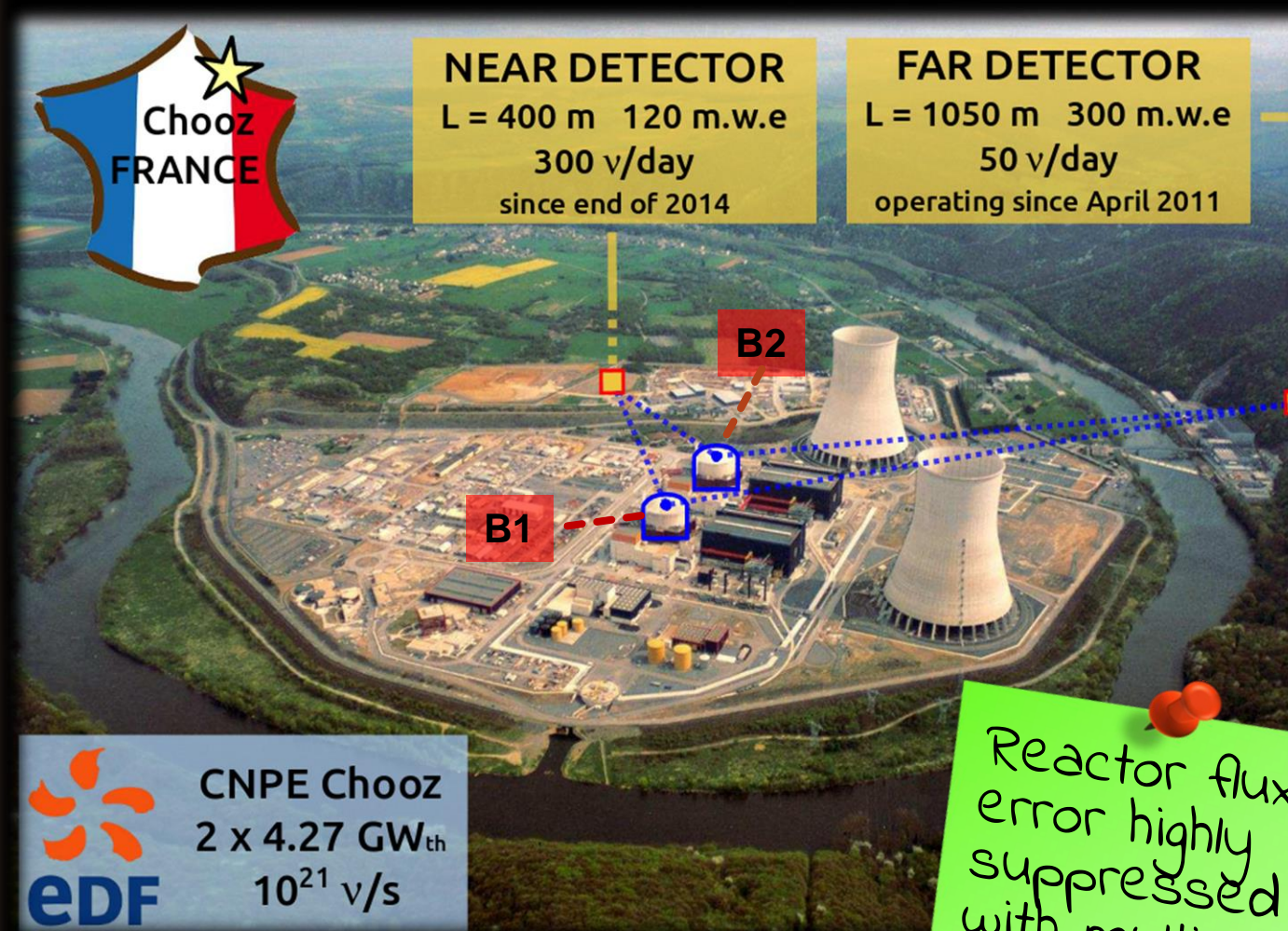# Background independent measurement of θ_{13} with the Double Chooz experiment
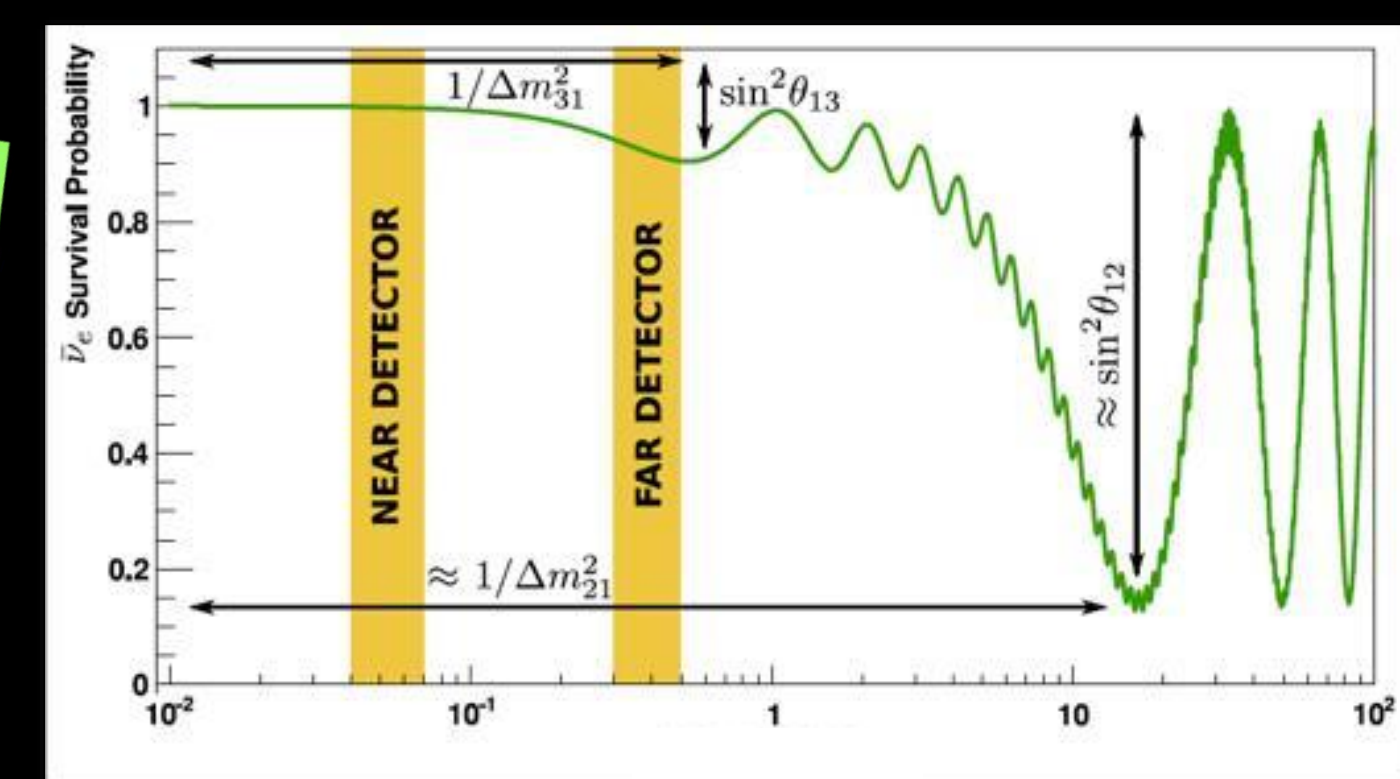
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on behalf of the Double Chooz Collaboration

