Reactor Experiments to measure ?$_{13}$
Double CHOOZ

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3 Flavor Transition Probabilities

(in vacuum, on atmospheric osc. scale)

LBL neutrino beams

$$\begin{aligned} P(\nu_\mu \to \nu_e) \simeq\ & \sin^2 2\theta_{13}\ \sin^2\theta_{23}\sin^2\Delta \\ \mp\ & \alpha\ \sin 2\theta_{13}\ \sin\delta_{\rm CP}\ \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin^3\Delta \\ +\ & \alpha\ \sin 2\theta_{13}\ \cos\delta_{\rm CP}\ \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\cos\Delta\sin^2\Delta \\ +\ & \alpha^2\ \cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2\Delta \end{aligned}$$

(anti-v)

?$_{13}$, d$_{CP}$, mass hierarchy
but degeneracies & correlations!

Reactor experiments

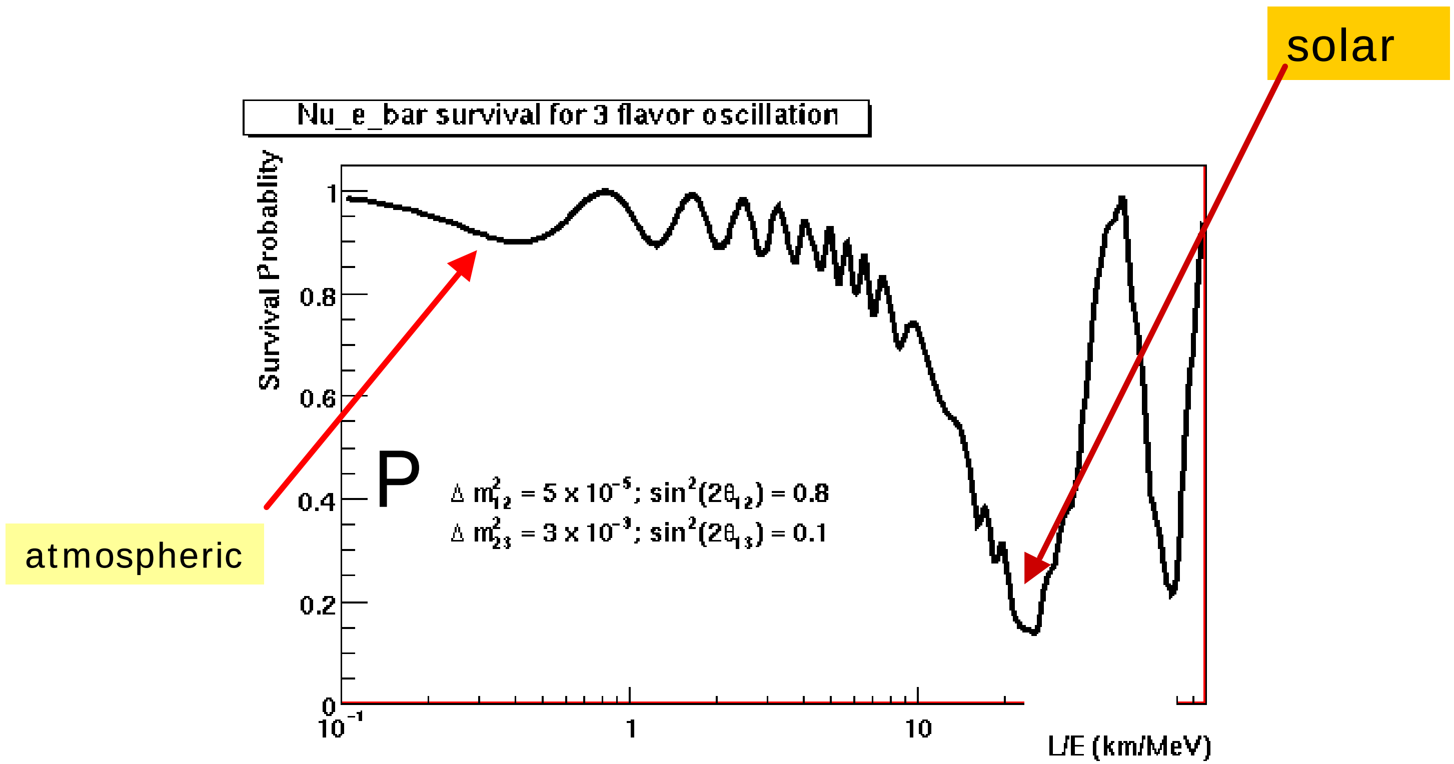
$$1 - P_{\bar{e}\bar{e}} \simeq \sin^2 2\theta_{13}\ \sin^2\Delta\ + \alpha^2\Delta^2\ \cos^4\theta_{13}\ \sin^2 2\theta_{12}$$

clean measurement of ?$_{13}$

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

from Huber, Lindner, Rolinec, Schwetz, Winter hep-ph/0403068

Anti Neutrino Survival Probability

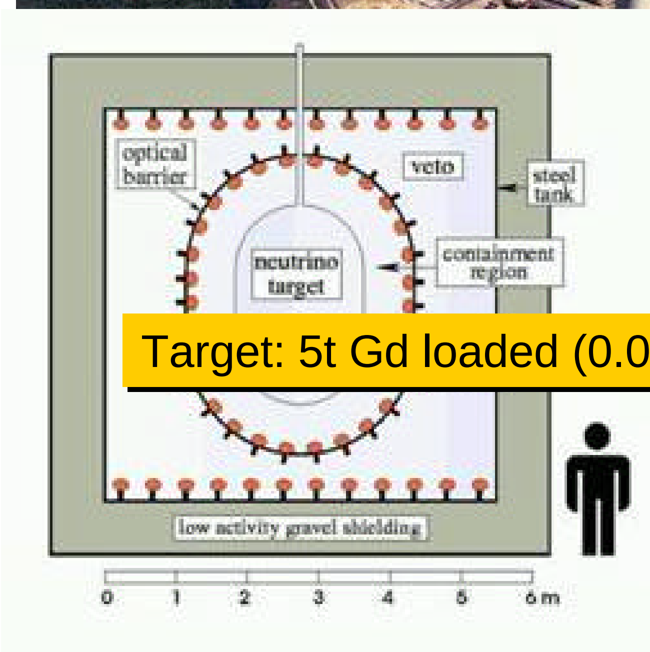


L/E(km/MeV)

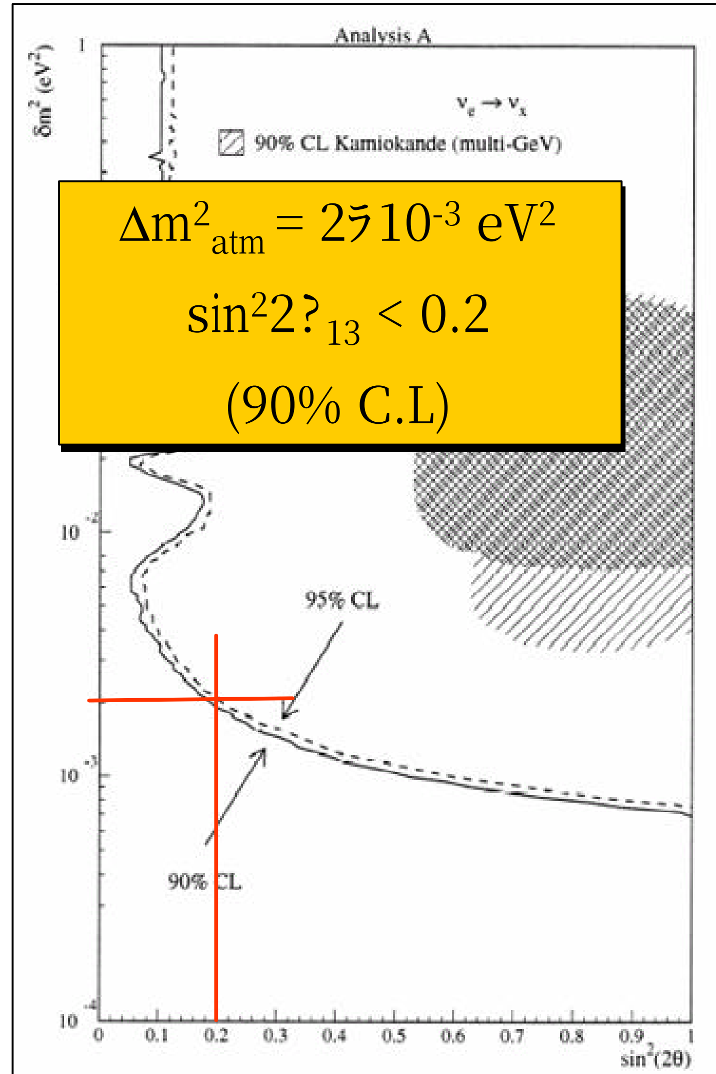
Best Limit on ?$_{13}$: CHOOZ

$\overline{n}_e \rightarrow \overline{n}_e$ (disappearance experiment)

