Measuring the neutrino mixing angle θ_{13} with the Double Chooz experiment

Romain Roncin

on behalf of the Double Chooz Collaboration

03/09/12

Contents

The Double Chooz Collaboration

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- CBPF
- UNICAMP
- UFABC

France
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  - SPP
  - SPhN
  - SEDI
  - SIS
  - SENAC
- CNRS/IN2P3:
  - Subatech
  - IPHC

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www.doublechooz.org/

From mixing to oscillation

- Neutrino oscillation is a quantum mechanic phenomenon --> a neutrino created with a given leptonic flavor can be measured at a distance L in an other one
- The « flavor » eigenstates (weak interaction --> ν_e, ν_μ, ν_τ) do not correspond to the « mass » eigenstates (propagation --> ν_1, ν_2, ν_3) --> linked with the U_{PMNS} matrix

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

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

U_{PMNS} depends on 4 parameters --> θ_{23}, θ_{13}, θ_{12} and δ

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$\sin^2 2\theta_{12} \approx 0.8$

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$\sin^2 2\theta_{12} \approx 0.8$

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Atmospheric | θ_{13} sector | Solar

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

U_{PMNS} depends on 4 parameters --> θ_{23}, θ_{13}, θ_{12} and δ

$\sin^2 2\theta_{23} \approx 1$

Limit from the CHOOZ experiment

$\sin^2 2\theta_{12} \approx 0.8$

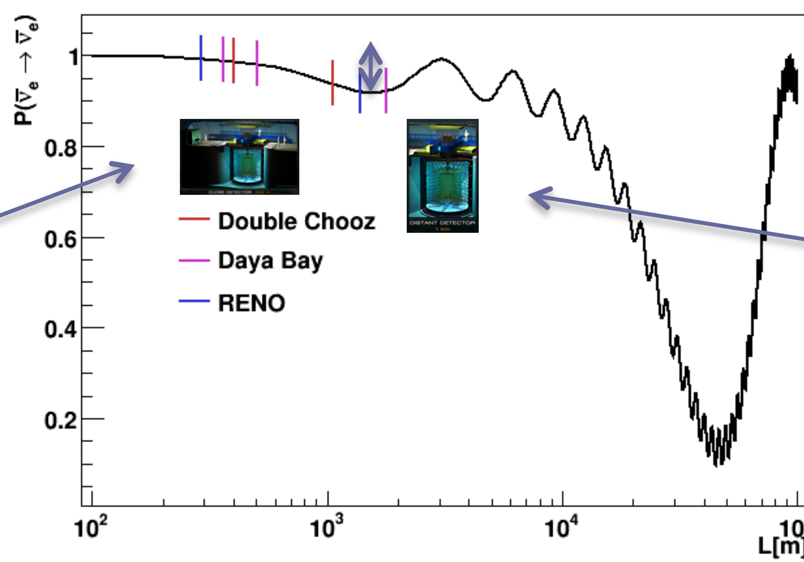
$\sin^2 2\theta_{13} < 0.15$ at 90 % C.L.

Measuring θ_{13} with nuclear reactors

- Due to β-decay of fission products, nuclear reactors are a free and rich anti-ν_e source --> around 10^{21} anti-ν_e per second are emitted in the case of the Double Chooz experiment

- Studying the disappearance of these anti-ν_e *via* the survival probability with two or more identical detectors --> to eliminate systematics from both the anti-ν_e production uncertainties and the detection efficiency

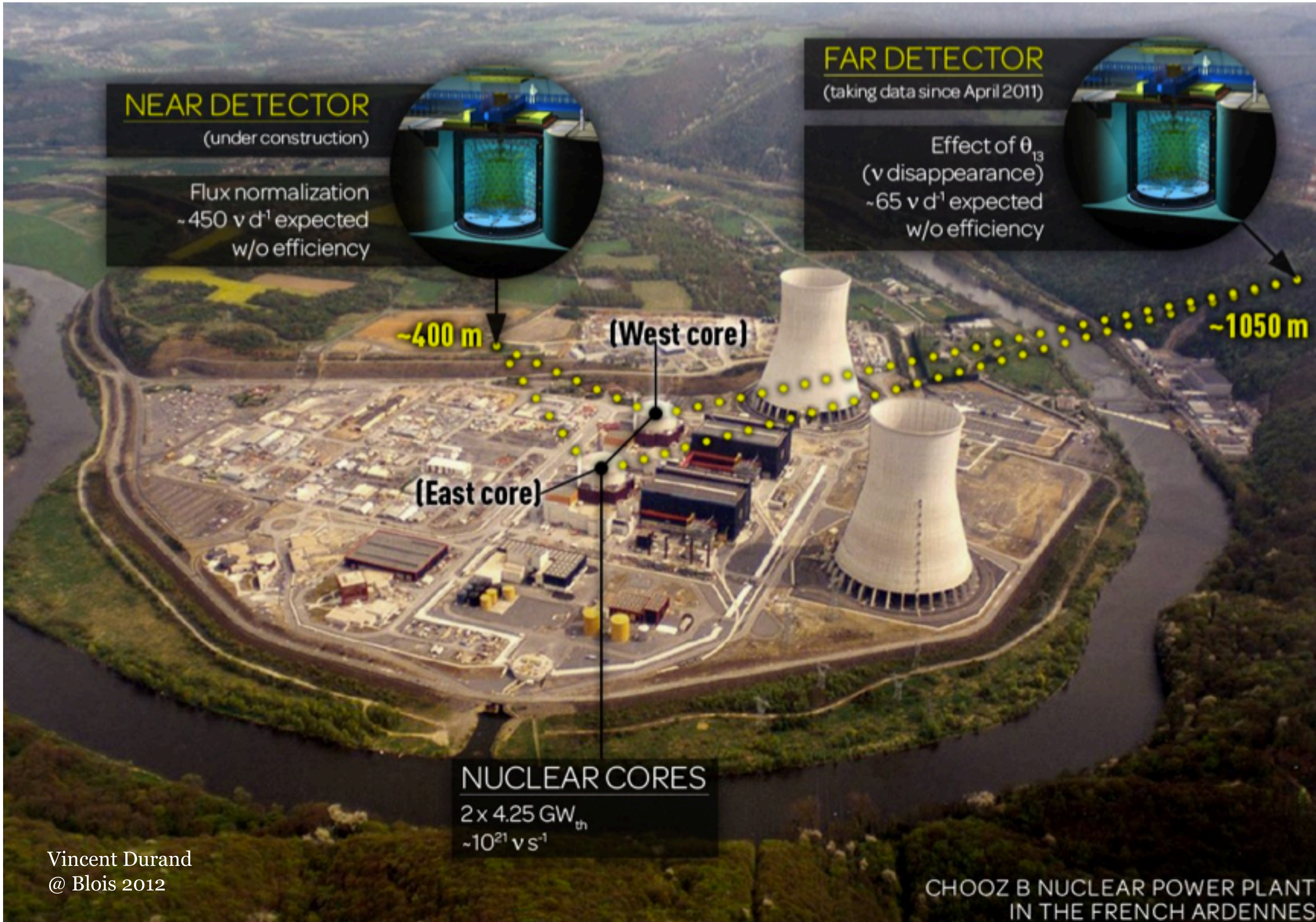
$$P(\bar{\nu}_e \to \bar{\nu}_e) \sim 1 - \sin^2 2\theta_{13} \sin^2\left(1.267\frac{\Delta m^2_{31}[\text{eV}^2]L[\text{m}]}{E_{\bar{\nu}_e}[\text{MeV}]}\right)$$



