energie atomique • energies alternatives

θ_{13} at the reactor antineutrino experiment Double Chooz

24th Rencontres de Blois
Neutrinos parallel session

CEA/SPP - APC

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on behalf of the Double Chooz collaboration

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Contents of this talk

Mixing, oscillations, and θ_{13} at Double Chooz

- **Neutrinos mixing and oscillation parametrization**

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

flavor (interaction) — mixing matrix U_{PMNS} — **mass (propagation)**

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

measured
$\sin^2(2\theta_{23}) \sim 1$

(was) unknown!
Limit (from CHOOZ) :
$\sin^2 2\theta_{13} < 0.15$ at 90 %
C.L. for $\Delta m_{31}^2 = 2.5\ 10^{-3}\ eV^2$

measured
$\sin^2(2\theta_{12}) \sim 0.8$

- **Why measuring θ_{13}?**
  - Fundamental unknown physics parameter
  - Necessary step before the search for CP violation in the leptonic sector (δ_{CP} scaled by $\sin^2 2\theta_{13}$)

Electron antineutrino disappearance at reactor

- **Source:**
  - > $\bar{\nu}_e$ from β-decay of fission products in Chooz B reactors, 2x4.25 GW_{th}
  - > **Pure, intense** and **MeV**
- **Disappearance experiment**
  - > **Survival probability:**

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \sim 1 - \sin^2(2\theta_{13}) \sin^2(1.27\, \Delta m_{31}^2\, L/E) - \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(1.27\, \Delta m_{21}^2\, L/E)$$

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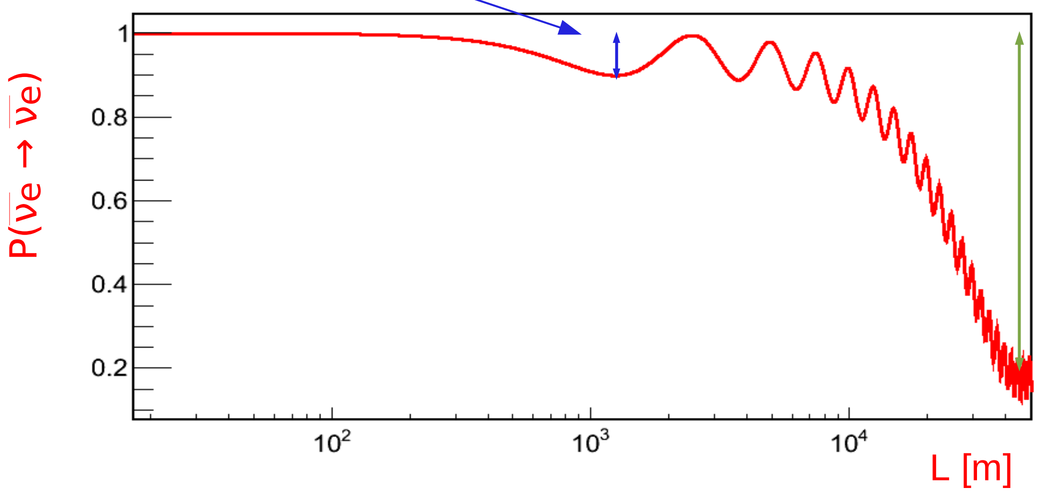


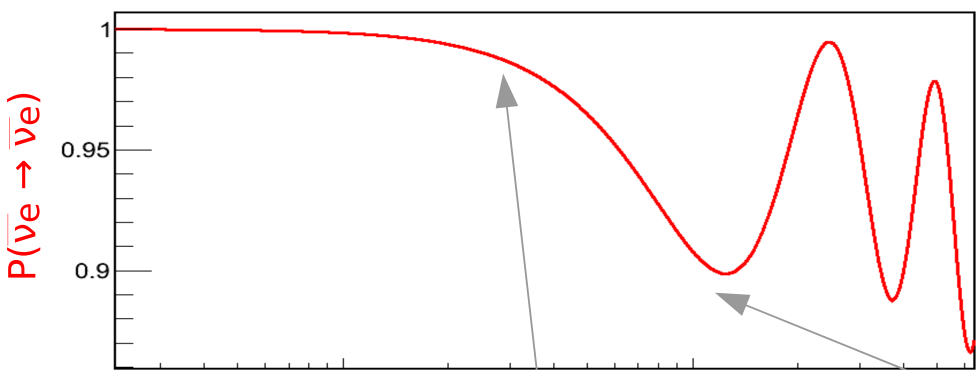
with:
- $\sin^2(2\theta_{13}) = 0.1$
- $\sin^2(2\theta_{12}) = 0.8$
- $\Delta m_{31}^2 = 2.5\ 10^{-3}\ eV^2$
- $\Delta m_{21}^2 = 8\ 10^{-5}\ eV^2$
- $E_\nu = 3$ MeV

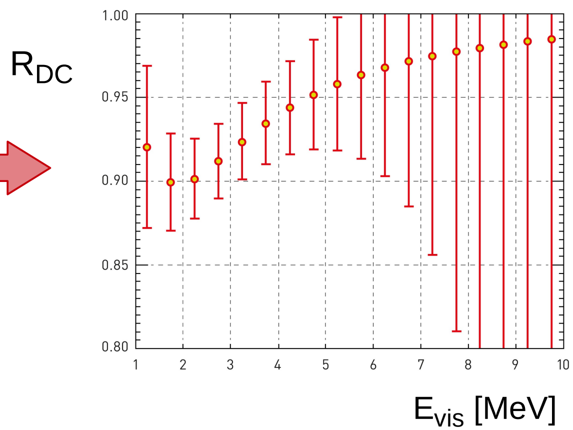
- Choice of L/E: **clean measurement of one parameter, $\sin^2 2\theta_{13}$**

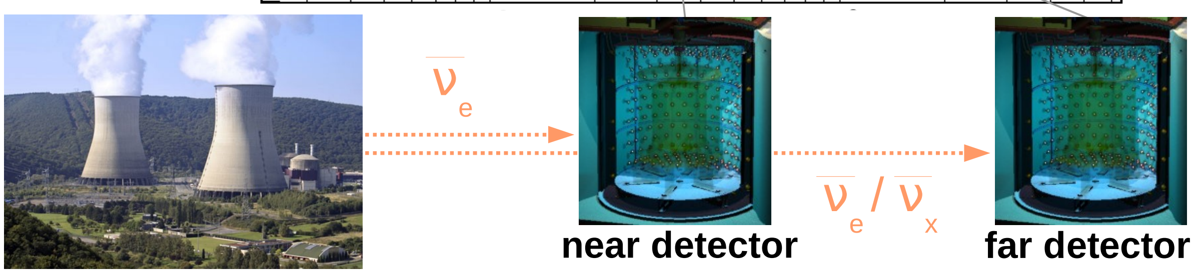
→ **Simplified survival probability:** $P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \sim 1 - \sin^2(2\theta_{13}) \sin^2(1.27\, \Delta m_{31}^2\, L/E)$

From CHOOZ to Double Chooz

- Former experiment **CHOOZ** limited by stat. and syst.:
  R_C = 1.01 ± 2.8 % (stat) ± 2.7 % (syst) = $N_{\nu\ obs}/N_{\nu\ exp\ w/o\ osc}$ (≠ 1 if osc)
- **Double Chooz concept:**
  - **Relative** measurement btw **2 identical detectors**
    (cancel systematic uncertainties on: ν flux, detector response, proton content)
  - **Buffer layer** to significantly reduce γ ray and neutron backgrounds
  - **Bigger target** volumes, **longer data taking**
    (work on liquid scintillator stability and material compatibility)





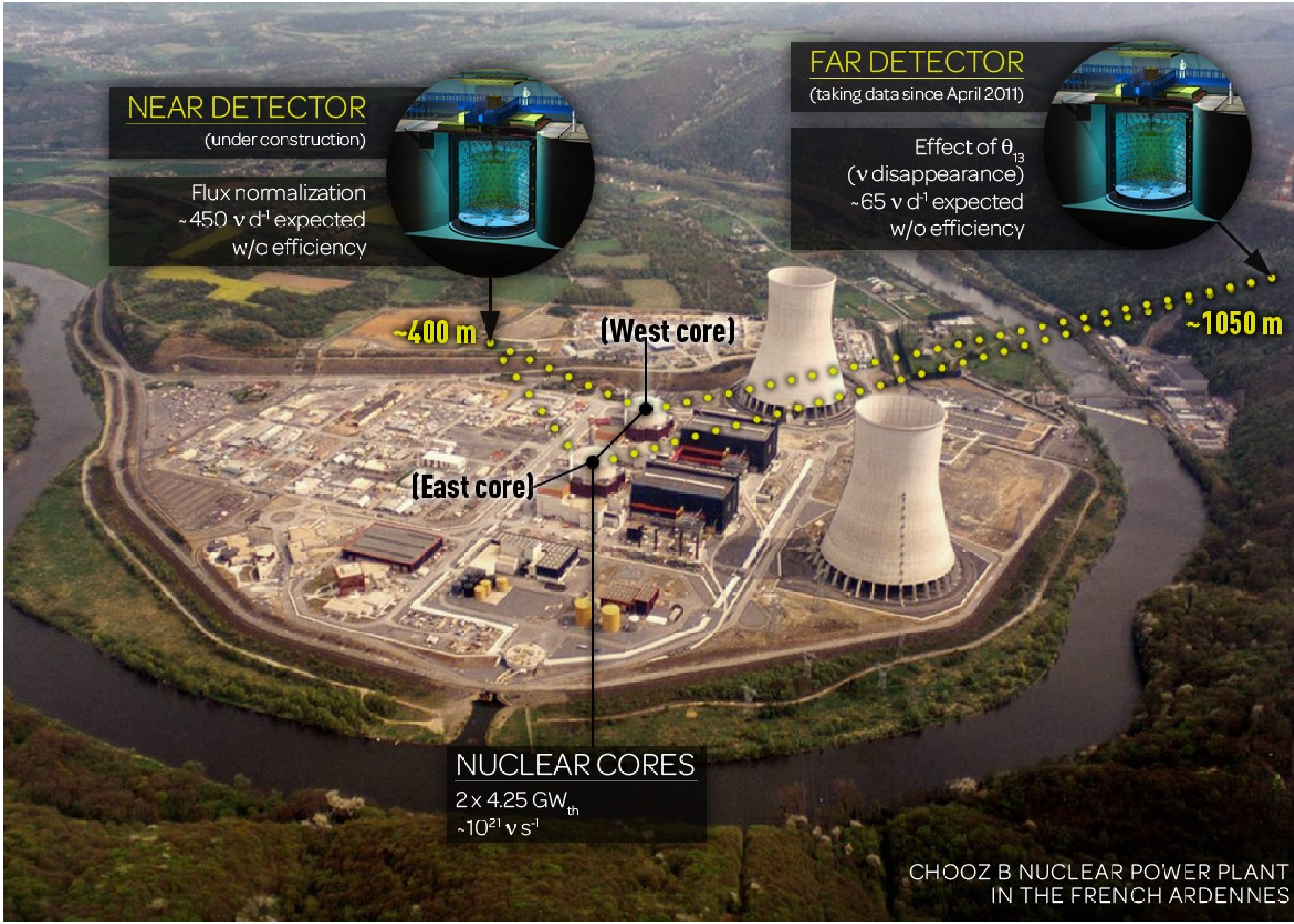


near detector ~ 400 m

far detector ~ 1,050 m

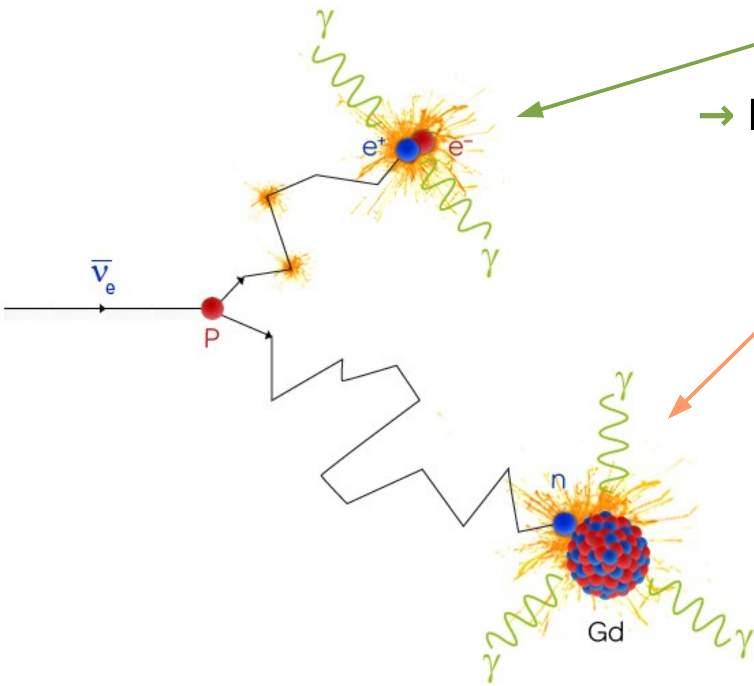
→ 0.5 % (stat) & 0.6 % (syst)

