# New Results of Double Chooz

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on behalf of **the Double Chooz Collaboration**

51st Rencontres de Moriond EW Session
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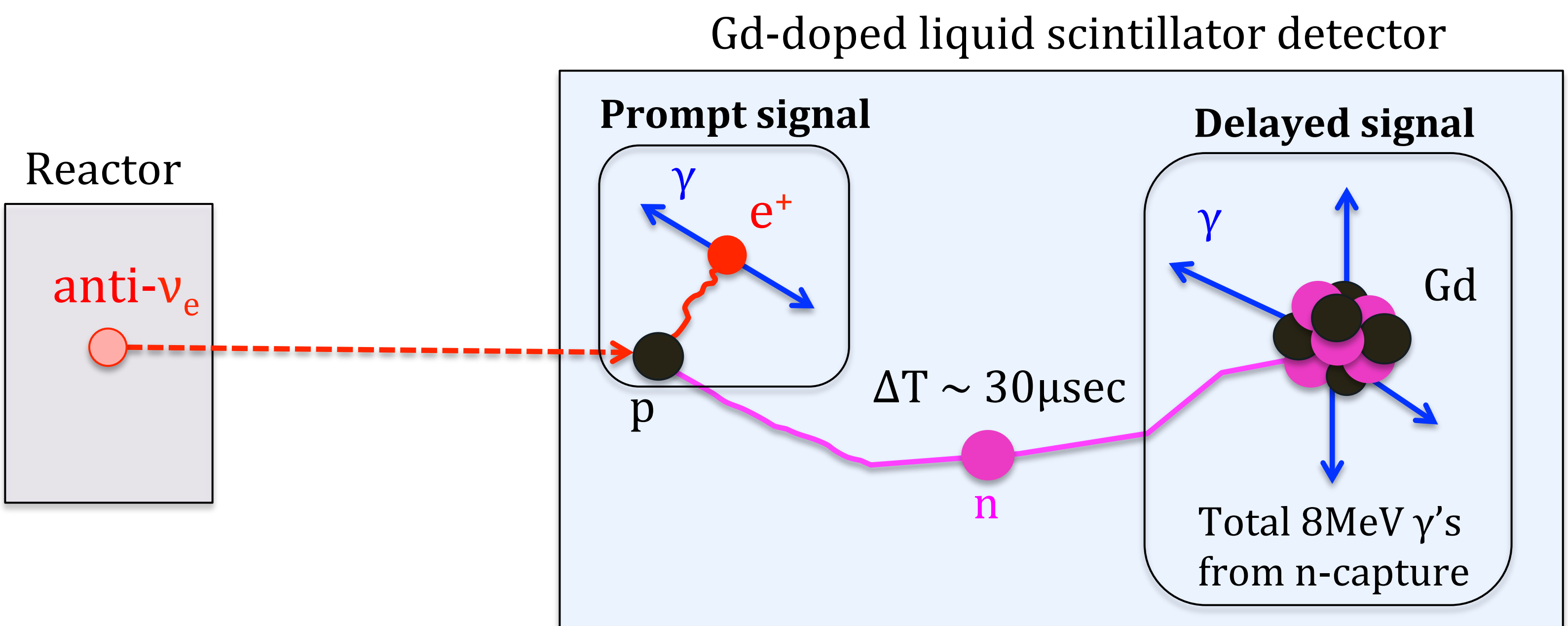
# Reactor neutrinos

- Reactor is a free and rich electron antineutrino source
  - β-decays in a commercial fission reactor core produce $10^{20}$ ν/sec
- Reactor anti-$\nu_e$ are detected via inverse β-decay (IBD) reaction
  - Cross-section well known
  - Prompt signal: positron + annihilation γ's ($E_\nu \sim E_{signal}$ + 0.8MeV)
  - Delayed signal: total 8MeV γ's from n-Gd (well above natural radioactivity)
  - Background is strongly suppressed by requiring time/space correlation



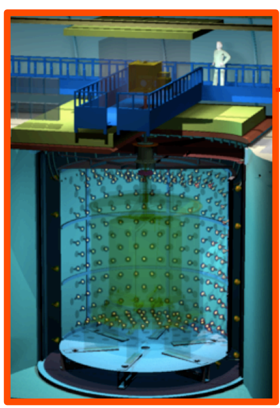
# Precision measurement of $\theta_{13}$

- Direct measurement of $\theta_{13}$ from energy dependent deficit
  - No parameter degeneracy/matter effects
- Suppression of systematic uncertainties (<< 1%) with multi-detectors at different baselines

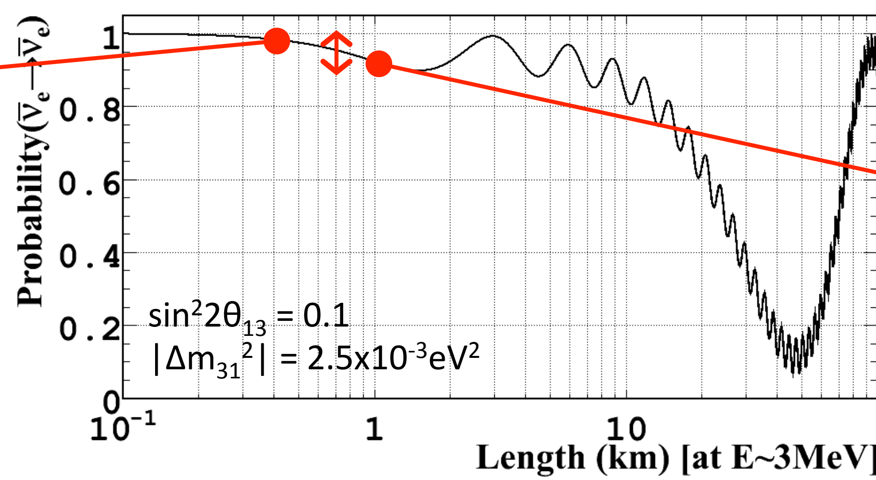
**Survival probability of reactor neutrinos**

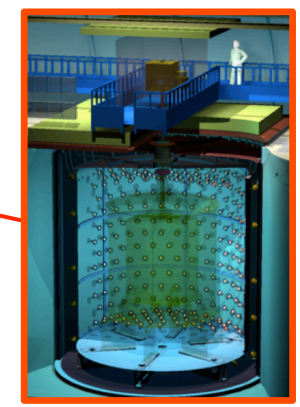
$$P\left[\overline{\nu_e} \rightarrow \overline{\nu_e}\right] \cong 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

… Simple two flavor oscillation formula is valid at L ~ 1km



Near Detector (ND)

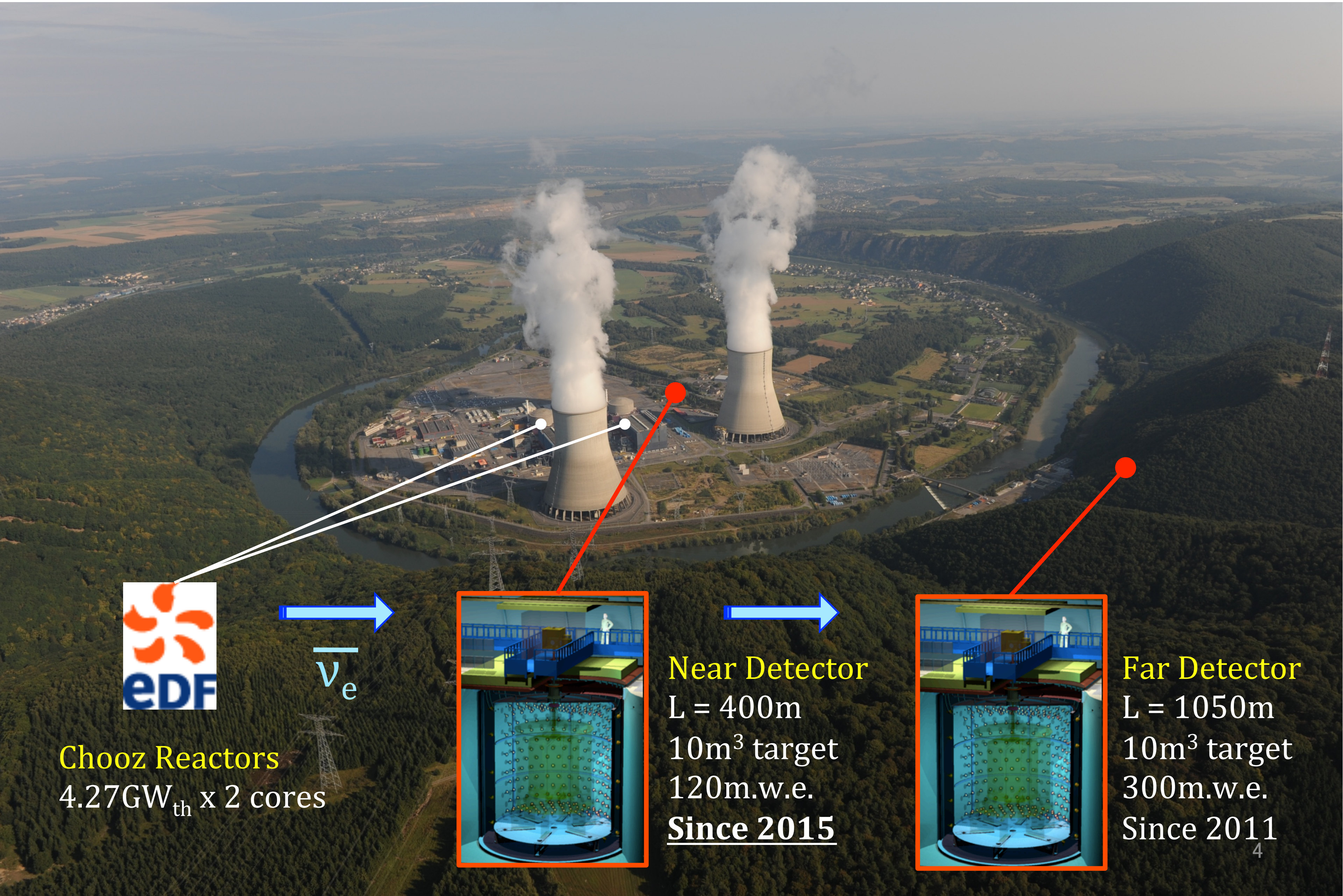


Far Detector (ND)

- Reactor $\theta_{13}$ (most precise) used as reference in current and future projects which aim to search for CP violation and mass hierarchy in neutrino sector.

