New Results of Double Chooz

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on behalf of **the Double Chooz Collaboration**

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28th Rencontres de Blois
Particle Physics and Cosmology

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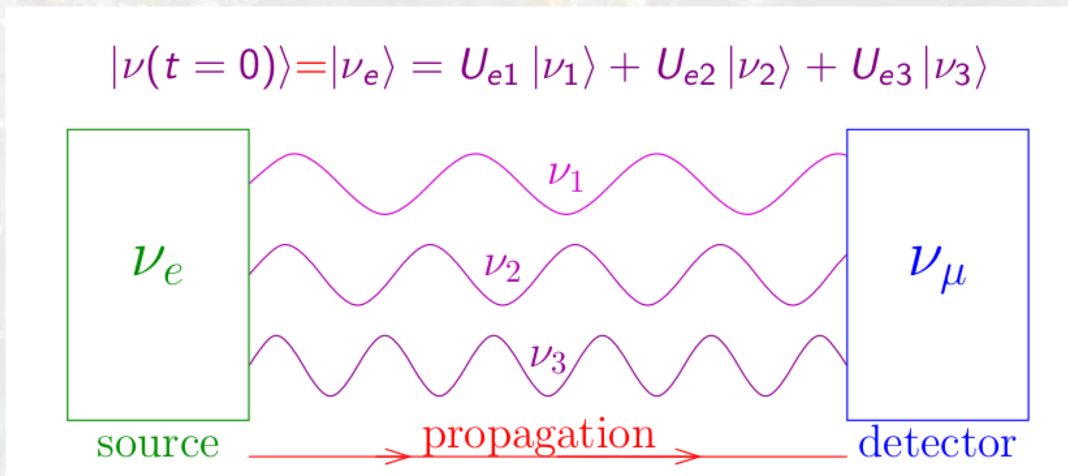
Neutrino Oscillations

- Phenomenon beyond Standard Model
- Flavour states (interaction) are mixing of mass states (propagation)
- First observed in ~1990 (dissapearance) and 2013 (appearance)



atmospheric	reactor & accelerator	solar
$P(\nu_\mu \to \nu_\mu)$	$P(\nu_e \to \nu_e)$ & $P(\nu_\mu \to \nu_e)$	$P(\nu_e \to \nu_x)$

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

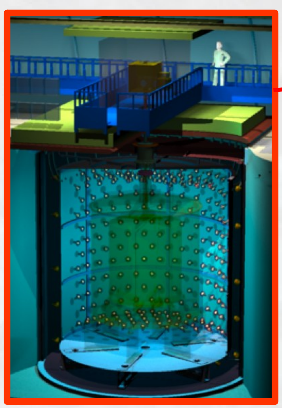
Precision measurement of θ_{13}

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

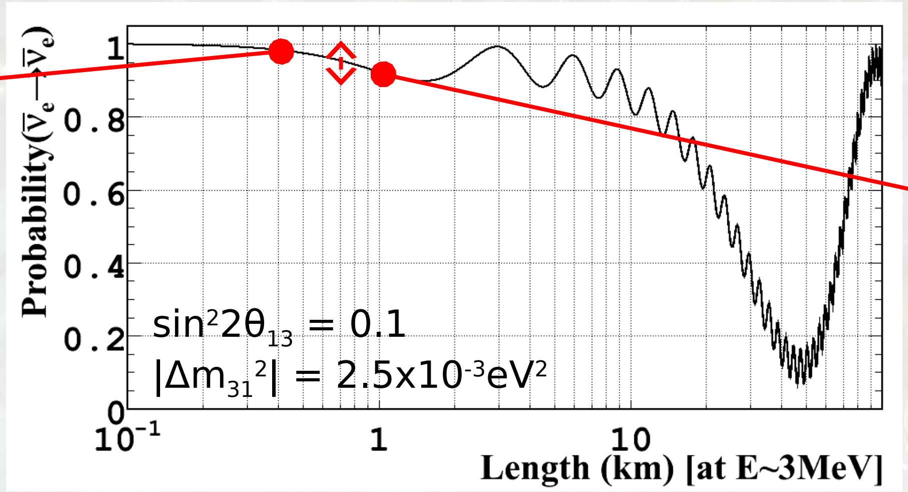
Survival probability of reactor neutrinos

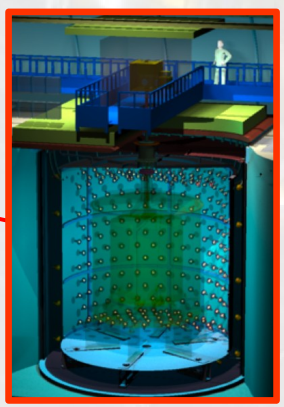
$$P\left[\overline{\nu}_e \rightarrow \overline{\nu}_e\right] \cong 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \cdots$$

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



Near Detector (ND)



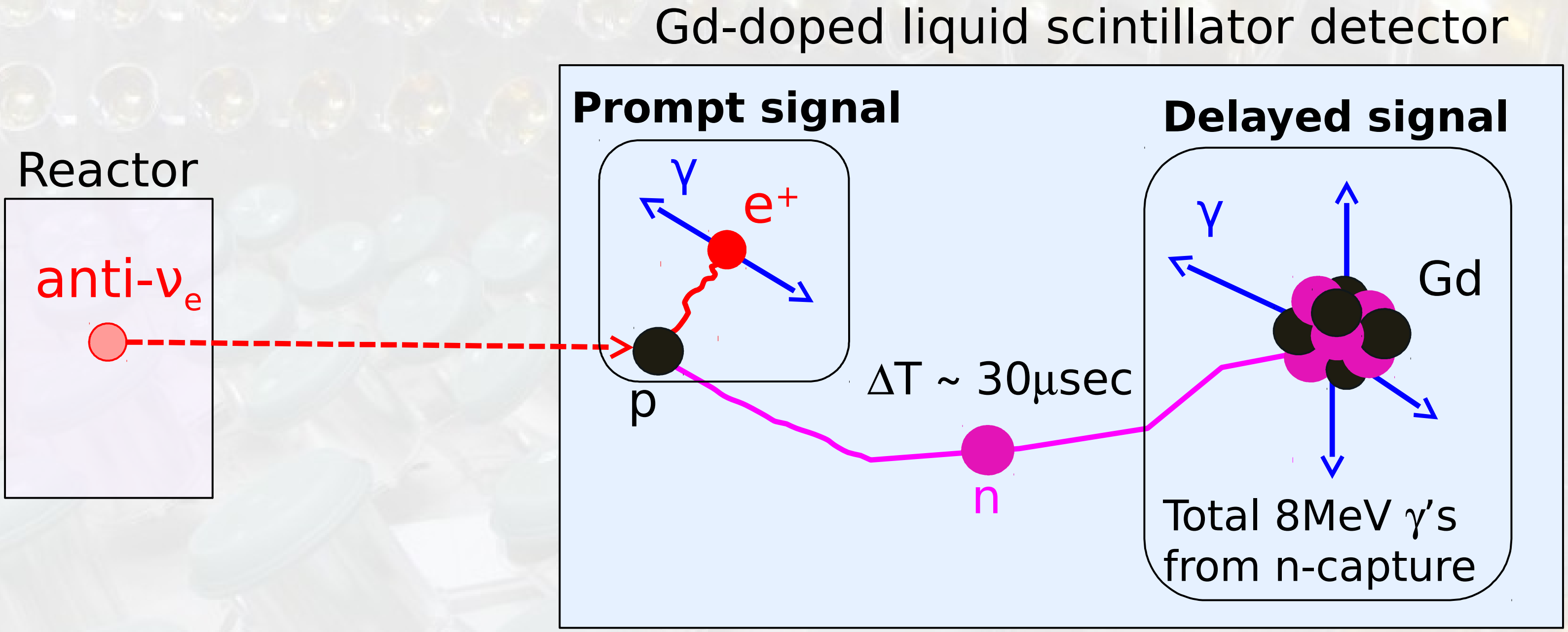


Far Detector (FD)

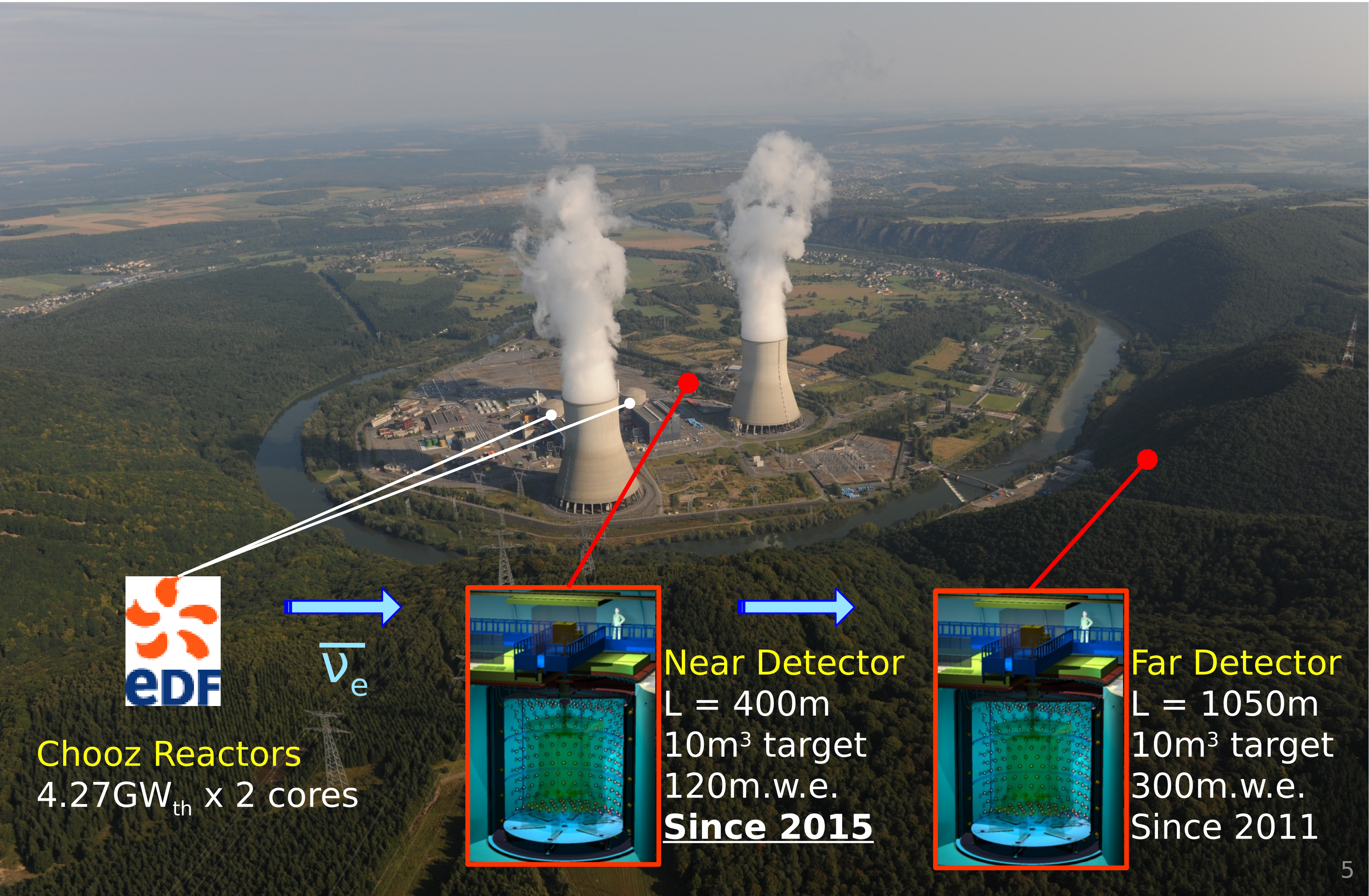
- Reactor θ_{13} (most precise) used as reference in current and future projects which aim to search for CP violation and mass hierarchy in neutrino sector.

