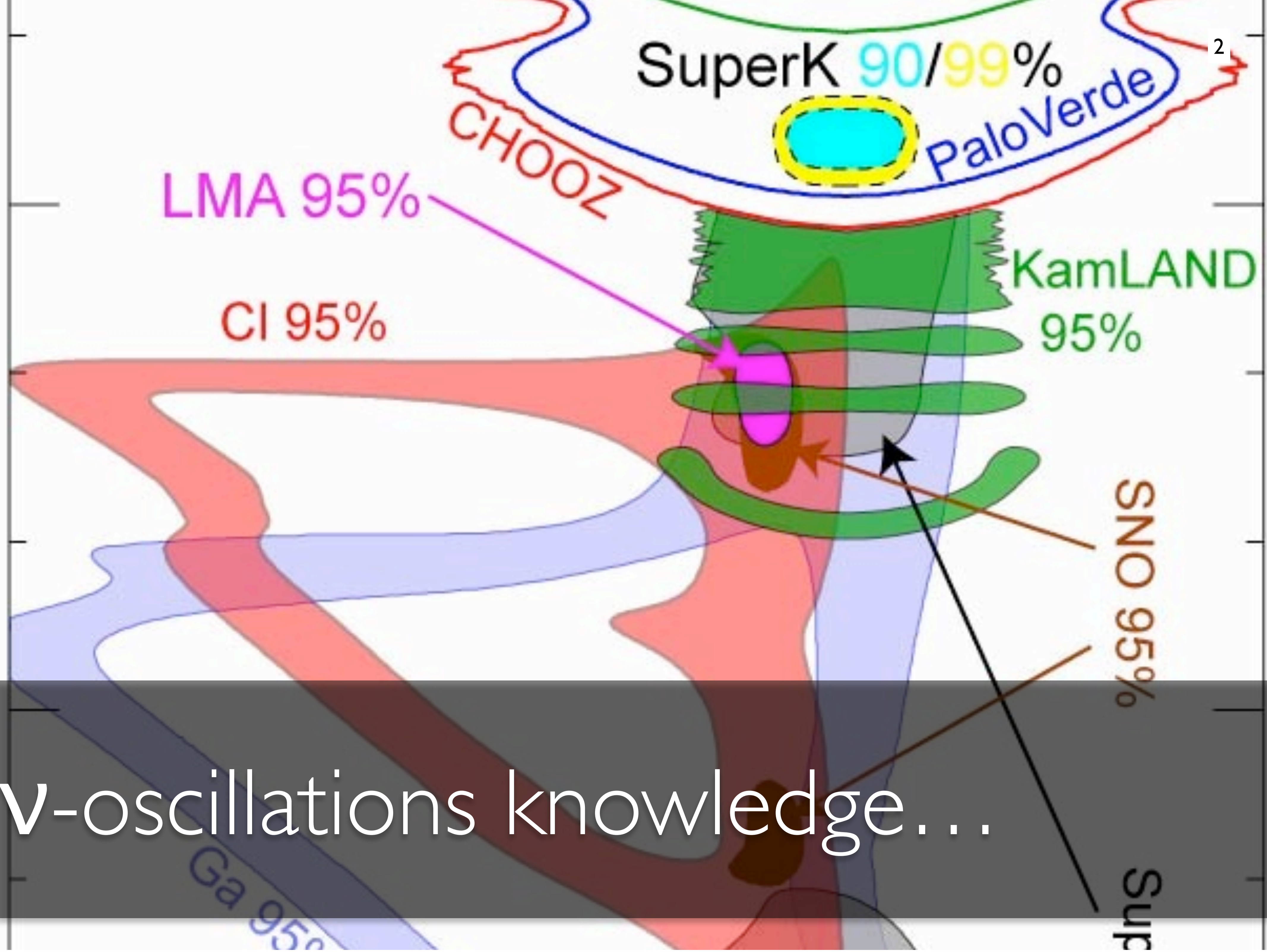
reactor θ13

(the ultimate measurement?)

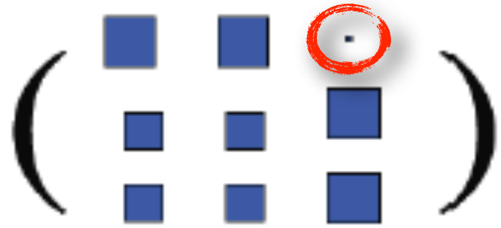
LIO Neutrinos @ Lyon (France)
October 2012

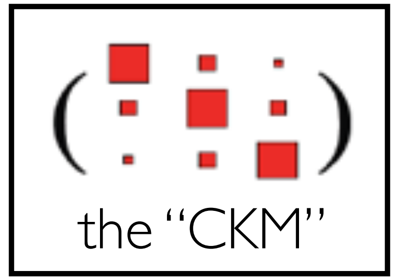
Anatael Cabrera
(アナタエル カブレラ)
CNRS / IN2P3
Double Chooz @ APC (Paris)



ν-oscillations knowledge…

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





"atmospheric" ⟹ θ_{23}~45° | θ_{13} <11° & "dirac" δ_{CP} | "solar" ⟹ θ_{12}~33°

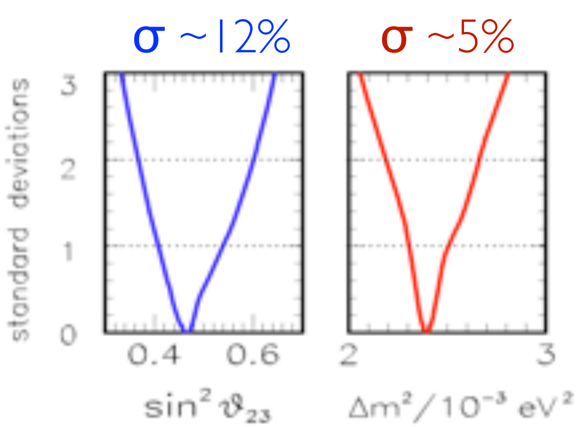
Δm^2_{31} | Δm^2_{31} | Δm^2_{21}

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

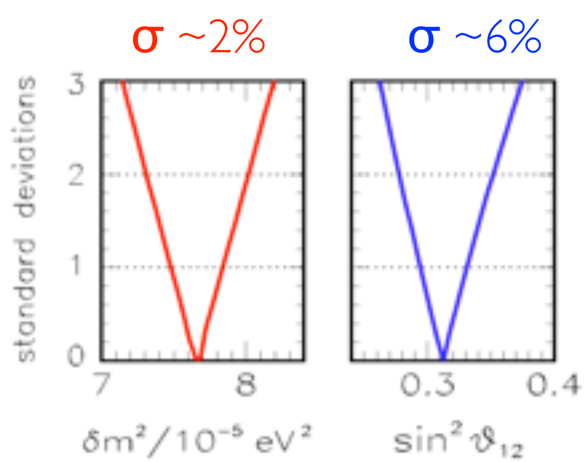
sub-leading → ← sub-leading

atmos+LBL(dis) | Chooz+LBL(app) | solar+KamLAND

$P(\nu_\mu \to \nu_\mu)$ | $P(\nu_e \to \nu_e)$ & $P(\nu_\mu \to \nu_e)$ | $P(\nu_e \to \nu_x)$



knowledge on θ_{13} & δ_{CP} [later]



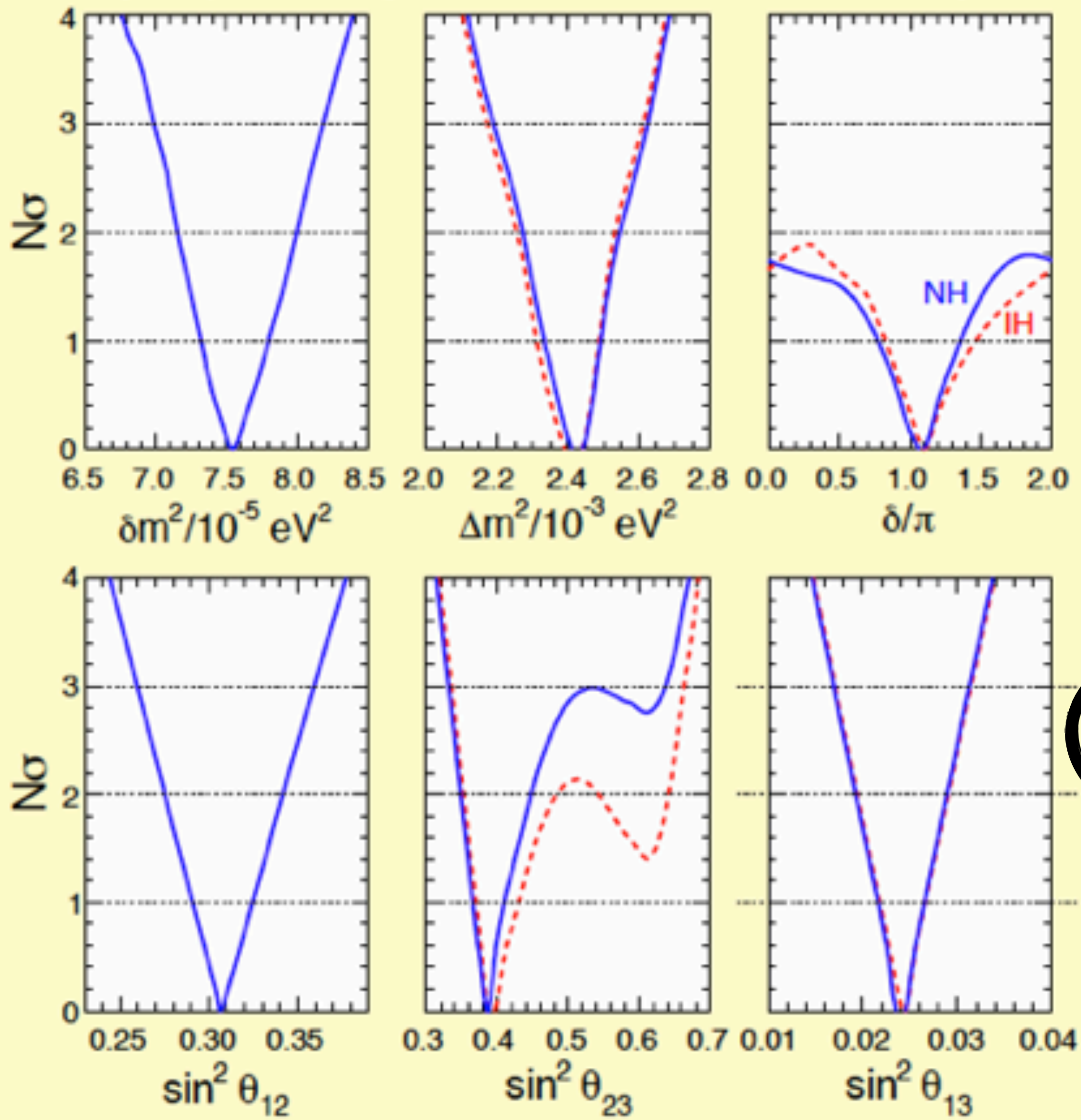
Fogli et al arXiv:1106.6028

Anatael Cabrera (CNRS-IN2P3 & APC)

Lisi et al opinion (Sept. 2012)

17

Synopsis of global 3ν oscillation analysis



Previous hints of $\theta_{13} > 0$ are now measurements! (and basically independent of old/new reactor fluxes)

Some hints of $\theta_{23} < \pi/4$ are emerging at $\sim 2\sigma$, worth exploring by means of atm. and LBL+reac. data

A possible hint of $\delta_{CP} \sim \pi$ emerging from atm. data [Is the PMNS matrix real?]

So far, no hints for NH ⟷ IH

Anatael Cabrera (CNRS-IN2P3 & APC)

Lisi et al opinion (Sept. 2012)

Numerical 1σ, 2σ, 3σ ranges:

18

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

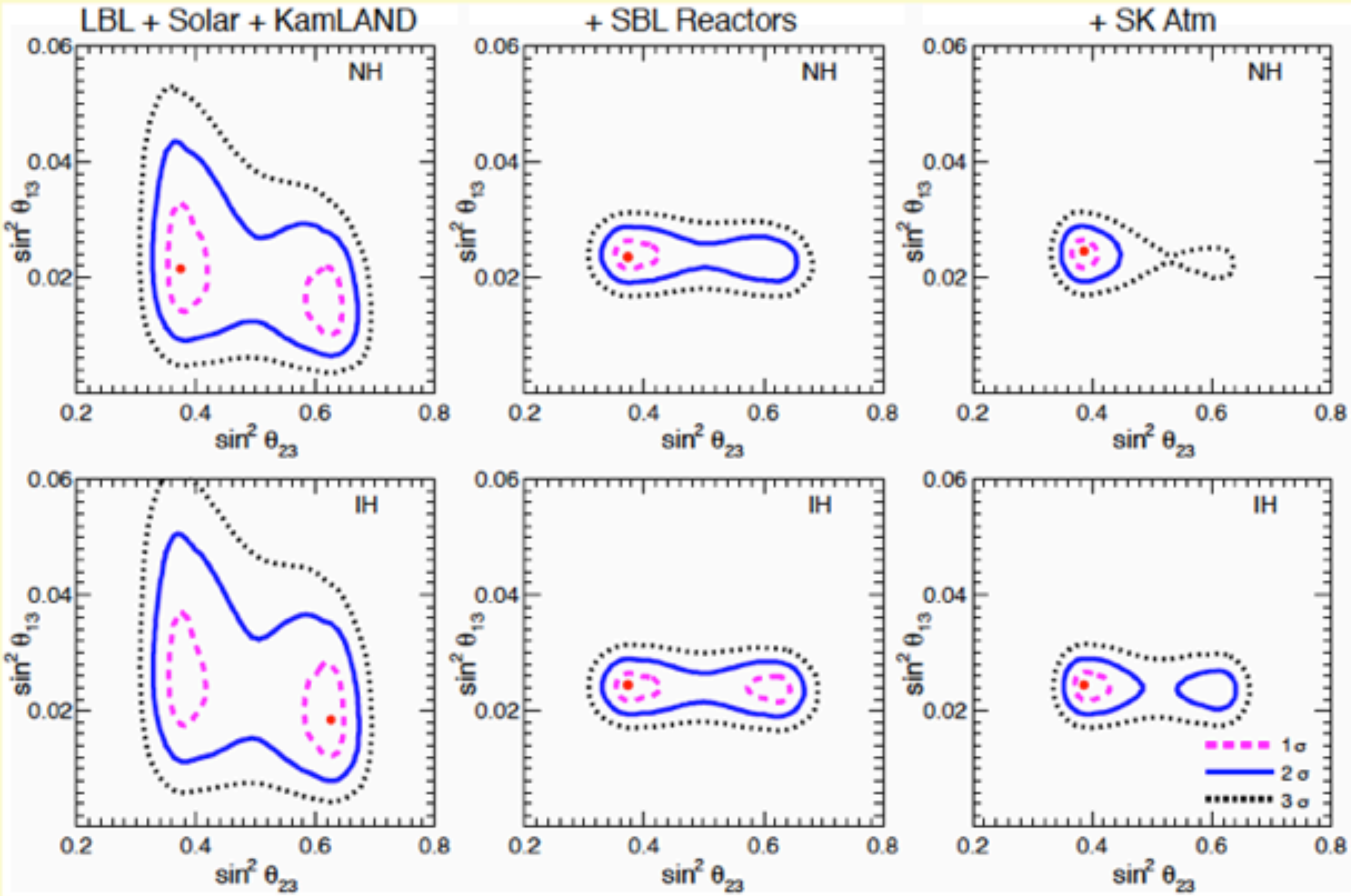
Anatael Cabrera (CNRS-IN2P3 & APC)

θ_{23} octant...