Experimental site



The Double Chooz detector

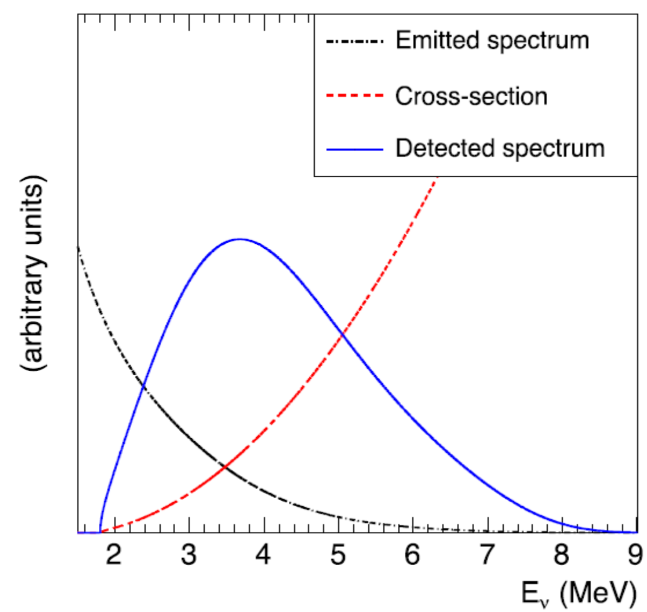
- **Inverse β-decay** in scintillator: $\bar{\nu}_e + p \rightarrow n + e^+$ (E_{thres} = 1.8 MeV)
  (~20% PXE, 80% dodecane, 0.1% dissolved Gd + wavelength shifters)



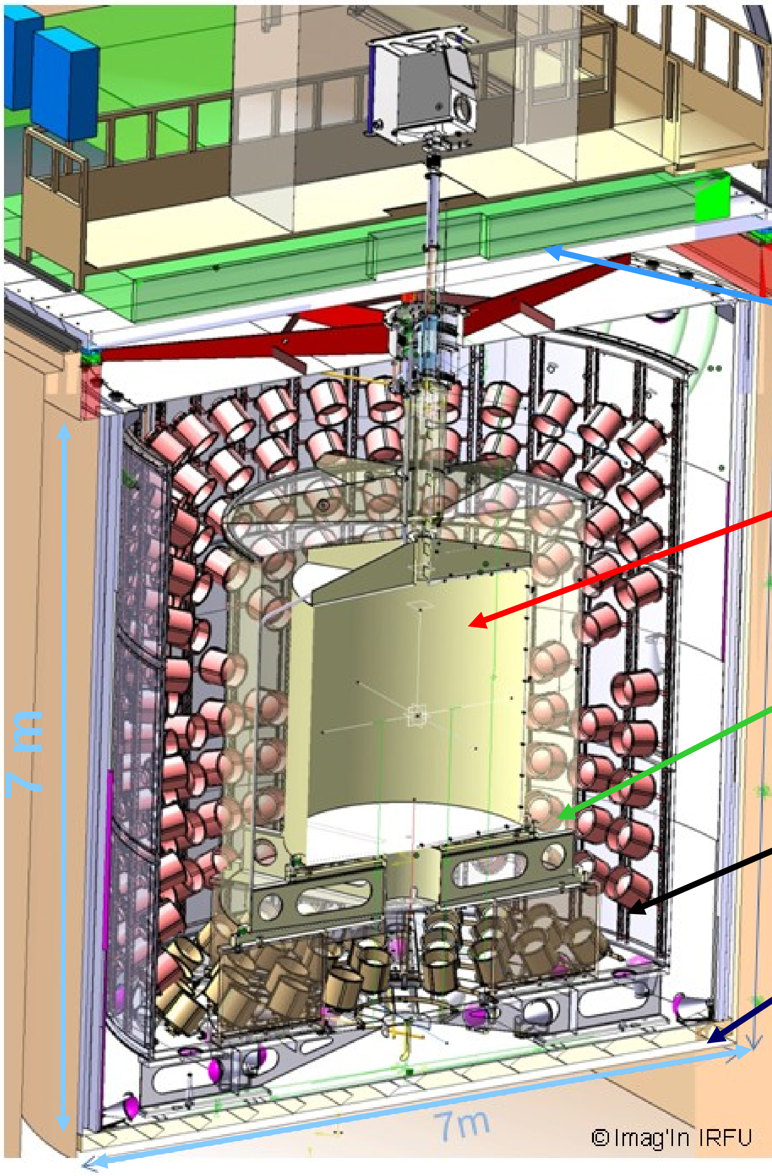
Prompt signal ~ [1-8] MeV = e^+ energy loss + e^+e^- annihilation

$\rightarrow E_{vis} = E_{e+} + m_e \sim E_{\nu_e} - \Delta + m_e$

Delayed signal ~ 8 MeV = n-capture on Gd → cascade γ



→ Correlated signals (time and space)
ΔT ~ 30 µs and **ΔR < 1 m**
seen by photomultipliers (PMT)



Design:

- Neutrinos detection
- Protection against backgrounds (internal and external)

Outer Veto: 82 m² of 400 mm thick plastic scintillator strips

ν-Target: 10.3 m³ liquid scintillator doped at 0.1 % in Gd, in a 8 mm thick acrylic vessel

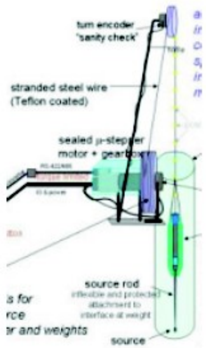
γ-catcher: 22.3 m³ liquid scintillator in a 12 mm thick acrylic vessel

Buffer: 110 m³ mineral oil in a 3 mm stainless steel vessel, seen by 390 PMT

Inner Veto + steel shielding: 90 m³ of liquid scintillator, seen by 80 PMT

Calibration devices

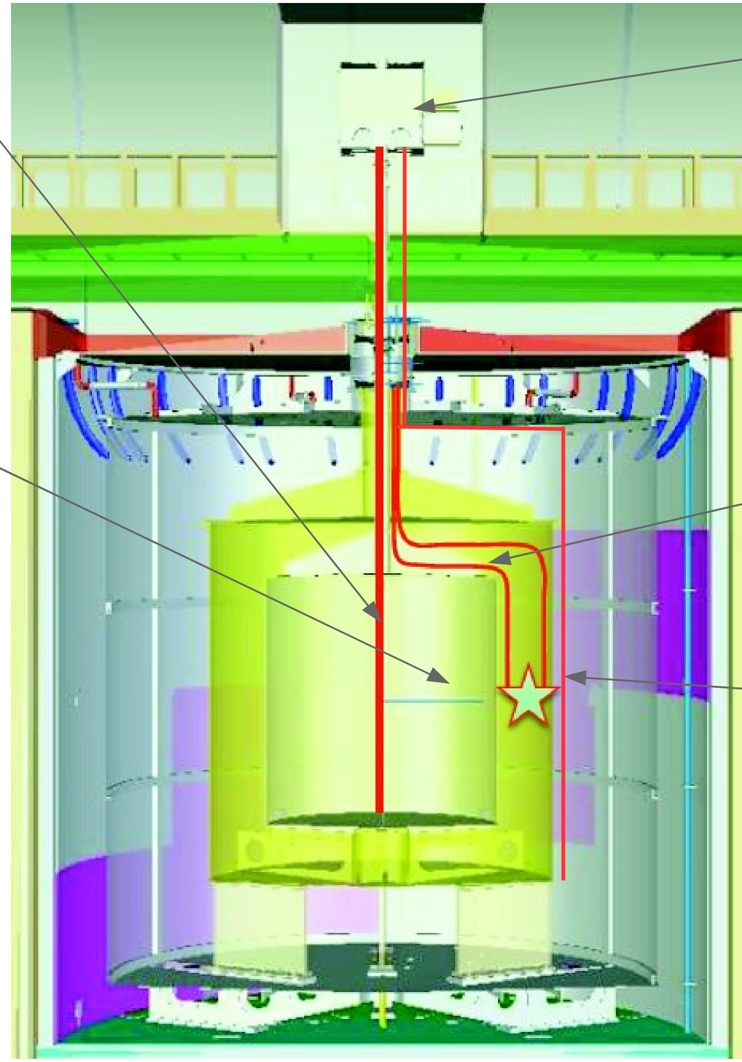
Z-axis system



+ articulated arm
(not installed yet)

+ Lasers
(UV and green)

+ Light injectors
(inner detector + inner veto)



Glove Box

Tube for radioactive sources (in GC)

Tube for radioactive sources (in Buffer)

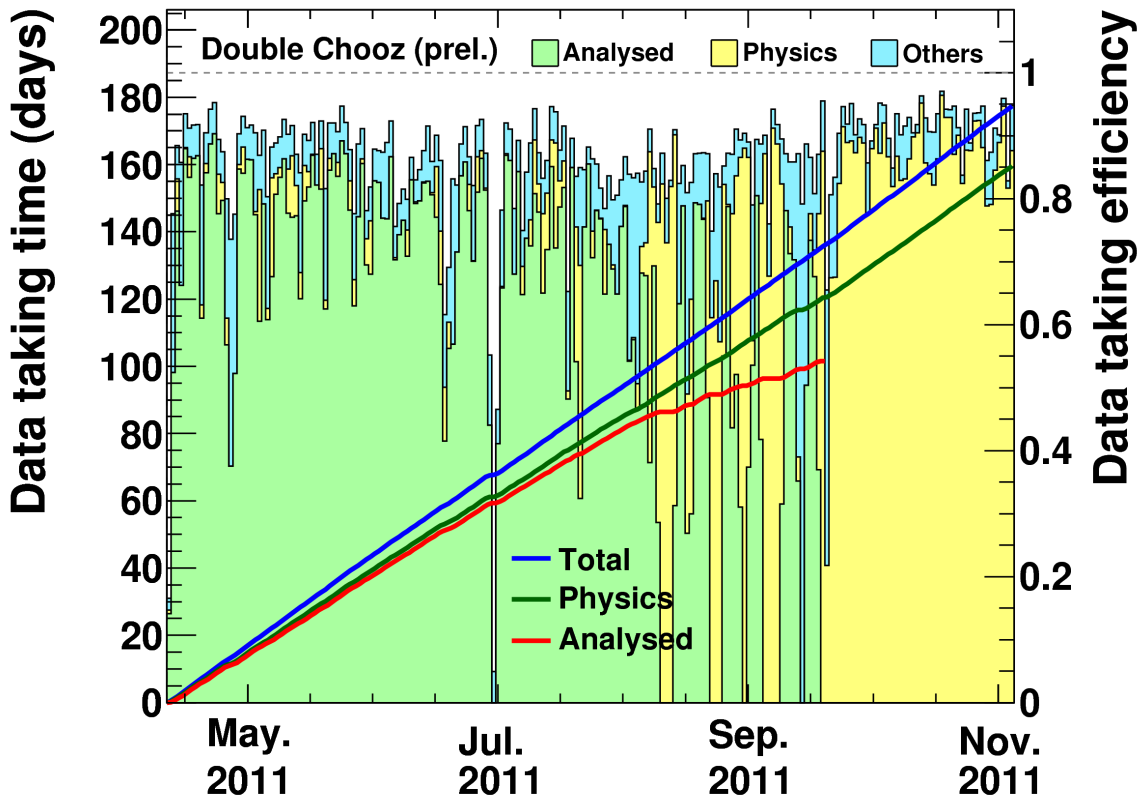
(radioactive sources ^{68}Ge, ^{137}Cs, ^{60}Co, ^{252}Cf)

Double Chooz data analysis
Neutrino search

Data Taking Efficiency

- Analysis performed on **102 days of physics** runs, including 16 days of one reactor OFF (+ 1 day of two reactors OFF), with **far detector only**

- Average data taking efficiency
  - in total: 86.2 %
  - in physics: 77.5 %



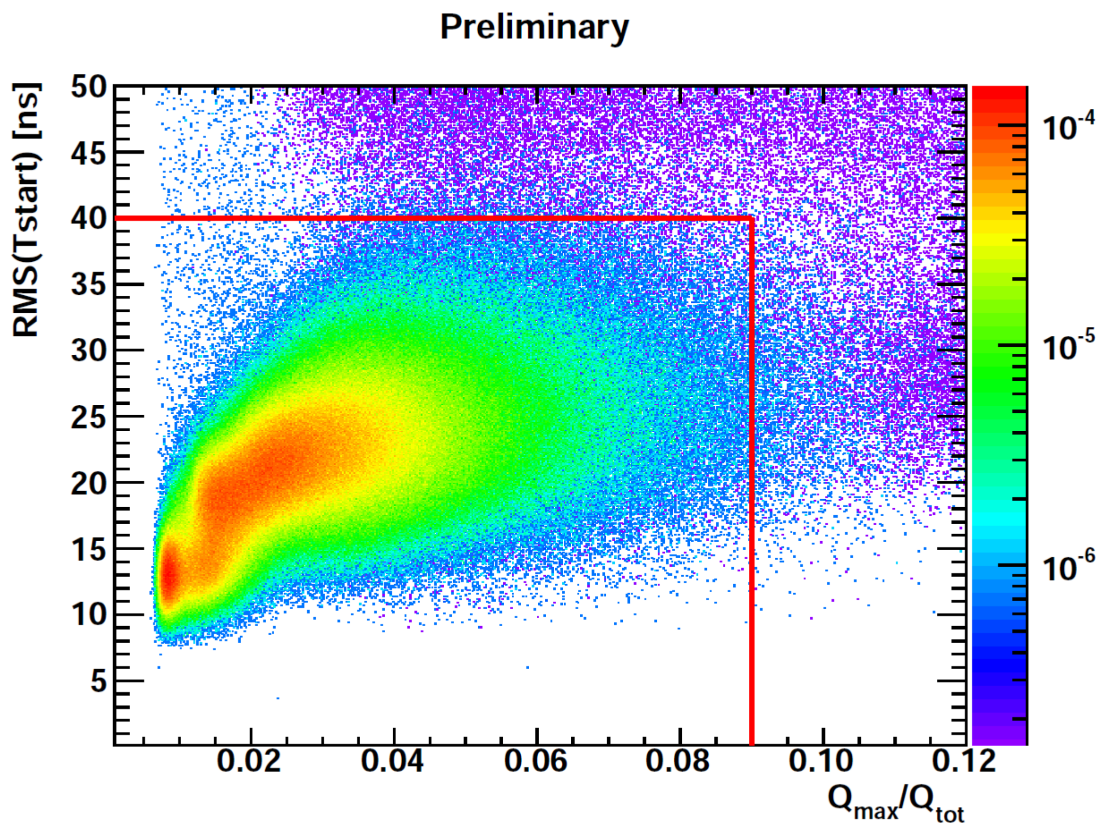
- Called "**Light-Noise**"
- **Parasitic light** emitted by some PMT bases
  - > 15 were turned off
  - > Offline rejection cuts based on anisotropic light collection

