Measuring θ $_{13}$ with Reactors

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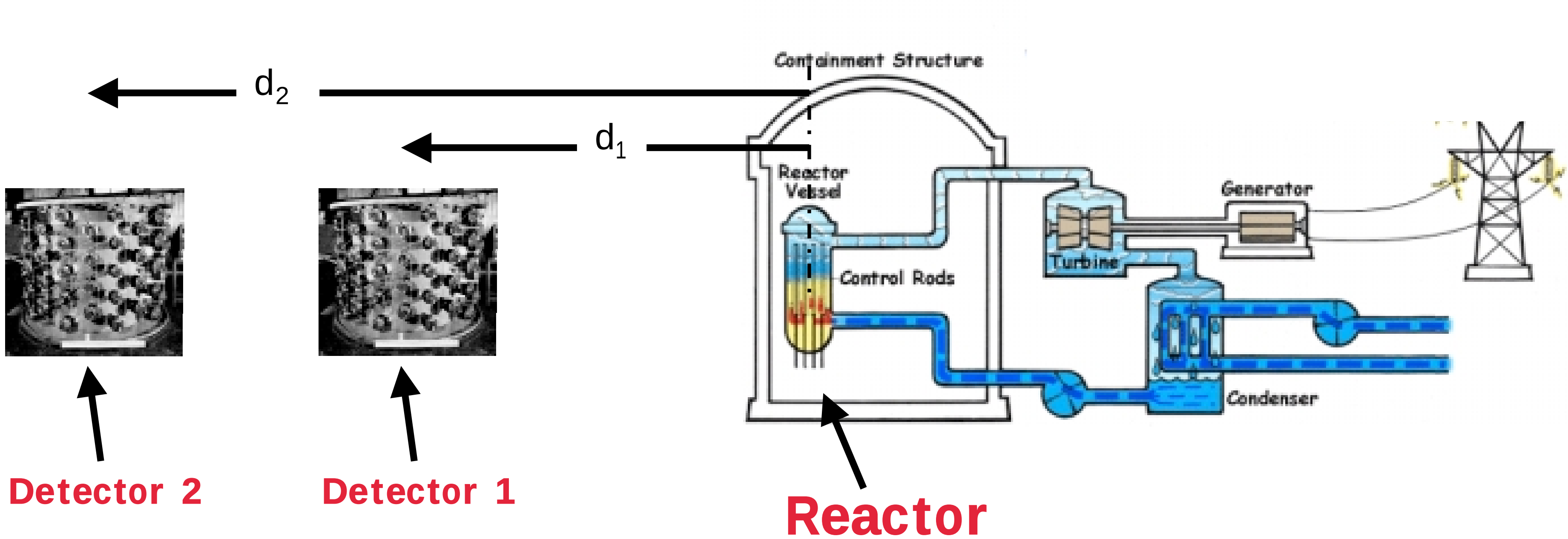
HEPAP July 24, 2003

Bethesda



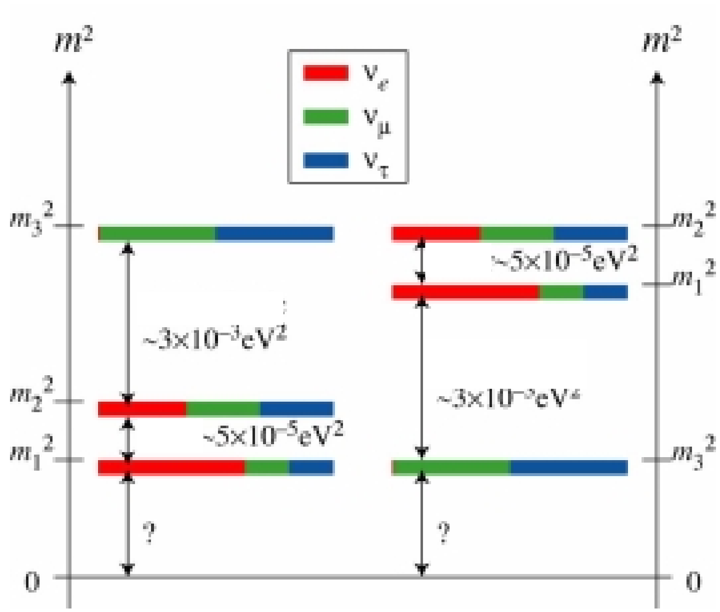
MNSP Matrix

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

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

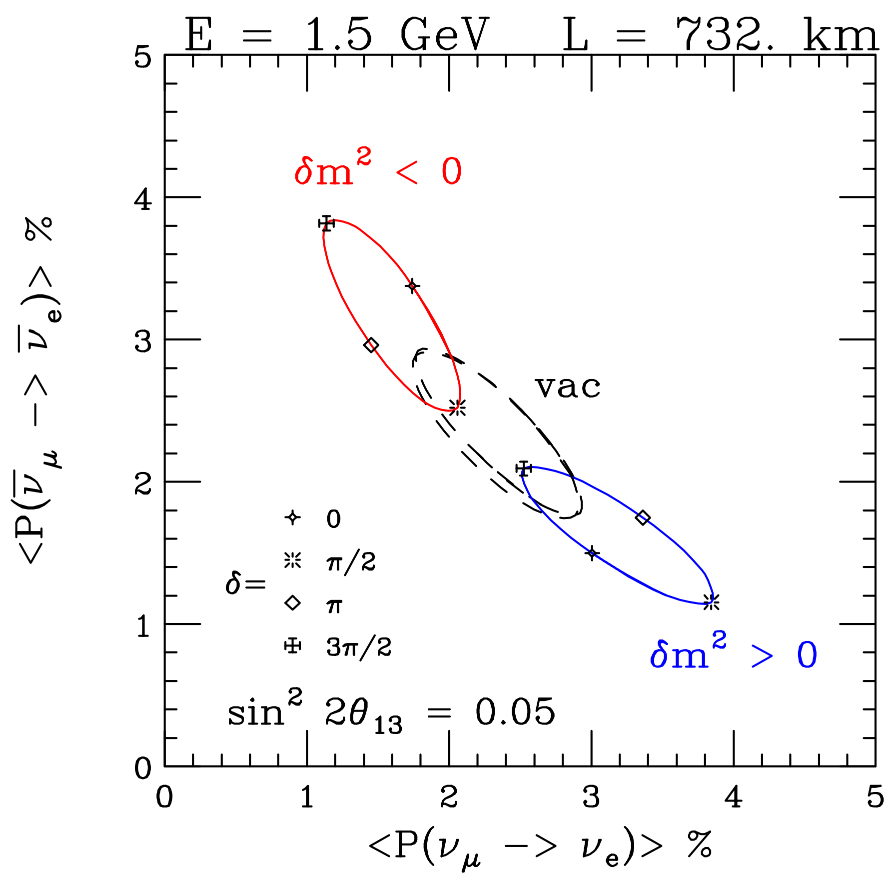
$\theta_{12} \sim 30°$ $\tan^2\theta_{13} < 0.03$ at 90% CL $\theta_{23} \sim 45°$

Mass Hierarchy



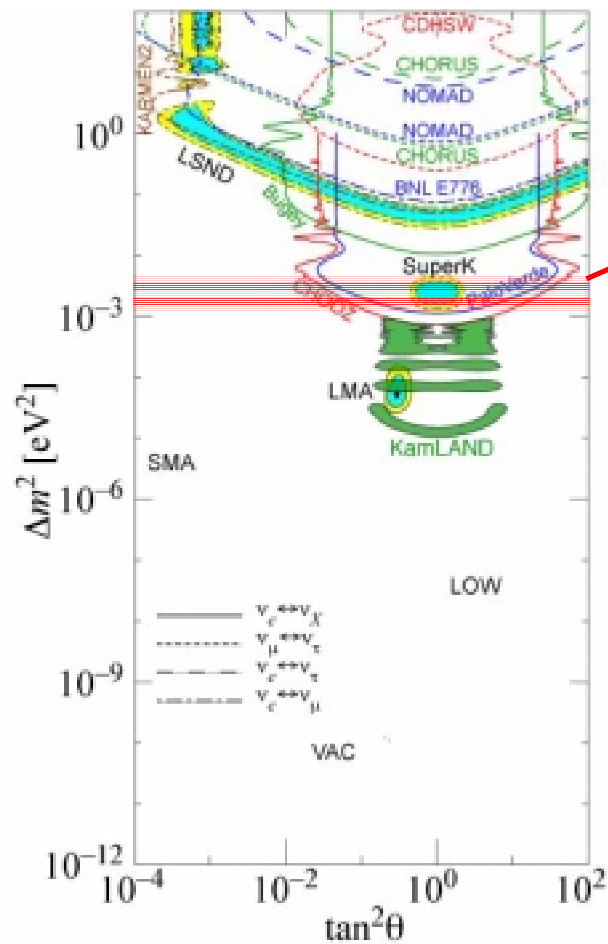
Figuring out CP for leptons

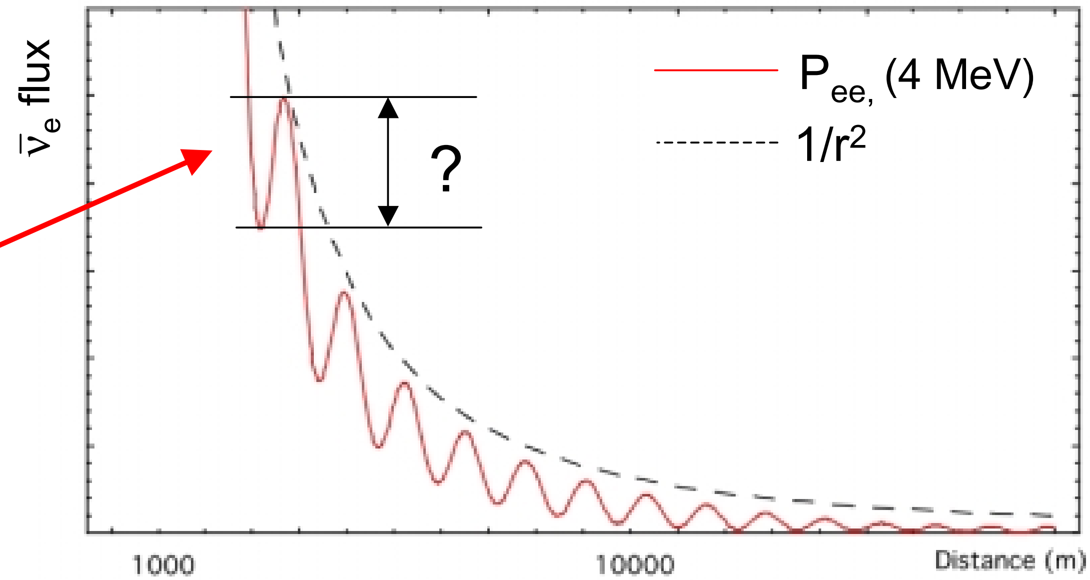
$$P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e) = -16\, s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$



Minakata and Nunokawa, hep-ph/0108085

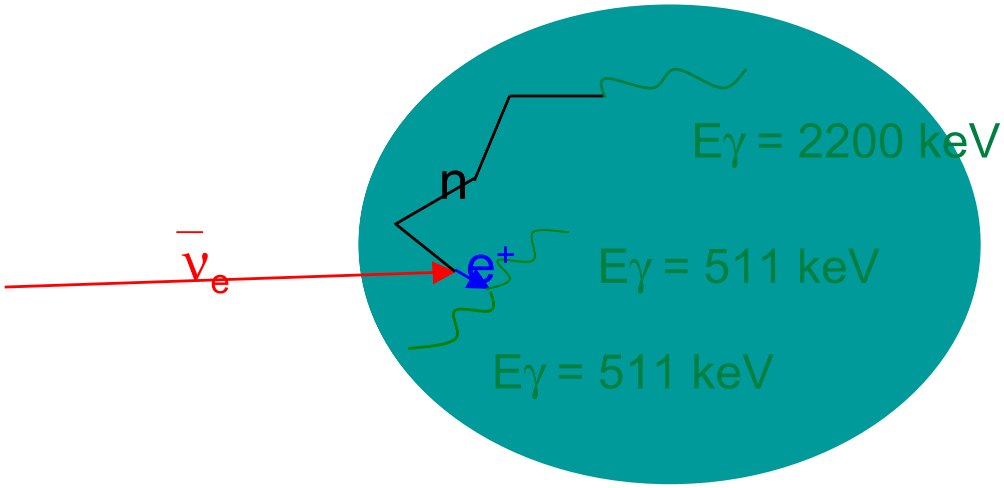
The Basic Idea





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

First Direct Detection of the Neutrino



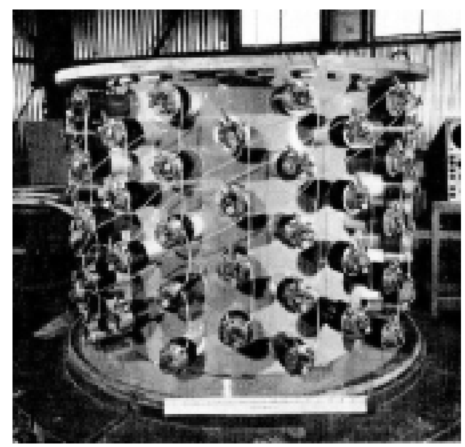
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$\tau \approx 210\ \mu s$$

