Reactor Induced Errors in Antineutrino Experiments

A.S. Cucoanes[☆], P.Novella[✪], A.Cabrera[✪], M.Fallot[☆], A.Onillon[☆], F.Yermia[☆]

[☆]Subatech Nantes ; [✪]APC Paris

GDR Neutrino – Lyon, Nov.2013

Outline

- A briefly look on neutrino oscillations and reactor antineutrinos
- ϴ13 experiments: Double Chooz, Daya Bay and Reno
- Neutrino Flux from reactors
- Isoflux condition and reactor induced uncertainty
- Simplest case: 1 reactor 2 detectors → Double Chooz phase 1
- 2 reactors / 2 detectors → Double Chooz phase 2
- >2 reactors / 2 detectors → Reno
- >2 reactors / >2 detectors → Daya Bay
- Final comparison between experiments
- Conclusions and outlook

Neutrino Oscillations

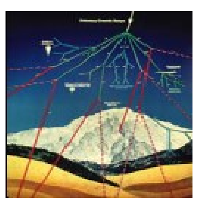
There is no known symmetry which would imply that the neutrino mass and flavor eigenstates are the same.

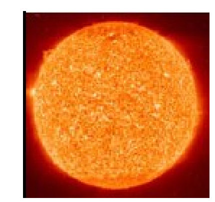
$$|\nu_i\rangle = \sum_{\alpha} U_{\alpha i} |\nu_\alpha\rangle$$

U – the mixing matrix - describe the coupling of the states (Pontecorvo-Maki-Nakagawa-Sakata)

The probability of finding a given state will change in time → the neutrinos will oscillate

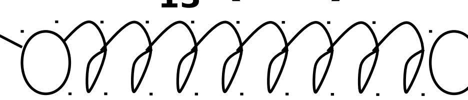
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$





Atmospheric oscillation:
Amplitude: θ_{23} (~45°)
Frequency: Δm_{31}^2
(~$2.4 \cdot 10^{-3}$ eV^2)

Coupling strength:
θ_{13} (~9°)



Sub-leading effects:
mass hierarchy, δ_{CP}

Solar oscillation
Amplitude: θ_{12} (~33°)
Frequency: Δm_{21}^2
(~$7.6 \cdot 10^{-5}$ eV^2)

Need sizable θ_{13} for the access to δ_{CP} . → **knowledge on the matter-antimatter asymmetry of the Universe**

The precise value of θ_{13} is needed for tuning the δ_{CP} experiments.

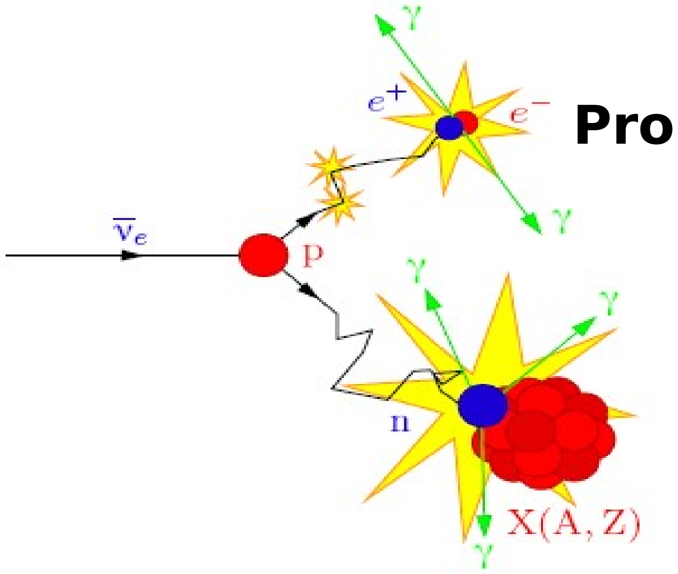
Why a Θ13 Measurement **at reactors ?**

$\overline{\nu}_e$ from fission products (^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu): → well-understood source.

Pure, intense and completely isotropic $\overline{\nu}_e$ flux.

<E>~3MeV, detection via inverse beta decay in liquid scintillator:

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



Prompt: dE/dx of e^+ and e^+e^- annihilation: E_p=1-8 MeV

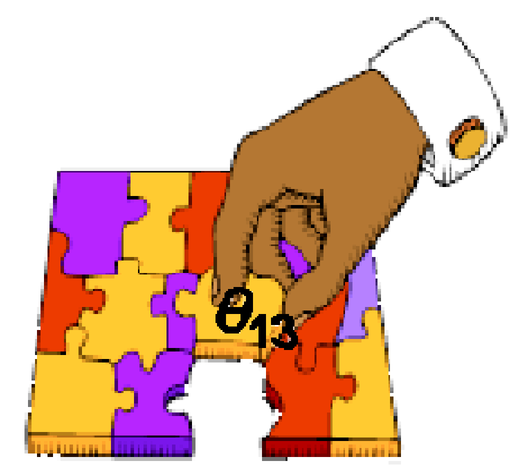
Delayed: nuclear capture: E_d= 8MeV (Gd)

- Space (1m) and time (30µs) correlation between prompt and delayed events → powerful background rejection.
- Antineutrino energy can be directly measured: $E_p = E_\nu - 0.8$MeV
- No background from other neutrino species.
- Protons abundant in liquid scintillator.
- Low energy threshold (1.8MeV).

How to do a θ13 measurement at reactors ?