P_{th} = 8.5 GW_{th}, L = 1,1 km, M = 5t
overburden: 300 mwe



Target: 5t Gd loaded (0.09%) Scintillator

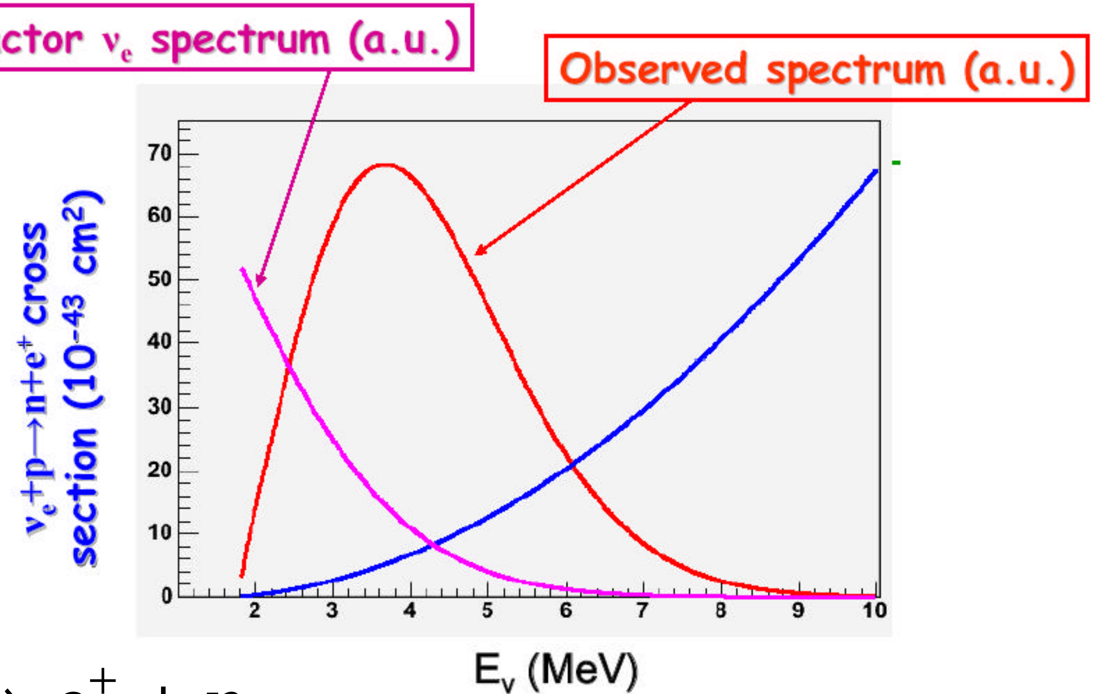


Δm^2_{atm} = 2?10^{-3} eV^2

sin^{2}2?$_{13}$ < 0.2

(90% C.L)

Reactor Anti-ν Spectrum and Detection

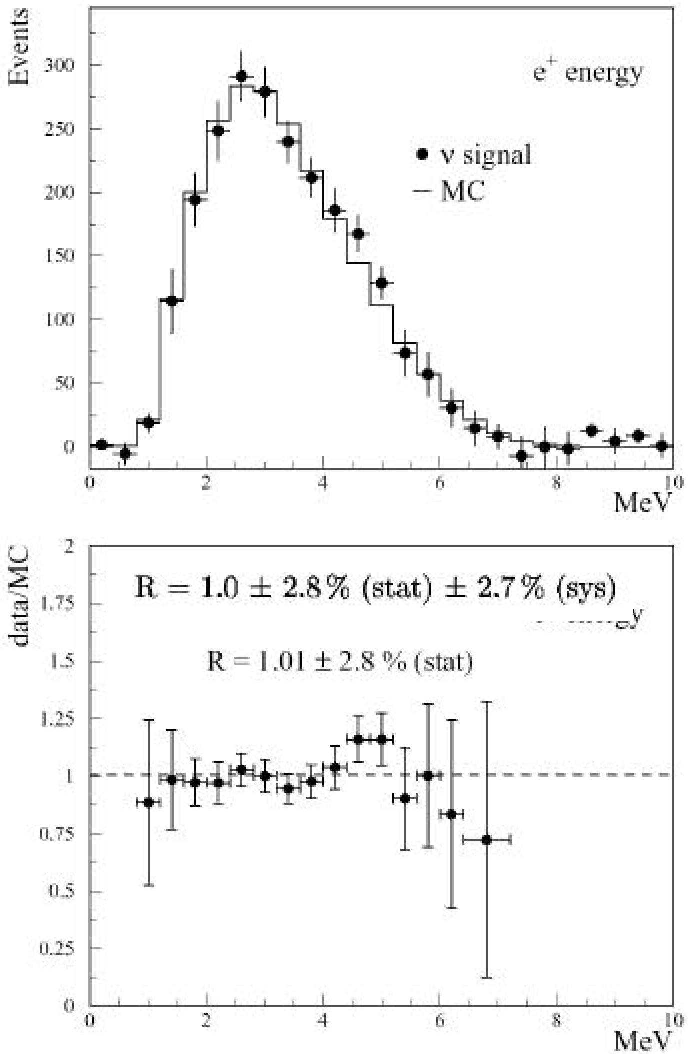


$$\bar{\nu}_e + p \rightarrow e^+ + n$$

prompt signal
E_ν – 0.77MeV

delayed signal:
n-capture on Gd
8MeV photons

CHOOZ



Systematic error (major sources):

- reactor uncertainties (2%)
- detector efficiency (1.5%)
- number of protons in liquid (0.8%)

How to improve the sensitivity?

The problem: Reactor exp. = **Disappearance** exp.

- compare total flux (and spectrum) with the no- oscillation hypothesis

- one depends on **systematic uncertainties**, like:

  absolute source strength,

  cross section,

  detection efficiency,

  fuel development over time...

The basic idea:

Use **2 identical detectors**

- oscillation frequency basically known

$$\Delta m^2 = (2.0 - 2.5)\, 10^{-3}\ \mathrm{eV}^2$$

- choose the right distance for the **signal** with the **far detector**

osc.length *L* ⇒ $L/2 \sim 1.0$ km - 2.0 km

- **monitor** the reactor with the **close detector (100m)**

(cancels also uncertainties like cross section, efficiencies etc.)

What you need:

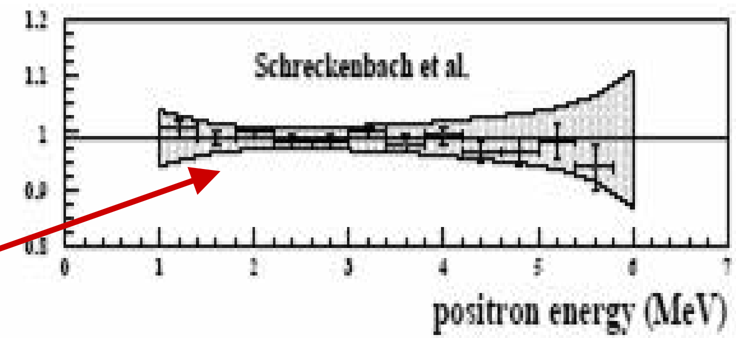
- Statistics — N(far) ~ 5 10^4
- energy uncertainty — s(E) < 1%
- normalization uncertainty — s_{rel} < 1%

s_{rel} { number of target protons; efficiencies (positron, neutron)

excellent calibrations required...

