Measurements of θ_{13} *Using* Reactor Neutrinos

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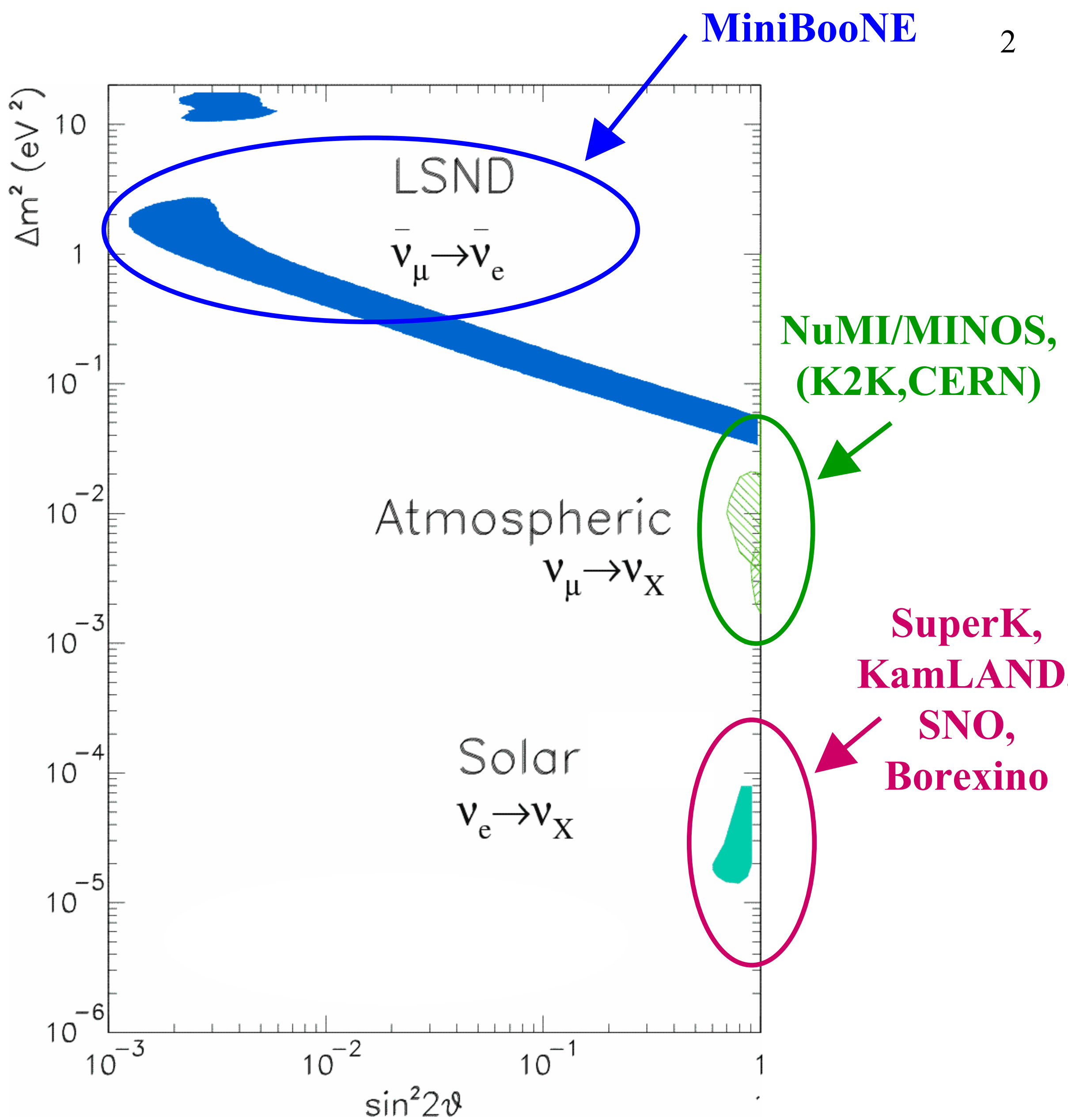
- With the recent confirmation by Kamland and isolation of the Δm_{solar}^2 in the LMA region, the field of neutrino oscillations is turning to measuring the last mixing angle θ_{13} and obtaining better precision on Δm_{solar}^2 and Δm_{atm}^2 (along with checking LSND)
  - $\Rightarrow$ **Road to measuring ν-mass hierarchy and ν-CP violation**

- For measuring θ_{13}, reactor measurements are a crucial ingredient if the required sensitivity can be reached.

- Outline:
  - Current situation
  - Next steps and precision requirements
  - Overview of reactor experiment issues
  - Plans, sites, and prospects

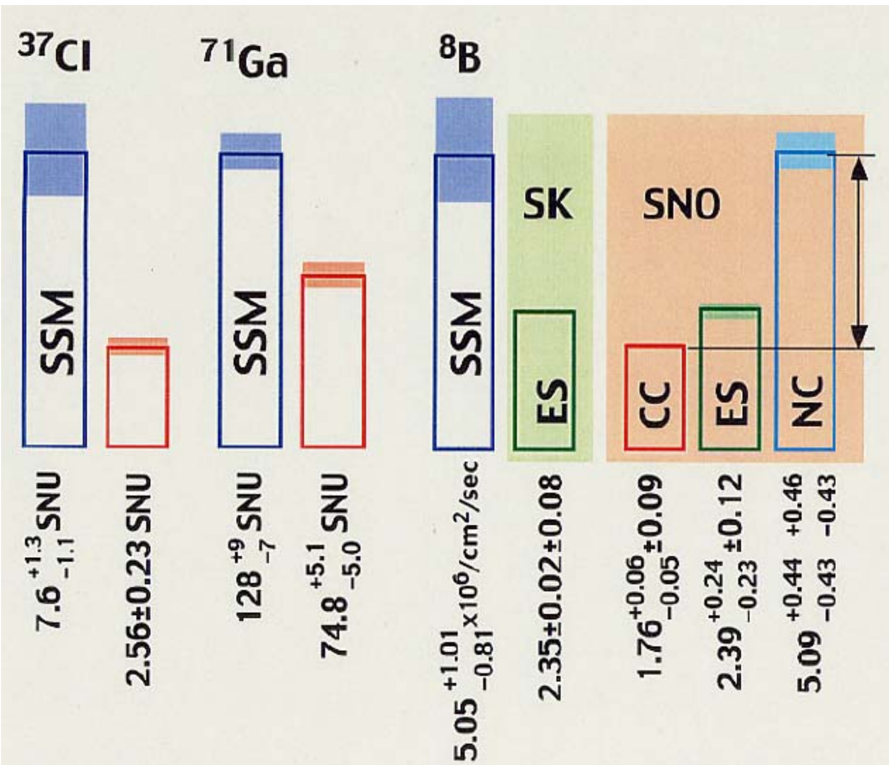
Questions addressed by Current Experiments:

- LSND Δm^2
  - Determination if osc.
  - Measure $\Delta m^2/\sin^2 2\theta$
- Atmospheric Δm^2
  - Know if $\nu_\mu \to \nu_\tau$ or ν_s
  - Measure $\Delta m^2/\sin^2 2\theta$
  - Maybe see $\nu_\mu \to \nu_e$
  - CERN observe ν_τ
- Solar Δm^2
  - Have restricted values to one solar solution
  - Know if $\nu_e \to \nu_{\mu,\tau}$ or ν_s
  - Measure $\Delta m^2/\sin^2 2\theta$

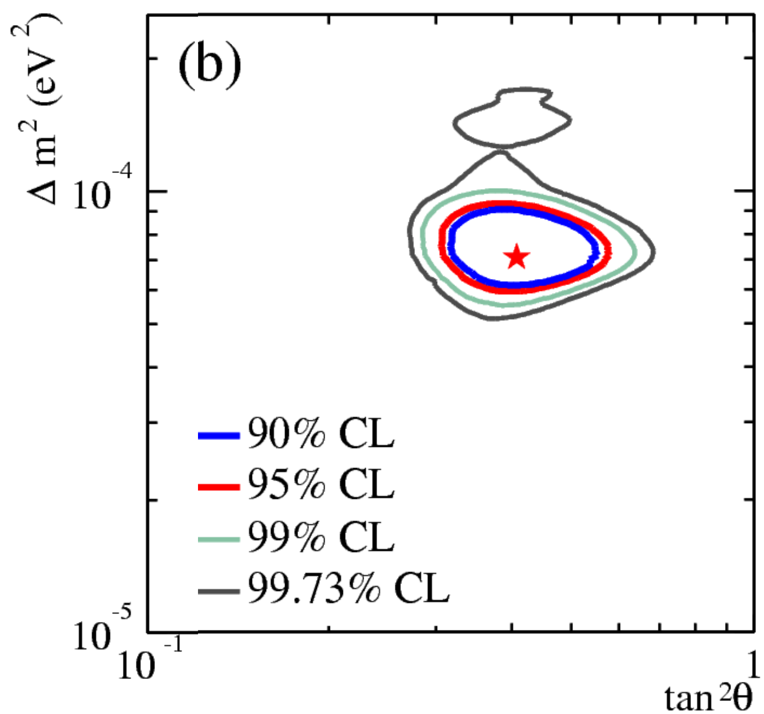


Solar Oscillation Experiments

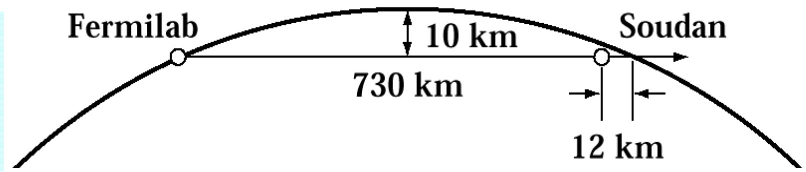
- All solar experiments see too few solar neutrinos
  - SNO sees expected total neutrino flux ($\nu_e+\nu_\mu+\nu_\tau$) $\Rightarrow \nu_e \rightarrow \nu_\mu+\nu_\tau$ mostly



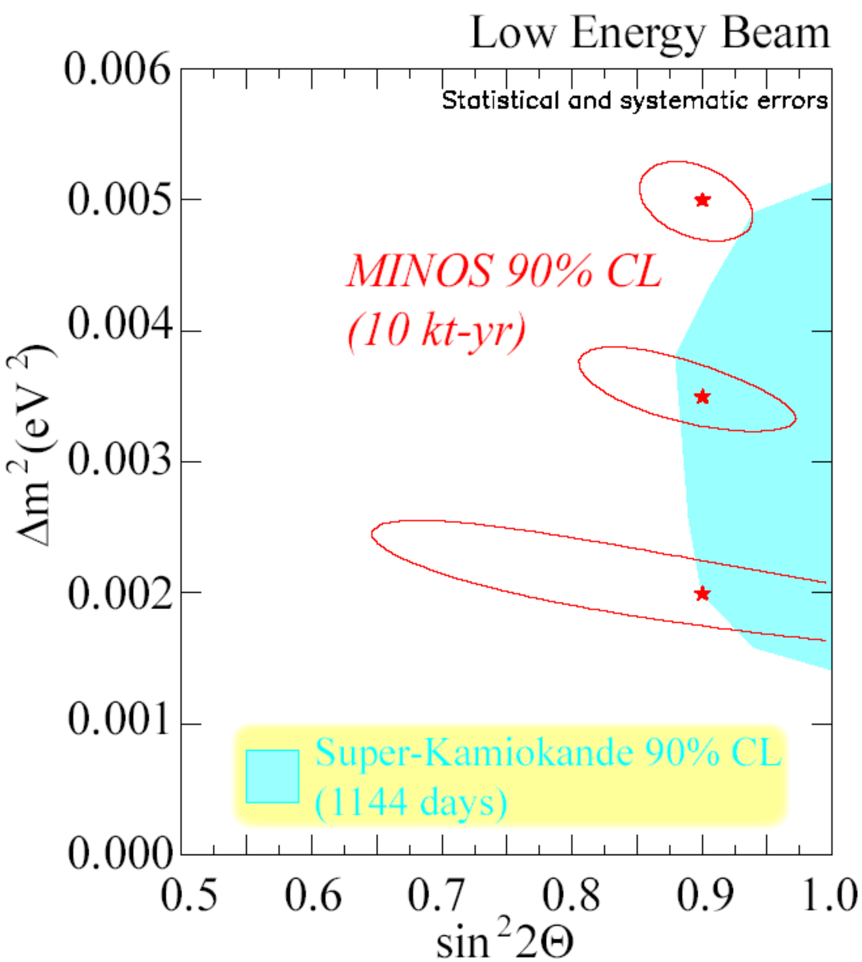
- New SNO and Kamland Reactor Results:
  - SNO: new salt data
  - Kamland: 54 events observed, 86±6 expected $\Rightarrow$ Osc. Probability = 0.39 ± 0.09
  - Global fit with all solar and Kamland data $\Delta m^2_{Solar} \approx 7.1 \pm 1.0 \times 10^{-5}$ eV^2



