The Double Chooz reactor neutrino experiment

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DISCRETE ´08

Symposium on Prospects in the Physics of Discrete Symmetries

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DOUBLE CHOOZ

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

Neutrino oscillations

$(\nu_e,\nu_\mu,\nu_\tau)^T = U\,(\nu_1,\nu_2,\nu_3)^T$ U = matrix PMNS : **3 angles, 1 complex phase**

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

atmospheric ν **leptonic ~~CP~~ phase δ** **solar ν**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\Phi_{ij} - 2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin 2\Phi_{ij}$$

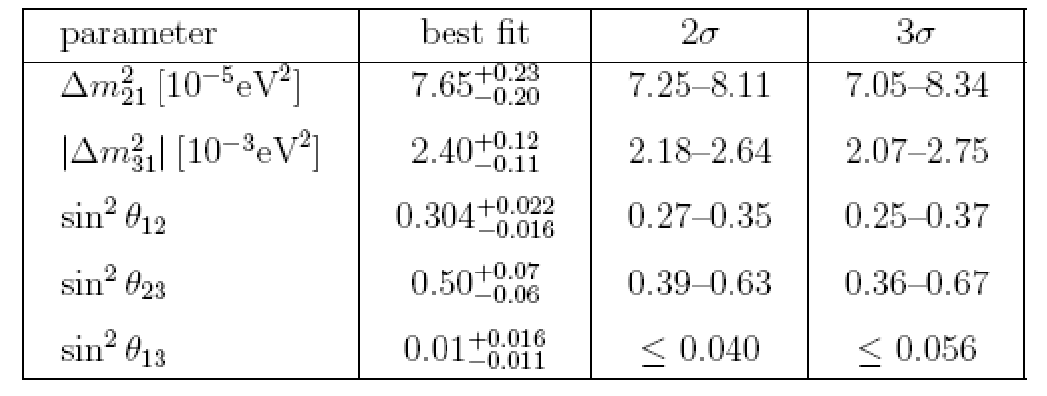
$$\Phi_{ij} = \frac{\Delta m^2_{ij} L}{4E} \quad \Delta m^2_{ij} = m^2_j - m^2_i$$

2 mass differences

Current knowledge on neutrino mixing parameters

Experimental measurements

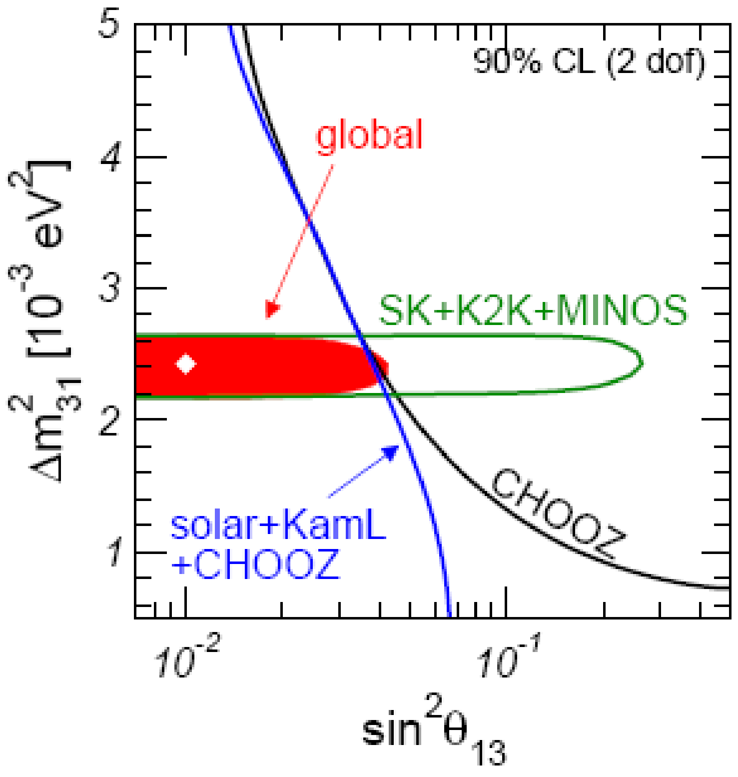
T. Schwetz et al.,
New J.Phys.10:113011,2008



parameter	best fit	2σ	3σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.65^{+0.23}_{-0.20}$	7.25–8.11	7.05–8.34
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	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

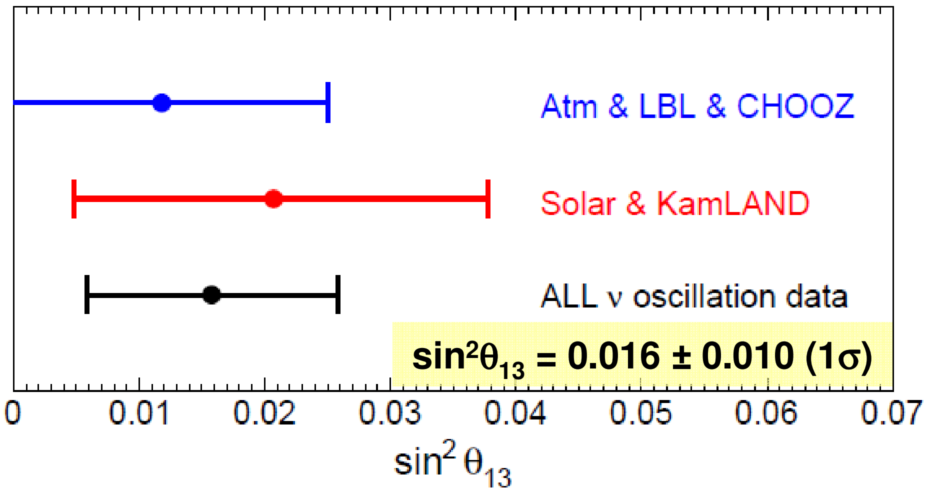
Best global limit on θ_{13}

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



Hints for $\theta_{13} > 0$

G.L. Fogli et al.,
Phys.Rev.Lett.101:141801,2008



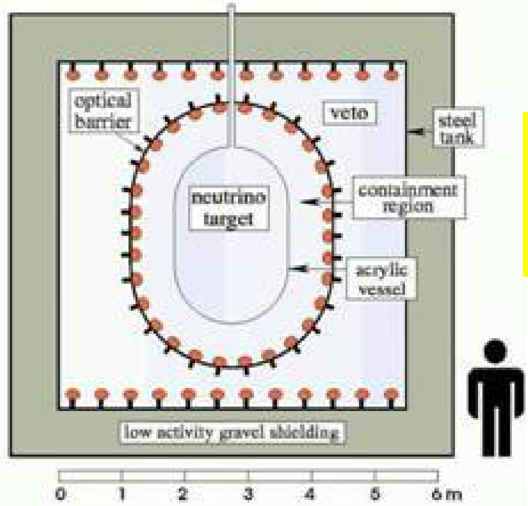
$\sin^2\theta_{13} = 0.016 \pm 0.010$ (1σ)

The θ_{13} mixing angle

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

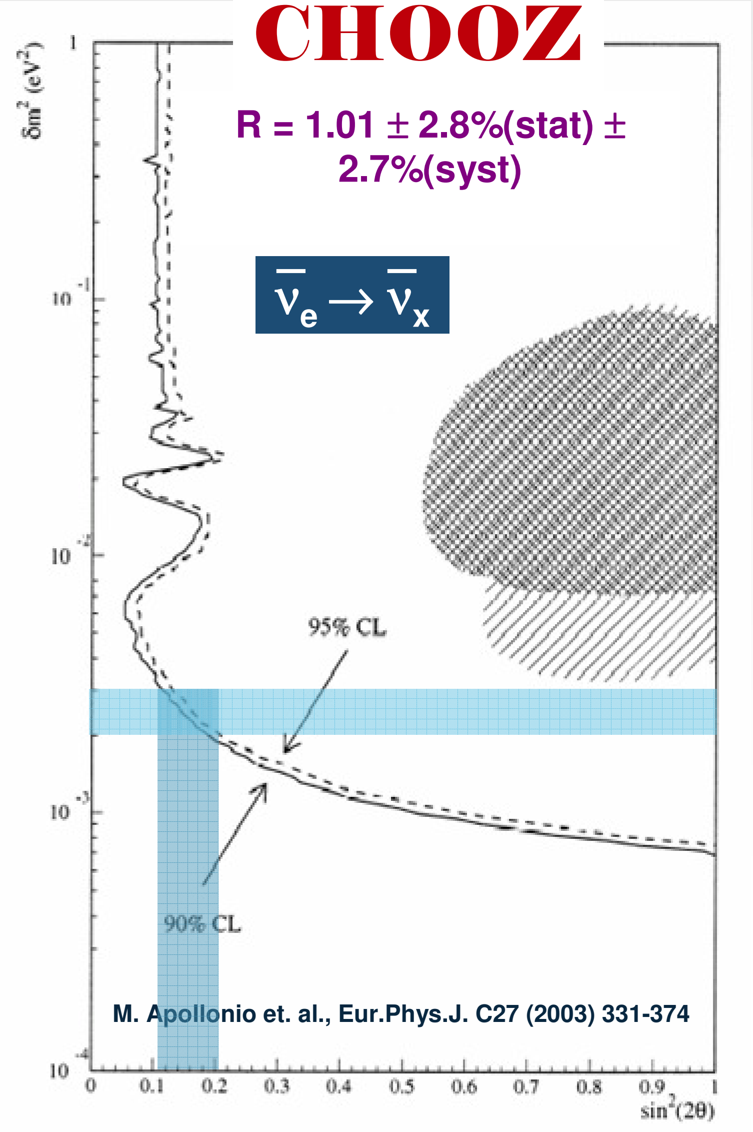
$\bar{\nu}_e \rightarrow \bar{\nu}_e$ (disappearance experiment)

$P_{th} = 8.4\ GW_{th}$, L = 1.050 km, M = 5 t
Overburden: 300 mwe



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

CHOOZ



R = 1.01 ± 2.8%(stat) ± 2.7%(syst)

$\bar{\nu}_e \rightarrow \bar{\nu}_x$

M. Apollonio et. al., Eur.Phys.J. C27 (2003) 331-374

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

- **Accelerator experiments**: appearance experiments
  - $P(\nu_\mu \rightarrow \nu_e)$ depends on $\sin^2(2\theta_{13})$, $\sin^2(\theta_{23})$, sign(Δm^2_{31}), 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^2_{12}

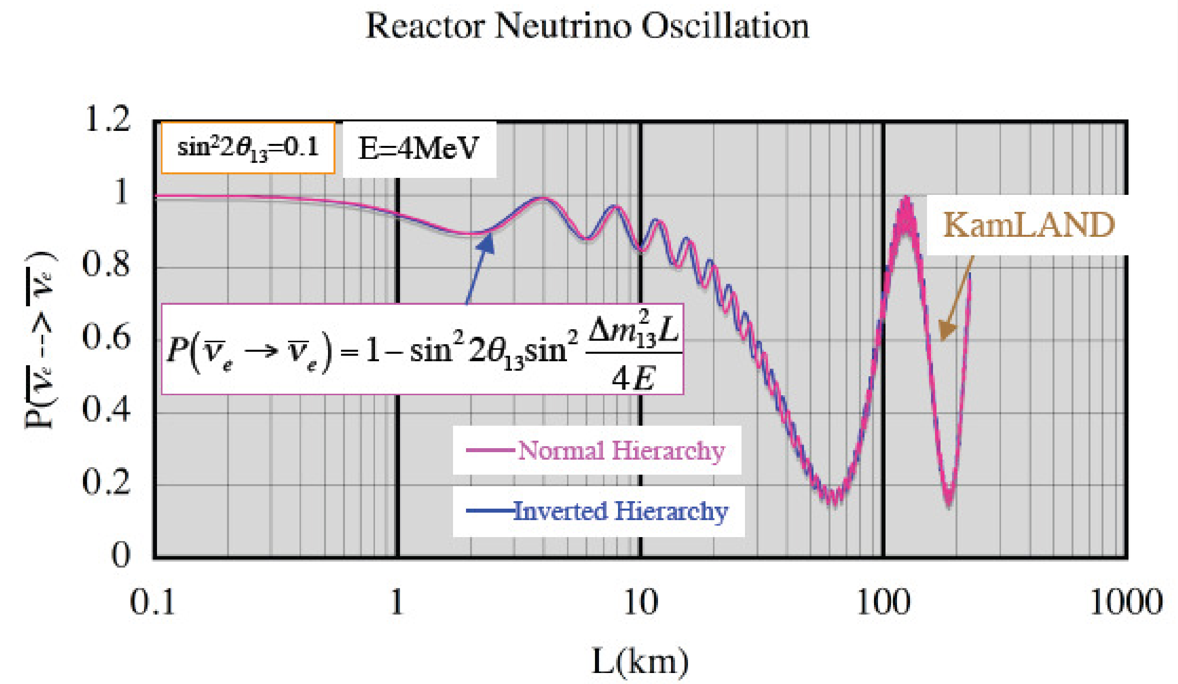
    No parameter degeneracies
    No matter effects
  - Resolve θ_{23} degeneracy combined with accelerator experiments
- **Reactor advantages with respect to accelerators**:
  - Pure θ_{13}
  - Pure $\bar{\nu}_e$, no flavor contamination
  - ν flux known at few%
  - Smaller detectors (cheaper)

