Towards Θ_{13} with DOUBLE Chooz

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On behalf of the Double Chooz collaboration

Content

- Neutrino physics:
  Θ_{13} - neutrino oscillations and reactor ν
- Status quo:
  The CHOOZ experiment
- Improving CHOOZ:
  "Next generation" concepts
- Focus on Double Chooz:
  Design, status, time schedule and sensitivity
- The Θ_{13} game is on:
  Reno and Daya Bay
- Summary

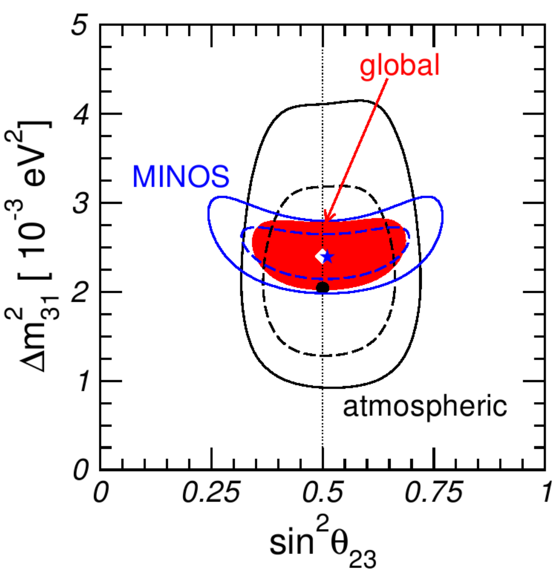
Θ_{13}

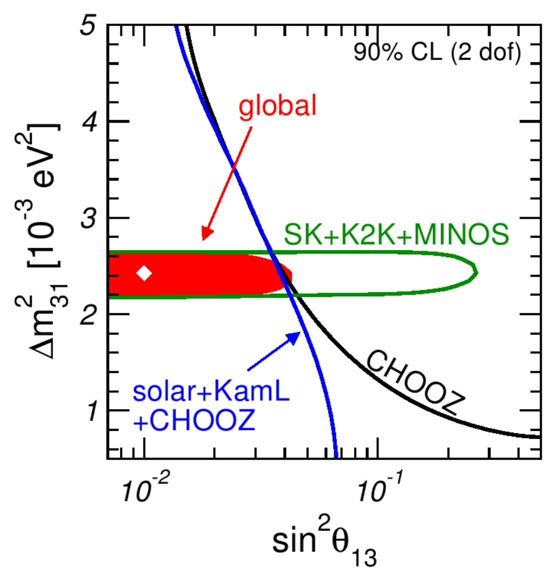
- Flavor vs mass eigenstates of (Dirac) neutrinos
  → Mixing matrix

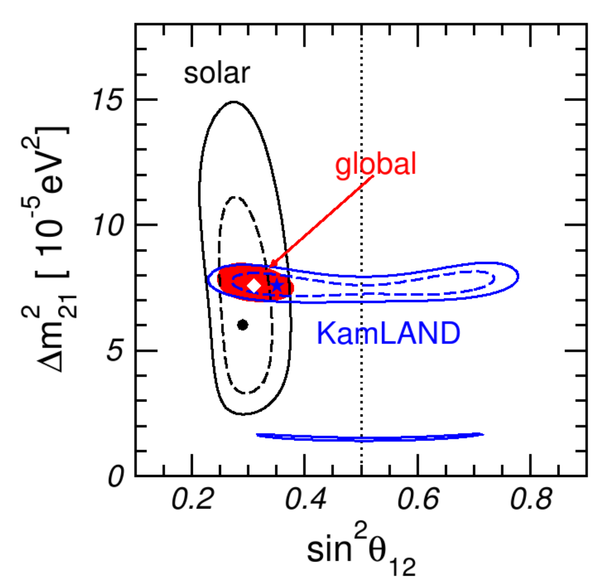
$c_{ij} = \cos \Theta_{ij}$ and $s_{ij} = \sin \Theta_{ij}$

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

Atmosph. + Accel. | reactor | Solar + KamLAND







Maltoni and Schwetz, PoS idm2008:072,2008

- Flavor vs mass eigenstates of (Dirac) neutrinos
  → Mixing matrix

$c_{ij} = \cos \Theta_{ij}$ and $s_{ij} = \sin \Theta_{ij}$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmosph. + Accel.}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{reactor}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar + KamLAND}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmosph. + Accel. | reactor | Solar + KamLAND

$\Theta_{23} = 42.3^{+5.3}_{-2.8}$ $\Theta_{13} = 6.8^{+2.6}_{-3.6}$ $\Theta_{12} = 34.4 \pm 1.0$

$$\Delta m^2_{12} = 7.59 \pm 0.20 \cdot 10^{-5} \, \text{eV}^2$$

$$\Delta m^2_{31} = -2.40 \pm 0.11 \cdot 10^{-3} \, \text{eV}^2 \, (\text{inverted})$$

$$\Delta m^2_{31} = 2.51 \pm 0.12 \cdot 10^{-3} \, \text{eV}^2 \, (\text{normal})$$

1 σ bounds

Gonzalez-Garcia et al. arXiv:1001.4524v1 [hep-ph]

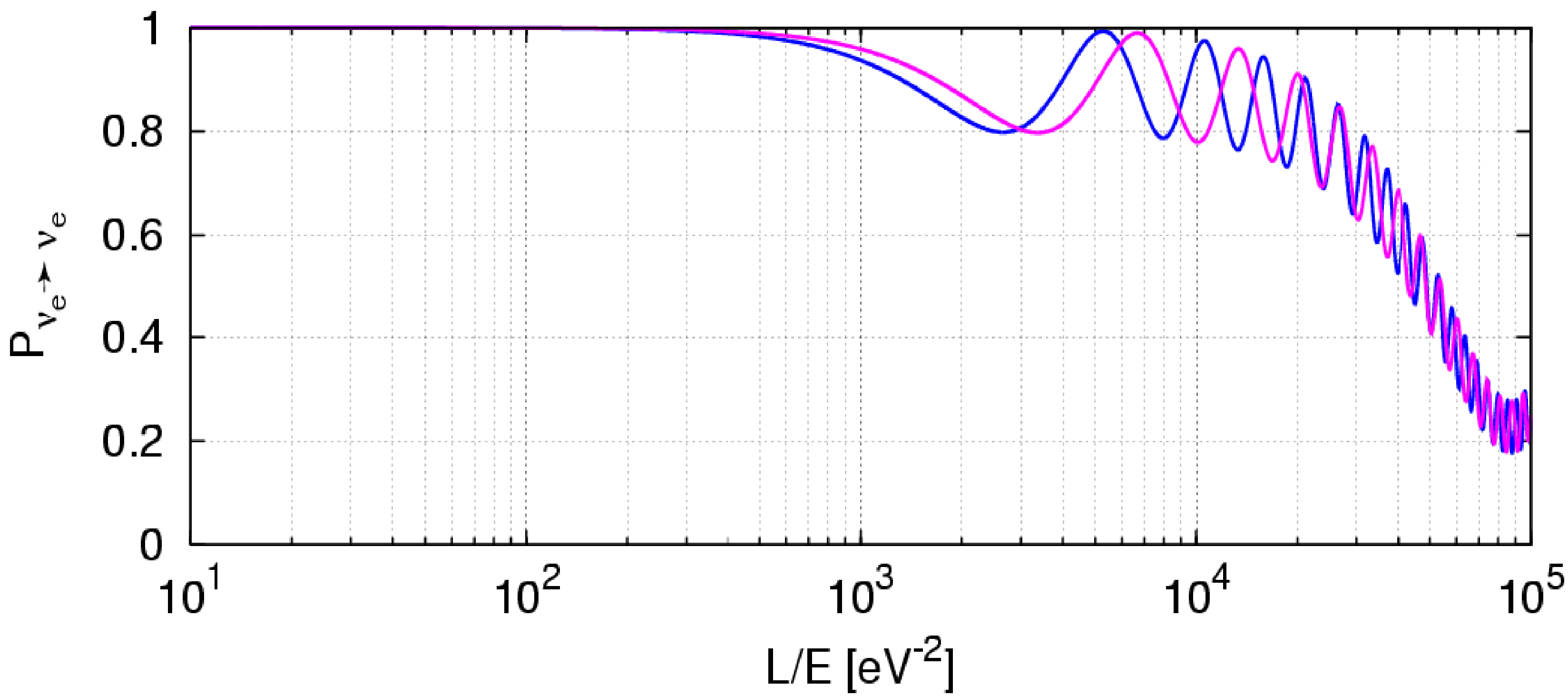
$$\bar{\nu}_e$$

- Reactor ν: pure $\bar{\nu}_e$ from β decay, E_ν < 10 MeV
- neutrino oscillation – flavor detection probability ***P(t)***

$$P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta | \nu_\alpha \rangle|^2 = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} \exp\left(-\frac{i}{\hbar}(E_k - E_j)t\right)$$

