Double Chooz

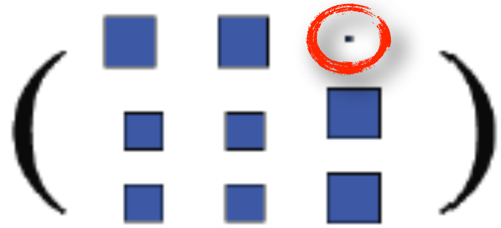
(latest θ_{13} measurements)

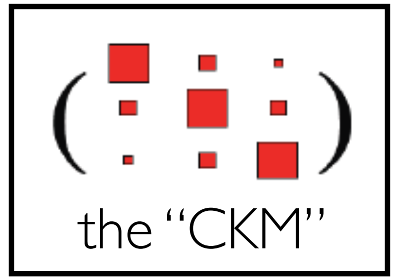
NuTel (Venezia, Italia)
Marzo 2013

(for the Double Chooz collaboration)

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

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





"atmospheric" $\Longrightarrow \theta_{23}\sim45°$

$\theta_{13} < 11°$ & "dirac" δ_{CP}

"solar" $\Longrightarrow \theta_{12}\sim33°$

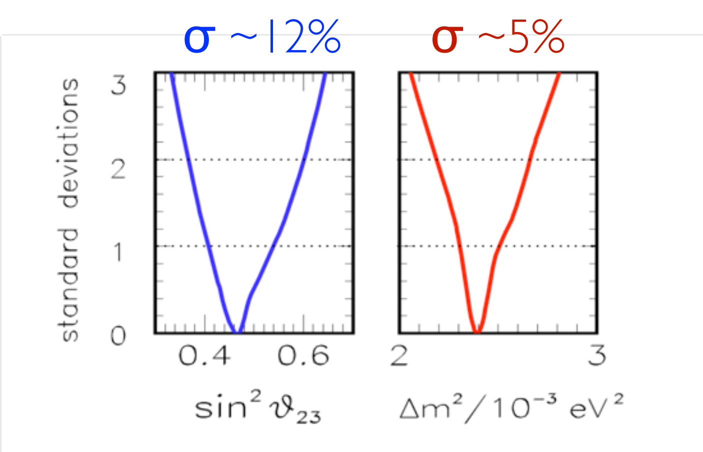
Δm^2_{31} Δm^2_{31} Δm^2_{21}

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

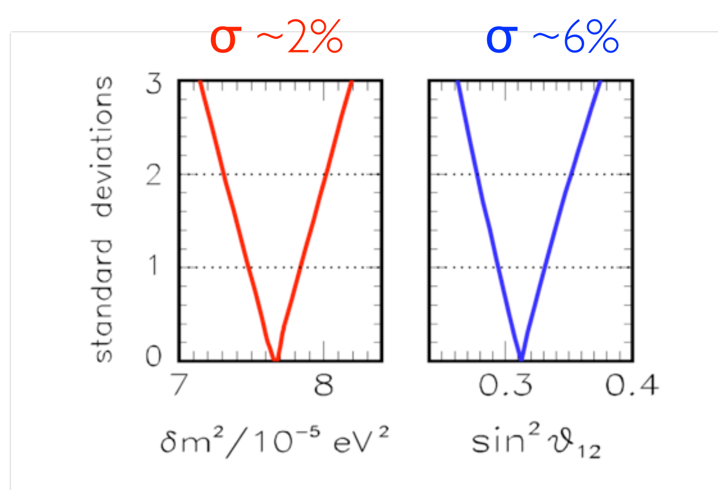
atmos+LBL(dis) — $P(\nu_\mu\to\nu_\mu)$

Chooz+LBL(app) — $P(\nu_e\to\nu_e)$ & $P(\nu_\mu\to\nu_e)$

solar+KamLAND — $P(\nu_e\to\nu_x)$



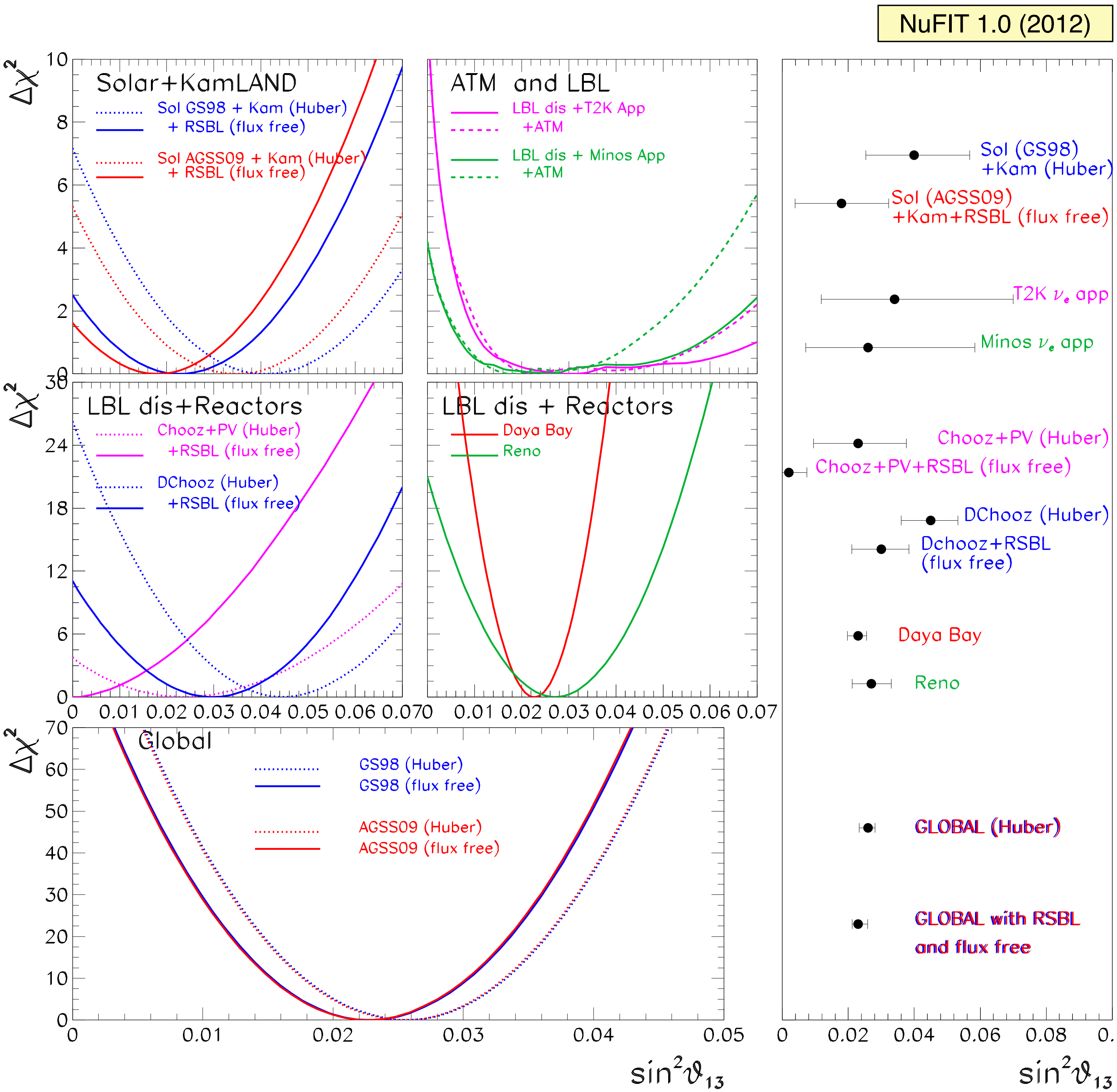
knowledge on θ_{13} & δ_{CP} [later]



Fogli et al arXiv:1106.6028

global status of θ13…

1209.3023v3

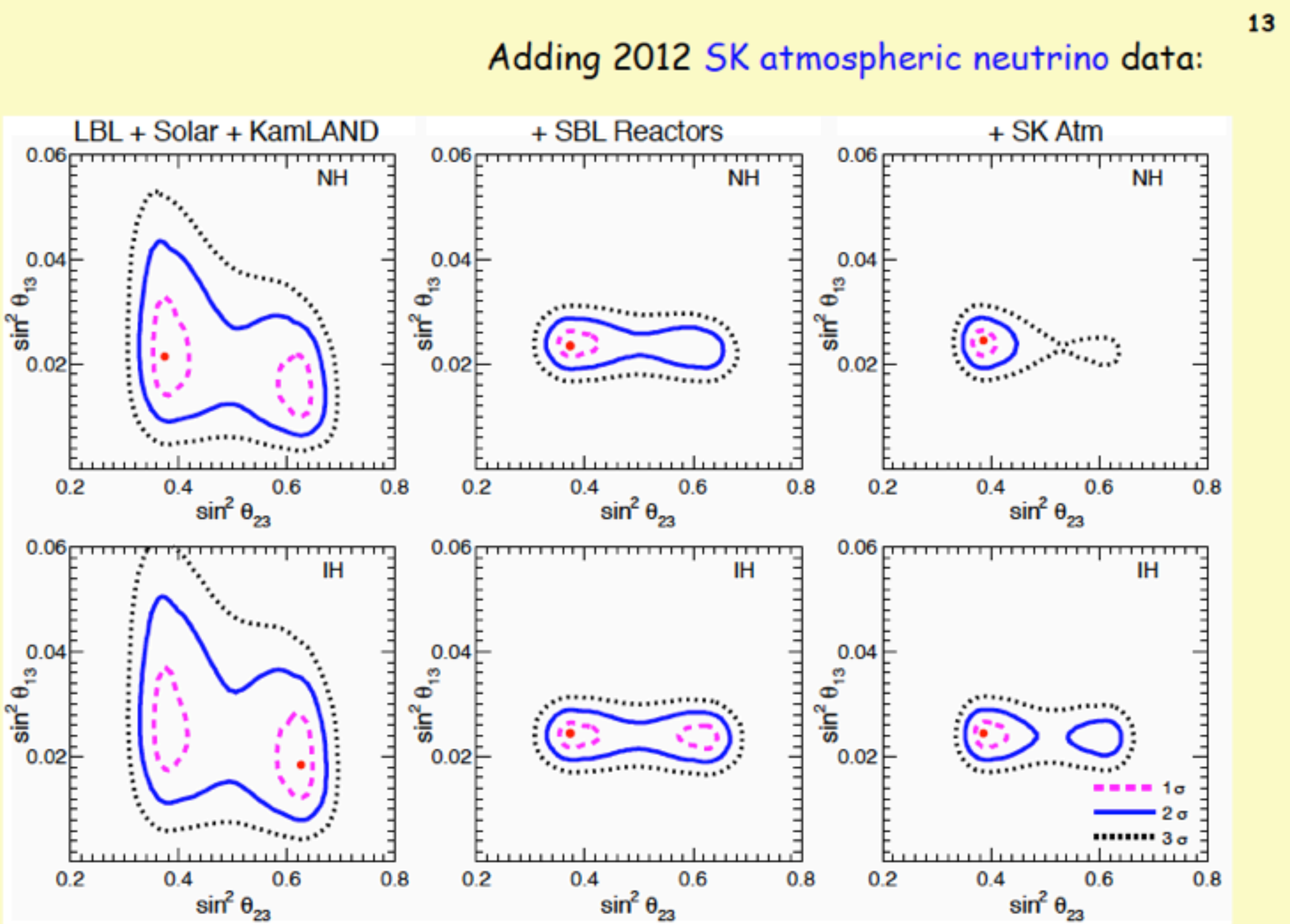


Anatael Cabrera (CNRS-IN2P3 & APC)

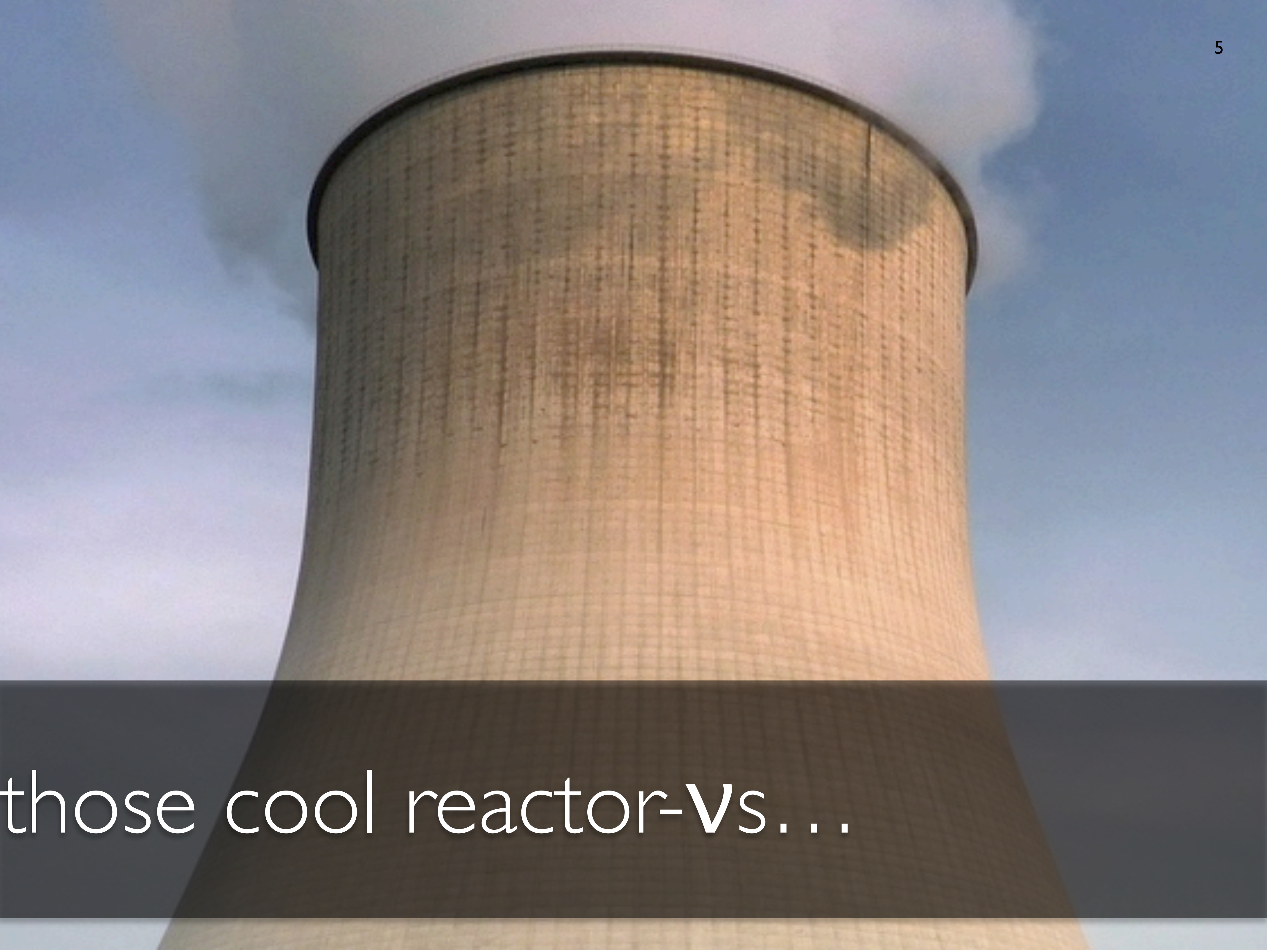
global impact of θ_{13} (Lisi @ Shenzhen'2012)

normal-H

inverted-H



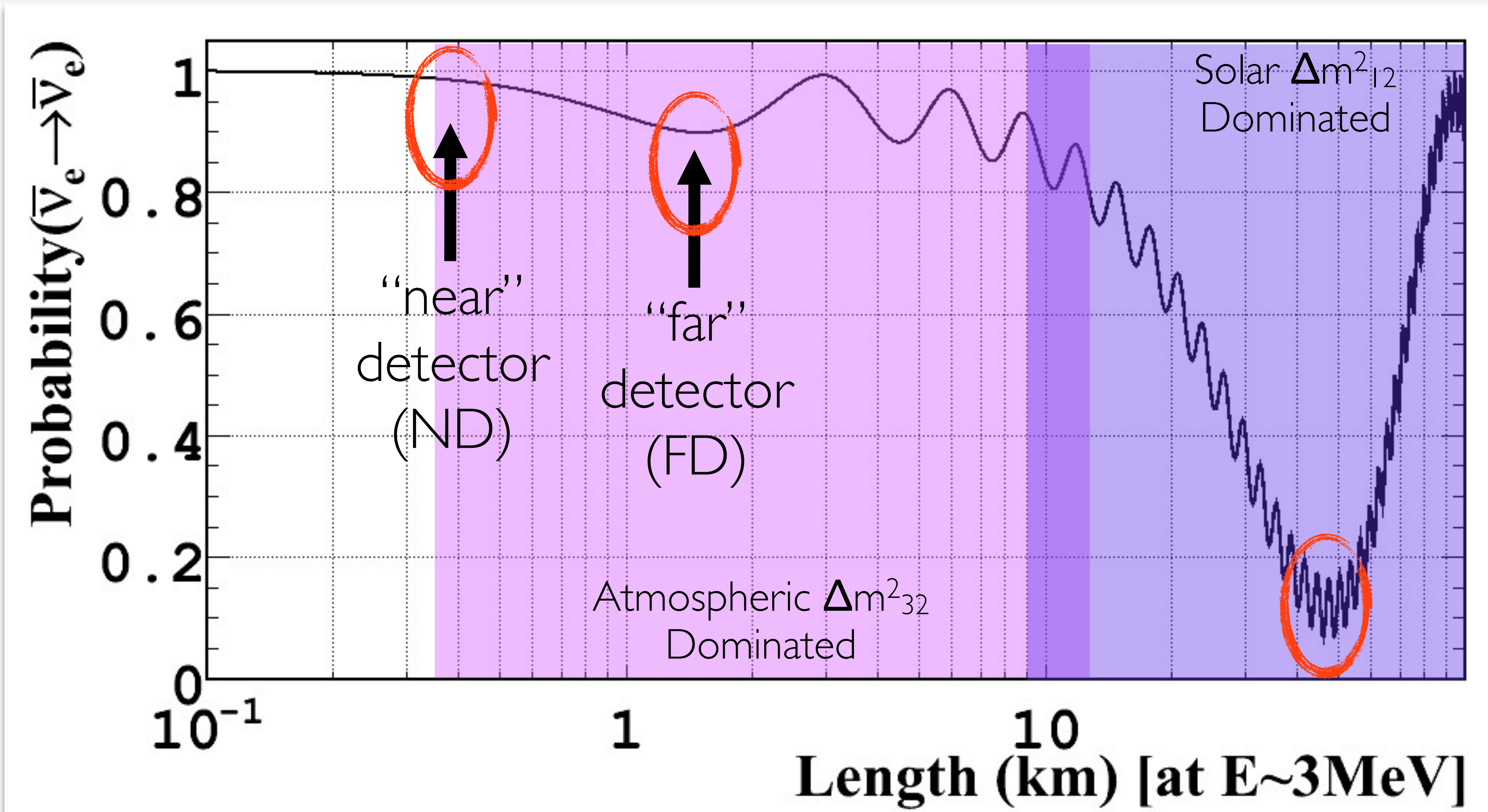
→both precision & accuracy in θ_{13} matter!


those cool reactor-vs…

the coolest reason for us...

$$P(\nu_e \rightarrow \nu_e) \sim 1 - \sin^2(2\theta_{13}) \sin^2(\Delta m^2_{31} L_o/E)$$

[plot: E(ν)@3MeV, $\sin^2(2\theta_{13})$ = **0.1** & $\Delta m^2_{31}=2.2\times10^{-3}eV^2$]



ND→ reduce correlated inter-detector systematic uncertainties

ND→ only θ13 (no other physics: hypothetical sterile-νs)

Anatael Cabrera (CNRS-IN2P3 & APC)

