Search for the θ_{13} mixing angle with reactor neutrinos

Dario Motta

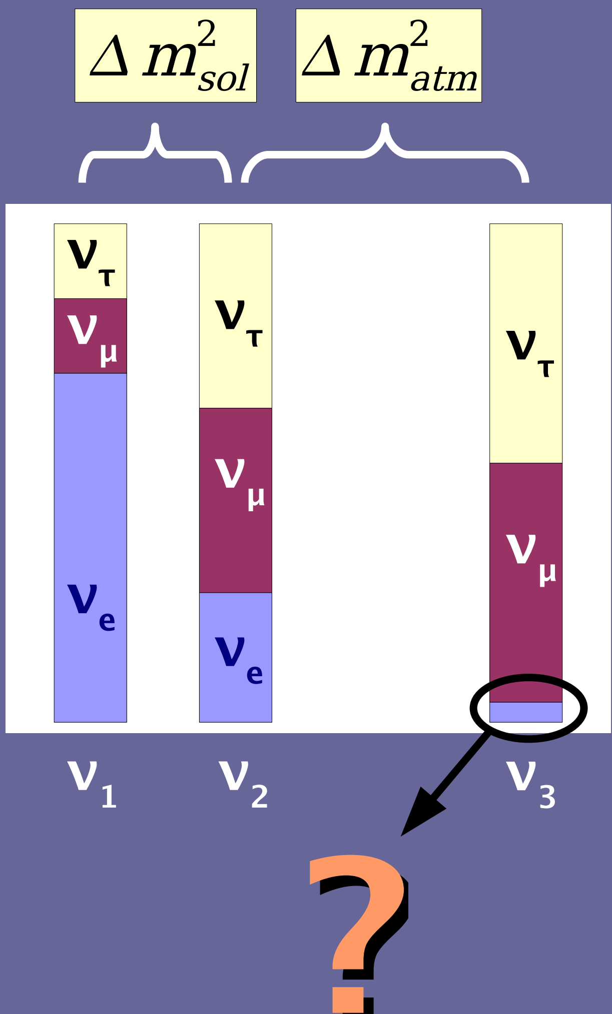
(CEA/Saclay)

6th Rencontres du Vietnam

Hanoi, August 6-12 2006

An Introduction to the Physics

Neutrino mixing : how much of ν_e is in ν_3 ?



$$U_{MNSP} = U_{atm} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{cp}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{cp}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times U_{sol} \times U^{diag}_{Maj}$$

θ_{13} is the key parameter to access:

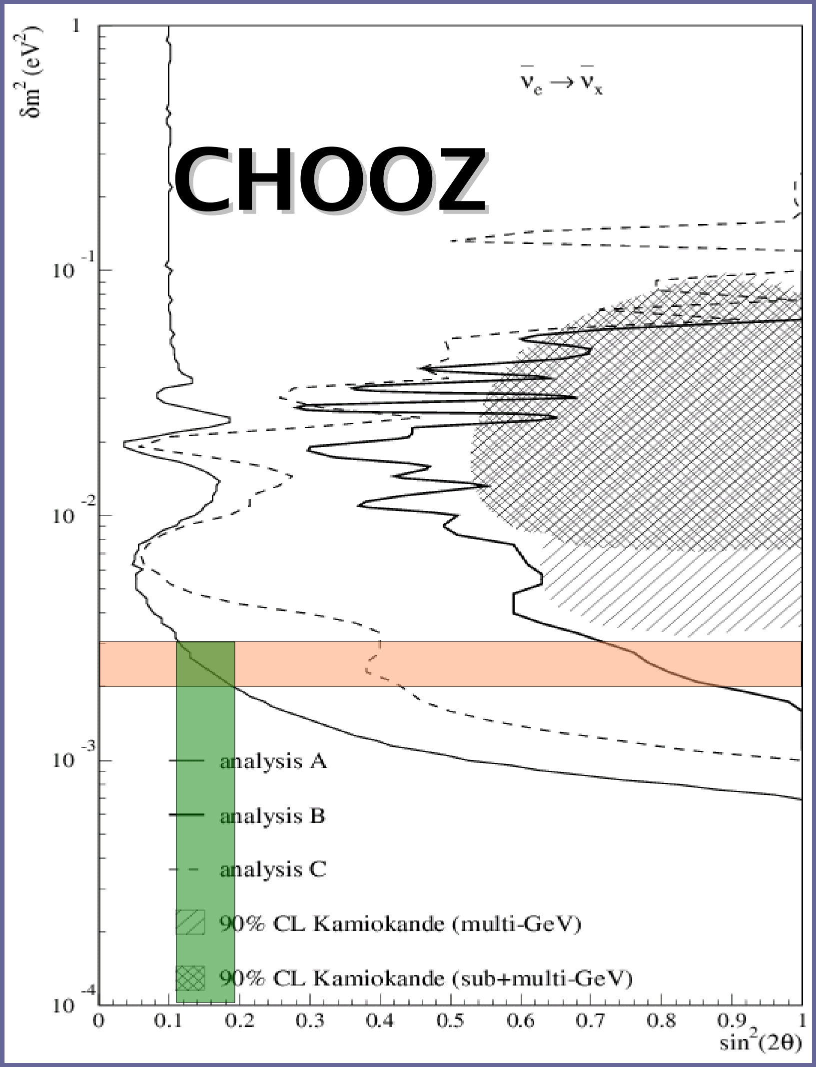
➔ genuine 3-flavors effects

➔ CP-violating phase δ

parameter	bf$\pm 1\sigma$	1σ acc.	2σ range	3σ range
Δm^2_{21} [10^{-5}eV^2]	7.9 ± 0.3	4%	7.3 – 8.5	7.1 – 8.9
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2]	$2.5^{+0.20}_{-0.25}$	10%	2.1 – 3.0	1.9 – 3.2
$\sin^2\theta_{12}$	$0.30^{+0.02}_{-0.03}$	9%	0.26 – 0.36	0.24 – 0.40
$\sin^2\theta_{23}$	$0.50^{+0.08}_{-0.07}$	16%	0.38 – 0.64	0.34 – 0.68
$\sin^2\theta_{13}$	–	–	≤ 0.025	≤ 0.041

(Thomas Schwetz, fit to global data, hep-ph/0606060)

Current constraint (90 % C.L.)



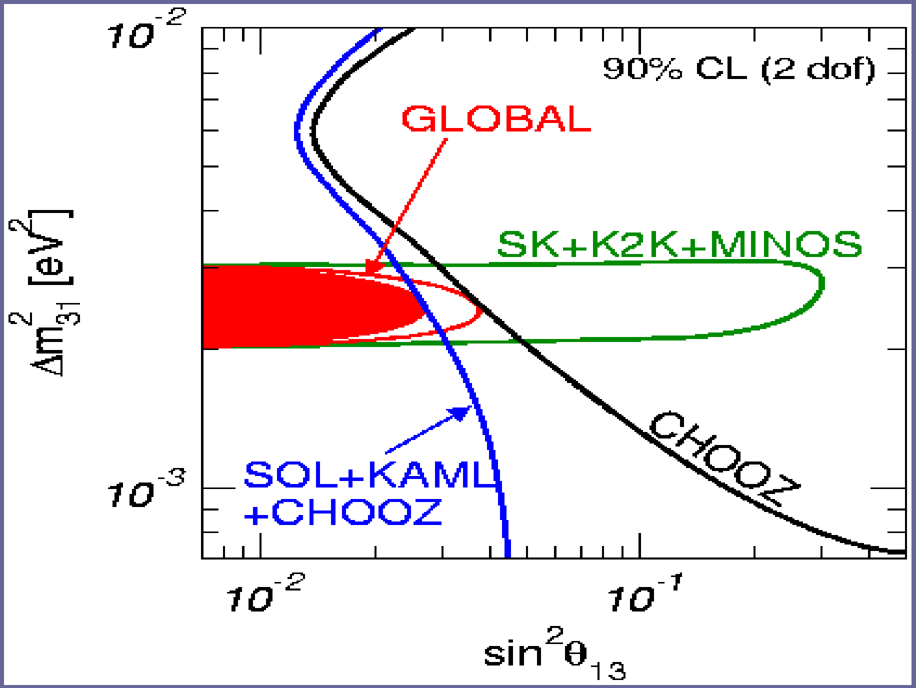
(M. Apollonio et. al., Eur.Phys.J. C27 (2003), 331)

$\sin^2 2\theta_{13} \lesssim 0.12 - 0.20$

(CHOOZ + allowed Δm^2)

$\sin^2 2\theta_{13} \lesssim 0.12$

(global analysis + best fit Δm^2)



(Thomas Schwetz, hep-ph/0606060)

Experimental search for θ_{13}

Look for $\nu_x \rightarrow \nu_y$ oscillations (x or y = e) driven by Δm^2_{13}

Appearance at Super-Beams (T2K, NOvA): $\nu_\mu \rightarrow \nu_e$ (E ~ GeV, L ~10^2– 10^3 km)

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

+ corrections for matter effects

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \qquad \Delta = \frac{\Delta m^2_{31} L}{4 E_\nu}$$

- ➢ θ_{13} signal entangled with unknown parameters
- ➢ Sensitivity to θ_{13} correlations/degeneracies-dominated
- ✔ Sensitivity to CP violation

Disappearance at reactors: $\bar{\nu}_e \rightarrow \bar{\nu}_e$ (E ~ 4 MeV, L ~ km)

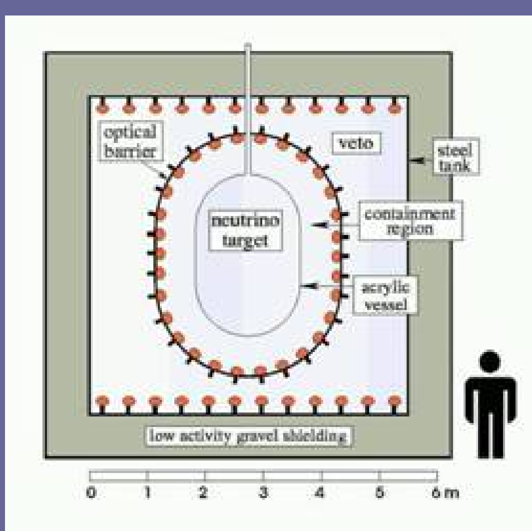
$1-P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = \sin^2(2\theta_{13})\sin^2\Delta$ (+ solar corrections)

- ✔ Clean measurement of θ_{13}
- ➢ Sensitivity to θ_{13} systematics-dominated

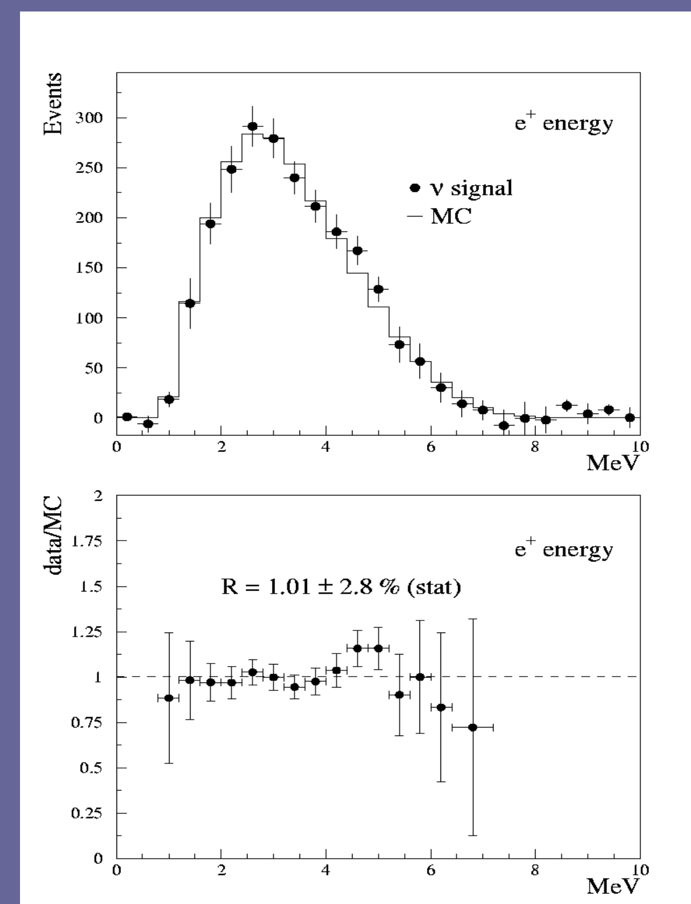
Reactor-based search: experimental concept

CHOOZ experiment

- 2 reactors: $P_{th} = 8.4\ GW_{th}$
- 1 detector: L = 1.05 km, M = 5 t
- Statistics: ~2700 ν-events



R = 1.01 ± 2.8% (stat) ± 2.7% (sys)



How to improve CHOOZ ?

There is still large room to exploit the reactor-based search !