Reactor neutrinos

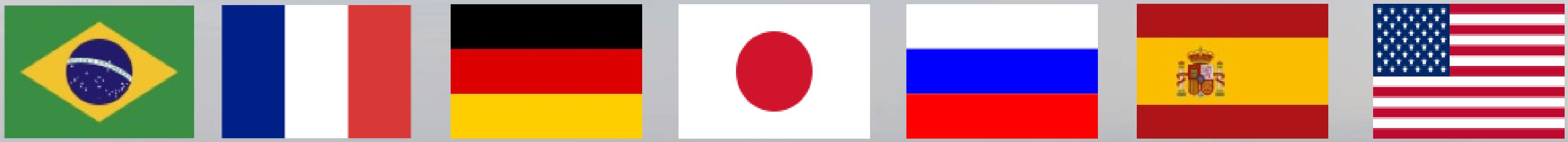
- Reactor is a free and rich electron antineutrino source
  - β-decays in a commercial fission reactor core produce 10^{20} ν/sec
- Reactor anti-ν_e are detected via inverse β-decay (IBD) reaction
  - Cross-section well known
  - Prompt signal: positron + annihilation γ's ($E_\nu \sim E_{signal} + 0.8$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



Double Chooz experiment



Double Chooz collaboration



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UFABC

France
APC
CEA/DSM/IRFU:
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- SPhN
- SEDI
- SIS
- SENAC

CNRS/IN2P3:
- Subatech
- IPHC

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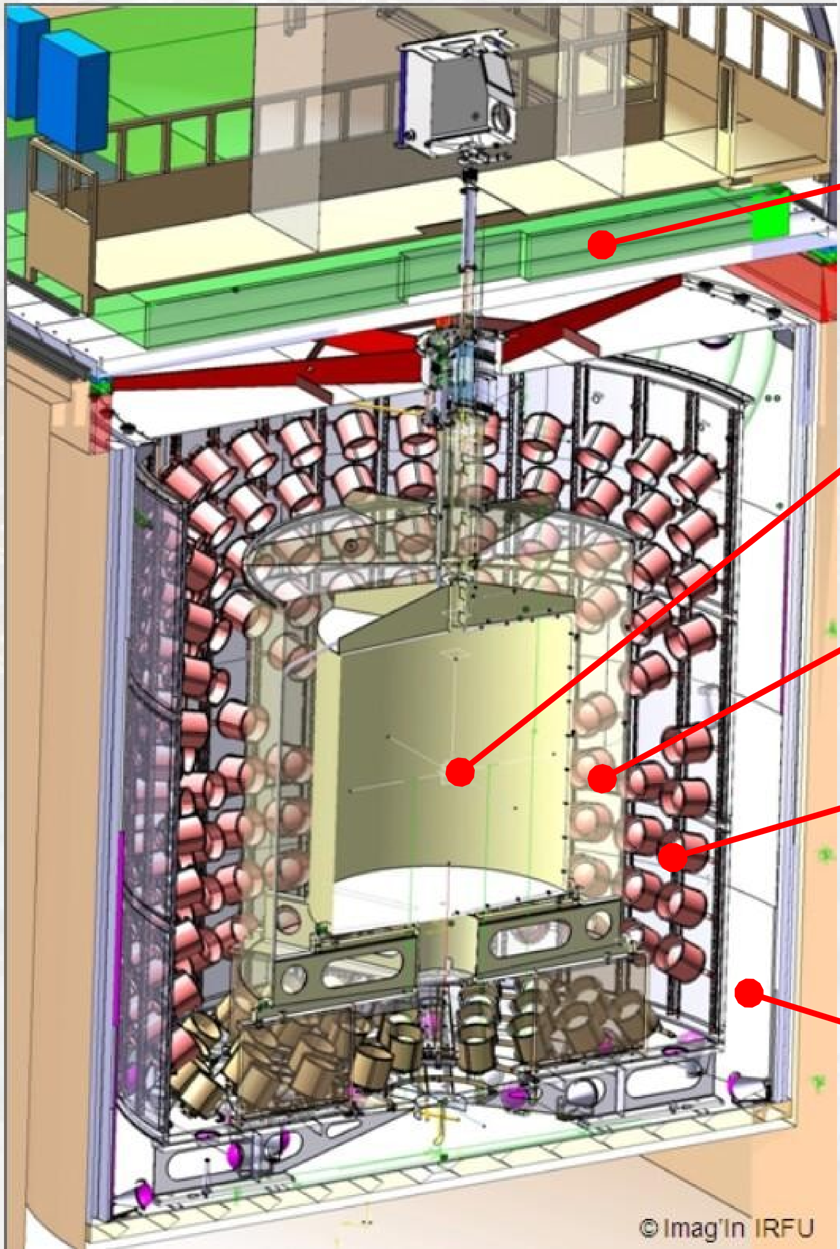
IIT
KSU
LLNL
MIT
U. Notre Dame
U. Tennessee

Spokesperson:
H. de Kerret (IN2P3)

Project Manager:
Ch. Veyssière (CEA-Saclay)

Web Site:
www.doublechooz.org/

Double Chooz detectors



Outer Veto (OV)
Plastic scintillator strips

Inner Detector (ID)

ν-target (NT)
- Gd loaded liquid scintillator (10m³)

γ-catcher (GC)
- Liquid scintillator (22m³)

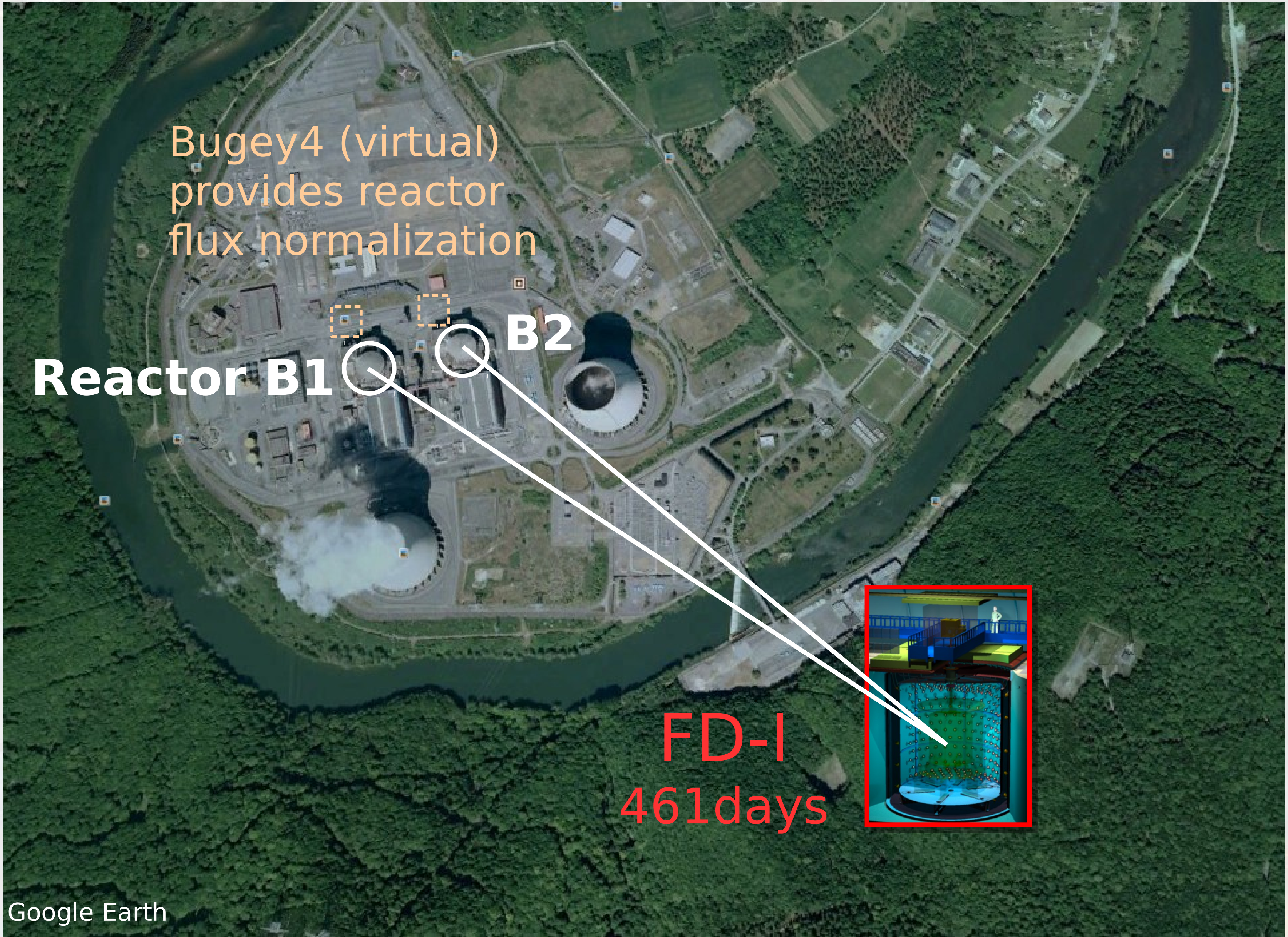
Buffer
- Mineral oil (110m³)
- 390 10-inch PMT

Inner Veto (IV)
- Liquid scintillator (90m³)
- 78 8-inch PMT

Double Chooz overview

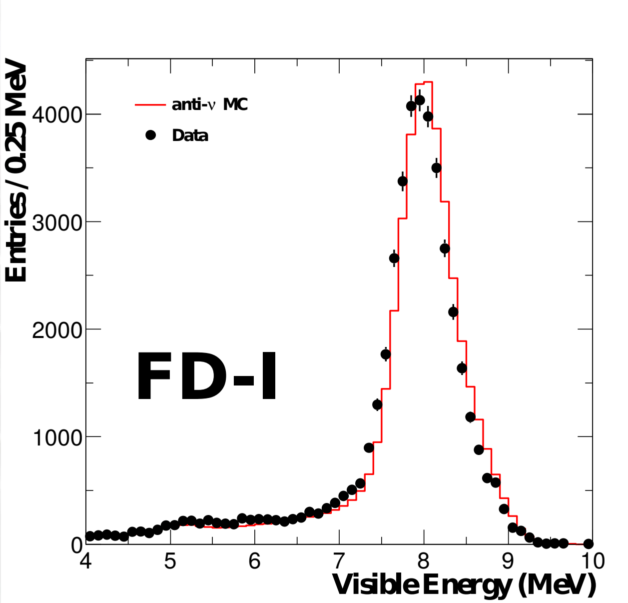
- Pioneered reactor experiments (improvements wrt CHOOZ)
  - Experimental concept to use two detectors
  - 4 layers detector structure (ν-target, γ-catcher, buffer and IV)
  - Stable Gd loaded liquid scintillator developed
  - Precise measurement of reactor neutrinos with single far detector
    - Various 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 θ_{13} in reactor oscillation since CHOOZ
    - Indication of non-zero θ_{13} at 94% CL (evidence at 3σ with LBL)
  - First θ_{13} using hydrogen capture signal
  - Observation of spectrum distortion at E_ν = 5-7MeV (E_{signal} = 4-6MeV)
  - **θ_{13} measurement with multi-detectors: last March**

