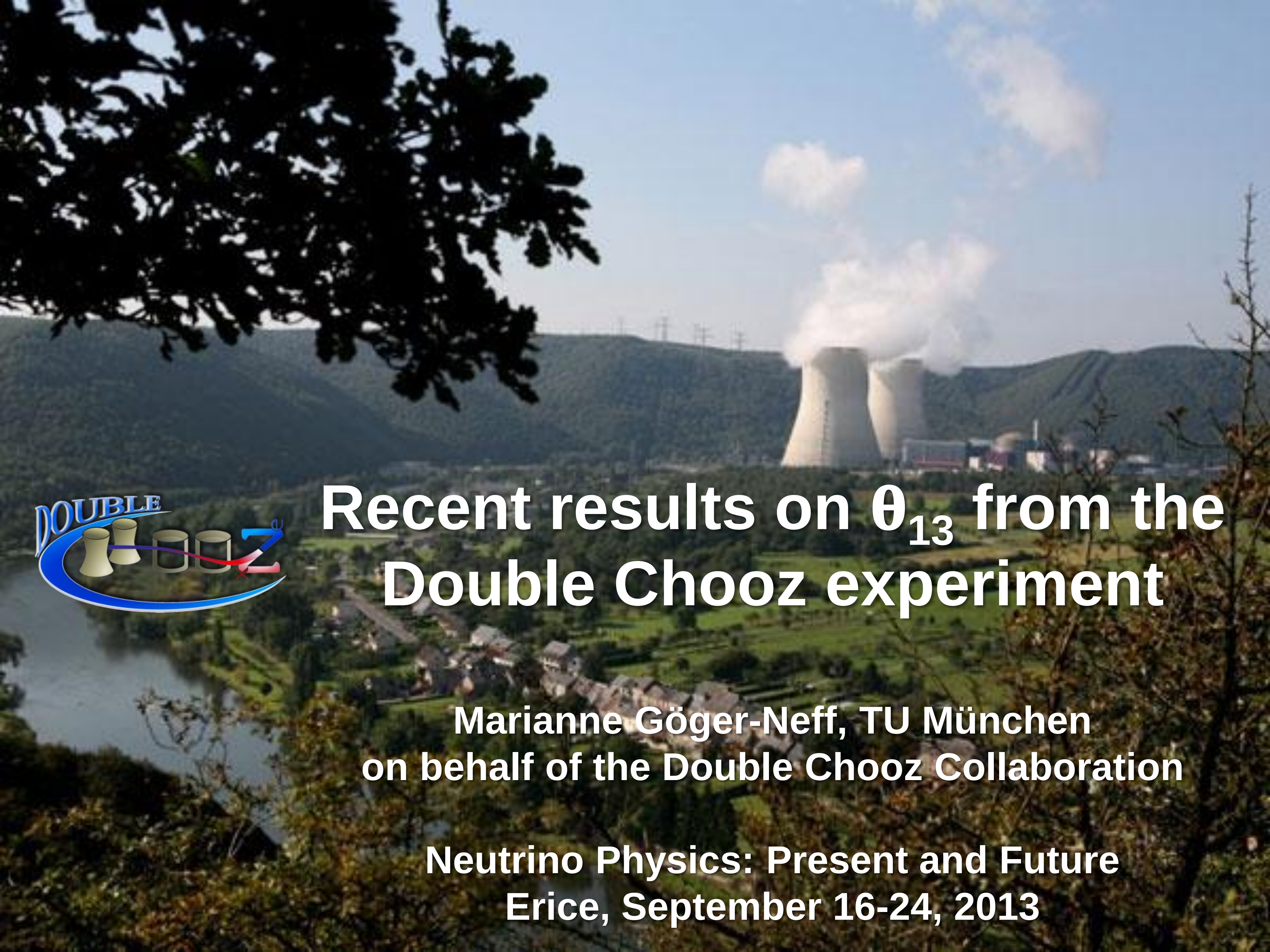


Recent results on θ_{13} from the Double Chooz experiment

Marianne Göger-Neff, TU München
on behalf of the Double Chooz Collaboration

Neutrino Physics: Present and Future
Erice, September 16-24, 2013

3 flavor neutrino mixing

mixing matrix $\boldsymbol{U_{PMNS}}$ parametrized with 3 mixing angles θ_{ij} , CP phase δ

+ 2 mass differences Δm^2_{atm} , Δm^2_{sol}

s_{13}= sinq$_{13}$
c_{13}= cosq$_{13}$

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

atmospheric n
+ K2K, MINOS

Δm^2_{32}= (2.32±0.12)· 10^{-3} eV^2

$\sin^2 2\theta_{23}$ >0.95

$\theta_{23} \approx 45°$

solar n
+ KamLAND

Δm^2_{21} = (7.50±0.20)· 10^{-5} eV^2

$\sin^2 2\theta_{12} = 0.857 \pm 0.025$

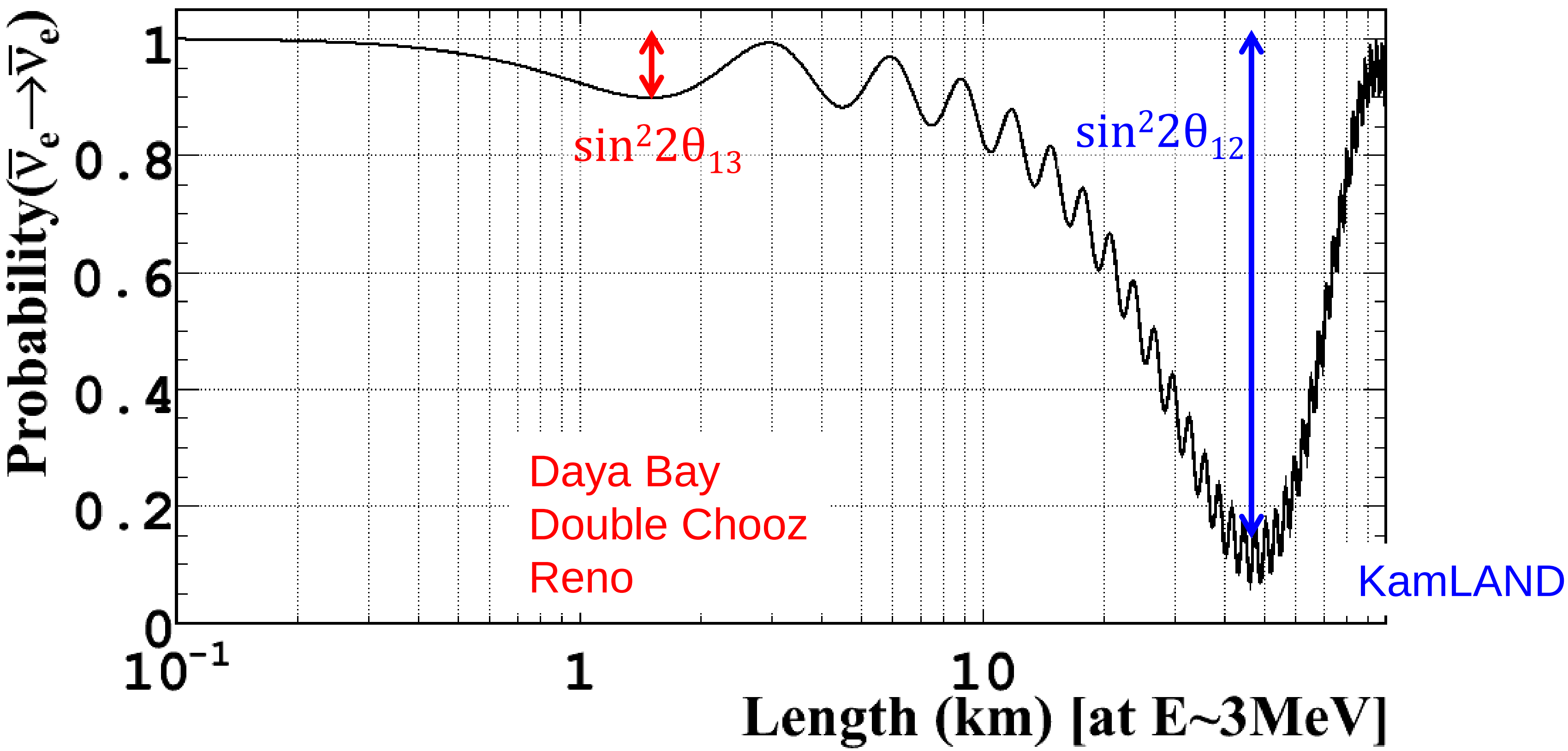
$\theta_{12} \approx 35°$

reactor n
+ LBL
$\sin^2 2\theta_{13} = 0.095 \pm 0.01$
$\theta_{13} \approx 9°$
δ = ?

PDG 2013

Survival probability for $\bar{\nu}_e$

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

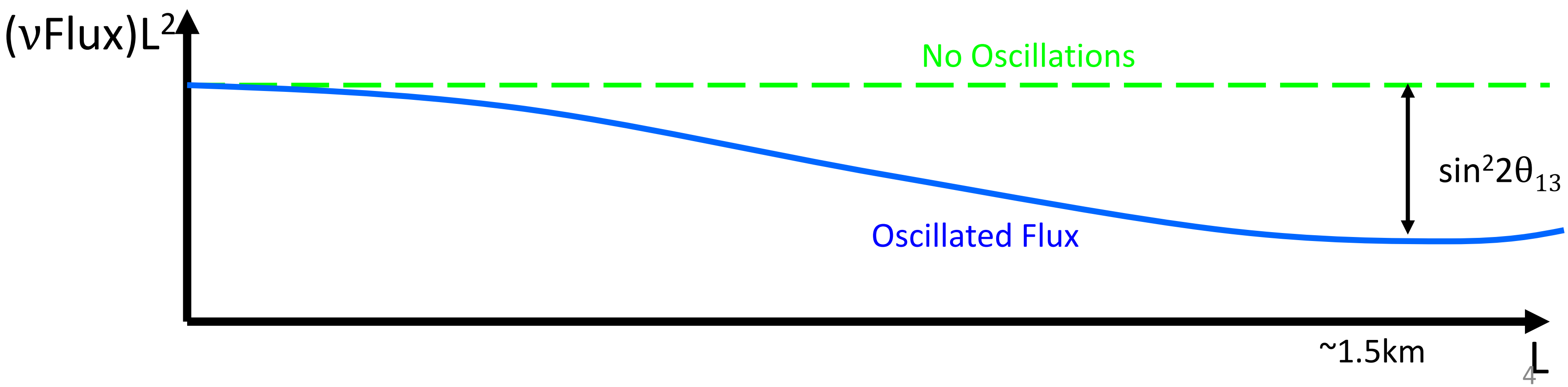


Oscillation experiments at nuclear reactors

nuclear reactor: intense, isotropic source of electron-antineutrinos, ‘for free’