From CHOOZ to next generation experiments

➔ **Statistical error : 2.8 % → ≤ 0.5 %**

➔ **Knowledge of source & detector : 2.7 % → better than 1%**

Proposed approach

✔ Improve statistics by running longer (⇔ scintillator stability), with a larger target mass and an intense source (⇔ reactor power)

✔ Cancel most of the systematics with a 2-detector concept

✔ Improve experimental design to control detector-related systematics

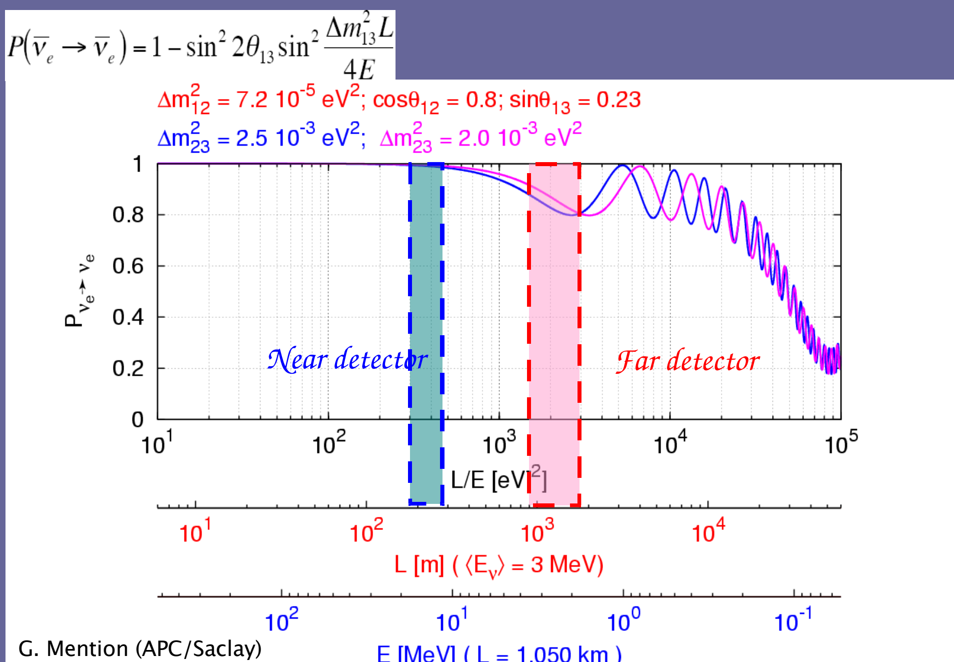
✔ Movable detectors may further reduce systematics (needs validation)

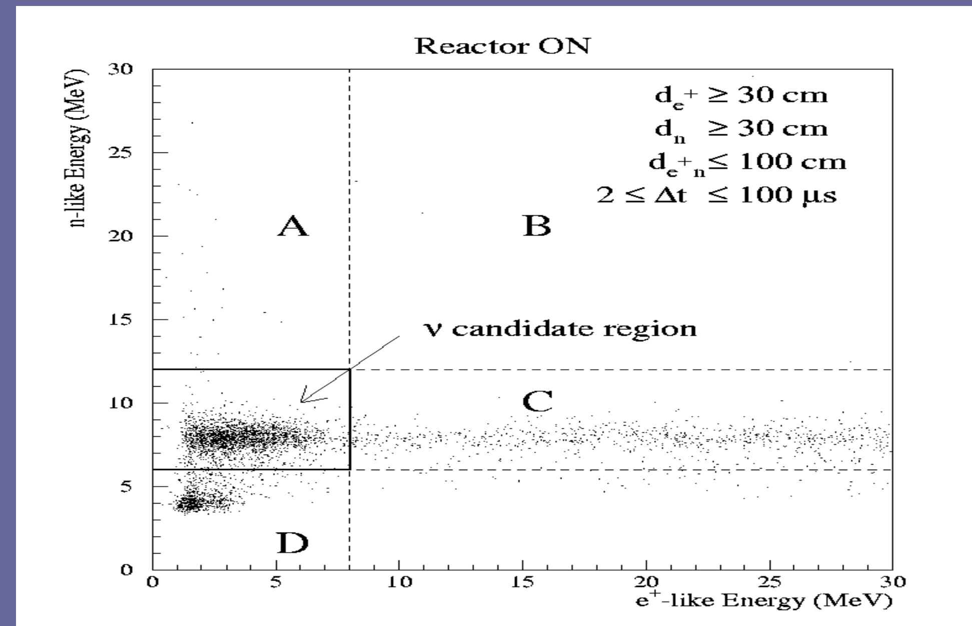
- Martemianov et al., Phys.Atom.Nucl. 66 (2003), 1934 (hep-ex/0211070)
- "White Paper Report on Using Nuclear Reactors to search for a value of θ_{13}", hep-ex/0402041 (125 authors, 40 Institutions, Editor: M. Goodman)

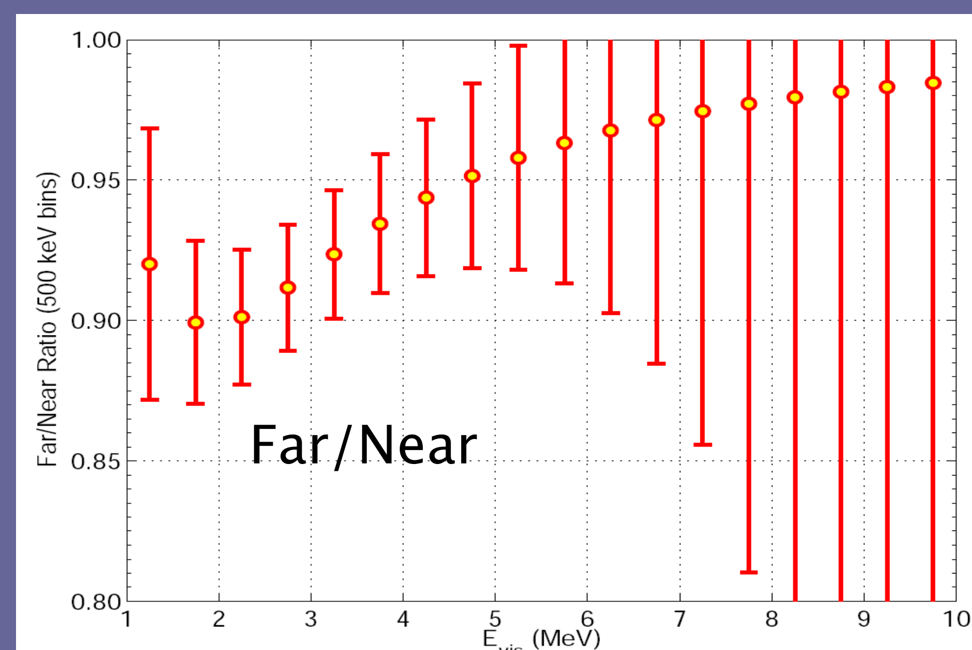
Experimental concept in a nutshell

$\bar{\nu}_e + p \rightarrow e^+ + n \; (Q = 1.8 \text{ MeV})$

$n_{th} + Gd \rightarrow Gd^* \rightarrow Gd + \sim 8\text{MeV}$







Expected signal in Double Chooz

$\sin^2 2\theta_{13} = 0.1$; $\Delta m^2_{13} = 2.5 \cdot 10^{-3}$ eV^2 ;

3y data ; error bars statistical only

Detector layout (Double Chooz)

Other projects discussed here have very similar design ...

$\bar{\nu}$ **Target** (~ 8.2 tons Gd-doped scintillator)

γ–catcher (t=55 cm, undoped scintillator)

Buffer (t= 105 cm, mineral oil)

Veto (t=50 cm, mineral oil + fluors)

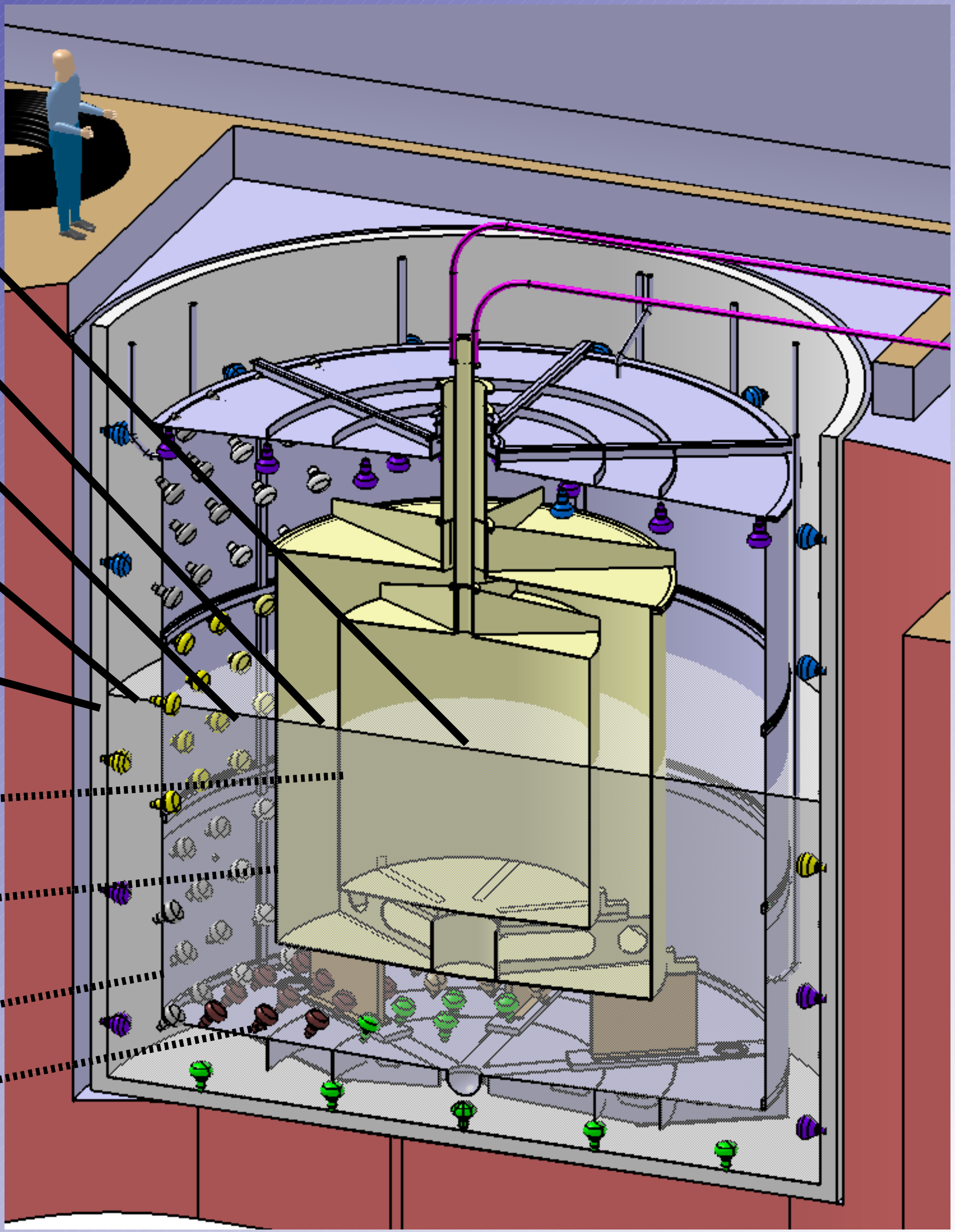
Shielding (17 cm steel)

Acrylic target vessel

Acrylic γ–catcher vessel

Buffer tank (stainless steel) & PMT support structure

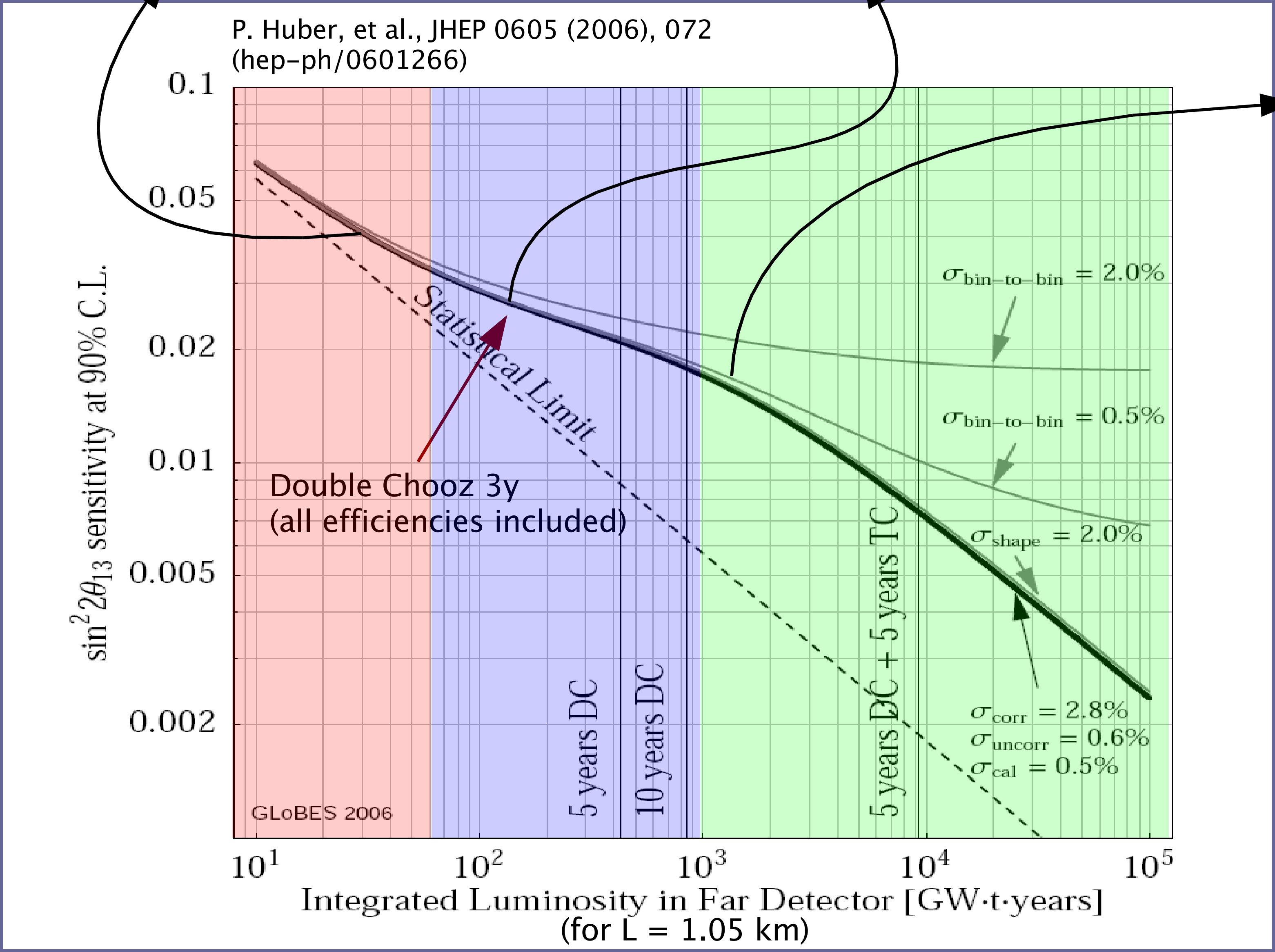
PMTs (534 + 80, 8")



Sensitivity (if no signal, 90% C.L.)

- dominated by Rate ratio
- limited by statistics

- mostly from Rate ratio, some from shape
- limited by σ_{norm} for R, by statistics for the shape



- mostly from shape distortion
- limited by spectral shape uncertainties due to uncorrelated $\sigma_{bin-to-bin}$ (bkg, ...)

Note:

calculation for Double Chooz base case (σ_{norm} = 0.6 %)

The fight for the reduction of systematics

		CHOOZ (single far detector)	Realistic now (Double Chooz proposal)	Wished for future (need further R&D)	Comments
Reactor	Power	~ 2 %	negligible	negligible*	*: ~ 0.1% for Multi-core site
	E/fission	0,6%	negligible	negligible	
	ν/fission	0,2%	negligible	negligible	
	σ	0,1%	negligible	negligible	
	Distances & finite size	negligible	0,2%	0,1%	distances known at 10 cm
	Tot Reactor	2,2%	0,2%	0,1%	
# target p		0,8% (absolute)	0,2% (relative)	0,1%	If same batch of scintillator only error on target M -> detector swapping ?
Efficiency	e^+ energy cut	0,8%	0,1%	0,05%	low threshold, γ-catcher
	Gd/H captures	1,0%	0,2%	< 0,1%	identical detectors
	n energy cut	0,4%	0,2%	< 0,1%	
	e^+ – n distance	0,3%	not necessary	not necessary	lower single rate (buffer)
	e^+ – n delay	0,4%	0,1%	0,03%	identical detectors
	n multiplicity	0,5%	negligible	negligible	lower single rate (buffer)
	dead-time near		0,2%	negligible	random fake-ν generator
	Tot efficiency	1,5%	0,4%	≲0,15%	
	Grand Total	**2,7%**	**≲0,5%**	**≲ 0,2%**	

A staged approach from 1st to 2nd generation ?