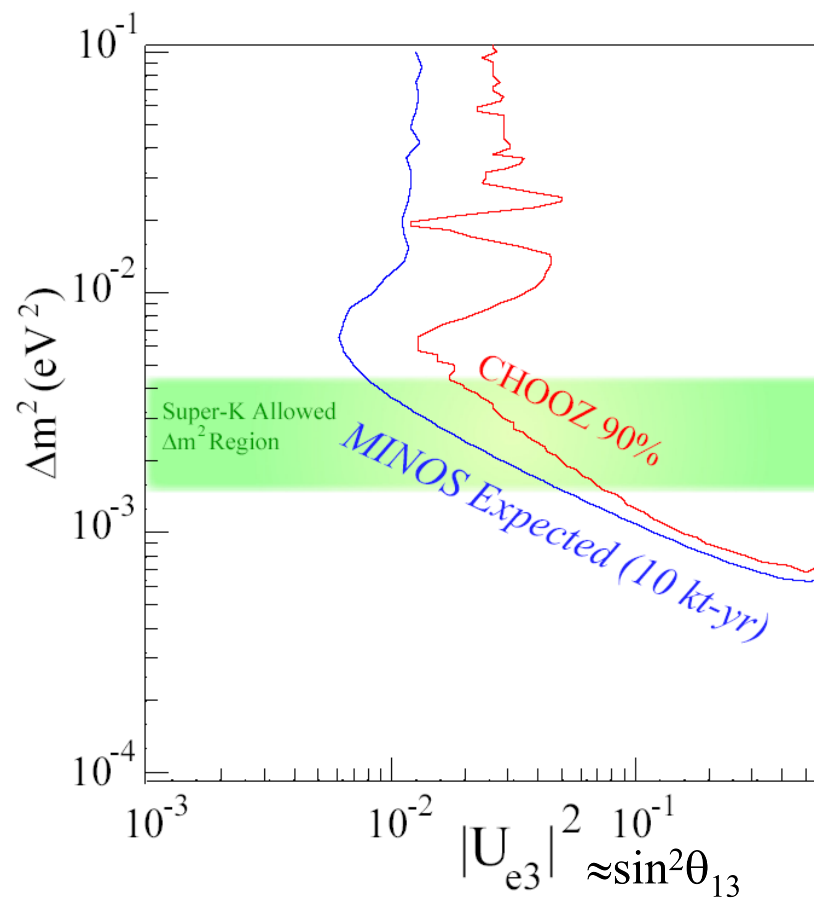
Atmospheric Oscillation Region: NuMI/MINOS Experiment



- From ν_μ disappearance signal
  - Measure $\Delta m_{23}{}^2$ to ~10%



- Probe for $\nu_\mu \rightarrow \nu_e$ appearance
  - Sensitivity at the level of $\sin^2 2\theta_{13}$> 0.06-0.08 @ 90%CL

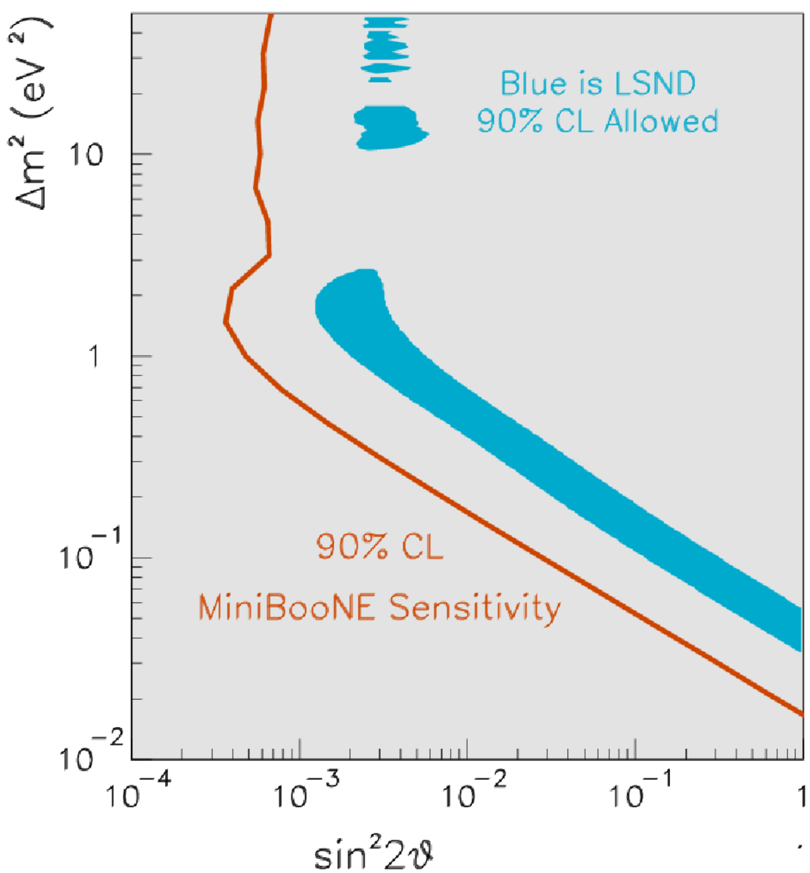


MiniBooNE

With ~two years of running MiniBooNE will completely include or exclude the entire LSND signal region at the 5σ level.

Expected events

- 500,000 ν_μ CC quasi-elastic
- **~1000 extra ν_e's if LSND correct**



- If MiniBooNE sees $\nu_\mu \rightarrow \nu_e$ oscillations then need to enhance oscillation program
  - Three distinct Δm^2 values
    $\Rightarrow$ Indicates some unexpected physics
    - More than three types of neutrinos – extra "sterile" neutrino types
    - Neutrinos and antineutrinos have different masses
  - Need more long and short-baseline exps probing high Δm^2
    - Follow-up BooNE experiment with two detectors
    - Moderate short-baseline ν_τ appearance experiments

If MiniBooNE Confirms LSND

- The mixing matrix would be an n×n matrix with n-3 sterile ν's.
- In many models the mixing between the active and sterile sectors is small. (See Sorel, Conrad & Shaevitz, hep-ph/0305255)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \nu_{s'} \\ \ldots \end{pmatrix} = \begin{pmatrix} \overset{\text{MNS}}{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}} & \text{small} & & \\ & U_{s4} & U_{s5} & \ldots \\ \text{small} & U_{s'4} & U_{s'5} & \\ & \ldots & & \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \nu_5 \\ \ldots \end{pmatrix}$$

- So reactors could still provide a direct measurement of Ue3!
- Also the sterile Δm^2 are so large that any mixing to sterile cancels in the near far ratio.

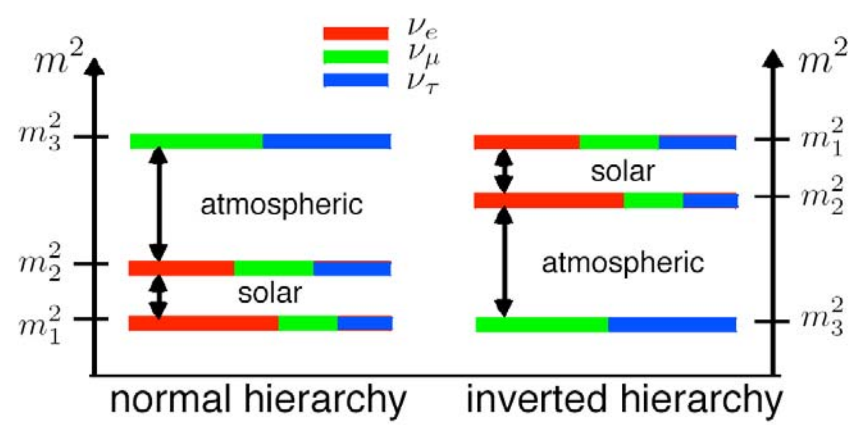
Near Term Steps of a Neutrino Oscillation Program

1. Measure $\sin^2 2\theta_{13}$
   - Last unmeasured element in the mixing matrix
   - Sets the scale for being able to observe CP violation and matter effects
   - Off-axis experiments
     - Off-axis gives beam with narrow energy distribution that is tunable osc. max
       - Fermilab NuMI to Offaxis detector
       - Japanese JHF to SuperK experiment
   - Reactor Experiments
     - Provides unambiguous measure of $\sin^2 2\theta_{13}$
       - Proposals being developed in US, Japan, and Europe

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix} \sim 0.7 & \sim 0.7 & \overset{\boxed{<0.2}}{\mathbf{\sin\theta_{13}e^{i\delta}\ ?}} \\ \sim -0.5 & \sim 0.5 & \sim 0.7 \\ \sim 0.5 & \sim -0.5 & \sim 0.7 \end{pmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$\Delta m^2_{12} << \Delta m^2_{23}$$

2. Determine the sign of Δm^2_{23} from matter effects in the earth
   - Only available with NuMI offaxis measurements



3. Probe for CP Violation (δ parameter)
   - Compare measurements for neutrinos with antineutrinos or with a reactor measurement

What $\sin^2 2\theta_{13}$ Sensitivity Is Needed?

- Theoretical / Phenomenology
  - Really no solid information or constraints.
    - $U_\nu \neq U_{CKM}$
    - Data driven not theory driven field
    - $\sin^2 2\theta_{13}$ could be very small if associated with some symmetry.
  - Models:
    - Simple models do not fit current oscillation data

      $\Rightarrow$ Put in small? perturbations

      $\theta_{13} = \Delta m_{solar}^2/\Delta m_{atmos}^2$ or $\sqrt{(..)}$

      or $\sqrt{(m_e/m_\mu)}$

      (i.e. Altarelli,Feruglio, hep-ph/0206077)

    ?? $\sin^2 2\theta_{13} \approx$ very small to CHOOZ limit??

- Practical / Political
  - Information for next step
    - Need $\sin^2 2\theta_{13} > \sim 0.01$ to measure neutrino mass hierarchy and CP violation with longbaseline superbeams
      - Probably will not embark on expensive (~500M$) project without a clear measurement of $\sin^2 2\theta_{13}$
  - Competition and Complementarity
    - Proposed longbaseline $\nu_\mu \rightarrow \nu_e$ appearance experiments have sensitivity in the $> \sin^2 2\theta_{13} \approx 0.01$ region
      - Combination of appearance and disappearance very powerful if comparable sensitivity

Conclusion: Need reactor experiment that measures $\sin^2 2\theta_{13}$ down to the 0.01 level

Methods to Measure $\sin^2 2\theta_{13}$

- Appearance $\nu_\mu \to \nu_e$ (Offaxis Exps.)

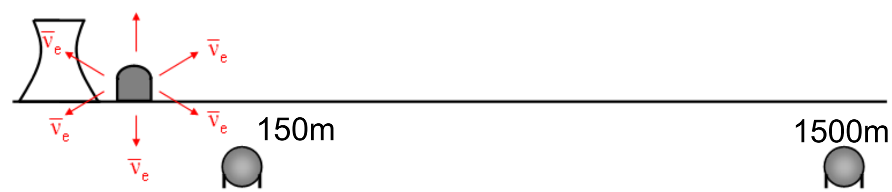
$$P[\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)] = s_{23}^2 \sin^2 2\theta_{13} \sin^2 \frac{\Delta_{31}}{2}$$

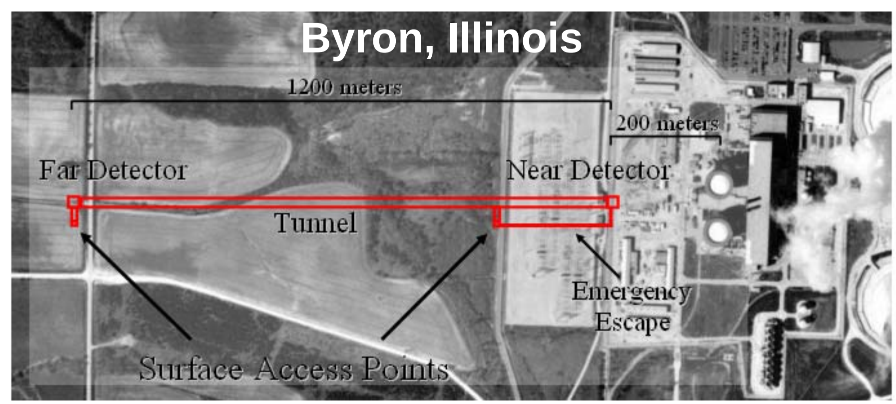
  – Use fairly pure, accelerator produced ν_μ beam with a detector at long distance (300 km - 900 km) from the source
    - Look for the appearance of ν_e events
    - Use near detector to measure background ν_e's (beam and misid)

- Disappearance $\bar{\nu}_e \to \bar{\nu}_e$ (Reactor Exp)

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

  – Use a set of reactors as a source of $\bar{\nu}_e$'s with a detector at few km
    - Look for a non- $1/r^2$ behavior of the ν_e rate
    - Use near detector to measure the un-oscillated flux





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

- Appearance $\nu_\mu \to \nu_e$ (Offaxis Exps.)