- With ultrarelativistic approximation and c=ħ=1

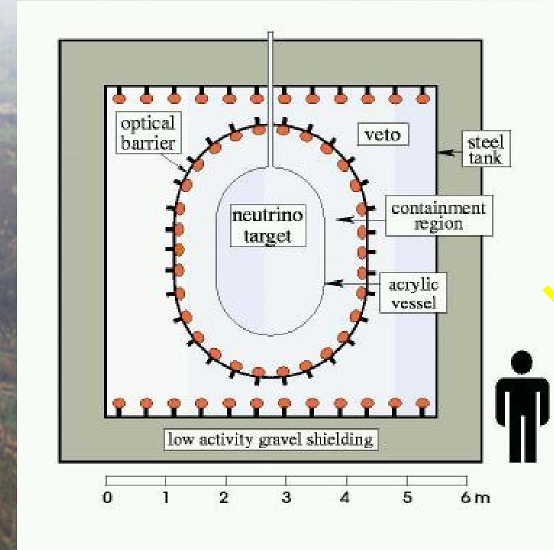
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\Theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \cos^4 \Theta_{13} \sin^2 2\Theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

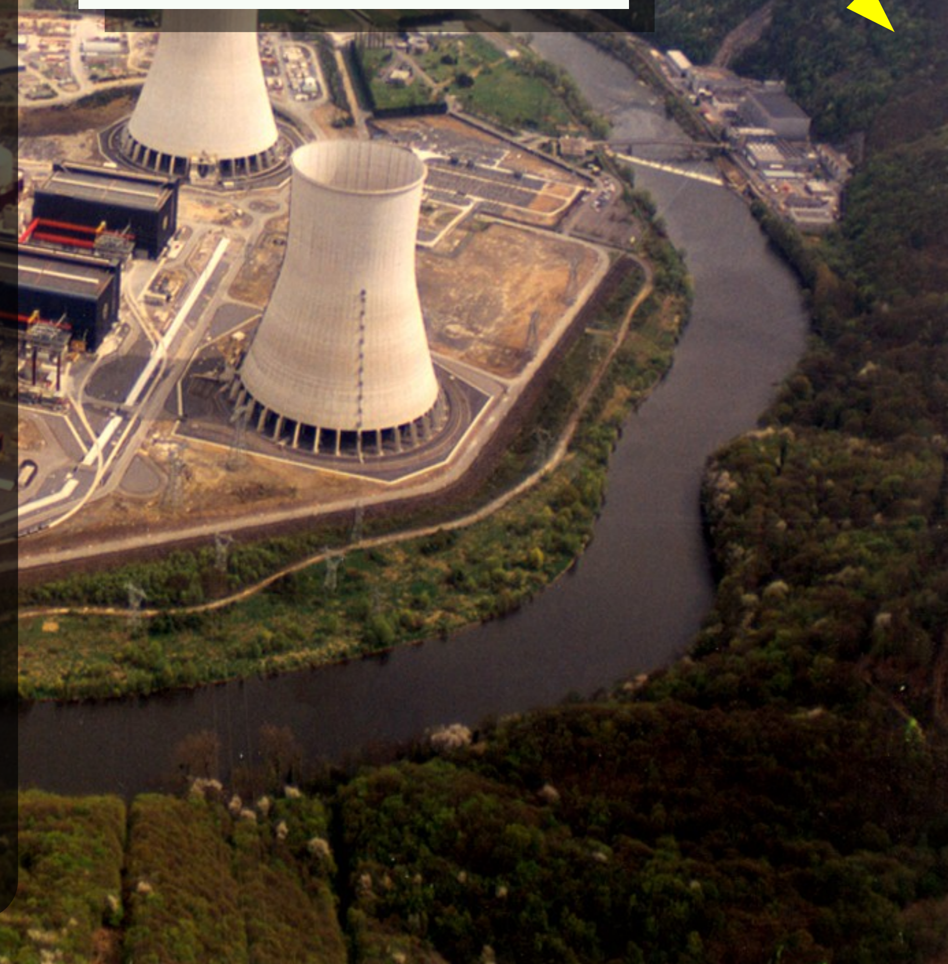


Double Chooz collaboration, arXiv:0606025 [hep_ex]

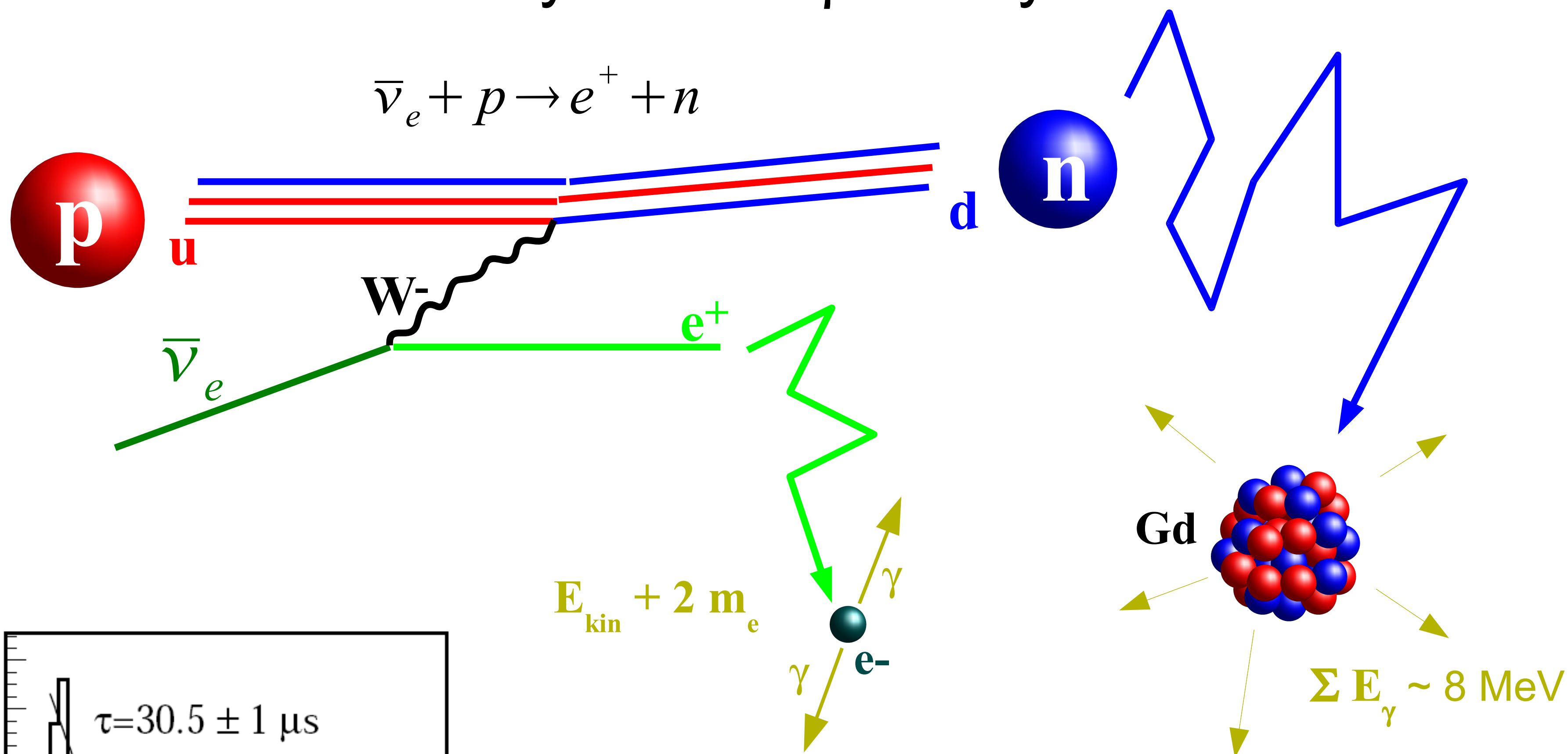
The CHOOZ experiment

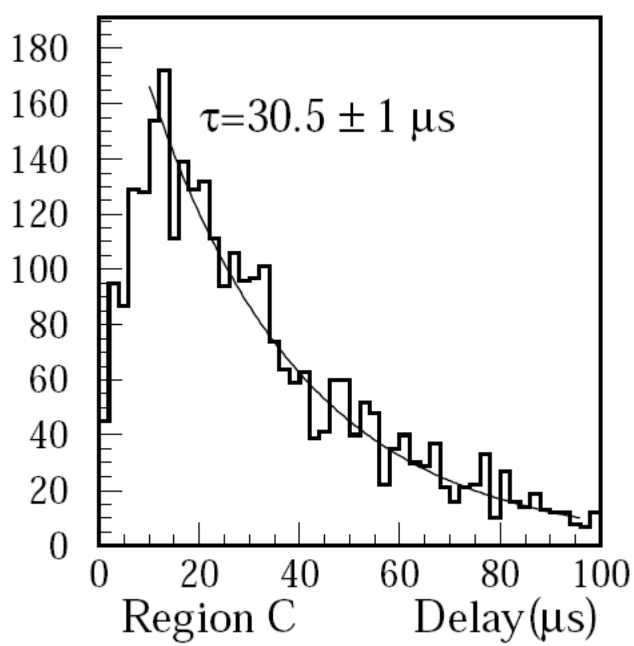
- Liquid scintillator detector
  Target mass 5t, **Gd**-doped
- ~ 1000 m from Chooz B1 and B2 reactor cores ($4\ GW_{th}$ each)
- Looking for $\bar{\nu}_e \rightarrow \bar{\nu}_x$ disappearance
- 300 mwe overburden
- Total run time ~ 15 months
  half of that background only
- Detection by neutrino cc interaction (inverse beta decay, delayed coincidence)





