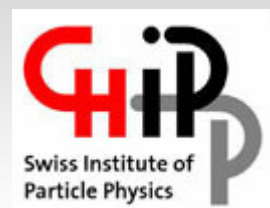


The Double Chooz reactor neutrino experiment

Inés Gil Botella



**3rd CHIPP Neutrino Meeting
November 17-18, 2008**



Overview

- ▣ The search for the θ_{13} mixing angle
- ▣ Neutrino measurements at reactor experiments
- ▣ The Double Chooz experiment
 - ◆ Physics goals
 - ◆ Experimental concept
 - ◆ Detector design
 - ◆ Present status
 - ◆ Expected sensitivity and schedule
- ▣ Summary



Current knowledge on neutrino mixing parameters

Experimental measurements

parameter	best fit	2σ	3σ
$\Delta m_{21}^2 [10^{-5} \text{eV}^2]$	$7.65^{+0.23}_{-0.20}$	7.25–8.11	7.05–8.34
$ \Delta m_{31}^2 [10^{-3} \text{eV}^2]$	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75
$\sin^2 \theta_{12}$	$0.304^{+0.022}_{-0.018}$	0.27–0.35	0.25–0.37
$\sin^2 \theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63	0.36–0.67
$\sin^2 \theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.040	≤ 0.056

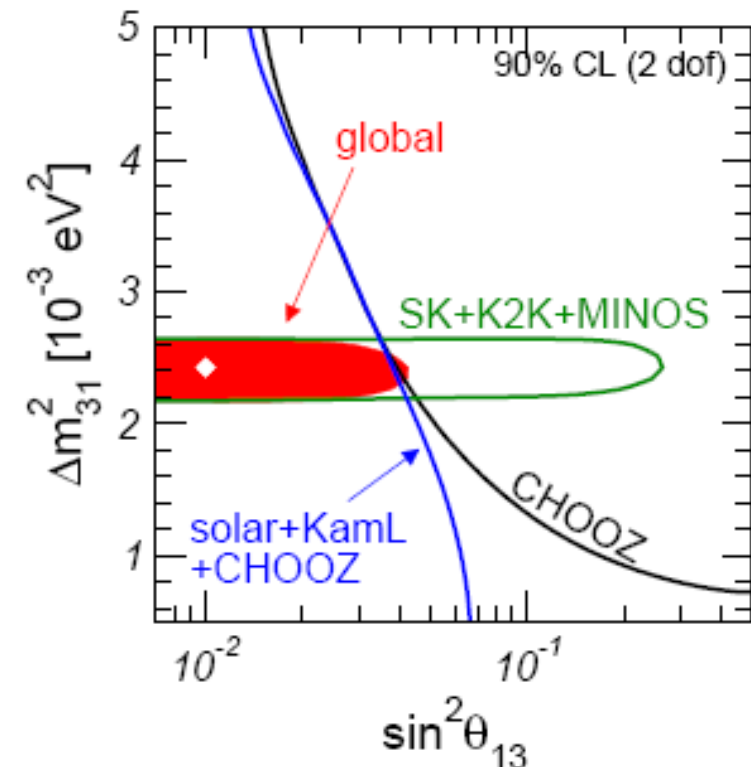
arXiv:0808.2016

θ_{13} , $\text{sign}(\Delta m_{31}^2)$, $\delta\text{-CP}$??

Best global limit on θ_{13}

arXiv:0808.2016

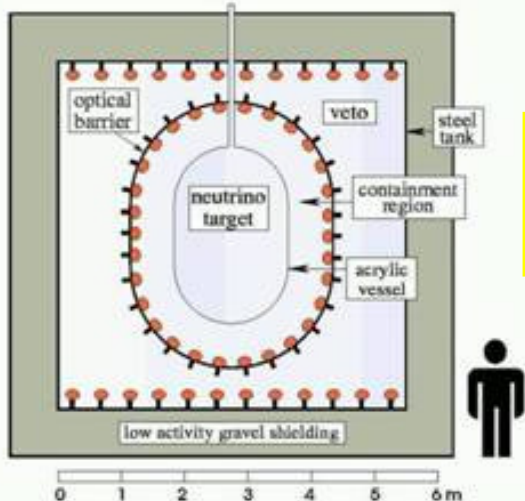
Global (90% CL)
 $\sin^2 \theta_{13} \leq 0.035$



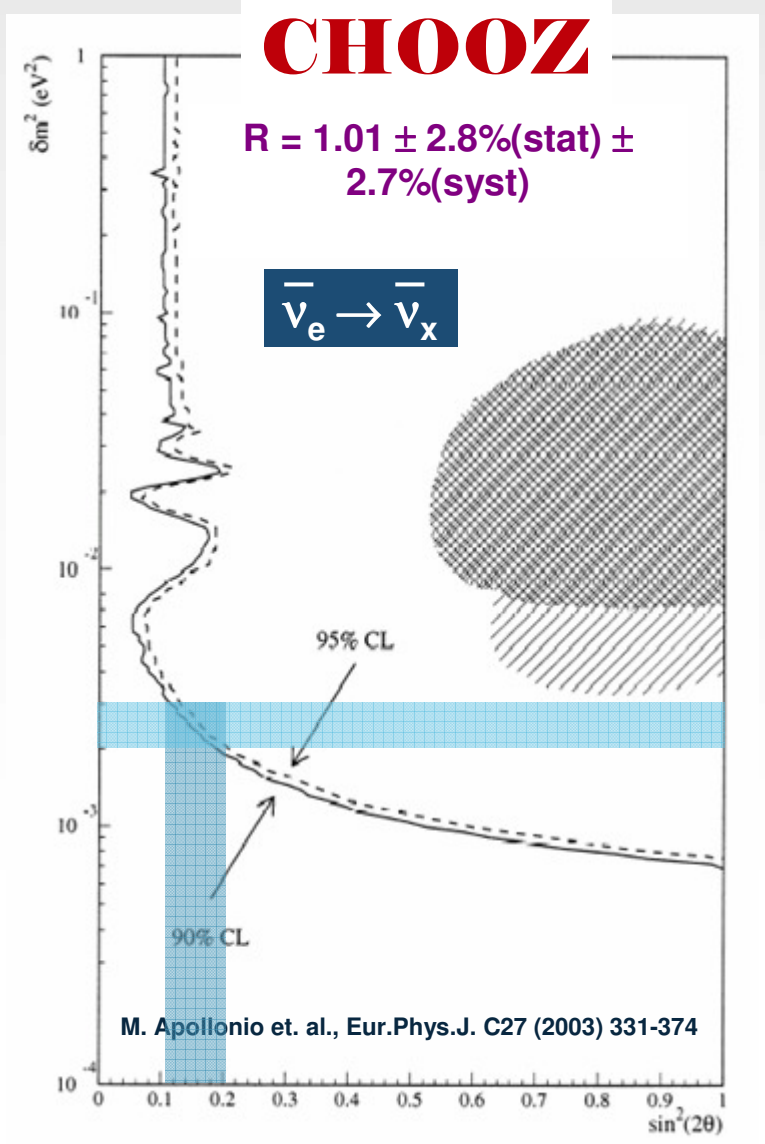
The θ_{13} mixing angle

- ▣ The only mixing angle unknown
 - ◆ Crucial for CP violation measurements in leptonic sector
- ▣ Best experimental limit:
 - ◆ **CHOOZ** reactor experiment

$\bar{\nu}_e \rightarrow \bar{\nu}_e$ (disappearance experiment)
 $P_{\text{th}} = 8.4 \text{ GW}_{\text{th}}, L = 1.050 \text{ km}, M = 5 \text{ t}$
 Overburden: 300 mwe



$\sin^2(2\theta_{13}) < 0.12 - 0.2$
 (90% C.L)



Measuring θ_{13} : ν -reactors vs super-beams

▣ Accelerator experiments: appearance experiments

- ◆ $P(\nu_\mu \rightarrow \nu_e)$ depends on $\sin^2(2\theta_{13})$, $\sin^2(\theta_{23})$, $\text{sign}(\Delta m_{31}^2)$, δ_{CP} phase
 - ◆ Parameter degeneracies and correlations
 - ◆ Matter effects sensitive

▣ Reactor ν experiments are unique for:

- ◆ Unambiguous determination of θ_{13}
 - ◆ no dependence on δ_{CP}
 - ◆ no dependence on mass hierarchy
 - ◆ weak dependence on Δm_{12}^2
 - ◆ Resolve θ_{23} degeneracy combined with accelerator experiments
- } No parameter degeneracies
No matter effects

▣ Reactor advantages with respect to accelerators:

- ▶ Pure $\bar{\nu}_{13}$
- ▶ Pure $\bar{\nu}_e$, no flavor contamination
- ▶ ν flux known at few%
- ▶ Smaller detectors (cheaper)

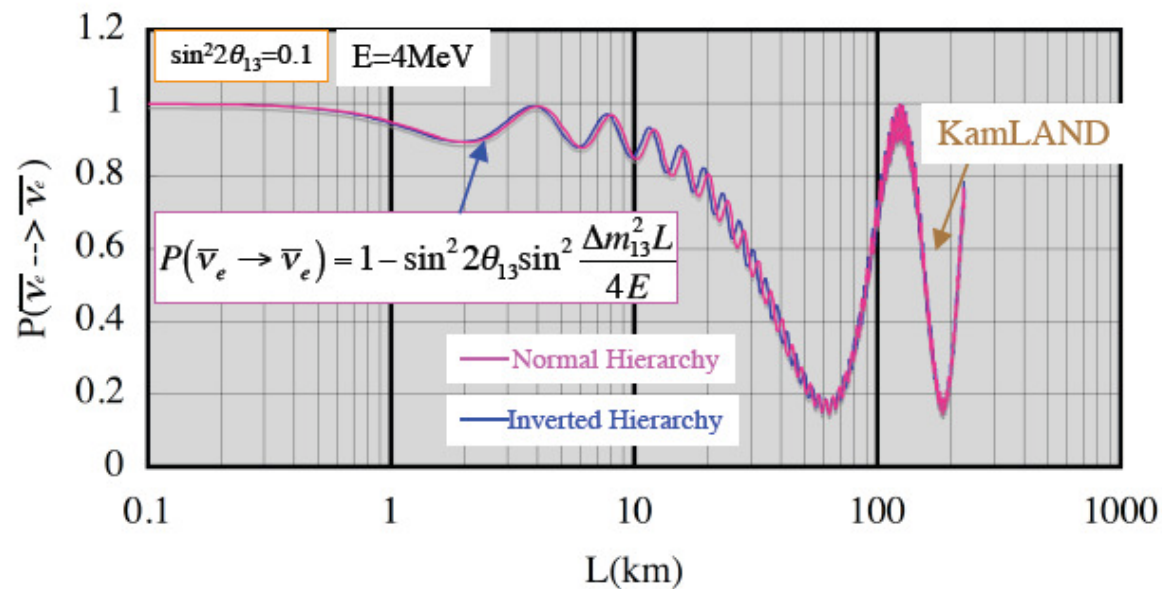
Both type of experiments
provide independent and
complementary
information

Neutrino oscillations at nuclear reactors

$\bar{\nu}_e$ disappearance searches

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{13}^2 L}{4E_\nu} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left(\frac{\Delta m_{21}^2 L}{4E_\nu} \right)$$

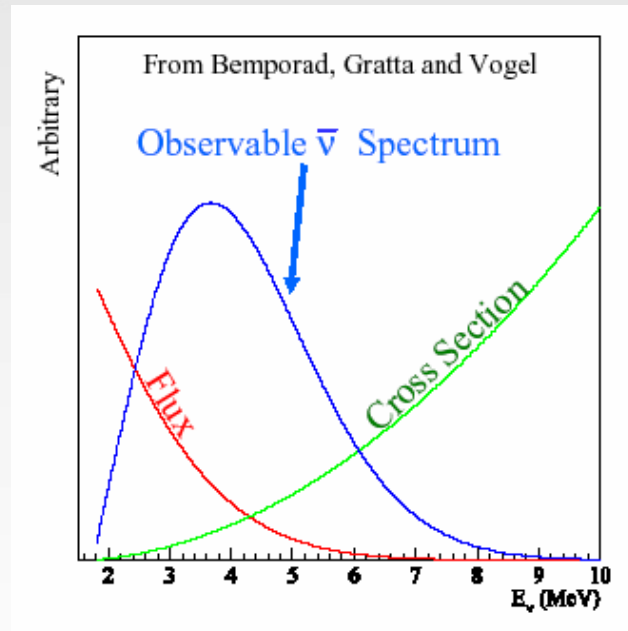
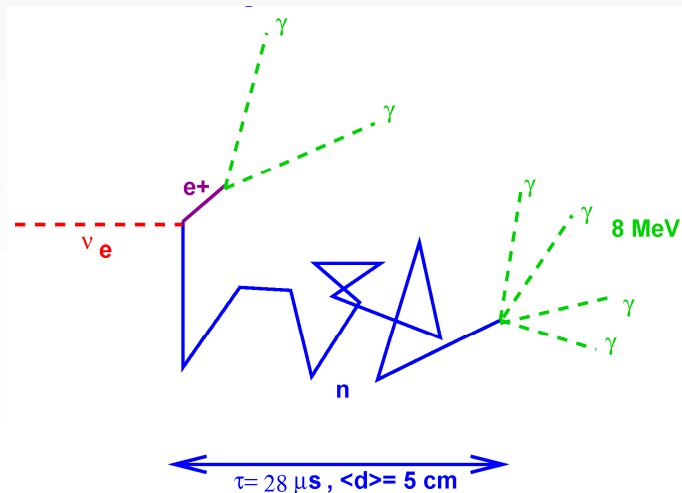
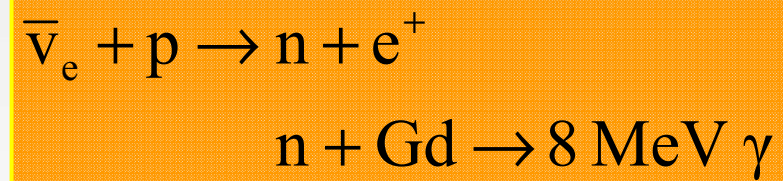
Reactor Neutrino Oscillation



