reactor θ13

(the ultimate measurement?)

Kyoto University (Japan)
December 2012

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Double Chooz @ APC (Paris)

will the reactor-θ13 be the ultimate measurement?

the best for long time…

(so must get it right!)

this seminar: tell you how we are doing that…

le menu…

- les apéritives...
  - neutrino oscillation (a fast reminder)
  - neutrino oscillation status
  - global impact of θ13 (a few examples)
- les plats…
  - reactor neutrinos: (a fast)why?
  - review on reactor θ_{13} experiments results
- le dessert…
  - today & tomorrow on reactor θ_{13} systematics
- conclusions?

neutrino oscillations…
(very fast reminder)

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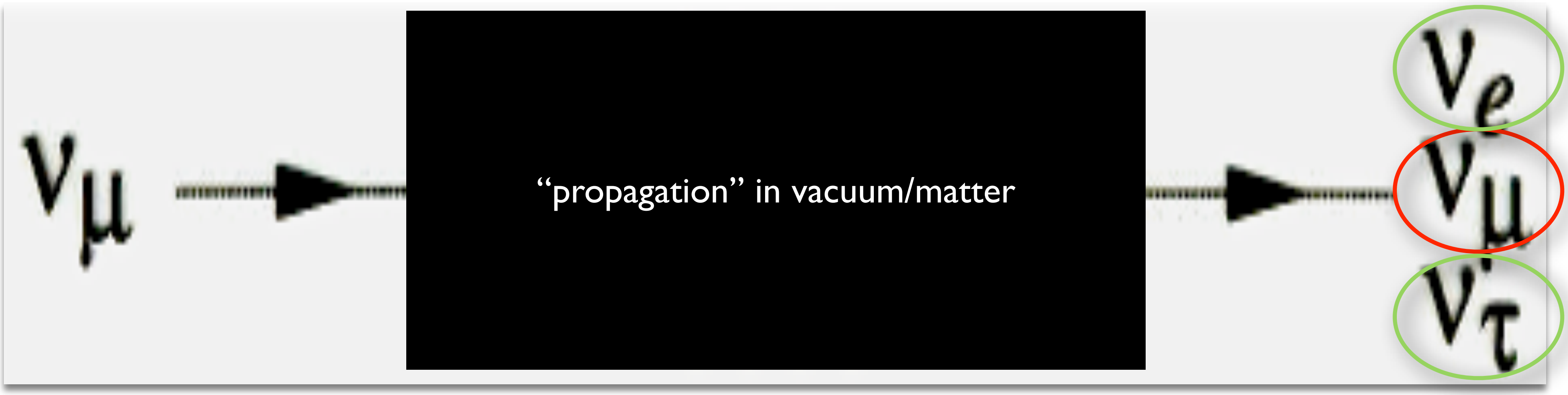
neutrino oscillations: a cartoon

Let’s take ν_μ (a good example) to start with…



disappearance experiment goal

appearance experiment goal

"**mixing**": a common phenomenon in Nature

$$\nu_\alpha = 0.5 \cdot \nu_1 + 0.5 \cdot \nu_2$$

a (CNRS-IN2P3 & APC)

12年12月6日木曜日

neutrino oscillations: the true ingredients…

Mixing in the leptonic sector (θ)→PMNS matrix (à la CKM)

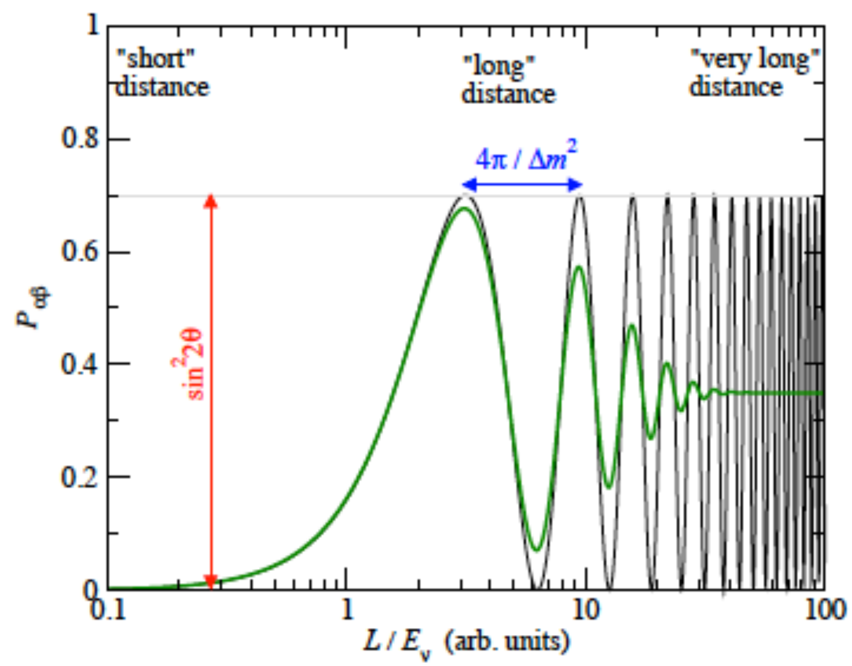
Non-degenerate mass spectrum (Δm^2)→macroscopic (i.e. over km's!!) quantum interference

L,**E** to be tuned (i.e. experimental setup)→measure P(L_o,**ΔE**)

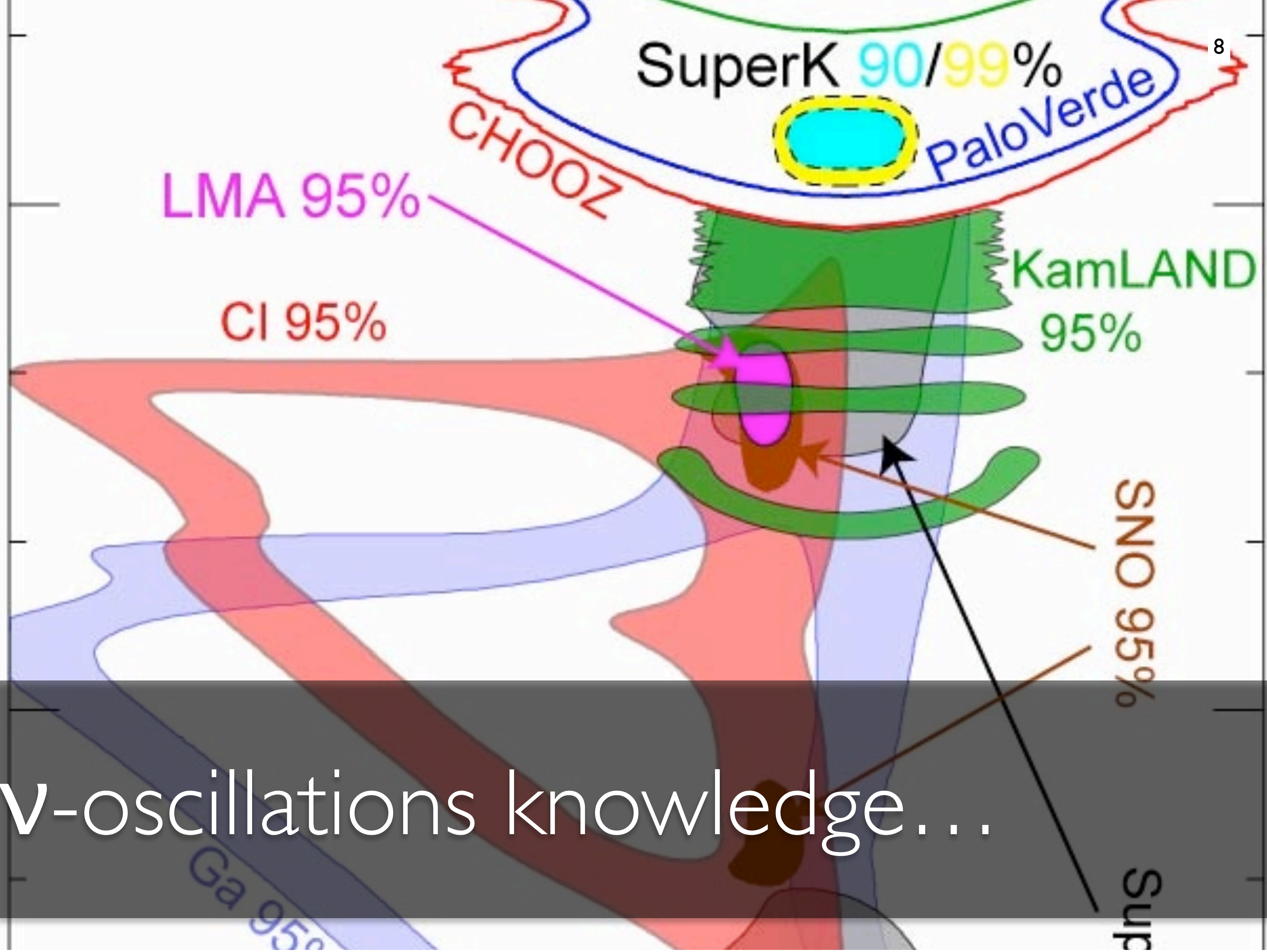
solution for 2ν's…

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

$$P = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E_\nu}$$

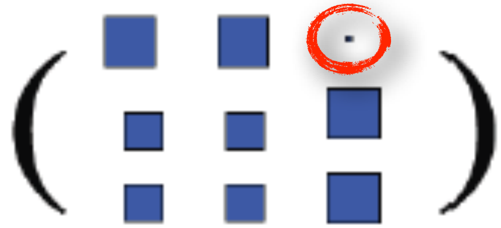


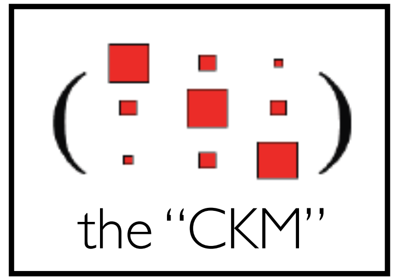
APC)



ν-oscillations knowledge…

$(\nu_e,\nu_\mu,\nu_\tau)^T = U\,(\nu_1,\nu_2,\nu_3)^T$, where U looks like



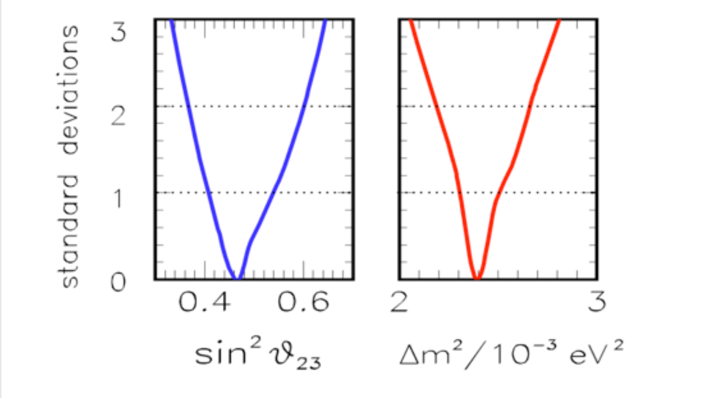


"atmospheric" θ23~45°	θ13 <11° & "dirac"δCP	"solar" θ12~33°
Δm^2_{31}	Δm^2_{31}	Δm^2_{21}

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \xrightarrow{\text{sub-leading}} \begin{pmatrix} c_{13} & 0 & e^{-i\delta}s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}s_{13} & 0 & c_{13} \end{pmatrix} \xleftarrow{\text{sub-leading}} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

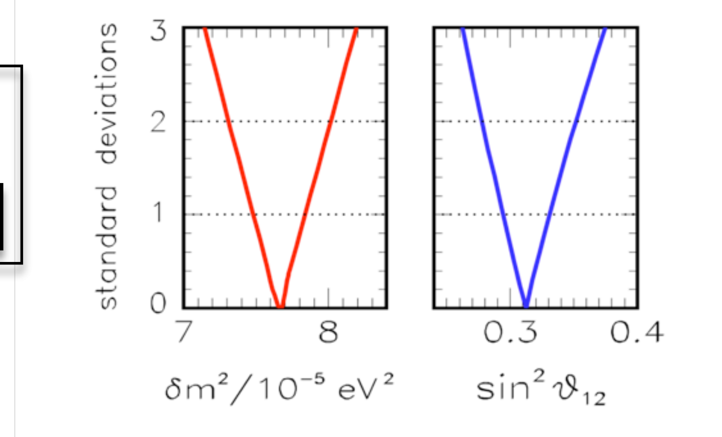
atmos+LBL(dis)	Chooz+LBL(app)	solar+KamLAND
$P(\nu_\mu \to \nu_\mu)$	$P(\nu_e \to \nu_e)$ & $P(\nu_\mu \to \nu_e)$	$P(\nu_e \to \nu_x)$

σ ~12% σ ~5%



knowledge on θ13 & δCP [later]

σ ~2% σ ~6%



Fogli et al arXiv:1106.6028

Lisi et al opinion (Sept. 2012)

Numerical 1σ, 2σ, 3σ ranges:

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TABLE I: Results of the global 3ν oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3σ ranges for the 3ν mass-mixing parameters. We remind that Δm^2 is defined herein as $m_3^2 - (m_1^2 + m_2^2)/2$, with $+\Delta m^2$ for NH and $-\Delta m^2$ for IH.

Parameter	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32 – 7.80	7.15 – 8.00	6.99 – 8.18
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.07	2.91 – 3.25	2.75 – 3.42	2.59 – 3.59
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.43	2.33 – 2.49	2.27 – 2.55	2.19 – 2.62
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.42	2.31 – 2.49	2.26 – 2.53	2.17 – 2.61
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.41	2.16 – 2.66	1.93 – 2.90	1.69 – 3.13
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.44	2.19 – 2.67	1.94 – 2.91	1.71 – 3.15
$\sin^2\theta_{23}/10^{-1}$ (NH)	3.86	3.65 – 4.10	3.48 – 4.48	3.31 – 6.37
$\sin^2\theta_{23}/10^{-1}$ (IH)	3.92	3.70 – 4.31	3.53 – 4.84 ⊕ 5.43 – 6.41	3.35 – 6.63
δ/π (NH)	1.08	0.77 – 1.36	—	—
δ/π (IH)	1.09	0.83 – 1.47	—	—

Fractional 1σ accuracy [defined as 1/6 of ±3σ range]

δm^2	Δm^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$
2.6%	3.0%	5.4%	10%	14%

Note: above ranges obtained for "old" reactor fluxes. For "new" fluxes, ranges are shifted (by ~ 1/3 σ) for two parameters only: $\Delta \sin^2\theta_{12}/10^{-1} = +0.05$ and $\Delta \sin^2\theta_{13}/10^{-2} = +0.08$

Hierarchy differences well below 1σ for various data combinations

why θ_{13}?

- θ_{13} **must be measured**
  - free parameterr in SM (like in CKM→ parameter constraints)
  - test U_{PMNS} unitarity (hard)→ sensitive to ≥3νs (steriles?)
- a non-zero θ13 is necessary (but not sufficient) to measure δ_{CP}…
  - value important to measure the Mass Hierarchy (MH): **$\pm\Delta m^2_{31}$**
- θ13 helps to improve **our global knowledge**…
  - via global analyses (**1205.5254**, **1205.4018**, **1209.3023**, etc)
    - **θ23 octant** [example later]
    - **δ_{CP}** (Dirac phase) [example later]
- **θ_{13} oscillations observed**→ validation of 3ν oscillation model
  - confirms 3ν families (like seeing the ν_τ in 2000 by DONUT)
  - a "discovery"? [within a well established framework]
    - "solar" & "atmospheric"→ main channels for oscillations so far
- θ13→ **discriminate flavour unification models**…
  - U_{PMNS} + U_{CKM}→ quark-lepton unification flavour model
  - example: Barr et al (**hep-ph/1208.6546**), etc…

global θ_{13}

impact...

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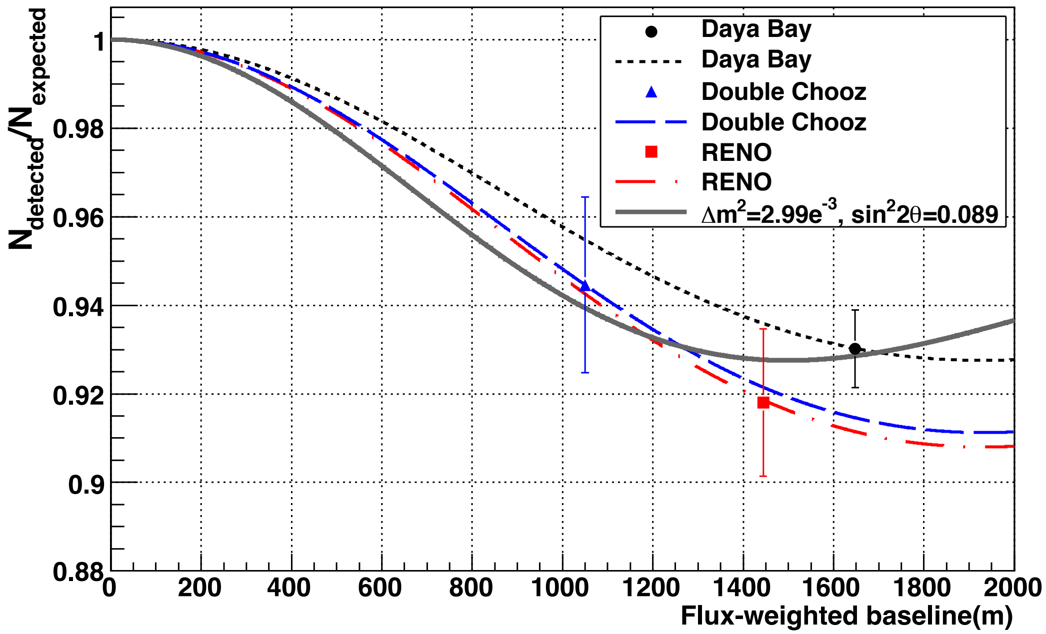
what we all want to know…

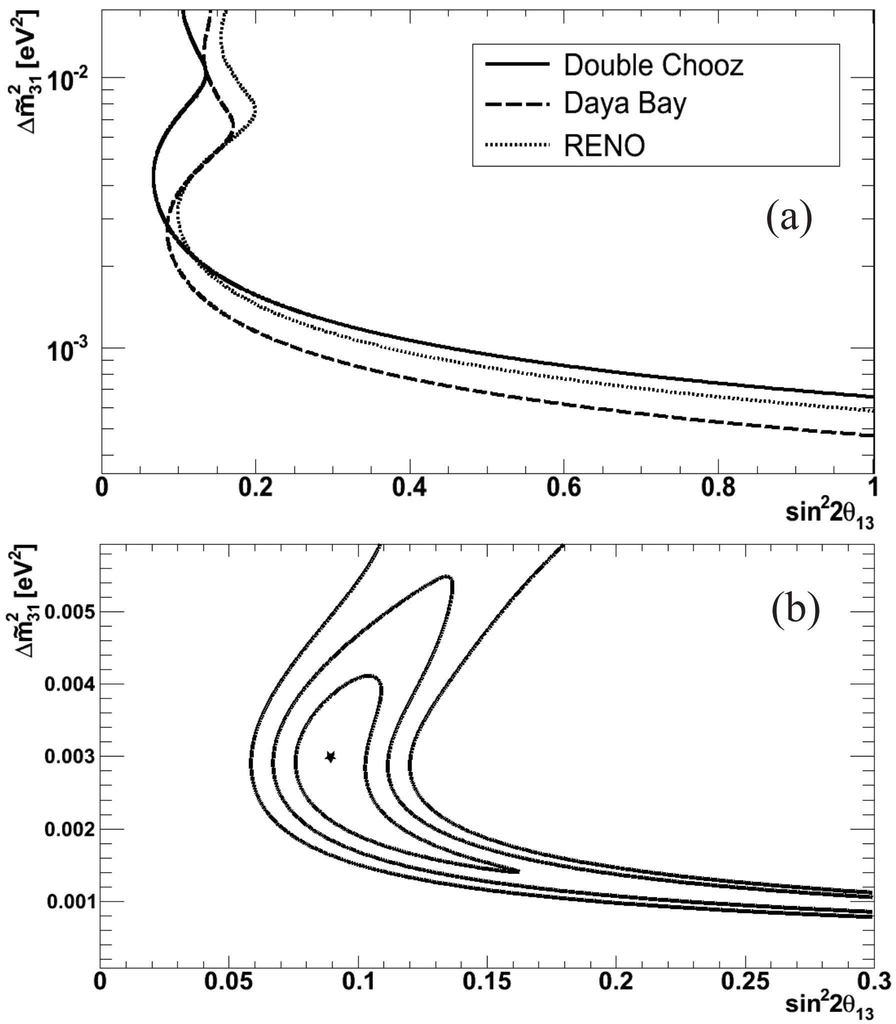
- consistent reactor-θ13 result (all reactor experiments)
  - good knowledge→**high precision**
    - constraint 3ν model & discriminate against predictions
  - good agreement→**high accuracy** (relevant when high precision)
    - constraint 3ν model & discriminate against predictions
    - **observe E/L distortion**
    - flux normalisation→flux(DB or RENO)< flux(DC) [FD only]
- consistency between reactor and beam θ13 too…
  - beam-θ13 less precise (other observables)→ (still) it must be consistent
  - δ_{CP} rather insensitive to θ13 (but need a θ13≠0)
- **mass hierarchy** is more sensitive to θ13
  - atmospheric-νs→ INO, PINGU, ORCA, etc
  - reactor-νs→ Daya Bay II (amplitude of interference term)
- if **inconsistency/tension** found→ **new physics/systematics?** (exciting!)

combining baselines→ Δm^2_{31} measurement?

1206.6017 by DC-Tohoku team (Suekane-sama)

3 experiments→ 3x θ13 measurements





- 3x difference baselines results on θ13
- combine results→ **better constraint Δm^2_{31}**
- beams (i.e. MINOS) measure Δm^2_{32} (complementary)
- important physics (even if less precision than MINOS)

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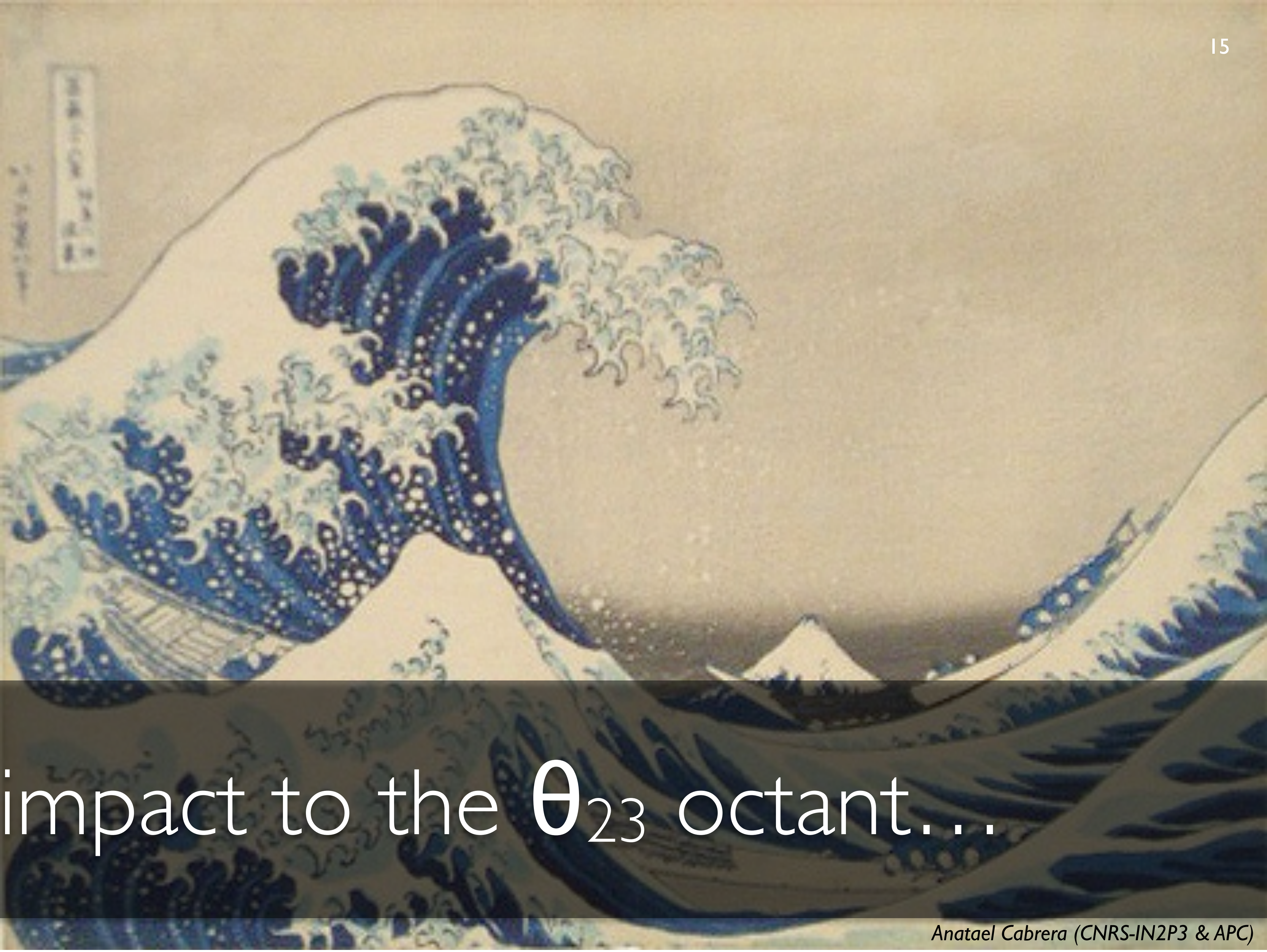

impact to the θ_{23} octant…

Lisi et al @ Shenzhen'2012

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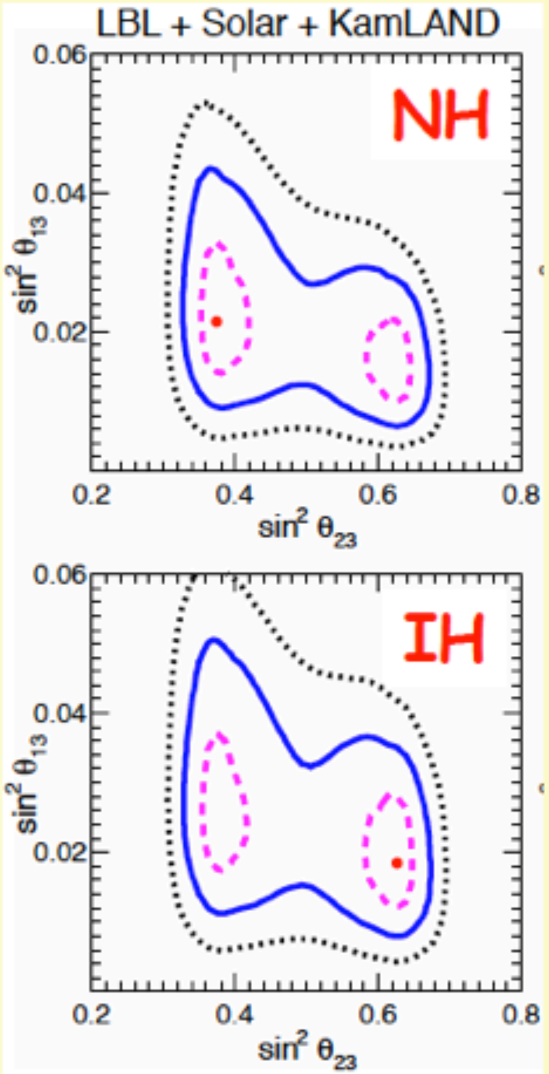
($\sin^2\theta_{13}$, $\sin^2\theta_{23}$) from LBL app. + disapp. data plus solar + KamLAND data:



Latest LBL disappearance data from T2K and MINOS favor nonmaximal θ_{23}

From LBL appearance+disappear. data, two quasi-degenerate θ_{23} solutions emerge, in anticorrelation with θ_{13} (one slightly above and the other slightly below $\sin^2\theta_{13} \sim 0.02$). The two solutions merge above ~1σ.

