Double Chooz

(latest results)

seminar @ CPPM (Marseille)
June 2014

Anatael Cabrera

CNRS / IN2P3 @ APC (Paris)

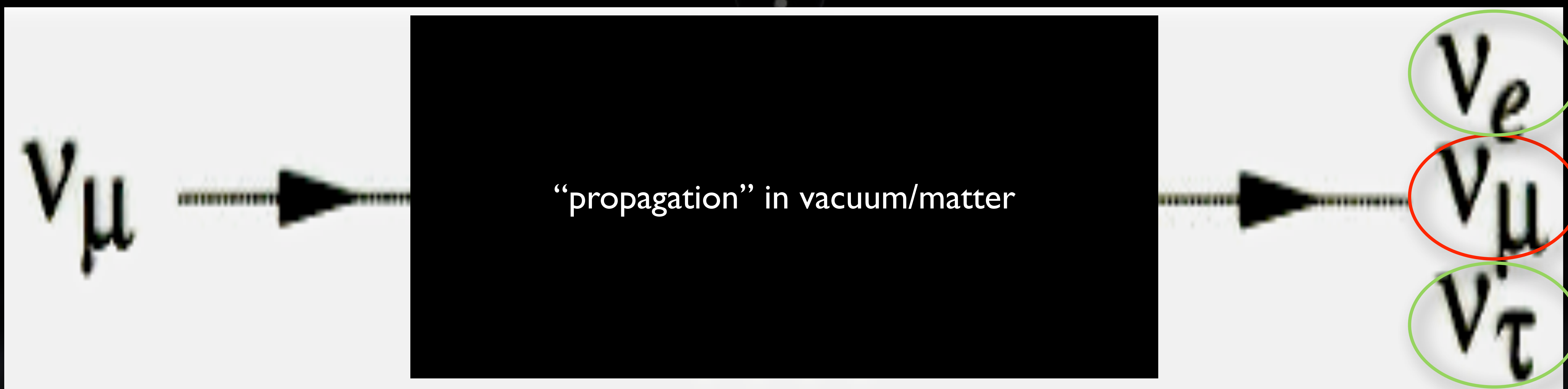
neutrino oscillations…

(very fast reminder)

neutrino oscillations: a cartoon

Let's take ν_μ (a popular example) to start with…

disappearance
appearance



observation: both disappearance (long ago) & appearance (July 2013) have been seen

all observations (many!) follow well one model: 3ν oscillation

"mixing": a common phenomenon…

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

ingredients for neutrino oscillations…

Non-degenerate mass spectrum (Δm^2) **+** Mixing in the leptonic sector (θ) **=** Oscillation Probability **$P=f(\theta,\Delta m^2)$**

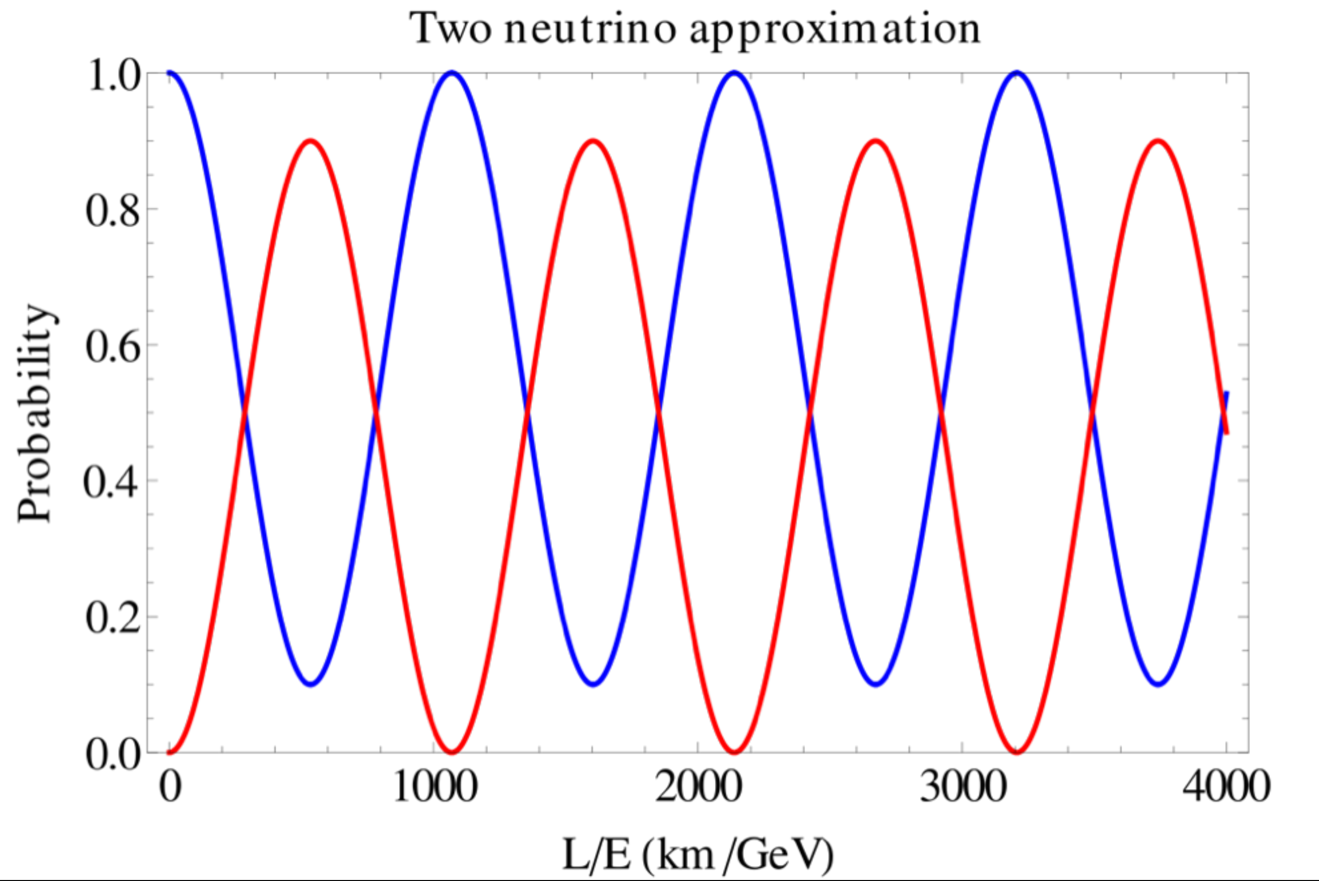
macroscopic quantum interference

U^{PMNS} matrix (à la CKM)

experimental setup
$P(L_o,\Delta E) \rightarrow f(\theta,\Delta m^2)$??
(measure a range of phase-space)

ν_α (start with) & ν_β (mixing: 90%)

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



"atmospheric" ⟹ $\theta_{23} \sim 45^\circ$

θ_{13} & "dirac" δ_{CP}

"solar" ⟹ $\theta_{12} \sim 33^\circ$

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

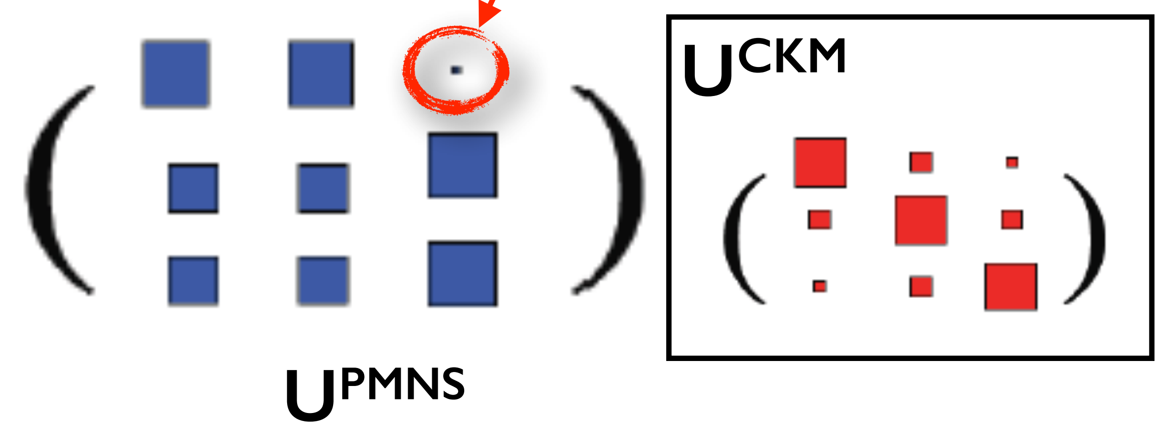
atmos+LBL(dis) | Chooz+LBL(app) | solar+KamLAND

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

knowledge on
θ_{13} & δ_{CP}
[**later**]

θ_{13} drives this!!!

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



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Lisi et al opinion (Jan. 2014)

Nσ ranges for single parameters (all data included):

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. See also Fig. 3 for a graphical representation of the results. 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. The CP violating phase is taken in the (cyclic) interval $\delta/\pi \in [0, 2]$. The overall χ^2 difference between IH and NH is insignificant ($\Delta\chi^2_{\mathrm{I-N}} = +0.3$).

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)	3.08	2.91 – 3.25	2.75 – 3.42	2.59 – 3.59
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.44	2.38 – 2.52	2.30 – 2.59	2.22 – 2.66
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.40	2.33 – 2.47	2.25 – 2.54	2.17 – 2.61
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.34	2.16 – 2.56	1.97 – 2.76	1.77 – 2.97
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.39	2.18 – 2.60	1.98 – 2.80	1.78 – 3.00
$\sin^2\theta_{23}/10^{-1}$ (NH)	4.25	3.98 – 4.54	3.76 – 5.06	3.57 – 6.41
$\sin^2\theta_{23}/10^{-1}$ (IH)	4.37	4.08 – 4.96 ⊕ 5.31 – 6.10	3.84 – 6.37	3.63 – 6.59
δ/π (NH)	1.39	1.12 – 1.72	0.00 – 0.11 ⊕ 0.88 – 2.00	—
δ/π (IH)	1.35	0.96 – 1.59	0.00 – 0.04 ⊕ 0.65 – 2.00	—

Fractional uncertainties (defined as 1/6 of 3σ ranges):

δm^2	2.6 %	→ KamLAND
Δm^2	3.0 %	→ MINOS/T2K and Reactor (@Nu2014)
$\sin^2\theta_{12}$	5.4 %	→ Solar
$\sin^2\theta_{13}$	8.5 %	→ Reactor
$\sin^2\theta_{23}$	~ 11 %	→ SuperKamiokande + T2K (@Nu2014)

non-accelerator experiments drive current knowledge…

the 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)

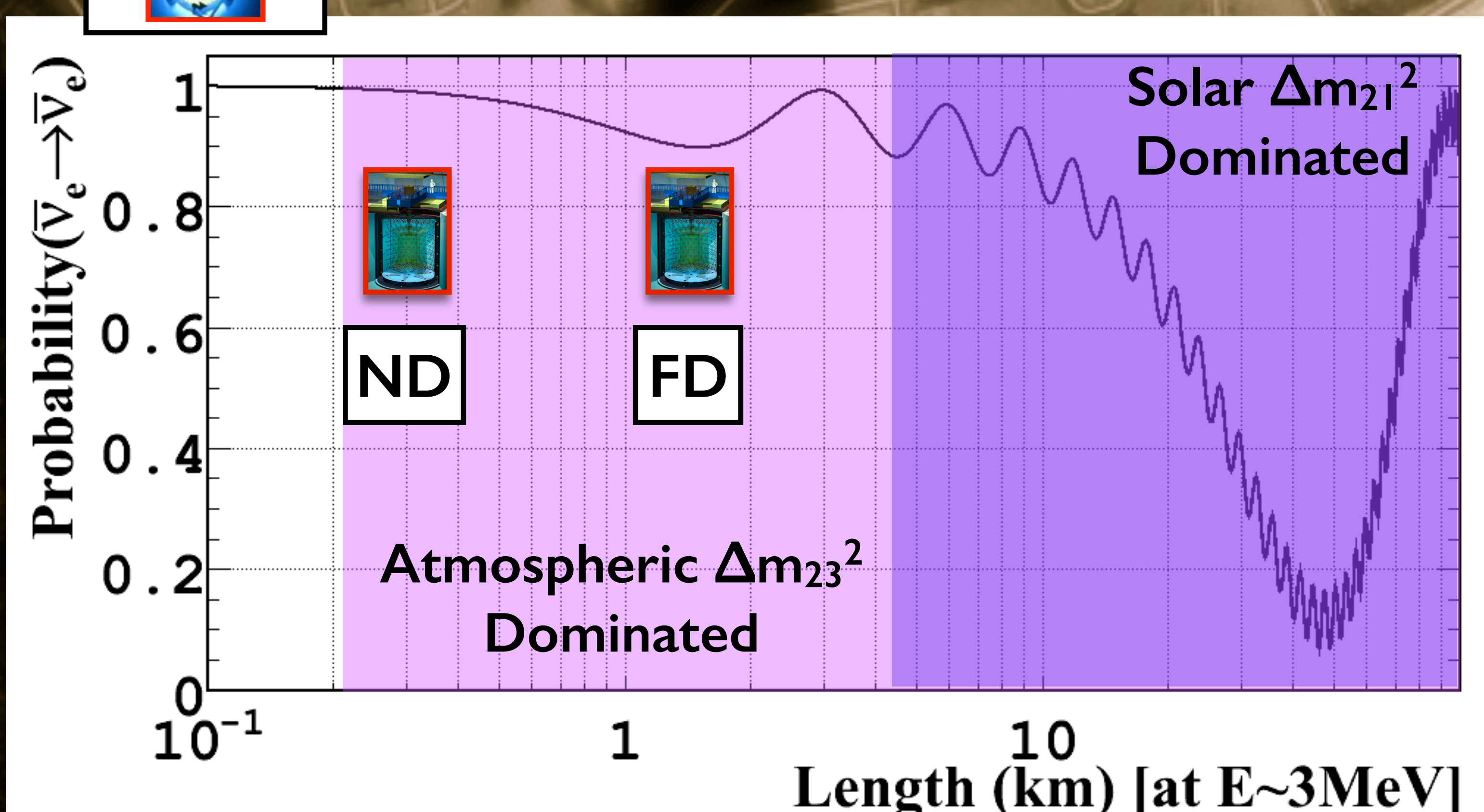
Web Site:
www.doublechooz.org/

the experiment's rationale…

experimental setup...

Chooz Reactors
Power: 8.5GWth
$\Longrightarrow \sim 10^{21} \nu/s$
(N4s: very powerful)

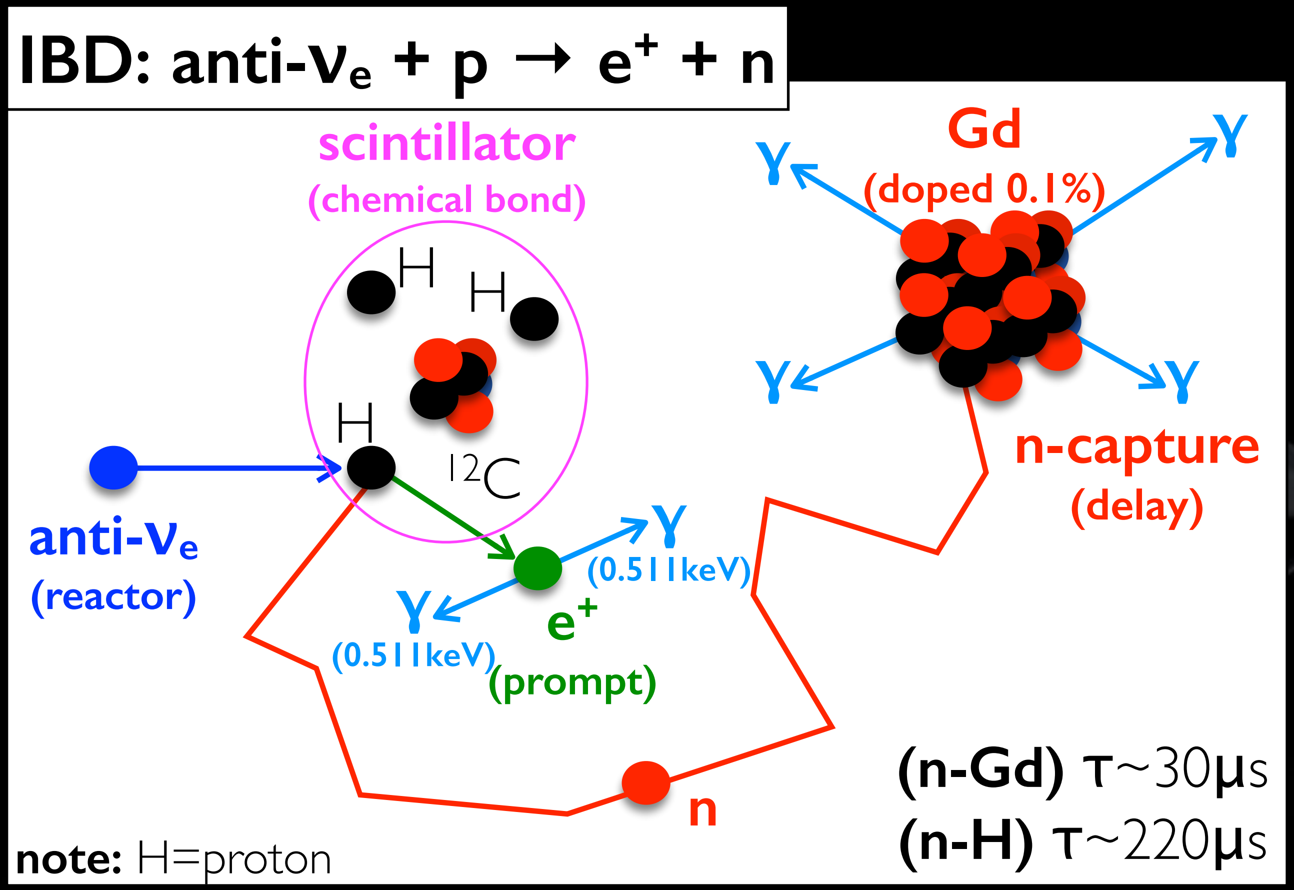
reactor

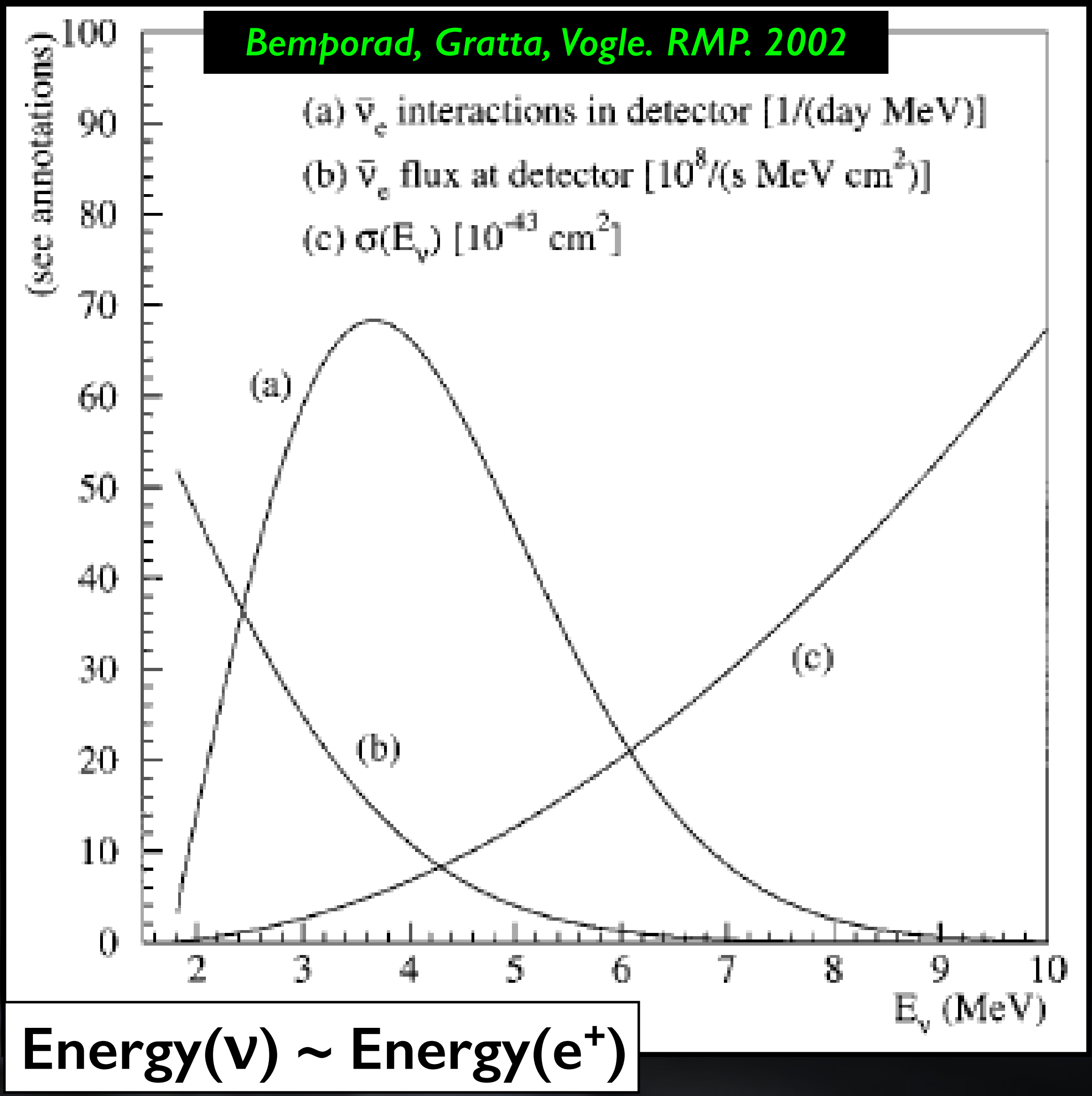


Near
<L>=408m
~270IBD/day
~120mwe
Target: 8.2t
Oct.2014

Far
<L>=1056m
~40IBD/day
~300mwe
Target: 8.2t
April 2011

IBD interaction (inverse-β decay)…





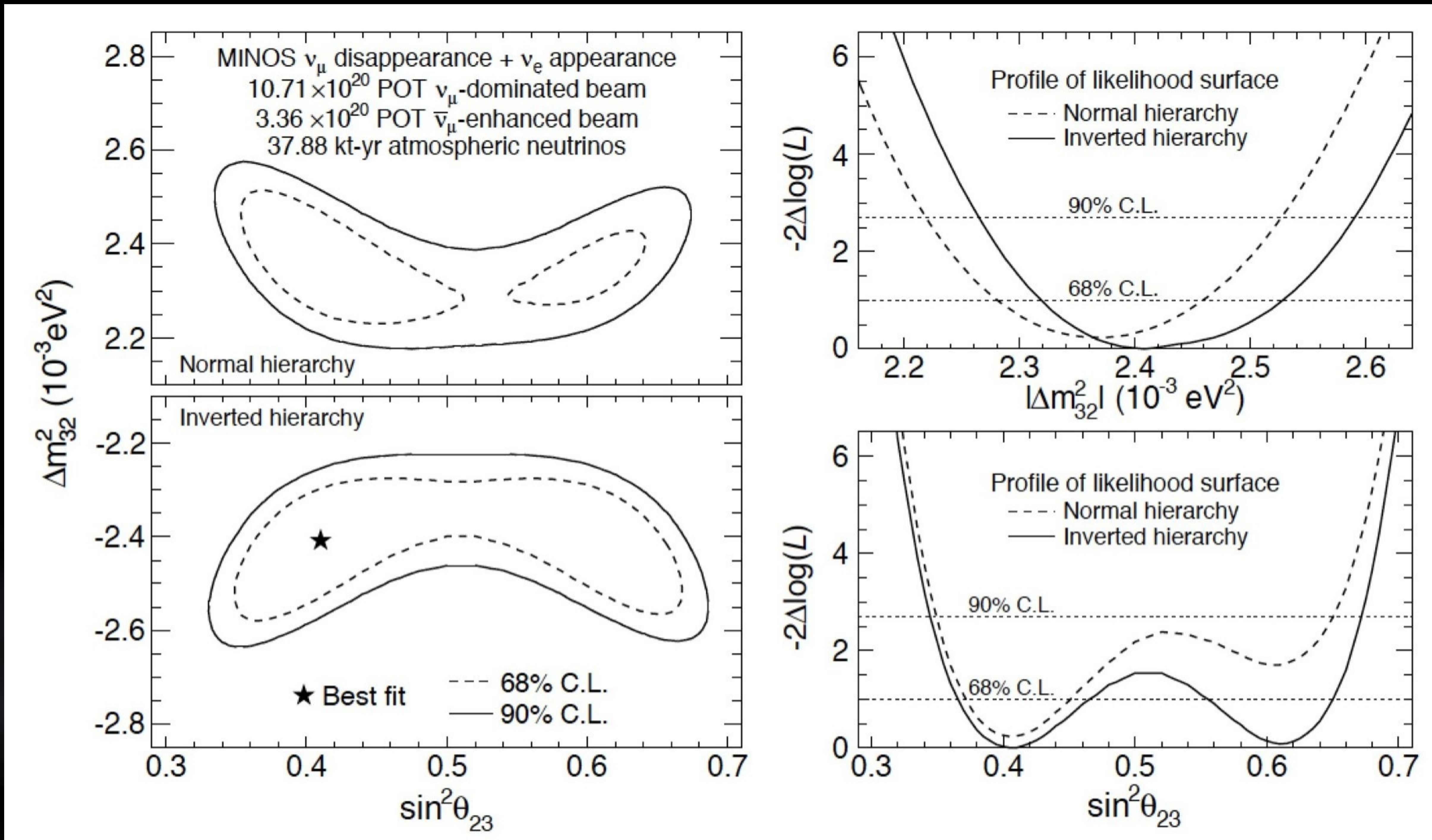
- **high & well known σ^{IBD}** [$\tau_{neutron}$=(881.5±1.5)s]
- IBD manifests via **trigger-coincidence**
  - 1st trigger→ **e+(prompt)** [ionisation ⊕ annihilation]
  - 2nd trigger→**n-Gd capture (delay @ ~8MeV)**
- **Energy(ν) ~ Energy(e+) + 0.8MeV**
- major rejection of radioactivity background…
  - time/space coincidence
  - delay @ 8MeV (radioactivity dominates ≤3MeV)

why IBD ⊕ Gd?
- small & shallow (high S/BG)
- no need for ultra-purity

⟹ **inexpensive ‰ precision!!**

MINOS' Δm_{32}^2 input (convert→Δm_{31}^2)…

arXiv:1403.4667



Δm_{32}^2=[2.28,2.46]x10^{3}eV^2 (@68LC NH)

Δm_{32}^2=[2.32,2.53]x10^{3}eV^2 (@68LC IH)

the world of θ_{13}…

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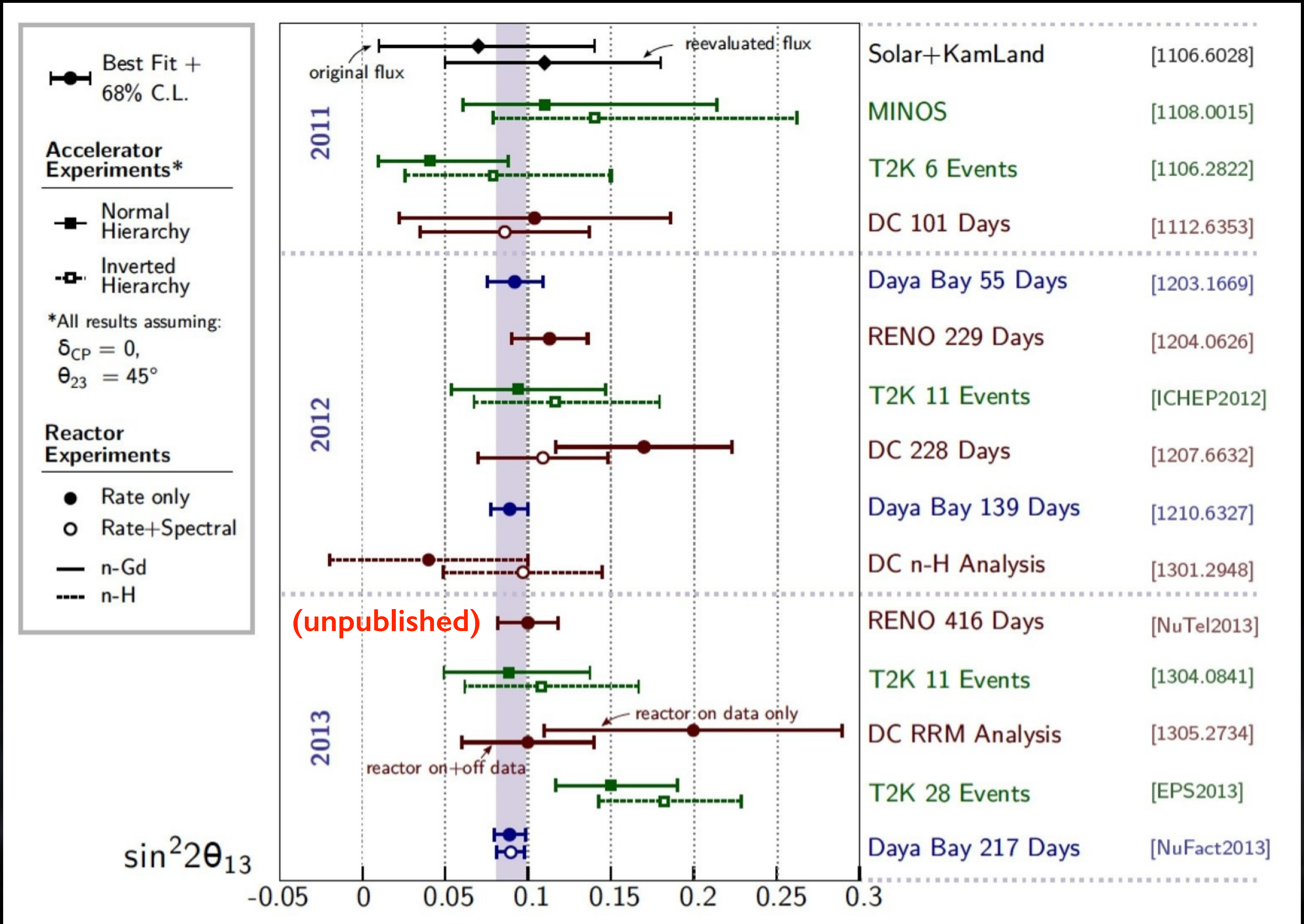
θ_{13}-reactor measurements…



reactor precision is unsurpassable→ setting θ_{13} for several decades to go!