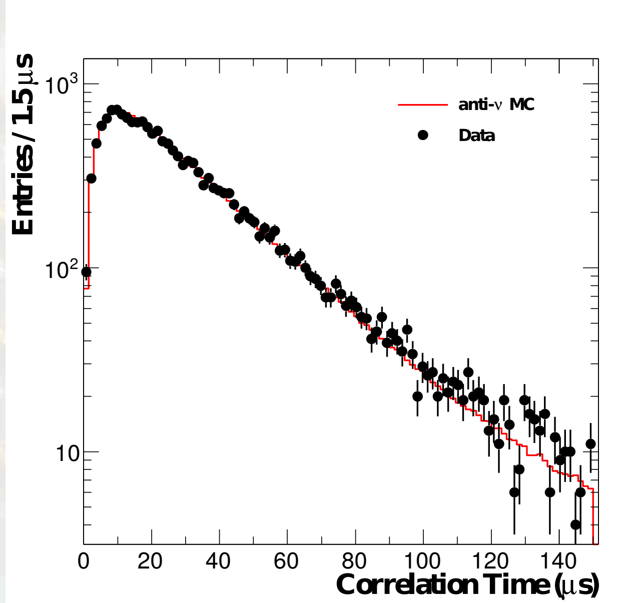
Single detector analysis

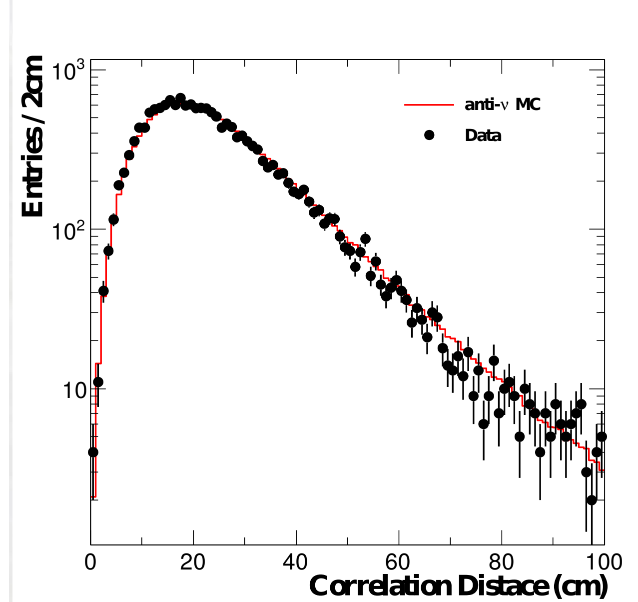


IBD coincidence condition

Delayed signal energy	Correlation time	Correlation distance
$4 < E_{vis} < 10\mathrm{MeV}$	$0.5 < \Delta T < 150\mu\mathrm{sec}$	$\Delta R < 100\mathrm{cm}$







⇒ Remaining BG

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

Fast neutron: $n + p \rightarrow p + n$

Stop-μ: $\mu \rightarrow e + \nu + \nu$

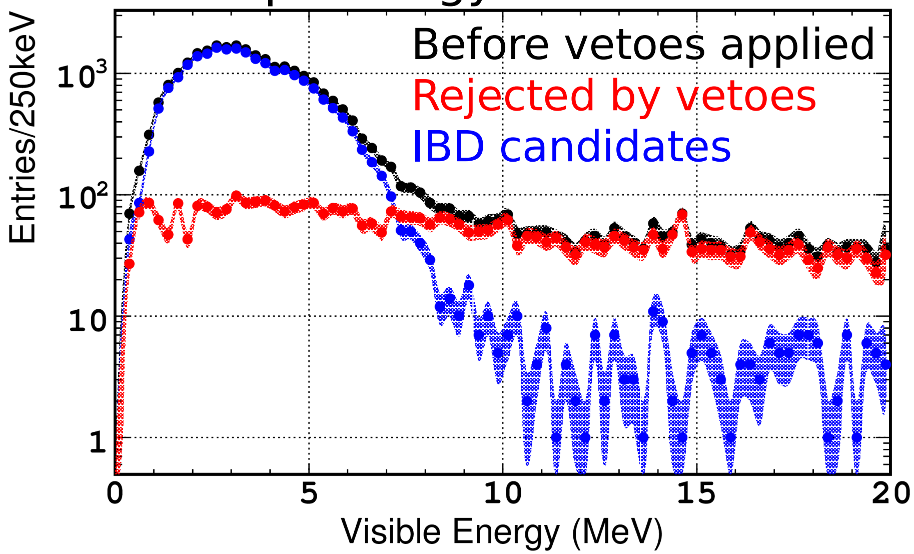
Accidental coincidence: e.g. γ + spallation n

Prompt (red circle)

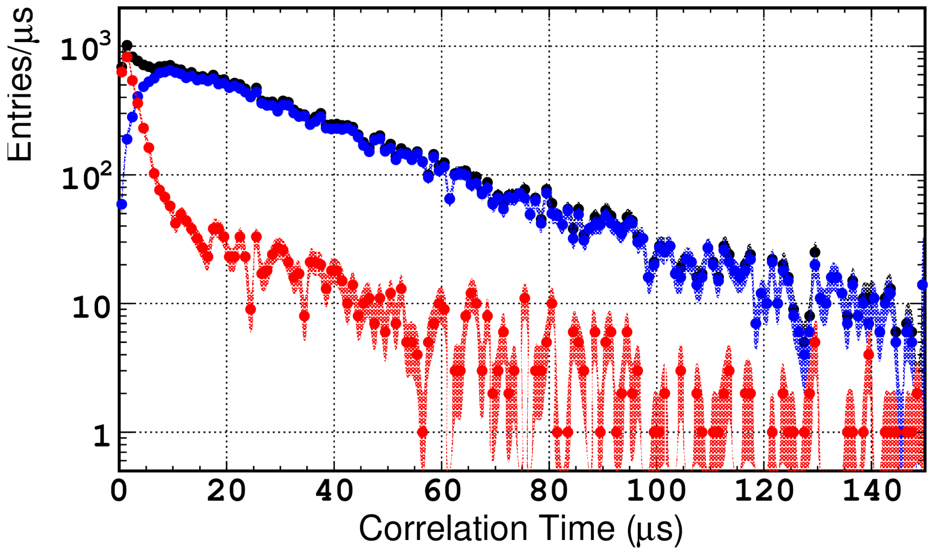
Delayed (blue circle)

Background vetoes

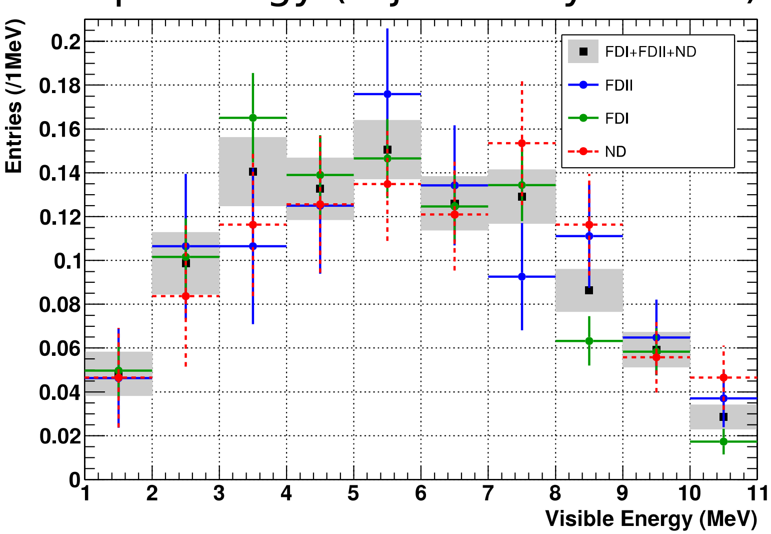
Prompt energy



Correlation time

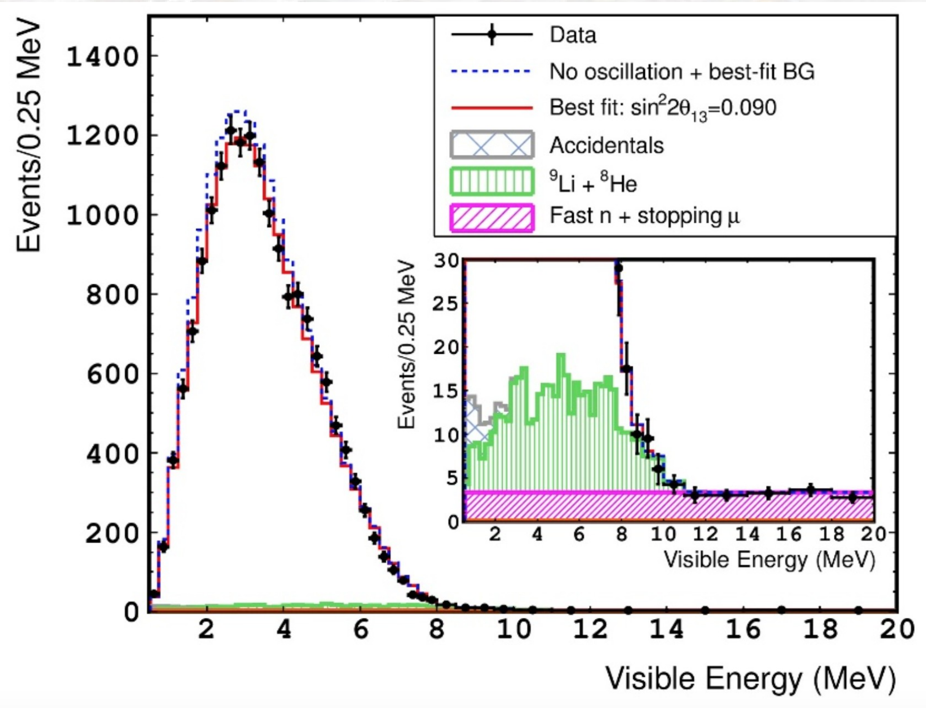


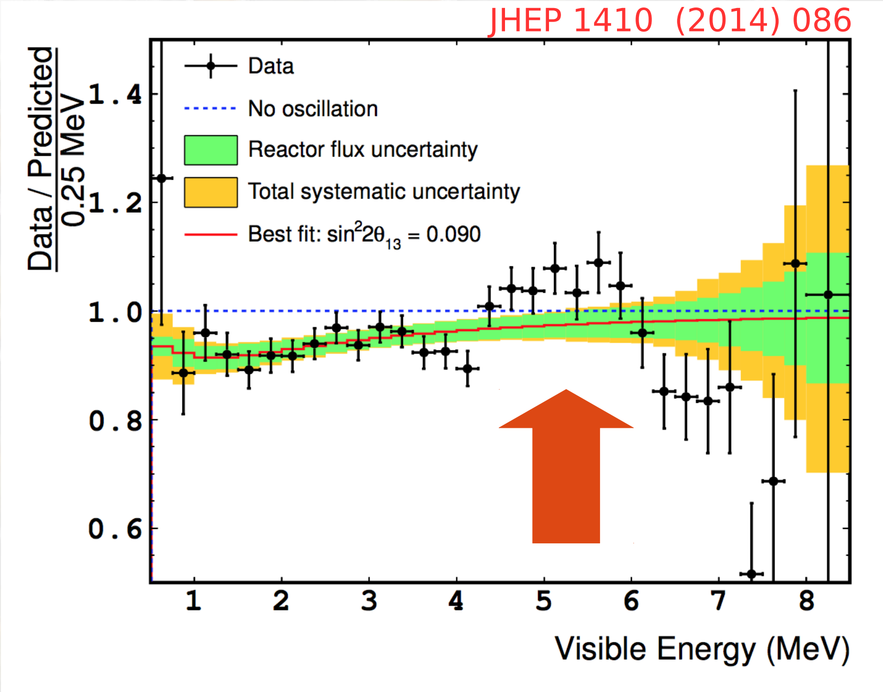
Prompt energy (rejected by Li veto)



