Lecture 2

New Multi-Detector Experiments

What $\sin^2 2\theta_{13}$ Sensitivity Is Needed for a Reactor Exp?

- 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 exp's
      - 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

Theoretical Guidance?

CAN MEASUREMENT OF θ_{13} TELL US ABOUT QUARK-LEPTON UNIFICATION ?

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- If $\theta_{Atmospheric}$ is close to 45^0, θ_{13} could be very small in many models (See below)
- If $\sin^2\theta_{13} < 0.007$, this would strongly suggest that there is no quark-lepton unification ………. ???

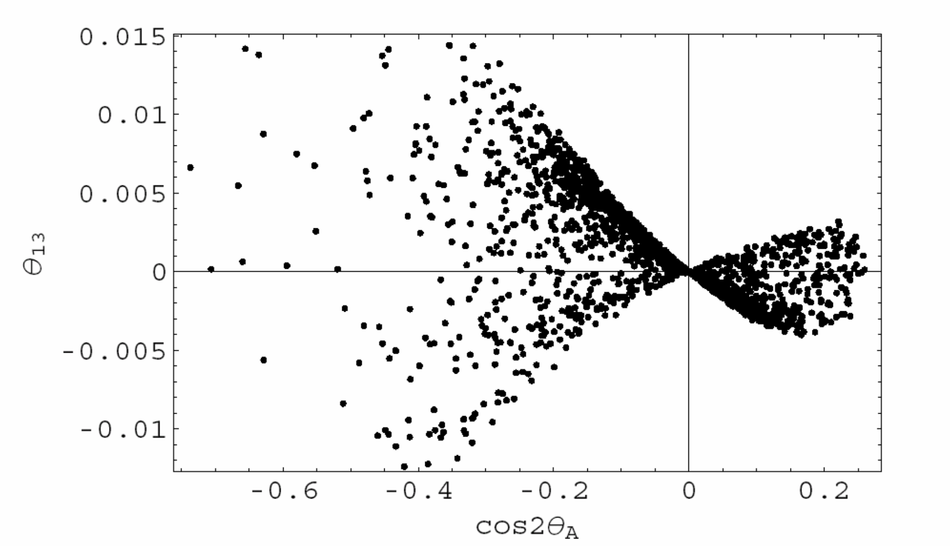
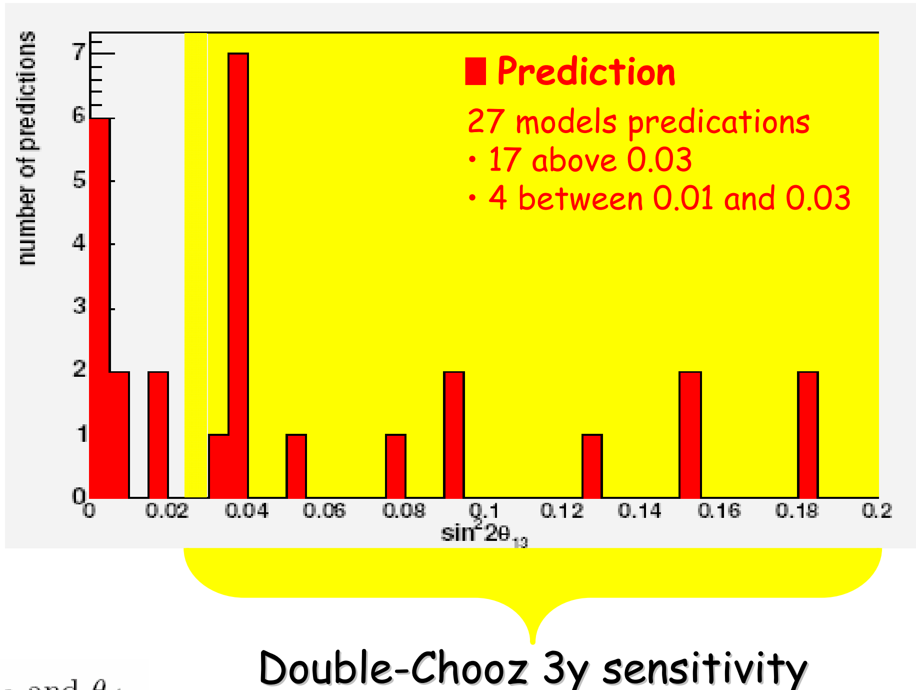


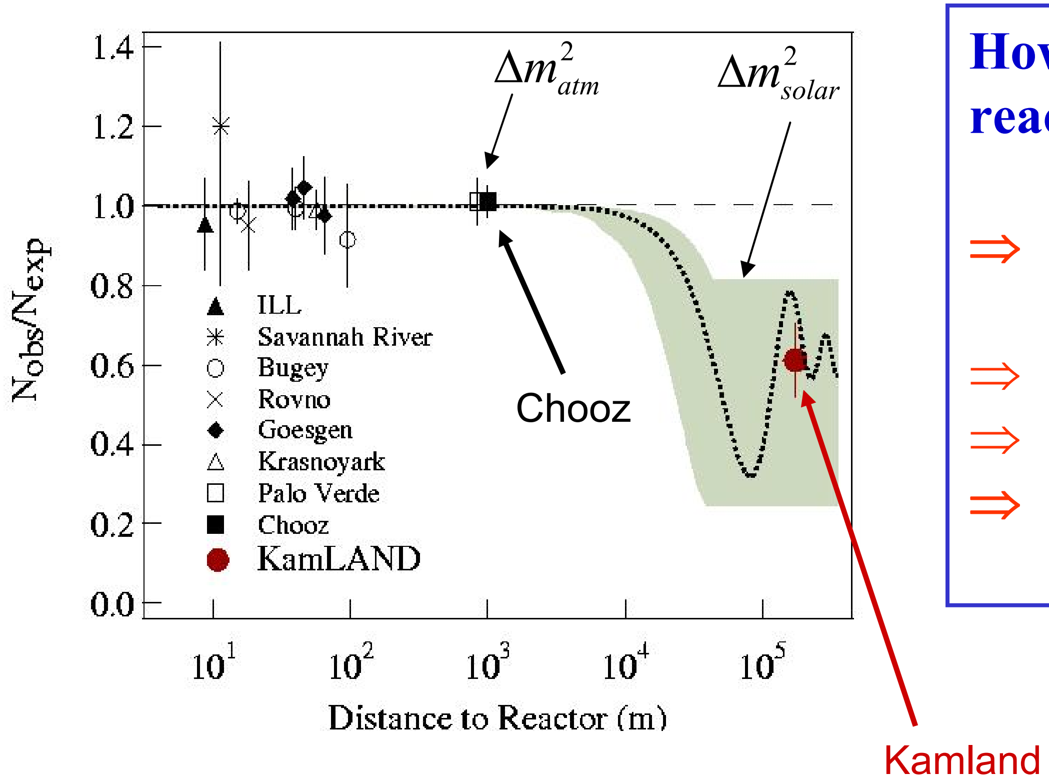
FIG. 4: Departure from $\mu - \tau$ symmetry and correlation between θ_{13} and θ_A.



Precision Reactor Disappearance Exp. Are Difficult

- Looking for a small change in the expected rate and/or shape of the observed event

Past reactor measurements:



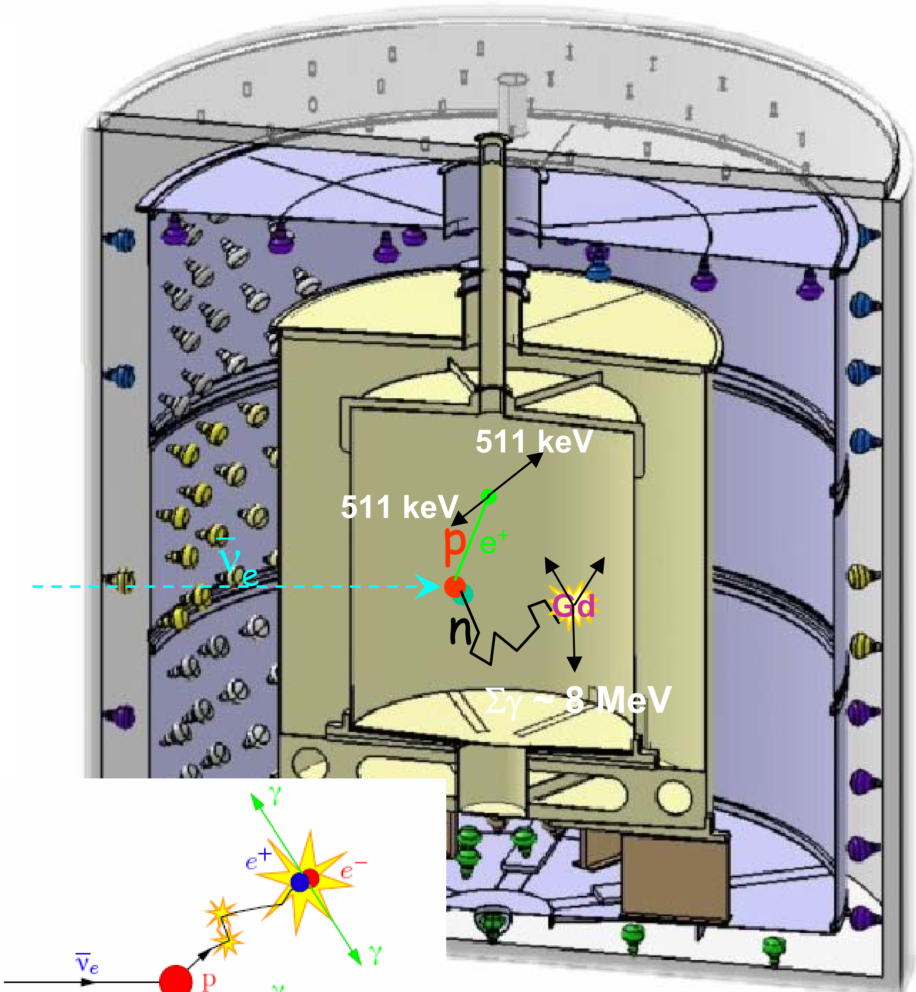
How to do better than previous reactor experiments?

⇒ **Reduce systematic uncertainties due to reactor flux and detector**
⇒ **Optimize baseline**
⇒ **Larger detectors**
⇒ **Reduce and control backgrounds**

Experimental Setup

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

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

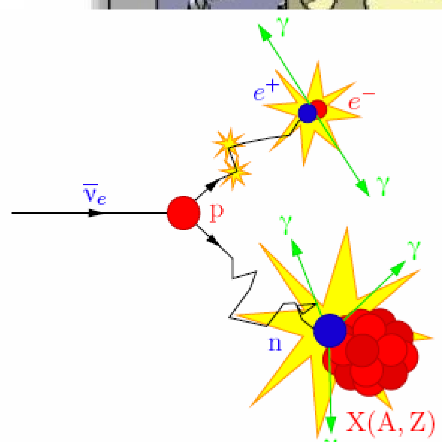


- Positron energy spectrum implies the neutrino spectrum ($e^+e^- \rightarrow \gamma\gamma$)

$$E_\nu = E_{vis} + 1.8 \text{ MeV} - 2m_e$$

- The scintillator will be doped with gadolinium to enhance capture

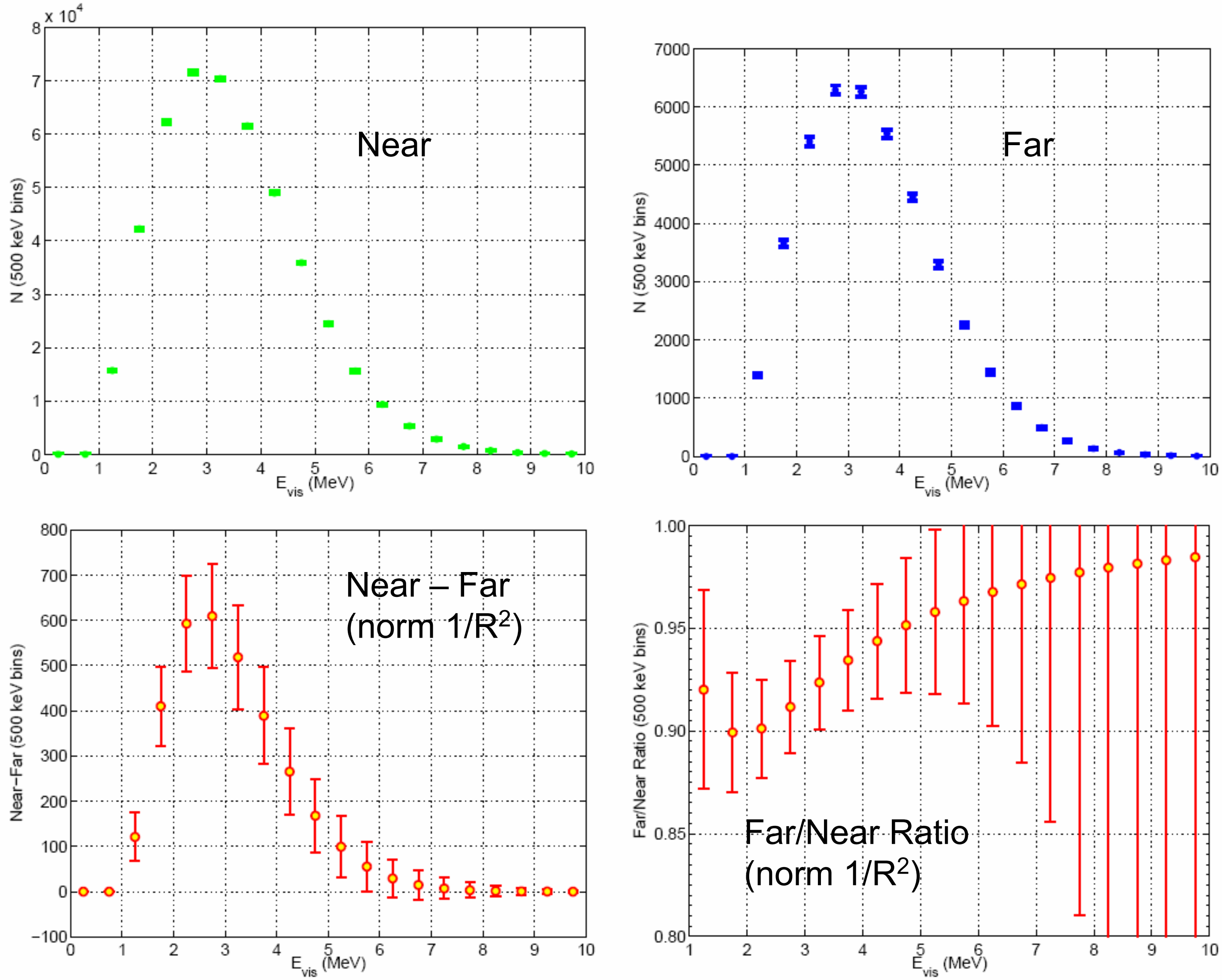
$$n\ {}^{m}Gd \rightarrow {}^{m+1}Gd\ \gamma\text{'s (8 MeV)}$$



- Veto system for cosmic–ray muons

Signal = Positron signal + Neutron signal within 100 μsec (5 capture times)

Example Measurement (Double Chooz 3 yrs)

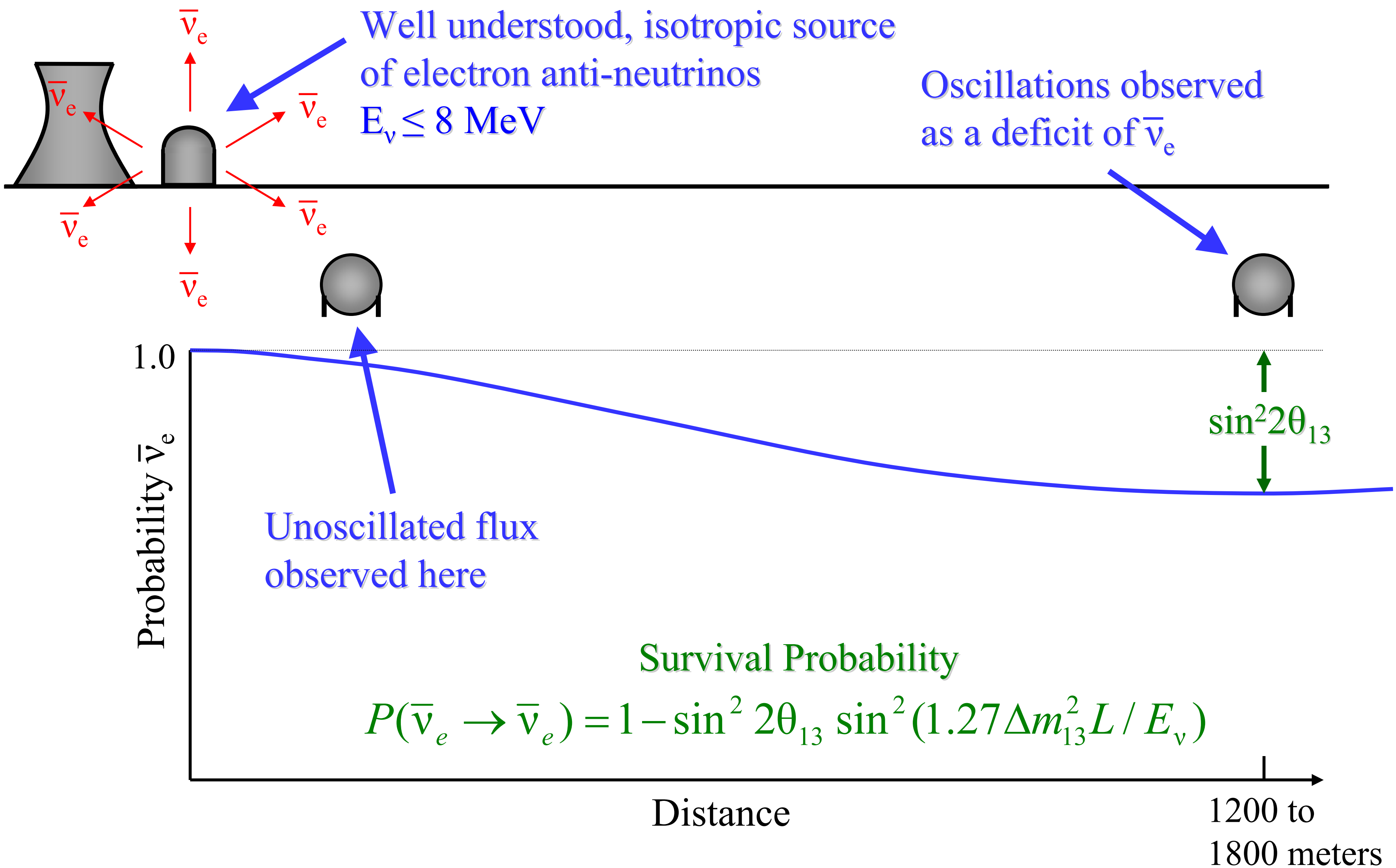


$$\sin^2(2\theta_{13}) = 0.1 \text{ and } \Delta m^2_{31} = 2.5 \times 10^{-3}\ eV^2$$

How Do You Measure a Small Disappearance?

