Measurement of the neutrino mixing angle θ13 in the Double Chooz experiment

Diana Navas Nicolás

Taller de Altas Energías

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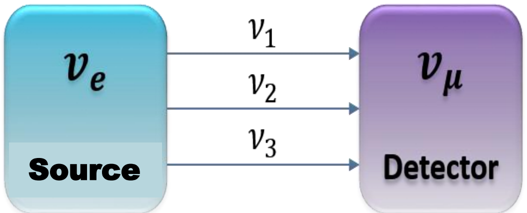
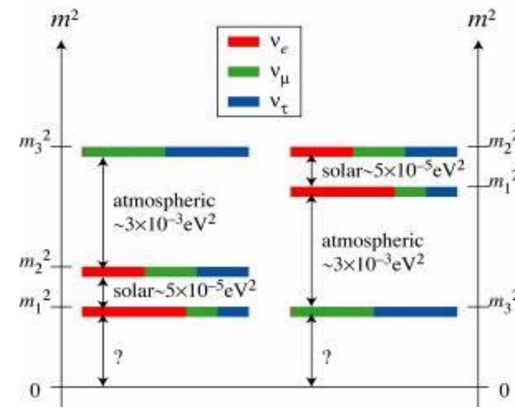
GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
EXCELENCIA MARÍA DE MAEZTU

Neutrino Oscillations



$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\,|\nu_i\rangle$$

mass ↑ PMNS Matrix ↑ flavor



$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & \sin\theta_{23} & \cos\theta_{23} \end{bmatrix} \begin{bmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{bmatrix} \begin{bmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Atmospheric ν Solar ν

Known

- $\sin^2 2\theta_{12} = 0.846 \pm 0.021$
- $\Delta m^2_{21} = (7.53 \pm 0.18)\cdot 10^{-5}\text{eV}^2$
- $\sin^2 2\theta_{23} = 0.999^{+0.001}_{-0.018}$
- $|\Delta m^2_{31}| = (2.43 \pm 0.06)\cdot 10^{-3}\text{eV}^2$

Unknown

- Δm^2_{23} sign
- CP δ violation

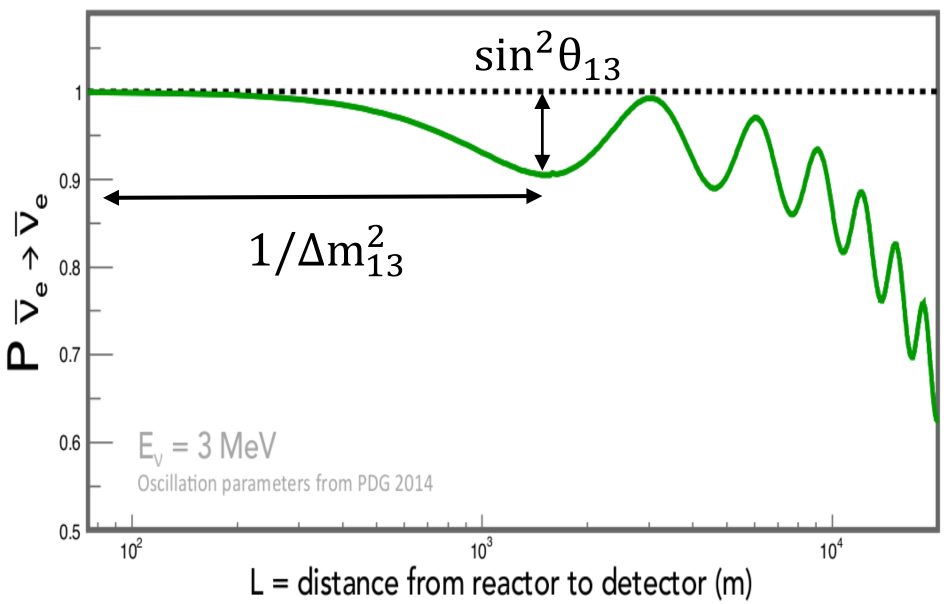
Double Chooz gave the first indication that $\theta_{13} \neq 0$

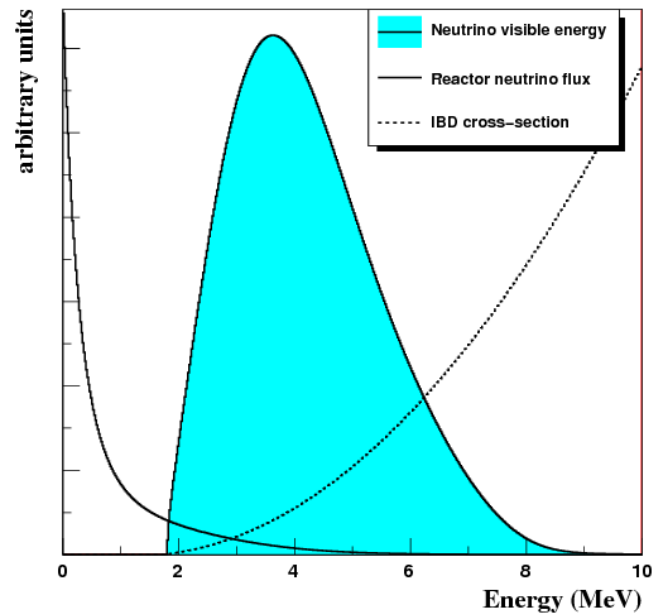
Known recently $\sin^2 2\theta_{13} = 0.084 \pm 0.005$