Near detector
--> normalization

Far detector
--> oscillation
measurement

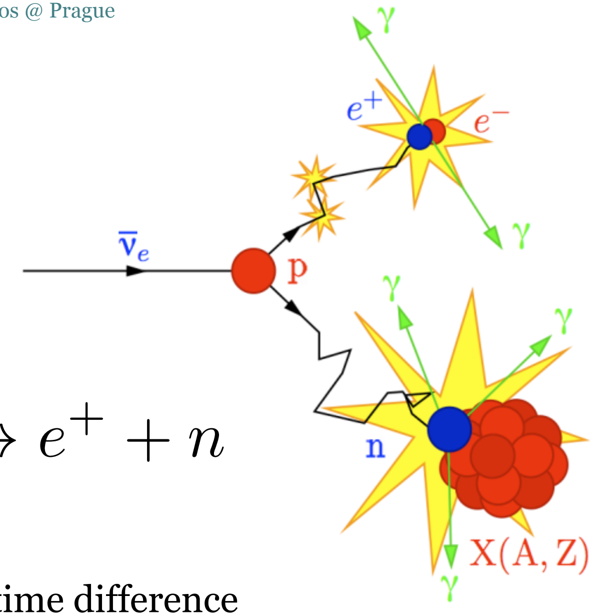
The Double Chooz experimental site



Vincent Durand
@ Blois 2012

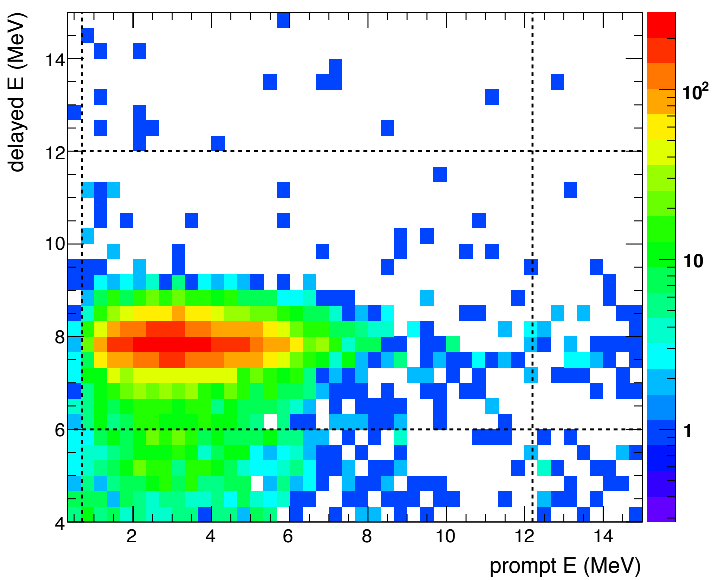
The detection method

- Detection of anti-ν_e by inverse β-decay (IBD)
- Prompt signal from the positron
  - ✓ $0.7 < E < 12.2$ MeV
- Delayed signal from the neutron capture on Gd
  - ✓ $6 < E < 12$ MeV
- Time coincidence
  - ✓ $2 < \Delta T < 100$ μs

