

# Reactor- $\theta$ <sub>13</sub>

## (status)

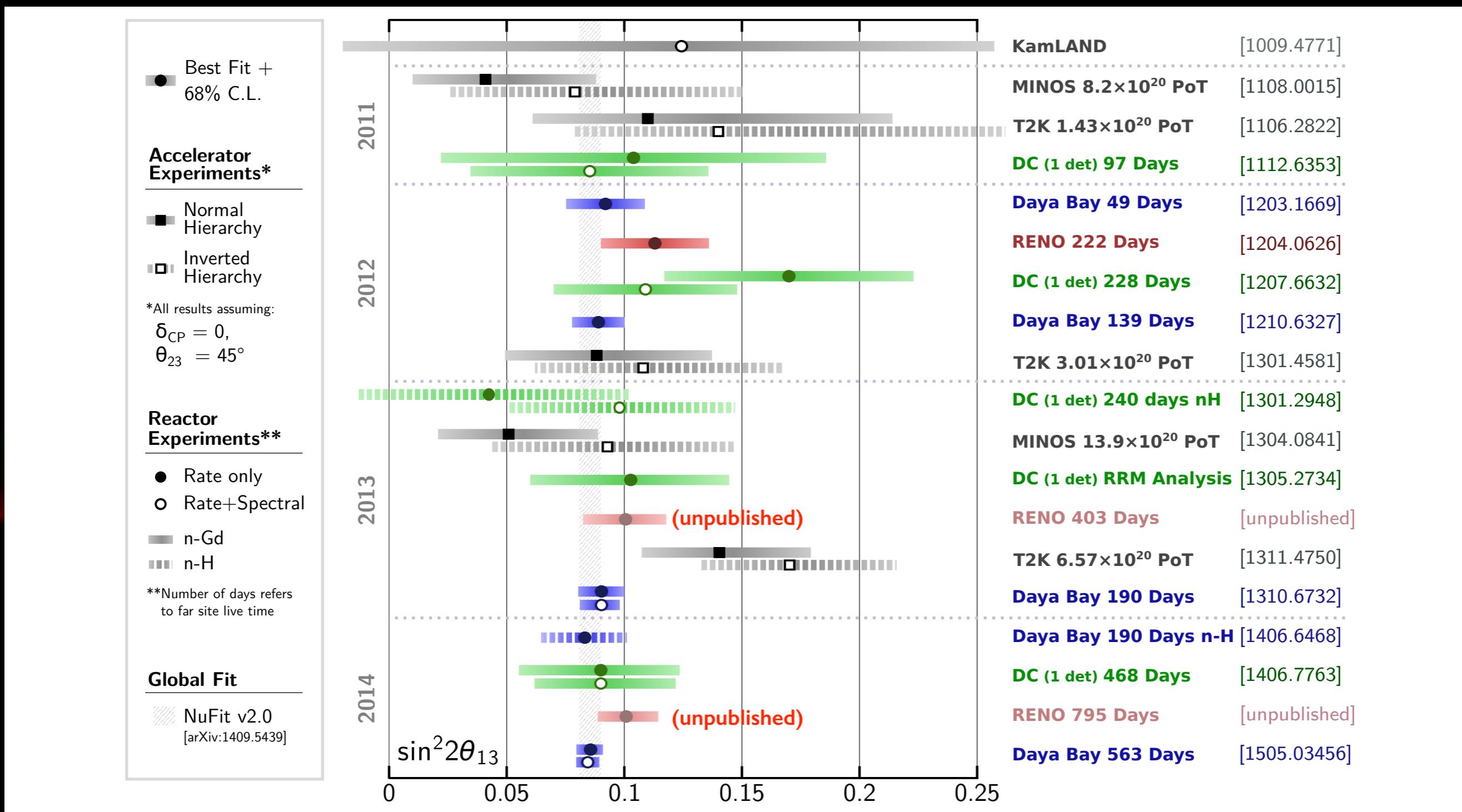
*Neutrino-GDR meeting @ Saclay*  
November 2015

Anatael Cabrera

CNRS / IN2P3 @ APC (Paris)

the world's  $\Theta_{13}$  knowledge....

# $\theta_{13}$ -reactor measurements (summer 2015)...



**unsurpassable reactor precision  $\rightarrow$  “reactor- $\theta_{13}$ ” for several decades to go!**  
(measurement by T2K, MINOS, KamLAND+Solar, etc)

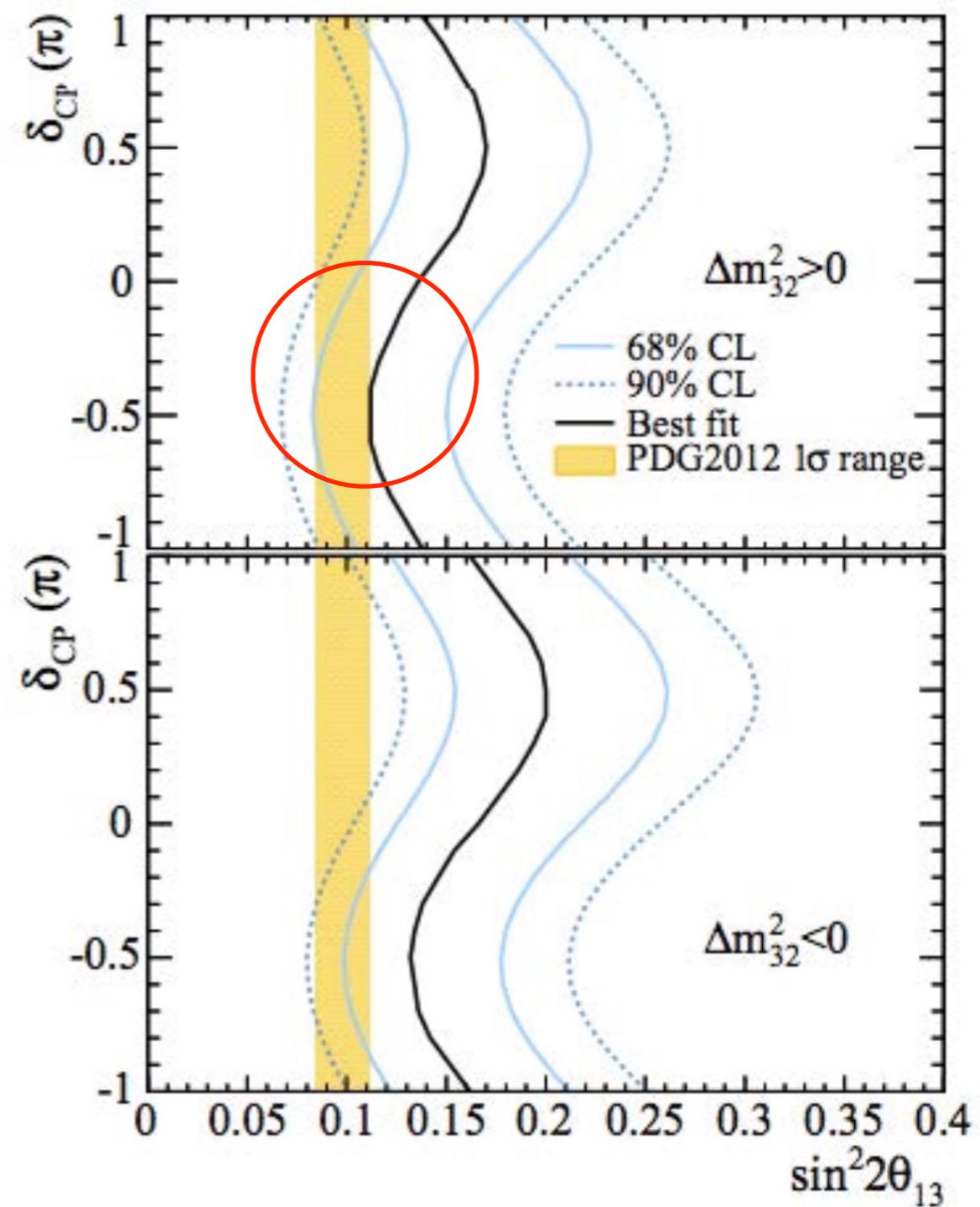
## Comparing T2K results with reactors

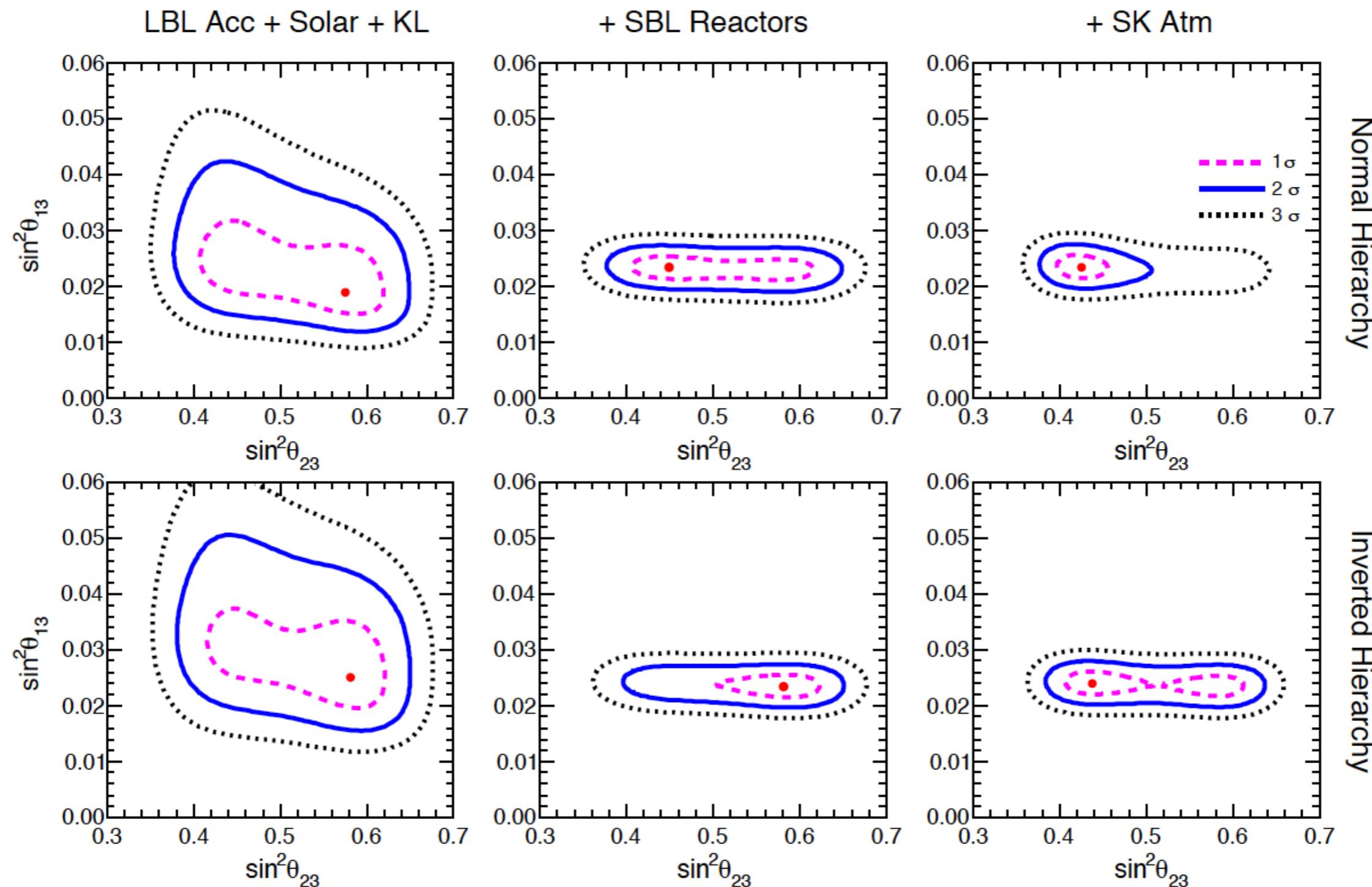
T2K  $\sin^2 2\theta_{13}$  result computed assuming  $\sin^2 \theta_{23}=0.5$ ,  $\delta_{CP}=0$ , and normal hierarchy (top), and inverted hierarchy (bottom)

Consistent at 90% CL ( $1.6\sigma$ )

...but excess by T2K nudges all remaining unknowns in direction to increase rates

- normal hierarchy
- $\theta_{23} > 45^\circ$
- $\delta_{CP} = -\pi/2$  (aka  $3\pi/2$ )



(Lisi et al Jan. 2014) impact to the  $\theta_{23}$  octant...

**SK atm:** We continue to find an overall preference of atmospheric data for the first octant – which currently wins over other data.

so, both...

$\theta_{13}$  central value

$\theta_{13}$  uncertainty

critical impact to global picture  
(3v oscillation)

a thought....

only one experiment providing  
 $\theta_{13}$  & claiming  $\sim 1\%$  errors?

(example: LEP)

# Reactor- $\theta_{13}$

(combining results)

*Daya Bay*  $\oplus$  *Double Chooz*  $\oplus$  *RENO*

**1<sup>st</sup> workshop** → Autumn 2016 (Seoul, South Korea)  
(systematics, results, etc)

**2<sup>nd</sup> workshop** → later on (allow full statistics samples)  
(towards the combined  $\theta_{13}$ )

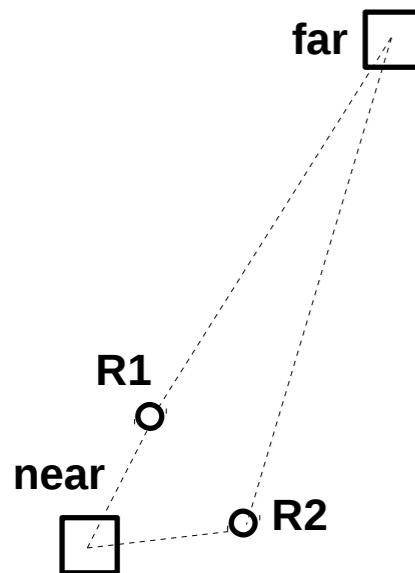
[the best  $\theta_{13}$  value for a long while]

the  $\theta_{13}$ -reactors rationale...

# reactor- $\theta$ |3 experiments: geometry...

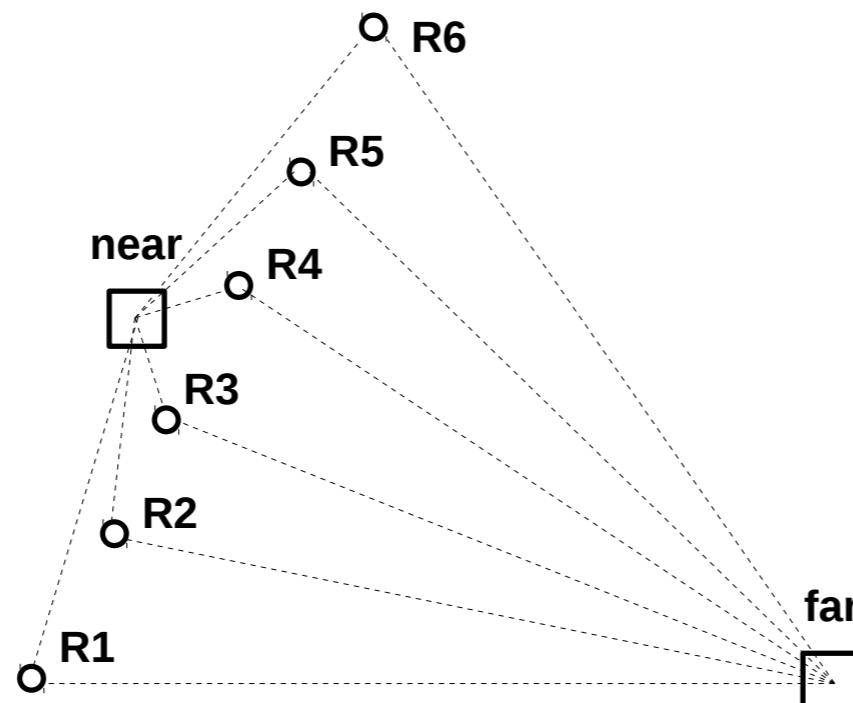
**Double Chooz**

R = reactor  
each detector



R1  
near  
R2

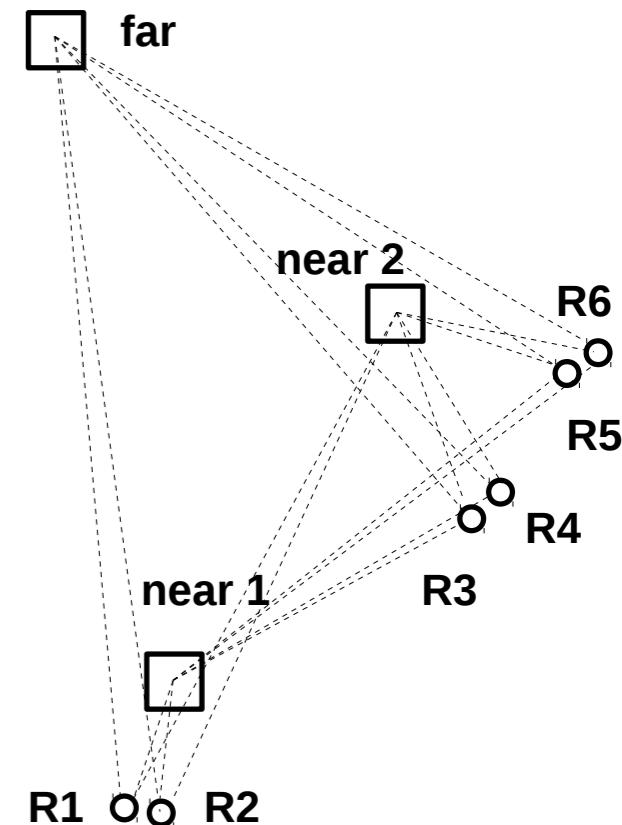
**RENO**



FD @ 450mwe  
(target: 16t) [2x DC]

FD @ 300mwe  
(target: 8t)

**Daya Bay**



FD @ 850mwe  
(target: 80t) [10x DC]

key design feature of experiment: **multi-detector(s) error cancellation**

- (if identical) **detection-systematics** (target composition, efficiency, response, etc):  $\sim 2\% \rightarrow \sim 0.2\%$
  - (if near/far) **flux systematics**:  $\sim 3.0\%(\text{raw?}) \rightarrow \sim 1.0\% \text{ (uncorrelated)} \rightarrow < 0.5\% \text{ (geometry)}$
- [deeper underground + radio-purity  $\Rightarrow$  less background per detector]**

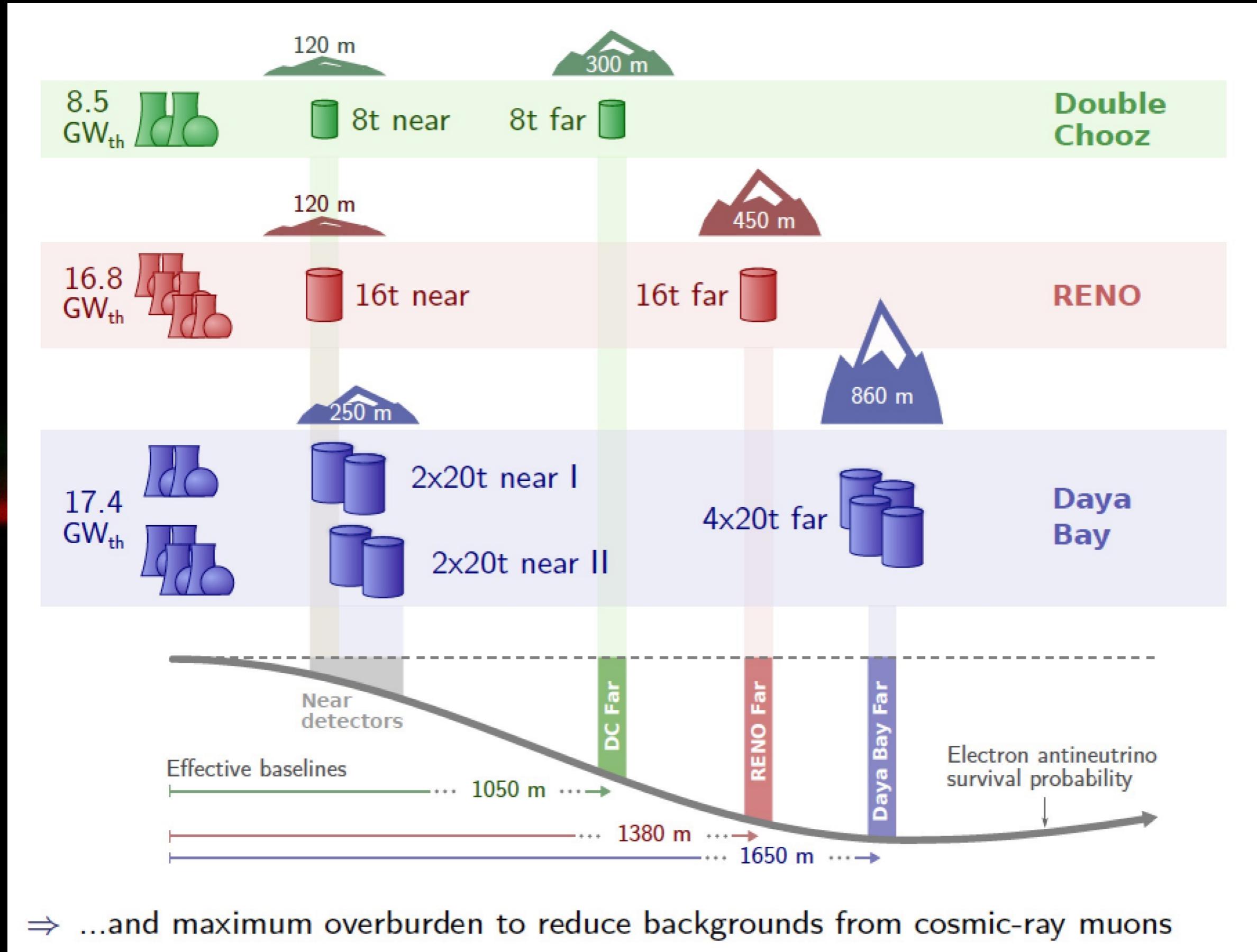
# multi-detector rationale...