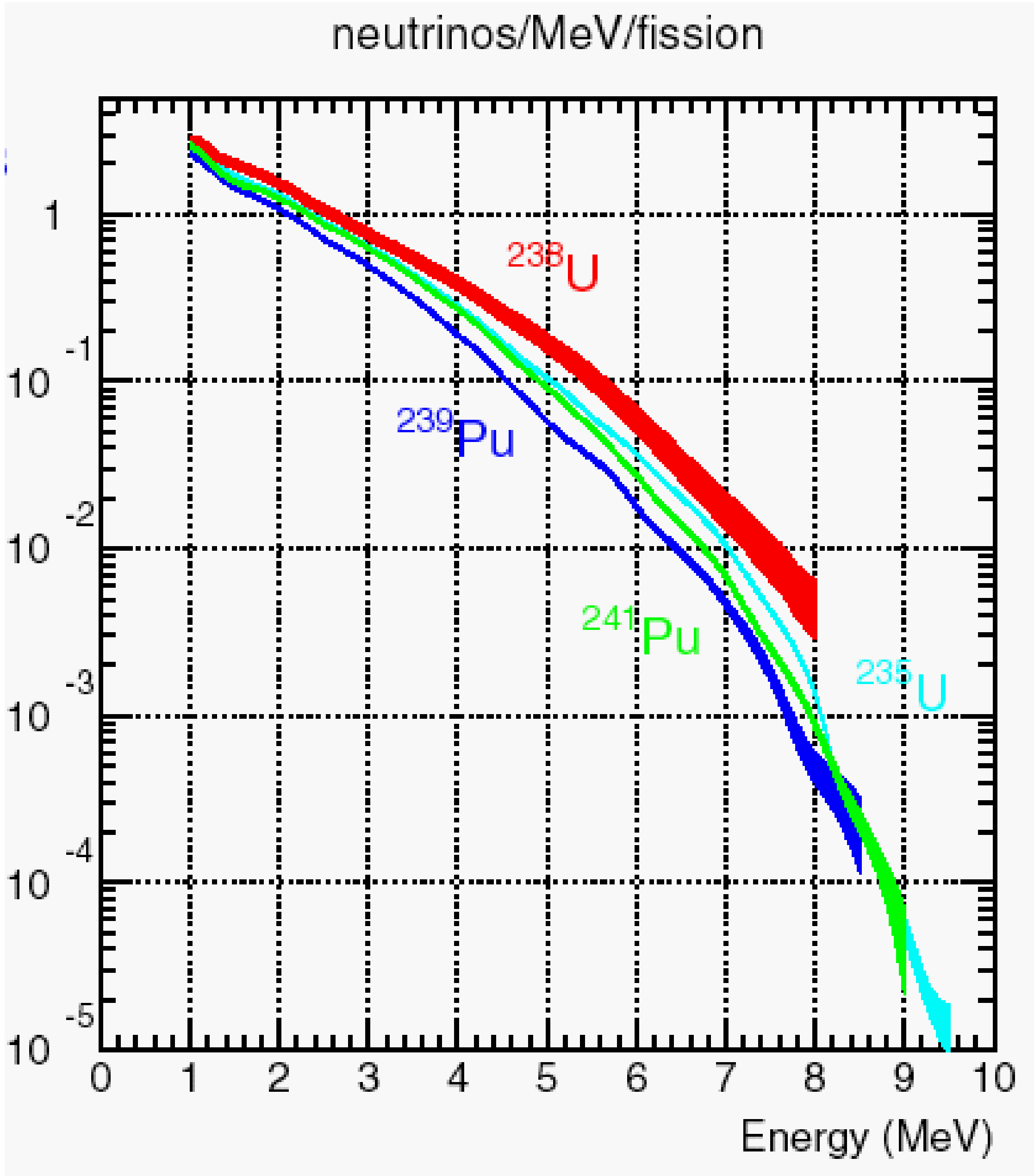
$$n + p \rightarrow d + \gamma(2.2\ MeV)$$

$$E_{prompt} \cong E_{\nu} - \overline{E}_n - 0.8\ MeV$$

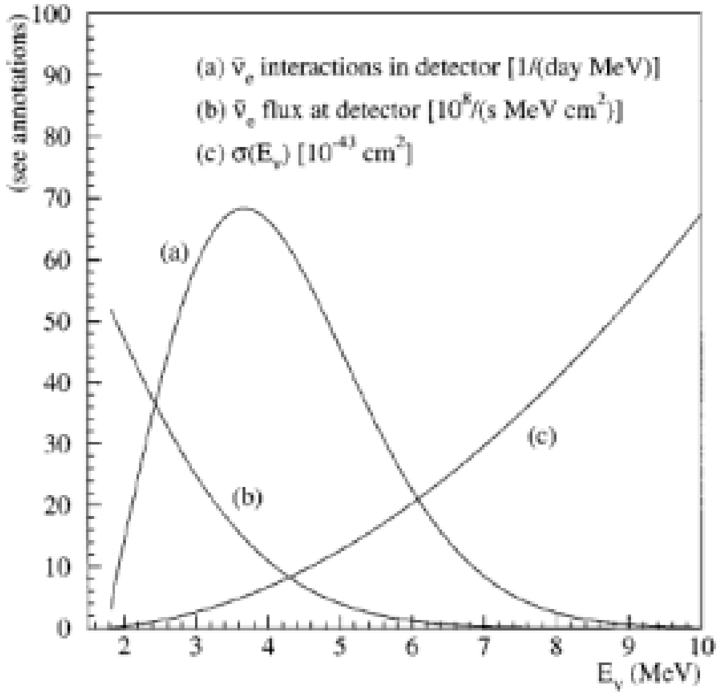
Reines and Cowan 1956



Neutrino Spectra from Principal Reactor Isotopes



Inverse Beta Decay Cross Section and Spectrum



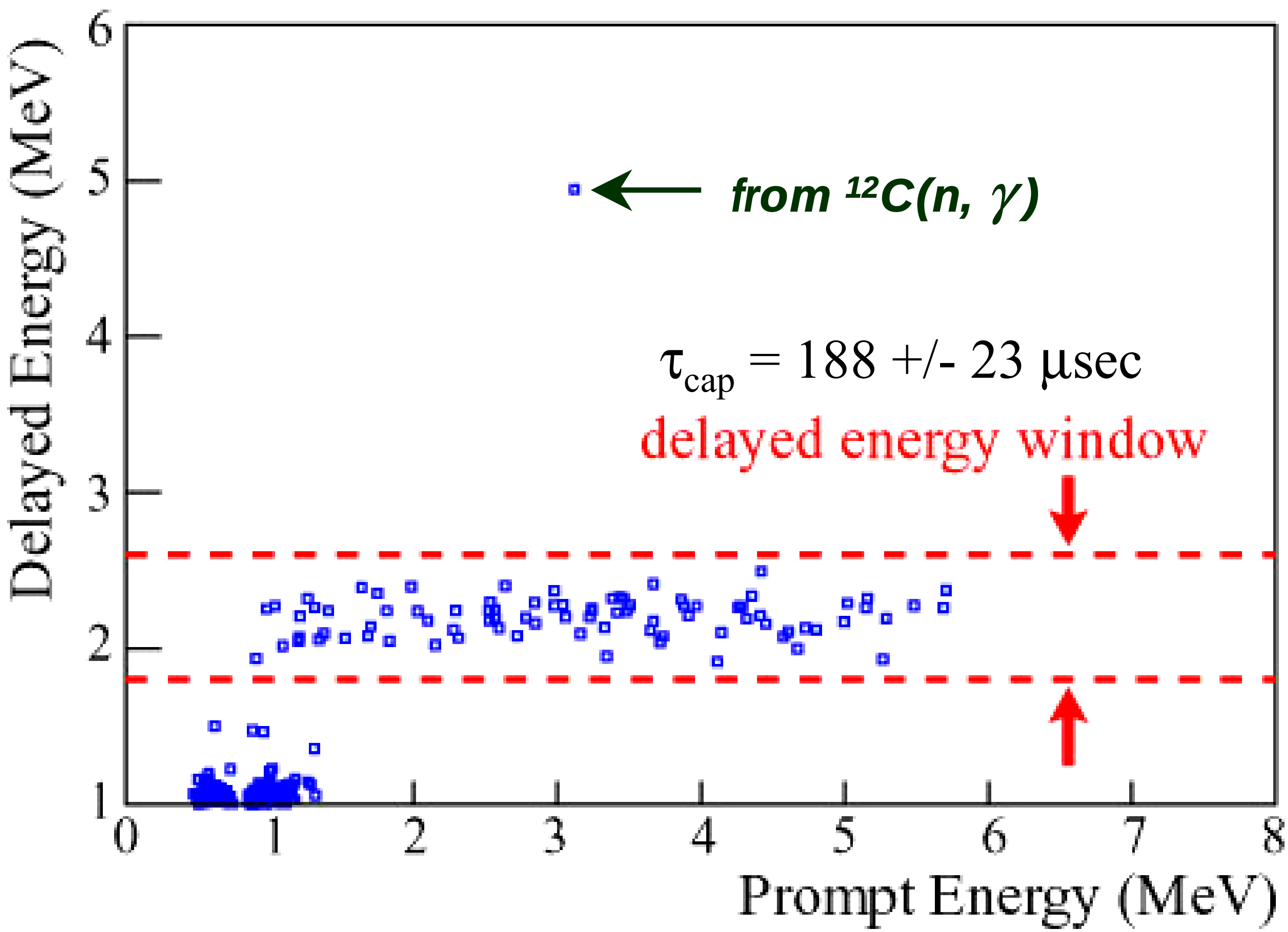
$$\sigma_{\text{tot}}^{(0)} = \sigma_0 (f^2 + 3g^2) E_e^{(0)} p_e^{(0)}$$

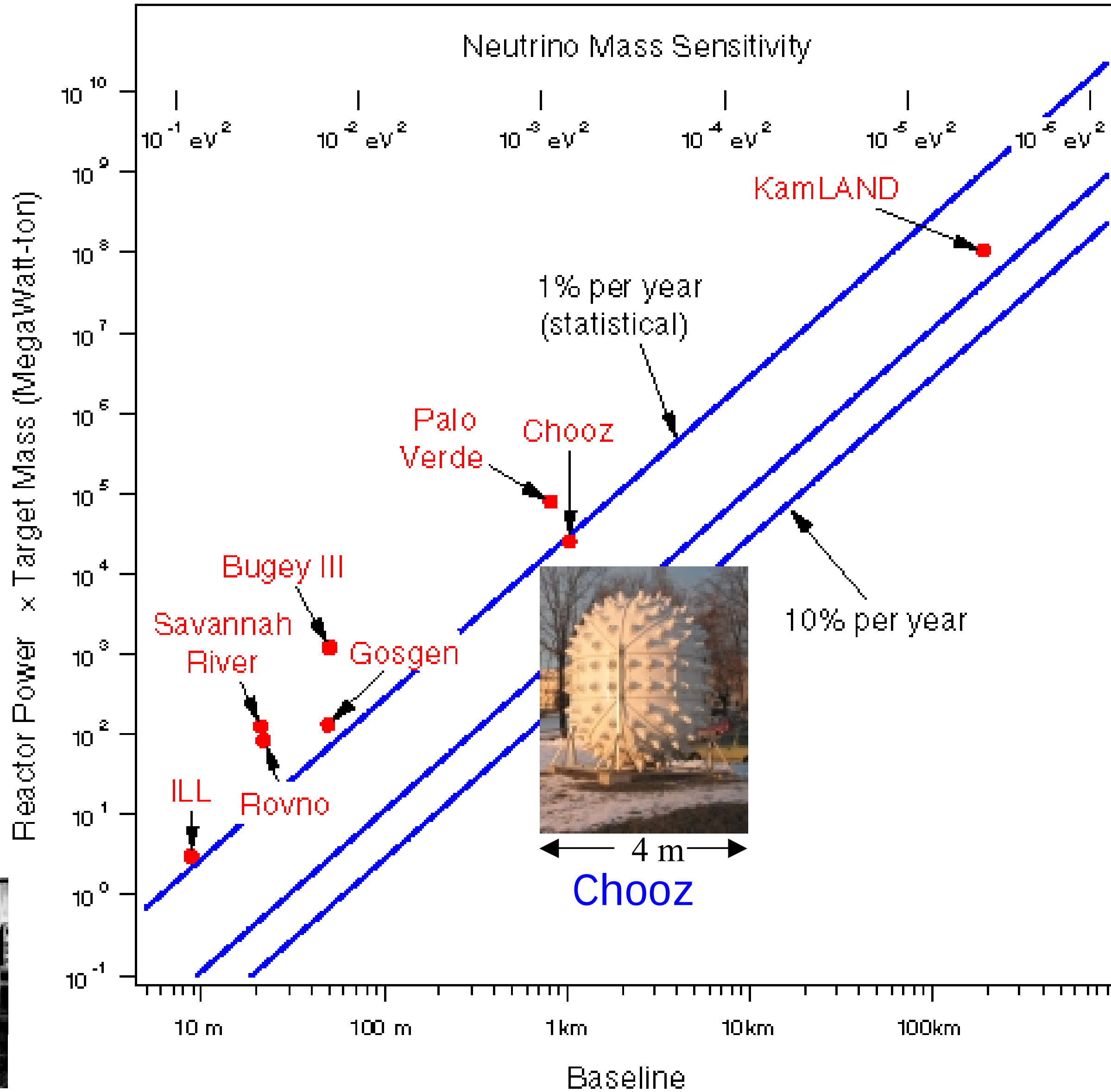
$$= 0.0952 \left(\frac{E_e^{(0)} p_e^{(0)}}{1 \text{ MeV}^2} \right) \times 10^{-42} \text{ cm}^2$$

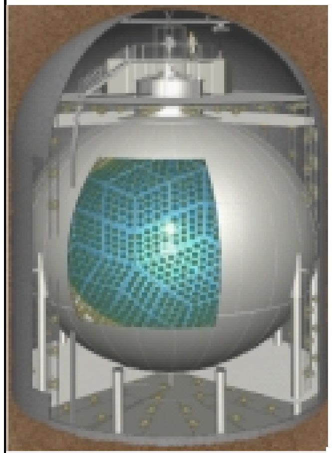
$$\sigma_0 = \frac{G_F^2 \cos^2 \theta_C}{\pi} (1 + \Delta_{inner}^R)$$

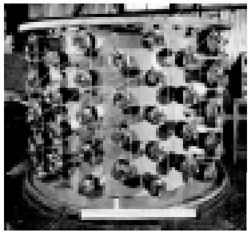
$$\sigma_{\text{tot}}^{(0)} = \frac{2\pi^2 / m_e^5}{f_{p.s.}^R \tau_n} E_e^{(0)} p_e^{(0)}$$