- Use identical near and far detectors to cancel many sources of systematics.

$Sin^2 2\theta_{13}$ Reactor Experiment Basics

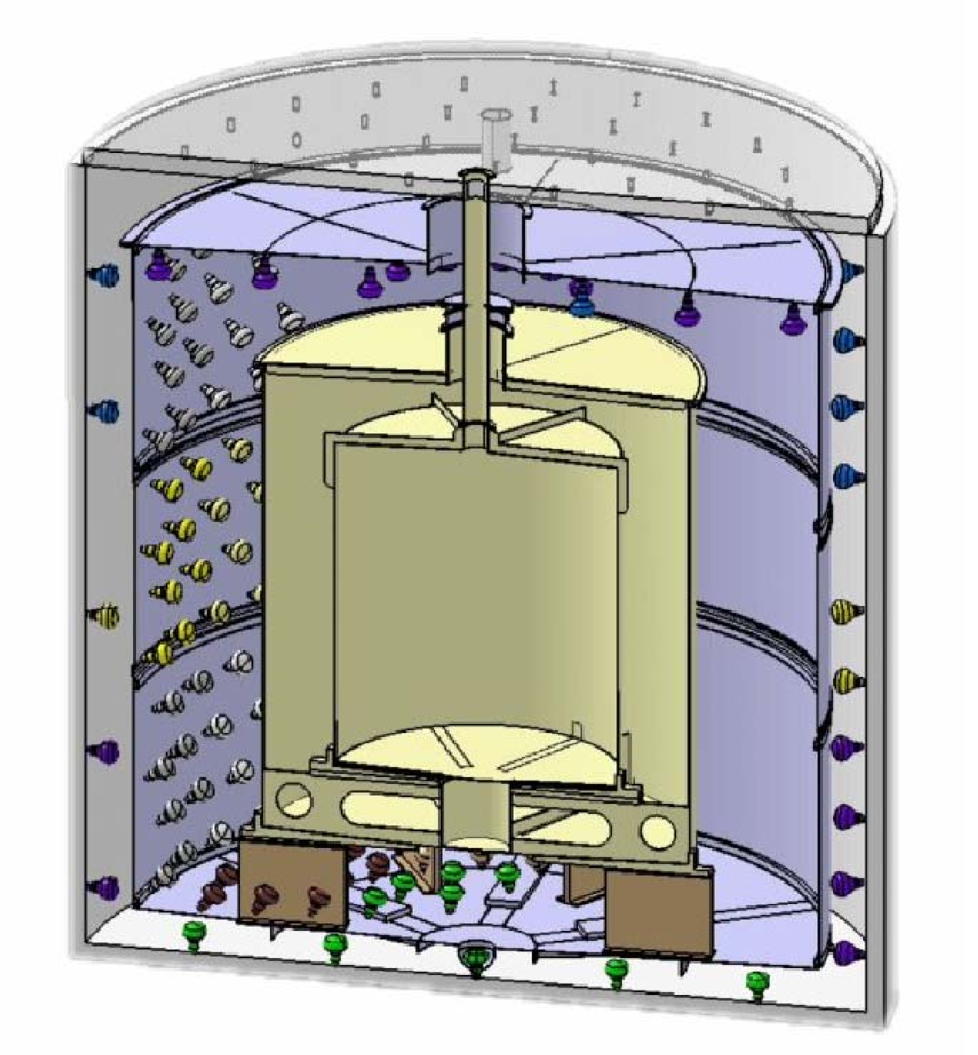


How Do You Measure a Small Disappearance?

- Use identical near and far detectors to cancel many sources of systematics.

- Design detectors to allow simple analysis cuts that will have reduced systematic uncertainty.

Detector Design Basics



- Multi-layer, high efficiency veto system

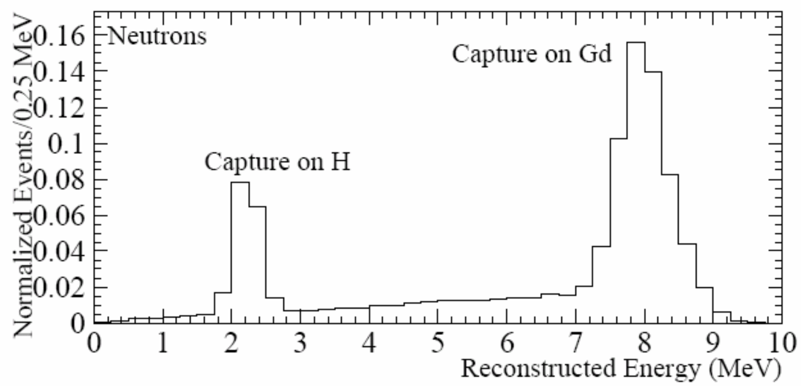
- Homogenous Volume
- Viewed by PMT's
  - Coverage of 10% or better
- Gadolinium Loaded, Liquid Scintillator Target
  - Enhances neutron capture
- Extra scintillator region to capture gammas that might leak out from Gd target region
- Pure Mineral Oil Buffer
  - To shield the scintillator from radioactivity in the PMT glass.

How Do You Measure a Small Disappearance?

- Use identical near and far detectors to cancel many sources of systematics.
- Design detectors to eliminate the need for analysis cuts that may introduce systematic error.
- Detector cross calibration may be used to further reduce the near/far normalization systematic error.

Use events and sources to cross calibrate

- For example, n capture peaks



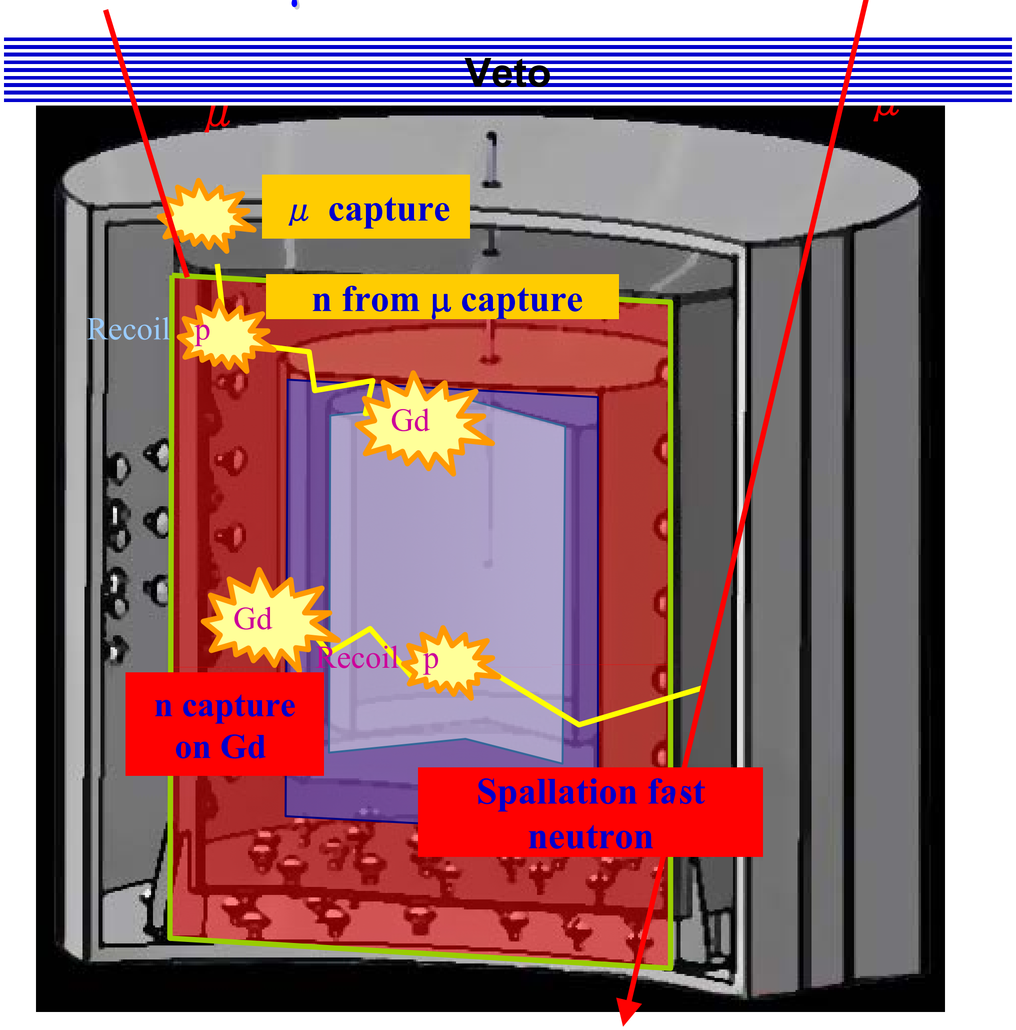
How Do You Measure a Small Disappearance?

- Use identical near and far detectors to cancel many sources of systematics.
- Design detectors to eliminate the need for analysis cuts that may introduce systematic error.
- Detector cross calibration may be used to further reduce the near/far normalization systematic error.
- Reduce background rate and uncertainty

Veto Background Events

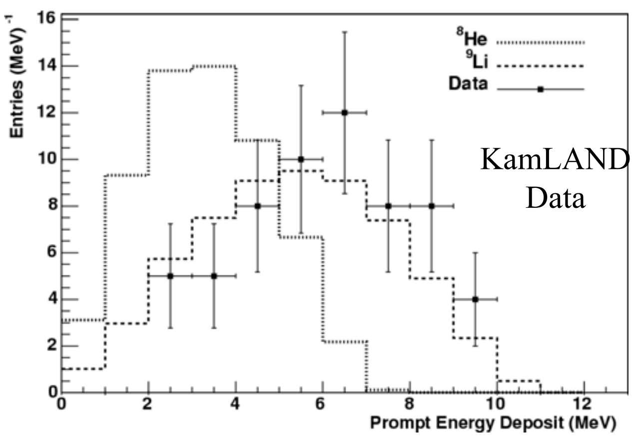
Fast neutrons

Veto μ's and shield neutrons



^{9}Li and ^{8}He

- Produced by a few cosmic ray muons through spallation
- Large fraction decay giving a correlated β+n



A few second veto after every muon that deposits more than 2 GeV in the detector or veto will reduce this rate.

How Do You Measure a Small Disappearance?

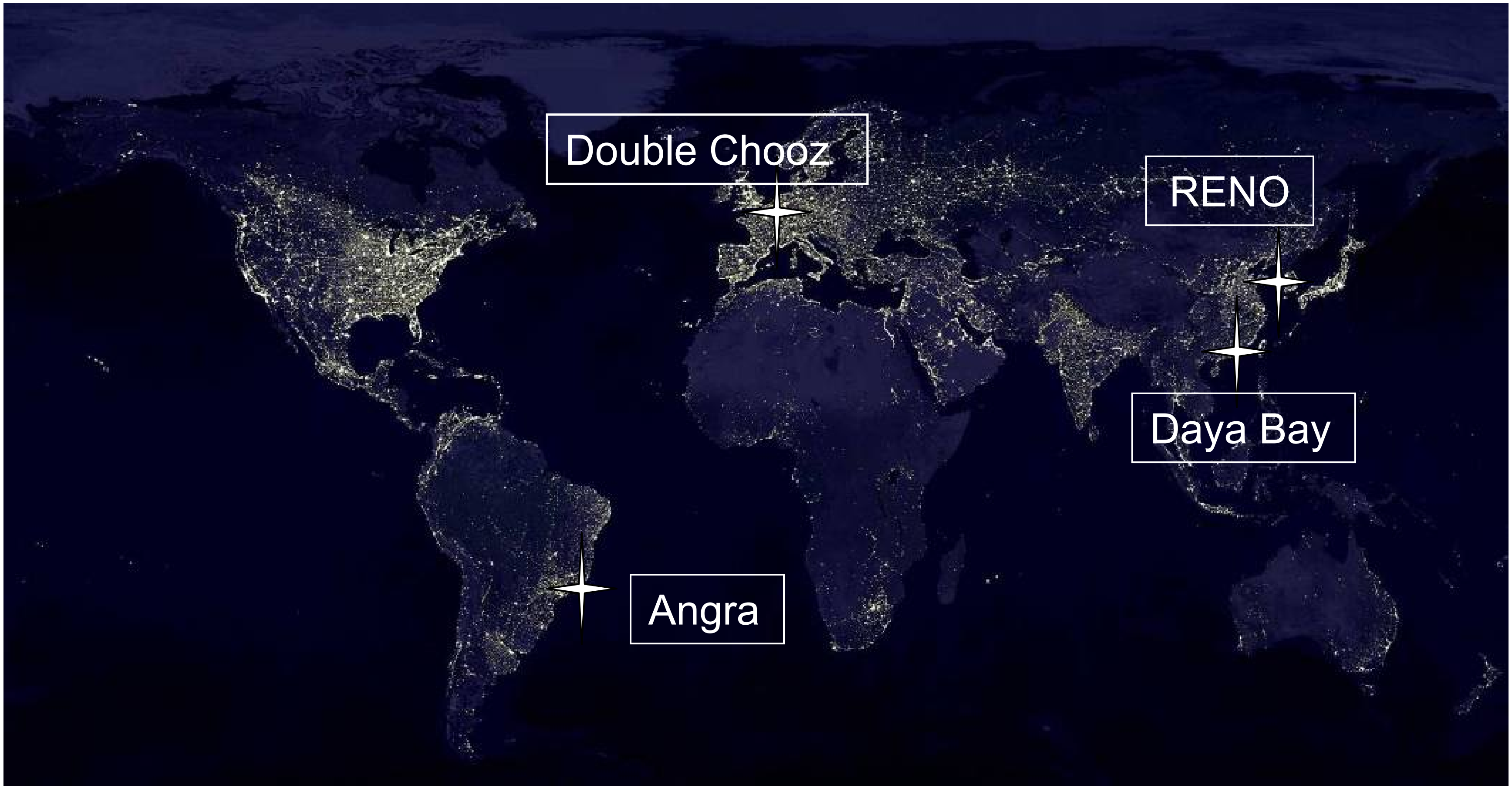
- Use identical near and far detectors to cancel many sources of systematics.

- Design detectors to eliminate the need for analysis cuts that may introduce systematic error.

- Detector cross calibration may be used to further reduce the near/far normalization systematic error.

- Reduce background rate and uncertainty
  - Go as deep as you can
  - Veto

Reactor θ_{13} Projects



Double Chooz Experiment

The Double Chooz Collaboration

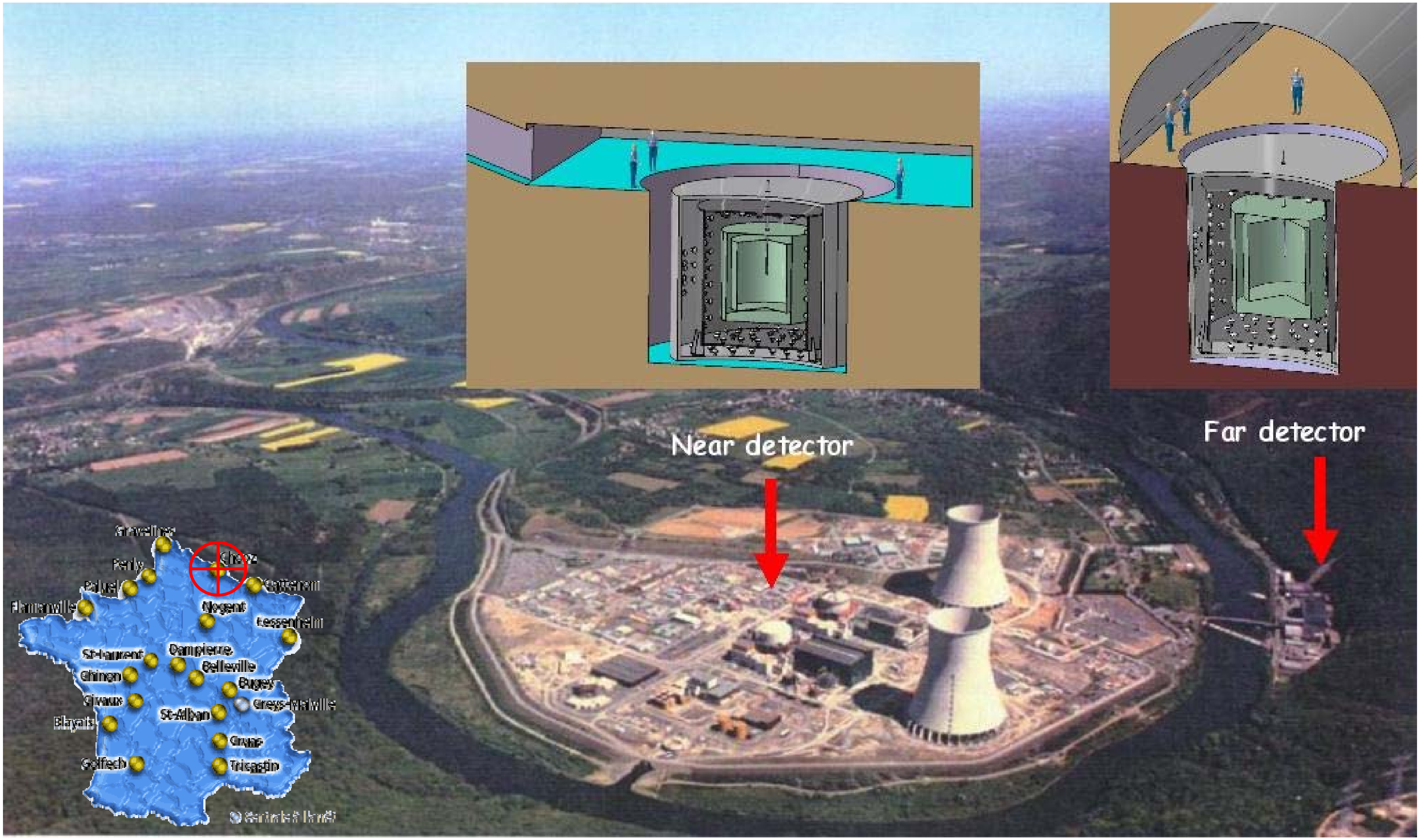
- **France:** CEA/Dapnia Saclay, APC Paris, Subatech Nantes
- **Germany:** MPIK Heidelberg, TU München, EKU Tübingen, Universität Hamburg, Aachen
- **Italy:** participation of LNGS
- **Japan:** Tohoku, Tokyo, Niigata, …
- **Russia:** RAS, Kurchatov Institute (Moscow)
- **Spain:** CIEMAT (Madrid)
- **UK:** Oxford, Sussex
- **USA:** Alabama, ANL, Barnard, Chicago, Columbia, Drexel, Kansas State, LSU, LLNL, Notre Dame, Tennessee