systematics	single detector (%)	multi-detector (%)
$\delta(\text{detection})$	$\sim 2.0$ (no fiducial volume)	$\sim 0.2$ (identical detectors)
$\delta(\text{flux})$	$\sim 3.0$ (prediction) [ $\sim 1.7$ via <b>Bugey4</b> ]	$\leq 0.5$ (ND: reactor monitor)
$\delta(\text{BG})$	$\leq 1.0$ (radio-purity+overburden)	$\cancel{\rightarrow} \leq 1.0$ (multi-detector insensitive)

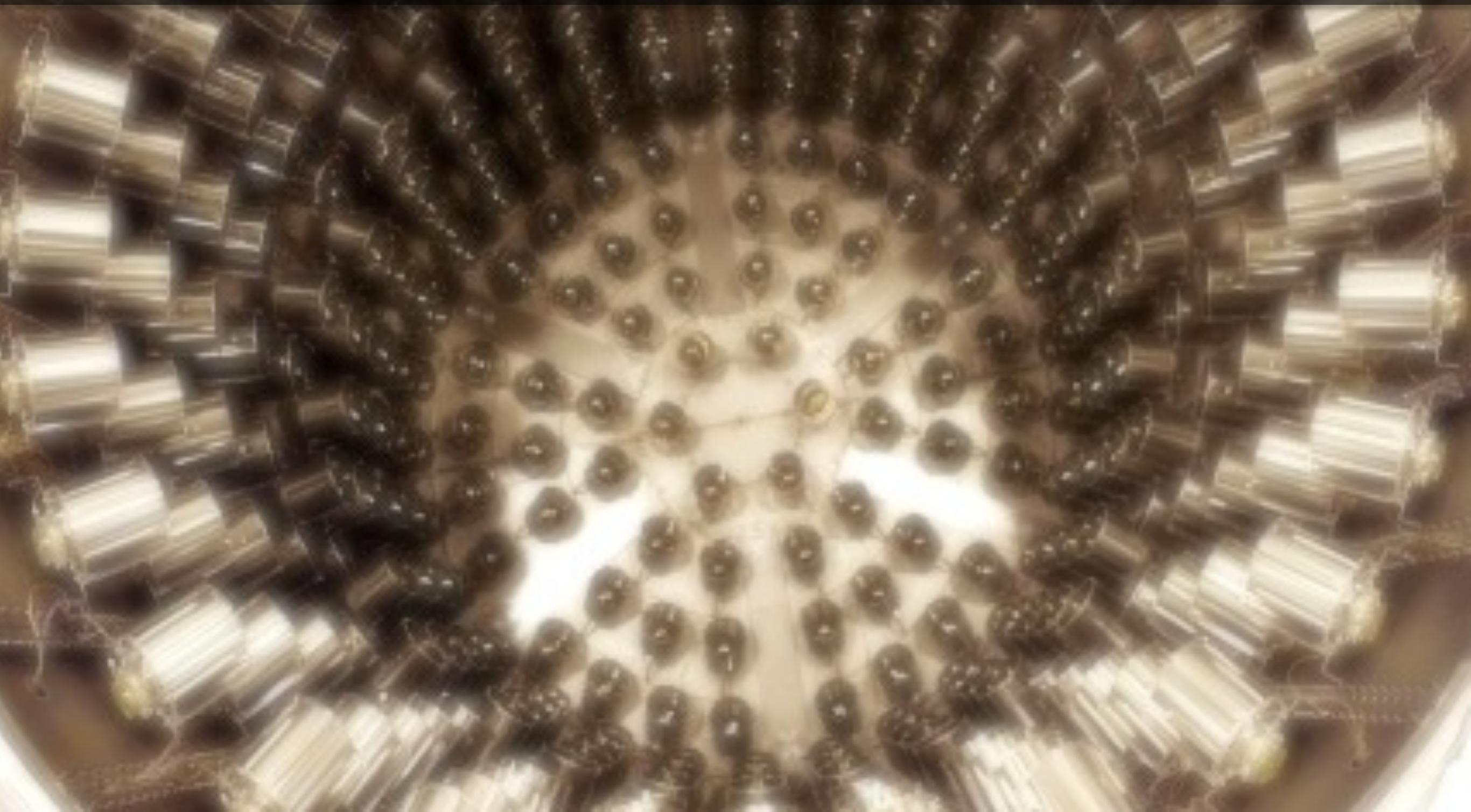
**absolute error (single detector) → hard to measure  $\theta_{13}$**   
**relative error(multi detector) → high precision on  $\theta_{13}$**

**could we improve the absolute errors after  $\theta_{13}$  effort?**

# reactor- $\theta$ |3 experiment: configuration...



our detectors...



# a generic $\theta_{13}$ -LAND...

## Outer $\mu$ -Veto (OV)

Plastic-Scintillator: strips ( $\rightarrow$ tracking)

## $\nu$ -Target (NT)

Liquid-Scintillator + Gd (0.1%)

## $\gamma$ -Catcher (GC)

Liquid-Scintillator

## Light Buffer

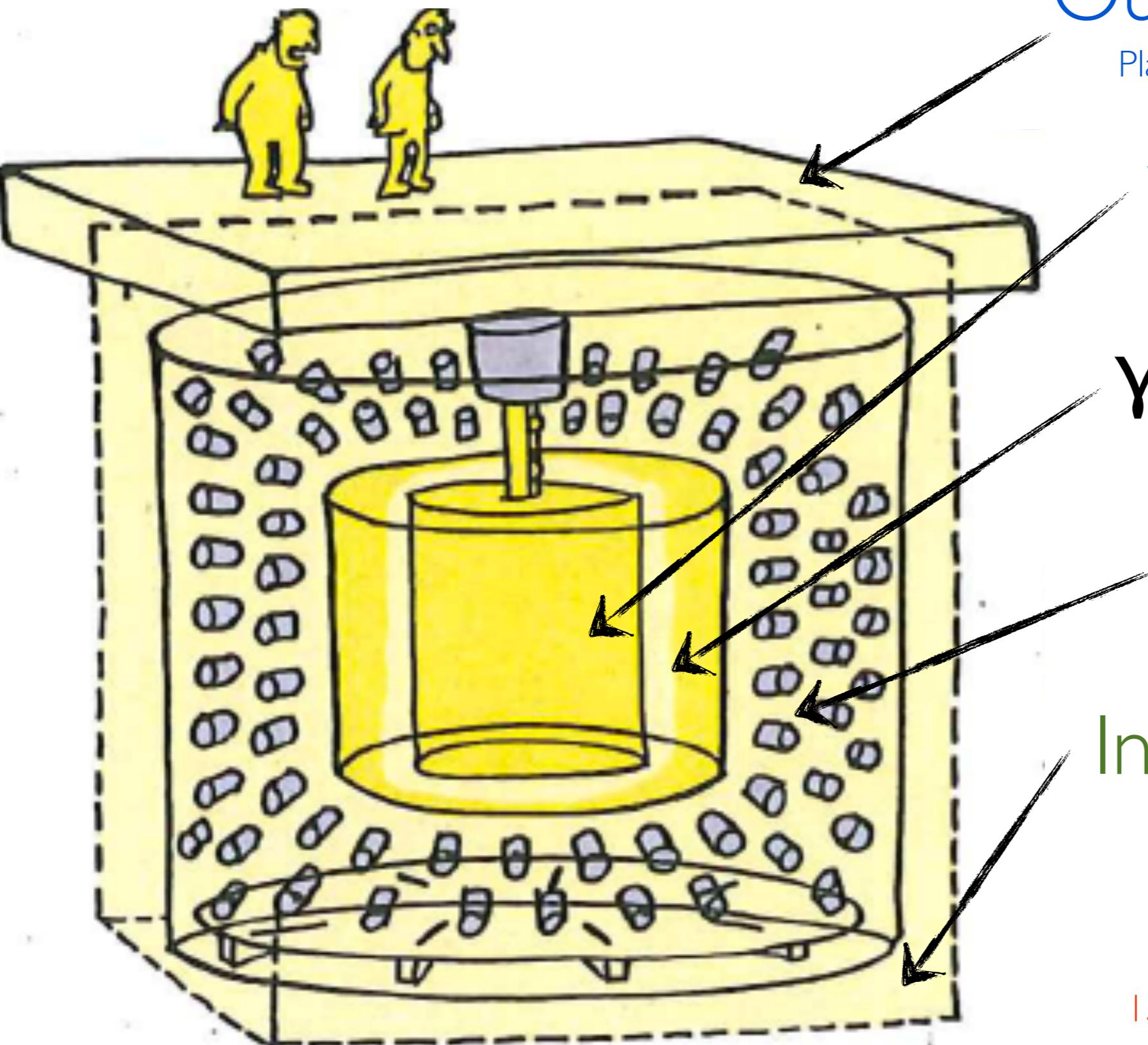
Oil (negligible scintillation)

## Inner $\mu$ -Veto (IV)

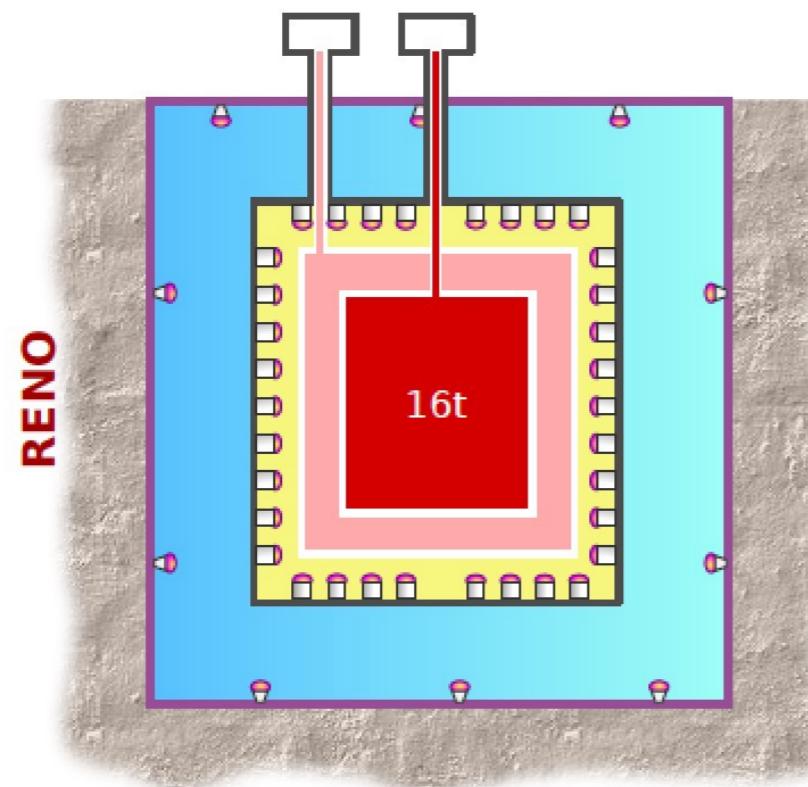
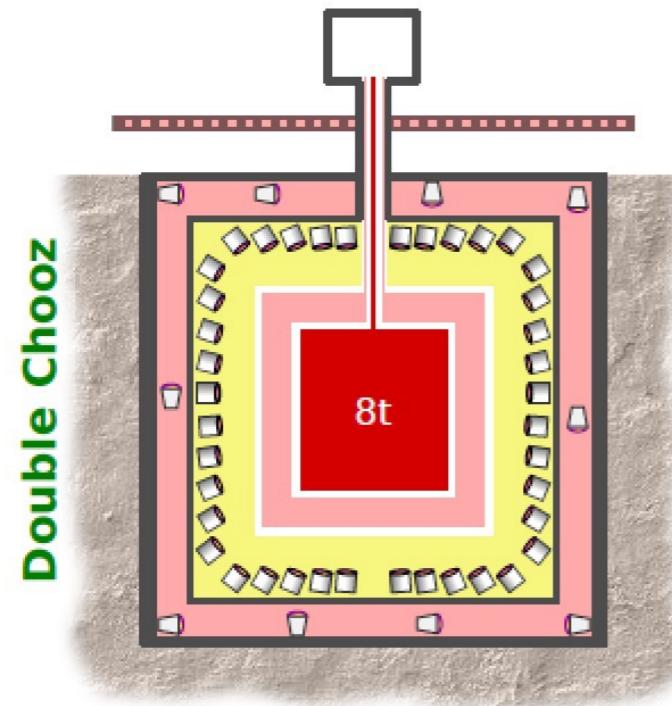
Liquid-Scintillator

## Inert $\gamma$ -Shield

15cm of steel (around all detector)



## Comparison of detector designs

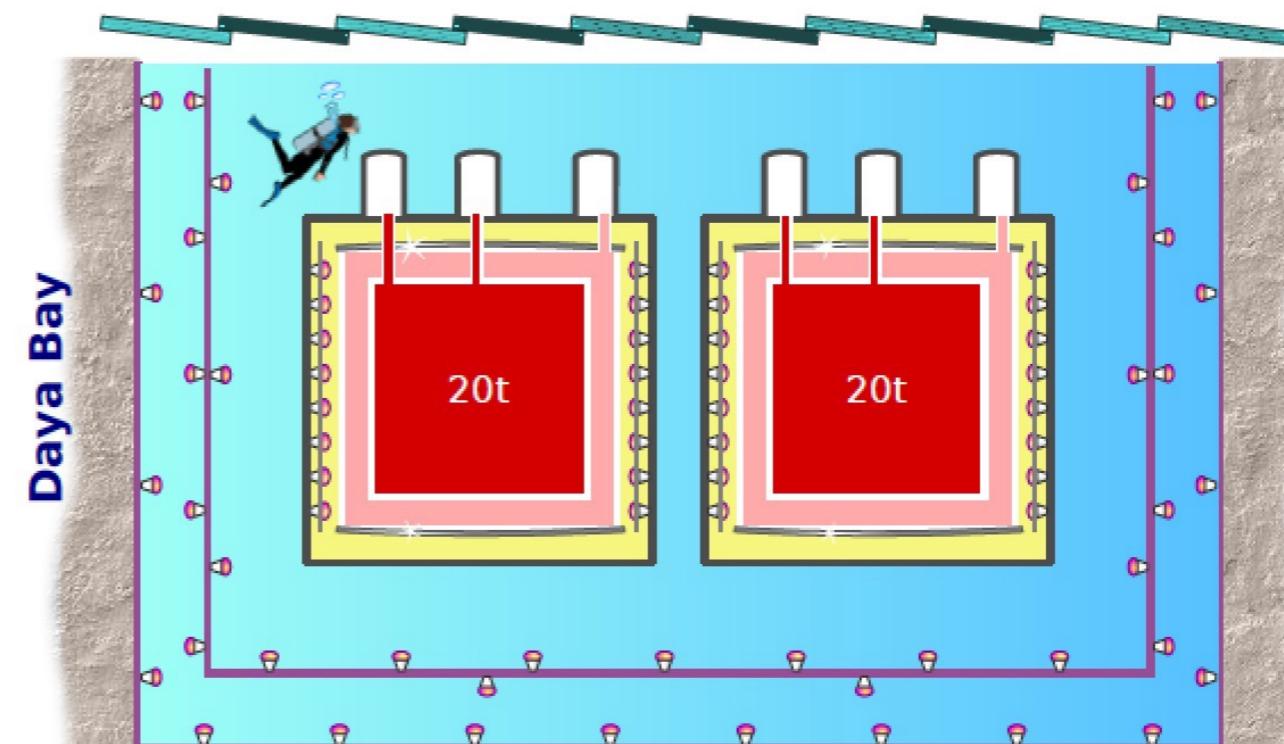


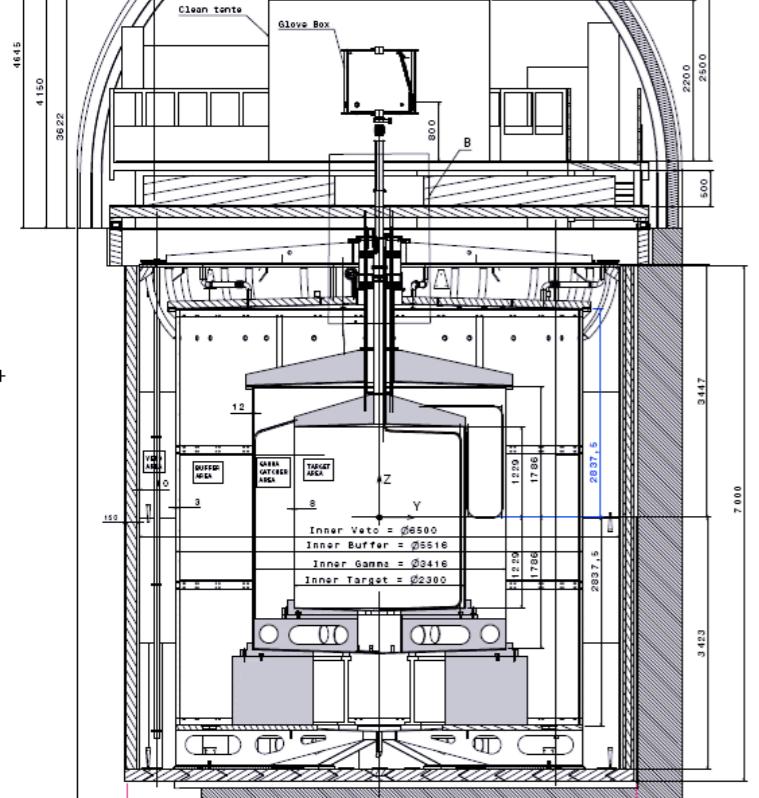
### Antineutrino detectors

- █ Target: Gd-doped LS
- █  $\gamma$  catcher: undoped LS
- █ Buffer: mineral oil
- Acrylic vessels
- Steel vessels
- █ Rock/concrete

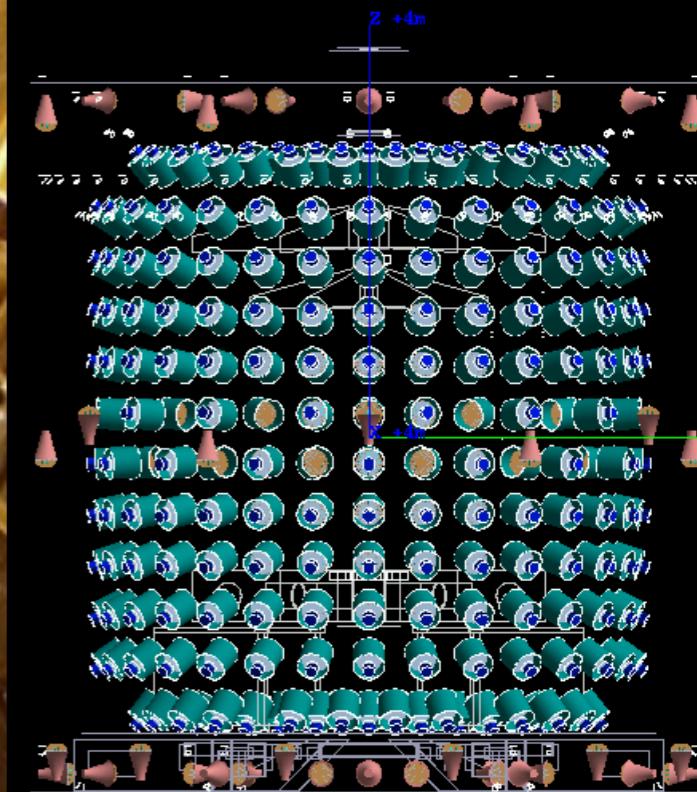
### Muon veto system

- █ LS inner veto (Double Chooz)
- █ Water cerenkov (RENO+DB)
- Plastic scintillator top (DC)
- █ RPC top (Daya Bay)
- Tyvek structures