Small deficit (= $\sin^2 2\theta_{13}$) \Rightarrow high precision is necessary

Antineutrino detection at nuclear reactors

$\bar{\nu}_e$ detection: inverse beta decay



□ Prompt photons from e^+ annihilation:

$$E_{\text{VIS}} \approx E_{\nu} - (M_n - M_p) + m_e$$

□ Delayed photons from n capture:

◆ on H : $\Delta t \sim 200 \mu\text{s}$, $E \sim 2 \text{ MeV}$

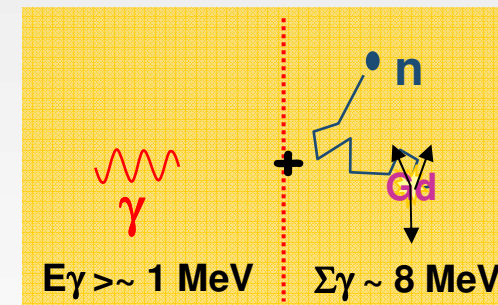
◆ on dedicated nuclei (Gd): $\Delta t \sim 30 \mu\text{s}$, $E \sim 8 \text{ MeV}$



Expected backgrounds at nuclear reactors

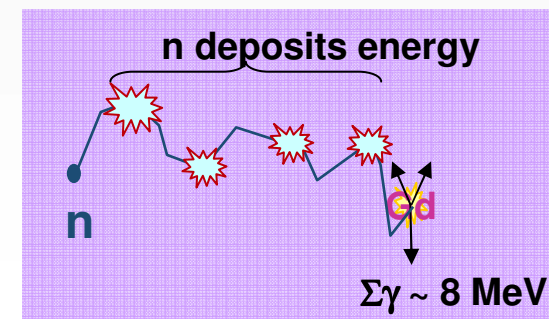
□ Accidental events:

- ◆ **e+ signal-like:** radioactivity from materials, PMTs, surrounding rock,...
- ◆ **n signal-like:** true neutrons from cosmic μ 's or gammas mimicking neutrons



□ Correlated events:

- ◆ **Fast n:** produced by cosmic μ 's
 - ◆ Recoil-p (low energy) + Gd-capture
- ◆ **Long-lived isotopes:** ${}^9\text{Li}$ & ${}^8\text{He}$ (β -n decay)

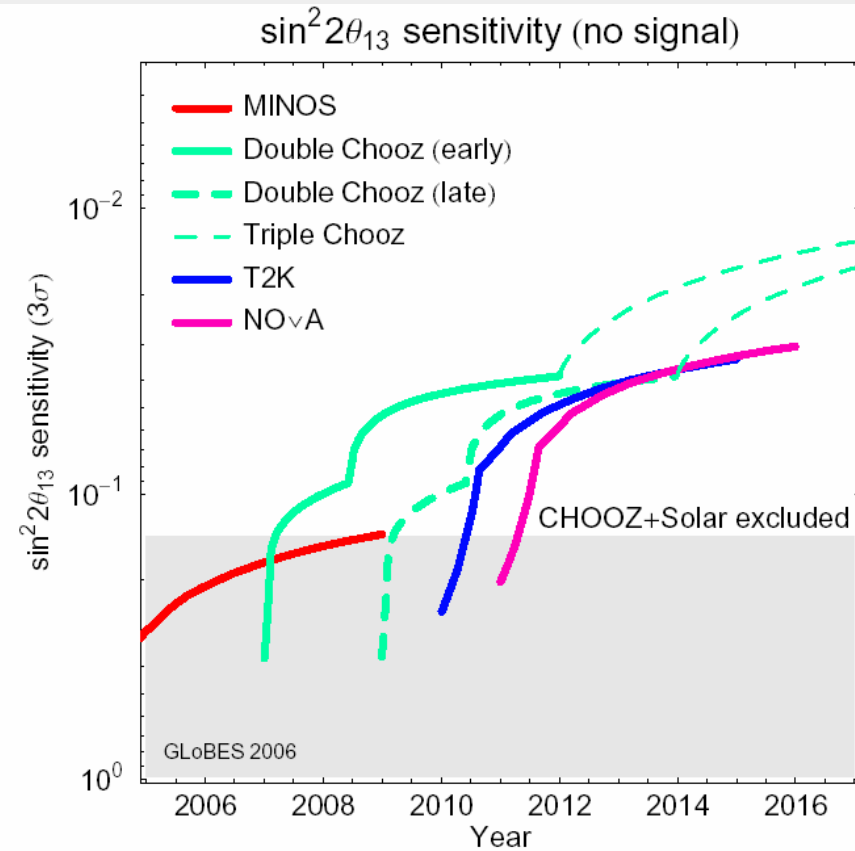
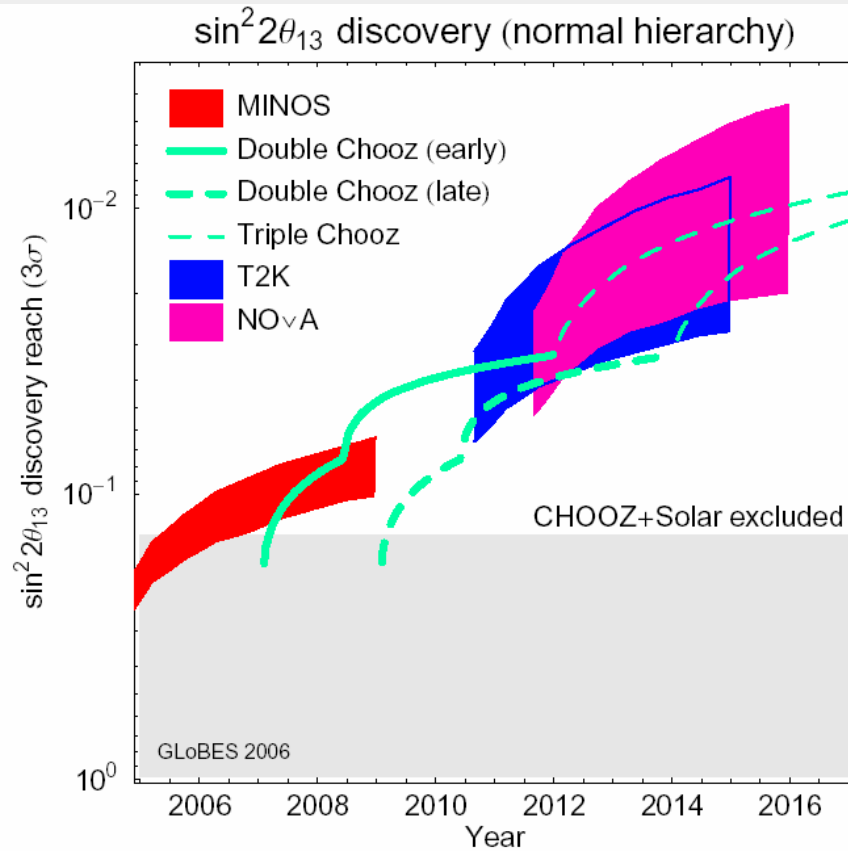


Complementarity with super-beams

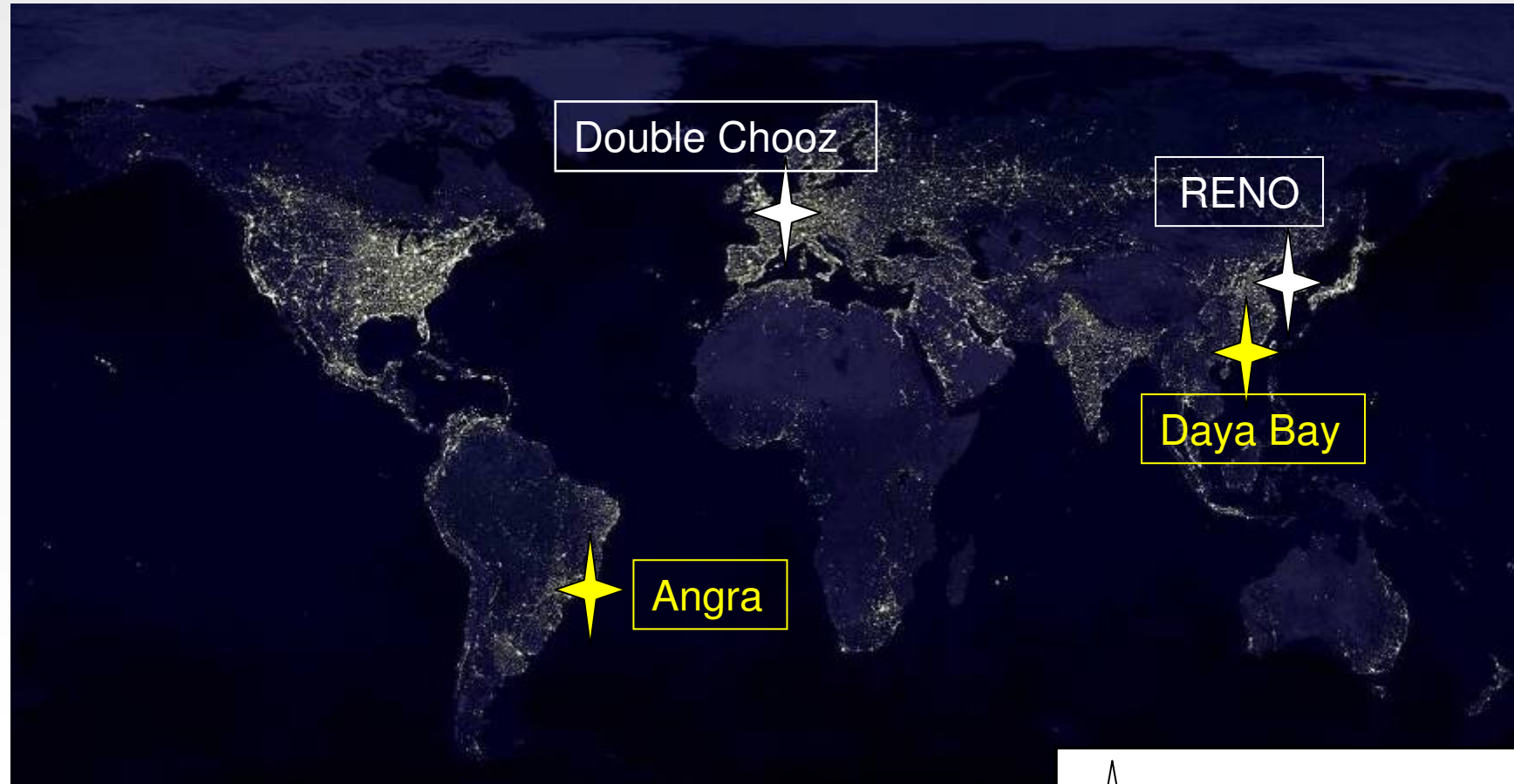
hep-ph/0601266

3σ discovery potential

3σ sensitivity (no signal)



Reactor neutrino experiments



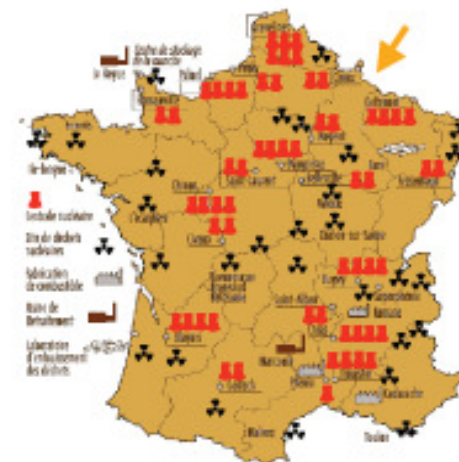
✦ 1st generation: $\sin^2(2\theta_{13}) \sim 0.02-0.03$
✦ 2nd generation: $\sin^2(2\theta_{13}) \rightarrow 0.01$

Comparison between reactor experiments

Experiments	Location	Thermal Power (GW)	Distances Near/Far (m)	Depth Near/Far (mwe)	Target Mass (tons)
Double Chooz	France	8.7	400/1050	115/300	10/10
RENO	Korea	16.4	290/1380	120/450	15/15
Daya Bay	China	11.6	360(500)/1985(1613)	260/910	40×2/80



The Double Chooz experiment



Double Chooz goals

▣ Measure the θ_{13} **mixing angle**

◆ **Goal:** $\sin^2 2\theta_{13} < 0.03$ @ 90% CL in 3 years

▣ **Needed improvements:**

◆ *Increase statistics*

- ◆ More powerful reactors
- ◆ Longer exposure
- ◆ Larger detector mass

◆ *Suppress backgrounds*

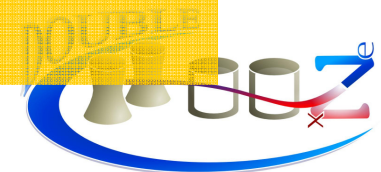
- ◆ Improve detector design
- ◆ Better cosmic muon veto detectors
- ◆ External shielding

◆ *Reduce systematic uncertainties*

- ◆ Near/Far detector comparison to minimize reactor errors
- ◆ Identical detectors to do relative measurements
- ◆ Detailed calibration program

▣ **Non-proliferation studies** (interest of IAEA)

◆ Use DC near detector as prototype for reactor monitoring



Double Chooz collaboration

Spokesman: Hervé de Kerret (APC)



France: APC Paris, CEA/Dapnia Saclay, Subatech Nantes, Strasbourg



Germany: Aachen, MPIK Heidelberg, TU München, EKU Tübingen, Hamburg



Spain: CIEMAT Madrid



UK: Univ. Sussex



Japan: HIT, Kobe, MUE, Niigata, TGU, TIT, TMU, Tohoku



Russia: RAS, RRC Kurchatov Institute



USA: Alabama, ANL, Chicago, Columbia, Drexel, Illinois, Kansas, LLNL, LSU, Notre Dame, Sandia, Tennessee, UCD



Brazil: CBPF, UNICAMP



Collaboration Meeting June 2008

Double Chooz concept

Near detector (400 m)
115 m.w.e.