The Double Chooz Experiment

NEAR DETECTOR
L = 400 m 120 m.w.e
300 ν/day
since end of 2014

FAR DETECTOR
L = 1050 m 300 m.w.e
50 ν/day
operating since April 2011

Chooz FRANCE

B2
B1

CNPE Chooz
2 x 4.27 GW$_{th}$
10^{21} ν/s
edF

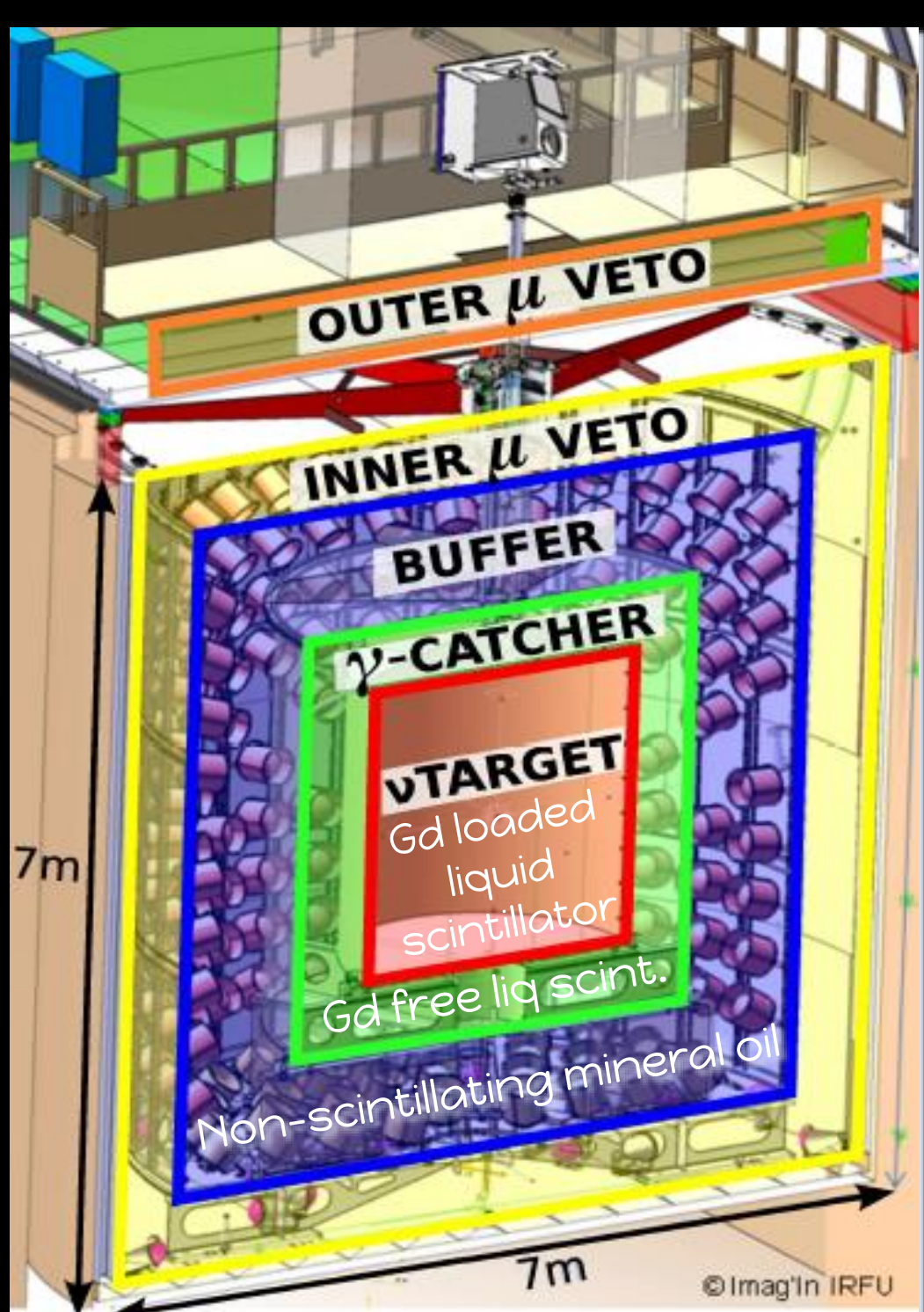Reactor flux error highly suppressed with multi-detectors