[It would be nice to see these plots in the official T2K and MINOS data analyses!]

Solar+KamLAND data happen to prefer just $\sin^2\theta_{13} \sim 0.02$, and are unable to lift the octant degeneracy: the depth of the two minima differ by only ~0.3σ.

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Lisi et al @ Shenzhen'2012

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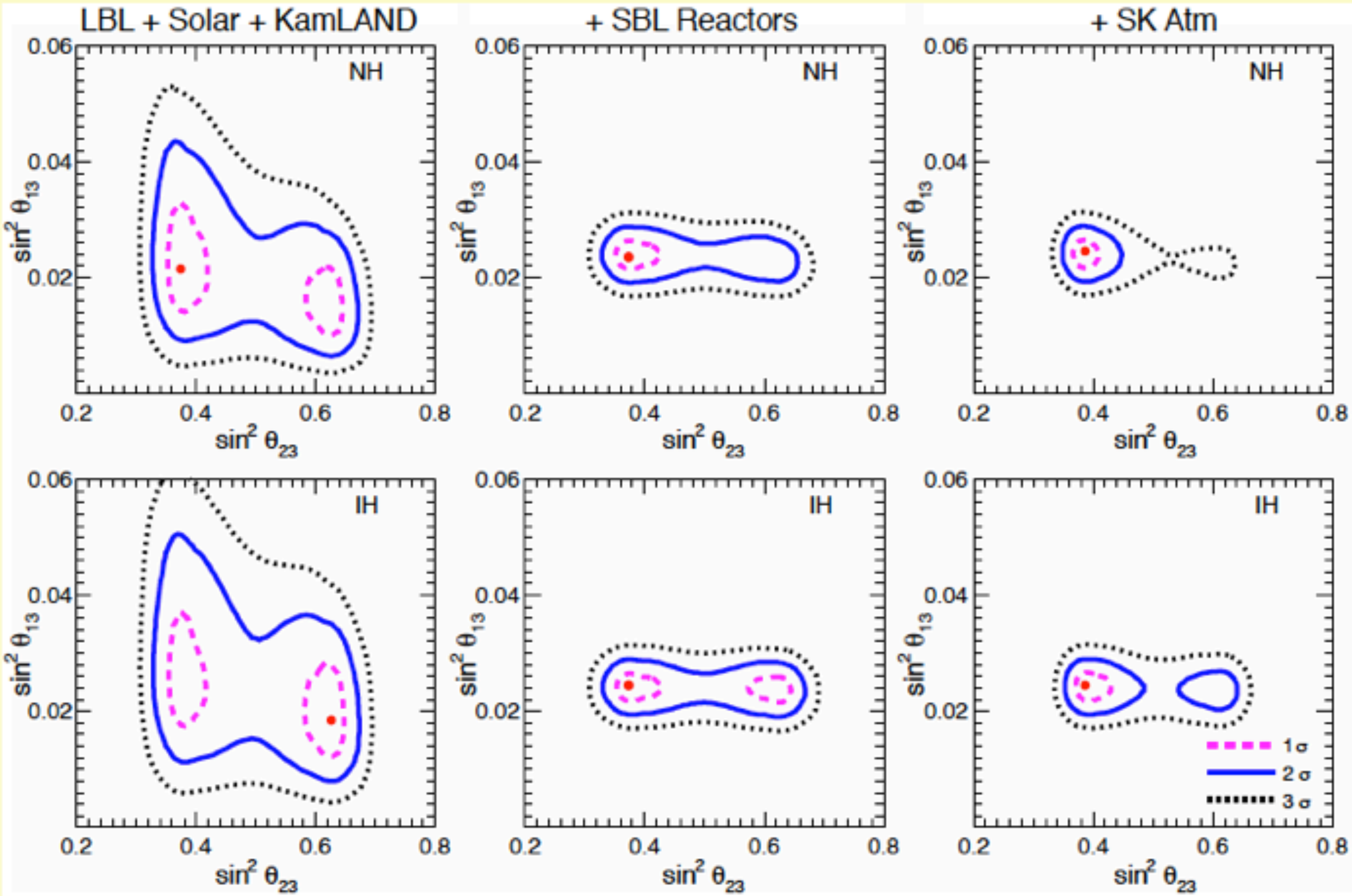
Adding 2012 SK atmospheric neutrino data:



Further hints for θ_{23} in 1st octant. But no significant hierarchy discrimination.

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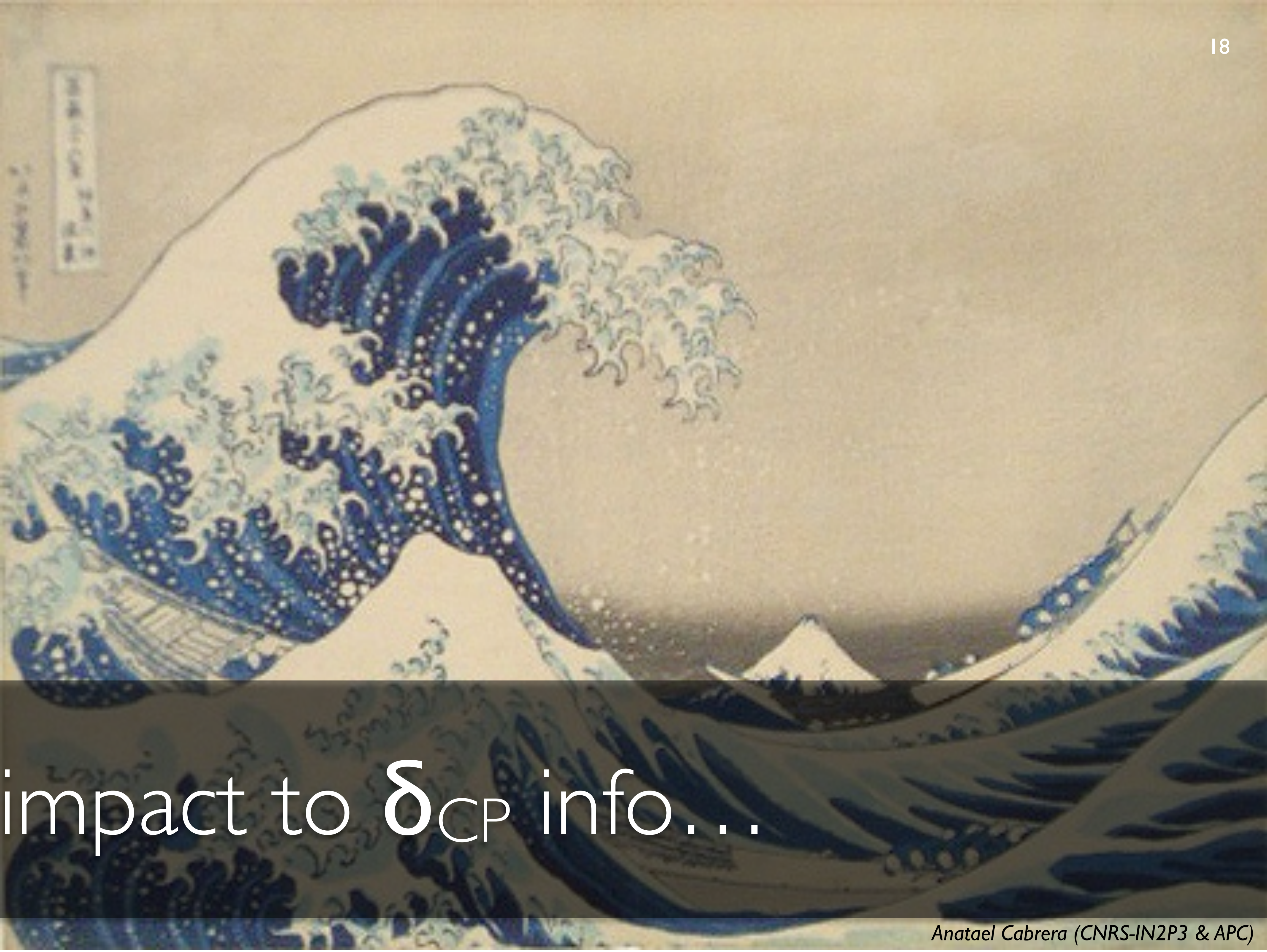

impact to δ_{CP} info…

Lisi et al @ Shenzhen'2012

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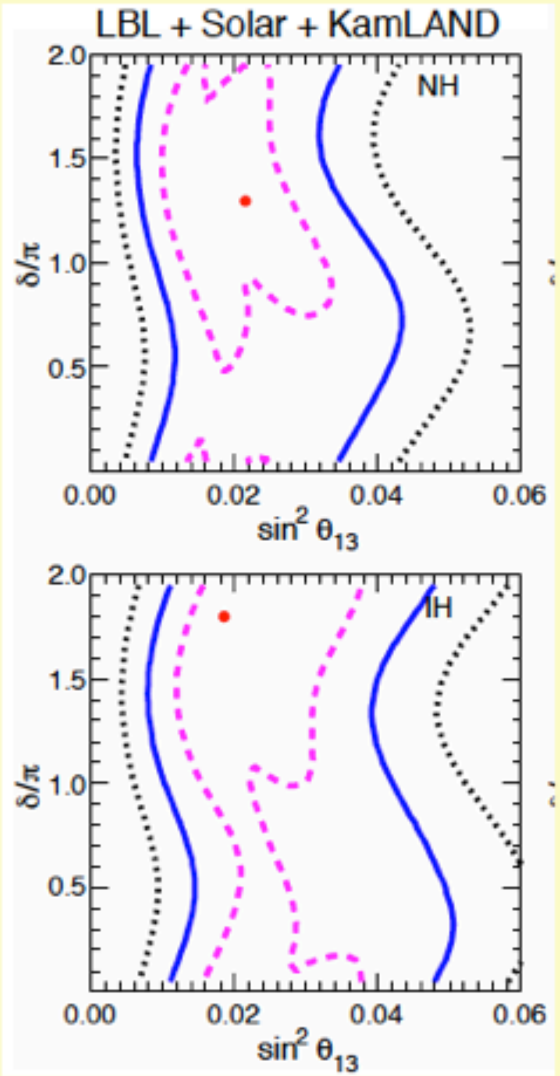
$(\sin^2\theta_{13}, \delta)$ from LBL app. + disapp. data plus solar + KamLAND data:



δ is basically unconstrained at ~1σ.

Fuzzy 1σ contours are a side effect of θ_{23} degeneracy: the two θ_{23} minima correspond to slightly different θ_{13} ranges and thus to two slightly overlapping "wavy bands" in the plot. Minima flip easily from one band to the other.

Fuzziness disappear at higher CL (degeneracy just enlarges bands).

Lisi et al @ Shenzhen'2012

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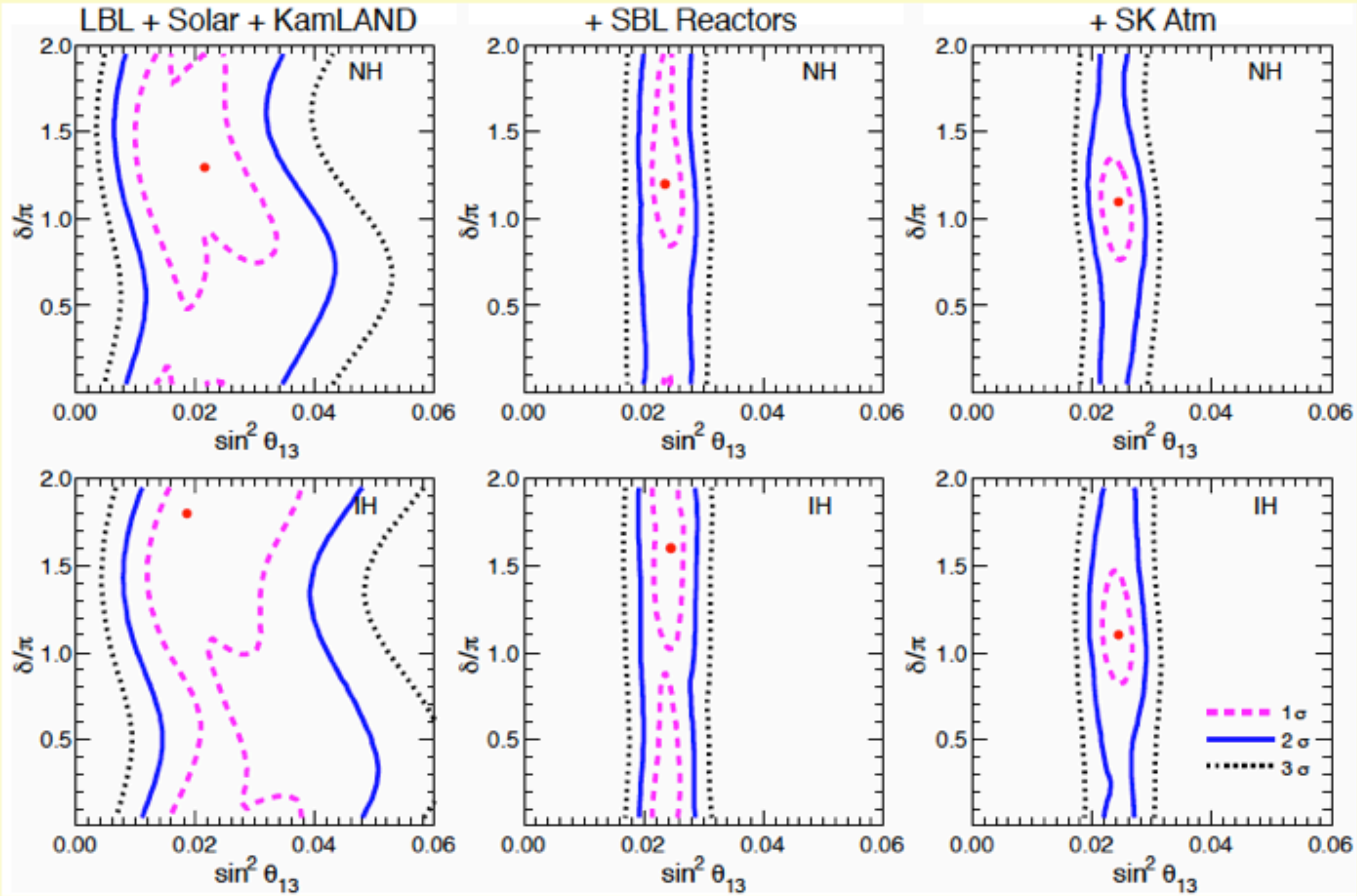
Adding 2012 SK atmospheric neutrino data:



We find a preference for $\delta \sim \pi$ (helps fitting sub-GeV e-like excess in SK)

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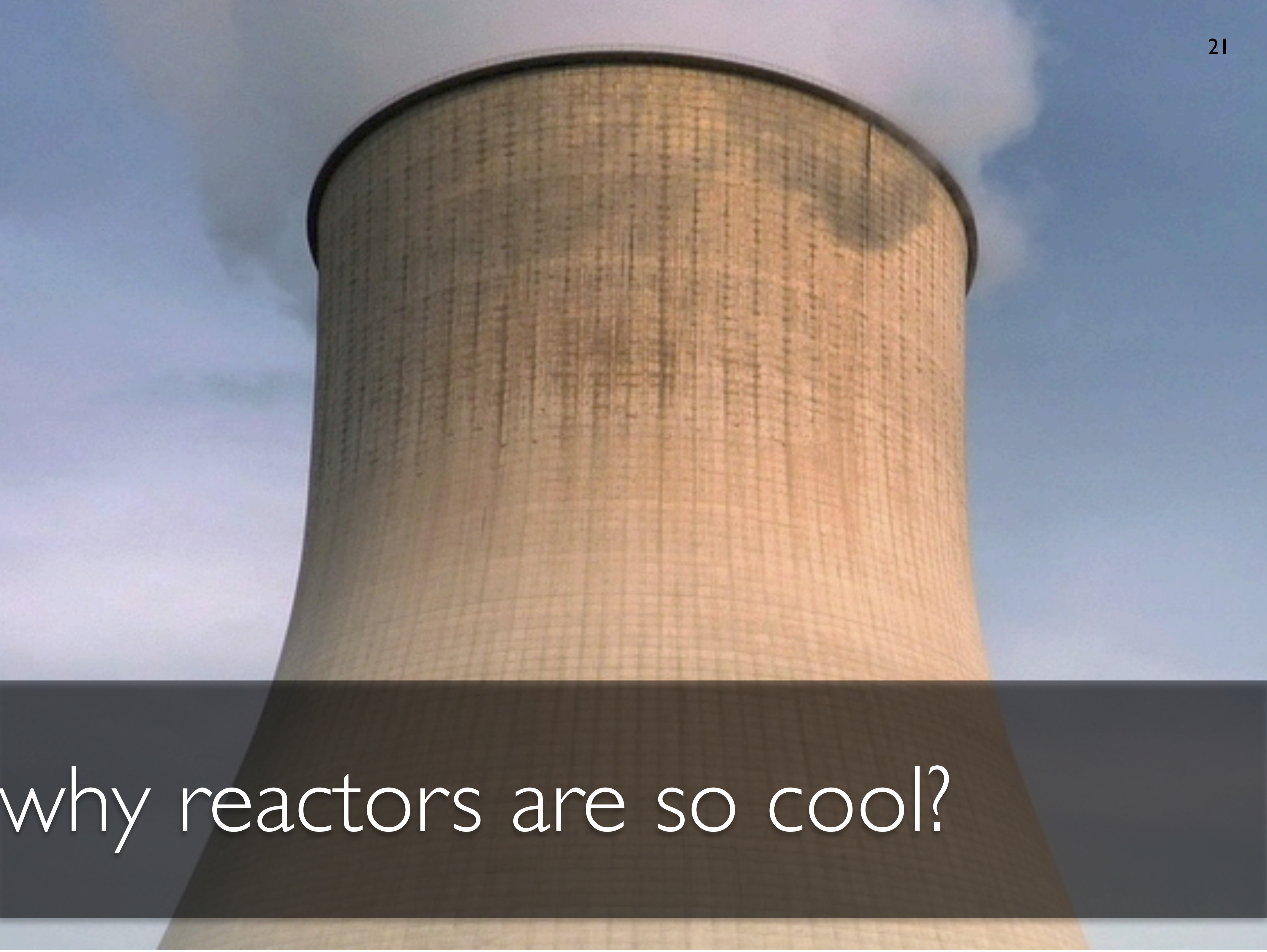
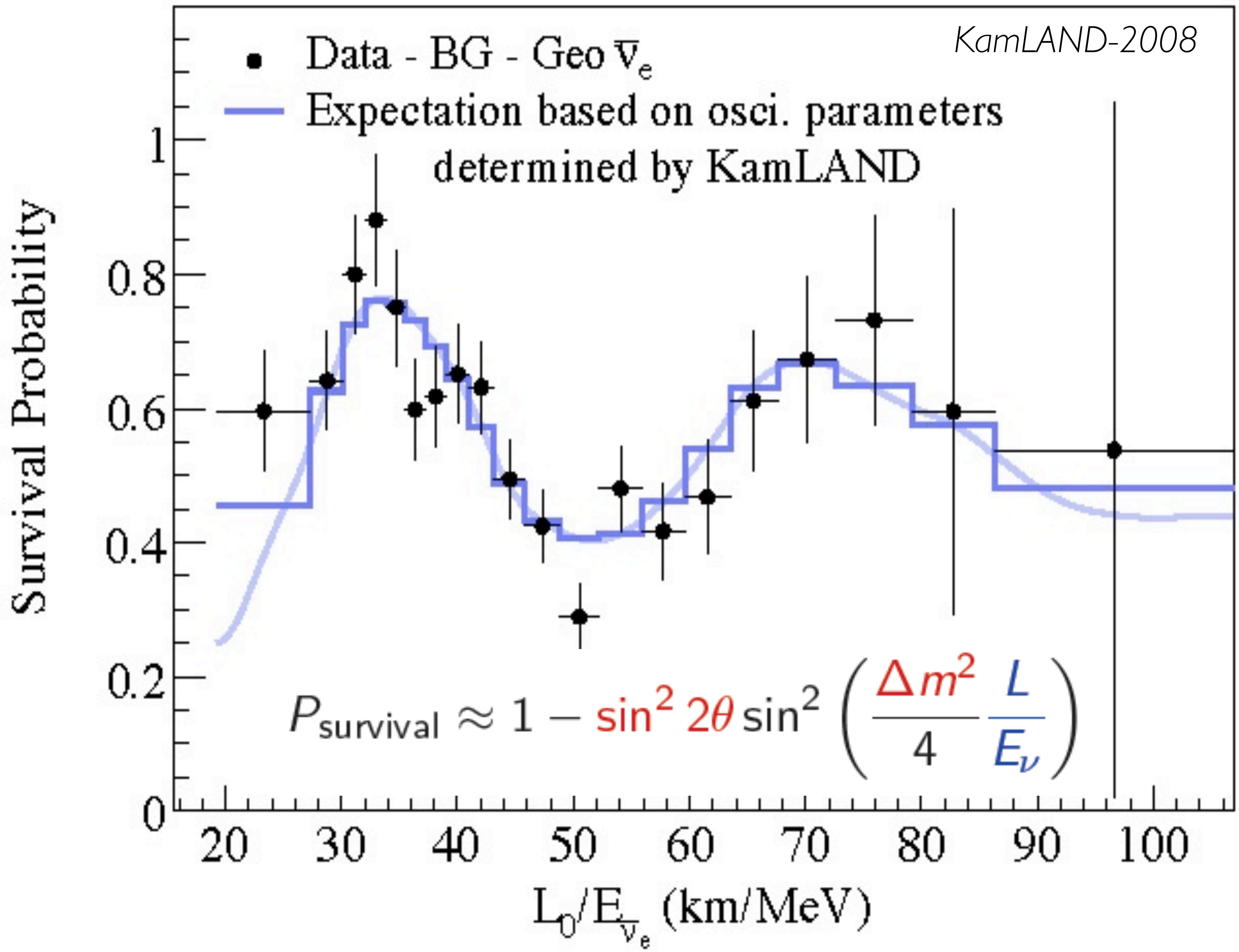

why reactors are so cool?

- discovery of neutrinos (1956→ Nobel Prize 1995)
  - Pauli's hypothesis (Nobel Prize)
- today's **best** measurement of **"solar" Δm^2_{12}** (KamLAND)
  - LMA solution & high precision "Solar-ν" physics
- **best** (ever?) measurement of **θ_{13}**…
  - **this talk**→ today's status (+ my prospect) review
- very sensitive way to explore **Sterile-ν** existence…
  - very-short baseline experiments→ "reactor anomaly"
  - ν industry→ IAEA non-proliferation
- (future) **best** precision **$\theta_{12}/\Delta m^2_{12}$ & Mass Hierarchy**
  - Daya Bay II in preparation(?)
- complementary input in the neutrino oscillation quest…
  - NSI (short L), over-constraint 3ν-model, etc…

KamLAND's E/L (reactor-νs)

the most beautiful (to me) E/L so far...

