ν-reactor flux systematics

(present & future)

The Status of Reactor Antineutrino Flux Modelling workshop
SUBATECH, Nantes

Anatael Cabrera

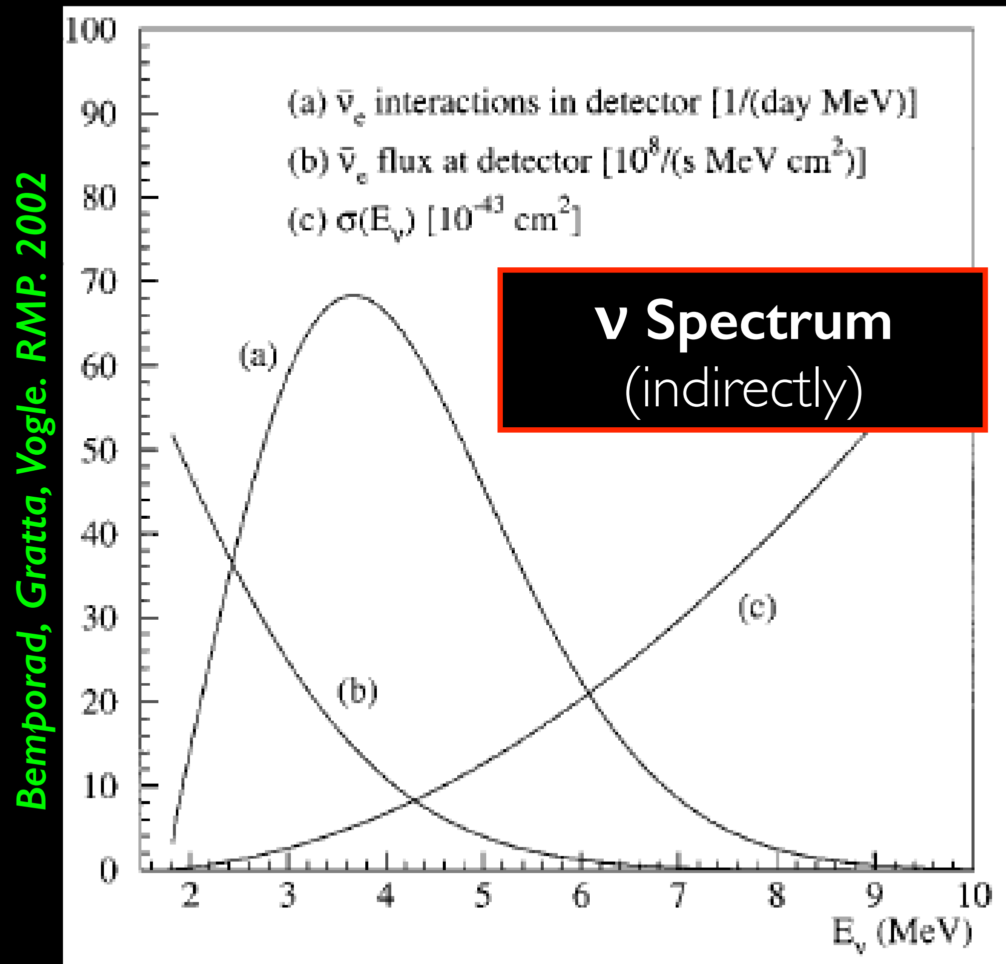
CNRS / IN2P3 @ APC (Paris)

reactor-ν experiments' view…

what the experiments need…

e+ Spectrum
(observable @ LAND)

S[E(e+)] ↔ **S***[E(ν)] = **σ**[E(ν)] × **flux**[E(ν)] × **p**[E(ν)]



interaction
(IBD→well known)

δ(σ): ~0.2%

reactor flux
(dominant uncertainty)

δ(flux): ~3.0%

other physics
(θ13, sterile, etc)

δ: ≥δ(flux)

since flux[E(ν)] is not well know (σ error being negligible), experiments (aiming for **p[E(ν)]**) will try bypass…

(very expensive trick) **multi-detector→** $\mathbf{S[E(e+)]^{FarD} / S[E(e+)]^{NearD}}$

(cancellation of detector correlated effects)

major cancellation of uncertainties:
- δ(cross-section)→ negligible
- δ(flux)→ non-negligible (event after multi-detector)

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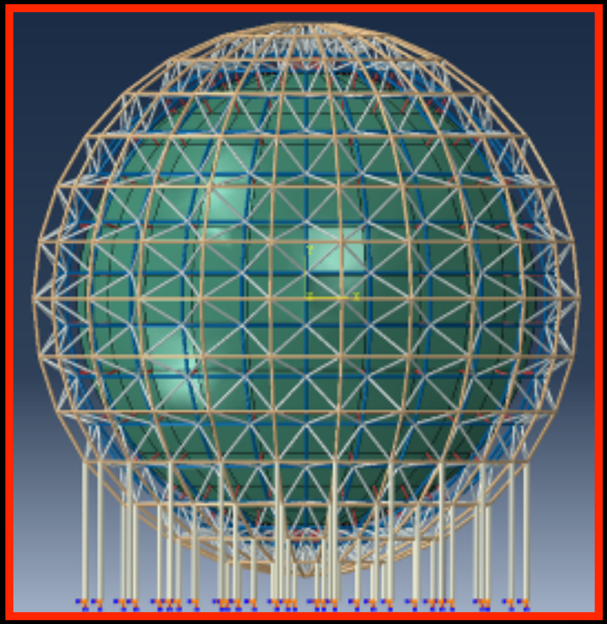
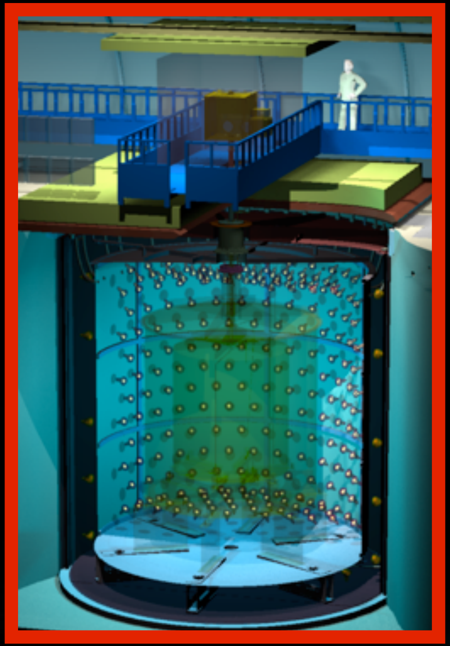
type of experiments…



- very far from reactor (>50km)
- excellent energy
- low BGs

→rely on δ(flux) input

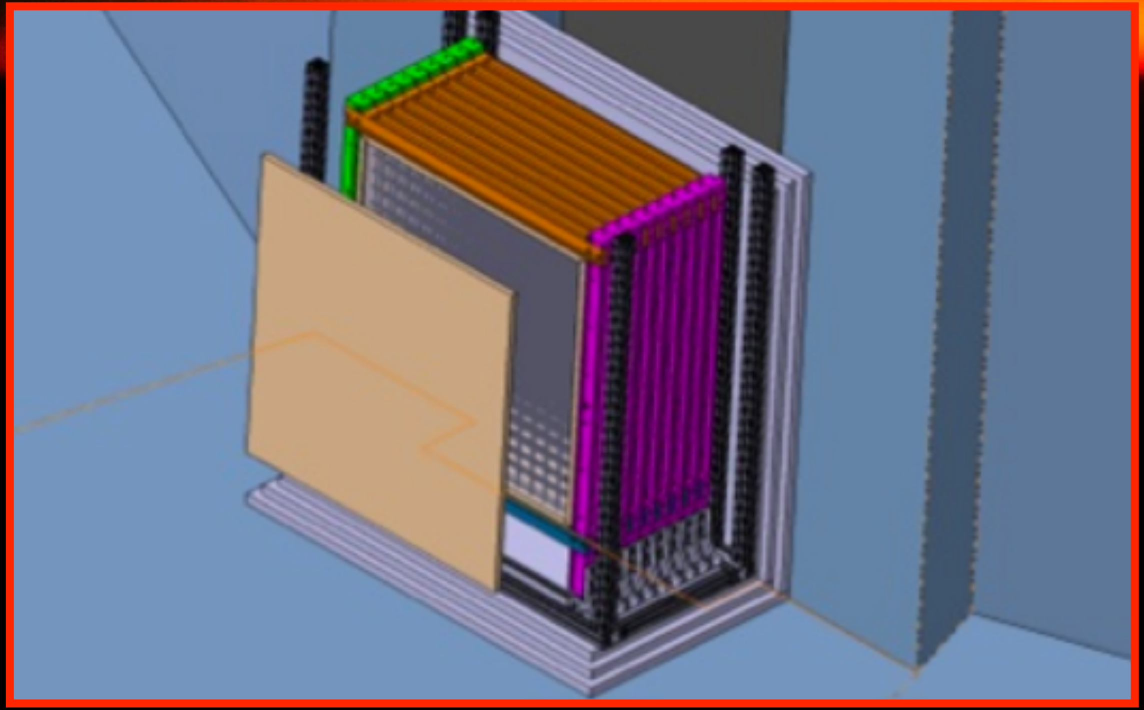
LARGE SINGLE-LANDs
(JUNO, SNO+, KamLAND, Borexino)



- near/far from reactor
- excellent energy
- low BGs

→try bypass δ(flux) input (not fully possible)

MIDDLE SIZED MULTI-LANDs (→θ13)
(Daya Bay, Double Chooz, RENO)



- very near reactor
- often bad-ish energy (typically worse, if segmented)
- high BGs→ distort spectrum observed)

→rely on δ(flux) input

→measure spectrum? not very clean

[many experiments in the past]

SMALL SINGLE MONOLITHICALLY/SEGMENTED LANDs
(SOLiδ, STEREO, PROSPECT, etc)

why identical detector...?

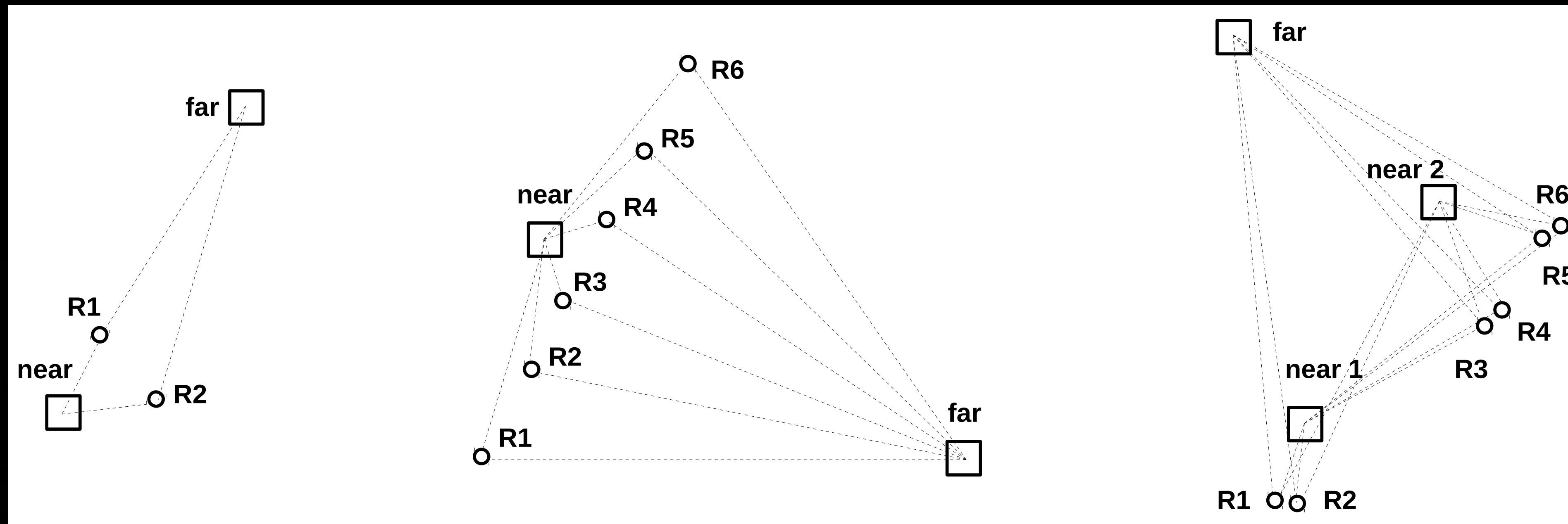
mainly cancellation of δ(detection) systematics

→ important for the control of energy spectrum shape
(full detector is used as calorimeter, else detector effects dominate)

[very expensive approach!!]

multi-reactor experiments (not only multi-detector)…

Double Chooz **RENO** **Day Bay**



JUNO
(10 reactors)