In reactor experiments, the determination of the θ_{13} mixing angle is extracted via the survival probability of $\bar{\nu}_e$:

$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L, E) \simeq 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4 E_\nu}\right)$$

$1/\Delta m^2_{31}$ $\sin^2\theta_{13}$

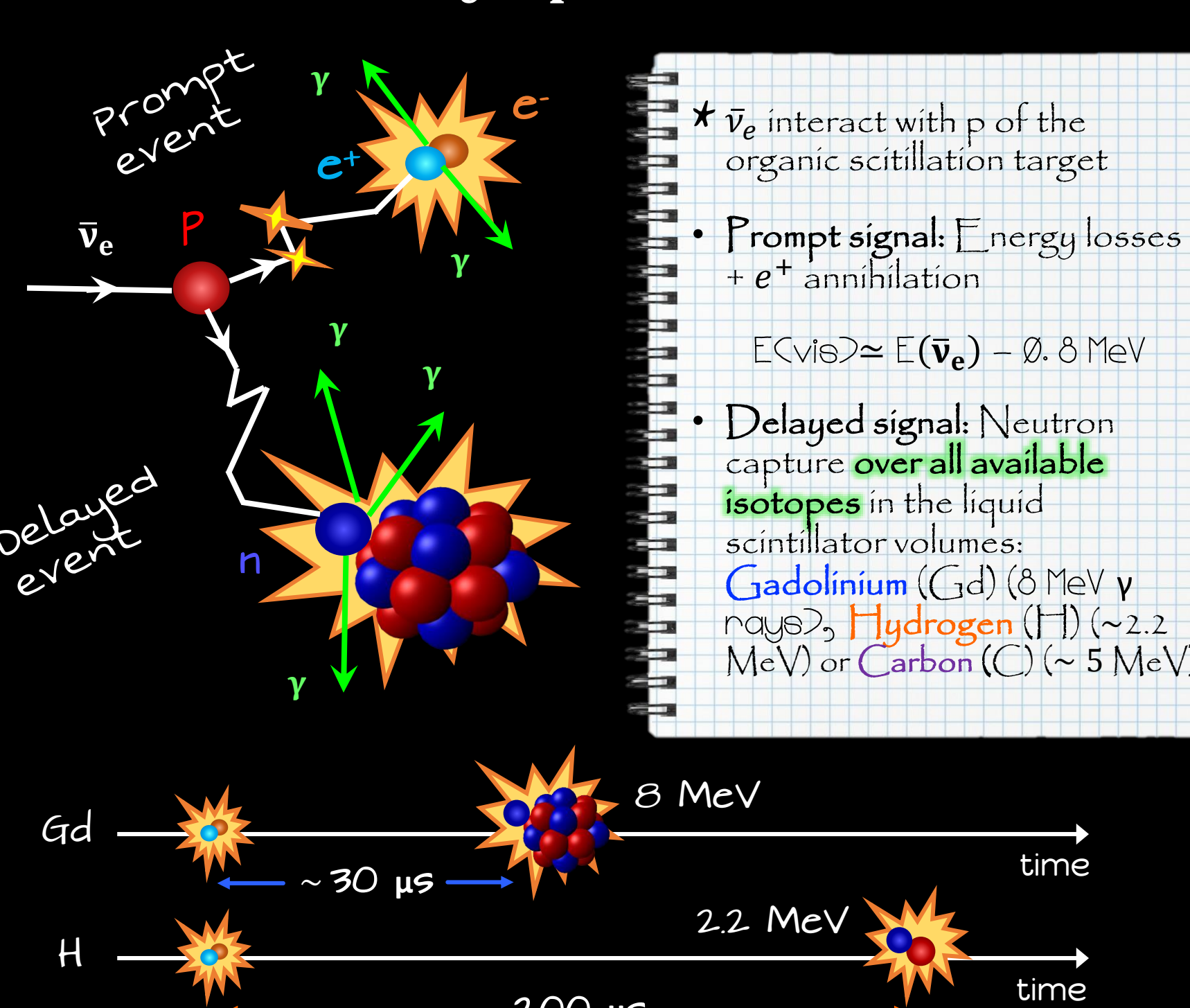NEAR DETECTOR   FAR DETECTOR

$\approx 1/\Delta m^2_{21}$ $\sin^2\theta_{12}$

Multi-detector analysis
- 455 days FD-I (single detector)
- 363 days FD-II (multi-detectors)
- 258 days ND (multi-detectors)

