Double Chooz:

A Reactor θ_{13} Experiment

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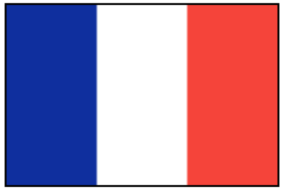
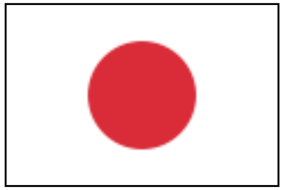
Tohoku Univ.

International Workshop on Double Beta Decay and Neutrinos

2007-6-13 @ Osaka

Double Chooz Collaboration




Collaboration

- Japan
  - Tohoku Univ.
  - Tokyo Metropolitan Univ.
  - Niigata Univ.
  - Tokyo Institute of Technology
  - Kobe Univ.
  - Tohoku Gakuin Univ.
  - Miyagi University of Education
  - Hiroshima Inst. of Technology
- USA
  - Livermore nat lab
  - Argonne
  - Columbia Univ
  - Chicago Univ
  - Kansas U
  - Notre Dame U
  - Tennesse U
  - Alabama U
  - Drexel U
  - Illinois Inst tech
- France
  - Saclay
  - APC (collège de France)
  - Subatech Nantes
- Germany
  - Max planck Heidelberg
  - Munich U
  - Hamburg U
  - Tubingen U
  - Aachen U
- Spain
  - CIEMAT Madrid
- England
  - Oxford
  - Sussex Univ
- Russia
  - Kurchatov inst
  - Sc. Acad.
- Brasil
  - CBPF
  - UNICAMP

Contents

A Quick Review of ν Oscillation

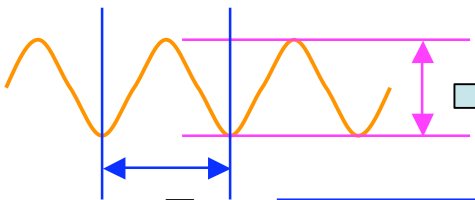
2 flavor mixing case

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad m_1, m_2$$

Anyway, if flavor and mass eigenstates mix & $m_1 \neq m_2$, => ν oscillates.

Since E>>m, →

$$P_{\nu_e \to \nu_\mu} = \sin^2 2\theta \sin^2 \frac{\left(m_2^2 - m_1^2\right) L}{4E}$$



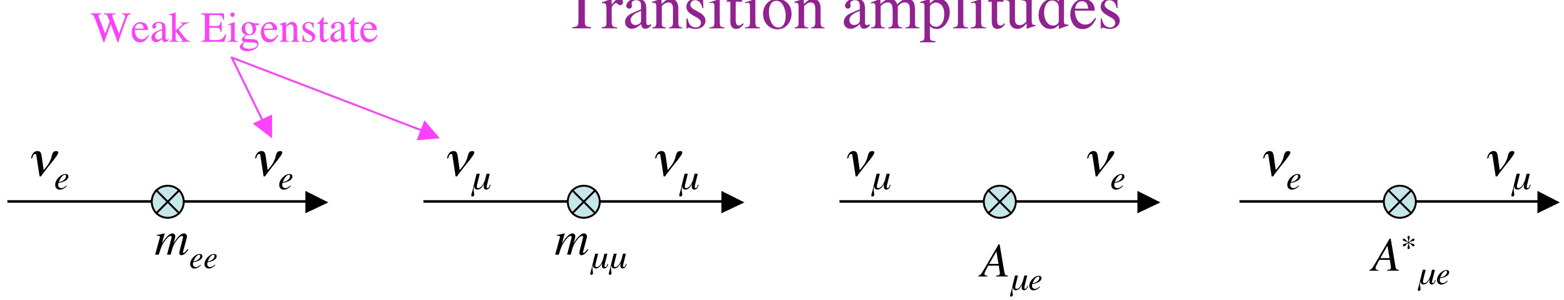
Amplitude ==> $\sin^2 2\theta$

Frequency ==> $\Delta m^2 = \left| m_2^2 - m_1^2 \right|$

What We Measure by ν Oscillation

$$\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}=\begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

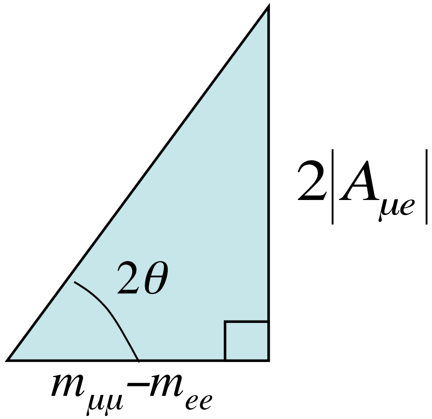
Transition amplitudes



ν equation of motion: $$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}=\begin{pmatrix}m_{ee} & A_{\mu e}\\ A^*_{\mu e} & m_{\mu\mu}\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

$$\sin^2 2\theta=\frac{1}{1+\left(m_{\mu\mu}-m_{ee}\right)^2 / 4\left|A_{\mu e}\right|^2}$$

$$\Delta m_{12}^2=\left|m_{\mu\mu}^2-m_{ee}^2\right|\sqrt{1+4\left|A_{\mu e}\right|^2/\left(m_{\mu\mu}-m_{ee}\right)^2}$$



ν Oscillations: 3 flavor case

Mixings

MNS Matrix

$$s_{ij} = \sin\theta_{ij}, \quad c_{ij} = \cos\theta_{ij}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \Rightarrow \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

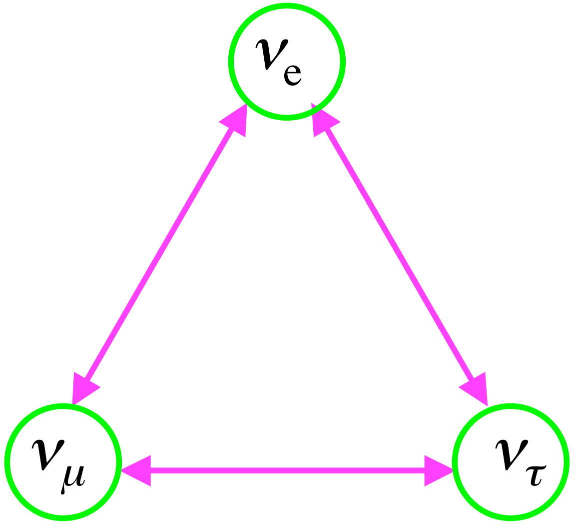
Oscillations

$$\begin{matrix} P(\nu_\alpha \to \nu_\beta) \\ P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \end{matrix} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) \sin^2\Phi_{ij} \mp 2\sum_{i>j} \mathrm{Im}\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) \sin 2\Phi_{ij}$$

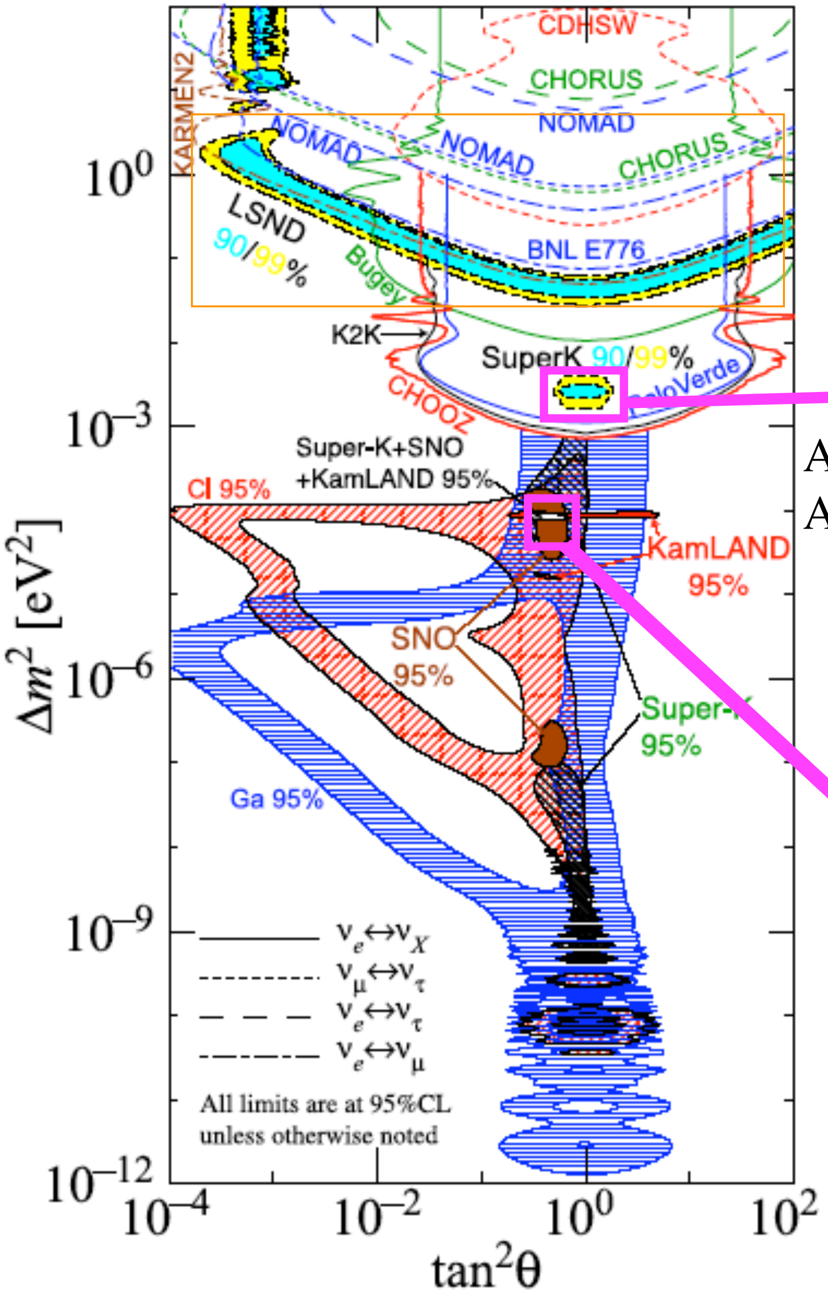
$$\left(\Phi_{ij} = \frac{\Delta m^2_{ij} L}{4E}, \quad \Delta m^2_{ij} = m^2_j - m^2_i \right)$$

$$\left|\Delta m^2_{12}\right|, \quad \left|\Delta m^2_{23}\right|, \quad \theta_{12}, \quad \theta_{23}, \quad \theta_{31}, \quad \delta$$

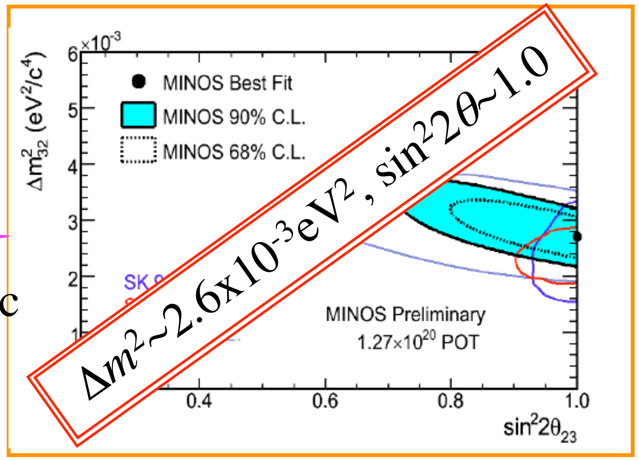
6 parameters can be accessible from neutrino oscillation.