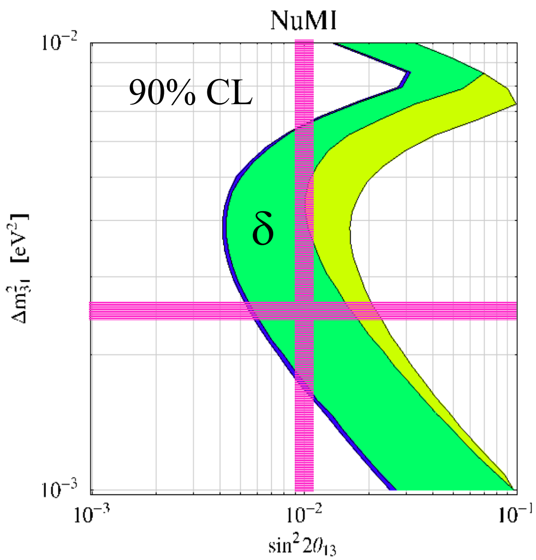
$$P[\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)] = s_{23}^2 \sin^2 2\theta_{13} \sin^2 \frac{\Delta_{31}}{2}$$

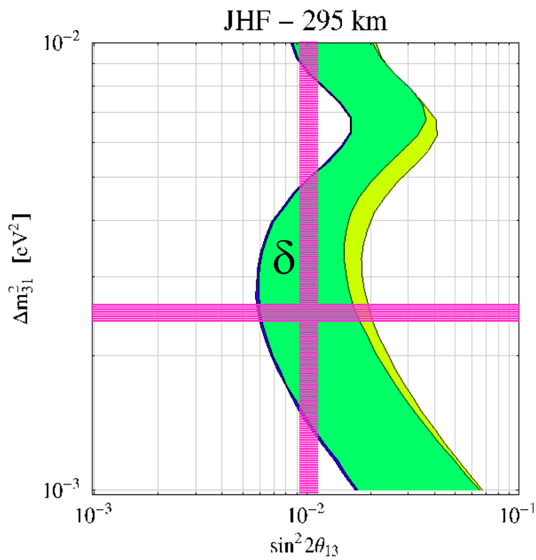
  – Ambiguity with s^2_{23} size
  – Matter effects can be important
  – CP violation (δ) effects can be important
  – Measurement difficult:
    - Look for small number of events over comparable background

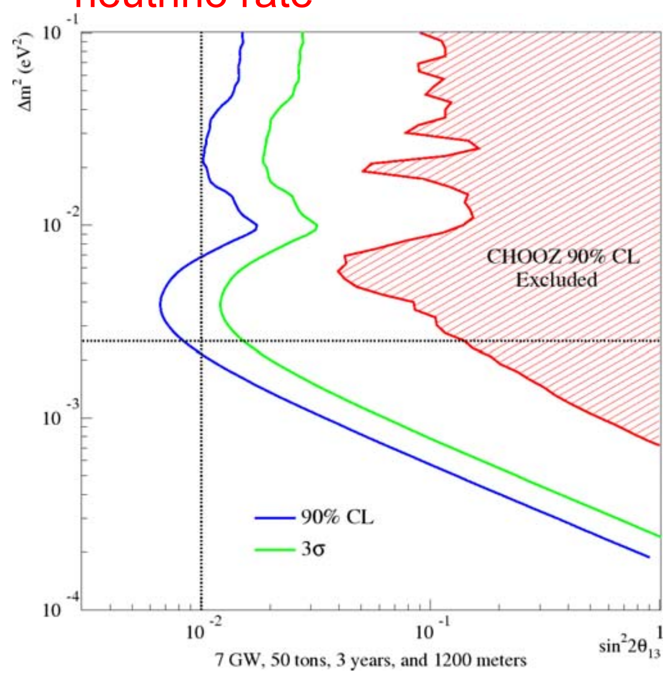
- Disappearance $\bar{\nu}_e \to \bar{\nu}_e$ (Reactor Exp)

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

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





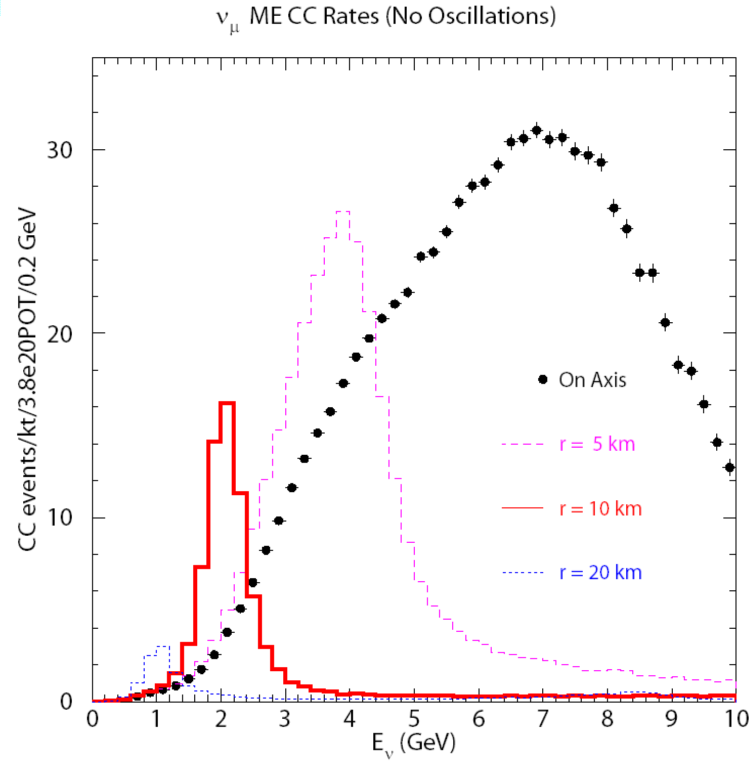


Concept of the Offaxis Beam

- By going offaxis, beam energy is reduced and spectrum becomes very sharp
  - Allows experiment to pick an energy for the maximum oscillation signal
  - Removes the high-energy flux that contributes to background

"Not magic but relativistic kinematics"

- Problem is reduced rate!
  - need large detectors and high rate proton source



$\Delta m^2 = 3.0\times10^{-3}$ eV^2, $\sin^2 2\theta_{13}=0.1$

NuMI Off-Axis,
5yrs @ 4E20 POT/yr
712 km baseline
(20kton detector)

	ν_μ CC	NC	Beam ν_e	Signal ν_e
all	10714	4080	292	302
after cuts	1.8	9.3	11	123

Pproton= 120 GeV
L = 712 km
ave. En = ~2 GeV
power = 0.4 MW

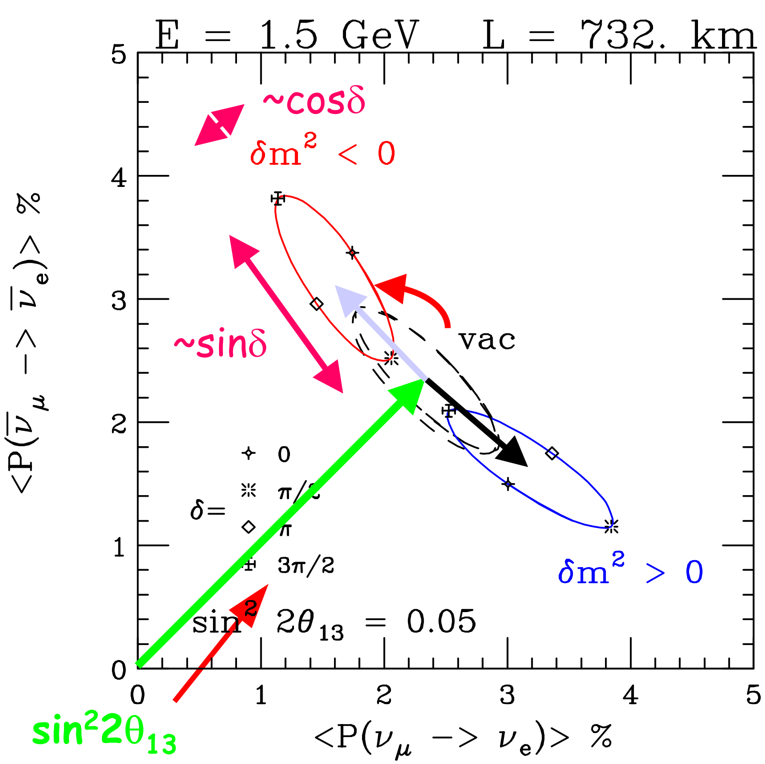
JHF Phase I,
5yrs @ 0.77MW
295 km baseline

	ν_μ CC	NC	Beam ν_e	Signal ν_e
all	12104	5696	295.4	293
after cuts		10.2	10.2	85.5

Pproton= 50 GeV
L = 295 km
ave. En = ~0.7 GeV
power = 0.77 MW

Ambiguities and Correlations in Offaxis Measurements

$$P(\nu_\mu \to \nu_e) \sim K_1 \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \pm K_2 \sin(2\theta_{23}) \sin(\theta_{13}) \, \mathrm{sign}(\Delta m^2_{31}) \cos(\delta) \pm K_3 \sin(2\theta_{23}) \sin(\theta_{13}) \sin(\delta)$$



Minakata and Nunokawa, hep-ph/0108085

Ambiguities due to :

- Need $\sin\theta_{23} = \sqrt{\dfrac{1 \pm \sqrt{1-\sin^2 2\theta_{23}}}{2}}$, not $\sin^2 2\theta_{23}$
- Sign of $\Delta m^2 \Rightarrow$ Overall shifts

Correlations :

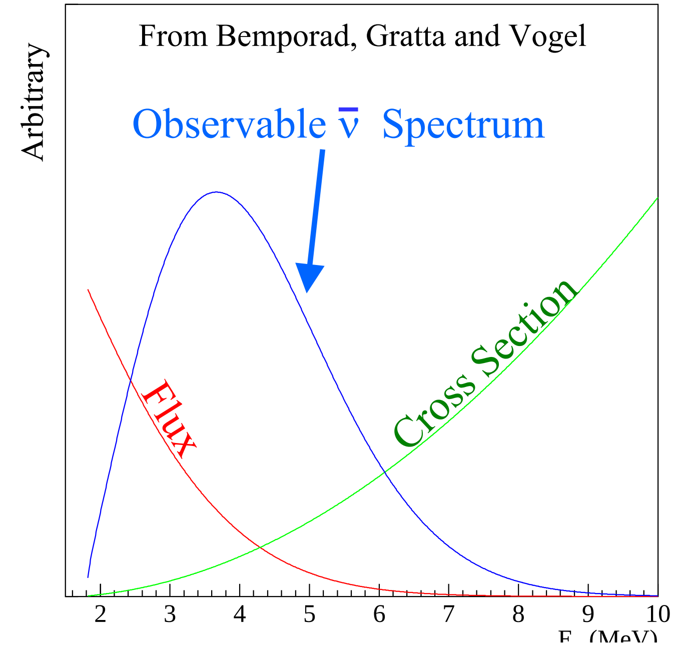
- CP violation phase $\delta \Rightarrow$ Ellipse Regions
- Interference with subdominant Δm^2_{12} terms

Need Reactor measurement

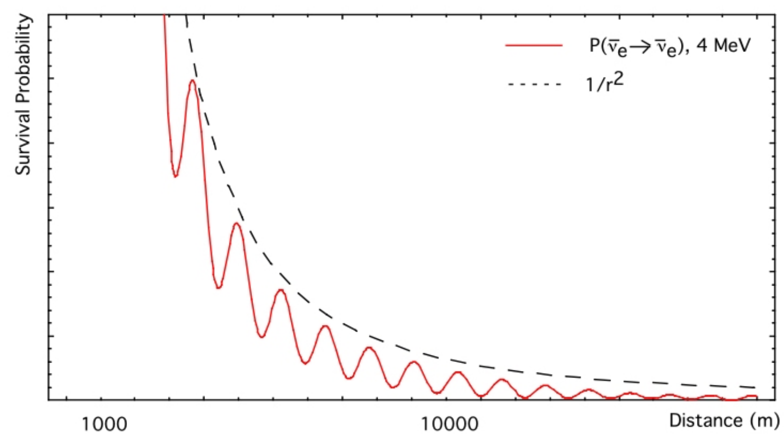
$$1 - P(\bar{\nu}_e \to \bar{\nu}_e) = \sin^2 2\theta_{13} \sin^2 \frac{\Delta_{31}}{2}$$

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

- Nuclear reactors are a very intense sources of $\bar{\nu}_e$ with a well understood spectrum
  - 3 GW ≈ 2×10^{21} MeV/s → 6×10^{20} $\bar{\nu}_e$/s
  - Reactor spectrum peaks at ~3.7 MeV
  - Oscillation Max. for $\Delta m^2 = 2.5\times10^{-3}$ eV^2 at L = 1.7 km



- Look for small rate deviation from $1/r^2$ measured at a near and far baselines
  - Counting Experiment
    - Compare events in near and far detector
  - Energy Shape Experiment
    - Compare energy spectrum in near and far detector



Reactor Neutrino Event Signature

- The reaction process is inverse β-decay followed by neutron capture
  - Two part coincidence signal is crucial for background reduction.

$$\bar{\nu}_e p \to e^+ n$$
$$\hookrightarrow n\ capture$$

- Positron energy spectrum implies the neutrino spectrum

$$E_\nu = E_e + 0.8\ \mathrm{MeV}$$

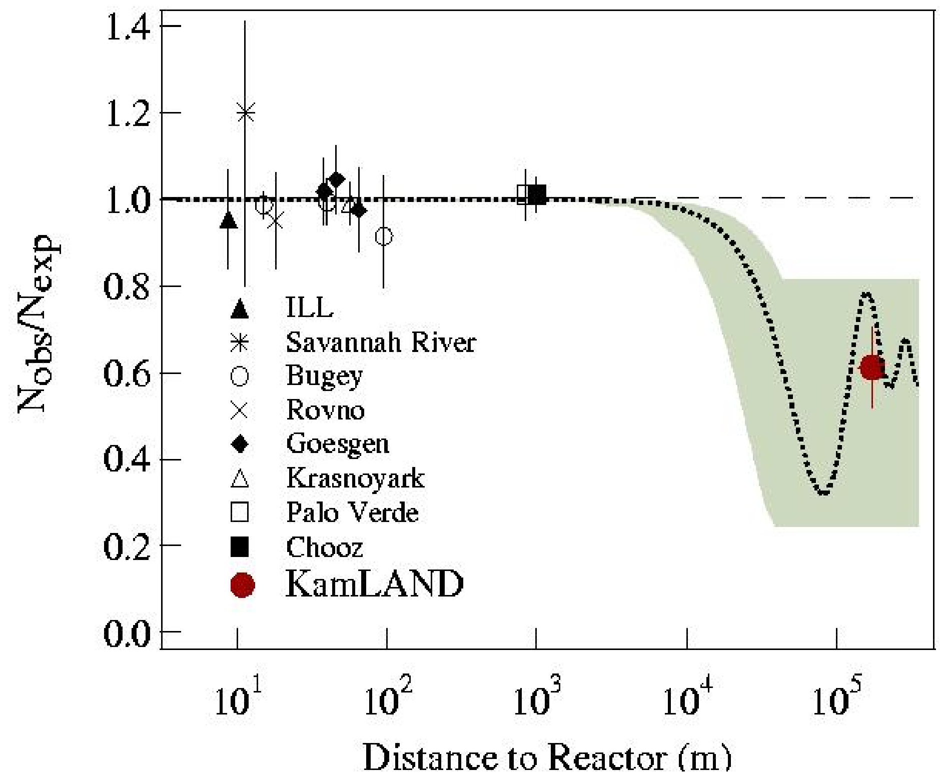
- In undoped scintillator the neutron will capture on hydrogen