Nuclear Reactor Neutrinos

$\bar{\nu}_e$ disappearance is directly related with θ_{13}

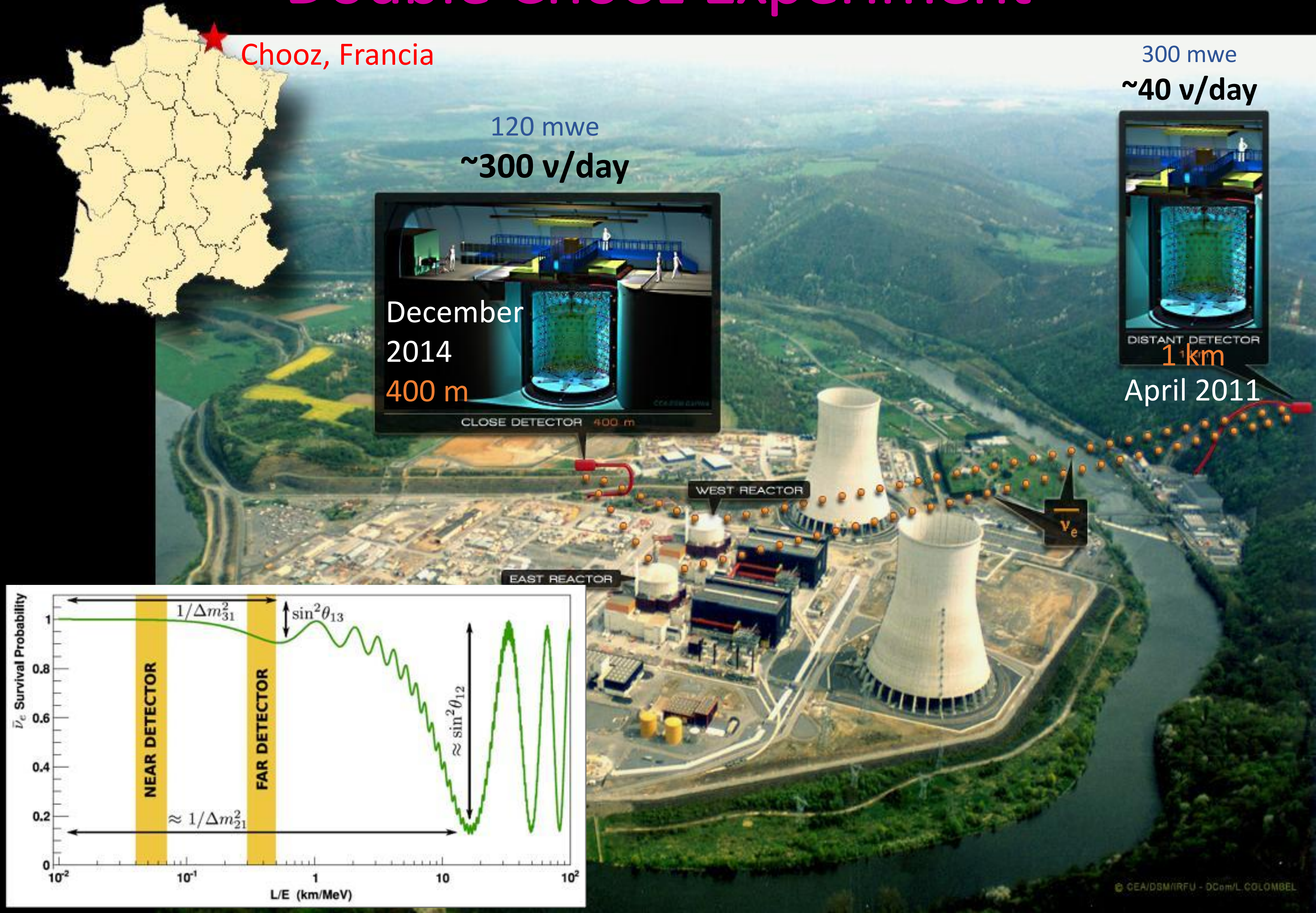
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\boldsymbol{\theta}_{13} \sin^2[1.27\Delta m^2_{13}(eV^2)L(m)/E_\nu(MeV)]$$



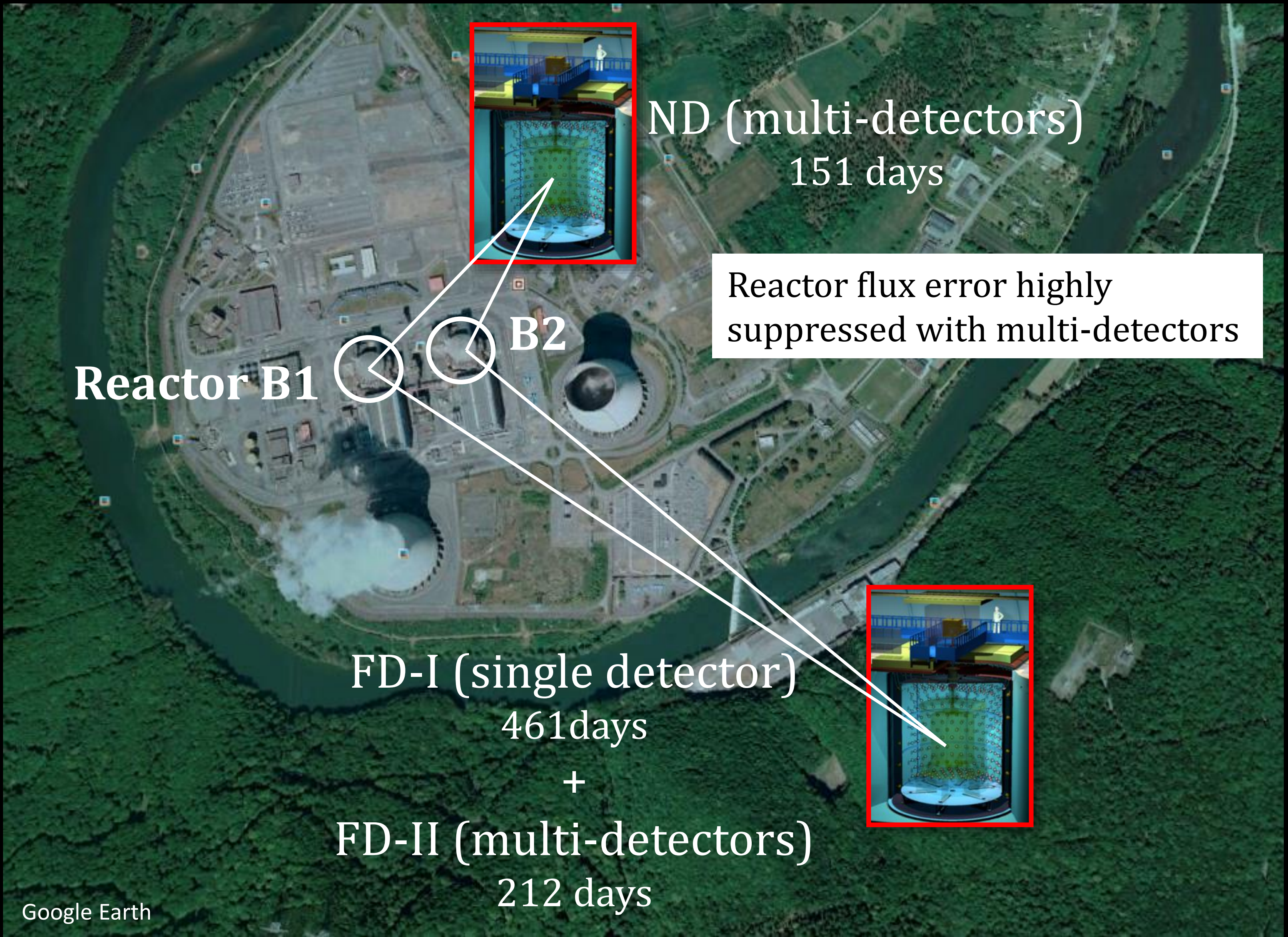


- Univocal determination of θ_{13}
  - No dependence with δ_{CP}
  - No dependence with mass hierarchy
- Reactor advantages
  - There is no matter effect
  - Pure $\bar{\nu}_e$ beam
  - High flux of low energy

