

Overview of Reactor θ_{13} Experiments

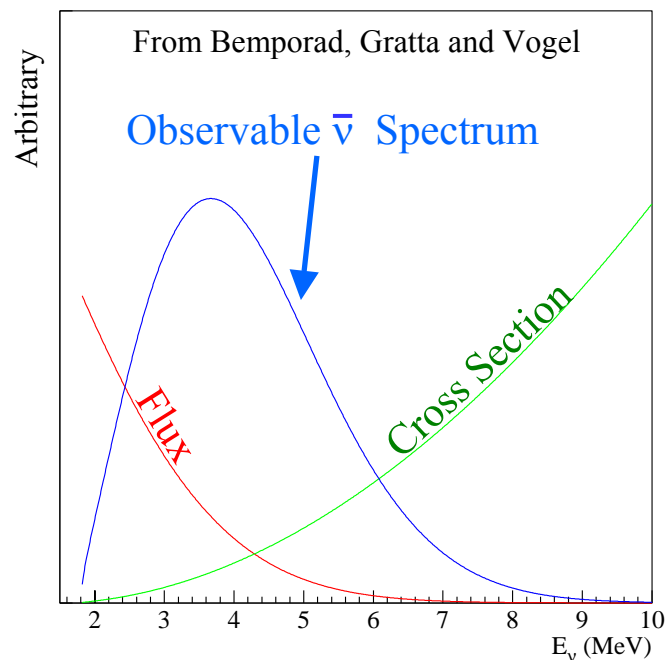
Michael Shaevitz, Columbia University

SAGENAP Meeting
April 16, 2004

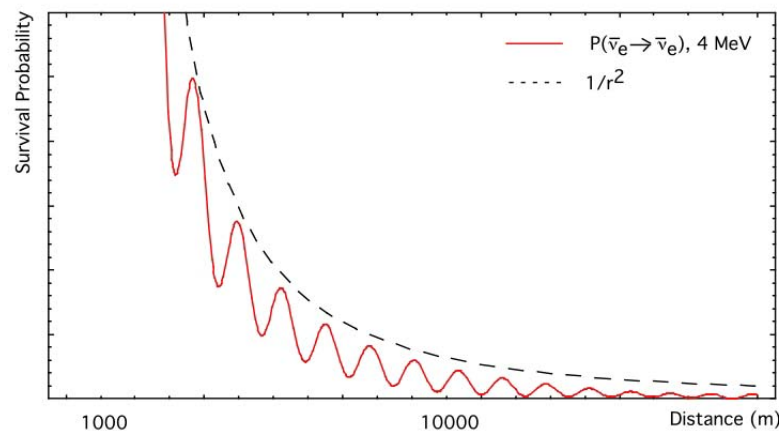
- Experimental challenges for reaching $\sin^2 2\theta_{13} \approx 0.01$
- Experiments and sites being considered
- Near term plans and requests

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

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



- 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.