engineer's view



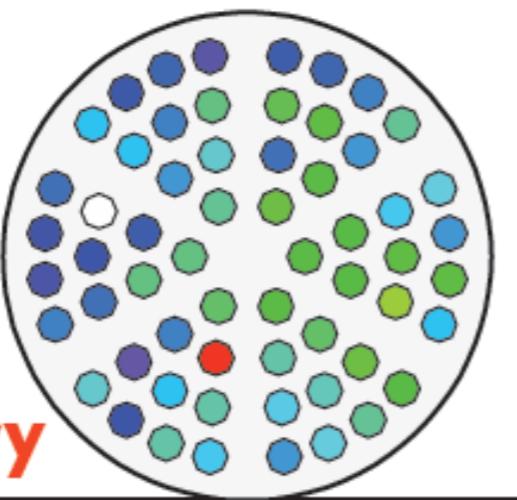
MC's view



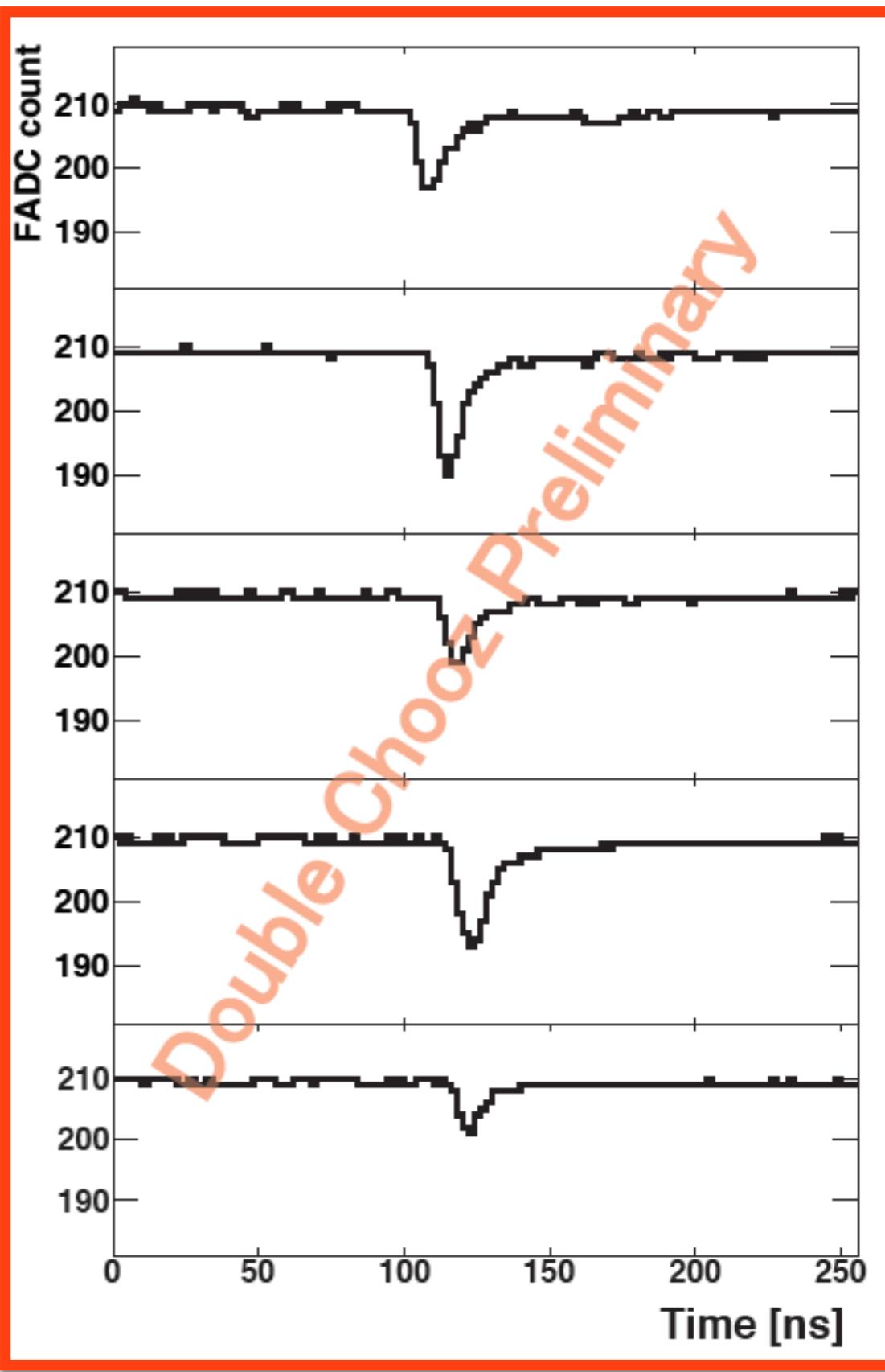
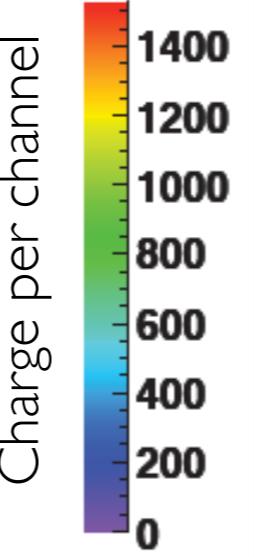
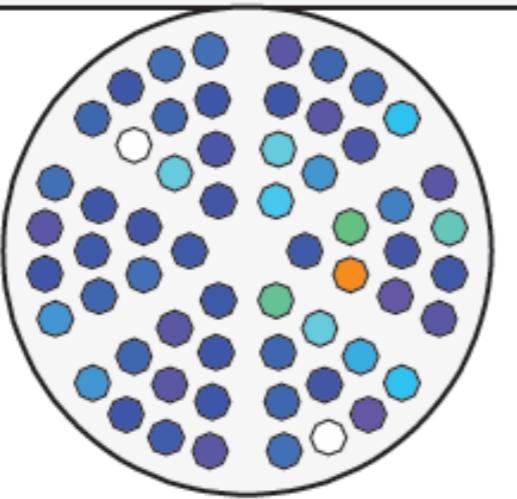
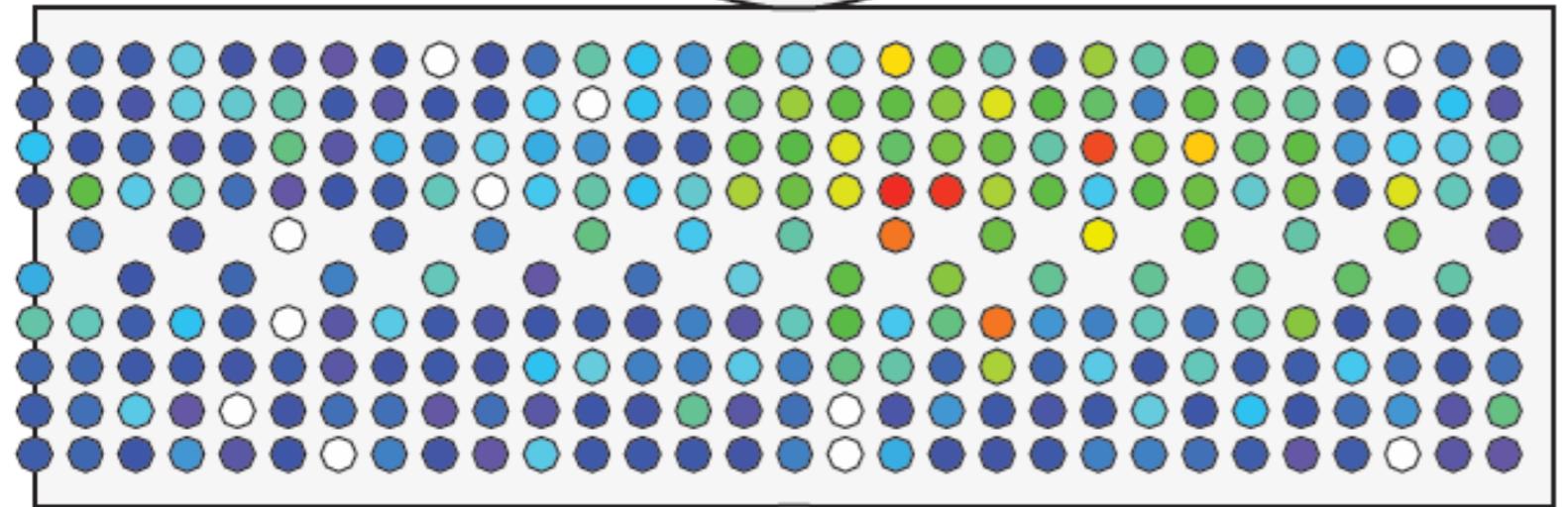
our favourite view...

# a point like event (no V activity)...

Energy ~8MeV

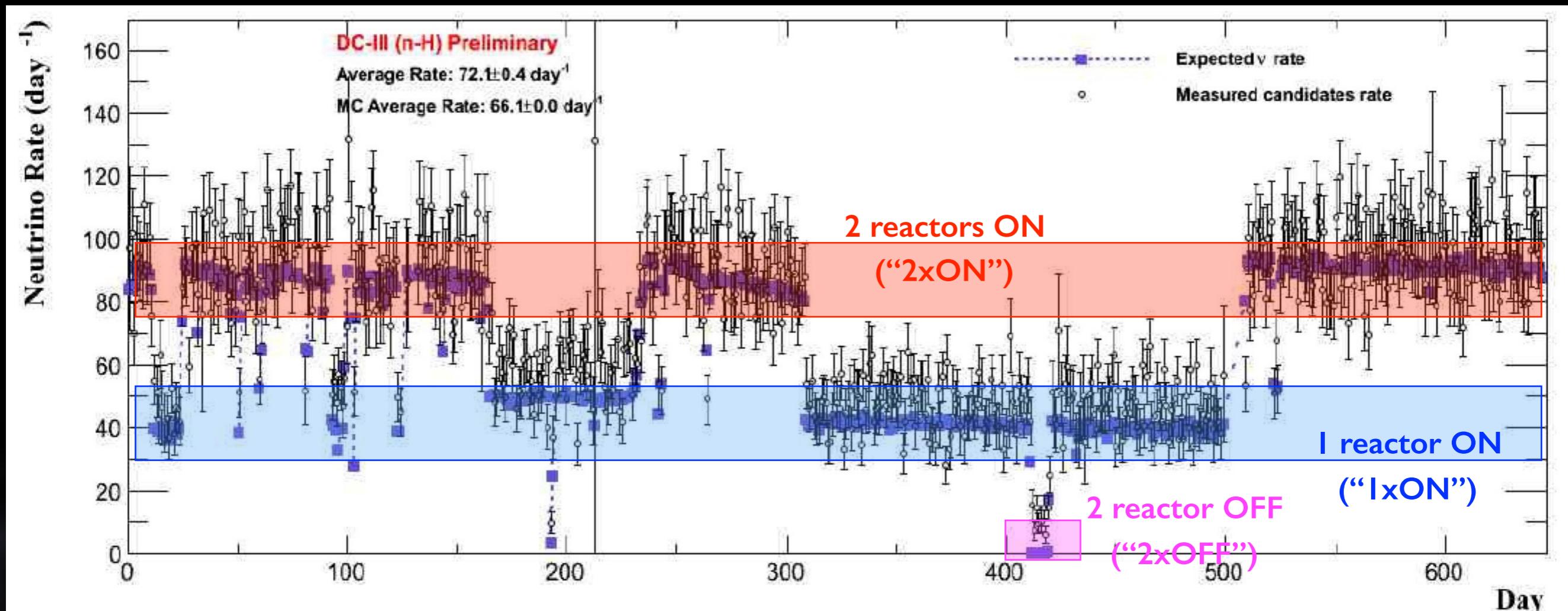


**DC Preliminary**



NOTE: all PMTs working (white means: no charge)

# H-n-IBD candidates track reactor activity...



accurate reactor power tracking (data~MC)

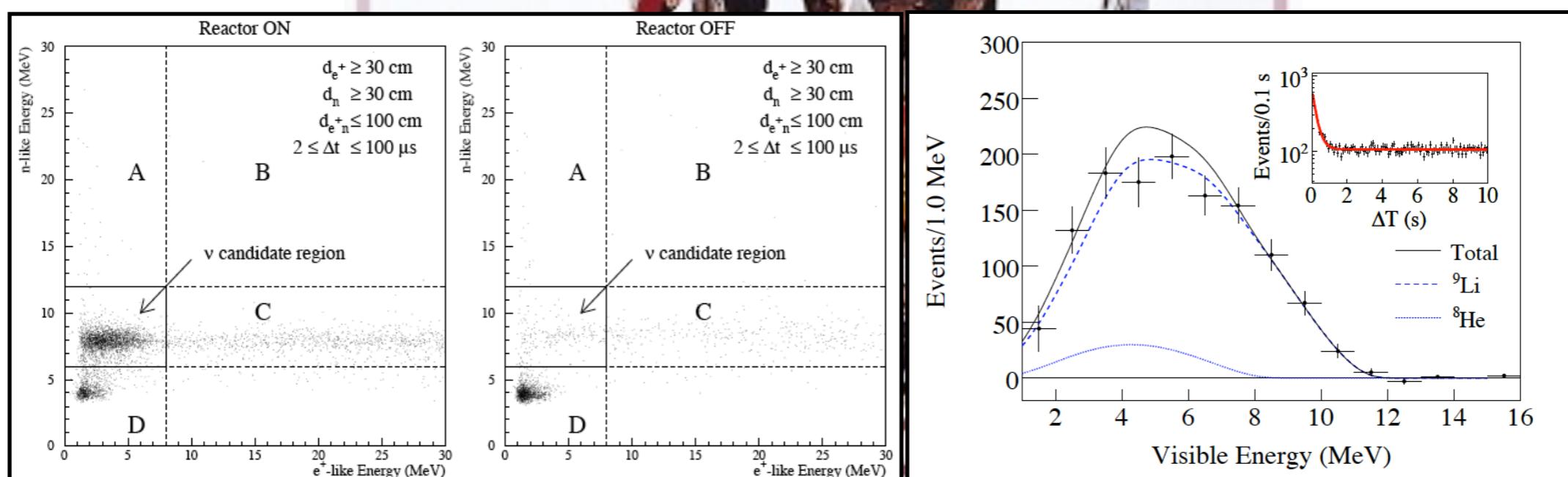
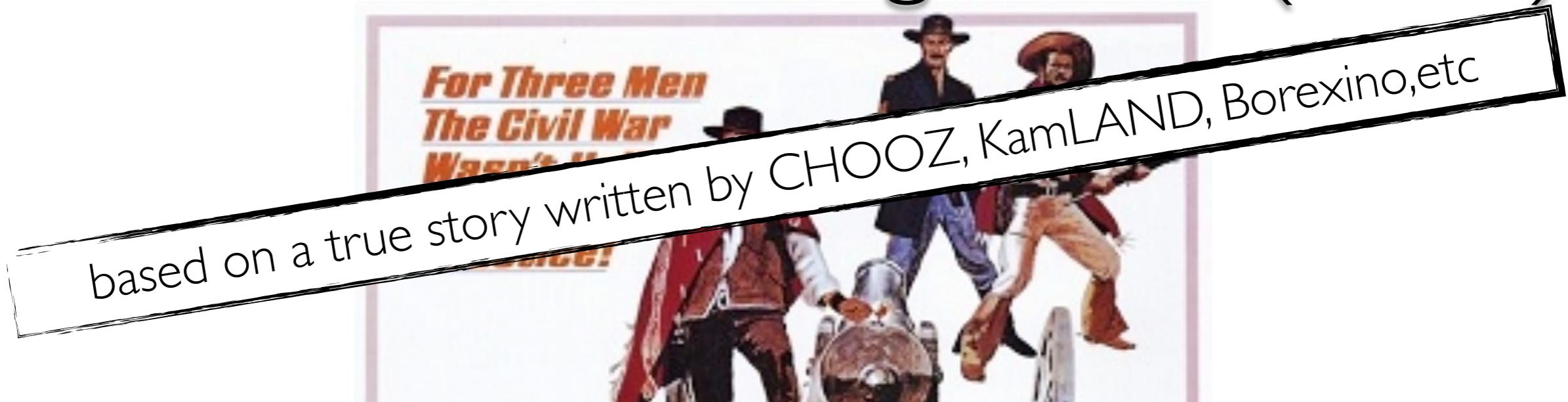
A black and white photograph of a subway station platform. In the center, there is a large, bright red circle that overlaps the entire image. Inside this red circle, there is a blue rectangular box containing the word "BACKGROUNDs" in white, bold, sans-serif capital letters.

# BACKGROUNDs

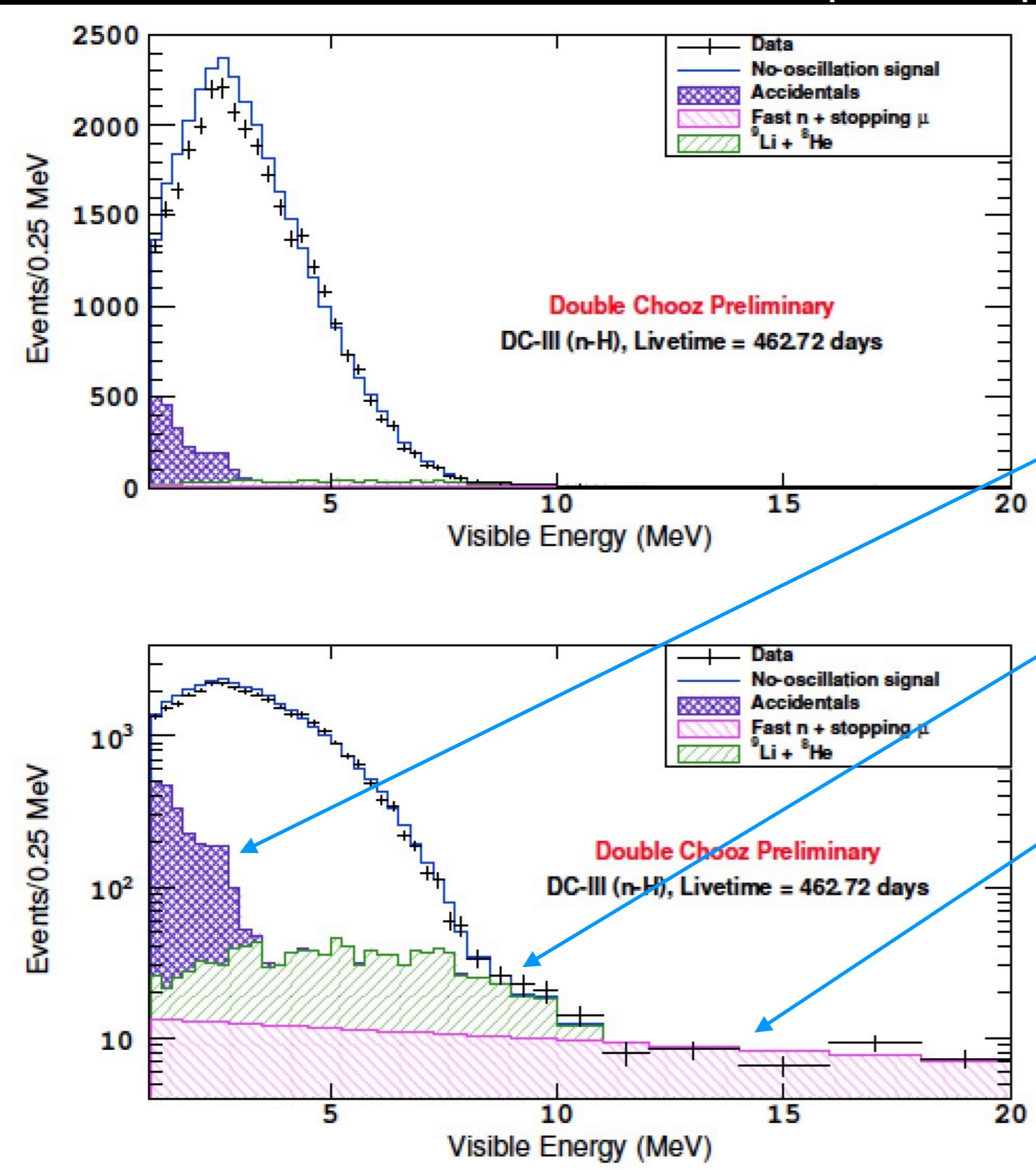
# our model: 3 backgrounds (so far)...