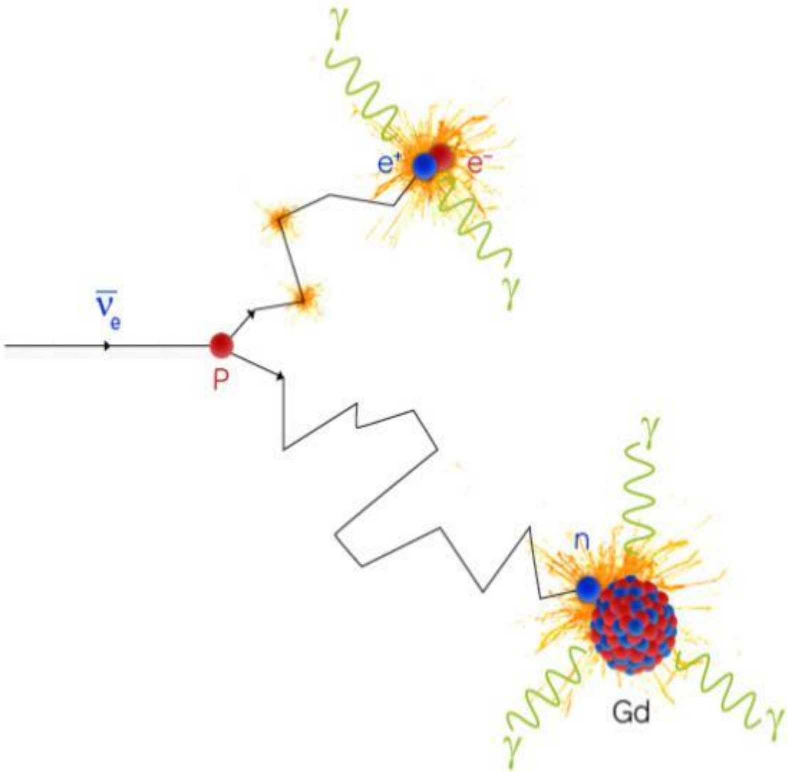
Double Chooz Experiment



Multi-detectors analysis



Inverse β decay



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

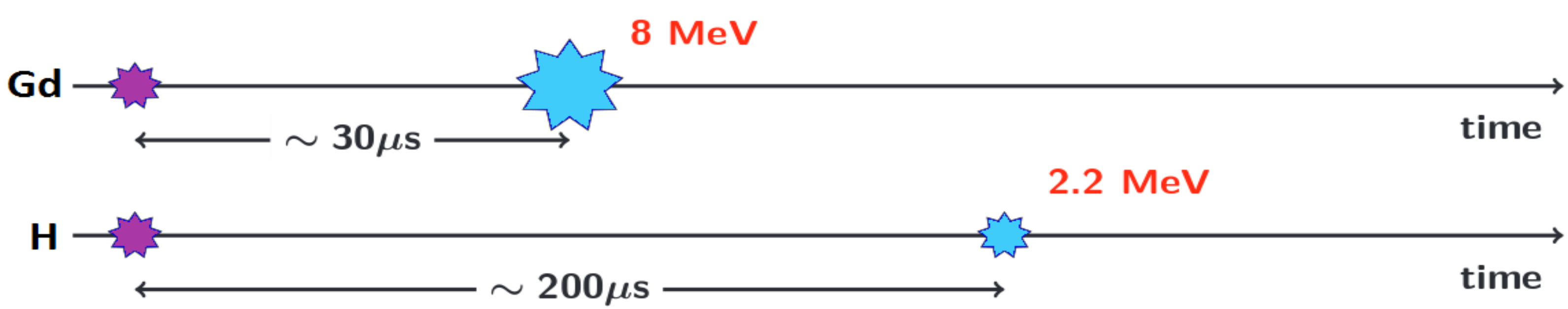
- **Prompt signal:** Energy loses + e^+ anihilation

$$E(e^+) \simeq E(\overline{\nu}_e) - 0.8\ \mathrm{MeV}$$

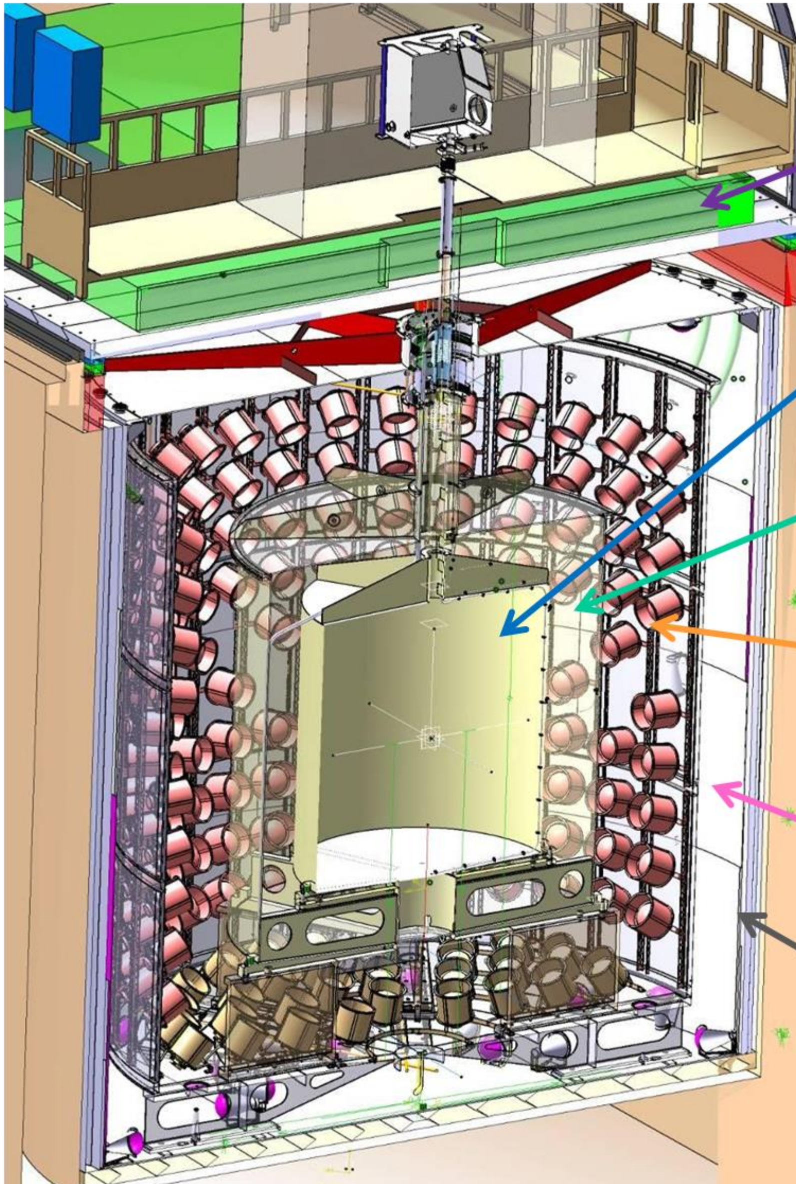
- **Delayed signal:** Neutron capture on Gadolium (Gd)