Double Chooz…

Double Chooz collaboration

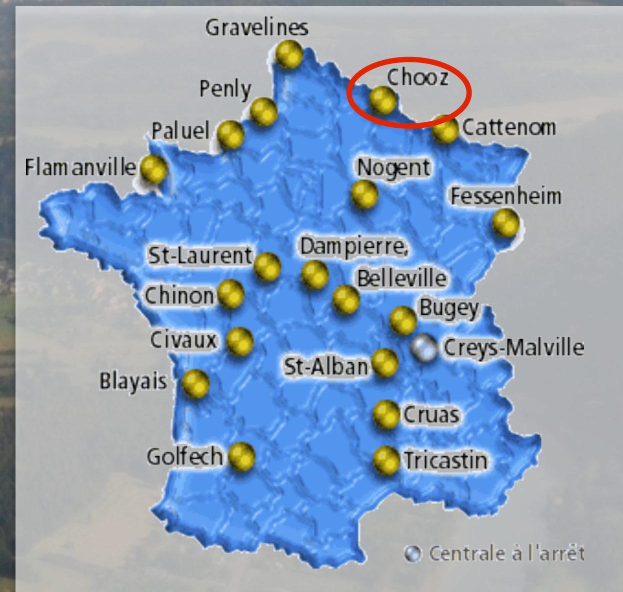
Brazil	France	Germany	Japan	Russia	Spain	USA
CBPF **UNICAMP** **UFABC**	**APC** **CEA/DSM/ IRFU:** **SPP** **SPhN** **SEDI** **SIS** **SENAC** **CNRS/IN2P3:** **Subatech** **IPHC**	**EKU Tübingen** **MPIK Heidelberg** **RWTH Aachen** **TU München** **U. Hamburg**	**Tohoku U.** **Tokyo Inst. Tech.** **Tokyo Metro. U.** **Niigata U.** **Kobe U.** **Tohoku Gakuin U.** **Hiroshima Inst. Tech.**	**INR RAS** **IPC RAS** **RRC Kurchatov**	**CIEMAT-Madrid**	**U. Alabama** **ANL** **U. Chicago** **Columbia U.** **UCDavis** **Drexel U.** **IIT** **KSU** **LLNL** **MIT** **U. Notre Dame** **U. Tennessee**

Spokesperson:
H. de Kerret (IN2P3)

Project Manager:
Ch. Veyssière (CEA-Saclay)

Web Site:
www.doublechooz.org/

our experimental setup…

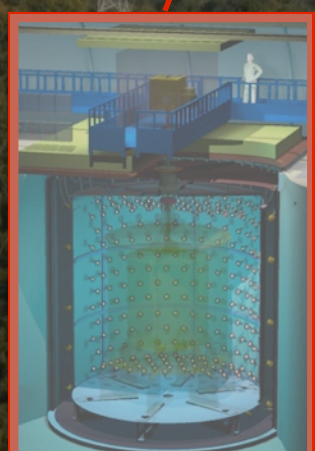


Chooz Reactors

Power: 8.5GW$_{th}$

$\Longrightarrow$ ~$10^{21}\nu$/s

(N4s: very powerful)



Near

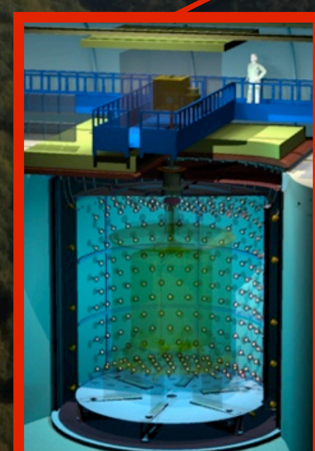
<L> 400m

~400ν/day

120mwe

Target: 8.2t

in 2014



Far

<L> 1050m

~50ν/day

300mwe

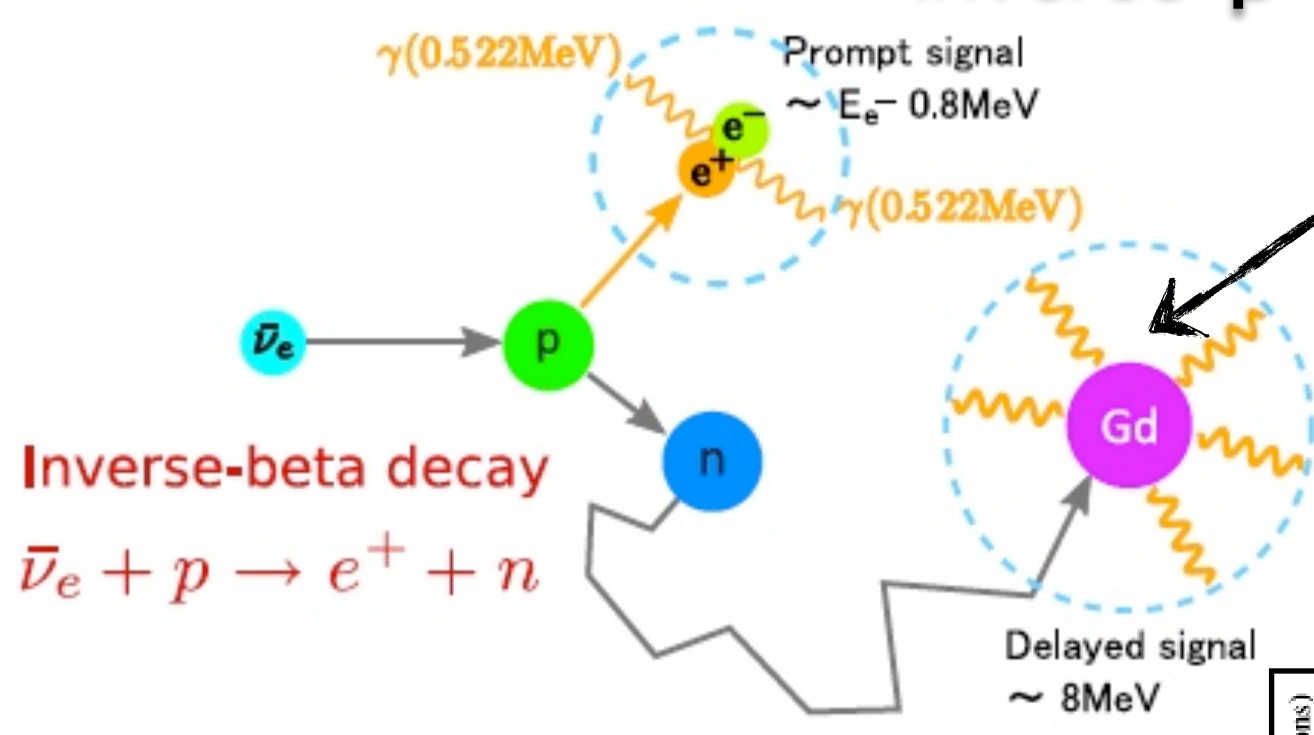
Target: 8.2t

April 2011

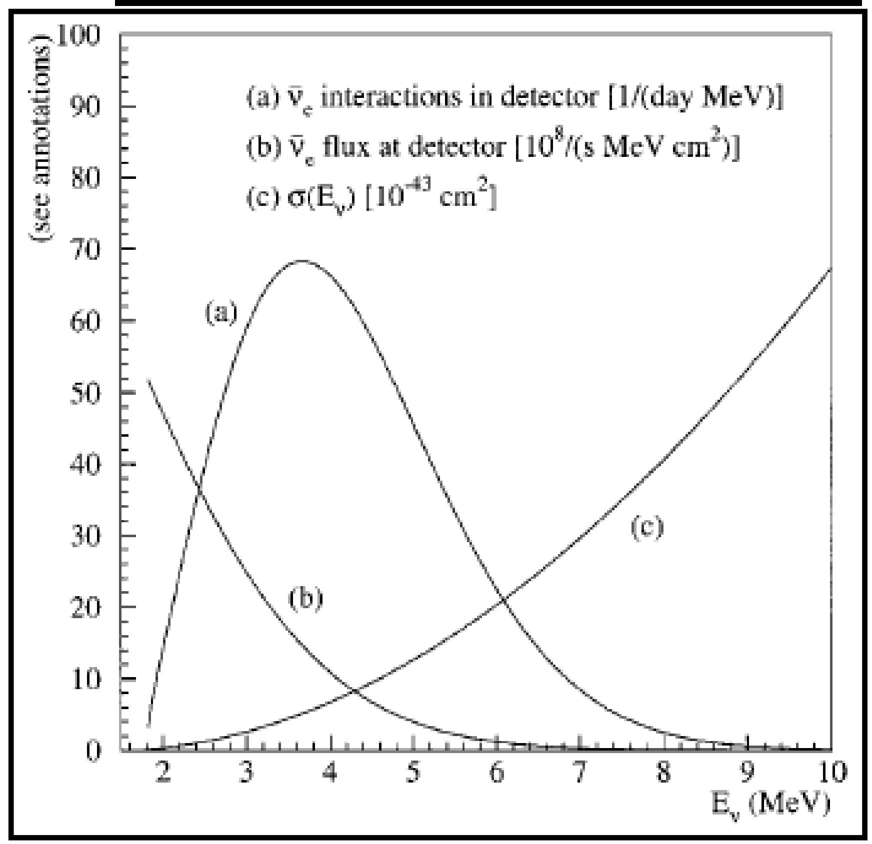

our neutrino “θ_{13}-telescope”…

inverse-β decay (a cartoon)…

NOTE: also capture on H (à la KamLAND, etc)



Bemporad, Gratta, Vogle. RMP. 2002



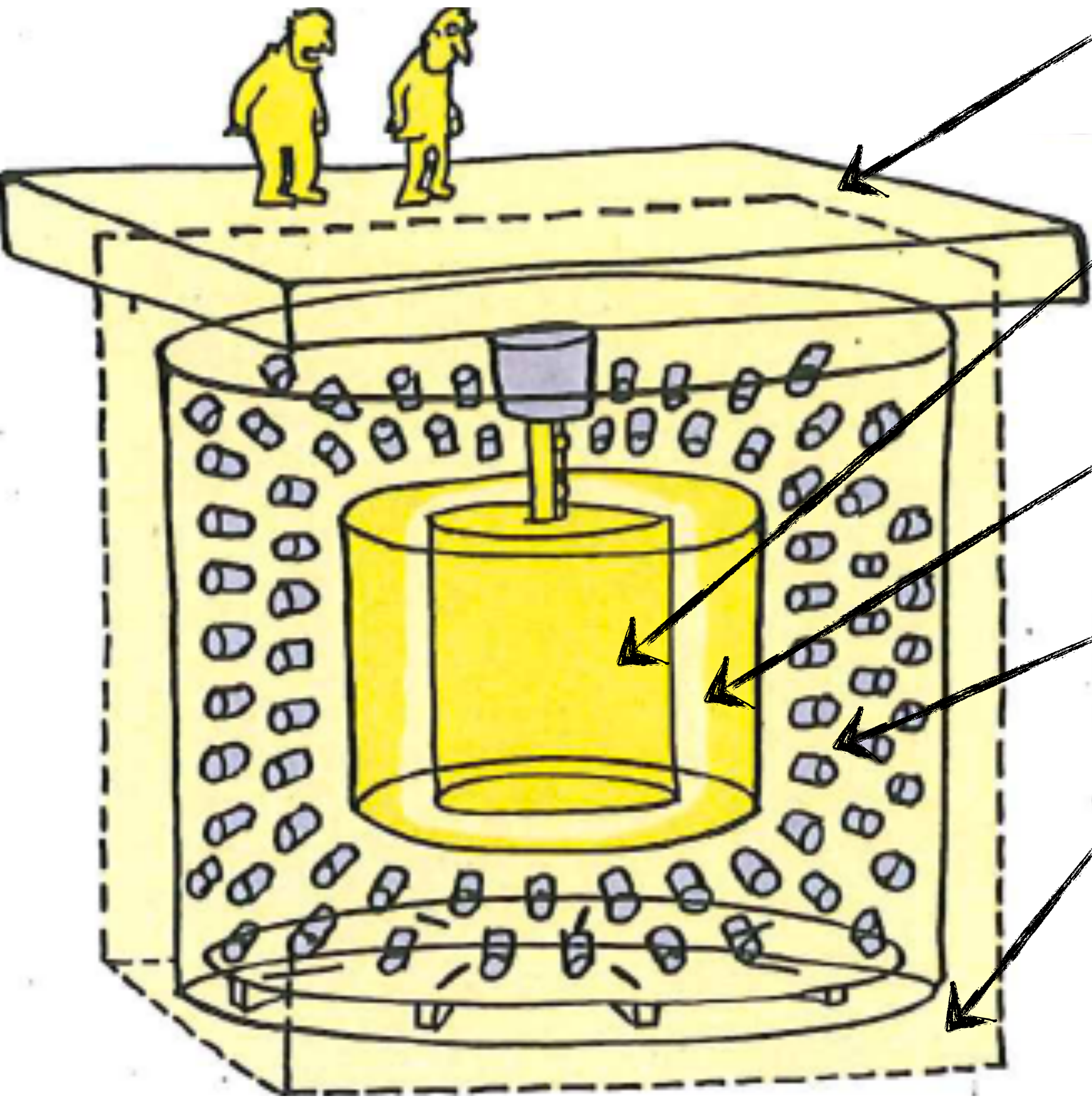
- high & well known σ_{IBD} [$\tau_{neutron}$=(881.5±1.5)s]
- 1ν manifests via **two** triggers:

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

  2nd event (**delay**): **n-Gd capture** (~8MeV)
- **Energy(ν) = Energy(e+) + 0.8MeV**
- both events are **time/space correlated**

  time/space coincidence→reduce BG!

a generic θ13-LAND…



Outer μ-Veto (OV)
Plastic Scintillator Strips (→tracking)

ν-Target (NT)
Liquid-Scintillator + **0.1% of Gd**

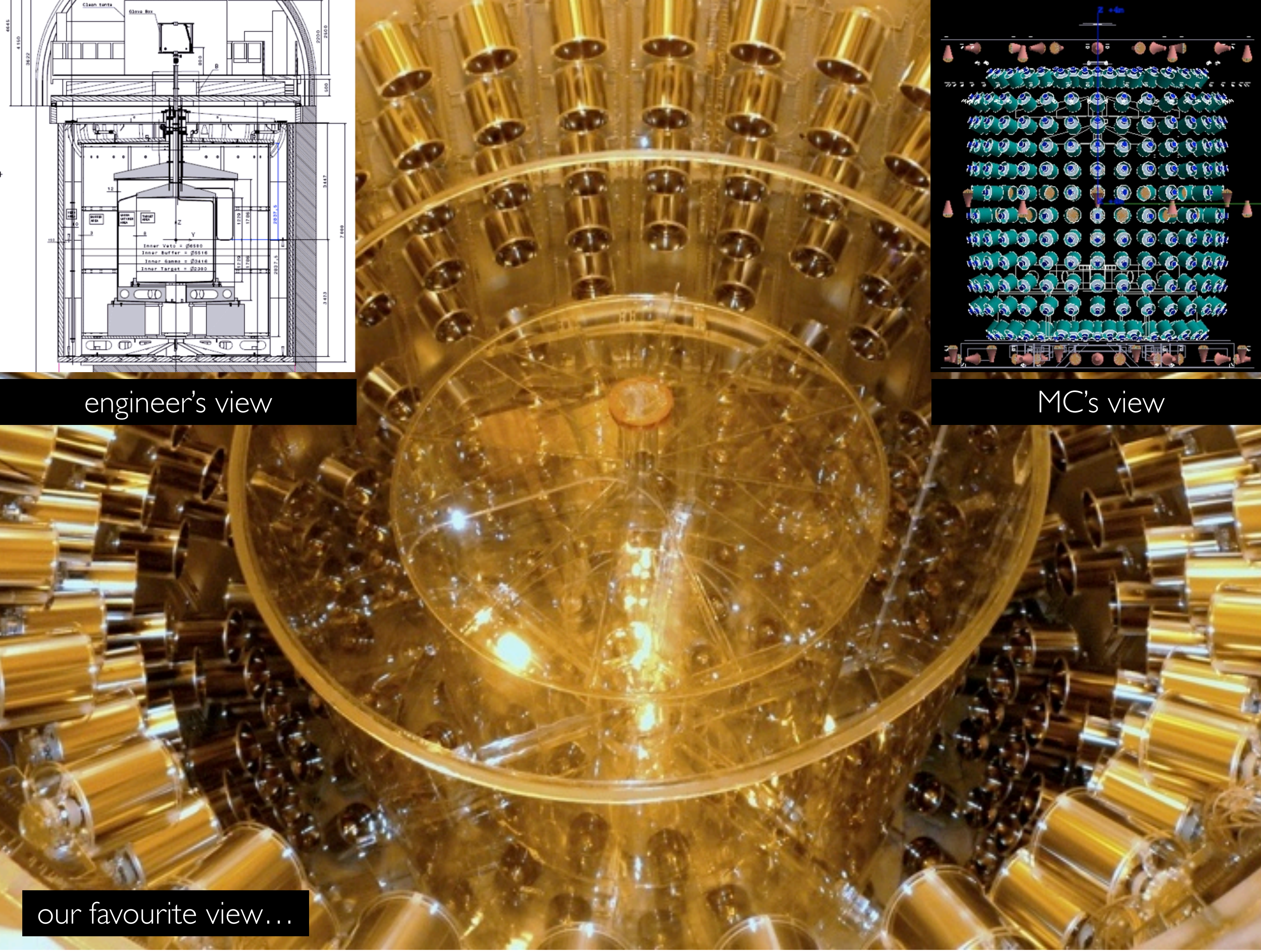
γ-Catcher (GC)
Liquid-Scintillator

Light Buffer
Oil (negligible scintillation)

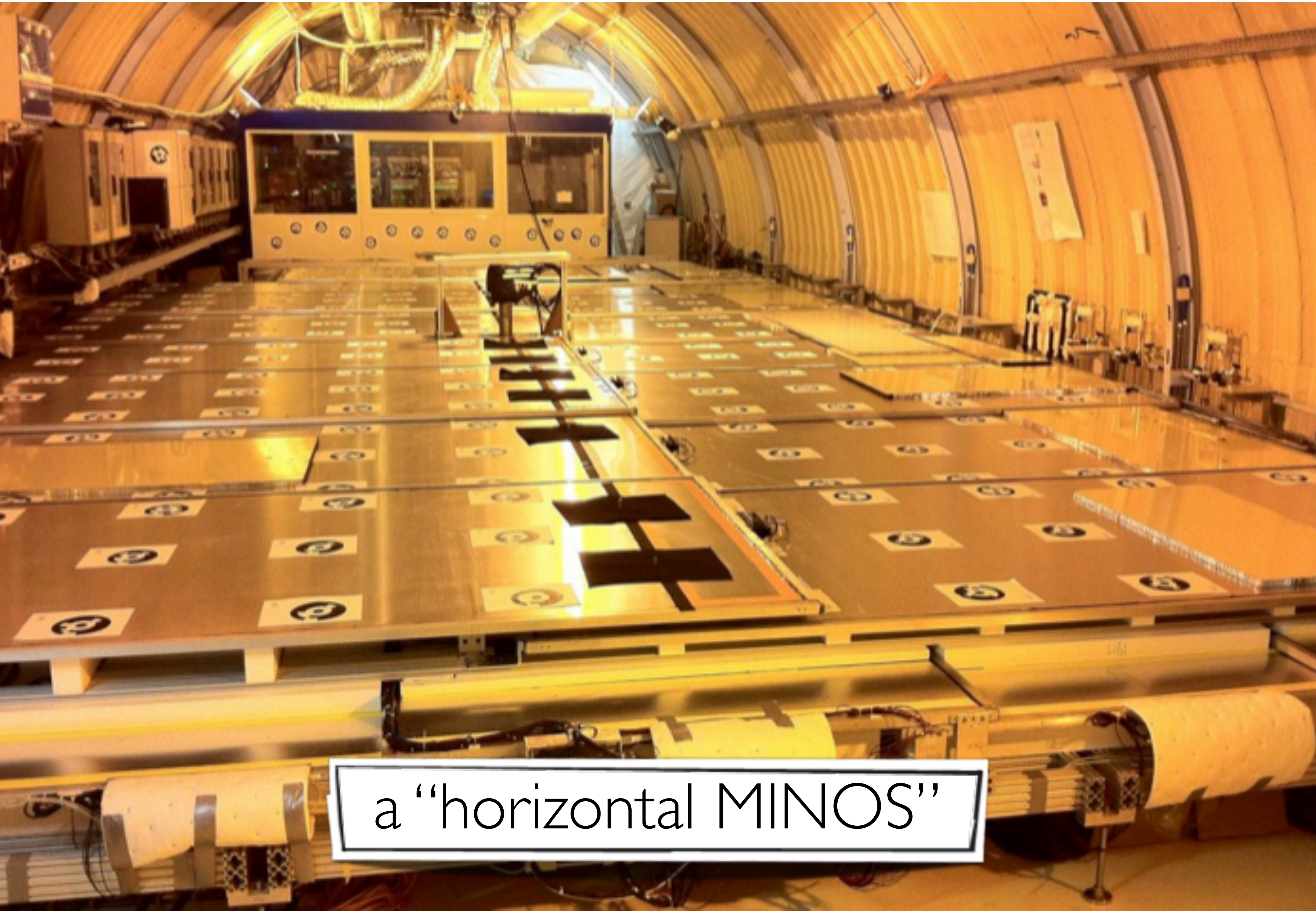
Inner μ-Veto (IV)
Liquid-Scintillator

Inert γ-Shield
15cm of steel (around all detector)