# our model: 3 backgrounds (so far)...



# prompt energy spectrum...

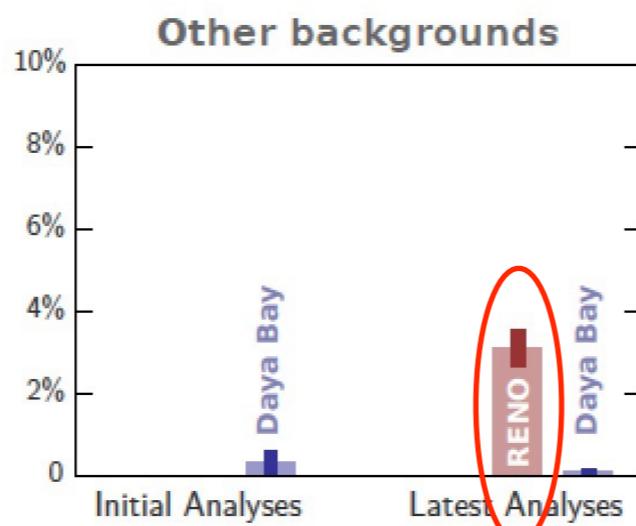
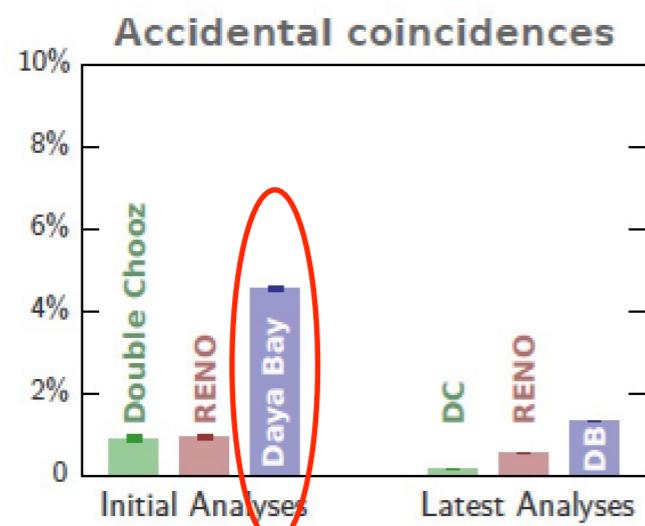
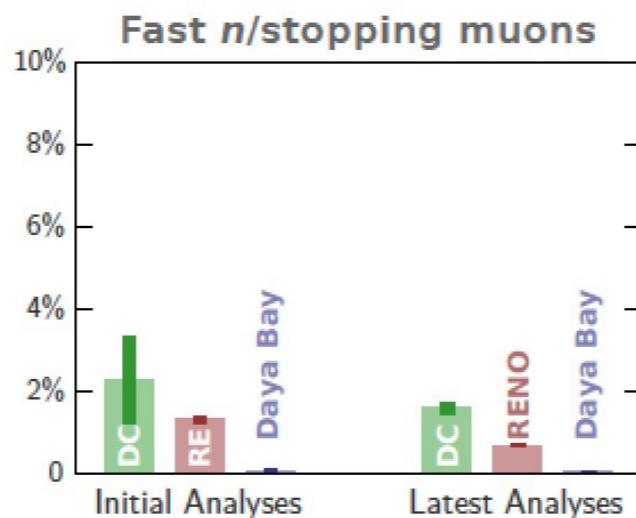
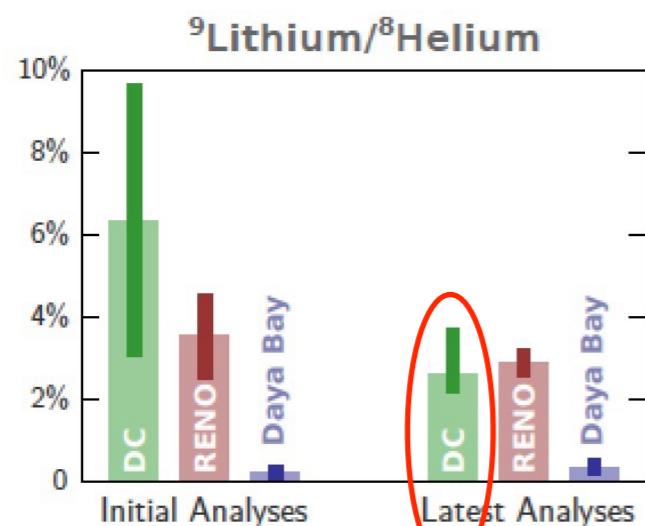


(hideous deformation <2.6MeV → dramatically reduced)

- accidentals:** well understood (negligible impact)
- **${}^9\text{Li}$  (+ a little  ${}^8\text{He}$ )** (dominant systematic)
- fast-n (+ little stopped- $\mu$ s)** (major rejection → minor impact)
- stopping- $\mu$ :** mostly rejected
- other BGs...**
  - ${}^{13}\text{C}(\alpha, n){}^{16}\text{O}$
  - ${}^{12}\text{B}$  related

# reactor- $\theta$ | 3 background summary...

## Background budgets at far detectors



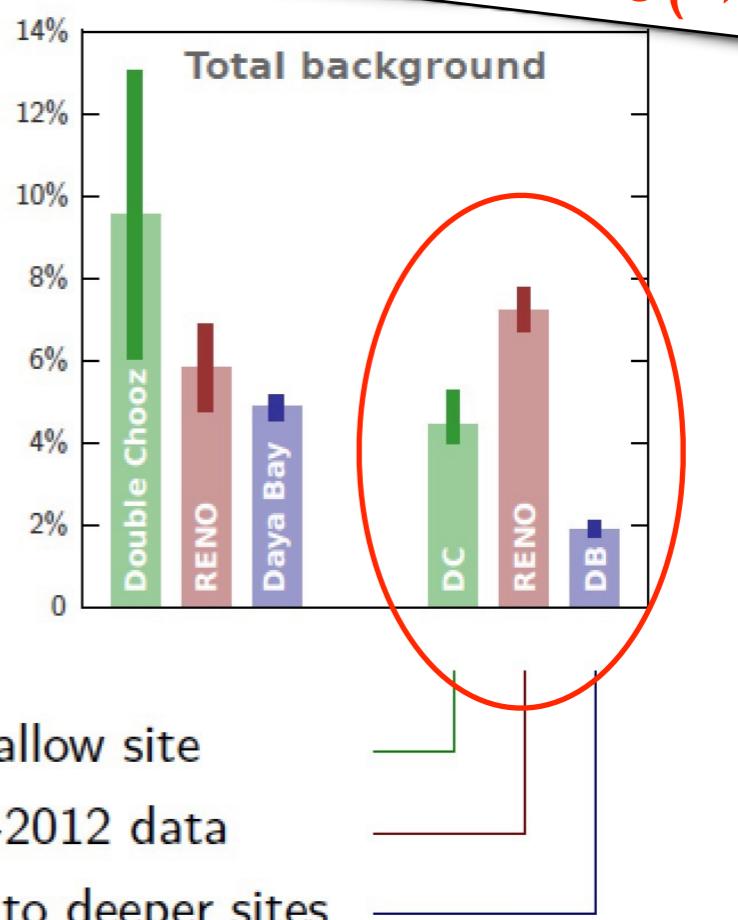
**Daya Bay:** very deep underground

- Li/He: tiny ( $\rightarrow$  negligible)
- fast-n: tiny ( $\rightarrow$  negligible)
- accidental: large ( $\rightarrow$  negligible)

**Double Chooz:** very shallow

- Li/He: large ( $\rightarrow$  dominant)
- fast-n: large ( $\rightarrow$  made negligible)
- accidental: tiny ( $\rightarrow$  negligible)

**RENO:** drop  $^{252}\text{Cf}$  source ( $\rightarrow$  ??)



- DC's background uncertainties dominated by  $^9\text{Li}$  due to shallow site
- RENO most affected by californium contamination in post-2012 data
- Daya Bay also impacted by  $^9\text{Li}$ , albeit at smaller scale due to deeper sites

# DC vs DYB: two philosophies...

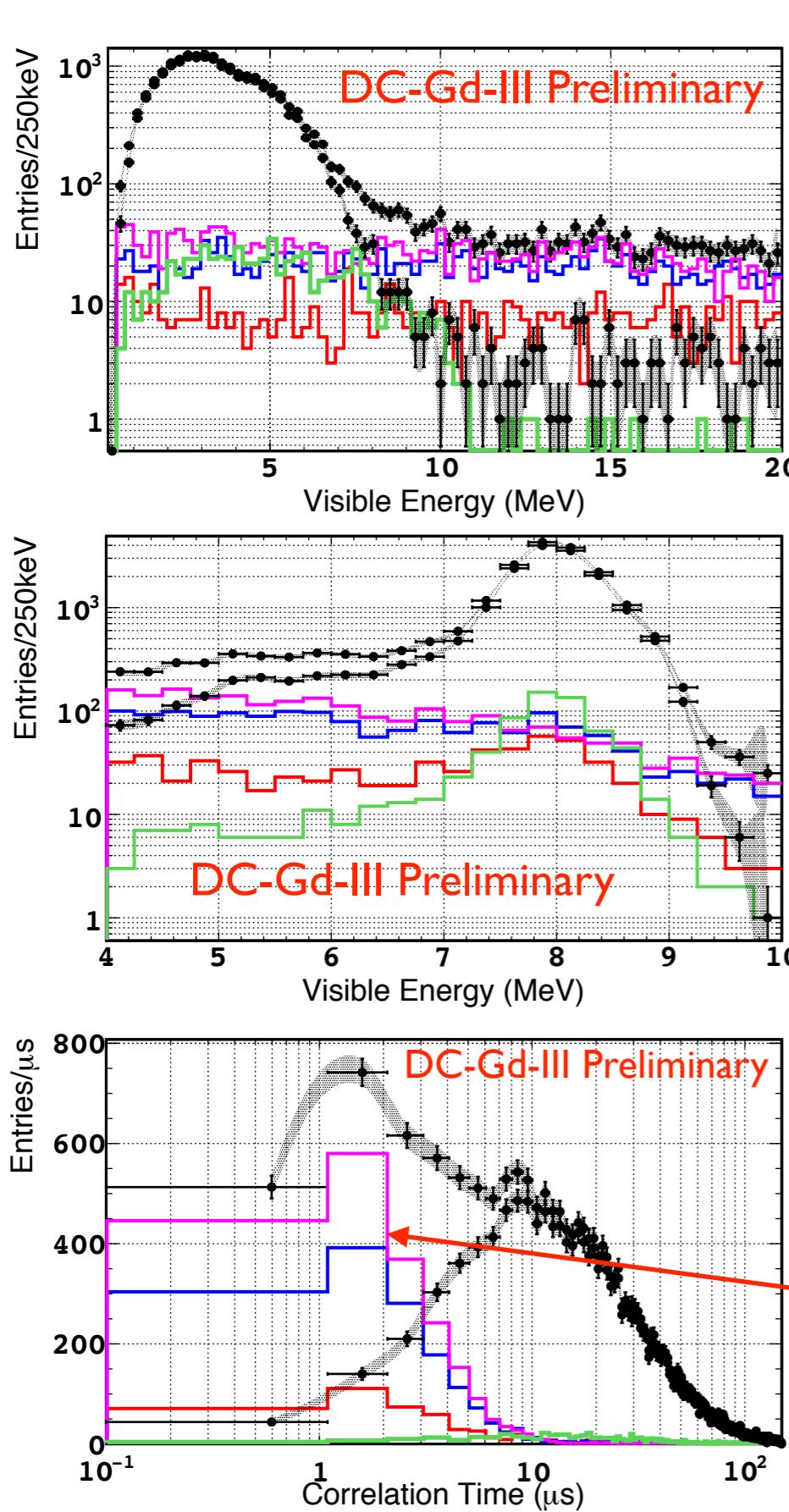
DC forced into unprecedented  
high precision BG

(DYB much less BG)

active BG rejection...

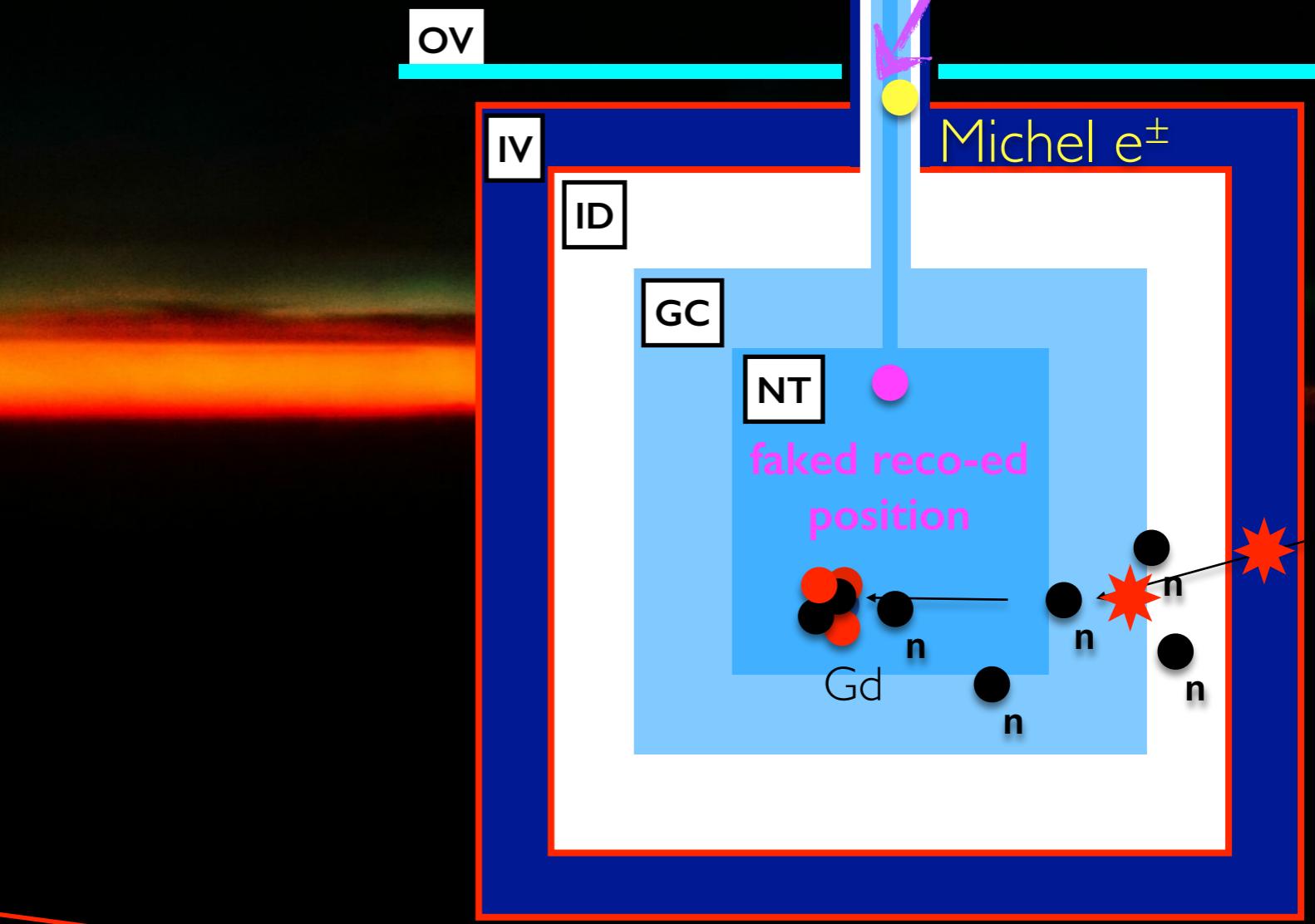


# our vetoes in action (one by one)...



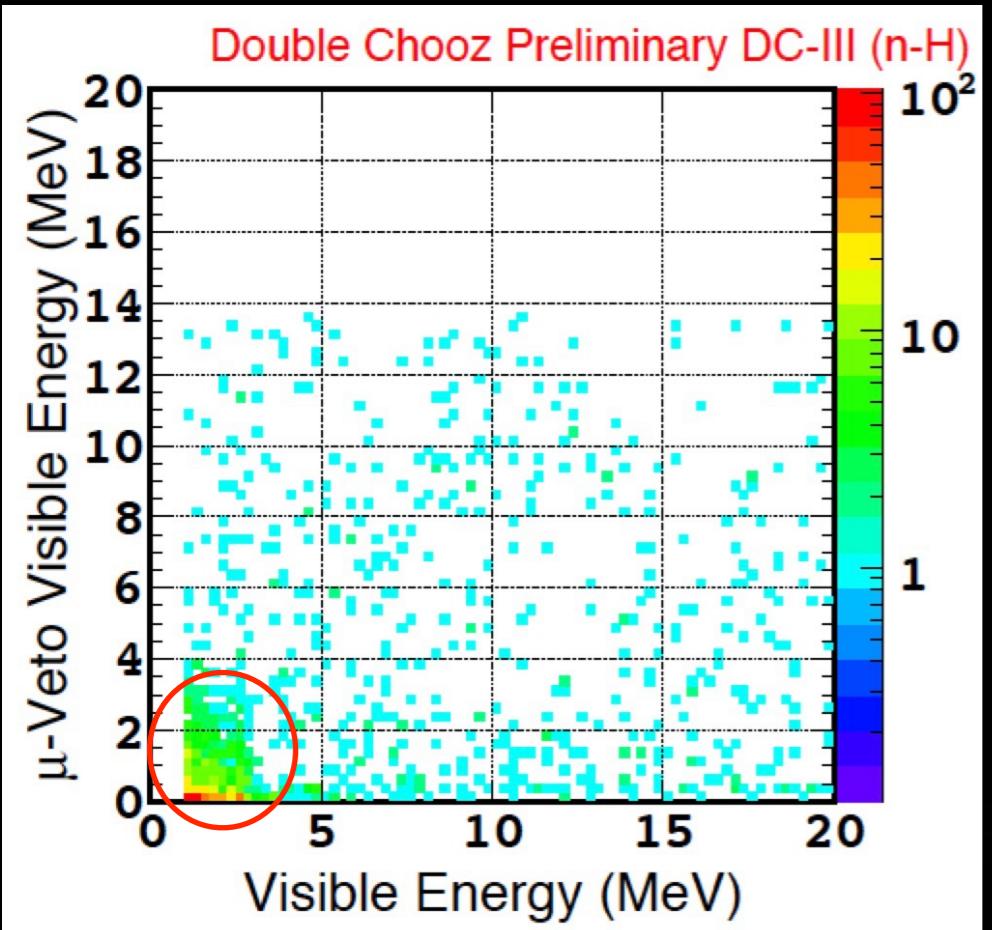
**Gd-III (veto OFF)**  
 FVV veto  
 Li+He veto  
 OV veto  
 IV veto  
**Gd-III (veto ON)**

**DC-III (novel rejection system)**  
 •  $\text{Li}/\text{He} \rightarrow \sim 50\%$  rejection  
 • fast- $n$  + stop- $\mu \rightarrow \sim 10\times$  rejection  
 • accidental  $\rightarrow > 10\times$  rejection



**stopped- $\mu$  largest BG**  
 (if not vetoed  $\rightarrow \sim$ fully rejected)

# IVT for AccBG (multi-Compton rejection)...



exploit  $\mu$ -veto (IV) power (LS not WC)

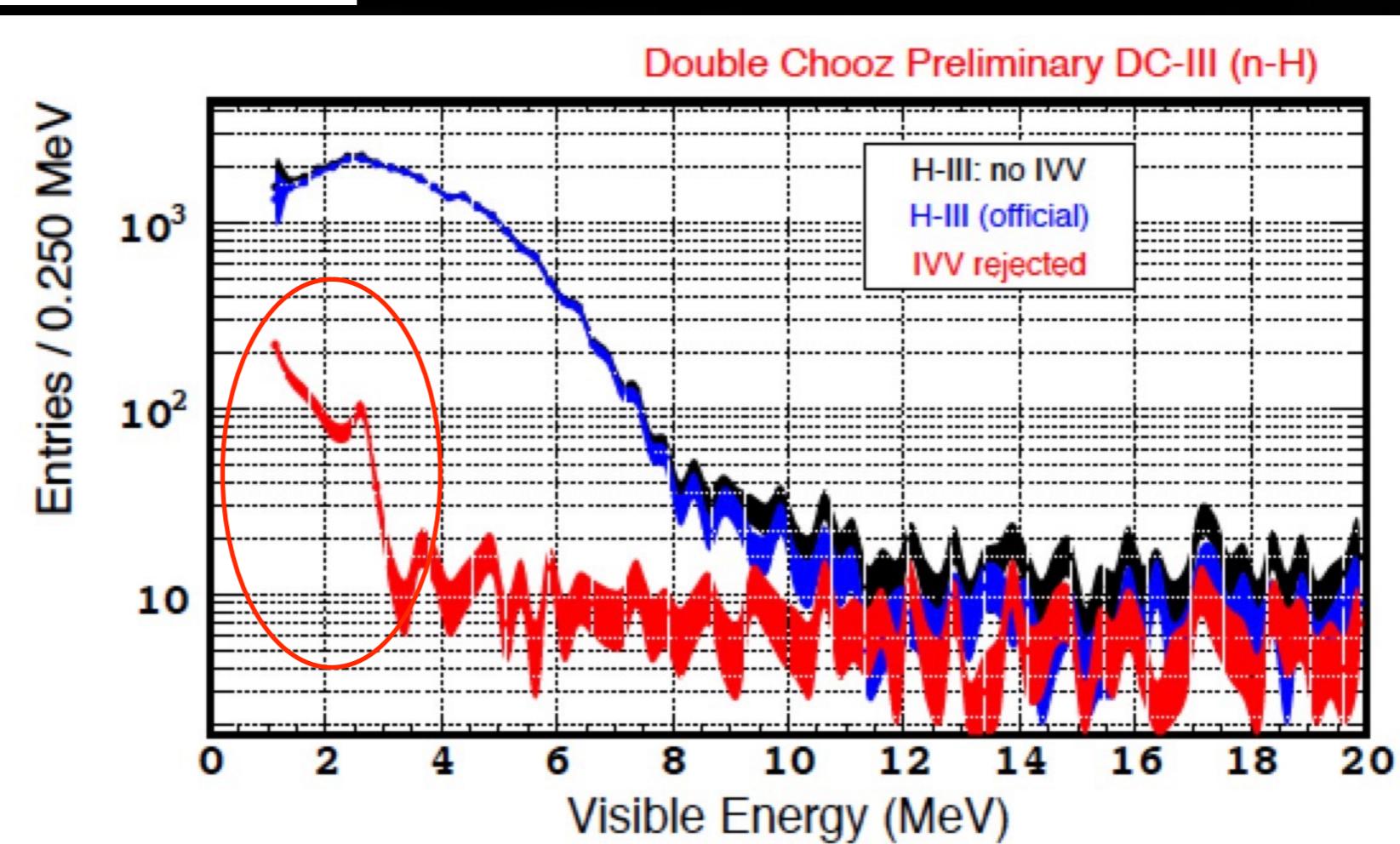
(first time) reject external  $\gamma$ 's (from rock)

[ $^{206}\text{TI}$  Compton-edge dominated  $\rightarrow$  BG for H-n]



