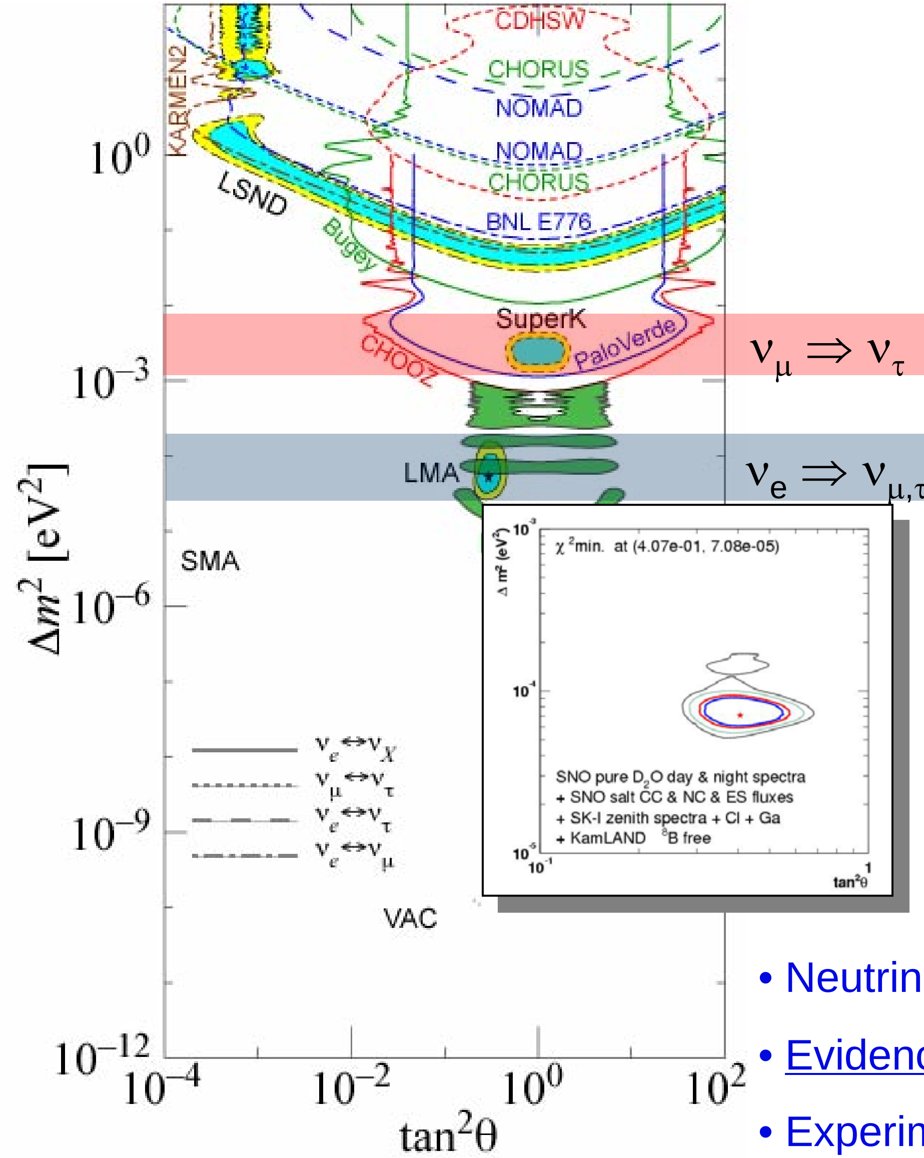
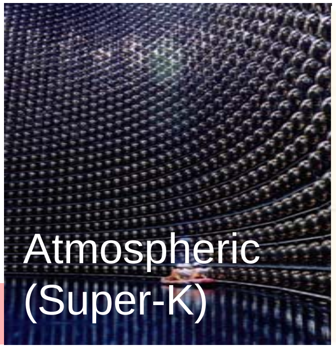
Proposals for a Reactor Neutrino Oscillation Experiment to Measure θ_{13}

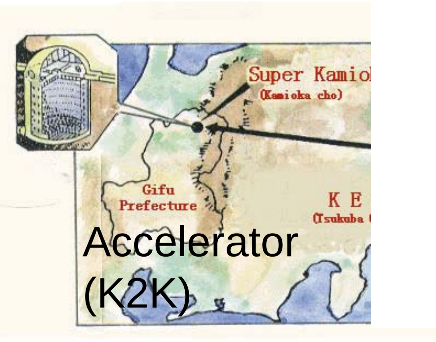
Karsten M. Heeger

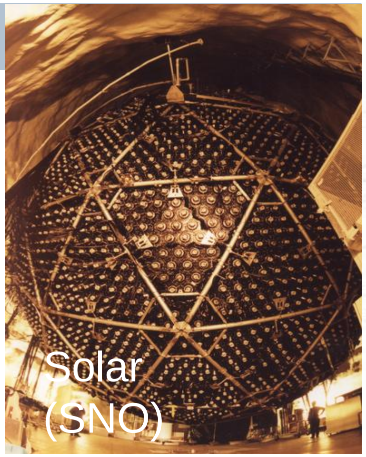
Lawrence Berkeley National Laboratory

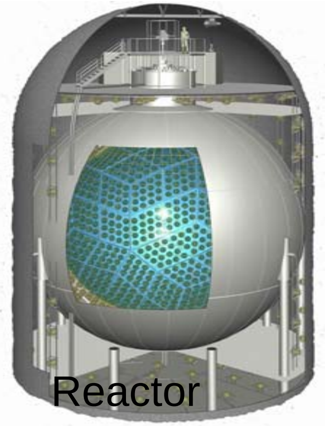
Recent Results in Neutrino Physics











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

U_{MNSP}, θ_{13}, and $\not{CP}$

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*

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

?

atmospheric, K2K — reactor and accelerator — SNO, solar SK, KamLAND — $0\nu\beta\beta$

$\theta_{23} = \sim 45^\circ$ — $\tan^2\theta_{13} < 0.03$ at 90% CL — $\theta_{12} \sim 32^\circ$

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

We Do Not Know ….

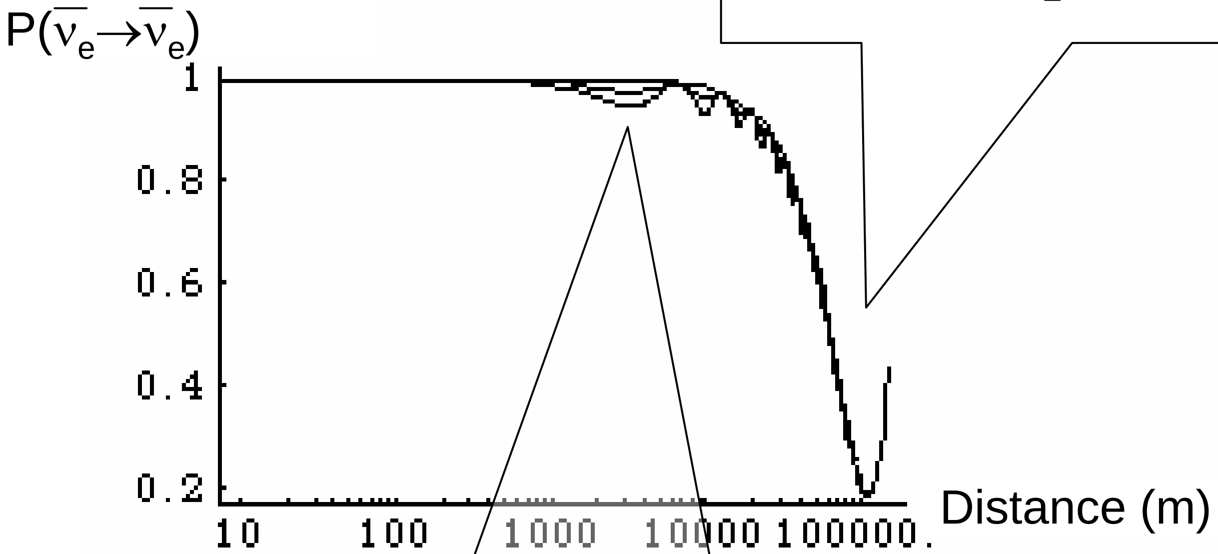
$\sin^2(2\theta_{13})$

sign of Δm_{13}^2

δ

Search for Subdominant Oscillation Effects

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



Dominant θ_{12} Oscillation

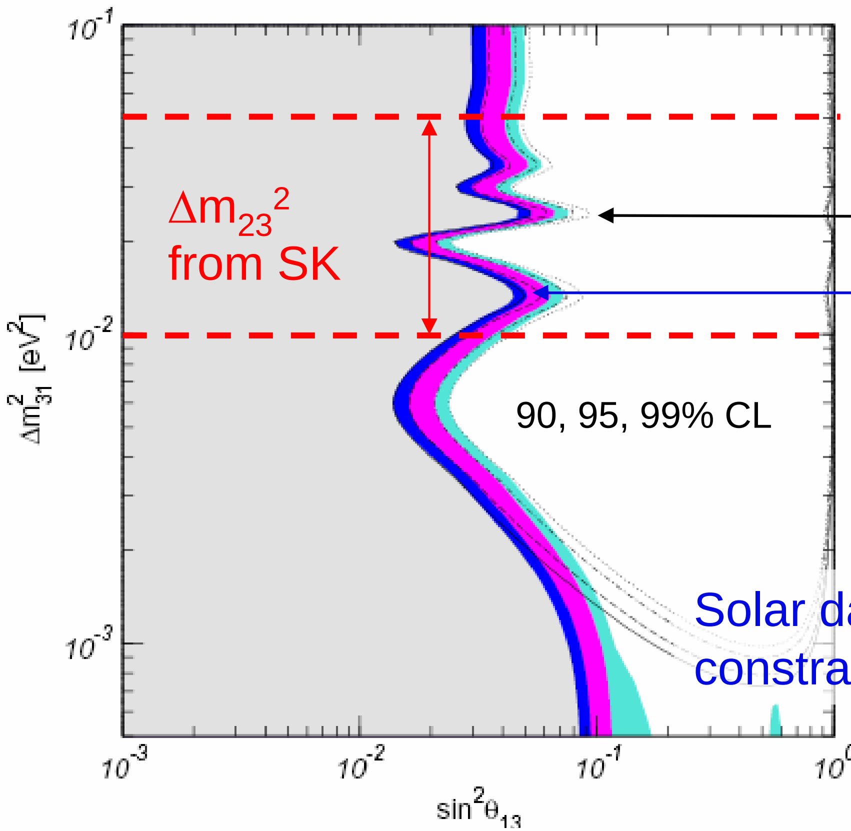
$$P_{ee} \approx 1 - \cos^4\theta_{13}\left[1 - \sin^2\theta_{12}\sin^2\left(\frac{\Delta m_{12}{}^2 L}{4E_\nu}\right)\right]$$

Subdominant θ_{13} Oscillation

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

Global Constraints on θ_{13}

Maltoni et al., hep-ph/0309130



Chooz

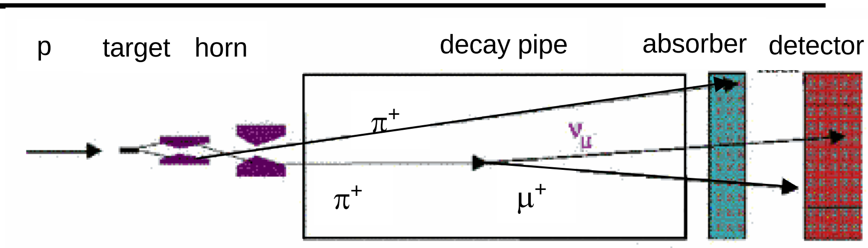
With added SNO CC/NC
+ KamLAND Constraint

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)

Measuring θ_{13}

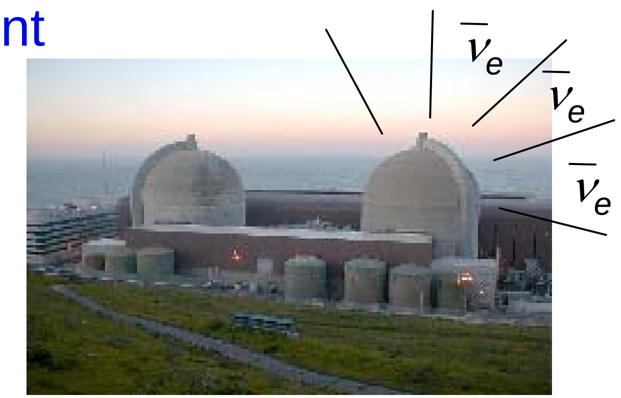
Method 1: Accelerator Experiments



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

- 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



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

- 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

Concept of a Reactor Neutrino Measurement of θ_{13}

scintillator $\bar{\nu}_e$ detectors

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

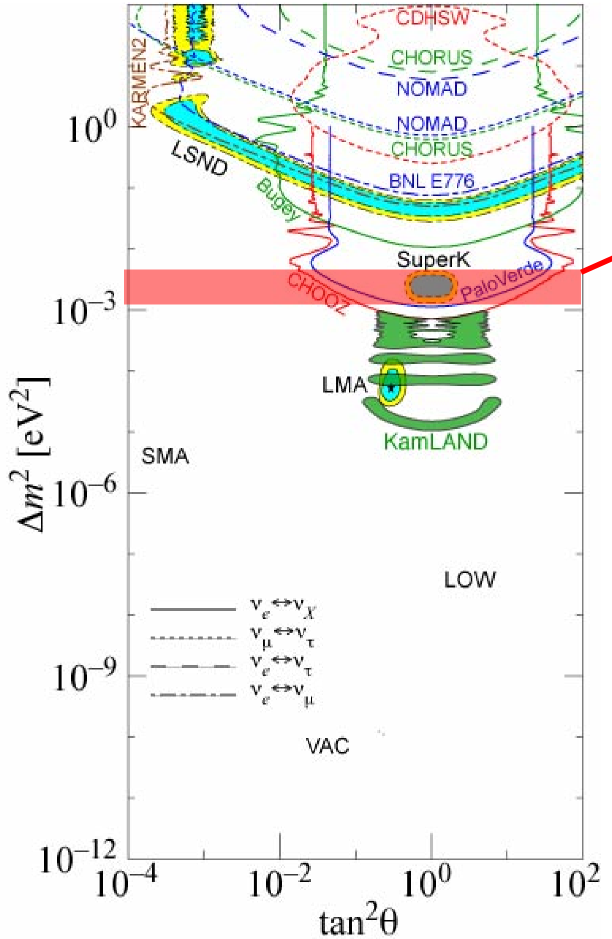
coincidence signal
prompt e^+ annihilation
delayed n capture (in μs)

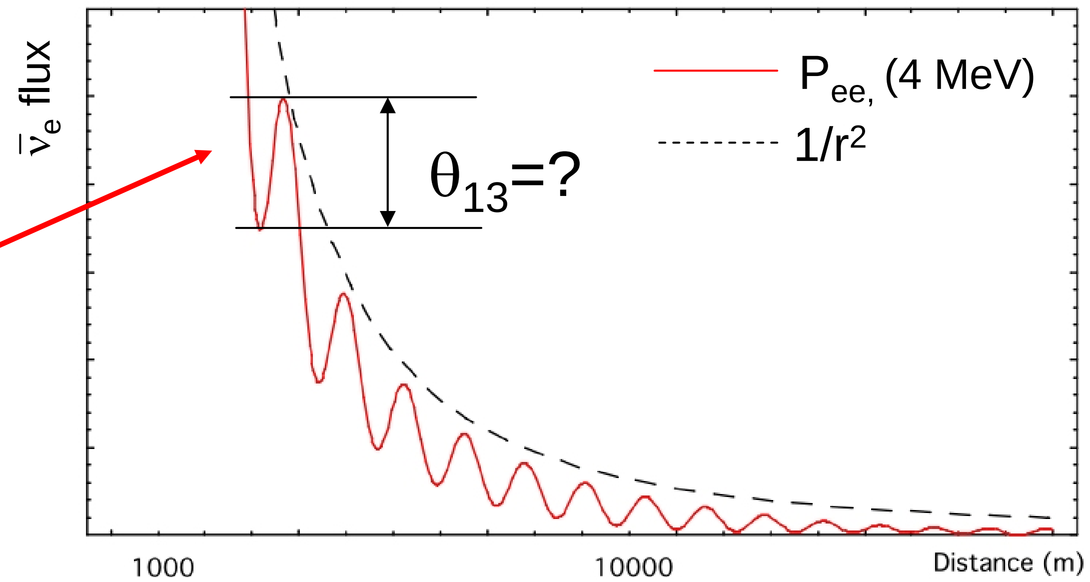
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}{}^2 L}{4E_\nu} + \left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right) \cos^4 \theta_{13} \sin^2 2\theta_{12}$$

- disappearance experiment
- 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

Partial cancellation of systematic errors in relative measurement

Reactor Neutrino Measurement of θ_{13} - Basic Idea





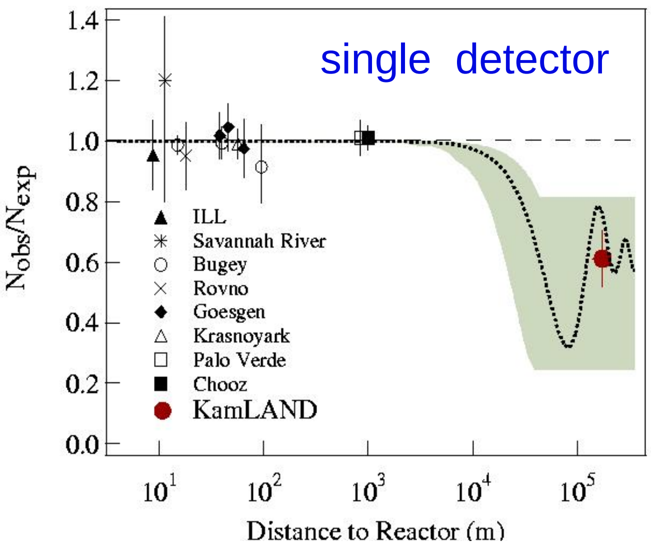
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E_\nu} + \left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right) \cos^4 \theta_{13} \sin^2 2\theta_{12}$$

atmospheric frequency dominant

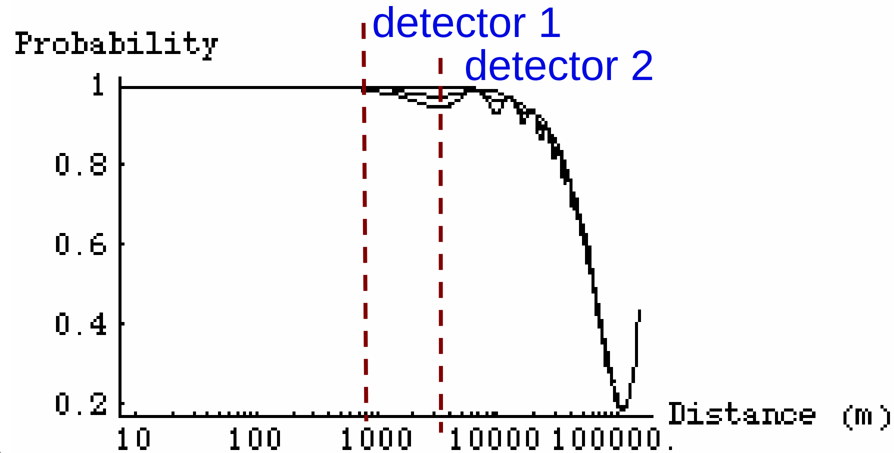
last term negligible for $\frac{\Delta m_{31}^2 L}{4E_\nu} \sim \pi/2$ and $\sin^2 2\theta_{13} \geq 10^{-3}$

Reactor Neutrino Measurement of θ_{13}

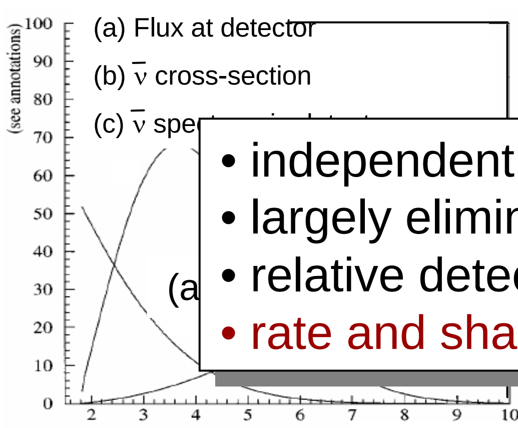
Present Reactor Experiments



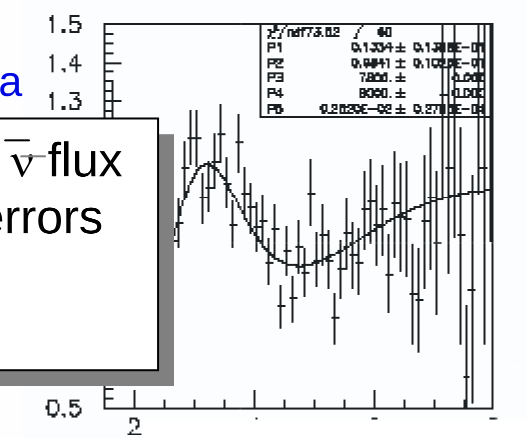
Future θ_{13} Reactor Experiment



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

Site Criteria for a θ_{13} Reactor Experiment

Site Criteria

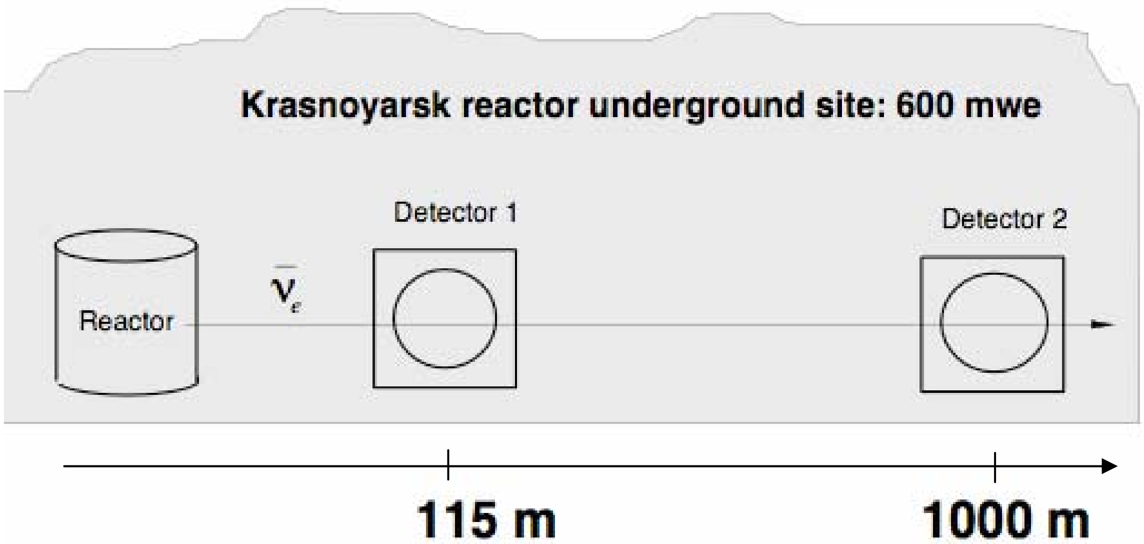
- powerful reactor
- overburden (> 300 mwe)
- underground tunnels or detector halls
- controlled access to site

$\rightarrow$ Variable/flexible baseline for *optimization to* Δm^2_{atm} and *to demonstrate subdominant* oscillation effect.