Inverse Beta Decay Signal from KamLAND



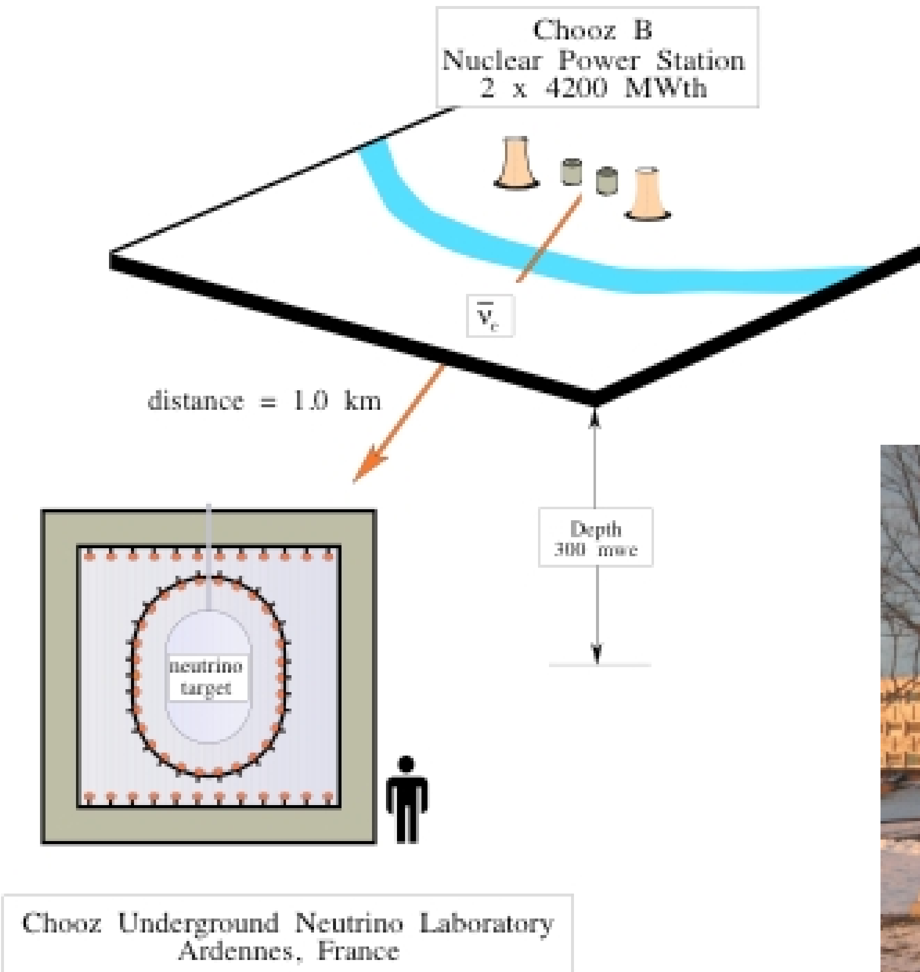




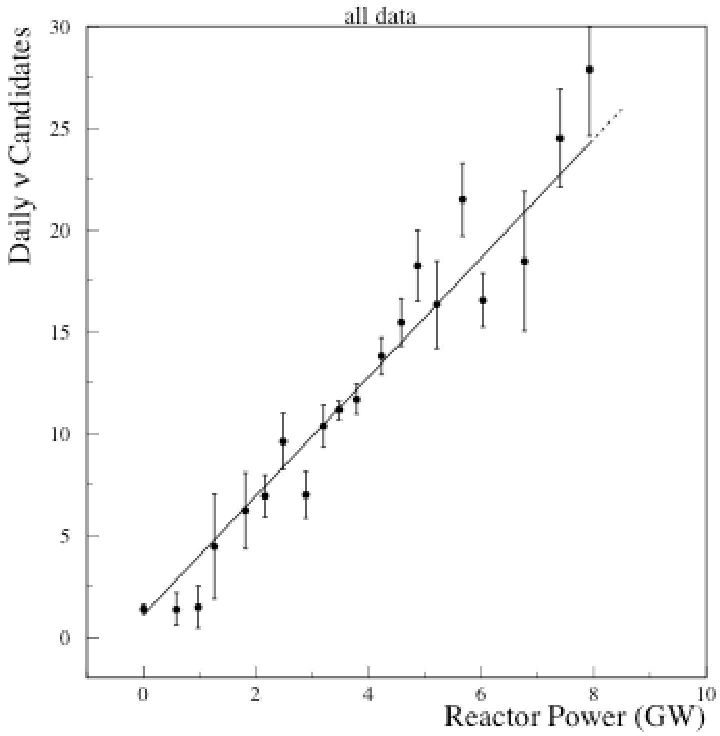


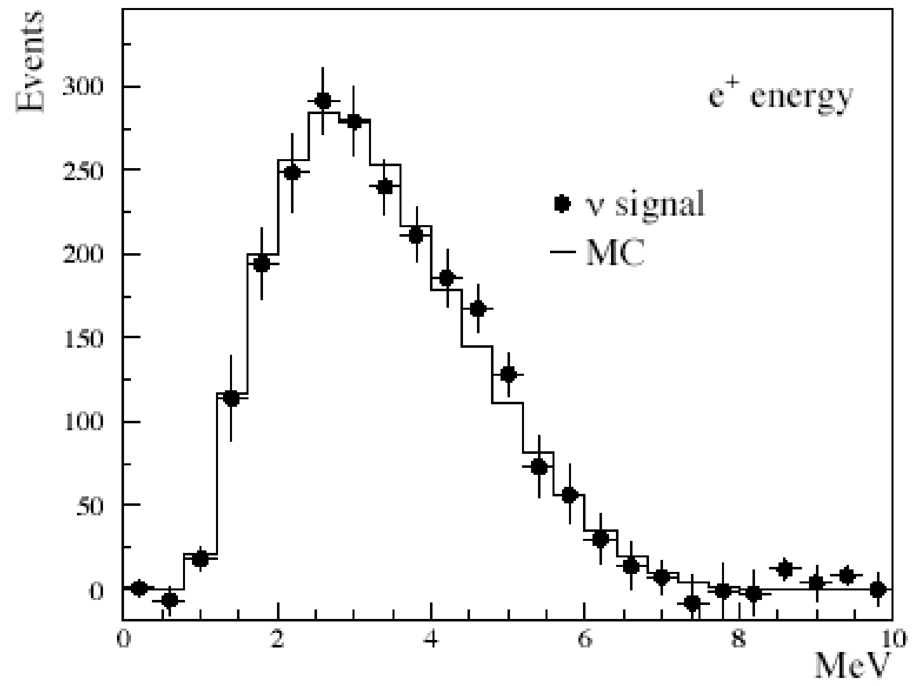
Long Baseline Reactor Neutrino Experiments

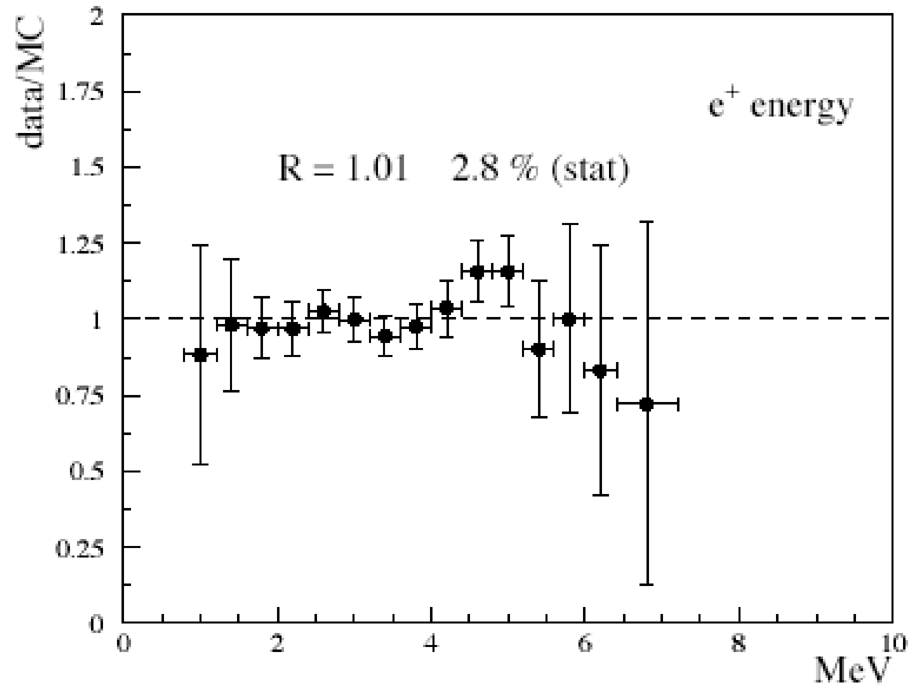
CHOOZ


Chooz B
Nuclear Power Station
2 x 4200 MWth
$\bar{\nu}_e$
distance = 1.0 km
Depth
300 mwe
neutrino
target
Chooz Underground Neutrino Laboratory
Ardennes, France

CHOOZ

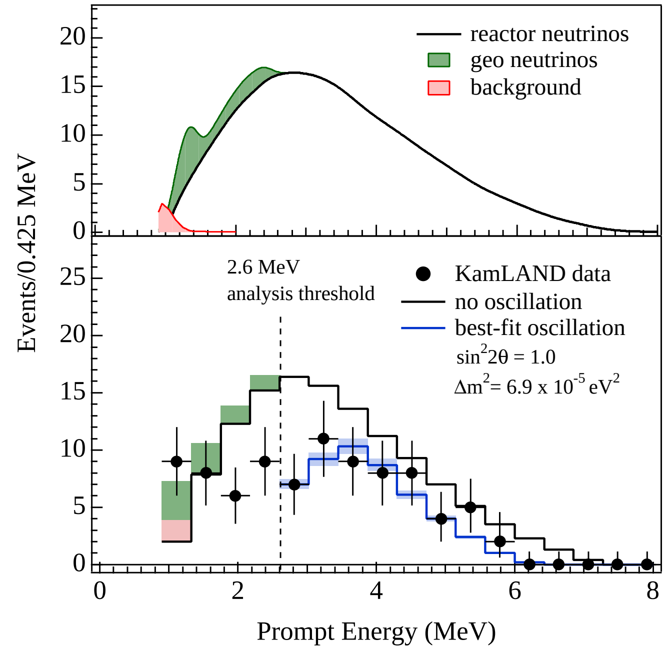

all data
Daily ν Candidates
Reactor Power (GW)

