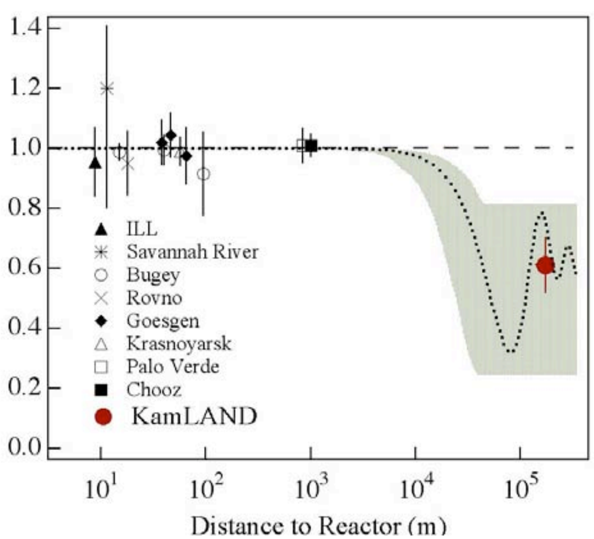
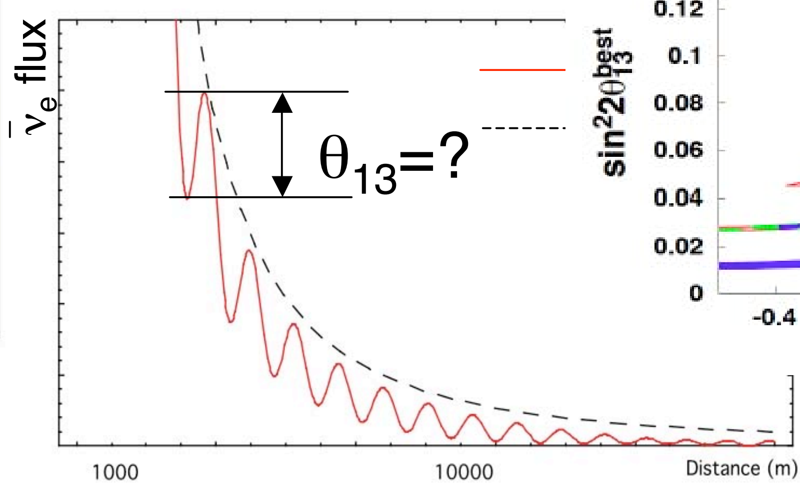
Measuring θ_{13} and the Search for Leptonic CP Violation

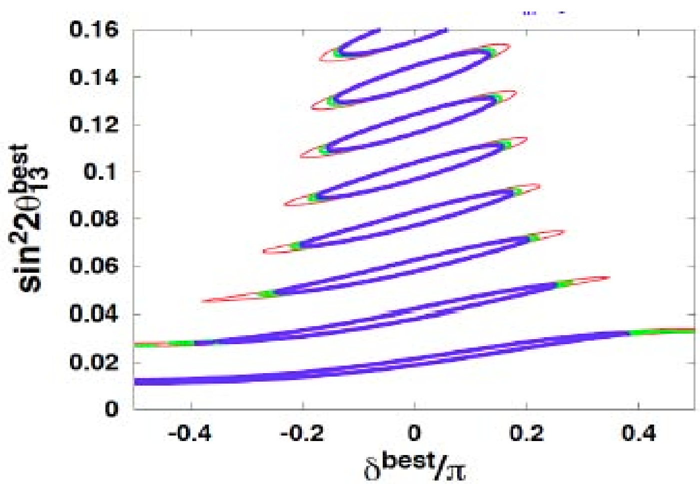
- Future Prospects in Oscillation Physics -

Karsten M. Heeger

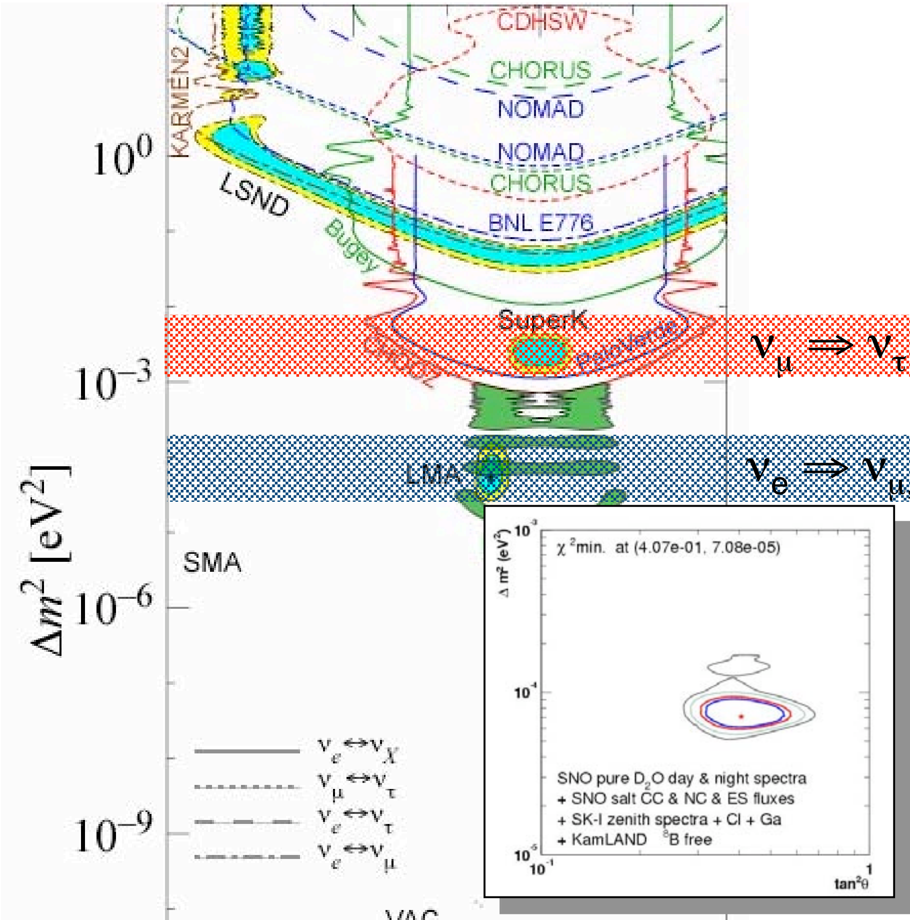
Lawrence Berkeley National Laboratory





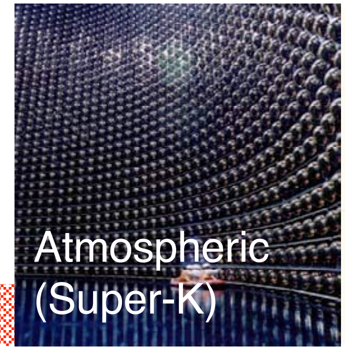


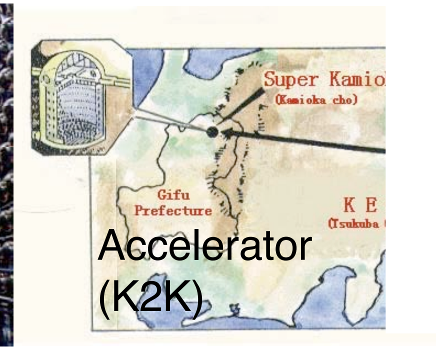
Evidence for Mixing of Massive Neutrinos

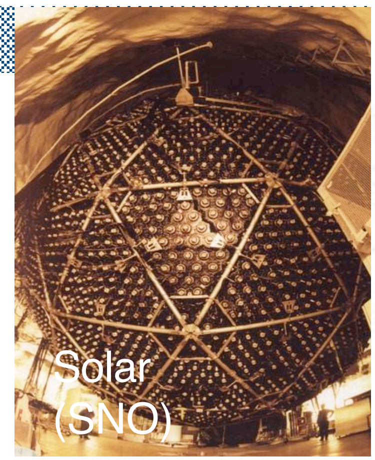


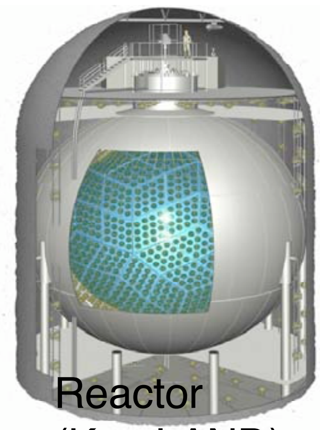
$\nu_\mu \Rightarrow \nu_\tau$

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









- Neutrinos are not massless
- Evidence for neutrino flavor conversion $\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$
- Experimental results show that *neutrinos oscillate*

Open Questions in Neutrino Physics

- Is $U_{13} = 0$?
- Is there CP violation for neutrinos?
- What are the values of Δm^2, U_{ij}?

→ Future reactor and accelerator experiments

- Is U 3-dimensional? 4? 6? ∞?

or, is the 3-D version unitary?

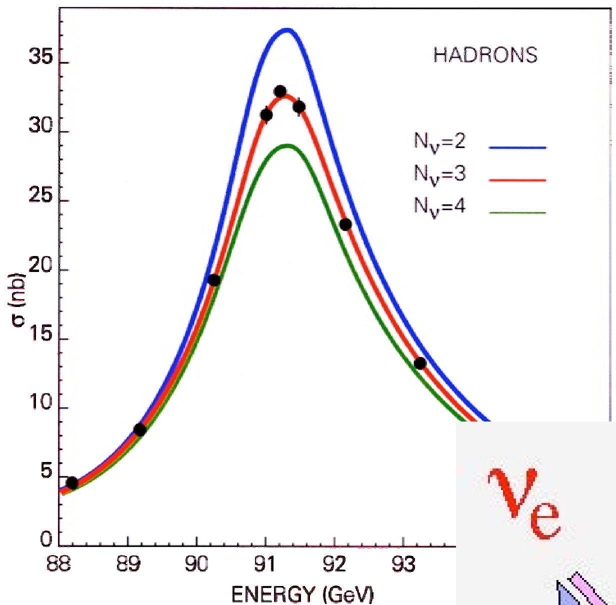
or, are there sterile ν?

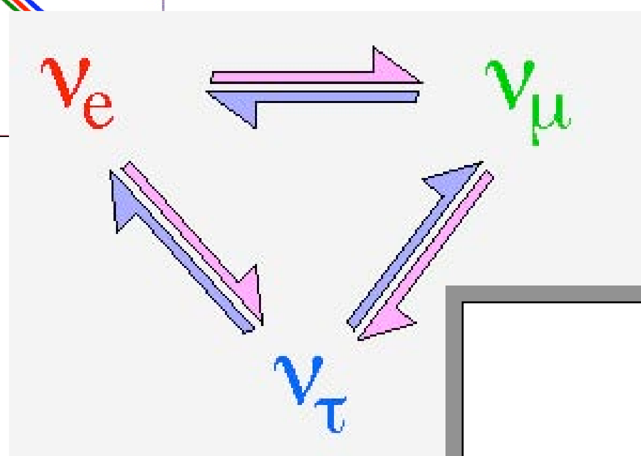
→ MiniBoone

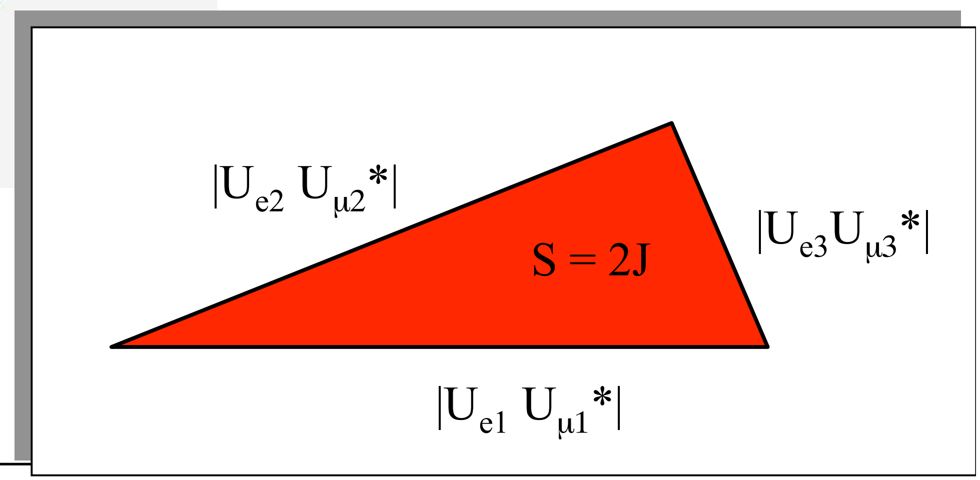
- What are the absolute masses?
- What is the level ordering of 2,3 (or 1,3)?
- Are ν's Dirac or Majorana particles?

→ Direct mass measurements and $0\nu\beta\beta$

Neutrino Mixing Angles and Leptonic Unitarity Triangle







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

U_{MNSP} Neutrino Mixing Matrix

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

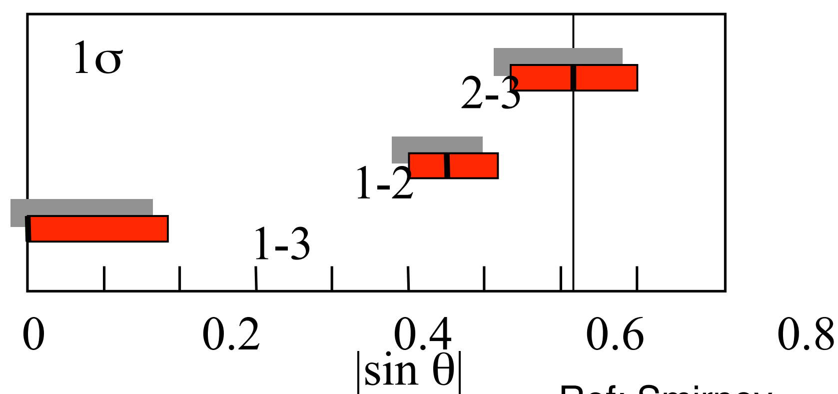
Dirac phase — *Majorana phases*

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

?

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 — $\theta_{12} \sim 32°$



Ref: Smirnov

U_{MNSP}, θ_{13}, and ~~CP~~

U_{MNSP} Neutrino Mixing Matrix

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

Dirac phase — *Majorana phases*

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?

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

Unknown Oscillation Parameters

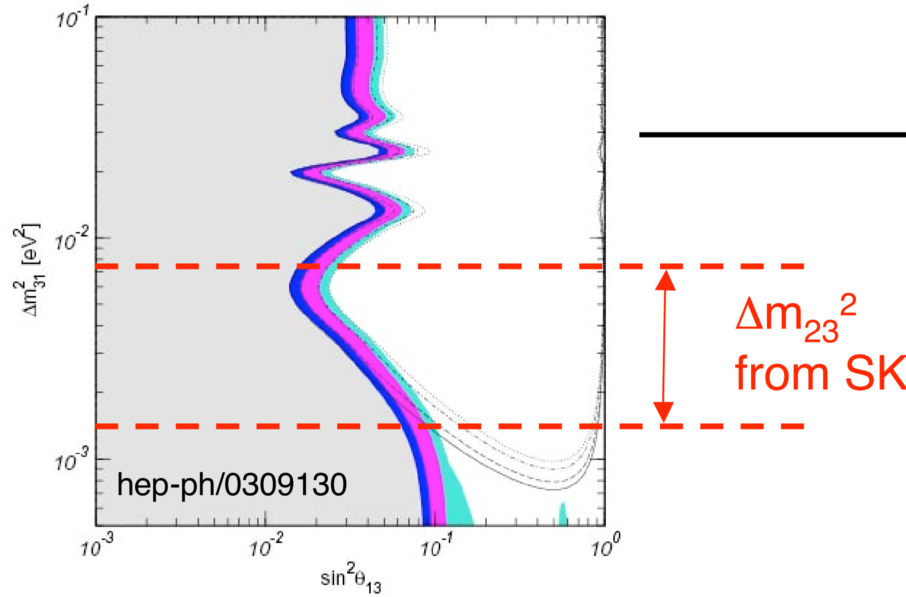
$\sin^2(2\theta_{13})$

sign of Δm_{13}^2

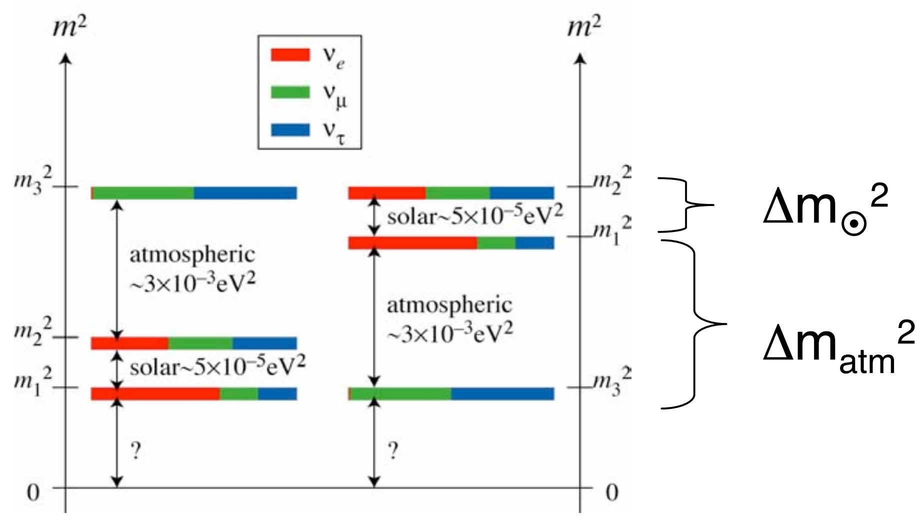
δ_{CP}

Three Questions

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



II) What is the 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

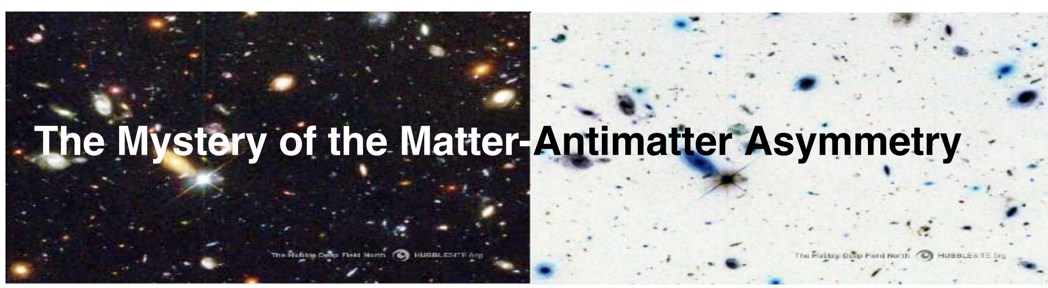
Physics at high mass scales, physics of flavor, and unification:

- 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?

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

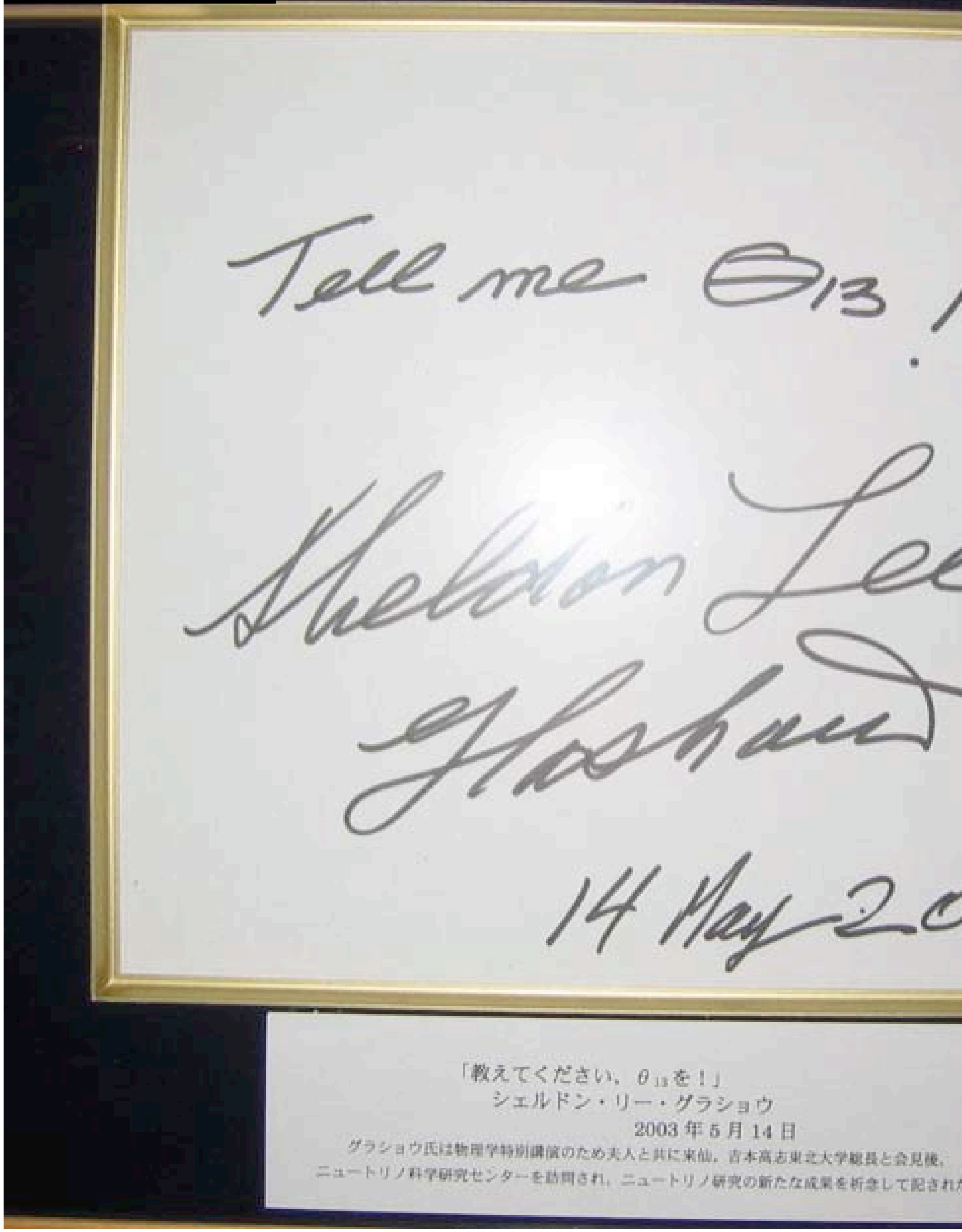
$$V_{CKM} = \begin{pmatrix} big & small & tiny \\ small & big & tiny \\ tiny & tiny & big \end{pmatrix}$$

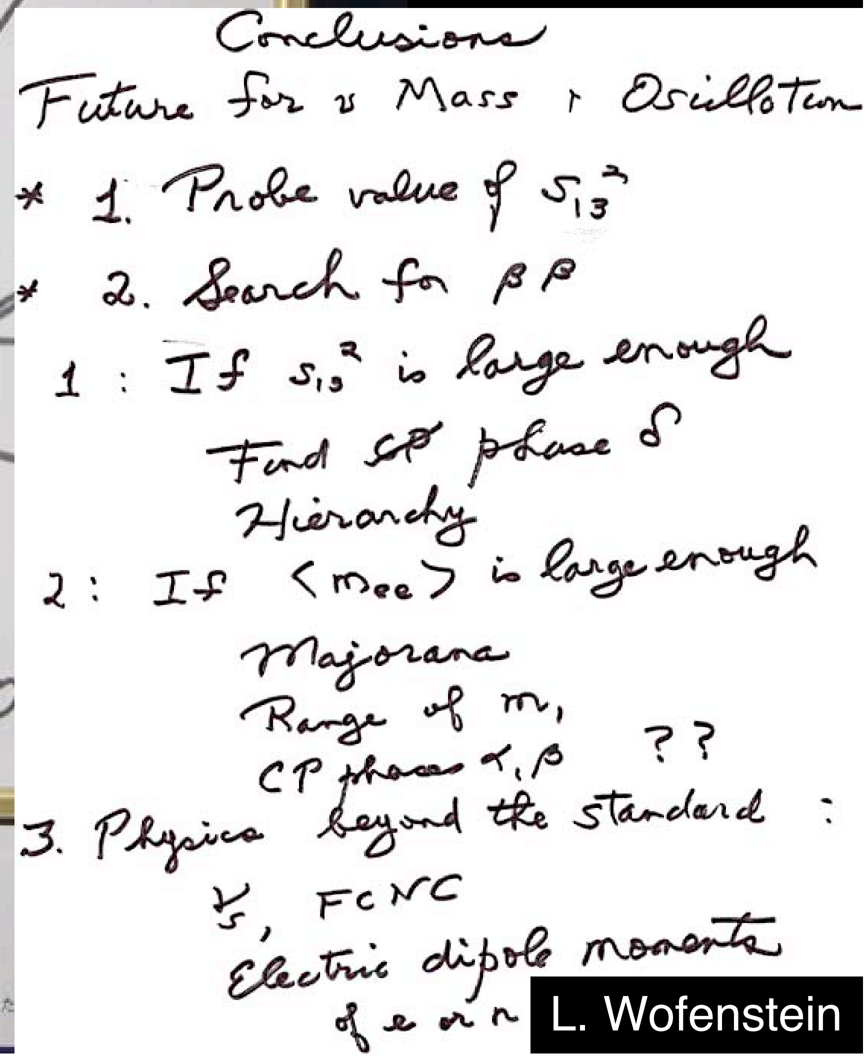
- Leptogenesis and the role of neutrinos in the early Universe



θ_{13}

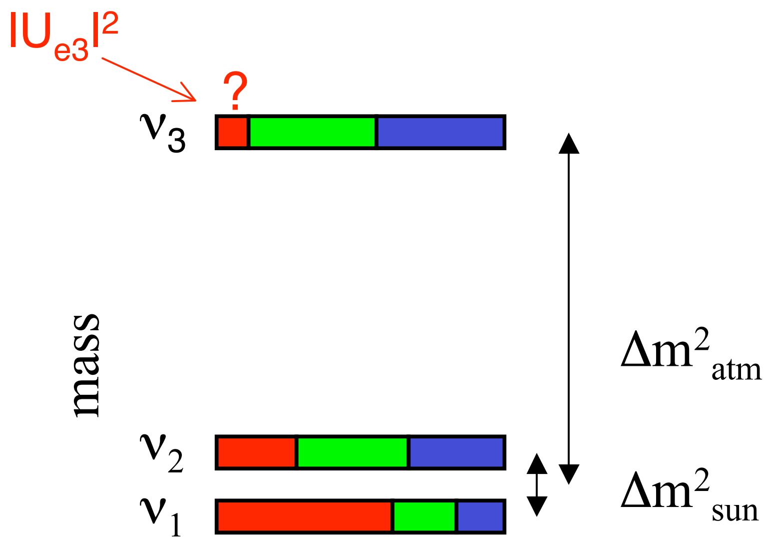
S. Glashow



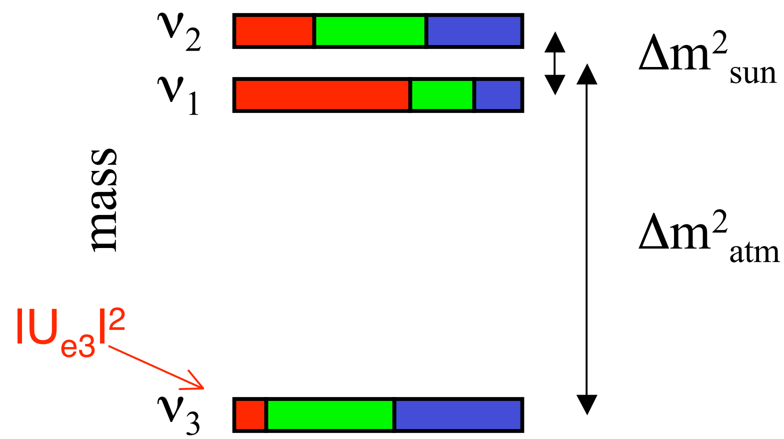


L. Wofenstein

Mass Spectrum and Mixing



Normal mass hierarchy
(ordering)



Inverted mass hierarchy
(ordering)

Type of mass spectrum: Normal, Inverted, Degenerate

Absolute mass scale

$U_{e3} = ?$

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 $\sin^2 2\theta_{13} < 0.01$.