(also measurement by T2K, MINOS, etc)

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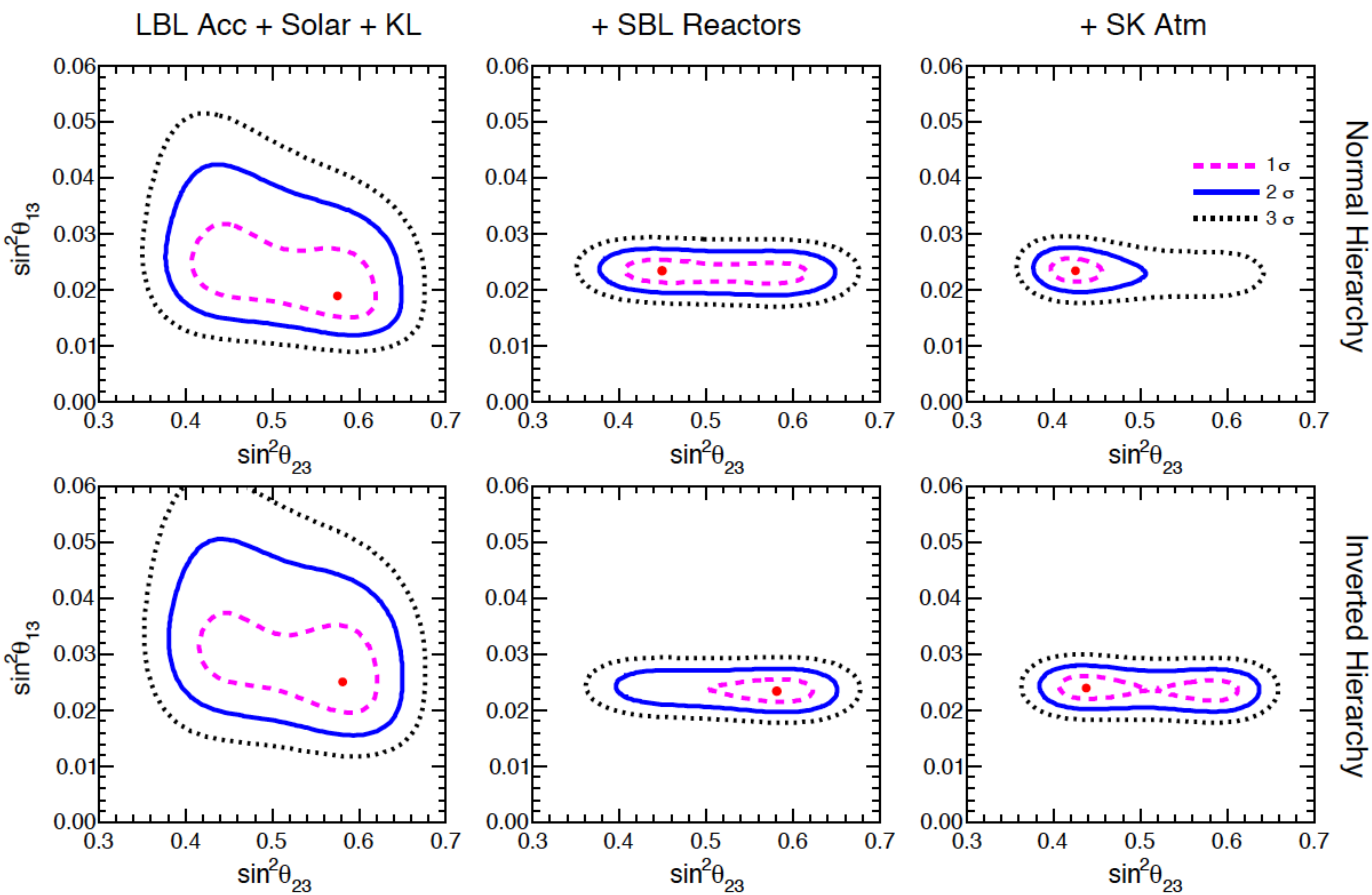
Lisi et al opinion (Jan. 2014)



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

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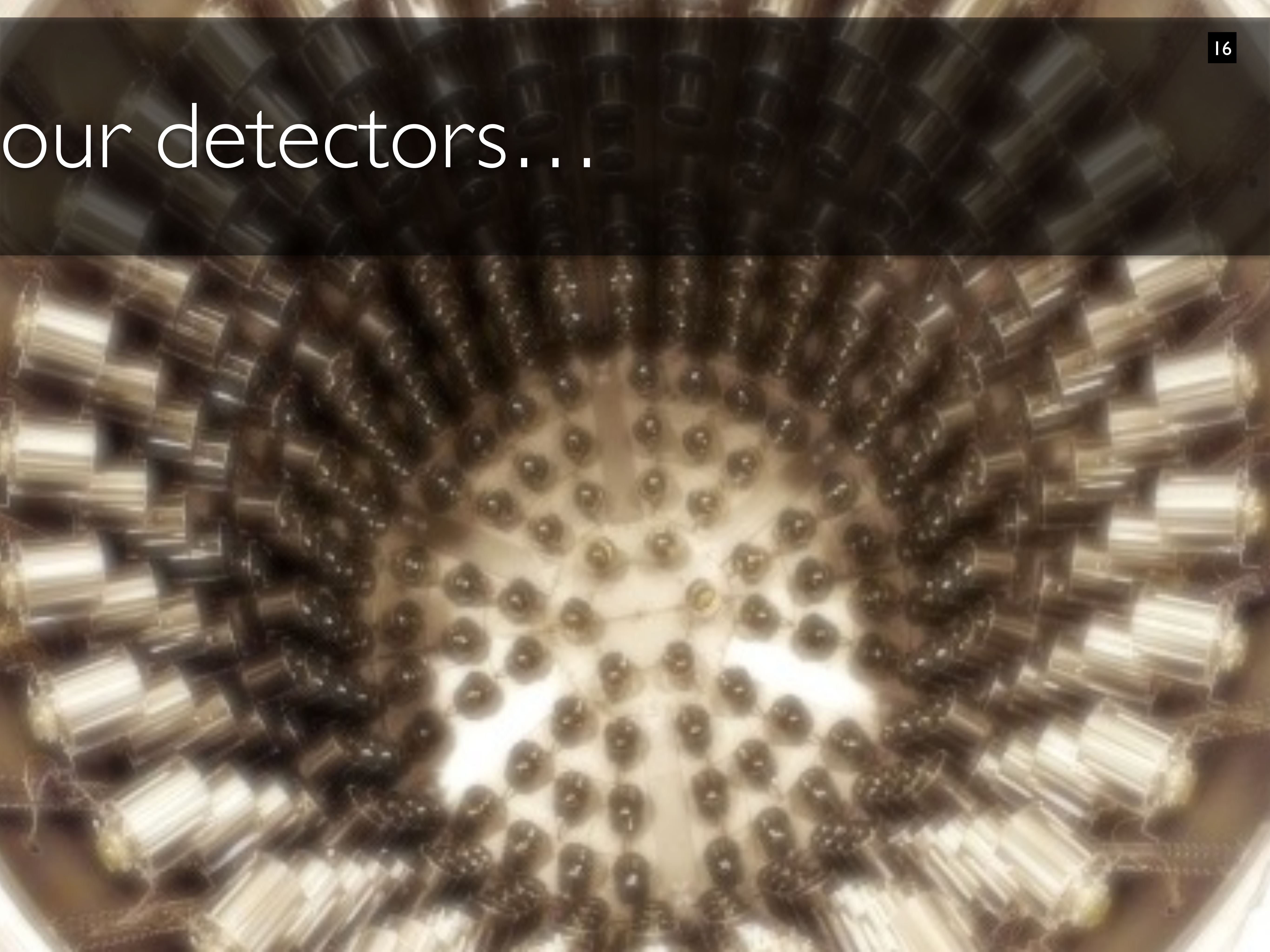
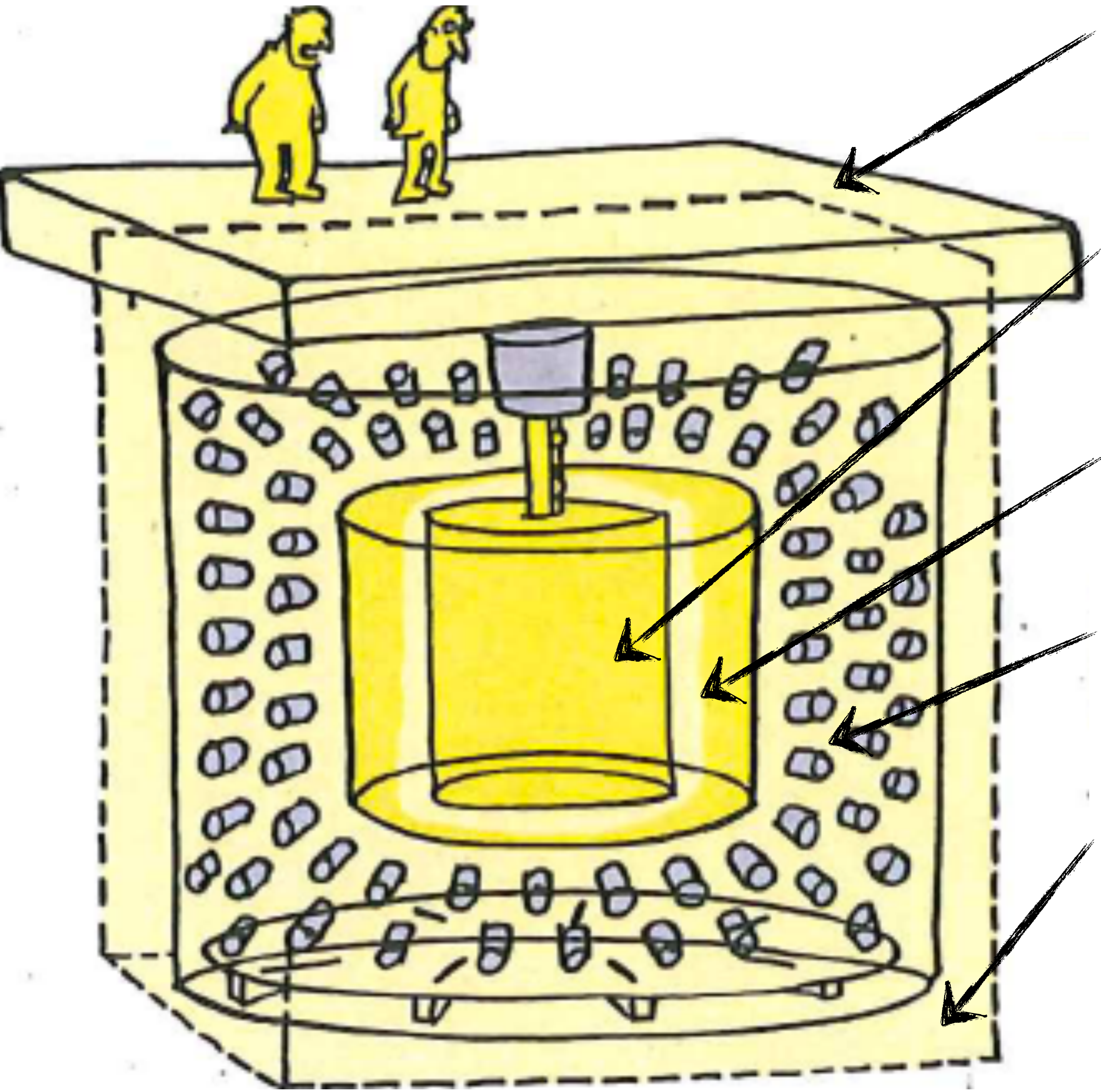
our detectors…



the DC detectors…

- **far detector (FD)**…
  - data taking since spring 2011
  - 3 data-releases: DC-I (Nov.2011), DC-II (June 2012), **DC-III (now) (!!!)**
  - **DC "single-detector" phase**→ virtually finished (systematics eclipse)
- **near detector (ND)**…
  - building→ summer 2014
  - **DC "multi-detector" phase**→ major systematics cancellation (appetiser later)
- **our virtual near detector (MC)** (man-power-wise most expensive detector)…
  - **CRITICAL during single-detector phase**→ **un-oscillated spectrum** (reference)
  - **ingredients…**
    - σ^{IBD} **cross-section normalisation** (neutron lifetime)
    - σ^{IBD} **shape** (kinematics by Vogle & Beacom)
    - **ILL data** (β^- spectrum data)$\Longrightarrow$ ν flux [by Schreckenbach et al + Huber + Muller et al]
    - **Bugey4 ν-spectrum** (nearby reactor core) [by Bugey4 collaboration]
      - reduce systematics (else ILL driven)
    - **Chooz-B1 and Chooz-B2 reactor data** [by Chooz EdF company]
    - **MC simulation based** (data + reactor + physics + detector)

a generic θ13-LAND…



Outer μ-Veto (OV)

Plastic-Scintillator: strips (→tracking)

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

γ-Catcher (GC)

Liquid-Scintillator

Light Buffer

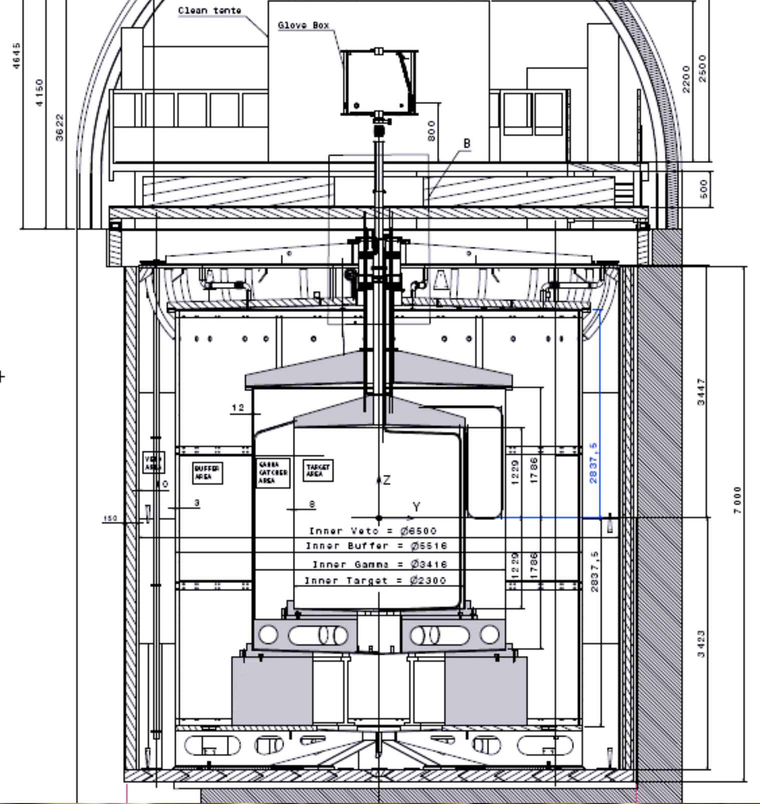
Oil (negligible scintillation)

Inner μ-Veto (IV)

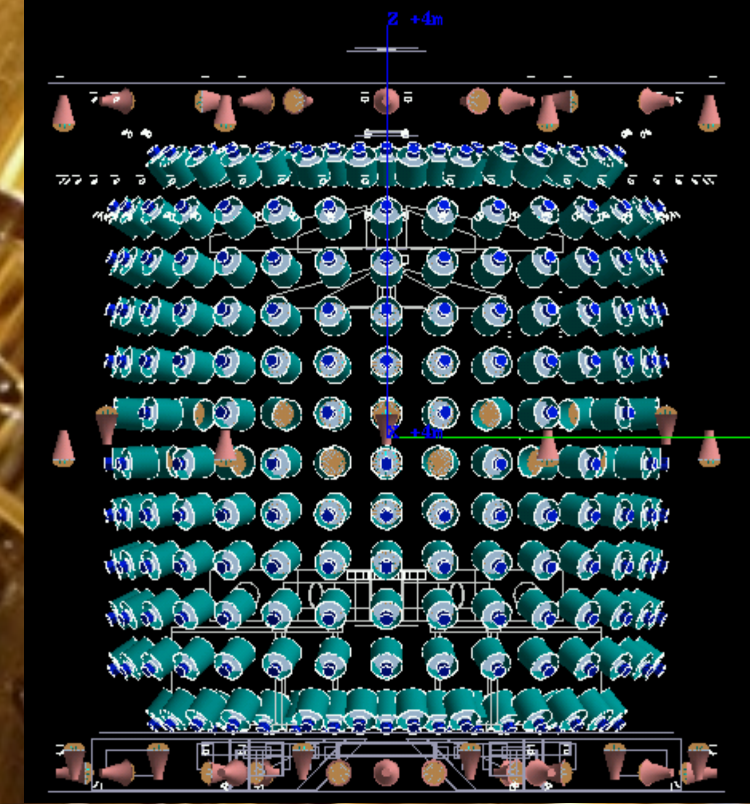
Liquid-Scintillator

Inert γ-Shield

15cm of steel (around all detector)



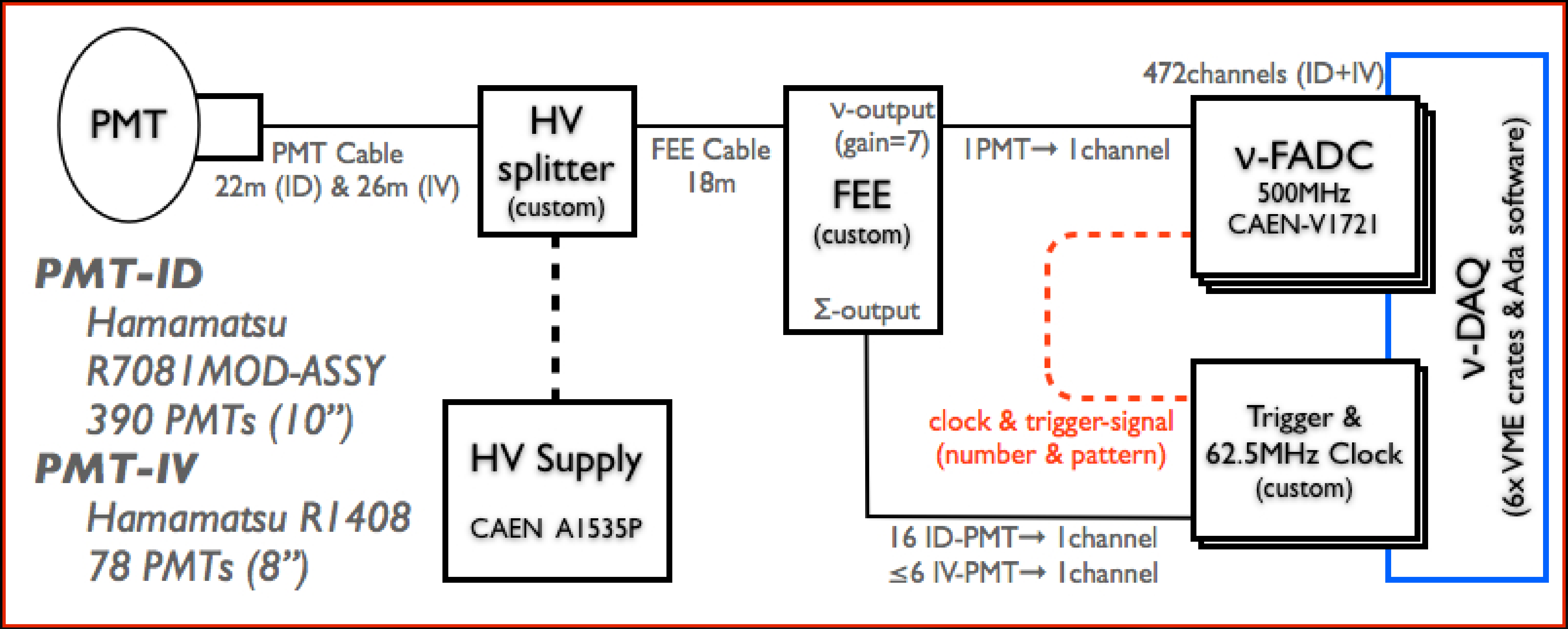
engineer's view



MC's view

our favourite view…

our readout…



state of the art FADC based waveform digitisers @ electronics readout

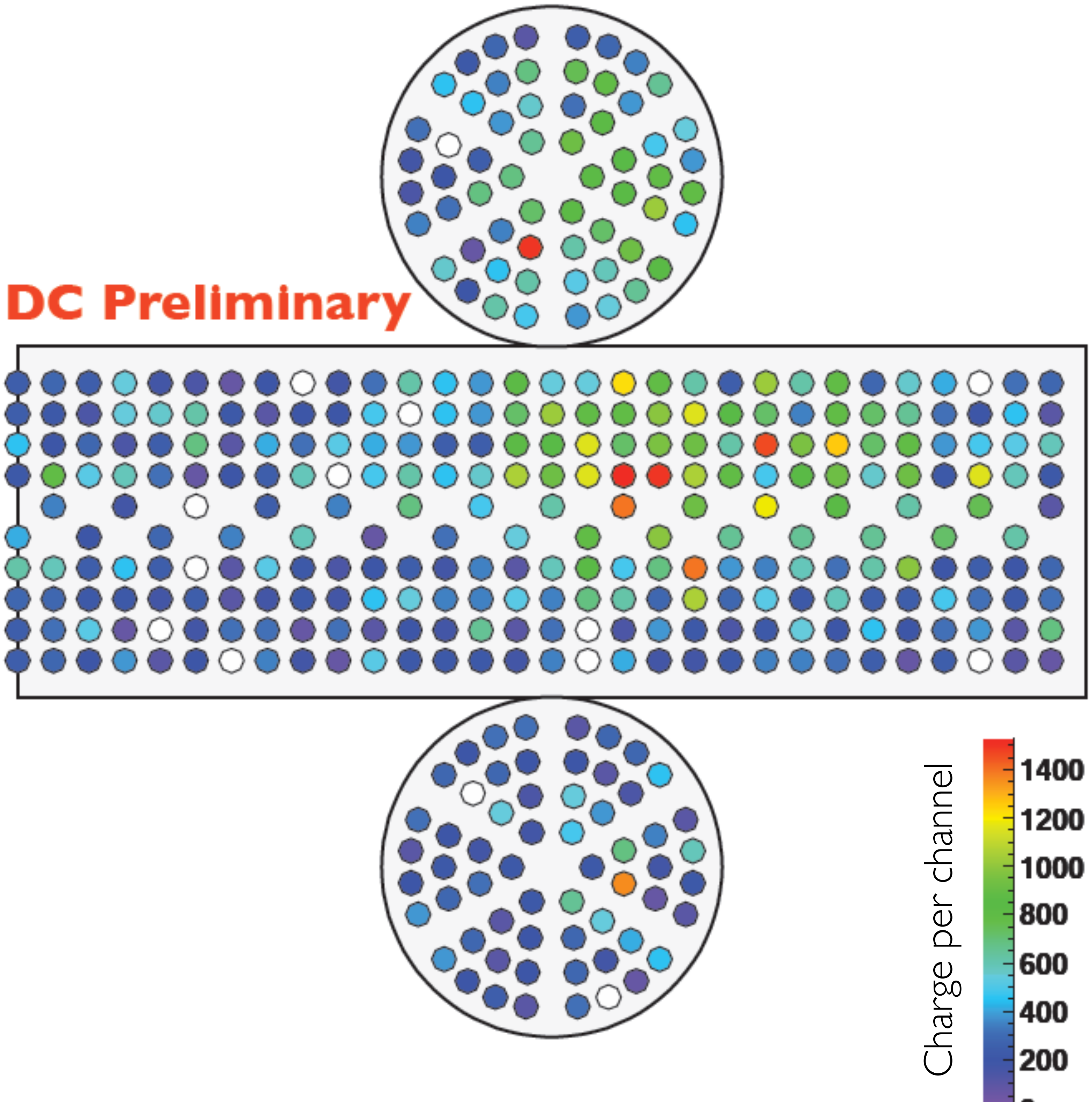
- event-wise data quality flagging (→ not a single cut to clean data)
- still squeezing further information for analysis (→ higher precision)

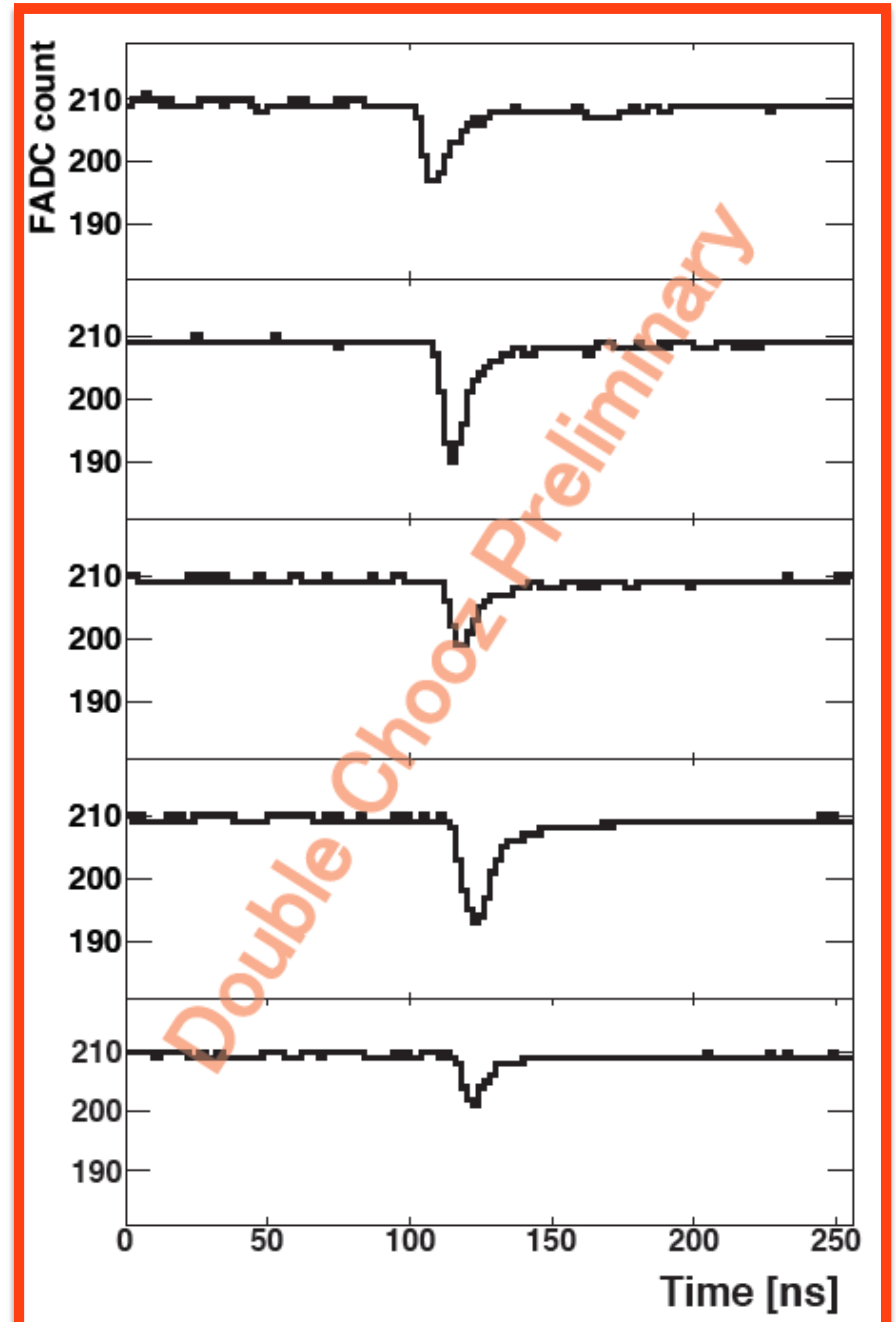
same readout+DAQ both ID and IV

(OV readout based on M64+MAROC, similar OPERA)

a point like event (no IV activity)...