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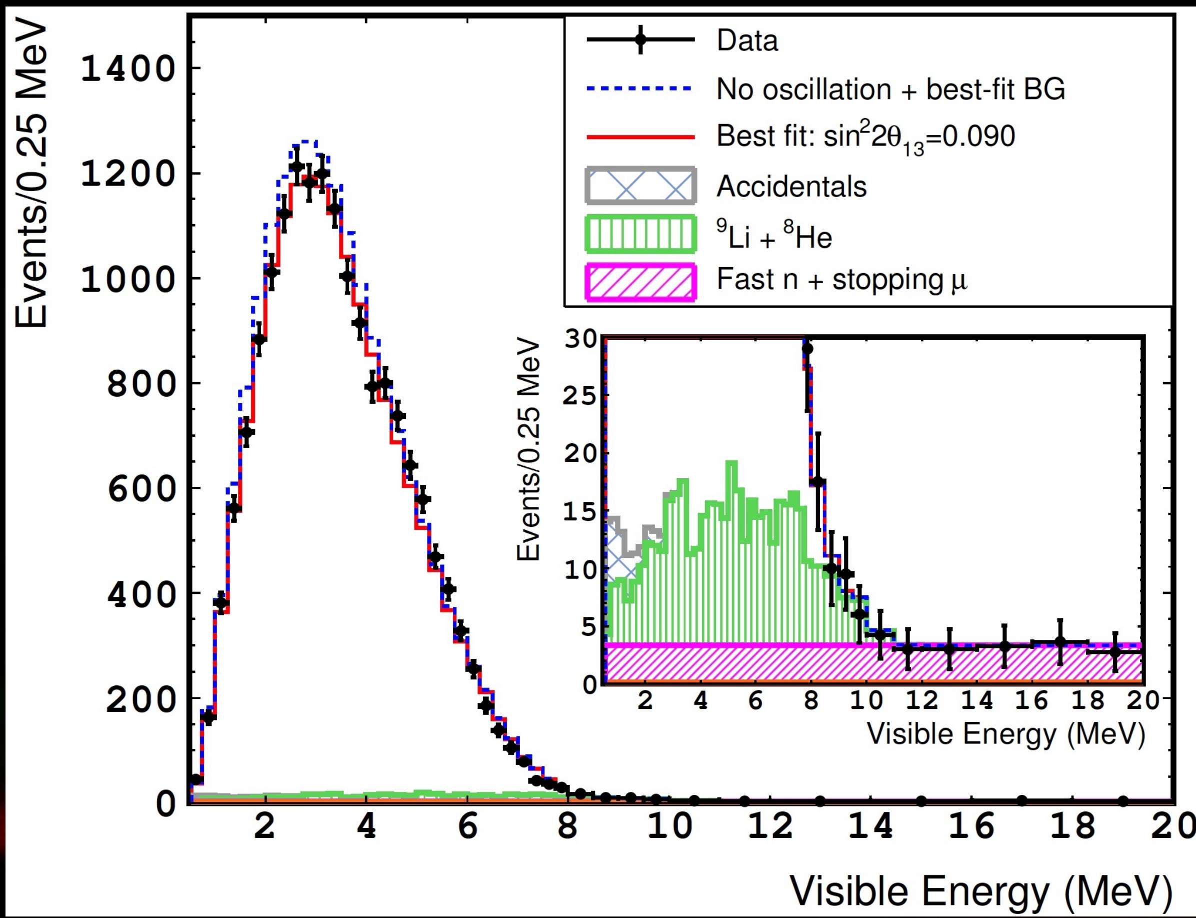
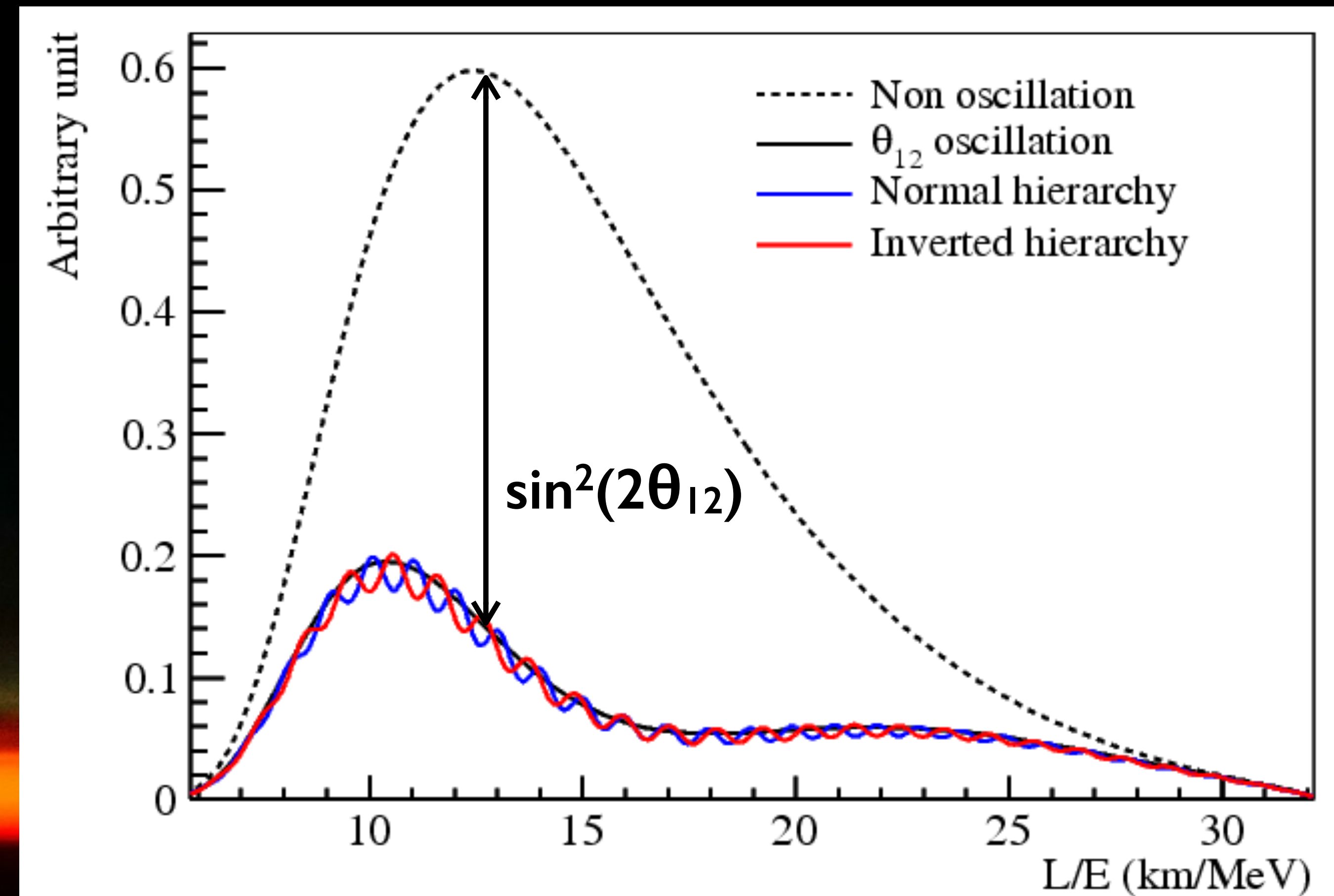
two famous single-LAND experiments…





Double Chooz

(FD only)

1σ[sin2(2θ13)]↔ δ(flux)

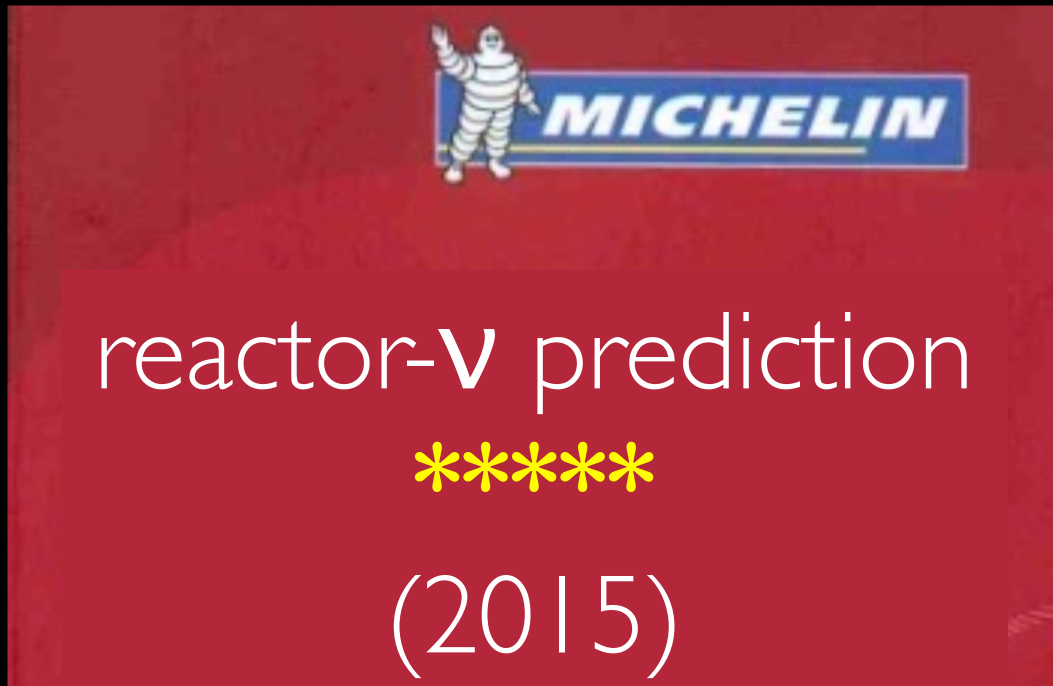
JUNO

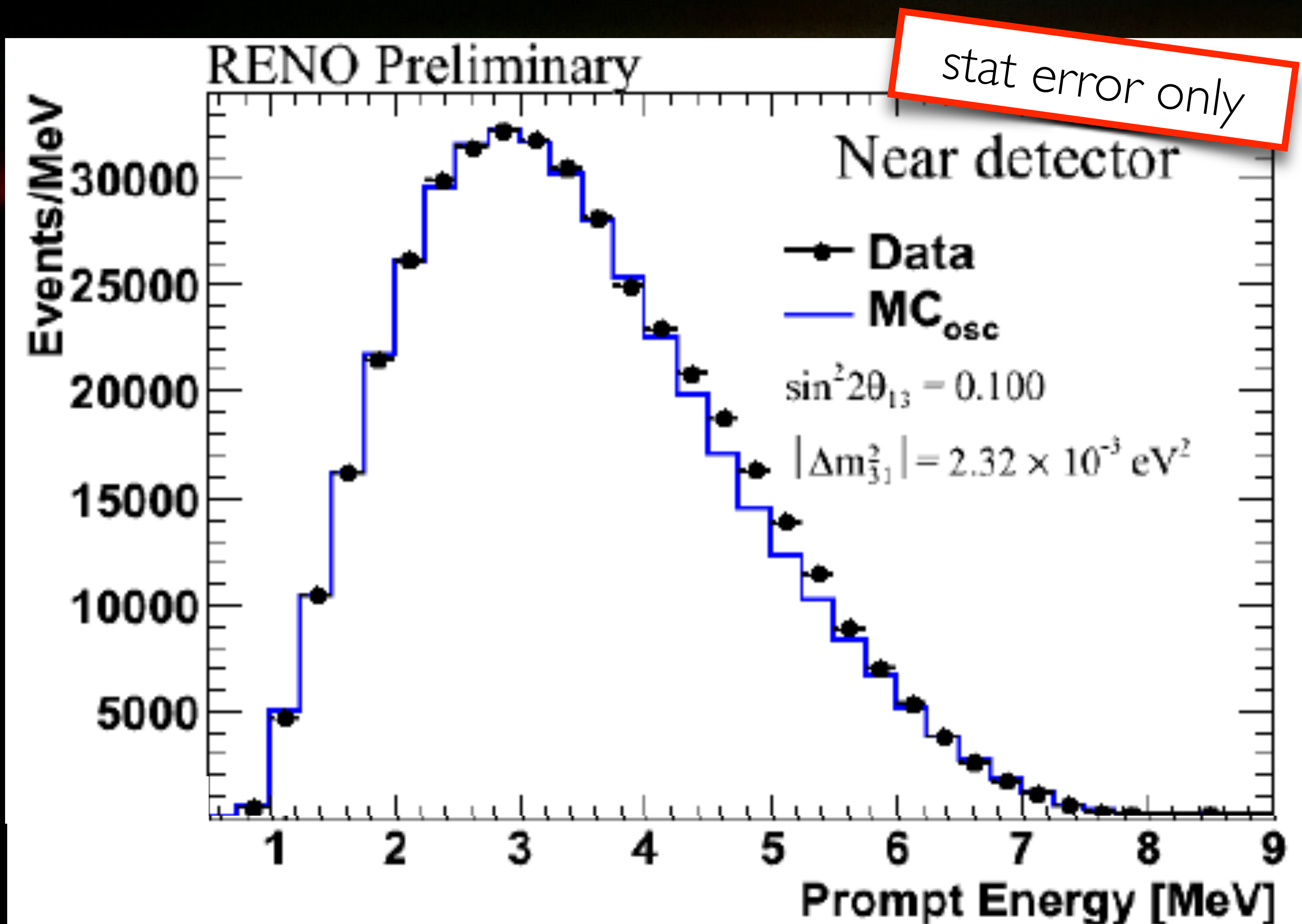
(one detector only)

fundamental physics (ν oscillations)→ strongly affected by δ(flux)

(ideal) improving δ(flux)…

reactor spectrum prediction/measurement…





S(E) prediction (hard/exquisite cooking)…

- $\delta(\text{flux})^{Norm}$ → normalisation error (dominant)
- $\delta(\text{flux})^{Shape}$ → shape error (fully understood?)

exclusive→ingredients [very hard physics!!]…

- each β-spectrum per isotope (data-bases)
  - →complete? and/or correct?
- ILL data (exclusive & incomplete)
  - →^{238}U data (missing low energy)
- nuclear physics (complete?)
- much more (not complete)

S(E) via anti-ν measurement (a big salad)…

- **inclusive** contribution (include unknown!)
- but specific configuration/time (extrapolate?)
- tune/validate prediction: high precision!

experimental errors…

- **δ(BG):** both normalisation & shape
- **δ(detection/efficiency):** normalisation
- **δ(energy):** both normalisation & shape

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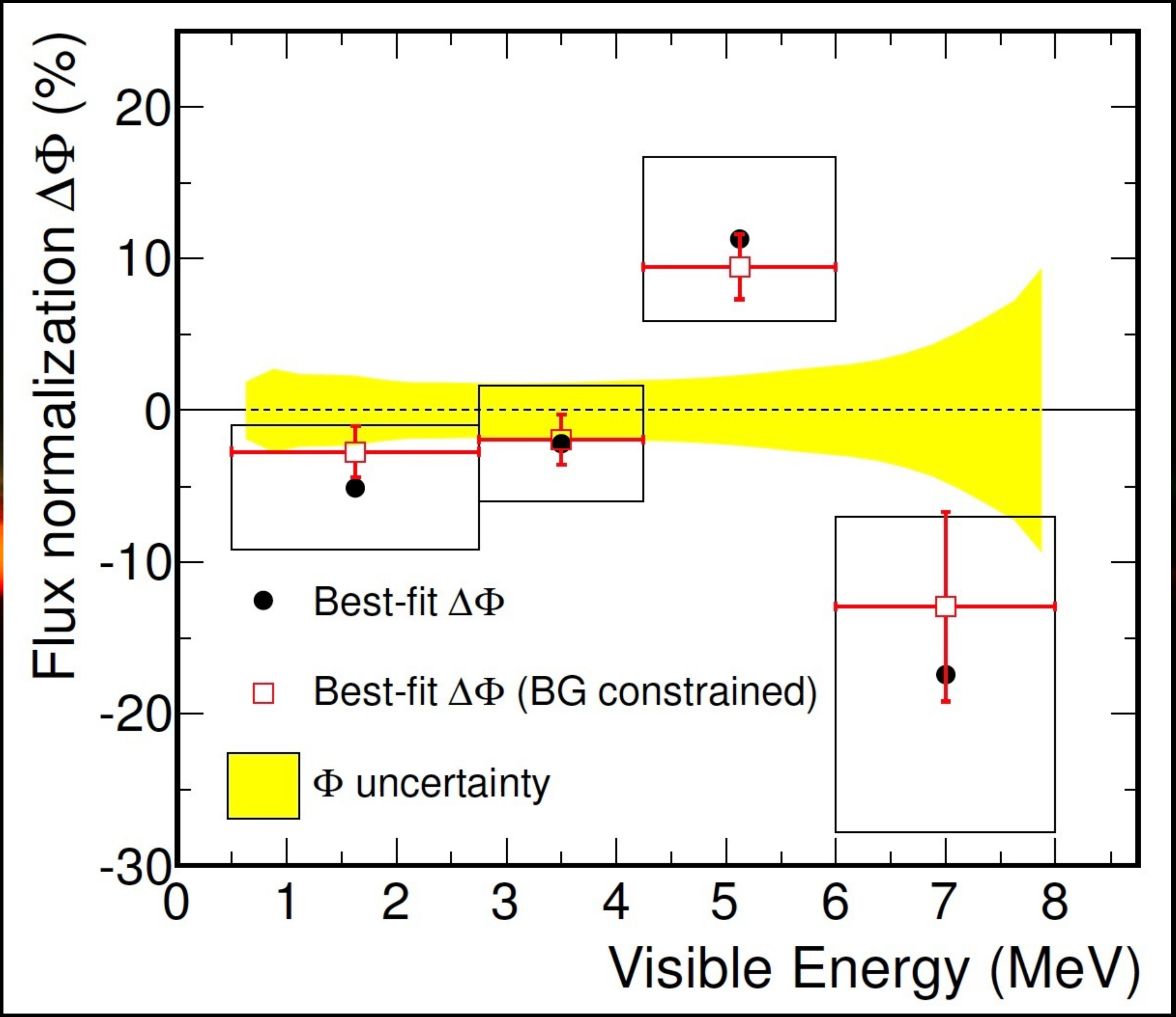
reactor flux normalisation error: $\delta(\text{flux})^{Norm}$…

DC assessing the reactor error consistency…

- limitation: **<20k IBDs** (DC-III FD data)
- our latest prediction…
  - include latest **^{238}U** data
  - **correct θ_{13} effect** (from DB latest)
  - all BG via data (no MC involved)
  - Bugey4 constraint→ **δ(flux): 1.7%**
- fold all our knowledge…
  - detection systematics
  - energy (extremely precise in the field)
    - →large energy bins (less stat scatter)
  - BG systematics (constrained or not)



•test for flux error consistency…

- some flux error tension (see plot)
  - absolute normalisation (not floating)
  - Bugey4 within normalisation
- tension in [4,6]MeV bin: ~3σ (indicative)

•what to conclude about δ(flux)?