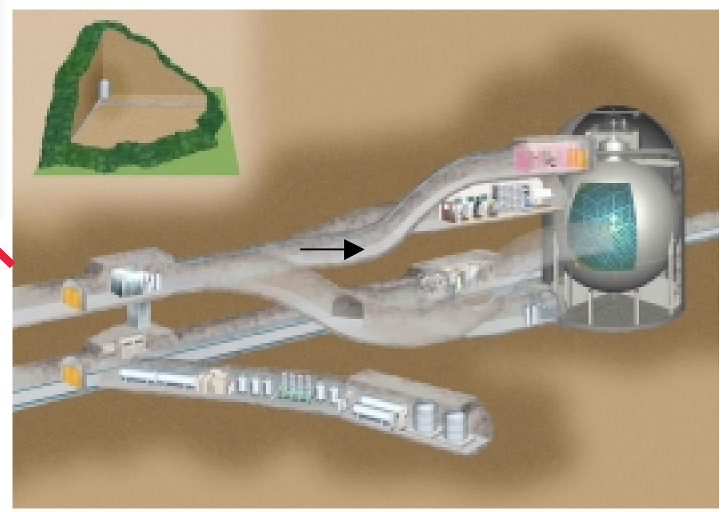

Events
e+ energy
ν signal
MC
MeV

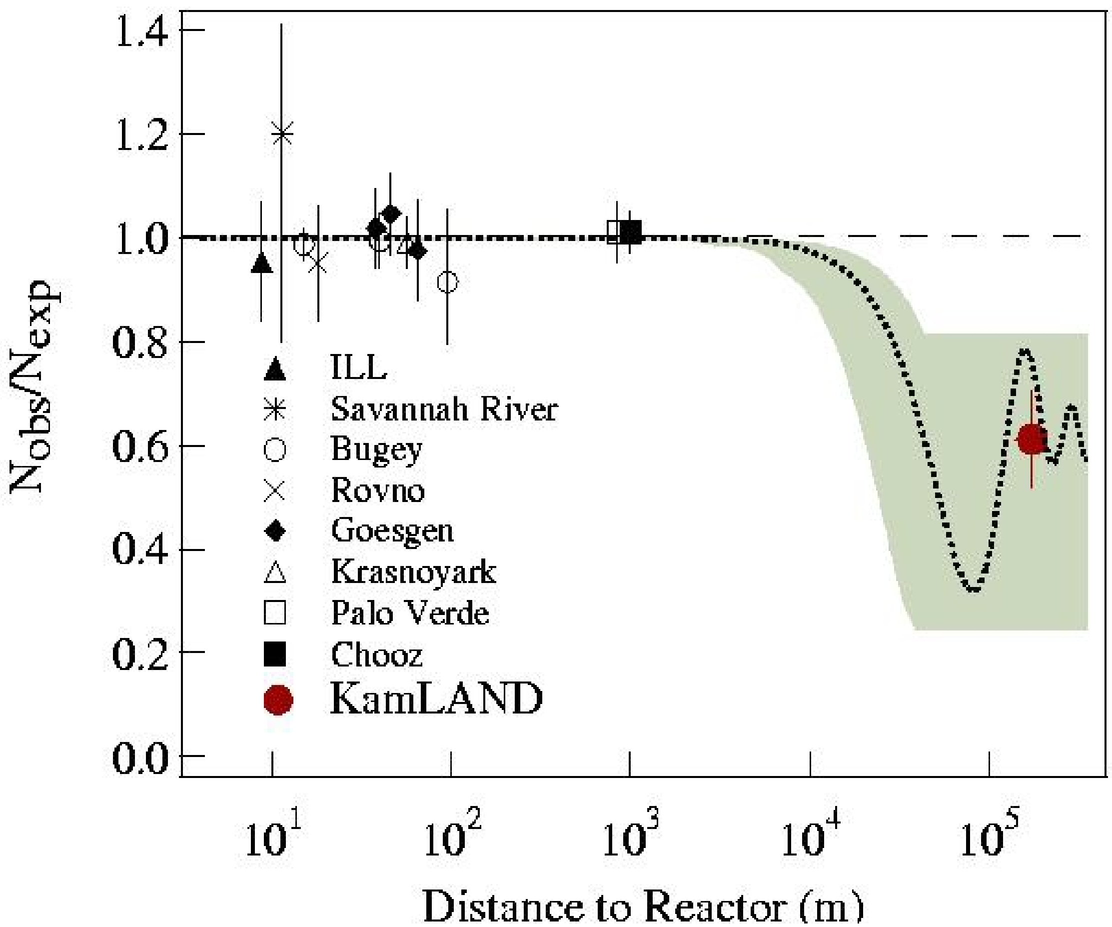

data/MC
e+ energy
R = 1.01 2.8 % (stat)
MeV

KamLAND

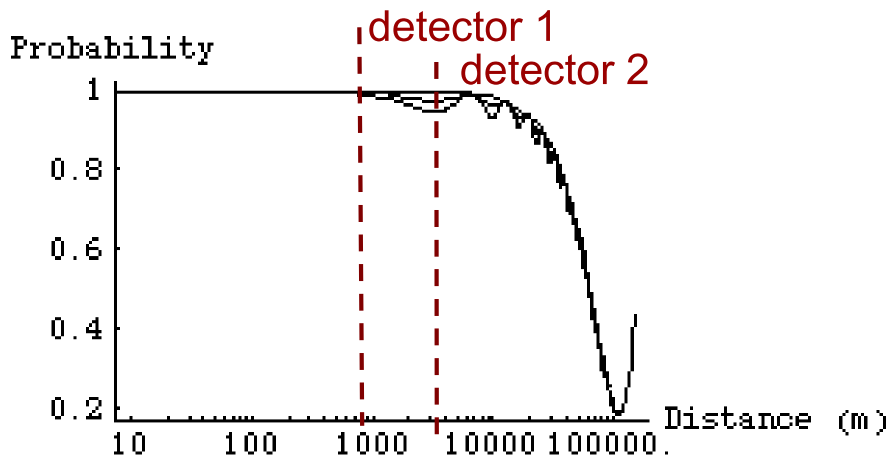

Russia
China
South Korea
Primorskaya
Tomari
Onagawa
Kashiwazaki Kariwa
Fukushima Daiichi
Fukushima Daini
Shika
Tsuruga
Fugen
Mihama
Tokai
Monju
Hamaoka
Ohi
Takahama
Shimane
Genkai
Ikata
Sendai
Ulchin
Wolsong
Kori
KamLAND


reactor neutrinos
geo neutrinos
background
Events/0.425 MeV
2.6 MeV
analysis threshold
KamLAND data
no oscillation
best-fit oscillation
sin²2θ = 1.0
Δm² = 6.9 x 10⁻⁵ eV²
Prompt Energy (MeV)

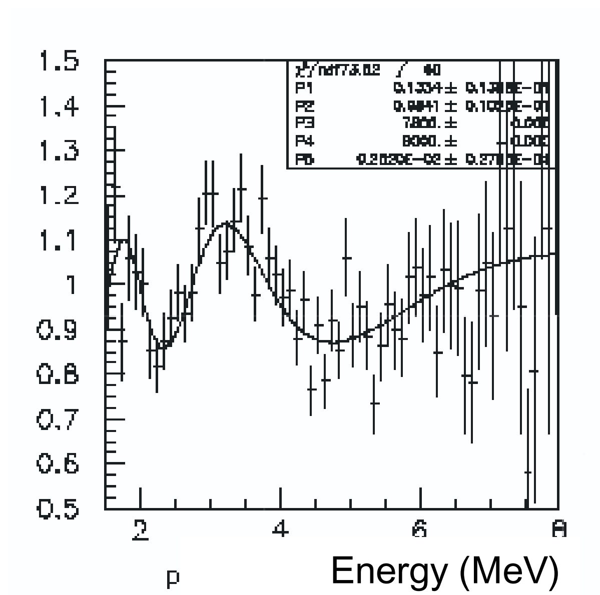



1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Nobs/Nexp
ILL
Savannah River
Bugey
Rovno
Goesgen
Krasnoyark
Palo Verde
Chooz
KamLAND
10^1
10^2
10^3
10^4
10^5
Distance to Reactor (m)

Two Detector Reactor Experiment



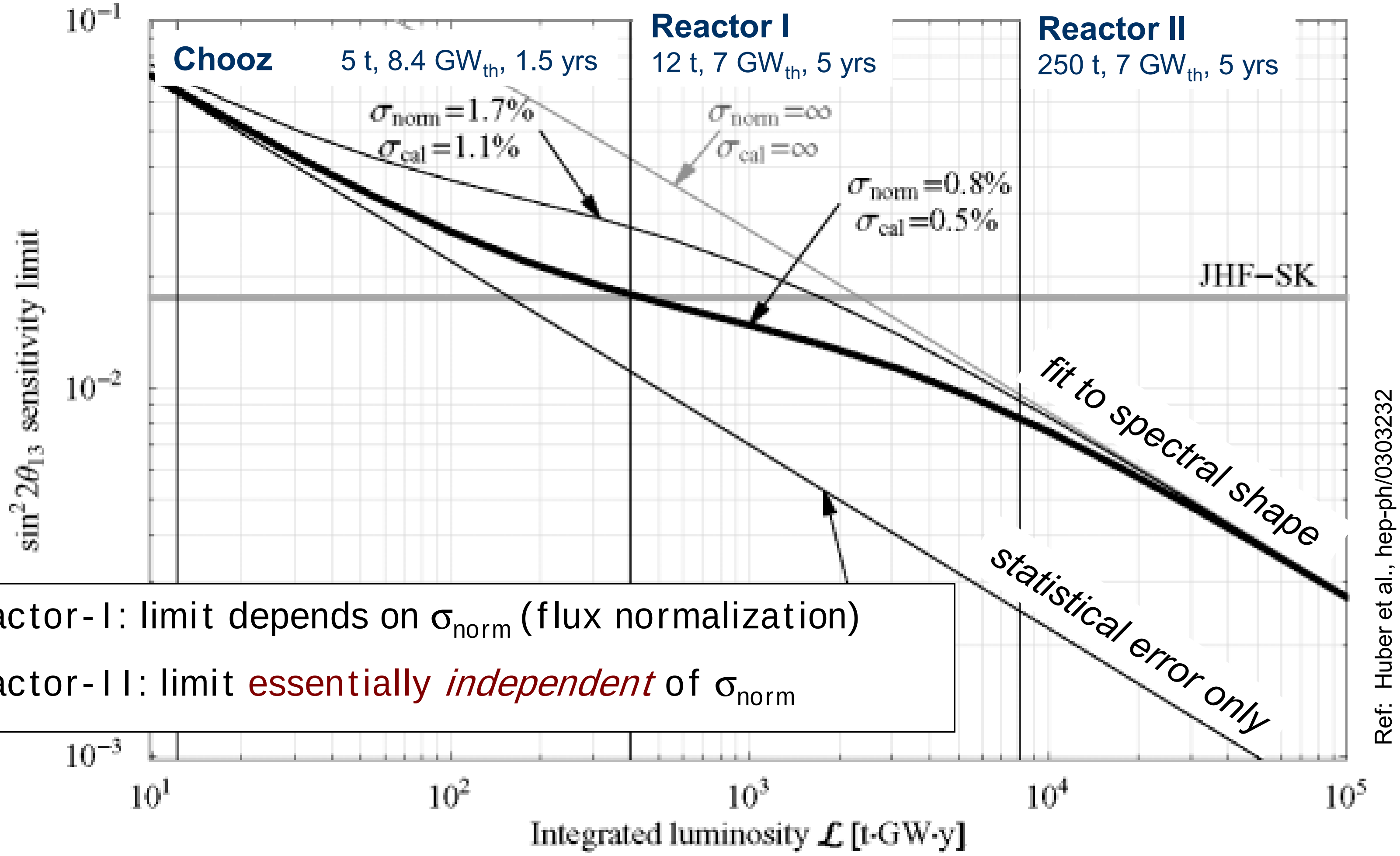
Spectral Ratio



Sensitivity to $\sin^2 2\theta_{13}$ at 90% CL

σ_{cal} relative near / far energy calibration

σ_{norm} relative near / far flux normalization



Reactor-I: limit depends on σ_{norm} (flux normalization)

Reactor-II: limit essentially *independent* of σ_{norm}

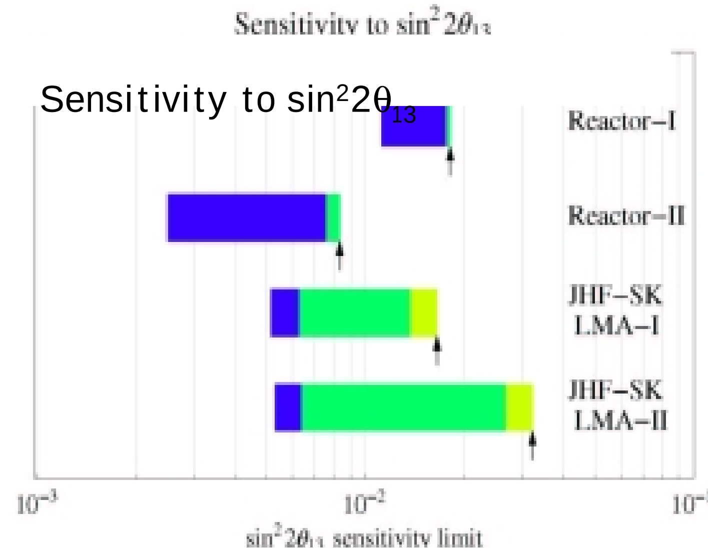
We need accelerators and reactors--Reactors first!

Reactor Neutrino Measurement of θ_{13}

- No matter effect
- Correlations are small, no degeneracies
- Independent of solar parameters θ_{12}, Δm_{21}^2

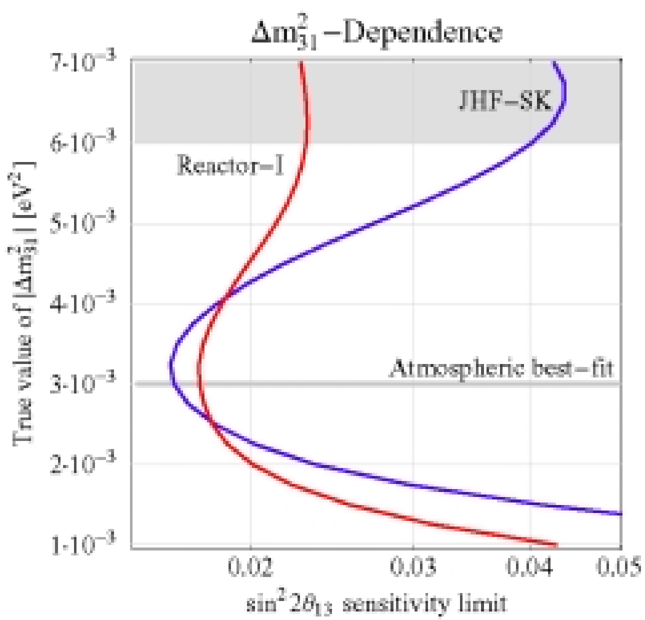
- $\sin^2 2\theta_{13} < 0.01$-$0.02$ @ 90 CL
  within reach of reactor θ_{13} experiments
- Knowing θ_{13} is useful for the "intelligent design" of a CP experiments.