- E_ν < 10 MeV $\Rightarrow$ disappearance experiment
- look for rate deviation from $1/r^2$ and spectral distortions in 1-2 km
- clean measurement of θ_{13} , independent of δ-CP & matter effects

$$P(\overline{\nu}_e \to \overline{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E_{\overline{\nu}}}$$



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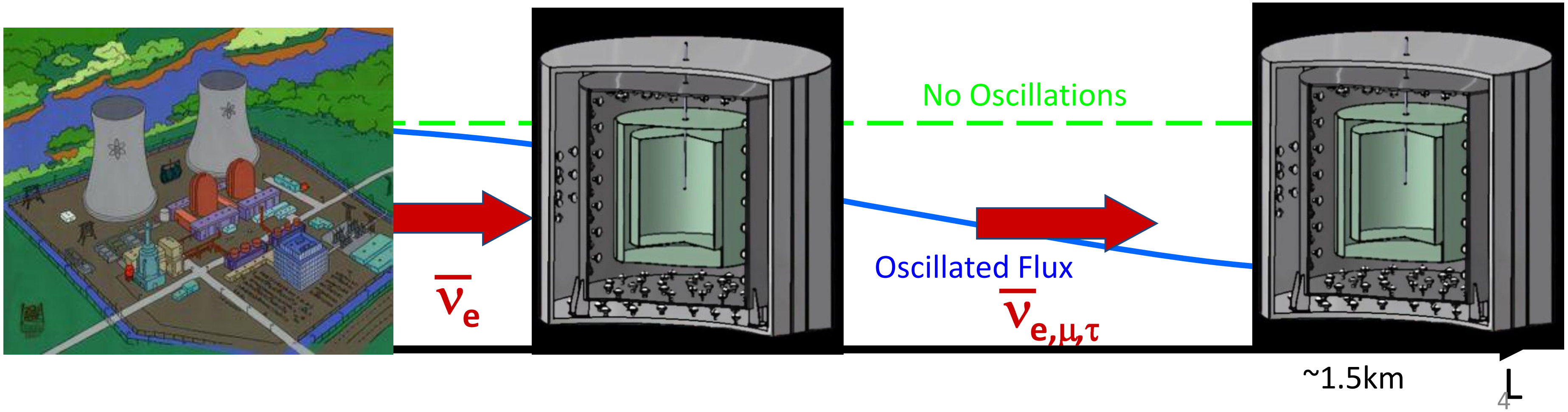
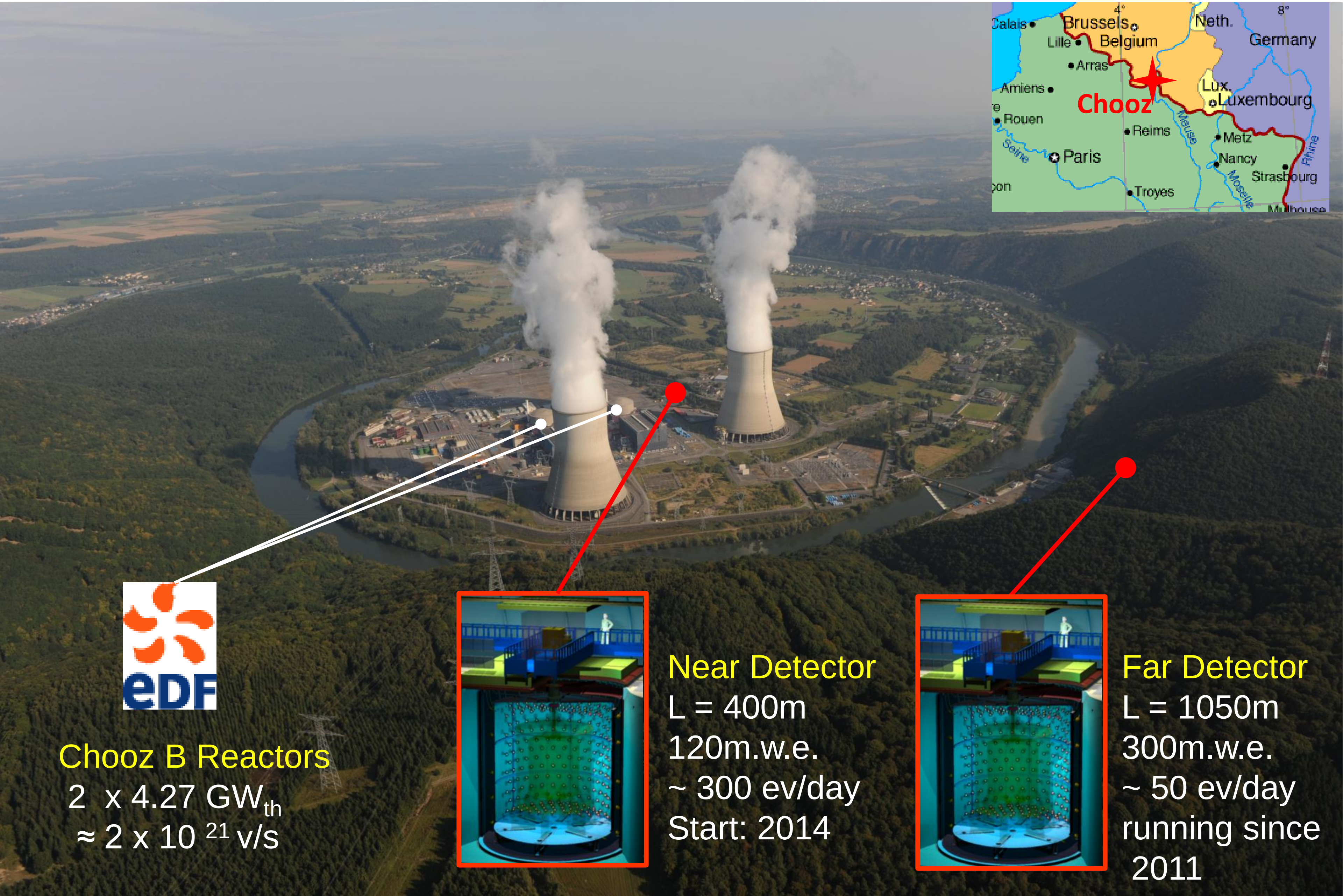
- E_ν < 10 MeV $\Rightarrow$ disappearance experiment
- look for rate deviation from $1/r^2$ and spectral distortions in 1-2 km
- clean measurement of θ_{13} , independent of δ-CP & matter effects
- reactor flux uncertainty ~2 % $\Rightarrow$ monitor absolute flux with near detector

$$P(\overline{\nu_e} \rightarrow \overline{\nu_e}) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E_{\bar{\nu}}}$$



The Double Chooz Experiment



Chooz B Reactors

2 x 4.27 GW_{th}

≈ 2 x 10^{21} ν/s

Near Detector

L = 400m

120m.w.e.

~ 300 ev/day

Start: 2014

Far Detector

L = 1050m

300m.w.e.

~ 50 ev/day

running since 2011

The Double Chooz 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 IT
- Tokyo Metro. U.
- Niigata U.
- Kobe U.
- Tohoku Gakuin U.
- Hiroshima IT

Russia
- INR RAS
- IPC RAS
- RRC Kurchatov

Spain
- CIEMAT-Madrid

USA
- U. Alabama
- ANL
- U. Chicago
- Columbia U.
- UCDavis
- Drexel U.
- IIT
- KSU
- LLNL
- MIT
- U. Notre Dame
- U. Tennessee

Spokesperson: H. de Kerret (APC)

Antineutrino Detection

Inverse Beta Decay (IBD) in Gd-loaded scintillator:

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

$$Q_{thr} = m_e + M_n - M_p \approx 1.8 \text{ MeV}$$

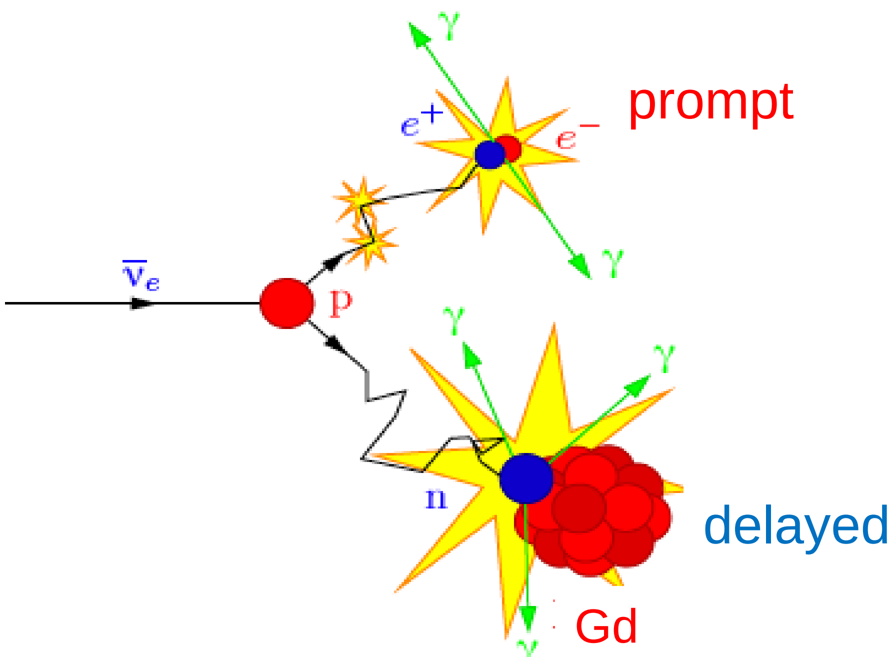
prompt event:

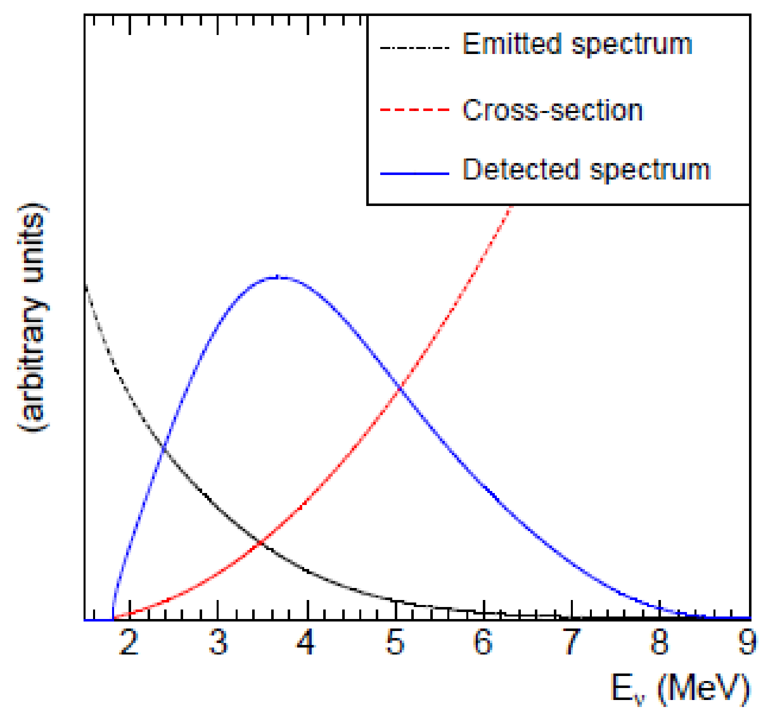
$$E_{vis} \cong E_\nu - E_n - 0.8\text{MeV}$$
$$\approx 1-10 \text{ MeV}$$

delayed event:

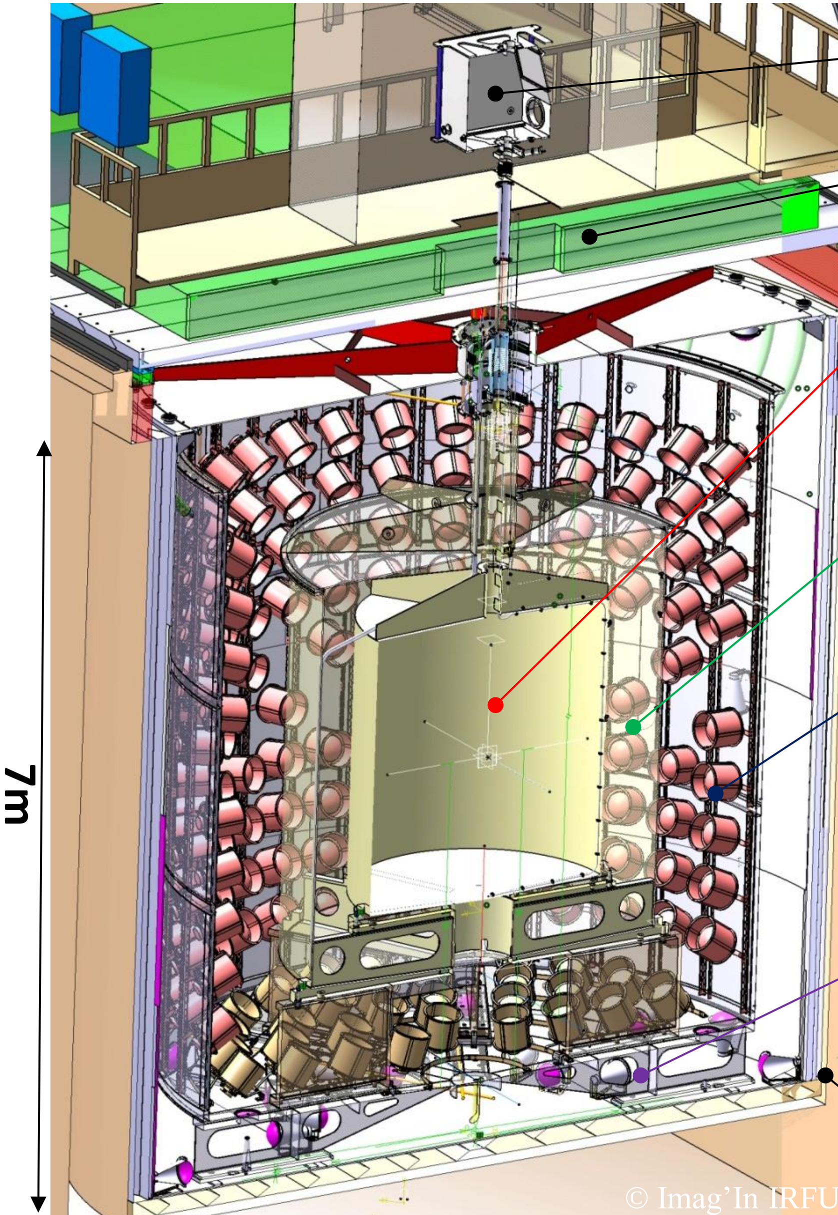
$$n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma\text{'s } (\sim 8\text{MeV})$$

$$E_{delayed} \sim 8\text{MeV} \qquad \tau \sim 30\,\mu\text{s}$$





Detector Design



- Calibration glove box
- **Outer Veto:** plastic scintillator strips
- **Neutrino Target**:

  10.3 m^3 Gd-loaded scintillator 0.1%
- **γ-Catcher**:

  22.4 m^3 unloaded scintillator
- **Buffer**:

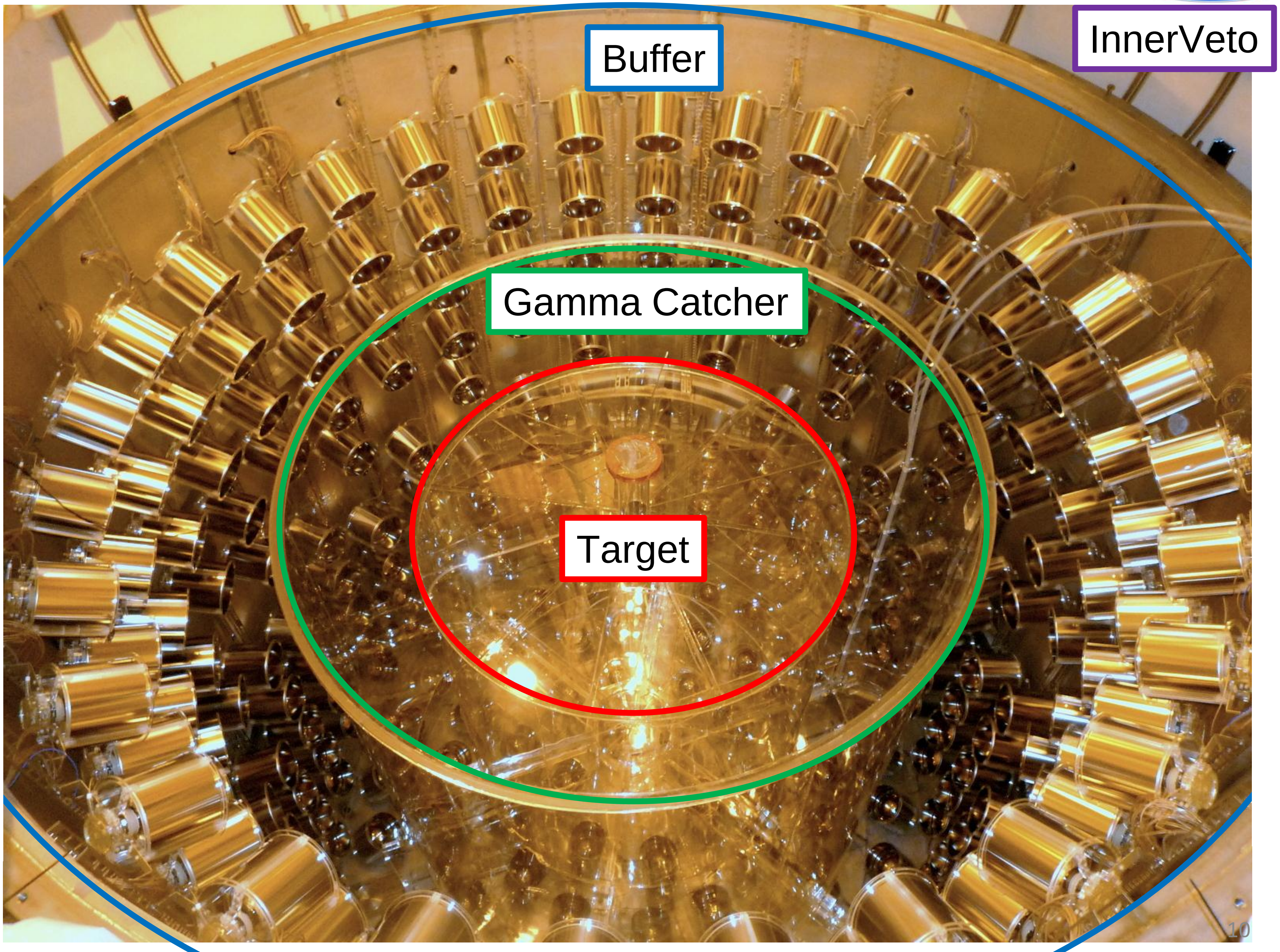
  100 m^3 non-scintillating mineral oil

  390 10" PMTs
- **Inner Veto**:

  90 m^3 liquid scintillator

  78 8" PMTs
- **Steel Shielding** (15 cm, 250 t)

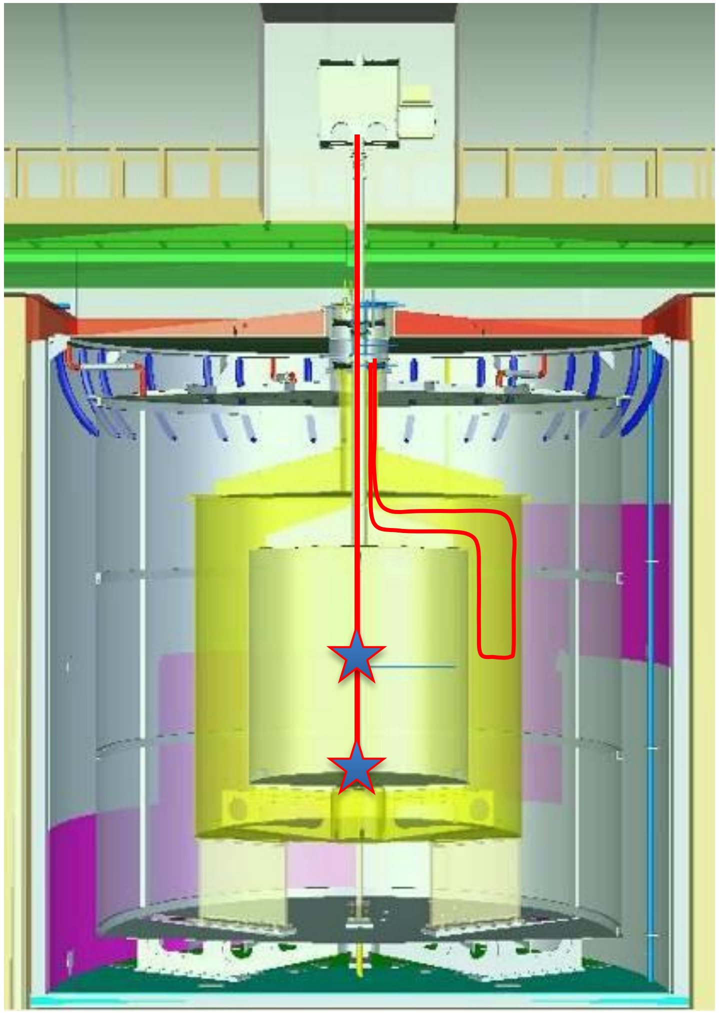
View inside the detector



Detector Calibration

Energy calibration

1. PMT and electronics gain non-linearity
   – LED light injection system
2. Correction for position dependence & time stability
   – spallation neutron captures on H and Gd
3. Energy scale
   – radioactive sources (^{137}Cs, ^{60}Co, ^{68}Ge, ^{252}Cf) deployed into ν-target and γ-catcher