  8 MeV γ rays

- Alternaly, neutrón capture on Hidrogen (H) (~2.2 MeV)



Double Chooz detector



Outer Veto
Plastic scintillation strips

ν – Target
10.3 m^3 Gd-loaded liquid scintillator

’Y - Catcher
22.5 m^3 Gd-free liquid scintillator

Buffer
110 m^3 non-scintillating mineral oil layer. 390 10’’ PMTs

Inner Veto
90 m^3 thick liquid scintillator layer. 78 8’’ PMTs

Steel shield (FD)
Water shield (ND)

IBD candidates selection

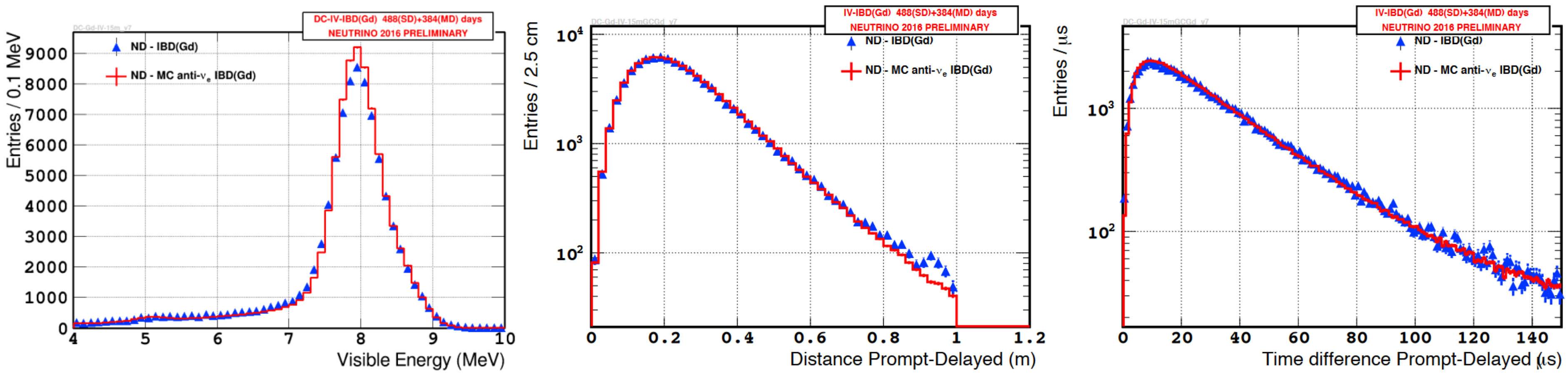
- **Preselection**

1. Valid trigger (E≥0.4 MeV)
2. Muon veto (Event is a muon if E_{IV} >16MeV o E_{ID} >20MeV)
3. Rejection of the events subsequent to a μ (Δt>1000 μs [Gd], Δt>1250 μs [H])
4. Rejection of light noise (LN) signals produced in the PMT basis

- **Selection**

	Análisis de Gd	Análisis de H
Isolation	[-200,600] μs	[-800,900] μs
Prompt energy	$0.5<E_{vis}<20$ MeV	$1.0<E_{vis}<20$ MeV
Delayed energy	$4.0<E_{vis}<10$ MeV	$1.3<E_{vis}<3$ MeV
Temporal coincidence	0.5<Δt<150 μs	0.5<Δt<800 μs
Distance coincidence	ΔR<100cm	ΔR<120cm
ANN	-	> -0.23

IBD selection



Good data:MC agreement!

Observed IBD rate: ~40 d^{-1} (FD) and ~300 d^{-1} (ND)

Remaining BG are:

- Accidental coincidence: e.g.) environmental γ + spallation neutrons n
- Fast neutron: n + p → recoil p + n
- Stopping muon: $\mu \rightarrow e + \nu + \nu$
- (β, n) emitter from spallation products : e.g.) $^{9}Li \rightarrow {}^{8}Be + e + \nu + n$

( ) : prompt (delayed) signal

Neutrino detection efficiency

To estimate the value of θ_{13} two different analyses are applied

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) = \begin{cases} \dfrac{N(E)^{XD}}{N(E)^{MC}} & \text{Single Detector} \\ \dfrac{N(E)^{FD}}{N(E)^{ND}} & \text{Multi Detector} \end{cases}$$

Being

$$N(E)^{Observed} = [\varepsilon_{tot} \times N(E)^{Exp} + N(E)^{BG}]$$

Observed neutrino candidates — **Neutrino detection efficiency** — **Expected neutrino flux** — **Background**

The detection efficiency is defined as

$$\varepsilon_{tot} = \varepsilon_{prompt} \times \boldsymbol{\varepsilon_{delay}} \times \varepsilon_{vetoes} \times \varepsilon_{proton\#}$$

$$\varepsilon_{delay} = \varepsilon_{n-captures} \times \varepsilon_{cut} \times \varepsilon_{spill}$$

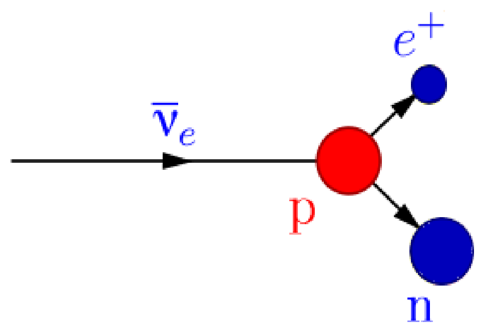
Efficiency correction ratios

$$c_\zeta = \frac{\varepsilon^{DATA\ FD}}{\varepsilon^{DATA\ ND}} \text{ or } \frac{\varepsilon^{DATA}}{\varepsilon^{MC}}$$

with ζ=each contribution of ε_{delay}

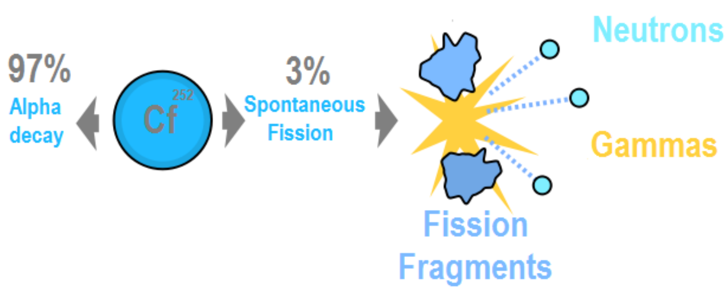
Neutron Sources

IBD neutrons



- **Homogeneously** distributed within the detector.
- Same neutron physics and event selection as the **oscillation signal**

Cf-source neutrons



- **Point-like fission source** emitting ~10 n/s. Deployed at **specific locations** within the detector
- Selected using delayed coincidence: prompt: fission γ; delayed: neutron captures

Gd-fraction

$\varepsilon_{\text{delay}} = \boldsymbol{\varepsilon_{\text{n-captures}}} \times \varepsilon_{\text{cut}} \times \varepsilon_{\text{spill}}$