Energy ~8MeV





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

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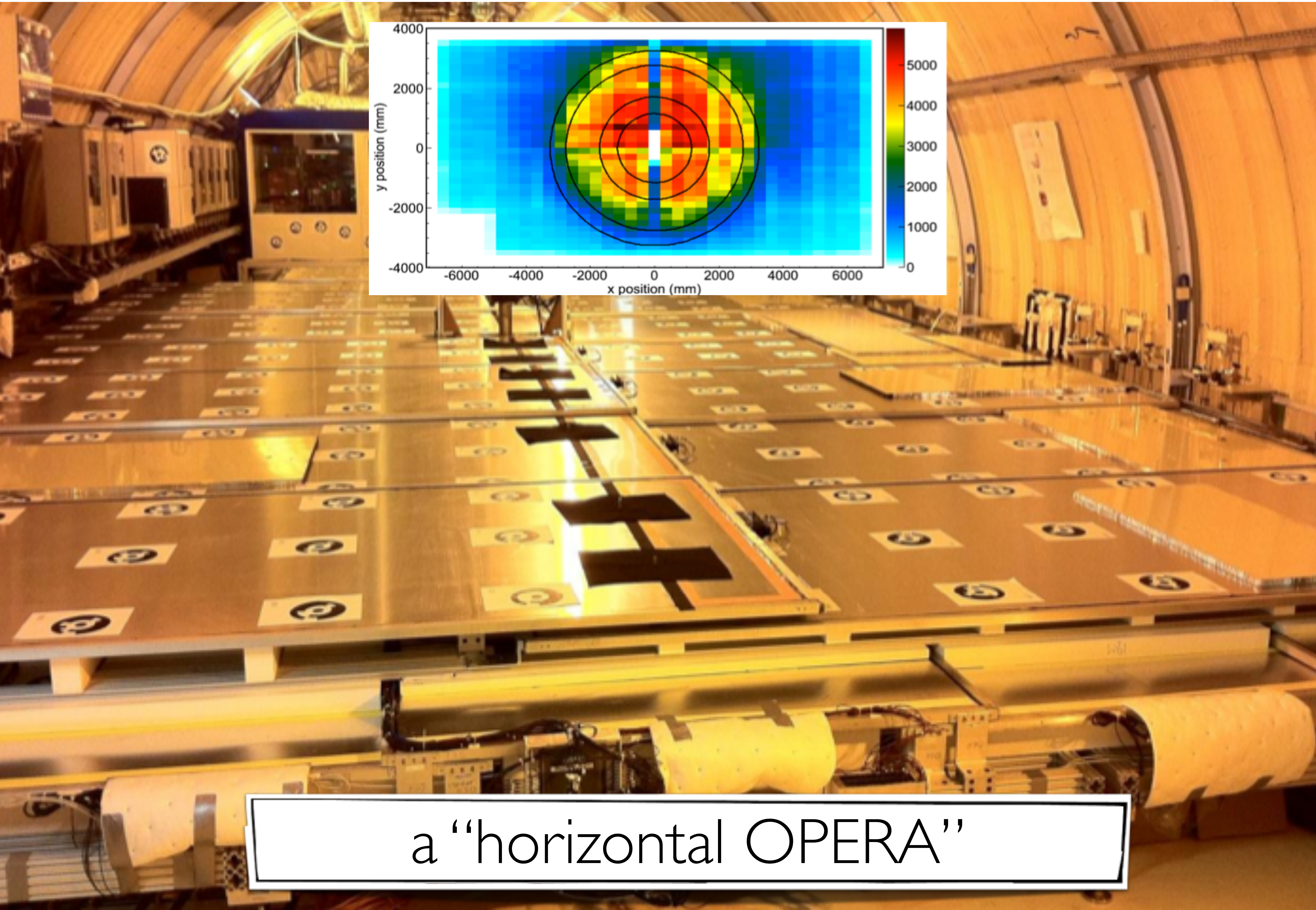
our top μ-tracker/veto (Outer-Veto)…



a “horizontal OPERA”

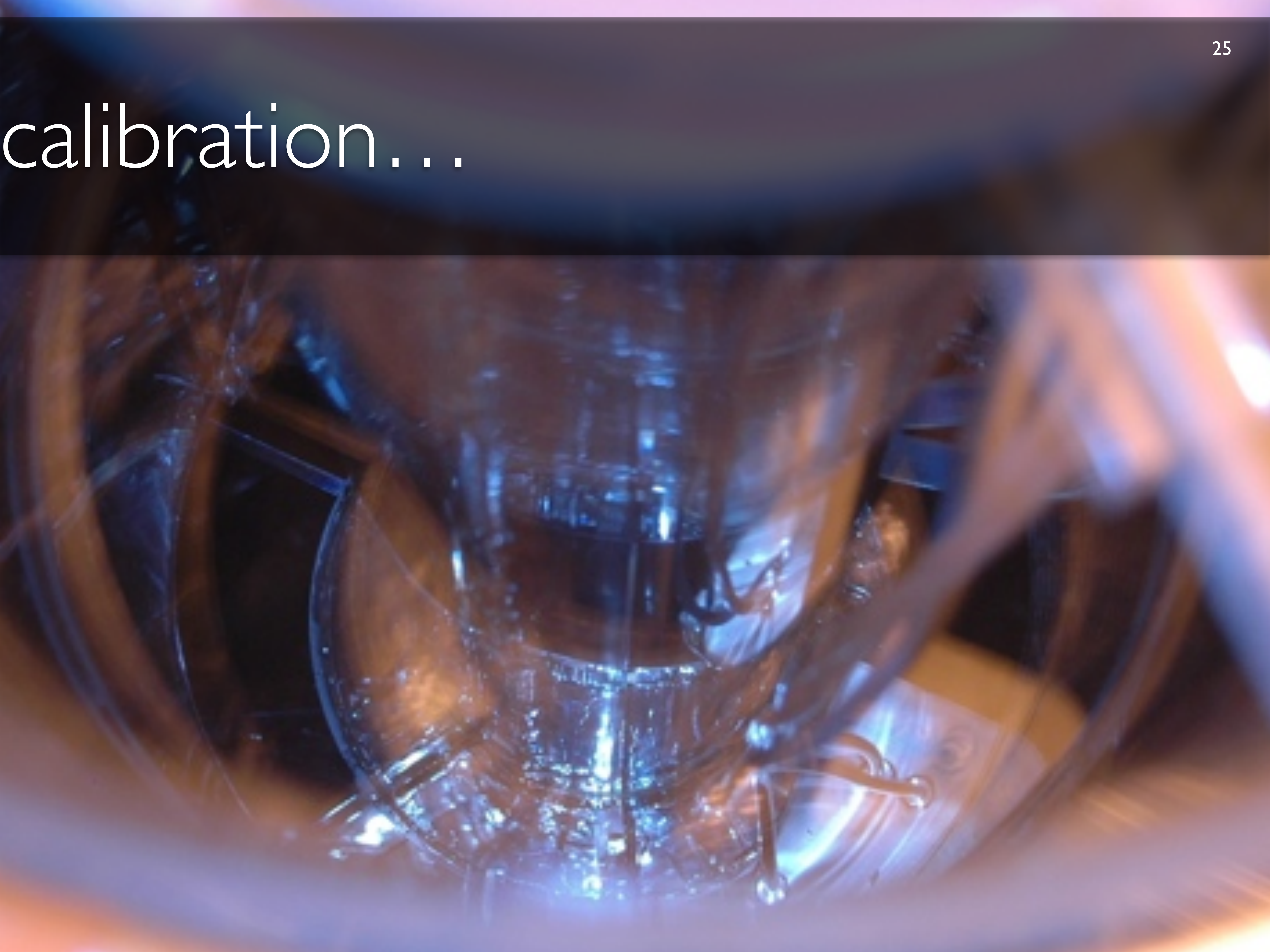
the near detector...

status

- IV instrumentation → **done**
- detector is closed → **done**
- chimney mechanics → june
- filling → summer
- shielding (water+steel) → summer
- data-taking commissioning → Sept.~Oct.

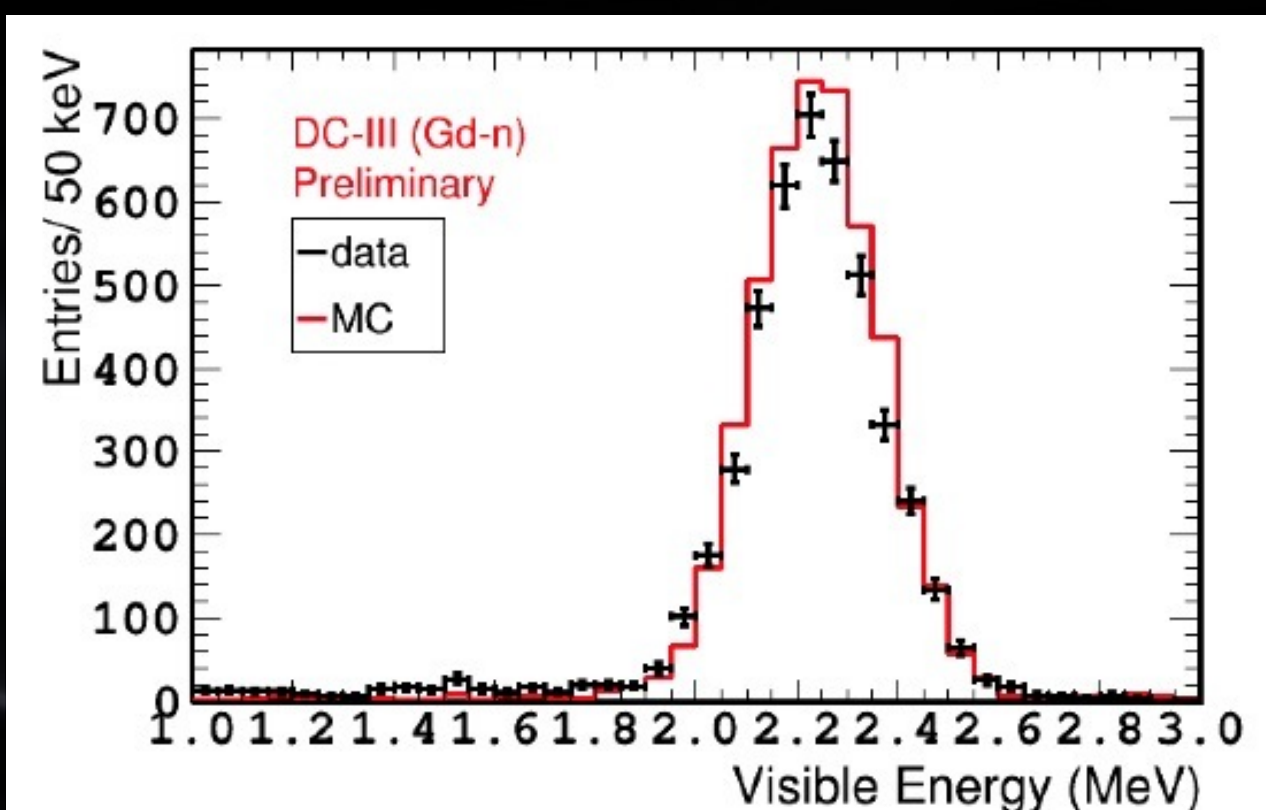
a hot summer for DC…

calibration…



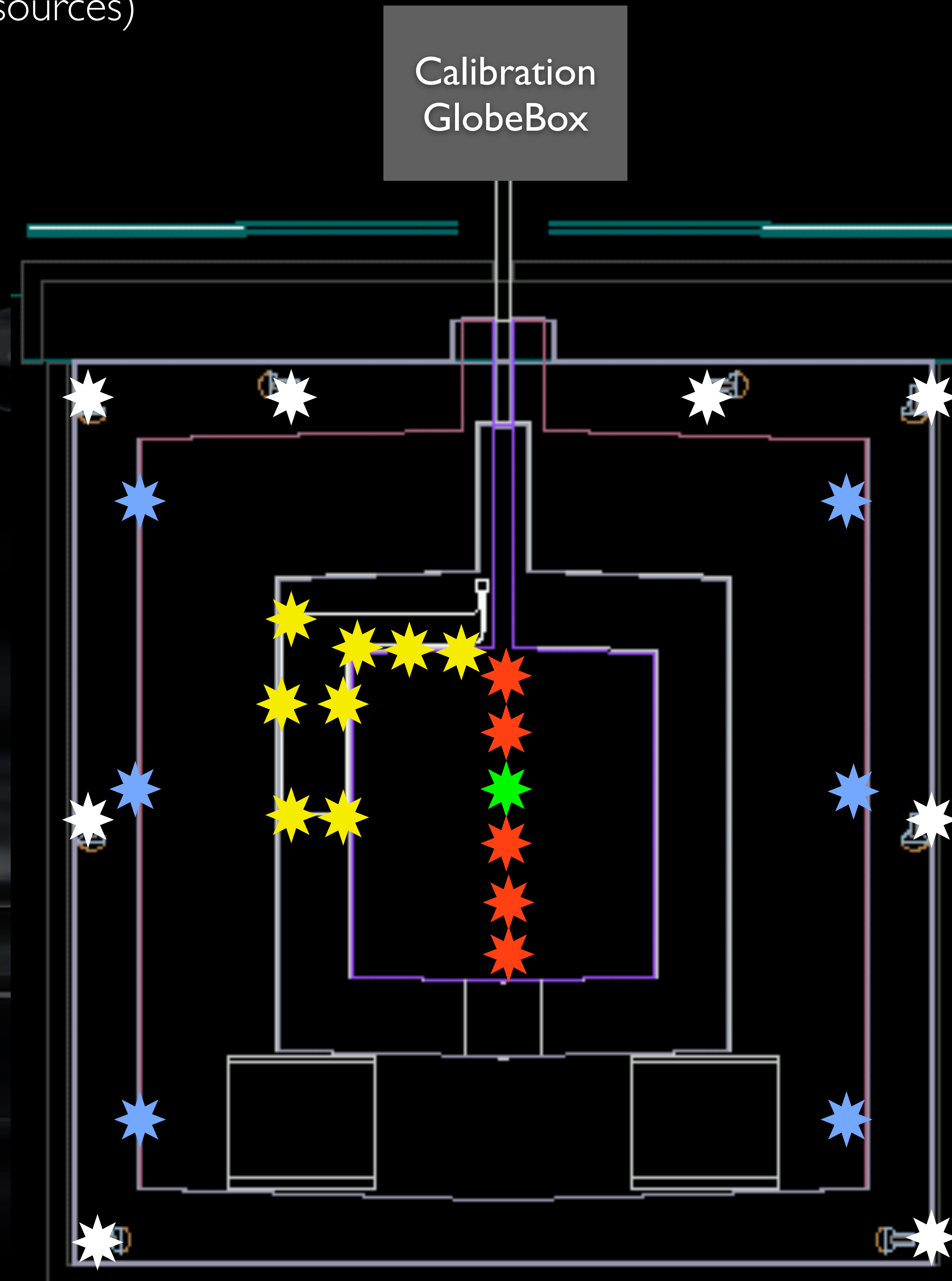
calibration system…

- **principle:** redundancy critical for systematics (→sources)
- **in-built:** light LED (**ID** + **IV**)
- **deployable** (^{137}Cs, ^{68}Ge, ^{60}Co, **^{252}Cf**, lasers)
  - **z-axis** (→ ν-target sampling)
  - **GC guide-tube** (→ GC sampling)
  - (not yet used) **Articulated Arm**
- **natural:** H-n, C-n, Gd-n peaks (μ's fast-n), BiPo, IBD (delay spectrum→validation)



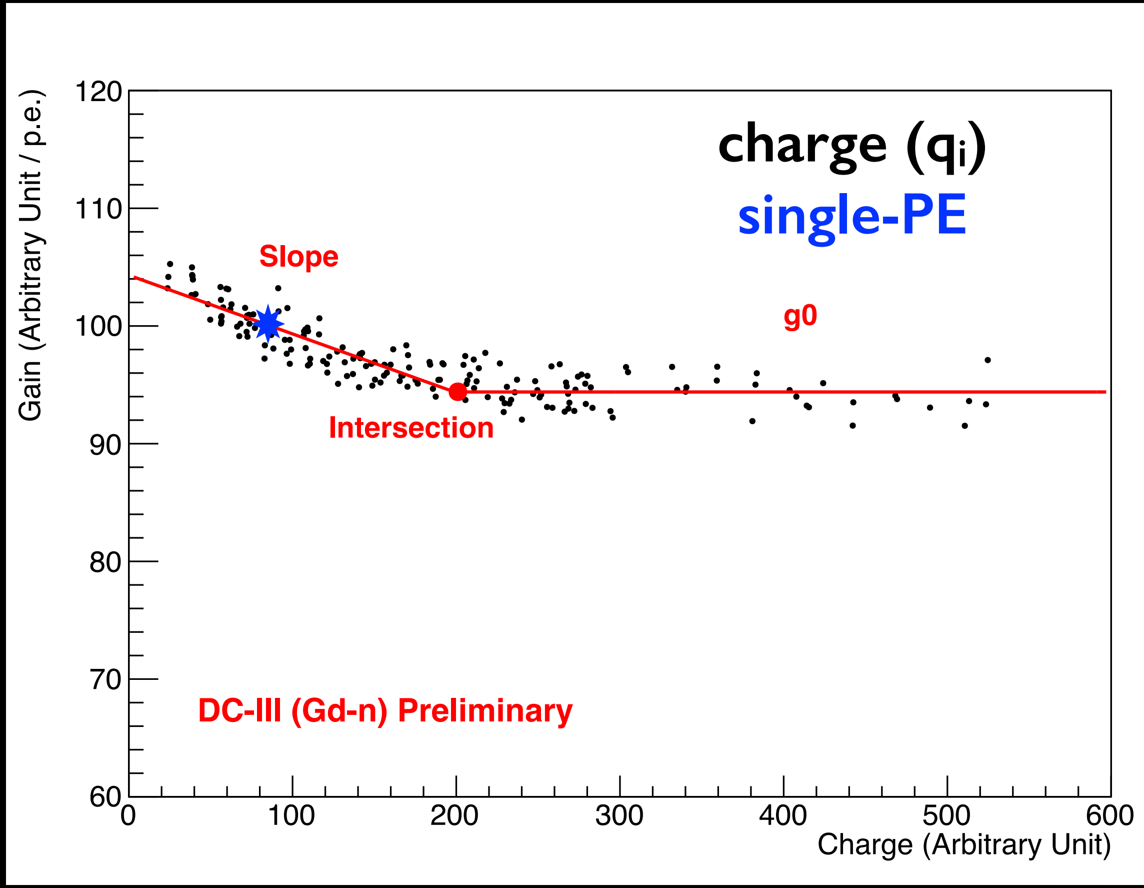
MeV definition (H-n peak @ center)

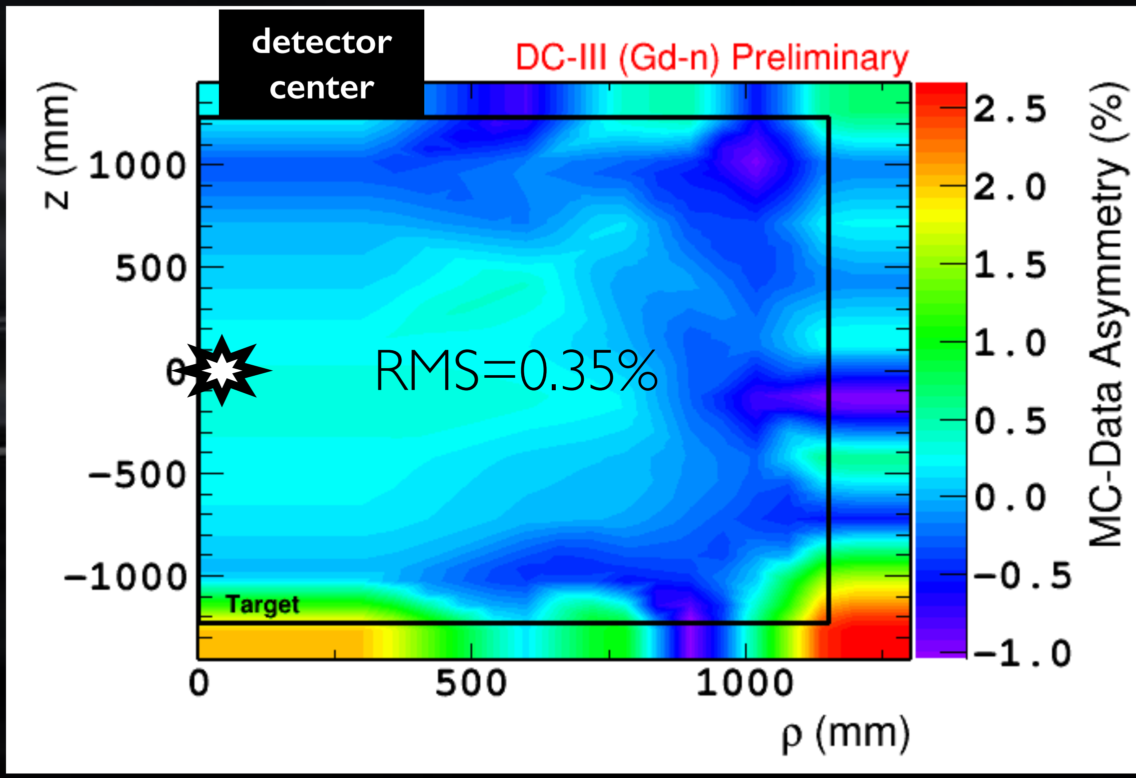
(our *standard candle*)



energy reconstruction (I)...

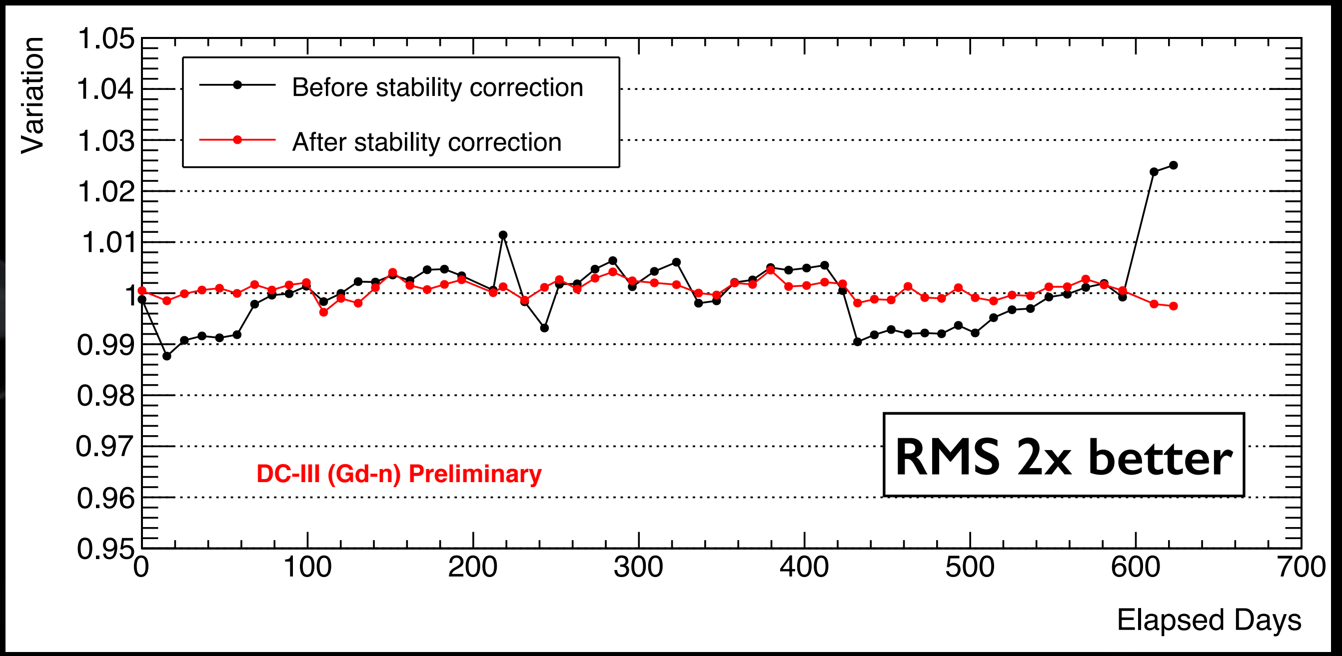
- **integrated data and MC calibration scheme...**
  - MC treated independently (as two detectors)
  - MC (no free knobs → lab measurement + calibration)
- **Linearised-PE & Alpha Calibration...**
  - def: **PE = α(PE,#PMT hit) x [Σqi x g(qi)]**
  - conversion **Q[Δ~5%]→PE[Δ≤0.5%]** @ H-n peak center
  - impact: **stability (+++)**, **linearity (++)**, uniformity (+)
  - source: gain non-linear [@electronics] + other (zeroes, etc)
- **Uniformity Calibration...**
  - def: create H-n response full volume MAP
  - conversion **PE(ρ,z)[Δ≤8%]→PE(center)** [Δ≤0.5%]
  - impact: **uniformity (+++)**
- **MeV (or absolute) Energy Calibration...**
  - conversion: PE(0,τ)→MeV(0, τ)
  - use ^{252}Cf @ (ρ=0, z=0, t=τ)→ H-n peak: 2.223MeV
  - DATA to MC equalisation (prior <0.5% agreement)

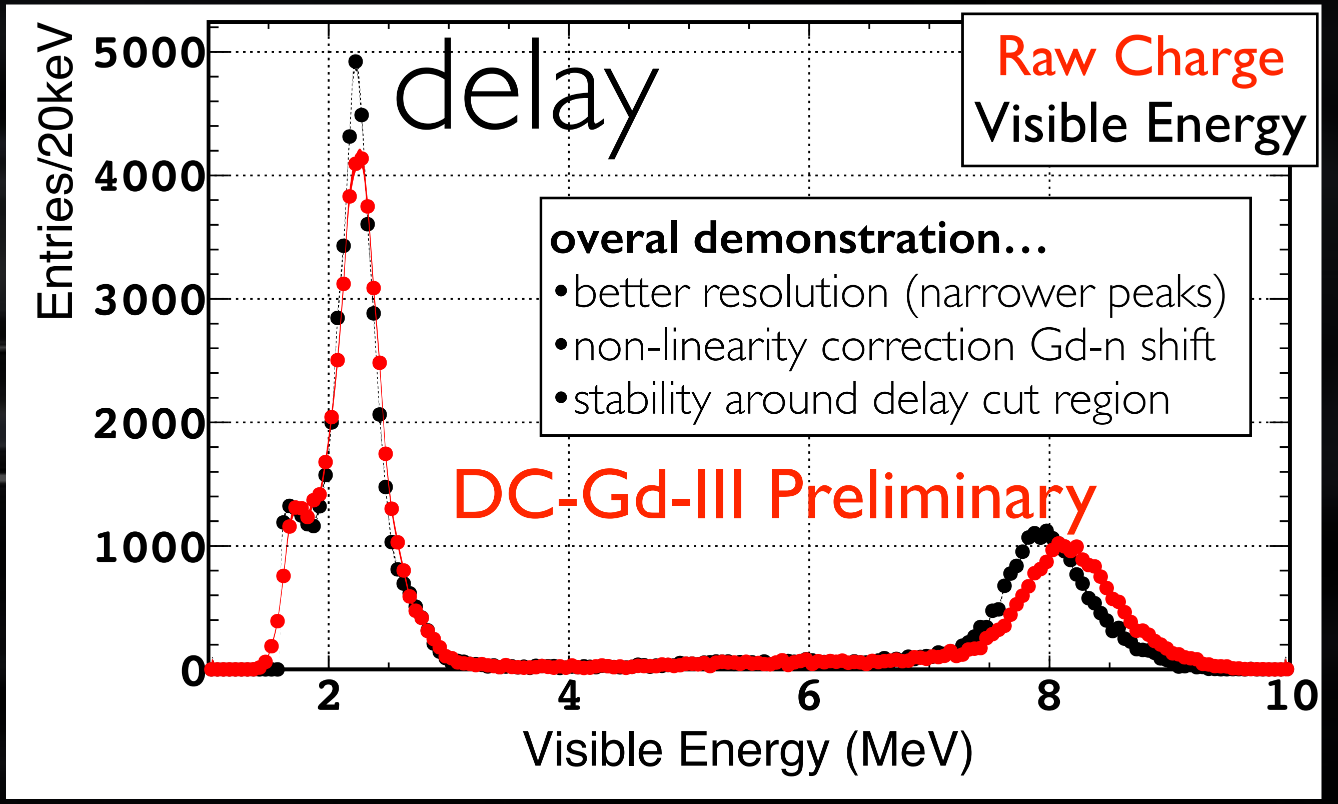




energy reconstruction (2)…

- **Drift Stability Calibration…**
  - def: **PE(t)→PE(τ)**, where **τ**: time MeV definition
  - response drift by +0.5%/years (unknown)
  - impact: **stability (+)**
- **Charge Non-Linearity Calibration…**
  - readout driven-non-linearity→ Δ(H-n,Gd-n)=~1%
  - validation with C-n peak @ 5MeV & ^{12}B spectrum
  - impact: **linearity (+)**
- **Light Non-Linearity Calibration…**
  - single-γ scintillation quenching measurement
    - many calibration sources @ center
  - conversion: **MeV(e+)→MeV(single-γ)** [only MC]
  - impact: **linearity (++)**
- **Overall performance…**
  - from Q(q,**ρ**,z,t) [RMS~10%] to MeV [RMS≤1.0%]
  - better detection systematics→ θ^{13}, BGs, Δm^2.