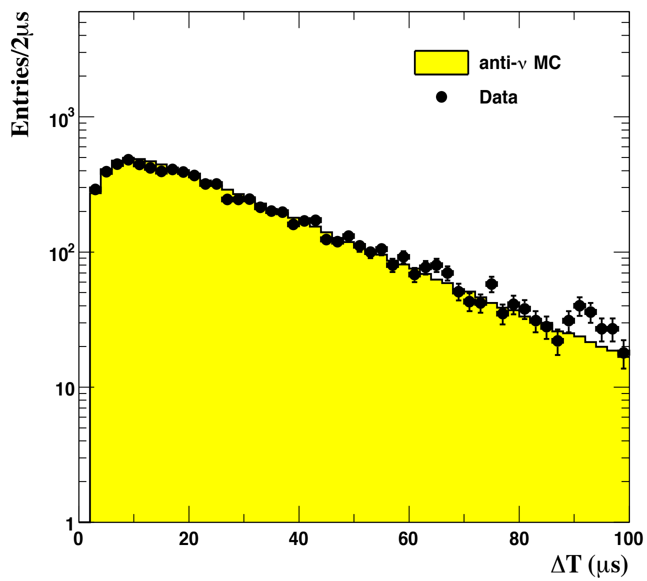


$$\bar{\nu}_e + p \rightarrow e^+ + n$$

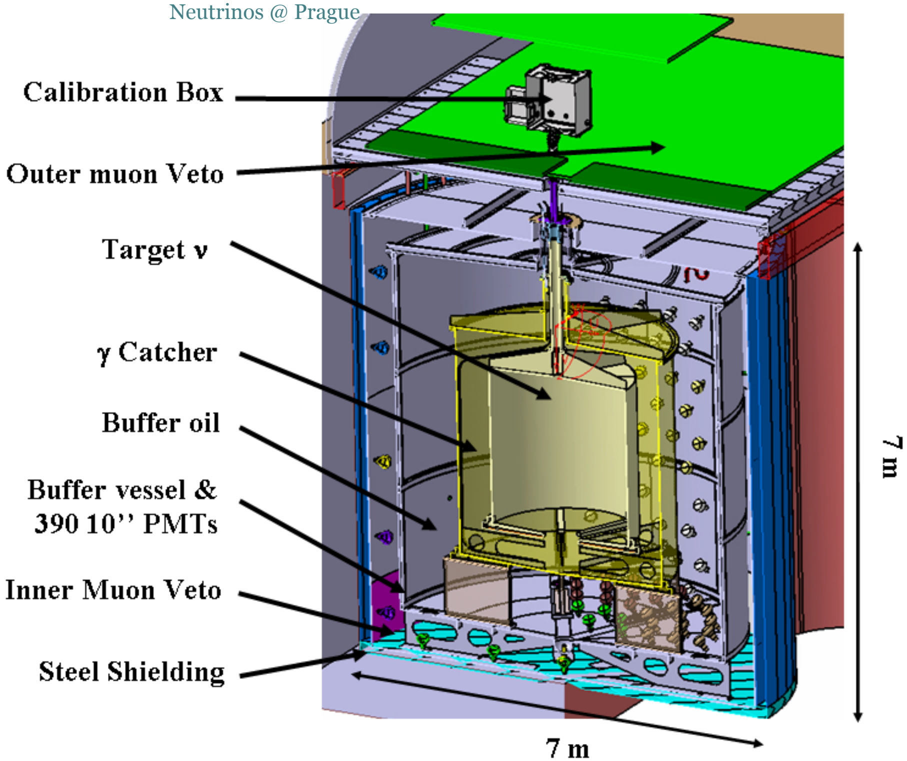
$E_{delayed}$ vs E_{prompt}

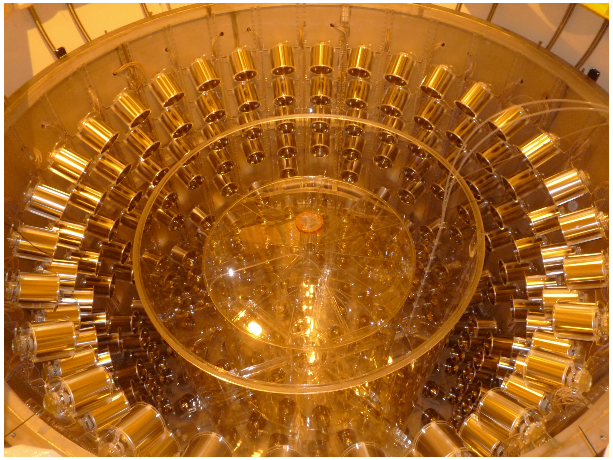


Prompt-delay time difference



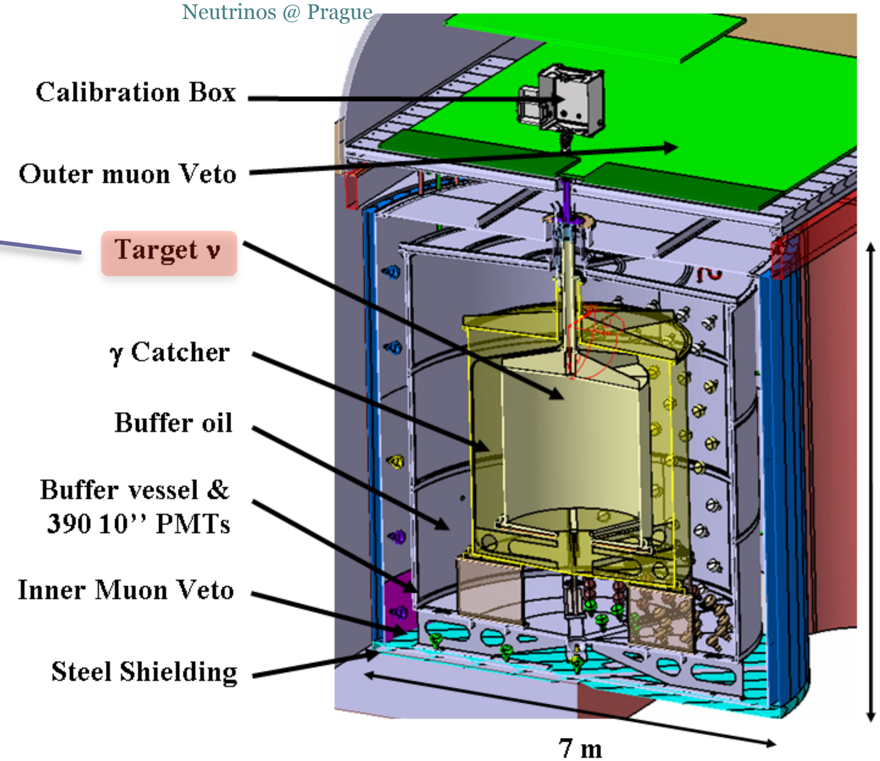
The Double Chooz detector

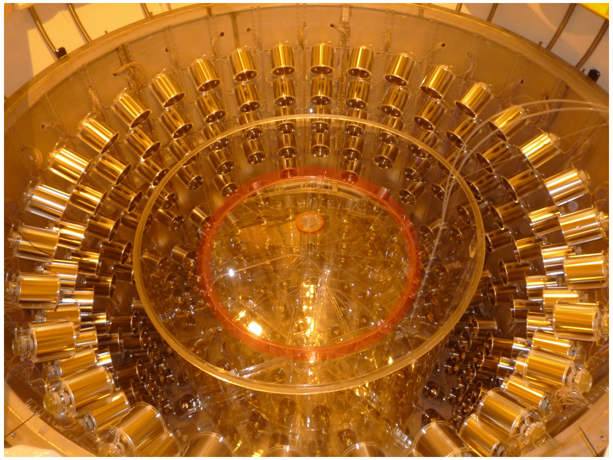




The Double Chooz detector

Filled with 10 m³ Gd-doped liquid scintillator
--> place of the anti-ν_e interaction





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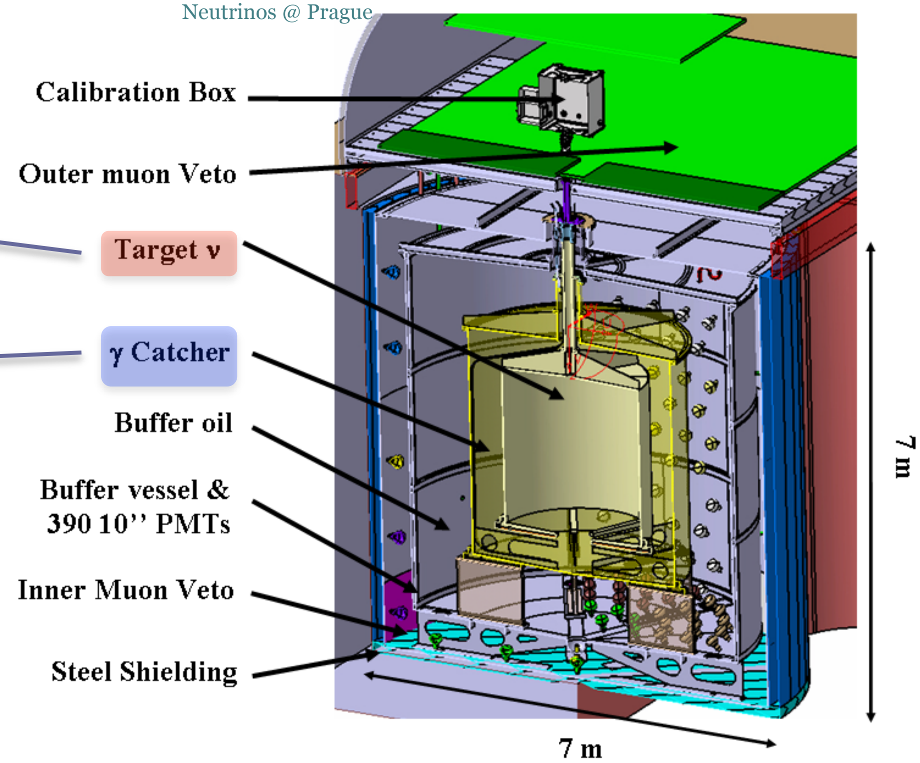
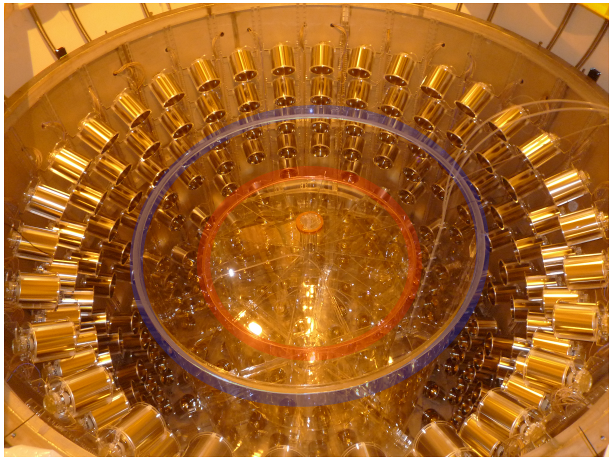
Filled with 22 m³ liquid scintillator
--> to discriminate the anti-ν_e interaction





