Latest results of the Double Chooz reactor neutrino experiment

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Neutrino oscillation

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \neq \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

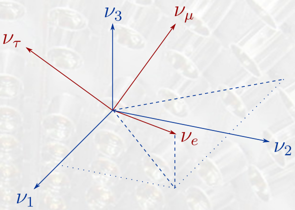
flavour eigenstates

mass eigenstates

Neutrino oscillation

PMNS mixing matrix
(Pontecorvo Maki Nakagawa Sakata)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



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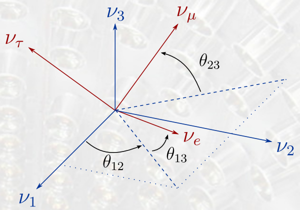
PMNS matrix is unitary : reduction of parameters to 3 mixing angles + 1 phase



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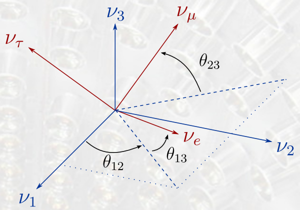

PMNS matrix is unitary : reduction of parameters to 3 mixing angles + 1 phase

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

δ : neutrino/antineutrino asymmetry (CP violation)

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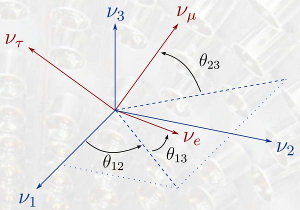

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- **Oscillation experiments optimised to study mixing between two states :**

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta_{ij} & \sin\theta_{ij} \\ -\sin\theta_{ij} & \cos\theta_{ij} \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix} \qquad \begin{matrix} \alpha, \beta = e, \mu, \tau \\ i, j = 1, 2, 3 \end{matrix}$$

- **Oscillation probability of a neutrino ν_α with energy E after a distance L :**

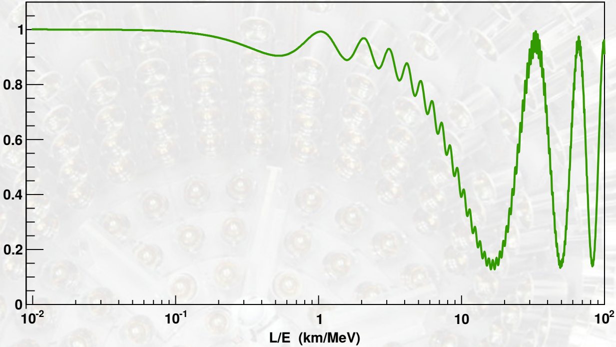
$$P_{\nu_\alpha \to \nu_\beta} \approx \sin^2(2\theta_{ij}) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) \quad \text{avec} \quad \Delta m^2_{ij} = m^2_i - m^2_j$$

Reactor neutrino oscillation and θ_{13} measurement

nuclear reactor = point-like, intense ($\sim 10^{21}$ ν/GWth) and free source of pure $\bar{\nu}_e$

Survival probability

$P_{\bar{\nu}_e \longrightarrow \bar{\nu}_e}$



- θ_{13} last unkown parameter until 2012
- measurement through disappearance of $\bar{\nu}_e$ in a **far detector** (at $\approx$ 1 km)
- **identical near detector** for high precision (reduce detection+flux errors)

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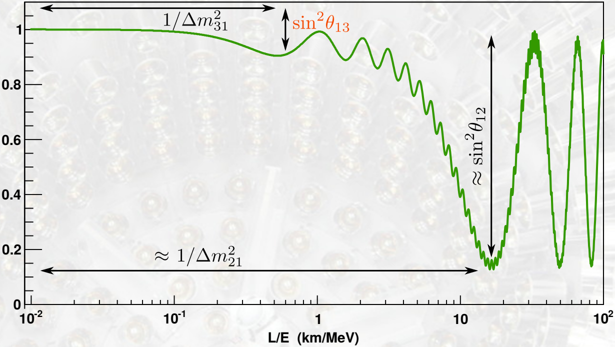

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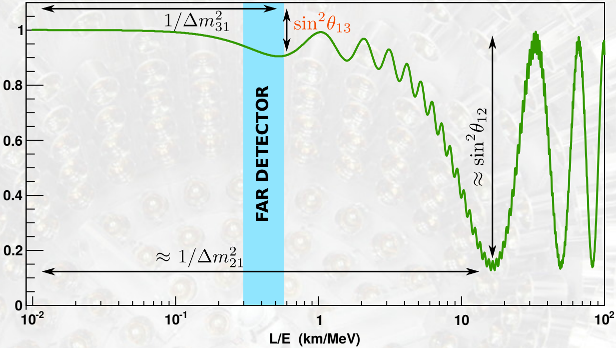