↳ *n capture*

- Positron energy spectrum implies the neutrino spectrum

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

- In undoped scintillator the neutron will capture on hydrogen



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

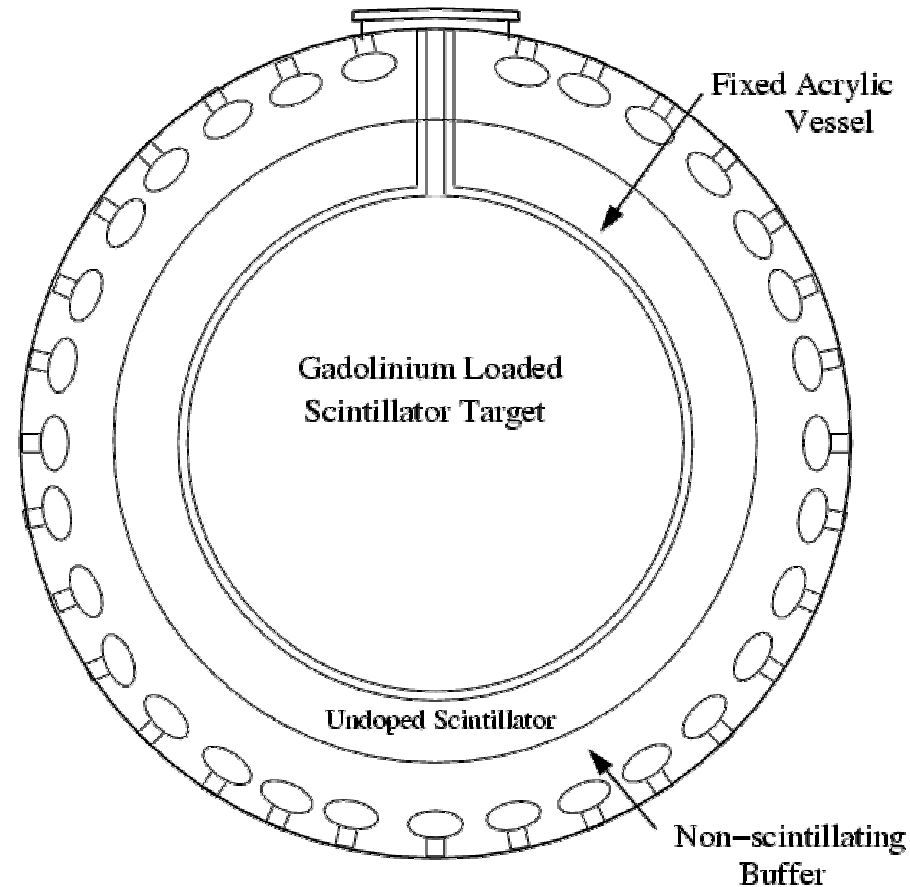


Going Beyond Previous Experiments

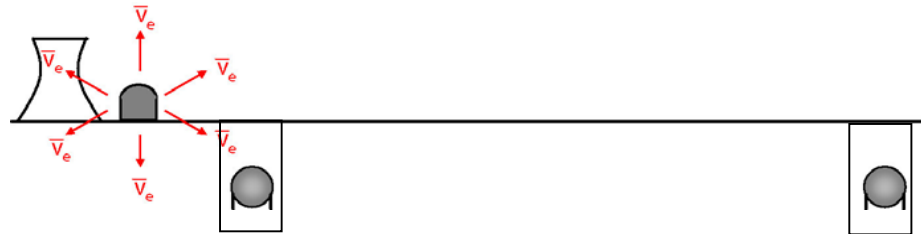
- Need higher statistics with longer baseline (~1.5km)
 - Use larger detectors \Rightarrow 25-50 ton units compared to previous 5-10 ton units
 - As before, use large power reactors
 - Probably multiple reactor sites
- Reduce dominant reactor flux spectrum uncertainty
 - Use two detectors at near and far locations
- Measure and/or reduce background rates
 - Go deeper 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 and energy scale
 - Make two detectors as identical as possible
 - Cross calibrate with sources and observed events
 - Move far detector to near site for cross calibration ?

Detector Design Issues

- Use extrapolation from previous experiments to a 25 - 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
 - Extensive veto with active and passive shielding
 - Extra gamma-catcher region for improved energy reconstruction
 - Calibration systems using sources, flashers, and lasers
- Improvements
 - Low activity PMTs
 - Improved veto/shielding system
 - Multiple buffer regions
 - Moveable detectors for cross calibrations



Scales of Experiments and Sensitivities



small: $\sin^2 2\theta_{13} \sim 0.04$

- Goal: fast experiment to explore region just below Chooz limit.
- Sensitivity through rate only
- Example: “Double-Chooz” experiment

medium: $\sin^2 2\theta_{13} \sim 0.01$

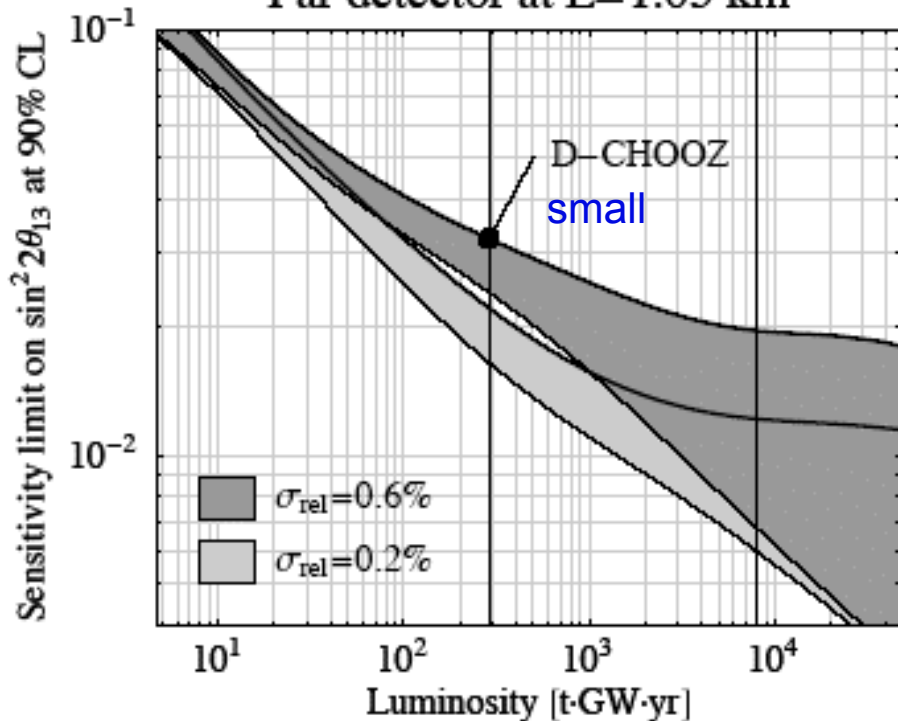
- Make a discovery of θ_{13} in region of interest for the next 10 year program
- Combinations with offaxis experiments (T2K and NuMI) give sensitivity to:
 - CP violation
 - The mass hierarchy
- Sensitivity mainly rate but also some energy shape