Design Report:
hep/ex 0606025

Double Chooz: A Search for the Neutrino Mixing Angle θ_{13}

Spokesperson: H. de Kerret (APC)

Double Chooz Site in Ardennes, France

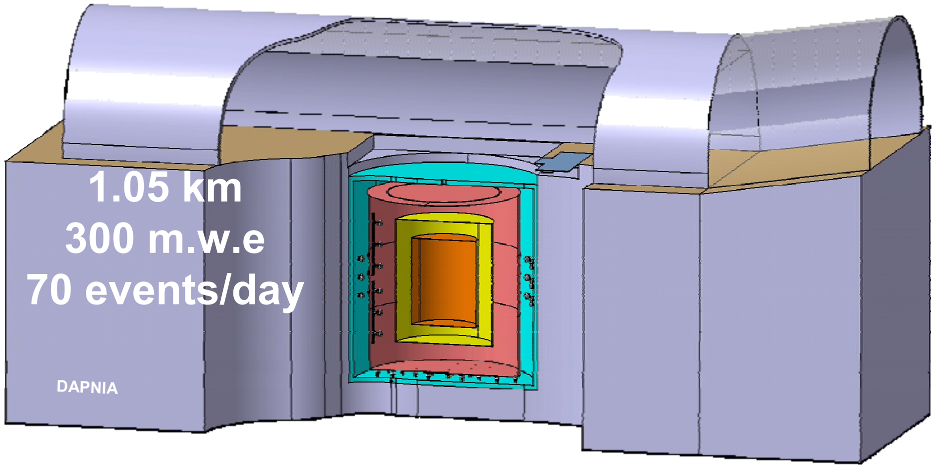


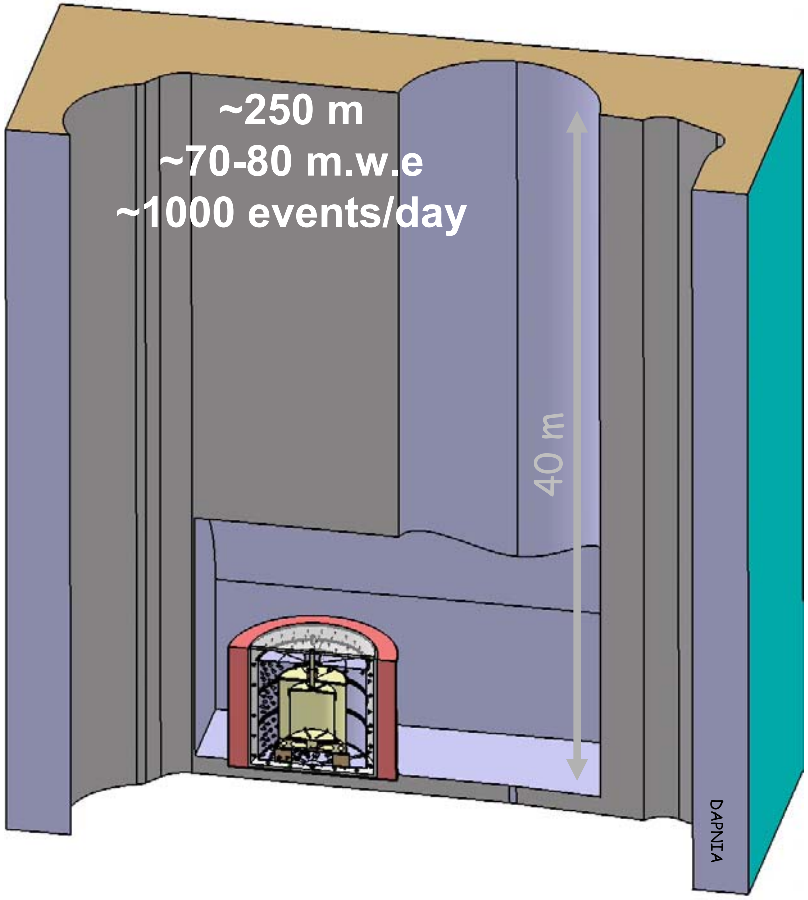

Chooz-far
Chooz-near

Double Chooz Experiment Château

Far site

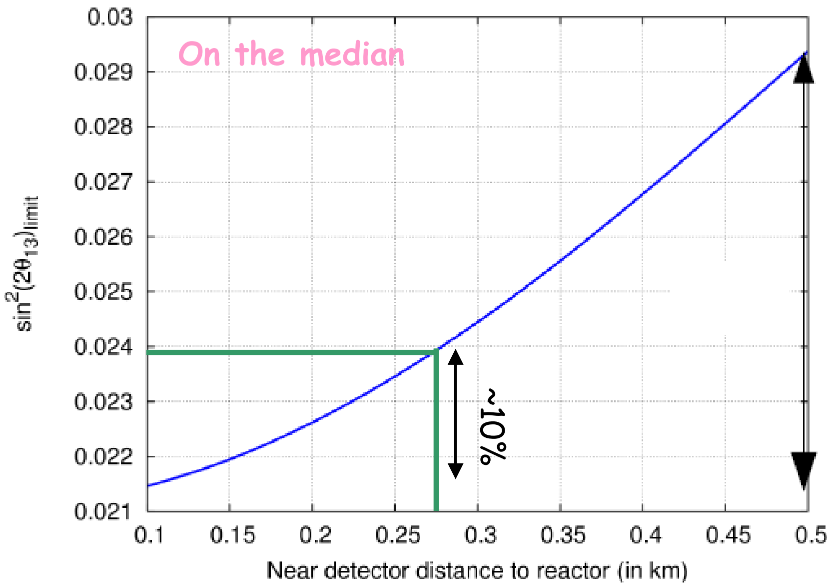
Near site

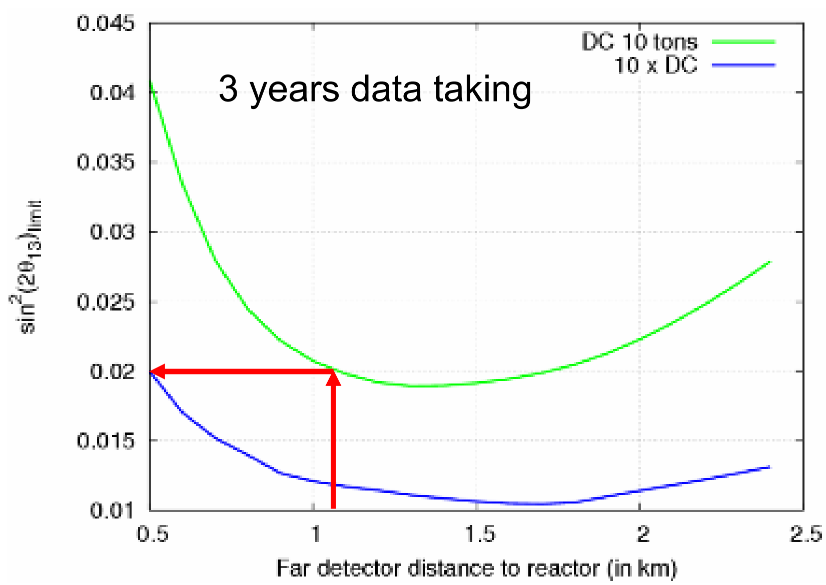




Detector Locations

- "Optimize" far detector for oscillation sensitivity at 2.5×10^{-3} eV^2
- Place near detector close enough so only small oscillations
- Place near and far detector so that distance ratio from two reactor cores is the same
- Uncertainties to include for optimization:
  - Uncorrelated fluctuations included
  - Relative Error : 0.6%
  - Spectral shape uncertainty 2%
  - Δm^2 known at 20%
  - Power fluctuation of each core: 3%

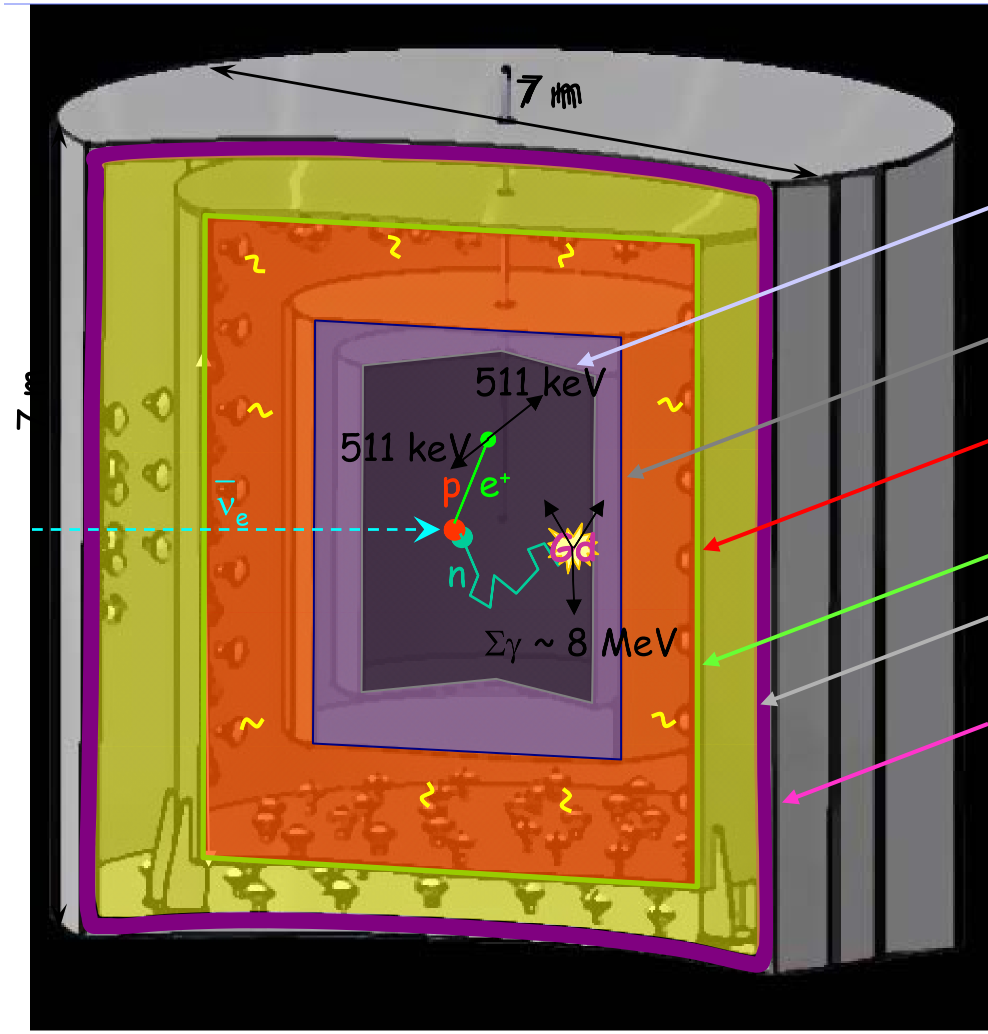




The detector design

Muon Outer-VETO:

7m x 7m Multi-Layer Scintillator Strips



ν target: 80% dodecane + 20% PXE + 0.1% Gd

γ-catcher: 80% dodecane + 20% PXE

Non-scintillating buffer oil

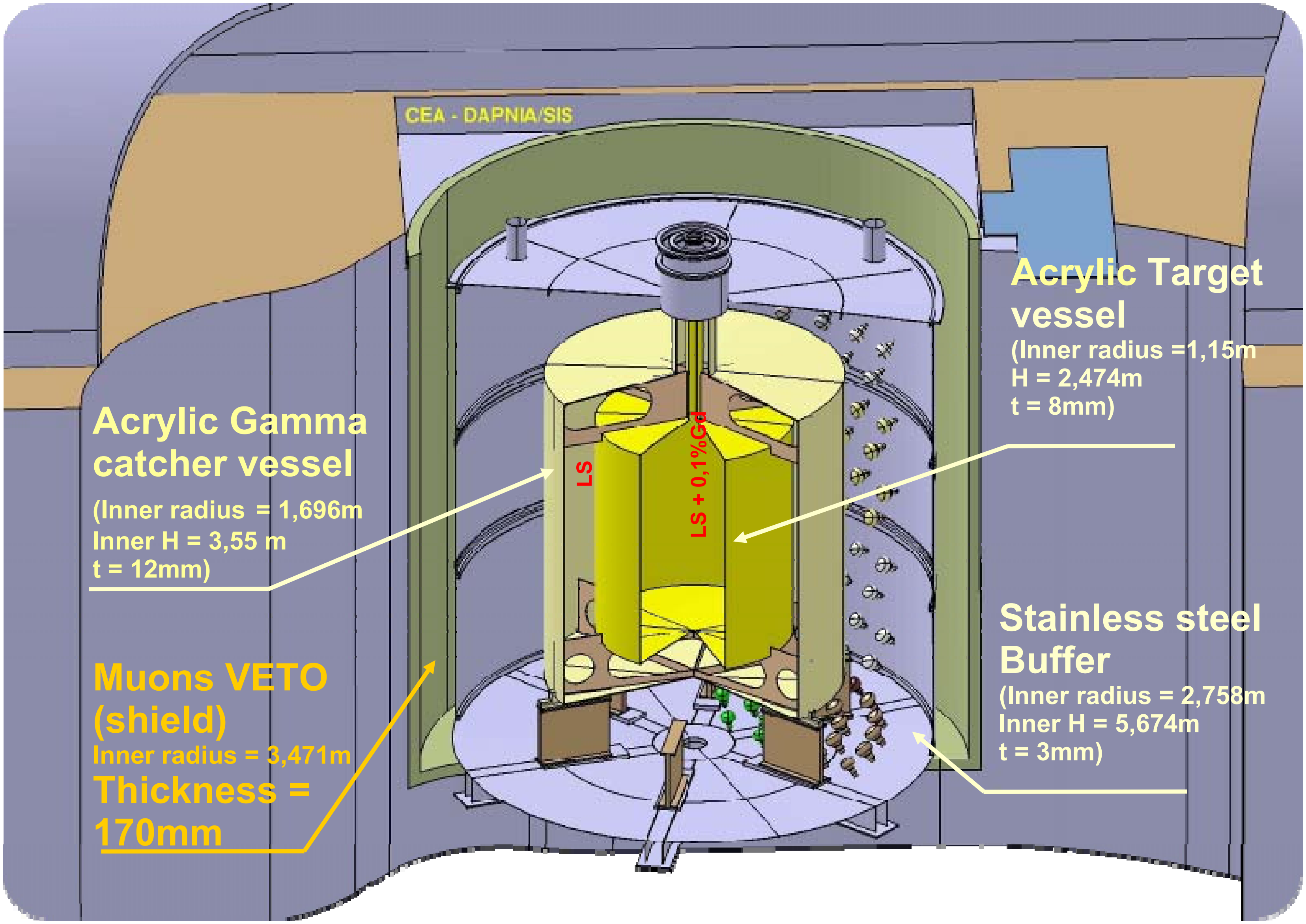
Buffer stainless steel tank + 534 PMTs

Inner Muon VETO: scintillating oil

Steel Shielding from neutrons

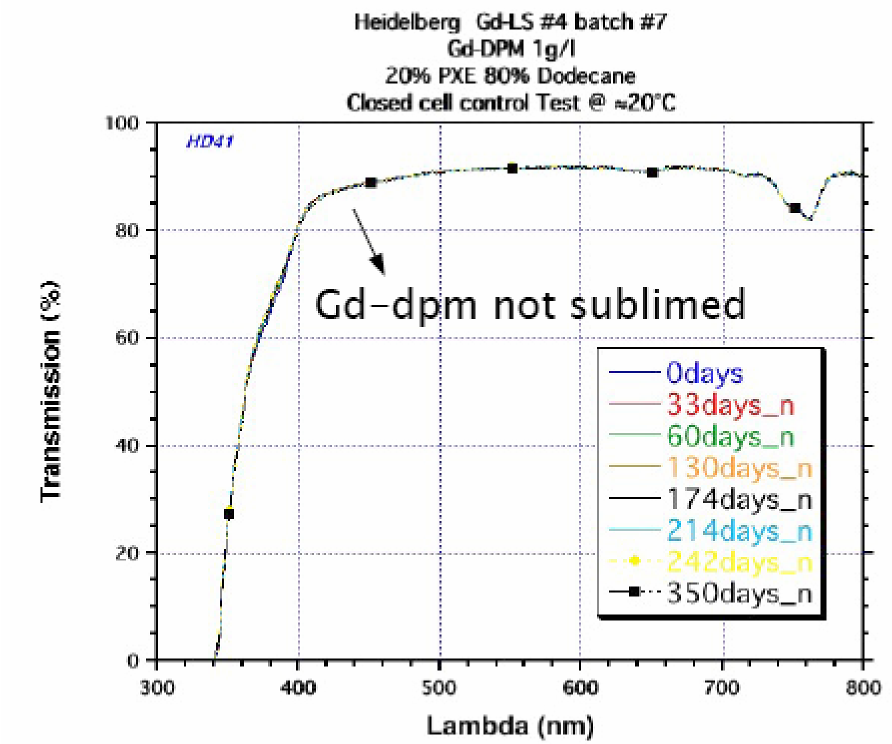
Detector layout

Detector dimensions have been frozen



Gd Doped Scintillator

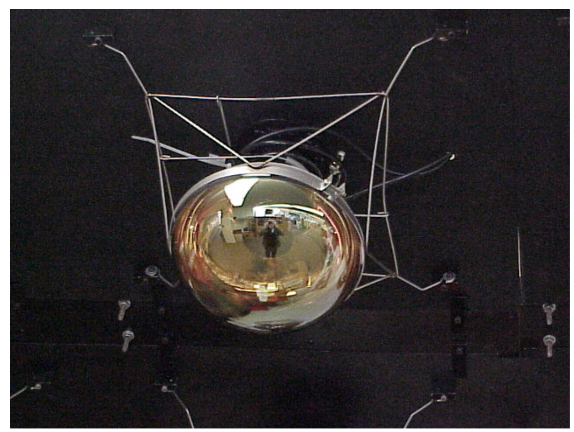
- Solvant: 20% PXE – 80% Dodecane
- Gd loading
  - **0.1% Gd loading**
  - **Long term Stability**
  - **LY ~7000 ph/MeV**
  - **Attenuation length: a few meters at 420 nm**
- Scintillator is very stable