# Double Chooz experiment



# 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 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
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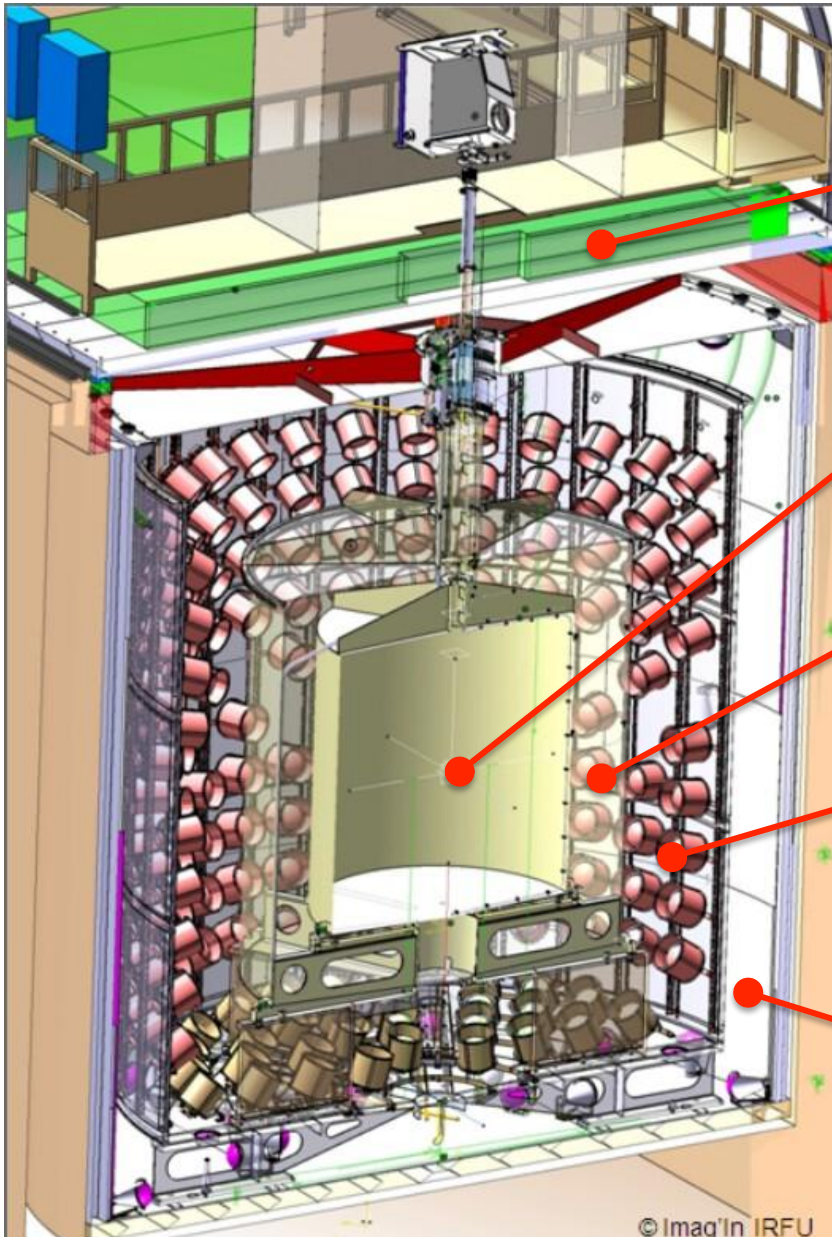
U. Tennessee

Spokesperson:
H. de Kerret (IN2P3)

Project Manager:
Ch. Veyssière (CEA-Saclay)

Web Site:
www.doublechooz.org/

# Double Chooz detector




**Outer Veto (OV):**
Plastic scintillator strips

**Inner Detector**

**ν-target (NT):**
- Gd loaded liquid scintillator (10m$^3$)

**γ-catcher (GC):**
- Liquid scintillator (22m$^3$)

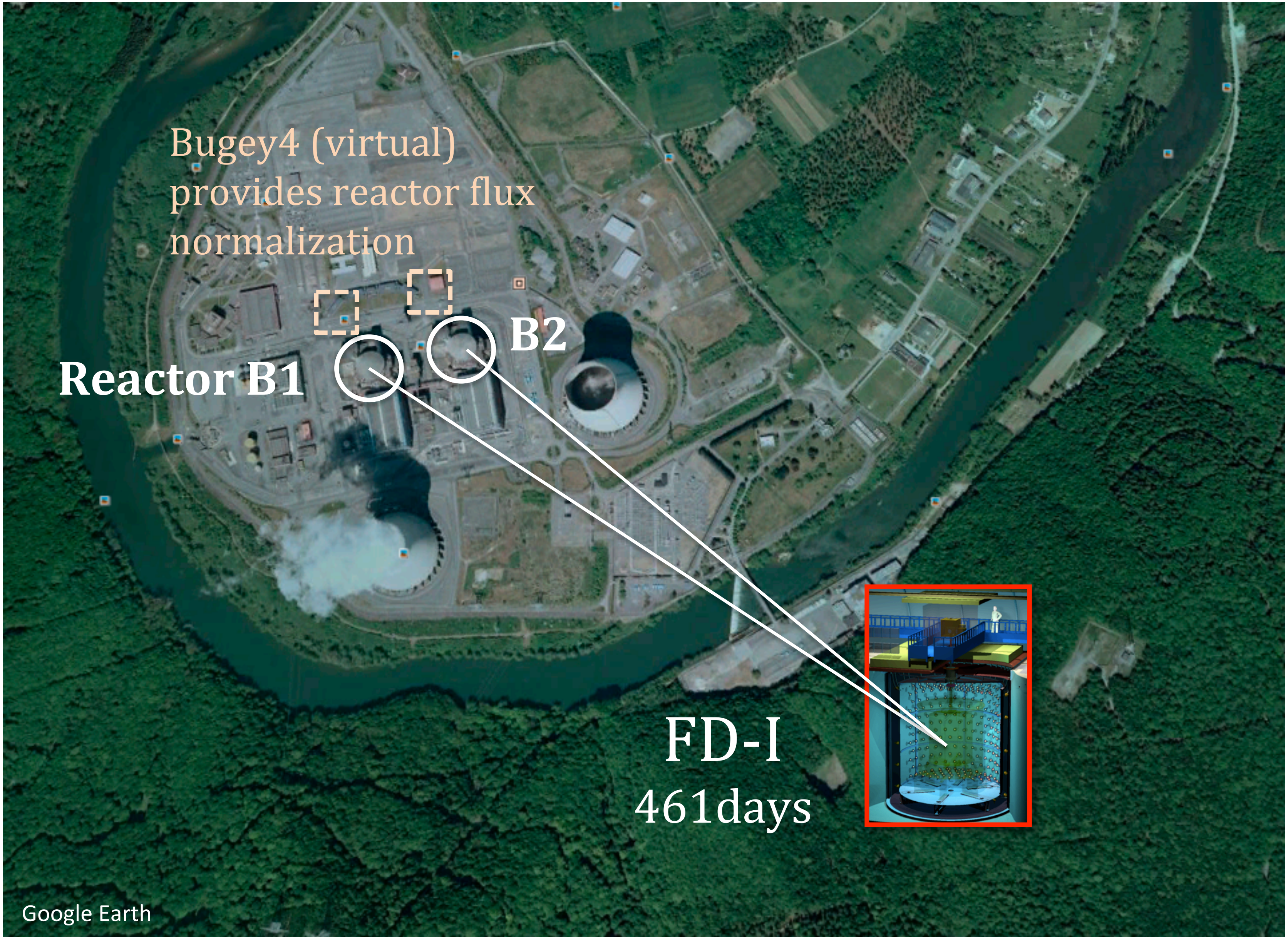
**Buffer:**
- Mineral oil (110m$^3$)
- 390 10-inch PMT

**Inner Veto (IV):**
- Liquid scintillator (90m$^3$)
- 78 8-inch PMT

# Double Chooz overview

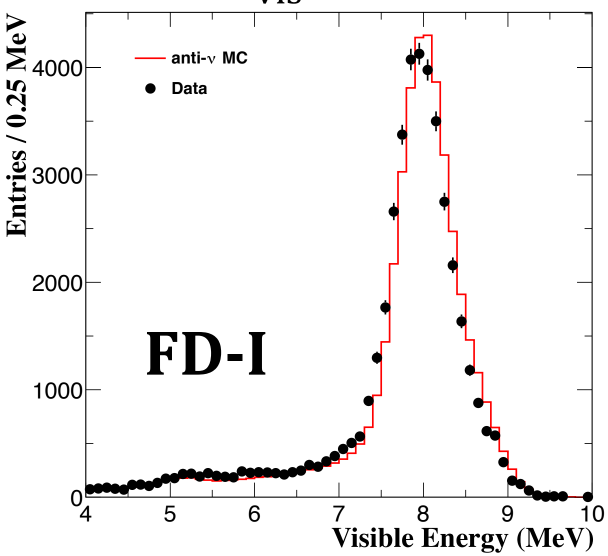
- Pioneered reactor experiments (improvements wrt CHOOZ)
  - Experimental concept to use two detectors
  - 4 layers detector structure ($\nu$-target, $\gamma$-catcher, buffer and IV)
  - Stable Gd loaded liquid scintillator developed
  - Precise measurement of reactor neutrinos with single far detector
    - Various vetoes → high purity IBD selection (n-Gd: S/N ~ 23, n-H: S/N~10)
    - Well controlled systematics at per-mille level (energy, detection, BG)
    - Use of Bugey4 as anchor of reactor flux normalization
- Achievements of Double Chooz
  - First $\theta_{13}$ in reactor oscillation since CHOOZ
    - Indication of non-zero $\theta_{13}$ at 94% CL (evidence at $3\sigma$ with LBL)
  - First $\theta_{13}$ using hydrogen capture signal
  - Observation of spectrum distortion at $E_\nu$ = 5-7MeV ($E_{signal}$ = 4-6MeV)
  - **$\theta_{13}$ measurement with multi-detectors: TODAY**

# Single detector analysis

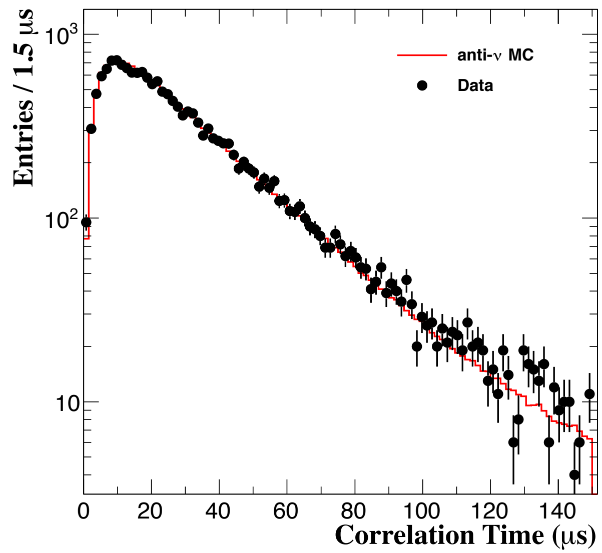


# IBD coincidence condition

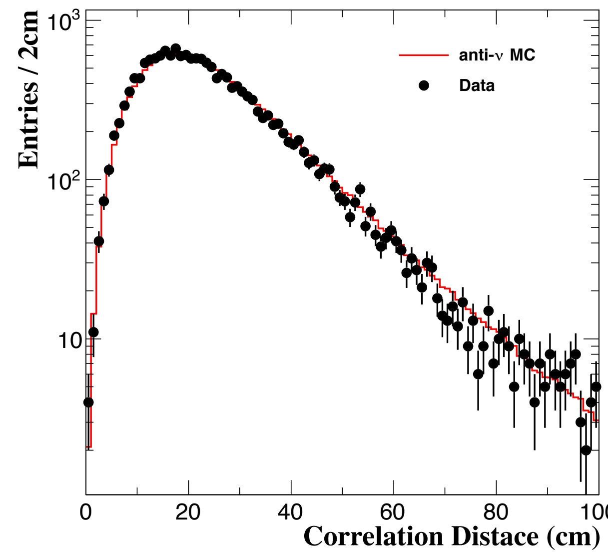
**Delayed signal energy**
$4 < E_{vis} < 10\text{MeV}$




**Correlation time**
$0.5 < \Delta T < 150\mu\text{sec}$




**Correlation distance**
$\Delta R < 100\text{cm}$




**⇒ Remaining BG**

Cosmogenic β-n emitter: $^9\text{Li} \rightarrow \alpha + \alpha + \mathbf{e} + \nu + \mathbf{n}$

