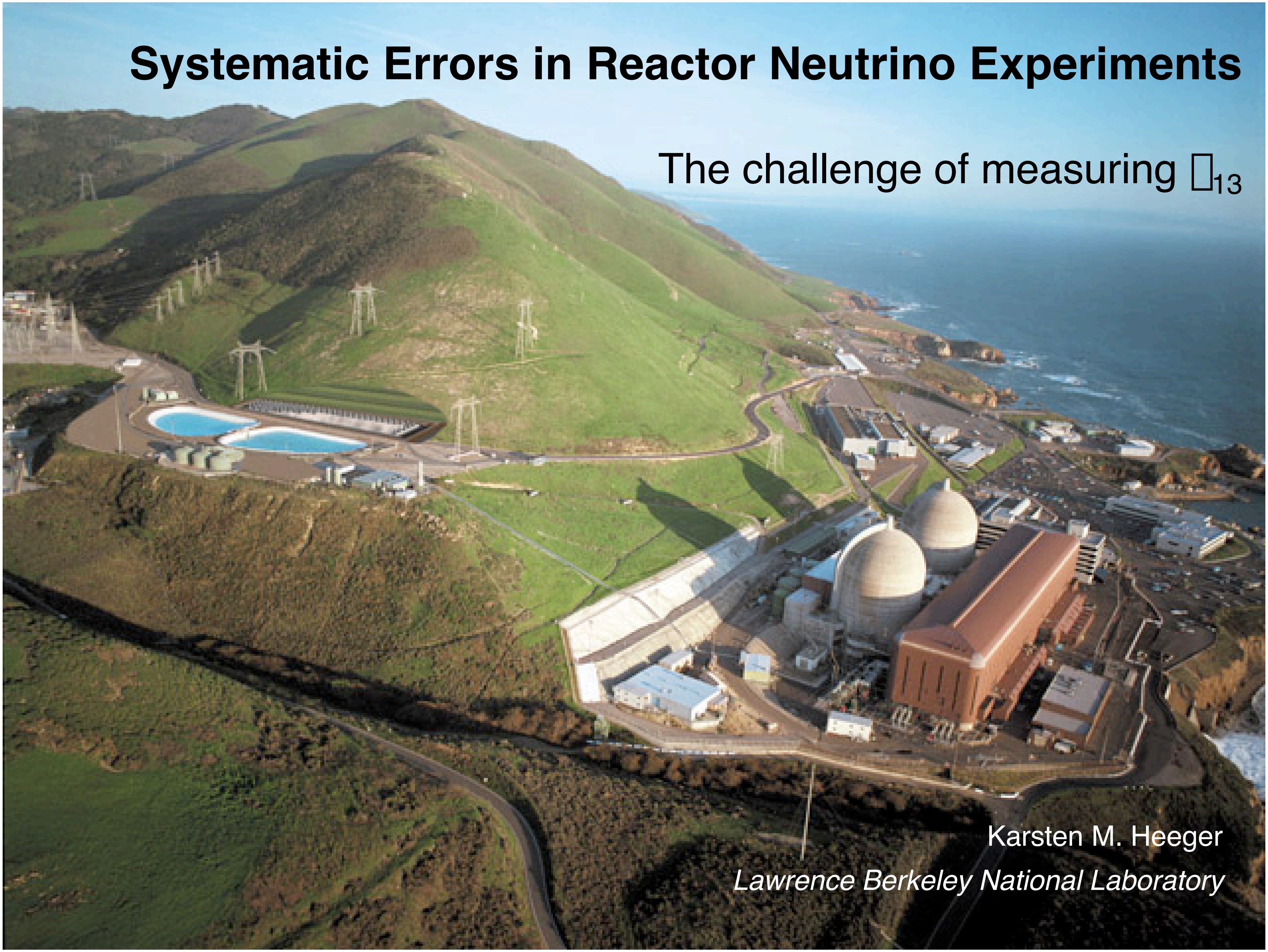
Systematic Errors in Reactor Neutrino Experiments

The challenge of measuring θ_{13}



Karsten M. Heeger
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Outline

Past and Present Experiments	**absolute measurements**
KamLAND	1 fixed detector
CHOOZ	1 fixed detector
Overview of Backgrounds and Systematics	
Detector Systematics	
Backgrounds	
Proposals for Next Generation Experiments	**relative measurements**
Kashiwazaki	3 fixed detectors
CHOOZ II?	2 fixed detectors
Diablo Canyon, Wolf Creek	2+ detectors with variable baseline

rate vs shape measurements of θ_{13}

KamLAND - Kamioka Liquid Scintillator Antineutrino Detector

Uses reactor neutrinos to study ν oscillation with a baseline of L ~ 140-210 km

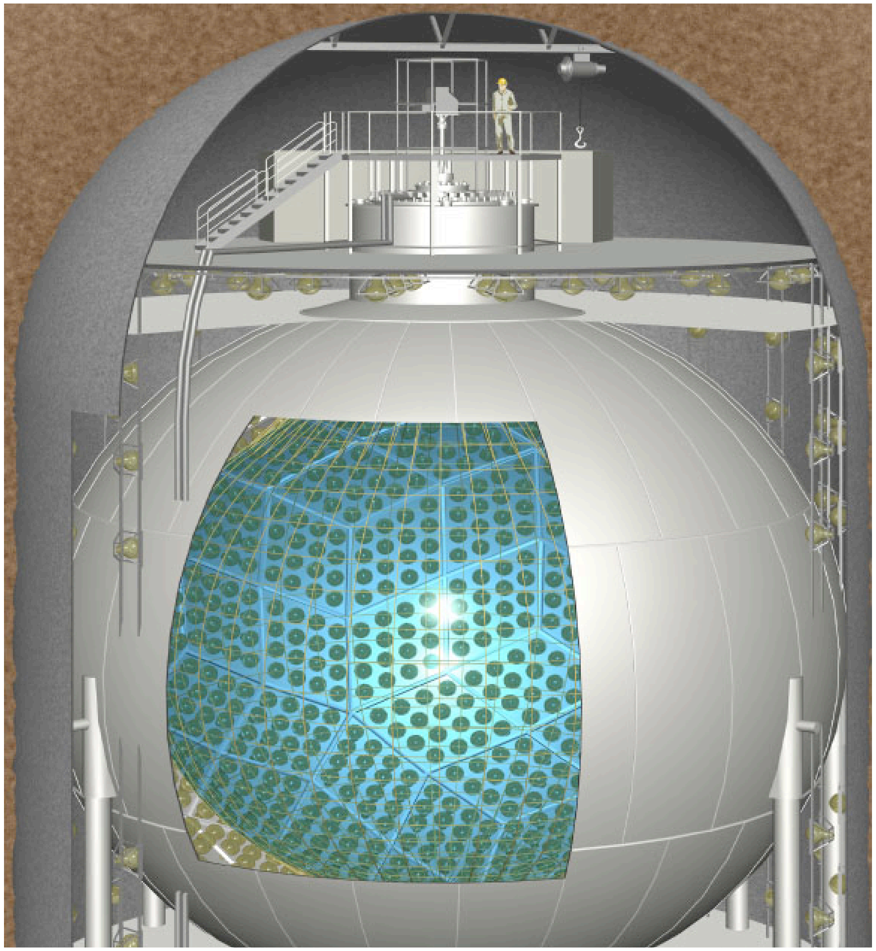
Coincidence Signal: $\bar{\nu}_e + p \rightarrow e^+ + n$

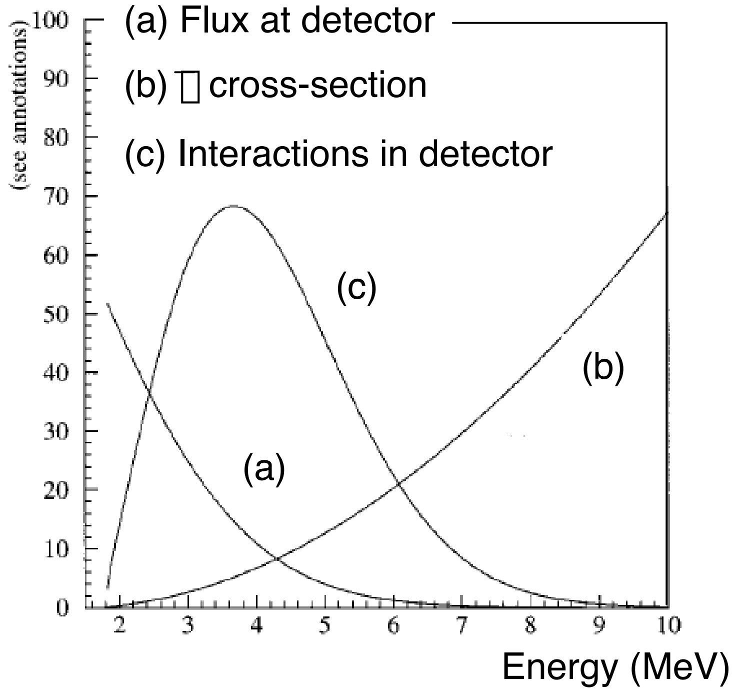
Prompt e^+ annihilation

Delayed n capture

time correlation □□ 200 μs

space correlation < 1m





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

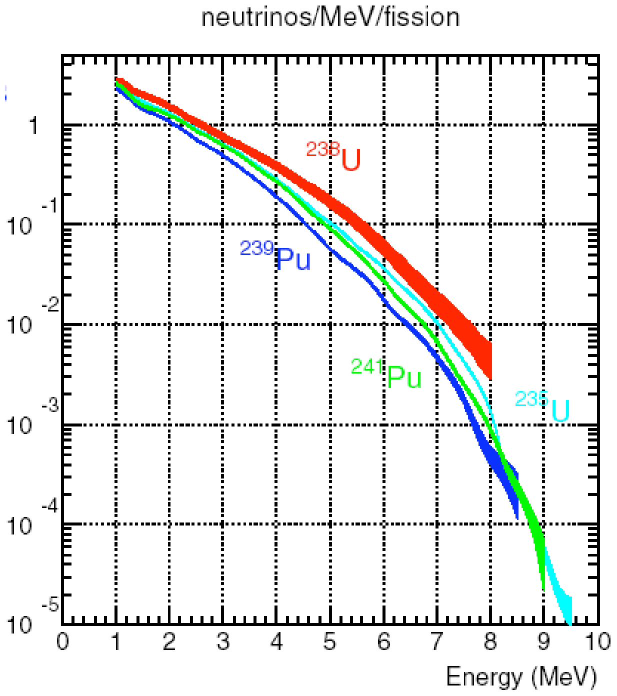
- interaction rate
- energy spectrum

Systematics in an Absolute Measurement

kinetic energy spectrum x detector response function

- thermal power
- fuel composition and time dependence

  number of fissions ()



- target volume/mass
- reaction cross-section
- candidate event selection
  - detection efficiency
- energy response and threshold
- time variation of detector response
- backgrounds
  - physics events
  - radioactivity
  - cosmic rays
    - correlated
    - accidental