~30% AccBG rejection

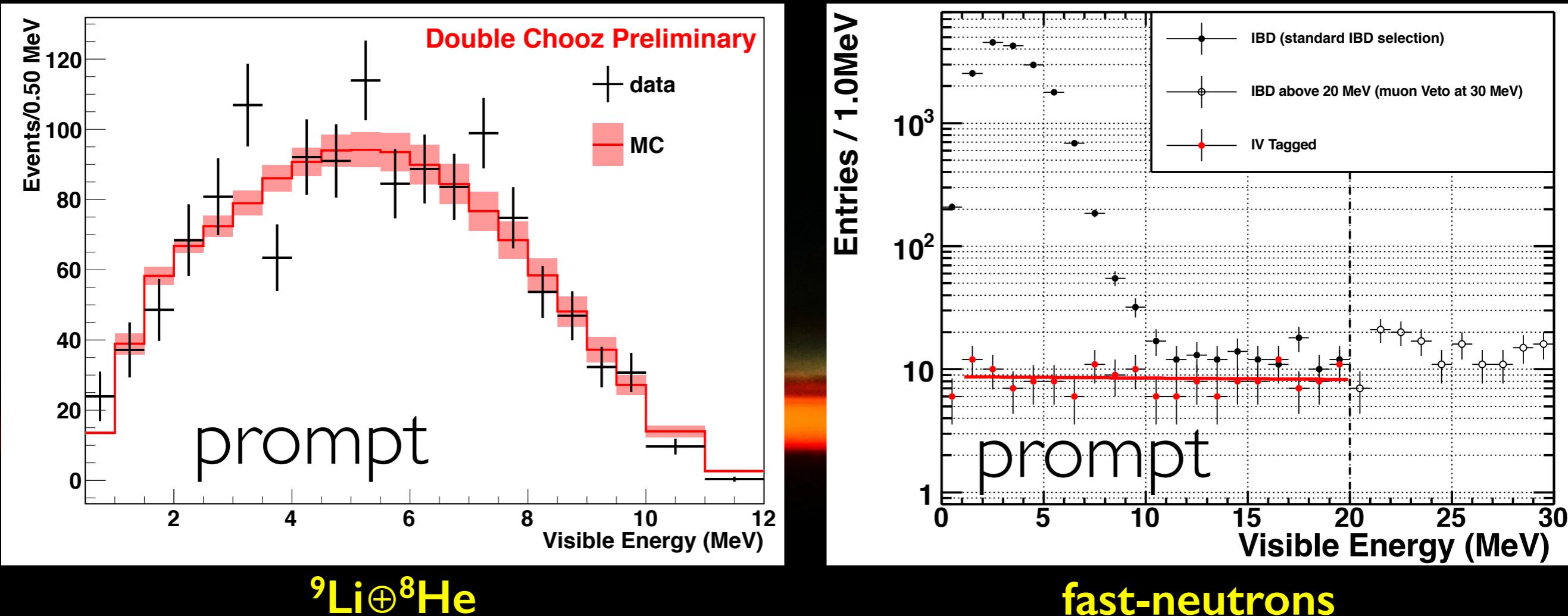
(also reject FN and stopping- $\mu$ 's  $\rightarrow$  ~0% IBD-inefficiency)



# measuring out BG in site (reactor ON data)...

**BG are data-driven (rate + shape) characterised & fit [0.5,20]MeV**

(only experiment in  $\theta_{13}$  doing that)

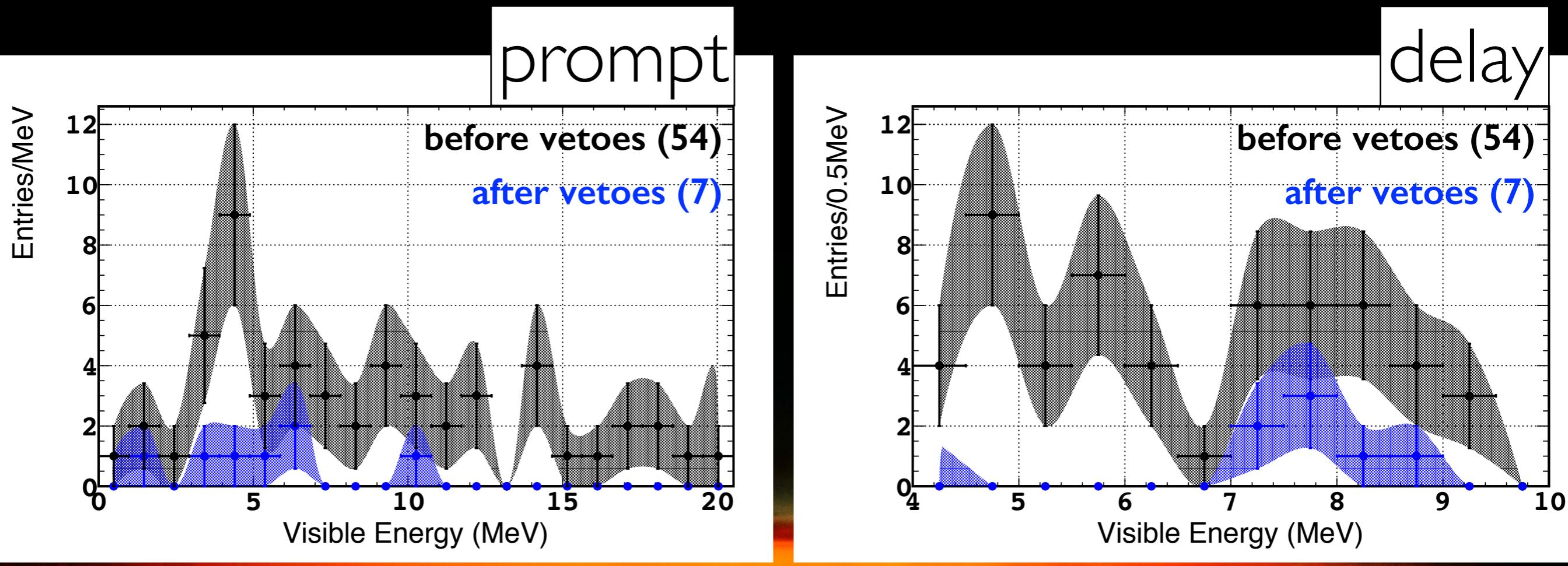


**rate+shape:** data measured using correlation  
to progenitor  $\mu$ s (spallation interaction)

**largest sample of Li+He ever shown and  
used for  $\theta_{13}$  analysis**

**shape:** data measured flat using IV-tagging  
(no extrapolation or MC $\rightarrow$  non-flat in GC)  
**rate:** measured in [20,30]MeV

(negligible contribution of stopped- $\mu$ )



2xOFF data: powerful information before/after veto evolution  
 (scrutinising a few event-wise BG-only)

1 week → poor stats (spectral info fluctuations dominated) → inconclusive

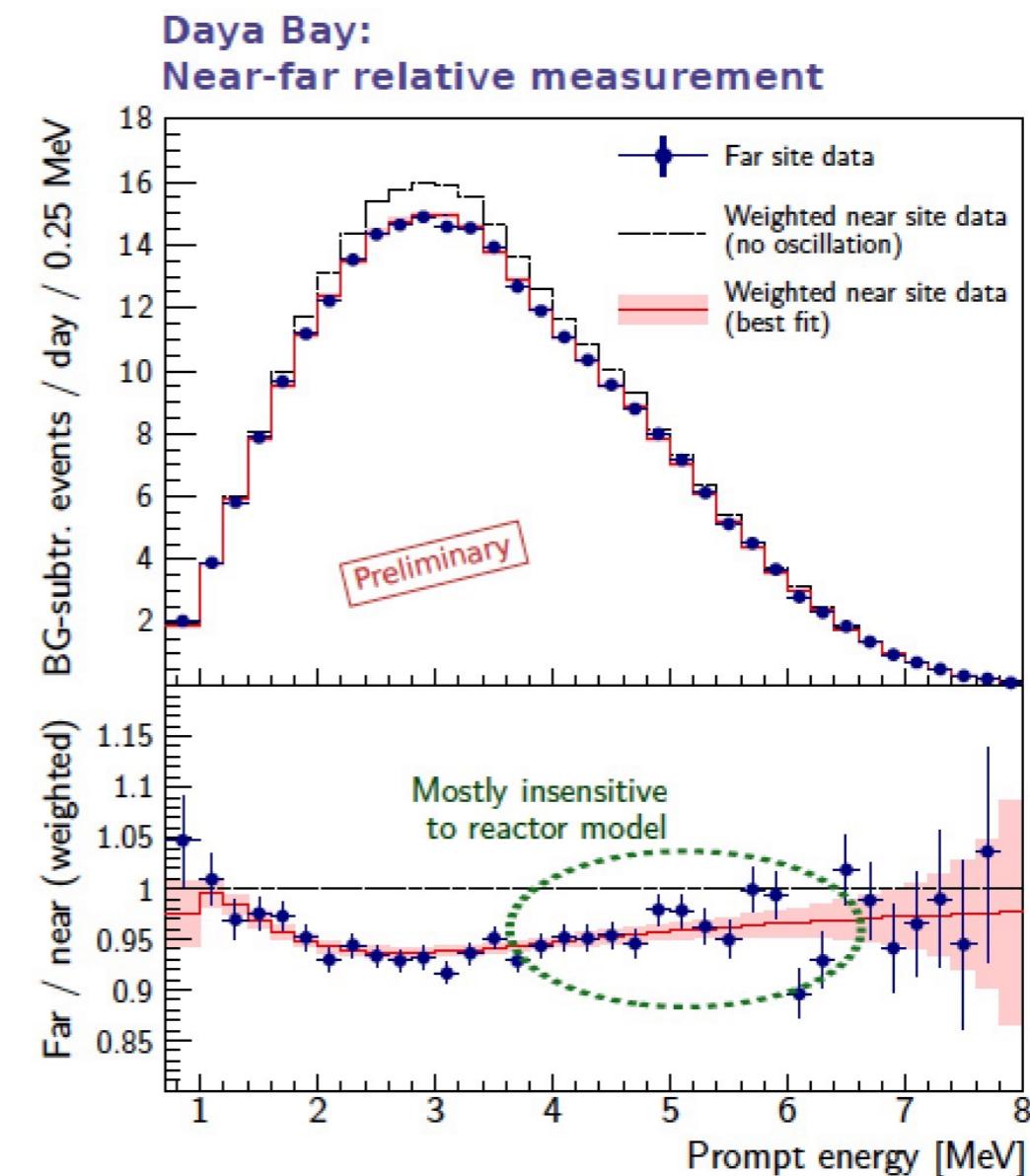
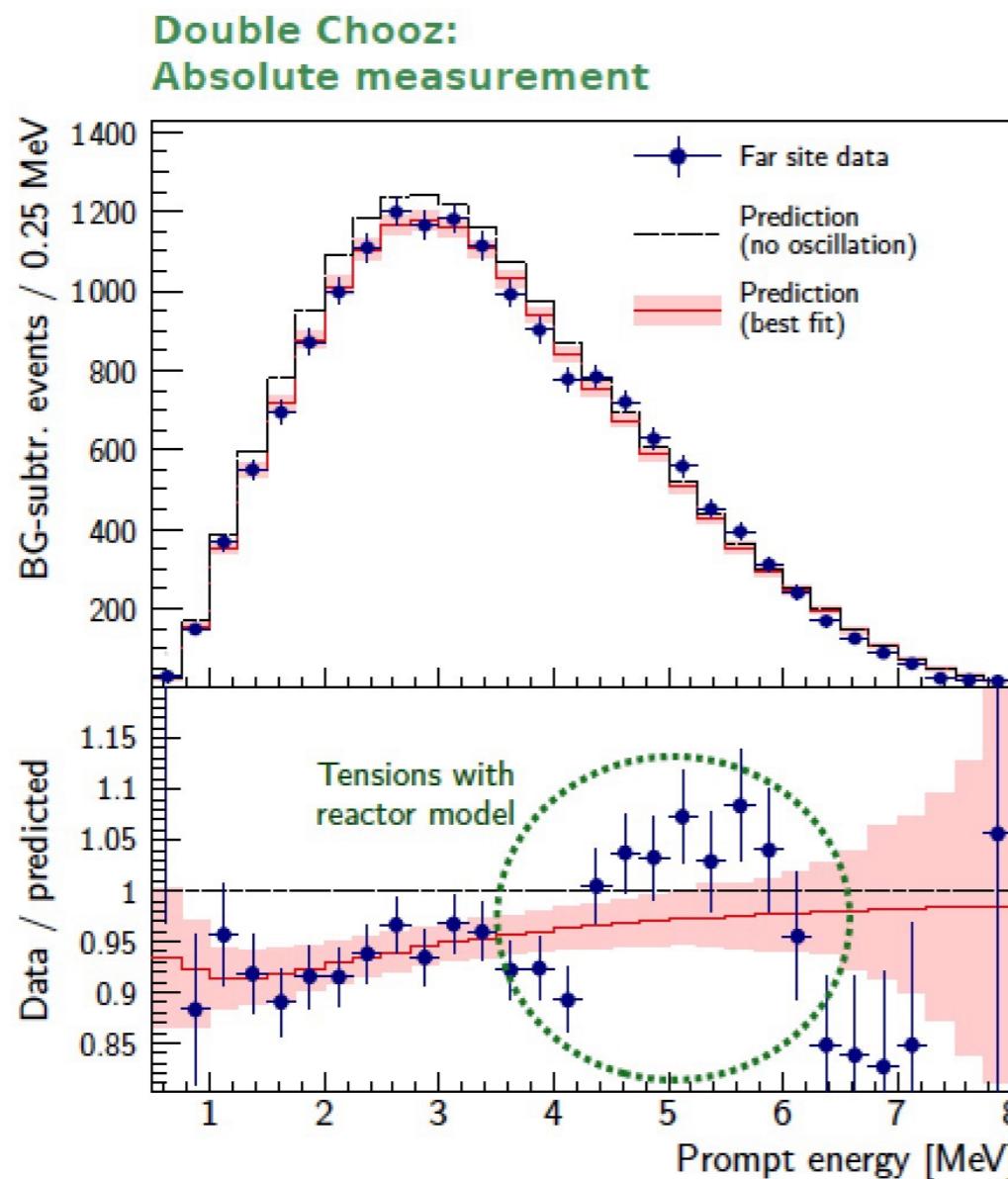
**P(rejection)=(7.7±3.1) @ Gd-III**  
 (in agreement with  $(9.9 \pm 1.0)$  estimated between [12,20]MeV)

$\theta \mid 3$  measurements...

(last with FD-only)

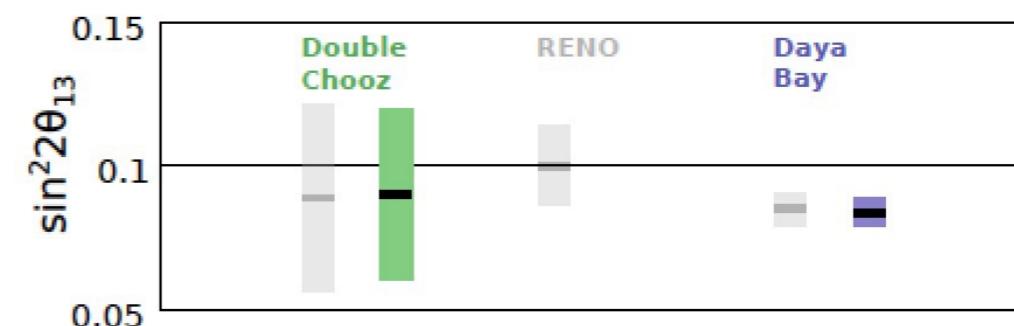
# $\theta_{13}$ spectral distortion (rate+shape) measurement...

## Rate+spectral oscillation analyses

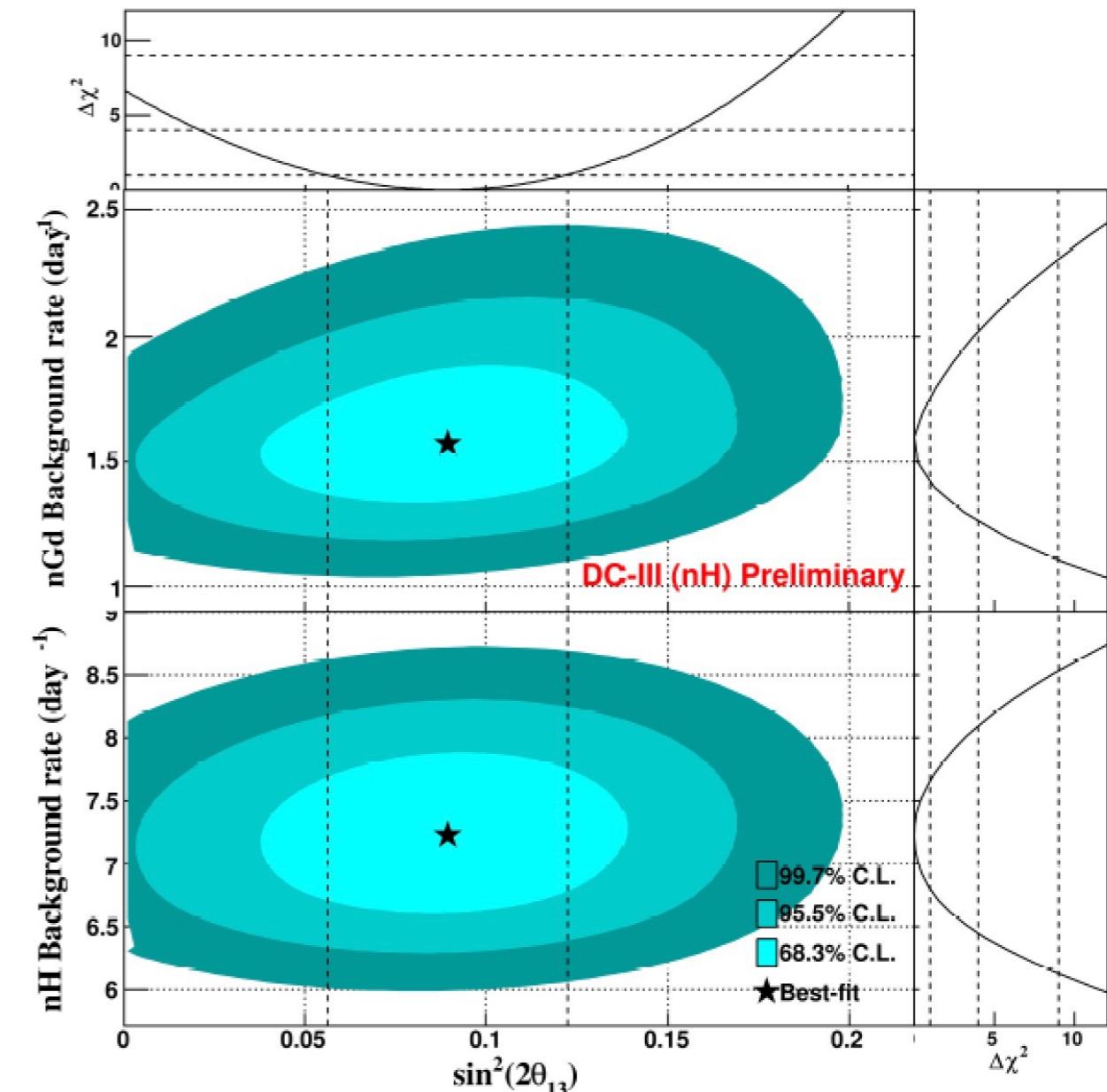
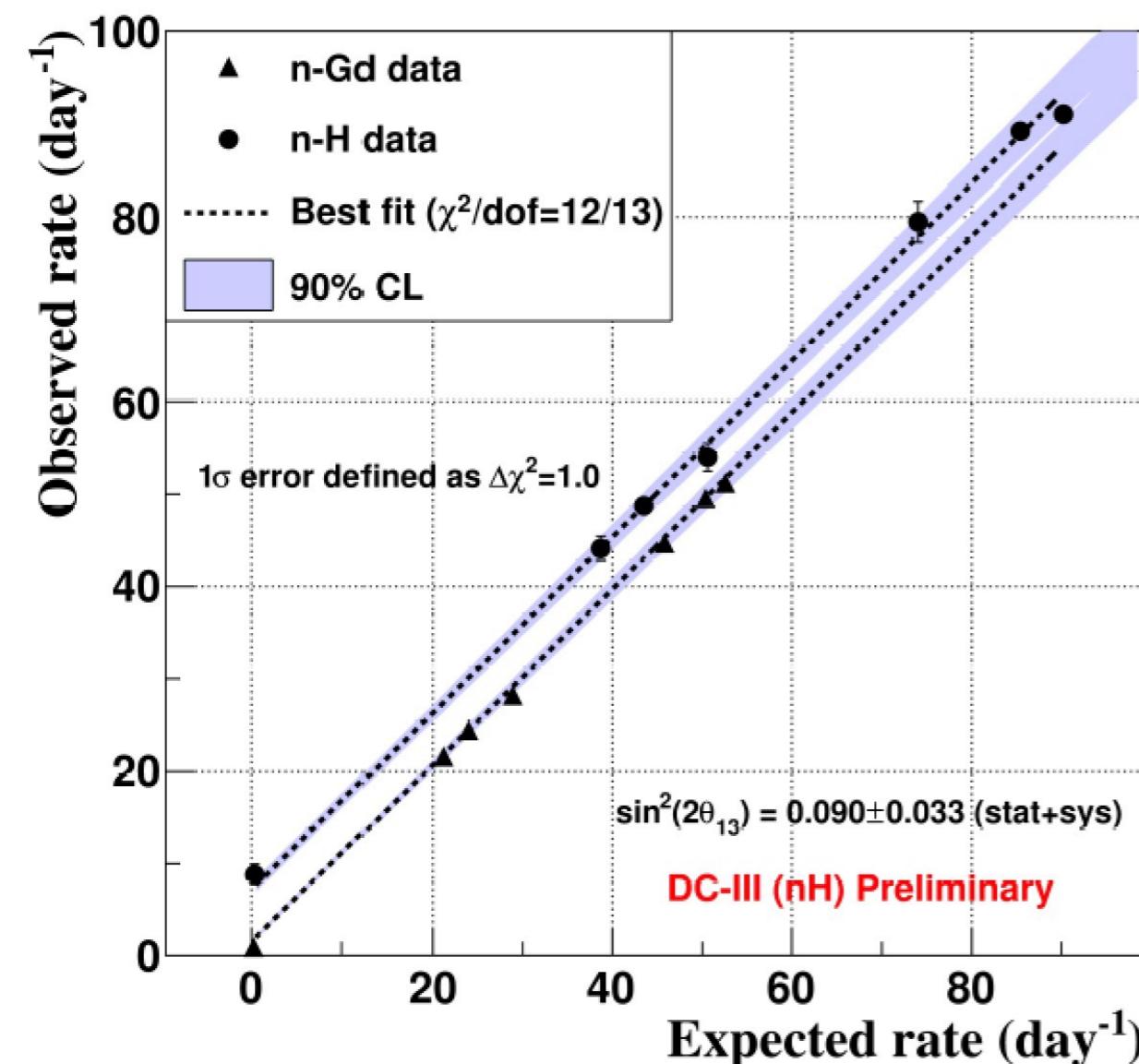