Two Oscillations

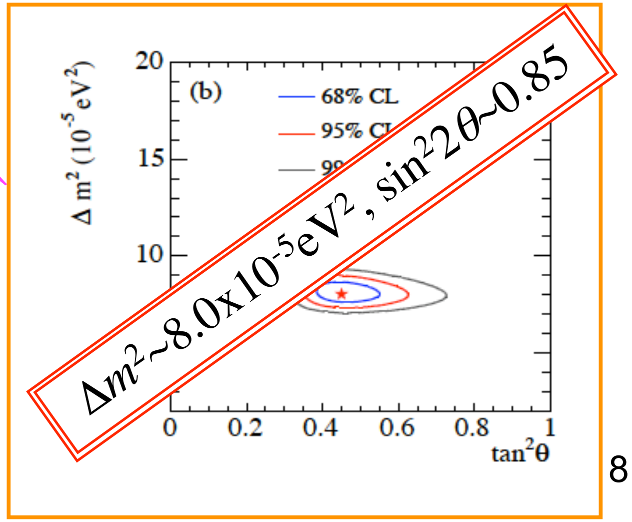


Atmospheric
Accelerator



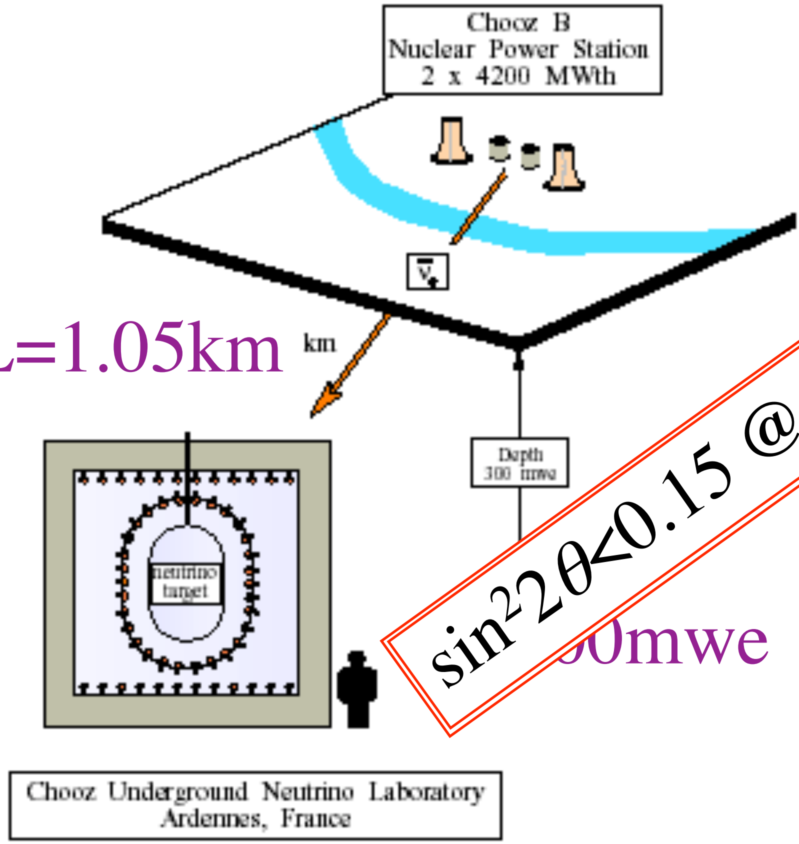
4/6 parameters were measured

Solar
Reactor



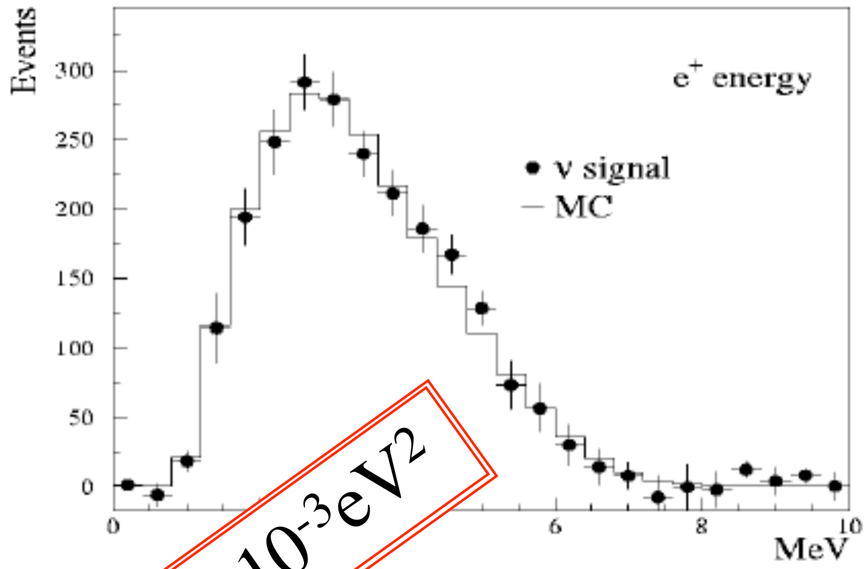
Upper limit

CHOOZ reactor ($\bar{\nu}_e$ --> $\bar{\nu}_e$) experiment

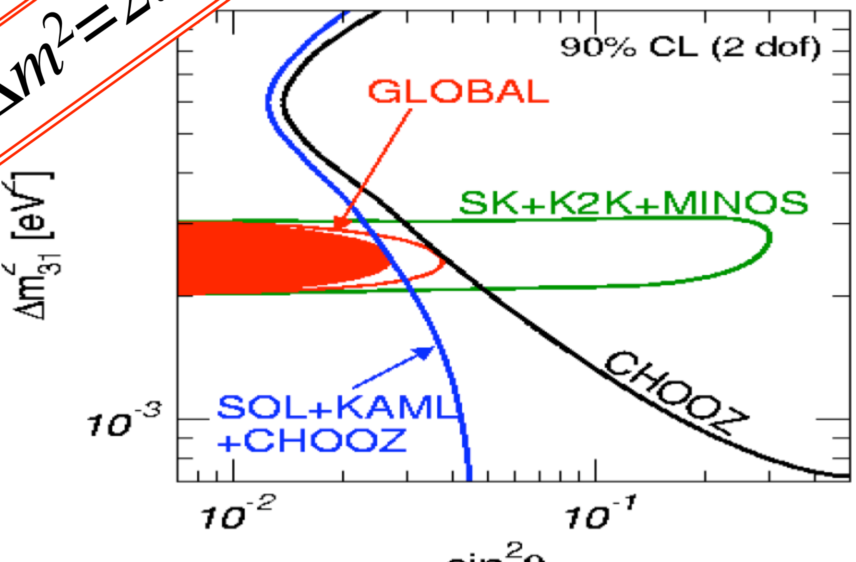


L=1.05km

300mwe



$\sin^2 2\theta < 0.15$ @ $\Delta m^2 = 2.5 \times 10^{-3} eV^2$

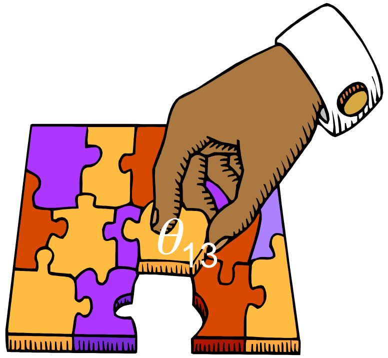


(Thomas Schwetz, hep-ph/0606060)

Our Current Knowledge

$$\left|m_3^2 - m_2^2\right| \sim 2.6\times10^{-3}\,\mathrm{eV}^2,\quad \left(m_2^2 - m_1^2\right) \sim 8.0\times10^{-5}\,\mathrm{eV}^2$$

$$U_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & s_{13}e^{i\delta} \\ -0.4 & 0.6 & 0.7 \\ 0.4 & -0.6 & 0.7 \end{pmatrix} \quad \left|s_{13}\right| < 0.2$$



Transition Amplitudes, if $m_1 << m_2 < m_3$

ν_e — ν_e: m_{ee}~5meV

ν_μ — ν_μ: $m_{\mu\mu}$~30meV

ν_τ — ν_τ: $m_{\tau\tau}$~30meV

ν_e — ν_μ: $A_{e\mu}\sim(30s_{13}e^{i\delta}+3)$meV

ν_e — ν_τ: $A_{e\tau}\sim(30s_{13}e^{i\delta}-3)$meV

ν_μ — ν_τ: $A_{\mu\tau}$~20meV

θ_{13} is a last piece

=> Measurement is important to complete the puzzle

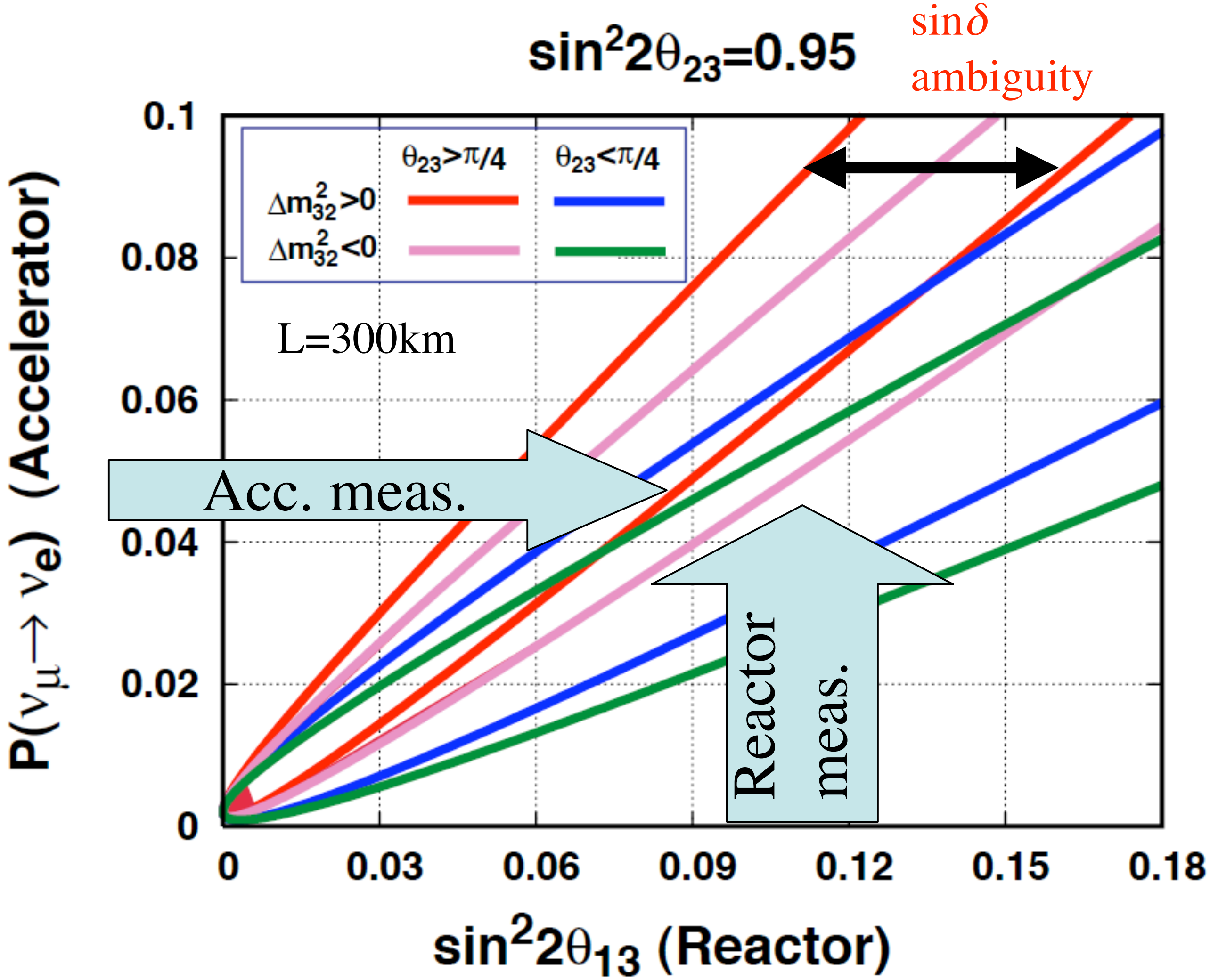
Remaining Issues of ν Oscillation Studies