Both type of experiments provide independent and complementary information

Neutrino oscillations at nuclear reactors

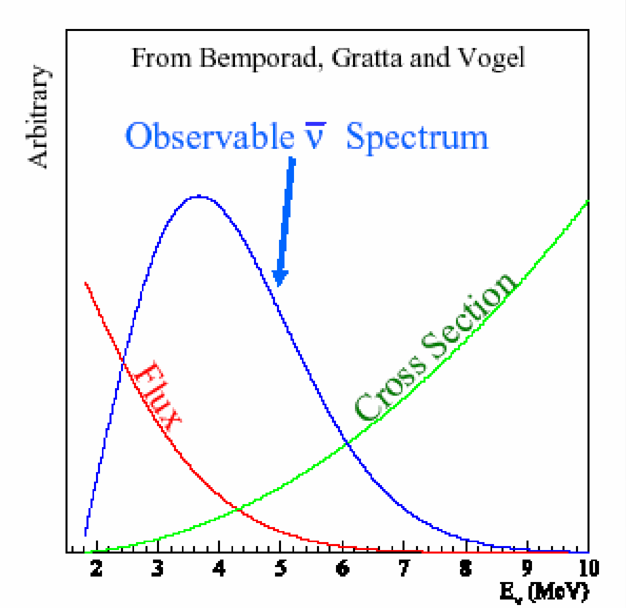
$\bar{\nu}_e$ disappearance searches

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



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

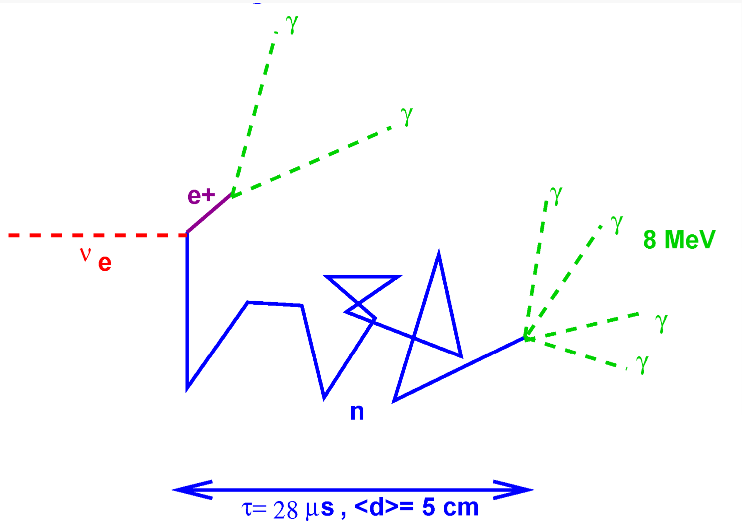
Antineutrino detection at nuclear reactors



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

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

$$n + Gd \rightarrow 8\ \mathrm{MeV}\ \gamma$$



- Prompt photons from **e^+** annihilation:

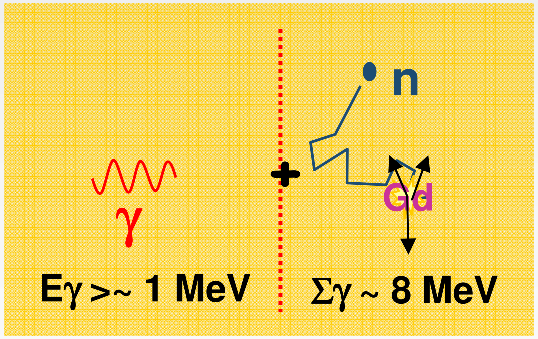
$$E_{VIS} \approx \mathbf{E_\nu} - (M_n - M_p) + m_e$$

- Delayed photons from **n** capture:
  - on H : Δt ~200 μs, E~2 MeV
  - on dedicated nuclei (Gd): Δt ~30 μs, E ~8 MeV

Backgrounds at nuclear reactors

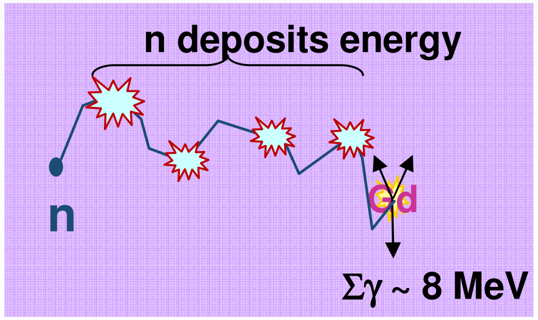
◻ Accidental events:

- **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}Li & ^{8}He (β-n decay)

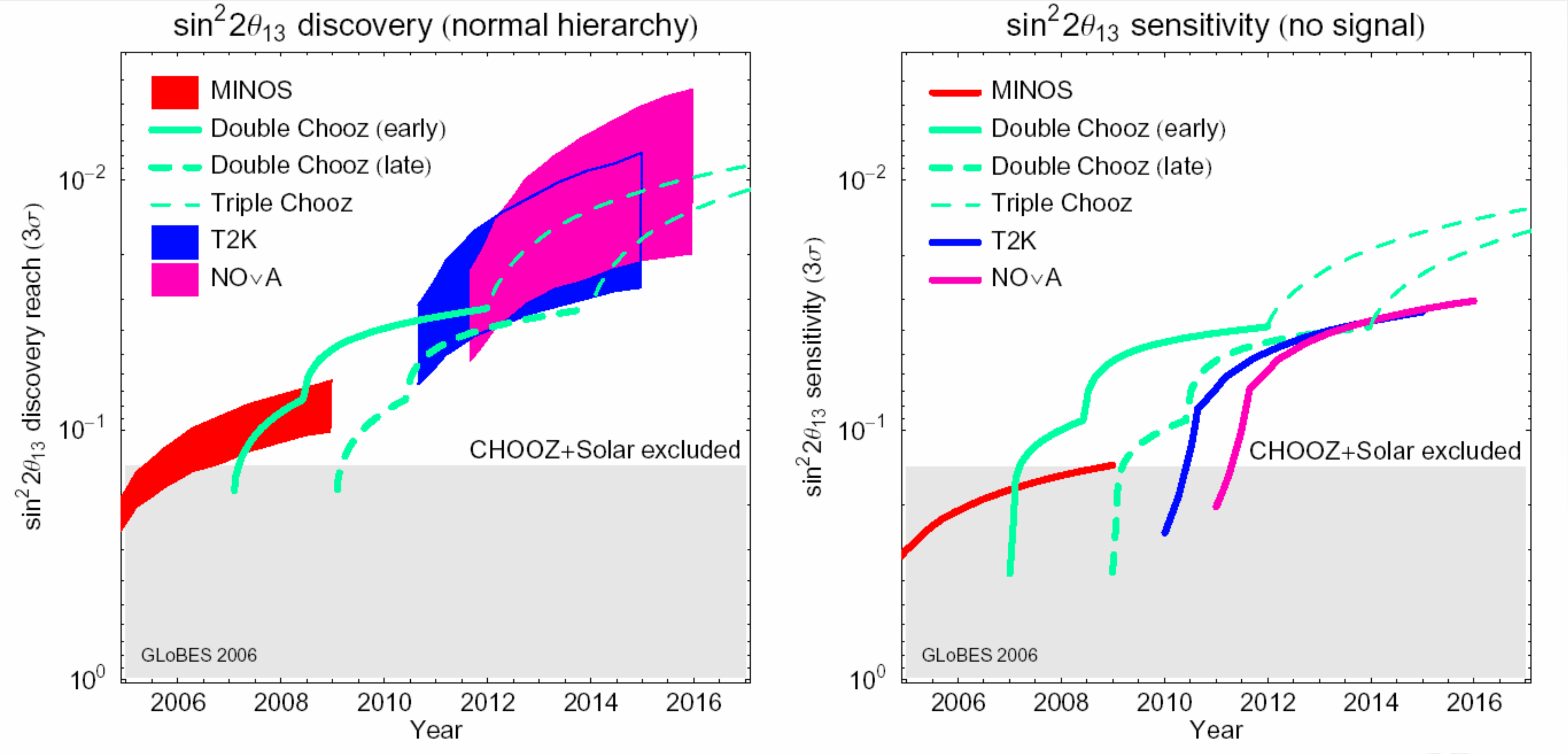


Evolution of the 3σ discovery and sensitivity

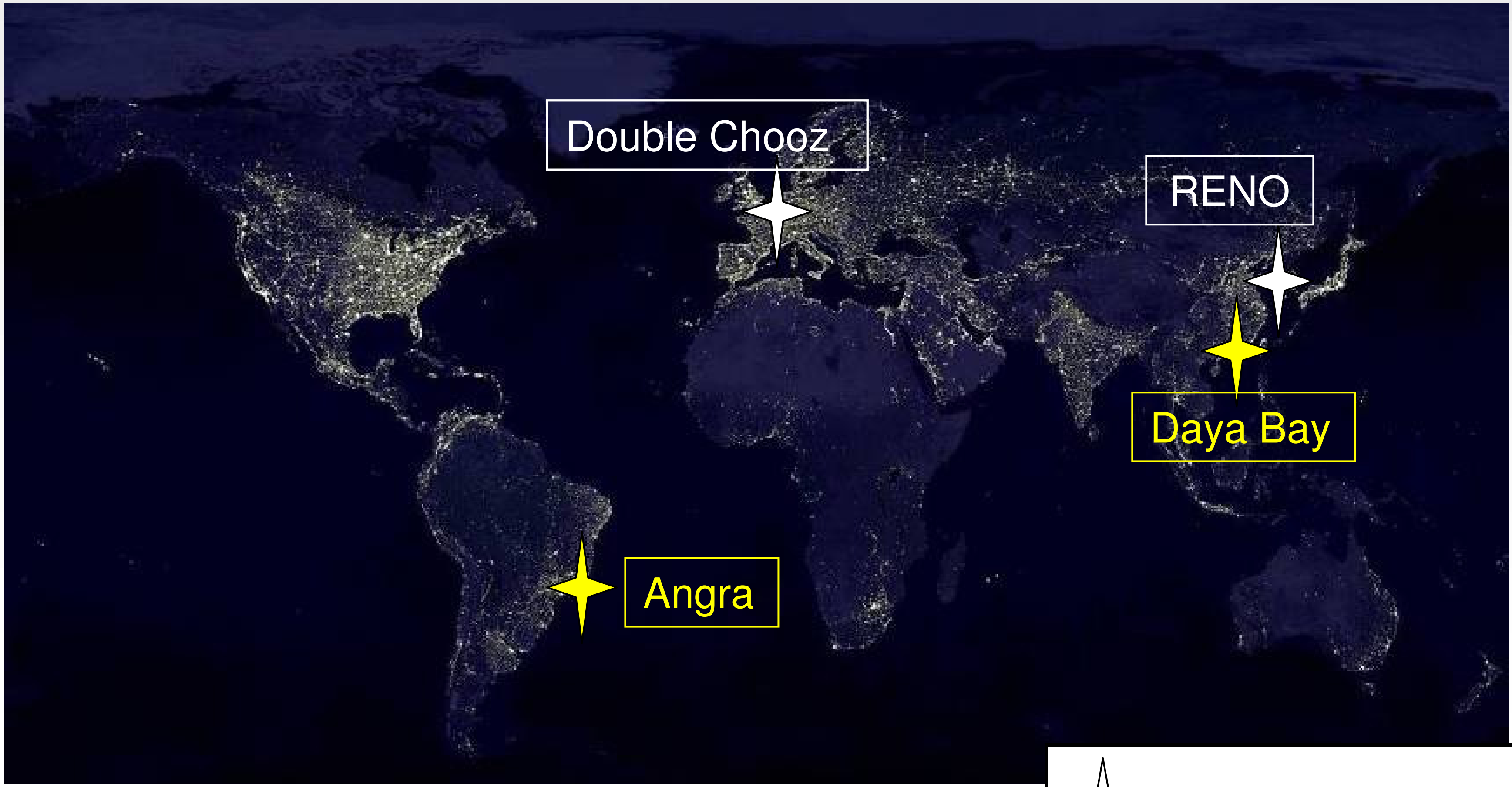
hep-ph/0601266

3σ discovery potential

3σ sensitivity (no signal)

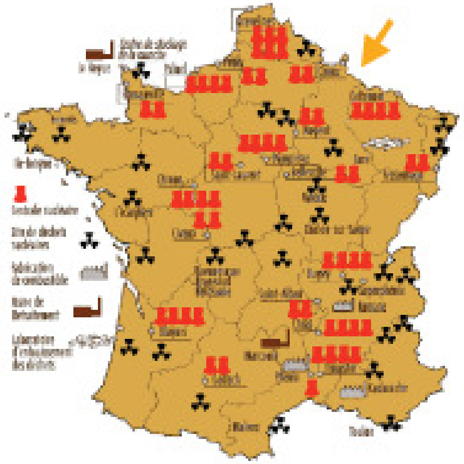


Reactor neutrino experiments



- ☆ 1st generation: $\sin^2(2\theta_{13})$~0.02-0.03
- ★ 2nd generation: $\sin^2(2\theta_{13}) \to 0.01$

