Using Reactors to Measure θ_{13}

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- Motivation for reactor θ_{13} measurements
  - What should be the sensitivity goal?
  - Appearance vs. Disappearance measurements
    - Phenomenology and ambiguities
- Limiting factors in a reactor disappearance measurement
  - How can sensitivity be improved
- Examples of possible measurements and comparisons

Neutrino Oscillation Roadmap

- Stage 0: Current near term program
  - NuMI (K2K) checks atmospheric oscillations and measures Δm^2_{23} to about 10%
  - MiniBooNE makes definitive check of LSND and measures associated Δm^2

- Stage 1 - Constrain / measure $\sin^2 2\theta_{13}$
  - NuMI /MINOS on-axis probes $\sin^2 2\theta_{13} > 0.06$ @ 90%CL
  - NuMI/JHF offaxis with 20-50 kton detectors to probe $\sin^2 2\theta_{13} > 0.01$ @ 3σ level
  - **Two-detector, longbaseline reactor experiments probe $\sin^2 2\theta_{13} > 0.01$ @ 3σ level**

- Stage 2 - Observe CP violation and determine the sign of Δm^2_{23} with conventional superbeams and very large detectors (>500 ktons)
  - Must have $\sin^2 2\theta_{13} > 0.01$
  - Need to measure $P(\nu_\mu \to \nu_e)$ then $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ or use constraint from a reactor $\nu_e \to \nu_e$
  - Need increased rate (especially for $\bar{\nu}$'s) $\Rightarrow$ Need high intensity proton sources

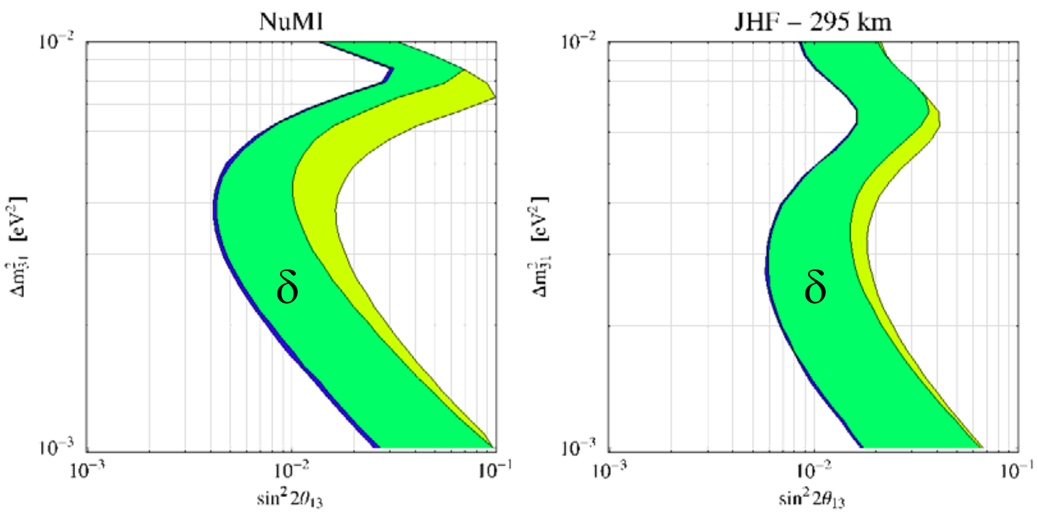
- Stage 3 - Measurements with a Neutrino Factory
  - Map out CP violation with precision for $\sin^2 2\theta_{13} > 0.01$
  - Probe $\nu_\mu \to \nu_e$ transitions down to $\sin^2 2\theta_{13} > 0.001$

Measurements of $\sin^2 2\theta_{13}$

- Appearance (Offaxis Exps.)

$$P[\nu_\mu(\bar{\nu}_\mu) \rightarrow \nu_e(\bar{\nu}_e)] = s_{23}^2 \sin^2 2\theta_{13} \sin^2 \frac{\Delta_{31}}{2}$$

  - Ambiguity with s^2_{23} size
  - Matter effects can be important
  - CP violation (δ) effects can be important
  - Measurement difficult:
    - Look for small number of events over comparable background



- Disappearance (Reactor Exps)

$$1 - P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = \sin^2 2\theta_{13} \sin^2 \frac{\Delta_{31}}{2}$$

  - Direct $\sin^2\theta_{13}$ measurement
  - No matter effects
  - No CP violation effects
  - Measurement difficult:
    - Look for slight change in overall neutrino rate

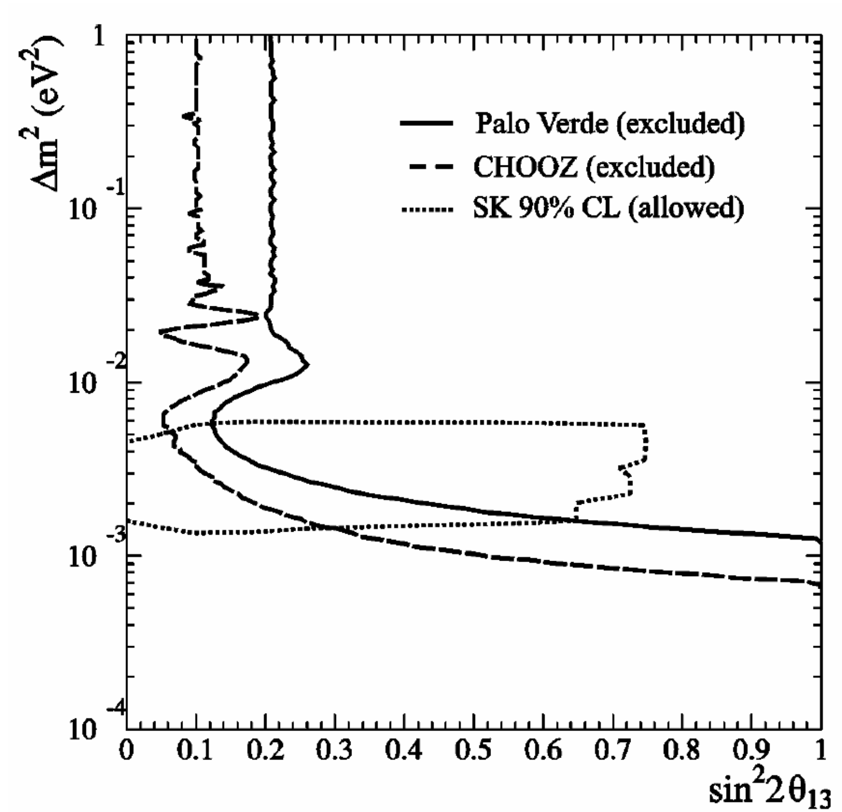
- *Question: Can we make reactor <u>measurements</u> for $\sin^2 2\theta_{13} \approx 0.01$*
  - *Limit for measuring CP violation with conventional superbeams*
  - *Level needed to combine with offaxis NuMI or JHF experiments*

