Reactor neutrino physics

Xiang Liu
April 1st, 2005
Physics session

- ✓Neutrino mixing parameters
- ✓What do reactor neutrino experiments (KamLand & Double-Chooz) measure?
- ✓KamLand results

- ✓KamLand technique
- ✓Double-Chooz technique

Neutrino Mixing Phenomenology

Simple case: two flavor mixing

α,β: flavor eigenstate
1,2: mass eigenstate

time 0
$$\begin{pmatrix}\nu_{\alpha 0}\\ \nu_{\beta 0}\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix} \times \begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

time t
$$\begin{pmatrix}\nu_{\alpha t}\\ \nu_{\beta t}\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix} \times \begin{pmatrix}e^{-iE_1 t} & 0\\ 0 & e^{-iE_2 t}\end{pmatrix} \times \begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

assume:
$$E_1 = \sqrt{P^2 + m_1^2} \approx P + m_1^2/2P \approx P + m_1^2/2E$$

$$\begin{pmatrix}\nu_{\alpha t}\\ \nu_{\beta t}\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix} \times \begin{pmatrix}exp(-i\frac{m_1^2}{2E}L) & 0\\ 0 & exp(-i\frac{m_2^2}{2E}L)\end{pmatrix} \times \begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

simplify:
$$\begin{pmatrix}\nu_{\alpha t}\\ \nu_{\beta t}\end{pmatrix} = \begin{pmatrix}c & s\\ -s & c\end{pmatrix} \times \begin{pmatrix}e1 & 0\\ 0 & e2\end{pmatrix} \times \begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix} = \begin{pmatrix}c\cdot e_1 & s\cdot e_2\\ -s\cdot e_1 & c\cdot e_2\end{pmatrix} \times \begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

surviving probability:
$$\boxed{P(\nu_\alpha \rightarrow \nu_\alpha) = |<\nu_{\alpha t}|\nu_{\alpha 0}>|^2}$$

Two flavor mixing (cont'd)

$$
\begin{aligned}
P(\nu_\alpha \to \nu_\alpha) &= |<\nu_{\alpha t}|\nu_{\alpha 0}>|^2 \\
&= |c^2 e_1 + s^2 e_2|^2 \\
&= (c^2 e_1 + s^2 e_2) \cdot (c^2 e_1^* + s^2 e_2^*) \\
&= c^4 + s^4 + c^2 s^2 \cdot 2\cos(\frac{\Delta m_{12}^2}{2E} L) \\
&= 1 - \sin^2(2\theta)\sin^2(\frac{\Delta m_{12}^2}{4E} L) \\
&\boxed{= 1 - \sin^2(2\theta)\sin^2(\frac{1.27\Delta m_{12}^2 L}{E})}
\end{aligned}
$$

Δm^2 is in the unit of eV^2, L in m and E in MeV

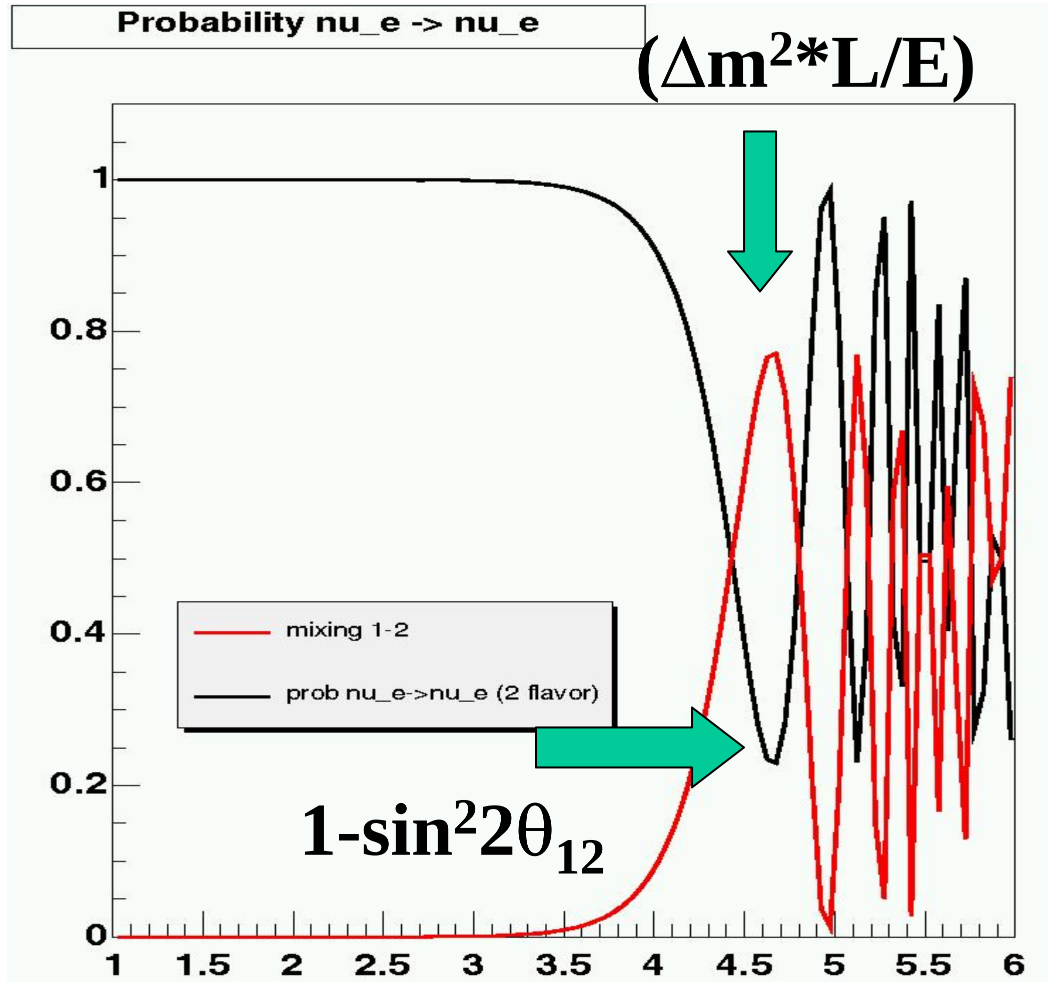
Mixing angle determines maximum amplitude

E/L determines where to oscillate

Two flavor mixing (cont'd)

$\sin^2 2\theta_{12}=0.8$
$\Delta m^2_{12}=8.2\ 10^{-5}\ eV^2$
assume E 3MeV

Mixing angle determines maximum amplitude
E/L determines where to oscillate



Log10L (m)

Three flavor mixing

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

$c_{ij} = \cos\theta_{ij}$, $s_{ij}=\sin\theta_{ij}$, δ Dirac phase

23: atmospheric neutrino (superK)
$\sin^2 2\theta_{23}=1.0$
$\Delta m^2_{23}=2.4\ 10^{-3}\ \mathrm{eV}^2$
(ν_μ will disappear completely)