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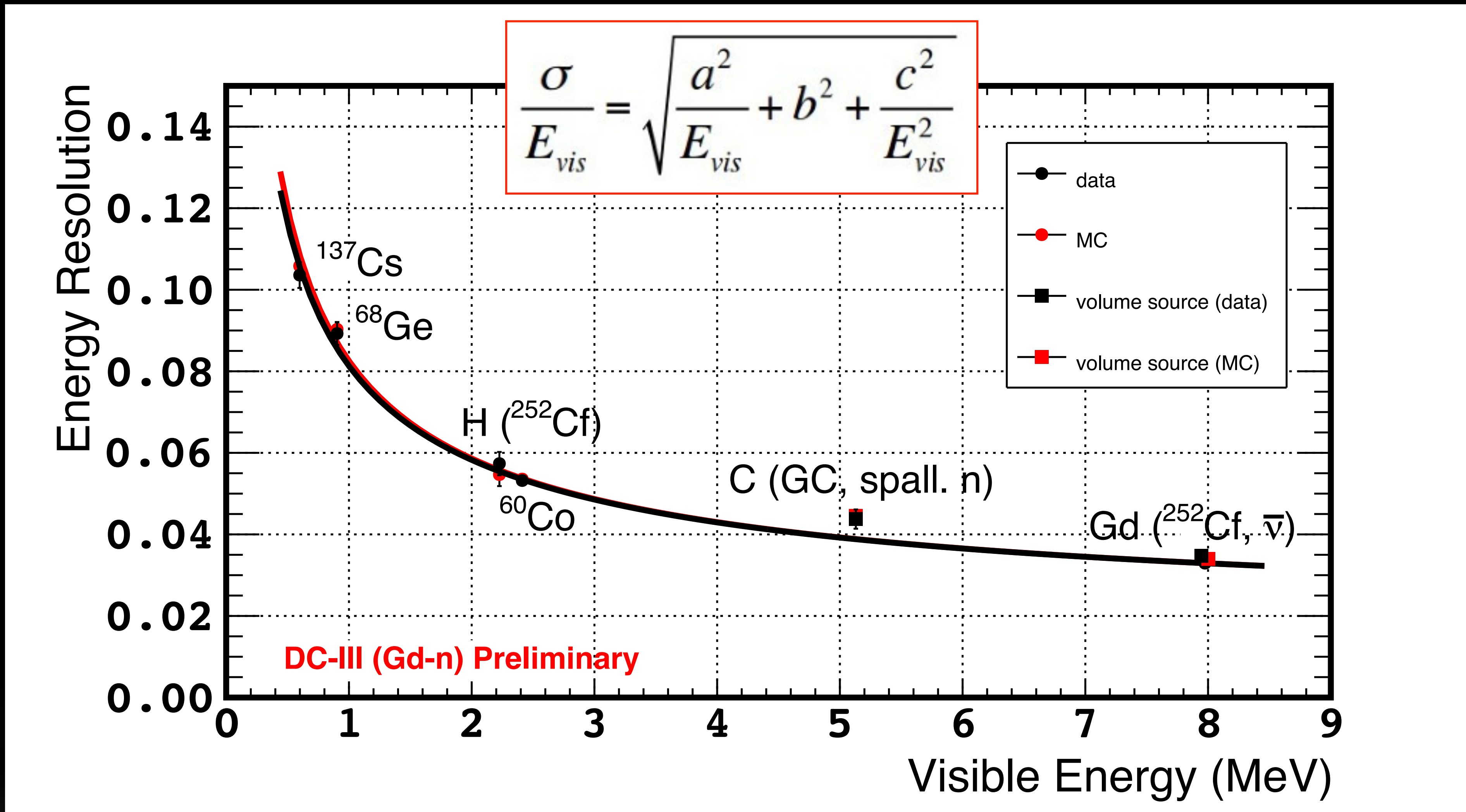
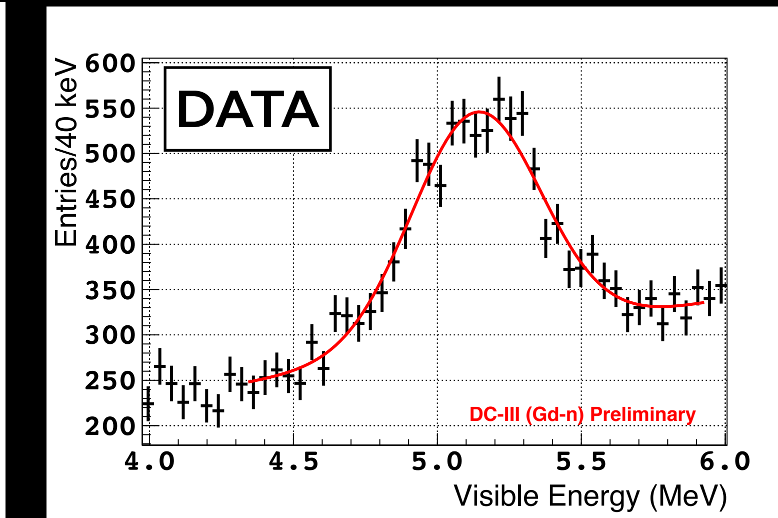
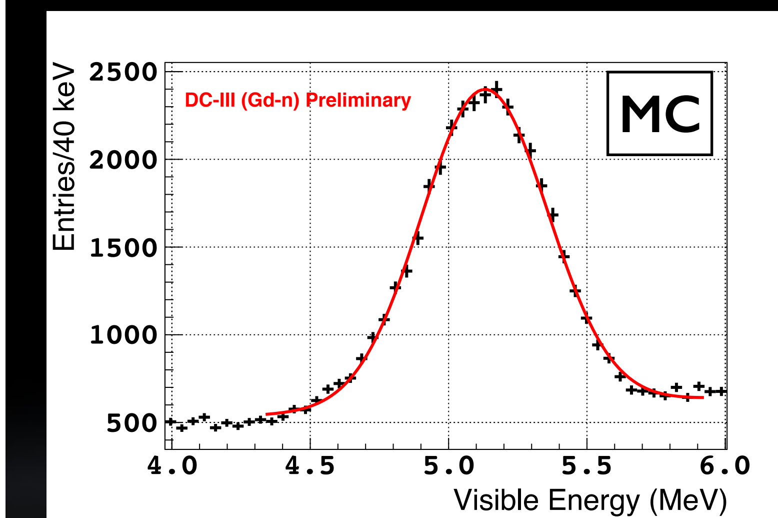
response coherence all throughout…







a: statistical term
b: constant term
c: e.g. electric noise

Data
a=0.0773±0.0025
b=0.0182±0.0014
c=0.0174±0.0107

MC
a=0.0770±0.0018
b=0.0183±0.0011
c=0.0235±0.0061

- **remarkable agreement data to MC** throughout full energy range
  - identical curves (→ no free knobs in MC)
  - most relevant region for θ_{13} is ≤4MeV
- **excellent precision:** peak position and widths (highly non-trivial)
  - true for peaks in center or anywhere in NT and GT
  - C-n peak (mainly from GC)→ slight different response in GC (worse)
- **constant term of resolution ~1.8%** (powerful calorimetry)
  - dominated by stochastic term

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our analyses (I,II and today III)...

status Gd-III improvement…

- **more statistics** (2x)
- **new selection Gd-III**
(wide-open + more efficient)
- **new energy**
(more accurate + non-linear correction)
- **new BG vetoes**
(remarkable active BG rejection)
- **all BGs measured by data (no MC)**
(reduce systematics when measuring θ_{13})

translates into

- **improvement of δ(stat)**
(better S/BG + more stats)
- **improvement of δ(BG)**
(~3x wrt Gd-II)
- **improvement of δ(detection)**
(~2x wrt Gd-II)
- **major improvement with ND**
(flux systematics now eclipses)

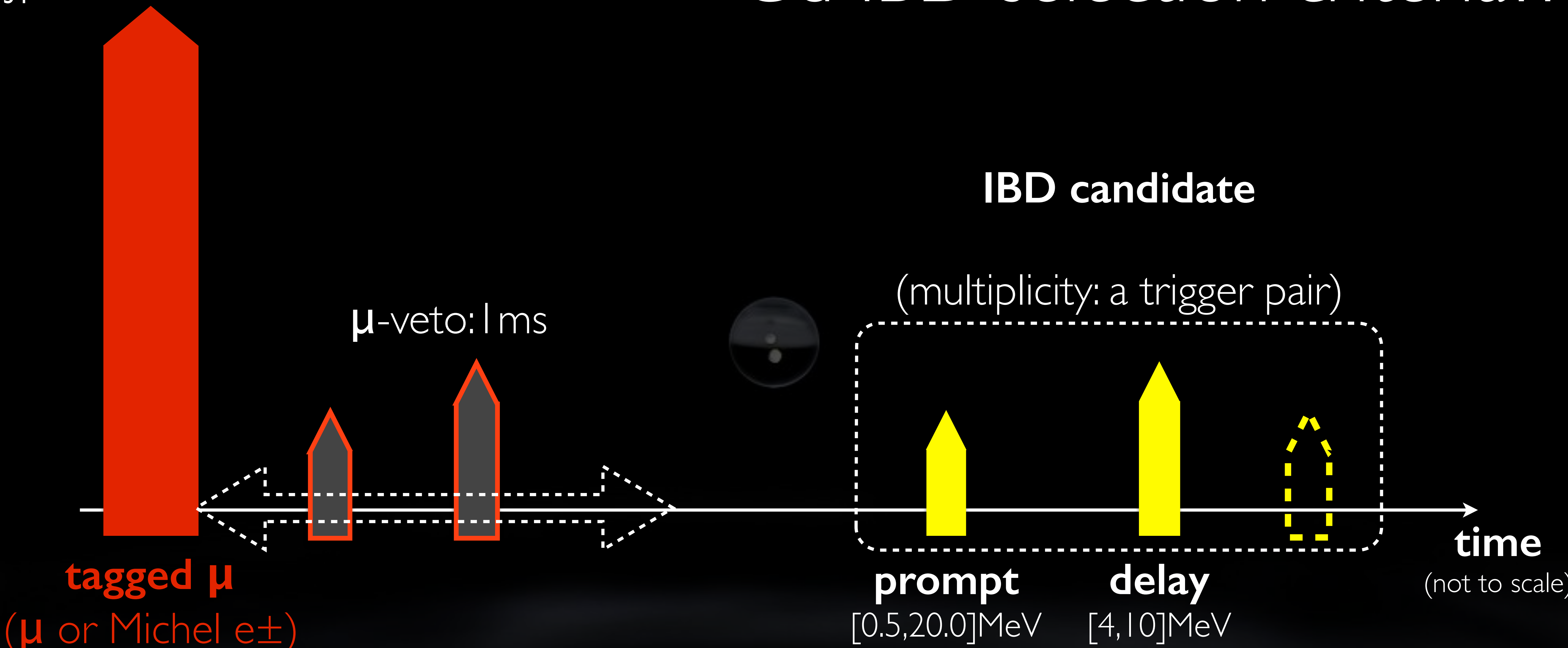
experiment systematics (nut-shell)

systematics	rate	shape **(energy spectrum)**	single detector (%)	multi detector (%)	suppression factor
δ(detection)	yes	no	0.6 **(relative to MC)**	≤0.2 **(cancellation)**	~3x
δ(flux)	yes	yes (smooth-ish)	1.7 **(relative to MC)**	0.1 **(cancellation)**	~10x
δ(BG)	yes	yes (sharp-ish)	0.3	0.3 **(no cancellation)**	none

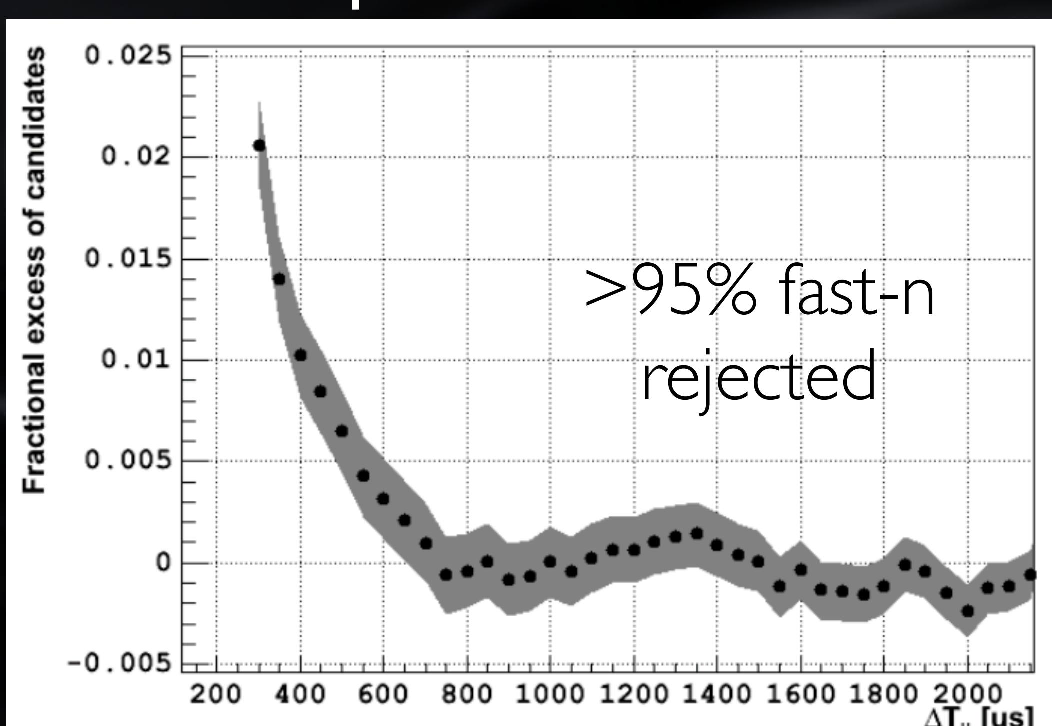
- **3 systematics** → all uncorrelated
- **multi-detector** → cancellation (large variations)
    - all errors are in the ‰ level
    - redundancy is a must (like in LEP, etc)

the new Gd-III selection…

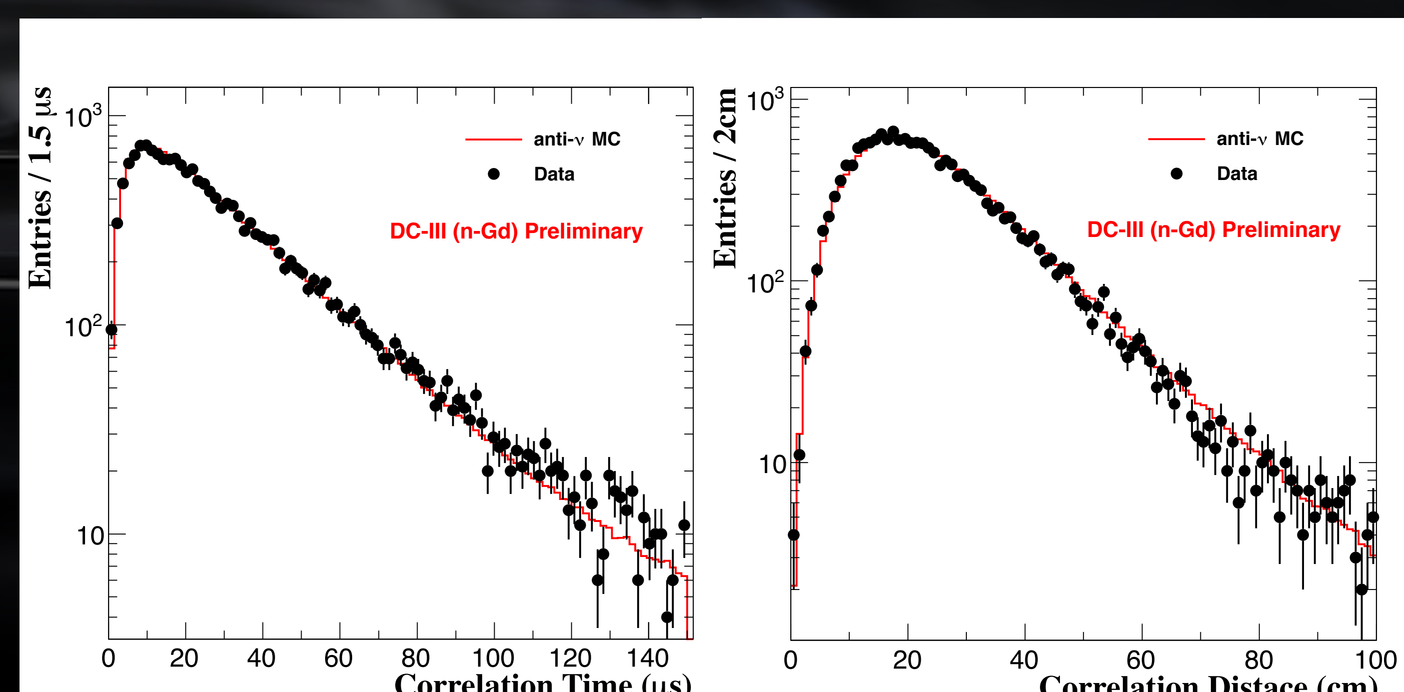
Gd-IBD selection criteria…



after-μ correlated IBDs



IBD time/space (e^+~n) correlation



selection details…

	Gd-III IBD candidate criteria
μ-tagging	Energy(ID)≥20MeV & Charge(IV)≥30k(a.u.) NEW!!
Δt(μ)	1ms
QmQt	≤0.12 NEW!!
RMS(time,charge)	2D cut NEW!!
ΔQ	30k(a.u.) NEW!!
	[0.5,150]μs NEW!!
	≤1m NEW!!
E(delay)	[4,10]MeV NEW!!
E(prompt)	[0.5,20.0]MeV NEW!!
Multiplicity	[-0.2,0.6]ms (relative to prompt) NEW!!
OV veto	yes
IV veto	yes NEW!!
FV veto	yes NEW!!
Li+He veto	yes NEW!!

μ-Veto Selection

Light Noise Selection

IBD Selection

BG Rejection

17359 IBD candidates (including BG)
no oscillation expectation: 17359 (only IBD)
467.9days

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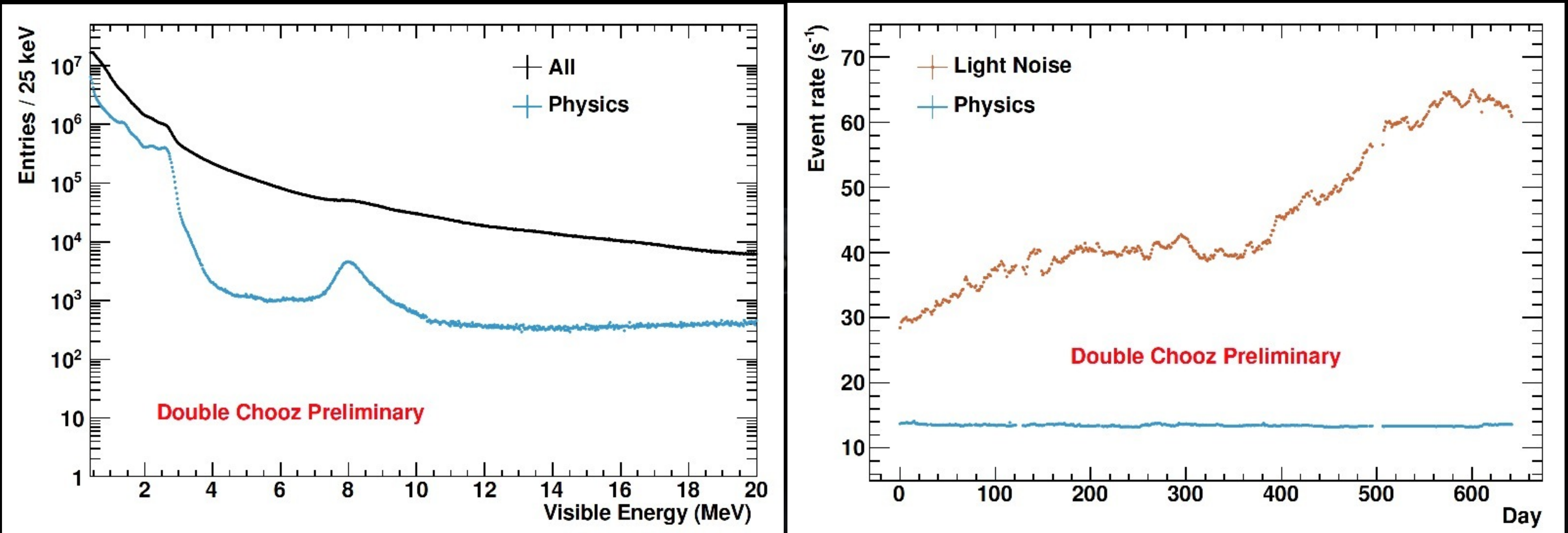
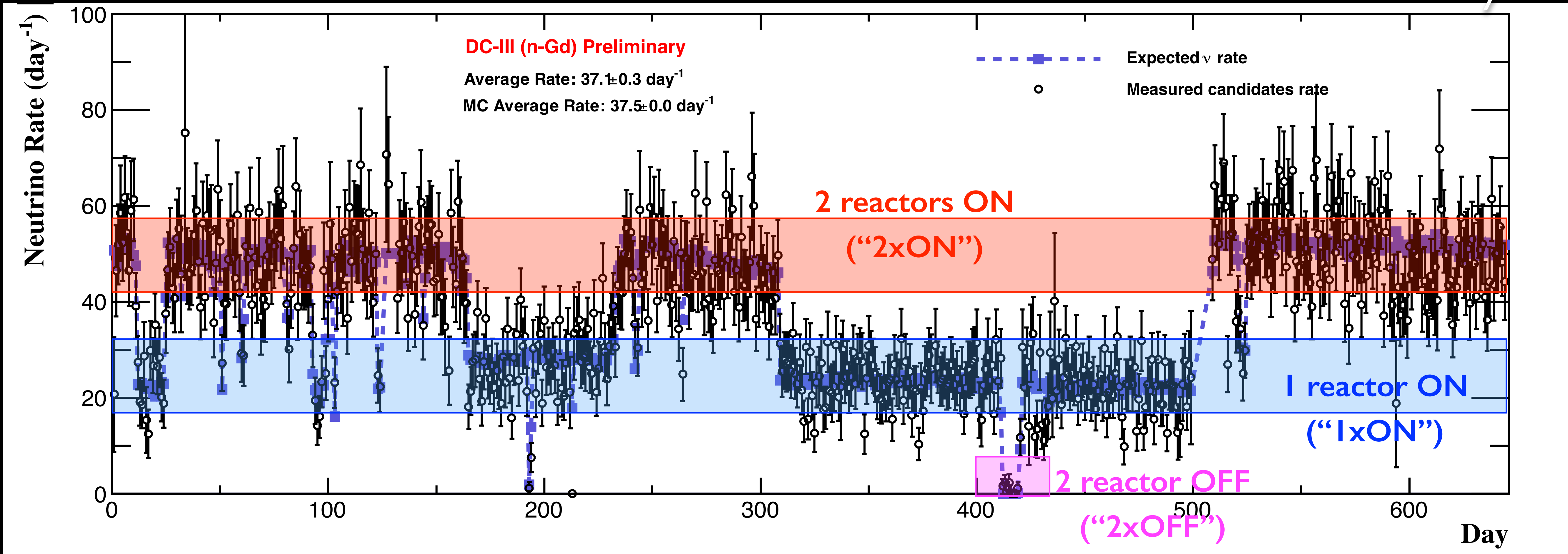
Light Noise rejection…



large (an increasing) amount of "light noise" (a few types)
(spontaneous light emission from PMT bases)

after light noise rejection (>99.9% rejection and inefficiency <0.012%)
• stable event rate (radioactivity dominated)
• clean energy spectra (>10x more light-noise than physics in trigger rate)