Anatael Cabrera (CNRS-IN2P3 & APC)


engineer's view
MC's view
our favourite view…

our Outer-Veto…

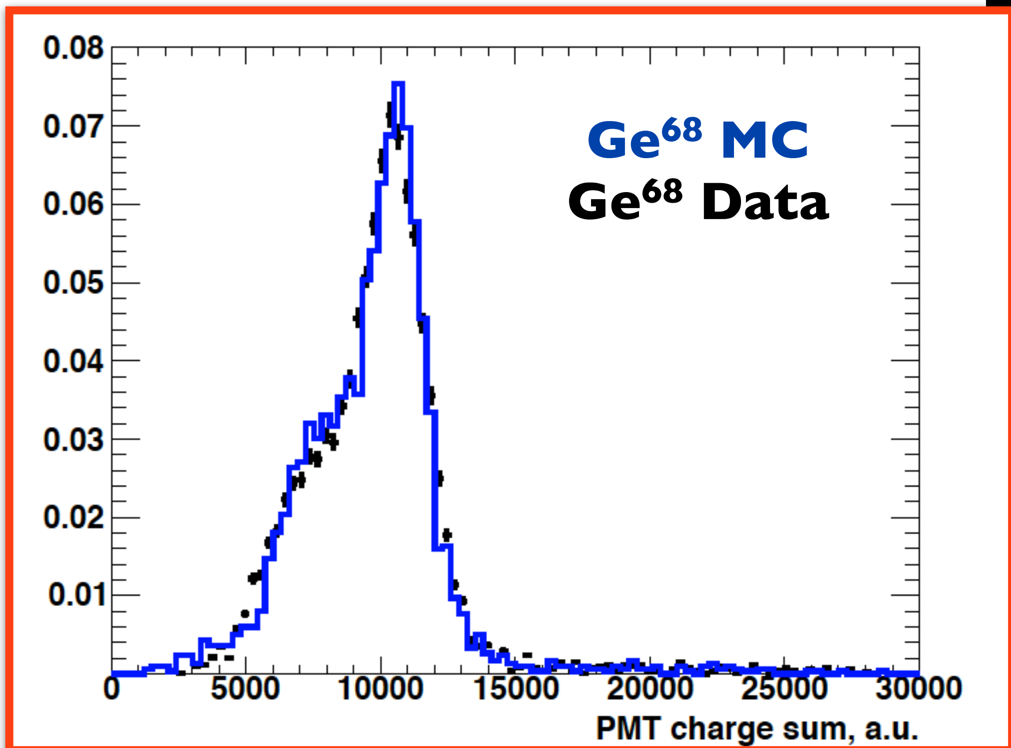


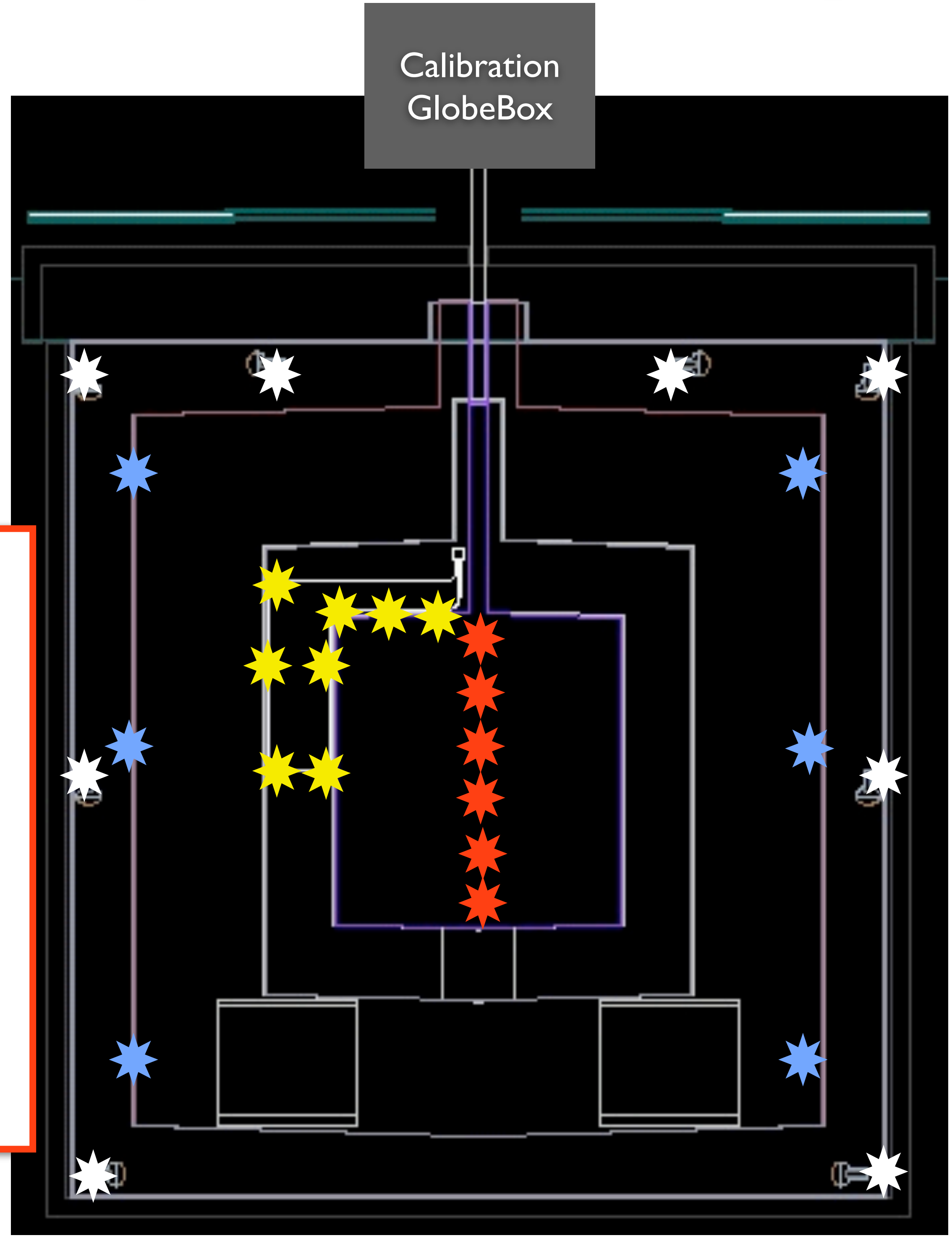
calibration…

DC calibration system: **redundancy**…

- **in-built:** light (LEDs) on **ID** and **IV**
- **z-axis** deployments
- **GC-tube** deployments
- (summer 2013) **3D articulated arm**

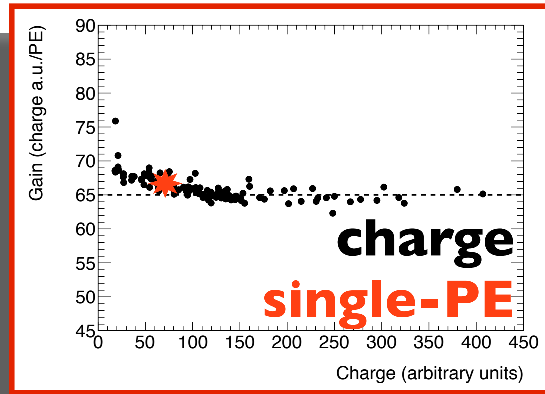
Sources: ^{137}Cs, ^{68}Ge, ^{60}Co, ^{252}Cf, Lasers



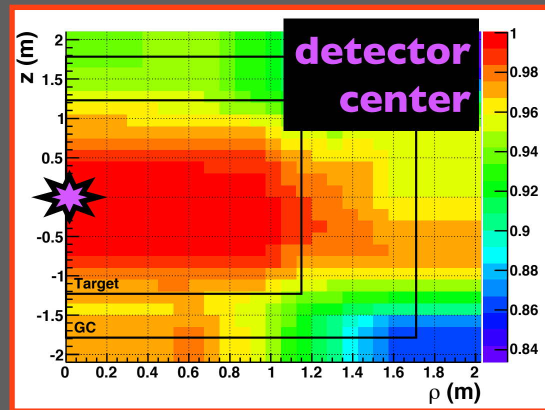


latest energy reconstruction…

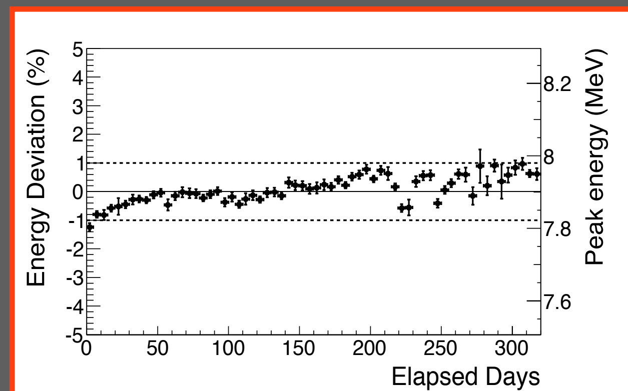
- **Linearised-PE Calibration:** Charge (DUQ)→PMT photo-electrons
  - non-linear gain [electronics] $g=f(q_i)$ [**variance ~10%**]
  - PE=Σ $q_i \times g(q_i)$ [less non-linear, but (ρ,z,t) dependent]
  - applied the same for DATA and MC



- **Uniformity Calibration:** PE(ρ,z) → PE(ρ→0,z→0)
  - response **varies by ~10%** across volume (DATA≠MC)
  - ^{response}MAPs using cosmogenic-n's 2.2MeV peak (H-n)



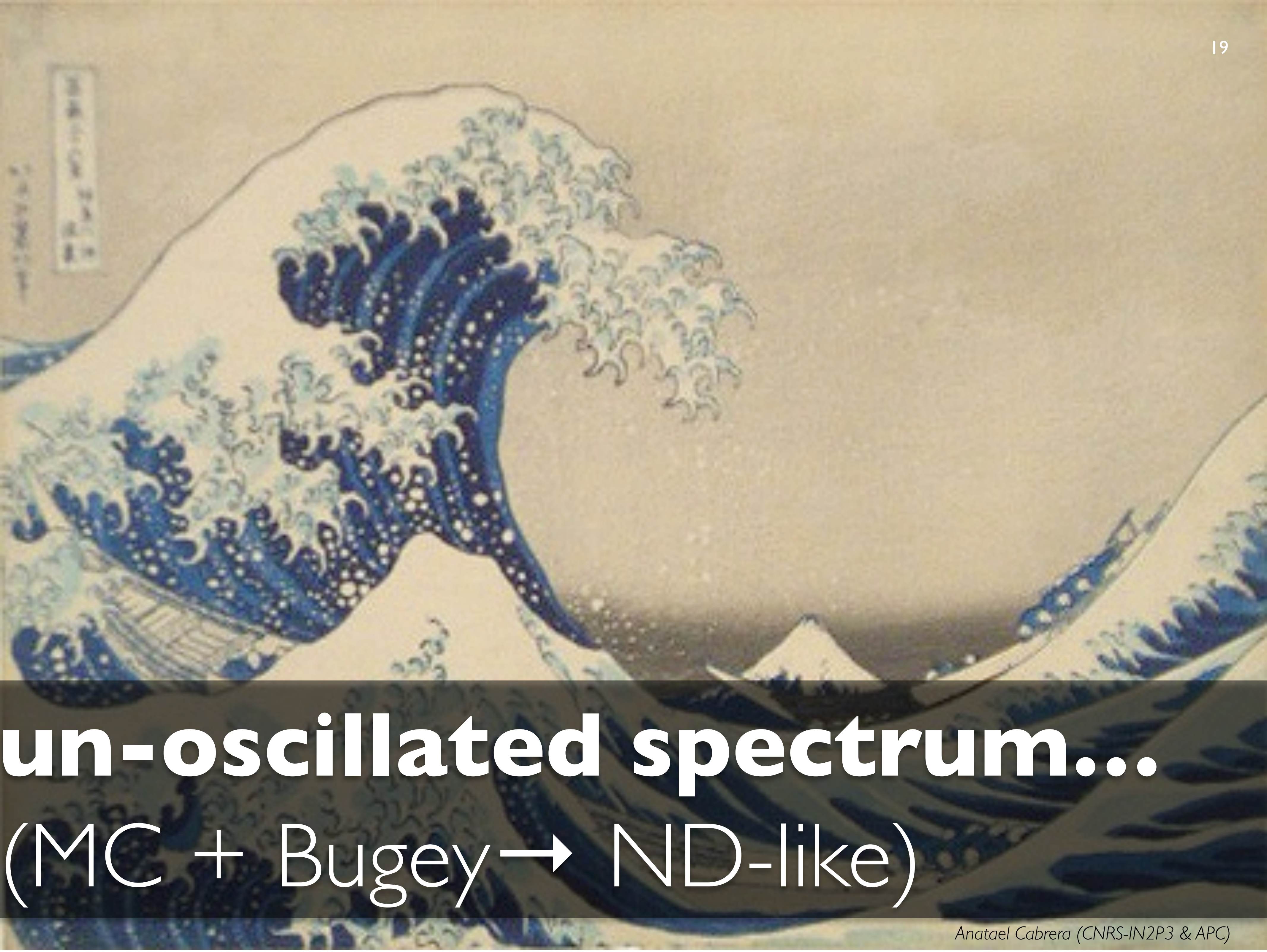
- **Stability Calibration:** PE(t) → PE(t→τ)
  - response **varies by 2%** (gain drift dominated)
  - use cosmogenic-n's capture on Gd drift as calibration
  - time reference @ **τ** (standard candle "MeV definition")
- **Absolute Energy Calibration:** PE(0,τ)→MeV(0, τ)
  - ^{252}Cf deployed @ (**ρ=0, z=0, t=τ**): **2.2MeV H-n peak**
  - **normalisation DATA and MC** (no arbitrary knobs)



- Performance: **any Q(q,ρ,z,t) [variance ~10%] to MeV [variance ~1.0%]**
  - **critical** for **δ(detection)** and **shape sensitivity to (θ_{13},BGs,Δm^2)**

Anatael Cabrera (CNRS-IN2P3 & APC)


ND ready in 1 year (first data in Spring'14)
ND lab: delivered in a few weeks!



un-oscillated spectrum...

(MC + Bugey→ ND-like)

reactor-ν flux prediction...

$$N_\nu^{\exp}(E,t) = \frac{N_p}{4\pi L^2} \times \frac{\boxed{P_{th}(t)}}{\langle E_f \rangle} \times \langle \sigma_f \rangle$$

Mean energy per fission:

$$\langle E_f \rangle = \sum_k \alpha_k(t) \langle E_k \rangle$$

k = ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

α_k : fractional fission rate

Mean cross-section per fission:

$$\langle \sigma_f \rangle_k = \int_0^\infty dE\, S_k(E)\, \sigma_{IBD}(E)$$

$$\langle \sigma_f \rangle = \langle \sigma_f \rangle^{Bugey} + \sum_k \left(\boxed{\alpha_k^{DC}(t)} - \alpha_k^{Bugey}(t) \right) \boxed{\langle \sigma_f \rangle_k}$$

Bugey4 anchor point

ν spectrum @ FD
for both Chooz reactors
(fuel cycle / exposure)
[^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu]

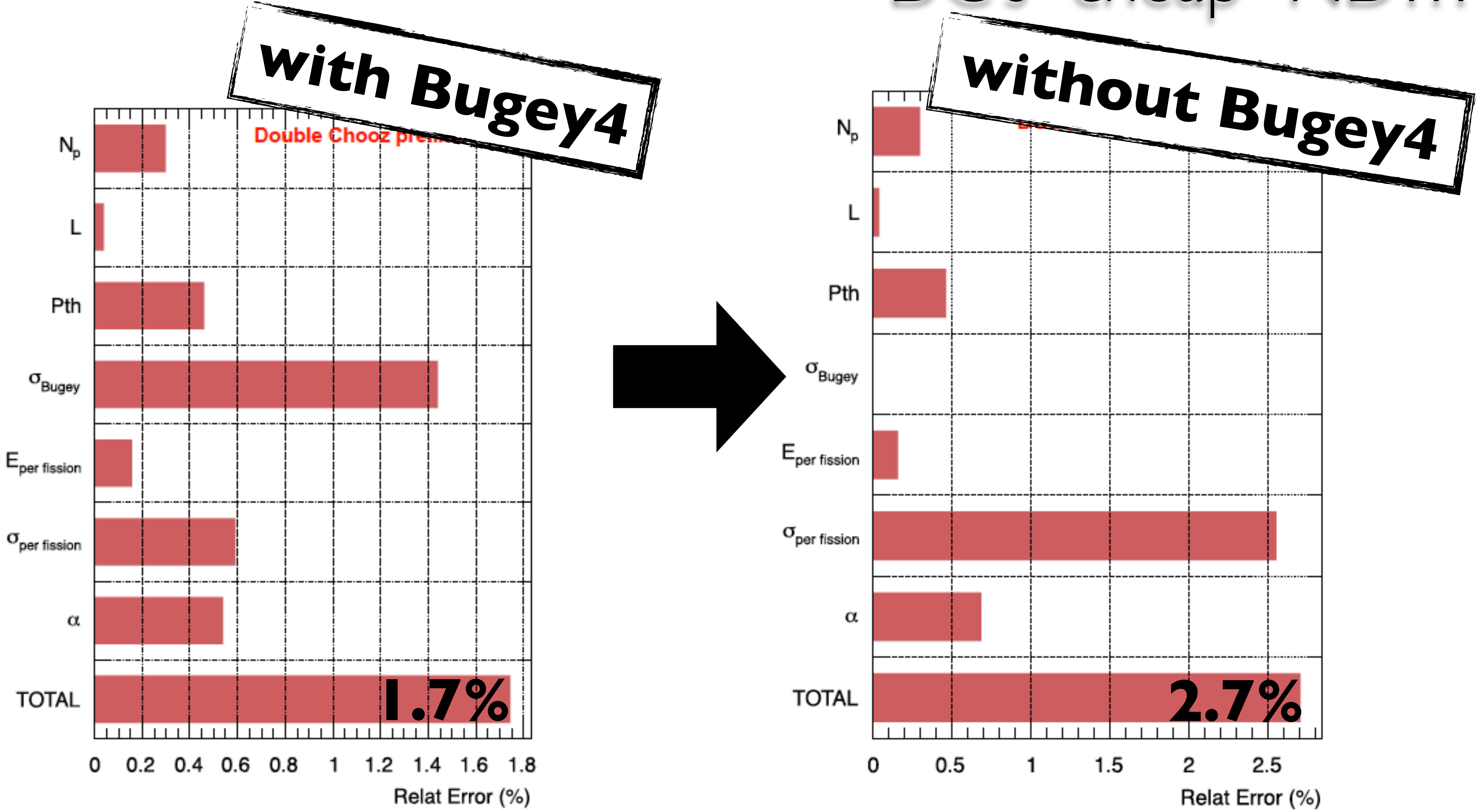
thermal power
(@Chooz)
δ=±0.46%

fission rates
[^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu]
(@Chooz)
[MURE simulation]

energy per fission &
$\sigma_{fission}$
[^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu]

fuel composition
(initial burn-up)
[^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu]
(@Chooz)