Neutron detection efficiency

energy & time window, Gd fraction, spill in/out effects

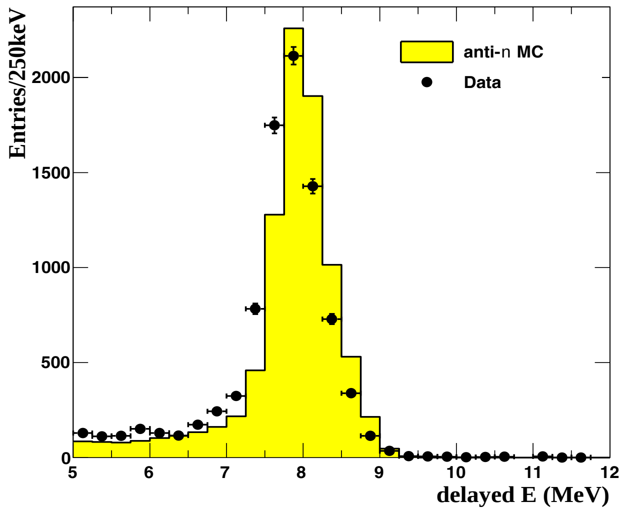
– ^{252}Cf source deployed into ν-target and γ-catcher

Gd and H analysis

Two channels are used for the neutrino detection

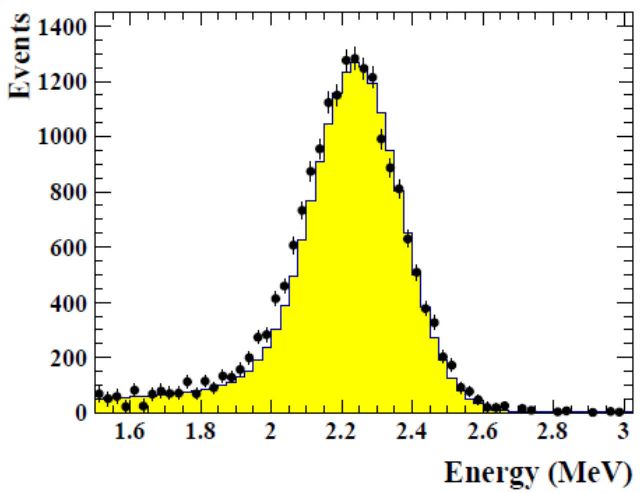
„Standard“ Gd analysis:

- high cross section for capture of thermal neutrons
- capture time τ ≈ 30 μs
- delayed energy: 8 MeV



H analysis: n+p →d + **γ** (2.2 MeV)

- Target + Gamma Catcher
  => 3 x more volume (2 x statistics)
- capture time: τ ≈ 180 μs
- delayed energy: 2.2 MeV
  ⇒ background!
- different systematics



Neutrino Selection Cuts

Gd selection cuts	H selection cuts
Energy:	
• E_{prompt} [0.7; 12] MeV	• E_{prompt} [0.7; 12] MeV
• $\mathbf{E_{delayed}}$ **[6; 12] MeV**	• $\mathbf{E_{delayed}}$ **[1.5; 3.0] MeV**
Coincidence:	
• time coincidence: **Δt [2, 100] μs**	• **Δt [10, 600] μs**
• **no spatial coincidence cut**	• **ΔR < 90cm**
Multiplicity:	
• no other trigger in **[-100; 400] μs** from prompt event	• no other trigger in **[-600; 1000] μs** from prompt event

Muon veto:

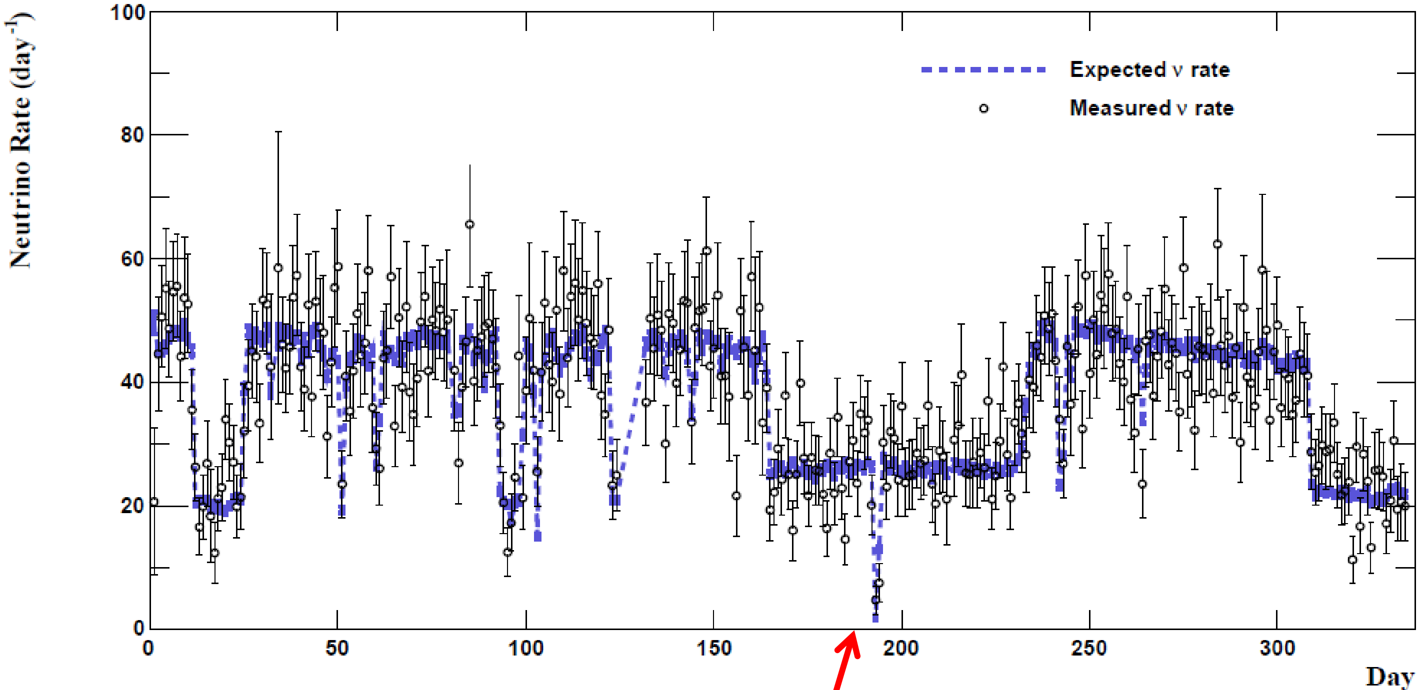
- 1 ms after each muon
- no coincidence with Outer Veto

Gd	H
• 0.5 s after a E>600 MeV muon	• (not applied)

PMT instrumental light emission:

- Q_{max}/Q_{tot} < 0.09 for prompt, < 0.06 for delayed
- $RMS(T_{start})$ < 40 ns

Neutrino candidates vs. time (Gd)