Phototubes

- 8" Ultra low background tubes
- 534 PMTs
  (360 side, rest top + bottom)
- 13 % coverage
- Energy resolution goal:
  7% at 1 MeV

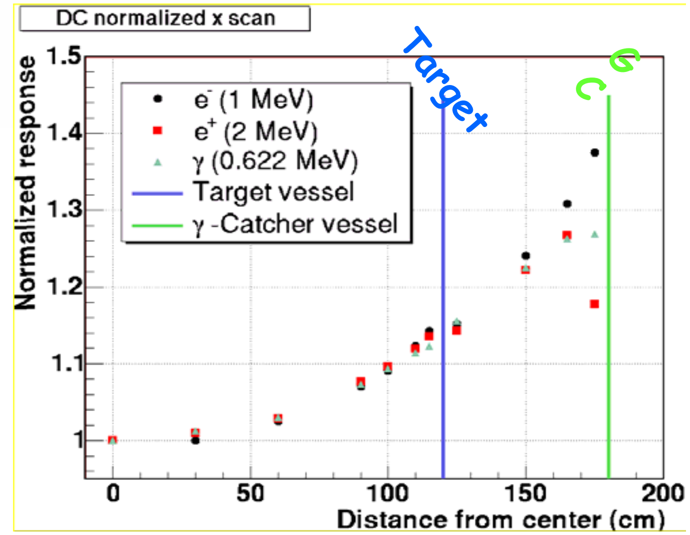
- Current work:
  - **PMT selection (radiopurity)**
  - **Angular sensitivity, Concentrators?**
  - **Tilting tube options**
    (to increase Npe/MeV)
  - **B fields shielding**

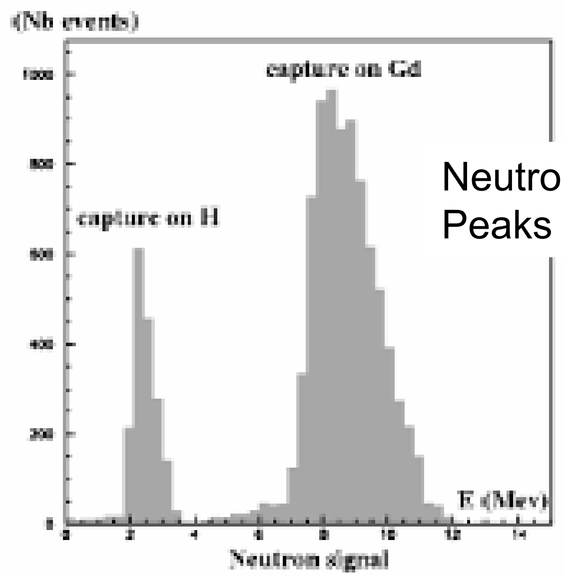


Calibration

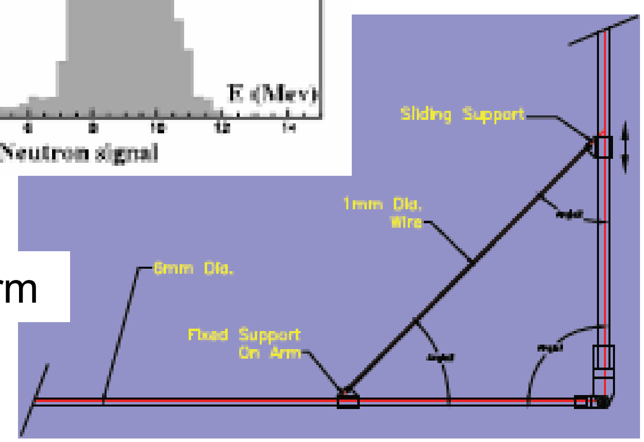
- **<u>Relative</u>** near/far detection uncertainty goal <0.6%
  - energy cut at threshold <0.1%
  - energy cut at 6 MeV for neutron capture <0.2%
  - neutron capture time distribution <0.1%
  - deadtime <0.25%
  - spatial cut (if used) <0.2%

- Calibration methods/sources
  - Gd capture peaks 2 and 8 MeV
  - γ sources: 0.289 MeV to 4.94 MeV
  - Neutron sources: Am-Be and Cf-252)
  - Laser





Neutron Capture Peaks

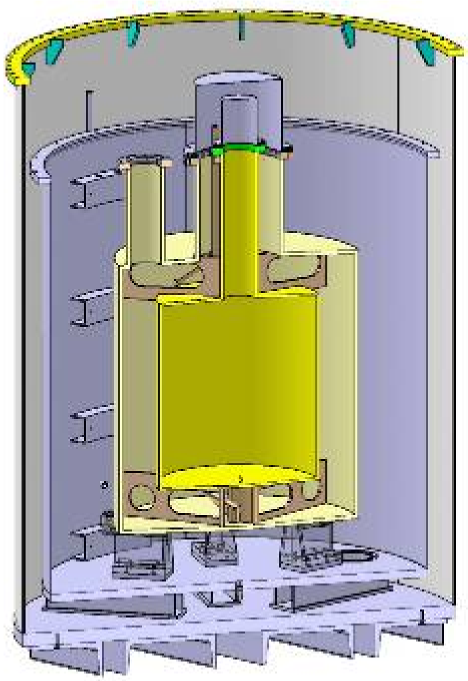


Articulated Arm

A 1/5 prototype

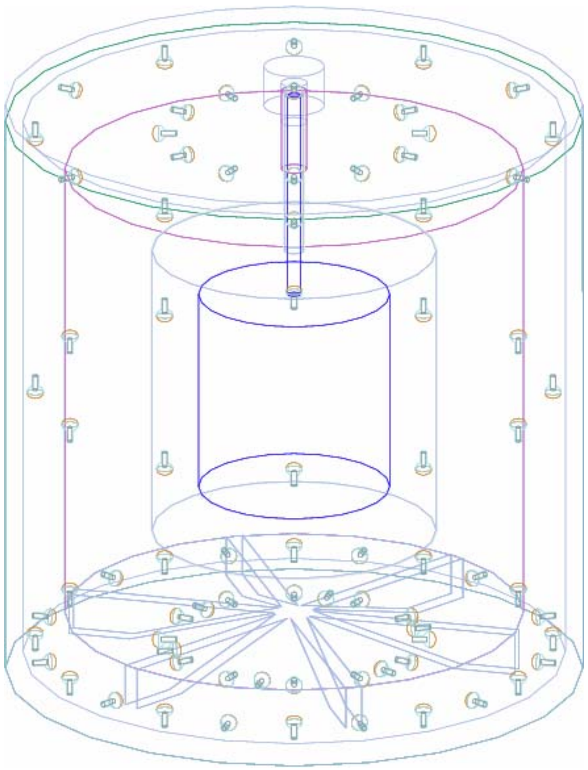
Last stage for the validation of the technical choices for vessels construction, material compatibility, filling, and the integration of the detector at the Chooz site

Total of 2000 l of oil
Filling 12/13/2005
Stable in the detector



- ***Inner Target:*** *120 l : 20%PXE+80%dodecane+0.1%Gd*
- ***Gamma Catcher:*** *220 l : 20%PXE+80%dodecane*

Inner Veto System



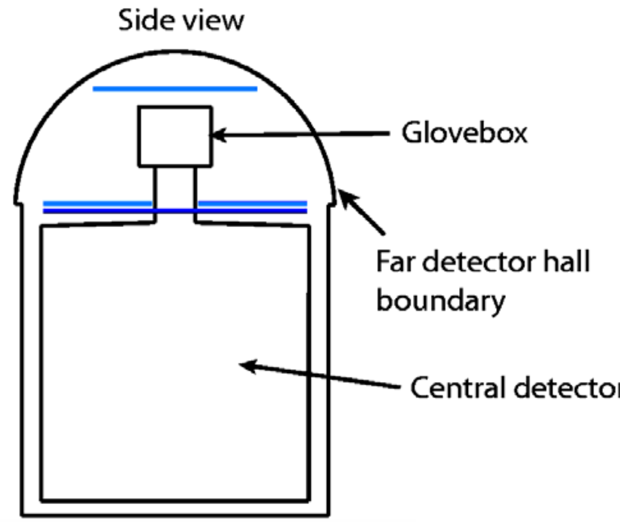
Baseline

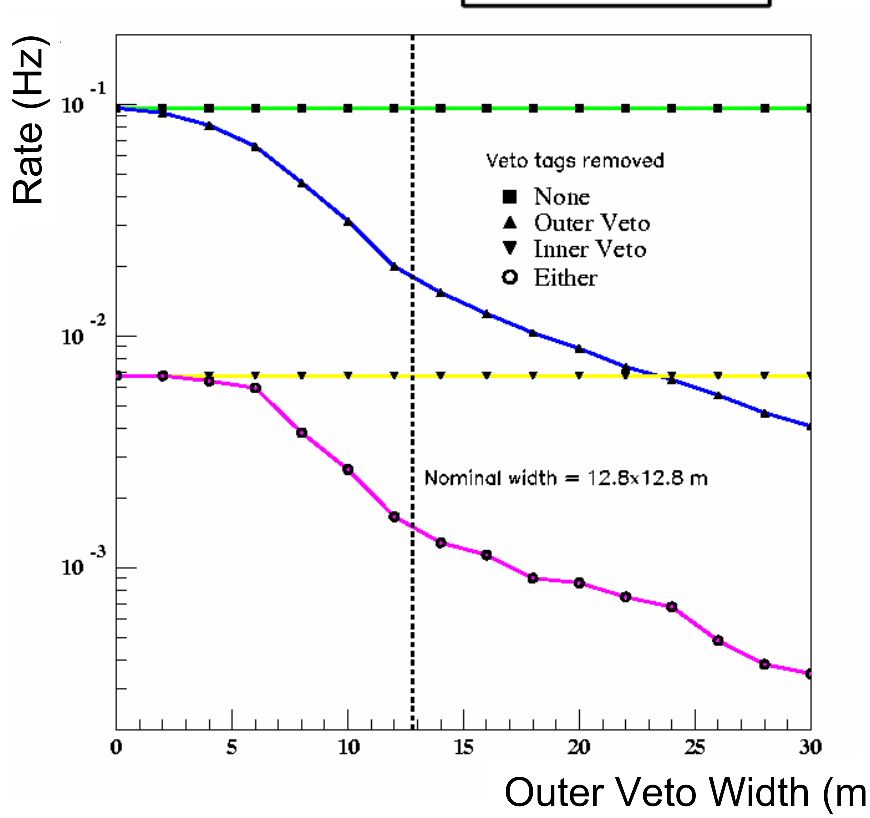
50 cm, scintillating mineral oil
60 – 100 PMTs
Reflective walls (paint + Tyvek)

Outer Veto System

Needed:

- Reduce spallation neutron rate
- Tag muons that can produce ^{9}Li background
- Track muons that could capture in dead material



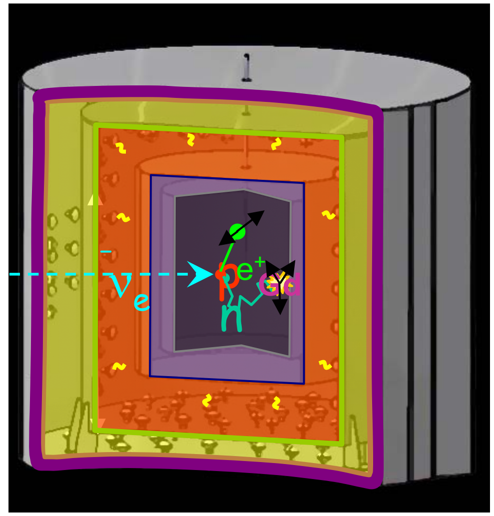


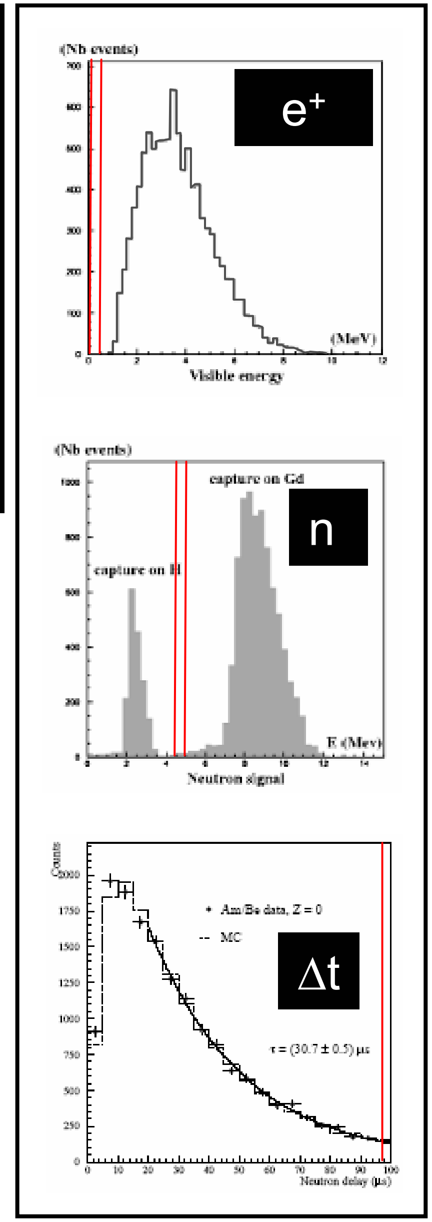
Relative Normalization: Analysis

✓ @Chooz: 1.5% syst. err.
 - 7 analysis cuts
 - Efficiency ~70%

✓ Goal Double-Chooz: ~0.3% syst. err.
 - 2 to 3 analysis cuts

Selection cuts
 - neutron energy
 (- distance e+ - n) [level of accidentals]
 - Δt (e+ - n)





	CHOOZ	Double-CHOOZ	
selection cut	rel. error (%)	rel. error (%)	Comment
positron energy*	0.8	0	not used
positron-geode distance	0.1	0	not used
neutron capture	1.0	0.2	Cf calibration
capture energy containment	0.4	0.2	Energy calibration
neutron-geode distance	0.1	0	not used
neutron delay	0.4	0.1	—
positron-neutron distance	0.3	0 – 0.2	0 if not used
neutron multiplicity*	0.5	0	not used
combined*	1.5	0.2-0.3	—

*average values

Background Rates and Uncertainties

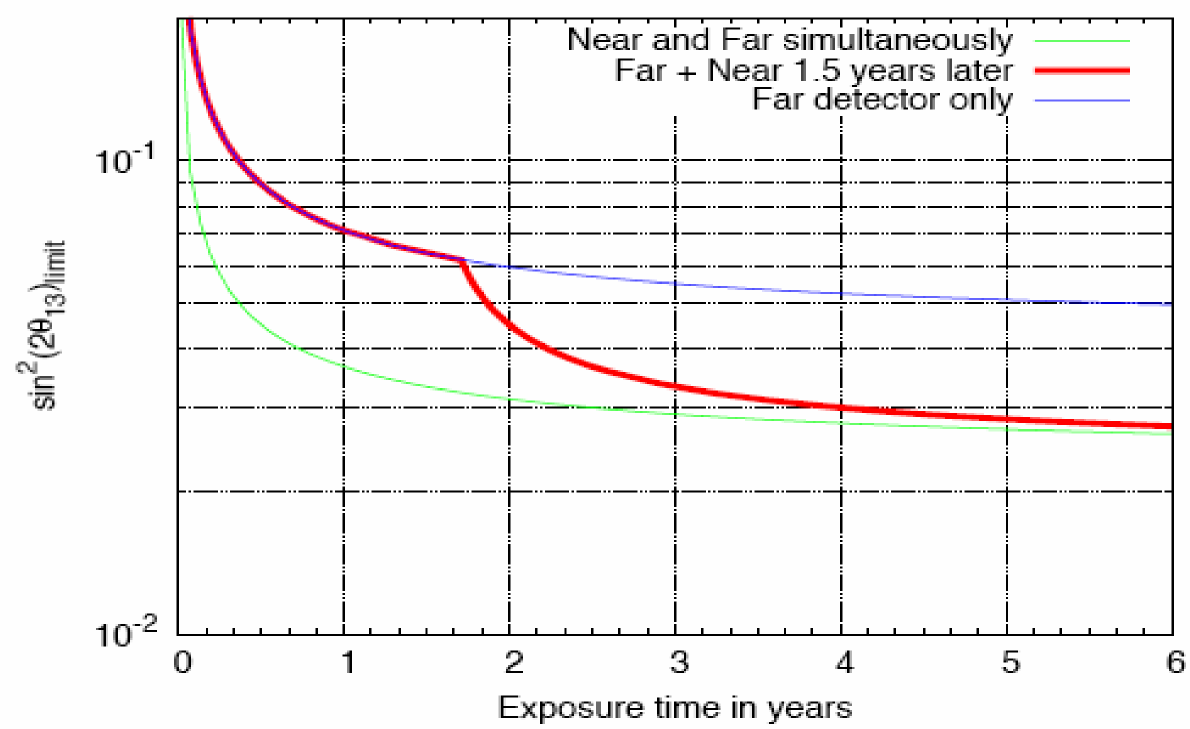
Detector	Site		Background				
			Accidental		Correlated		
			Materials	PMTs	Fast n	μ-Capture	^{9}Li
CHOOZ		Rate (d^{-1})	—	—	—	—	0.6 ± 0.4
(24 ν/d)		Rate (d^{-1})	0.42 ± 0.05		1.01 ± 0.04(stat) ± 0.1(syst)		
	Far	bkg/ν	1.6%		4%		
		systematics	0.2%		0.4%		
Double Chooz		Rate (d^{-1})	0.5 ± 0.3	1.5 ± 0.8	0.2 ± 0.2	< 0.1	1.4 ± 0.5
(69 ν/d)	Far	bkg/ν	0.7%	2.2%	0.2%	<0.1%	1.4%
		systematics	<0.1%	<0.1%	0.2%	<0.1%	0.7%
Double Chooz		Rate (d^{-1})	5 ± 3	17 ± 9	1.3 ± 1.3	0.4	9 ± 5
(1012 ν/d)	Near	bkg/ν	0.5%	1.7%	0.13%	<0.1%	0.9%
		systematics	<0.1%	<0.1%	<0.1%	<0.1%	0.5%

Table 7: Summary of the background subtraction error at the far and near detectors. Background rates and shapes with their corresponding uncertainties are used. For 9-Li, the fact that we can measure the rate with reactor off data is not used in calculating the systematic error, which will further lower the uncertainty.