Far detector (1050 m)
300 m.w.e.

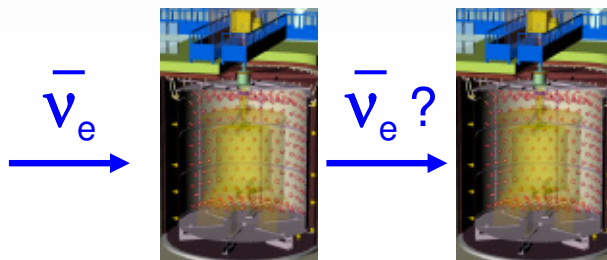
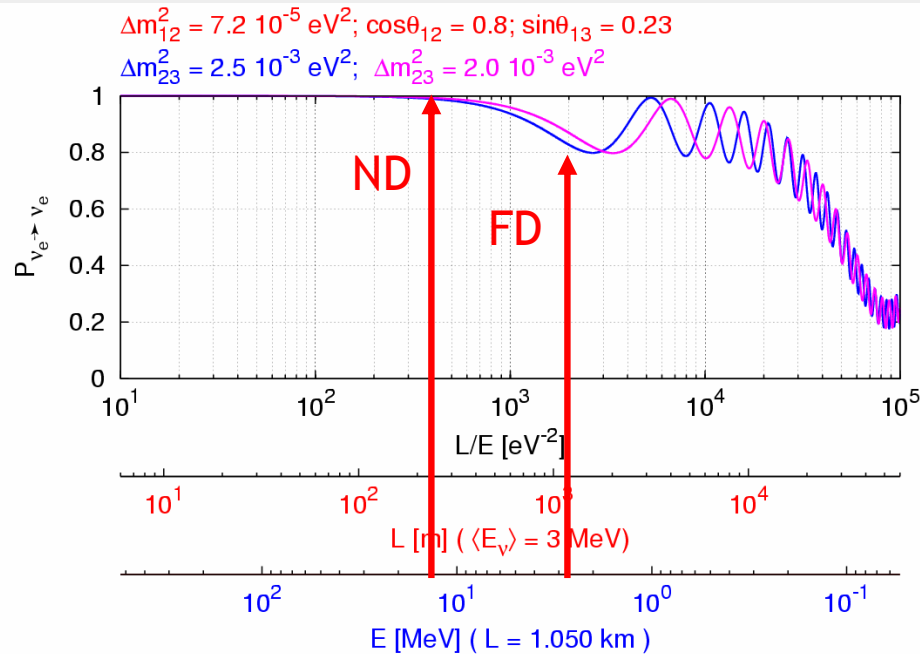


Far site already exists

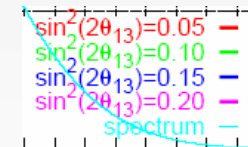
- ⇒ 2 reactors - 8.5 GW_{th}
- ⇒ 2 identical detectors:
 - ▶ Target: 2 x 8.3 t
- ⇒ Comparison of neutrino rate & energy spectrum
- ⇒ Civil work:
 - ▶ 1 near lab is foreseen
 - ▶ 1 far lab is available

Chooz B nuclear power plant
Ardennes, France

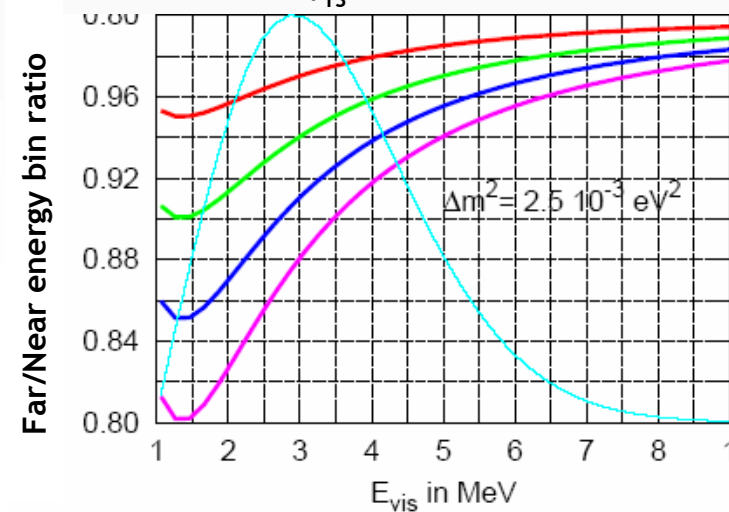
Survival probability



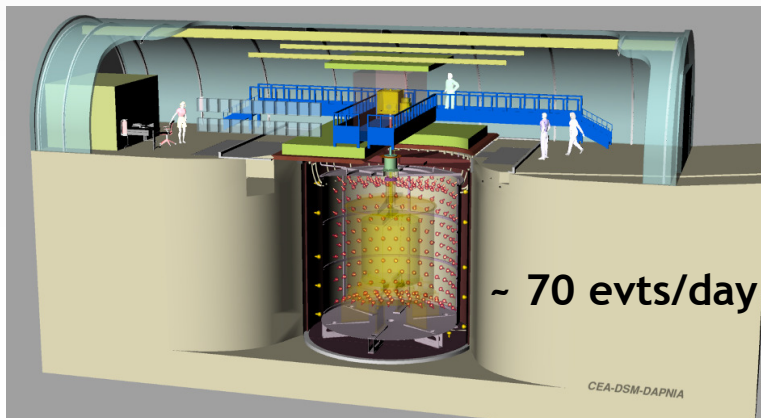
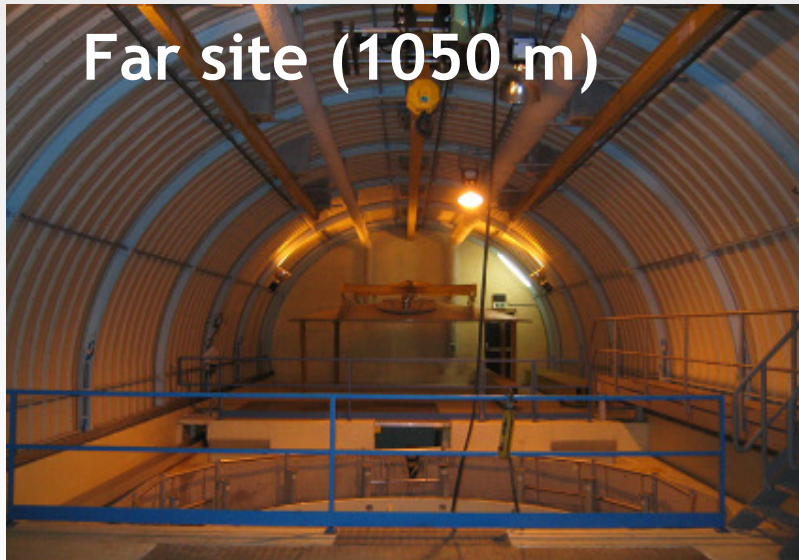
- ▣ 2 “identical” detectors
- ▣ Rate comparison
- ▣ Spectral distortion
- ▣ Limit:
 - ◆ Systematics
 - ◆ Backgrounds



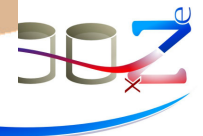
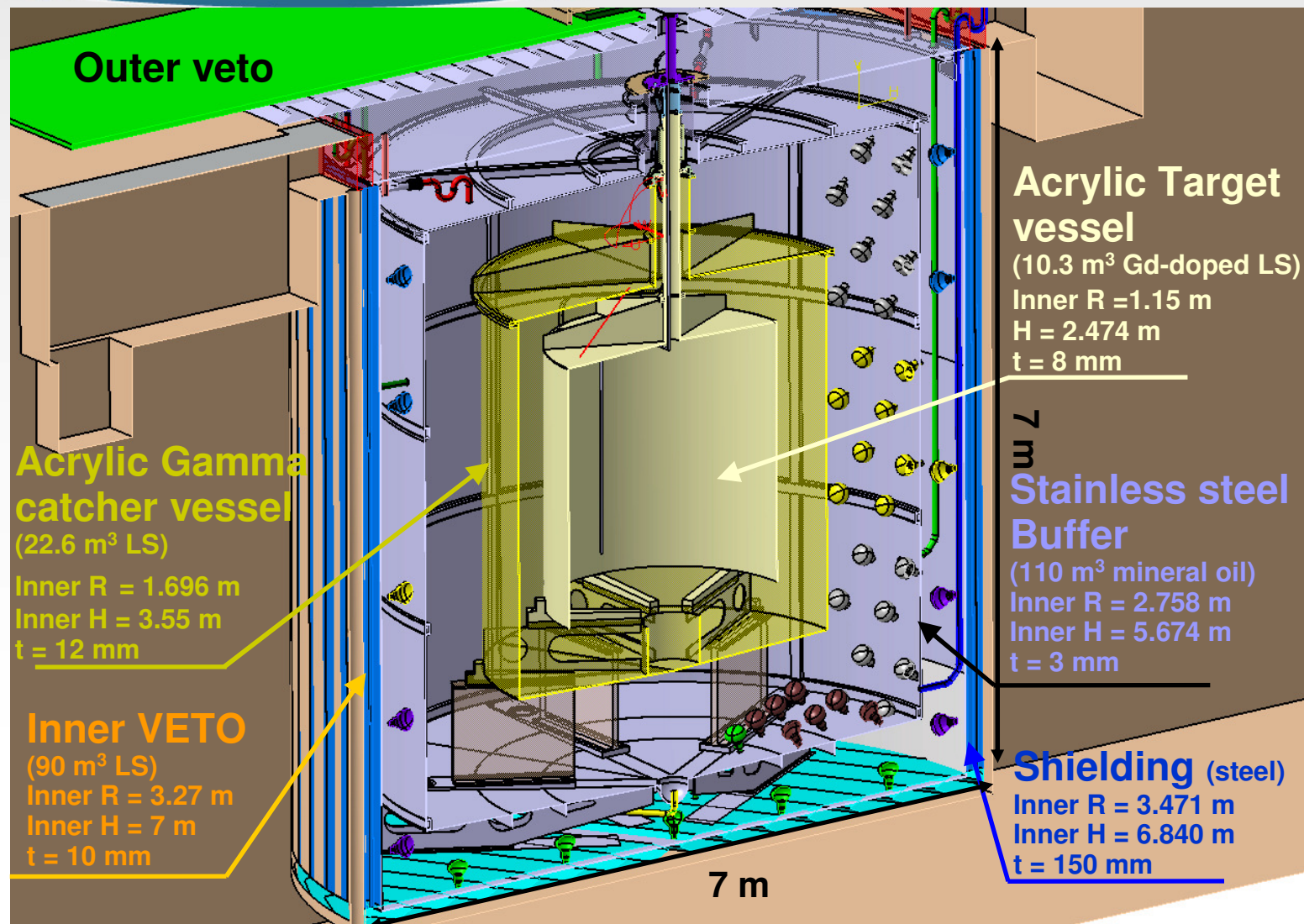
Rate + shape information
if θ_{13} not too small