$\rightarrow$ Optimization of experiment specific to site. Site selection critical

World of Proposed Reactor Neutrino Experiments

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

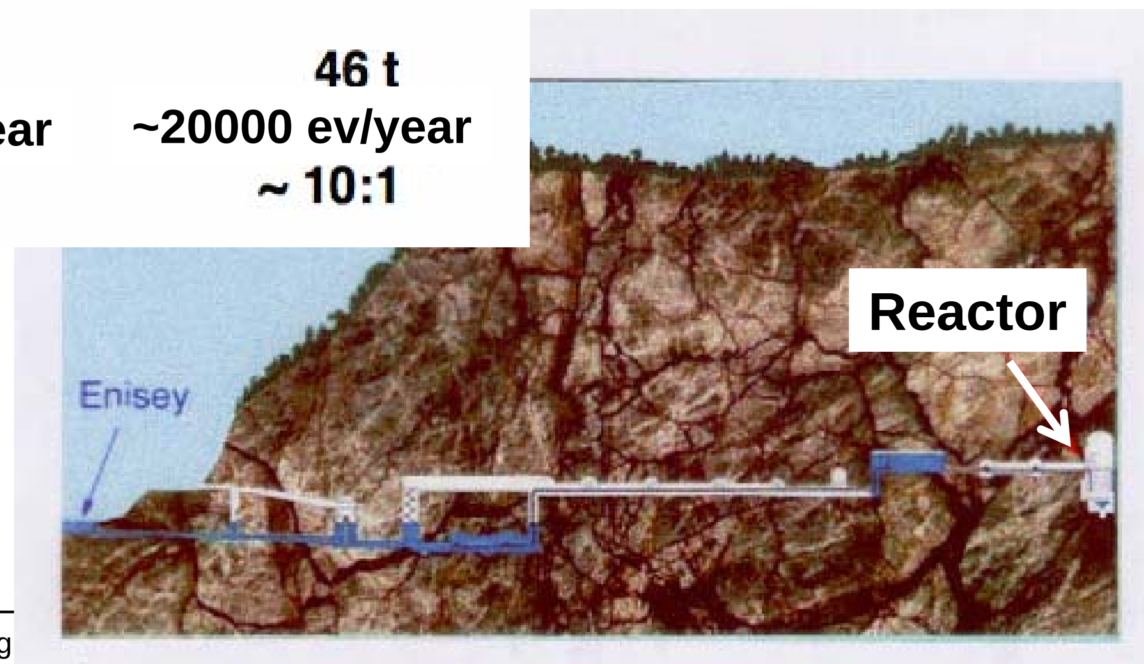


Target:	**46 t**	**46 t**
Rate:	**~1.5 x 10^6 ev/year**	**~20000 ev/year**
S:B	**>>1**	**~ 10:1**

Unique Feature

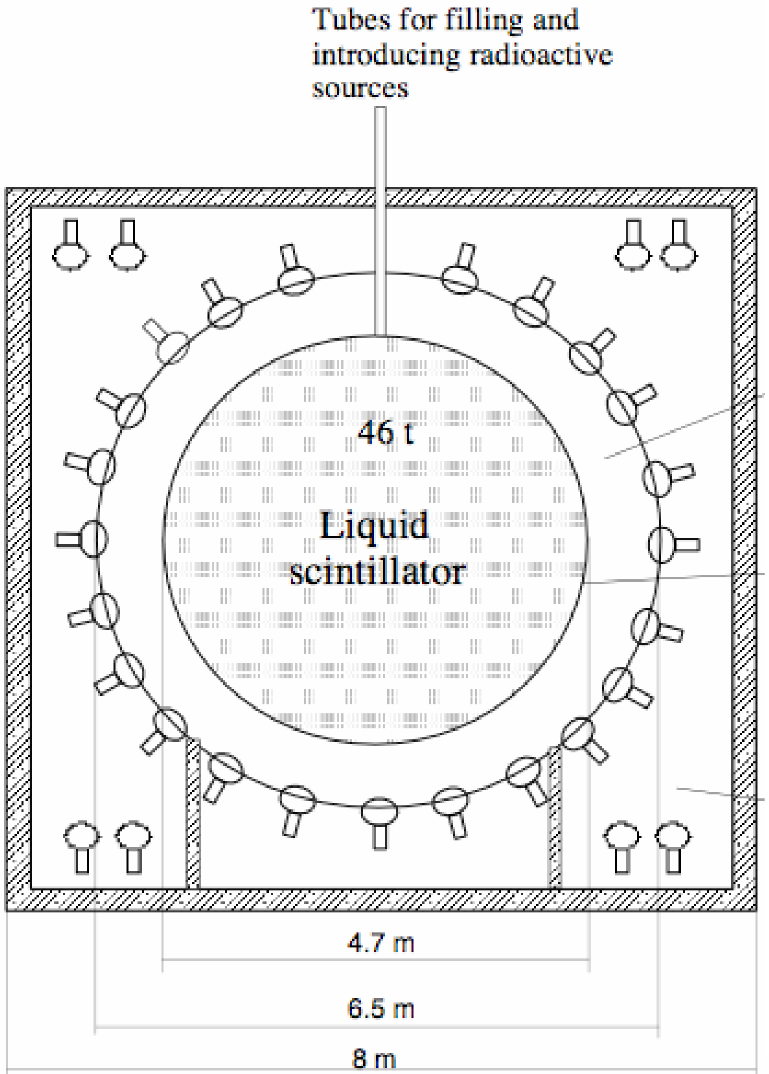
- underground reactor
- existing infrastructure

Detector locations determined by infrastructure

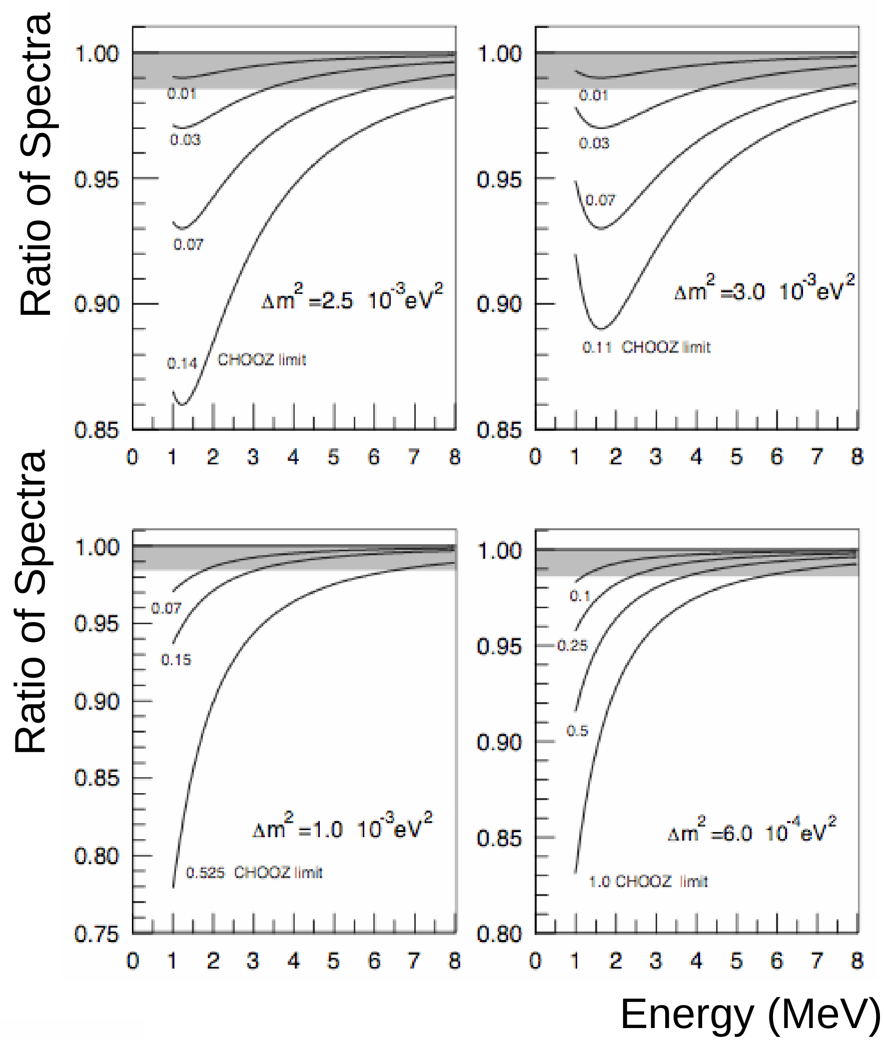


Ref: Marteyamov et al, hep-ex/0211070

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



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

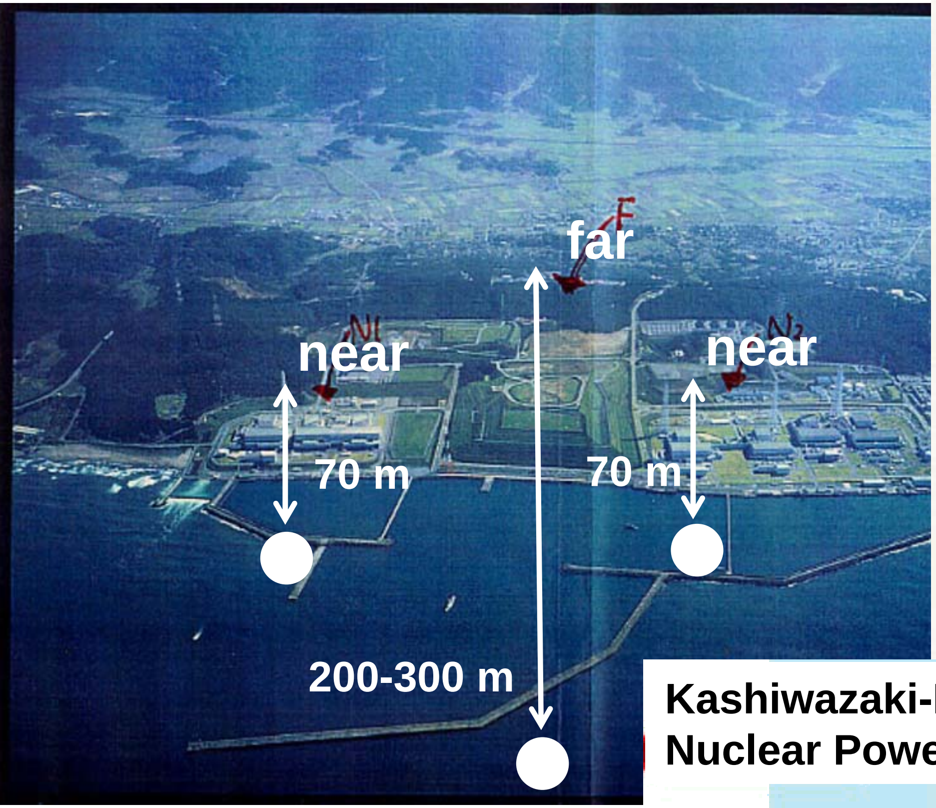


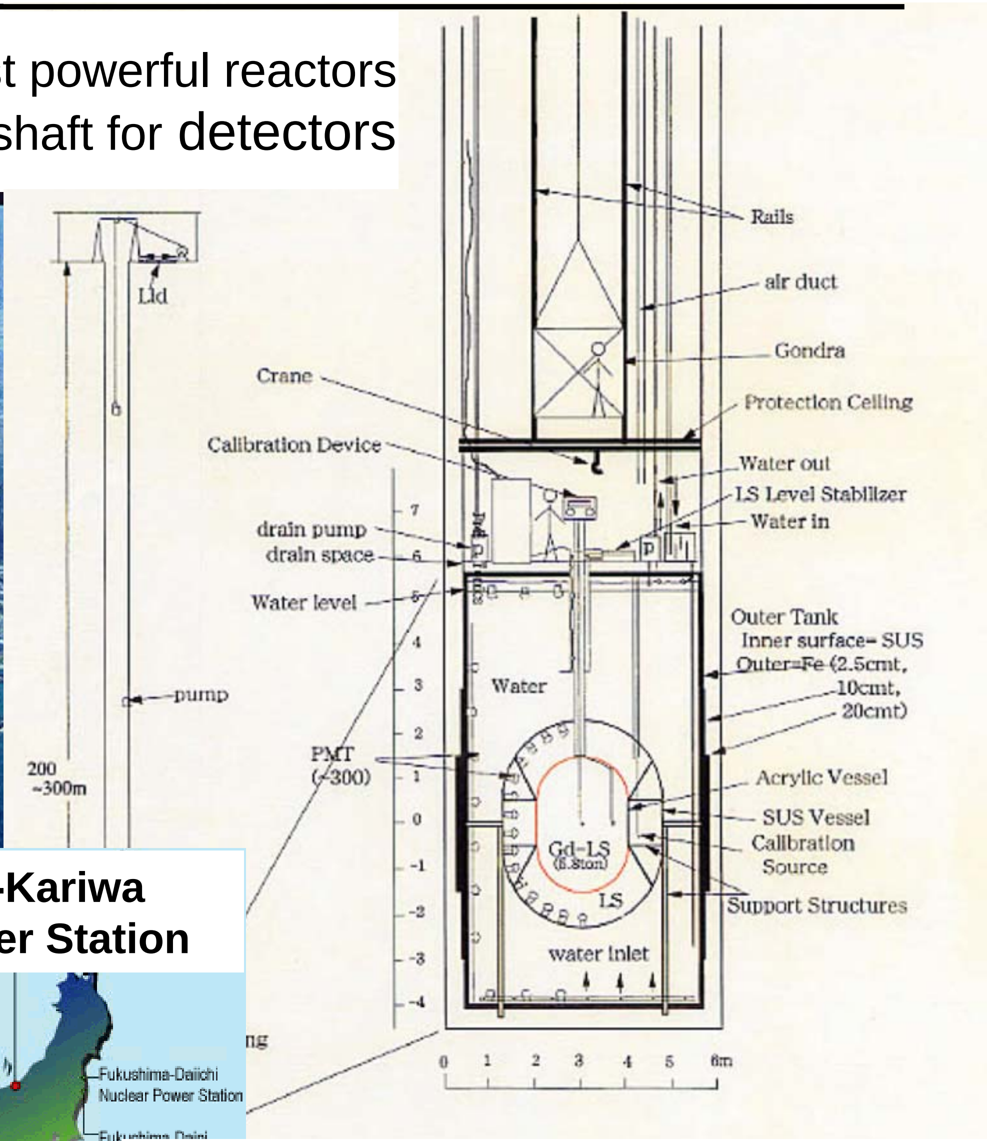
Ref: Marteyamov et al., hep-ex/0211070.

World of Proposed Reactor Neutrino Experiments

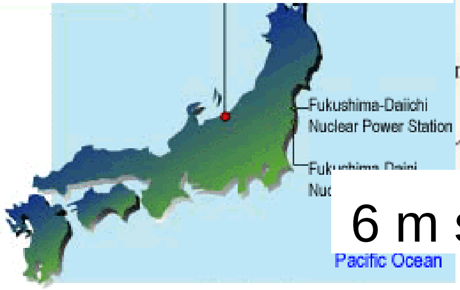
Kashiwazaki, Japan

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





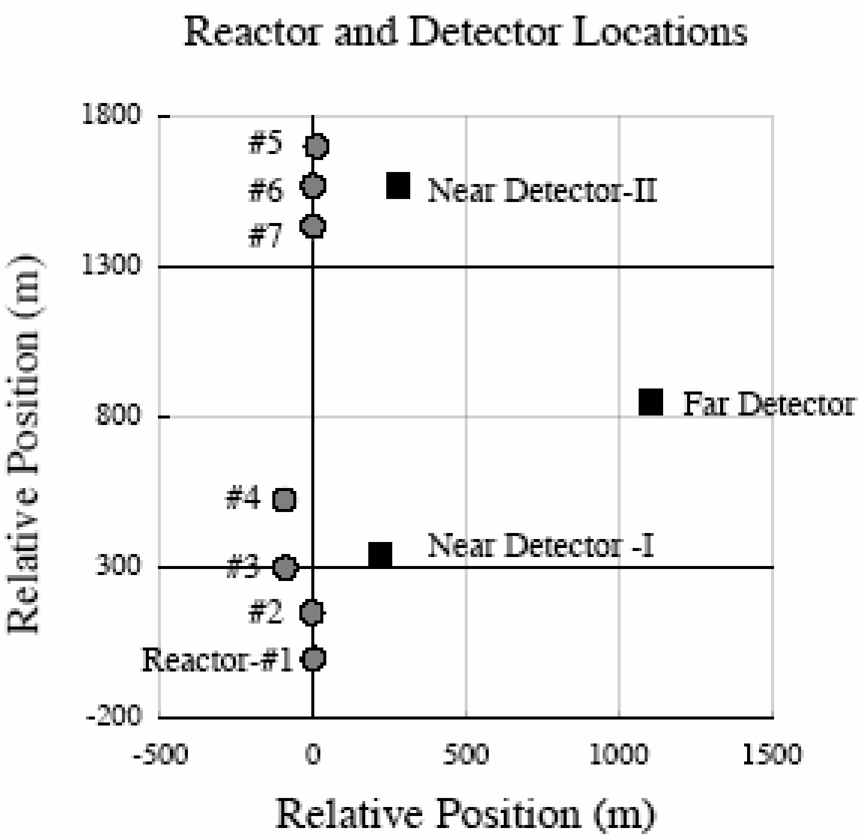
Kashiwazaki-Kariwa Nuclear Power Station