KamLAND - Systematic Uncertainties

E > 2.6 MeV

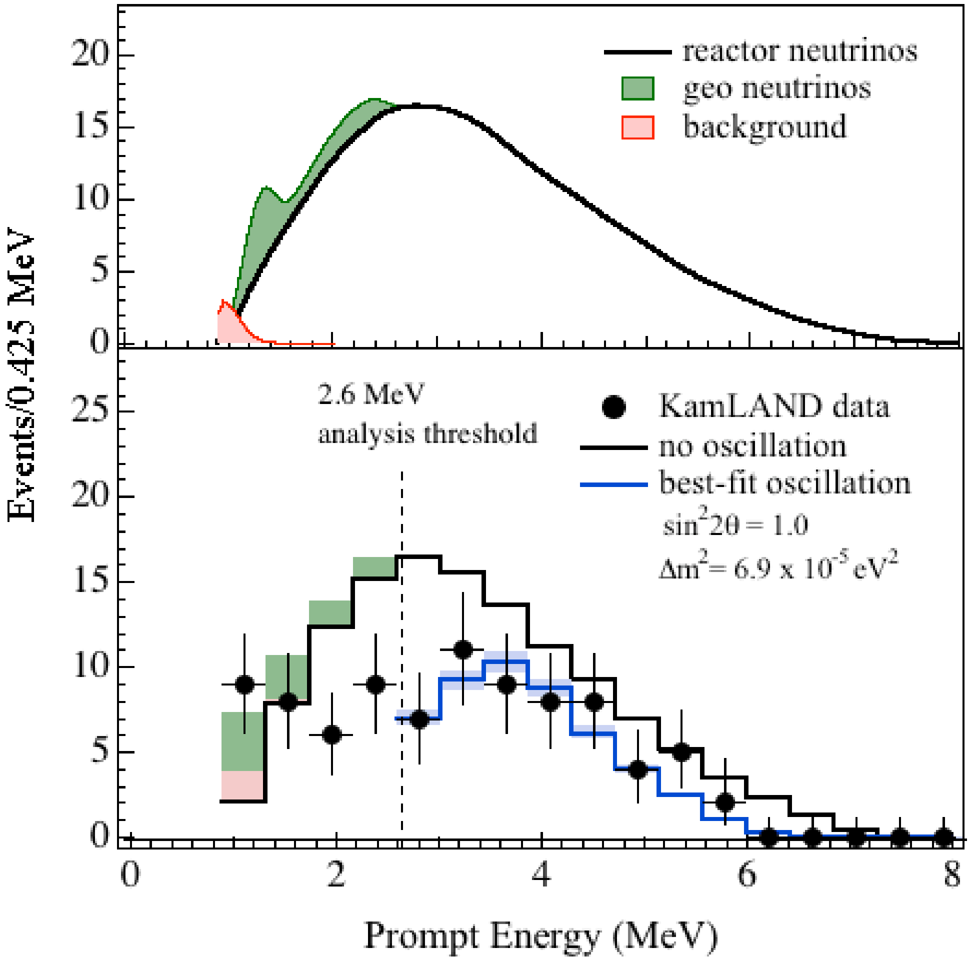
	%		
Total liquid scintillator mass	2.1	FV	• volume calibration
Fiducial mass ratio	4.1		
Energy threshold	2.1		• energy calibration or analysis w/out threshold
Tagging efficiency	2.1		• detection efficiency
Live time	0.07		
Reactor power	2.0	*given by reactor company, difficult to improve on*	
Fuel composition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

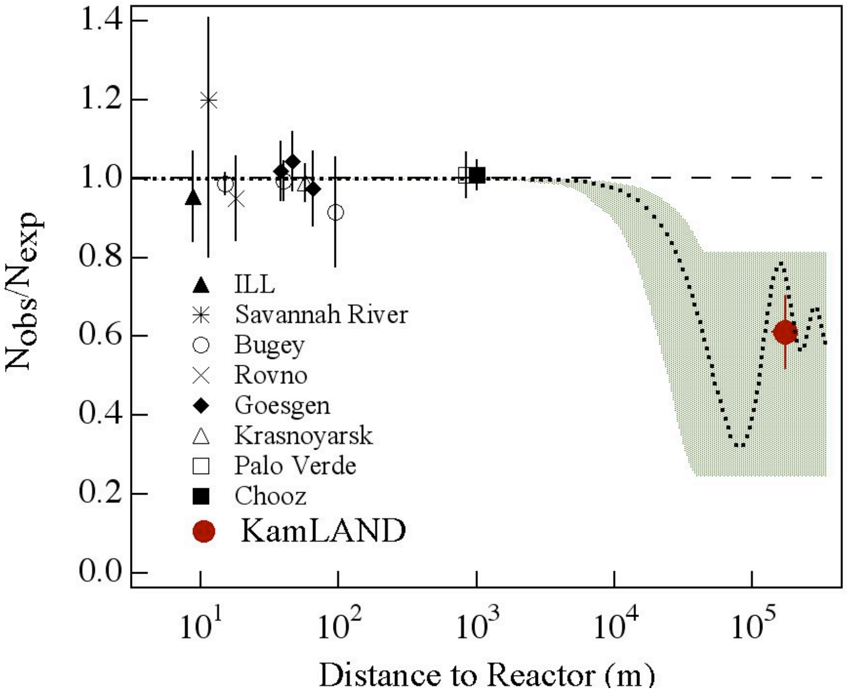
Event Rates at KamLAND

Observed	**54 events** 162 ton•yr, $E_{prompt} > 2.6$ MeV	*Excludes physics background from geo-□*
Expected	**86.8 ± 5.6 events**	
Background	1 ± 1 events	
accidental	*0.0086 ± 0.0005*	*Measured: □t_{pd}=0.02-20 s.*
$^{9}Li/^{8}He$	*0.94 ± 0.85*	*Confirmed by □within 3%.*
fast neutron	< 0.5	*From observed n signal and known neutron production in rock.*

Note: error from background << total systematic error

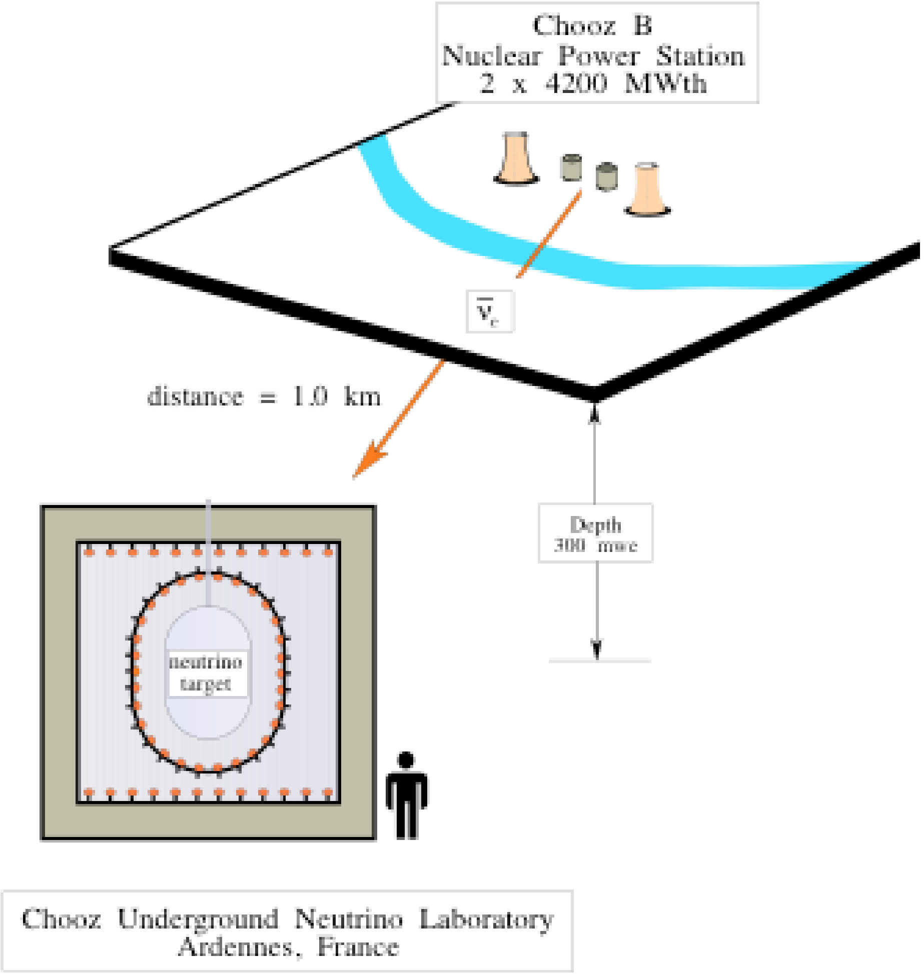
Evidence for Reactor $\bar{\nu}_e$ Disappearance



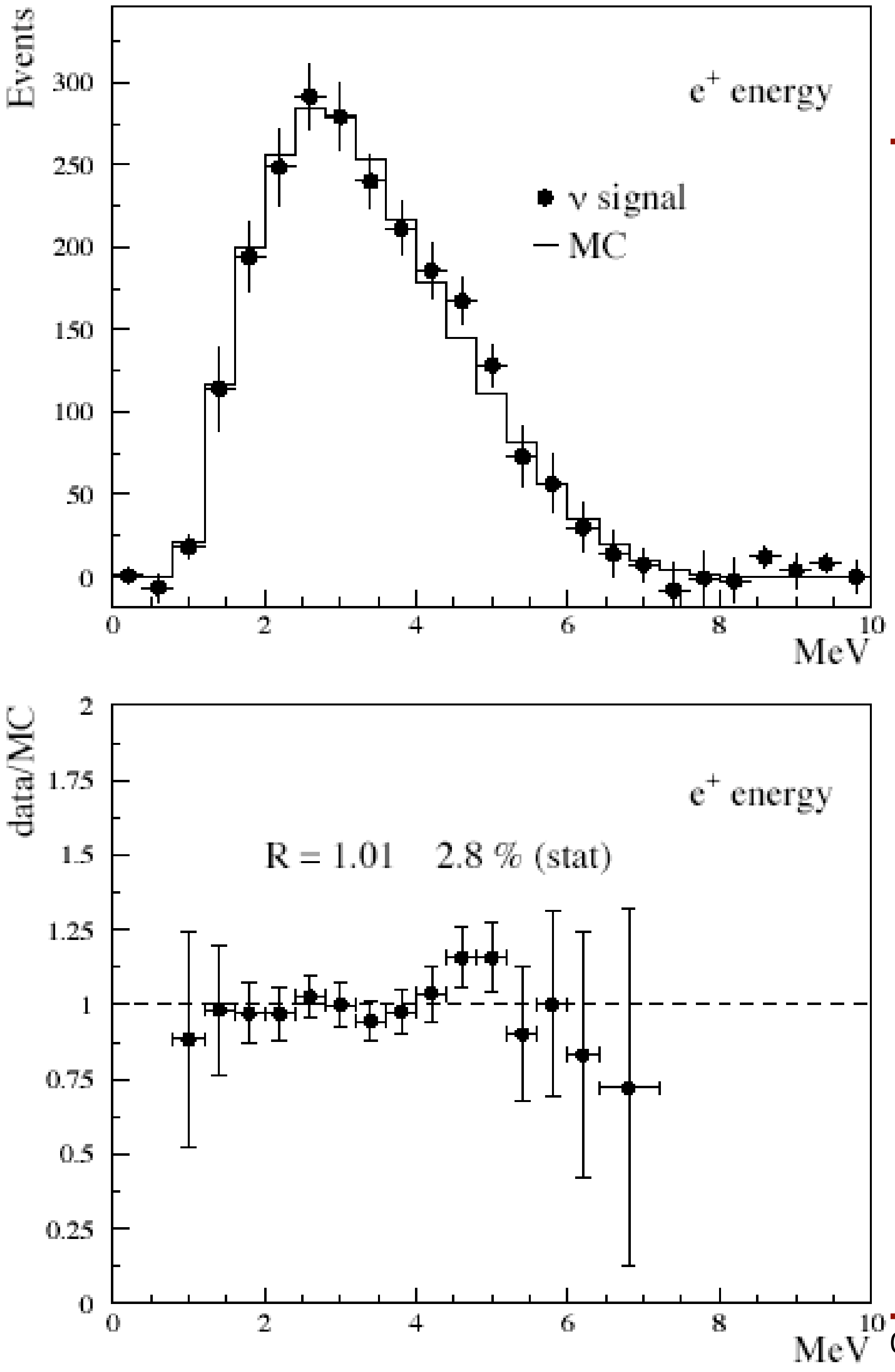


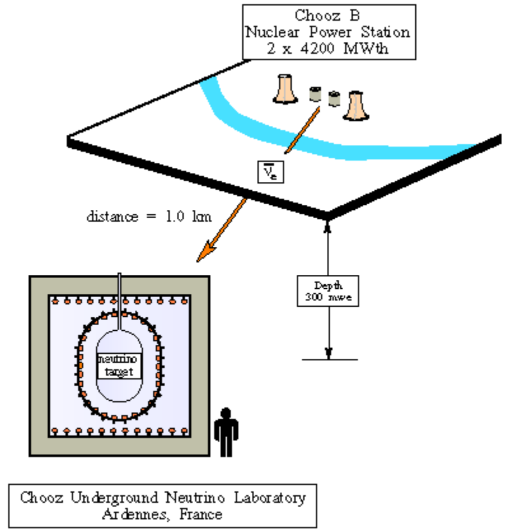
$$\frac{N_{obs} - N_{BG}}{N_{expected}} = 0.611 \pm 0.085\ (\text{stat}) \pm 0.041\ (\text{syst})$$