Anatael Cabrera (CNRS-IN2P3 & APC)

Lisi et al @ Shenzhen'2012

Adding 2012 SK atmospheric neutrino data:



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

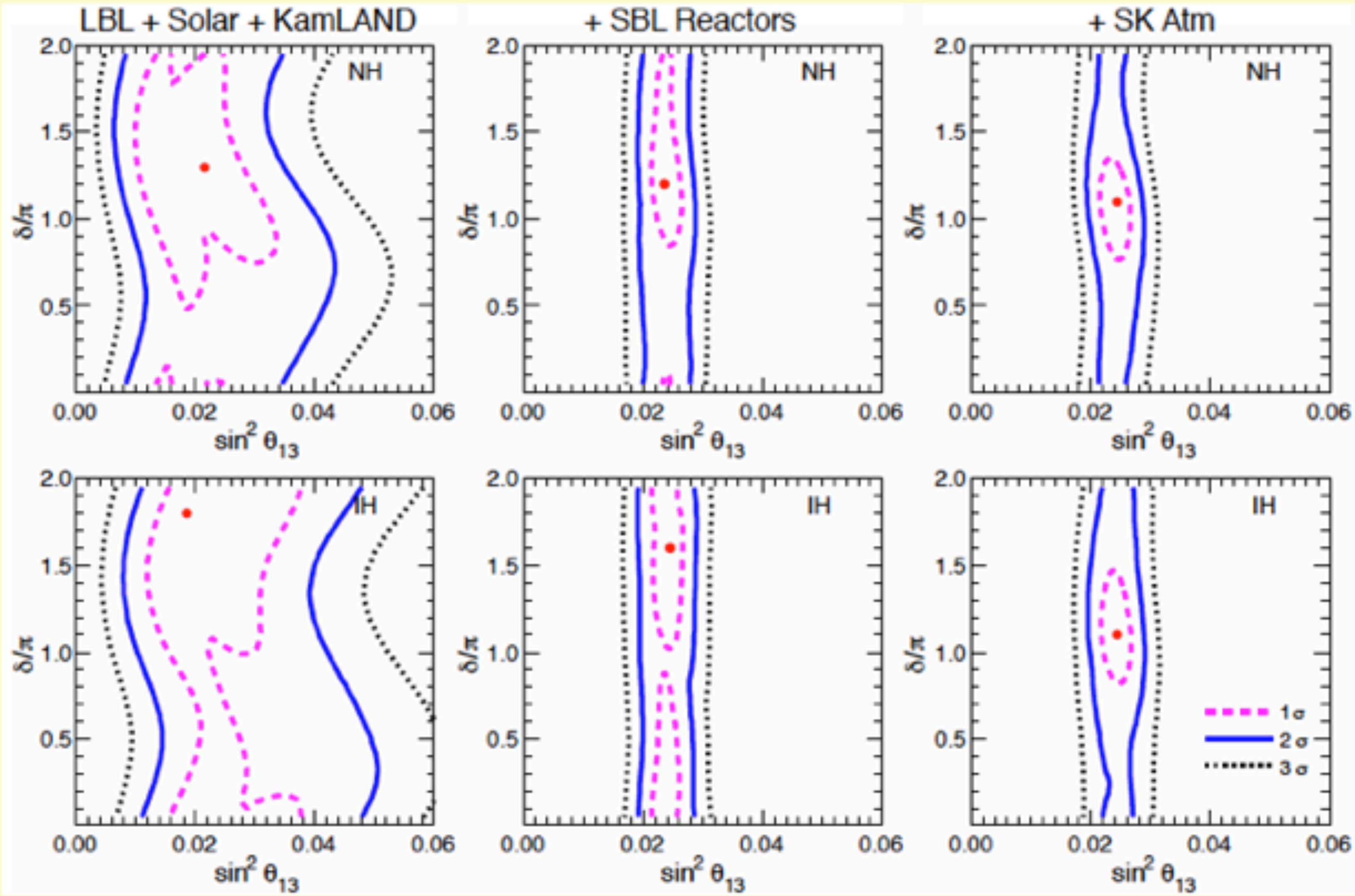
Anatael Cabrera (CNRS-IN2P3 & APC)

δ_{CP} global info…

Lisi et al @ Shenzhen'2012

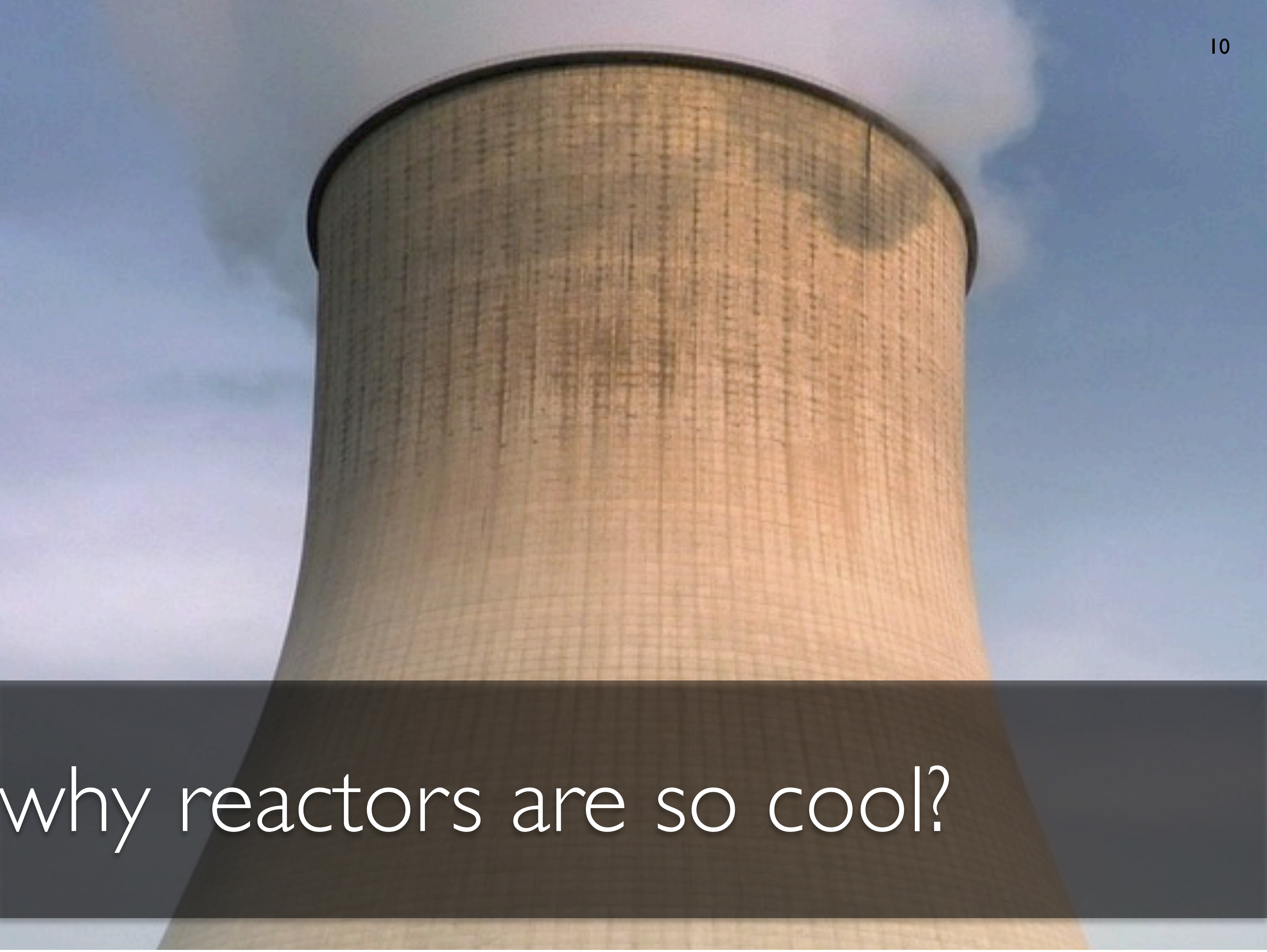
16

Adding 2012 SK atmospheric neutrino data:



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

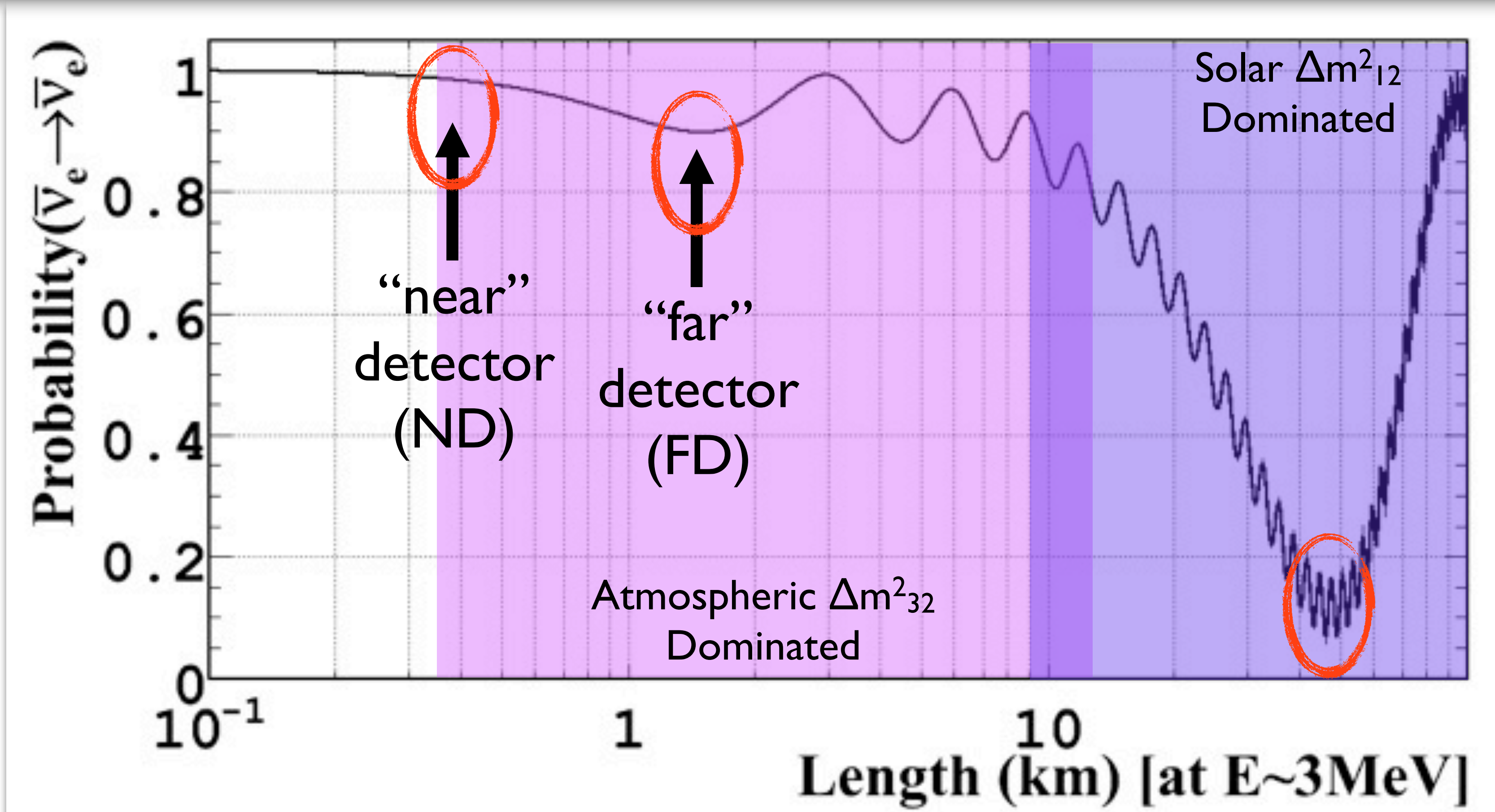
Anatael Cabrera (CNRS-IN2P3 & APC)


why reactors are so cool?

the coolest reason for us...

$$P(\nu_e \rightarrow \nu_e) \sim 1 - \sin^2(2\theta_{13}) \sin^2(\Delta m^2_{32} L_0/E)$$

[plot: E = 3MeV, $\sin^2(2\theta_{13})$ = 0.1, Δm^2_{32}=2.5×10^{-3}eV^2]



ND⟹ reduce several systematic uncertainties (mainly flux rate & shape) wrt FD

ND⟹ isolates from reactor anomaly (fast oscillation→ averge effect) [DC: Bugey4]

Anatael Cabrera (CNRS-IN2P3 & APC)

why reactors?