Backgrounds

CHOOZ measured Reactor-off background ...

Chance for a "signal-free" background measurement:

- **2-core sites** ⇒ both reactor off is extremely rare, but possible (in addition, ~ a few weeks/y with 1 reactor off for re-fueling)
- **Multi-core sites** ⇒ impossible ... (just modulations of total power)

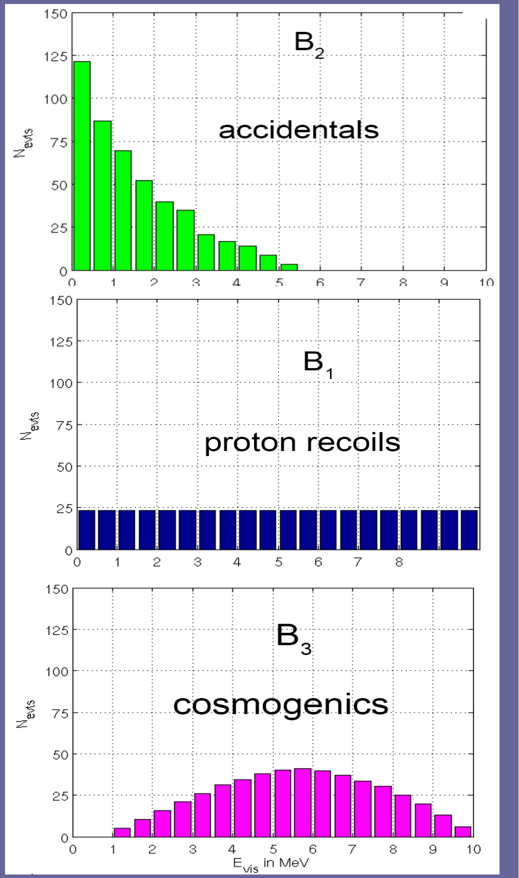
Note: some backgrounds can be measured in-situ with reactors on

3 types of background

➔ Accidentals: γ + delayed n-like

➔ Fast n: p-recoil + n capture by "near-miss" μ

➔ Cosmogenics: β-n emitters (^{9}Li, ^{8}He) created by showering μ



Remember that background is tolerable if

~ 10t Target ⇒ uncertainty/En-bin ~ 1% of the signal

≳100 t Target ⇒ uncertainty/En-bin ≲ 0.5% of the signal

All backgrounds are suppressed with <u>increasing overburden</u> ...
Further handles from detector design:

Accidentals
- material radio-purity
- shielding

} Can be measured ***in-situ***

Fast n (recoil p + n capture)
- large and effective μ-veto
- shielding

} Can be measured ***in-situ*** for E above and below $\bar{\nu}$ signal (shape known ~ flat)

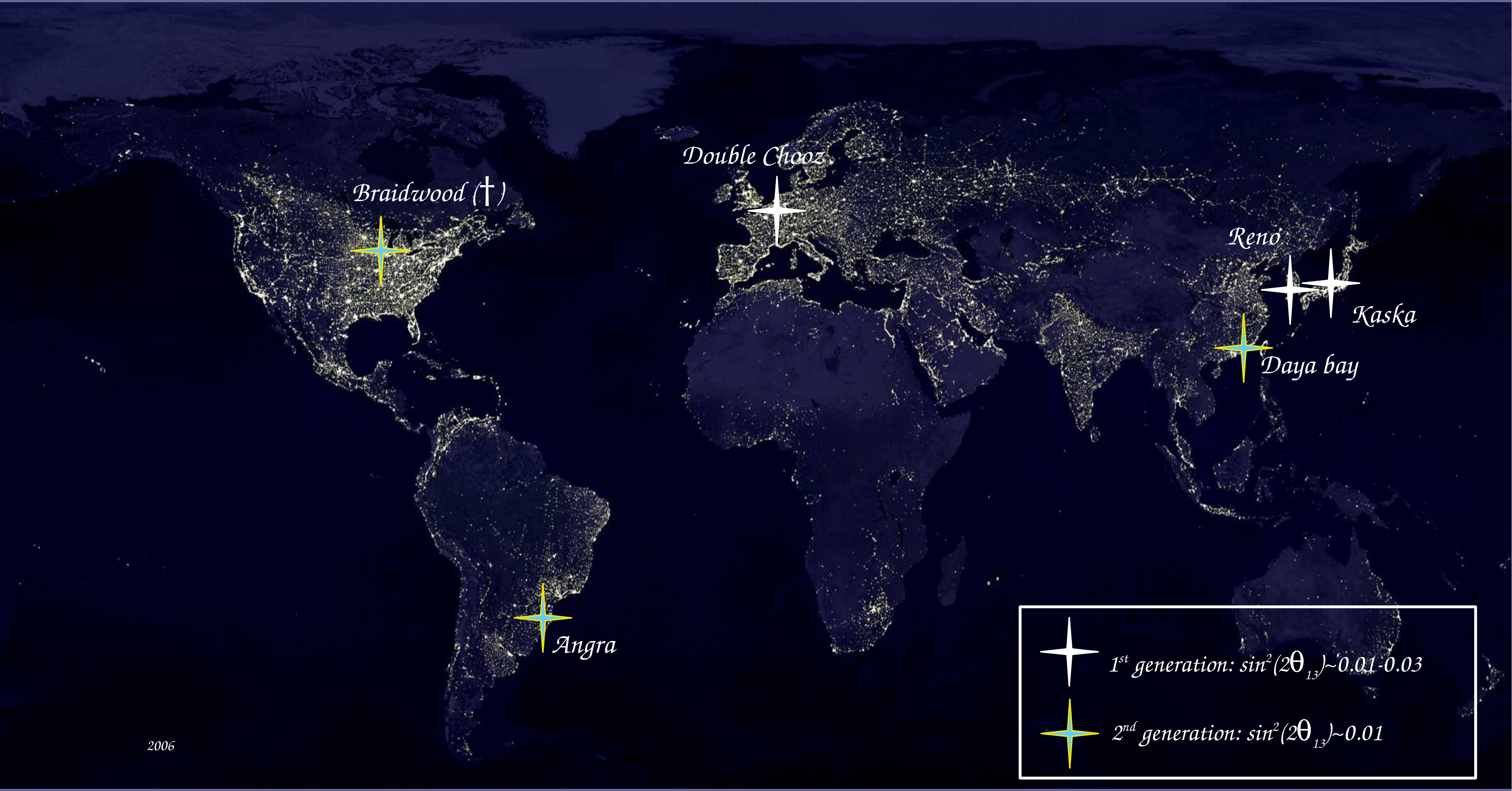
Cosmogenics (^{9}Li, ^{8}He)
- overburden !
- veto for showering μ

} Shape known. Rate to evaluate with MC, past measurements (CHOOZ, KamLAND, ...) or dedicated experiments

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		$1.01 \pm 0.04(stat) \pm 0.1(sys)$		
	Far	bkg/ν	1.6%		4%		
		Systematics	0.2%		0.4%		
Double Chooz		Rate (d^{-1})	1 ± 0.1	1 ± 0.1	0.15 ± 0.15	0.42 ± 0.2	1 ± 0.5
(69 ν/d)	Far	bkg/ν	1.4%	1.4%	0.2%	0.6%	1.4%
		Systematics	0.2%	0.2%	0.2%	0.3%	0.7%
Double Chooz		Rate (d^{-1})	7.2 ± 1.0	7.2 ± 1.0	1.4 ± 0.14	2.6 ± 1.2	5.2 ± 3.2
(990 ν/d)	Near	bkg/ν	0.7%	0.7%	0.14%	0.26%	0.6%
		Systematics	0.1%	0.1%	0.2%	0.1%	0.3%

Table from
Double Chooz proposal
hep-ex/0606025

Proposed Experiments



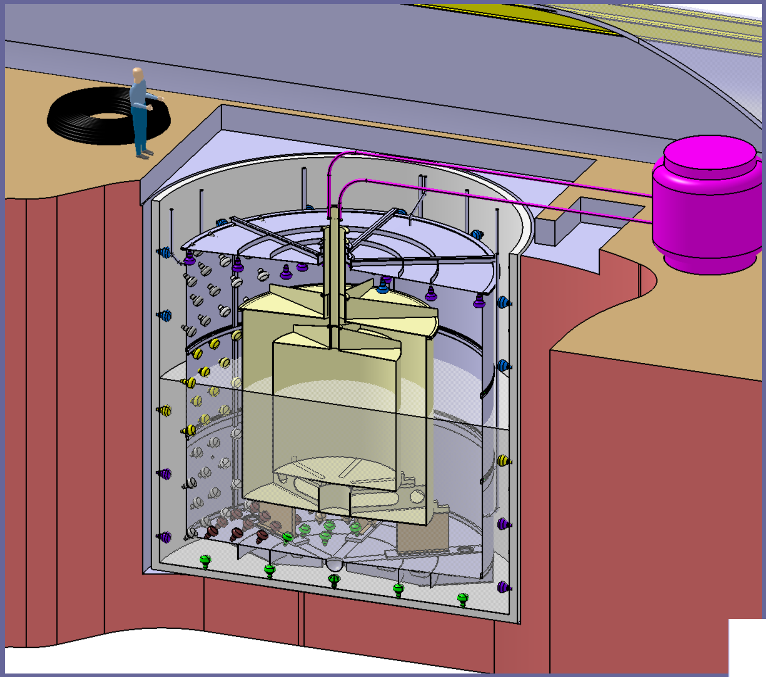
Double Chooz

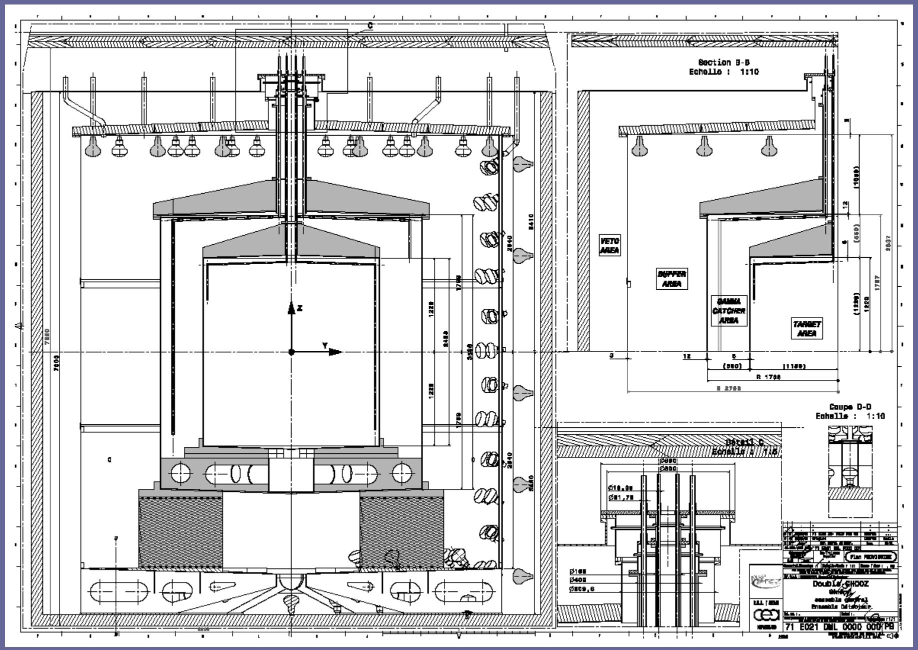
Far site: L = 1050 m
available from CHOOZ
~ 300 mwe

Near site: L ~ 280 m
(to build, ~ 80 mwe)

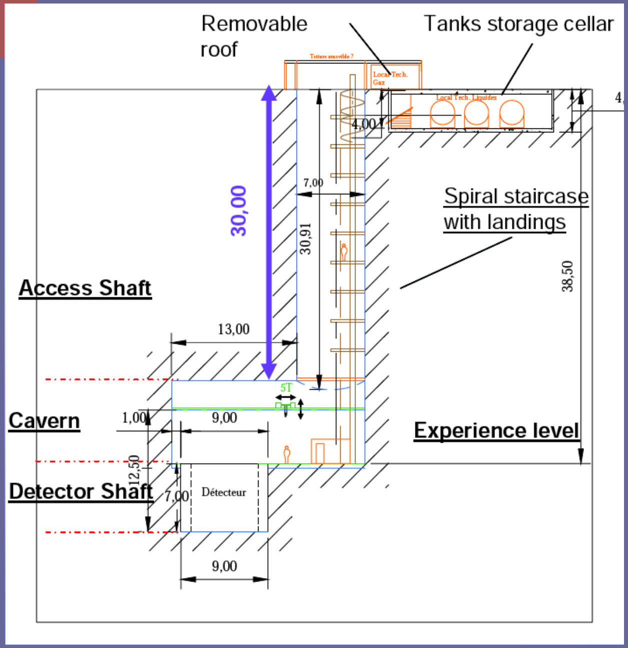
- **2 cores – 1 site – 8.5 GW_{th}**
- **1 near, 1 far position (the latter available!)**
  - 2x8.2t target masses
- **Civil constructions**
  - 1 near shaft ~ 40 m, Ø 6m
  - 1 laboratory
- **Statistics (including ε)**
  - far: ~ 50 events/day
  - near: ~ 550 events/day
- **Systematics**
  - reactor: ~ 0.2%
  - detector: ~ 0.5%
- **Backgrounds**
  - $\sigma_{bin-bin}$ at far site: $\lesssim$ 1%
  - $\sigma_{bin-bin}$ at near site: $\lesssim$ 0.5%
- **Planning**
  1. Far detector only
     - 2008-2009
     - Sensitivity (1.5 years) ~ 0.06
  2. Far + Near detector
     - from 2010
     - Sensitivity (3 year) $\lesssim$ 0.03