large: $\sin^2 2\theta_{13} \sim 0.002-0.004??$

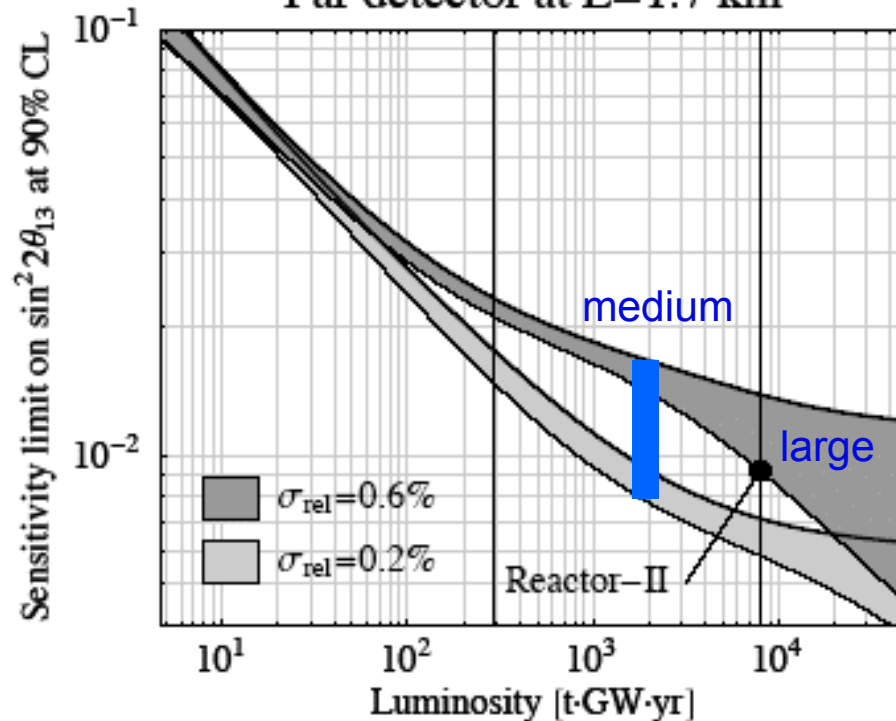
- Measurement capability comparable to second generation offaxis experiments
- Sensitivity mainly through energy shape distortions

Sensitivity Estimates

Far detector at $L=1.05$ km



Far detector at $L=1.7$ km



$$\Delta m^2 = 2 \times 10^{-3} \text{ eV}^2$$

Ref: hep-ph/0403068

Experimental Challenges for Two Detector Disappearance Exp's

- Backgrounds

Uncorrelated Backgrounds

- ambient radioactivity
- accidentals

Correlated Backgrounds

- cosmic rays induce neutrons in the surrounding rock and buffer region of the detector
- cosmogenic radioactive nuclei that emit delayed neutrons in the detector
 - eg. ^8He (T1/2=119ms)
 - ^9Li (T1/2=178ms)