$$\mathrm{n\ H} \to \mathrm{D}\ \gamma\ \ (2.2\ \mathrm{MeV})$$

- More likely the scintillator will be doped with gadolinium to enhance capture

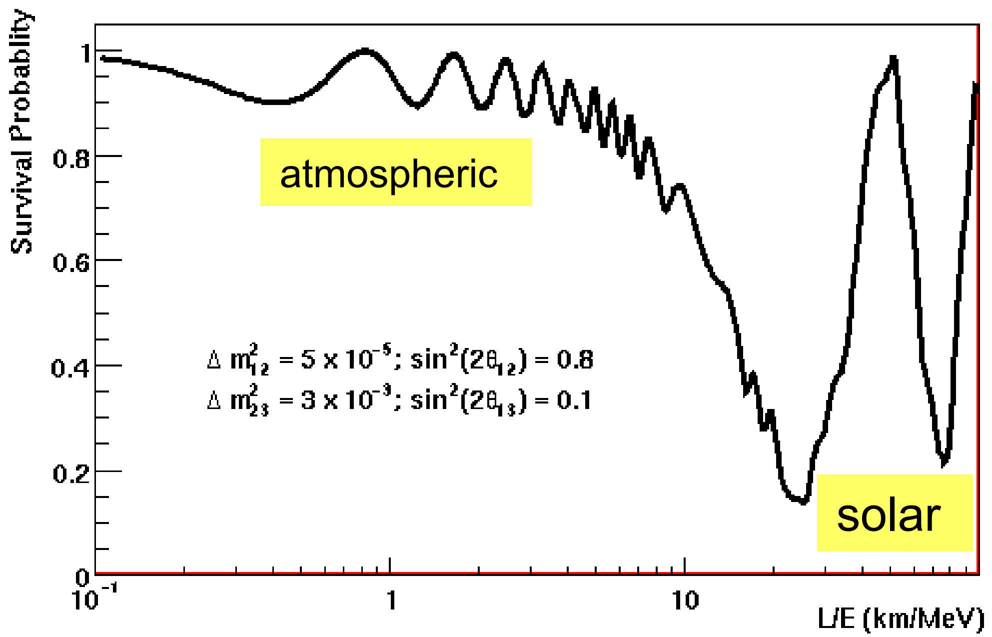
$$\mathrm{n}\ {}^{m}\mathrm{Gd} \to {}^{m+1}\mathrm{Gd}\ \gamma\text{'s}\ (8\ \mathrm{MeV})$$

Going Beyond the Previous Reactor Experiments



$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}{}^2 L}{4E_\nu}$$

$$+ \left(\frac{\Delta m_{21}{}^2 L}{4E_\nu} \right) \cos^4 \theta_{13} \sin^2 2\theta_{13}$$

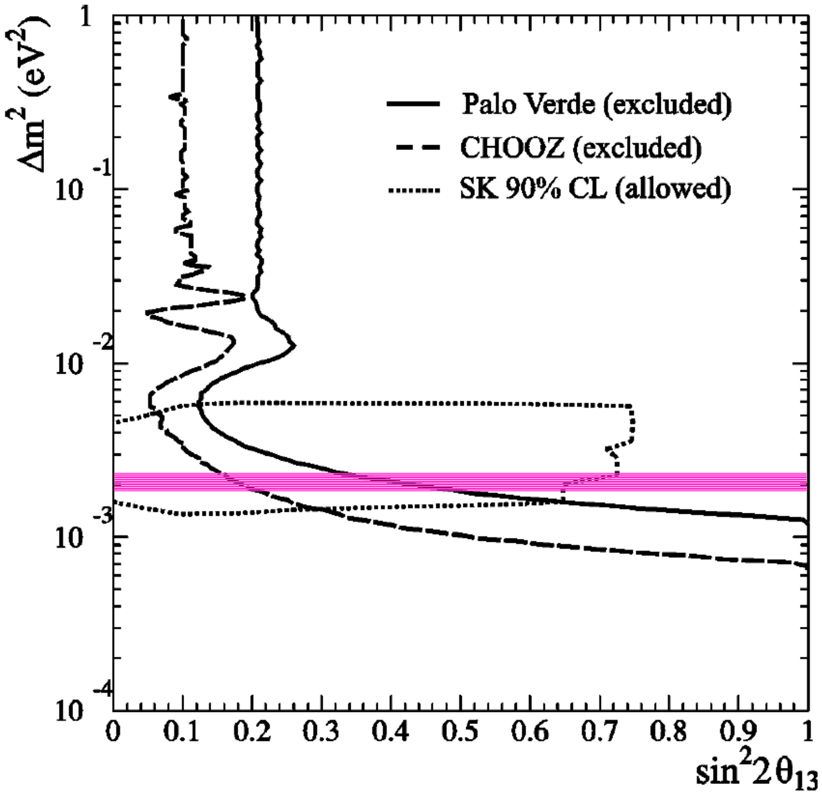


Previous CHOOZ Reactor Experiment

- CHOOZ Experiment 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
  - 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

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
    - Probably multiple reactors if background can be controlled
- Reduce dominant reactor flux spectrum uncertainty
  - Use two detectors at near and far locations
- Measure and/or reduce background rates
  - Detector underground (> 300 mwe?)
  - Need in situ measurements and reduction system
    - Passive shielding plus hermetic veto system
- **Reduce uncertainty in relative near to far detector efficiency (most important systematic uncertainty)**
  - 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

Can one reach the $\sin^2 2\theta_{13} \approx 0.01$ level at $\Delta m^2 = 2.5\times10^{-3}$ 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
    - Reduce by factor of 20 with veto and shielding
    - Measure residual background to ~25% $\Rightarrow$ **$\delta\sin^2 2\theta_{13} <$ 0.001**
- Near/Far comparison
  - Identical detectors imply ~1% relative error $\Rightarrow$ **$\delta\sin^2 2\theta_{13} \approx$ 0.01-0.02**
  - Moveable far detector ~0.3% relative error $\Rightarrow$ **$\delta\sin^2 2\theta_{13} \approx$ 0.004-0.008**

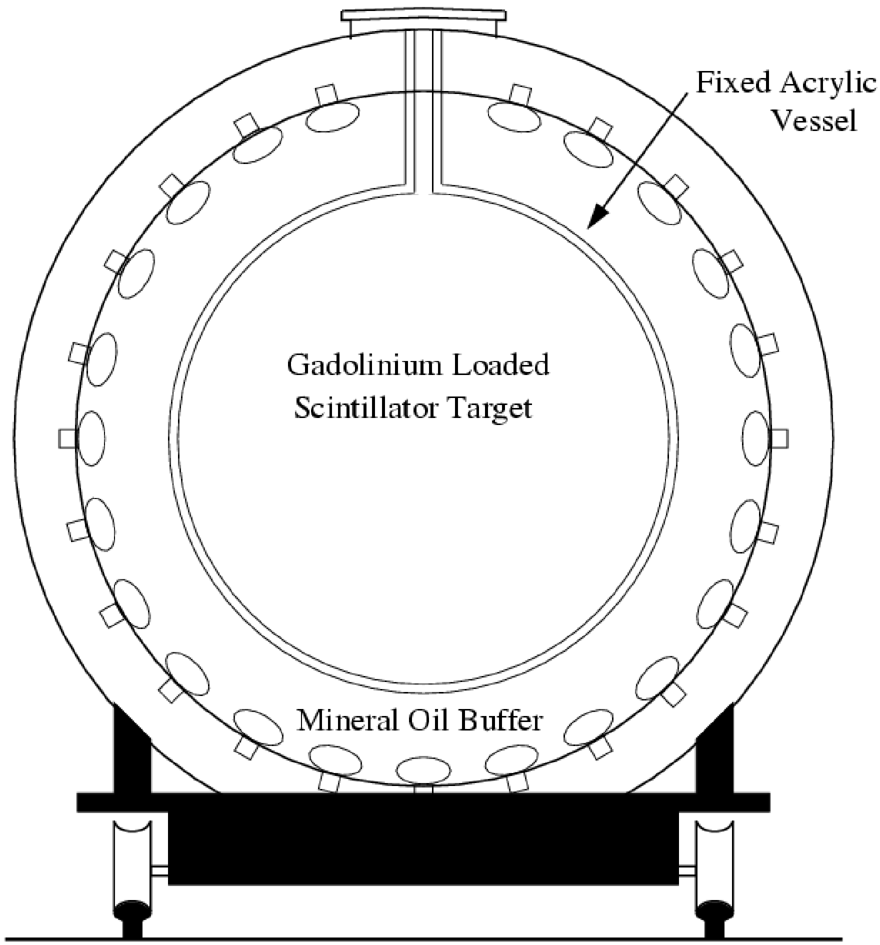
Detector Design Issues

- 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

- Improvements
  - Low activity PMTs
  - Improved veto/shielding system
  - Multiple buffer regions
  - Moveable detectors for cross calibrations



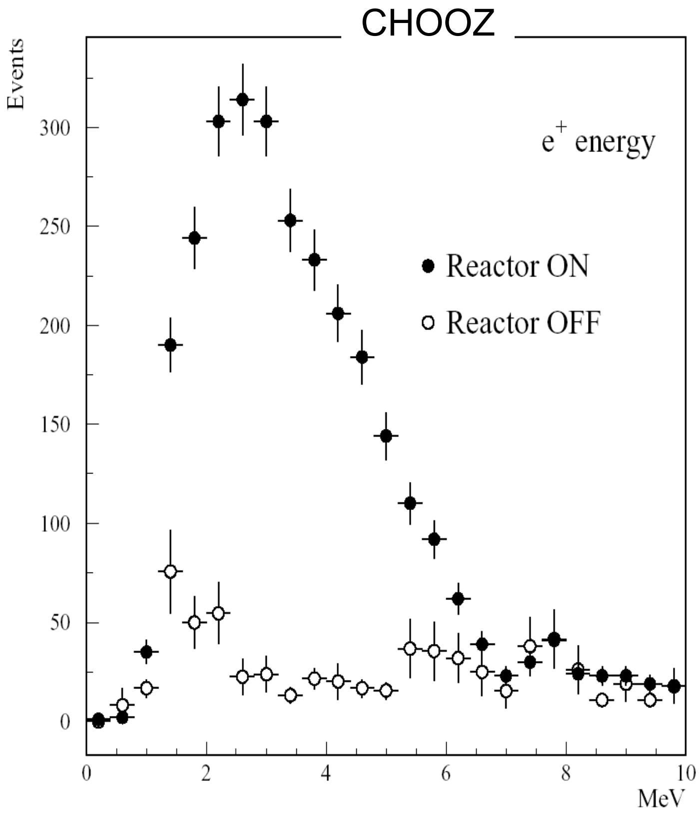
Backgrounds

- 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.

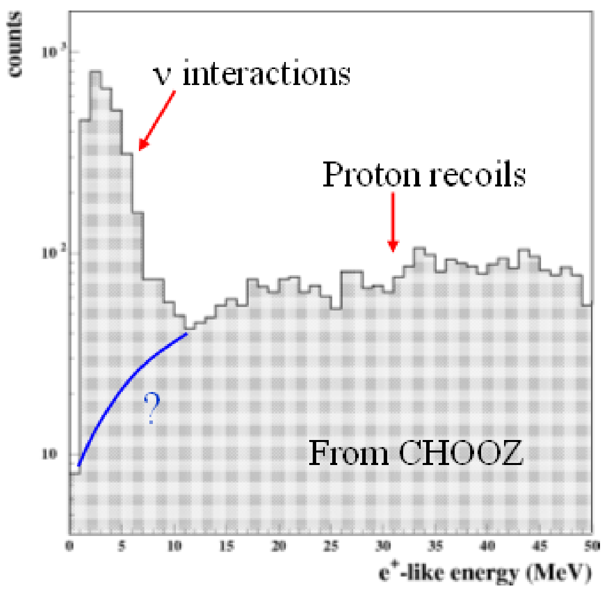


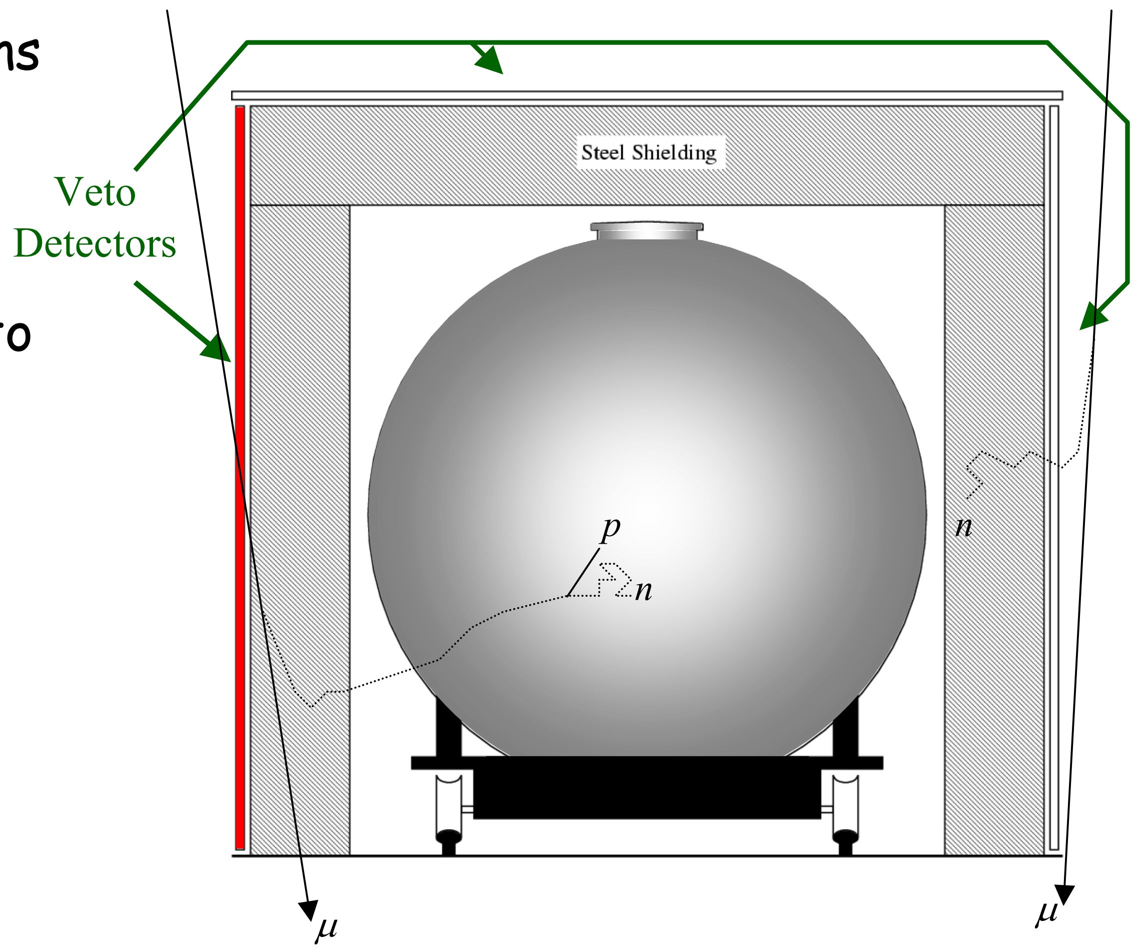
Reducing Correlated Background

- Go as deep at you can (300 mwe → 0.2 BG/ton/day at CHOOZ)