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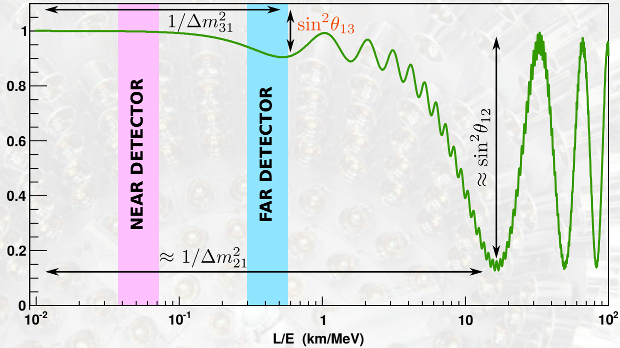

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Double Chooz international collaboration

BRAZIL
CBPF
UNICAMP
UFABC

FRANCE
APC
CEA/DSM/IRFU:
SPP, SPhN, SEDI,
SIS, SENAC.
CNRS/IN2P3:
Subatech, IPHC.

GERMANY
EKU Tübingen
MPIK Heidelberg
RWTH Aachen
TU München
U. Hamburg

JAPAN
Tohoku U.
Tokyo Inst. Tech.
Tokyo Metro. U.
Niigata U.
Kobe U.
Tohoku Gakuin U.
Hiroshima Inst. Tech.

RUSSIA
INR RAS
IPC RAS
RRC Kurchatov

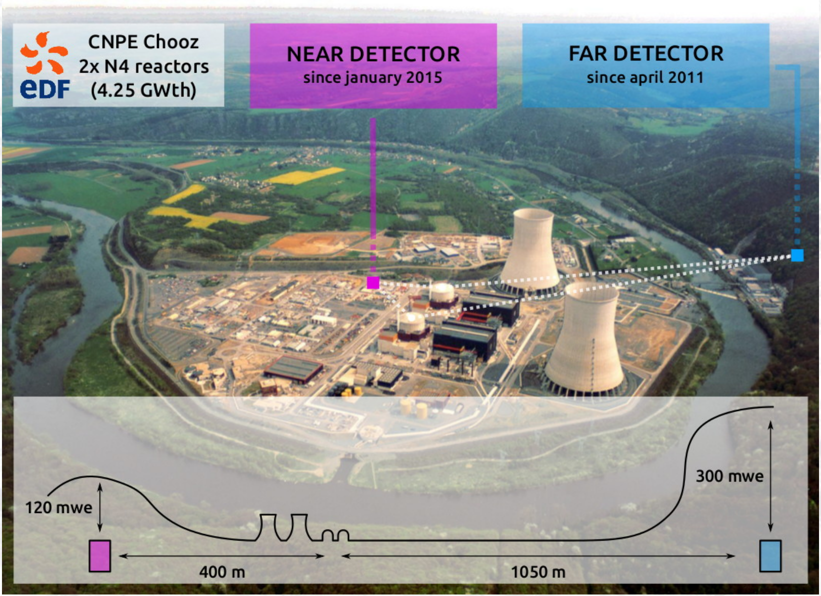
SPAIN
CIEMAT-Madrid

USA
U. Alabama
ANL
U. Chicago
Columbia U.
UC Davis
Drexel U.
U. Hawaii
IIT
KSU
LLNL
MIT
U. Notre Dame
U. Tennessee

150 physicists/engineers from 7 countries

Spokesperson : Hervé de Kerret (CNRS/IN2P3)
Project Manager : Christian Veyssière (CEA Saclay)

Double Chooz experiment layout



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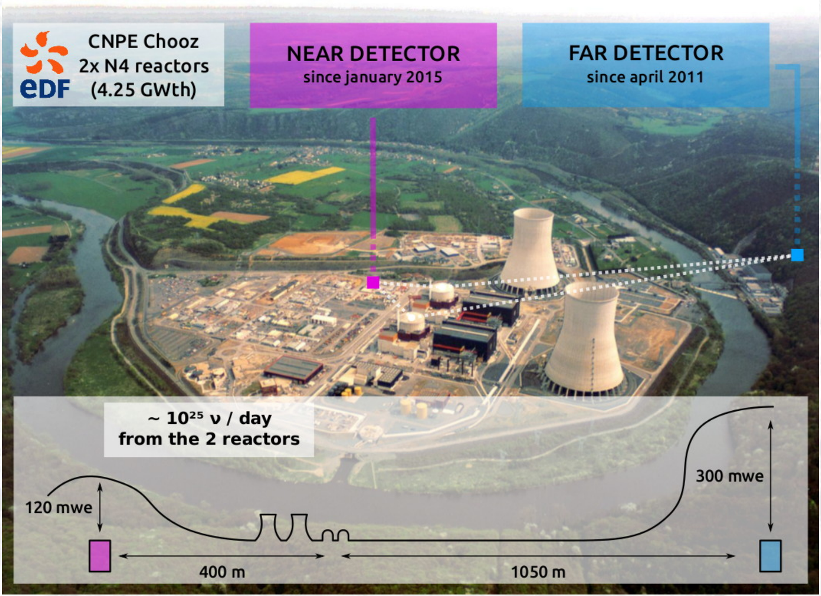