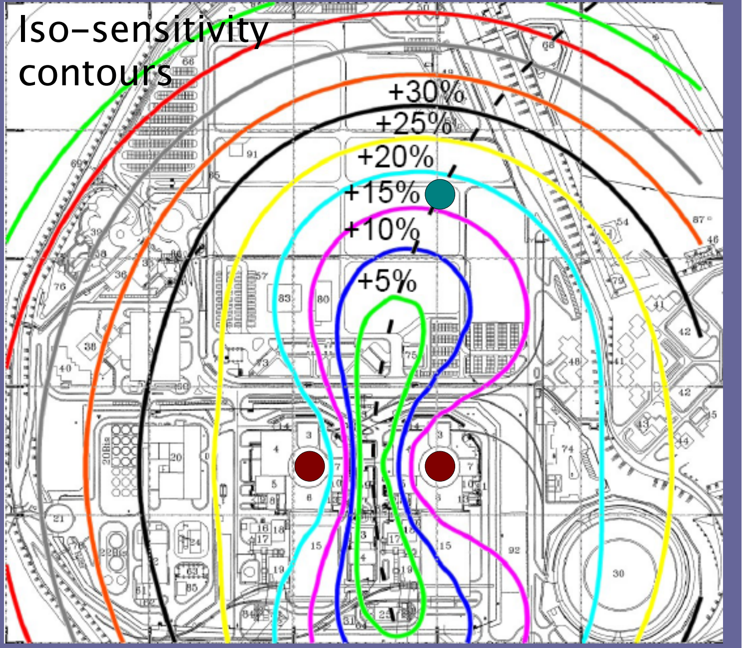
Detector design finalized





Pre-study for the design and optimization of the near laboratory concluded





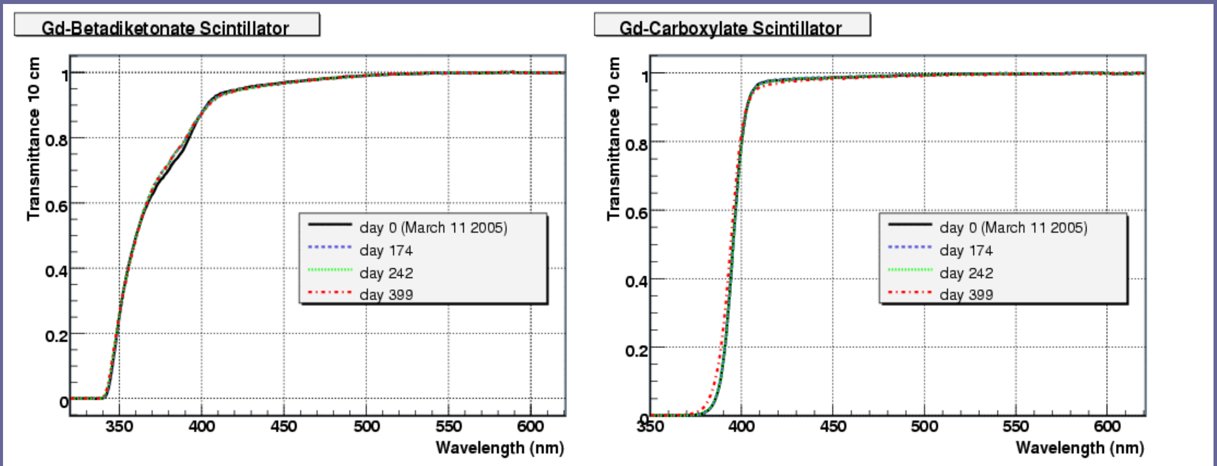
See proposal for details of all sub-systems:

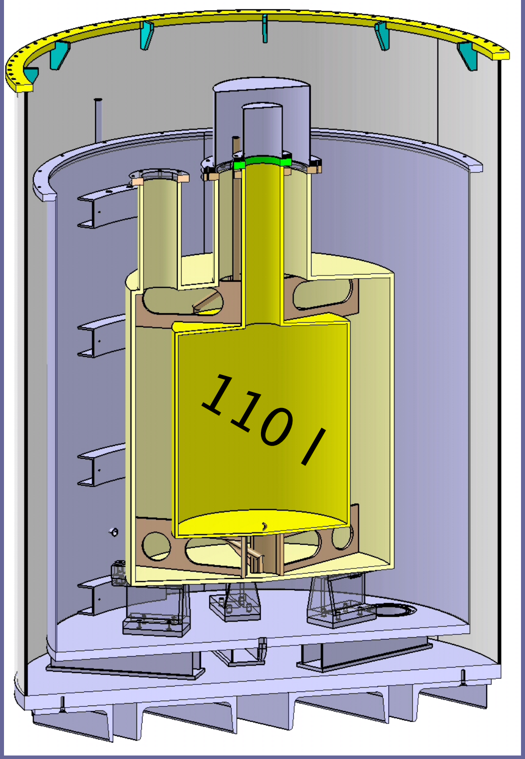
hep-ex/0606025

R&D on Gd-doped scintillators and acrylic

- ✔ 2 formulations of Gd-doped LS developed and successfully tested (Gd-cbx and Gd-bdk)
- ✔ Chemical project now scaling from ~ 100 l to industrial production

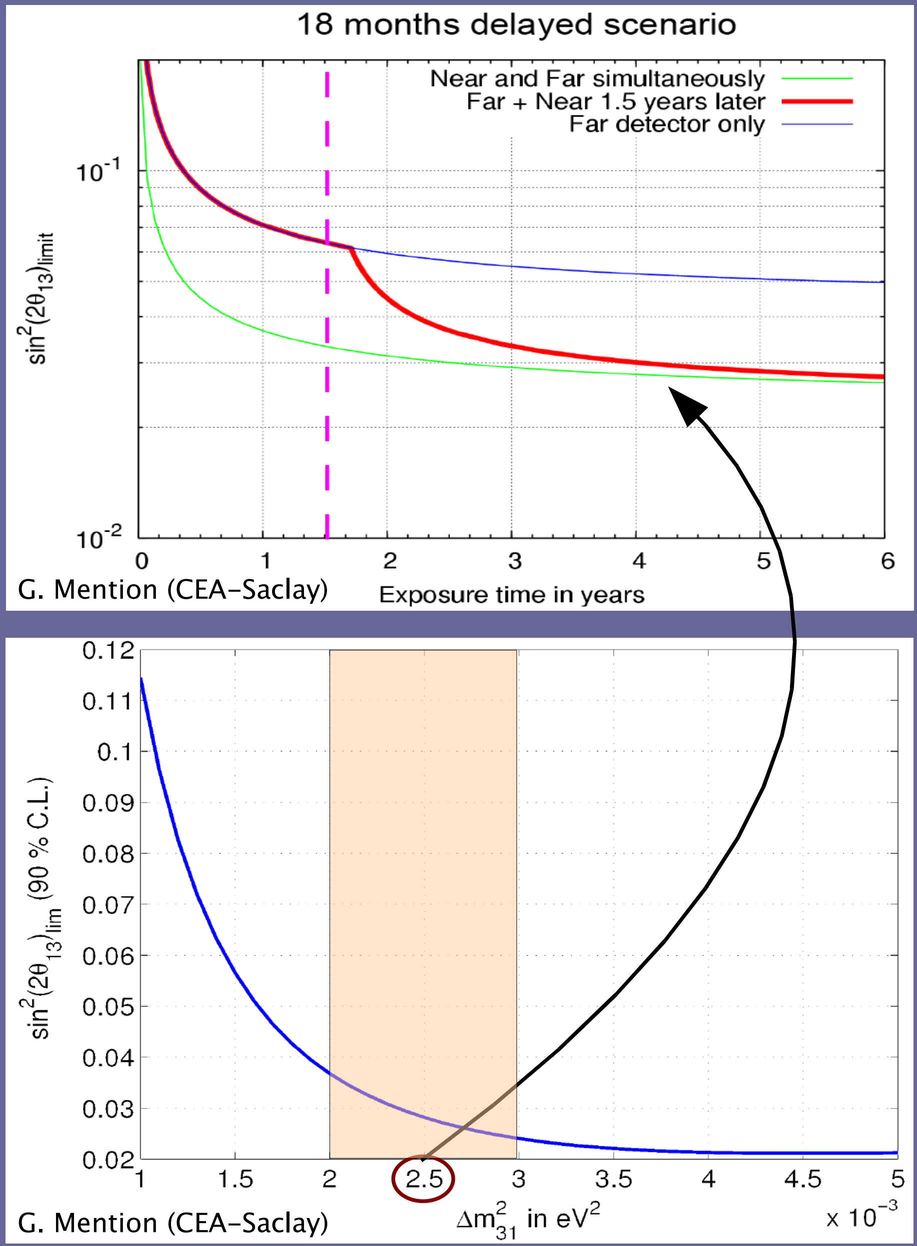
Test of the long-term stability of Gd-doped LS samples



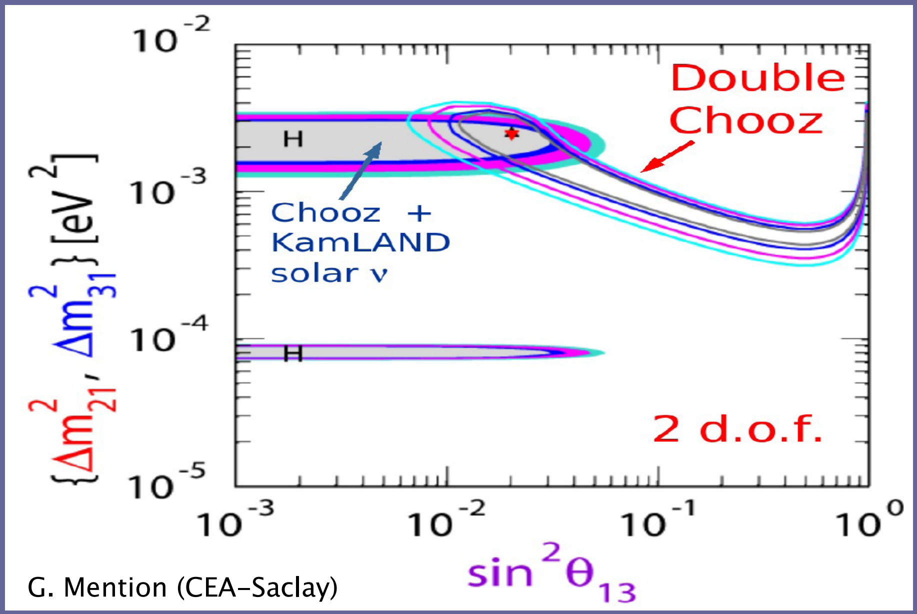


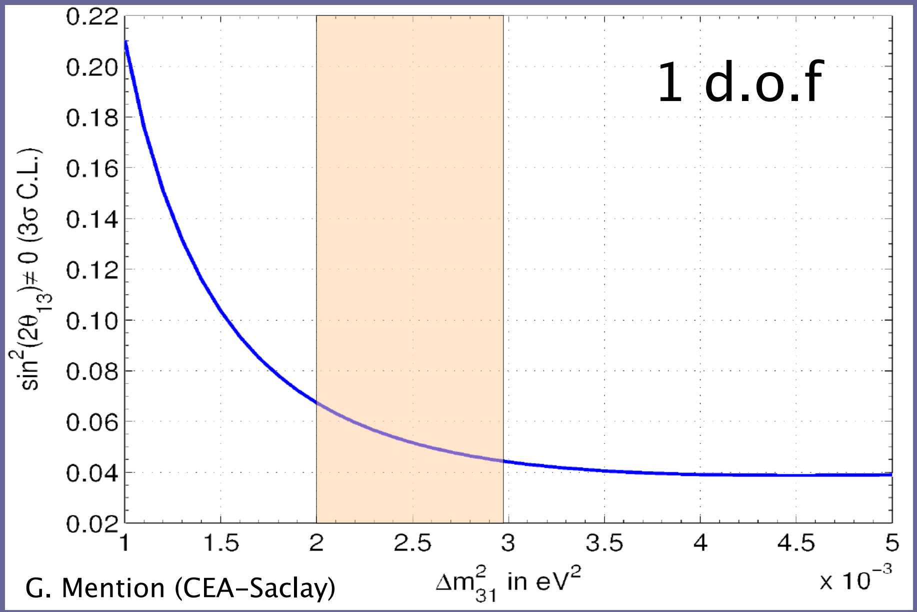
1/5 technological mock-up
Target filled with 110 l Gd-loaded scintillator
⇒ comprehensive validation test (concluded, analysis ongoing)

Sensitivity



Discovery potential





Double Chooz status & prospects

✔ Double Chooz approved and funded in France
✔ Funded by Max Planck Society, first approval by German BMBF
✗ DOE rejected the US R&D proposal (stating there is not enough money for a participation in both Double Chooz and Daya Bay)
✔ The reaction of the French agencies was doubling their initial investment ... Strong French commitment to not delay the project
✔ New collaborators: Madrid; Oxford (Braidwood migration ...)