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

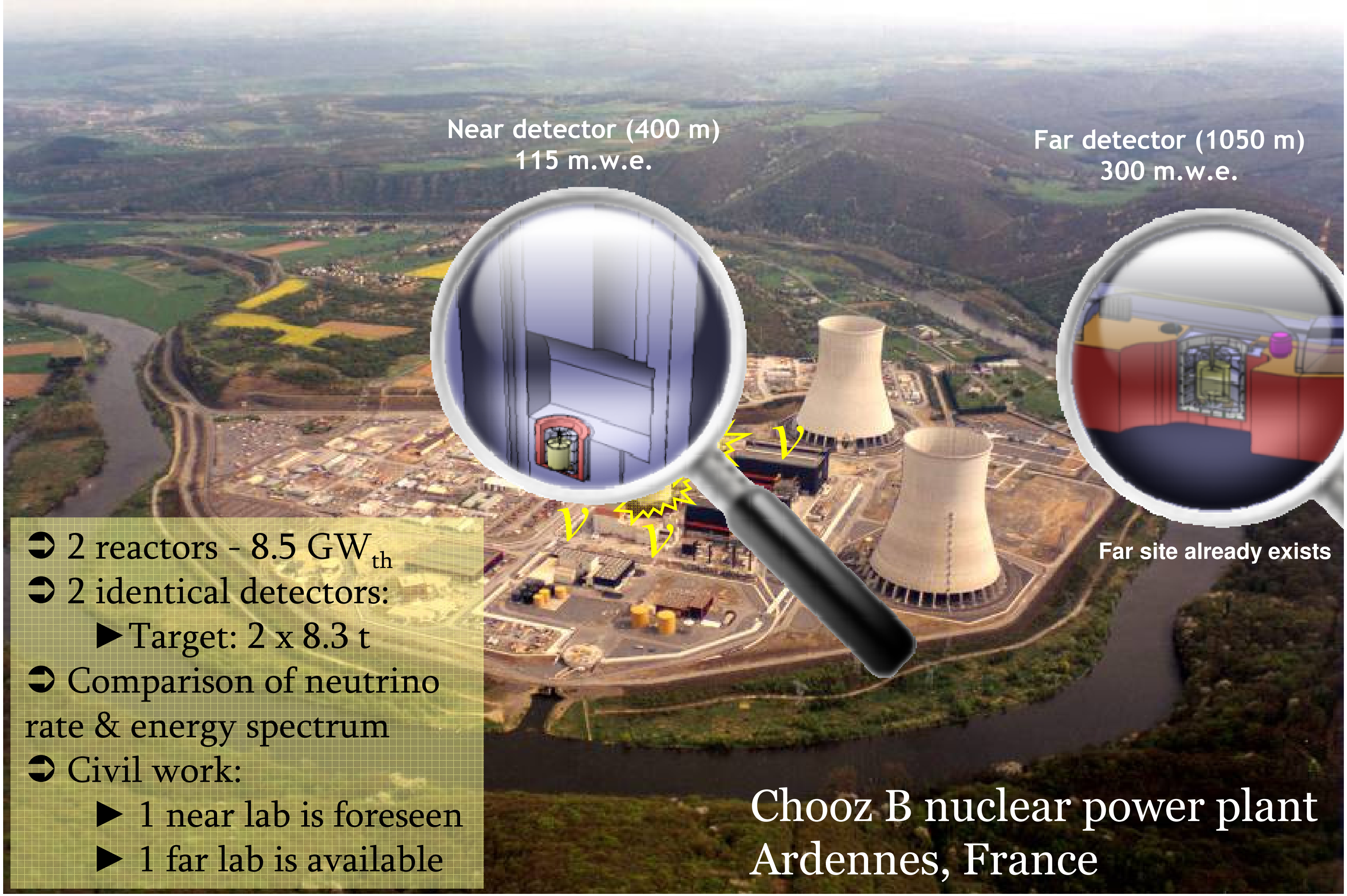
Russia: RAS, RRC Kurchatov Institute

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

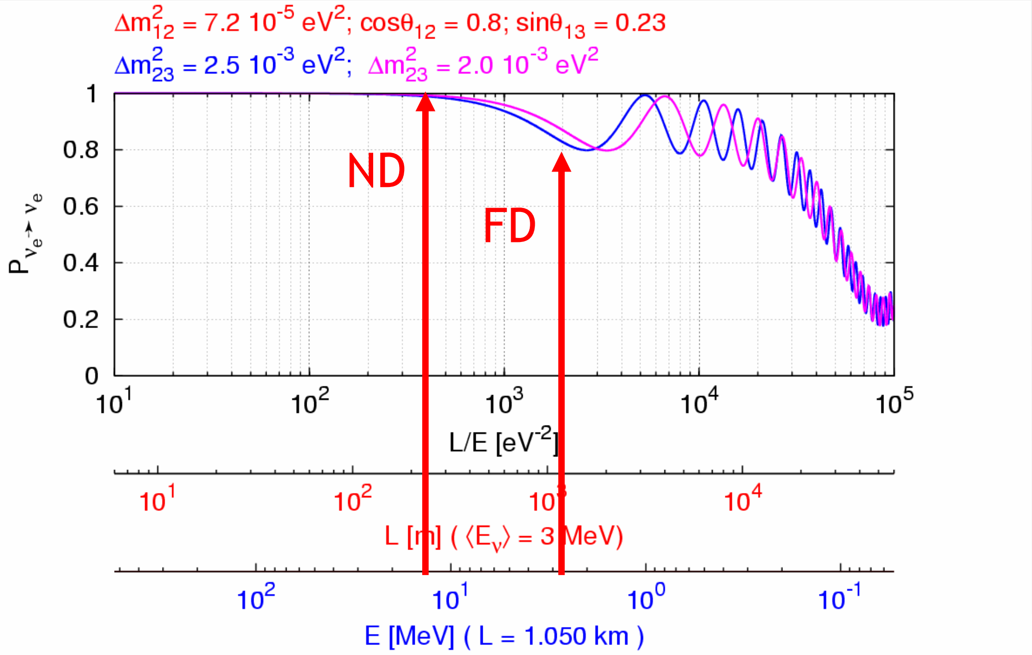


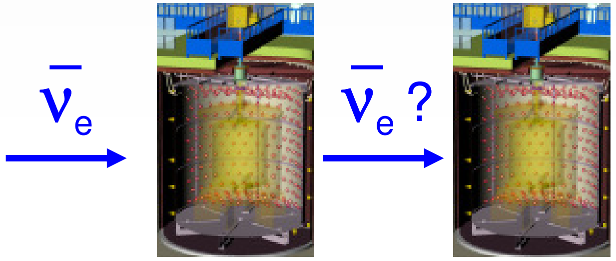
- 2 reactors - 8.5 GW_{th}
- 2 identical detectors:
  - ▶ Target: 2 x 8.3 t
- Comparison of neutrino rate & energy spectrum
- Civil work:
  - ▶ 1 near lab is foreseen
  - ▶ 1 far lab is available

Chooz B nuclear power plant
Ardennes, France

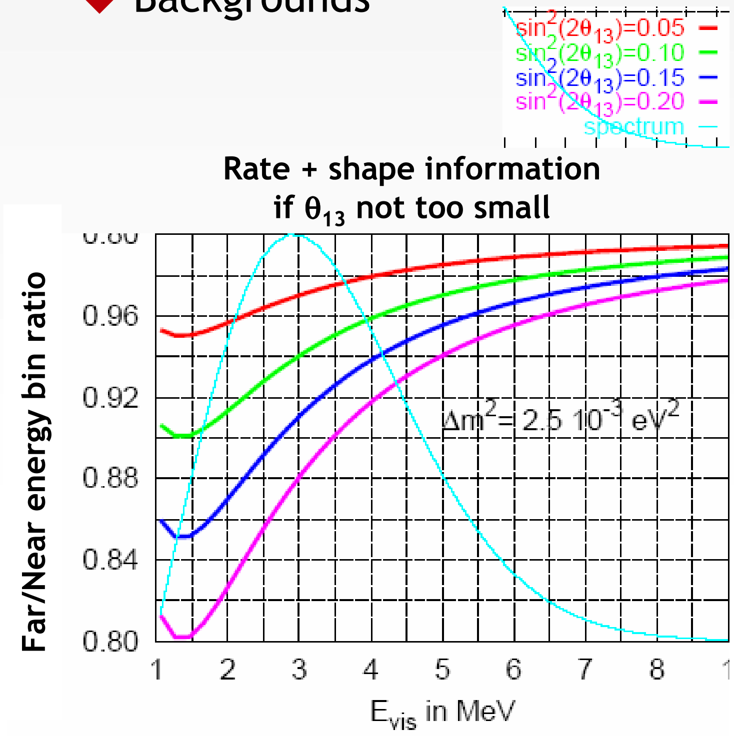
Survival probability

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

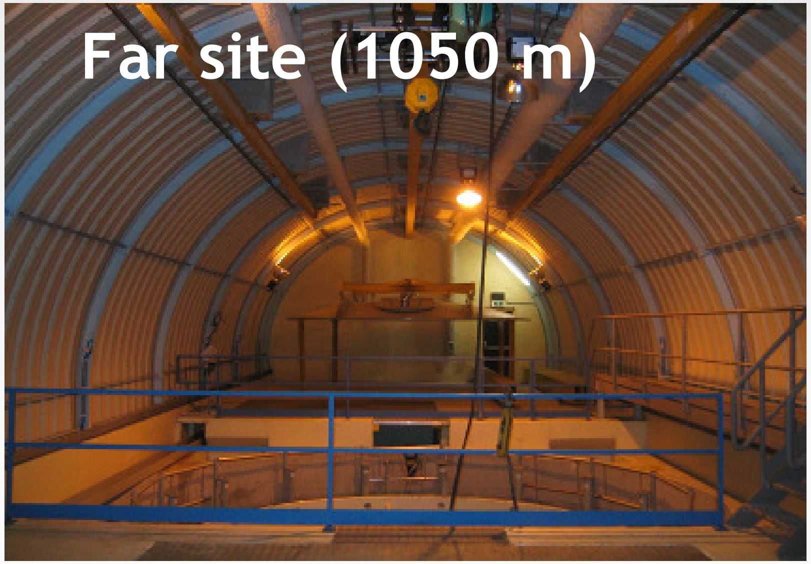


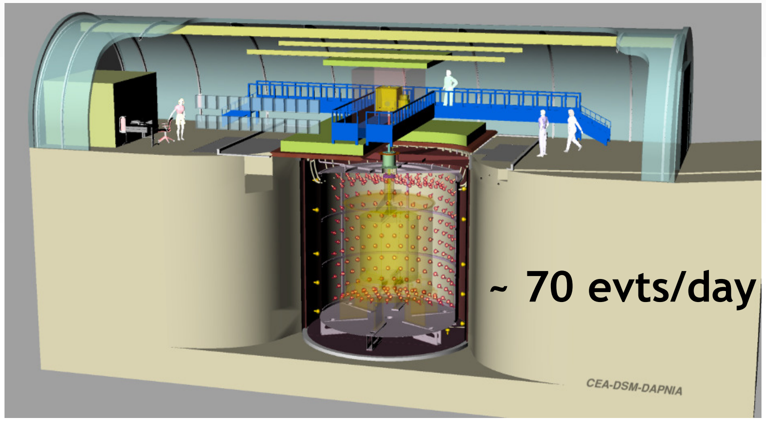


Rate + shape information
if θ_{13} not too small

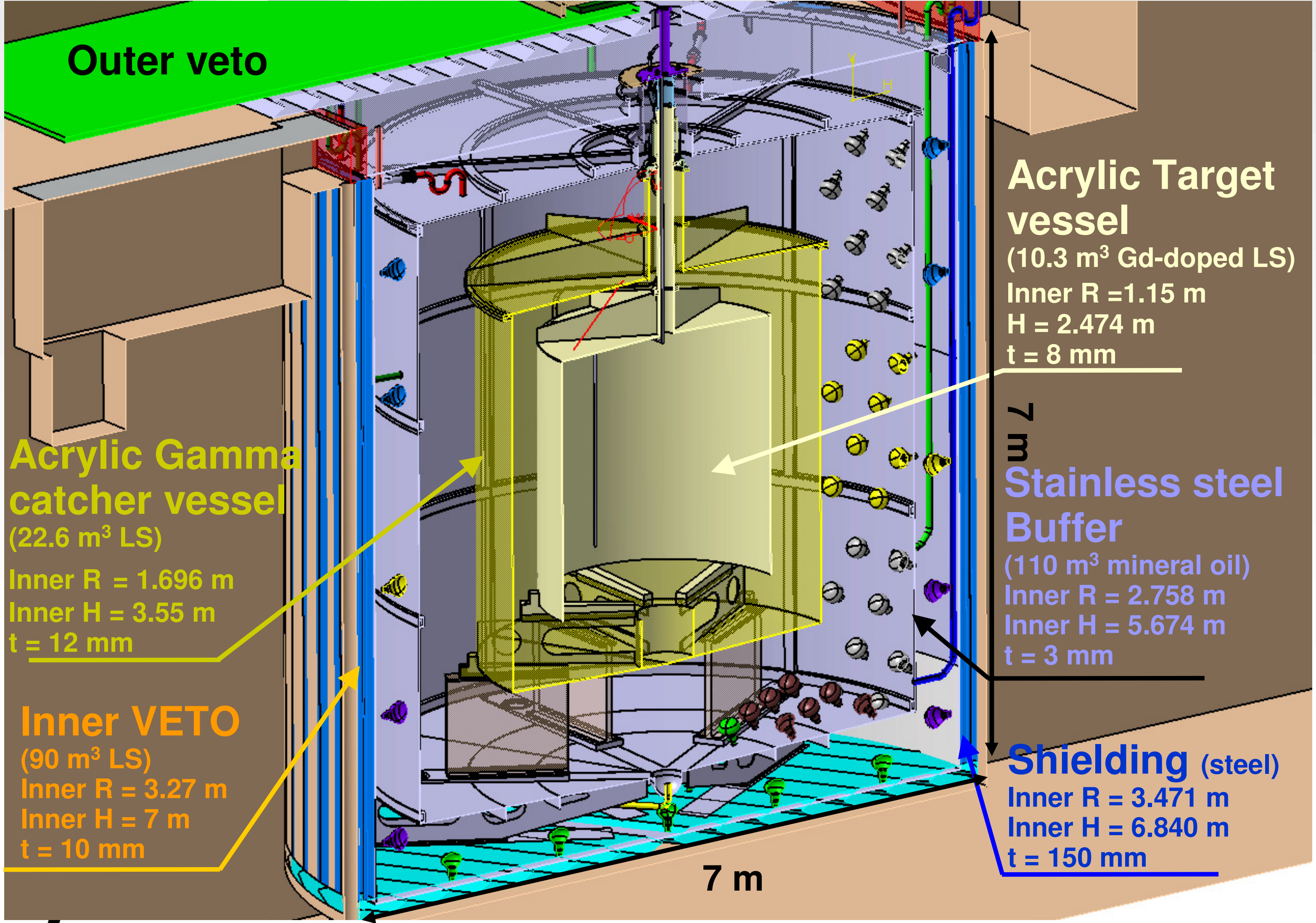


Far and near labs





Detector design



Acrylic Target vessel
($10.3\ m^3$ Gd-doped LS)
Inner R =1.15 m
H = 2.474 m
t = 8 mm