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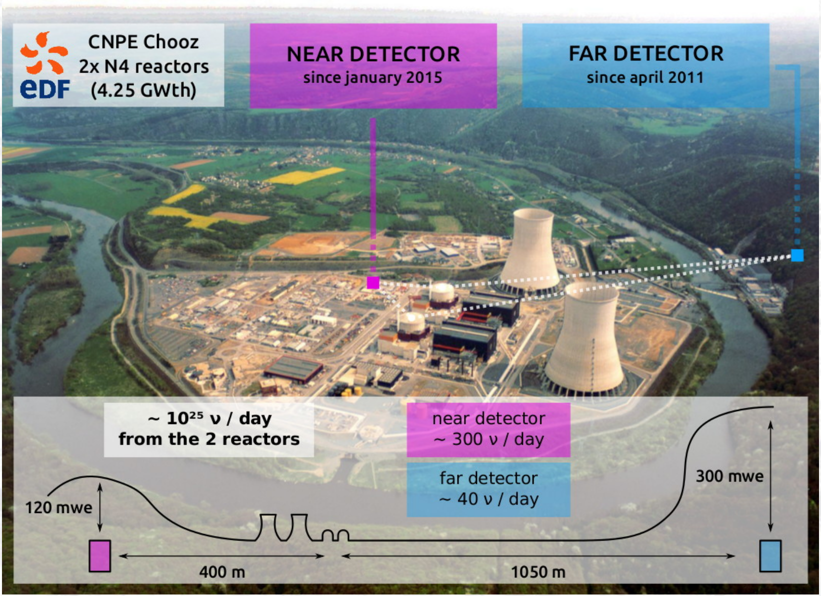

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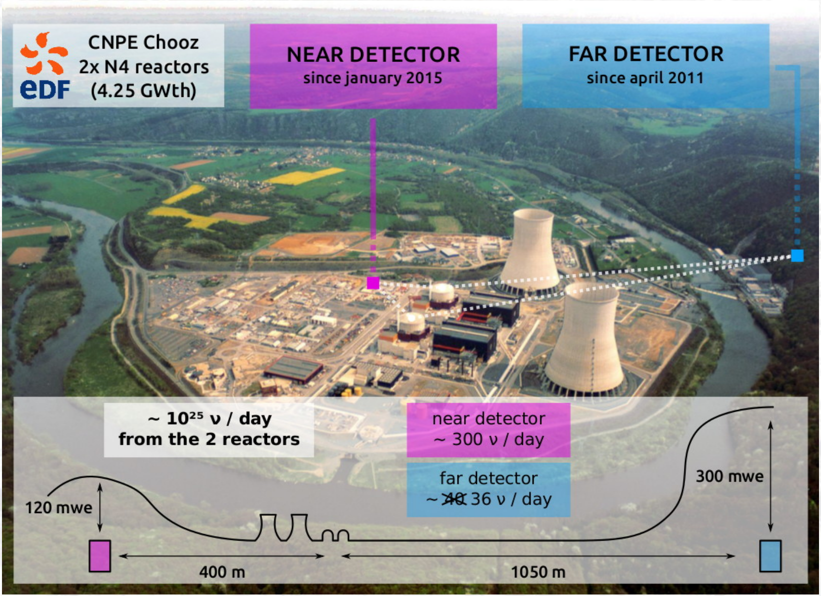
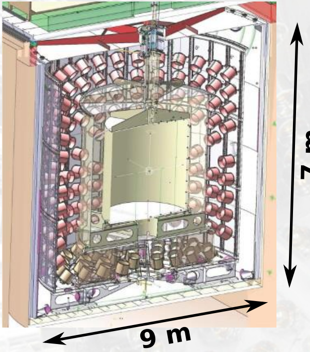
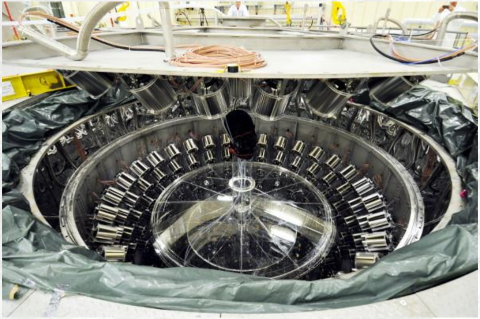