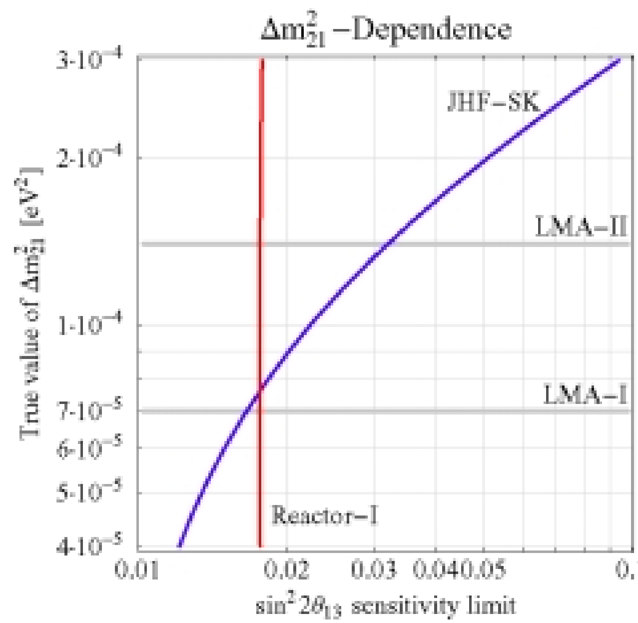
Sensitivity to $\sin^2 2\theta_{13}$

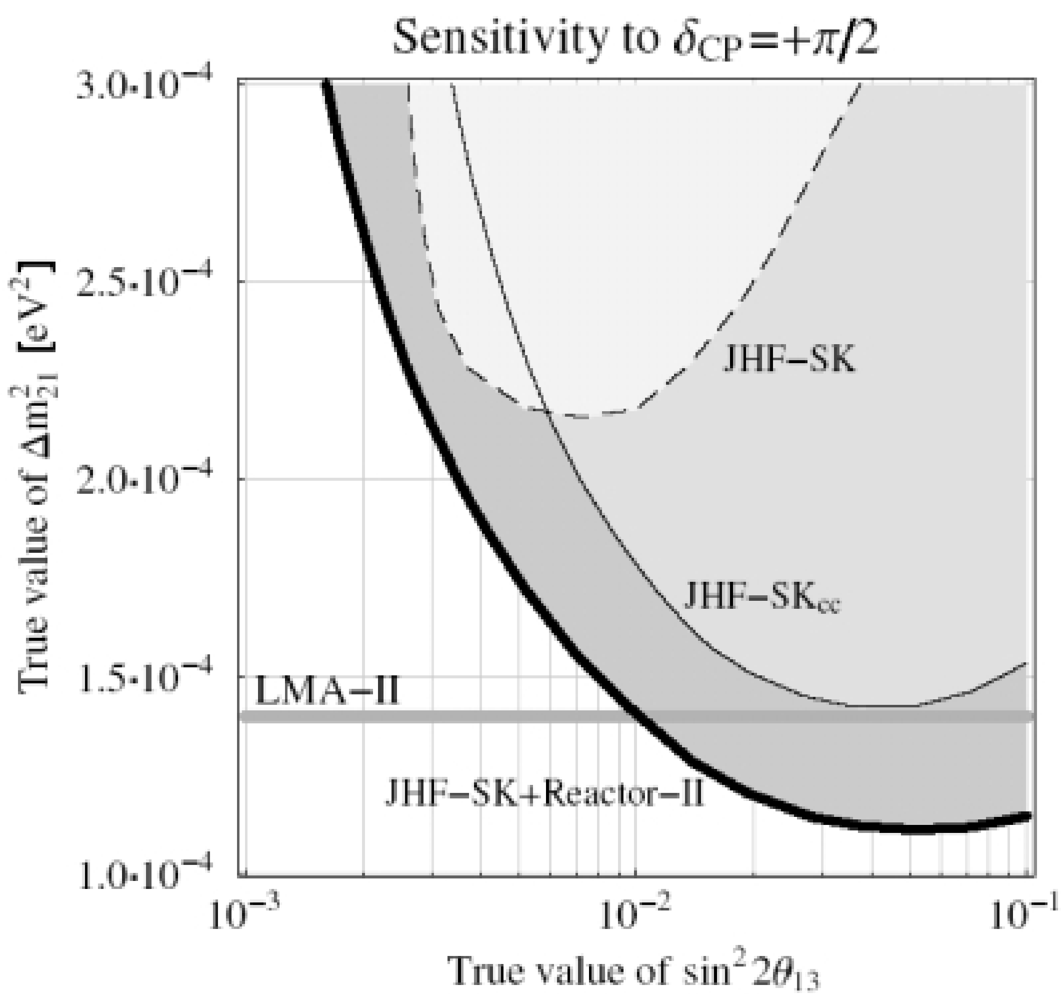


10^{-3} 10^{-2} 10^{-1}

Ref: Huber et al., hep-ph/0303232



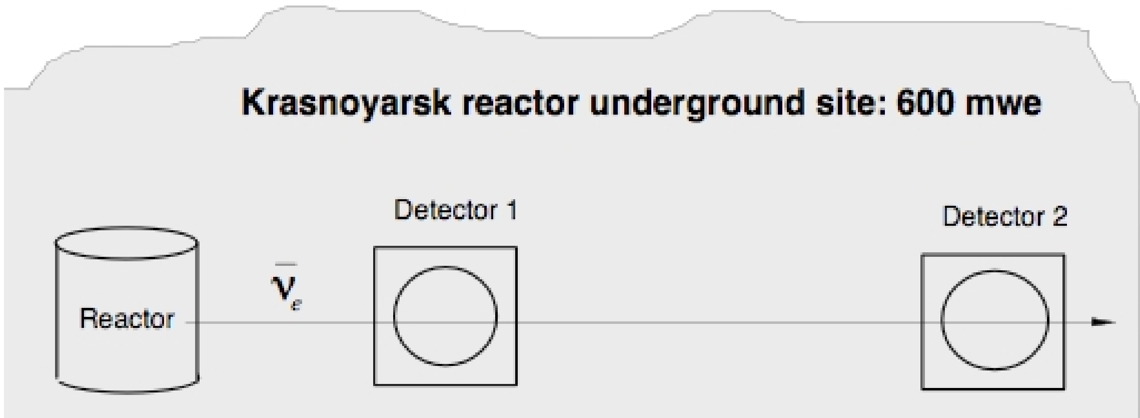




Huber et al hep-ph/03030232

$$
\begin{aligned}
P_{\mu e} \simeq\ & \sin^2 2\theta_{13}\, \sin^2\theta_{23} \sin^2\Delta_{31} \\
\mp\ & \alpha\, \sin 2\theta_{13}\, \sin\delta_{\rm CP}\, \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3\Delta_{31} \\
-\ & \alpha\, \sin 2\theta_{13}\, \cos\delta_{\rm CP}\, \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta_{31} \sin^2\Delta_{31} \\
+\ & \alpha^2\, \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2\Delta_{31},
\end{aligned}
$$

Kr2Det: Reactor θ_{13} Experiment at Krasnoyarsk

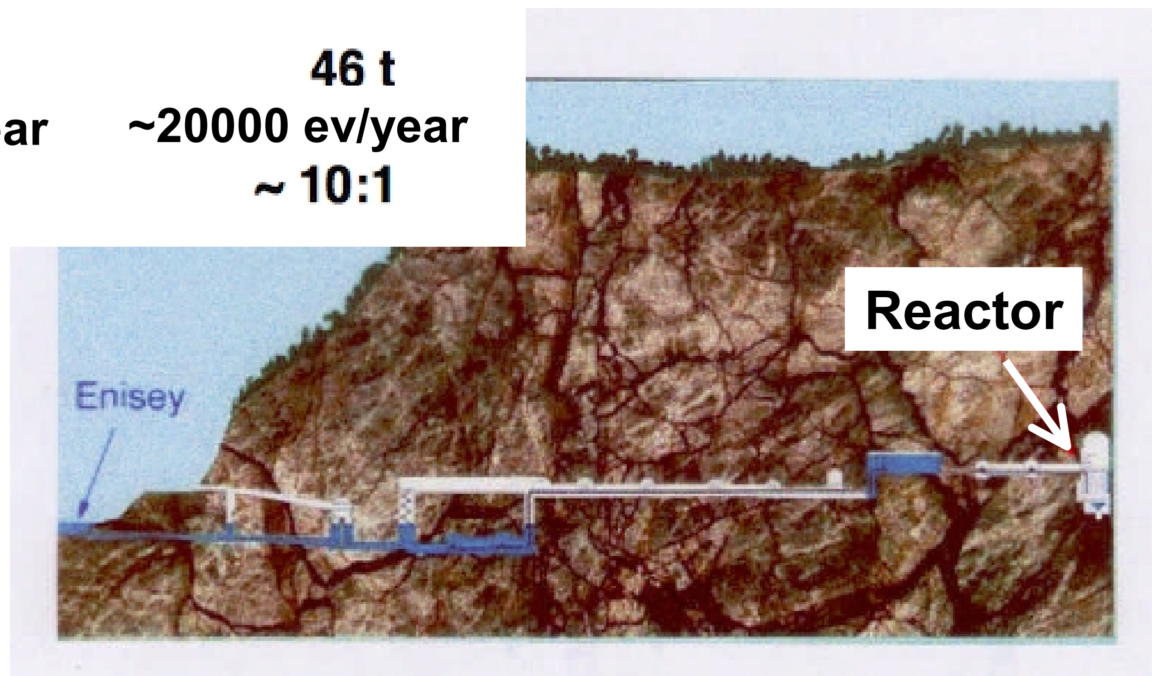


	115 m	1000 m
Target:	**46 t**	**46 t**
Rate:	**~1.5 x 10^6 ev/year**	**~20000 ev/year**
S:B	**>>1**	**~ 10:1**

Features

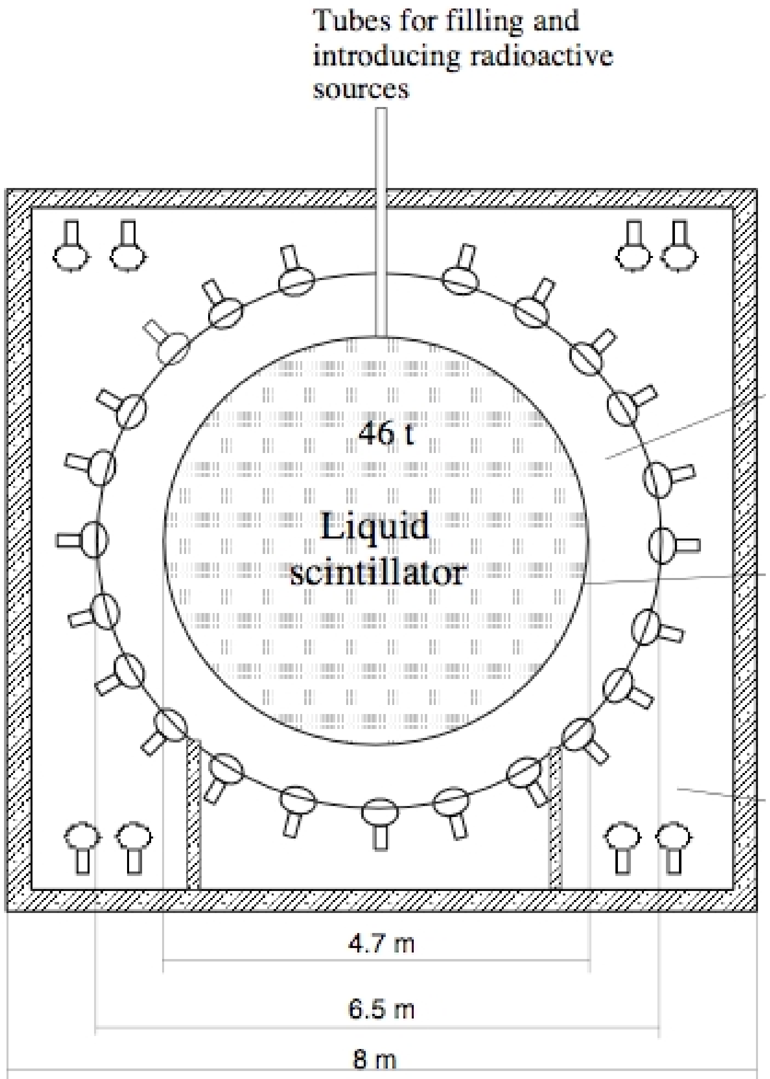
- underground reactor
- existing infrastructure