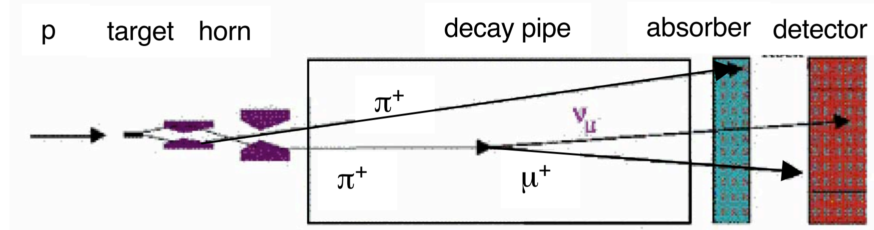
• Precision of the order of quantum corrections to neutrino masses and mixings interesting.

• 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~~

Measuring θ_{13}

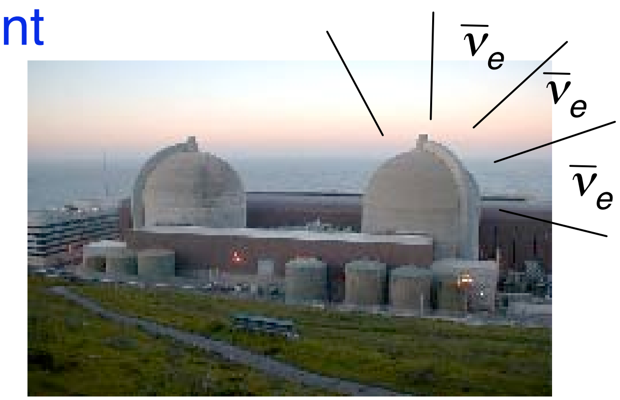


Method 1: Accelerator Experiments

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

- 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

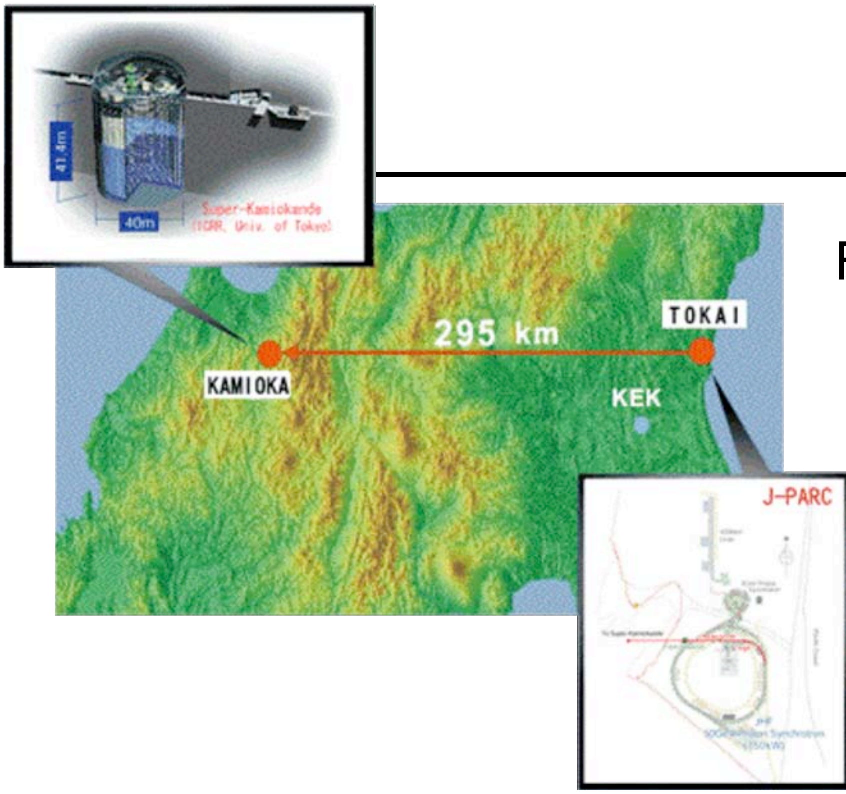
Method 2: Reactor Neutrino Oscillation Experiment



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

- disappearance experiment $\overline{\nu_e} \rightarrow \overline{\nu_x}$
- 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

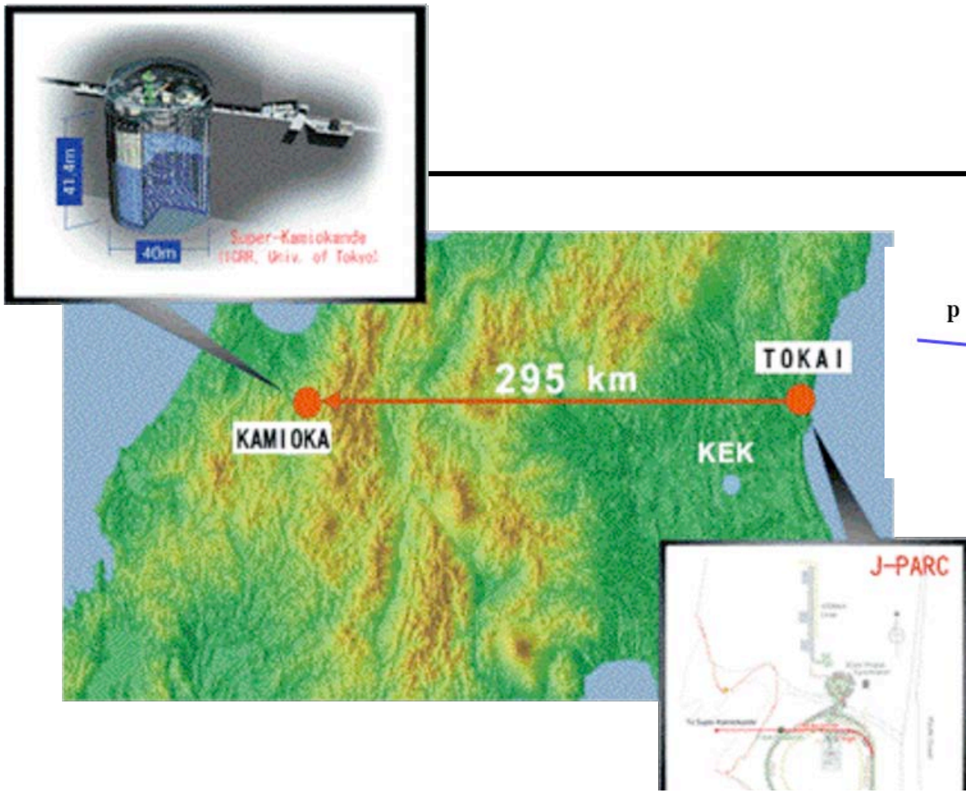
mass hierarchy

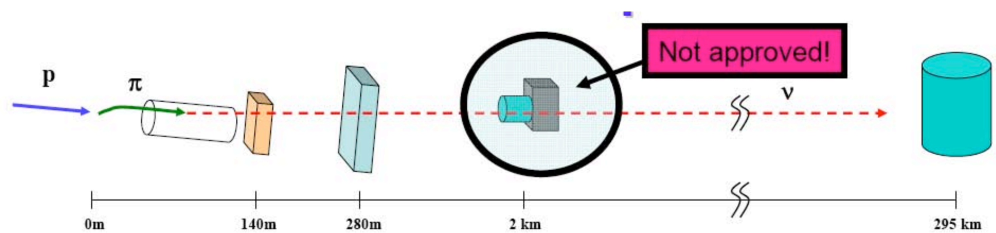
CP violation

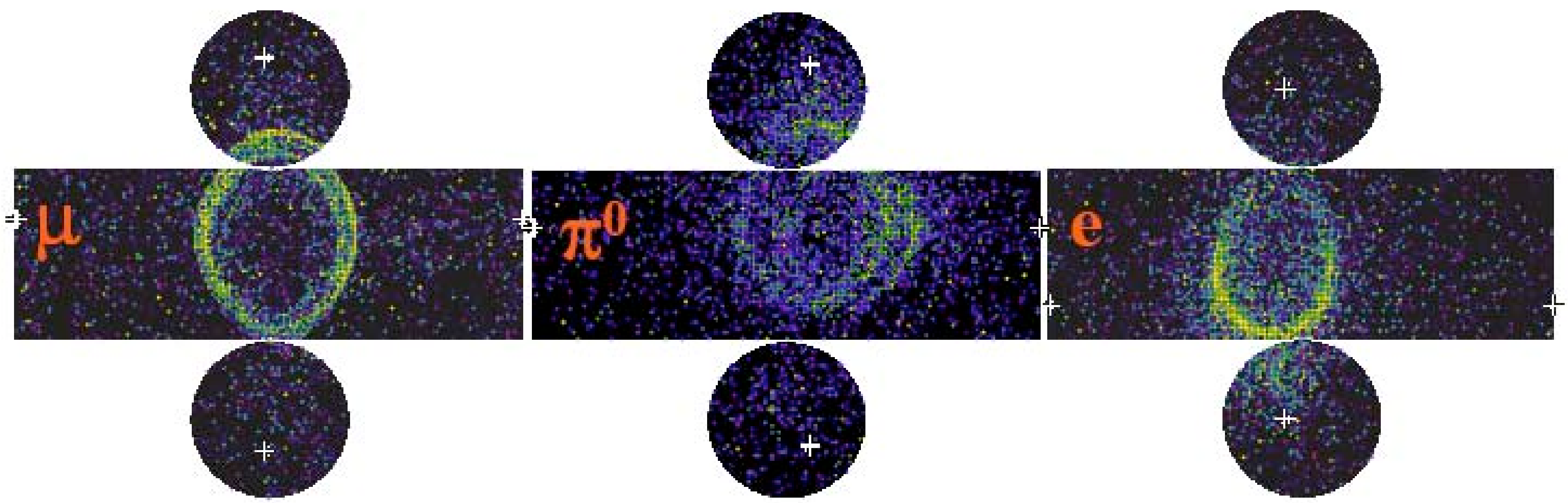
matter

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

Tokai to Kamioka (T2K)







Concept of the Off-Axis Beam

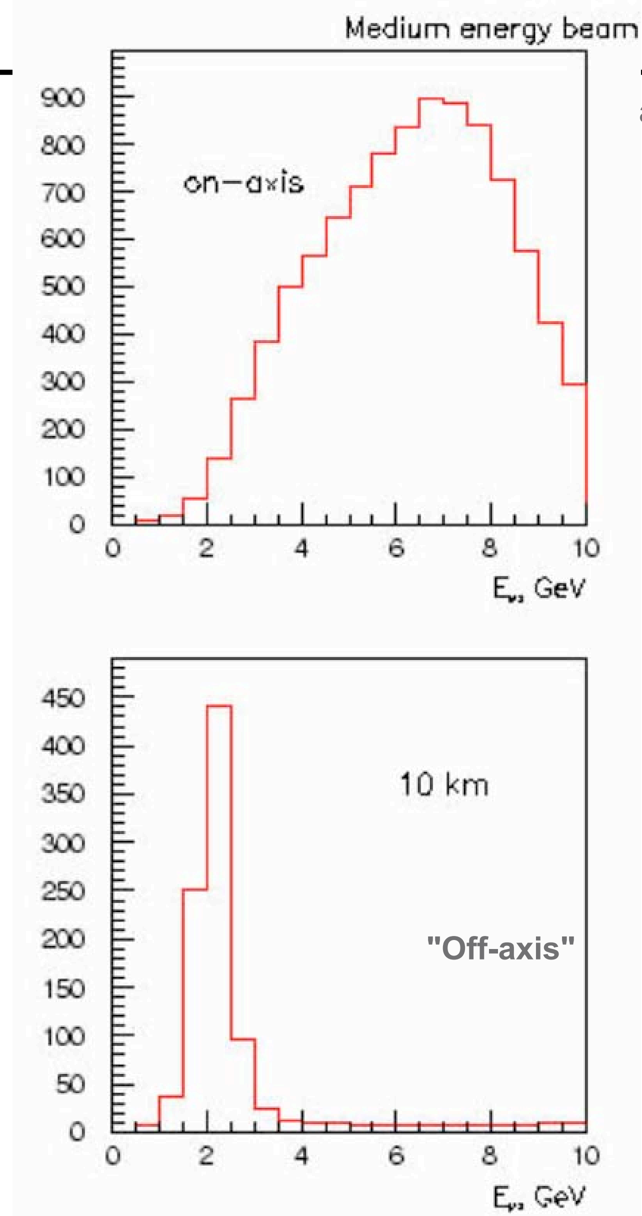
By going off axis, beam energy is reduced and spectrum becomes very sharp

Allows experiment to pick an energy for the maximum oscillation signal

Removes the high-energy flux that contributes to background

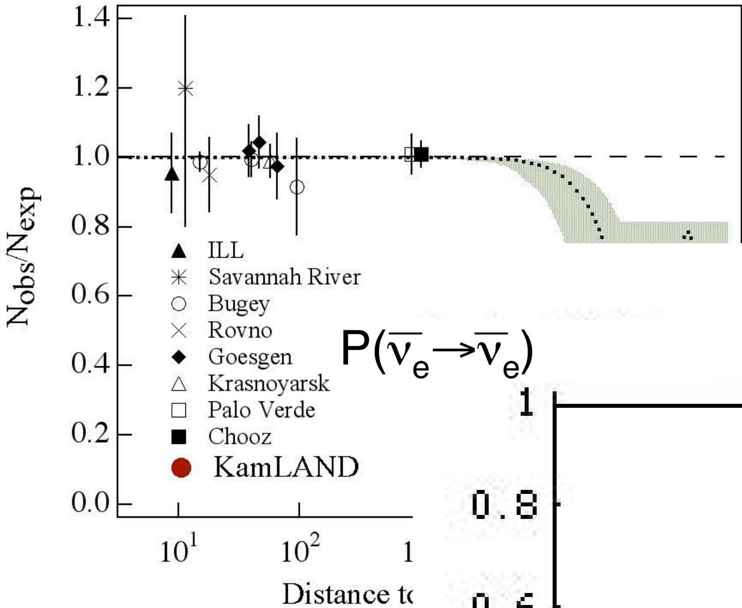
"Not magic but relativistic kinematics"

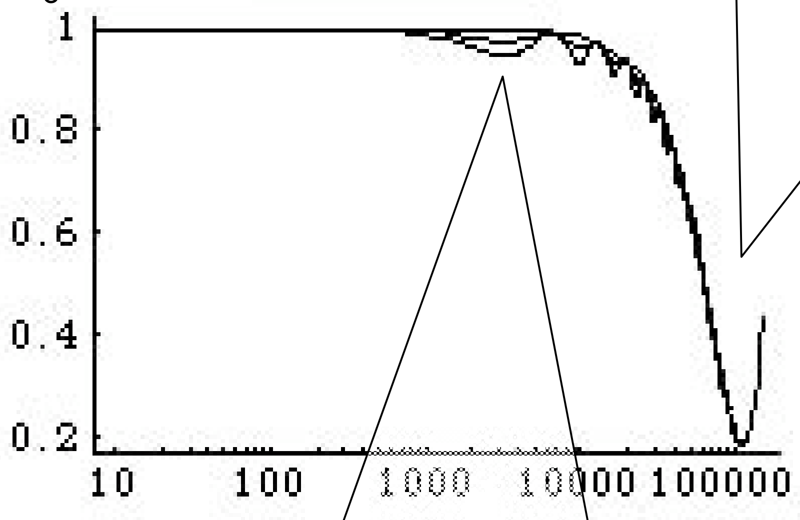
At Fermilab
- Allows experiment to use the NuMI beam for several experiments simultaneously
- Minos ν_μ disappearance on-axis
- Off axis $\nu_\mu \rightarrow \nu_e$ search



at 730 km

Search for $\sin^2(2\theta_{13})$ & Subdominant Oscillation Effects





Dominant θ_{12} Oscillation

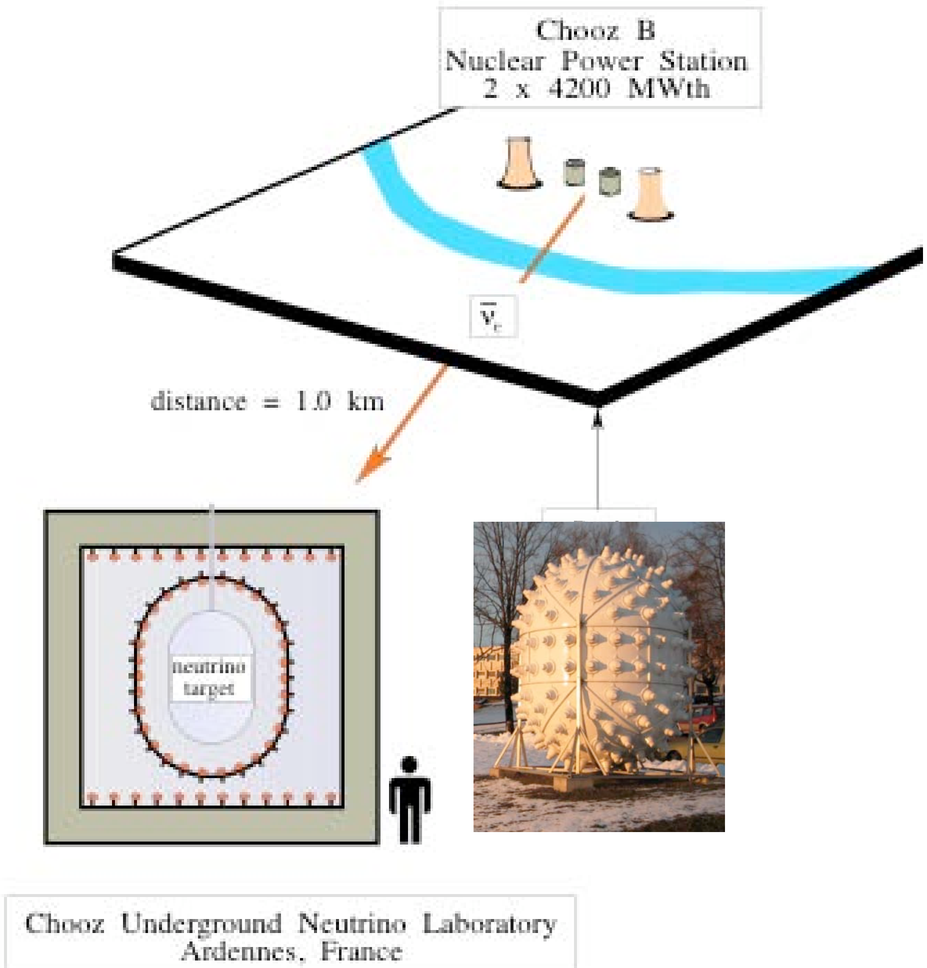
$$P_{ee} \approx 1 - \cos^4\theta_{13}\left[1 - \sin^2\theta_{12}\sin^2\left(\frac{\Delta m_{12}{}^2 L}{4E_\nu}\right)\right]$$

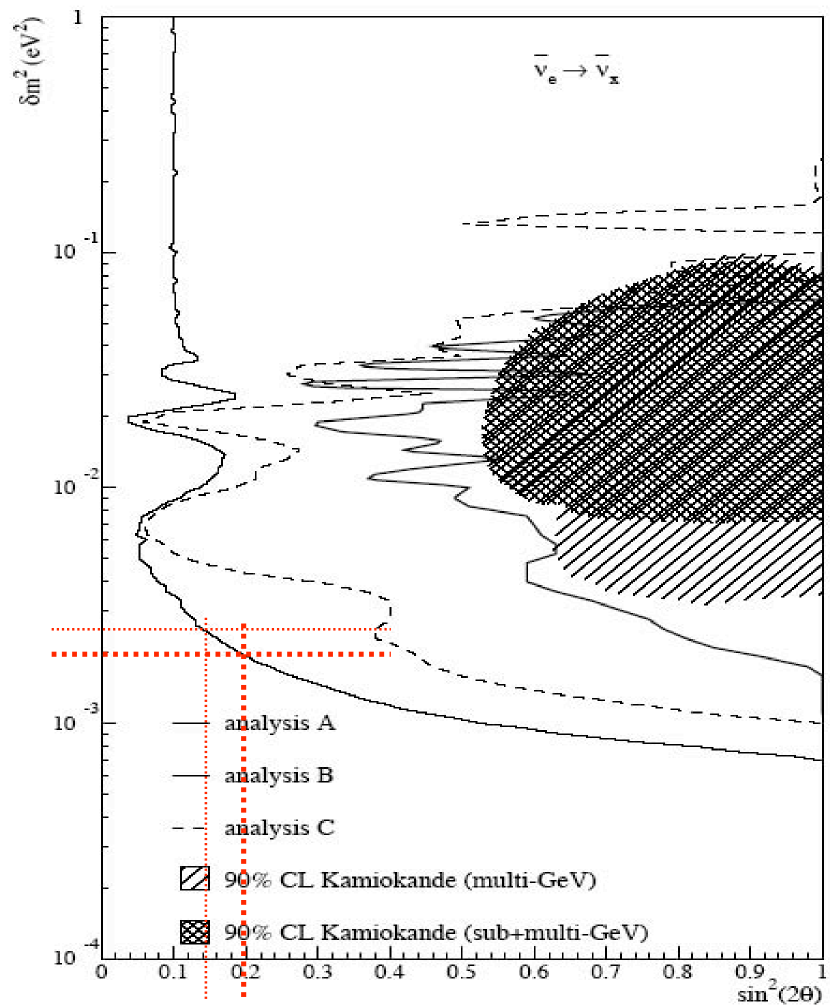
Subdominant θ_{13} Oscillation

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

Current Knowledge of θ_{13} from Reactors

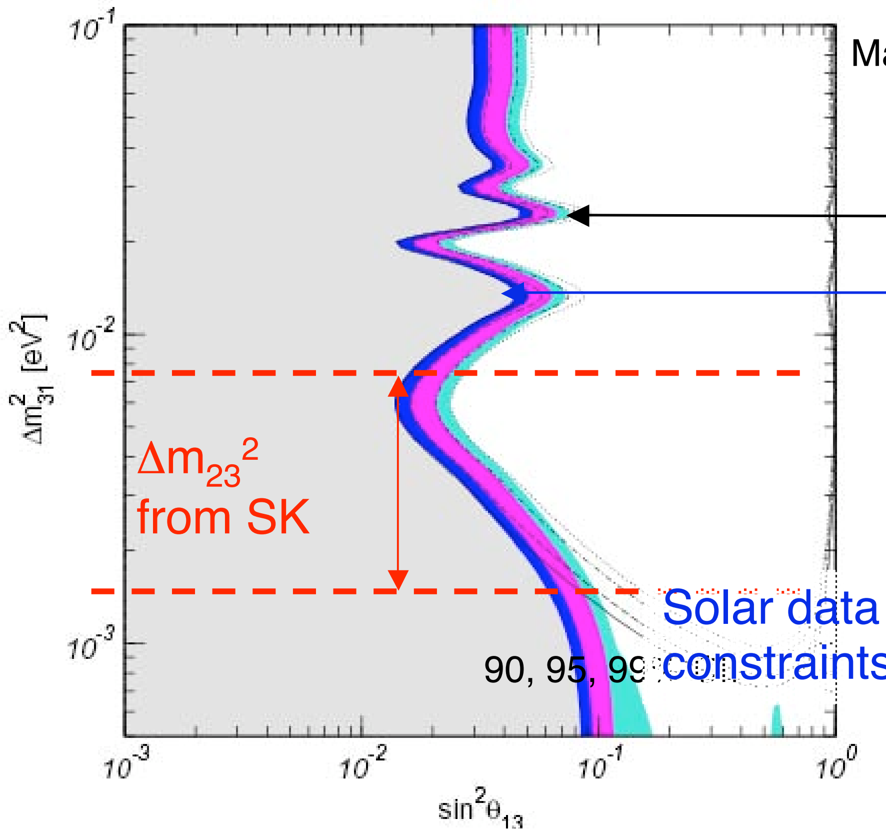
Reactor anti-neutrino measurement at 1 km at Chooz + Palo Verde: $\bar{\nu}_e \rightarrow \bar{\nu}_x$





