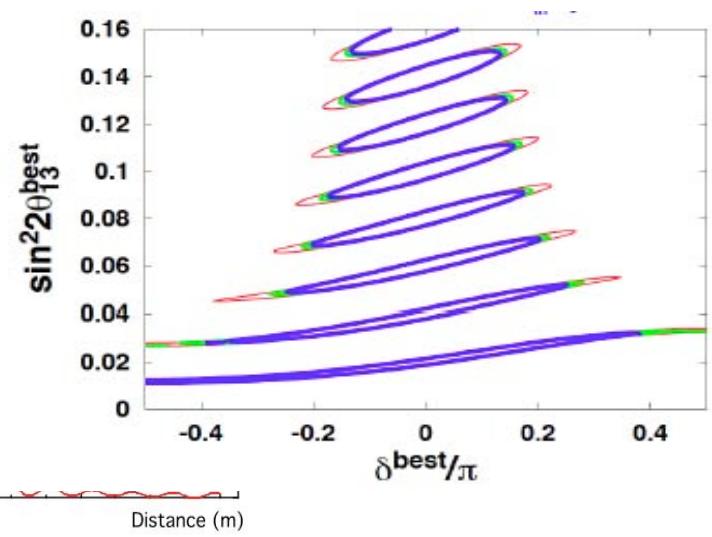
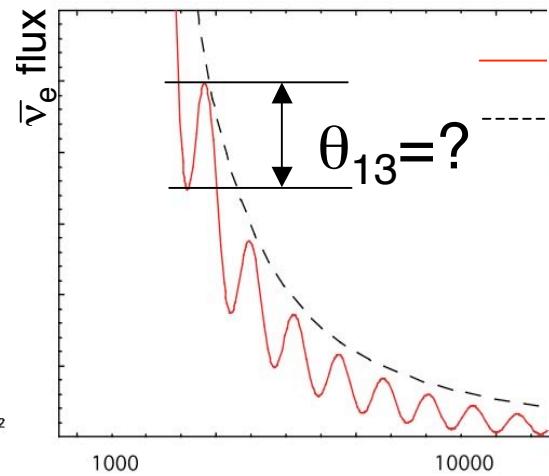
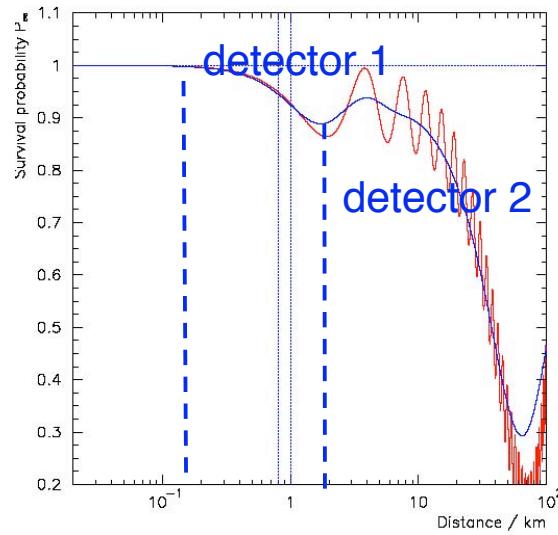