Additional Uncertainties

- **shape (~ 2%)**



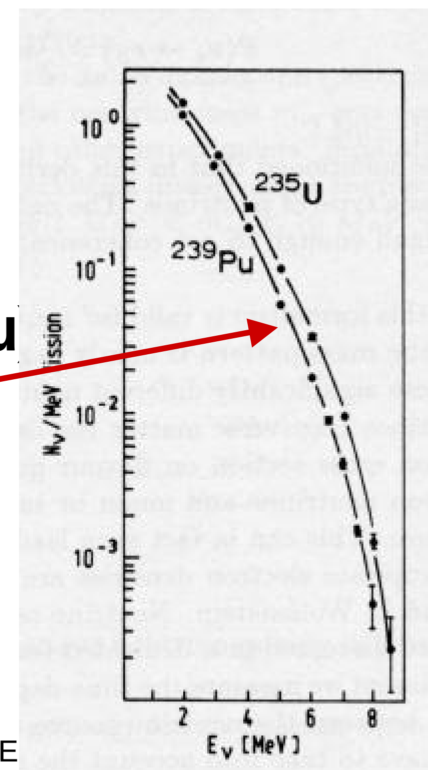
Bugey; comparison with spectrum deconvoluted from exp. determined beta spetra

- **cross section (~ 1.9%)**

should cancel !

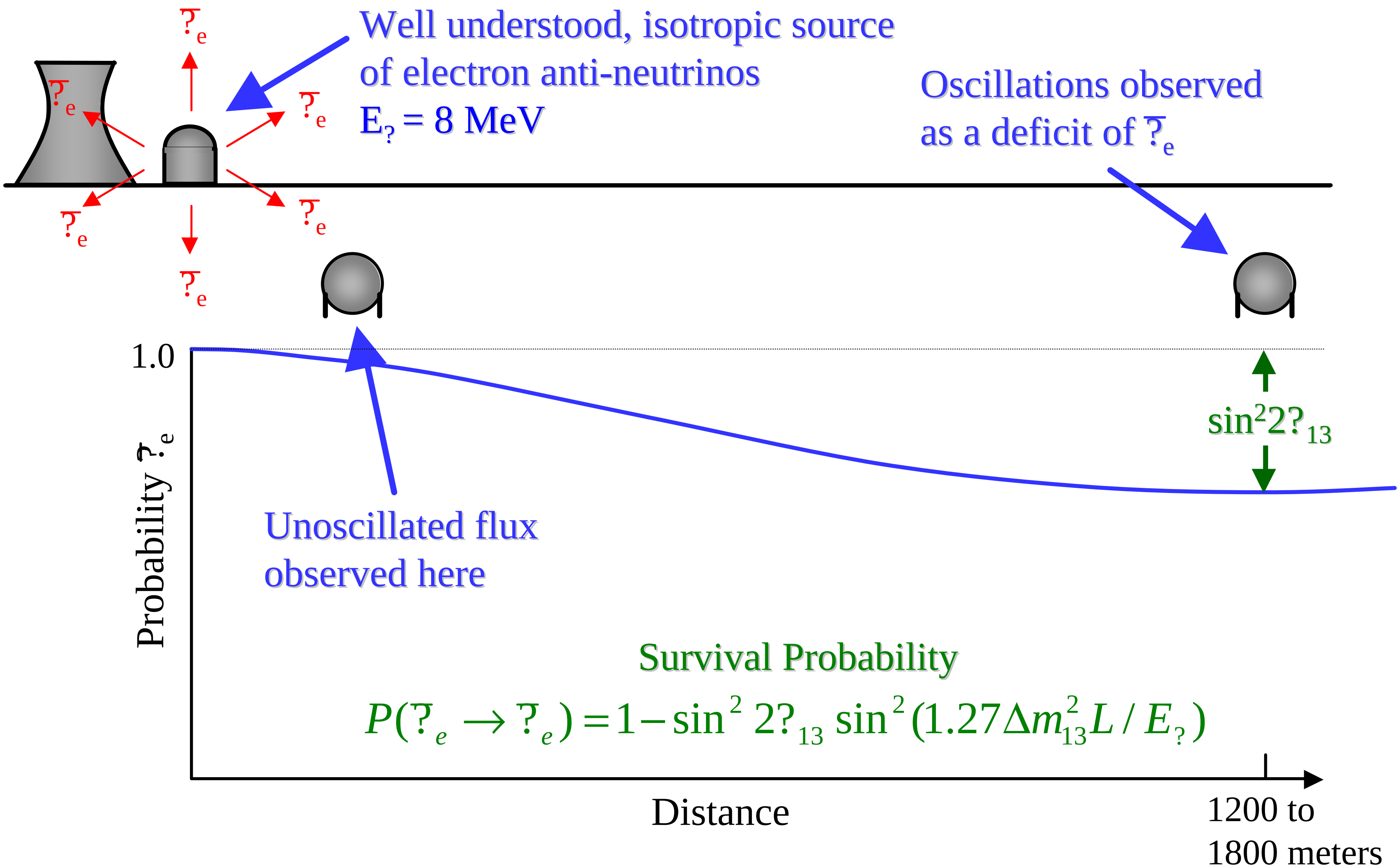
- **fuel composition (^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu)**

Feilitzsch, Schreckenbach;
used for analysis of the G sgen experiment



should cancel !

Basic Principle



Towards a Reactor experiment

WHITE PAPER REPORT on
Using Nuclear Reactors to Search for a value of θ_{13}
January 2004

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November 2, 2004

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This document is available at
http://www.hep.anl.gov/minos/reactor13/white.html
or by writing:
Maury Goodman
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Argonne Illinois 60439

Sites under discussion

Proposed Sites

Site (proposal)	Power (GW)	Baseline Near/Far (m)	Detector Near/Far(t)	Overburden Near/Far (MWE)
Angra dos Reis (Brazil)	4.1	300/1300	25/25	60/600
Braidwood (US)	6.5	200/1500	25/50	250/250
Chooz-II (France)	8.4	150/1050	10/10	50/300
Daya Bay (China)	11.6	300/1500	25/50	200/1000
~~Diablo Canyon (US)~~	~~6.4~~	~~400/1800~~	~~25/50~~	~~100/700~~
Kashiwazaki (Japan)	24.3	300/1300	8.5/8.5	140/600
Krasnoyarsk (Russia)	3.2	115/1000	46/46	600/600

Scales of Experiments and Sensitivities

small: $\sin^2 2\theta_{13}$~0.03

- Goal: fast experiment to explore region x3-4 below the Chooz limit.
- Sensitivity through rate mainly
- Example: "Double-Chooz" experiment (300 GW-ton-yrs)

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

- Make a discovery of θ_{13} in region of interest for the next 10-20 year program
- Sensitivity enough to augment the physics of offaxis measurements
- Sensitivity both to rate and energy shape
- Example: Braidwood, Daya Bay (3000 GW-ton-yrs)

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

- Measurement capability comparable to second generation offaxis experiments
- Sensitivity mainly through energy shape distortions
- MiniBooNE/Kamland sized detector (20,000 GW-ton-yrs)

A personal point of view (M. Goodman, CH agrees)