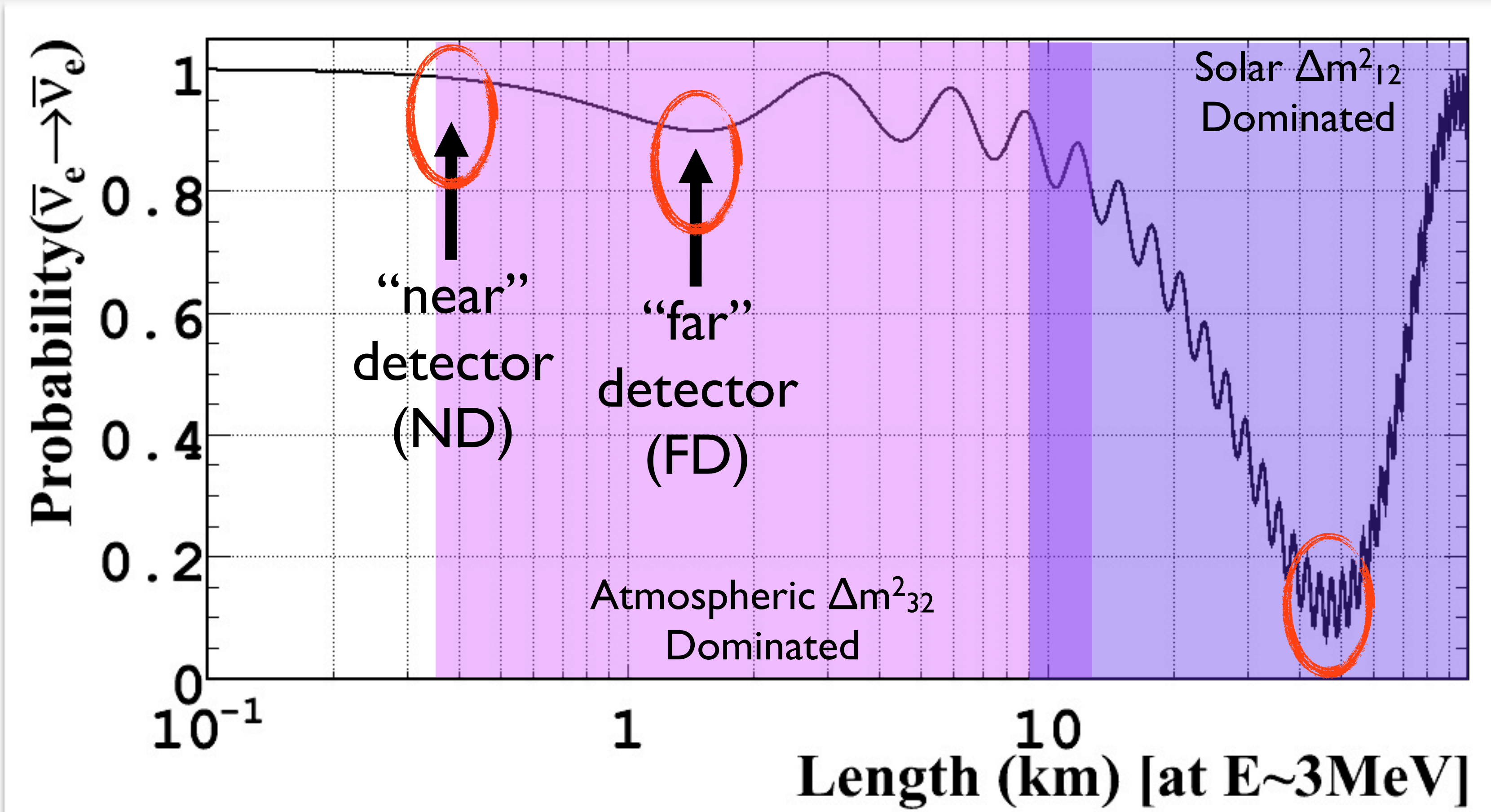


3 & APC)

the coolest reason for us...

$$P(\nu_e \rightarrow \nu_e) \sim 1 - \sin^2(2\theta_{13}) \sin^2(\Delta m^2_{32} L_o/E)$$

[plot: $E = 3\text{MeV}$, $\sin^2(2\theta_{13}) = 0.1$, $\Delta m^2_{32} = 2.5\times10^{-3}\text{eV}^2$]



ND→ reduce all correlated systematic uncertainties

ND→ isolates from other physics (reactor anomaly→ fast oscillation)

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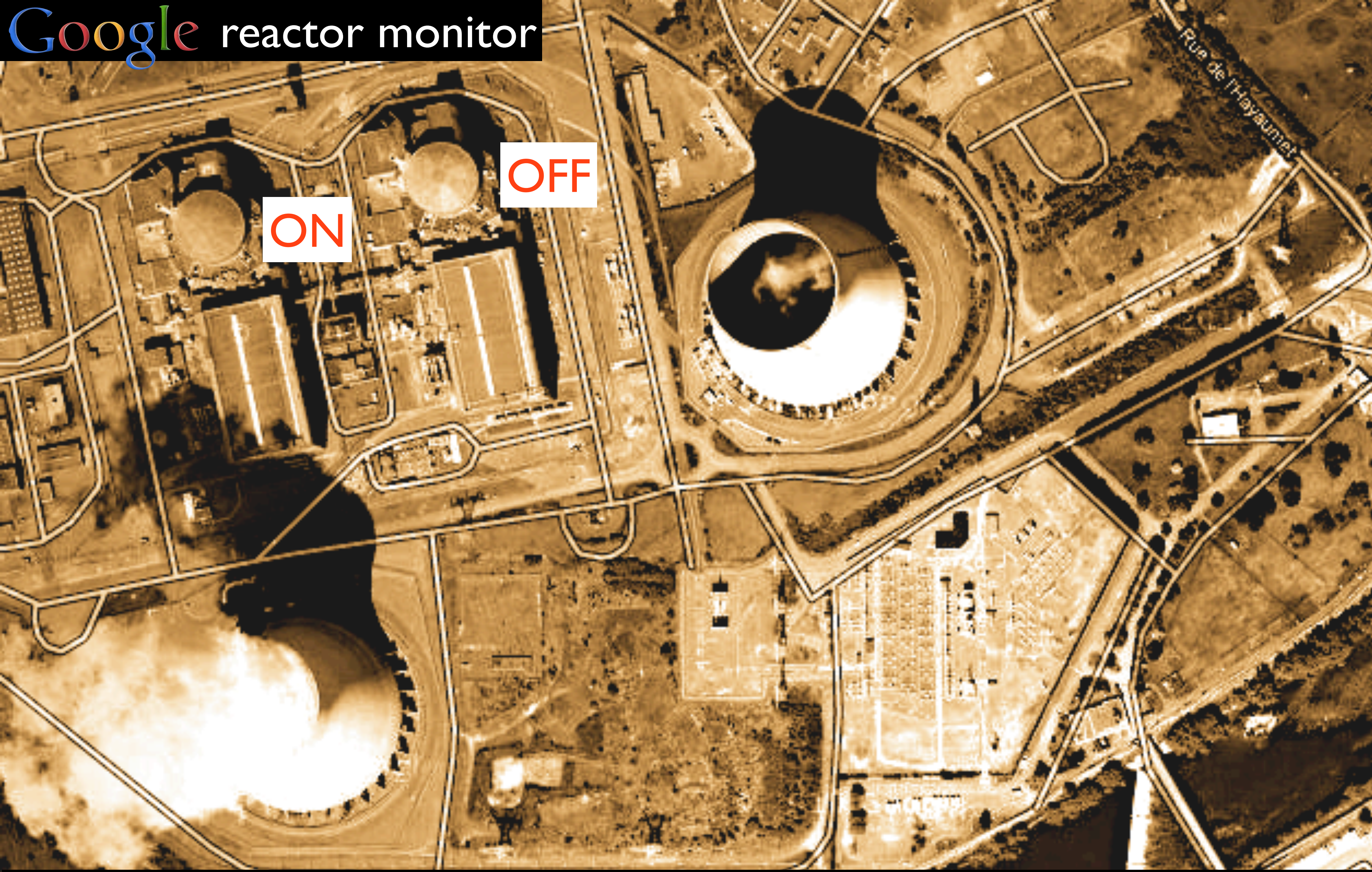
Google reactor monitor



Backgrounds always ON (radio-activity & μ-related)

→ signal can be OFF (or significantly reduce)

[ask your solar-neutrino colleagues how cool this might be…]

reactor θ_{13} measurement...

$\theta 13$ measurement by reactors

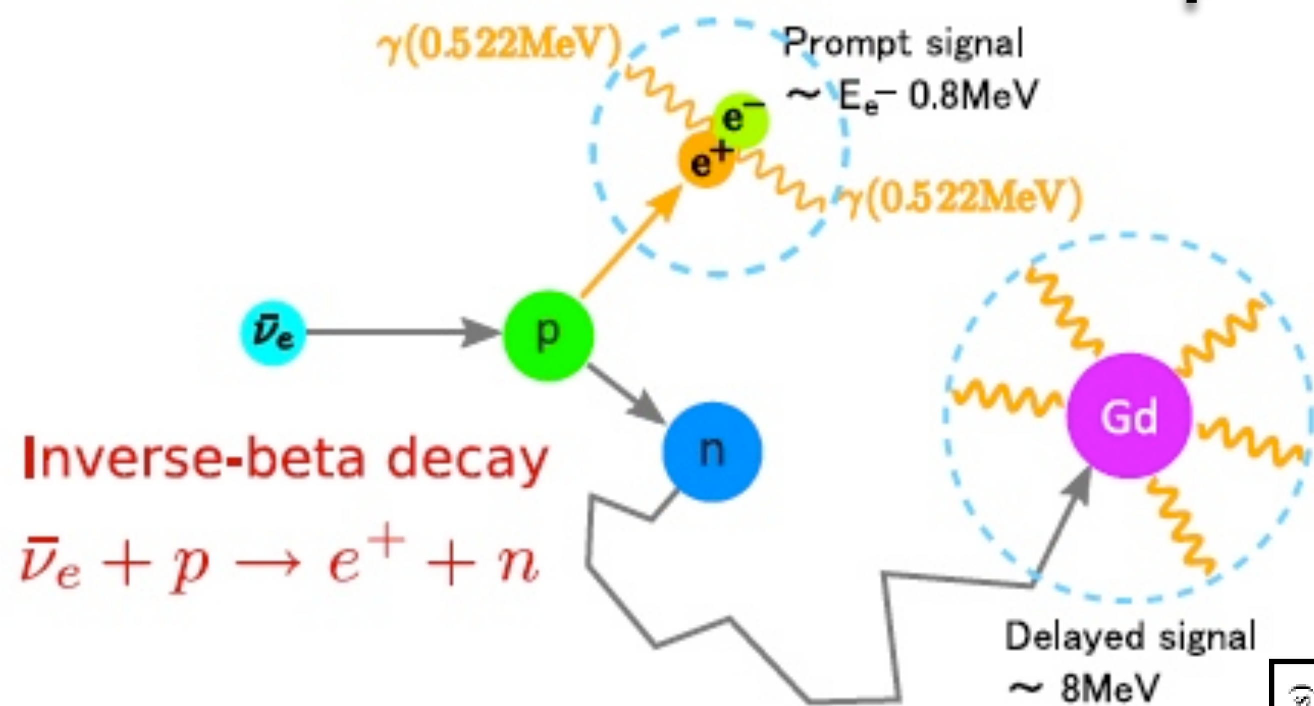
- **3** experiments→ **Daya Bay** (DB), **Double Chooz** (DC) & **RENO**
- **θ_{13} best measurement worldwide from reactors**
    - **hard to improve** (or re-trigger dedicated experimental activity)
    - $\theta 13$ measurement to ~5% precision (eventually)→ use by beams
        - **high precision**→ due to multi-detector technique
        - **high accuracy**→ due to several experiments (any bias?)
    - **oscillation signature**→ $\theta 13$ measure via **both rate+shape**
        - **rate-only** = "any deficit" is numerically associated to $\theta 13$ (BG, etc)
        - results are rate driven→ only DC uses shape to some extent
- **beams to use the "reactor $\theta 13$"**→ further insight in neutrino oscillations
    - **ν_e appearance:** first appearance experiment (T2K→ 5σs soon!!)
    - rich physics…
        - O(1%) precision measurement of $\Delta m^2 32$, $\theta 23$ (T2K, NOνA)
        - further (with some luck)→ δ and MH (also with atmospheric)
        - over-constraint 3ν oscillation scenario→ NSI, sterile, exotic, etc

highlights on experiments…

- **RENO** (1204.0626)
  - **first multi-detector** running→ **rate only analysis** (229days)
  - remarkable effort/success by small (rather local) collaboration (Korea)
- **Double Chooz** (1112.6353,1207.6632,1210.3748, **today**)
  - **the (slow) pioneer: first detector design** (influenced the field)
  - **first result** (Nov.11) after **CHOOZ**→ θ13 large (**rate+shape**)
    - small detectors (8t target) & less overburden (still excellent BGs)
    - **FD+Bugey4** ("ND" via MC)→ high precision absolute knowledge
    - **best 1 detector results ever** (wrt CHOOZ)→ analysis quality
      - ND by spring 2014 but **5 publication (+3 prepation)**
- **Daya Bay** (1203.1669,1210.6327)
  - **huge multi-detector complex**→ FD running since 25th Dec. 2011
    - largest θ13-detection complex→ full configuration (Sept. 2012)
    - large detectors (20t) & deepest overburden (low cosmogenic BG)
  - most precise result today→ **rate-only analysis** (139days, 6 detectors)
    - fantastic first results within 55days of data-taking

reactor-ν detection technology…

inverse-β decay (a cartoon)…



NOTE: n can also capture on H
(à la Reynnes, KamLAND)

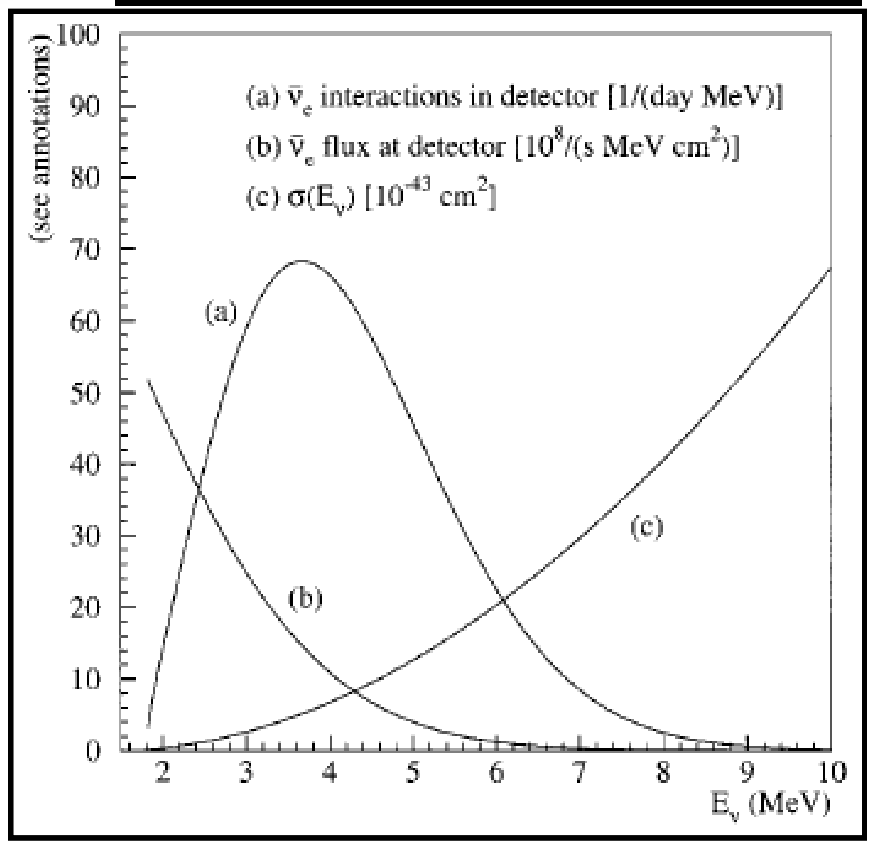
- **Energy(ν) = Energy(e+) - 0.8MeV**
- high & well known σ_{IBD} [$\tau_{neutron}$=(881.5±1.5)s]
- 1ν manifests via **two** triggers:

  1st event (**prompt**): e+

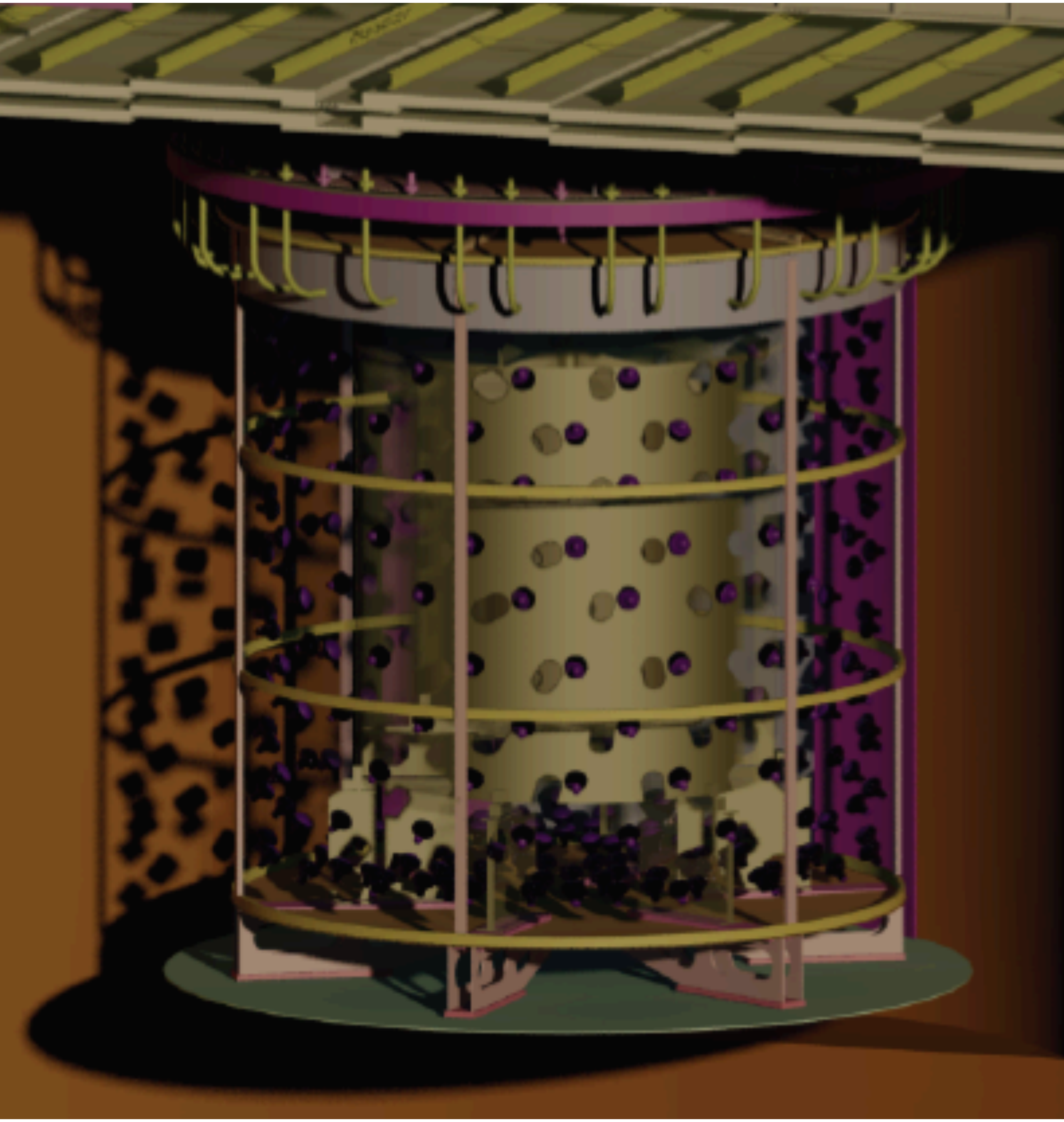
  2nd event (**delay**): n-Gd capture (8MeV)
- both events are **time/space correlated**

  time/space coincidence→reduce BG!

Bemporad, Gratta, Vogle. RMP. 2002



a generic θ13-LAND…



Outer μ-Veto
DC: Plastic Scintillator
DB: RPCs

ν-Target
Liquid-Scintillator + 0.1% of Gd

γ-Catcher
Liquid-Scintillator

Light Buffer
Oil (negligible Scintillation)

Inner μ-Veto
DC: Liquid-Scintillator
DB/RENO: Water Cherenkov

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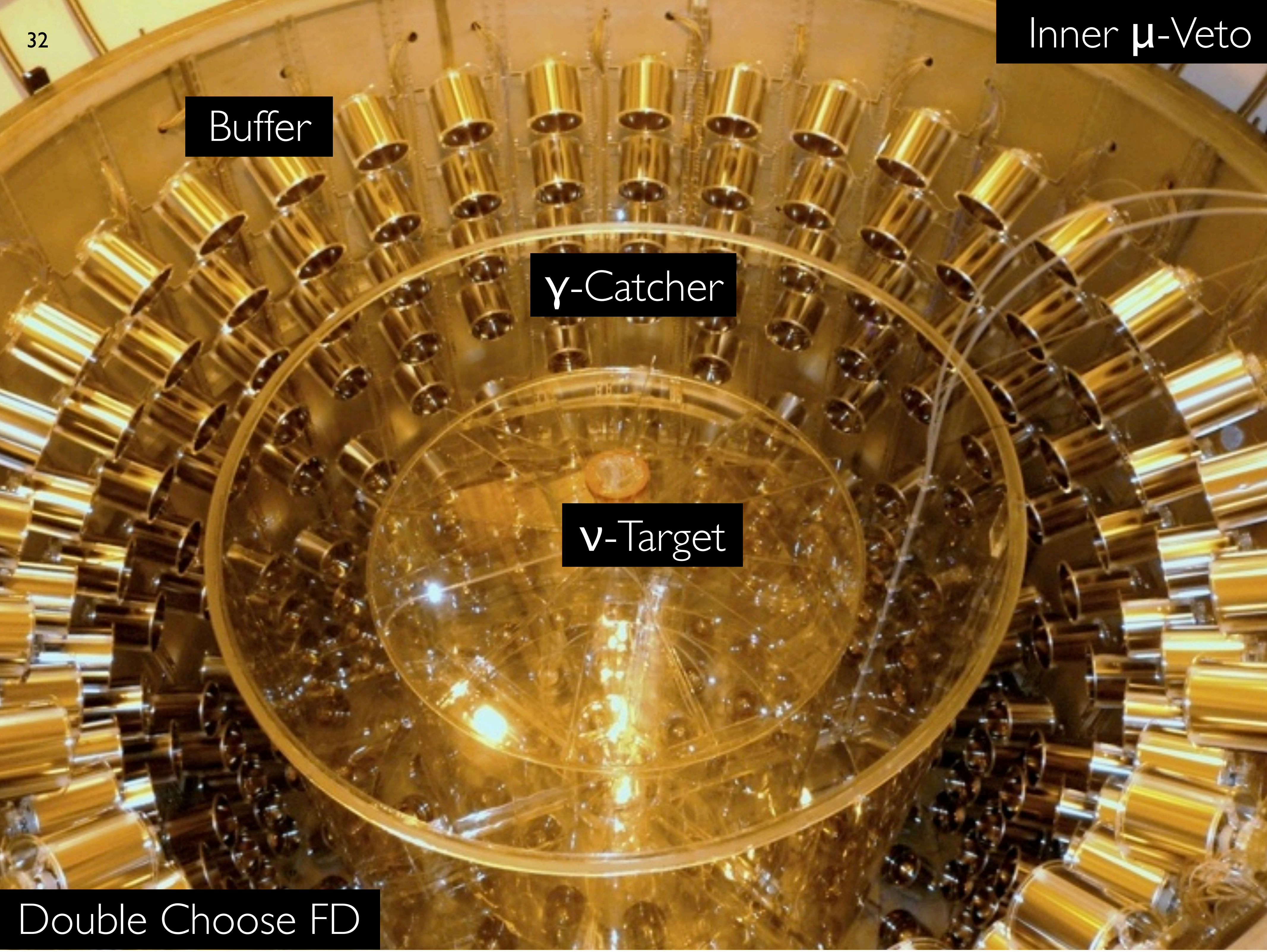
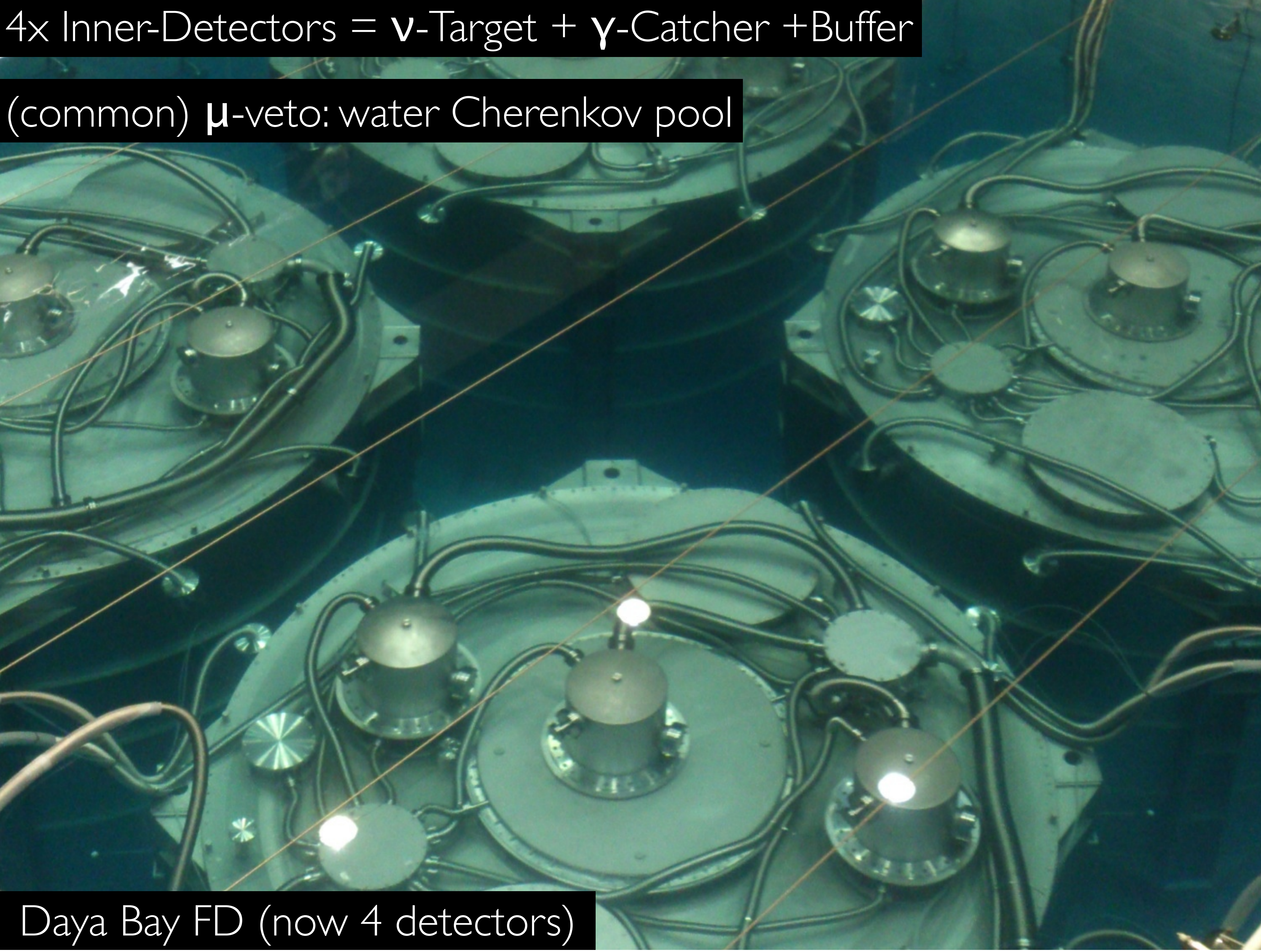