OUTER μ VETO
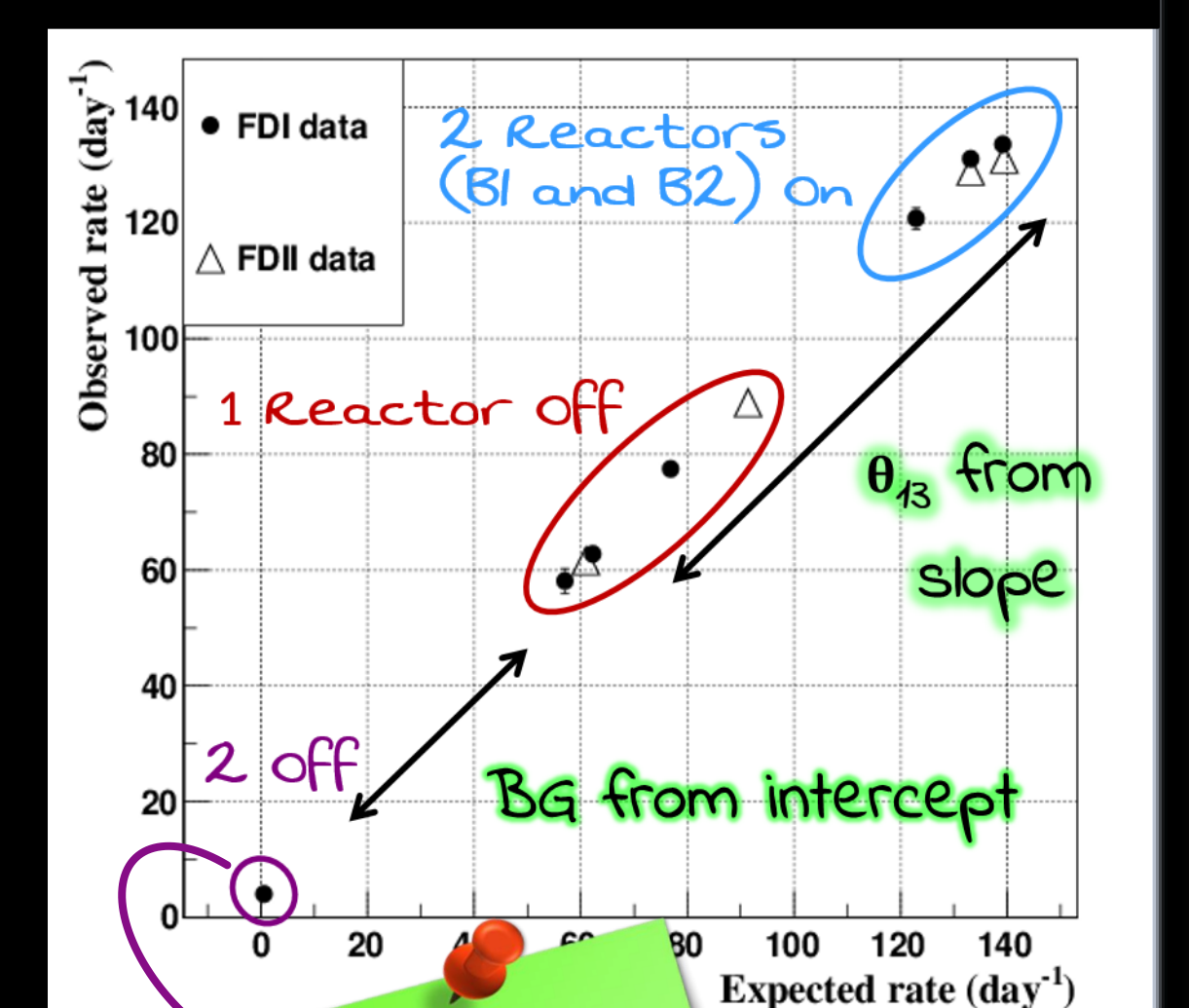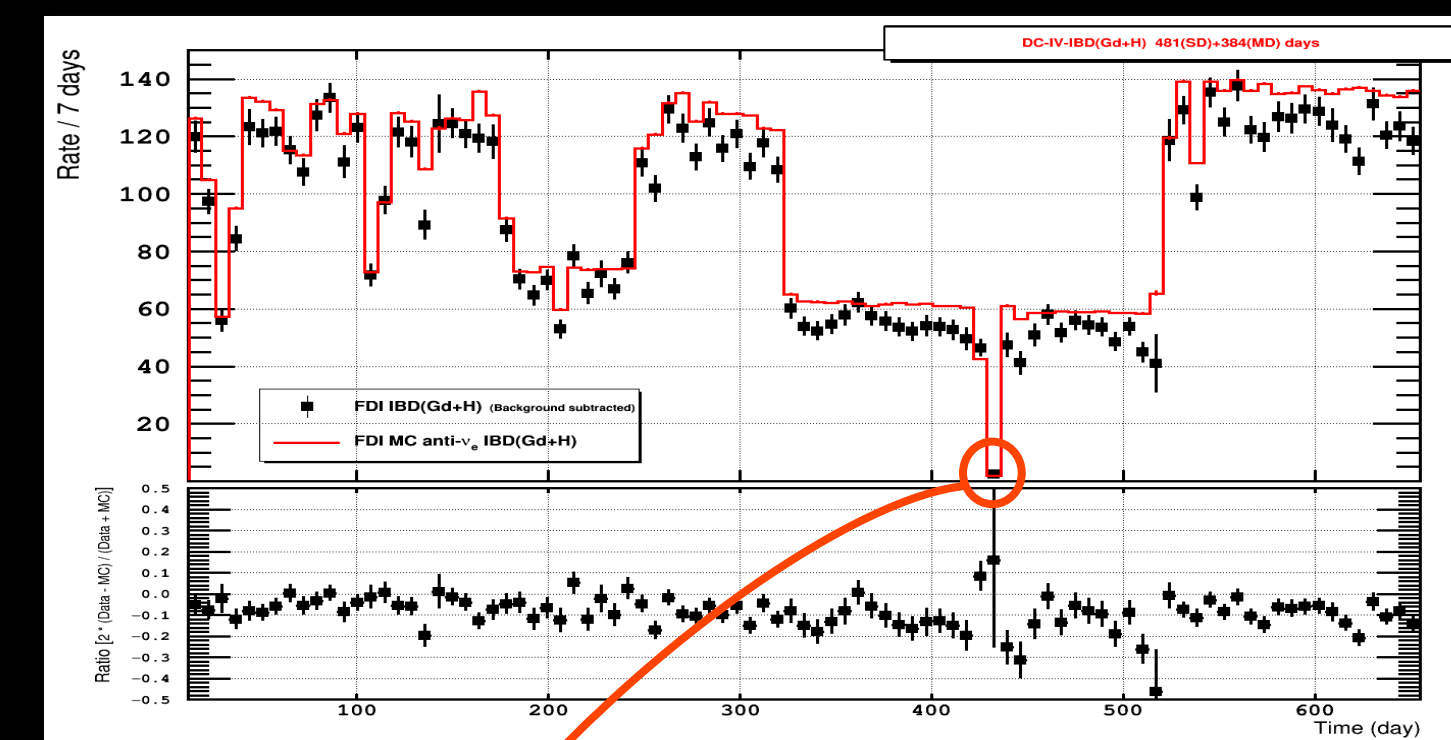INNER μ VETO
BUFFER
ν-CATCHER
νTARGET
Gd loaded liquid scintillator
Gd-free liq. scint.
Non-scintillating mineral oil

