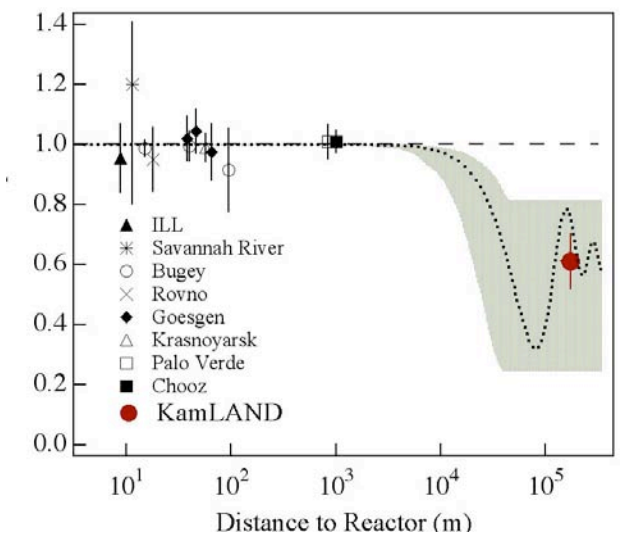
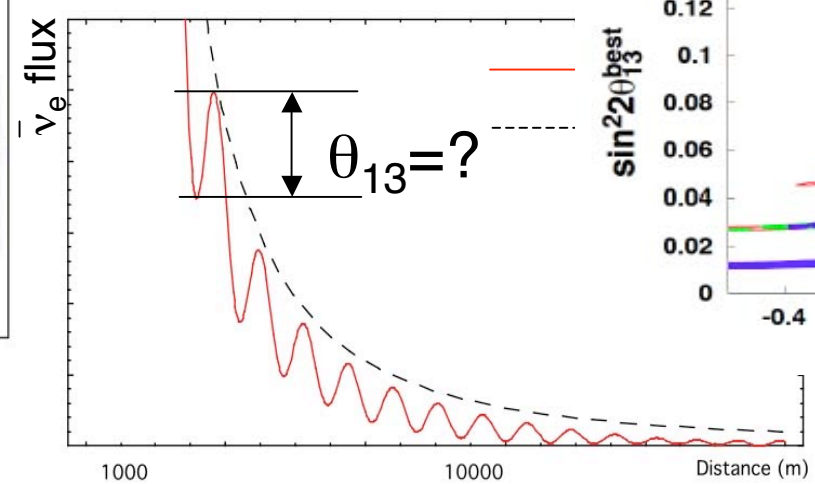
Measuring θ_{13} with Reactors and the Search for Leptonic CP Violation

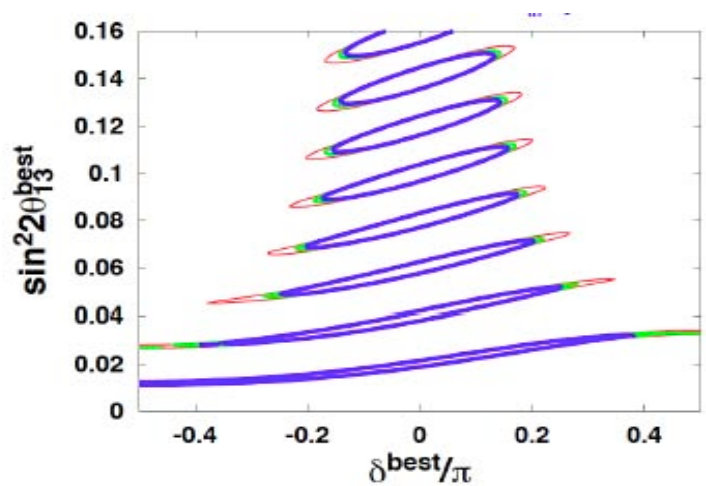
- Future Prospects in Neutrino Oscillation Physics -

Karsten M. Heeger

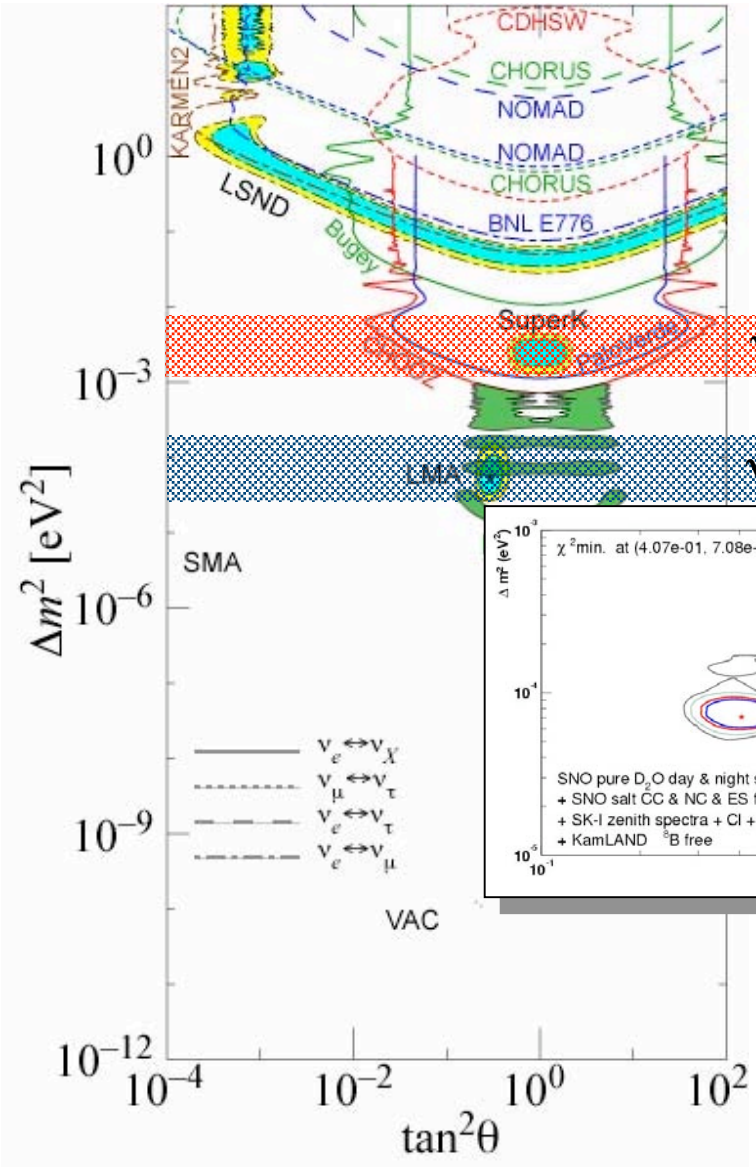
Lawrence Berkeley National Laboratory





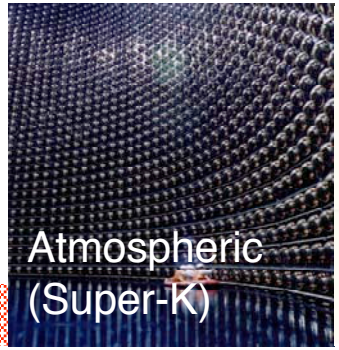


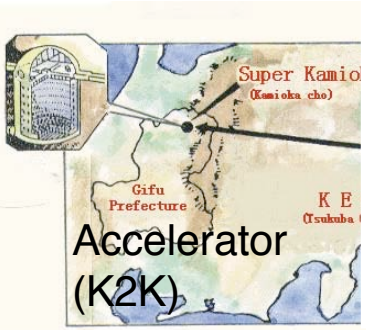
Recent Discoveries in Neutrino Oscillation Physics



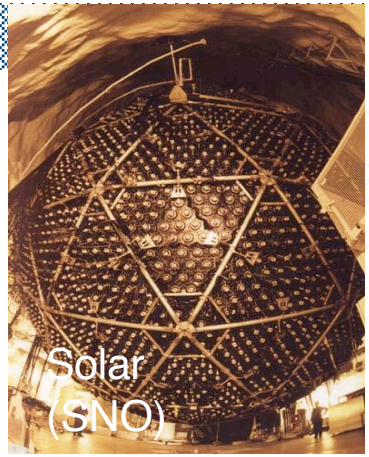
$\nu_\mu \Rightarrow \nu_\tau$

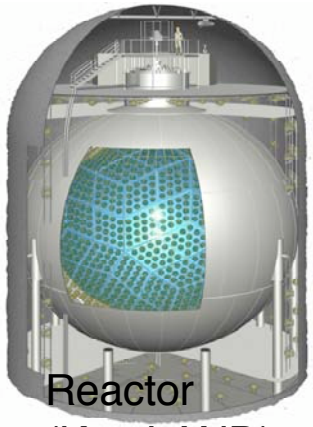
$\nu_e \Rightarrow \nu_{\mu,\tau}$





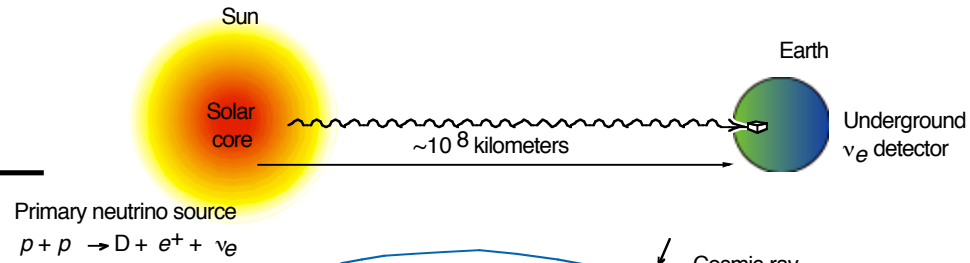
Accelerator
(K2K)





- Neutrinos are <u>not massless</u>
- <u>Evidence</u> for neutrino flavor conversion $\nu_e \Leftrightarrow \nu_\mu \Leftrightarrow \nu_\tau$
- Experimental results show that <u>*neutrinos oscillate*</u>

Experimental Studies



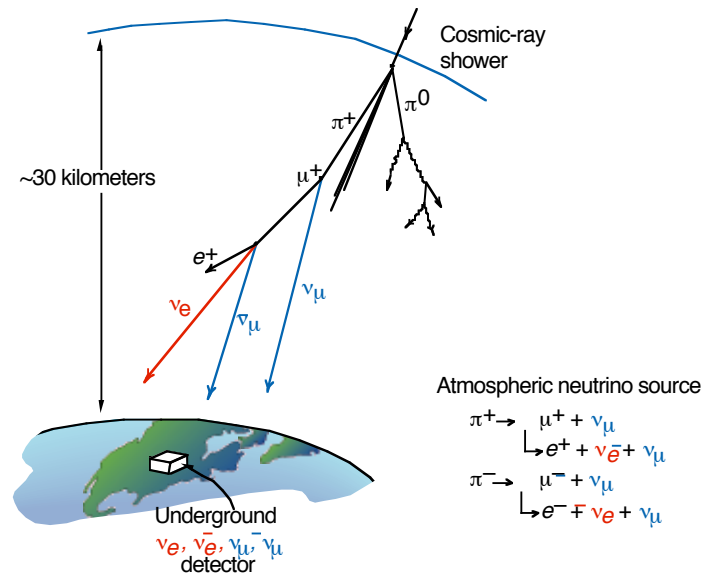
Natural Sources

The Sun

^{37}Cl	Kamiokande
GALLEX	SuperKamiokande
SAGE	SNO ★

Atmospheric Neutrinos

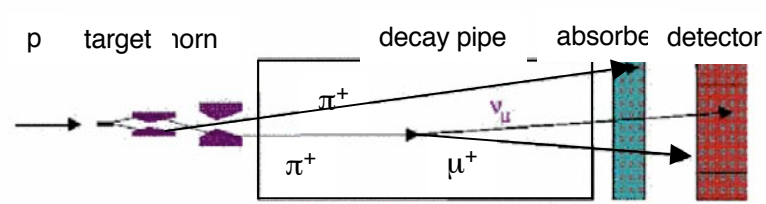
IMB	Kamiokande ★
Soudan	SuperKamiokande
MACRO	•••



Man-Made Sources

Accelerators

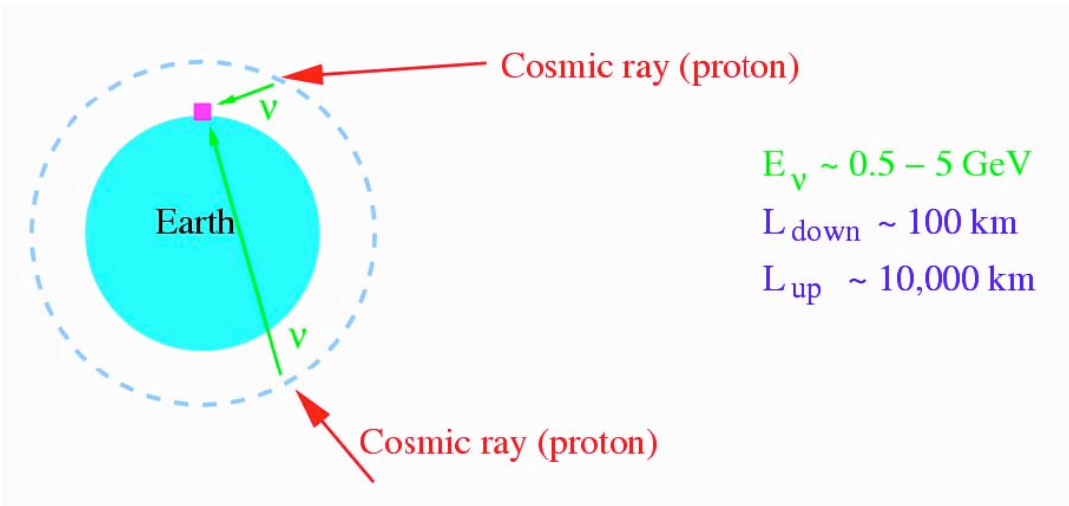
K2K ★	Chorus
Opera	(LSND)
…	

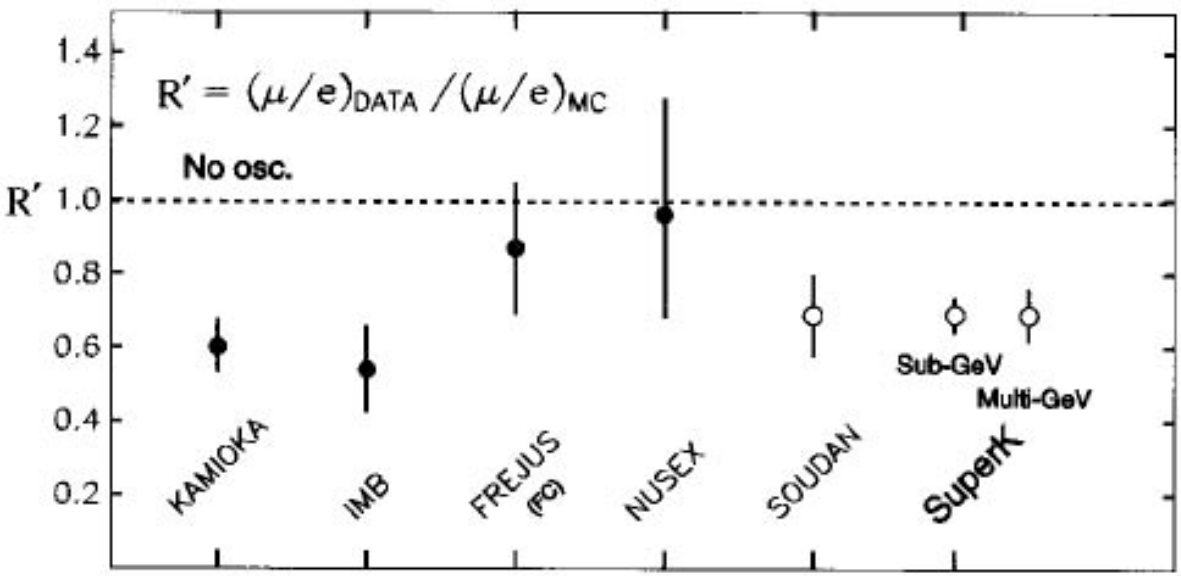


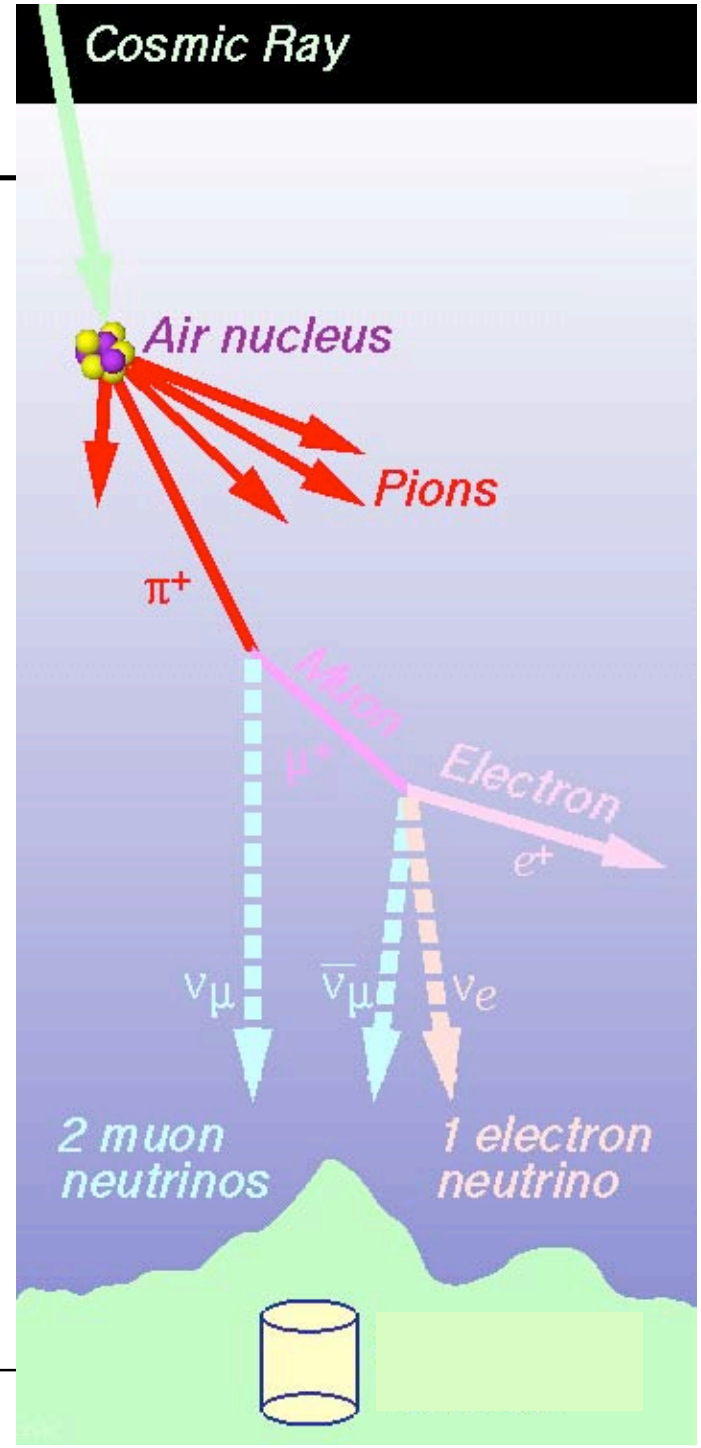
Nuclear Reactors

Bugey	Goesgen
ILL	Chooz
Palo Verde	KamLAND ★

Atmospheric Neutrino Studies

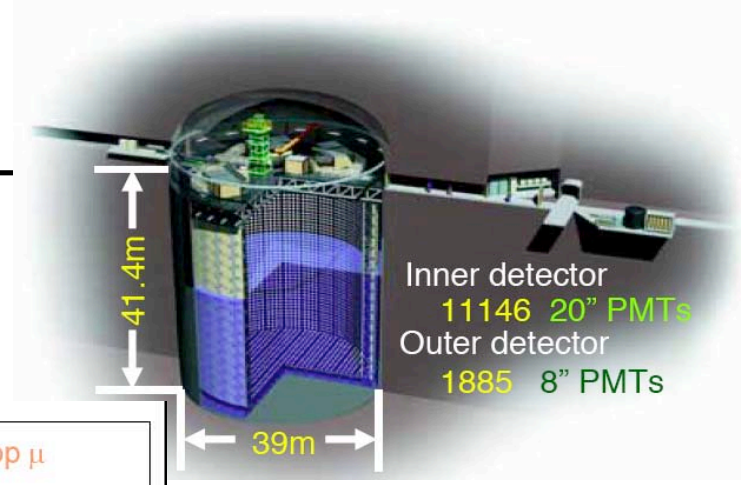


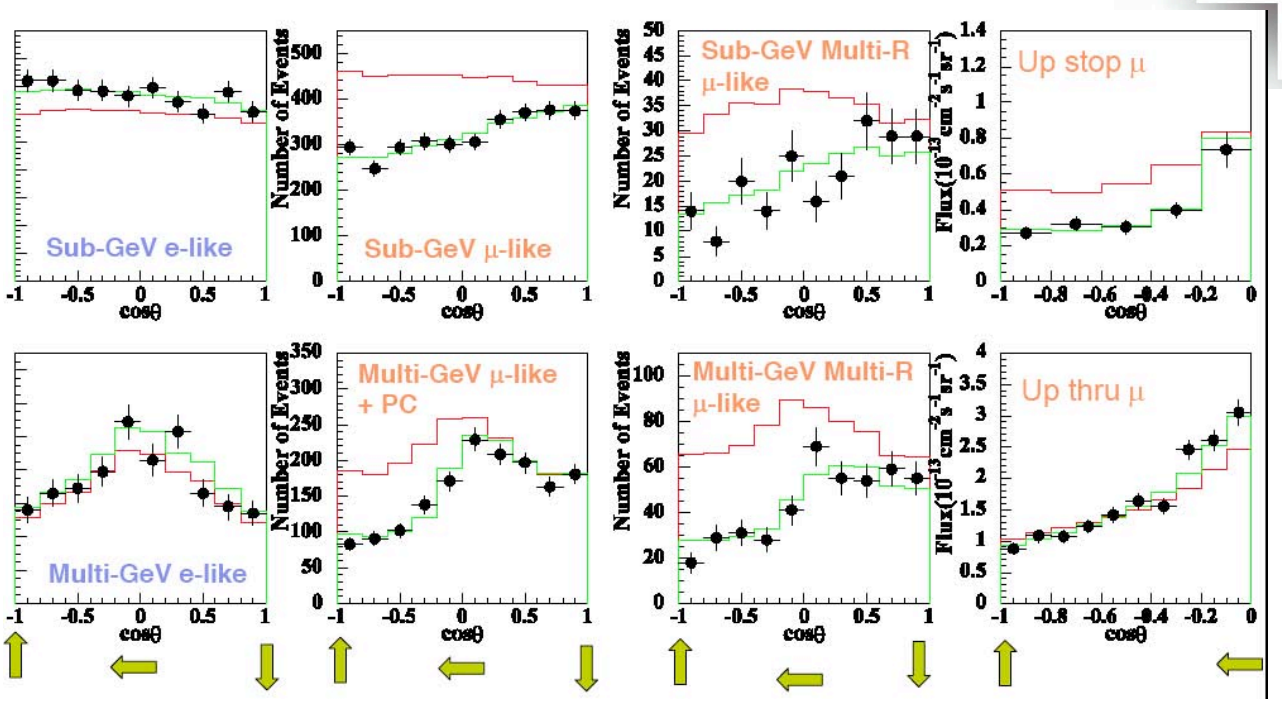




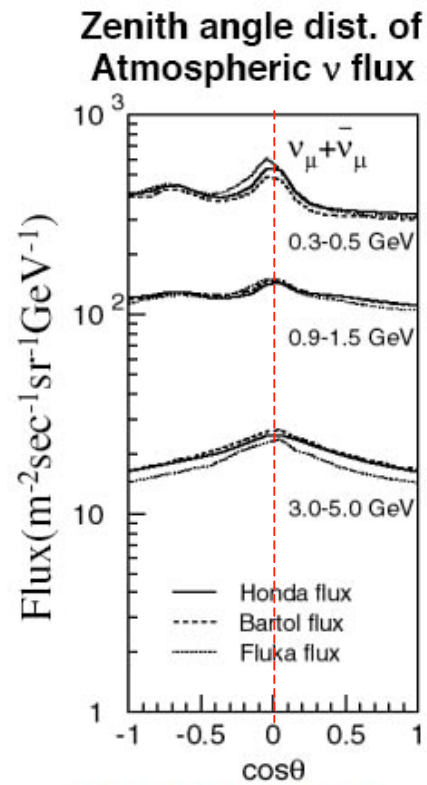
Super-Kamiokande

Atmospheric Neutrino Studies





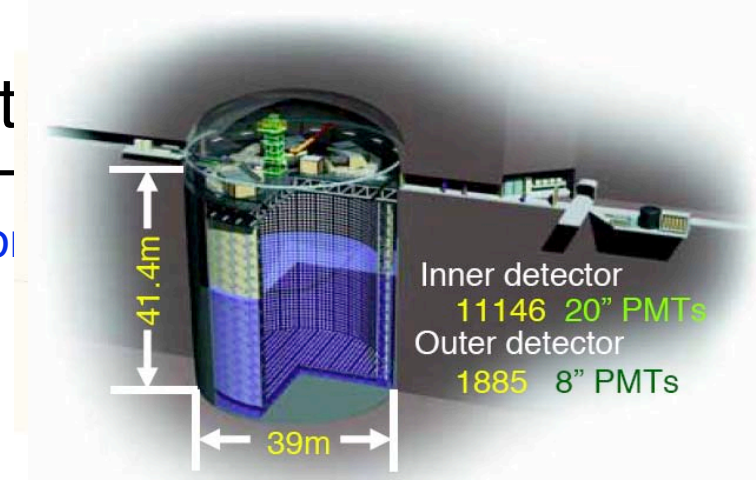
Best fit $\nu_\mu \rightarrow \nu_\tau$ 2-flavor osc.
$\sin^2 2\theta = 1.0$, $\Delta m^2 = 2.0 \times 10^{-3}$ eV^2
Null oscillation



Eν > a few GeV
Up/Down Symmetry

KEK to Kamioka (K2K) Experiment

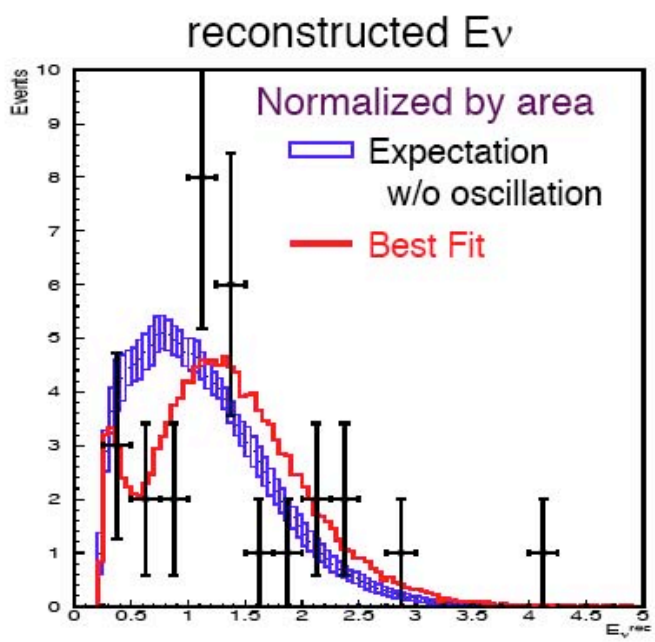
Accelerator-based long baseline neutrino oscillation experiment to test atmospheric oscillations

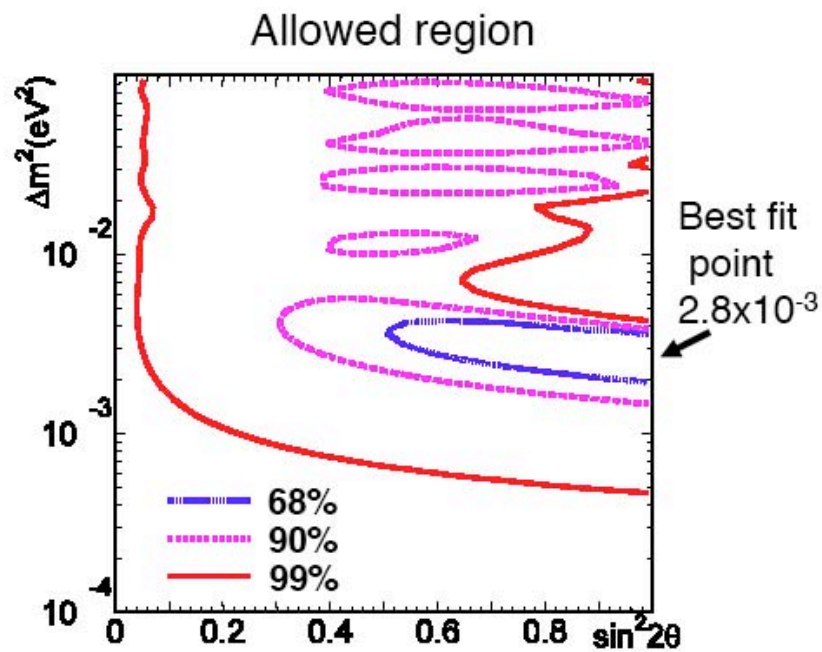


	atm	K2K
L	$10\text{-}10^4$ km	250 km
E_ν	0.1~100 GeV	~ 1.3 GeV
Δm^2	$10^{-1}\sim10^{-4}$ eV^2	> 2×10^{-3} eV^2
ν_e/ν_μ	50%	~1%

data from 1999-2001

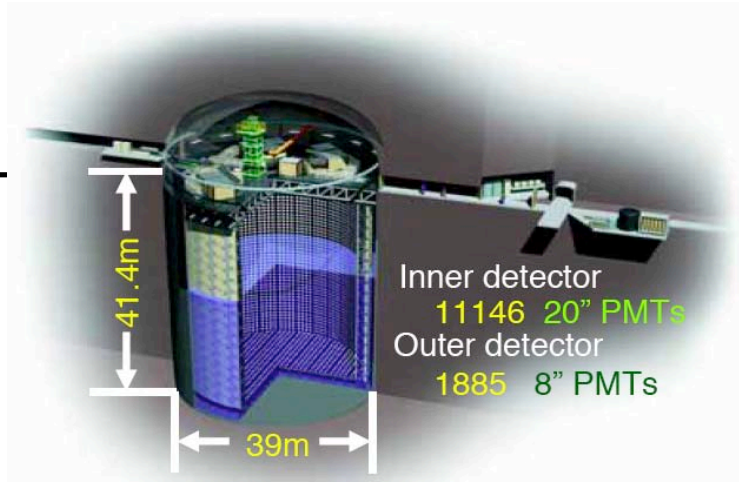
expected: 80.1 events
observed: 56 events