- **copious** (high statistics) source and **free** νs
  - highly reliable "beam" (reactor-OFF⟹ very expensive, even "strike" proof)
- excellent **δ(E/L) resolution** ⟹ disappearance experiment
- [for θ_{13} searches] **short baselines**⟹
  - small detectors (less expensive)
  - negligible matter & "NSI" effects (global analysis input)
- high & **known cross-section**⟹ exciting situation (so called reactor anomaly)
- **BGs**⟹ overburden, shielding, radio-purity (possible "reactor OFF")
- trivial **multi-detector extrapolation**⟹ flux scales with $1/L^2$ (isotropic)
- rich **energy calibration**⟹ many radioactive sources @ few MeV
- one unknown & one observable⟹ unambiguous θ_{13} signature (measurement/limit)
  - compelling *synergy to beam results (several unknown's)⟹ global picture!*

reactor θ_{13}

θ13 measurement by reactors

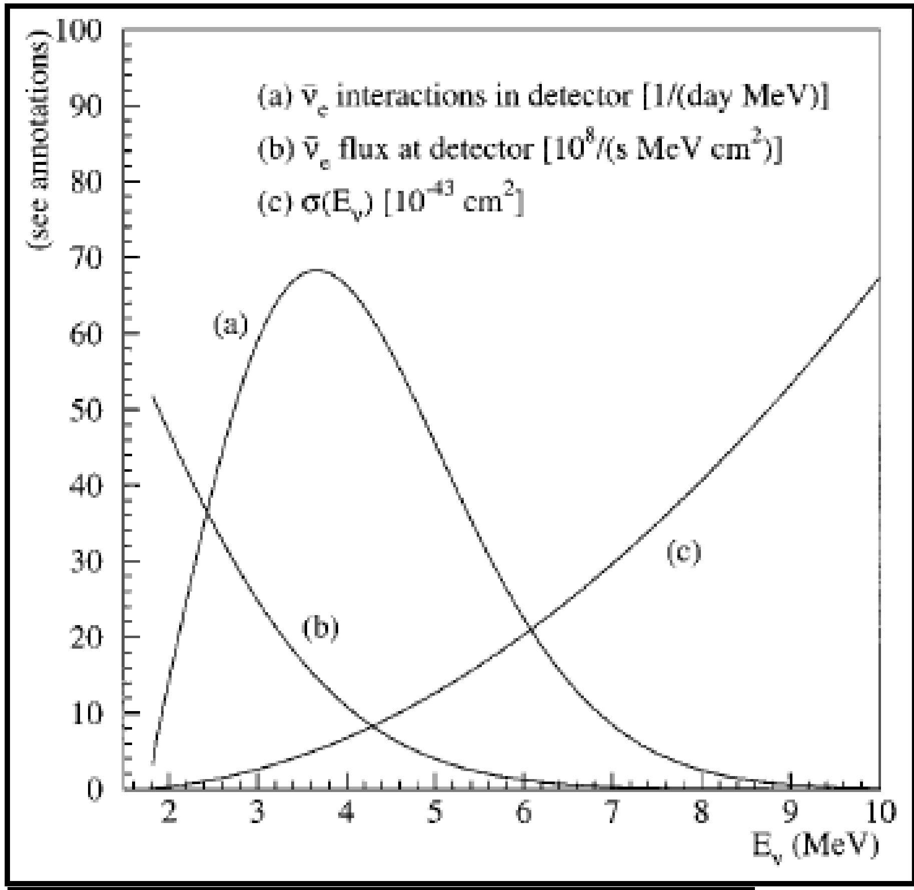
- **3 experiments**: Double Chooz (DC), Daya Bay (DB) and RENO
- **θ_{13} (large) will be measured by reactors**
  - **hard to improve results** (or re-trigger dedicated experimental activity)
  - θ13 measurement to ~5% precision (eventually)→ used on by everyone else!
    - high precision→ multi-detector approach
    - high accuracy→ several experiments (bias-free?)
  - **oscillation signature→** θ13 **via both rate & shape**
    - rate-only analysis: "any deficit" is numerically associated to θ13 (BG, etc)
    - all results so far are rate-driven→ DC uses shape to some extent
- **beams to use the "reactor θ13"→** further insight in neutrino oscillations
  - ν_e appearance⟹ first(??) appearance experiment (→ 5σs soon)
  - rich physics…
    - O(1%) precision measurement of $\Delta m^2 32$, θ23 (T2K, NOνA)
    - further information on δ and MH (with atmospheric)
    - over-constraint 3ν oscillation scenario→ NSI, sterile, exotic stuff, etc

Anatael Cabrera (CNRS-IN2P3 & APC)

common technology…

Anatael Cabrera (CNRS-IN2P3 & APC)

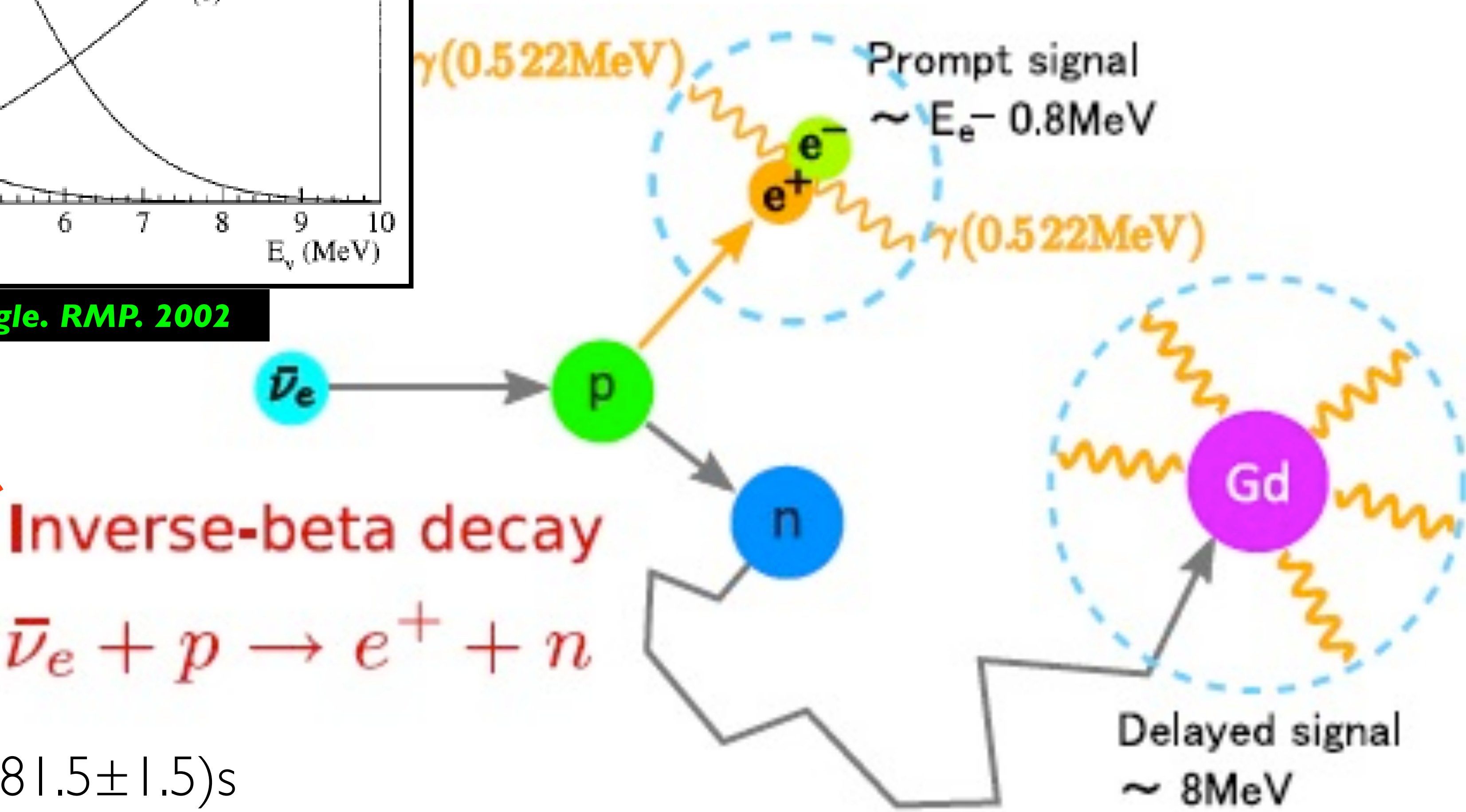
inverse-β decay…



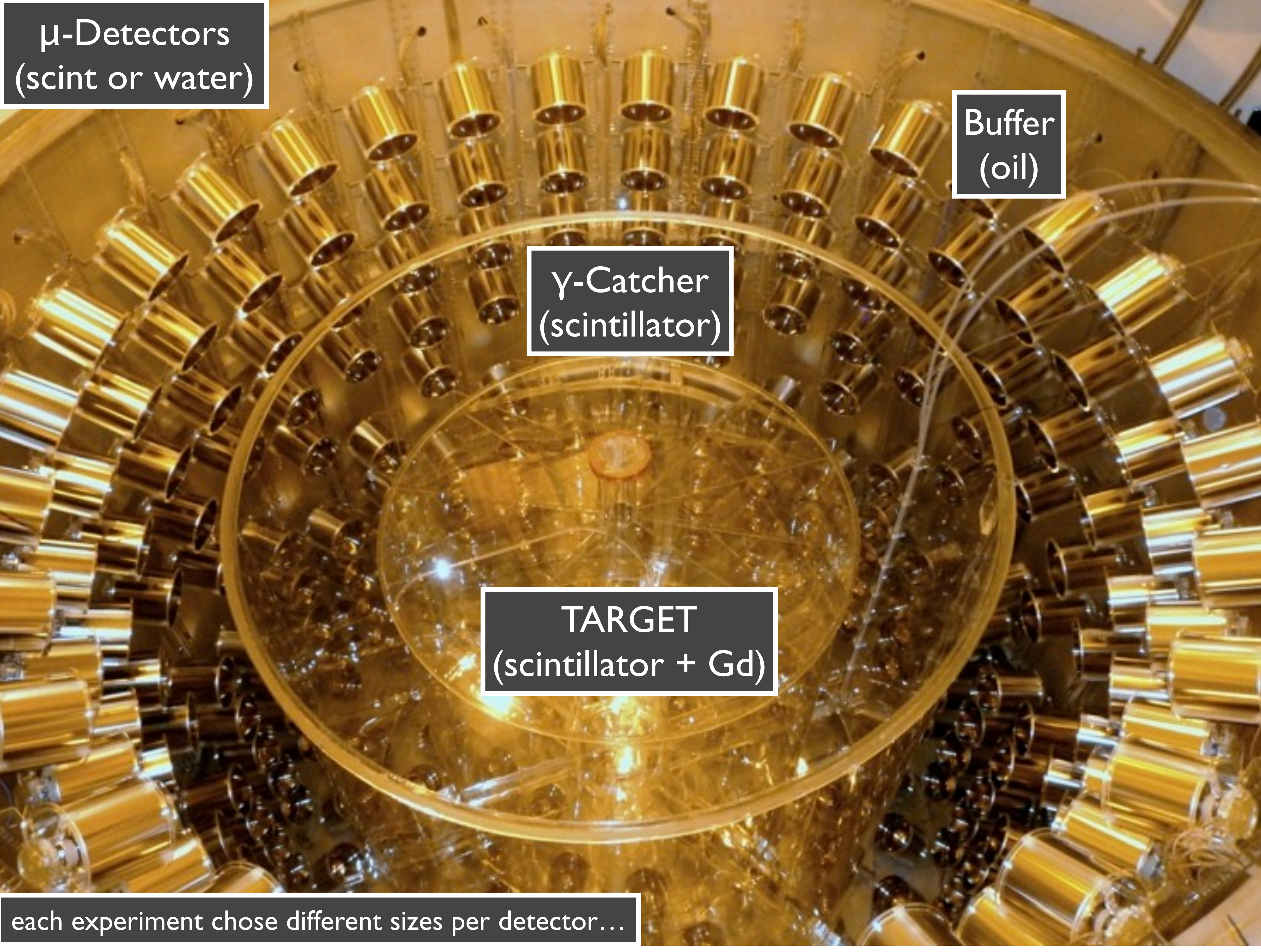
Bemporad, Gratta, Vogle. RMP. 2002

- two trigger in coincidence ⟹ low BG
  - 1st: "prompt" (e+ like)
  - 2nd: "delay" (capture in Gd): ~8MeV
- correlation in time and space

Gd important for "shallow" detectors



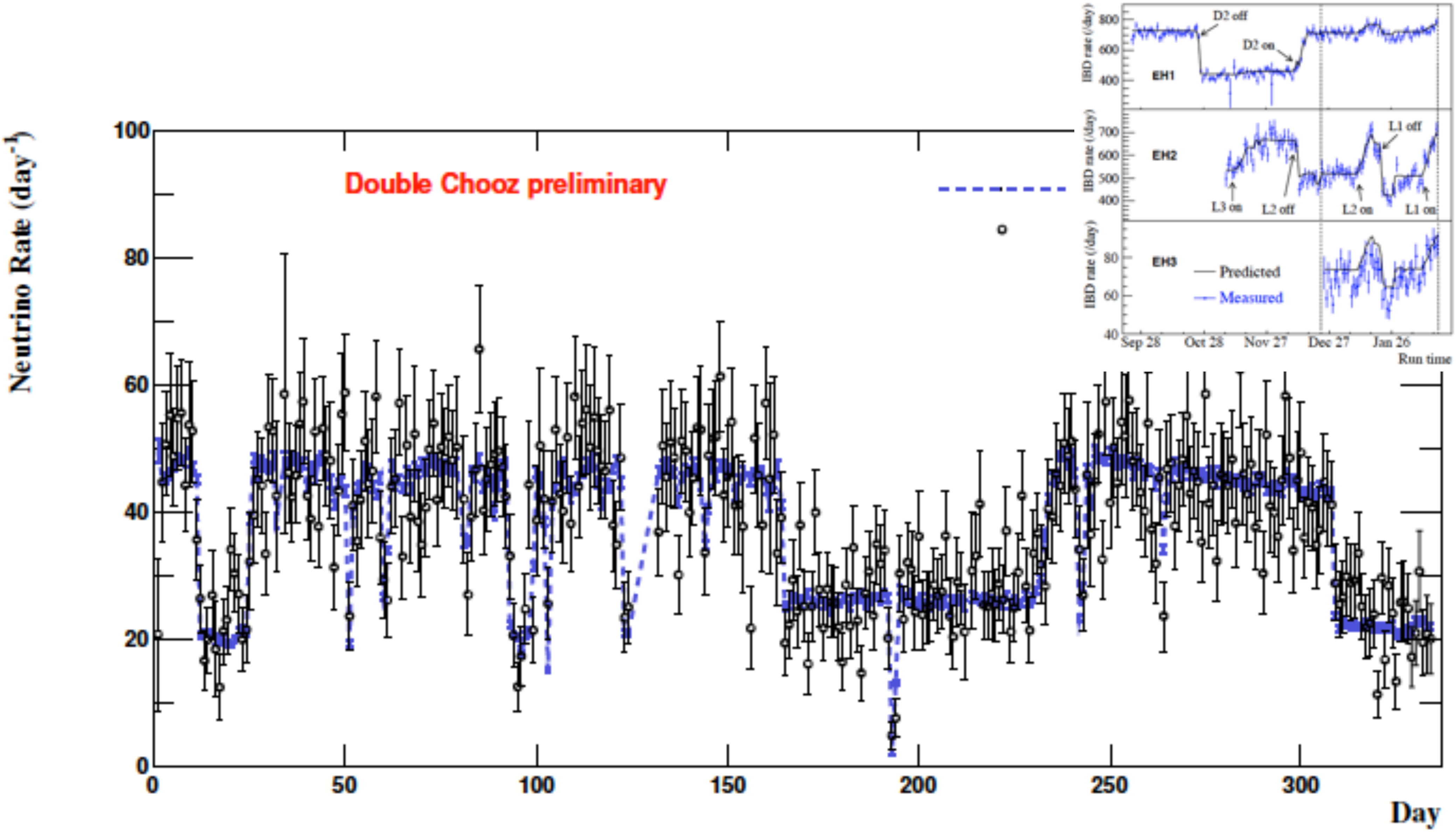
$\sigma_{IBD} \rightarrow \tau_{neutron} = (881.5 \pm 1.5)$s