M. Appollonio, hep-ex/0301017

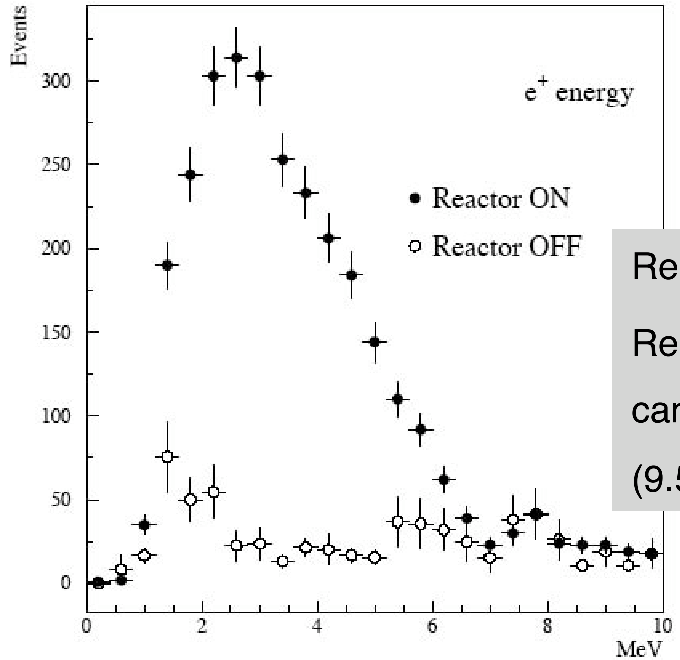
Global Constraints on θ_{13}



parameter	best fit	2σ	3σ	5σ
Δm_{21}^2 [10^{-5}eV^2]	6.9	6.0–8.4	5.4–9.5	2.1–28
Δm_{31}^2 [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)

Chooz, France

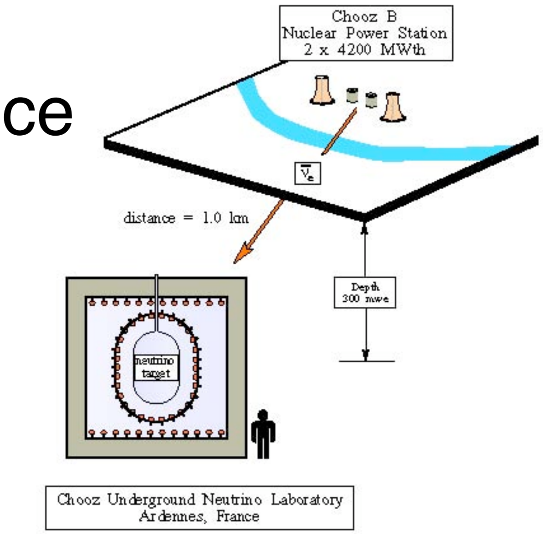


Reactor on: 2991

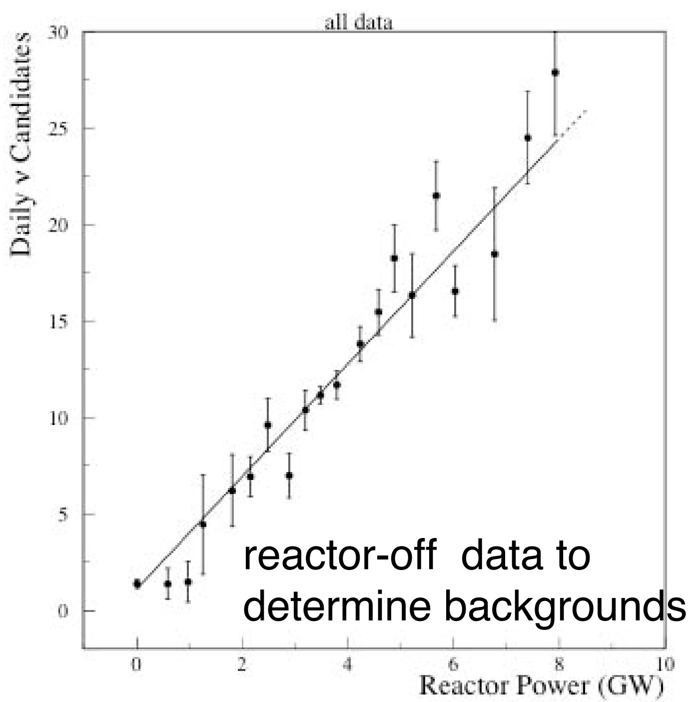
Reactor off: 287

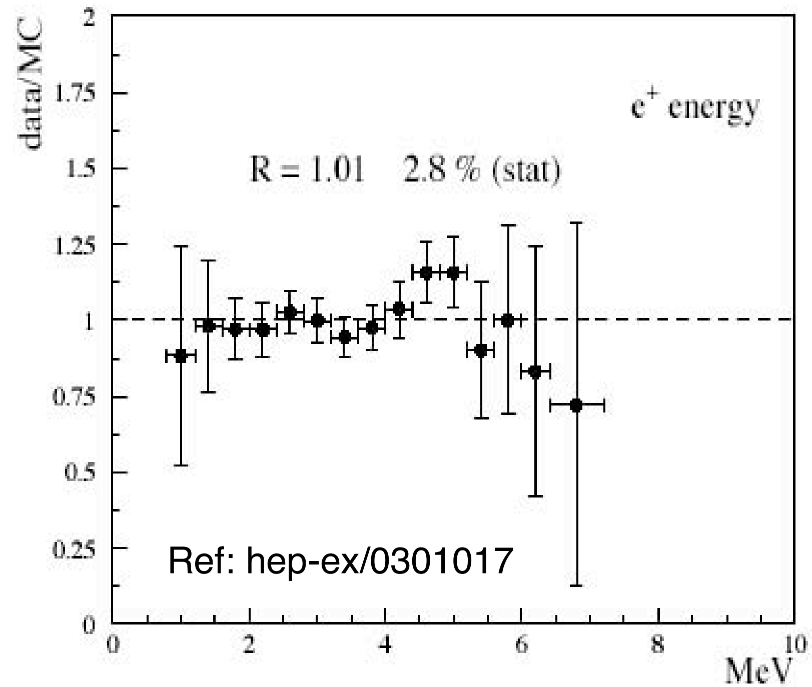
candidate $\overline{\nu}_e$ events.

(9.5% backgrounds!)



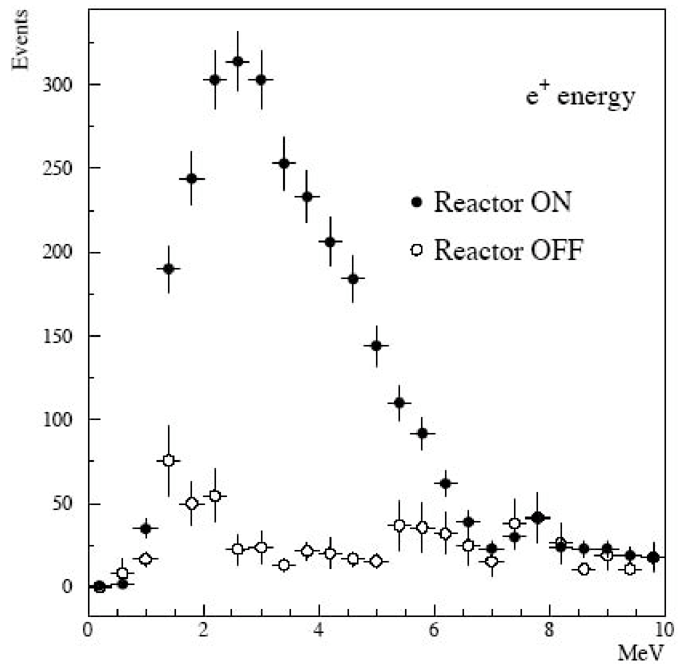
Chooz was unique! Determined backgrounds during reactor-off period





Overburden Requirements for Reactor Experiments

Chooz



candidate $\overline{\nu}_e$ events

2991

287

Ref: hep-ex/0301017

Chooz subtracted 9.5% of backgrounds, presumably
- fast neutrons, and
- spallation backgrounds.

Minimum Overburden

Scaling Chooz background with muon spectrum that generates spallation backgrounds:

bkgd	depth (mwe)
10%	300
< 5%	> 400
< 2%	> 560
< 1%	> 730

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

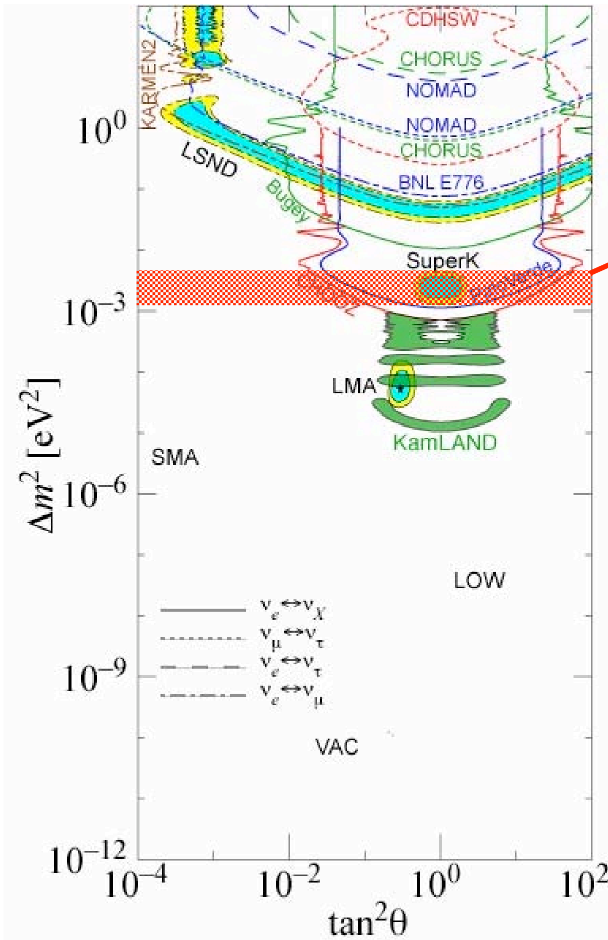
Absolute measurements are difficult!

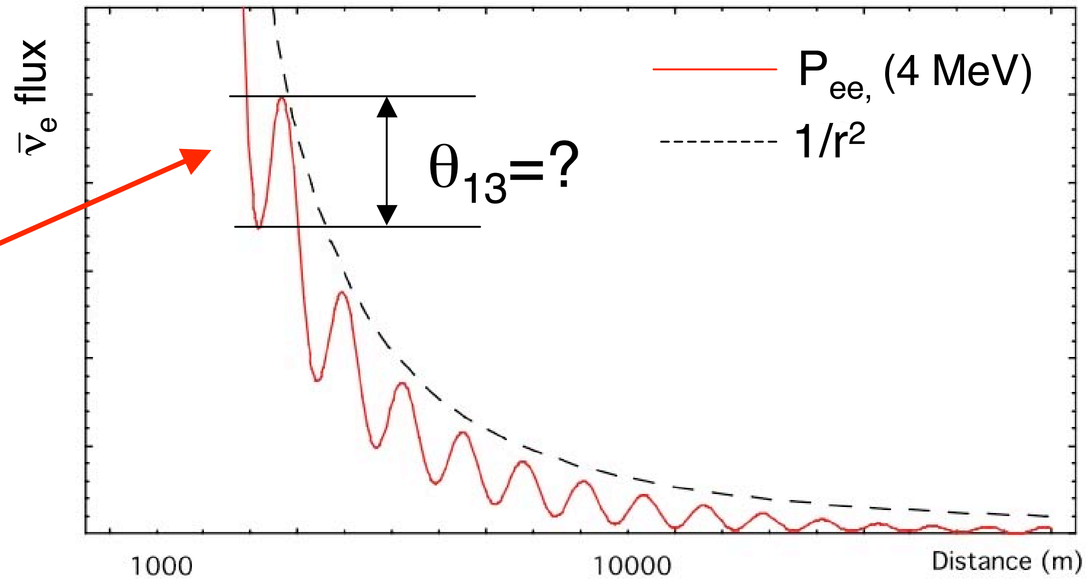
KamLAND - Systematic Uncertainties

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 %		

Reactor Neutrino Measurement of θ_{13} - Basic Idea





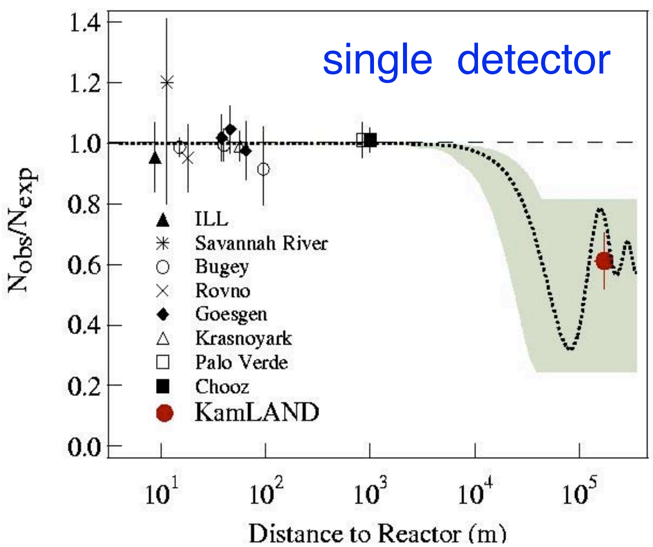
$$P_{ee} \approx 1 - \left(\sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}{}^2 L}{4E_\nu} + \left(\frac{\Delta m_{21}{}^2 L}{4E_\nu} \right) \cos^4 \theta_{13} \sin^2 2\theta_{12} \right)$$

atmospheric frequency dominant

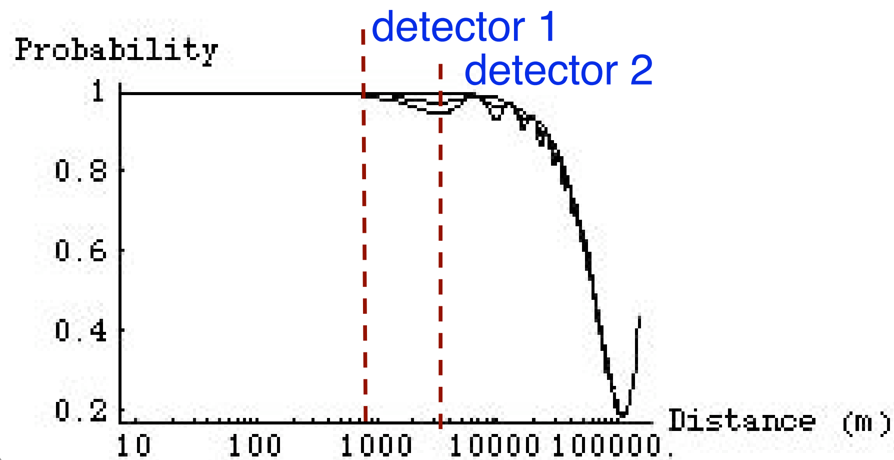
last term negligible for $\frac{\Delta m_{31}{}^2 L}{4E_\nu} \sim \pi/2$ and $\sin^2 2\theta_{13} \geq 10^{-3}$

Reactor Neutrino Measurement of θ_{13}

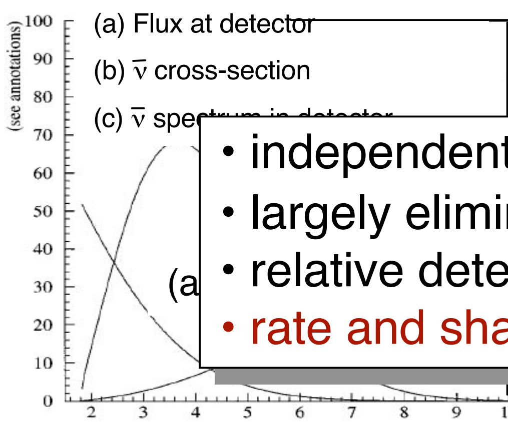
Present Reactor Experiments



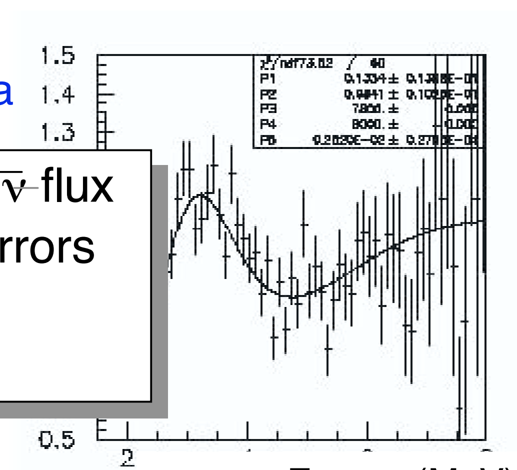
Future θ_{13} Reactor Experiment



Absolute Flux and Spectrum



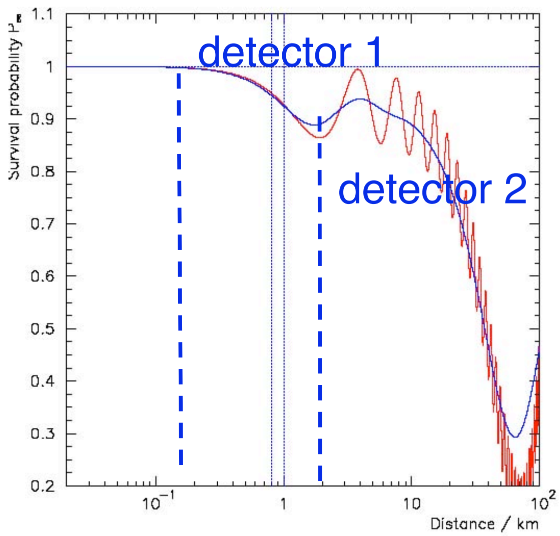
Ratio of Spectra



- independent of absolute reactor $\bar{\nu}$ flux
- largely eliminate cross-section errors
- relative detector calibration
- rate and shape information

Measuring θ_{13} with Reactor Neutrinos

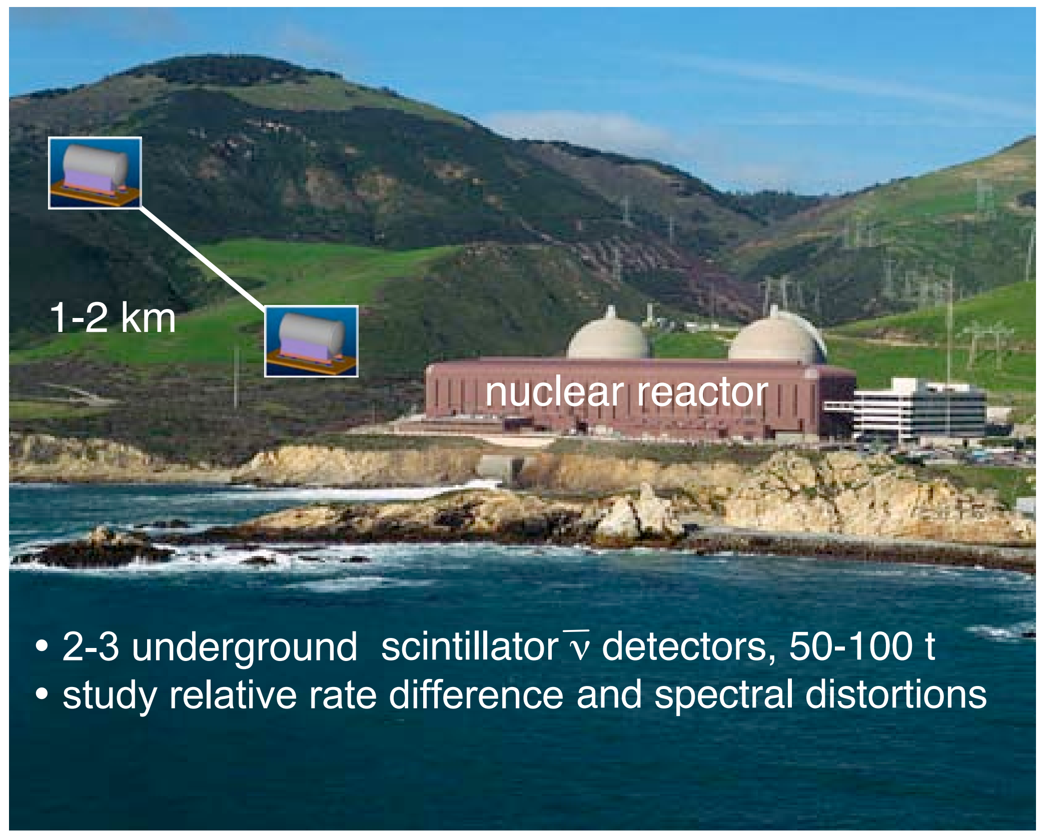
Novel Oscillation Experiment with Multiple Detectors



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

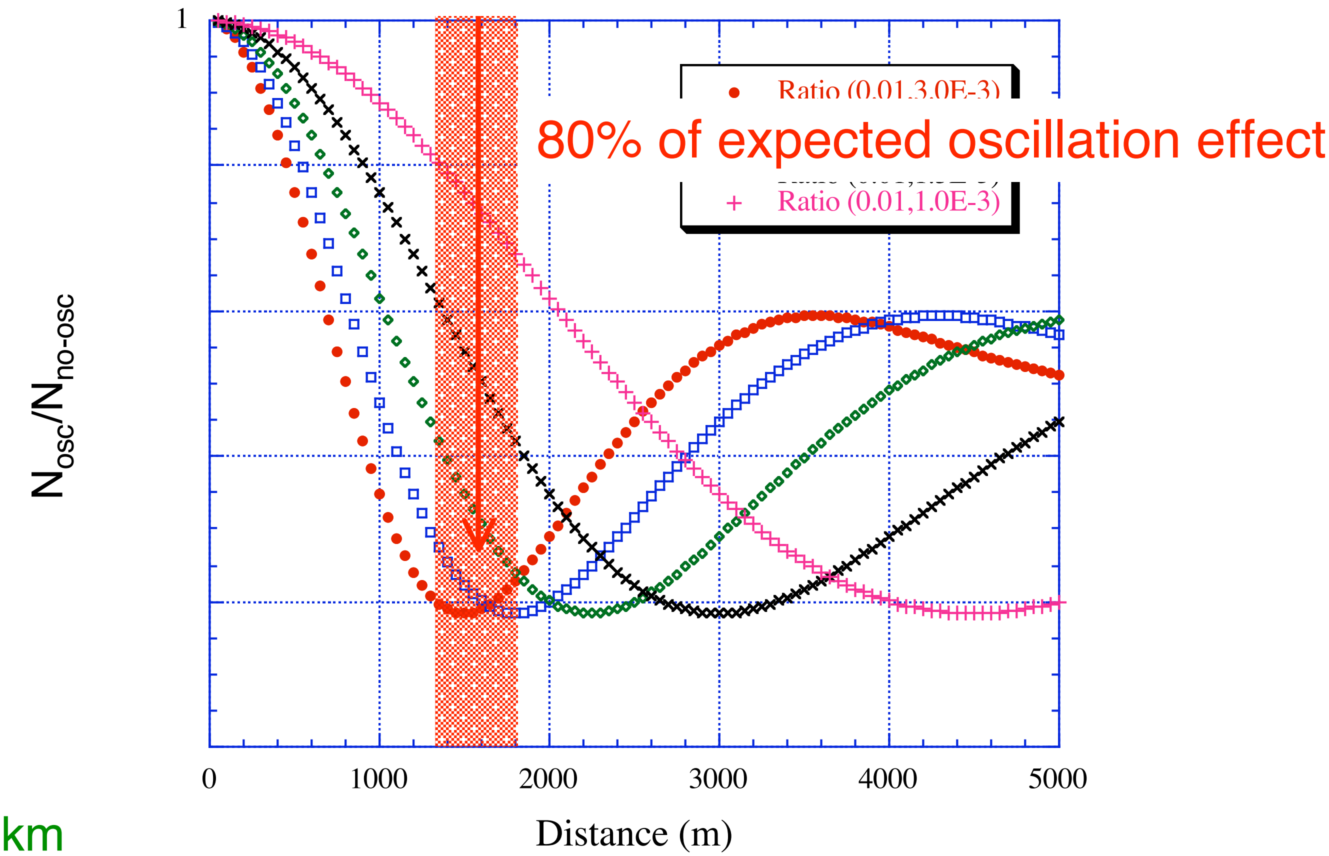
- relative ν flux measurement between 2 detectors
- eliminates most systematic errors
- projected sensitivity:
  $\sin^2 2\theta_{13} \approx 0.01\text{-}0.02$