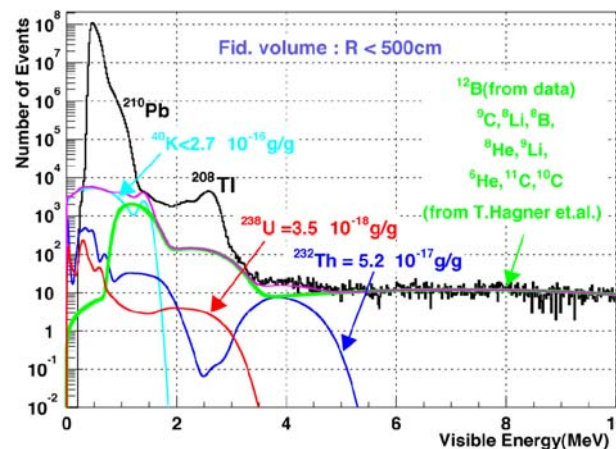
- Relative Detector Uncertainties

Acceptance

Energy scale and linearity

Deadtime

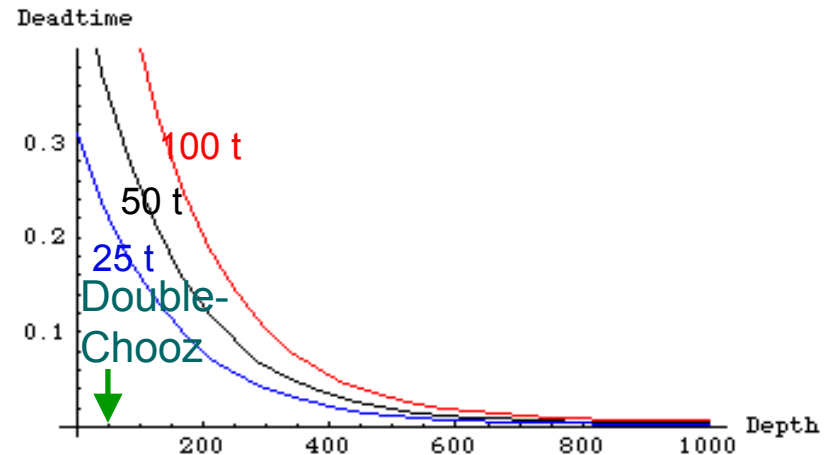
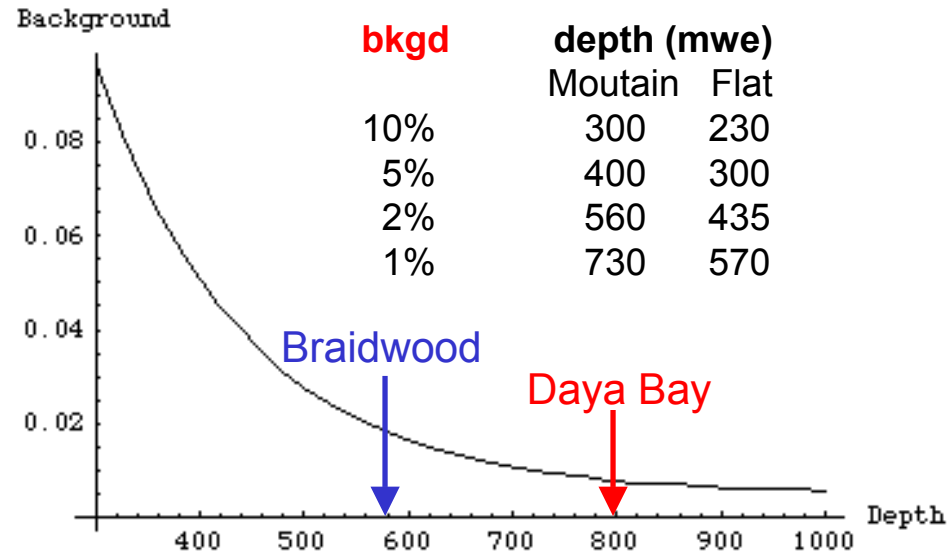
- Detector size (fiducial volume):
signal statistics and muon induced deadtime



Reduce Muon Induced Backgrounds with Depth

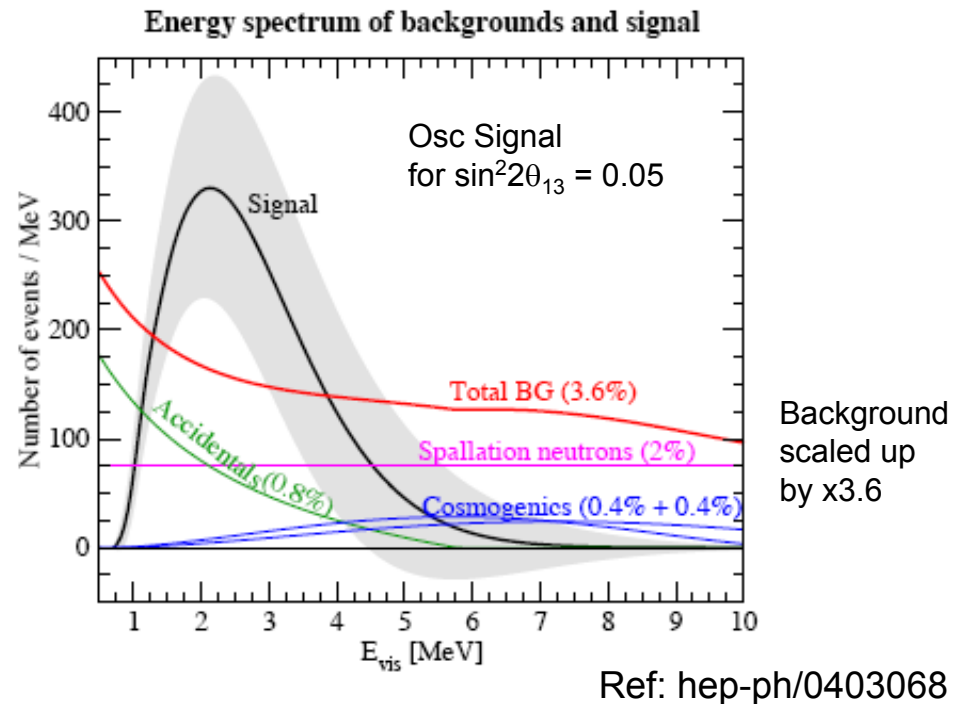
Go As Deep As You Can

- Correlated backgrounds are highly related to cosmic ray muon rates
 - Neutron production
 - Isotope production
- High muon rates can also introduce deadtime effects in comparing the near and far det.
 - Relative rate can be effected



Background Estimates and Mitigation

- Reduce with veto and shielding
 - Veto μ 's and shield neutrons (Big effective depth)
 - 98% veto (Chooz) \rightarrow 99.9% (x20)
- Uncorrelated background can be measured by swapping coincidence components
- Use energy shape to measure other background levels if shape is known



Background type	Spectral shape	BG/Reactor events	σ_{BG}
Backgrounds with known shape			
Spallation neutrons	Flat	0.4%	50%
Accidentals	Low energies	0.2%	50%
Cosmogenic ${}^9\text{Li}$	β -spectrum (end point 13.6 MeV)	0.2%	50%
Cosmogenic ${}^8\text{He}$	β -spectrum (end point 10.6 MeV)	0.2%	50%
Bin-to-bin correlated BG total:		1.0%	
Bin-to-bin uncorrelated background			
Unknown source	Flat	0.5%	50%