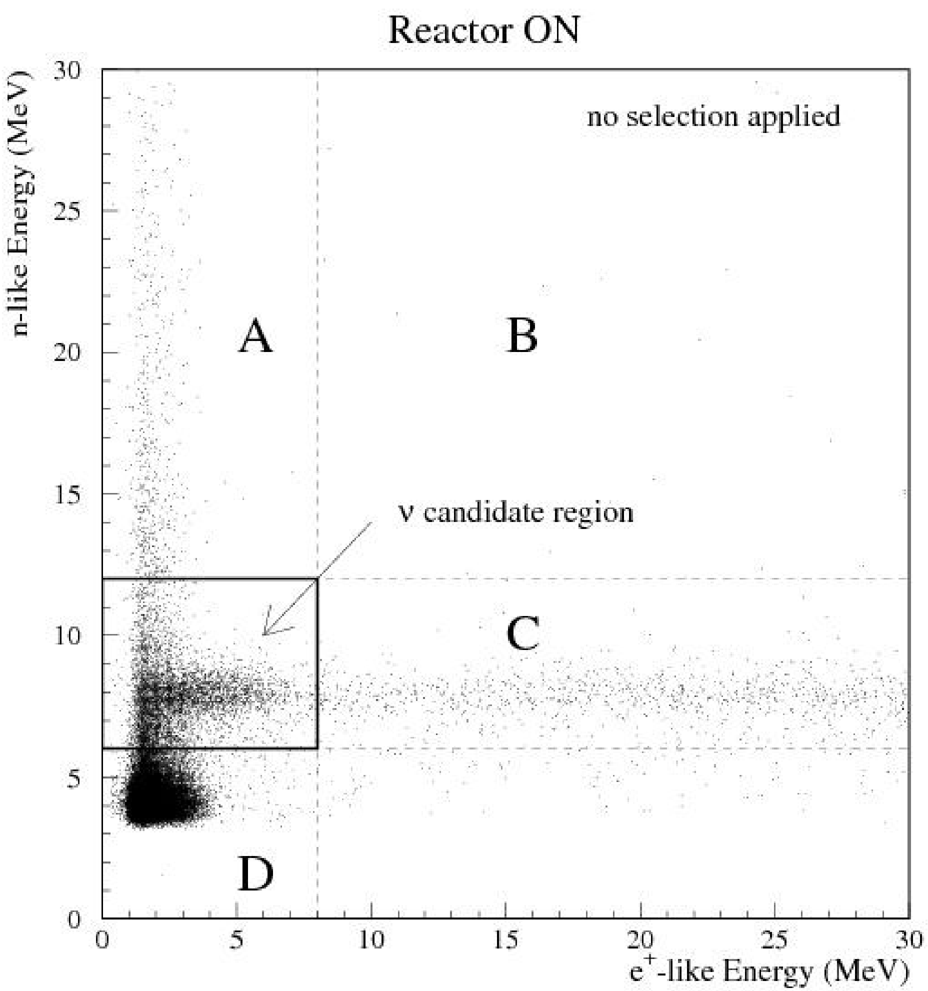
- Neutrino detection by inverse β decay





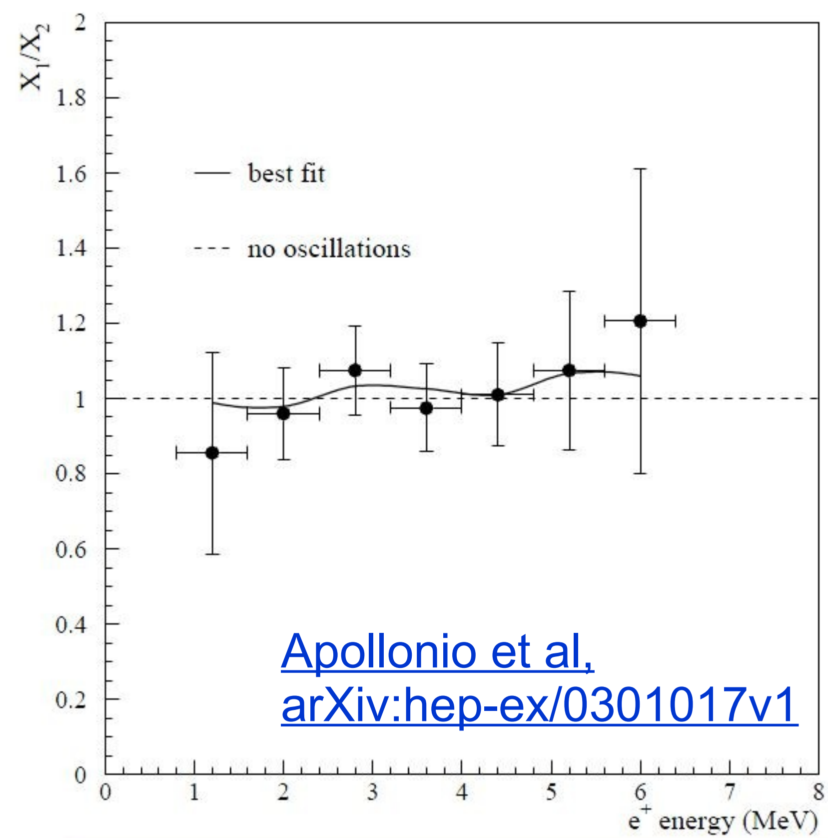
- Delayed coincidence: radiative capture on Gd with τ ~ 30 μs

Apollonio et al, arXiv:0301017 [hep-ex]



parameter	relative error (%)
reaction cross section	1.9 %
number of protons	0.8 %
detection efficiency	1.5 %
reactor power	0.7 %
energy absorbed per fission	0.6 %
combined	2.7 %

Apollonio et al, PLB 466 (1999) 415



Apollonio et al, arXiv:hep-ex/0301017v1

- ~ 3000 ν candidates after cuts
- Result compatible with no oscillation hypothesis @ 90 % CL

Improving CHOOZ

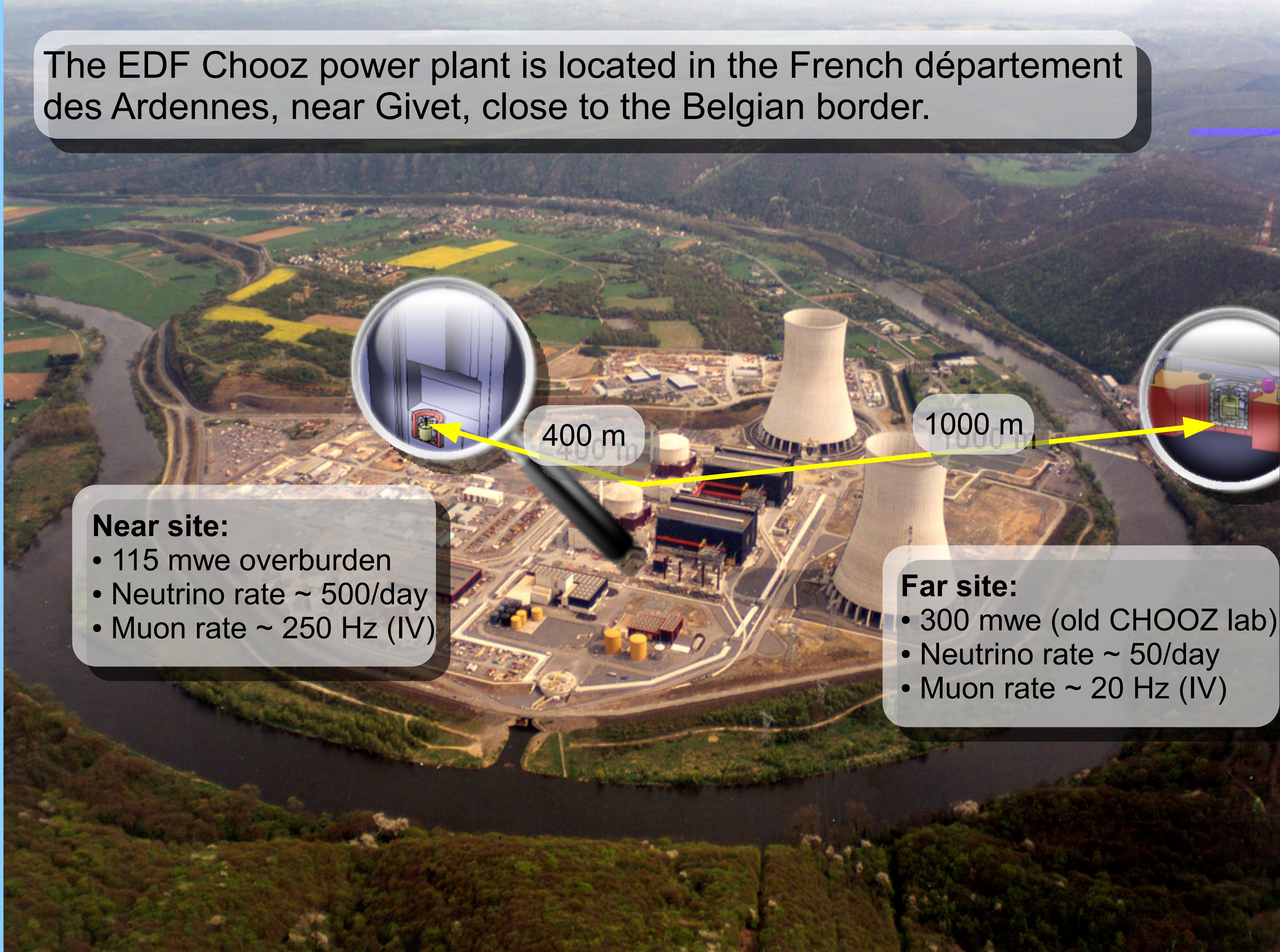
- Statistics limitations
  - larger target mass
  - longer run time (CHOOZ limited by scintillator degradation)
- Systematics limitations
  - Dominating uncertainty from neutrino flux
    → Do relative measurement with (at least) two detectors at different distances from the source(s)