Fast neutron: $n + p \rightarrow \mathbf{p} + \mathbf{n}$

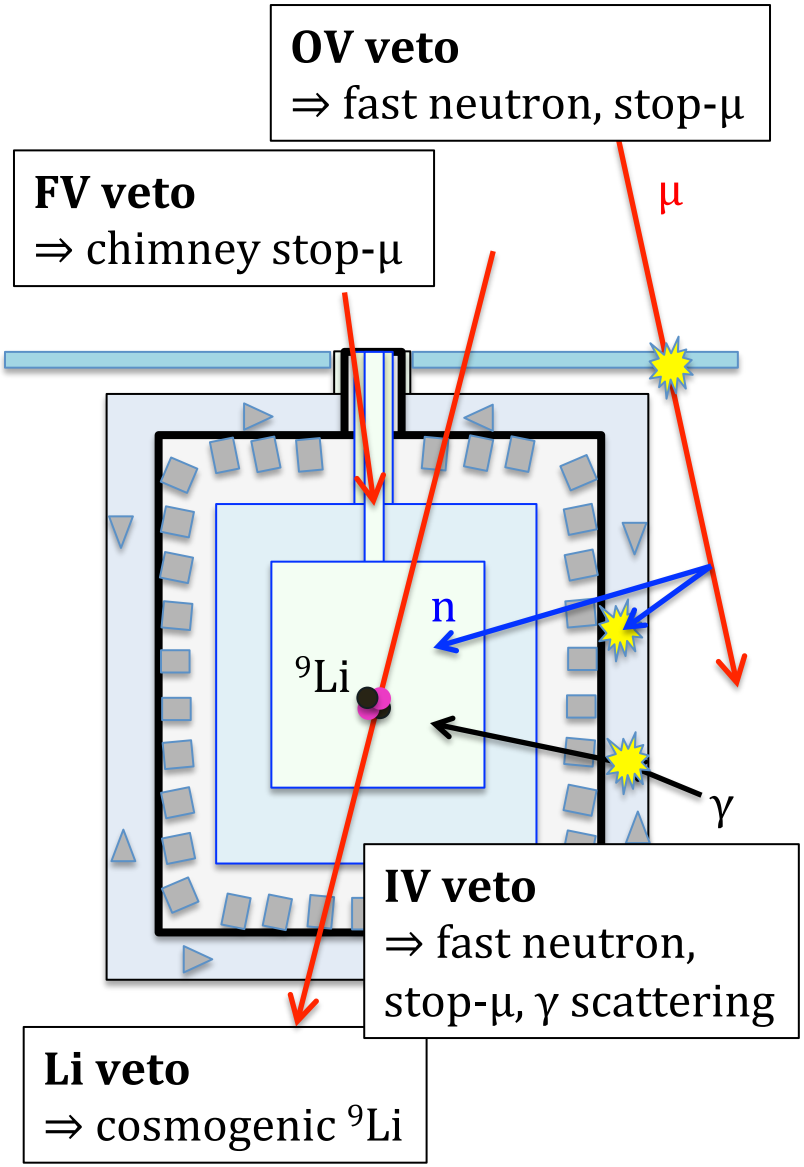
Stop-μ: $\boldsymbol{\mu} \rightarrow \mathbf{e} + \nu + \nu$

Accidental coincidence: e.g. **γ** + spallation **n**

Prompt

Delayed

# Background vetoes

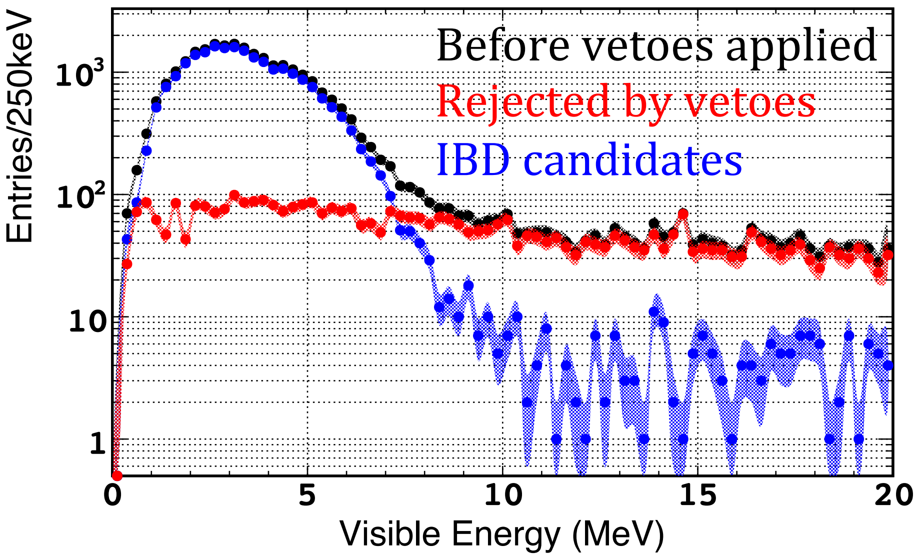



| Cut | Information used | Target of cut |
|---|---|---|
| μ veto | 1ms veto after μ | μ, cosmogenic |
| Multiplicity | unicity condition | multiple-n |
| FV veto | vertex likelihood | chimney stop-μ |
| IV veto | IV activity | fast n, stop-μ, γ scattering |
| OV veto | OV activity | fast n, stop-μ |
| Li veto | Li-likelihood | cosmogenic |
| LN cut | PMT hit pattern & time | light emission from PMT |
| (CPS veto) | chimney likelihood | stop-μ |
| (Qratio) | Max Q/Tot. Q | ND buffer stop-μ |

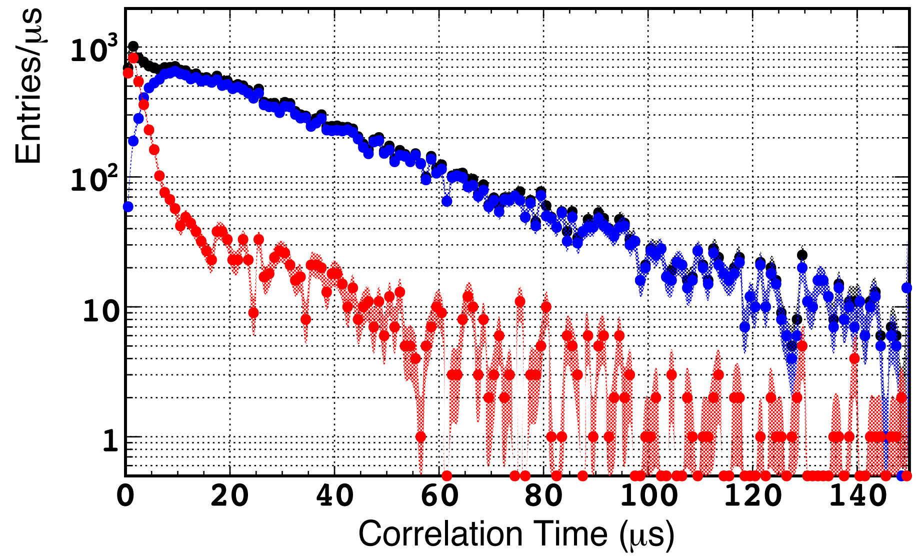
(only applied in multi-detector analysis)

# Background vetoes

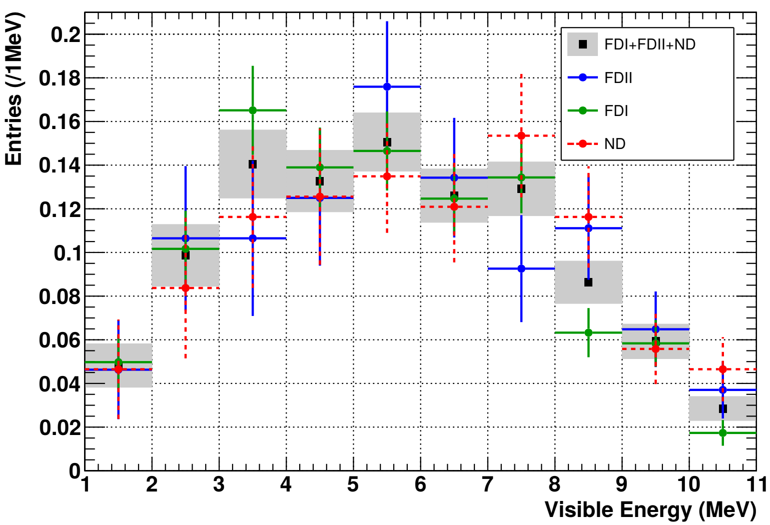
Prompt energy




Correlation time



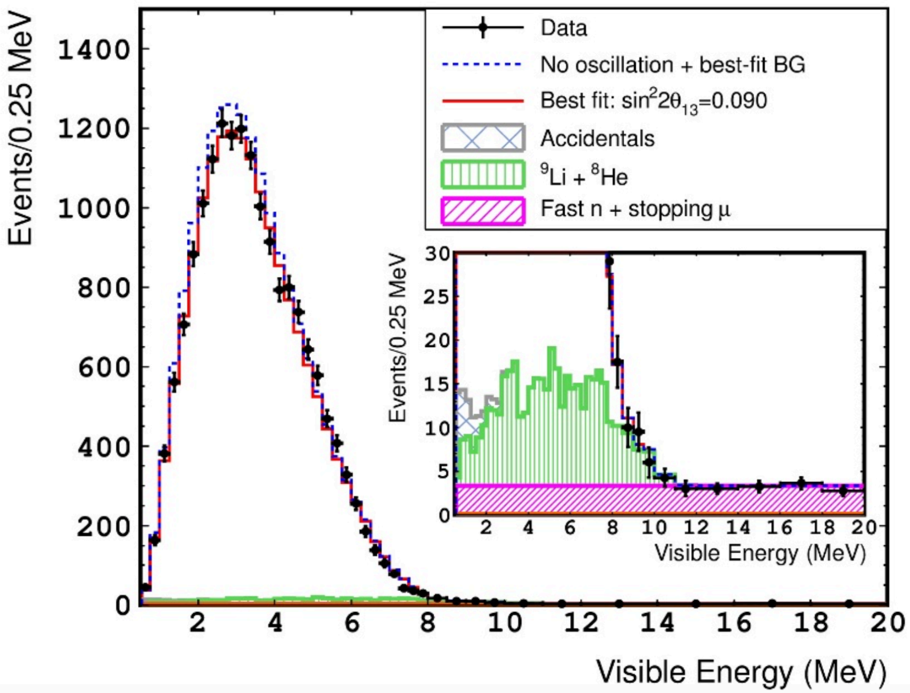

Prompt energy (rejected by Li veto)

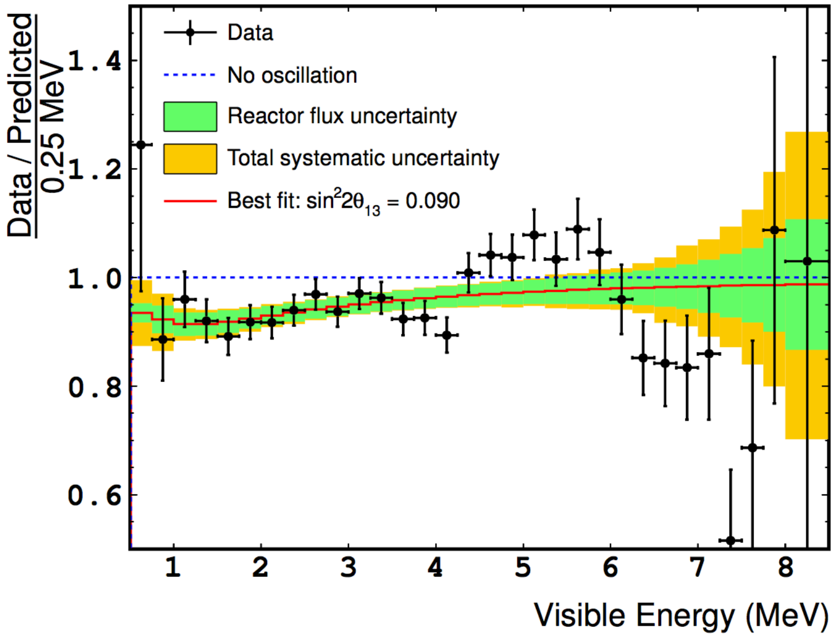



- Significant reduction of background: stop-μ, fast n, $^9$Li, natural radioactivity ⇒ Rejected (tagged) events are used to evaluate residual background
- IBD inefficiency: <1% (besides μ veto)