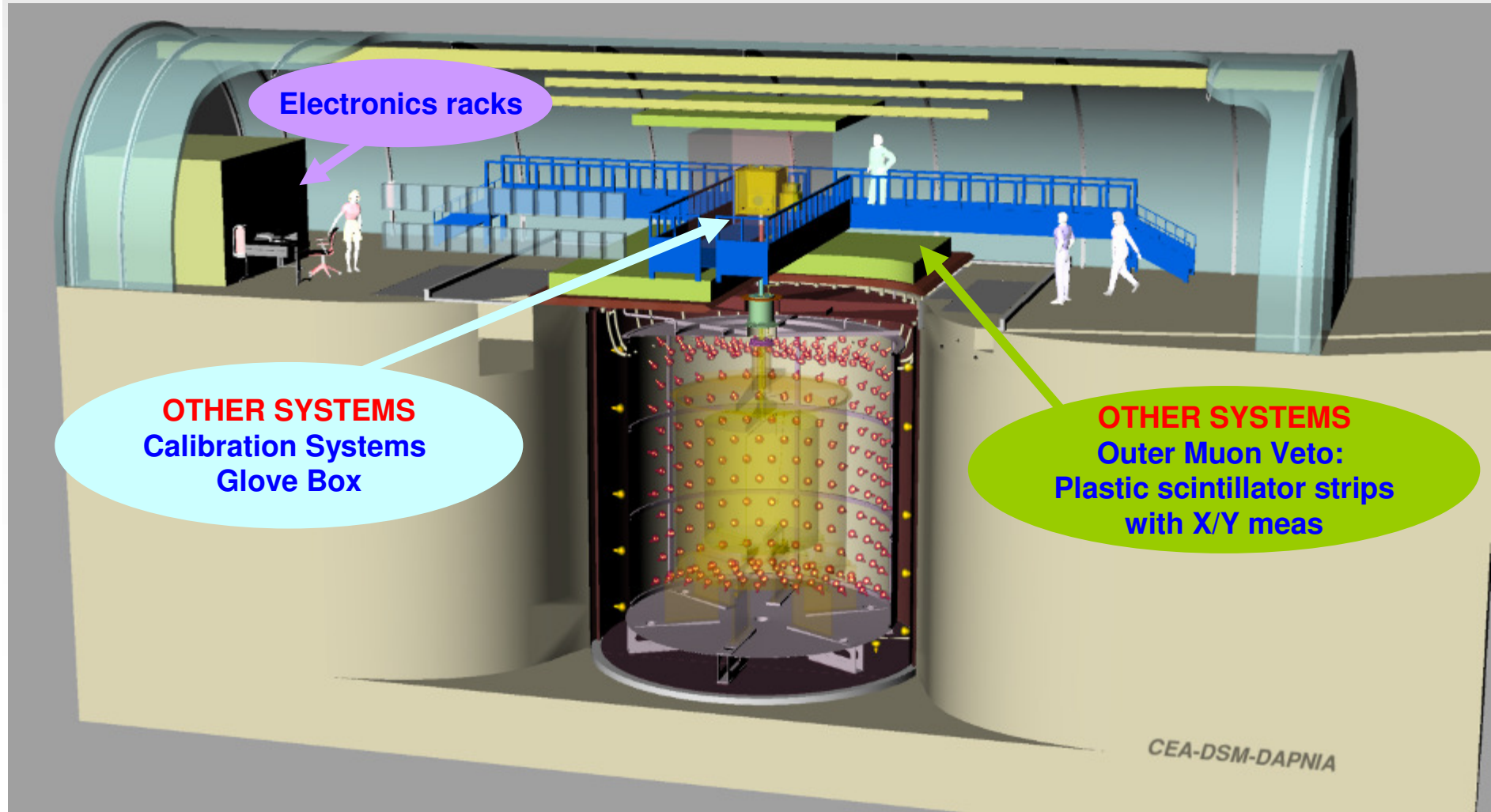
Far and near labs



Detector design



Detector in the lab

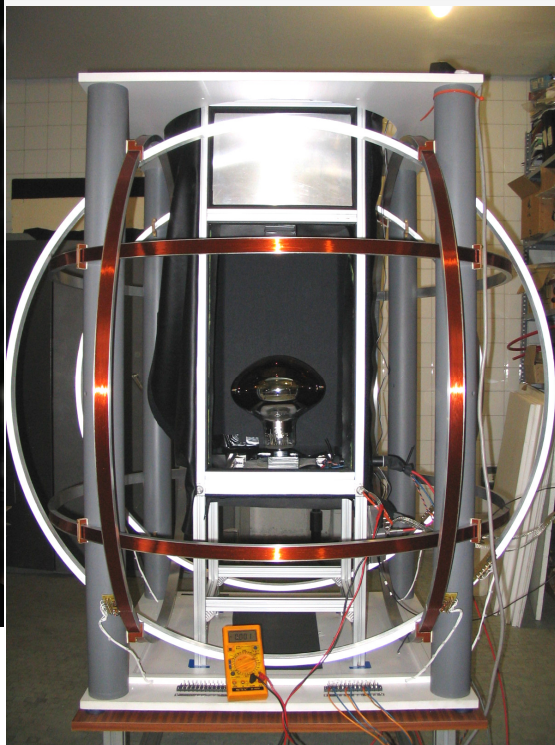


R&D activities and tests

1/5 mockup @ Saclay



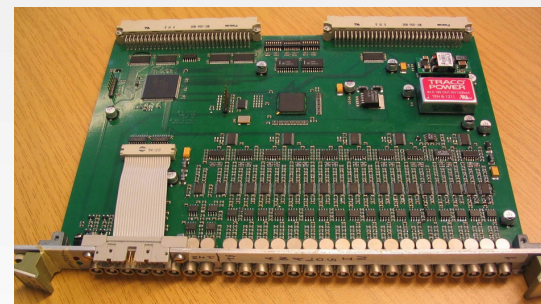
Magnetic tests @ CIEMAT



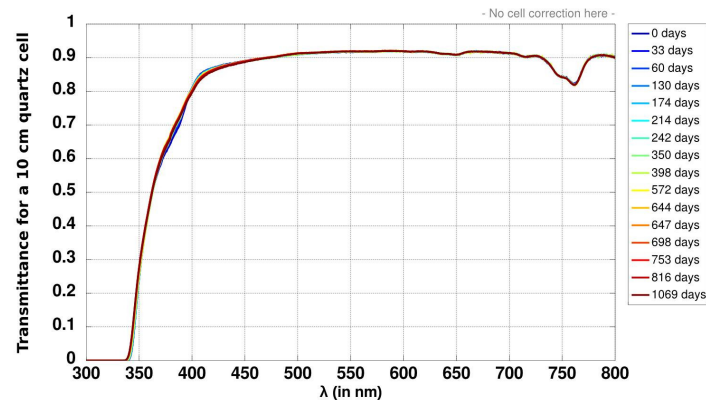
fADCs CAEN VI721 @ APC



L1 Trigger board @ Aachen

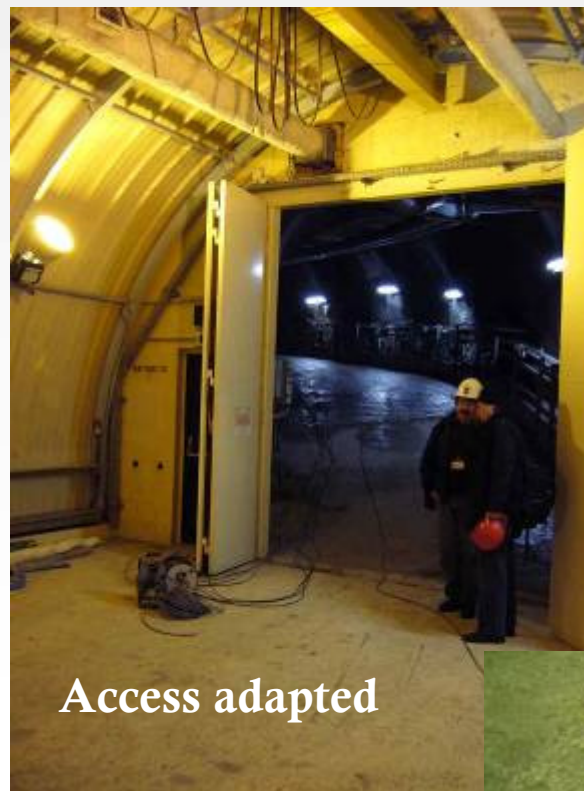
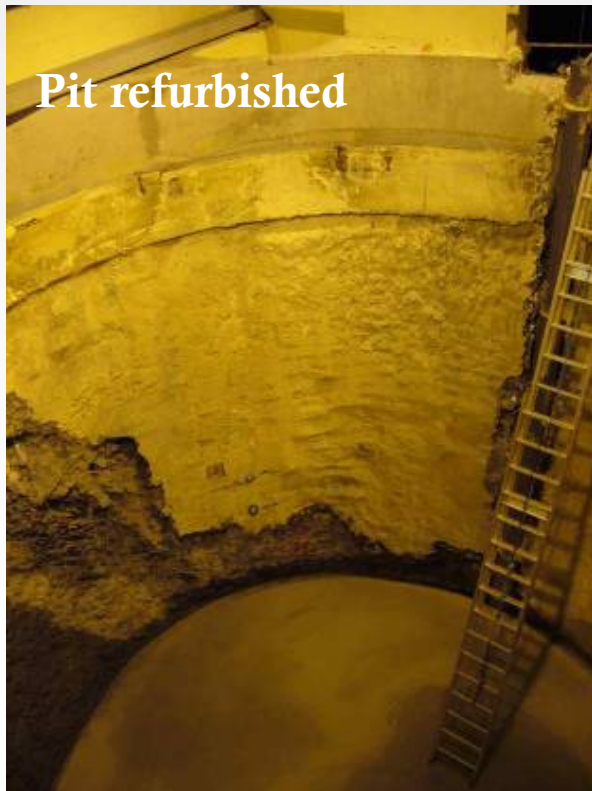


Gd doped scintillator development @ MPIK



Current activities: Far lab integration

Civil engineering work completed

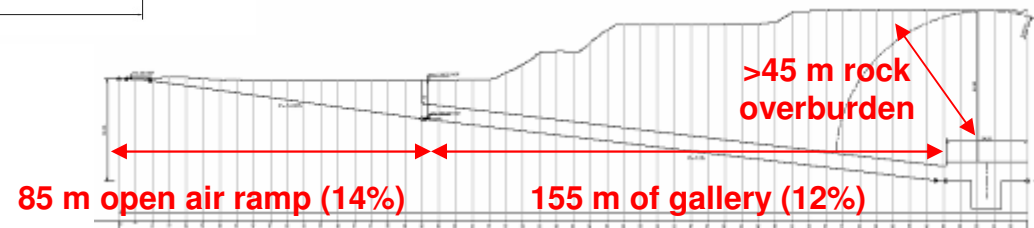
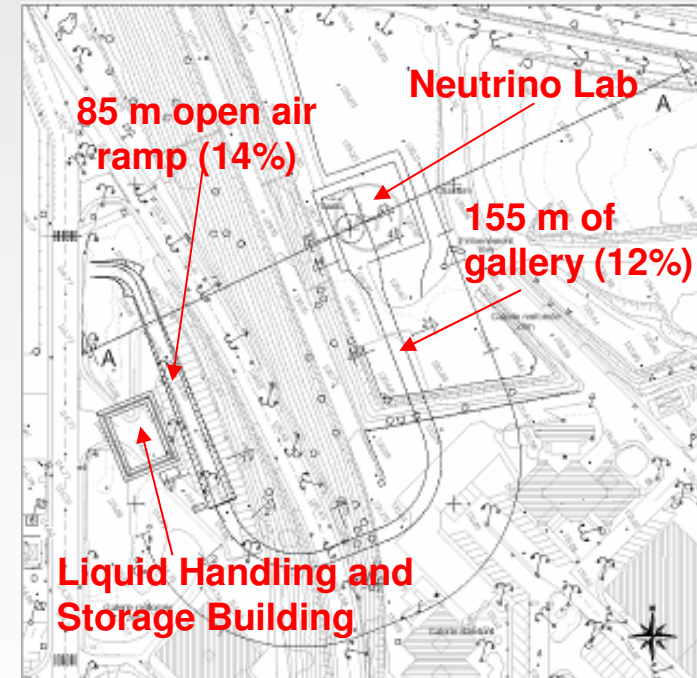
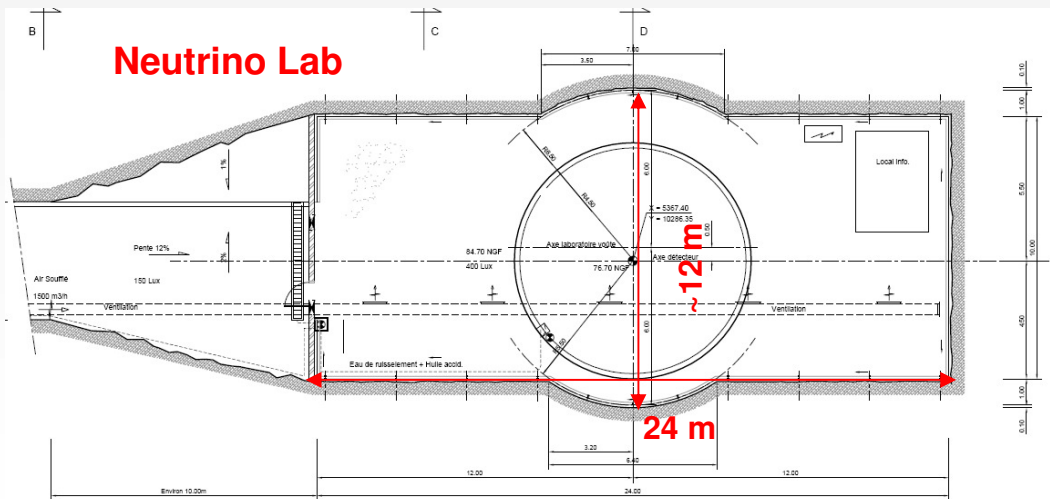