Inner μ-Veto
Buffer
γ-Catcher
ν-Target
Double Choose FD

4x Inner-Detectors = ν-Target + γ-Catcher +Buffer

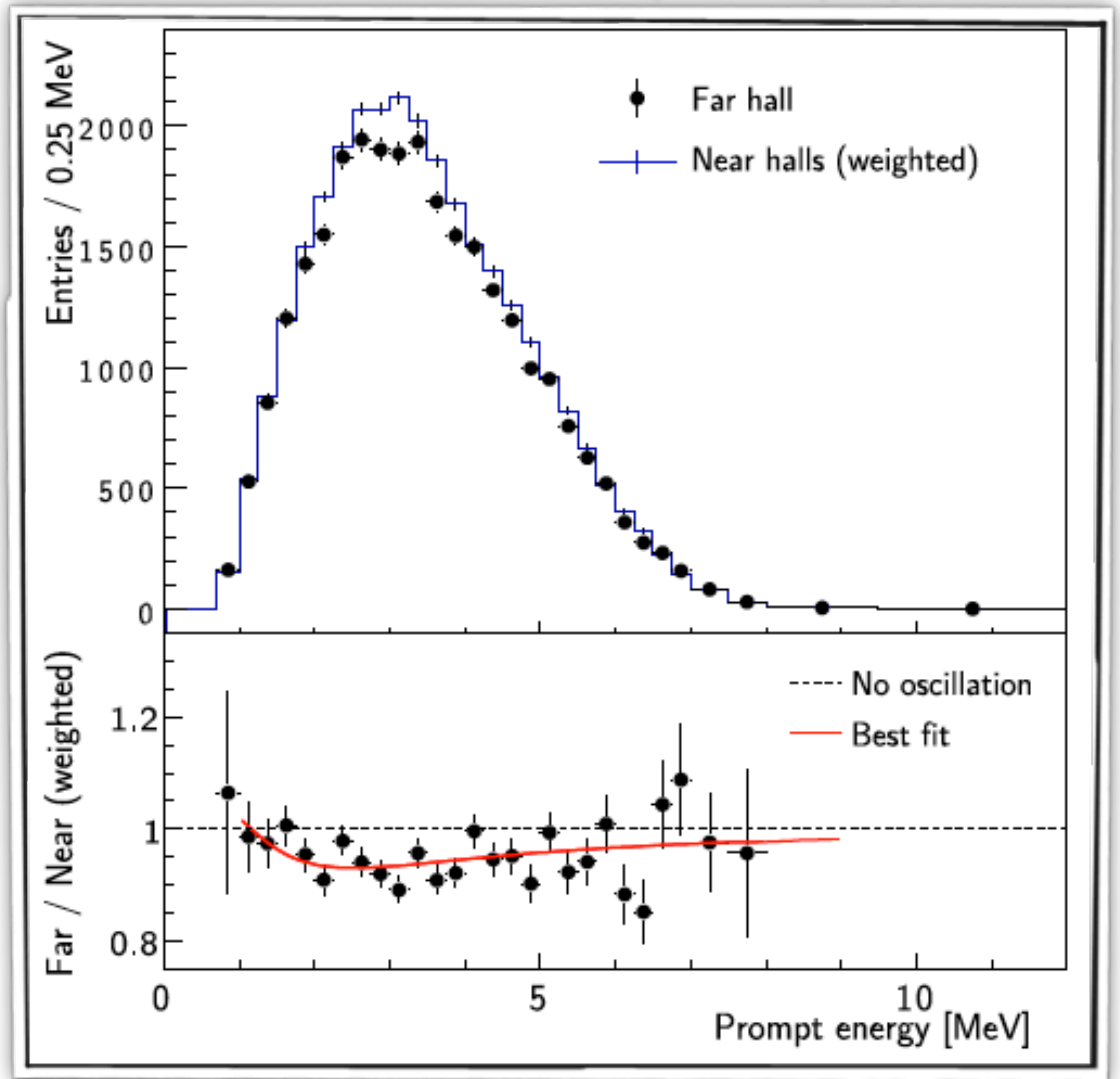
(common) μ-veto: water Cherenkov pool



Daya Bay FD (now 4 detectors)

θ13 results…

latest Daya Bay (@ Nu2012)…



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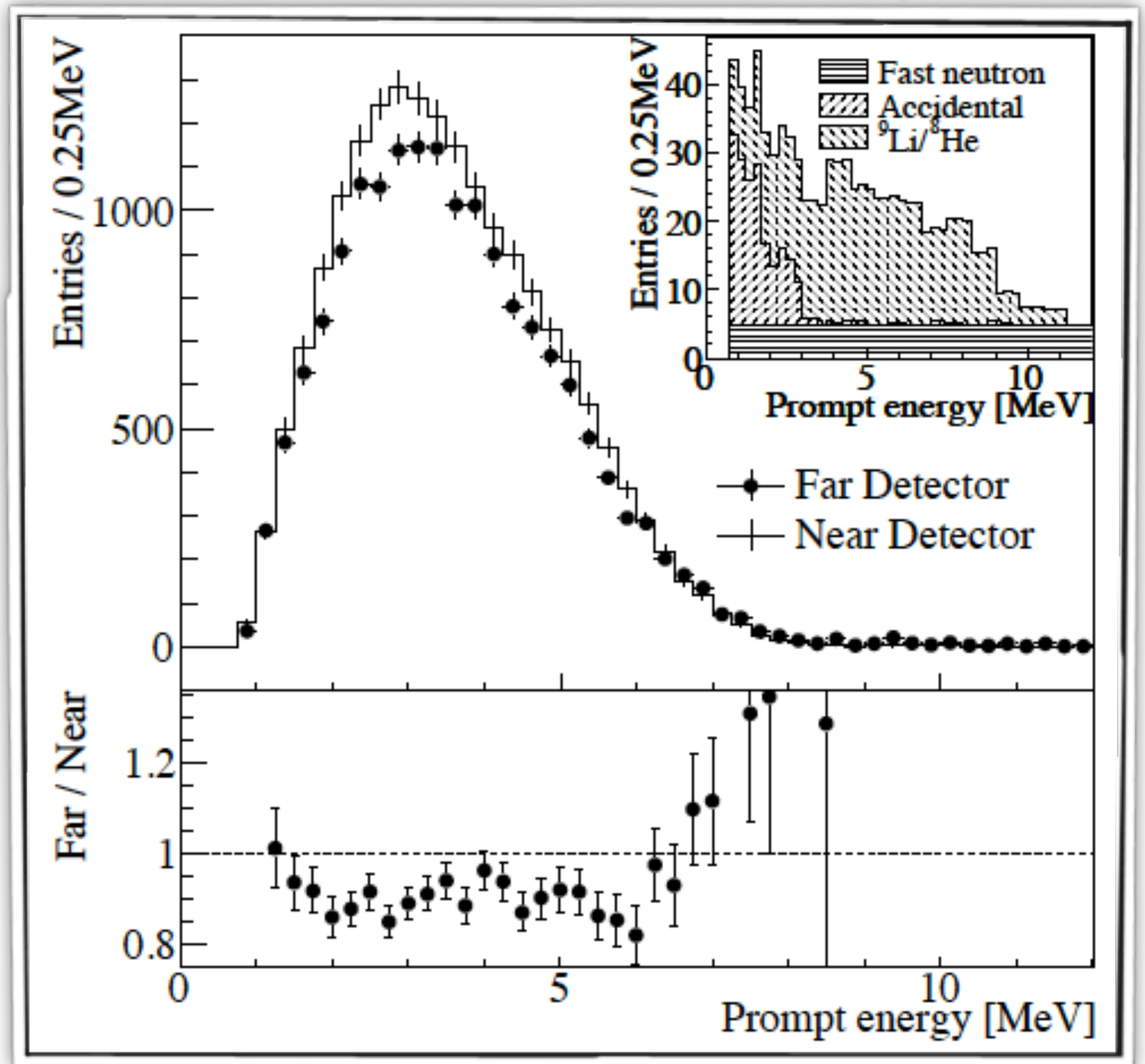
latest RENO (@ Nu2012)…



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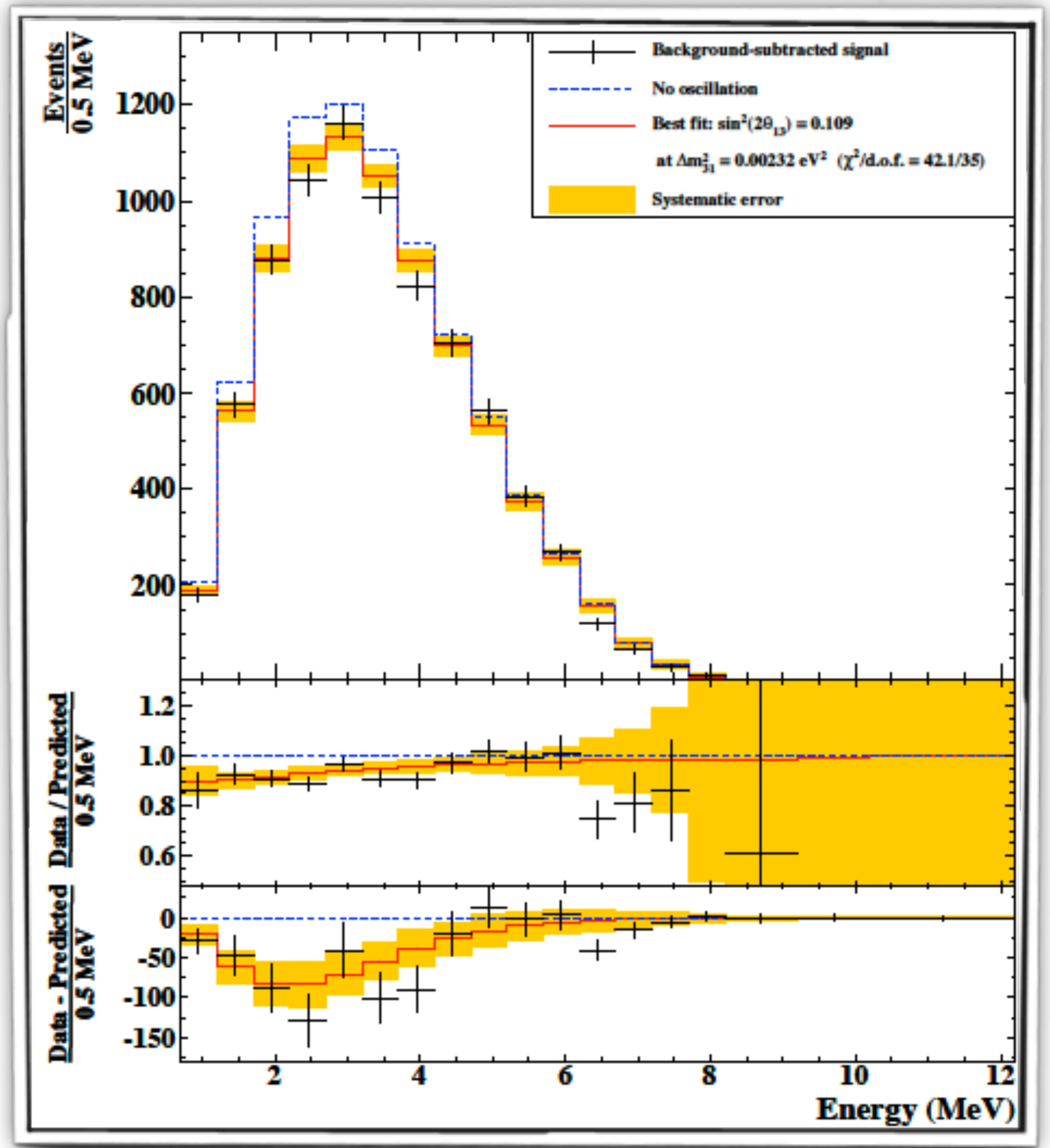
latest DC$_{Gd}$-II (@ Nu2012)…



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12/12/3 @ APC(Paris)
official data release

new results by DC (**now**)...

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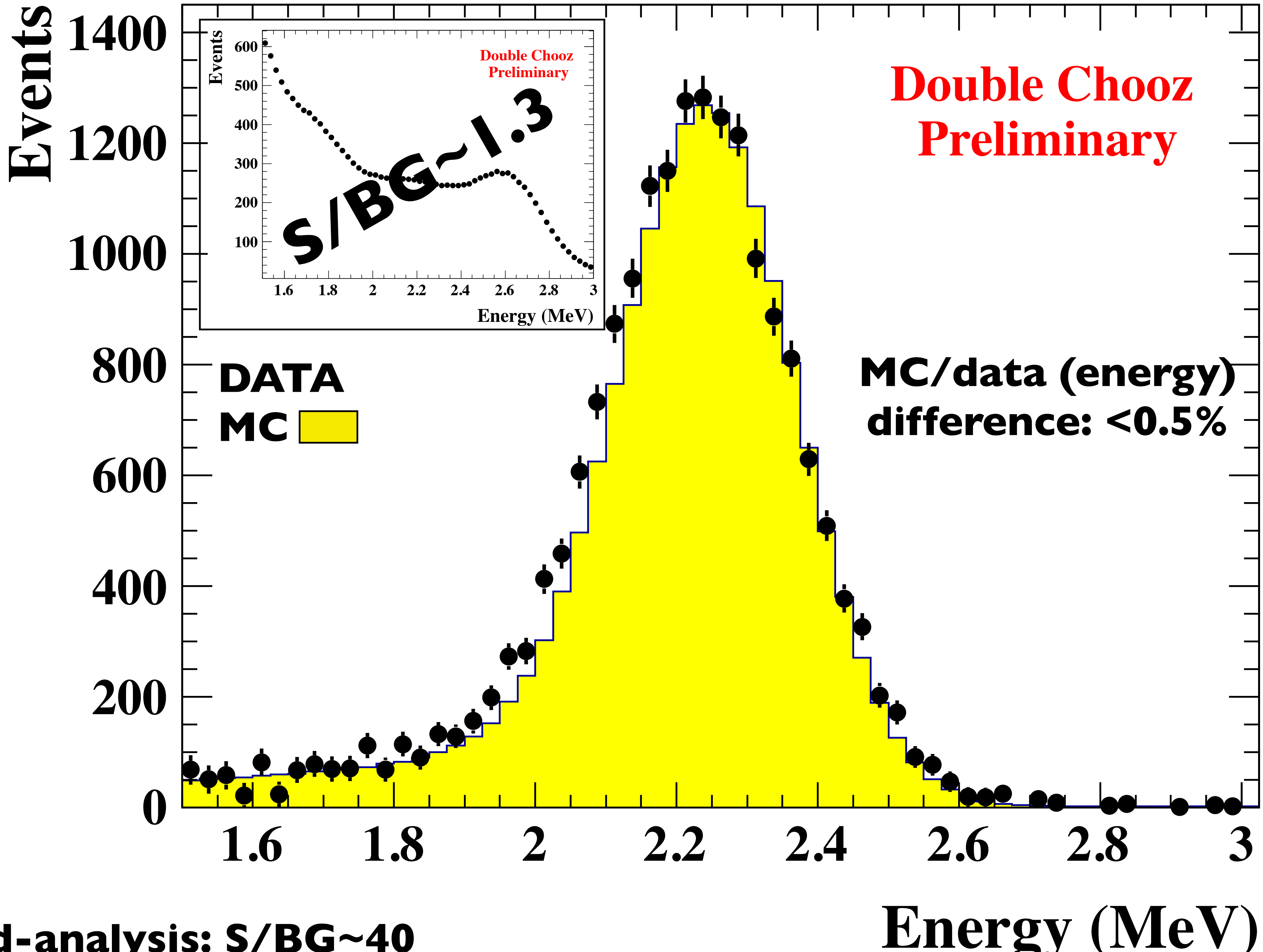
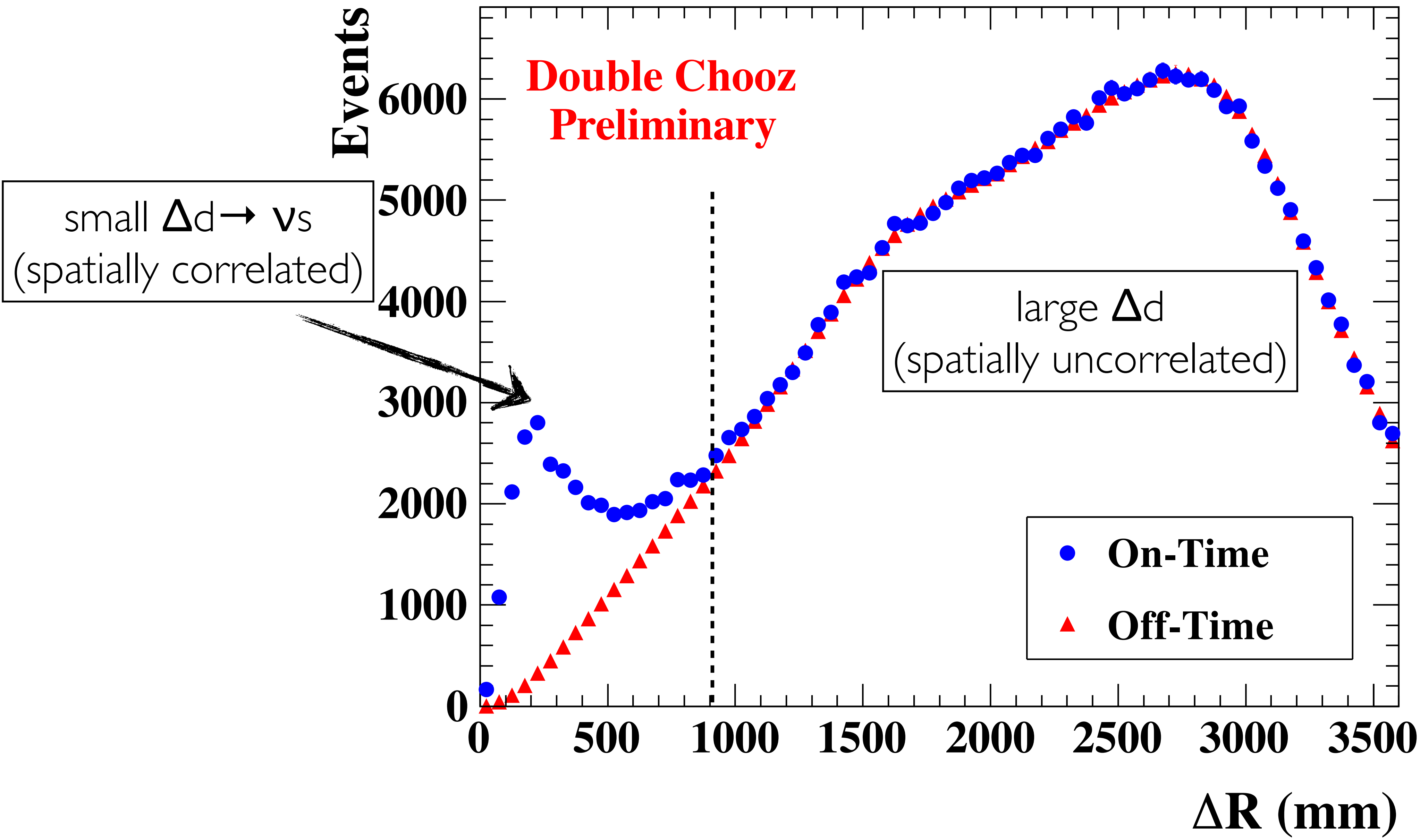
select IBD by capturing on H…



Gd-analysis: S/BG~40

killing accidentals: cut on Δd(prompt-delay)…

excellent precision on vertex-reco→**narrow Δd** (correlated events)



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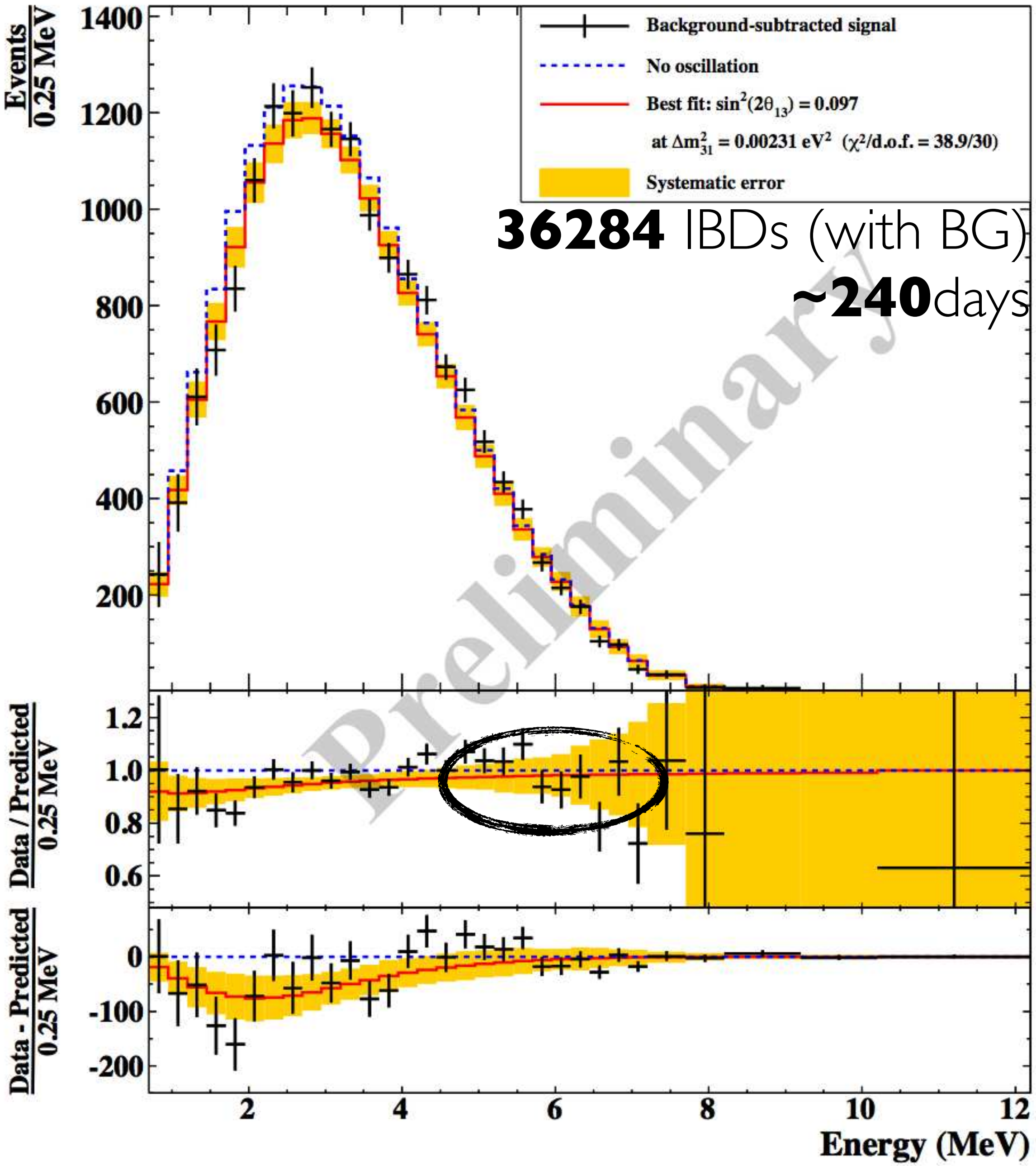
DC-II(H) rate+shape θ13 measurement…