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Filled with 110 m³ mineral oil
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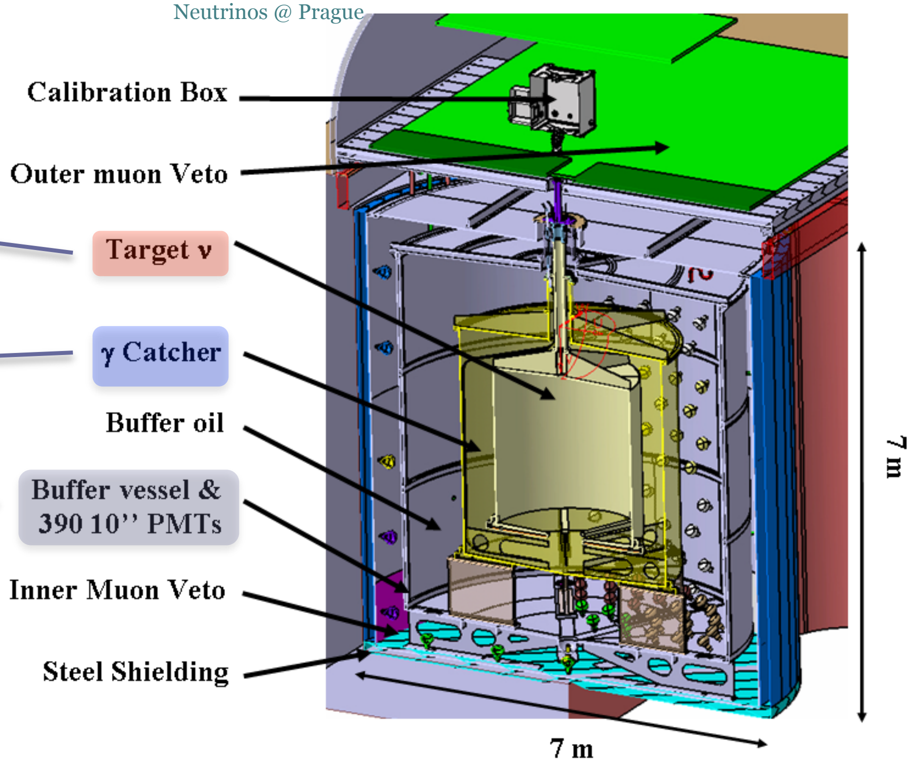

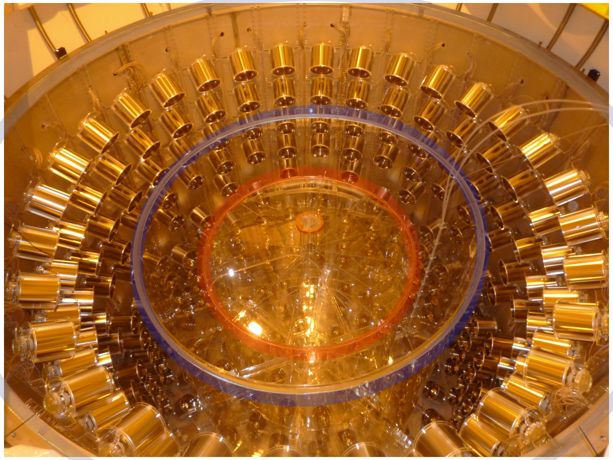

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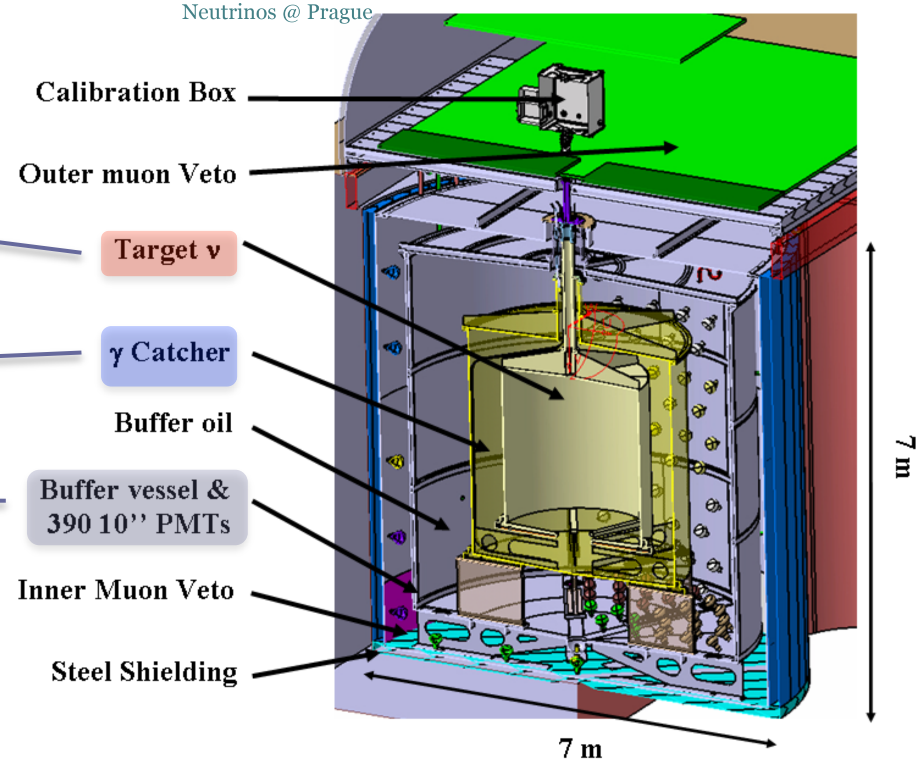