- 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)

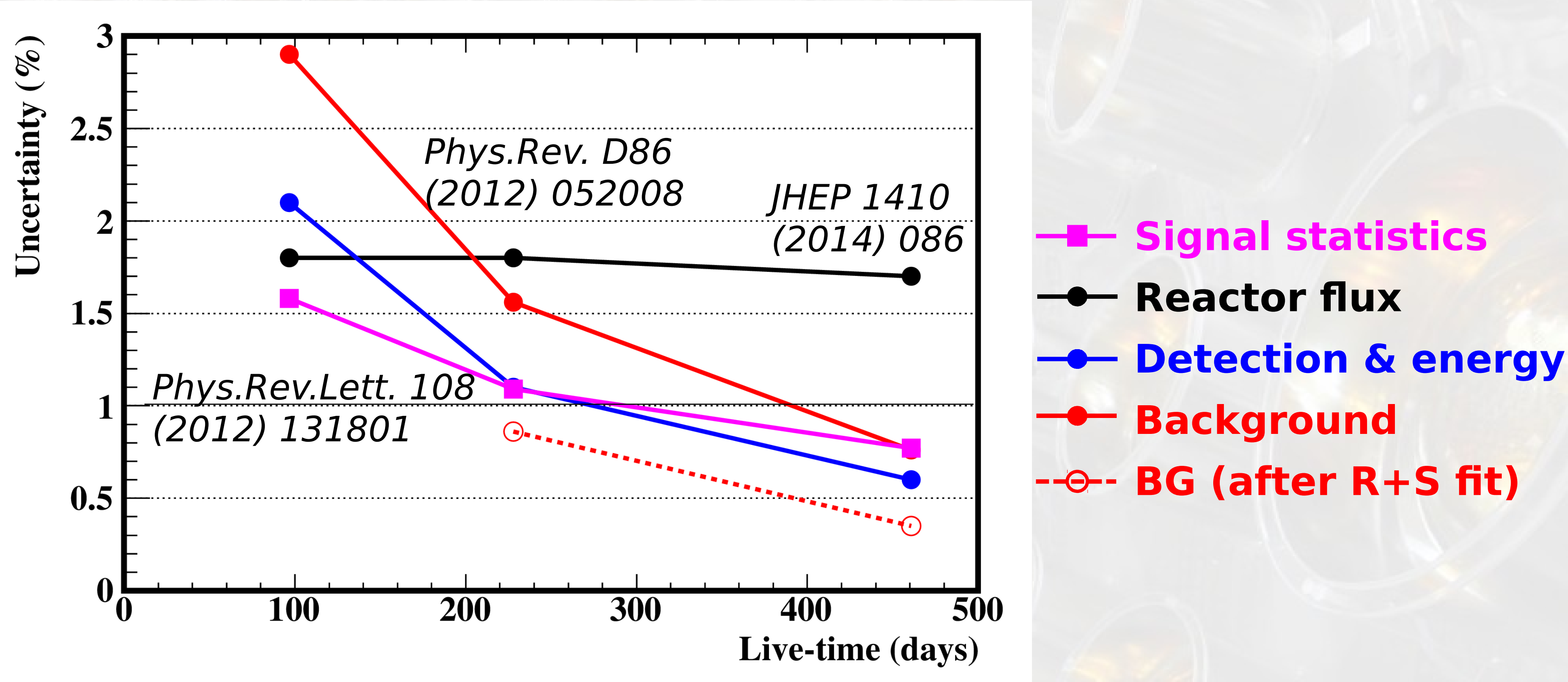
Oscillation fit: rate + spectrum shape





- Background and other uncertainties constrained by shape information
  - **$\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$**
- **Unexpected spectrum distortion observed at 4-6MeV (May 2014)**
  - ✓ Negligible impact to θ_{13} measurement
  - ✓ Magnitude of excess proportional to reactor power
  - ✓ Same distortion later confirmed by RENO (Jun/14), Daya Bay (Jul/14) and our n-H capture analysis

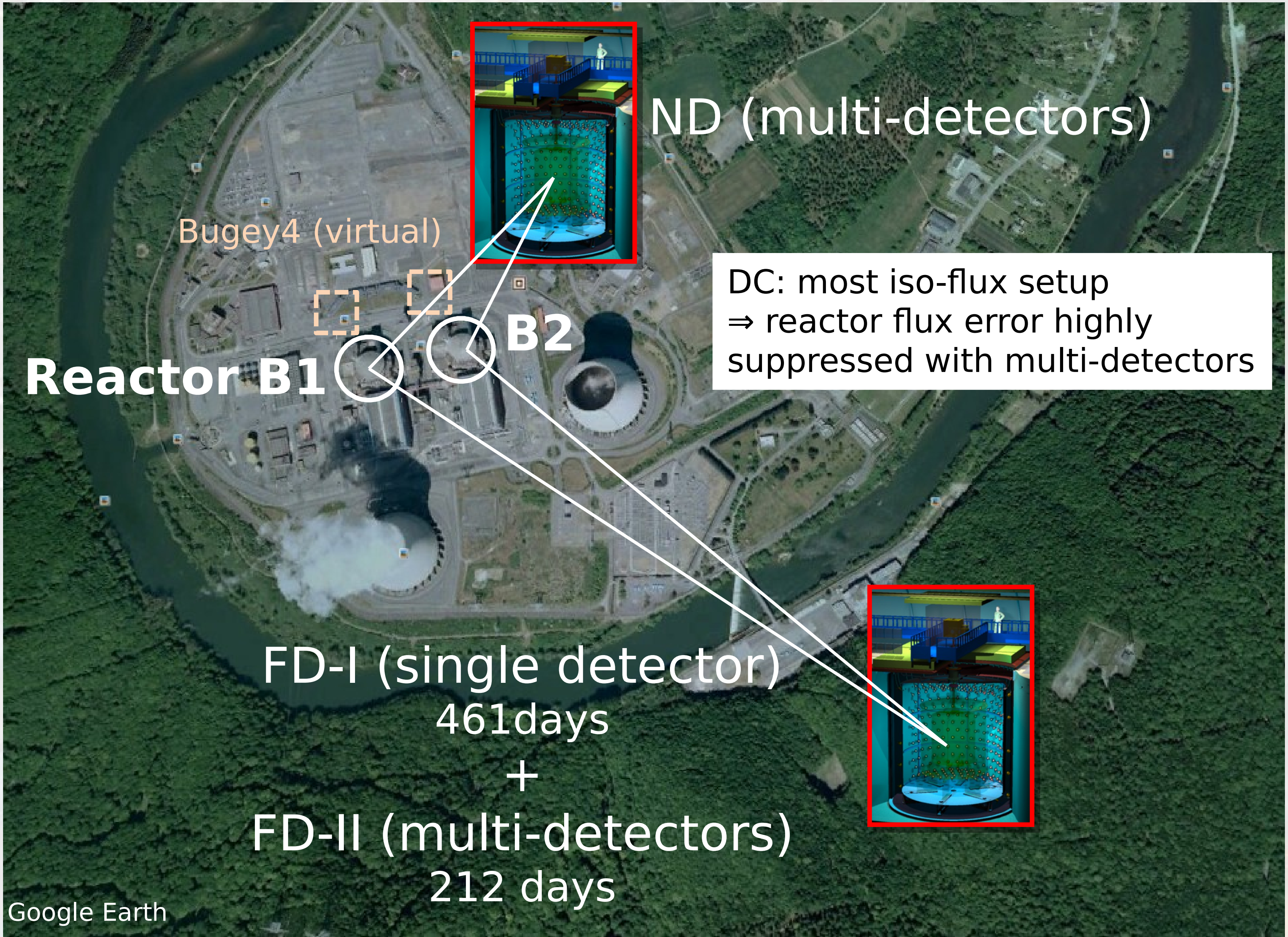
Analysis improvements



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

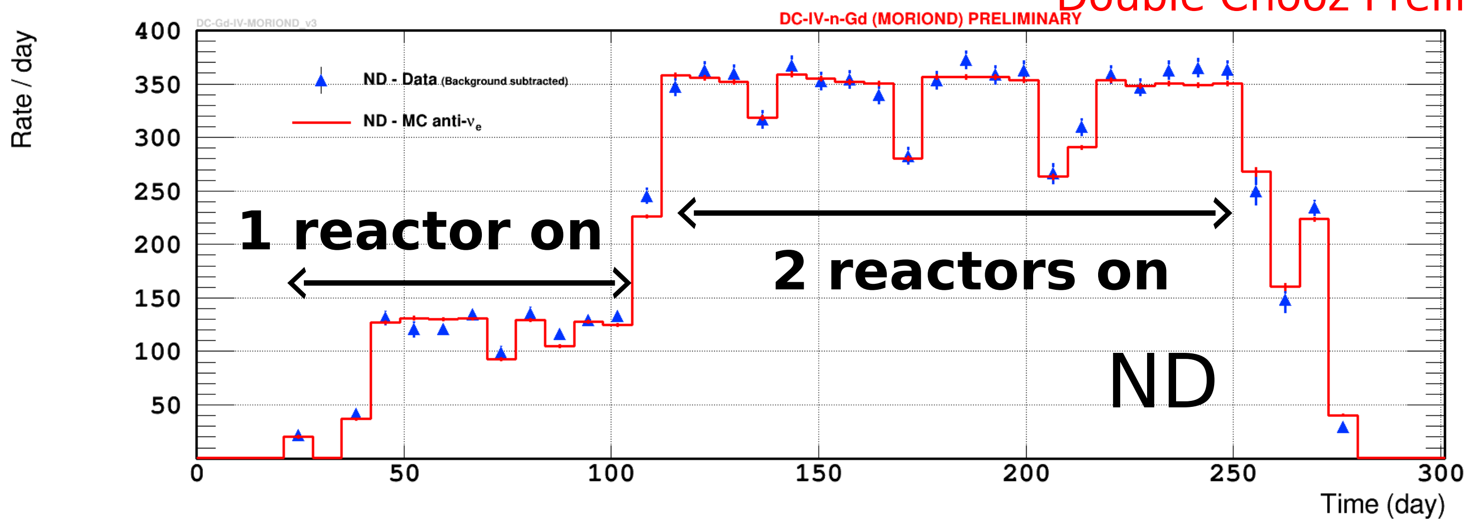
⇒ Reactor flux and detection systematics to be suppressed with two detectors