DC's "cheap" ND…



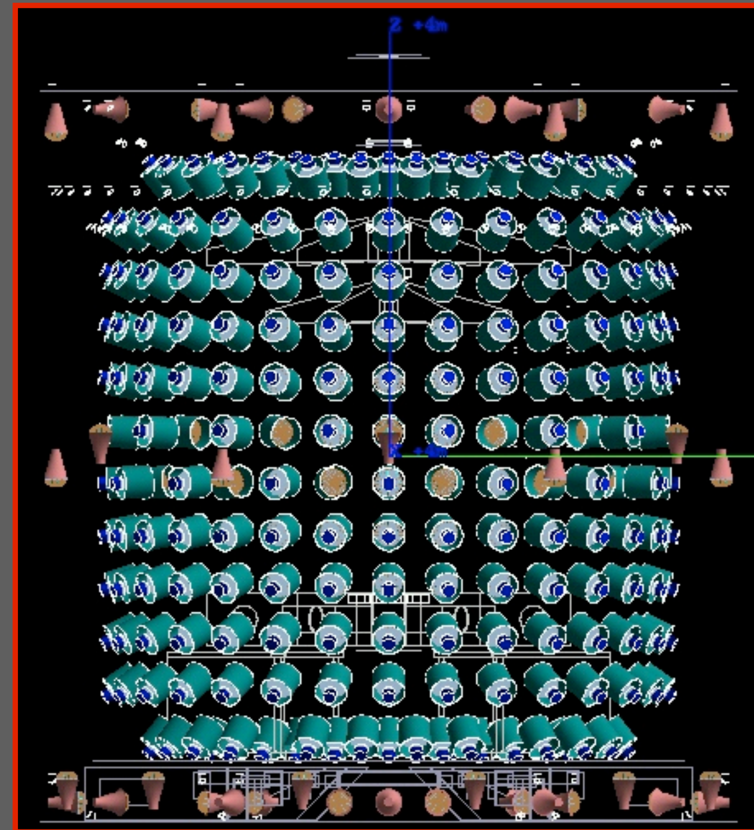
Bugey as ND…

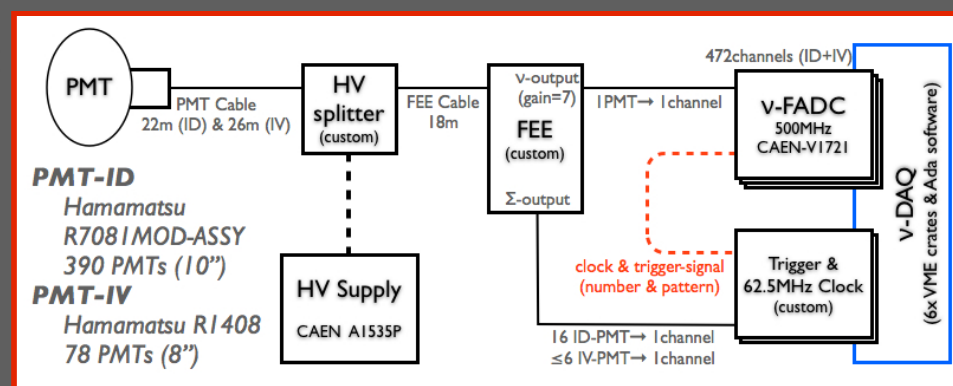
- **no hypothetical sterile-ν** (@ short baselines) contribution
- <u>most precise flux calculations so far</u>→interesting results

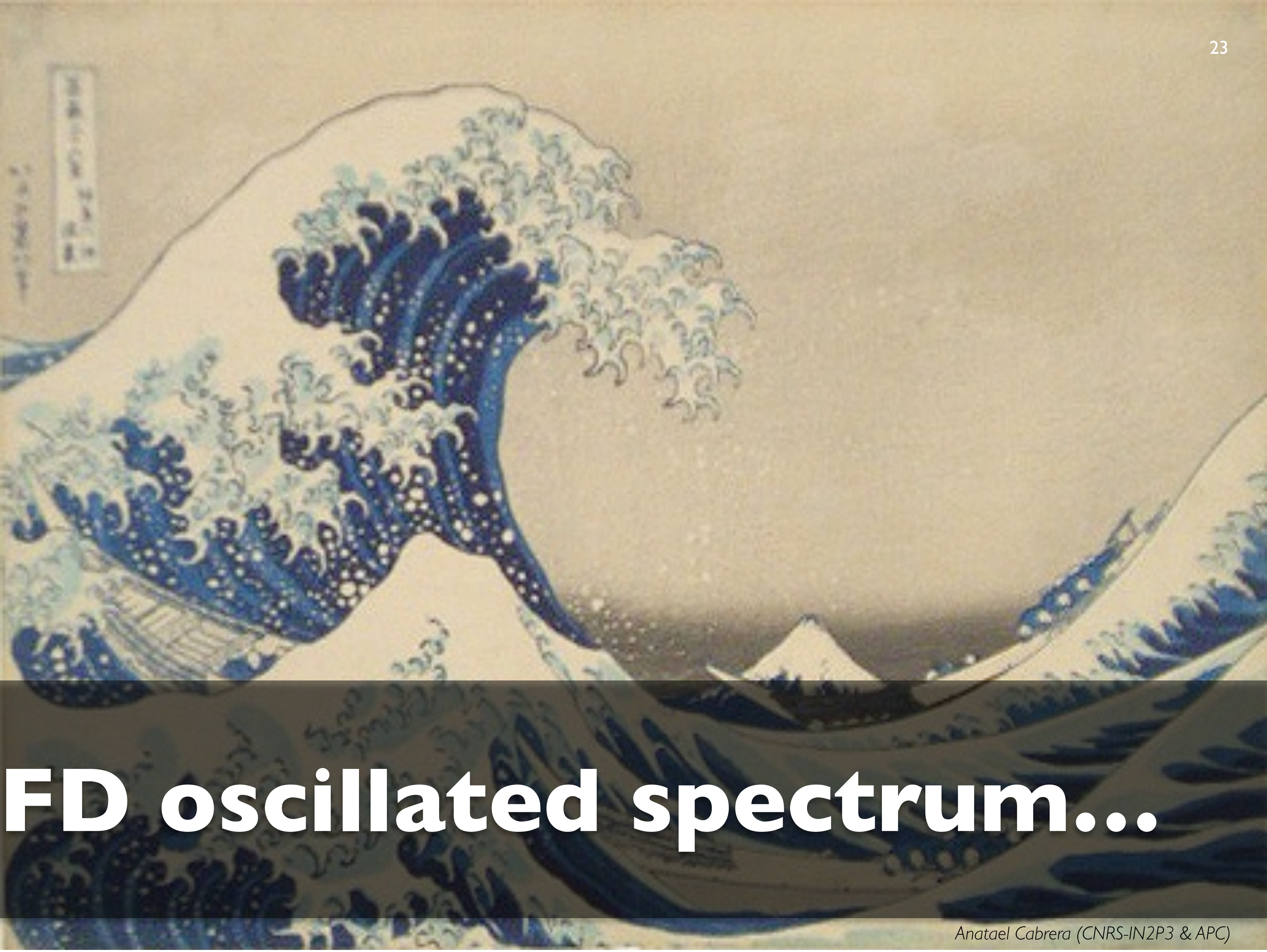
Anatael Cabrera (CNRS-IN2P3 & APC)

detector & readout simulation…

- **physics:** generators (G4 + customs)
  - IBD prediction @ FD: **δ(flux): 1.7%**
- **DATA/MC detector remarkable agreement**
  - **δ(response): 1.13% (target)**
  - **δ(detection): 1.0%** (n physics modelling)
- **physical detector…**
  - geometry (data tuned)
  - scintillator response (data tuned)
  - optical interfaces (data tuned)
  - **conversion: MeV→γ→PE (@ PMT)**
- **detector readout…**
  - PMT, FEE, FADC, Trigger (data tuned)
    - pulse shapes, charge, digitisation, etc
  - **conversion: PE→Charge**
- **detector calibration…**
  - calibrate MC exactly as DATA (data tuned)
    - biases & precision (systematics)
  - **conversion: Charge→PE→MeV**



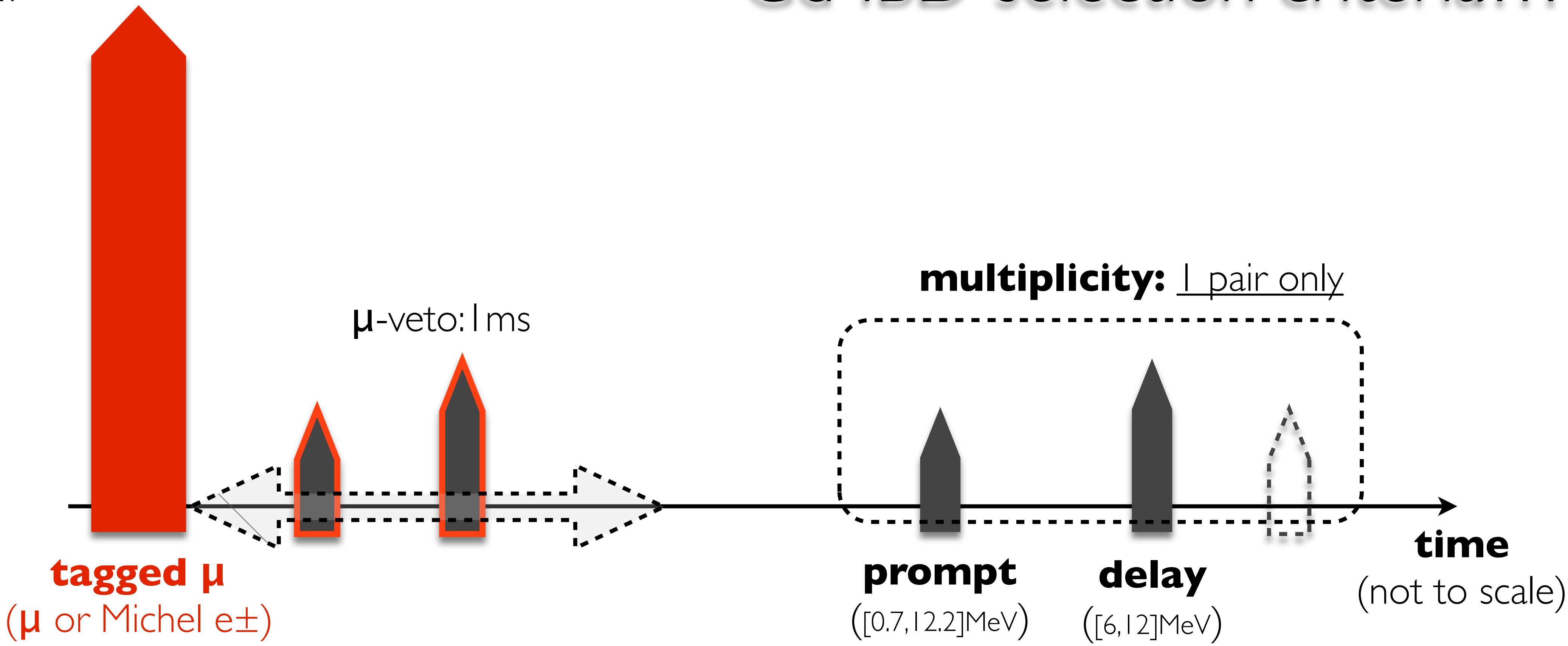




FD oscillated spectrum...

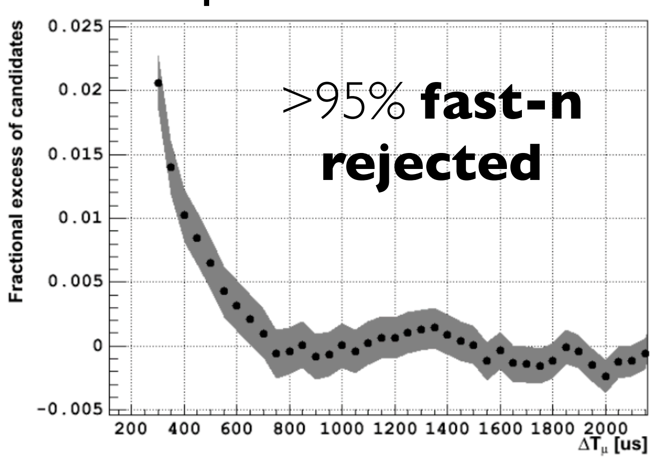
Anatael Cabrera (CNRS-IN2P3 & APC)

Gd-IBD selection criteria…

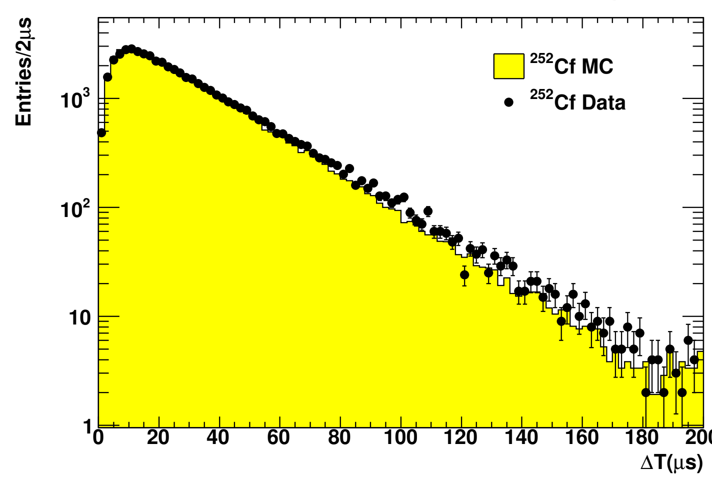


after-μ correlated IBDs

A.Remoto's PhD



IBD Δt(n~e+) correlation (**Cf@Target**)



Anatael Cabrera (CNRS-IN2P3 & APC)

selection details…

	Gd-IBD	H-IBD
μ-tagging	E(ID)≥30MeV & Q(IV)≥30kDUQ	
Δt(μ)	1ms	
LN[QmQt]	≤0.09 (prompt) ≤0.06 (delay)	
LN[RMS(t_{PMT})]	40ns	
Δt(n~e+)	[2,100]μs	[10,600]μs
Δd(n~e+)	-	≤0.9m
E(delay)	[6,12]MeV	[1.5,3.0]MeV
E(prompt)	[0.7,12.2]MeV	
Multiplicity	[-0.1,0.4]ms	[-0.6,1]ms
OV veto	yes	no
Spallation-μ veto	yes	no

Single Selection

IBD Selection

BG Rejection

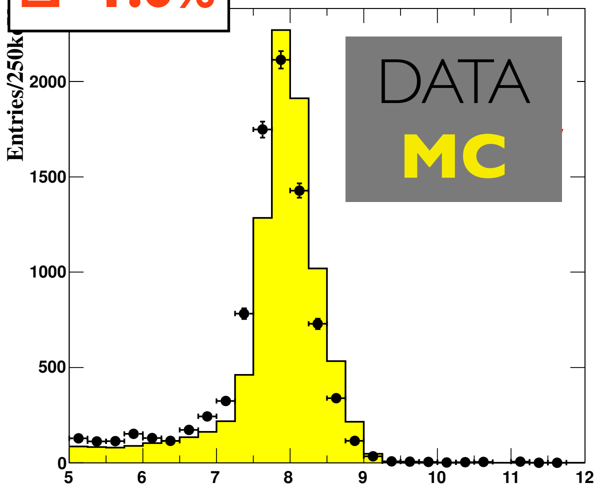
8249 IBDs (with BG)
227.9days

36284 IBDs (with BG)
240.1 days

Anatael Cabrera (CNRS-IN2P3 & APC)

selections output…

Δ~1.0%

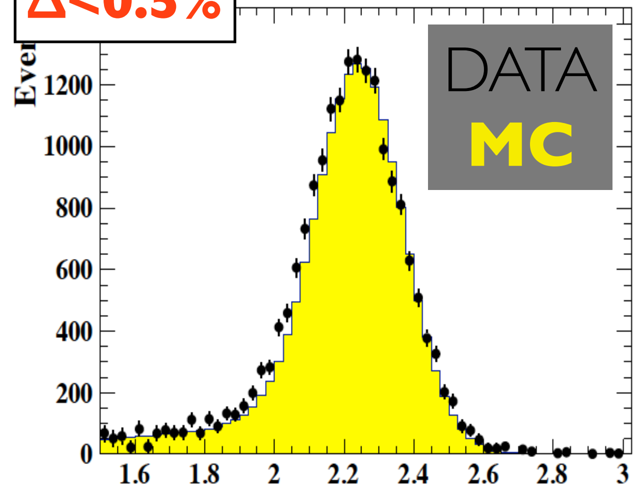


energy (MeV)

δ(energy):1.13%

~1.0%
(non-linear)

Δ<0.5%



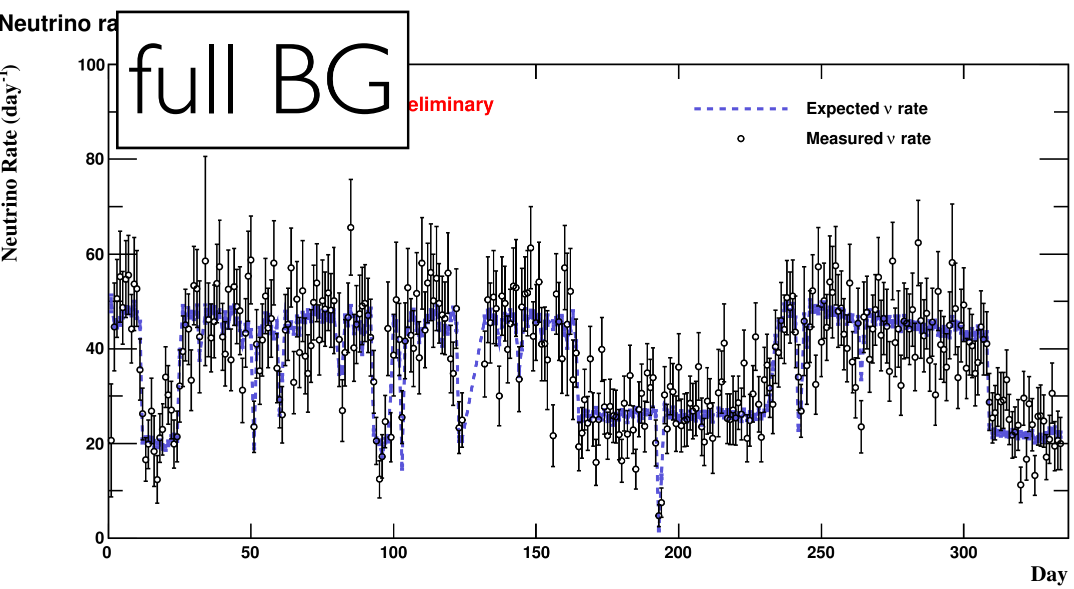
energy (MeV)