# Oscillation fit: rate + spectrum shape

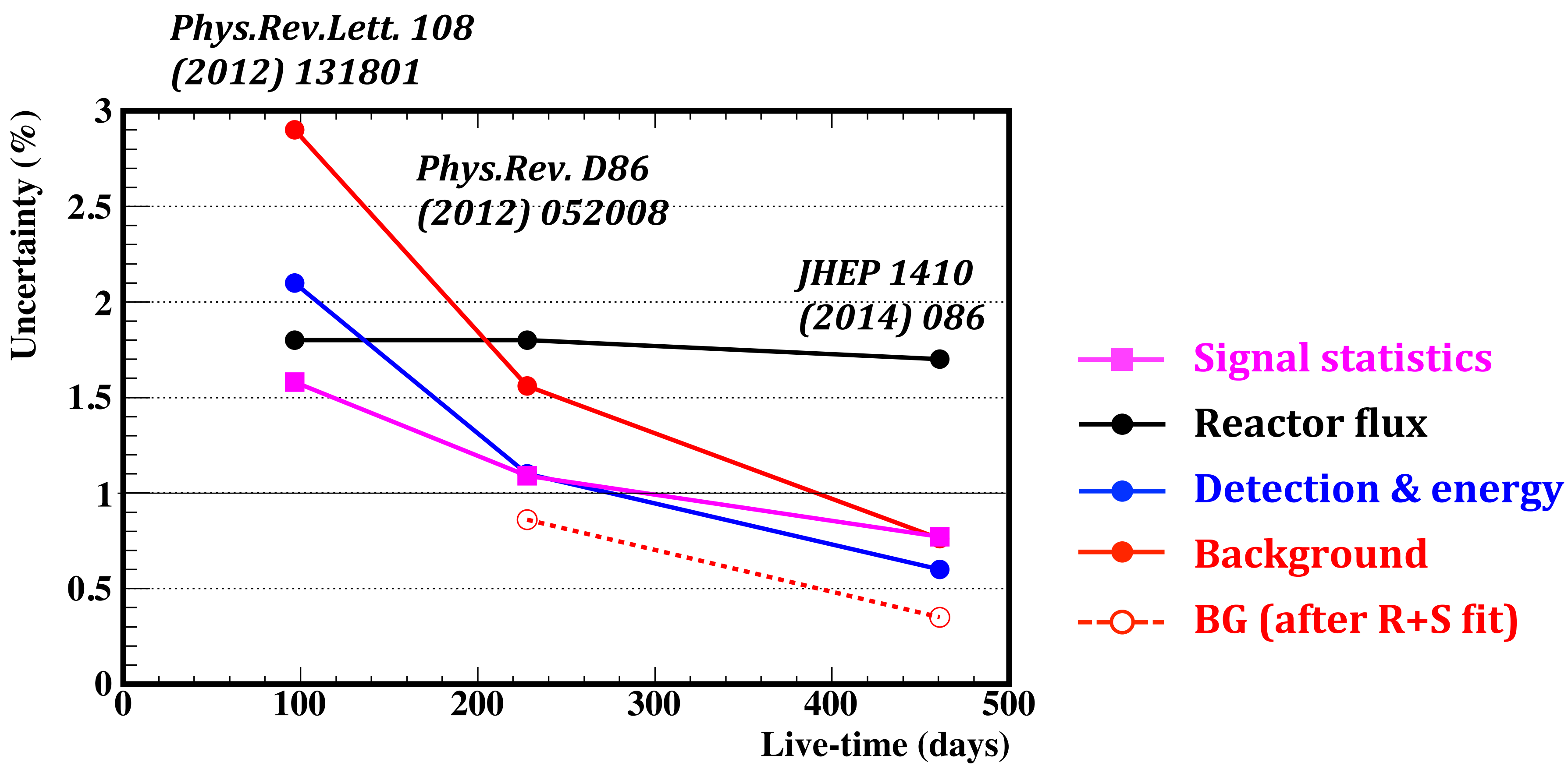
JHEP 1410 (2014) 086




- Background and other uncertainties constrained by shape information
  - $\mathbf{sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}}$
- **Unexpected spectrum distortion observed at 4-6MeV**
  - ✓ Negligible impact to $\theta_{13}$ measurement
  - ✓ Magnitude of excess proportional to reactor power
  - ✓ Same distortion later confirmed by RENO, Daya Bay and n-H capture in DC

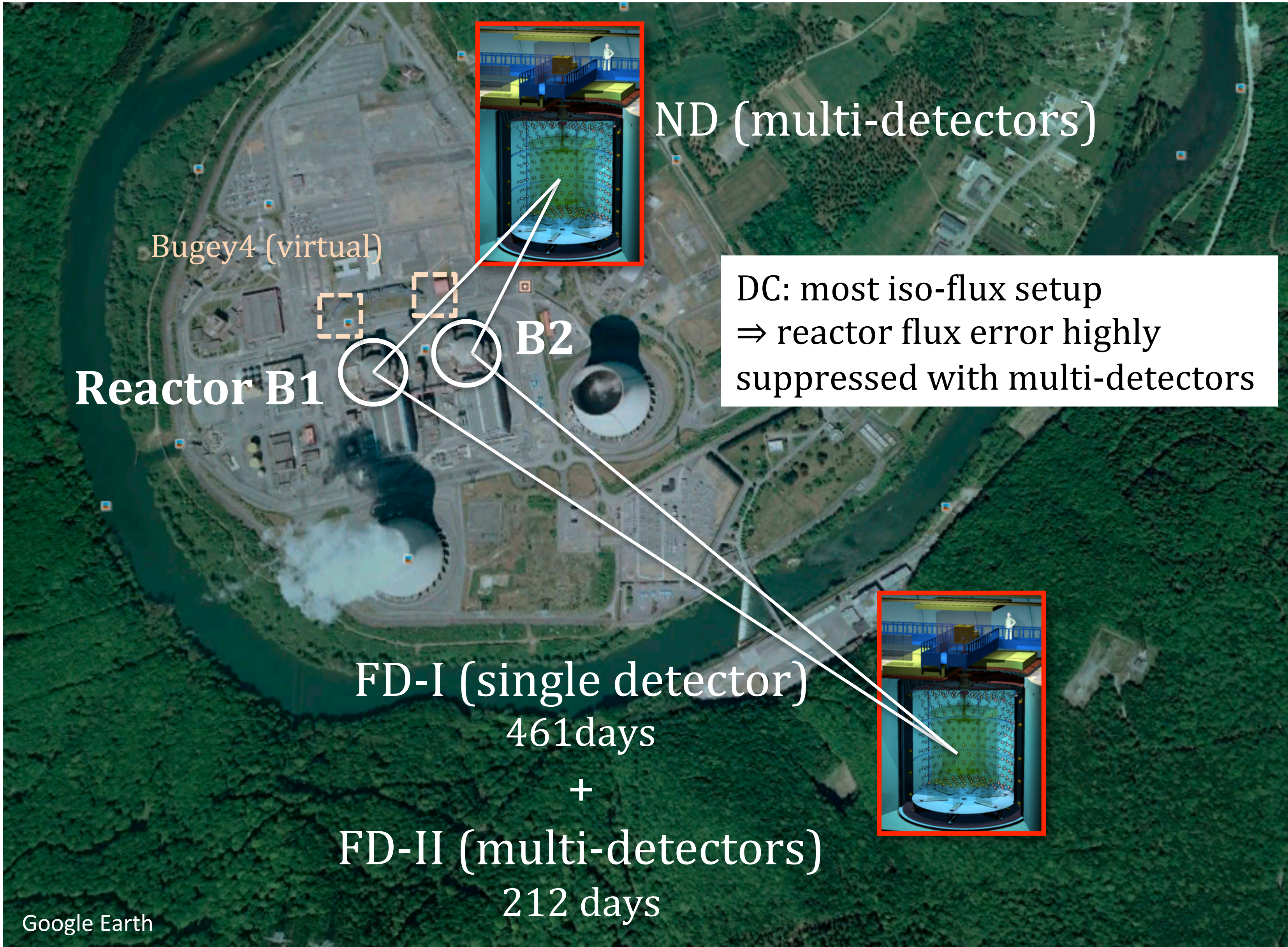
# Analysis improvements




- Detector and background uncertainties are suppressed to per-mille level by analysis improvements
  - Reactor flux uncertainty (1.7%) dominant in last FD-only analysis

⇒ Reactor flux and detection systematics to be suppressed with two detectors

# Multi-detectors analysis



# Reactor flux uncertainties

Double Chooz Preliminary

| | FD-I (%) | FD-II (%) | ND (%) |
|---|---|---|---|
| Bugey4 | 1.40 | 1.40 | 1.40 |
| Energy per fission | 0.16 | 0.16 | 0.16 |
| Spectrum⊕$\sigma_{IBD}$ | 0.20 | 0.20 | 0.20 |
| Baselines | < 0.01 | < 0.01 | 0.01 |
| Fission fraction ($\alpha_k$) | 0.82 | 0.74 | 0.73 |
| Thermal power ($P_{th}$) | 0.44 | 0.44 | 0.44 |
| **Total** | **1.70** | **1.66** | **1.66** |
| **ρ(FD-I:FD-II)** | **0.72 (0.90% relative)** | | |
| **ρ(FD-II:ND)** | | **>0.99 (0.07% relative)** | |

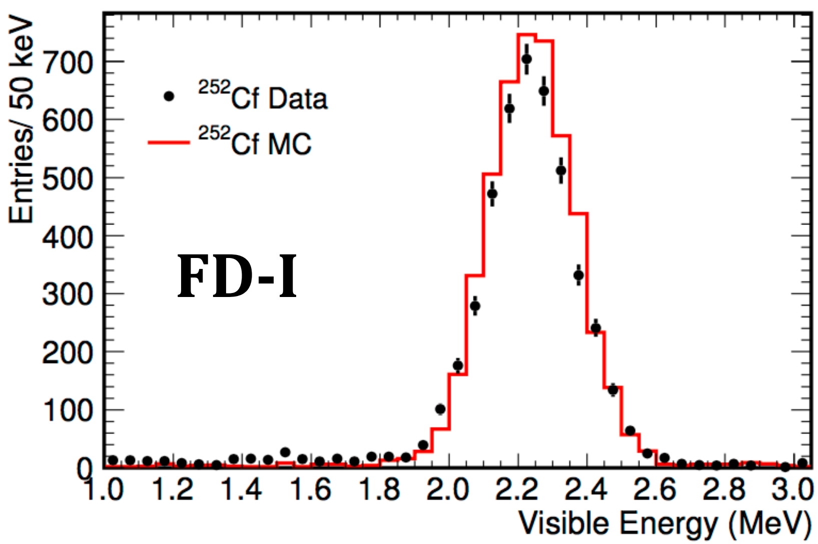
Bugey4, Energy per fission, Spectrum⊕$\sigma_{IBD}$: **Correlated** across FD-I, FD-II and ND

Baselines, Fission fraction, Thermal power: **Uncorrelated** ⇒ suppressed with two detectors (in parallel operation)

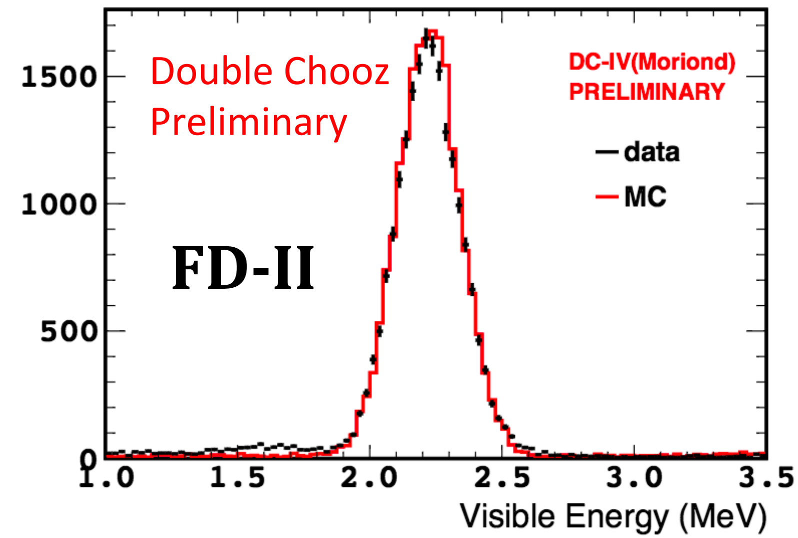
Inter-reactor correlation for $\alpha_k$ and $P_{th}$: $\rho_{B1/B2} = 0.78$
(most conservative assumption with current data set)