7m
7m
©Imag'In IRFU

$\bar{\nu}_e$ are detected via the **inverse β decay** (IBD)

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

Prompt event
γ e⁻
$\bar{\nu}_e$ P e⁺ γ
γ γ
Delayed event
n γ

* $\bar{\nu}_e$ interact with p of the organic scintillation target
- Prompt signal: Energy losses + e^+ annihilation

$E(vis) \simeq E(\bar{\nu}_e) - 0.8$ MeV

- Delayed signal: Neutron capture over all available isotopes in the liquid scintillator volumes: Gadolinium (Gd) (8 MeV γ rays), Hydrogen (H) (~2.2 MeV) or Carbon (C) (~ 5 MeV)

Gd   8 MeV   time
~ 30 μs
H   2.2 MeV   time
~ 200 μs

The Reactor Rate Modulation (RRM) Approach

θ_{13} and cosmogenic BG rates (BG) are determined **simultaneously** by comparing the observed $\bar{\nu}_e$ candidates rate (R^{obs}) with the expected one (R^{exp}) for different **reactor power conditions**:

$$R^{obs} = BG + R^{exp} = BG + (1 - \sin^2(2\theta_{13})\eta_{osc}) R^\nu$$

FDI data   FDII data

2 Reactors (B1 and B2) on
1 Reactor off
θ_{13} from slope
2 off
BG from intercept

Observed rate (day⁻¹)
Expected rate (day⁻¹)

Unique feature in DC that allows a direct measurement of the BG

During 2-Off period, a few β-decays in the reactor core: **Residual ν** emitted

Systematics Uncertainties

	Detector	Parameter	Uncertainty	Correlated
Detection efficiency	FD	ϵ^{FD}	σ^{FD}_{det} = 0.39%	No
	ND	ϵ^{ND}	σ^{ND}_{det} = 0.22%	No
Reactor flux	FDI	$\alpha^{FDI}_{B1}\omega^{FDI}_{B1}, \alpha^{FDI}_{B2}\omega^{FDI}_{B2}$	σ^{FDI}_R = 0.91%	No
	FDII	$\alpha_{B1}\omega^{FDII}_{B1}, \alpha_{B2}\omega^{FDII}_{B2}$	σ_R = 0.91%	No
	ND	$\alpha^{ND}_{B1}\omega^{ND}_{B1}, \alpha^{ND}_{B2}\omega^{ND}_{B2}$	σ^{ND}_R = 0.91%	No

Residual ν rate in FDI in the 2-Off period α_ν = 0.584 ± 0.175 day⁻¹

Overall normalization and correlated errors included in η_{norm} (σ_{norm}=1.4%), dominated by the constraint imposed by Bugey4 data