    Eliminates ν production cross section, reactor power and energy per fission errors (if detectors are identical)
  - Reduce number of cuts (CHOOZ used 7, resulting in 1.5 % relative error)
  - Background reduction – strict material selection, remove PMTs from scintillating fluid, better shielding and deeper site

Anderson et al, arXiv:0402041v1[hep-ex]

Double Chooz: Design

The EDF Chooz power plant is located in the French département des Ardennes, near Givet, close to the Belgian border.

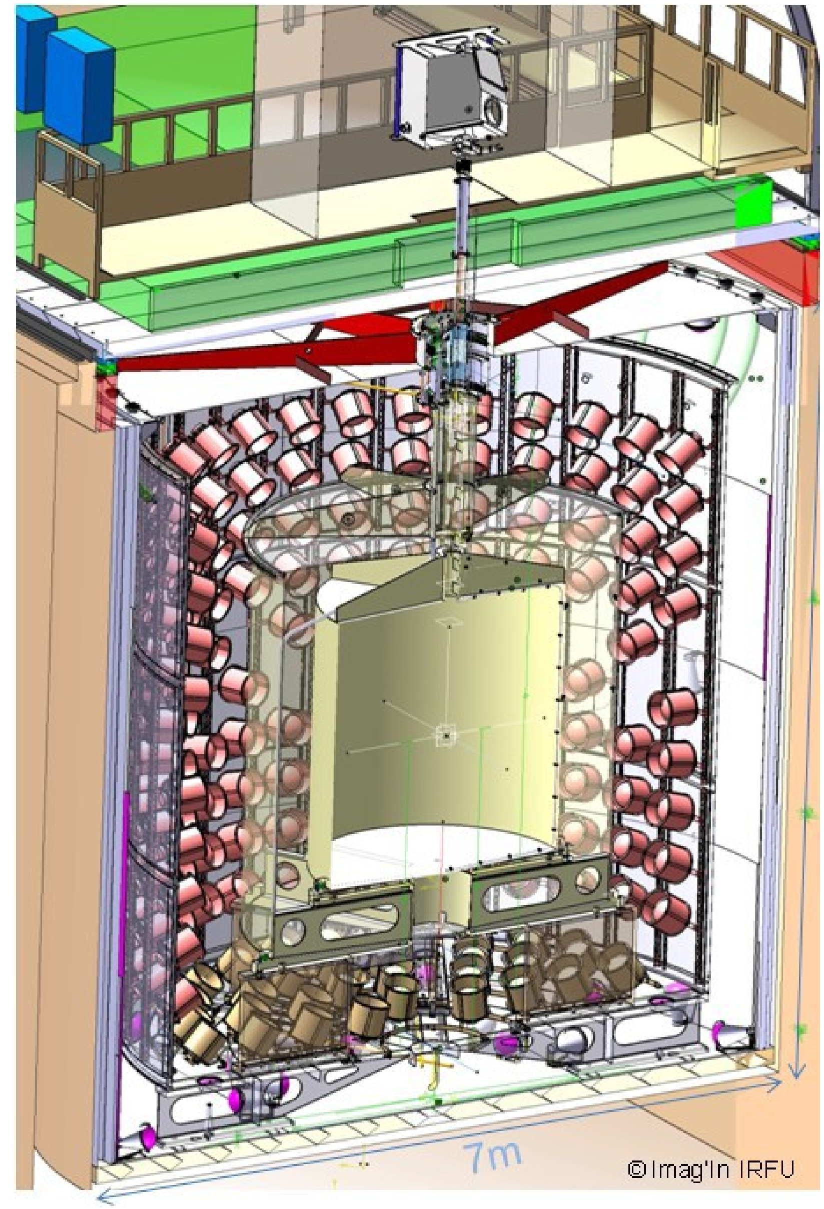


Near site:
- 115 mwe overburden
- Neutrino rate ~ 500/day
- Muon rate ~ 250 Hz (IV)

Far site:
- 300 mwe (old CHOOZ lab)
- Neutrino rate ~ 50/day
- Muon rate ~ 20 Hz (IV)

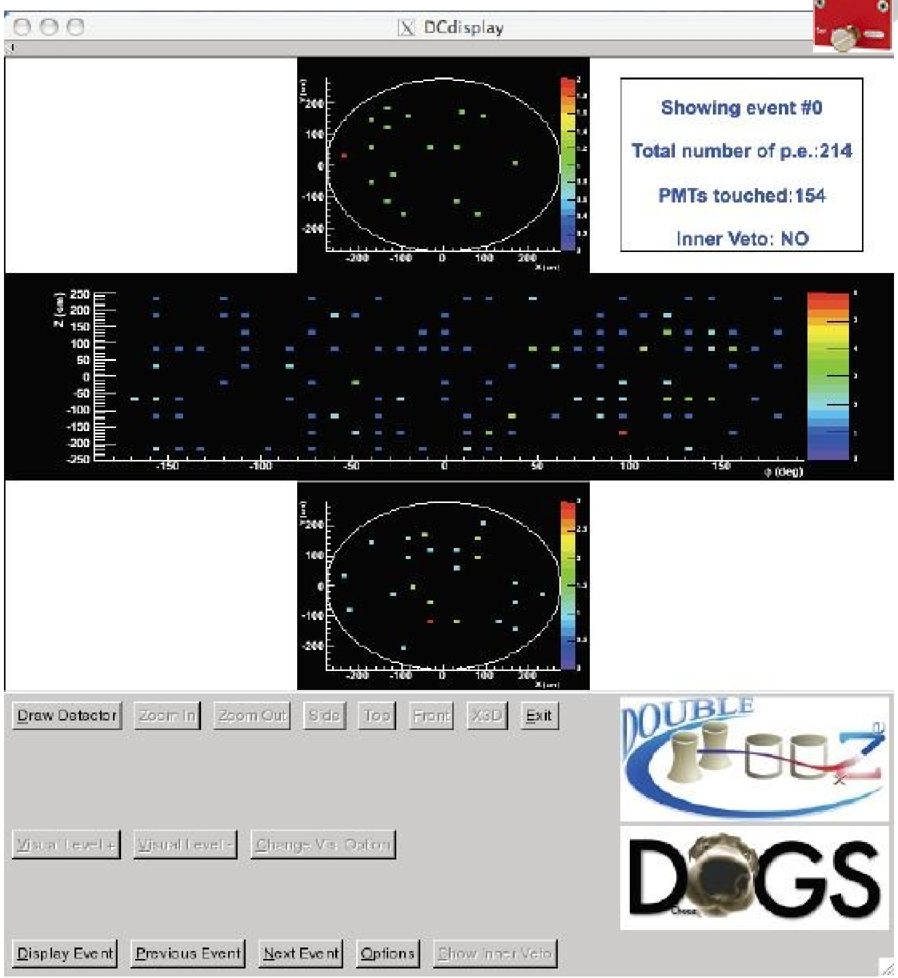
Detector volumes and instrumentation:

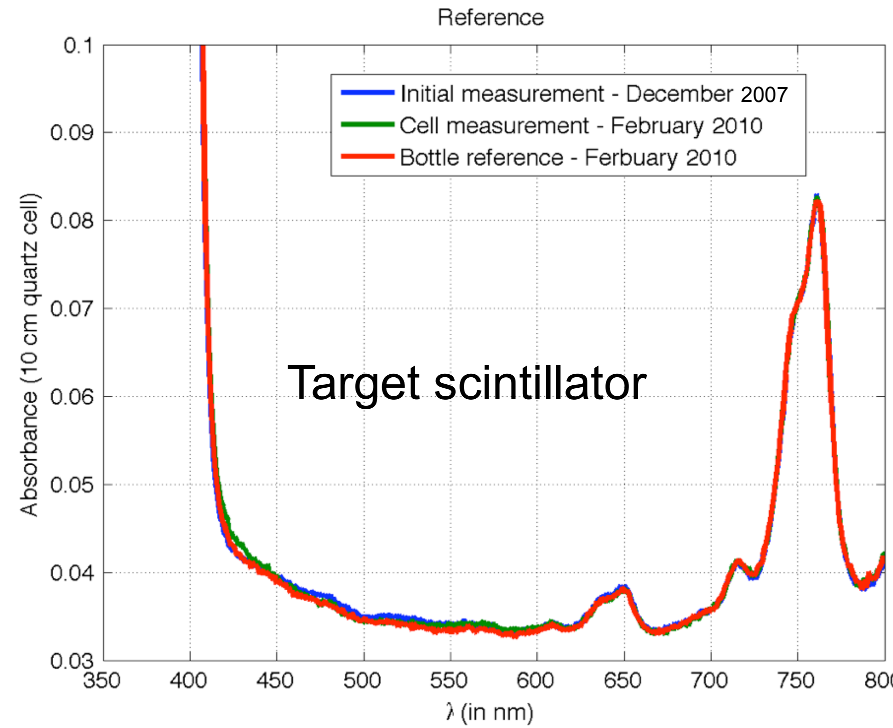
- **Outer veto:** four layers of plastic scintillator panels covering the top of the detector and the glove box
- **Shield:** 17 cm steel
- **Inner veto:** 50 cm of LAB based scintillator, 78 8” PMTs LED calibration system
- **Buffer**: 105 cm of mineral oil, 390 10” PMTs, calibration source guide tube, LED system
- **γ-catcher**: acrylics vessel, 55 cm of PXE based scintillator calibration source guide tube
- **Target**: acrylics vessel, ~8t of **Gd**-doped PXE based scintillator, fish line and articulated arm calibration

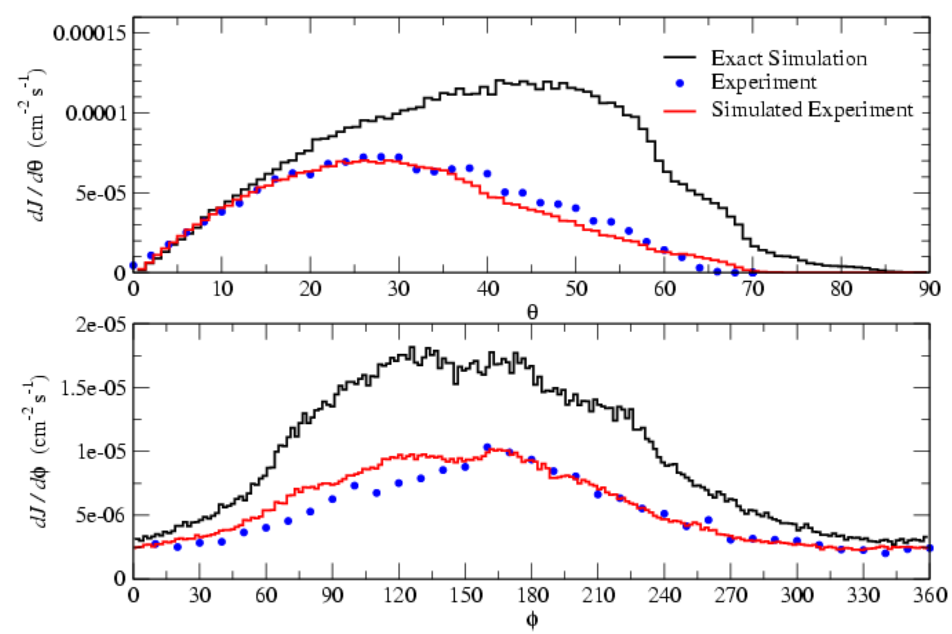


Substantial R&D effort

- Scintillator development
- Detector Monte Carlo
- Reactor spectrum

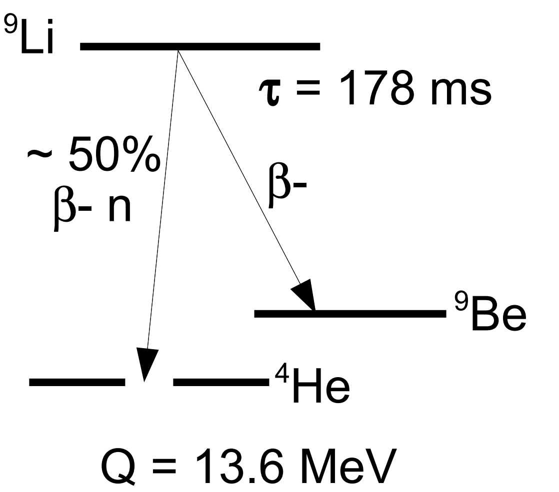


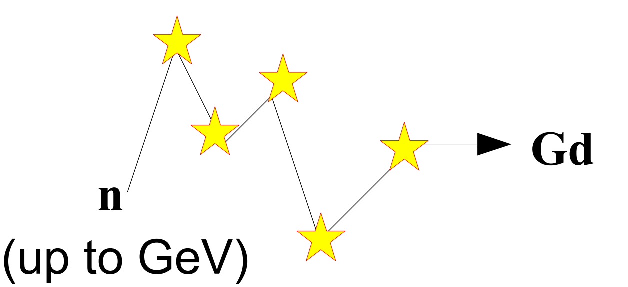




Double Chooz: Backgrounds

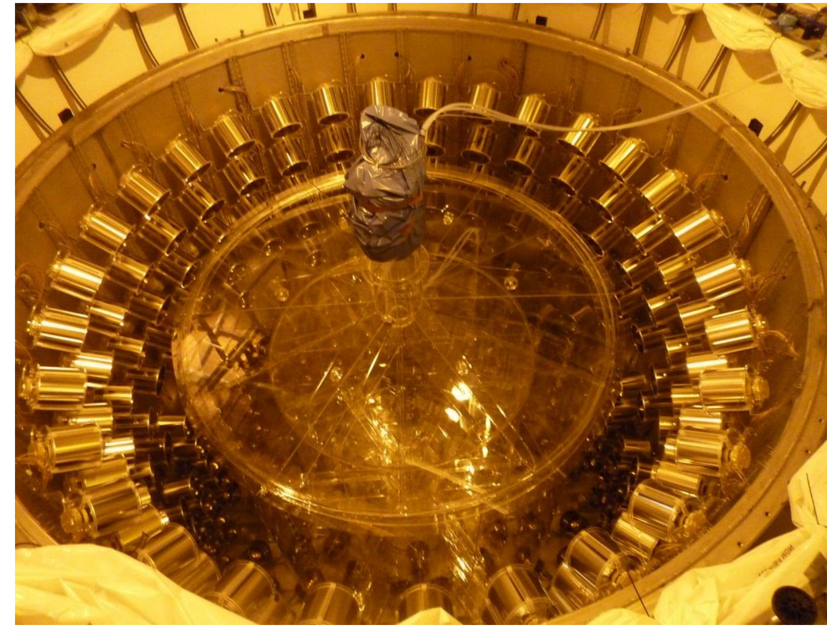
- **Accidental background**
  "2 independent processes happen to look like ν event"
  - Natural radioactivity of components or rock
  - Secondaries of μ interaction
  - High purity materials, shielding & μ veto
  - Expected rates: ~ 12 / day (near detector)
    ~ 2 / day (far detector)
- **Correlated background**
  "single process mimicking ν signature"
  - Spallation product **β-n** cascades
  - Fast **n** created by μ outside of detector
  - Deeper site, μ monitoring, modelling
  - Expected rates: ~ 8 / day (near detector)
    ~ 2 / day (far detector)