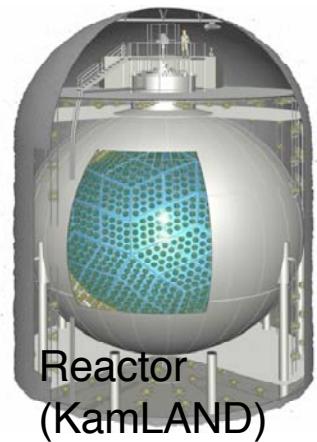
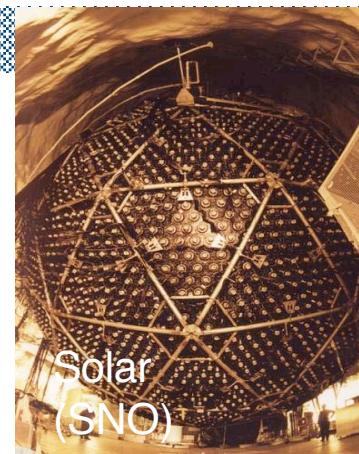
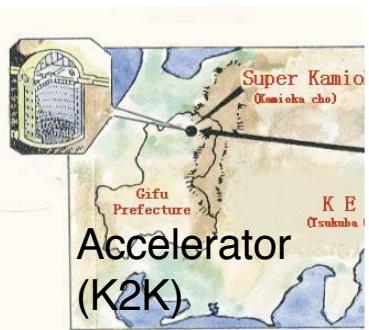
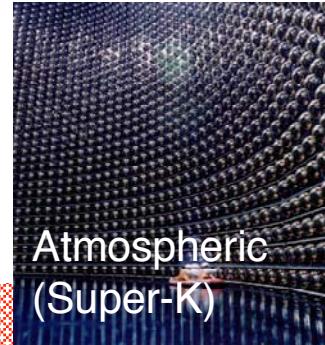
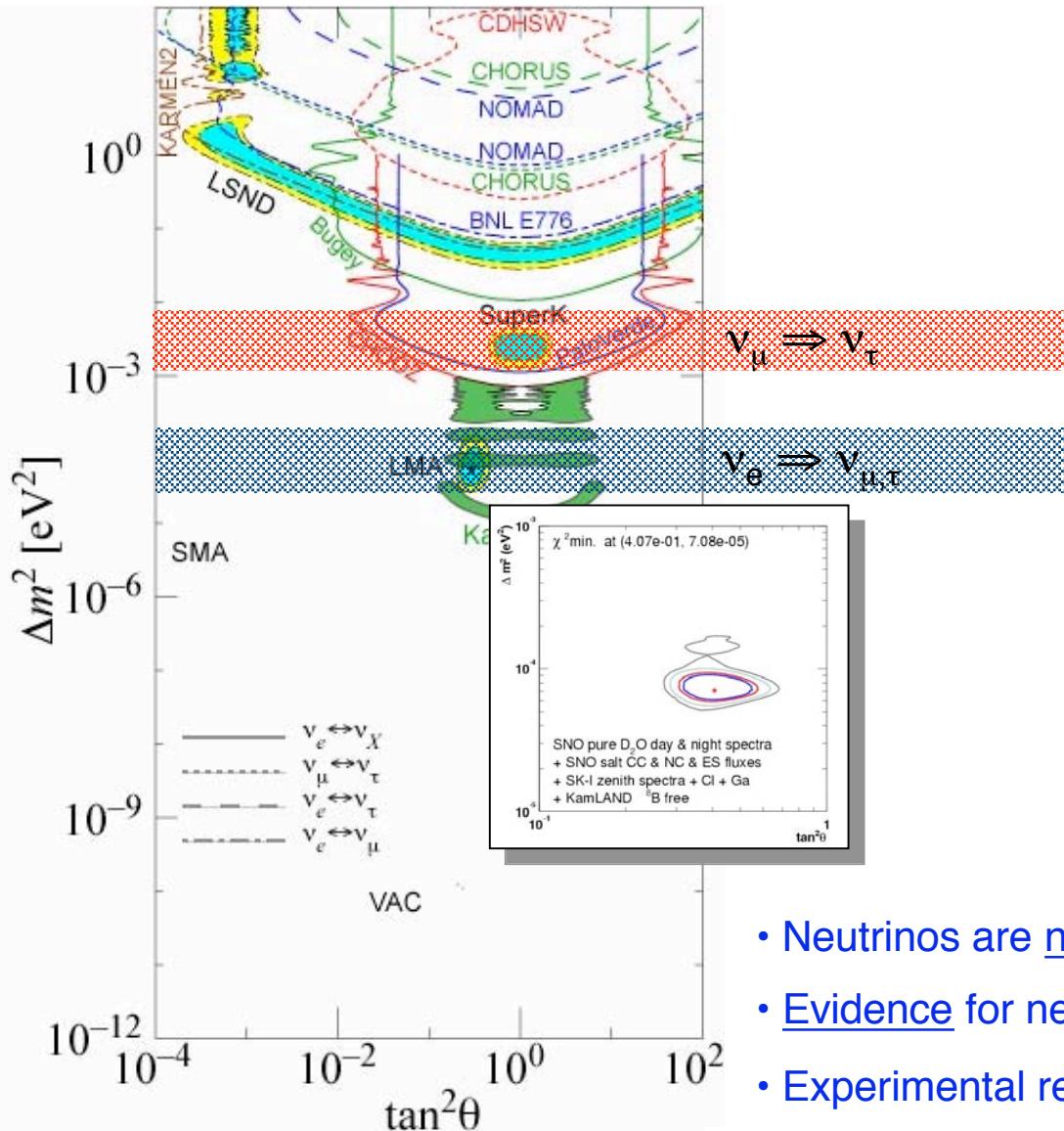
Measuring θ_{13} in a Reactor Neutrino Oscillation Experiment

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Recent Results in Neutrino Physics



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

Except for LSND, Δm_{ij}^2 measured and confirmed.

U_{MNSP} , θ_{13} , and ~~CP~~

U_{MNSP} Neutrino Mixing Matrix

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \underbrace{\quad}_{\text{atmospheric, K2K}} \times \underbrace{\begin{pmatrix} \cos \theta_{13} & 0 & e^{-i\delta_{CP}} \sin \theta_{13} \\ 0 & \cos \theta_{13} & 0 \\ -e^{i\delta_{CP}} \sin \theta_{13} & 0 & \cos \theta_{13} \end{pmatrix}}_{\text{reactor and accelerator}} \underbrace{\quad}_{\text{?}} \times \underbrace{\begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{SNO, solar SK, KamLAND}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{\text{0}\nu\beta\beta}}$$

