Double Chooz

(new Gd-III results)

Laboratoire de l'Accélérateur Linéaire
(Orsay, France)
May 2014

on behalf of the Double Chooz collaboration

Anatael Cabrera

CNRS / IN2P3 @ APC (Paris)

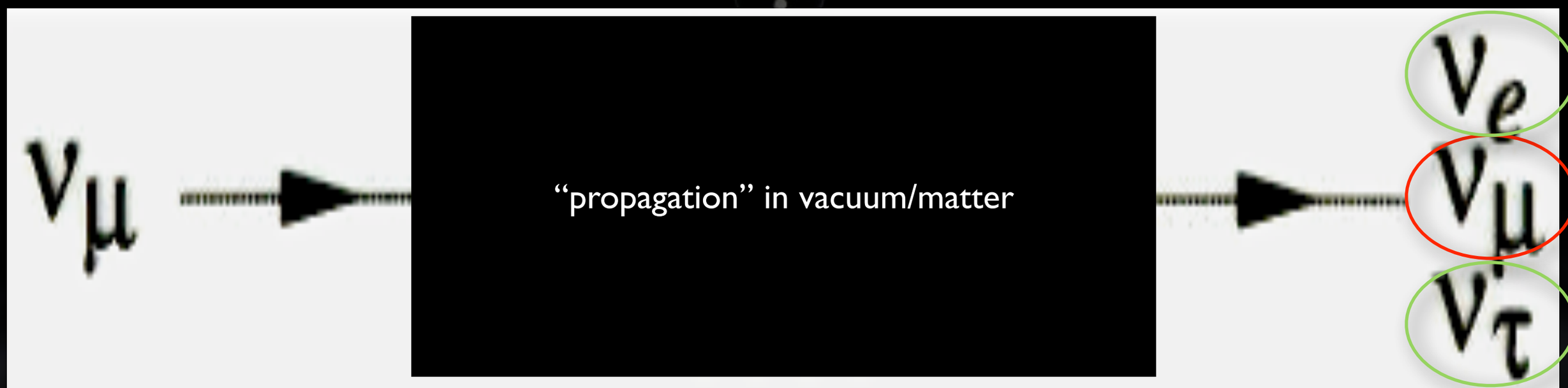
neutrino oscillations…