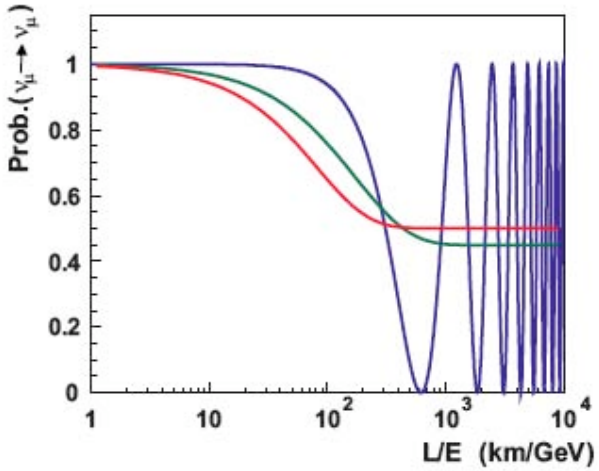




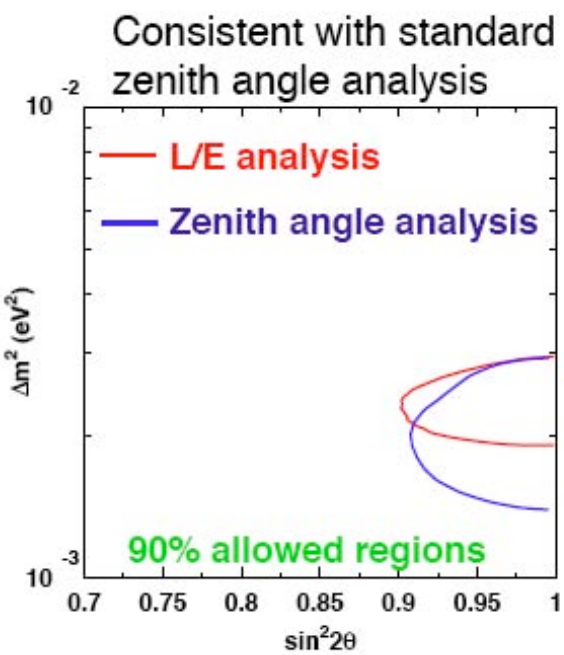
Super-Kamiokande L/E Analysis

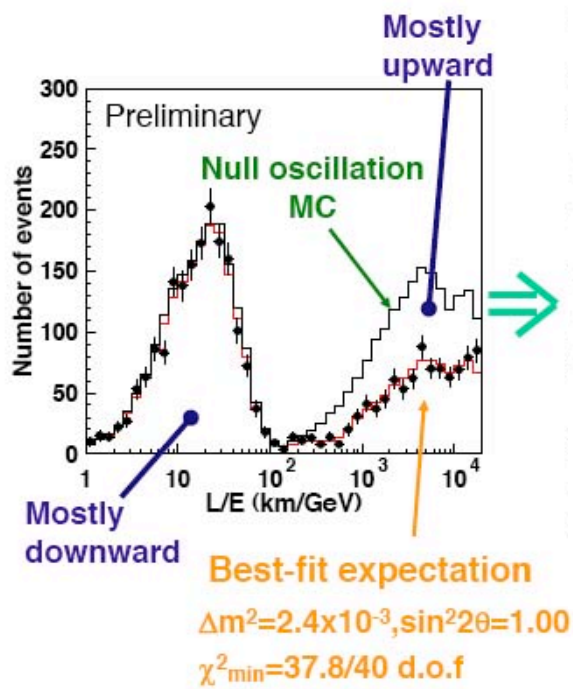
Searching for Direct Evidence of Oscillations

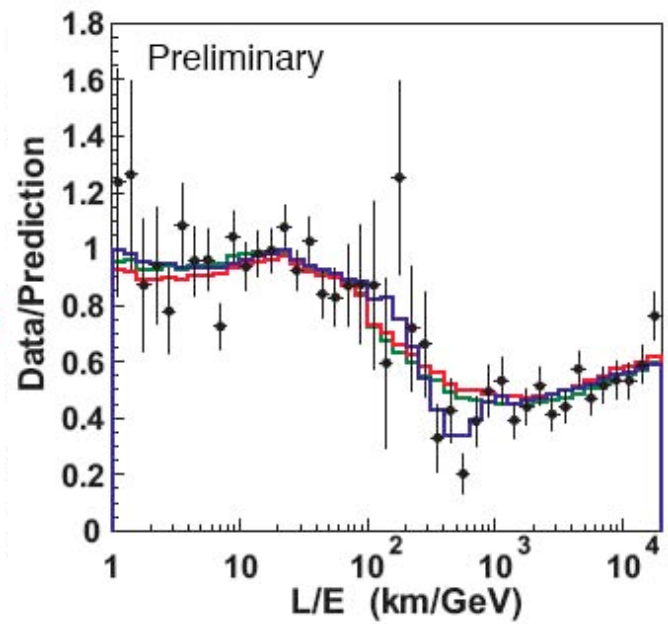




Neutrino oscillation
Neutrino decay
Neutrino decoherence

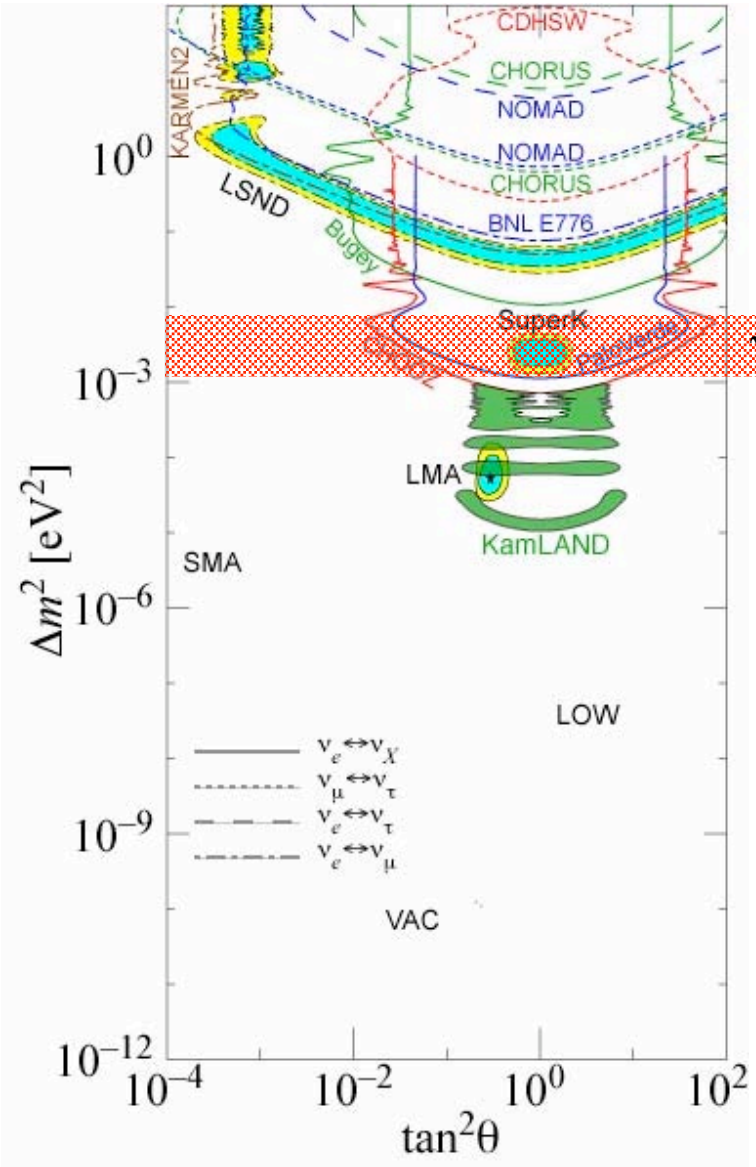




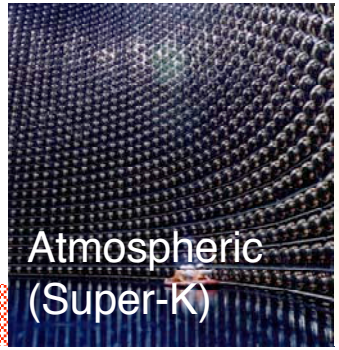


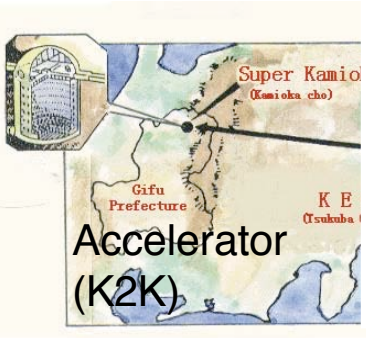
First dip is observed as expected from neutrino oscillation

Atmospheric Neutrino Oscillations



$\nu_\mu \Rightarrow \nu_\tau$





Atmospheric ν data explained extremely well by oscillations

- primarily $\nu_\mu \rightarrow \nu_\tau$ conversion
- mixing angle θ_{23} is near maximal
- $\Delta m^2 \sim 2 \times 10^{-3}$ eV^2

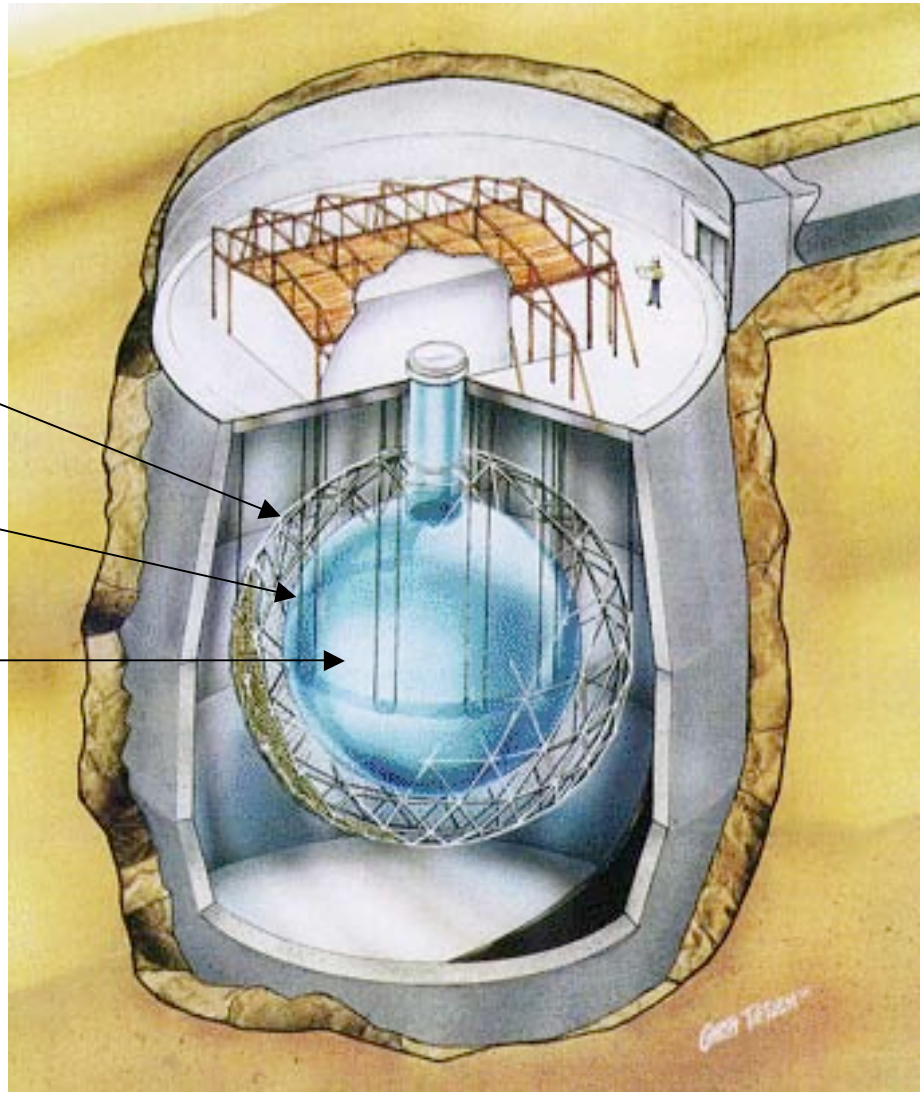
Sudbury Neutrino Observatory

2092 m to Surface (6010 m w.e.)

PMT Support Structure, 17.8 m
9456 20 cm PMTs
~55% coverage within 7 m

Acrylic Vessel, 12 m diameter

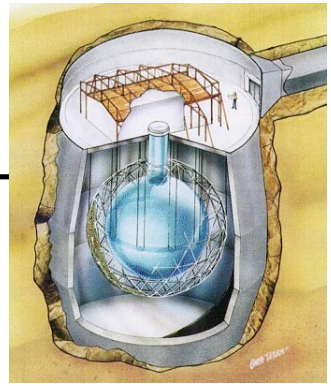
1000 Tonnes D_2O



Need solar model-independent measurement.

Need experiment that measures ν_e and $\nu_{\mu,\tau}$ separately.

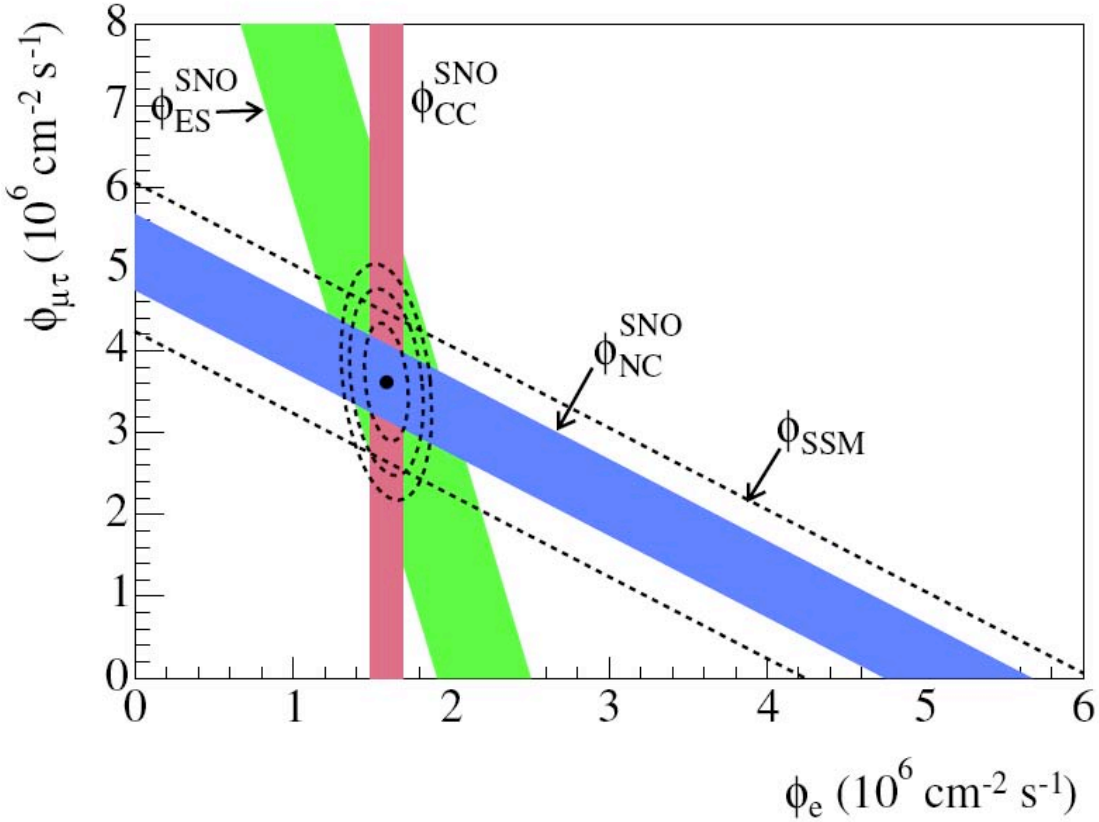
Flavor Content of ^{8}B Solar Neutrino Flux



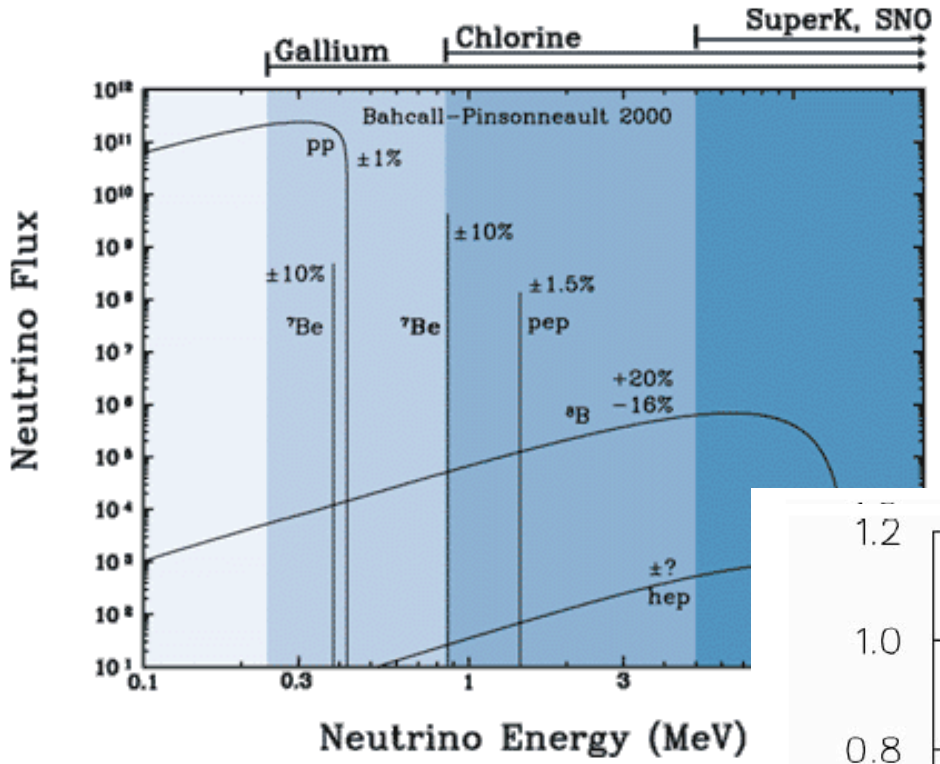
^{8}B Standard Solar Model (SSM01)	5.05	x 10^6 cm^{-2} s^{-1}
NC Salt Constrained	4.90 ± 0.38 x 10^6 cm^{-2} s^{-1}	
NC Salt Unconstrained	5.21 ± 0.47 x 10^6 cm^{-2} s^{-1}	

CC/NC Ratio

0.306 ± 0.026 (stat) ± 0.024 (sys)

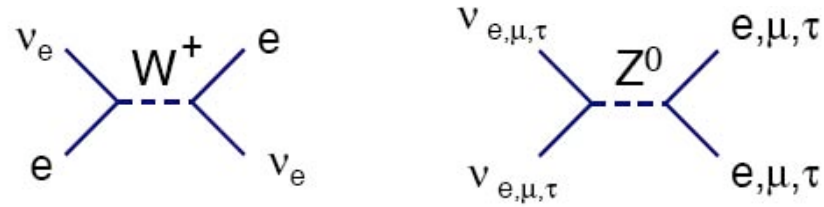


Oscillation Interpretation of Solar Neutrino Data

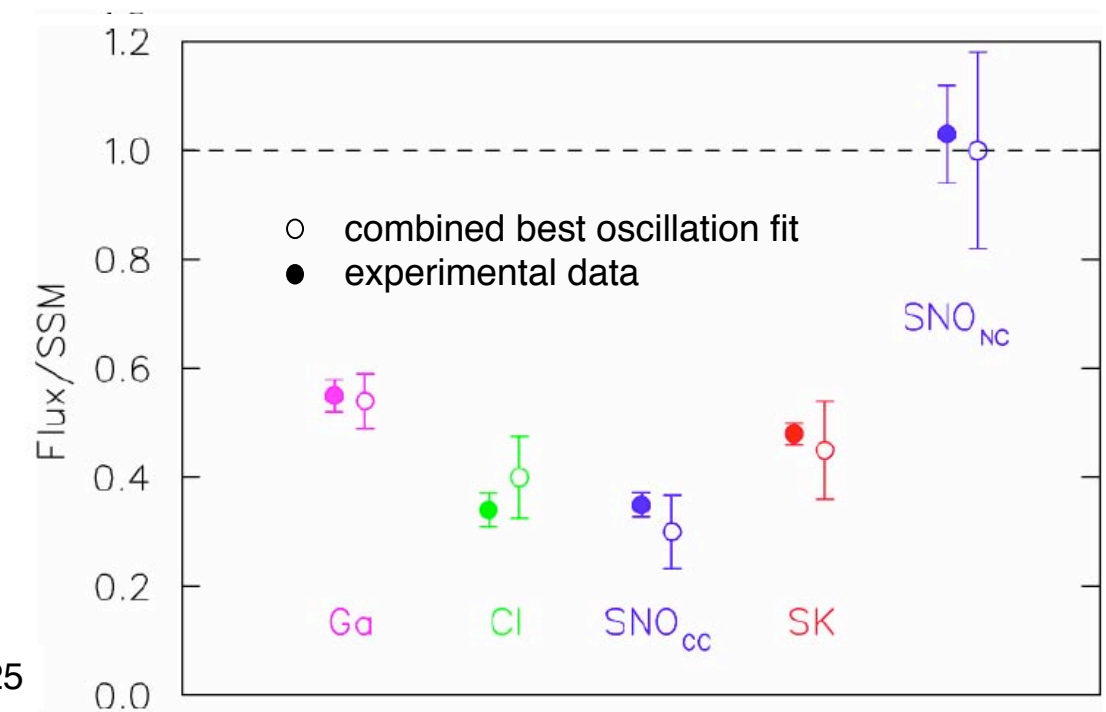


Energy-dependent effect

Neutrinos interact with matter in Sun and Earth (MSW)



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{23} \times U_{13} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



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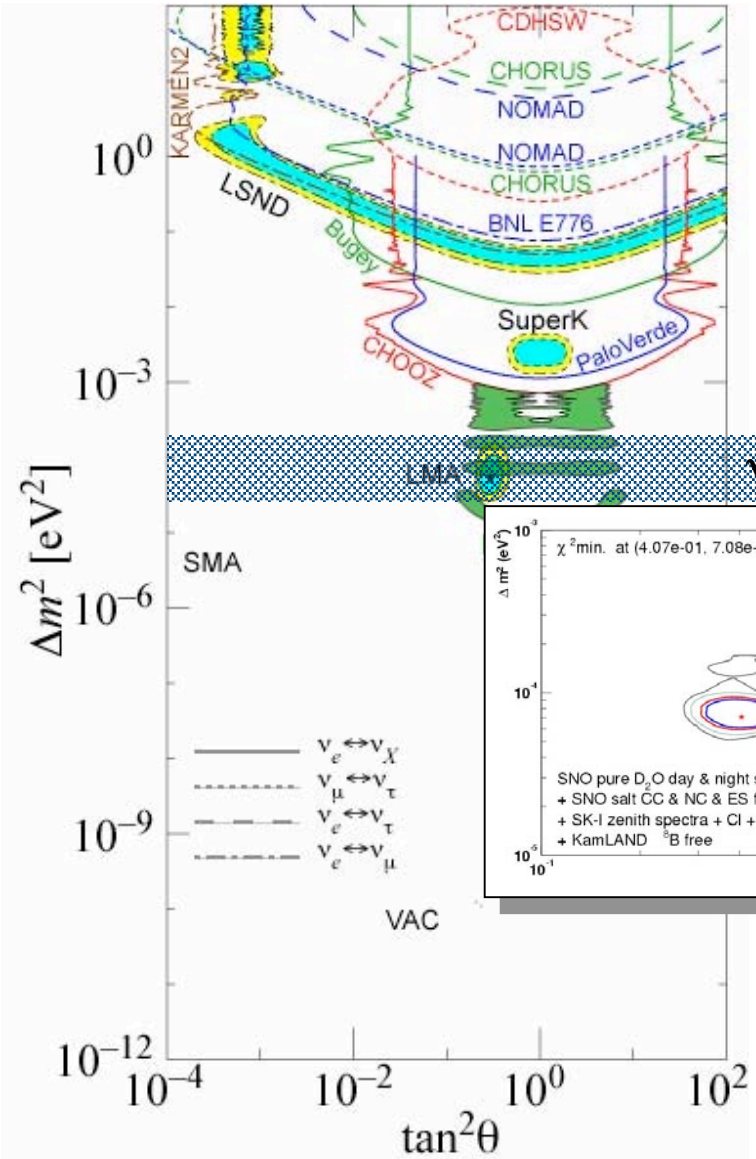
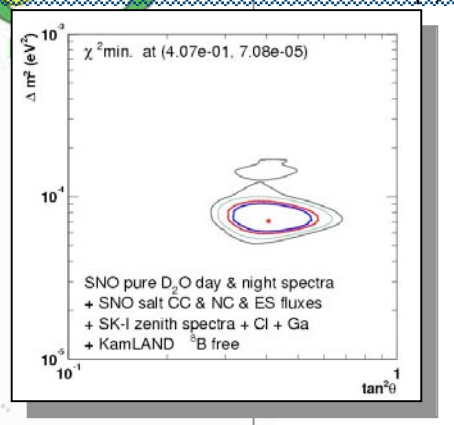
Solar Neutrino Oscillations

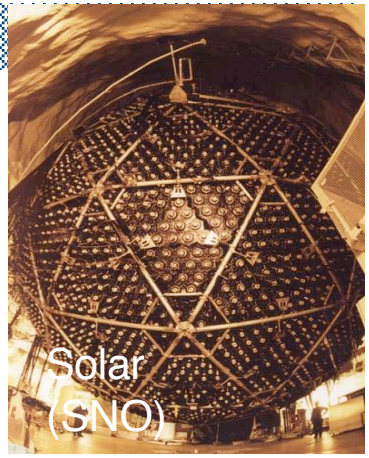


Flavor conversion of solar $\nu_e \rightarrow \nu_{\mu,\tau}$

mixing angle θ_{12} is large but not maximal, $\Delta m_{12} \sim 7 \times 10^{-5}$ eV^2

$\nu_e \Rightarrow \nu_{\mu,\tau}$





- matter effects enhance oscillation
- other modes for solar neutrino flavor transformation (sterile, RSFP, CPT …) can play only a subdominant role.

Neutrino Oscillation Experiments

Reactor and Beamstop Neutrinos

$\nu_\mu \Rightarrow \nu_s \Rightarrow \nu_e$

Atmospheric and Reactor Neutrinos

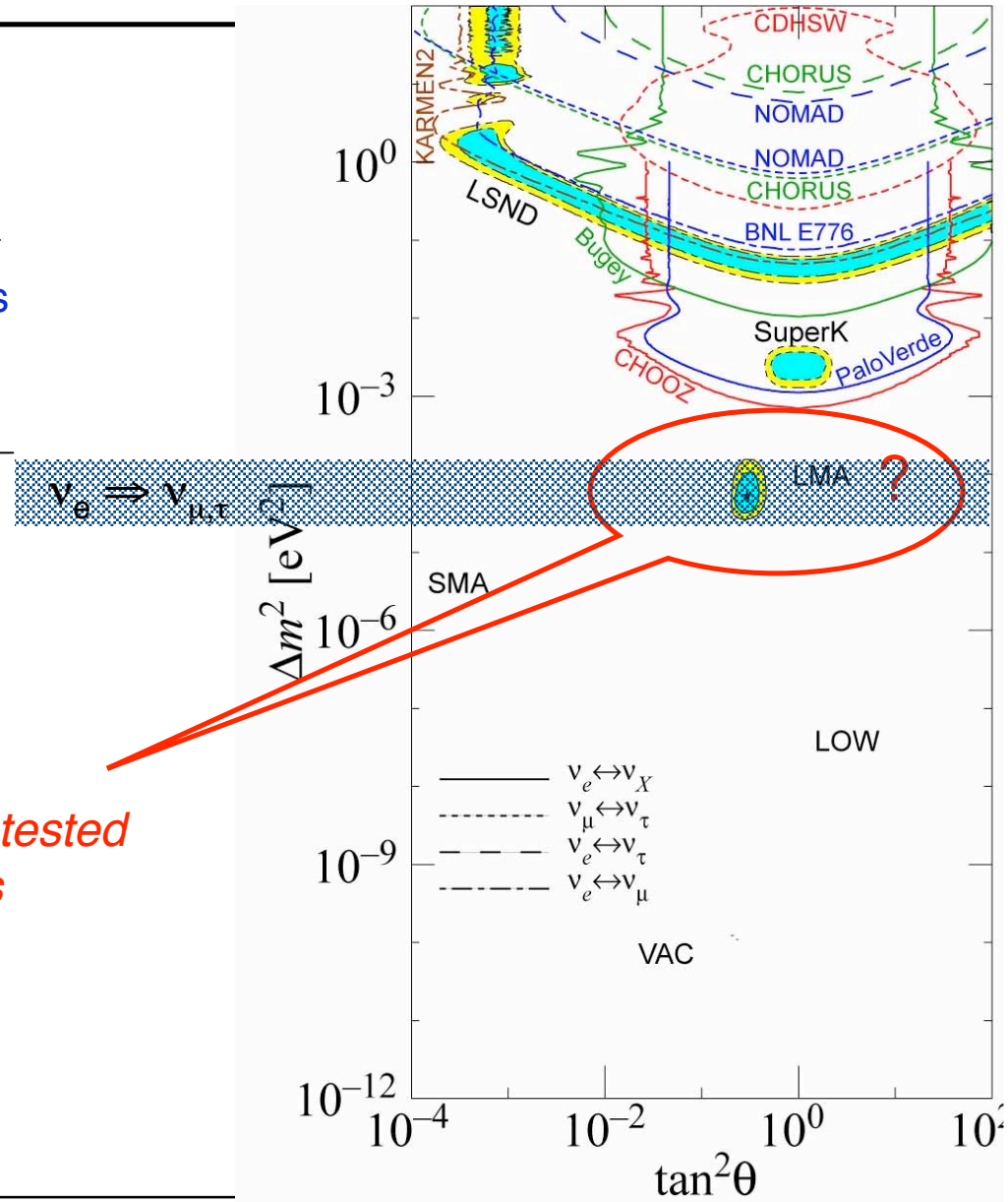
$\nu_\mu \Rightarrow \nu_\tau$

Solar and Reactor Neutrinos

$\nu_e \Rightarrow \nu_{\mu,\tau}$

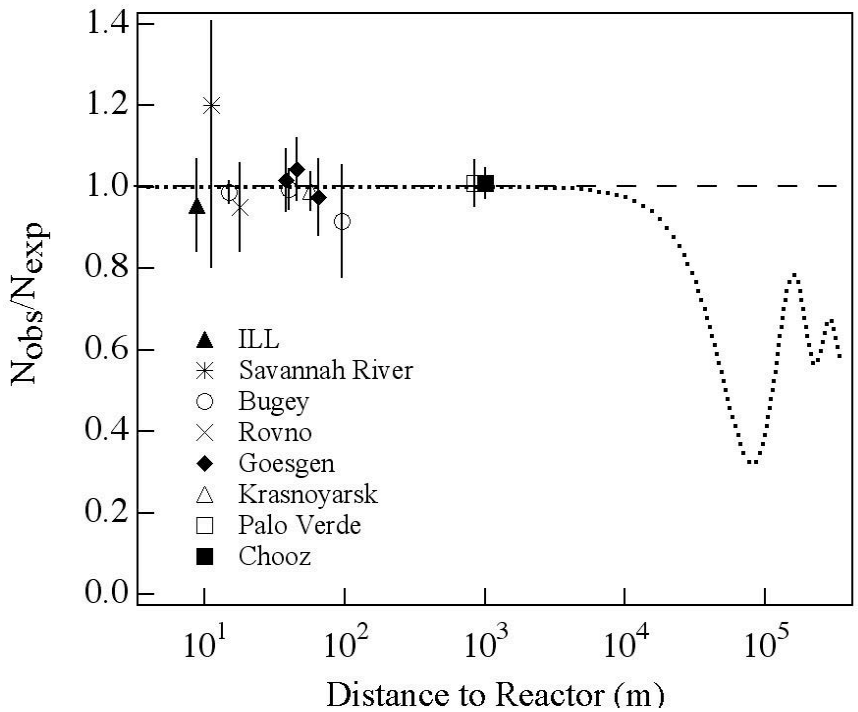
Large mixing favored

***LMA** solution can be tested with reactor neutrinos*



Status: Summer 2002

Search for Neutrino Oscillations with Reactor Neutrinos



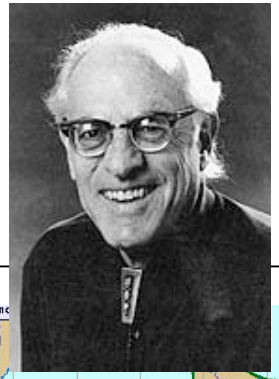
50 Years of Reactor Neutrino Physics

1953 First reactor neutrino experiment

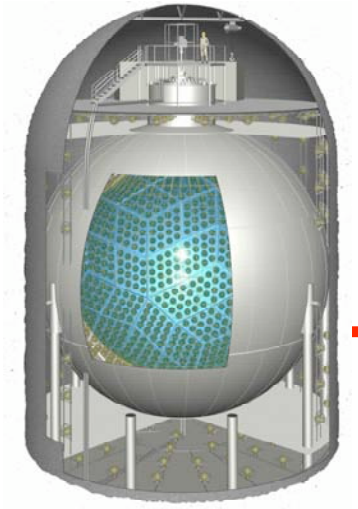
1956 *"Detection of Free Antineutrino"*, Reines and Cowan

→ Nobel Prize in 1995

No signature of neutrino oscillations until 2002!