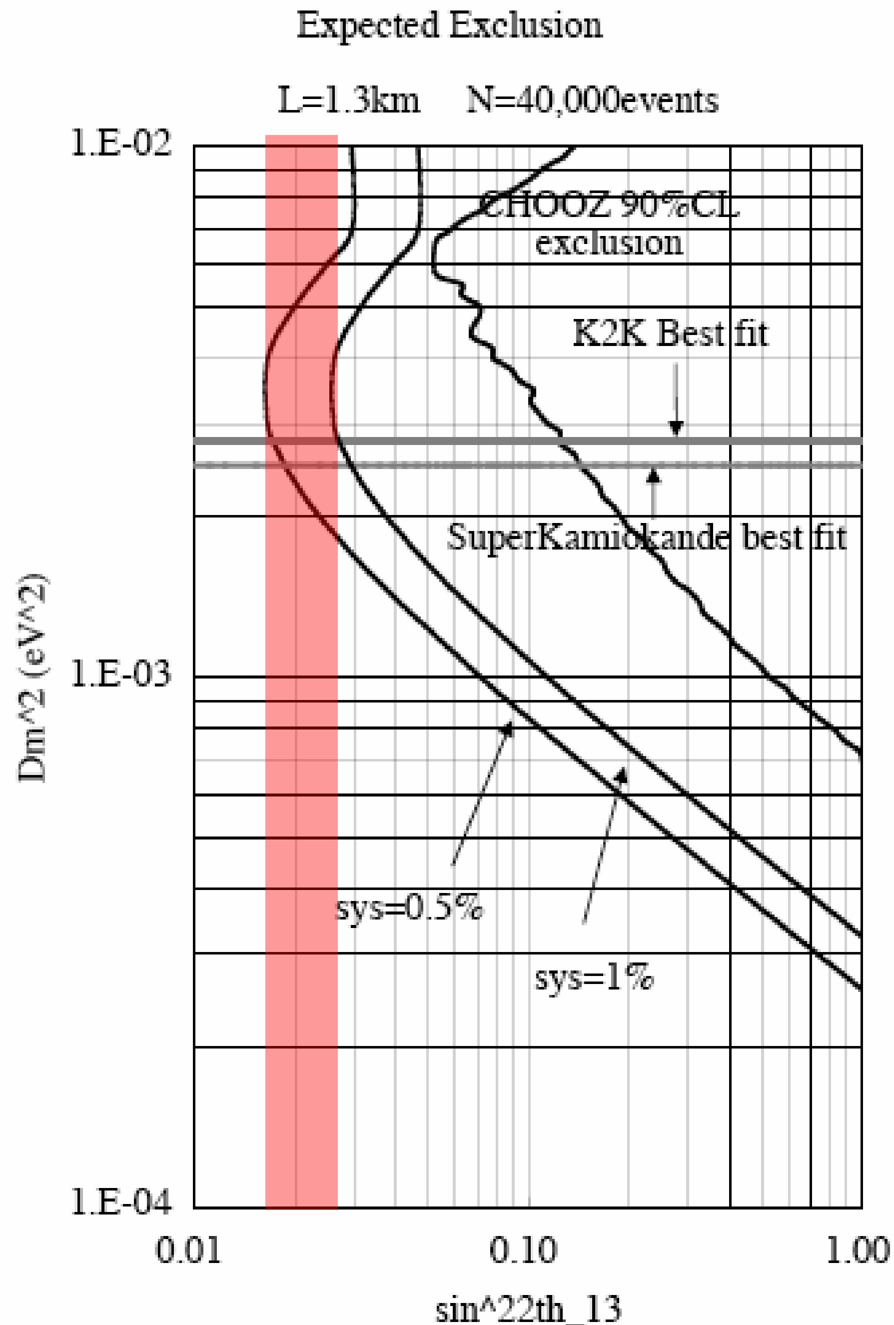


6 m shaft hole, 200-300 m depth

Kashiwazaki, Japan

Layout of Experiment and Sensitivity

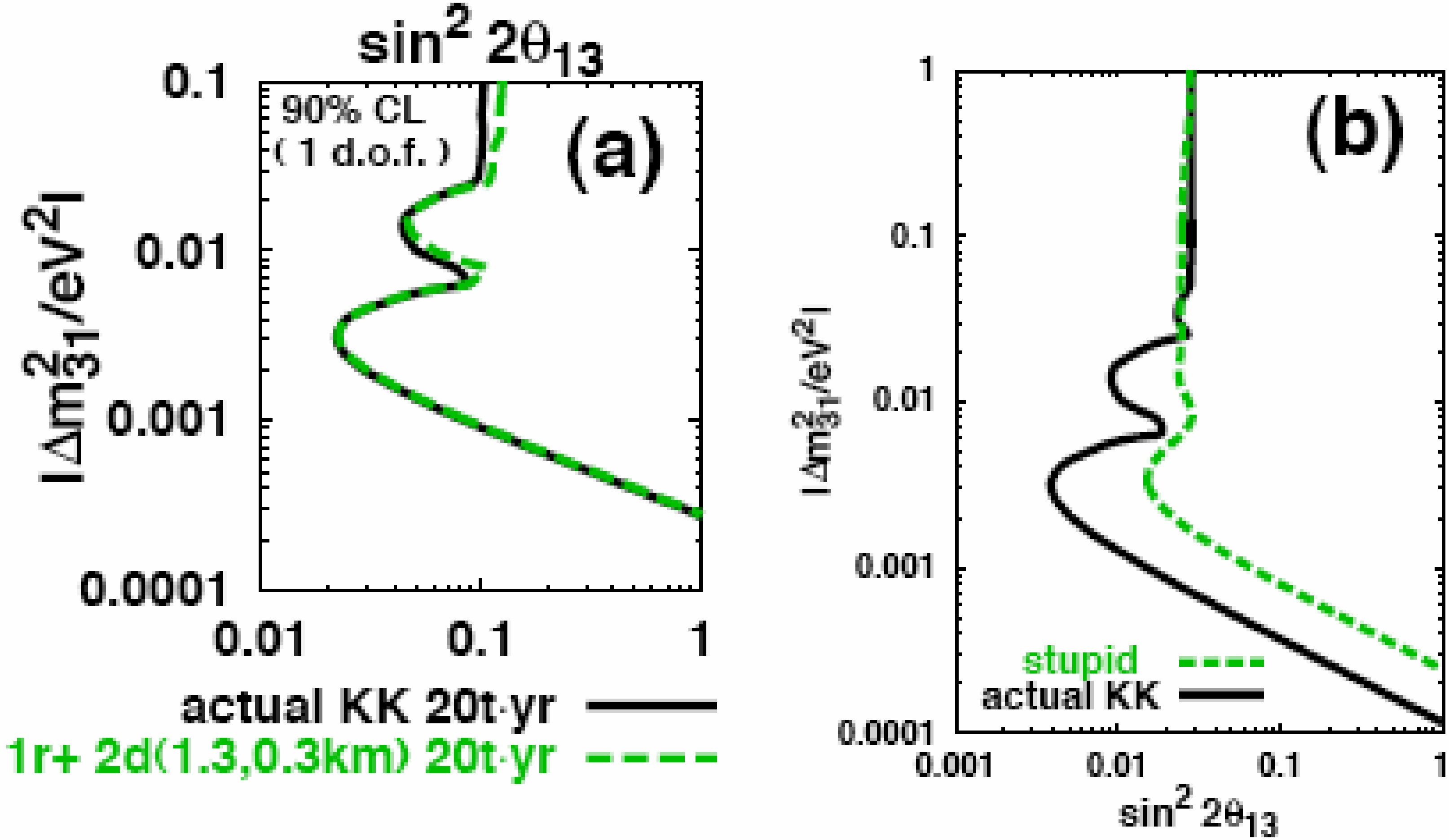




Ref: Suekane, Yasuda et al.

Kashiwazaki, Japan

Effect of Multiple Reactors



Ref: Suekane, Yasuda et al.

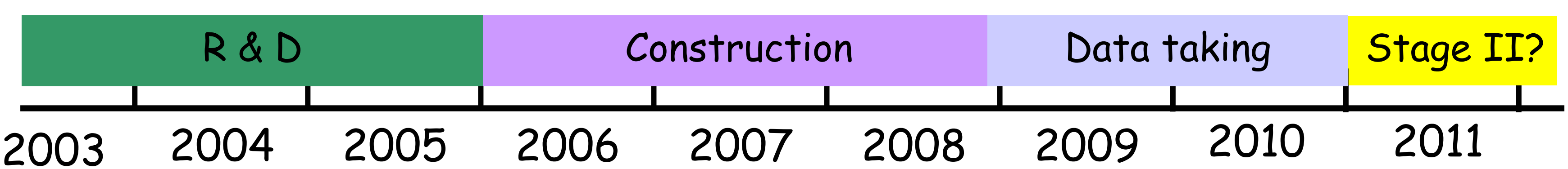
The Kashiwazaki-Kariwa Initiative

- Has the most powerful nuclear power plant in the world: 24.3 GW_{th}
- Plan to carrying in two stages:

stage I: - quick and cheap
- use existing technologies
- with less overburden and smaller detectors
- carry out only rate analysis
- with a 8.5 t far detector, in 2 years, collect 40,000 events

stage II: - optimize the distance
- with more overburden and bigger detectors
- carry out shape analysis
- pay more attention to systematic issues

Tentative Milestones

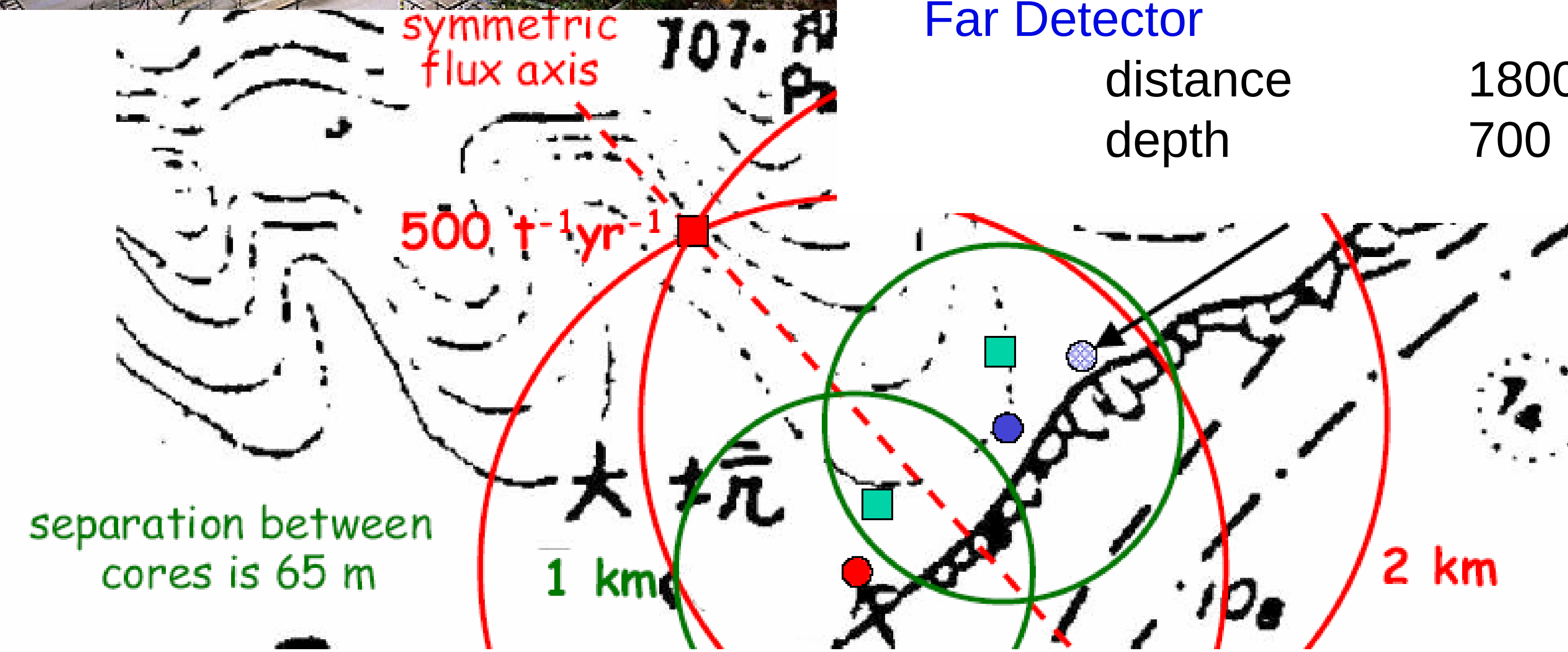


World of Proposed Reactor Neutrino Experiments

Daya Bay, China

My assumptions ….

Reactor		11.6 GW
Near Detectors		
	distance	~ 300 m
	depth	~100 mwe
Far Detector		
	distance	1800 m
	depth	700 mwe



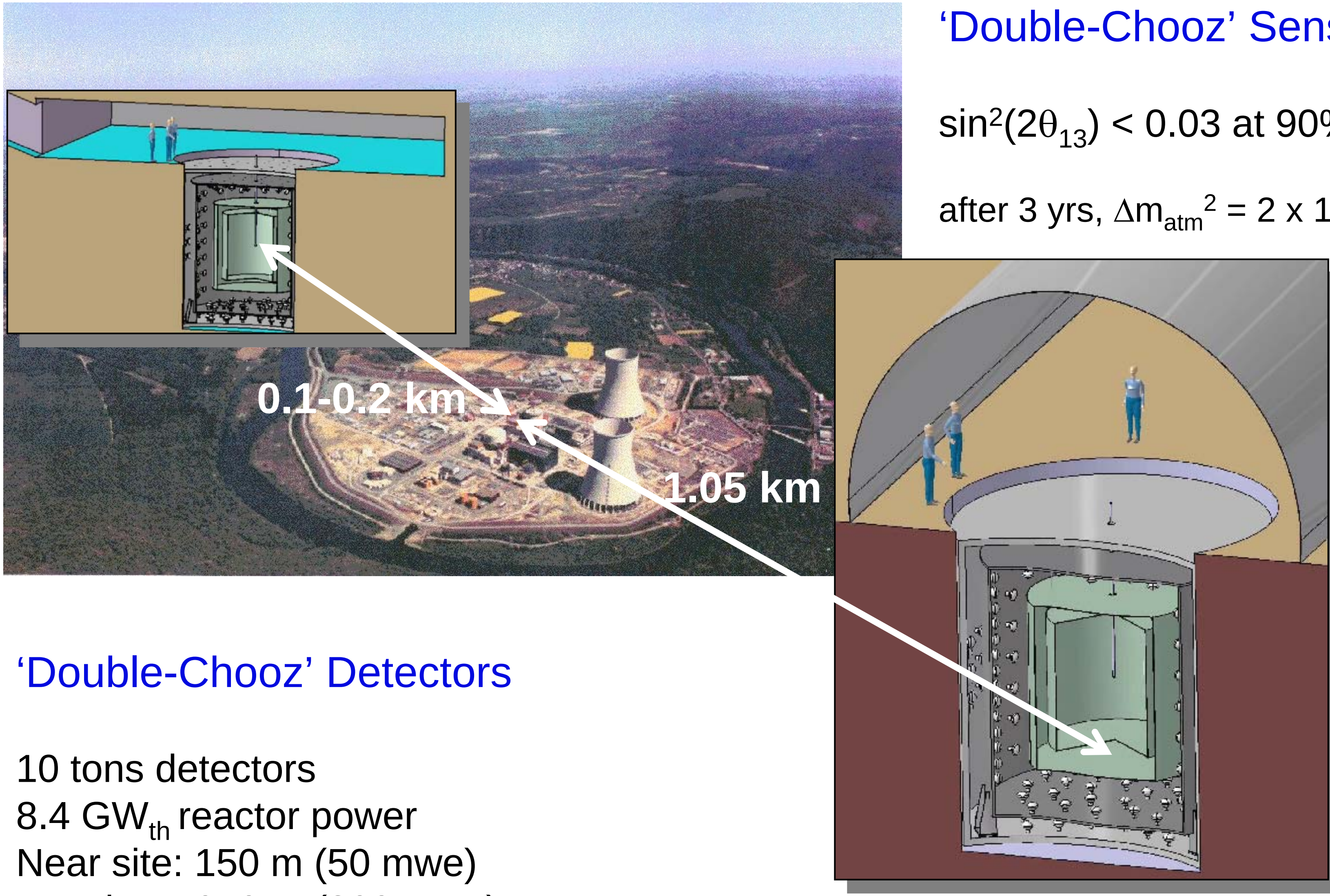
World of Proposed Reactor Neutrino Experiments

Chooz, France

‘Double-Chooz’ Sensitivity

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

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



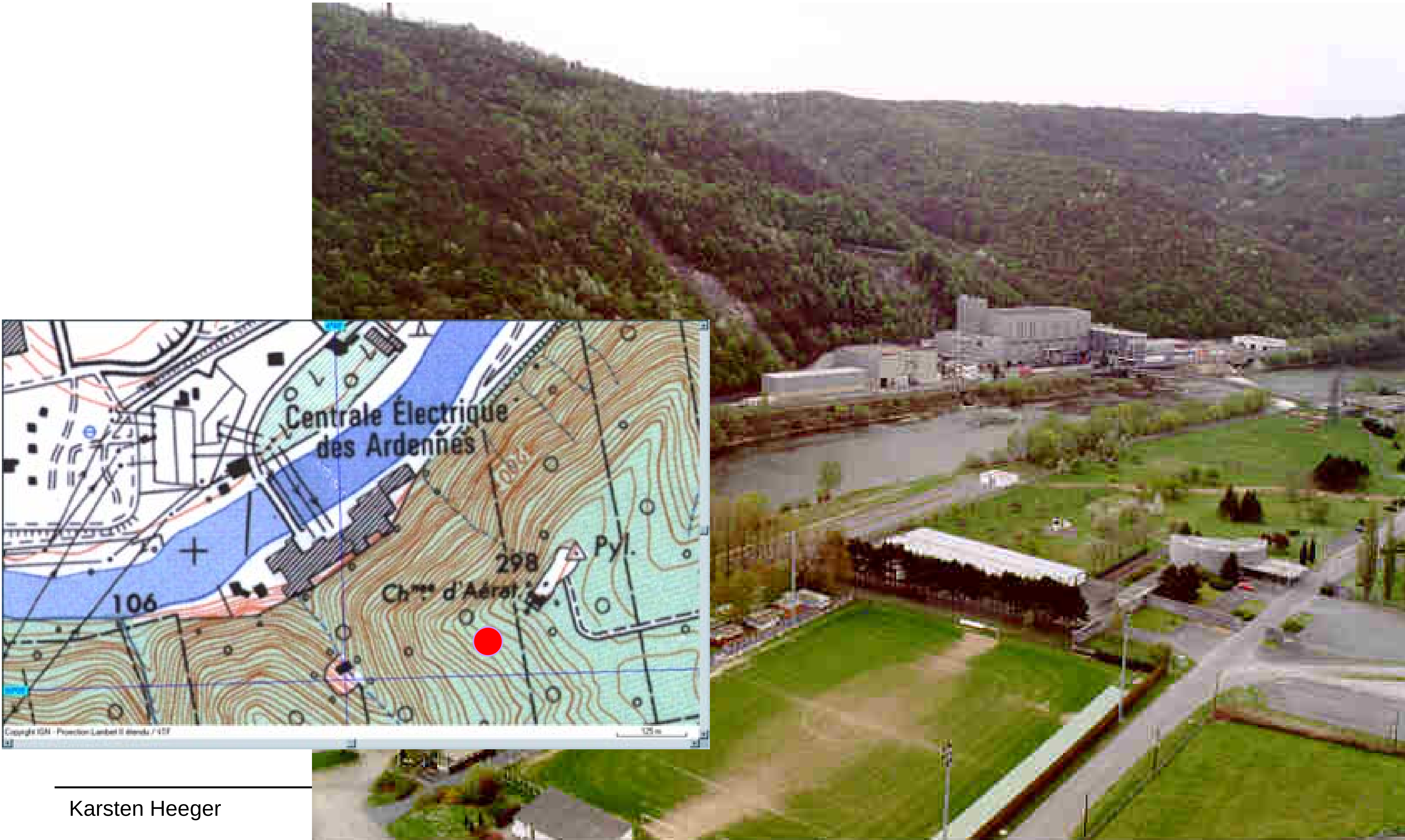
‘Double-Chooz’ Detectors

10 tons detectors
8.4 GW_{th} reactor power
Near site: 150 m (50 mwe)
Far site: 1050 m (300 mwe)

Ref: Lasserre, de Kerret
http://

Chooz, France

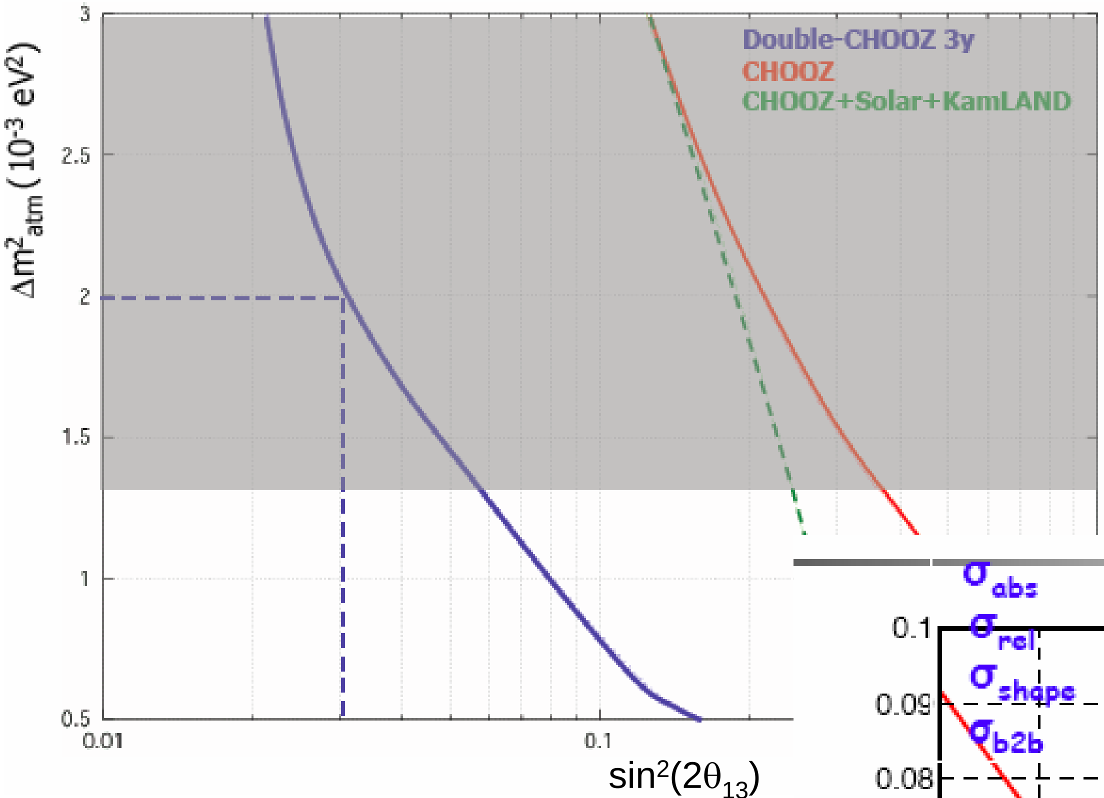
Existing Underground Laboratory at Far Site (1 km)

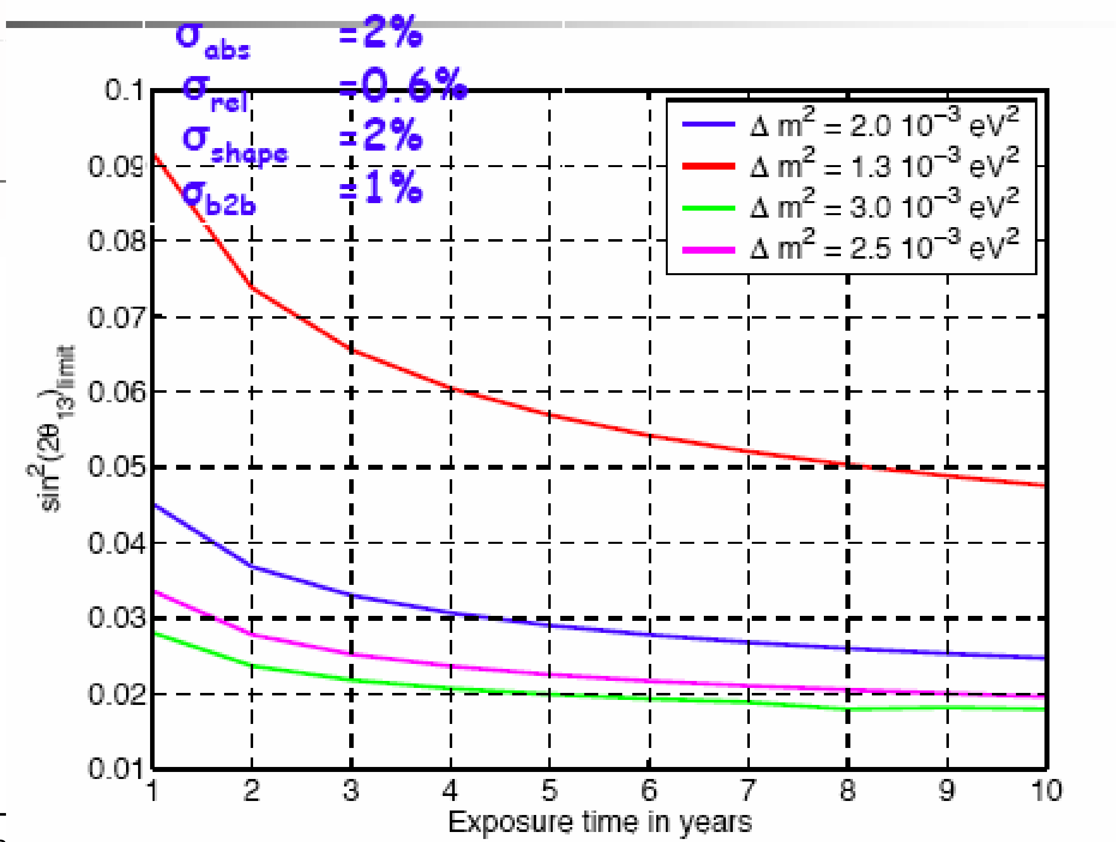


Chooz, France

Existing Underground Laboratory at Far Site (1 km)

Chooz, France





Chooz, France

Status

Received strong support from the EDF power company to carry out CHOOZ II; EDF will finance the civil-engineering study of the near site.