Double Chooz detector





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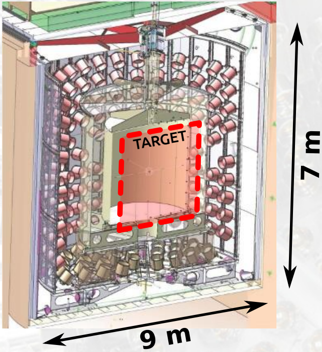
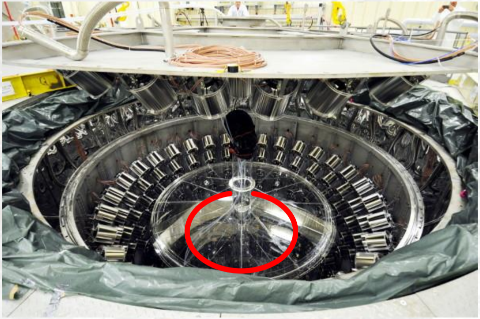
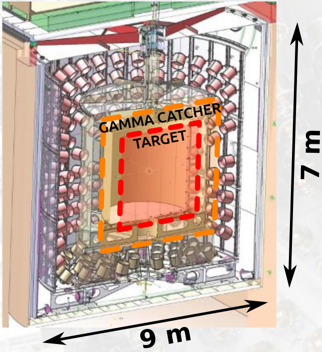
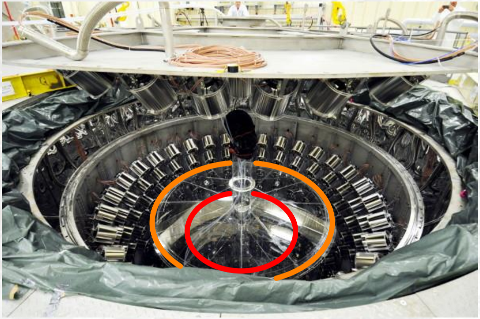




Neutrino target
liquid scintillator
with Gd (8 tons)

Double Chooz detector





Neutrino target
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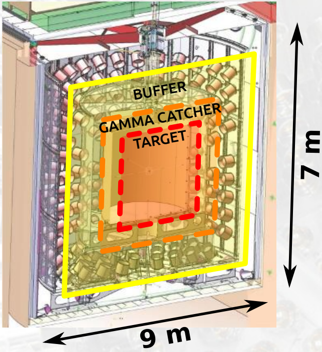
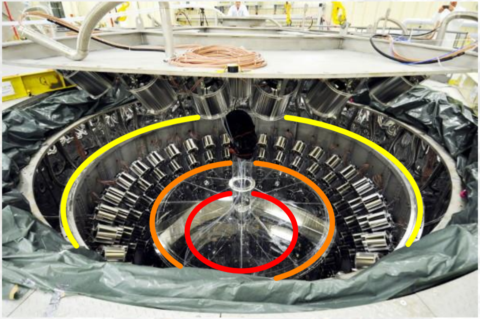
Gamma catcher
liquid scintillator
without Gd

Double Chooz detector





Neutrino target
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Gamma catcher
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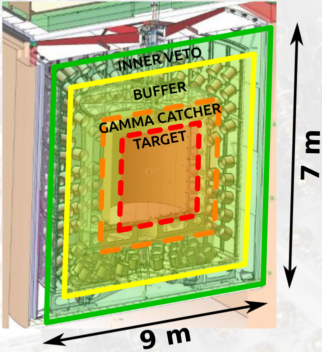
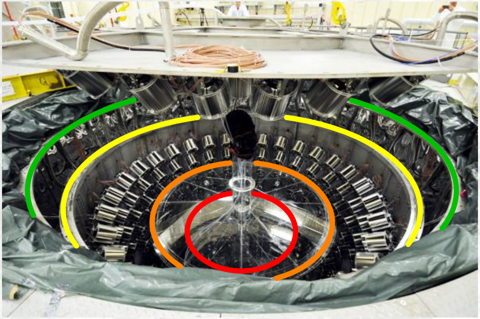
Buffer
mineral oil
390x 10" PMTs

Double Chooz detector





Neutrino target	Gamma catcher	Buffer	Inner Veto
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Detection principle

"IBD" (Inverse Beta Decay)

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

prompt signal : positron
$E_{prompt} \approx E(\nu_e)$ - 0,78 MeV

delayed signal : radiative neutron capture

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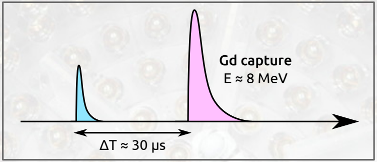

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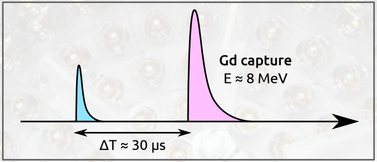

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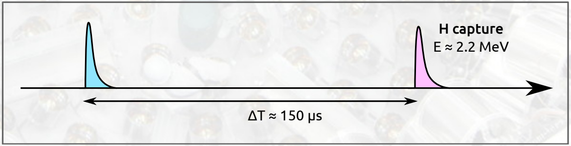