Oscillation and Cosmogenic BG fit

Rate-only fit that relies on a χ^2 minimization:

$$\chi^2 = \sum_i \chi^2_i + \chi^2_{FD-off} + \chi^2_{BG} + \chi^2_{pen} + \chi^2_{norm} \qquad \sum_i \chi^2_i = \chi^2_{FDI} + \chi^2_{FDII} + \chi^2_{ND}$$

$$\chi^2_i = \left(\frac{1}{\sigma^i_{stat}}\right)^2 \left[R^i_{obs} - R^i_{exp}\left(1 + \eta_{norm} + \sum_{r=B1,B2}(\omega^i_r \alpha^i_r) + \epsilon^i\right) - BG^i\right]$$

$$\chi^2_{FD-Off} = 2\left(N^{obs} \ln\frac{N^{obs}}{BG_{FD} + N^{exp}[1 + \epsilon^{FD} + \alpha^\nu]} + BG_{FD} + N^{exp}[1 + \epsilon^{FD} + \alpha^\nu] - N^{obs}\right)$$
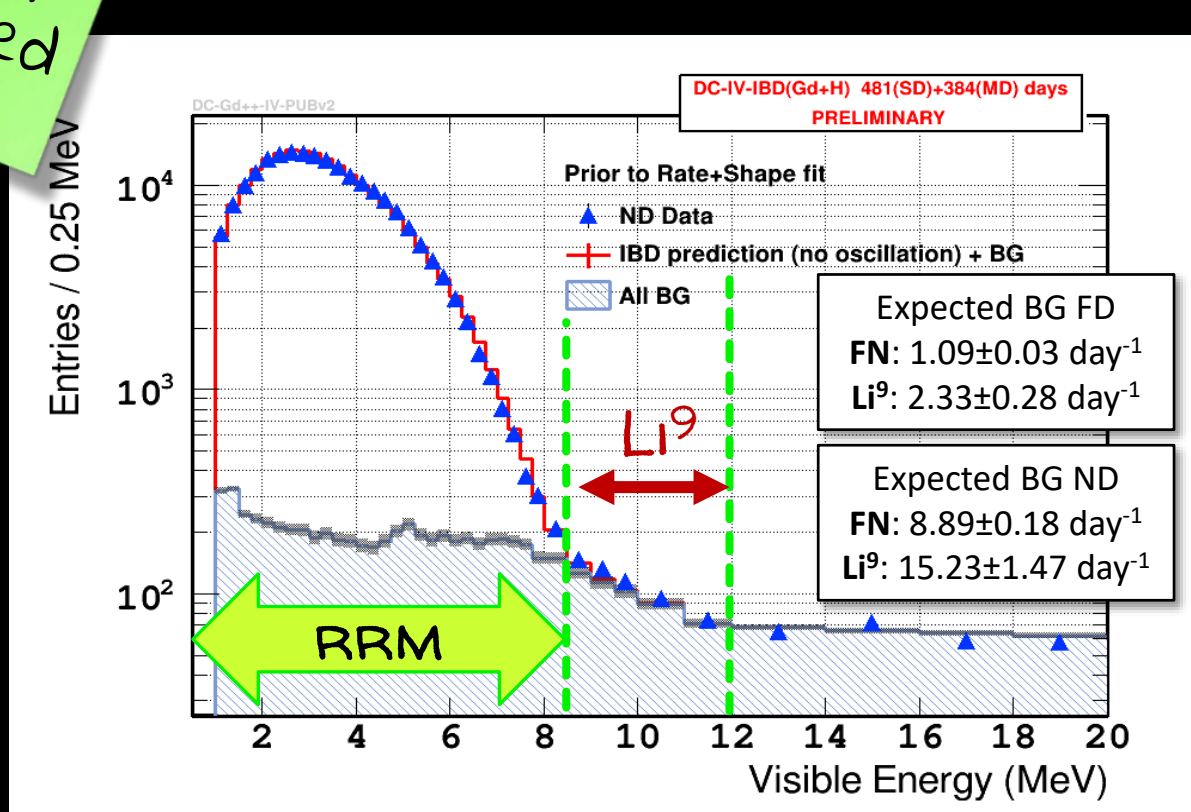
2 ways of performing RRM fit:
1. **Constrained** background: priori knowledge of BG is required, θ_{13} determined with high precision
2. **Unconstrained** background: measurement of θ_{13} independent of the BG model and best fit values of the BG can be confronted to the BG model