Scintillator work is proceeding at MPI and LNGS. Systematic tests of stability and compatibility of Gd-loaded scintillator will also start before end of January in Saclay.

Engineers have started to look at the inner vessel design and integrationscenarios of the detectors in the cavities.

Proto-collaboration is working on LOI.

Chooz, France

European Proto-Collaboration

25 physicists
4 countries

including ..

Saclay
College de France

MPI Heidelberg
TU Munich

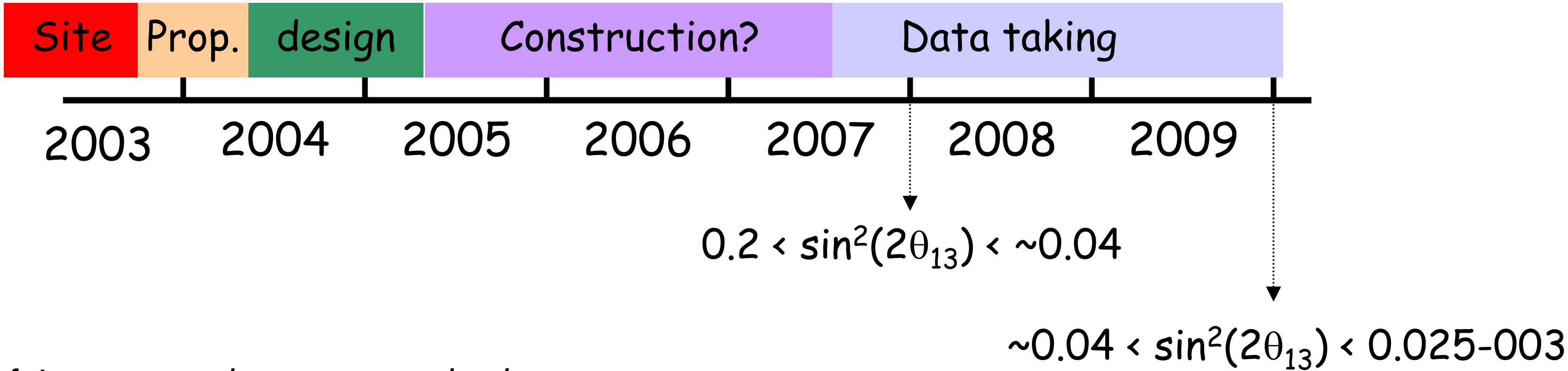
Chooz, France

Schedule

In the next 3 months the Double-Chooz project will be presented to the scientific councils of the French laboratories:

March 1, 2004:	APC (new astroparticle lab in Paris)
Mach 10, 2004:	Saclay
March 29-30,2004:	CNRS/IN2P3

Tentative Milestones



Ref: Lasserre, *private communication*

World of Proposed Reactor Neutrino Experiments

Angra dos Reis, Brazil

Reactor

– Primary 4.1 GW reactor
– Secondary 1.5 GW reactor
(mostly off, may be decommisioned

Far Detector

– 1.3 km baseline
– 200-250 m granite overburden (600-700mwe)

Near Detector

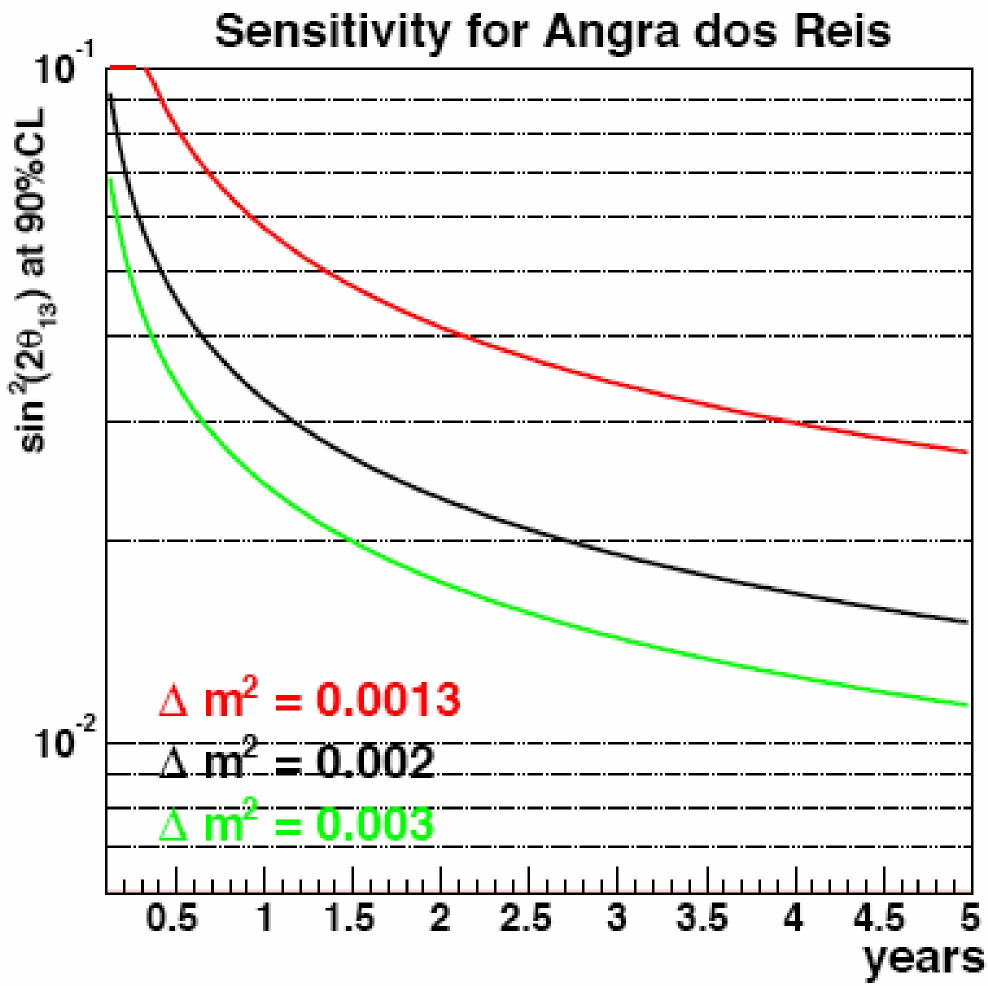
– 300-350 m baseline
– 20m granite overburden (~60 mwe)

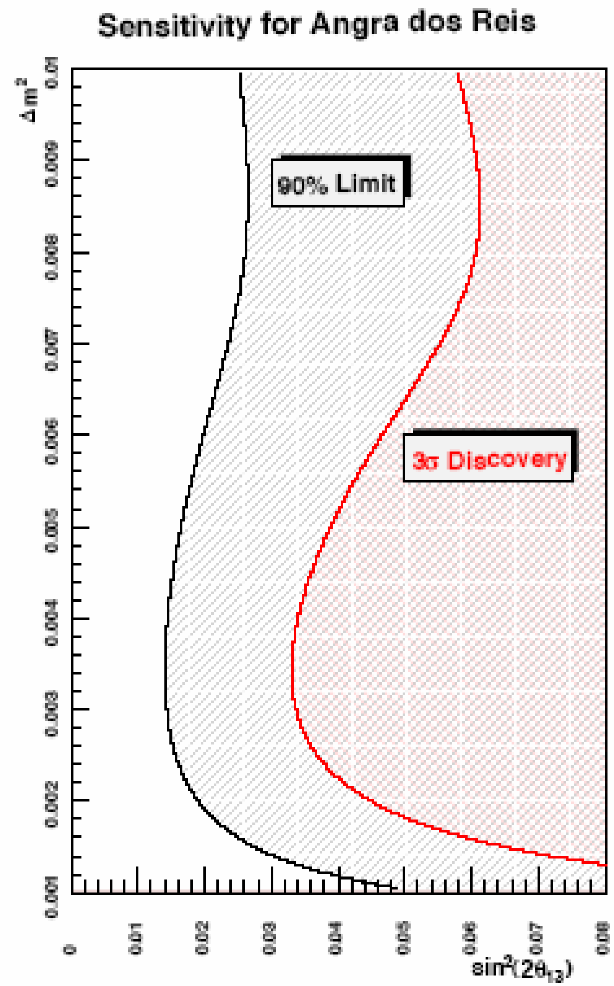
Ref: D. Reyna, ANL
theta13 white paper

Angra dos Reis, Brazil

Ref: D. Reyna, ANL
theta13 white paper

Angra dos Reis, Brazil





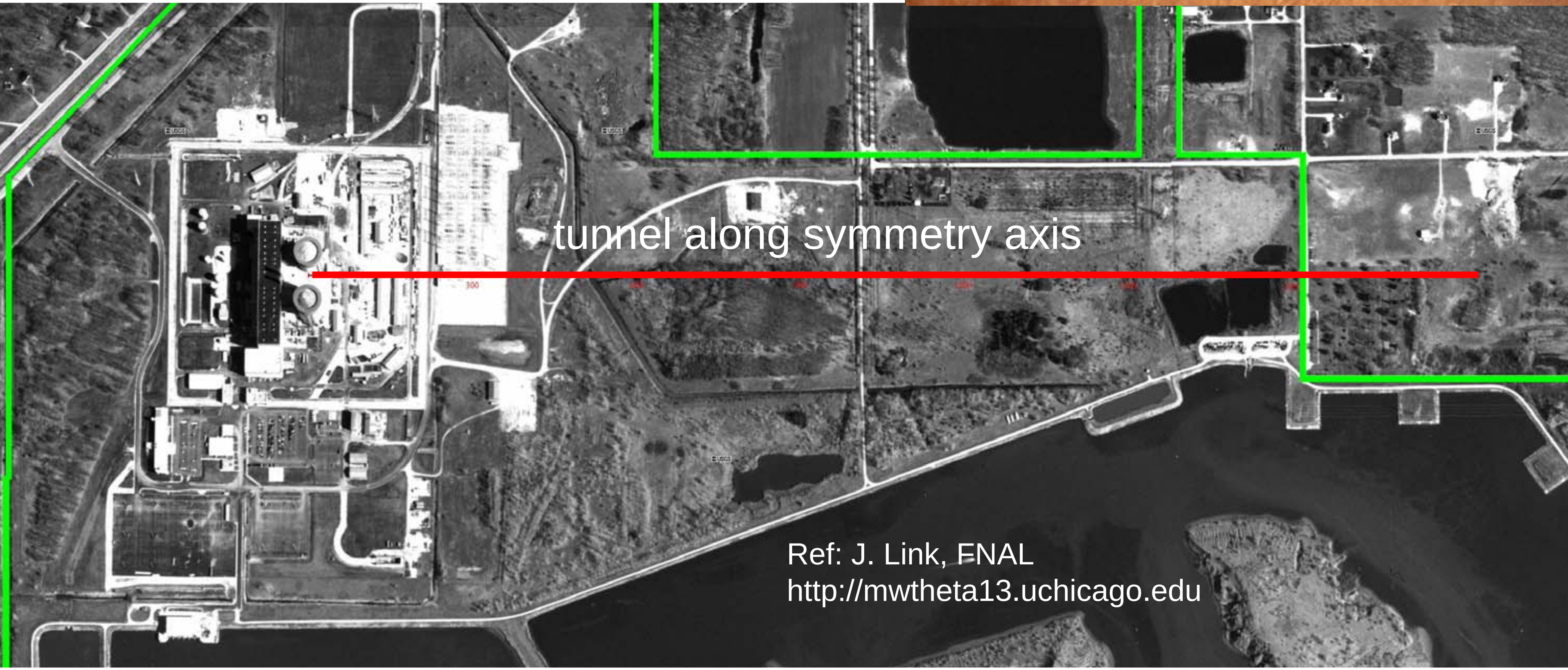
Ref: D. Reyna, ANL
theta13 white paper

World of Proposed Reactor Neutrino Experiments

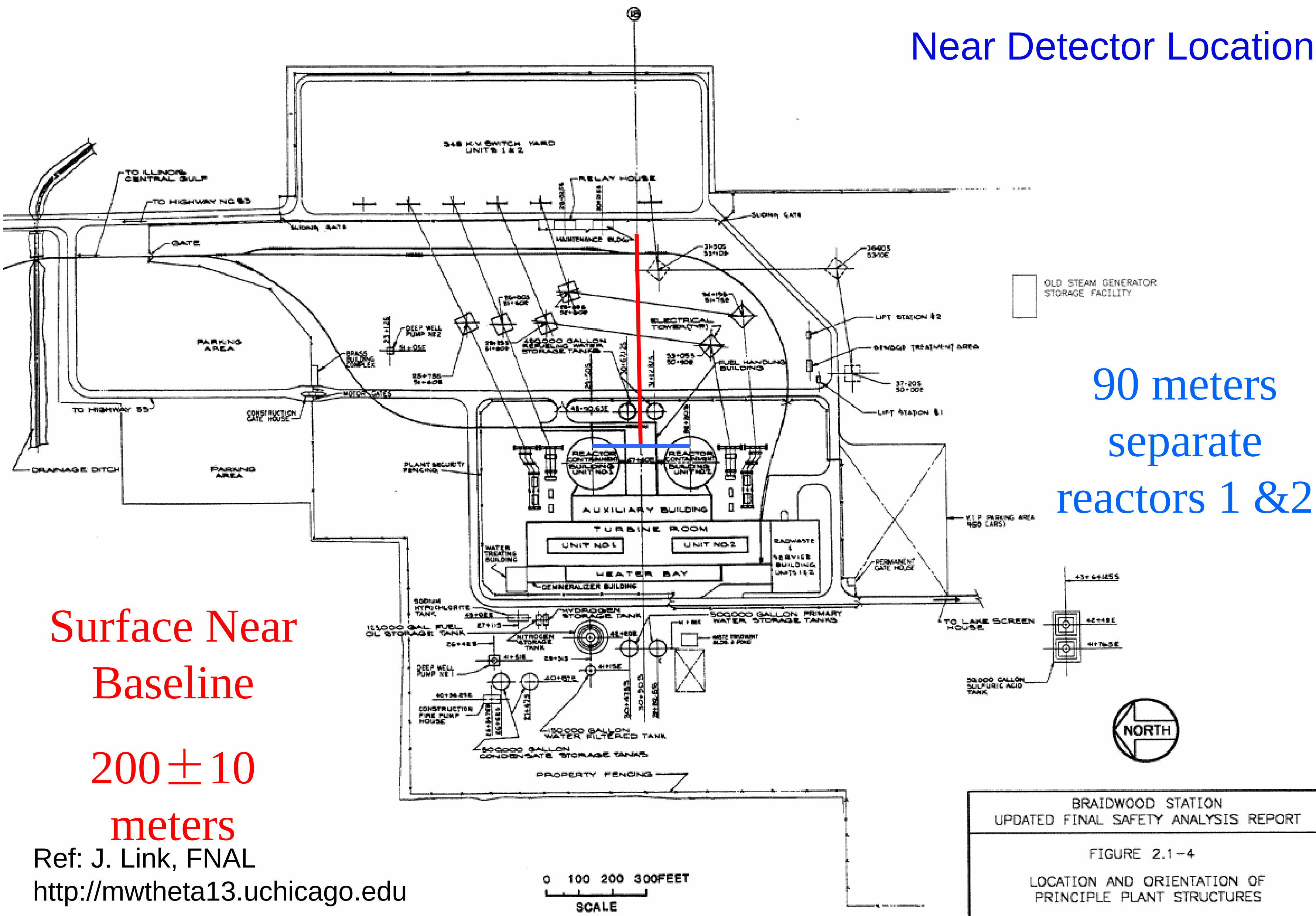
Search for a Reactor Site in the US

Braidwood, Il

Reactor	6.5 GW_{th}
Near Detector	200 m
Far Detector	1500 m (1800 m)



Braidwood, Il



Near Detector Location

90 meters separate reactors 1 &2

Surface Near Baseline

200±10 meters

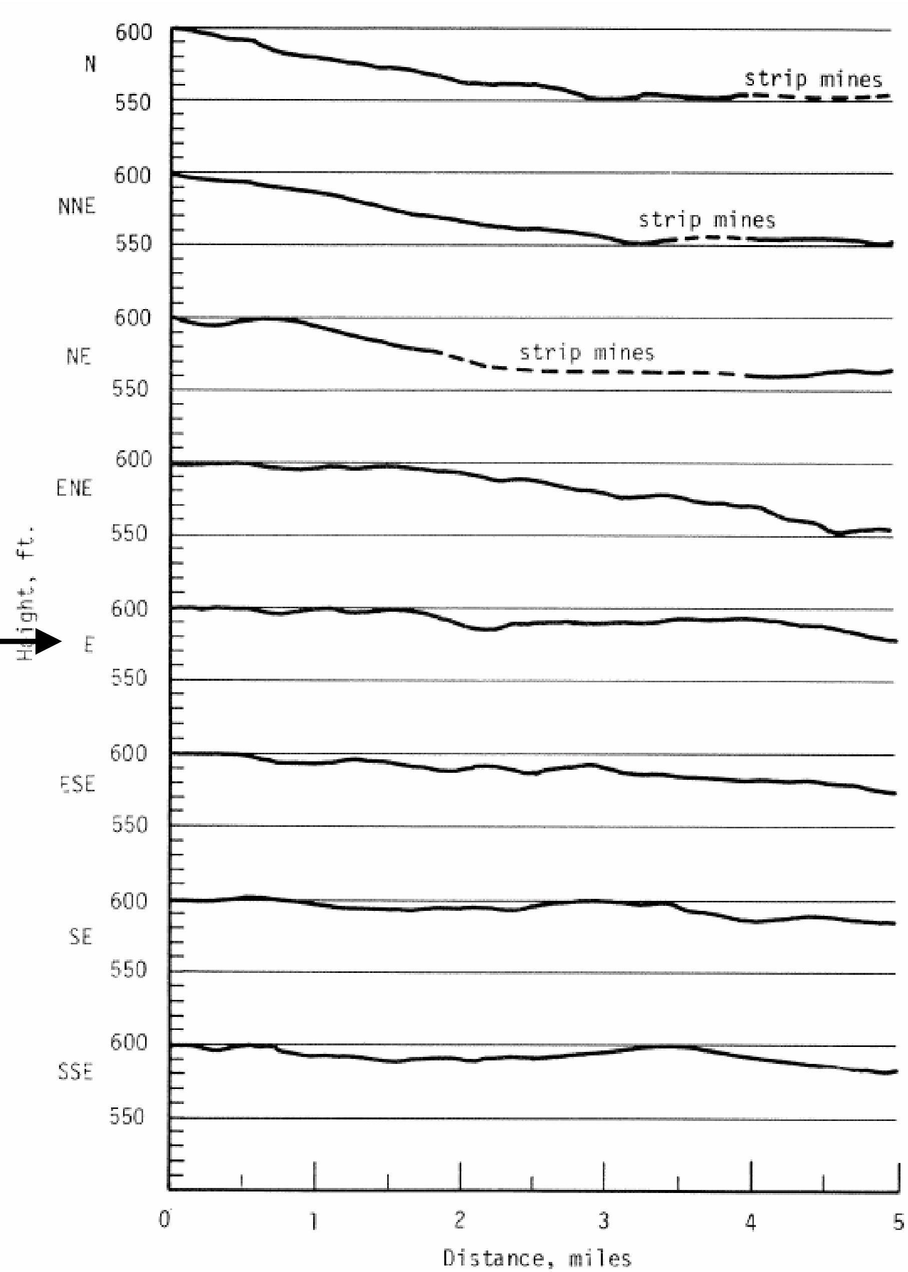
Ref: J. Link, FNAL
http://mwtheta13.uchicago.edu

Braidwood, Il

Elevation Along Experimental Line

The preferred experimental line runs due east from the plant.