12:solar neutrino (GNO, K, superK, SNO)
$\sin^2 2\theta_{12}=0.8$
$\Delta m^2_{12}=8.2\ 10^{-5}\ \mathrm{eV}^2$
(Confirmed by KamLand)

13: reactor (Chooz) $\sin^2 2\theta_{13}<0.2$

Three flavor mixing (cont'd)

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

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

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

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}_t = U \begin{pmatrix} e_1 & & \\ & e_2 & \\ & & e_3 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \qquad \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}_0 = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$< \nu_e(t)|\nu_e(0) >= c_{12}^2 c_{13}^2 e_1 < \nu_1|\nu_1 > + c_{13}^2 s_{12}^2 e_2 < \nu_2|\nu_2 > + s_{13}^2 e_3 < \nu_3|\nu_3 >$$

ν_e survive probability

$$P(\nu_e \to \nu_e) = |<\nu_e(t)|\nu_e(0)>|^2$$
$$= c_{12}^4 c_{13}^4 + c_{13}^4 s_{12}^4 + s_{13}^4$$
$$+ c_{12}^2 c_{13}^4 s_{12}^2 2\cos_{12} + c_{12}^2 c_{13}^2 s_{13}^2 2\cos_{13} + s_{13}^2 c_{13}^2 s_{12}^2 2\cos_{23}$$

$$\cos_{12} = \cos\left(\frac{(m_2^2 - m_1^2)}{2E} L\right) = \cos\left(\frac{\Delta m_{12}^2}{2E} L\right)$$

$$P(\nu_e \to \nu_e) = 1 - 4c_{13}^4 c_{12}^2 s_{12}^2 \sin^2\left(\frac{1.27\Delta m_{12}^2 L}{E}\right)$$
$$- 4c_{13}^2 s_{13}^2 \sin^2\left(\frac{1.27\Delta m_{13}^2 L}{E}\right)$$
$$- 4c_{13}^2 s_{12}^2 s_{13}^2 \left(\sin^2\left(\frac{1.27\Delta m_{13}^2 L}{E}\right) - \sin^2\left(\frac{1.27\Delta m_{23}^2 L}{E}\right)\right)$$

Mixing θ12

Mixing θ13

interference

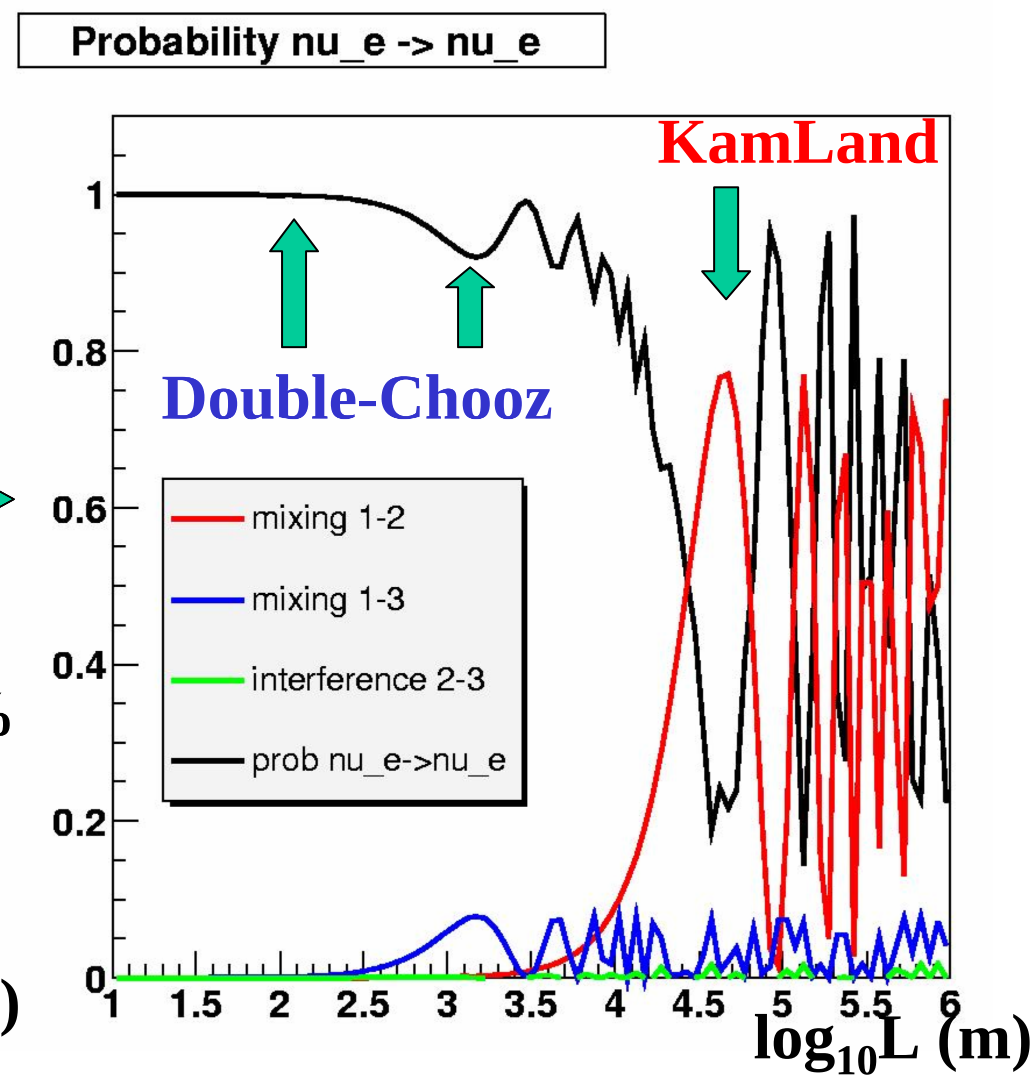
same for anti-neutrino

Reactor neutrino disappearance

- ✓Reactor provides anti-nu up to 8MeV
- ✓Detect through CC

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

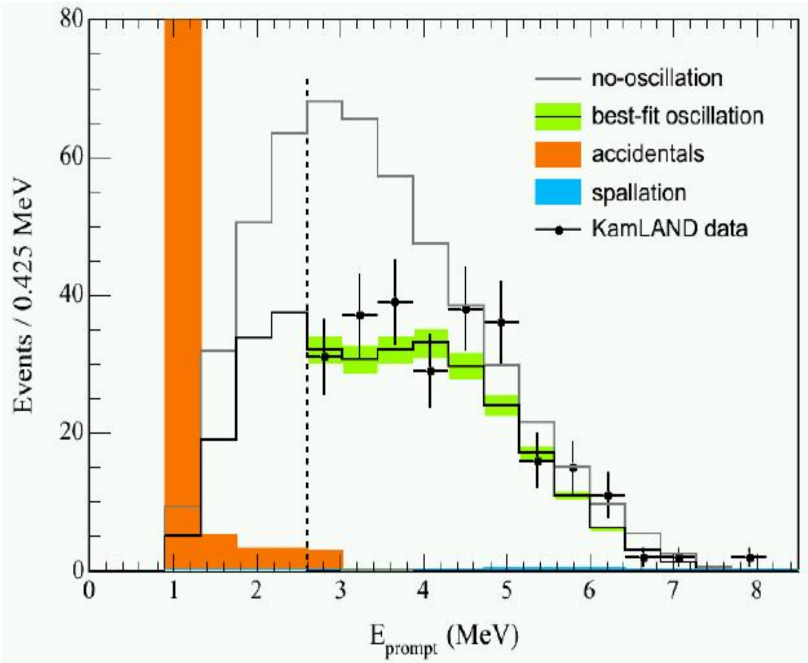
- ✓Eν threshold 1.8MeV
- ✓Eν mean ~ 3-5 MeV
- ✓assume $\sin^2 2\theta_{13}=0.08$