$\Longrightarrow$ (with all current data) **is [1.7,3.0]% a representative 1σ error?**

reactor flux normalisation error: $\delta(\text{flux})^{Shape}$...

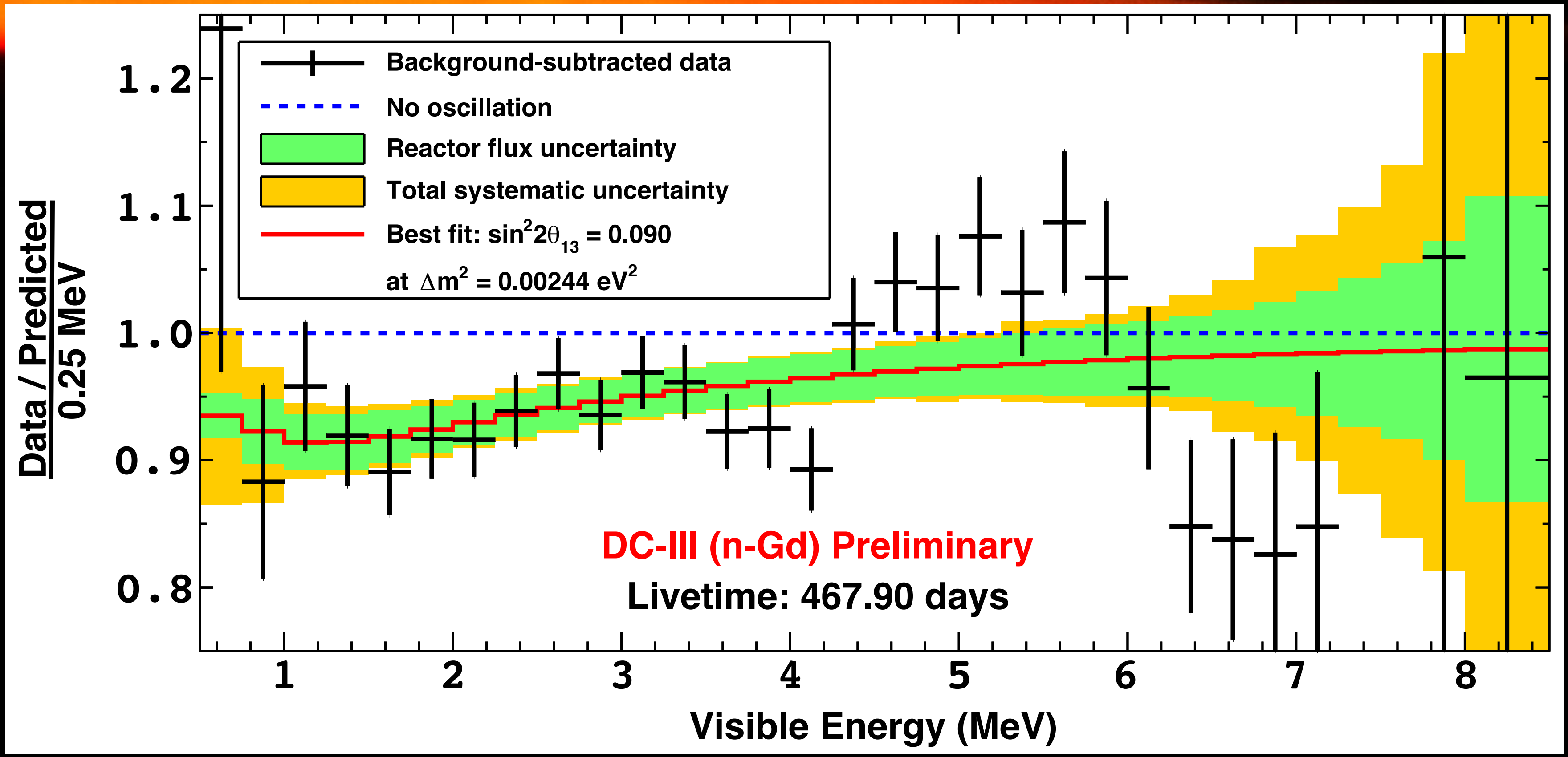
shape error effects...

- missing β-spectra?
- conversion strategy (summation vs conversion)
- incorrect β-spectra shapes (→ end-point)?
- missing forbidden contribution? (not in prediction)
- other nuclear physics?
- consistency of ILL data? (→ calibration to all predictions)
- other issues?

clearly there is a problem...

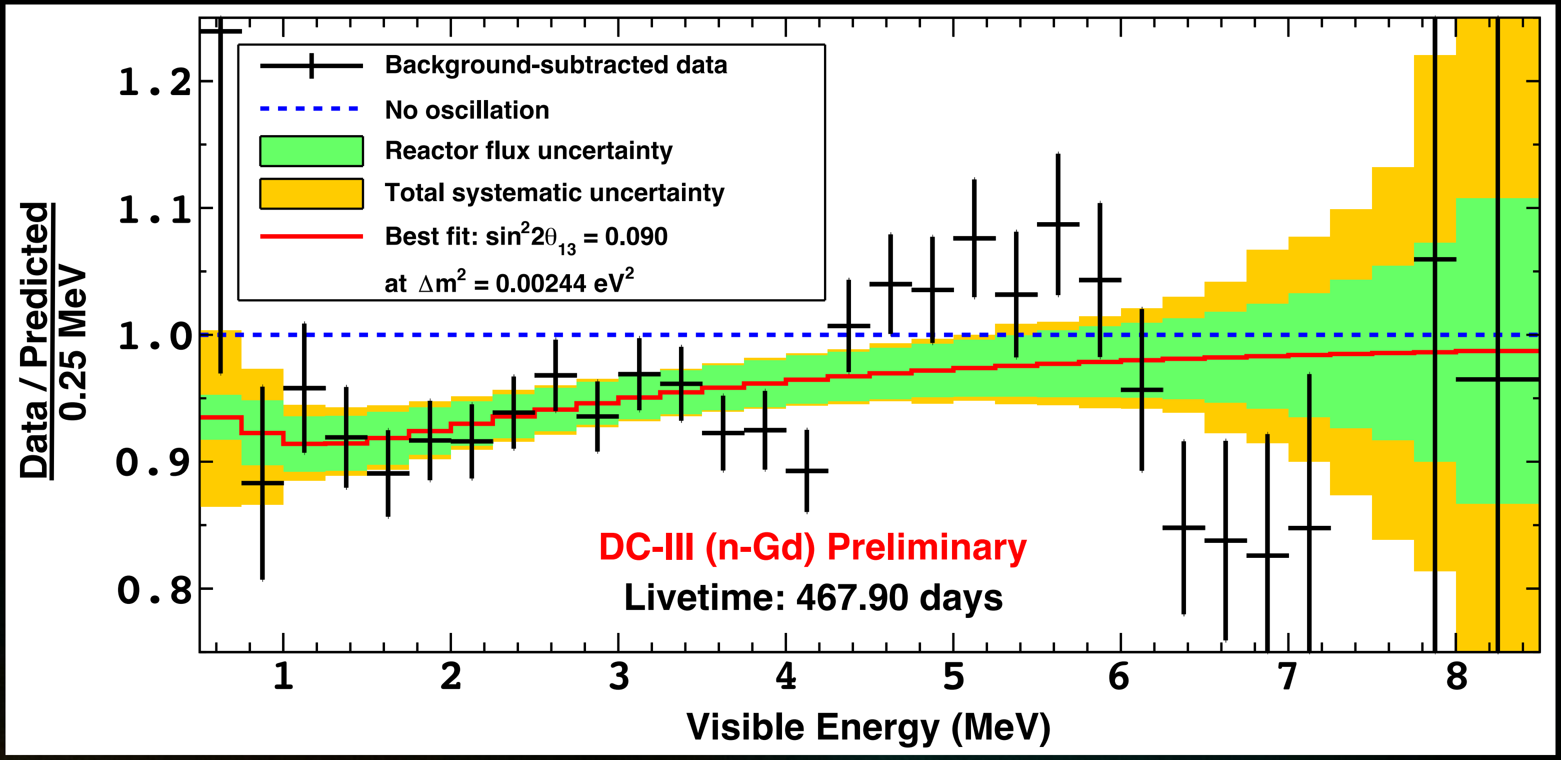
- (in the meantime) what error shall we quote?
- **the field needs a reference (hunting for sterile?/error-debugging?)**

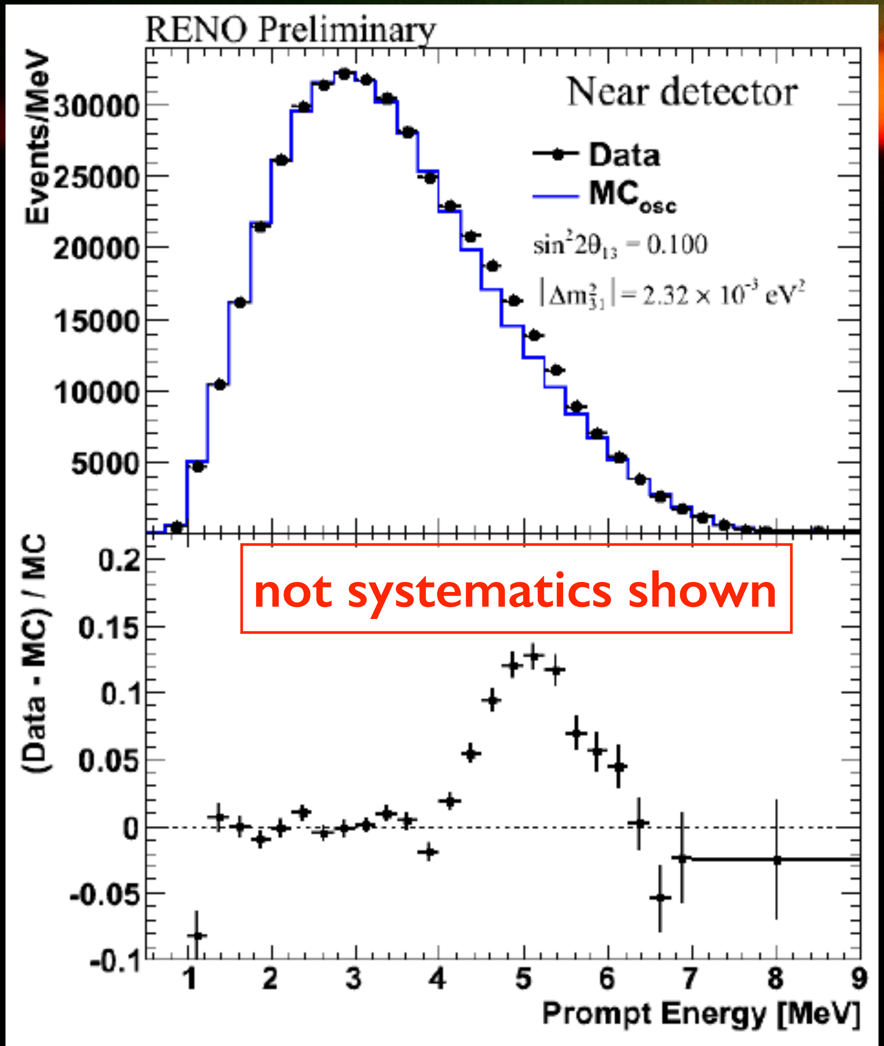
source	status
detection?	**discarded**
BG?	**discarded?** (OFF data & reactor power)
flux ⊕ σ^{IBD}?	**possible**
energy?	**disfavoured** (C-n & ^{12}B)
several?	**not impossible**



θ13 experiments input into reactor spectra…

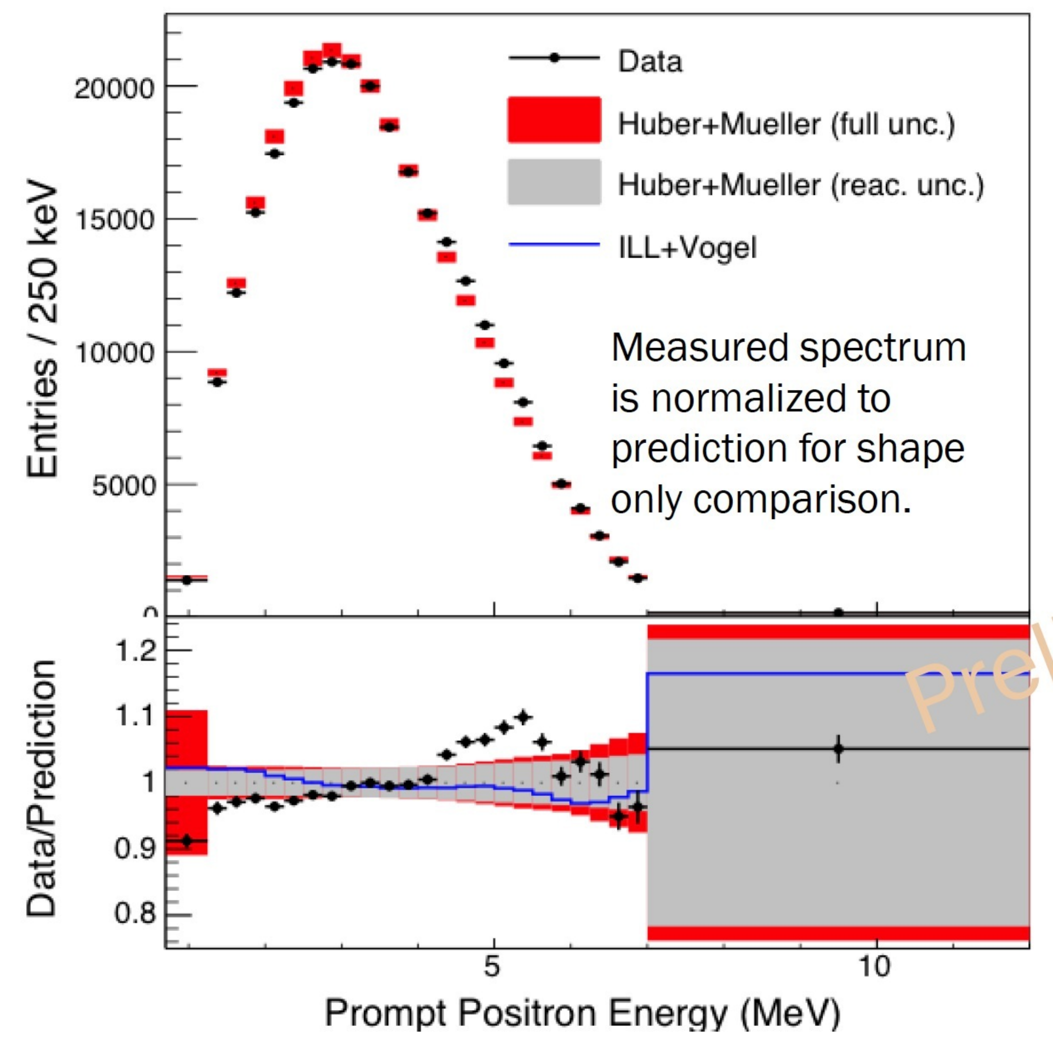
Double Chooz (May 2014)
~3.0σ (~17k events @ FD)