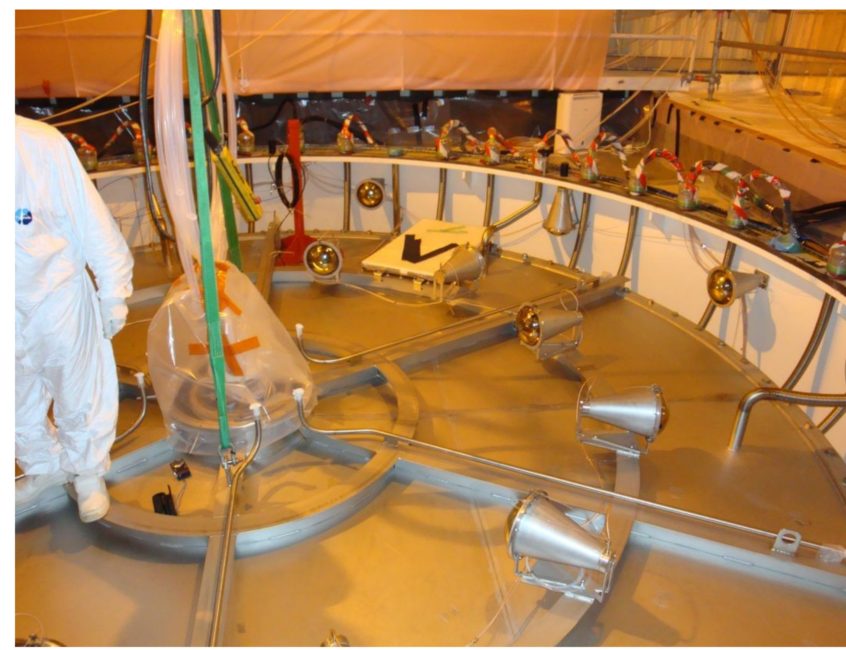


Double Chooz: Status & Time schedule

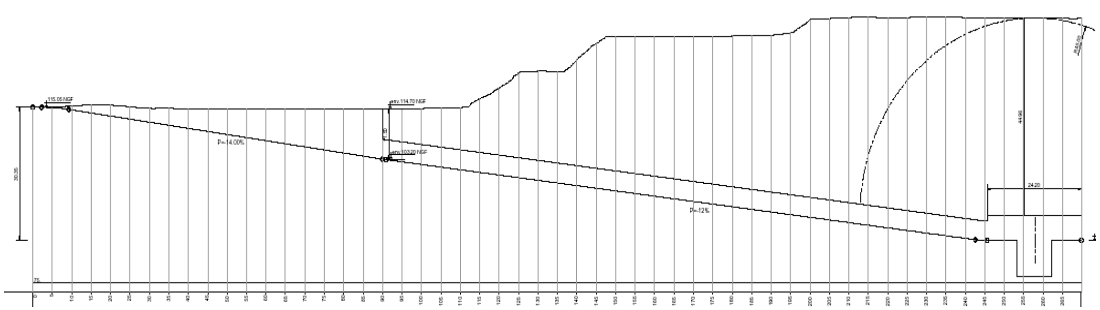
- Far detector closing imminent
  - Electronics installation ongoing
  - Awaiting fluid delivery
  - Commissioning run ~ May
  - In parallel: closing of steel shield and outer veto installation
- Near laboratory construction starting
  - Fully funded
  - Design approved by EDF
  - To be finished till end 2010



Acrylics integration, 10/2009



Top veto PMT installation, 1/2010

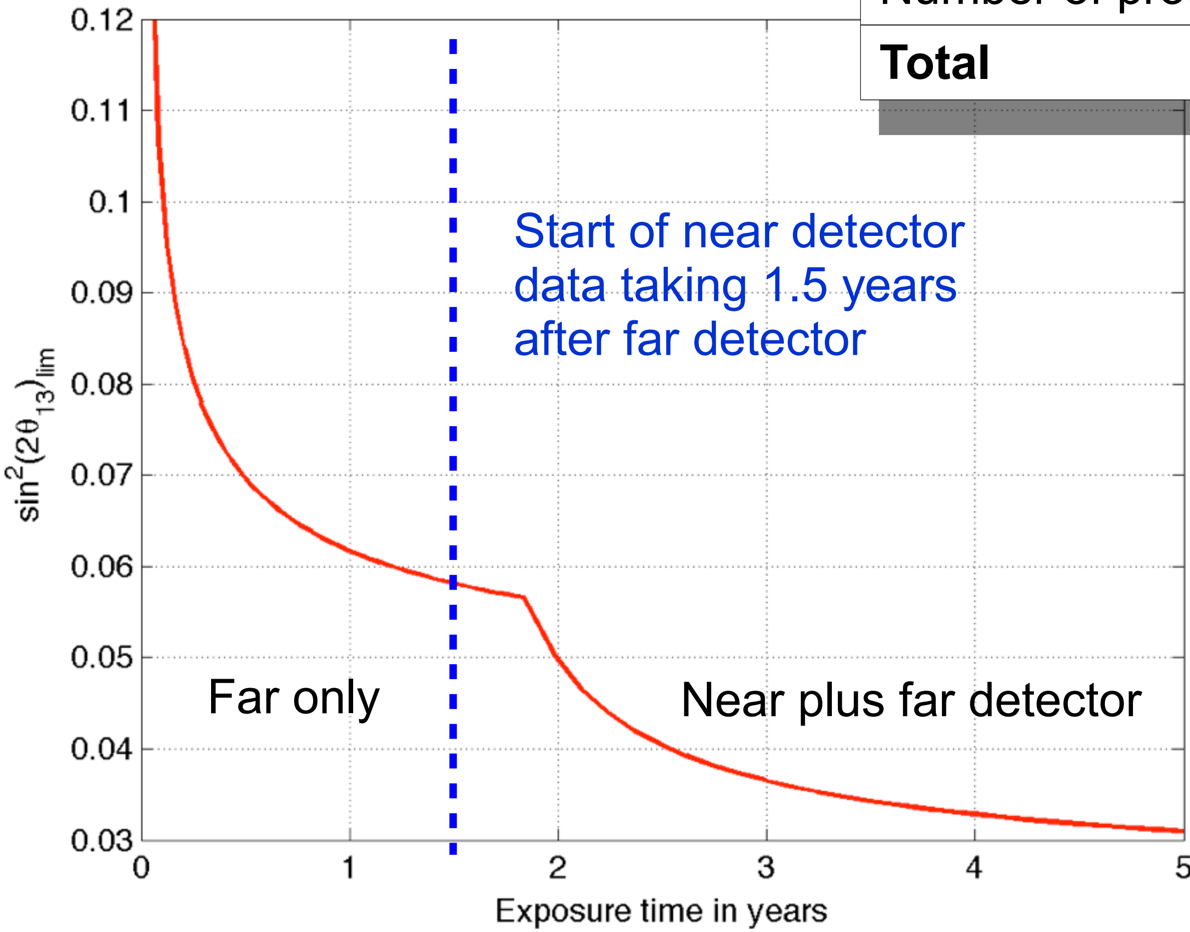


Side view of near lab planning sketch

Double Chooz: Sensitivity

- Two distinct phases:
  - Far detector only
  - Near plus far detector

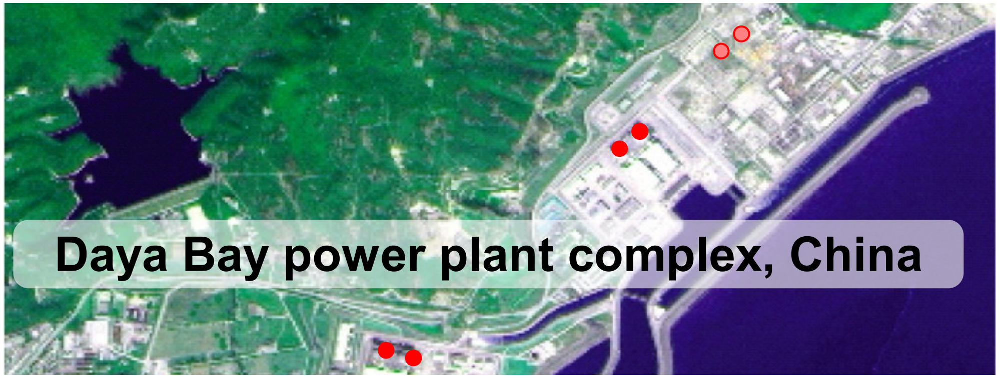
Systematic errors	Absolute	Relative
Production σ	1.9 %	-
Reactor power	0.7 %	-
Energy per fission	0.6 %	-
Detector efficiency	1.5 %	0.5 %
Number of protons	0.8 %	0.2 %
Total	**2.7 %**	**0.6 %**