2 reactors on

1 reactor off

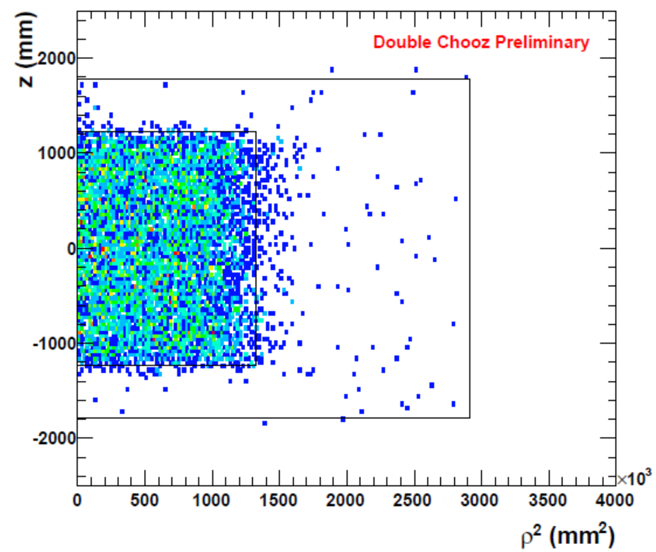
2 reactors off for 1 day

8249 candidates in 227.9 days

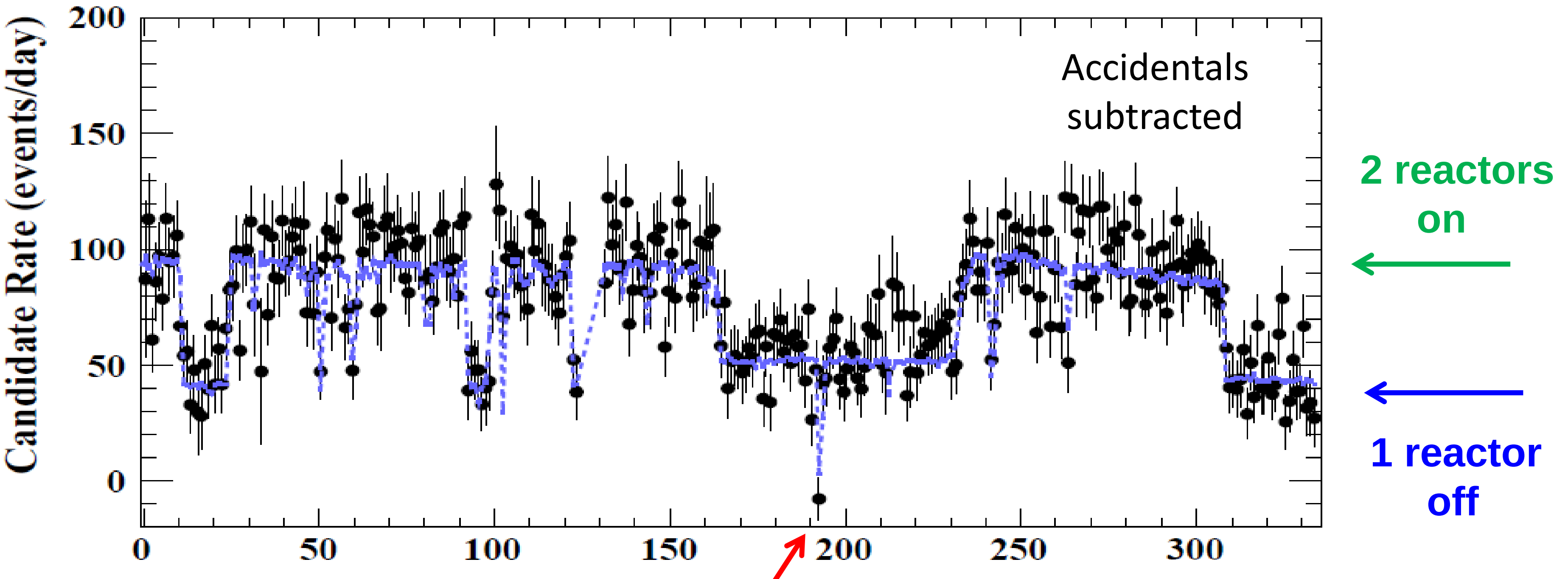
8440 expected for no-oscillation

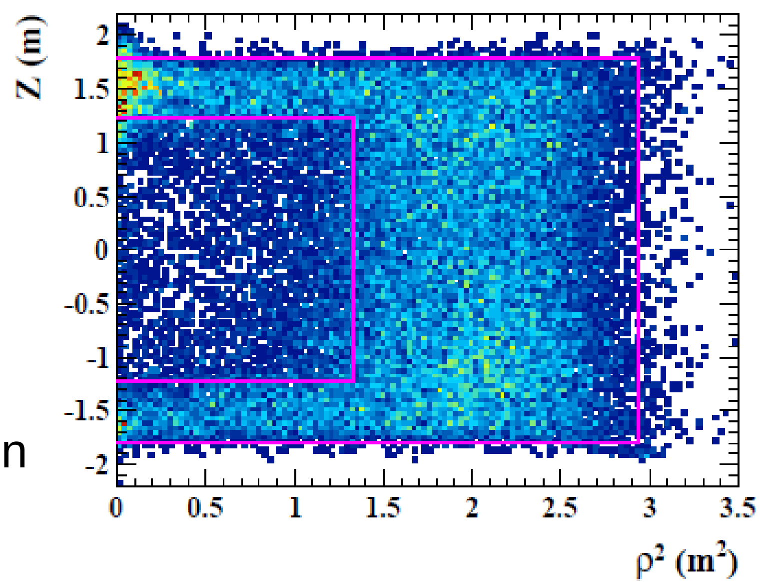
S/B ≈ 17

events are well localized in target region => no fiducial volume cut



Neutrino candidates vs. time (H)





36284 candidates in 240.1days

17690 expected for no-oscillation

S/B ≈ 1

95% of events in GC region

Accidental Background

rate can be calculated from single rates
or measured by offtime-window:
same cuts as for neutrino selection, but
coincidence time window shifted by 1 s

Accidental rate (Gd):

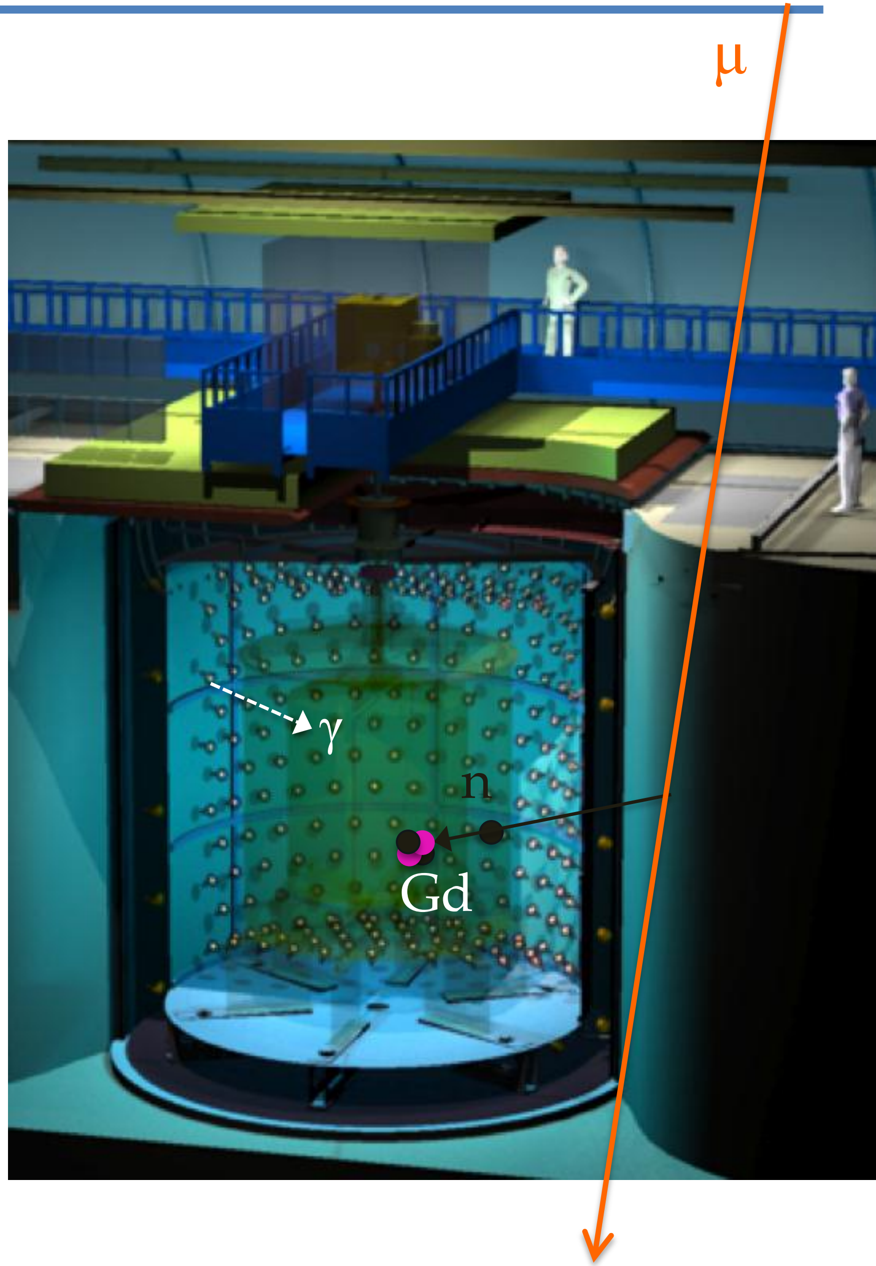
(0.261 ± 0.002) ev/day

factor 7 lower than proposal
(low background of detector components:
scintillator, PMTs…)

high accidental rate in nH-region
⇒ spatial cut ΔR<90 cm

Accidental rate (H):

(73.5 ± 0.2) ev/day



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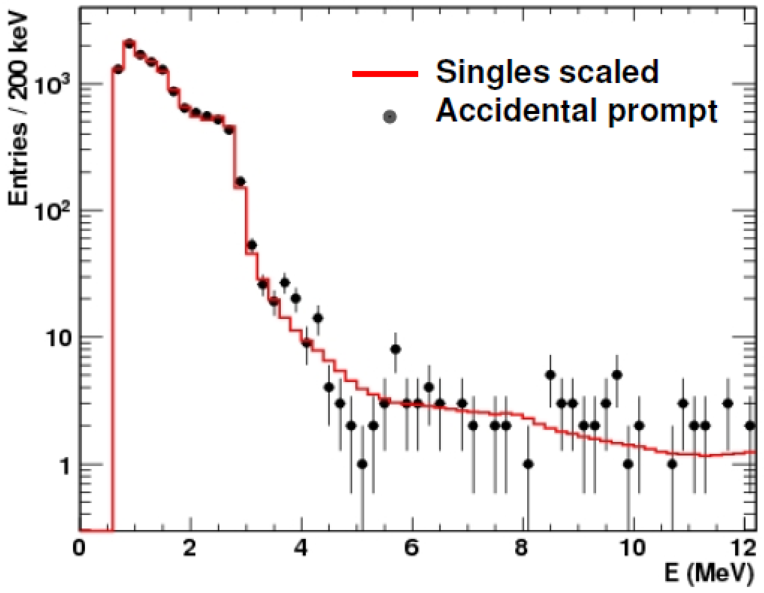

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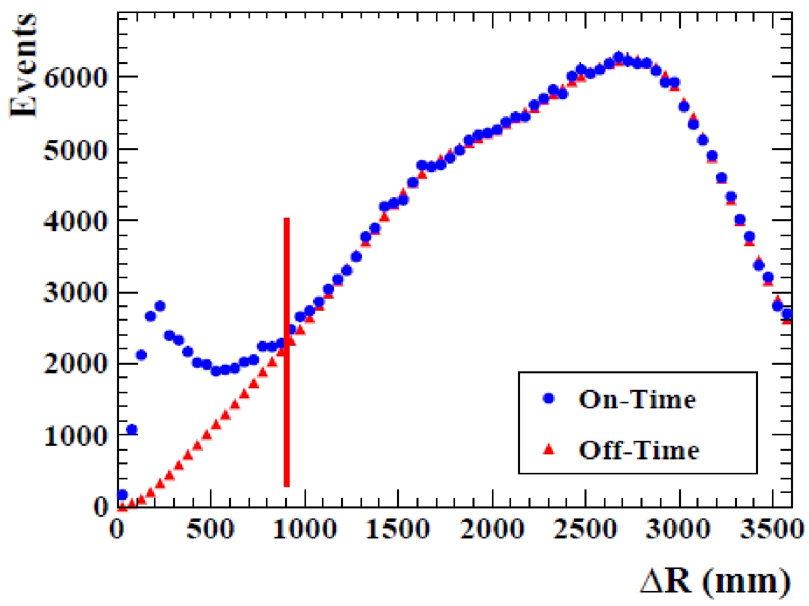

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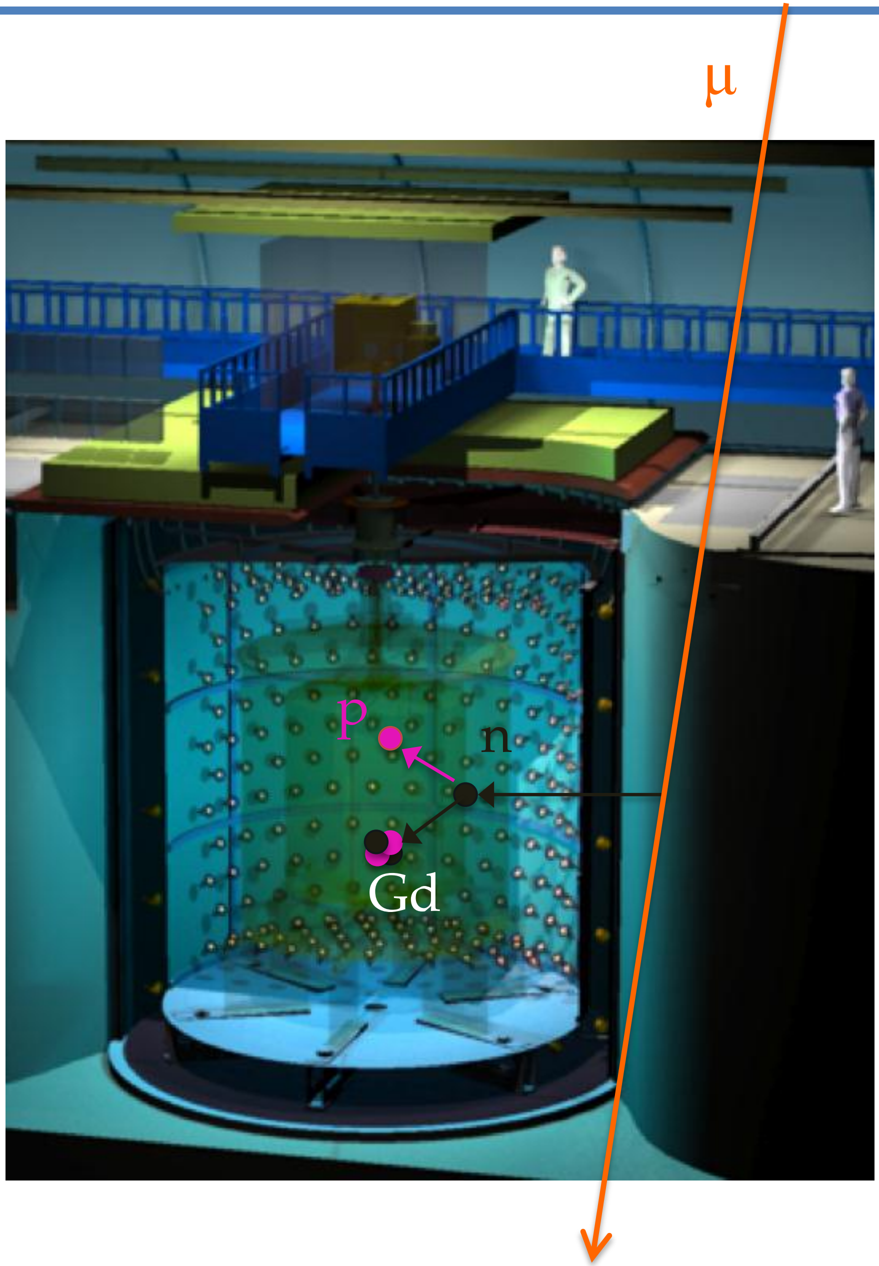
Fast neutrons and stopping muons