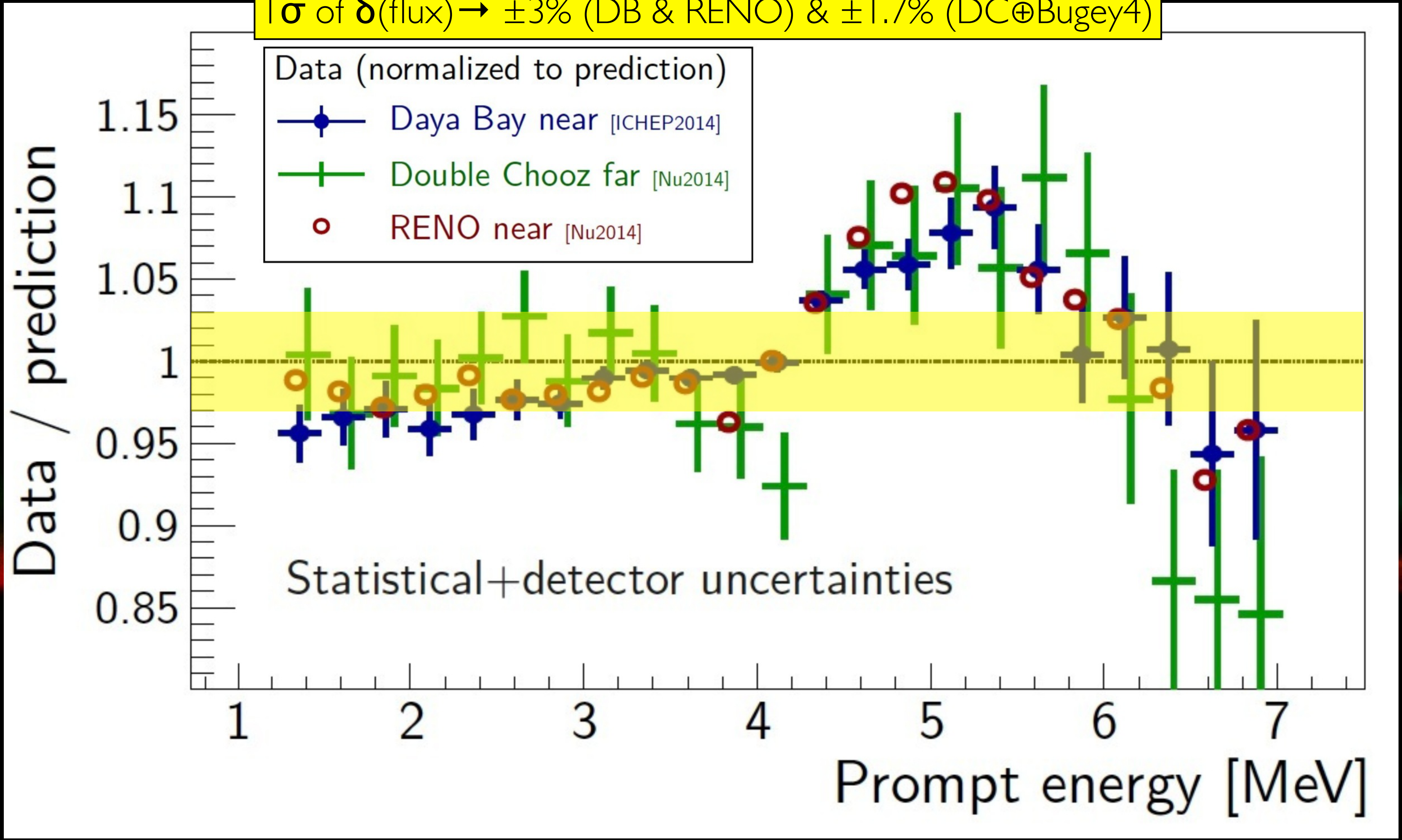
RENO (June 2014)
~3.6σ (~500k events @ ND)

Daya Bay (July 2014)
~4σ (~300k events @ 3xNDs)



(θ13 experiments) spectral distorsion [4,8]MeV…

1σ of δ(flux)→ ±3% (DB & RENO) & ±1.7% (DC⊕Bugey4)



3 different experiments→ pointing (almost) consistently to one effect

•shape & normalisation consequences (not just shape)

•**δ(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]

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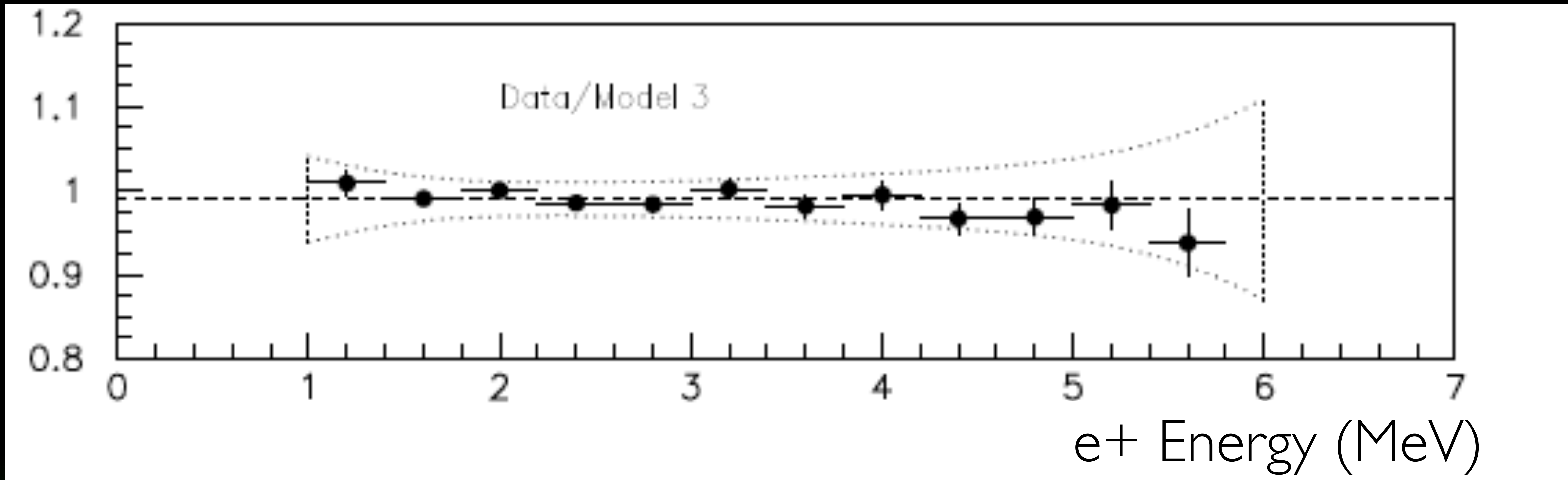
the Bugey3 issue…



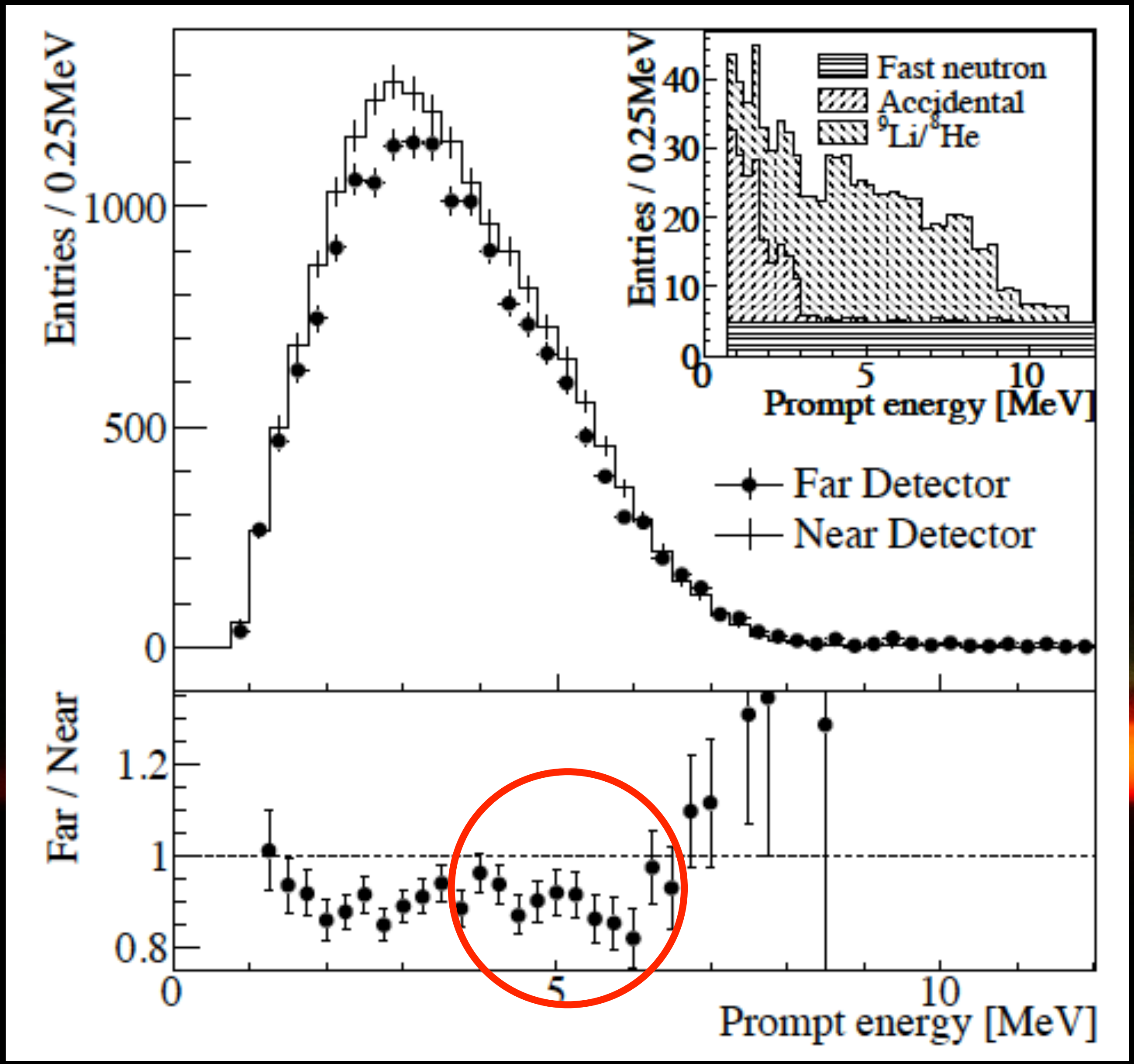
Bugey3 does not exhibit evidence of energy distorsion…

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

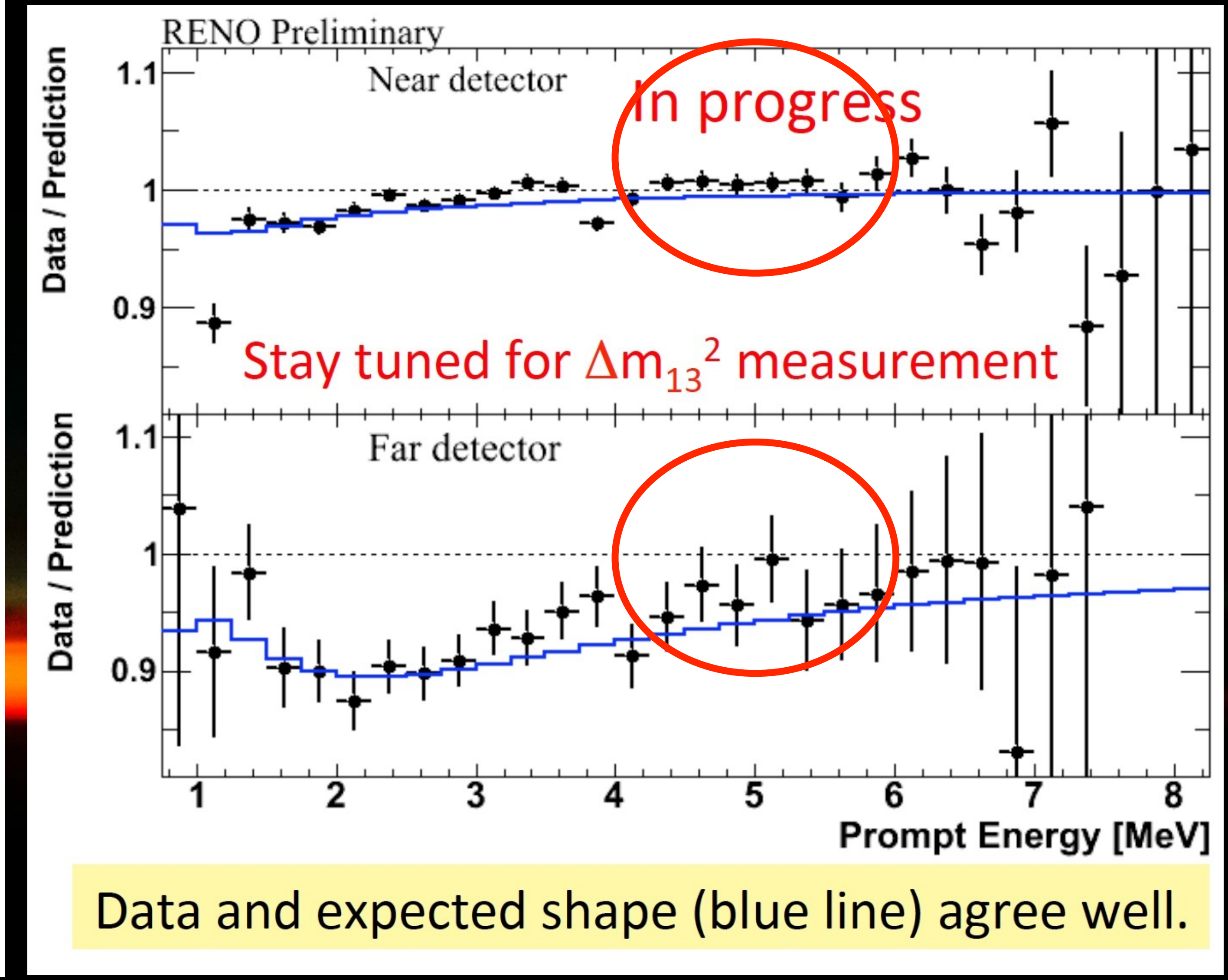
speculations…

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

the RENO issue…



(publication PRL 2012)