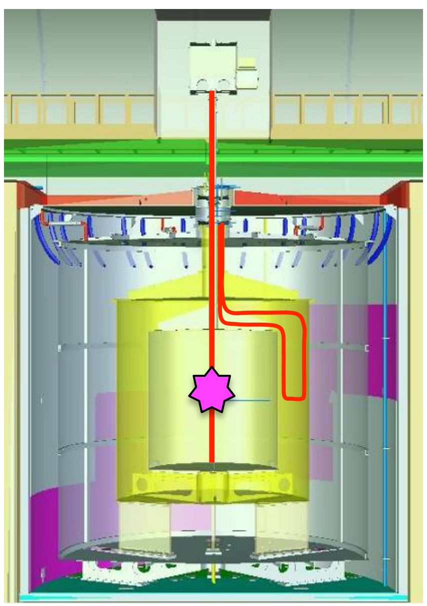
- Reactor flux uncertainty suppressed to **< 0.1%** in multi-detector analysis thanks to nearly **iso-flux** experimental setup in DC

# Detector performance



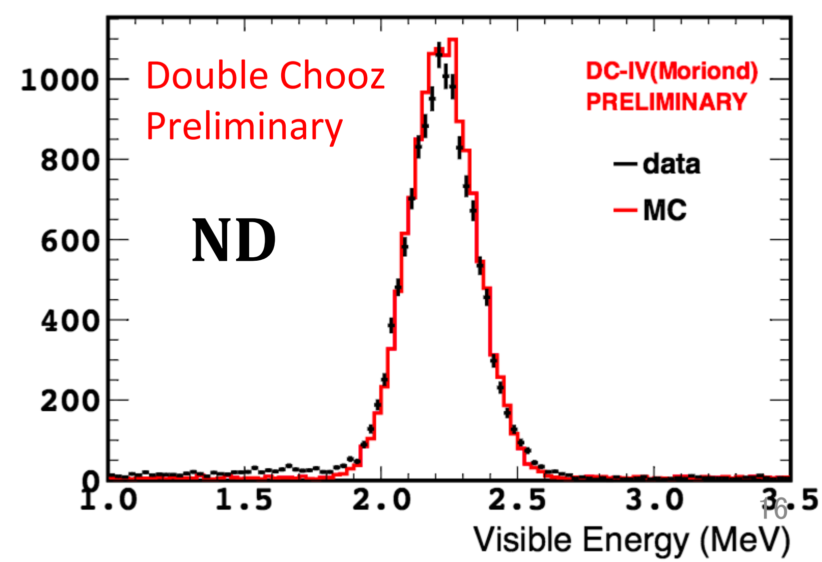

FAR DETECTOR



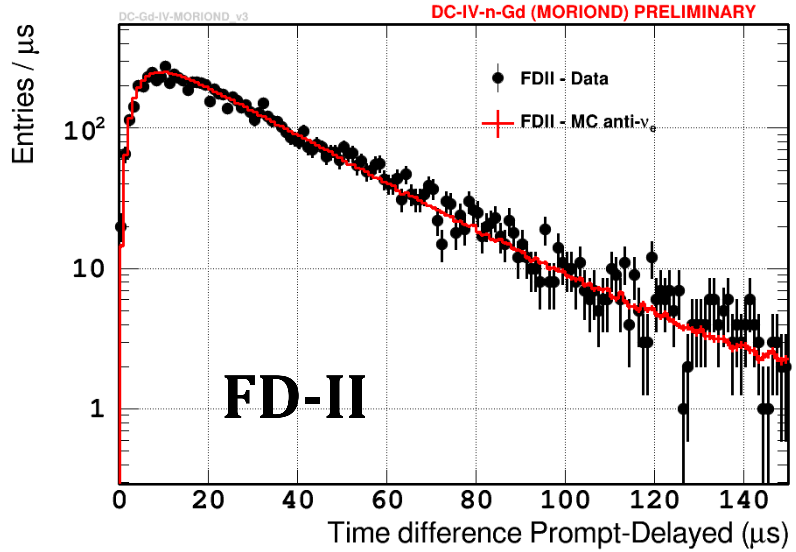
Cf neutron source deployed at center

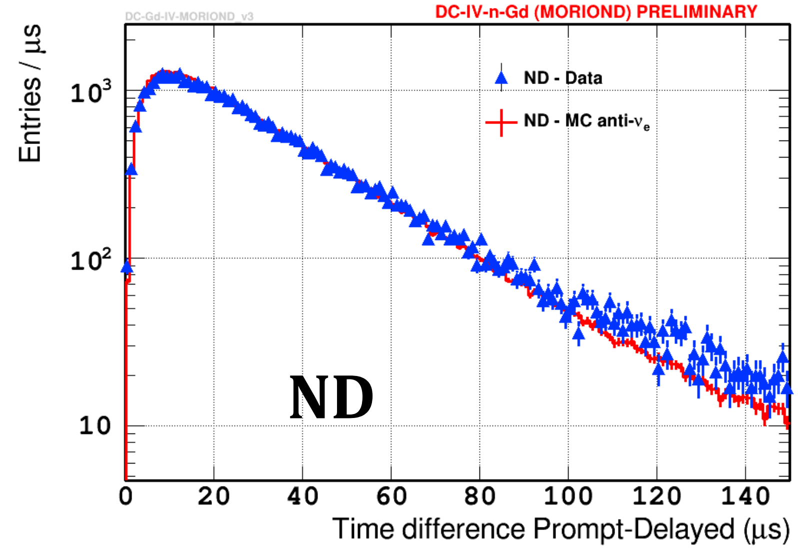
NEAR DETECTOR



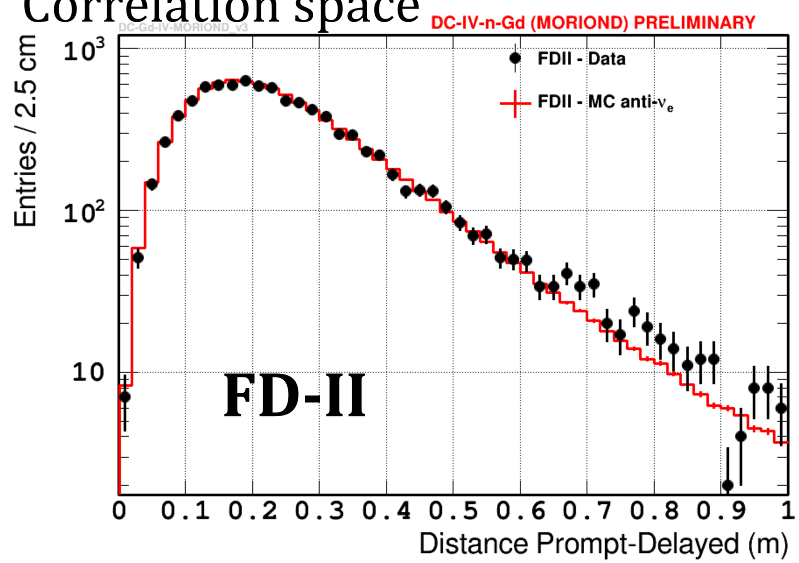
# IBD selection

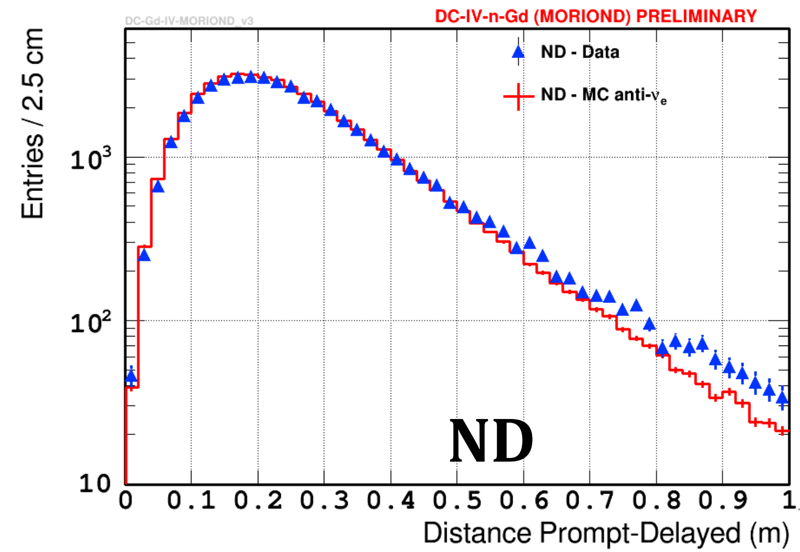
Correlation time



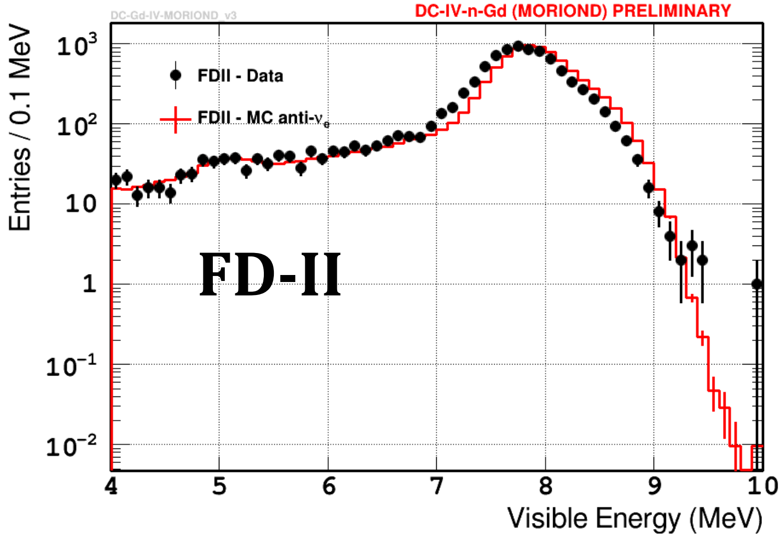

Correlation space

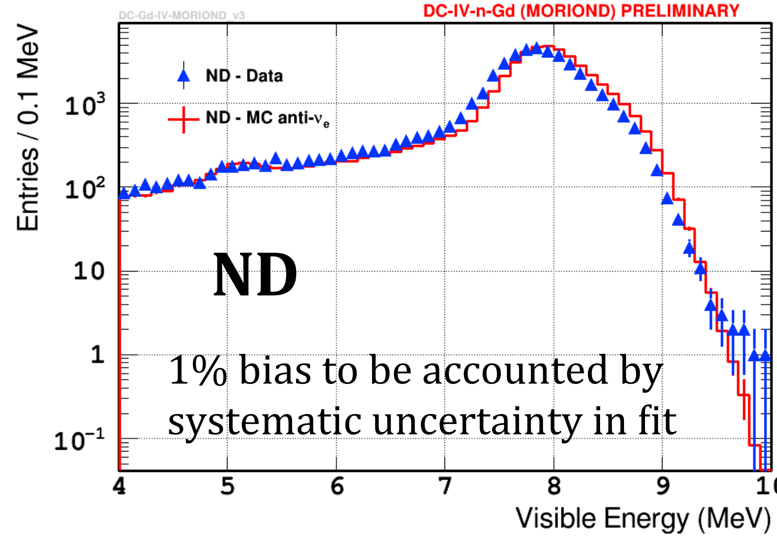


# IBD selection

Delayed energy



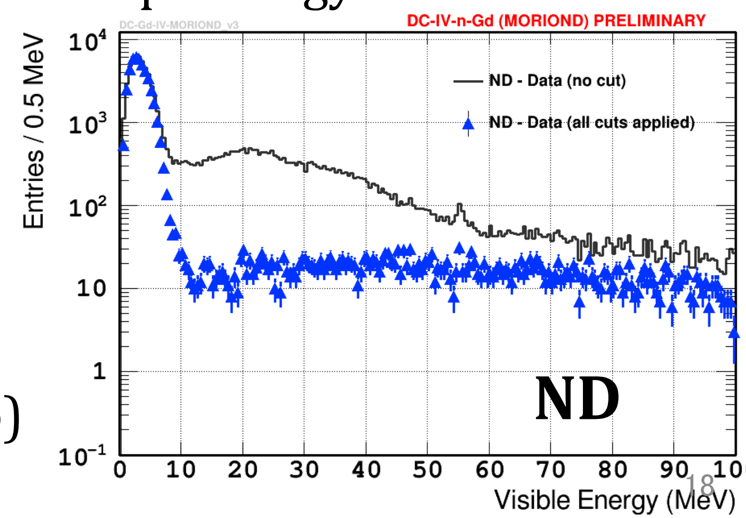

1% bias to be accounted by systematic uncertainty in fit

Contamination of liquid scintillator in ND Buffer causes buffer stop-μ background