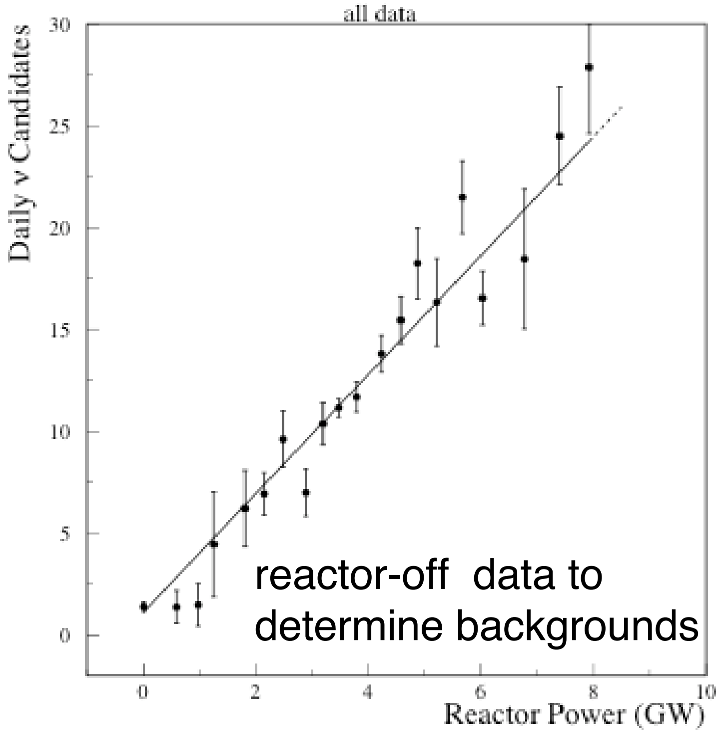
Chooz


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







reactor-off data to determine backgrounds

Chooz Systematics

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

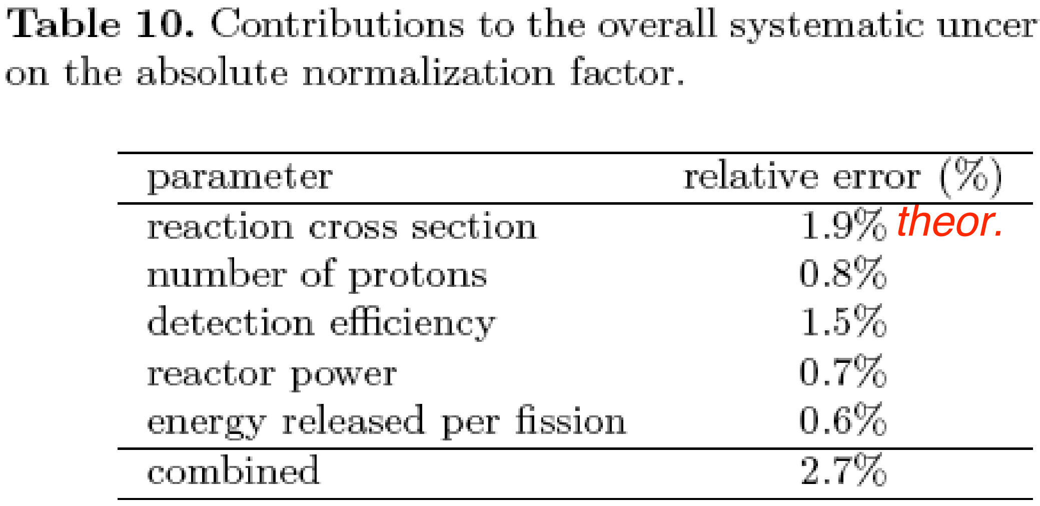


Table 10. Contributions to the overall systematic uncertainty on the absolute normalization factor.

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%

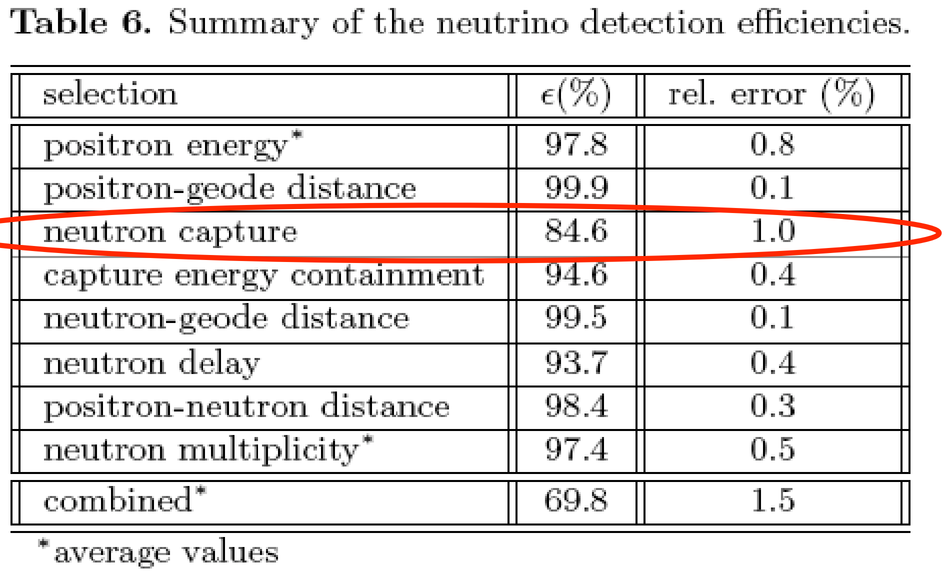


Table 6. Summary of the neutrino detection efficiencies.

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

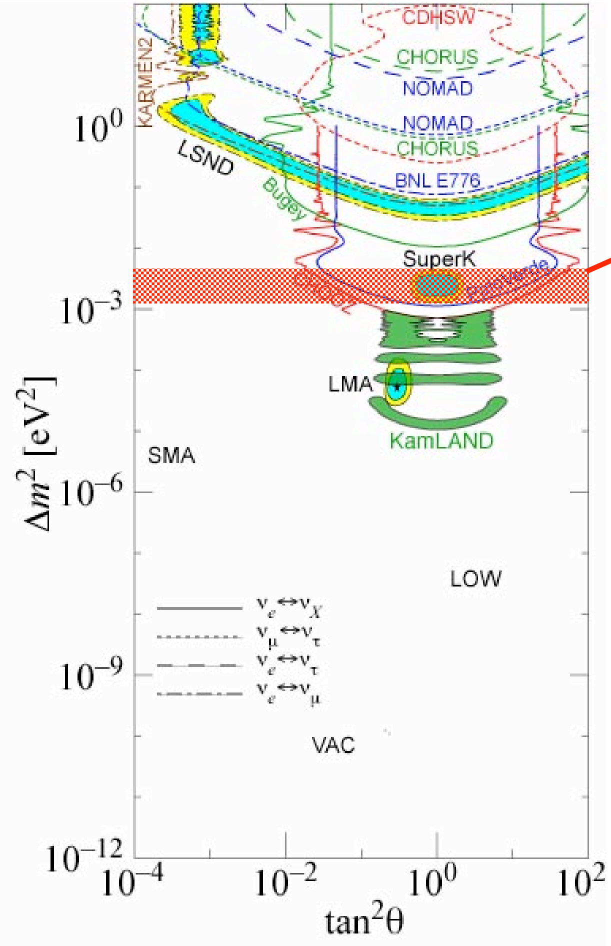
neutron capture:

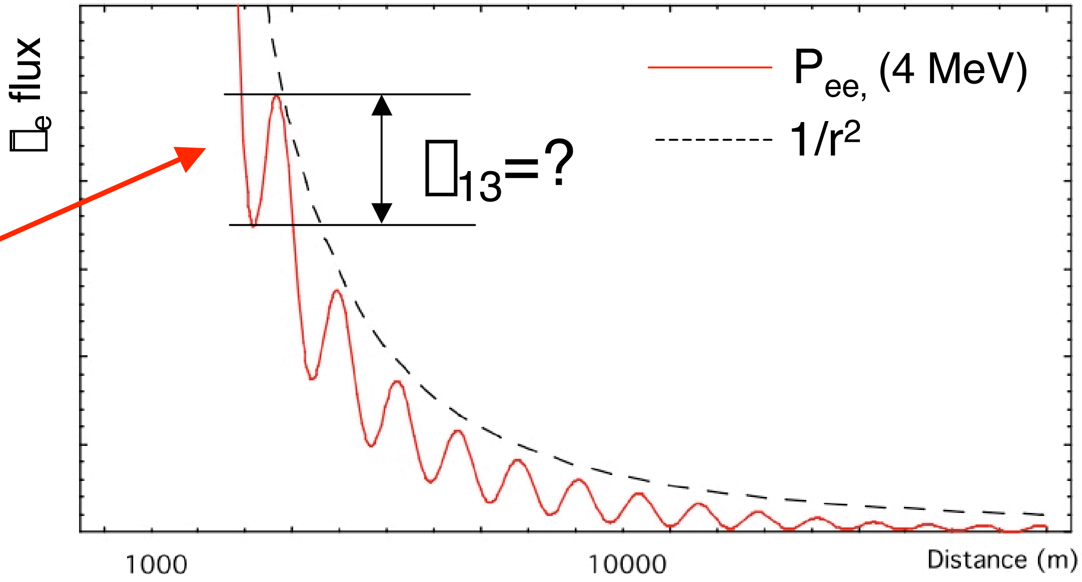
lowest efficiency, largest relative error

Absolute measurements are difficult!

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 $\sin^2 2\theta_{13} \geq 10^{-3}$

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

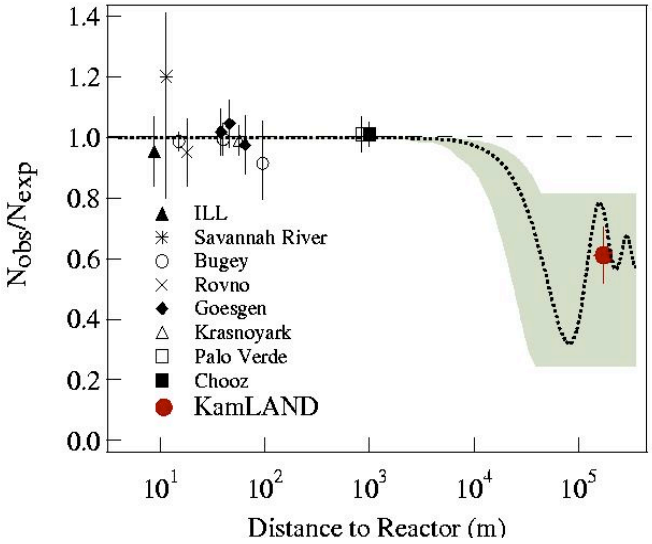
delayed n capture (in μs)

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

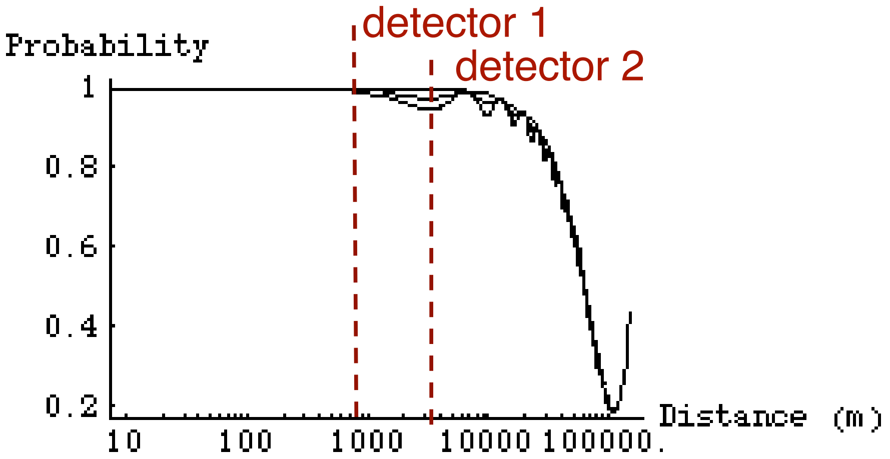
- disappearance experiment
- look for rate deviations from $1/r^2$ and spectral distortions
- observation of oscillation signature with 2 or multiple detectors
- baseline *O(1 km),* no matter effects