- Veto μ's and shield neutrons (Big effective depth)

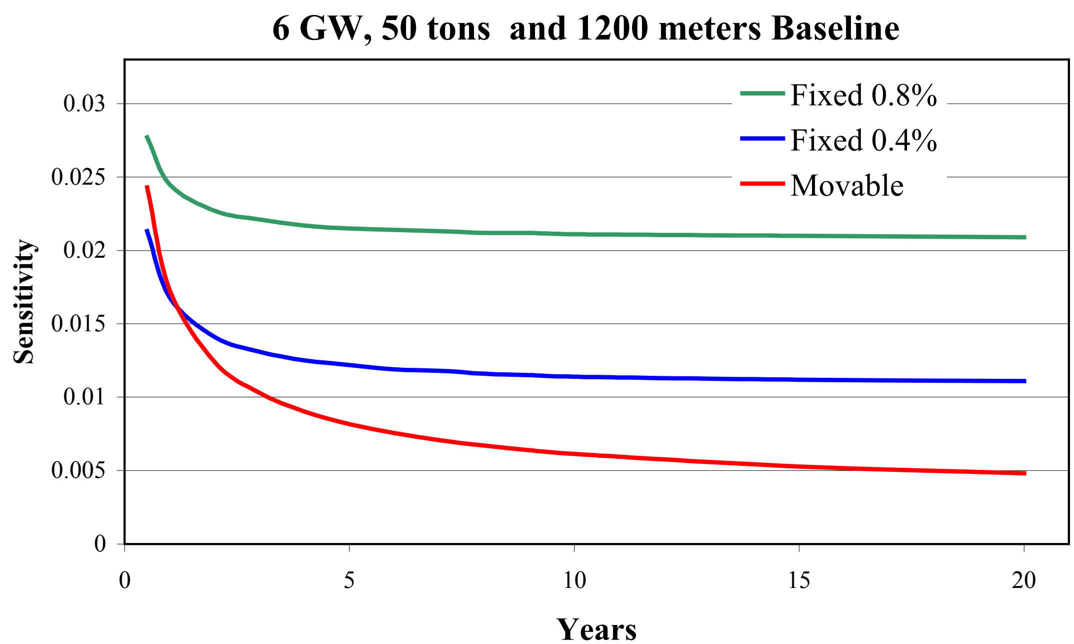
- Measure the recoil proton energy and extrapolate into the signal region.



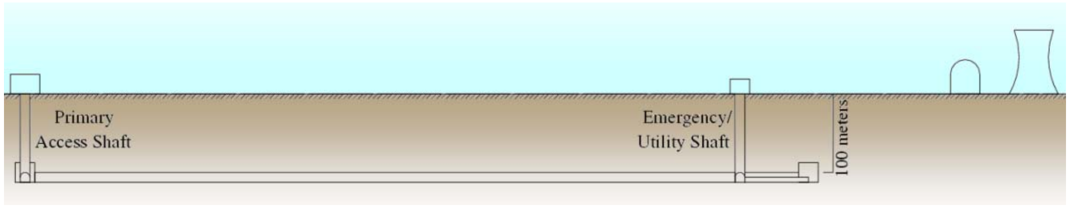


Reduction of Near/Far Systematic Uncertainty

- Compare event rate in near and far detector
  - Main systematic is associated with the relative normalization and efficiency between near and far (~0.8%)

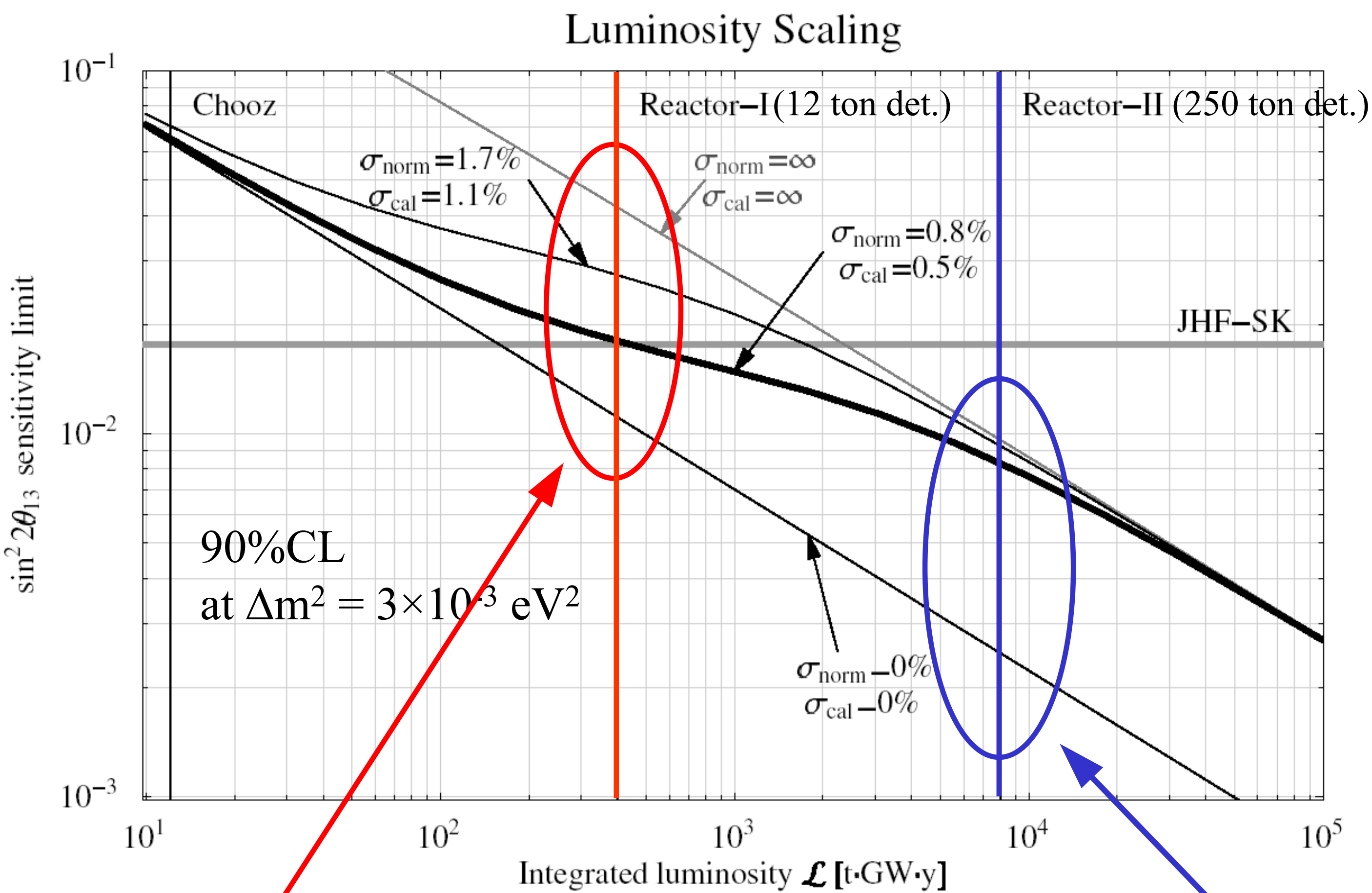


- Move far detector to near location for 10% time gives precision cross calibration
  - Relative normalization uncertainty reduced to ~0.25%
  - Difficult/expensive to construct a tunnel connecting near and far sites



Analysis Using Counting and Energy Spectrum

(Huber *et al.* hep-ph/0303232)



σ_{cal} relative near/far energy calibration

σ_{norm} relative near/far normalization

Counting exp. region

Spectrum & Rate region

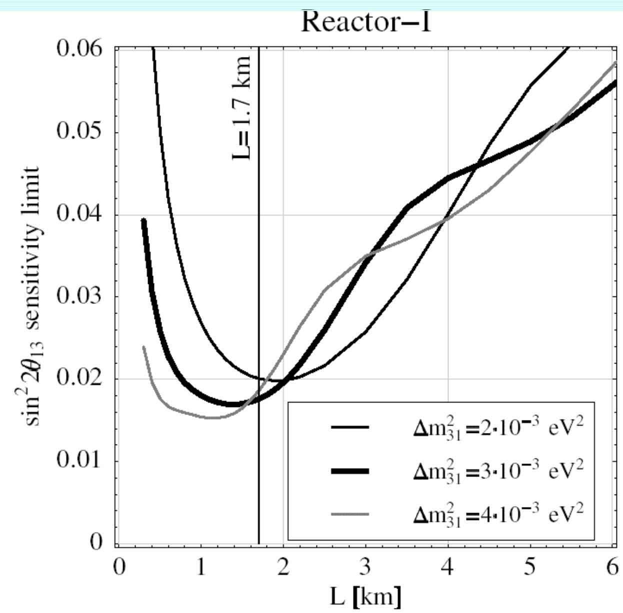
Scenarios:

Reactor I = 12ton×7GW×5yrs = ~400 ton-GW-yr

Reactor II = 250ton×7GW×5yrs = ~9000 ton-GW-yr

Baselines and Number of Detectors

- Optimum baseline has broad range
  - Some degradation if near detector too far away from reactor (>500m)
  - Best discovery sensitivity for near-far setup (200m plus 1500m)
- For larger values of $\sin^2\theta_{13}$>0.04, a far-farther setup (i.e. 1km and 2.5km) can show sizeable energy shape distortions
  - Allows one to show oscillatory behavior of a signal
  - May be important for more accurate measurements
- May want more flexibility
  - Detectors at three locations
  - Ability to change detector location later



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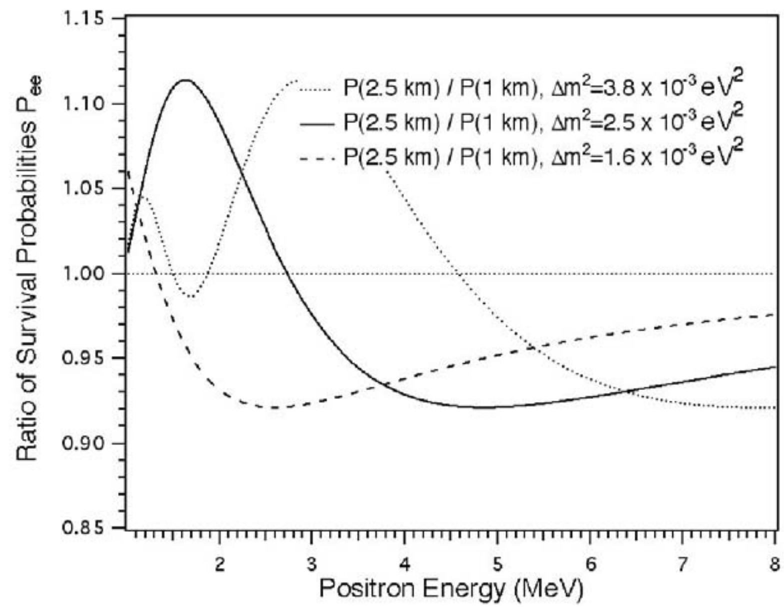


Worldwide Effort towards Realizing an Experiment

- Many possible high power multiple reactors sites
  - Proximity to hills could make excavation of halls and tunnels easier
  - Challenge in getting reactor operators to agree to an experiment

- Groups:
  - Europe:
    - PCC & CEA/Saclay & APC, MPI Heidelberg, TU Munchen, INFN/Bologna
  - USA:
    - Alabama, Argonne, Berkeley, Caltech, Chicago, Columbia, Fermilab, Kansas State, LBNL, Lousiana State, Michigan, Stanford, Tennessee, UCLA
  - Japan:
    - Tohoku Univ. , Tokyo M. Univ.
  - Russia:
    - Kurchatov Institute
  - Also Taiwan and Brazil