Ref: theta13.lbl.gov, hep-ex/0402041



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

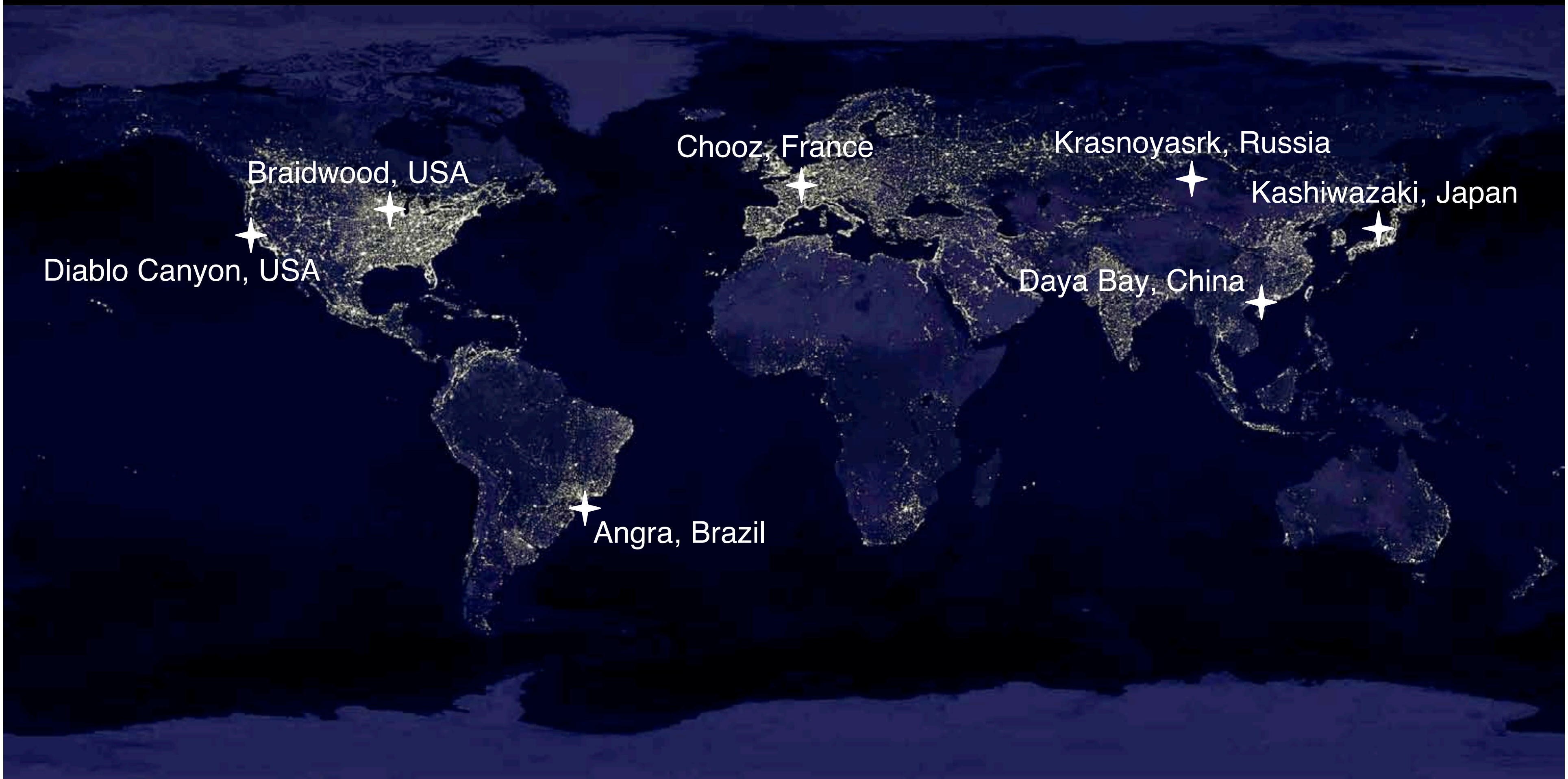
$$P_{ee} \approx 1 - \left(\sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}{}^2 L}{4E_\nu} + \left(\frac{\Delta m_{21}{}^2 L}{4E_\nu} \right) \cos^4 \theta_{13} \sin^2 2\theta_{12} \right)$$



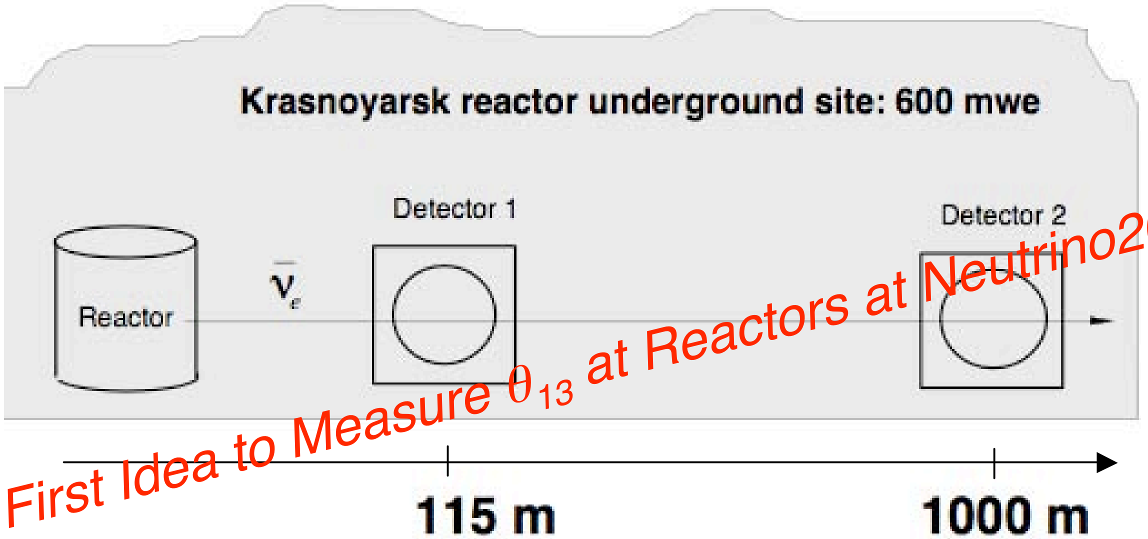
Ideal baseline ~1.5-2 km

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

World of Proposed Reactor Neutrino Experiments



Reactor θ_{13} Experiment at Krasnoyarsk

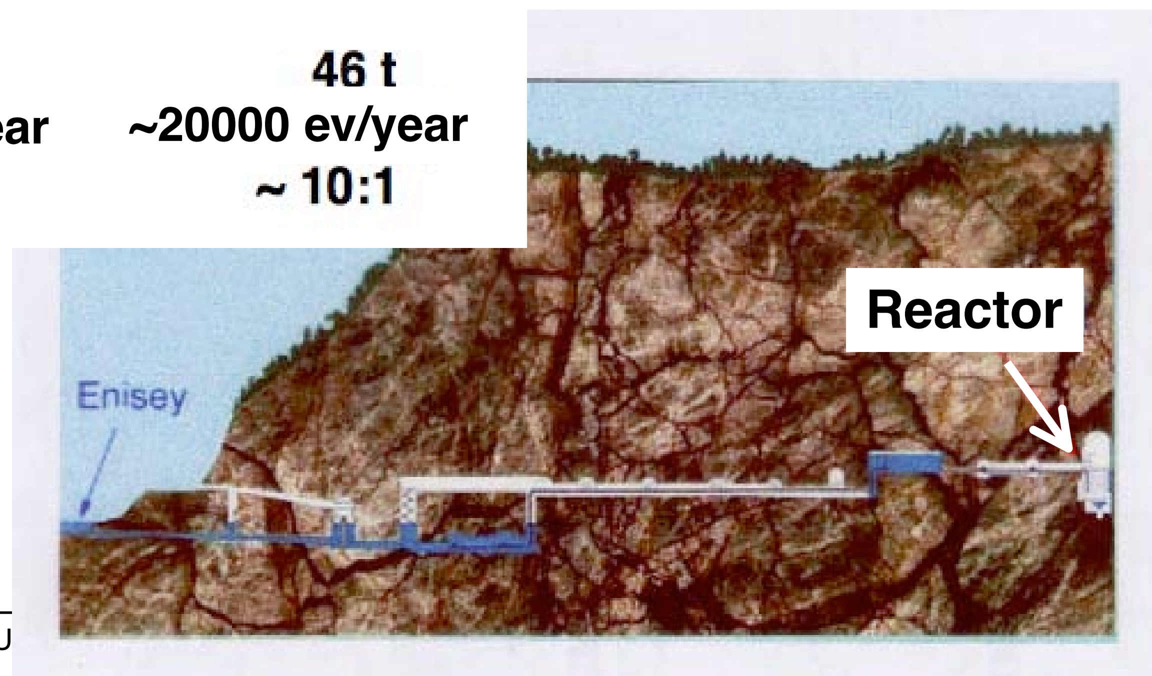


First Idea to Measure θ_{13} at Reactors at Neutrino2000

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

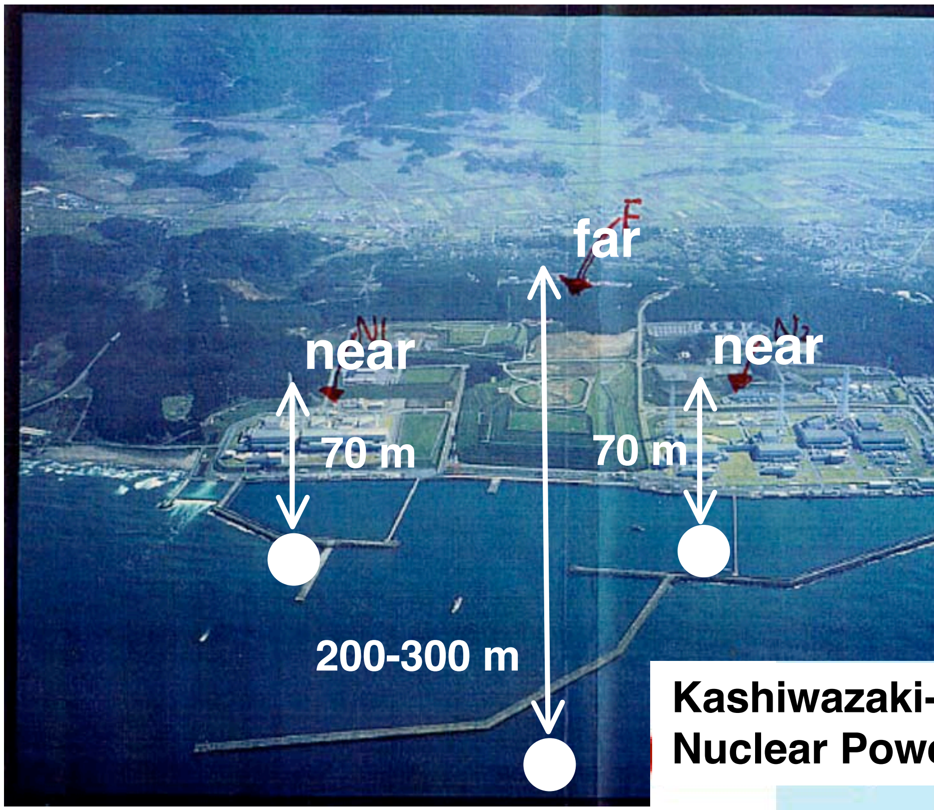
Detector locations determined by infrastructure

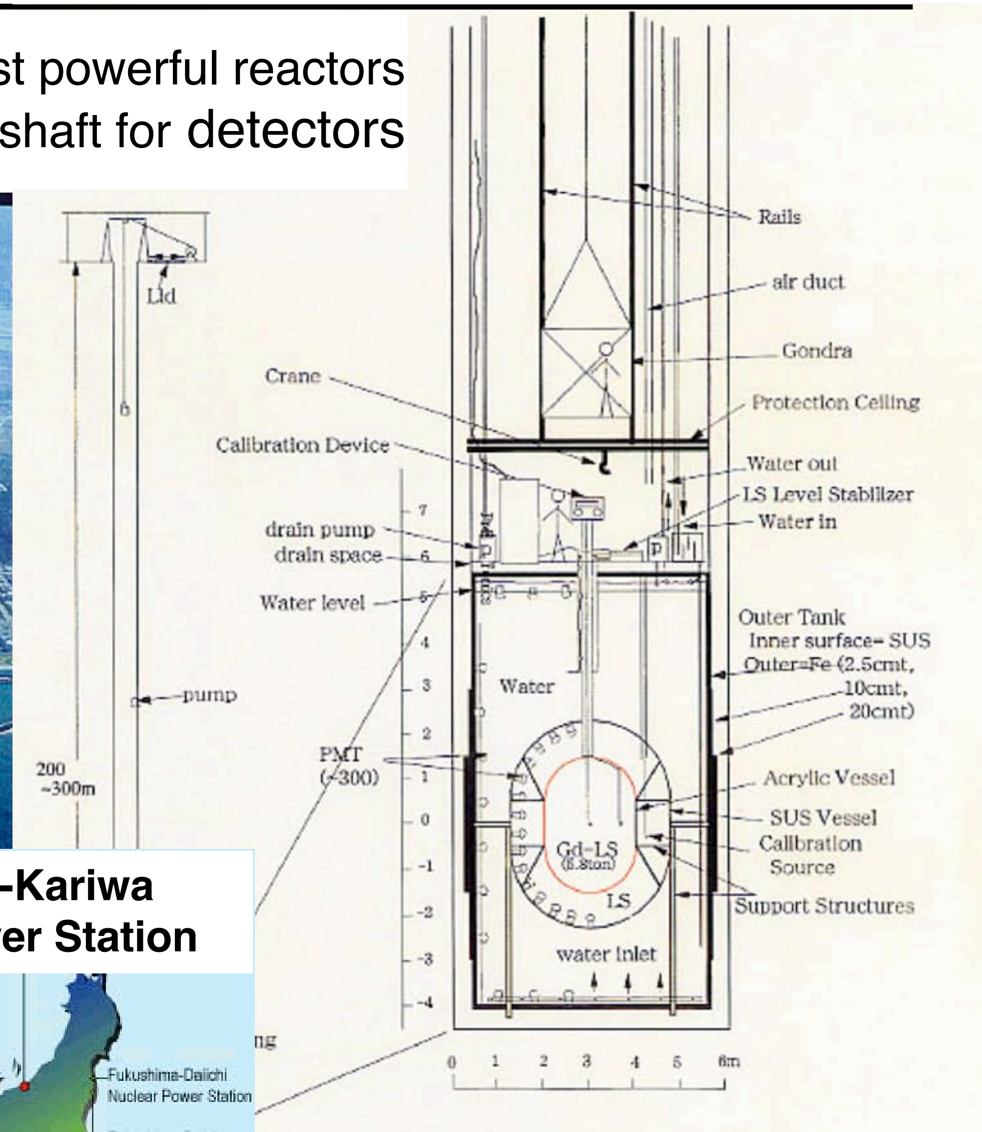


Ref: Marteyamov et al, hep-ex/0211070

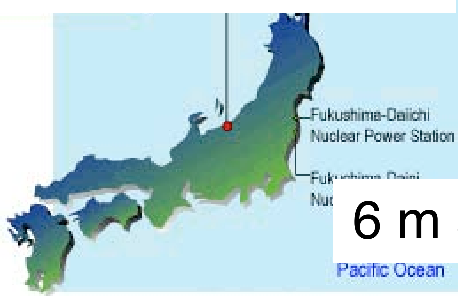
Kashiwazaki, Japan

- 7 nuclear power stations, World's most powerful reactors
- requires construction of underground shaft for detectors



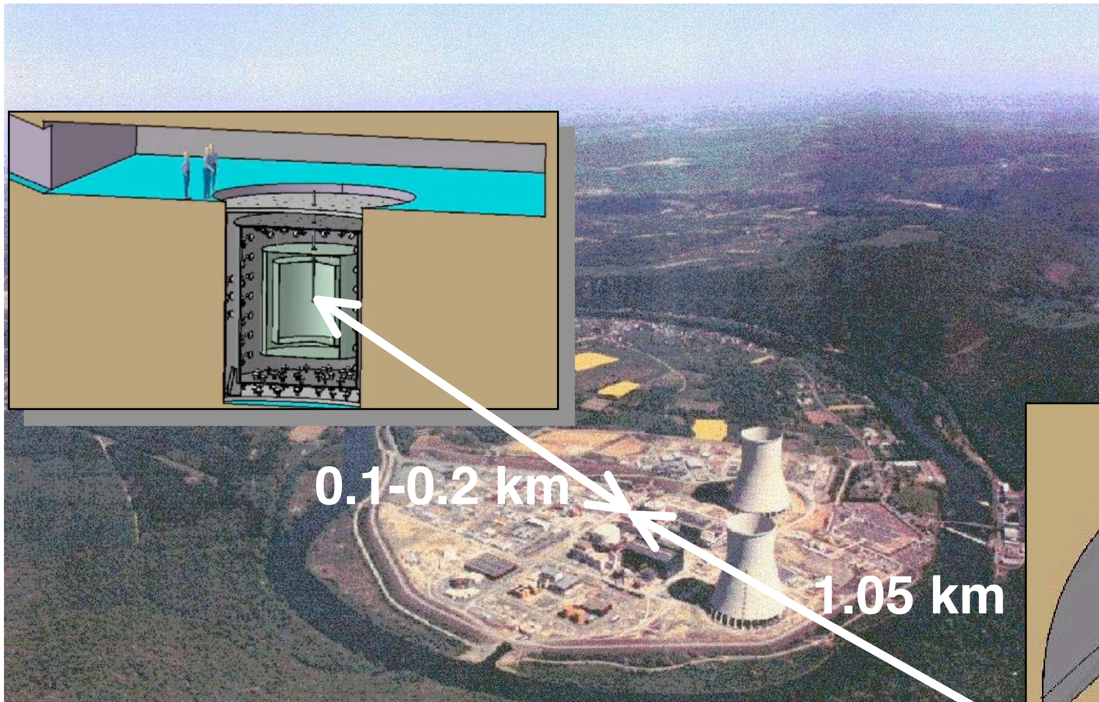


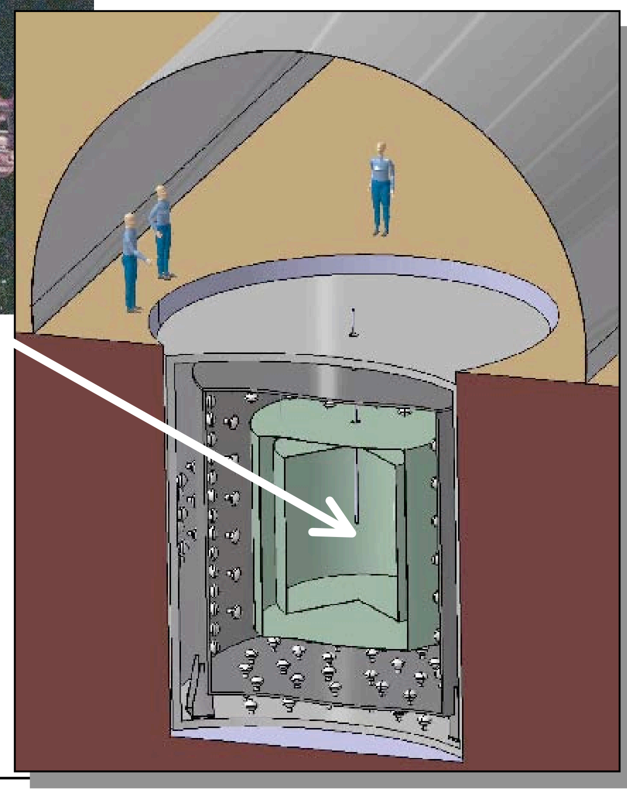
Kashiwazaki-Kariwa Nuclear Power Station



6 m shaft hole, 200-300 m depth

Improving Chooz …





‘Double-Chooz’ Project

10 tons detectors
8.4 GW_{th} reactor power
300 mwe overburden at far site
50 mwe overburden at near site

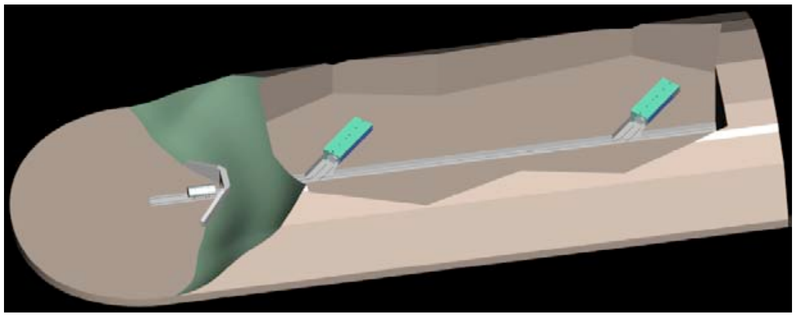
‘Double-Chooz’ Sensitivity

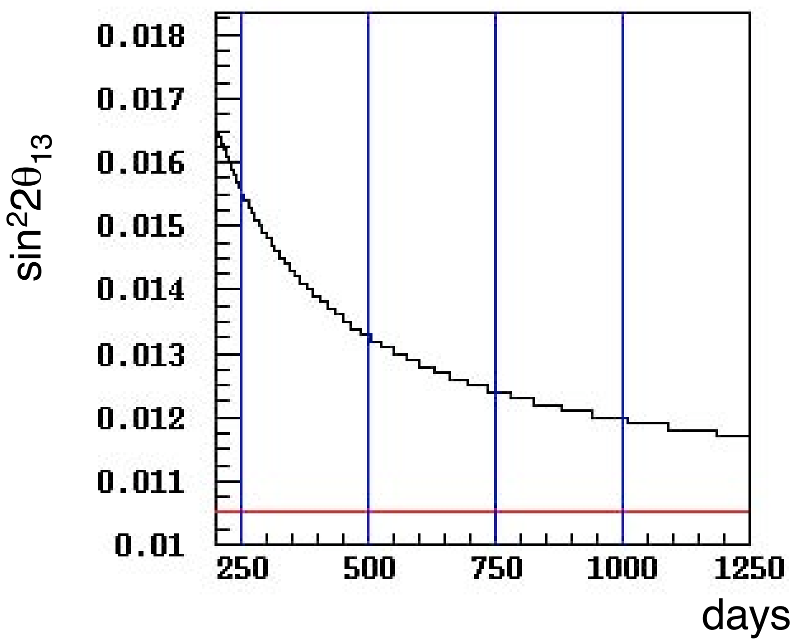
$\sin^2(2\theta_{13}) < 0.03$ at 90% CL

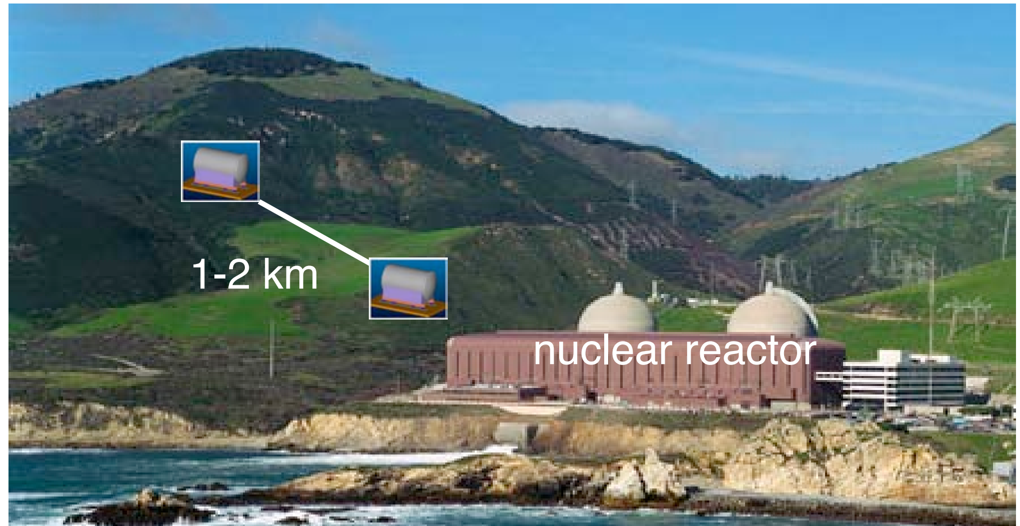
after 3 yrs, $\Delta m_{atm}^2 = 2 \times 10^{-3}$ eV^2