Previous Reactor Experiments

- CHOOZ and Palo Verde Experiments probed this region
  - One detector experiments
    - Major systematic associated with reactor flux
  - Detectors used liquid scintillator with gadolinium and buffer zones for background reduction
  - Shielding:
    - CHOOZ: 300 mwe
    - Palo Verde: 32 mwe
  - Fiducial mass:
    - CHOOZ: 5 tons @ 1km, 5.7 GW
      - ~2.2 evts/day/ton with 0.2-0.4 bkgnd evts/day/ton
      - ~3600 $\bar{\nu}$ events
    - Palo Verde: 12 tons @ 0.85km, 11.6 GW
      - ~7 evts/day/ton with 2.0 bkgnd evts/day/ton
      - ~26000 $\bar{\nu}$ events

CHOOZ

parameter	relative error (%)
reaction cross section	1.9%
number of protons	0.8%
detection efficiency	1.5%
reactor power	0.7%
energy released per fission	0.6%
combined	2.7%



Going Beyond Previous Experiments

- Need higher statistics with long baseline (1-2 km)
  - Use larger detectors $\Rightarrow$ 50 ton units compared to previous 5-10 ton units
  - As before, use large power reactors
    - Possibly multiple reactors but see caveat below

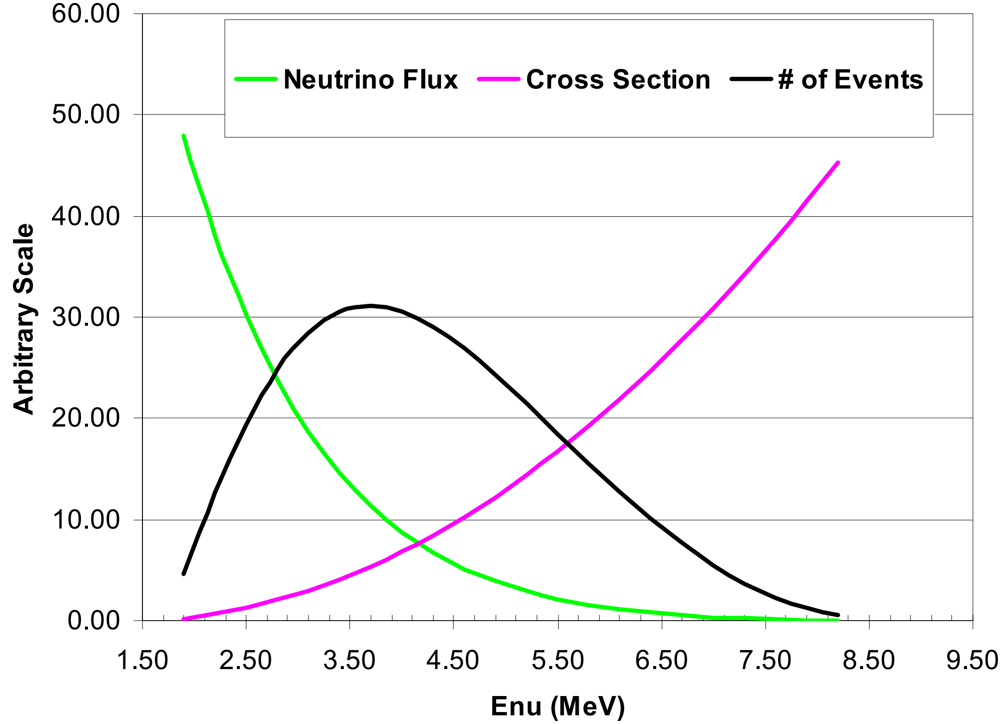
- Reduce dominant reactor flux spectrum uncertainty
  - Use two detectors at near and far locations

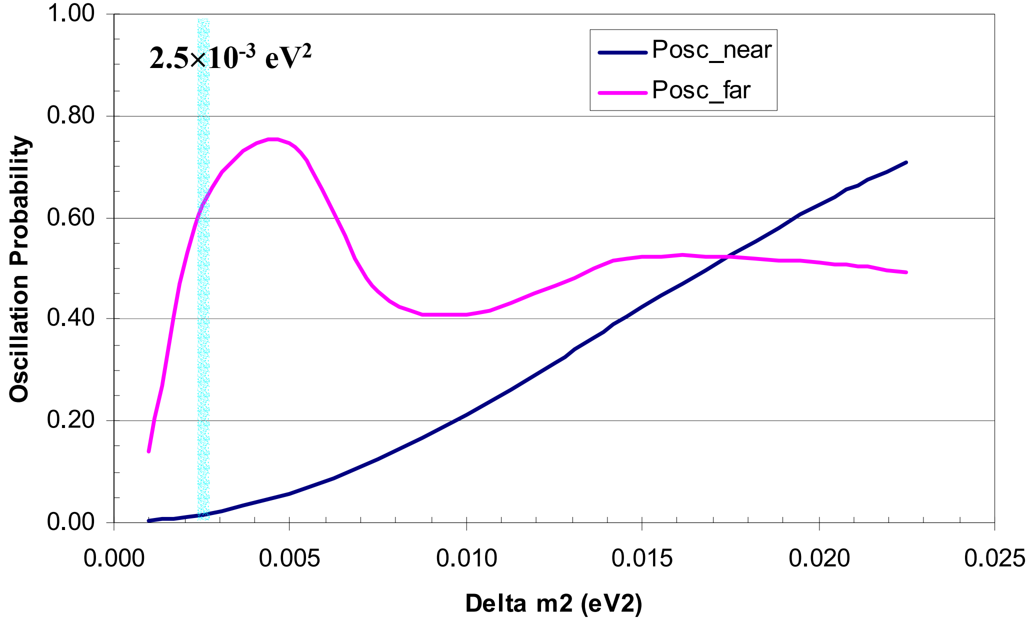
- Reduce uncertainty in relative near to far detector efficiency
  - Make two detectors as identical as possible
  - Systematic uncertainty in relative efficiency can be reduced by moving far detector to near site for cross calibration

- Measure and/or reduce background rates
  - Measurements during reactor off periods best
    - Can be compromised with multiple reactors
  - Use shielding and detector improvements to reduce background

Can one reach the $\sin^2 2\theta_{13} \approx 0.01$ level at $\Delta m^2 = 2.5\times10^{-3}$ eV^2 ??