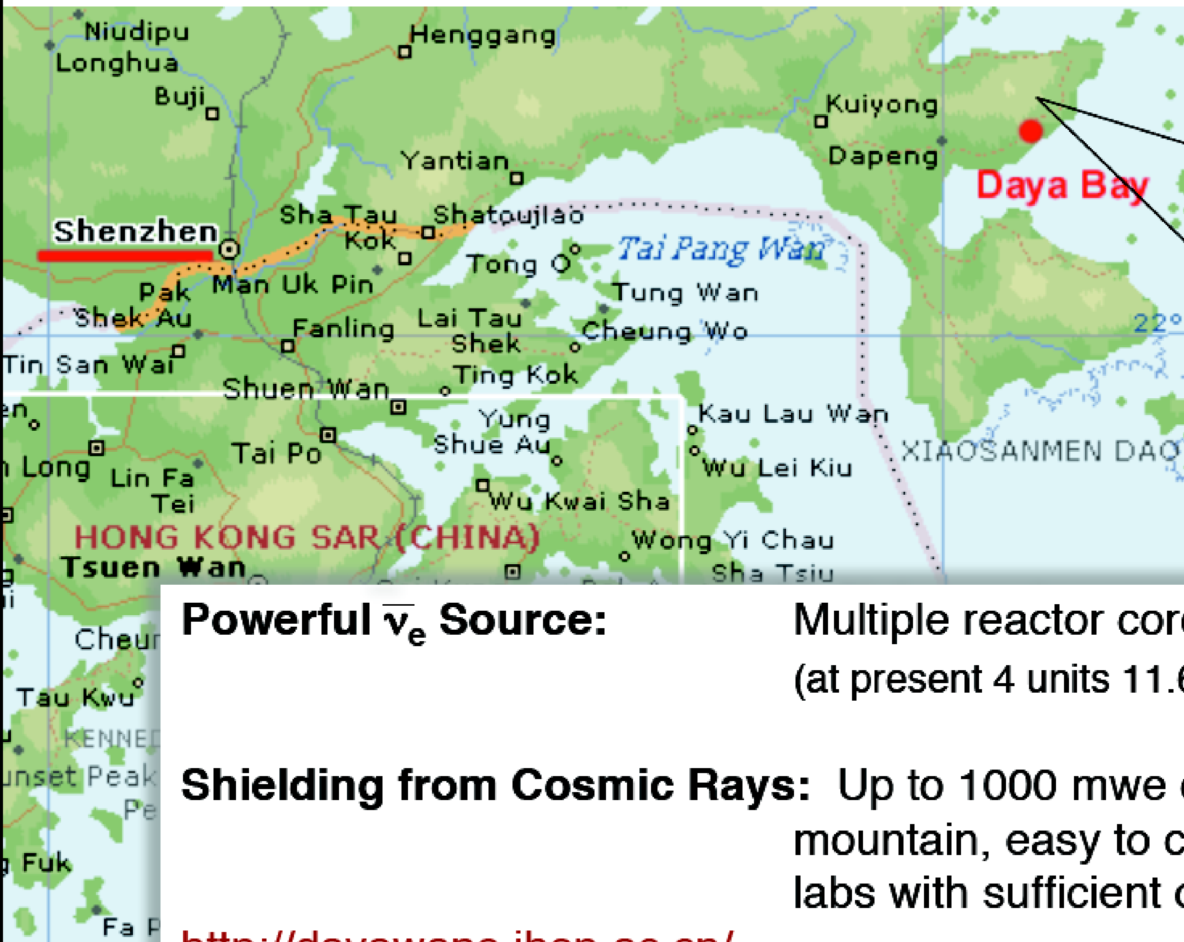
The largest part of the **funding is secured**
R&D is concluded

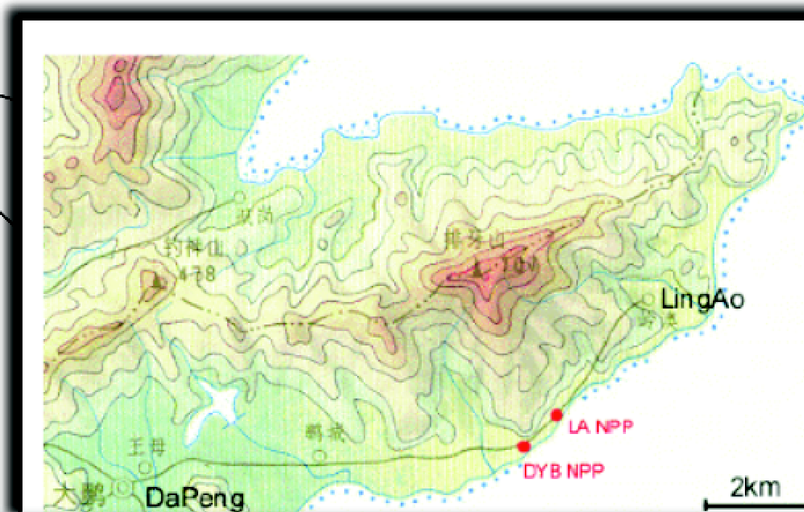
Project shifting now to construction phase

- Proposal: hep-ex/0606025 (157 pages, 113 authors, 24 institutions)
- now → 2007: material procurement
- Oct 2007: start far detector construction
- June 2008: far detector commissioning
- 2008: near lab construction
- Spring 2009: near lab available
- Fall 2009: near detector commissioning

Daya Bay, China

Nice slide from
K. Heeger
Neutrino 2006





Powerful $\overline{\nu}_e$ Source: Multiple reactor cores.
(at present 4 units 11.6 GW_{th}, in 2011 6 units with 17.4 GW_{th})

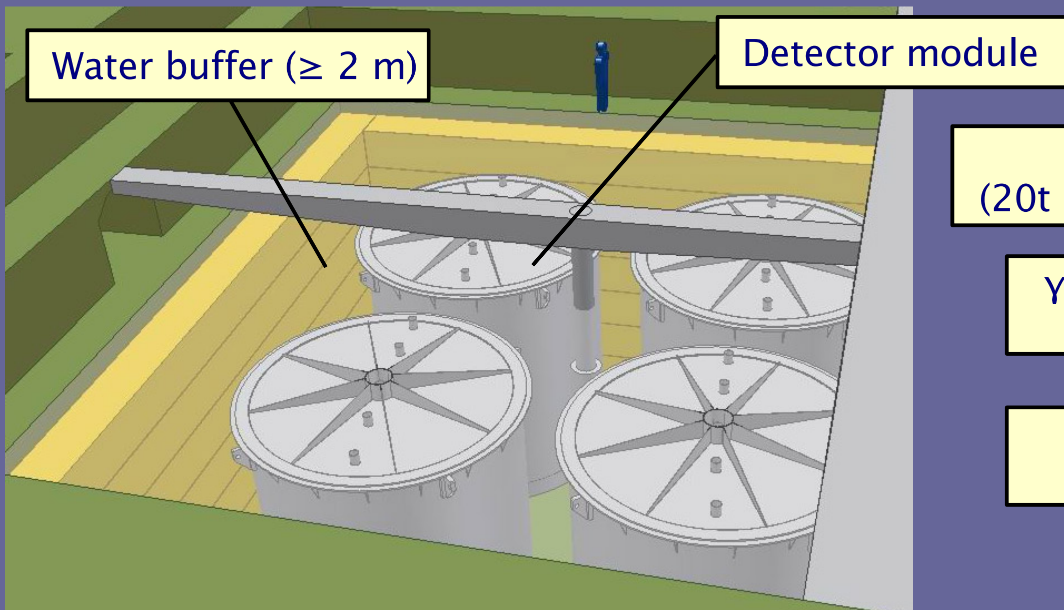
Shielding from Cosmic Rays: Up to 1000 mwe overburden nearby. Adjacent to mountain, easy to construct tunnels to reach underground labs with sufficient overburden to suppress cosmic rays

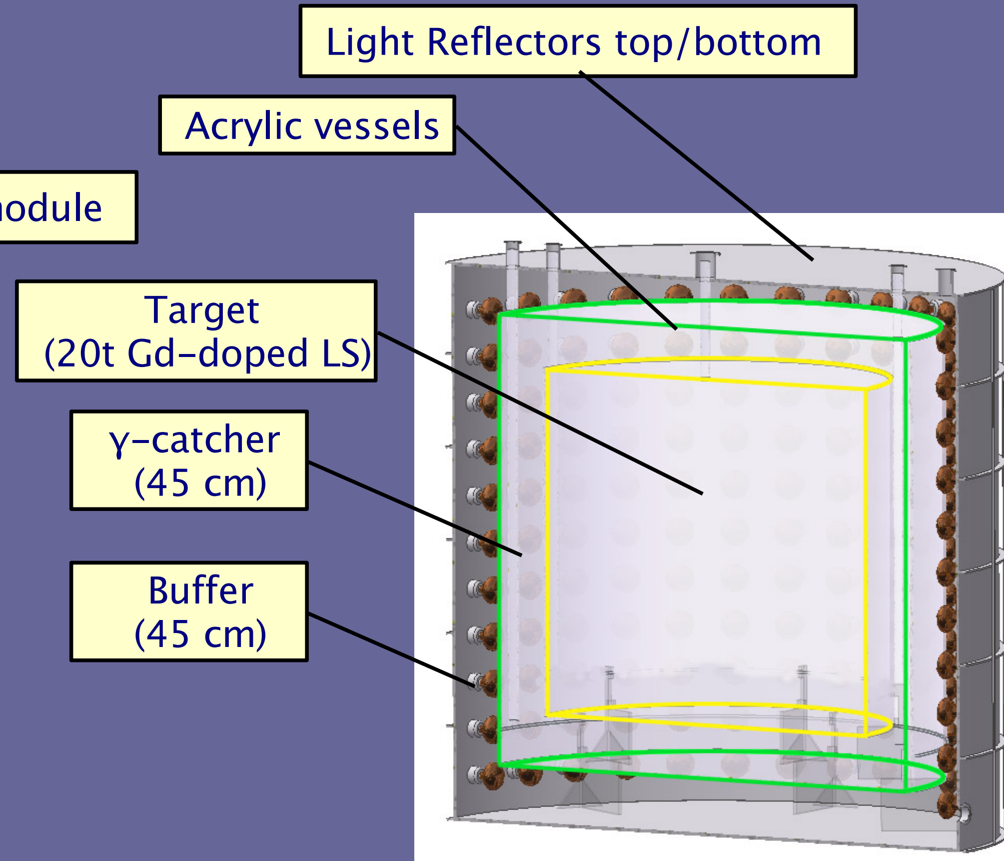
http://dayawane.ihep.ac.cn/

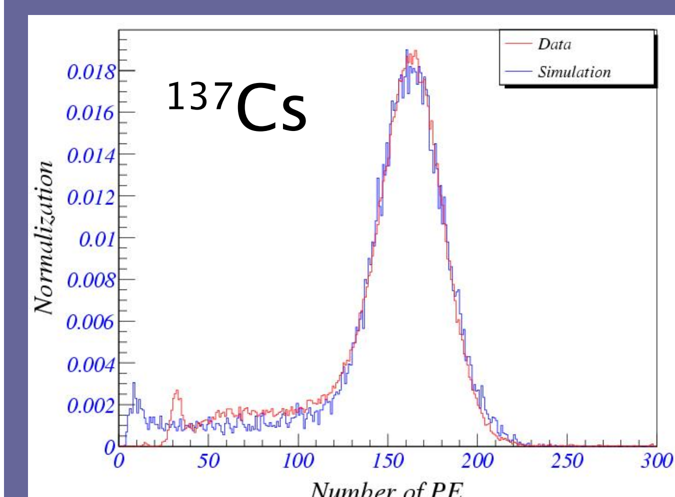
Overview of the Daya Bay experiment

- **4 cores – 2 sites – 11.6 GW_{th}**
  -> 6 – 3 in 2011, 17.4 GW_{th}
- **2 near, 1 mid, 1 far position**
  - far: 4x20t modules
  - near: 2 x 2 x 20t
- **Civil constructions**
  - ~ 3.4 km galleries
  - 4 laboratories
- **Statistics**
  - far: 80 events/day
  - near: 560 events/day
- **Movable modules** -> **swap**
- **Systematics**
  - reactor: ~ 0.1%
  - detector: ~ 0.2%
- **Backgrounds**
  - B/S at near site: ~ 0.5%
  - B/S at far site: ~ 0.2%
- **Planning**
  1. Fast measurement
     - DYB+Mid, 2008–2009
     - Sensitivity (1 year) ~ 0.03
  2. Full Measurement
     - DYB+LA+Far, from 2010
     - Sensitivity (3 year) <0.01

Design and R&D



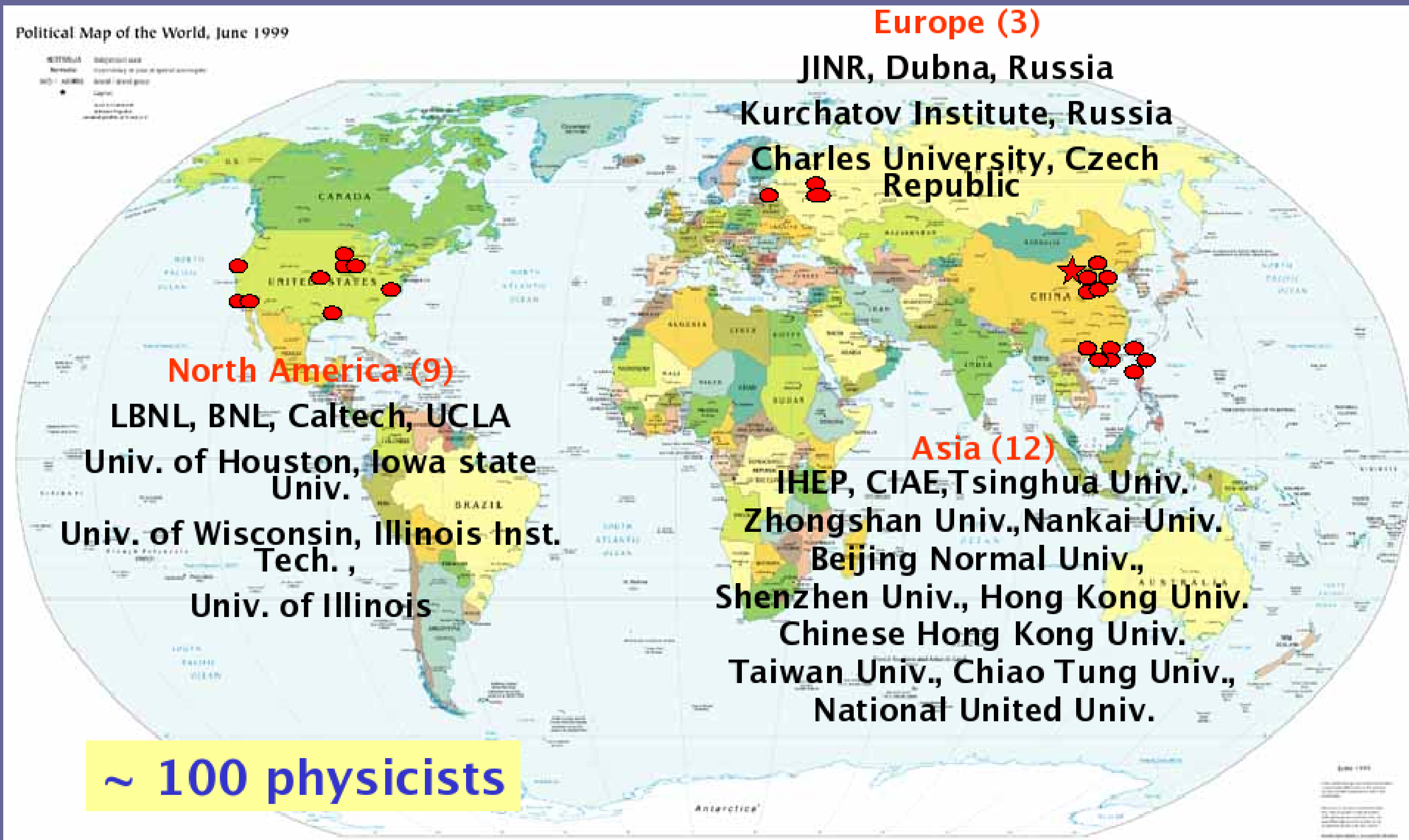




Prototype

- 0.6 t (undoped)
- 45 PMTs
- takes data !