Cleanliness + radiopurity
measurements ongoing

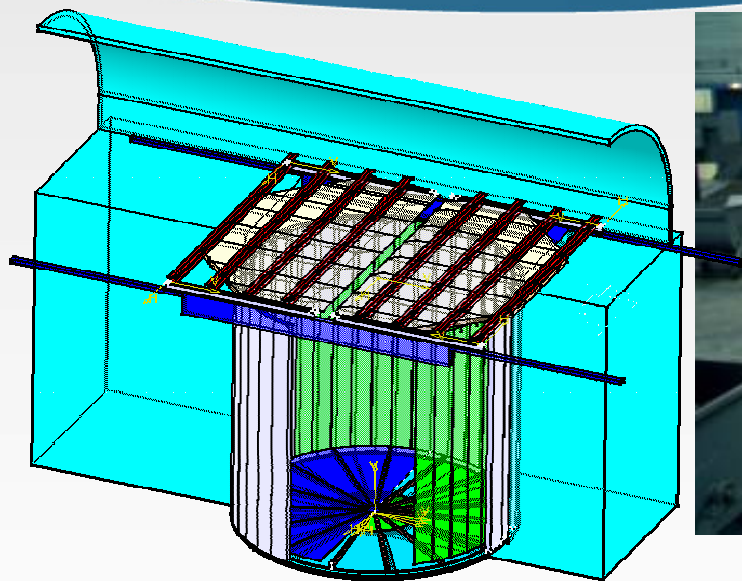


Current activities: Near lab preparation

- ◆ Site engineering study completed
- ◆ Tender process for construction soon
- ◆ Schedule: lab finished beginning 2010



Current activities: Steel shield installation finished



Assembly of each side of
the bottom part



Connection of two bars



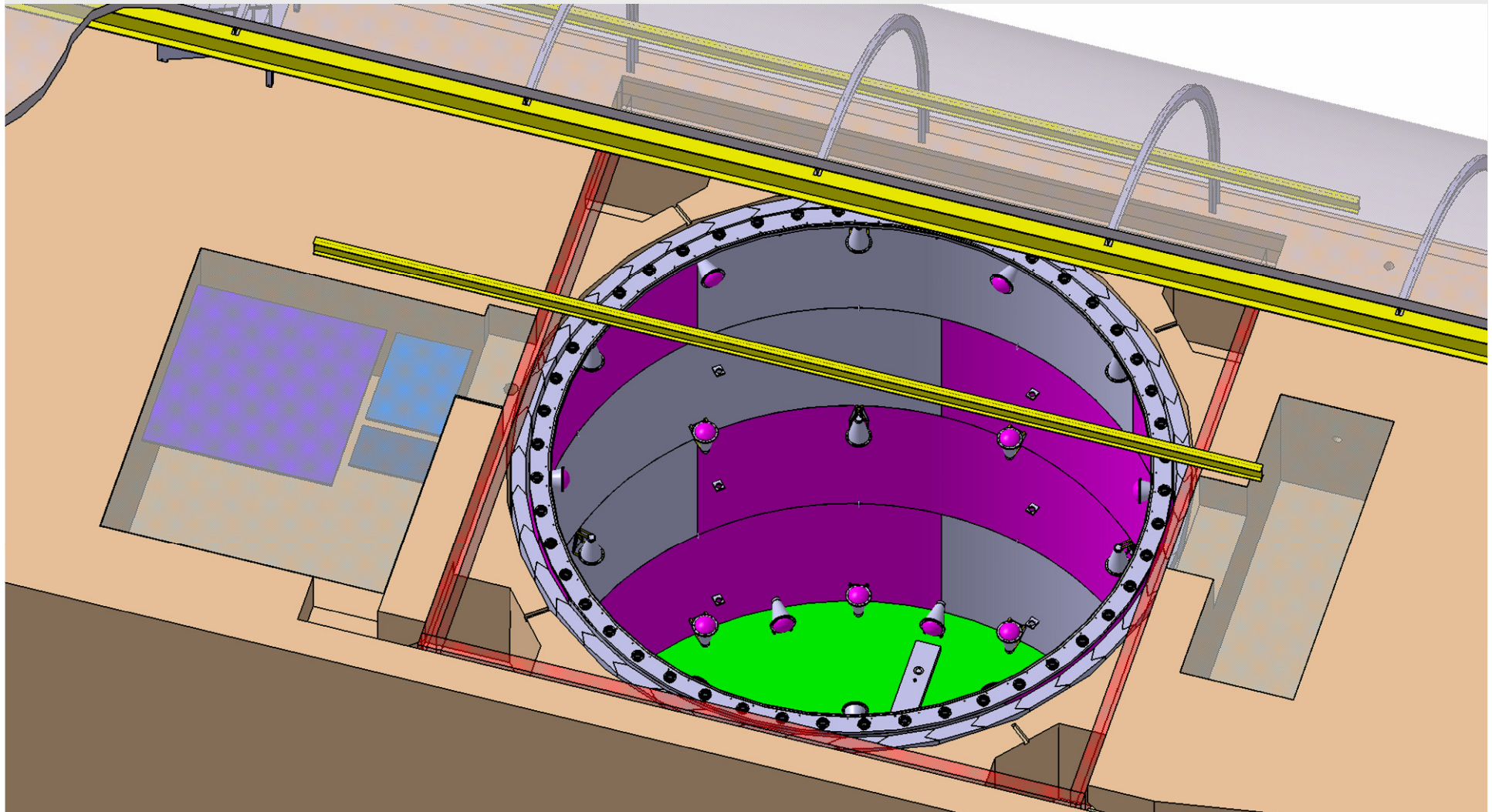
Integration completed



Demagnetization of steel
shielding bars

8m

Current activities: Inner veto vessel installation in progress



Current activities: Inner detector components

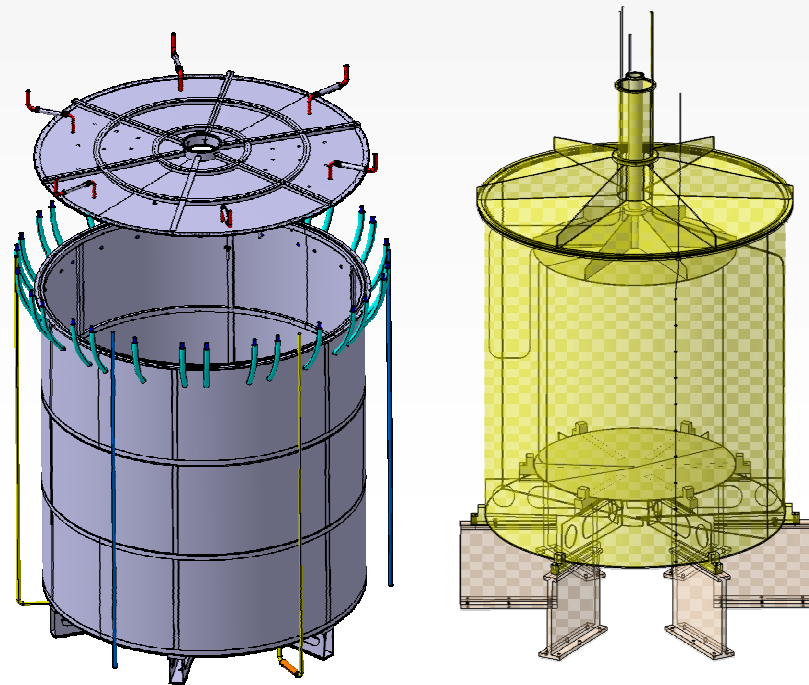
▣ Scintillator production

- ◆ Main components needed for both detectors have been delivered and checked



▣ Mechanical vessels: acrylics and buffer

- ◆ Design completed
- ◆ Manufacturing is on going



Current activities: Tools for acrylics handling

Target vessel tool



Gamma-catcher vessel tool



Current activities: PMT production completed

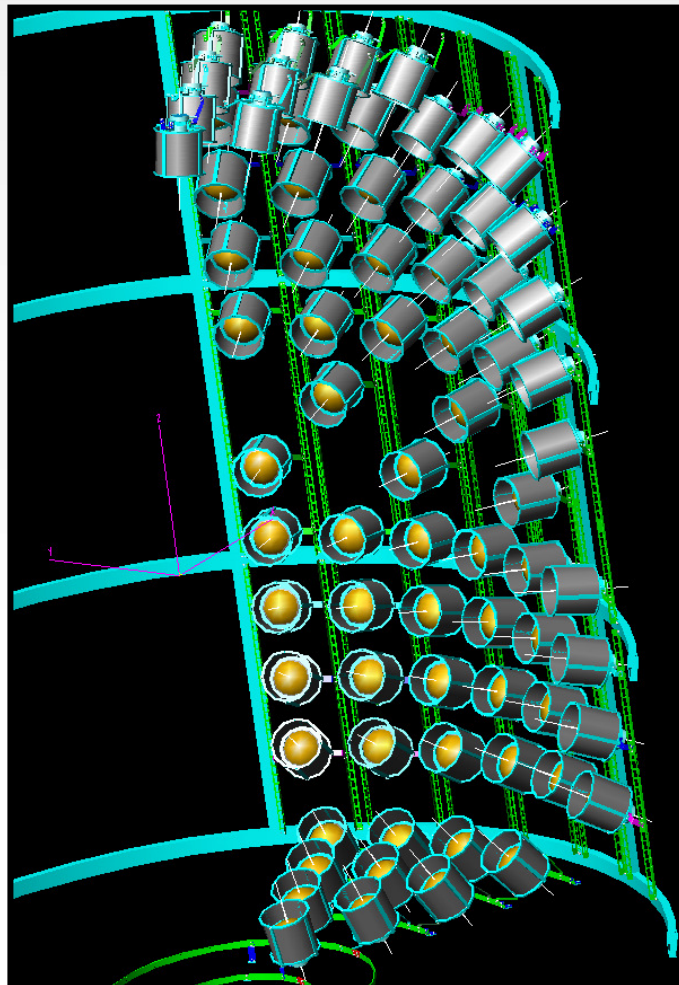
Low background glass
10" R7081 Hamamatsu PMTs



HV splitters



PMT geometry baseline
(390 PMTs/detector)

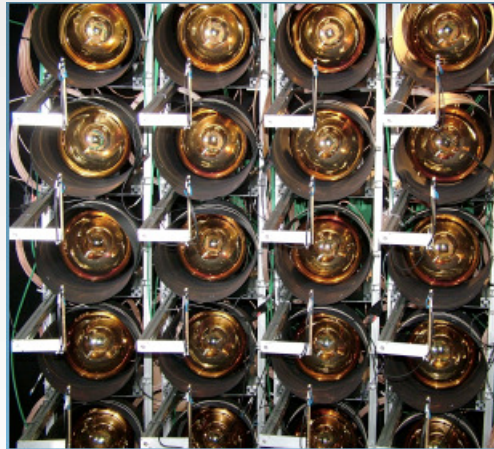


PMT mechanical support
& magnetic shield

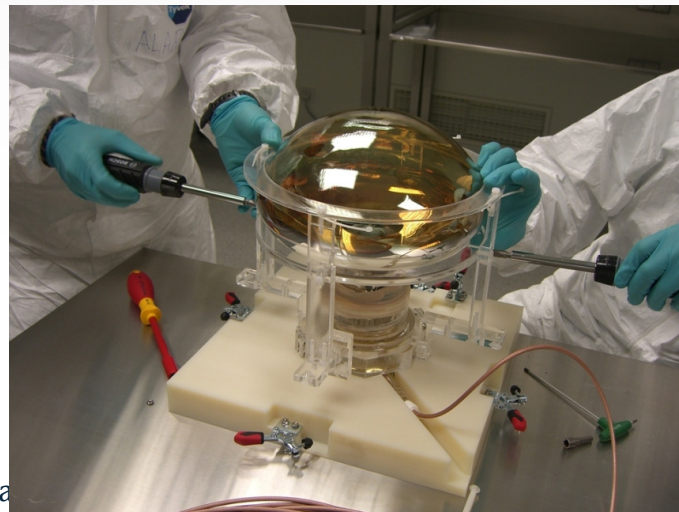


Current activities: PMT testing and assembly

PMT testing almost finished



PMT assembly in progress



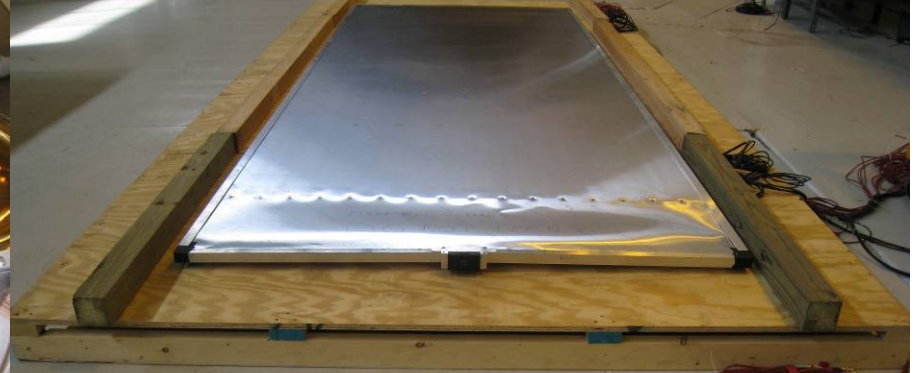
Current activities: Inner & Outer veto systems