Reactor Energy Spectrum

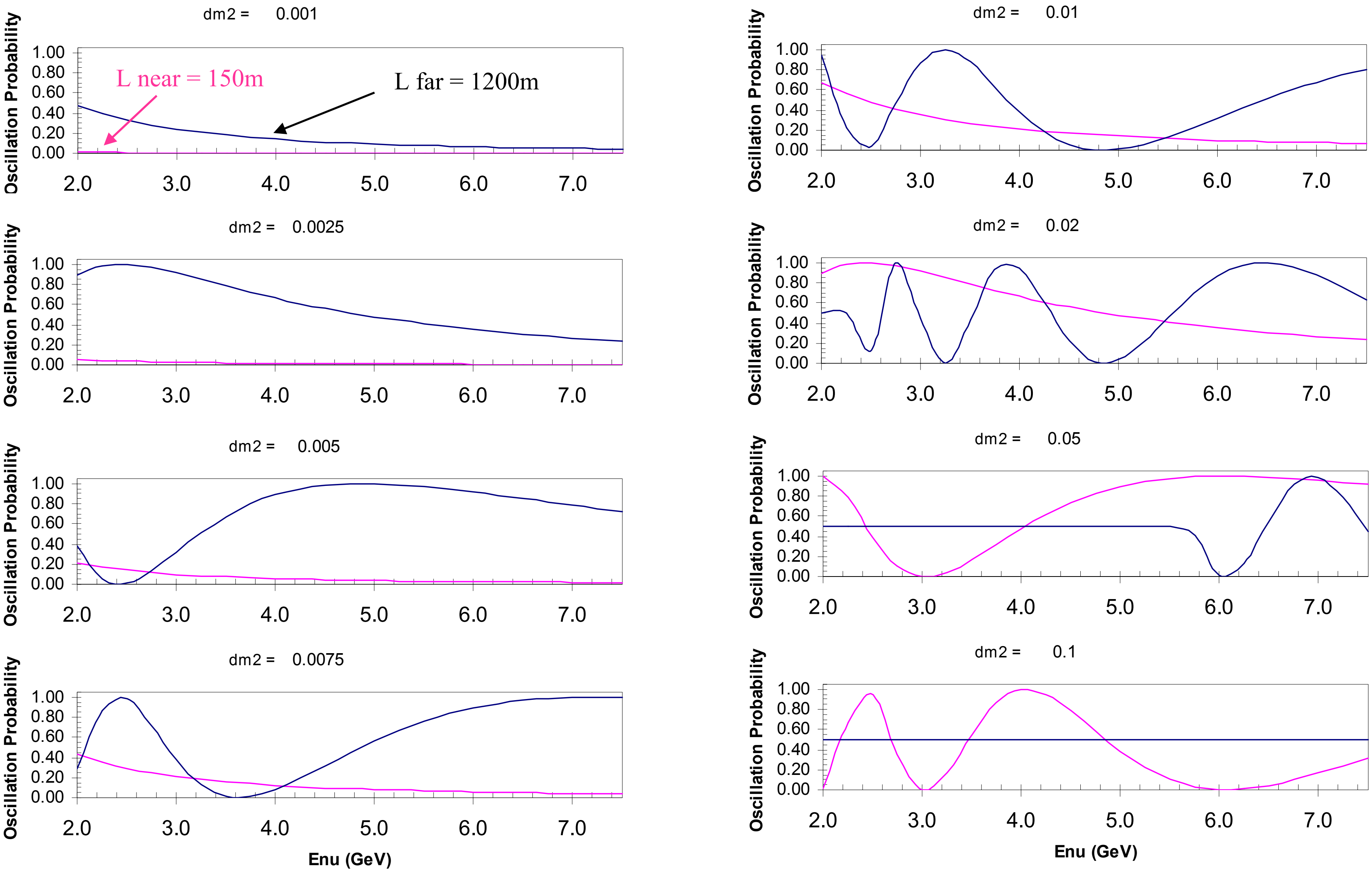




Oscillation Probability
(150m near and 1200m far)

Reactor Oscillation Probabilities

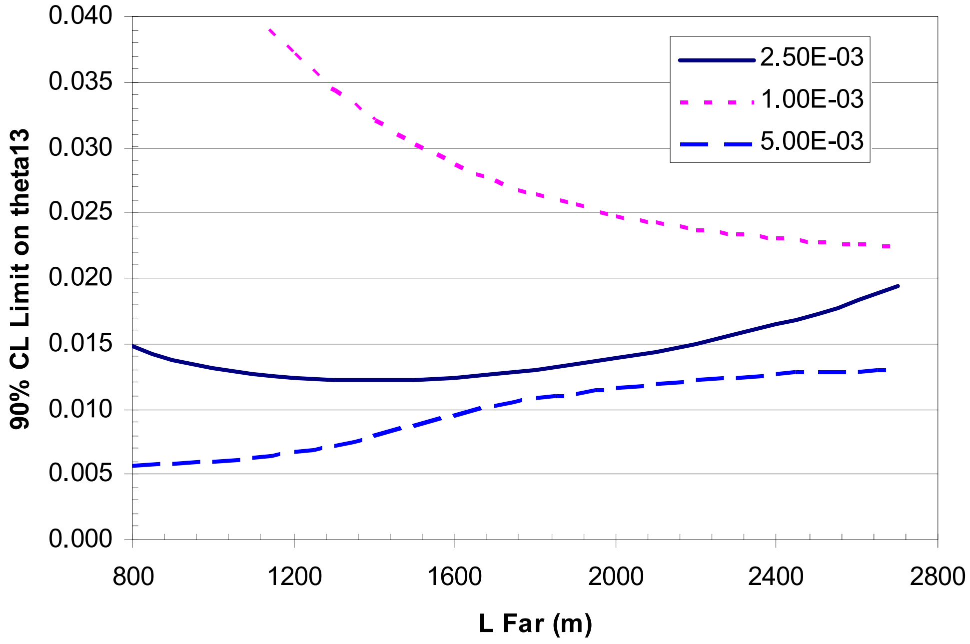
L near = 150m   L far = 1200m



Optimum Baseline Length

- For $\Delta m^2 = 2.5\times10^{-3}$ eV^2, broad minimum between 900m and 2000m
  - Minimum at 1500m gives $\sin^2 2\theta_{13} < 0.012$ at 90% CL