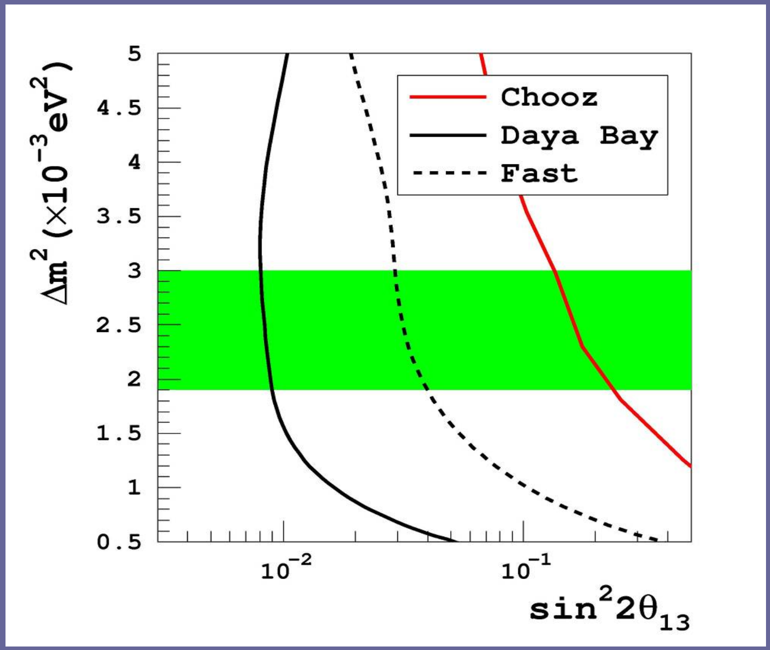
The Daya Bay collaboration
A strong US-China commitment !



Daya Bay status & prospects

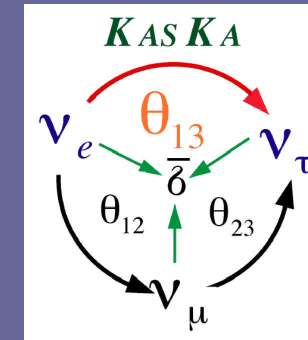
- Project approved in China
- Chinese Atomic Energy Agency and the Daya Bay nuclear power plant are very supportive to the project
- Funding agencies in China are supportive, R&D funding in China approved and available
- R&D funding from DOE approved
- Site survey including bore holes completed
- R&D underway, prototype operational
- Proposals in preparation

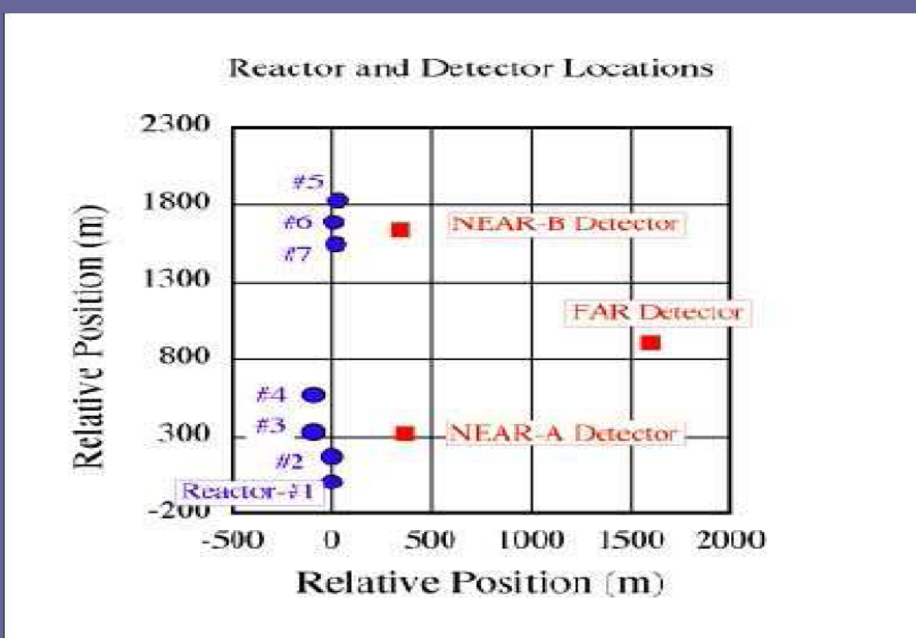
Anticipated sensitivity



KASKA

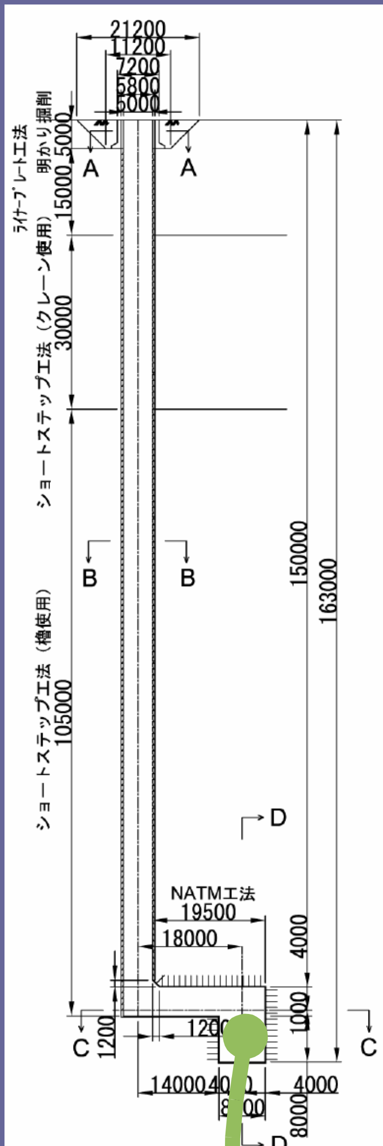
(*Kas*hiwazaki-*Ka*riwa Nuclear Power Station)

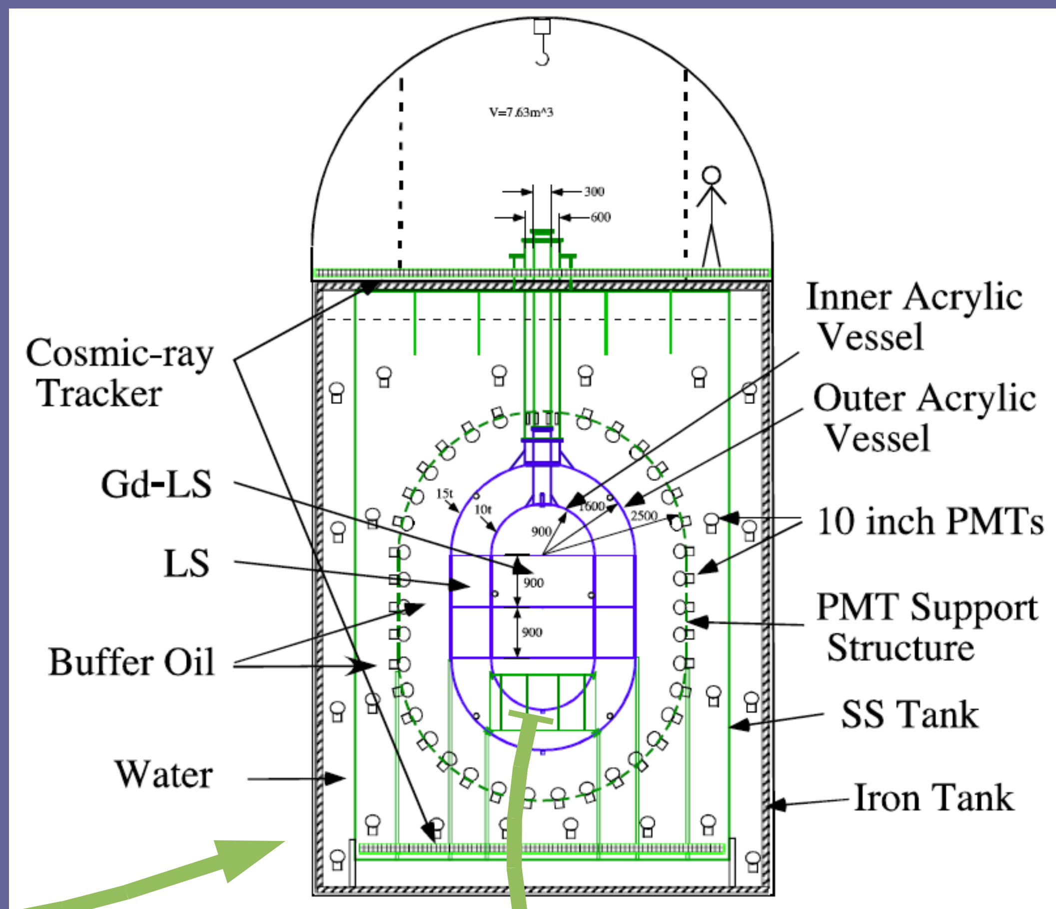


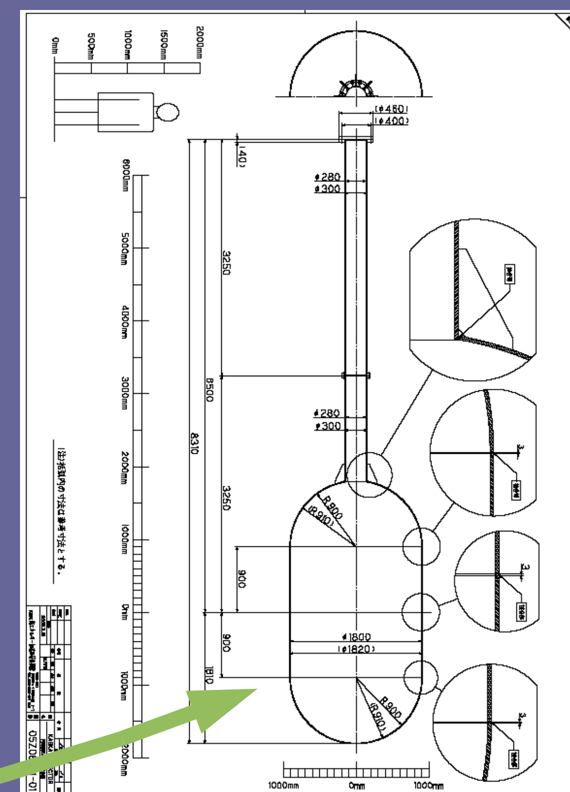


- **7 cores – 2 sites – 24.3 GW_{th}**
- **2 near, 1 far position**
  - 3 x 6t target mass
- **Civil constructions**
  - 2 near shafts: ~ 50 m, Ø 6m
  - 1 far shaft: ~ 150 m, Ø 6m
  - 3 laboratories
- **Statistics**
  - 0.4 % after 3 y data-taking
- **Systematics**
  - reactor: ~ 0.2%
  - detector: < 0.8%
- **Background**
  - subtraction error < 0.6%
- **Planning**
  - pending funding, 3y construction
  - sensitivity (after 3 year) <u><0.025</u>

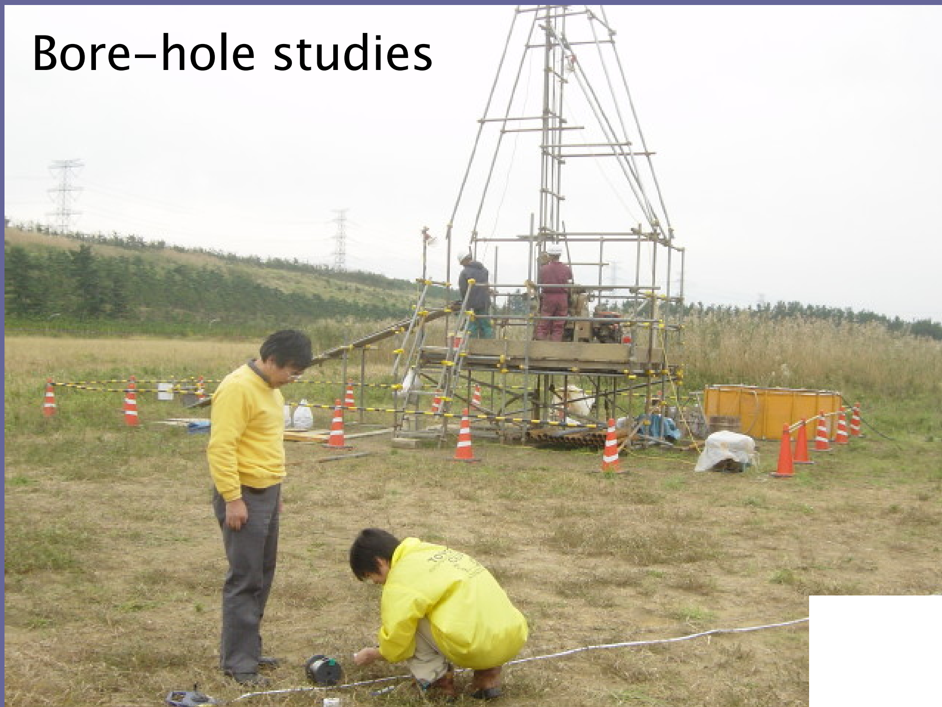
A mature design ...