Detector locations constrained by existing infrastructure

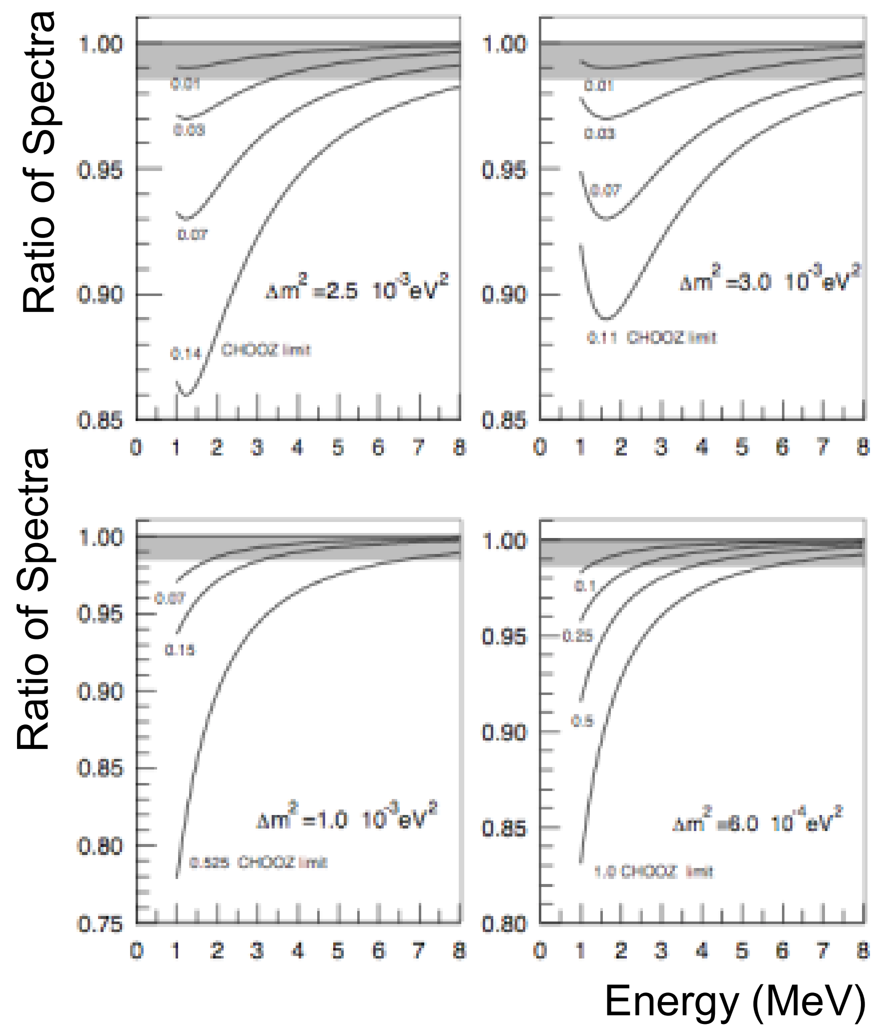


Ref: Marteyamov et al, hep-ex/0211070

***Kr2Det*: Reactor θ_{13} Experiment at Krasnoyarsk**



L_{near}= 115 m, L_{far}=1000 m, N_{far} = 16000/yr

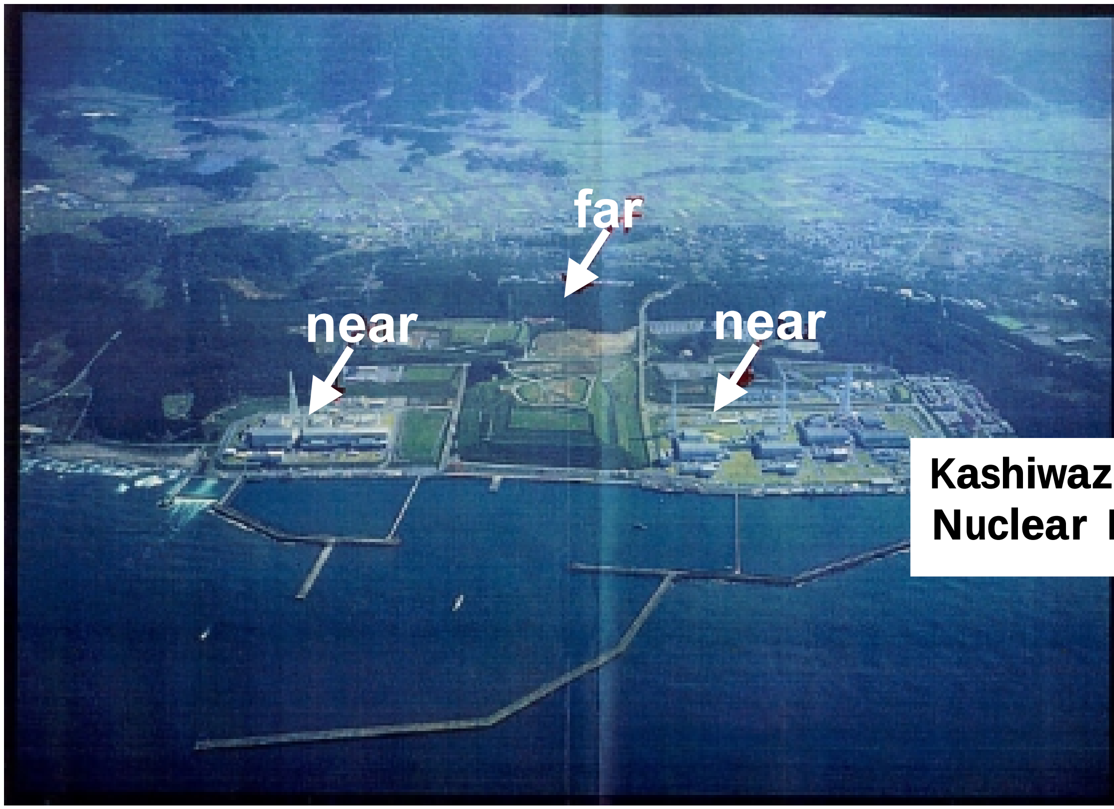


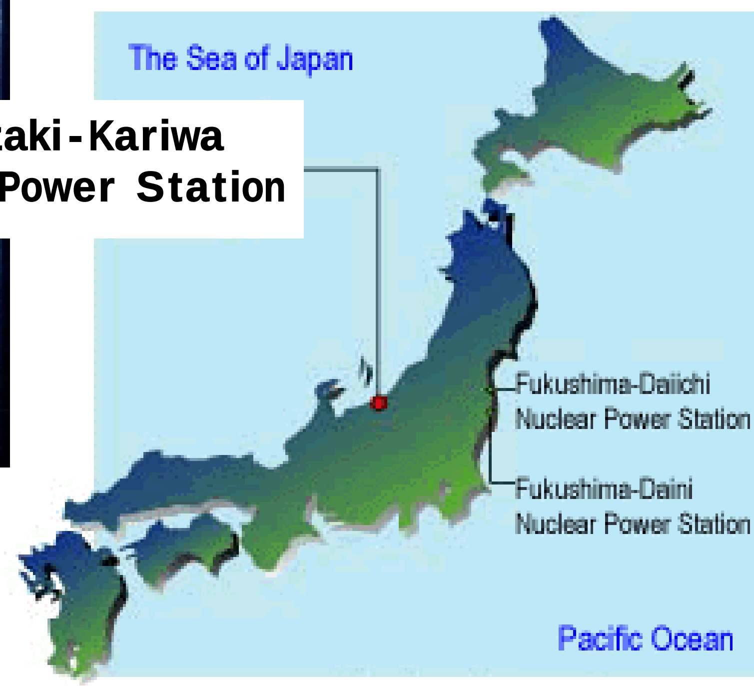
Ref: Marteyamov et al., hep-ex/0211070.

Proposal for Reactor θ_{13} Experiment in Japan

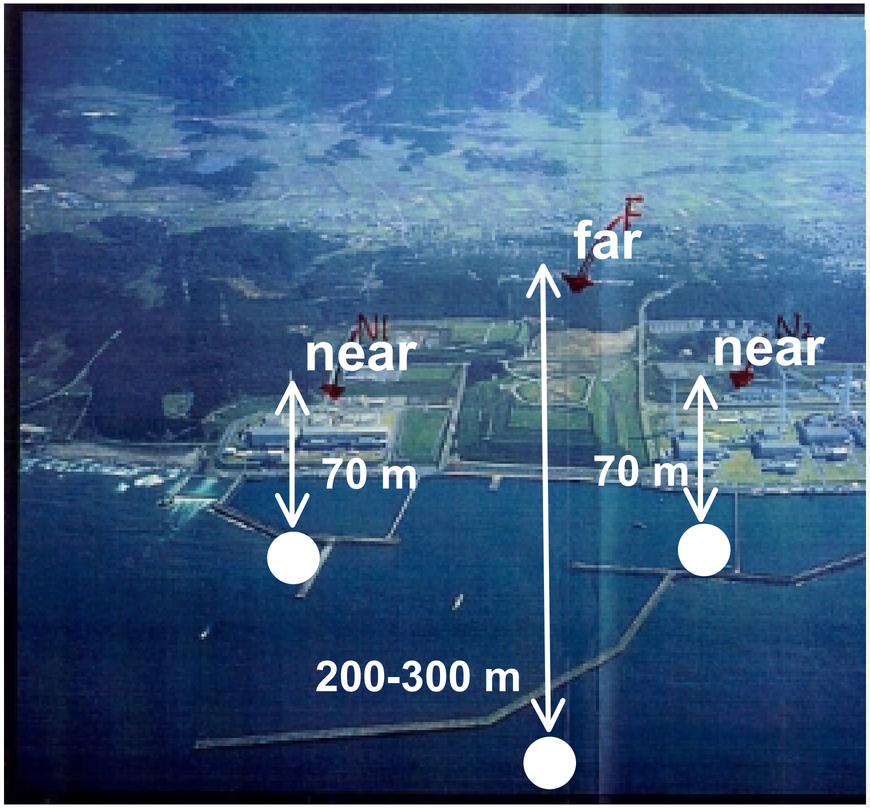
Kashiwazaki

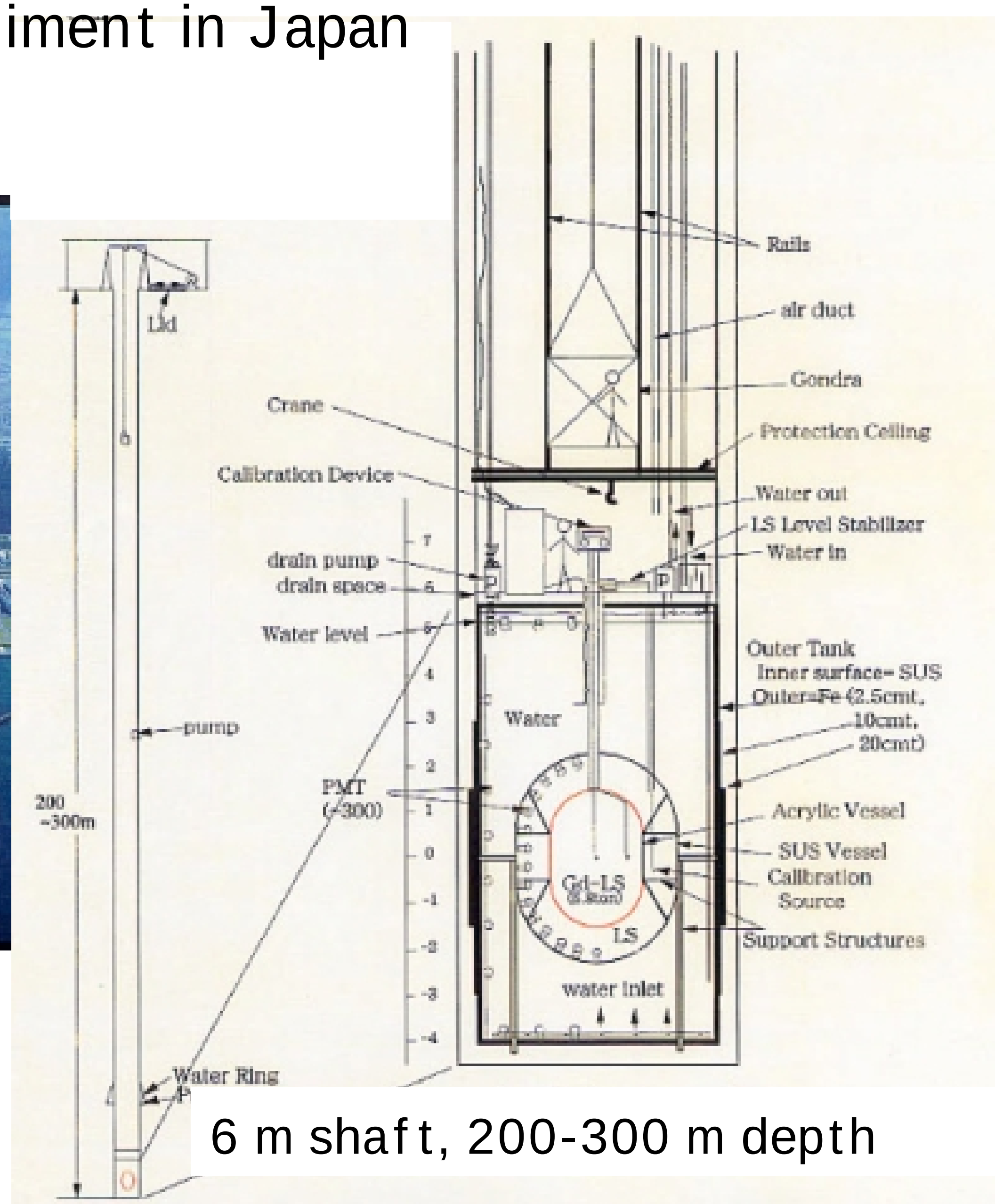
-7 nuclear power stations, World's most powerful reactors
- requires construction of underground shaft for detectors





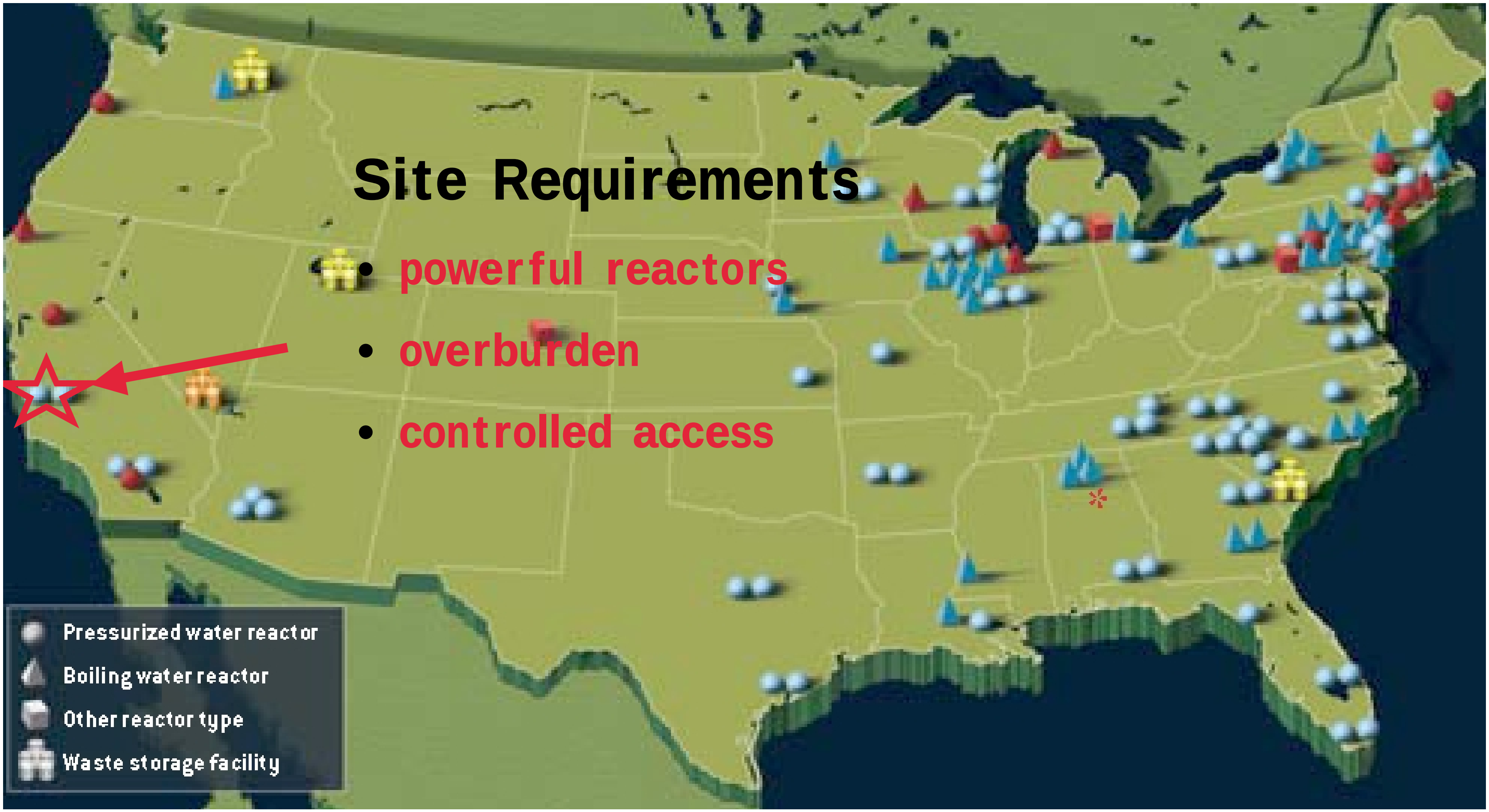
Kashiwazaki: Proposal for Reactor θ_{13} Experiment in Japan