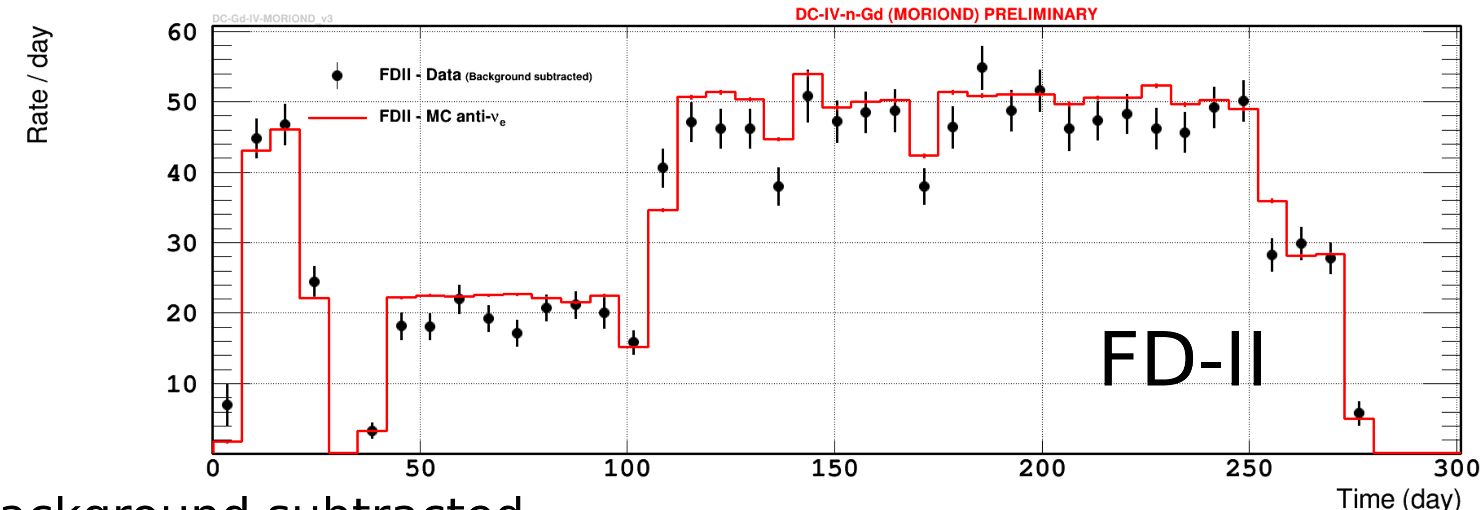
Multi-detectors analysis



IBD rate vs time

Double Chooz Preliminary





Background subtracted

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$\oplus\sigma_{IBD}$	0.20	0.20	0.20
Baselines	< 0.01	< 0.01	0.01
Fission fraction (α_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)	

Correlated across FD-I, FD-II and ND

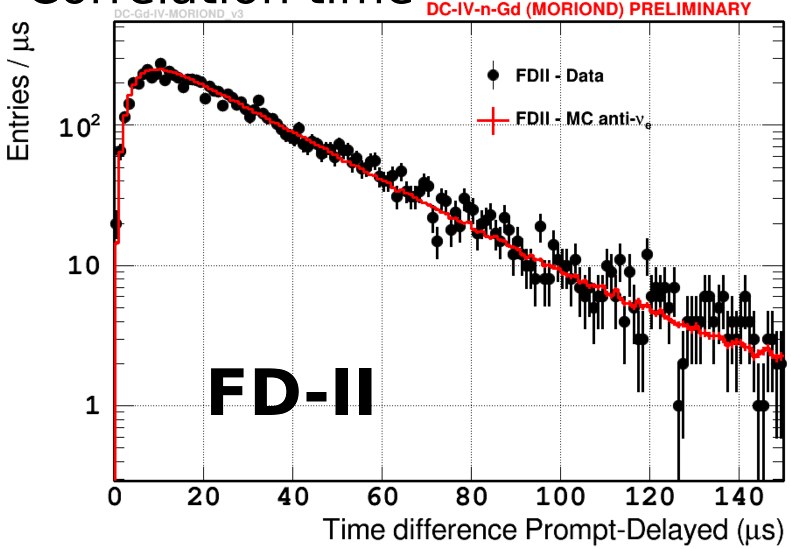
Uncorrelated ⇒ suppressed with two detectors (in parallel operation)

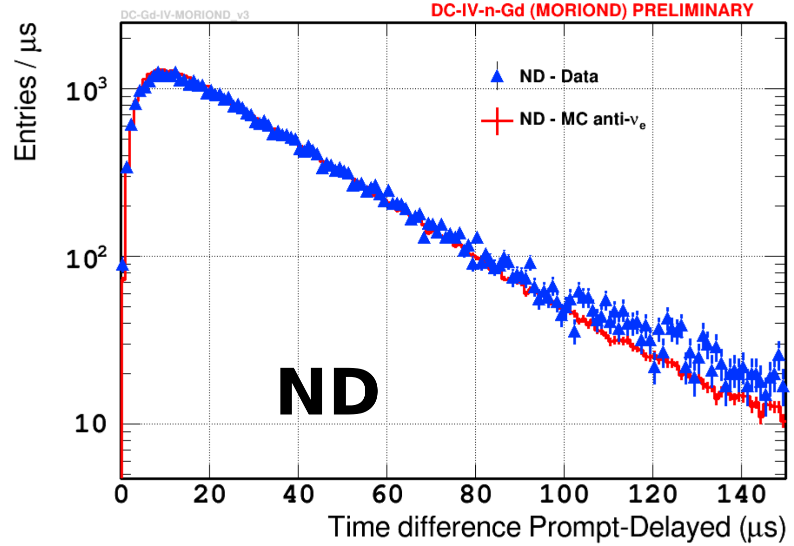
Inter-reactor correlation for α_k and P_{th}: $\rho_{B1/B2} = 0.78$
(most conservative assumption with current data set)

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

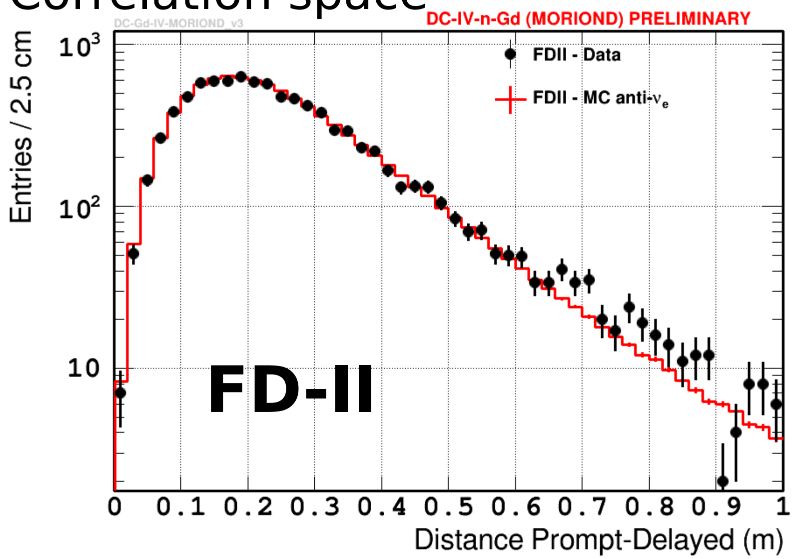
IBD selection

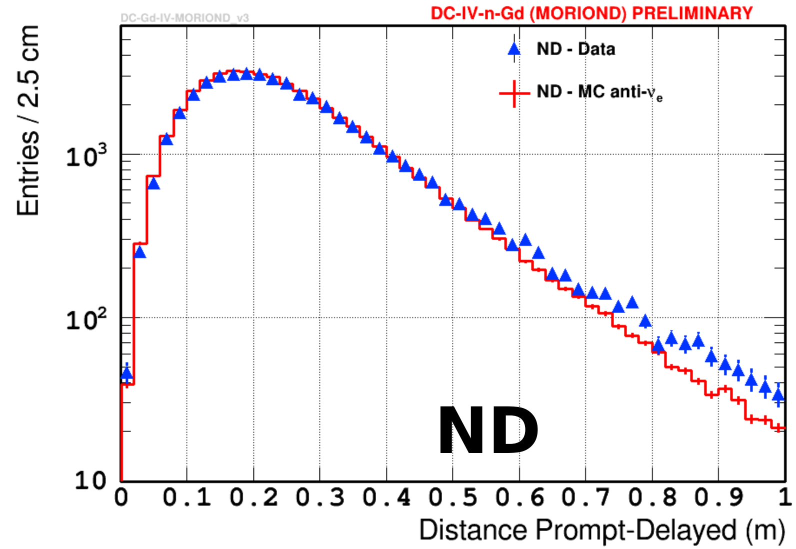
Correlation time





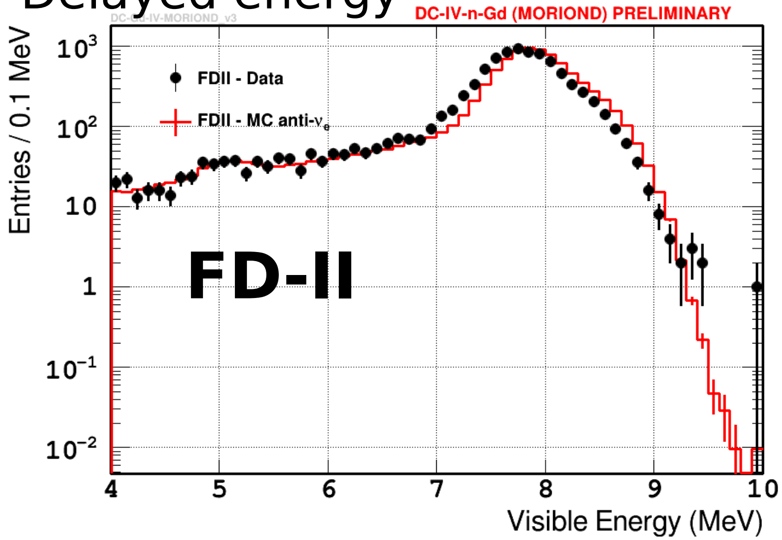
Correlation space

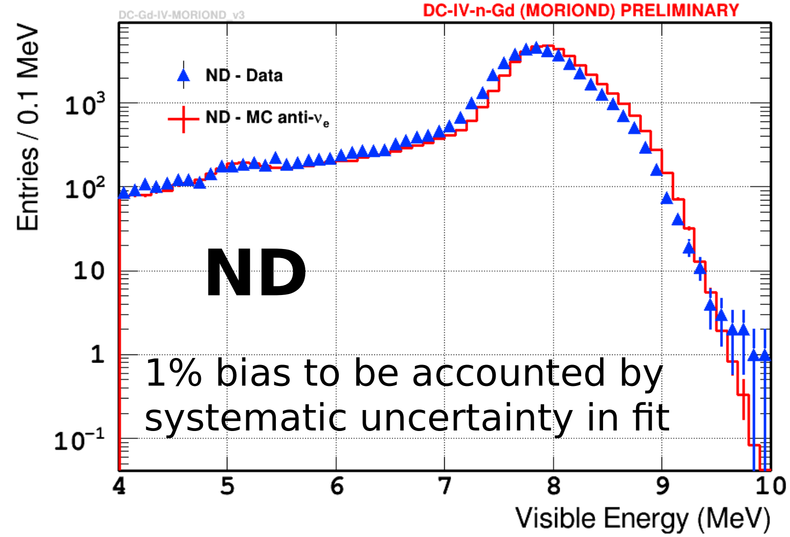




IBD selection

Delayed energy



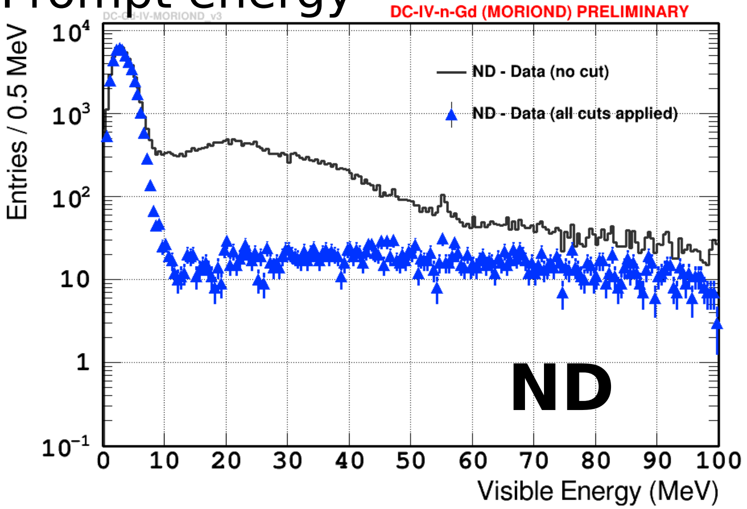


Contamination of liquid scintillator in ND Buffer causes buffer stop-μ background

⇒ 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)