μ-Detectors
(scint or water)
Buffer
(oil)
γ-Catcher
(scintillator)
TARGET
(scintillator + Gd)
each experiment chose different sizes per detector…

pseudo common-analysis

- 3 experiments performed very similar analysis (almost same selection strategy)
  - differences arise in BG reduction: DC and DB (detector/site dependent)
    - RENO→ no BG reduction strategy
  - different instrumental noise reduction and calibration (definition MeV)
- PMT light noise (or flashers) rejection (singles→ accidental)
- tagged μ (or μ related physics)
  - veto 1ms upon each μ (most fast-n eliminated)
- prompt→ [0.7~12.0] MeV
- delay→ [6.0~12.0]MeV
- time-correlation cut used
  - no space-correlation used for cut
- showering-μ ID (tagged on total energy)
  - veto ~1s upon each μ_{shower} (reduce Li candidates ~1/2)
- veto on some activity on external μ detectors
  - reduce fast-n and stopped-μ

signal variations @ FD…



- no BG subtraction⟹ 2 reactors (2 ON, 1 ON and 2 OFF)
- signal dominated and signal prediction excellent evolution tracking

Anatael Cabrera (CNRS-IN2P3 & APC)

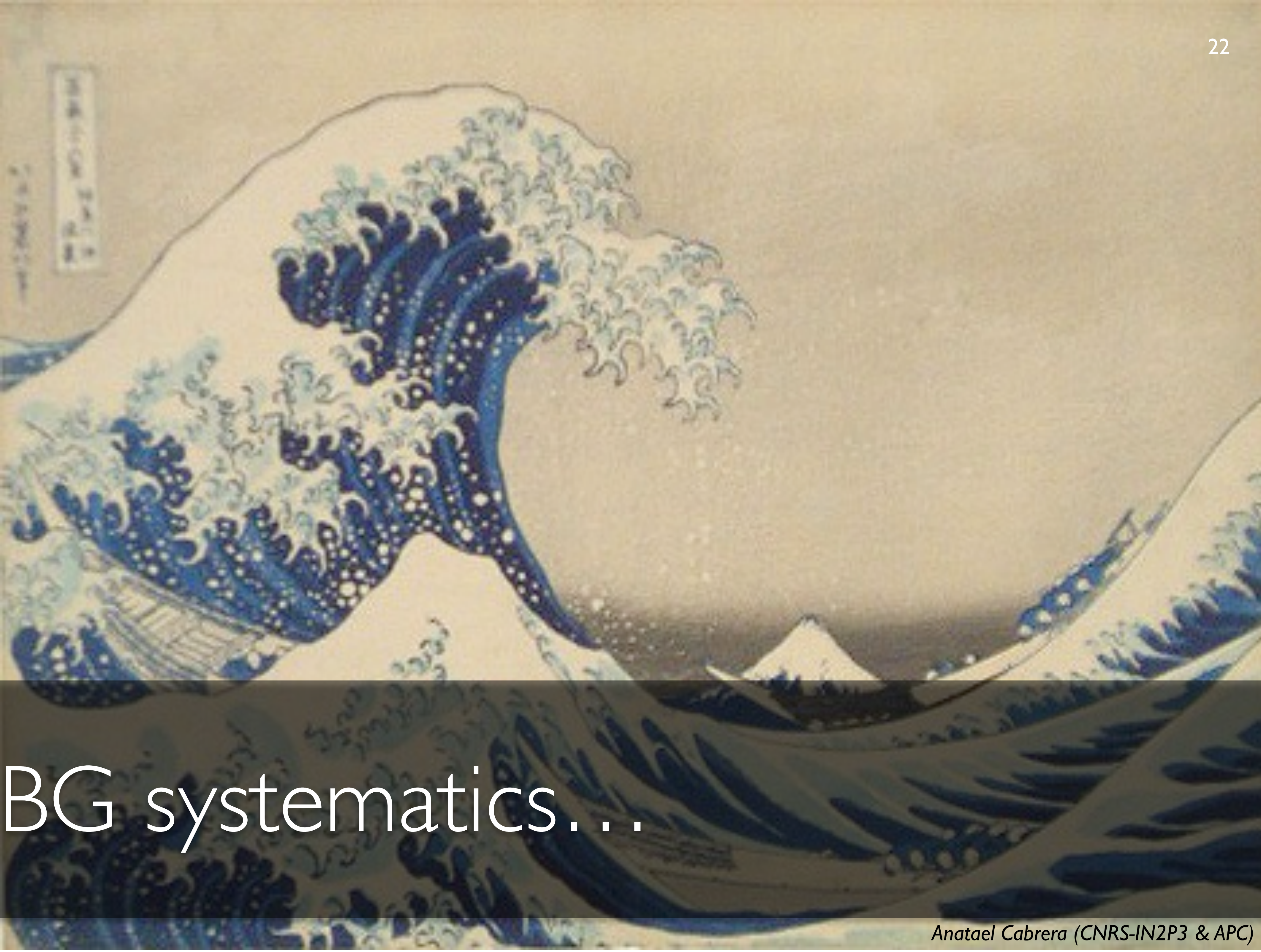
θ13 reactor challenges

- **statistics**
  - no problem→ eventually all experiments **plenty (>2**x $\sigma^{stat} = \sigma^{syst}$**)**
  - with large θ13→ even faster than expected (biggest, 2 detectors, etc)
- **systematics I: inter-detector systematics (and MC)**
  - ND eliminates uncertainties→ reactor knowledge & common detection
  - highest precision→ excellent detector understanding (**calibration** and **MC**)
- **systematics II: backgrounds rates & shapes**
  - each site→ different backgrounds (both rate and shape)
    - ND more signal but also more BG (a priori not only normalisation)
  - **BG spectra measurement** with reactor ON→ very challenging
    - BG (un)knowledge→ systematics [but statistics dominated→ improving]
- **warning: high-precision physics** (i.e. systematics at "per-mil" level)
  - **first word** (**fast**)→ impressive θ_{13} measurement "overnight"
  - **final legacy** (**slow**)→ cross-checks for best θ_{13} world knowledge

Anatael Cabrera (CNRS-IN2P3 & APC)

highlights on experiments...

- **Double Chooz** (1112.6353,1207.6632,1210.3748, etc)
  - **the (slow) pioneer: first detector design** (influenced the field)
    - 1 detector (building of ND)→ European physics signature?
  - **first result: θ13 large (Nov.11) rate+shape analysis**
    - best 1 detector results ever→ better than design
    - **Bugey4 ("ND")+FD**: current results (1 detector→ challenging)
- **RENO** (1204.0626,Nu2012)
  - **first multi-detector running in the world**→ results after 229days
  - remarkable effort/success for a small collaboration (almost entirely Korean)
- **Daya Bay** (1203.1669,Nu2012)
  - **huge multi-detector complex**→ FD running since 25th December 2011
    - **ultimate θ13 detector**→ final configuration running since Sept. 2012
  - **most precise measurement of θ13** (even with 55days)



BG systematics…

Anatael Cabrera (CNRS-IN2P3 & APC)

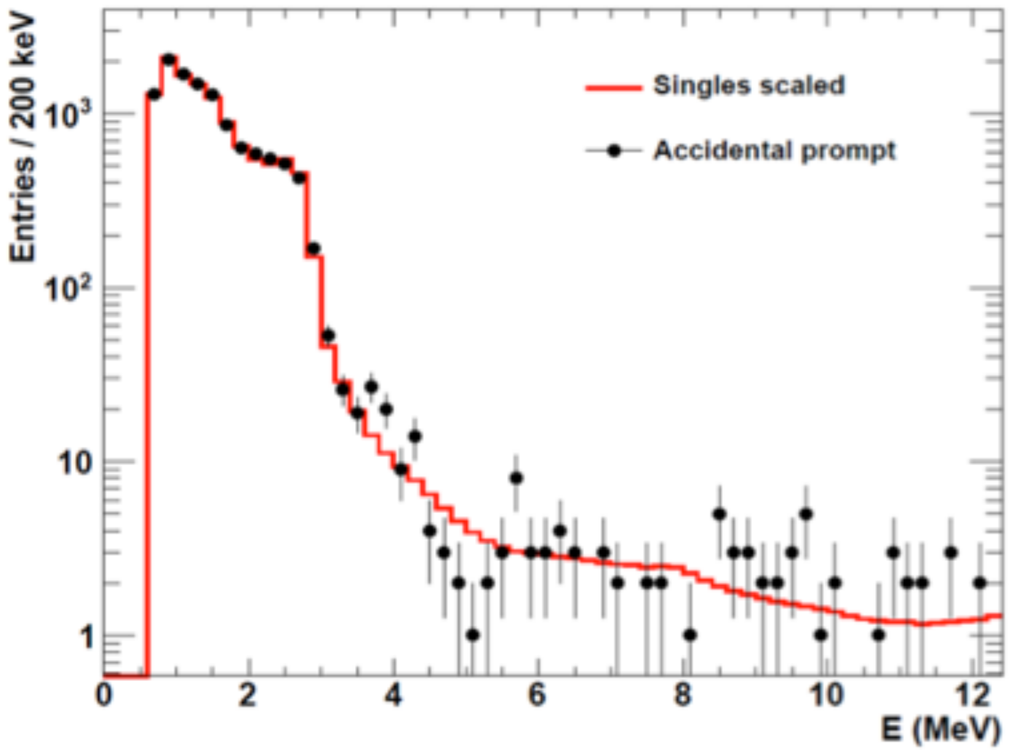
how to measure/validate BGs?

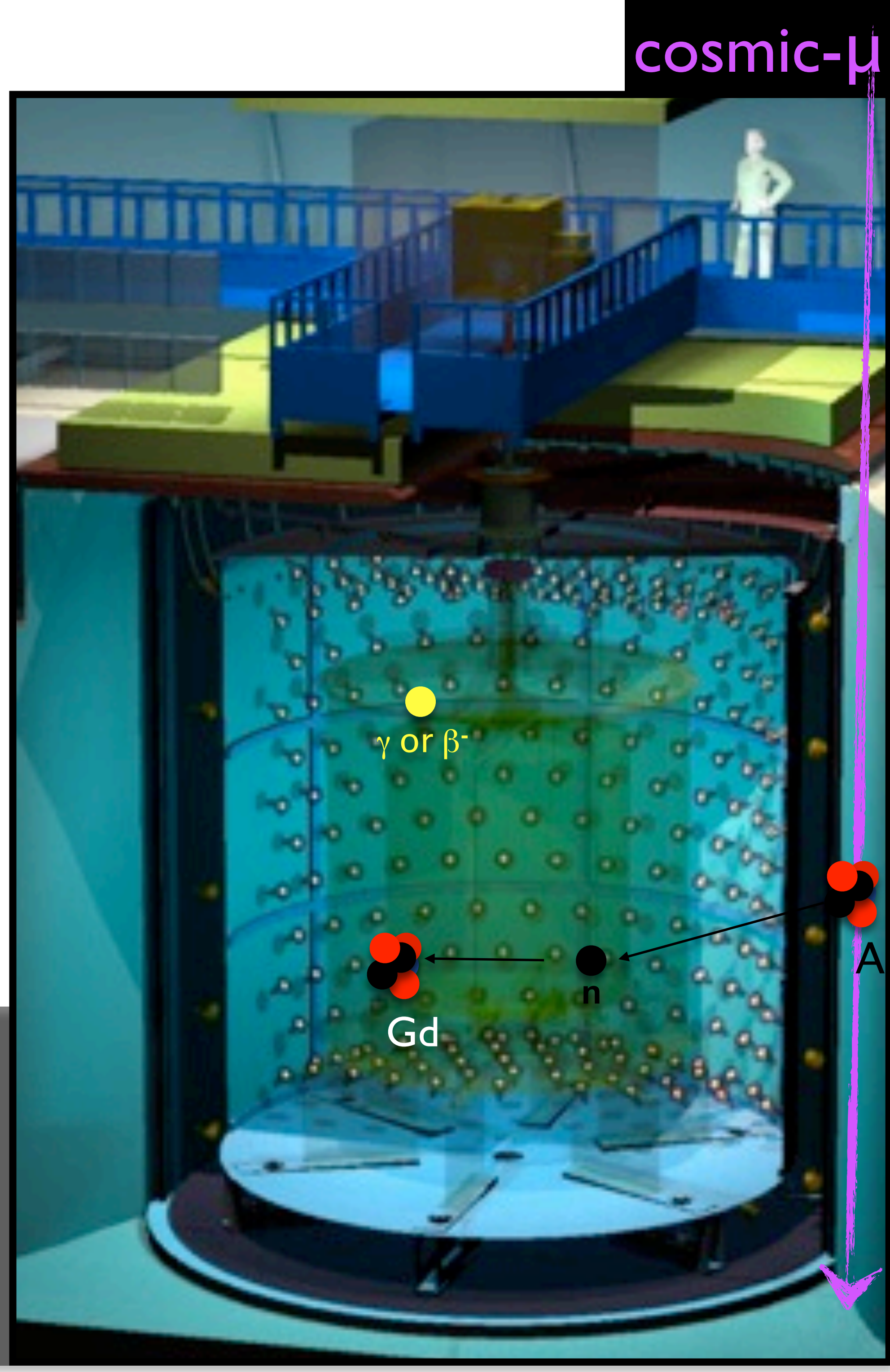
- **BG measurement:** rate (much easier) & shape (statistics limited knowledge)
  - CHOOZ BGs→ no say on Li (reactor OFF)→ KamLAND observed it!
- **method 1:** measure each dedicated BG (sample) component with reactor ON
  - **cons:** sub-sample (different selection) & approximations
    - correction/scaling⟹ hard to validate accuracy (precision easy)
- **method 2:** fit θ13 and all BGs (shape analysis) with reactor ON [**only DC**]
  - **pro:** use all knowledge a priori (method 1)⟹ propagate to θ13 (correlations)
  - **cons:** hard to interpret pull-info (degeneracies) and lack of knowledge still
- **method 3:** direct measurement of total BG (rate) [**only DC**]
  - **pro:** a dream possibility (like CHOOZ)→ easy to validate rate measurements
  - **cons:** stats limited→ hard to infer BG shape information
- **method 4:** observed vs expected correlation plot (next slides) [**only DC**]
  - **pro:** combined and direct use of reactor ON and OFF data⟹ powerful!
  - **cons:** not used yet (→ not systematics accounted)⟹ soon!!