- Sensitivity degrades for $\Delta m^2 < 2.5\times10^{-3}$ eV^2



Limiting Factors in Reactor Disappearance Measurements

Example 50 kton detector for 3 years
with baselines of 1-2km to match Δm^2_{atm}

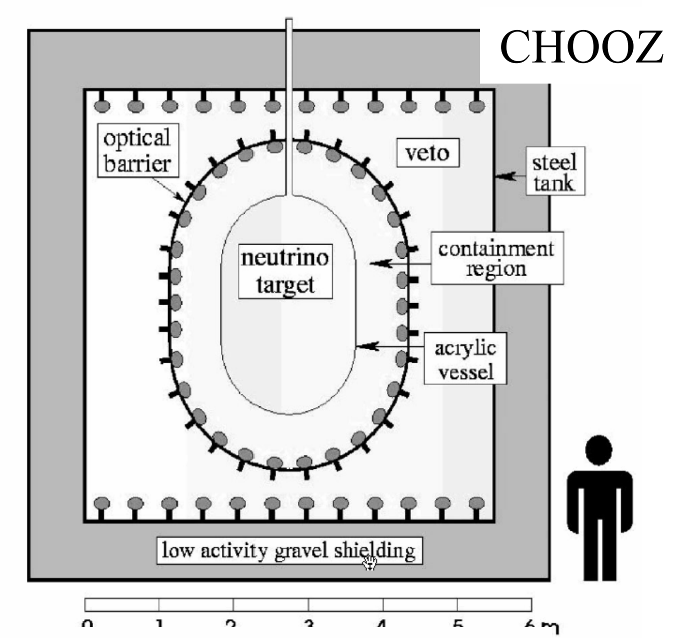
- Statistics:
  - 70,000 (1km) to 18,000 (2km) events for one typical (3GW) reactor
    $\Rightarrow \delta\sin^2 2\theta_{13} \approx$ 0.004 to 0.007
- Backgrounds (0.2 events/kton/day @ 300 mwe)
  - 9,000 background events (measured to 3.5% to ~14%)
    $\Rightarrow \delta\sin^2 2\theta_{13} \approx$ 0.002-0.005 (reactor off with 1 reactor exp.1 km)
    0.01 – 0.02 (extrapolation with a two reactor exp.)
- Near/Far comparison
  - Identical detectors imply ~1% relative error $\Rightarrow \delta\sin^2 2\theta_{13} \approx$ 0.01-0.02
  - Moveable far detector ~0.4% relative error $\Rightarrow \delta\sin^2 2\theta_{13} \approx$ 0.004-0.008

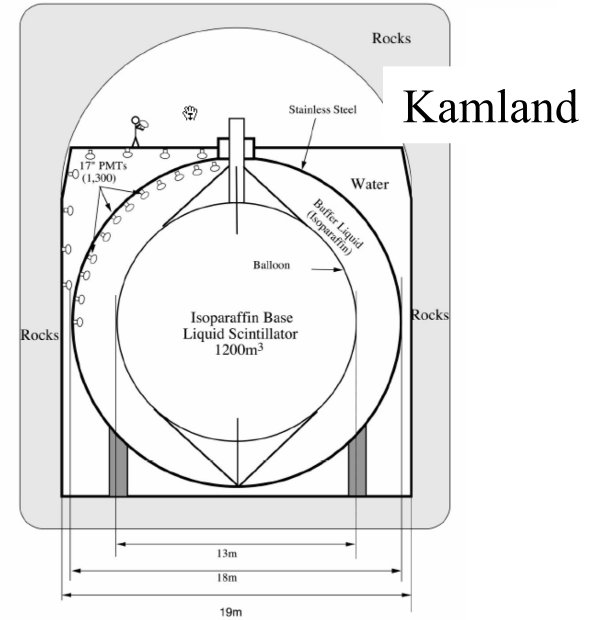
Detector and Statistics Issues

- Use extrapolation from previous experiments to a ~50 ton detector

  CHOOZ (5 tons), Palo Verde (12 tons), and Kamland (1000 tons)

  - Liquid scintillator based detectors
    - Buffer region to cut down backgrounds from PMT and cosmic rays
    - Veto region for cosmic source reduction
    - Passive shielding
- Possible improvements
  - Low activity PMTs
  - Ultra pure Gadolinium loading to reduce detection time
  - Moveable detectors for cross calibrations