⇒ Almost all such backgrounds are rejected by new selections based on

- Energy dependent MaxQ/TotQ cut
- Likelihood at chimney vs. vertex (CPS veto)

Prompt energy



# 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)

# Signal and background

Double Chooz Preliminary

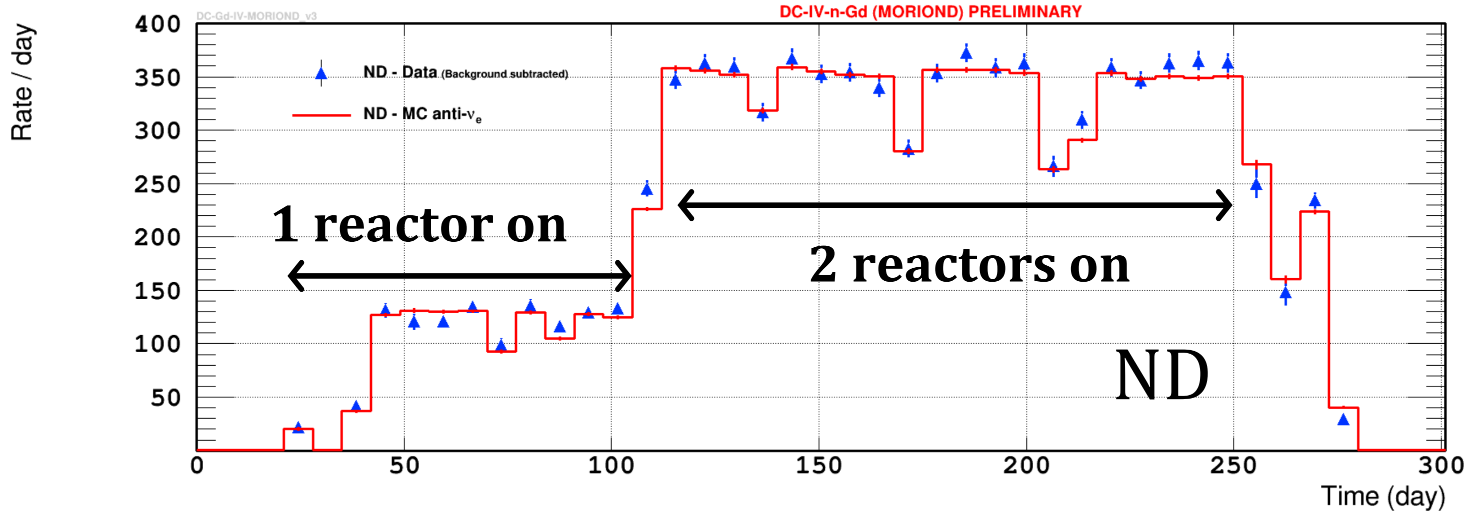
| | FD-I | Rector-off | FD-II | ND |
|---|---|---|---|---|
| Live-time (d) (after μ veto) | 460.93 | 7.24 | 212.21 | 150.76 |
| IBD prediction ($d^{-1}$) | 38.04±0.67 | 0.217±0.065 | 40.39±0.69 | 280.5±4.7 |
| Accidental BG ($d^{-1}$) | 0.070±0.003 | | 0.106±0.002 | 0.344±0.002 |
| Fast-n + stop-μ ($d^{-1}$) | 0.586 ±0.061 | | | 3.42 ±0.23 |
| Cosmogenic ($d^{-1}$) | $(0.97^{+0.41}_{-0.16})$ | | | (5.01 ±1.43) |
| **Total prediction ($d^{-1}$)** | **39.63±0.73** | **1.85±0.30** | **42.06±0.75** | **289.3±4.9** |
| **IBD candidates ($d^{-1}$)** (number of events) | **37.64** (17351) | **0.97** (7) | **40.29** (8551) | **293.4** (44233) |

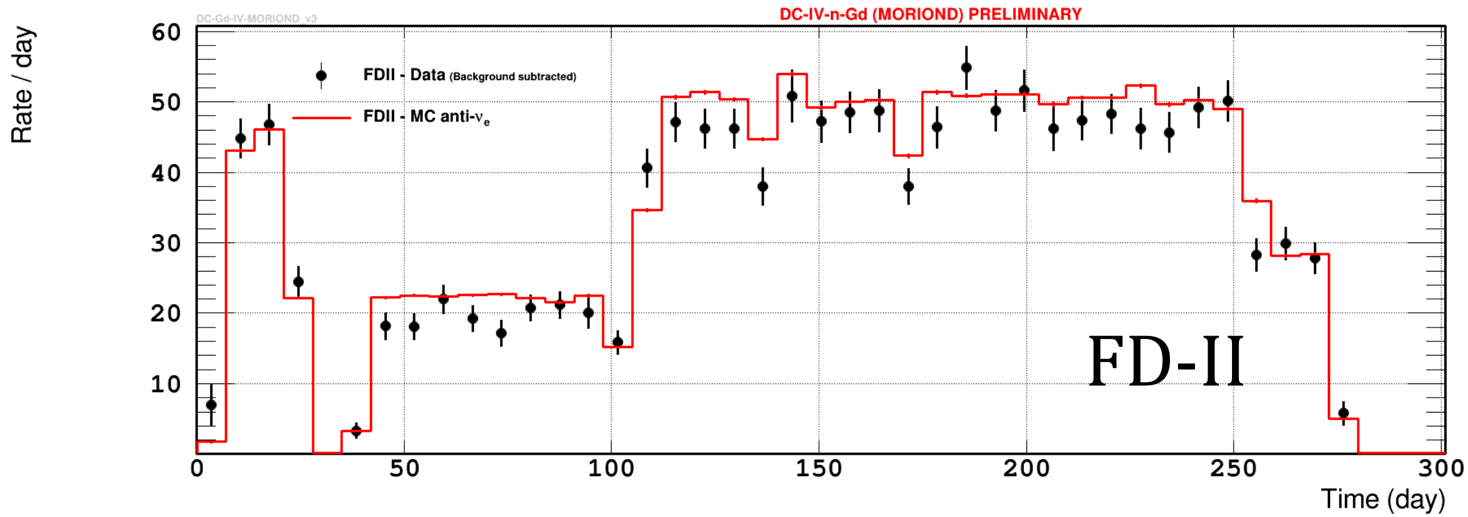
- Background shape measured by off-time coincidence (accidental), IV and OV tagged events (fast-n + stop-μ) and Li-enriched data (cosmogenic)
- Li background rate estimations are not used as input to rate+shape fit ⇒ rates are constrained in the fit with the shape information

# IBD rate vs. time

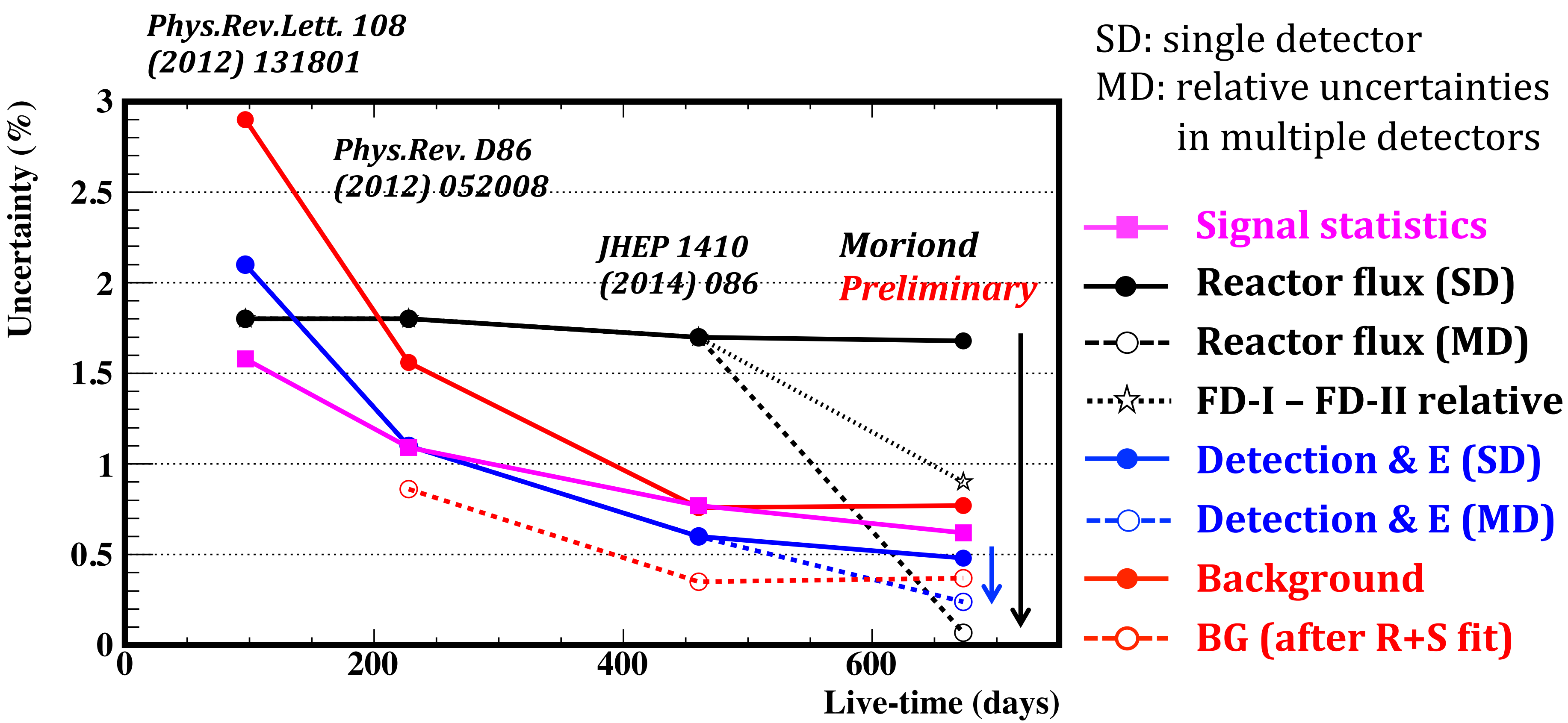
Background subtracted

Double Chooz Preliminary



# Uncertainties in multi-detectors analysis



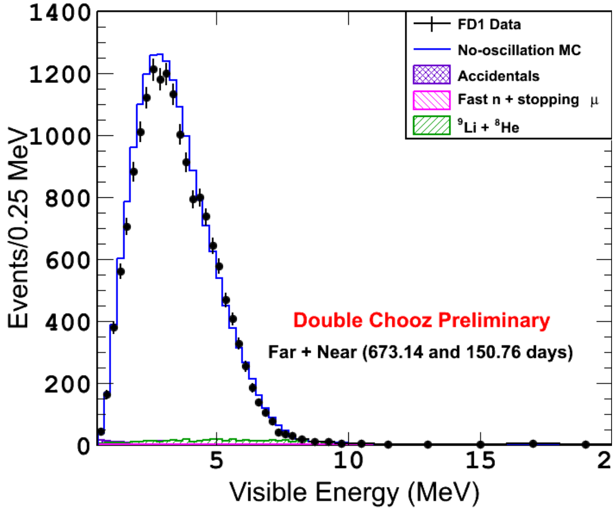

- Systematic errors suppressed with two detectors and in rate+shape fit

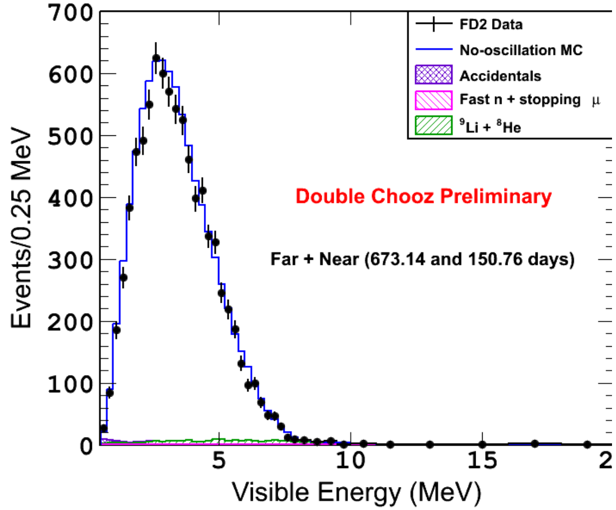
⇒ All systematic uncertainties below < 0.4% (after R+S fit)