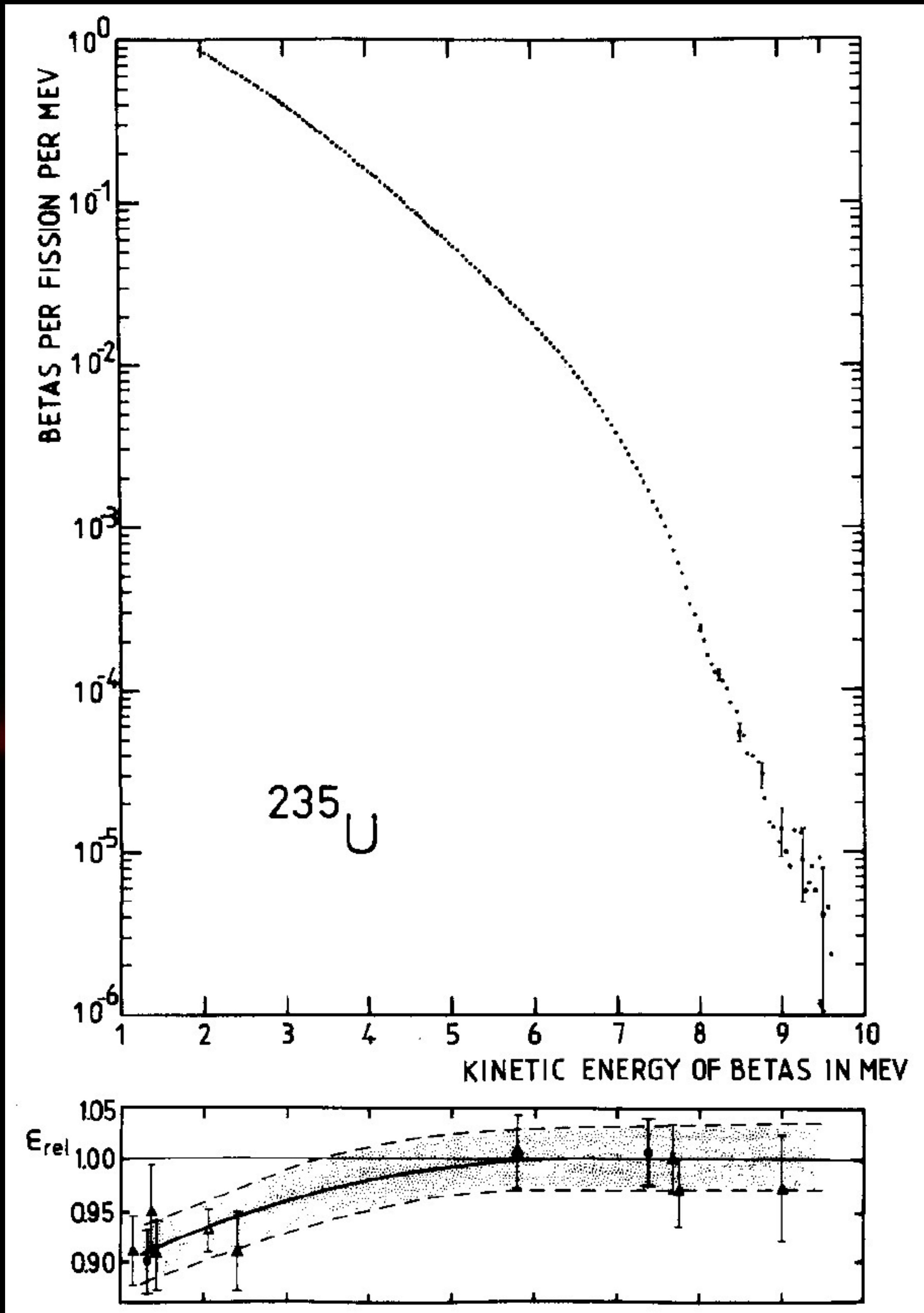
(no publication yet)

RENO: strange energy distorsion→ consistent across ND & FD?

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

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

the ILL efficiency calibration…



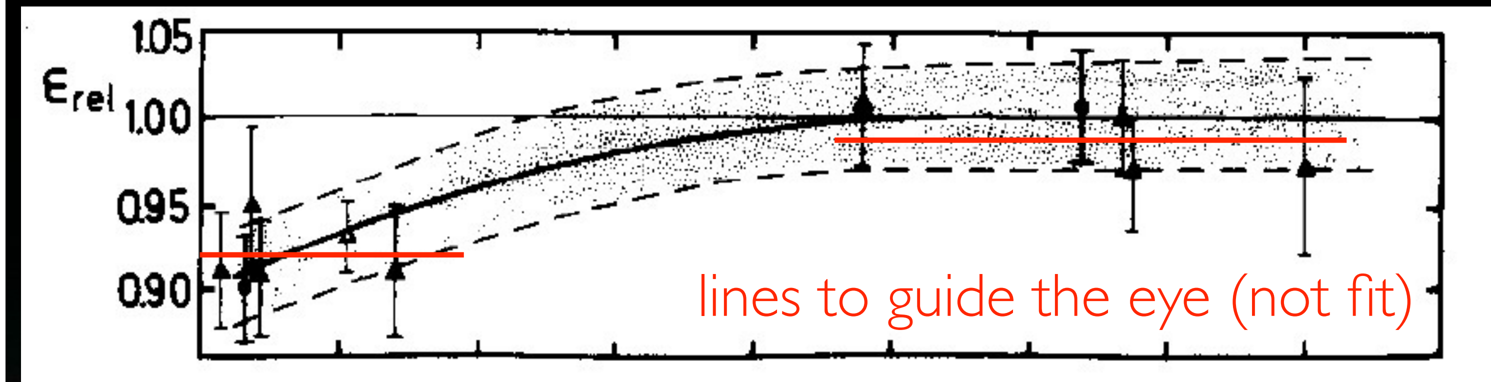


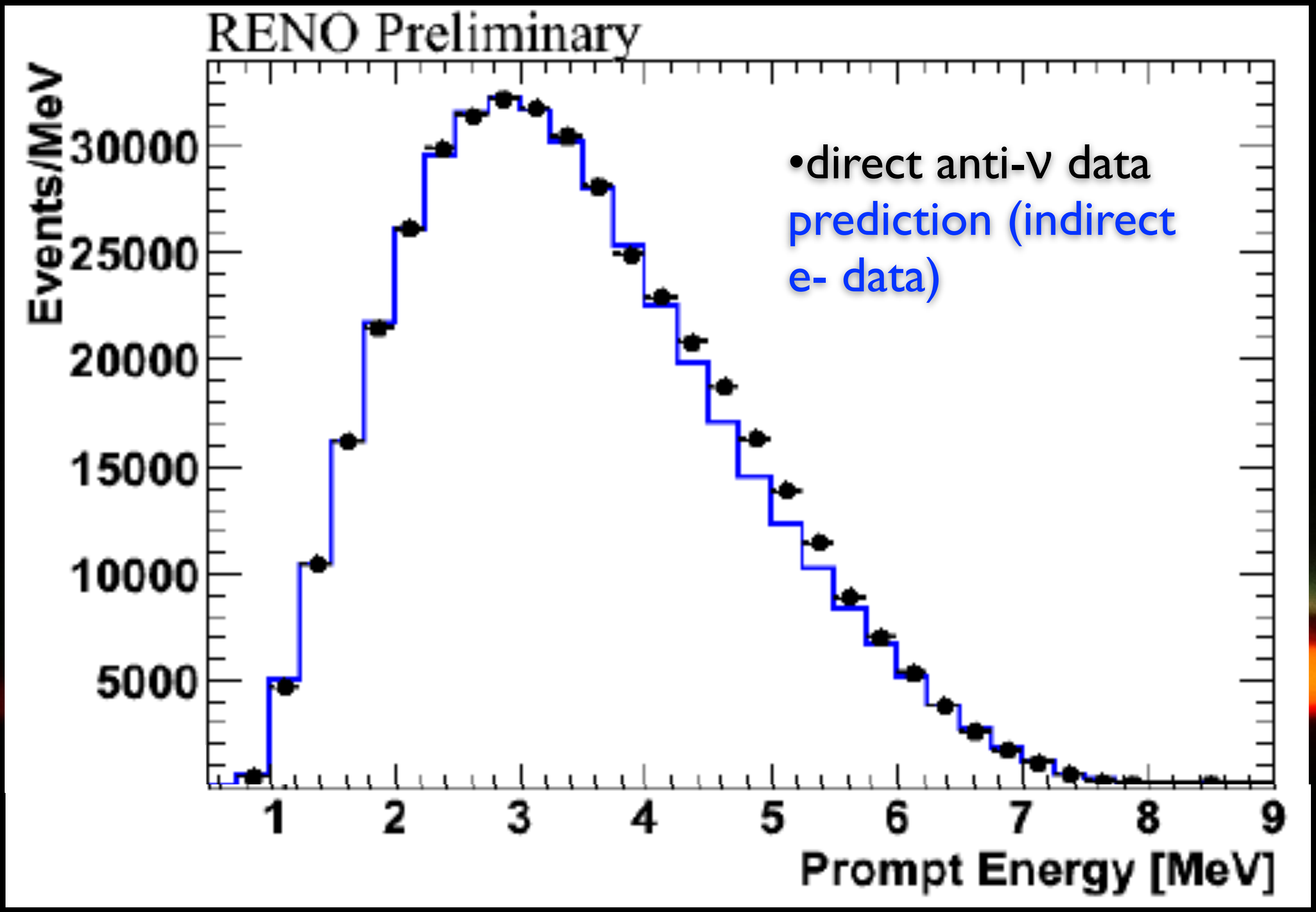
Fig. 1. Experimental beta spectrum of ^{235}U fission products. The error bars in the spectrum illustrate the statistical accuracy for bins of 50 keV (90% CL). In the lower part the determined efficiency curve $\epsilon(E_\beta)$ with the uncertainty range (shadowed area) is shown. The errors given for the absolute calibration points (dots) are independent values. For the relative calibration points (triangles) the errors are dominated by correlated uncertainties (see text). The unfilled triangle denotes the 2.1 MeV line in the ^{116m}In decay.

response curve: motivated by data points?

⟹ is this a problem (mismatch low-high energies)?

(I do not know myself→ experts feedback, please)

two ways towards the ν spectrum→ synergies



constructive interfere between the two?
(now we know more than before)

$S^{\nu}(E)$ prediction vis "reactor-cooking"...

- combination exclusive inputs
  - start from e- data (EM corrections)
  - (if no data) theoretical input
- risk of missing something (since exclusive)
  (in fact) we know it misses several things
- suffer from integral effect over imprecisions and inaccuracies→ wash out & biassed?

main features for reactor-ν physics...

- power prediction ≤10% (for sure)
- accommodate any situation (vary the inputs)

$S^{\nu}(E)$ measured vis "reactor-cooking"...

- high precision→ challenge predictions
- specific to a site/moment (not just reactor)
- hard (impossible?) to extrapolate elsewhere

what to do...?

- improve predictions with this unique data!!
  - what missing/wrong? (long standing issues)
  - **provide us with new δ(flux): urgent!**
- use ν data beyond specific sites ever?

key issues (to me)…

- **reactor→ high precision & for-free ν sources**…
  - critical tool for high precision fundamental physics
    - **δ(flux) is reliable** (accuracy→a must) **& small** (precision→ as much as reasonable)
    - reactor-experts critical input to provide ν-experts with your best δ(flux) (even if large)
      - δ(flux) should have some degree of field consensus & (best if) a priori
    - commercial reactors science: non-trivial expertise among ν-experts ("black box" approach)
      - we need you!!!
  - note: ν-beams → δ(flux) is large (even up to ~20% in some cases)!

- **if δ(flux)=~3% is not consistent with observed spread**…
  - can we at least rule out 3% with some confidence?
  - what's the reasonable 1σ (68%CL) conservative value in the mean time?
  - what do you need to improve error (reliability & magnitude)? [→field coherence]
    - excellent funding scenario (thanks to observations by θ13 experiments)

(else) suppression of **δ**(flux)…

reference…

Reactor Neutrino Flux Uncertainty Suppression on Multiple Detector Experiments

A. S. Cucoanes[2*], P. Novella,[1] A. Cabrera[1†], M. Fallot,[2] A. Onillon,[2] M. Obolensky,[1] and F. Yermia[2]

[1] *APC, Astro-Particule et Cosmologie, CNRS/IN2P3, Université Paris Diderot, 75205 Paris Cedex 13, France*

[2] *SUBATECH, CNRS/IN2P3, Université de Nantes, Ecole des Mines de Nantes, F-44307 Nantes, France*

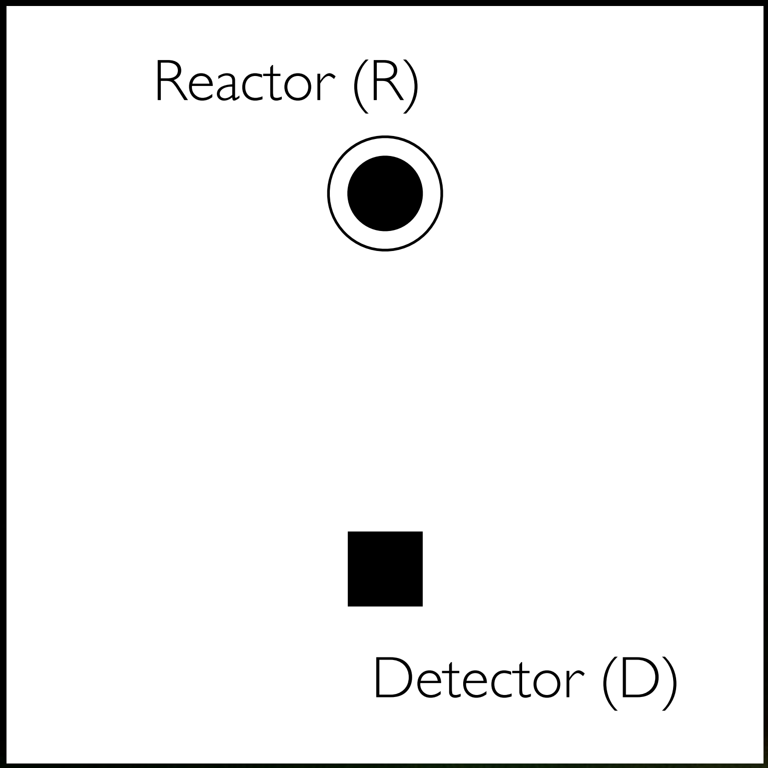
(Dated: January 16, 2015)

This publication provides a coherent treatment for the reactor neutrino flux uncertainties suppression, specially focussed on the latest θ_{13} measurement. The treatment starts with single detector in single reactor site, most relevant for all reactor experiments beyond θ_{13}. We demonstrate there is no trivial error cancellation, thus the flux systematic error can remain dominant even after the adoption of multi-detector configurations. However, three mechanisms for flux error suppression have been identified and calculated in the context of Double Chooz, Daya Bay and RENO sites. Our analysis computes the error *suppression fraction* using simplified scenarios to maximise relative comparison among experiments. We have validated the only mechanism exploited so far by experiments to improve the precision of the published θ_{13}. The other two newly identified mechanisms could lead to total error flux cancellation under specific conditions and are expected to have major implications on the global θ_{13} knowledge today. First, Double Chooz, in its final configuration, is the only experiment benefiting from a negligible reactor flux error due to a $\sim$90% geometrical suppression. Second, Daya Bay and RENO could benefit from their partial geometrical cancellation, yielding a potential $\sim$50% error suppression, thus significantly improving the global θ_{13} precision today. And third, we illustrate the rationale behind further error suppression upon the exploitation of the inter-reactor error correlations, so far neglected. So, our publication is a key step forward in the context of high precision neutrino reactor experiments providing insight on the suppression of their intrinsic flux error uncertainty, thus affecting past and current experimental results, as well as the design of future experiments.

arXiv:1501.00356v1 [hep-ex] 2 Jan 2015

beware: in discussion with DB (a few modifications maybe)

the "zero-th" case & suppression logic…



consider simplest scenario: 1R and 1D…

δ(flux for 1R with 1D) **= δ$_o$**

where **δo** is the key **δ**(flux) prediction error ~[1,7,3.0]% (per reactor)

if experiment with 1R and 1D, **δ**(flux) can only improve via a priori estimation by reactor-experts
→ critical dialogue by measurements from **ν**-experts to reactor-experts

what if we have many detector (N_D) and many reactors (N_R)…?