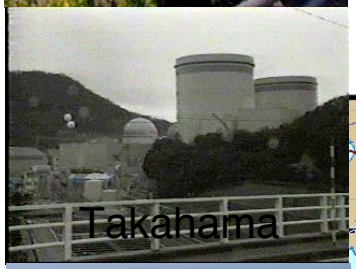


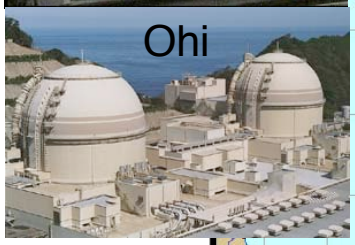
Results from solar experiments suggest study of reactor neutrinos with a baseline of ~ 70 km

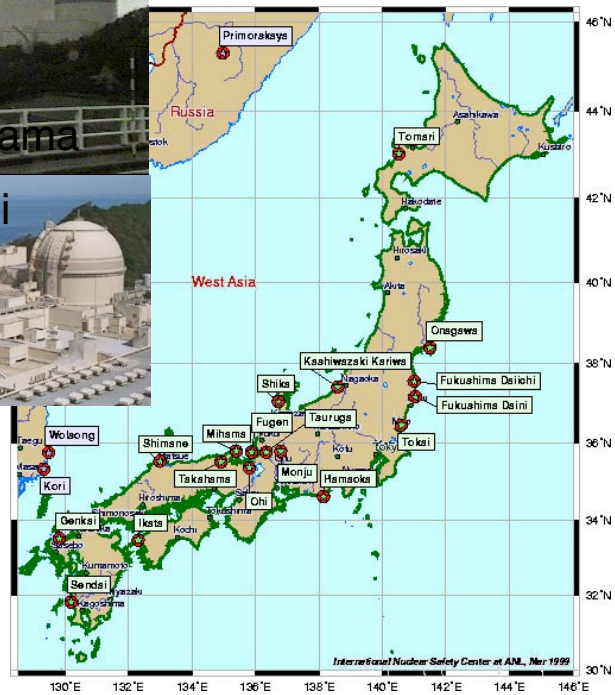


Reactor Antineutrinos

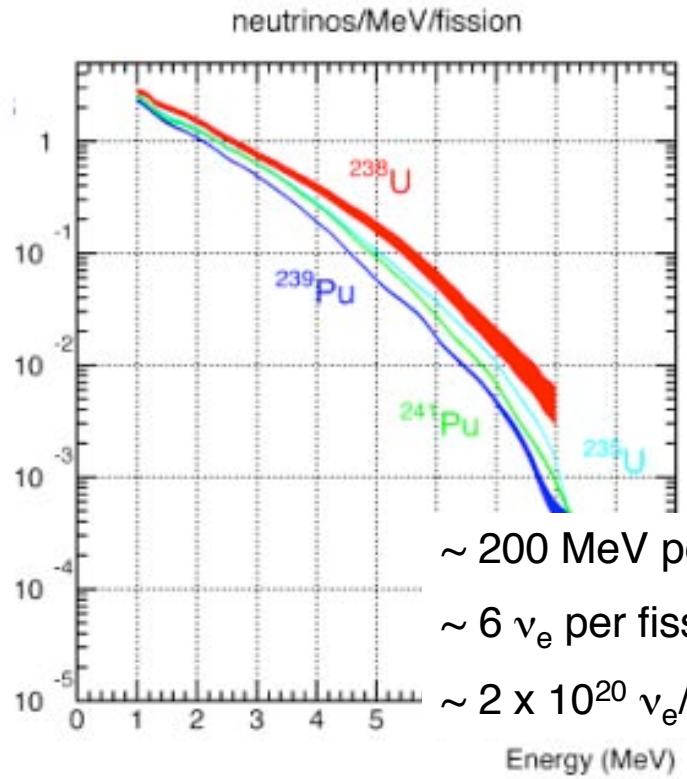
From Japanese Reactors







Spectrum from Principal Reactor Isotopes

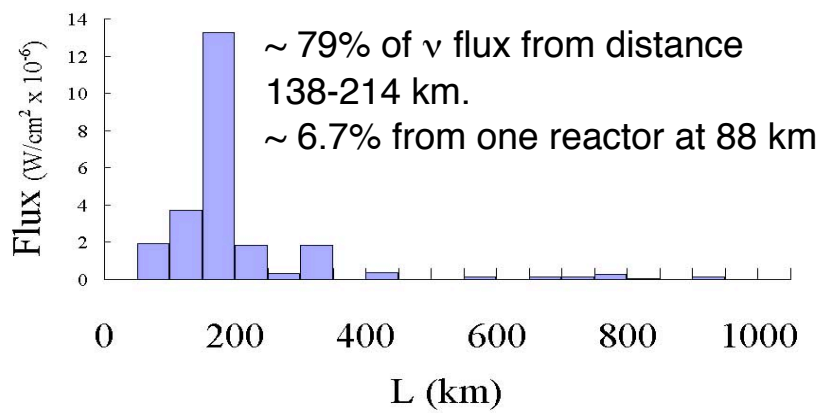


~ 200 MeV per fission

~ 6 ν_e per fission

~ 2 x 10^{20} ν_e/GW_{th}-sec

Neutrino Flux at KamLAND



~ 79% of ν flux from distance 138-214 km.

~ 6.7% from one reactor at 88 km.

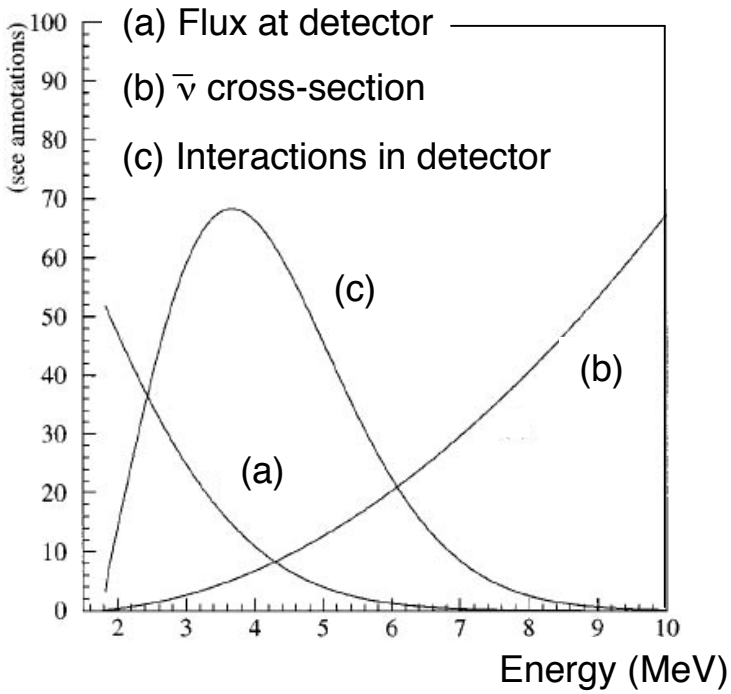
KamLAND - Kamioka Liquid Scintillator Antineutrino Detector

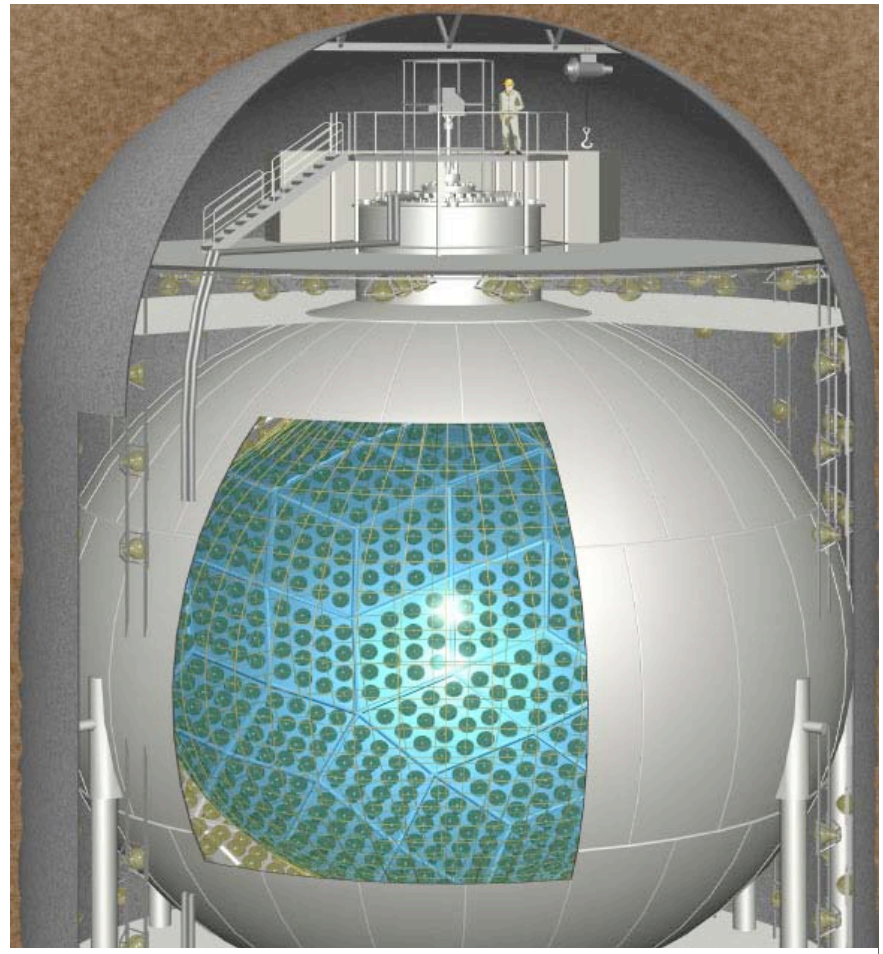
Uses reactor neutrinos to study $\bar{\nu}$ oscillation with a baseline of L ~ 140-210 km

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

Prompt e^+ annihilation

Delayed n capture, ~ 190 μs capture time

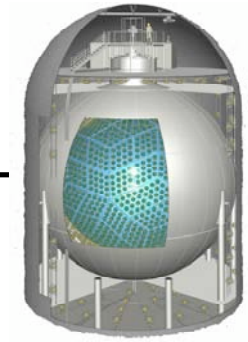




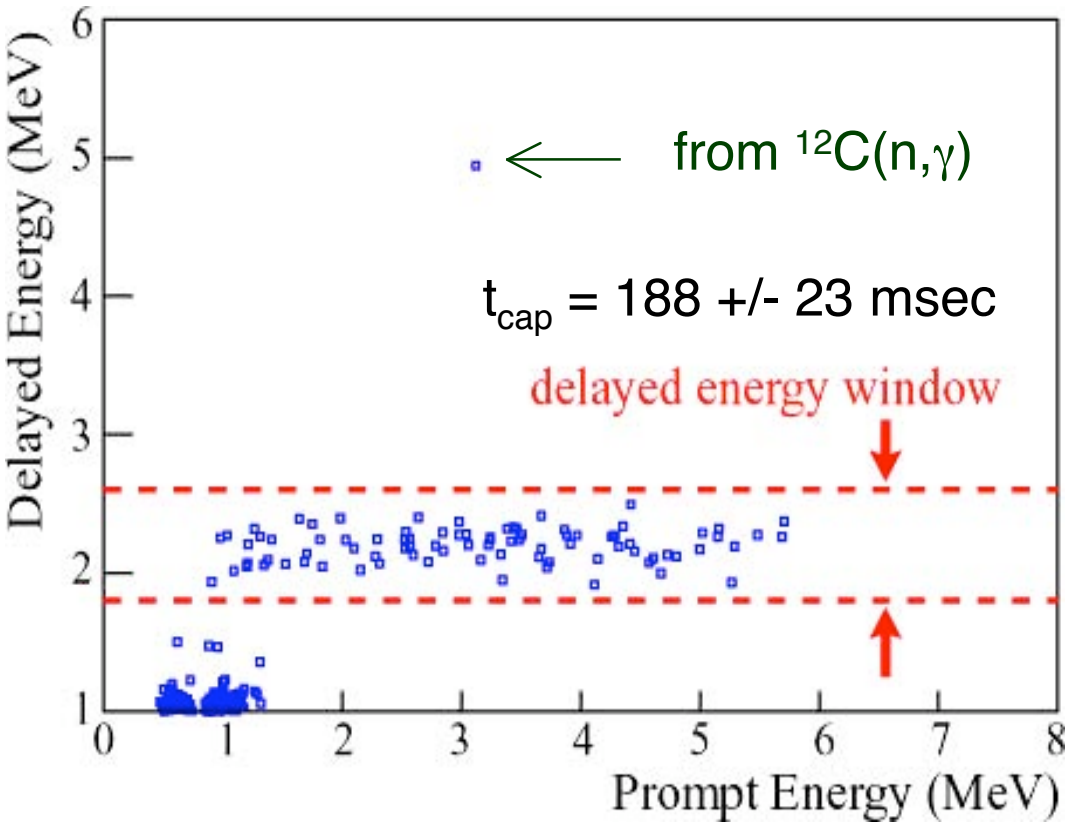
KamLAND studies the disappearance of $\bar{\nu}_e$ and measures

- interaction rate
- energy spectrum

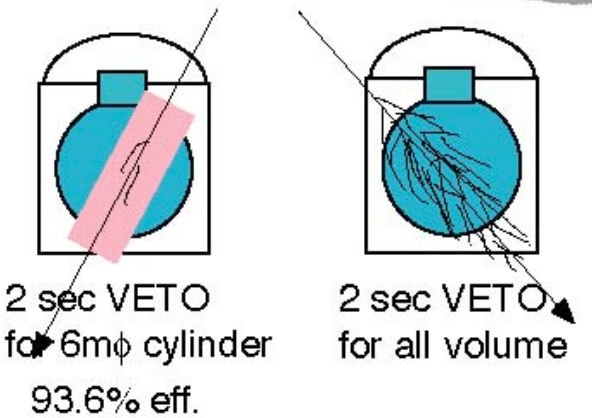
Event Selection



Delayed Energy Window



Muon veto



Vertex and Time Correlation

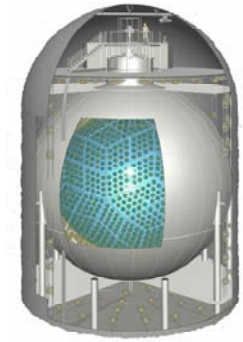
R < 5 m

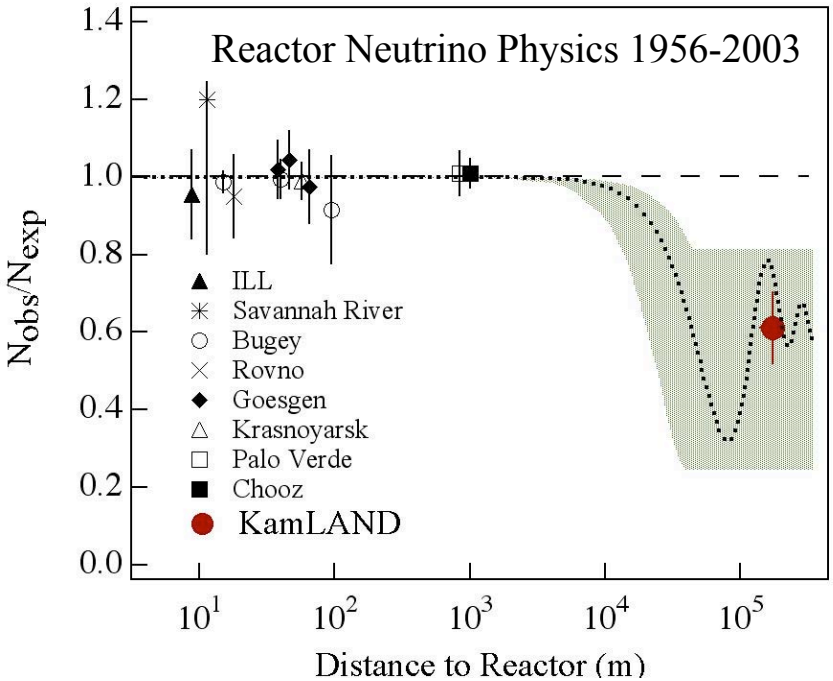
0.5 < |dT| < 660 μsec

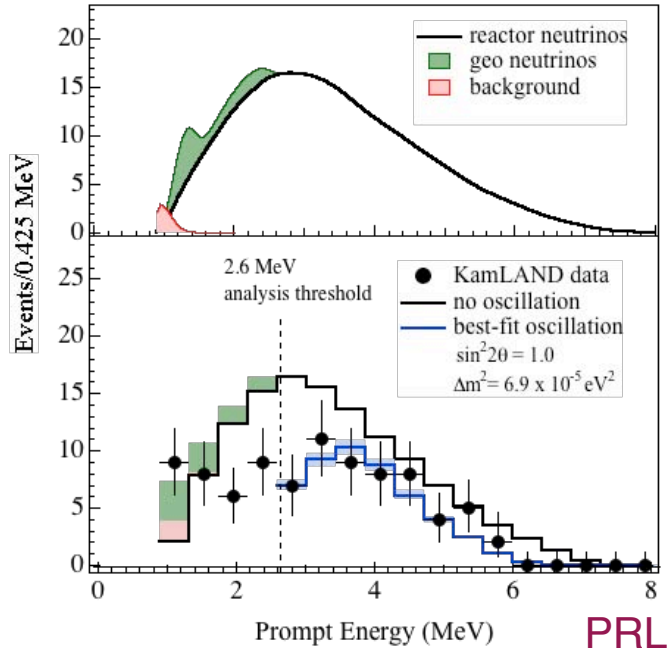
|dR| < 1.6 *m*

|dZ| > 1.2 *m*

First Direct Evidence for Reactor $\overline{\nu}_e$ Disappearance





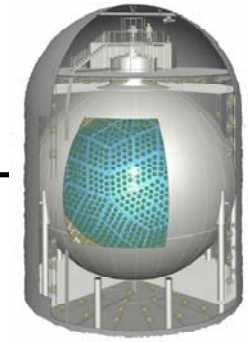


PRL 90:021802, 2003

Observed	**54 events**	syst err. 6.4%
	162 ton•yr, $E_{prompt} > 2.6$ *MeV*	
No-Oscillation	**86.8 ± 5.6 events**	
Background	1 ± 1 events	
accidental	*0.0086 ± 0.0005*	
^{9}Li/^{8}He	*0.94 ± 0.85*	
fast neutron	*< 0.5*	

KamLAND provides evidence for neutrino oscillations together with solar experiments.

KamLAND - Systematic Uncertainties

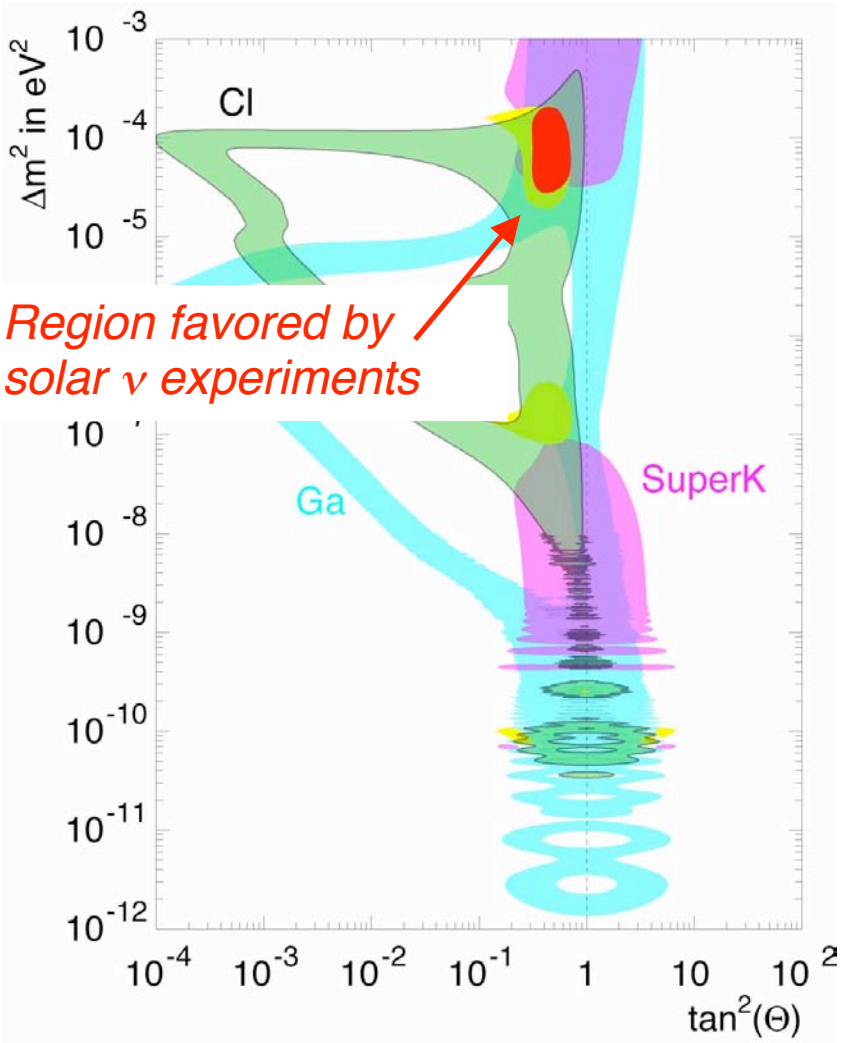


E > 2.6 MeV

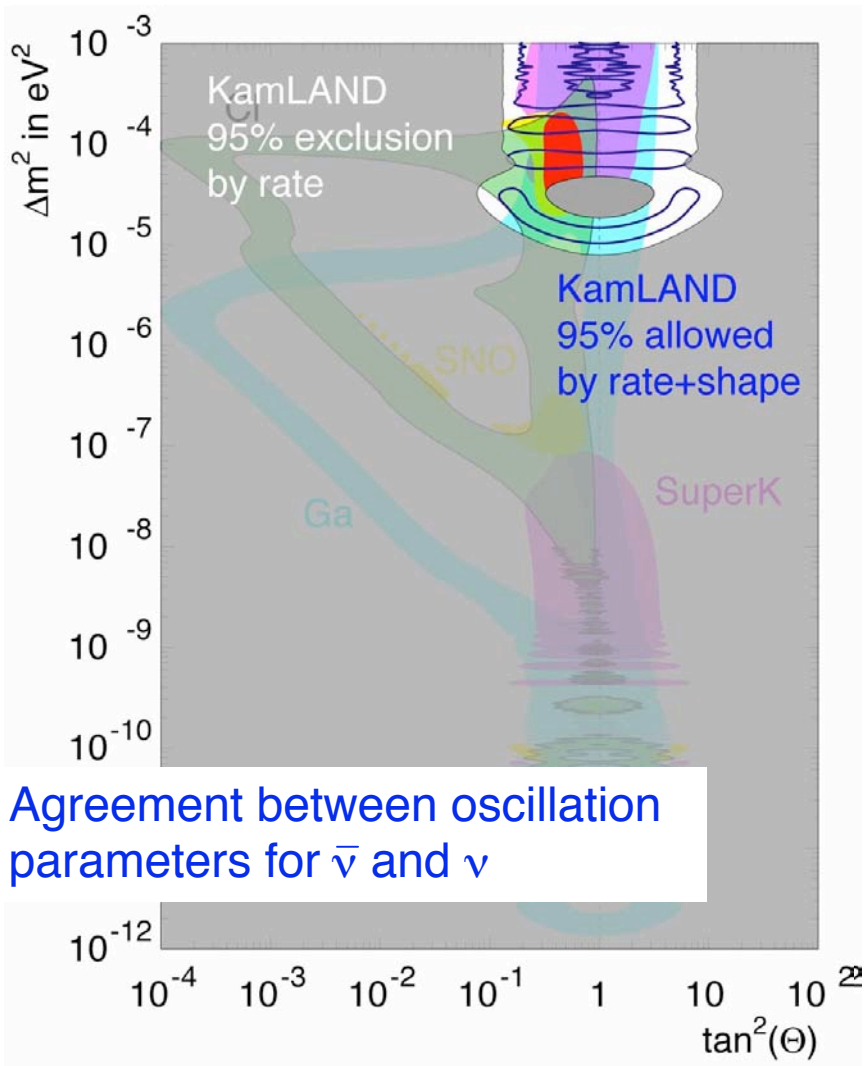
	%		
Total liquid scintillator mass	2.1	FV	• volume calibration
Fiducial mass ratio	4.1		
Energy threshold	2.1		• energy calibration or analysis w/out threshold
Tagging efficiency	2.1		• detection efficiency
Live time	0.07		
Reactor power	2.0		*given by reactor company, difficult to improve on*
Fuel composition	1.0		
$\bar{\nu}_e$ spectra	2.5		*theoretical, model-dependent*
cross section	0.2		
Total uncertainty	6.4 %		

Oscillation Parameters *Before* and *After* KamLAND

Before KamLAND

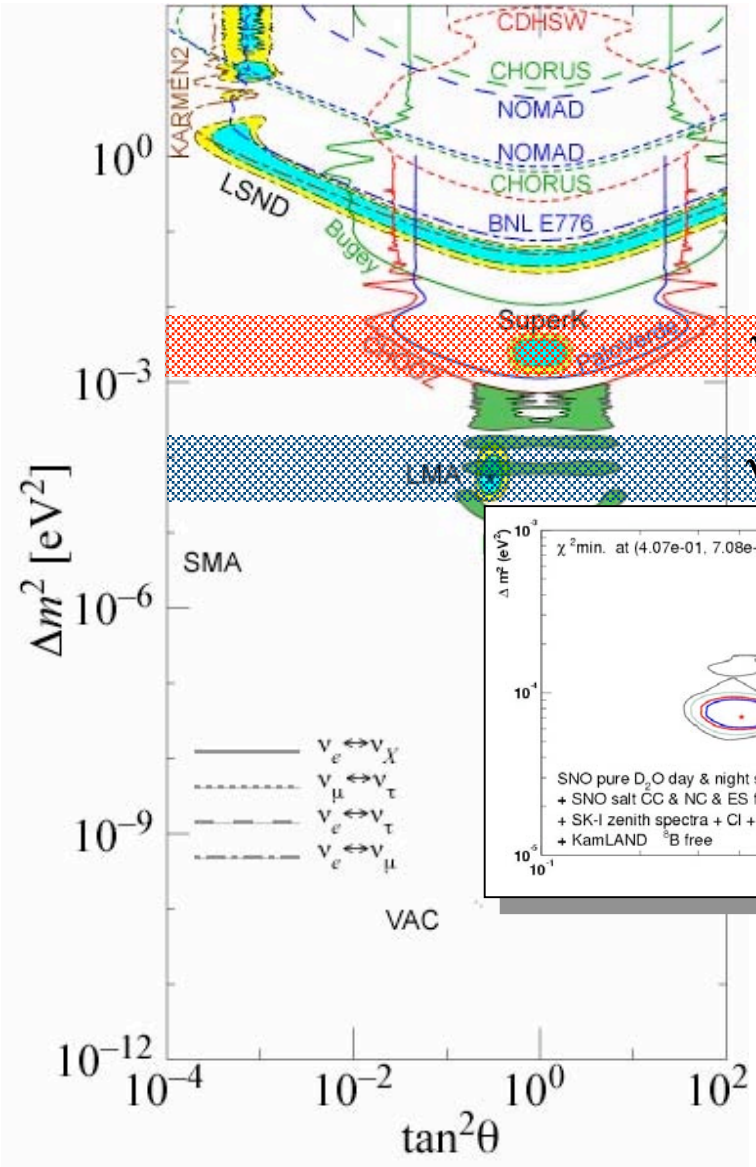


After KamLAND



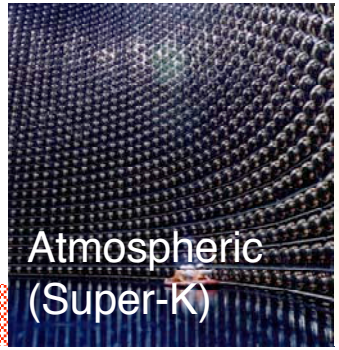
Agreement between oscillation parameters for $\bar{\nu}$ and ν

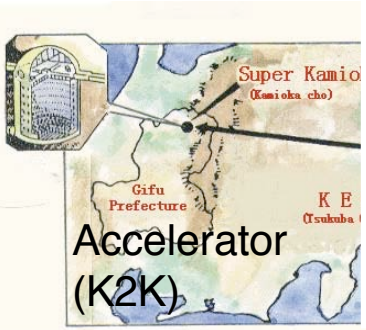
Evidence for Mixing of Massive Neutrinos



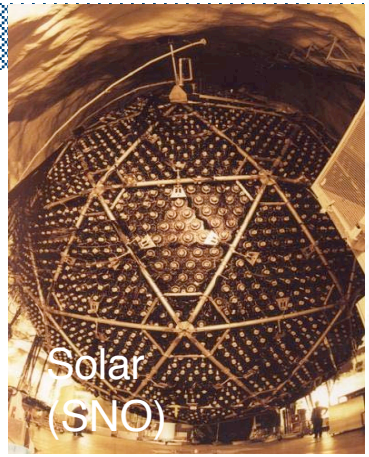
$\nu_\mu \Rightarrow \nu_\tau$

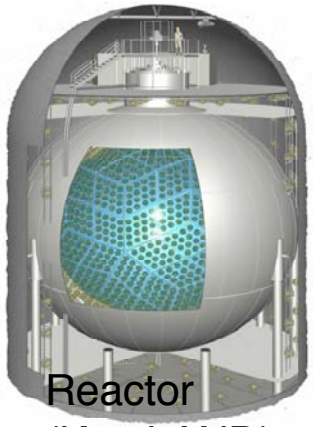
$\nu_e \Rightarrow \nu_{\mu,\tau}$





Accelerator
(K2K)





Reactor
(KamLAND)

- Neutrinos are <u>not massless</u>
- <u>Evidence</u> for neutrino flavor conversion $\nu_e \Leftrightarrow \nu_\mu \Leftrightarrow \nu_\tau$
- Experimental results show that *<u>neutrinos oscillate</u>*

U_{MNSP}, θ_{13}, and $\not{C}\not{P}$

U_{MNSP} Neutrino Mixing Matrix

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

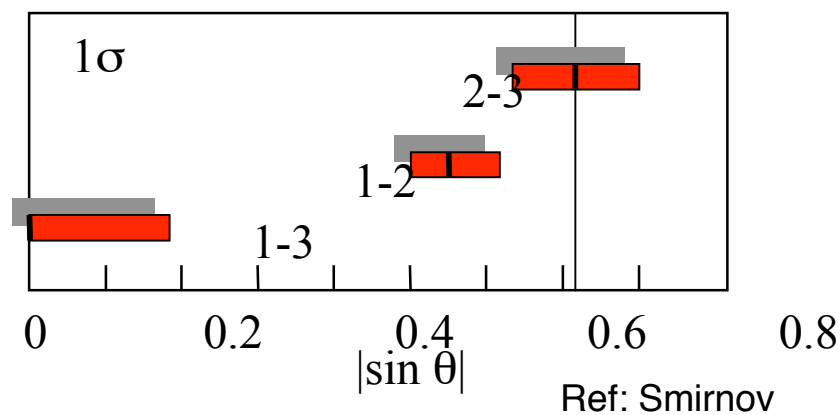
$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{atmospheric, K2K}} \times \underbrace{\overbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}^{\text{Dirac phase}}}_{\text{reactor and accelerator}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{SNO, solar SK, KamLAND}} \times \underbrace{\overbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}^{\text{Majorana phases}}}_{0\nu\beta\beta}$$

?