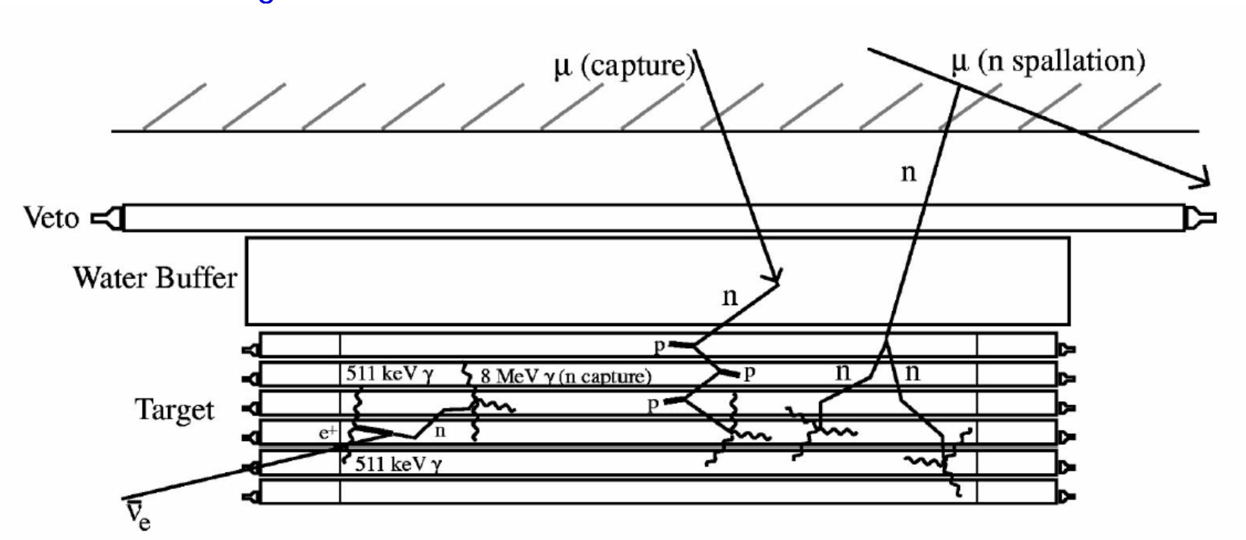


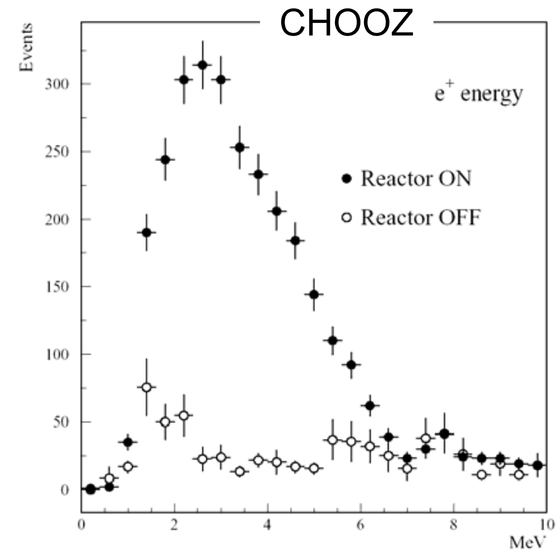


Backgrounds

- The signal: Inverse β Decay followed by Neutron Capture

$\bar{\nu}_e + p \rightarrow e^+ + n$ $\qquad$ $n + Gd \rightarrow$ 8 MeV of light





There are two types of backgrounds:

- Uncorrelated: Two separate events randomly occur in close proximity in time and space.
  - Can be measured to high precision by swapping the order of the signal components in the trigger.

- Correlated: Both parts of the signal come from the same parent event.
  - Such as two spallation neutrons from the same cosmic muon.
  - Or a proton recoil produced by a fast neutron that later gets captured.

Background Measurements and Mitigation

- Rates for both correlated and uncorrelated backgrounds are tied to the cosmic rate (depth). The uncorrelated rate is also related to radioactivity in the detector materials and surrounding rock.
  - Background events/ton/day: 0.1 for 600mwe, 0.2 for 300mwe, 2.0 for 32mwe (compared to signal rate at 1km of ~1.3 event/ton/day/reactor)

- Single reactor experiment:
  - Background rate can be measured during reactor off time (about 1 month/year)
    - Measure background rate to ~3.5% and contribute **~0.3% or less**.

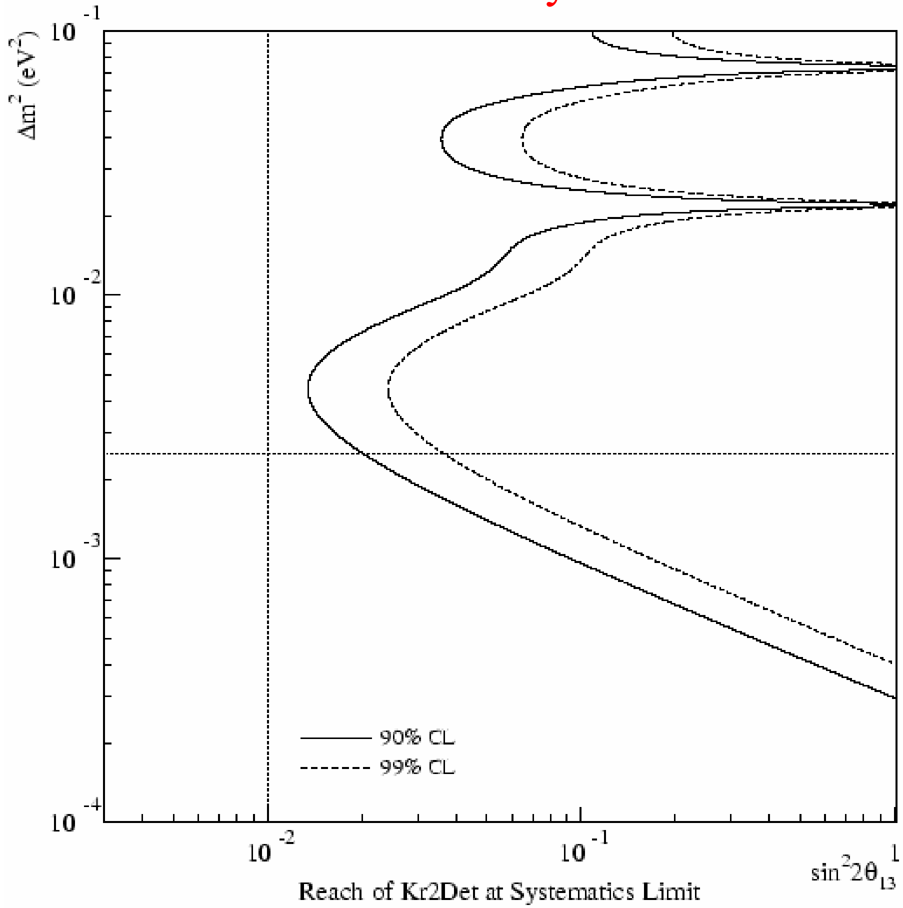
- Two or more reactors, typically no "all reactor off" data ⇐ ***Possible Show Stopper??***
  Use other methods:
  - Compare rates during 1 and 2 reactor operation and extrapolate to zero power
    - Measure background rates to ~15% leading to ~few % systematic error
  - Use swap method (~0.3%) (Wang, Miller & Gratta, PRD62:013012)
  - Use spatial effects like cosmic BGs are more likely at the top
  - Reduce backgrounds by:
    - Deeper experimental hall
    - Improved veto efficiency
    - Reduced neutron capture time ⇒ Isotopically pure Gd-157 could reduce capture time by factor of 5, but not yet feasible

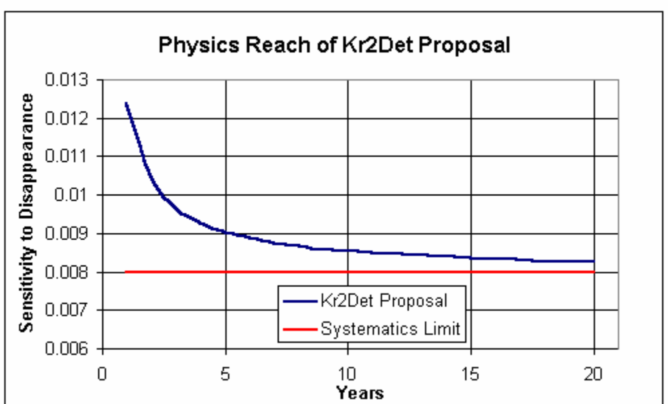
Proposed Kr2Det Experiment (Krasnoyarsk Reactor (~2 GW) in Russia)