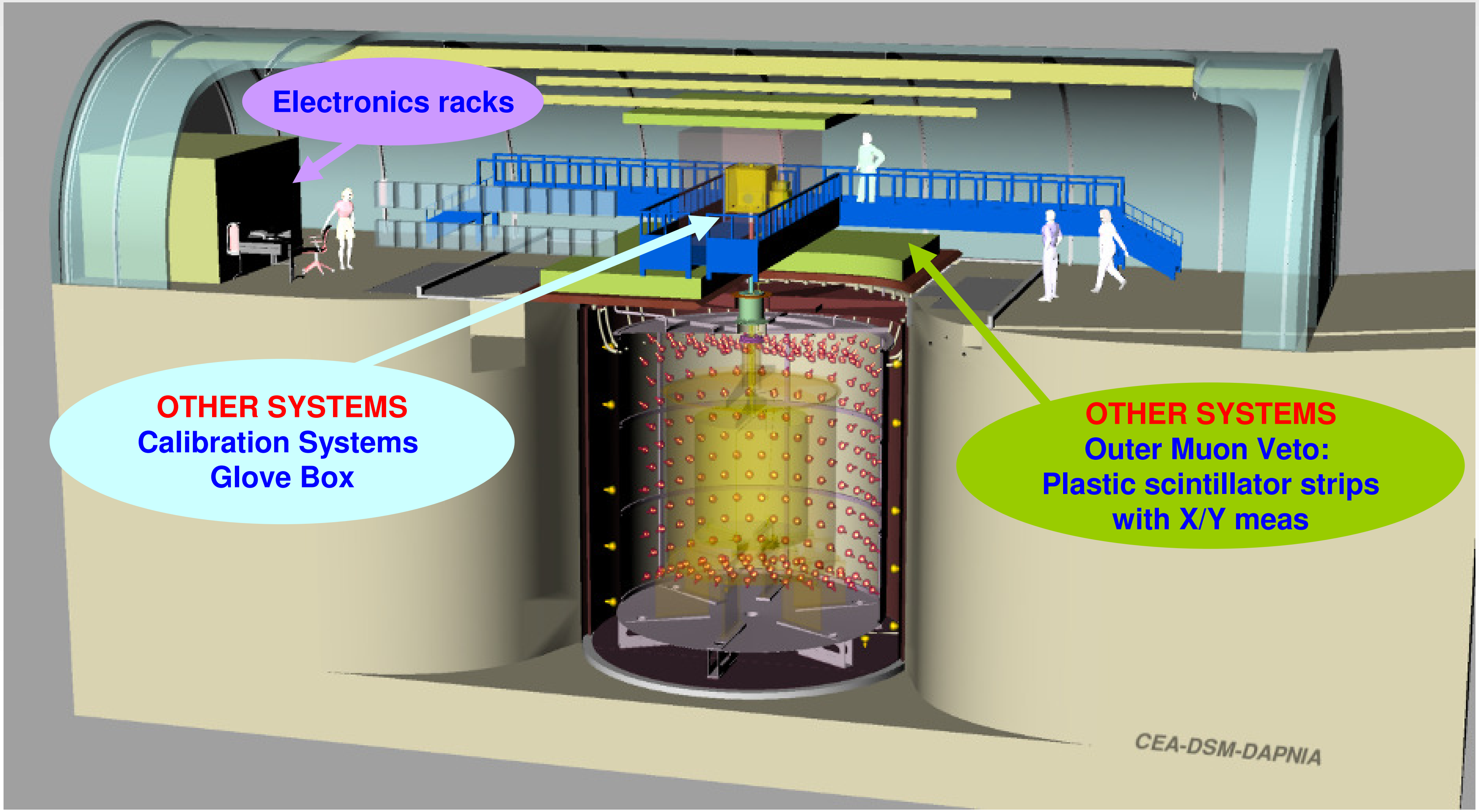
Acrylic Gamma catcher vessel
($22.6\ m^3$ LS)
Inner R = 1.696 m
Inner H = 3.55 m
t = 12 mm

Stainless steel Buffer
($110\ m^3$ mineral oil)
Inner R = 2.758 m
Inner H = 5.674 m
t = 3 mm

Inner VETO
($90\ m^3$ LS)
Inner R = 3.27 m
Inner H = 7 m
t = 10 mm

Shielding (steel)
Inner R = 3.471 m
Inner H = 6.840 m
t = 150 mm

Detector in the lab



Electronics racks

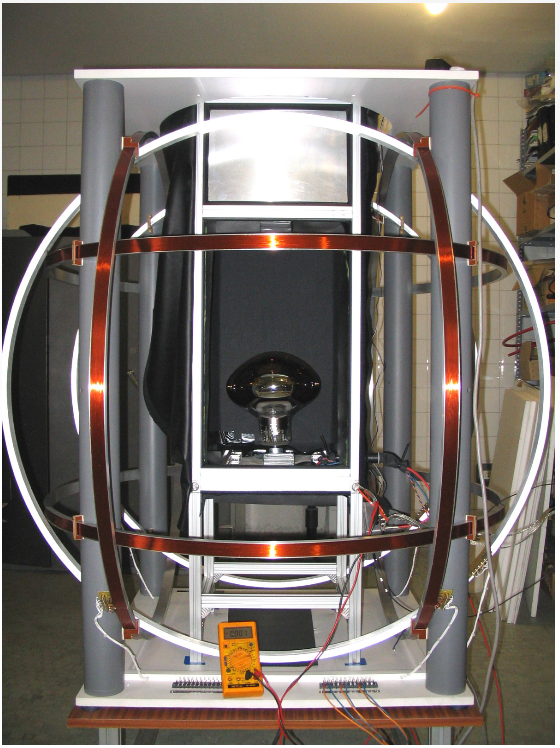
OTHER SYSTEMS
Calibration Systems
Glove Box