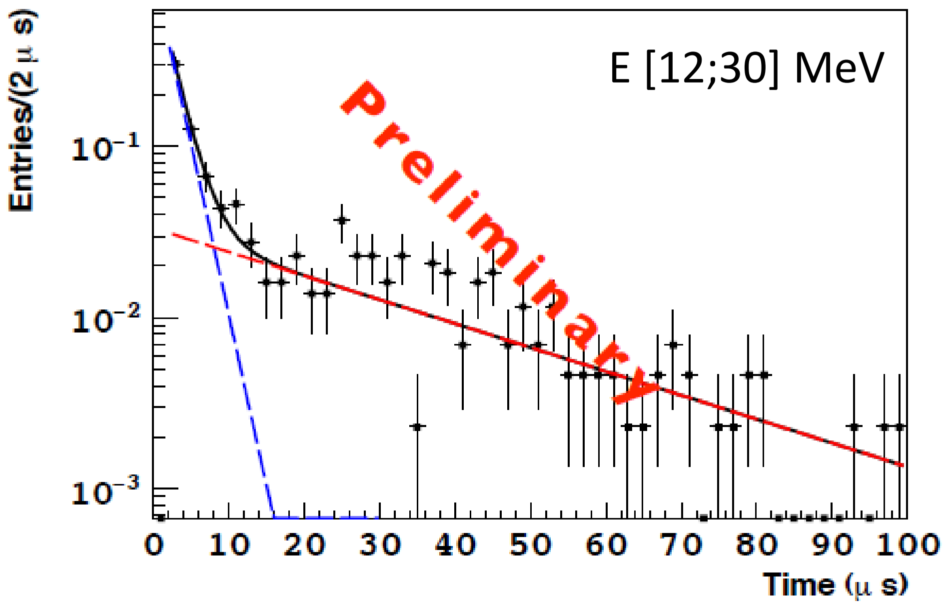
fast neutrons:
prompt event = proton recoil
delayed = neutron capture on Gd
τ = 30 μs

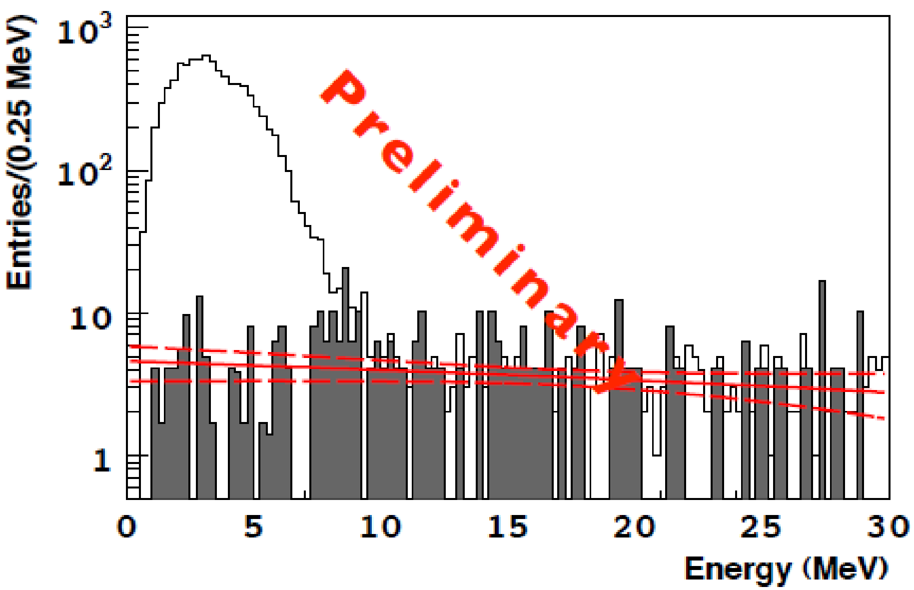
stopping muons:
prompt event = muon energy loss
delayed = muon decay (Michel electron)
τ = 2.2 μs

Background rate estimated from IV and OV coincident events:

0.7± 0.2 ev/day	**Gd**
2.5± 0.5 ev/day	**H** (only fast n)

Fast neutrons and stopping muons





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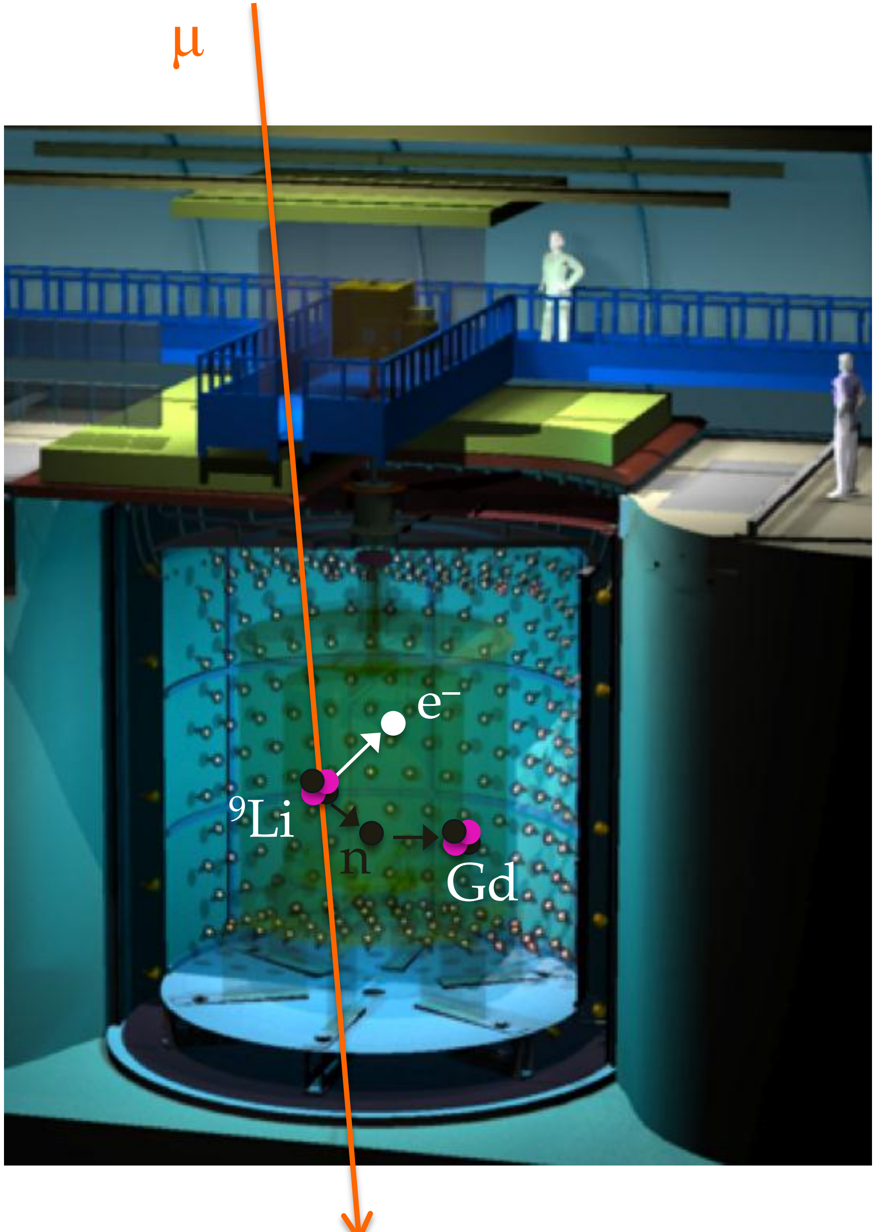
Correlated Background: ^{9}Li



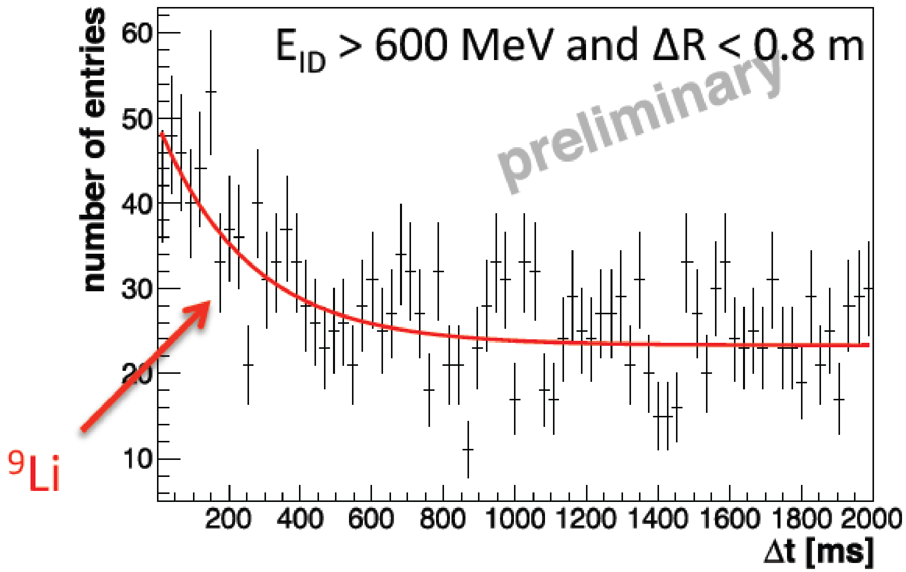
- ^{9}Li created by spallation through cosmic muon
- decay via beta-neutron-cascade: $^{9}Li \rightarrow {}^{8}Be + n + e^{-}$