$\theta_{23} = \sim 45°$

$\tan^2\theta_{13} < 0.03$ at 90% CL

$\theta_{12} \sim 32°$



Ref: Smirnov

U_{MNSP}, θ_{13}, and $\not{C}\not{P}$

U_{MNSP} Neutrino Mixing Matrix

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

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{atmospheric, K2K}} \times \overbrace{\underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{reactor and accelerator}}}^{\textit{Dirac phase}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{SNO, solar SK, KamLAND}} \times \overbrace{\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{0\nu\beta\beta}}^{\textit{Majorana phases}}$$

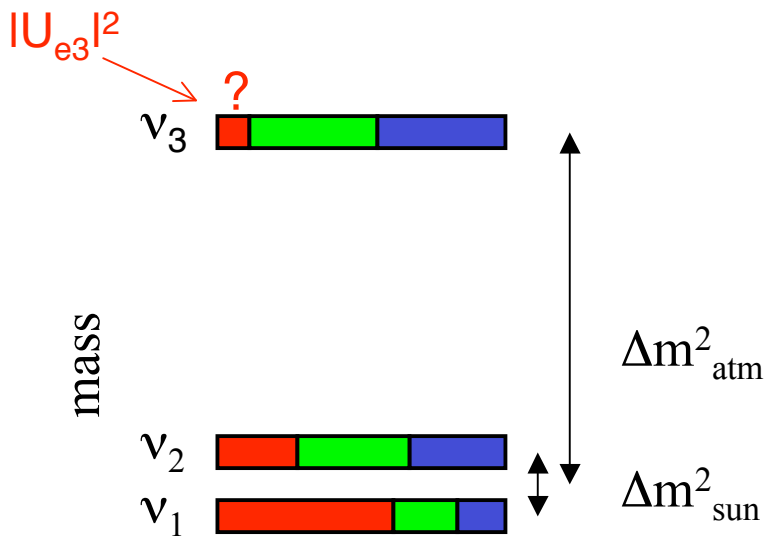
?

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

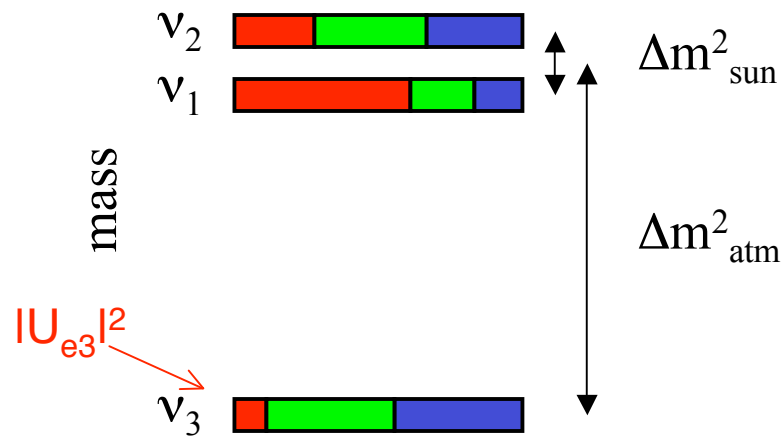
No good 'ad hoc' model to predict θ_{13}.
If $\theta_{13} < 10^{-3}\ \theta_{12}$, perhaps a symmetry?

θ_{13} yet to be measured
determines accessibility to CP phase

Mass Spectrum and Mixing



Normal mass hierarchy (ordering)



Inverted mass hierarchy (ordering)

Type of mass spectrum: Normal, Inverted, Degenerate

Absolute mass scale

U_{e3} = ?

Unknown Oscillation Parameters

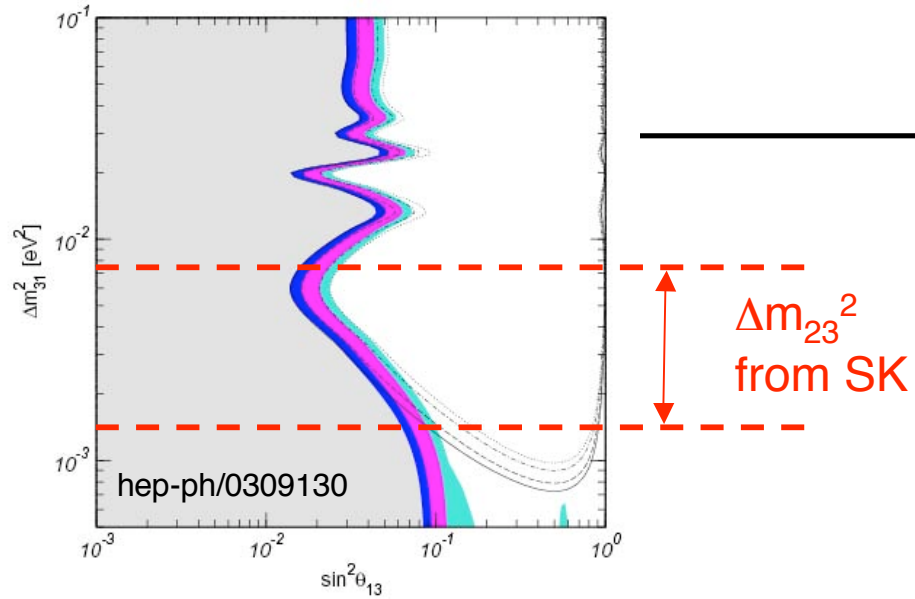
$\sin^2(2\theta_{13})$

sign of Δm_{13}^2

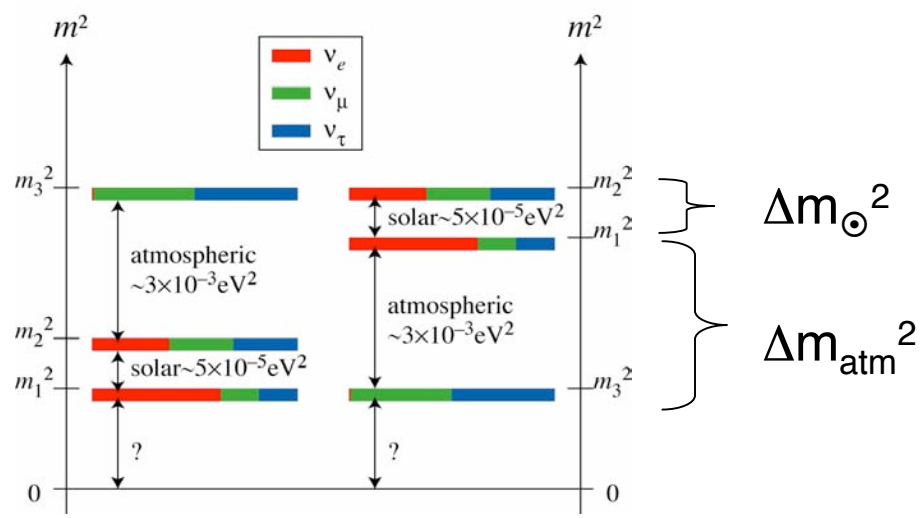
δ_{CP}

Three Questions

I) Size of $\sin^2(2\theta_{13})$?



II) Mass hierarchy?
Sign of Δm_{13}^2



III) Is there CP violation?
Measure δ.

Amount of CP violation is given by $J_{lepton} \sim \underbrace{\cos^2(\theta_{13})}_{\sim 1}\underbrace{\sin(2\theta_{12})}_{\sim 0.9}\underbrace{\sin(2\theta_{23})}_{\sim 1}\sin(2\theta_{13})\sin(\delta_{CP})$

Oscillation Measurements Probe Fundamental Physics

Physics at high mass scales, physics of flavor, and unification:

- Why are the mixing angles *large, maximal, and small*?
- Is there CP violation, T violation, or CPT violation in the lepton sector?
- Is there a connection between the lepton and the baryon sector?

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

θ_{13}

- Leptogenesis and the role of neutrinos in the early Universe

Matter-Antimatter Asymmetry ($\Delta B \neq 0$) from Leptogenesis

Cannot generate observed baryon asymmetry ($\Delta B \neq 0$) using quark matrix CP violation

Generate $\Delta L \neq 0$ in the early universe from CP (or CPT) violation in heavy neutrino N_3 vs. $\overline{N}_3$ decays (only needs to be at the 10^{-6} level)

B-L processes then convert neutrino excess to baryon excess.

Sign and magnitude ~correct to generate baryon asymmetry in the Universe with $m_N > 10^9$ GeV and $m_\nu < 0.2$ eV

Amount of CP violation is given by $J_{lepton} \sim \underbrace{\cos^2(\theta_{13})}_{\sim 1}\underbrace{\sin(2\theta_{12})}_{\sim 0.9}\underbrace{\sin(2\theta_{23})}_{\sim 1}\sin(2\theta_{13})\sin(\delta_{CP})$

S. Glashow

Tell me θ_{13}!

Sheldon Lee Glashow

14 May 20

「教えてください，θ_{13}を！」
シェルドン・リー・グラショウ
2003年5月14日
グラショウ氏は物理学特別講演のため夫人と共に来仙，吉本高志東北大学総長と会見後，
ニュートリノ科学研究センターを訪問され，ニュートリノ研究の新たな成果を祈念して記された

Conclusions

Future for ν Mass + Oscillation

* 1. Probe value of s_{13}^2

* 2. Search for ββ

1 : If s_{13}^2 is large enough

Find CP phase δ

Hierarchy

2 : If $\langle m_{ee} \rangle$ is large enough

Majorana

Range of m_1

CP phases α, β ??

3. Physics beyond the standard :

ν's, FCNC

Electric dipole moments

of e or n

L. Wofenstein

Desired Experimental Sensitivity to θ_{13}?

- smaller values of θ_{13} harder to understand.

- For MSSM shift of $\Delta\sin^2 2\theta_{13} > 0.01$ is plausible.

→ Can bound model parameters if experiment sets limit in the range of $\sin^2 2\theta_{13} < 0.01$.

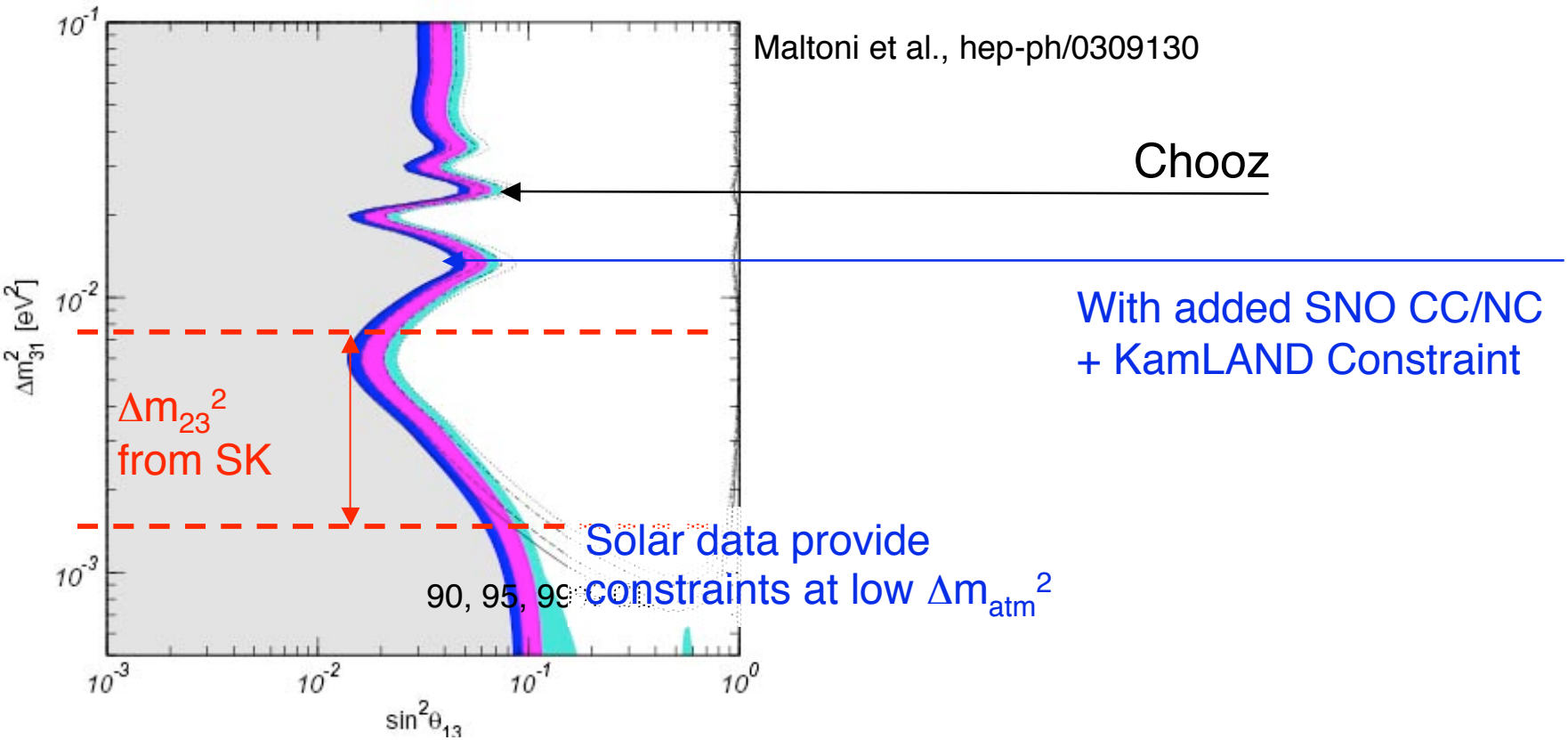
- Precision of the order of quantum corrections to neutrino masses and mixings interesting.

- Small θ_{13}: numerical coincidence or underlying symmetry?

$\sin^2 2\theta_{13} < 0.01$ is interesting sensitivity

Reference	$\sin\theta$	if $\sin^2 2\theta_{13} < 0.01$
SO(10)		
Goh, Mohapatra, Ng [40]	0.18	~~0.13~~
Orbifold SO(10)		
Asaka, Buchmüller, Covi [41]	0.1	~~0.04~~
SO(10) + flavor symmetry		
Babu, Pati, Wilczek [42]	$5.5 \cdot 10^{-4}$	$1.2 \cdot 10^{-6}$
Blazek, Raby, Tobe [43]	0.05	0.01
Kitano, Mimura [44]	0.22	~~0.18~~
Albright, Barr [45]	0.014	$7.8 \cdot 10^{-4}$
Maekawa [46]	0.22	~~0.18~~
Ross, Velasco-Sevilla [47]	0.07	~~0.02~~
Chen, Mahanthappa [48]	0.15	~~0.09~~
Raby [49]	0.1	~~0.04~~
SO(10) + texture		
Buchmüller, Wyler [50]	0.1	~~0.04~~
Bando, Obara [51]	0.01 .. 0.06	$4 \cdot 10^{-4}$ .. 0.01
Flavor symmetries		
Grimus, Lavoura [52, 53]	0	0
Grimus, Lavoura [52]	0.3	~~0.3~~
Babu, Ma, Valle [54]	0.14	~~0.08~~
Kuchimanchi, Mohapatra [55]	0.08 .. 0.4	~~0.03 .. 0.5~~
Ohlsson, Seidl [56]	0.07 .. 0.14	~~0.02 .. 0.08~~
King, Ross [57]	0.2	~~0.15~~
Textures		
Honda, Kaneko, Tanimoto [58]	0.08 .. 0.20	~~0.03 .. 0.15~~
Lebed, Martin [59]	0.1	~~0.04~~
Bando, Kaneko, Obara, Tanimoto [60]	0.01 .. 0.05	$4 \cdot 10^{-4}$ .. 0.01
Ibarra, Ross [61]	0.2	~~0.15~~
3×2 *see-saw*		
Appelquist, Piai, Shrock [62, 63]	0.05	0.01
Frampton, Glashow, Yanagida [64]	0.1	~~0.04~~
Mei, Xing [65] (normal hierarchy)	0.07	~~0.02~~
(inverted hierarchy)	> 0.006	$> 1.6 \cdot 10^{-4}$
Anarchy		
de Gouvêa, Murayama [66]	> 0.1	~~> 0.04~~
Renormalization group enhancement		
Mohapatra, Parida, Rajasekaran [67]	0.08 .. 0.1	~~0.03 .. 0.04~~

Global Constraints on θ_{13}

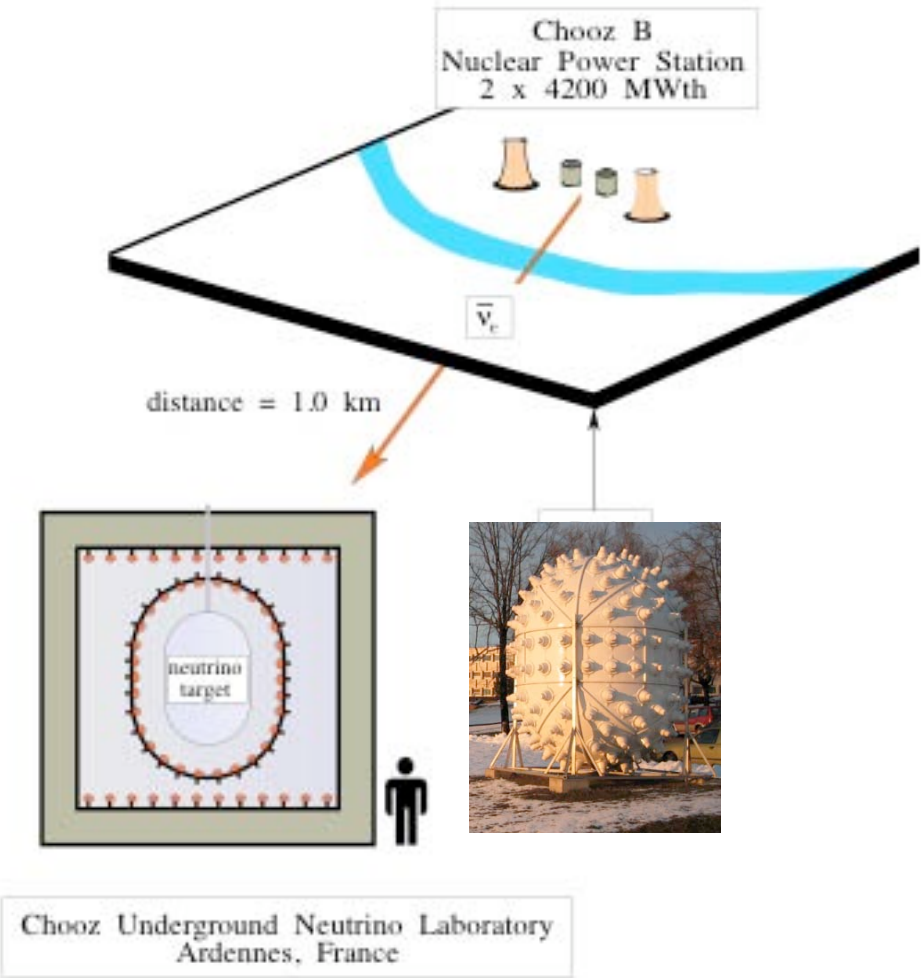


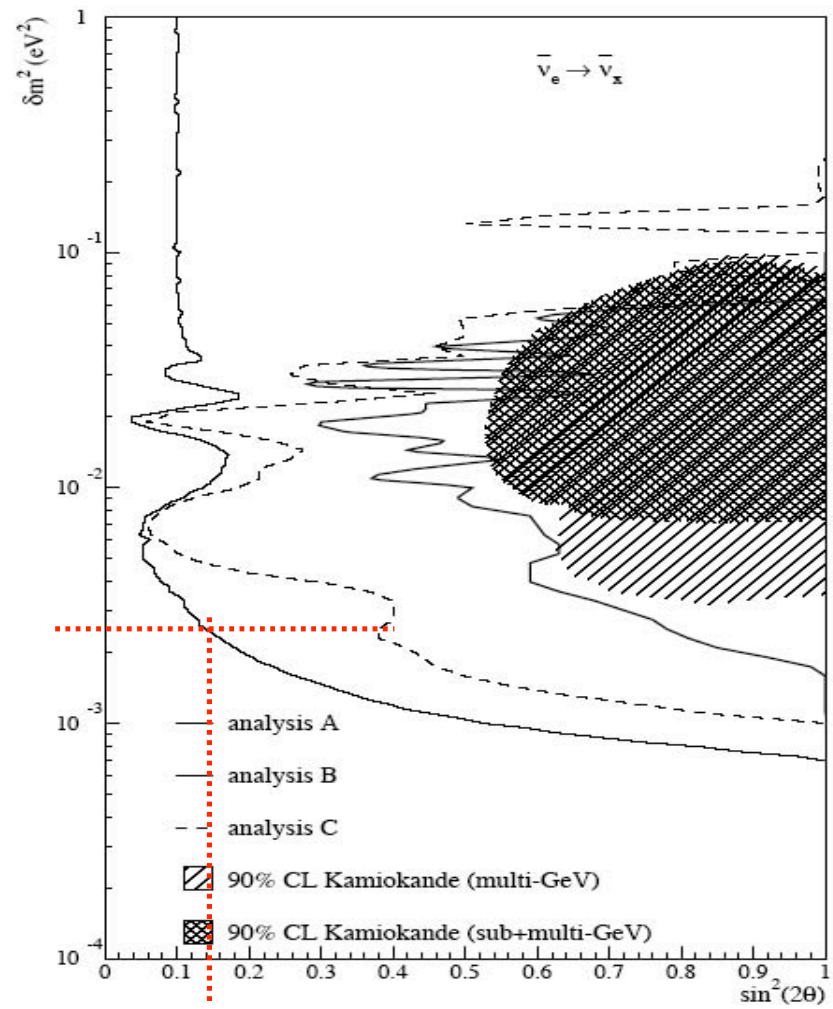
parameter	best fit	2σ	3σ	5σ
Δm^2_{21} [10^{-5}eV^2]	6.9	6.0–8.4	5.4–9.5	2.1–28
Δm^2_{31} [10^{-3}eV^2]	2.6	1.8–3.3	1.4–3.7	0.77–4.8
$\sin^2\theta_{12}$	0.30	0.25–0.36	0.23–0.39	0.17–0.48
$\sin^2\theta_{23}$	0.52	0.36–0.67	0.31–0.72	0.22–0.81
$\sin^2\theta_{13}$	0.006	≤ 0.035	≤ 0.054	≤ 0.11

$\sin^2(2\theta_{13}) = 0.02$ (global best fit)

Current Knowledge of θ_{13} from Reactors

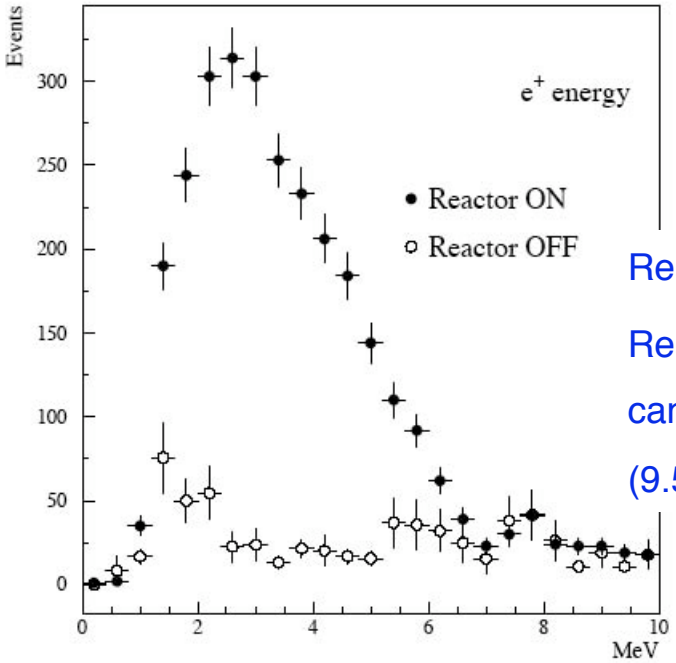
Reactor anti-neutrino measurement at 1 km at Chooz + Palo Verde: $\bar{\nu}_e \rightarrow \bar{\nu}_x$





M. Appollonio, hep-ex/0301017

Chooz, France

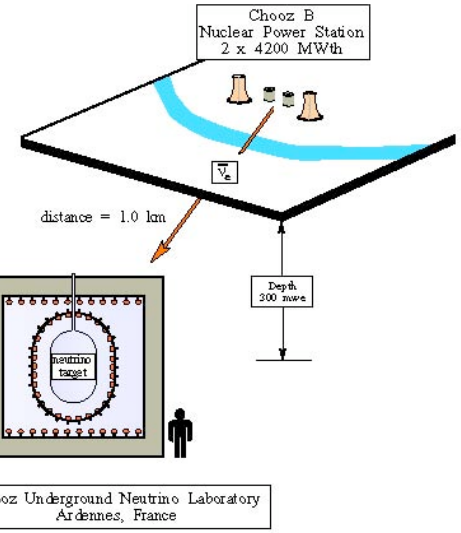


Reactor on: 2991

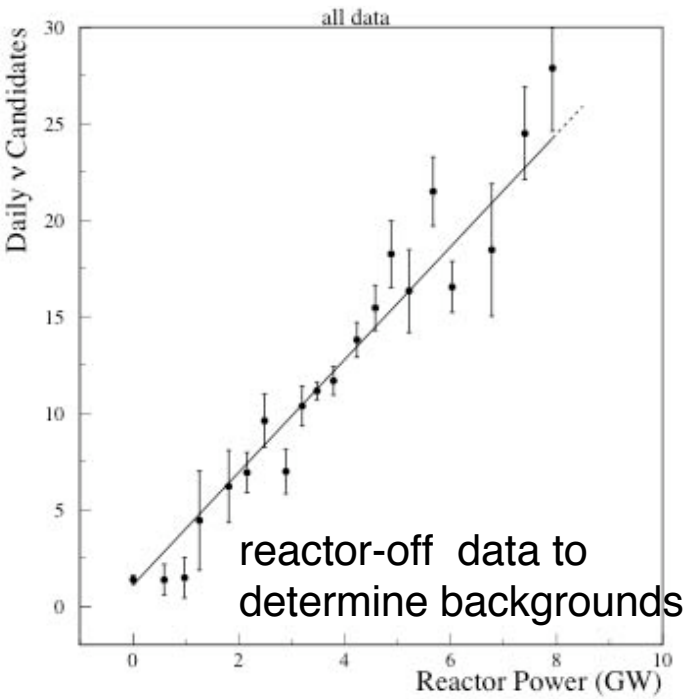
Reactor off: 287

candidate $\overline{\nu}_e$ events.

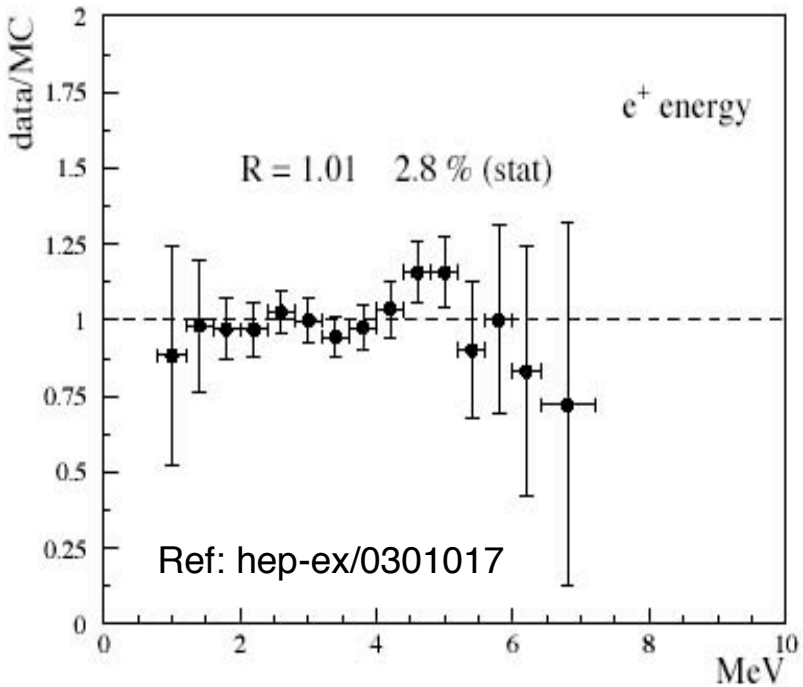
(9.5% backgrounds!)