BG subtracted…

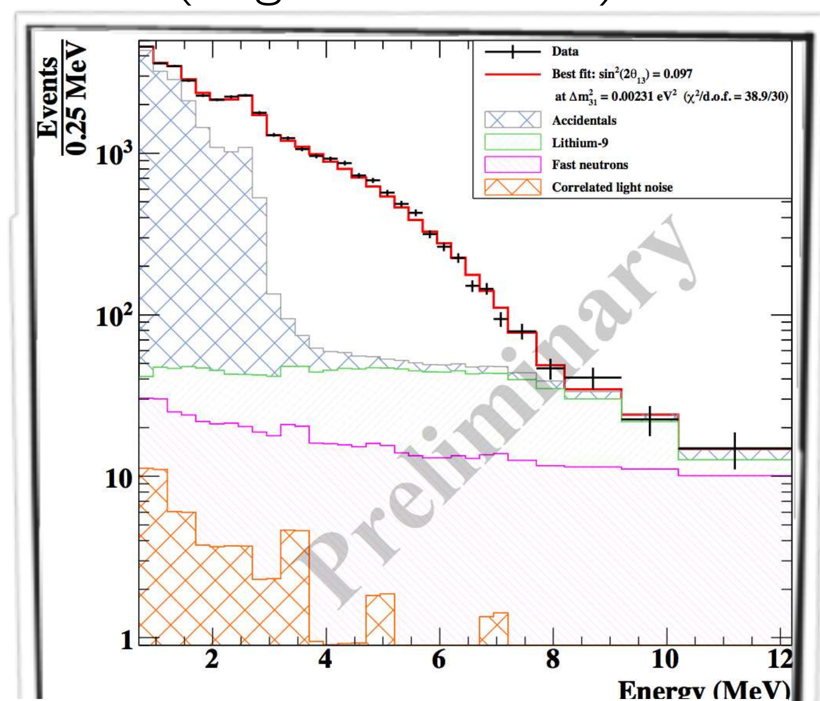


systematics budget…

Source of uncertainty	n-H variance	n-Gd variance
Total statistical error	1.05%	1.12%
Accidentals	0.21%	0.01%
Li-9	1.50%	1.46%
Fast neutrons	0.61%	0.54%
Correlated light noise	0.09%	N/A
Energy scale	0.34%	0.32%
Detection efficiency	1.57%	1.01%
Reactor	1.75%	1.76%

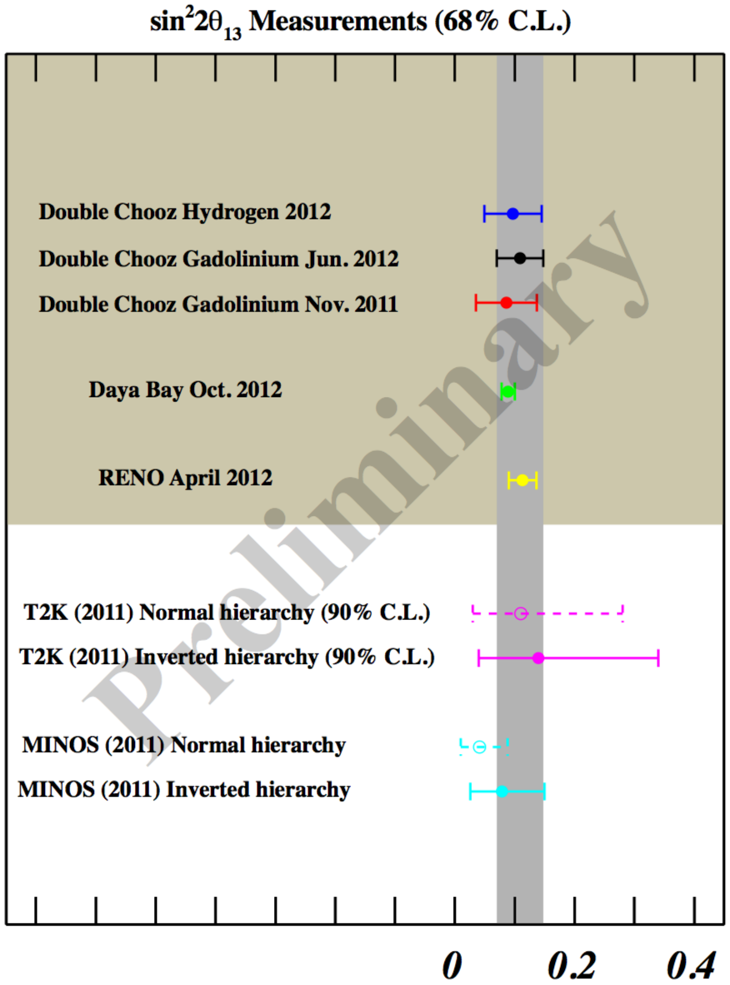
p on target: $6.75\times10^{29}\pm0.3\%$(T)+$1.58\times10^{30}\pm1.0\%$(GC)

with BGs (huge accidentals)…



DC-II(Gd) and DC-II(H) compatible to (68-84)% (depending on correlation)

results summary…

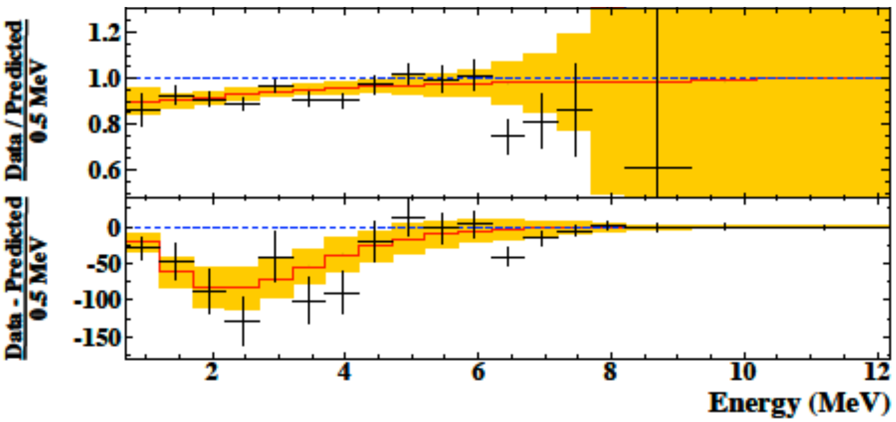


- amazing progress end-2011/2012…
- **all results are consistent**…
    - coherent picture: **θ13 is LARGE**
    - coherence test not tight (more precision)
- accuracy→most important with higher precision
    - **Daya Bay leads the way** (for now)
    - redundancy is a must (& on the way)

	$\sin^2(2\theta_{13})$	exposure (days)	arXiv
DC_{Gd}I(rate+shape)	$0.086\pm0.051(0.041^{stat}\pm0.030^{sys})$	96.8	1112.6353
DB-I(rate)	$0.092\pm0.017(0.016^{stat}\pm0.005^{sys})$	55	1203.1669
RENO-I(rate)	$0.113\pm0.023(0.013^{stat}\pm0.019^{sys})$	229	1204.0626
DC_{Gd}II(rate)	$0.170\pm0.053(0.035^{stat}\pm0.040^{sys})$	251	1207.6632
DC_{Gd}II(rate+shape)	$0.109\pm0.039(0.030^{stat}\pm0.025^{sys})$	251	1207.6632
DB II(rate)	$0.089\pm0.011(0.010^{stat}\pm0.005^{sys})$	139	1210.6327
DC_{H}II(rate+shape)	$0.097\pm0.048(0.034^{stat}\pm 0.034^{sys})$	240	**last monday**

E/L disappearance effects…

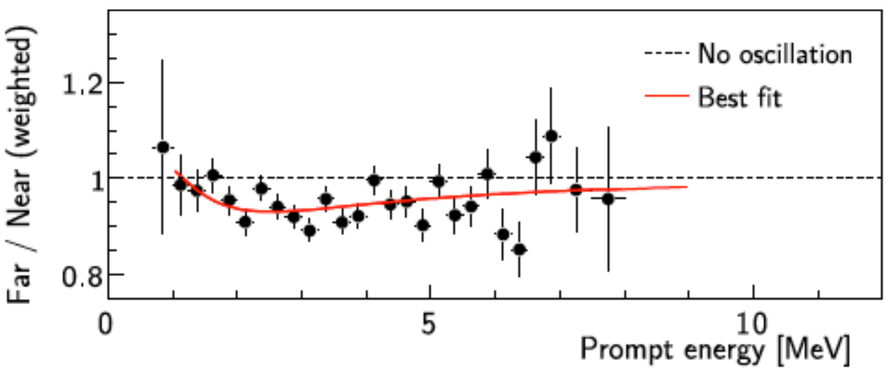
N(obs)/N(exp) vs Energy...



DC-II (Gd) (June'12)

<L>= 1050m

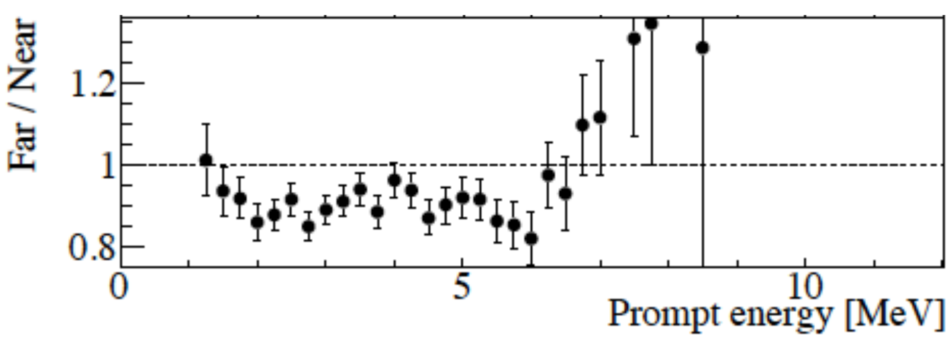
- short L→ hard to see rise (low constrain in Δm^2)
- **rate+shape** analysis (+ θ13 below <6MeV)
- DC-II(H)→ no structure @ 6MeV



DB (June'12)

<L>= 1648m

- L/E shape→ more sensitive to Δm^2
- "healthy" shape but **rate only** (no p-value)



RENO (April'12)

<L>= 1383m

- shape: **consistent with only θ13**?
- **rate-only** analysis→ all assumed to be θ13

strage behaviour (@ ~6MeV)?→ **rate+shape analysis a MUST!**

Anatael Cabrera (CNRS-IN2P3 & APC)

the θ_{13} challenge (systematics)…

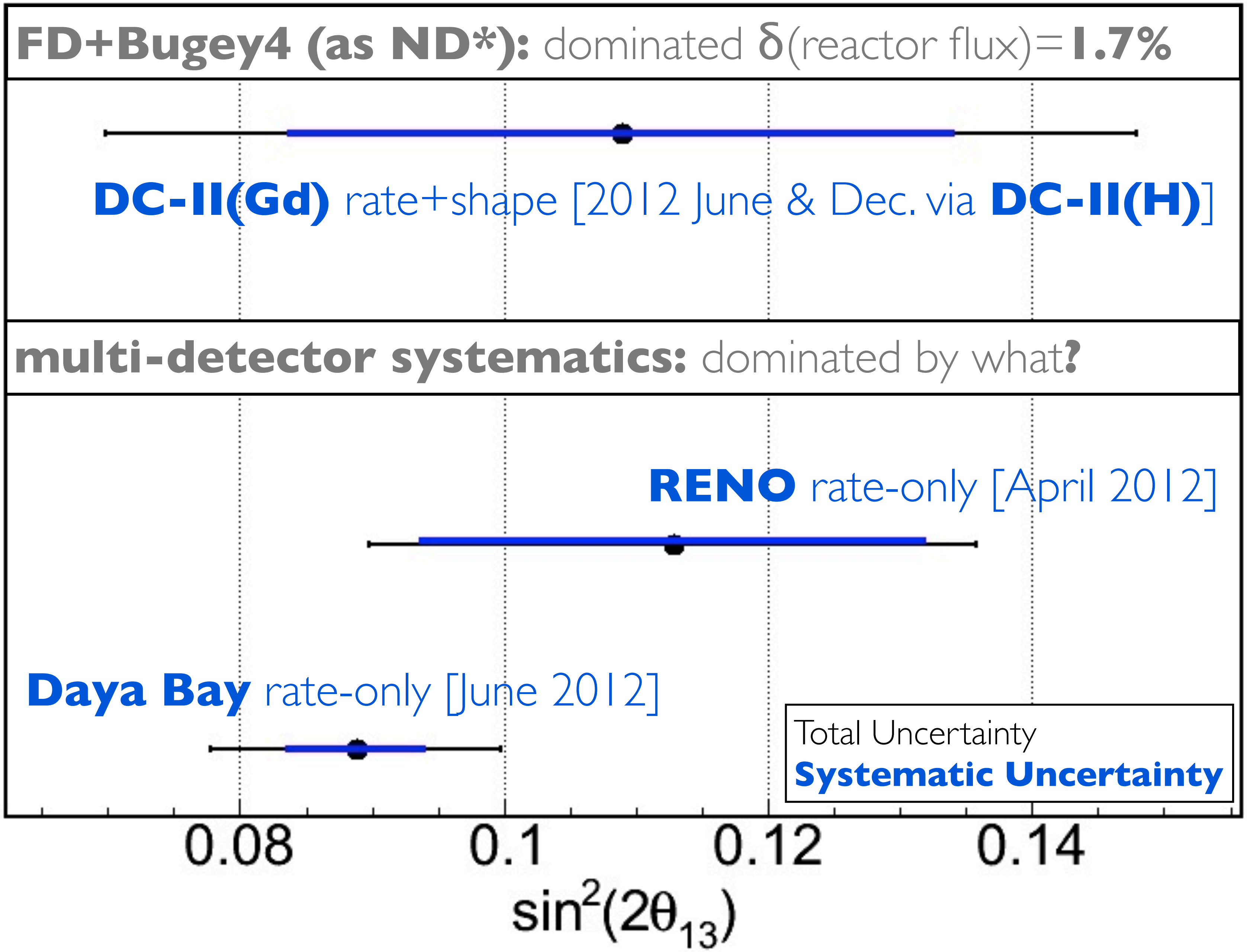
Anatael Cabrera (CNRS-IN2P3 & APC)

θ13 reactor challenges

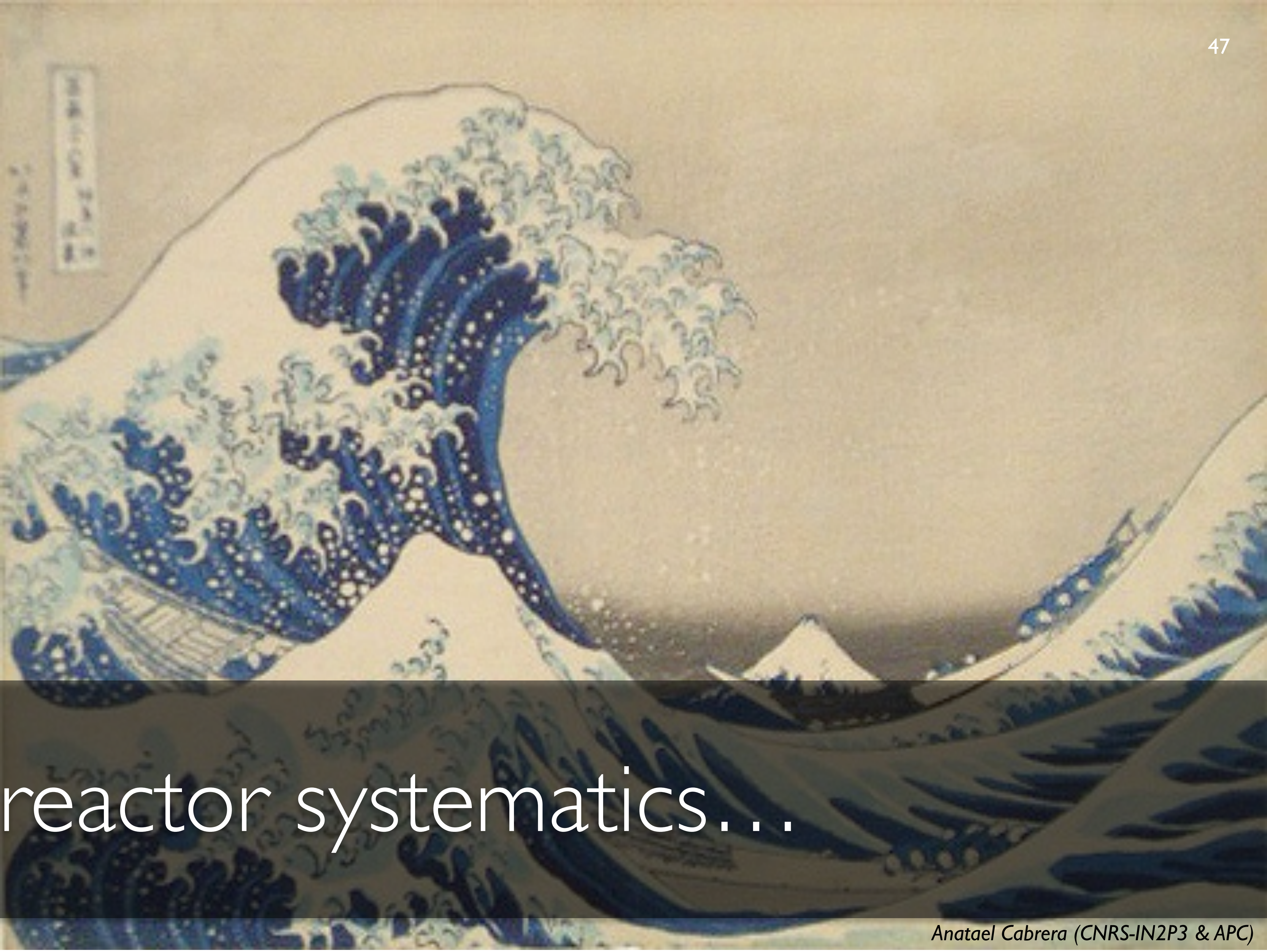
- **statistical uncertainty**
  - generally all experiments enough (DC a little too small)
- **δ(flux): flux uncertainty (→impacts mainly rate)**
  - ND critical→ eliminates primary reactor flux and spectral shape uncertainties
  - issue: **uncorrelated reactor** systematics
- **δ(detection): detection uncertainty (→impacts mainly rate)**
  - ND critical→ eliminates many inter-detector detection systematics
  - excellent detector understanding (**energy-reco** and **MC**)
  - issue: **uncorrelated inter-detector** systematics
- **δ(BG): backgrounds uncertainties (→impact both rate & shape)**
  - each site a different BG☐ rate and shape (specially correlated BG)
    - ND more signal but also more BG→ shapes can also be different
  - issue: **normalisation and shape of each BG** (with reactor ON→hard!)
- **warning: high-precision physics** (i.e. systematics @ "per-mil" level)
  - **first word** (**fast**)→ impressive θ_{13} (large) measurement "overnight"
  - **final legacy** (**slow**)→ cross-checks for best θ_{13} world knowledge

it's all about systematics...

my goal: explain to you ***how systematics are controlled***...
(please note **per-mil** systematics→ very careful)



√2P3 & APC)



reactor systematics…

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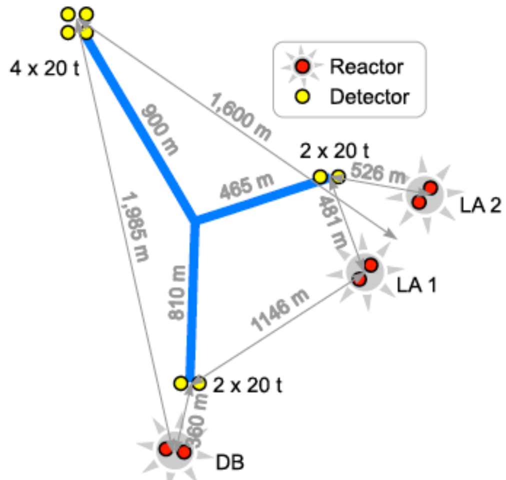
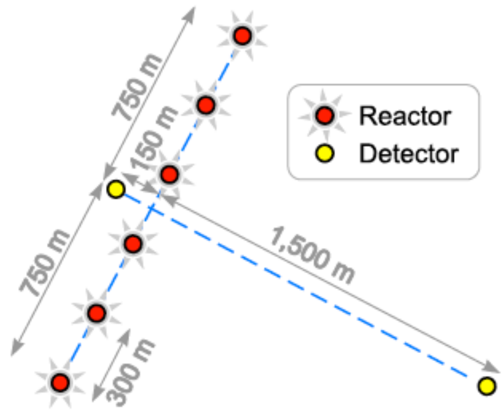
reactors vs detectors interplay…

multi-detector: "kill" δ(flux) totally? yes…? (proposals)

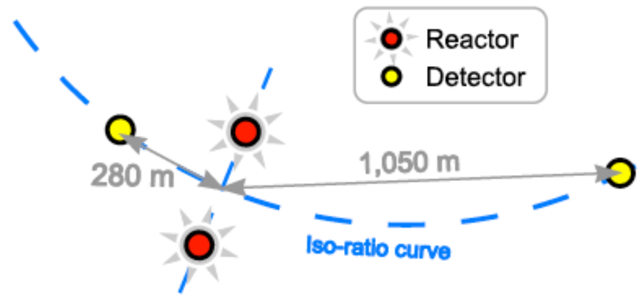
Daya Bay



RENO



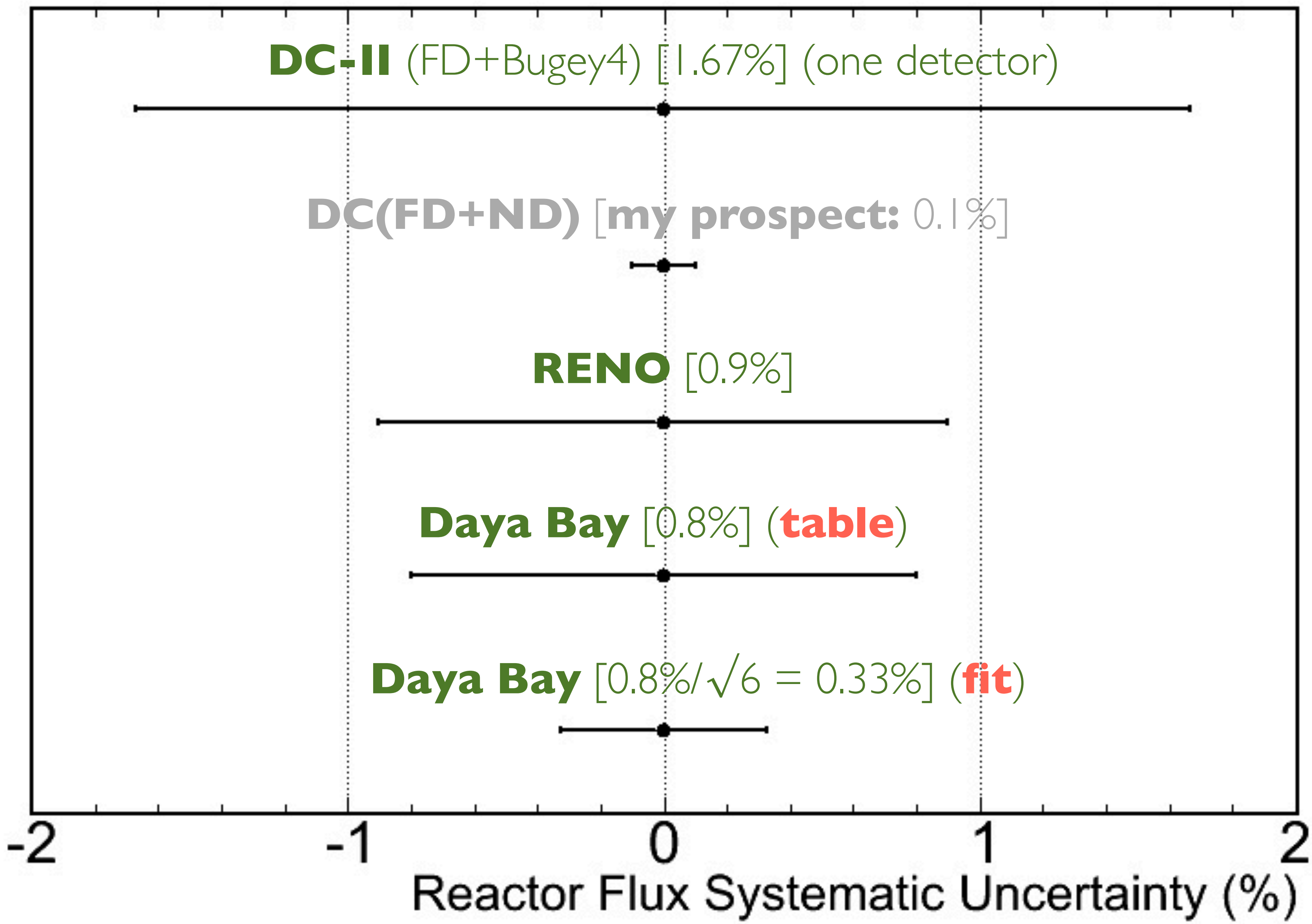
DC



δ(flux): 0.8% (DB), 0.9% (RENO), ?(0.1~0.3)% (DC)
(*"uncorrelated reactor flux uncertainty"*)