OTHER SYSTEMS
Outer Muon Veto:
Plastic scintillator strips
with X/Y meas

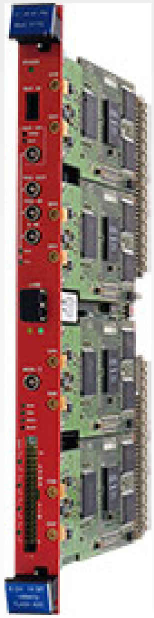
R&D activities and tests

1/5 mockup @ Saclay

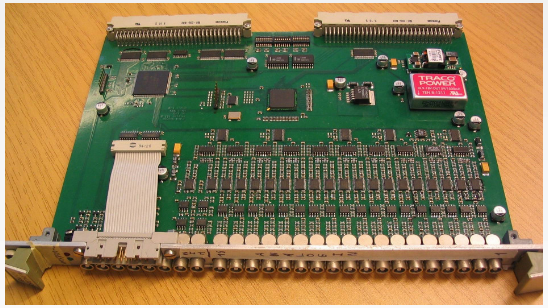
Magnetic tests @ CIEMAT



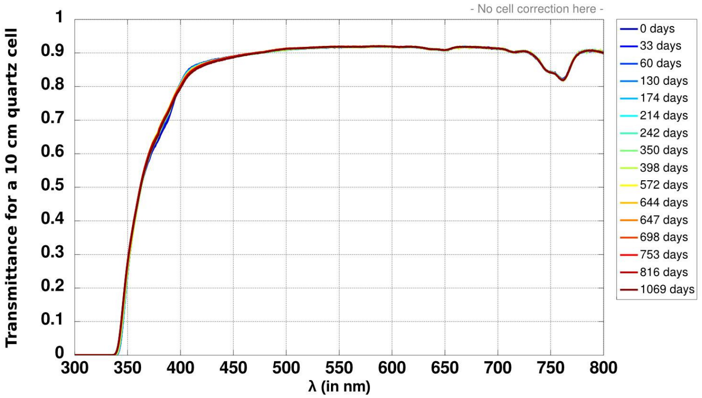
fADCs CAEN V1721 @ APC



L1 Trigger board @ Aachen

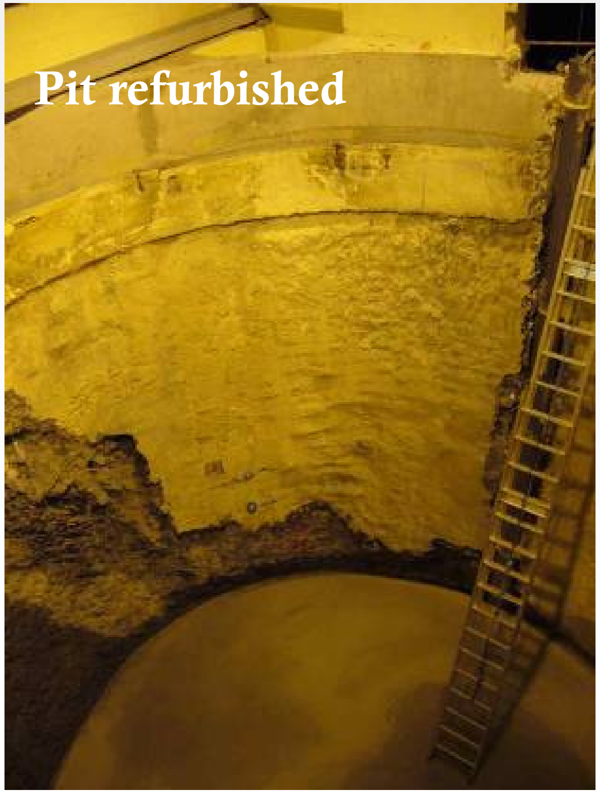


Gd doped scintillator development @ MPIK



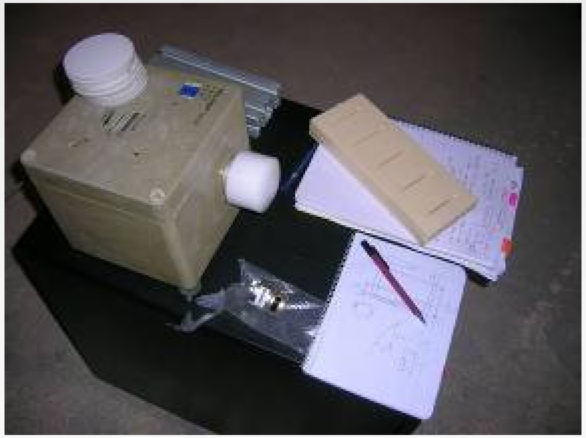
Current activities:
Far lab integration

Civil engineering work completed


Pit refurbished

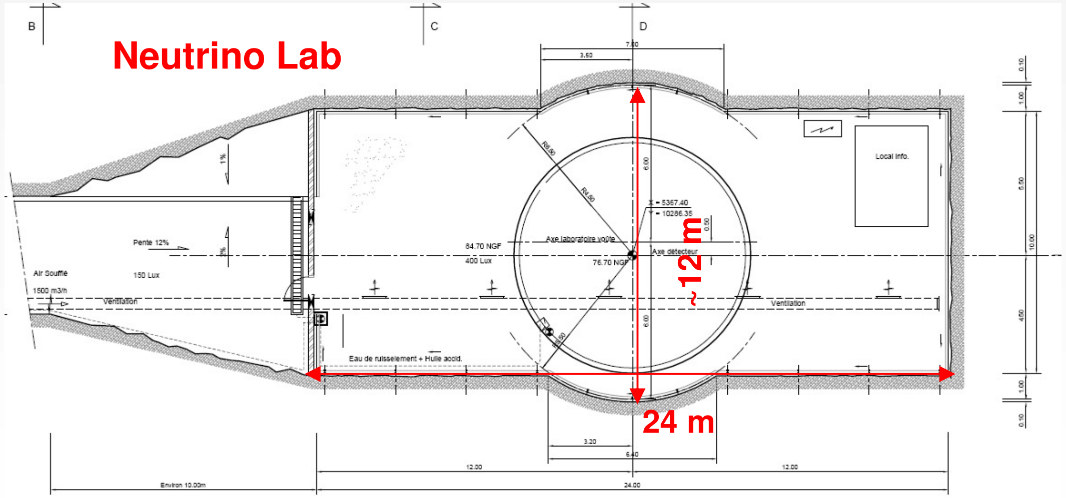

Access adapted

Cleanliness + radiopurity measurements ongoing



Current activities:
Near lab preparation

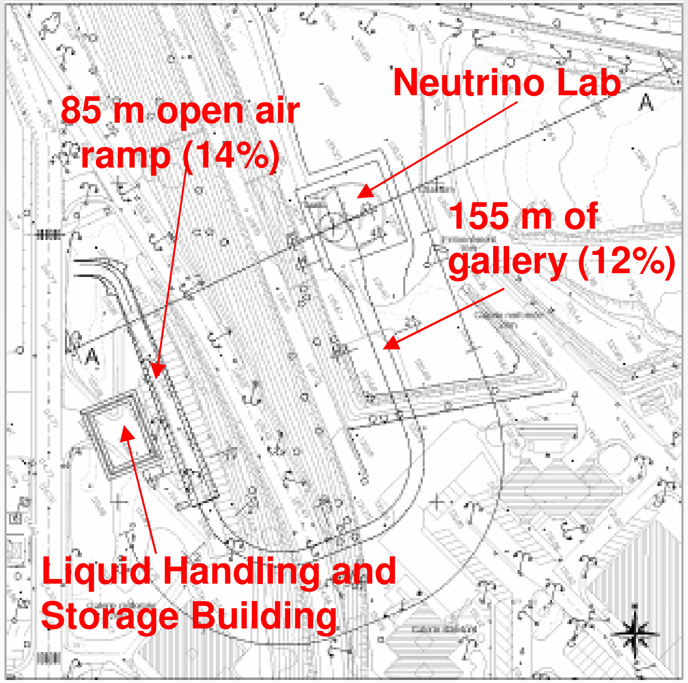
- ✦ Site engineering study completed
- ✦ Tender process for construction soon
- ✦ Schedule: lab finished in 2010



Neutrino Lab

~12 m

24 m

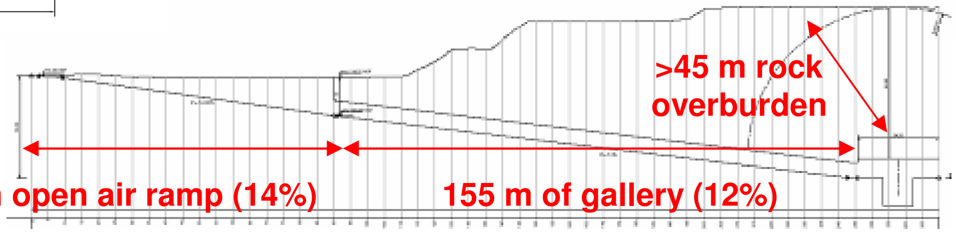


Neutrino Lab

85 m open air ramp (14%)

155 m of gallery (12%)

Liquid Handling and Storage Building

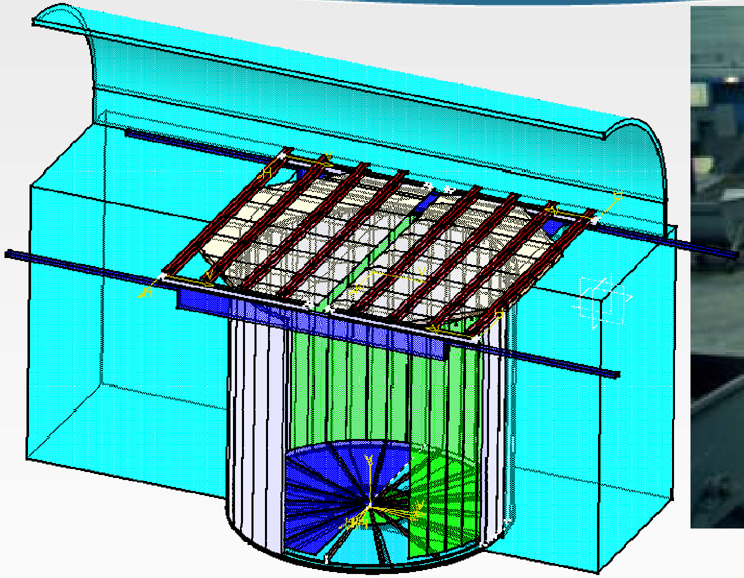


>45 m rock overburden

85 m open air ramp (14%)

155 m of gallery (12%)

Current activities:
Steel shield installation finished



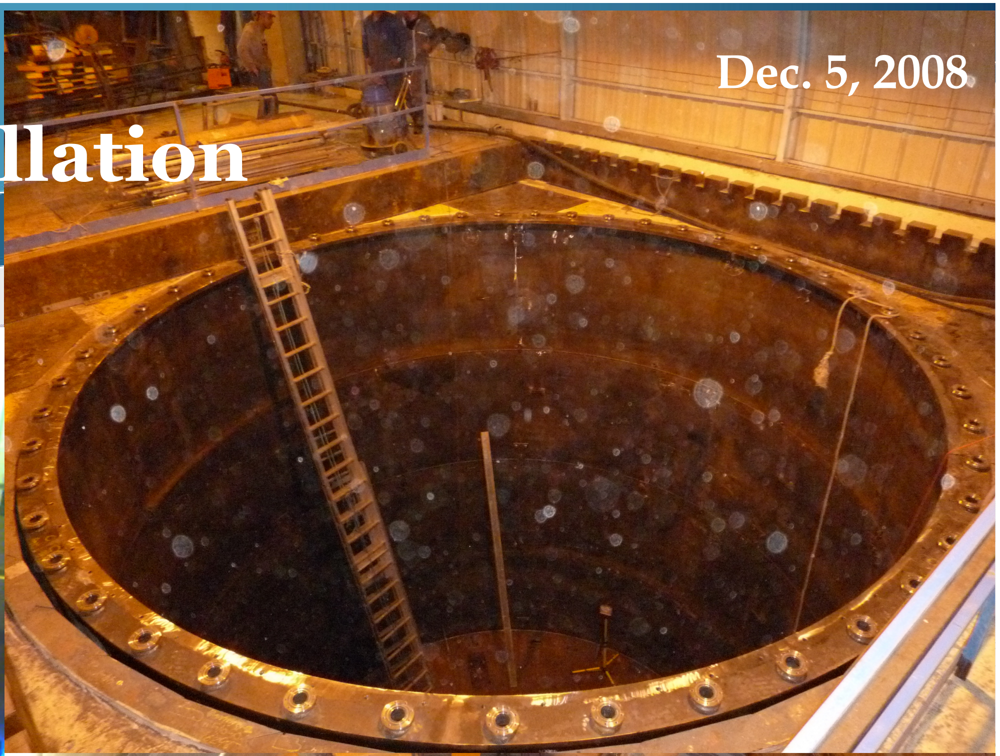
Assembly of each side of the bottom part

Connection of two bars

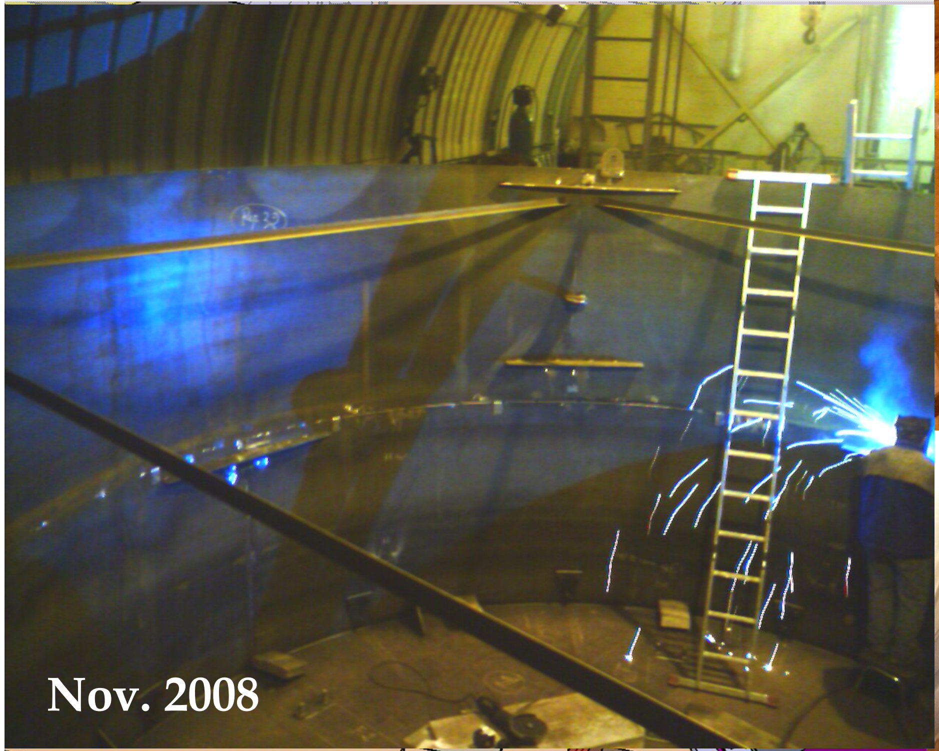
Integration completed

Demagnetization of steel shielding bars

Current activities: Inner veto vessel installation in progress

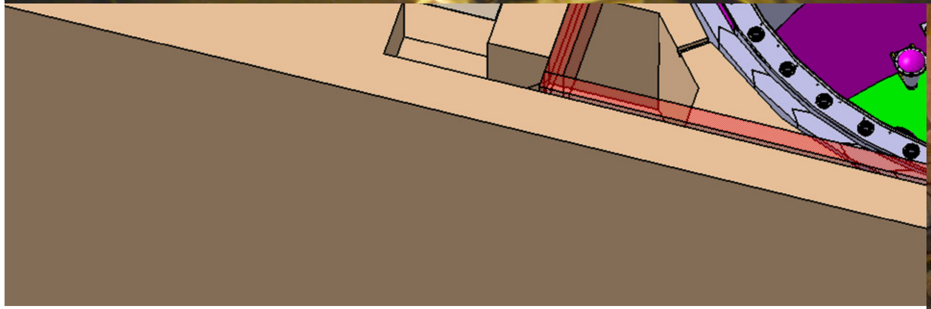


Dec. 5, 2008



Nov. 2008

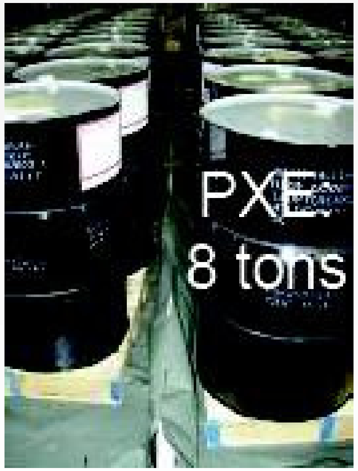
Dec. 5, 2008



Current activities:
Inner detector components

Scintillator production

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



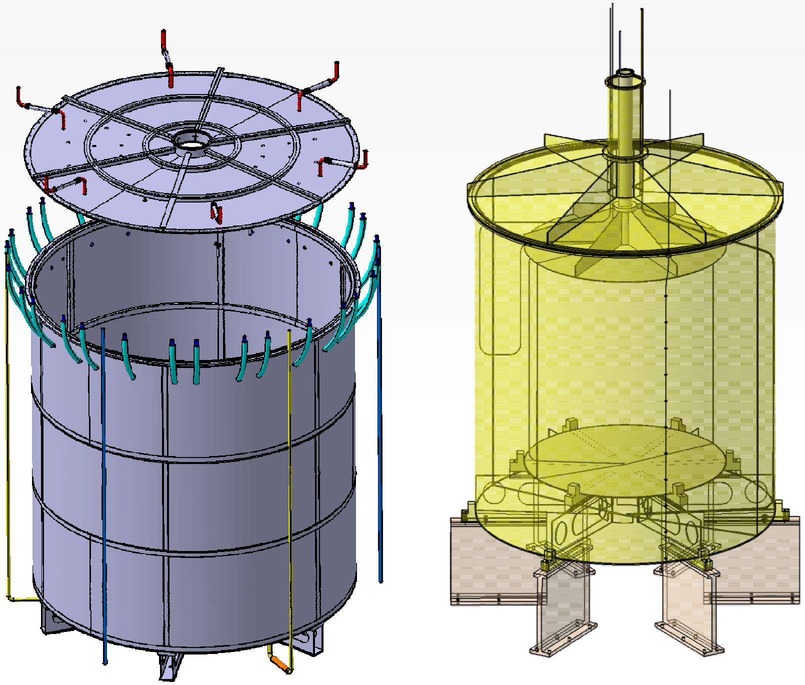

Scintillator hall ready


Gd delivered


Iso-tank for GC liquid

Mechanical vessels: acrylics and buffer

- Design completed
- Manufacturing is on going



Current activities:
Tools for acrylics handling

Target vessel tool

COMPLETED!!