Reactor Neutrino Measurement of $\square_{13}$

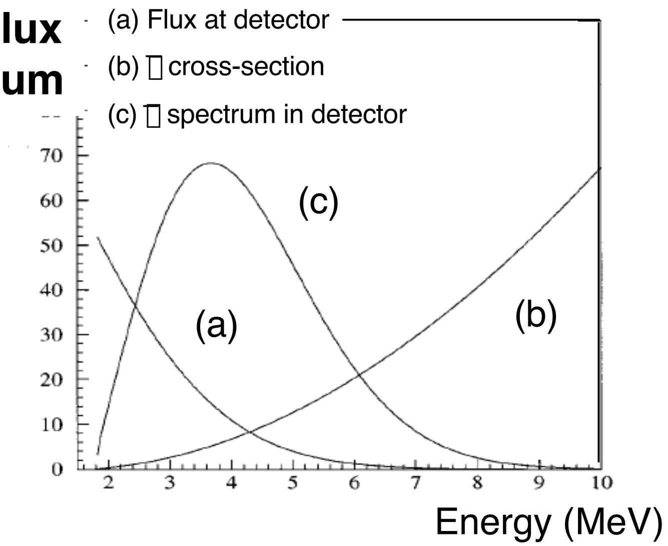
Present Reactor Experiments



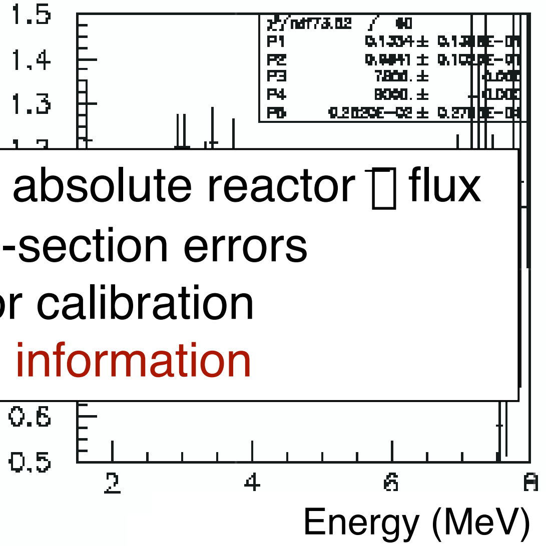
Future $\square_{13}$ Reactor Experiment



Absolute Flux and Spectrum



Ratio of Spectra

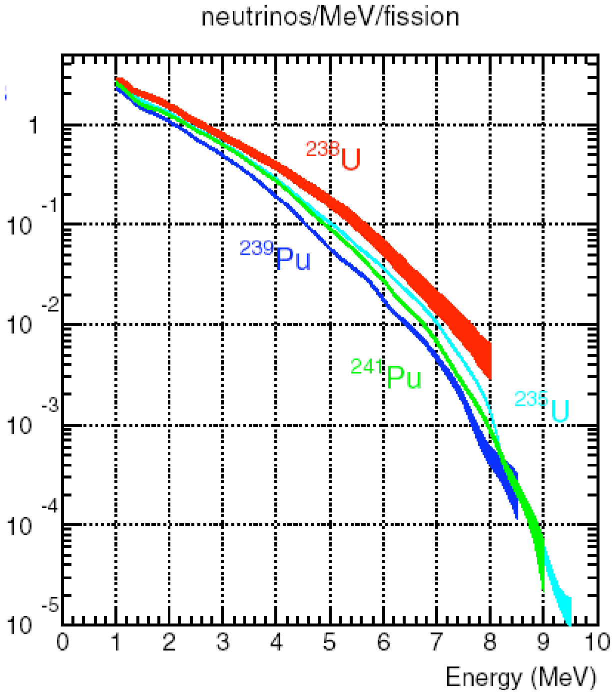


- independent of absolute reactor □ flux
- eliminate cross-section errors
- relative detector calibration
- rate and shape information

Systematics in a Relative Measurement

kinetic energy spectrum x detector response function

- ~~thermal power □ number of fissions (□)~~
- ~~fuel composition and time dependence~~



- ~~target volume/mass~~
- ~~reaction cross-section~~
- candidate event selection
  - ~~detection efficiency~~
- ~~energy response and threshold~~
- time variation of detector response
- backgrounds
  - physics events
  - radioactivity
  - cosmic rays
    - correlated
    - accidental

Detectors are never “identical”. Only partial cancellation of systematic errors.

Event Identification: Positron Detection

Fiducial Volume

(0.8% in CHOOZ)

FV cut requires position reconstruction (cannot be controlled at the O(%) level), or accurate knowledge of target mass.

Fiducial Volume Boundary

(1% in CHOOZ based on MC)

non-scintillating buffer: □'s can escape without being detected

scintillating buffer: full e^+ energy detected within the target,
but e+ efficiency non zero outside the target volume

Energy Threshold Effect

(0.8% in CHOOZ)

$E_{th} > E_{min}$: systematics due to threshold

$E_{th} < E_{min}$: no systematics on energy threshold

start of the spectrum may provide calibration point between near and far detector

will allow measurement of background at low energy (<1 MeV)

□ lower threshold requires lower backgrounds(accidental + correlated)

effects will largely cancel in ratio of 2 detectors

Event Identification: Neutron Detection

Energy Window

Gd (8 MeV γs) vs H_2 (2.2 MeV),
loaded vs unloaded liquid scintillator

ratio of Gd/H_2 capture (~80% on Gd)
error will depend on detector geometry

Fiducial Volume Boundary

non-scintillating buffer:	γs can escape without being detected
scintillating buffer:	full e^+ energy detected within the target, but e+ efficiency non zero outside the target volume

effects will largely cancel in ratio of 2 detectors

Event Identification: (e^+-n) tag

Distance Cut (*d*(e^+-n) < 100 cm) (0.1% in Chooz)

distance cut requires position reconstruction, cannot be controlled at the O(%) level

not required if accidental background very low

Time Cut (neutron capture time) (0.4% in Chooz)

(non) exponential behavior of neutron time capture on Gd and H_2

▯ Gd may increase systematics

no need for Gd in case of lower accidental backgrounds

effects will largely cancel in ratio of 2 detectors

Backgrounds in a Reactor Neutrino Experiment

Goal: error from background << total systematic error

Geophysical anti-ν_e's

Background from radioactivity
rocks, detector material, water shielding, scintillator

Background induced by cosmic rays
- radioactive nuclei produced in the detector
- neutrons induced by muons in detector & rocks

depends
on depth

Backgrounds from Radioactivity

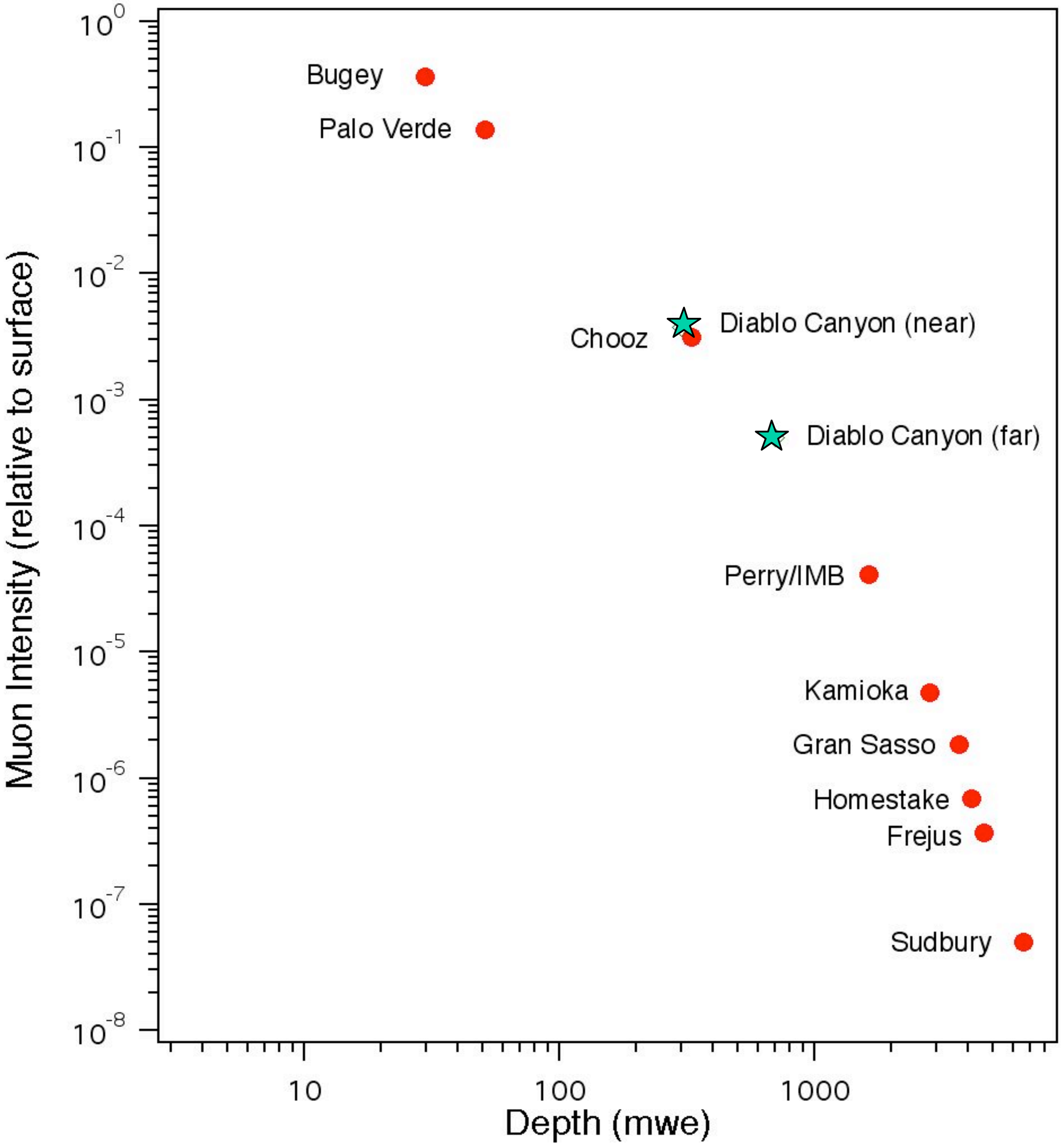
Correlated

U-chain: Radon daughters ^{214}Bi-^{214}Po decays (□□ 237 □s) □ mimick □ tag
E$_{□}$=0.8 MeV (quenched) □ >10□ from E$_{d}$=2.2 MeV (□ = 5% @ 1 MeV)

Accidental

Liquid Scintillator	^{40}K	<< 10-5	(ng/g) for KamLAND
	^{238}U	<< 10-5	
	^{232}Th	<< 10-5	
PMTs + Concentrators	^{40}K	80	
	^{238}U	480	
	^{232}Th	470	
Acrylic	^{40}K	0.008	
	^{238}U	0.008	
	^{232}Th	0.05	
Passive Shield (water)	^{40}K	~1	may be able to use low-background concrete
	^{238}U	~1	
	^{232}Th	~1	
Rock	^{40}K	1500	
	^{238}U	1600	
	^{232}Th	3800	

Muon Flux Underground



depth (mwe)	muon rate for 100-t detector	
	mountain	*flat*
300	31.1	17.3
500	9.1	4.8
800	2.6	1.3

Muon-Induced Production of Radioactive Isotopes in LS

	Isotope	$T_{1/2}$	E_{max} (MeV)	Type
$□^-$	^{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
$□^+$, **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:
□-n cascade, □~few 100ms.
Only ^{8}He, ^{9}Li, ^{11}Li (instable isotopes).

uncorrelated:
single rate dominated by ^{11}C

rejection through muon tracking

Muon-Induced Neutrons

Muons in passive (water) shielding

Muon preceding a neutron (need to have less than 0.1% of this background)