▣ Inner Veto

- ◆ Tag efficiently cosmic ray muons & external fast neutrons entering the detector
- ◆ 78 8" PMTs **delivered and tested**

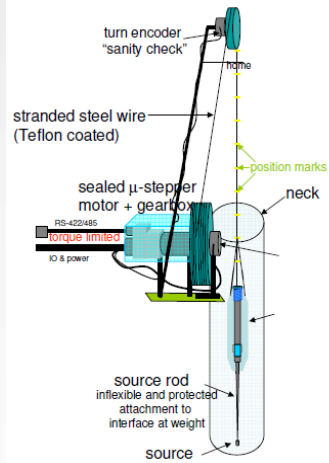
▣ Outer Veto

- ◆ Redundancy for higher rejection power
- ◆ Full prototype **built and tested**



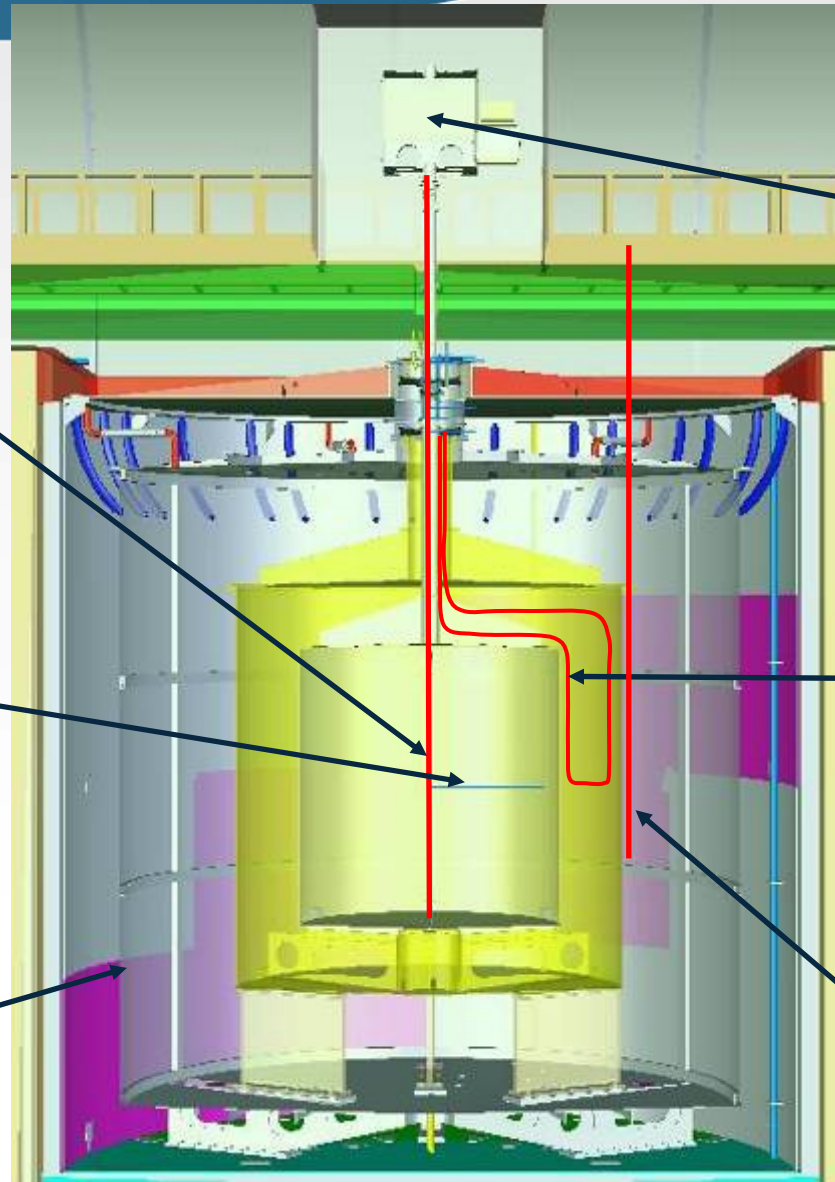
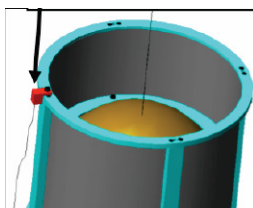
Calibration systems

Fish-line (Z-axis)



Articulated Arm

Embedded LED calibration system 385, 420, 470 nm



Glove Box



GC guide Tube



Buffer guide Tube

Statistical and systematic errors

@CHOOZ: $R = 1.01 \pm 2.8\%(\text{stat}) \pm 2.7\%(\text{syst})$

– Statistical error –

$$\text{Luminosity} = \Delta t \times P(\text{GW}) \times N_p(\text{target})$$

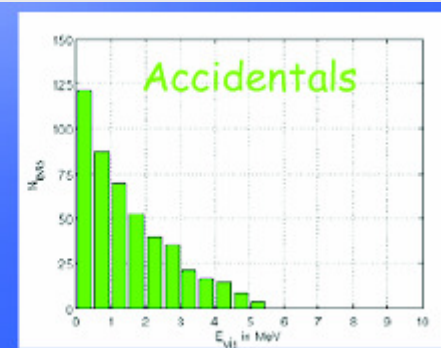
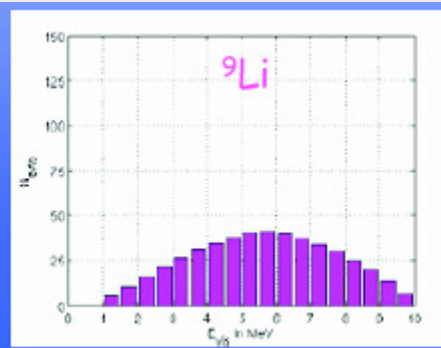
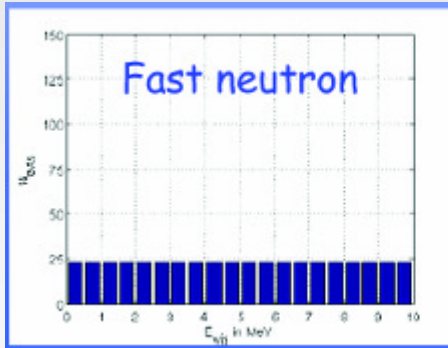
	CHOOZ	Double-Chooz
Target volume	5.55 m ³	10.3 m ³
Target composition	6.77 10 ²⁸ H/m ³	6.55 10 ²⁸ H/m ³
Data taking period	Few months	3-5 years
Event rate	2700	CHOOZ-far : 40 000/3 y CHOOZ-near: ~1 10 ⁶ /3 y
Statistical error	2.8%	0.5%

– Systematic errors –

	Chooz	Double-Chooz
Reactor cross section	1.9 %	—
Number of protons	0.8 %	0.2 %
Detector efficiency	1.5 %	0.5 %
Reactor power	0.7 %	—
Energy per fission	0.6 %	—

- Improve the detector design
- Two identical detectors:
→ towards $\sigma_{\text{relative}} \sim 0.6\%$
- Careful backgrounds control:
→ subtraction error < 1%

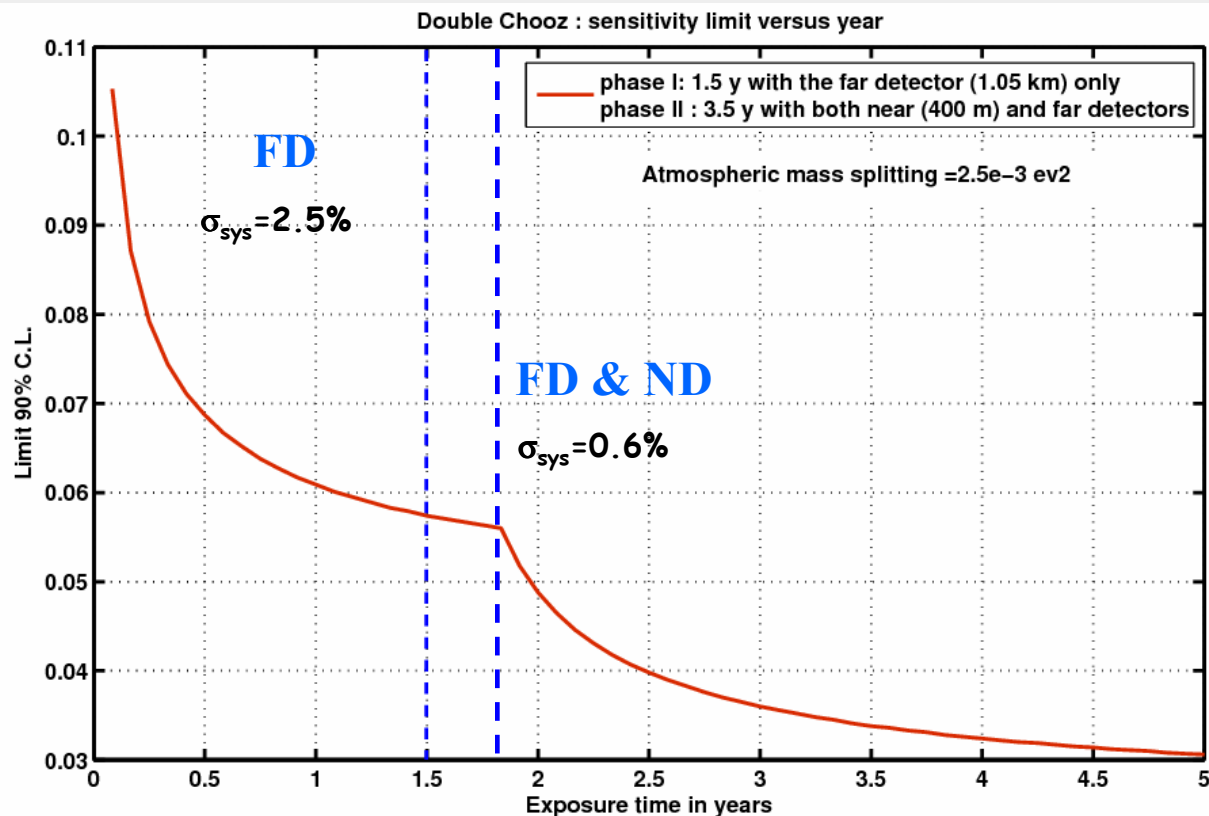
Background rates



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

Expected θ_{13} sensitivity



2 phases expected:

1. Far detector only:
10 x CHOOZ statistics
 $\sin^2 2\theta_{13} < 0.06$
2. Far + near detectors:
shape analysis
 $\sin^2 2\theta_{13} < 0.03$

Double-Chooz can surpass the original CHOOZ result in 3 months (even with a single detector)



Schedule

- Proposal of the experiment (*hep-ex/0606025*)
- Technical Design Report finished
- The first detector is being installed!
- **Schedule:**

- ◆ 2008-Summer 2009: Far detector integration
- ◆ Summer 2009: Far detector commissioning
- ◆ Beg. 2010: Near lab completed
- ◆ 2010: Near detector installation
- ◆ 2011: Near and far detectors data taking



Summary

- ▣ Double Chooz is the **first new generation reactor neutrino experiment** using two identical detectors at different distances to measure θ_{13}
- ▣ Far detector **installation has started!**
- ▣ First data taking expected to start in 2009 with far detector:
 - ◆ **$\sin^2 2\theta_{13} < 0.06$ in 1.5 years (90% CL)** (if no oscillation)
- ▣ Data taking with far and near detectors in 2011:
 - ◆ **$\sin^2 2\theta_{13} < 0.03$ in 3 years (90% CL)** (if no oscillation)



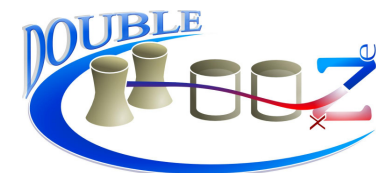


Danke schön!
Merci!