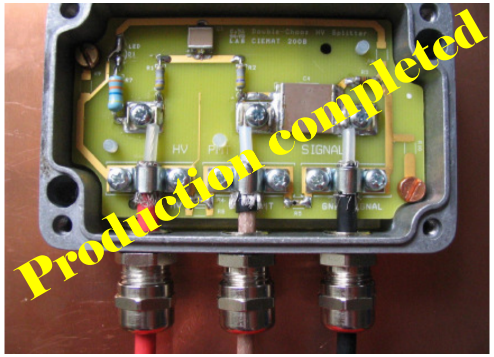
Gamma-catcher vessel tool

Current activities:
PMT production completed

Low background glass
10” R7081 Hamamatsu PMTs

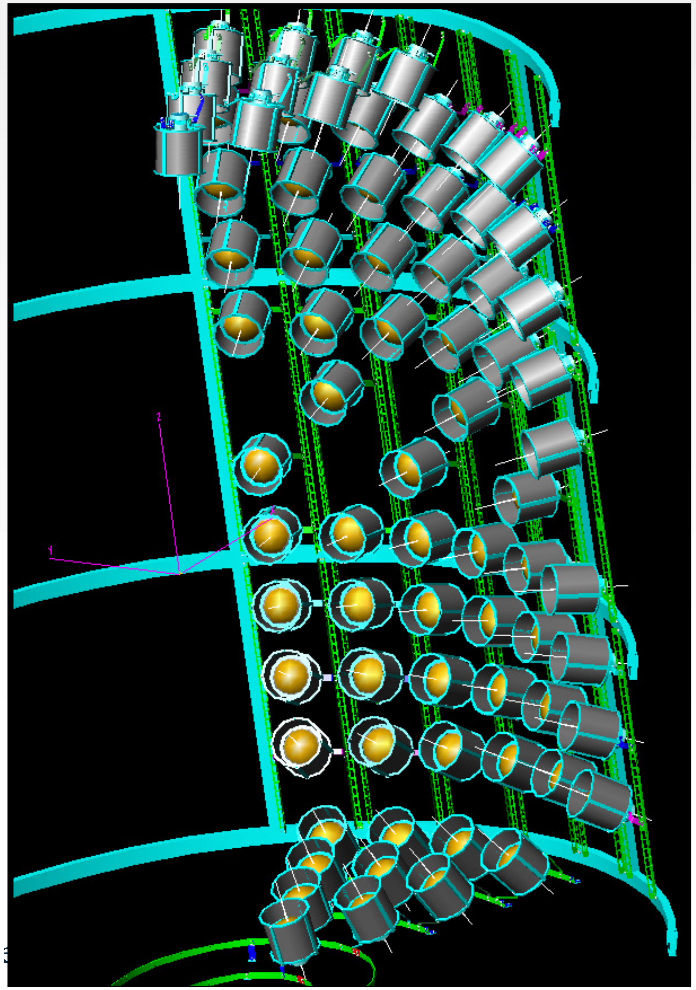
Tested

HV splitters



Production completed

PMT geometry baseline
(390 PMTs/detector)



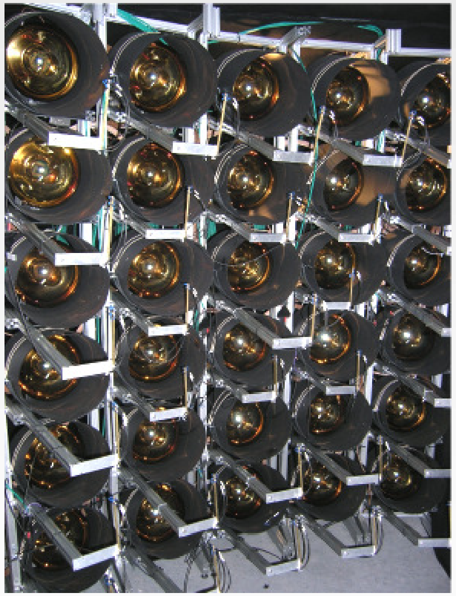
PMT mechanical support
& magnetic shield

Production completed

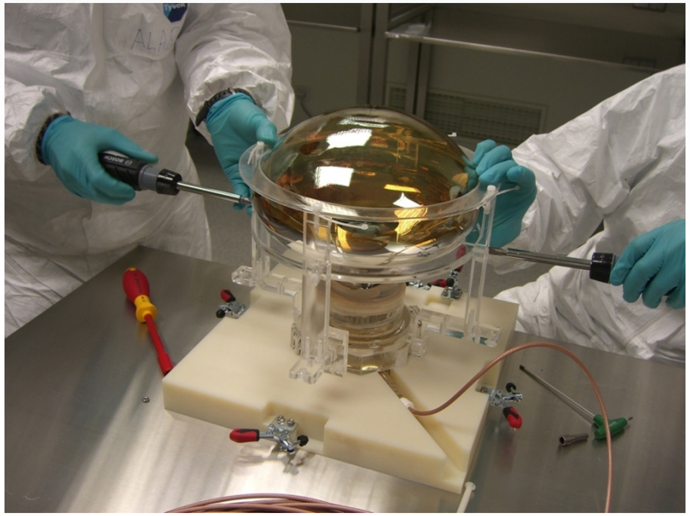
Delivered

Current activities:
PMT testing and assembly

PMT testing finished



PMT assembly almost finished



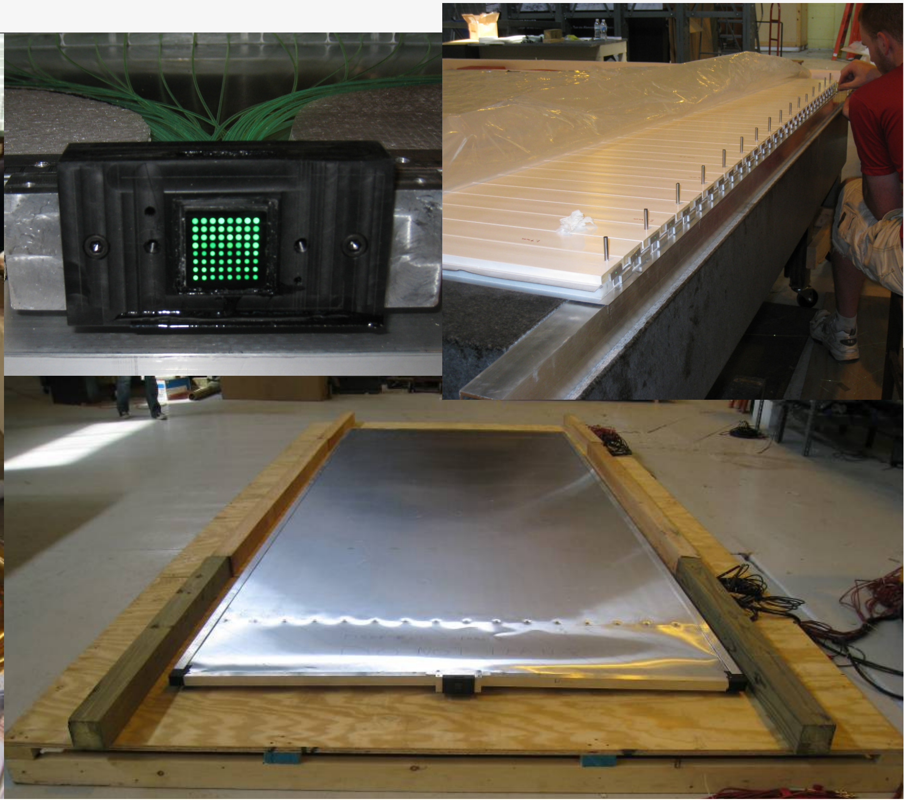
Current activities: Inner & Outer veto systems

Inner Veto

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

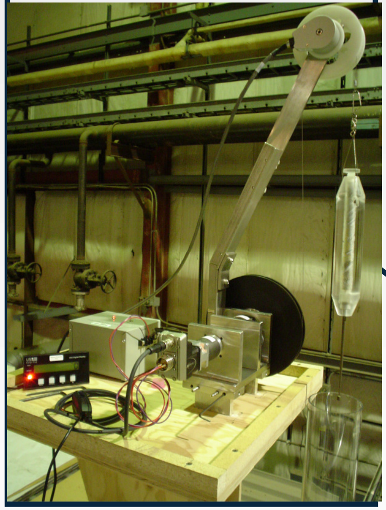
Outer Veto

- Redundancy for higher rejection power
- Full prototype **built and tested**
  - ► **shipped to Chooz in Nov. 08**



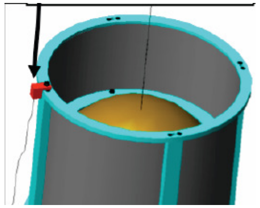
Calibration systems

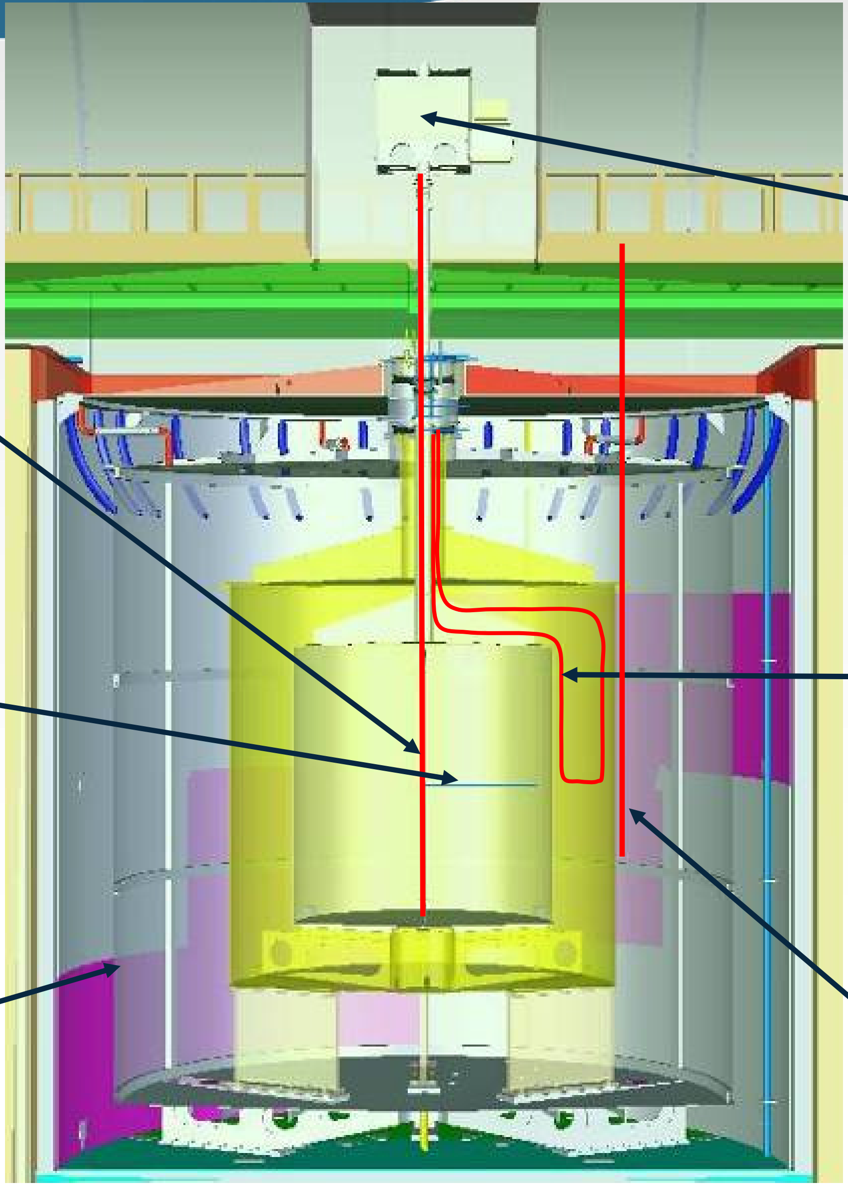
Fish-line (Z-axis)



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 ± 2.8%(stat) ± 2.7%(syst)

– Statistical error –

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

	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**
Number of events	**2700**	**CHOOZ-far : 40 000/3 y** **CHOOZ-near: ~1 10^6/3 y**
Statistical error	**2.8%**	**0.5%**

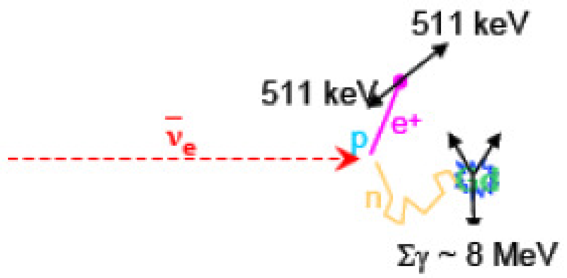
– Systematic errors –

	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 **σ_{relative}~0.6%**
- Careful backgrounds control:
  ➔ subtraction error<1%

Signal and background events in Double Chooz

e^- antineutrino Signature

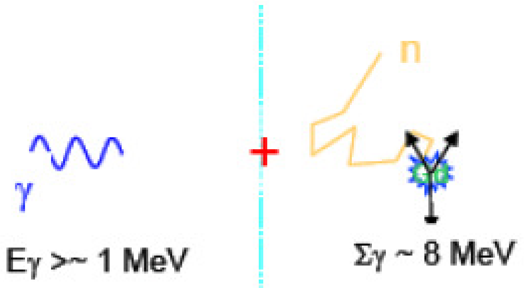


Prompt e^+ (1-8 MeV) Delayed n Gd-capture (8 MeV)