Precision Measurement of θ_{13} with Reactor Neutrinos

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



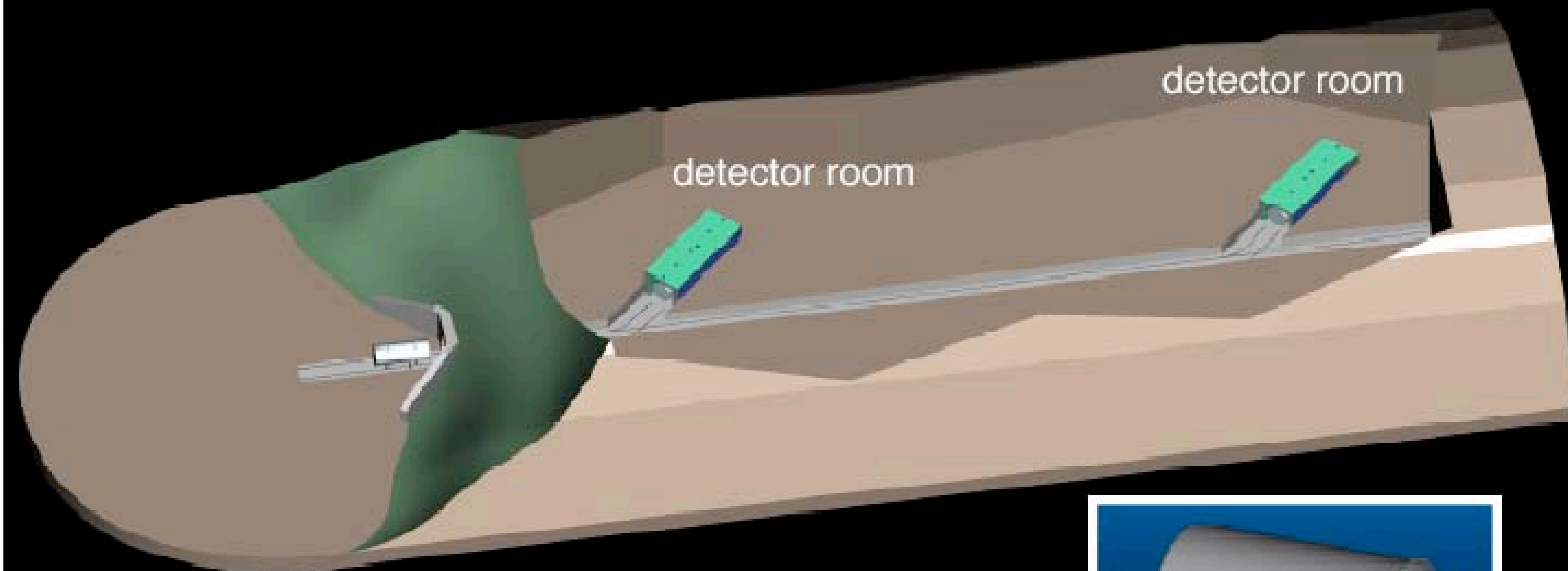


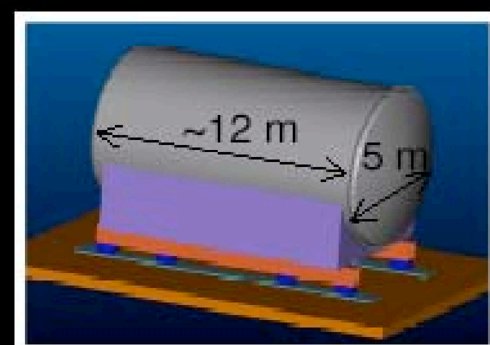


- scintillator $\bar{\nu}$ detectors, 50-100 t
- study relative rate difference and spectral distortions
- projected sensitivity: $\sin^2 2\theta_{13} \approx 0.01$

Overburden:	Near 200-300 mwe Far >700 mwe
Possible Sites:	Diablo Canyon, CA Daya Bay, China

Tunnel with Multiple Detector Rooms and Movable Detectors

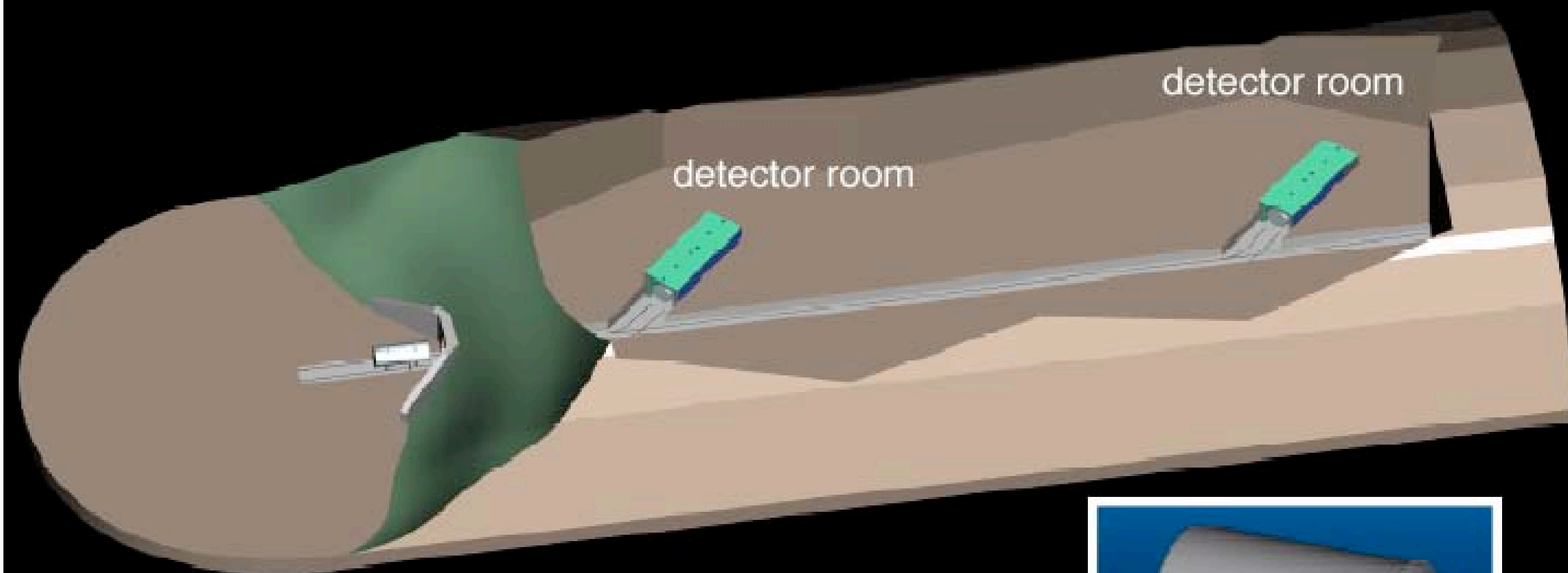


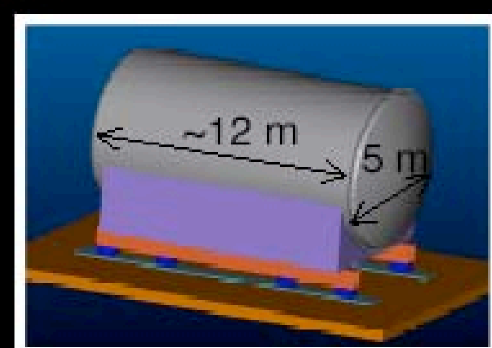


Adjustable Baseline

- to maximize oscillation sensitivity
- to demonstrate oscillation effect

Tunnel with Multiple Detector Rooms and Movable Detectors

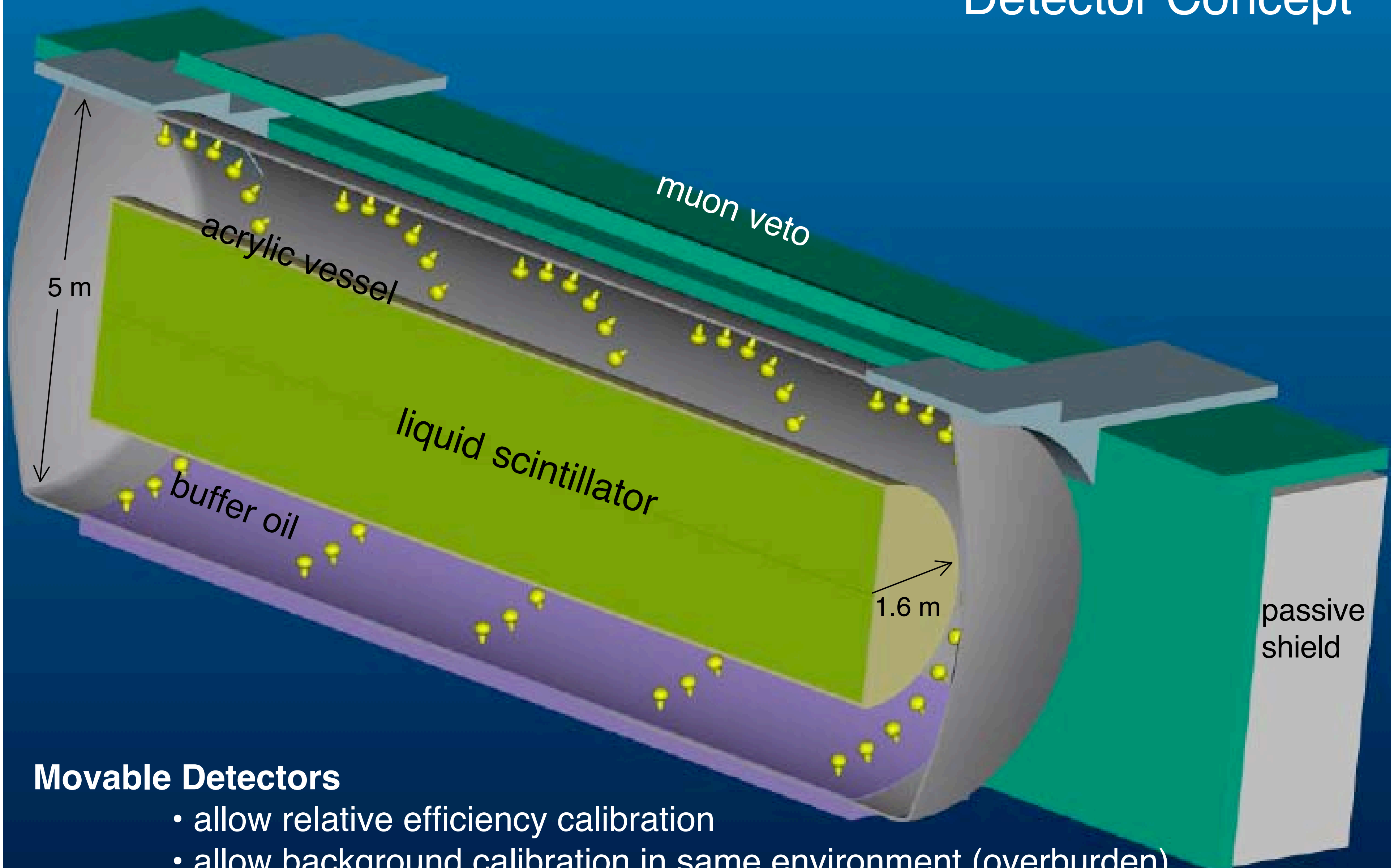




Movable Detectors

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

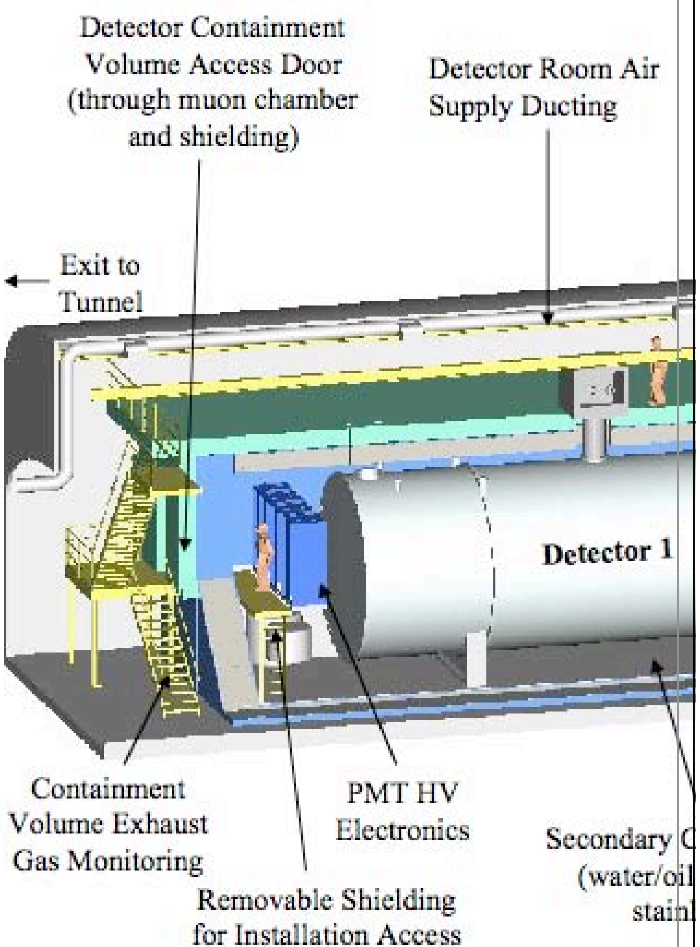
Detector Concept

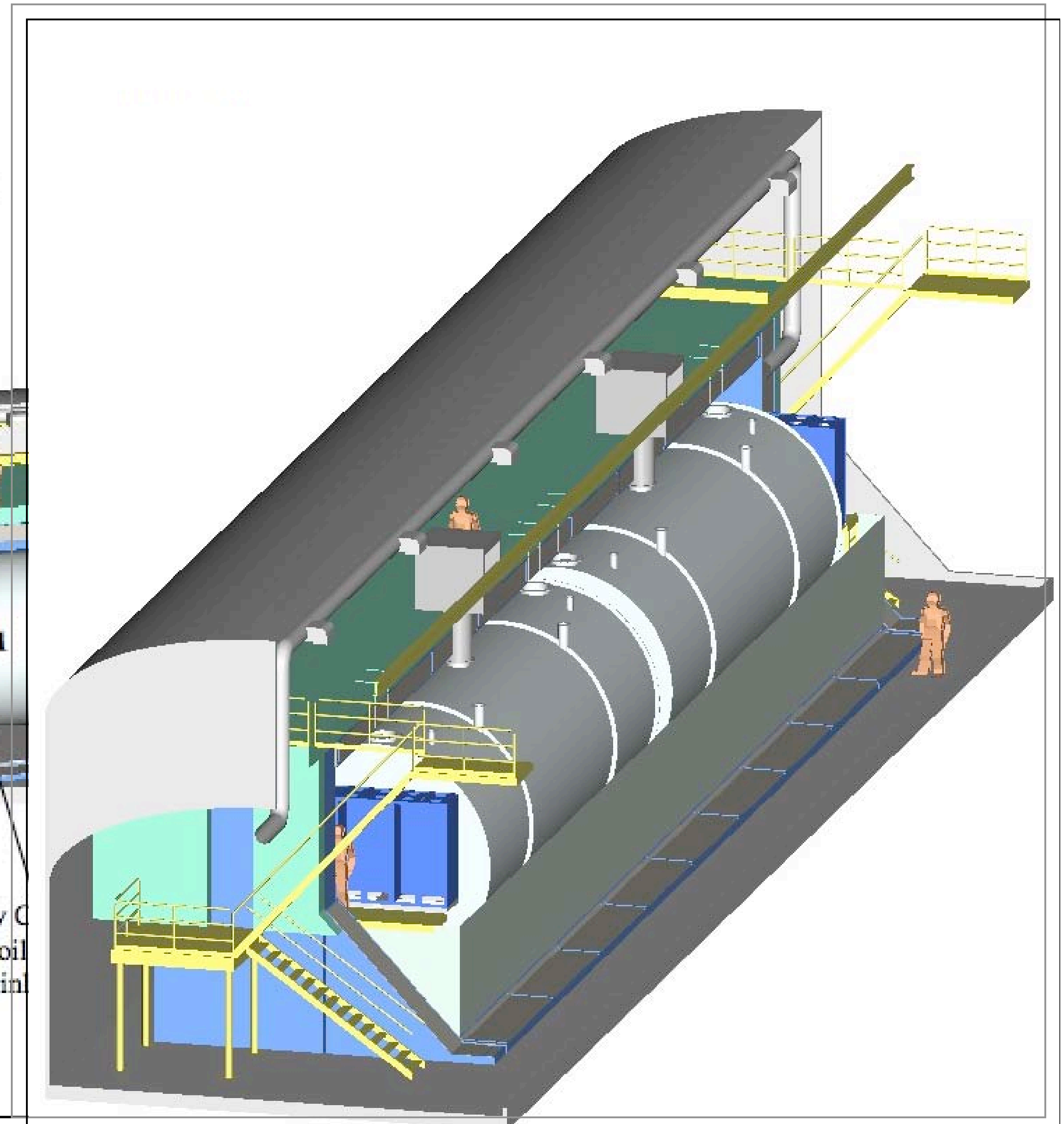


Movable Detectors

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

Detector Room Concept





Experimental Challenges of a θ_{13} Measurement at Reactors

I. 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)

II. Relative Uncertainty

Acceptance
Energy scale and linearity

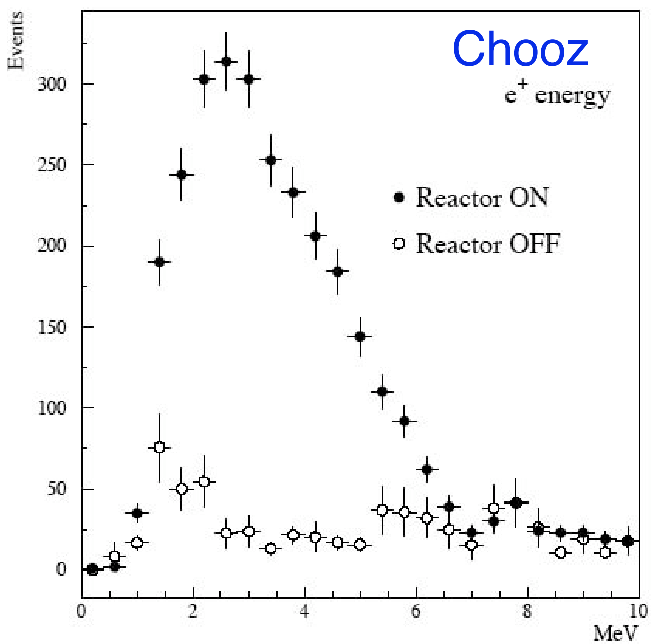
III. Detector size (fiducial volume)

signal statistics and muon deadtime

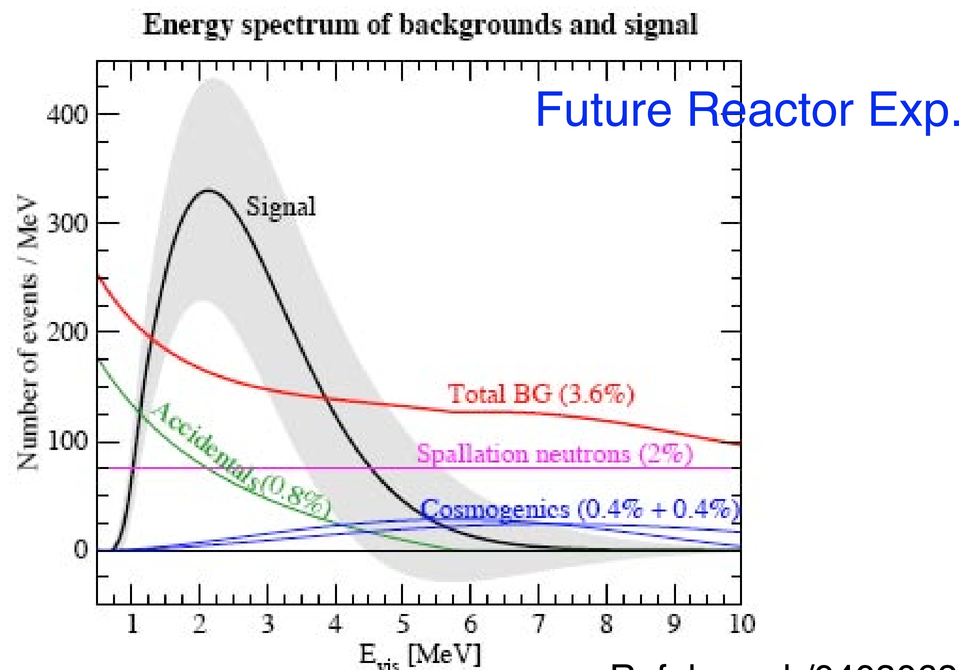
A Disappearance Measurement of θ_{13} with Reactor Neutrinos

Experimental Challenges

- Backgrounds



Ref: hep-ph/030107



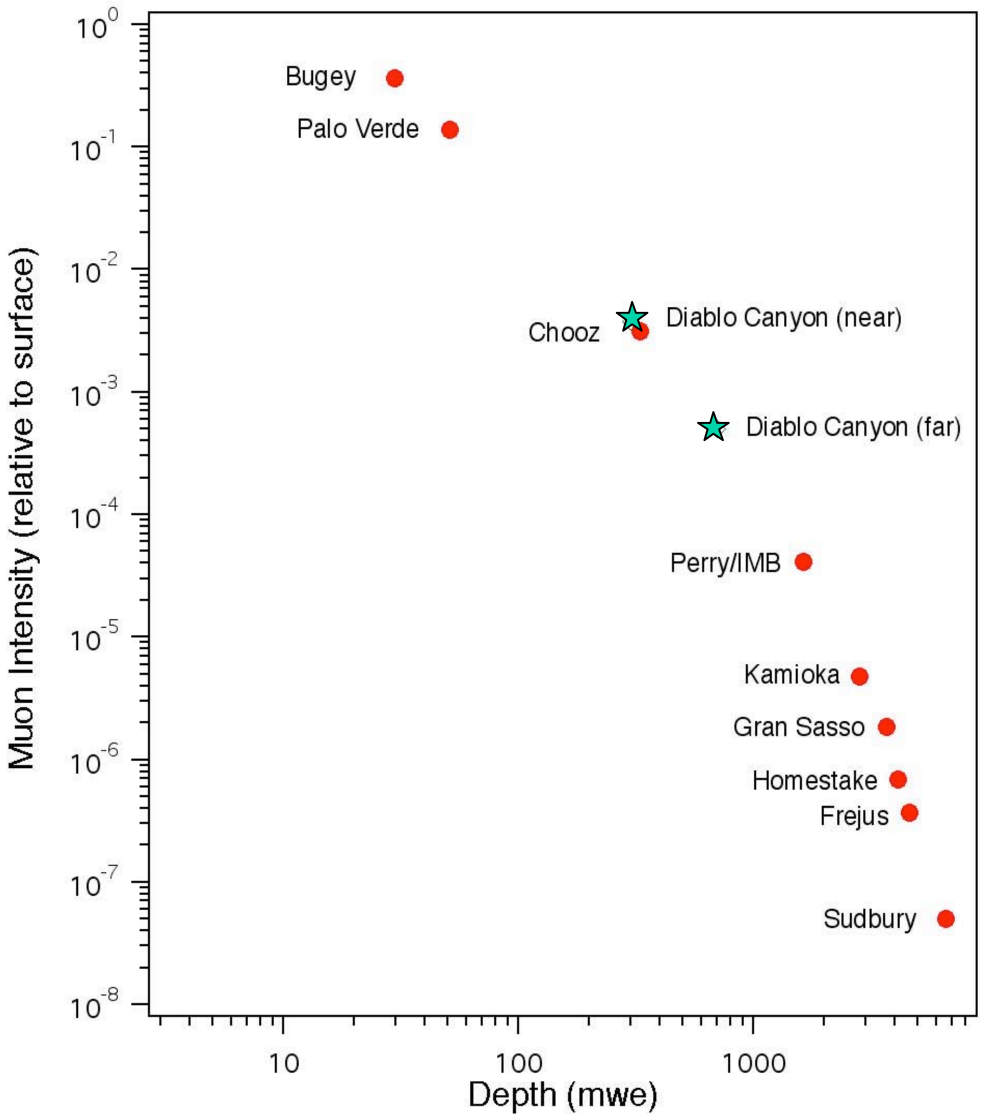
Ref: hep-ph/0403068

Background type	Spectral shape	BG/Reactor events	σ_{BG}
			50%
			50%
Cosmogenic [illegible]	β-spectrum (end point [illegible] MeV)	[illegible]	50%
Cosmogenic ^8He	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%