Background sources:
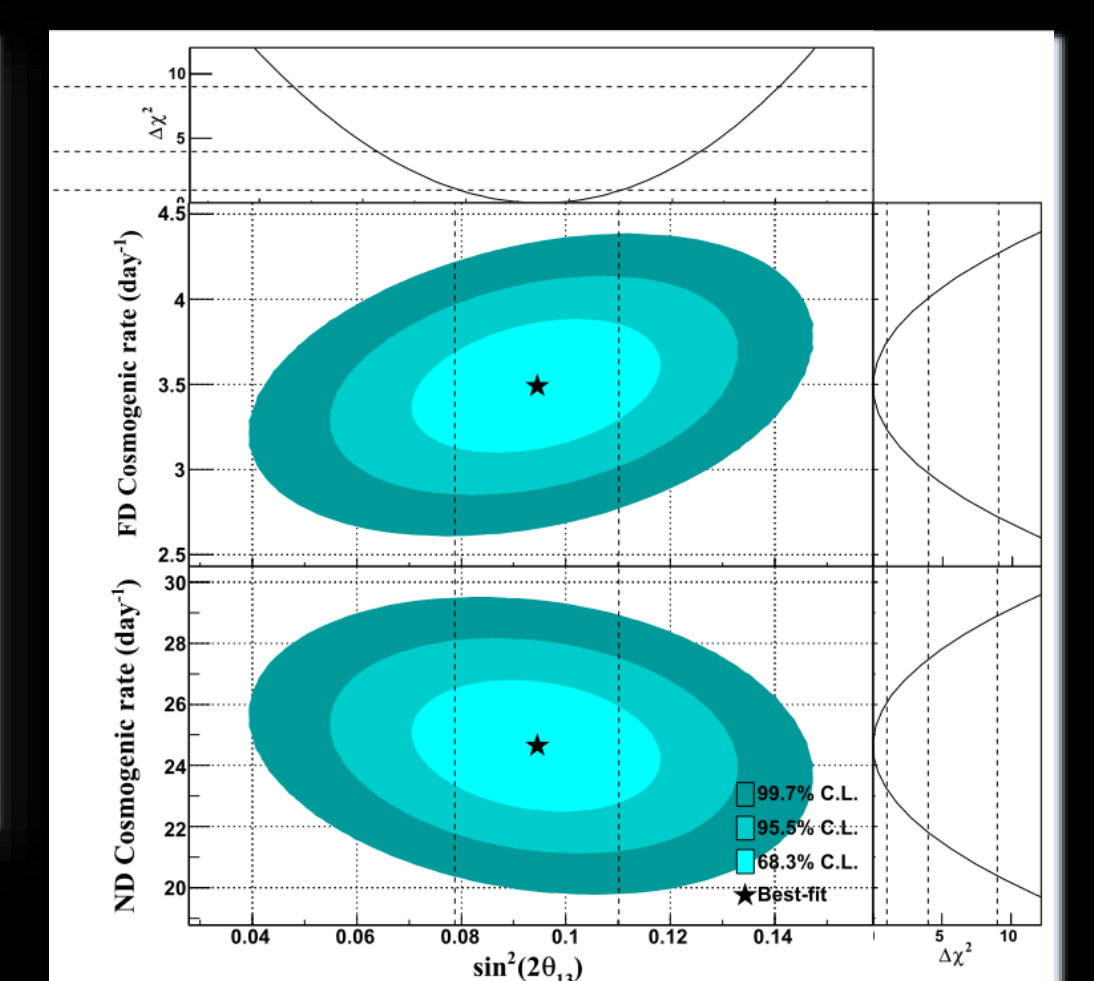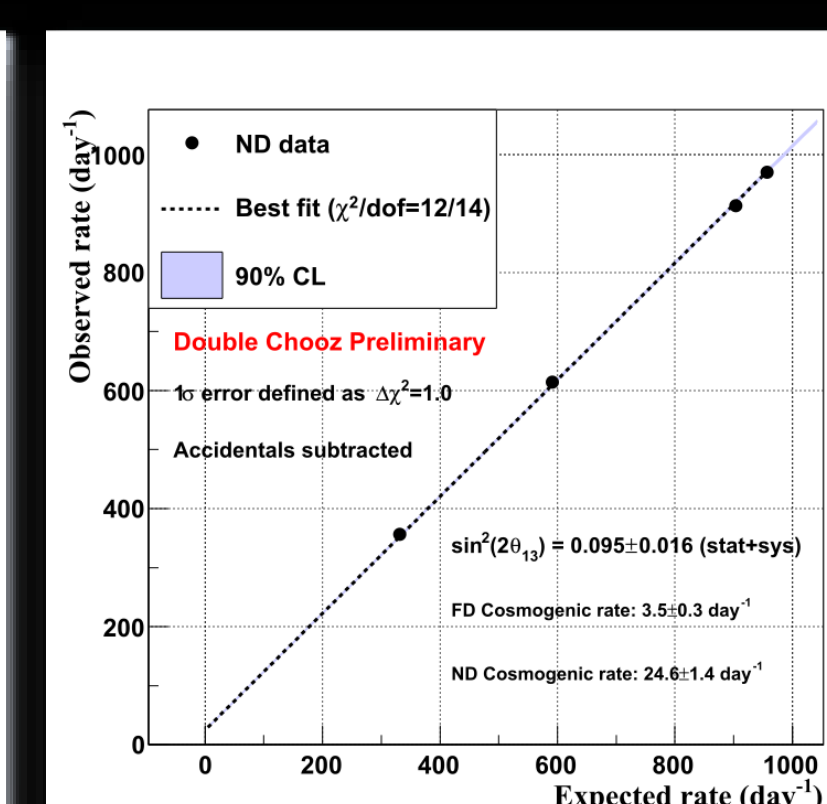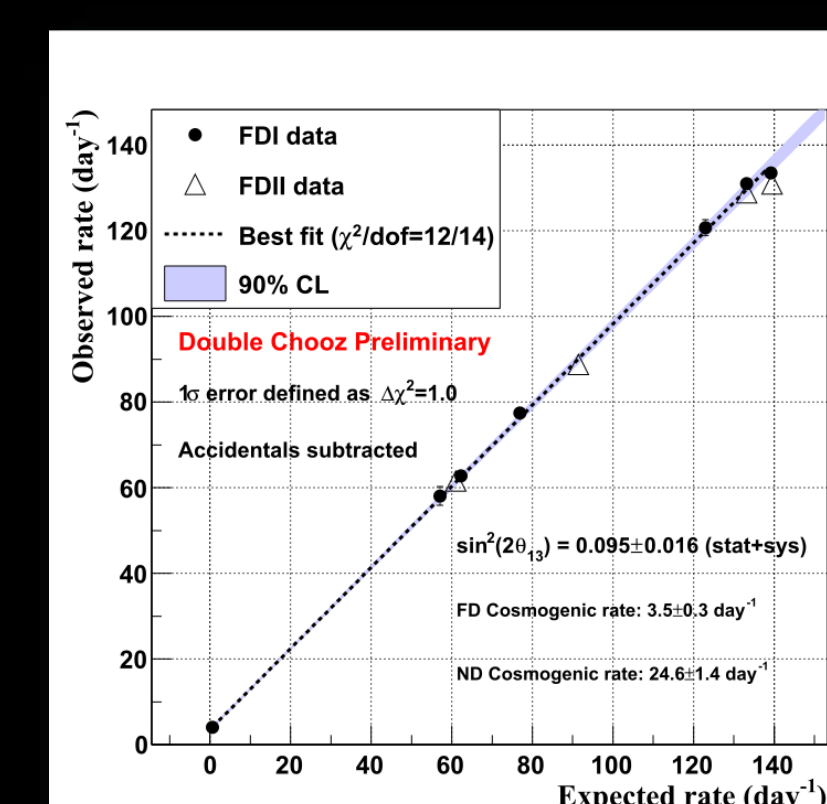**Cosmogenic background: Fast neutrons + Cosmogenic Isotopes (Li⁹)**