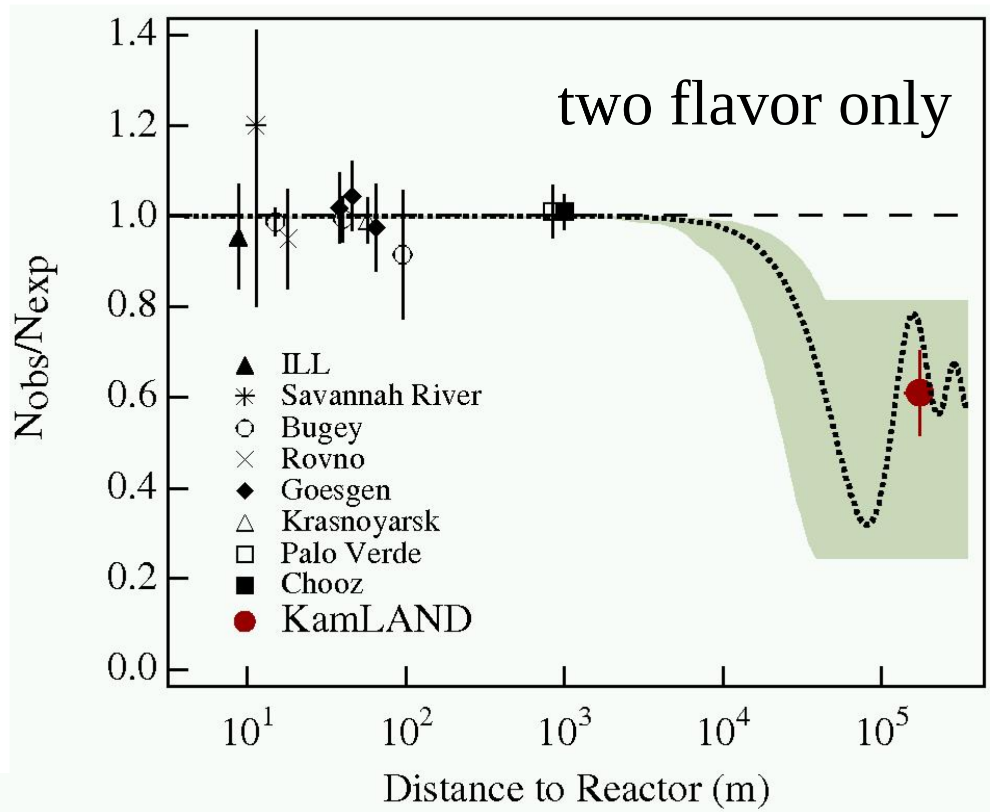
Double-Chooz: θ_{13}
Need two detectors (for 8% effect here)

KamLand : θ_{12}
One detector enough (60%)