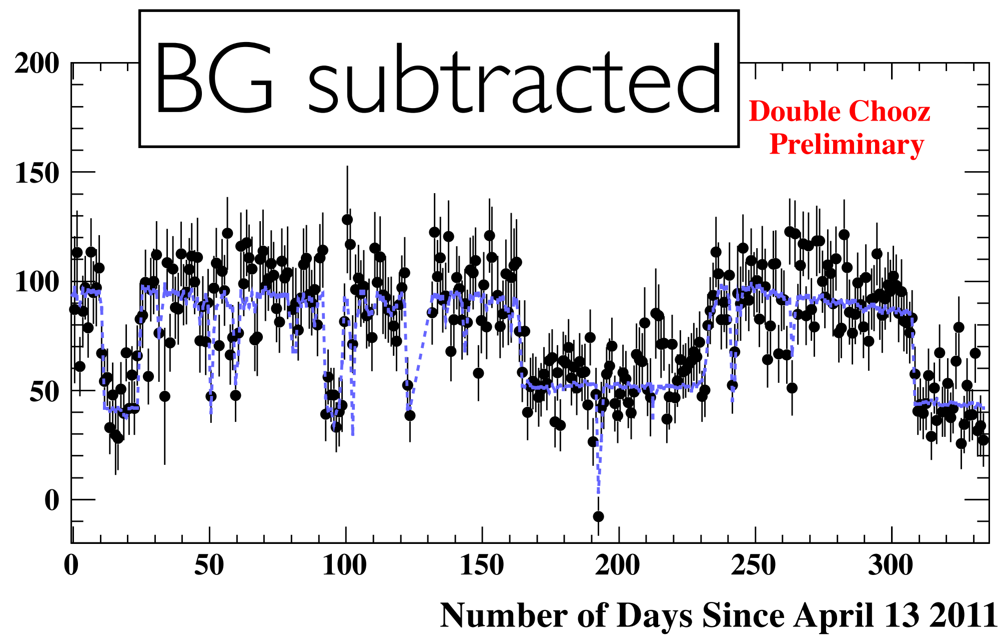
Gd-IBD

Signal/BG ~18

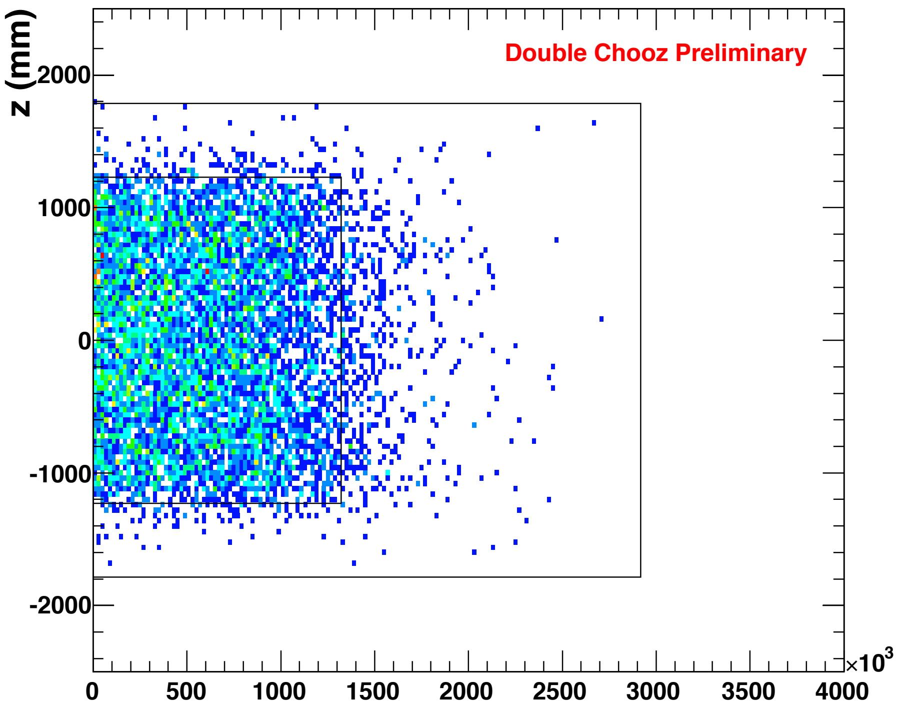
H-IBD

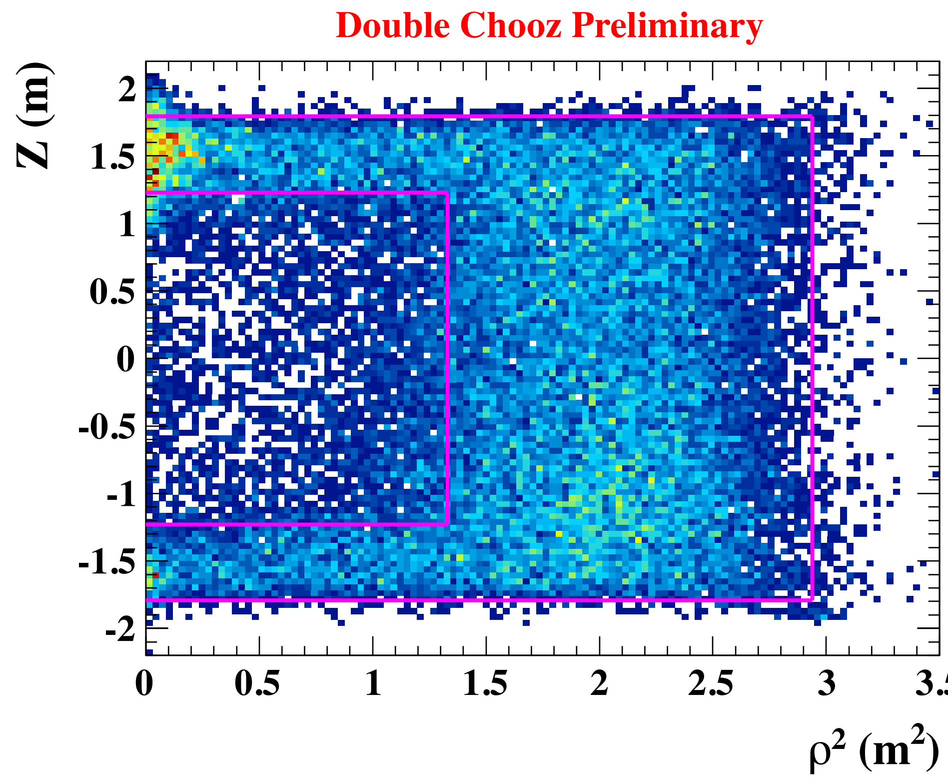
Signal/BG ~0.95





IBD features...





Gd-IBD

Signal/BG ~19

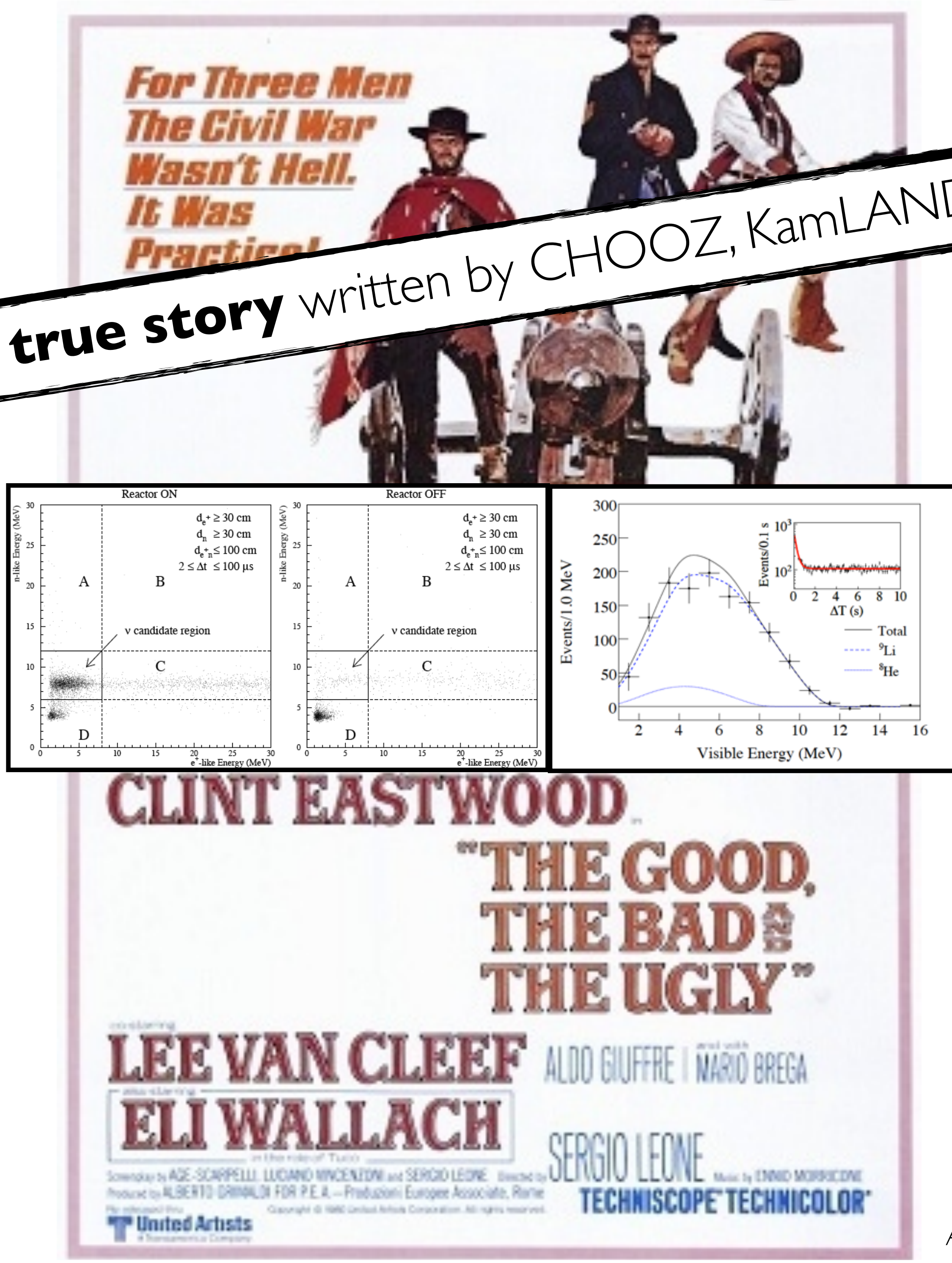
H-IBD

Signal/BG ~0.95

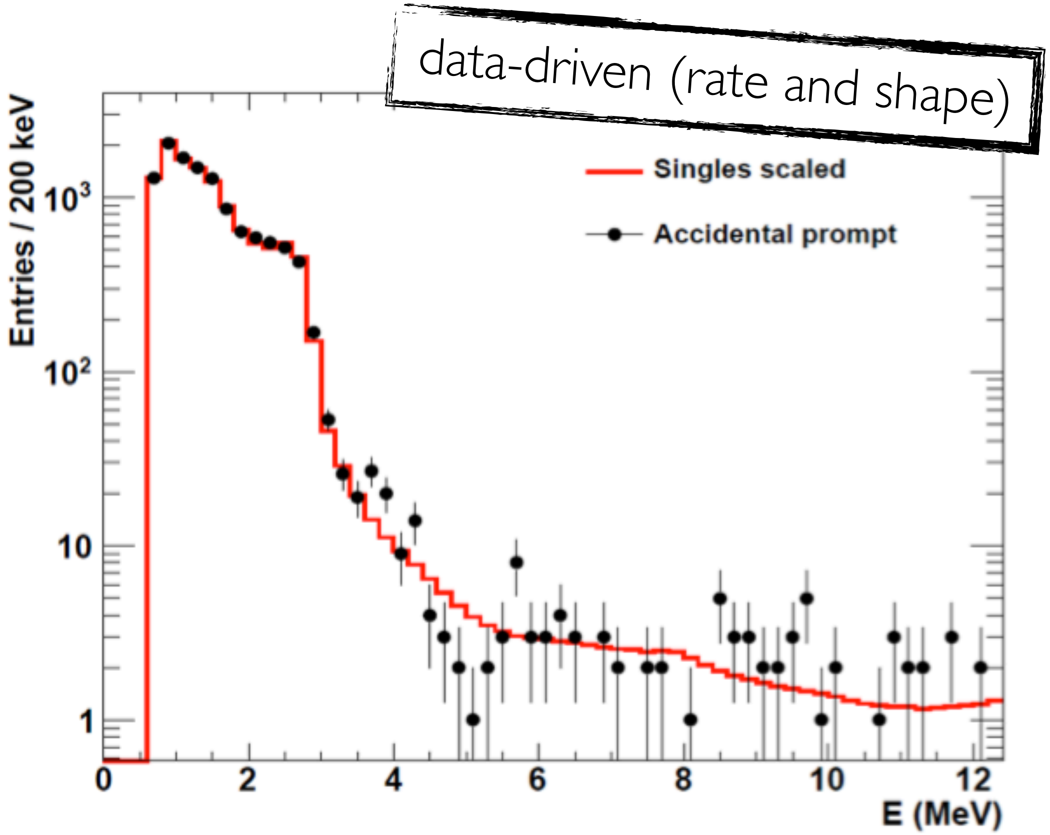

BACKGROUNDs

our model: 3 backgrounds (so far)…

based on a **true story** written by CHOOZ, KamLAND, Borexino,etc



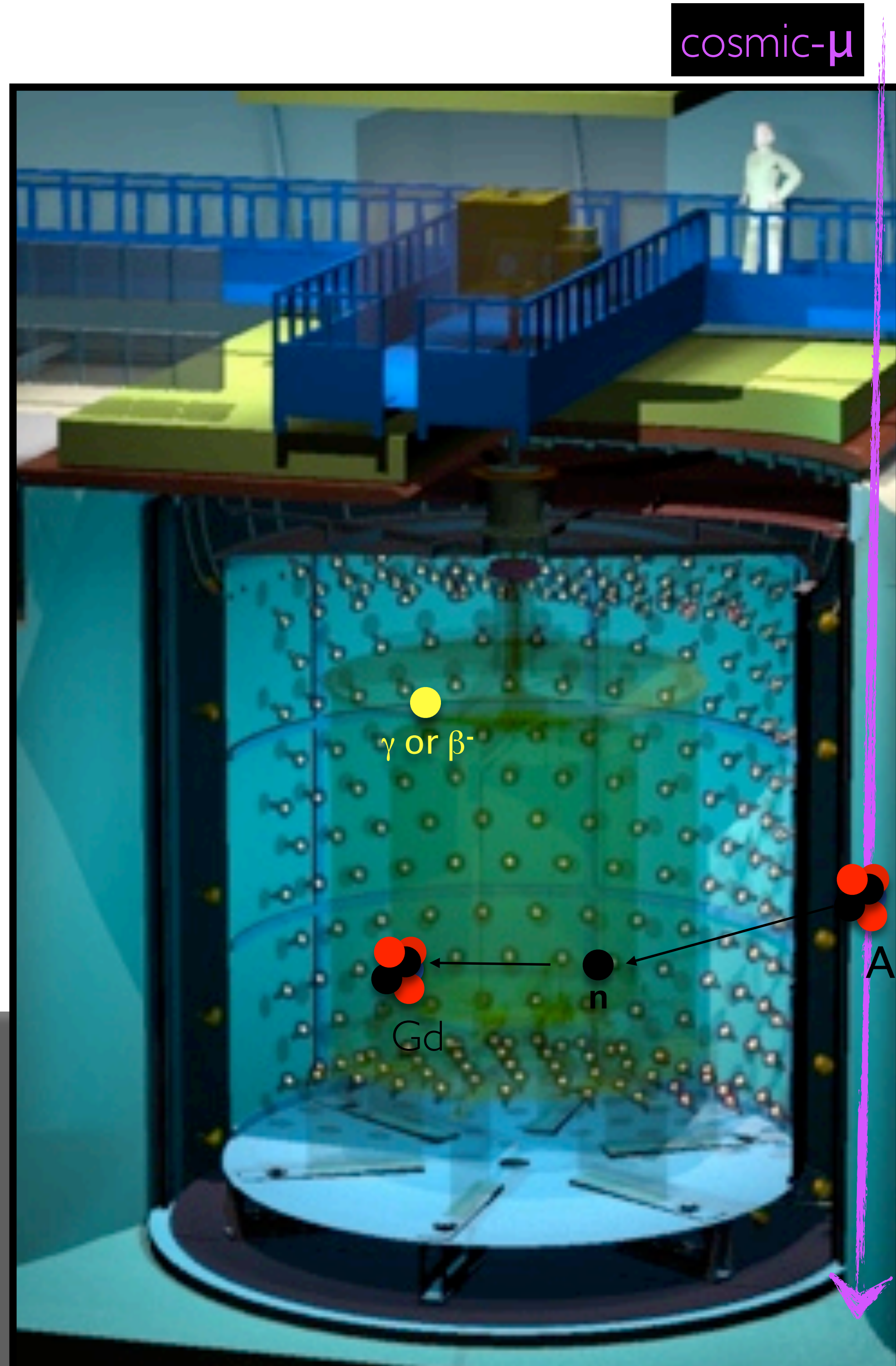
Anatael Cabrera (CNRS-IN2P3 & APC)



best known…

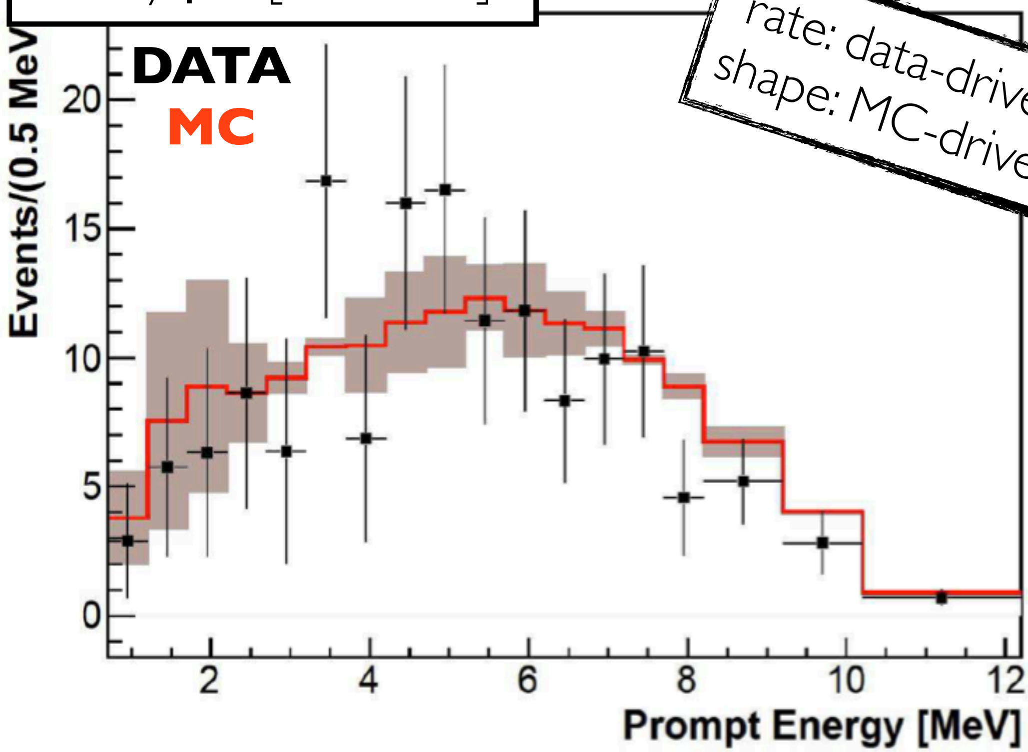
- δBG/Signal→<0.01%(negligible rate uncertainties)
- pile @ oscillation minima region (<u>Δm² resolution</u>)

accidental…
(the <u>good</u> one)



Anatael Cabrera (CNRS-IN2P3 & APC)

decay β-n [τ~100ms]



rate: data-driven
shape: MC-driven

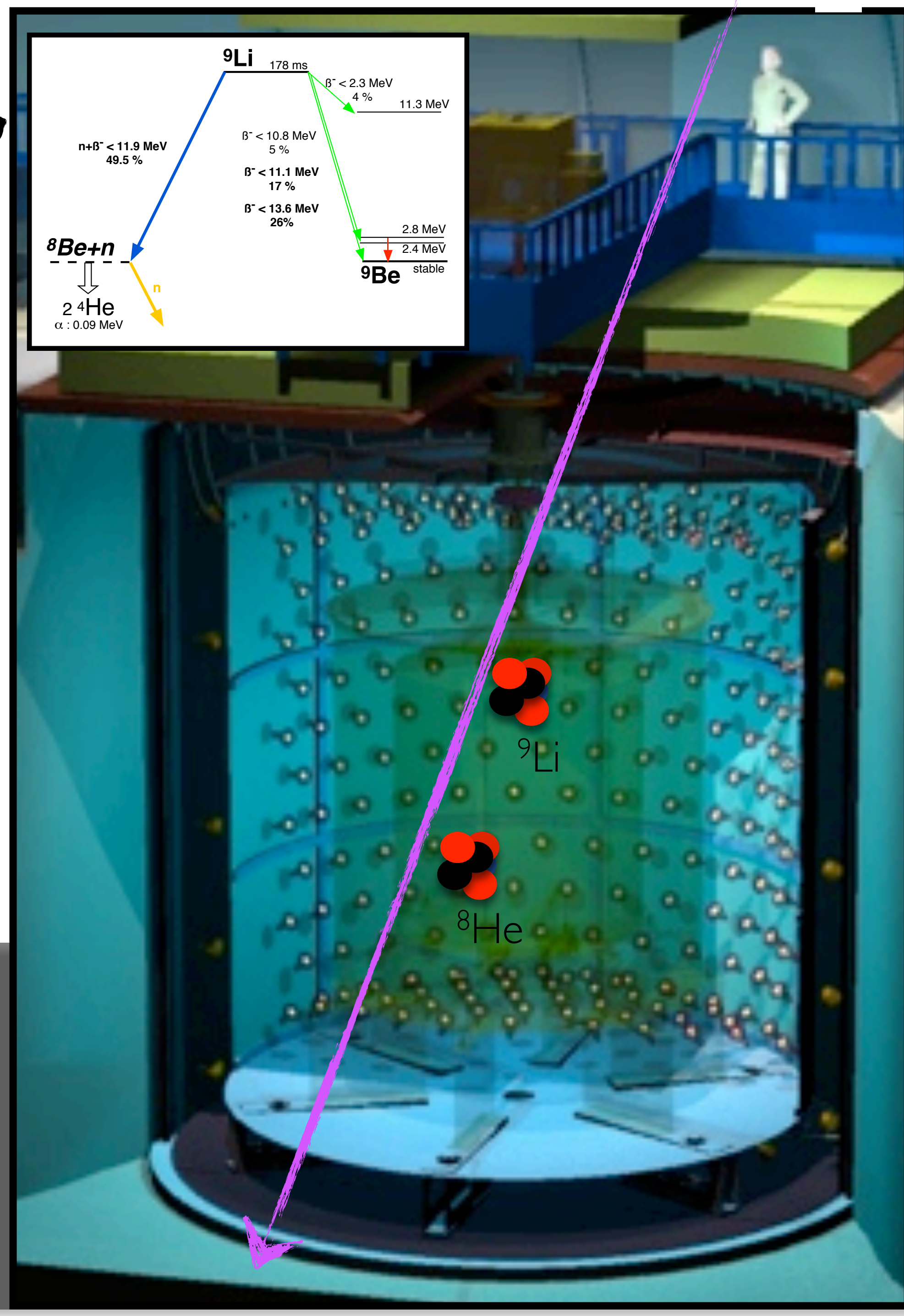
worst known...