atmospheric, K2K

$\theta_{23} = \sim 45^\circ$

maximal

reactor and accelerator

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

small ... at best

SNO, solar SK, KamLAND

$\theta_{12} \sim 32^\circ$

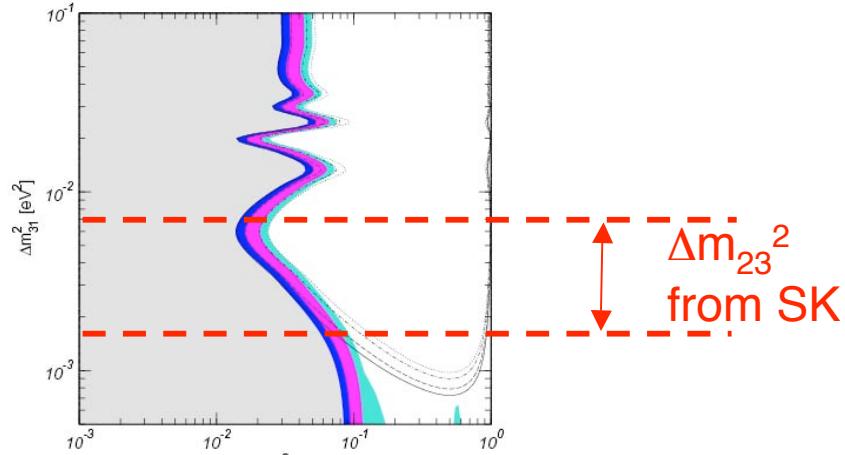
large

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

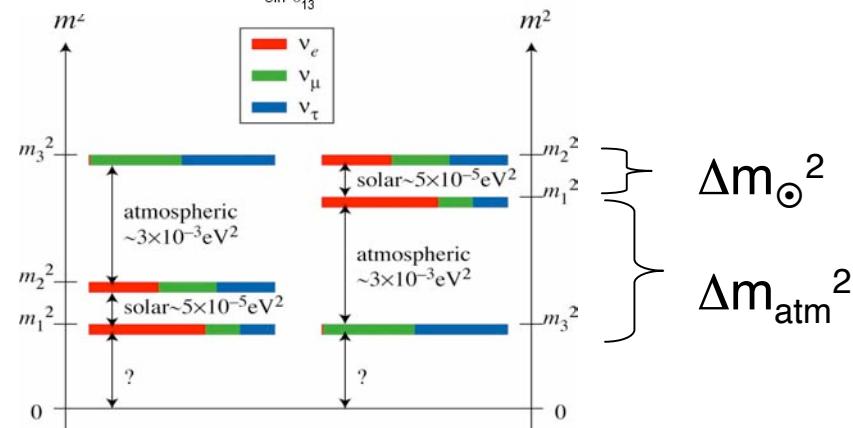
θ_{13} yet to be measured
determines accessibility to CP phase

Key Questions in Oscillation Physics

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



sign of Δm_{13}^2
mass hierarchy



δ_{CP}

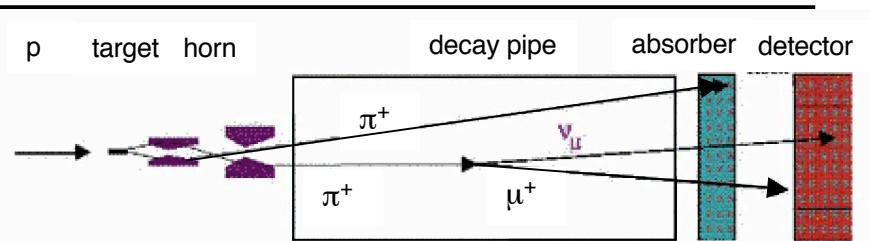
Amount of CP

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

Measuring θ_{13}

Method 1: Accelerator Experiments

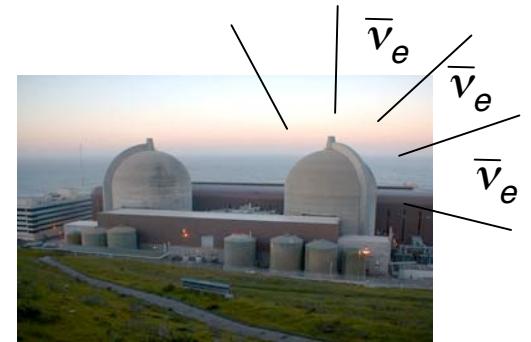
$$P_{\mu e} \approx \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{31}^2 L}{4E_\nu} + \dots$$



- 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 $O(100 - 1000 \text{ km})$, matter effects present

Method 2: Reactor Neutrino Oscillation Experiment

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

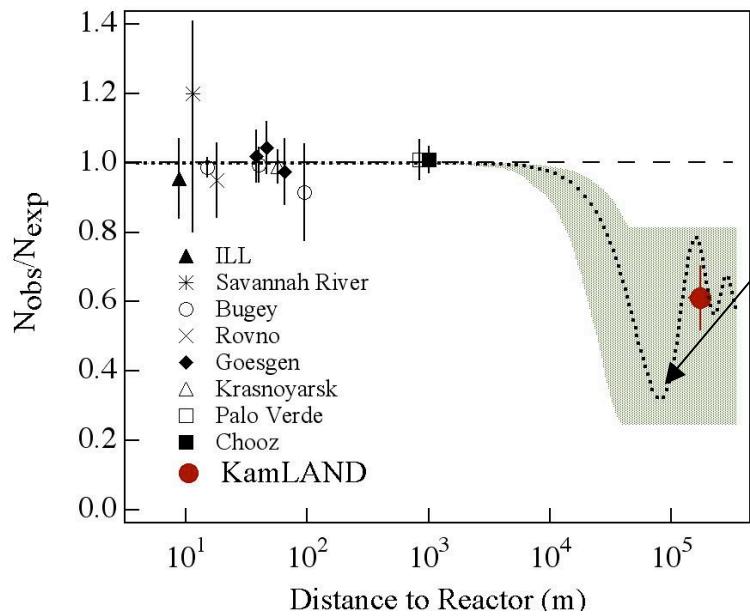


- disappearance experiment $\bar{\nu}_e \rightarrow \bar{\nu}_e$
- look for rate deviations from $1/r^2$ and spectral distortions
- observation of oscillation signature with 2 or multiple detectors
- baseline $O(1 \text{ km})$, no matter effects

