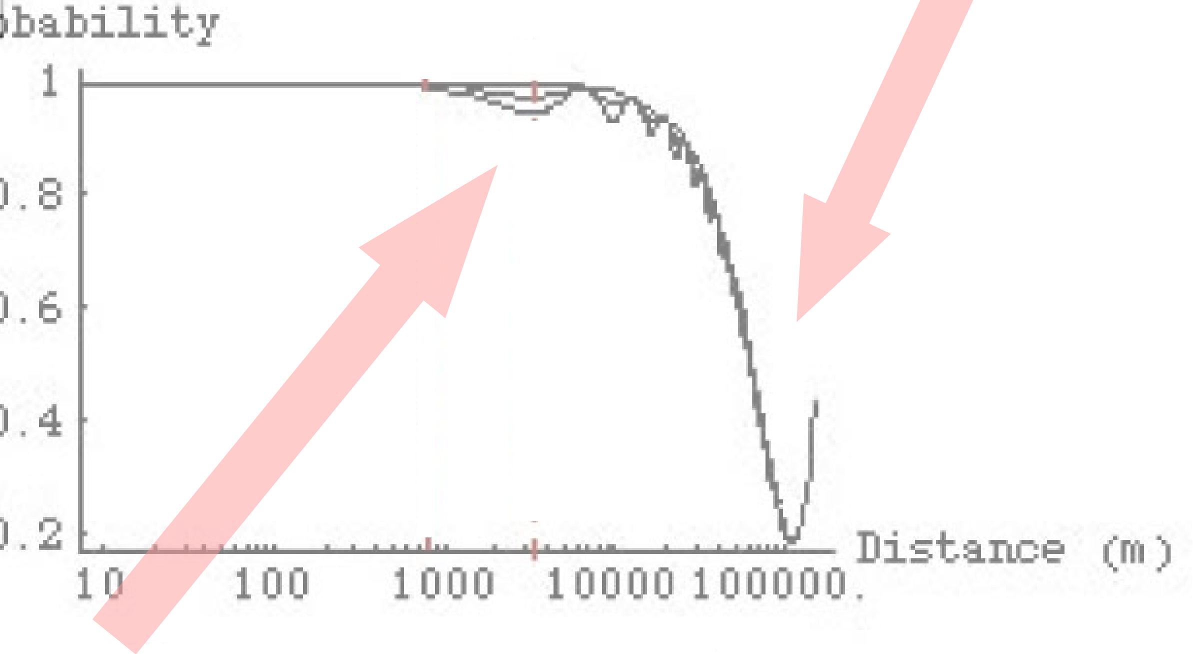
Reactor experiments: the past



Reactor experiments : the future

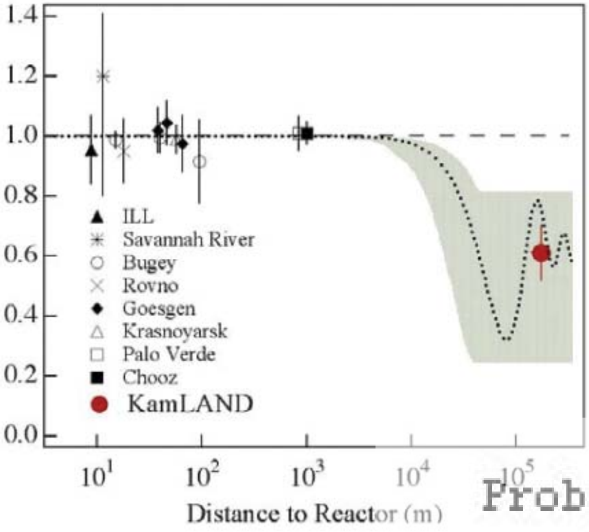


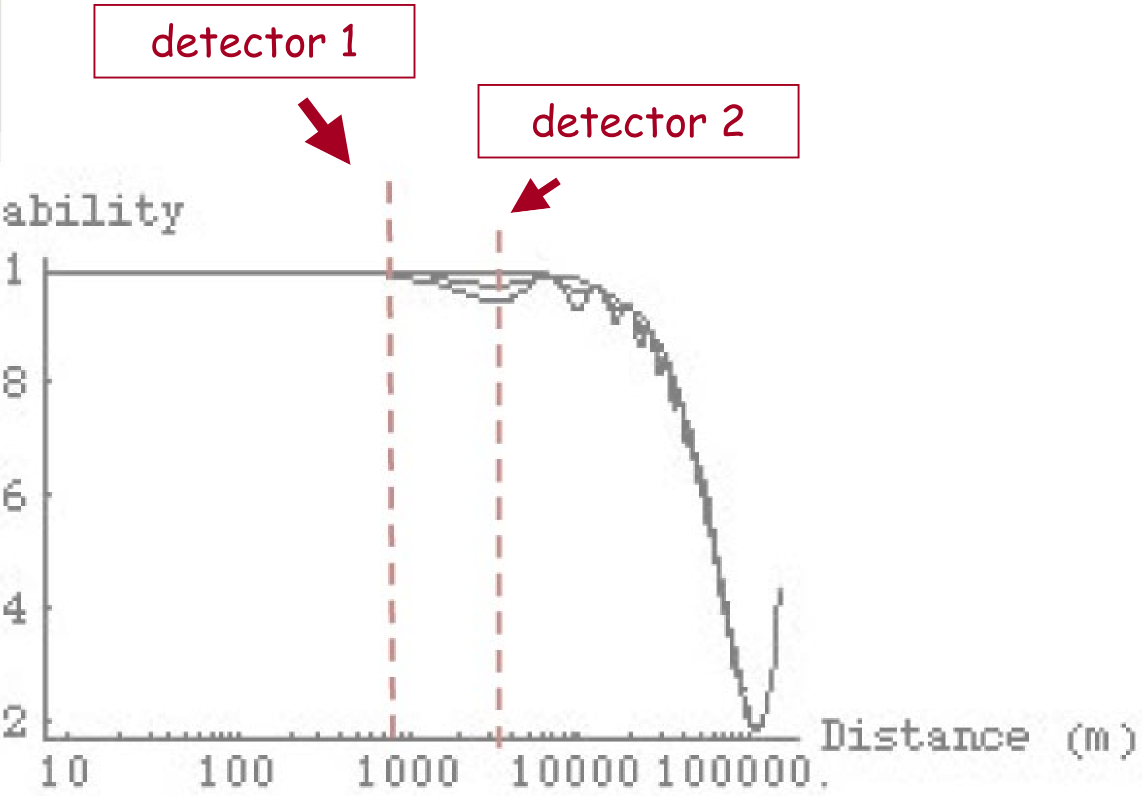
$$P_{ee} \approx 1 - \cos^4\theta_{13}\left[1 - \sin^2\theta_{12}\sin^2\left(\frac{\Delta m_{12}{}^2 L}{4E_\nu}\right)\right]$$



$$P_{ee} \approx 1 - \left(\sin^2 2\theta_{13}\sin^2\frac{\Delta m_{31}{}^2 L}{4E_\nu} + \left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)\cos^4\theta_{13}\sin^2 2\theta_{12}\right)$$