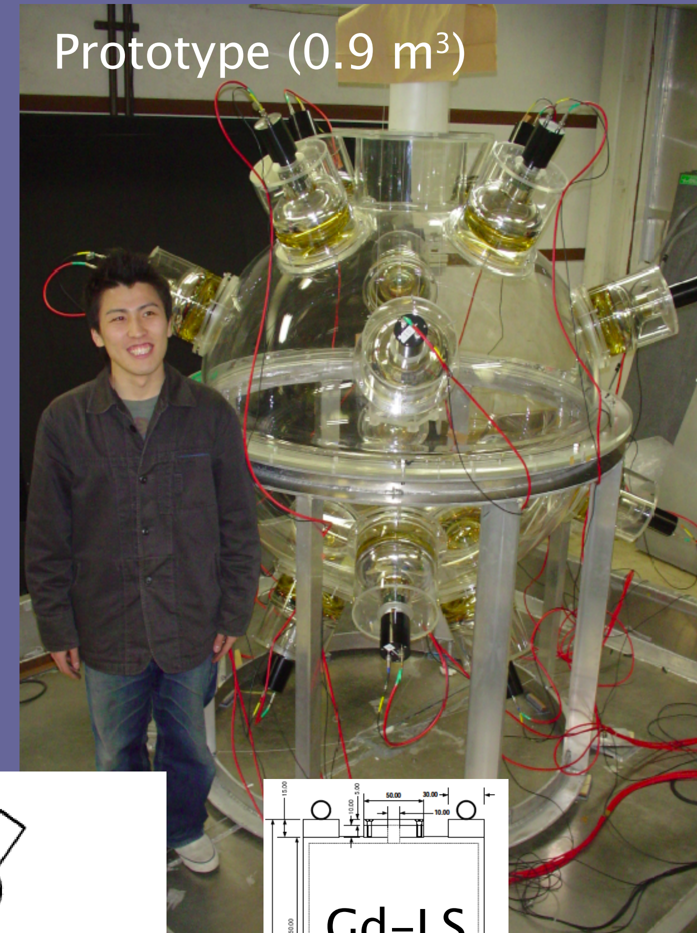


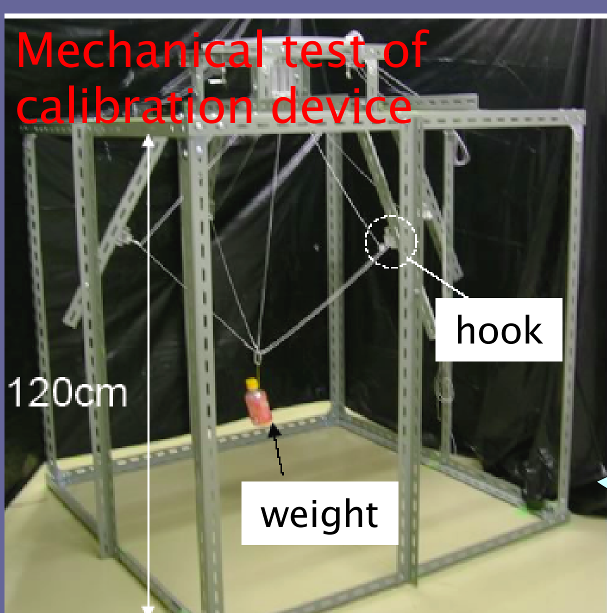


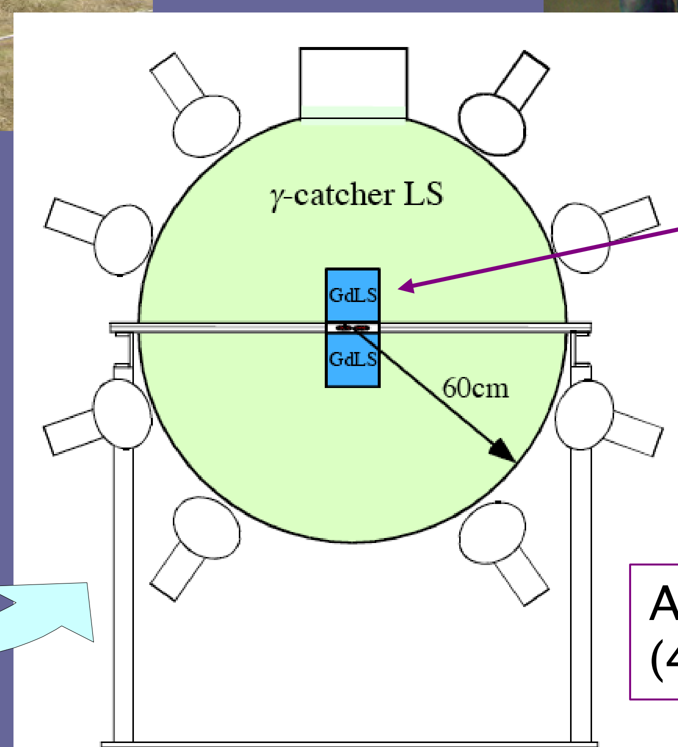


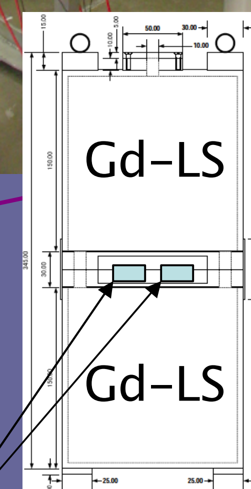
… And a lot of R&D





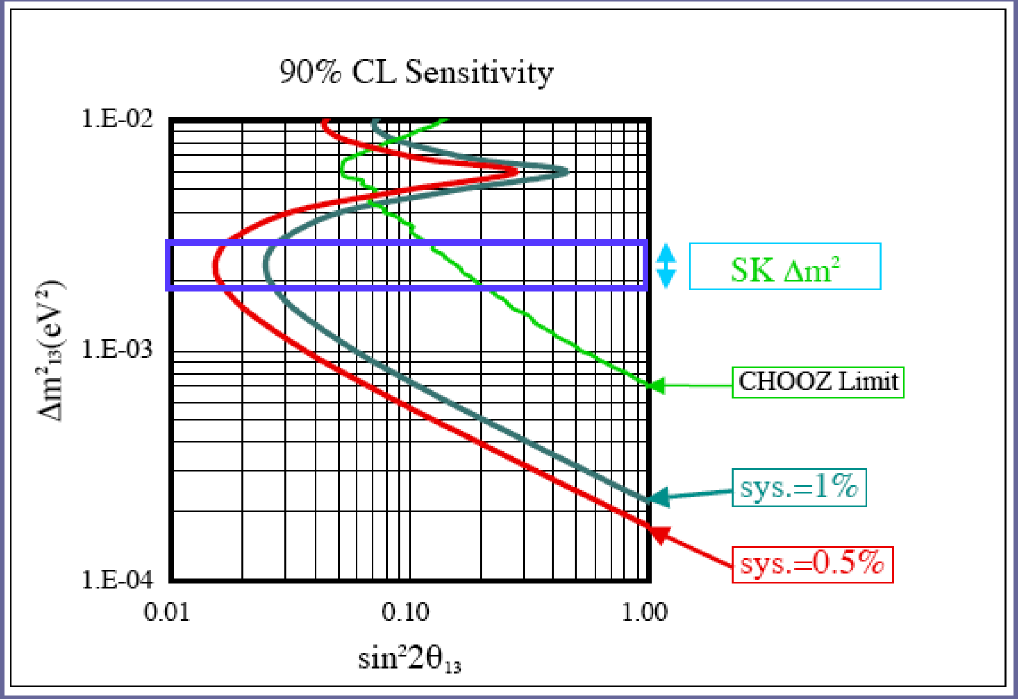






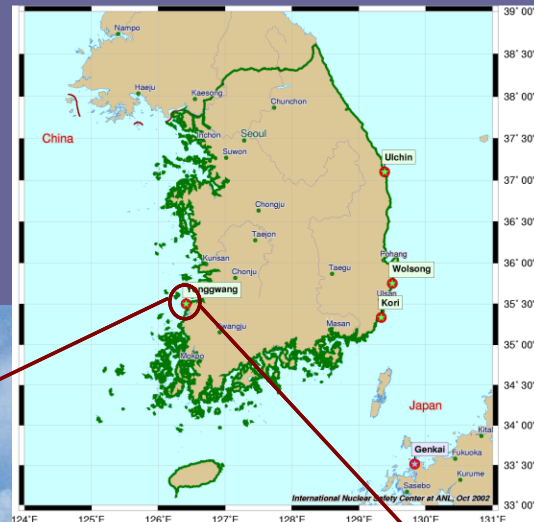
Kaska
status & prospects

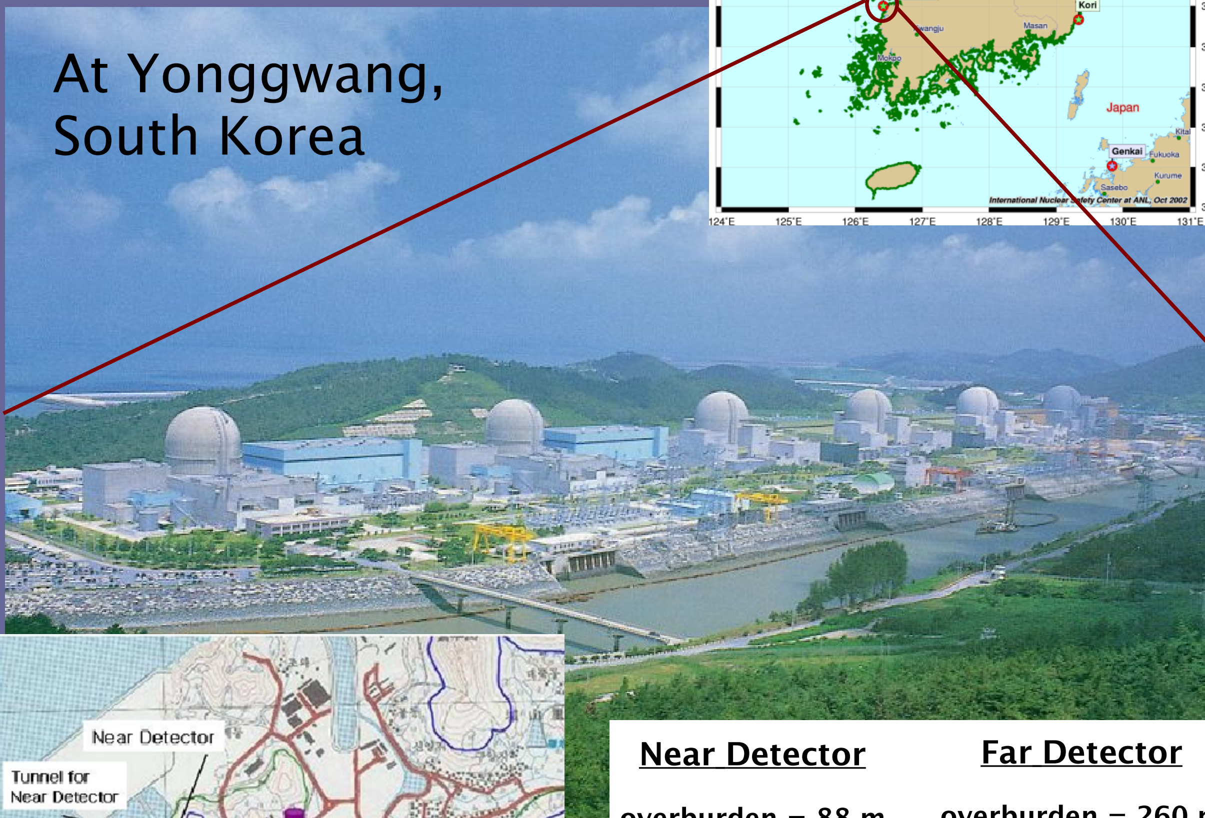
- Proposal submitted to japanese funding agencies:
  - hep-ex/0607013
  - 82 pages, 37 authors, 10 institutions
- Struggling hard for funds
- Possible start: 2010
- Sensitivity: ~ 0.02

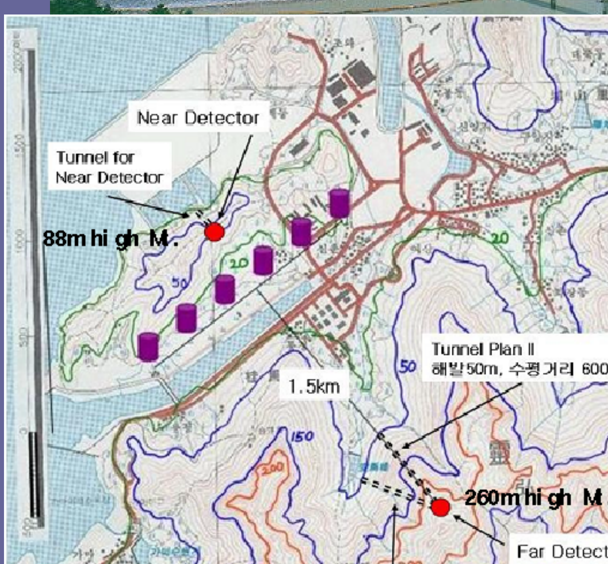


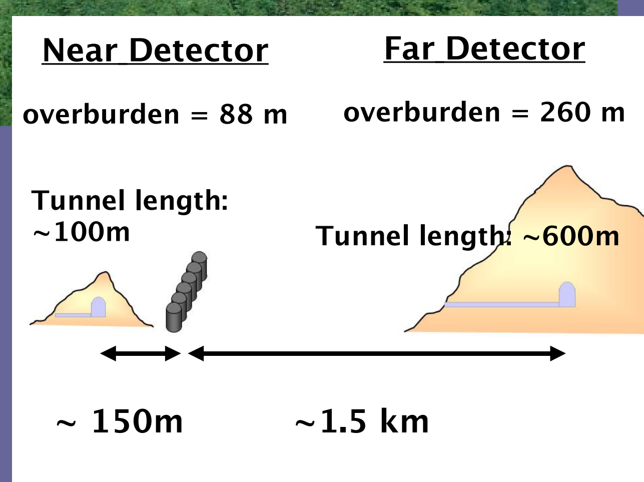
RENO

(Reactor Experiment for Neutrino Oscillations)









- **6 cores – 1 site – 17.3 GW_{th}**
- **1 near, 1 far, 3 "nearest" positions**
  - 2 x 20t target mass
  - 3 x ~ 300 kg target mass
- **Civil constructions**
  - ~ 700 m galleries
  - 2 laboratories
- **Statistics**
  - far: ~ 100 events/day
  - near: ~ 5000 events/day
- **Systematics**
  - total: ~ 1%
- **Overburden**
  - far: ~ 700 mwe
  - near: ~ 240 mwe
- **Planning**
  - start of construction in 2007 (??)
  - sensitivity: ~ 0.02

RENO
status & prospects

- ➔ RENO is the “last-comer” in this business, R&D is still at a very early stage
- ➔ Nevertheless, RENO can take advantage of the know-how and technical solutions developed in other projects, and thus catch up relatively quickly
- ➔ RENO has a good site and a strongly motivated collaboration, eager to develop this physics in Korea
- ➔ In 2006 working groups have been formed
- ➔ South Korea is very supportive: 9M$ approved
- ➔ Wait and see ...

Ideas for the future ...

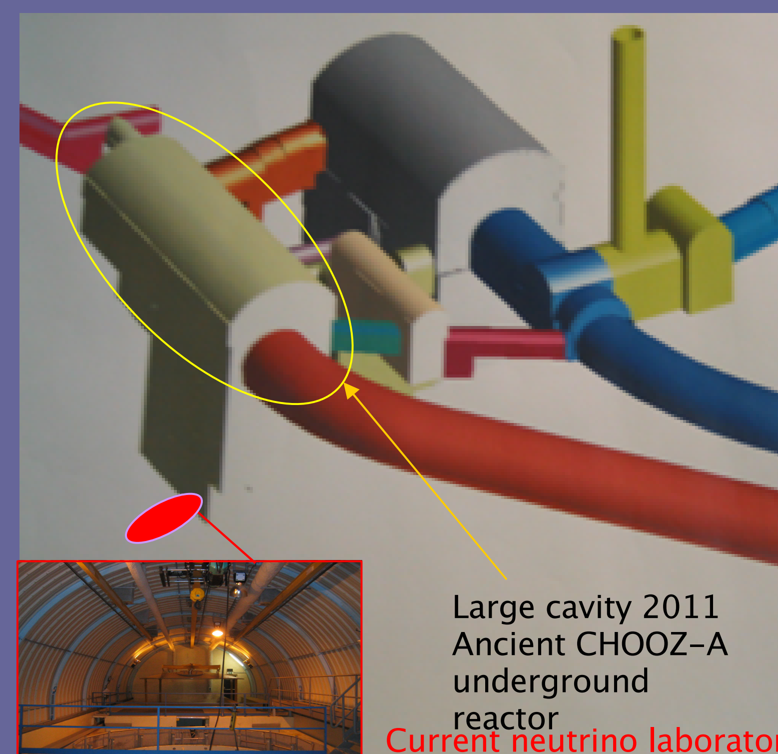
- 1 reactor + 1 in construction
- topography ok for overburden
- very large target mass (~ 200 t)
- sensitivity from spectral distorsion
- strategy: learn from Double Chooz and plan the next step
- Brasilian physicists enthusiastic, local authorities supportive

Triple Chooz

Just an idea ... !