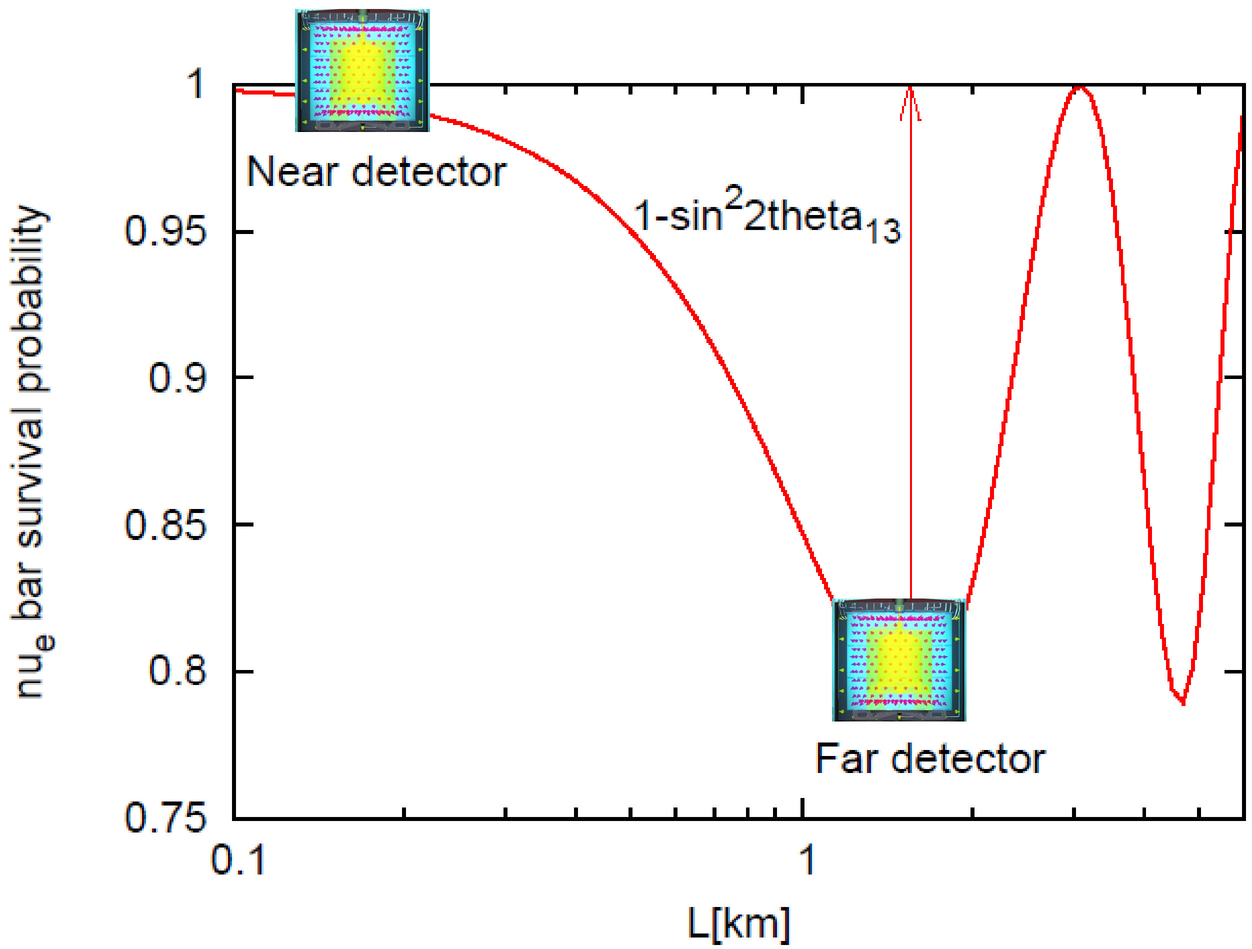
–

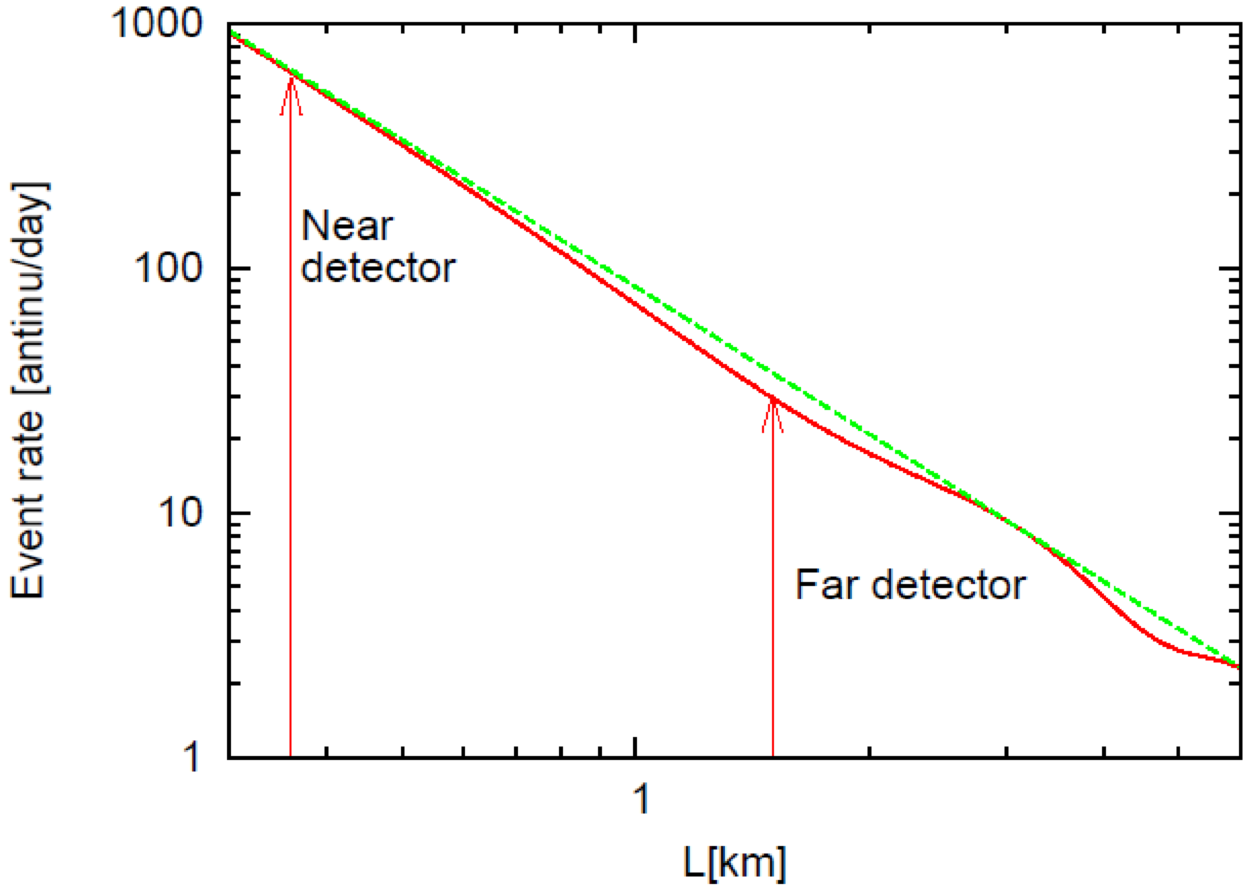
=



more precisely ...

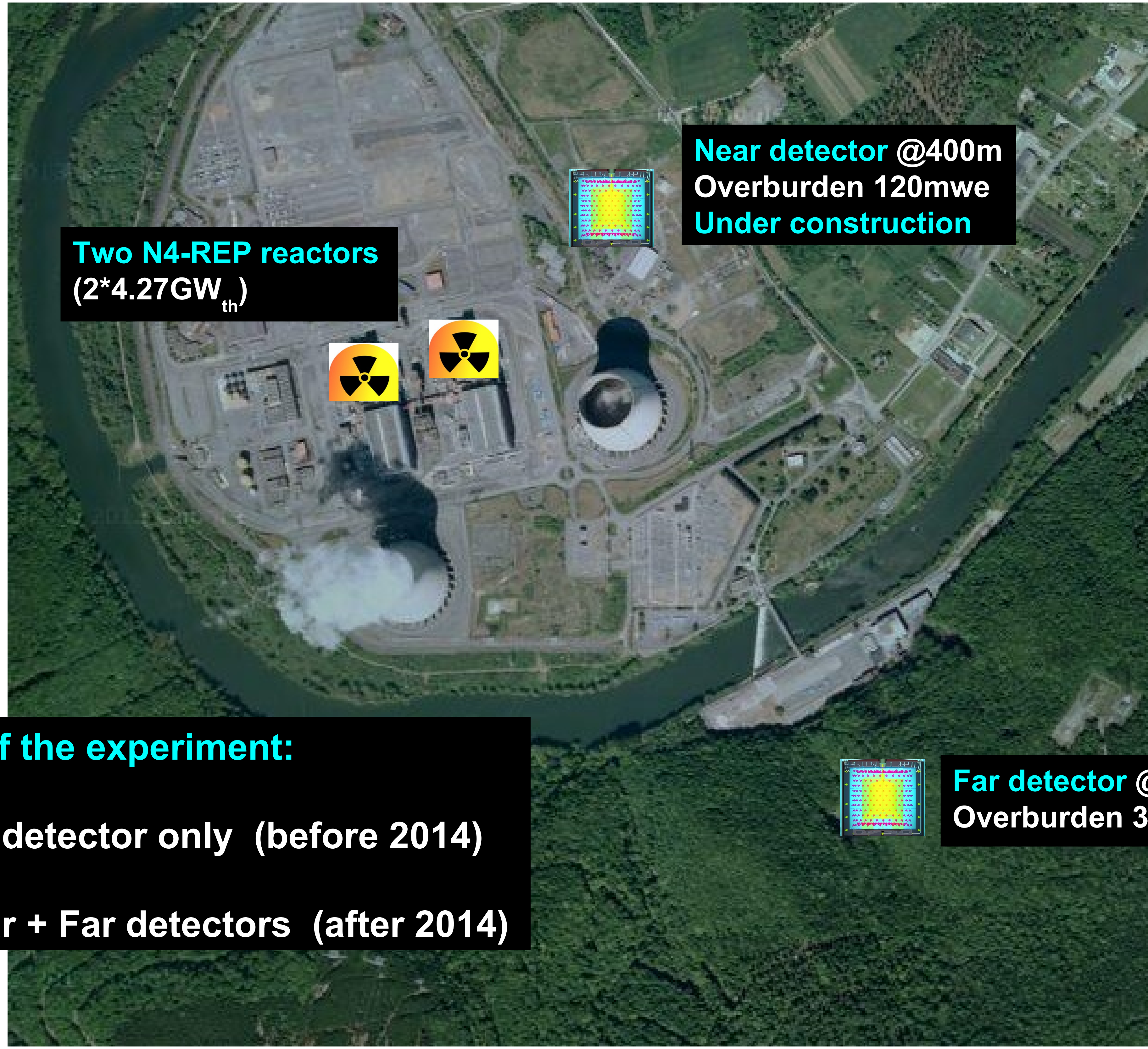
$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2(2\theta_{13}) \cdot \sin^2\left(\frac{1.27 \cdot \Delta m^2_{31}[eV^2] \cdot L[m]}{E[MeV]}\right)$$