Anatael Cabrera (CNRS-IN2P3 & APC)

individual measurement… (all experiments)

Anatael Cabrera (CNRS-IN2P3 & APC)

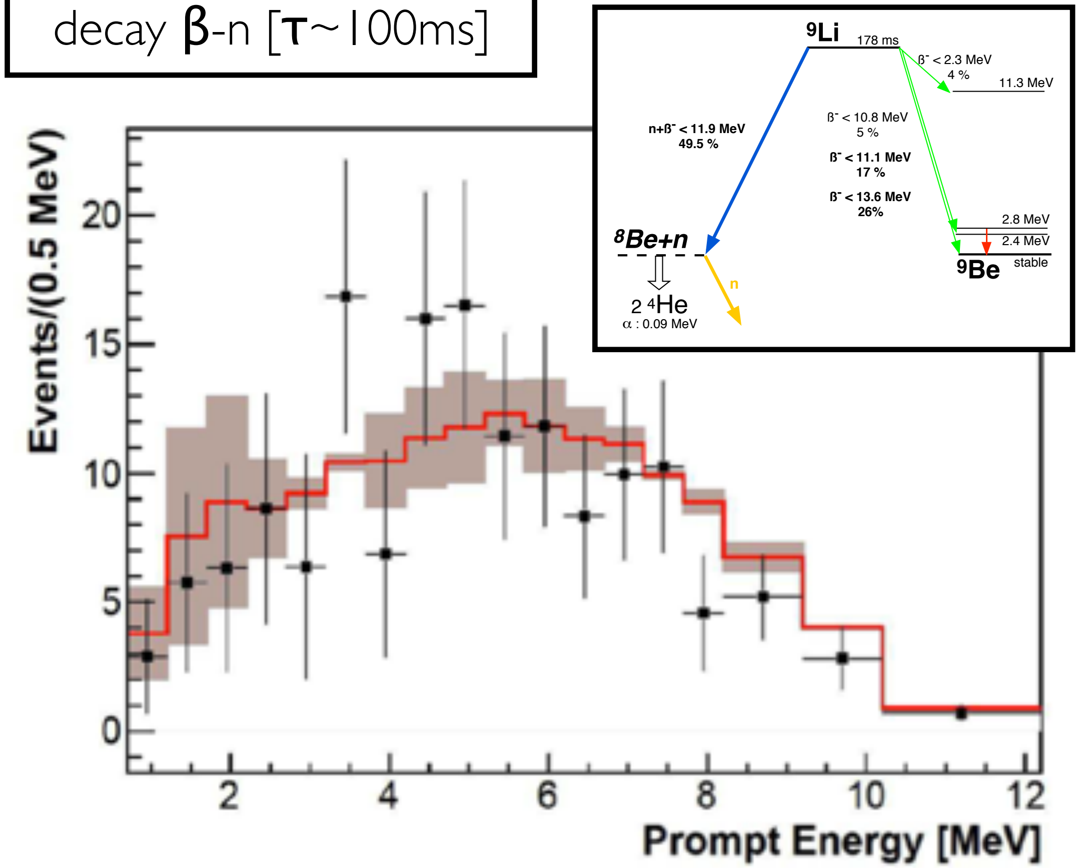


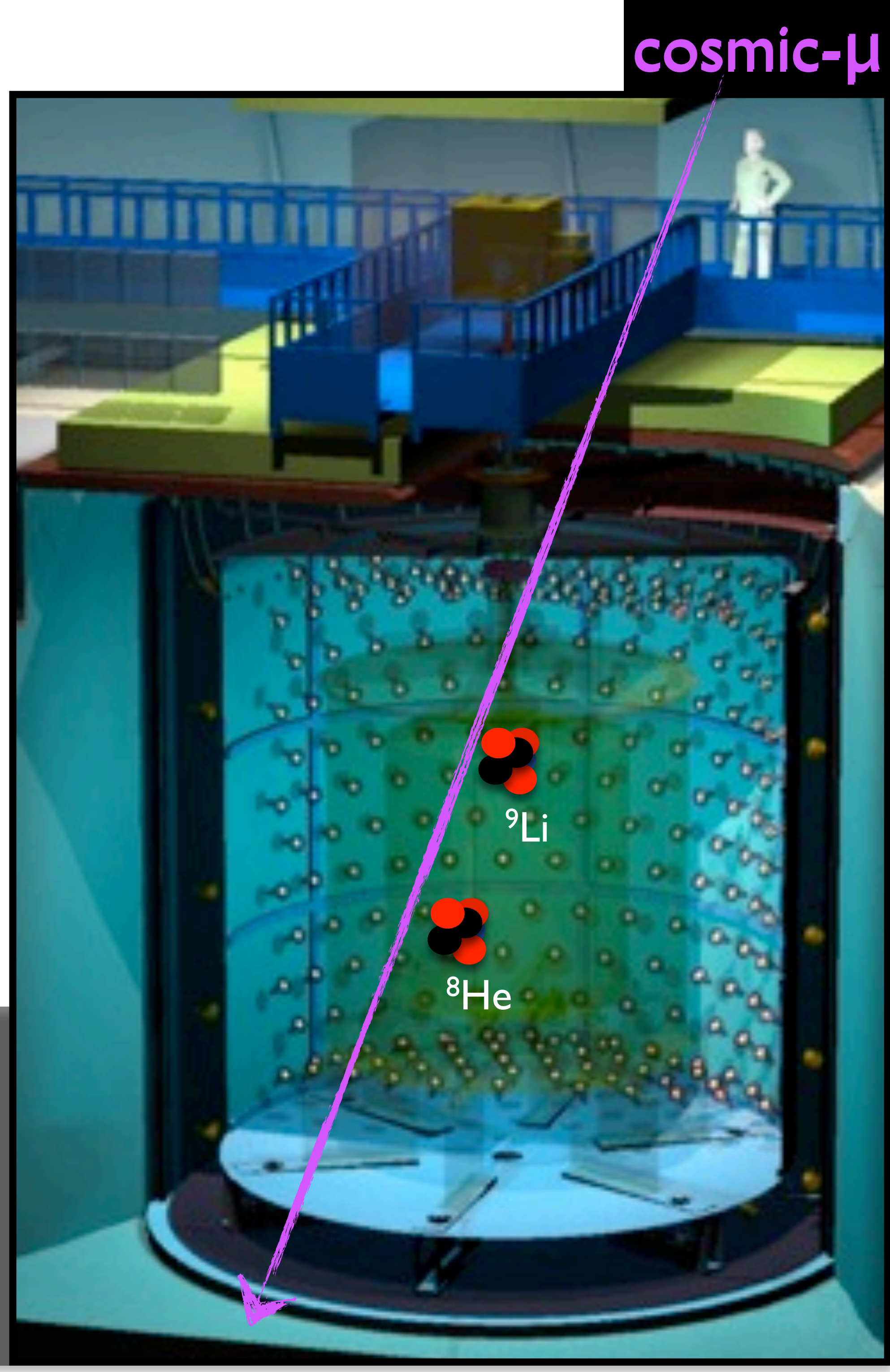


accidental BG...

Anatael Cabrera (CNRS-IN2P3 & APC)

decay β-n [τ~100ms]

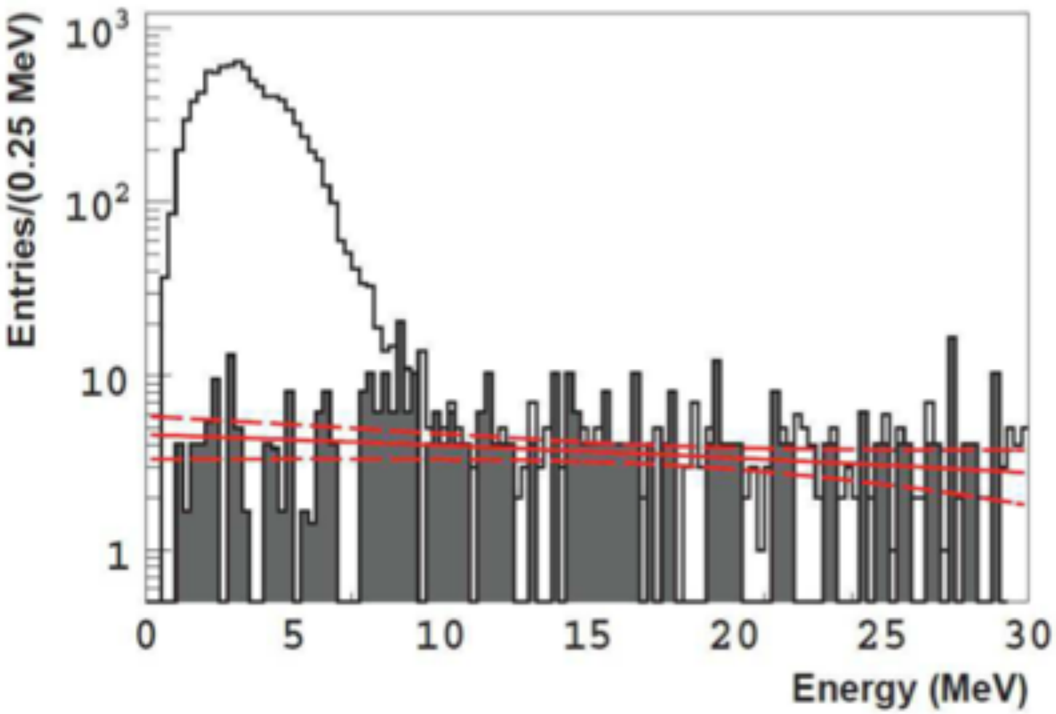




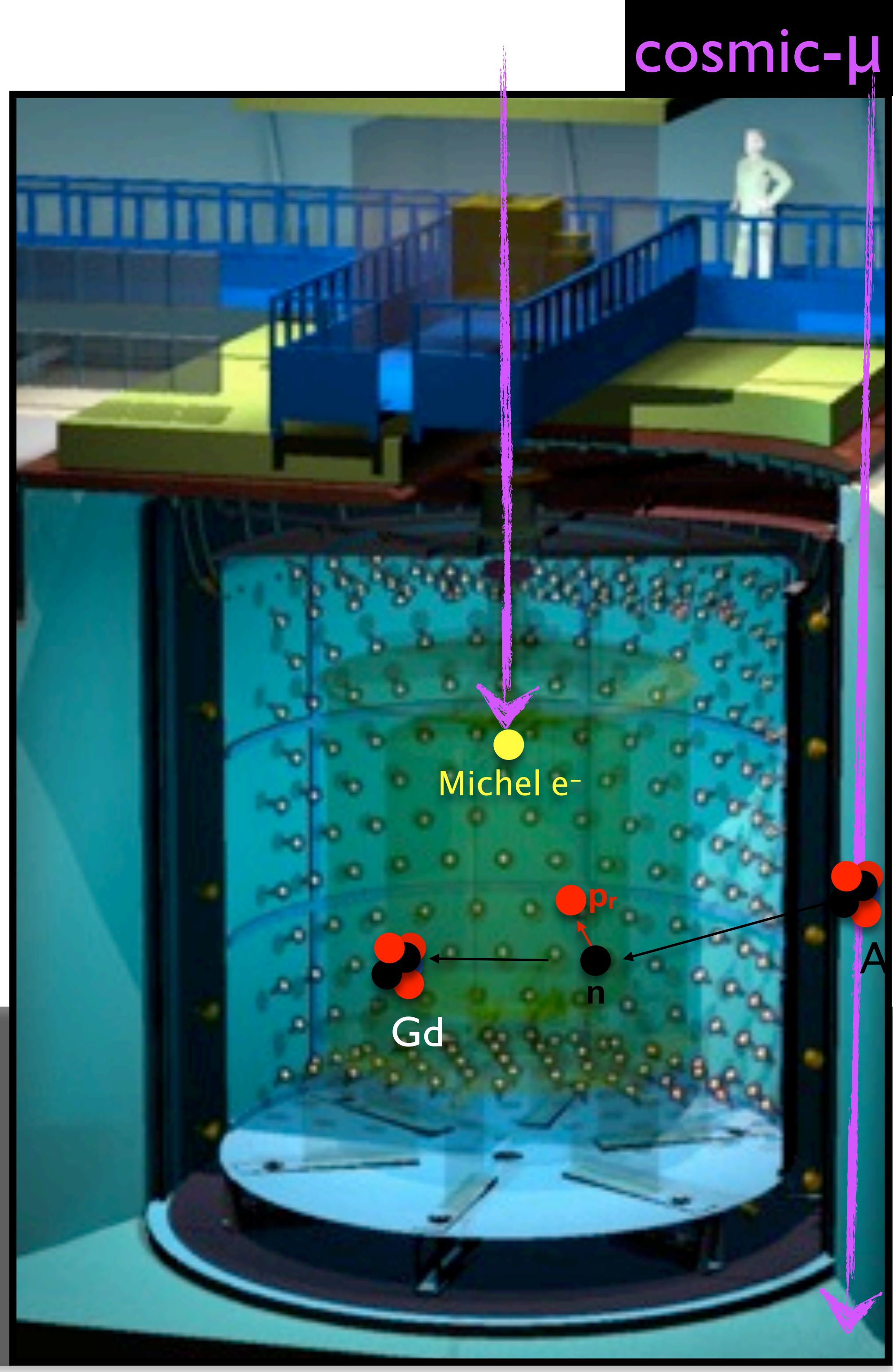
cosmogenic BG… (^{9}Li and ^{8}He)

Anatael Cabrera (CNRS-IN2P3 & APC)

Red: Best-fit Spectrum
Grey: Tagged background events
White: IBD Signal



correlated BG… (fast-n & stopping-μ)