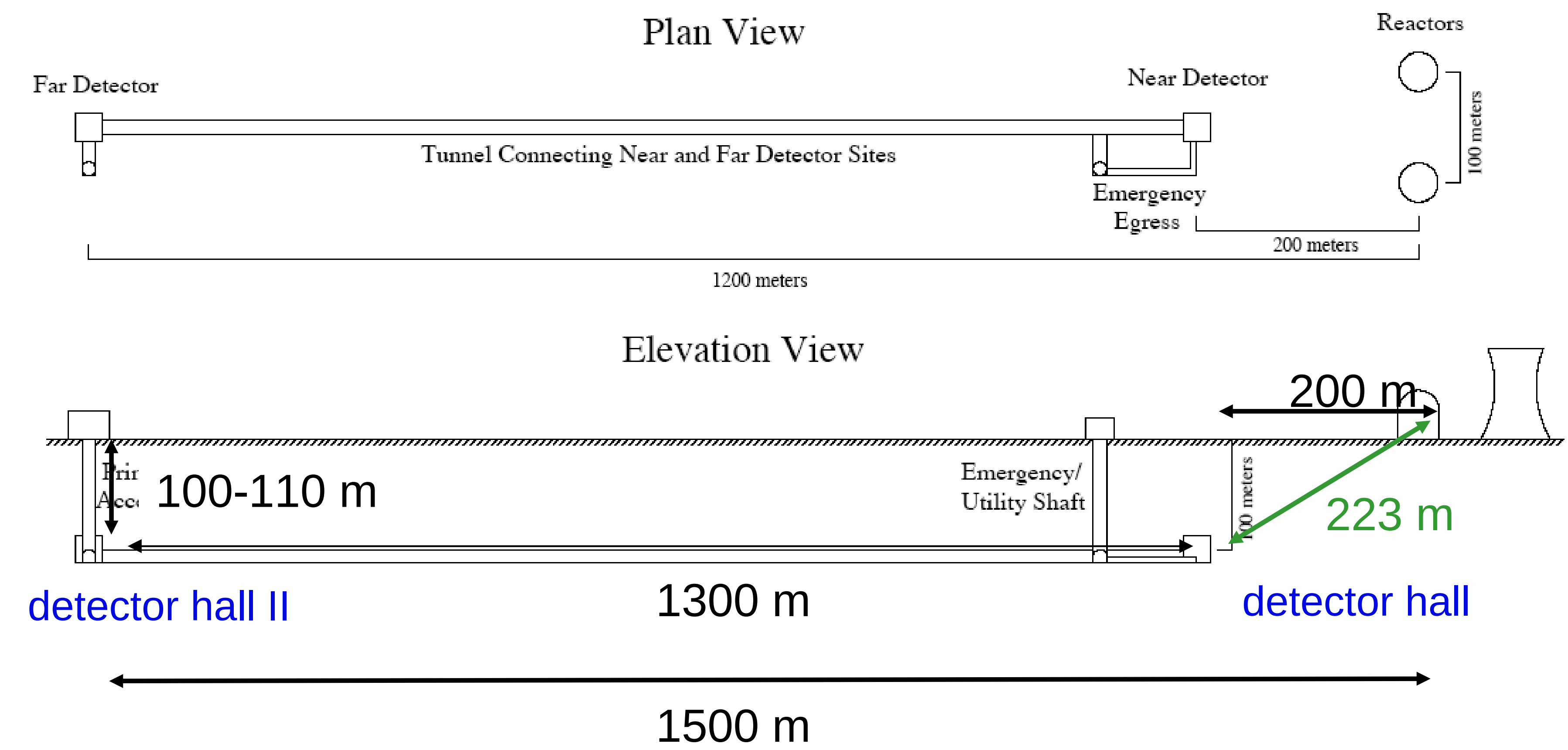
The elevation plot shows it to be flat for over a mile and a half due east of the plant.



Ref: J. Link, FNAL
http://mwtheta13.uchicago.edu

Braidwood, Il

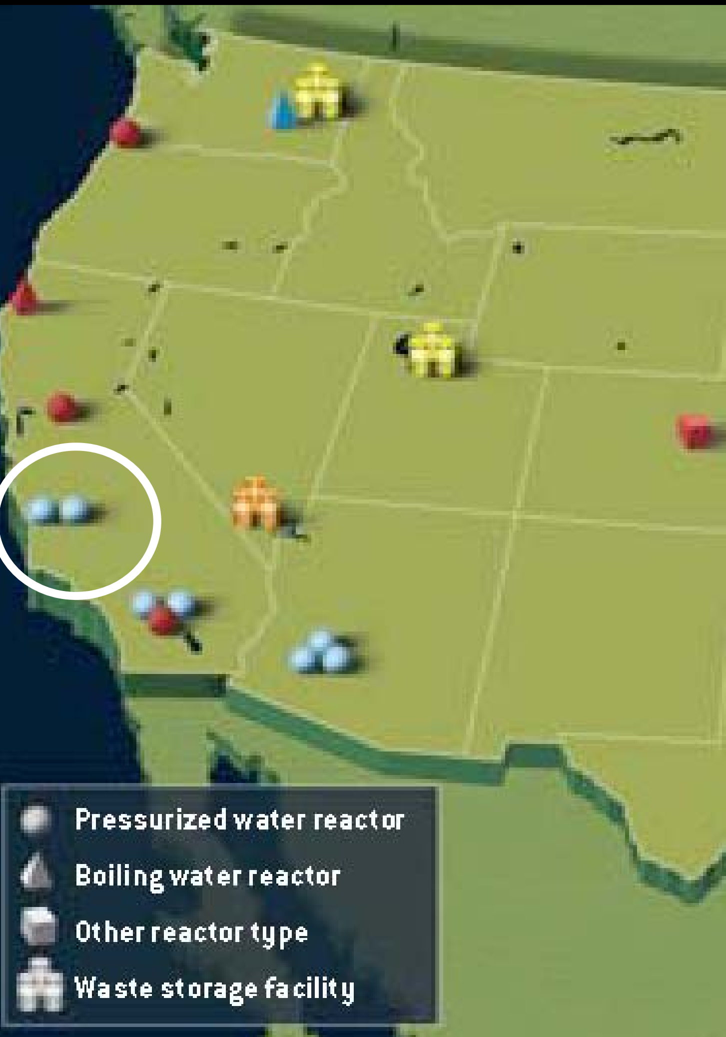
Layout

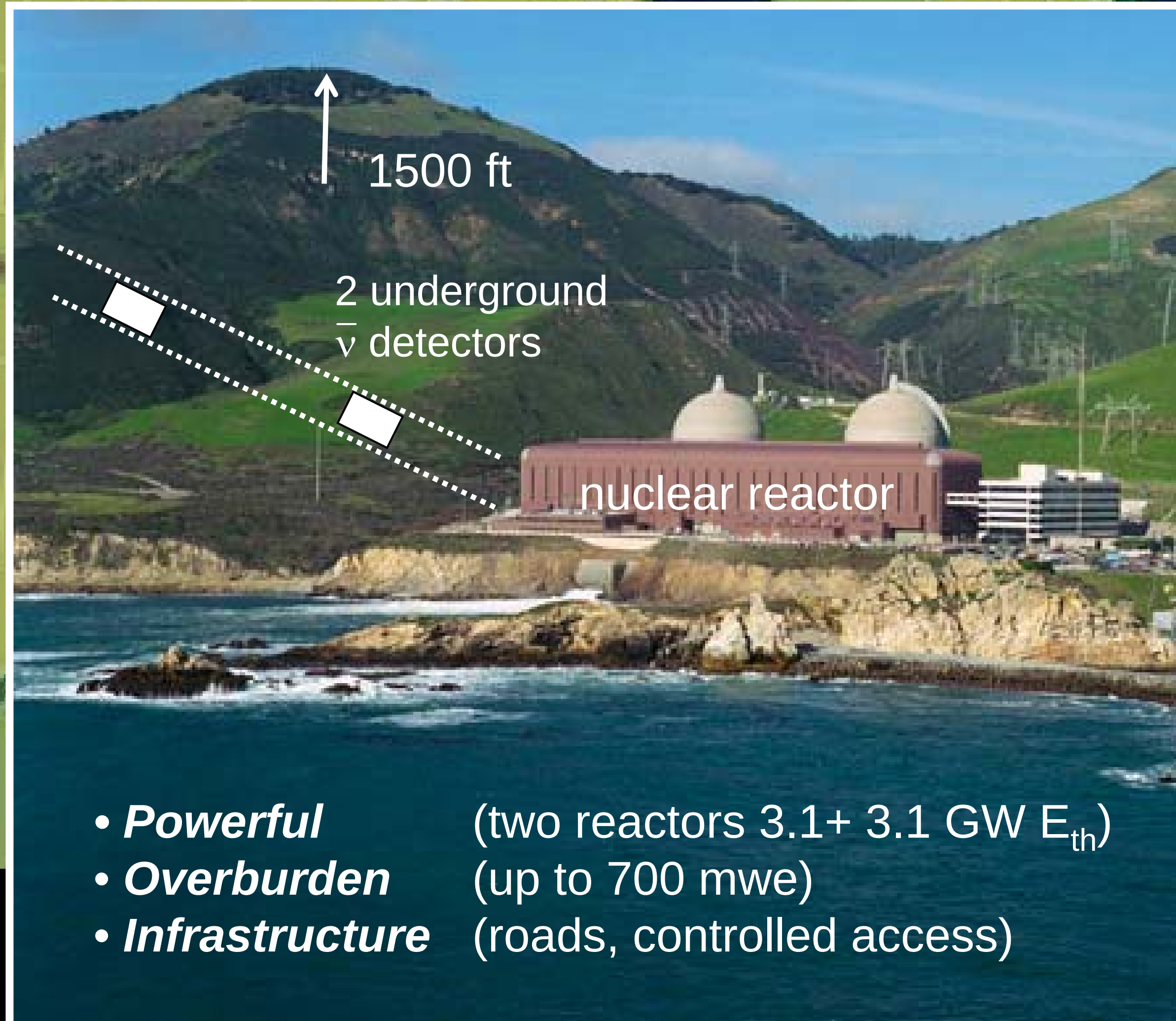


Detector halls suitable for two 6 meters spherical detectors

Ref: theta13 white paper

Diablo Canyon, CA

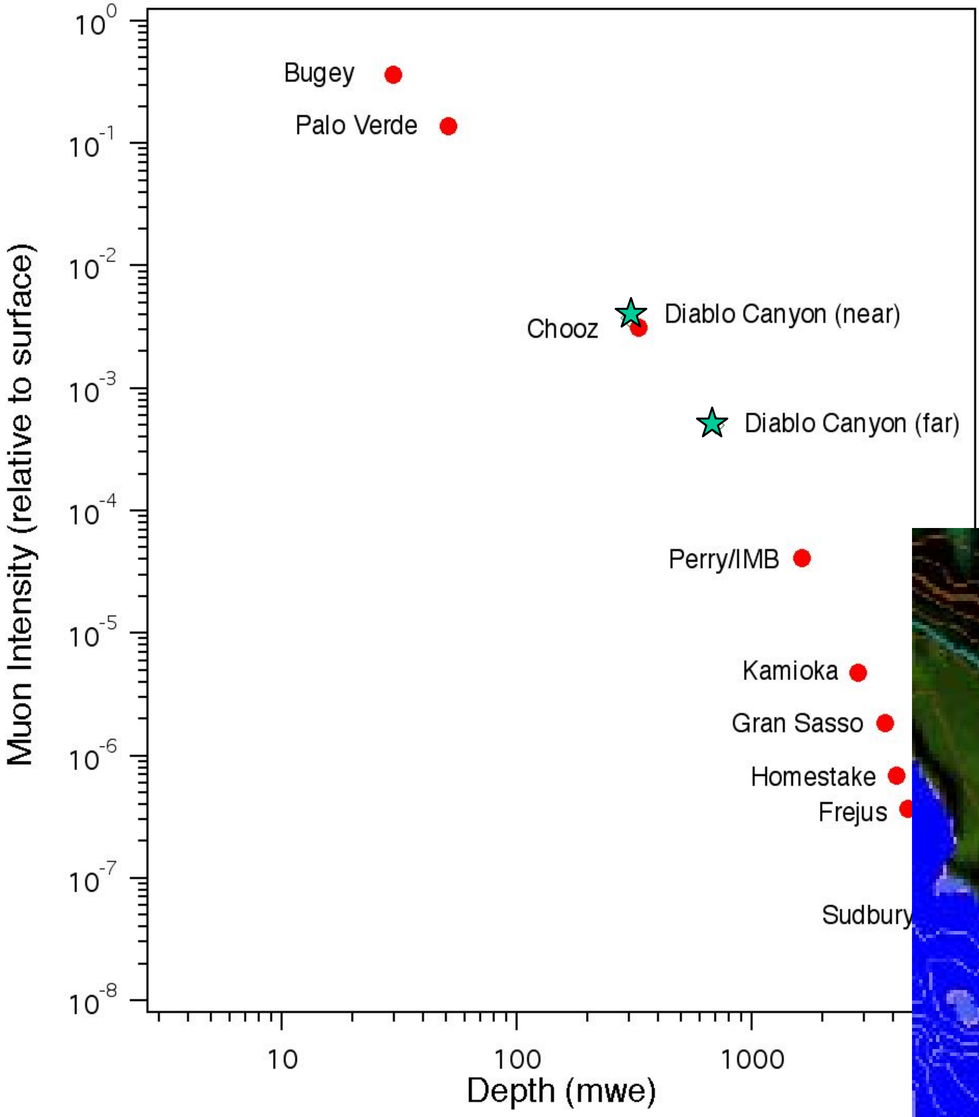


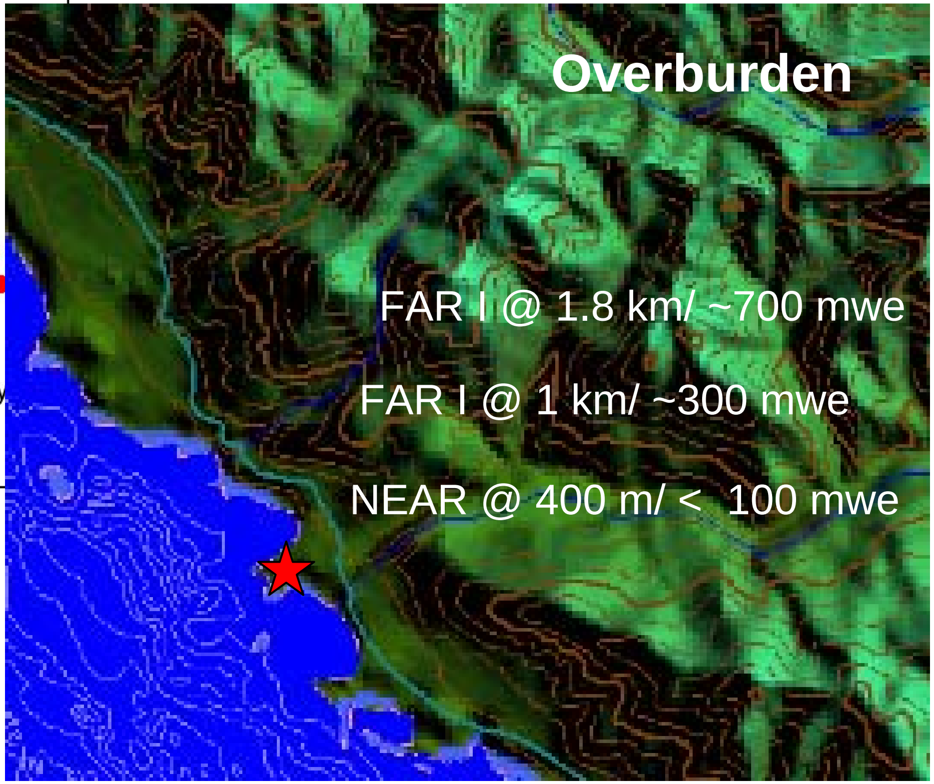


- ***Powerful*** (two reactors 3.1+ 3.1 GW E_{th})
- ***Overburden*** (up to 700 mwe)
- ***Infrastructure*** (roads, controlled access)

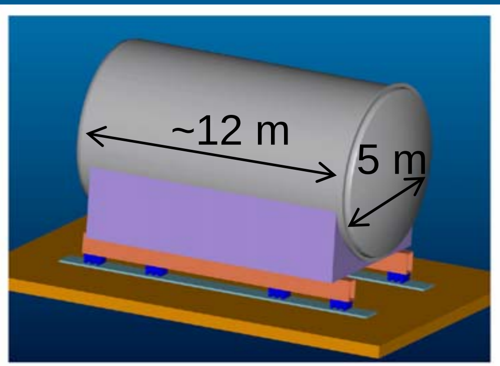

1-2 km
area of landfill and site restoration
area III
area II
area I
> 1 km
0.4 km

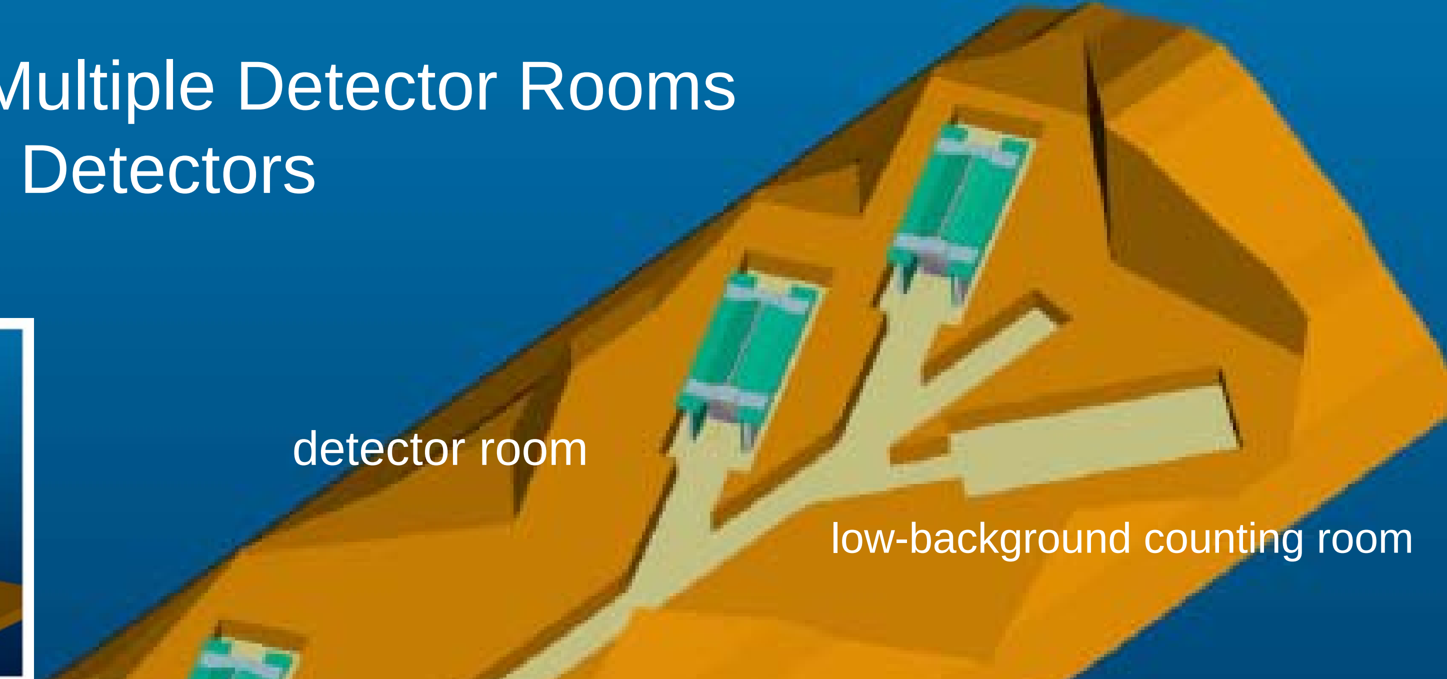
Overburden and Muon Flux

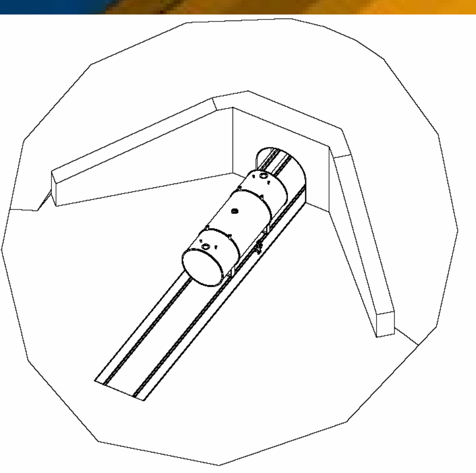




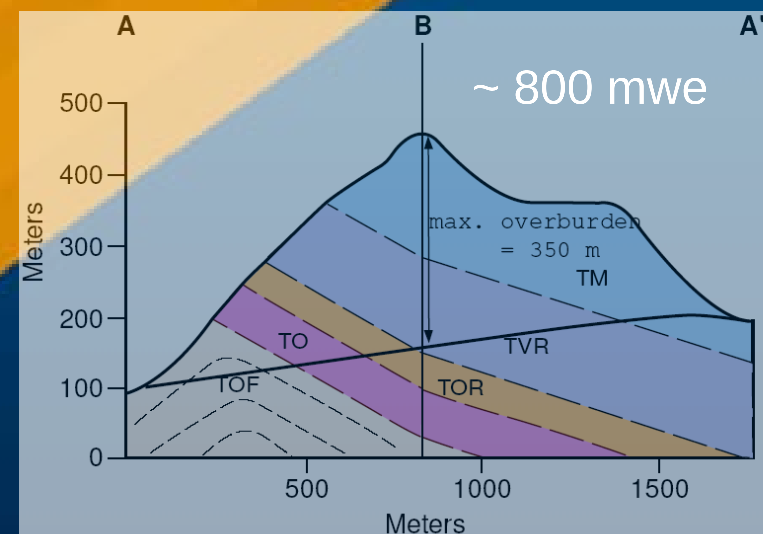
Tunnel with Multiple Detector Rooms and Movable Detectors