- **S(E)-predicted:** error **δ**(flux) [many R's→ superposition!]
- **S(E)-measured:** folded contribution (each R modulated $1/L^2$)

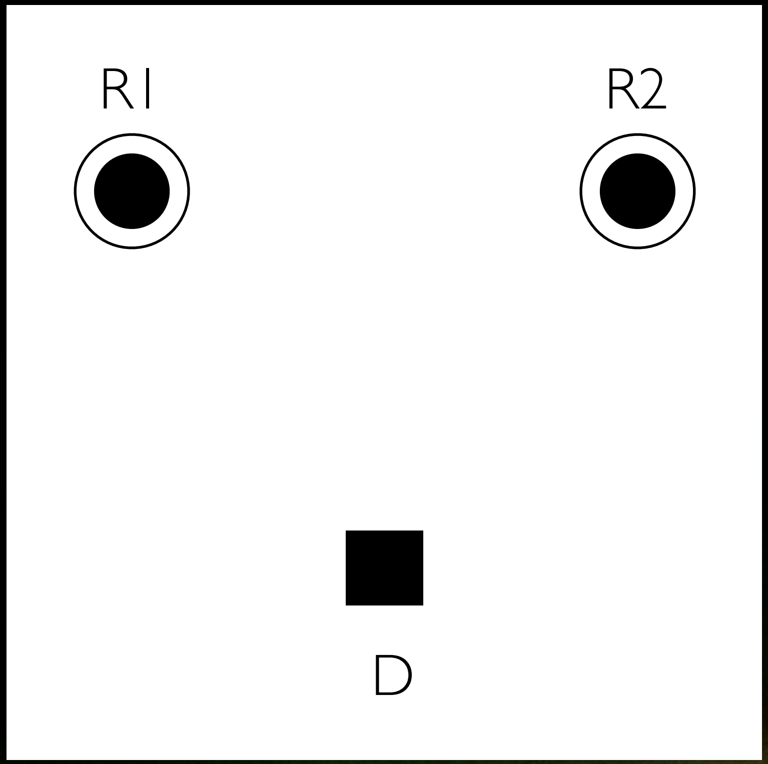
multiple sampling⟹ reduce δ(flux)

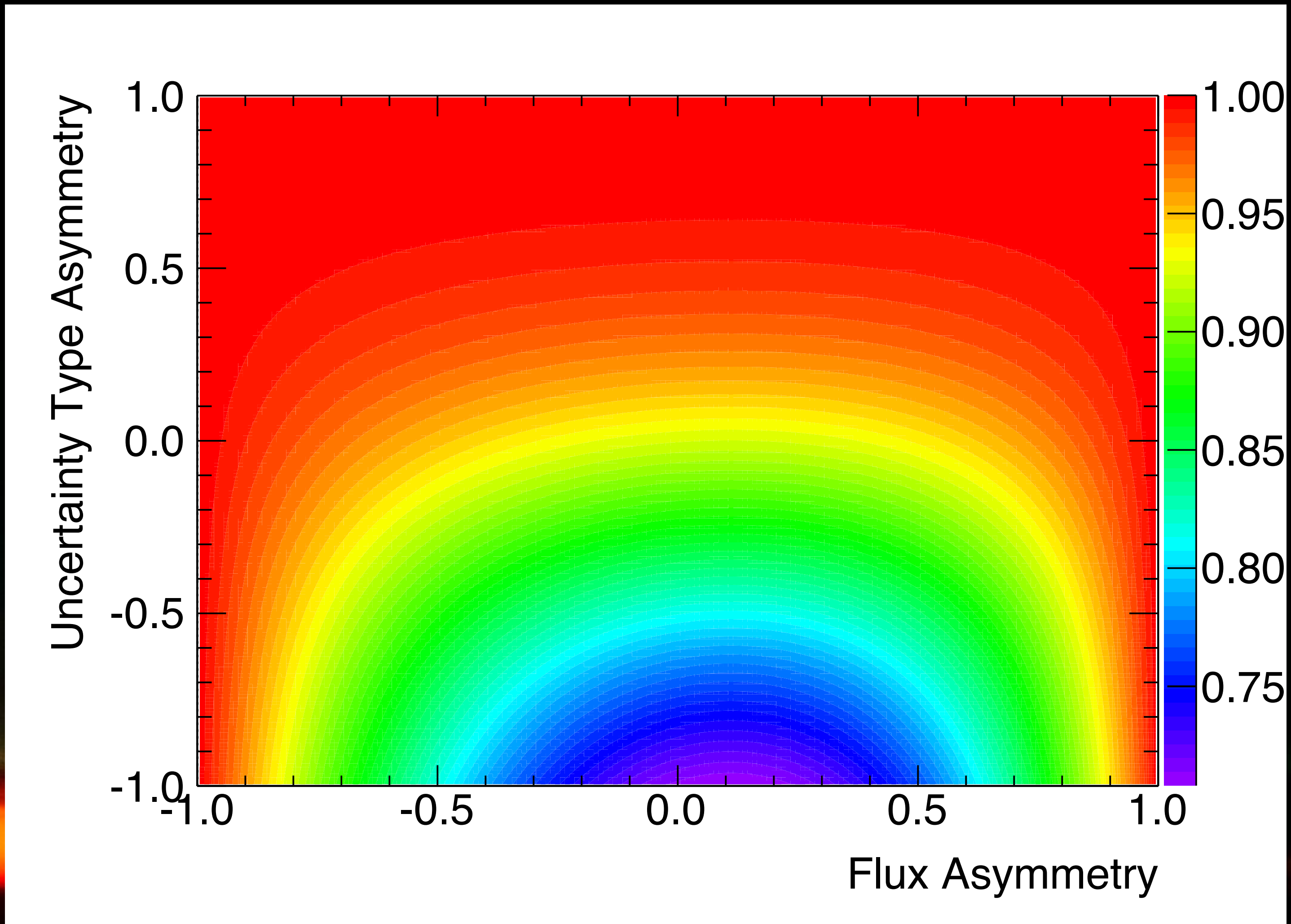
δ(flux effective) **= δ$_o$ x SF(…)**

SF: suppression factor

(even if **δ$_o$** not improved)

suppression case D=1 & R>1 (i.e. 2…N_R)…





$\delta^2 = \delta^2_c + \delta^2_u$ (orthogonal relation)

(correlation across reactors)

one can define two asymmetry terms…

$$A_\Phi = (\Phi_1 - \Phi_2) / (\Phi_1 + \Phi_2) \rightarrow \text{which reactor}$$

$$A_\delta = (\delta_c - \delta_u) / (\delta_c + \delta_u) \rightarrow \text{fraction of error type}$$

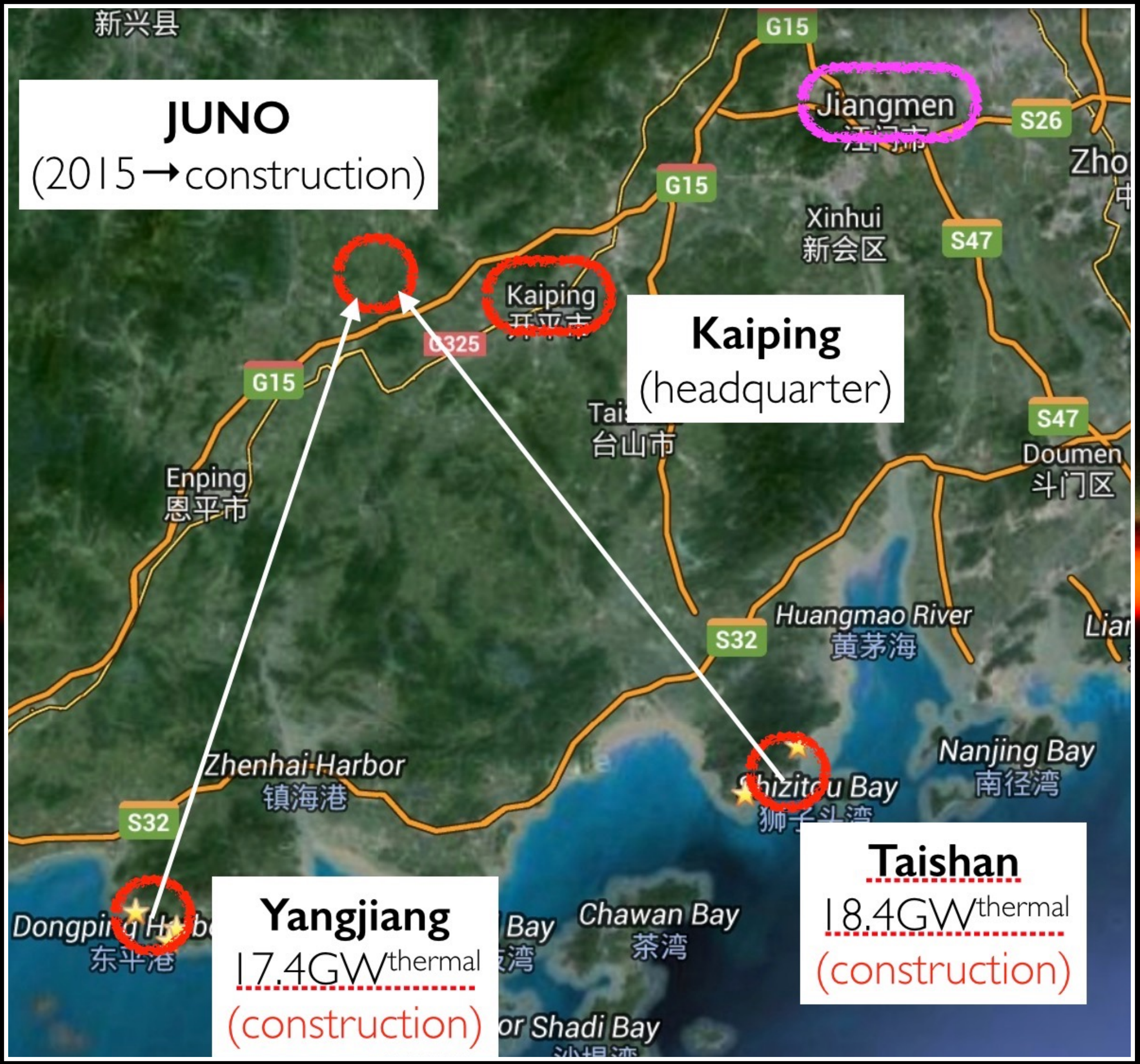
outcome…

A$\delta \rightarrow$+1.0 (i.e. δ(flux) is fully correlated across R1 and R2)$\Longrightarrow$ is like D sees only one R*

A$\delta \rightarrow$-1.0 (i.e. δ(flux) is fully uncorrelated across R1 and R2)$\Longrightarrow$ suppression $1/\sqrt{2}$ (~0.7)

multi-reactor sites…

JUNO (10 reactors)



- let's **pretend all reactor are identical** as far as error handling goes
  → likely not correct (to be studied)

- if **totally uncorrelated** $\Longrightarrow$ **$1/\sqrt{10}$ suppression**
  → unlikely!

- nonetheless, **some error reduction expected** upon exploiting inter-reactor error correlation (we do not know exactly how to do this)

single detector site→error assumed correlated

(no suppression; i.e. conservative)

no consensus about inter-reactor error correlation

multi-detector remaining error (per reactor)...

Source	Uncertainty (%)
Bugey4 measurement	1.4
Fractional fission rate of each isotope	0.8
Thermal power	0.5
IBD cross-section	0.2
Mean energy released per fission	0.2
Distance to reactor core	< 0.1
Total	1.7

~3.0% (DB)
~2.0% (RENO)

inter-detector correlated δ(flux) component→ cancel out (multi-detector)

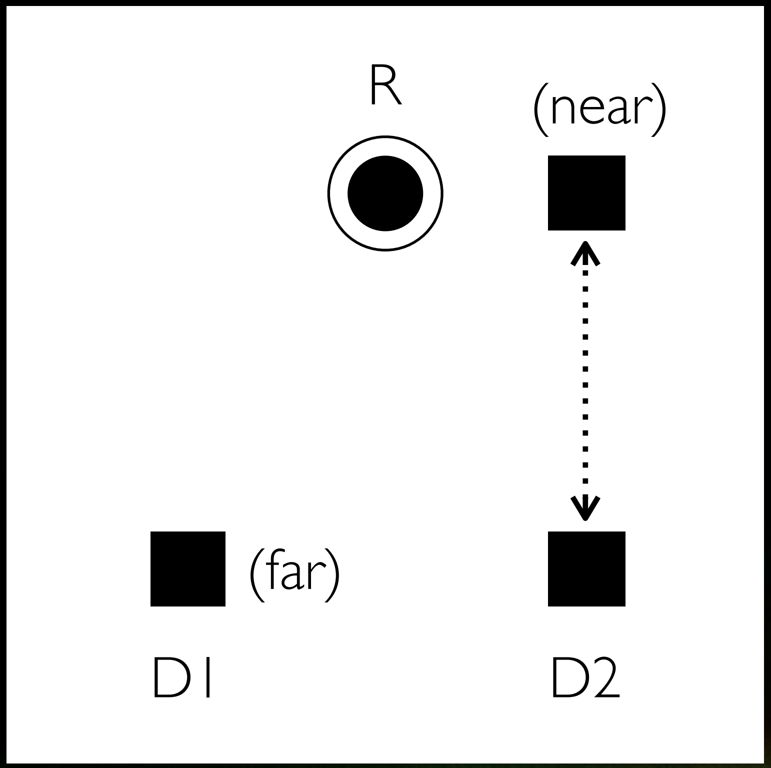
but **a priori δ(flux)≠0** systematic error

	P_{th} (%)	α_f (%)	Spent Fuel (%)	Total (%)
Double Chooz	0.5	0.9	included	1.0
Daya Bay	0.5	0.6	0.3	0.8
RENO	0.5	0.7	unknown	0.9

reactor instrumentation driven

reactor MC driven

suppression case D=[2...N$_D$] & R=1...