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

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



Conclusive Remarks
&
Conclusive Conclusions

Measurement of θ_{13} by 2013 ?

Difficult to explain vanishing θ_{13} with large θ_{12} and θ_{23} ...

If numerical coincidence, discovery could be round the corner !

Consequence: U_{MNSP} fully determined

➔ strong constraints to theory

➔ possible early indications of CP violation from T2K and NOνA combined with reactors

If not ...

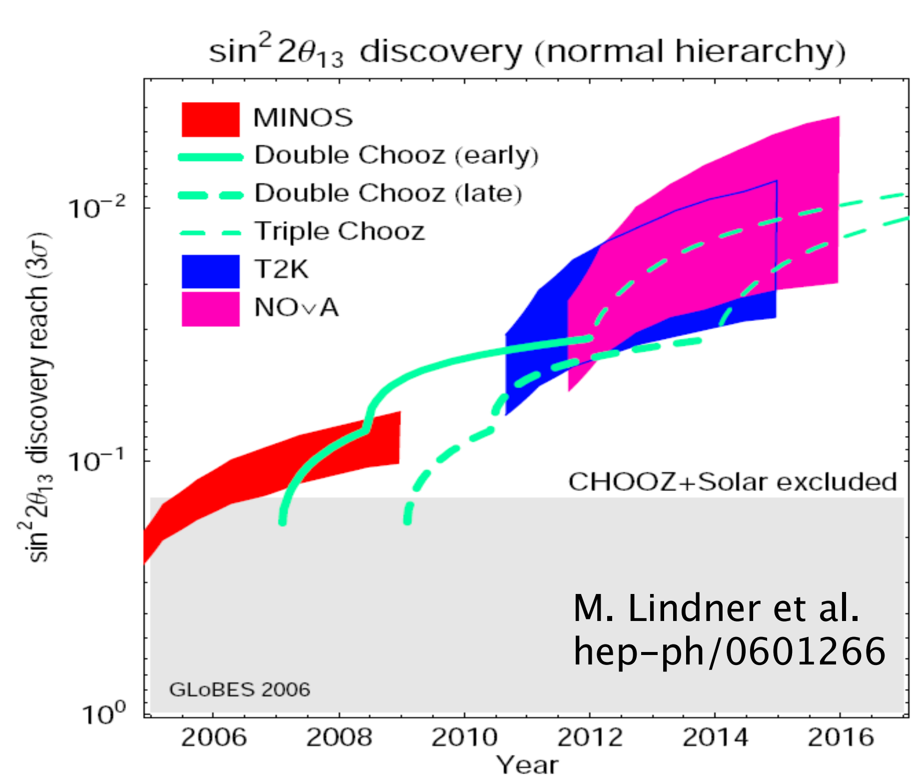
➔ very strong constraints to theory, as well !

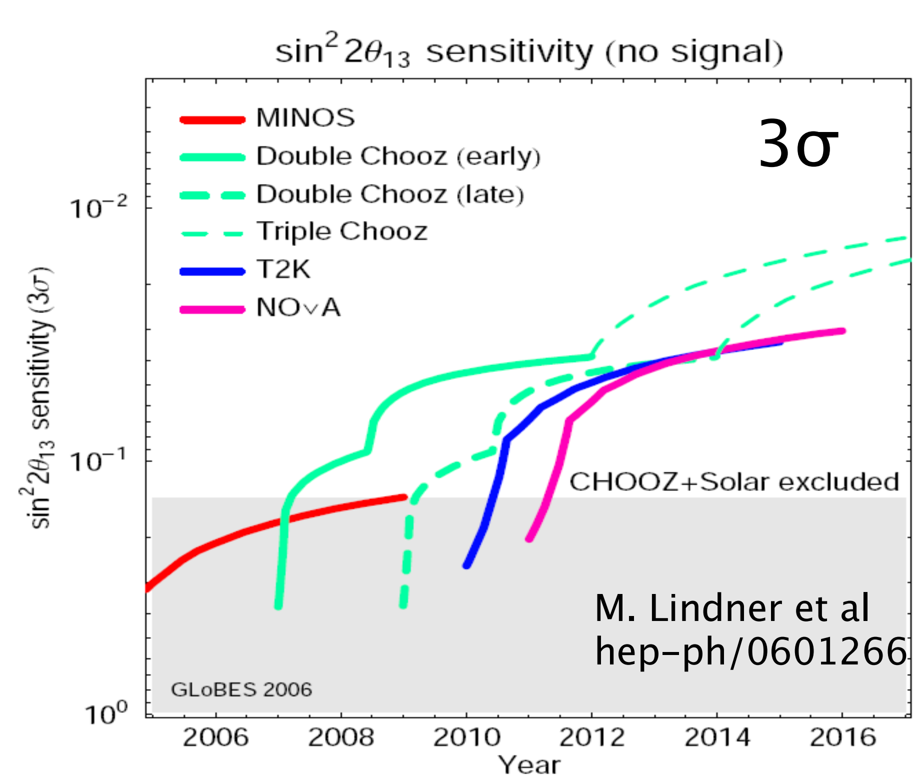
➔ synergies between Super-Beams and 2nd generation reactor experiments (class $\sin^2 2\theta_{13} < 0.01$)

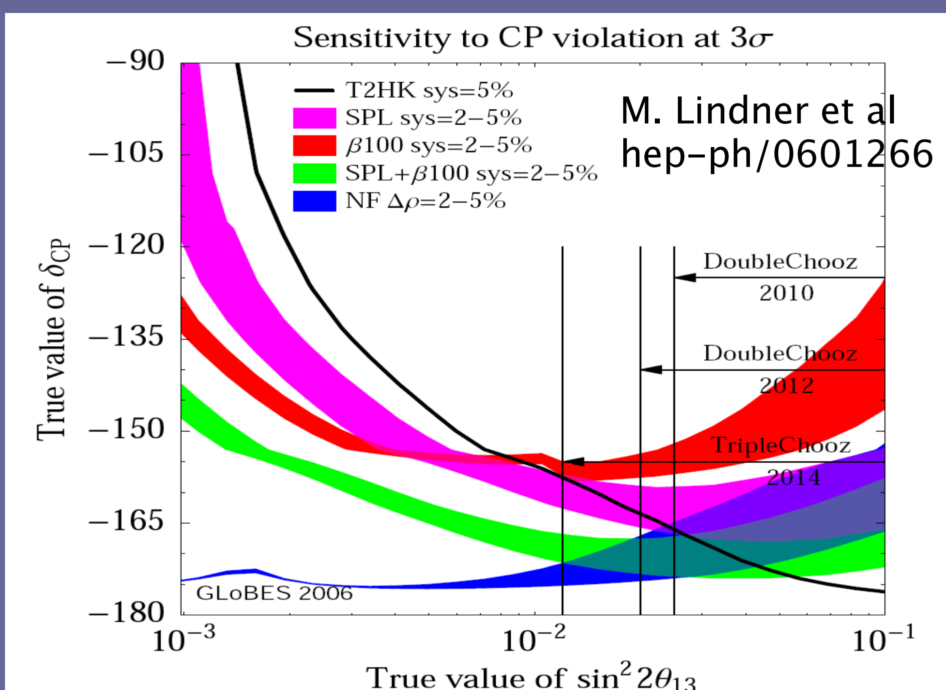
Conclusions

- **Double Chooz**
  - funding is secured, R&D concluded, construction is beginning !
  - $\sin^2\theta_{13} < 0.03$ (90% C.L) (3σ discovery at ~ 0.05)
- **Daya Bay**
  - approved by China, R&D supported by DOE
  - strong US-Chinese commitment !
  - aimed sensitivity: $\sin^2 2\theta_{13} < 0.01$ (large mass and movable detectors)
  - staged approach ? From 1st to 2nd generation ...
- Other interesting 1st generation projects starting R&D (**RENO**) or struggling for funds (**KASKA**)
- 1st generation will set fundamental benchmarks for the future reactor search (Daya Bay full, Angra, Triple-Chooz)

Back-up & Cut Slides



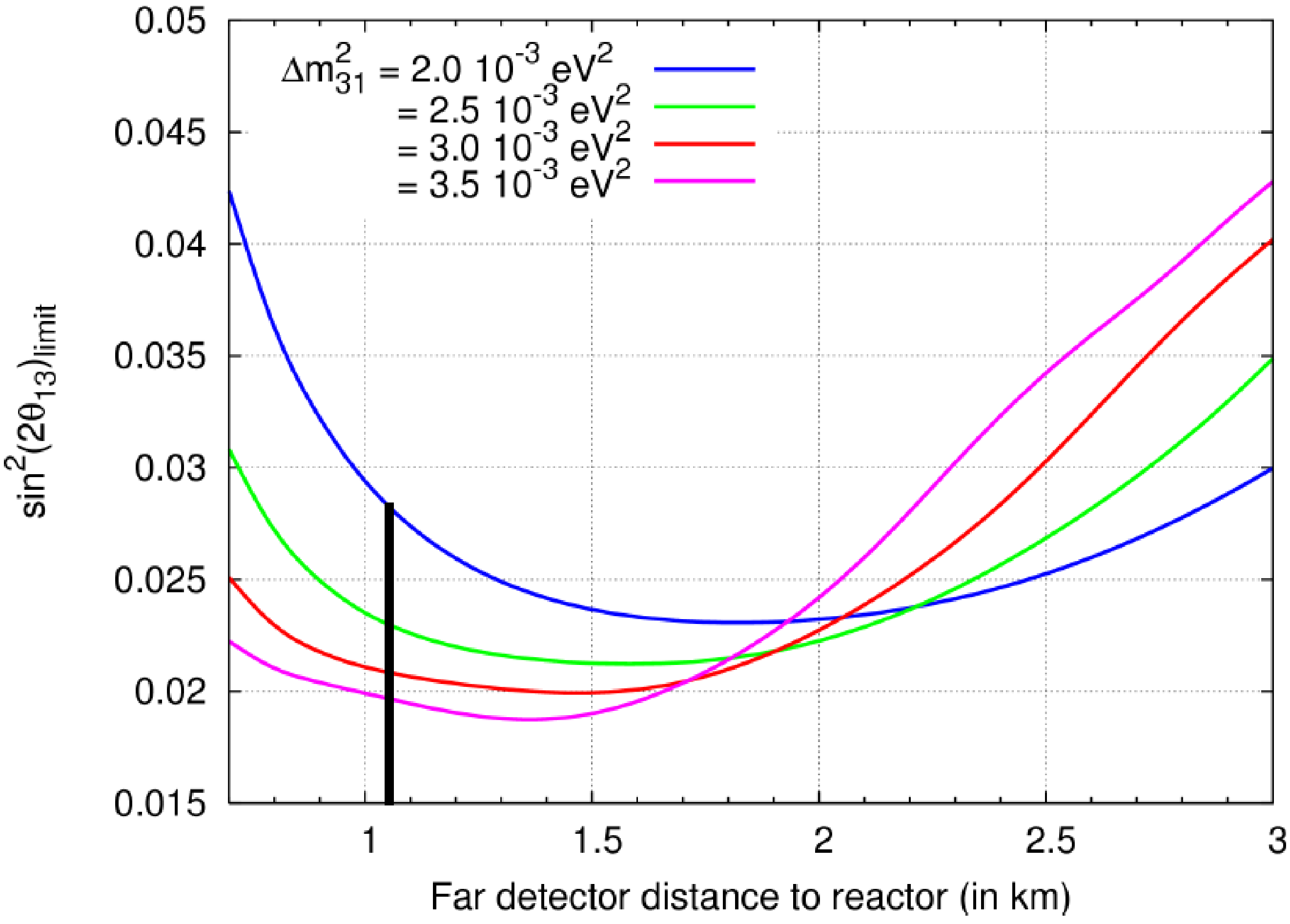




The choice of the future technology to explore leptonic CP-violation depends critically on the size of θ_{13}

Reactor and Super-beams searches are complementary

Far detector distance
Δm^2_{31} = from 2.0 to 3.5 10^{-3} eV^2



Near detector distance: 280 m

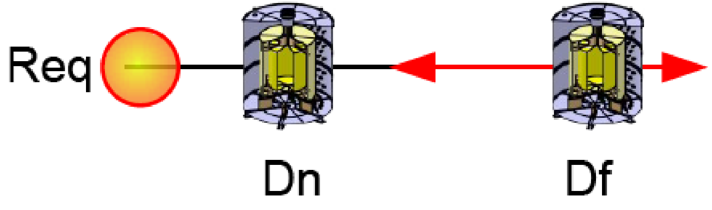
Systematics included:

- σ_{abs} = 2.0 %
- σ_{rel} = 0.6 %
- σ_{shp} = 2.0 %
- $\sigma_{\Delta m2}$ = 10.0 %

Energy resolution: σ_E = 7 %

Oscillation parameters chosen:

- Δm^2_{31} = 2.0 to 3.5 10^{-3} eV^2
- $\sin^2(2\theta_{13})=0$



Overview of the current projects

- **Double Chooz (France, Germany, US, Spain, England, Russia)**

  ~ Fully funded, strong international support (however US participation weaker after DOE decision), R&D concluded, launching construction. Start-up with far + near detector by 2010, targeted sensitivity: $\sin^2 2\theta_{13} < 0.03$

- **Daya Bay (China, US)**

  Approved in China, supported by DOE, strong US - Chinese commitment. R&D well underway. Aggressive schedule (competitive with Double Chooz), likely staged approach ($\sin^2 2\theta_{13} < 0.03 \rightarrow 0.01$).

- **1st generation projects ($\sin^2 2\theta_{13} \lesssim 0.025$) pursued in a single country**
  - **Kaska (Japan)**: advanced R&D, struggling for funds in Japan
  - **Reno (South Korea)**: initial R&D, grant of 9M$ from South Korea
- **2nd generation projects ($\sin^2 2\theta_{13} < 0.01$)**
  - **Braidwood**: stopped after DOE refusal to support the project
  - **Angra**: preliminary feasibility studies, collaboration with Double Chooz
  - **Triple Chooz**: an idea ... a large cavity beside the far lab will be available from 2011