- δBG/Signal→largest (poor statistics)
- poorly known data-shape (MC→KamLAND,etc)

isotopes…

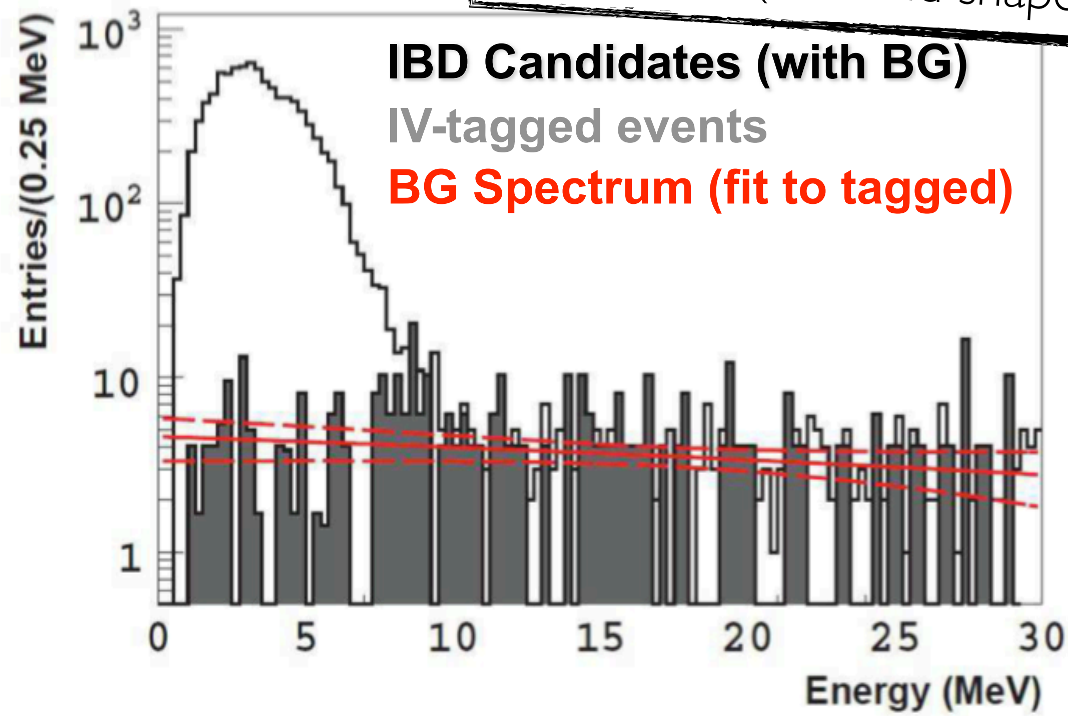
(the ugly one)

cosmic-μ



Anatael Cabrera (CNRS-IN2P3 & APC)

data-driven (rate and shape)

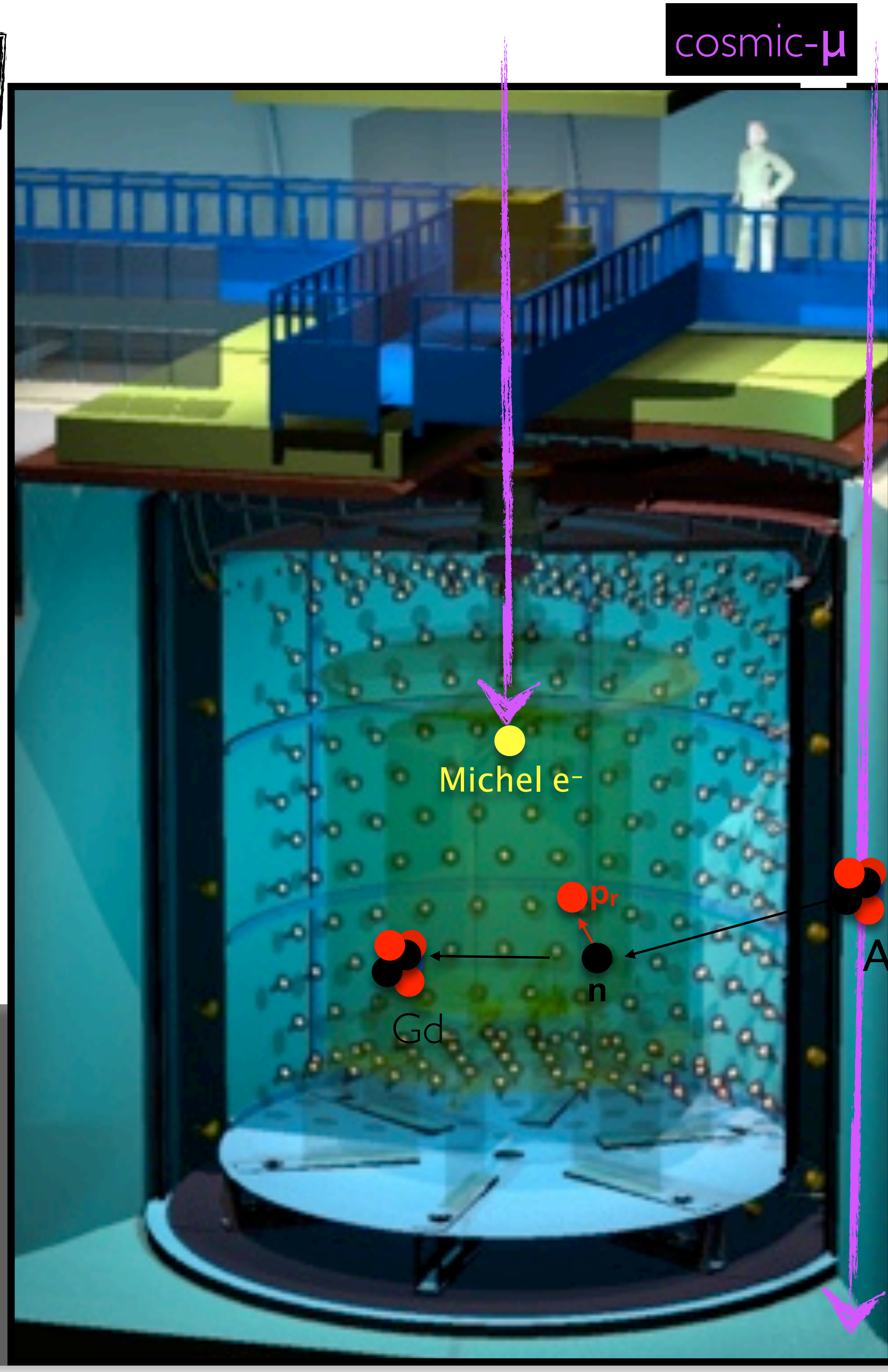


most dangerous...

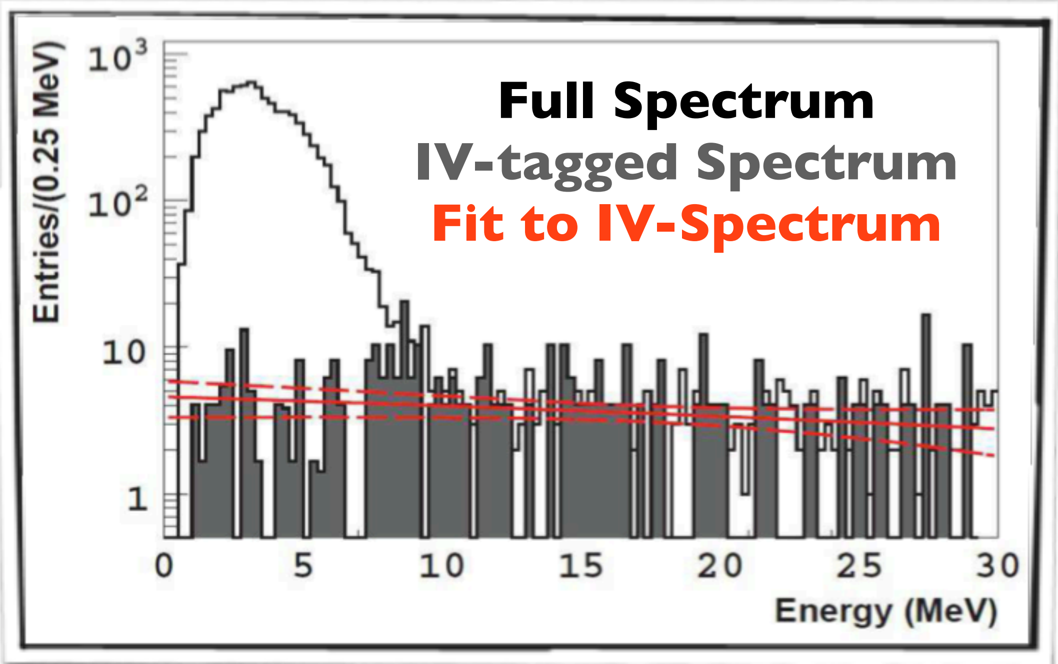
- slope @ low-energy: modelling (hard)
- shape measured via IV tagging→**mimics θ_{13}?**

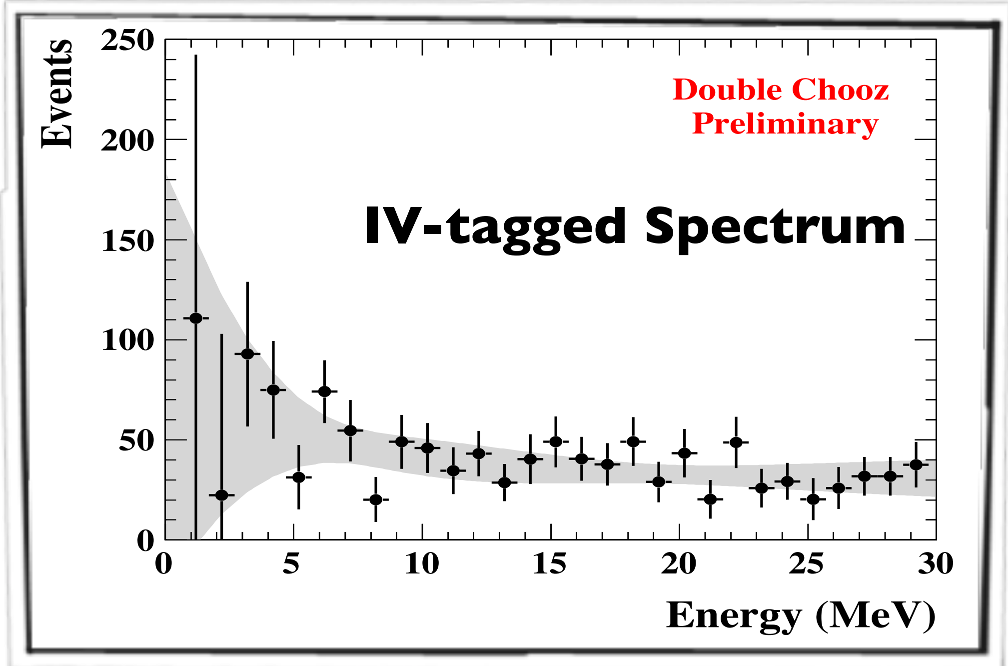
correlated...

(the <u>bad</u> one)



p-recoil spectrum (with reactor ON)





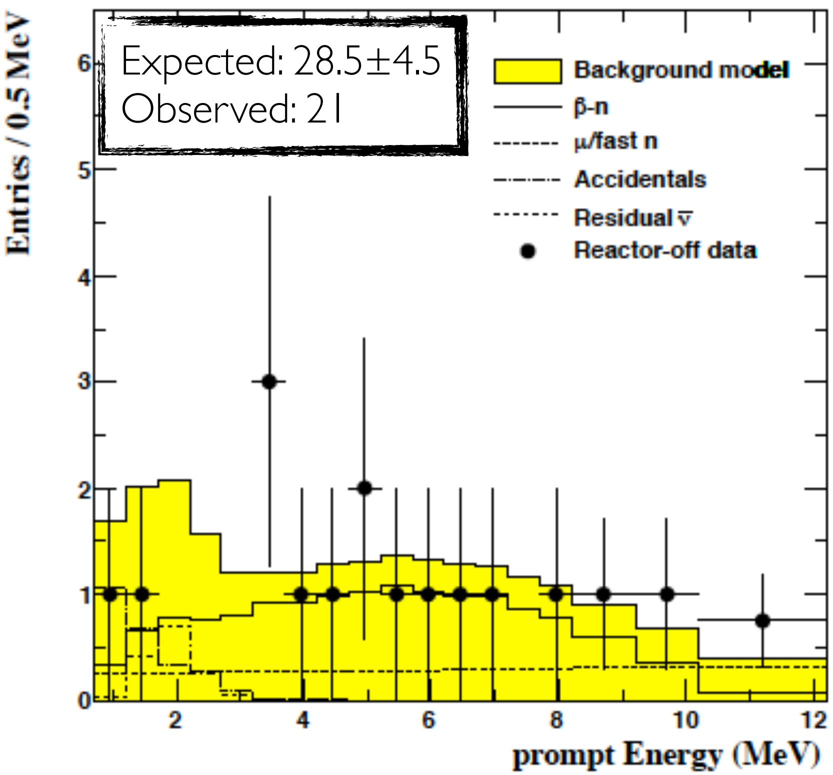
Correlated-BG (Gd-IBD)

Correlated-BG (H-IBD)

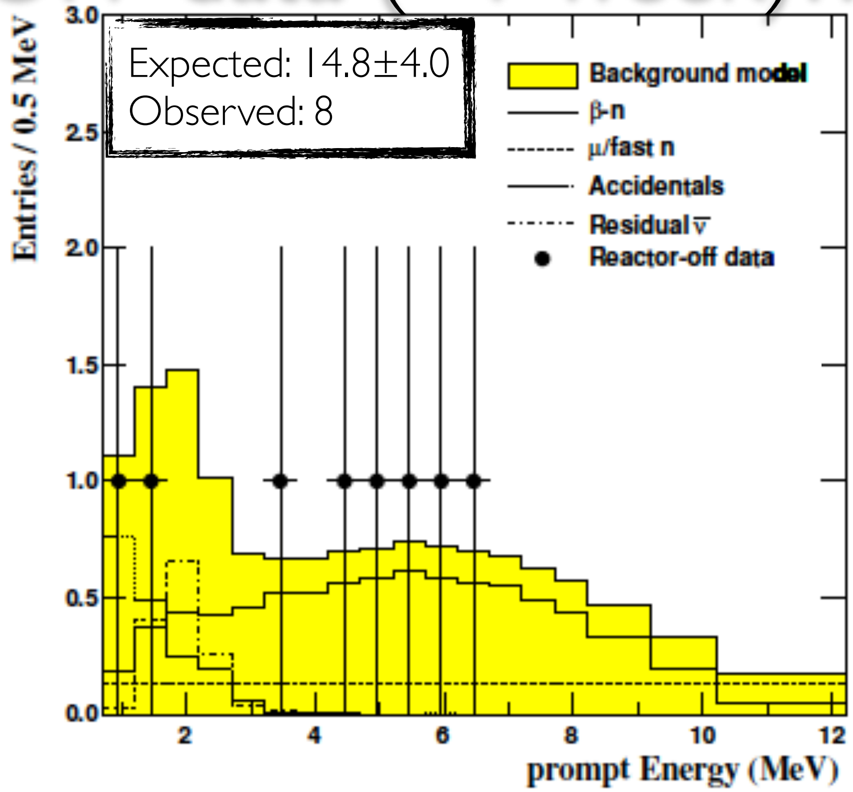
- a composite spectrum: **fast-n** (p-recoil) + **stopping-μ** (Bragg spectrum)
- (fast-n) **p-recoil spectrum @ low energies** (**very challenging**)
    - huge (100x) ν BG during reactor ON over fitting region **[0.7,12.2]MeV**
    - DC measures: **NOT necessarily flat** (quenching+acceptance)
- data measurement (accurate)→ **IV & OV tagging** (only DC)
- how about **"extrapolation as flat"** from HE**?**
    - **DC:** rate biassed by **1.5σ**(Gd)~**7.4σ**(H) and **incorrect shape**
    - biassed slope→ **bias (**similar signature**)** θ_{13} (bad)

Anatael Cabrera (CNRS-IN2P3 & APC)

reactor OFF data (~1 week)...