Systematic uncertainties

		Chooz	Double-Chooz	
Reactor-induced	ν flux and σ	1.9 %	<0.1 %	Two ''identical'' detectors, Low bkg
	Reactor power	0.7 %	<0.1 %	
	Energy per fission	0.6 %	<0.1 %	
Detector - induced	Solid angle	0.3 %	<0.1 %	Distance measured @ 10 cm + monitor core barycenter
	Volume	0.3 %	0.2 %	Precise control of detector filling
	Density	0.3 %	<0.1 %	Accurate T control (near/far)
	H/C ratio & Gd concentration	1.2 %	<0.1 %	Same scintillator batch + Stability
	Spatial effects	1.0 %	<0.1 %	Identical detectors and monitoring
	Live time	-----	0.25 %	Special electronic systems and monitoring
Analysis	From 7 to 3 cuts	1.5 %	0.2 - 0.3 %	Simplified cuts due to detector design
	Total	2.7 %	< 0.6 %	

Double Chooz Timescale



2005	2006	2007	2008	2009	2010	2011

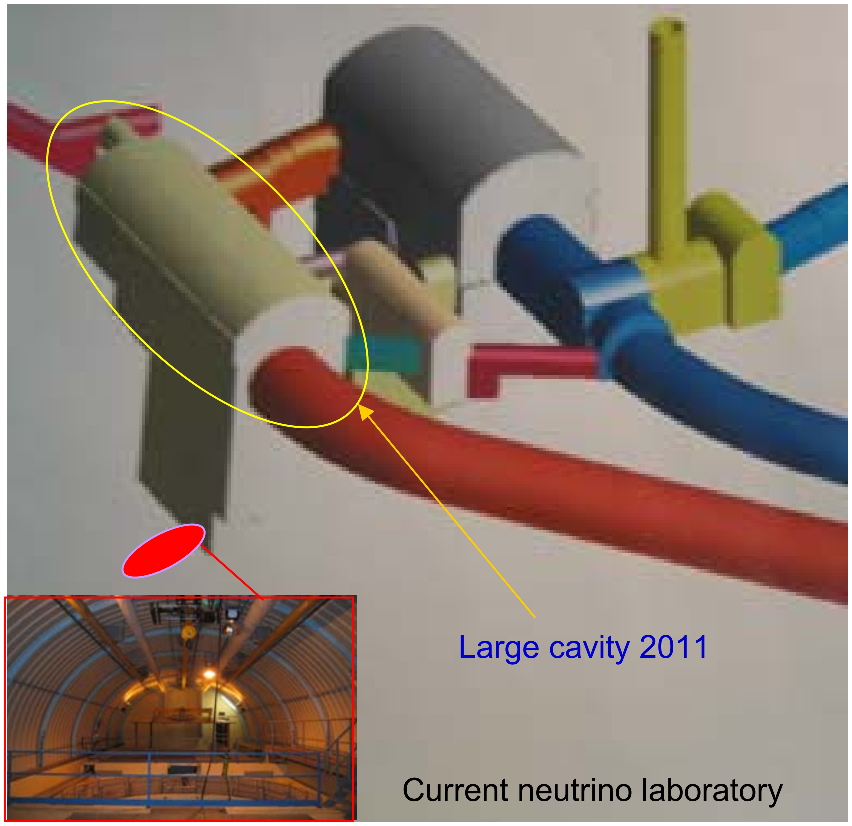
Site | **Prop.** | **design+test simulation** | **Construction** | **Data taking and analysis**

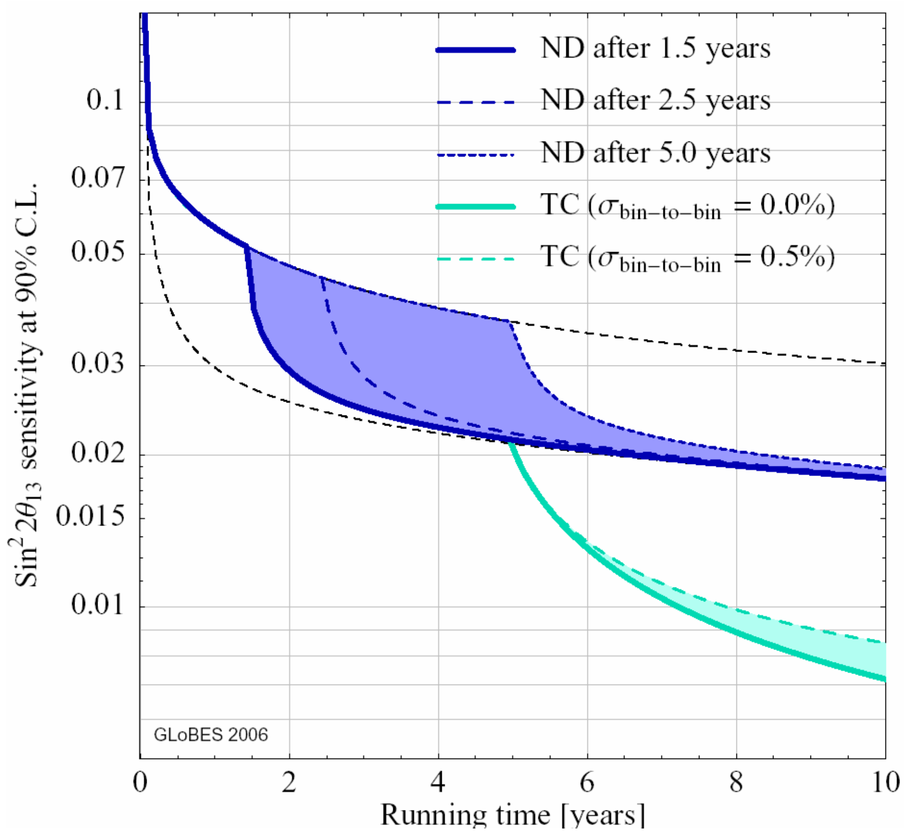
MINOS.
Opera

T2K

Triple Chooz (hep/0601266)

- **Old underground reactor Chooz A being dismantled**
- **Large cavities 30x30 m available in 2010-2011**
- **Opportunity for an additional >few hundreds tons detector**



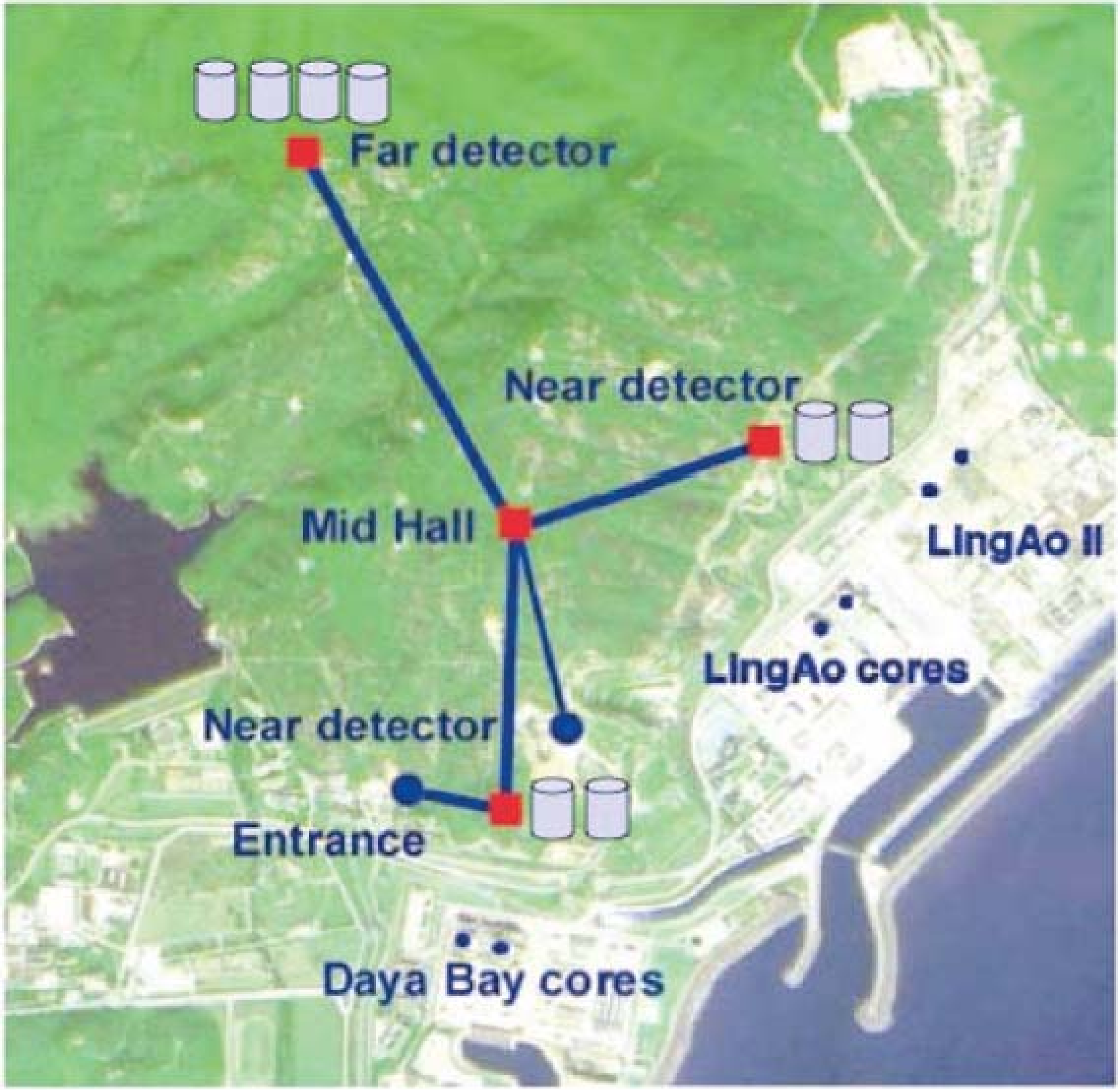


Daya Bay Experiment

Daya Bay nuclear power plant

- 4 reactor cores, 11.6 GW
- 2 more cores in 2011, 5.8 GW
- Mountains provide overburden to shield cosmic-ray backgrounds

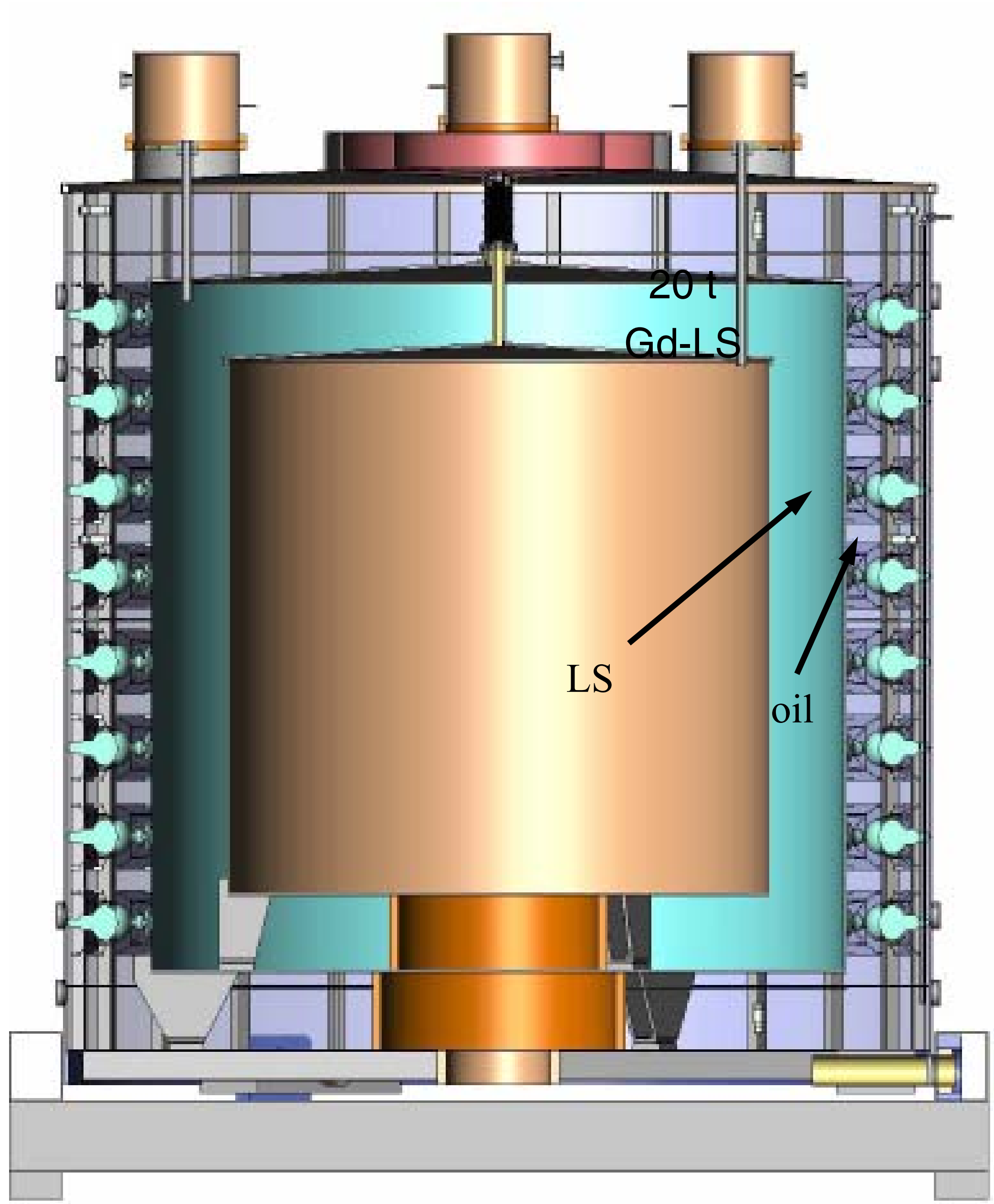
Experiment Layout



Detector modules

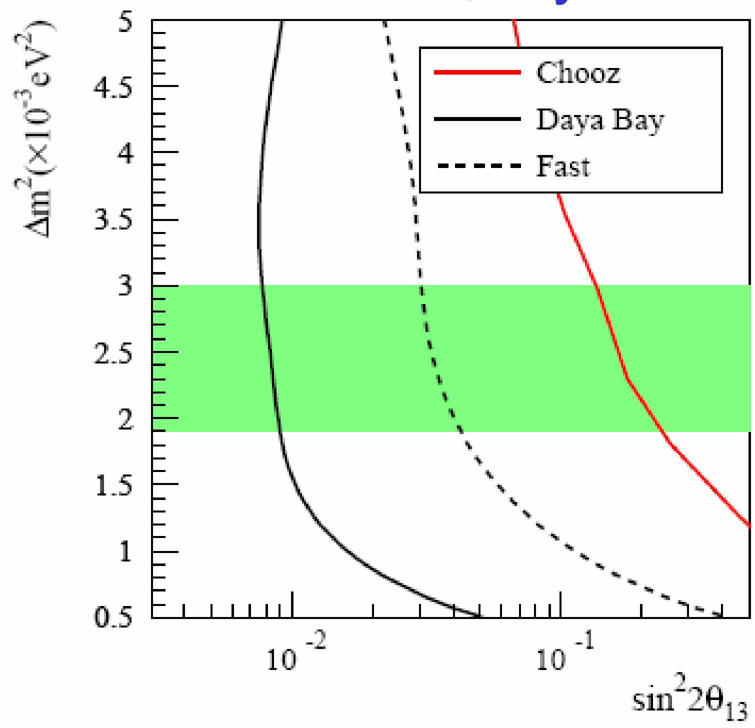
- Three zone modular structure:
  - I. target: Gd-loaded scintillator
  - II. g-catcher: normal scintillator
  - III. Buffer shielding: oil
- Reflector at top and bottom
- 192 8"PMT/module
- Photocathode coverage:
  5.6 % ➔ 12%(with reflector)

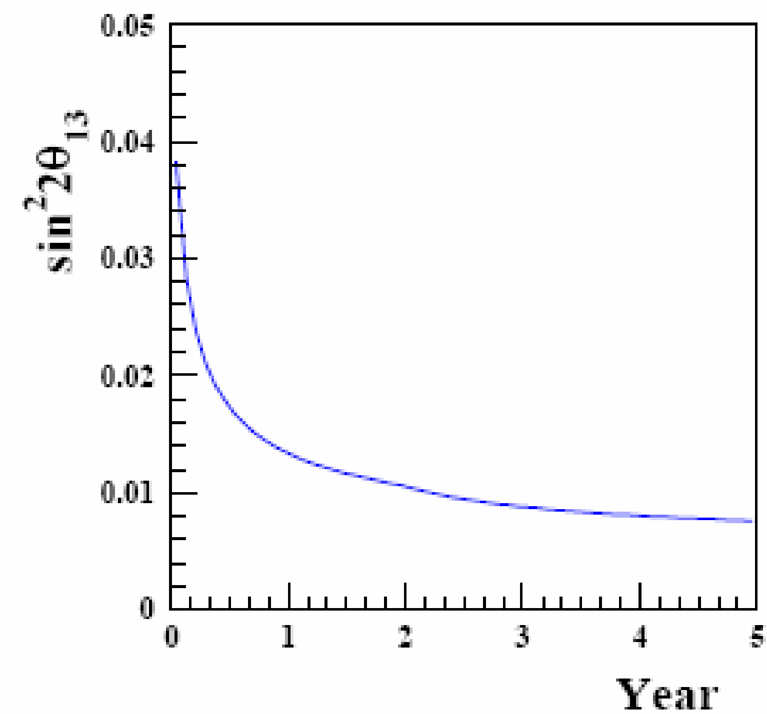
Target: 20 t, 1.6m
g-catcher: 20t, 45cm
Buffer: 40t, 45cm