Neutrons can be **captured on Gd, H or C nuclei .**

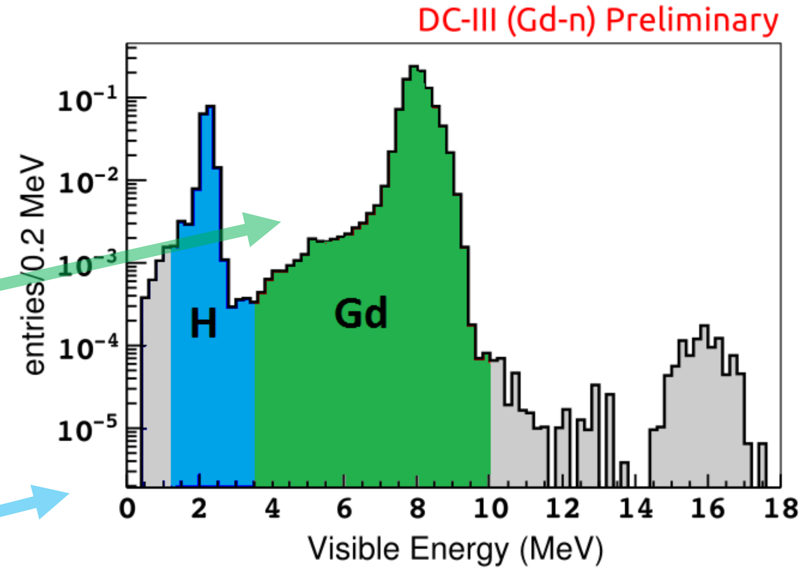
Number of Gd capture events

$$\varepsilon_{\text{n-captures}} = \frac{N_{Gd}}{N_{Gd} + N_{H}}$$

Number of H capture events

The $\varepsilon_{\text{n-captures}}$ allow to study the **fraction of n-captures on Gd** and to estimate the **concentration of Gd** in the νtarget liquid scintillator.

Gadolinium capture efficiency definition



$$N_{Gd} = N(3.5 < E_{vis} < 10 \text{ MeV})$$
$$N_{H} = N(1.3 < E_{vis} < 3.5 \text{ MeV})$$

Efficiency fractions at target center to be introduced in θ_{13}fit:

$$c_0 = \frac{\varepsilon_{\text{n-captures}}^{\text{DATA ND}}}{\varepsilon_{\text{n-captures}}^{\text{DATA FD}}} \text{ or } \frac{\varepsilon_{\text{n-captures}}^{\text{DATA}}}{\varepsilon_{\text{n-captures}}^{\text{MC}}}$$

Volume-wide detection (I)

$$\varepsilon_{\mathrm{delay}} = \varepsilon_{\mathrm{n-captures}} \times \boxed{\boldsymbol{\varepsilon_{\mathrm{cut}}}} \times \varepsilon_{\mathrm{spill}}$$

- The $\varepsilon_{\mathrm{cut}}$ studies the **impact of the neutrino selection criteria**.
- Efficiency definition including the selection cuts.
- Only non-neutron delayed events are background (BG).
  Accidental BG is subtracted using an off-time selection.

IBD cut efficiency definition

Number of IBD candidates

$$\varepsilon_{\mathrm{cut}} = \frac{\mathrm{N}(4 < \mathrm{E_n} < 10\ \mathrm{MeV}\ \cap 0.5 < \Delta\mathrm{t} < 150\ \mu\mathrm{s}\ \cap \Delta\mathrm{R} < 1\mathrm{m})}{\mathrm{N}(3.5 < \mathrm{E_n} < 10\ \mathrm{MeV}\ \cap 0.5 < \Delta\mathrm{t} < 800\ \mu\mathrm{s}\ \cap 0 < \Delta\mathrm{R} < 1.2\mathrm{m})}$$

Number of Gd capture events

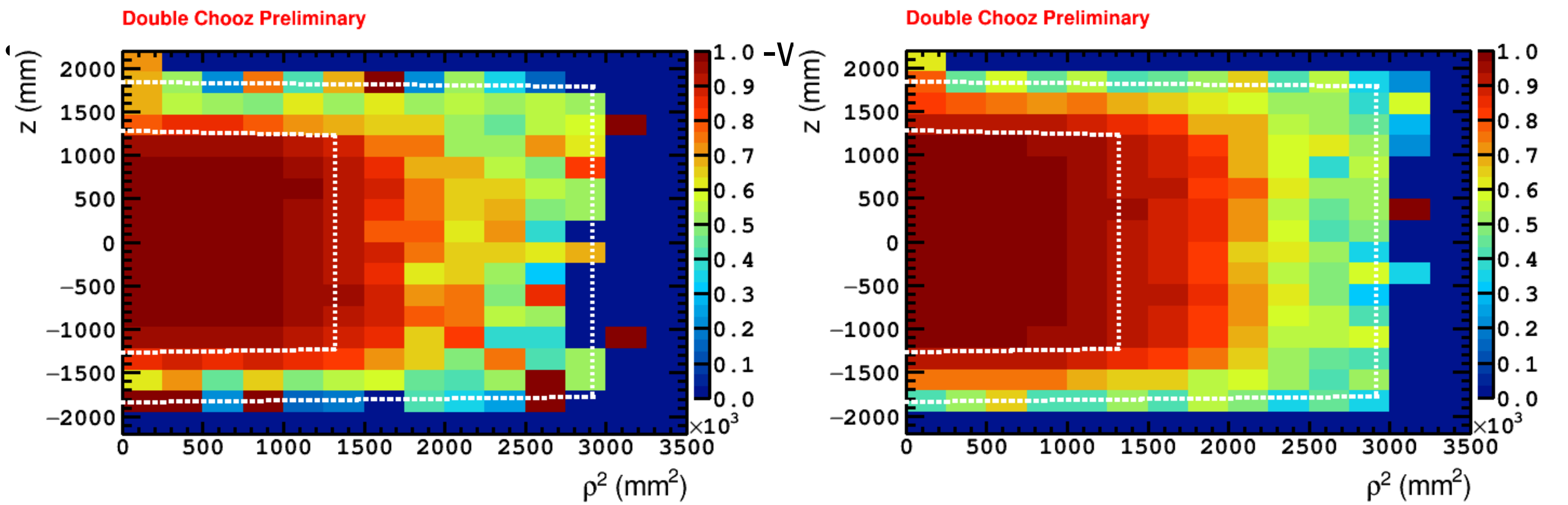
Candidate isolation cuts

$$c_v = \frac{\varepsilon_{\mathrm{cut}}{}^{\mathrm{DATA\ FD}}}{\varepsilon_{\mathrm{cut}}{}^{\mathrm{DATA\ ND}}}\ or\ \frac{\varepsilon_{\mathrm{cut}}{}^{\mathrm{DATA}}}{\varepsilon_{\mathrm{cut}}{}^{\mathrm{MC}}}$$

Efficiency fractions in the detector volume to be introduced in θ_{13} fit.