Compared with KamLand results



Energy other than neutron

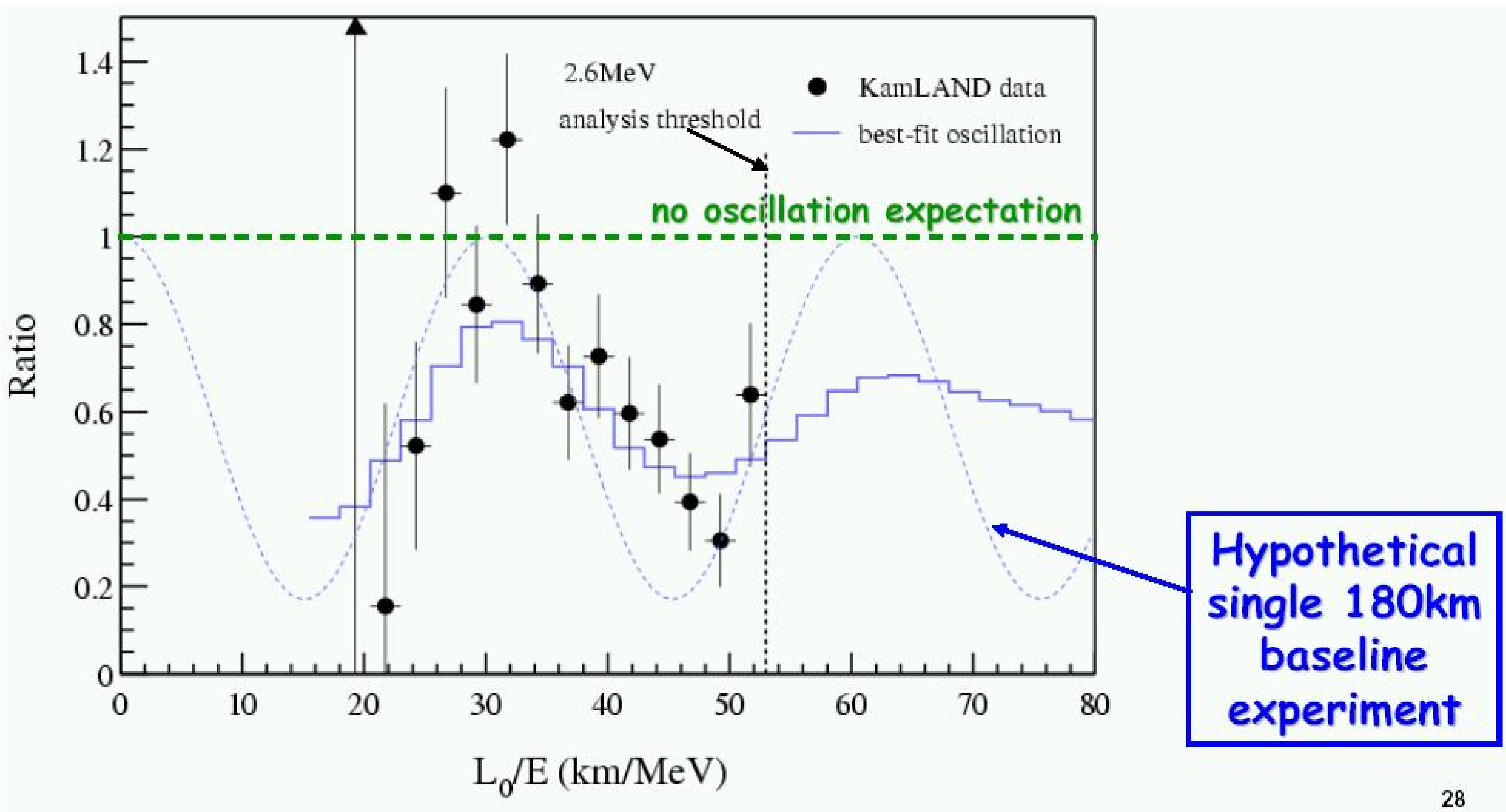


Observed events	258
No osc. expected	365±24(syst)
Background	7.5±1.3

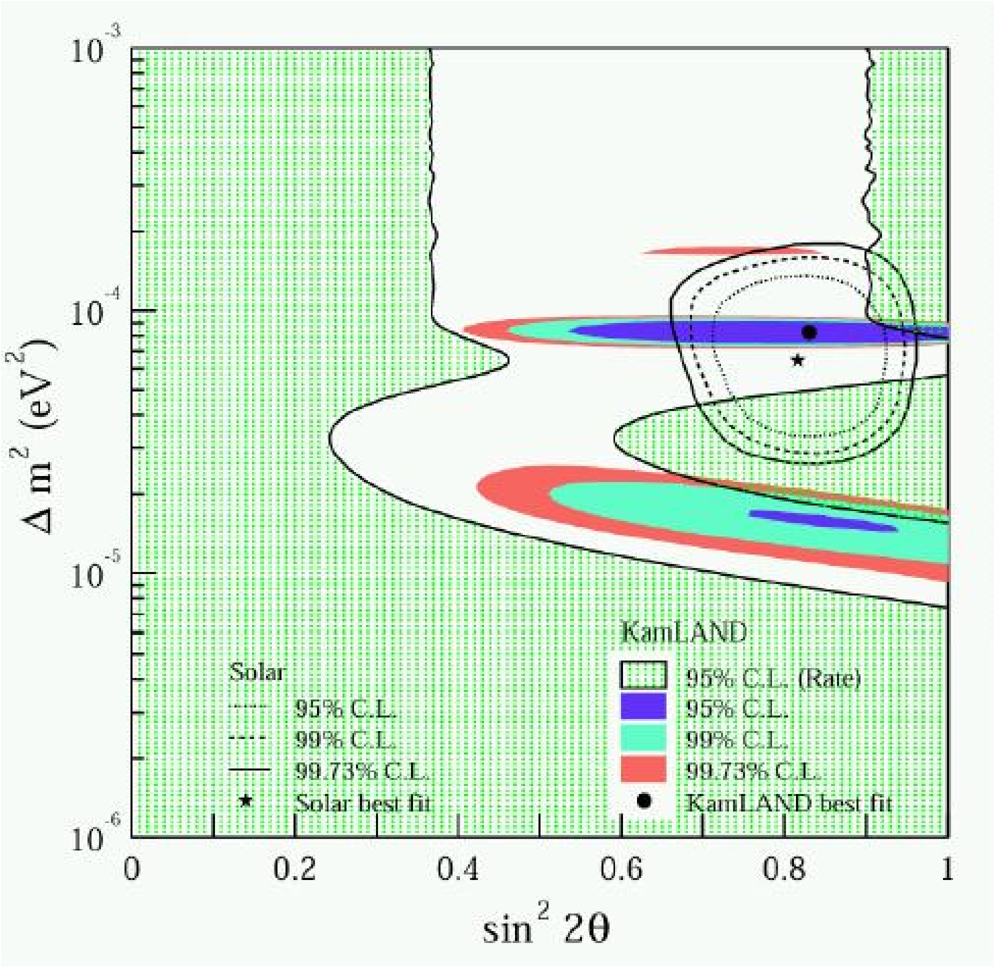
hep-ex/0406035

KamLand results: spectrum distortion

No distance information, but can take L_0=180km (true L/E smeared)