Reactor Neutrino Oscillation Measurements

Past Measurements

single antineutrino detector, absolute flux measurement



Dominant θ_{12} Oscillation

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

Future θ_{13} Reactor Neutrino
Oscillation Experiment

multiple detectors, relative flux measurement

$P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$

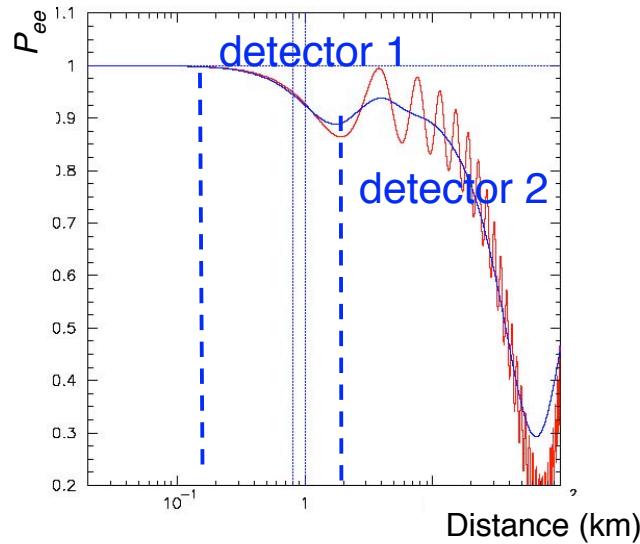
Subdominant θ_{13} Oscillation

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



Measuring θ_{13} with Reactor Neutrinos

Novel Oscillation Experiment with Multiple Detectors



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

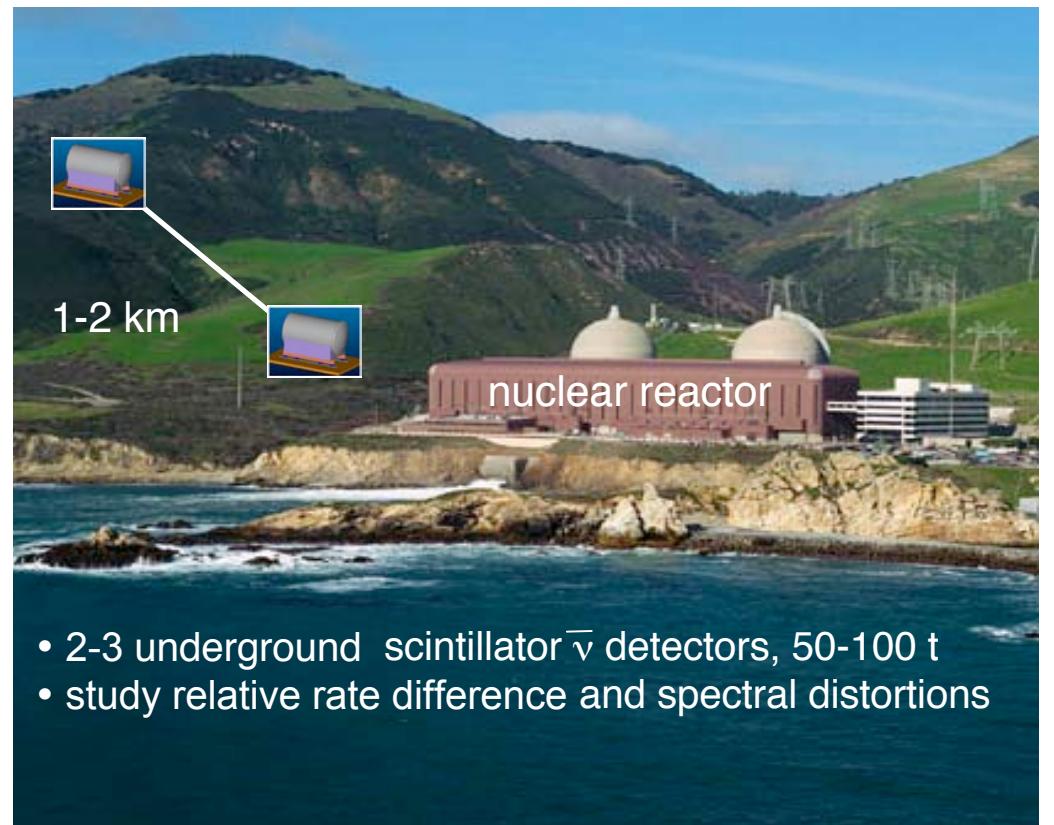


- eliminates most systematic errors
- projected sensitivity:

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

Ref: hep-ex/0402041

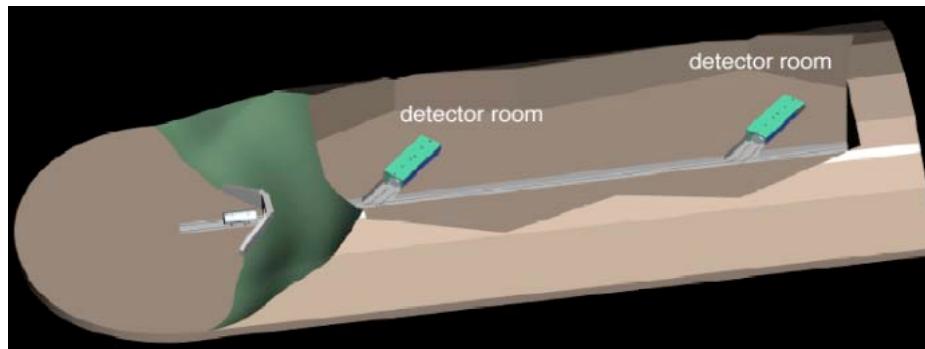
$$P_{ee} \approx 1 - \left(\sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E_\nu} + \left(\frac{\Delta m_{21}^2 L}{4E_\nu} \right) \cos^4 \theta_{13} \sin^2 2\theta_{12} \right)$$