Issue	Method
θ_{13}	$[\nu_\mu \to \nu_e]_A \sim \sin^2\theta_{23}\underline{\sin^2 2\theta_{13}} \mp 0.05\cdot\sin\theta_{13}\sin\delta$ $[\bar{\nu}_e \to \bar{\nu}_e]_R = 1 - \underline{\sin^2 2\theta_{13}}$
δ	$[\nu_\mu \to \nu_e]_A - [\bar{\nu}_\mu \to \bar{\nu}_e]_A \sim \underline{\sin 2\theta_{13}}\sin\delta$
θ_{23} degeneracy $\sin\theta_{23} = \frac{1 \pm \sqrt{1-\sin^2 2\theta_{23}}}{2}$	$[\nu_\mu \to \nu_e]_A \sim \sin^2\theta_{23}\underline{\sin^2 2\theta_{13}} \mp 0.05\cdot\underline{\sin\theta_{13}}\sin\delta$
mass hierarchy *($m_2<m_3$ or $m_3<m_2$)*	$[\nu_\mu \to \nu_e] - [\bar{\nu}_\mu \to \bar{\nu}_e]$ $\sim 0.00017L[km]\cdot sign(\Delta m_{23}^2)\underline{\sin^2 2\theta_{13}}$

θ_{13} plays key roles => Measurement is urgent

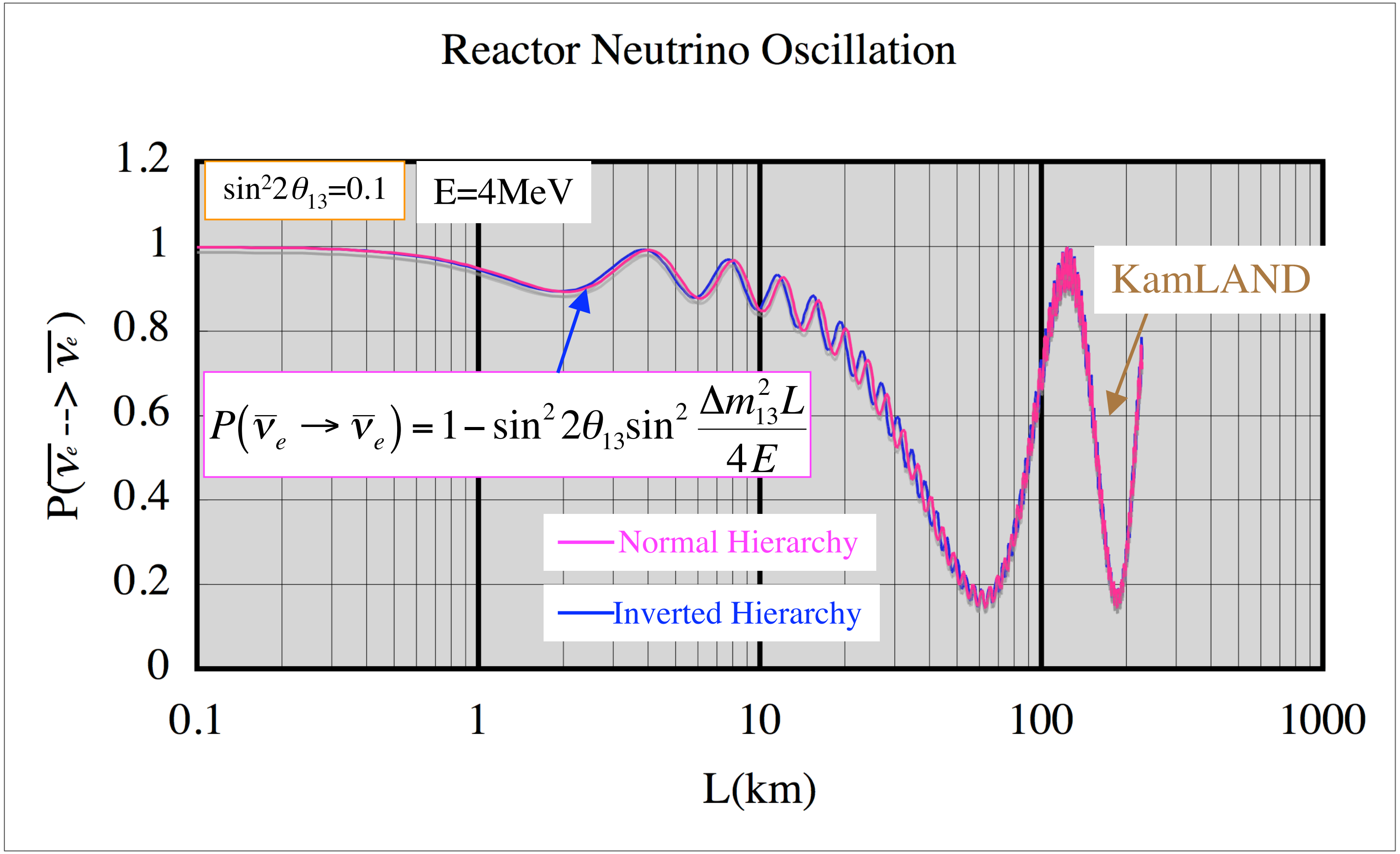
Complementarity to Accelerator-θ_{13}

$$
\begin{aligned}
P_{app} \simeq\ & \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
& \pm \alpha \sin 2\theta_{13}\, \xi \sin\delta_{CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
& + \alpha \sin 2\theta_{13}\, \xi \cos\delta_{CP} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
& + \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2},
\end{aligned}
$$



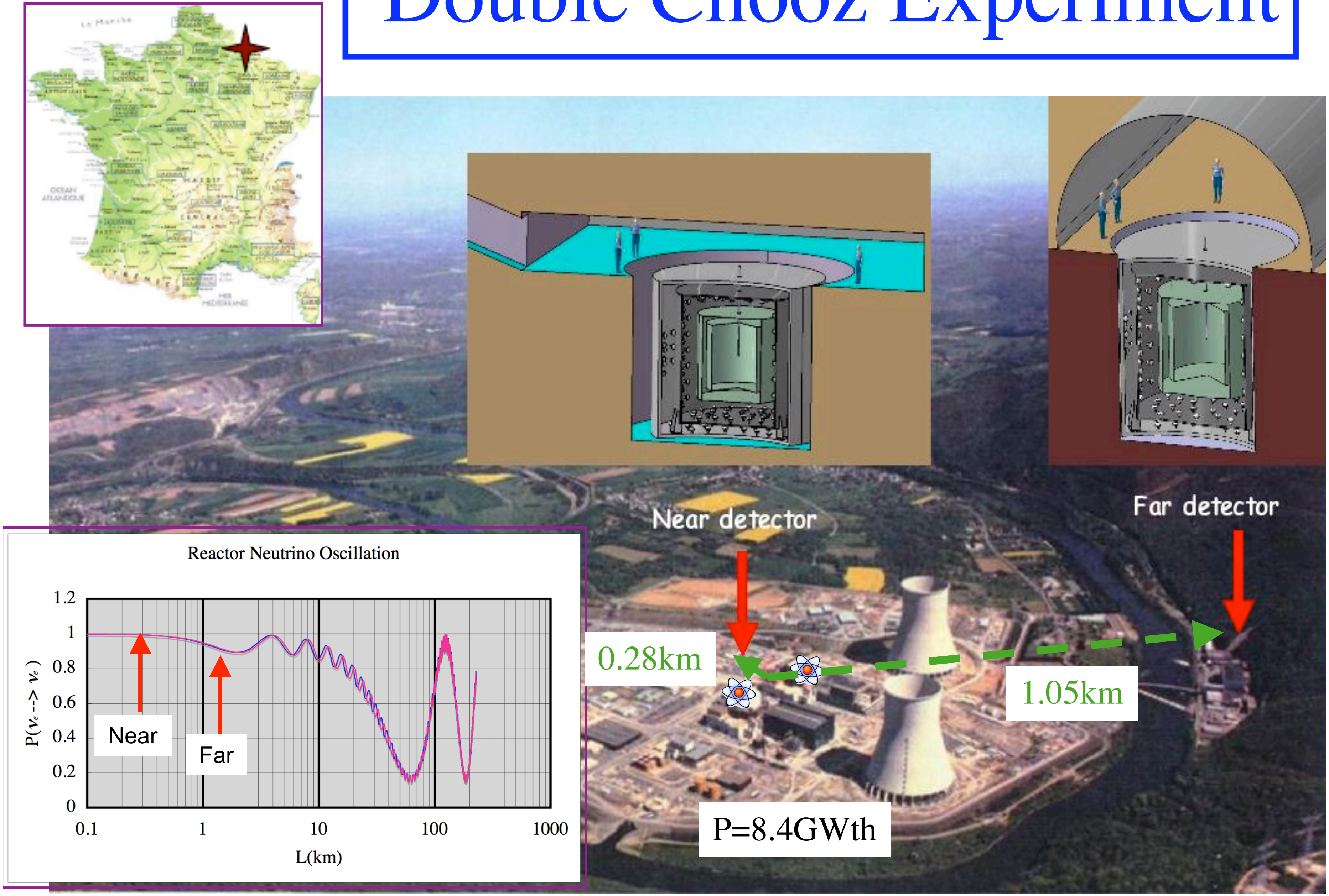
Reactor Measurement is Important

Reactor θ_{13} measurement



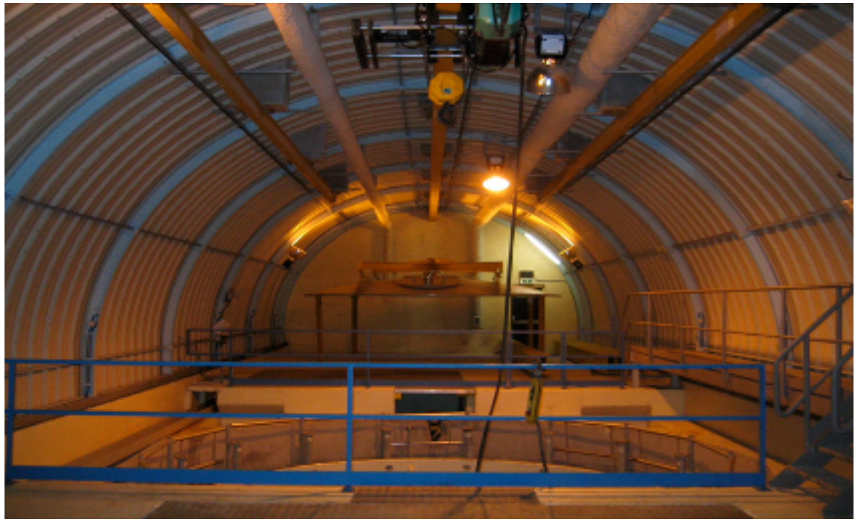
Small deficit (=$\sin^2 2\theta_{13}$) ==> High Precision is necessary （δ<1%）