Double Chooz:  $\sin^2 2\theta_{13} = 0.09 \pm 0.03$   
 $|\Delta m_{ee}^2|$  fixed

Daya Bay:  $\sin^2 2\theta_{13} = 0.084 \pm 0.005$   
 $|\Delta m_{ee}^2| = 2.44^{+0.10}_{-0.11} \text{ meV}^2$



Combining this H-based result with latest Gd-based result (2014):

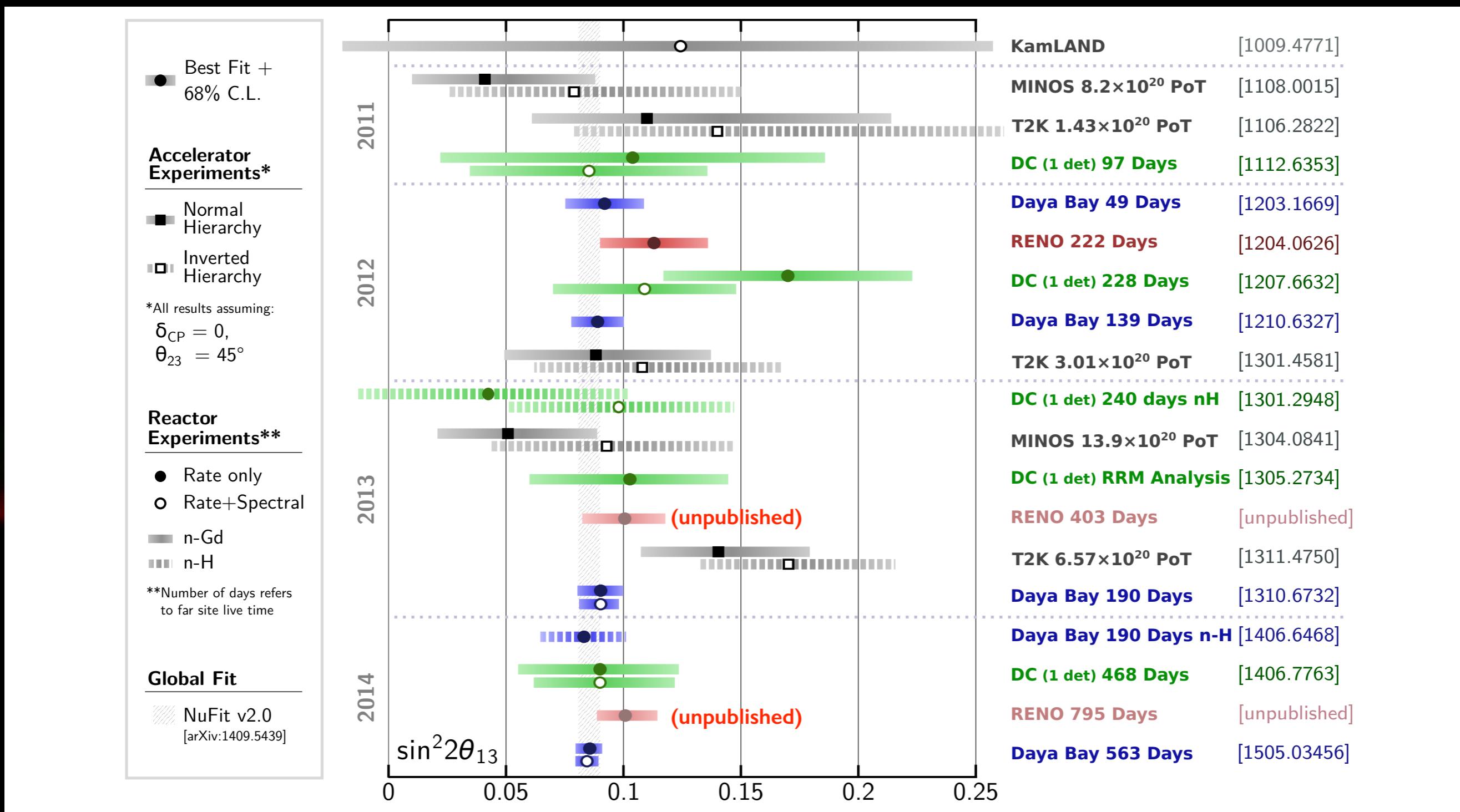


$$\sin^2 2\theta_{13} = 0.090 \pm 0.033$$

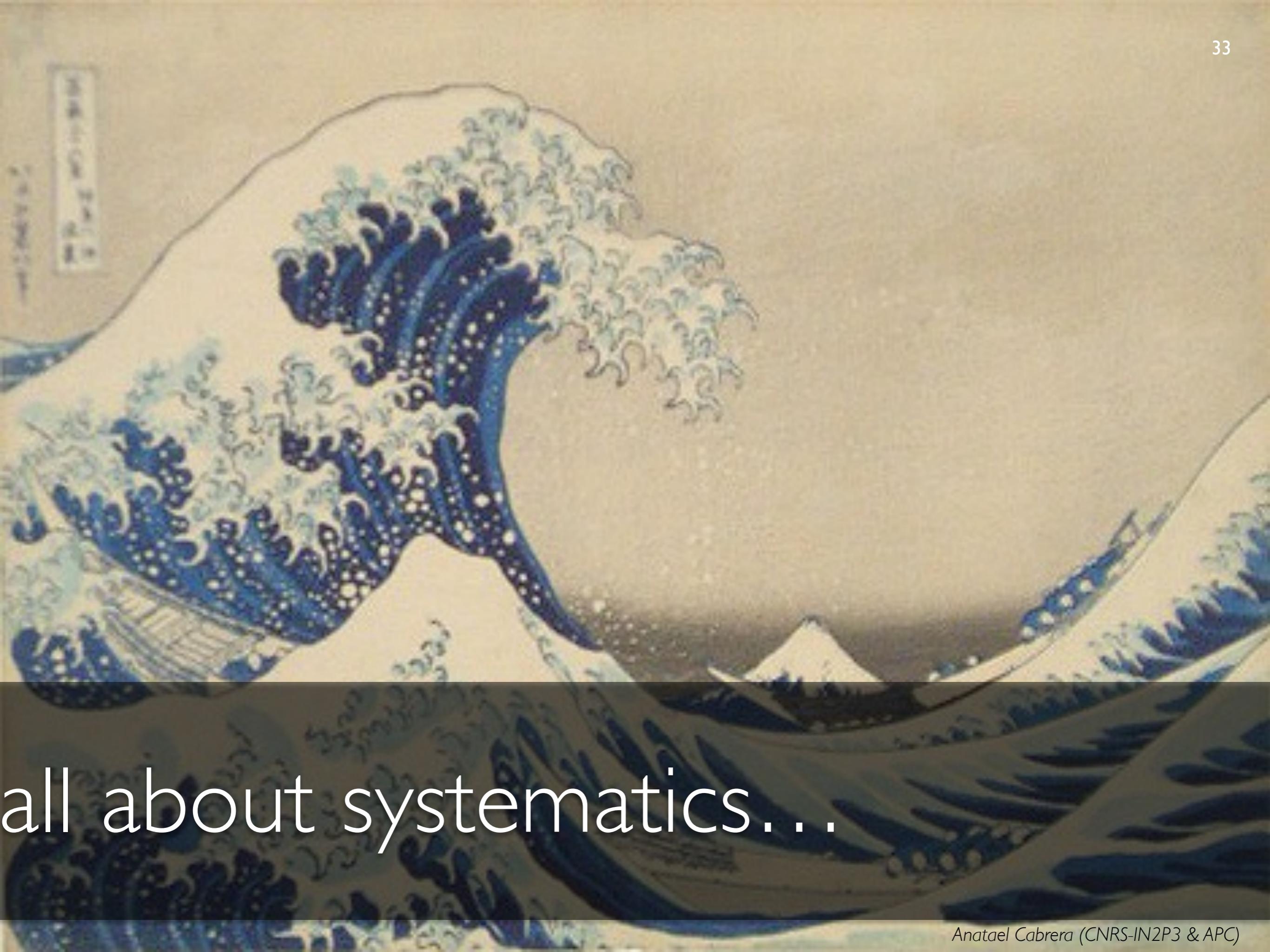
H only:  $\sin^2 2\theta_{13} = 0.098^{+0.038}_{-0.039}$ , Gd only:  $\sin^2 2\theta_{13} = 0.090^{+0.034}_{-0.035}$

Correlations between Gd and H have minimal impact. This result assumes no correlation.

# $\theta_{13}$ -reactor measurements (summer 2015)...



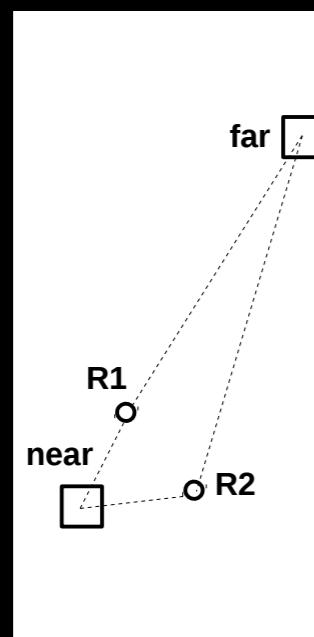
**unsurpassable reactor precision → “reactor- $\theta_{13}$ ” for several decades to go!**  
(also measurement by T2K, MINOS, KamLAND+Solar, etc)



all about systematics...

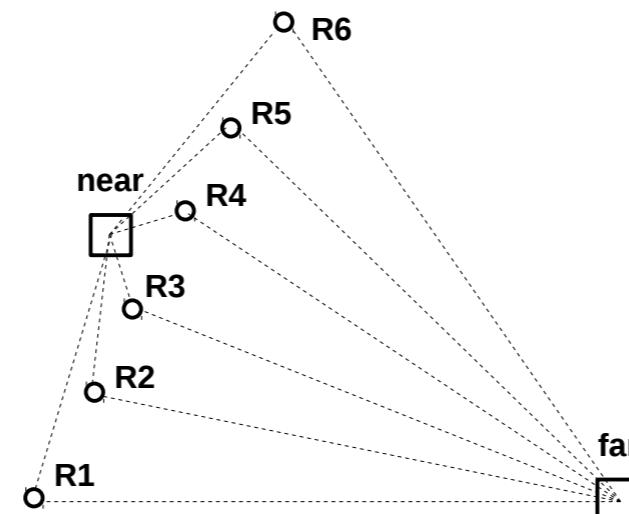
# thinking of systematics...

**Double Chooz**



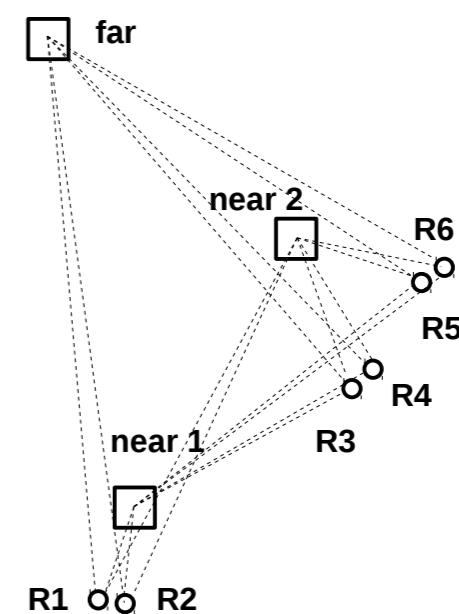
FD @ 300mwe  
(target: 8t)

**RENO**



FD @ 450mwe  
(target: 16t) [2x DC]

**Daya Bay**



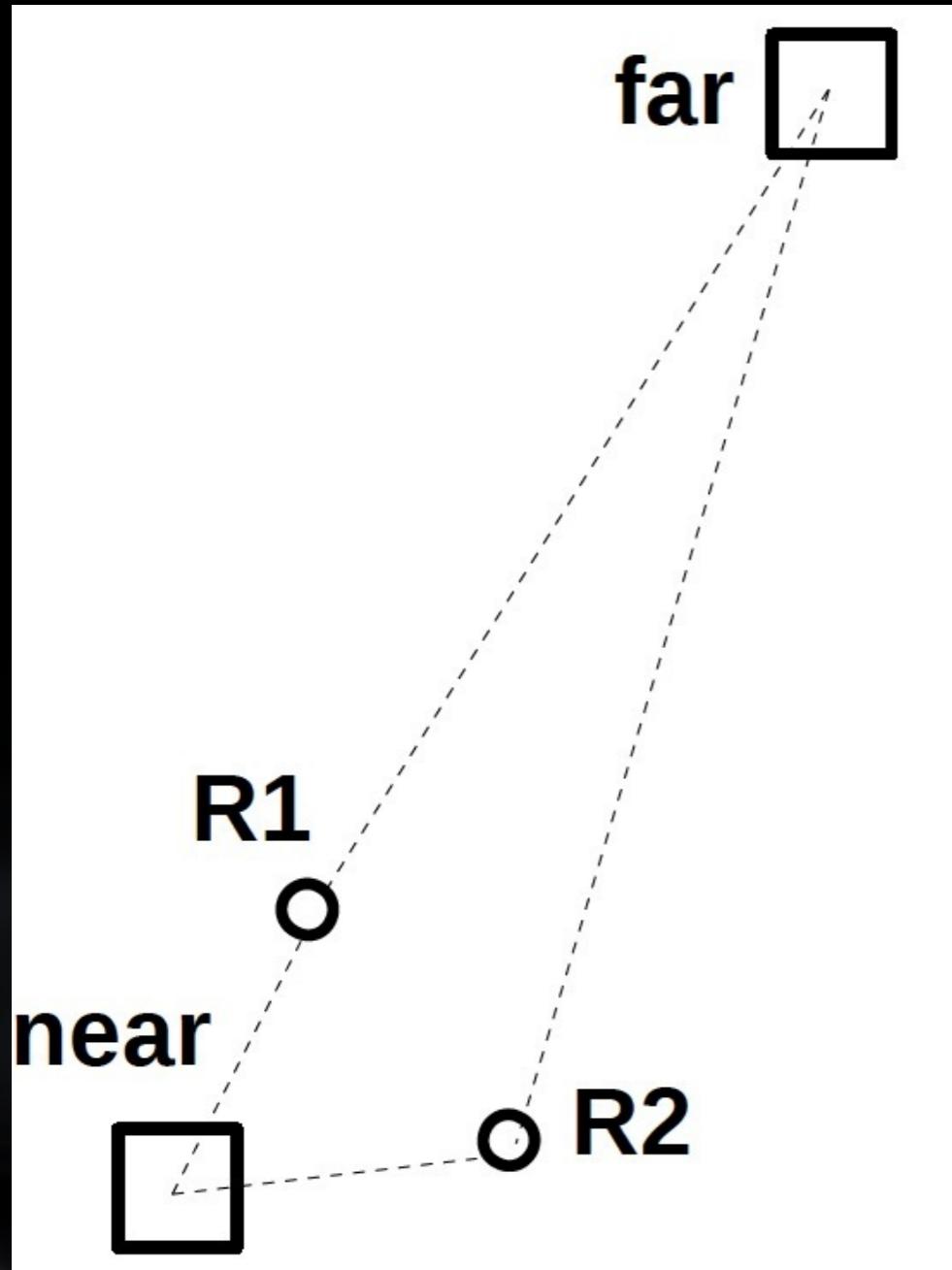
FD @ 850mwe  
(target: 80t) [10x DC]

R systematics (%)	DC FD only	DC FD+ND (prospected)	DB FDs+NDs	RENO FD+ND
$\delta(\text{flux})$	<b>1.7</b> (Bugey4) [~3.0 no Bugey4]	<b>&lt;0.1</b> (projected)	<b>0.8 → ≤0.3</b> (latest PRL)	<b>0.9 → ??</b> (PRL 2012)
$\delta(\text{detection})$	<b>0.6</b> (no Fiducial Volume)	<b>~0.2</b> (projected)	<b>0.2</b> (NIM-A)	<b>0.2</b> (PRL 2012)
$\delta(\text{BG})$	<b>0.3</b> (DC-III R+S)	<b>0.3</b> (DC-III R+S)	<b>~0.2</b> (latest PRL)	<b>1.0</b> (PRL 2012)

reactor flux systematics...

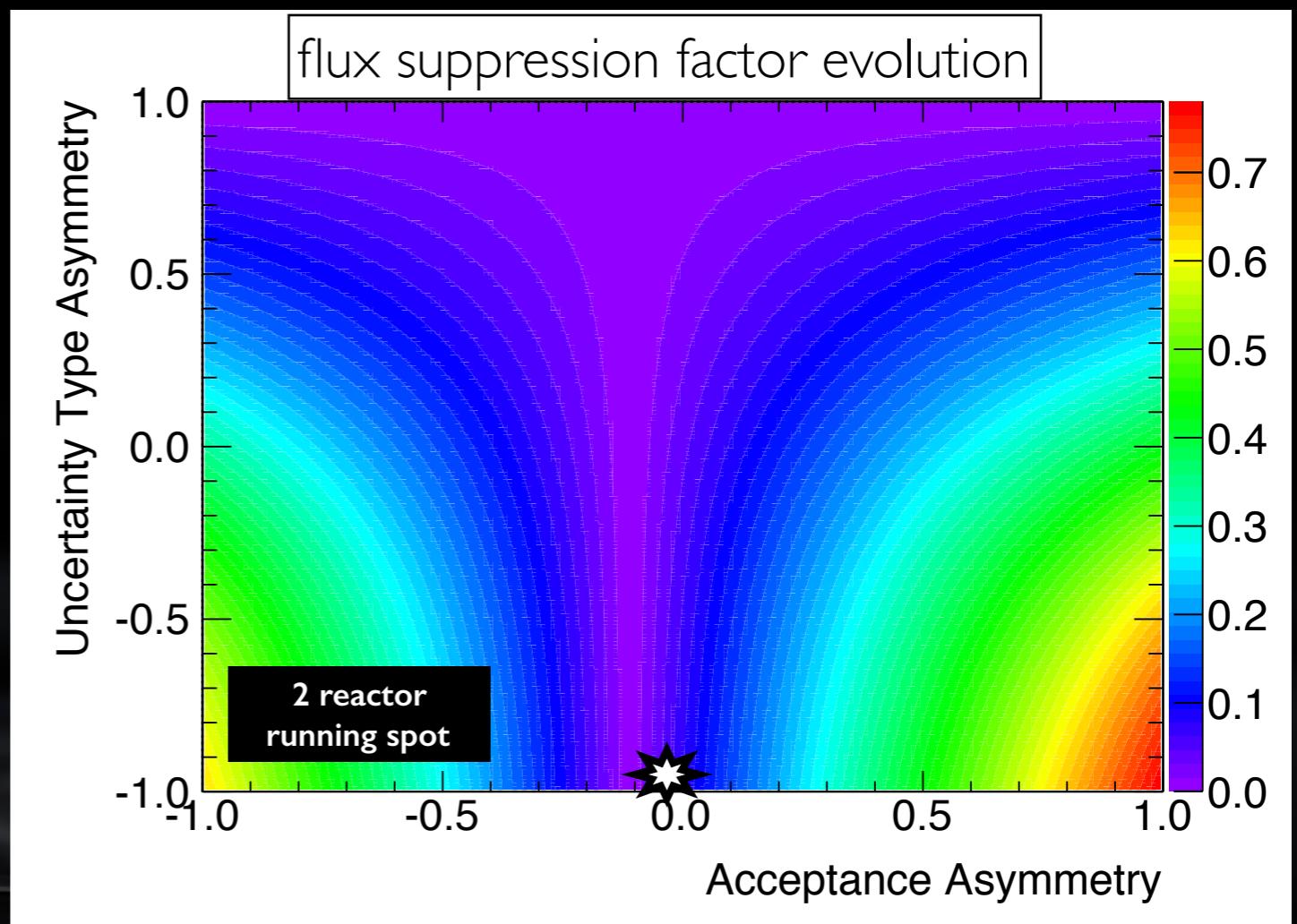
(no total cancellation)