- 2-3 underground scintillator $\bar{\nu}$ detectors, 50-100 t
- study relative rate difference and spectral distortions

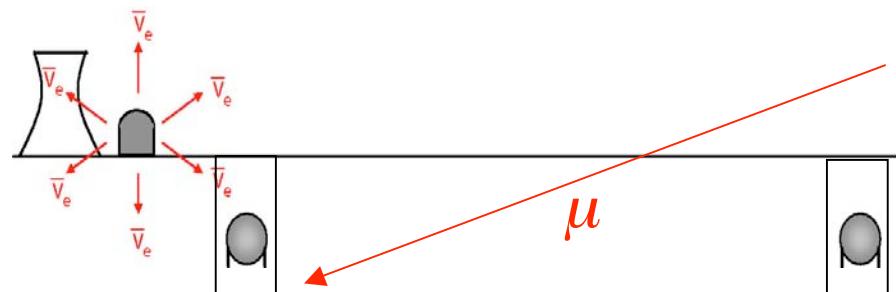
Design & Location

Mountainous sites with horizontal access tunnel

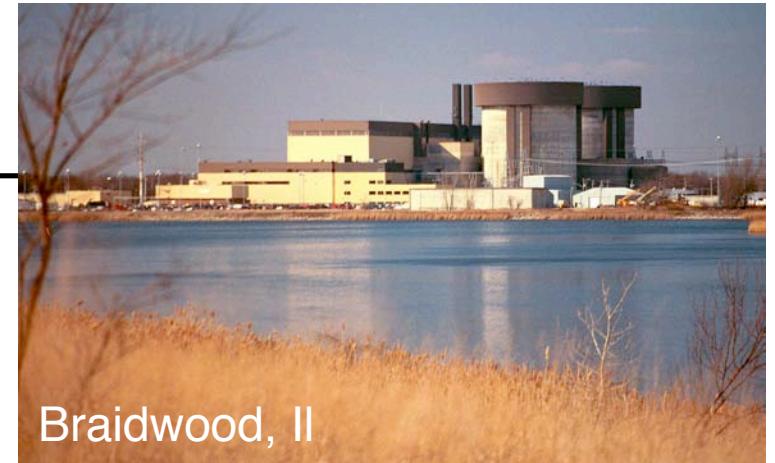


- detector positioning flexibility
- access to large overburden

Flat sites with vertical shaft access



- placement and location flexibility
- good shielding per unit depth



Braidwood, IL



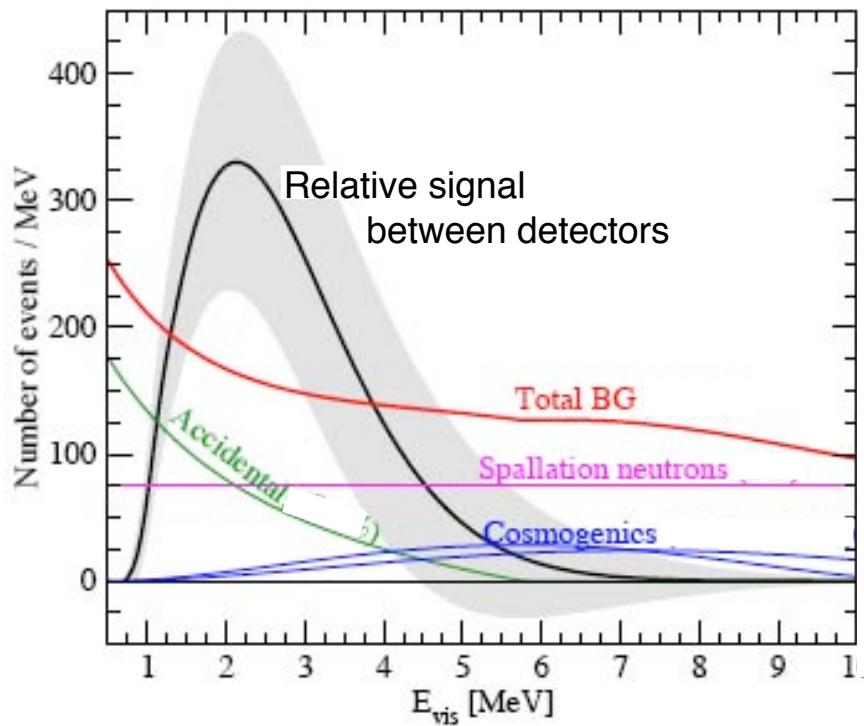
Daya Bay, China



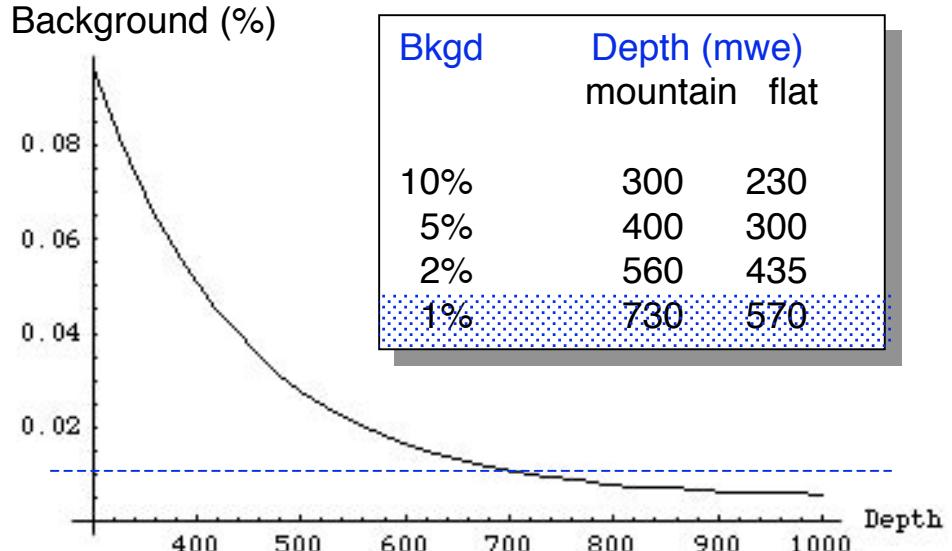