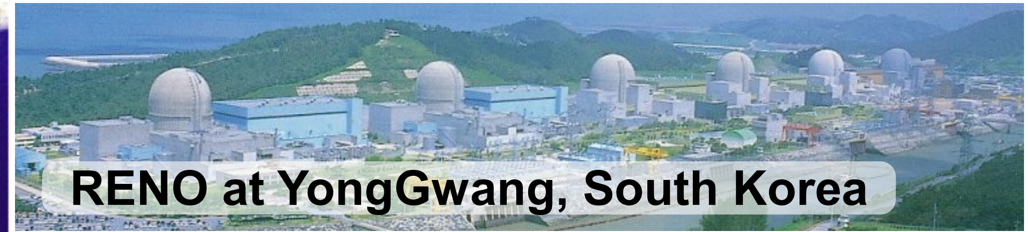


Sensitivity limit
90 % CL

- 1.5 years far only data:
  $\sin^2 2\Theta_{13} < 0.06$
- 4 years of near + far data
  $\sin^2 2\Theta_{13} < 0.03$

Daya Bay & Reno



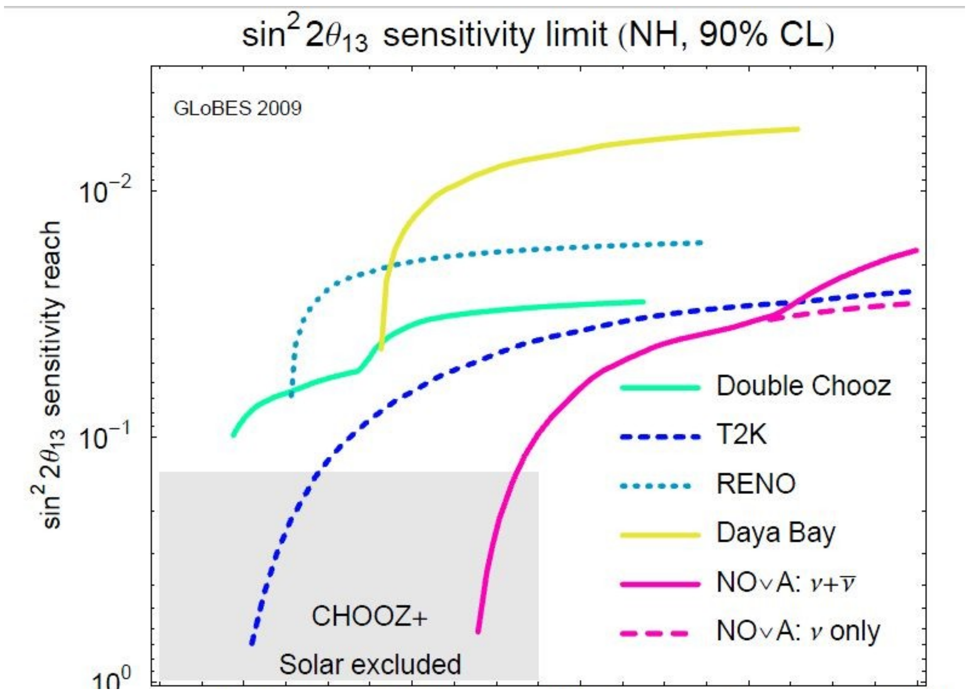


Reno expects to start mid-2010

DB near detectors to start mid-2010, far mid-2011

	Power $[GW_{th}]$	L_{near} [m]	L_{Far} [m]	M_{target} [t]	s_{stat} [%]	s_{syst} [%]	$\sin^2 2\Theta_{13}$ > (90 % CL)
DC	8.6	400	1050	8.3	0.5	0.6	0.03
RENO	17.3	290	1380	16	0.3	0.5	0.02
Daya Bay	17.4	360 (500)	1990 (1620)	80	0.2	0.4	0.01

- **Daya Bay:** 2 near sites, two 20t detectors each and one far site with four. Exchange detectors between sites for cross calibration.
- **RENO** consists of one near and one far detector, similar to DC
- Both have comparable detector design, but use water Cerenkov veto instead of LS
- Both sites need to correct for differing **ν** flux contributions @ near and far site(s). No reactor-off data for both sites available – and total shutdown of complex unlikely



Summary

- Double Chooz aims at measuring Θ_{13}, the last undetermined neutrino mixing angle.
- Fixing Θ_{13} allows to solve degeneracies of beam experiments → access to δ_{CP}, mass hierarchy.
- DC far detector will start data taking ~ June and reach sensitivity of $\sin^2 2\,\Theta_{13} < 0.06$ (90 % CL) after 1.5 years, improving the current limit by a factor of two.
- With four years of both near and far detector data the limit will be $\sin^2 2\,\Theta_{13} < 0.03$ (90 % CL) in 2015.
- Very active field – several experiments start data taking in the near future.
- Expect to learn more about neutrino nature soon!

~ Fin ~

CBPF, UNICAMP

CIEMAT Madrid

Hiroshima Inst. Tech.,
Kobe Univ.,
Miyagi Univ.,
Niigata Univ.,
Tohoku Univ.,
Tohoku Gakuin Univ.,
Tokyo Metro. Univ.,
Tokyo Inst. Tech.

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Univ. of Alabama, ANL,
Univ. of Chicago, Columbia,
U.C. Davis, Drexel Univ.,
Kansas State, Illinois Inst. Tech.,
LLNL, Notre Dame,
SNL, Univ. of Tennessee

Oscillation probabilities

$$P_{reactor} \simeq \sin^2 2\theta_{13} \sin^2 \Delta + \alpha^2 \Delta^2 \cos^4 \theta_{13} \sin^2 2\theta_{12},$$

$$\begin{aligned} P_{long-baseline} \simeq\ & \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta \\ & \mp \alpha \sin 2\theta_{13} \sin \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \Delta \\ & + \alpha \sin 2\theta_{13} \cos \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos \Delta \sin^2 \Delta \\ & + \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta \end{aligned}$$

with $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{23}$ and $\Delta \equiv \Delta m^2_{31} L/(4E_\nu)$.

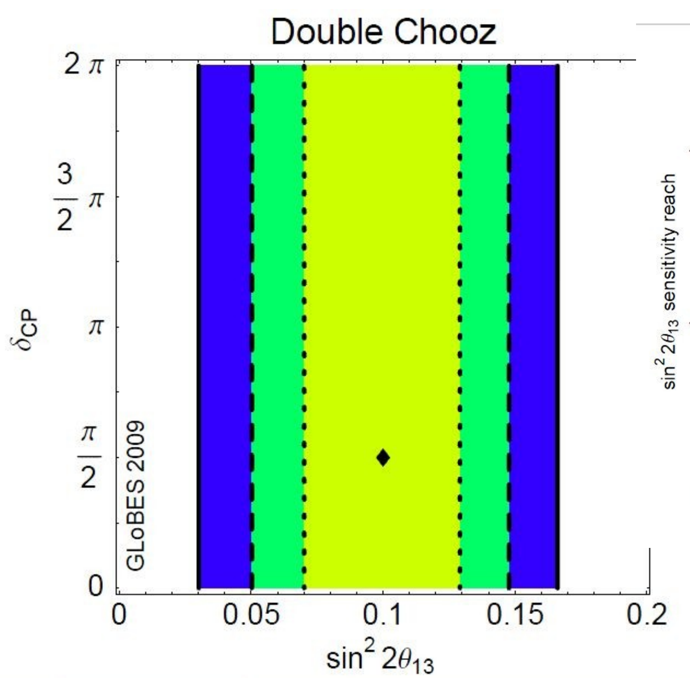
Mahn et al
hep-ex/0409028v4

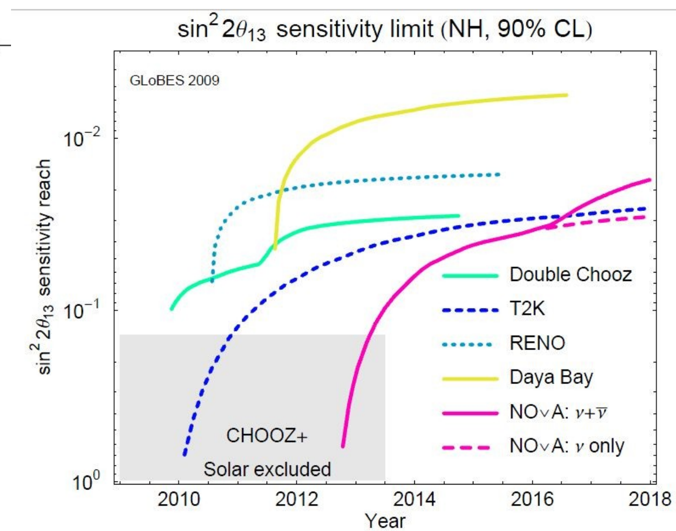
Reactor experiments

- Disappearance: $\bar{\nu}_e \rightarrow \bar{\nu}_x$
- Clean Θ_{13} measurement
- No information on δ_{CP}