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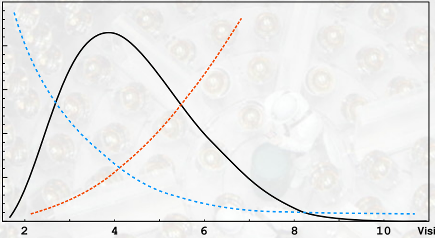
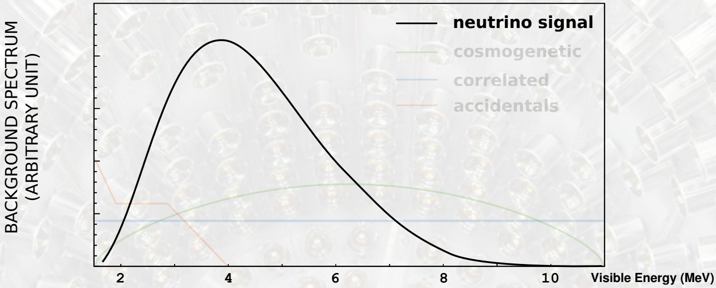


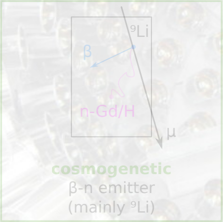
REACTOR NEUTRINO SPECTRUM

INTERACTION CROSS SECTION

DETECTED SPECTRUM

Background components





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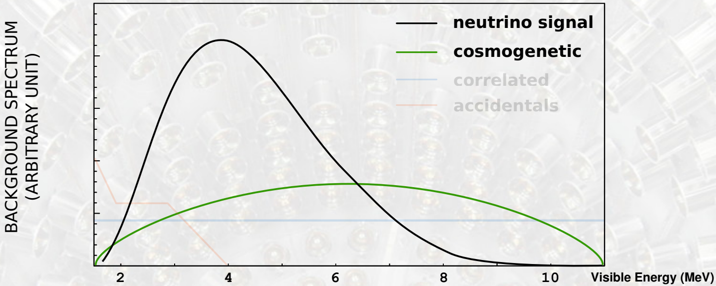
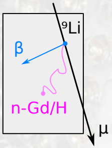


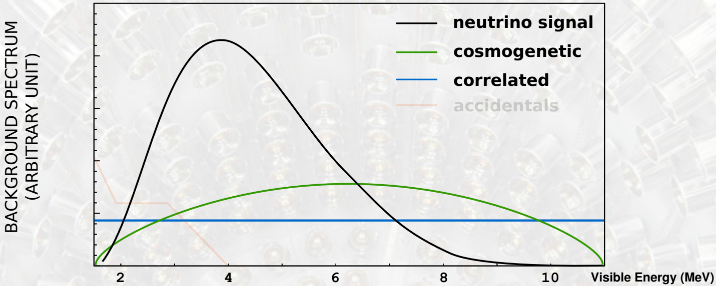


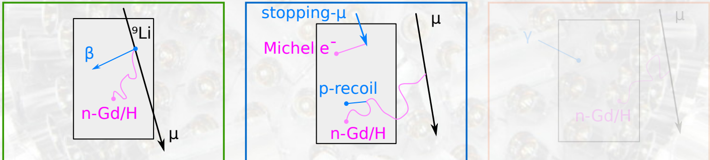
cosmogenetic
β-n emitter
(mainly ^{9}Li)

correlated
fast-neutrons,
stopping muons

accidentals
natural radioactivity
(^{208}Tl, ^{40}K, ...)

Background components





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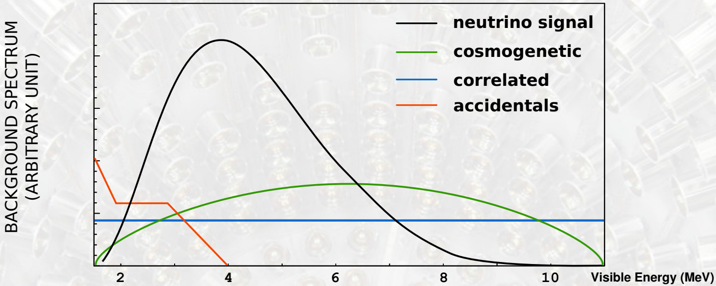

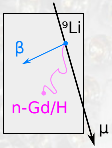

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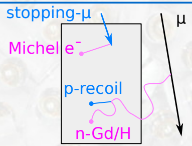

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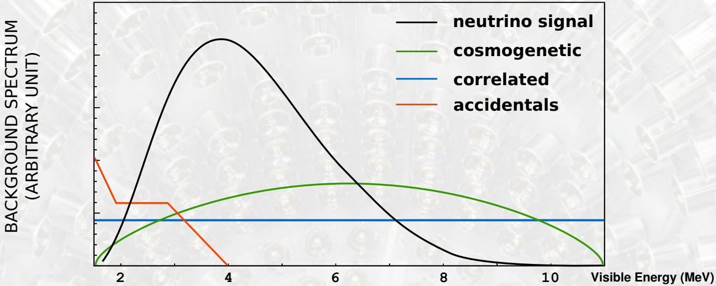