Worldwide Effort towards Realizing an Experiment

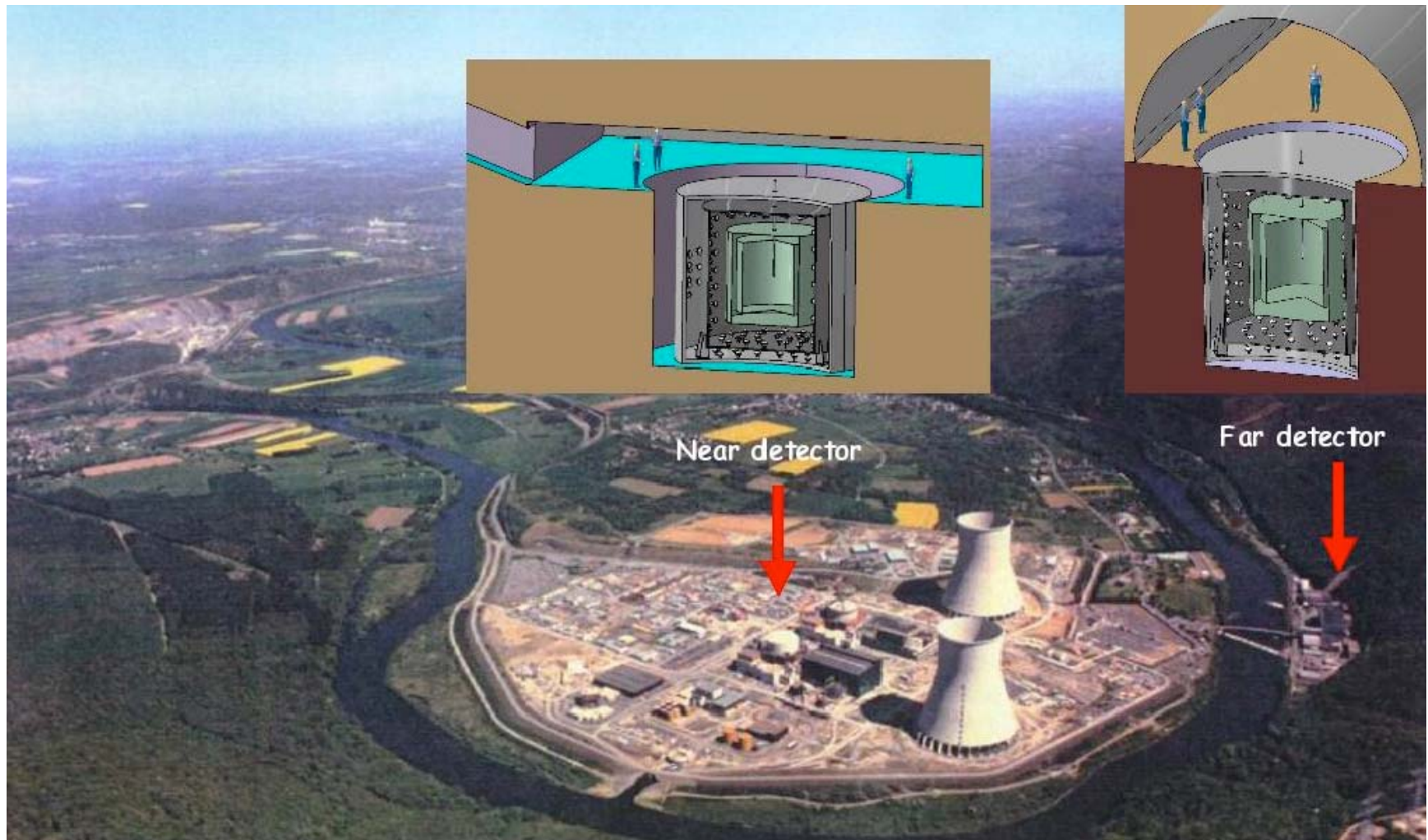
- Many possible high power multiple reactors sites with different characteristics
 - Flat sites with shaft access allow placement flexibility, surface transportation and better shielding per depth
 - Proximity to hills allow excavation of tunnels with horizontal access, detector positioning flexibility, and access to large depths for the far detector
 - Challenge in getting reactor operators to agree to an experiment
- Groups working towards realizing a reactor oscillation experiment(s):
 - Europe: PCC & CEA/Saclay & APC, MPI Heidelberg, TU Munchen, INFN/Bologna
 - USA: Alabama, Argonne, Berkeley, Caltech, Chicago, Columbia, Fermilab, Kansas State, LBNL, Louisiana State, Michigan, Stanford, Tennessee, UCLA, UWash
 - Japan: Tohoku Univ. , Tokyo M. Univ.
 - China: IHEP, Chinese Inst. Of Atomic Energy, Tsinghua, Hong Kong, Hong Kong Chinese
 - Also Russia (Kurchatov Inst.) and Brazil
- Workshops on Future Low-Energy Neutrino Experiments
 - Paris, France June 20-21, 2004
 - Niigata, Japan March 20-22, 2004
 - Munich, Germany October 9-11, 2003
 - Univ.of Alabama; April 30-May 2, 2003