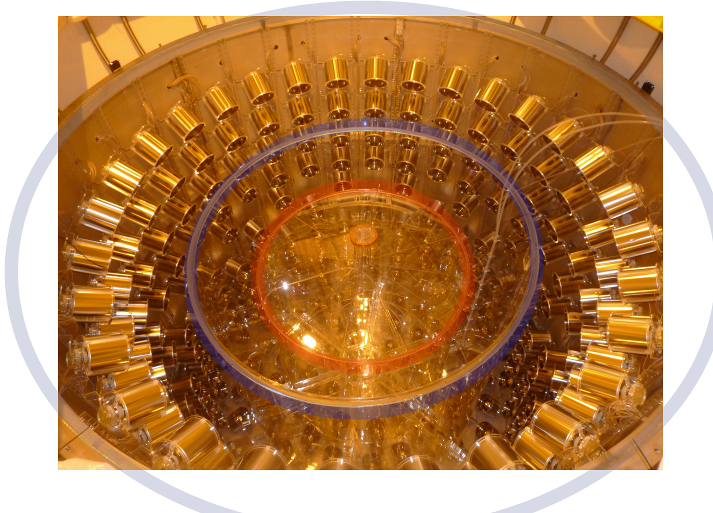

The Double Chooz detector

82 m² of 400 mm thick plastic scintillator strips

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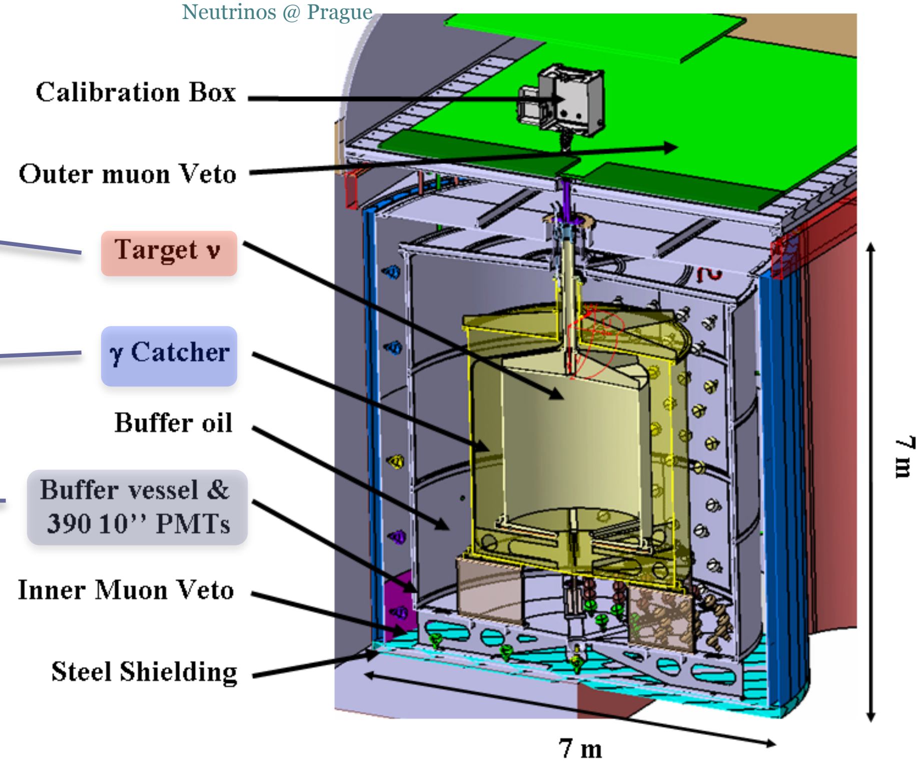

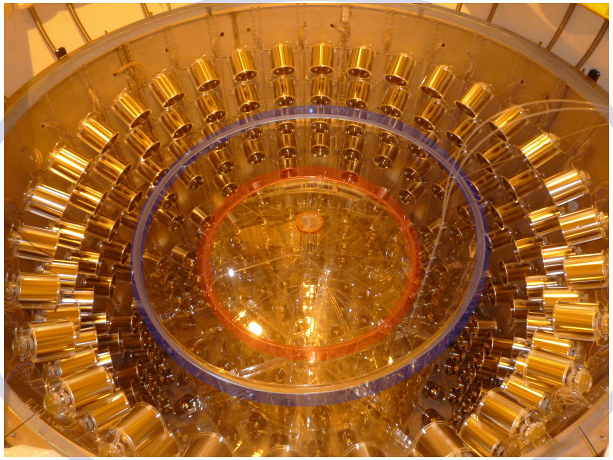

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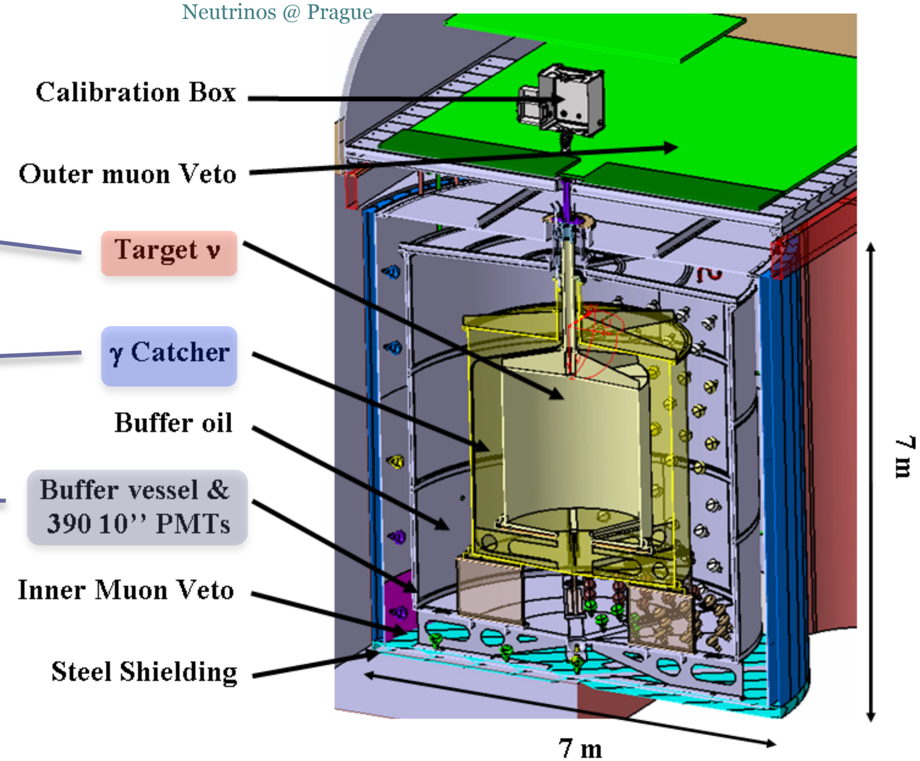
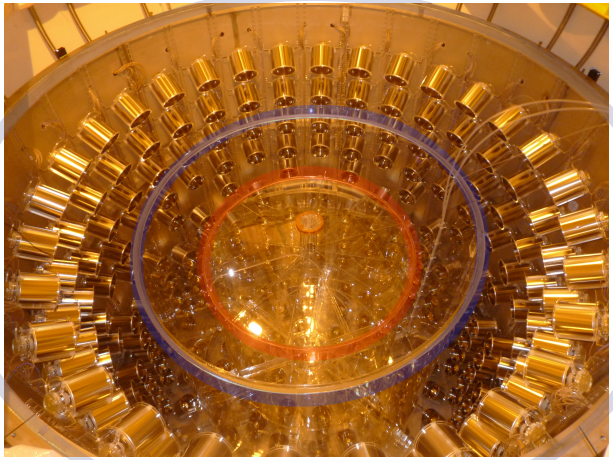
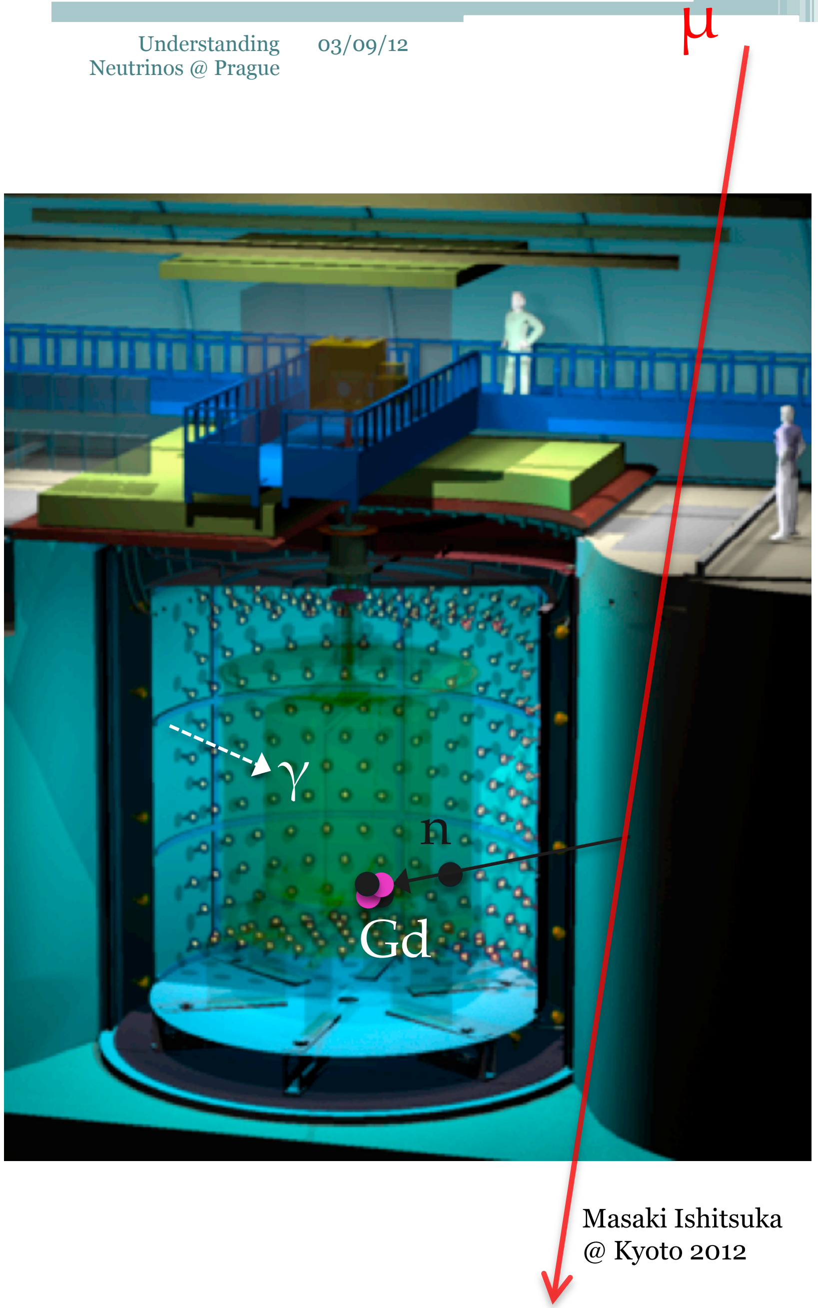