Reference	$\sin\theta_{13}$	$\sin^2 2\theta_{13}$
SO(10)		
Goh, Mohapatra, Ng [40]	0.18	0.13
Orbifold SO(10)		
Asaka, Buchmüller, Covi [41]	0.1	0.04
SO(10) + flavor symmetry		
Babu, Pati, Wilczek [42]	$5.5 \cdot 10^{-4}$	$1.2 \cdot 10^{-6}$
Blazek, Raby, Tobe [43]	0.05	0.01
Kitano, Mimura [44]	0.22	0.18
Albright, Barr [45]	0.014	$7.8 \cdot 10^{-4}$
Maekawa [46]	0.22	0.18
Ross, Velasco-Sevilla [47]	0.07	0.02
Chen, Mahanthappa [48]	0.15	0.09
Raby [49]	0.1	0.04
SO(10) + texture		
Buchmüller, Wyler [50]	0.1	0.04
Bando, Obara [51]	0.01 .. 0.06	$4 \cdot 10^{-4}$ .. 0.01
Flavor symmetries		
Grimus, Lavoura [52, 53]	0	0
Grimus, Lavoura [52]	0.3	0.3
Babu, Ma, Valle [54]	0.14	0.08
Kuchimanchi, Mohapatra [55]	0.08 .. 0.4	0.03 .. 0.5
Ohlsson, Seidl [56]	0.07 .. 0.14	0.02 .. 0.08
King, Ross [57]	0.2	0.15
Textures		
Honda, Kaneko, Tanimoto [58]	0.08 .. 0.20	0.03 .. 0.15
Lebed, Martin [59]	0.1	0.04
Bando, Kaneko, Obara, Tanimoto [60]	0.01 .. 0.05	$4 \cdot 10^{-4}$ .. 0.01
Ibarra, Ross [61]	0.2	0.15
3×2 see-saw		
Appelquist, Piai, Shrock [62, 63]	0.05	0.01
Frampton, Glashow, Yanagida [64]	0.1	0.04
Mei, Xing [65] (normal hierarchy)	0.07	0.02
(inverted hierarchy)	> 0.006	$> 1.6 \cdot 10^{-4}$
Anarchy		
de Gouvêa, Murayama [66]	> 0.1	> 0.04
Renormalization group enhancement		
Mohapatra, Parida, Rajasekaran [67]	0.08 .. 0.1	0.03 .. 0.04

Table 1: Incomplete selection of predictions for θ_{13}. The numbers should considered as order of magnitude statements.

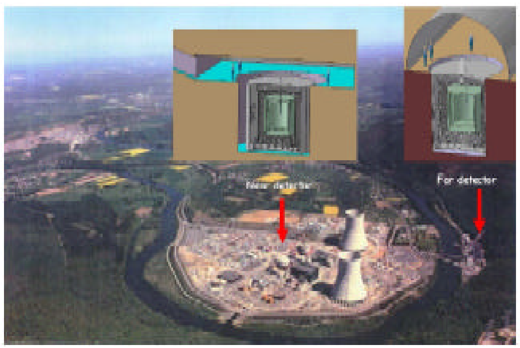
- θ_{13} is in reach
- A generally accepted observation of non-zero θ_{13} will take :
  - 2 experiments *or*
  - 2 techniques (rate & shape)
- Double-CHOOZ is a great opportunity
- We need one & probably more than one experiment beyond Double-CHOOZ

Double CHOOZ

arXiv:hep-ex/0405032 v1 14 May 2004

Letter of Intent for Double-CHOOZ:

a Search for the Mixing Angle θ_{13}



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May 2004

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US proposal to participate in Double-CHOOZ

Proposal for U.S. participation in Double-CHOOZ: A New θ_{13} Experiment at the Chooz Reactor

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October 14, 2004

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Abstract

It has recently been widely recognized that a reactor anti-neutrino disappearance experiment with two or more detectors is one of the most cost-effective ways to extend our reach in sensitivity for the neutrino mixing angle θ_{13} without ambiguities from CP violation and matter effects[1]. The physics capabilities of a new reactor experiment together with superbeams and neutrino factories have also been studied [2, 3] but these latter are considered by many to be more ambitious projects due to their higher costs, and hence to be farther in the future.

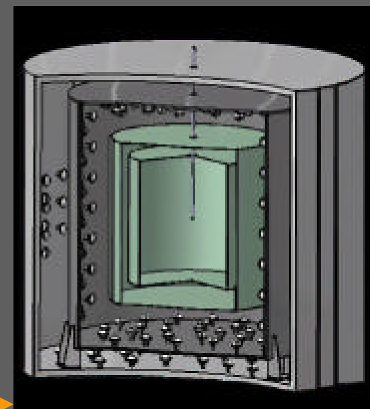
We propose to contribute to an international collaboration to modify the existing neutrino physics facility at the Chooz-B Nuclear Power Station in France. The experiment, known as Double-CHOOZ, is expected to reach a sensitivity of $\sin^2 2\theta_{13} > 0.03$ over a three year run, 2008-2011. This would cover roughly 85% of the remaining allowed region. The costs and time to first results for this critical parameter can be minimized since our project takes advantage of an existing infrastructure.

to DOE
(particle physics)

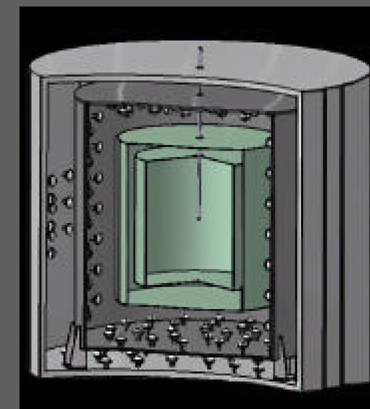
Double CHOOZ Concept

CHOOZ
8.4 GW

$\overline{n}_{e}$



$\overline{n}_{e,m,t}$



D_1 = 100 - 200m

D_2 = 1050m

Near detector
5-30 t
> 50 mwe

Far detector
5-30 t
> 200 mwe

2 IDENTICAL detectors (CHOOZ, KamLAND, BOREXINO/CTF type)

Minimalize uncertainties of reactorflux & spectrum
(2 % in CHOOZ)
Cancelation of uncertainty in cross section (1.9 %)
Challenge: relative normalisiation between detectors < 1% !