BACKUP SLIDES

Systematics

		Chooz	Double-Chooz	
Total		2.7 %	< 0.6 %	
Reactor-induced	ν flux and σ	1.9 %	<0.1 %	two "identical" detectors, monitor flux with near det.
	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 %	same weight sensor for both det.
	Density	0.3 %	<0.1 %	accurate T control (near/far)
	H/C ratio & Gd concentration	1.2 %	<0.1 %	same scintillator + stability of scintillator
	Spatial effects	1.0 %	<0.1 %	"identical" target geometry & LS
	Live time	few %	0.25 %	measured with several methods
Analysis	From 7 to 2-3 cuts	1.5 %	0.2 - 0.3 %	Low backgr., reduction of accidentals



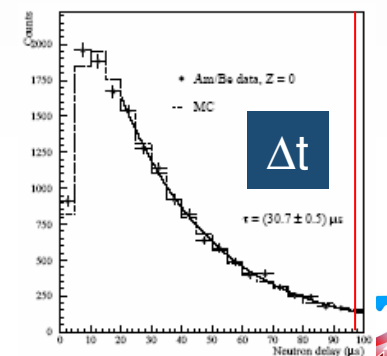
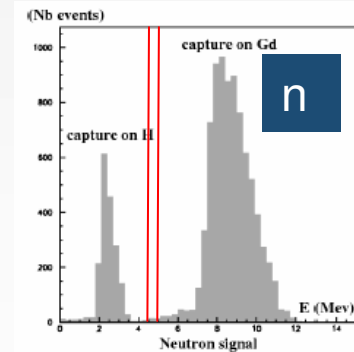
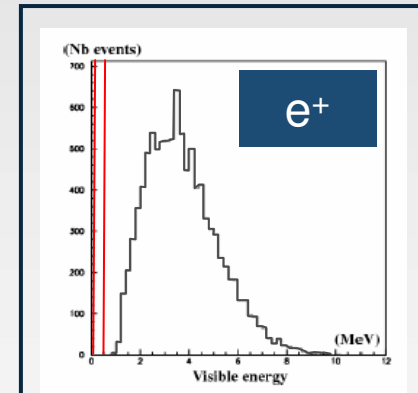
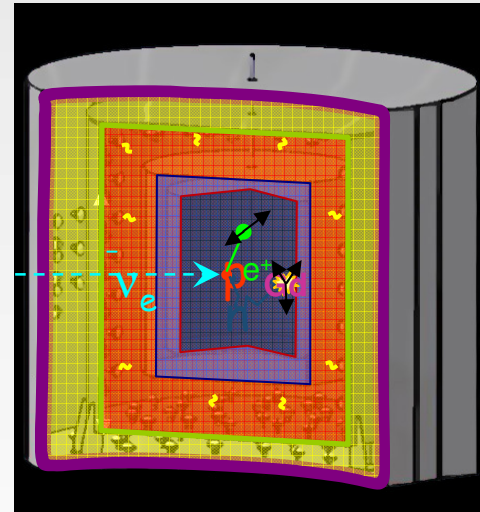
Relative normalization: analysis

- ◆ @Chooz: 1.5% syst. err.
 - 7 analysis cuts
 - Efficiency ~70%
- ◆ Double-Chooz goal: ~0.3% syst. err.
 - 2 or 3 analysis cuts

Selection cuts:

- neutron energy
- (- distance e+ - n) [rate of accidentals]
- Δt (e+ - n)

Detector designed to **minimize the need** for analysis cuts



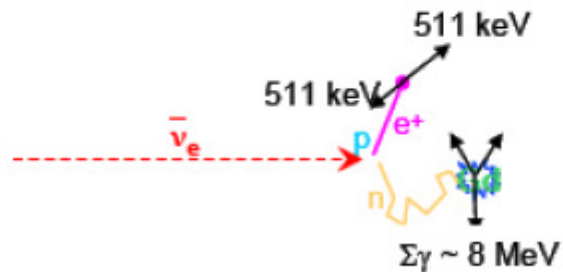
selection cut	CHOOZ		Double-CHOOZ	Comment
	rel. error (%)	rel. error (%)		
positron energy*	0.8	0		not used
positron-geode distance	0.1	0		not used
neutron capture	1.0	0.2		Cf calibration
capture energy containment	0.4	0.2		Energy calibration
neutron-geode distance	0.1	0		not used
neutron delay	0.4	0.1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



Signal and background

e^- antineutrino Signature

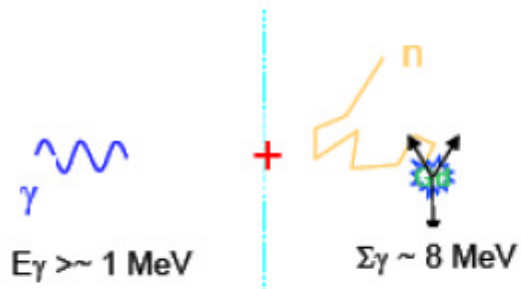


Prompt e^+ (1-8 MeV) Delayed n Gd-capture (8 MeV)

Time correlation: $\tau \sim 30 \mu\text{s}$ Space correlation: $< 1 \text{ m}$

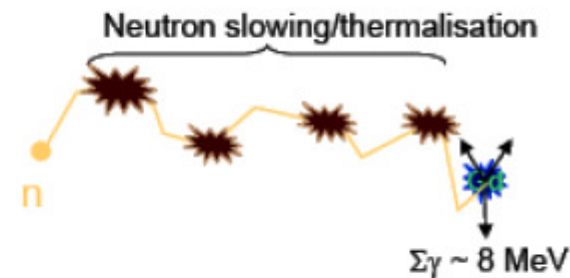
Far: 70 neutrinos d^{-1}
Near: 500 neutrinos d^{-1}

Accidental Background



Far: 2 neutrinos d^{-1}
Near: 11 neutrinos d^{-1}

Correlated Background



Far: 1.6 neutrinos d^{-1}
Near: 5.2 neutrinos d^{-1}



Background studies

Accidentals

- radioactivity (dominated by PMTs) + neutrons induced by cosmic muons
- request singles rate $\sim 5\text{Bq}$ (above 0.7 MeV)

Radiopurity constraints on detector materials single rate $< 0.1\text{ Hz}$ from each contribution

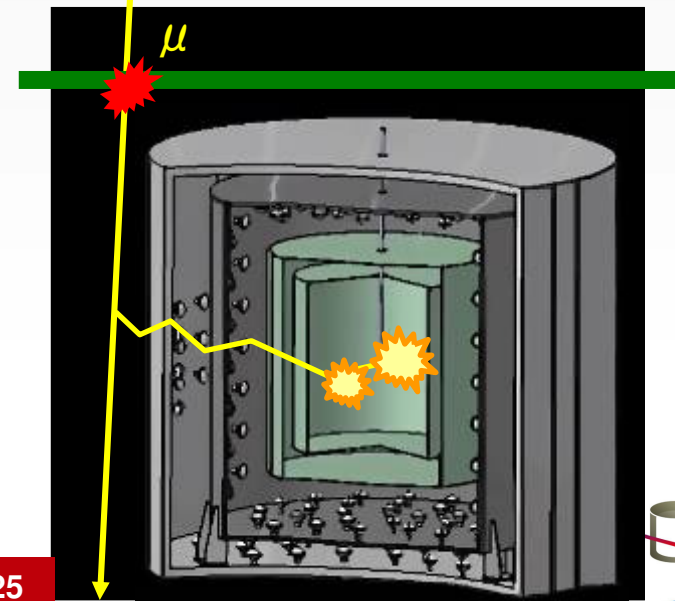
Less stringent than KamLAND and Borexino, but needs care

	^{40}K	^{238}U	^{232}Th	^{60}Co
	g/g	g/g	g/g	mBq/Kg
Target LS	10^{-10}	10^{-13}	10^{-13}	—
Target Acrylics	10^{-8}	10^{-11}	10^{-11}	—
GC LS	10^{-10}	10^{-13}	10^{-13}	—
GC Acrylics	10^{-8}	10^{-11}	10^{-11}	—
Buffer Oil	—	10^{-12}	10^{-12}	—
Buffer Vessel	—	10^{-9}	10^{-9}	15
Veto LS	—	10^{-10}	10^{-10}	—

Correlated

- old Chooz reactor-off data = $\sim 1.5\text{d}^{-1}$
 $\sim 50\%\text{fast-n}/\sim 50\%{}^9\text{Li}$
- validate simulation (Geant-4, Fluka)
- extrapolate to Far and Near detector

Measurements in correlation with muon signal in the Outer Veto will provide important information



The Daya Bay Nuclear Power Complex



- 12th most powerful in the world ($11.6 \text{ GW}_{\text{th}}$)
- One of the top five most powerful by 2011 ($17.4 \text{ GW}_{\text{th}}$)
- Adjacent to mountain \otimes underground labs with sufficient overburden

Ling Ao: $2 \times 2.9 \text{ GW}_{\text{th}}$



Ling Ao II: $2 \times 2.9 \text{ GW}_{\text{th}}$



Ready by 2010-2011



Daya Bay: Experimental Setup

Far site
Overburden: 355 m



Empty detectors: moved to underground halls via access tunnel.
Filled detectors: transported between halls via horizontal tunnels.

Ling Ao Near
Overburden: 112 m



Ling Ao II cores

Water hall
Liquid Scintillator hall

Construction tunnel

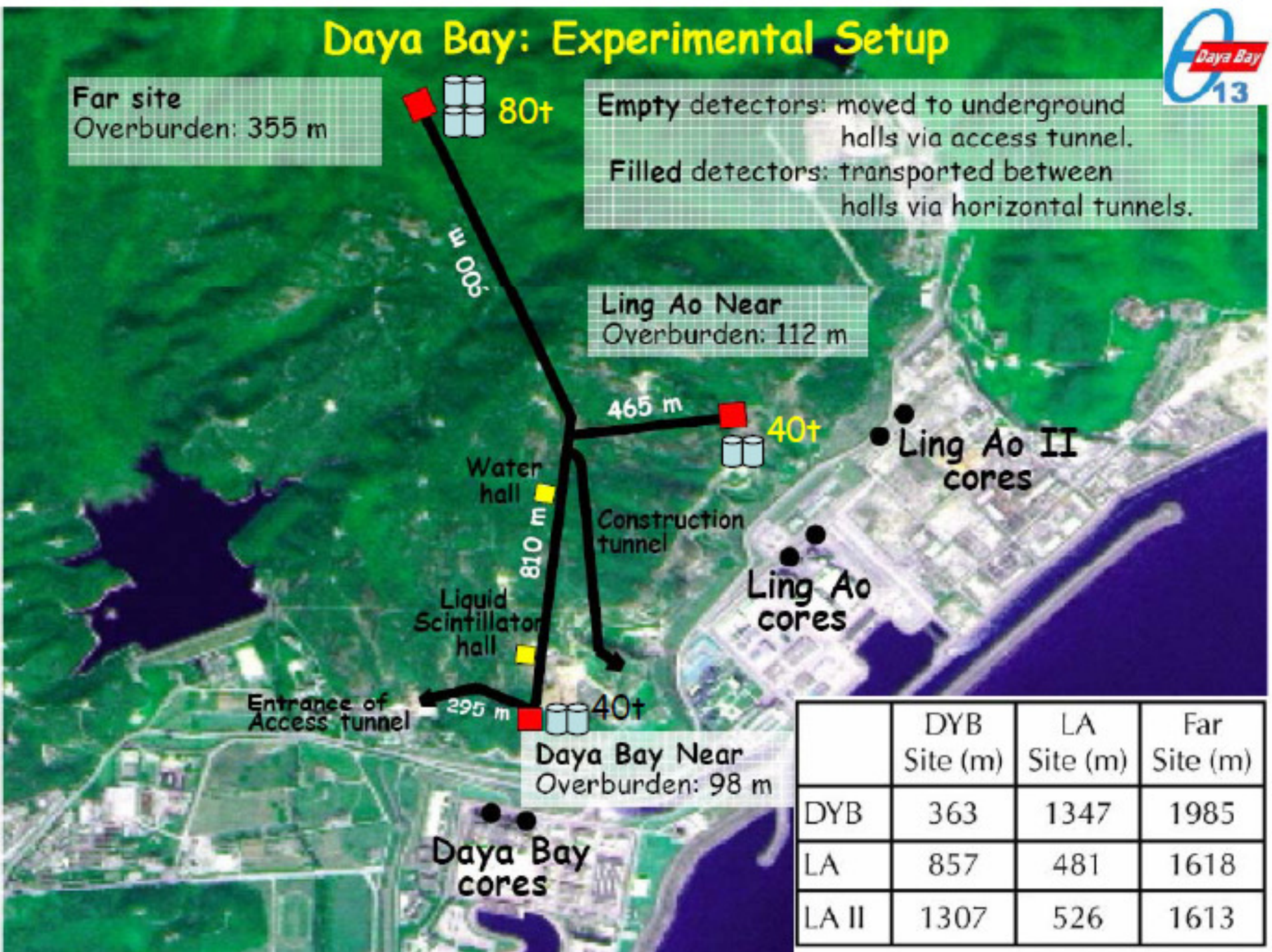
Ling Ao cores

Entrance of Access tunnel

Daya Bay Near
Overburden: 98 m

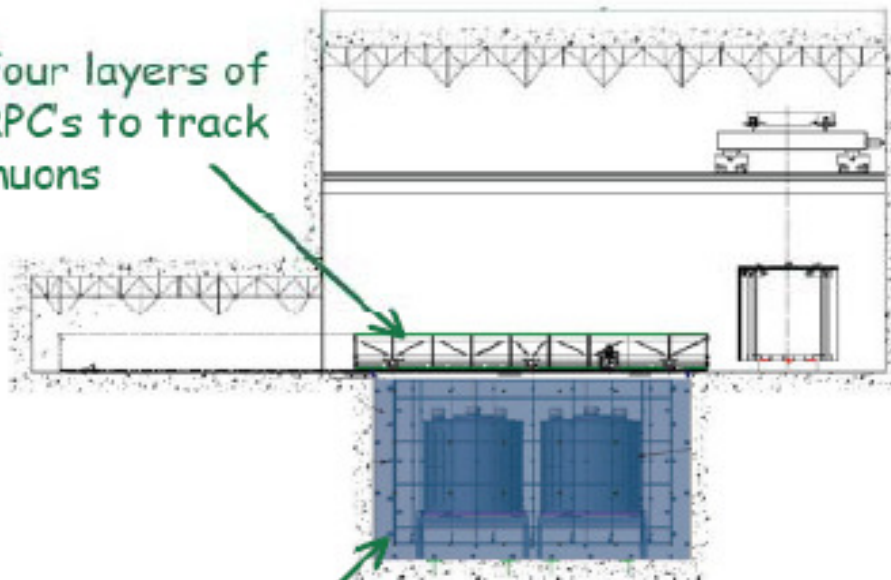
Daya Bay cores

	DYB Site (m)	LA Site (m)	Far Site (m)
DYB	363	1347	1985
LA	857	481	1618
LA II	1307	526	1613