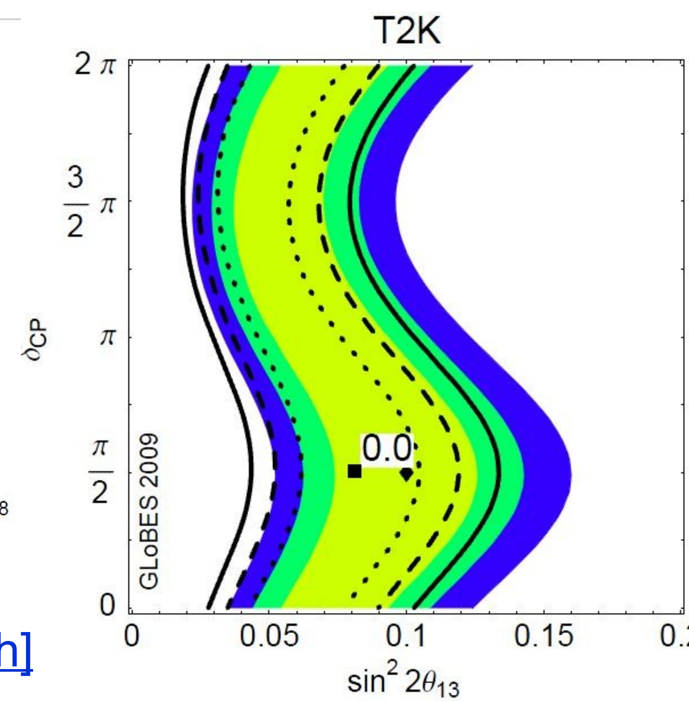
Beam experiments

- Appearance $\nu_\mu \rightarrow \nu_e$
- Θ_{13} coupled to δ_{CP} and Θ_{23}
- δ_{CP} if Θ_{13} not too small



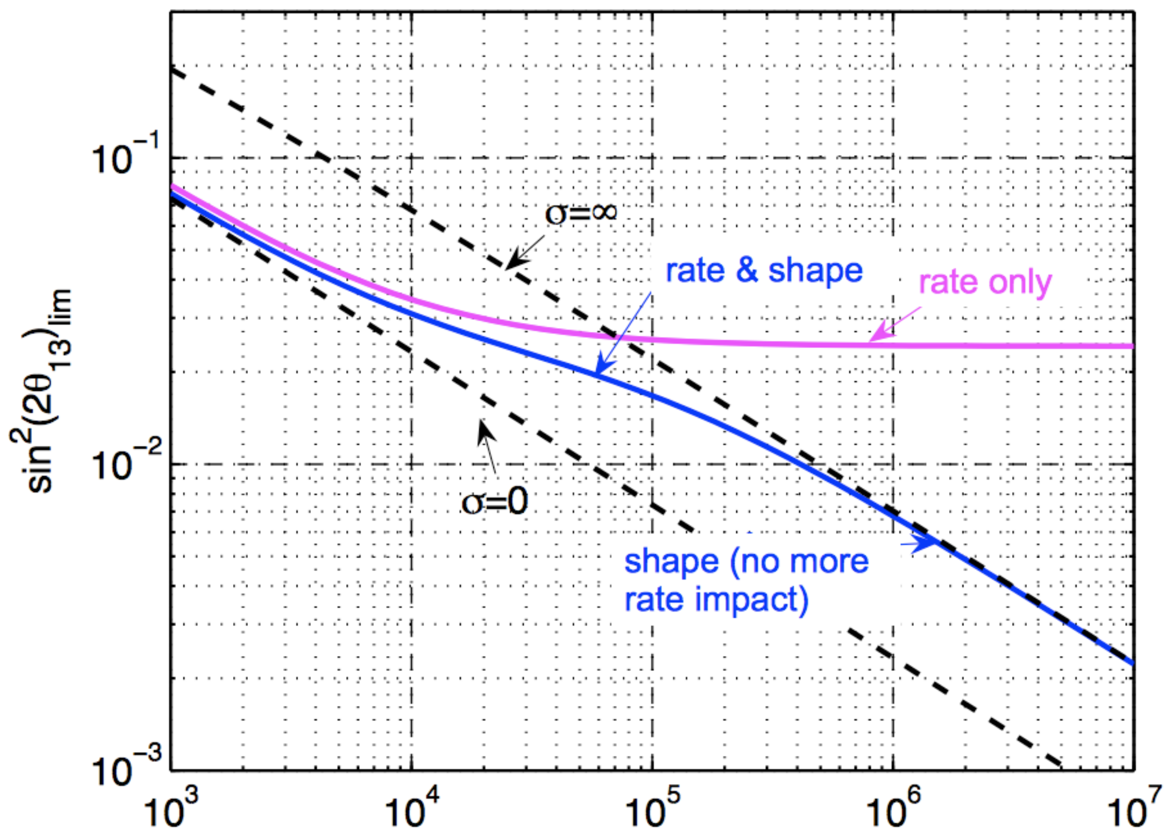


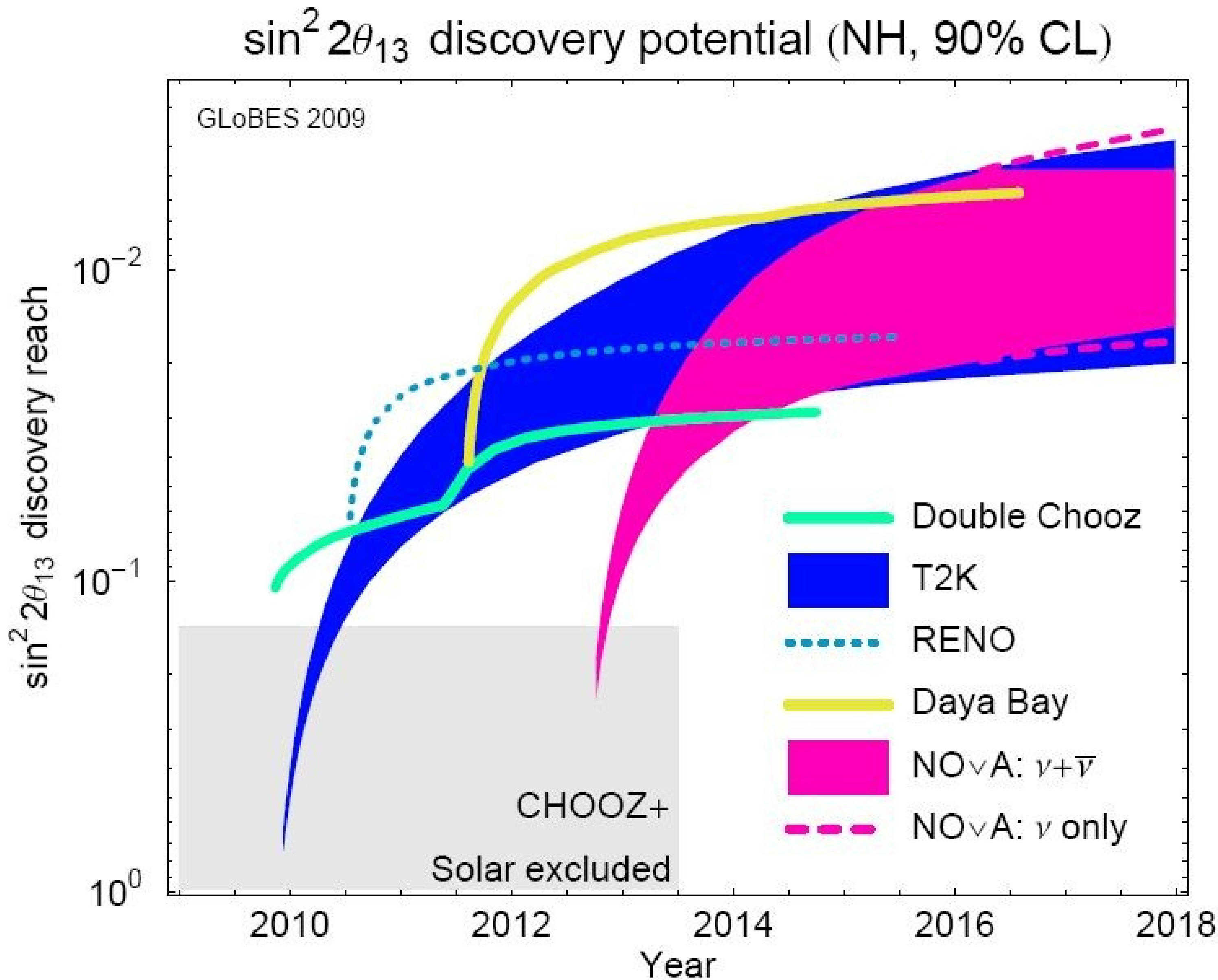
[Huber et al., arXiv:0907.1896v1 [hep-ph]]



→ Need information from both to determine ν parameters

- Shape vs rate information




$\sin^2 2\theta_{13}$ discovery potential (NH, 90% CL)
GLoBES 2009
$\sin^2 2\theta_{13}$ discovery reach
10^{-2}
10^{-1}
10^{0}
2010
2012
2014
2016
2018
Year
CHOOZ+
Solar excluded
Double Chooz
T2K
RENO
Daya Bay
NOνA: $\nu+\overline{\nu}$
NOνA: ν only