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

90% CL, 3 years

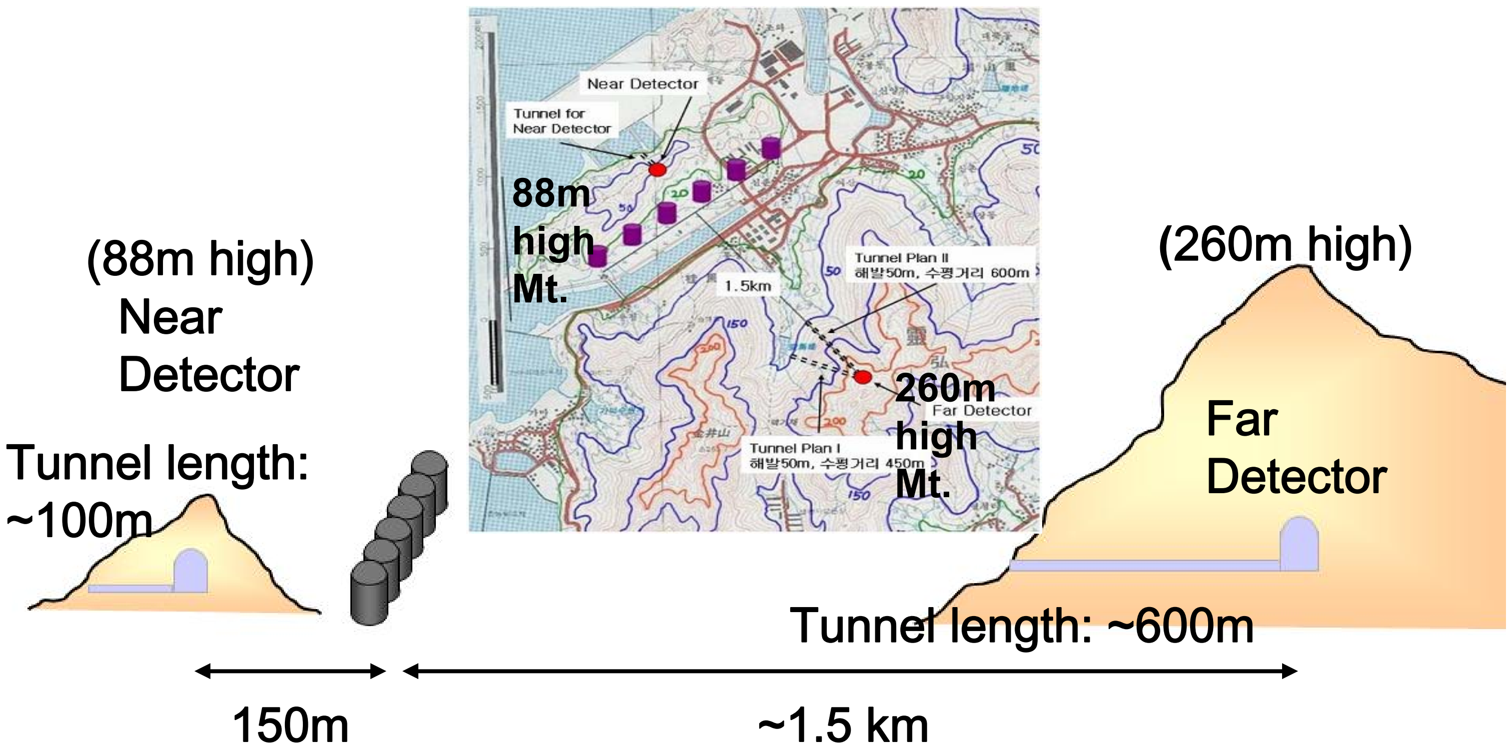




- Experiment construction: 2008-2010
- Start acquiring data: 2010
- 3 years running

Other Near Term Experiments

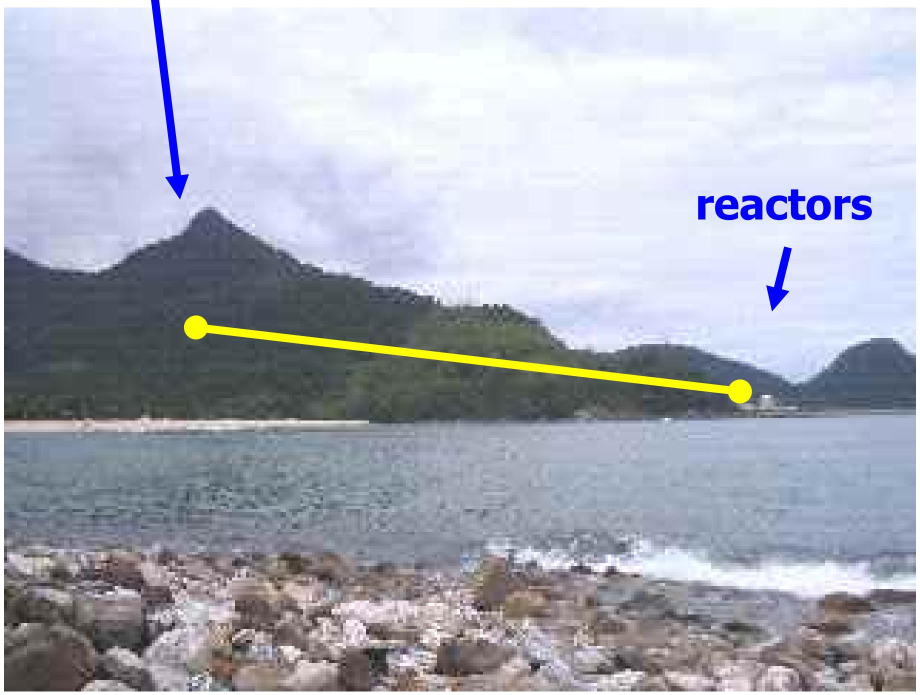
Reactor Experiment for Neutrino Oscillations at YoungGwang in Korea



ANGRA Experiment - Brazil

Far Detector Location

Very large far detector ⇒ Mainly sensitive the energy shape



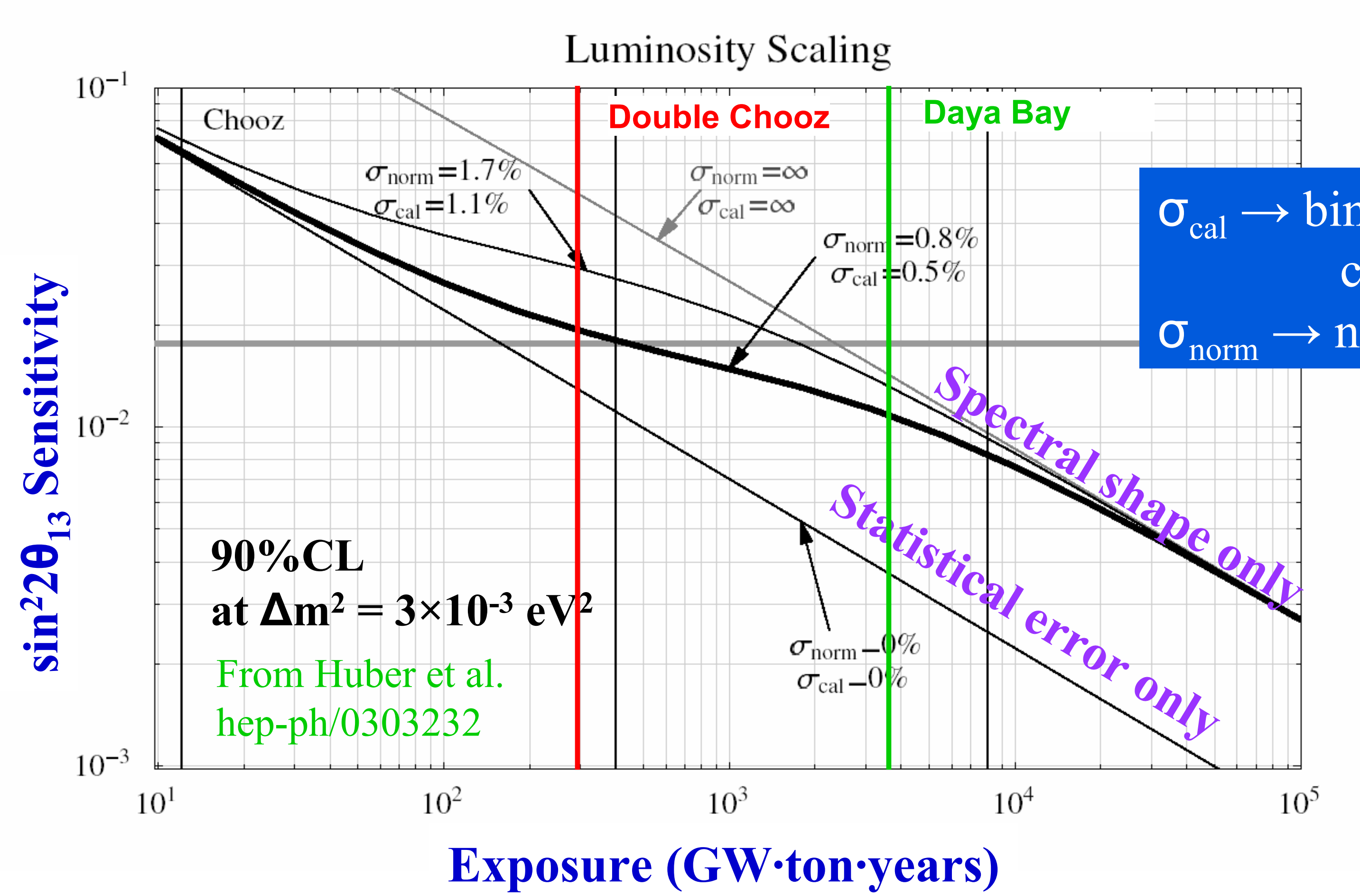
- **Near (reference) detector:**
  - 50 ton detector (7.2 m dia)
  - 300 m from core
  - 250 m.w.e.
- **Far (oscillation) detector:**
  - 500 tons (12.5 m dia)
  - 1500 m from core
  - 2000 m.w.e.
- **Very Near detector:**
  - 1 ton prototype project
  - < 50m of reactor core

Use **Very Near detector** to make accurate measurement of the reactor flux spectrum

Oscillation Search Sensitivity

- The oscillation search is made by comparing the events in the near and far detectors using:
  - Total number of events integrated over energy (Counting Meas.)
  - The distribution of events binned in energy (Shape Meas.)
  - Both counting plus shape (Combined Meas.)
- For the “Counting Measurement”, systematic uncertainties associated with the near to far event ratio dominate over statistical errors
  - Relative target mass
  - Relative efficiencies
- For the “Shape Measurement”, statistical uncertainties become an important component

Energy Spectrum Shape vs. Event Rate Luminosity and Systematic Effects



$\sigma_{cal} \rightarrow$ bin-to-bin energy calibration error

$\sigma_{norm} \rightarrow$ normalization error

Experiments are dominated by systematic uncertainties for the "Counting" measurement.

Reactor ν Experiments: Parameter Comparison

	Power GW_{th}	<Power> GW_{th}	Location	Detectors km/ton/MWE
Angra	6.0	5.3	Brazil	0.05/1/20 0.3/50/250 1.5/500/2000
RENO	17.3	16.4	Korea	0.15/15/230 1.5/15/675
Daya Bay	11.6 (17.4 after 2010)	9.9 (14.8 after 2010)	China	0.36/40/260 0.50/40/260 1.75/[40×2]/910
Double Chooz	8.7	7.4	France	0.15/10.2/60 1.067/10.2/300

Reactor ν Experiments: Physics Comparison

Reactor	Estimated start date	GW-t-yr (yr)	90% CL $Sin^2 2\theta_{13}$ sensitivity	for Δm^2 ($10^{-3} eV^2$)	efficiencies	Far event rate
ANGRA	2013(full)	9000(3)	0.0060	2.5	0.8×0.9	350,000/yr
RENO	Late 09	750(3)	0.025	2.5	0.8	35,000/yr
Daya Bay	2010	3500(3)	0.008	2.5	0.75×0.83	70,000/yr 110,000/yr (before/after 2010)
Double Chooz	Oct 08(far) Oct 09(near)	75(1) 300(1+3)	0.07 0.025	2.5	0.8 ×0.9	18,000/yr

Combining Reactor and Accelerator Measurements

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

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

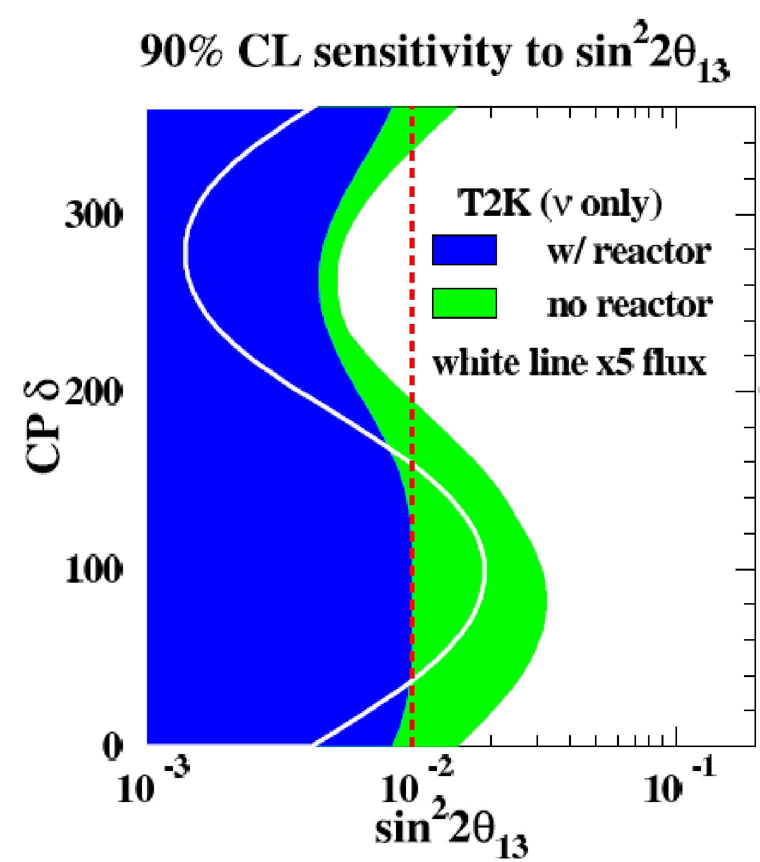
$$P[\nu_\mu(\bar{\nu}_\mu) \rightarrow \nu_e(\bar{\nu}_e)] = s_{23}^2 \sin^2 2\theta_{13} \sin^2 \frac{\Delta_{31}}{2}$$

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

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

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



Ambiguities and Correlations in Offaxis Measurements

$$
\begin{aligned}
P_{long-baseline} \simeq\ & \sin^2 2\theta_{13}\ \sin^2\theta_{23} \sin^2\Delta \\
& \mp\ \alpha\ \sin 2\theta_{13}\ \sin\delta_{CP}\ \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3\Delta \\
& +\ \alpha\ \sin 2\theta_{13}\ \cos\delta_{CP}\ \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \sin^2\Delta \\
& +\ \alpha^2\ \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2\Delta
\end{aligned}
$$

with $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{23}$ and $\Delta \equiv \Delta m^2_{31} L/(4E_\nu)$

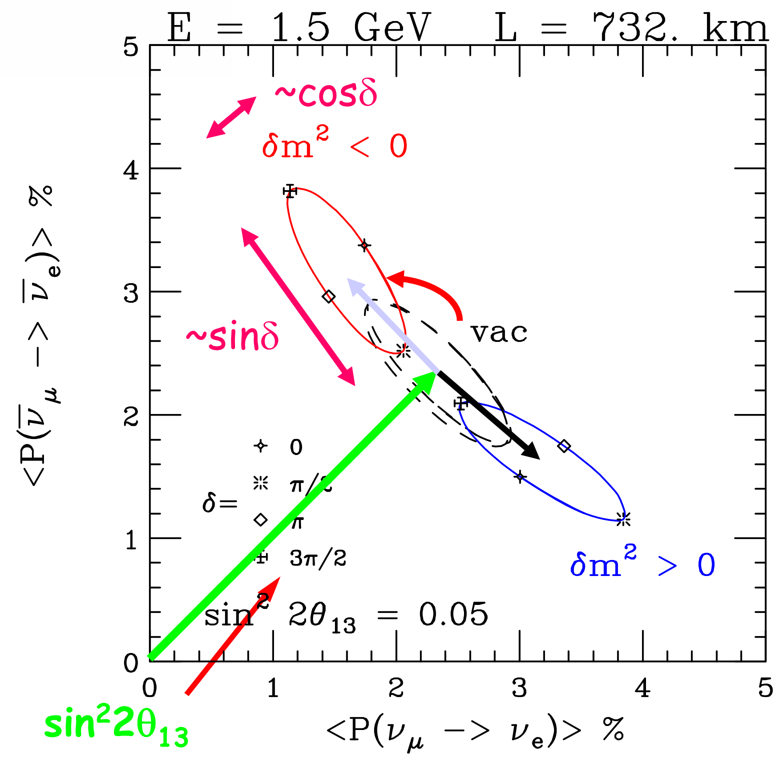
Expansion to second order in α and Δ

Ambiguities due to:

- Need $\sin^2\theta_{23} = \dfrac{1 \pm \sqrt{1-\sin^2 2\theta_{23}}}{2}$, not $\sin^2 2\theta_{23}$
- Sign of $\Delta m^2_{31} \Rightarrow$ Overall shifts

Correlations:

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



Minakata and Nunokawa, hep-ph/0108085

Reactor Sensitivity Studies
(Comparing and Combining with Offaxis Measurements)

(K. Mahn and M. Shaevitz – hep-ex/0409028)