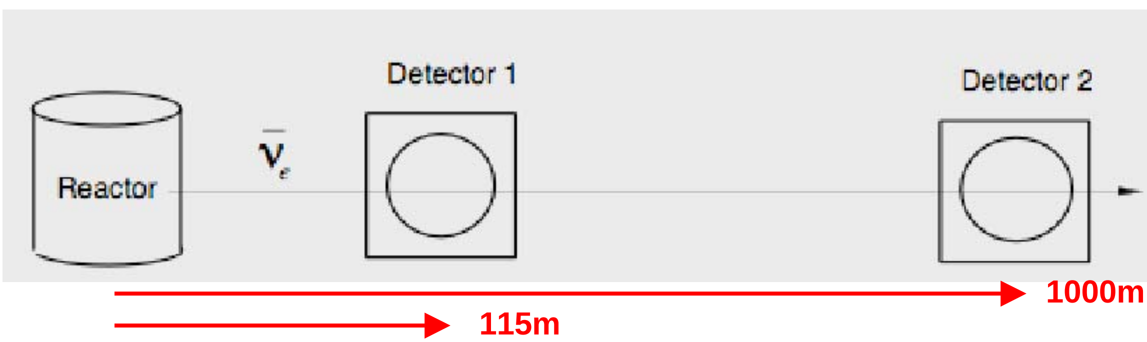
- Workshops on Future Low-Energy Neutrino Experiments
  - Munich, October 9-11, 2003
  - Univ.of Alabama; April 30-May 2, 2003

Partial List of Possible Reactor Sites

Reactor	Location	N/F Distances	Thermal Power	Overburden	Target mass
Chooz	France	1100 m	8.5 GW (2)	300 mwe	5 t
Krasnoyarsk	Russia	115/1000 m	1.6 GW (1)	600 mwe	54 t
Kashiwasaki	Japan	300m/1.3 km	24.3 GW (7)	500 mwe	5 t
Braidwood	US (IL)	?/?	7.2 GW (2)	300 mwe	?
Diablo Canyon	US (CA)	?/?	6.1 GW (2)	600-800 mwe	30-40 t ?
Angra	Brazil	?/?	~ 4 GW (1)	?	?
Texono	Taiwan	?/~2 km ?	4.1 GW (1)	?	?
Penly	France	<500m/1.8 km	8.5 GW (2)	150-300 mwe	28 t
Flamanville	France	<500m/1.8 km	8.5 GW (2)	300 mwe	28 t
Paluel	France	<500m/1.8 km	17 GW (4)	150-300 mwe	14 t
Cruas	France	>500m/1.8 km	11.7 GW (4)	>500 mwe	20 t

T. Lasserre

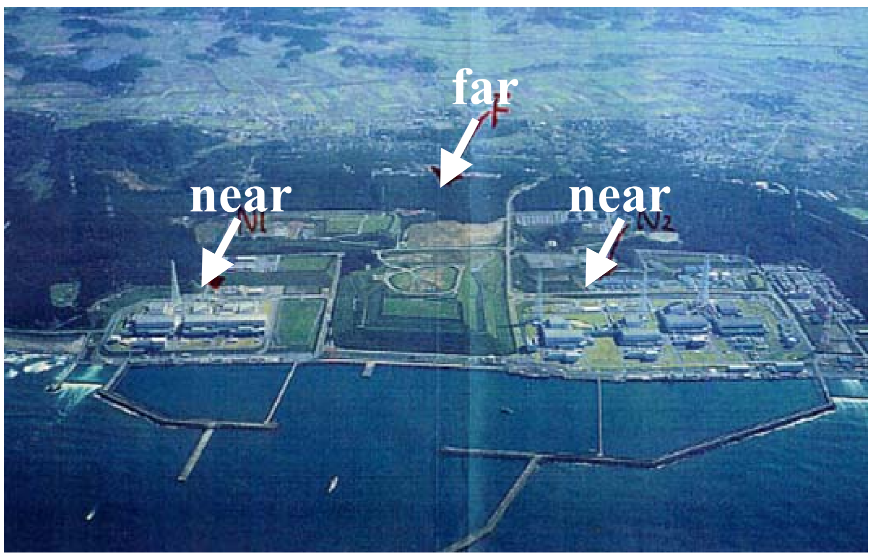
Krasnoyarsk, Russia (Martemyanov, Mikaelyan, Sinev, Kopeikin and Kozlov hep-ex/0211070)

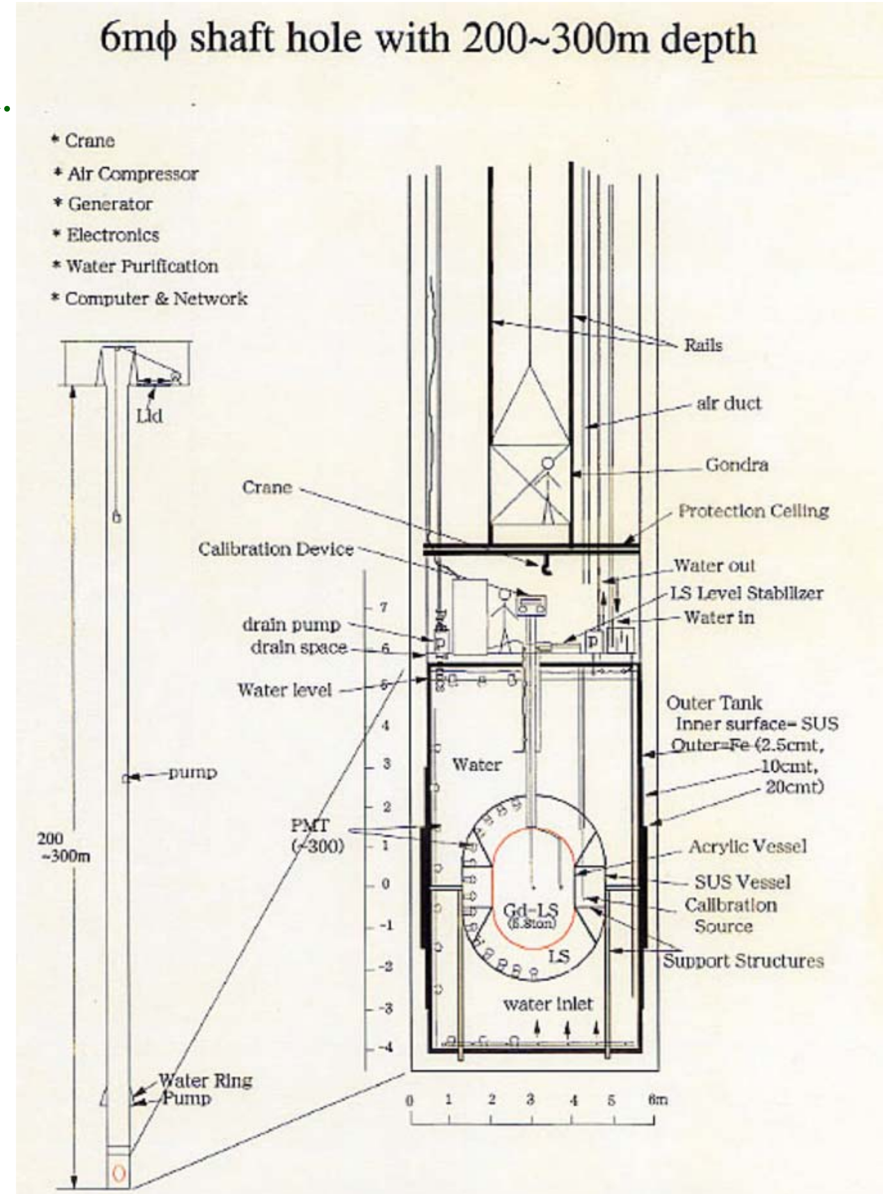


- One reactor $\leq$ 2 GW_{th}
- Two 50 ton detectors
- Near detector at 115 meters
- Far detector at 1000 meters
  Hall are pre-existing (Inexpensive!)
- ~60 days reactor off running per year
  Good for measuring BG
- Sensitivity: $\sin^2 2\theta_{13} \leq 0.025$ with 3 to 4 years of running

Kashiwazaki, Japan (Minakata, Sugiyama, Yasuda, Inoue, and Suekane hep-ph/0211111)

- 7 Reactors, 24 GW_{th}
  Most powerful reactor site in the world.
- Three ~8.5 ton detectors
- Two near detectors at baselines of 300 to 350 meters
- One far detector at ~1300 meters
  21 different baselines!
- Sensitivity of $\sin^2 2\theta_{13} \leq 0.02$ in 2 years
  Fast! Could starts as early as 2007.





French Nuclear Power Plants

Nuclear plants embedded in chalk cliff
Near and Far sites candidates

Flat and swampy

Flat topography
H = 0 meter

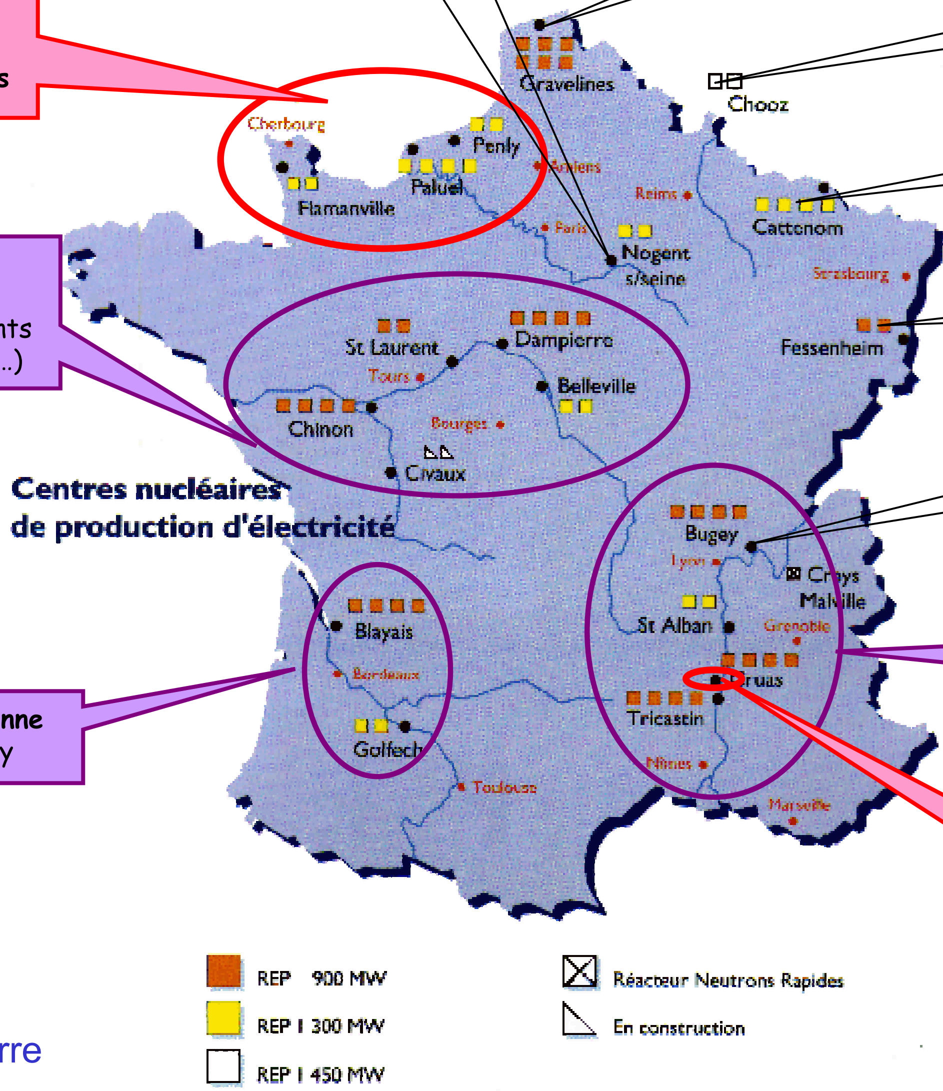
Cavity at 700 m for the near site … too far away

Close site OK ?
Problem for the far site ?

Very flat topography, but a lot's of space

Around: La Loire
Flat topography all around the power plants
(vut no detail check …)

Small cliff at 2km from the reactors, but problem to find the near site



Around: Le Rhone
Problem to find a near site close to the river
Near site swampy

St Alban: Far site OK ?