IBD candidates track reactor activity…

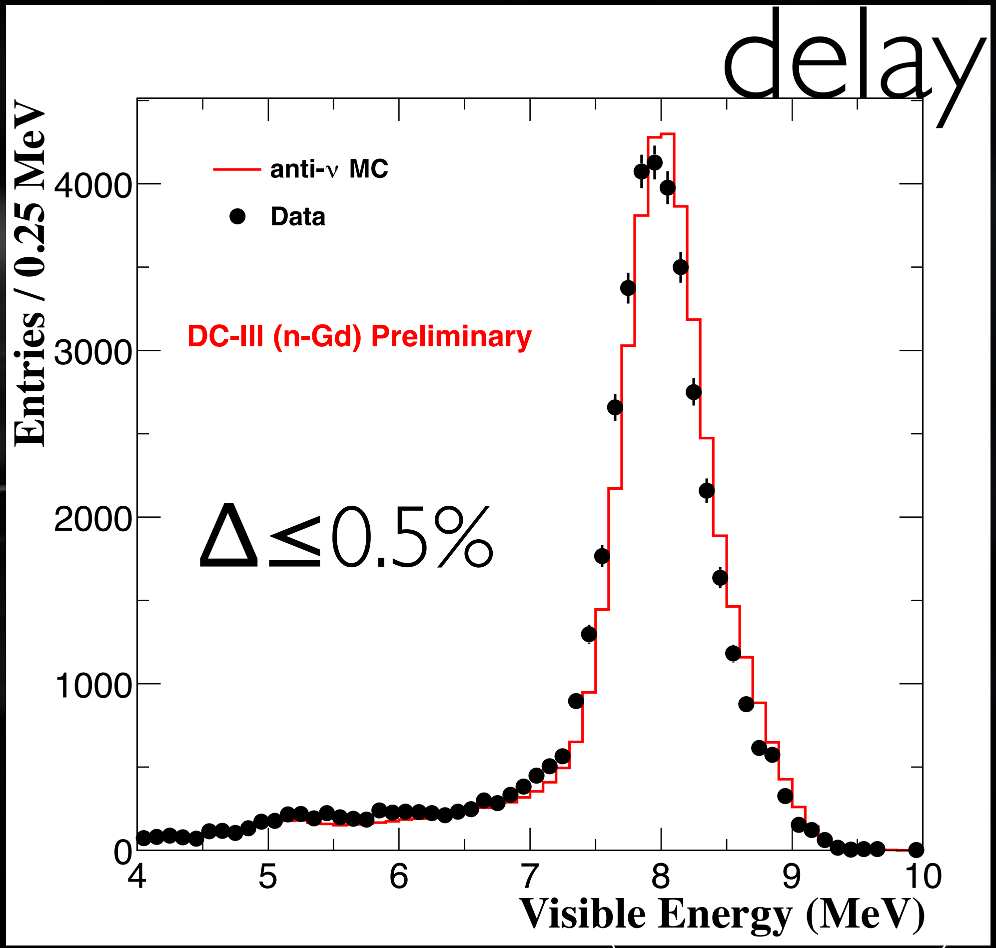


daily IBD candidate variation (no BG subtraction)

- MC uses reactor power info (100x→ negligible stats)
- accurate reactor power tracking (data~MC)

excellent data/MC agreement on Gd-n peak

- energy reconstruction (dominating still?)
- Gd multi-γ de-excitation physics model
    - scintillator quenching (non-linearity)
- n-capture physics model (thermalisation)



flux systematics…

Bugey4 our "near" detector now…

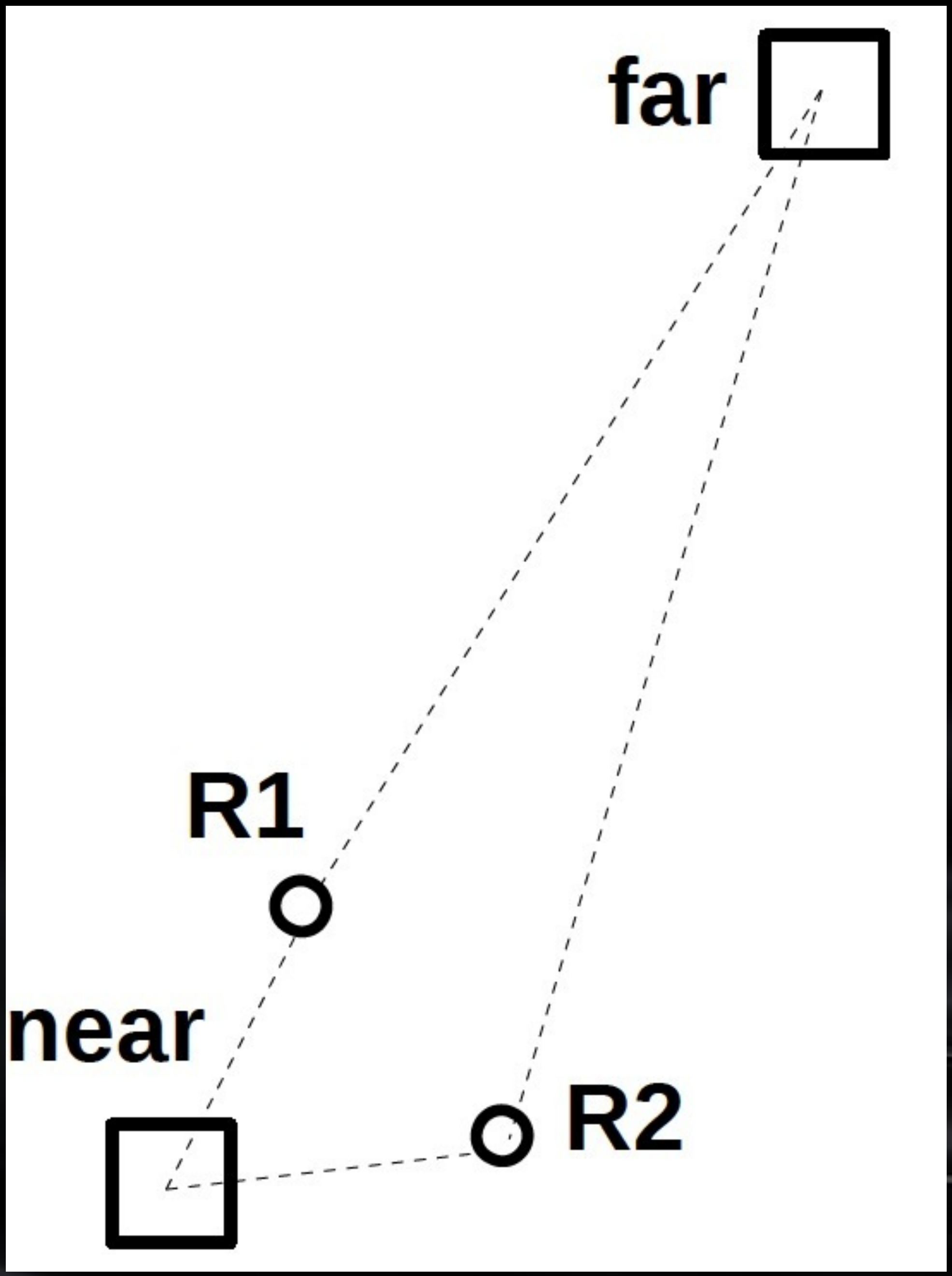
DC used Bugey as effective ND (via MC)

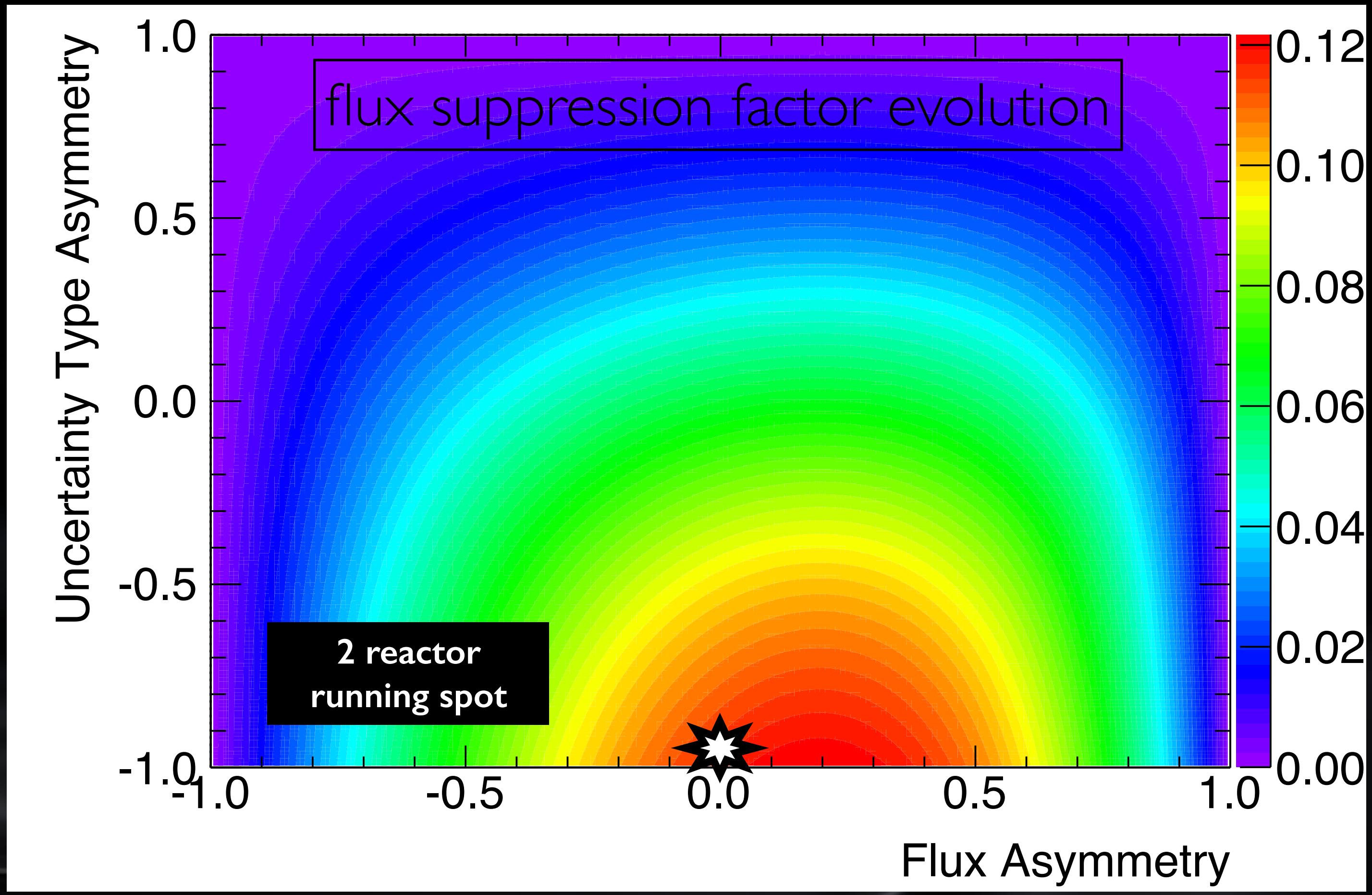
(technique reduces ~30% the dominant flux uncertainty→ used by KamLAND, etc)

major δ(flux) cancellation (with ND)...

DC most isoflux experimental setup

$\Longrightarrow$ ~90% δ(flux) suppression





reactor error correlations → δ(flux) suppression

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

“Reactor Induced Systematics for Multi-Detector 13 Experiments”
Cucoanes, Novella, Cabrera et al. (**preparing for submission**)

detection systematics…

δ(detection) systematics budget…

component	efficiency	error (FD only)	error (FD+ND)
1ms μ veto (offline)	95.5%	<0.1%	<0.1%
DAQ & Trigger	100.0%	<0.1%	<0.1%
vetoes inefficiency	99.3%	0.1%	<0.1%
IBD selection	98.9%	0.2%	<0.2%??
Spill in/out (MC)	100.0%	0.3%	<0.1%
Gd Fraction	97.5%	0.4%	<0.1%
Scintillator Proton#	100.0%	0.3%	<0.1%
total	91.5%	**0.6%**	**0.2%**

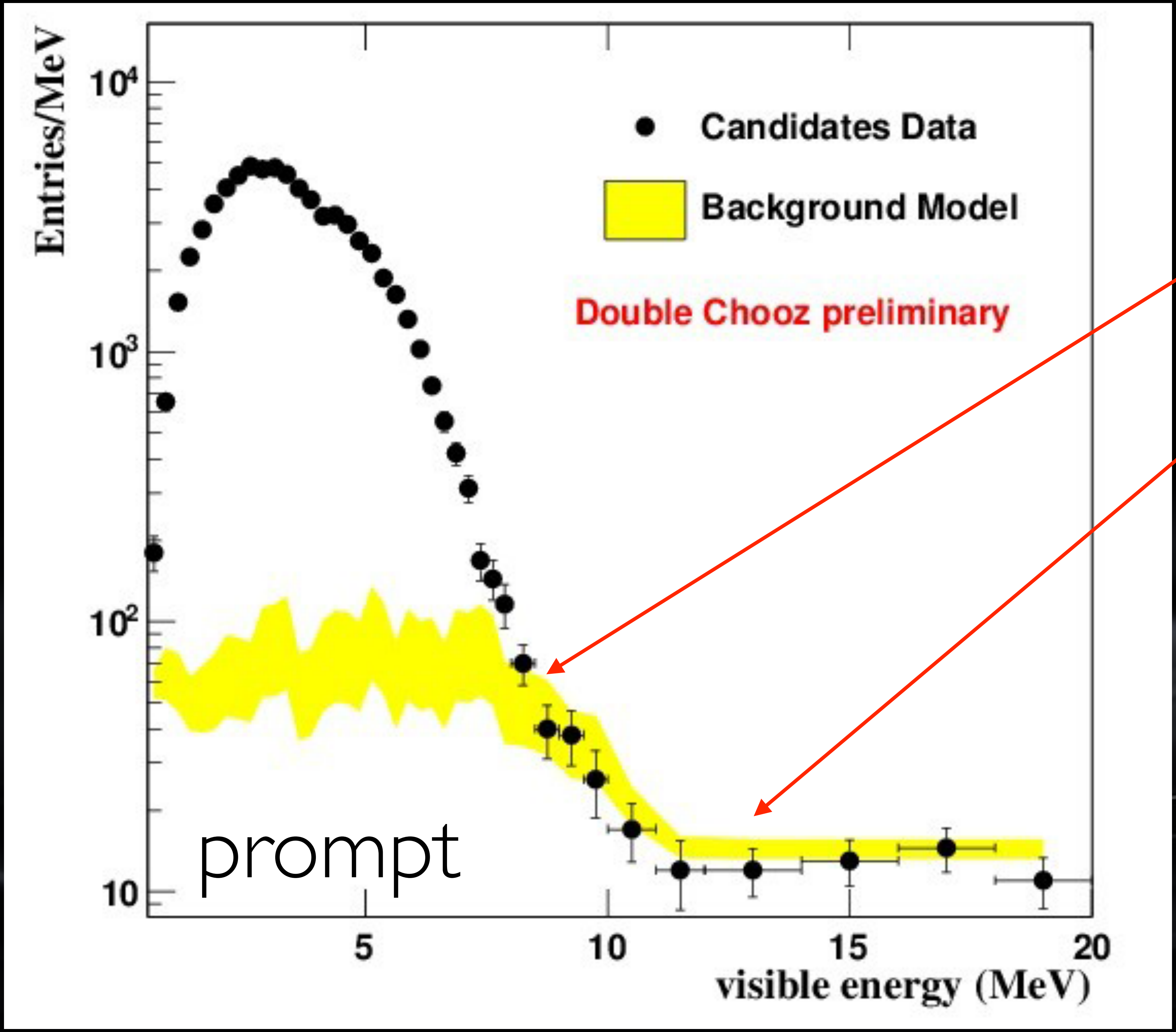
δ(detection)$^{\text{FD only}}$ = 0.63%

- **~0.5%** dominated by MC inaccuracies (major ND cancellation→ no MC)
- **~0.3%** N_{proton} (major ND cancellation→ same scintillator)
- some cancellation since functionally identical detectors (response, acceptance, etc)

δ(detection)$^{\text{FD+ND}}$→ 0.2% (seems feasible) [à la Daya Bay]

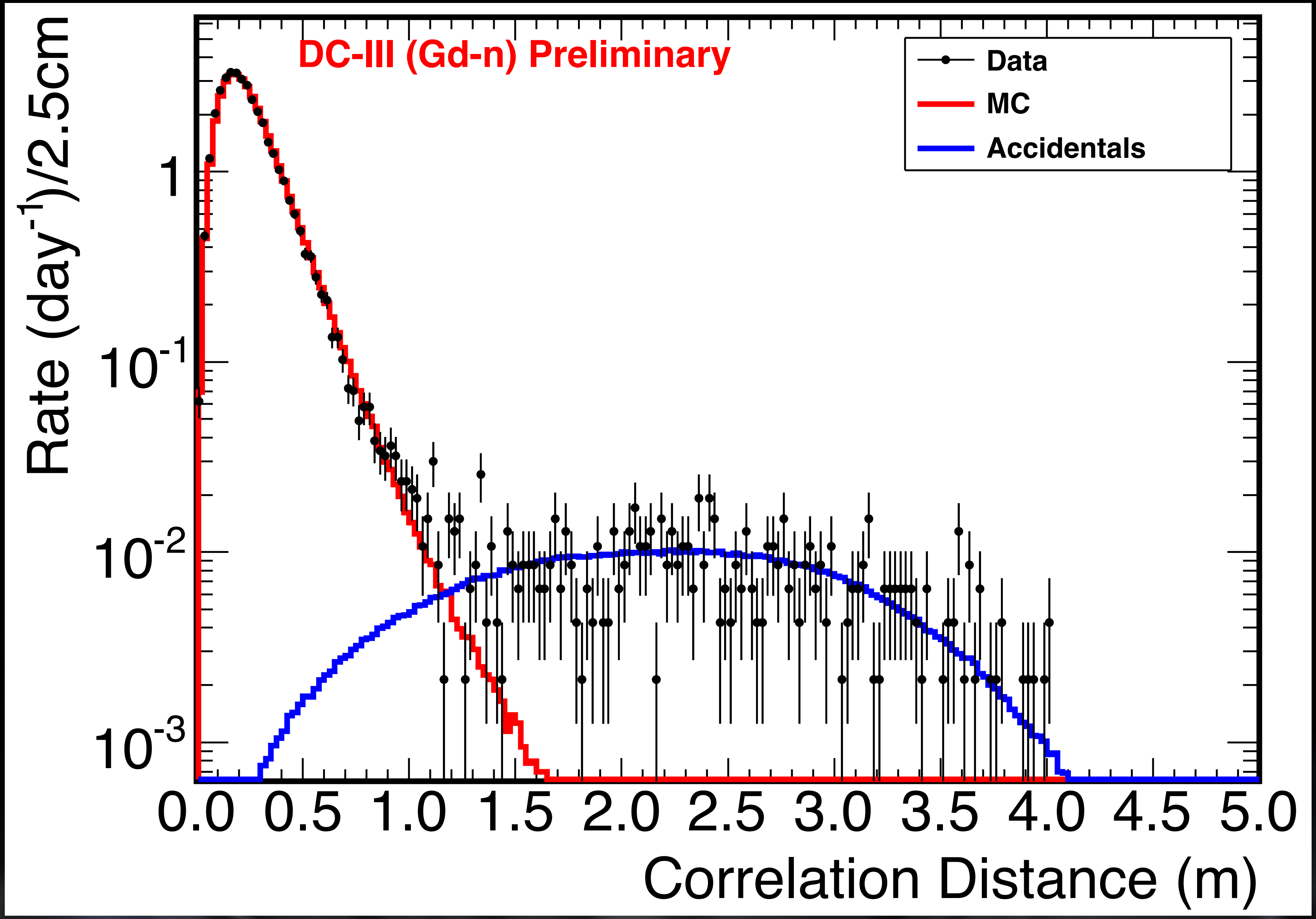

BACKGROUNDs

our background (BG) model…



- **^{9}Li (+ a little ^{8}He)**
  (dominant & knowledge @ 20%)
- **fast-n (+ little stopped-μs)**
  (still visible & knowledge @ <10%)
- **stopping-μ:** ~fully rejected
- **all the rest negligible**
  - accidentals
  - $^{13}C(\alpha,n)^{16}O$
  - ^{12}B related

DC goes accidentals-less…



e^+~n correlation distance → >10x rejection on accidental BG

S/BG(accidental)<0.2% (negligible)

wide-open selection (→3x less IBD inefficiency wrt DC-Gd-II)

heavily studied for long (→ spatial reconstruction + detector model dependence): negligible

(excellent spatial-reco tuning) sharpest distribution + spectacular data/MC agreement

(**IBD inefficiency @ 1m <0.4%**)

BGs @ DC…

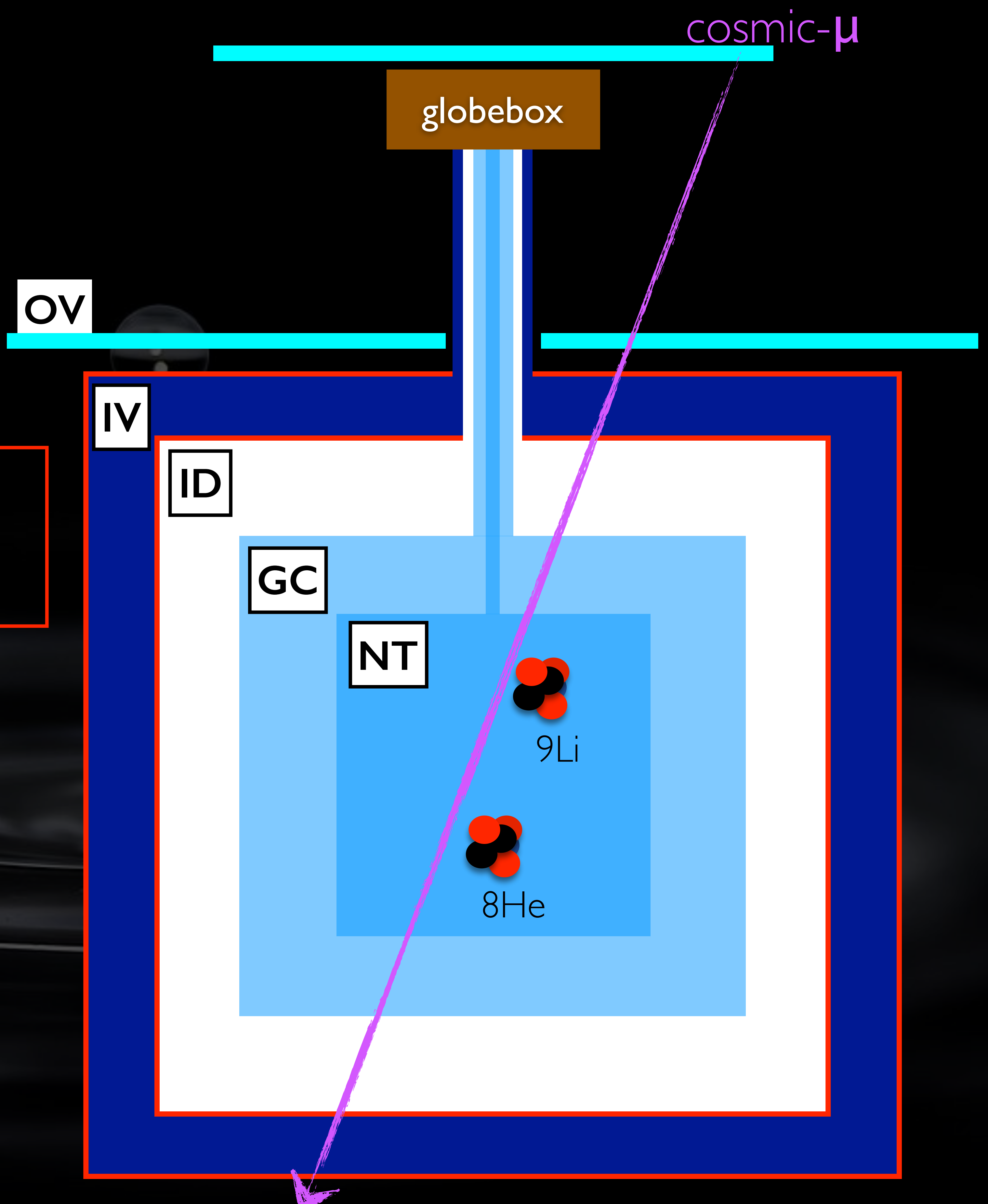
- (one way another) **all BG related to μ's**

⟹ μ-veto is starting point

- existence BG→ missed the μ-correlation
  - **μ beyond acceptance**
  - **μ correlation untraceable**

DC BGs (must have ≥1 n in final state)

- **Li+He** (by μ-spallation)
  - unstable isotope decay: β-n
  - **tagging:** trace the progenitor μ
- **fast-n** (by μ-spallation nearby)
  - many n's together upon μ
  - **tagging:** sub-sample (characterise)
- **stopped-μ** (by μ and decay $e^{\pm}$)
  - acceptance hole in chimney
  - **tagging:** sub-sample (characterise)
- **accidental** (by radioactivity + fast-n)
  - no space/time correlation (easy)
    - space/time correlation→reject
  - **measure:** time/space uncorrelated



all about ^{9}Li (the rest is ~negligible)…

BG	rate (day	shape	energy range	S/BG (%)	δ(BG) (%)	suppression (wrt Gd-II)
9	**0.97**	data (Li+He tag)	[0,12]MeV	2.6	**0.78**	1.3
fast-n stopped-μ	**0.60±0.05**	data (IV tag)	[0,20]MeV	1.6	0.13	1.9
accidental	0.070±0.005	data (off-time)	<3MeV	0.2	0.01	3.7
12	<0.003@68CL	neglected	[0,13]MeV	-	-	>7.0
13	<0.1	neglected	<2MeV	-	-	same

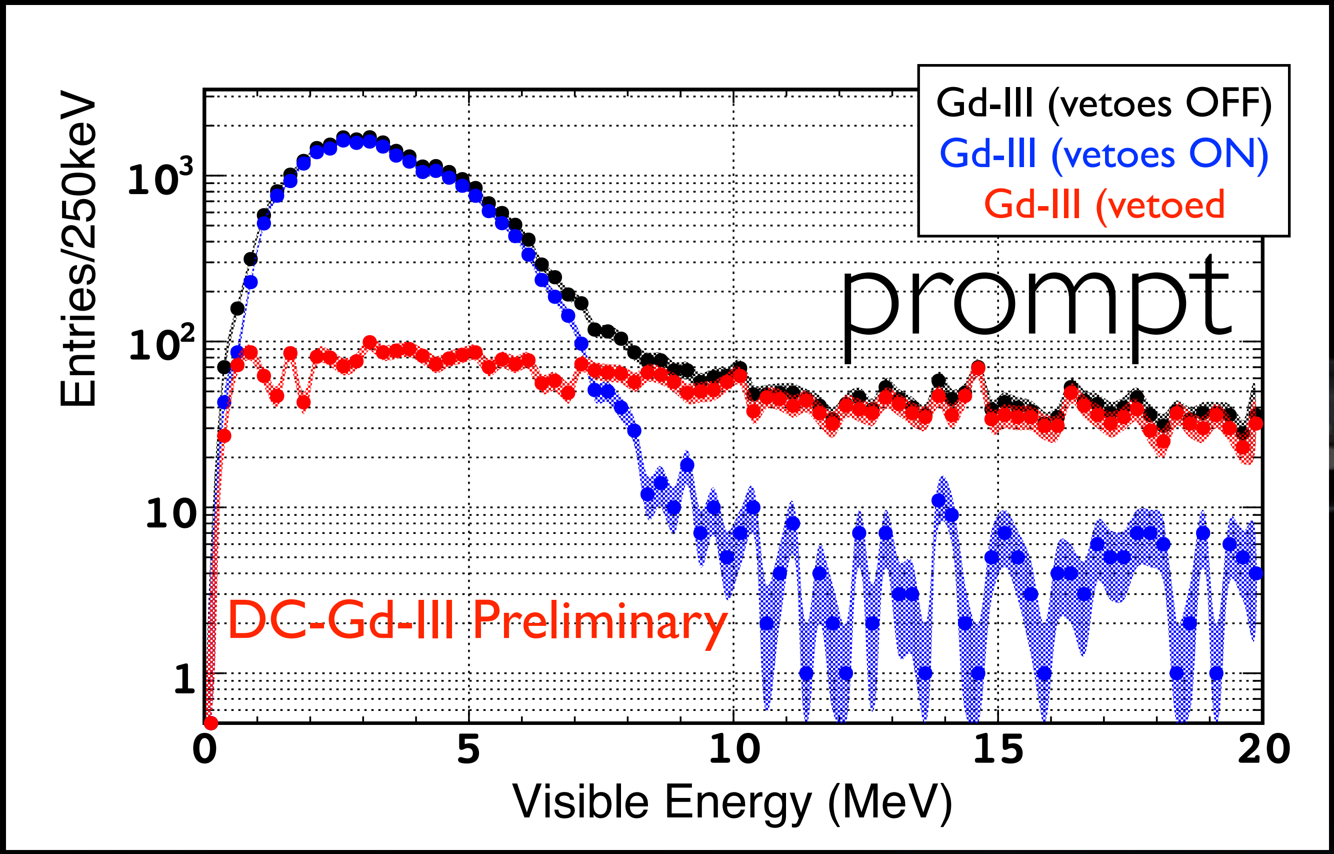
Li+He (He ≤10%) dominates BG systematics budget by >90%