Neutrino Energy Spectra

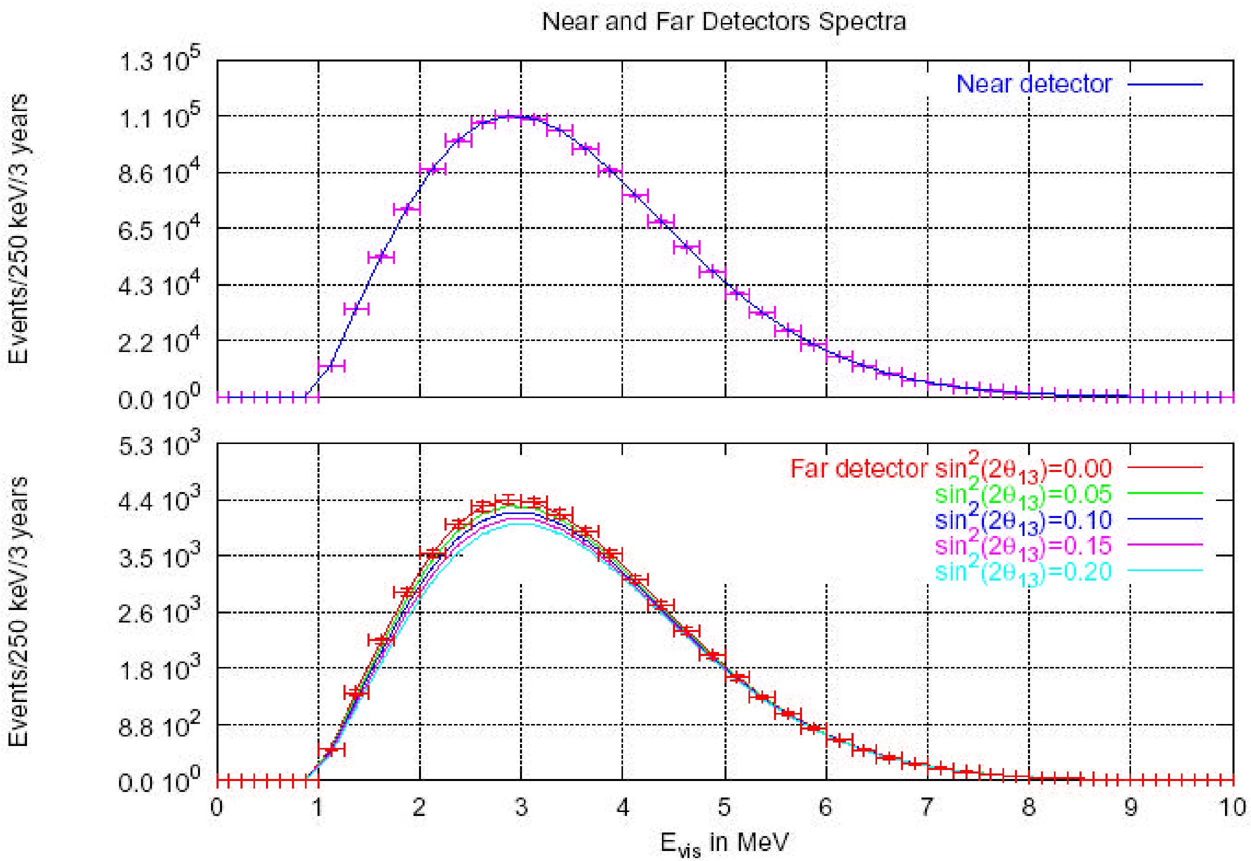
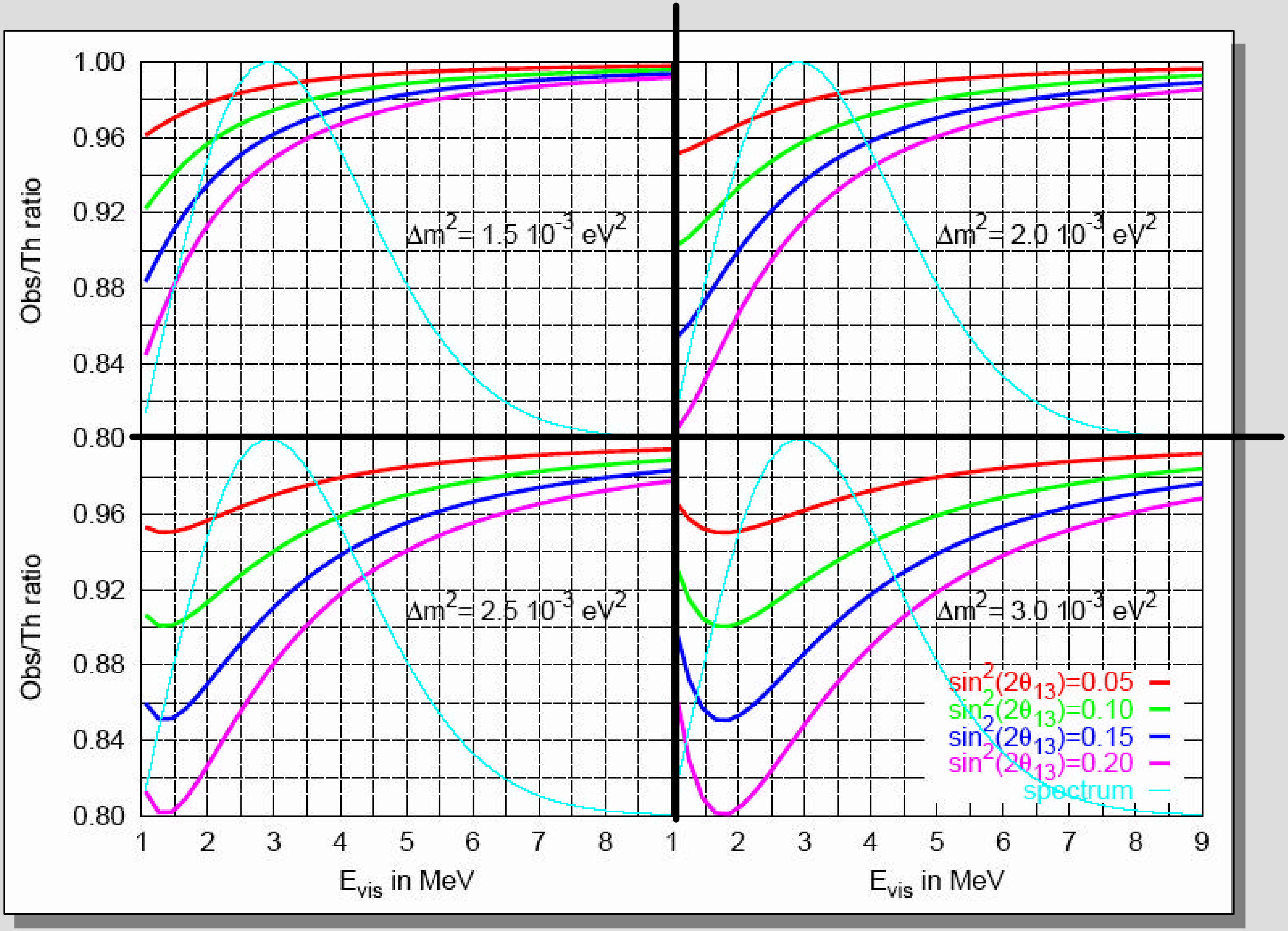


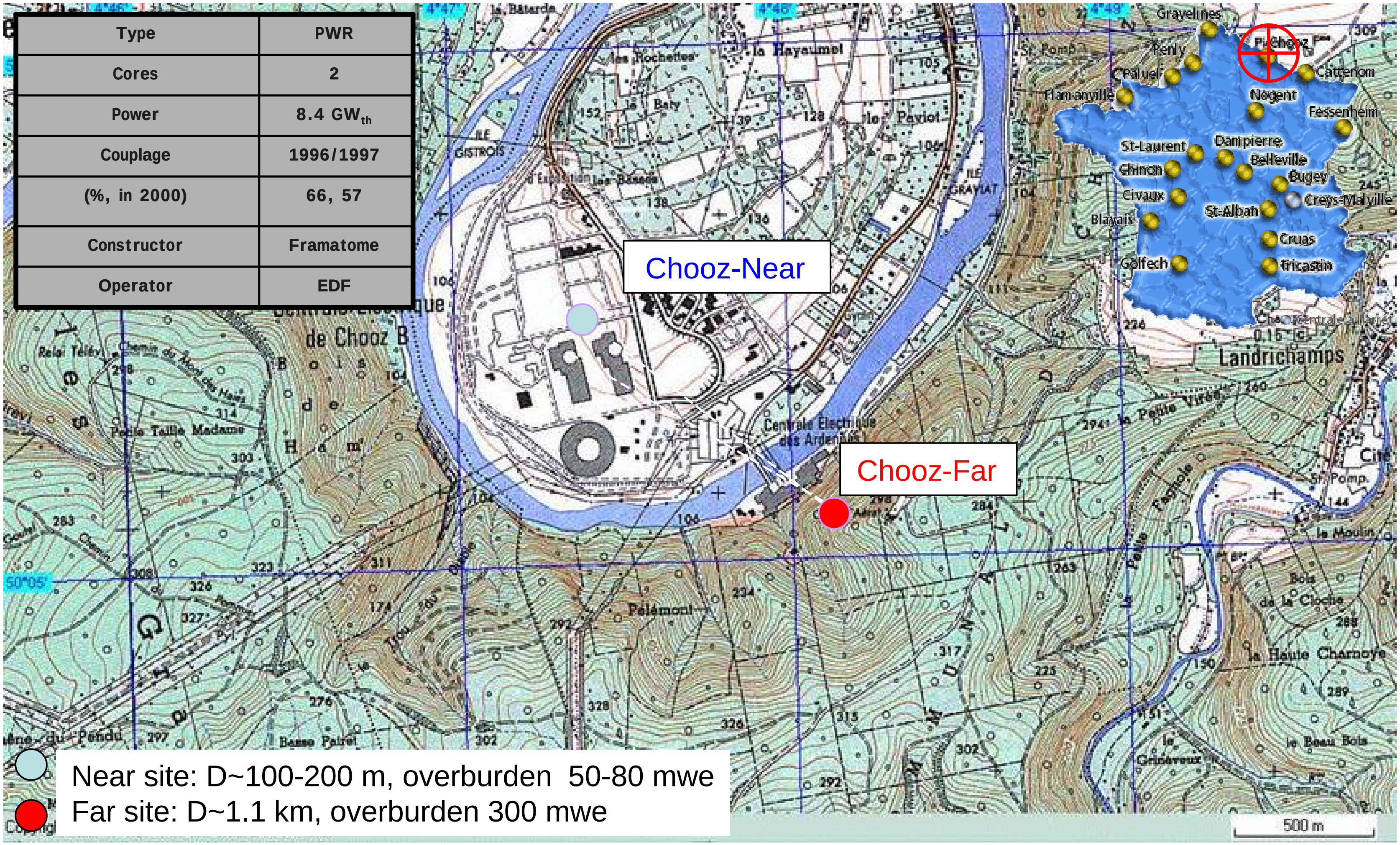
Figure 3.6: Positron spectrum (visible energy, MeV) simulated for the CHOOZ-near and far detectors