Chooz was unique! Determined backgrounds during reactor-off period.



reactor-off data to determine backgrounds



Ref: hep-ex/0301017

Chooz

Systematics

Table 10. Contributions to the overall systematic uncertainty on the absolute normalization factor.

parameter	relative error (%)
reaction cross section	1.9% *theor.*
number of protons	0.8%
detection efficiency	1.5%
reactor power	0.7%
energy released per fission	0.6%
combined	2.7%

kinetic energy spectrum	2.1%
detector response	1.7%
total	2.7%

Ref: Apollonio et al., hep-ex/0301017

Table 6. Summary of the neutrino detection efficiencies.

selection	ϵ(%)	rel. error (%)
positron energy*	97.8	0.8
positron-geode distance	99.9	0.1
neutron capture	84.6	1.0
capture energy containment	94.6	0.4
neutron-geode distance	99.5	0.1
neutron delay	93.7	0.4
positron-neutron distance	98.4	0.3
neutron multiplicity*	97.4	0.5
combined*	69.8	1.5

*average values

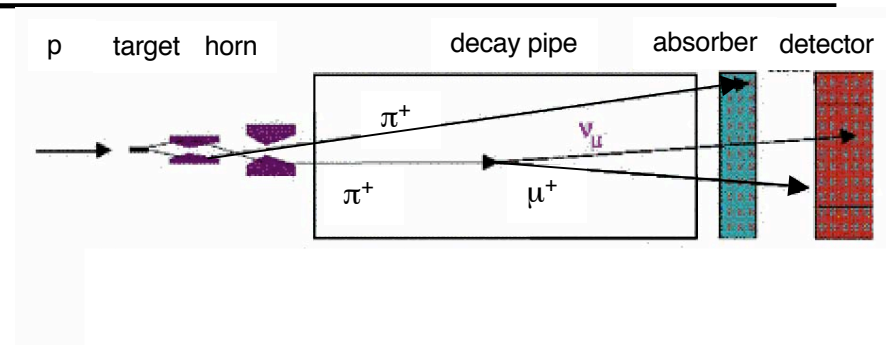
neutron capture:

lowest efficiency, largest relative error

Absolute measurements are difficult!

Measuring θ_{13}

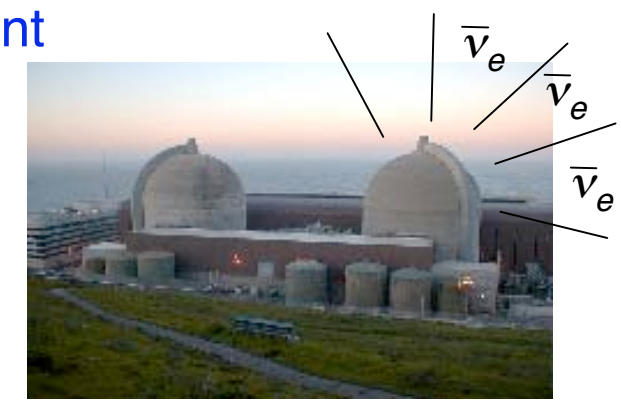
Method 1: Accelerator Experiments



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

- appearance experiment $\nu_\mu \rightarrow \nu_e$
- measurement of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ yields θ_{13}, δ_{CP}
- baseline *O(100 -1000 km),* matter effects present

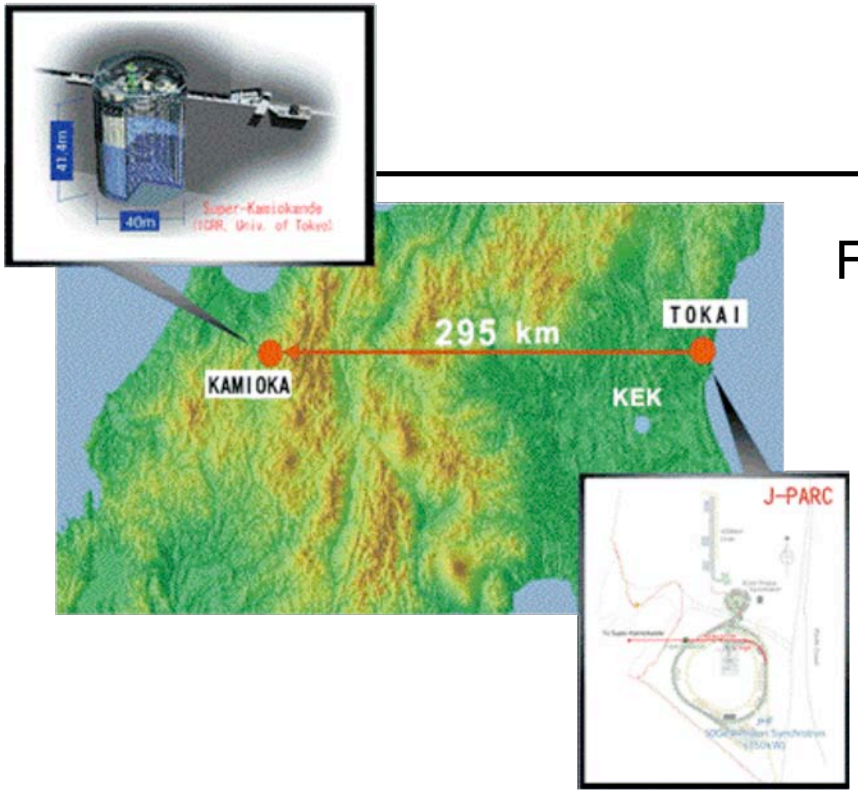
Method 2: Reactor Neutrino Oscillation Experiment



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

- disappearance experiment $\bar{\nu}_e \rightarrow \bar{\nu}_x$
- look for rate deviations from $1/r^2$ and spectral distortions
- observation of oscillation signature with 2 or multiple detectors
- baseline *O(1 km),* no matter effects

ν_e Appearance Experiments



For example, T2K- From Tokai To Kamioka

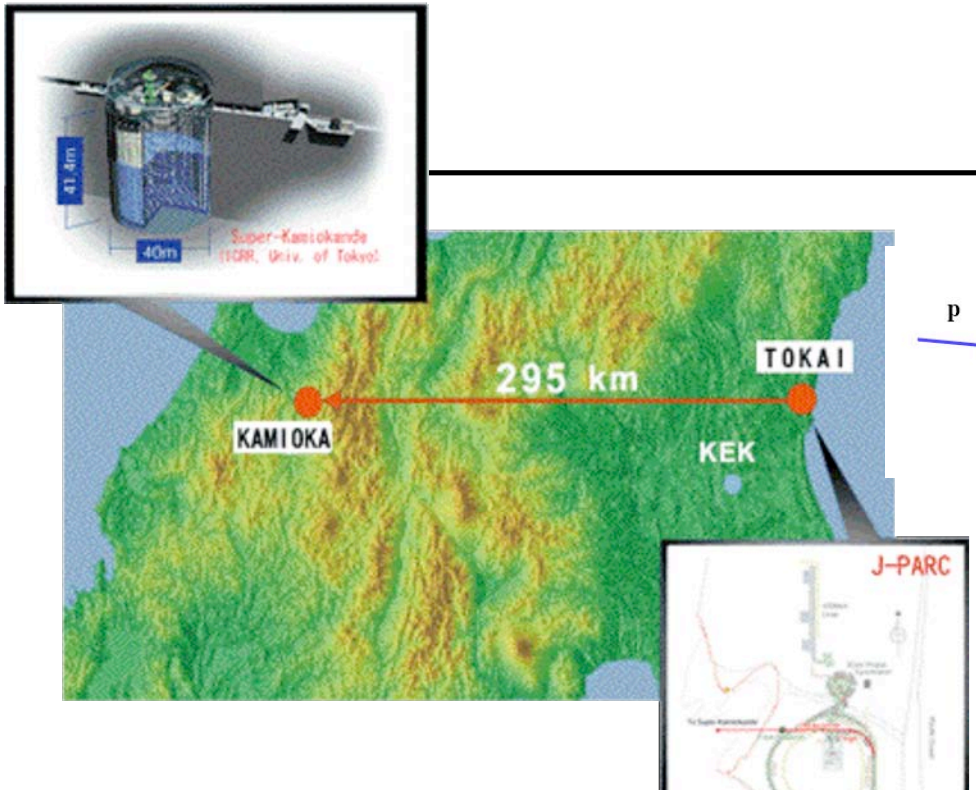
mass hierarchy

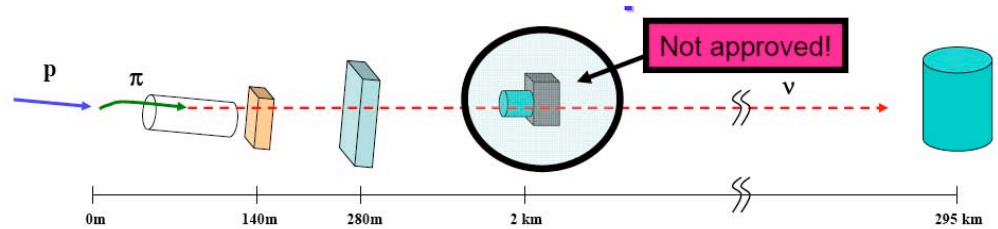
CP violation

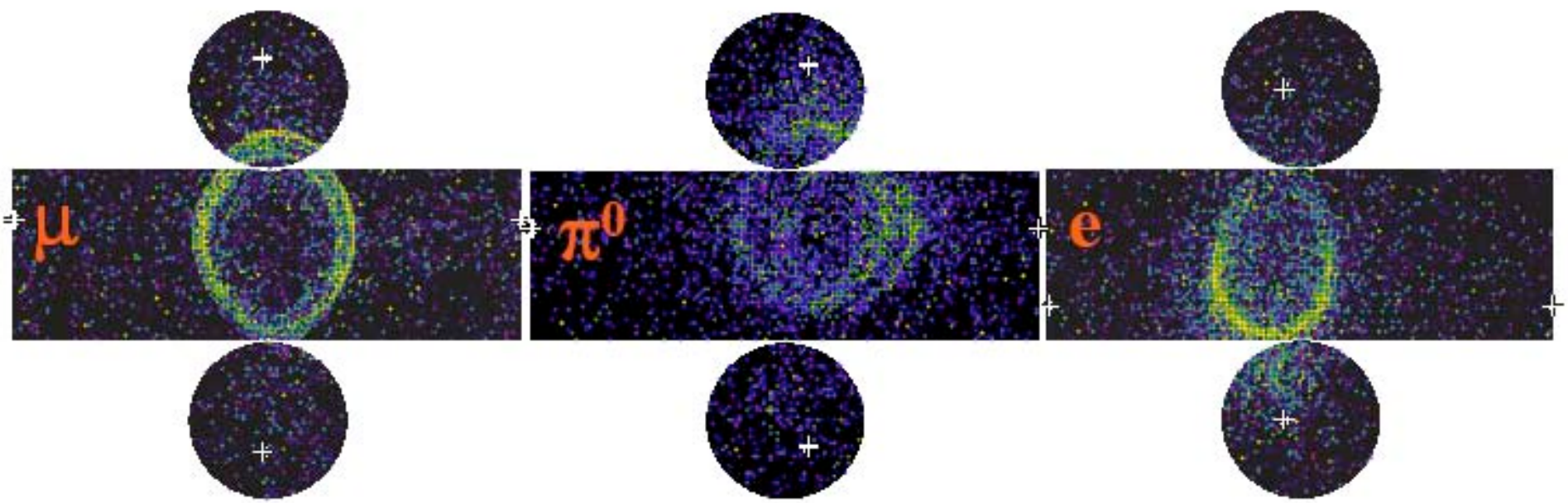
matter

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31} \\
& + 8c_{13}^2 s_{13} s_{23} c_{23} s_{12} c_{12} \sin \Delta_{31} [\cos \Delta_{32} \cos \delta - \sin \Delta_{32} \sin \delta] \sin \Delta_{21} \\
& - 8c_{13}^2 s_{13}^2 s_{23}^2 s_{12}^2 \cos \Delta_{32} \sin \Delta_{31} \sin \Delta_{21} \\
& + 4c_{13}^2 s_{12}^2 [c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos \delta] \sin^2 \Delta_{21} \\
& - 8c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2) \frac{aL}{4E_\nu} \sin \Delta_{31} \left[\cos \Delta_{32} - \frac{\sin \Delta_{31}}{\Delta_{31}} \right] .
\end{aligned}
$$

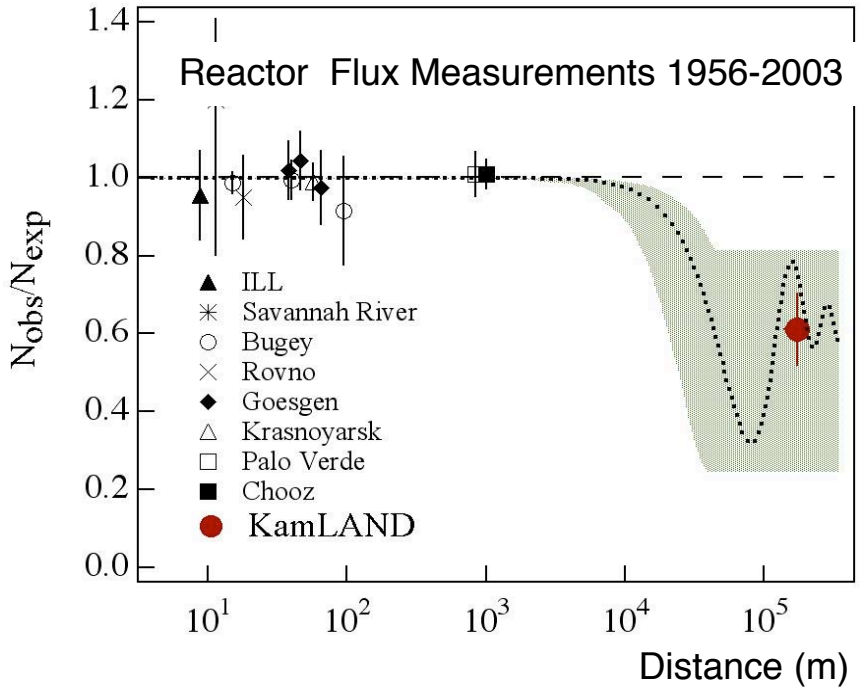
Tokai to Kamioka (T2K)

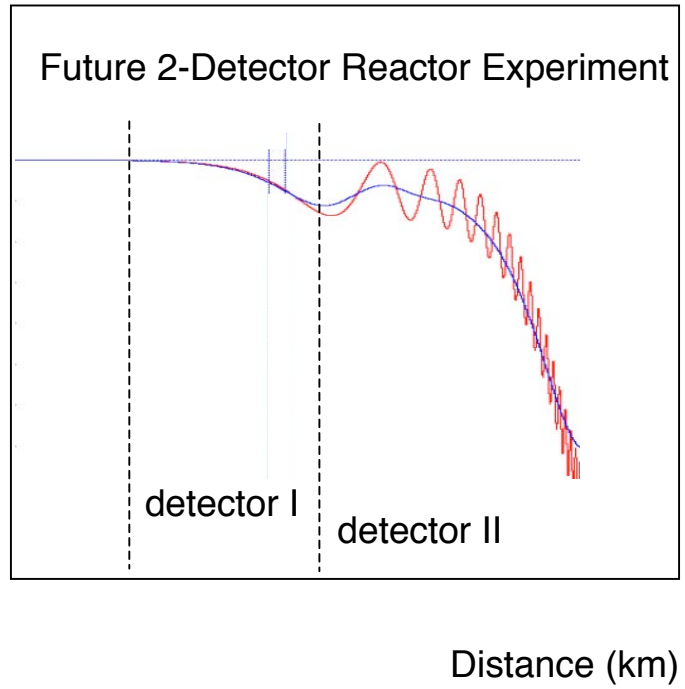






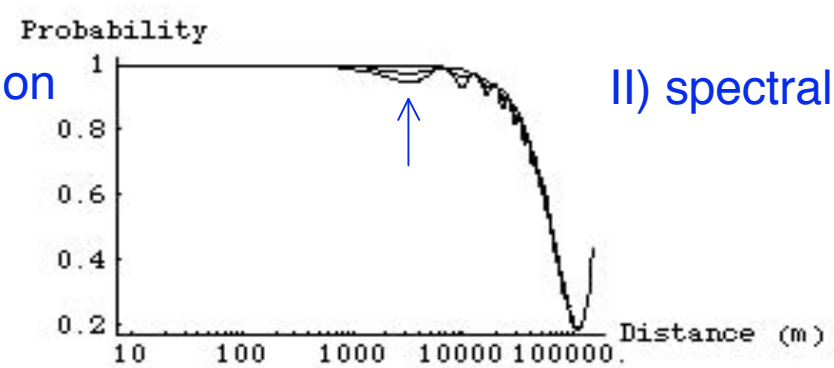
A Reactor Neutrino Oscillation Experiment with Multiple Detectors



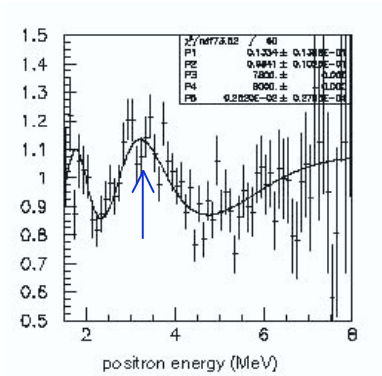


Measure

I) rate suppression

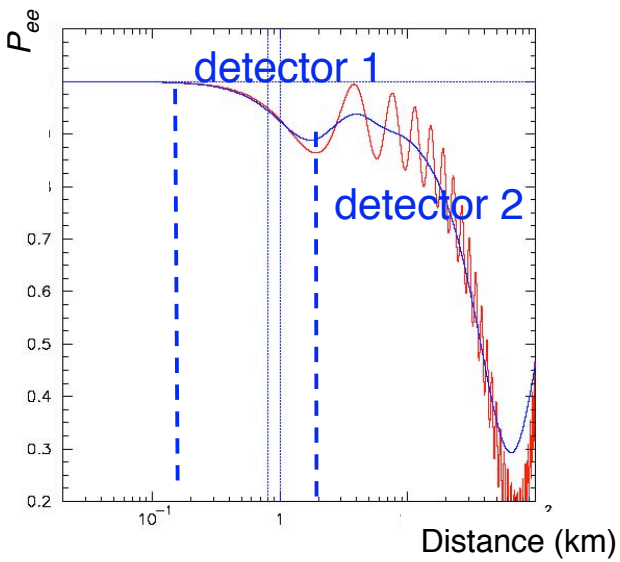


II) spectral distortions



Measuring θ_{13} with Reactor Neutrinos

Novel Oscillation Experiment with Multiple Detectors



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

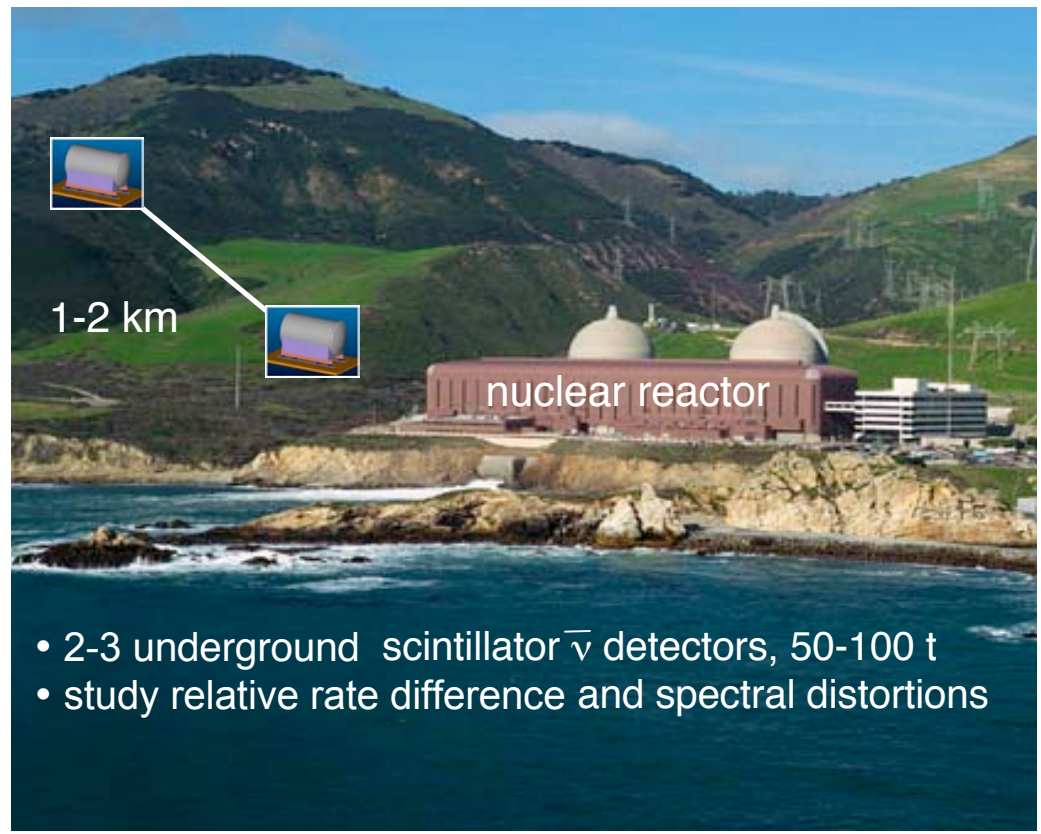
relative ν flux measurement between 2 $\bar{\nu}$ detectors

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

- eliminates most systematic errors
- projected sensitivity:

$\sin^2 2\theta_{13} \approx 0.01\text{-}0.02$

Ref: hep-ex/0402041



Experimental Challenges of a θ_{13} Measurement at Reactors

I. Choice of Baseline and suitable underground site

II. Detector size (fiducial volume)

signal statistics and muon deadtime

III. Relative Detector Acceptance

detection efficiency

energy scale and linearity

IV. Backgrounds

Uncorrelated Backgrounds

- ambient radioactivity
- accidentals

Correlated Backgrounds

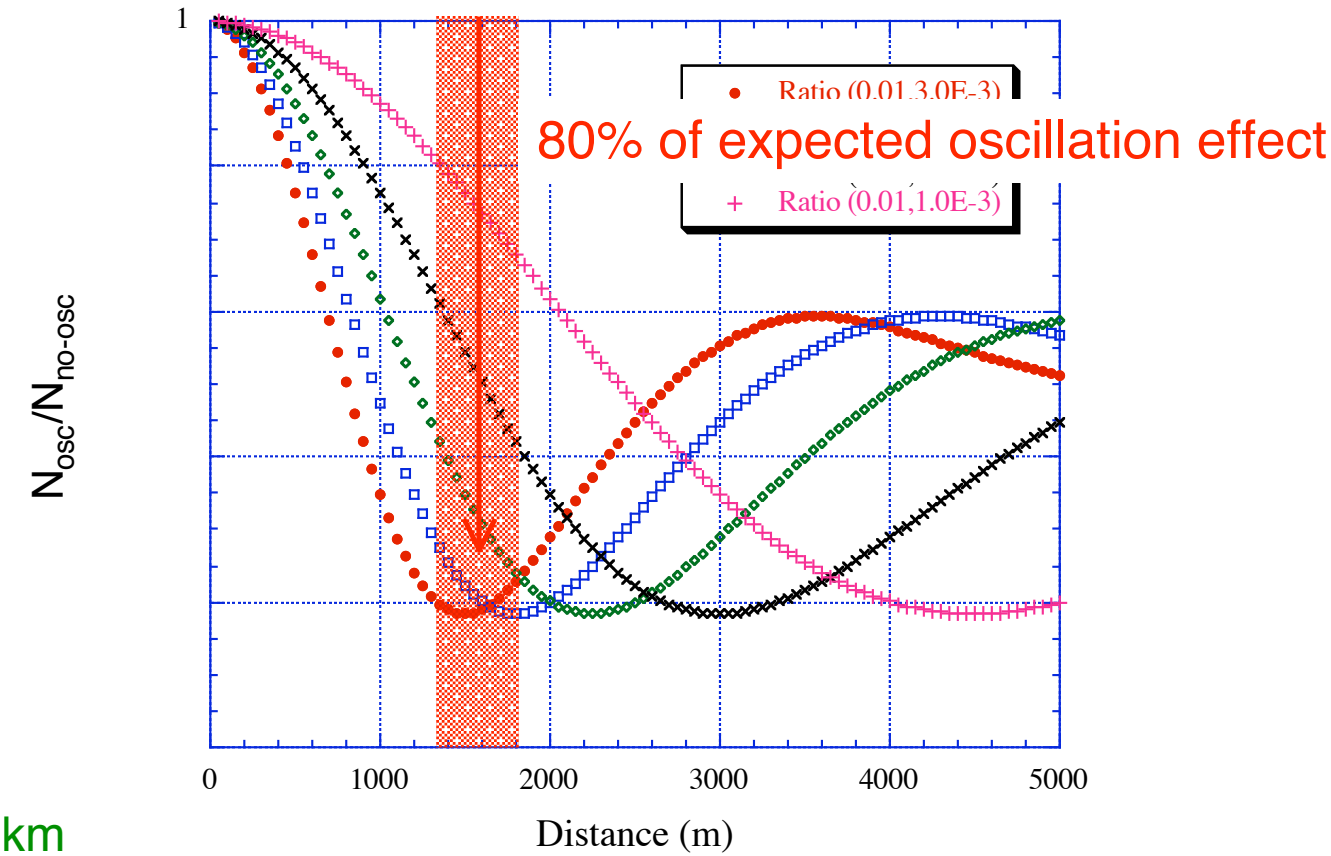
- cosmic rays induce neutrons in the surrounding rock and buffer region of the detector
- radioactive nuclei that emit delayed neutrons in the detector

eg. ^{8}He ($T_{1/2}$=119ms)

^{9}Li ($T_{1/2}$=178ms)

Detector Baseline and $\sin^2 2\theta_{13}$ Sensitivity

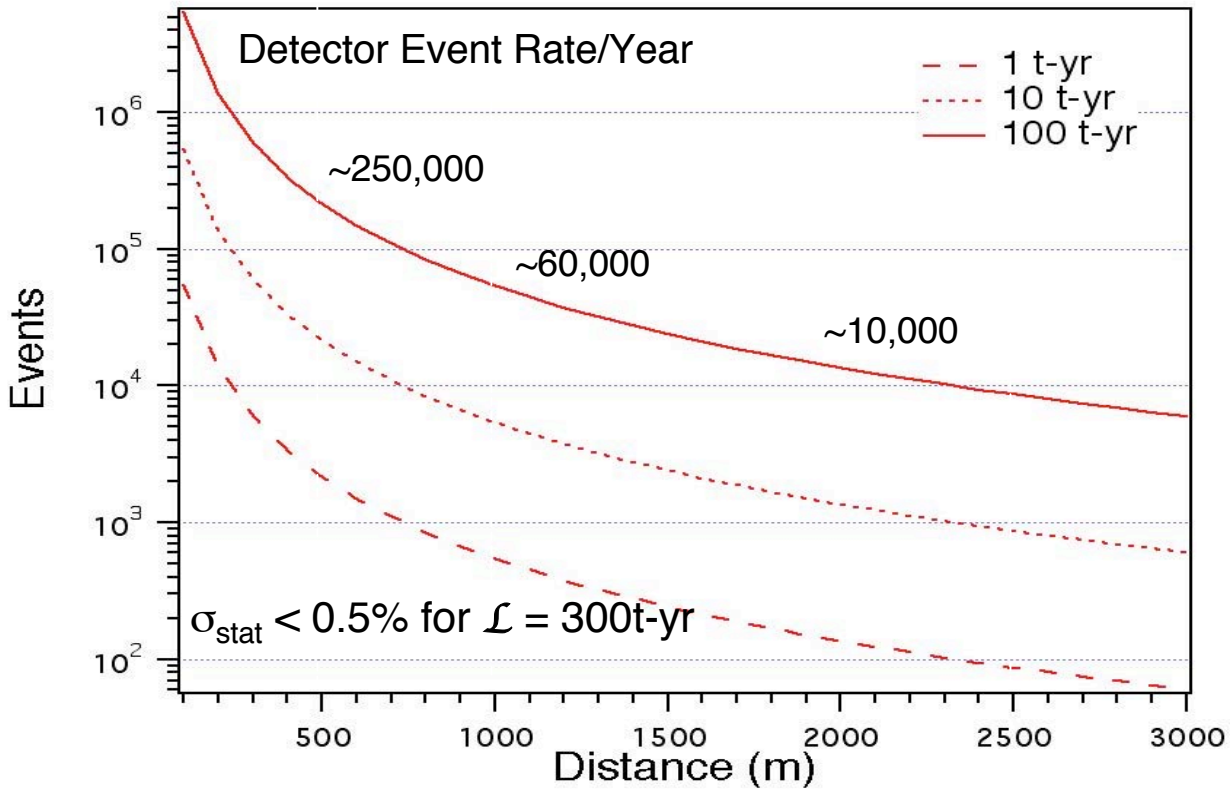
$$P_{ee} \approx 1 - \left(\sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}{}^2 L}{4E_\nu} + \left(\frac{\Delta m_{31}{}^2 L}{4E_\nu} \right) \cos^4 \theta_{13} \sin^2 2\theta_{12} \right)$$



Ideal baseline ~1.5-2 km

Would like to choose and optimize baseline as Δm^2_{23} becomes better known

Event Statistics



Chooz-like detector

$P_{reactor} = 6.5\ GW_{th}$

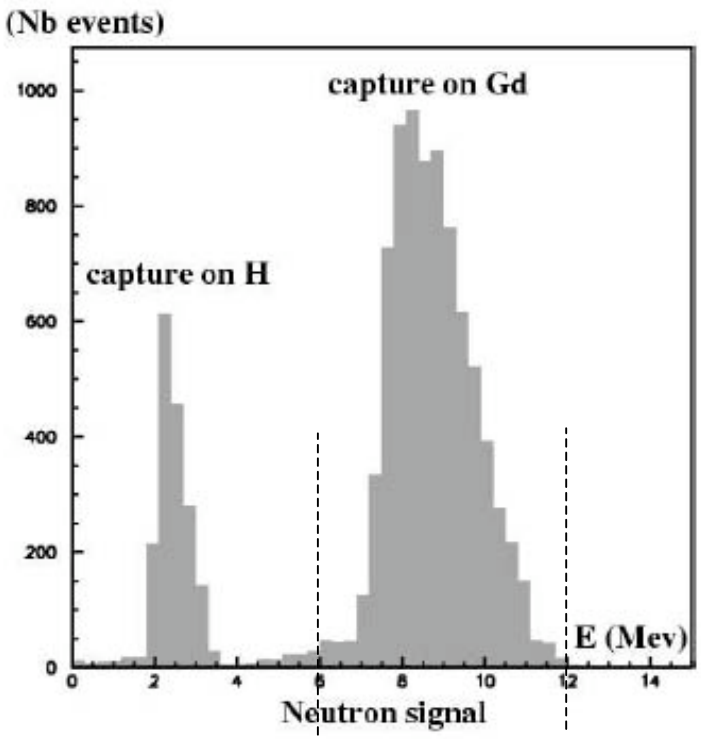
227 signal events per yr-ton-GW @ 1km (no osc)