- **Flux and spectrum** are compared with the no-oscillation hypothesis
- **Identical detectors placed at isoflux** → total cancellation of the source induced uncertainties

Double Chooz Experiment in France

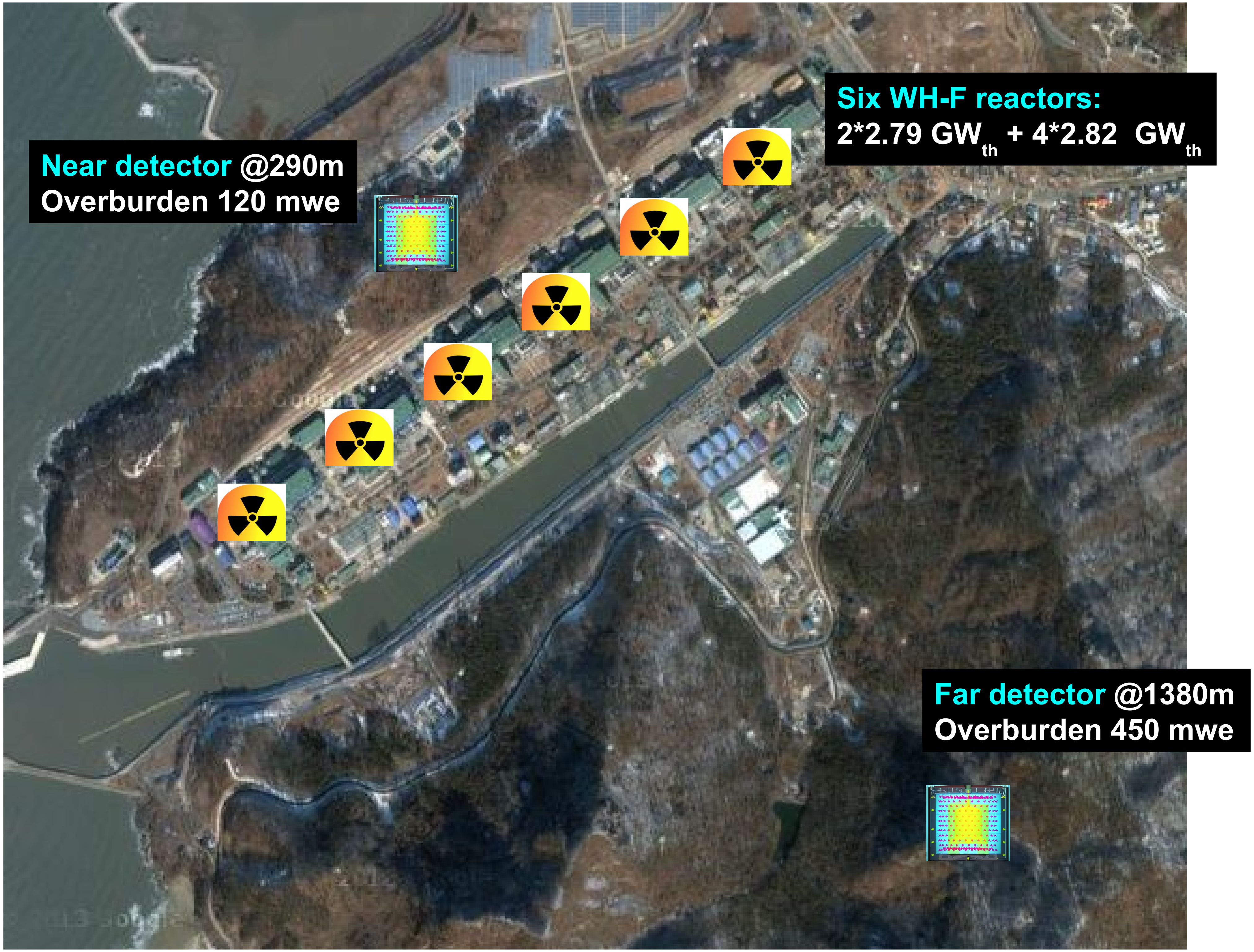


Two phases of the experiment:

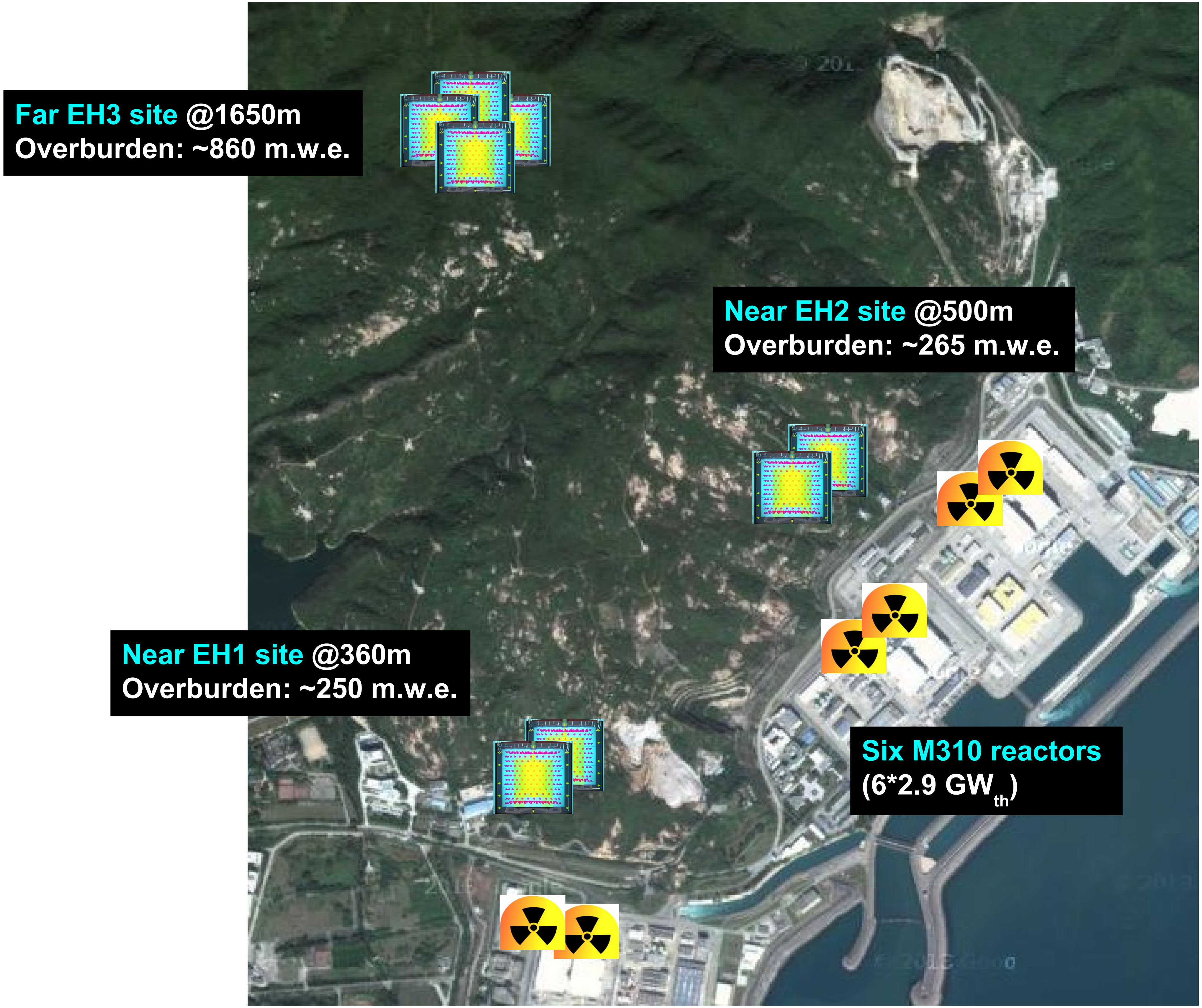
PHASE 1: Far detector only (before 2014)