$\delta^2 = \delta^2_c + \delta^2_u$ (orthogonal relation)

(correlation across detector)

if observable can be defined via **ratio of $S(E)^{D1}/S(E)^{D2}$→ cancellation!**

δ_c cancels across detectors ⟹ $\delta = \delta_u$

multi-detector suppression (→ very expensive)

(only one source R) both detectors will "see" the same contribution by both reactor

- regardless of correlated (or not)
- variations are the same for both detector

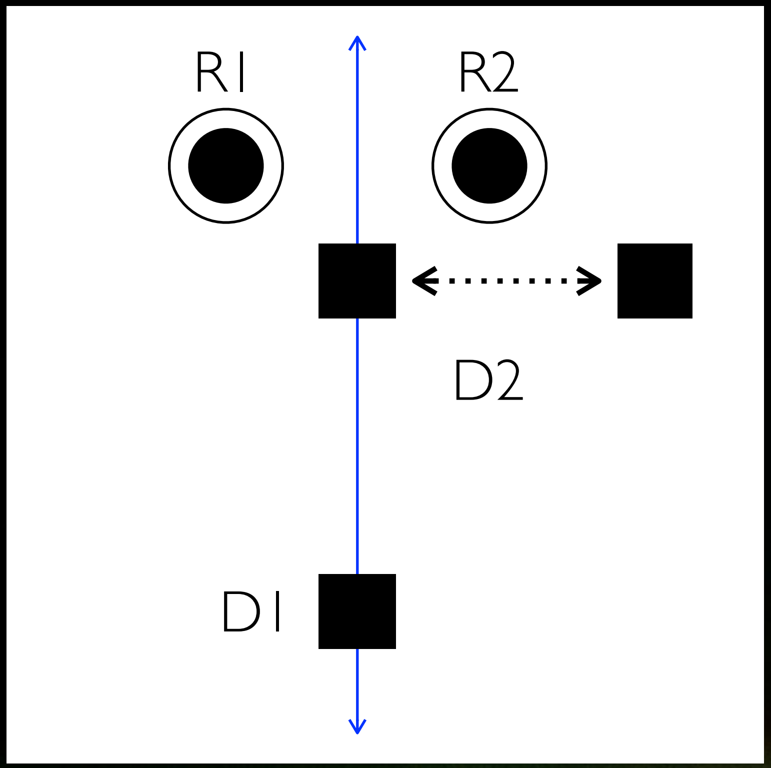
$\delta = 0$

this implies that **D1 and D2 are relatively perfect monitors one another**, by construction

(ideal configuration→ true for any isotropic source)

but one reactor alone→ enough statistics? (when detectors km's away)

suppression case D=2 & R=2…



many reactor (more ν's) and **many detector** (cancel systematics)

⟹ more complex configurations!

- careful geometry of sites has to be considered
- symmetries might help us (again)!

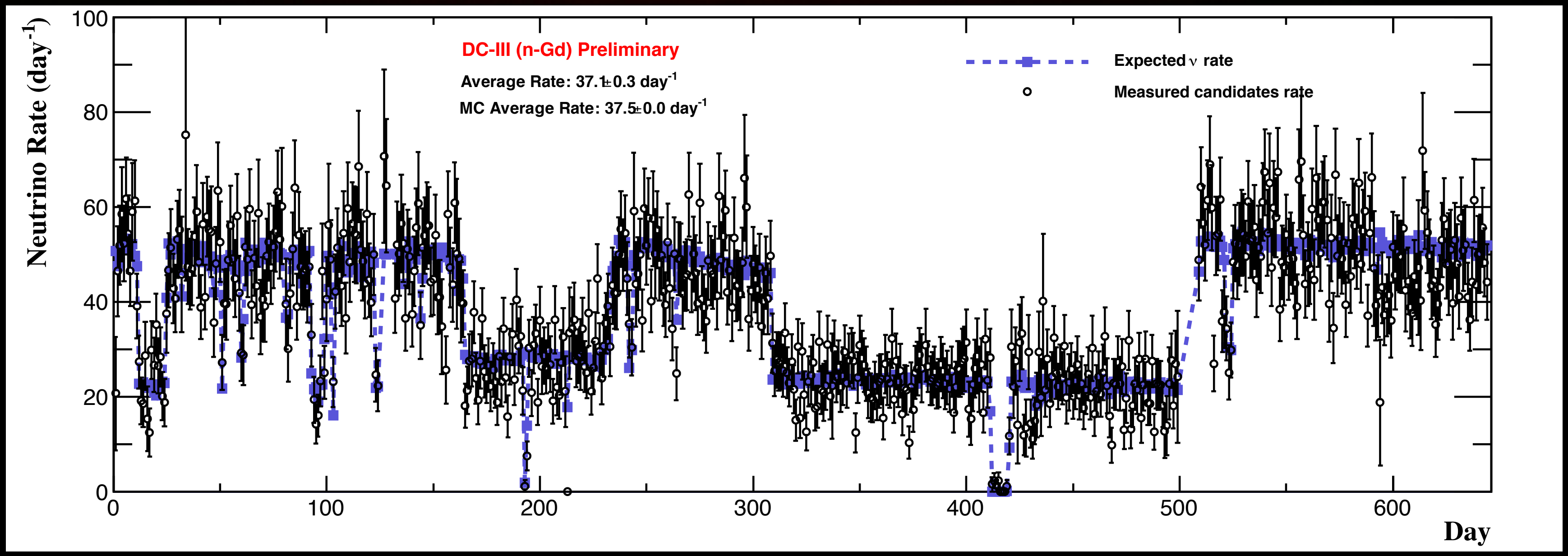
if detector **along iso-flux symmetry** line…

⟹ (acceptance symmetry across detector) **δ→ 0!!! [total iso-flux]**

if detectors **NOT along iso-flux symmetry** line…

⟹ (acceptance asymmetry across detector) **δ≤δo [partially iso-flux]**

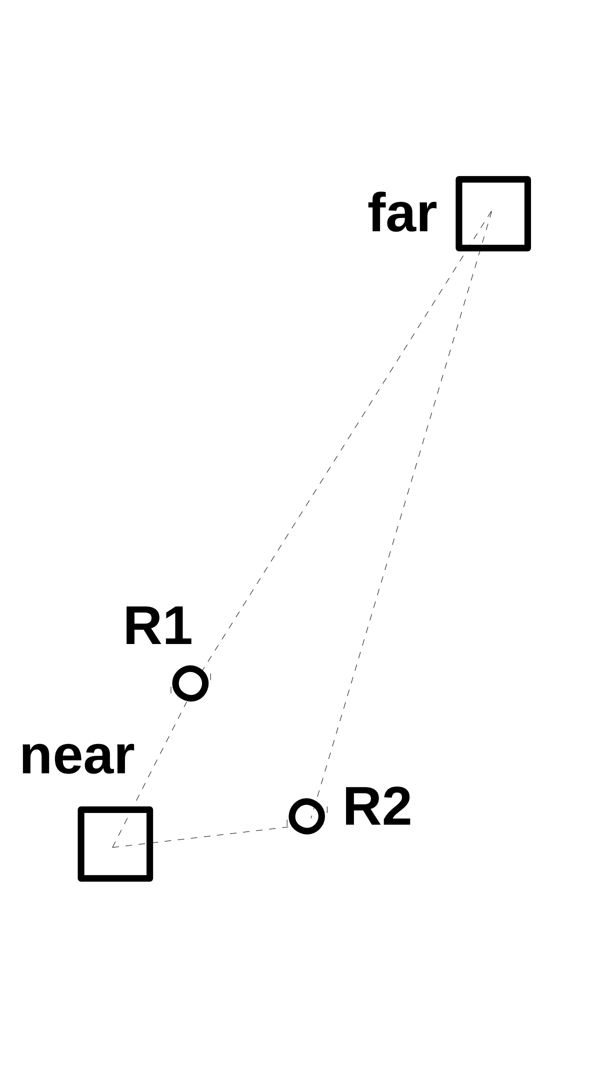
iso-flux does not care whether errors are correlated (or not)



all θ13 conceived to maximise iso-flux-ness (→ "perfect" ND monitoring), but succeeded

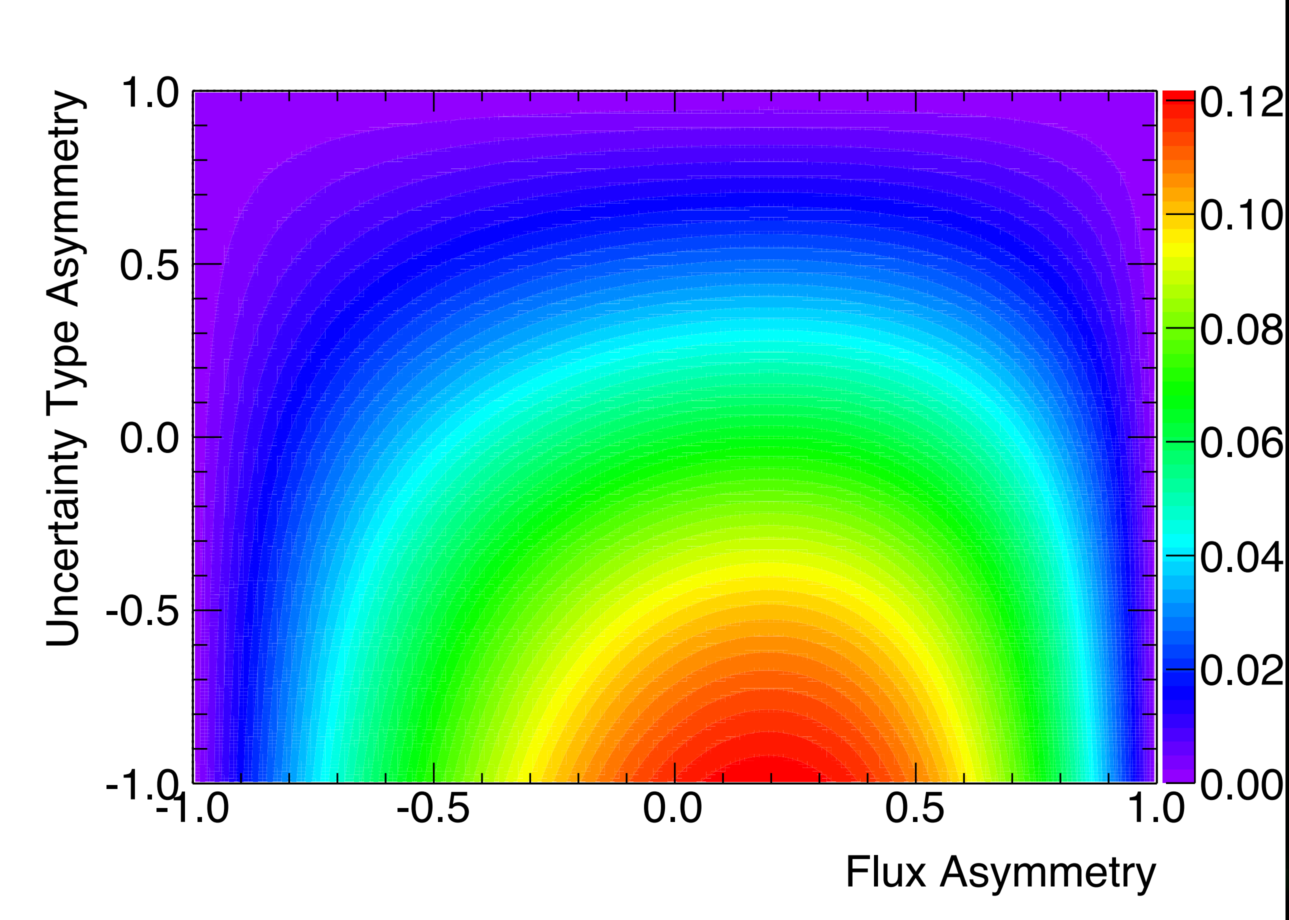
suppression case D=2 & R=2…

DC slightly off-axis (acceptance asymmetry)

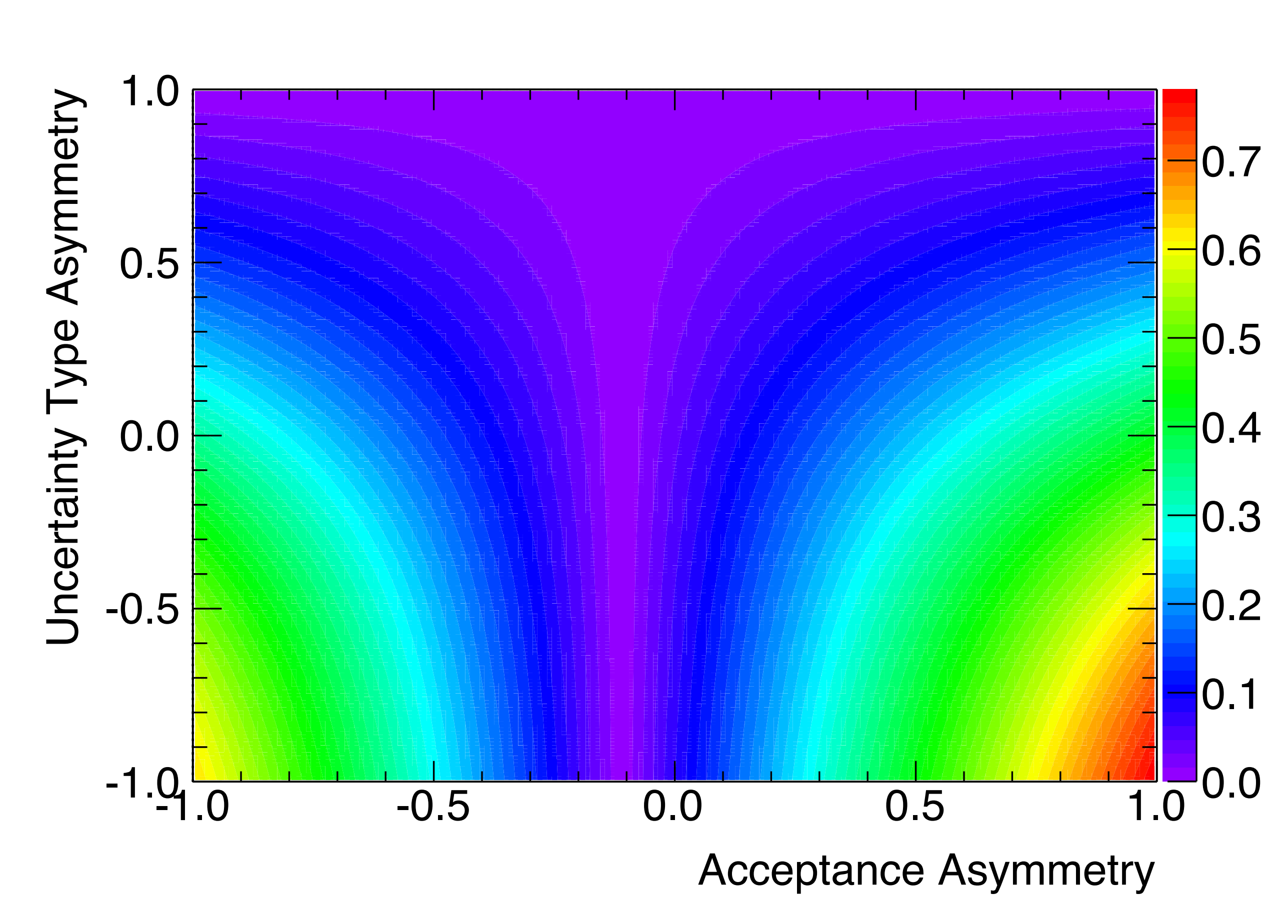


error type
vs
R1-R2 asymmetry

(opposite to 1D config)