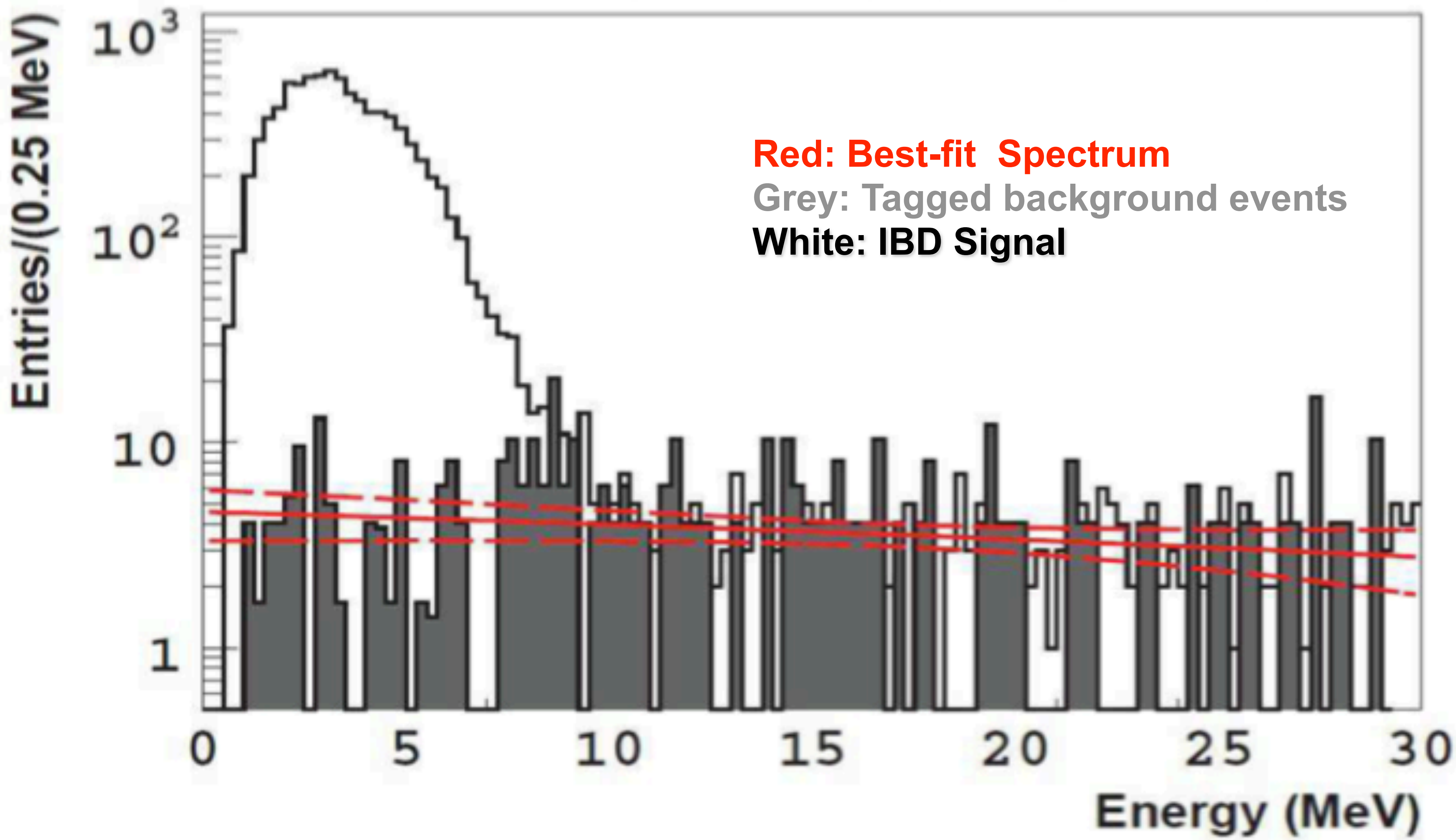


Anatael Cabrera (CNRS-IN2P3 & APC)

more on BGs…

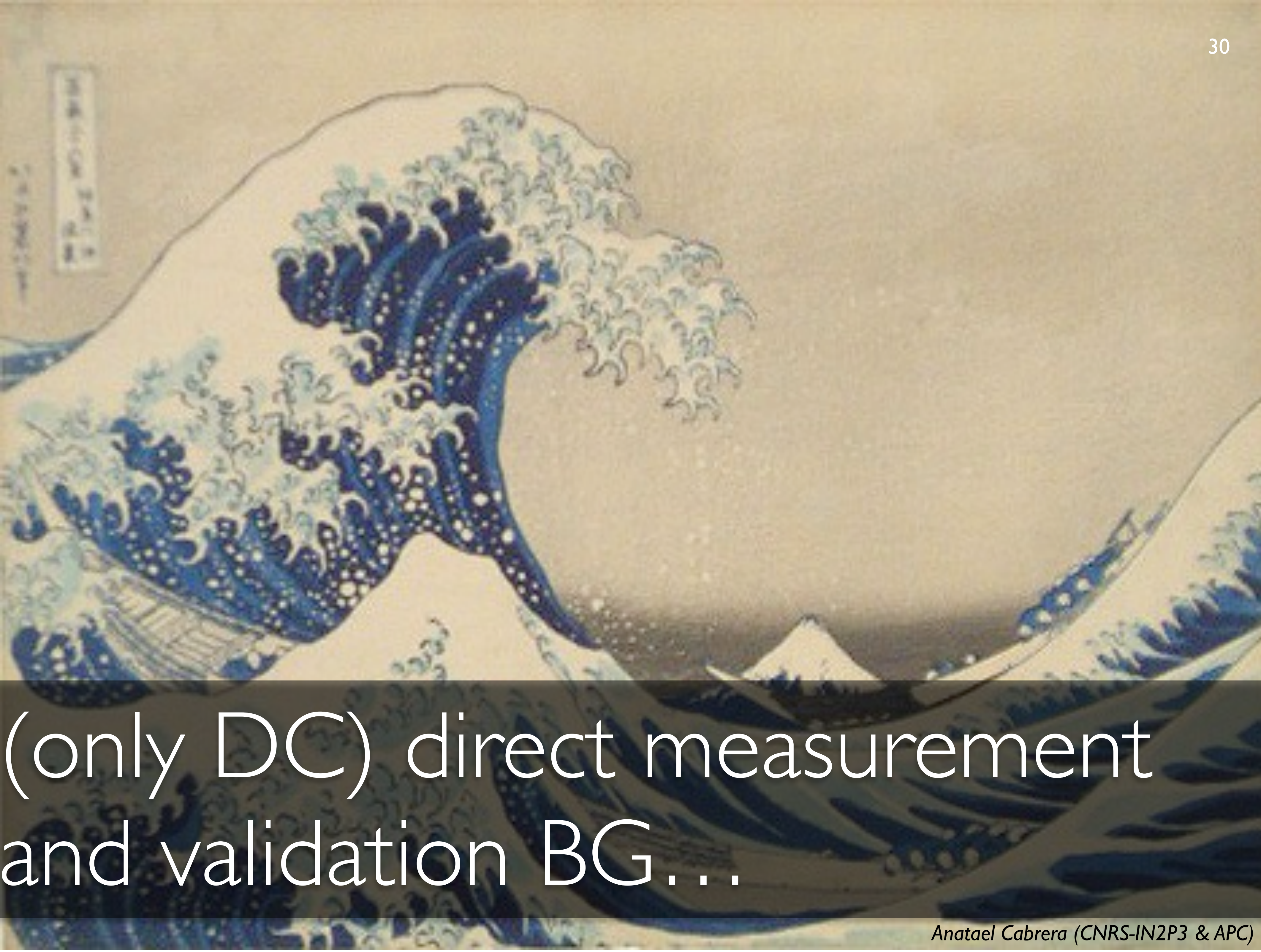
- **Accidental BG** (radio-purity + overburden)
  - ~94% dominant in DB→ easy to reduce!
  - appears easy to measure (if stable: rate and shape) but several components
    - all correlations well taking into account? [needs validation]
- **Cosmogenic Isotopes BG** (overburden)
  - ~60% dominant in DC (reduced) and RENO (not reduced)
  - **unavoidable**→ reduced by ~1/2 (DC & DB) (hard to reduce more)
  - not difficult to measure but **long integration** (~1 event per day)
    - ⟹ spectral shape limited info (useful for shape analysis) [DC soon]
- **Correlated BG** (overburden→ fast-neutrons and stopped-μs)
  - DC and RENO→ stopping-μs (but DC will kill with μ-Veto)
  - **hard to measure spectrum at low energies** (reactor ON region)
    - each detector-site (overburden and acceptance)⟹ different shapes?
      - extrapolation from >12MeV→ can be biassed at low-energies
    - DC: **tagging with 2 μ-detectors** (IV and OV)→ spectral shape
      - validated with reactor OFF data (low stats)

Correlated BG measurement



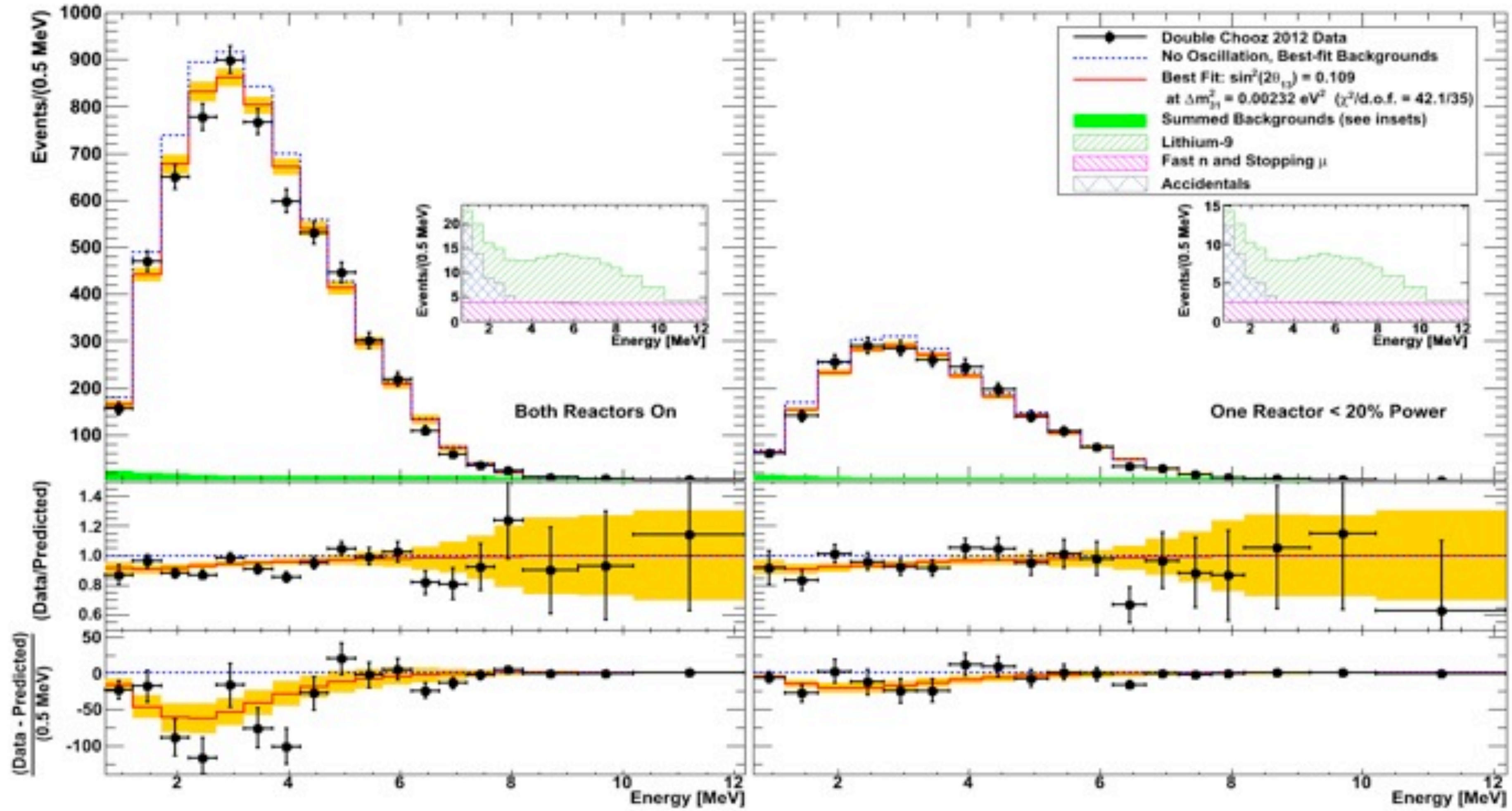
- **correlated-BG spectrum resembles θ13 signature** (slope-like)
  - →bias best value of θ13 if subtracted incorrectly (ND and FD)
- **naive method:** high-energy (12~30MeV) to extrapolate to low-energy
  - →tested in DC: this can bias the correlated BG estimation by up to 25%
  - →DC relies on 2 tags (2 independent μ-detectors + PSD under study)

Anatael Cabrera (CNRS-IN2P3 & APC)



(only DC) direct measurement and validation BG…

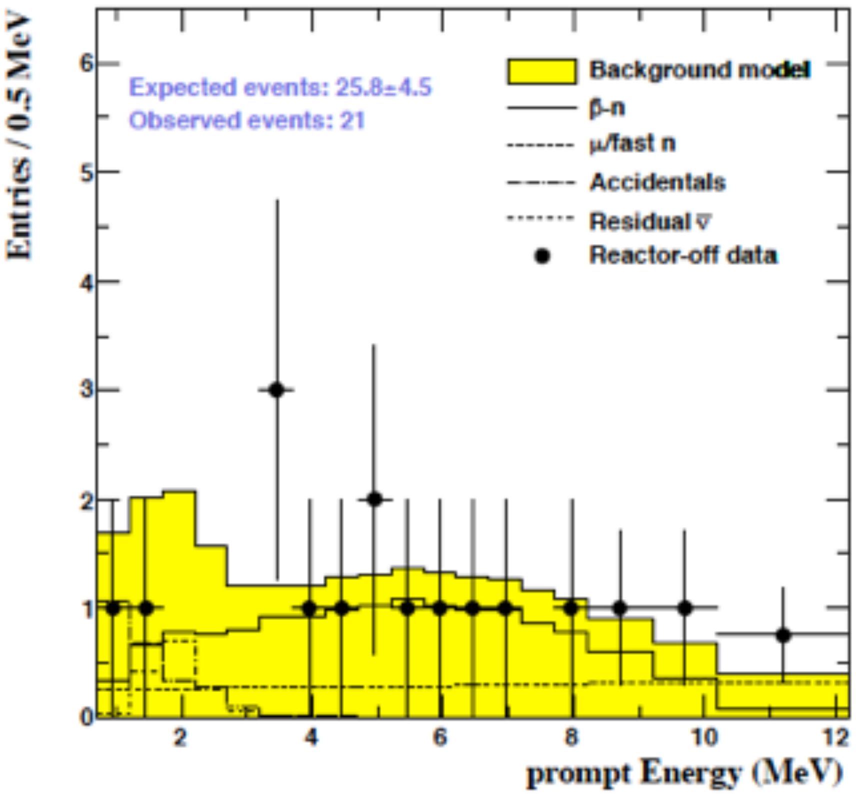
fit both θ_{13}+BGs (rate+shape) simultaneously…

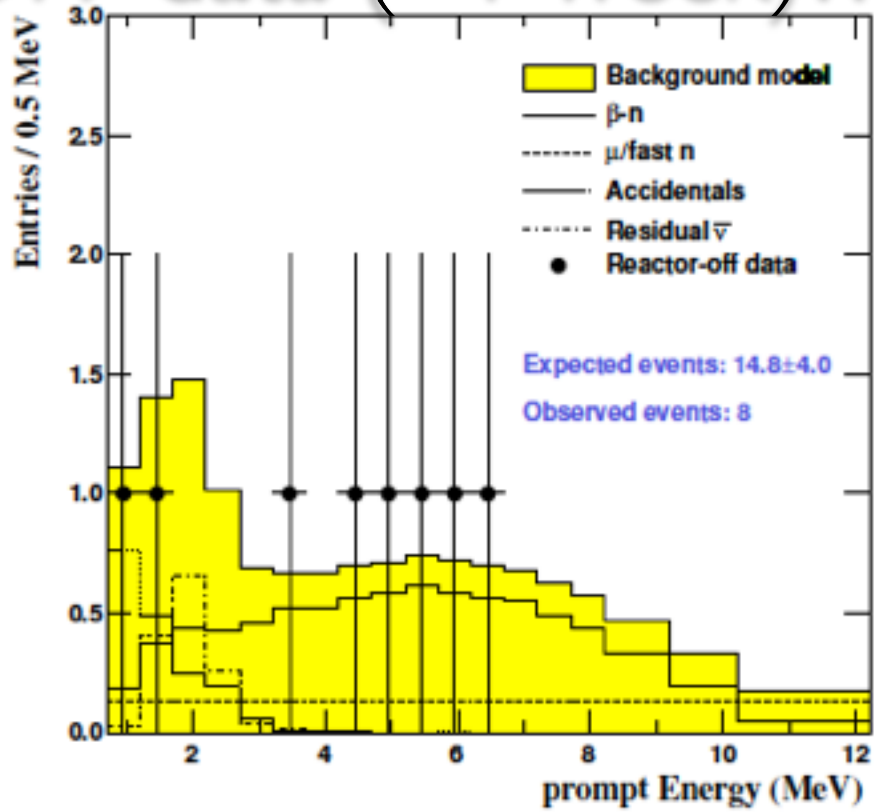


- fit input (a priori)→ BGs rate and shape as measured individually
- fit output (a posteriori)→ fit for θ13 while allowing BG (rate & shape) to accommodate (within uncertainties)→ newBG measurement (not independent)
- **BG(after fit) < 85% BG (before fit) [⟹ less subtraction]**
- also fit θ13 and BGs with 3 different selections⟹ **all consistent!**

Anatael Cabrera (CNRS-IN2P3 & APC)

reactor OFF data (~1 week)...