ND and FD are identical within statistical dominated errors (0.29%)

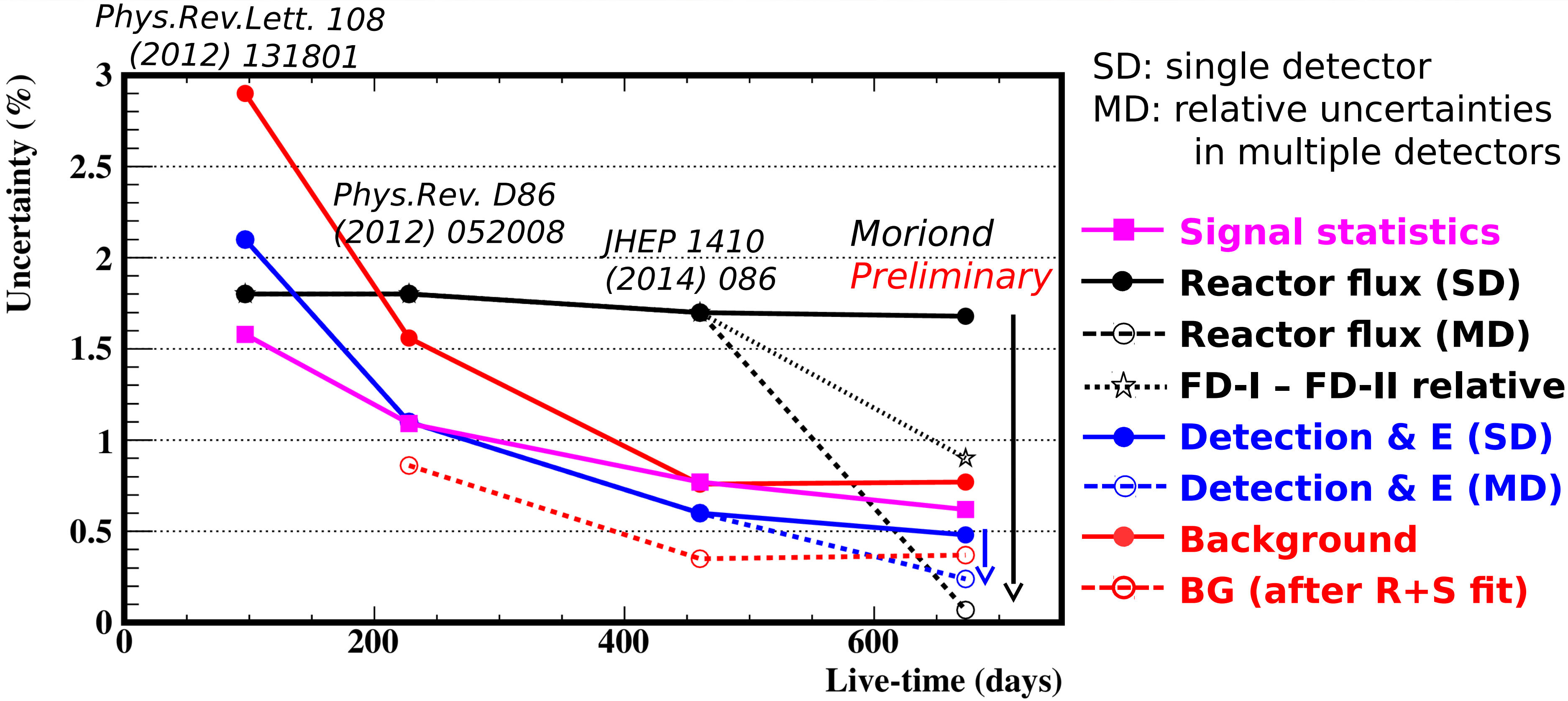
Signal and background

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

Uncertainties in multi-detectors analysis

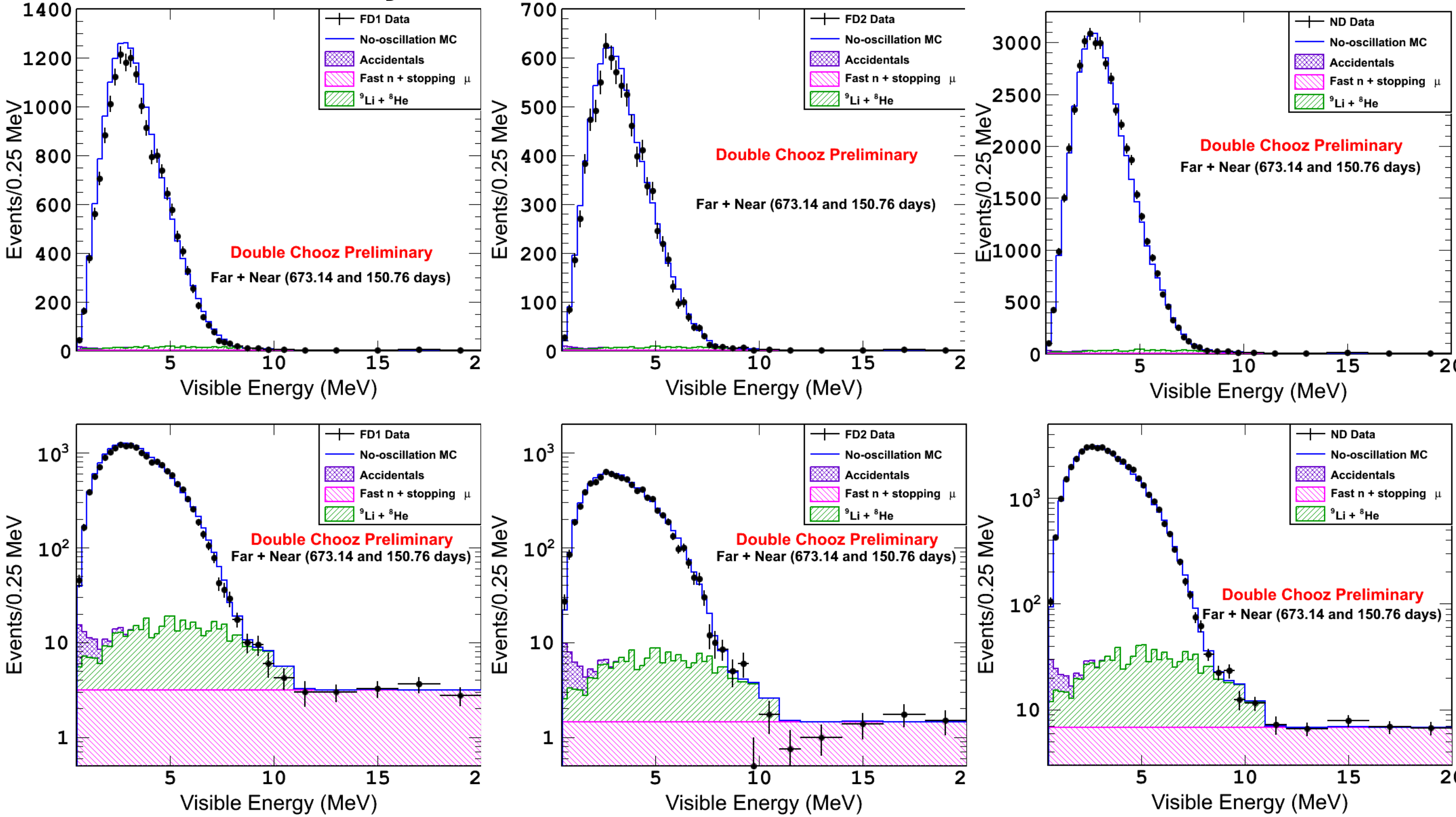


- Systematic errors suppressed with two detectors and in rate+shape fit

  ⇒ All systematic uncertainties below < 0.4% (after R+S fit)
- Current precision (9 months ND) is limited by the statistical uncertainty

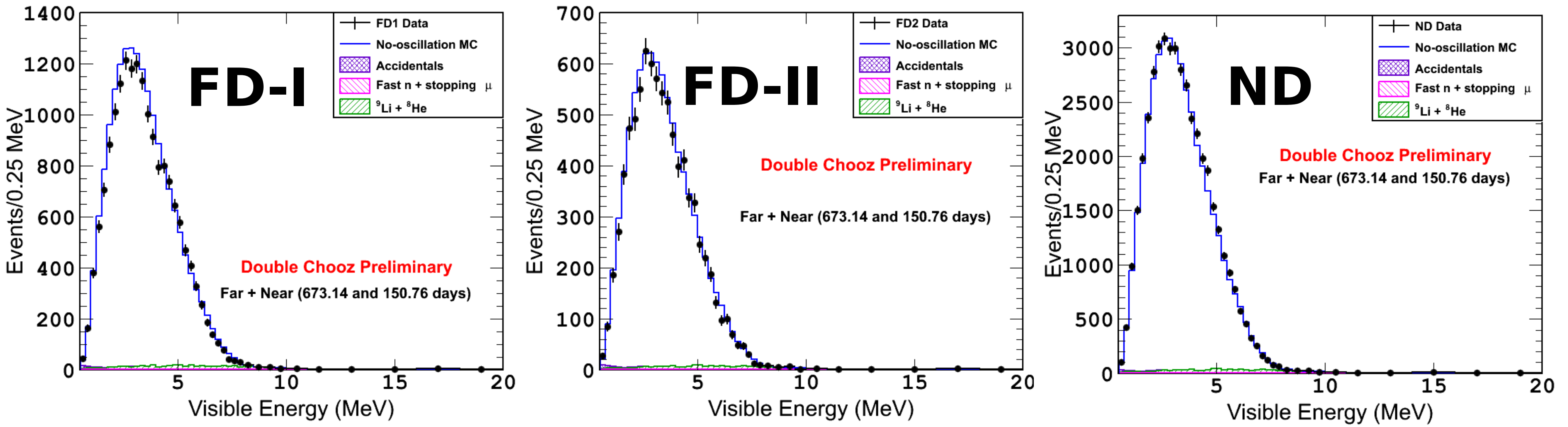
Prompt energy spectrum

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



Extraction of θ_{13} by oscillation fit

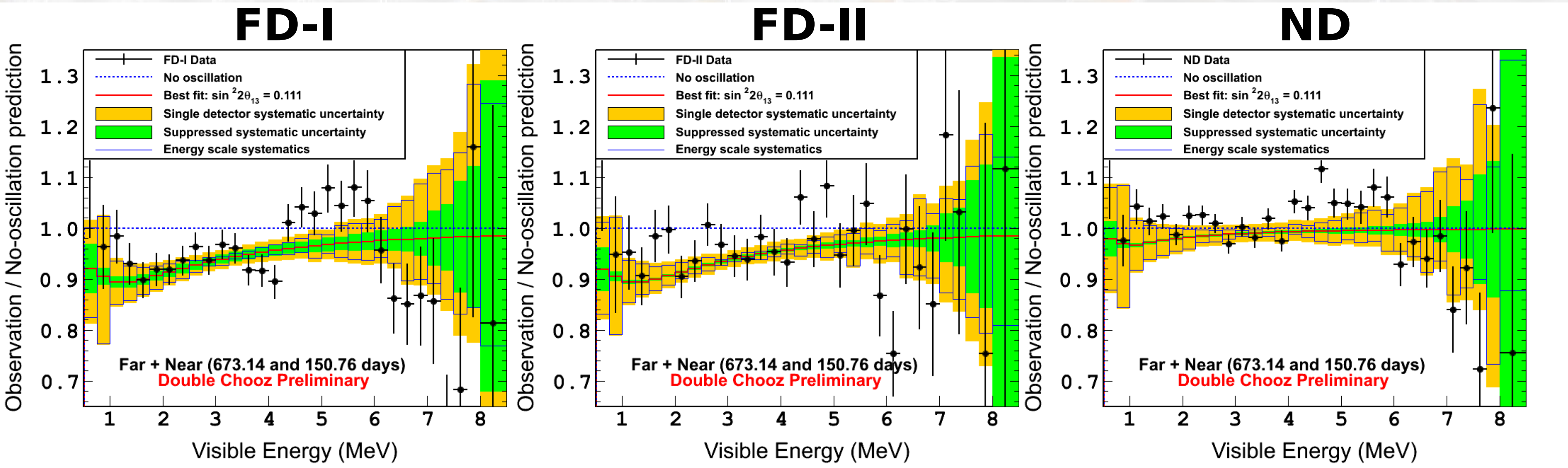
- Compare FD-I, FD-II and ND data simultaneously to predictions
  - Background rate and shape estimated by data (Li rate not constrained)
  - Observed data in reactor off as separate term ⇒ BG constraint