- **RENO/DB:** ~0.5% (thermal power) & ~0.6% (fission fractions)
    - **extremely hard to improve this** (impossible?)
- geometry is **critical**…
    - *"Rate(FD)/Rate(ND) per reactor and per ND?"*
        - **DB→ δ(flux)=0.8%/√6** (fit)
        - **RENO→ δ(flux)=0.9%** (impossible to improve?)
        - **DC:** almost isoflux→ **δ(flux)≤0.3%** (**under study**)
- **δ(flux) dominant uncertainty for DB & RENO [→ not DC!]**

reactor flux uncertainty…



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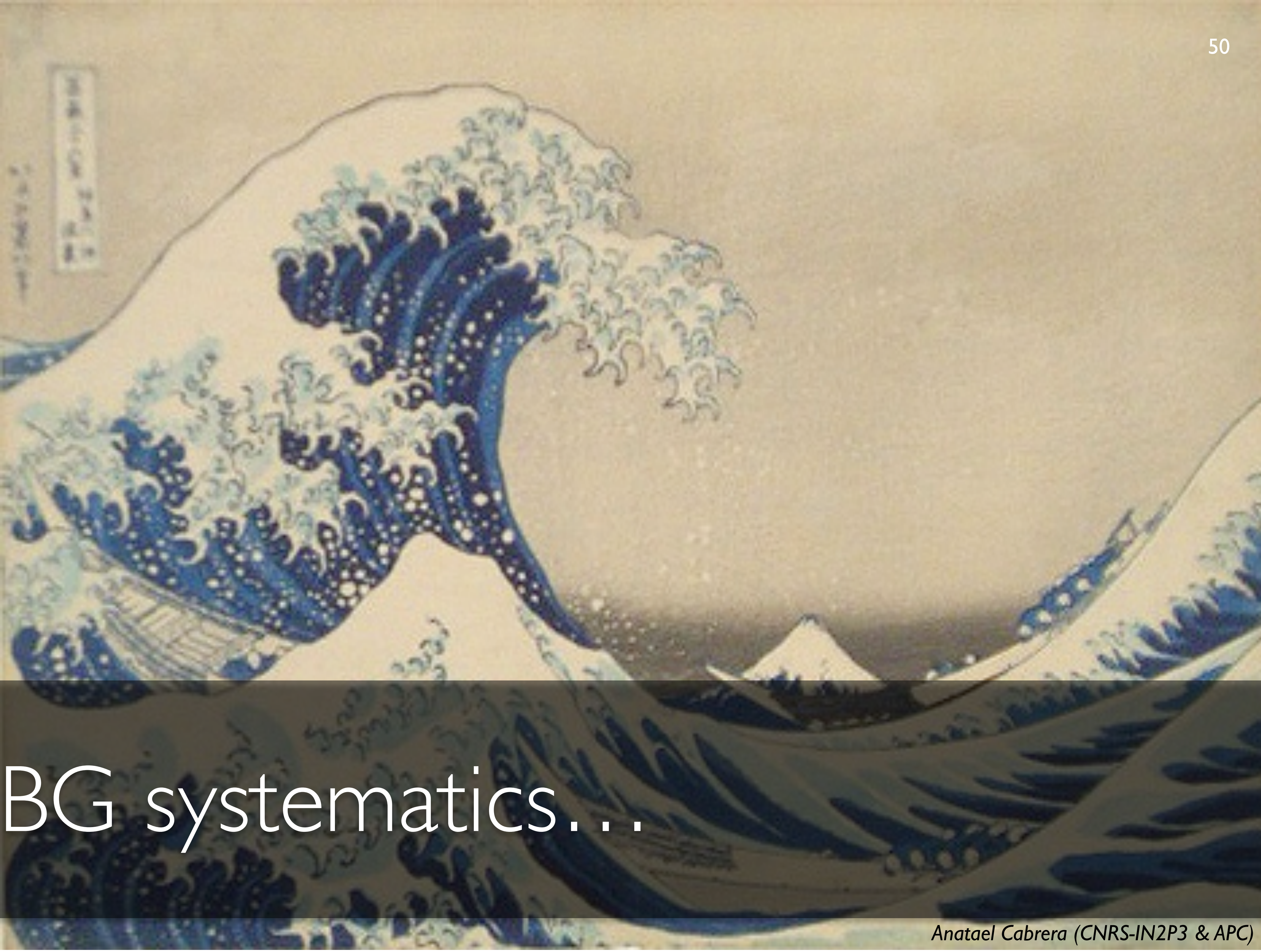
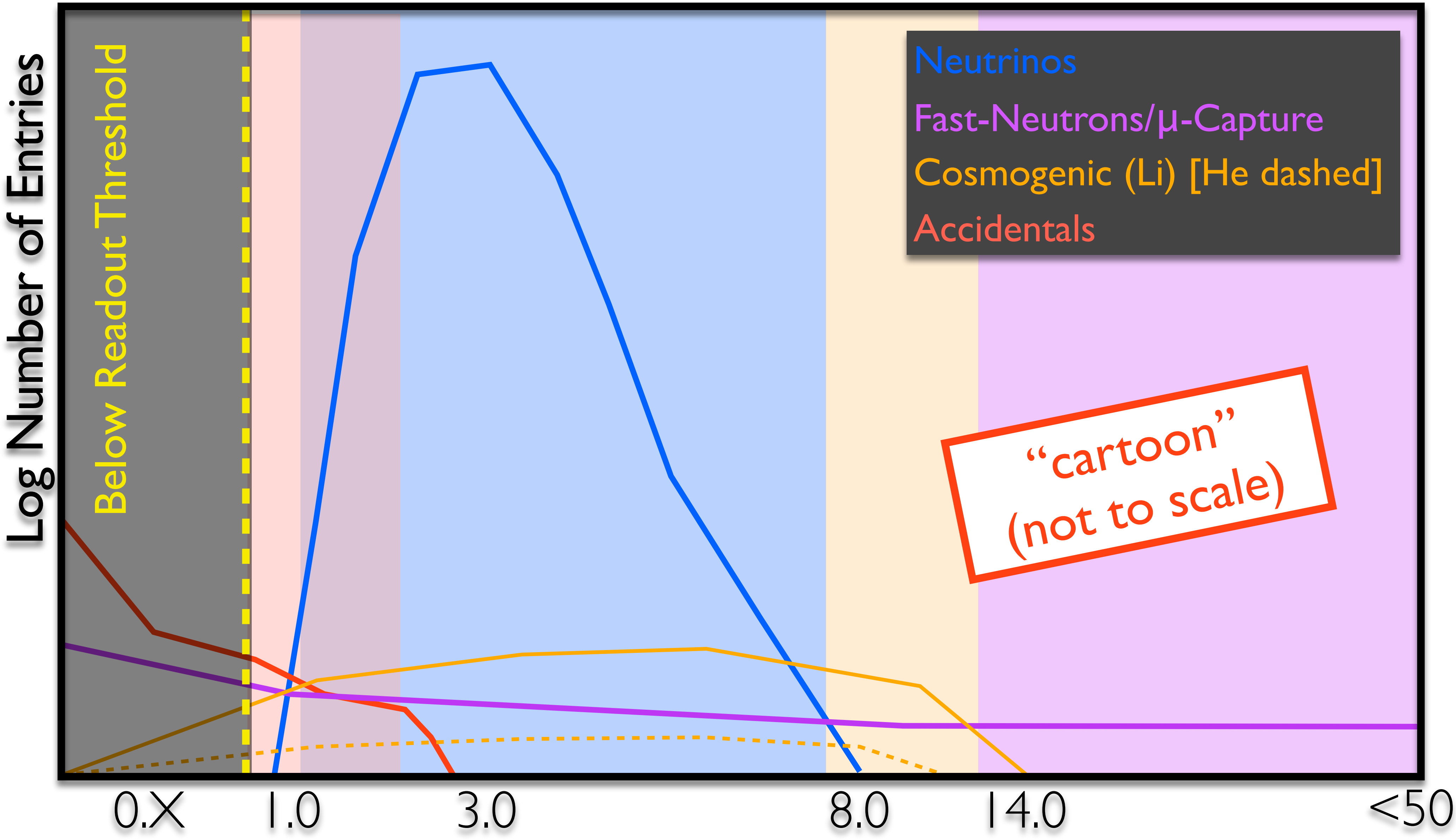


BG systematics…

Anatael Cabrera (CNRS-IN2P3 & APC)

BG model (CHOOZ+KamLAND)…

is this the full story?
(so far, entirely assumed by all experiments)



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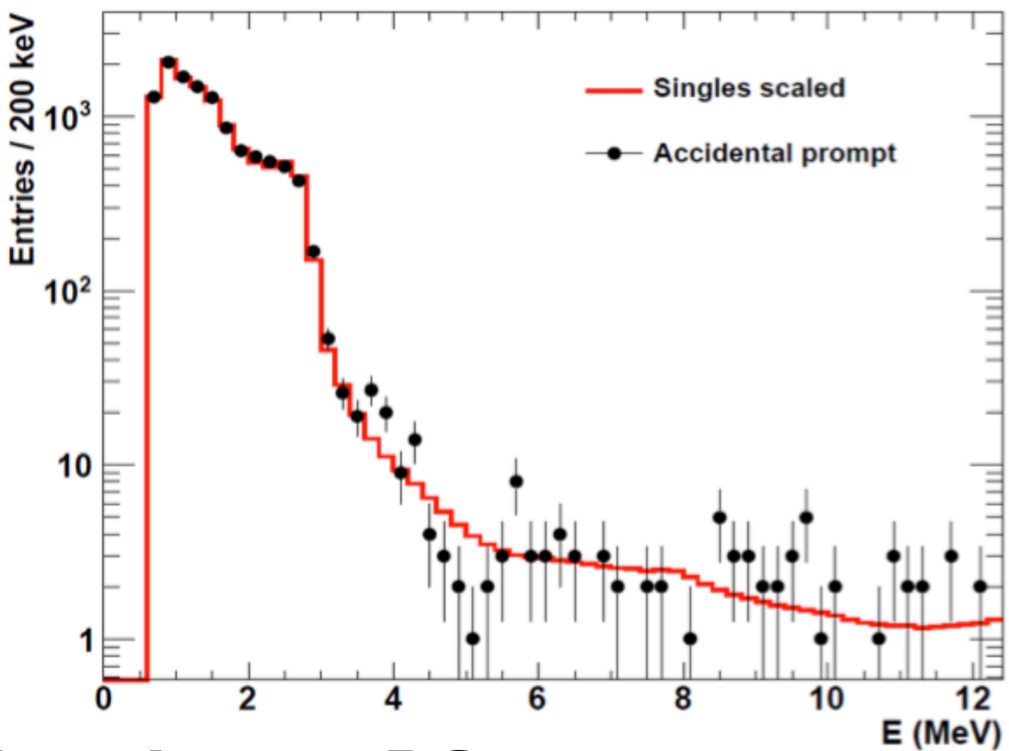
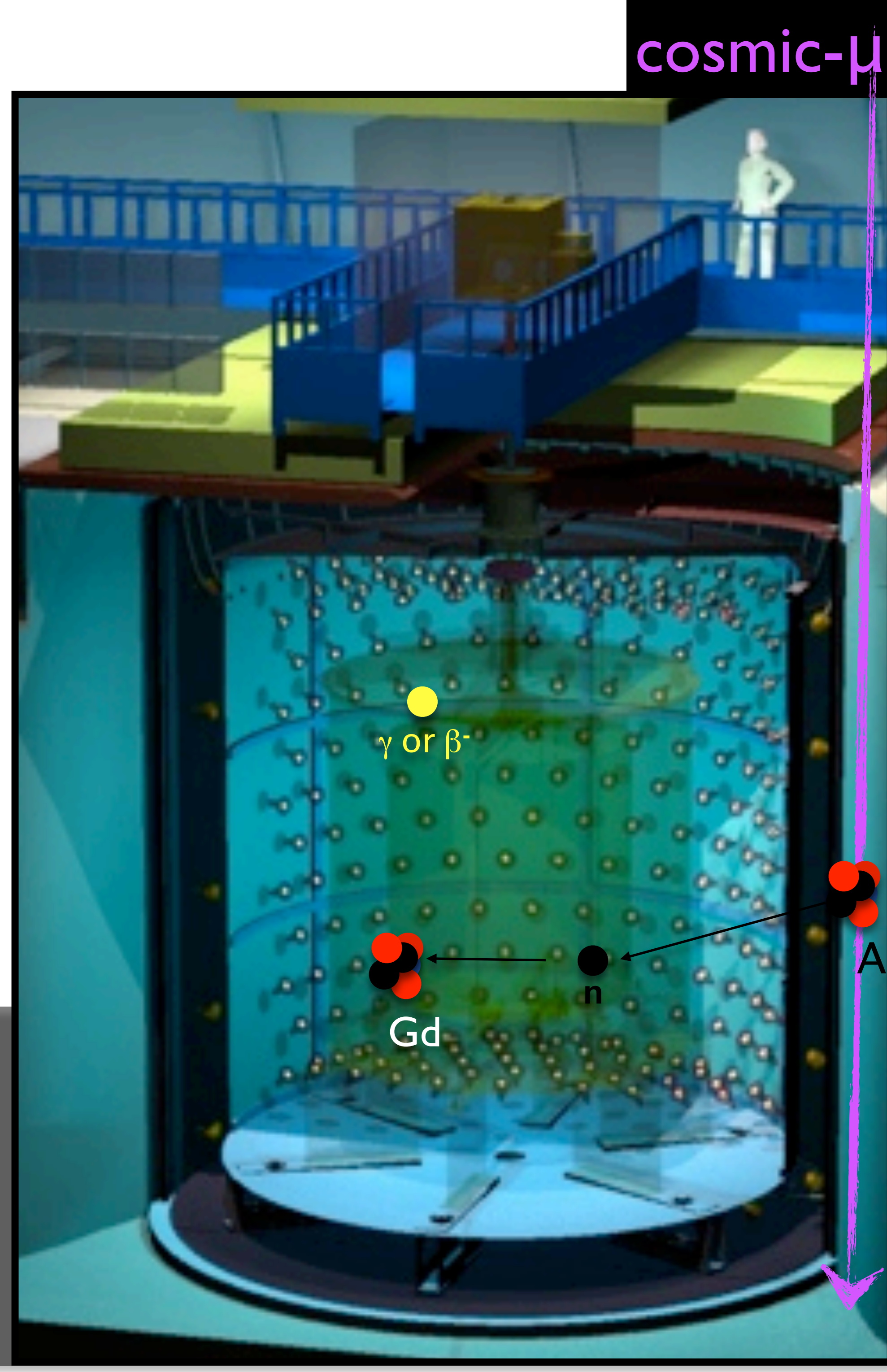
individual measurement…
(all experiments)



best known BG...

- δBG/Signal→0 (i.e. no rate systematics)
- (if large) distort shape @ oscillation region

accidental BG...



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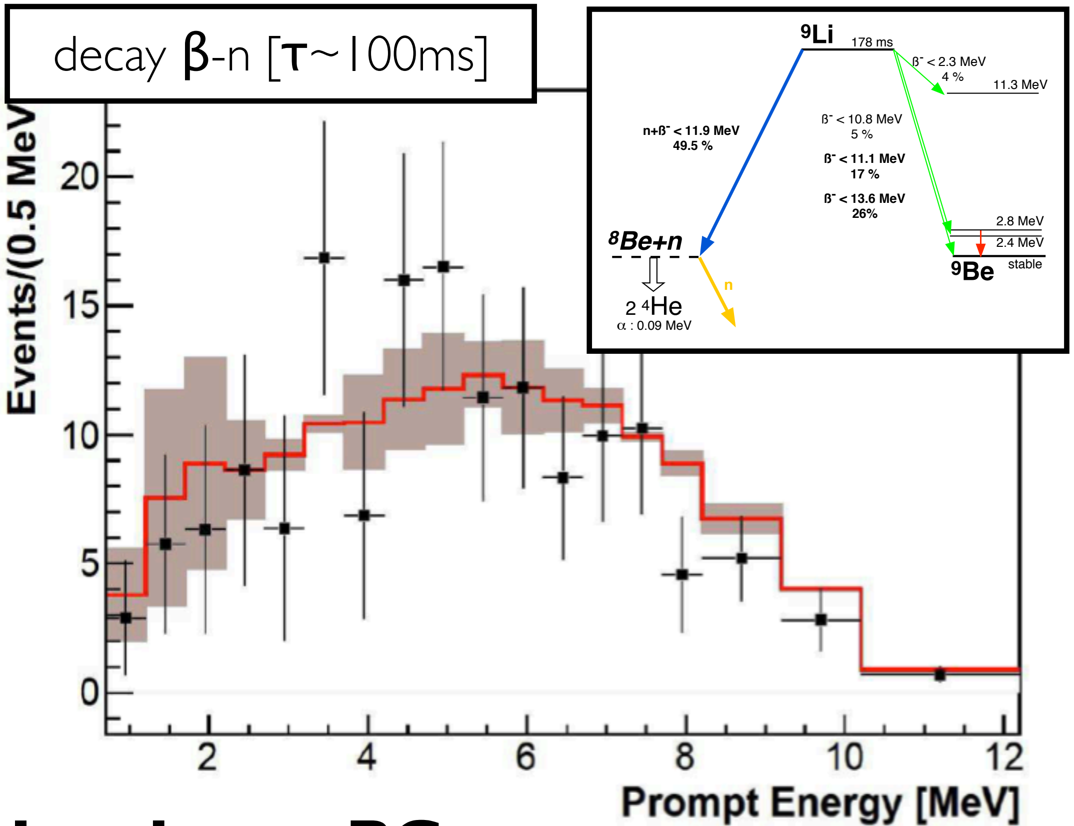
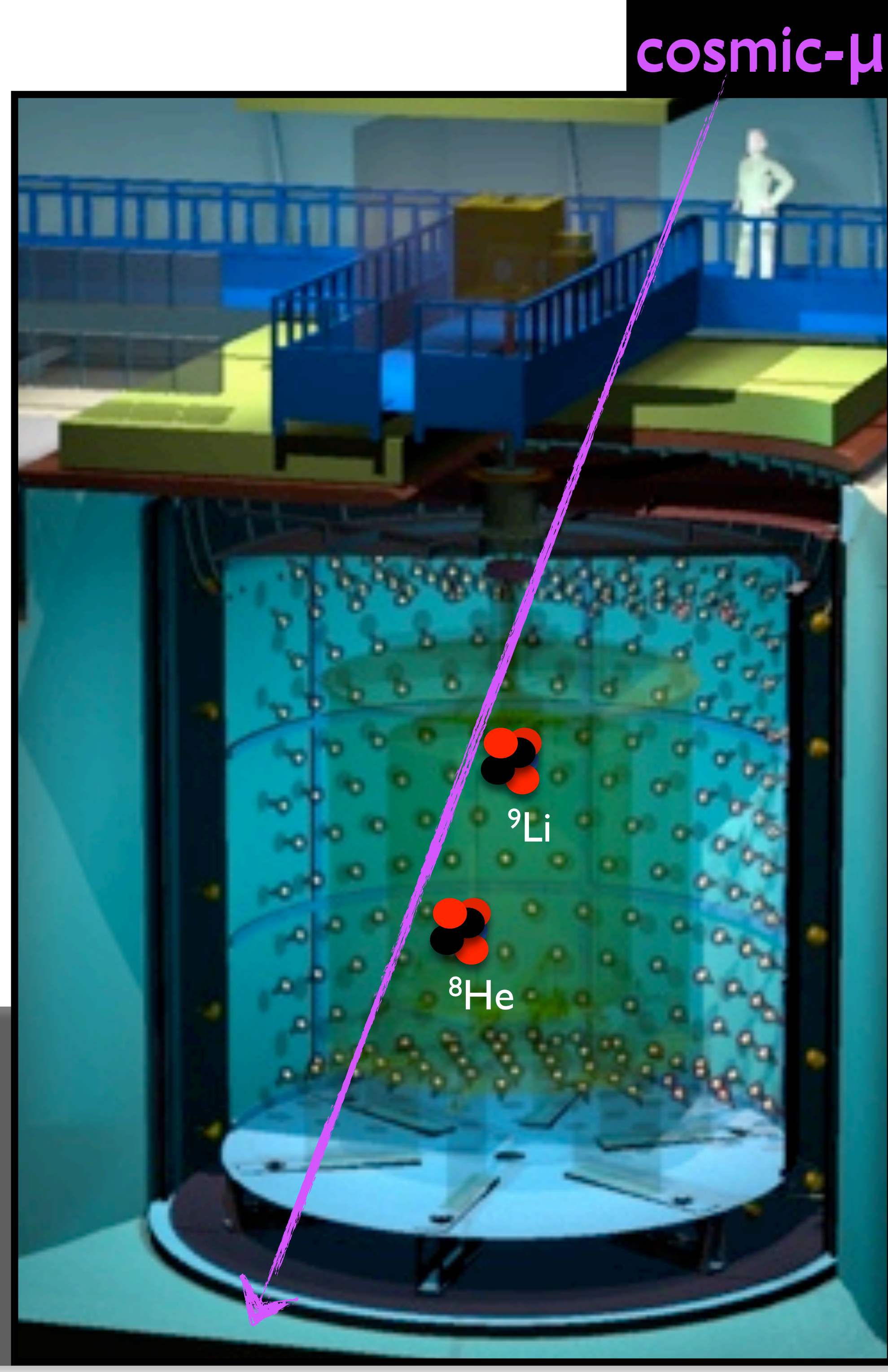


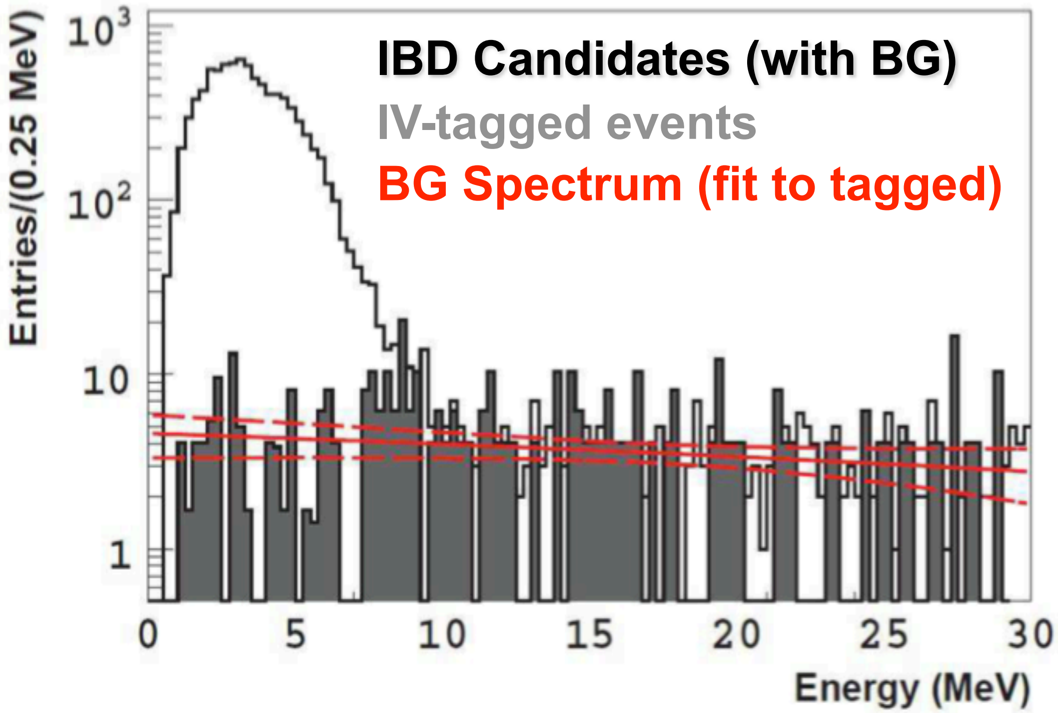
less know BG...