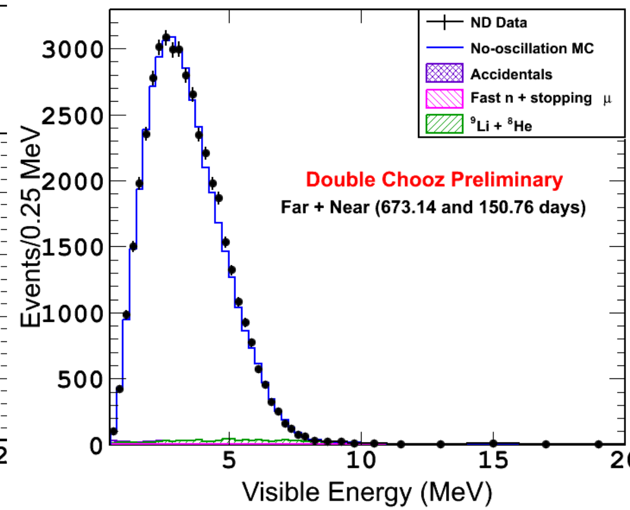
- Current precision (9 months ND) is limited by the statistical uncertainty

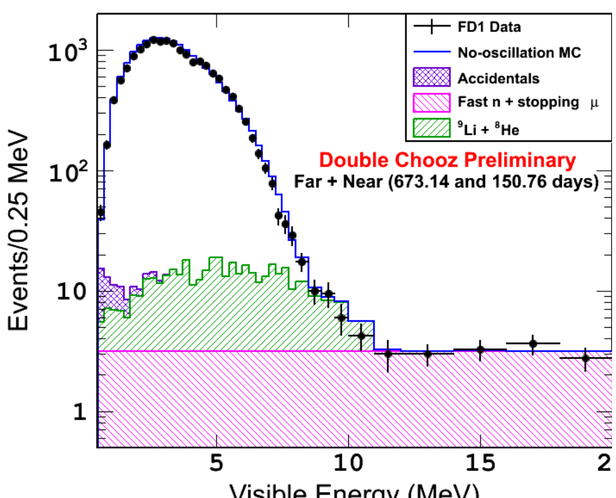
# Prompt energy spectrum

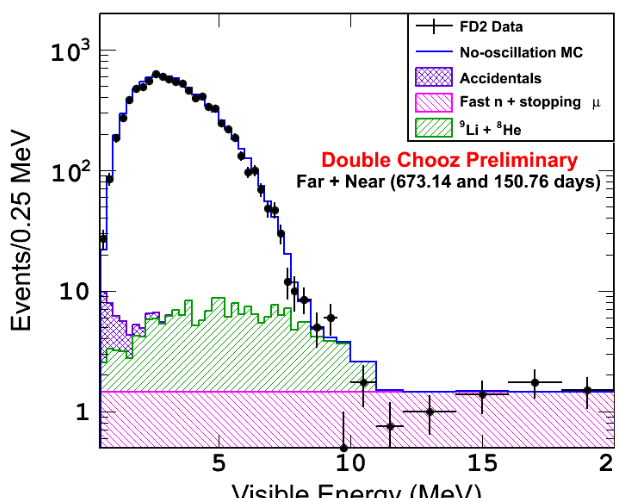
| **FD-I** | **FD-II** | **ND** |
|---|---|---|
| 460.93days | 212.21days | 150.76days |

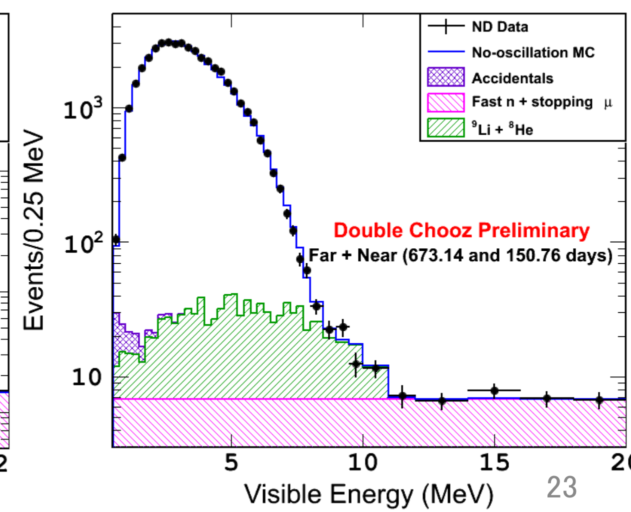


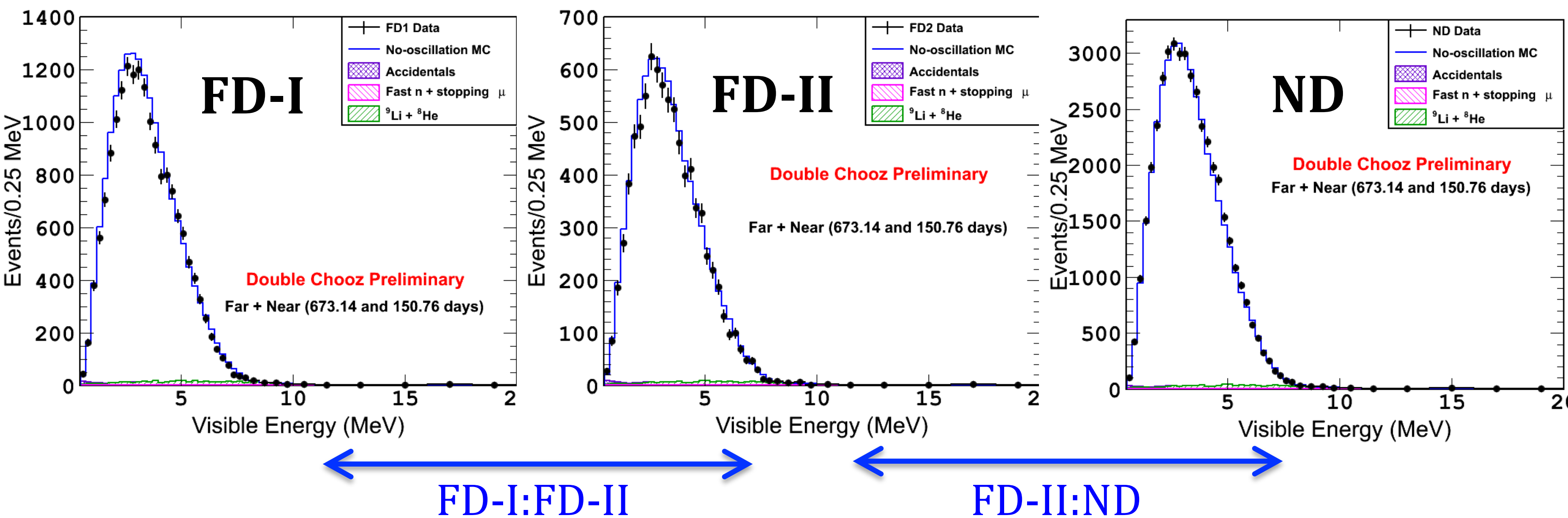



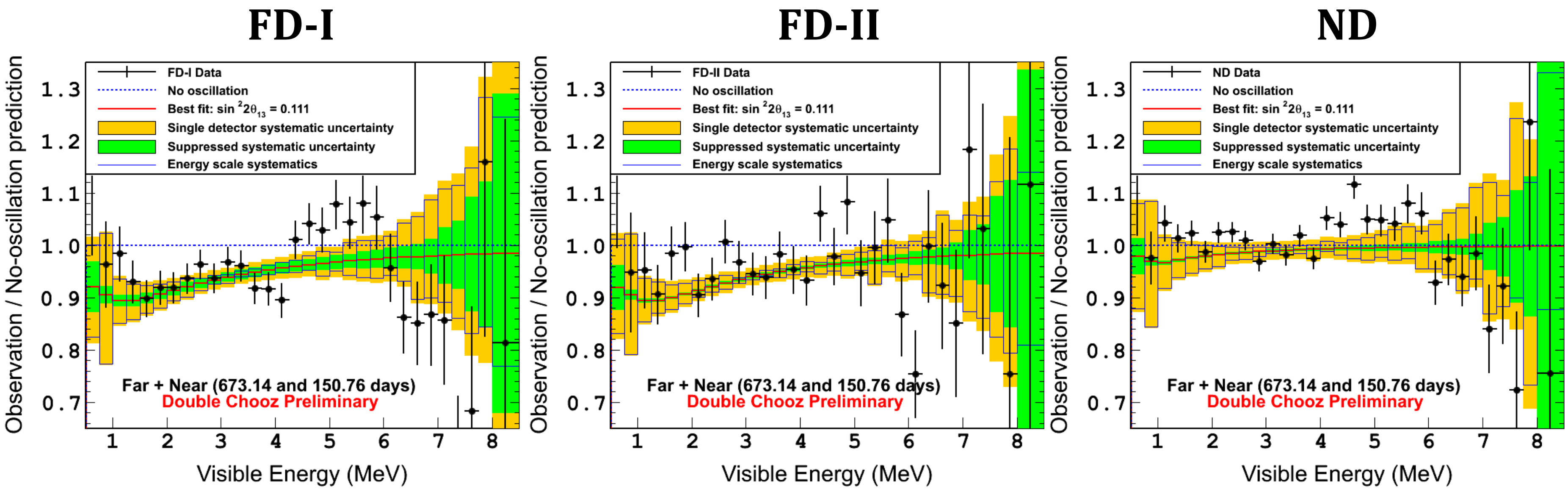
# Extraction of $\theta_{13}$ by oscillation fit

- Compare FD-I, FD-II and ND data simultaneously to predictions
  - Background rate and shape estimated by data (Li rate not constrained)
  - Observed data in reactor off as separate term ⇒ BG constraint




- Correlation of systematic uncertainties are taken into account
- Energy non-linearity effectively corrected in rate+shape fit
- Cross-checked by independent fits based on $\chi^2$ and likelihood and a fit based on comparison of FD data and ND data