- The Far detector is taking data since April 2011 while the near detector is under construction



Background

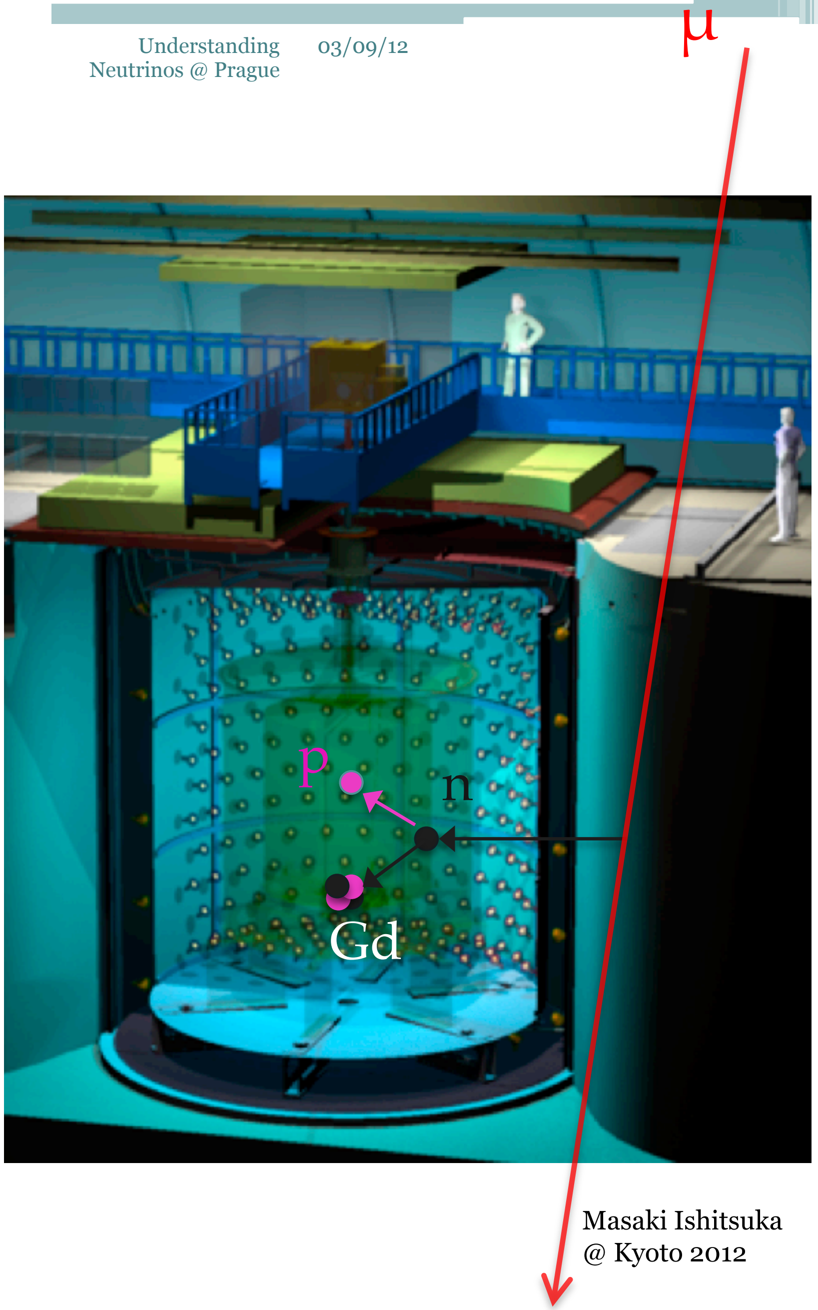
- Accidental coincidence --> random association between a prompt-like signal and a delayed-like signal --> **0.261 ± 0.002 event/day**