- Try to do estimates including all effects:
  - $\Delta m_{23}^2 = 2.5\times10^{-3}$ eV^2 and allowed to vary with $\sigma = 0.1\times10^{-3}$ eV^2
  - Include both mass hierarchies $\Delta m_{23}^2 > 0$ and $\Delta m_{23}^2 < 0$
  - $\sin^2 2\theta_{23} = 0.95$ and allowed to vary with $\sigma = 0.01$
  - Include ambiguity of $\theta_{23} < 45^\circ$ or $> 45^\circ$
  - Δm_{12}^2 and θ_{12} fixed at current values
  - δ_{CP} allowed to vary between 0° to 360°

- Reactor experimental inputs:
  - Small scale: $\delta(\sin^2 2\theta_{13}) = 0.03$
  - Medium scale: $\delta(\sin^2 2\theta_{13}) = 0.01$
  - Large scale: $\delta(\sin^2 2\theta_{13}) = 0.005$
    (90% CL upper limit sensitivities at $\Delta m^2 = 2.5\times10^{-3}$ eV^2)

- Offaxis experimental inputs:
  - JPARC to SuperK (T2K) exp.
    - Rates for ν and $\bar{\nu}$ from LOI
    - with / without upgrade x5 rate
  - Offaxis NuMI (Nova) exp.
    - Rates for ν and $\bar{\nu}$ new LOI appendix
    - with / without proton driver upgrade (x5 rate)

(Also include some new plots from Nova)

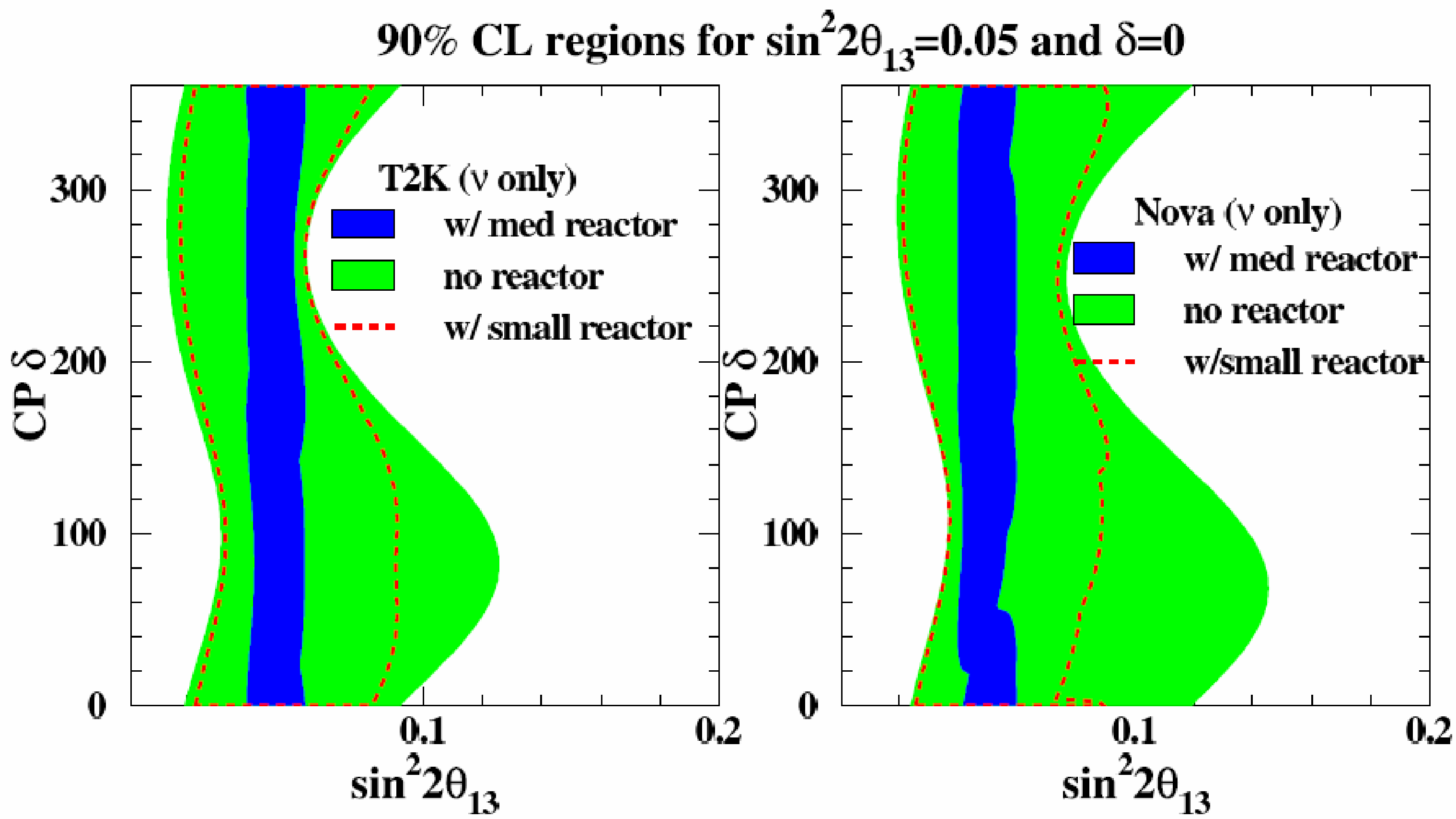
Assumptions for Study

Experiment	Basis of Estimate	Osc. Prob. and σ for $\sin^2 2\theta_{13} =$ 0.02	0.05	0.10	
Reactor ($E_\nu = 3.6$ MeV)	$\sin^2 2\theta_{13}^{Limit}$				
Small 1.05 km	$0.03@90\%CL$	0.013 ± 0.012	0.033 ± 0.012	0.064 ± 0.012	Double Chooz
Medium 1.8 km	$0.01@90\%CL$	0.022 ± 0.006	0.052 ± 0.006	0.102 ± 0.006	Daya Bay
Large 1.8 km	$0.005@90\%CL$	0.022 ± 0.003	0.052 ± 0.003	0.102 ± 0.003	Triple Chooz
T2K ($E_\nu = 650$ MeV)	Number of events in 5 yrs:				
$\langle L \rangle = 295$ km					
ν	105.0 signal / 17.8 bkgnd	0.010 ± 0.003	0.023 ± 0.004	0.044 ± 0.006	
$\overline{\nu}$	30.8 signal / 10.2 bkgnd	0.009 ± 0.007	0.020 ± 0.008	0.038 ± 0.010	
Nova ($E_\nu = 2.1$ GeV)	Number of events in 5 yrs:				
$\langle L \rangle = 810$ km					
ν	227.4 signal / 39.0 bkgnd	0.010 ± 0.002	0.024 ± 0.003	0.045 ± 0.004	
$\overline{\nu}$	109.0 signal / 18.5 bkgnd	0.008 ± 0.003	0.017 ± 0.005	0.032 ± 0.006	

$m^2_{23} = 2.5 \times 10^{-3} eV^2$ for all estimates and
$\sin^2 2\theta_{13} = 0.1$, CP $\delta = 0$ for the long baseline event rates.

Comparison of $\sin^2 2\theta_{13}$ Measurement Capability

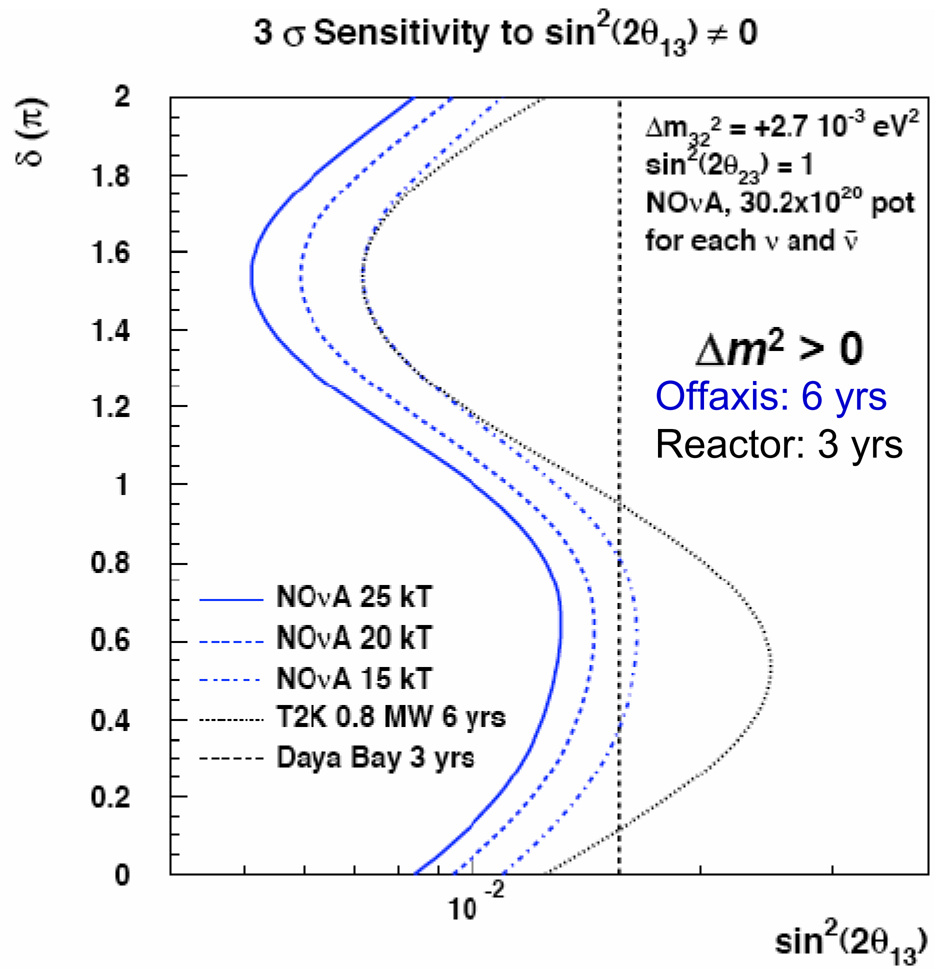
Reactor exp's determines $\sin^2 2\theta_{13}$ with less ambiguity than offaxis exp's (ν – only)

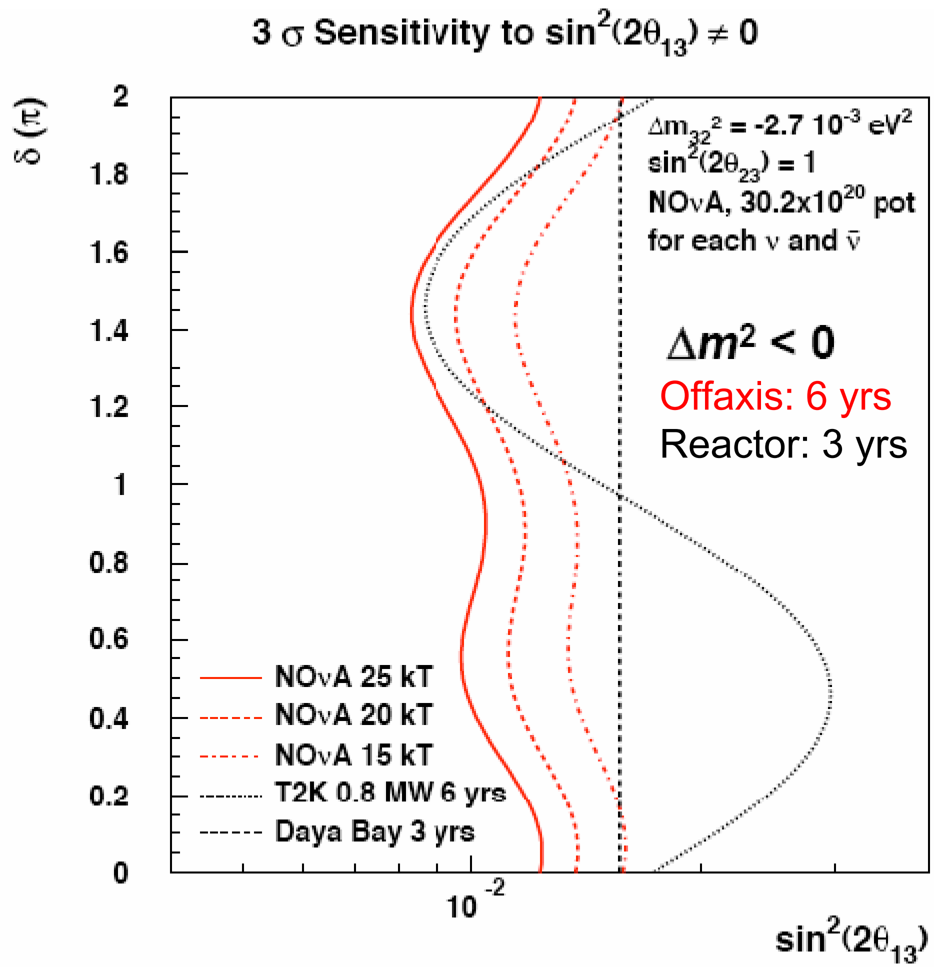


Green: Offaxis exp. Only
Blue: Combined Medium Reactor plus Offaxis
Red: Combined Small Reactor plus Offaxis

Comparison of $\sin^2 2\theta_{13}$ Measurement Capability

Offaxis becomes better when combined ν and $\bar{\nu}$ running is combined.

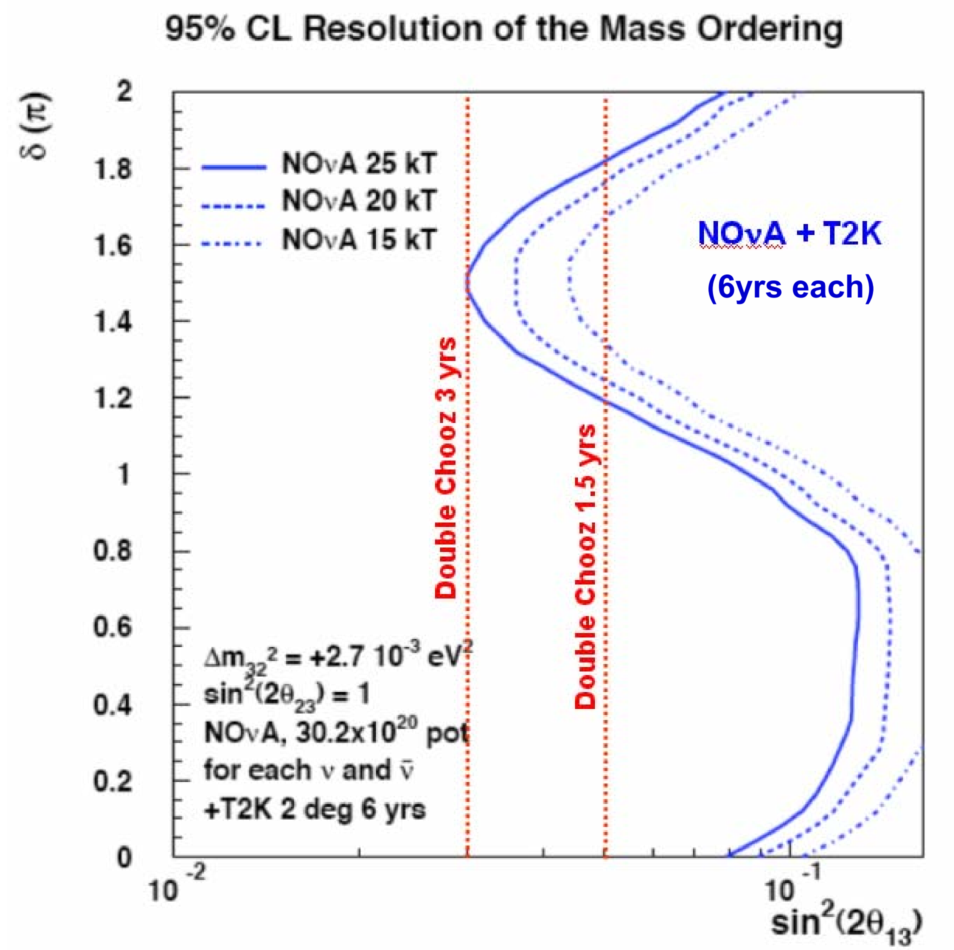




Determining the Mass Hierarchy

- Determining the mass hierarchy will be difficult due to all the ambiguities and correlations
  - Both ν and $\bar{\nu}$ running are necessary

- If Double Chooz does not see an oscillation signal, probably not possible to make this measurement with T2K plus Nova.