# DC major $\delta(\text{flux})$ cancellation with ND...



**DC most iso-flux experimental setup**

$\Rightarrow \sim 90\% \delta(\text{flux})$  suppression



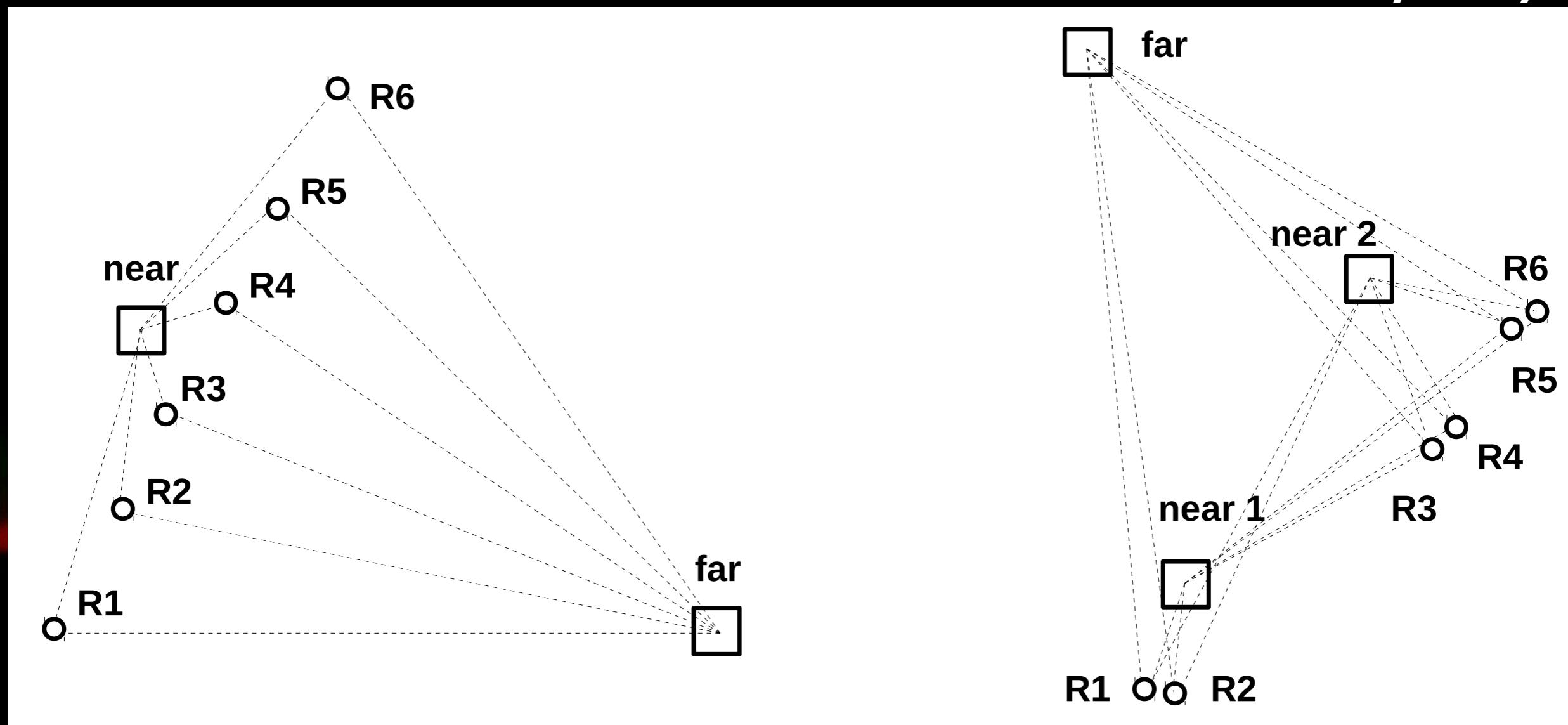
reactor error correlations  $\rightarrow \delta(\text{flux})$  suppression

$\delta(\text{flux})^{\text{FD}} = 1.7\% \rightarrow \delta(\text{flux})^{\text{FD+ND}} \leq 0.1\% \text{ (preliminary)}$

**"Reactor Neutrino Flux Uncertainty Suppression on Multiple Detector Experiments"**

Cucoanes, Novella, Cabrera et al. ([arXiv:1501.00356](https://arxiv.org/abs/1501.00356))

Anatael Cabrera (CNRS-IN2P3 & APC)

**RENO****Daya Bay****RENO site**

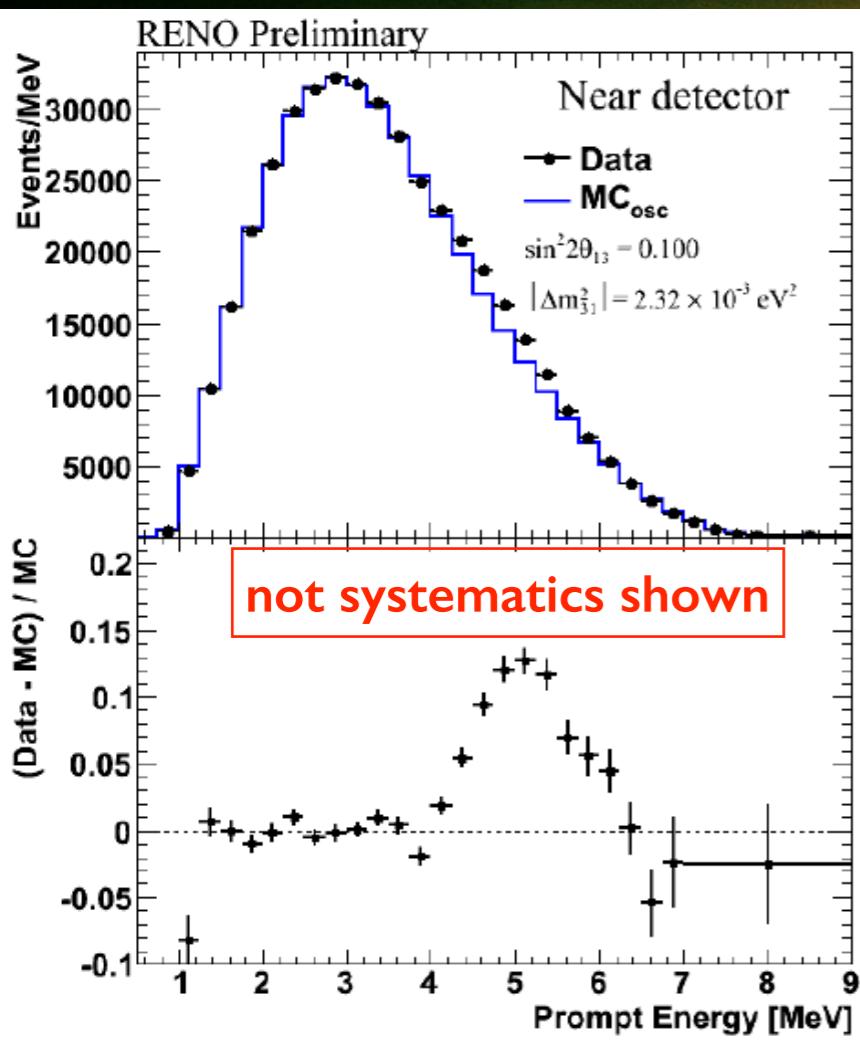
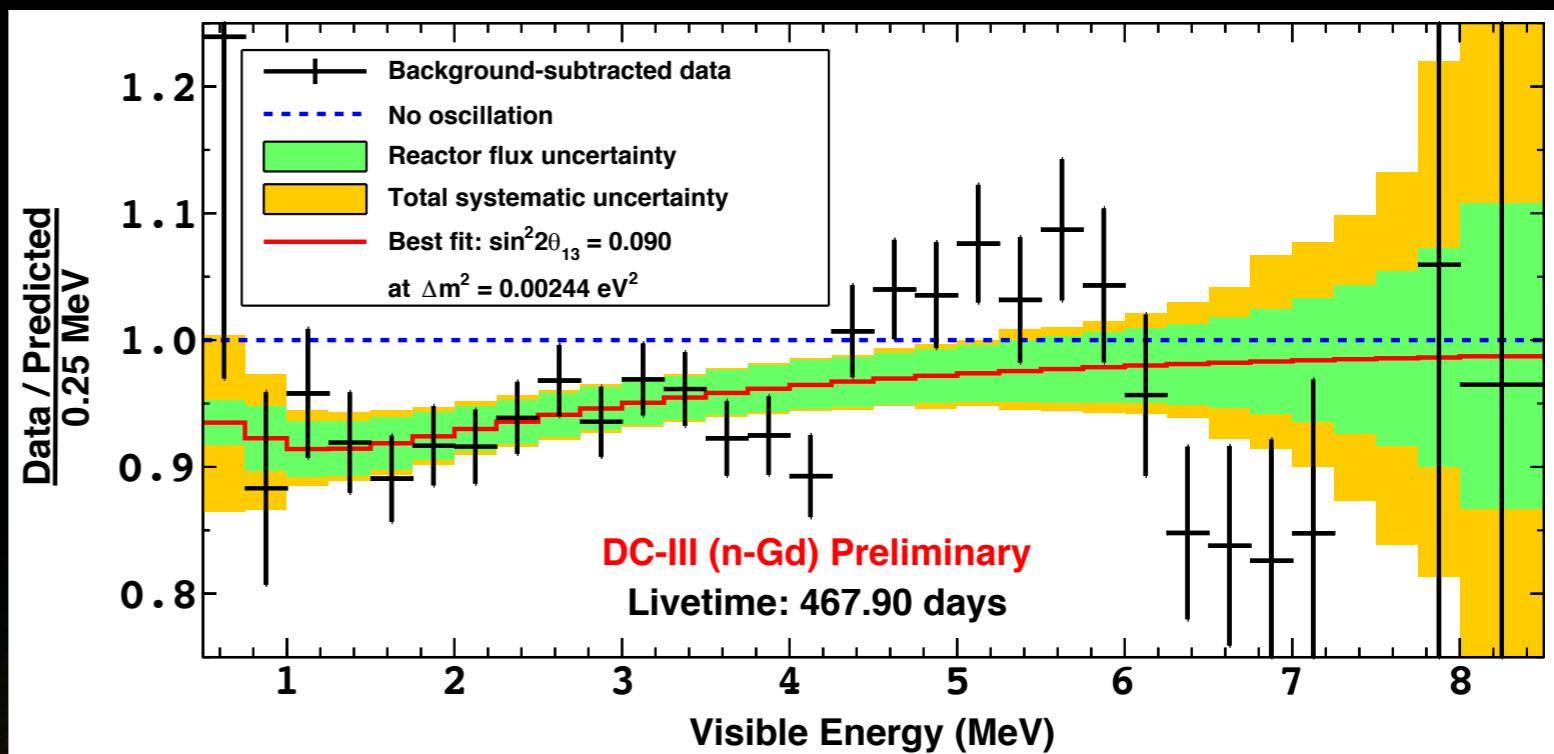
- geometrically very appealing
- ND does NOT see the same as FD  
    ⇒ large acceptance differences
- **partial effective iso-flux-ness is possible: ~40%**

**Daya Bay site**

- geometrically much harder but well designed
- NDs do NOT see the same as FD  
    ⇒ double-counting of reactors
- **partial effective iso-flux-ness is possible: ~50%**

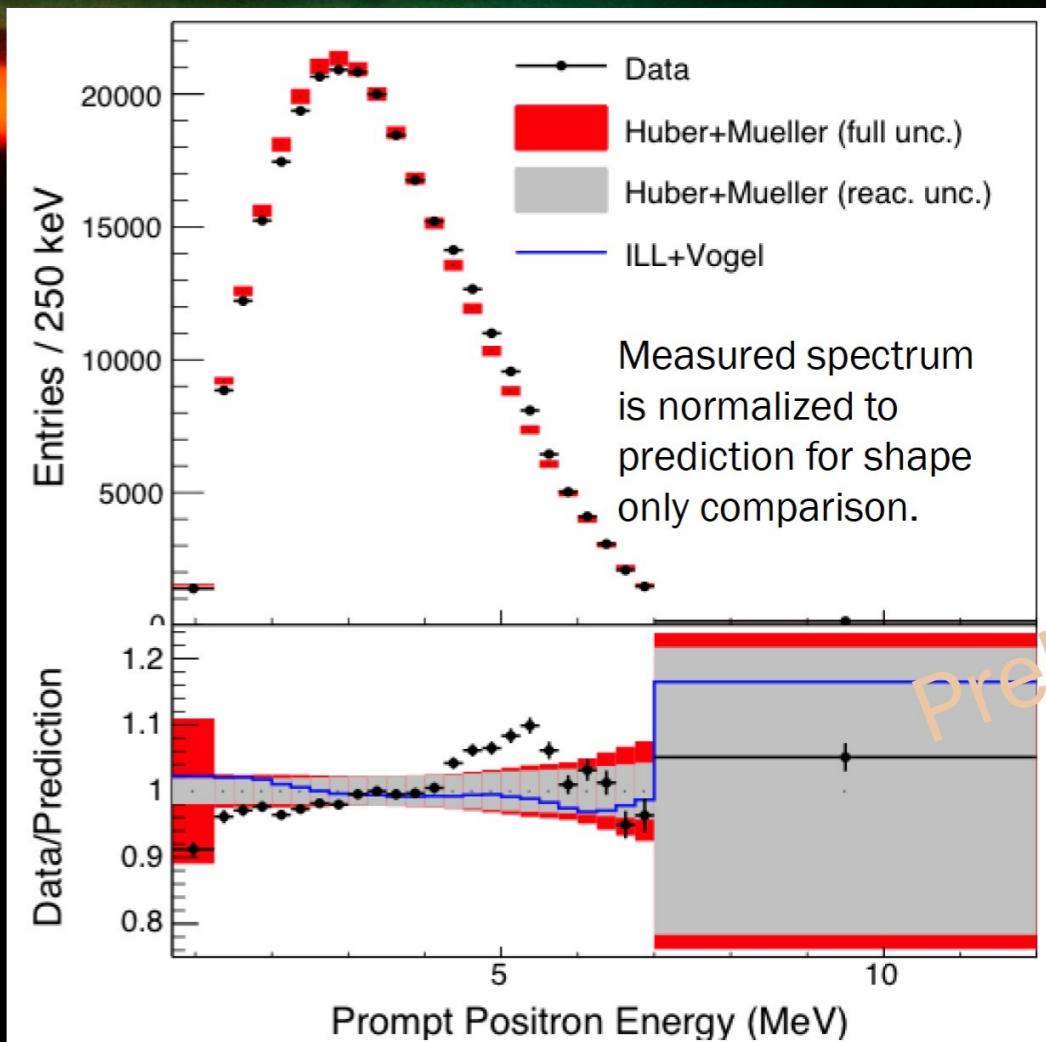
# $\theta_{13}$ experiments → high precision spectrum...

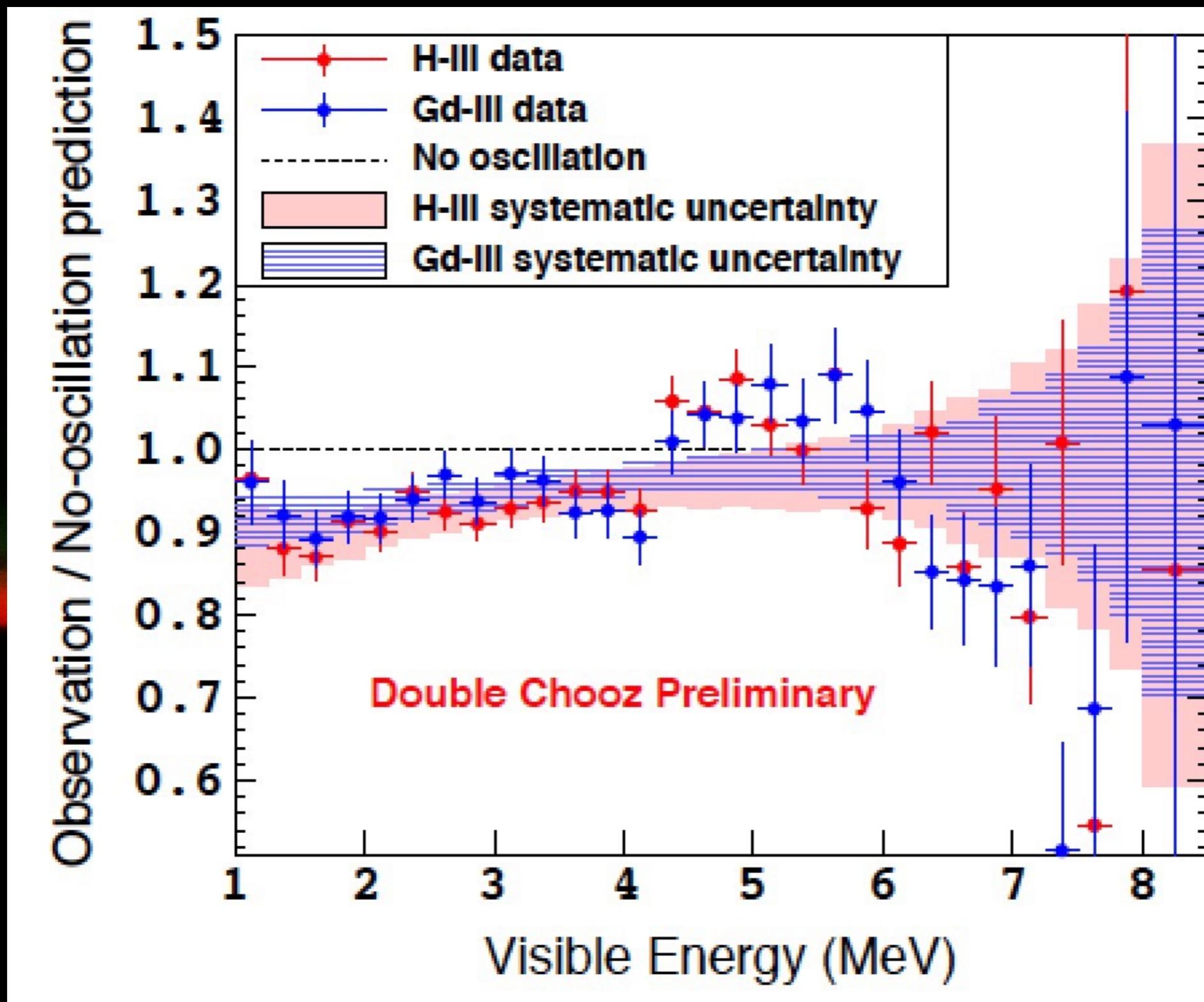
**Double Chooz (May 2014)**  
 $\sim 3.0\sigma$  ( $\sim 17k$  events @ FD)



**RENO (June 2014)**  
 $\sim 3.6\sigma$  ( $\sim 500k$  events @ ND)

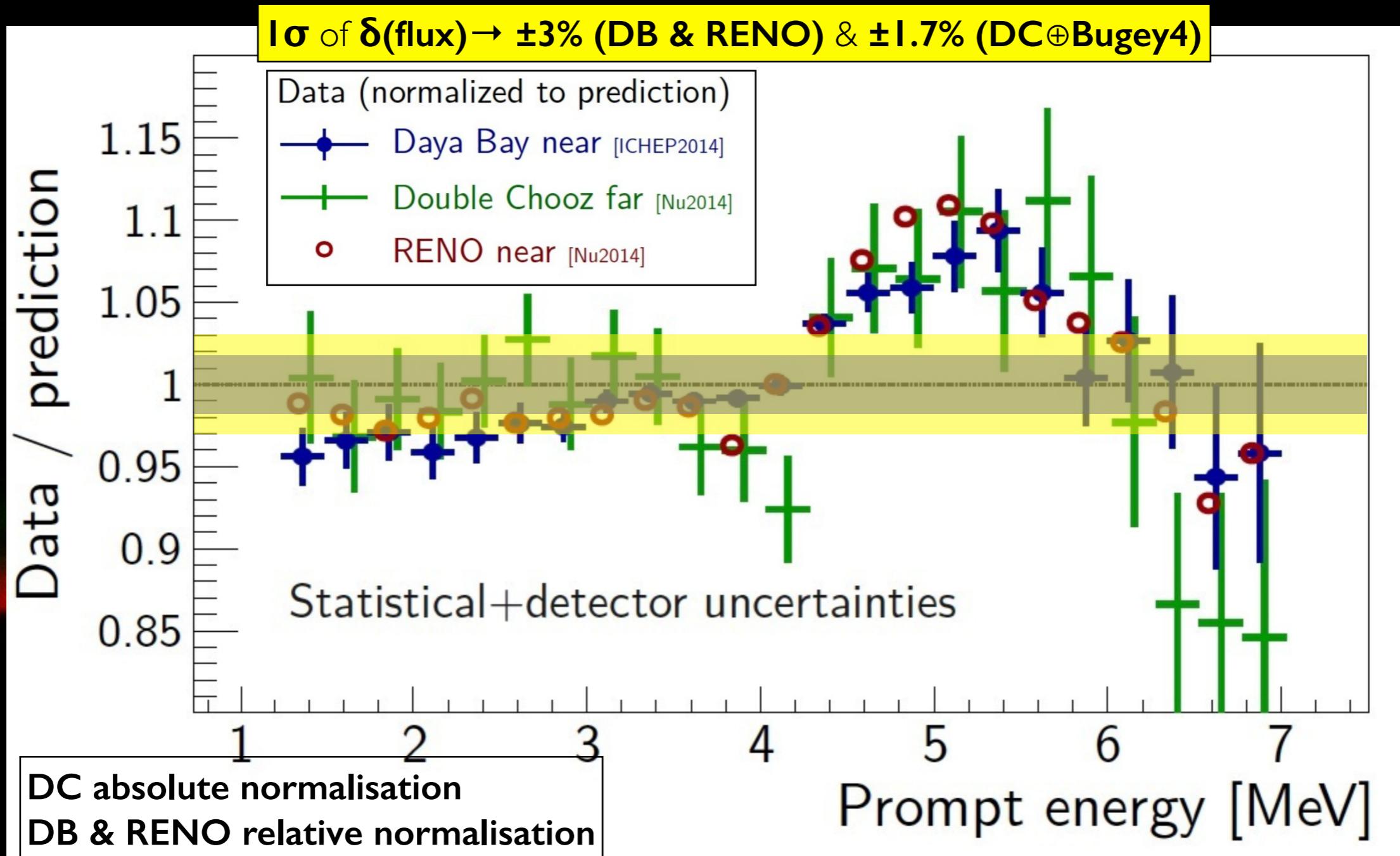
**Daya Bay (July 2014)**  
 $\sim 4.0\sigma$  ( $\sim 300k$  events @ 3xNDs)





consistent result with both Gd-n and H-n IBDs (independent)  
(but different BGs, detection volume, capture mechanism)

# 40 ( $\theta$ | 3 experiments) spectral distortion [4,8]MeV...

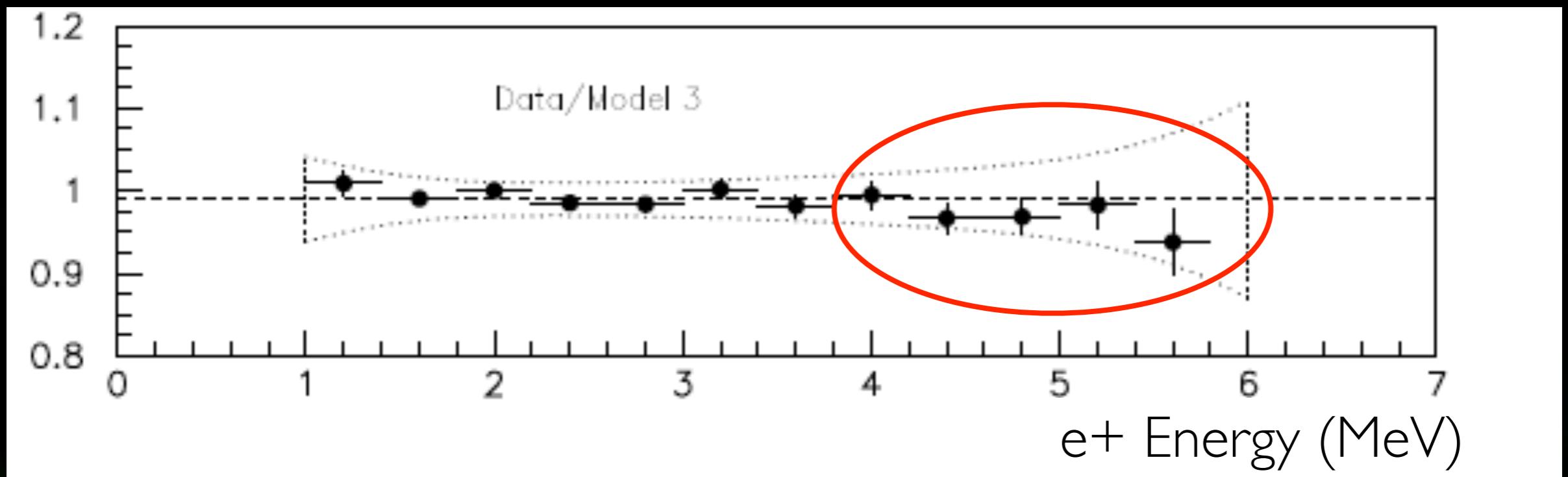


3 different experiments  $\rightarrow$  pointing (almost) consistently to one effect

- shape & normalisation consequences (not just shape)
- **$\delta(\text{flux})$  error is very likely to increase** (hard to believe otherwise)

3 experiments wrong in the same way is very unlikely (no evidence or reason)  
[unless you believe the reactor-flux effects are better understood than reactor detector results]

not everything is clear...