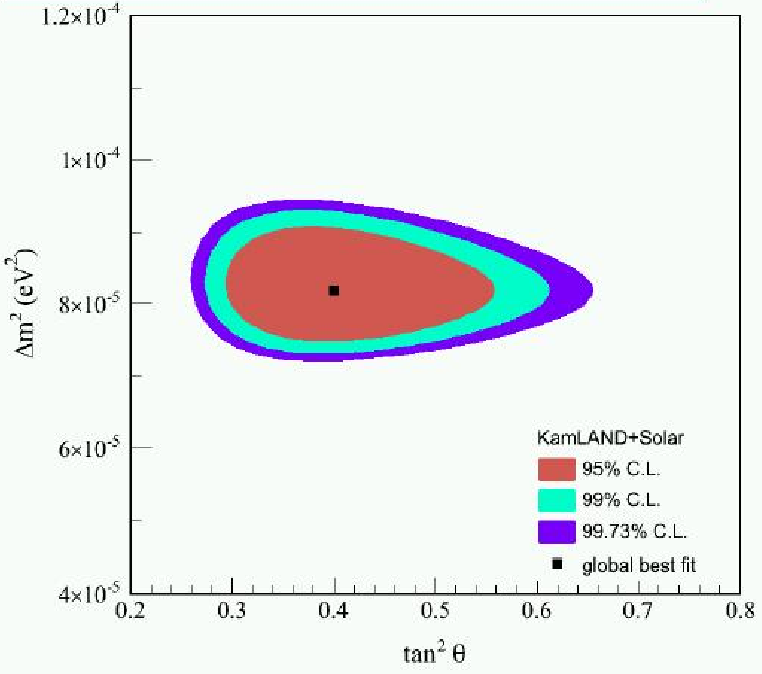


KamLand results



$$\Delta m^2_{12} = 8.2^{+0.6}_{-0.5} \times 10^{-5}\, eV^2$$

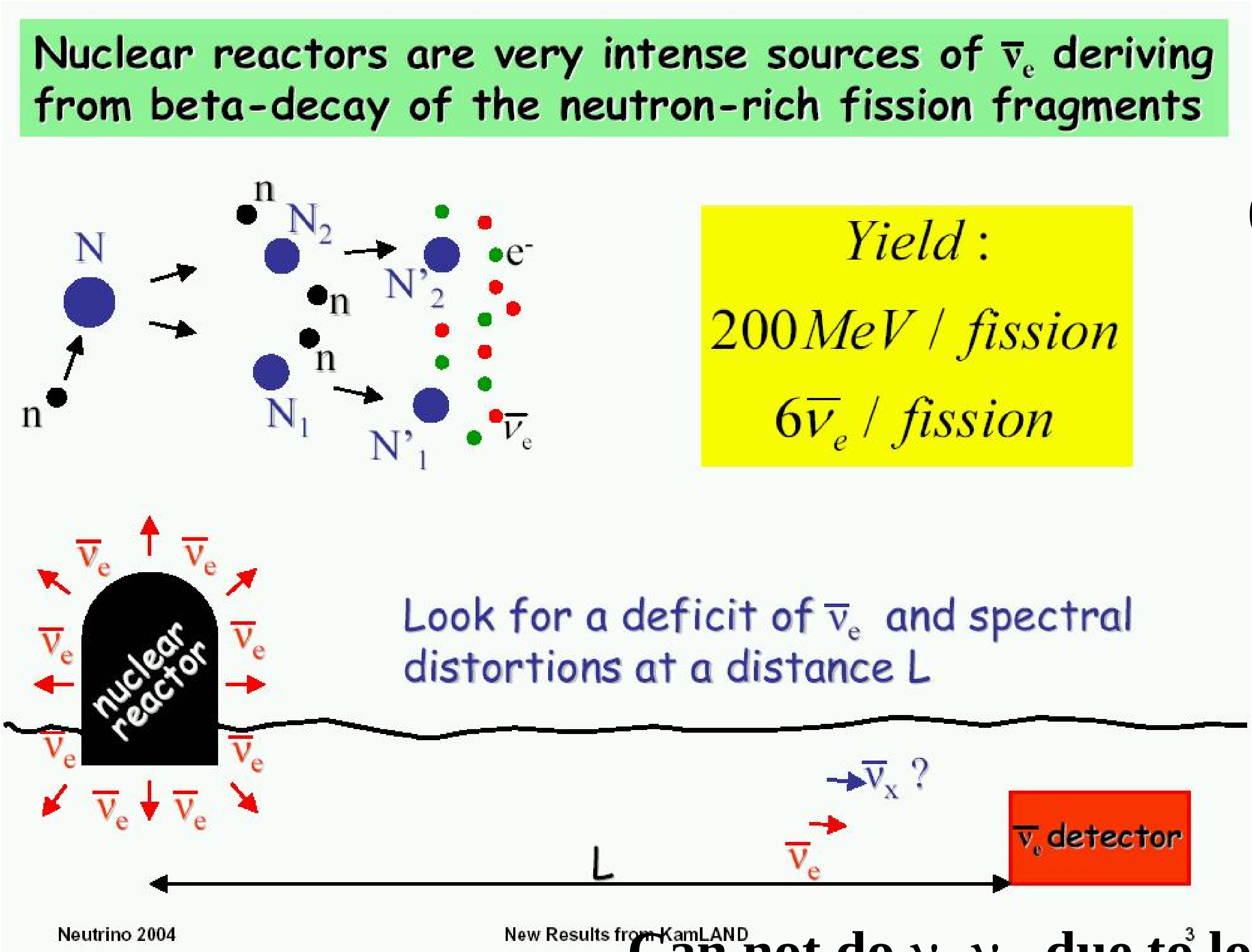
$$\tan^2\theta_{12} = 0.40^{+0.09}_{-0.07}$$



Now experimental details

Reactor neutrinos
& detecting technique

Reactor neutrinos



(G. Gratta Nu2004)

Can not do ν_μ ν_τ, due to low energy

How to detect them

A specific signature is provided by the inverse-β reaction

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

$\tau \approx 200\ \mu s$

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

(KamLand has 1ms window)

(n capture on Gd-LS ~8MeV)

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

E_ν measurement

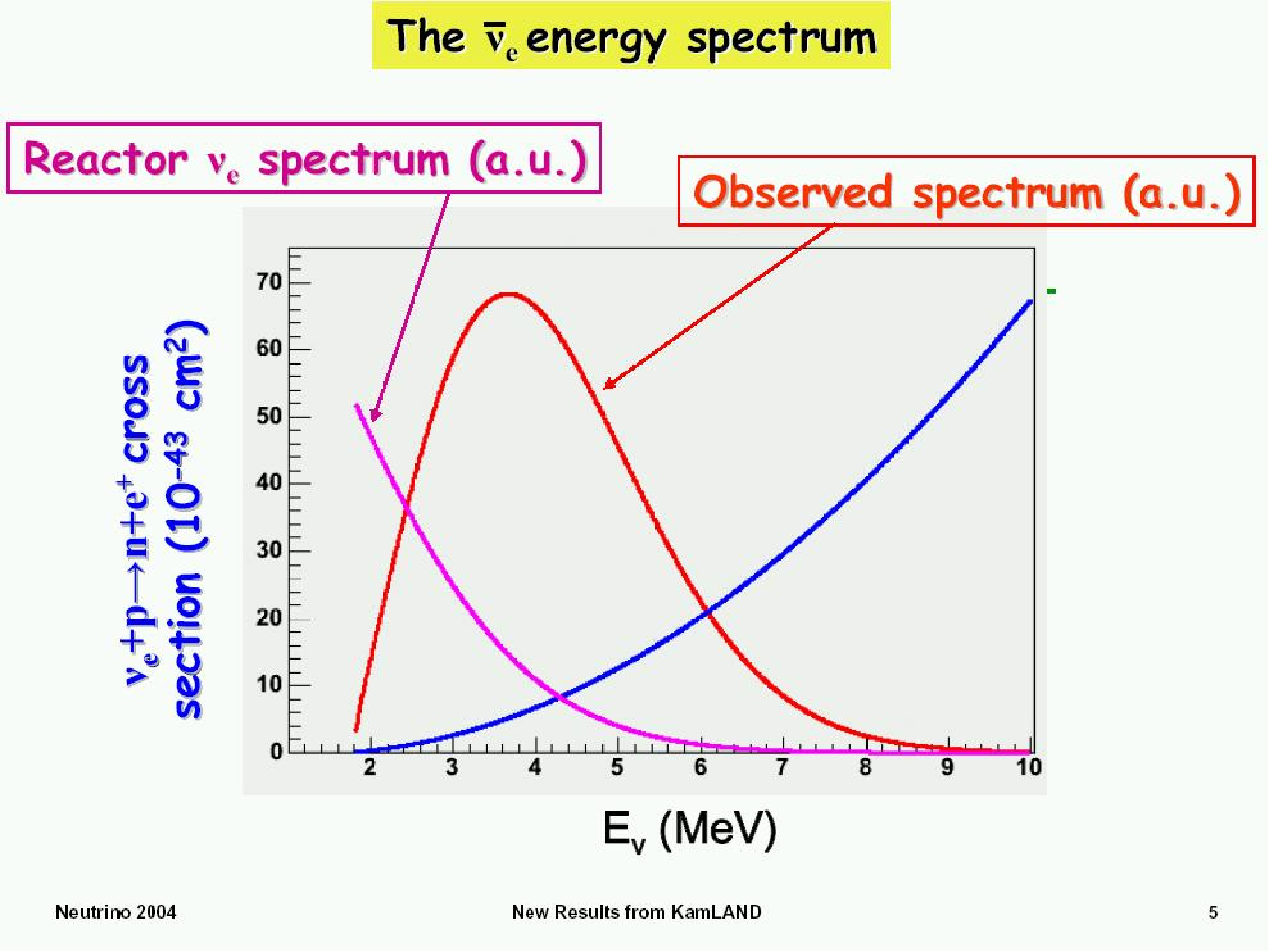
$$E_{\bar{\nu}} \simeq \underbrace{T_{e^+} + T_n}_{10\text{-}40\ keV} + \underbrace{(M_n - M_p) + m_{e^+}}_{1.8\ MeV}$$