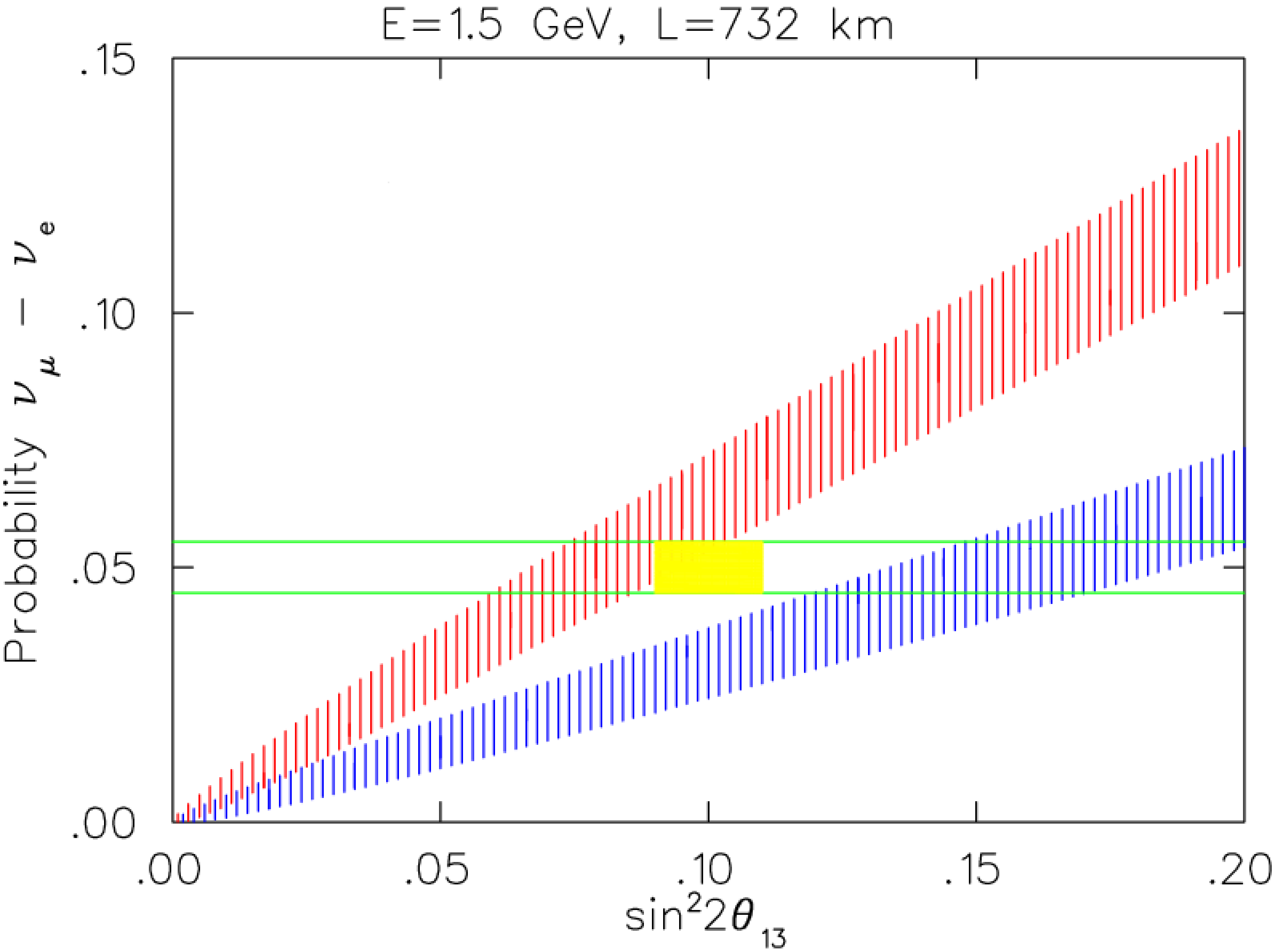
Reactor experiments : the future





detector 1

detector 2

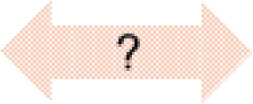

E=1.5 GeV, L=732 km
Probability $\nu_\mu - \nu_e$
$\sin^2 2\theta_{13}$
.00
.05
.10
.15
.20

R. McKeown

What do we hope to get ?

Some understanding of the physics at high mass scale, the physics of flavor and unification.

$$U_{MNSP} = \begin{pmatrix} big & big & small? \\ big & big & big \\ big & big & big \end{pmatrix}$$



$$V_{CKM} = \begin{pmatrix} big & small & tiny \\ small & big & tiny \\ tiny & tiny & big \end{pmatrix}$$

What do we hope to get ?

Some understanding of the physics at high mass scale, the physics of flavor and unification.

$$U_{MNSP} = \begin{pmatrix} big & big & small \\ big & big & big \\ big & big & big \end{pmatrix} \Leftrightarrow ? \quad V_{CKM} = \begin{pmatrix} big & small & tiny \\ small & big & tiny \\ tiny & tiny & big \end{pmatrix}$$

Stay tuned

The next to next to next step