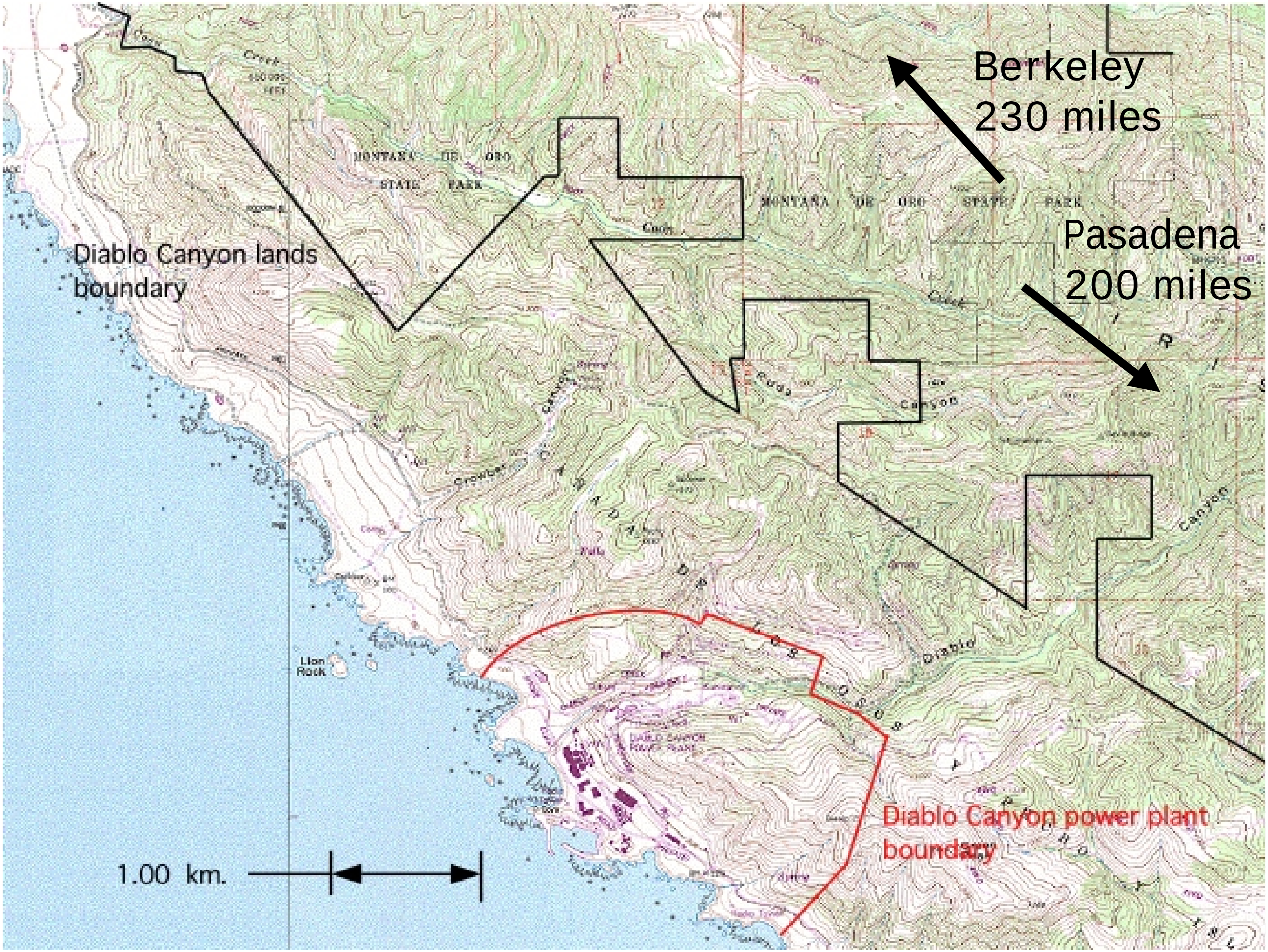
6 m shaft, 200-300 m depth

θ_{13} at a US nuclear power plant?



Site Requirements

- powerful reactors
- overburden
- controlled access



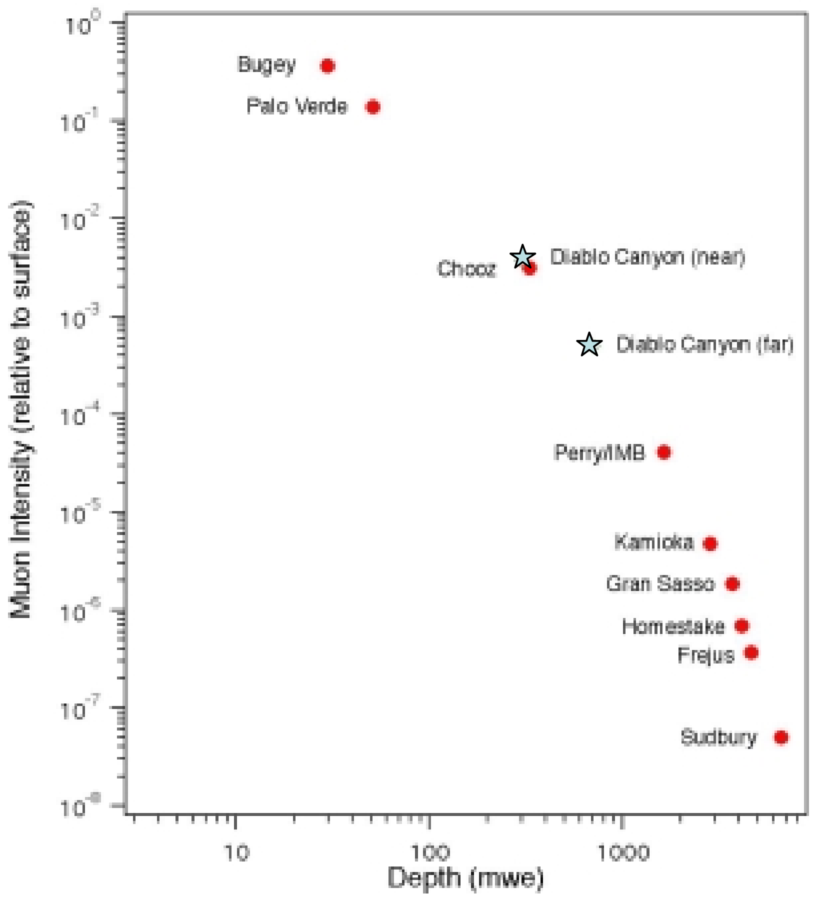
Berkeley
230 miles
Pasadena
200 miles
Diablo Canyon lands
boundary
MONTAÑA DE ORO
STATE PARK
MONTAÑA DE ORO STATE PARK
Lion
Rock
Diablo Canyon power plant
boundary
1.00 km.

Diablo Canyon Nuclear Power Plant

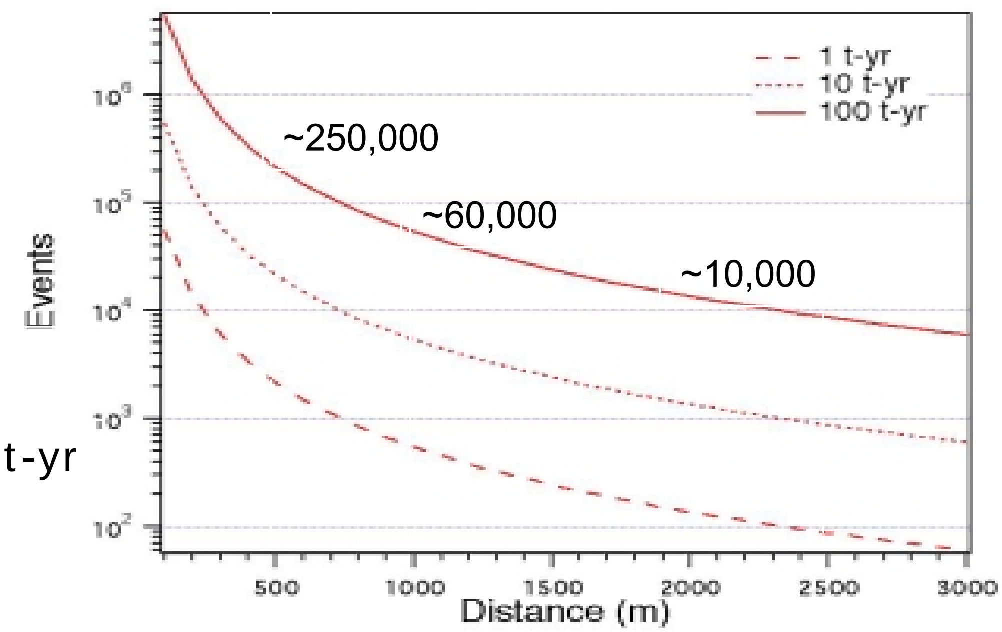
- ***Powerful:*** Two reactors (3.1+ 3.1 GW E_{th})
- ***Overburden:*** Horizontal tunnel could give 800 mwe shielding
- ***Infrastructure:*** Construction roads. Controlled access. Close to wineries.