- Two identical 46 ton detectors @ 1000m and 115m
  - ~900 8” pmts for 20% coverage
  - Signal rates: 4200 events/day near and 55/day in far detector
  - Depth 600 mwe $\Rightarrow$ Background rate is 5 events/day
    - Measured during reactor off to ~5% $\Rightarrow \delta\sin^2 2\theta_{13} \approx 0.004$
  - Relative near/far efficiency yields systematic uncertainty of 0.8%

- Advantage: Existing reactor and deep detector halls
- Disadvantage: hard to reach sensitivity to $\sin^2 2\theta_{13} \approx 0.01$

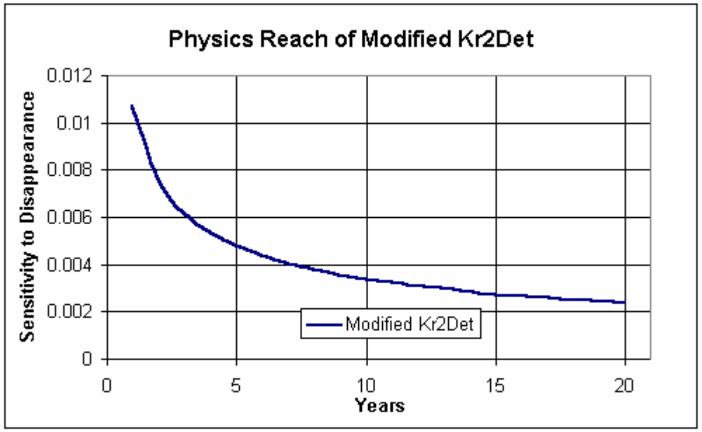
Systematics Limit



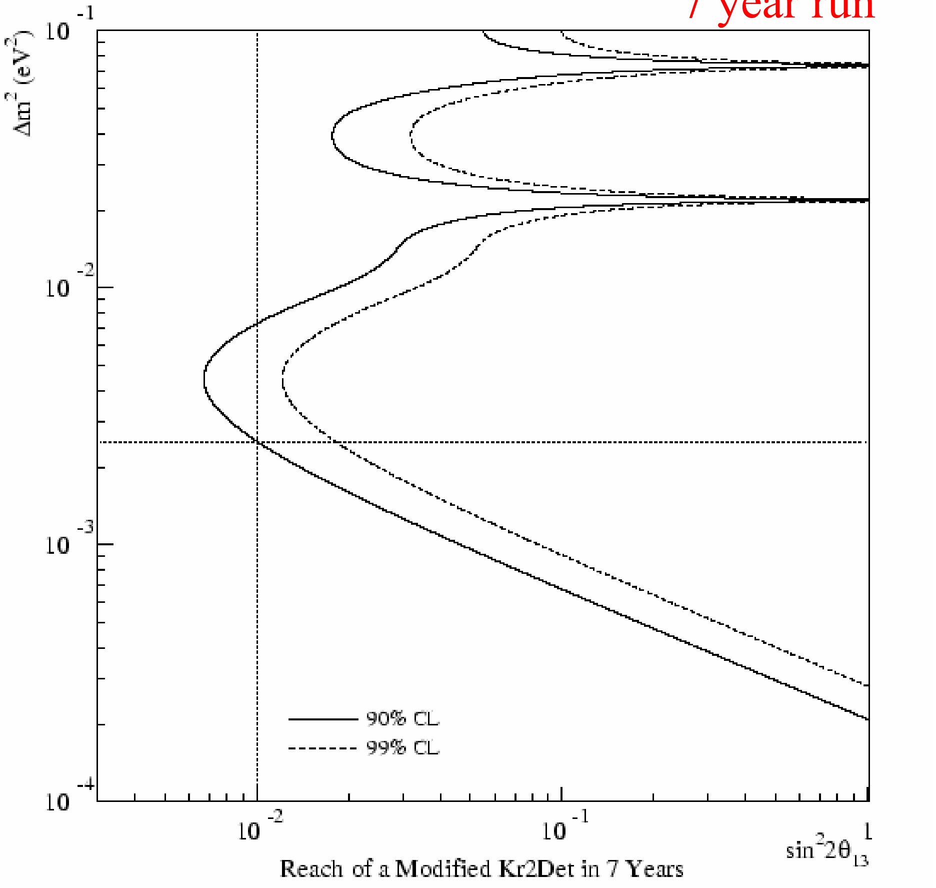


Modified Kr2Det Experiment (Moveable Far Detector)

- Two identical 46 ton detectors @ 1000m and 115m
  - Move far detector to near site for 10% of the running to measure relative efficiency
  - Relative near/far systematic uncertainty reduced significantly



7 year run



Possible Reactors and Sites in the US

- Requirements
  - Highest power for statistics
    - Single reactor desirable
    - Multiple reactors give increased flux but no full reactor off data
  - Ability to construct halls and possibly tunnels
    - Hills/Mountains allow horizontal tunneling that may be best
    - Shallow sites possible but increased backgrounds
  - Ability to move far detector to near site very desirable
    - Tunnel connecting near/far sites
    - Or transport by truck

Sites with a Single Reactor

Reactor Site	State	Max GW th	Avg GW th	% of Best
Grand Gulf	MS	3833.0	3502.7	100.0
Wolf Creek	KS	3565.0	3226.3	92.1 ←
Callaway	MO	3565.0	3203.2	91.4
Perry	OH	3758.0	3164.9	90.4
Waterford	LA	3390.0	3160.6	90.2
Watts Bar	TN	3411.0	3047.2	87.0
Seabrook	NH	3411.0	2885.7	82.4
Hope Creek	DE	3339.0	2733.5	78.0
Fermi	OH	3430.0	2686.8	76.7
River Bend	LA	3039.0	2613.5	74.6
Columbia	WA	3486.0	2466.9	70.4