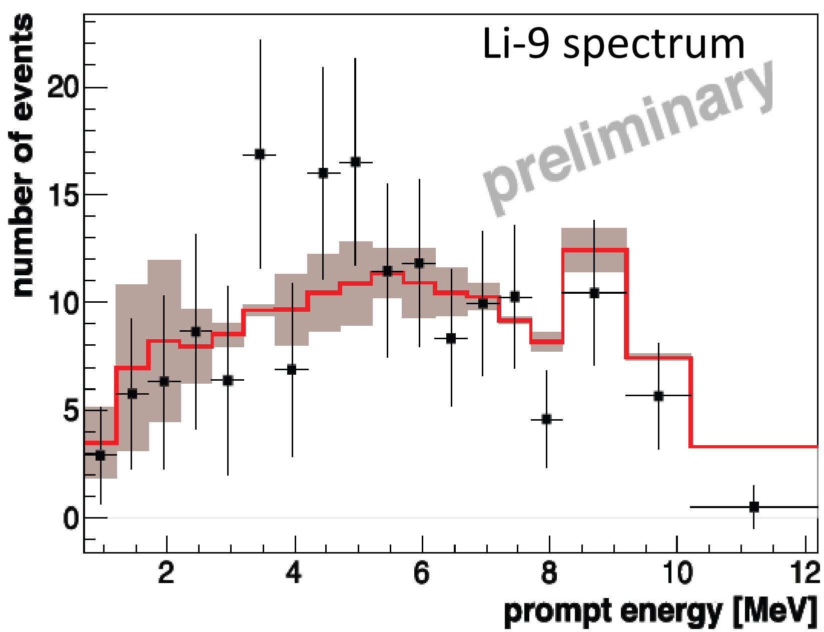
  τ = 257 ms , too long for veto
- background estimated from time and spatial coincidence with muons
- veto of 0.5 s after HE muon with E_{ID}> 600 MeV (only for Gd)
- **residual ^{9}Li-rate:**

  1.3 $\pm$ 0.5 ev/day Gd

  2.8 $\pm$ 1.3 ev/day H

Correlated Background: ^{9}Li





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  1.3 ± 0.5 ev/day Gd

  2.8 ± 1.3 ev/day H

Predicted neutrino rate

Far detector-only analysis relies on $\overline{\nu}_e$ rate prediction:

$$N_{\nu}^{exp}(E,t) = \frac{\varepsilon N_p}{4\pi} \times \sum_{R=1,2} \frac{1}{L_R^2} \frac{P_{th,R}(t)}{\langle E_f \rangle_R} \times \langle \sigma_f \rangle_R$$

Neutrino cross section per fission:

$$\langle \sigma_f \rangle = \langle \sigma_f \rangle^{Bugey} + \sum_k \left(\alpha_k^{DC}(t) - \alpha_k^{Bugey} \right) \langle \sigma_f \rangle_k$$

k = fuel isotopes
^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

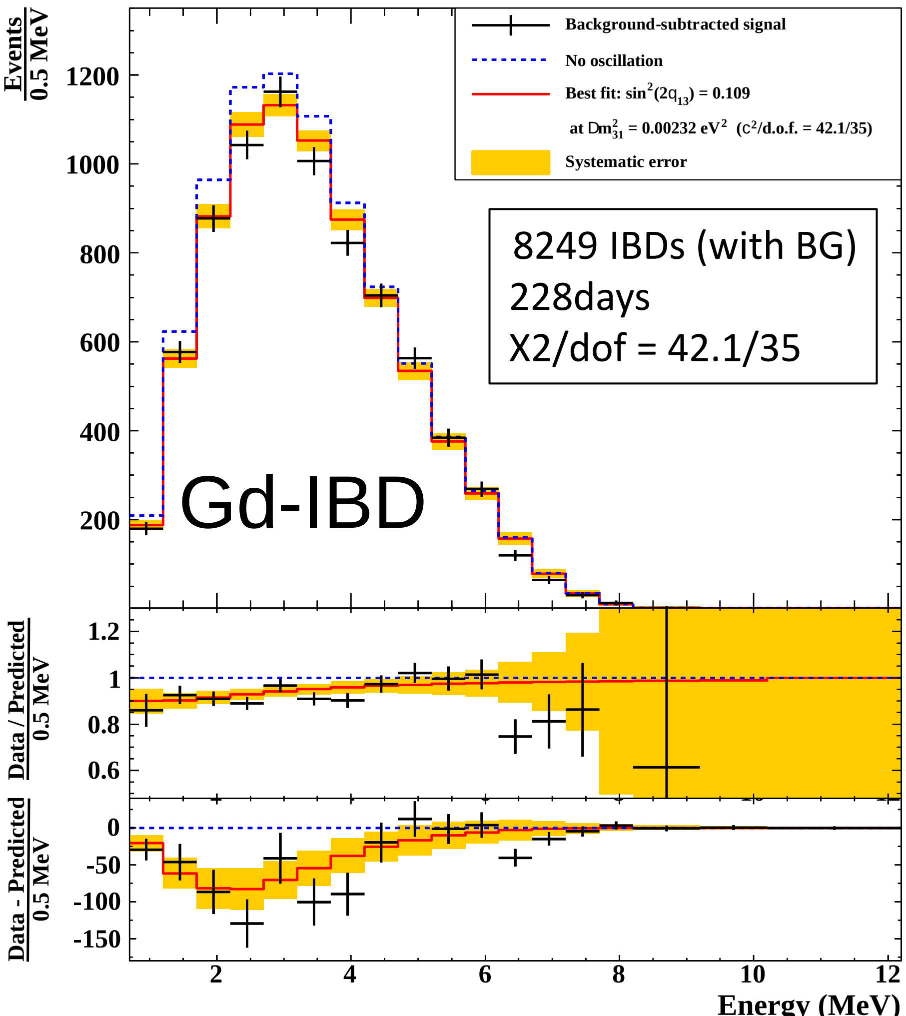
Bugey4 measurement as anchor point

Fission fraction in CHOOZ core

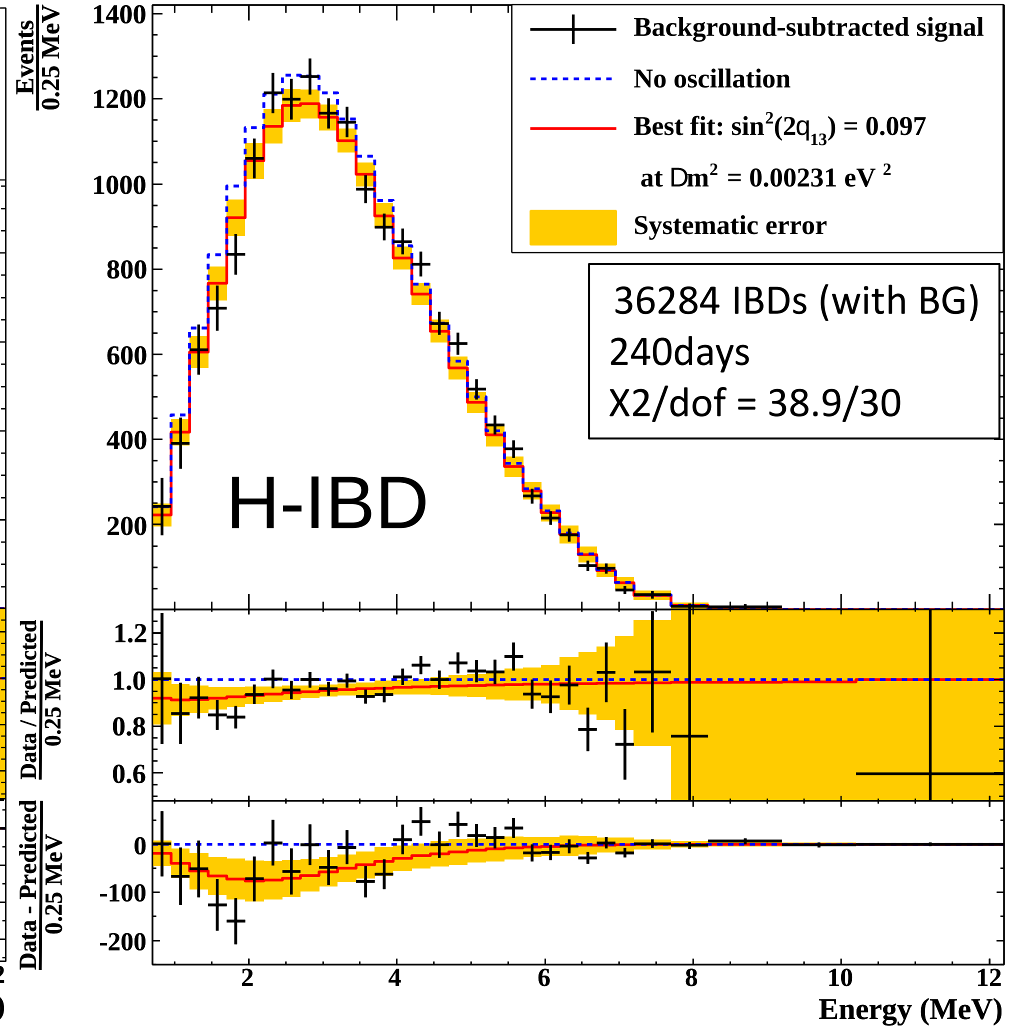
Uncertainty on neutrino flux suppressed using Bugey4 measurement (at L=15m): 2.7% →1.8%

Rate & Shape Analysis

Phys. Rev. D86 (2012) 052008



Phys. Lett. B723 (2013) 66-70



Rate+Shape fit:

$\sin^2 2\theta_{13} = 0.109 \pm 0.039$

$\sin^2 2\theta_{13} = 0.097 \pm 0.048$

Reactor Off measurement

Phys. Rev. D 87, 011102 (2013)

- Unique capability of Double Chooz: **background measurement** with both reactors off
- Two reactor off-off periods so far:

  Oct.2011, **0.84 days** (live time)

  Jun.2012, **6.00 days** (live time)