Muon track used for discrimination

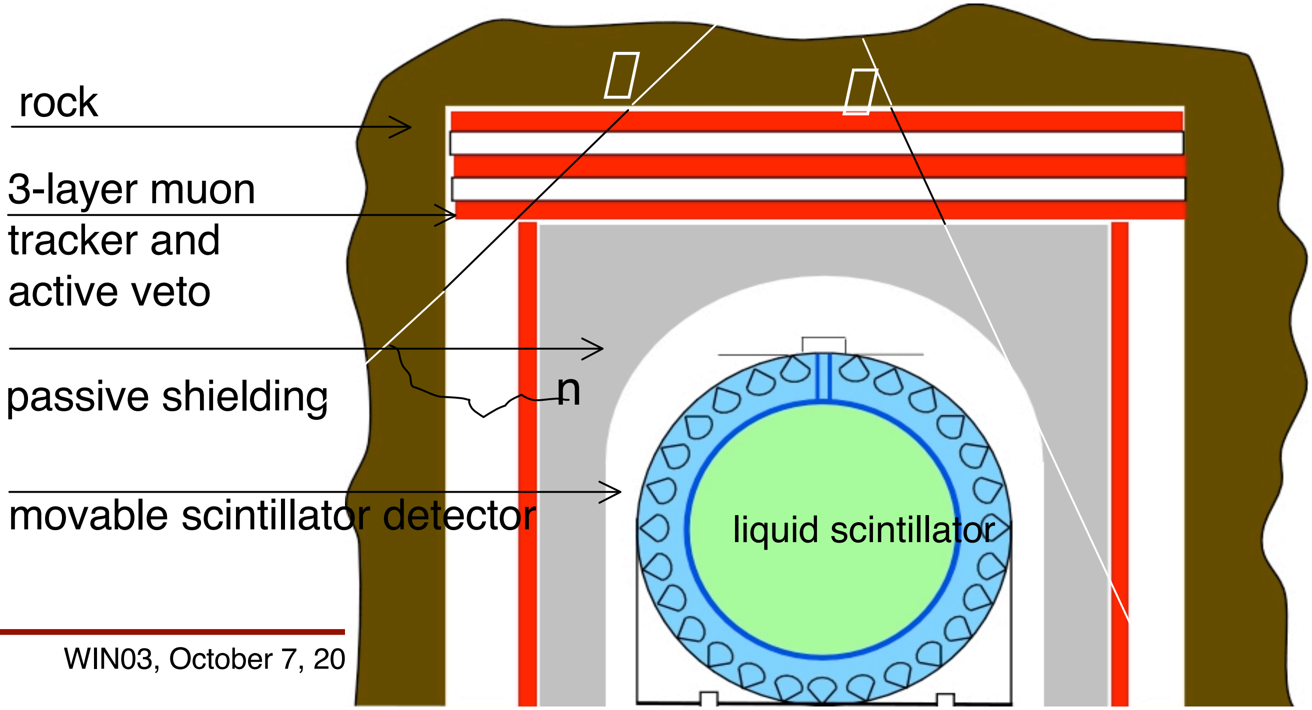
Muons in surrounding rocks

From high energetic shower developing in the rocks (up to GeV)

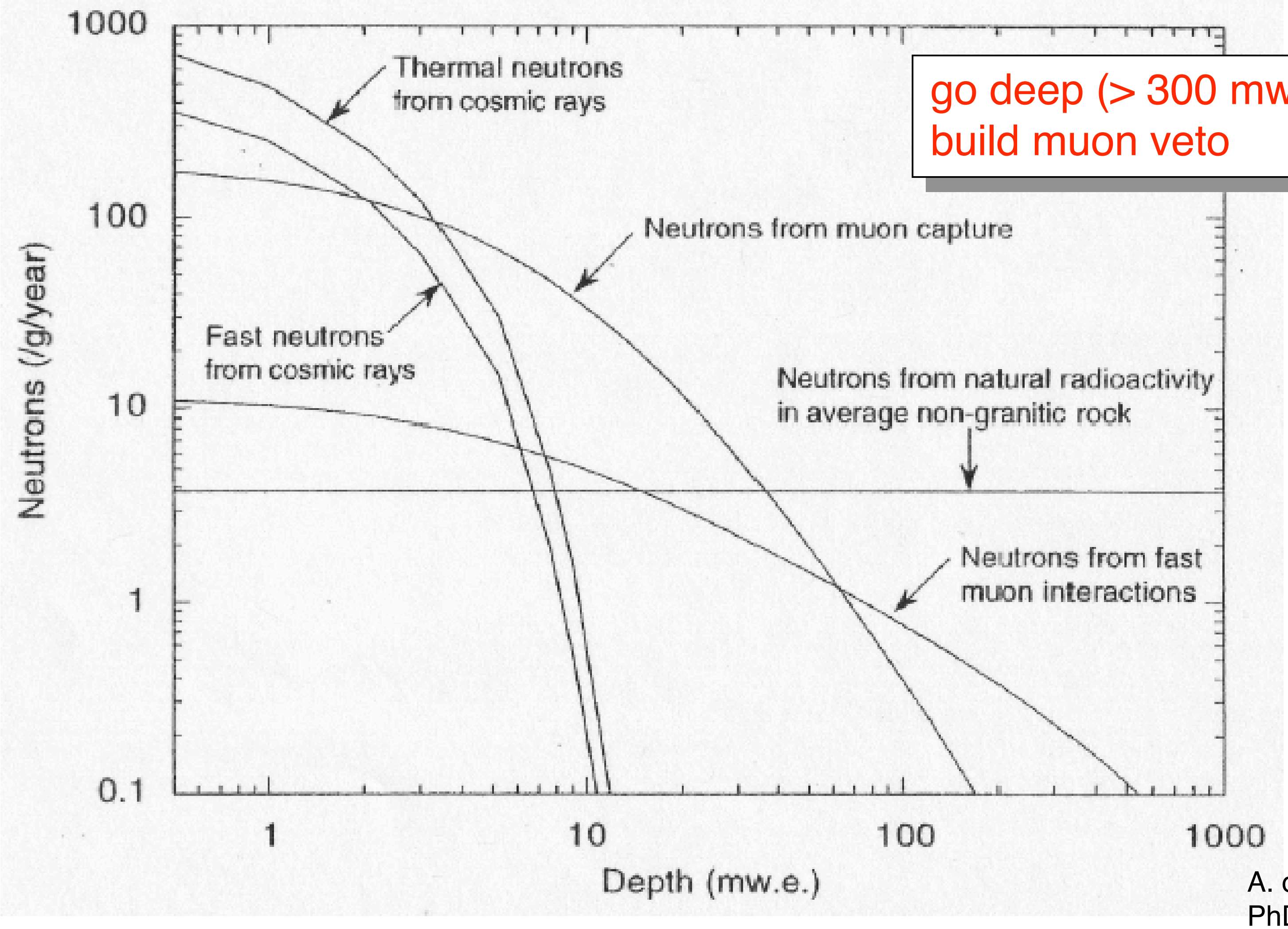
From (μ,n) reactions (few MeV)

Use muon track in outer veto for estimate but no complete discrimination

Passive and active shielding to be optimized



Neutron Production in Rock



go deep (> 300 mwe) and build muon veto

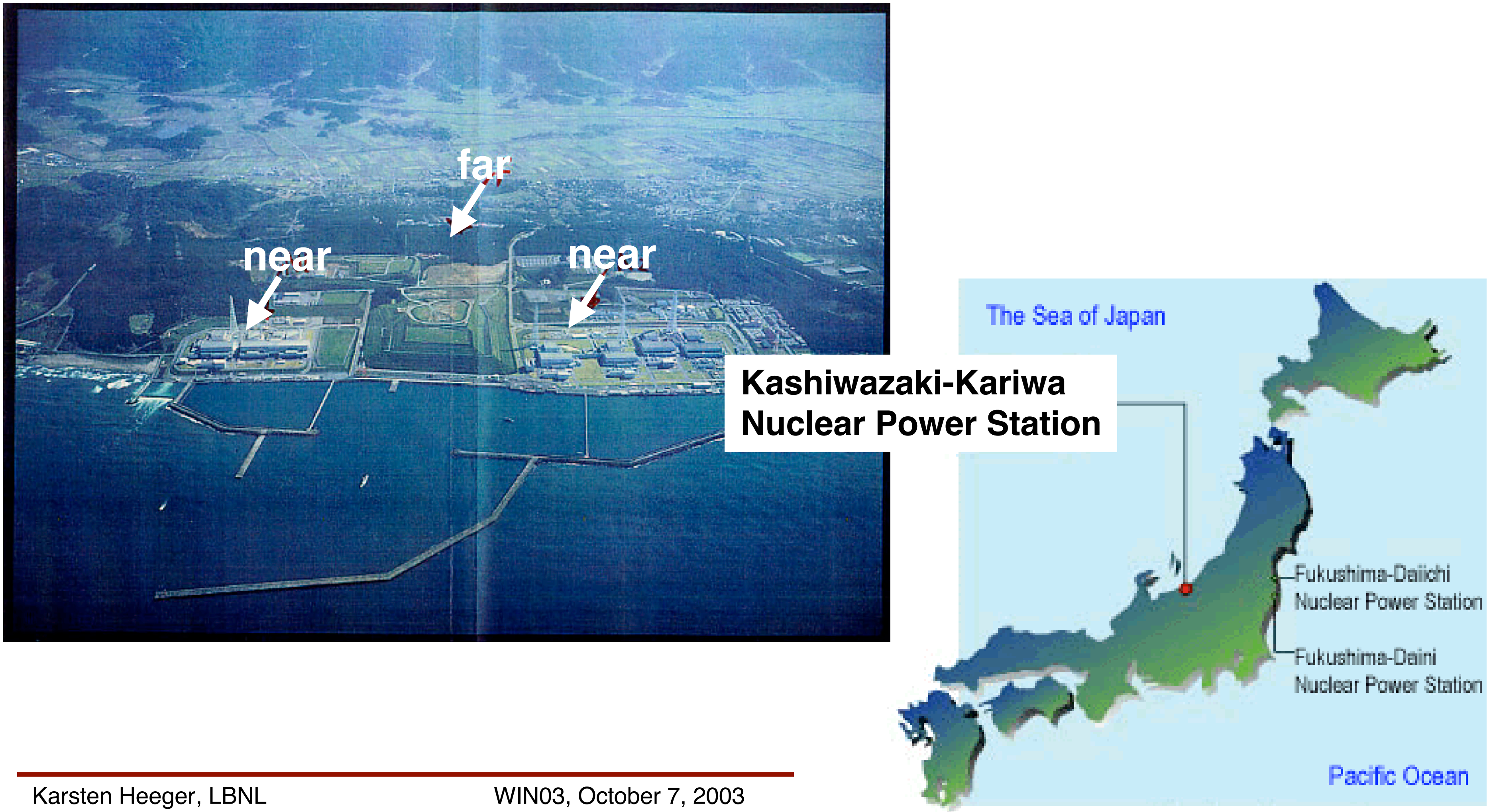
A. da Silva
PhD thesis, UCB 1996

Proposals for Relative Measurements

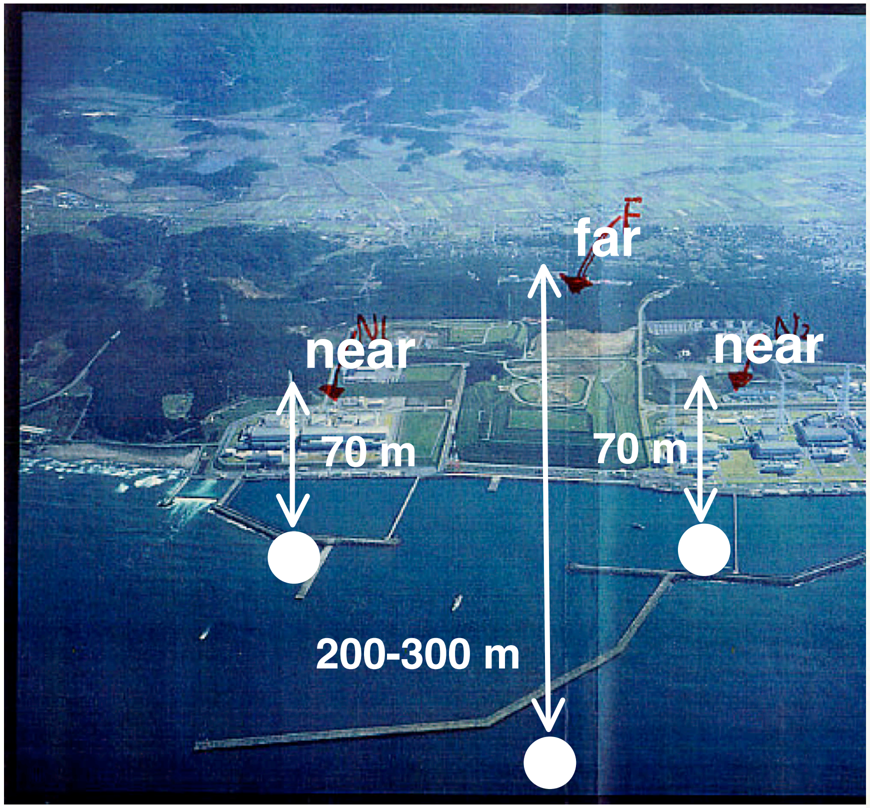
Kashiwazaki: Proposal for Reactor θ_{13} Experiment in Japan