The θ_{23} Degeneracy Problem

Disappearance neutrino measurements are sensitive to $\sin^2 2\theta_{23}$

Super-K / Minos / T2K Measures → $P(\nu_\mu \to \nu_x) = \boxed{\sin^2 2\theta_{23}} \sin^2\left(\frac{1.27\Delta m^2_{23} L}{E_\nu}\right)$

But the leading order term in offaxis $\nu_\mu \to \nu_e$ oscillations is

Offaxis θ_{13} Measures → $P(\nu_\mu \to \nu_e) = \boxed{\sin^2 \theta_{23}} \sin^2 2\theta_{13} \sin^2\left(\frac{1.27\Delta m^2_{13} L}{E_\nu}\right)$

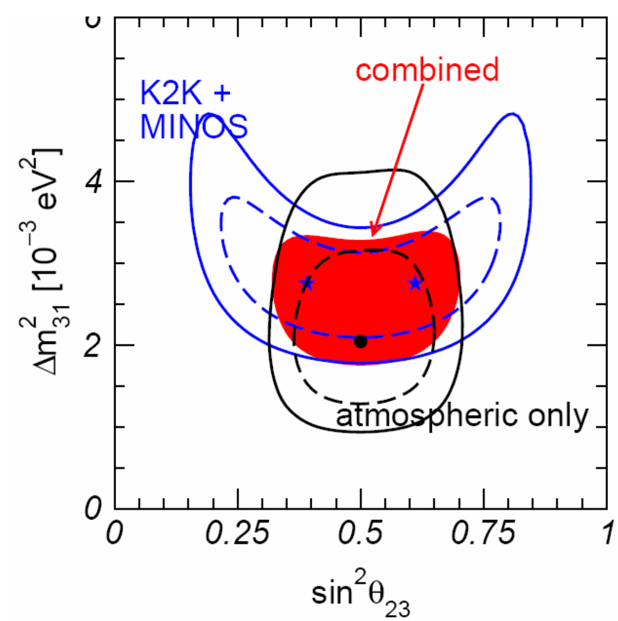
Example: If future measurement of $\sin^2 2\theta_{23} = 0.95$

$\Rightarrow \theta_{23} = 38° \text{ or } 52°$

Prediction for appearance rate $\propto \sin^2\theta_{23}$

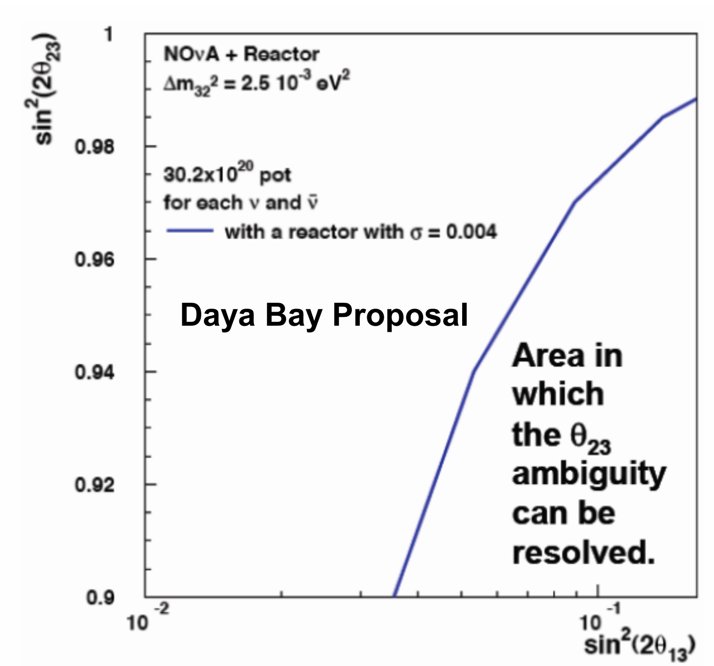
$\Rightarrow \sin^2\theta_{23} = 0.38 \text{ or } 0.62$ (x1.6 uncertainty)

This degeneracy can be resolved by combining the offaxis measurement with reactor data



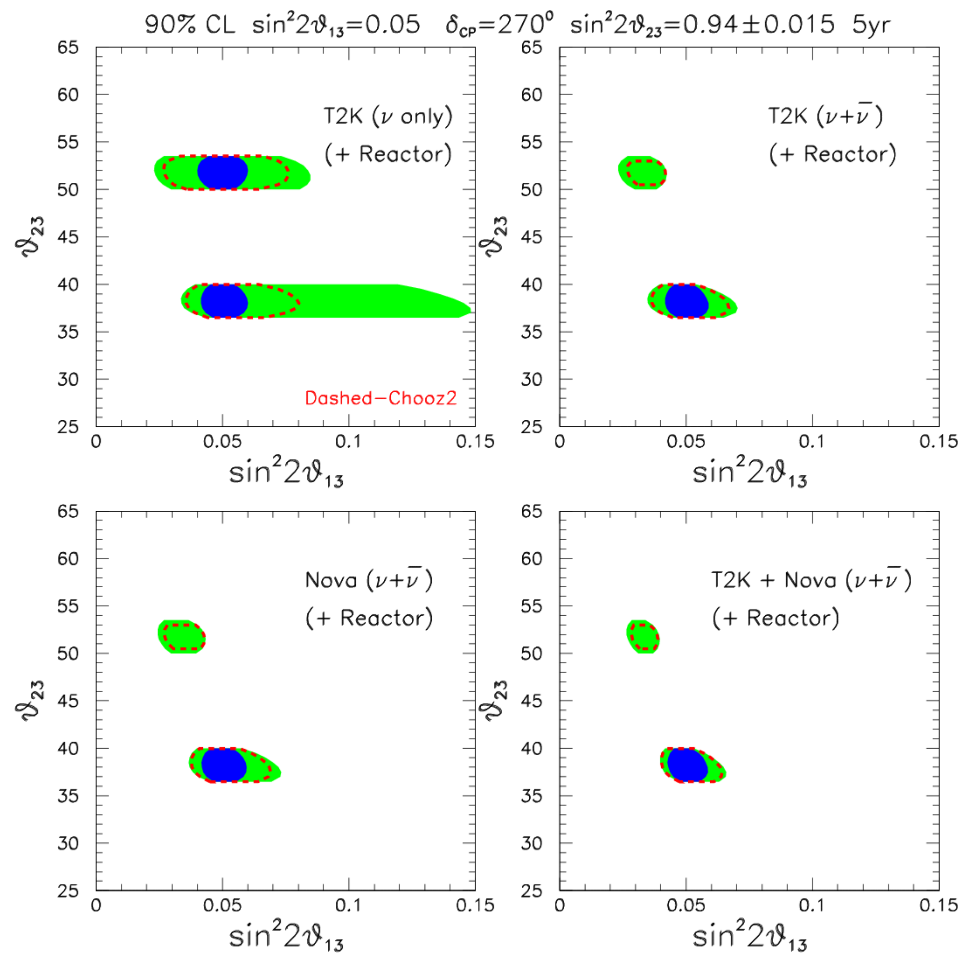
Determining the Mass Hierarchy

- Combining offaxis measurements with a medium reactor measurement can resolve the θ_{23} degeneracy
  - Reason is that degenerate solutions would cause large changes in offaxis ν and $\bar{\nu}$ rates.
  - To do this, θ_{23} must be known with sufficient accuracy
- Double Chooz accuracy is not sufficient to resolve the degeneracy at these levels.



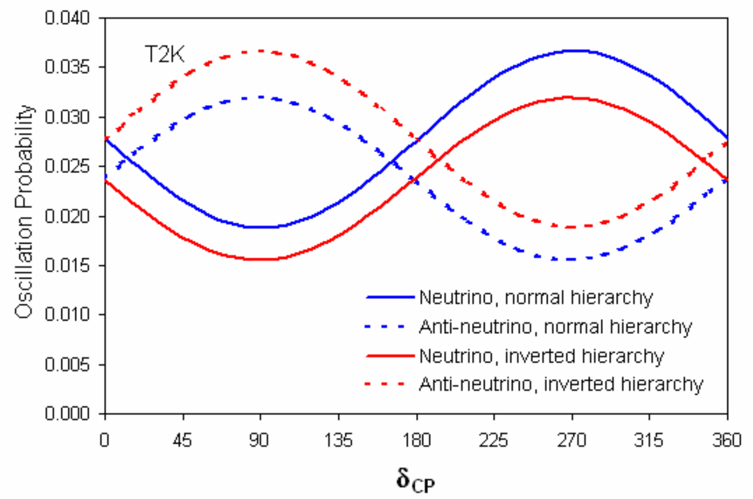
Green: Offaxis exp. Only

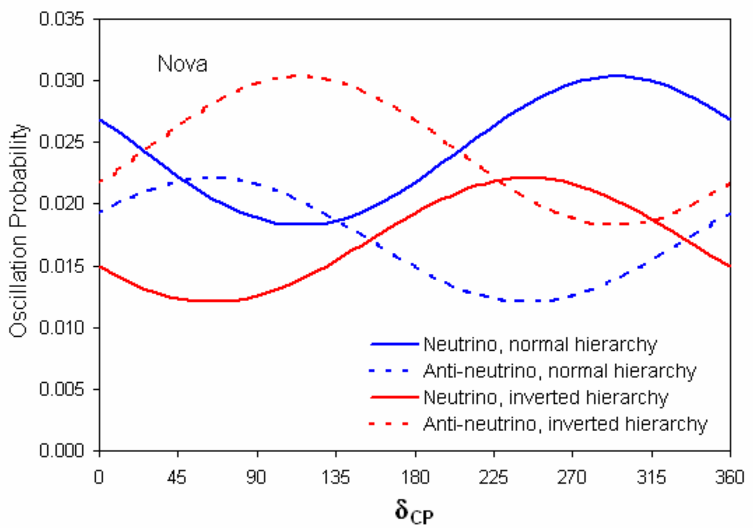
Blue: Combined Reactor plus Offaxis



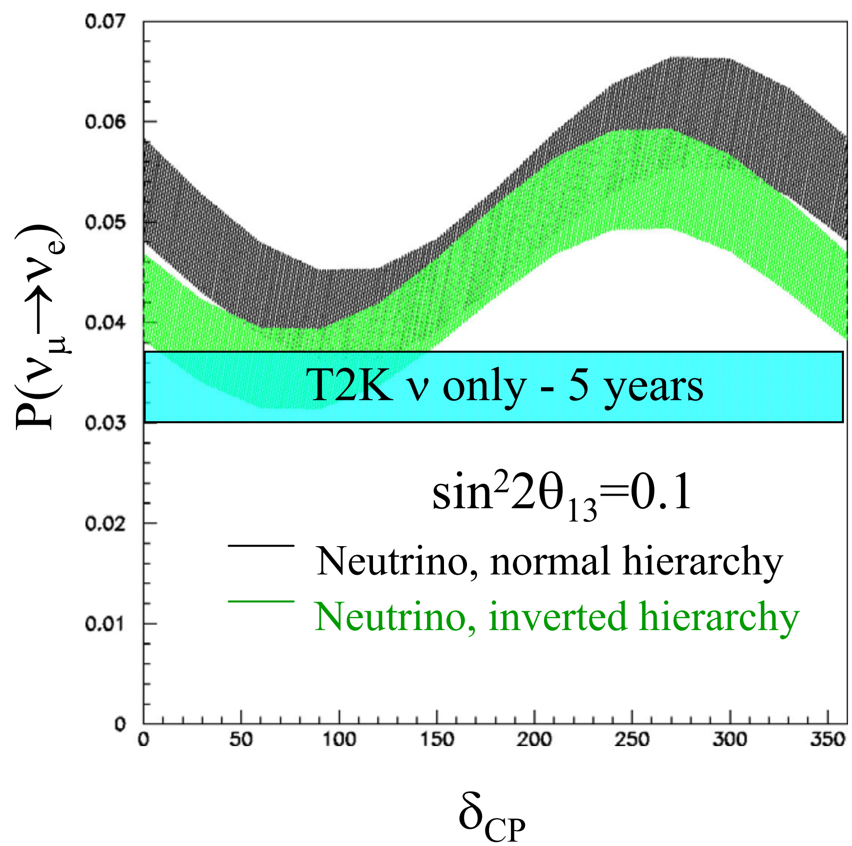
Early Constraints on δ_{CP} and the Mass Hierarchy

- Oscillation probability vs δ_{CP} for offaxis exp ($\Delta m^2 = 2.5 \times 10^{-3}$ eV^2 , $\sin^2 2\theta_{13} = 0.05$)

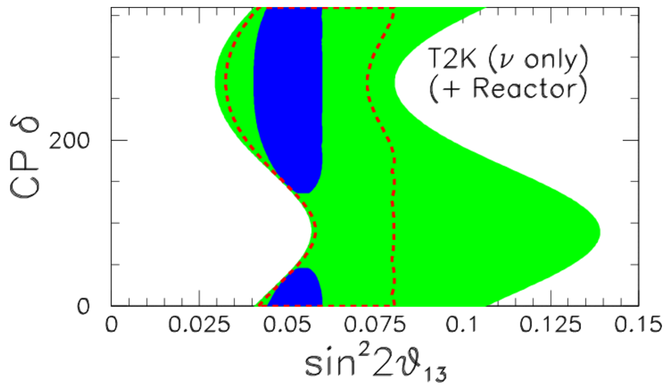




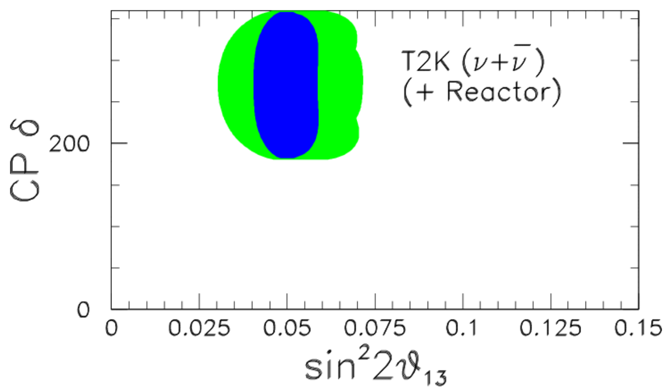
- Medium reactor ($\delta(\sin^2 2\theta_{13}) = \pm 0.01$) measurement constrains the offaxis oscillation probability
  $\Rightarrow$ Comparing to offaxis observation then can limit δ_{CP} and the mass hierarchy



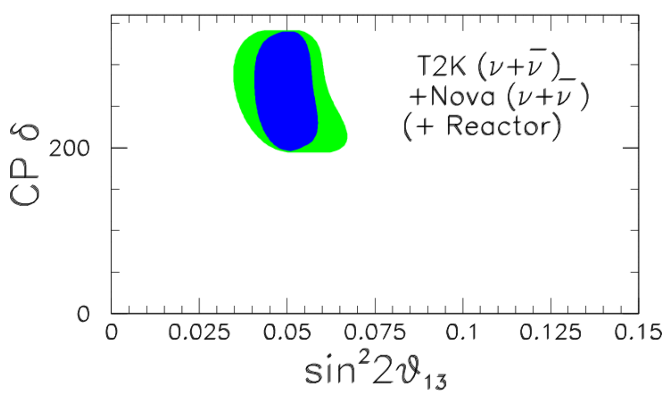
And Maybe We Will Get Lucky!



- For δ_{CP} = 270º the reactor measurement eliminates some of the range in CP phase when combined with off-axis ν only running.



- Off-axis anti-neutrino running resolves the CP problem on its own, after an additional 3 to 5 years.



- Combining all data sets, the best precision on $\sin^2 2\theta_{13}$ comes from the reactor experiment.

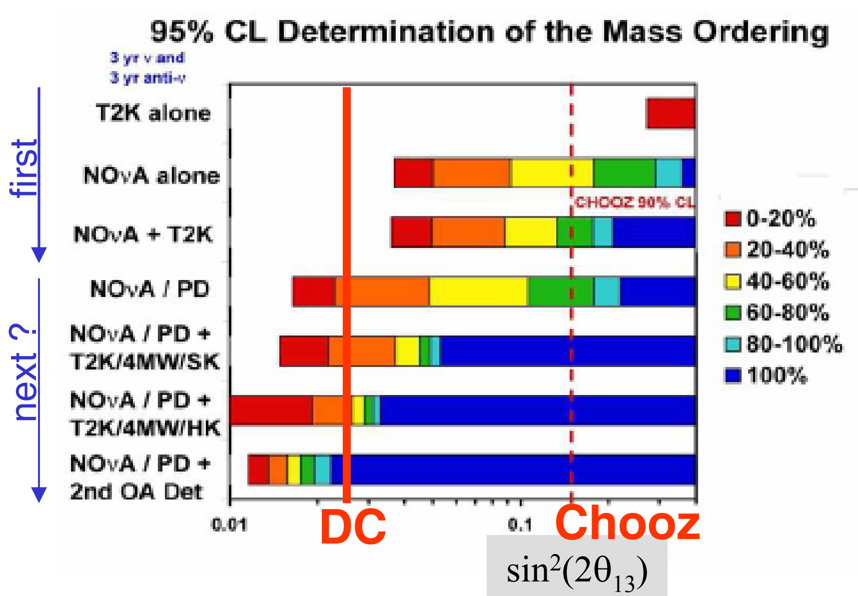
Green: Offaxis exp. Only
Blue: Combined Medium Reactor plus Offaxis
Red: Combined Small Reactor plus Offaxis

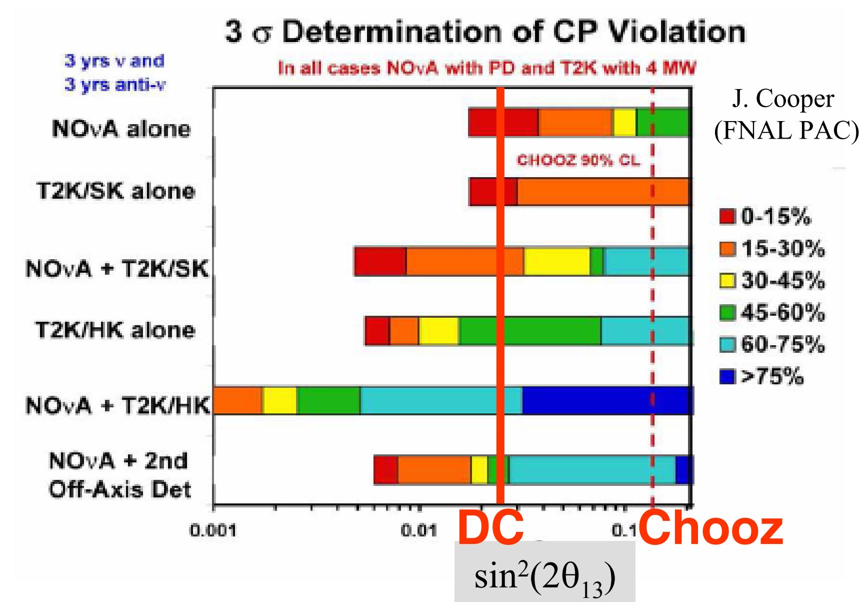
Double Chooz in Context with Future Long-Baseline Accelerator Experiments

- Double Chooz can limit $\sin^2 2\theta_{13}$ to 0.02-0.03 as soon as year 2011

- If θ_{13} is below this range, first generation long-baseline accelerator experiments will not be able to address the mass hierarchy or CP-violation questions

  $\Rightarrow$ Will need intensity upgrades and/or larger detectors





Conclusions

- A reactor experiment is an unambiguous way to measure θ_{13}
  - θ_{13} is a important physics parameter
    - Needed to constrain the models of lepton mixing matrix
    - If very small, probably indicates a new symmetry
  - θ_{13} is key for planning future long-baseline experiments to measure CP violation and the mass hierarchy
    - If $\sin^2 2\theta_{13}$ is > ~0.03, T2K and Nova can make important measurements
    - If $\sin^2 2\theta_{13}$ is < ~0.01, need other techniques to access the physics (1^{st},2^{nd} max. measurements; Superbeam exps, Neutrino Factory….)
- Reactor measurements are important for sorting out the θ_{23} ambiguity (θ_{23} vs 90^0- θ_{23})
  - Again this is an important, fundamental physics parameter (like θ_{13})
  - May be important for CP violation and mass hierarchy measurements
- Reactor experiments are on the way and results will become available in the next several years.

Hallelujah !

Maybe it was the ν's !