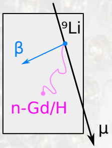

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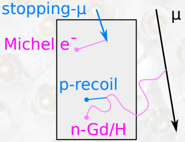

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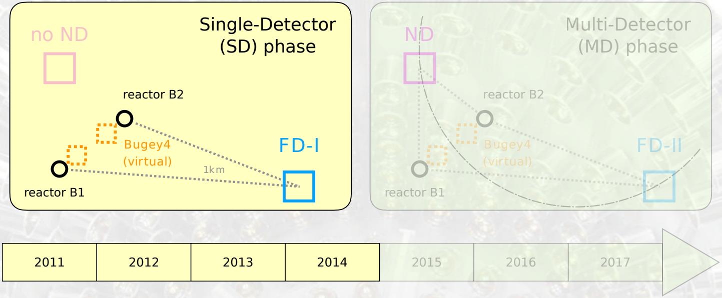
⇒ **rate+shape information (from data) are exploited in oscillation fit**

Double Chooz' Single-Detector phase



- SD phase with only far detector (FD-I)
- Bugey4 used as anchor of flux (1.4 % precision)

– indication of non-zero θ_{13} [Phys. Rev. Lett. 108 (2012) 131801]
– 1st n-H capture analysis [Phys. Lett. B723 (2013) 66-70]
– 1st reactor rate modulation analysis [Phys. Lett B735 (2014) 51-56]
– 1st publication on spectrum distortion [JHEP 1410 (2014) 86]

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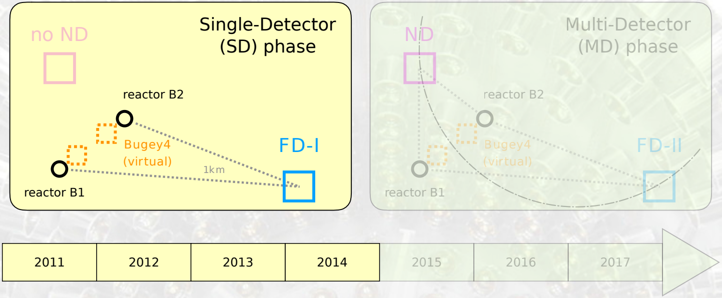

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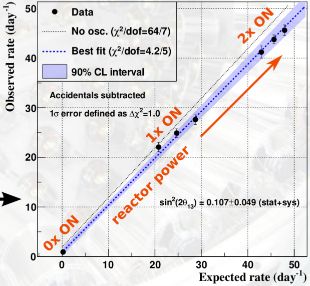
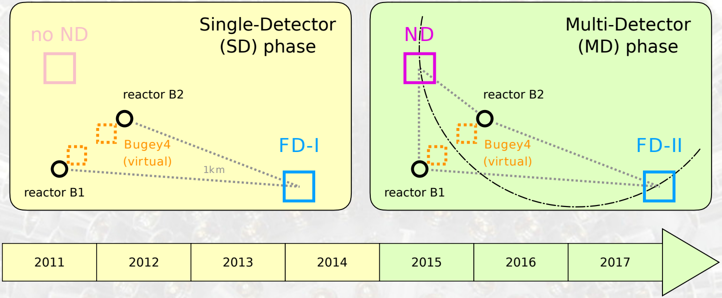
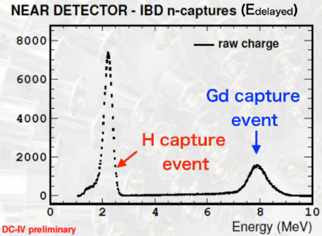


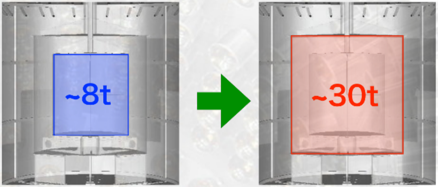
Double Chooz' Multiple-Detector phase



- MD phase with far detector (FD-II) and near detector (ND)
- **identical detectors** cancels correlated errors (ex: detection efficiency)
- **nearly iso-flux** configuration : flux error ~ 0.1 %

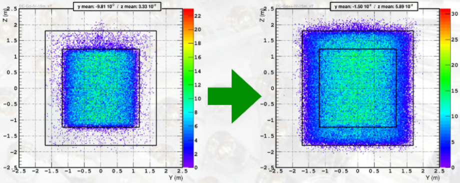
statistics is limiting factor for about 10 years @ Double Chooz
$\Rightarrow$ **new strategy: enlarge effective volume by Gd+H analysis**