- PMT sees its own light
  → Qmax/Qtot cut

(ν signals should be homogeneously spread across the PMTs)

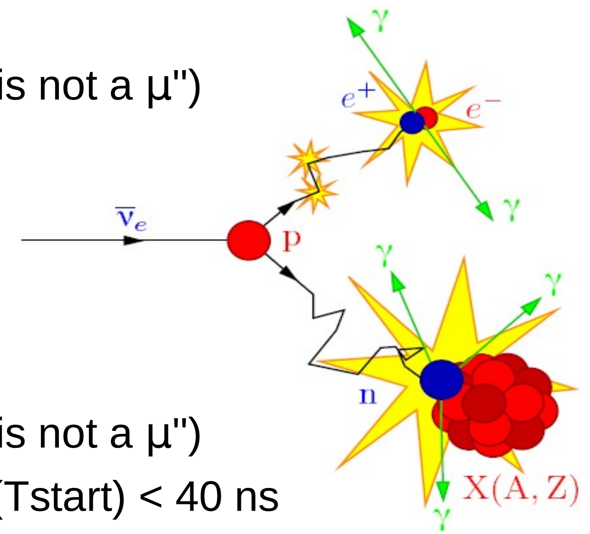
- Large dispersion of start time of PMT signals
  → RMS(Tstart) cut

(ν signals should have small spread in arrival times)



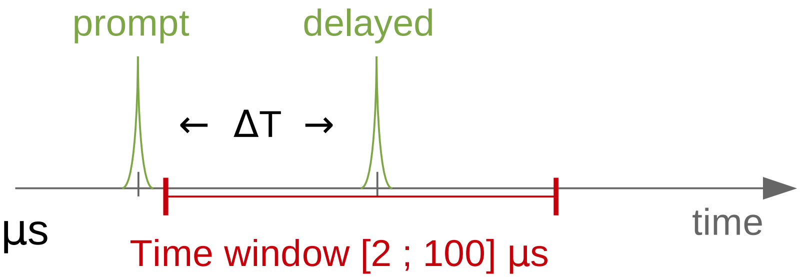
Neutrino search – Analysis cuts

- **Prompt event:**
  - > No Inner Veto Energy Deposition (*i.e.*, "event is not a μ")
  - > Light-Noise cuts:
    Qmax/Qtot < 0.09 and RMS(Tstart) < 40 ns
  - > Energy in [0.7 ; 12] MeV



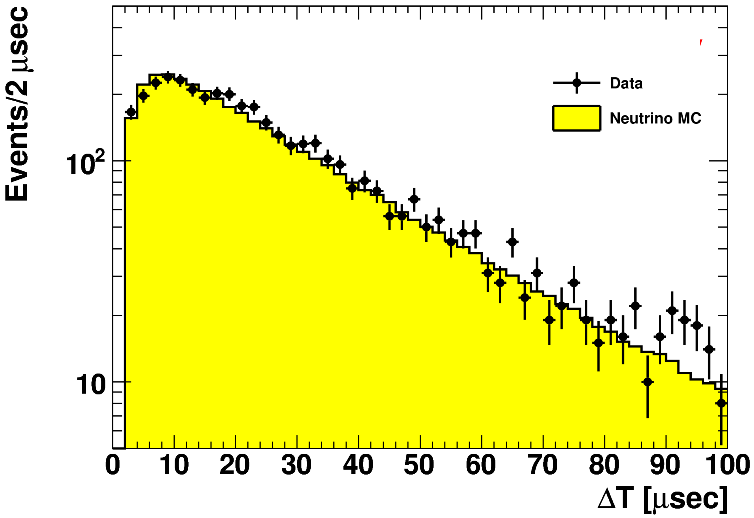
- **Delayed event:**
  - > No Inner Veto Energy Deposition (*i.e.*, "event is not a μ")
  - > Light-Noise cuts: Qmax/Qtot < 0.06 and RMS(Tstart) < 40 ns
  - > Energy in [6 ; 12] MeV

- **Coincidence:**
  - > No space coincidence cut applied
  - > Time coincidence: 2 μs < ΔT < 100 μs

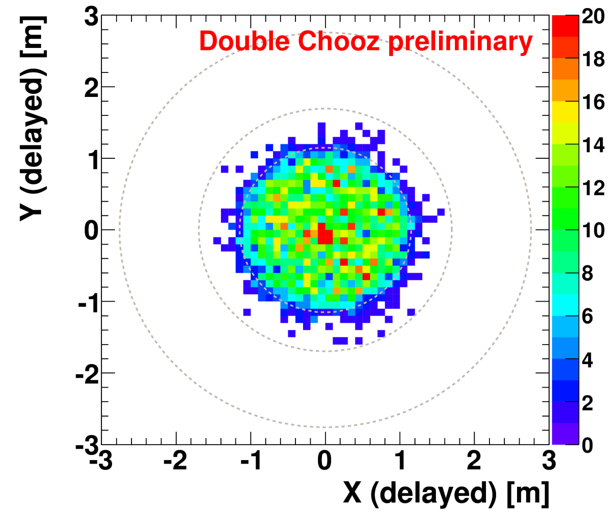


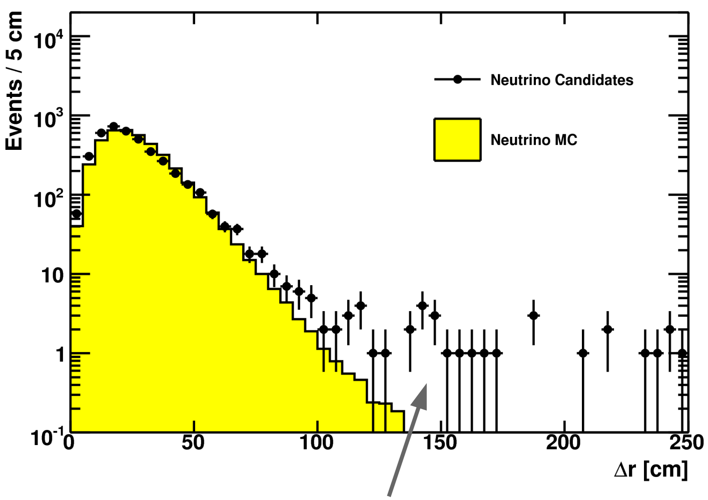
- **Multiplicity:**
  - > No trigger (> 0.5 MeV, no light-noise, no μ) in the 100 μs preceding the prompt
  - > Time window from 2 μs to 100 μs following the prompt can only contain one valid trigger: the delayed event
  - > No valid trigger in the time window 100 μs through 400 μs after prompt

Neutrino search – Vertices, ΔT, and ΔR



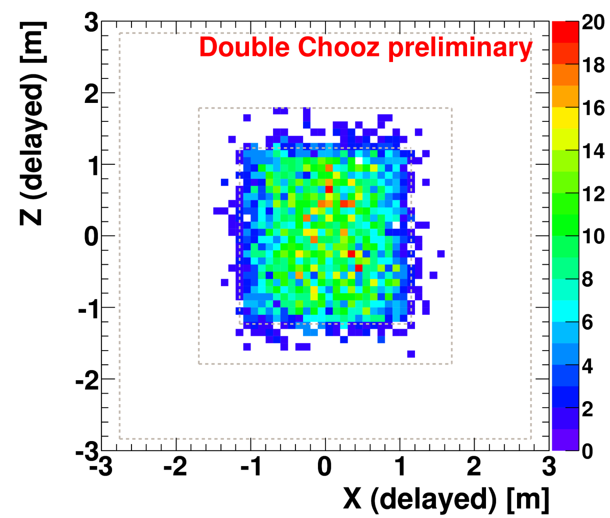
- keV neutrons thermalize within a few µs
- Then they get captured on Gd with **τ ≃ 27 µs**





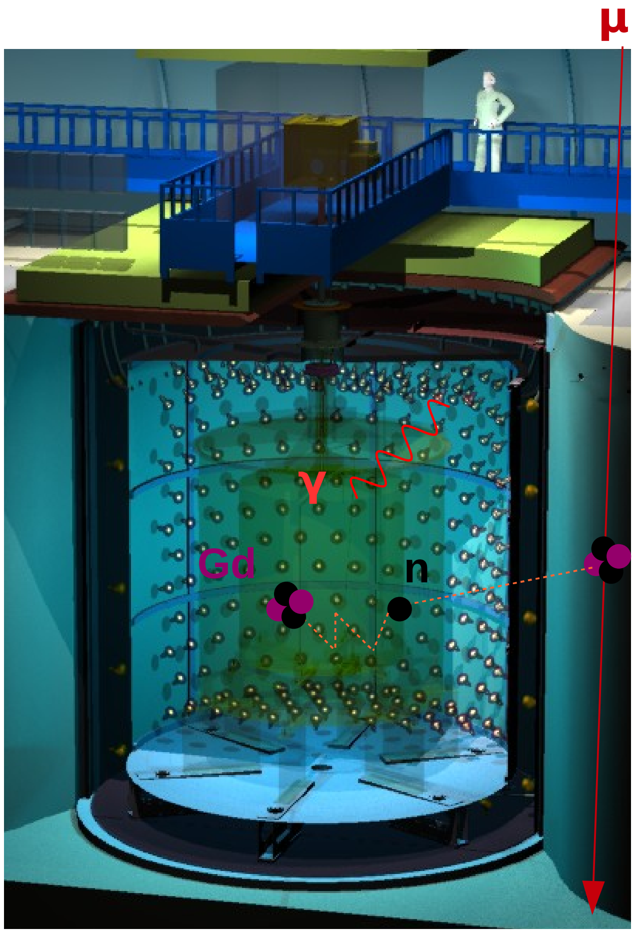
- ΔR: 3D distance between prompt and delayed
- Low level of accidental background: ΔR cut is not needed

Few background events passed the selection cuts (called "accidental coincidences")



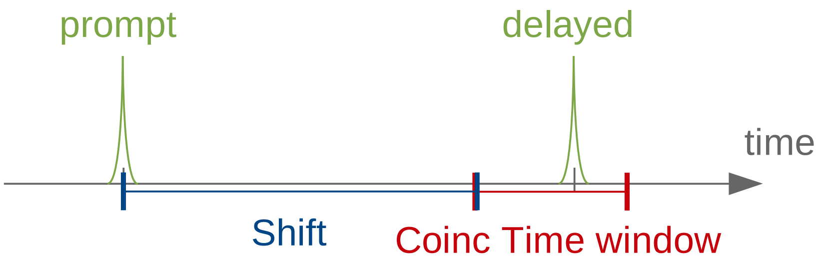
Double Chooz data analysis
Backgrounds studies

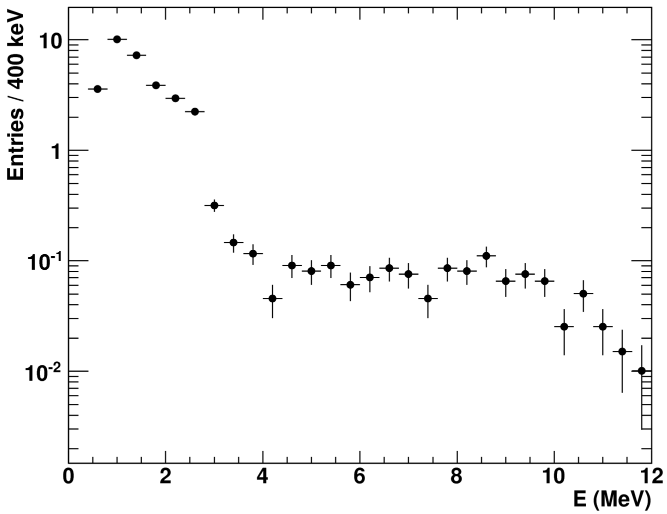
Backgrounds studies – Accidentals



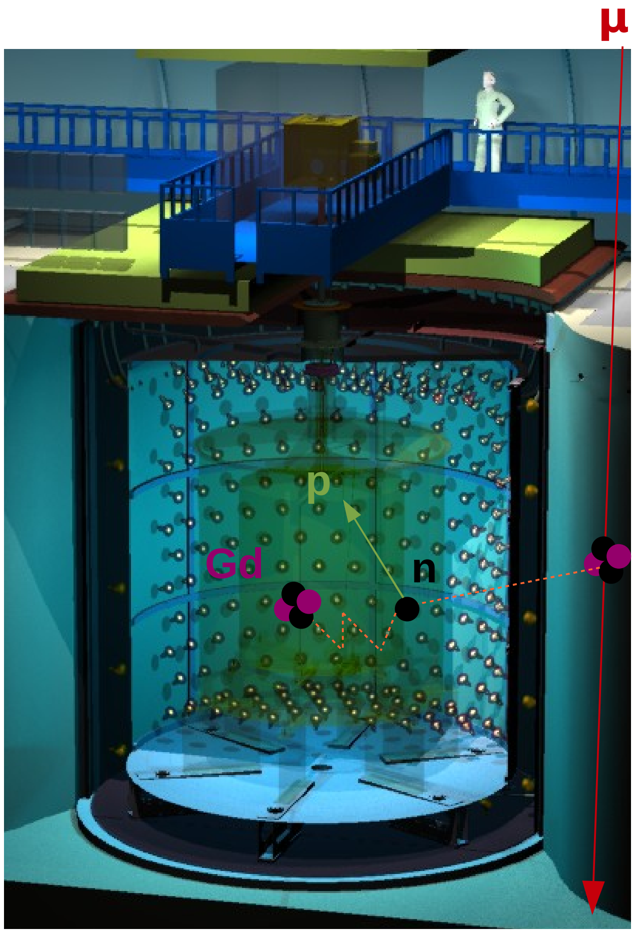
Fortuitous coincidences between:
– **radioactivity γ** from PMT (for instance)
– μ-induced **fast neutron** captured on Gd
→ 2.0 ± 0.9 d^{-1} expected