Masaki Ishitsuka @ Kyoto 2012

Background

- Accidental coincidence --> random association between a prompt-like signal and a delayed-like signal --> **0.261 ± 0.002 event/day**
- Correlated --> **0.67 ± 0.20 event/day**
  - ✓ Fast neutrons --> induced by muons traversing rocks, fast neutrons lead to proton recoil followed by capture on Gd
  - ✓ Stopping muons --> going through the chimney, stopping muons deposite energy before producing Michel electrons



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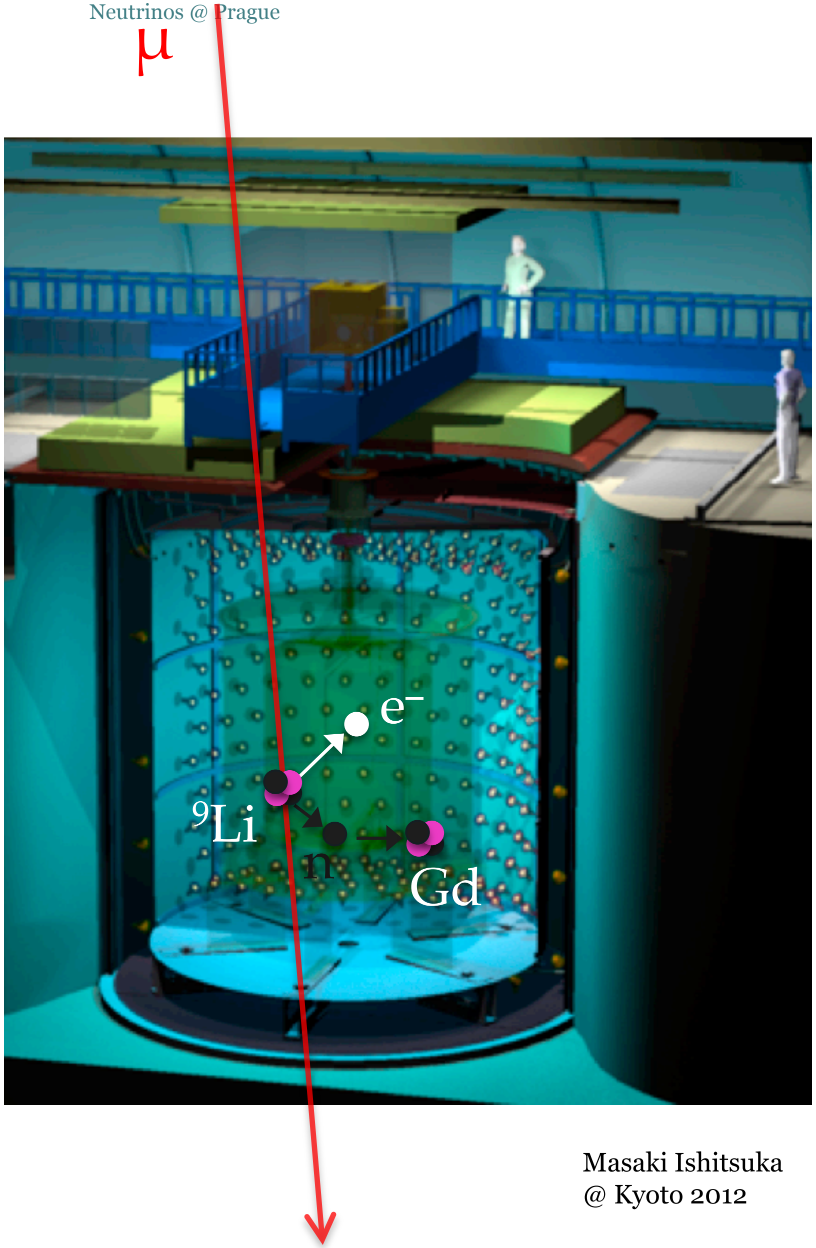
- ^{9}Li --> produced by energetic muons, ^{9}Li decays into ^{8}Be with emission of an electron and a neutron --> **1.25 ± 0.54 event/day**



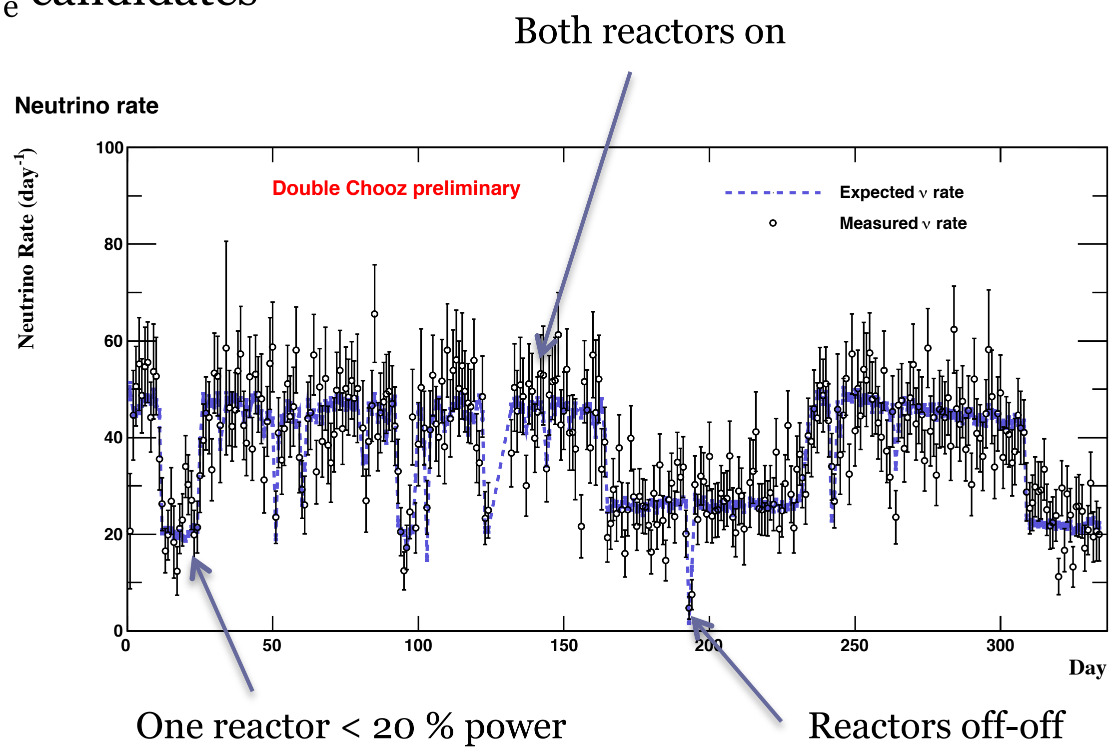
Masaki Ishitsuka @ Kyoto 2012

The Double Chooz results

- 1st results announced in November 2011 --> PRL **108** (2012) 131801
  - ✓ 1st θ_{13} measurement since the CHOOZ experiment
  - ✓ Indication of non-zero θ_{13} at 94 % C.L. and hint for a large value of θ_{13}

- Since, statistics was doubled
  - ✓ 96.8 --> **227.9** days of livetime
  - ✓ 4121 --> **8249** anti-ν_e candidates