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

→ only ~1.5 antineutrinos/fission can be detected

Neutrino 2004 New Results from KamLAND 4

Expected energy spectrum

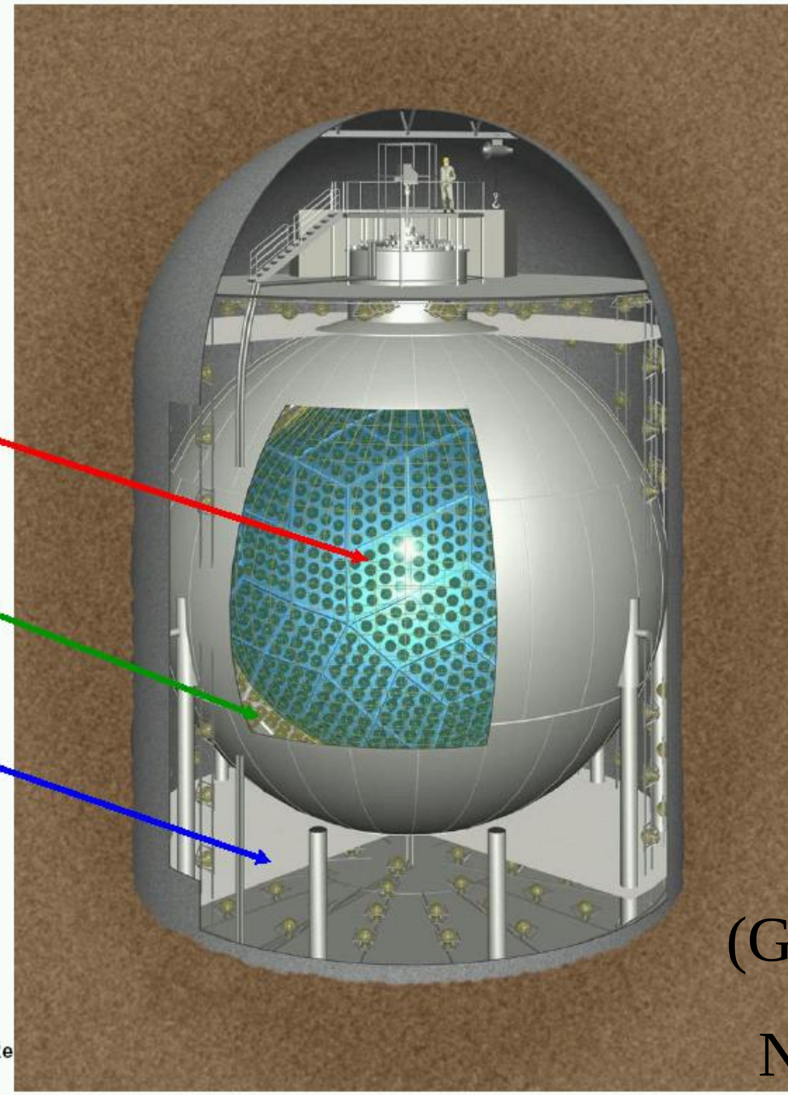


KamLand

KamLand detector setup

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



Fiducial volume R=5m

Neutrino 2004

New Re

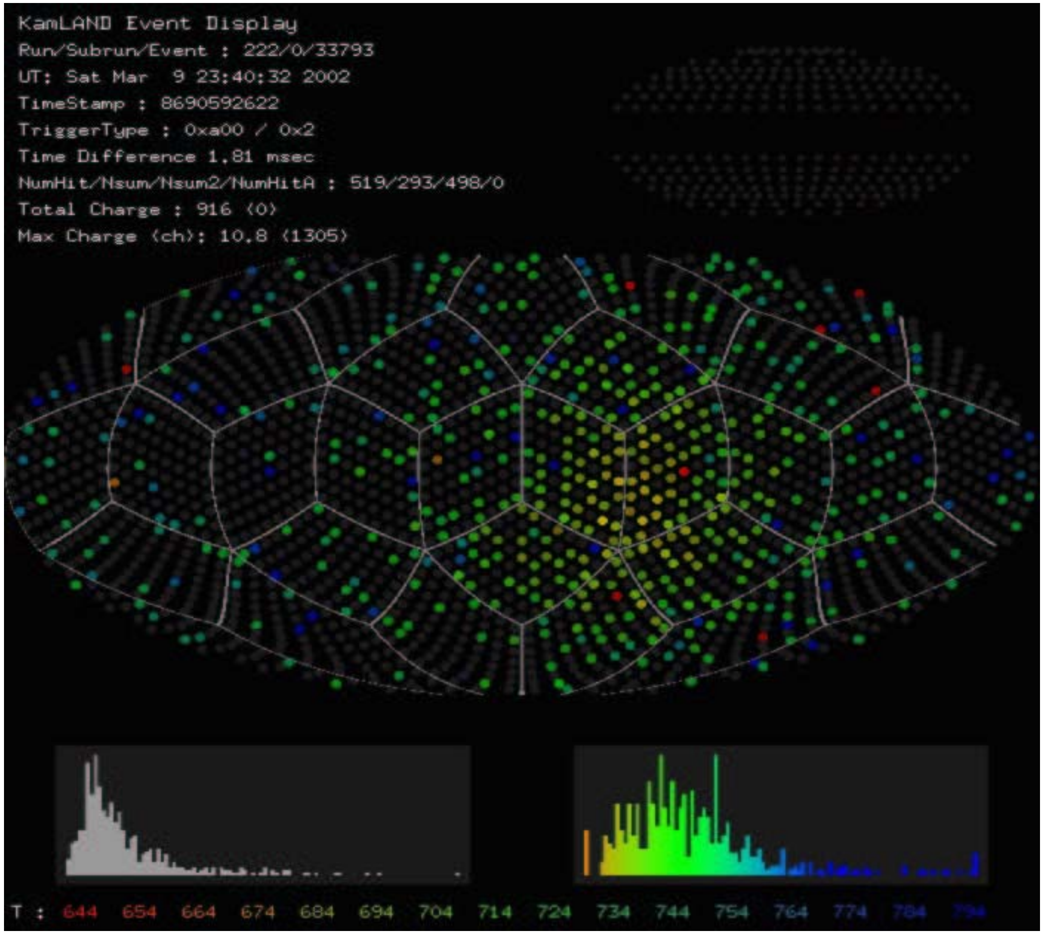
(G. Gratta Nu2004)