Double-CHOOZ Signal



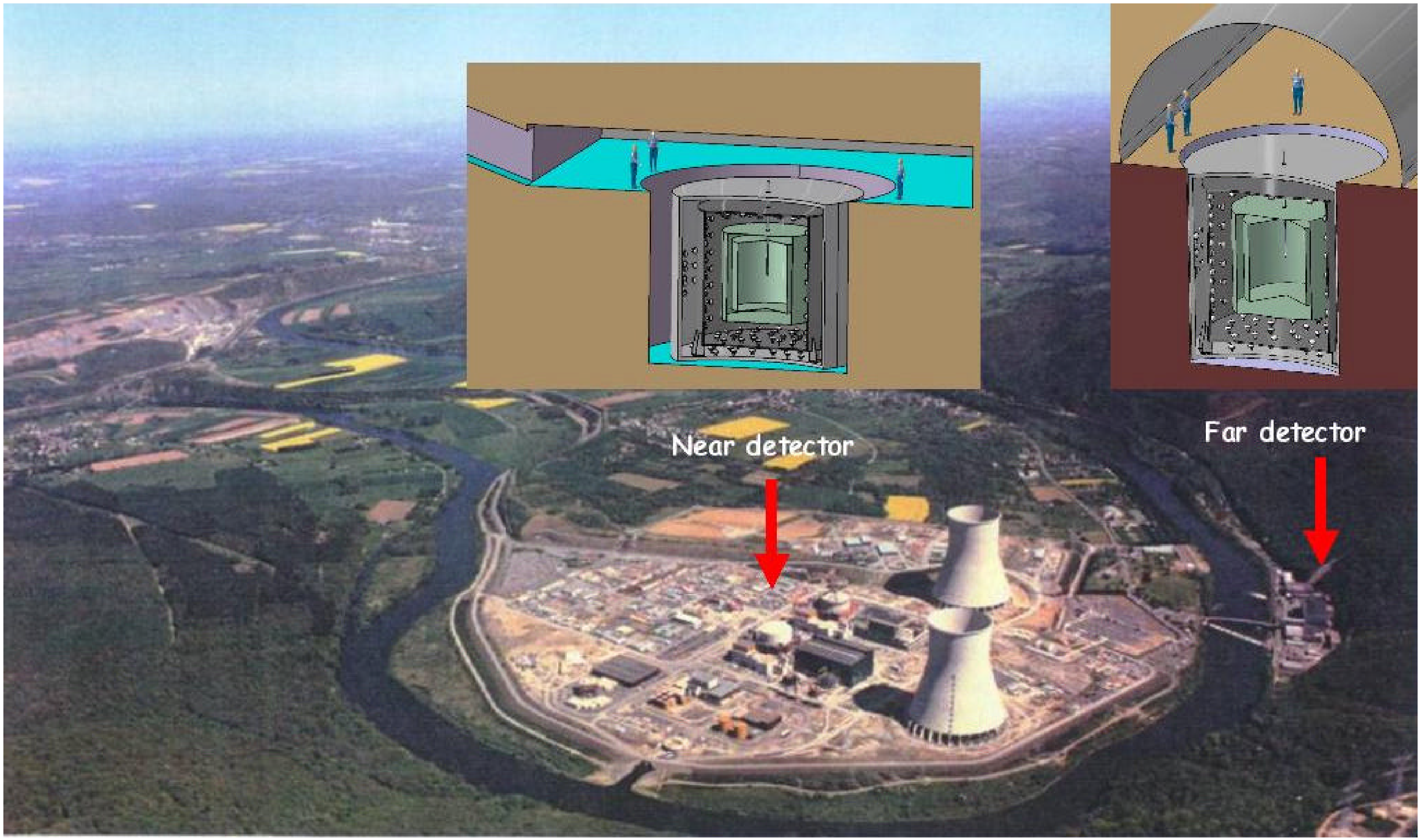
Double CHOOZ Site

Type	PWR
Cores	2
Power	8.4 GW_{th}
Couplage	1996/1997
(%, in 2000)	66, 57
Constructor	Framatome
Operator	EDF