Double Chooz Experiment

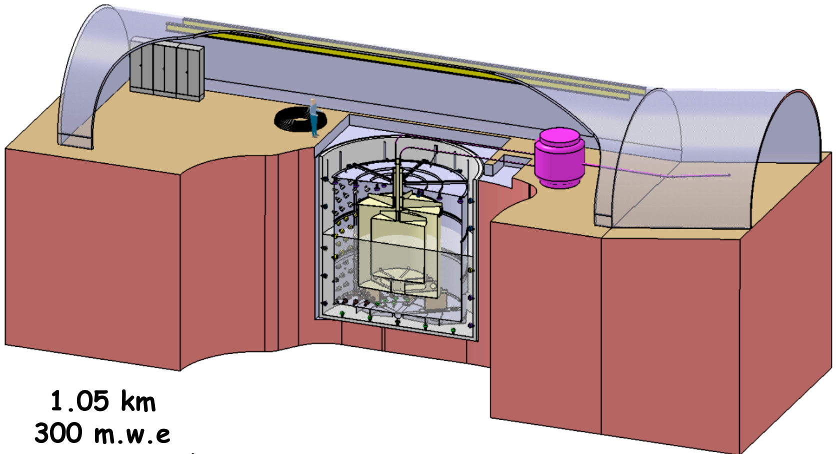


1 km site

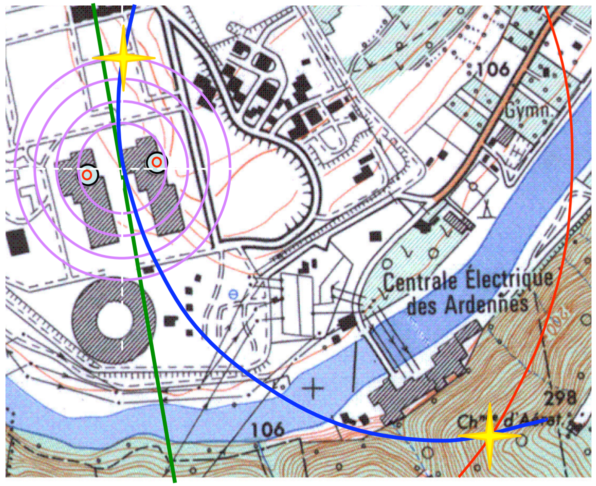
280 m site

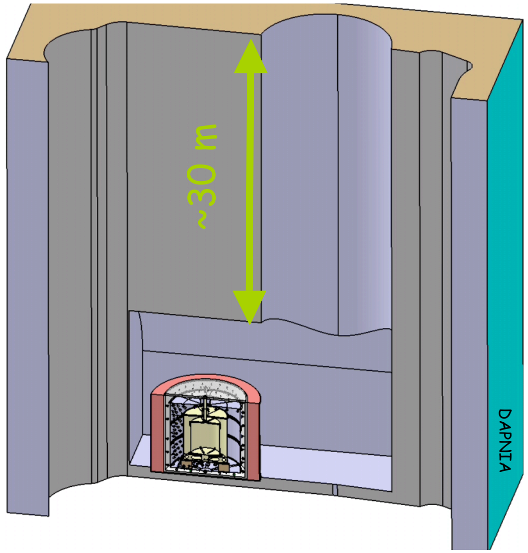


Integration to start mid-2007



1.05 km
300 m.w.e
15 000 events/y





280 m
80 m.w.e
150 000 events/y

Integration end of 2009

2004-2007: Detector design

Calibration Glove-Box :

Outer Veto :
Scintillator panels

Target ν : 10,3 m^3
LS; 80% $C_{12}H_{26}$+ 20% PXE +0,1% Gd
+ PPO + Bis-MSB

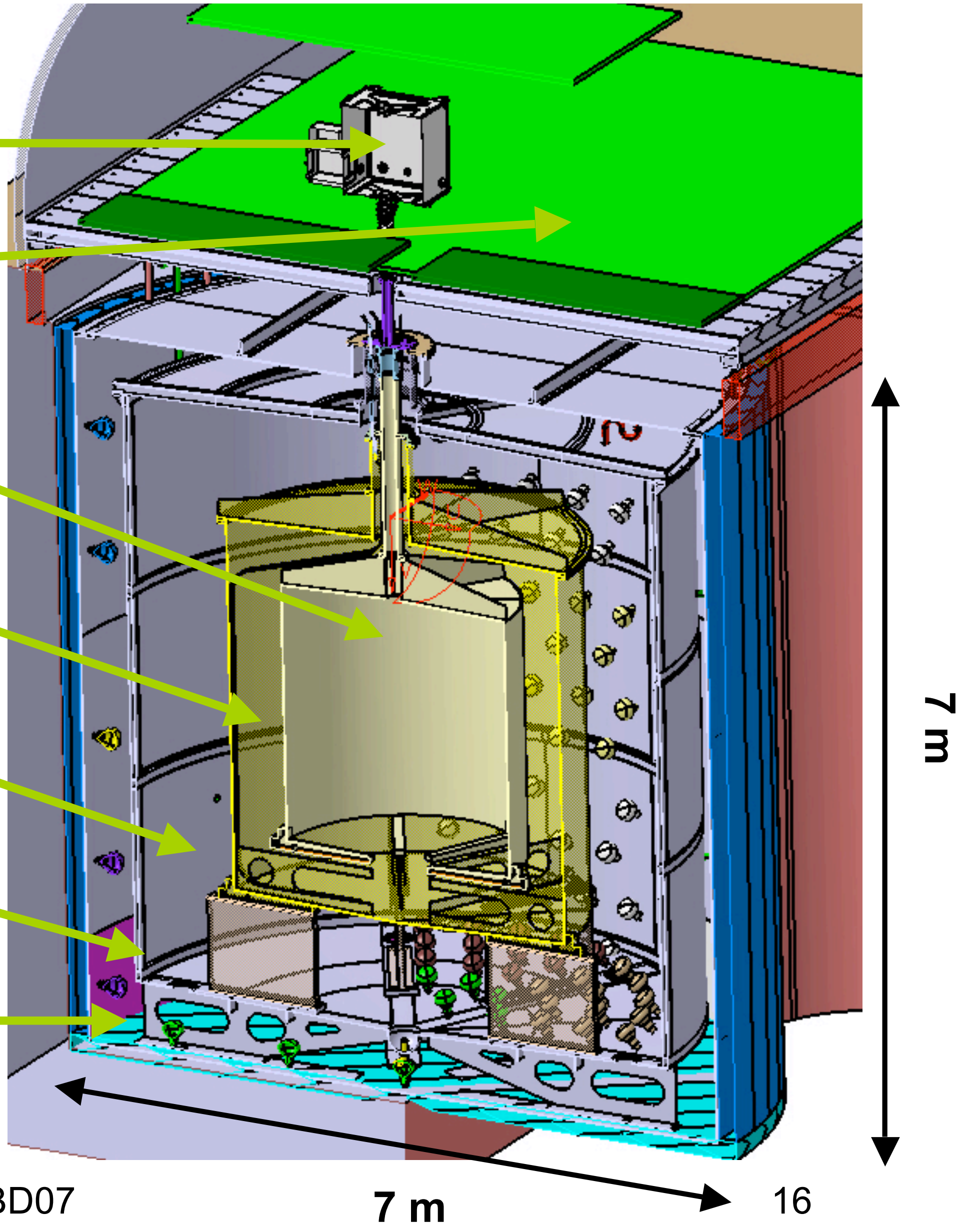
γ Catcher : 22,6 m^3
LS; 80% $C_{12}H_{26}$ + 20% PXE + PPO + Bis-MSB

Non scintillating Buffer : 114 m^3
mineral oil

Buffer vessel & 390 10'' PMTs :
Stainless steel 3 mm

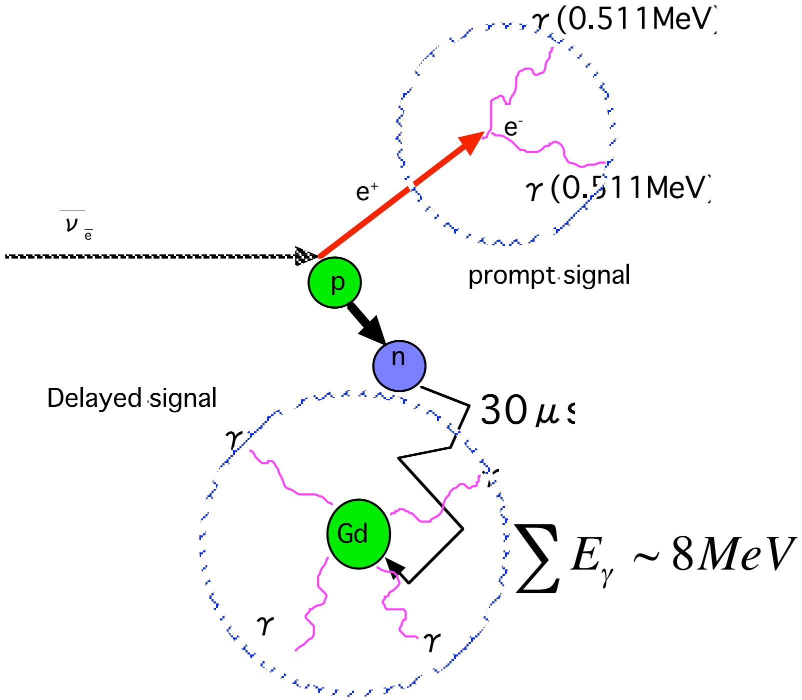
Inner Muon Veto : 90 m^3
mineral oil + 70 8'' PMTs

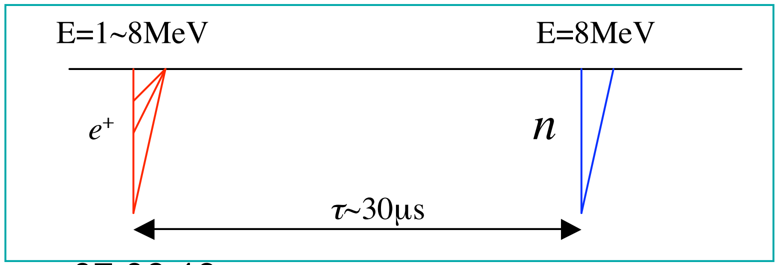
Steel Shielding :
17 cm steel, All around