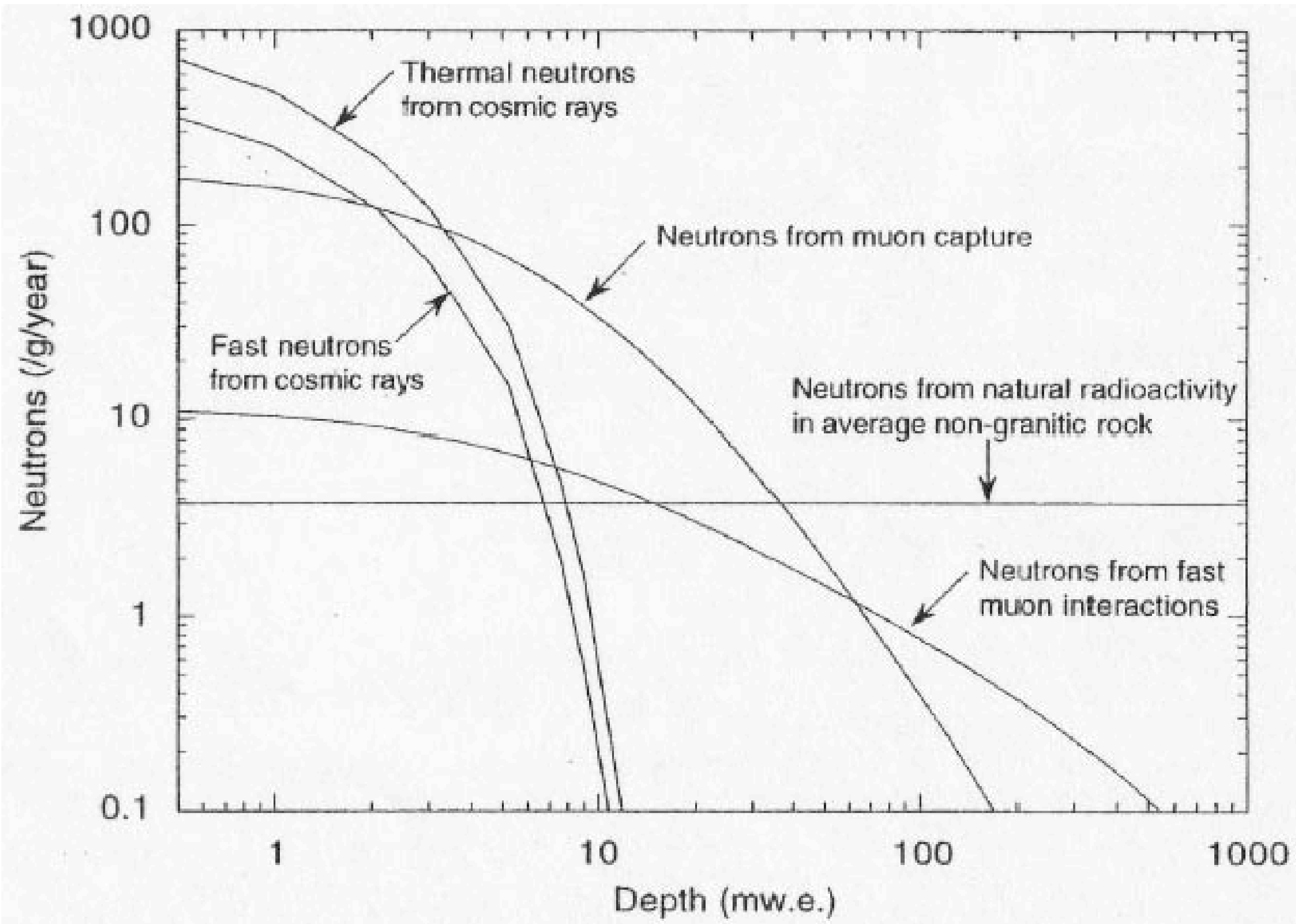
→ Will we be able to measure background contributions?

→ Backgrounds in near and far detector will be different.

Overburden and Muon Flux



Neutron Production in Rock



A. da Silva
PhD thesis, UCB 1996

Muon-Induced Production of Radioactive Isotopes in LS

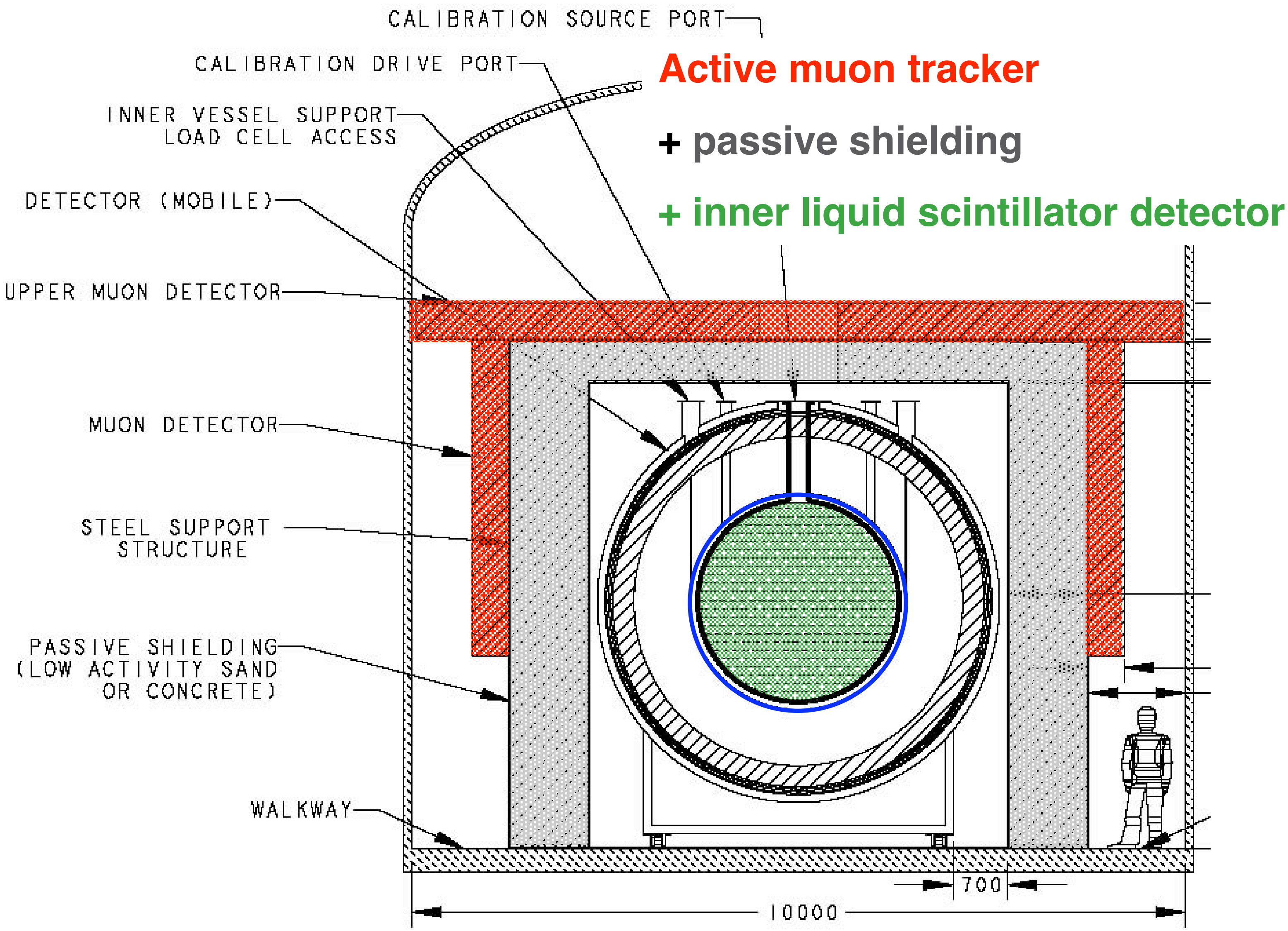
	Isotope	**$T_{1/2}$**	**E_{max} (MeV)**	**Type**
β^-	^{12}B	0.02 s	13.4	Uncorrelated
	^{11}Be	13.80 s	11.5	Uncorrelated
	^{11}Li	0.09 s	20.8	Correlated
	^{9}Li	0.18 s	13.6	
	^{8}Li	0.84 s	16.0	
	^{8}He	0.12 s	10.6	
	^{6}He	0.81 s	3.5	Uncorrelated
β^+, EC	^{11}C	20.38 m	0.96	
	^{10}C	19.30 s	1.9	
	^{9}C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

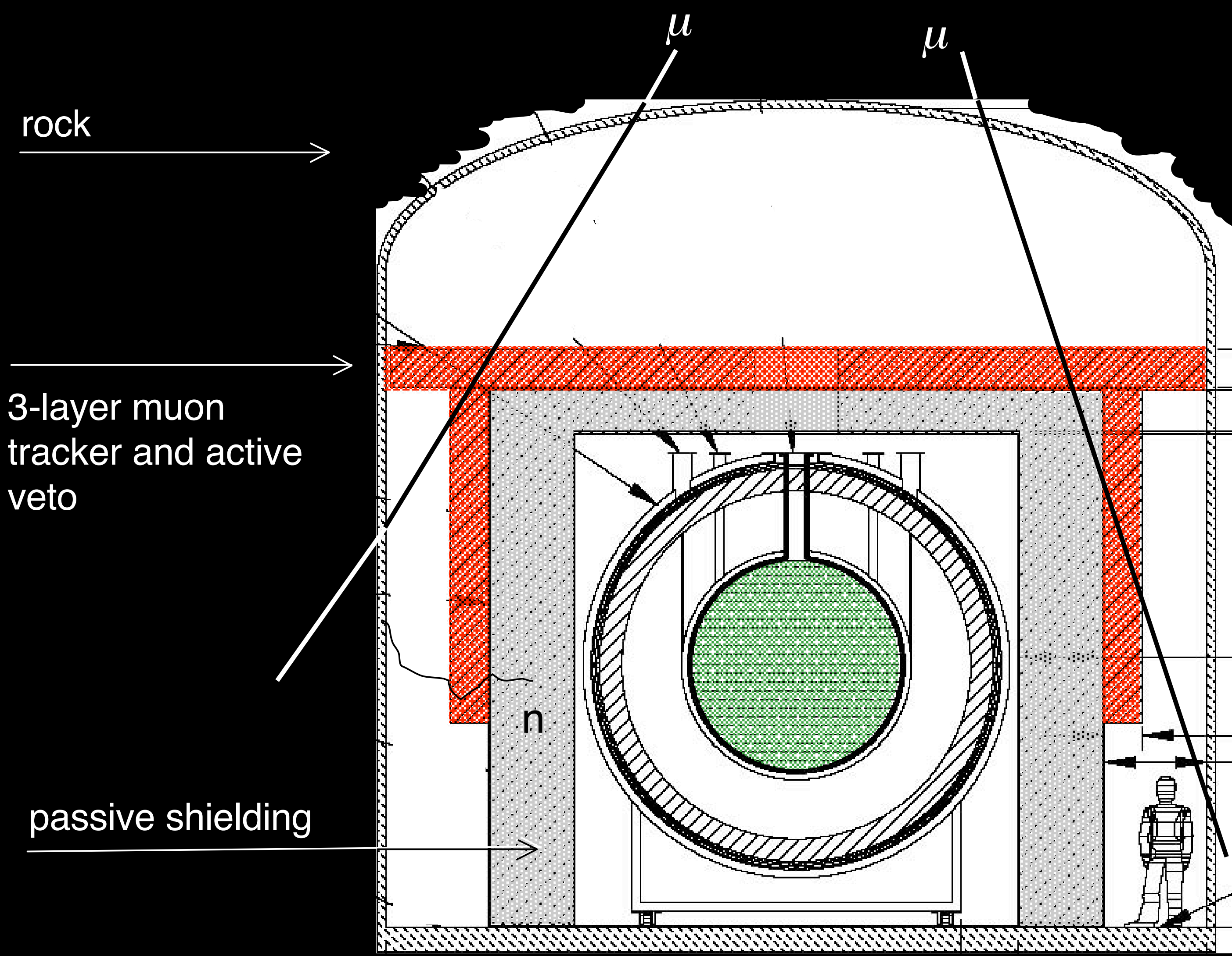
uncorrelated:
single rate dominated by ^{11}C

rejection through muon tracking and depth

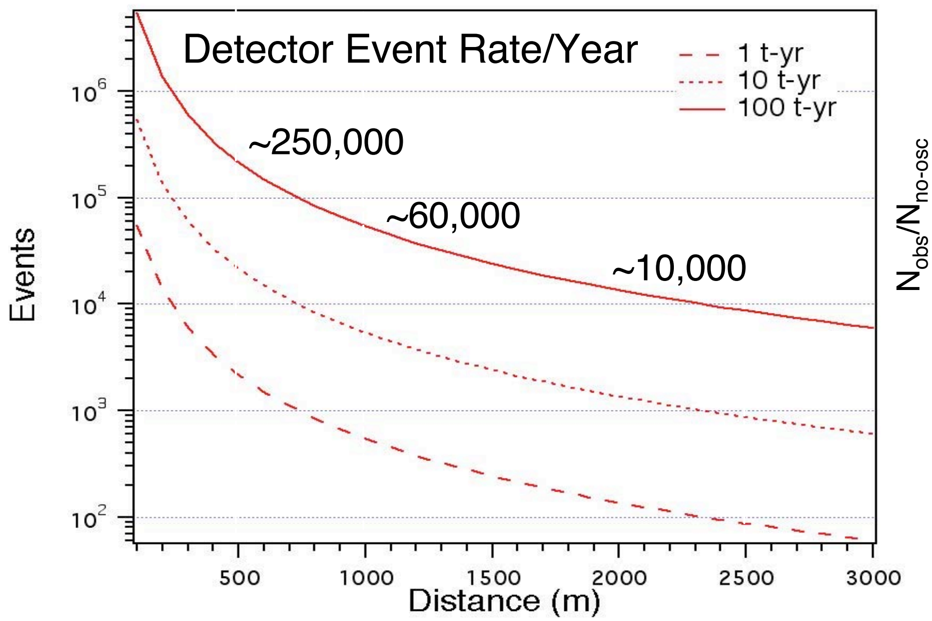
Detector and Shielding Concept



Detector and Shielding Concept



Statistics and Systematics

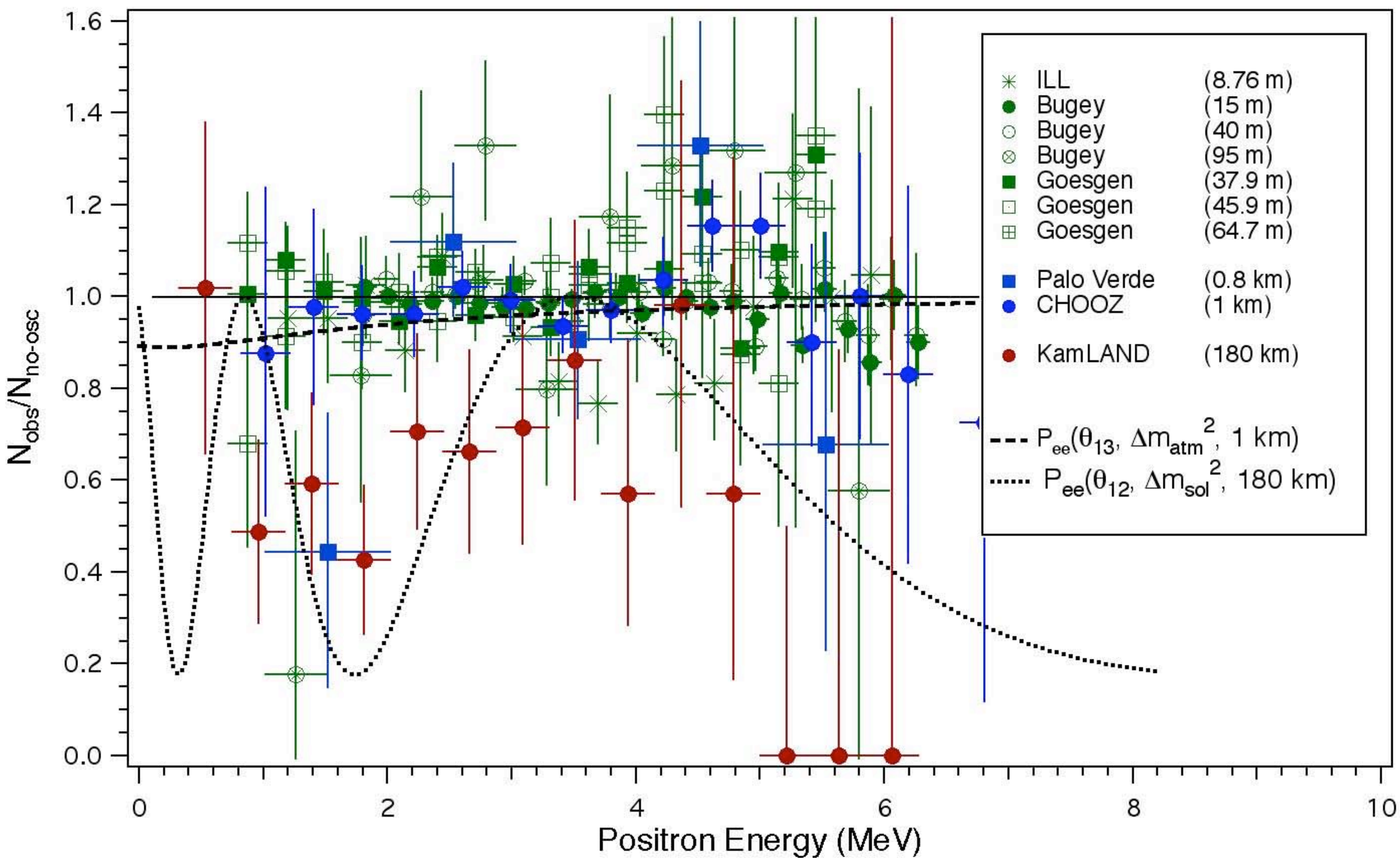


Statistical error: σ_{stat} ~ 0.5% for $\mathcal{L}$ = 300t-yr

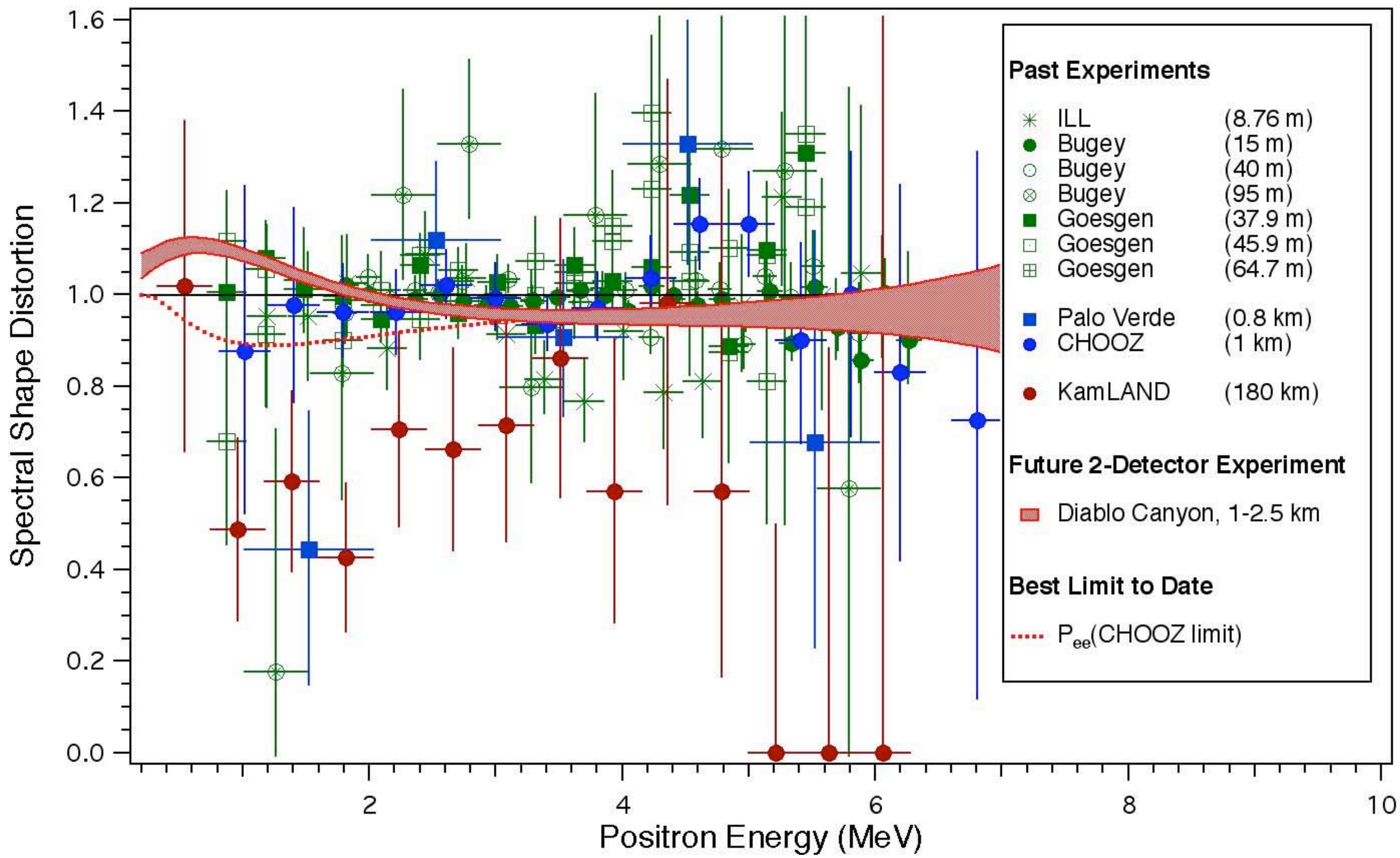
Reactor Flux	• near/far ratio, choice of detector location	$\sigma_{flux} < 0.2\%$
Detector Efficiency	• near and far detector of same design • calibrate *relative* detector efficiency	$\sigma_{rel\ eff} \leq 1\%$
Target Volume &	• no fiducial volume cut	$\sigma_{target} \sim 0.3\%$
Backgrounds	• external active and passive shielding	$\sigma_{acc} < 0.5\%$ $\sigma_{n\ bkgd} < 1\%$

Total Systematics σ_{syst} ~ 1-1.5%

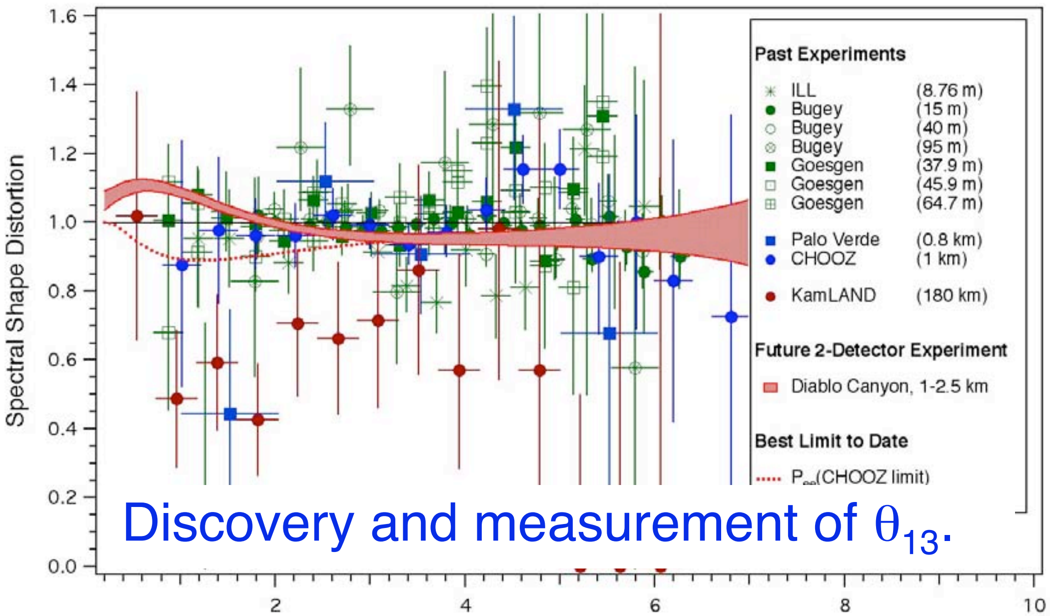
Past and Present Reactor Neutrino Experiments



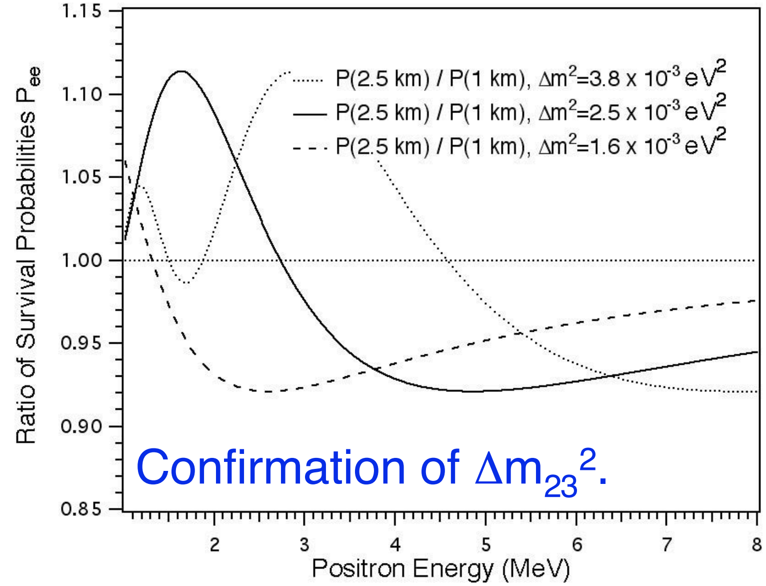
Future Diablo Canyon Experiment



Goals of a Reactor Neutrino Oscillation Experiment

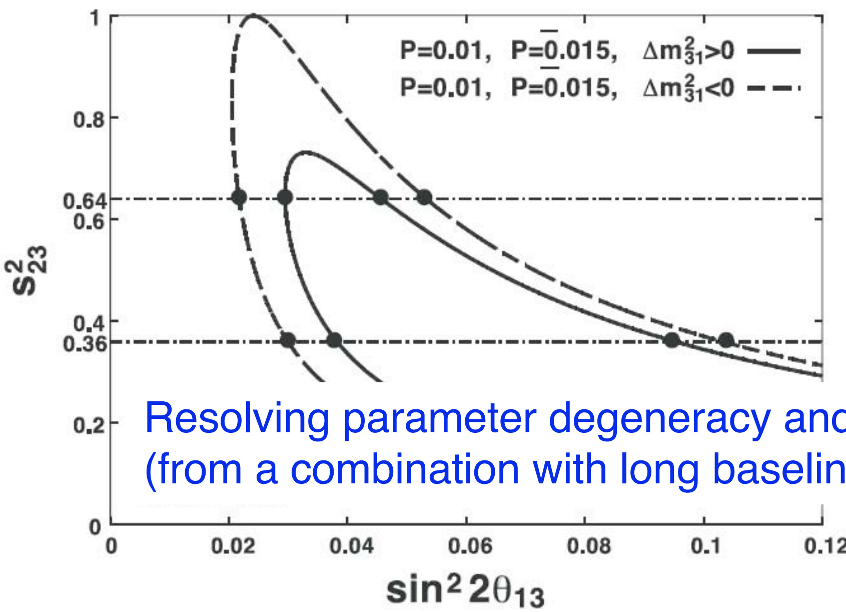


Discovery and measurement of θ_{13}.