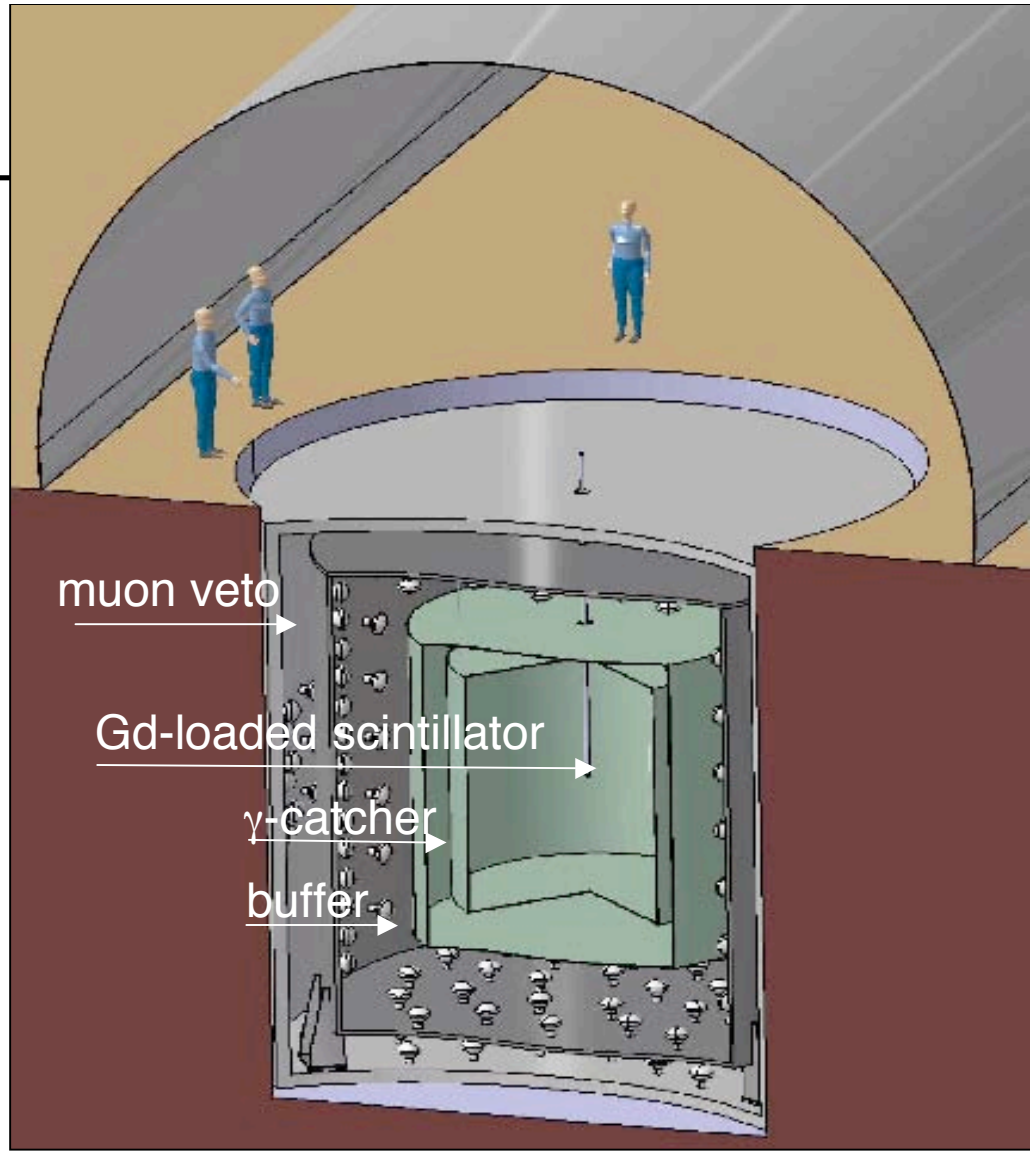
Event Detection

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

Prompt e^+ annihilation

Delayed n capture





Energy selection of delayed neutron
(precision of thresholds ~ 100keV)

Muon-Induced Production of Radioactive Isotopes in LS

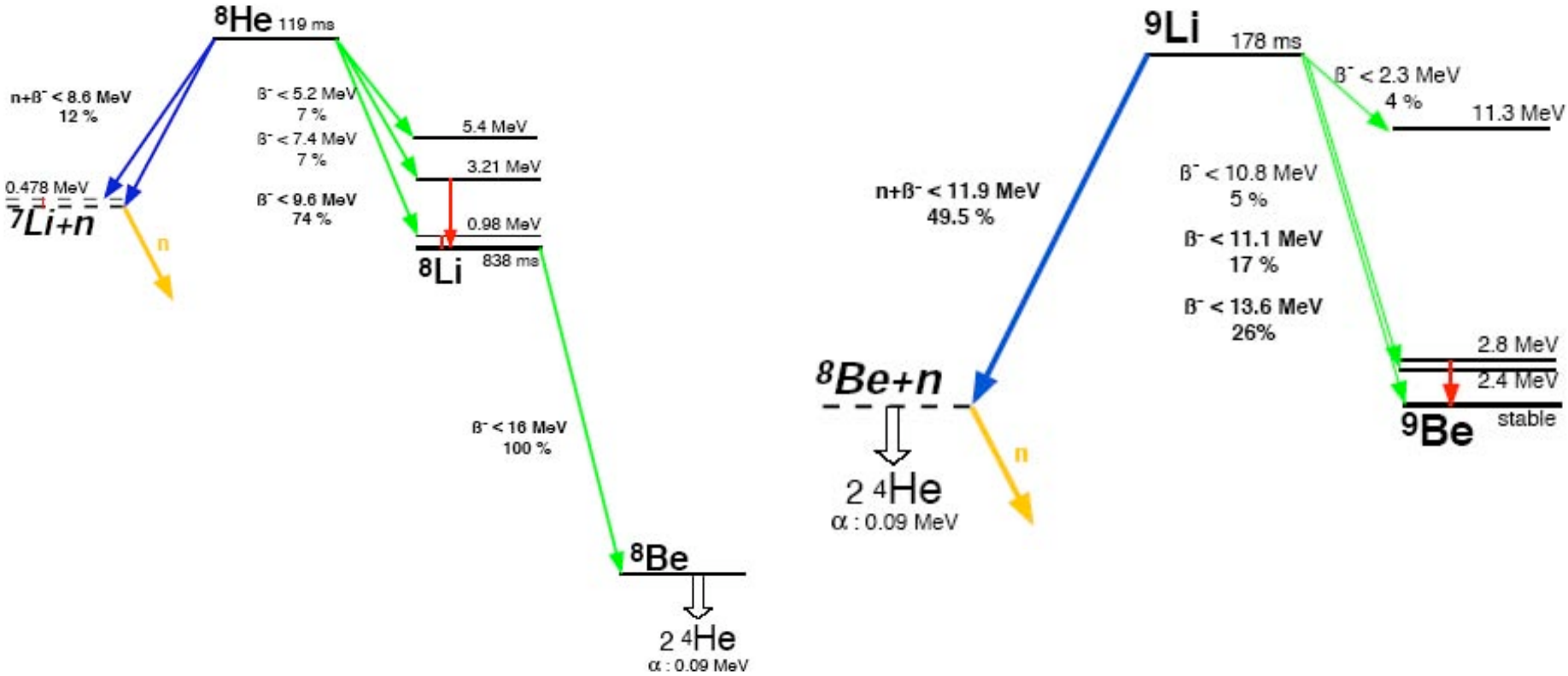
	Isotope	$T_{1/2}$	E_{max} (MeV)	Type
β^-	^{12}B	0.02 s	13.4	Uncorrelated
	^{11}Be	13.80 s	11.5	Uncorrelated
	^{11}Li	0.09 s	20.8	Correlated
	^{9}Li	0.18 s	13.6	
	^{8}Li	0.84 s	16.0	
	^{8}He	0.12 s	10.6	
	^{6}He	0.81 s	3.5	Uncorrelated
β^+, EC	^{11}C	20.38 m	0.96	
	^{10}C	19.30 s	1.9	
	^{9}C	0.13 s	16.0	Uncorrelated
	^{8}B	0.77 s	13.7	Uncorrelated
	^{7}Be	53.3 d	0.48	Uncorrelated

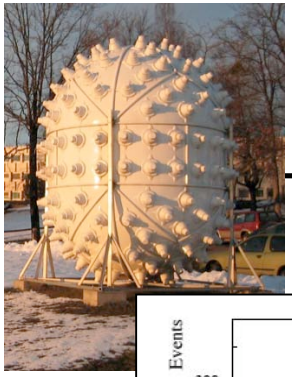
correlated:
β-n cascade, τ~few 100ms.
Only ^{8}He, ^{9}Li, ^{11}Li (instable isotopes).

uncorrelated:
single rate dominated by ^{11}C

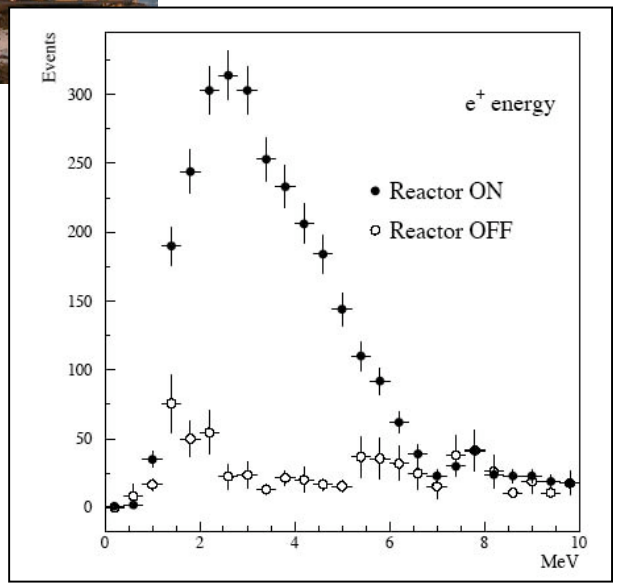
rejection through muon tracking and depth

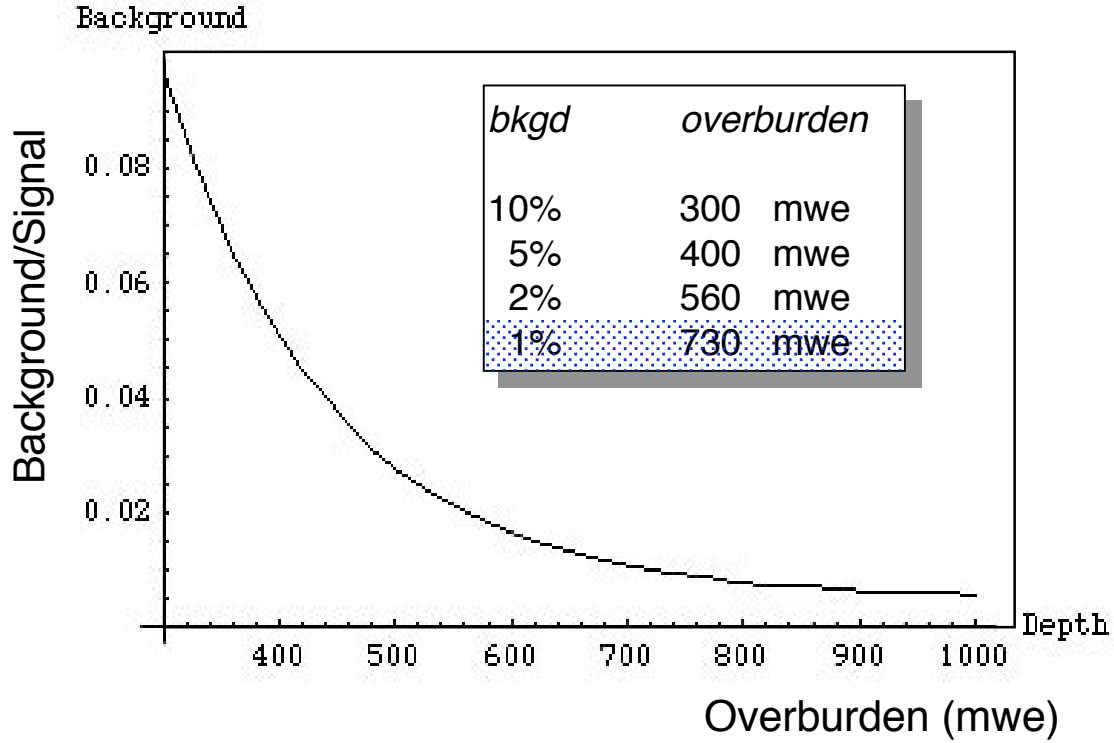
^{8}He/^{9}Li Background





Backgrounds vs Depth (Chooz-like Site)



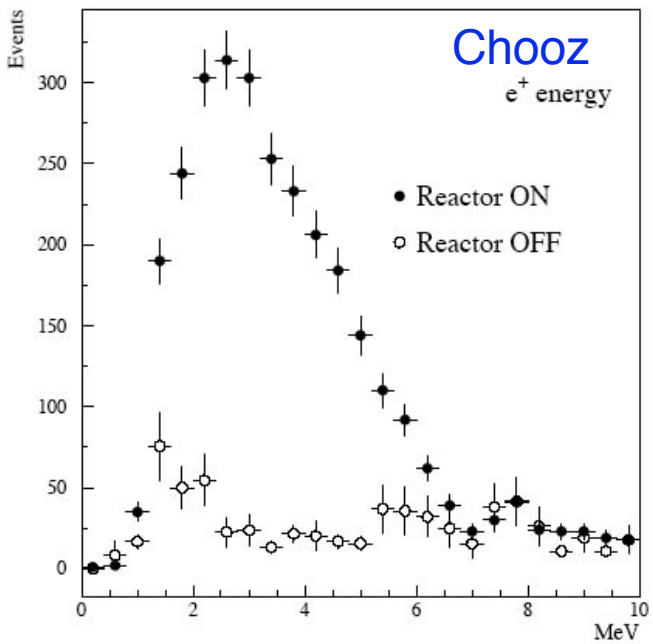


Both neutron and isotope backgrounds scale as

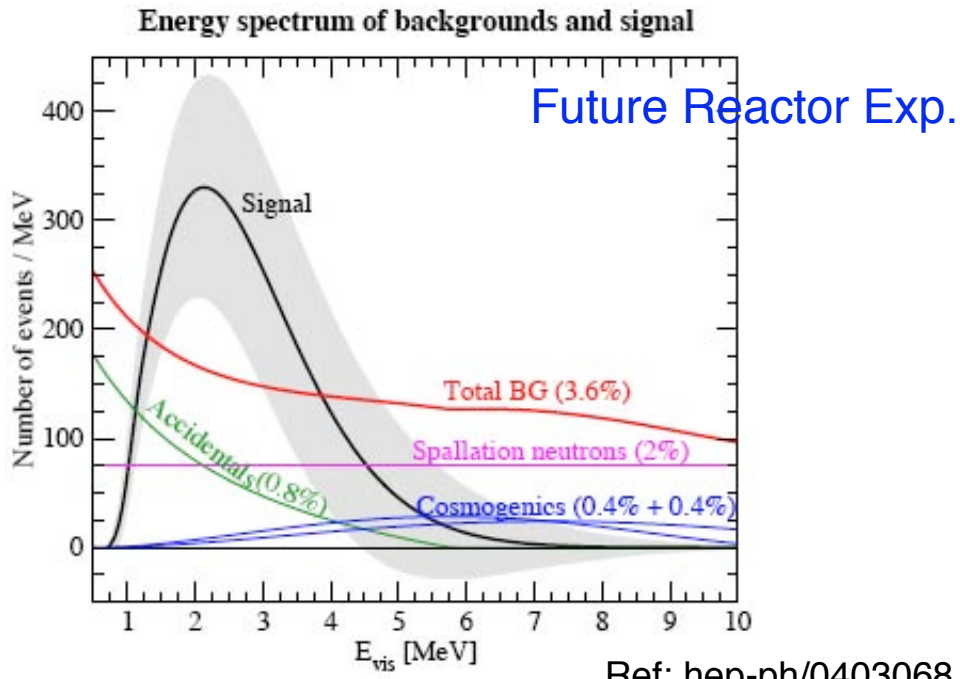
Bkgd = $A < E_\mu >^\kappa \Phi_\mu$ k~ 0.73-0.74

Use Chooz background measurement *with reactors off* as normalization
A = 9.5% at 1.05 km, 5.7 GW (th)

How well will we be able to determine the backgrounds?



Ref: hep-ph/030107



Ref: hep-ph/0403068

Will we be able to measure background contributions?

Backgrounds in near and far detector will be different.

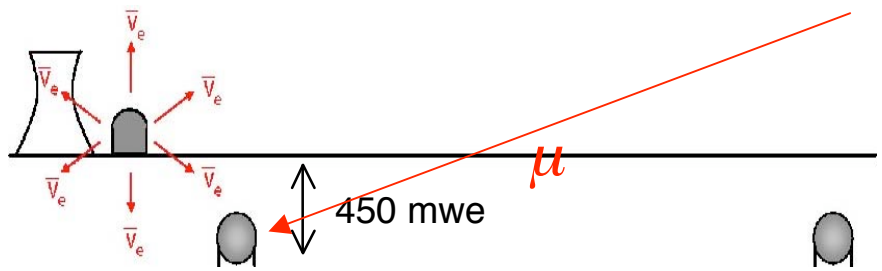
Background type	Spectral shape	BG/Reactor events	σ_{BG}
Backgrounds with known shape			
Spallation neutrons	Flat	0.4%	50%
Accidentals	Low energies	0.2%	50%
Cosmogenic ^{9}Li	β-spectrum (end point 13.6 MeV)	0.2%	50%
Cosmogenic ^{8}He	β-spectrum (end point 10.6 MeV)	0.2%	50%
Bin-to-bin correlated BG total:		1.0%	
Bin-to-bin uncorrelated background			
Unknown source	Flat	0.5%	50%

Build experiment as deep as possible

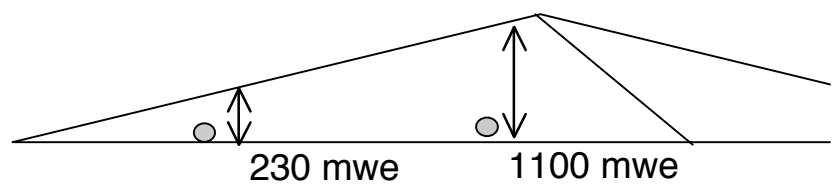
Backgrounds in Different Reactor θ_{13} Experiments

Signal/background ratio and background estimation

Flat

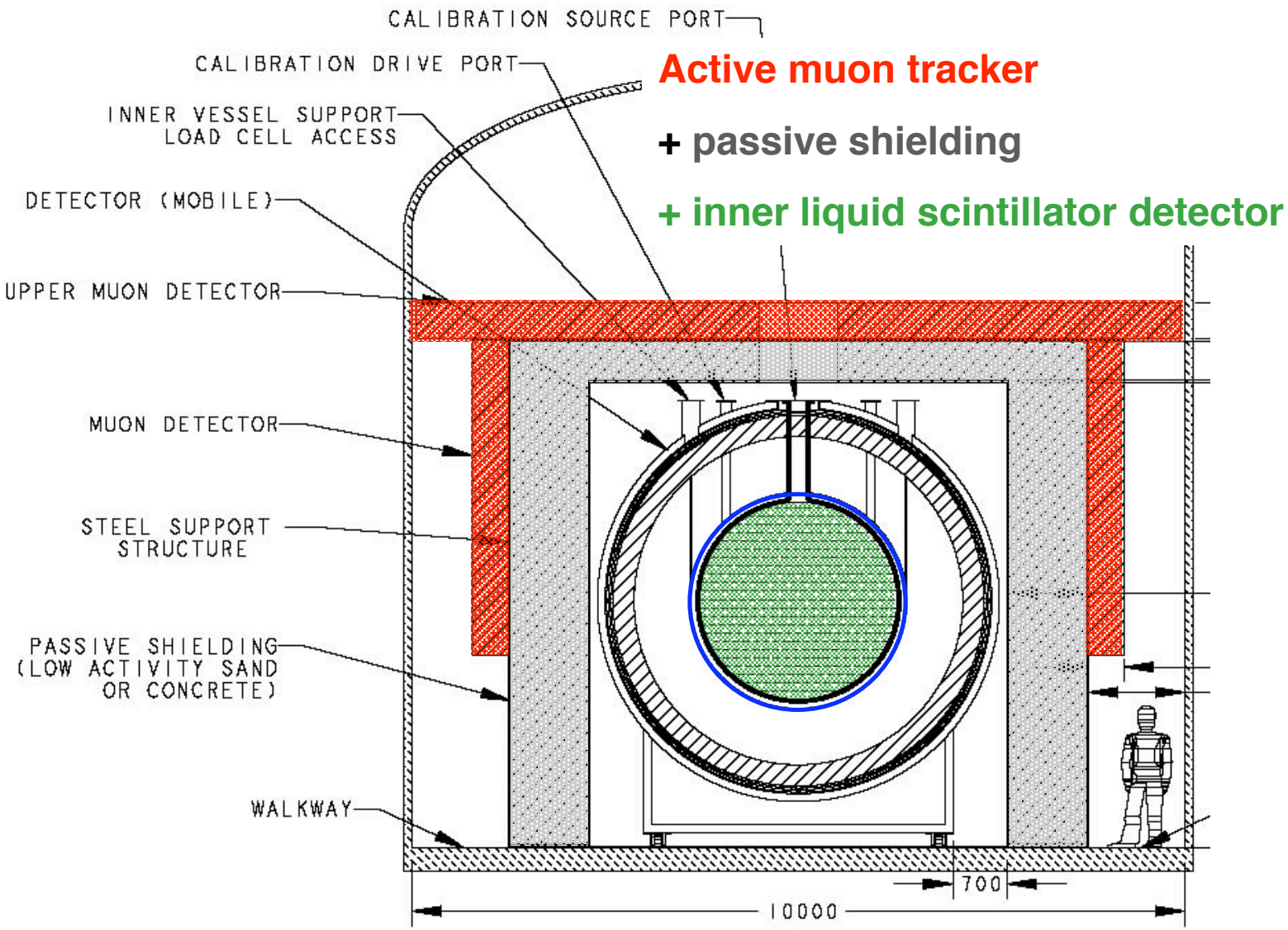


Mountain

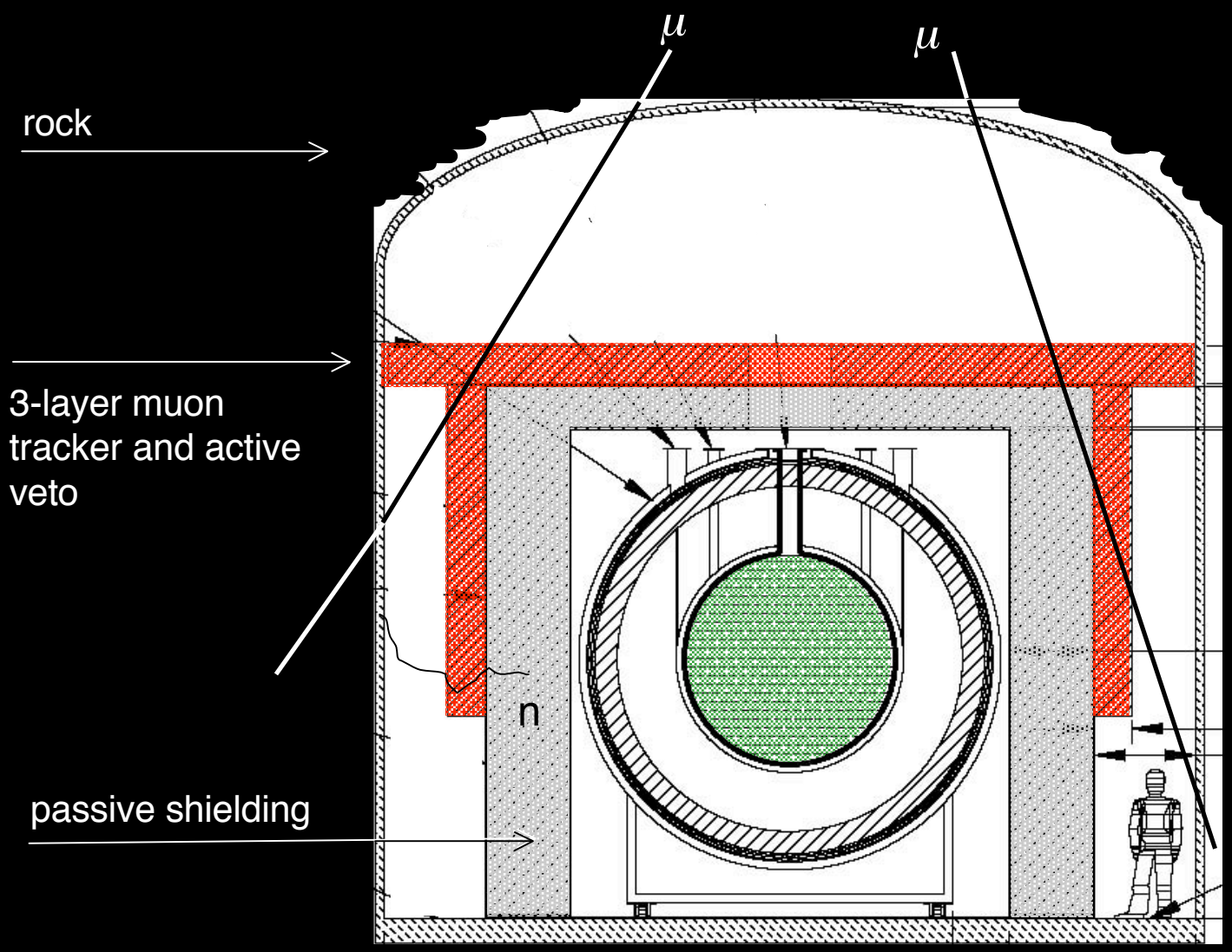


	flat, 450 mwe	mountain, 230 mwe	mountain, 1100 mwe
muon flux ($m^{-2}s^{-1}$)	0.194	1.63	0.024
neutron rate (ton^{-1} day^{-1})	161	824	30.0
$^{8}He+^{9}Li$ (ton^{-1} day^{-1})	0.076 $\pm$ 0.026	0.4 $\pm$ 0.4	0.014 $\pm$ 0.002

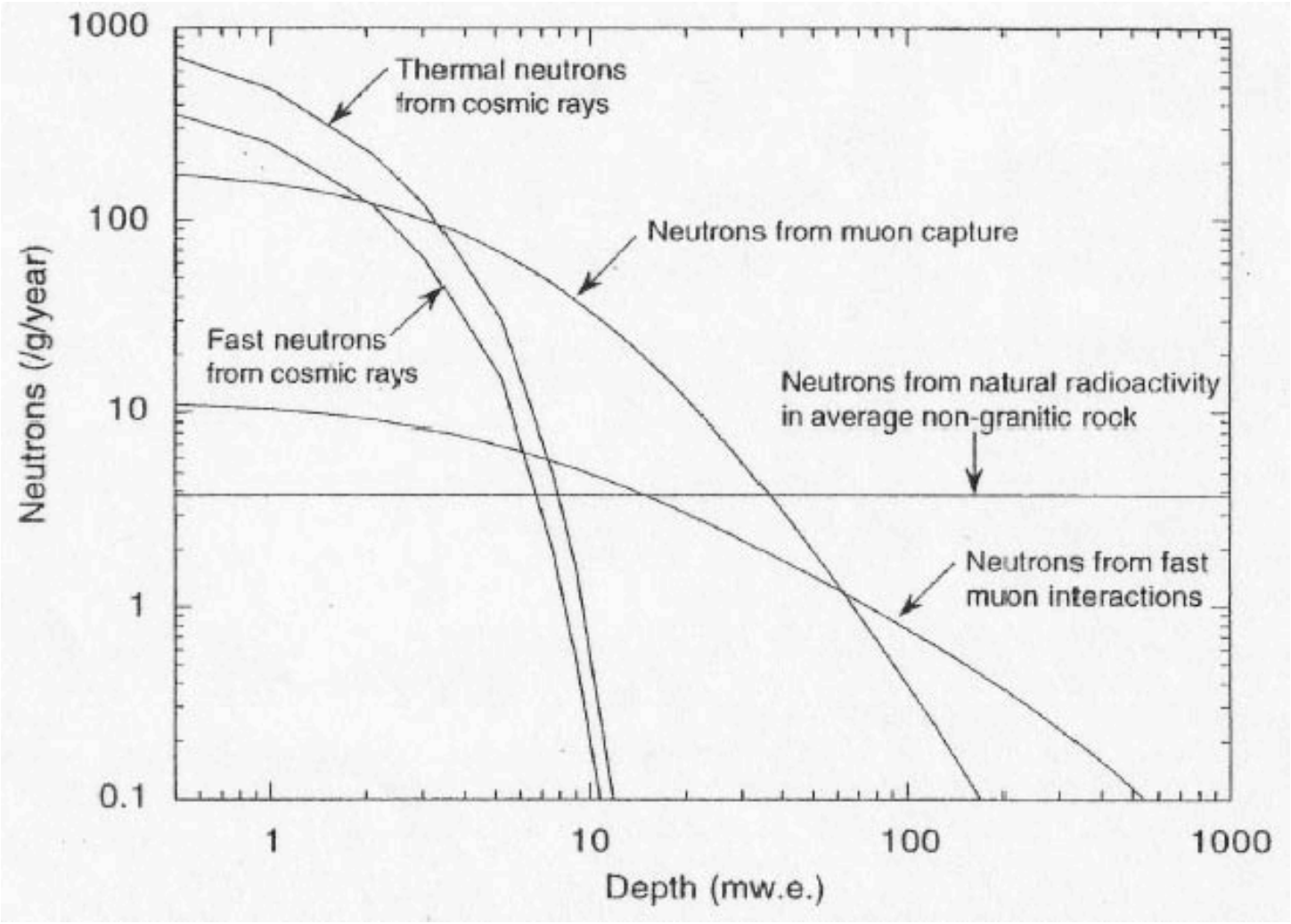
Detector and Shielding Concept



Detector and Shielding Concept



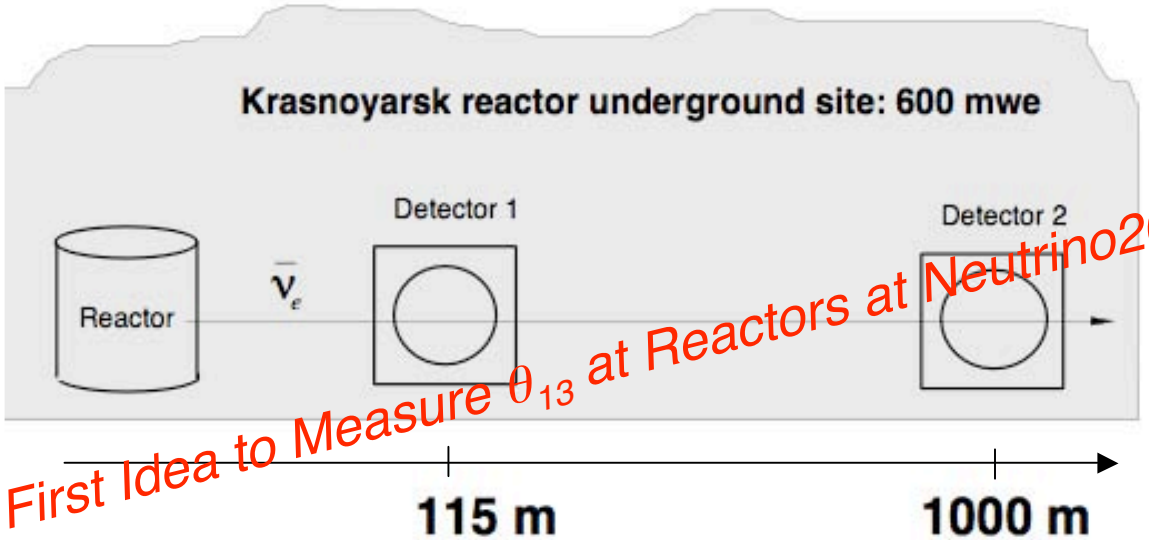
Neutron Production in Rock



A. da Silva
PhD thesis, UCB 1996

World of Proposed Reactor Neutrino Experiments

Reactor θ_{13} Experiment at Krasnoyarsk



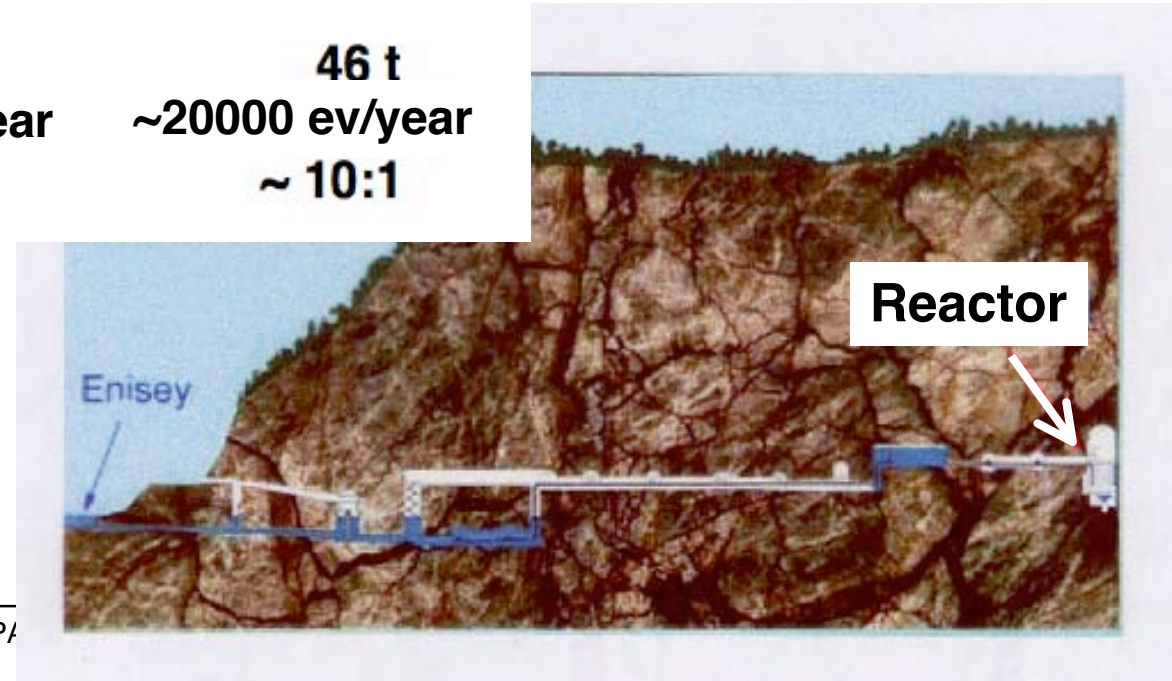
First Idea to Measure θ_{13} at Reactors at Neutrino2000