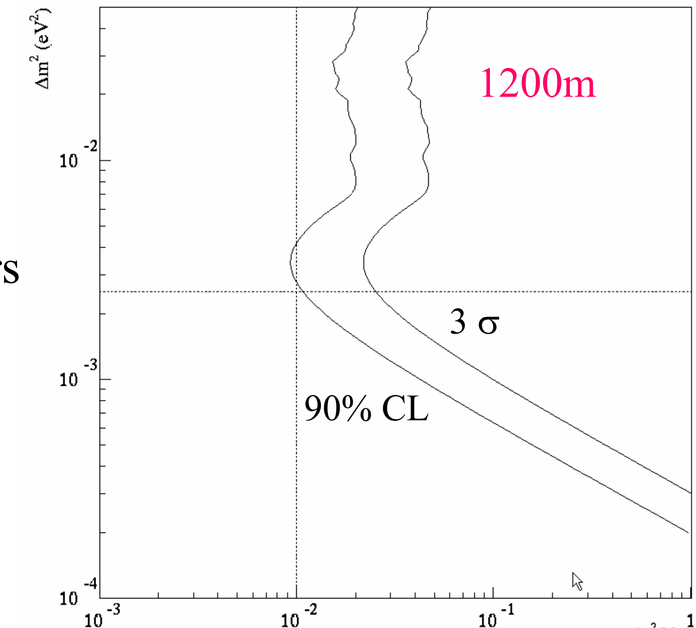
Sites with Two Reactors

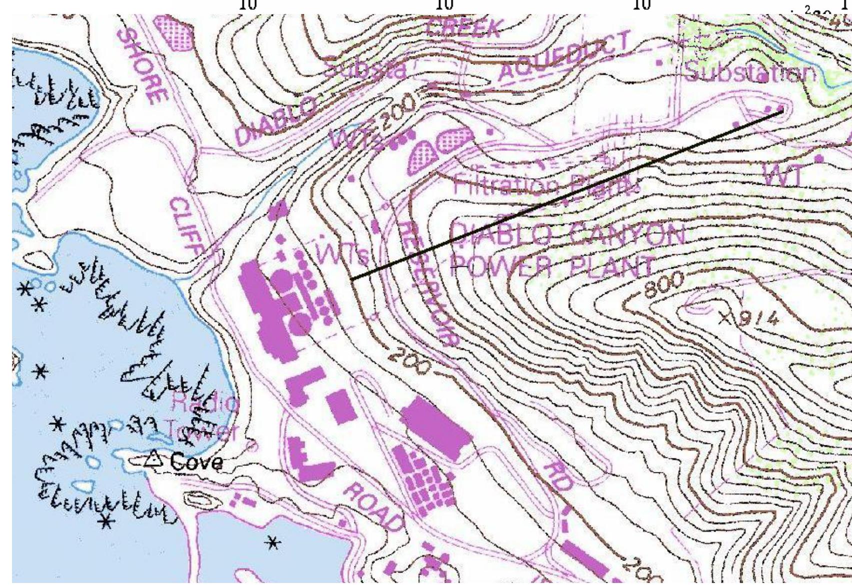
Reactor Site	State	Max GW th	Avg GW th	% of Best
South Texas Project	TX	7600.0	6908.4	100.0
Vogtle	GA	7130.0	6533.5	94.6
Braidwood	IL	7172.0	6434.5	93.1
Byron	IL	7172.0	6386.7	92.4
Limerick	PA	6916.0	6297.0	91.2
Peach Bottom	PA	6916.0	6261.3	90.6
Sequoyah	TN	6822.0	6195.5	89.7
Susquehanna	PA	6978.0	6144.1	88.9
Diablo Canyon	CA	6749.0	6104.9	88.4 ←
Catawba	SC	6822.0	6021.0	87.2
Comanche Peak	TX	6916.0	6008.9	87.0
San Onofre	CA	6876.0	5971.2	86.4
McGuire	NC	6822.0	5868.6	84.9
North Anna	VA	5786.0	5246.9	76.0
Edwin Hatch	GA	5526.0	4885.0	70.7
Calvert Cliffs	MD	5400.0	4877.6	70.6
St. Lucie	FL	5400.0	4866.8	70.4

Diablo Canyon Site

- Two reactor (3.1 + 3.1 GWE) site near hill on the California coast
  - Horizontal tunnel could give 600mwe shielding
  - Single reactor off data measures bkgnd to 14%
  - 115,000 far events over 4900 background events
    - $\sin^2 2\theta_{13}$= 0.011 @ Δm^2 = 2.5x10^{-3} 90% CL
  - Possible improvements:
    - Techniques needed to measure/reduce background since no both reactor off time

3 yrs

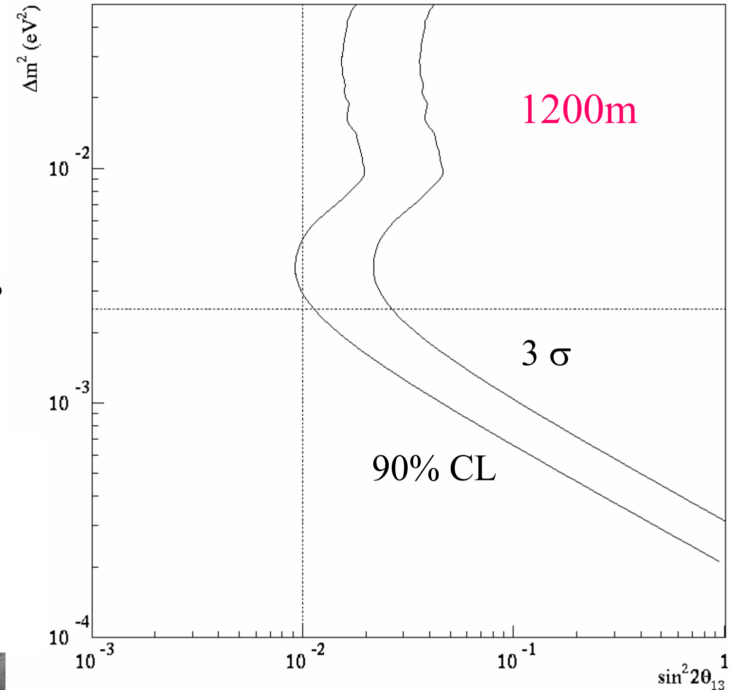




Wolf Creek (Kansas) Site

- One reactor (3.6 GW) site on flat plan
  - Shafts needed to reach 300mwe depth along with tunnel
  - 57,000 far events over 9100 background events
    - Reactor off measures bkgnd to 3.5%
    - $\sin^2 2\theta_{13}$= 0.012 @ Δm^2 = 2.5×10^{-3} 90% CL
  - Possible improvements:
    - Measurement is statistics limited with moveable detector
      ⇒ Add second 50 ton far detector

3 yrs



Comparison of Possible Scenarios

- Example scenarios with 3 year data runs
  - 50 ton far (near) detector at 1200m (150m)
  - One (or two) 3 GW reactors
- Costs
  - Detector based on similar MiniBooNE detector
  - Tunnel/hall cost estimates from NuMI engineer
  - Should add +50% contingency to cost