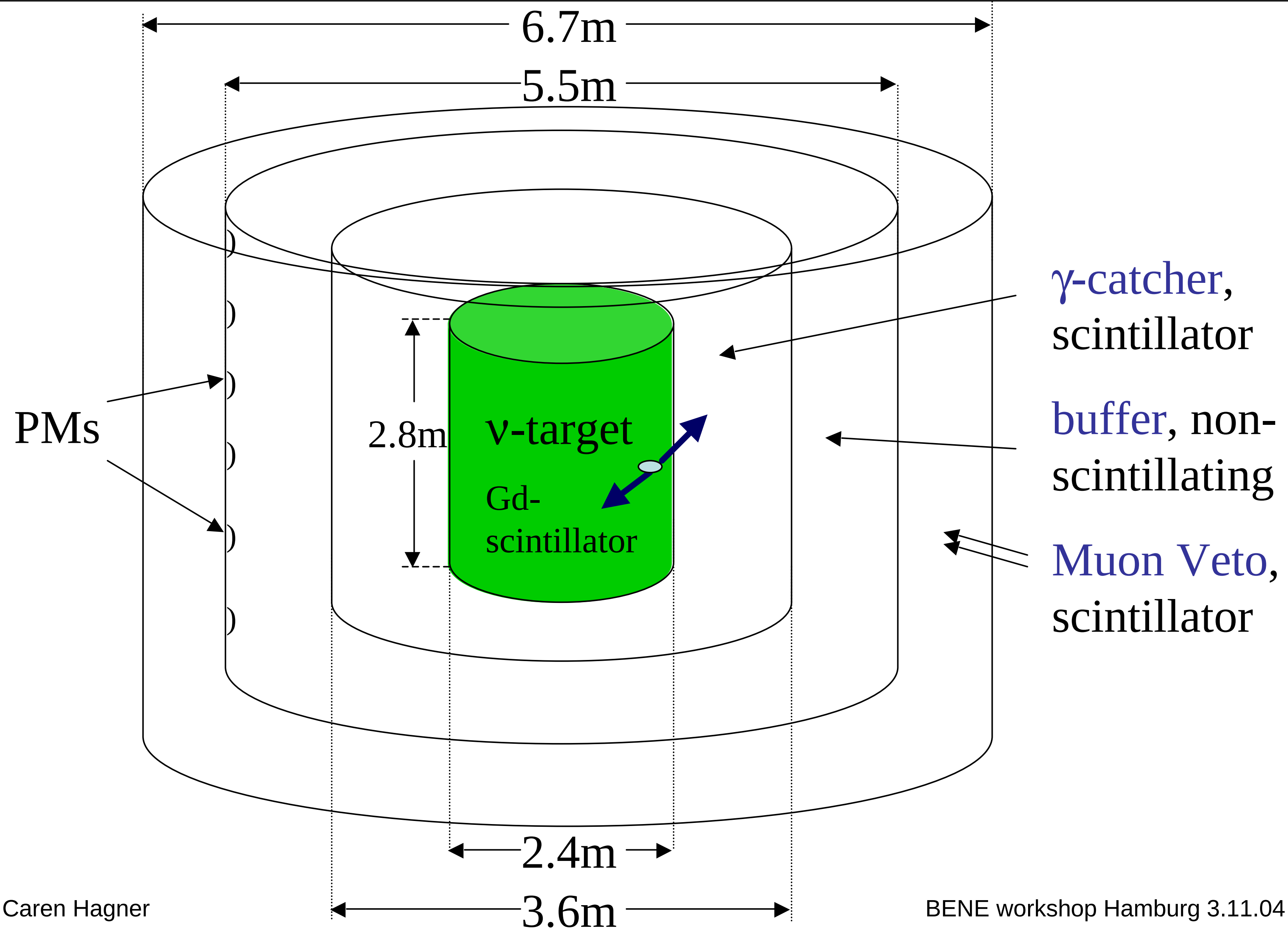


Near site: D~100-200 m, overburden 50-80 mwe
Far site: D~1.1 km, overburden 300 mwe