Target:	**46 t**	**46 t**
Rate:	**~1.5 x 10^6 ev/year**	**~20000 ev/year**
S:B	**>>1**	**~ 10:1**

Unique Feature

- underground reactor
- existing infrastructure

Detector locations determined by infrastructure

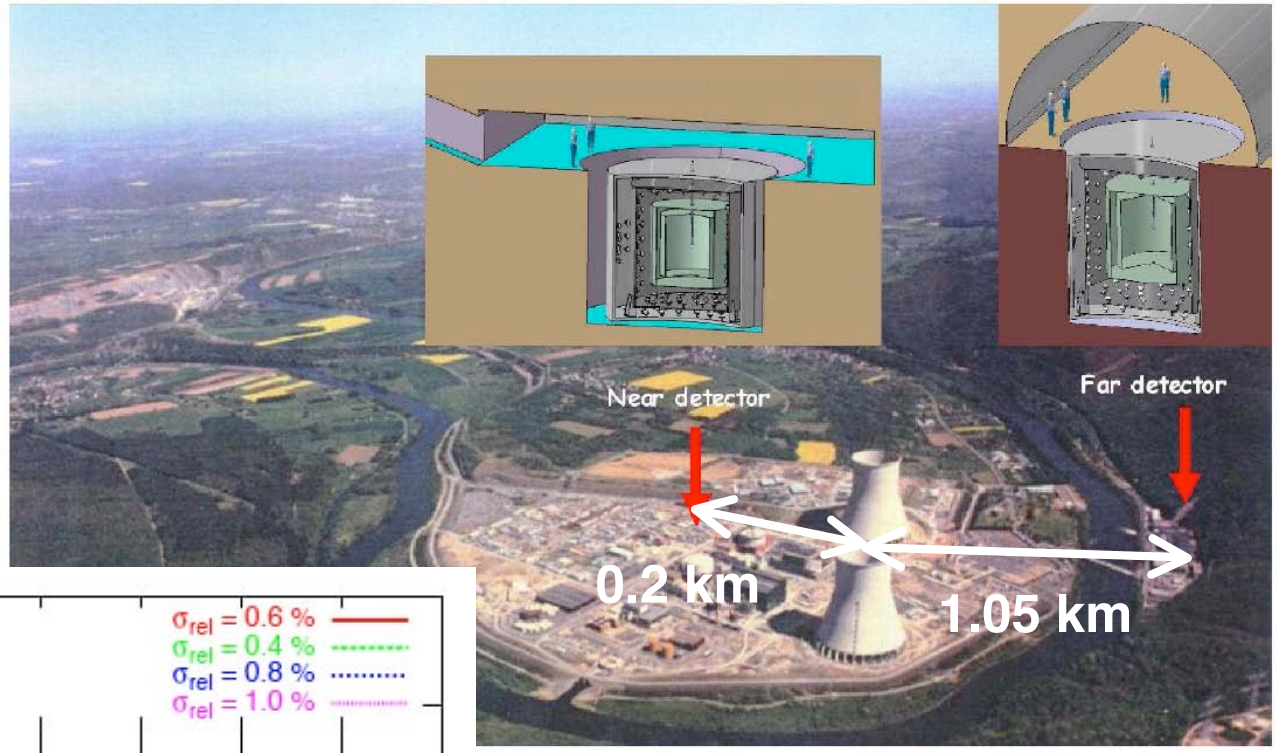


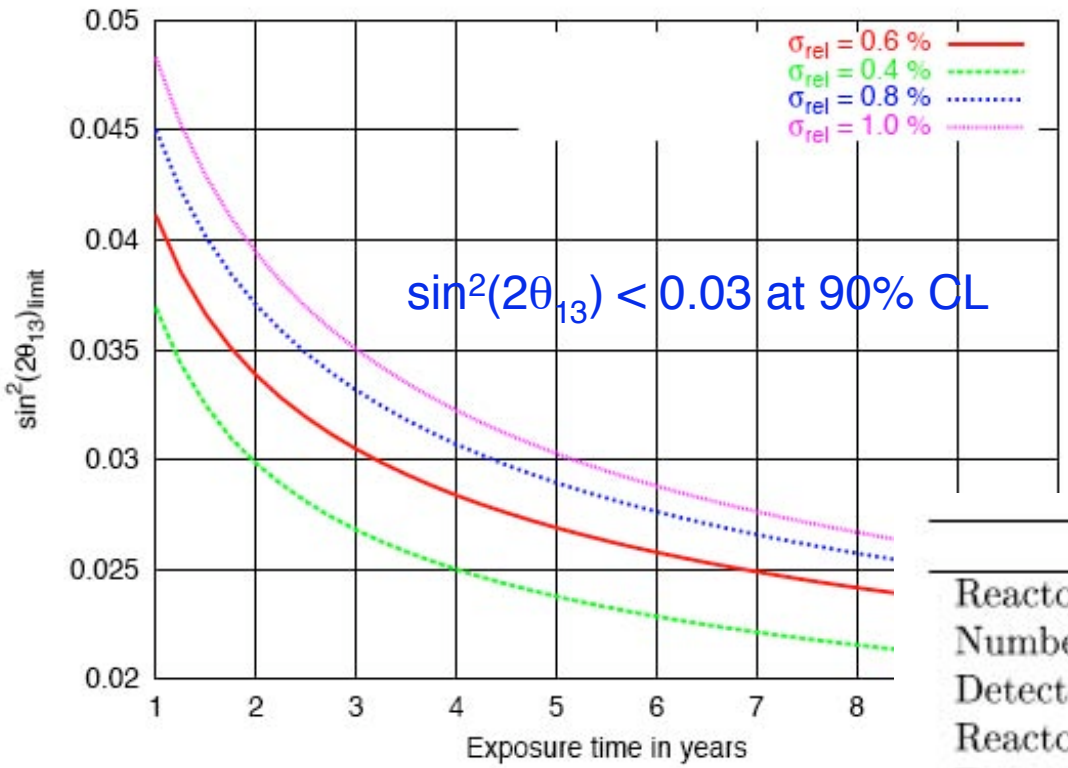
Ref: Marteyamov et al, hep-ex/0211070

Double-Chooz

10 tons detectors
8.4 GW_{th} reactor power

far site: 300 mwe
near site: 50 mwe



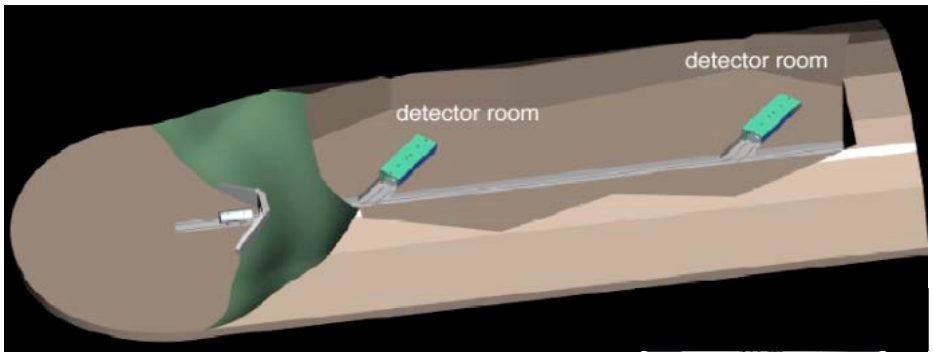


hep-ex/040503

	CHOOZ	Double-CHOOZ
Reactor cross section	1.9 %	—
Number of protons	0.8 %	0.2 %
Detector efficiency	1.5 %	0.5 %
Reactor power	0.7 %	—
Energy per fission	0.6 %	—

US Effort

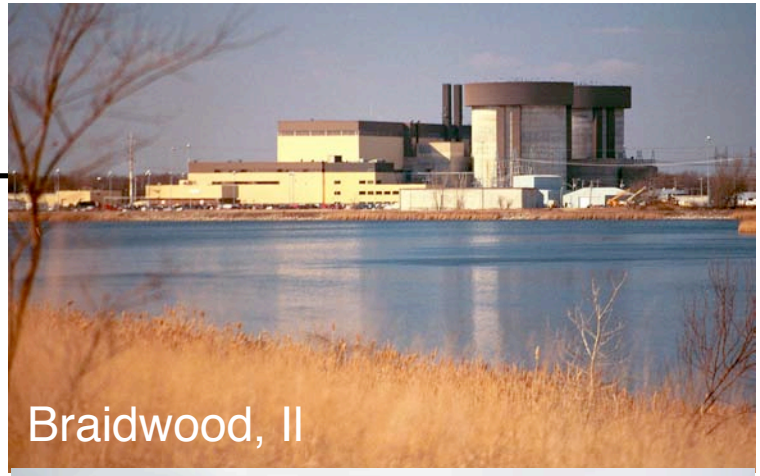
I) Mountainous sites with horizontal access tunnel



- flexibility to adjust baseline
- access to large overburden

II) Flat sites with vertical shaft access

- placement and location flexibility
- good shielding per unit depth

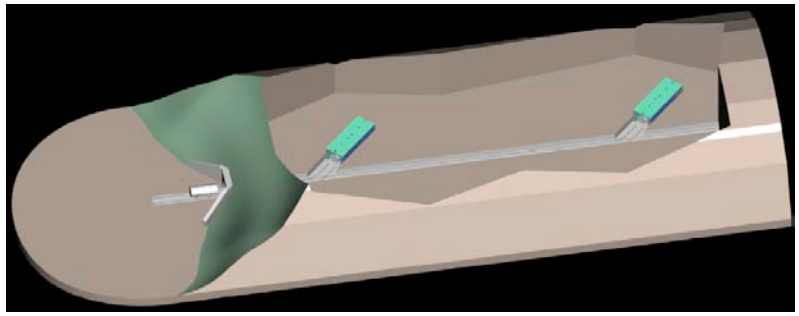

Braidwood, Il

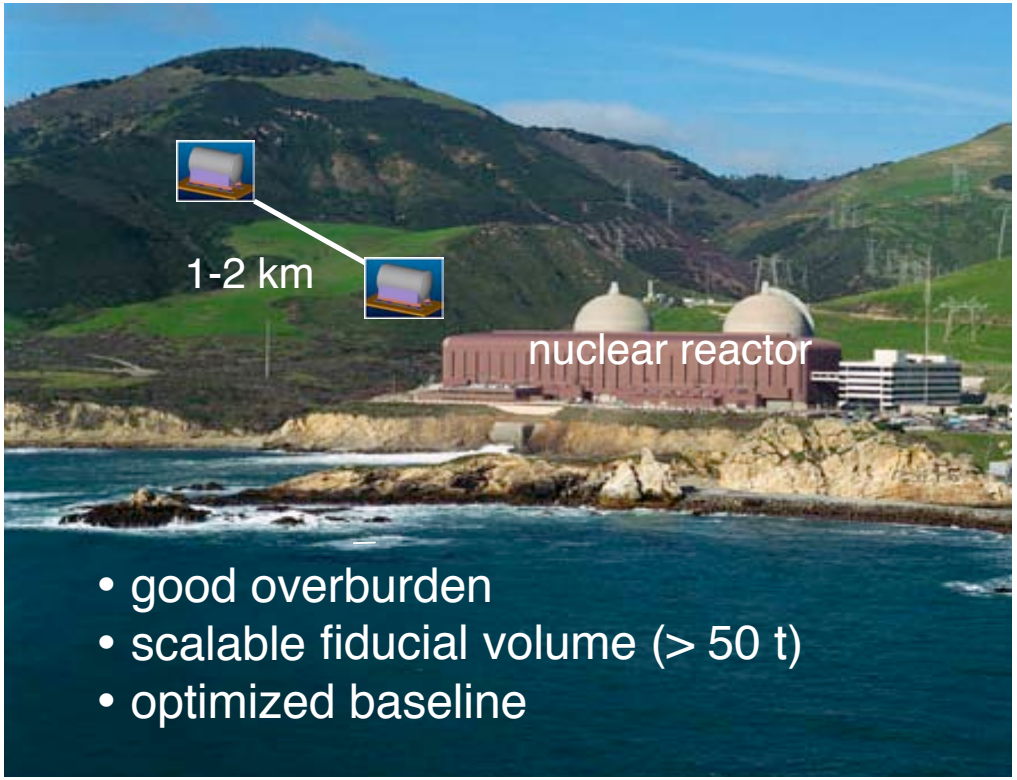
Daya Bay, China

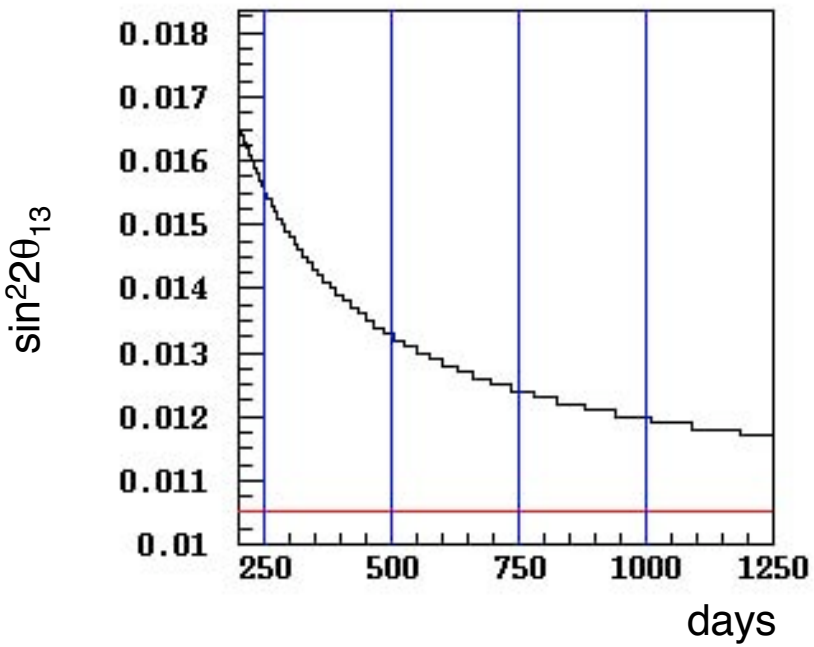
Diablo Canyon, CA

Precision Measurement of θ_{13} with Reactor Neutrinos

Deep Horizontal-Access Experiment
to reach $\sin^2 2\theta_{13} < 0.01$

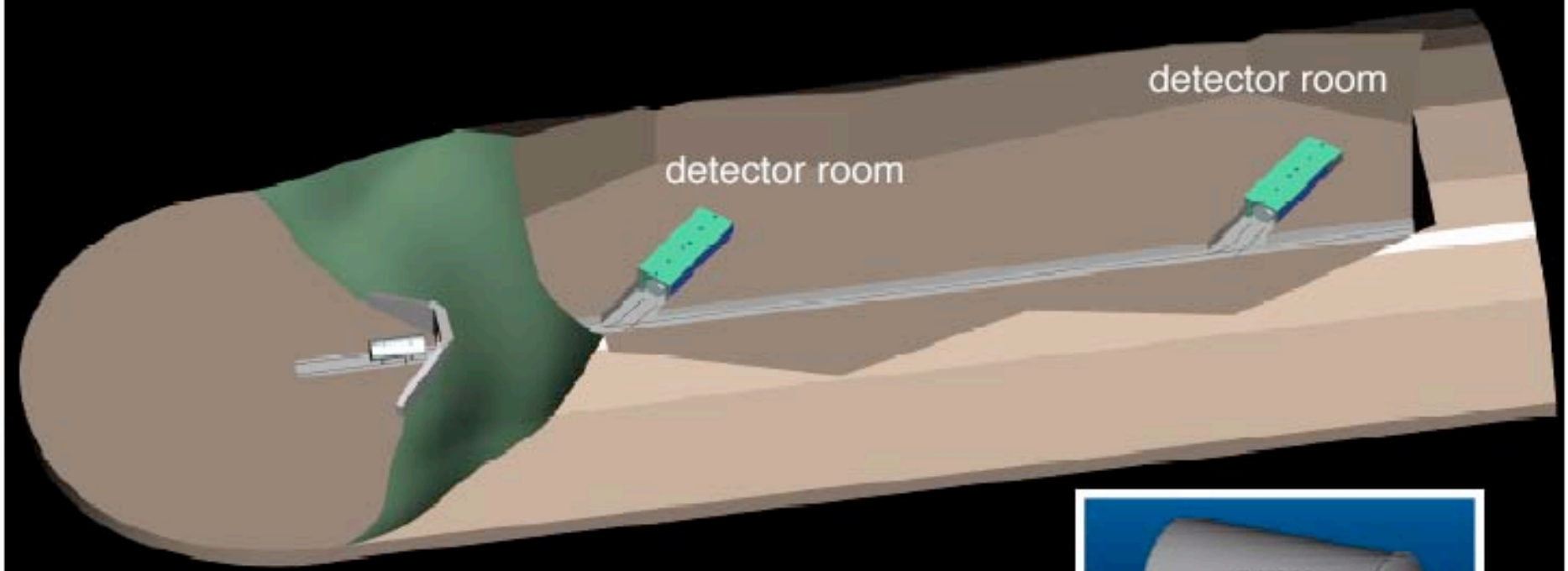


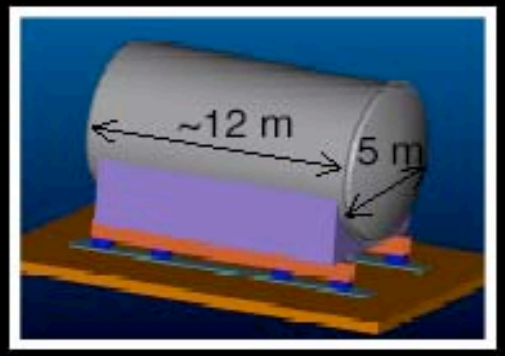




Overburden:	Near 200-300 mwe Far >1100 mwe
Possible Sites:	Diablo Canyon, CA Daya Bay, China

Tunnel with Multiple Detector Rooms and Movable Detectors

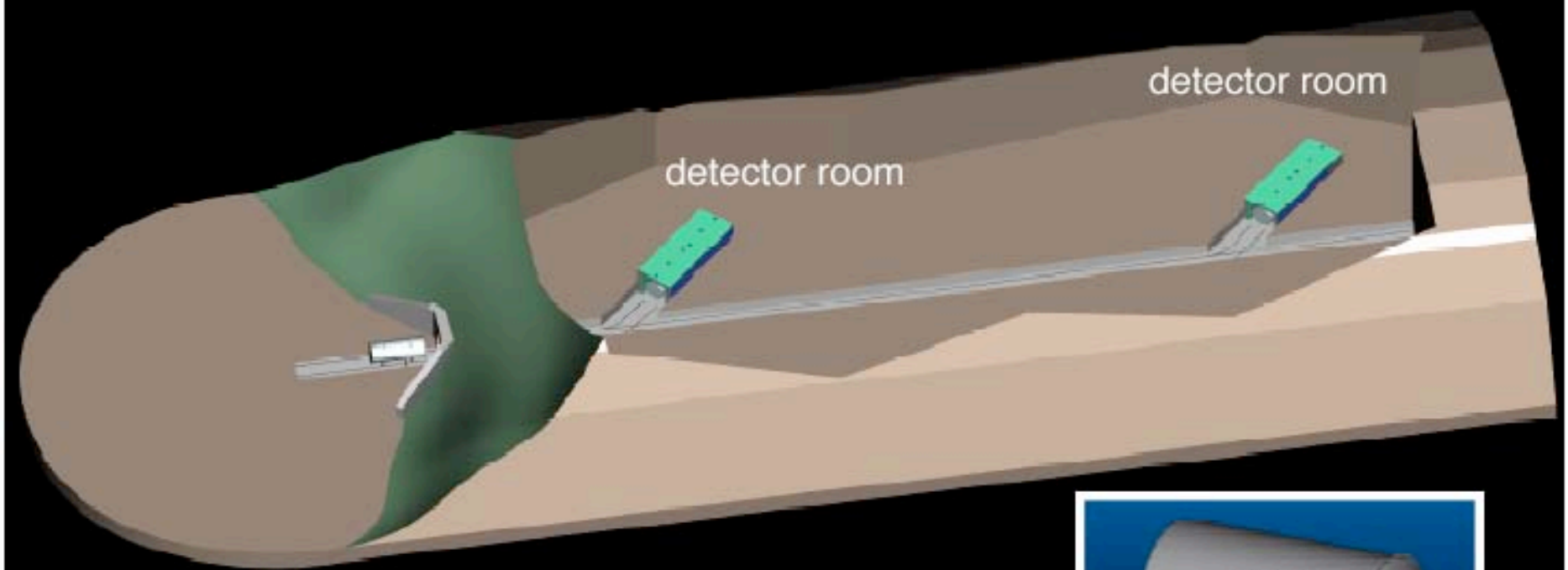


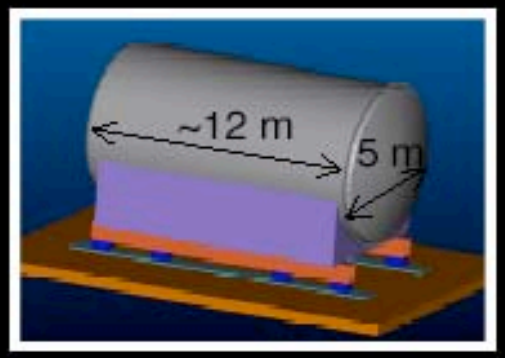


Adjustable Baseline

- to maximize oscillation sensitivity
- to demonstrate oscillation effect

Tunnel with Multiple Detector Rooms and Movable Detectors

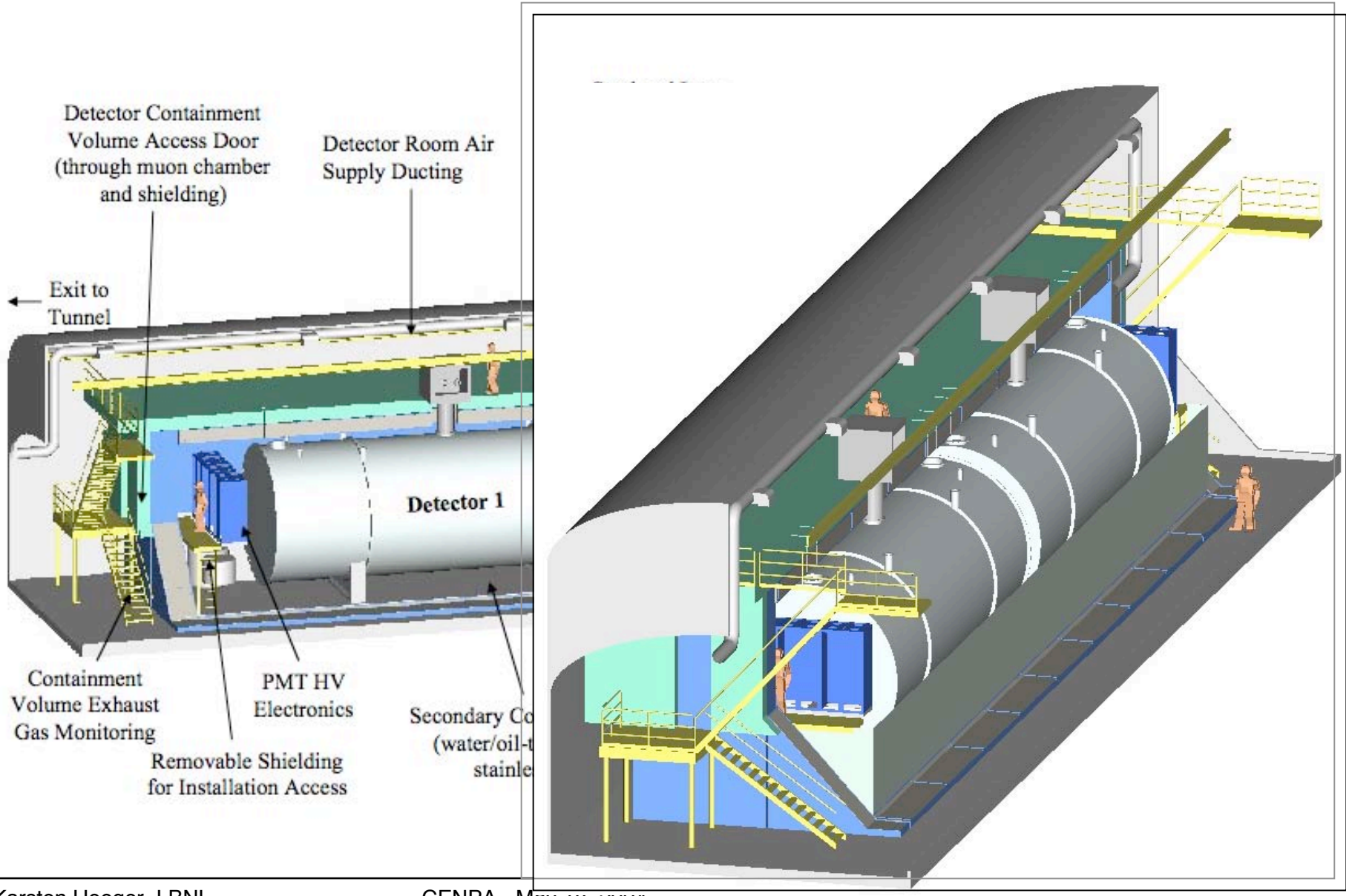




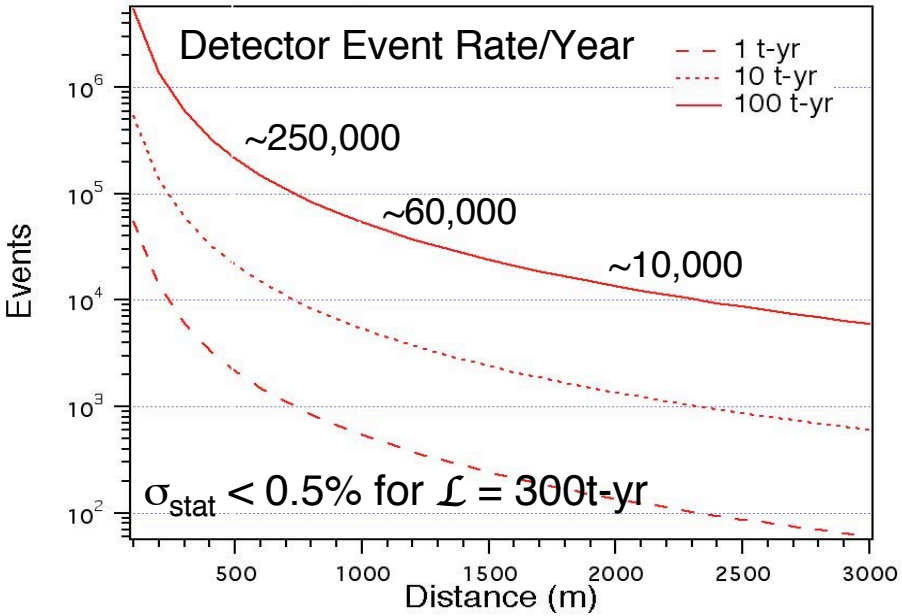
Movable Detectors

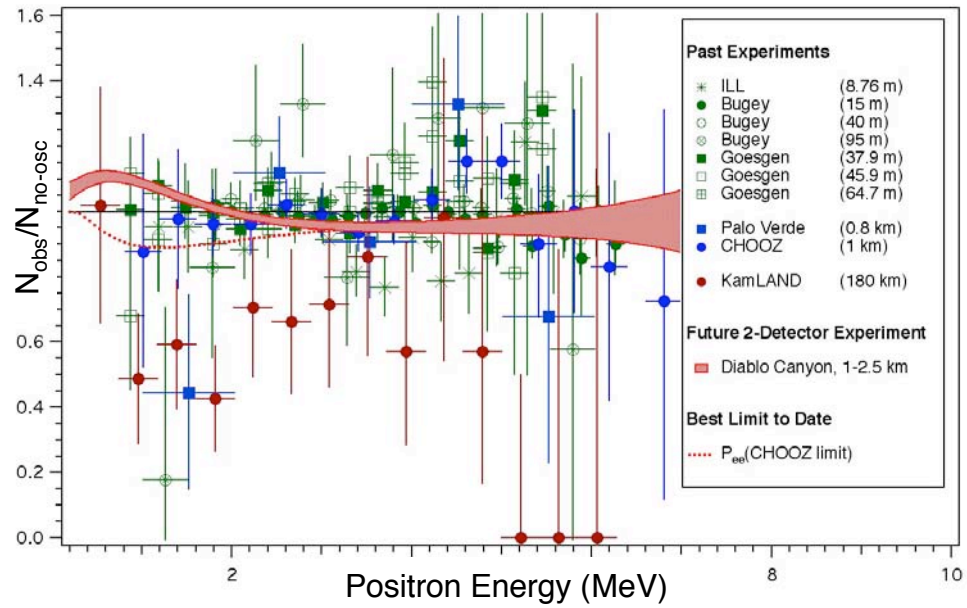
- allow relative efficiency calibration
- allow background calibration in same environment (overburden)
- simplify logistics (construction off-site)