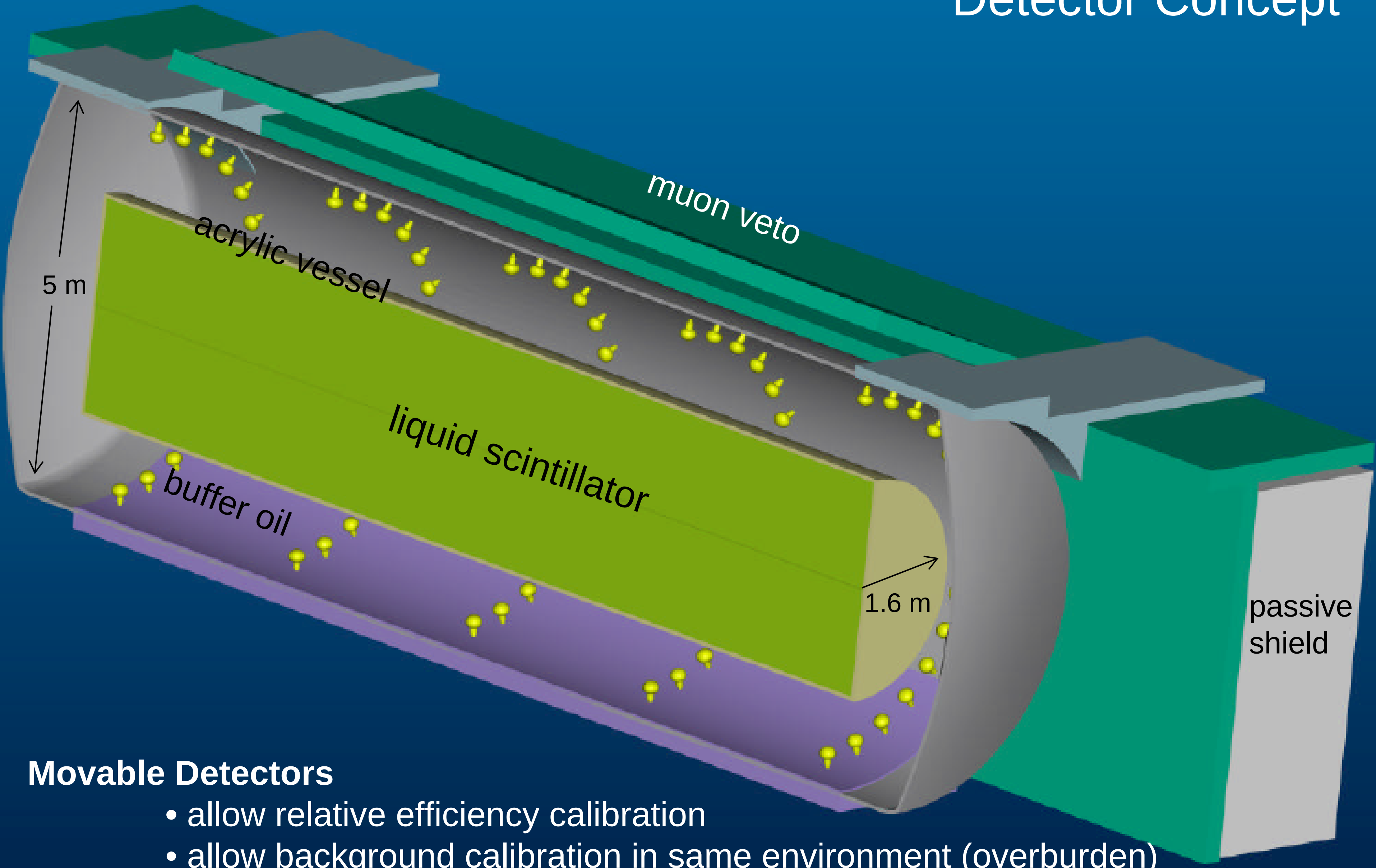


Geology



- Suitable for tunneling
- Opportunity for geoscience program

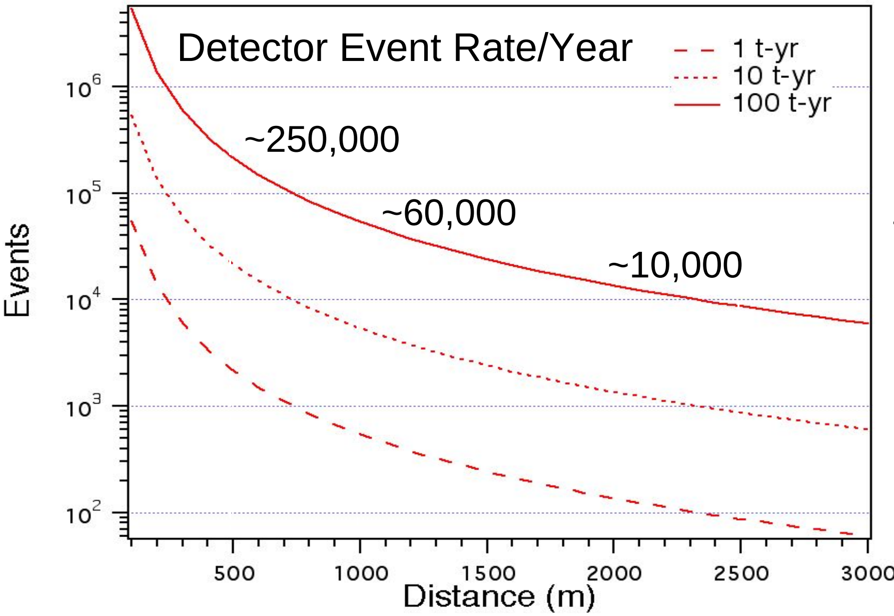
Detector Concept

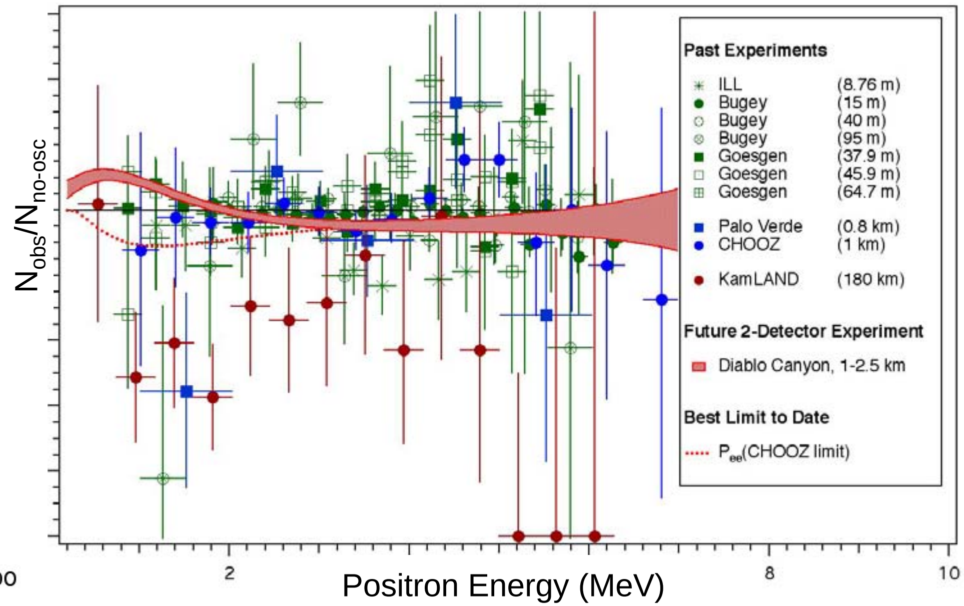


Movable Detectors

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

Statistics and Systematics





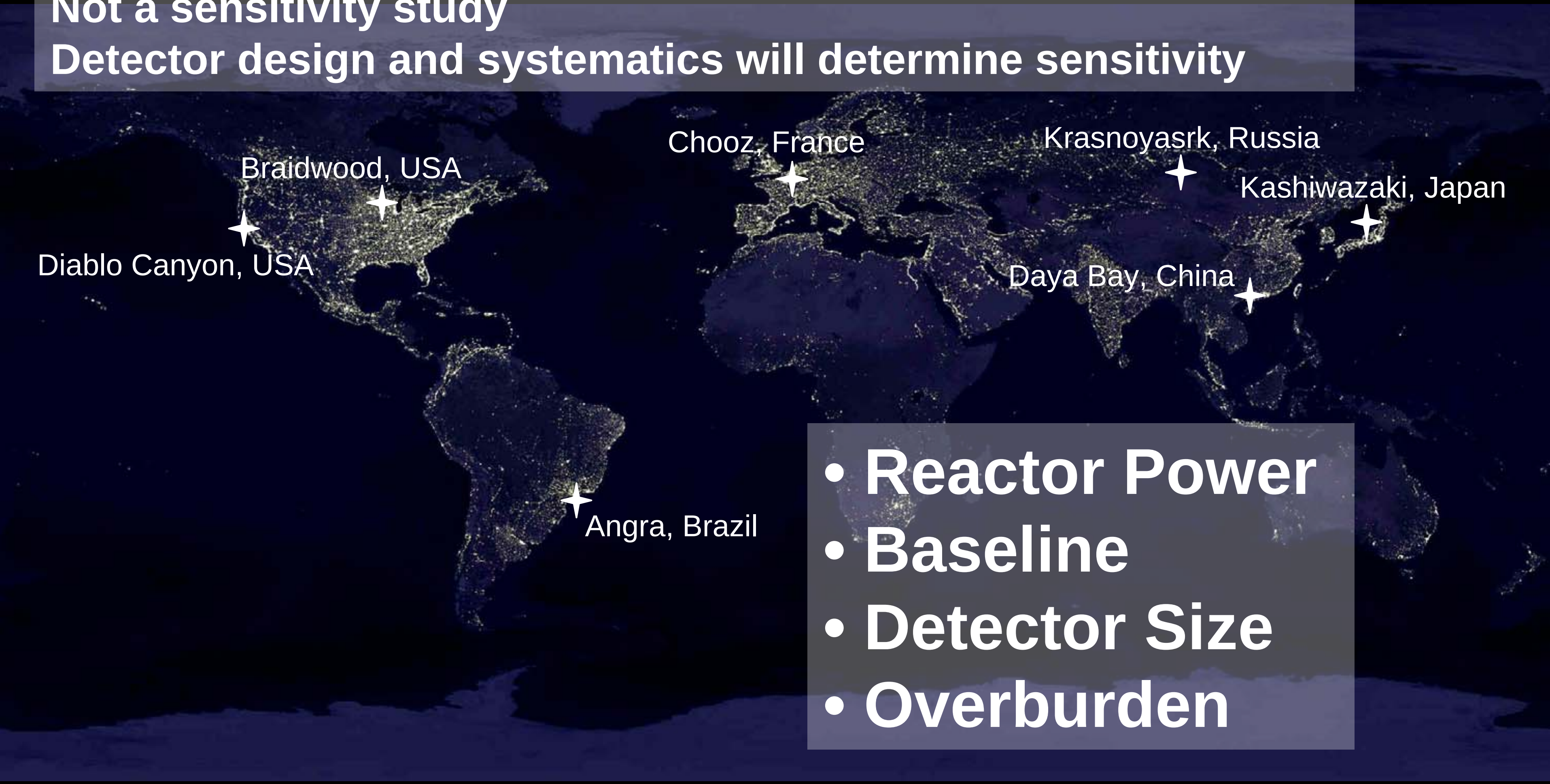
Statistical error: σ_{stat} ~ 0.5% for **L** = 300t-yr

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	$\sigma_{rel\ eff} \leqslant 1\%$
Target Volume &	• no fiducial volume cut	σ_{target} ~ 0.3%
Backgrounds	• external active and passive shielding	$\sigma_{acc} < 0.5\%$ $\sigma_{n\ bkgd} < 1\%$

Total Systematics σ_{syst} ~ 1-1.5%

A Comparison of Site Parameters

Not a sensitivity study
Detector design and systematics will determine sensitivity



- **Reactor Power**
- **Baseline**
- **Detector Size**
- **Overburden**

Constructing a Figure of Merit (I)

statistical precision $$\sigma_{stat} \propto 1/\sqrt{Signal[power, d, volume]}$$

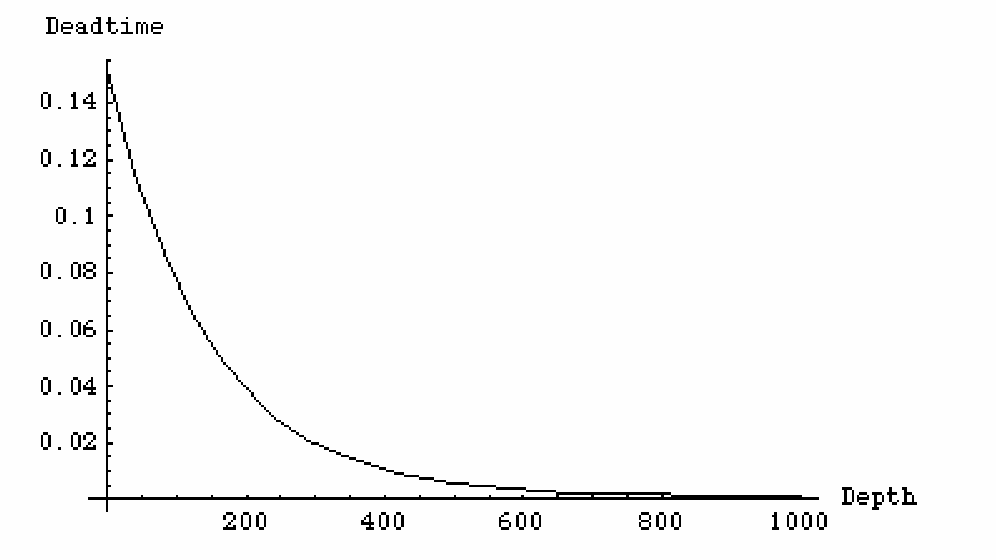
$$FOM1 = \frac{\sqrt{Signal[power, d, volume]}}{\sqrt{Bkgd[depth, volume]}}$$

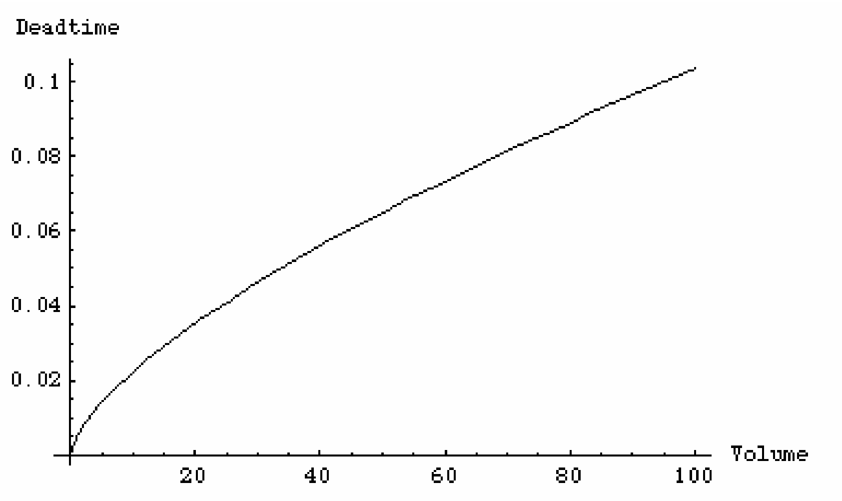
Constructing a Figure of Merit (II)

Chooz 2% deadtime

Detector deadtime

$$Deadtime[depth,volume] = 0.02 \times \frac{Muonrate[depth,volume]}{Muonrate[300,8.5]}$$





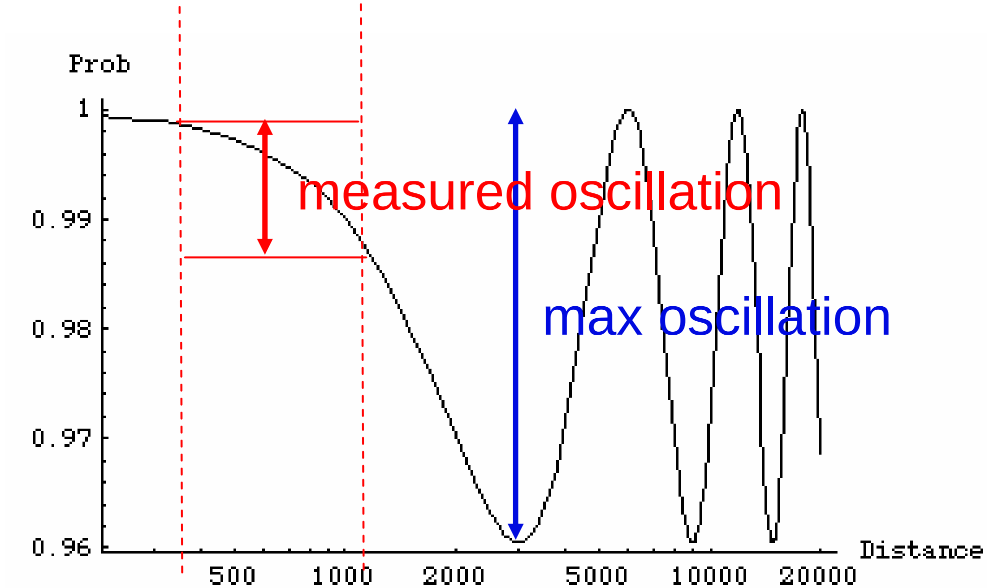
$$FOM2 = \frac{\sqrt{Signal[power,d,volume]**(1-Deadtime[depth,volume])}}{\sqrt{Bkgd[depth,volume]}}$$

Constructing a Figure of Merit (III)

Oscillation Sensitivity

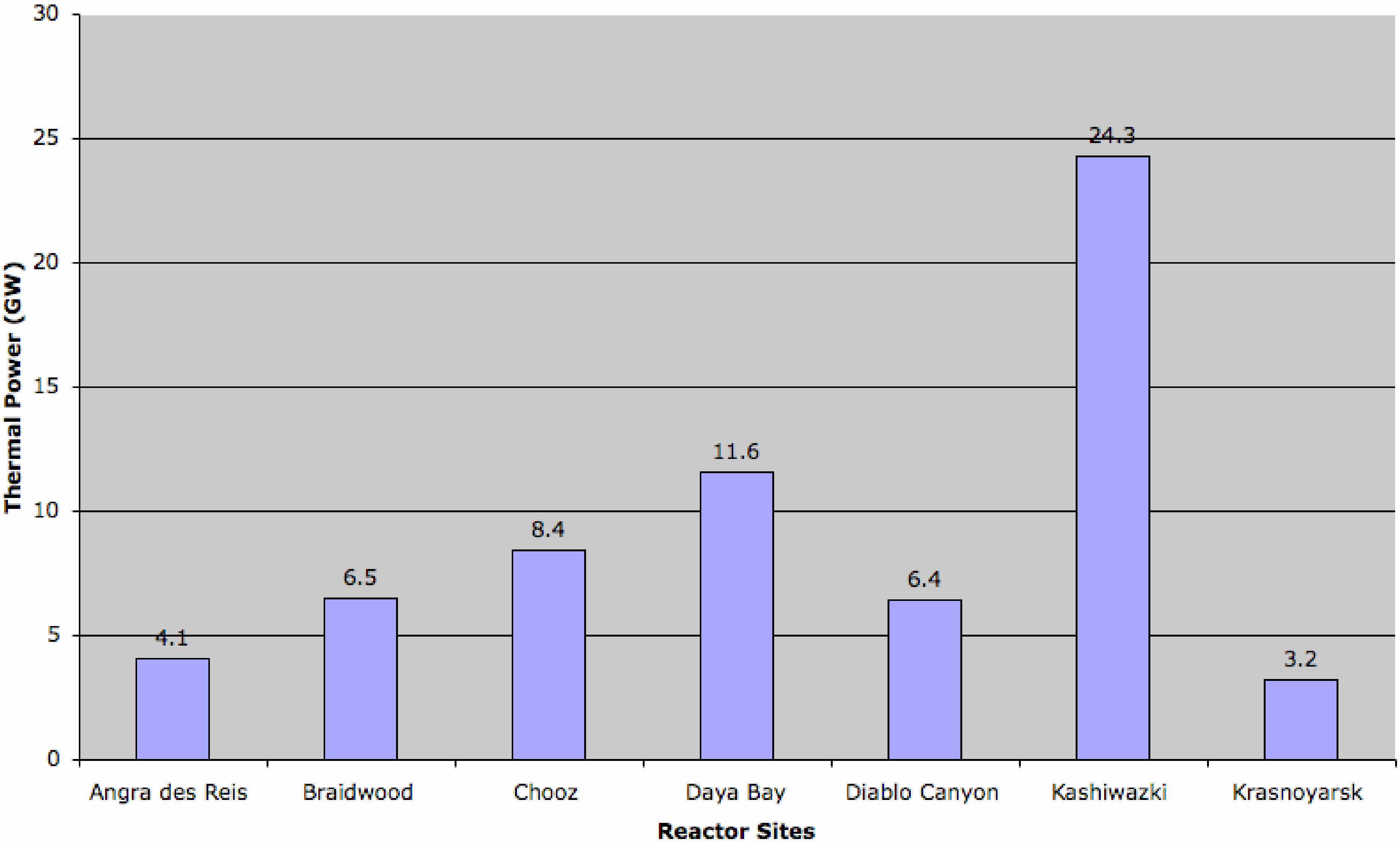
$$FractionofMaxOsc[d] = \left(1 - \frac{\Pr ob[d_1]}{\Pr ob[d_2]}\right) \Big/ \left(1 - \frac{\Pr ob[0]}{\Pr ob[d_{\min}]}\right)$$

measured osc — max osc

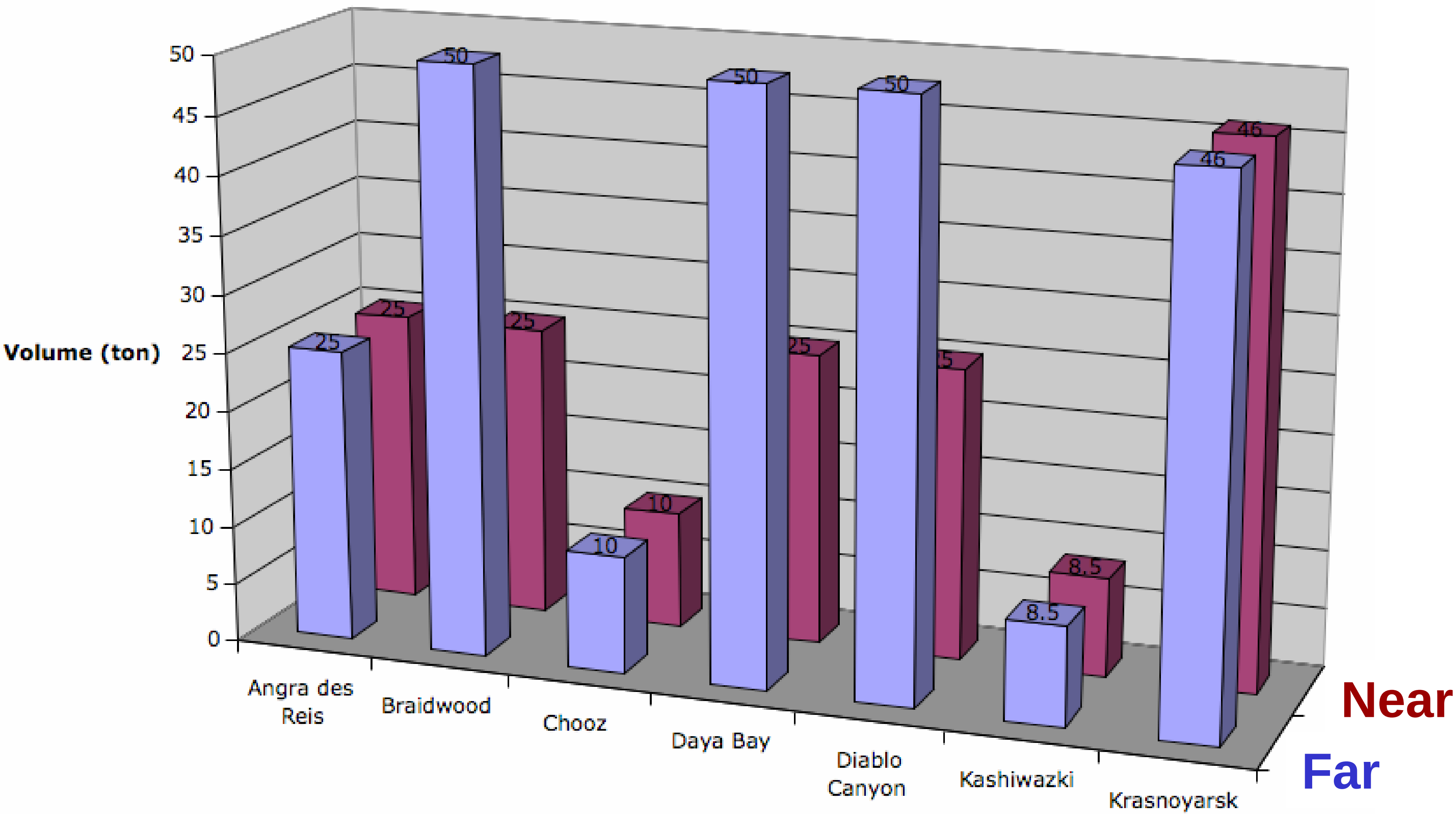


$$FOM3 = \frac{\sqrt{Signal[power,d,volume]*(1-Deadtime[depth,volume])}}{\sqrt{Bkgd[depth,volume]}} \times FractionofMaxOsc[d]$$