PHASE 2: Near + Far detectors (after 2014)

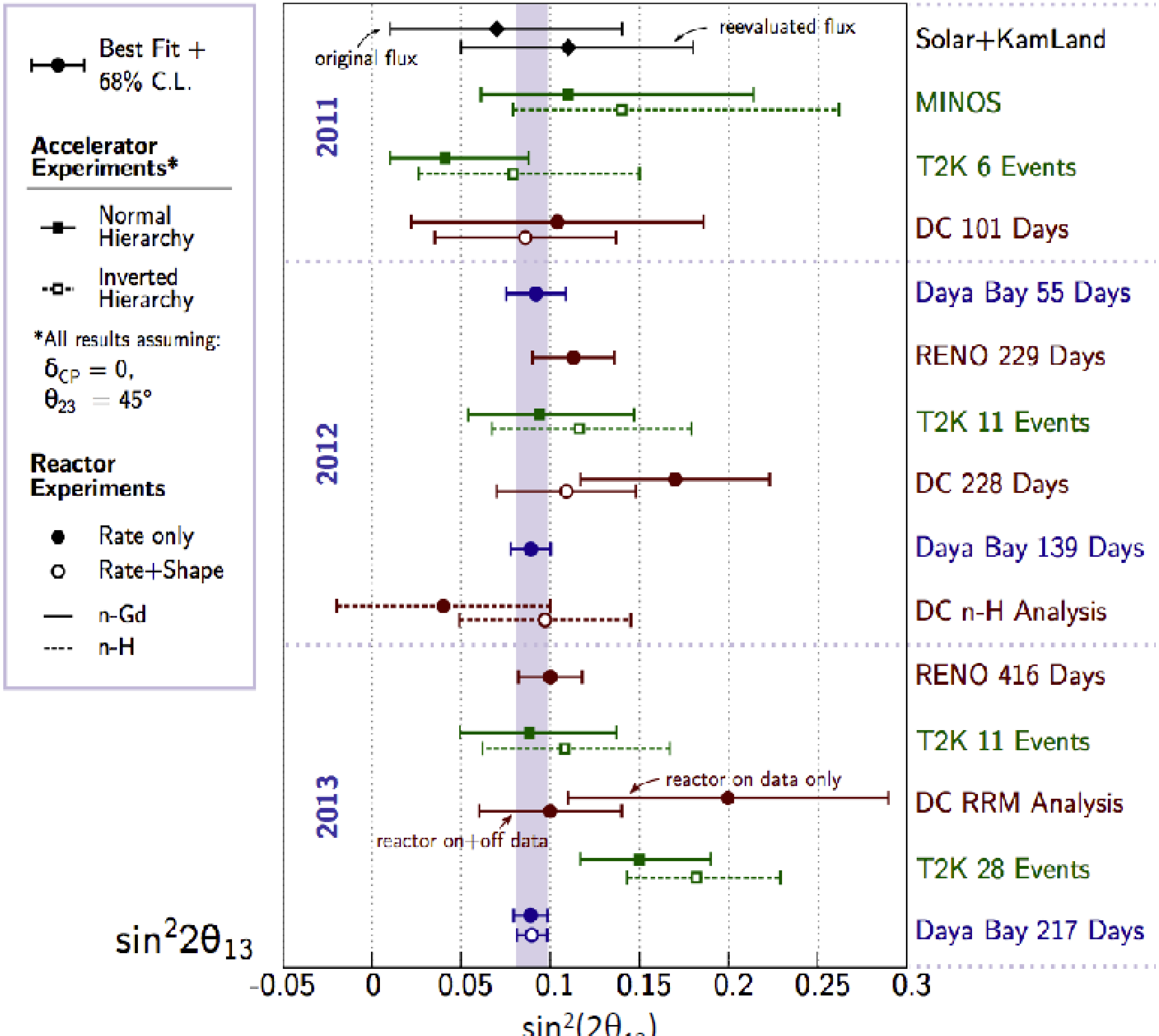
Reno Experiment in South Korea



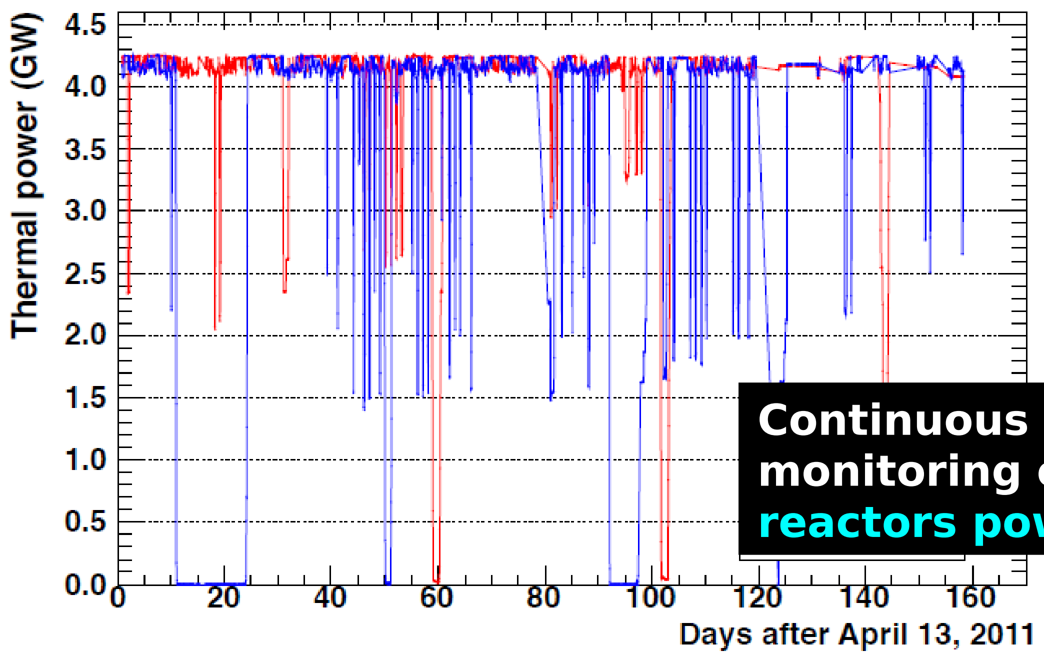
Daya Bay Experiment in China

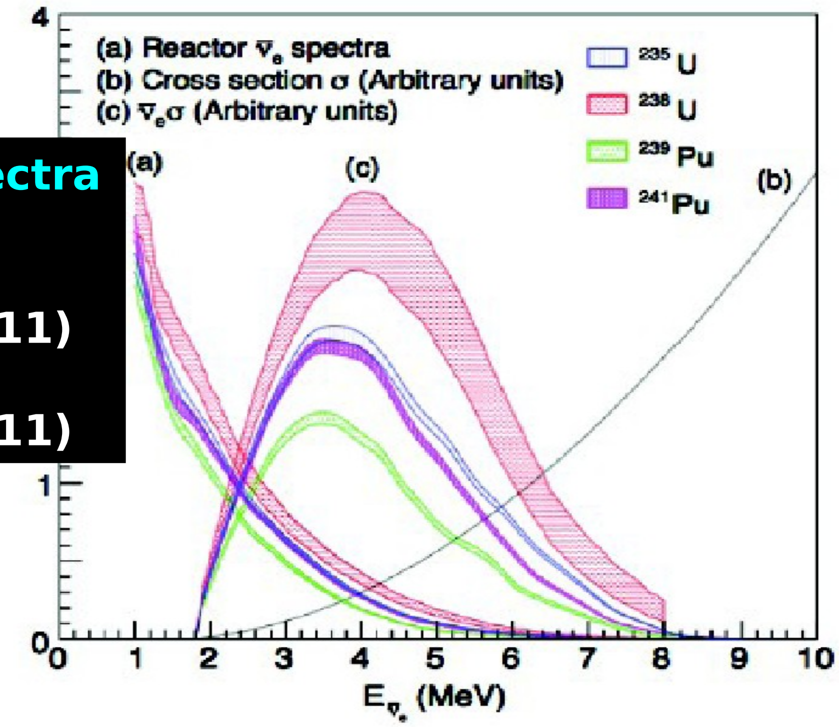


θ13 Measurements → a Global View



Antineutrino Flux from Reactors





Continuous monitoring of the reactors power

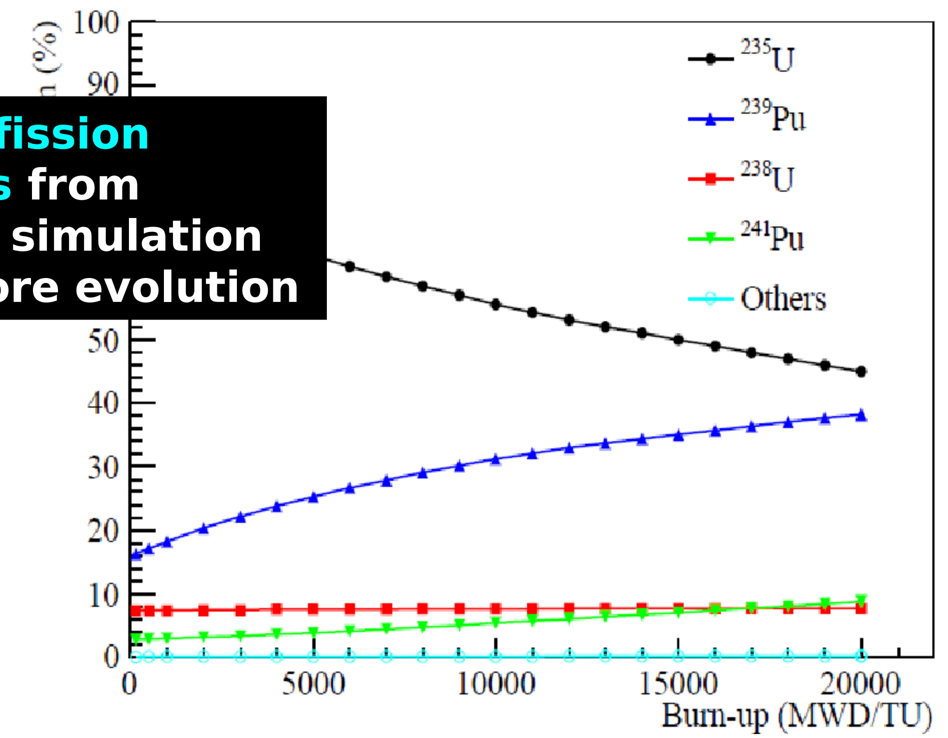
Antineutrino spectra per fission from Mueller et al., Phys.Rev.C83(2011) P.Huber, Phys.Rev.C84(2011)

Antineutrino flux emitted by reactor

$$S(E_\nu) = \frac{P_{th}}{\sum_k^{isotopes} \alpha_k W_k} \sum_k^{isotopes} \alpha_k S_k(E_\nu)$$

Energy release per fission from V. Kopekin et al., Phys. Atom. Nucl. 67(2004)

Isotope fission fractions from detailed simulation of the core evolution



Antineutrino Flux Uncertainties

- The **uncertainties** of the neutrino flux parameters could be either **correlated**, either **uncorrelated** either **partially correlated** **between reactors**.

- 2 main uncorrelated (or partially correlated) uncertainties in Near/Far setups: **thermal power** and **fission fractions.**

- The error associated to the **thermal power** depends on the measurement method used by the electricity company, on the installed sensors and on the calibration and measurement procedures employed.