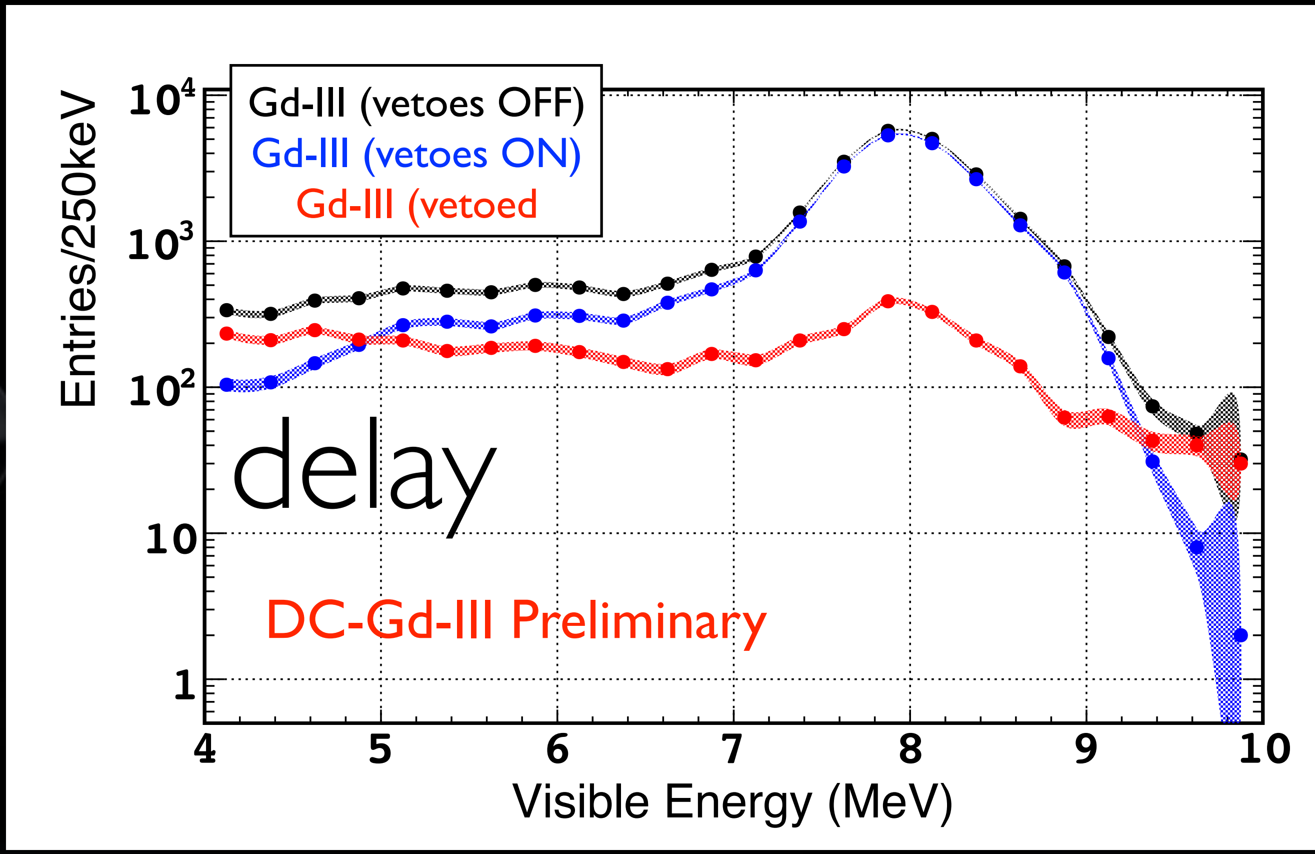
(energy spectrum data-driven→ poor statistics)

all other BG becoming negligible→ DC-III = IBDs + ^{9}Li (effectively)

(fast-n is high but well know spectrum makes it innocuous)

our BG active BG rejection vetoes…





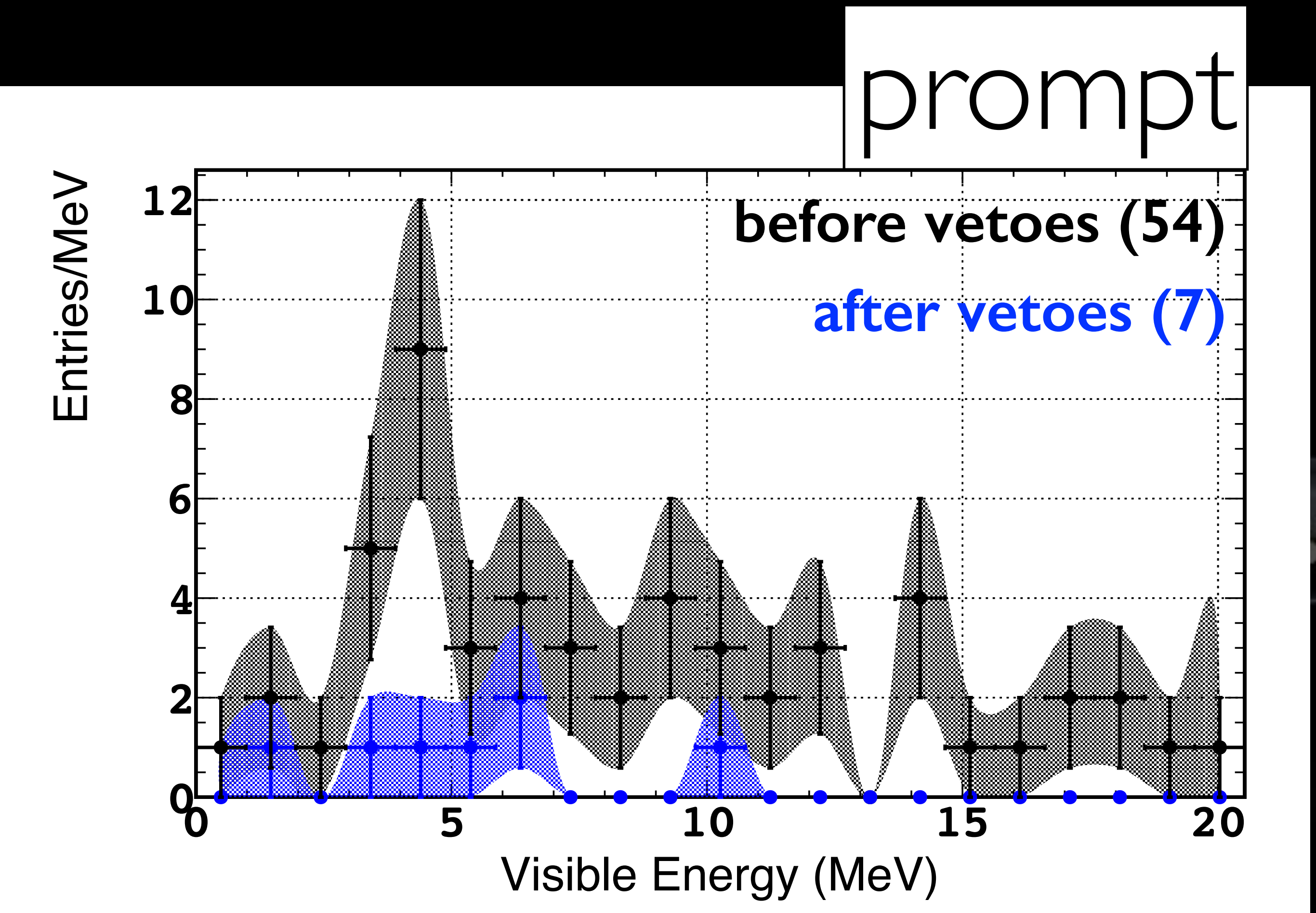
veto efficiency (%)	absolute (per veto)	uncorrelated fraction	relative (with all other vetoes)
IV veto	24	7	40
OV veto	62	7	41
FV veto	71	**19**	66
all vetoes	**90**	**33**	

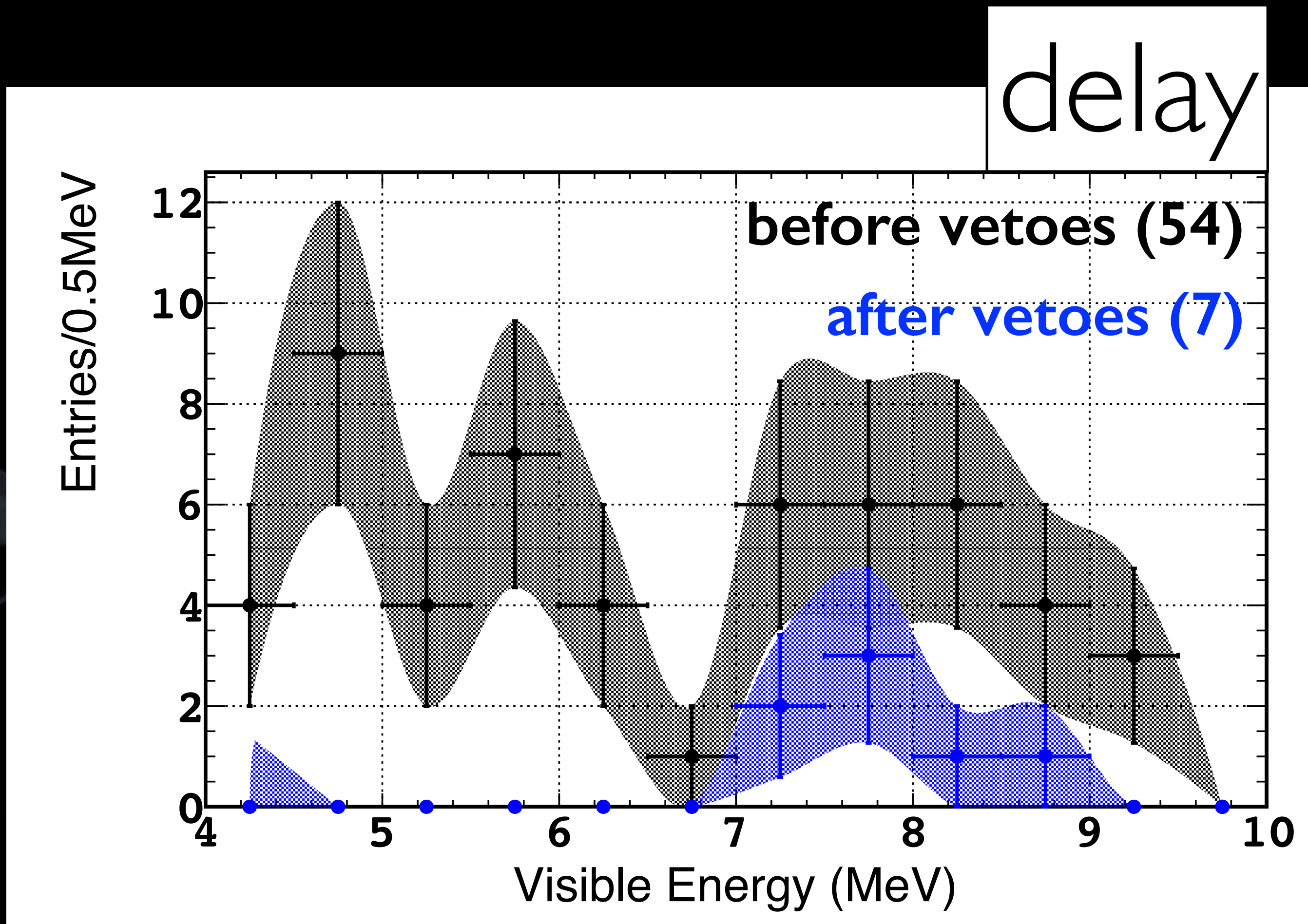
Power(rejection) ~90%, estimated [12,20]MeV (high redundancy)

(VERY unusual for LS detector→ a volume of liquid flashing)

Anatael Cabrera (CNRS-IN2P3 & APC)

reactor 2xOFF data…





2xOFF data: powerful information before/after veto evolution

(scrutinising a few event-wise BG-only)

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

P(rejection)=(7.7±3.1) @ Gd-III

(in agreement with (9.9±1.0) estimated between [12,20]MeV)

Gd-III measurement of θ_{13}…

Anatael Cabrera (CNRS-IN2P3 & APC)

- (R+S) **rate+shape analysis** (**baseline**)
  - (**++**) exploit full spectra and E/L signature of θ13 (ν-oscillations)
  - (**±**) BG model dependent (hard not to)→ need to measure BG before (data ON)
    - (**++**) better BG estimation→ higher precision on θ13
    - (**++**) includes 2xOFF data (pure inclusive BG: no model)
- (RRM) **reactor rate modulation analysis** (**baseline**)
  - (**++**) exploits 100% variations reactor power @ Chooz [only @ Chooz]
  - (**++**) measure **inclusive BG** (no model input or 2xOFF data)
    - (**++**) includes 2xOFF data (pure inclusive BG: no model)
    - (**±**) BG model dependent→ added precision(!!)
  - (**unique DC**) remarkable cross-check θ13 with and without BG model
- (RO) **rate-only analysis** (**cross-check only**)
  - (**-**) BG model dependent (hard not to be)→ need to measure BG before (data ON)
    - (**++**) include 2xOFF data too

systematics recapitulation…

systematics	DC-Gd-II (%)		DC-Gd-III (%)	
δ(flux)	1.7		1.7	
δ(detection)	1.0		**0.6**	
exposure (days)	227.9 (8249 IBDs)		467.9 (17358 IBDs)	
δ(BG) (input | output)	1.6	0.9 (R+S) 1.1 (RRM)	0.8	**0.3** (R+S) **0.5** (RRM)

RRM input

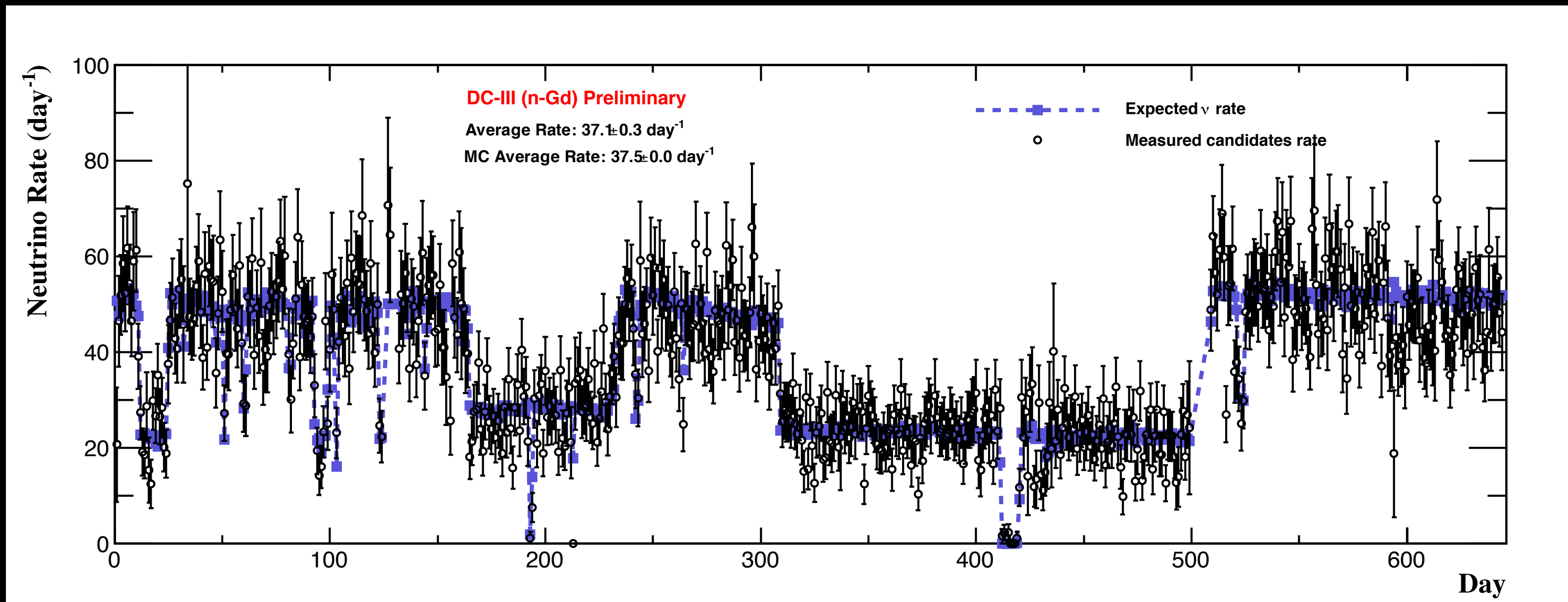
R+S input

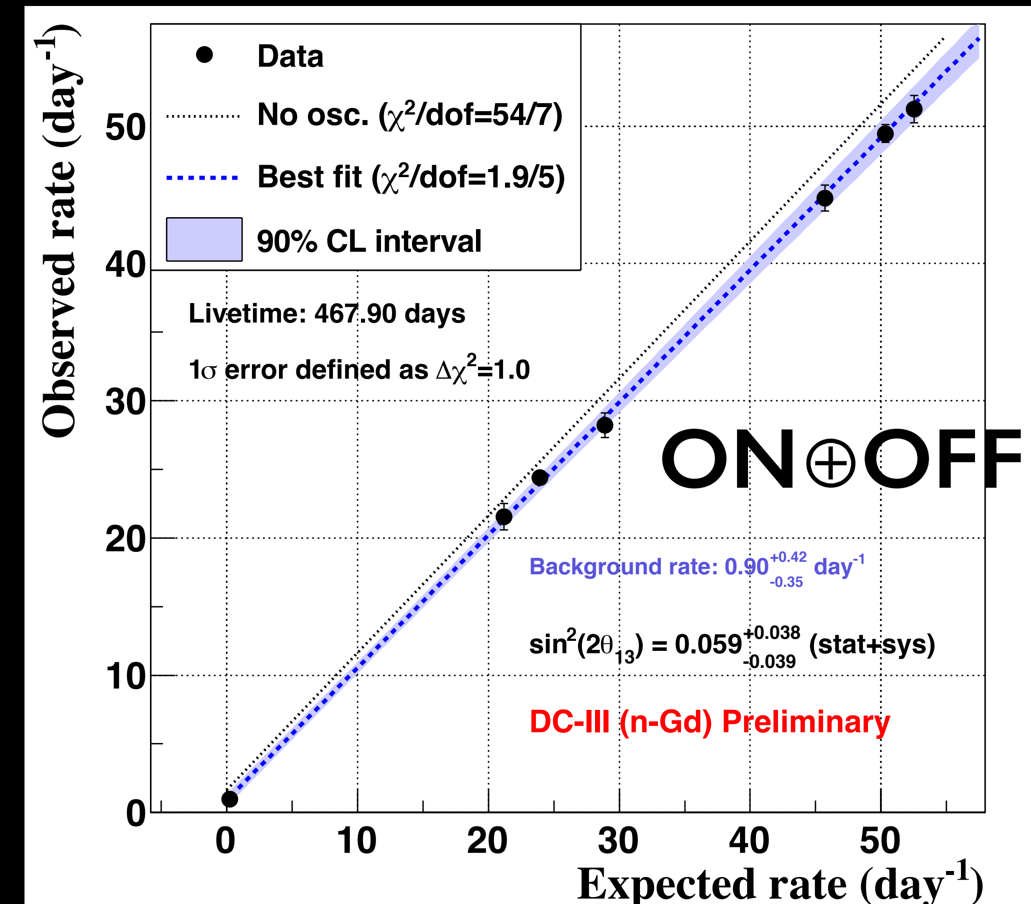
δ(BG) independent estimation: no spectral info used

⟹ input to R+S (mandatory) and RRM (optional)

δ(BG) re-estimated by both R+S (spectra) and RRM

RRM analysis…



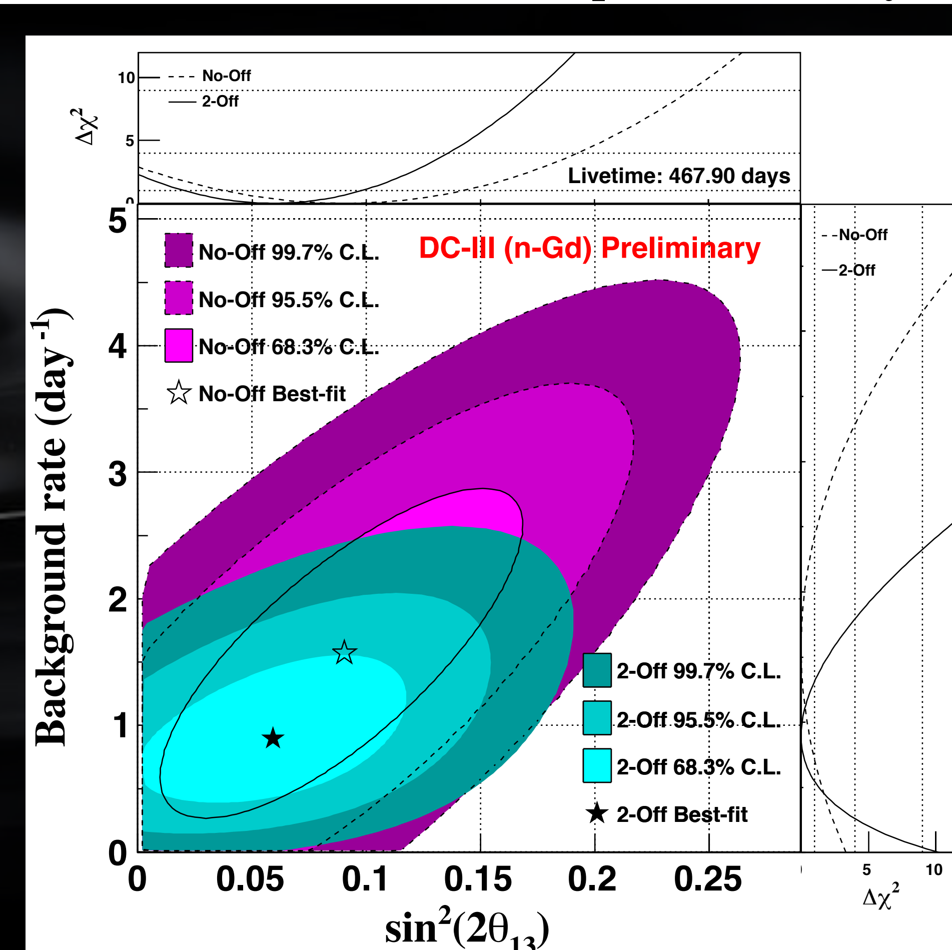


- exploit our 100% variations in reactor power…
  - **measure BG and $\sin^2(2\theta_{13})$ simultaneously**
  - **BG is inclusive**→ account for unknown contributions

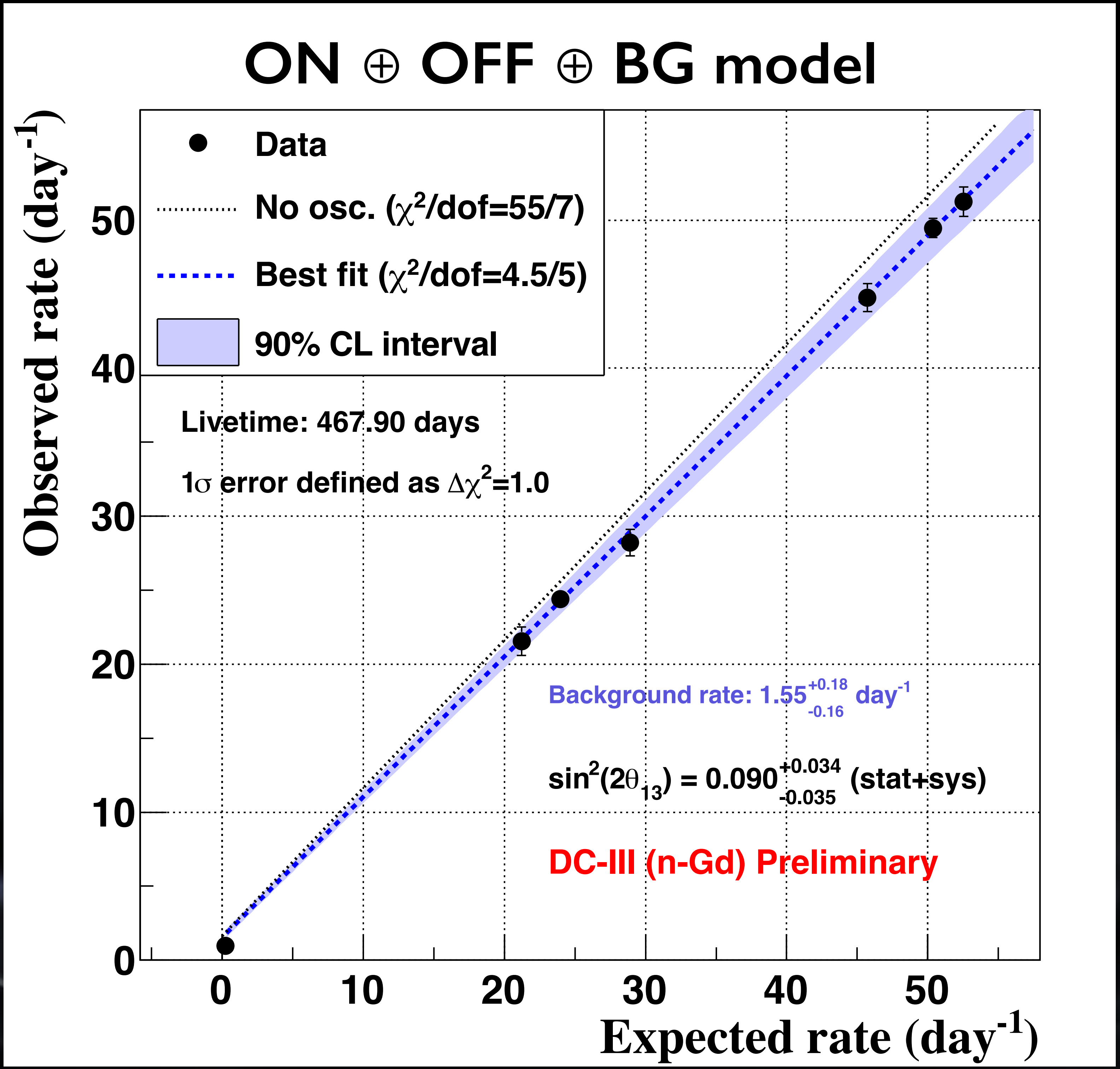
    ⟹ BG measurement without BG model
- (trivial) fit is straight line…
  - **$BG^{inclusive}$**→ intercept
  - **$\sin^2(2\theta_{13})$**→ slope
- additionally, aid fit with extra BG constraints (pulls)…

  +2xOFF data (independent $BG^{inclusive}$ measure)
  - provide a precious precise BG model cross-check
    - successful validation <1.5σ agreement