Time correlation: τ~30 μs Space correlation: <1 m

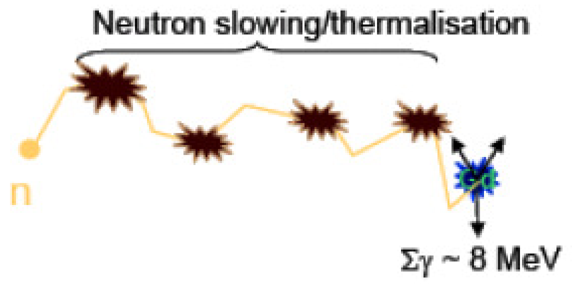
Far:	70 neutrinos d^{-1}
Near	500 neutrinos d^{-1}

Accidental Background



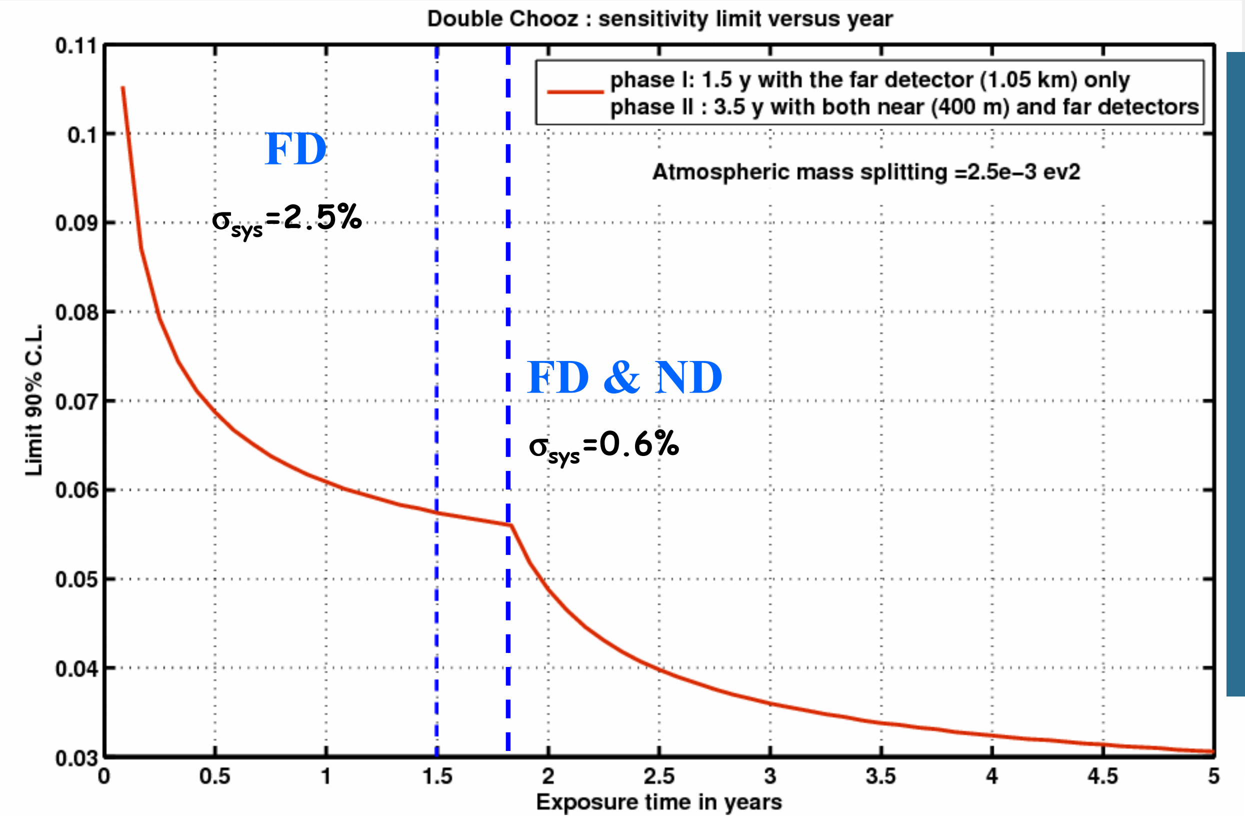
Far:	2 neutrinos d^{-1}
Near	11 neutrinos d^{-1}

Correlated Background



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

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)

General 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

◆ **Mid. 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 in progress!**
- 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)

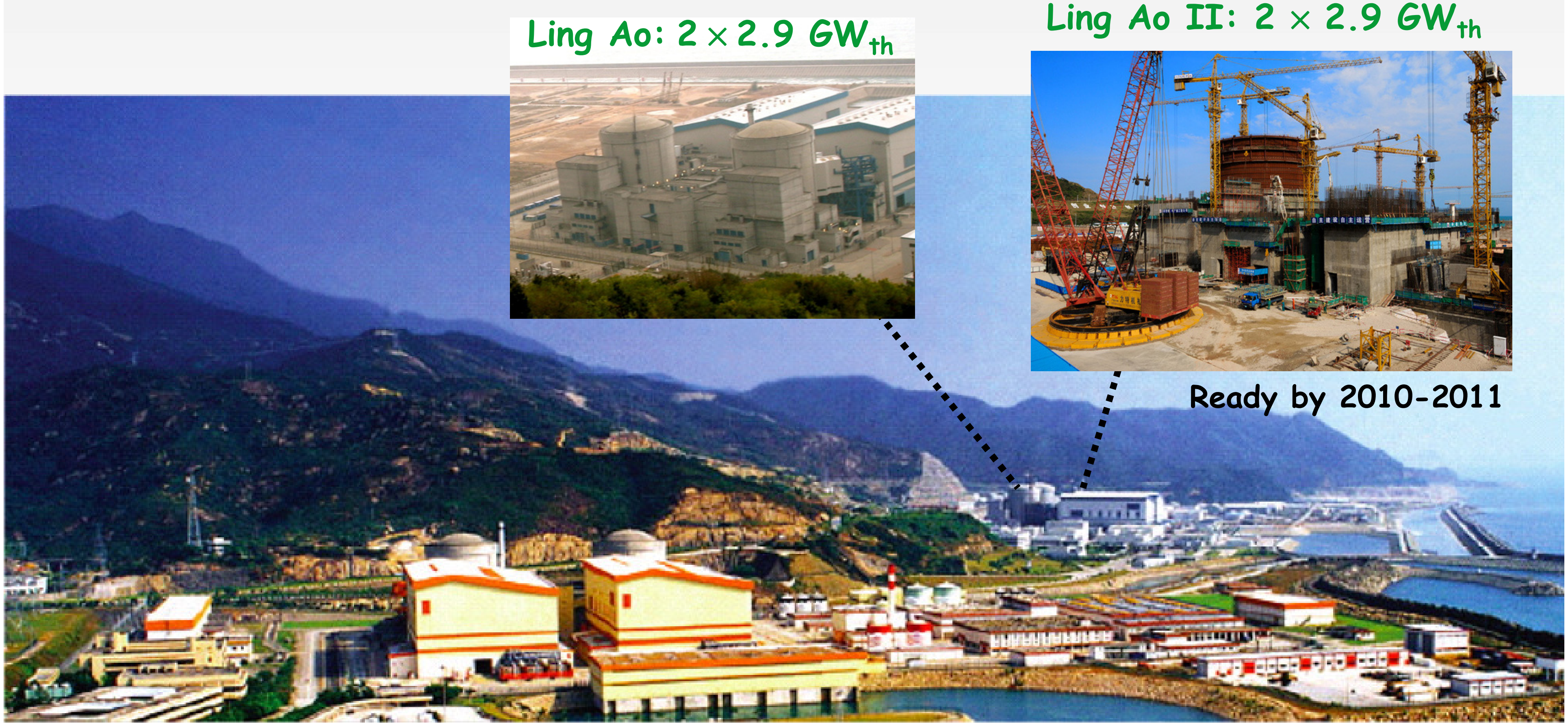
BACKUP SLIDES

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 Daya Bay Nuclear Power Complex

- 12th most powerful in the world (11.6 GW_{th})
- One of the top five most powerful by 2011 (17.4 GW_{th})
- Adjacent to mountain ⌫ underground labs with sufficient overburden

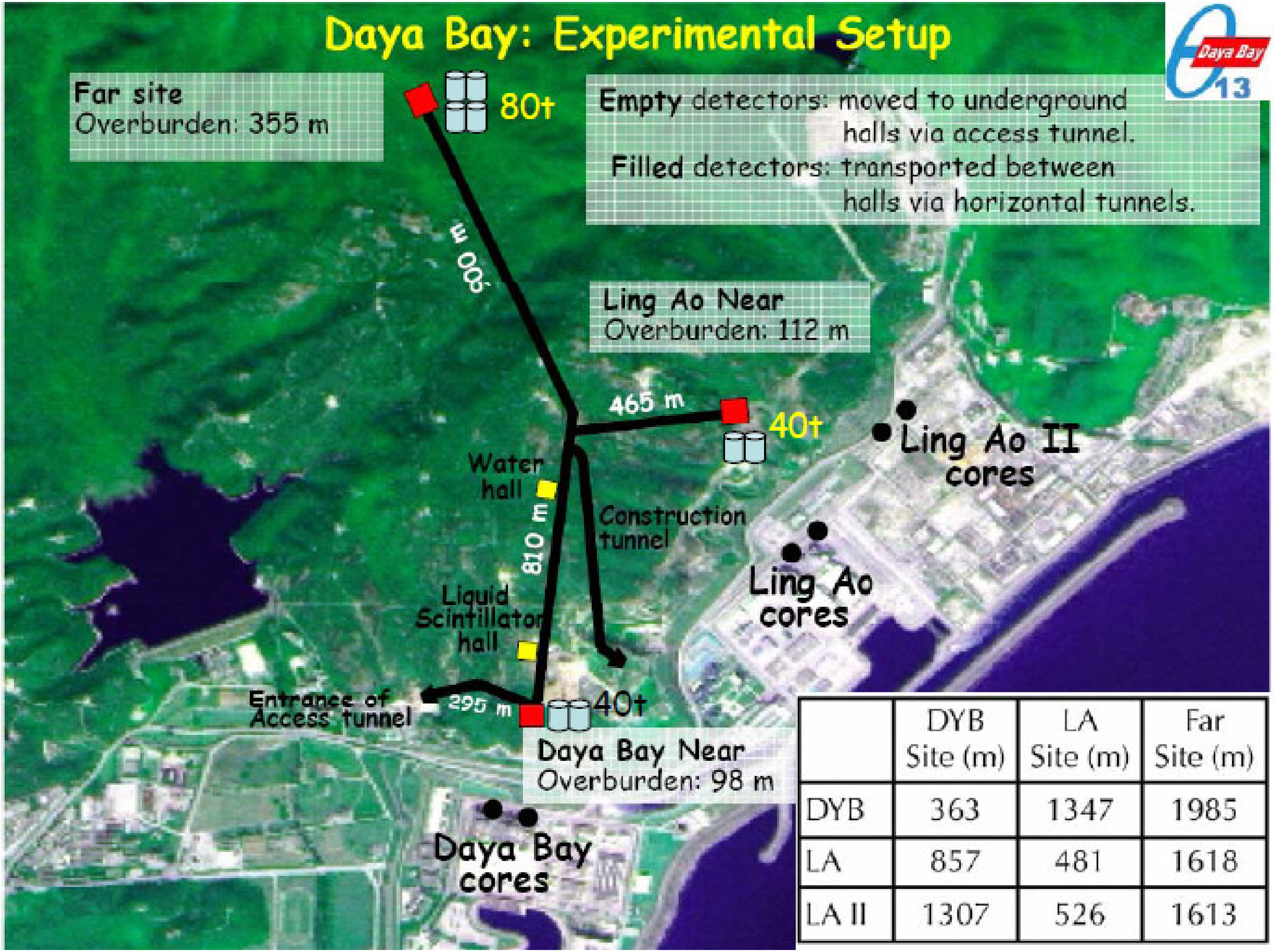


Ling Ao: 2 × 2.9 GW_{th}

Ling Ao II: 2 × 2.9 GW_{th}

Ready by 2010-2011

Daya Bay: Experimental Setup



Far site
Overburden: 355 m

Empty detectors: moved to underground halls via access tunnel.

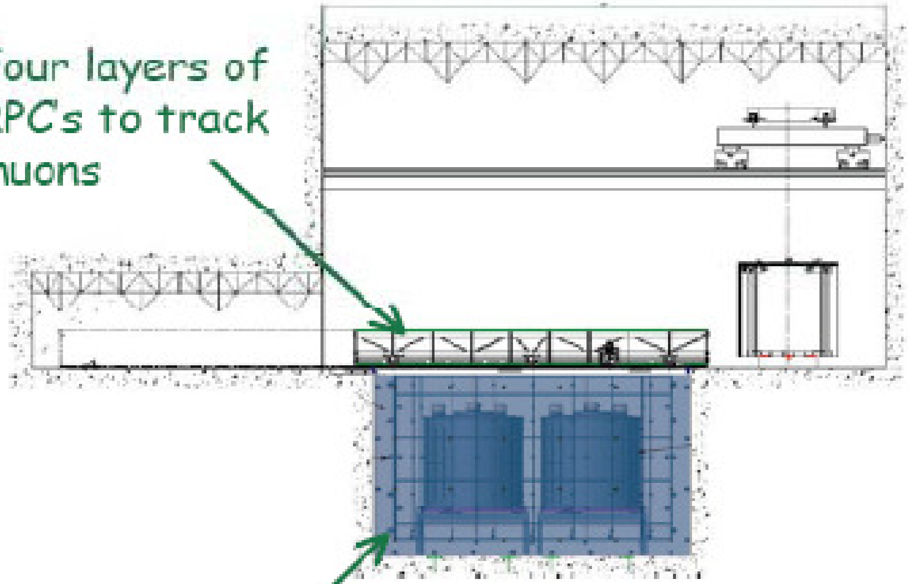
Filled detectors: transported between halls via horizontal tunnels.