- The **fission fractions** are determined by dedicated core simulations allowing to compute and reduce the associated systematic errors.

Double Chooz phase1: Phys.Rev.D86 (2012)

Source	Normalization Only	Uncertainty [%]
P_{th}	yes	0.5
$\langle \sigma_f \rangle^{Bugey}$	yes	1.4
$S_k(E)\sigma_{IBD}(E_\nu^{true})$	no	0.2
$\langle E_f \rangle$	no	0.2
L_R	yes	<0.1
α_k^R	no	0.9
Total		1.8

RENO: Phys.Rev.Lett. 108 (2012)

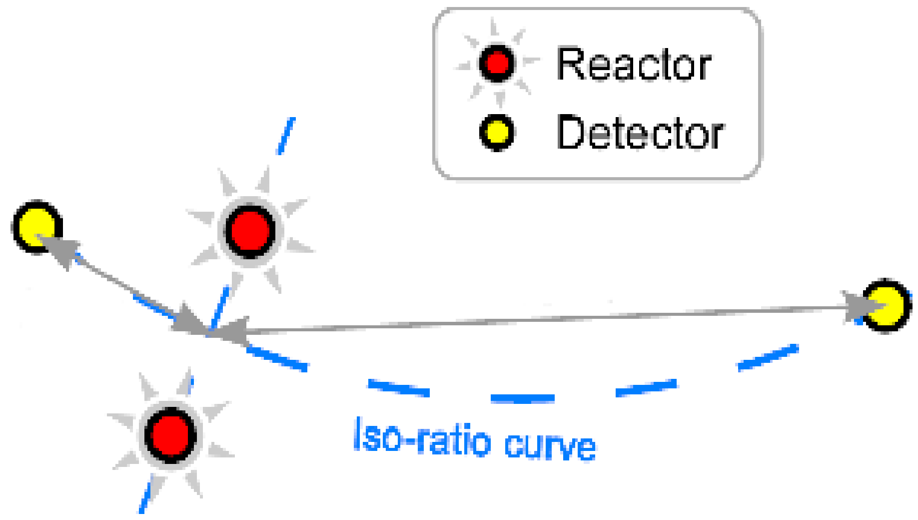
	Uncorrelated	Correlated
Thermal power	0.5%	–
Fission fraction	0.7%	–
Fission reaction cross section	–	1.9%
Reference energy spectra	–	0.5%
Energy per fission	–	0.2%
Combined	0.9%	2.0%

Daya Bay: Chin.Phys.C37 (2013)

Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
IBD reaction/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

Isoflux

- **"Isoflux from detectors view"**: The Near and Far detectors "see" the same relative fluxes from all reactors.
- **"Isoflux from reactors view"**: the relative contribution made by a given reactor to the total detected antineutrino flux is the same for all the detectors.



- **The Isoflux condition depends on the magnitude of the reactor fluxes and the distances between detectors and reactors.**
- **At isoflux → total cancellation of the uncertainties related to the generated fluxes.**
- **If not isoflux → partial cancellation of the uncertainties related to the generated fluxes.**