Volume-wide detection (II)

$$\varepsilon_{\text{delay}} = \varepsilon_{\text{n-captures}} \times \boxed{\boldsymbol{\varepsilon_{\text{cut}}}} \times \varepsilon_{\text{spill}}$$



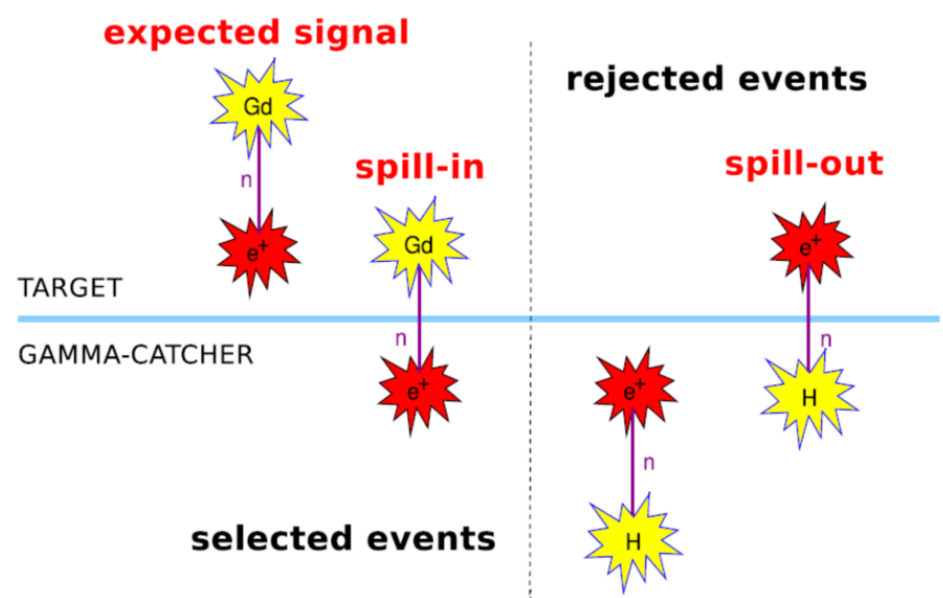
▲ Near detector efficiency map for 15 months of ND DATA (**Left** plot) and for a ND MC (**Right** plot). White dotted lines delimite target, gamma catcher and buffer volumes.

Neutron migration

$$\varepsilon_{\mathrm{delay}} = \varepsilon_{\mathrm{n-captures}} \times \varepsilon_{\mathrm{cut}} \times \boldsymbol{\varepsilon_{\mathrm{spill}}}$$

- ν**Target** constitutes the **fiducial volumen** in which the occurring IBD events are selected.
- Due to **neutron migrations** between ν**Target** and γ**-catcher** volumes, the **IBDs can be captured in either volumes**.

Estimated by the **comparison of two MC**: Double Chooz MC (Geant4 + custom thermalization based on an analytical model) vs Tripoli-4 (neutron transport code developed for reactor physics based on experimental nuclear data).



Spill-in

n from a IBD-event happening in the γcatcher is captured on the νtarget

Spill-out

n from IBD-event happening in the νtarget is captured in the γcatcher

Summary detection systematics

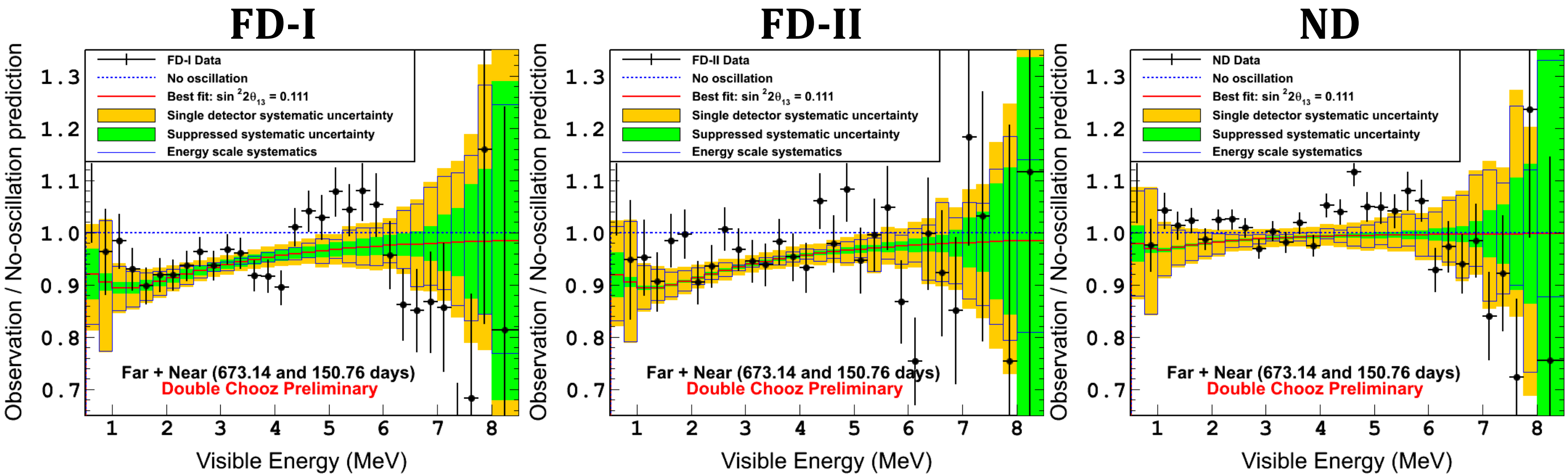
Double Chooz Preliminary

	FD-I	FD-II	ND
BG vetoes (%)	0.11 (0.11)	0.09 (0.09)	0.02 (0.02)
Gd fraction (%)	0.25 (0.14)	0.26 (0.15)	0.28 (0.19)
IBD selection (%)	0.21 (0.21)	0.16 (0.16)	0.07 (0.07)
Spill in/out (%)	0.27 (0)	0.27 (0)	0.27 (0)
Proton number (%)	0.30 (0)	0.30 (0)	0.30 (0)
Total (%)	**0.49 (0.26)**	**0.47 (0.22)**	**0.38 (0.15)**

Numbers in parentheses are uncorrelated uncertainties in multi-detectors analysis (FD-I, FD-II and ND)

Neutron detection efficiency uncertainty:
0.34% for FD-I (previous analysis FD-I 0.53%)
0.41% for FD-II and 0.40 % for ND