Ling Ao Near
Overburden: 112 m

Daya Bay Near
Overburden: 98 m

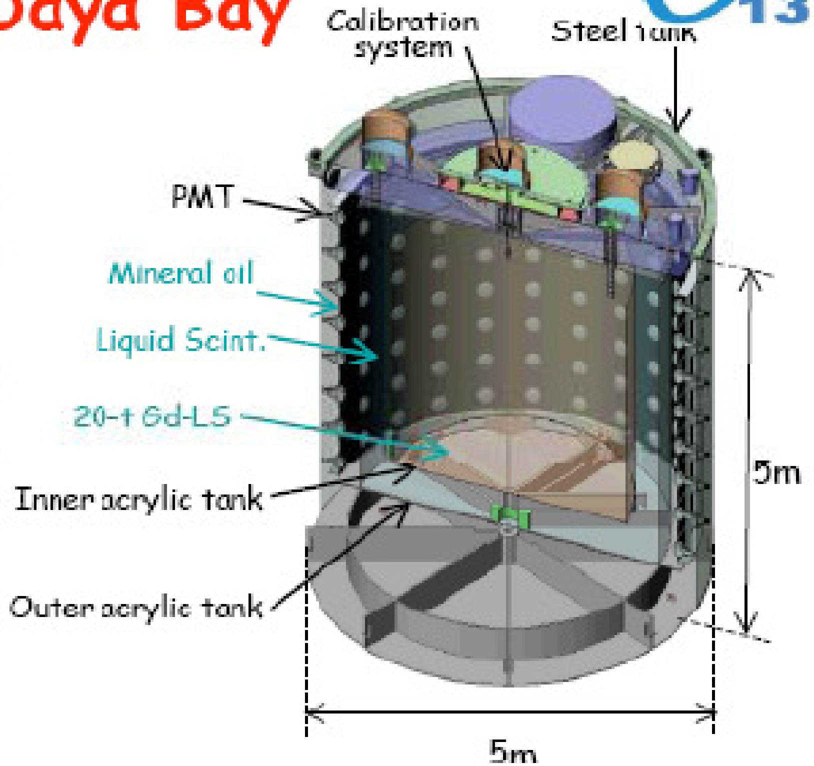
	DYB Site (m)	LA Site (m)	Far Site (m)
DYB	363	1347	1985
LA	857	481	1618
LA II	1307	526	1613

Detector Of Daya Bay



Four layers of RPCs to track muons

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

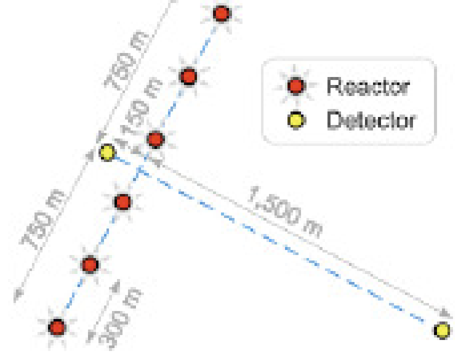


- Three-zone cylindrical detector design
  - Target: 20 t (0.1% Gd-doped LAB LS), 3.1 m
  - Gamma catcher: 20 t (LAB LS), 0.42 m
  - Buffer : 40 T (mineral oil) , 0.48 m
- Low-background 8" PMT: 192
- Reflectors at top and bottom of outer acrylic vessel
- Photocathode coverage:
  5.6 % → 12% (with reflectors)

RENO @ YONGGWANG

REACTOR EXPERIMENT FOR NEUTRINO OSCILLATION

Collaboration:
South Korea + Russia



ArXiv 0704.0408v2 [hep-ex]

Total reactor power of the 6 cores: 17.3 $\mathrm{GW_{th}}$
(although 2 contribute >80% of observed ϕ_ν)

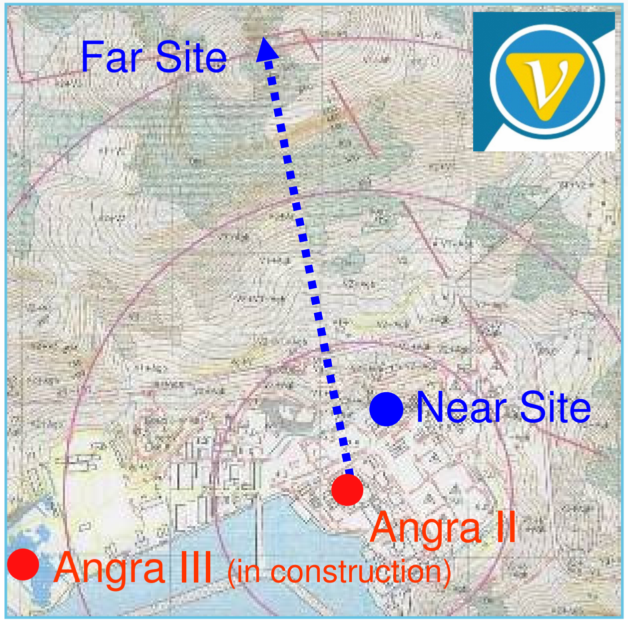
Angra

θ_{13} @ANGRA
In STAND BY

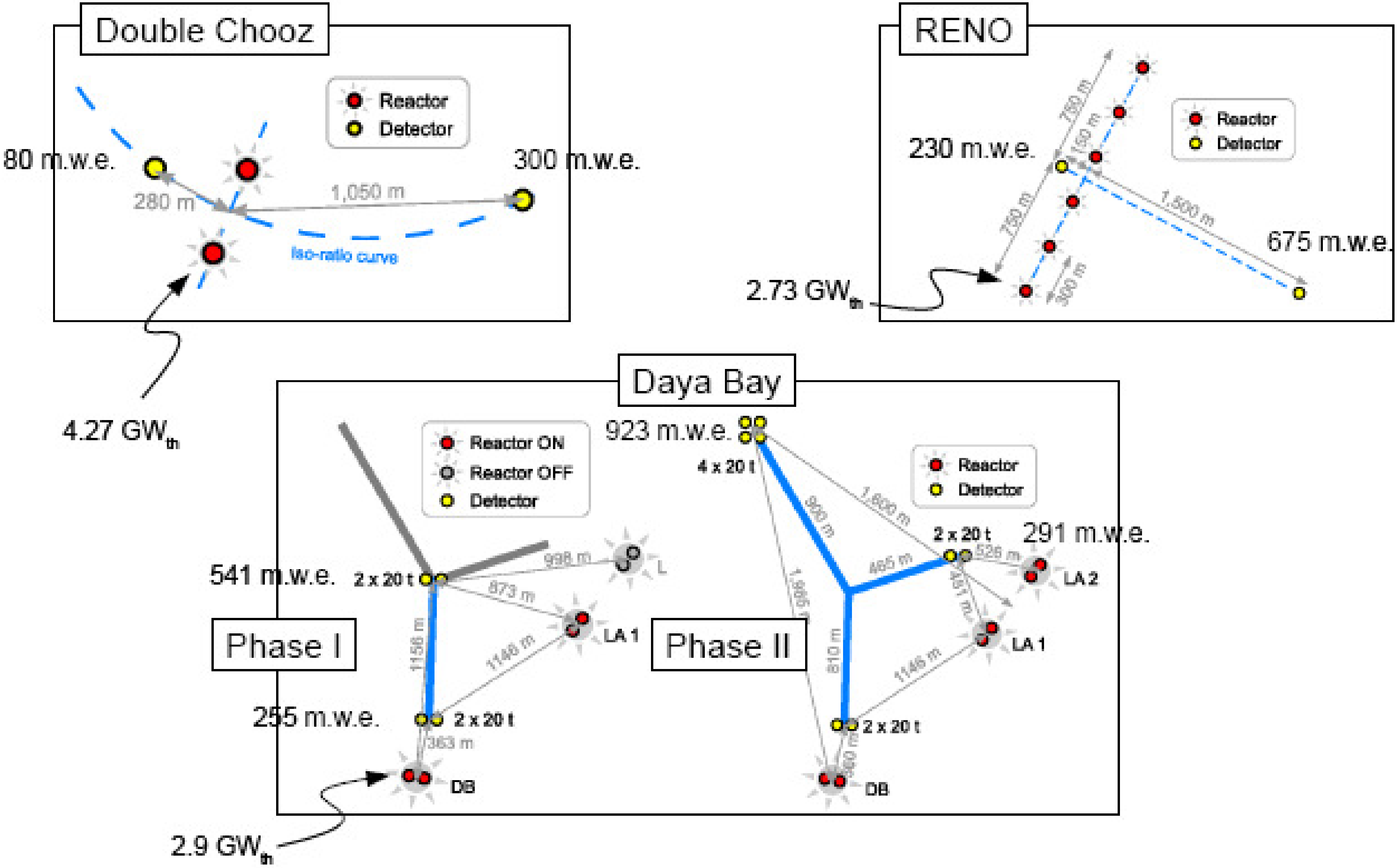
- **Prospect for a sin2(2θ_{13})<0.01 after Double Chooz**
  - Angra II-III reactors (2 x 4.0 GW) ,
  - 1.5 km tunnel to escavate for the far det. + a shaft/tunnel for the near det.
  - Large detector (***a few hundreds tons***) focusing on spectral measurement

- **Angra collaboration merged with Double Chooz in 2006**

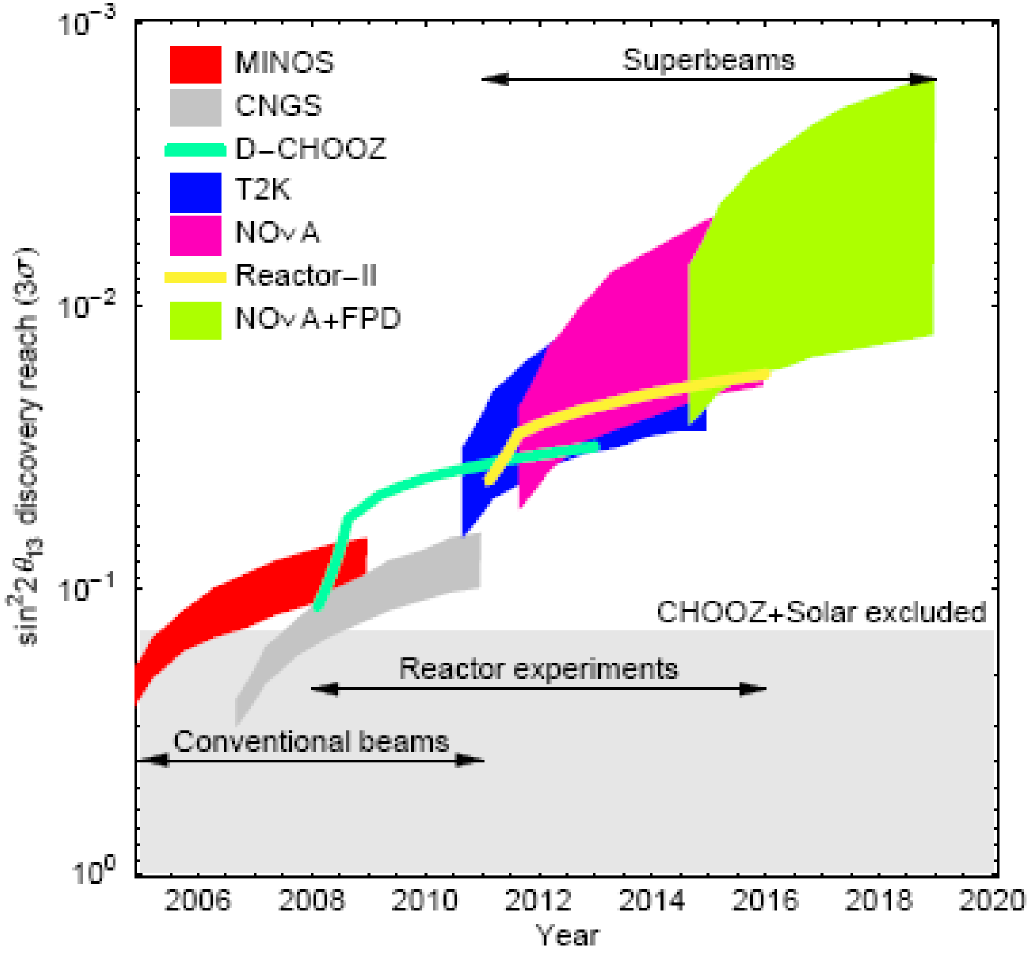
- **Realization of a Small Neutrino Detector for Non Proliferation**



The inputs: *experiment site setups*



Expected sensitivity to θ_{13} vs time



arXiv:0710.5027