- **Search: offtime window method**
  delayed **1 s** after prompt: **uncorrelated**



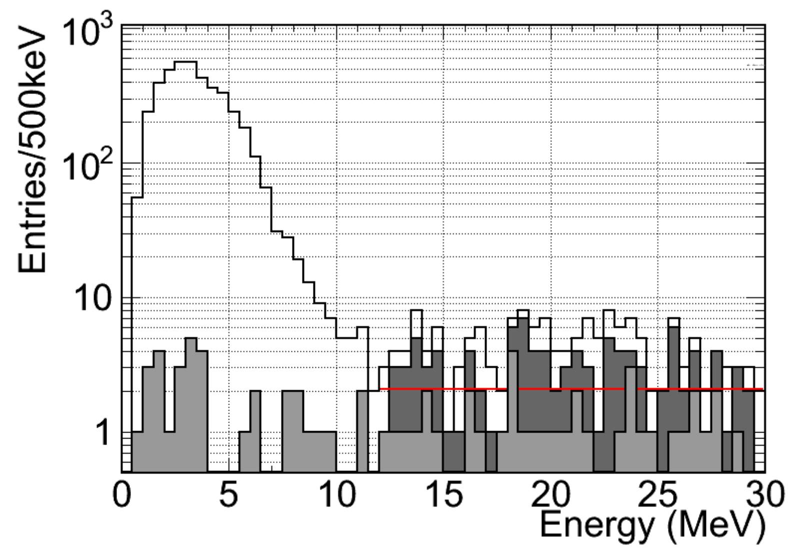


- **Measured rate: 0.33 ± 0.03 d^{-1}**
  – 5 times lower than in the proposal!
  – Stable in time



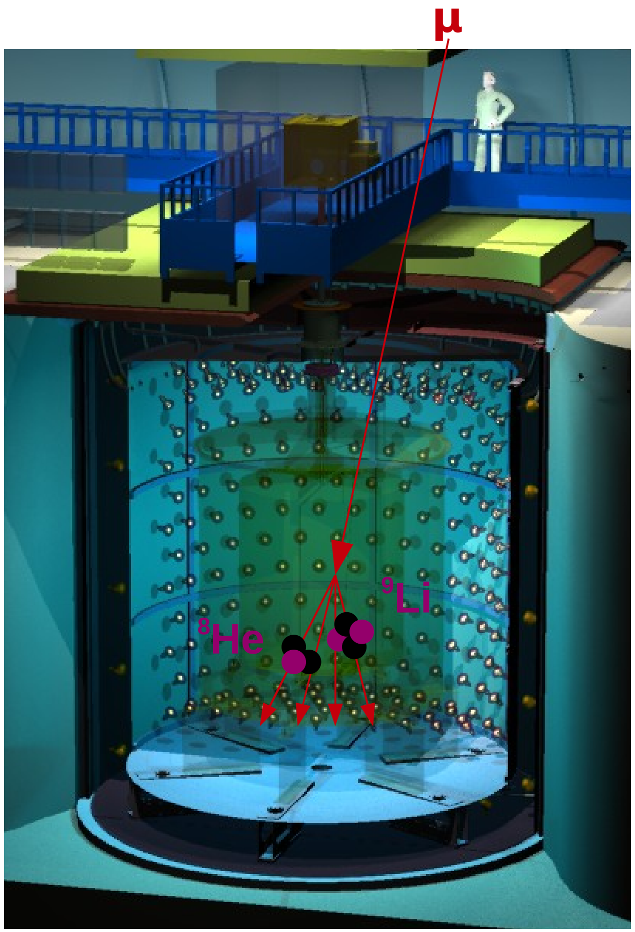
Coincidences physically correlated:
– **recoil proton** from neutron collision
– **neutron** captured on a Gd nucleus
→ 0.2 ± 0.2 d^{-1} expected

- **Search:**
  – Extended selection energy range
  – Extrapolation **to lower energy** (flat spectrum)



- **Measured rate: 0.83 ± 0.38 d^{-1}**
- **Two populations:**
  – fast neutrons
  – stopping muons (→ shape uncertainty)

Backgrounds studies – Cosmogenics



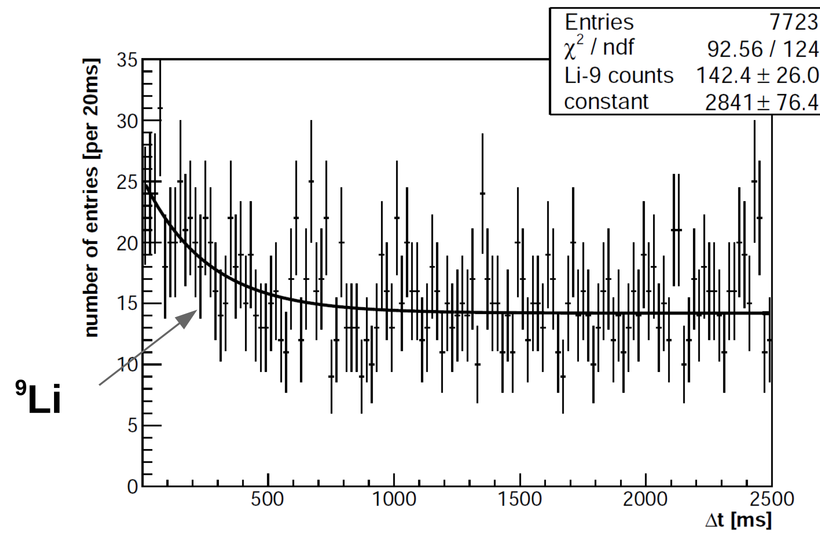
Coincidences physically correlated:

– β-n decaying isotopes **^{9}Li and ^{8}He** μ-produced by spallation processes

– Cannot be vetoed: $t_{1/2}$ = 178 ms

→ 1.4 ± 0.5 d^{-1} expected

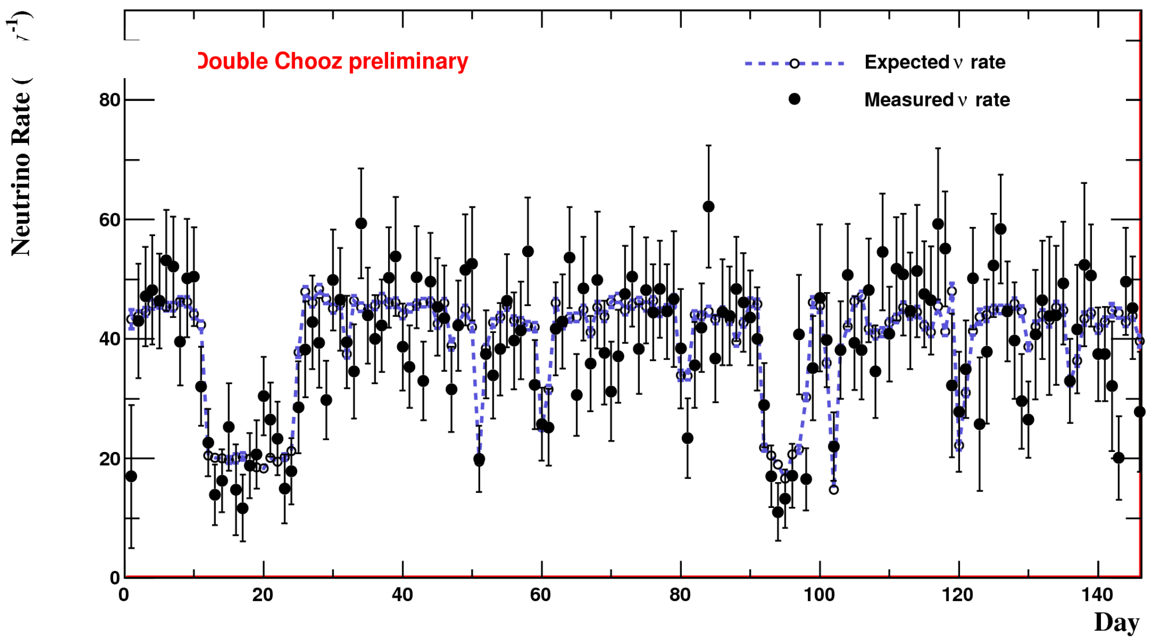
- **Search:**
  - – **Statistical**
  - – **Triple coincidences** btw a high energy deposition (~ **showering μ**), E > 600 MeV, and a **ν-like event**
  - – **ΔT fit** btw high energy muon and prompt event is **given by ^{9}Li lifetime**



- **Measured rate: 2.3 ± 1.2 d^{-1}**
- **Spectrum:** from nuclear database

Signal and background selection results

	# of events	Rate (d^{-1})	σ (d^{-1})
Neutrino candidates	4121	42.6	0.7
Accidentals	32.0	0.33	0.03
^{9}Li	227.3	2.3	1.2
Fast-neutrons	69.2	0.83	0.38

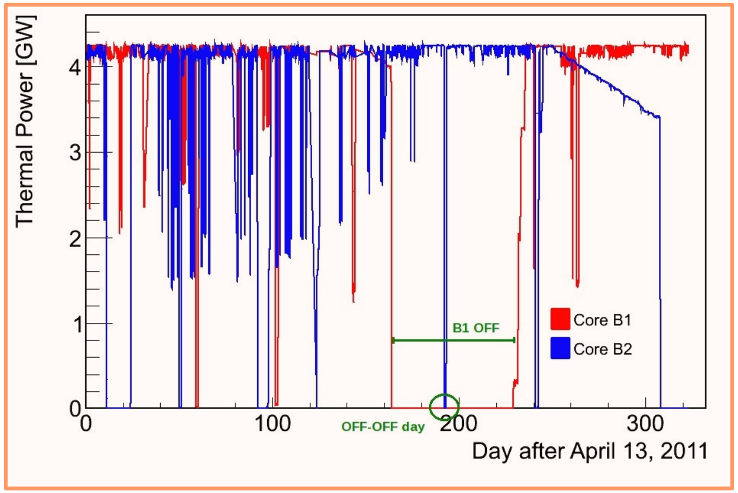


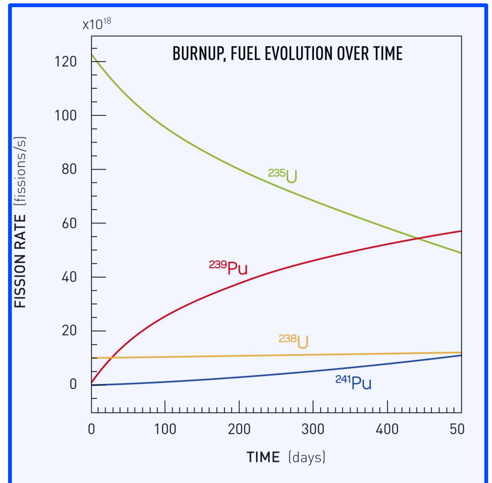
Oscillation fit

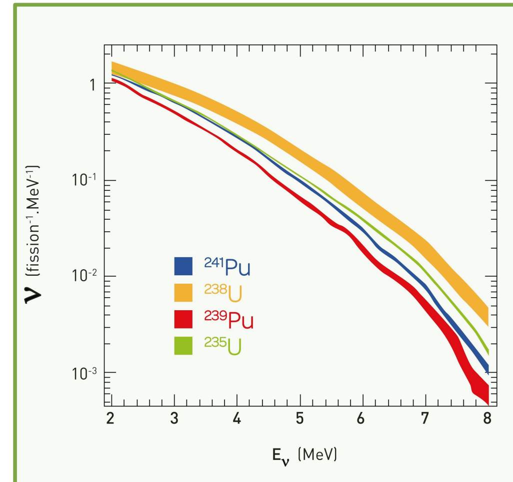
Reactor antineutrino flux prediction

- **One detector phase** → need flux prediction

> $N_{\nu}^{exp}(E,t) = N_p\, \varepsilon / 4\pi L^2 \times P_{th}(t) / \langle E_f \rangle \times \langle \sigma_f \rangle$







(with k = ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu)

Mean energy per fission:

$$\langle E_f \rangle = \Sigma\, \alpha_k(t) \langle E_f \rangle_k$$

$\alpha_k(t)$: fractional fission rate (simulations)

Mean cross-section per fission:

$$\langle \sigma_f \rangle = \langle \sigma_f \rangle^{Bugey4} + \Sigma\, [\alpha_k^{DC}(t) - \alpha_k^{Bugey4}(t)] \langle \sigma_f \rangle_k$$

$$\langle \sigma_f \rangle_k = \int dE\, S_k(E)\, \sigma_{IBD}(E)$$

- Use of **Bugey4 flux** measurement ("anchor point") after **correction** for differences in **core composition** (same as CHOOZ)