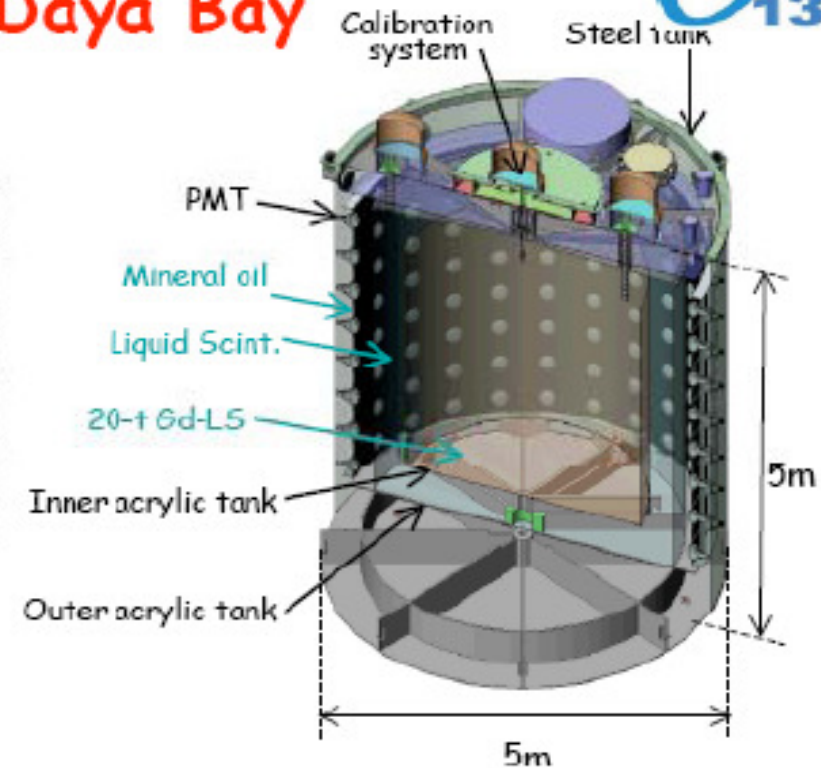


Detector Of Daya Bay

Four layers of RPC's to track muons



2.5m water shield also serves as Cherenkov counter for tagging muons

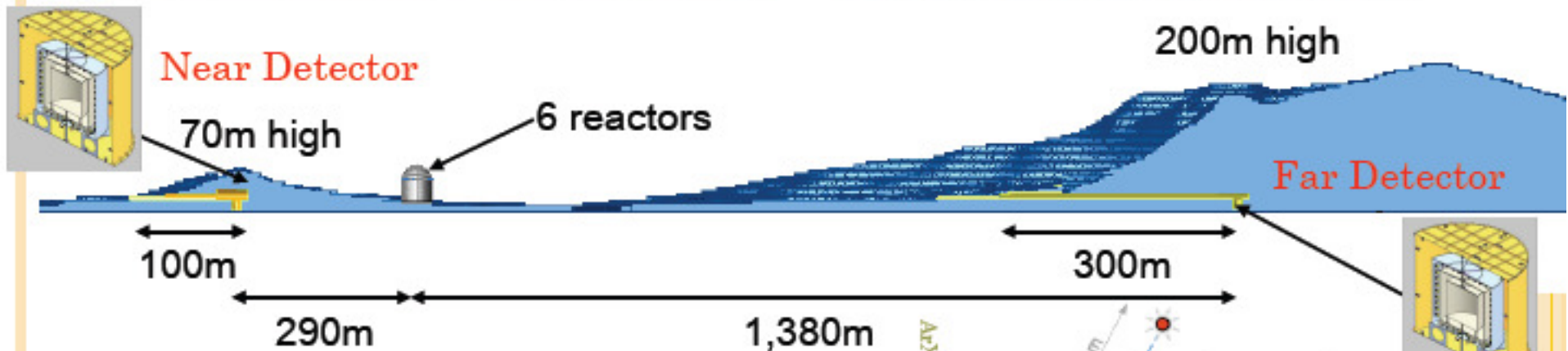


- Three-zone cylindrical detector design
 - Target: 20 + (0.1% Gd-doped LAB LS), 3.1 m
 - Gamma catcher: 20 + (LAB LS), 0.42 m
 - Buffer : 40 T (mineral oil) , 0.48 m
- Low-background 8" PMT: 192
- Reflectors at top and bottom of outer acrylic vessel
- Photocathode coverage:
 - 5.6 % → 12% (with reflectors)

RENO @ YONGGWANG

REACTOR EXPERIMENT FOR NEUTRINO OSCILLATION

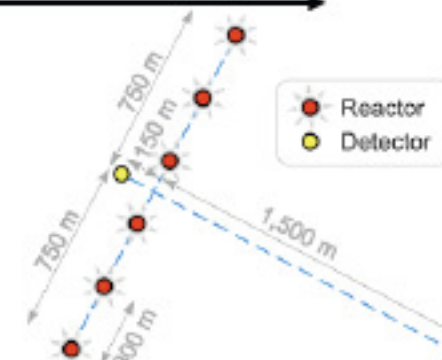
Collaboration:
South Korea + Russia



Total reactor power of the 6 cores: $17.3 \text{ GW}_{\text{th}}$
(although 2 contribute $>80\%$ of observed ϕ_{ν})



arXiv:0704.0498v2 [hep-ex]



Angra

-Prospect for a $\sin^2(2\theta_{13}) < 0.01$ after Double Chooz

- Angra II-III reactors (2 x 4.0 GW) ,
- 1.5 km tunnel to excavate for the far det. + a shaft/tunnel for the near det.
- Large detector (*a few hundreds tons*) focusing on spectral measurement

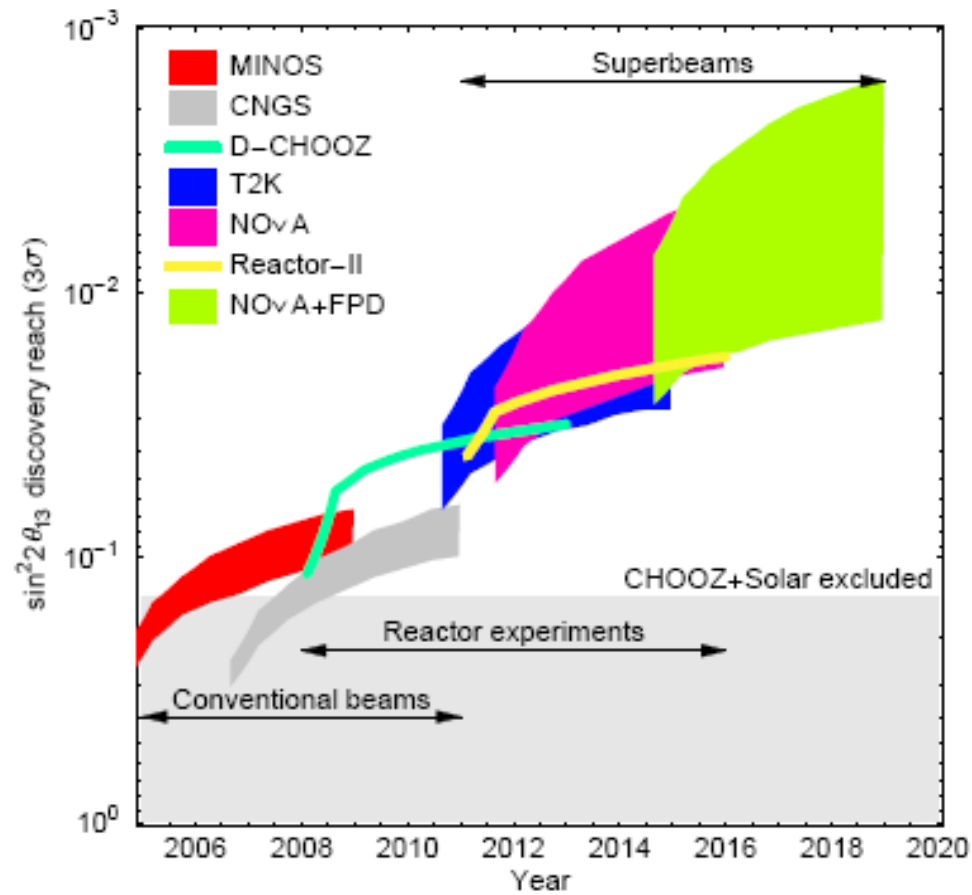
θ_{13} @ ANGRA
IN STAND BY

-Angra collaboration merged with Double Chooz in 2006

-Realization of a Small Neutrino Detector for Non Proliferation



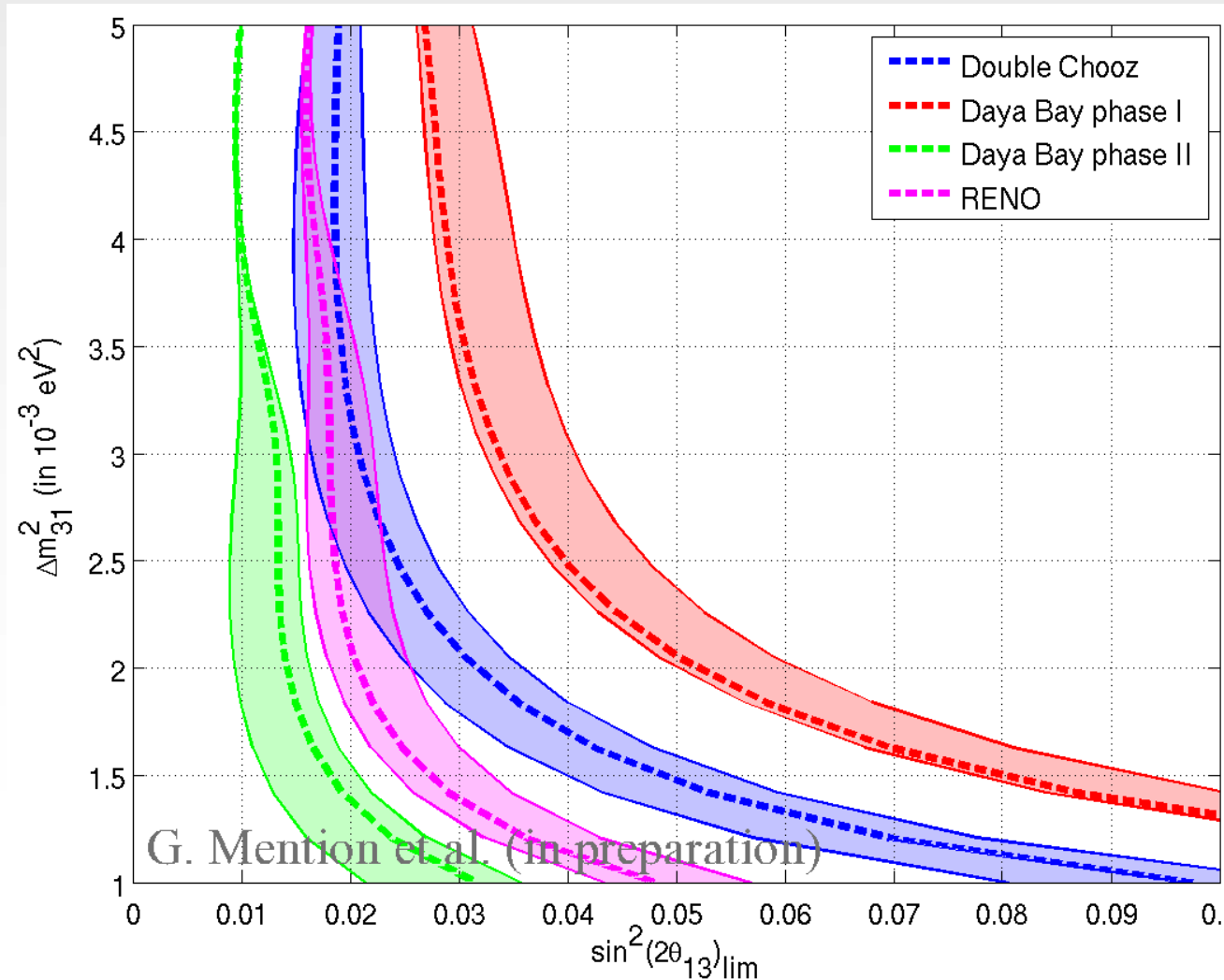
Expected sensitivity vs time



hep-ex/0509019



Reactor experiments comparison



The inputs: *experiment site setups*