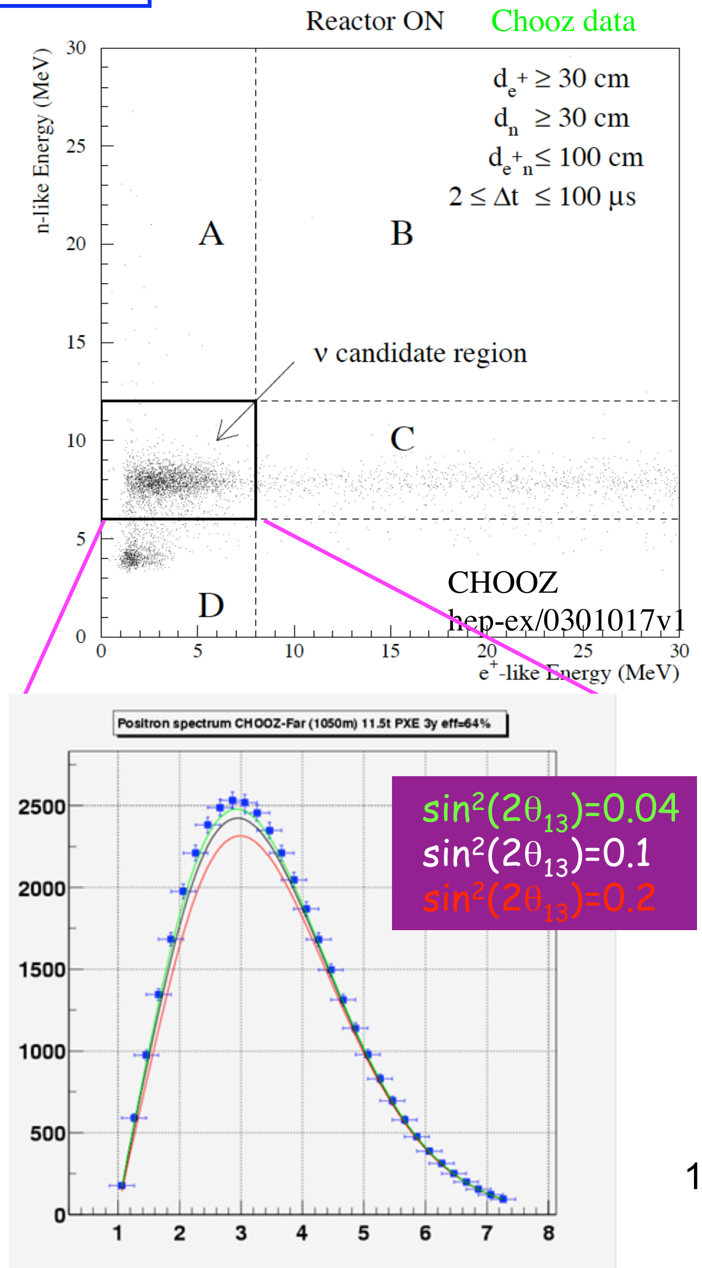


$\bar{\nu}_e$ Detection

Gd doped liquid scintillator

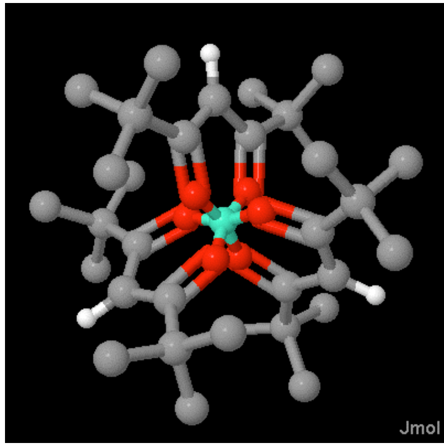




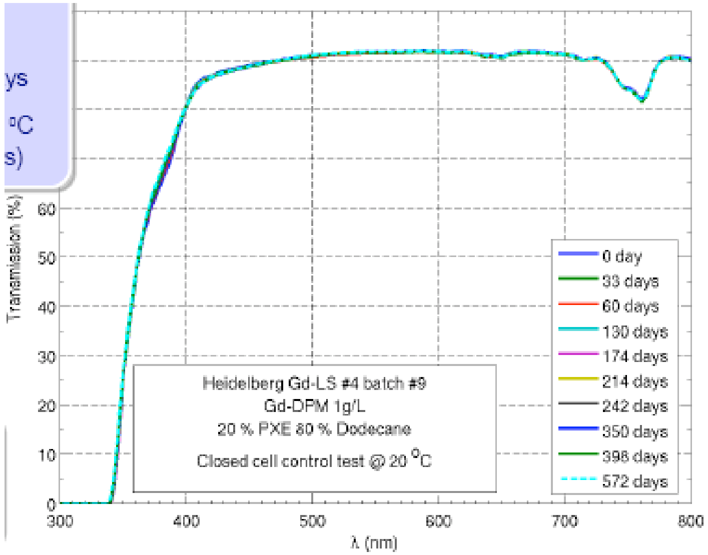


Gd doped scintillator

- **Solvent: 20% PXE – 80% Dodecane**
- **Gd loading: being developed @MPIK**
  - 0.1% Gd loading of Gd-dmp (Beta Dikitonate)
  - Long term Stability promising
  - LY ~7000 ph/MeV: 6 g/l PPO + 50 mg/l Bis-MSB
  - Attenuation length: 5-10 m meters at 420 nm
  - Radiopurity → U: 10^{-12} g/g - Th: 10^{-12} g/g - K: 10^{-9} g/g



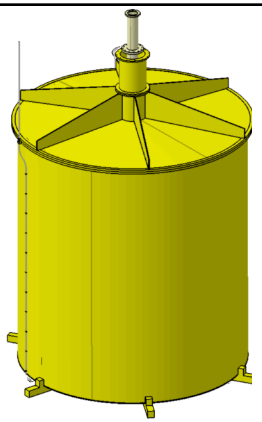
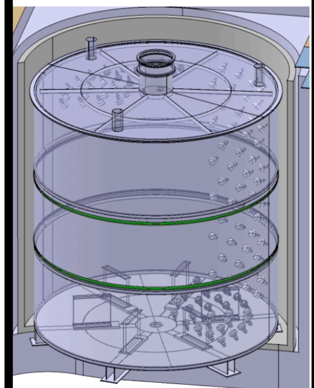
$Gd(dpm)_3$



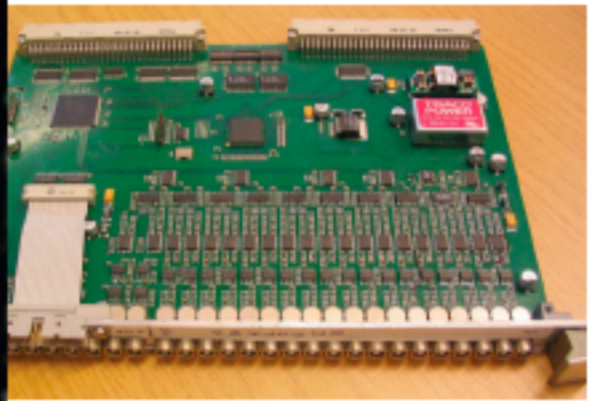
UV-VIS-IR scintillator transmission

- Heidelberg MPIK →Transition to industrial production of 100 kg of Gd → summer 2007
- On-site storage building *available* at Chooz → Upgrade will be done in 2007

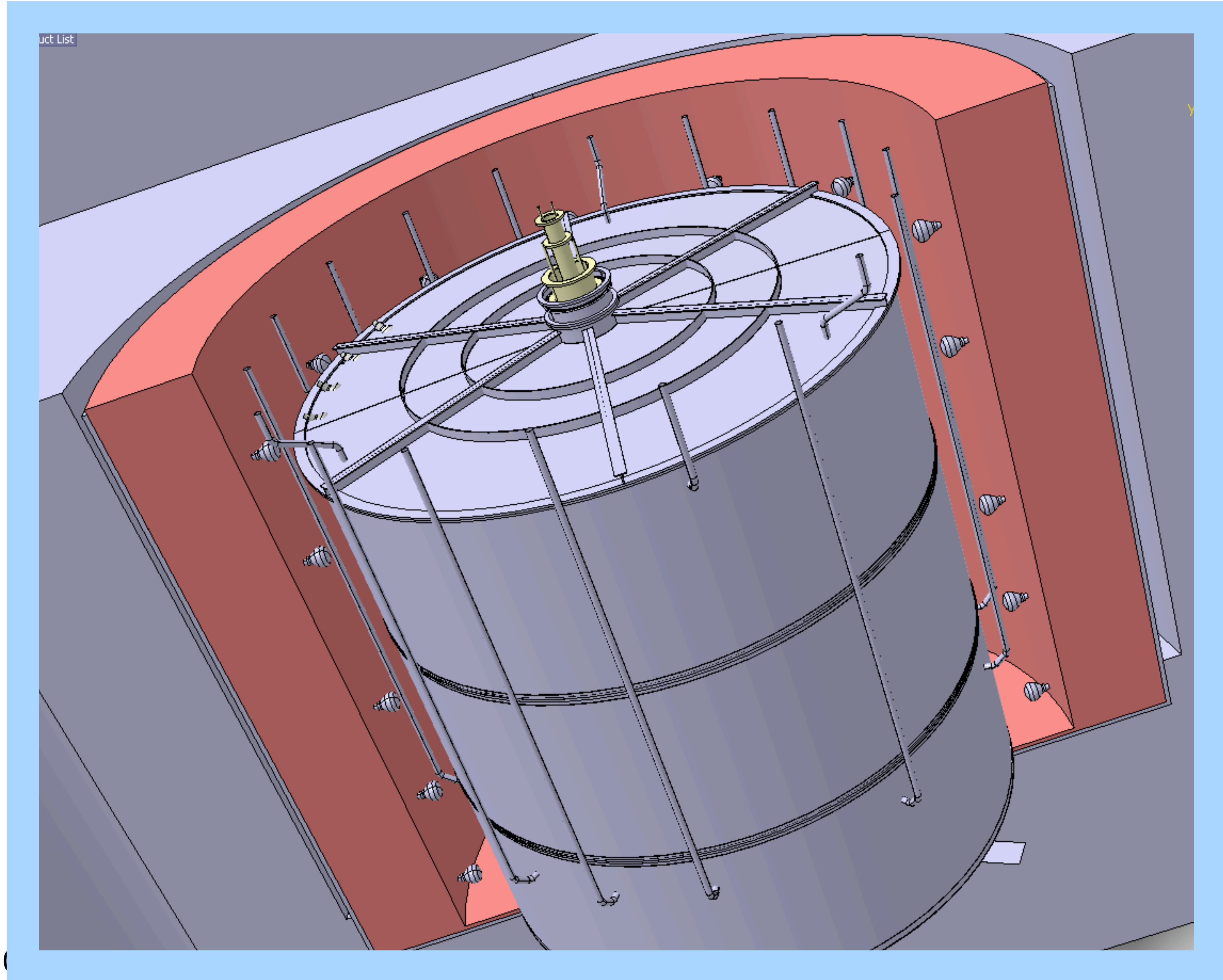
d Buffer

Vessel		& Integration
		
		

DoubleChooz

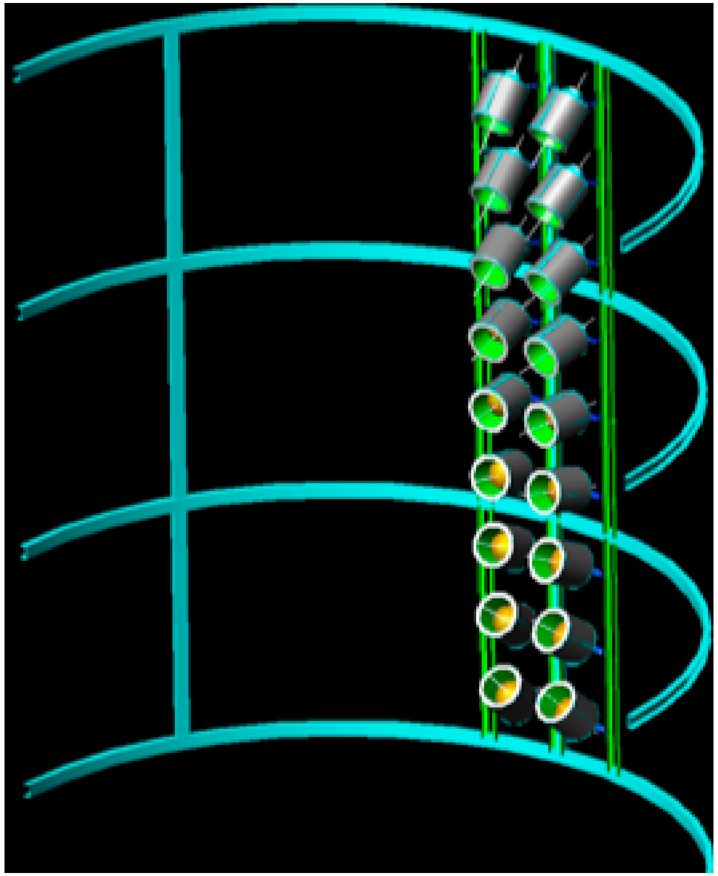


Detector design



PMT & B Shield and Support

PMT geometory
390/detector



Magnetic Shield
Support Structure
Spain

high performance
low background
10" PMT
Japan

Improving CHOOZ:

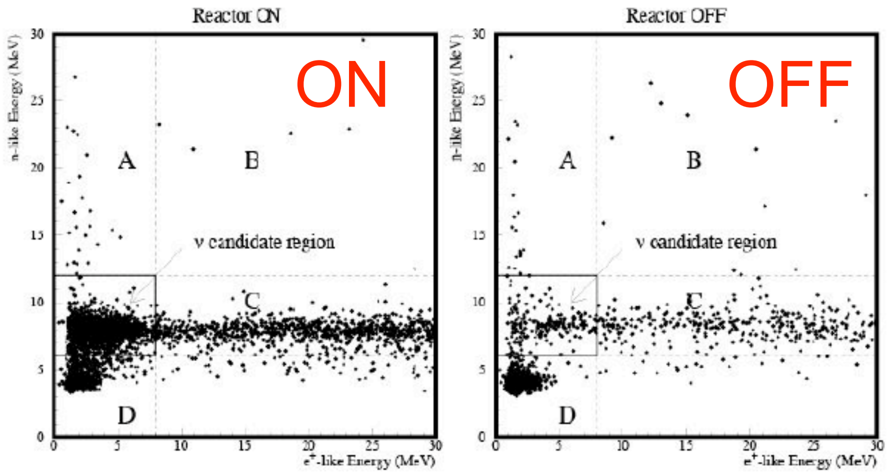
@CHOOZ: R = 1.01 ± 2.8%(stat)±2.7%(syst) → current θ_{13} limit

– Statistical error –

	CHOOZ	Double-Chooz
Target volume	5.6 m^3	10.3 m^3
Target composition	6.8×10^{28} H/m^3	6.8×10^{28} H/m^3
Data taking period	Few months	3-5 years
# of Events	2700	CHOOZ-far : 40 000/3 y CHOOZ-near: >1×10^6/3 y
Statistical error	2.7%	0.5%

Luminosity incerase L = Δt x P(GW) x Np

Backgrounds



CHOOZ reactor
off data

Detector	Site		Background				
			Accidental		Correlated		
			Materials	PMTs	Fast n	μ-Capture	^{9}Li
CHOOZ		Rate (d^{-1})	—	—	—	—	0.6 ± 0.4
$(24\ \nu/\mathrm{d})$		Rate (d^{-1})	0.42 ± 0.05		$1.01 \pm 0.04(stat) \pm 0.1(sys)$		
	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
$(69\ \nu/\mathrm{d})$	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
$(1012\ \nu/\mathrm{d})$	Near	bkg/ν	0.5%	1.7%	0.13%	<0.1%	1%
		Systematics	<0.1%	<0.1%	0.2%	<0.1%	0.2%

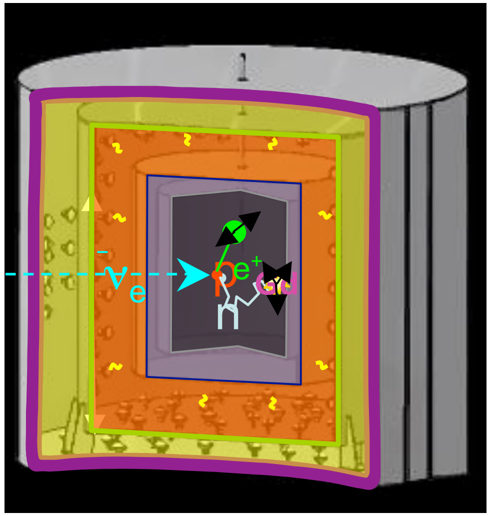
hep-ex/0606025

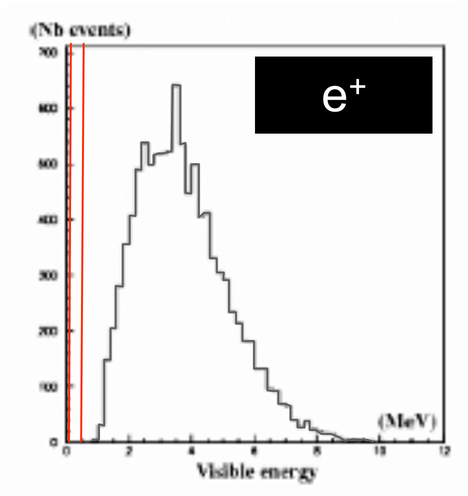
Systematics

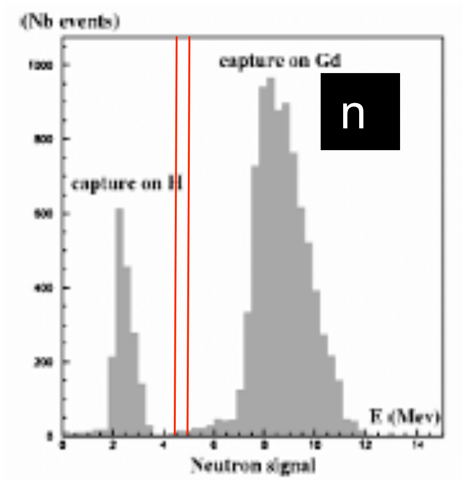
		Chooz	Double-Chooz	
Reactor-induced				
Detector - induced				
	Volume	0.3 %	0.2 %	Same weight sensor for both det.
	Live time	few %	0.25 %	Measured with several methods
Analysis	From 7 to 3 cuts	1.5 %	0.2 - 0.3 %	(see next slide)
	Total	**2.7 %**	**< 0.6 %**	

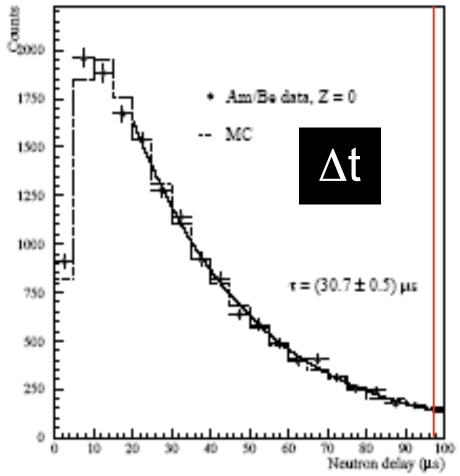
Relative Normalization: Analysis

- ✓ @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)









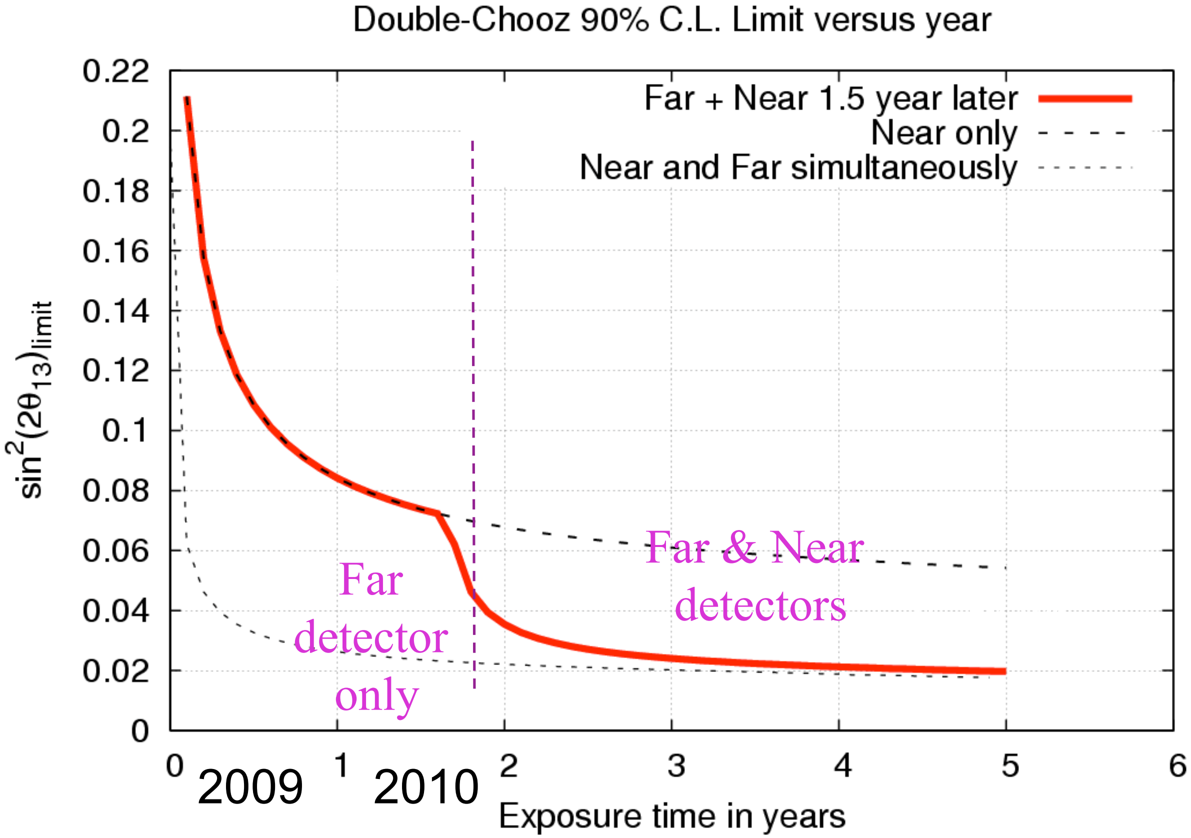
* Efficiency is insensitive to the energy scale error