# Fit results

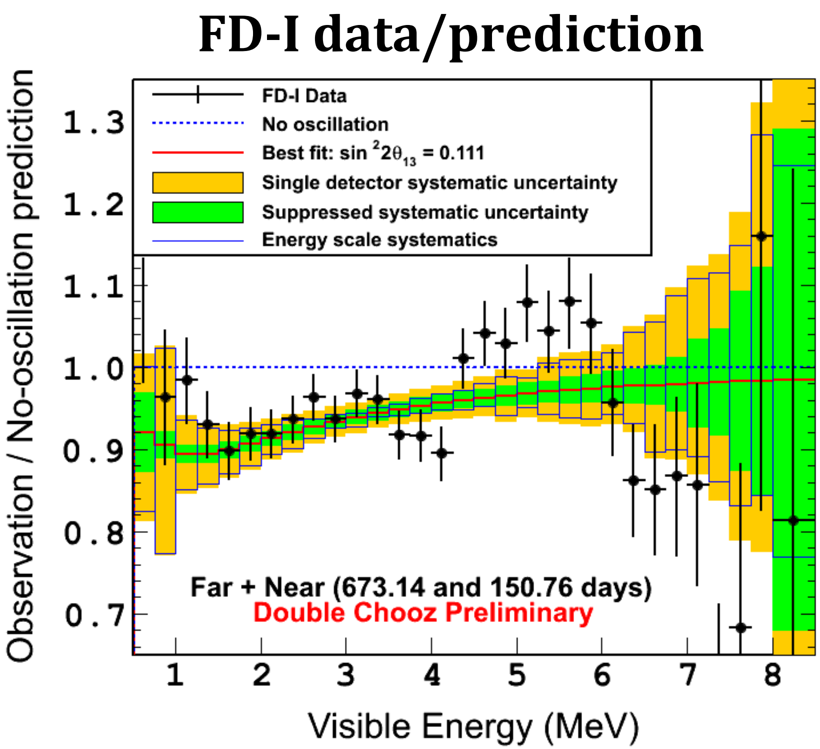


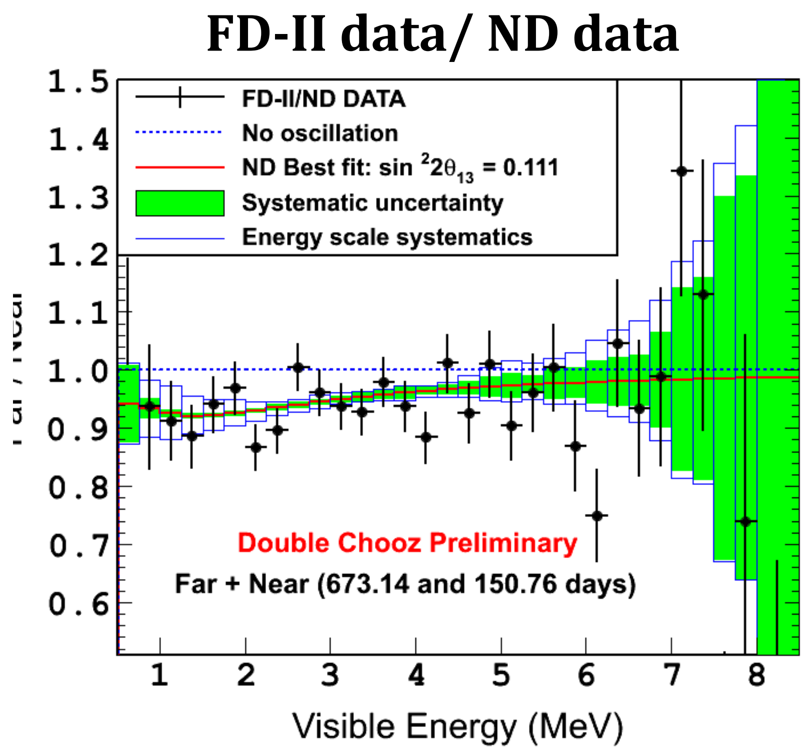

- Best-fit: $\mathbf{sin^2 2\theta_{13} = 0.111 \pm 0.018}$ (stat.+syst.) ($\chi^2$/dof = 128.8/120)
  - **Non-zero $\theta_{13}$ observation at 5.8σ C.L.**

Double Chooz Preliminary

  - Cosmogenic $^9$Li BG: 0.75±0.14 $d^{-1}$(FD), 4.89±0.78 $d^{-1}$(ND)
  - Fast-n+stop-μ BG: 0.535±0.035 $d^{-1}$(FD), 3.53±0.16 $d^{-1}$(ND)
  - Energy non-linearity: consistent across data sets and with calibration

# FD / ND ratio

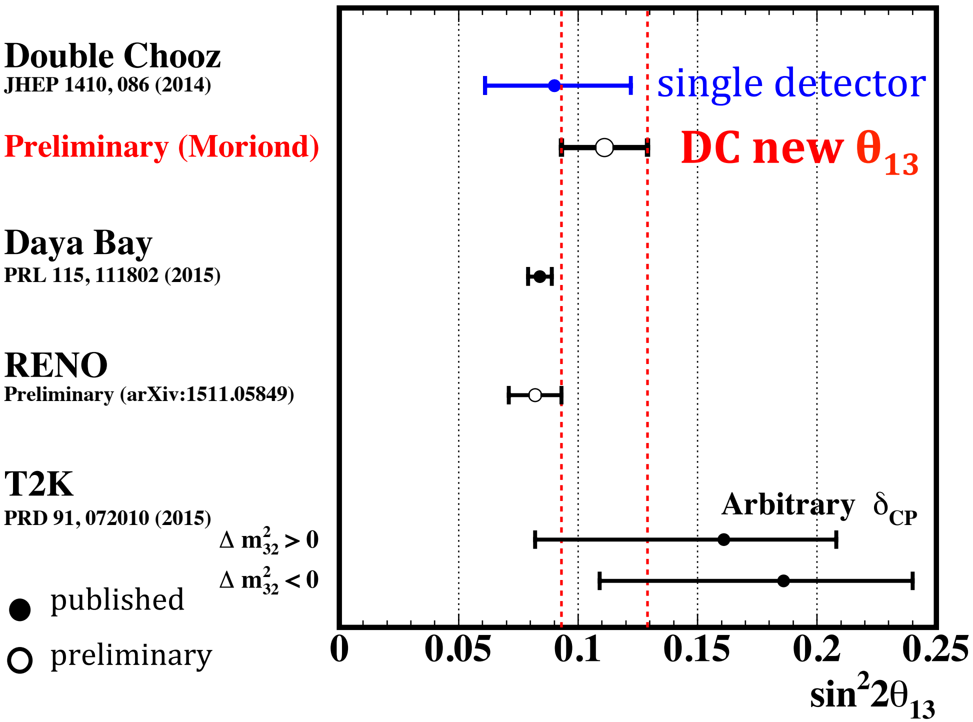


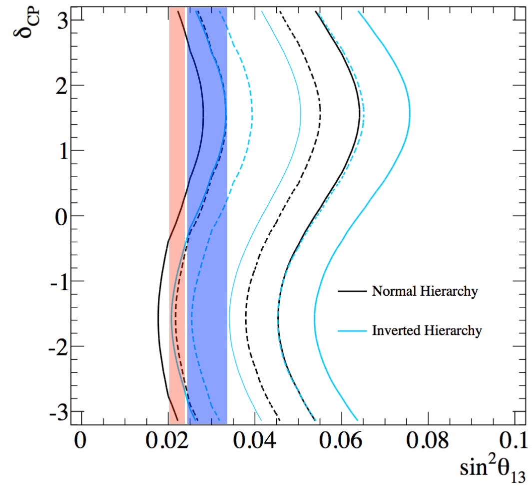




- Systematic uncertainties suppressed in FD-ND relative comparison
- Currently energy uncertainties are assumed to be uncorrelated across detectors (conservative approach)
  ⇔ strong correlation expected with the same scintillator and electronics

# Double Chooz $\theta_{13}$ in the world

World $\theta_{13}$ comparison




Reactor vs. T2K

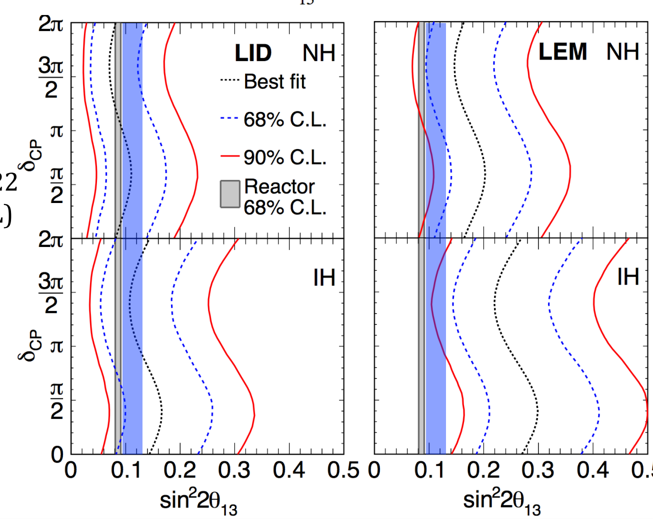
PRD91 072010 (2015)

Double Chooz 1σ

Daya Bay 1σ

Reactor vs. NOvA

arXivL1601.05522 (accepted by PRL)



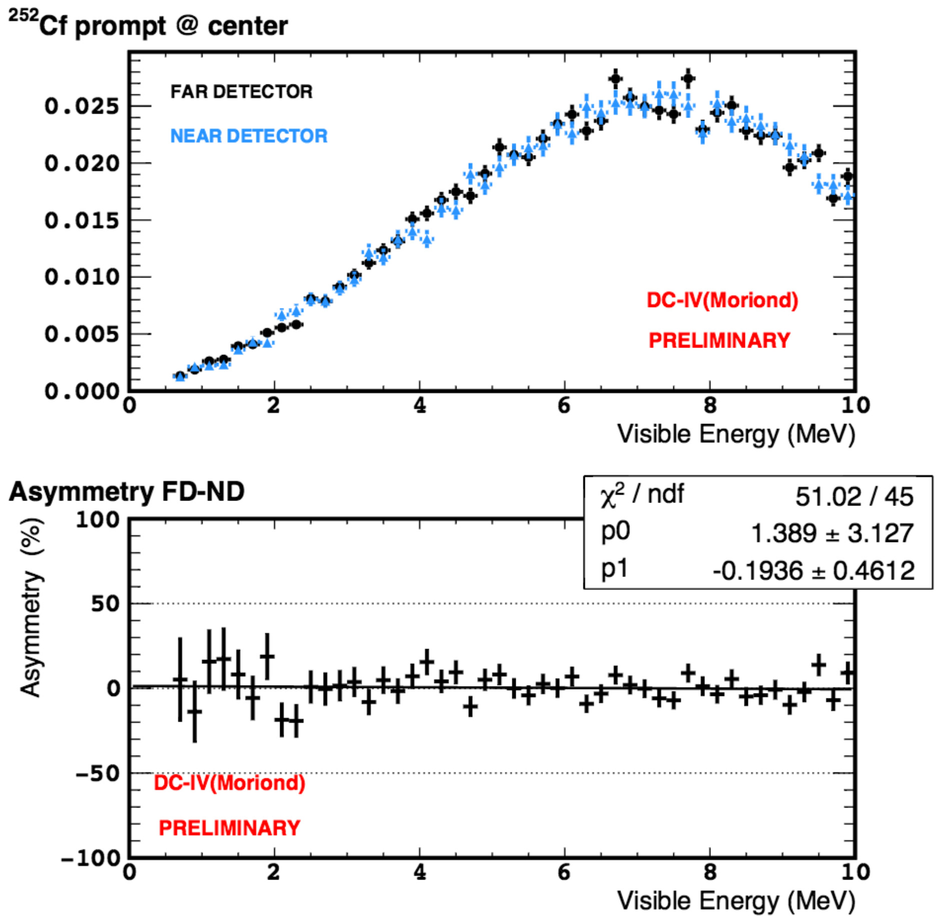

- DC $\theta_{13}$ is higher than other reactor $\theta_{13}$ by ~30% (1.4σ wrt Daya Bay)
- Long baseline (T2K, NOvA) weakly favors higher $\theta_{13}$ than reactor average
- Reactor $\theta_{13}$ is key parameter to solve CP-violation and mass hierarchy

# Summary

- Double Chooz collaboration reported first $\theta_{13}$ measurement with two detectors (FD-I: 460.93 days + FD-II: 212.21days + ND:150.76days)
  - **$\sin^2 2\theta_{13}$=0.111 ± 0.018** (stat.+syst.)
  - Reactor flux uncertainty is strongly suppressed to < 0.1% thanks to nearly iso-flux condition
  - Other systematic uncertainties are suppressed well below 1% (after analysis improvements made in single detector phase)
- Reactor $\theta_{13}$ is a key for current and future neutrino projects aim to solve still unknown CP-violation and mass hierarchy
  ⇒ Validation by multiple-experiments is essential
- Precision is currently limited by statistics
  ⇒ **Further improvements expected from Double Chooz**

# Backup

# Prompt energy of $^{252}$Cf data




- $^{252}$Cf emits ~10 $\gamma$ with 1MeV in average.
- Comparison of FD and ND data with $^{252}$Cf at the center of detector