Thermal Reactor Power

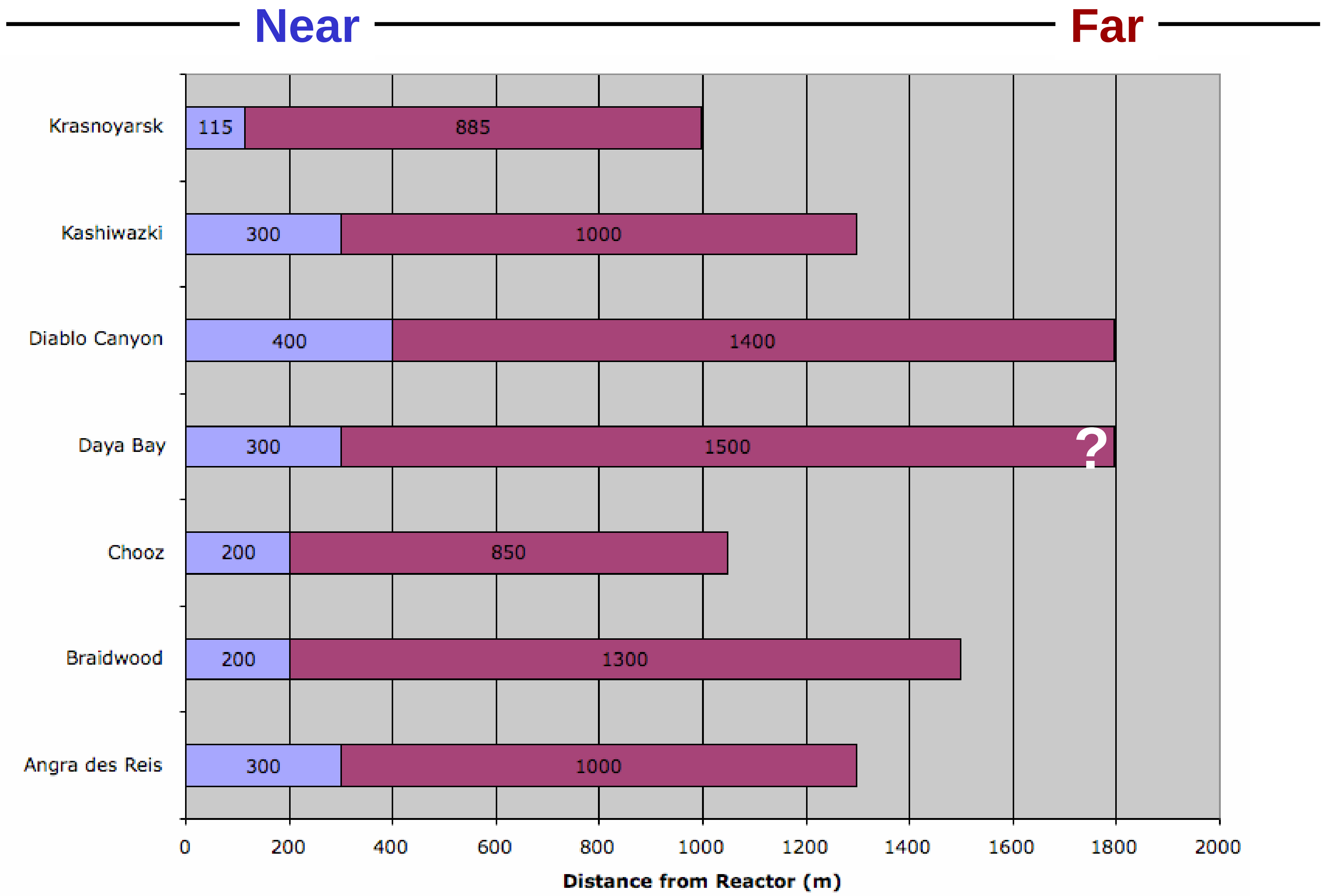


Detector Volumes



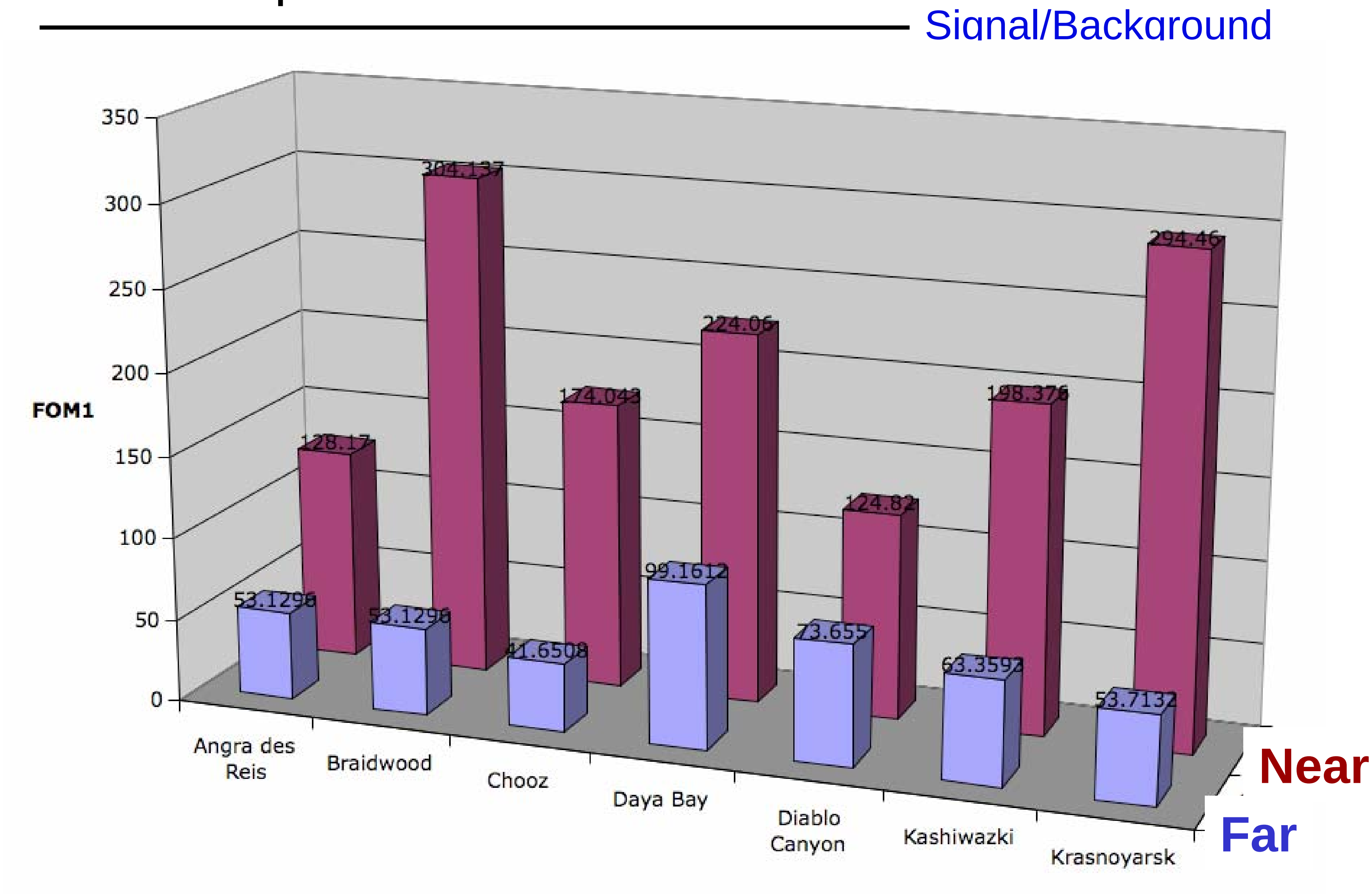
Volume assumptions based on recent talks, papers, and discussions.

Baselines



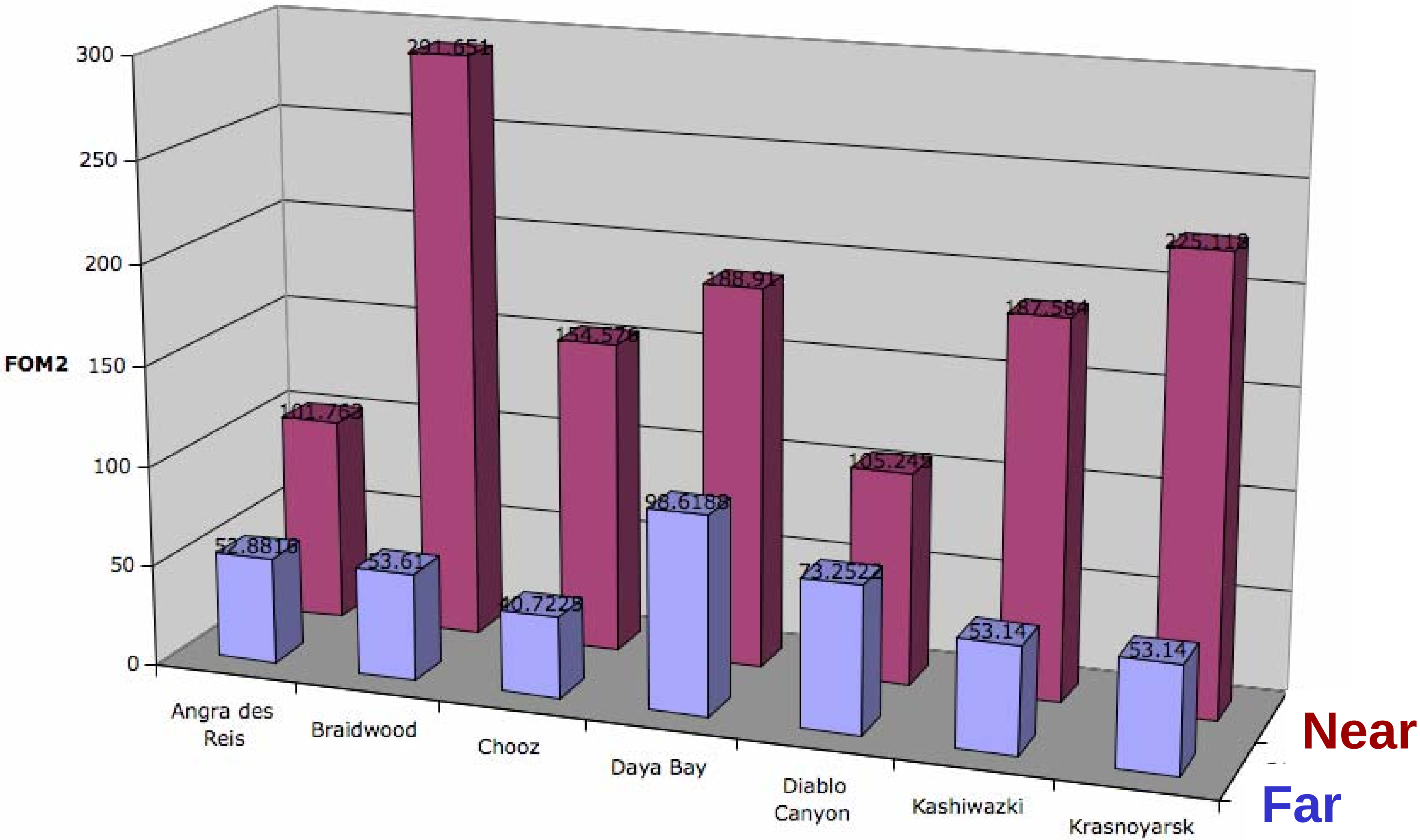
Near
Far
Krasnoyarsk
115
885
Kashiwazki
300
1000
Diablo Canyon
400
1400
Daya Bay
300
1500
?
Chooz
200
850
Braidwood
200
1300
Angra des Reis
300
1000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Distance from Reactor (m)