Diablo Canyon, CA

Experimental Challenge: Muon-Induced Backgrounds

Energy Spectrum



Total Background



Correlated backgrounds are related to cosmic ray muon rates

- Neutron production
- Isotope production: ${}^9\text{Li}$ ($t_{1/2}=0.18\text{s}$) , ${}^8\text{He}$ ($t_{1/2}=0.12\text{s}$) $\beta-\text{n}$ emitters

High muon rates can also introduce deadtime effects.

→ Winslow W9 14

Detector Shielding and Background Mitigation

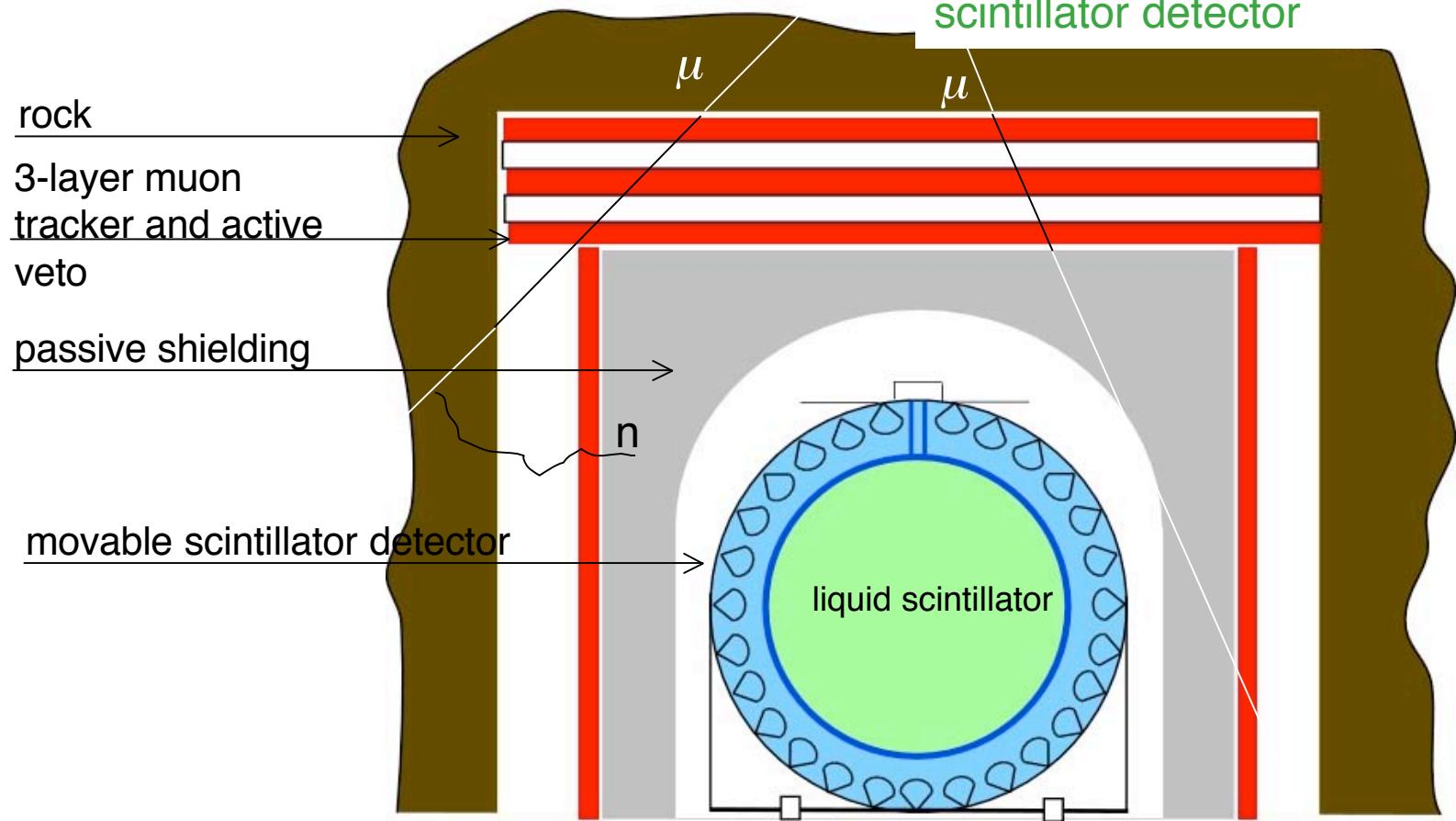
Reduce with Veto and Shielding

Veto μ 's and shield neutrons
(increase effective depth)