FD-I:FD-II FD-II:ND

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

Fit results

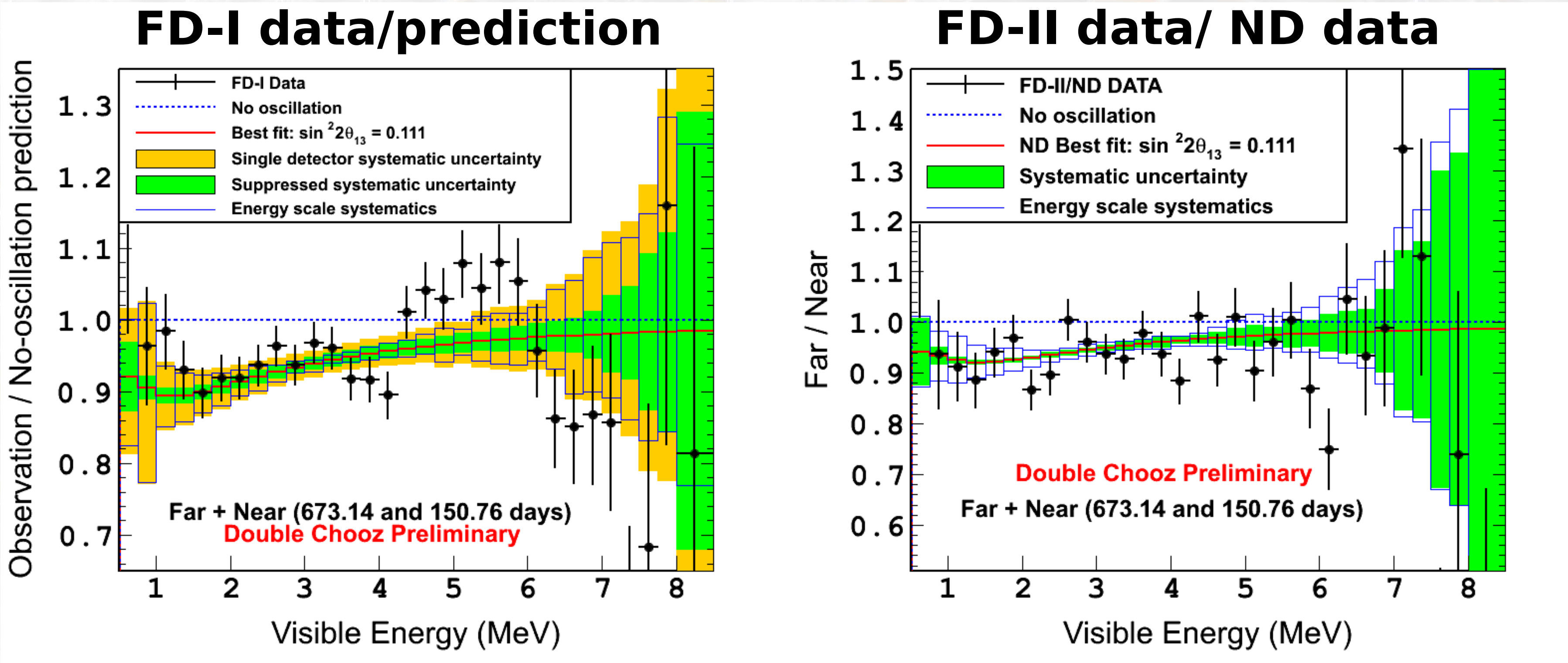


- Best-fit: **$\sin^2 2\theta_{13}$=0.111 ± 0.018** (stat.+syst.) (χ^2/dof = 128.8/120)
  - **Non-zero θ_{13} observation at 5.8σ C.L.**

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

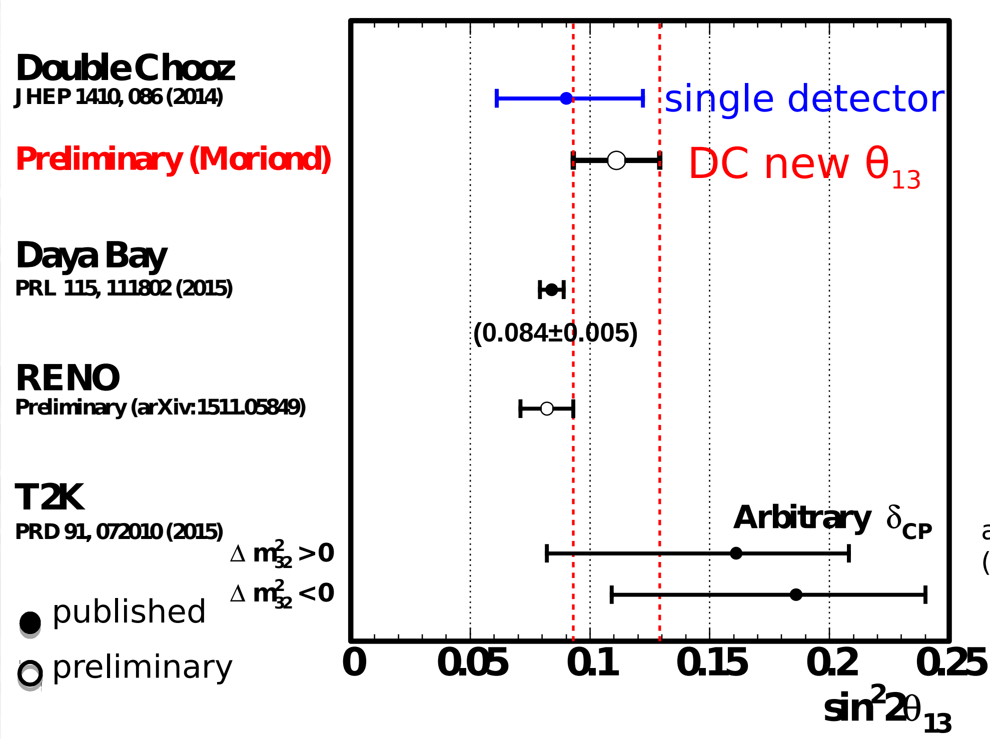
FD / ND ratio



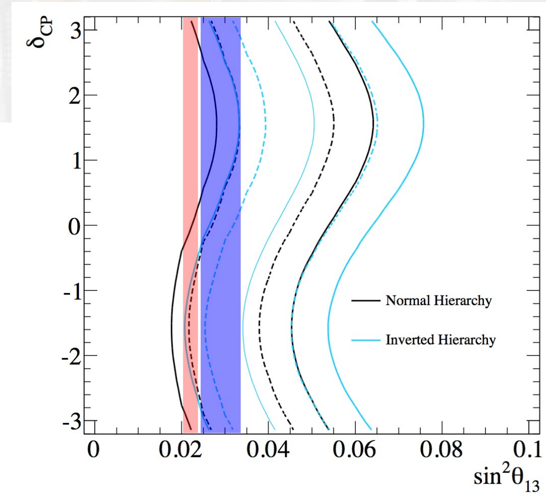
- Systematic uncertainties suppressed in FD-ND relative comparison
- Currently energy uncertainties are assumed to be uncorrelated across detectors (conservative approach)
  ⇔ strong correlation expected with the same scintillator and electronics

Double Chooz θ_{13} in the world

World θ_{13} comparison



@Moriond/2016: DYB nGd+nH: 0.082±0.004



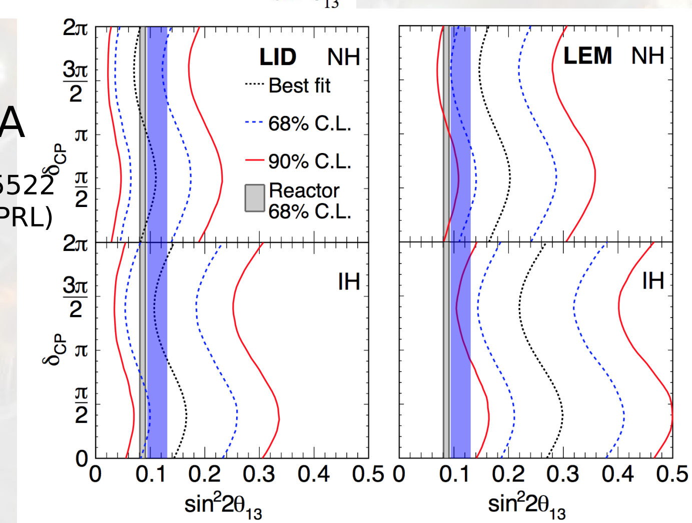
Reactor
vs. T2K

PRD91 072010 (2015)

Double Chooz 1σ
Daya Bay 1σ

Reactor
vs. NOνA

arXivL1601.05522
(accepted by PRL)



- DC θ_{13} is higher than other reactor θ_{13} by ~35% (1.6σ wrt Daya Bay)
- Long baseline (T2K, NOνA) weakly favors higher θ_{13} than reactor average
- Reactor θ_{13} is key parameter to solve CP-violation and mass hierarchy