(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 $P=f(\theta,\Delta m^2)$

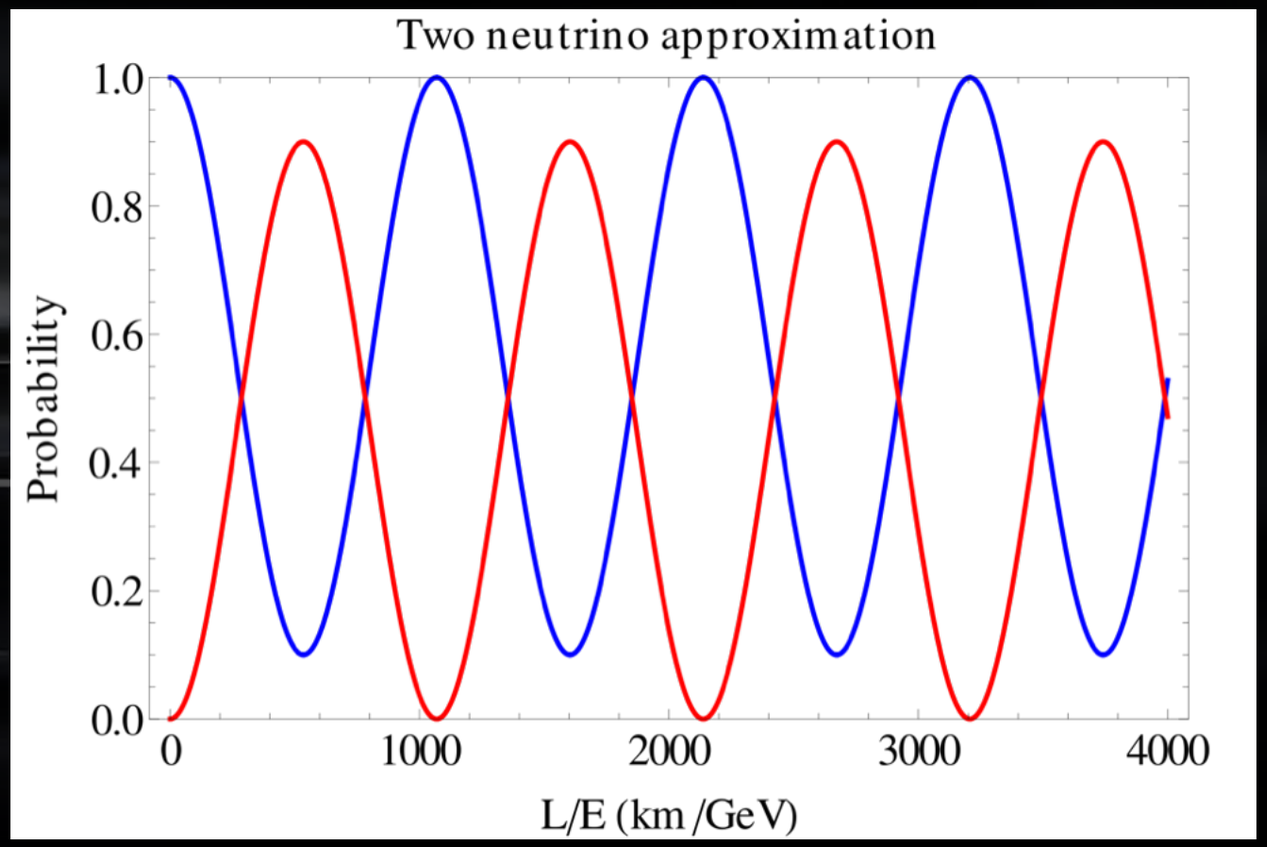
macroscopic quantum interference

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)

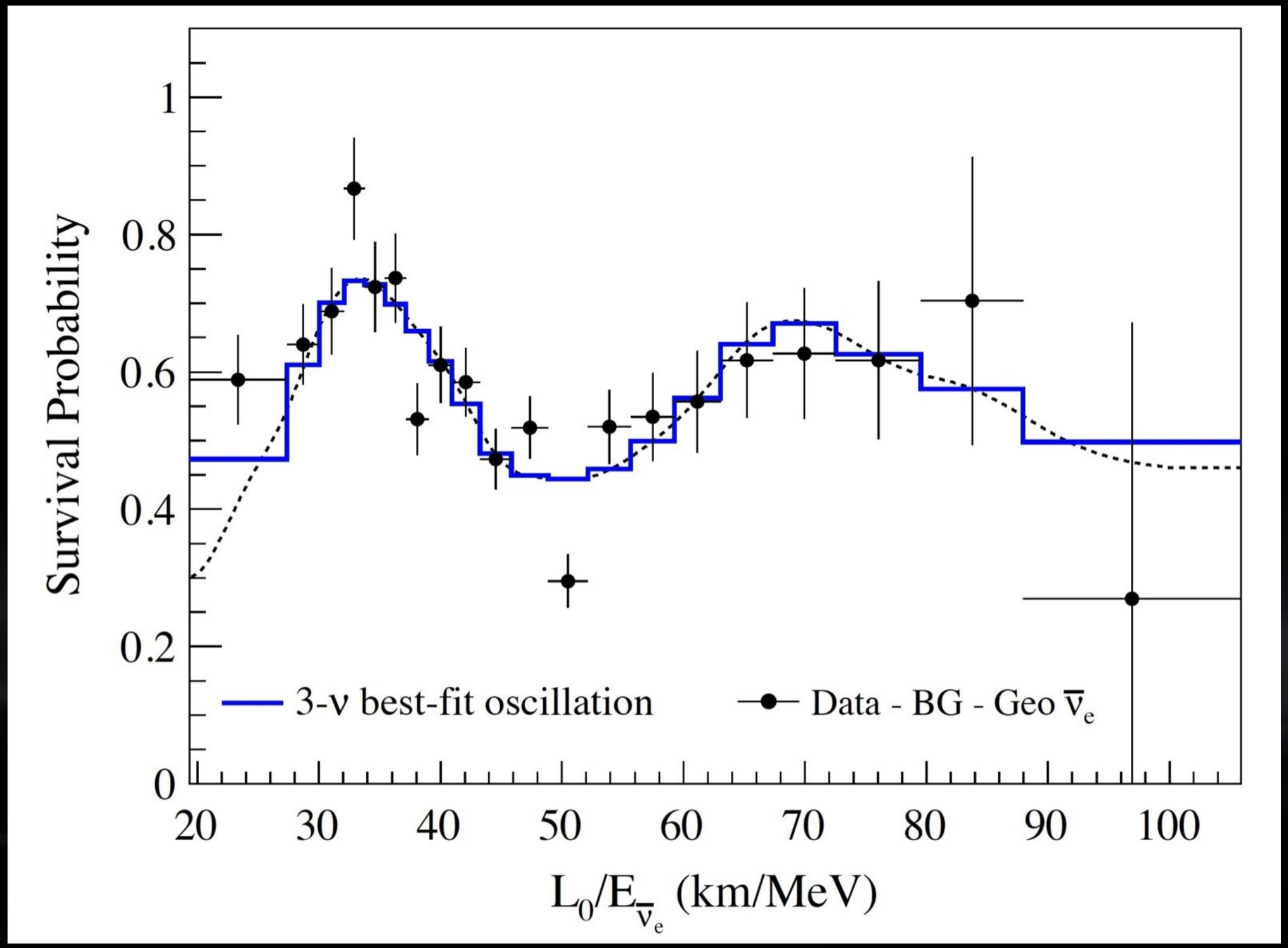
ν_α (start with) & ν_β (mixing: 90%)