Multidetector fit results



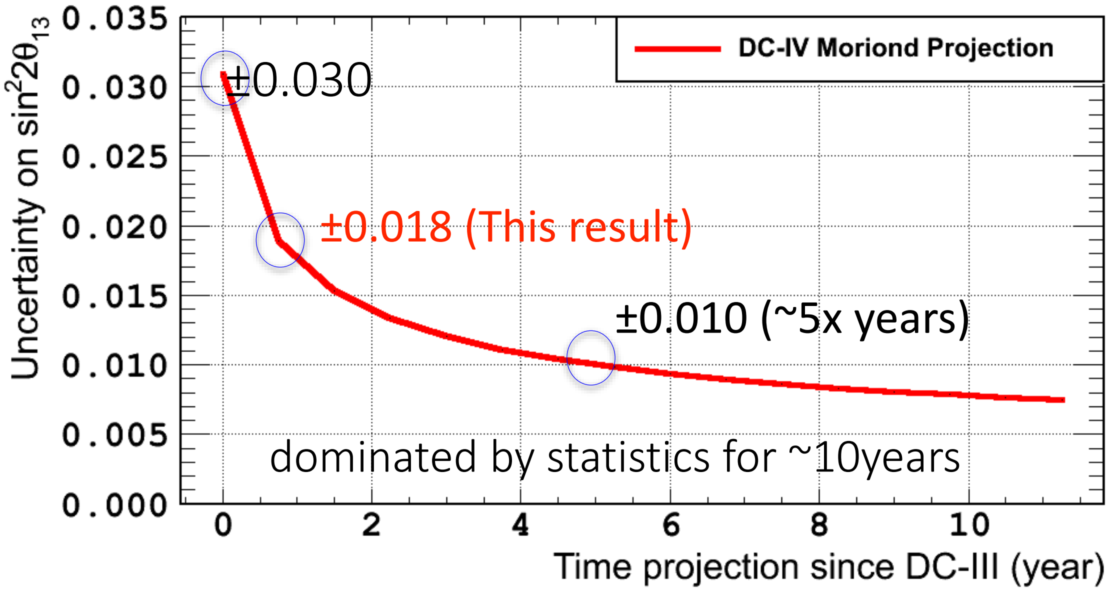
- Best-fit: $\mathbf{\sin^2 2\theta_{13} = 0.111 \pm 0.018}$ (stat.+syst.) (χ^2/dof = 128.8/120)
  - **Non-zero θ_{13} observation at 5.8σ C.L.**

Double Chooz Preliminary

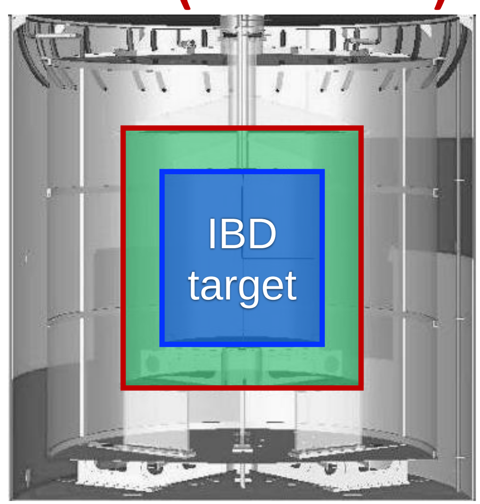
- Spectral distortion between 4 – 6 MeV.
  - Scales with reactor power.
  - Also observed in the Daya Bay and RENO experiments.
  - Unaccounted $\bar{\nu}_e$ component in the reactor flux model.
  - Out of the oscillation range. θ_{13} unaffected.

Single detector analysis:
$\sin^2(2\theta_{13}) = 0.090^{+0.032}_{-0.029}$

Expected Future Improvements



IBD (Gd) → IBD (Gd + H)



Current analysis (Gd-only) is **statistically limited**

→ **Inclusion of H-capture event (Gd+H analysis!)**

Improve statistics by almost factor 3!

Conclusions

- Double Chooz is taking data **with 2 detectors** since beginning of 2015
- Preliminary result: $\mathbf{sin^2(2\theta_{13}) = 0.111 \pm 0.018}$ (stat.+syst.) (Previous analysis: $\sin^2(2\theta_{13}) = 0.090^{+0.032}_{-0.029}$)
  - Reactor flux uncertainty strongly suppressed to < 0.1%
  - Other systematic uncertainties ≤ 0.5%
- Completely new analysis since Moriond 2016 **(Gd+H) in progress** ⇒ Update results **soon**
  - Improved statistics. Since March 2016: 5x more statistics in 3 months
  - New result with **improved sensitivity**!

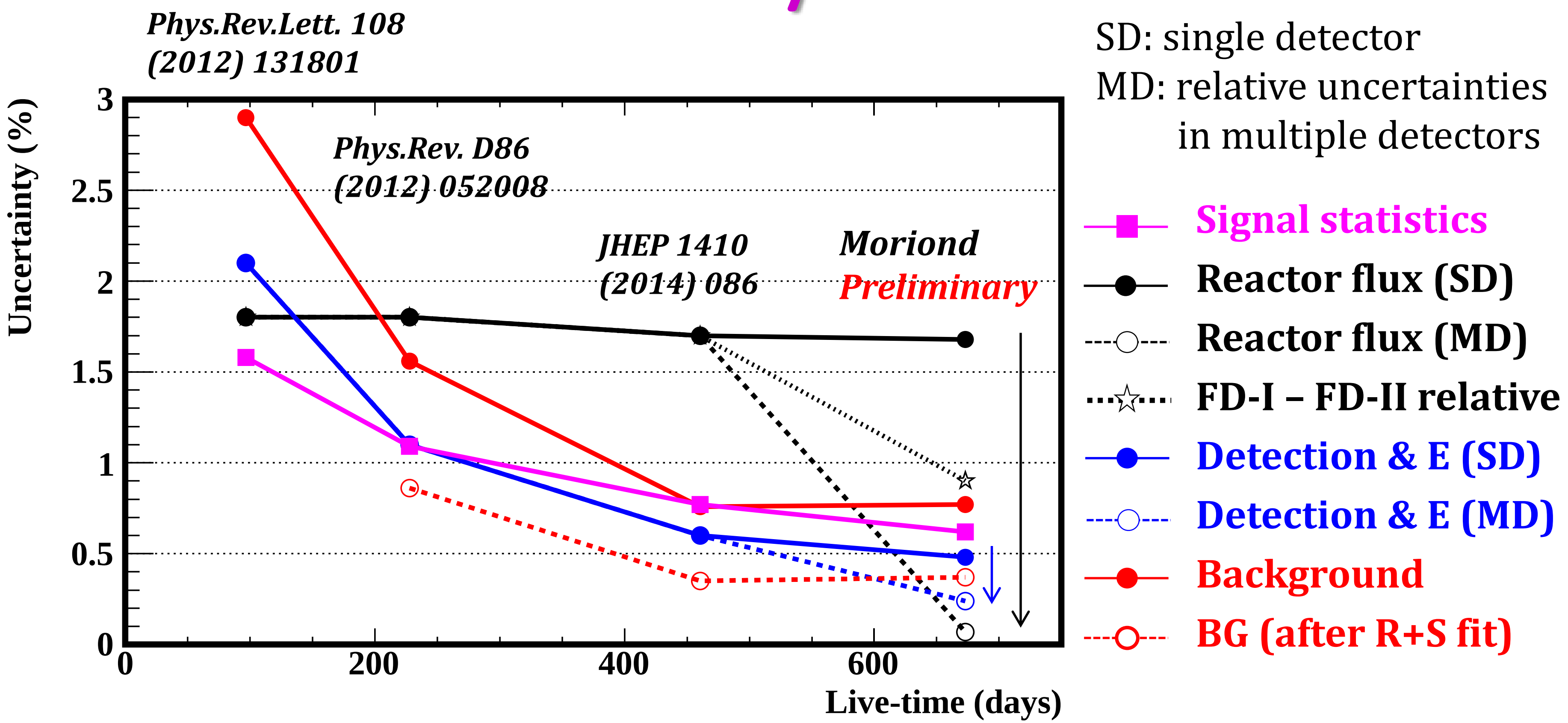
Thank you!