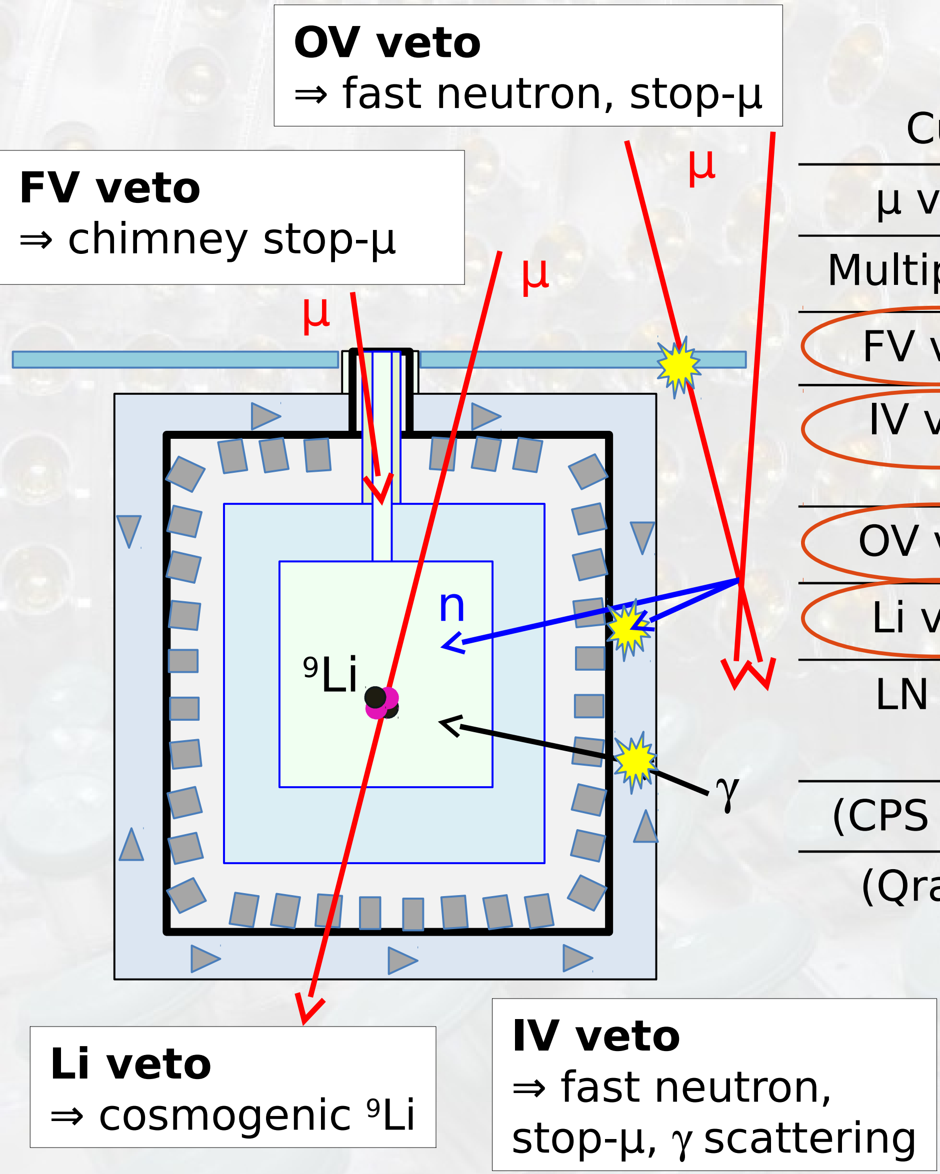
Summary

- Double Chooz collaboration reported first θ_{13} measurement with two detectors (FD-I: 460.93 days + FD-II: 212.21days + ND:150.76days)
  - **$\sin^2 2\theta_{13} = 0.111 \pm 0.018$** (stat.+syst.)
    - Reactor flux uncertainty is strongly suppressed to < 0.1% thanks to nearly iso-flux condition
    - Other systematic uncertainties are suppressed well below 0.5% (after analysis improvements made in single detector phase)
- Reactor θ_{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: agreement?
- Precision is currently limited by statistics (systematics also dominated by statistics)
  ⇒ **Further improvements expected from Double Chooz** **(very soon!)**


Thank you!

Backup

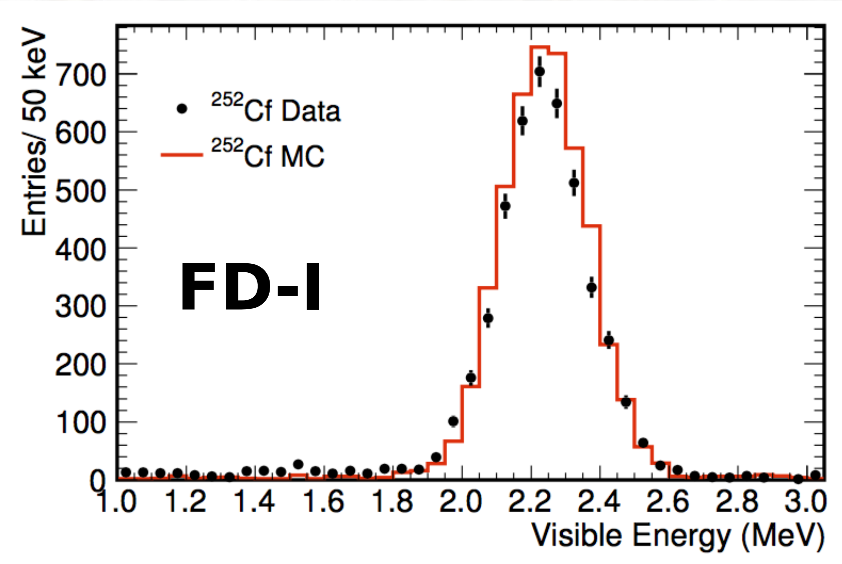
Background vetoes

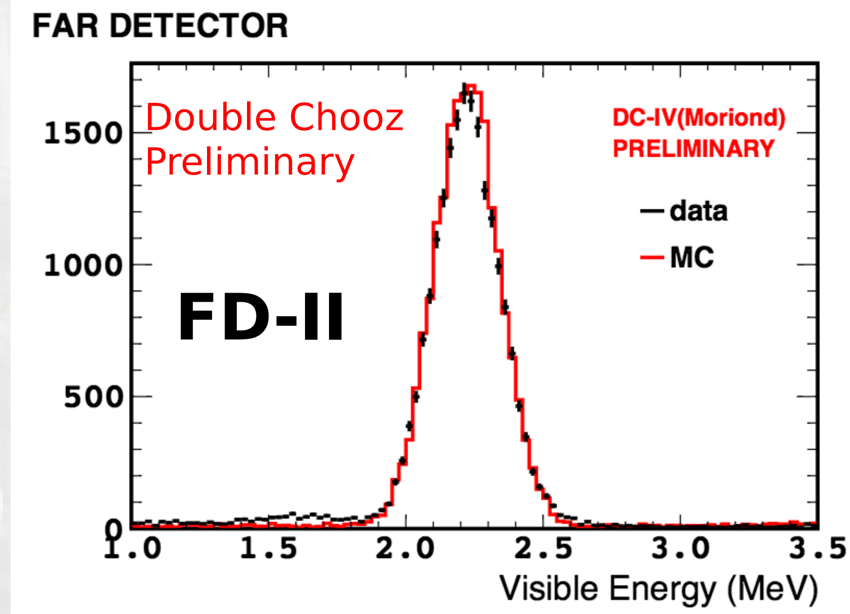


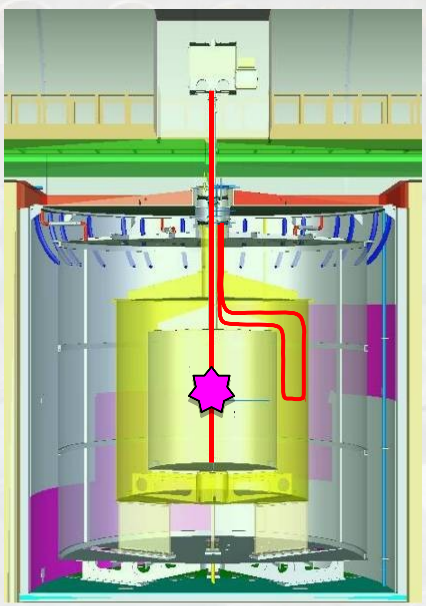
Cut	Information used	Target of cut
μ veto	1ms veto after μ	μ, cosmogenic
Multiplicity	unity condition	multiple-n
FV veto	vertex likelihood	chimney stop-μ
IV veto	IV activity	fast n, stop-μ, γ scattering
OV veto	OV activity	fast n, stop-μ
Li veto	Li-likelihood	cosmogenic
LN cut	PMT hit pattern & time	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)

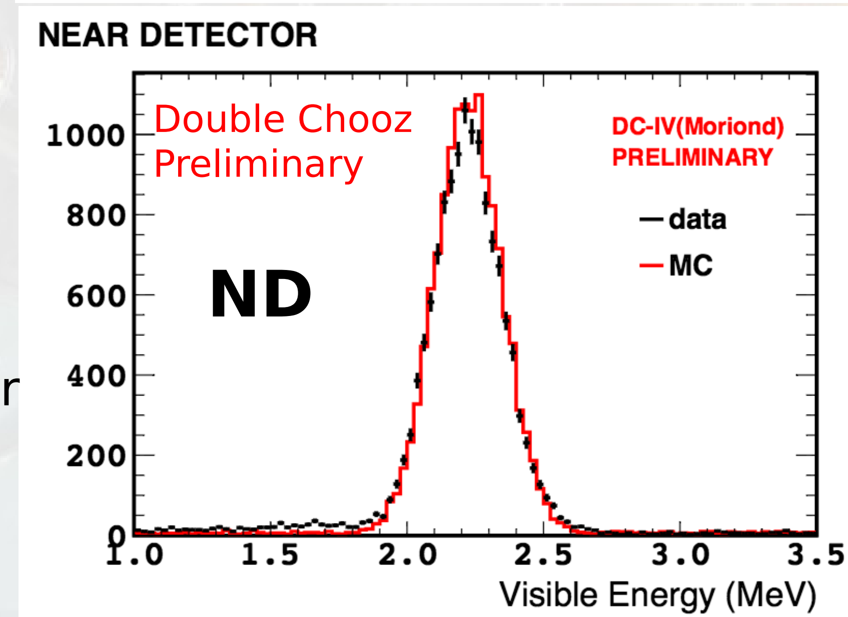
Detector performance



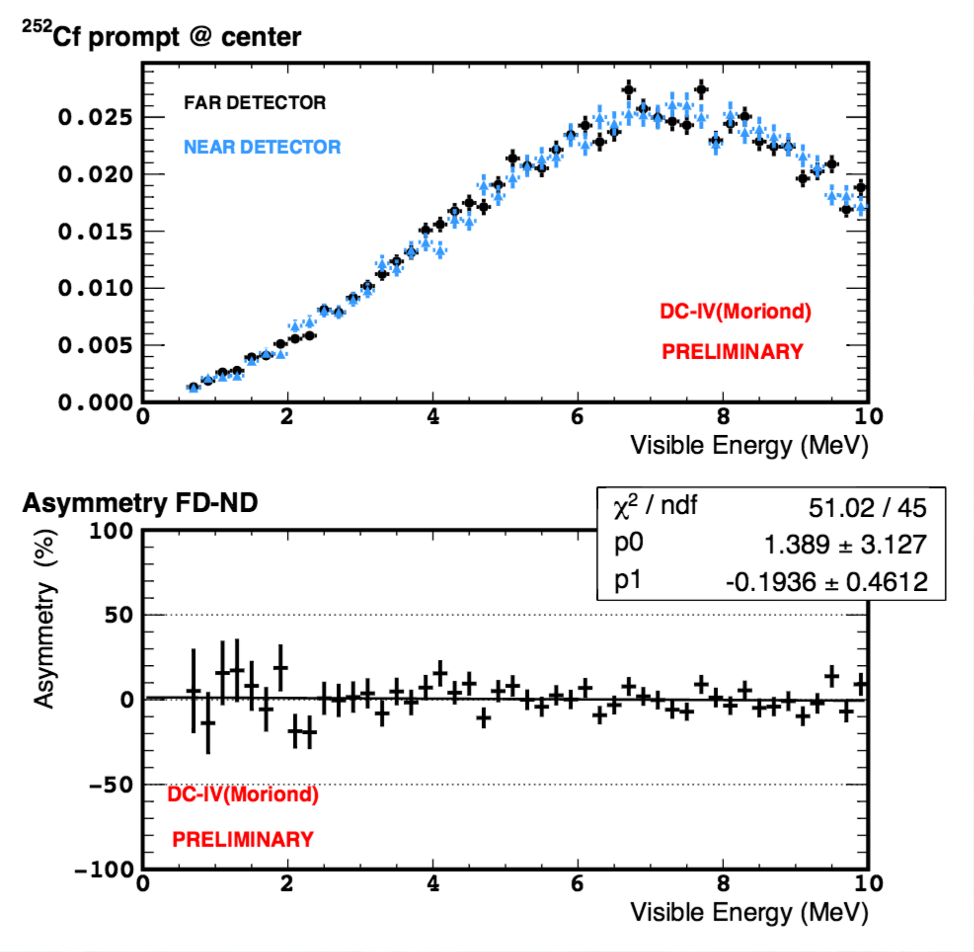




Cf neutron source deployed at center



Prompt energy of ^{252}Cf data



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