List of Reactor Experiments

Experiment	Baseline (Near/Far)	Overburden (Near/Far) [access]	Detector Size (Near/Far)	Sensitivity $\sin^2 2\theta_{13}$ @ 90% CL	Comments
Double Chooz 2 x 4.2 GW	0.2 / 1.05 km	50 / 300 mwe [tunnel]	10 / 10 tons	0.03-0.04	Being reviewed Shallow near site and only 1km far
Braidwood (Illinois) 2 x 3.6 GW	0.2 / 1.8 km	450 / 450 mwe [shaft]	50 / 2x50 tons	0.01-0.02	Deep near detector
Diablo Canyon (California) 2 x 3.1 GW	0.4 / 1.7 km	150 / 700 mwe [tunnel]	50 / 2x50 tons	0.01-0.02	Reactor company issues?
Daya Bay (China) 4 x 2.9 GW	0.35/ 1.9 km	200 / >700 mwe [tunnel]	2x8.5/4x8.5 tons	0.01-0.02	Use multiple small detectors
Kashiwazaki (Japan) 7 x 3.5 GW	0.3 / 1.3 km	120 / 350 mwe [shaft]	2x8 / 8 tons	0.02-0.03	Big reactor and small detectors
Angra dos Reis (Brazil) 1 x 4.1 GW	0.3 / 1.4 km	60 / 600 mwe [tunnel]	25 / 25 tons	0.02-0.03	Single reactor

Double – CHOOZ Experiment (Ardennes, France)

Example of small reactor θ_{13} experiment



Double-CHOOZ Experimental Group

**I. Barbanov¹⁰, J.C. Barrière⁶, L. Bezroukov¹⁰, C. Buck¹¹, C. Cattadori^{8,9},
 M. Cribier^{1,3}, F. Dalnoki-Veress¹¹, N. Danilov², H. de Kerret^{1,12},
 F. Ardellier⁵, A. Di Vacri^{8,15}, A. Etenko¹³, C. Grieb¹⁴, M. Goeger¹⁴,
 C. Jeanney⁵, Y.S. Krilov², D. Kryn^{1,12}, W. Hampel¹¹, F.X. Hartmann¹¹,
 P. Huber¹⁴, J. Jochum⁷, T. Lachenmaier¹⁴, Th. Lasserre^{*,1,3}, C. Lendvai¹⁴,
 M. Lindner¹⁴, F. Marie⁴, G. Mention^{1,12}, A. Milsztajn³, J.P. Meyer³,
 D. Motta¹¹, L. Oberauer¹⁴, M. Obolensky^{1,12}, L. Pandola^{8,15}, W. Potzel¹⁴,
 S. Schönert¹¹, U. Schwan¹¹, T. Schwetz¹⁴, L. Scola⁶, M. Skorokhvatov¹³,
 S. Sukhotin^{12,13}, A. Letourneau⁴, D. Vignaud^{1,12}, F. von Feilitzsch¹⁴,
 W. Winter¹⁴, E. Yanovich¹⁰**

¹ APC, 11 place Marcelin Berthelot, 75005 Paris, France

² Department of Physical Chemistry, RAS, Moscow, Russia

³ DSM/DAPNIA/SPP, CEA/Saclay, 91191 Gif-sur-Yvette, France

⁴ DSM/DAPNIA/SPhN, CEA/Saclay, 91191 Gif-sur-Yvette, France

⁵ DSM/DAPNIA/SEDI, CEA/Saclay, 91191 Gif-sur-Yvette, France

⁶ DSM/DAPNIA/SIS, CEA/Saclay, 91191 Gif-sur-Yvette, France

⁷ Eberhard Karls Universität, Wilhelmstr. 772074 Tübingen, Germany

⁸ INFN, LGNS, I-67010 Assergi (AQ), Italy

⁹ INFN Milano, Via Celoria 16, 20133 Milano, Italy

¹⁰ INR, 7a, 60th October Anniversary prospect, Moscow 117312, Russia

¹¹ MPI für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg, Germany

¹² PCC Collège de France, 11 place Marcelin Berthelot, 75005 Paris, France

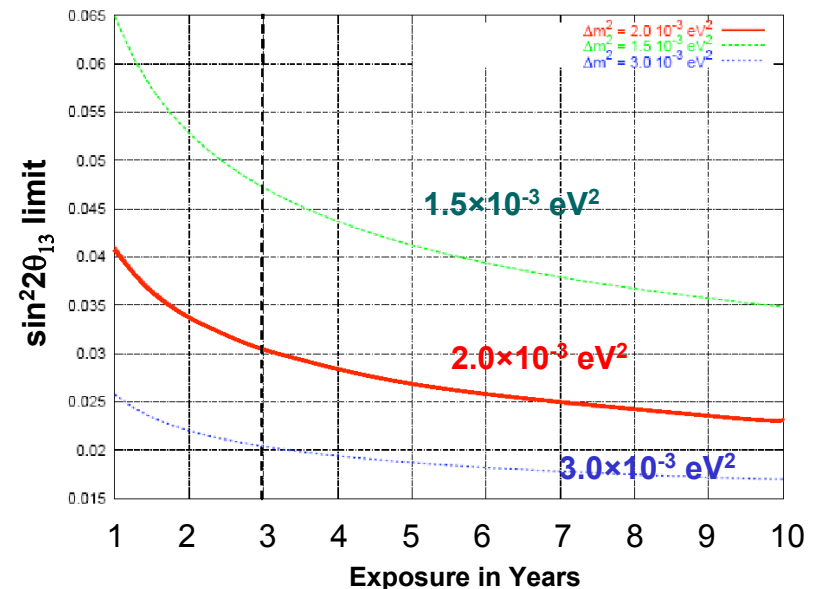
¹³ RRC Kurchatov Institute, 123182 Moscow, Kurchatov sq. 1, Russia