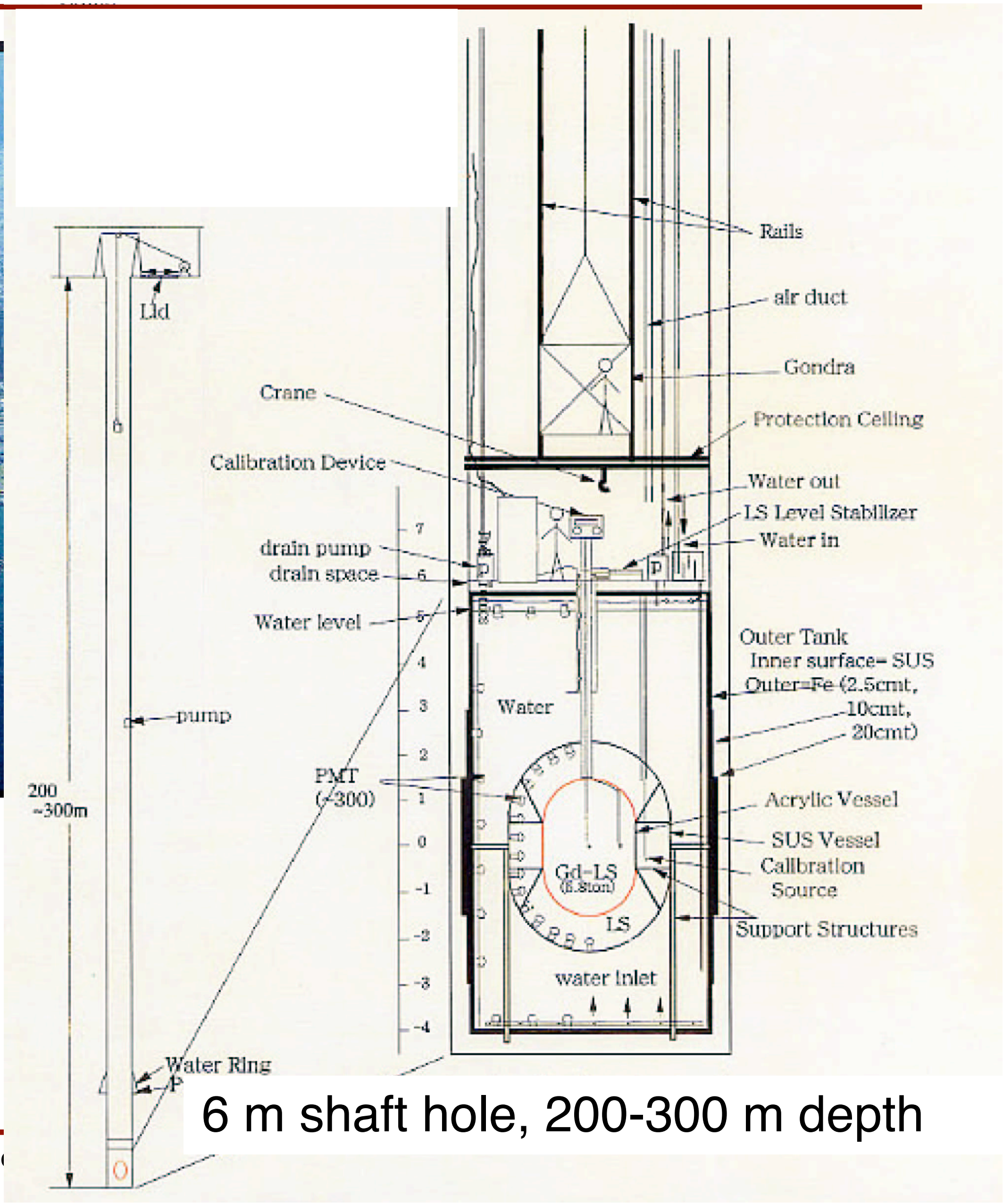
Kashiwazaki

- 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





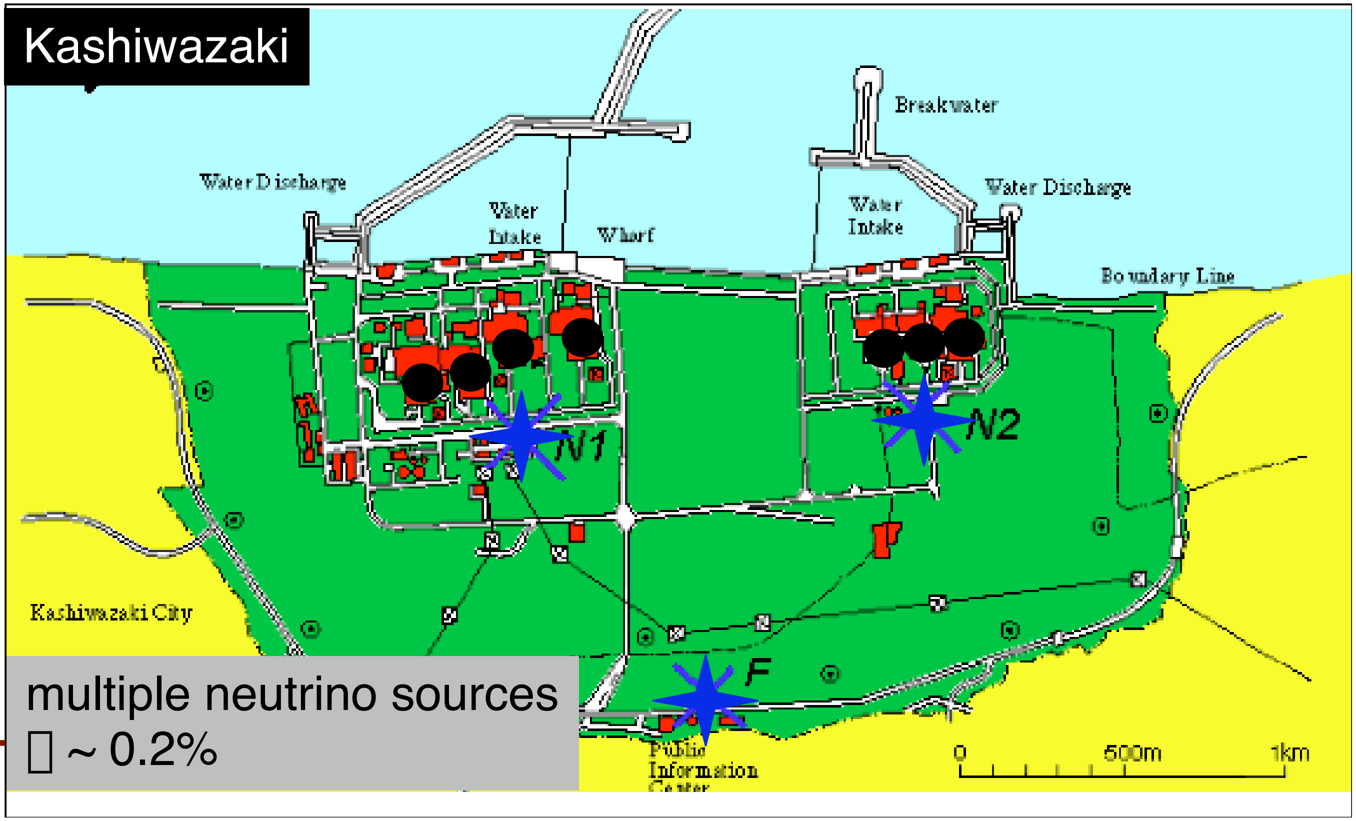
6 m shaft hole, 200-300 m depth

- Chooz-style detector
- Gd concentration 1.5 x CHOOZ to increase neutron absorption efficiency
- background rate < 2%:
  major component from fast n

Kashiwazaki: Systematics

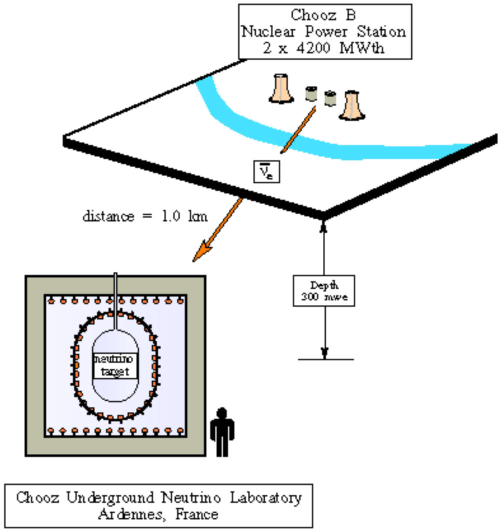
	CHOOZ	**Kashiwazaki**
Detector systematics	1.7% □	1.1%
Far/near ratio of detector systematics	N/A	0.5%-1%
Far/near ratio of flux systematics	N/A	0.2%
Total		**< 1%**

rate-based measurement



multiple neutrino sources
□ ~ 0.2%

CHOOZ II (?): Systematics

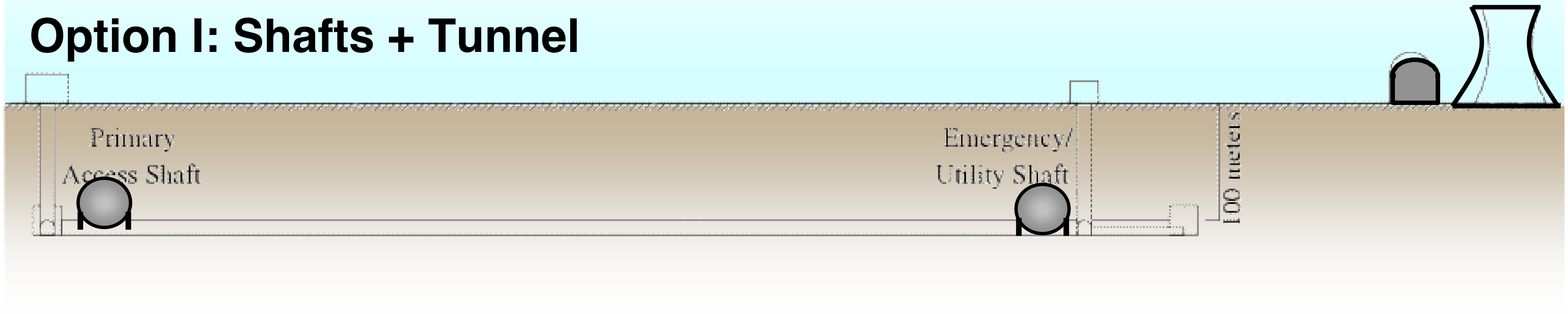


Systematics	**Error**	**CHOOZ**	**CHOOZ II** (2 det, lower bkgd)	
Reactor Complex	cross section/fission	1.9%	-	
	power	0.7%	-	
	E/fission	0.6%	-	
		2.1%	**<< 1%**	
Detector	scintillator density	0.1%	-	+difficult with Gd
	target volume	0.3%	- (□V)	
	% H	1.2%	-	+difficult with Gd
	Fiducial volume boundary	1.0%	-	Scint. buffer
		2.5%	**<< 1%**	
Analysis Cuts E_e+ < 8 Mev 6 < E_n (MeV) < 12 d(e^+-geode) < 30cm d(n-geode) < 30cm d(e^+-n) < 100 cm 2 < n delay < 100 □s n multiplicity = 1	e^+ energy	0.8%	No threshold: 0%	scint. buffer
	e^+ pos. cut / vessel (30cm)	0.1%	-	
	n capture	1.0%	-	scint buffer
	n energy	0.4%	-	Gd 8 MeV □s
	n pos. cut / vessel (30 cm)	0.1%	-	
	(e^+-n) distance	0.3%	No distance cut: 0%	
	(e^+-n) time delay	0.4%	-	No Gd ➔ ~0%
	n multiplicity	0.5%	better	
		1.5%	**<< 1% ?**	