Back-up

Double Chooz Collaboration

Brazil	France	Germany	Japan	Russia	Spain	USA
CBPF UNICAMP UFABC	APC CEA/DSM/IRFU: SPP, SPhN SEDI, SIS SENAC CNRS/IN2P3: Subatech IPHC	EKU Tübingen MPIK Heidelberg RWTH Aachen TU München	Tohoku U. Tokyo Inst. Tech. Tokyo Metro. U. Niigata U. Kobe U. Tohoku Gakuin U. Hiroshima Inst. Tech.	INR RAS IPC RAS RRC Kurchatov	CIEMAT- Madrid	U. Alabama ANL,U. Chicago Columbia U. UC Davis Drexel U. IIT, KSU, MIT, U. Notre Dame U. Tennessee Virginia Tech

Uncertainties in multi-detectors analysis

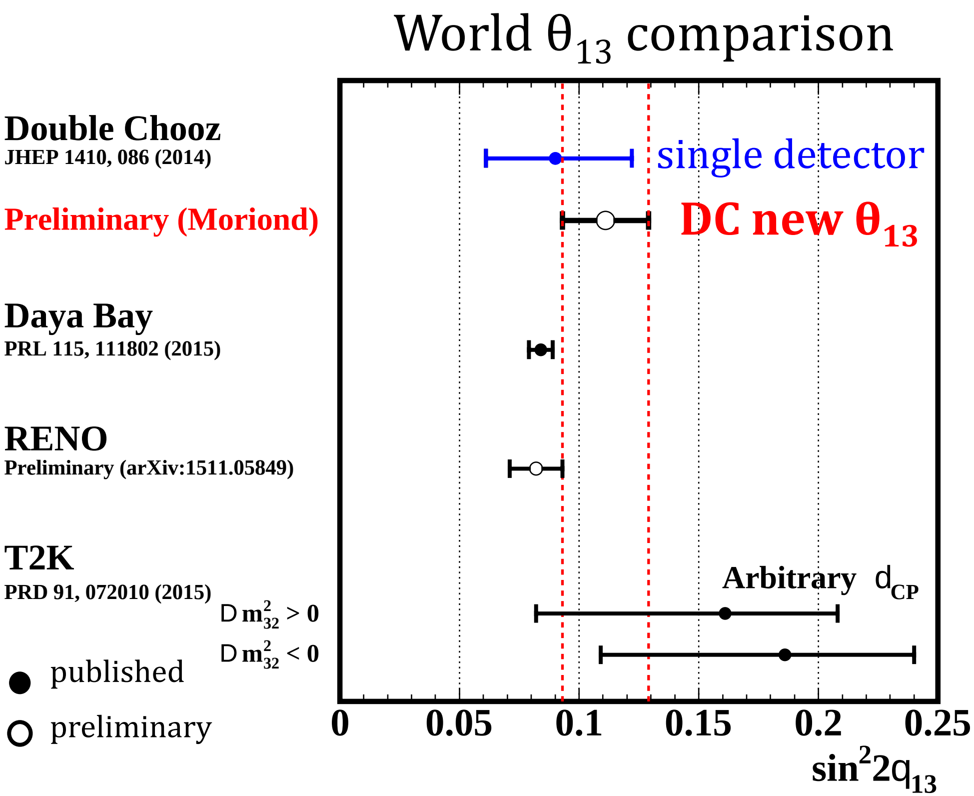


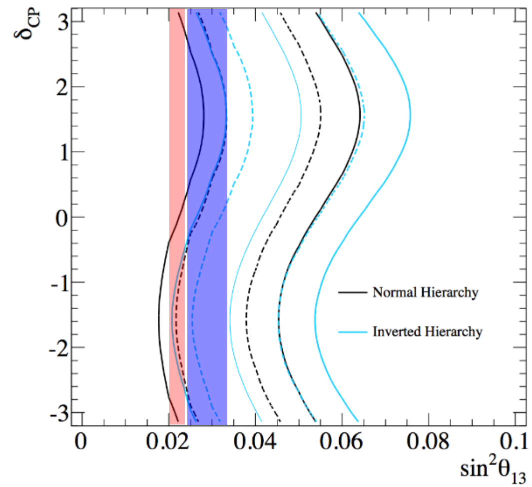
- Systematic errors suppressed with two detectors and in rate+shape fit

⇒ All systematic uncertainties below < 0.4% (after R+S fit)

- Current precision (9 months ND) is limited by the **statistical uncertainty**

Double Chooz θ13 in the world





Reactor vs. T2K

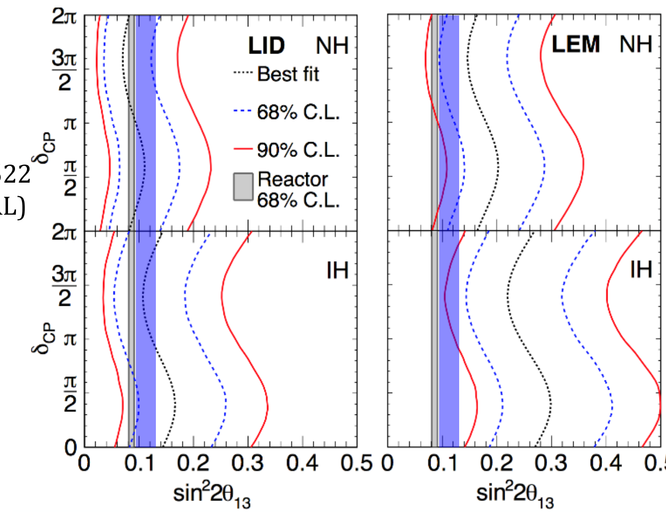
PRD91 072010 (2015)

Double Chooz 1σ

Daya Bay 1σ

Reactor vs. NOvA

arXivL1601.05522 (accepted by PRL)



- DC θ_{13} is higher than other reactor θ_{13} by ~30% (1.4σ wrt Daya Bay)
- Long baseline (T2K, NOvA) weakly favors higher θ_{13} than reactor average
- Reactor θ_{13} is key parameter to solve CP-violation and mass hierarchy