Site Comparison



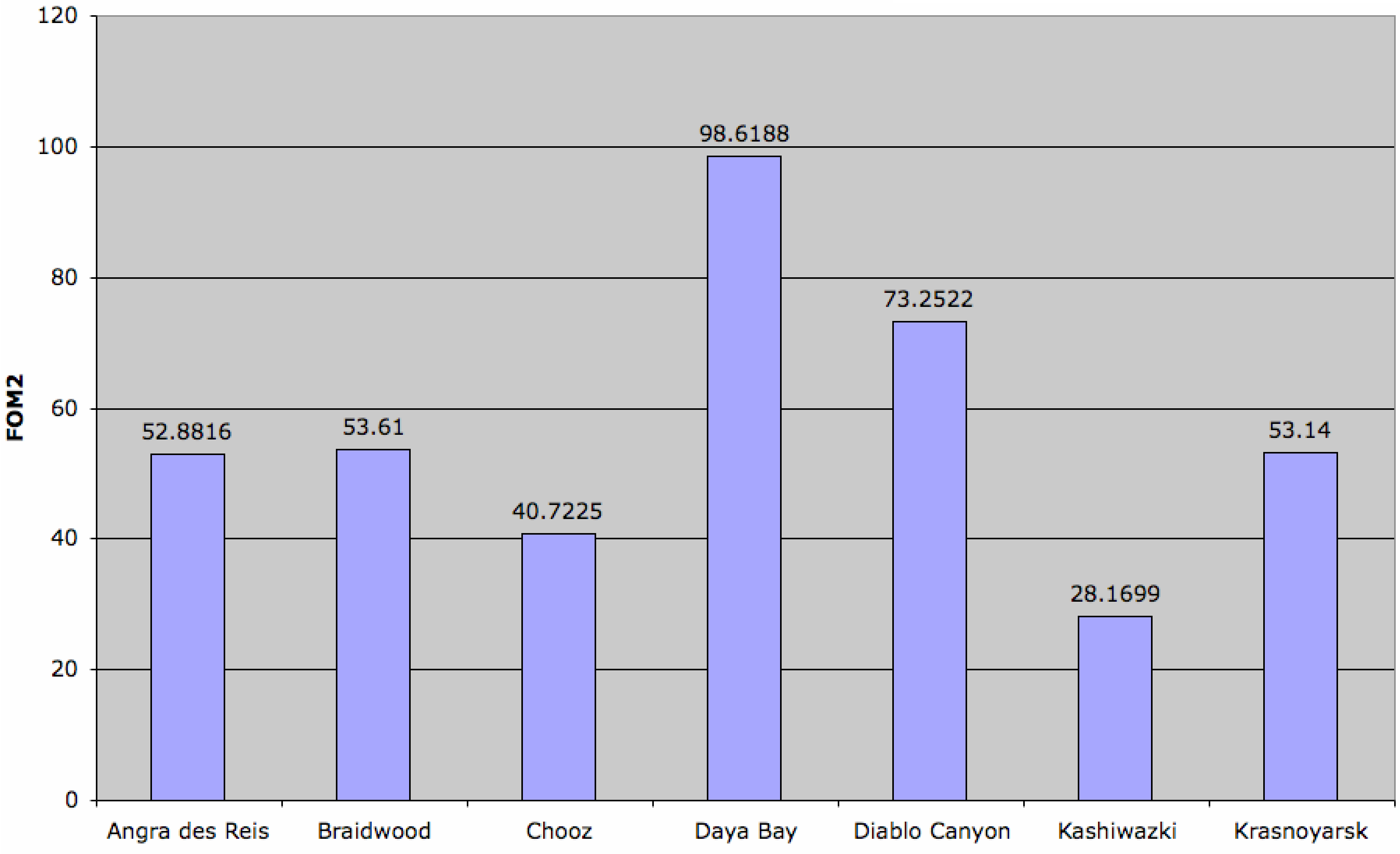
Site Comparison

SignalxLivetime/Background



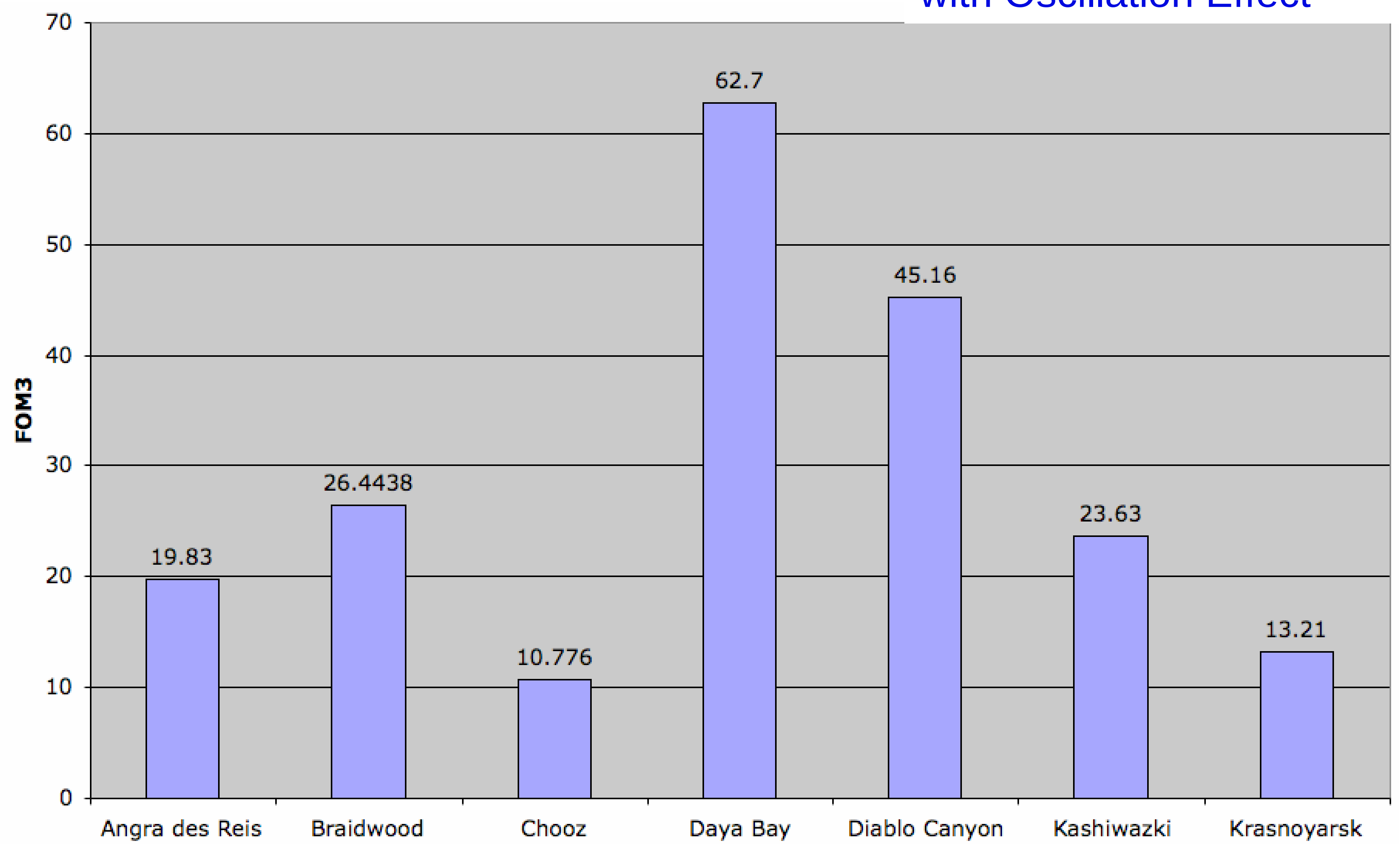
Site Comparison

Far Detector Performance
without Oscillation Effect



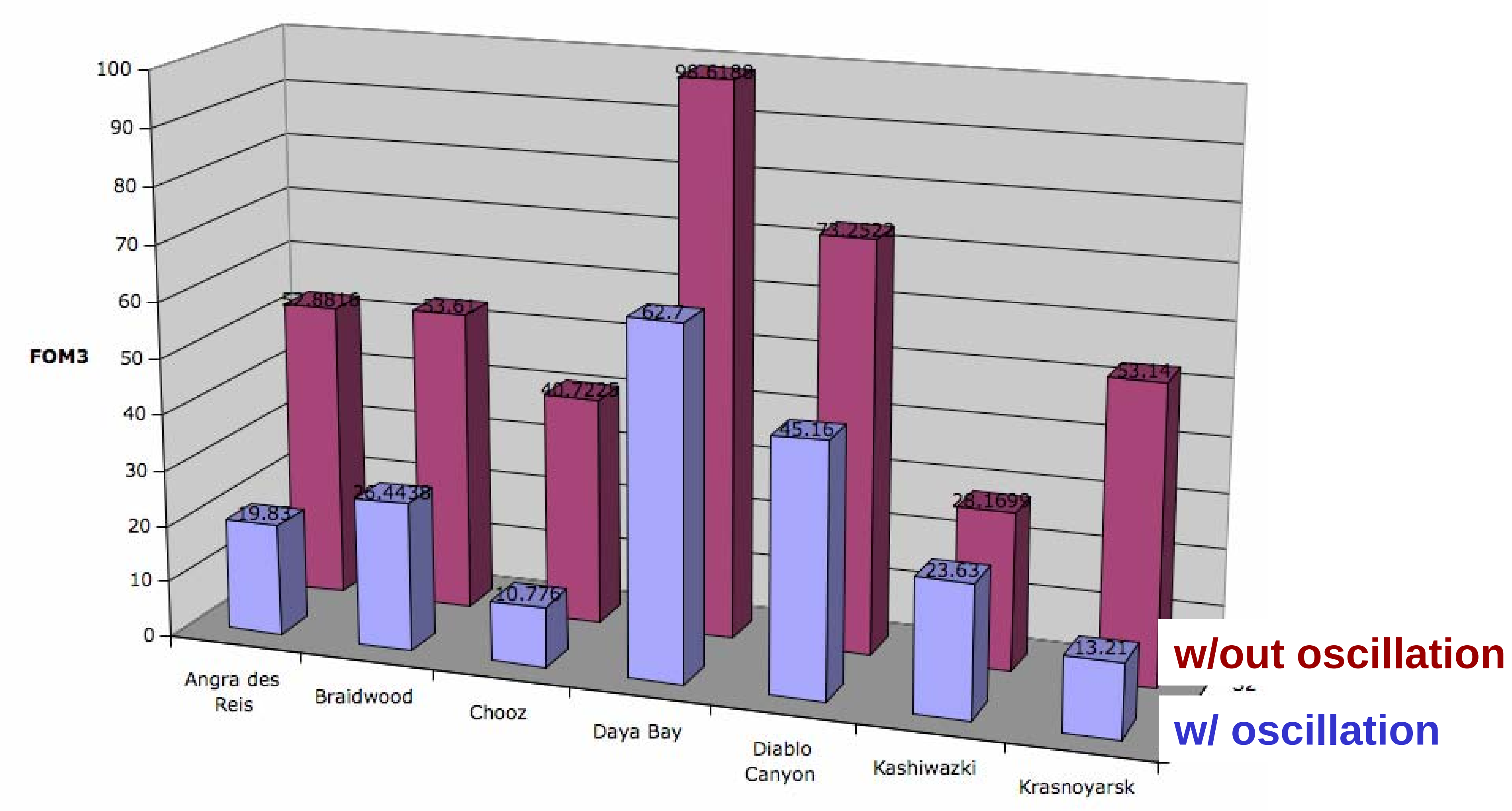
Site Comparison

Far Detector Performance with Oscillation Effect

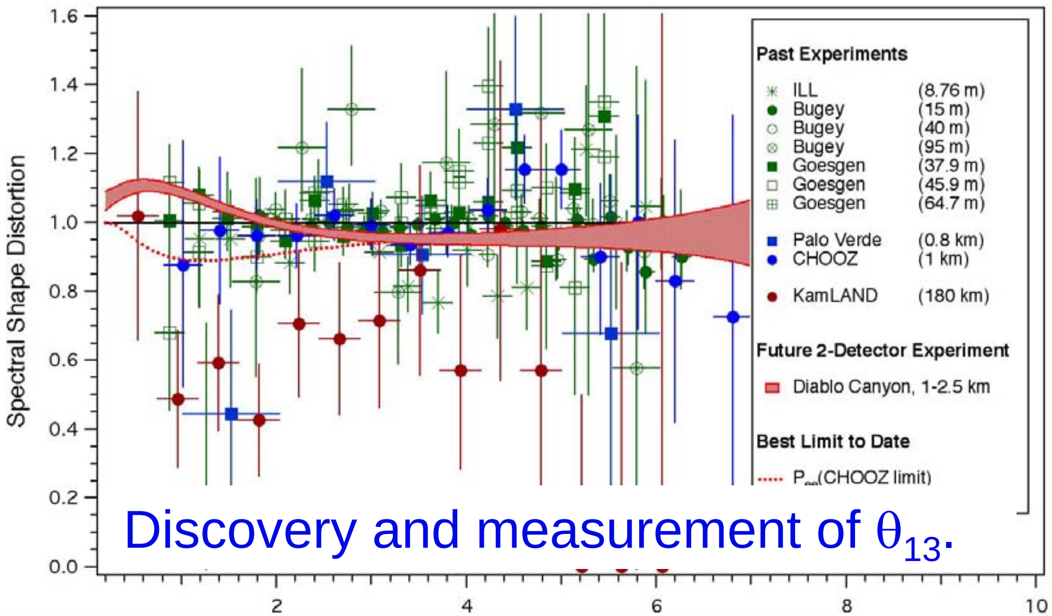


Site Comparison

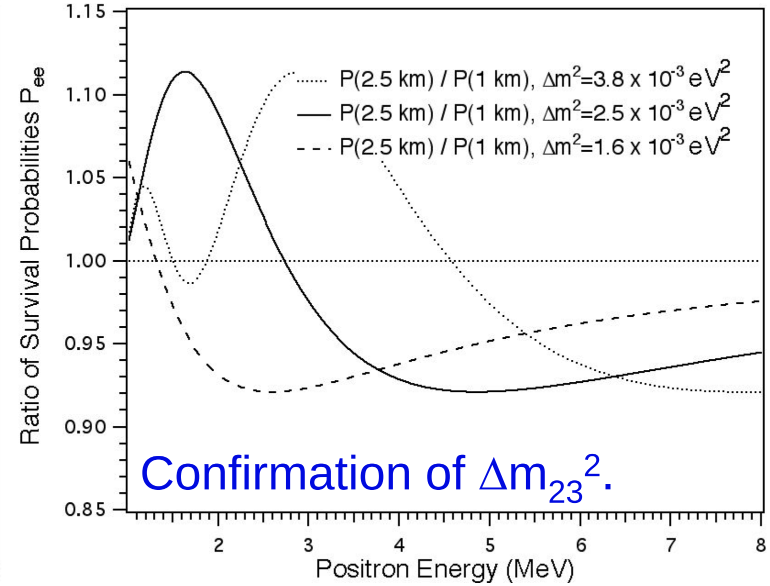
Far Detector Performance with and without Oscillation Effect



Goals of a Reactor Neutrino Oscillation Experiment

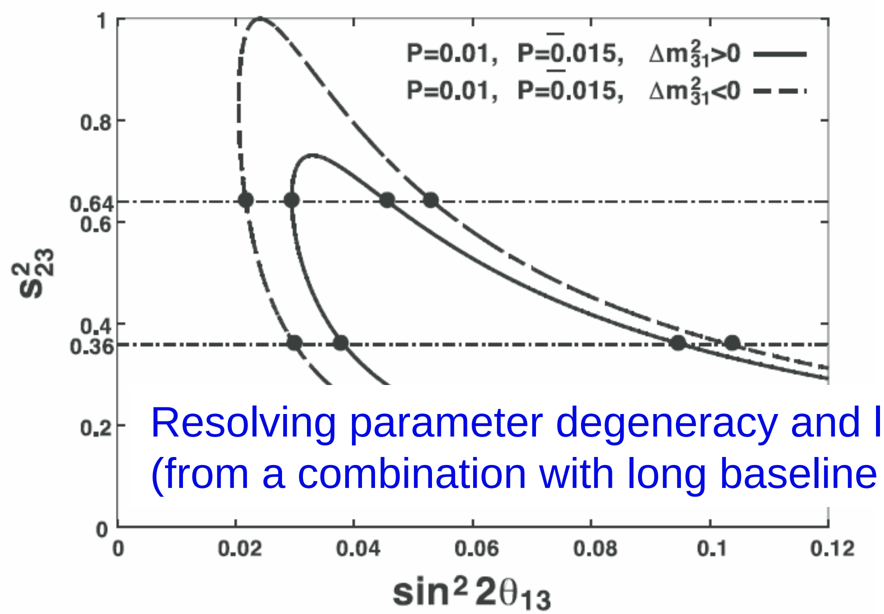


Discovery and measurement of θ_{13}.

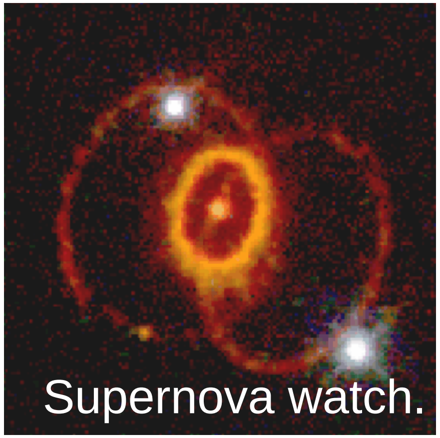


Confirmation of Δm_{23}^2.

Search for the effect of sterile ν.



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



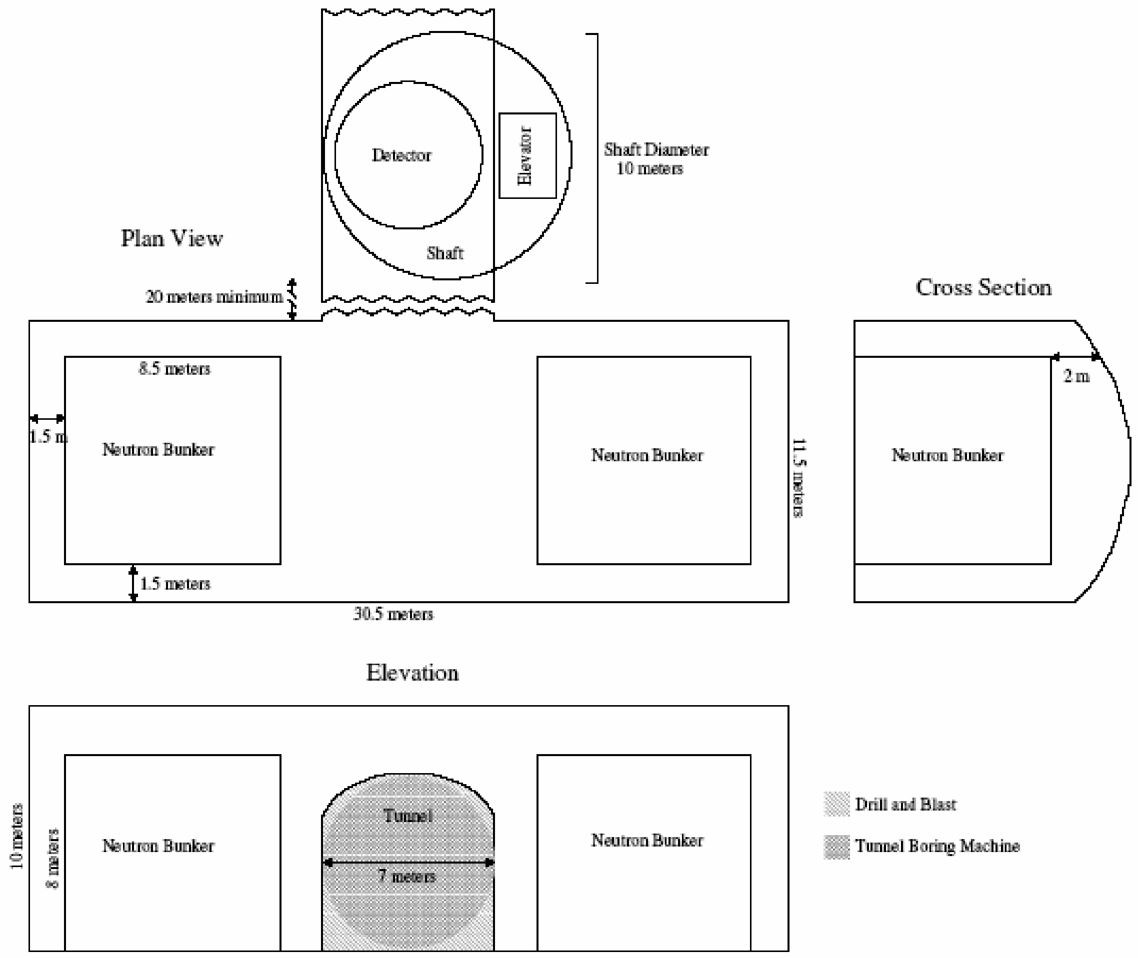
Supernova watch.

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)	< 0.01-0.02	< 2.9	[2009]
Chooz-II (France)	< 0.03	< 5.0	[2009]
Daya Bay (China)			
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.

Detector Hall Baseline

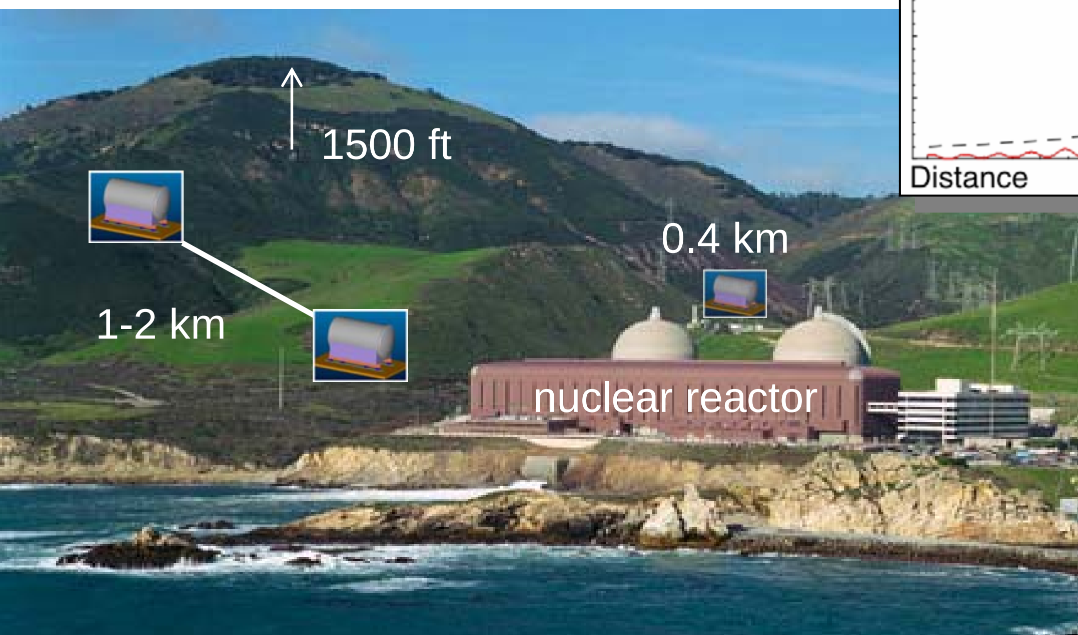


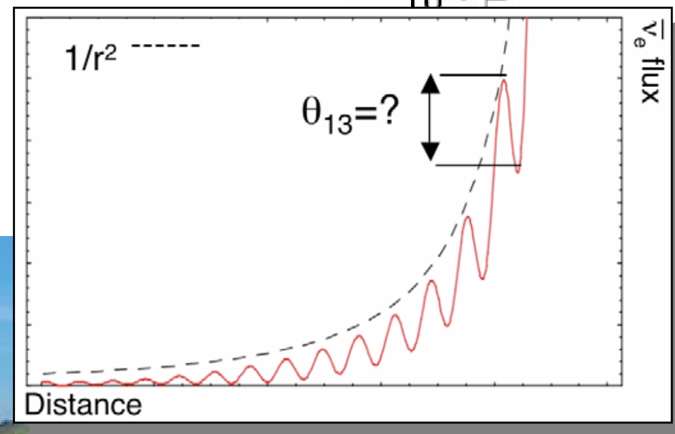
Measuring θ_{13} with Reactor Neutrinos

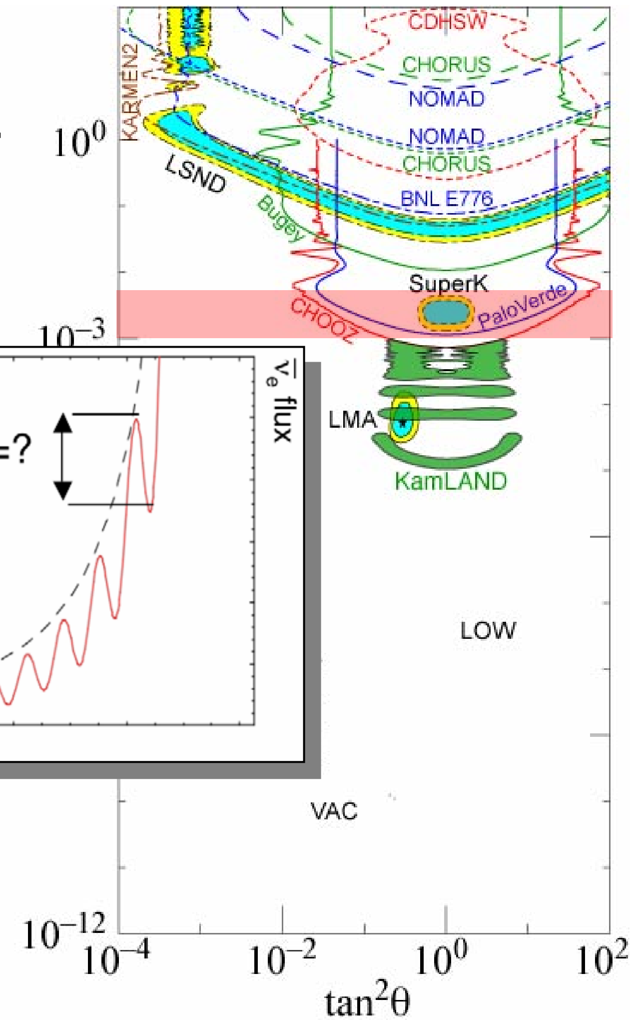
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}{}^2 L}{4E_\nu} + \left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right) \cos^4 \theta_{13} \sin^2 2\theta_{12}$$

$$- \sin^2 2\theta_{sterile} \sin^2 \frac{\Delta m_{sterile}{}^2 L}{4E_\nu}$$

atmospheric frequency dominant,
sterile contribution possible







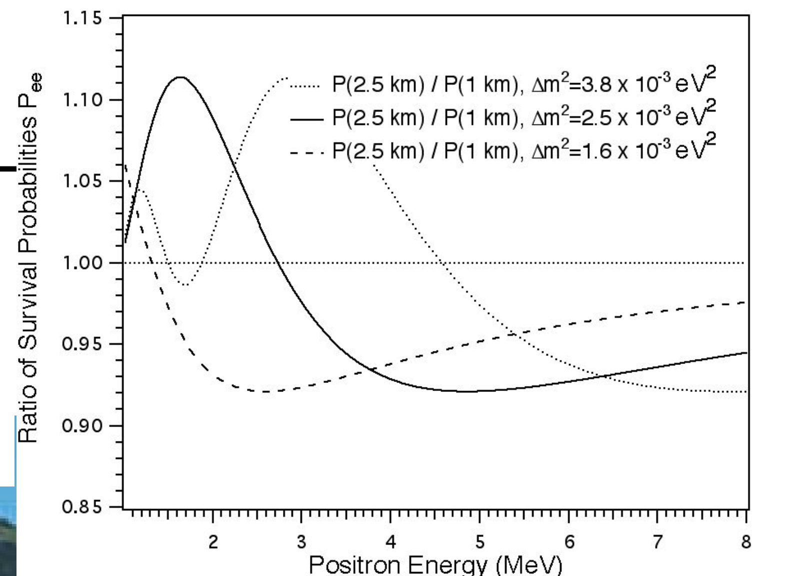
- 2-3 underground scintillator $\overline{\nu}$ detectors, 50-100 t
- study relative rate difference and spectral distortions
- projected sensitivity: $\sin^2 2\theta_{13} \approx 0.01\text{-}0.02$

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

coincidence signal
prompt e^+ annihilation
delayed n capture (in μs)

Detector Baseline

- Detector baselines sensitive to Δm_{atm}^2.
- Tunnel (1-2 km) + fixed detector (0.4 km) preserves option to adjust/optimize baseline



Near detector

Normalizes flux for rate analysis.

Far detectors

Useful for shape analysis, more robust to Δm_{atm}^2.