Detector Concept

Requirements: Overburden and Large Detectors



Detector Event Rate/Year

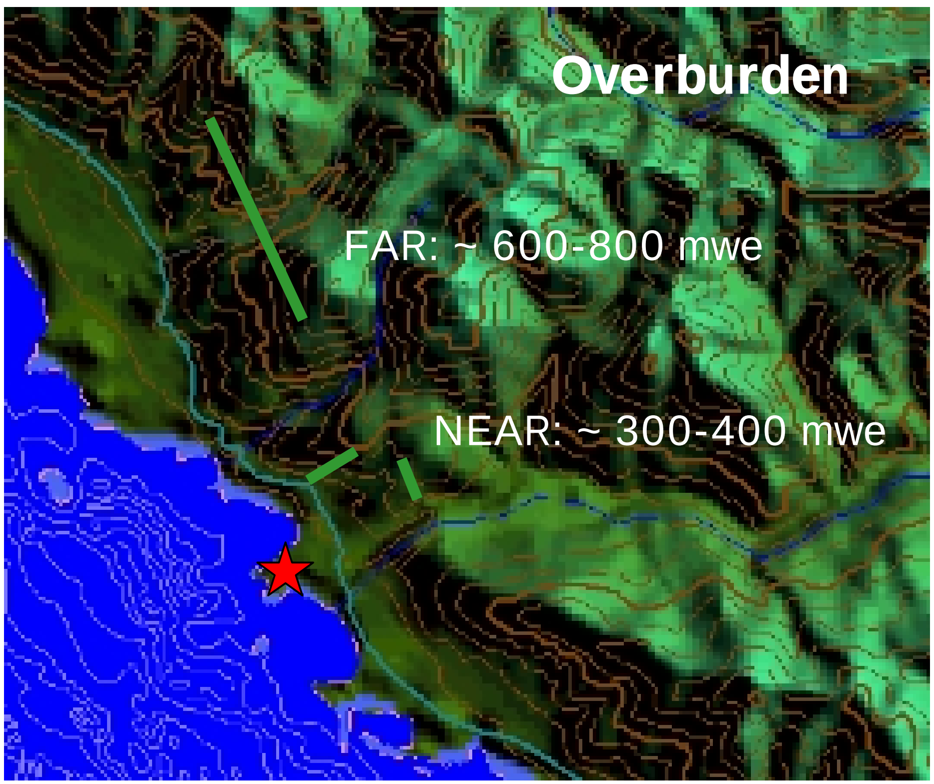


Statistical error: $\sigma_{stat} \sim 0.5\%$ for L = 300t-yr

Neutrino Detectors at Diablo Canyon

- 2 neutrino detectors, railroad-car size
- in tunnels at (variable) distance of

NEAR/FAR I:	0.5-1 km
FAR II:	1.5-3 km



Optimization

'far - far' L_1=6 km, L_2=7.8 km

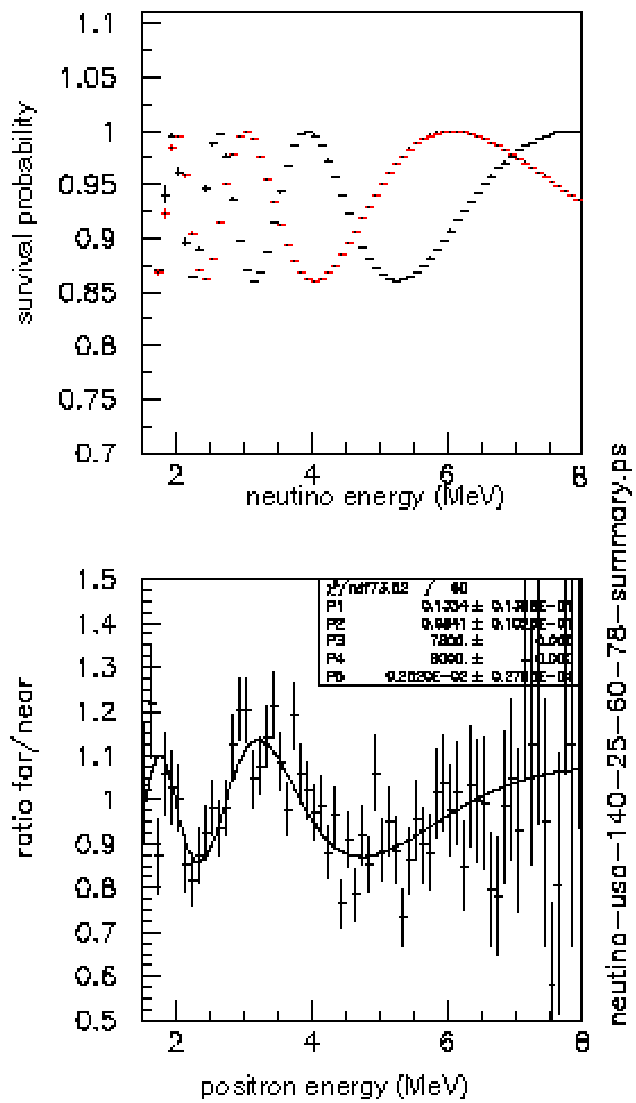
'near - far' L_1 = 1 km, L_2 = 3 km

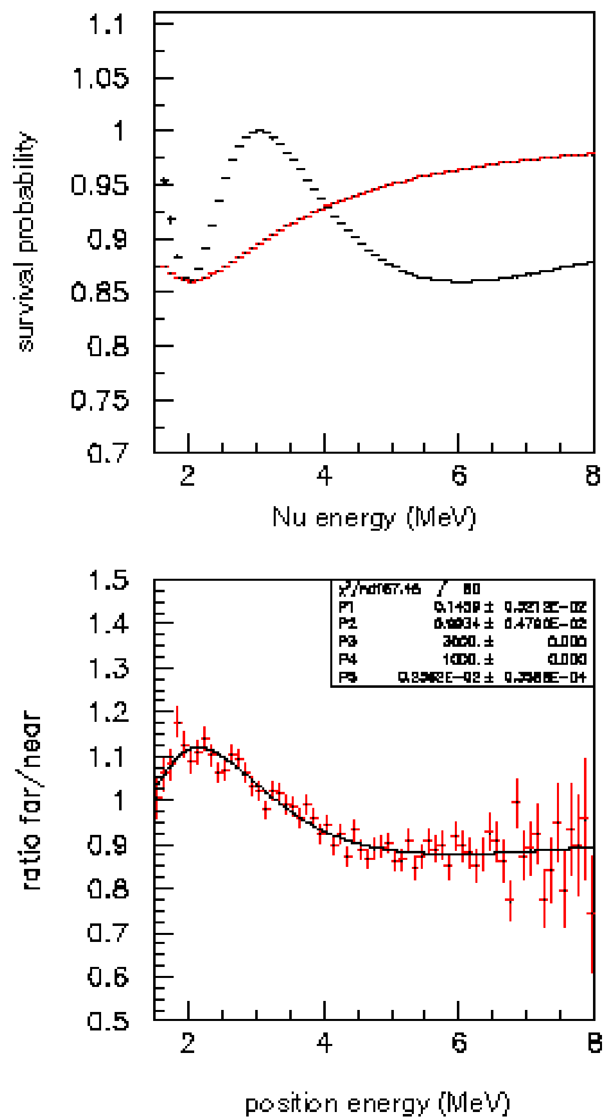
$$P(\nu_e \to \nu_e) \approx \sin^4\theta_{13} + \cos^4\theta_{13}\left\{1 - \sin^2(2\theta_{12})\cdot\sin^2\left(\frac{\Delta m_{12}^2 L}{4E_\nu}\right)\right\}$$

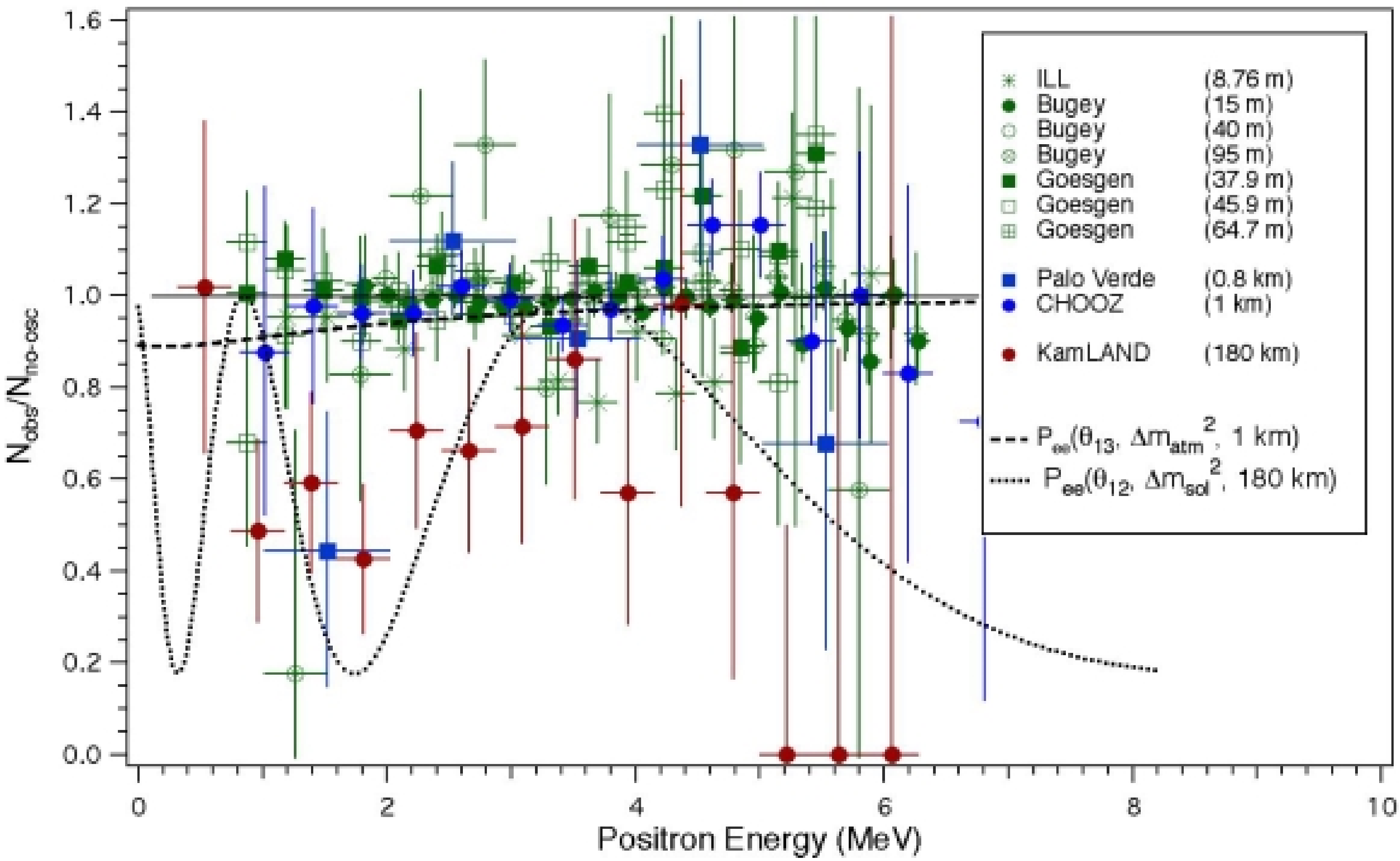
Oscillation Parameters:

$\sin^2 2\theta_{13}$ = 0.14

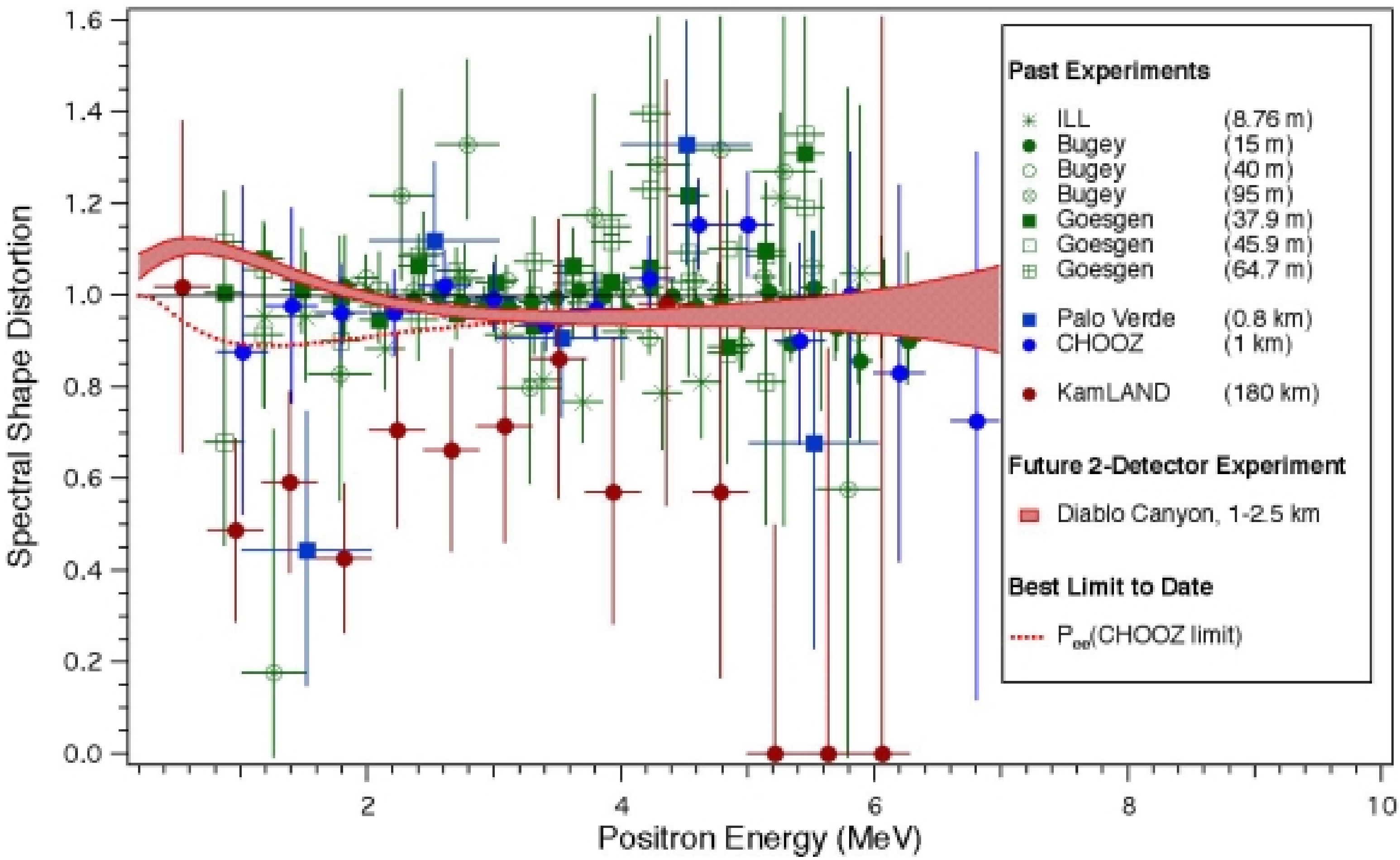
Δm^2= 2.5 x 10^{-3} eV^2







ILL (8.76 m)
Bugey (15 m)
Bugey (40 m)
Bugey (95 m)
Goesgen (37.9 m)
Goesgen (45.9 m)
Goesgen (64.7 m)
Palo Verde (0.8 km)
CHOOZ (1 km)
KamLAND (180 km)
$P_{ee}(\theta_{13}, \Delta m_{atm}^2, 1\ km)$
$P_{ee}(\theta_{12}, \Delta m_{sol}^2, 180\ km)$
$N_{obs}/N_{no\text{-}osc}$
Positron Energy (MeV)



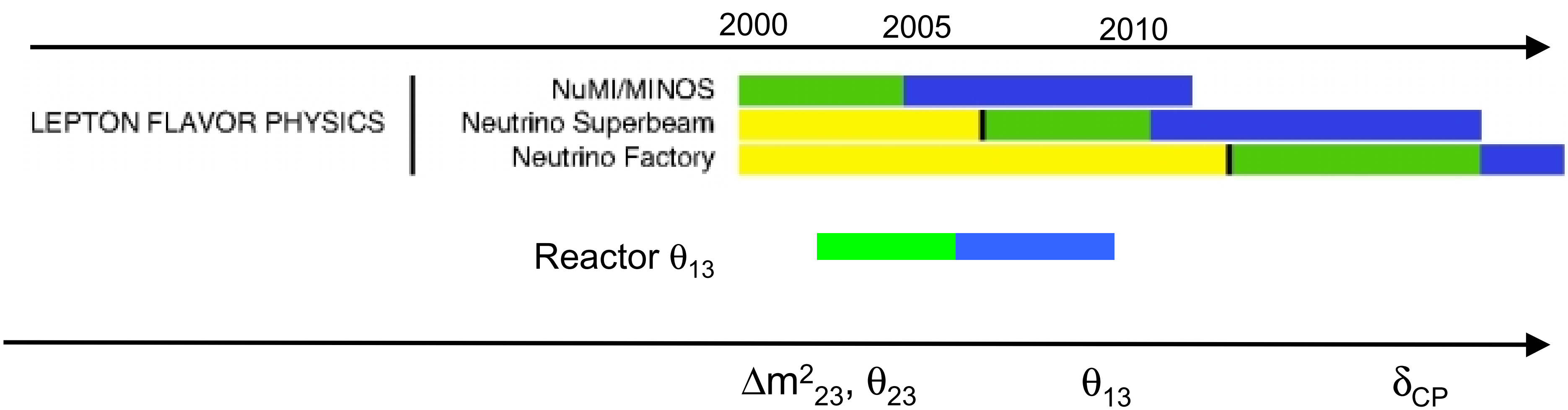
Spectral Shape Distortion
Positron Energy (MeV)
Past Experiments
ILL (8.76 m)
Bugey (15 m)
Bugey (40 m)
Bugey (95 m)
Goesgen (37.9 m)
Goesgen (45.9 m)
Goesgen (64.7 m)
Palo Verde (0.8 km)
CHOOZ (1 km)
KamLAND (180 km)
Future 2-Detector Experiment
Diablo Canyon, 1-2.5 km
Best Limit to Date
P_{ee}(CHOOZ limit)

Timescale and Size of a θ_{13} Reactor Project

Moderate Scale (< $50M)

Medium-size, low-energy experiment
Little R&D necessary (KamLAND, SNO, CHOOZ)
Construction time ~ 2-3 yrs
Start in 2007/2008?

The Particle Physics Roadmap (in the US)



Reactor results will define the future of $\not{CP}$ searches in the lepton sector and complement accelerator experiments

Conclusions

- Top priorities in neutrino physics include pinning down MNS matrix elements and discovering CP violation.

- We will need a number of experiments to resolve ambiguities from matter effects and correlations.

- Reactor experiments and accelerator experiments are complementary.

- Reactor experiments have the potential of being faster, cheaper and better for establishing the value of θ_{13}.

- Executing a reactor experiment at an appropriate site should be put on a fast track.