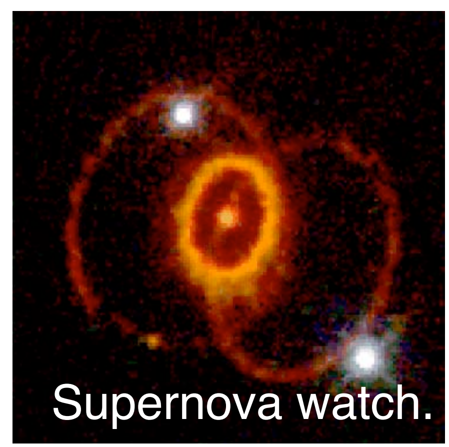


Confirmation of Δm_{23}^2.

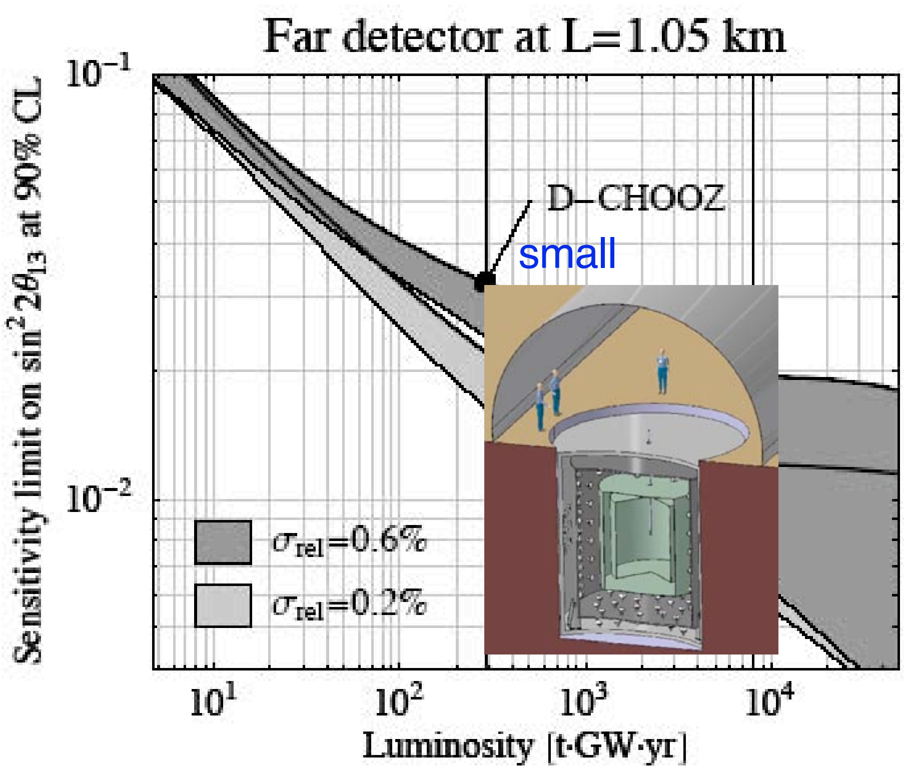
Search for the effect of sterile ν.

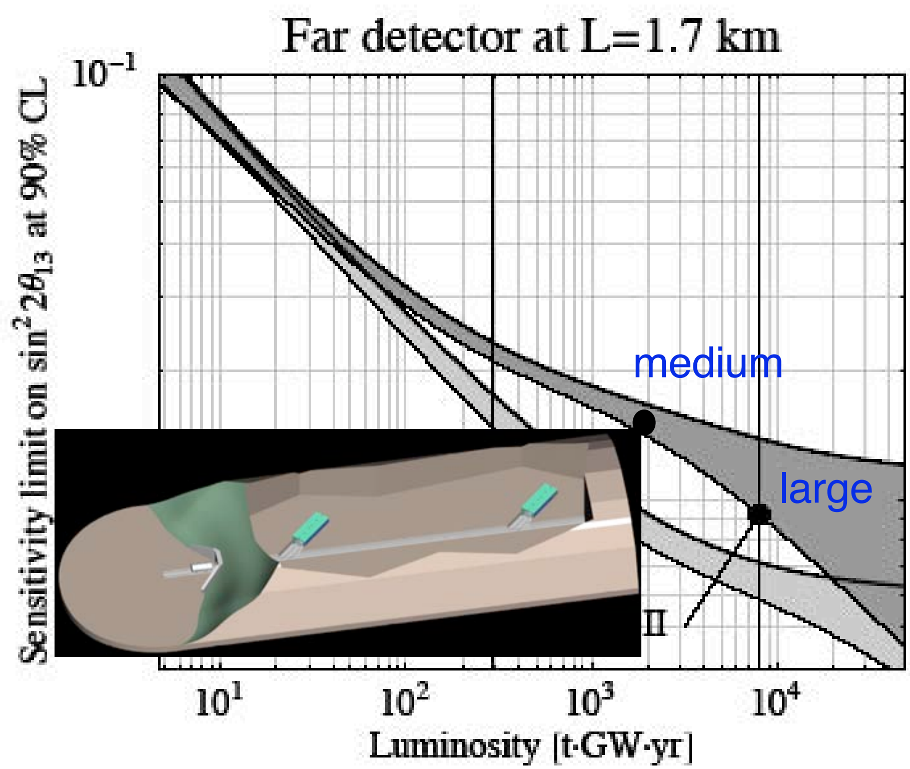


Resolving parameter degeneracy and limits on ~~CP~~ (from a combination with long baseline exp.)



Classes of Reactor θ_{13} Experiments & Sensitivity





- existing underground facility

- deep, good overburden
- optimized baseline and detector size

Future Constraints on θ_{13}

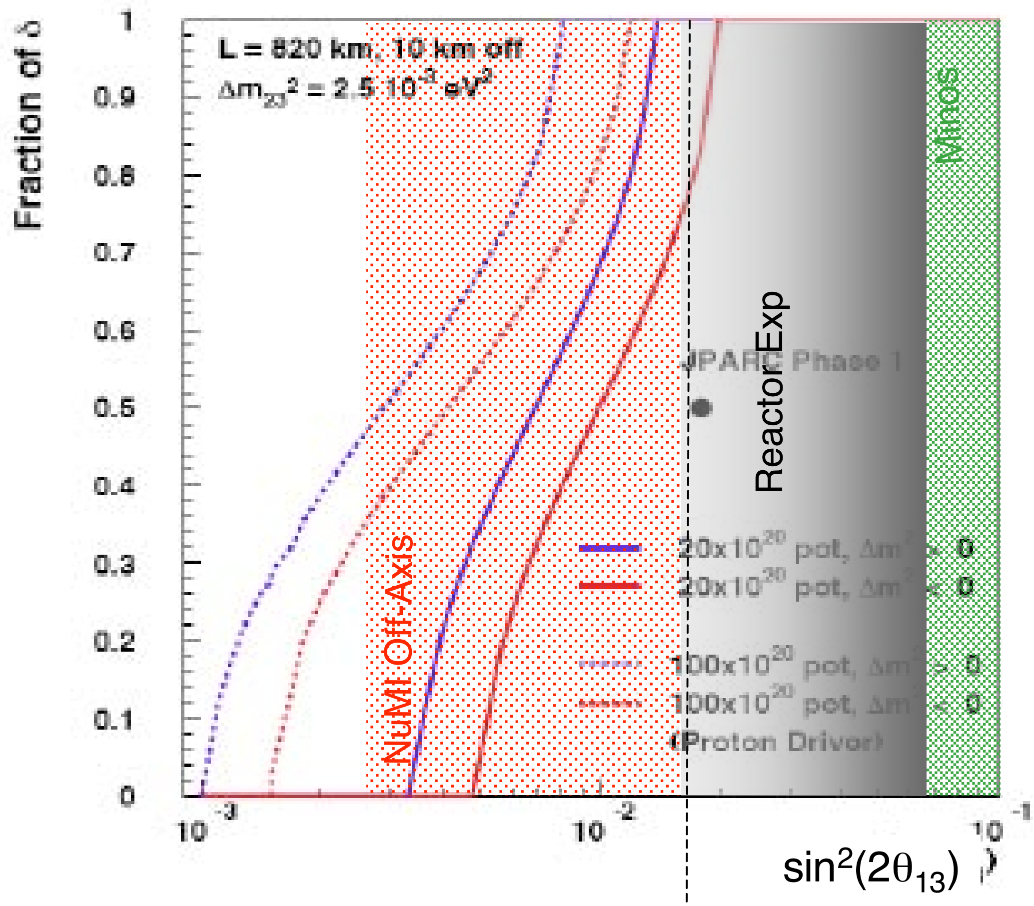
Experiment	***$\sin^2(2\theta_{13})$***	***θ_{13}***	***When?***
CHOOZ	< 0.11	< 10	
NUMI Off- Axis (5 yr)	< 0.006-0.015	< 2.2	2012
JPARC-nu (5 yr)	< 0.006-0.015	< 2.2	2012
MINOS	< 0.07	< 7.1	2008
ICARUS (5 yr)	< 0.04	< 5.8	2011
OPERA (5 yr	< 0.06	< 7.1	2011
Angra dos Reis (Brazil)	< 0.02-0.03	< 5	?
Braidwood (US)	< 0.02-0.03	< 5	[2009]
Chooz-II (France)	< 0.03	< 5	[2009]
Daya Bay (China)	< 0.012	< 3	[2009]
Diablo Canyon (US)	< 0.01-0.02	< 2.9	[2009]
Krasnoyarsk (Russia)	< 0.016	< 3.6	?
Kashiwazaki (Japan)	< 0.026	< 4.6	[2008]

Upper limits correspond to 90% C.L.

Reactor & Long Baseline Experiments

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

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



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

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

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

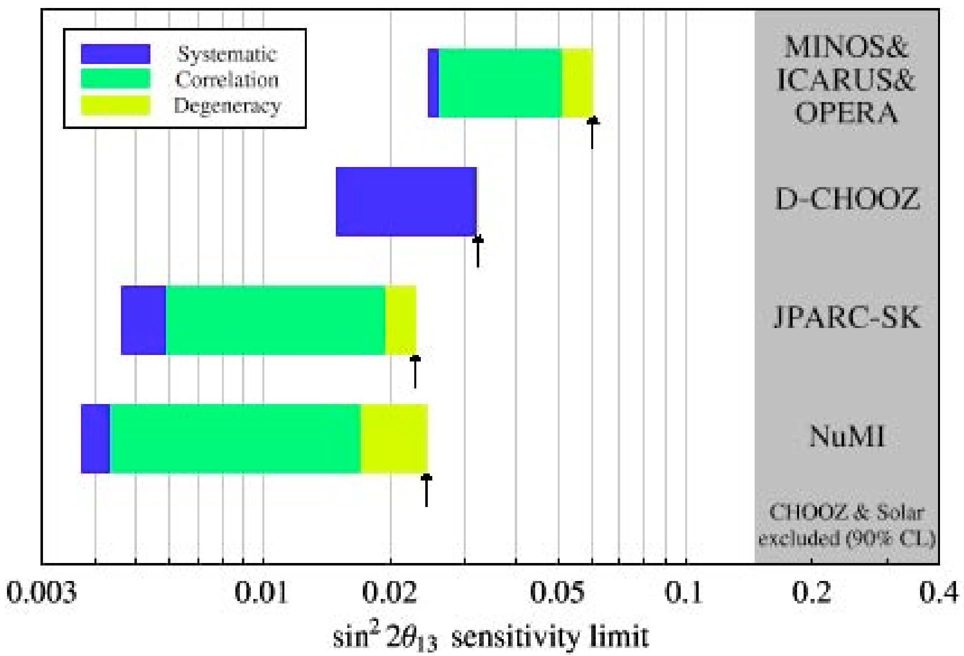
θ_{13} Reactor Exp
90% CL — $\sin^2(2\theta_{13}) < 0.01\text{-}0.02$

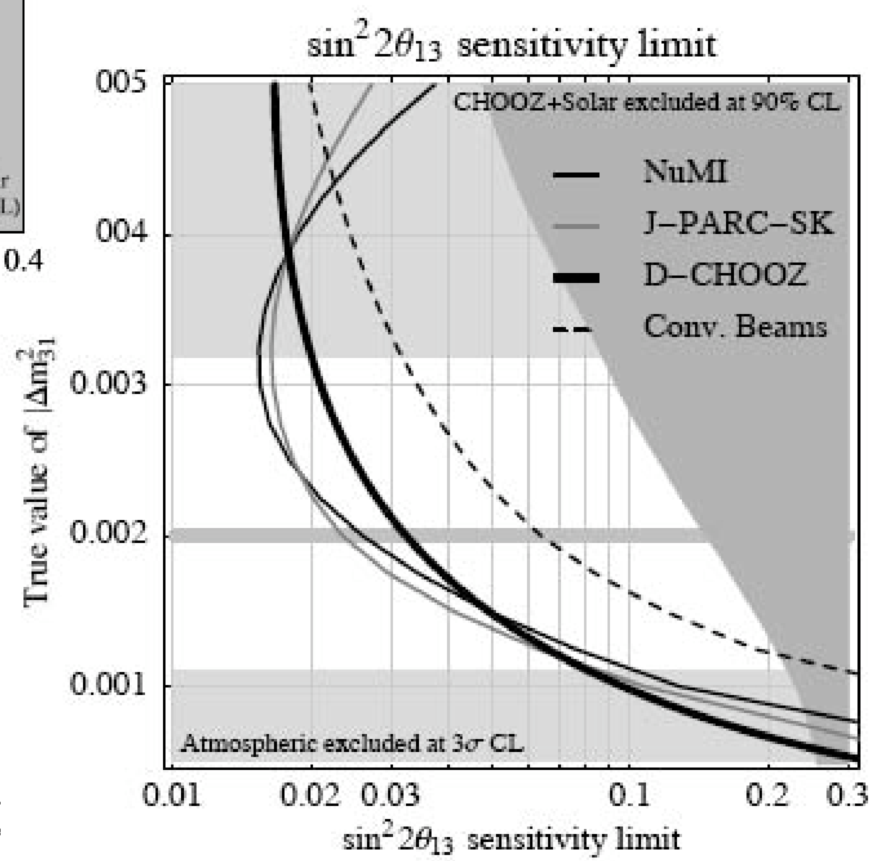
NuMI Off-Axis
3-σ sens. — $\sin^2(2\theta_{13}) < 0.007$

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

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

$\sin^2 2\theta_{13}$ Sensitivity Limits ….10 Years From Now





Ref: Huber et al., hep-ph/0403068

Oscillation Parameters … 10 years from now

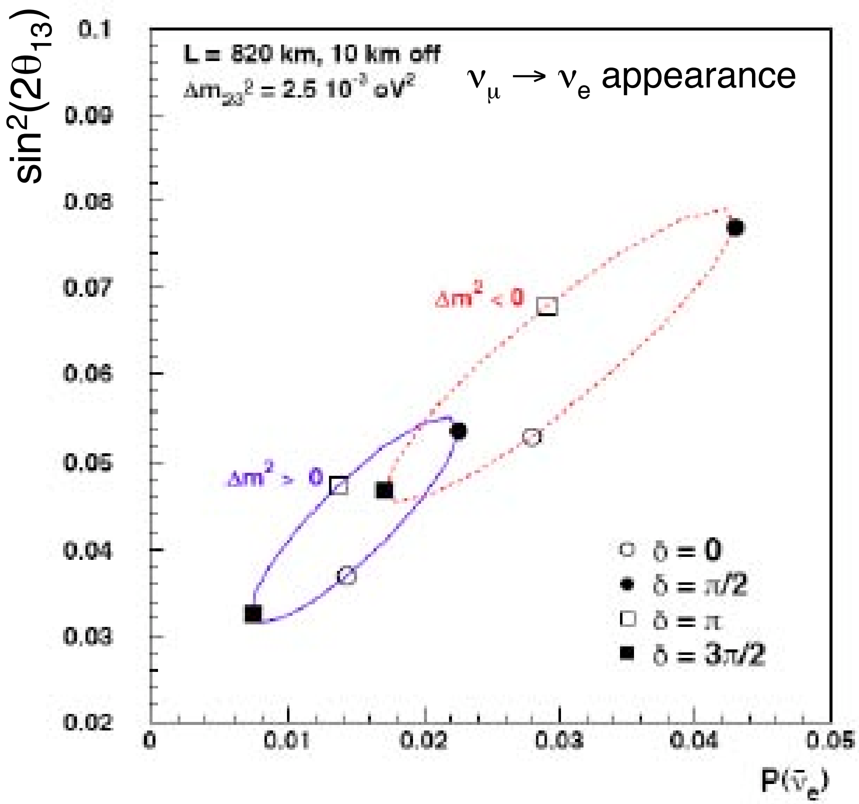
	Current	Beams	D-Chooz	JPARC-SK	NuMI	Reactor-II	Comb.
$\sin^2 2\theta_{13}$ sensitivity limit (90% CL)							
$\sin^2 2\theta_{13}$	0.14	0.061	0.032	**0.023**	0.024	(0.014)	(0.012)
$(\sin^2 2\theta_{13})_{\mathrm{eff}}$	0.14	0.026	0.032	0.006	**0.004**	(0.014)	(0.003)
Allowed ranges for leading atmospheric parameters (3σ)							
$\frac{\lvert\Delta m^2_{31}\rvert}{10^{-3}\,\mathrm{eV}^2}$	$2^{+1.2}_{-0.9}$	$2^{+0.34}_{-0.18}$	–	$2^{+\mathbf{0.15}}_{-0.09}$	$2^{+0.43}_{-\mathbf{0.07}}$	–	$2^{+0.12}_{-0.06}$
θ_{23}	$(\frac{\pi}{4})^{+0.20}_{-0.20}$	$(\frac{\pi}{4})^{+0.22}_{-0.19}$	–	$(\frac{\pi}{4})^{+\mathbf{0.13}}_{-\mathbf{0.10}}$	$(\frac{\pi}{4})^{+0.24}_{-0.21}$	–	$(\frac{\pi}{4})^{+0.13}_{-0.10}$
Measurements for large $\sin^2 2\theta_{13} = 0.1$ (90% CL)							
$\sin^2 2\theta_{13}$	–	$0.1^{+0.104}_{-0.052}$	$0.1^{+0.034}_{-0.033}$	$0.1^{+0.067}_{-0.034}$	$0.1^{+0.083}_{-0.043}$	$0.1^{+\mathbf{0.016}}_{-\mathbf{0.011}}$	$0.1^{+0.013}_{-0.010}$
δ_{CP}	Combination can exclude up to 40% of all values						
CP violation	No sensitivity to CP violation of any tested experiment or combination						
$\mathrm{sgn}(\Delta m^2_{31})$	Combination has sensitivity to normal mass hierarchy close to $\delta_{\mathrm{CP}} = -90°$						