$$\chi^2_{BG} = \sum_{i=FD,ND}\left(\frac{BG_i - BG^{exp}_i}{\sigma^{exp}_{BG_i}}\right)^2$$

Accidental coincidences subtracted from DATA (not included in the fit)

ND Data
Prior to Rate+Shape analysis
IBD prediction (no oscillation) + BG
All BG
Li⁹
RRM

Expected BG FD
FN: 1.09±0.03 day⁻¹
Li⁹: 2.33±0.28 day⁻¹

Expected BG ND
FN: 8.89±0.18 day⁻¹
Li⁹: 15.23±1.47 day⁻¹

Visible Energy (MeV)

- RRM fit: 1.0-8.5 MeV energy window
- Li⁹ extracted from candidates in the 8.5-12.0 MeV window:
  - Subtract FN estimation in the 8.5-20.0 MeV range
  - Remaining candidates in the 8.5-12 MeV provide the Li⁹ rate
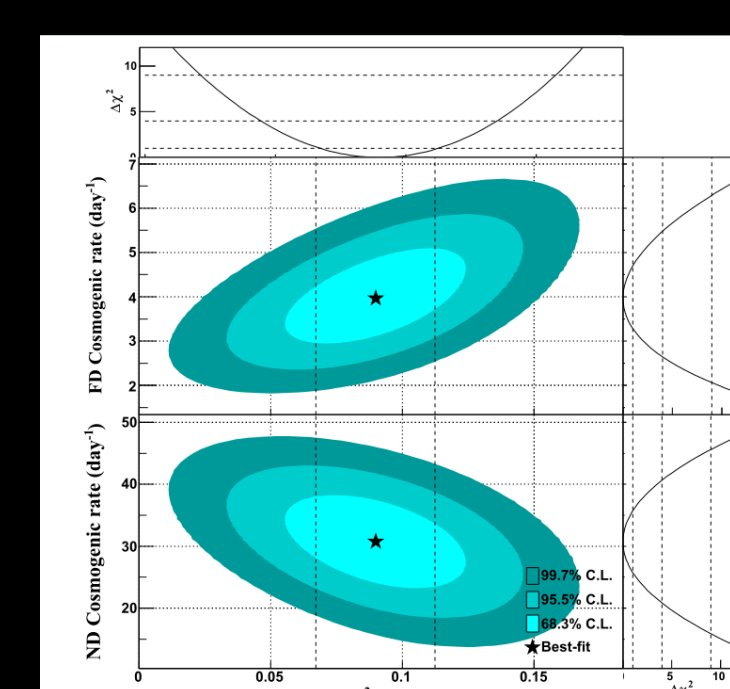 - Extrapolate rate to 1.0-8.5 MeV according to shape spectrum

RRM Oscillation fit Results

a. RRM fit with background constraint

FDI data
FDII data
90% CL
Double Chooz Preliminary
1σ error defined as $\Delta\chi^2$=1.0
Accidentals subtracted
$\sin^2(2\theta_{13})$ = 0.095±0.016 (stat+sys)
FD Cosmogenic rate: 3.5±0.3 day⁻¹
ND Cosmogenic rate: 24.6±1.4 day⁻¹

ND data
Best fit (χ^2/dof=12/14)
90% CL
Double Chooz Preliminary
1σ error defined as $\Delta\chi^2$=1.0
Accidentals subtracted
$\sin^2(2\theta_{13})$ = 0.095±0.016 (stat+sys)
FD Cosmogenic rate: 3.5±0.3 day⁻¹
ND Cosmogenic rate: 24.6±1.4 day⁻¹

Observed rate (day⁻¹)
Expected rate (day⁻¹)

$$\boxed{\sin^2(2\theta_{13}) = 0.095 \pm 0.016}$$

b. RRM fit without background constraint
- BG treated as free parameter in the fit
- $\sin^2(2\theta_{13})$ = 0.090 ± 0.023
- θ_{13} independent of the BG model
- BG_{FD} = 4.0 ± 0.7, BG_{ND} = 30.7 ± 5.0 events/day (FN+Li⁹) consistent within 1σ with the BG model
- The constraint on the total BG rate given by the 2-Off data improves precision of θ_{13}

c. Crosscheck of the Rate+Shape fit
- Same energy window (1.0-20.0 MeV) assumed
- $\sin^2(2\theta_{13})$ = 0.110 ± 0.018
- R+S fit: $\sin^2(2\theta_{13})$ = 0.105 ± 0.014

RRM fit yields almost same precision as R+S fit

d. Flux normalization consistent with expectation: η_{norm} = -0.1 ± 0.7 %
- Fit compatible with flux reactor model!
- σ_{norm} is reduced from 1.4 % to 0.7 % thanks to relative comparison FD to ND