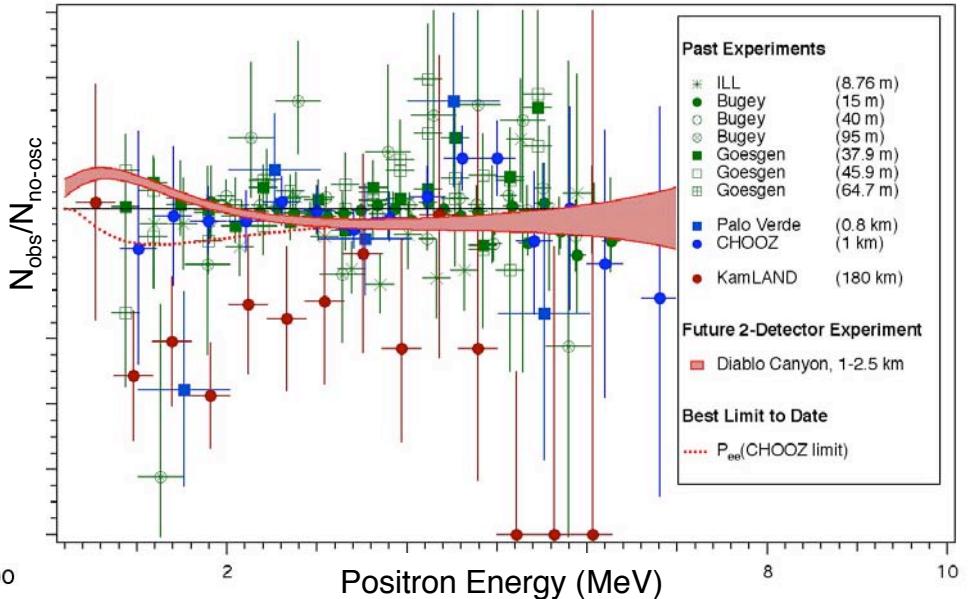
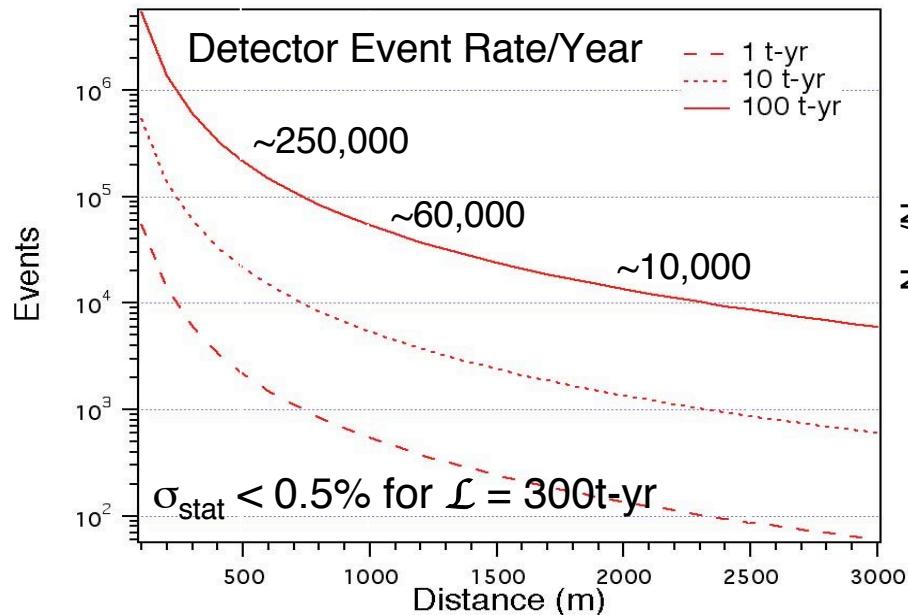
Active muon tracker

+ passive shielding

+ movable, inner liquid
scintillator detector



Statistics and Systematics



Reactor Flux near/far ratio $\sigma_{\text{flux}} < 0.2\%$

Detector Efficiency near and far detector of same design
calibrate relative detector efficiency $\sigma_{\text{rel eff}} \leq 1\%$