¹⁴ TU Muenchen. James-Franck-Str. 1, D-85747 Garching, Germany

Double – CHOOZ Experiment

- **Experimental Goals:**
 - Statistical error = 0.4%
 - Background error = 1%
 - Relative detector error = 0.6%
- **Advantages:**
 - Infrastructure exists for far site
 - Reactor company would build near site if approved
- **Disadvantages:**
 - Shallow near detector site (50 mwe)
 - Deadtime = 500 μs / muon \Rightarrow 50% Deadtime
 - Higher cosmogenic bkgnd.
 - Far baseline only 1km which limits sensitivity especially for low Δm^2

- **Cost estimate:**
 - Detectors: ~ \$7M
 - Civil Construction: ~ \$10M
- **Schedule:**
 - Now : Securing approvals from agencies and company
 - Feb. 05: If approved, complete design and put out bids
 - May 07: Complete far detector
 - Nov. 07: Complete near detector



Braidwood Experiment (Illinois)

- 2×3.6 GW reactors – 7.17 GW maximum power
- Flat: flexibility, equal overburden at near and far sites, surface transportation of detectors
- Favorable geology (dolomitic limestone): good for excavation, low radioactivity (order of magnitude lower U, Th than granite)
- Reactor company (Exelon) cooperative and supportive



Braidwood Experimental Group

Midwest θ_{13} Collaboration

ANL: Maury Goodman, David Reyna

Chicago: Erin Abouzaid, Kelby Anderson, Ed Blucher, Jim Pilcher, Matt Worcester

Columbia: Janet Conrad, Jon Link, Mike Shaevitz

FNAL: Larry Bartoszek, Dave Finley, Hans Jostlein, Chris Laughton, Ray Stefanski

Kansas: Tim Bolton, Noel Stanton

Oxford: Steve Biller, Nick Jelley

Pittsburgh: Donna Naples, Vittorio Paolone

Texas: Josh Klein

Braidwood Experiment

- **Experimental Goals:**
 - Statistical error = 0.15%
 - Background error = 0.4%
 - Relative detector error = 0.4%
- **Advantages:**
 - Shaft access
 - Flat overburden gives better shielding
 - Deep near site allows other reactor physics measurements
 - Surface transport of detectors for cross calibration
 - Favorable geology and low bkgnd
 - Keep vibrant neutrino program in US with opportunities for education and outreach
- **Disadvantages:**
 - Infrastructure costs high due to green field site