Error Suppression Factor

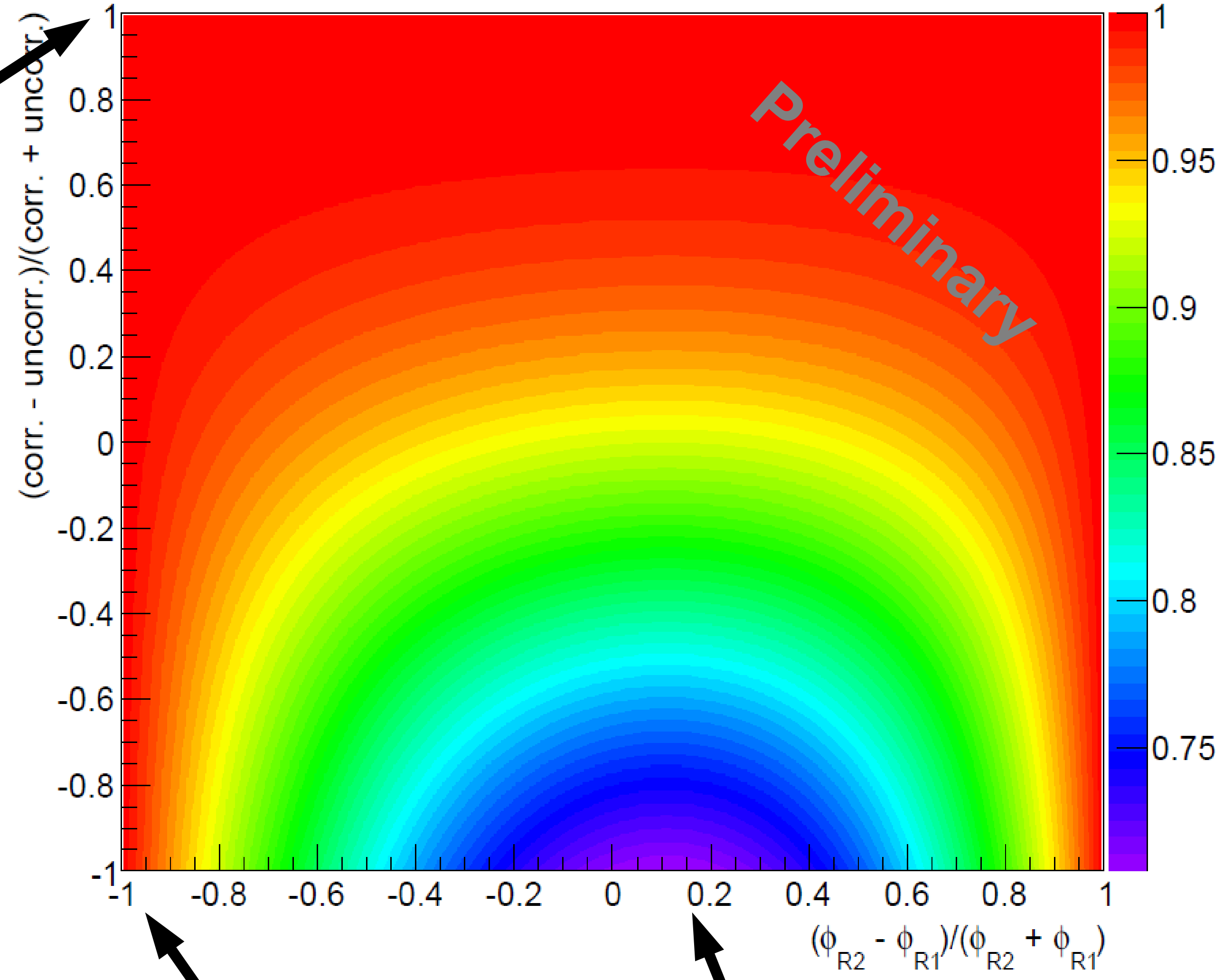
- **No one of the present Θ13 experiments is at isoflux → partial cancellation of the uncertainties related to the generated fluxes.**

- **The error suppression factor → the fraction between the relative error on the flux in a near/far measurement or a single detector measurement and the (individual) reactor flux relative uncertainty.**

- **The error suppression factor depends on the isoflux parameters (reactors power and distances) but also on the correlation between the reactors uncertainties.**

- **The error suppression factor can be considered as “the distance to the isoflux curve”.**

Error suppression factor for **Double Chooz phase 1** (2 reactors/1 detector)



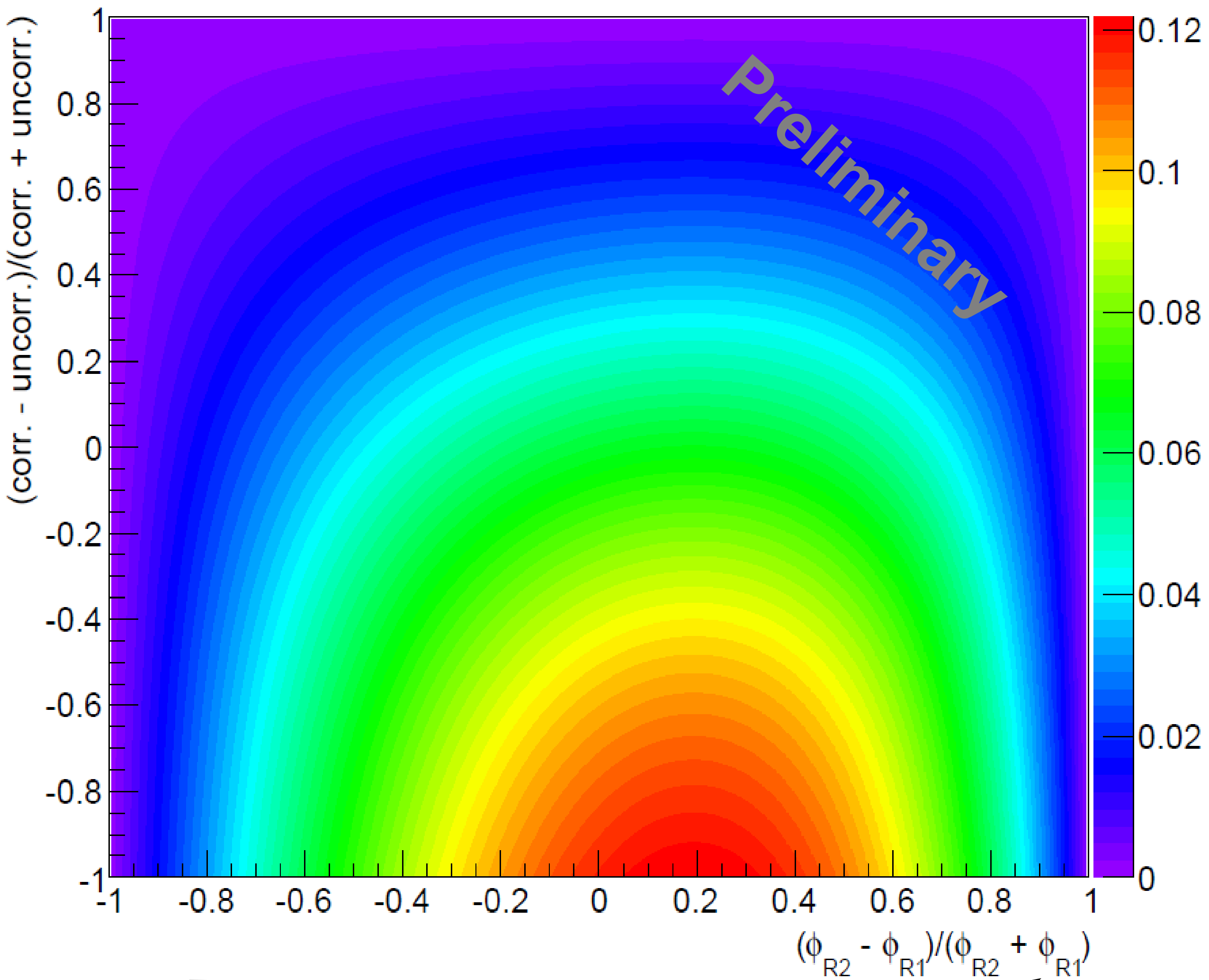
Total correlation of the reactor error → no suppression of the reactor error

One dominant reactor → no suppression of the reactor error

Total uncorrelation of the reactor error and equal fluxes → suppression equal with 1/sqrt(no. of reactors)