- δBG/Signal→largest (rate systematics)
- poorly known shape (MC→KamLAND)

cosmogenic BG... (^{9}Li and ^{8}He)



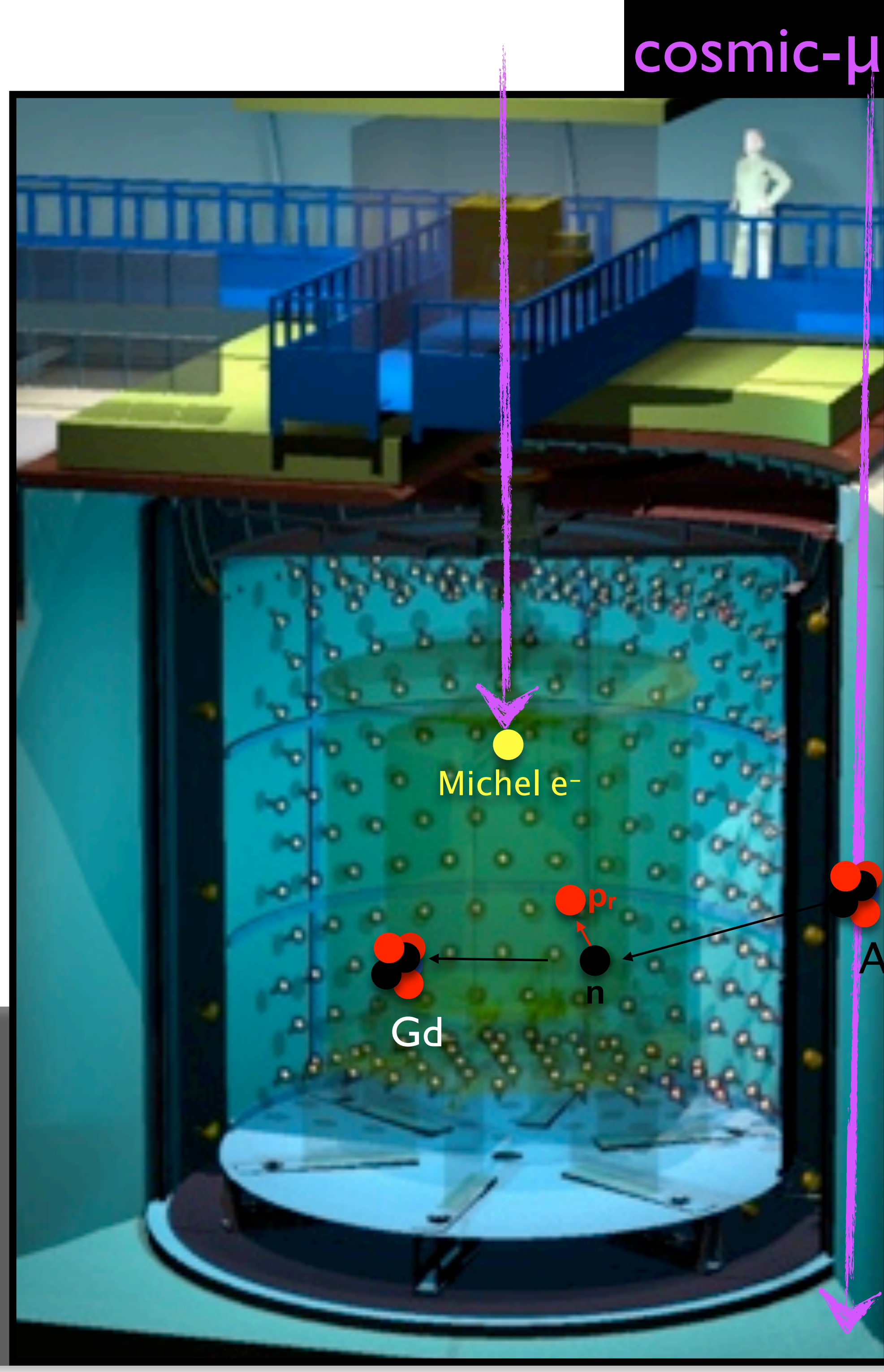
Anatael Cabrera (CNRS-IN2P3 & APC)



most difficult BG...

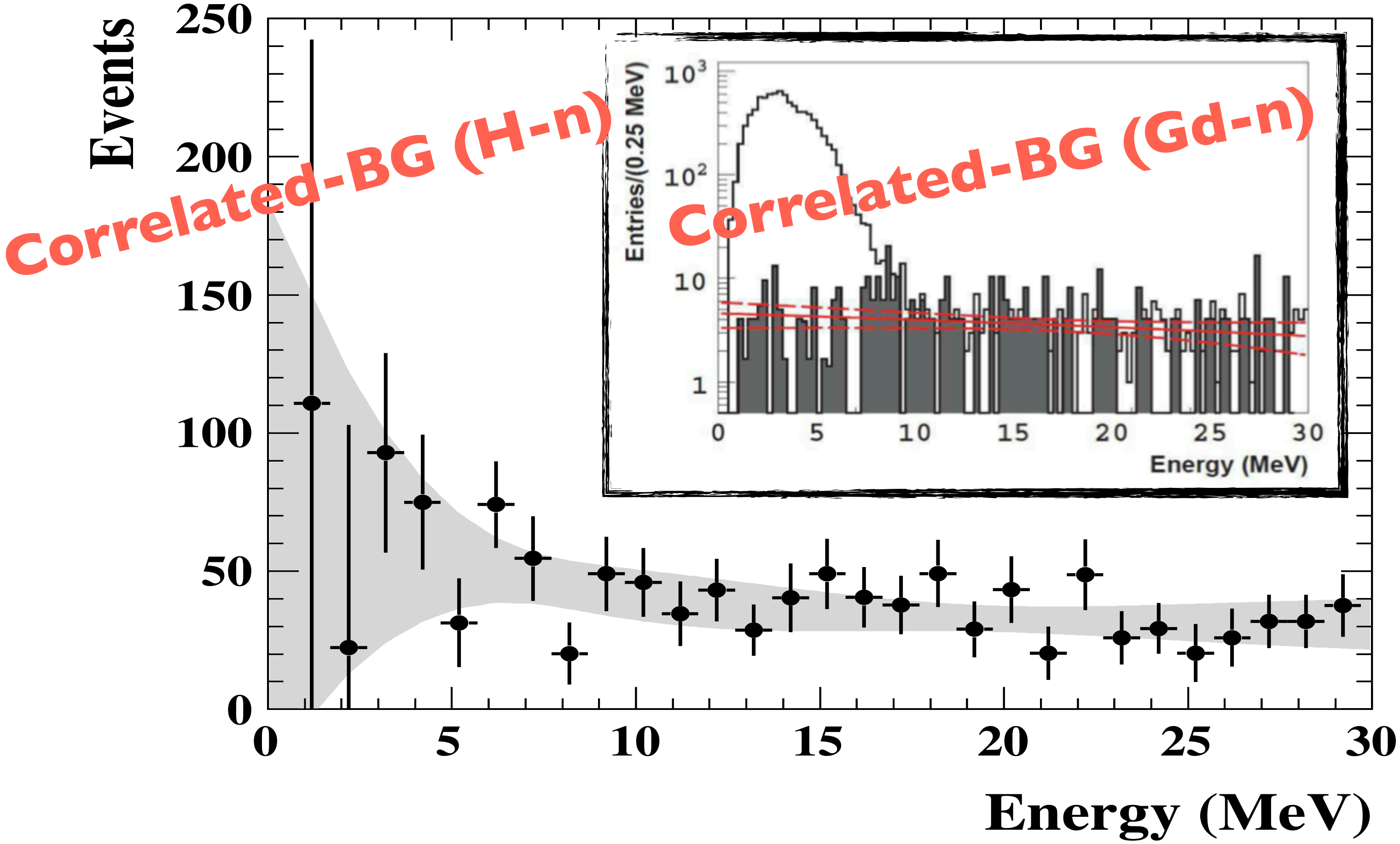
- shape varies per detector (acceptance & overburden)→ shapes could mimics θ13
- poorly known shape (not easy to MC)

correlated BG... (fast-n & stopping-μ)



Anatael Cabrera (CNRS-IN2P3 & APC)

Correlated BG measurement

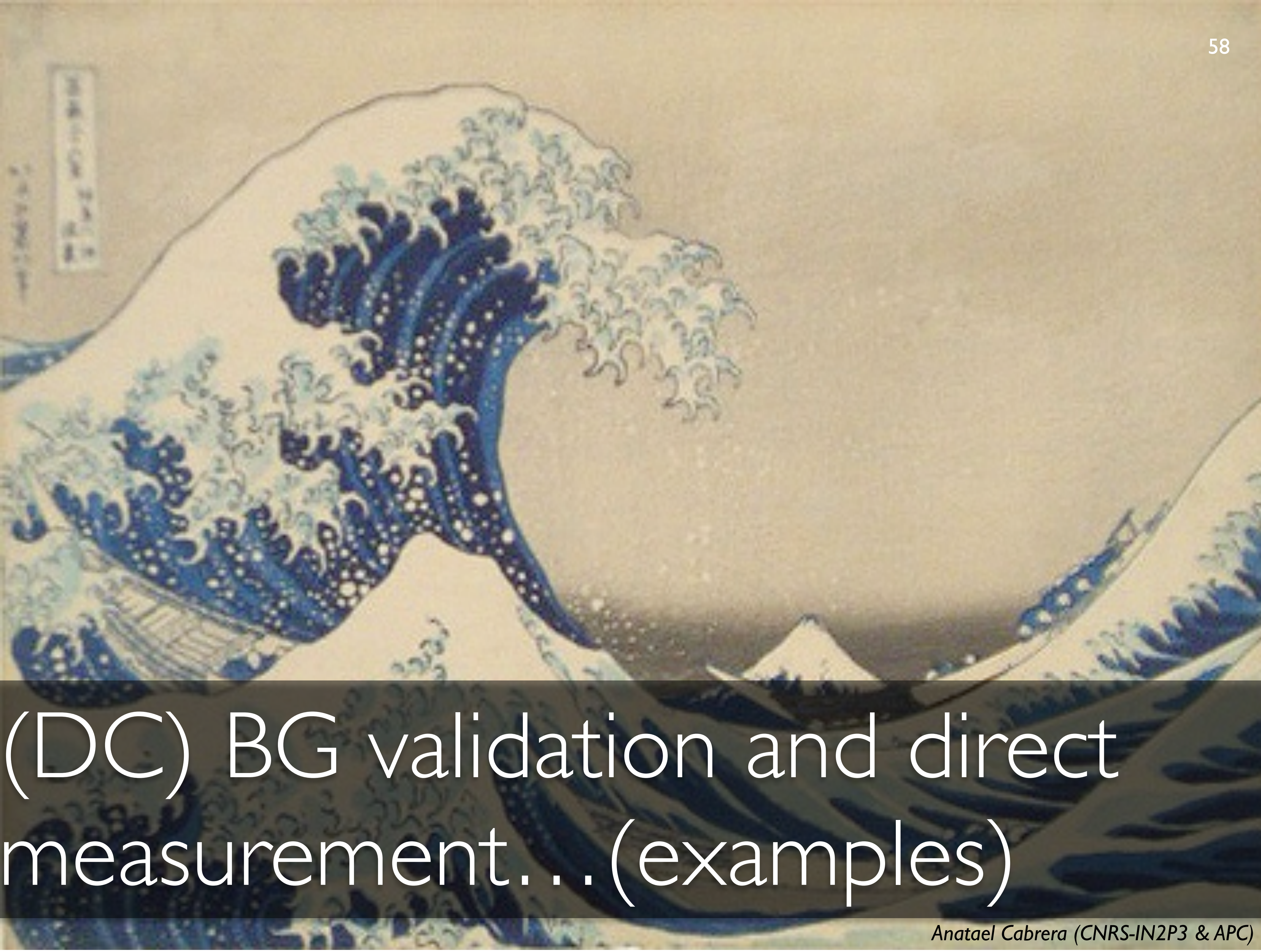


- **proton-recoil spectrum @ low energies** (**very challenging**)
  - neutron energy dependence→ size of buffer and γ-catcher
  - proton quenching effects→ difficult to MC (data-driven)
- **must measure with data**→(DC) IV & OV tagging mechanisms
- **DB/RENO:** extrapolate from high-energy (>14MeV): **too naive?**
  - **DC:** up to **~25% bias** in normalisation (rising shape @ low energies)
  - BG-spectrum **resembles θ13 signature** (slope-like)→**bias θ13?**

Anatael Cabrera (CNRS-IN2P3 & APC)

measuring & validating BG model…

- **BG measurement:** rate (much easier) & shape (statistics limited knowledge)
  - CHOOZ BG (reactor OFF: no need for a model)→ Li (by KamLAND)
  - **BG improves with time:** ≤1BG per day
- **1(all): measure each BG** (sample) **with reactor ON**
  - **cons:** sub-sample (different selection) & approximations/extrapolations
    - corrected/scaled (**accuracy?**) & complete (**new BG?**)
- **2(DC): fit θ13+BGs** (shape analysis) **with reactor ON**
  - **pro:** use knowledge a priori (method-1)→propagate to θ13 (correlations)
  - **cons:** interpretation of pull-info (degeneracies) & and lack of knowledge still
- **3(DC): reactor OFF direct measurement** (total rate validation)
  - **pro:** direct measurement (no assumptions)→**complete** (à la CHOOZ)
  - **cons:** stats very limited (DC: 1 week only)→ no info on BG shape
- **4(DC): observed vs expected correlation**
  - **pro:** combined use of both reactor ON/OFF→**BG rate estimation**
- **5(DC): 2 Integration Periods** fit (a la "2-1 reactor" analysis)
  - **validation:** θ13 outcome is the same for 2IP~1IP (DC-II)→**BG robust!**



(DC) BG validation and direct measurement…(examples)

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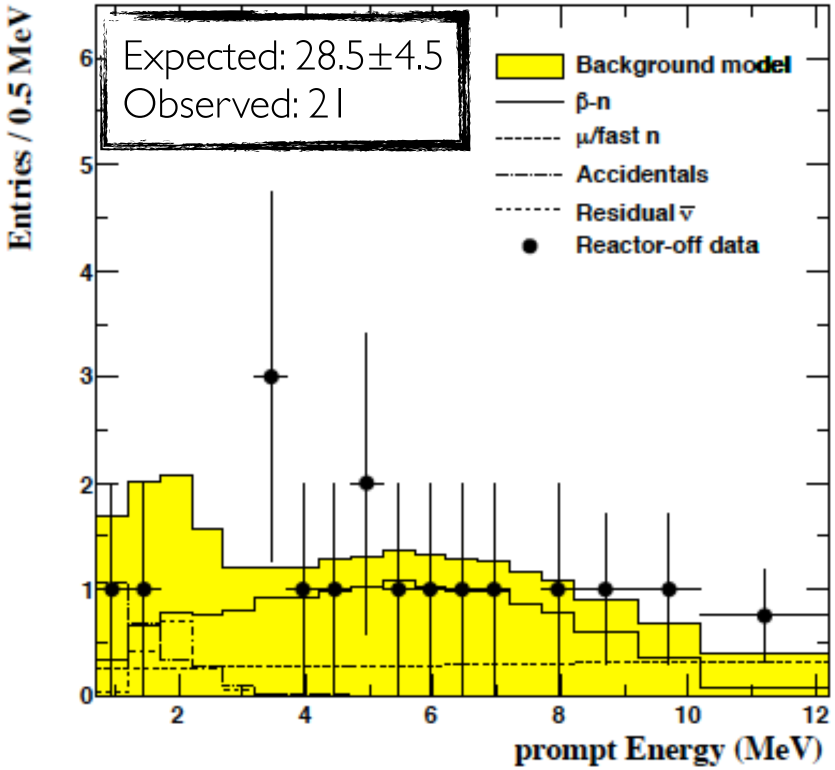
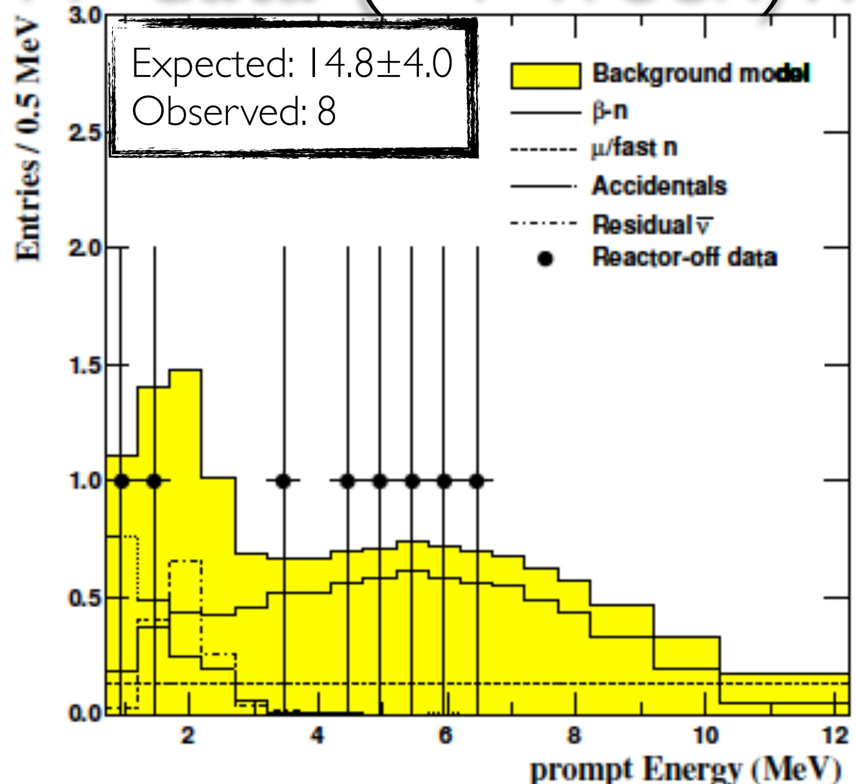
reactor OFF data (~1 week)...



DC-I(Gd) Selection

(2x more BG)



DC-II(Gd) Selection

(less BG → μ_{shower}-veto)

Rate (day^{-1})	β-n	Accidental	μ/fast n	Total Est.	Total Obs.
DCI	2.10±0.57	0.35±0.02	0.93±0.26	3.4±0.6	2.7±0.6
DCII	1.25±0.54	0.26±0.02	0.44±0.20	2.0±0.6	1.0±0.4

validation with two BG-selections DC-I and DC-II (BG varies by ~2x)

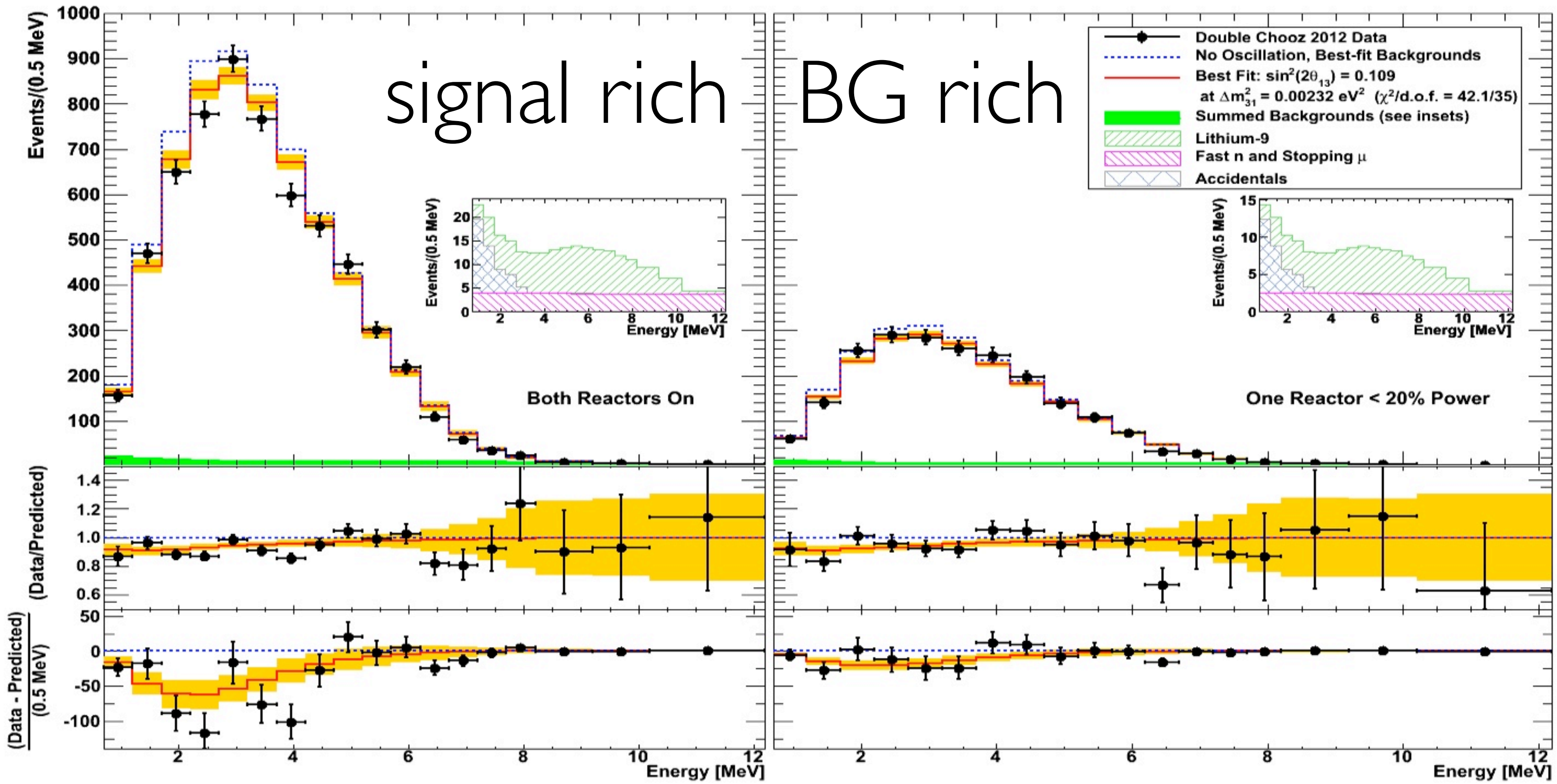
BG(observed) < BG(expected)

→**fluctuation?** σ^{stats} < 1.5σ, but **same trend seen shape-fit!**

Anatael Cabrera (CNRS-IN2P3 & APC)

rate+shape fit→θ13+BGs measure…

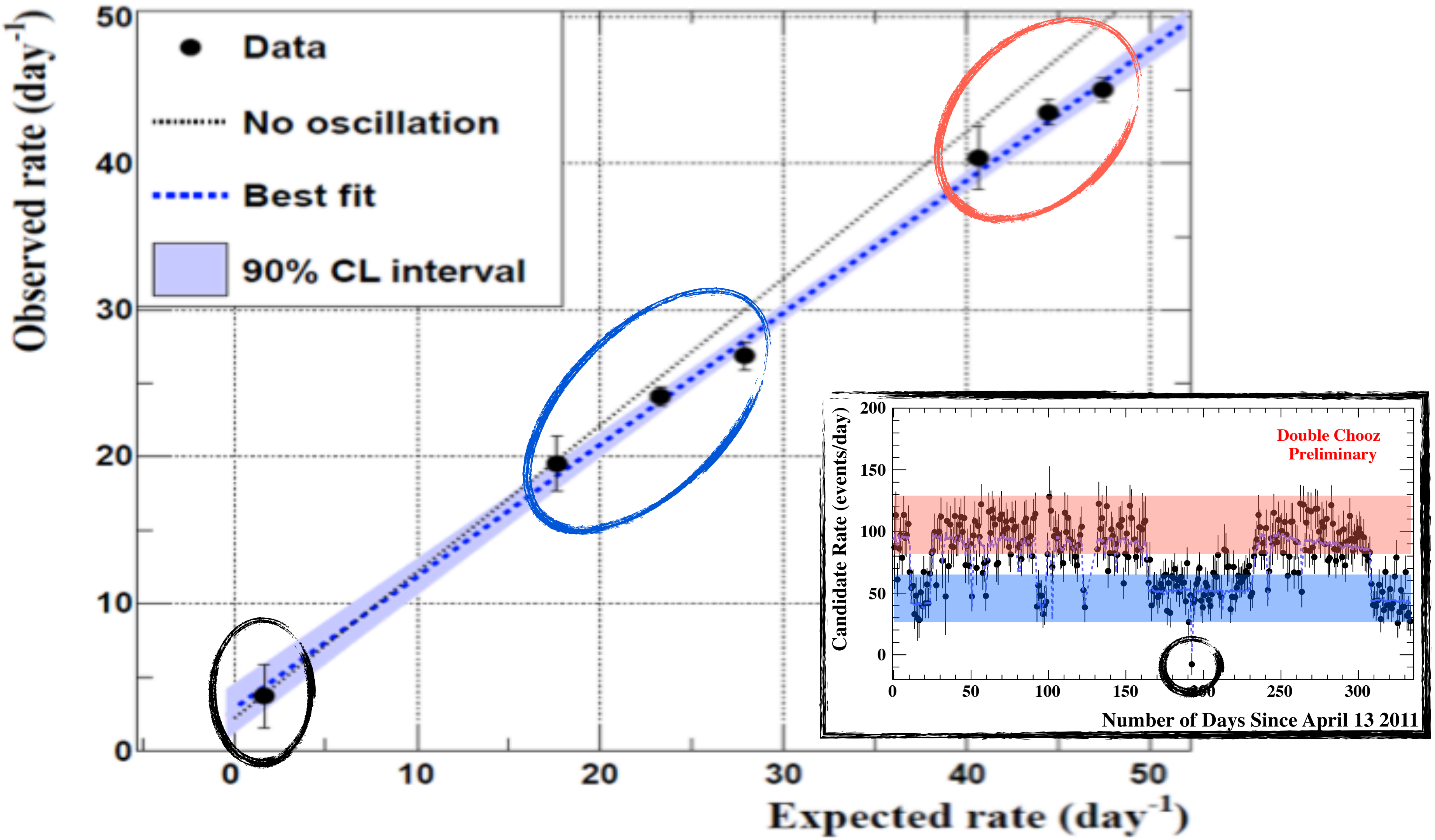
- **fit input:** full data + BGs rate&shape measurements (each)
- **fit output:** θ13 & (constraint) re-measurement of BGs (using shape)



- **BG(fit) <85% BG (rate-only)→ less subtraction (smaller θ13?)**
  - BG(fit) in excellent agreement with direct reactor-OFF measurements
  - all other experiment rely on rate BG measurement→ BG bias impact?
- θ13 is approx. the same with 1 or 2 Integration Periods→ result is BG robust

Anatael Cabrera (CNRS-IN2P3 & APC)

(**only validation**) observed vs expected rate…



- **disappearance** (i.e. $\theta_{13} \neq 0$)→ shallower slope
- **total BG measurement** is intercept (when expected rate→0)
  - Rate(BG) with and without reactor OFF data point→consistent
  - reactor-OFF data to constraint θ13→future (stay tuned)

Anatael Cabrera (CNRS-IN2P3 & APC)

summary BGs (@ FD)...