* No fiducial cuts

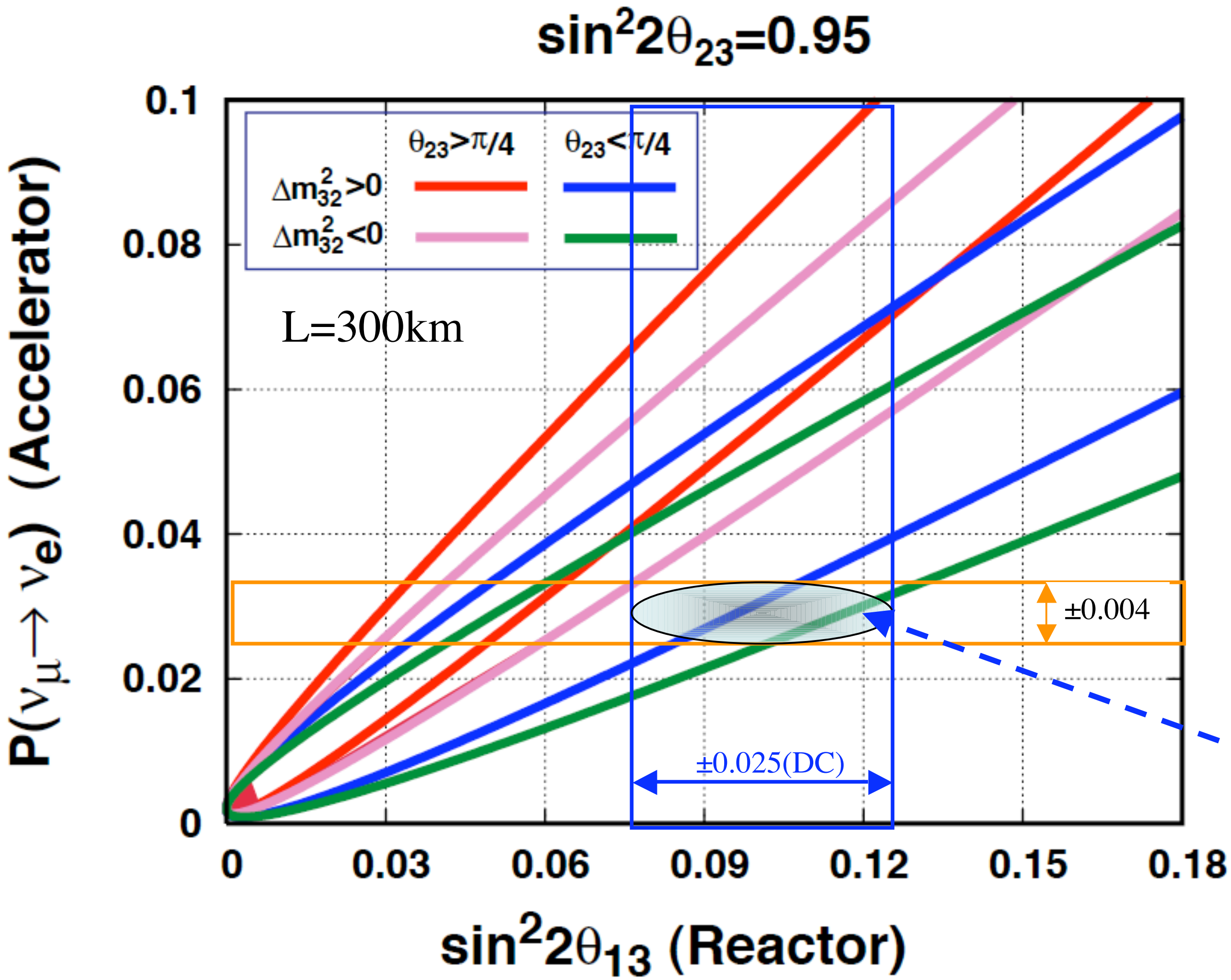
Sensitivity

Double-Chooz Far Detector starts in 2008
Double-Chooz Near detector follows 16 months later

90% C.L. contour if $\sin^2(2\theta)=0$
$\Delta m^2_{atm} = 2.8\times10^{-3}\ eV^2$ is supposed to be known at 20% by MINOS



One possible case of Complementarity to Accelerator-θ_{13}

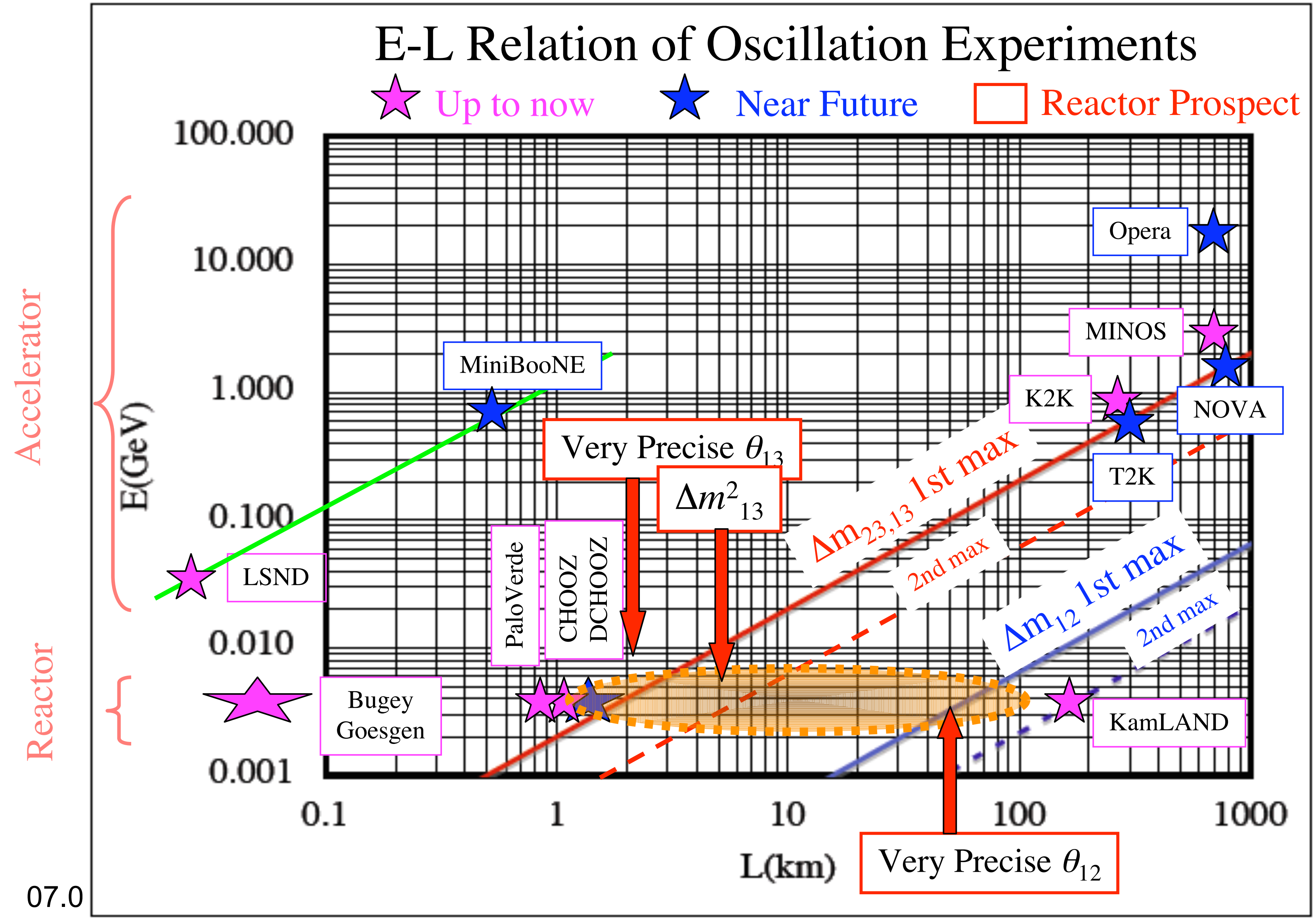


If ..

Degeneracy
Solved!

$\theta_{23}<\pi/4$

Potential of Reactor ν experiments



07.0

Conclusions & outlook

Double Chooz R&D's are in final stages & Detector Construction starts this year.

First data taking expected to start in 2008 with far detector only

=> $\sin^2(2\theta_{13}) < 0.06$ in 1,5 year

In 2010 take data with both near and far detectors

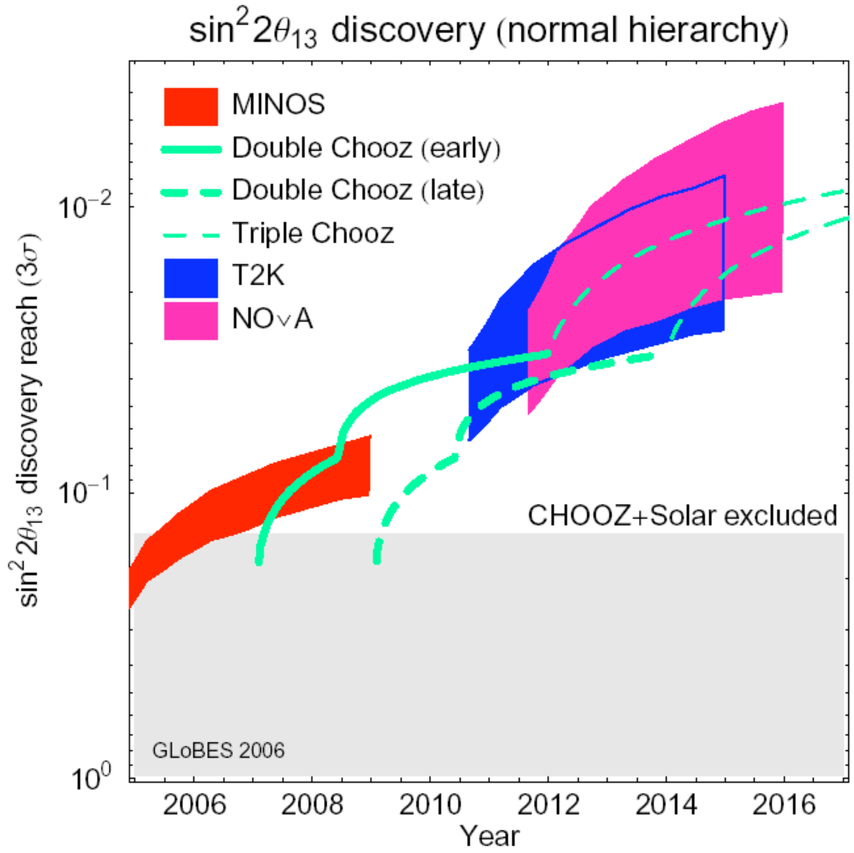
=> $\sin^2(2\theta_{13}) < 0.025$ in 3 years

We will know or set a strong limit on the size of θ_{13} within a few years & the neutrino oscillation studies will go in a new phase.