Gd Selection (no BG rejection cuts)
(2x more BG)



Gd Selection (standard)
(mainly Spallation-μ veto)

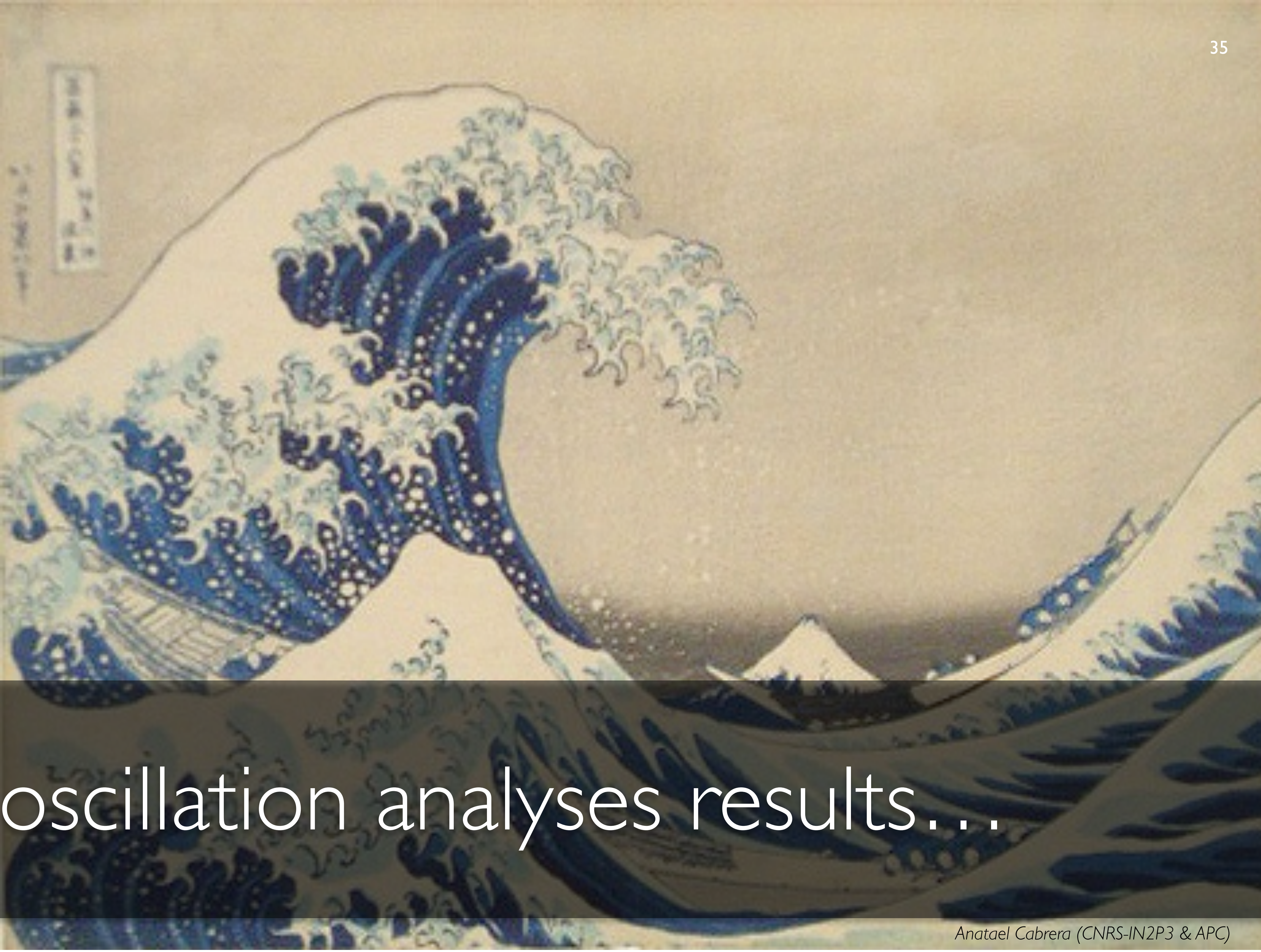
Rate (day^{-1})	β-n	Accidental	μ/fast n	Total Est.	Total Obs.
DCI	2.10±0.57	0.35±0.02	0.93±0.26	3.4±0.6	2.7±0.6
DCII	1.25±0.54	0.26±0.02	0.44±0.20	2.0±0.6	1.0±0.4

two different selections "DC-I" & "DC-II" (BG rate varies ~2x)

BG(observed) < BG(expected)

agreement within ~1.5σ (statistics limited)

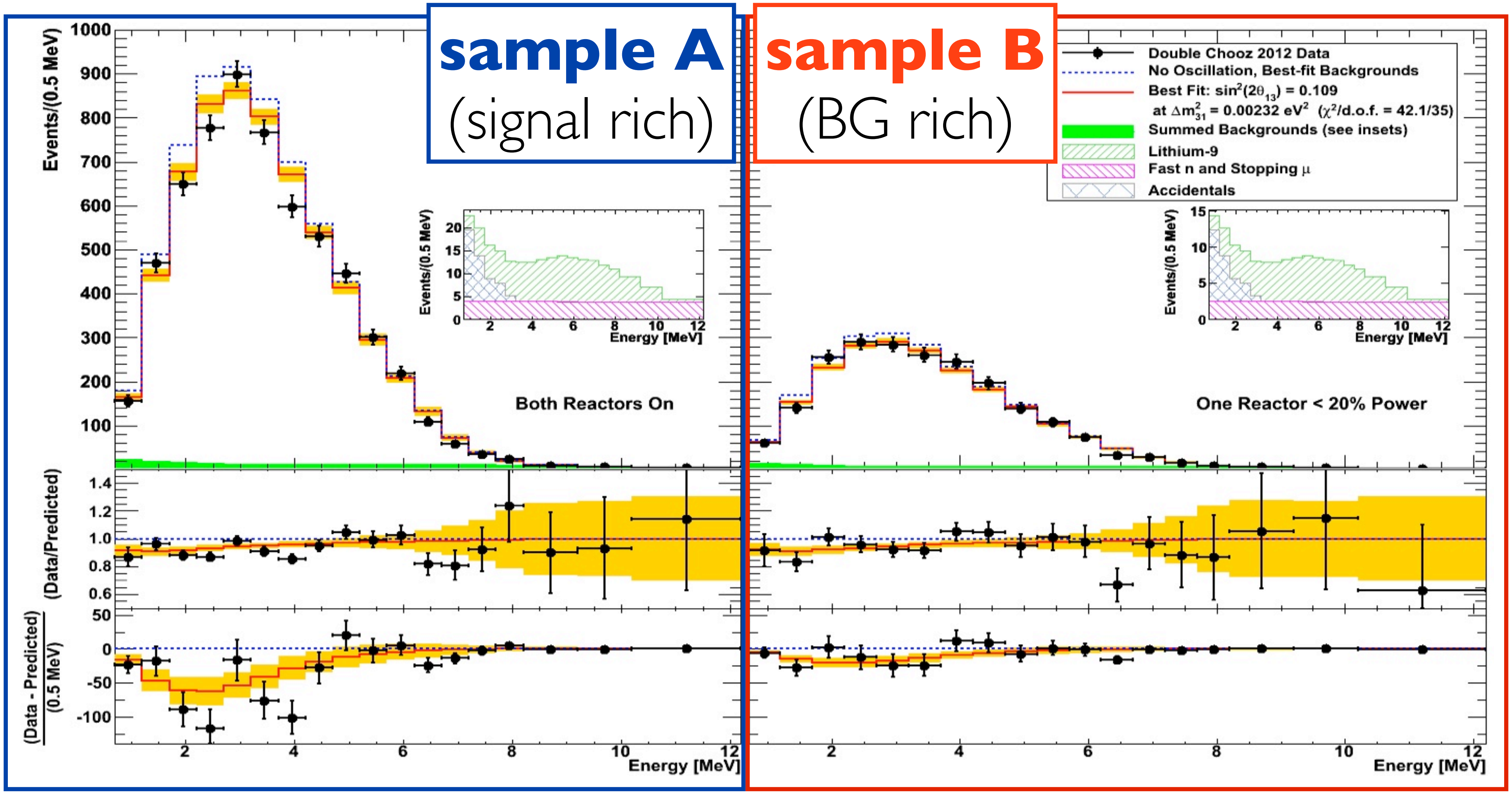
Anatael Cabrera (CNRS-IN2P3 & APC)



oscillation analyses results…

(Gd) rate+shape fit→θ_{13}+BG estimation…

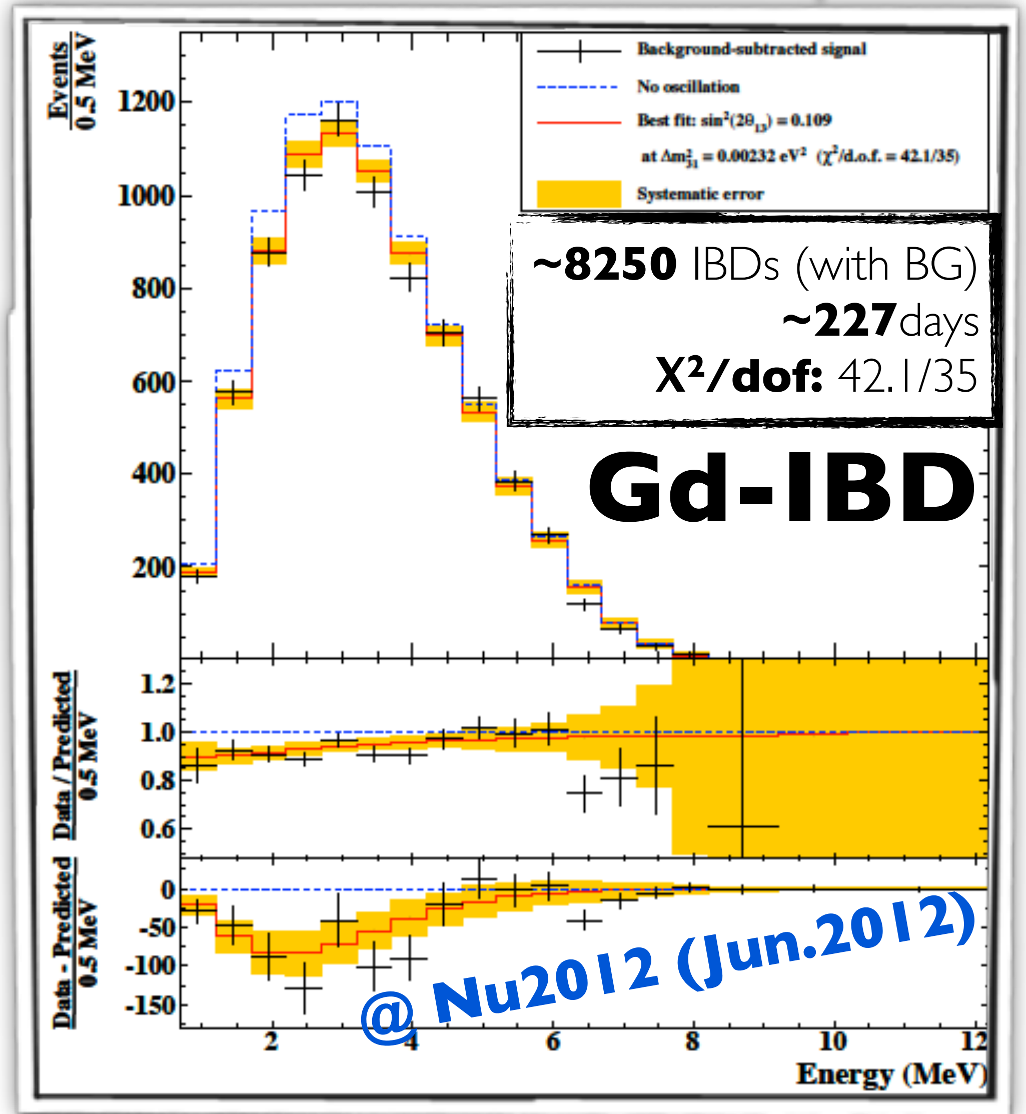
- **input:** θ13 model & full BG model (3 BGs and their rates and spectra)
- **output:** θ13 & cosmogenic BG re-evaluated (via pulls)

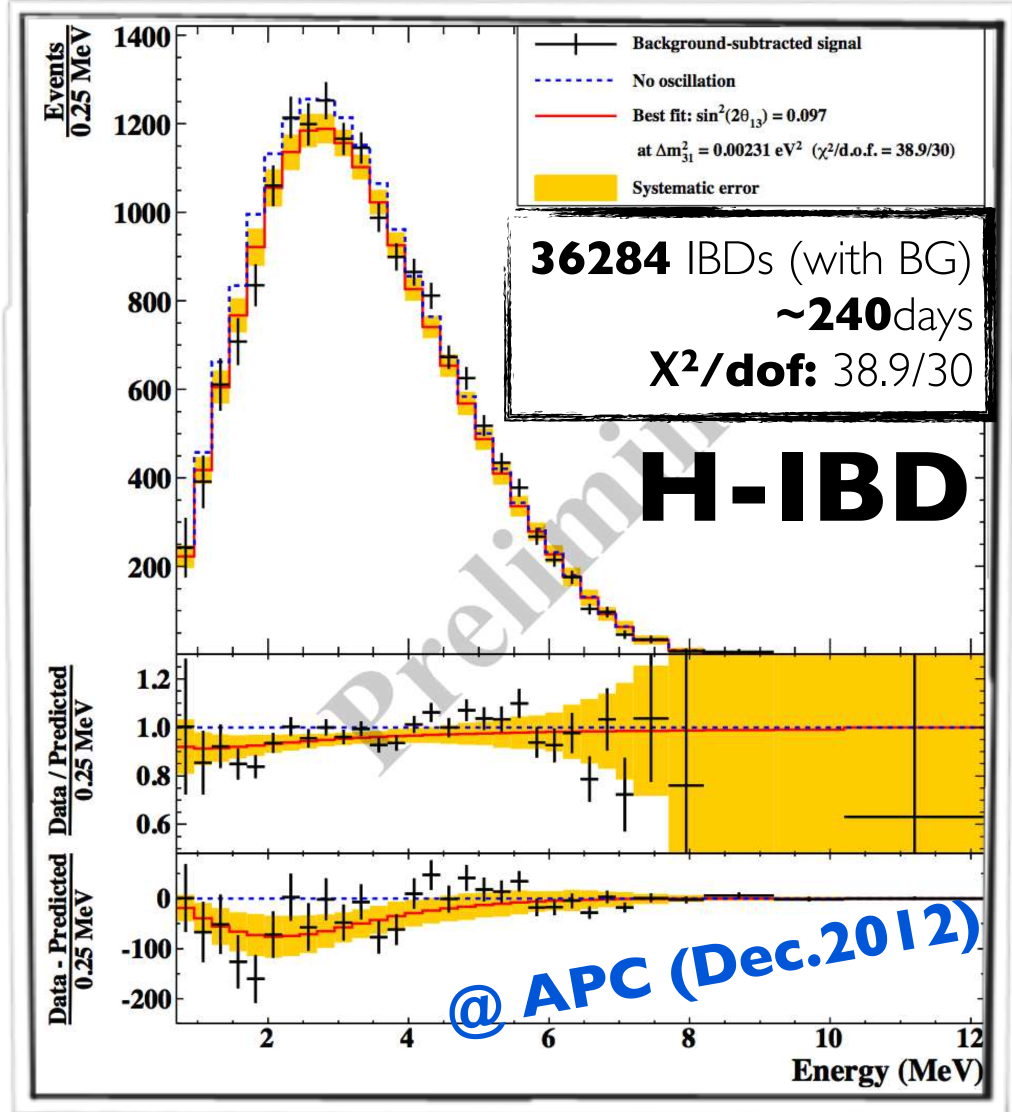


- **BG re-evaluation→ ~15% less BG (wrt rate)**
  - **θ_{13} & BG fully correlated→** BG re-estimation varies θ13 (consistency)
  - BG(fit) in <u>better agreement wrt reactor-OFF</u> (only DC)
- <u>same θ13 with 1 or 2 Integration Periods</u>→ **result robust BG robust**

Anatael Cabrera (CNRS-IN2P3 & APC)

two independent measurements of θ_{13}...





rate+shape analysis→ clear θ_{13} E/L pattern & BG constrains

DC-II(Gd): $\sin^2(2\theta_{13})=0.109\pm0.04$ $[0.030^{stat}\pm0.025^{syst}]$

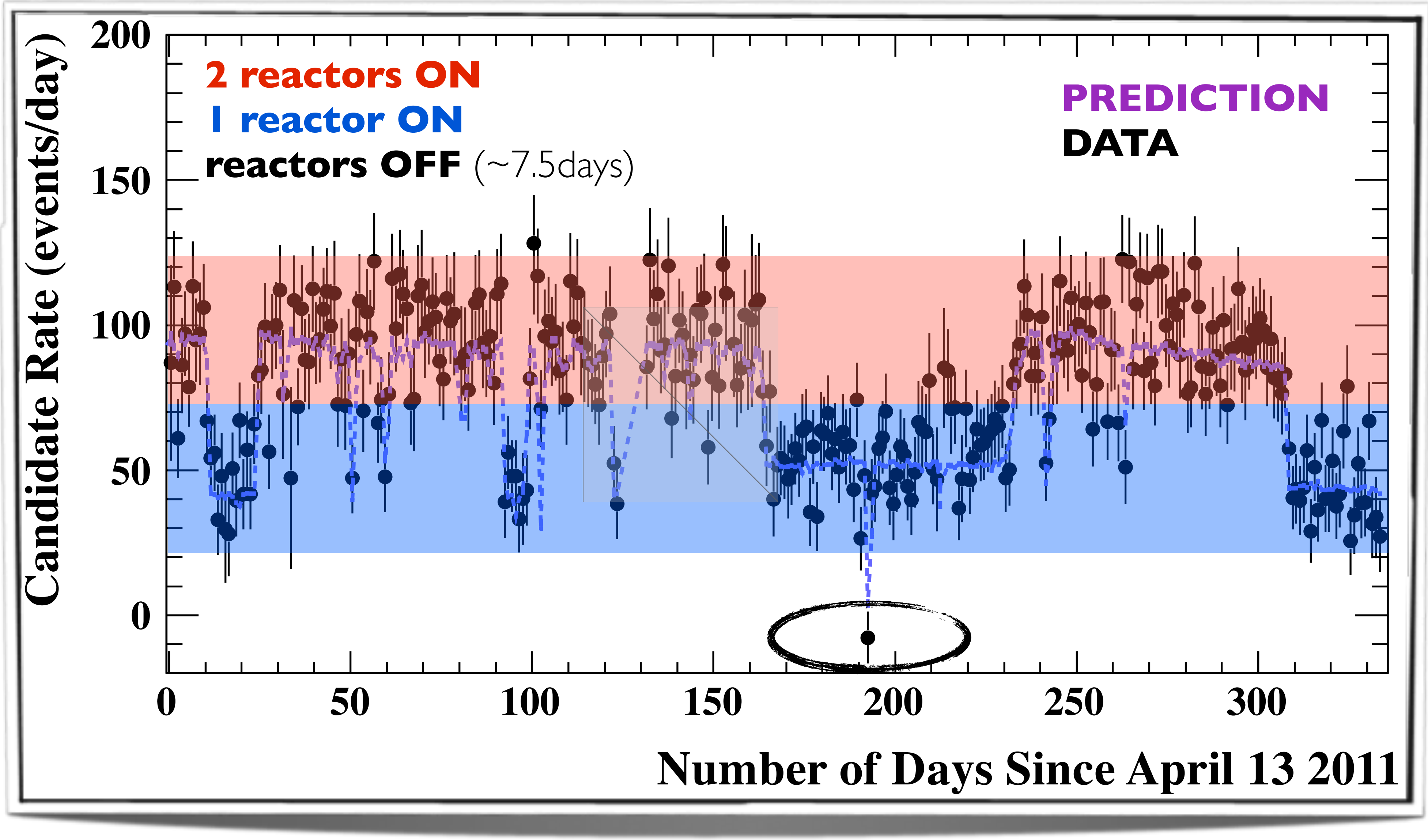
DC-II(H): $\sin^2(2\theta_{13})=0.097\pm0.05$ $[0.034^{stat}\pm0.034^{syst}]$

Anatael Cabrera (CNRS-IN2P3 & APC)

rate systematics breakdown…

	Gd-IBD (%)	H-IBD (%)
δ(flux)	**1.75**	
δ(accidental-BG)	0.01	0.22
δ(correlated-BG)	0.54	0.64
δ(isotopes-BG)	1.46	1.56
δ(light Noise-BG)	~0	0.10
δ(response)	0.3	0.3
δ(detection)	**1.01**	**1.56**
δ(stat)	**1.12**	**1.08**

observed vs expected rate…

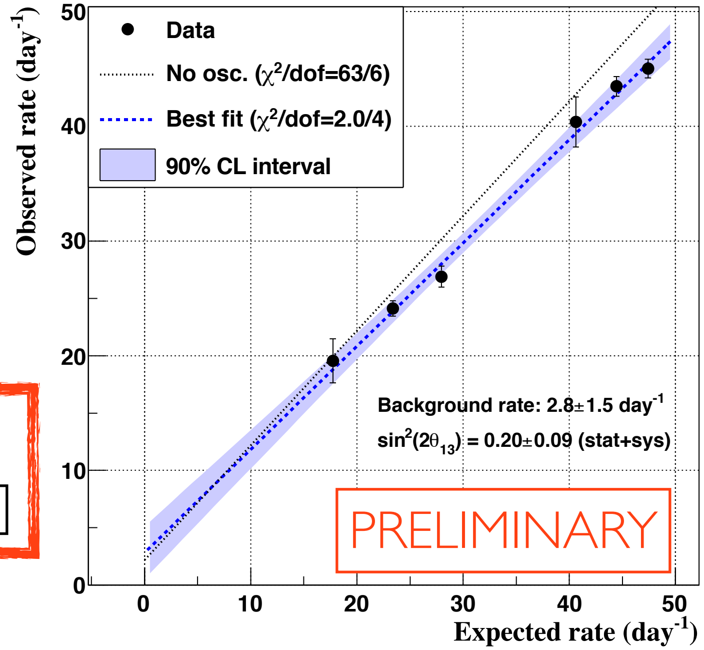


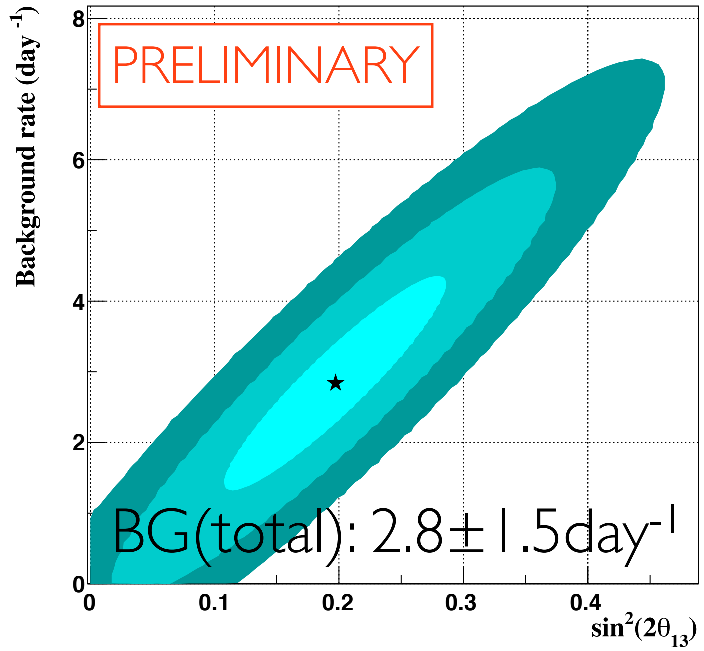
next: plot observed vs expected IBD rate per day