(Bugey3) everything ok → error  $\leq 3\%$ ?

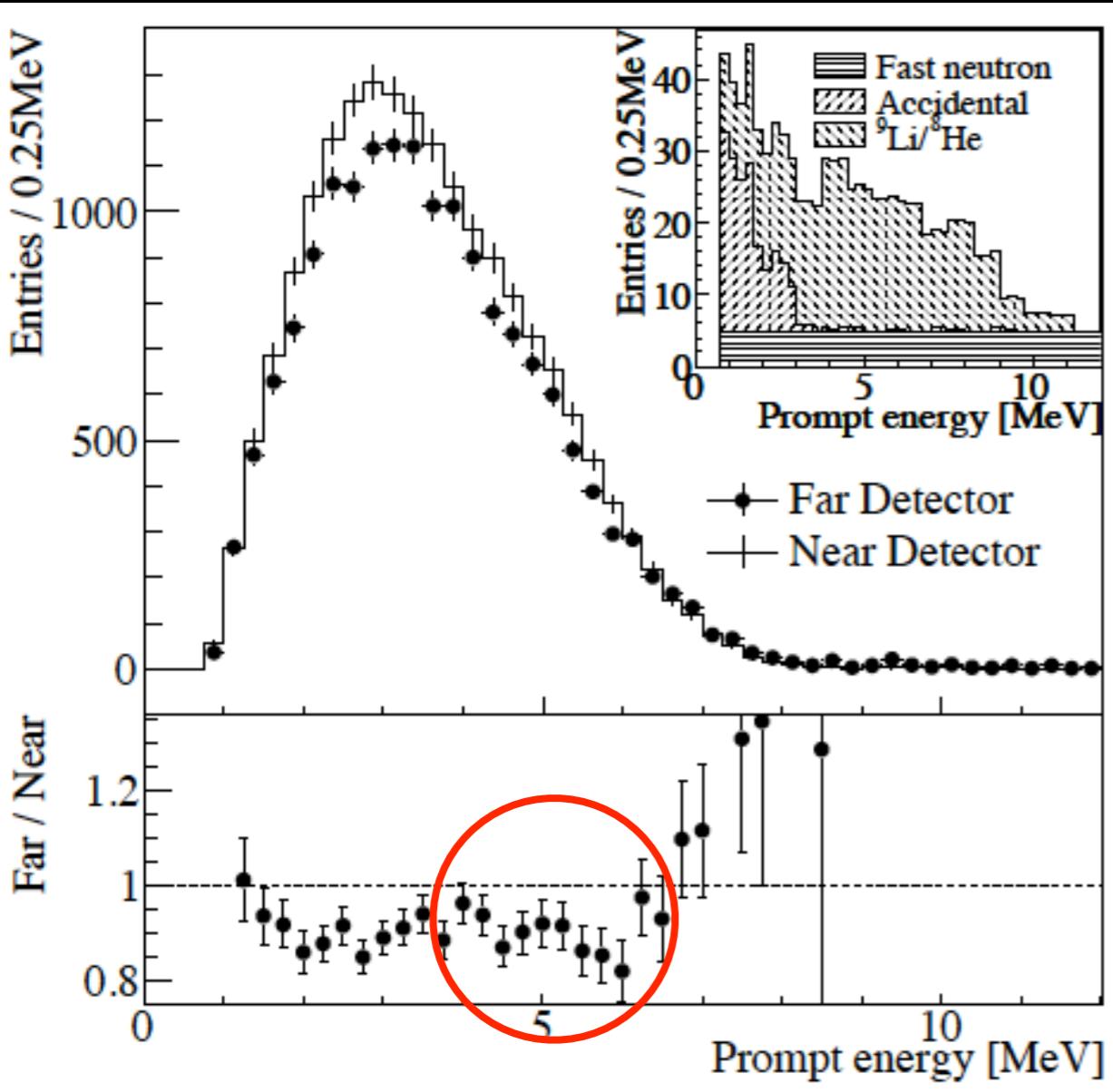
Bugey3 does not exhibit evidence of energy distortion...

- (suggested explanation by a Bugey3 member) **energy resolution is poor due to segmentation(?)**  
    **⇒ wash out?**

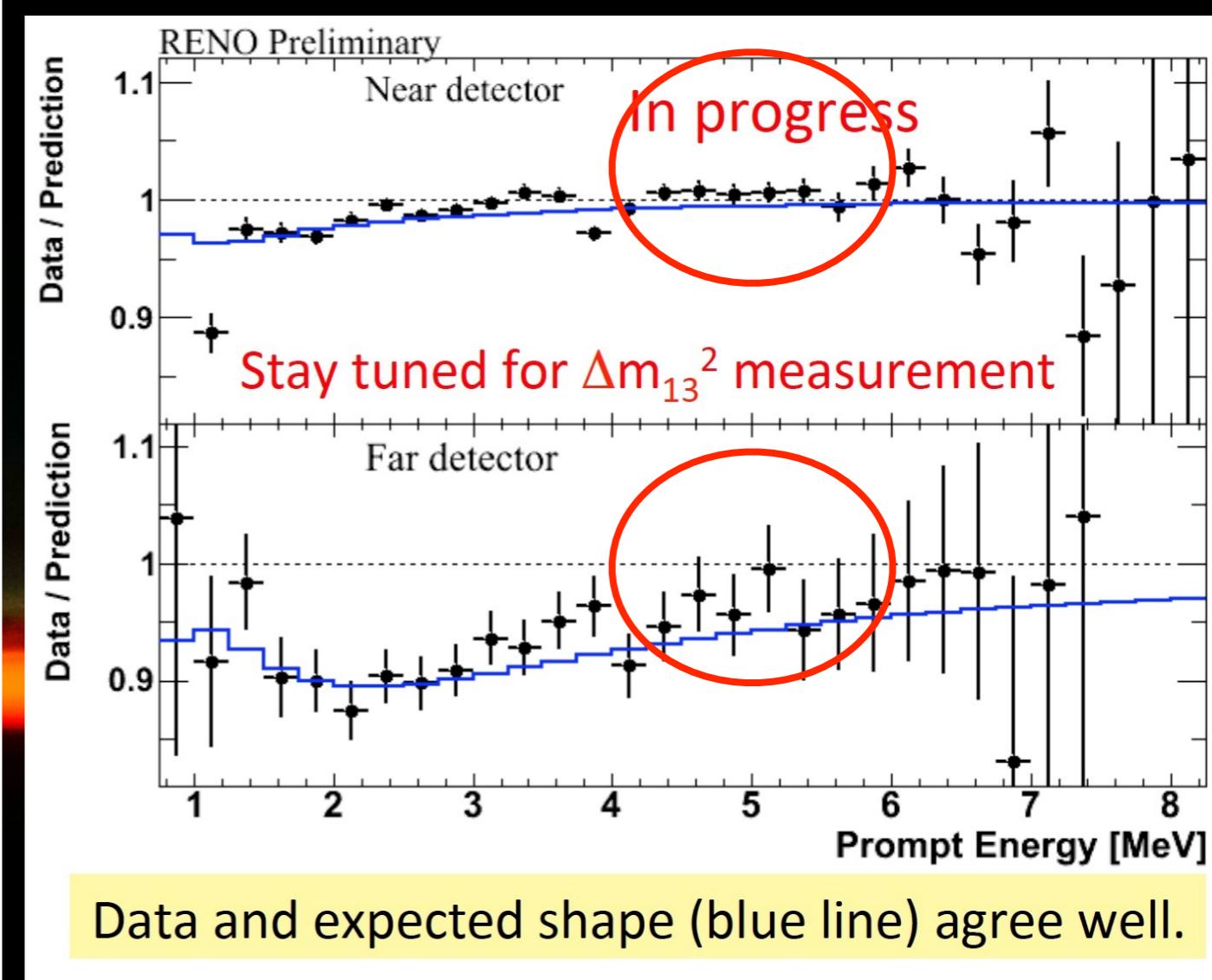
speculations...

- different reactors
- different detector (no Gd → Li capture based)
- difference BGs
- etc... (accommodate all possible opinions)

# the “RENO issue” (no more anomalies, please)...



(publication PRL 2012)



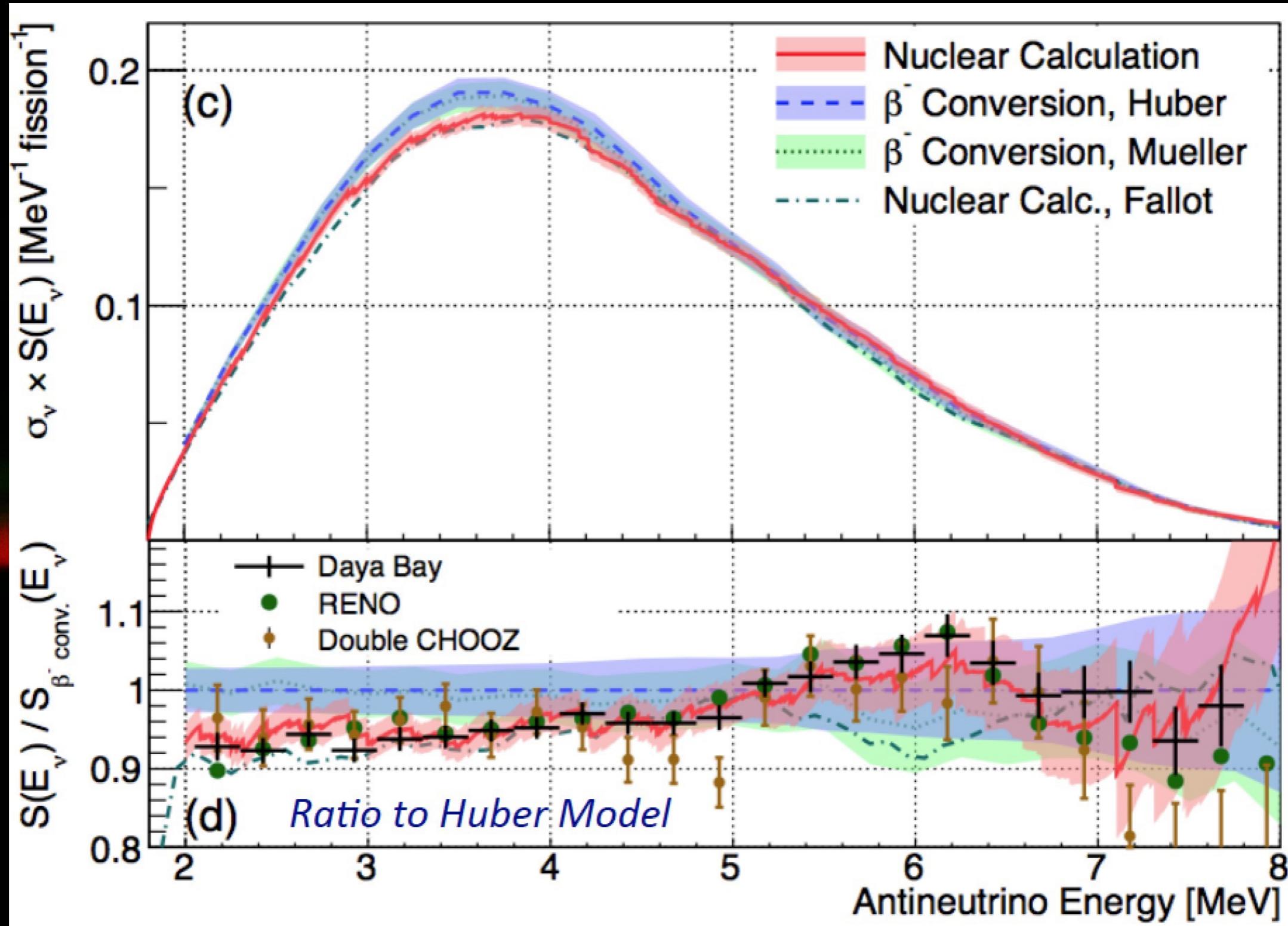
(no publication yet)

**RENO: strange energy distortion → consistent across ND & FD?**

(RENO only 1 paper → mid-2012, else several presentations)

**DB suggests distortion FD~ND → fully demonstrated? (no publication yet)**

# “conversion” vs “summation” methods...



uncertainty is hard to estimate ( $\leq 10\%$ )

# what to remember?

- **world reactor- $\theta_{13}$ ...**

- both central value & error (critical impact to 3v oscillation picture) → constrain  $\theta_{23}$ ,  $\delta_{CP}$ ?
- **3 experiments redundancy critical for precision/accuracy** →  $\theta_{13}^{\text{reactor}}$  (**several decades**)
  - **DB $\oplus$ DC $\oplus$ RENO combination** → first workshop by Autumn 2016
  - **reactor $\oplus$ T2K $\oplus$ NOvA combination** → **hint towards  $\delta_{CP}$ ?**

- **world reactor flux knowledge: reactor-v high precision discovery tools...**

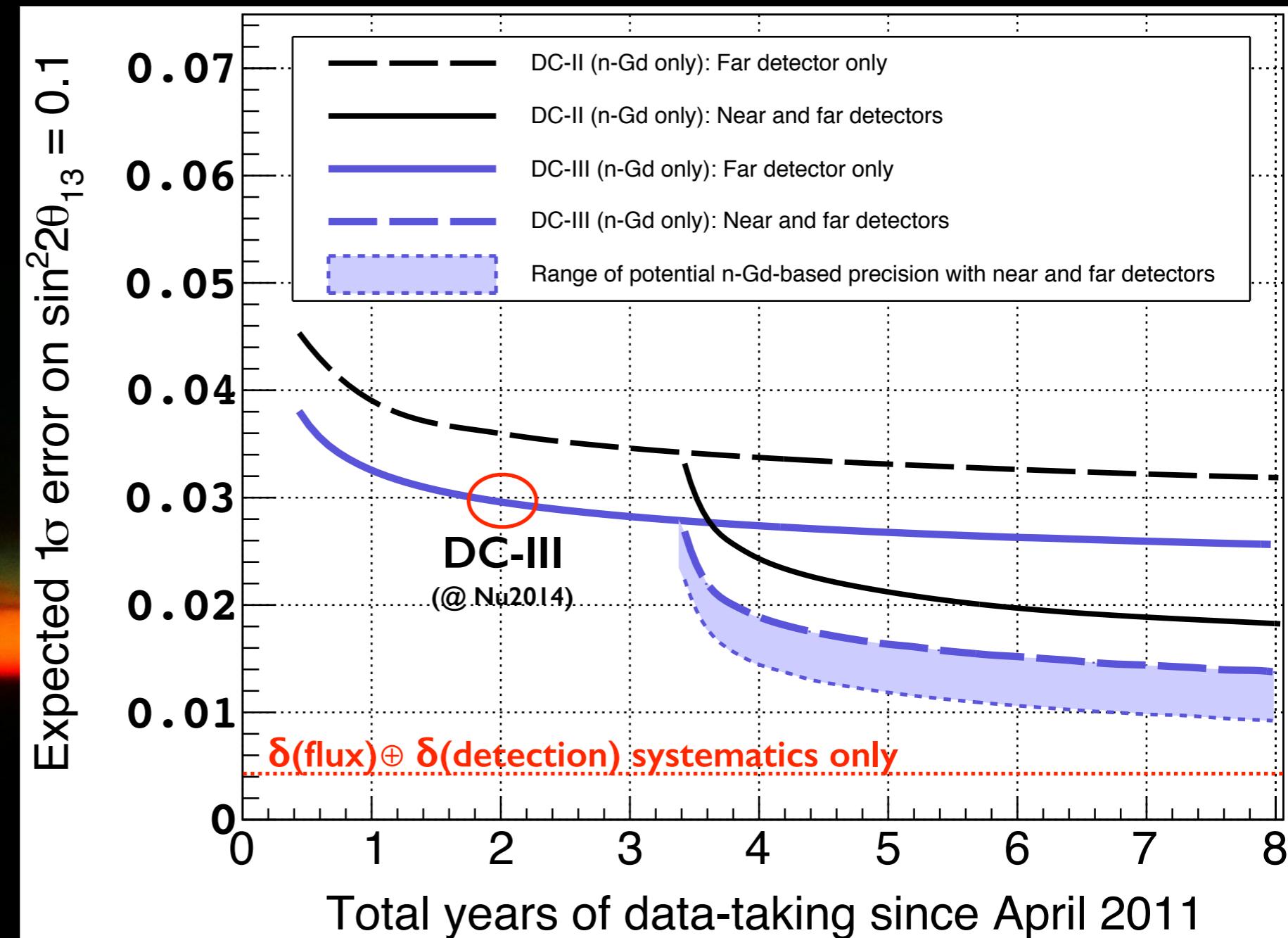
- despite multi-detector configuration → **non-negligible impact** (open debate among experts)
  - **final contribution of  $\delta(\text{flux})$  error?** (single and multiple detector setups)
  - **sterile hypothesis interpretation is impacted:** **not quantified yet** (→ not easy!)
- **unexpected behaviour in [4,6]MeV region**
  - **all reactor- $\theta_{13}$  experiment consistent but inconsistent with Bugey3** (⇒ 3% error?)
  - other experiments? → not easy!! (large BG, energy resolution/containment, etc)

merci...  
thank you...

# $\pm \sigma$ error projection (via R+S analysis)...

## Gd-n analysis FD+ND prospect inputs

- $\delta(\text{flux}) \sim 0.1\%$  (**preliminary**)
  - iso-flux suppression dominated
- $\delta(\text{detection}) \sim 0.2\%$  (**preliminary**)
  - à la Daya Bay / RENO
- $\delta(\text{BG}) \sim \text{DC-III} + \text{R+S constraint}$ 
  - @DC-III  $\sim 0.3\%$  (2 years data)
- note:**
- $\delta(\text{stat})$  not just  $1/\sqrt{N^{\text{FD}}}$  (**dominant**)
  - several effects  $N^{\text{BG}}$ ,  $N^{\text{ND}}$ , etc



**remarkable improvement of DC-III new analysis (wrt DC-II)**

**$\pm \sigma$  within [0.010,0.014] with 3 years FD+ND: BG systematics dependent → statistics dominated**  
 (rate+spectrum projection uses latest BG model from DC-III)

have been described in the White Paper, “A New Nuclear Reactor Neutrino Experiment to Measure  $\theta_{13}$ ” [6]. But since its publication the worldwide situation has changed and the projects still being considered are Angra [7] in Brazil, Daya Bay [8] in China, Double Chooz in France (see [9, 10] and this proposal), KASKA [11] in Japan and RENO [12] in South Korea. A recent comparison of the capabilities of these experiments can be found in [13, 14]. Double Chooz is particularly attractive because it could limit  $\sin^2(2\theta_{13})$  to 0.022-030 (for  $\Delta m_{31}^2 = 3.5 - 2.5 \times 10^{-3} \text{ eV}^2$ ), within an unrivaled time scale and a modest cost. Installation of the experiment will start with the far detector located



**Double Chooz performance is better than ever expected...**  
(despite the LONG wait for the ND)

stay tuned!