Detector Room Concept



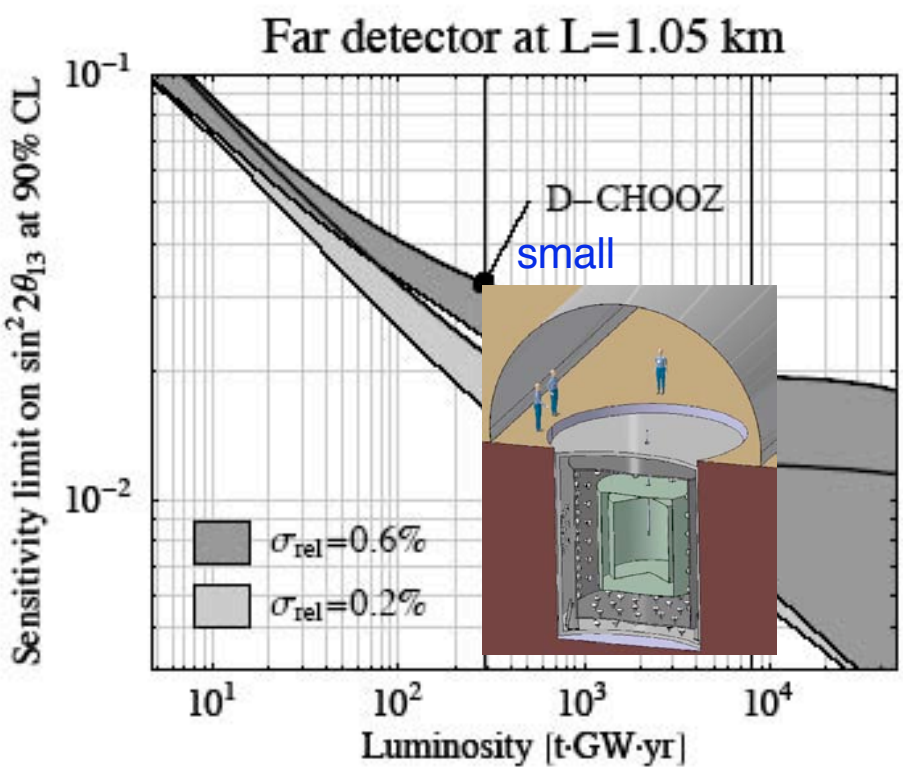
Statistics and Systematics

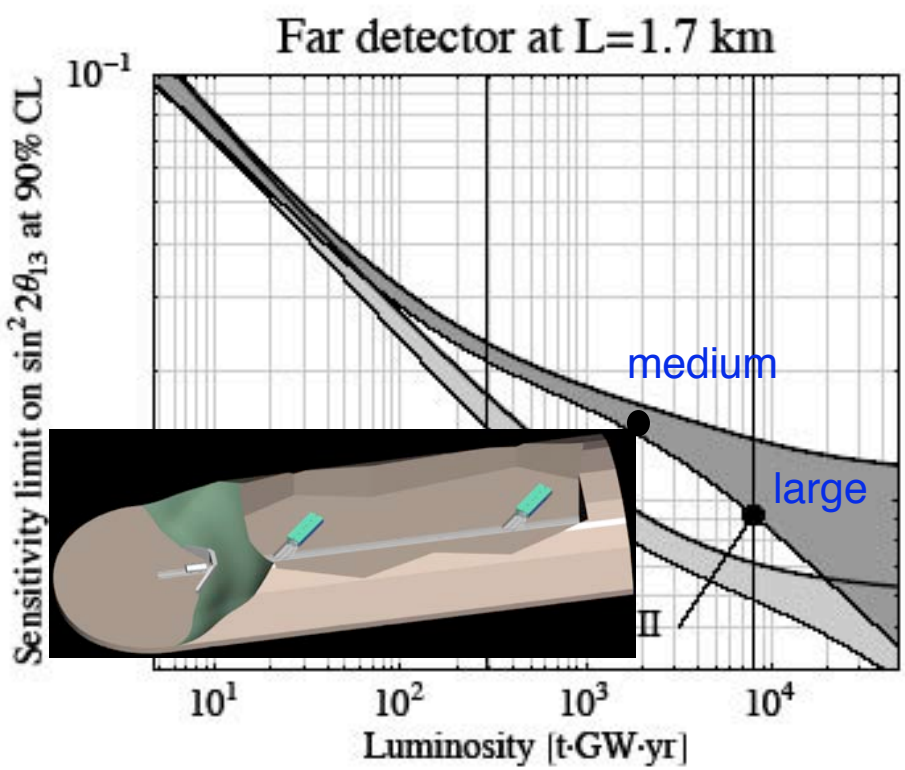




Effect	Error Estimate	Method
reactor flux uncertainty	$\leq 0.2\%$	relative measurement at different distances
detection efficiency	$\leq 0.8\%$	calibration of relative det. efficiency
target volume	$\leq 0.3\%$	no fiducial volume cut in Gd scintillator, flow and weight measurement of target
backgrounds	$\leq 1.0\%$	sufficient overburden, active and passive shielding
Total Systematics	$\sim 1\%$	

Classes of Reactor θ_{13} Experiments & Sensitivity





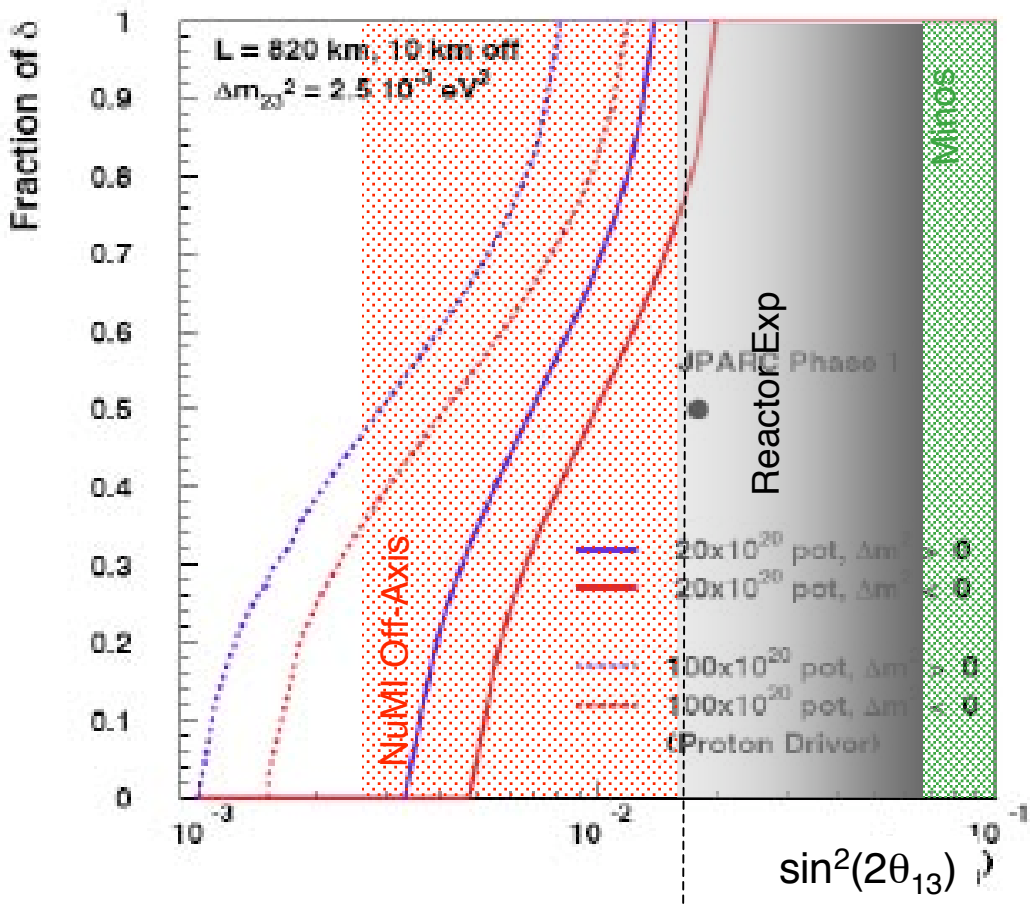
- existing underground facility

- deep, good overburden
- optimized baseline and detector size

Reactor & Long Baseline Experiments

Measuring $\sin^2(2\theta_{13})$

3 σ Sensitivity to $\sin^2(2\theta_{13})$



Chooz
90% CL $\sin^2(2\theta_{13}) \leq 0.14$

Minos
3-σ sensitivity $\sin^2(2\theta_{13}) = 0.07$

θ_{13} Reactor Exp $\sin^2(2\theta_{13}) < 0.01\text{-}0.02$
90% CL

NuMI Off-Axis
3-σ sens. $\sin^2(2\theta_{13}) < 0.007$

at $\Delta m_{atm}^2 = 2.5 \times 10^{-3}\ eV^2$

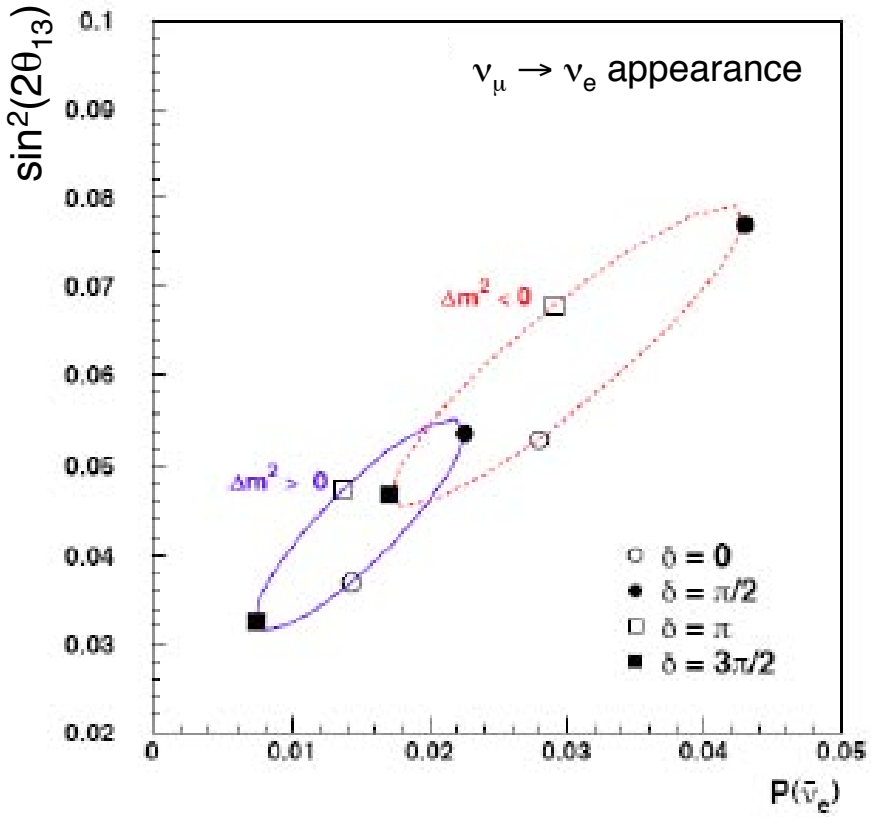
reactor 90% CL= 0.01 and $\delta(\sin^2(2\theta_{13})) = 0.006$

Ref: NuMI Off-Axis Collaboration, Progress Report 12/2003

Reactor & Long Baseline Experiments

Determining Mass Hierarchy

$\sin^2(2\theta_{13})$ vs $P(\bar{\nu}_e)$ for $P(\bar{\nu}_e)$=0.02



$P(\nu_\mu \rightarrow \nu_e)$ depends on

$\sin^2(2\theta_{13})$

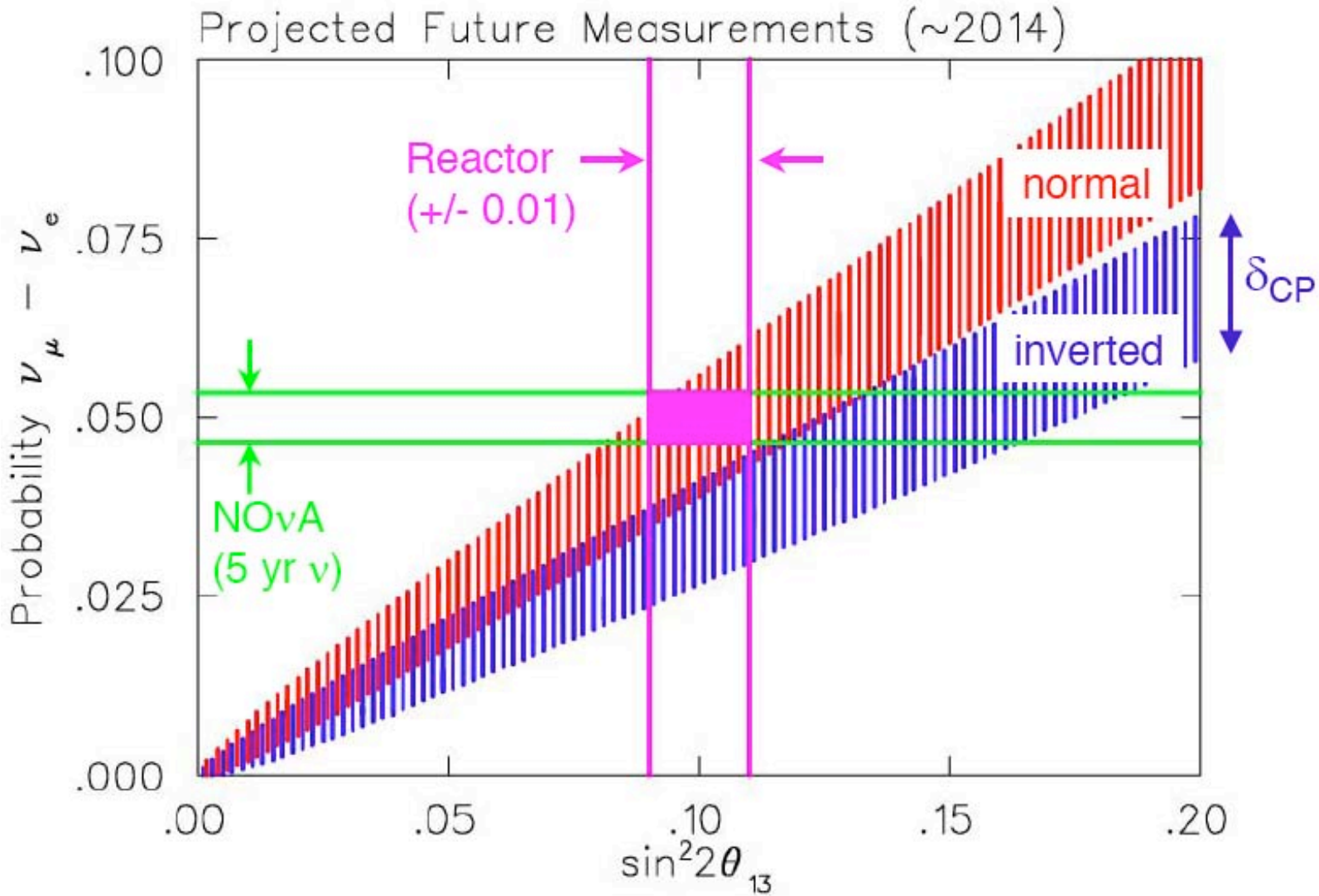
sign of Δm_{13}^2

δ_{CP}

Accelerator experiments measure ν_e appearance: $P(\nu_\mu \rightarrow \nu_e)$

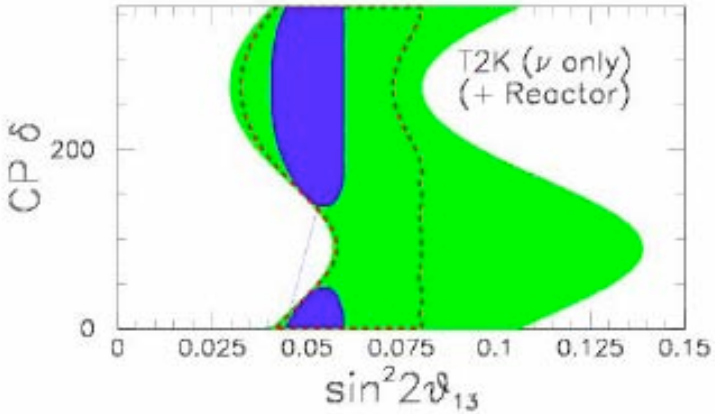
Ref: NuMI Off-Axis Collaboration, Progress Report 12/2003

Combined Analysis (Accelerator + Reactor)



Ref: McKeown

Combined Analysis (Accelerator + Reactor)

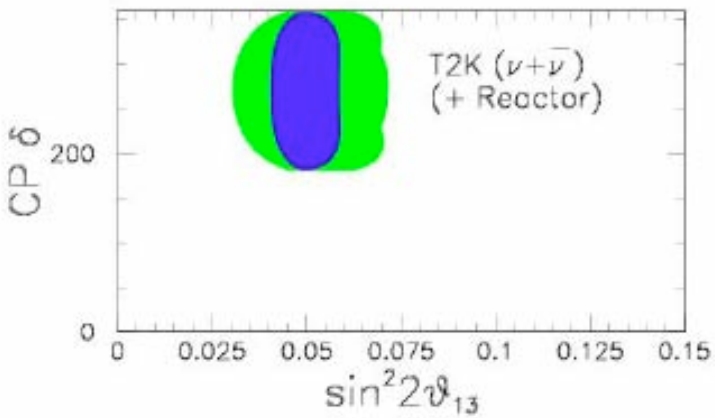


90% CL

$\sin^2(2\theta_{13}) = 0.05$,

$\Delta m^2 = 2.5 \times 10^{-3}$ eV^2

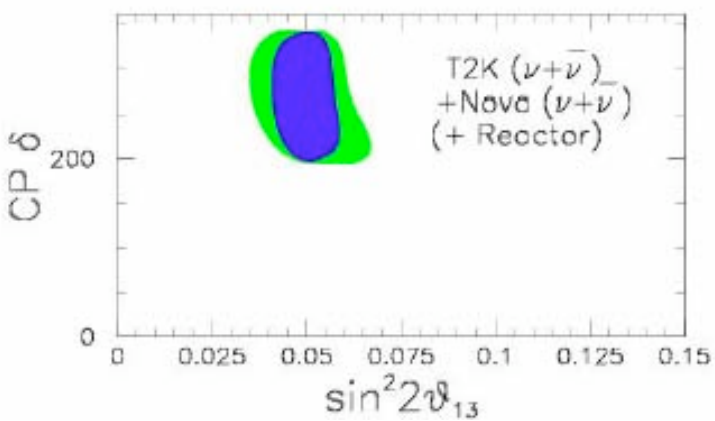
$\delta_{CP} = 270$

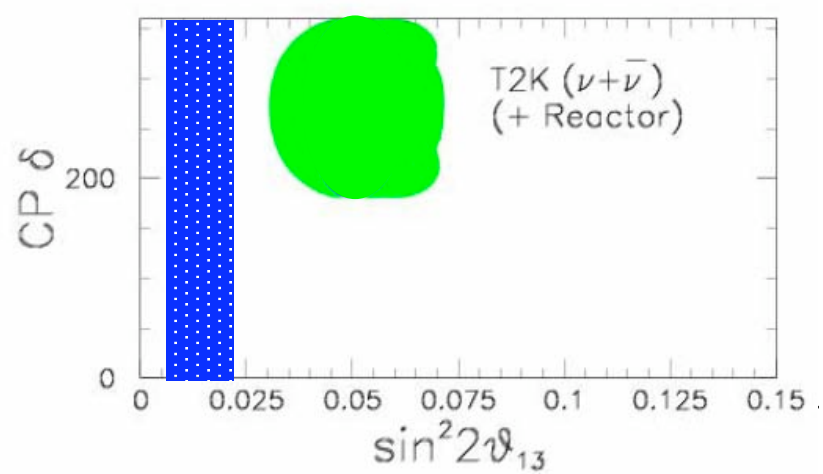


reactor experiments give best measurement of $\sin^2 2\theta_{13}$

accelerator experiments constrain δ_{CP}

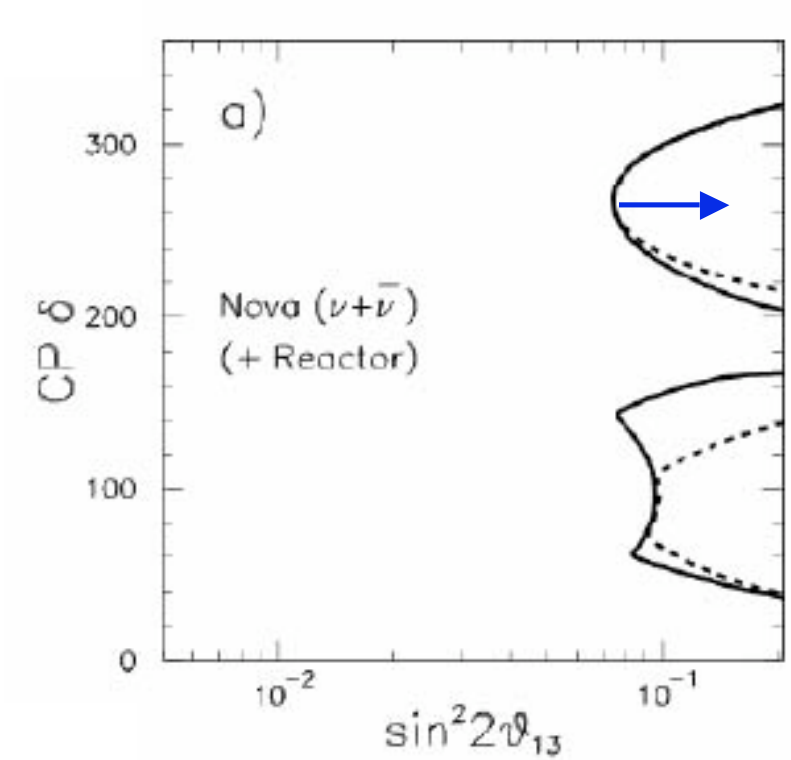
What if …



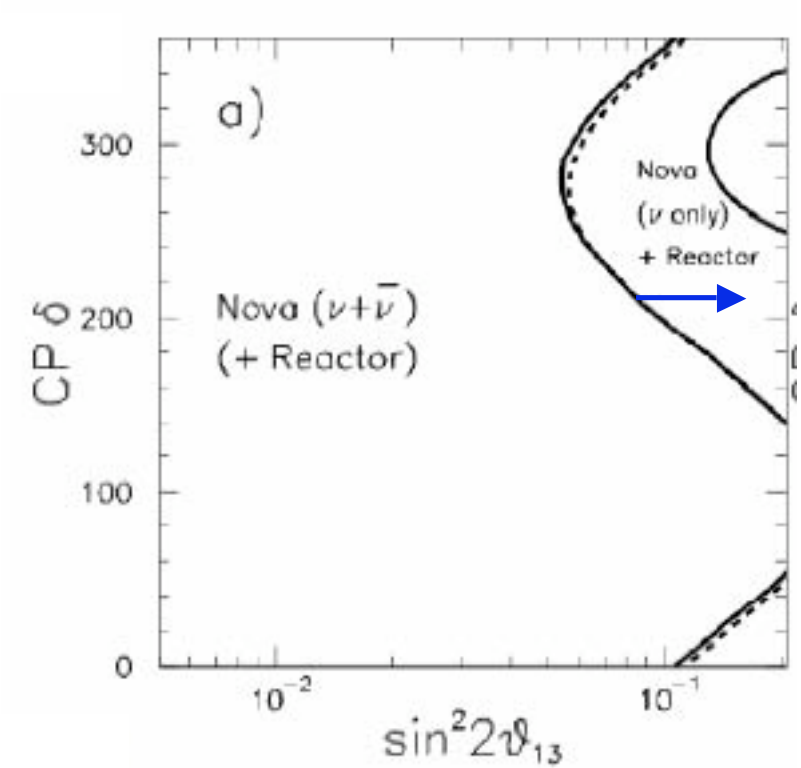


Combined Analysis (Accelerator + Reactor)

δ_{CP}=0 excluded region



mass hierarchy resolution



2σ regions,
solid line = with reactor

Ref: Shaevitz

Motivation for Reaching $\sin^2 2\theta_{13} < 0.01$

Measurement of Fundamental Parameter

• θ_{13} is one of the twenty six parameters of the standard model, the best model of electroweak interactions for energies below 100 GeV, worthy of high precision measurement independently of other considerations.

Input to Future Neutrino Program

• Reactor measurement of $\sin^2 2\theta_{13}$ sets the scale for pursuing mass hierarchy and CP violation. If too small ($\sin^2 2\theta_{13} < 0.01$), they will be out of reach for off-axis experiments.

Complementarity with Accelerator Experiments

• Ambiguities in off-axis experiments ($\sin^2 2\theta_{13,}$ $\sin^2 2\theta_{23,}$ mass hierarchy, δ). Reactor measurements help extract physics parameters.

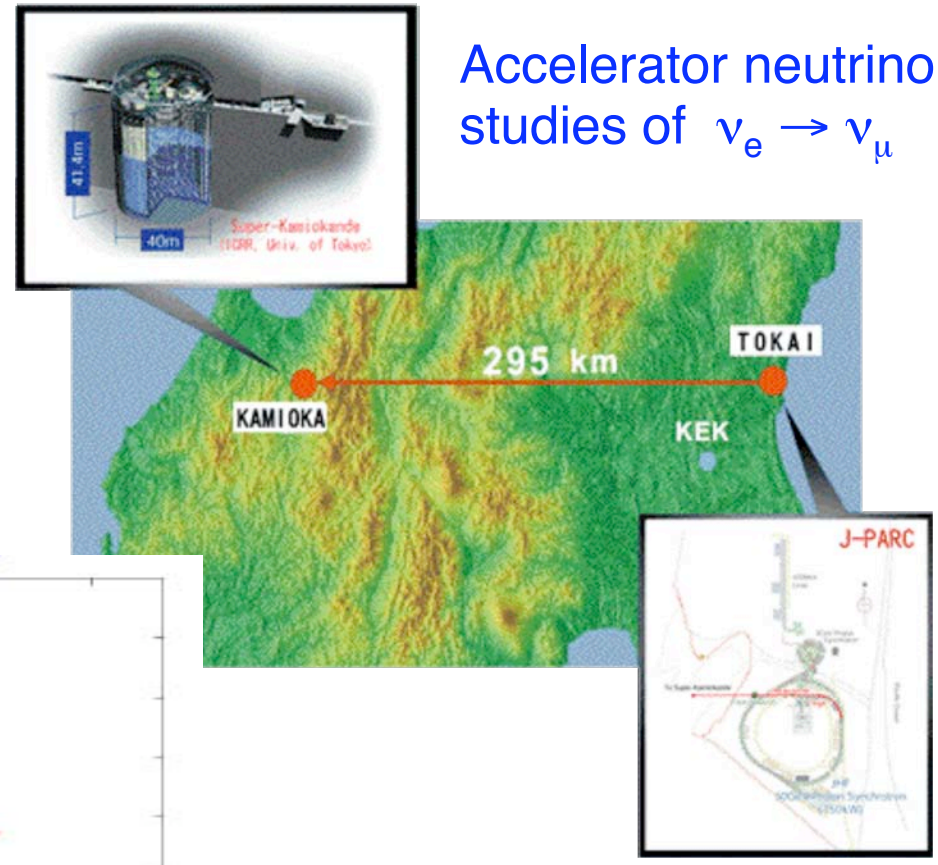
Theory and Model Building

• Reactor experiments can reach precision that probe quantum correction to neutrino mass and mixings. Limits on model parameters can be obtained if $\sin^2 2\theta_{13} < 0.01$.

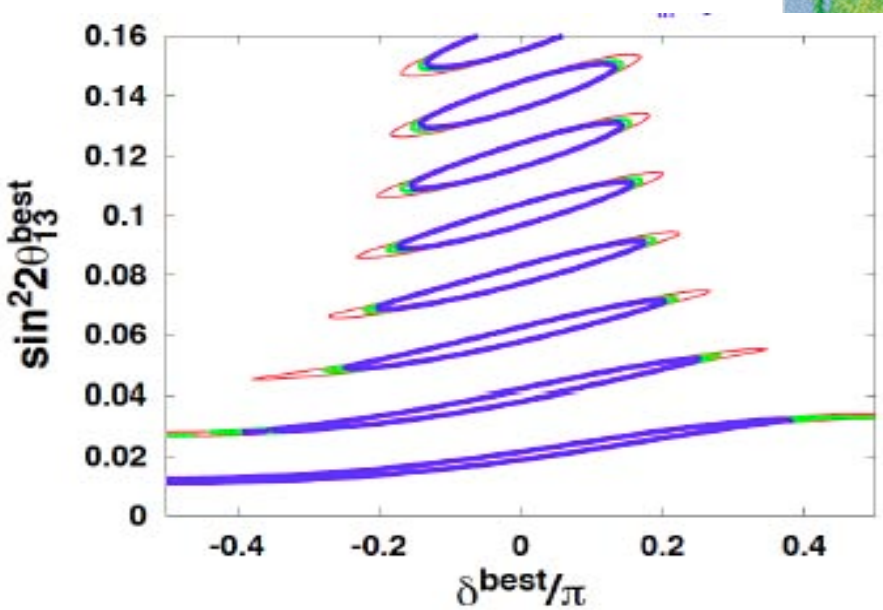
Possible Future of Neutrino Oscillation Physics

The Next 10 Years

Measurement of θ_{13} with reactor neutrinos



Accelerator neutrino studies of $\nu_e \rightarrow \nu_\mu$



Constraining CP-violating parameters in combined analysis