rate-based measurement

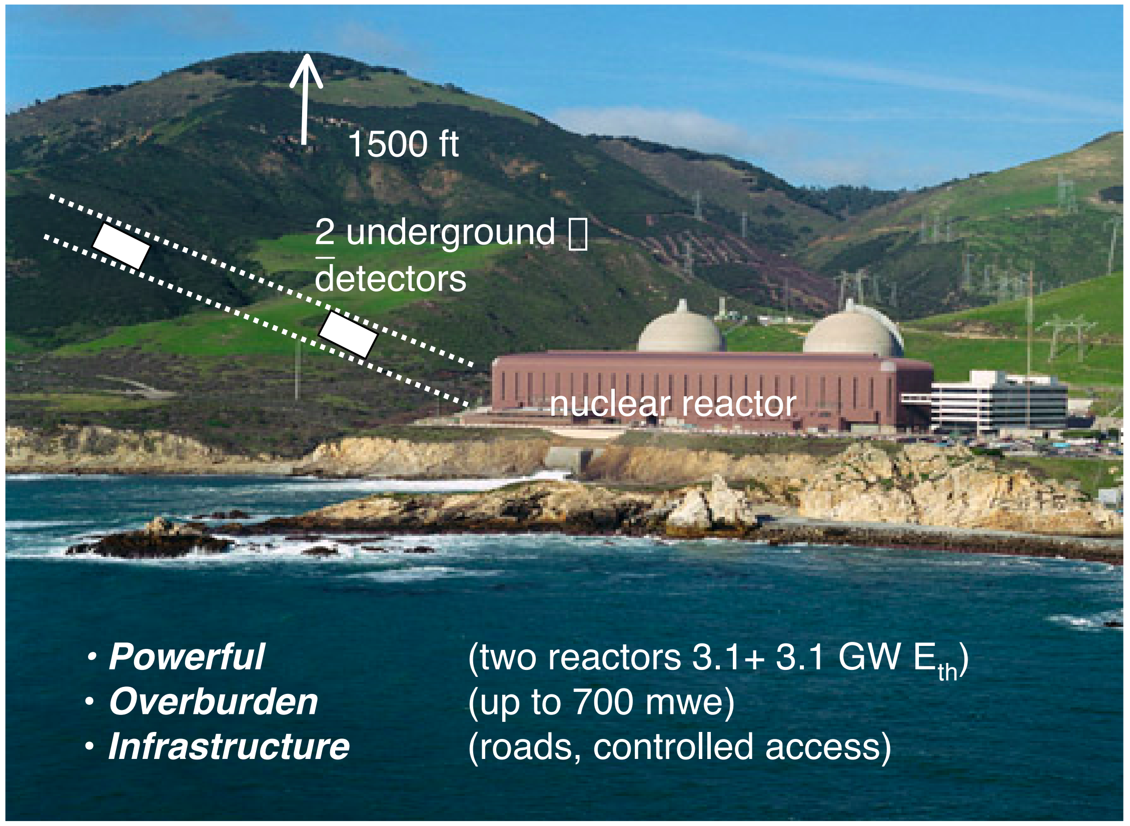
Reactor Experiments with Variable Baseline

Option I: Shafts + Tunnel



Option II:

Tunneling into Hillside



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

Flux Systematics with Multiple Reactor Cores

$$\square_i = \square_A^0 \frac{1}{R_A^2} P_A + \square_B^0 \frac{1}{R_B^2} P_B$$

Indivual reactor flux contributions and systematics cancel *exactly* if

Condition I: $\frac{R_A{}^2}{R_B{}^2} = const.$ *1/r² fall-off of reactor flux the same for all detectors.*

Condition 2: $P_A \square P_B \square P$ *Survival probabilities are approximately the same*

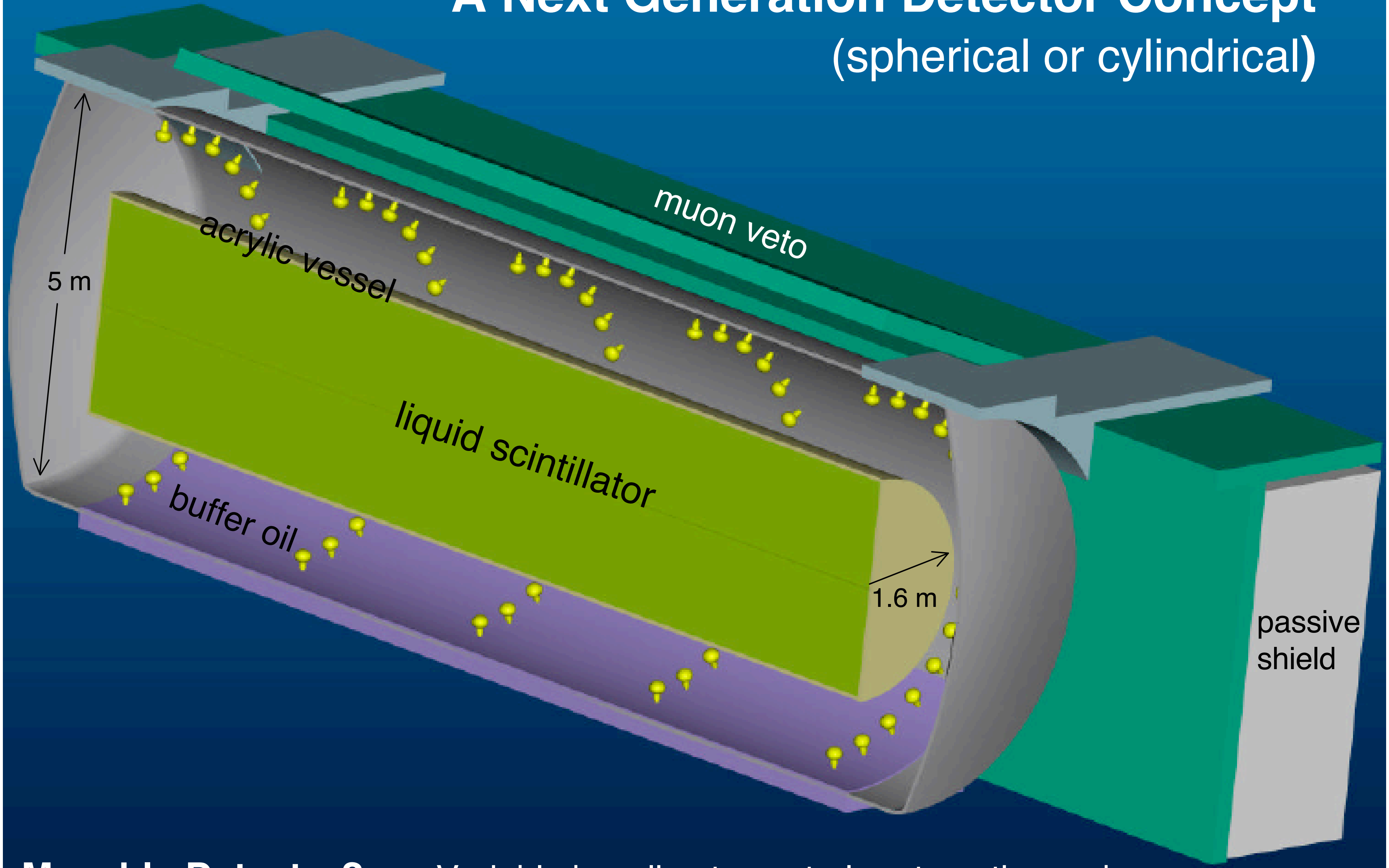
□ Approximate flux cancellation possible at other locations

	Relative Error Between Detector 1 and 2	
	rate	**shape**
Relative flux error (1%)	< 0.6%	< 0.01%
Reactor core separation (100 m)	< 0.14%	< 0.1%
Finite detector length (10 m)	< 0.2%	< 0.1%

□ Shape analysis largely insensitive to flux systematics.
□ Distortions are robust signature of oscillations.

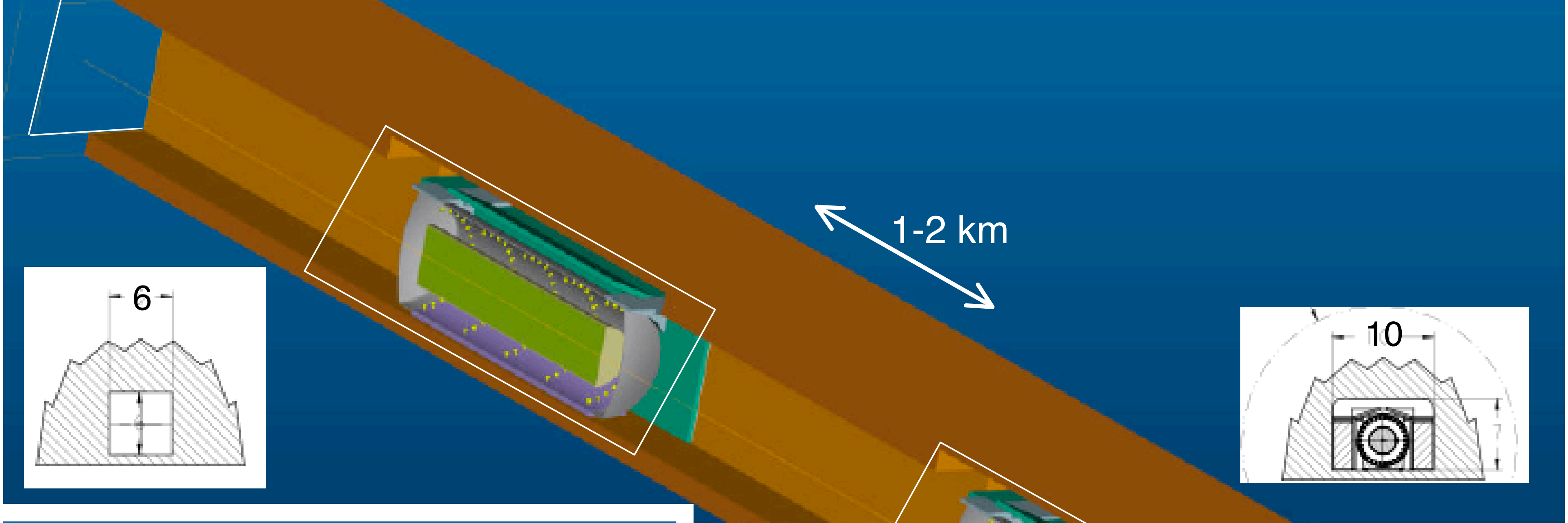
A Next Generation Detector Concept

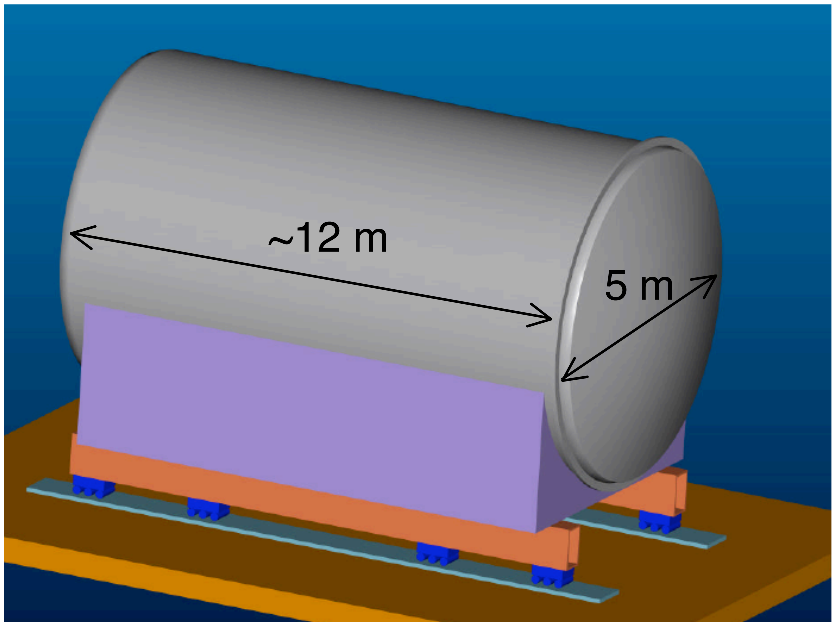
(spherical or cylindrical)



Movable Detector? Variable baseline to control systematics and demonstrate oscillation effect (if $|\square_{13}| > 0$)

Tunnel with Multiple Detector Rooms and Movable Detectors





- Modular, movable detectors
- Volume scalable
- V_{fiducial} ~ 50-100 t/detector