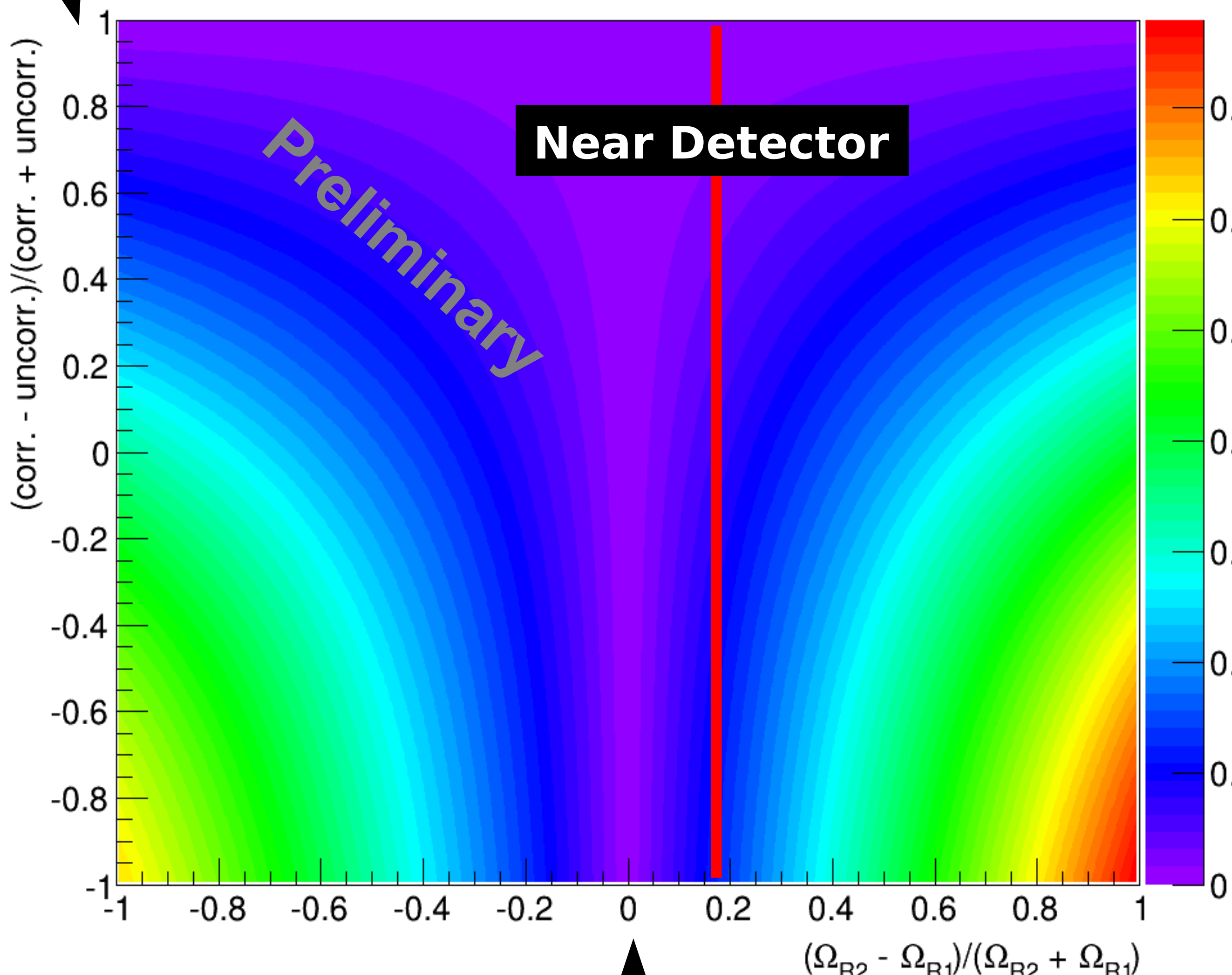
Error suppression factor for **Double Chooz phase 2** (2 reactors/2 detector)

Total correlation of the reactor error → total suppression of the reactor error



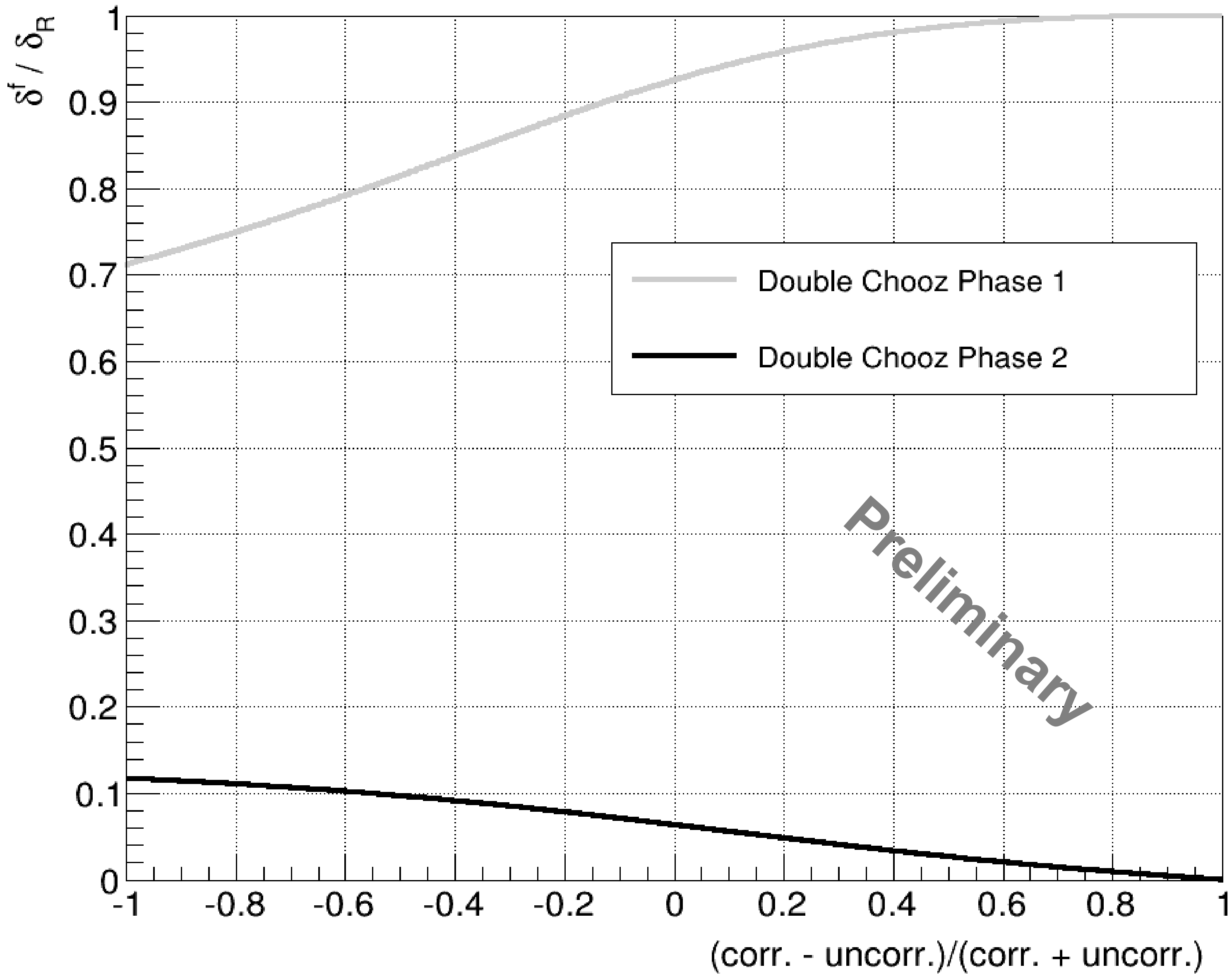
One dominant reactor → total suppression of the reactor error