KamLand signal event

resolutions

- ✓Energy 6.2% at 1MeV
- ✓Timing 2-7 ns
- ✓Position <25cm

efficiency 90%

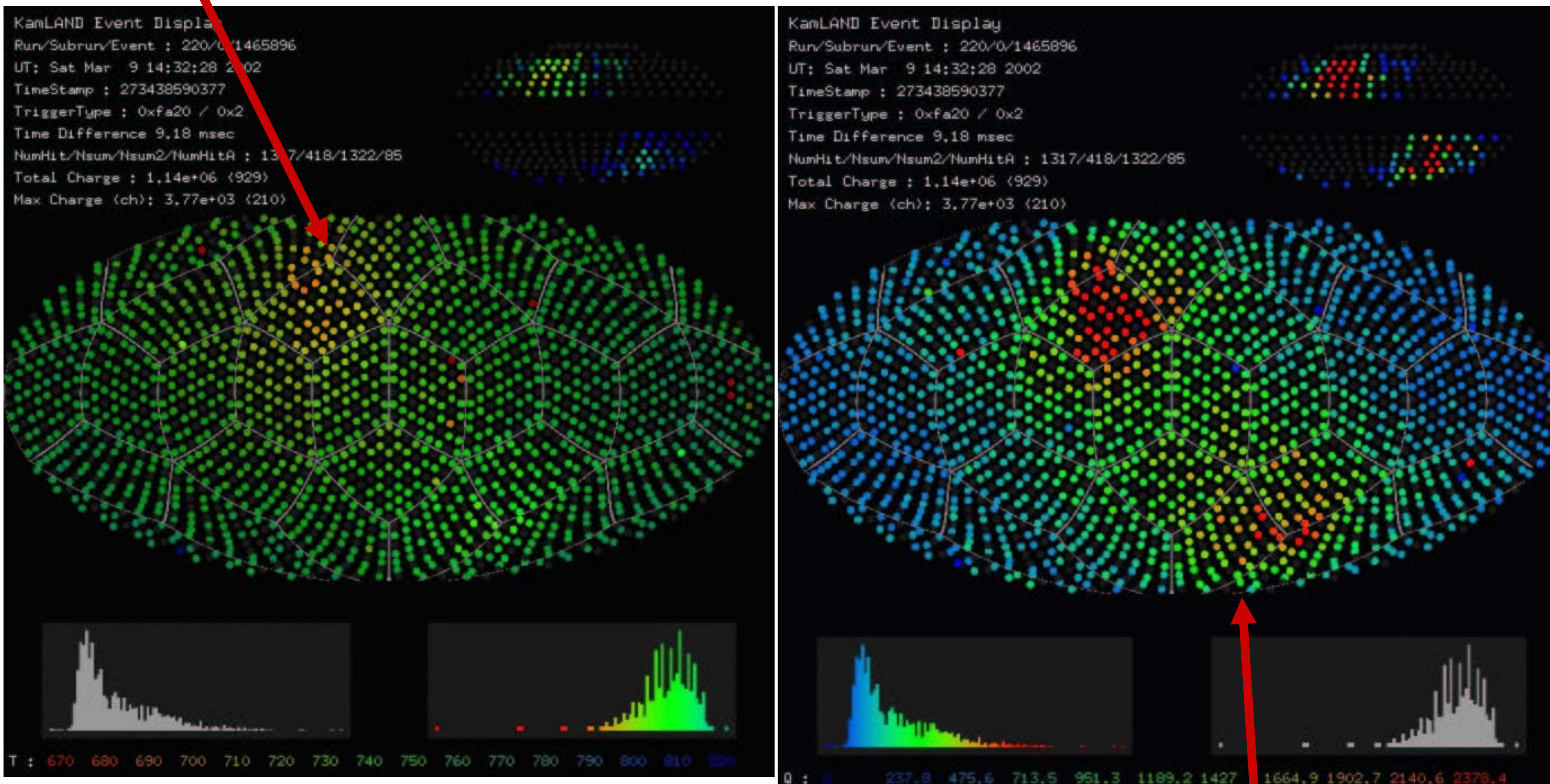


energy timing

KamLand background muon event

Largest bg: ^{8}He, ^{9}Li etc, β decay + neutron emission

enter



timing

energy

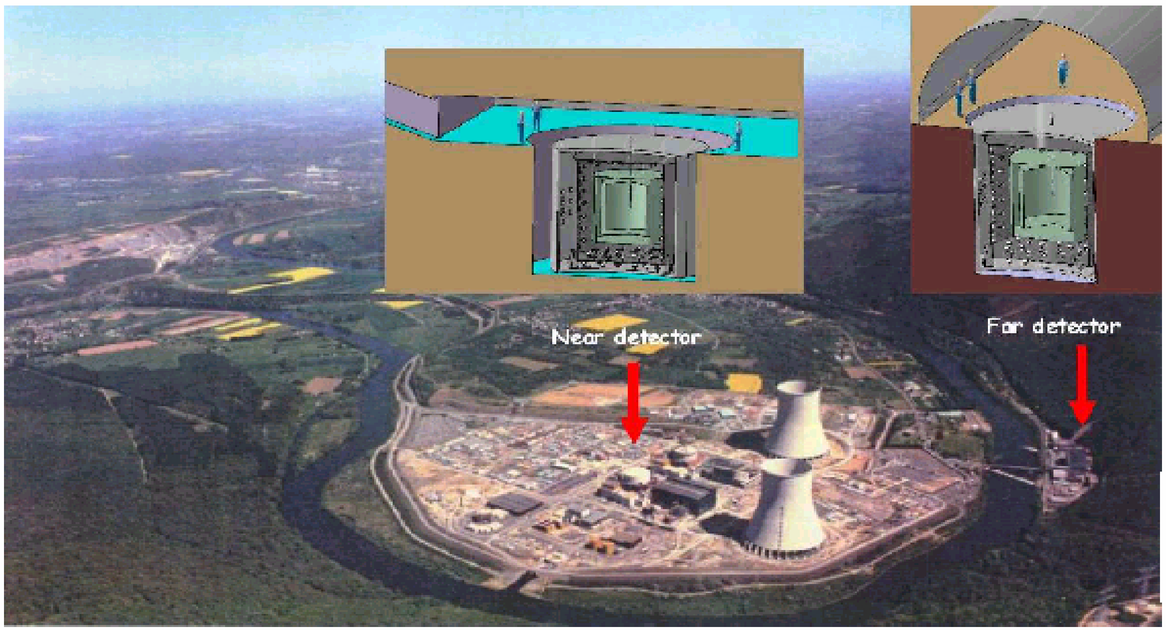
exit

Reject 2ms after muon

Double-Chooz

Double-Chooz site

Letter of Intent for Double-CHOOZ:
a search for the mixing angle θ_{13}

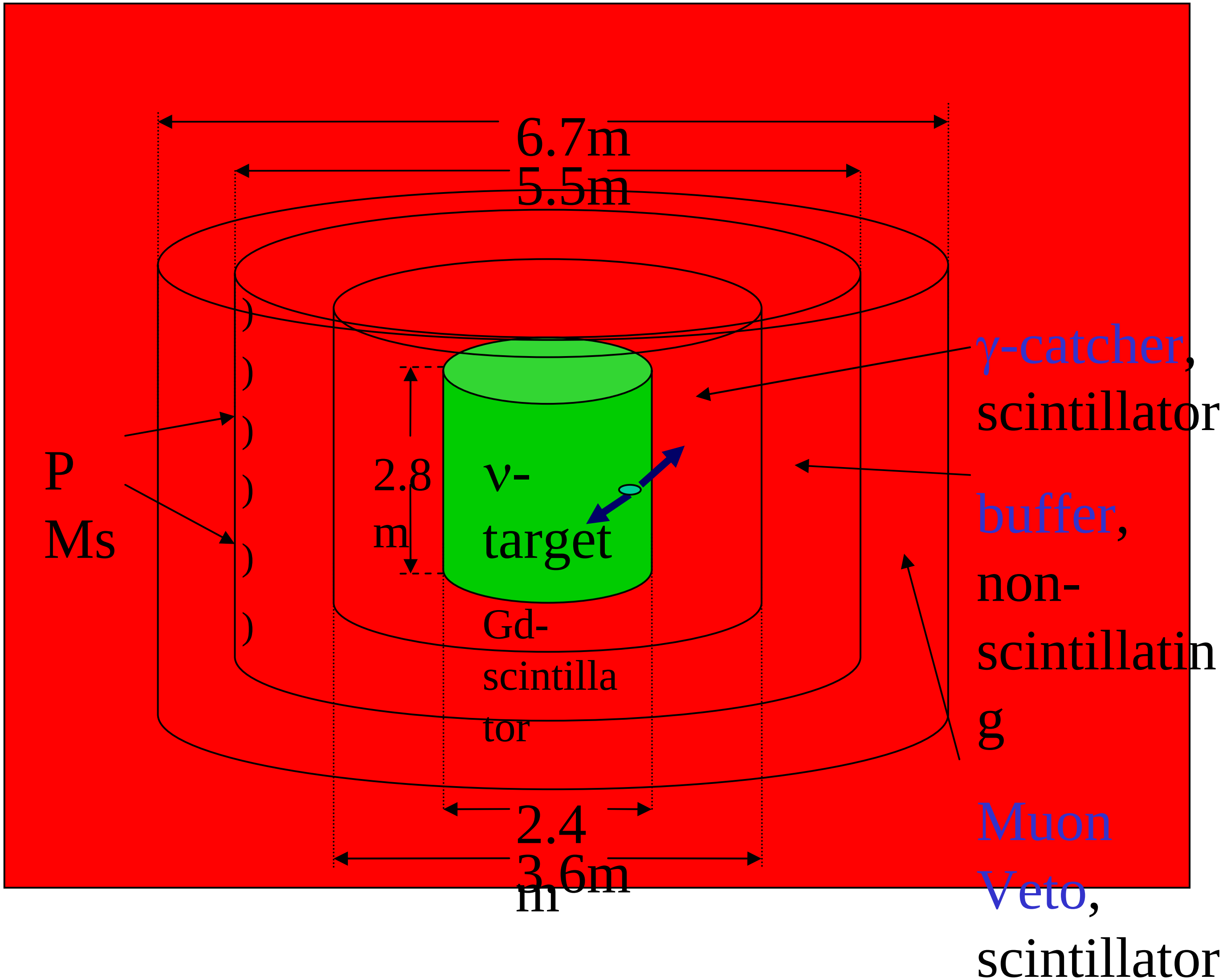


APC, Paris - RAS, Moscow - DAPNIA, Saclay - EKU-Tübingen - INFN, Assergi & Milano -MPIK, Heidelberg -Insitute Kurchatov, Moscow- TUM-München - University of l'Aquila -Universität Hamburg