- **Two detectors phase** → near detector data

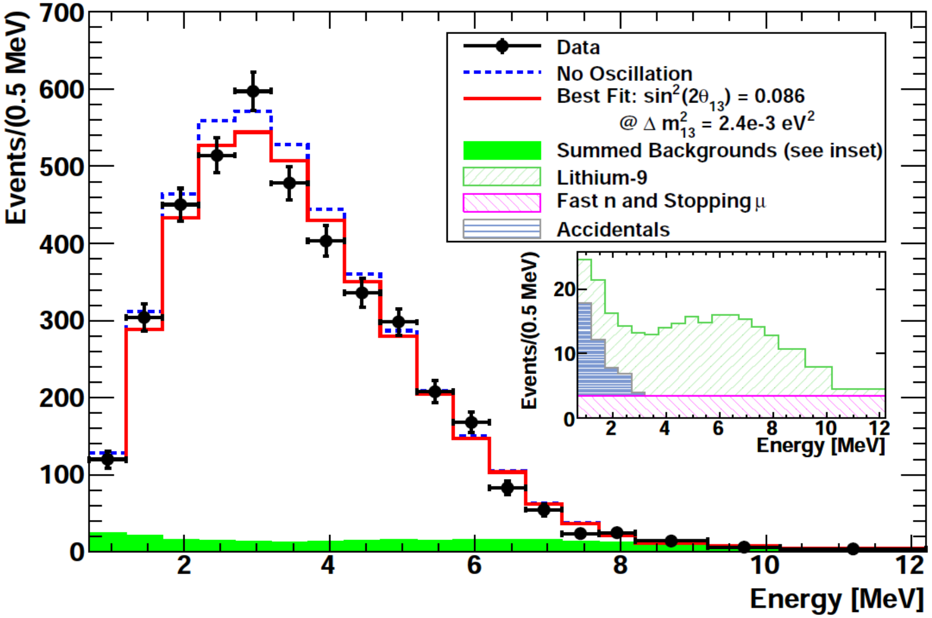
Detector and reactor systematics

Detector (in %)		Reactor (in %)	
Energy response	1.7	**Bugey4 measurement**	1.4
E_{delay} containement	0.6	**Fuel composition**	0.9
Gd fraction	0.6	**Thermal power**	0.5
ΔT	0.5	**Reference spectra**	0.5
Spill in/out	0.4	**Energy per fission**	0.2
Trigger efficiency	0.4	**IBD cross section**	0.2
Target H	0.3	**Baseline**	0.2
Total	**2.1**	**Total**	**1.8**

Oscillation fit strategy and results

$$\chi^2 = \left(N_i - \sum_{R}^{\text{Reactors}} N_i^{\nu,R*}\right) \times \left(M_{ij}^{\text{Reactors}} + M_{ij}^{\text{detector}} + M_{ij}^{\text{stat}} + \sum_{b}^{\text{bkgnds.}} M_{ij}^{\text{b}}\right)^{-1} \times \left(N_j - \sum_{R}^{\text{Reactors}} N_j^{\nu,R*}\right)^{\text{T}}$$

- **Covariance matrices:** uncertainties for:
  - > ν-signal from reactors,
  - > detector response,
  - > signal and backgrounds stats,
  - > backgrounds spectral shape
- Fit using two types of information:
  - > **Rate** (number of events)
  - > **Shape** (spectra)



→ Rate-only: **$\sin^2 2\theta_{13}$ = 0.104 ± 0.030 (stat) ± 0.076 (syst)**

→ Rate+Shape: **$\sin^2 2\theta_{13}$ = 0.086 ± 0.041 (stat) ± 0.030 (syst)**

No oscillation excluded at 94.6 %, 0.015 < $\sin^2 2\theta_{13}$ < 0.160 at 90 % CL

Conclusion and prospects

Conclusion and prospects

- **Double Chooz pioneered** the experimental **concept** to measure $\boldsymbol{\theta_{13}}$
- **Double Chooz first analysis on 100 days**
  - RS: $\sin^2 2\theta_{13} = 0.086 \pm 0.041\ (stat) \pm 0.030\ (syst)$
- **Results confirmed** by Daya Bay and RENO
- **Next analysis soon**
  - Statistics x2
  - Improvements energy scale
  - ^{9}Li reduction
- Near lab delivered, **near detector** installation in **2013**
- **With 2 detectors → 5σ reached in less than 3 years**
- **Double Chooz strengths**
  - Detectors almost on iso-rate line
  - Reactors OFF-OFF, background measurement
  - Low level of accidental background
  - Numerous calibration devices

Thank you very much for your attention!

Any questions?

References:

- **CHOOZ final paper**, *Search for neutrino oscillation on a long base-line at the CHOOZ nuclear power station*, M. Apollonio *et al.*, **arXiv:hep-ex/0301017v1 13 Jan 2003**
- **Double Chooz proposal**, *Double Chooz: A Search for the Neutrino Mixing Angle* θ_{13}, F. Ardellier *et al.*, **arXiv:hep-ex/0606025v4 30 Oct 2006**
- **Double Chooz first physics paper**, *Indication of the disappearance of reactor* $\overline{\nu}_e$ *in the Double Chooz experiment*, Y. Abe *et al.*, **arXiv:hep-ex/1112.6353v3 13 Mar 2012**
- **New reactor antineutrino flux,** *Improved Predictions of Reactor Antineutrino Spectra,* Th. A. Mueller *et al.*, **arXiv:hep-ex/1101.2663v3 11 Mar 2011**

The Double Chooz collaboration

Brazil	France	Germany	Japan	Russia	Spain	UK	USA
CBPF UNICAMP UFABC	APC CEA/DSM/IRFU: SPP SPhN SEDI SIS SENAC CNRS/IN2P3: Subatech IPHC ULB (Belgium)	EKU Tübingen MPIK Heidelberg TU München RWTH Aachen U. Hamburg	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	Sussex	U. Alabama ANL U. Chicago Columbia U. UCDavis Drexel U. IIT KSU LLNL MIT U. Notre Dame Sandia National Laboratories U. Tennessee

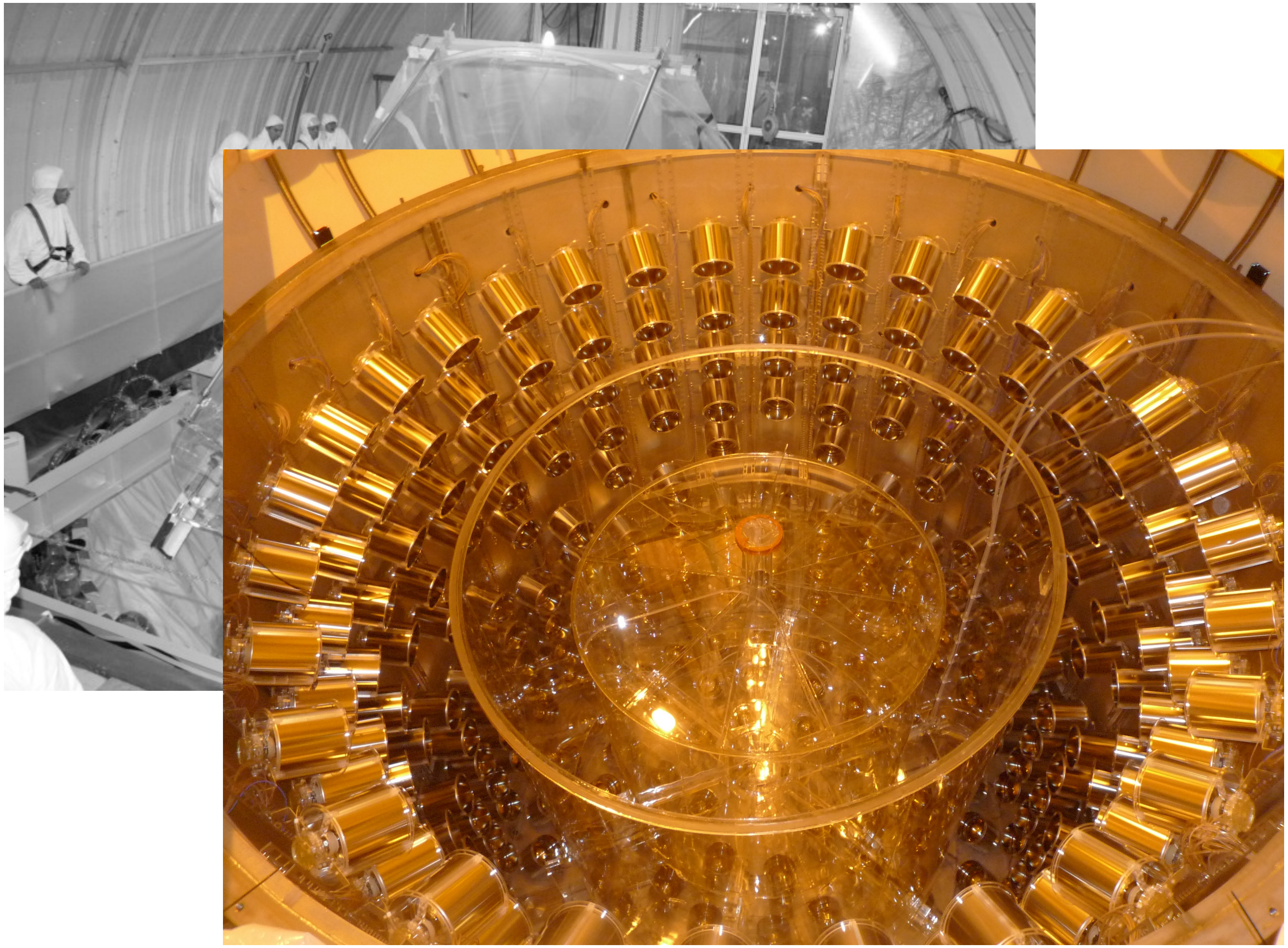
Spokesperson: H. de Kerret (IN2P3)
Project Manager: Ch. Veyssière (CEA-Saclay)