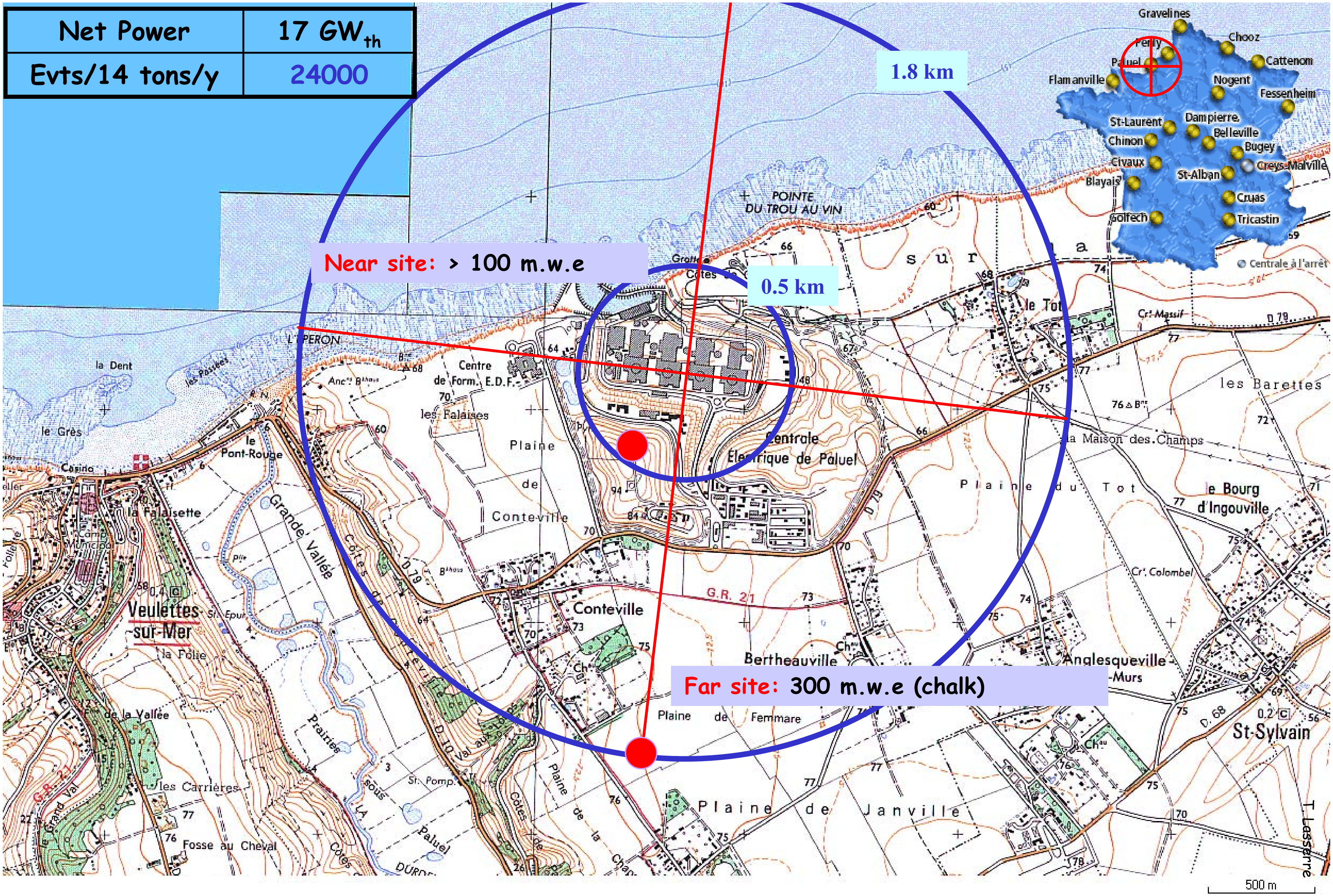
Around: La Garonne
Flat topography

Cruas is interesting because the far site is well shielded h~300 m rocks

From T.Lasserre

French Sites: The Paluel (5 Reactor) Complex

Net Power	17 GW_{th}
Evts/14 tons/y	24000



Reactor Sites in the US

Braidwood, Illinois 7.17 GW

Located 24 miles southwest of Joliet. Operated by Exelon Nuclear.

Diablo Canyon, California 6.75 GW

Located 12 miles west of San Luis Obispo. Operated by Pacific Gas and Electric.

Braidwood, etc.

Fermilab, Argonne, Columbia, et. al.

Exelon (a.k.a. ComEd) is the largest producer of nuclear power in the U.S. Among their holding are the following seven, "Top 30" sites:

Braidwood, IL, Byron, IL,
Limerick, PA, Peach Bottom, PA,
Dresden, IL, Quad Cites, IL,
La Salle, IL

Jed Brown, Fermilab (AD of Operations and Support) is leading negotiations with Exelon.

(Fermilab is still exploring its commitment to this project. It is providing support in dealing with Exelon. Also Chris Laughton, Fermilab engineer, has helped with tunneling and other underground issues.)

Diablo Canyon

Lawrence Berkeley Lab

LBL is in negotiations with Pacific Gas & Electric for use of Diablo Canyon.

Preparing an environmental impact report.

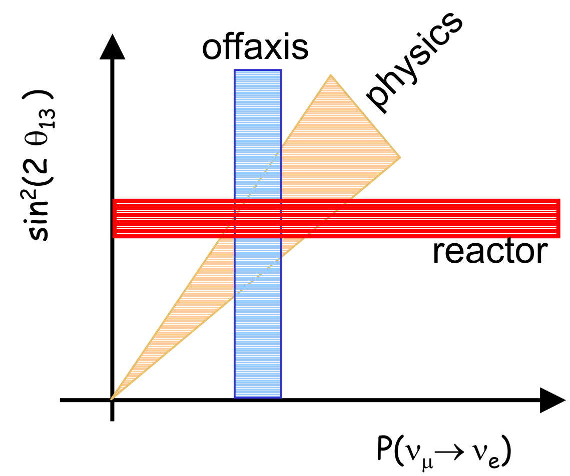
This will be an important issue in California especially with a coastal site.

LBL is supporting this effort with LDRD money.

Experimental Comparisons and Combinations

- Assume setups for "Phase I" experiments:
  - Reactor Experiment:
    - 50ton detector for 3 years with 7.0 GW reactor
      $\Rightarrow$ ~1000 ton-GW-yr (=x2.5 Reactor I scenario)
    - Relative near/far syst. uncertainty = 0.25% (Moveable detector)
      $\Rightarrow$ **$\delta\sin^2 2\theta_{13}$=0.005**
  - JHF to SuperK:
    - 5 years ν_μ only with 20 kton SuperK detector
    - JHF Phase I intensities
  - NuMI Offaxis:
    - 6 years with 50 kton detector
    - 2 yrs. ν_μ and 4 yrs. $\bar{\nu}_\mu$ (or for some plots 5 years ν_μ only)
    - $4\text{x}10^{20}$ protons on targer per year ("realistic improvements" from current)

Need to combine experimental measurements to get at physics parameters



- Physics Parameters:
  - Measurements: $\sin^2 2\theta_{13}$
  - Correlations: δ
  - Ambiguities: sign(Δm^2_{23}) and $\sin^2\theta_{23}$
- Measurements:
  - Reactors measure $\sin^2 2\theta_{13}$

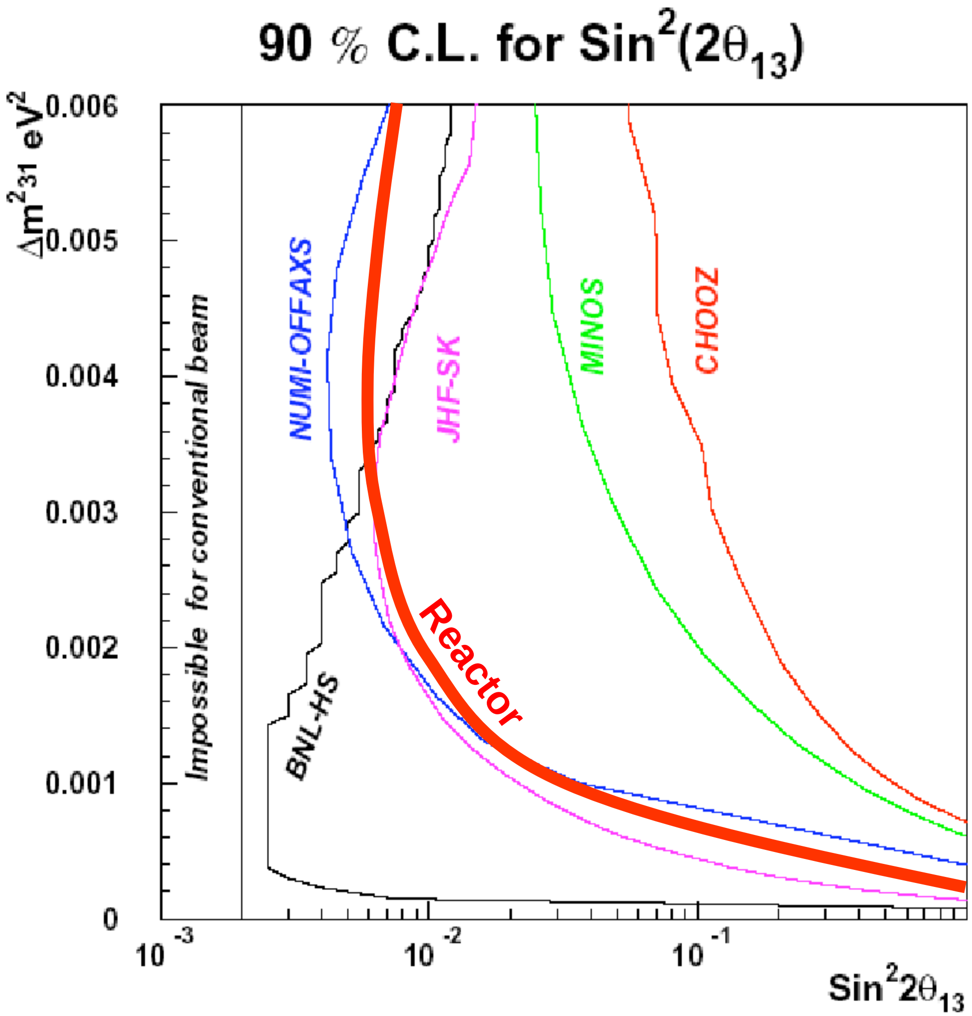
$$1-P(\nu_e \to \nu_e) = \sin^2(2\theta_{13})\sin^2(\Delta m^2_{31}L/4E) + O(\Delta m^2_{21}/\Delta m^2_{31})$$

  - Offaxis $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$

$$P(\nu_\mu \to \nu_e) \sim K_1 \sin^2(\theta_{23})\sin^2(2\,\theta_{13}) + K_2 \sin(2\theta_{23})\sin(\theta_{13})\,\mathrm{sign}(\Delta m^2_{31})\cos(\delta) \oplus K_3 \sin(2\theta_{23})\sin(\theta_{13})\sin(\delta)$$

- Combine ν_μ and $\bar{\nu}_\mu$ running at various baselines to measure δ and sign(Δm^2_{23})

Crude Comparison of Sensitivities
(Ignoring correlations and ambiguties)



Experiment	$\sin^2(2\theta_{13})$	Timescale
CHOOZ	<0.14	Completed
MINOS	< 0.06	2009?
ICARUS 5 years	< 0.04	2011 ?
NUMI-OA 5 years	< 0.006-0.015	2012 ?
JHF2K 5 years	< 0.006-0.015	2012 ?
Kr2Det (Russia)	< 0.016	?
US proposals	< 0.01	?
Kashiwasaki (Jp)	< 0.026	2010 ?
French proposals	< 0.02	2010 ?

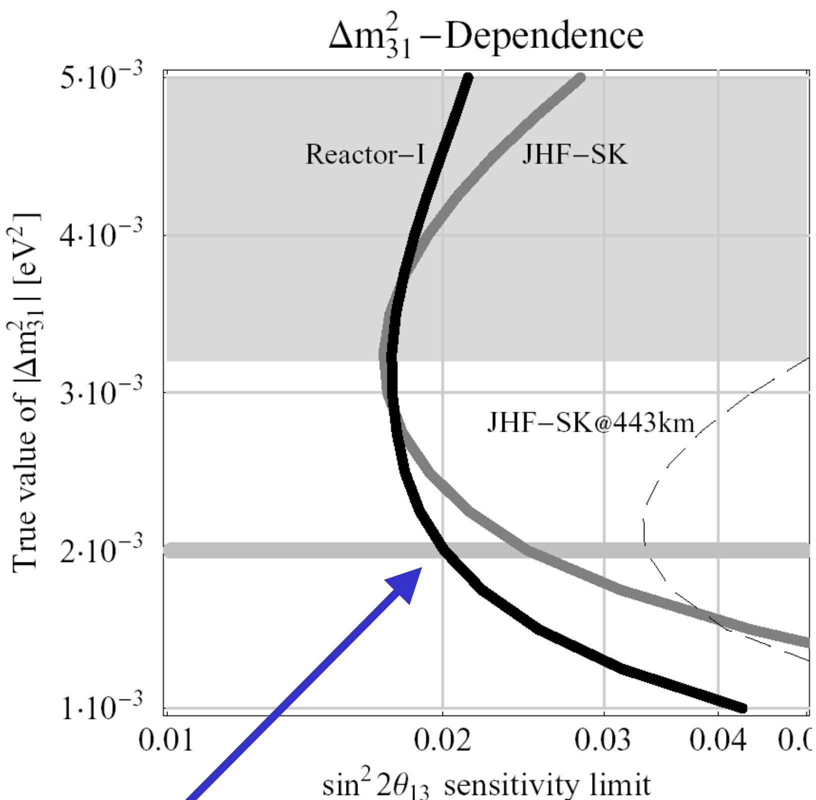
Δm^2_{atm}= 2.5 10^{-3} eV^2

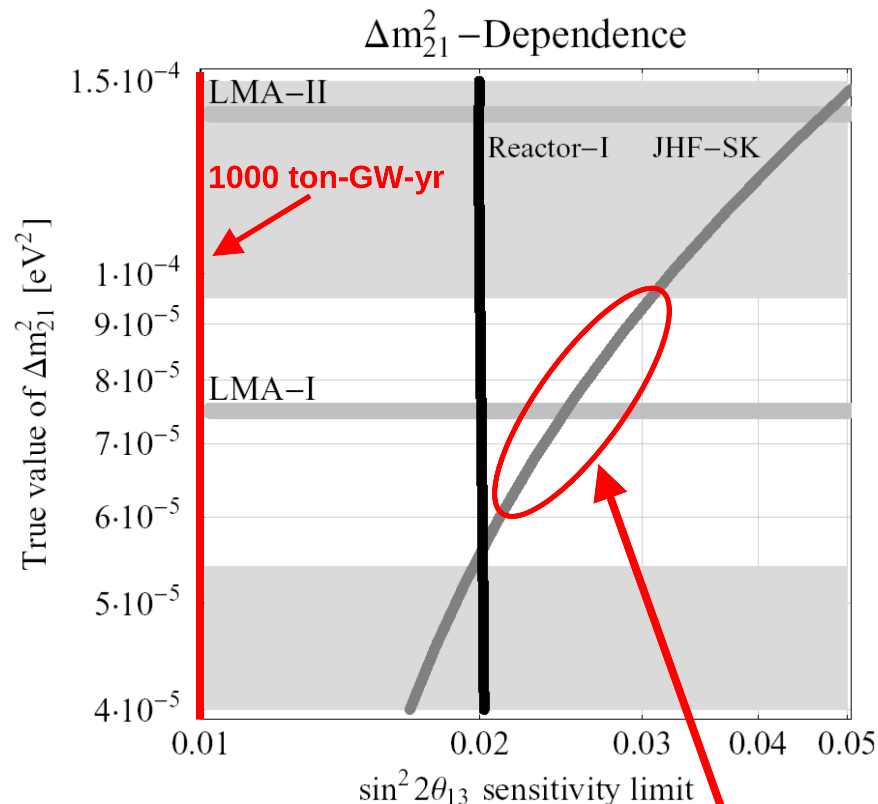
Simple comparison of $\sin^2 2\theta_{13}$ sensitivity (approx. average over δ and sign(Δm^2) for appearance)

Comparison to Offaxis Experiments

- Modest size 10-50 ton reactor experiment gives comparable sensitivity to JHF-SK and NuMI offaxis experiments.