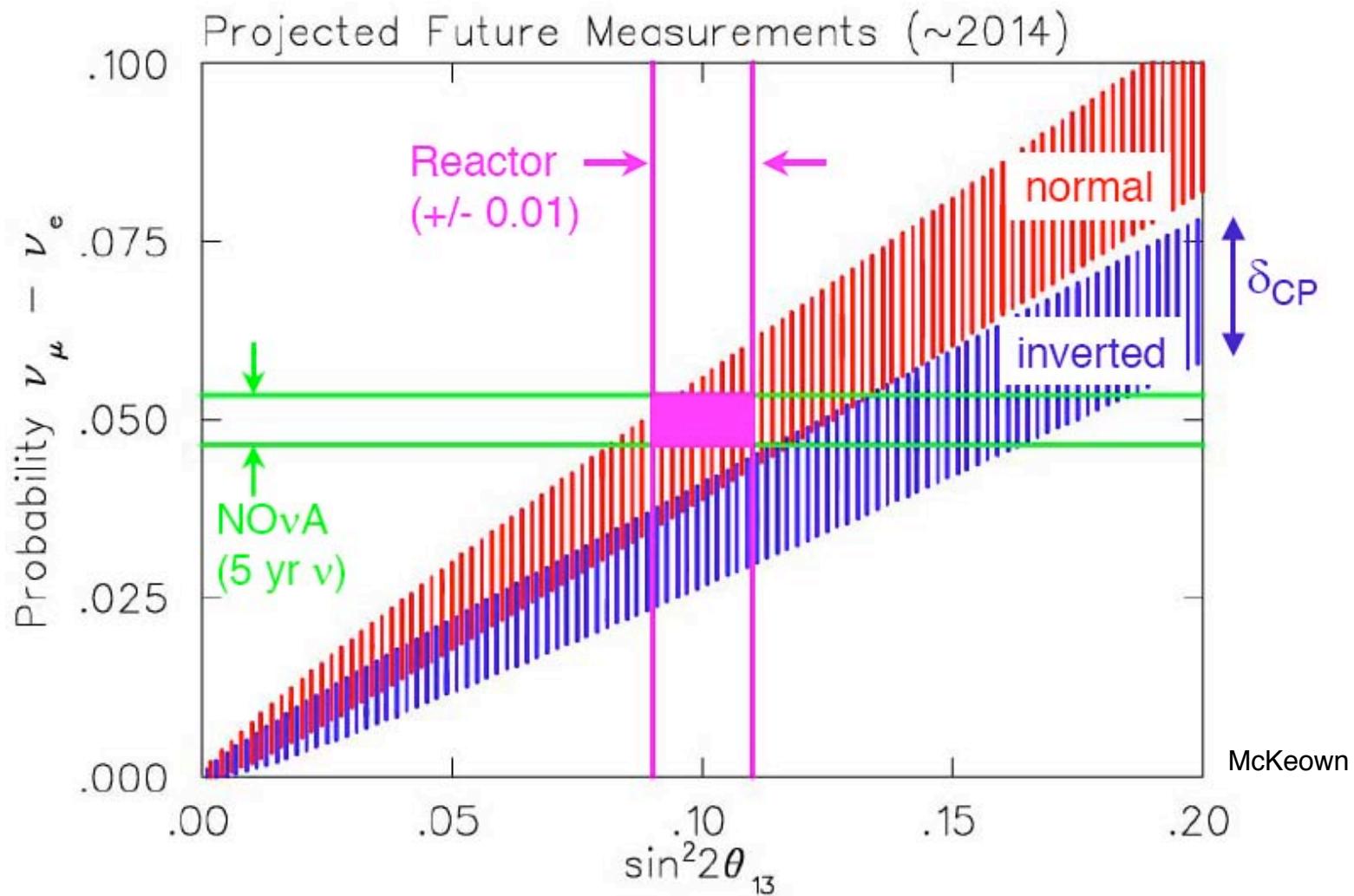
Target Volume & no fiducial volume cut $\sigma_{\text{target}} \sim 0.3\%$

Backgrounds external active and passive shielding $\sigma_{\text{acc}} < 0.5\%$
 $\sigma_{n \text{ bkgd}} < 1\%$

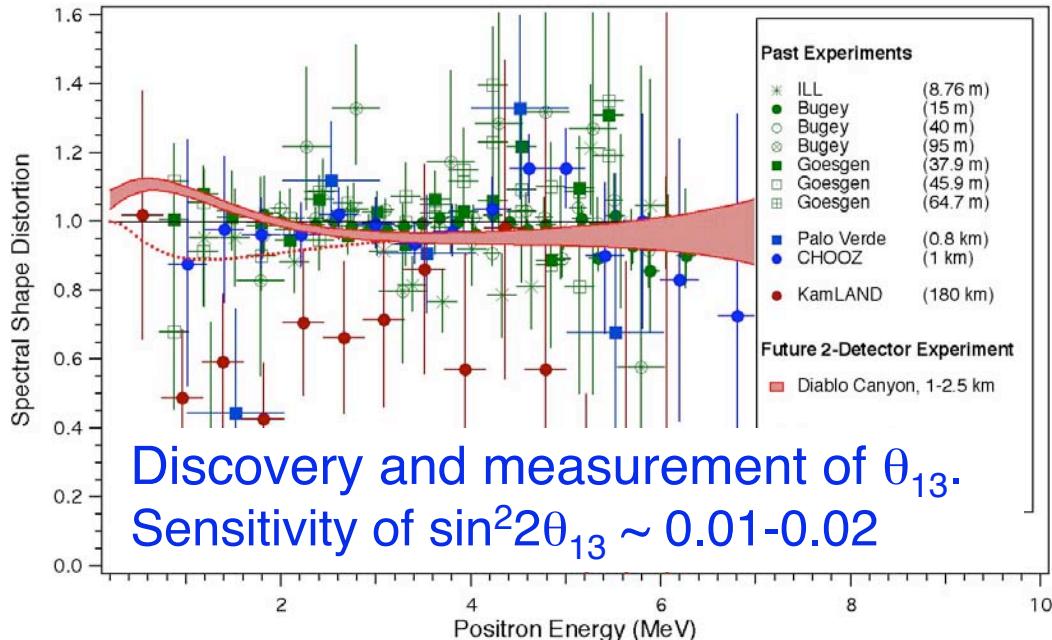
Total Systematics $\sigma_{\text{syst}} \sim 1-1.5\%$

Reactor Experiments & Off-Axis Experiments

Combining the Results of Future Reactor and Accelerator Experiments



Summary: Scientific Goals



May help distinguish mass hierarchy and constrain CP (from a combination with accelerator exp.)