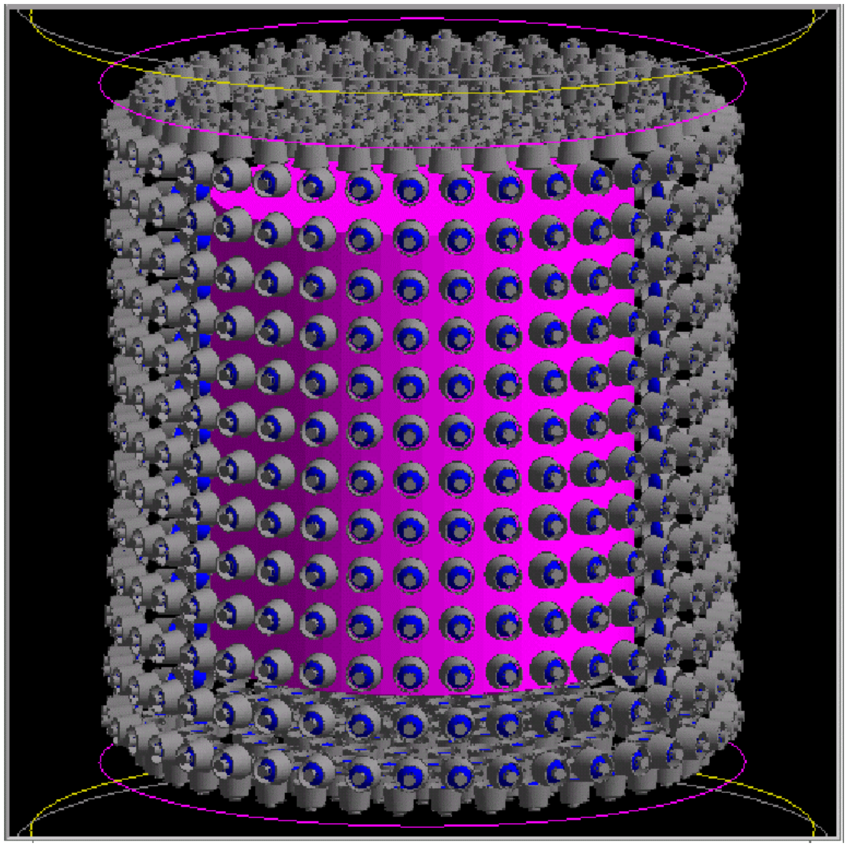
Two Detectors



Detector design, Double-Chooz



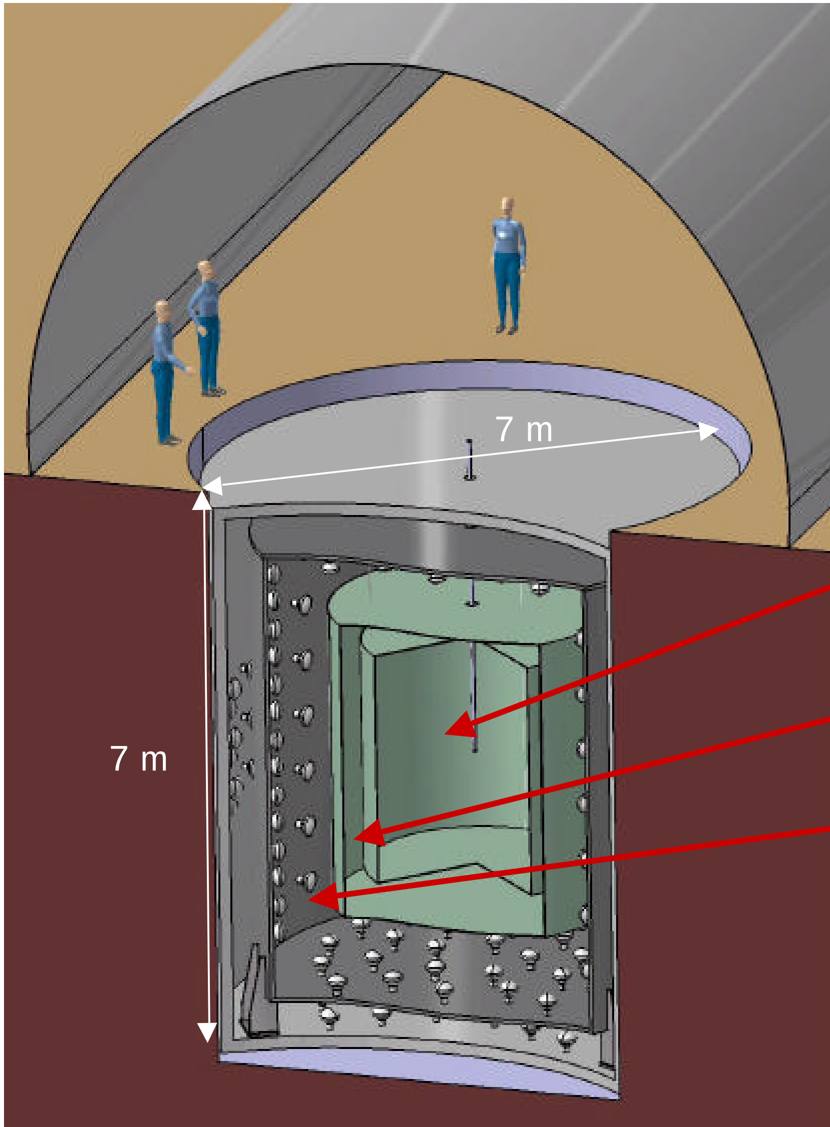
PMTs



- CHOOZ experiment 192 PMTs
  42 m^2
  for a coverage of 14.4%

- current plan for Double-CHOOZ:
  12.9% with 512 20-cm PMTs

Double-CHOOZ Far Detector



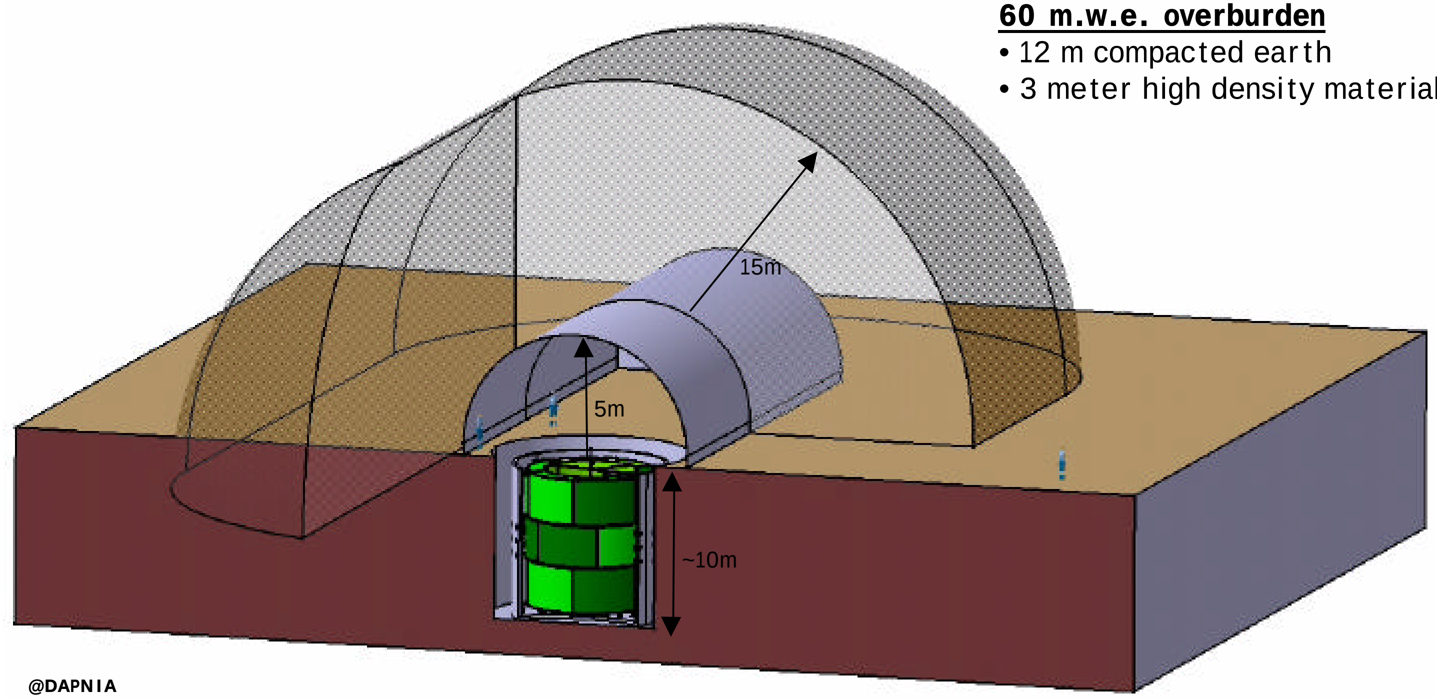
n - target: 80% dodécane + 20% PXE + 0.1% Gd
(r=1,2m, h = 2,8m, 12,7 m³)

g-catcher: 80% dodécane + 20% PXE
(r+0,6m – V= 28,1 m³)

Non-scintillating buffer:
scintillateur+quencher DMP
(r+0.95m, , V=100 m³)

Near Lab Outline

60 m.w.e. overburden
- 12 m compacted earth
- 3 meter high density material



Shielding (m.w.e.)	Muon rate (sec^{-1})	Mean muon energy (GeV)
40	$1.1 \cdot 10^3$	14
60	$5.7 \cdot 10^2$	19
80	$3.5 \cdot 10^2$	23
100	$2.4 \cdot 10^2$	26
300	$2.4 \cdot 10^1$	63

Distance Reactor-detector	Required overburden (m.w.e)
100	45 - 53
150	55 - 65
200	67,5 - 80

How to improve CHOOZ: Statistics

	Chooz	Double-Chooz
Target volume	5.55 m^3	12,67 m^3
Target composition	6.77 10^{28} H/m^3	6.82 10^{28} H/m^3
Data taking period	Few months	3-5 years
Number of events	2700	Chooz-far : 60 000/3 y Chooz-near: > 3 10^6/3 y
Statistical error	2.7%	0.4%

Improve Systematics: 2 identical Detectors

systematics	Error type	Chooz	2 identical detectors Low background
Reactor	Flux, cross section	1.9%	O(0.1%)
	Thermal power	0.7%	O(0.1%)
	E/Fission	0.6%	O(0.1%)
	Σ	**2.1%**	**O(0.1%)**

Main Challenges on Syst. Errors

✓**Solid angle**

- Reactor cores to near detector distance to be measured @10 cm
- Monitoring of the ν source barycenter…

✓ **Target volume**

- @Chooz : 0.3% [simple measurement]
- Goal ~ 0.2% [same apparatus for both detectors] – feasible but not trivial…

✓**Live time** to be measured accurately by several methods

KamLAND : dead-time ➔10% and s_{syst} = 0.6%

Double-Chooz: dead-time(near)

➔25% and goal: s_{syst} ~ 0.25%

Background Estimates

- **Chooz: N/S ~ 4%**

- **Double-Chooz-Far (300 mwe): 12.7 m^3 ➔ Signal x 2.4**

  - Uncorrelated (β,γ + n capt. on Gd):
    N/S(Chooz) ~ 4% : Double-Chooz: Sx3 & N/3 → can be measured and subtracted

  - Correlated events (neutrons):
    Chooz : ~<1 recoil proton per day
    Double-Chooz: liquid active buffer +30 cm
    ➔ ~0.3 events per day → **N/S<1%**

- **Double-Chooz-near (50 mwe): Signal x 50-100 S_{FAR}**

  - Key advantage: D_{near} ~ 100-200 m ➔ Signal x 50-100 !

  - Uncorrelated: Chooz-Far backgrounds x 50 ➔ can be measured and subtracted

  - Correlated events: Chooz-Far x <30 ➔ **N/S < 1%**

  (but not a comprehensive list of backgrounds …)

Neutron induced Background

- ✓**Cosmic muons create fast neutrons through spallation and muon capture in the rock surrounding the detector**
- ✓**Fast neutron slows down by scattering into the scintillator; it could deposit between 1-8 MeV and be later captured on Gd !**
- ✓Full simulation – Geant + Fluka
- ✓Old Chooz simulation: 300 m.w.e. 31hours – MC is reliable !
  - Simulated: N_b<1.6 evts/day (90% C.L.)
  - Measured in-situ: N_b=1.1 evts/day
- ✓Double-Chooz simulation:
  - 338 10^6 μ tracked – 580 10^3 neutrons tracked
  - 1 neutron created a muon event
  - Far detector: N_b<0.5 evt/day (90% C.L.)
  - Near detector: N_b<3.2 evts/day (90%C.L.)

Conclusion and Outlook

- **Double-Chooz sensitivity**:
  can set limit **$\sin^2(2\theta_{13})<0.025-0.03$**, 90% C.L. (if Δm^2 = 2.0-2.5 10-3 eV2)
  & can see $\sin^2(2\theta_{13})>0.04-0.05$, 3s C.L. (if Δm^2 = 2.0-2.5 10-3 eV2)
  Current limit: Chooz : $\sin2(2\theta_{13})<0.2$ ➔ discovery potential !

- **Technology / design well known** (Chooz, BOREXINO, KamLAND,...)
  ➔ few R&D needed : Gd loading (stability) + material compatibility
  (Started, to be completed in half a year)

- Collaboration: APC Paris, Saclay, Subatech, TU Munich, MPIK Heidelberg, Tubingen Univ. Hamburg Univ., Kurchatov, RAS Moscow, Univ. Alabama, Univ. Tennessee, Univ. Louisiana, Univ. Drexel, Argonne, + Italian groups discussing…
  ➔ (maxi-)**letter of intent (May 2004)** ➔ final proposal end of 2004

- Approved in France.
- Proposal to DOE in US

- **Our Goal @Double-Chooz:**
  Construction starts in 2006
  Start data taking in **2007 (far) & 2008 (near + far)**

APS multi-divisional ν study

- ❶ One of (two) high priority recommendations is for a concerted program to measure θ_{13} including:
  - ➔ A reactor experiment
  - ➔ An accelerator experiment (with NOνA in mind).