Huber *et al.* hep-ph/0303232





Reactor measurement better (even at 400 ton-GW-yr)

Less sensitive to Δm^2_{31}

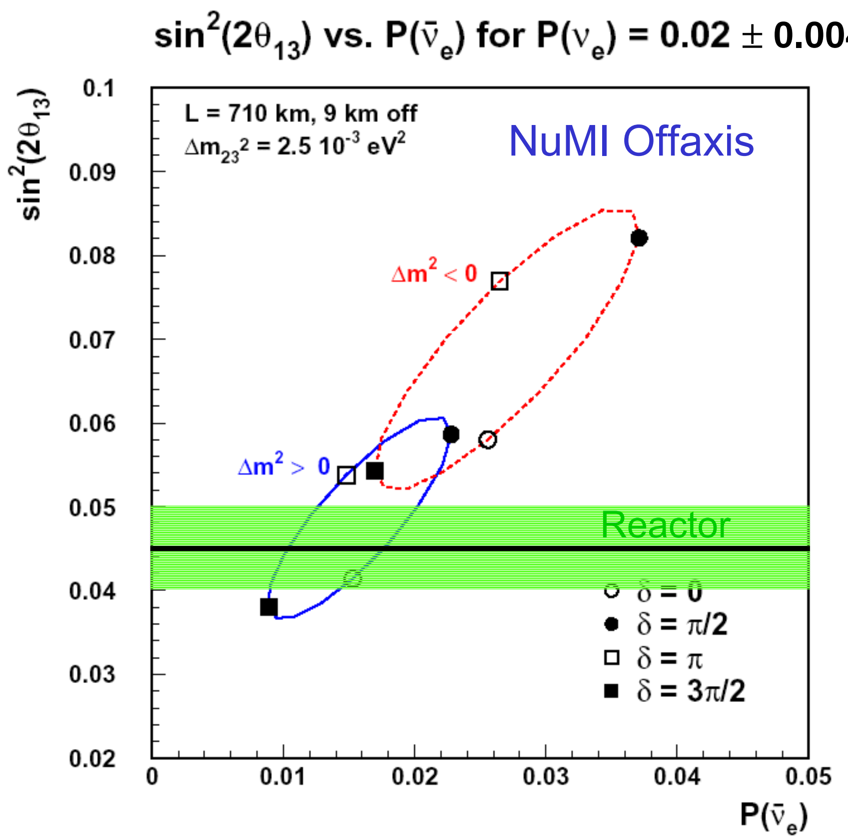
Reactor experiment insensitive to Δm_{12}^2 value which is important for LMA I region

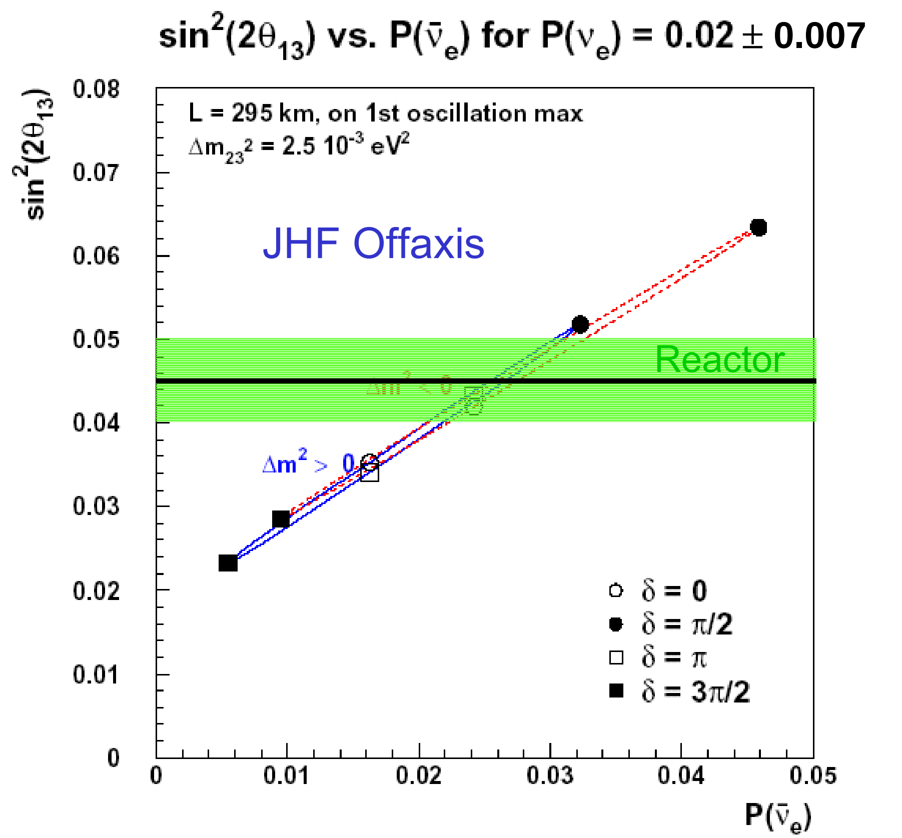
Combination of Offaxis and Reactor

Including ambiguities ($\Delta m^2<0$ or $\Delta m^2>0$) and correlations (δ=CP phase)

Assume Phase I reactor measurement ($\delta\sin^2 2\theta_{13}=0.005$)

Plots from G. Feldman

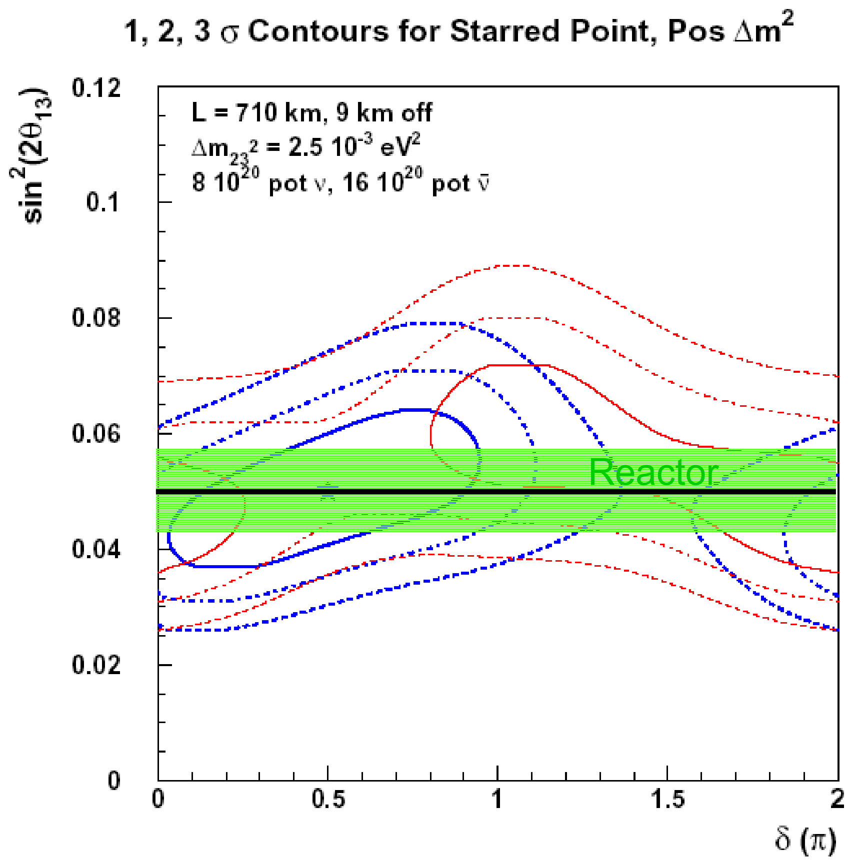




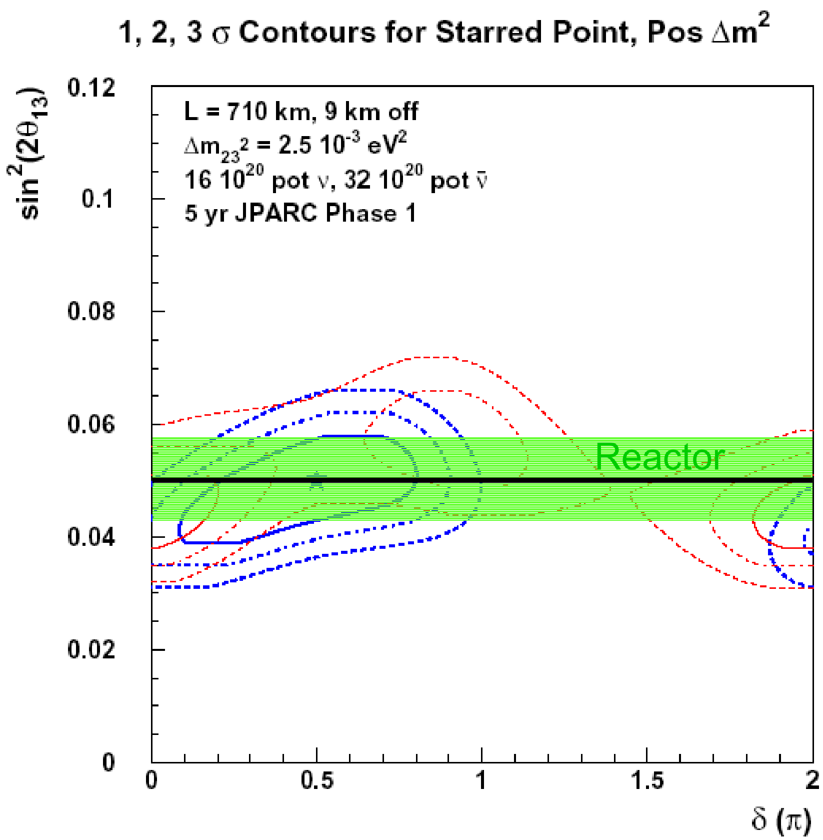
- Reactor measurement may be more accurate than $\bar{\nu}_\mu \to \bar{\nu}_e$ and $\bar{\nu}_\mu$ runs hard
- Combination of $\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_e$, and reactor measurement may resolve situation

Reactor Combined with NuMI Offaxis with ν_μ and $\bar{\nu}_\mu$ Running (Plus JHF)

NuMI offaxis: 2 yrs. ν_μ and 4 yrs. $\bar{\nu}_\mu$



NuMI offaxis: 2 yrs. ν_μ and 4 yrs. $\bar{\nu}_\mu$ plus 5 yrs JHF

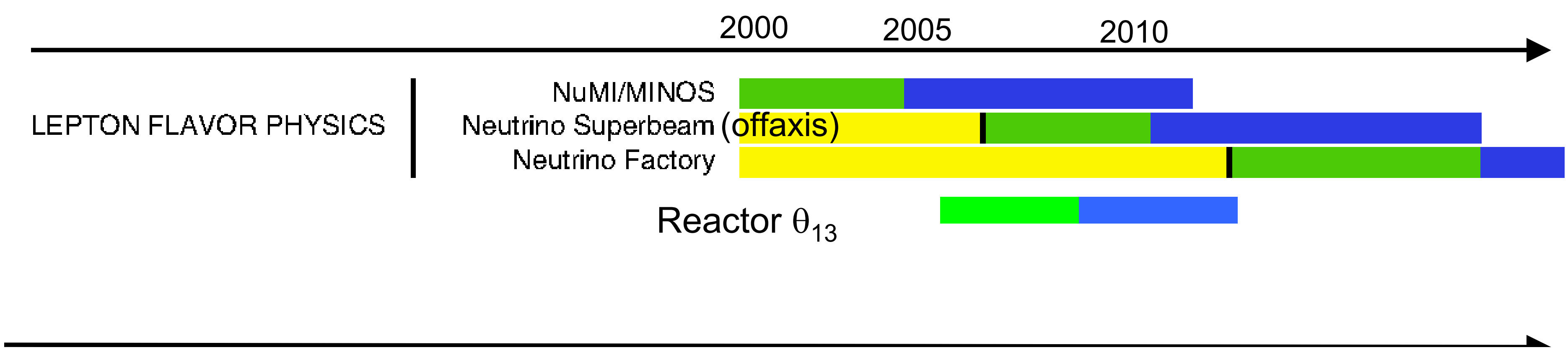


Plots from G. Feldman

Cost and Schedule

- Cost: Moderate Scale Project (< $50M)
  - Detector scale of MiniBooNE ~$5M
  - Civil construction - Halls $3M and 1km tunnel ~$20M
  - Need to identify site and develop proposal
  - R&D needed especially for Gd-liq.scint. and moveable detector
- Schedule:
  - After site selection, approval process 1? year
  - Construction ~2-3 years
  - Start in 2008/2009?

The Particle Physics Roadmap (in the US)



Summary

- A two detector reactor oscillation experiment can accurately measure or constrain $\sin^2 2\theta_{13}$ at the 0.01 level.
  – Sensitivity depends on control of systematic uncertainties

- The results from a reactor experiment on θ_{13} important for defining an oscillation program
  – Measurements are competitive and complementary with longbaseline appearance experiments
  – Combining results will give improved constraints on the oscillation parameters as well as access to possible matter and CP violation effects.

- The longer term program to make accurate measurements of the neutrino masses and mixing matrix will require a broad program of measurements including reactors, superbeam, and neutrino factories.