DC-I Selection
(no BG reduction)

DC-II Selection
(BG reduction)

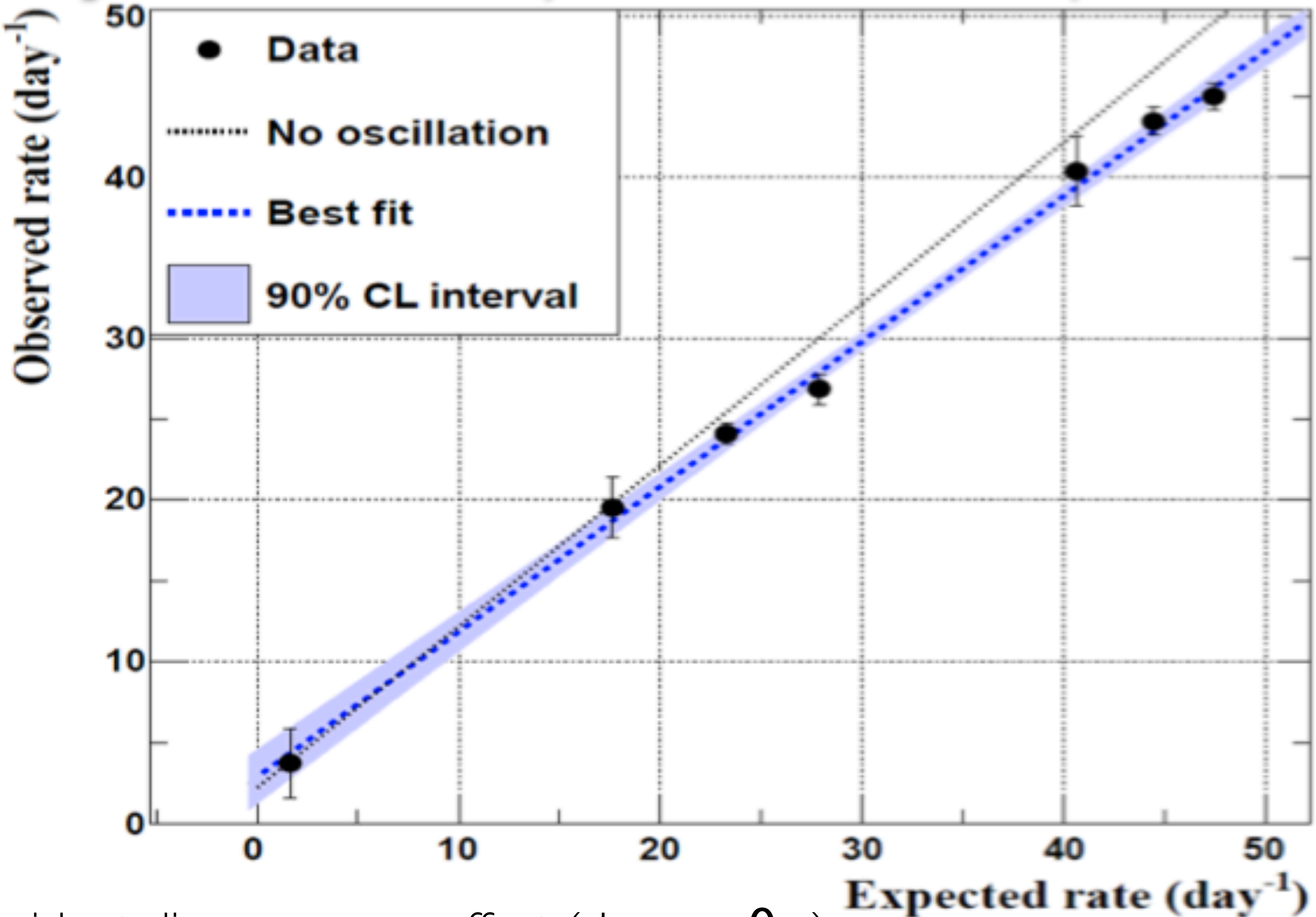
Rate (day^{-1})	β-n	Accidental	μ/fast n	Total Est.	Total Obs.
DCI	2.10±0.57	0.35±0.02	0.93±0.26	3.4±0.6	2.7±0.6
DCII	1.25±0.54	0.26±0.02	0.44±0.20	2.0±0.6	1.0±0.4

validation of BG models with 2 selections (BG changed by ~2x)

observed < expected ($\Longrightarrow$ fluctuation? $\sigma^{stats} < 1.5\sigma$)

Anatael Cabrera (CNRS-IN2P3 & APC)

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



- evident disappearance effect (slope→ θ_{13})
- BG total (intercept)→ with and without reactor 2xFF data
- direct use of both reactor ON (1 or 2 cores) and OFF data sets
- systematics uncertainties under study⟹ use for oscillation in future?

Anatael Cabrera (CNRS-IN2P3 & APC)

summary BGs (per each FD)...

experiment (@FD)	accidental [day^{-1}]	correlated [day^{-1}]	cosmo [day^{-1}]	BG	δBG	δBG/BG (%)	max. signal	BG/S (%)	δBG/S (%)
DC-I	0.35±0.02	0.93±0.26	2.10±0.57	3.38	0.63	18.5	45	7.5	1.4
DC-II	0.261±0.002	0.67±0.20	1.25±0.54	2.18	0.58	26.4	45	4.8	1.3
DC-II (fit)	0.261±0.002	0.64±0.13	1.00±0.29	1.90	0.32	16.7	45	4.2	0.7
DC-II (OFF*)	X	X	X	1.00	0.40	40.0	45	2.2	0.9
RENO	0.68±0.03	0.97±**0.06**	2.59±0.75	4.24	0.75	17.8	80	5.3	0.9
DB (3xFD)	~3.30±0.03	~0.04±0.04	~0.16±0.11	10.50	0.21	2.0	80	13.1	0.3

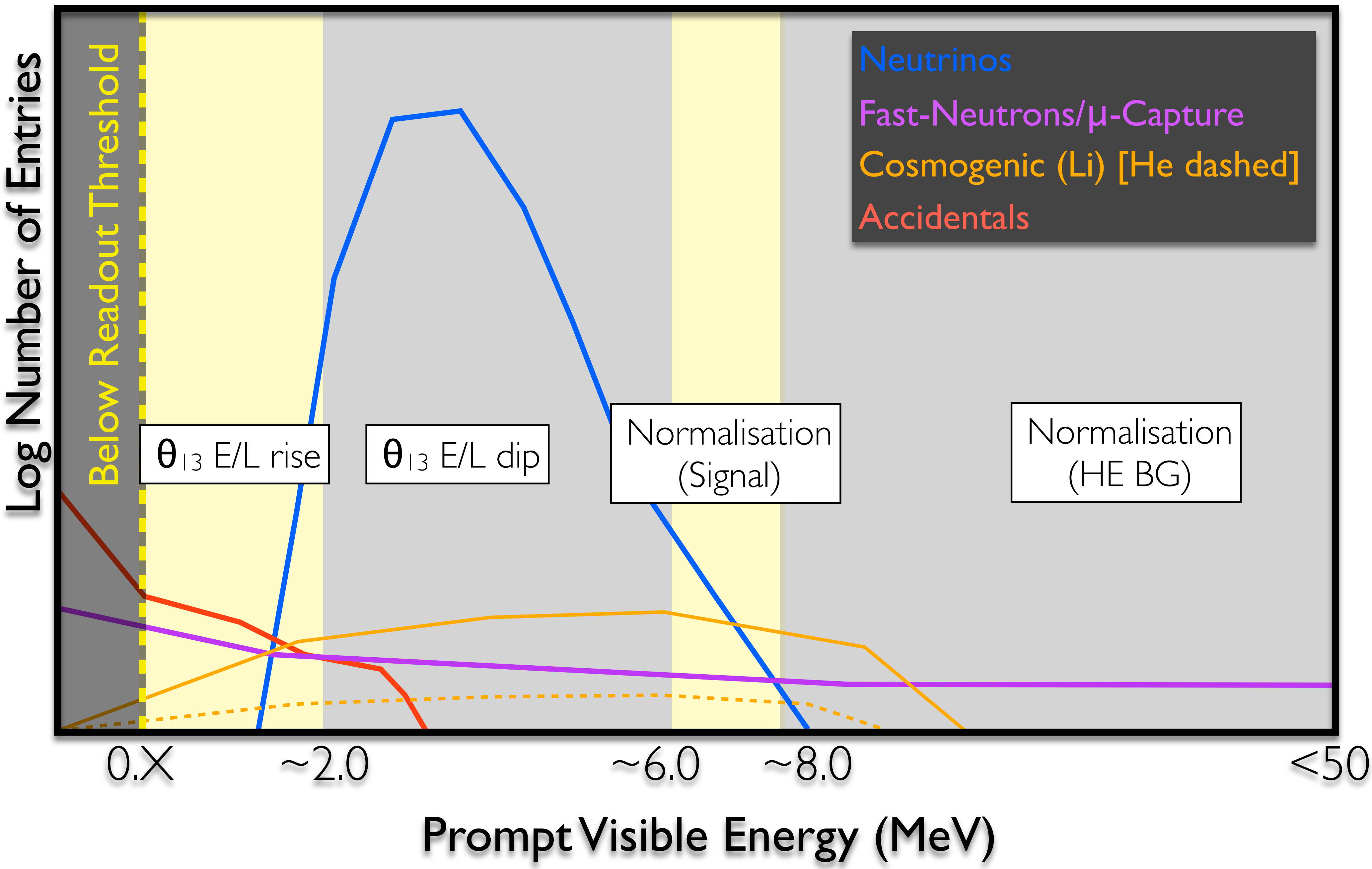
- cosmo & correlated **BG knowledge is statistics dominated**
- DC surprisingly (less overburden) **best BG/S** (excellent **δS/BG**)→ high quality analysis (precise BG estimation & 3x validation/cross-checks)
- **DC/DB lowest BGs** (largest overburden and reduce Accidentals)

Anatael Cabrera (CNRS-IN2P3 & APC)

θ_{13} results…

Anatael Cabrera (CNRS-IN2P3 & APC)

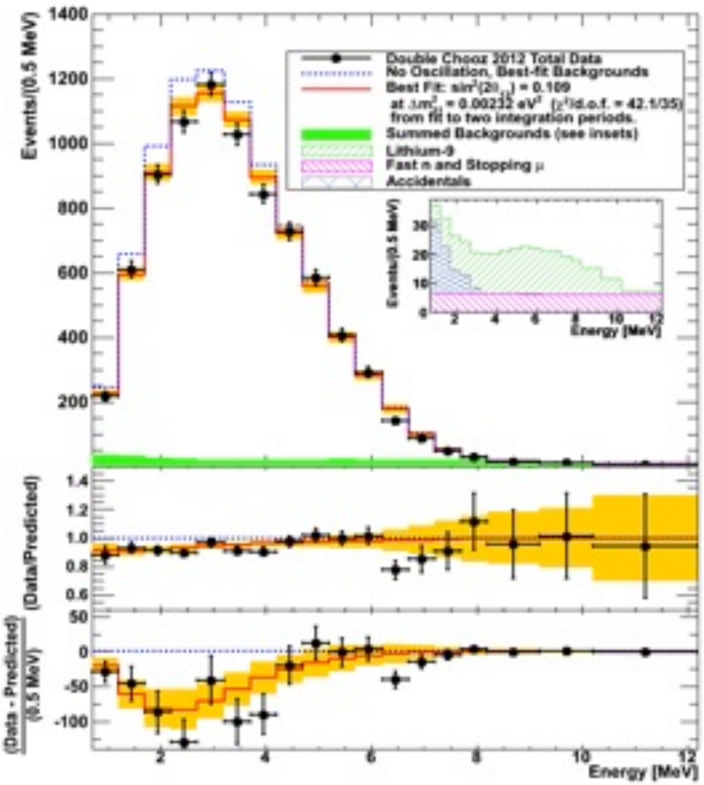
DC Energy Spectra…



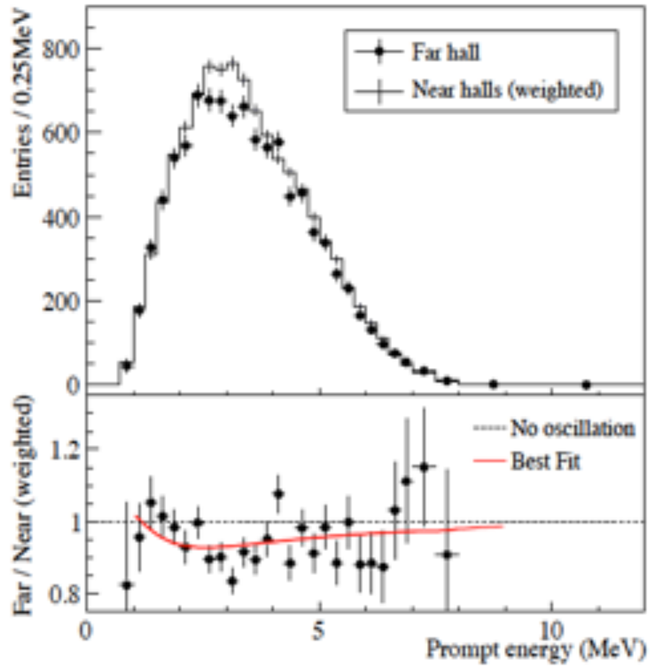
Anatael Cabrera (CNRS-IN2P3 & APC)