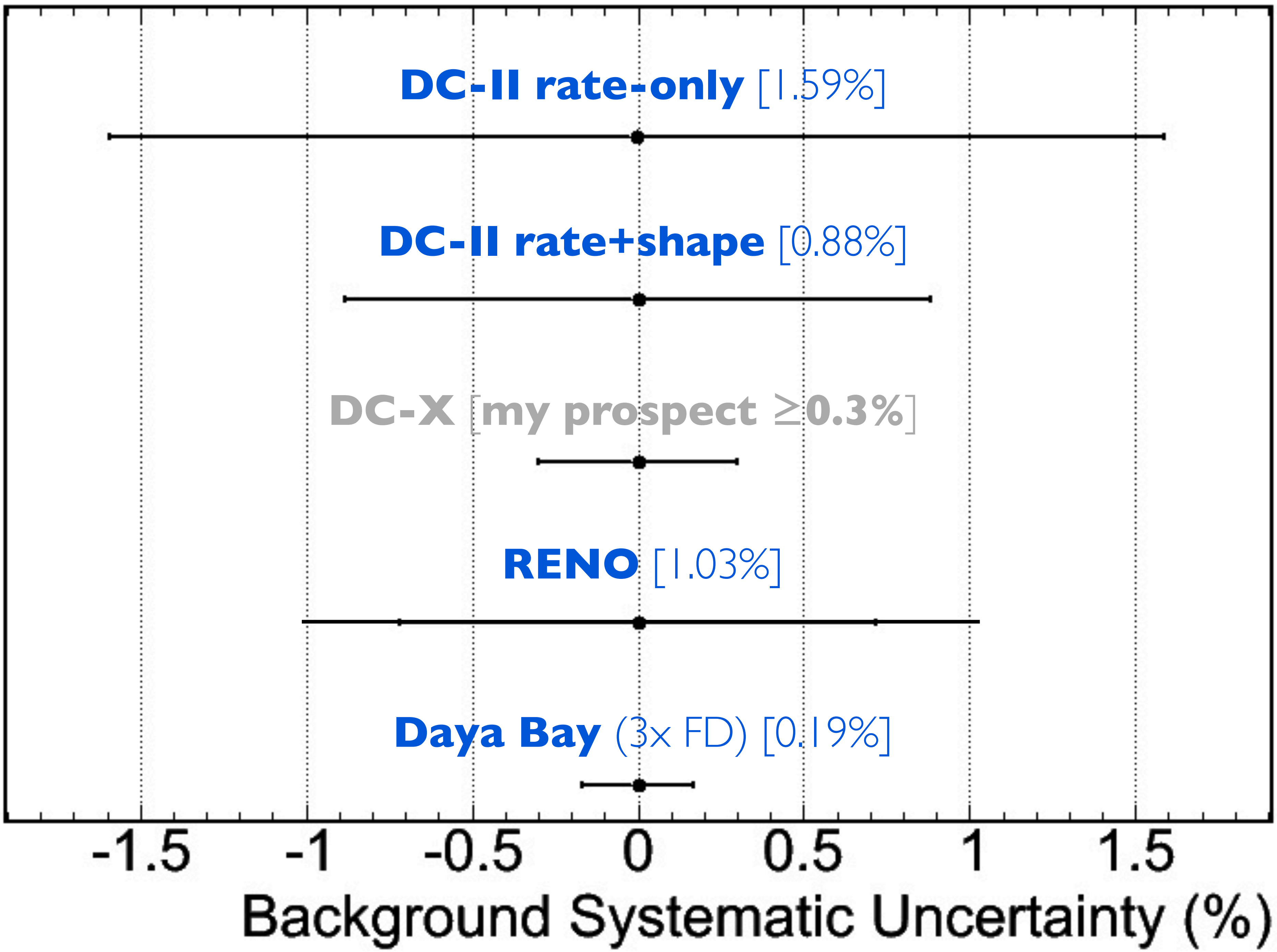
@FD	accidental [day^{-1}]	correlated [day^{-1}]	cosmo [day^{-1}]	"Am-C" [day^{-1}]	BG	δBG	δBG/BG (%)	BG/S (%)	δBG/S (%)	max. signal
DC-II	0.261±0.002	0.67±0.20	1.25±0.54	×	2.2	0.58	26.4	4.8	1.28	45
DC-II (fit)	0.261±0.002	0.64±0.13	1.00±0.29	×	**1.9**	**0.32**	16.7	**4.2**	0.71	45
DC-II (OFF)*	×	×	×	×	1.0	0.40	40.0	2.2	0.89	45
DC (H-n)*	73.45±0.16	2.50±0.47	3.00±1.00	×	79.0	1.12	**1.4**	79.0	1.12	100
RENO	0.68±0.03	0.97±**0.06**	2.59±0.75	×	4.2	0.75	17.8	5.3	0.94	80
DB (1xFD)	~3.30±0.03	~0.04±0.04	~0.16±0.11	0.2±0.2	3.7	0.23	6.3	5.3	0.33	70
DB (3xFD)	3x more	3x more	3x more	3x more	11.1	0.40	**3.6**	5.3	**0.19**	210
DB (4xFD)	4x more	4x more	4x more	4x more	14.8	0.47	3.2	5.3	0.17	280

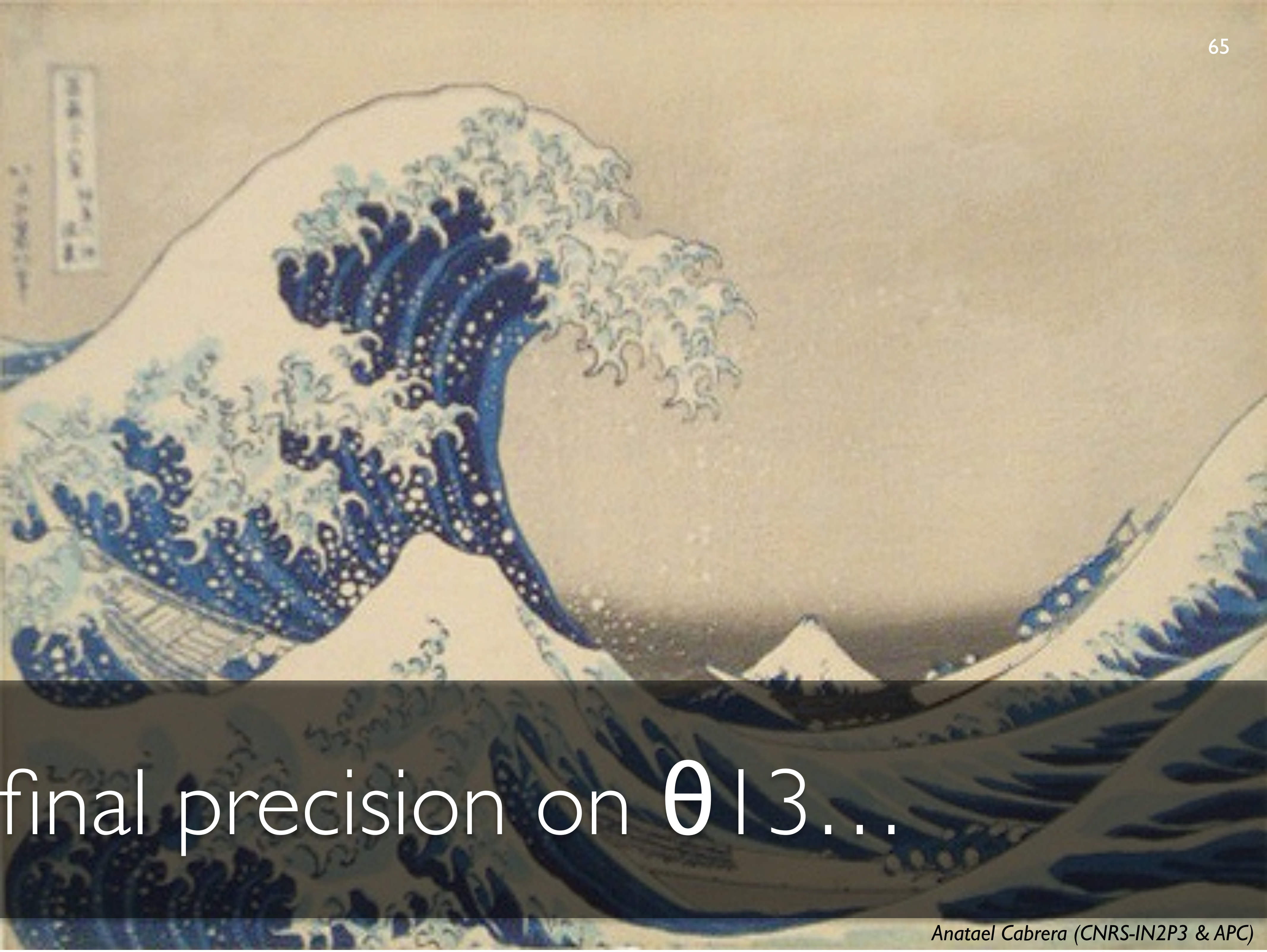
- cosmo & correlated **BG knowledge is statistics dominated**
- **DB lowest cosmo BGs** (largest overburden and reduce Acc-BG)
- **DC** surprisingly (less overburden) **best BG/S** (excellent **δS/BG**)→ high quality analysis (precise BG estimation & 4x validation/cross-checks)

BG world summary…

- the **worst BGs**…
  - **Acc-BG: DB**, but will improve some (cut on Δd)
  - **Cor-BG: RENO**, but will improve little (no OV or scint-IV)
    - claimed measurement is suspicious (6% precision + extrapolation)
  - **Cosmo-BG: RENO**, but will improve with showering-μ vetoing
  - Surprising success **DC**→shallowest overburden ("deeper" via analysis)
- the **best BGs**…
  - DC lowest Acc BG ever (~10x better with cut on Δr)
  - DB lowest μ-BGs (expected→ deeper+vetoing+huge water pool)
- the **best understood BGs** (i.e. lowest δBG and δBG/BG)…
  - DB & DC→ the best understood BG (lowest δBG and δBG/BG)
- the **best BG systematics**…
  - DB best rate BG knowledge (δBG/S)→huge signal and deep overburden)
  - DC best shape BG knowledge (BG/S)→ exploited in rate+shape analysis
  - DC powerful redundant BG→ 4x methods (stat limited) to handle BG bias

BG systematics (rate-only analysis)...





final precision on θ_{13}…

rate-driven uncertainties...

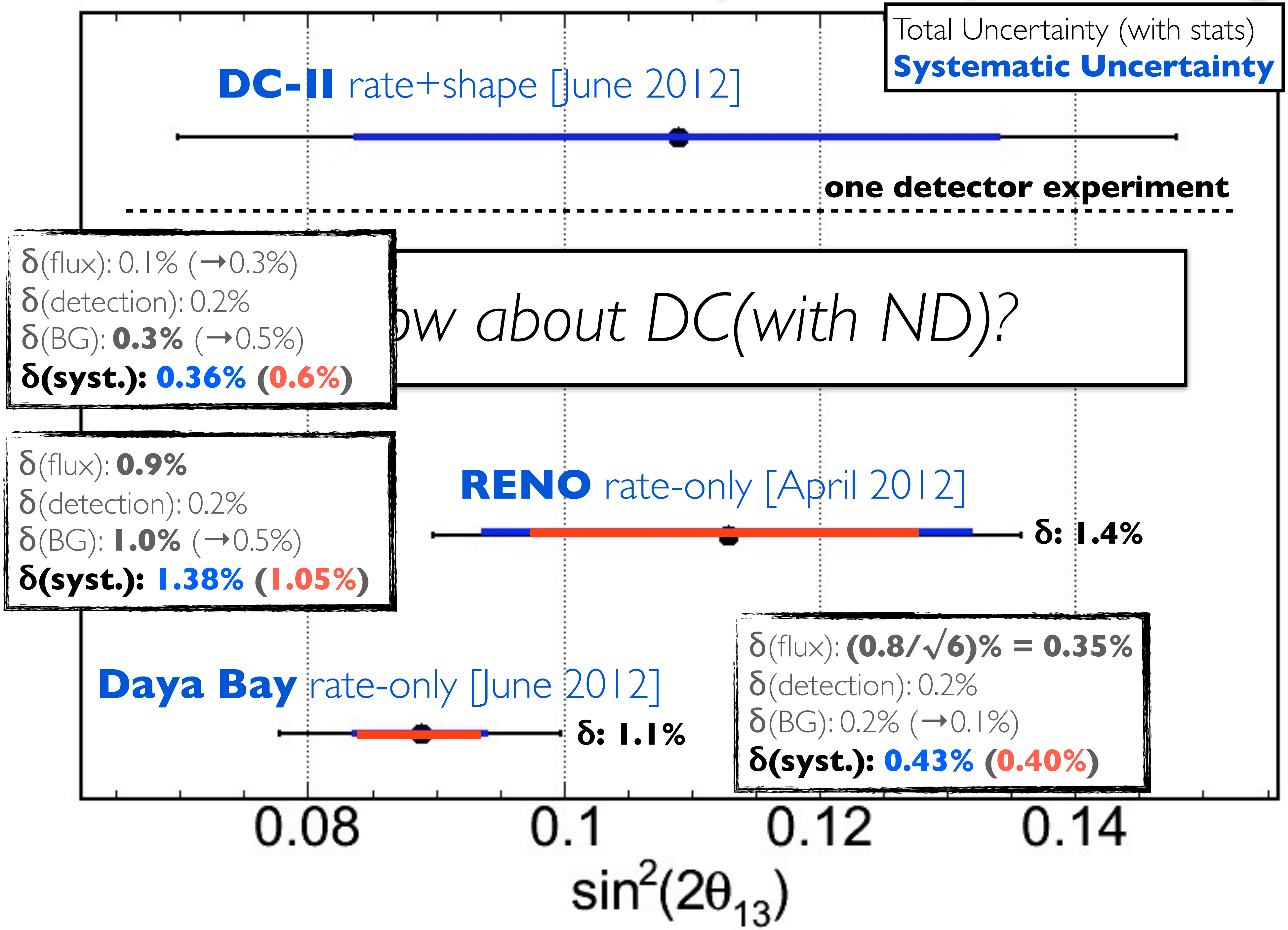
uncertainty (%)	DC-I (rate)	DC-II (rate)	DC-II (r+s)	DC-II (OFF*)	RENO (abs & relative)		DB (abs & relative)	
flux								
reactor	1.67	1.67	**1.67**	1.67	2.00	**0.90**	3.00	**0.80**
detection								
efficiency	1.14	0.95	**0.95**	0.95	1.50	**0.20**	1.90	**0.20**
response	1.7	0.3	0.3	0.3	X	X	X	X
background for rate analysis (δBG/S)								
cosmogenic	2.82	1.49	0.80	X	1.03	1.03	0.09	0.09
correlated	0.89	0.55	0.36	X	0.08	0.08	0.03	0.03
accidental	0.07	0.01	0.01	X	0.04	0.04	0.02	0.02
"Am-C"	X	X	X	X	X	X	0.16	0.16
BG (Σ)	2.96	1.59	**0.88**	1.10	1.03	**1.03**	0.19	**0.19**
syst total	**3.58**	**2.49**	**2.11**	**2.22**	**2.70**	**1.38**	**3.56**	**0.85**
stat total	1.56	1.10	1.10	1.10	0.76	0.76	0.99	0.99

DB best multi-detector & DC best single detector

***(debatable numbers)**

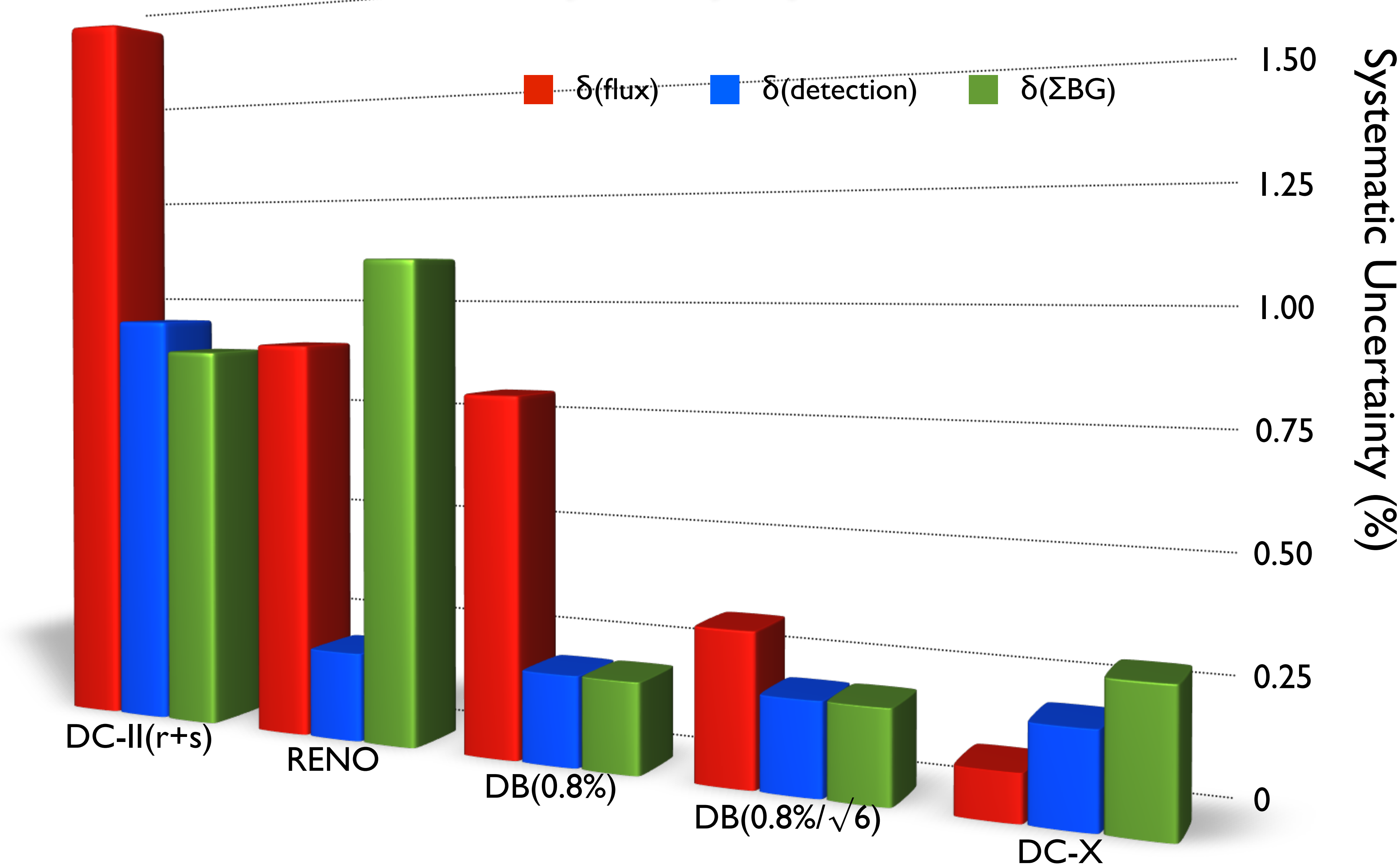
Anatael Cabrera (CNRS-IN2P3 & APC)

reactor θ13 rate (ultimate?) knowledge…



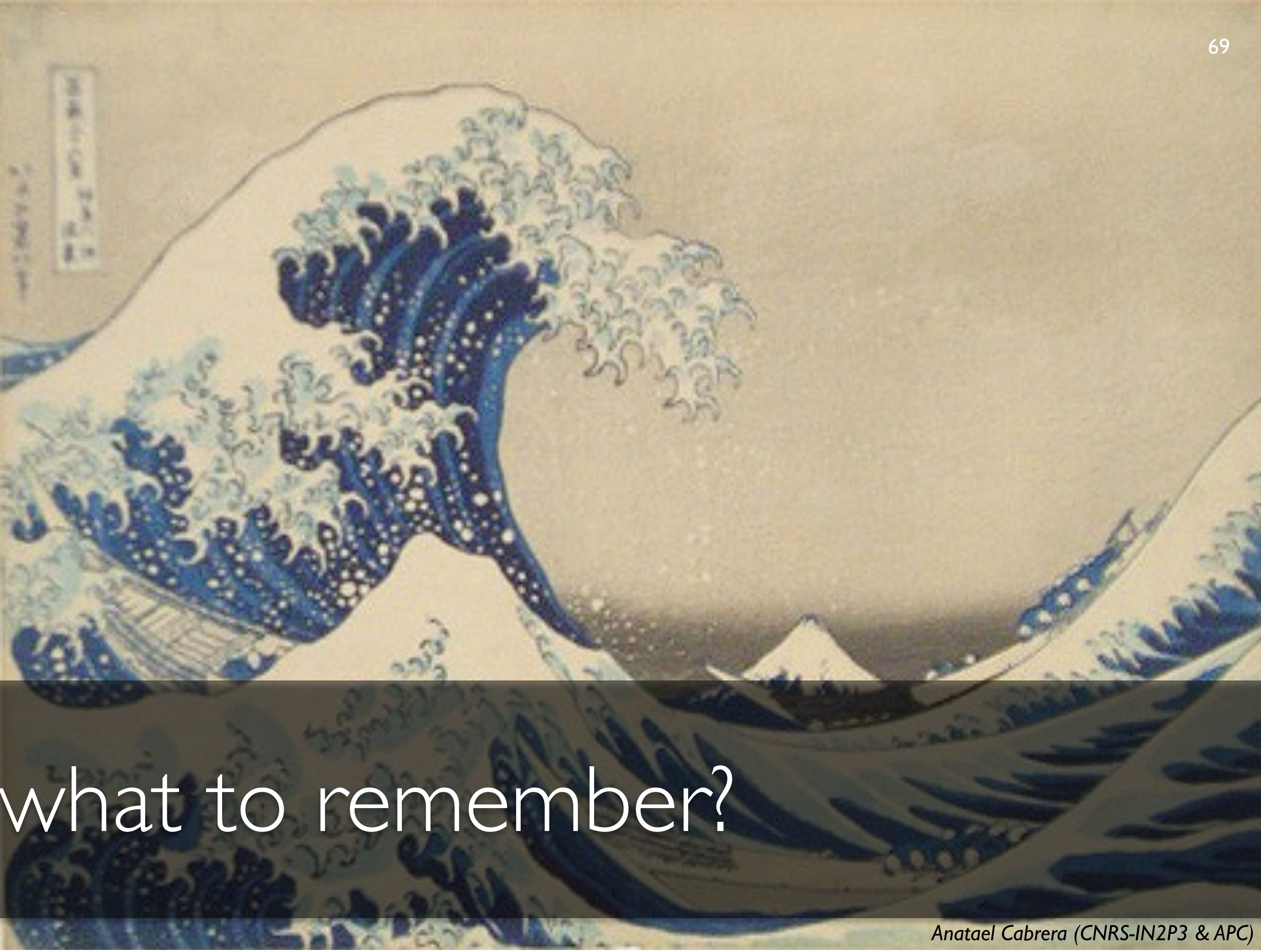
Anatael Cabrera (CNRS-IN2P3 & APC)

$\sin^2(2\theta_{13})$ systematics breakdown



only 2 experiments <10% precision→ test accuracy
(validate systematics**)**

Anatael Cabrera (CNRS-IN2P3 & APC)



what to remember?

what to remember?

- **θ13 measured** by reactor experiments (→ **dominate for long!**)
  - **sure!**→ precise rate-only (DB) & clean rate+shape (DC)
  - **high precision** (*uncertainty*) & **high accuracy** (*what's the true value?*)
    - to measure/constrain 3ν oscillation model
- **high precision on θ13**→ final **~5% uncertainty** expected
  - multi-detector→ cancellation of all correlated uncertainties
- **high accuracy on θ13**→ unbiassed measurements?
  - **rate+shape analysis** (E/L & BGs) to measure θ13→**a must!**
  - **cross-check** among all experiments→ on-going effort (transparent)
    - different sites/BGs/systematics/baselines,etc→ the ONLY way!
- regardless **θ13 is LARGE**
  - …if you were waiting for this, **please go ahead**! **:-)**
  - combined θ13 (a few years time)→**best θ_{13} for very long!**

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thank you…