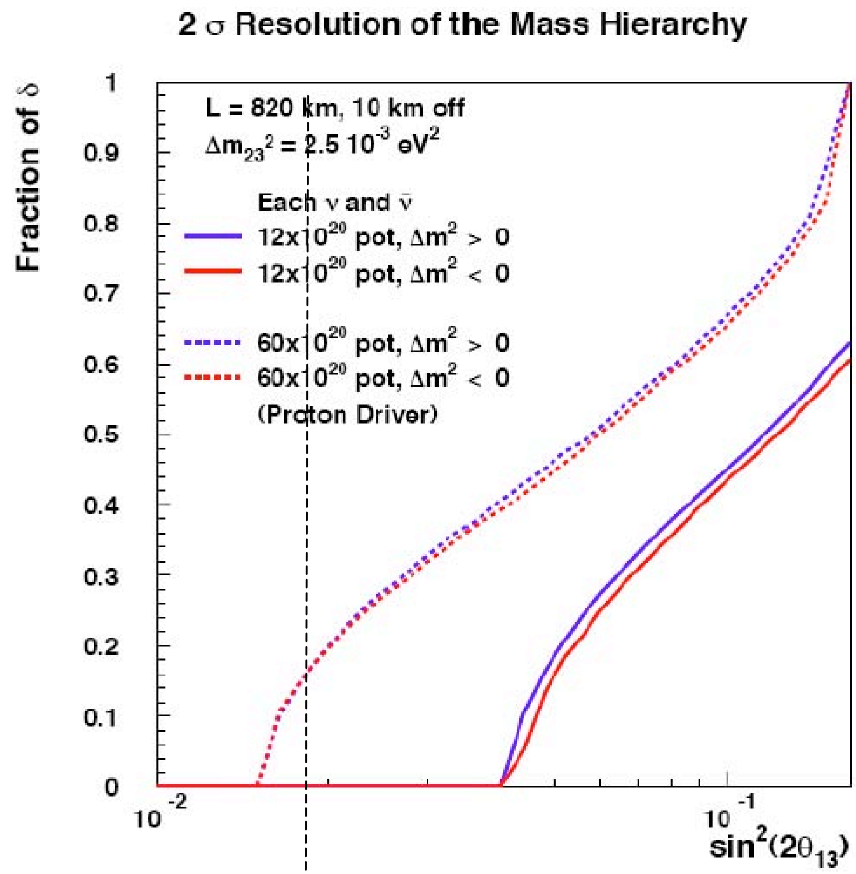
Ref: Huber et al., hep-ph/0403068

Reactor & Long Baseline Experiments

Determining Mass Hierarchy

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

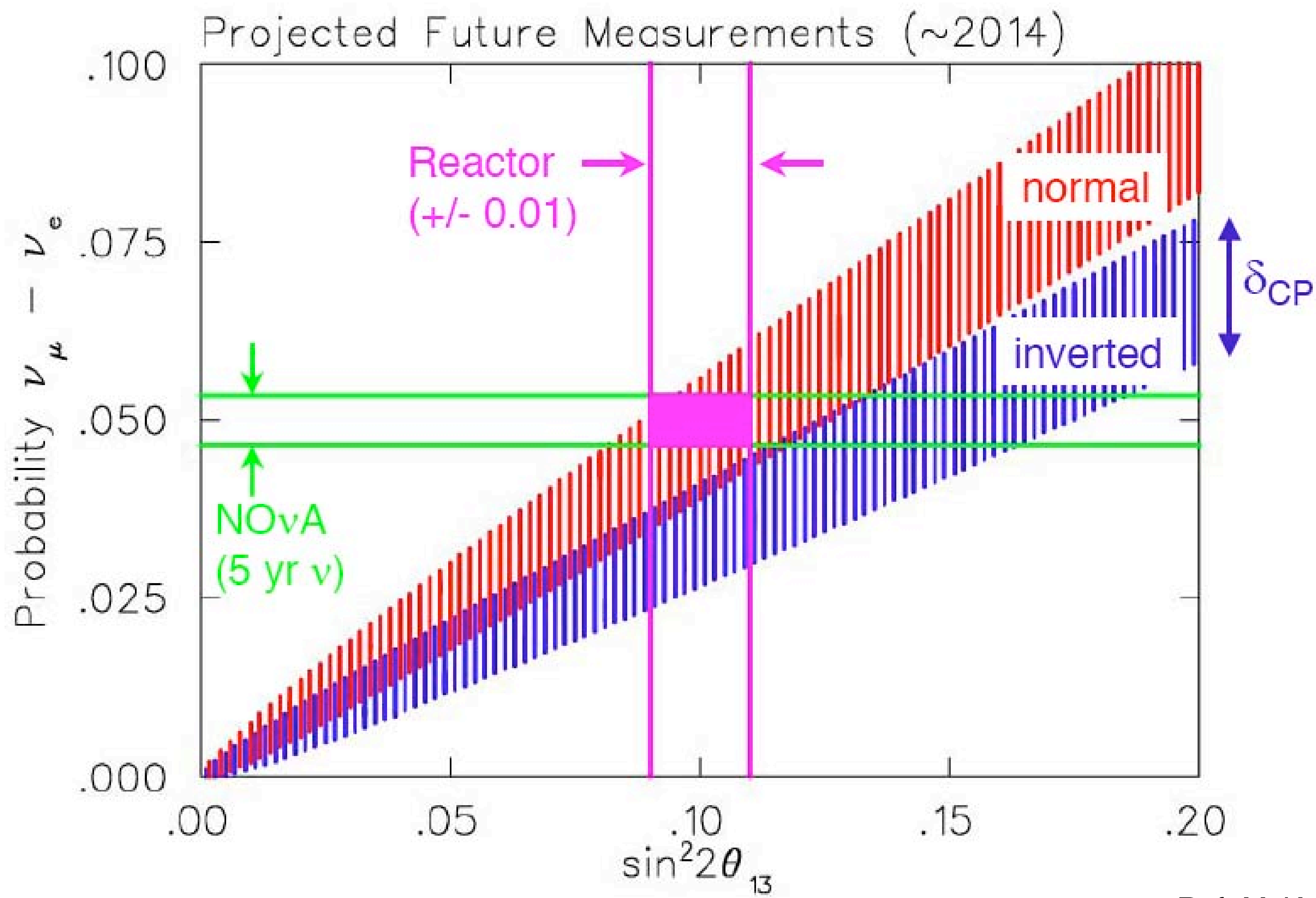




reactor 90% CL= 0.01
and $\delta(\sin^2(2\theta_{13}))$ = 0.006

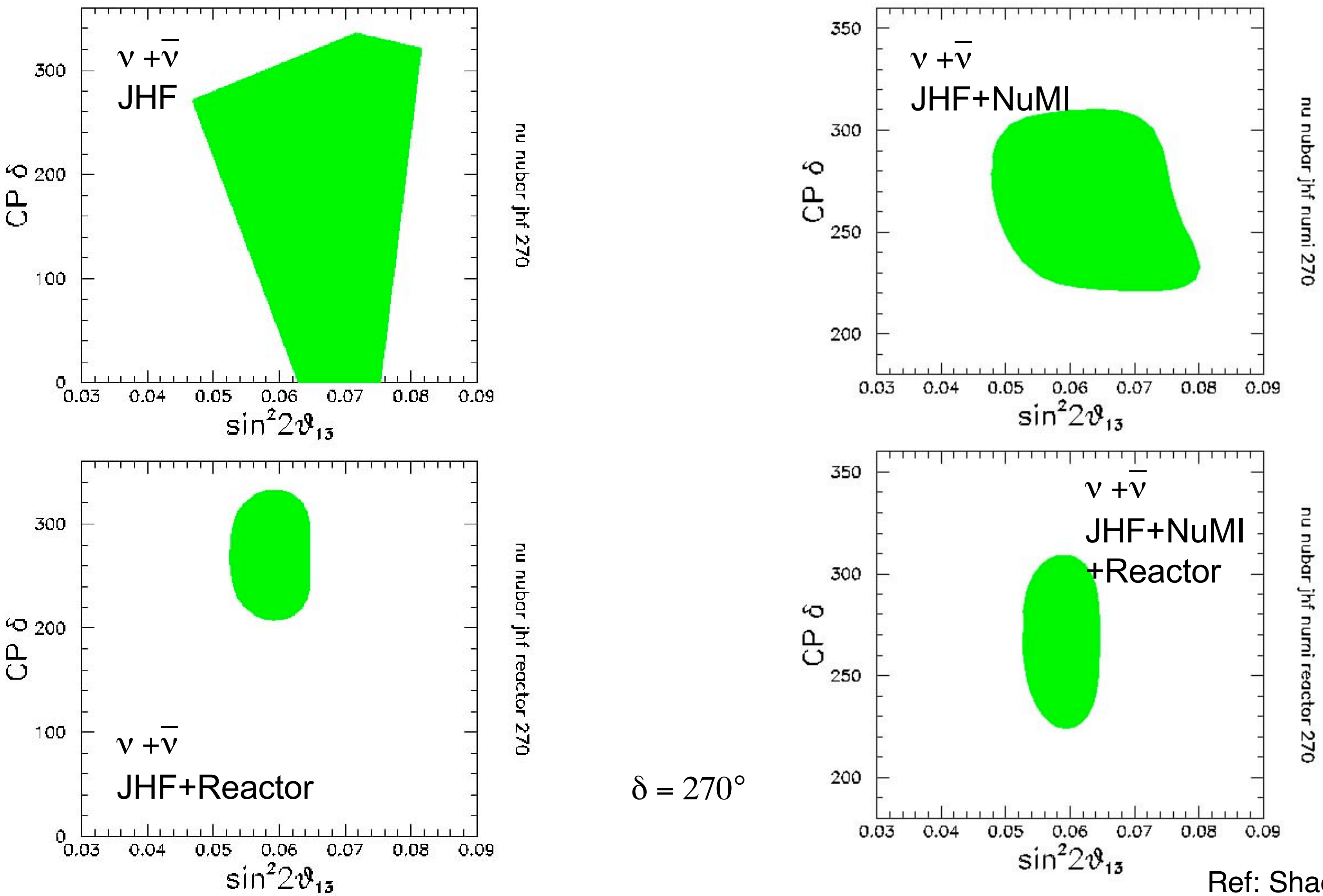
Ref: NuMI Off-Axis Collaboration, Progress Report 12/2003

Reactor Experiment & Noν



Ref: McKeown

δ_{CP} Measurement (with / without Reactor)



$\delta = 270°$

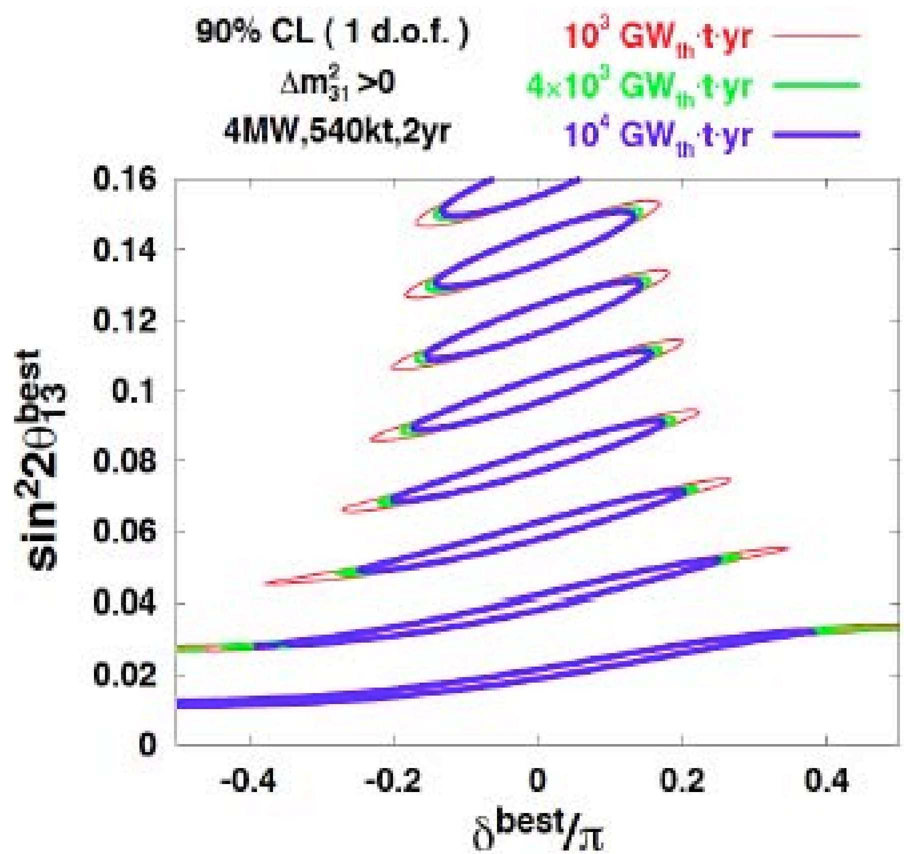
Ref: Shaevitz

Reactor & Long Baseline Experiments

Combination of Experiments Can Detect CP Violation

$$\sin\delta = \frac{P(\nu_\mu \to \nu_e) - P_{solar} - X_\pm s_{13}^2}{\mp Y_\pm s_{13}}$$

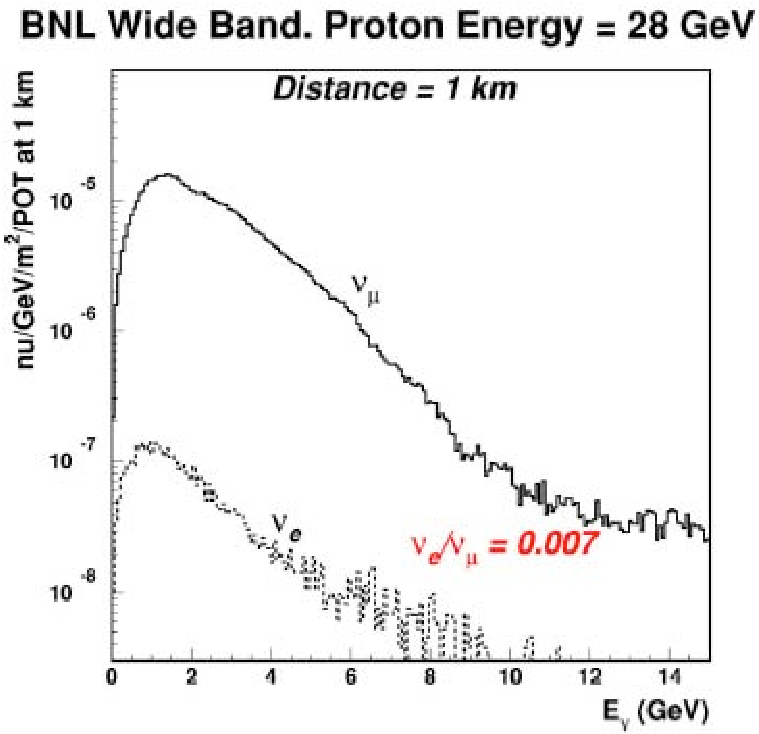
Accelerator ν_e appearance + reactor disappearance measurement δ_{CP}

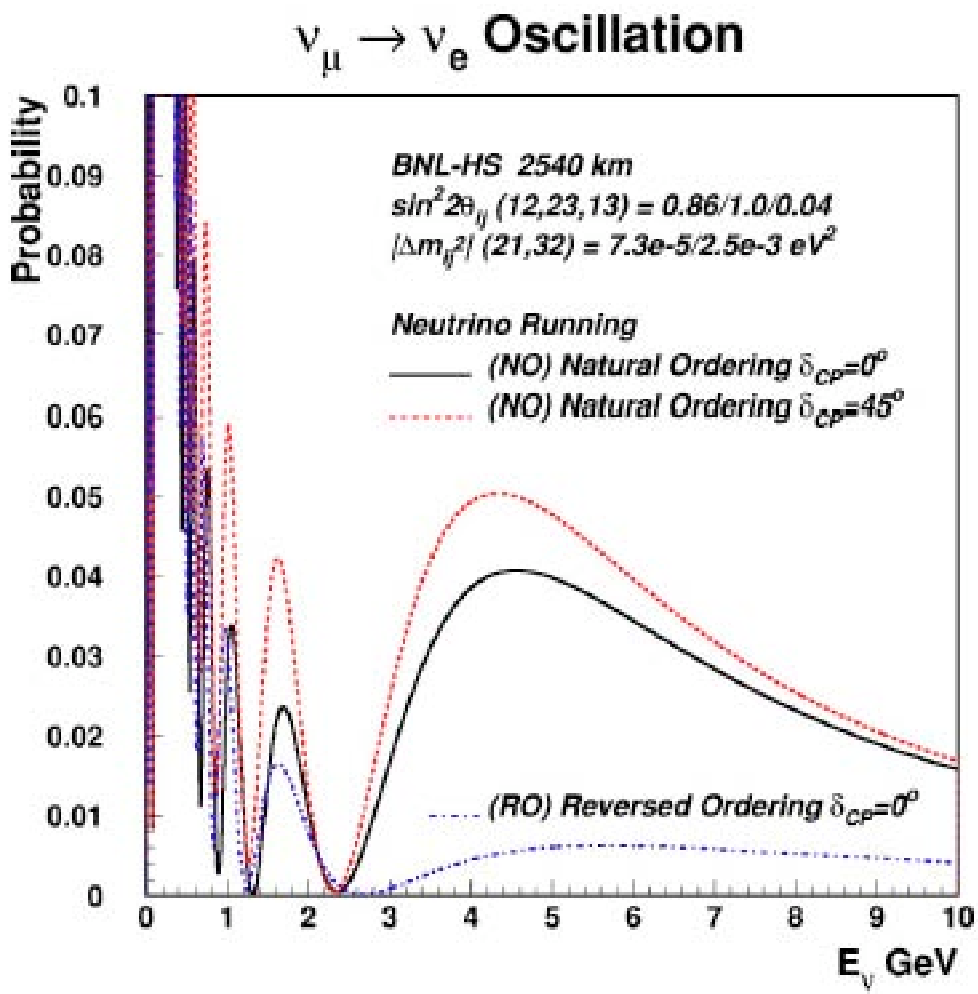


Ref: hep-ph/0309323

Superbeams and Beyond - Another Approach …

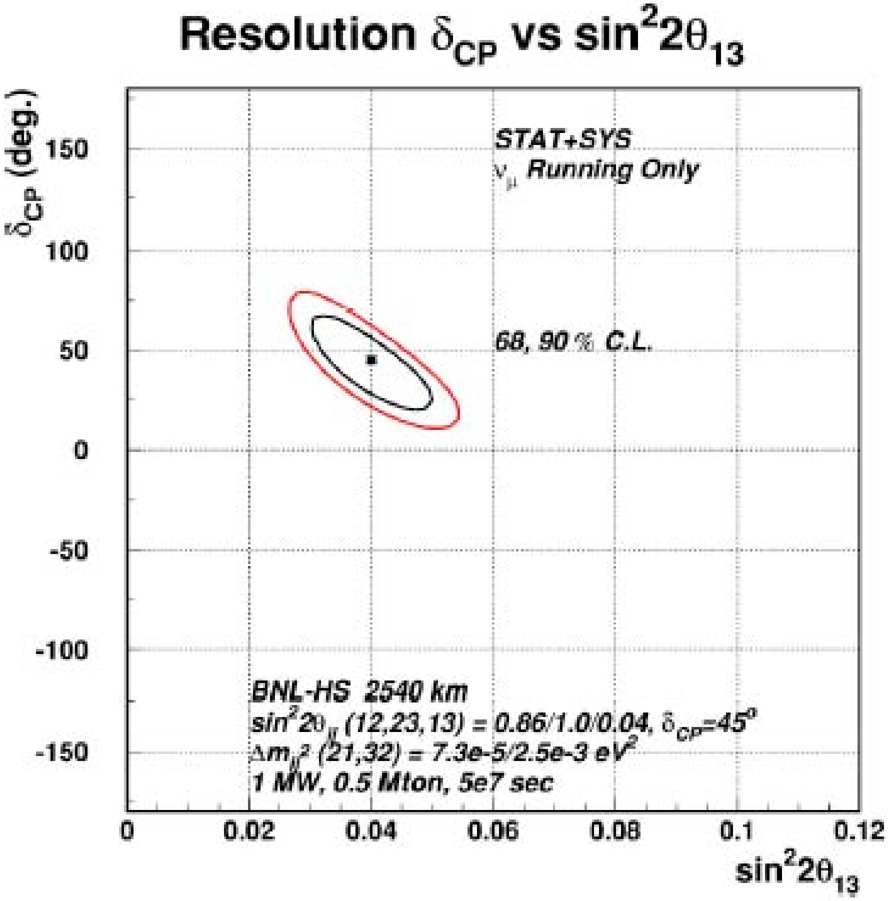
Wide Band Beam Over Long Distance

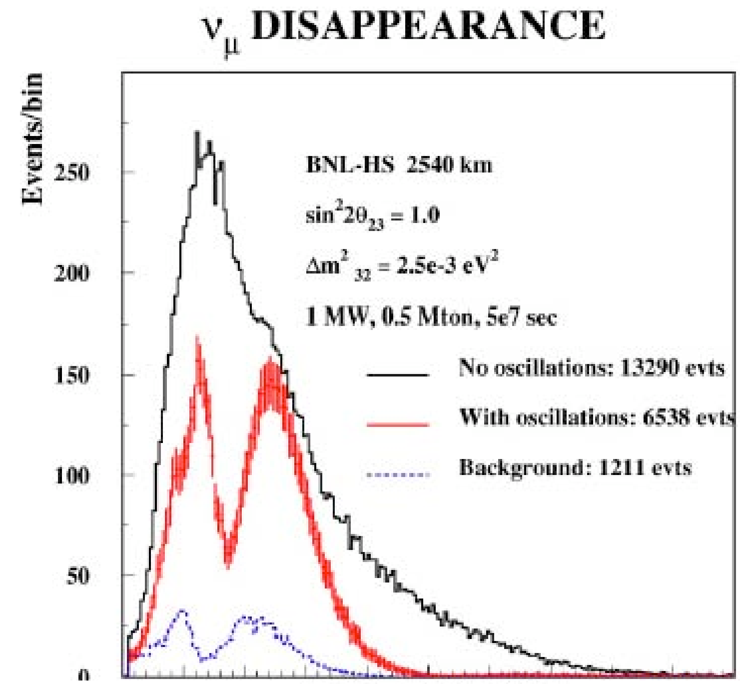


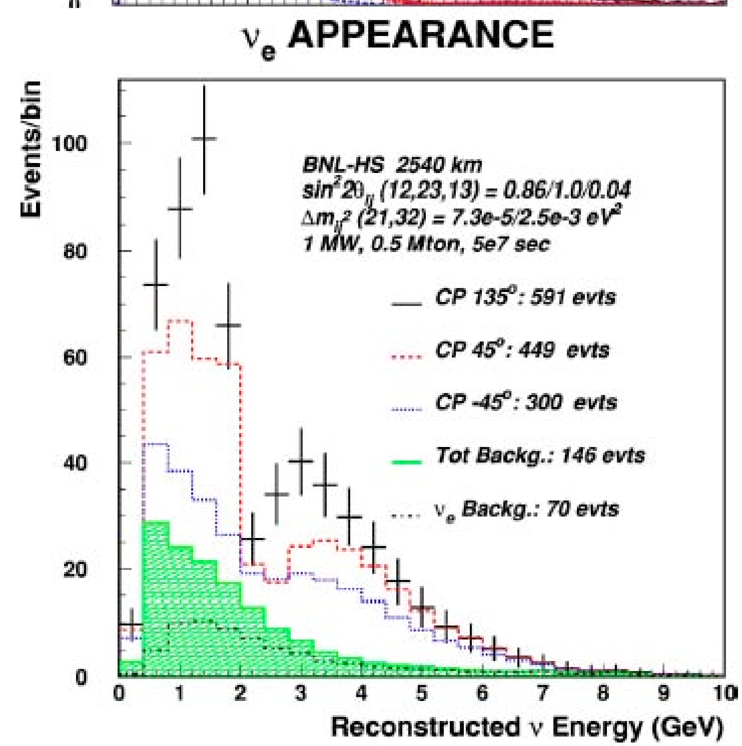


Ref: Diwan et al. PRD 68, 012002 (2003)

Superbeams and Beyond







Ref: Diwan et al. PRD 68, 012002 (2003)

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

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 $\sin^2 2\theta_{13} < 0.01$.

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.

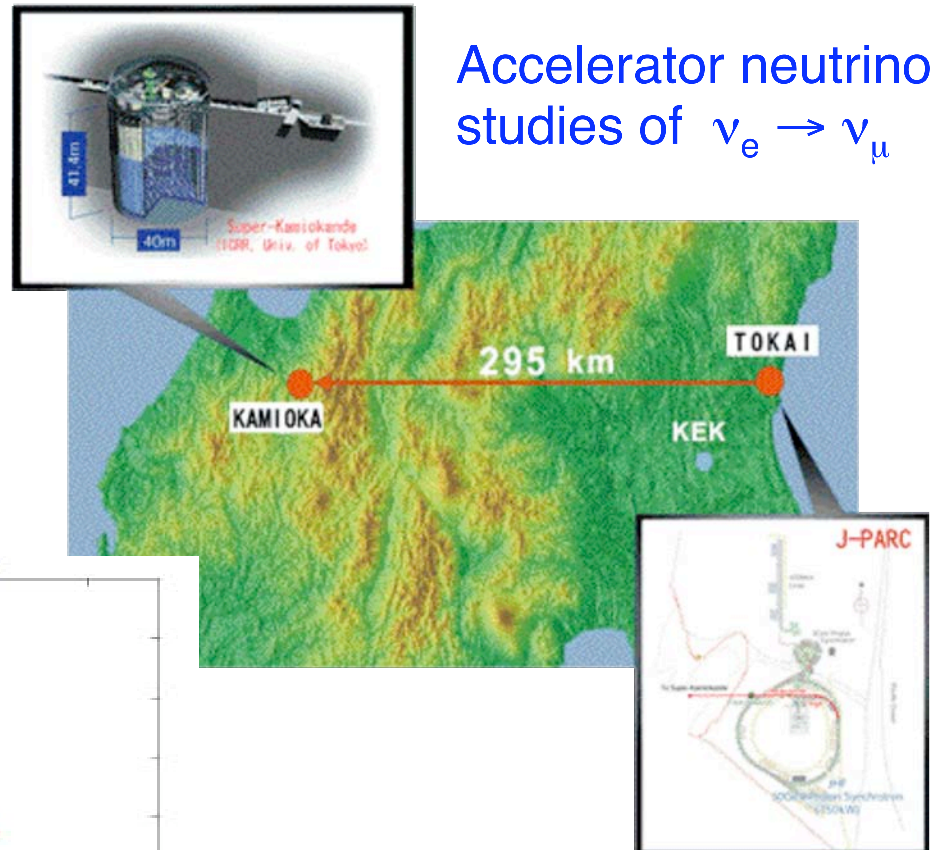
If lucky, may find indication of ~~CP~~ and mass hierarchy with next-generation experiments (precision θ_{13} reactor + off-axis acc. experiment)!

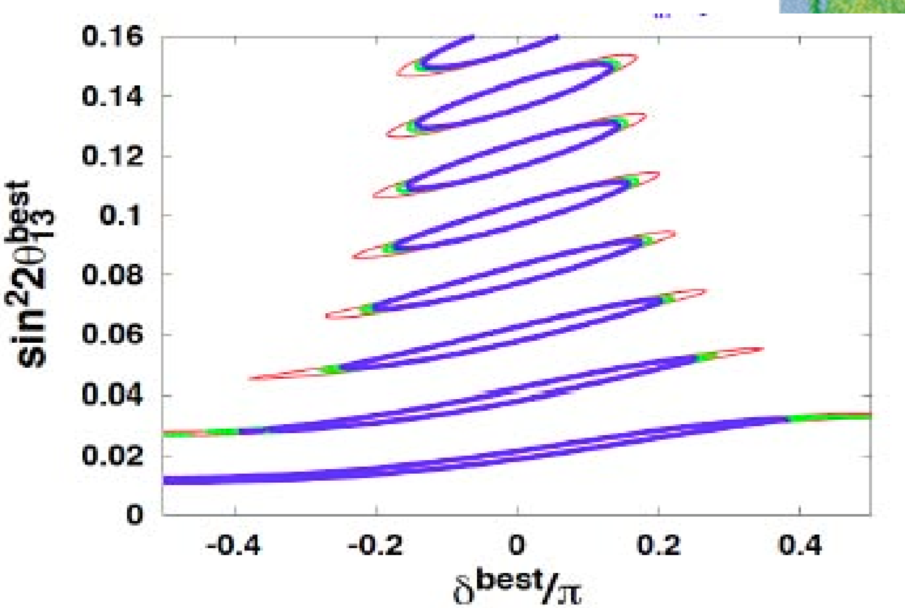
Possible Future of Neutrino Oscillation Physics

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