  +BG estimation (introduce BG model dependence)
  - even more precision (once validated coherent)



the ultimate RRM results…

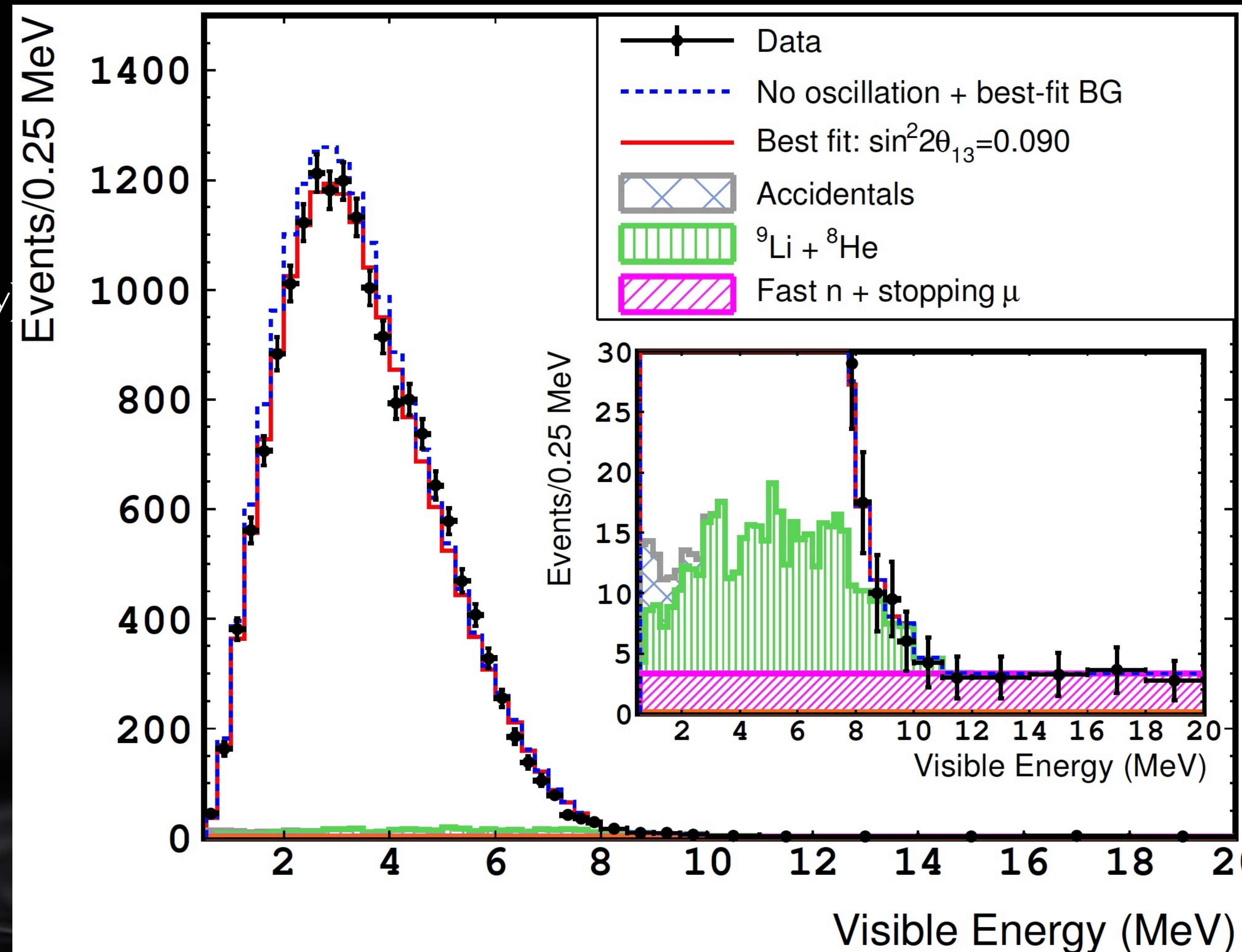


most precise rate-only (→i.e. not spectral info used)

(complementary to R+S although correlations exists)

R+S results…

- many improvements…
  - NEW!! • 250keV binning and [0.5,20]MeV
  - NEW!! • **BG fully data driven** (first time)
- **signal treatment…**
  - NEW!! • new spectrum with ^{238}U (low energy)
  - Δm^2 from MINOS (+ T2K)
- **BG treatment…**
  - NEW!! • 2xOFF data constraint (extra bin)
  - **accidental pull term**
    - NEW!! • **rate:** syst. dominated
    - **shape:** data measured
  - **fast-n pull term** (~no stopping μs)
    - **rate:** stats dominated
    - **shape:** data measured
  - **Li+He pull term**
    - NEW!! • **rate:** stats driven
    - NEW!! • **shape:** data measured (no MC!!!)
  - negligible ^{12}B and BiPo
- **energy treatment…** NEW!!
  - e+ energy model (via tuned MC)
  - scintillator non-linearity (3 parameters)

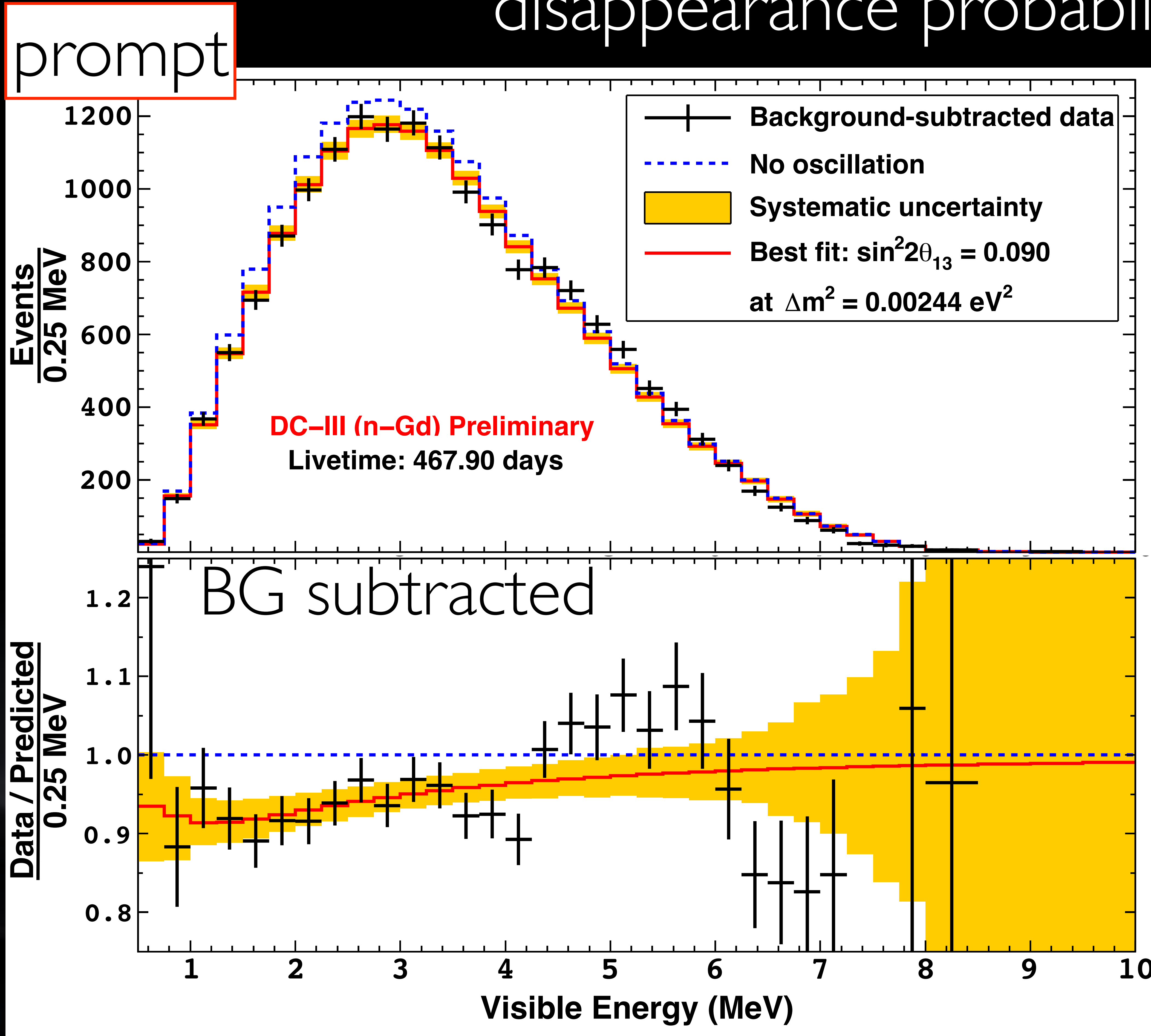


$\sin^2(2\theta_{13})=(0.09\pm0.03)$

(χ^2/n.d.f. = 51.4/40)

δ(BG)^{III} ~3x time better than DC-II

disappearance probability…



R+S results…(2)

Parameter	Input C.V.	Input Error	Output C.V.	Output Error
E-scale a'	-0.027	0.006	-0.026	$+0.006, -0.005$
E-scale b'	1.012	0.008	1.011	$+0.004, -0.007$
E-scale c'	-0.0001	0.0006	-0.0006	$+0.0006, -0.0005$
FN+SM rate (d^{-1})	0.60	0.05	0.56	0.04
Li+He rate (d^{-1})	0.97	$+0.41, -0.16$	0.80	$+0.15, -0.13$
Accidentals rate (d^{-1})	0.0701	0.0054	0.0708	0.0053
Residual $\bar{\nu}_e$	1.57	0.47	1.49	0.47
Δm^2 (10^{-3} eV^2)	2.44	$+0.09, -0.10$	2.44	$+0.09, -0.10$
$\sin^2 2\theta_{13}$	—	—	0.090	$+0.033, -0.028$
χ^2/d.o.f.	—	—	51.4/40	—

remarkable improvement of Li+He constraint using spectral information (aided by rate)
→ lower rate and more precise (improve S/BG too)

all results consistent between input and output (no tensions >1σ)

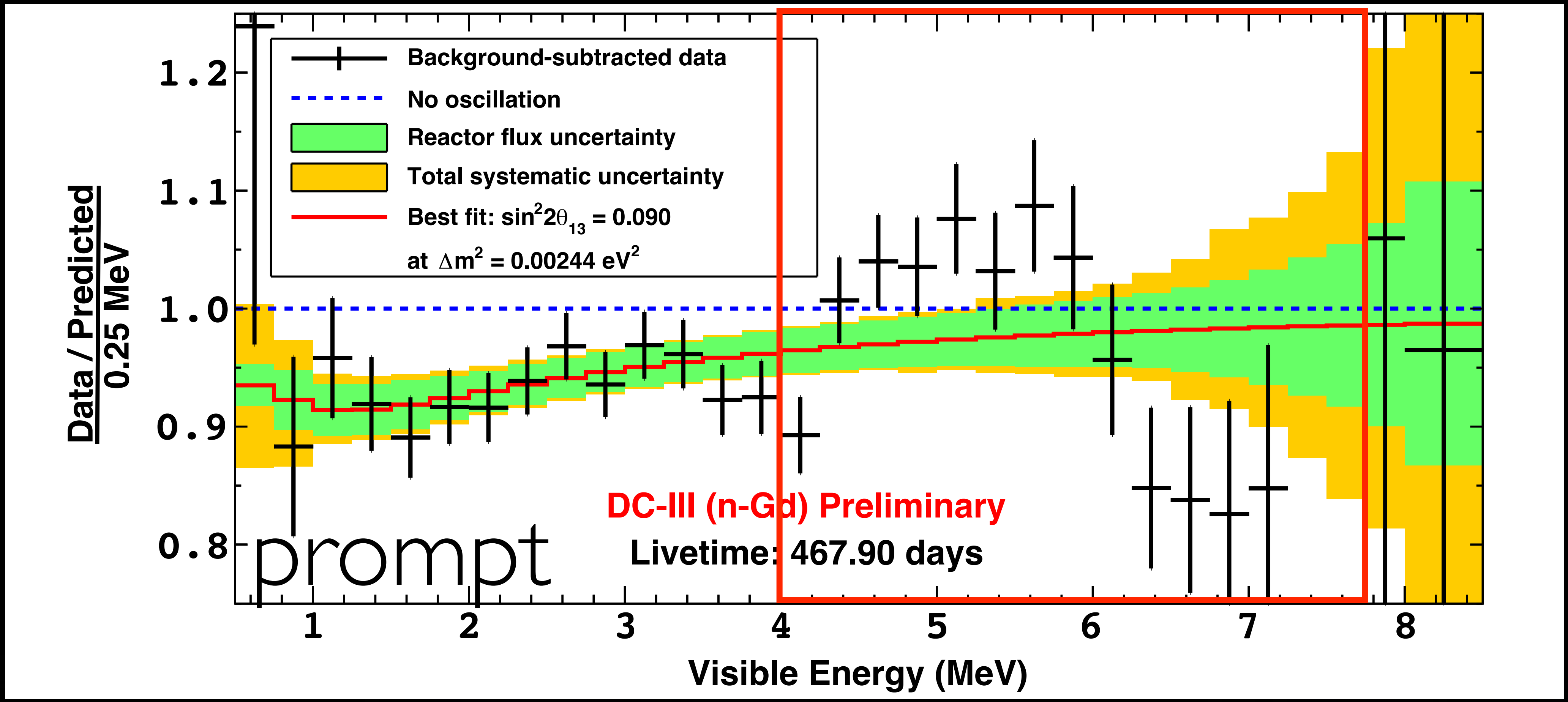
many cross-checks done (not shown)→ robust θ13 result
(release input BG constraints, IH vs MH, w/o 2xOFF data, etc)

Anatael Cabrera (CNRS-IN2P3 & APC)

a closer look to our P($\nu_e \rightarrow \nu_e$)…

(colloquially named "E/L plot")

non-understood structure from ~[4,8]MeV…



- **range [0.5,4)MeV:** excellent θ_{13} driven spectral distorsion
  - (θ_{13} direct impact) θ_{13} fits constrained mainly by info <4MeV (R+S analysis)

- **range [4,8)MeV:** structure (deviations $\leq$1.5σ)
  - ~**[4,6]MeV: excess?** (stats available→ attempt to understand)
  - ~**[6,8]MeV: deficit?** (IBD spectrum dies off→ unknown)
  - (θ_{13} indirect impact) affect θ_{13}^{R+S} via a bias on the BG constraint? (i.e. ^{9}Li mainly)

    ⟹ excellent agreement between R+S (shape sensitive) vs RRM (integral over all)

- negligible integrated effect→ **all θ_{13} in excellent agreement!!** (<1σ)

our understanding today…

(regardless of origin) **no direct impact to θ_{13} measurement**

→ **negligible indirectly impact ⟹ δ(Li+He) and $\delta(\sin^2(2\theta_{13}))$ immune**

→tested R+S with hypothetical **C-n-like peak ~5MeV**→ maximal variation $\leq 0.3\sigma$

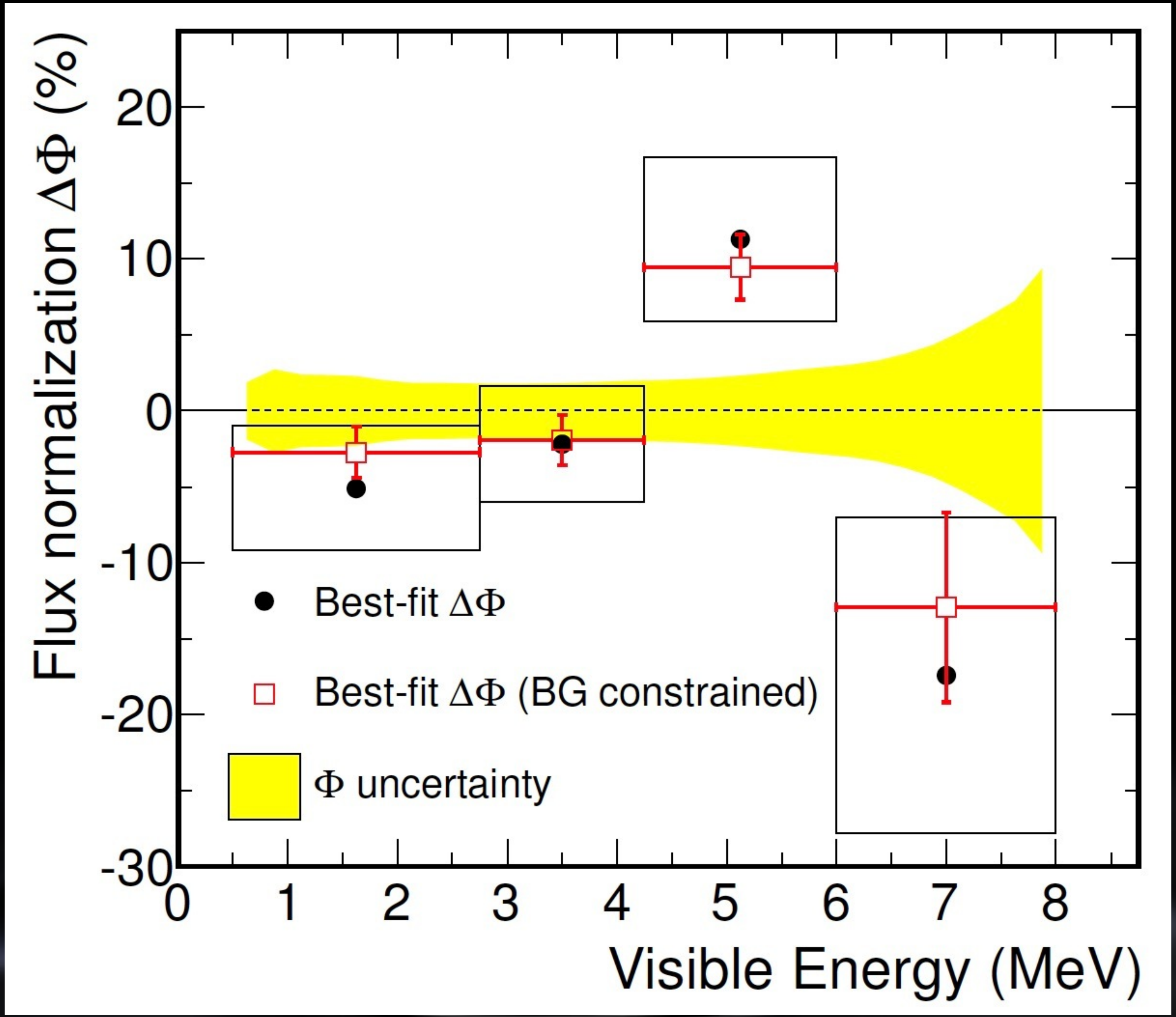
source	status	rationale
detection	**discarded**	•no impact on shape
energy	**disfavoured**	•remarkable match full energy scale data/MC [0.5,8]MeV •C-n peak (@5MeV) data/MC agreement to <0.5% •shifted energy spectrum by $\pm 1\sigma$→ not reproduced the observed E/L shape
background	**disfavoured (tension)**	•reactor-OFF data tension @ 2σ→ no room for unknown BG (else tension will increase) •all known BG well constrained (several methods)→ inconsistency on shape? (constrained to be small) •BG only possible cause for excess→ what about deficit? (approx. equal significance)
flux	**possible**	•large uncertainties at higher energies due to ILL e- conversion, correction, burn-up, etc •cause for both excess and deficit, but unknown effect •**data favours tension to flux constraint @ ~1.5σ** (not significance still)
combination	**possible**	•impossible to discard

no significant unambiguous origin found but strong hints…

(rule out most possible scenario)

flux error consistency: binned-RRM analysis…

(similar to R+S pattern)



(energy) binned-RRM using world best θ_{13} as input

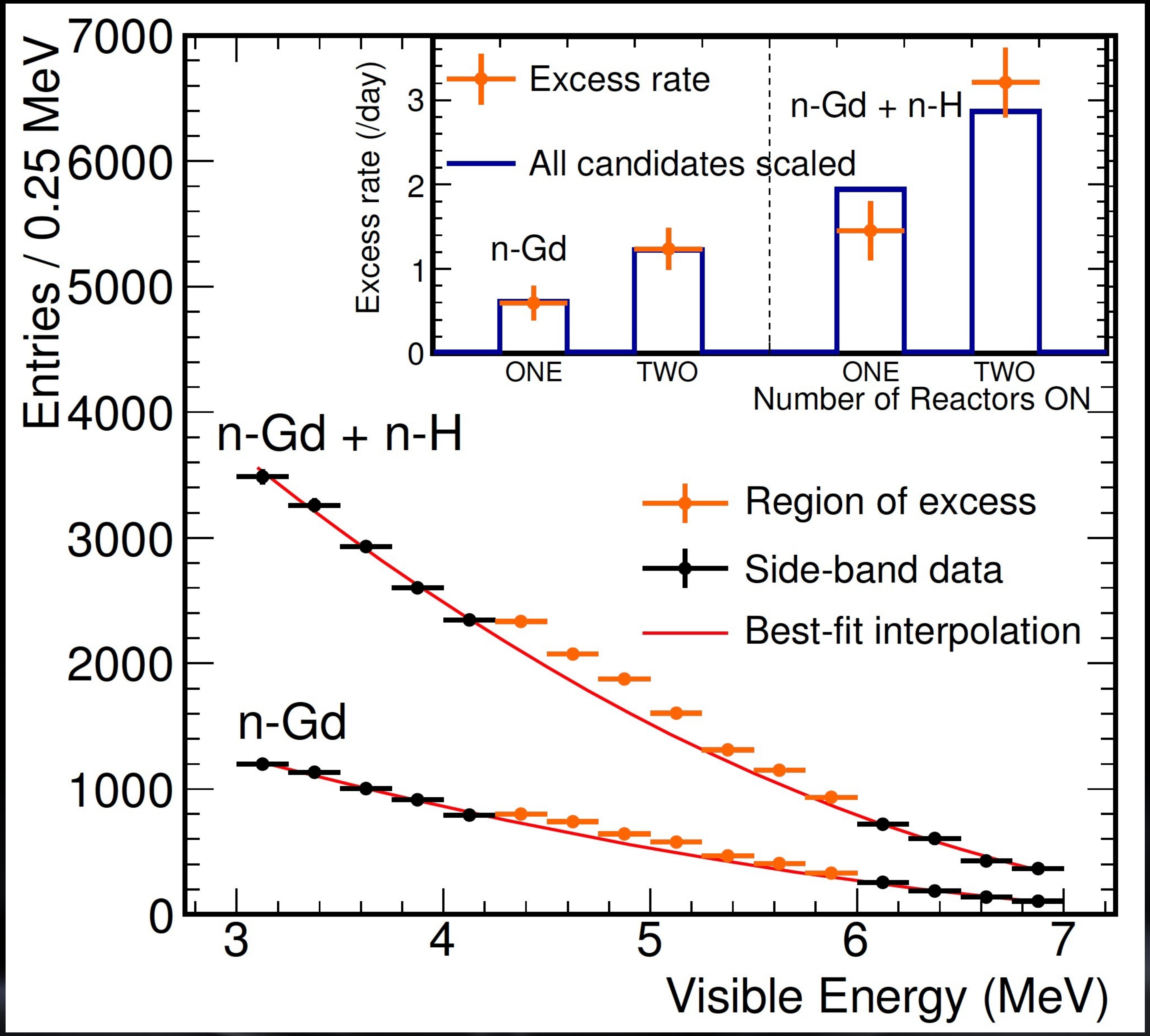
⟹ consistency check for possible BG and/or flux deviations (simultaneously)

3.0σ tension relative to flux input error (yellow shaded)

negligible tension <1σ relative to BG

(other pieces of evidence consistently in the same direction)

(if flux related) does it correlated to reactor?…



search for empirical correlations in “difference” region ~[4,6]MeV

(deficit region: no enough statistics)

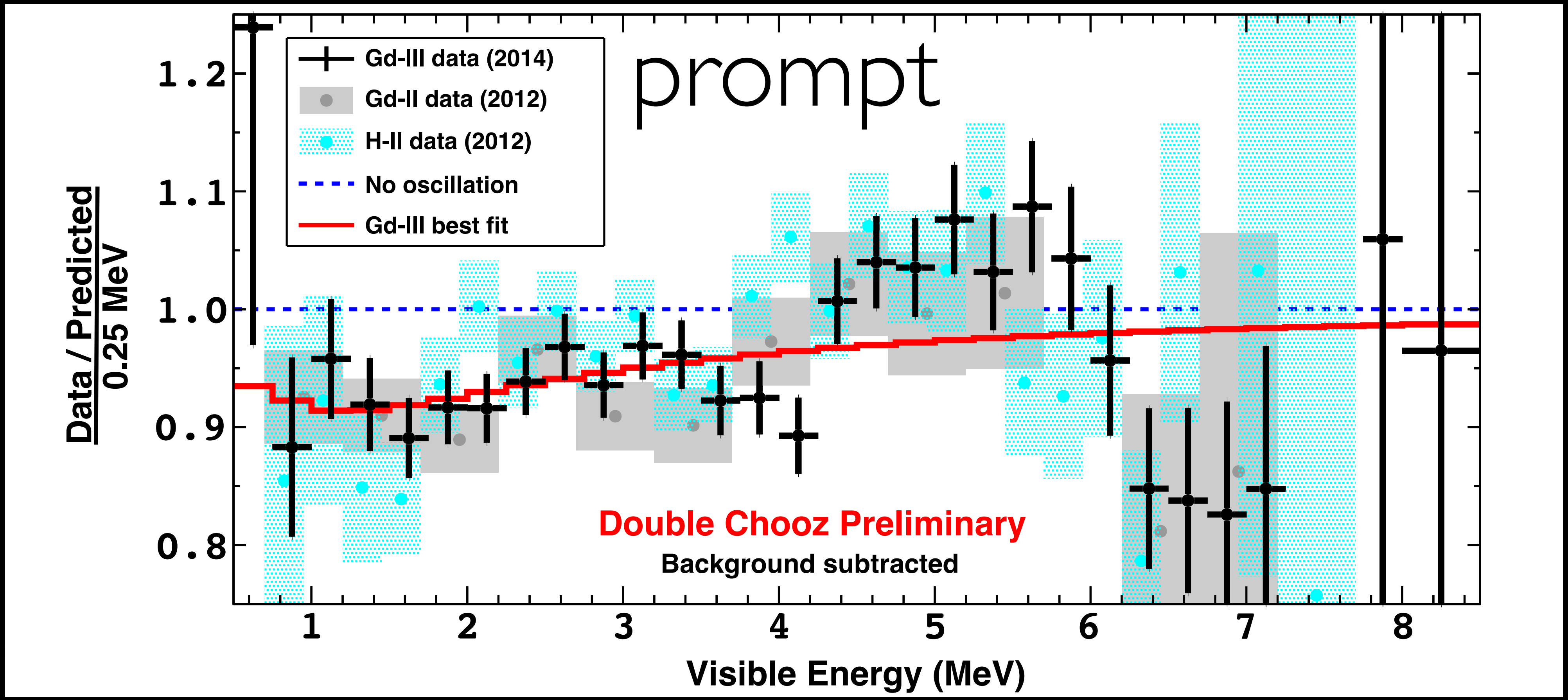
no correlation was found on any BG-sensitive variable (time to last **μ**, etc)

strong correlation with reactor power→ <u>more data (H) stronger correlation</u>

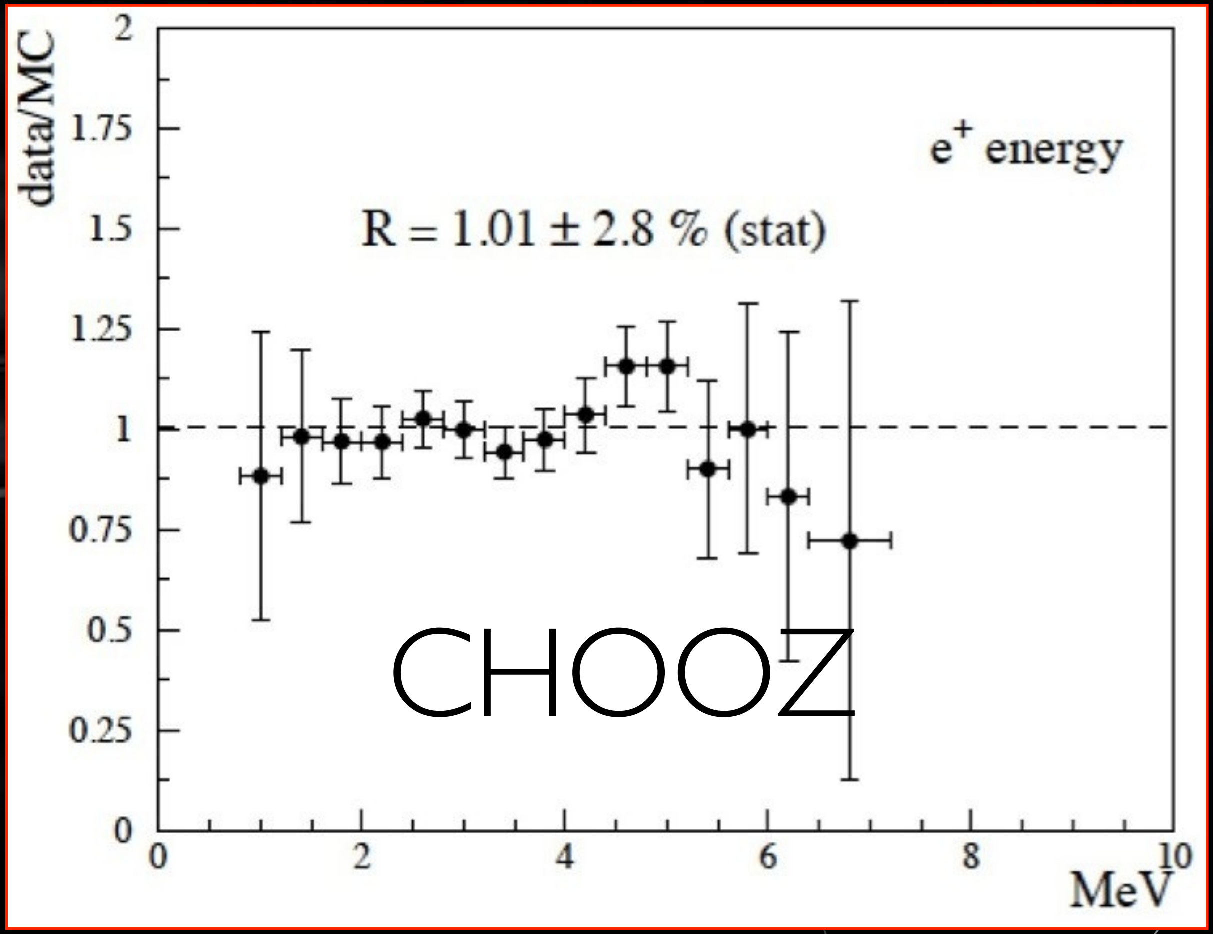
(empirical data-driven observation)