error type
vs
acceptance asymmetry



multi-detector site→error assumed uncorrelated

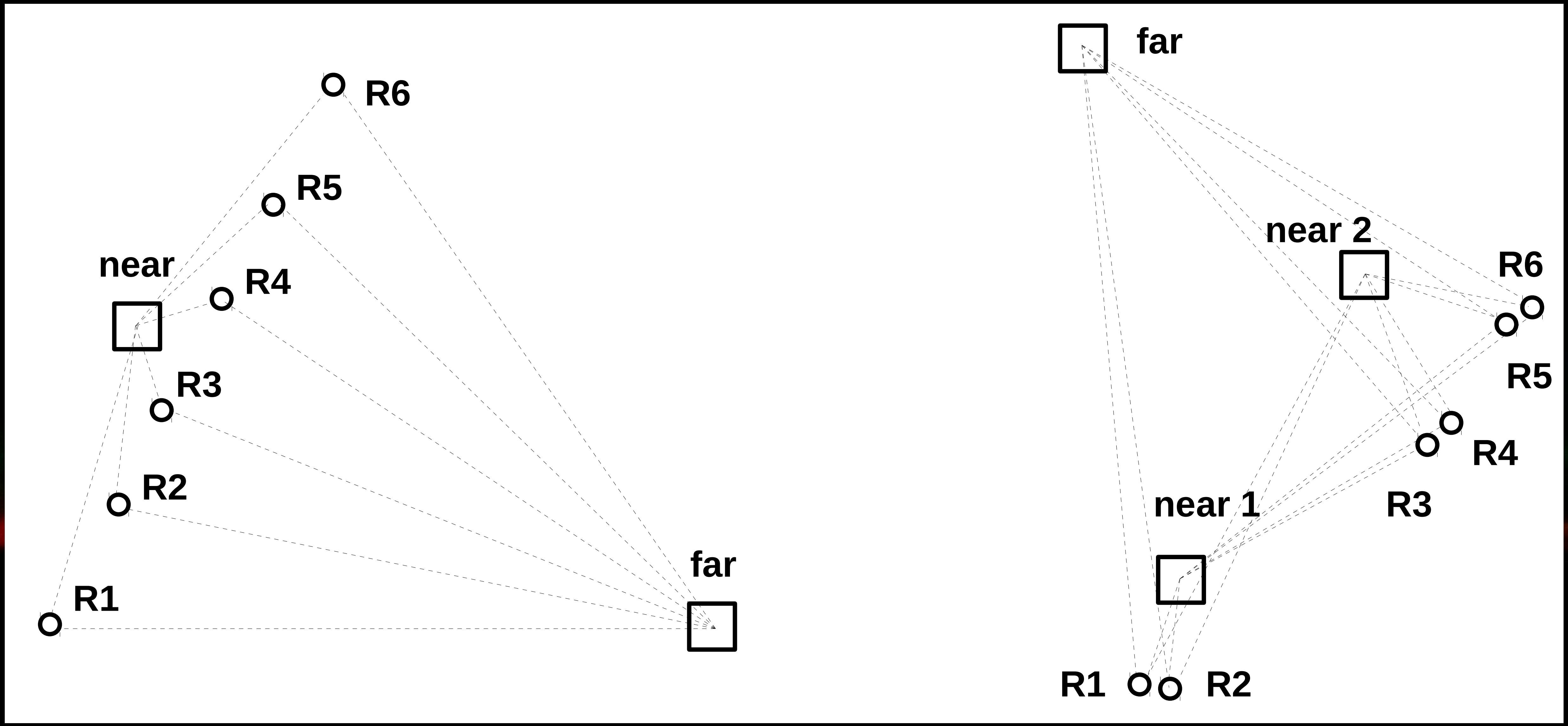
(minimal suppression; i.e. conservative)

(again)

no consensus about inter-reactor error correlation

suppression case D=[2…N$_D$] & R=[6…N$_R$]…

RENO **Daya Bay**



RENO site

- geometrically very appealing
- ND does NOT see the same as FD

⟹ large acceptance differences

- **still partial 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

- **still partial iso-flux-ness is possible: ~50%**

suppression error implementation…

(example) **DB-RO** in their 1203.1669 [hep/ex] (1st paper)

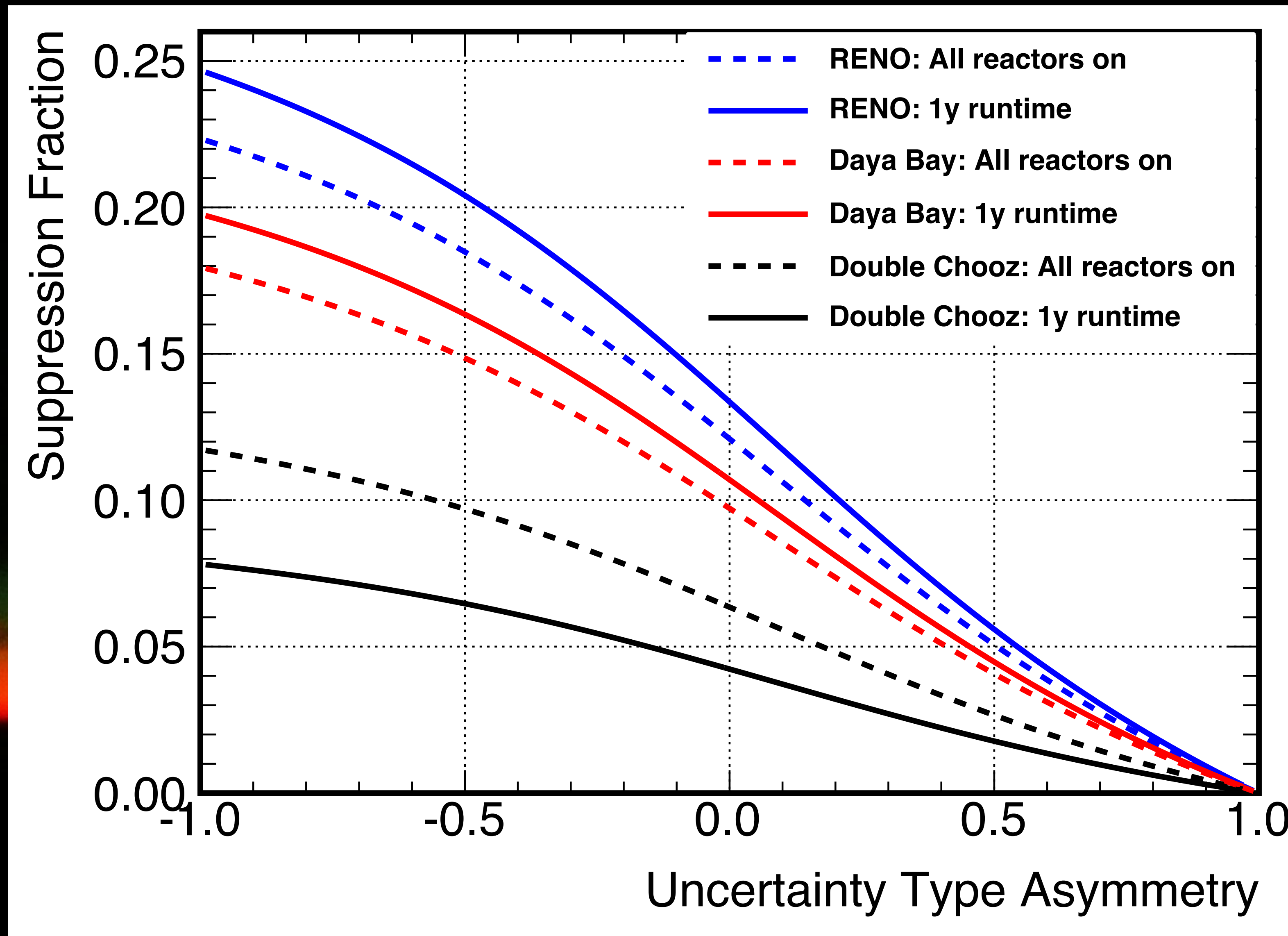
$$\chi^2 = \sum_{d=1}^{6} \frac{\left[M_d - T_d\left(1 + \varepsilon + \sum_r \omega_r^d \alpha_r + \varepsilon_d\right) + \eta_d\right]^2}{M_d + B_d} + \boxed{\sum_r \frac{\alpha_r^2}{\sigma_r^2}} + \sum_{d=1}^{6} \left(\frac{\varepsilon_d^2}{\sigma_d^2} + \frac{\eta_d^2}{\sigma_B^2}\right),$$

effective behaviour during minimisation of χ^2…

δ(flux)effective = δ(flux)per reactor / √6

suppression via reactor error correlations…

inter-reactor correlated error impact…

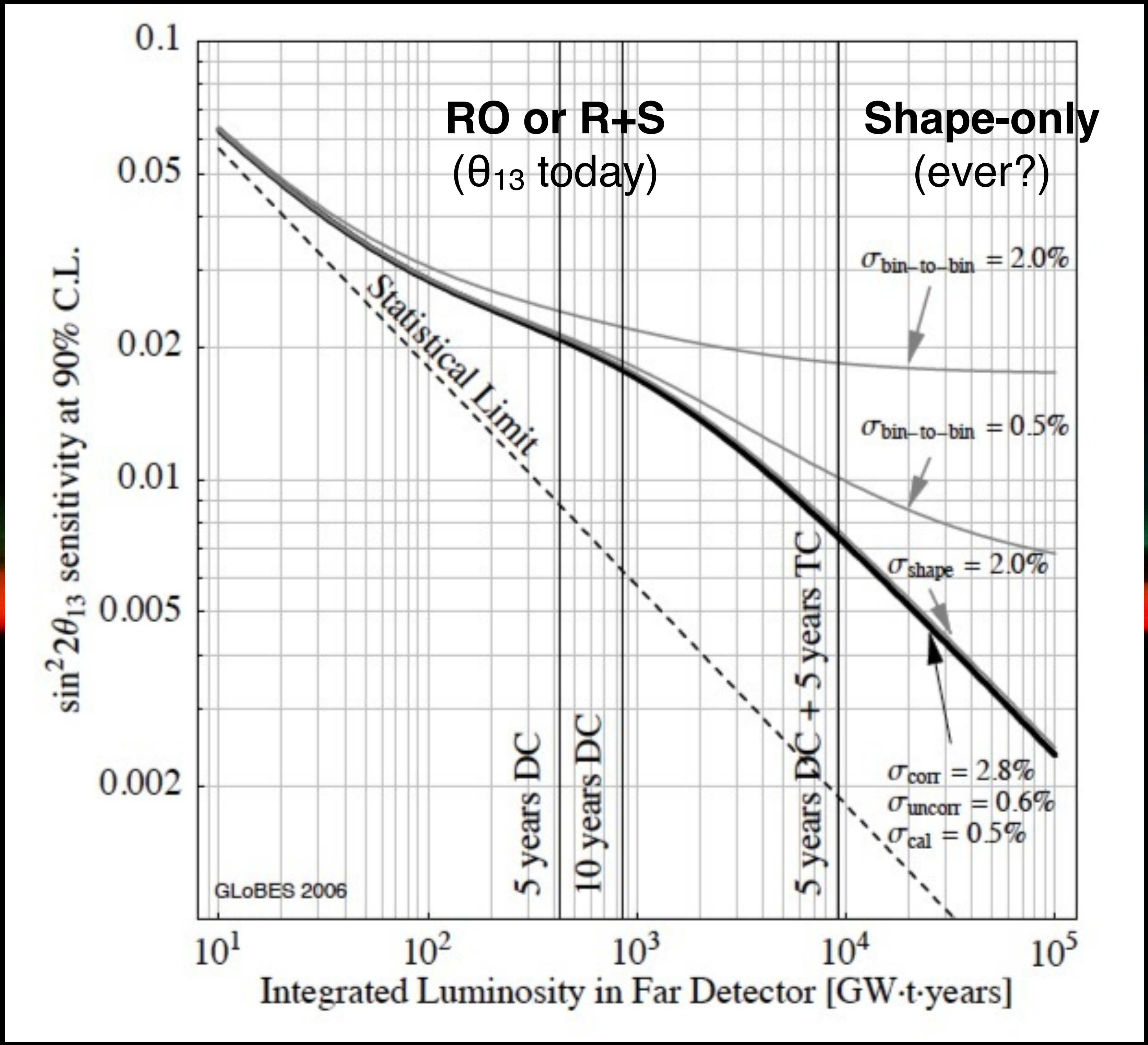


$A_\delta = (\delta_c - \delta_u) / (\delta_c + \delta_u)$ → fraction of error type

(not evident what's the best knowledge on A_δ → reactor dependent)

Experiment	N_R (via MC)	SF(full-power)	SF(refuelling)	SF(iso-flux)	SF(N_R)
Daya Bay	6 (∼6.0)	0.18	0.20	0.49	0.41
Double Chooz	2 (∼2.0)	0.12	0.08	0.11	0.71
RENO	6 (∼5.8)	0.23	0.24	0.59	0.41

another suppression approach: shape-only…



DC/RENO & (maybe?) DB not expected to reach sufficient shape-only (ultra high stats) for θ13

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suspression error final remarks…

- all experiments depends strong on δ(flux) a priori estimated upon reactor-cooking construction…
    - entire field depends on reactor-expertise input
- single-detector experiments…
    - gain (much?) from inter-reactor correlations studies
- **multi-detector experiments do NOT cancel δ(flux) automatically**…
    - much of the literature says otherwise
- **strong site geometry dependence** (not geometrical symmetry but acceptance symmetry)
    - **iso-flux configuration→ δ(flux) = 0 across detectors**
    - **partial iso-flux** configuration have partial suppression…
        - **DC ~90% suppression** (almost iso-flux→ much simpler site)
        - **RENO ~40% and DB ~50% suppression** (more complex site)
- **strong on error type dependence** (inter-reactor error correlation)
    - inter-reactor correlated error cancel across detector (it's like originating from one effective source)
- inter-reactor correlation needs further studies…
    - 1 detector→ assumed <u>totally correlated</u> (no suppression)
    - multi-detector→ assumed <u>totally uncorrelated</u> (minimal suppression)
    - clearly neither is right⟹ **must study/understand/agree on what to do** (reactor dependent)

what to remember…?

conclusions…

- **extraordinary & unique** input from anti-ν experiments…
  - to be **exploited by reactor-expert community** (what do you need from us?)
- **critical input from reactor expert to anti-ν community**…
  - what's today the most reasonable **δ(flux) (per reactor)** to be using?
  - **δ(flux) has to be representative/reliable & as tight as possible** (→ too small is very misleading!)
- anti-ν community finding **ways to bypass lack of knowledge (hard problem) on δ(flux)**…
  - however, **benefit all by improving δ(flux)** ["tricks" will get us even further!!]
  - most physics past and future will have one-detector→ **δ(flux) critical for future of field**
    - note: multi-detector approach is anything but cheap!!
- **[4,8]MeV energy distorsion** (relative model discrepancy)…
  - (strong indication & suspected): **current knowledge (mean & error) are not accurate enough**
    - exciting as input new thoughts/calculations→ minimise biassed approach: low energy is critical!
  - unique opportunity to improve δ(flux)→ **topic is @ world's spotlight!!**