Two identical
Near 100-200m
Far 1050m
12.7 m^3 Liquid scintillator loaded with 0.1%Gd.

hep-ex/0405032

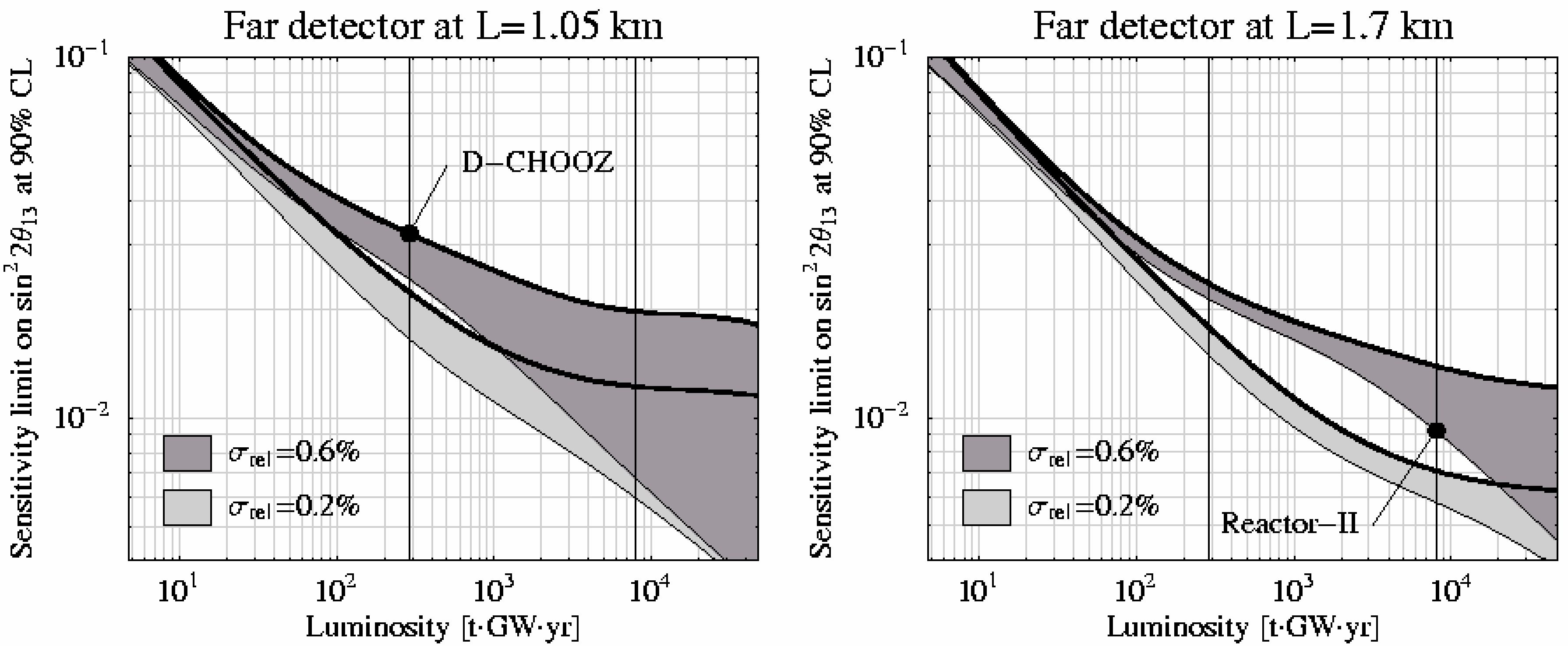
Detector



6.7m
5.5m
γ-catcher, scintillator
P Ms
2.8 m
ν-target
buffer, non-scintillating
Gd-scintillator
2.4 m
3.6m
Muon Veto, scintillator

Double-Chooz sensitivity on $\sin^2 2\theta_{13}$

Systematic uncertainty 0.6% (2.7% Chooz, with 2% from reactor)



sensitivity between 0.02 and 0.03

after ~3 years (for Δm2 = 2.0 10-3 eV2)

Start 2008, reach 0.05 in 2009 and 0.03 in 2011

Conclusion

I hope you learned something here…