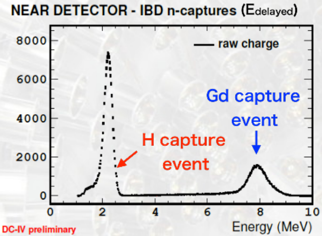
IBD rate	Gd analysis	Gd+H analysis
FD	$\sim$40 d^{-1}	$\sim$100 d^{-1}
ND	$\sim$300 d^{-1}	$\sim$800 d^{-1}

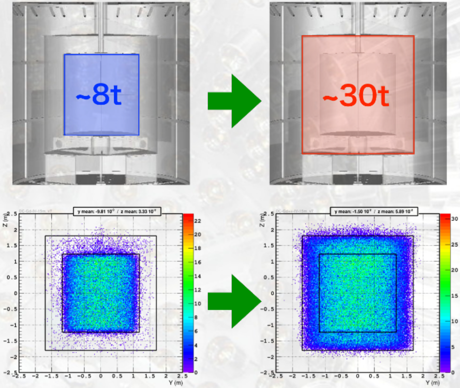
~2.5 times



Increased stats Gd+H

statistics is limiting factor for about 10 years @ Double Chooz
⇒ **new strategy: enlarge effective volume by Gd+H analysis**





IBD rate	Gd analysis	Gd+H analysis
FD	$\sim 40\ d^{-1}$	$\sim 100\ d^{-1}$
ND	$\sim 300\ d^{-1}$	$\sim 800\ d^{-1}$

~2.5 times

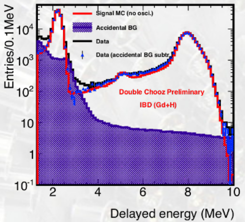
challenge of Gd+H analysis: accidental background, detection efficiency

Accidental background rejection with ANN

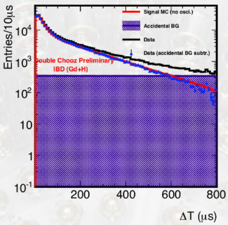
Artificial Neutral Network (ANN) based on 3 observables

before ANN

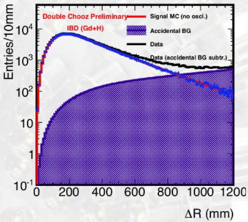
Delayed signal energy



Correlation time

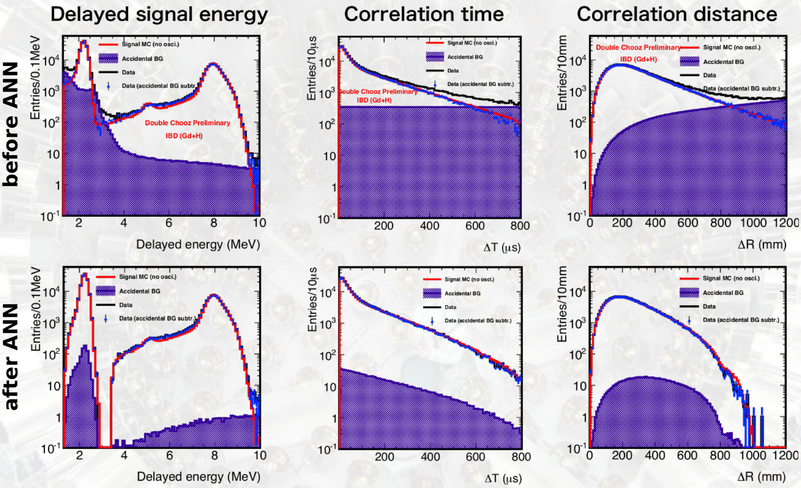


Correlation distance



Accidental background rejection with ANN

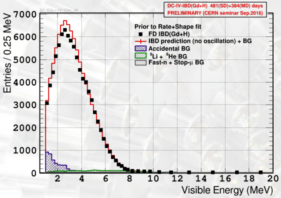
Artificial Neutral Network (ANN) based on 3 observables

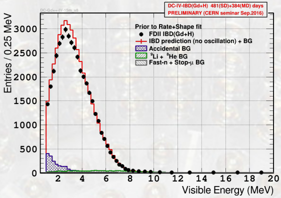


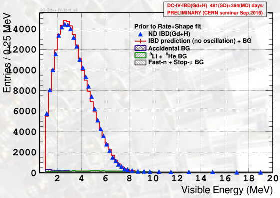
unprecedented accidentals reduction $\rightarrow$ negligible impact on θ_{13} measurement

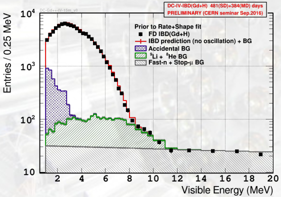
Prompt energy spectra

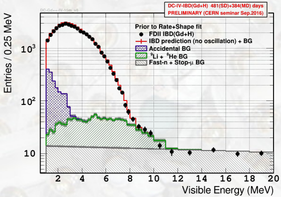
FD-I	FD-II	ND
∼ 40k IBD	∼ 40k IBD	∼ 200k IBD