θ_{13} reactor side by side…

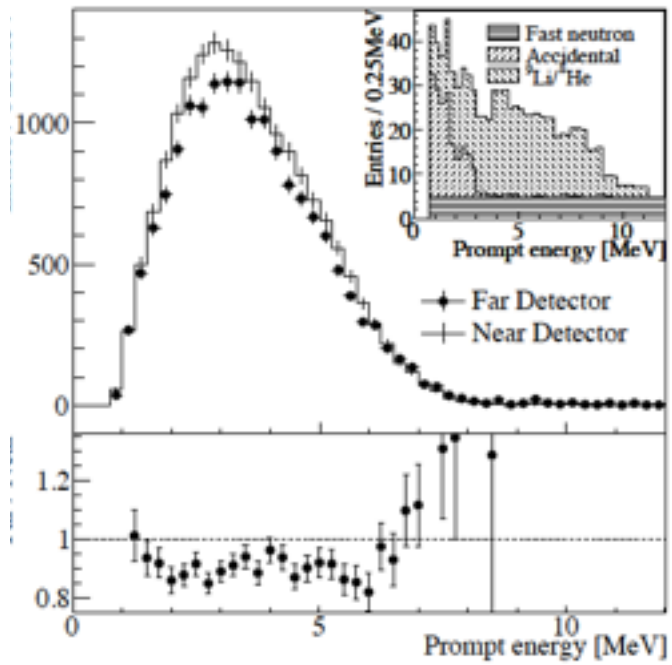
DC (June'12)



DB (March'12)

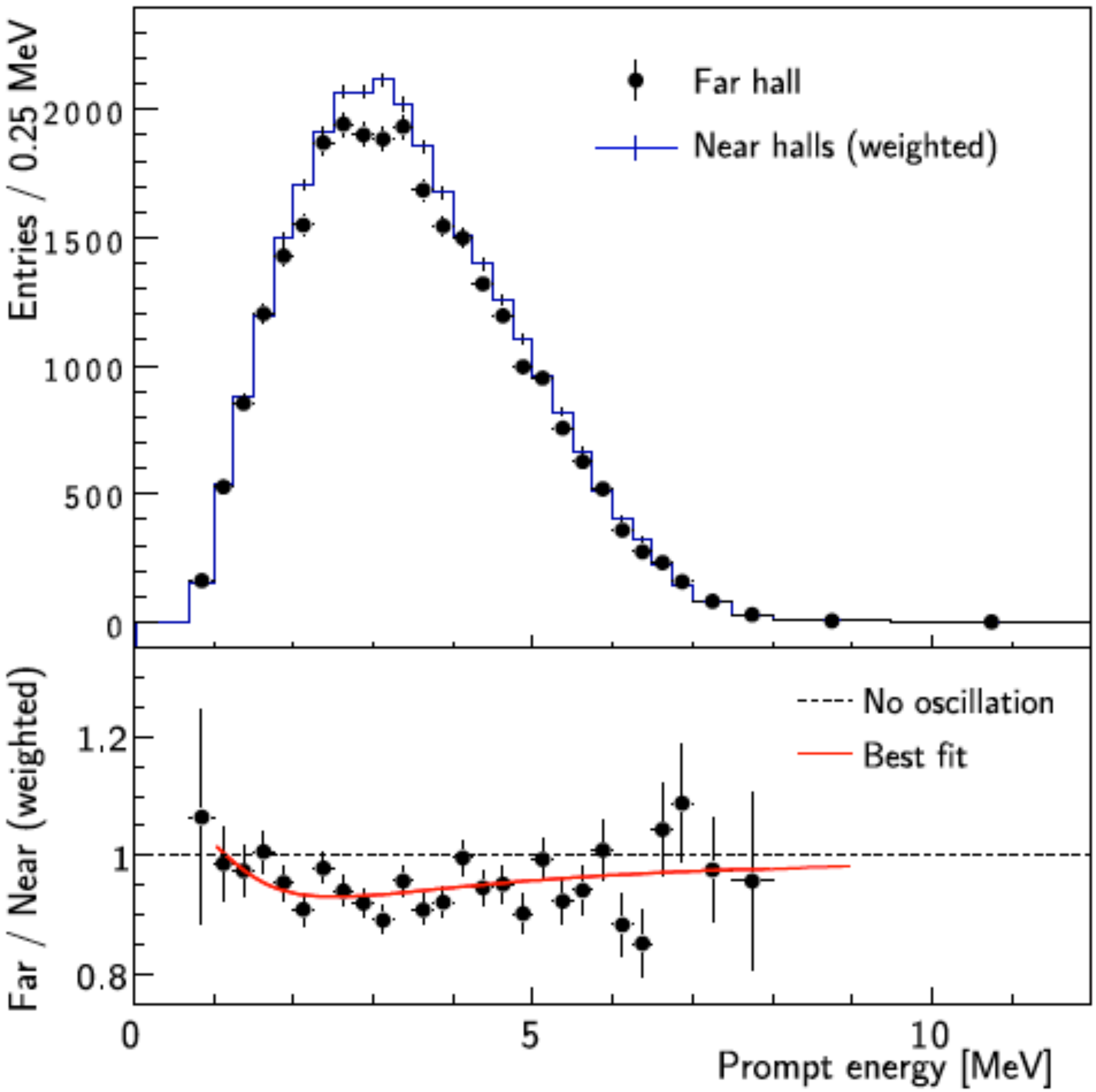


RENO (April'12)



	measured $\sin^2(2\theta_{13})$	exposure (days)	arXiv
DC-I(rate+shape)	$0.086\pm0.051(0.041^{stat}\pm0.030^{sys})$	96.8	1112.6353
DB(rate only)	$0.092\pm0.017(0.016^{stat}\pm0.005^{sys})$	55	1203.1669
RENO(rate only)	$0.113\pm0.023(0.013^{stat}\pm0.019^{sys})$	229	1204.0626
DC-II(rate only)	$0.170\pm0.053(0.035^{stat}\pm0.040^{sys})$	251	1207.6632
DC-II(rate+shape)	$0.109\pm0.039(0.030^{stat}\pm0.025^{sys})$	251	1207.6632
DB-II(rate only)	$0.089\pm0.011(0.010^{stat}\pm0.005^{sys})$	126	Nu2012

DB @ Nu2012 (not yet published)



Anatael Cabrera (CNRS-IN2P3 & APC)

highlights…

- **different baselines** (assuming MINOS-driven Δm^2)…
  - DC a bit **too short**→ hard to see the rise on E/L
  - RENO and DB longer→ should expect to see E/L (if BGs well understood)
  - RENO and DB: many baselines→ more diffused E/L pattern?
- **E/L shape** (neutrino oscillation expectation)→ **a must to measure θ_{13}**
  - **BG rate & spectra** (subtracted FD and ND)
    - important: lowest S/BG (DC) and also δBG/S (DB)
  - **energy systematics** (non-linearities, MC, etc)
- **RENO & DB→ rate analysis ("any deficit" assumed to be θ_{13})**
  - **no oscillations shape compatibility**→ p-value, χ^2/ndf,…
  - RENO's spectral shape is unique (oscillations only?)
  - all experiments show some "effect" at high energies (in deficit rate)
- **DC→ full spectral to fit θ13+BG** (constrain both)
  - else (rate only) DC will measure a larger $\sin^2(2\theta_{13})=0.17\pm0.05$ (1.5σ tension)
  - **DC consistent with MINOS** [hard to constraint Δm^2]

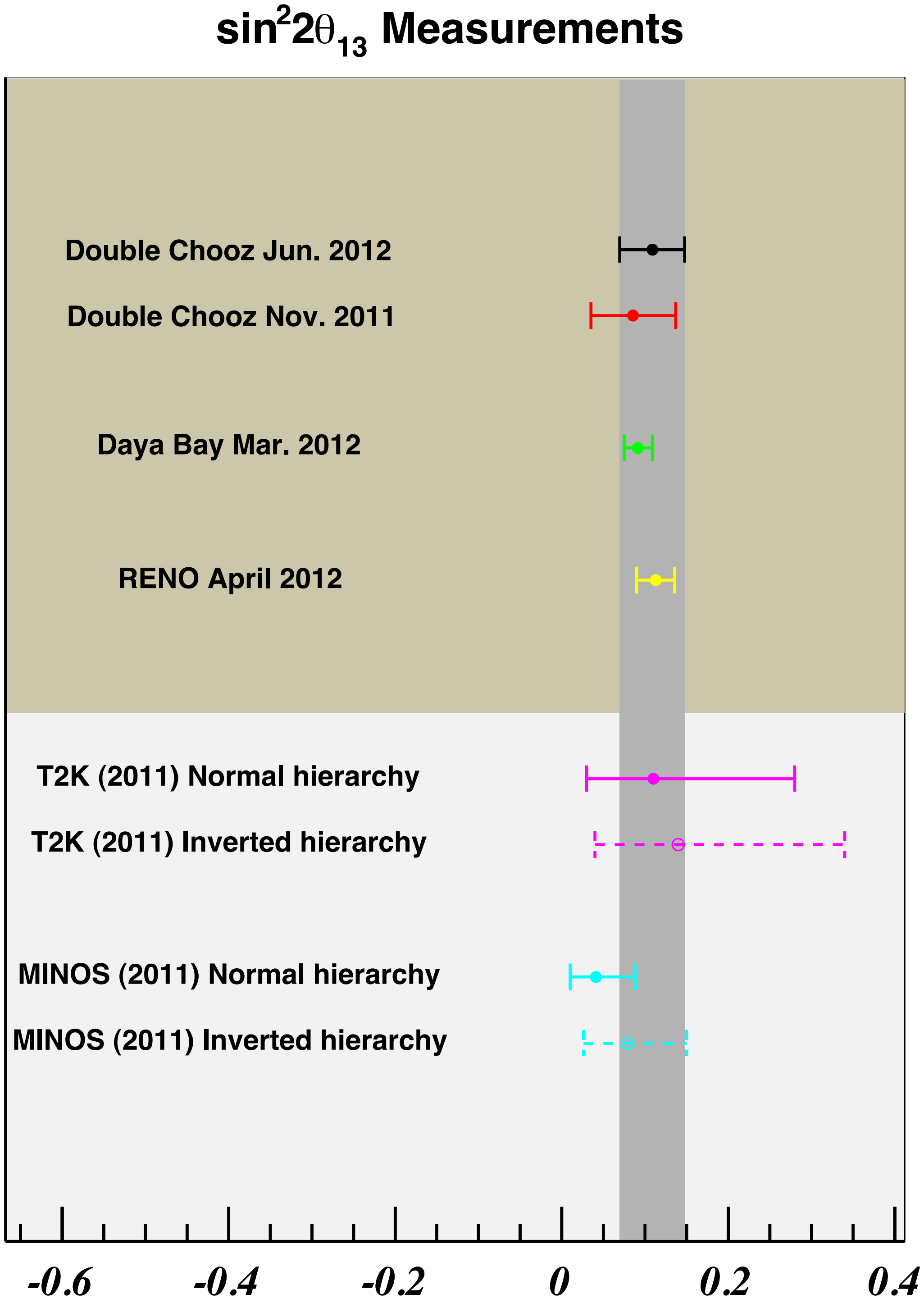
Anatael Cabrera (CNRS-IN2P3 & APC)

rate-driven uncertainties table...

uncertainty (%)	DC-II (rate)	DC-II (shape) published	DC-II (OFF*)	DC-III (FD only) my guesstimate	DC (ND) my guesstimate	RENO (abs)	RENO (rel) published	DB (abs)	DB (rel) published
flux									
reactor	1.7	1.7	1.7	1.7	0.8	2.0	0.9	3.0	0.8
detection									
efficiency	1.1	1.1	1.1	0.8	0.2	1.5	0.2	1.9	0.2
response	0.3	0.3	0.3	0.2	0.1	X	X	X	X
background for rate analysis (δBG/S)									
cosmogenic	1.49	0.80	X	0.28	0.28	0.71	0.71	0.27	0.27
correlated	0.55	0.36	X	0.06	0.06	0.08	0.08	0.10	0.10
accidental	0.01	0.01	X	0.00	0.00	0.04	0.04	0.07	0.07
total	1.59	0.88	1.10	0.28	0.28	0.72	0.72	0.30	0.30
syst total	**2.6**	**2.2**	**2.3**	**1.9**	**0.9**	**2.6**	**1.2**	**3.6**	**0.9**
stats total	**1.1**	**1.1**	**1.1**	**0.7**	**0.5**	**0.8**	**0.8**	**1.0**	**1.0**

BG uncertainties without shape uncertainty→ (only DC) increase uncertainties

published θ13 results summary…



DB

- leading precision now 15% (still rate only)
- $\sin^2(2\theta_{13})=0.89\pm0.10\text{stat}\pm0.05\text{syst}$

RENO

- rate only measurement
- published disappearance shape→ features

DC

- rate+shape analysis: θ_{13}+BG constraints
- 4 ways to estimate total BGs (all consistent)
- DC final (my guesstimate by scaling from DB)
  - ND-FD ~ $(0.10\pm0.010^{\text{total}})$

world-wide: at least 2 experiments to validate accuracy of the measurement (different systematics: E/L, BGs, calibration, etc)

Anatael Cabrera (CNRS-IN2P3 & APC)

what to remember?

Anatael Cabrera (CNRS-IN2P3 & APC)

- **θ13 measured** by reactor experiments (will **dominate for long**)
  - the measured value will help us to measure/constrain 3ν oscillation model
  - **high precision** (uncertainty) and **high accuracy** (what's the true value?)
- **high precision on θ13** ⟹ ~5% uncertainty within 3 years
  - multi-detector approach helps via cancellation of many uncertainties
- **high accuracy on θ13** ⟹ how to know for sure?
  - cross-check among different experiments ⟹ on-going slow process (transparency of collaboration is important)
  - different sites, BGs, systematics, baselines, etc help ⟹ the ONLY way?
  - rate+shape (E/L and BG-shape information) measurement of θ13 a **must**
- regardless **θ13 is LARGE**
  - …if you were waiting for this, **please go ahead**! ;-)
  - Asia leads… (DC slowly moving, but much of this field is DC's success)