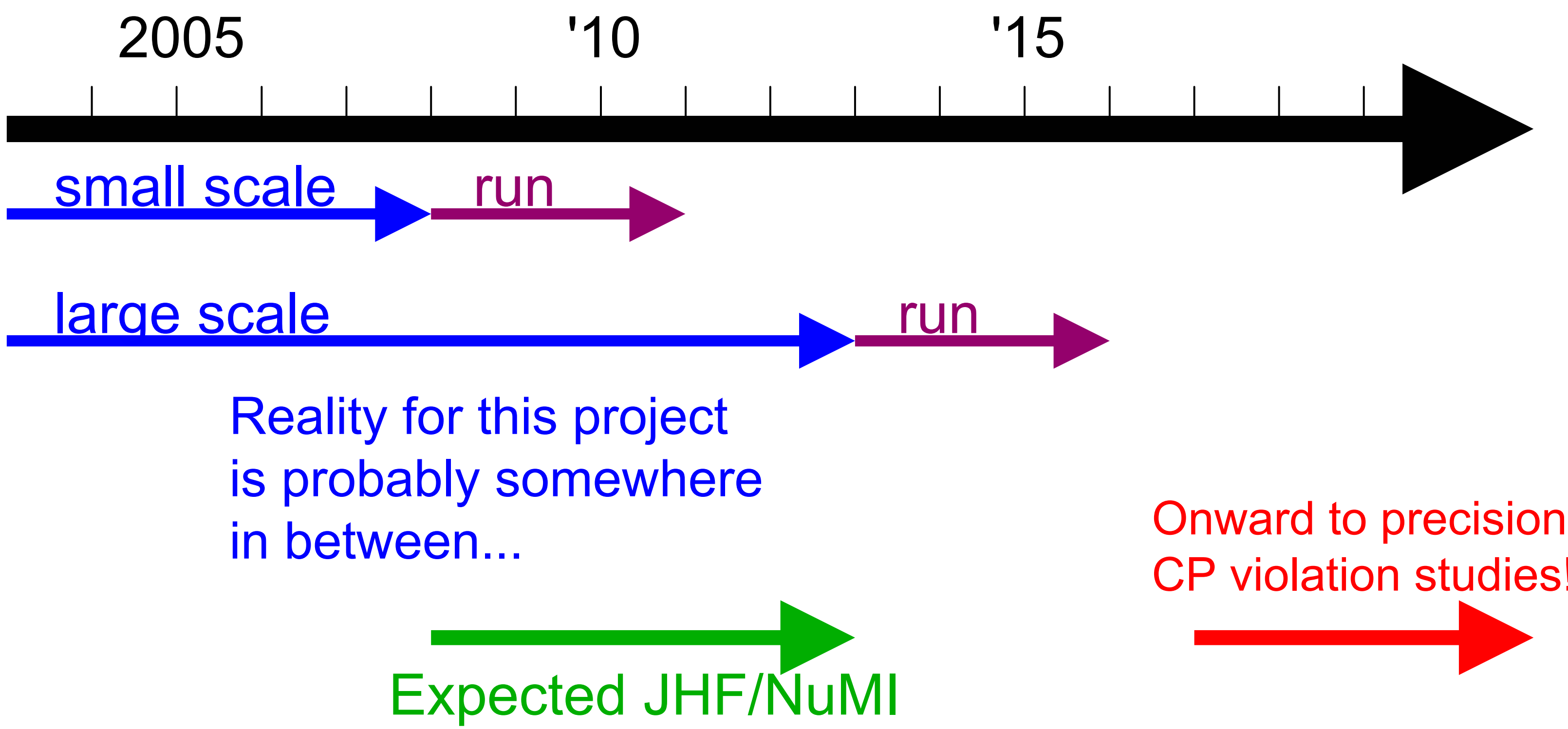
Unit	Cost ($M)
Detector	5
Hall at 32ft	1
Hall at 300ft	2
Hall at 600ft	3
Tunnel&Halls at 32ft	5
Tunnel& Halls at 300ft	15
Tunnel&Halls at 600ft	17

							$\sin^2 2\theta_{13}$ @ $\Delta m^2 = 2.5 \times 10^{-3}$	
Source	**Depth (mwe)**	**Detector**	**Events Far**	**Background**	**Rel Norm Err**	**Cost ($M)**	**90% CL**	**3 σ**
One Reactor	32	Fixed	64,000	101,000	0.008	12	0.056	0.132
		Moveable	57,000	91,000	0.0023	15	0.052	0.122
	300	Fixed	64,000	10,1000	0.008	14	0.024	0.057
		Moveable	57,000	9100	0.0023	25	0.012	0.029
	600	Fixed	64,000	5100	0.008	16	0.024	0.055
		Moveable	57,000	4600	0.0023	27	0.011	0.027
Two Reactors	32	Fixed	128,000	110,000	0.008	12	0.040	0.093
		Moveable	115,000	99,000	0.0016	15	0.033	0.077
	300	Fixed	128,000	10,900	0.008	14	0.025	0.059
		Moveable	115,000	9900	0.0016	25	0.013	0.031
	600	Fixed	128,000	5500	0.008	16	0.024	0.056
		Moveable	115,000	4900	0.0016	27	0.011	0.025

Timescale depends on the size of project, *especially construction!*

Small scale -- MiniBooNE (~$10M), 5 years from LOI to run
(CHOOZ also ~5 years from proposal to run)

Large scale -- NuMI (> $50M), 10 years from "idea" to run



Reactor results will be on a
reasonable timescale
to complement the off axis results

Summary and Conclusions

- A next generation reactor experiment could reach sensitivity to oscillations with $\sin^2 2\theta_{13} \approx 0.01$ and $\Delta m^2 = 2.5\text{x}10^{-3}$ @ 90% CL

- Timescales appear reasonable as a complement to the expected appearance measurements and costs do not look prohibitive
  – Reactor measurements can be combined with neutrino only offaxis running to get at the θ_{13} physics (Offaxis antineutrino running will take a long time)

- To design a 3σ measurement experiment at this level will require improvements:
  – For a multiple reactor site, the measurement and reduction of the background is crucial
  – For a single reactor site, one probably needs to add more far detectors
    - An experiment with multiple 50 ton far detectors and one 50 ton near detector could reach the required sensitivity

As in the past, an international collaboration mounting the experiment at

Sensitivities using Energy Dependent Fits

- Need to include energy dependent systematic uncertainty in near/far comparison and background