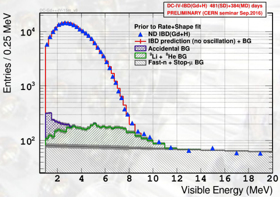








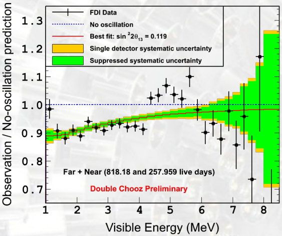




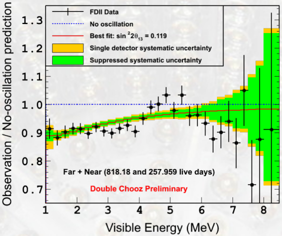
Fit results

simultaneous χ^2 fit DATA/MC for each data set

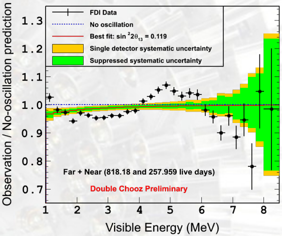
FD-I



FD-II



ND

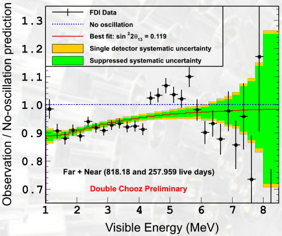


$$\sin^2 2\theta_{13} = 0.119 \pm 0.016 \quad (\chi^2/\text{NDF} = 236.2/114)$$

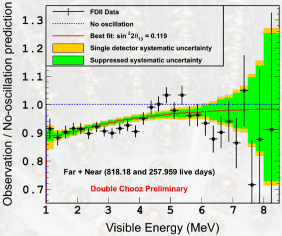
Fit results

simultaneous χ^2 fit DATA/MC for each data set

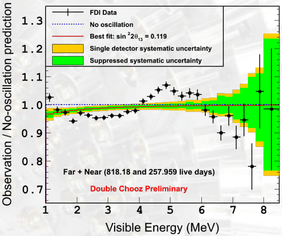
FD-I



FD-II



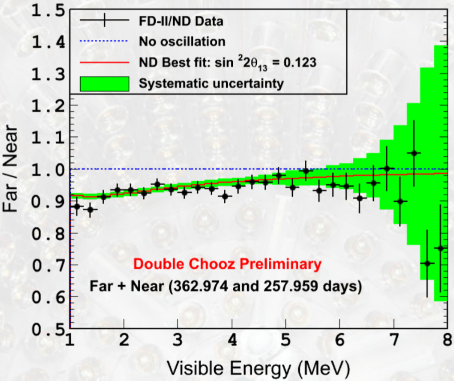
ND



$$\sin^2 2\theta_{13} = 0.119 \pm 0.016 \quad (\chi^2/\text{NDF} = 236.2/114)$$

background	FD estimation	FD fit output	ND estimation	ND fit output
cosmogenic (^{9}Li)	2.59 ± 0.61	2.55 ± 0.23	11.1 ± 3.0	14.4 ± 1.2
correlated (fast-n)	2.54 ± 0.10	2.51 ± 0.05	20.8 ± 0.4	20.9 ± 0.3

FD-II/ND data ratio



$$\sin^2 2\theta_{13} = 0.123 \pm 0.023 \quad (\chi^2/\mathrm{NDF} = 10.6/38)$$

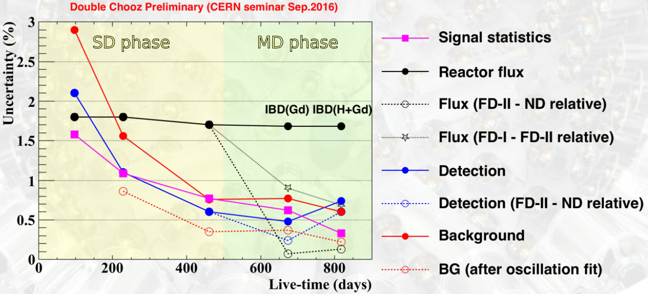
data/MC fit : $0.119 \pm 0.016 \quad (\chi^2/\mathrm{NDF} = 236.2/114)$

spectral distortion is well cancelled with data/data ratio

Conclusions and prospects

- SD phase (2011–2014) : reactor flux error dominant
- MD phase (2015–2018) : improved statistics (Gd+H) and flux error suppressed
- **current result: $\sin^2 2\theta_{13} = 0.119 \pm 0.016$** (latest Daya Bay: 0.084 ± 0.003)
- largest systematic from detection (proton number uncertainty)
  $\rightarrow$ work in progress to reach a precision ≤ 0.01

reactor θ_{13} will be key paramater to solve CP in lepton sector




THANK YOU
FOR YOUR
ATTENTION