- **for Gd selection:**

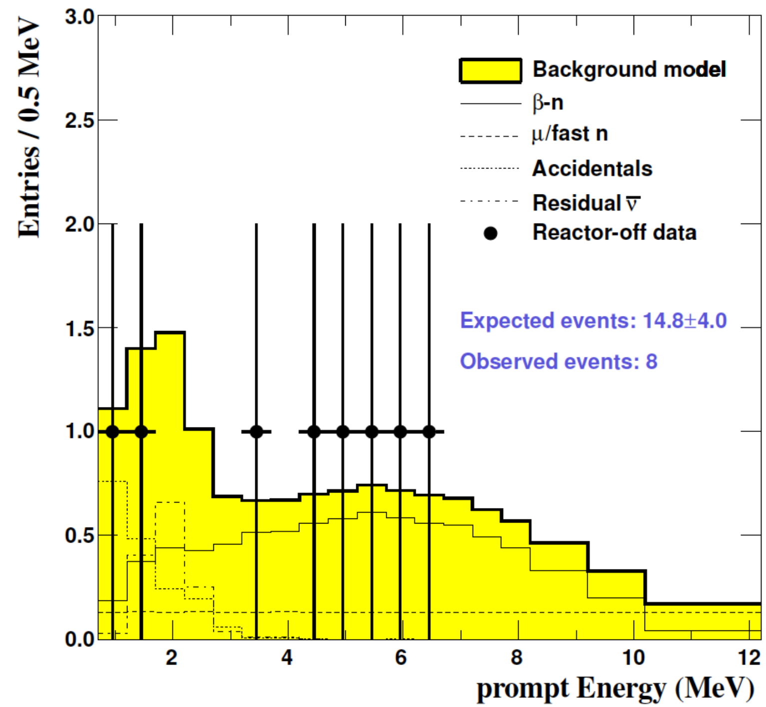
  Observed rate: **1.0 ± 0.4 evt/d**

  Expected rate: **2.0 ± 0.6 evt/d**

- **for H selection:**

  Observed rate: **11.3 ± 3.4 evt/d**

  Expected rate: **5.8 ± 1.3 evt/d**



new constraint for oscillation fits

NEW:

Combined Gd and H analysis

Correlation Coefficients	
Accidental bg	0
Correlated bg	0
^{9}Li rate	0.003
^{9}Li shape	1
efficiency	0.09
Energy scale	0.4
Reactor flux	1

First combined Gd and H fit:

- data set from April 2011- March 2012
- include backgr. constraints by reactor off-off
- fit includes correlation of systematic errors

Preliminary Result:

Gd result for comparison:

Rate+Shape fit:

$\sin^2 2\theta_{13} = 0.109 \pm 0.035$ $\chi^2/\text{dof} = 61.2/50$

$\sin^2 2\theta_{13} = 0.109 \pm 0.039$

Rate-only fit:

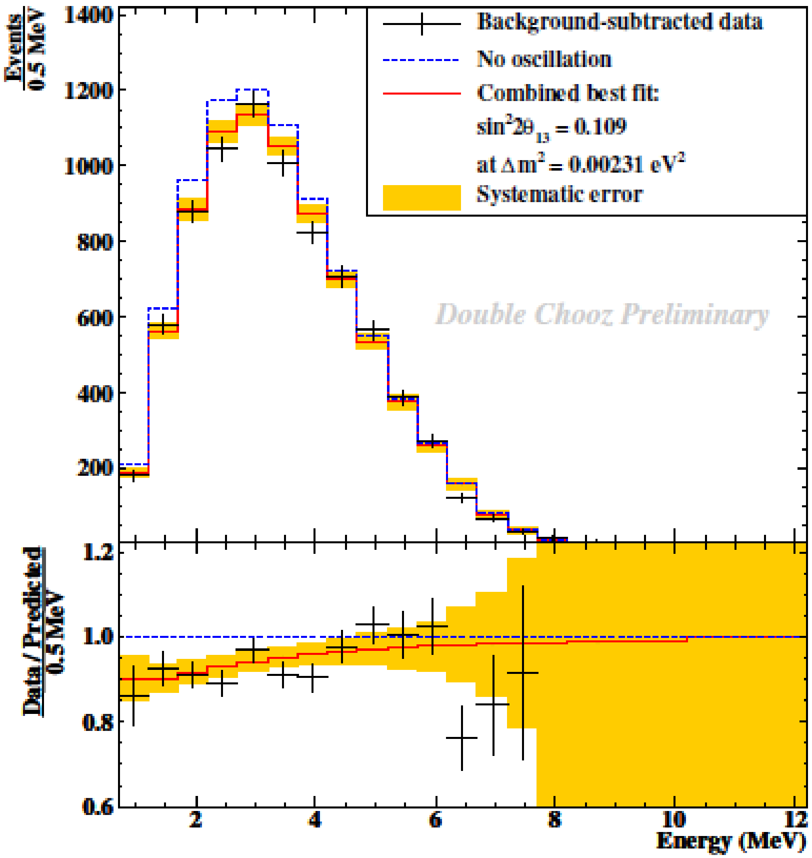
$\sin^2 2\theta_{13} = 0.107 \pm 0.045$ $\chi^2/\text{dof} = 6.1/3$

$\sin^2 2\theta_{13} = 0.170 \pm 0.052$

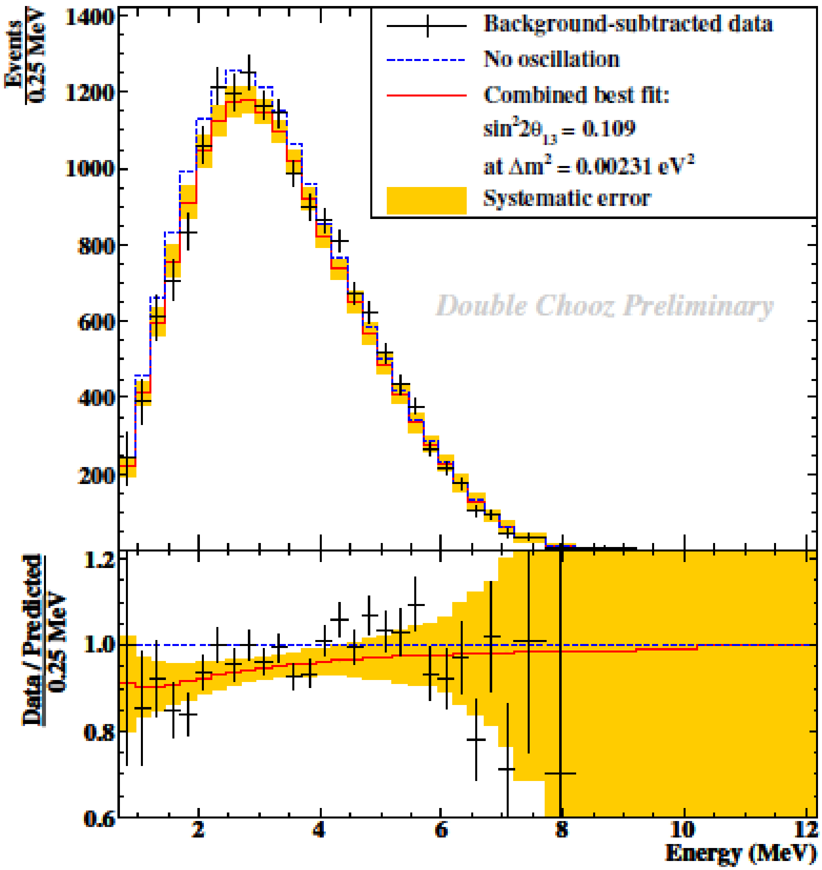
NEW:

Combined Gd and H analysis

Gd data



H data



Combined Rate+Shape fit:

$\mathbf{sin^2 2\theta_{13} = 0.109 \pm 0.035}$ $\chi^2/dof = 61.2/50$

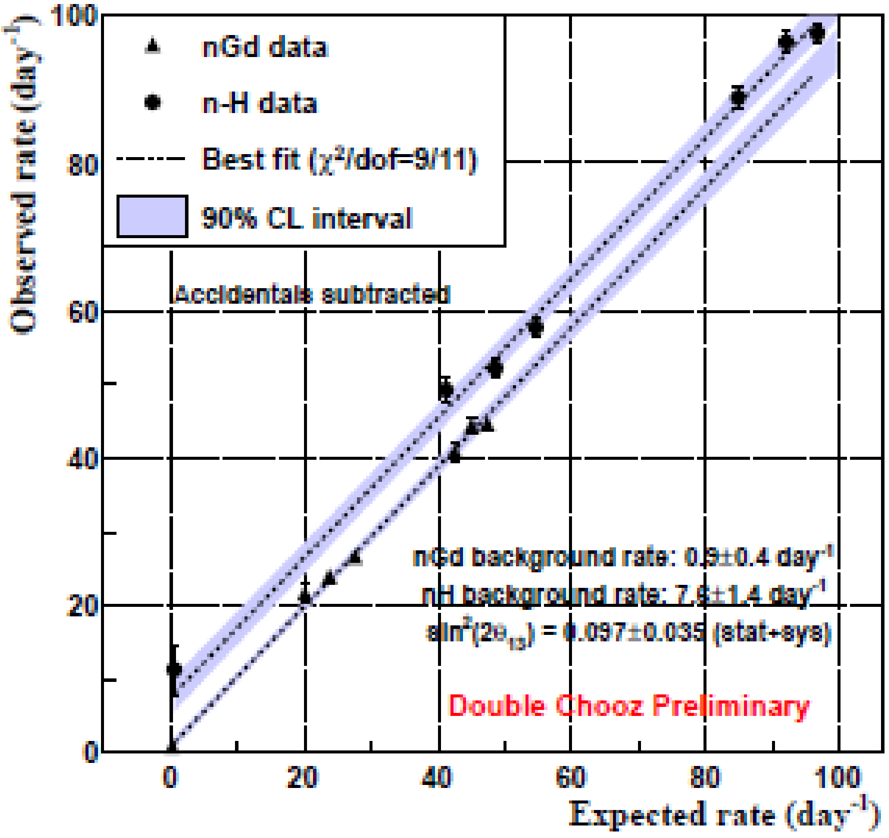
NEW: Reactor Rate Modulation Analysis

Rate only analysis with independent background estimation

including off-off data

no background model assumed

$$R_{obs} = B + \left(1 - \sin^2 2\theta_{13}\ \alpha_{osc}\right) R_{exp}^{noosc}$$



Combined Gd + H RRM analysis:

$\sin^2 2\theta_{13} = 0.097 \pm 0.035$

in agreement with rate+shape fit

B(nH) = 7.6 $\pm$ 1.4 ev/day

B(nGd) = 0.9 $\pm$ 0.4 ev/day

(accidentals subtracted)

The Future

Near detector

- construction ongoing
- expected to begin data taking spring 2014

Data analysis

- far detector only:

  working on combined analysis with expanded

  data set (~ 490 live days)

  projected sensitivity: σ~ 0.03

- with two detectors:

  reactor uncertainties nearly cancel

  projected final sensitivity σ~ 0.01

Conclusions & Outlook

$\theta_{13} \neq 0$ already established by first results from DC, Daya Bay and RENO

New results from Double Chooz using 11 months of data (April '11 – March'12):

Combined analysis of Gd and H data sets

$\mathbf{sin^2(2\theta_{13}) = 0.109 \pm 0.035}$

Reactor rate modulation analysis

$\mathbf{sin^2(2\theta_{13}) = 0.097 \pm 0.035}$

Future prospects towards a precise measurement of θ_{13} :

- working on improved far detector-analysis with ~ 2 x more statistics
- unique possibility of in-situ background determination during reactor-off-periods (1 week in 2012, more to come)
- first result with 2 detectors in 2014

Thank you for your attention!

Summary of Double Chooz results