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



the latest KamLAND's $P(\nu_e \rightarrow \nu_e)$…

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



"atmospheric" $\Longrightarrow$ $\theta_{23}\sim45^\circ$

θ_{13} & "dirac" δ_{CP}

"solar" $\Longrightarrow$ $\theta_{12}\sim33^\circ$

Δm^2_{31} Δm^2_{31} Δm^2_{21}

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

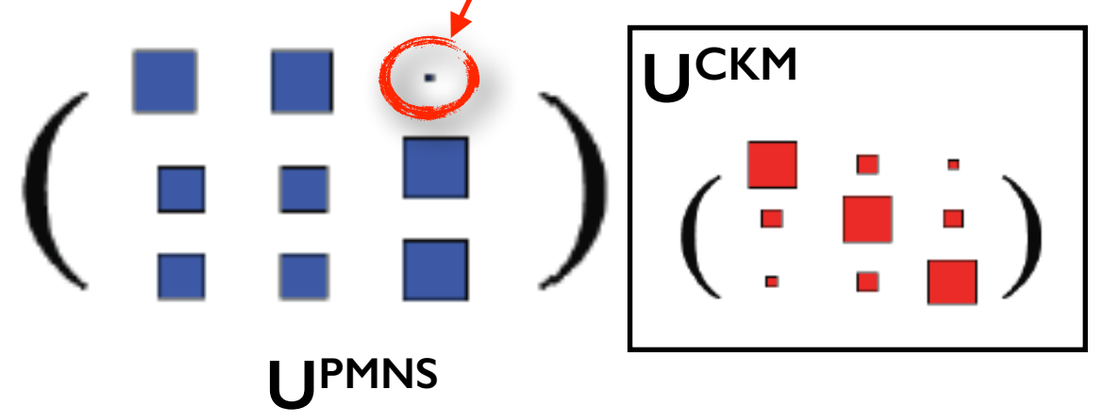
atmos+LBL(dis) Chooz+LBL(app) solar+KamLAND

$P(\nu_\mu\rightarrow\nu_\mu)$ $P(\nu_e\rightarrow\nu_e)$ & $P(\nu_\mu\rightarrow\nu_e)$ $P(\nu_e\rightarrow\nu_x)$

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



Fogli et al arXiv:1106.6028

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 $\oplus$ 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 $\oplus$ 0.88 – 2.00	—
δ/π (IH)	1.35	0.96 – 1.59	0.00 – 0.04 $\oplus$ 0.65 – 2.00	—

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

δm^2	2.6 %	→ KamLAND
Δm^2	3.0 %	→ MINOS + T2K (beam ν's)
$\sin^2\theta_{12}$	5.4 %	→ Solar experiments
$\sin^2\theta_{13}$	8.5 %	→ Reactor experiments
$\sin^2\theta_{23}$	~ 11 %	→ SuperKamiokande

non-accelerator experiments drive current knowledge…

the Double Chooz collaboration

Brazil

CBPF
UNICAMP
UFABC

France

APC
CEA/DSM/IRFU:
- **SPP**
- **SPhN**
- **SEDI**
- **SIS**
- **SENAC**

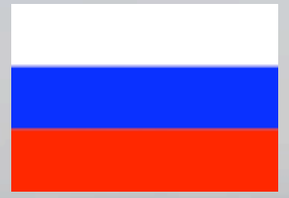
CNRS/IN2P3:
- **Subatech**
- **IPHC**

Germany

EKU Tübingen
MPIK Heidelberg
RWTH Aachen
TU München
U. Hamburg

Japan

Tohoku U.
Tokyo Inst. Tech.
Tokyo Metro. U.
Niigata U.
Kobe U.
Tohoku Gakuin U.
Hiroshima Inst. Tech.