Anatael Cabrera (CNRS-IN2P3 & APC)

DC-III-Gd vs DC-II-Gd and DC-II-H

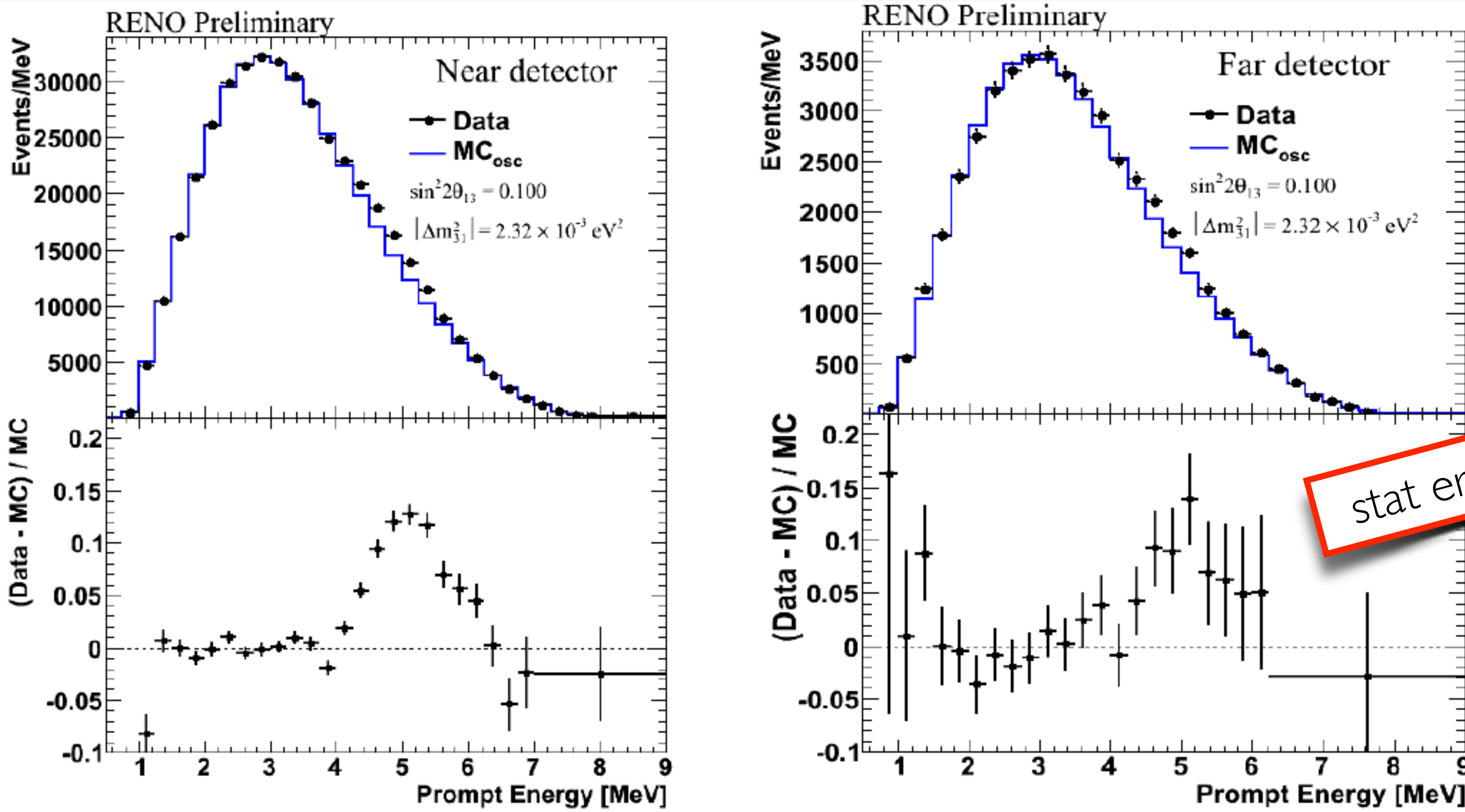


- **not new!! just better resolved…**
  - better stats (x2) (same flux info)
  - better energy (+50% better systematics)
  - better BGs (x3 better systematics)
- **same DC-III-Gd pattern visible with…**
  - **DC-II-Gd…** [also **DC-I-Gd**]
    - different selection (→ different BGs)
  - **DC-II-H…**
    - very different BGs
    - different detector volume (less precision)
  - **also CHOOZ?** (same reactors, different everything)



RENO @ Nu2014…

Observation of new reactor ν component at 5 MeV

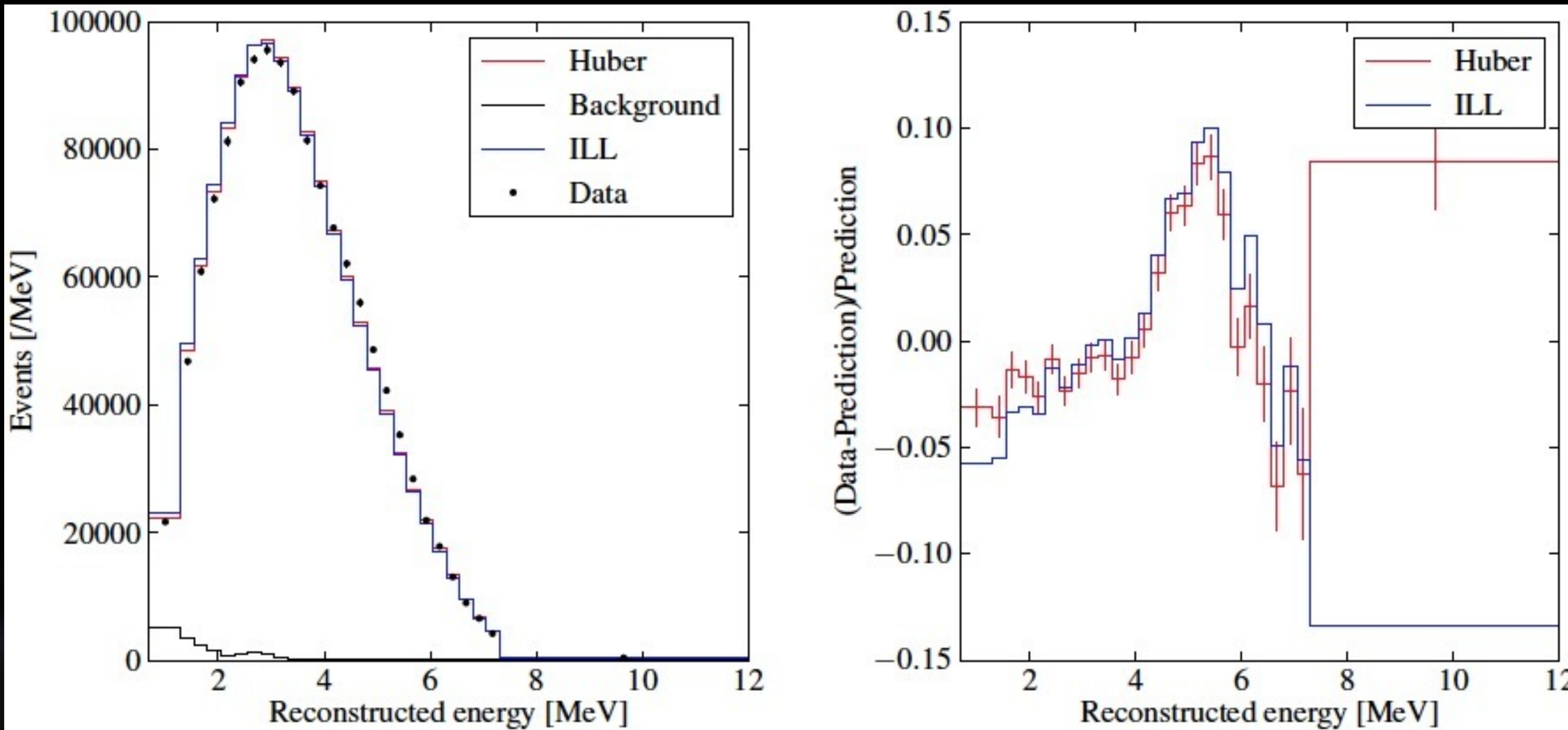


stat error only?

<u>Fraction of 5 MeV excess (%) to expected flux</u>

- Near : 2.303 +/- 0.401 (experimental) +/- 0.492 (expected shape error) → ~3.6σ
- Far : 1.775 +/- 0.708 (experimental) +/- 0.486 (expected shape error) → ~2.0σ

how about Daya Bay?



Daya Bay PhD-thesis @ US (not official result)

→ first presentation @ ICHEP (next week)

beyond Gd-III…

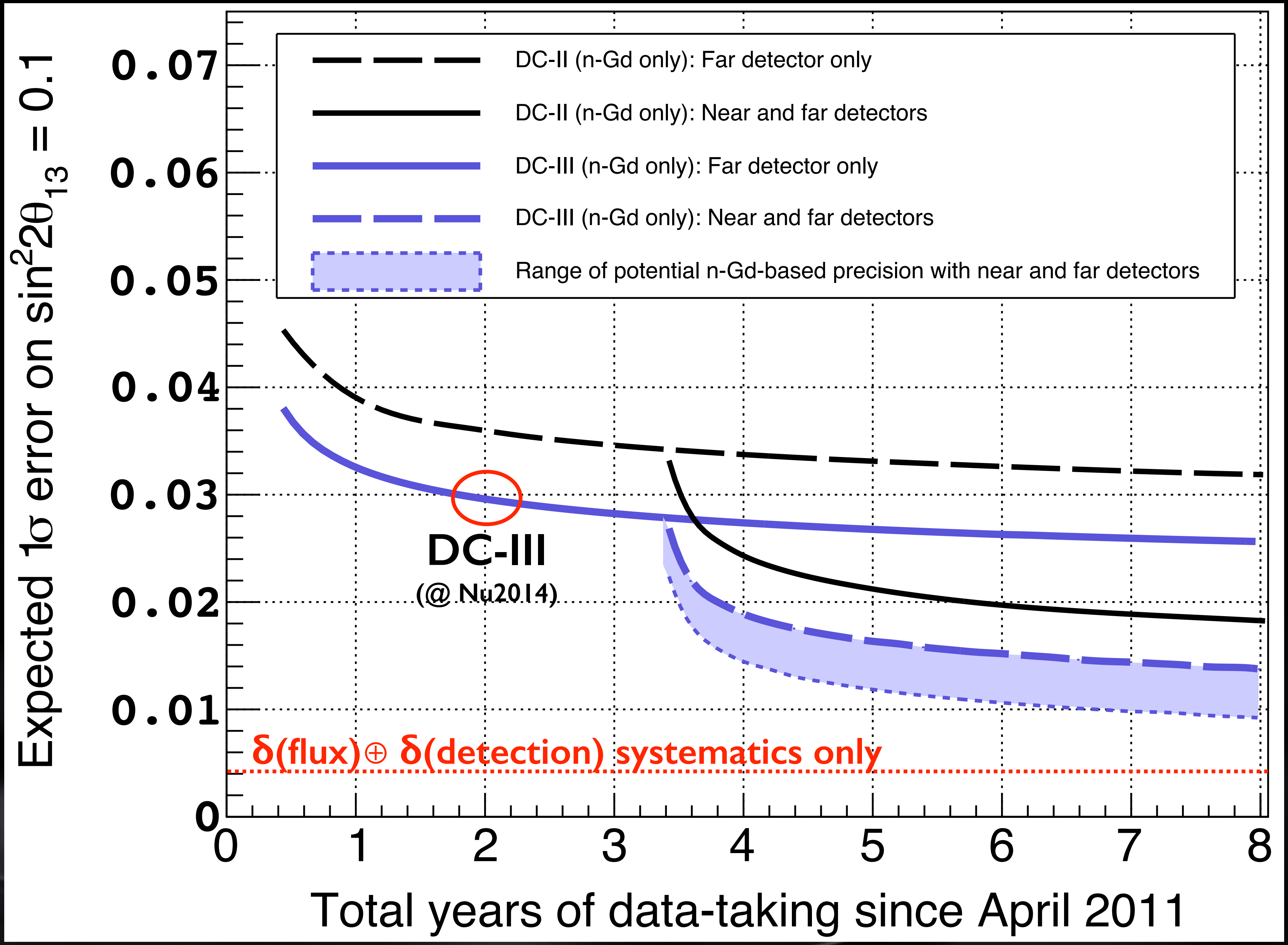
1σ error projection (via R+S analysis)...

Gd-n analysis FD+ND prospect inputs

- **δ(flux)~0.1%** (**preliminary**)
  - iso-flux suppression dominated
- **δ(detection)~0.2%**
  - à la Daya Bay / RENO
- **δ(BG)~ DC-III + R+S constraint**
  - @DC-III~0.3% (2 years data)

note:

- **δ(stat) not just $1/\sqrt{N^{FD}}$ (dominant)**
  - several effects N^{BG}, N^{ND}, etc



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

1σ within [0.010,0.014] with 3years FD+ND: BG systematics dependent→ **statistics dominated**

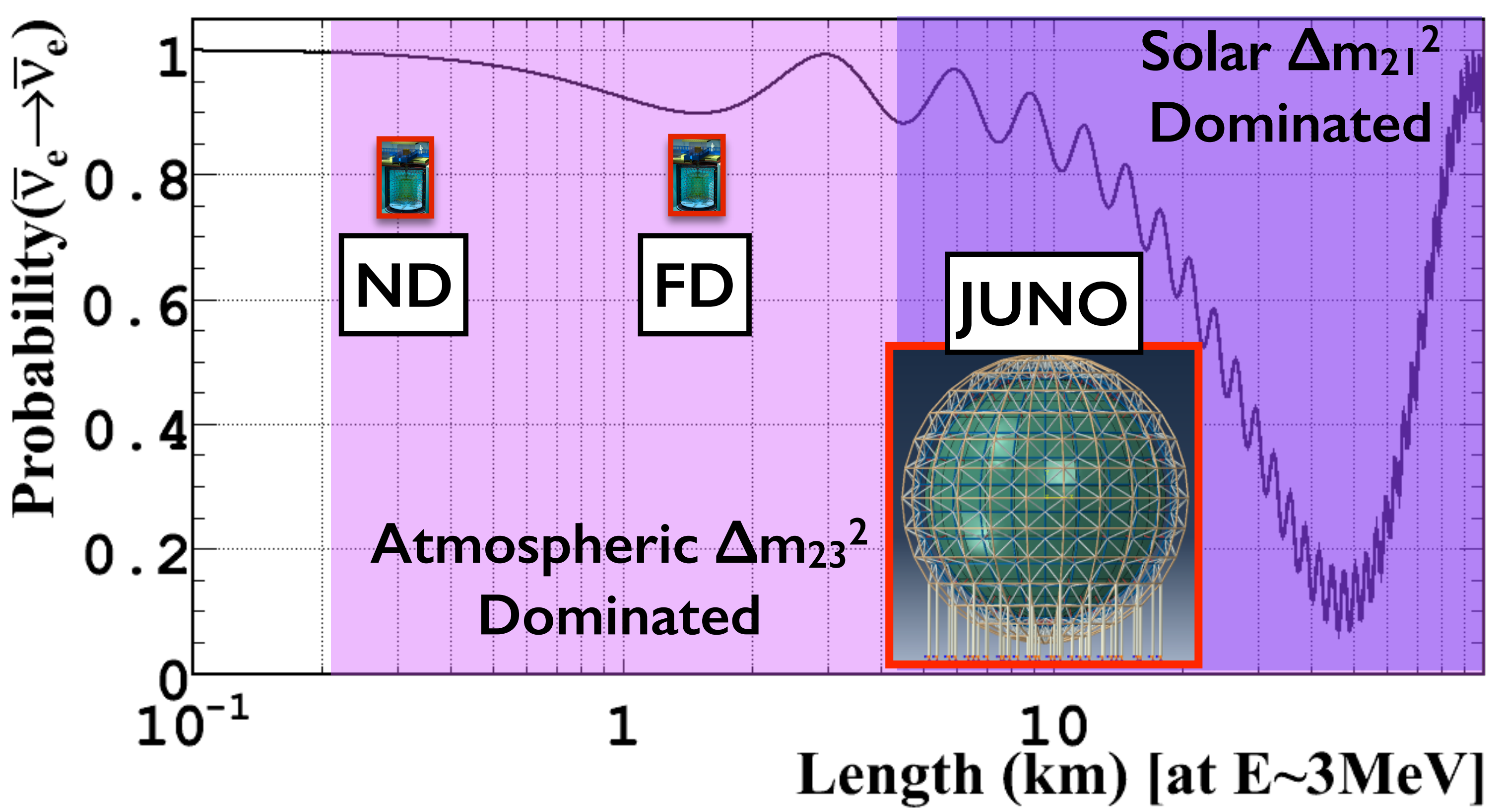
(rate+spectrum projection uses latest BG model fromDC-III)

DC goals @ proposal…

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

reactors $\boldsymbol{\nu}$s: future?

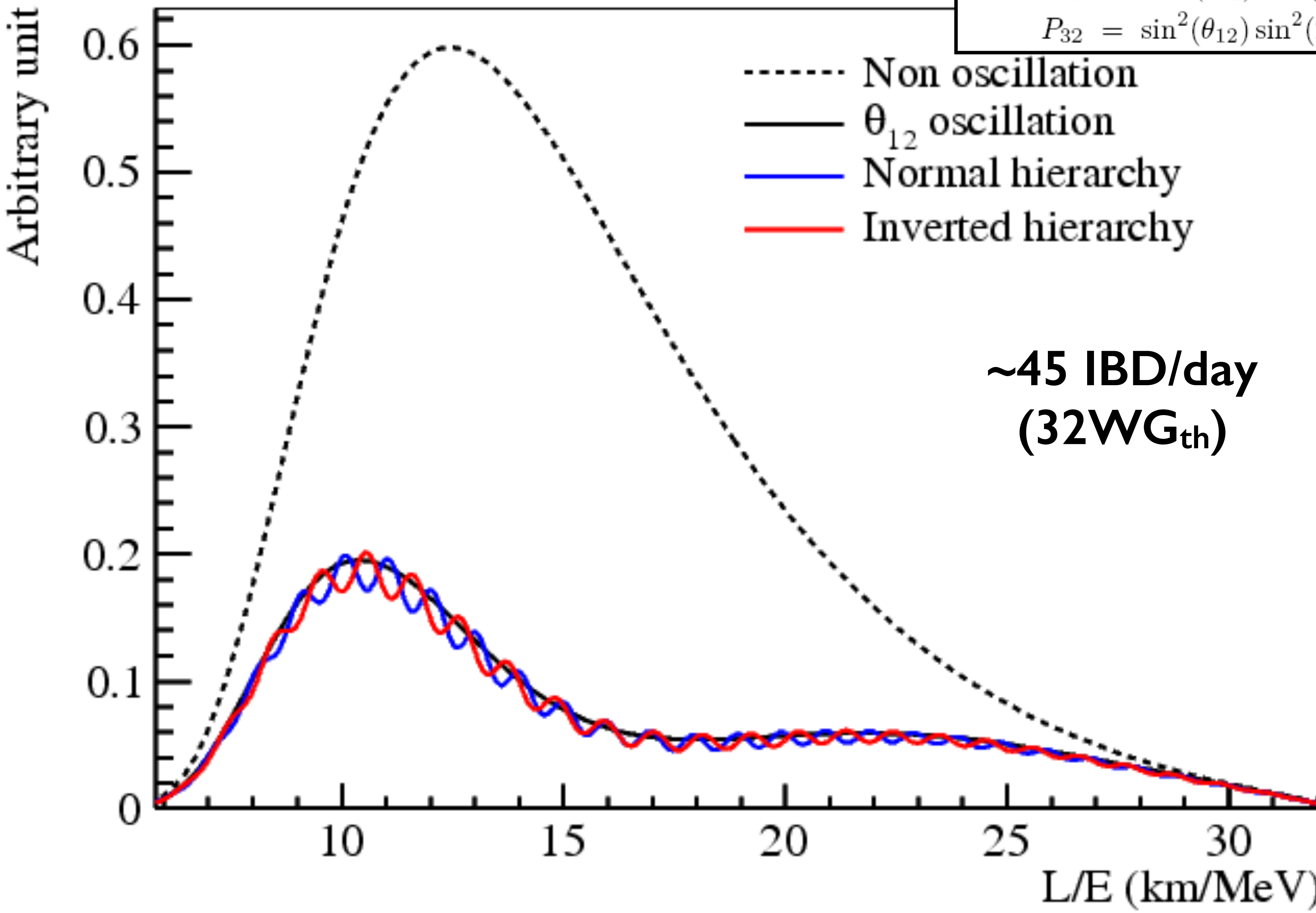
experimental setup…



(atmospheric) Mass Hierarchy @ JUNO…

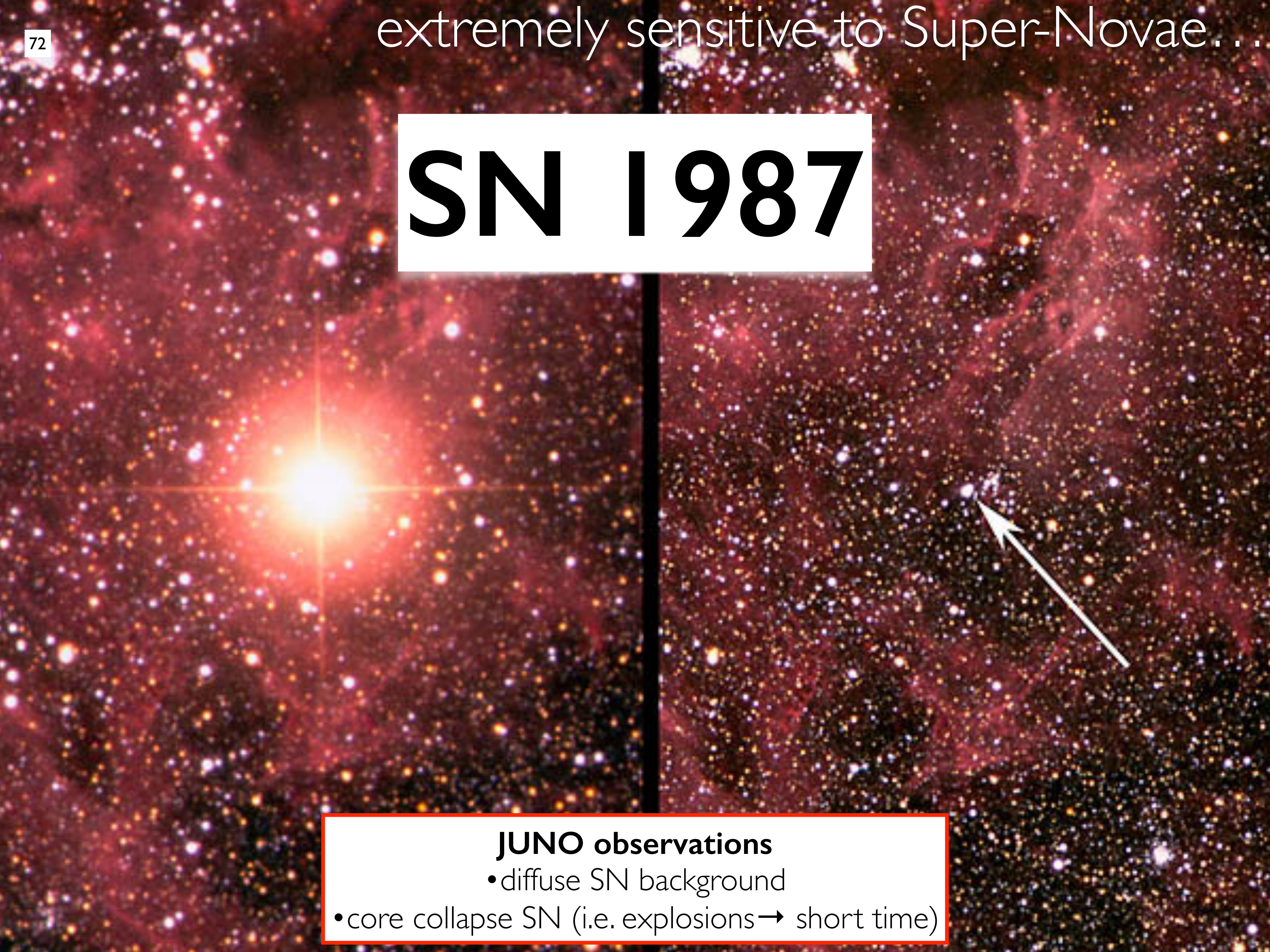
illustration of the concept…

$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$



- **Mass Hierarchy not via Matter Effects**⟹ unique complementary to ORCA/PINGU/SK/LBNE
- **Δm^2, δm^2 and $\sin^2(2\theta_{12})$ to <1% error** (→ input to δ_{CP} searches & 3ν model)

extremely sensitive to Super-Novae…



SN 1987

JUNO observations
- diffuse SN background
- core collapse SN (i.e. explosions → short time)

what to remember?

conclusions…

- DC-Gd-III have been presented (@ LAL and Nu2014)…
  - Gd-III improves everything by factors relative to Gd-II
    - higher efficiency, less BG (active BG rejection), data-driven BG estimations, etc
      - δ(detection)^{III} ~2x more precise δ(detection)^{II}
      - δ(BG)^{III} ~3x more precise δ(BG)^{II}
      - better energy reconstruction (fully accounting for non-linearities)
  - (powerful) analysis is now ready for ND→ more already under preparation
- DC-Gd-III results…
  - (relative Gd-II) ~2x more stats, but factor improvement in systematics…
  - (**R+S**) **$\sin^2(2\theta_{13})$ = (0.09±0.03)** [corresponding BG **(1.43±0.15)day^{-1}**]
  - (**RRM-All**) **$\sin^2(2\theta_{13})$ = ($0.09^{+0.03}_{-0.04}$)** [corresponding BG: **(1.55±0.17)day^{-1}**]
    - (**RRM-2xOFF**) **$\sin^2(2\theta_{13})$ = (0.06±0.04)** [corresponding BG **(0.90±0.39)day^{-1}**]
- DC projections…
  - ND will run from end of summer 2014
  - **major systematics cancellation boosting 1σ error on $\sin^2(2\theta_{13})$ up to 0.01** [**only Gd-n**]
    - improvement in analysis are already in preparation