- **Cost estimate:**

Civil: ~ \$30M

Detectors: \$15M

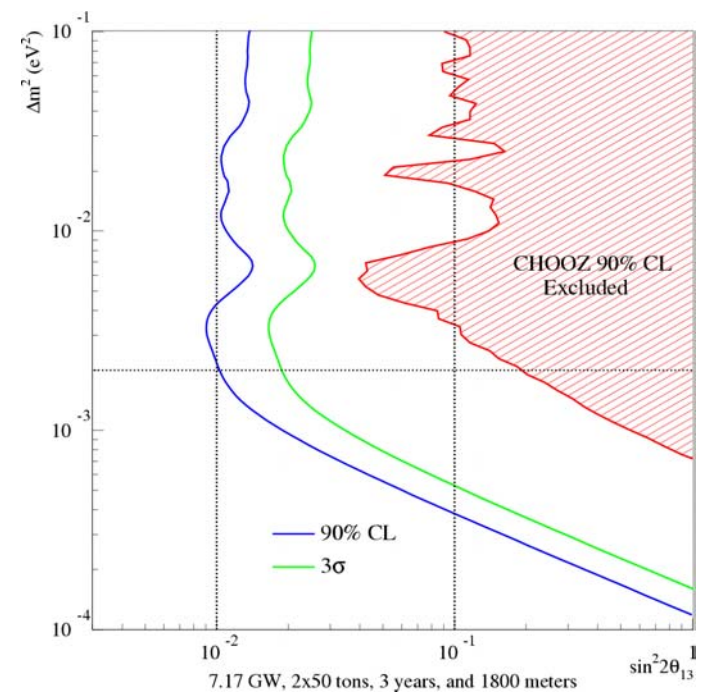
- **Schedule:**

2005: R&D and full proposal preparation

2006: Project approval

2007: Construction

2009: Start data collection



Daya Bay - Lingao, China



Power

11.6 GW_{th} (17.4 GW_{th} by 2010)

Overburden

Near 200-300 mwe

Far >700 mwe

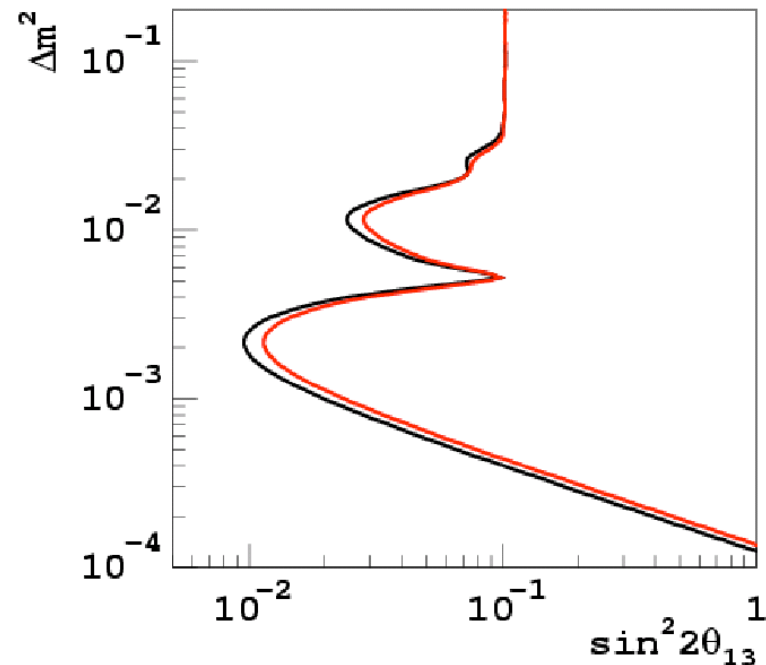


Daya Bay Experimental Group

- Collaborators in China:
 - Institute of High Energy Physics
 - China institute of atomic energy
 - Tsinghua University
 - Hong Kong University
 - Hong Kong Chinese University
- People who are involved:
 - K.B. Luk, Berkeley;**
 - B.L. Young, K. Whistnat, Iowa State;**
 - J. Peng, Urbana-Champaign;**
 - K. Lau, Houston**
- Collaboration on R&D
 - S. Freedman, K.B. Luk, R. Kadel, K. Heeger**
 - Berkeley
 - R. McKeown**
 - Caltech

Daya Bay Experiment

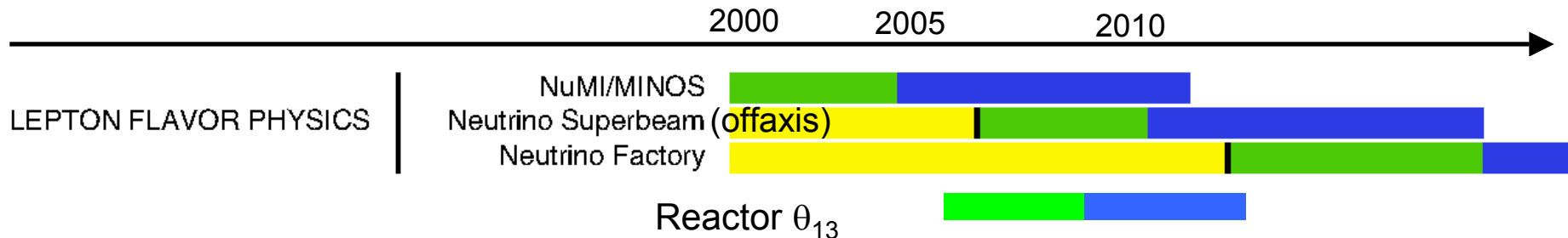
- Experimental Goals:
 - Statistical error = 0.2%
 - Background error = 0.3%
 - Relative detector error = 0.4%
- Advantages:
 - Horizontal access tunnel approach
 - Large overburden reduces bkgnd
 - Flexibility to change baseline
 - Easy to service detector
 - Cross calibration by moving detectors to near site
 - Multiple small detectors
- Disadvantages:
 - Chinese politics and approval system
 - Multiple small detectors
- Cost estimate:
 - ~ \$25M
- Schedule:
 - 2005: R&D, engineering design, and secure funding
 - 2006-2007: Construction
 - 2008: Start data collection



Cost and Schedule for Medium Reactor

- **Cost: Moderate Scale Project (< \$50M)**
 - Detector scale of MiniBooNE ~\$8M / detector
 - Civil construction – Tunnels or Shafts and Halls ~\$20 - 30M
 - Need to identify site, do engineering and develop proposal
 - R&D needed especially for Gd-liq.scint. and moveable detector
- **Schedule:**
 - After site selection, approval process 1? year
 - Construction ~2 years
 - Start in 2008/2009?

The Particle Physics Roadmap (in the US)



Summary

- An optimized “medium scale” two detector reactor oscillation experiment can precisely measure or constrain $\sin^2 2\theta_{13}$ at the 0.01 level.
- The results from a reactor experiment on θ_{13} are important for defining an oscillation program
- Reactor measurements are competitive and complementary with long-baseline appearance experiments and can be combined to give better sensitivity to the mass hierarchy and CP violation
- In the near term, a “medium scale” reactor oscillation program could go ahead rapidly if timely support is made available.

What we need from SAGENAP?

- An endorsement of the physics goals of a reactor oscillation experiment

and

- Support for strong US participation and leadership in a reactor neutrino program.