ΦR1 = ΦR2



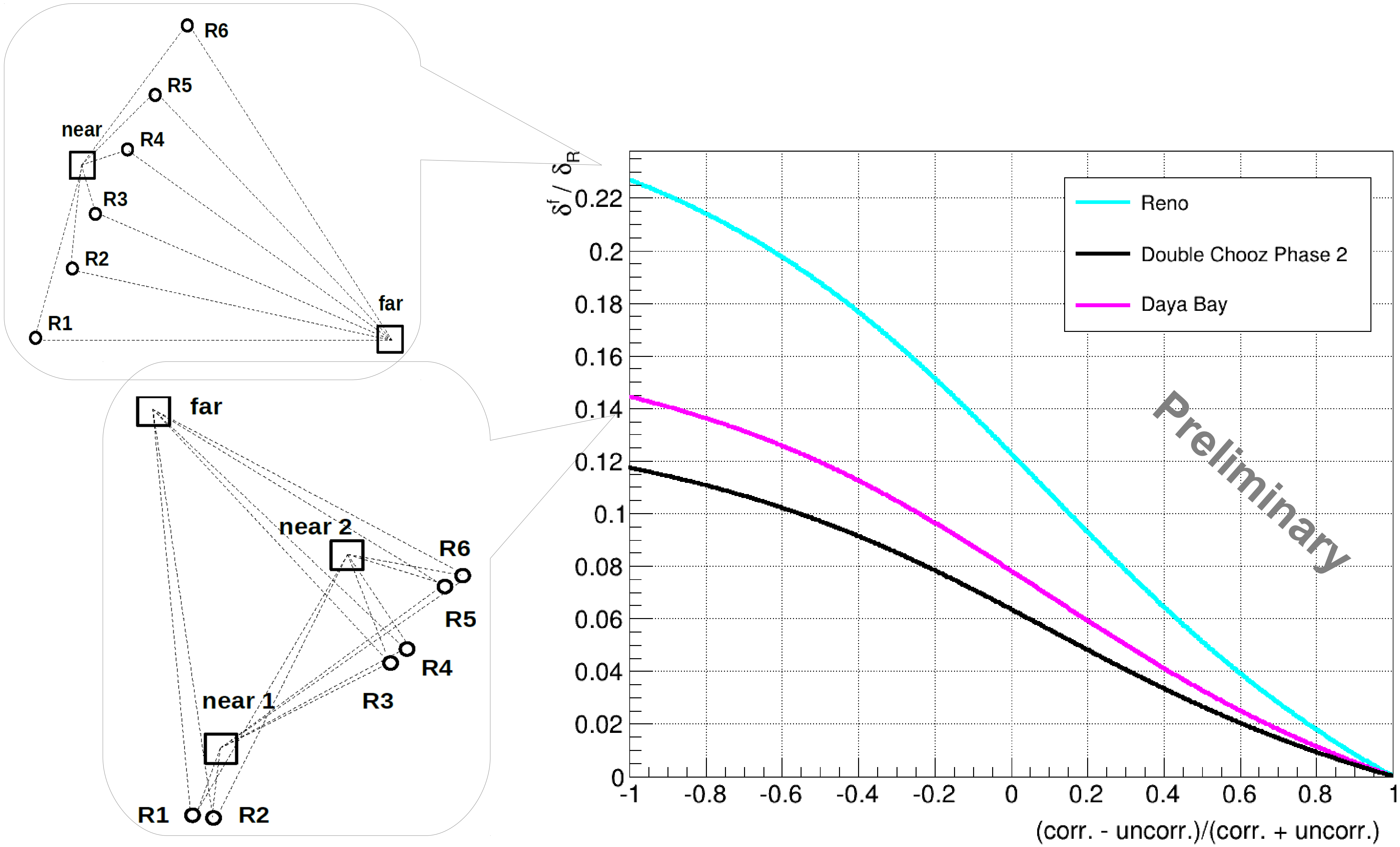
Isoflux → total suppression of the reactor error

Double Chooz ph. 2 vs. Double chooz ph.1



Huge improvement for Double Chooz phase 2 w.r.t. Double Chooz phase 1 (~100X for correlated uncertainty)

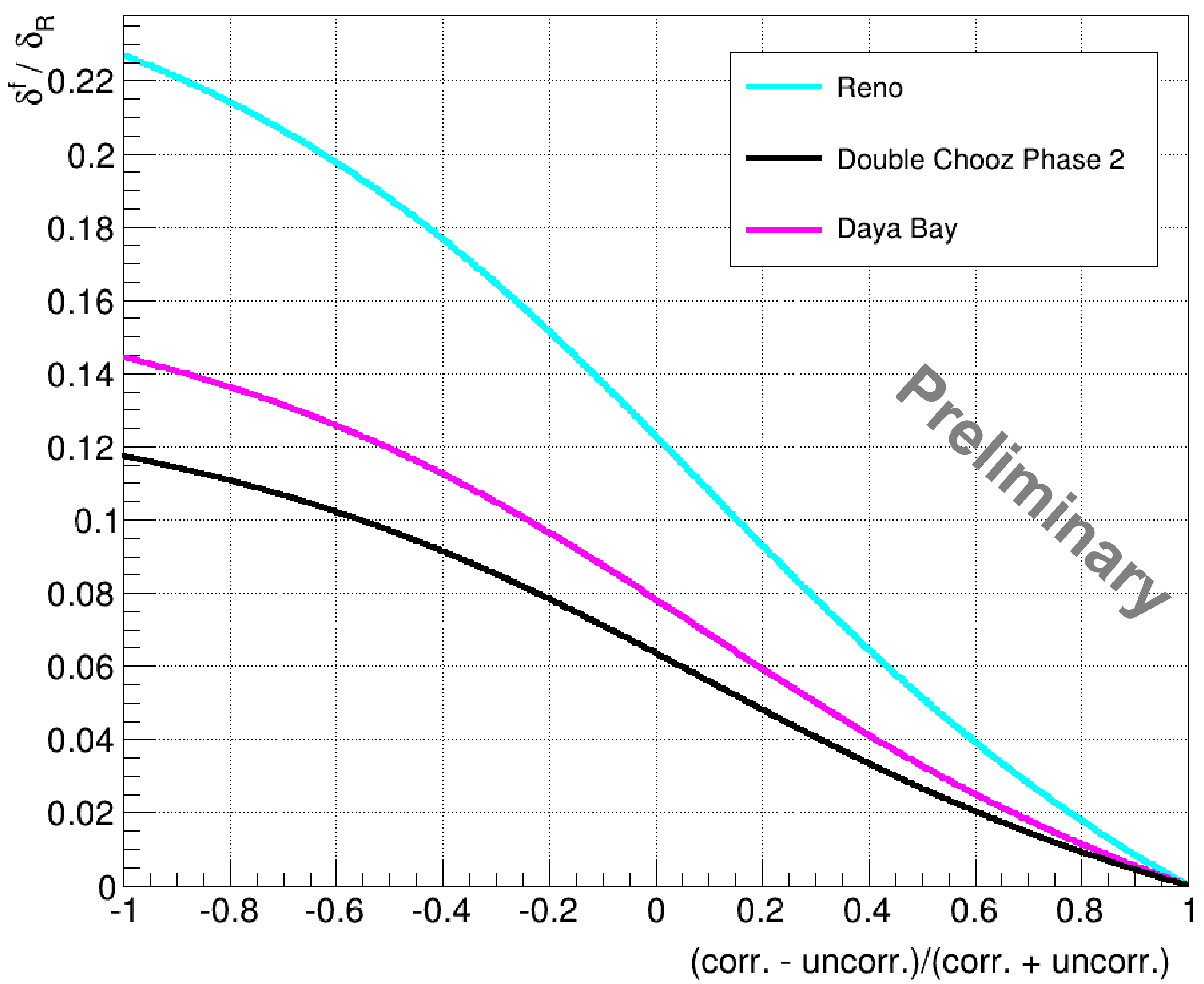
Error suppression factor for **DayaBay and Reno**



- **The model presented for Daya Bay can be "improved" or "worsened" depending on the power histories of the involved reactors.**

- **As a cross-check of our model, we have reproduced successfully the value of the suppression factor quoted in F. P. An et al. 2013 Chinese Phys. C 37 (hep-ex/1210.6327) which was a best case. The DB suppression factor thus changes depending on the reactor configurations.**

Comparison between experiments



- **The differences between experiments decrease if the correlation part is dominant.**
- **The best suppression factor → Double Chooz phase 2 (simplest setup)**

Conclusions and Outlook

- The “isoflux problem” plays an important role on the reactor systematic error remaining a large contribution to the total systematic error of the various experiments.
- We computed analytically the error suppression factors for the present Θ13 experiments and we checked our formalism with dedicated Monte Carlo simulations.
- The error suppression factors depends on the thermal power and isotopic composition of the reactor cores and demand a good evaluation of the uncorrelated/correlated parts of the reactor induced error.
- Outlook: The calculation of the Double Chooz, Reno and Daya Bay cases as a function of the reactor histories
- The understanding the fitting procedure of Daya Bay is not trivial and that is an on-going research topic.