Anatael Cabrera (CNRS-IN2P3 & APC)

Reactor Rate Modulation Analysis…

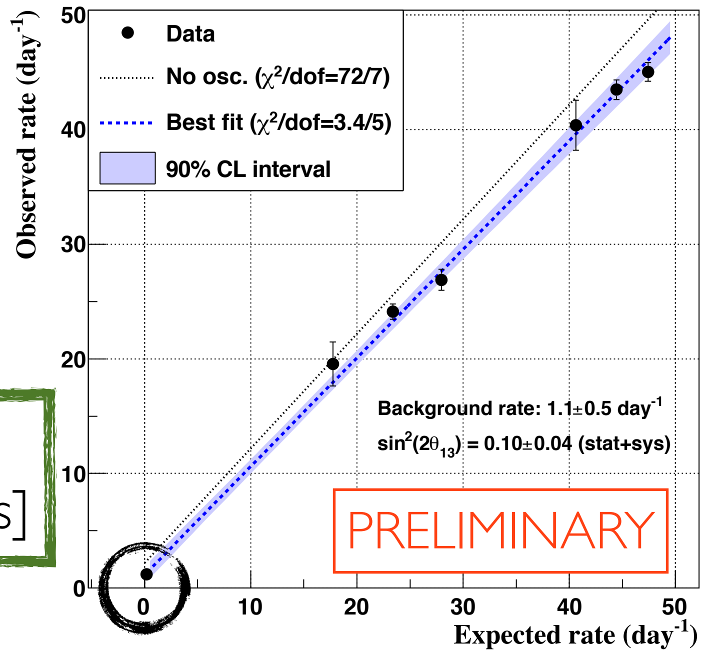
DC-II-data
(reactor-ON)

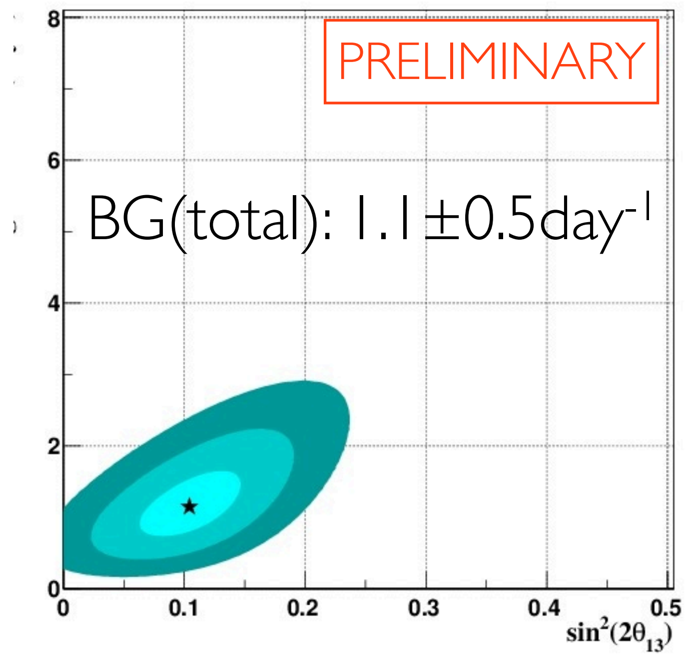




larger BG→larger $\sin^2(2\theta_{13})$
[deficit due to BG subtraction]

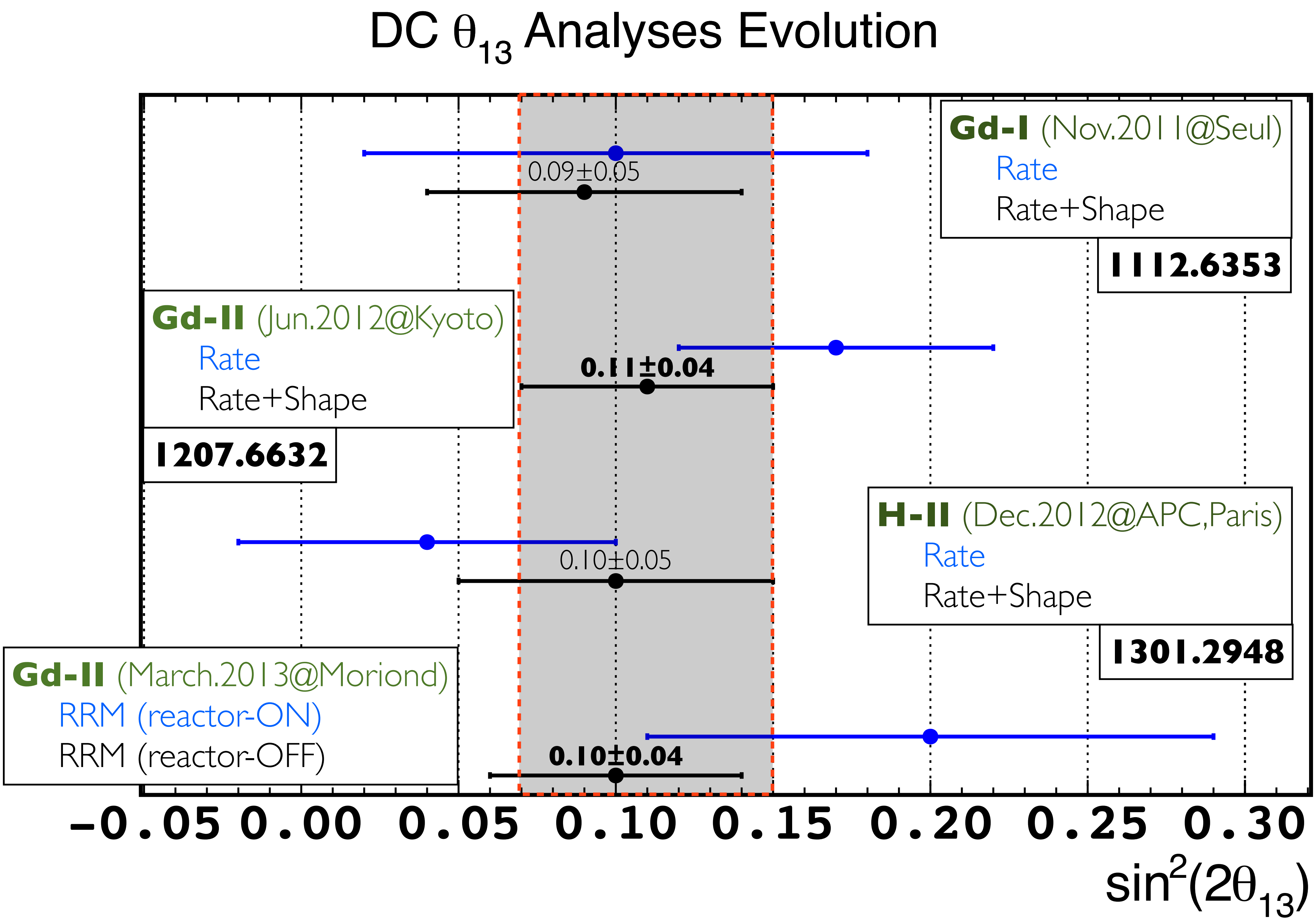
DC-II-data
(reactor-OFF)





reactor-OFF→constrains BG
[lower $\sin^2(2\theta_{13})$, similar to r+s]

evolution of DC measurements…



(error bars: 68% CL)

Anatael Cabrera (CNRS-IN2P3 & APC)

measuring/validating BGs…

- **BG knowledge:** rate (easier) & shape (limited statistics)
  - CHOOZ BG: reactor OFF (no need for a model)→ Li (by KamLAND)
  - **cosmogenic BG knowledge** limited by statistics (**~1day^{-1}**) (slowly improving)
- **[1] exclusive measurement: each BG** [difficult with reactor ON]
  - *technique:* sub-samples (approximations/extrapolations)→ systematics?
  - *limitation:* **assumes BG-model**→ completeness? (i.e. accuracy)
- **[2] exclusive measurement: each BGs upon rate+shape fit**
  - *technique:* relies on a priori knowledge (rate & shapes) & relative interplay
  - *advantage:* **robust θ_{13}** (full model: E/L & all known BG spectra)
- **[3] inclusive (direct) measurement: reactor-OFF**
  - *technique:* rate & shape of complete BG (no models)→ validate BG model
  - *limitation:* (so far) 1 week (poor stats)→ (virtually) no spectral info
- **[4] inclusive (indirect) measurement: RRM analysis (w/o reactor-OFF)**
  - *technique:* compare expected vs observed IBDs→measure θ_{13} & BG (correlation)
  - *advantage:* use **reactor-OFF→ impact to ^{inclusive}BG, θ_{13}**

Anatael Cabrera (CNRS-IN2P3 & APC)

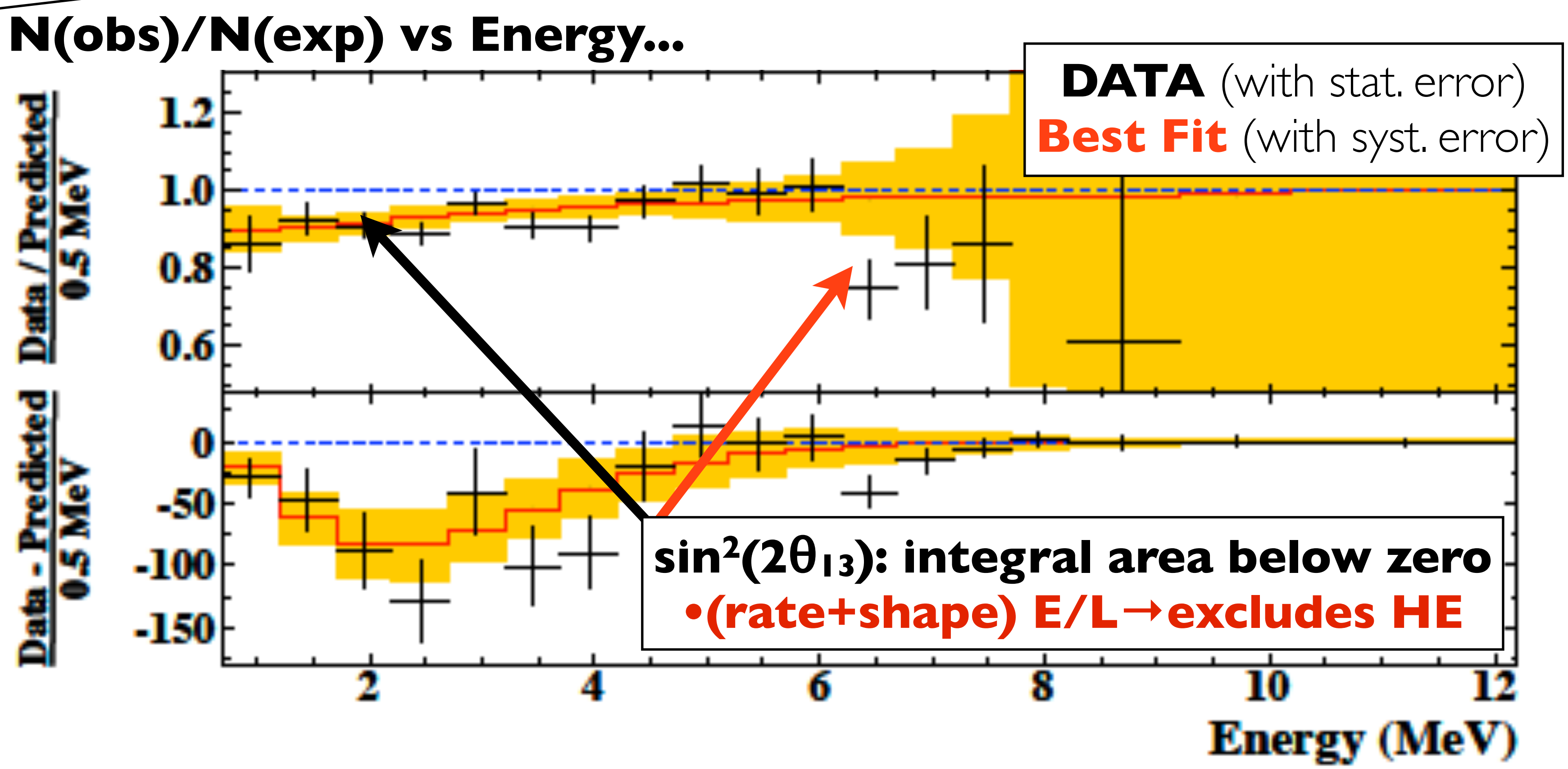
background estimation summary…

	Gd-IBD		H-IBD	
	rate	rate+shape	rate	rate+shape
accidentals	0.261±0.002 (0.7%)		73.45±0.16 (0.2%)	
cosmo-isotopes	1.3±0.54	1.00±0.29	2.8±1.2	3.9±0.6
correlated	0.67±0.20	0.65±0.13	2.50±0.47	2.60±0.40
fast-n	~0.20	N/A	all	all
stopping-μ	~0.47	N/A	N/A	N/A
Light Noise	N/A	N/A	0.32±0.07	
total (Σ exclusive)	**2.2±0.6**	**1.9±0.3**	79.1±1.3	80.3±0.7
reactorOFF (inclusive)	**1.0±0.4**		N/A (yet)	
modulation (inclusive)	**2.8±1.5**	**1.1±0.5**	N/A (yet)	N/A (yet)

Anatael Cabrera (CNRS-IN2P3 & APC)

E/L disappearance pattern…

DC-II (Gd) (June'12)



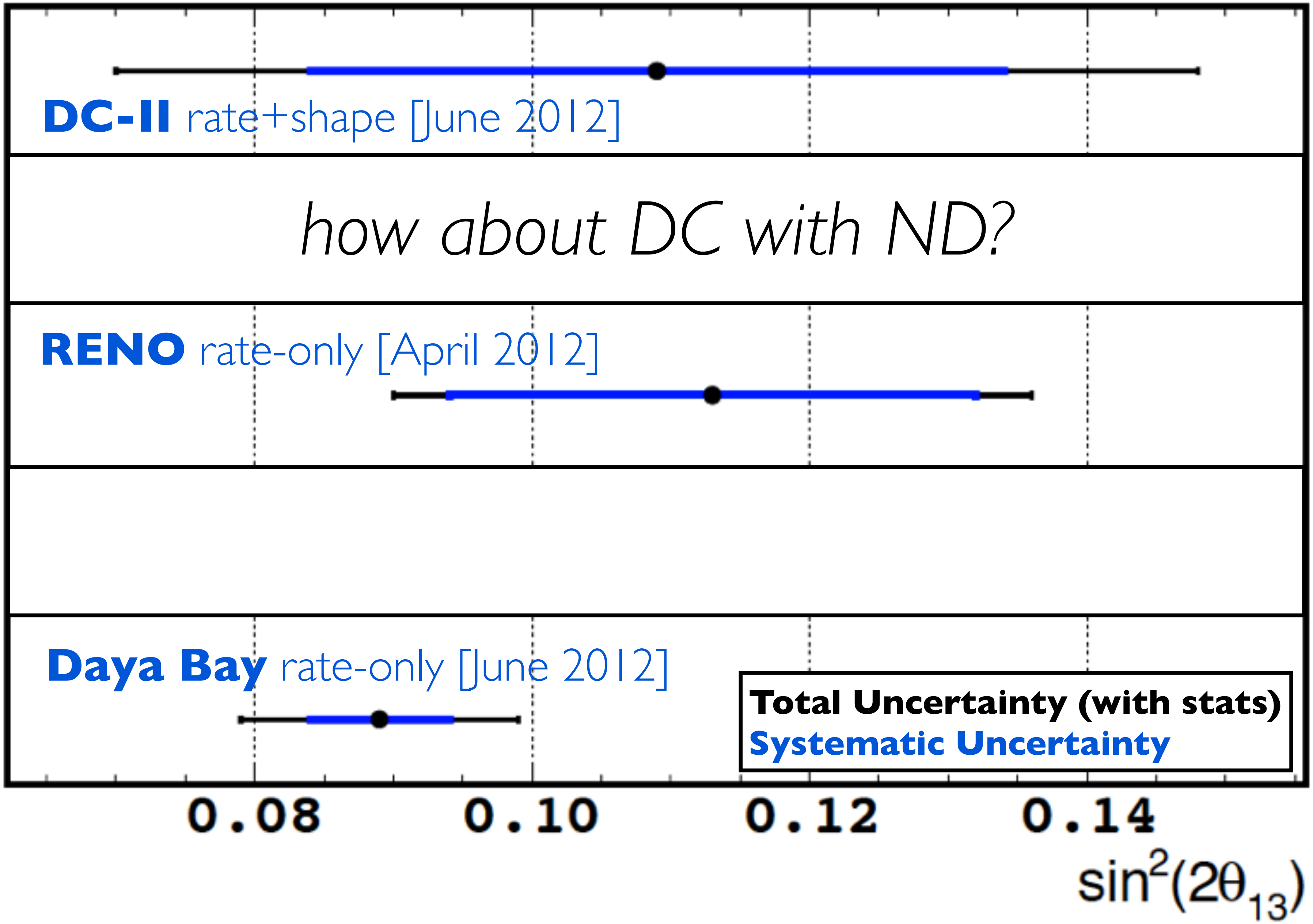
- **DC short baseline (1050m)**→ hard to see "rise" (poor constrain in Δm^2)
  - coarse binning (Gd) 500keV
- **rate+shape:** challenges all knowledge…
  - neutrino oscillation model: E/L shape (using MINOS Δm2)
  - BG model (completeness + rate + shape)
- **feature @ 6MeV**→new BG vs fluctuation (**large systematics**)?
  - (regardless) E/L (for DC is short-ish) & rate+shape→ **robust θ13**

Anatael Cabrera (CNRS-IN2P3 & APC)

prospects…

measurements by DC…

(assumed a rate analysis à la DB & RENO)



Anatael Cabrera (CNRS-IN2P3 & APC)

rate-like uncertainties…

$\boxed{R = N^{obs}/N^{exp}}$

uncertainty on R	FD only (%)	ND+FD (%)
δ(response)	0.3	<0.3
δ(flux)	1.7	≤0.2**?** **~iso-flux**
δ(detection)	1.0	0.2**?** à la DB/RENO
δ(BG)	0.9	~0.5**?** BG rejection **(my view)**
δ^{rate}(total)	**2.2**	**~0.6**
δ(statistics)	**~1.1** (now)	**~0.6** (3 years ND+FD)

δ(R)→δ(sin²(2θ₁₃)) increase (DC: shortest baseline**)**

Anatael Cabrera (CNRS-IN2P3 & APC)

what to remember?

conclusions…

- **θ13 reactor measurement will dominate for long…**
  - **precision**→ multi-detector technique (combined: **~5%**)
  - **accuracy**→ better analyses (time) & inter-experiment validation
  - global impact to neutrino oscillations→ **constraints & predictions**
- **Double Chooz…**
  - few **θ13 measurements**→**consistent** (cross-check precision & accuracy)
    - **improving all analyses**→**surprises are coming!!**
    - BG is most critical (but ***that's what we do best***: 4 fold cross-checks)
  - **δ(systematics): 2.2%→ ~0.6%** (prospected with ND)
    - FD-only: **$\sigma[\sin^2(2\theta_{13})]$: ~0.03** [dominated by δ(flux)]
    - ND+FD: **$\sigma[\sin^2(2\theta_{13})]$: ~0.01** [i.e. **~10%** for $\sin^2(2\theta_{13})=0.1$]
- **Global: final precision & accuracy of θ13…**
  - several experiments (different systematics)→ validate accuracy of θ13
    - **DC:** sensitive BG to δ(BG) [also **RENO**]
    - **RENO/DB:** sensitive to δ(flux)

Anatael Cabrera (CNRS-IN2P3 & APC)