Experimental Systematics

Best experiment to date: CHOOZ

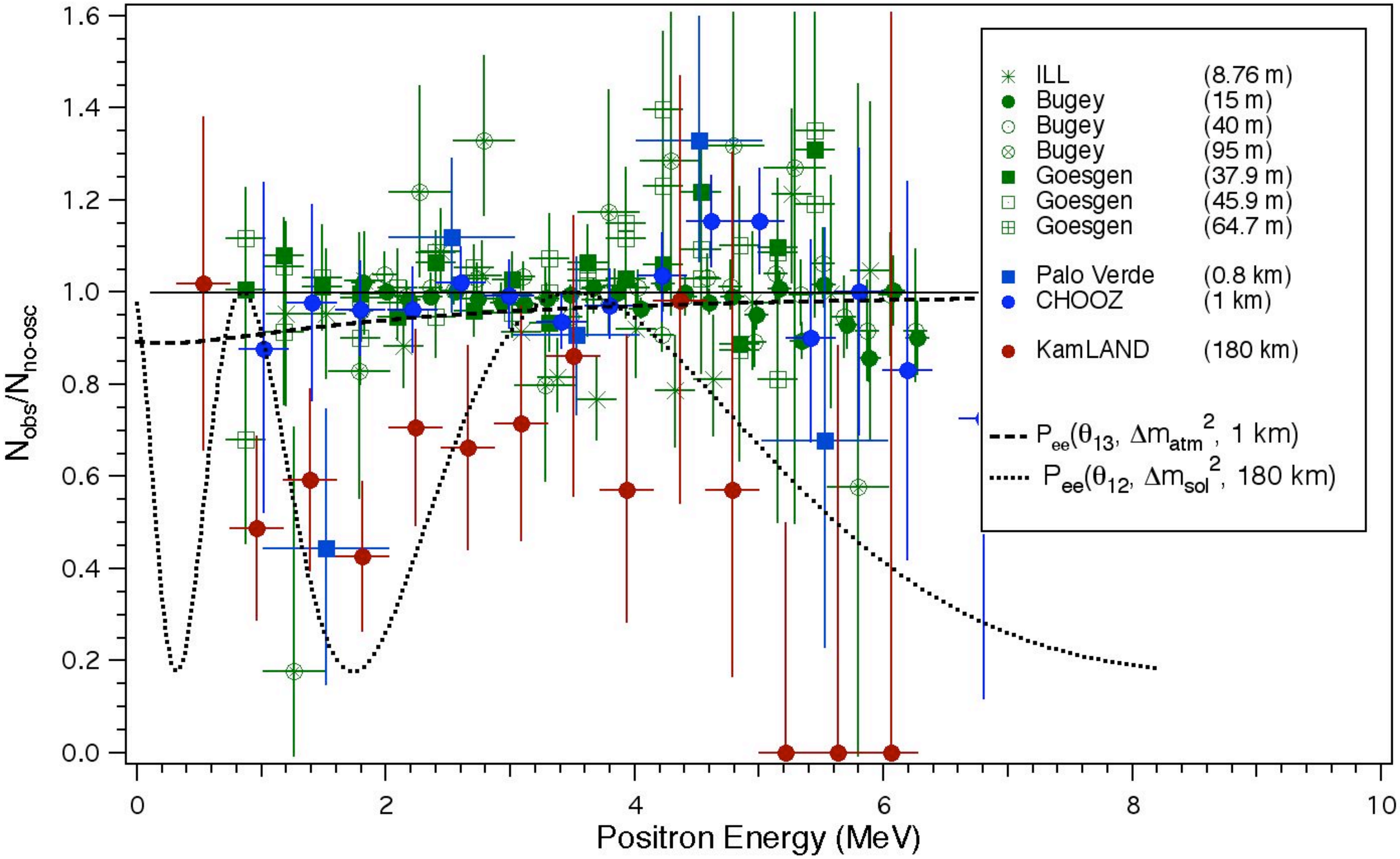
	parameter	relative error (%)
	reaction cross section	1.9%
	relative fiducial vol.	~ 0.3%
rel	detection efficiency	≤ 1%
	reactor power	0.7%
	energy released per fission	0.6%
	combined	2.7%

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

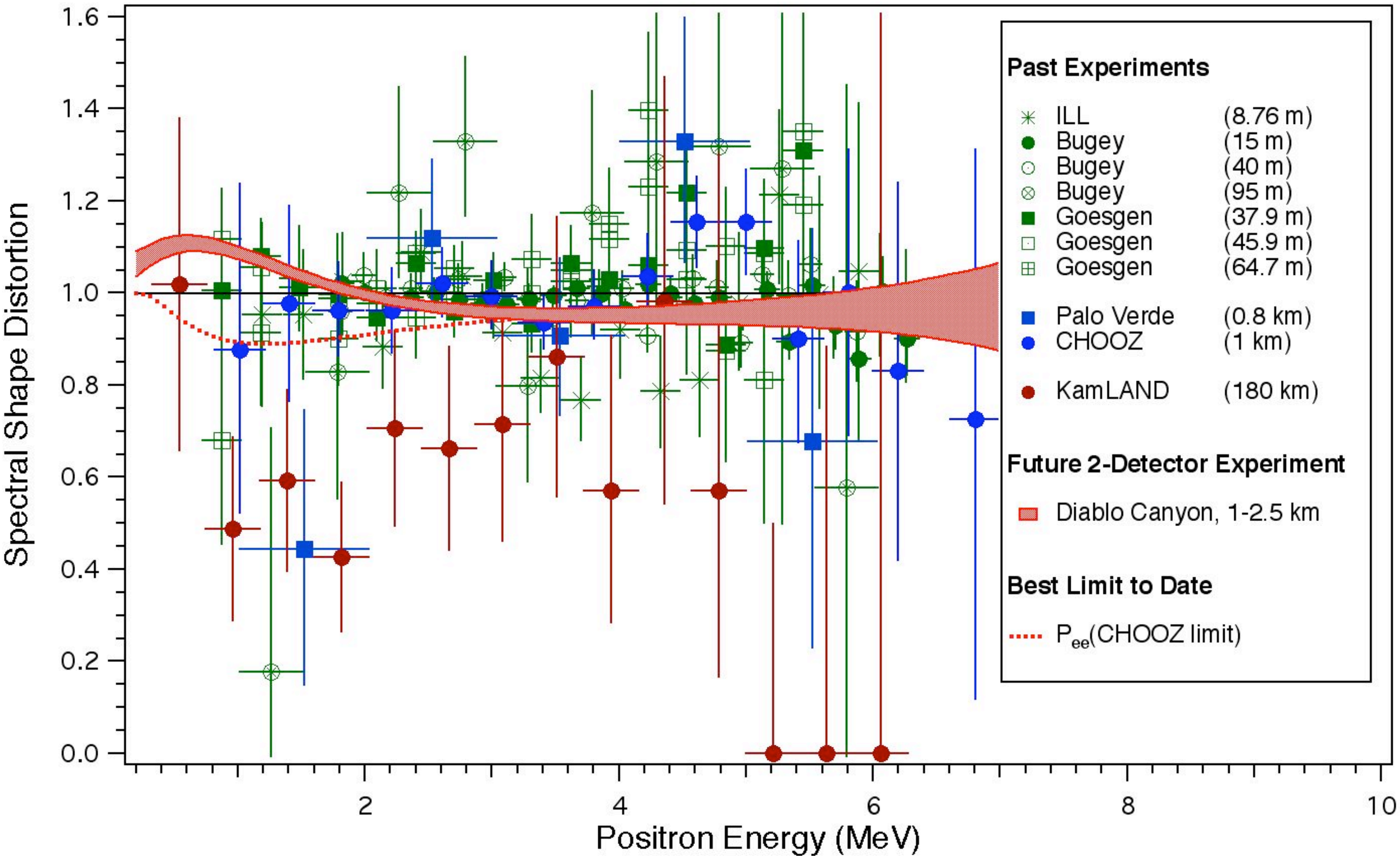
Note: list not comprehensive

Total $\square_{syst}$ ~ 1-1.5%

Past and Present Reactor Neutrino Experiments

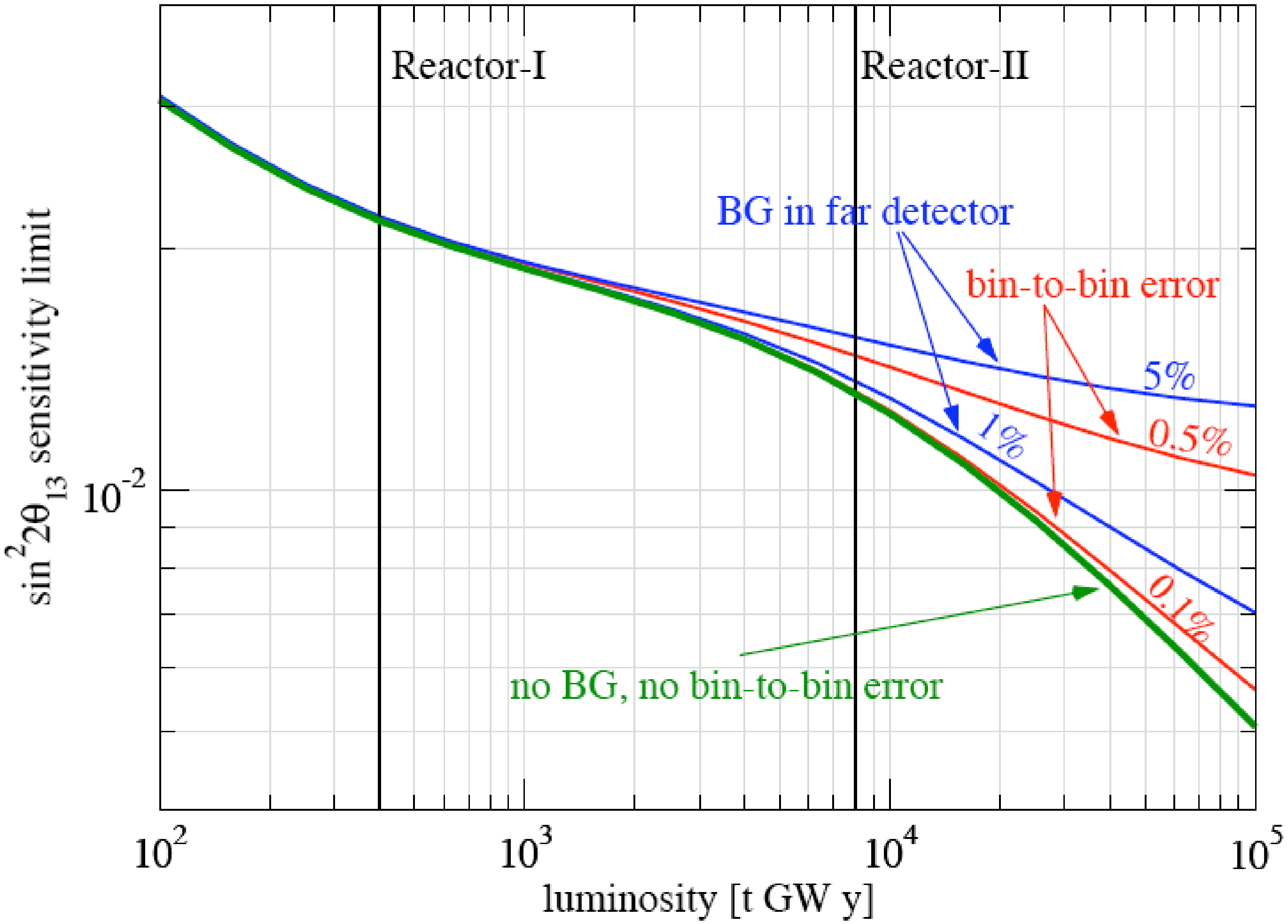


A Future 2-Detector Experiment



e.g. Diablo Canyon

θ_{13} Sensitivity Scaling with Backgrounds and Exp. Errors



Nominal setup:
L_{near} = 0.2 km
L_{far} = 1.7 km

σ_{shape} = 2%

$\Delta m_{23}^2 = 2 \times 10^{-3}$ eV^2

Ref: Huber, Winter, Linder et al.

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)	< 0.006-0.0015	< 2.3	2012
MINOS	< 0.06	< 7.1	2008
ICARUS (5 yr)	< 0.04	< 5.8	2011
OPERA (5 yr)	< 0.06	< 7.1	2011
KR2DET (Russia)	< 0.016	< 3.6	?
Kashiwazaki (Japan)	< 0.026	< 4.6	[2008]
Penly/Cruas (France)	< 0.025	< 4.5	[2010]
Diablo Canyon (US)	< 0.01-0.02	< 2.9	[2009]

Upper limits correspond to 90% C.L.

Summary: Reactor Measurement of θ_{13}

- Reactor neutrino oscillation experiment is promising option to measure θ_{13} and gives clean measurement of $\sin^2 2\theta_{13}$ (no degeneracies, no matter effects).

- Sensitivity of $\sin^2 2\theta_{13} \sim 0.01$ comparable to next-generation accelerator experiments. Complementary to long-baseline program. Allows combined analysis of reactor and superbeam experiments.

- Measurement will be systematics limited. Do not expect to go beyond $\sin^2 2\theta_{13} \sim 0.01$.

- Minimum setup: 2 detectors, overburden, and muon veto.
- Better to have *2 or 3 detectors and variable baseline.*
- Be careful of detector design and backgrounds.

[redacted]