Web Site: www.doublechooz.org/

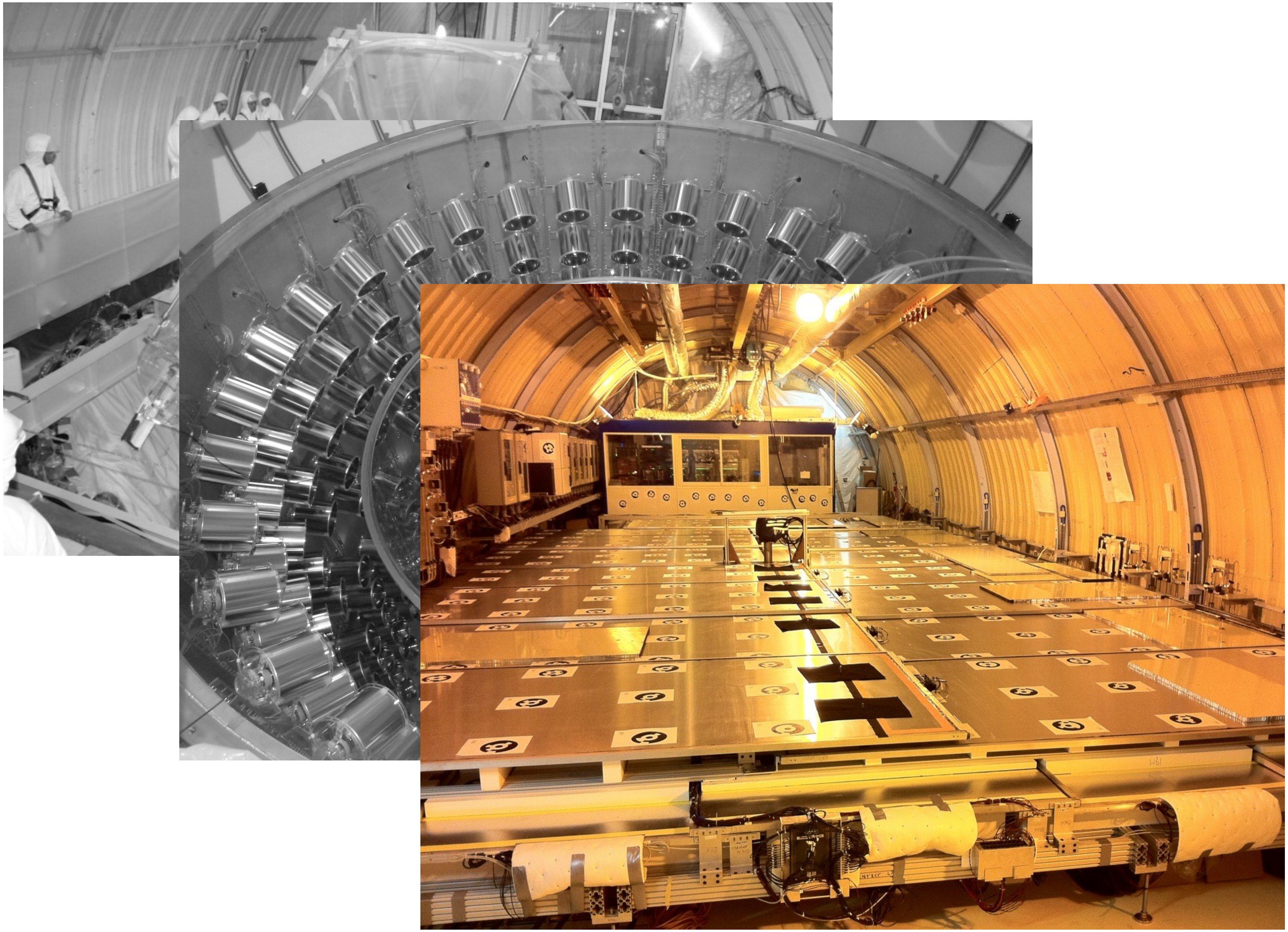
Backup slides

The Double Chooz detector

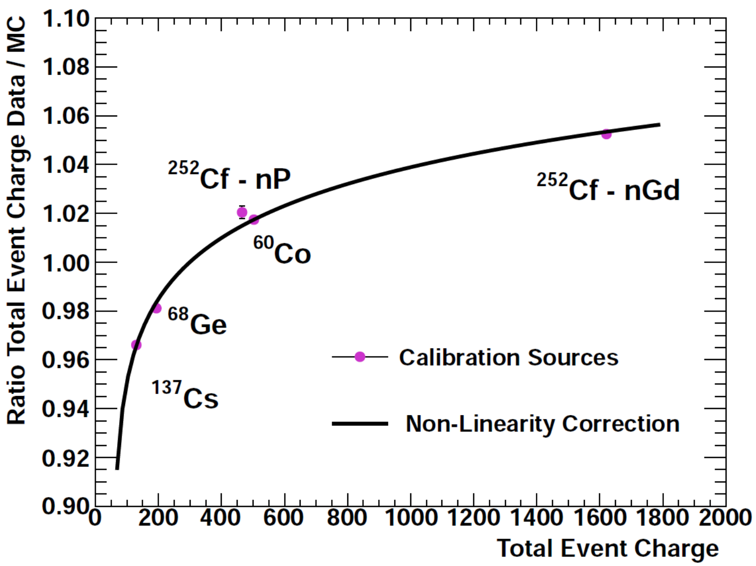
The Double Chooz detector



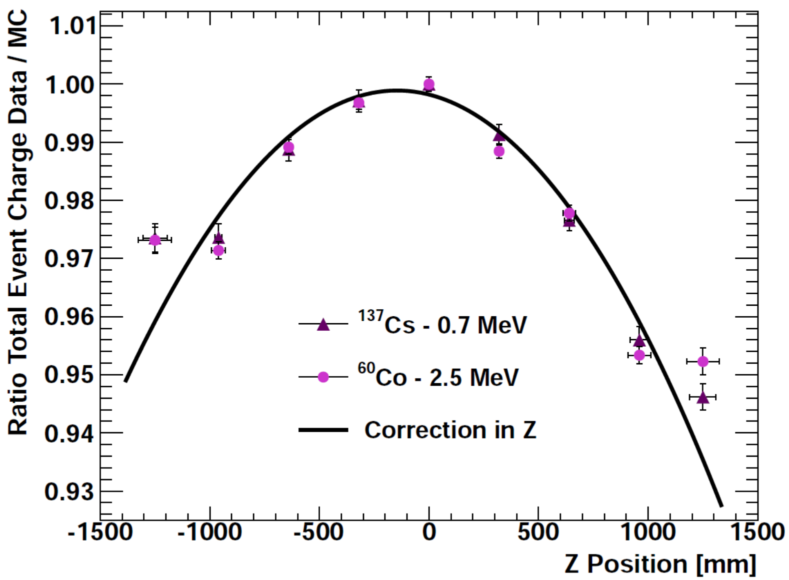
The Double Chooz detector



- **Charge correction:** calibrate non-linearity (charge reconstruction and electronics effects)

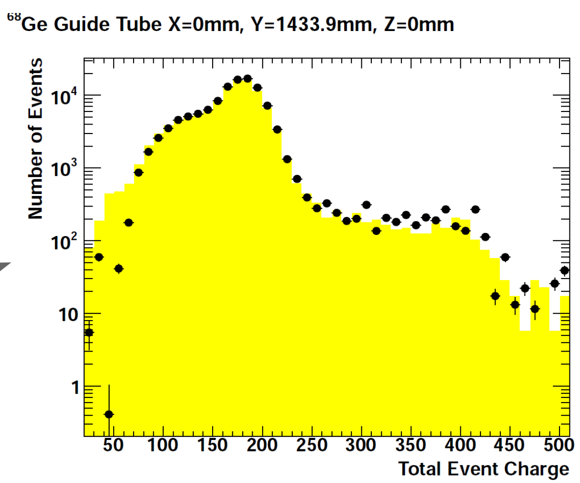


- **Z correction:** calibrate the Z-bias (geometrical effect)

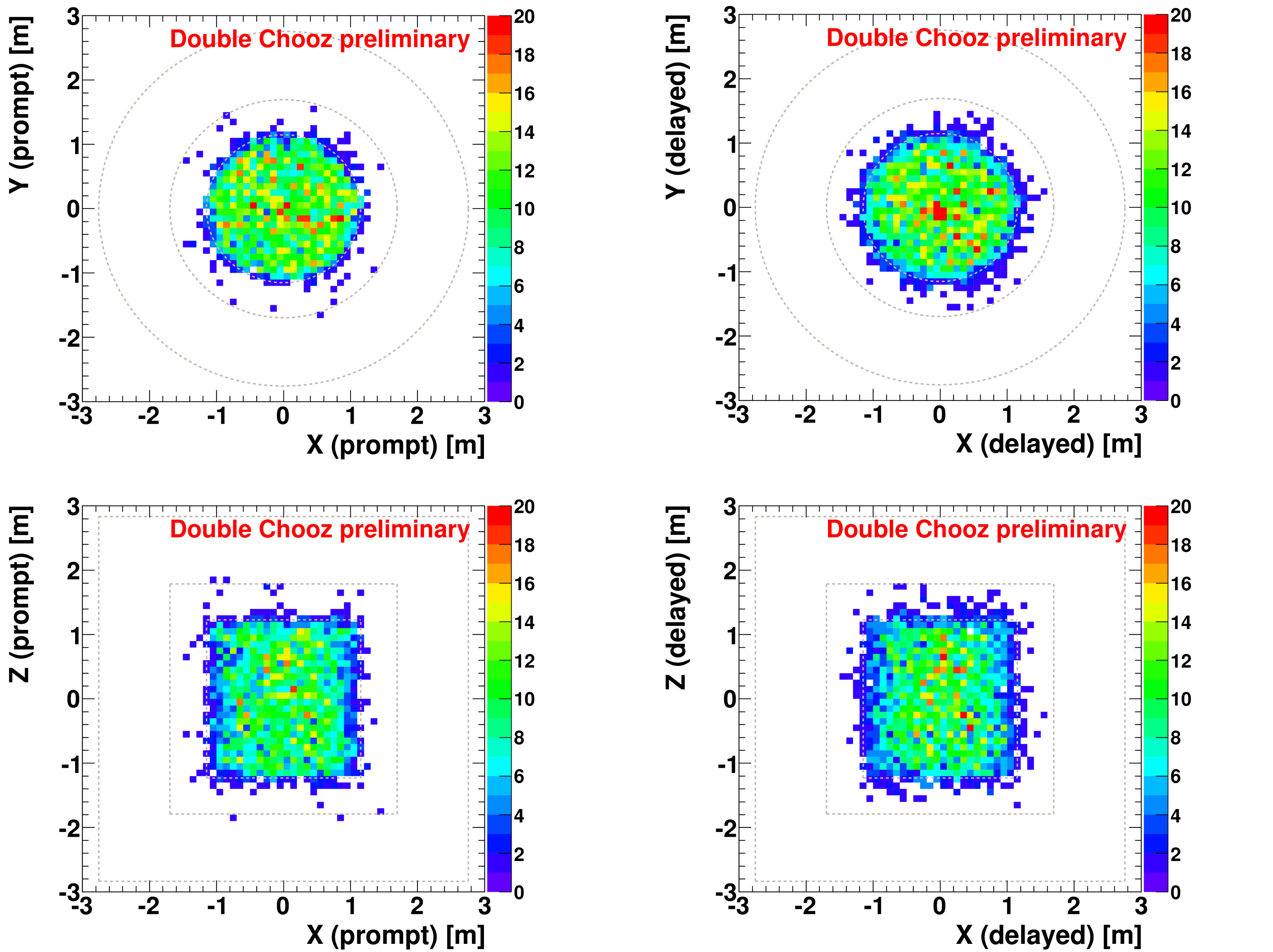


→ **Empirical energy correction function:** removes MC and data discrepancies

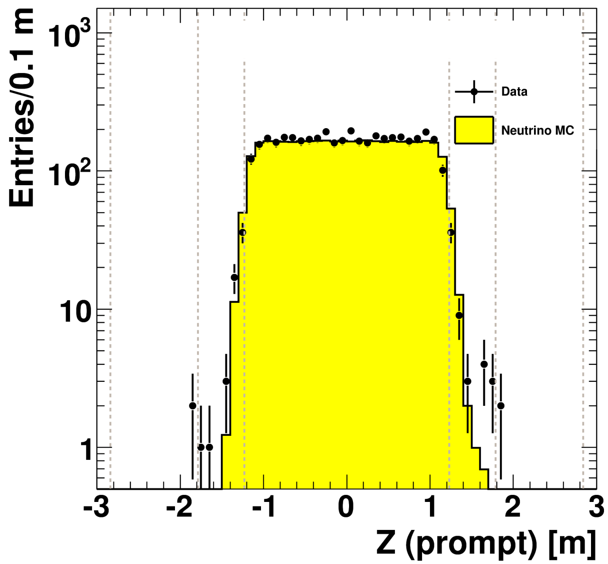
→ ^{68}Ge source in a calibration tube: **correction works well, spectrum well modeled**

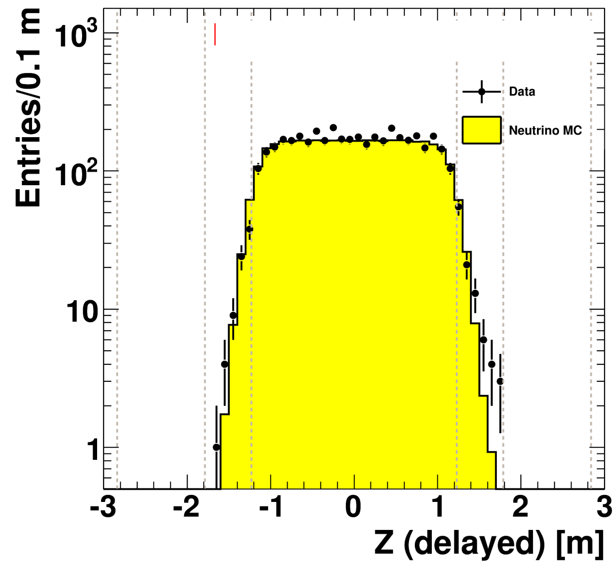


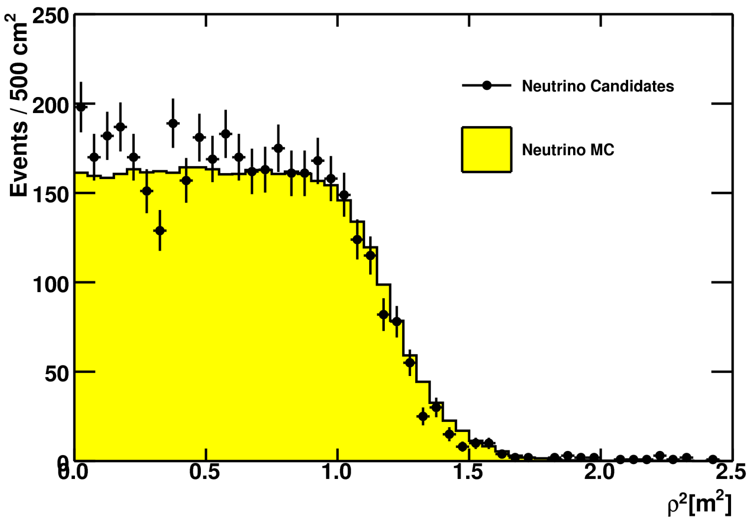
Neutrino search – Vertices distributions