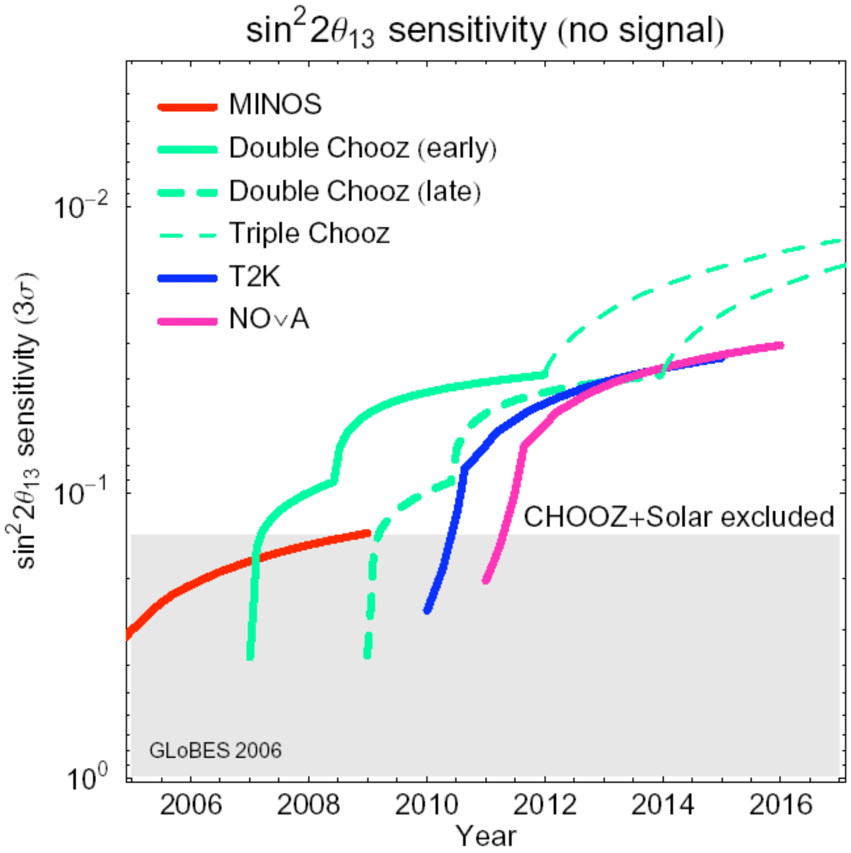
Back ups

Experimental context

3σ discovery potential

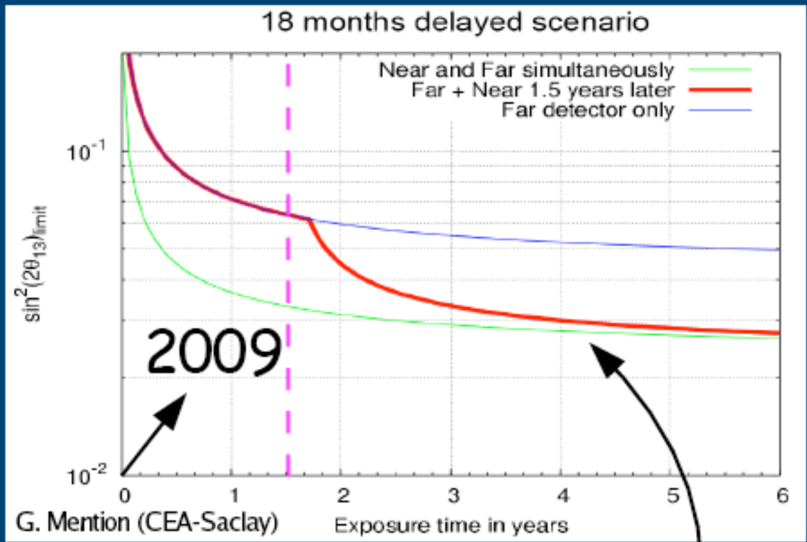


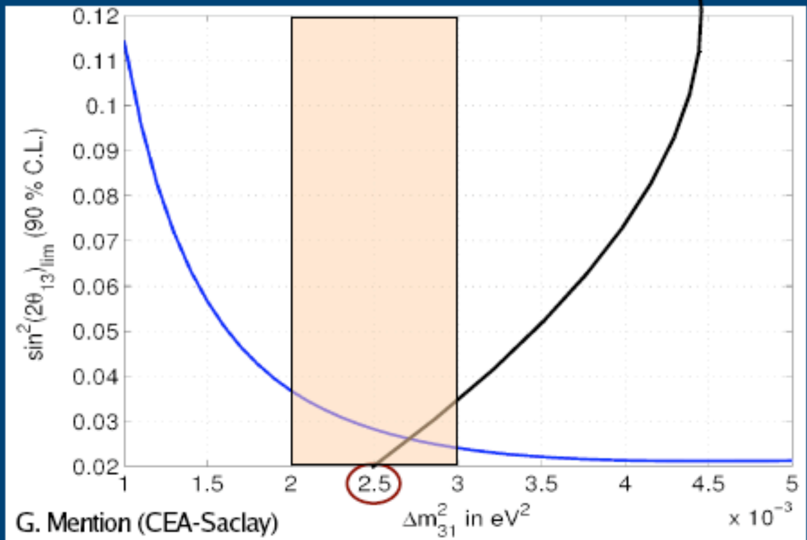
3σ sensitivity (no signal)



Sensitivity

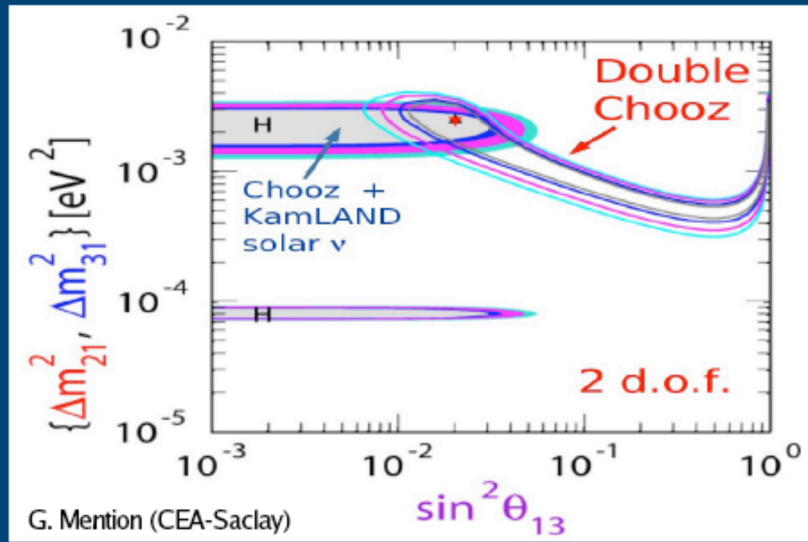
(a limit is put)

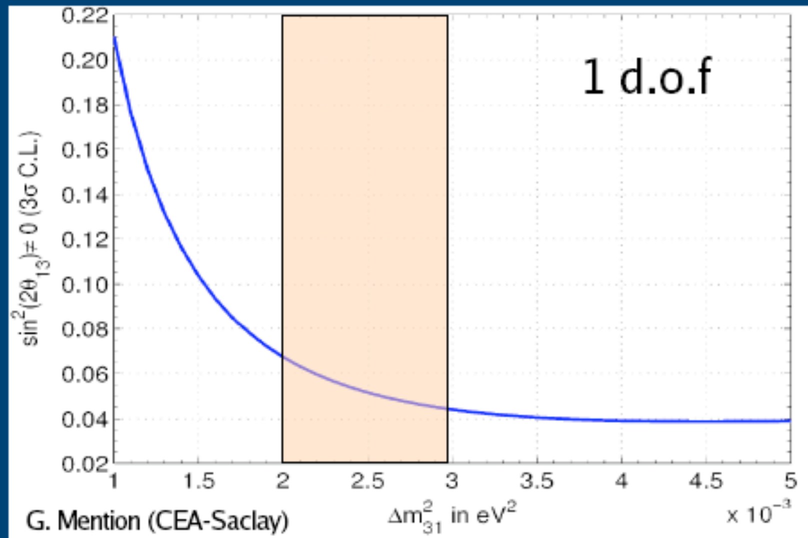




Discovery potential

(a measurement is done)



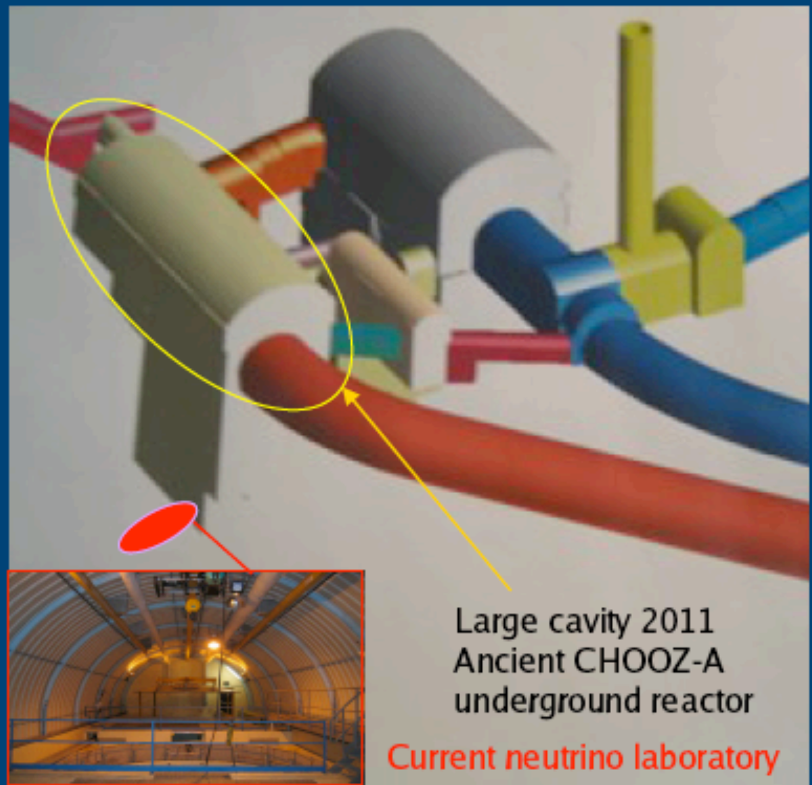


Triple Chooz

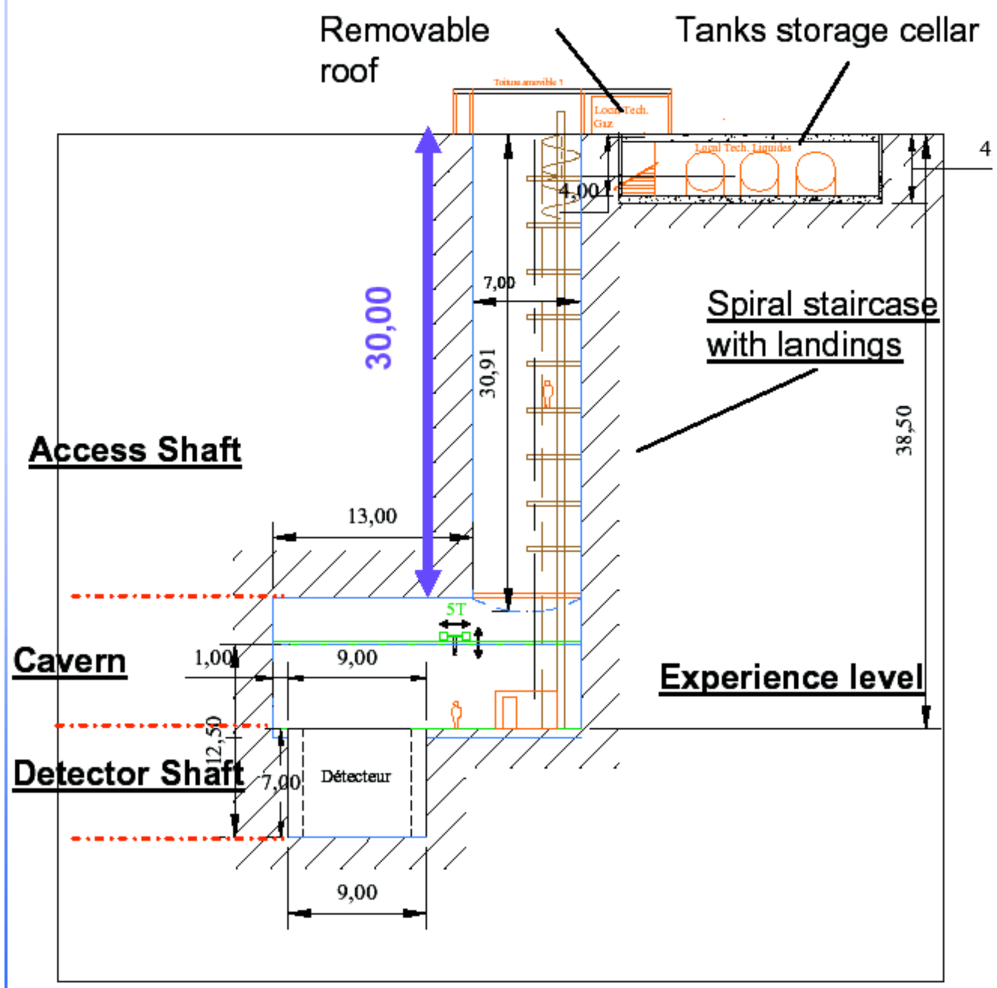
Just an idea ... !

Large cavity next to existing lab, available from 2011 (after dismountling of the ancient CHOOZ-A underground reactor).

A >100t detector could add to Double Chooz to investigate spectral distorsions



Near laboratory infrastructure



Preliminary civil engineering study beginning 2006

Detailed study 2006-2007

Autorisation & call for the bid 2007-2008

Construction 2008-2009
- 45 m shaft
- Liquid storage area
- Buildings & equipements

Integration from end of 2009