- Since, Analysis was improved
  - ✓ Energy calibration was improved
  - ✓ Additionnal muon veto was implemented
  - ✓ OV veto was implemented



Systematic uncertainties

Source		Uncertaincty w.r.t. signal (previous analysis)	
Statistics		**1.1 %** (1.6 %)	
Flux		**1.7 %**	
Detector	Energy response	**0.3 %** (1.7 %)	**1.0 %** (2.1 %)
	E_{delay} containment	0.7 %	
	Gd fraction	0.3 %	
	Δt cut	0.5 %	
	Spill in/out	0.3 %	
	Trigger efficiency	< 0.1 %	
	Target H	0.3 %	
Background	Accidental	< 0.1 %	**1.6 %** (3.0 %)
	Fast neutrons + stopping muons	0.5 % (0.9 %)	
	^{9}Li	1.4 % (2.8 %)	

The Double Chooz new results --> arXiv:1207.6632v2 accepted for publication in PRD

- Measured prompt energy spectrum

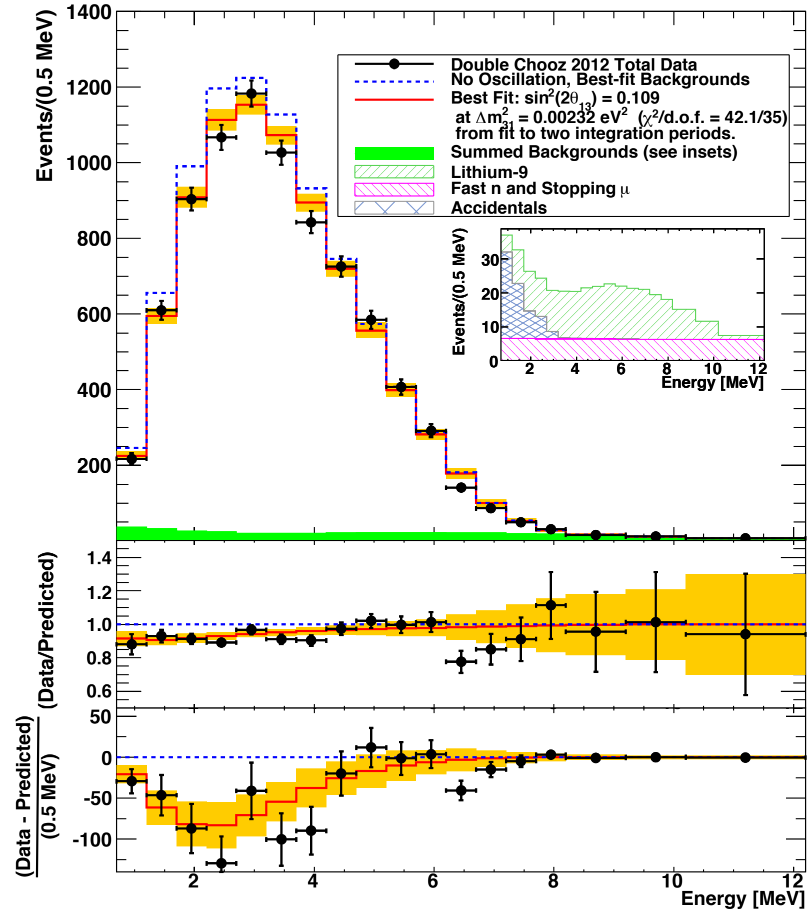
- Fit using two types of information
  - ✓ Rate --> number of events
  - ✓ Shape --> spectra

Rate only
$\sin^2 2\theta_{13} = 0.170 \pm 0.035$ (stat) ± 0.040 (syst)

Rate + Shape
$\sin^2 2\theta_{13} = 0.109 \pm 0.030$ (stat) ± 0.025 (syst)

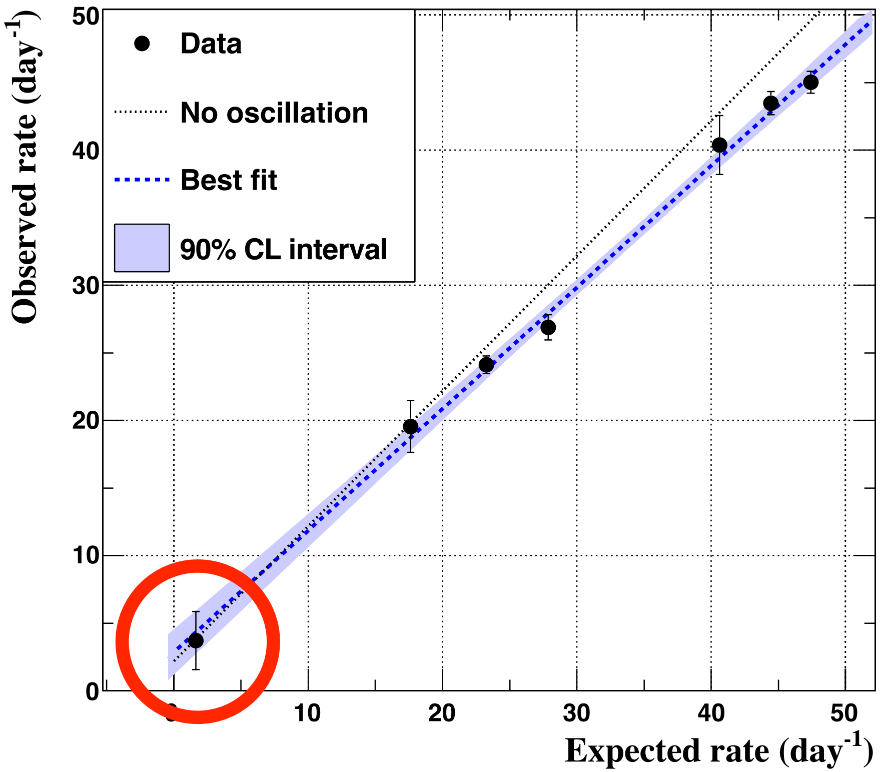
$\sin^2 2\theta_{13} = 0$ excluded at 99.8 % (2.9 σ)

NB : dataset is divided into two periods based on reactor power



Observed vs expected rate

- Daily number of anti-ν_e as a function of the expected number of anti-ν_e
- Three events observed in 0.84 day livetime with both reactors off
  - ✓ Background rate consistent with estimation --> 2.2 ± 0.6 events/day
  - ✓ Background rate obtained from the fit --> 2.9 ± 1.1 events/day



Conclusion

- Double Chooz initiated the new generation of experiments with multiple detectors to measure θ_{13}
- Double Chooz was the 1st experiment able to measure θ_{13} --> results confirmed then by Daya Bay and RENO
  - ✓ $\sin^2 2\theta_{13} = 0.109 \pm 0.030\ (\text{stat}) \pm 0.025\ (\text{syst})$
  - ✓ $\sin^2 2\theta_{13} = 0$ excluded at 99.8 % (2.9 σ)
- The Near detector laboratory excavation is completed
- The Near detector data taking will start by the end of 2013

Thank you for your attention !!
Any questions ?

Double Chooz 1st results on CBS : The Big Bang Theory S05E11