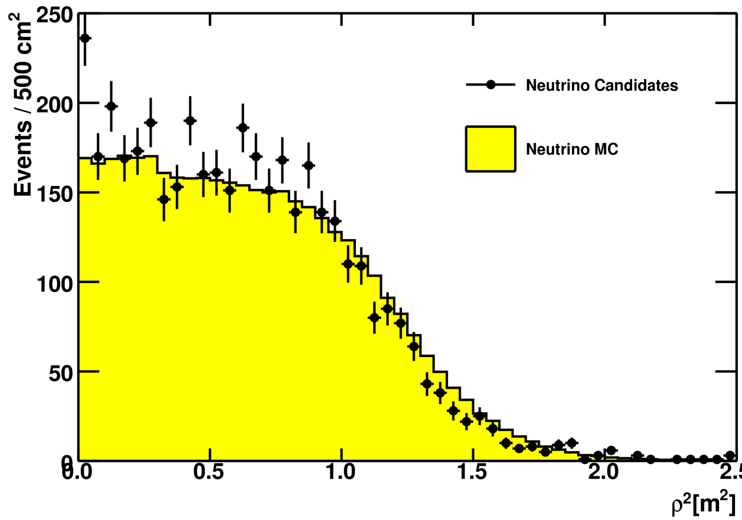


Neutrino search – Vertices distributions

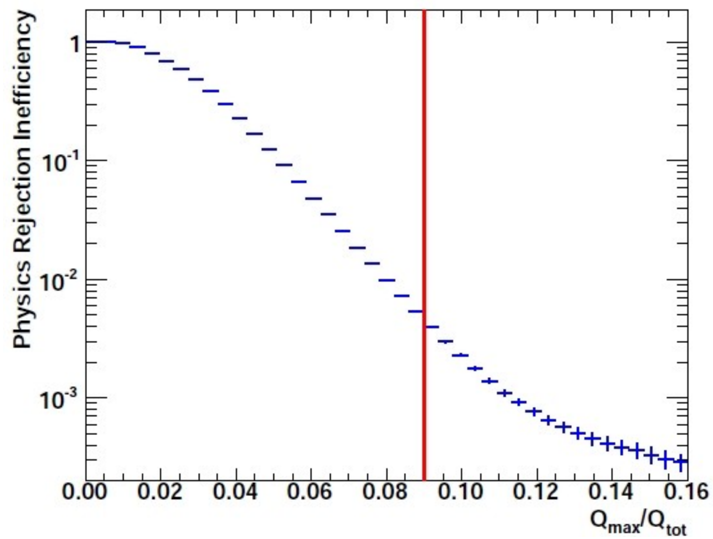


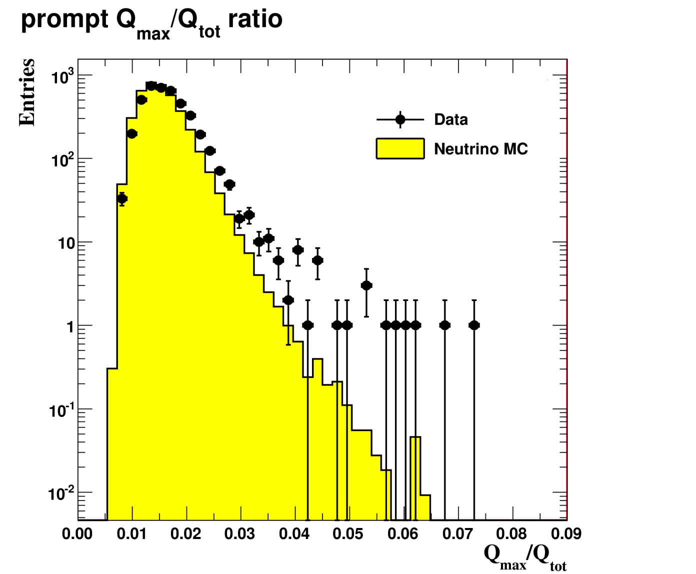


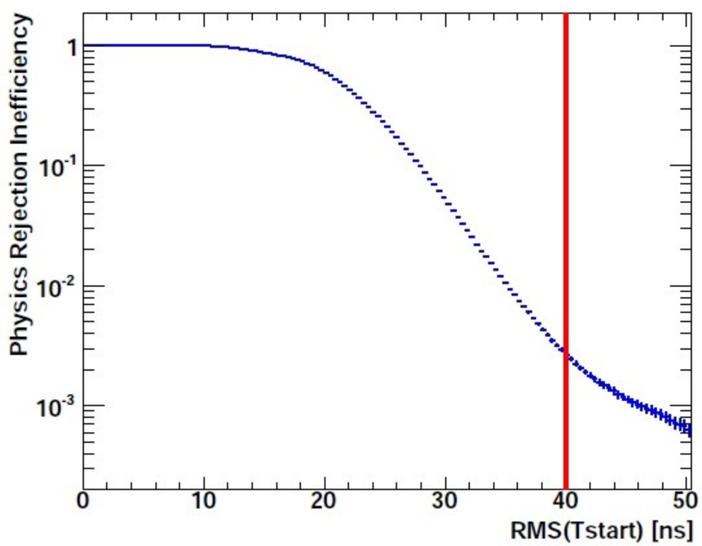


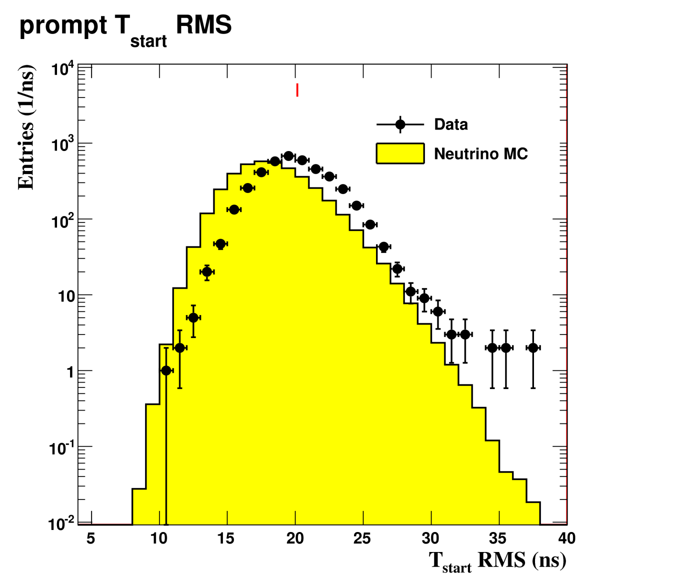


Neutrino search – Light-noise rejection

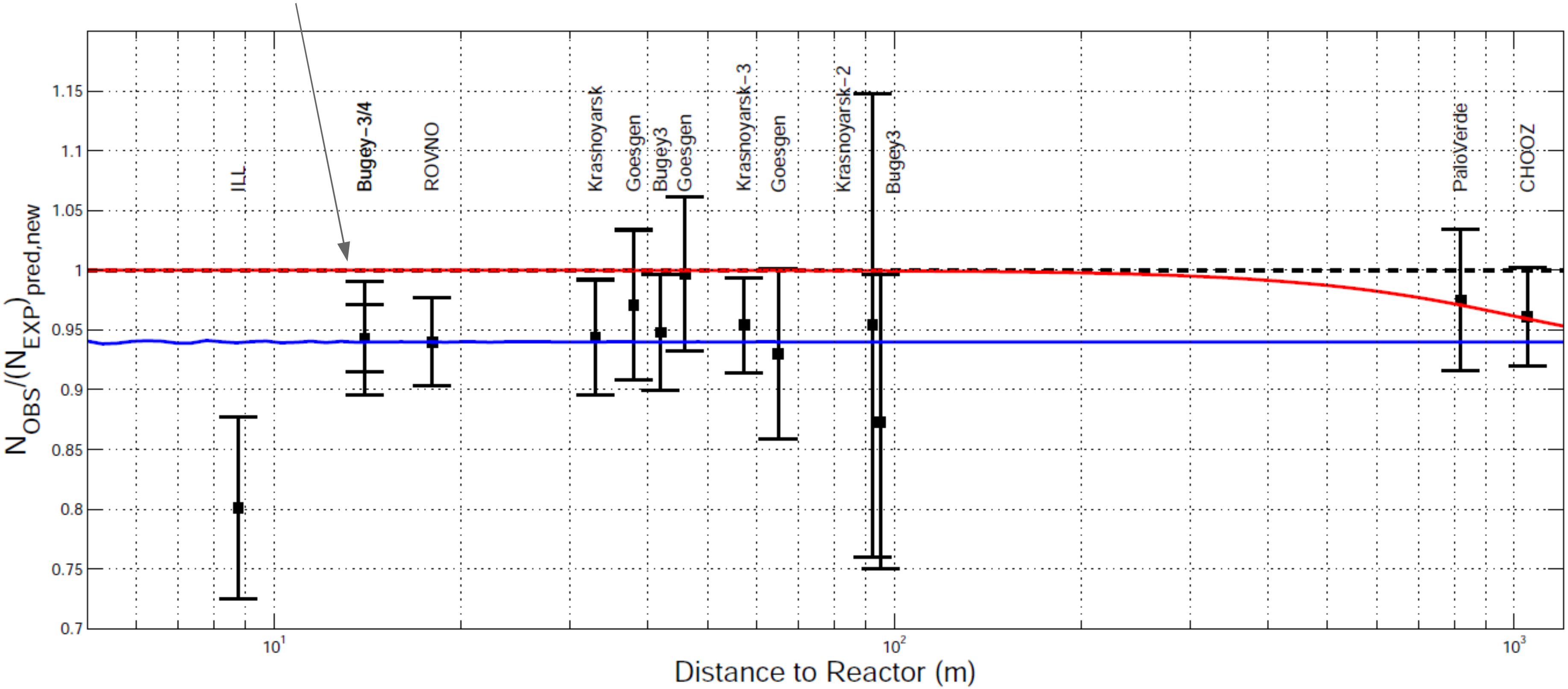




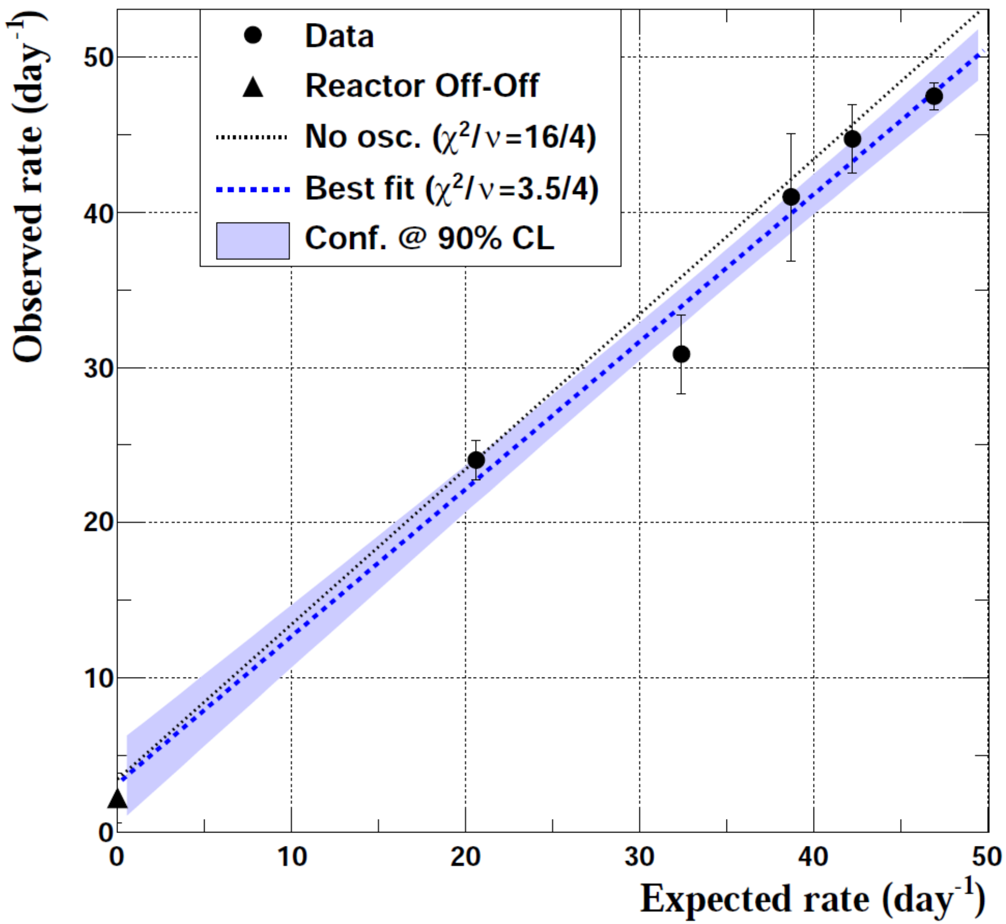




- Possible **short baseline oscillation** (*cf.* Reactor Neutrino Anomaly, G. Mention *et al.*,), Double Chooz phase I normalized to the Bugey4 measurement, and uses the reference electron spectra from ILL irradiation experiment
  - > accounting for differences in core inventories (btw Double Chooz and Bugey4)
  - > taking into account long-lived fission products (off-equilibrium effects)
- Bugey4: most precise measurement of the IBD cross section per fission



Neutrino rate vs reactor power

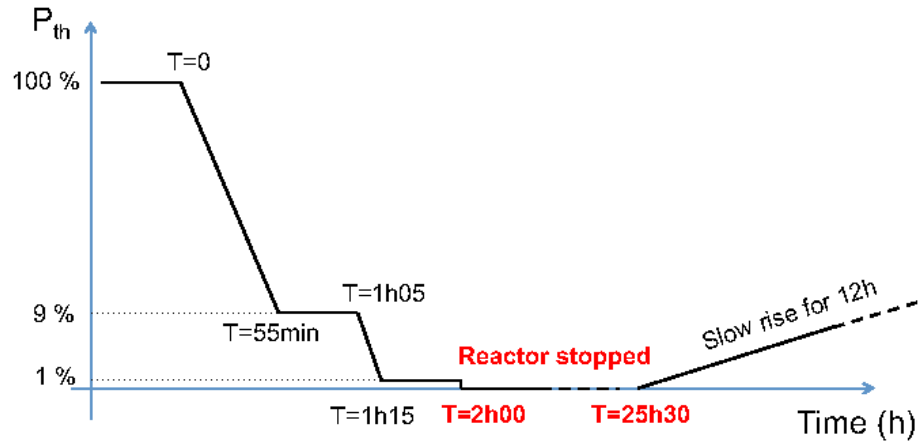


→ **3.2 ± 1.3 d^{-1}**

(excellent agreement with our background estimate and reactors OFF-OFF data)

Both reactors OFF data

- During reactor **B1 refueling**, reactor **B2 went OFF** for more than a day
- **$T_{OFF\text{-}OFF}$ = 23h30**
  - After shutdown, still neutrinos emission by residual power
  - Safe after 2 hours (< 0.3 events expected)

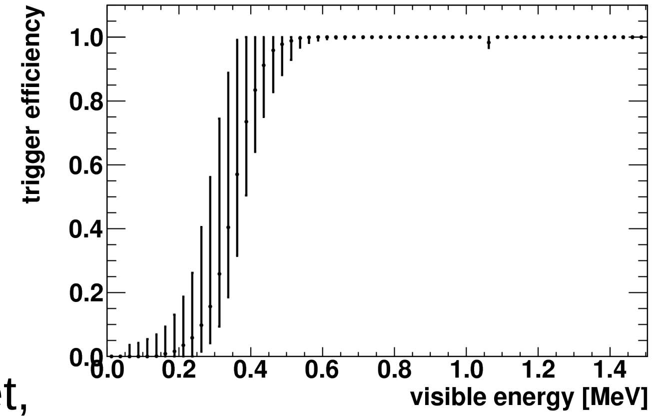


- **Coincidence search: 3 candidates**, with E_{prompt} < 30 MeV
  - **2 ^{9}Li candidates**, 4.8 and 9.8 MeV (+ correlation to track)
  - **1 stopping-muon candidate**, 26.5 MeV
- Compatible with total background estimation:

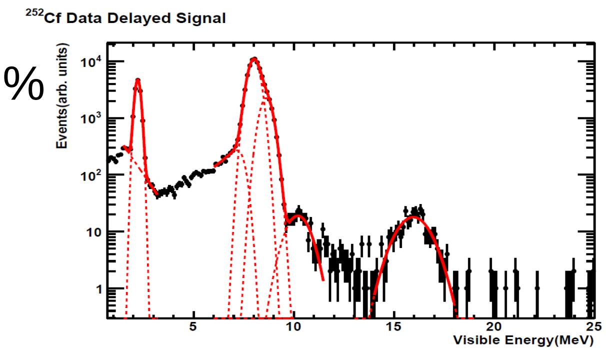
→ **3.45 ± 1.26 d^{-1}**

Efficiencies

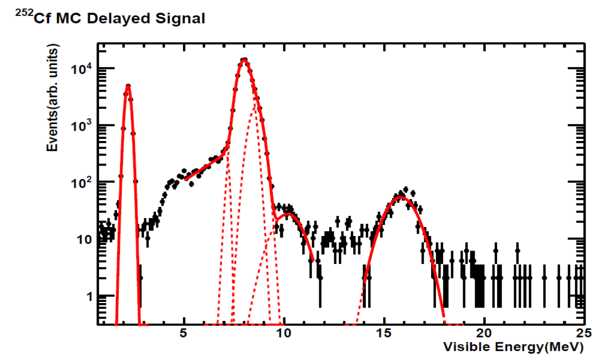
- **E_{prompt} and trigger efficiency**
  - trigger threshold at 350 keV
  - trigger efficiency: **(100 + 0 – 0.4) %** for E > 700 keV



- **Gd/H ratio**
  - calibration with ^{252}Cf source in ν-target, along the Z-axis
  - Gd/(H+Gd) → capture rate: (86.0 ± 0.5) %
  - but 2 % difference with MC

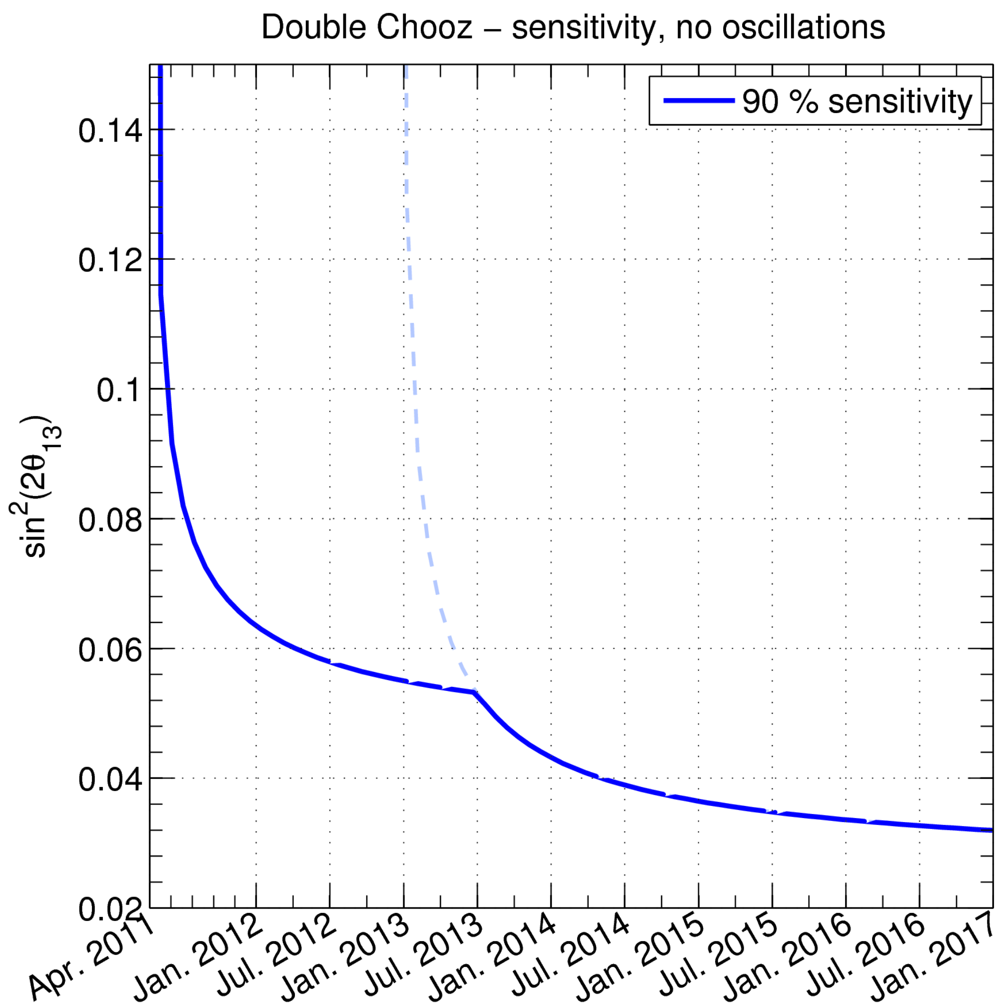


- **6 MeV cut efficiency**
  - 6 < E_d < 12 MeV / 4 < E_d < 12 MeV
  - MC and ^{252}Cf in good agreement
  - **(94.5 ± 0.5) %**



- **ΔT efficiency**
  - #[2;100] µs / #[0;200] µs
  - MC and ^{252}Cf in good agreement
  - **(96.5 ± 0.5) %**

Double Chooz sensitivity

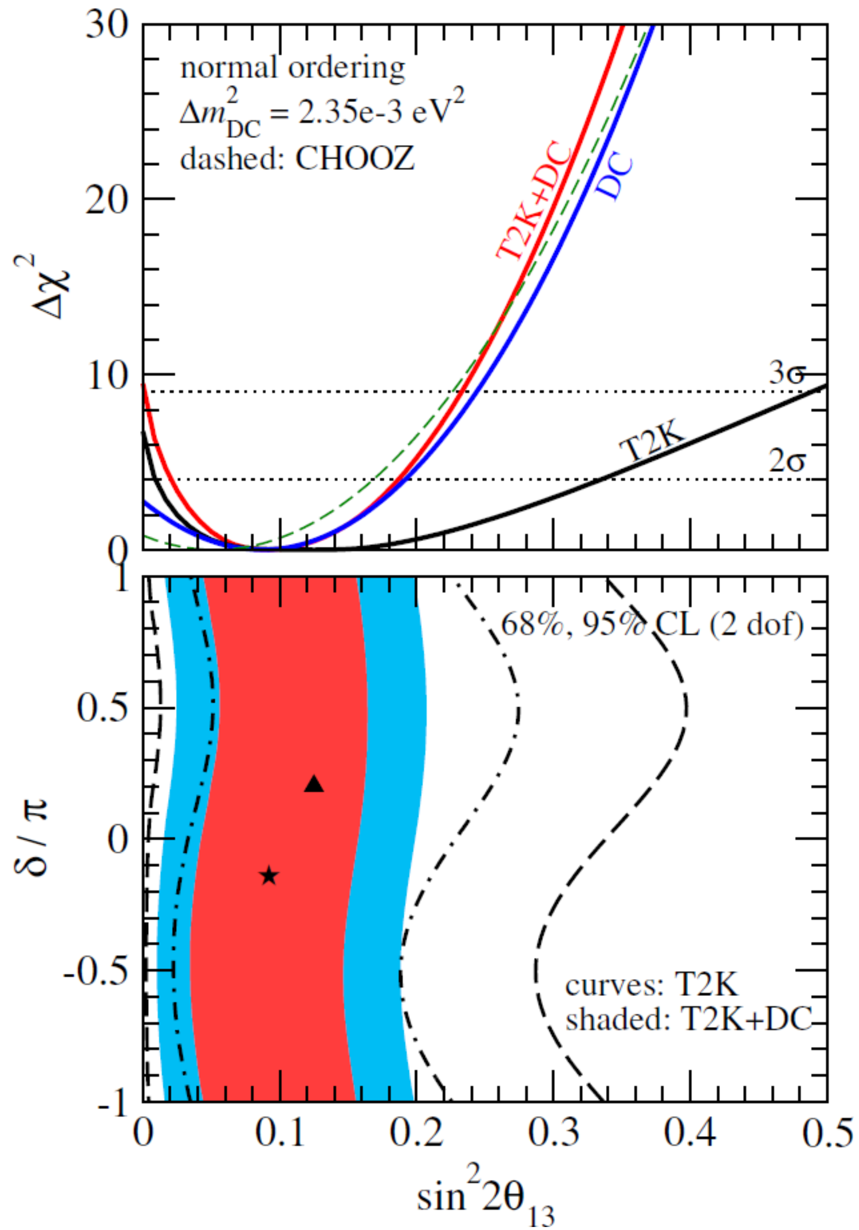


With 1 detector
→ 3 σ is the limit

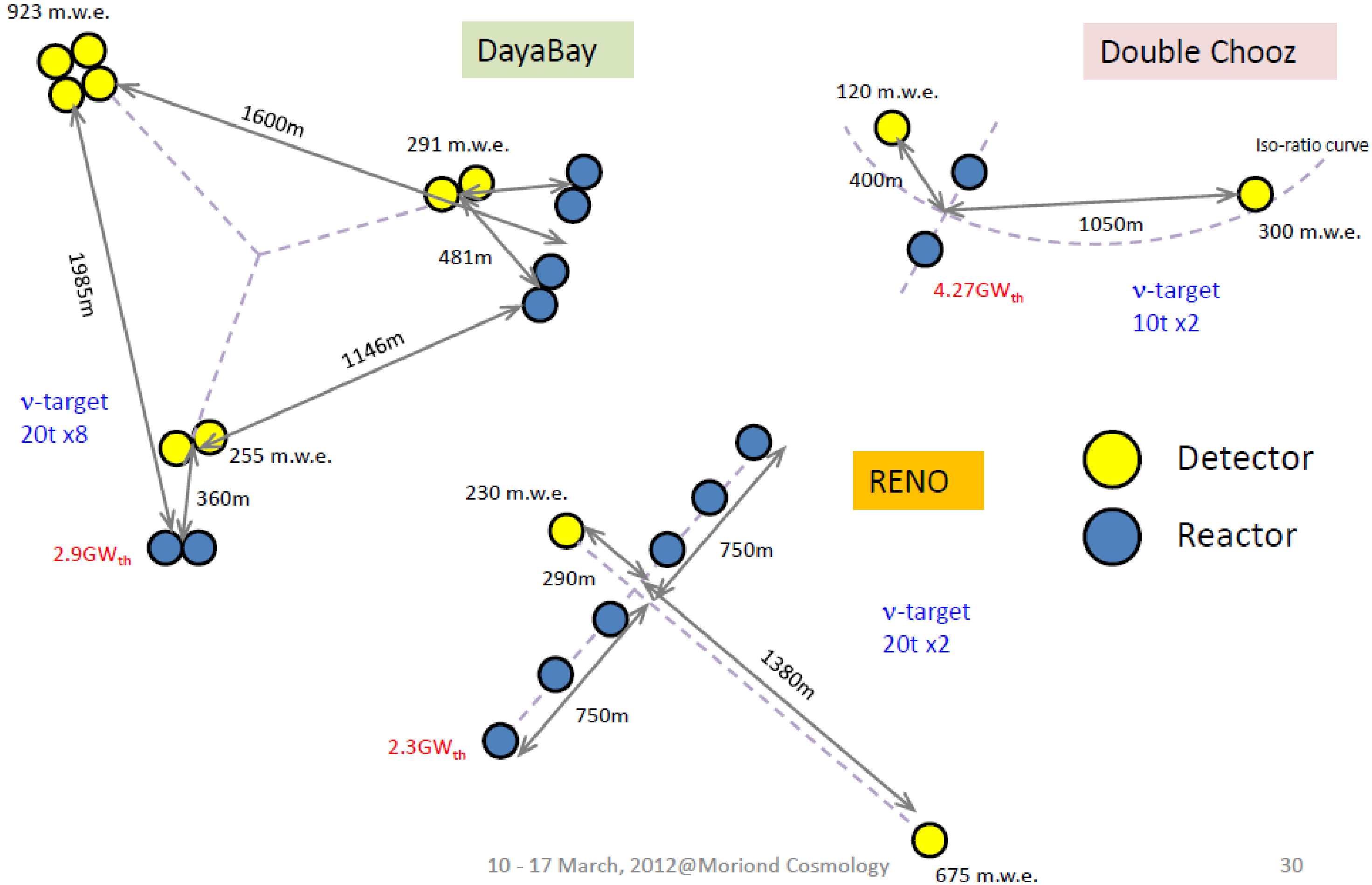
With 2 detectors
→ 5 σ reached
in less than 3 years

Combined results on θ_{13}

- Double Chooz and T2K results are consistent
- **θ_{13} = 0 is excluded at 3σ** from T2K+Double Chooz



Reactor electron antineutrinos experiments



(Tomoyuki Konno, TIT, @Moriond)

Double Chooz results on CBS...

energie atomique • energies alternatives

Double Chooz other paper (Journal de Spirou)