Russia

INR RAS
IPC RAS
RRC Kurchatov

Spain

CIEMAT-Madrid

USA

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)

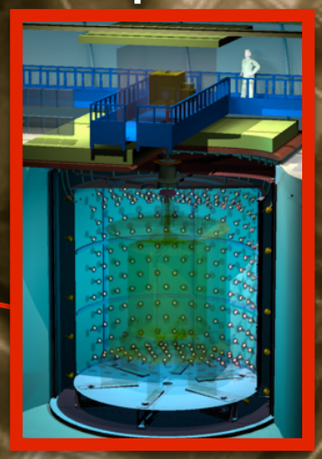
Web Site:
www.doublechooz.org/

the experiment's rationale…

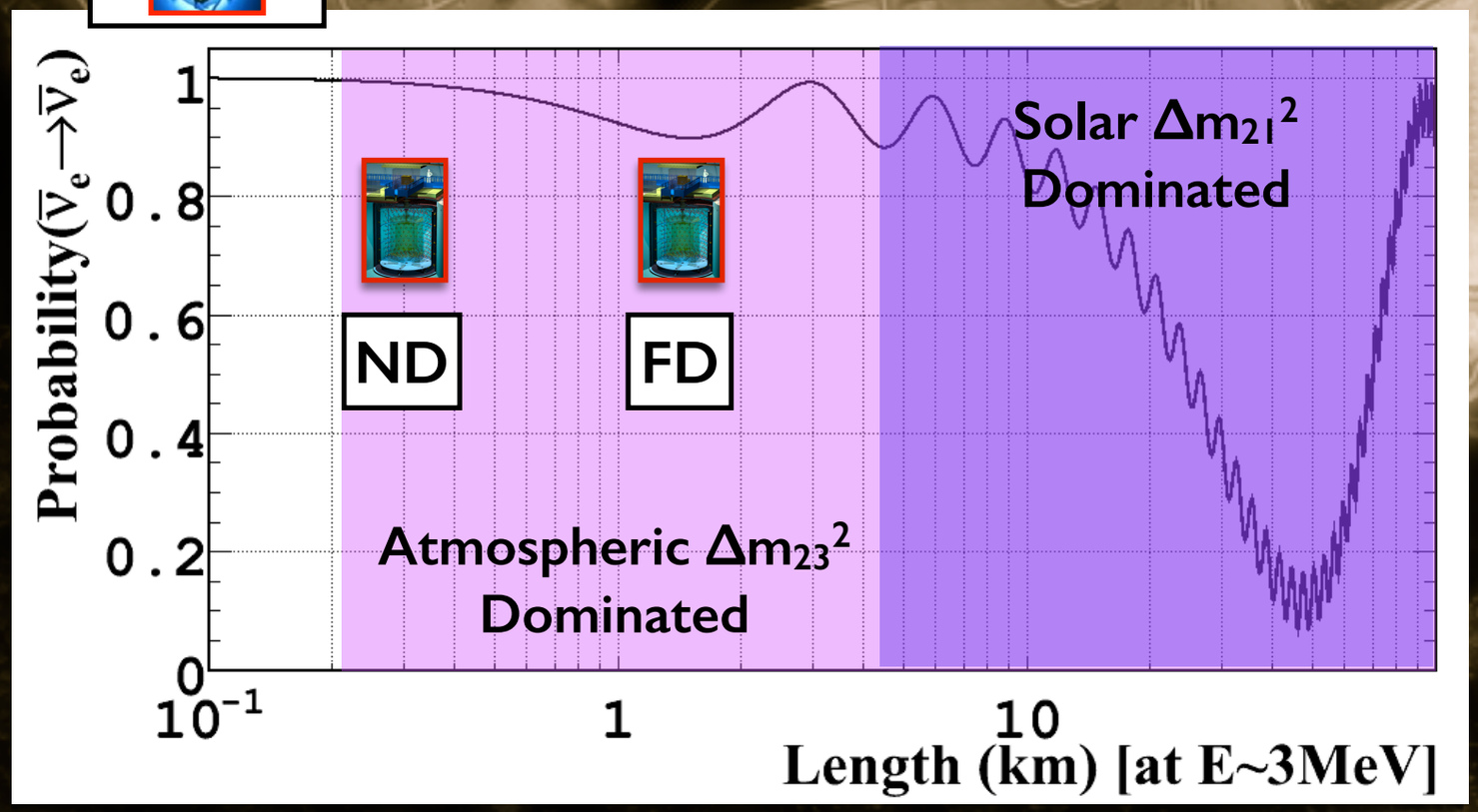
experimental setup…

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

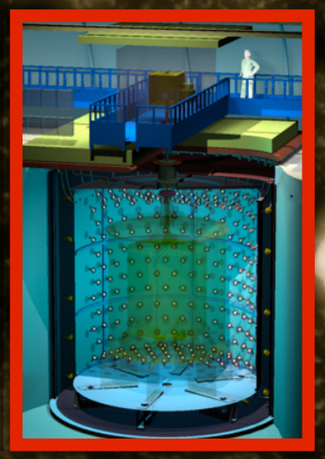
Near
<L> 400m
~300ν/day
120mwe
Target: 8.2t
2014(!!!)



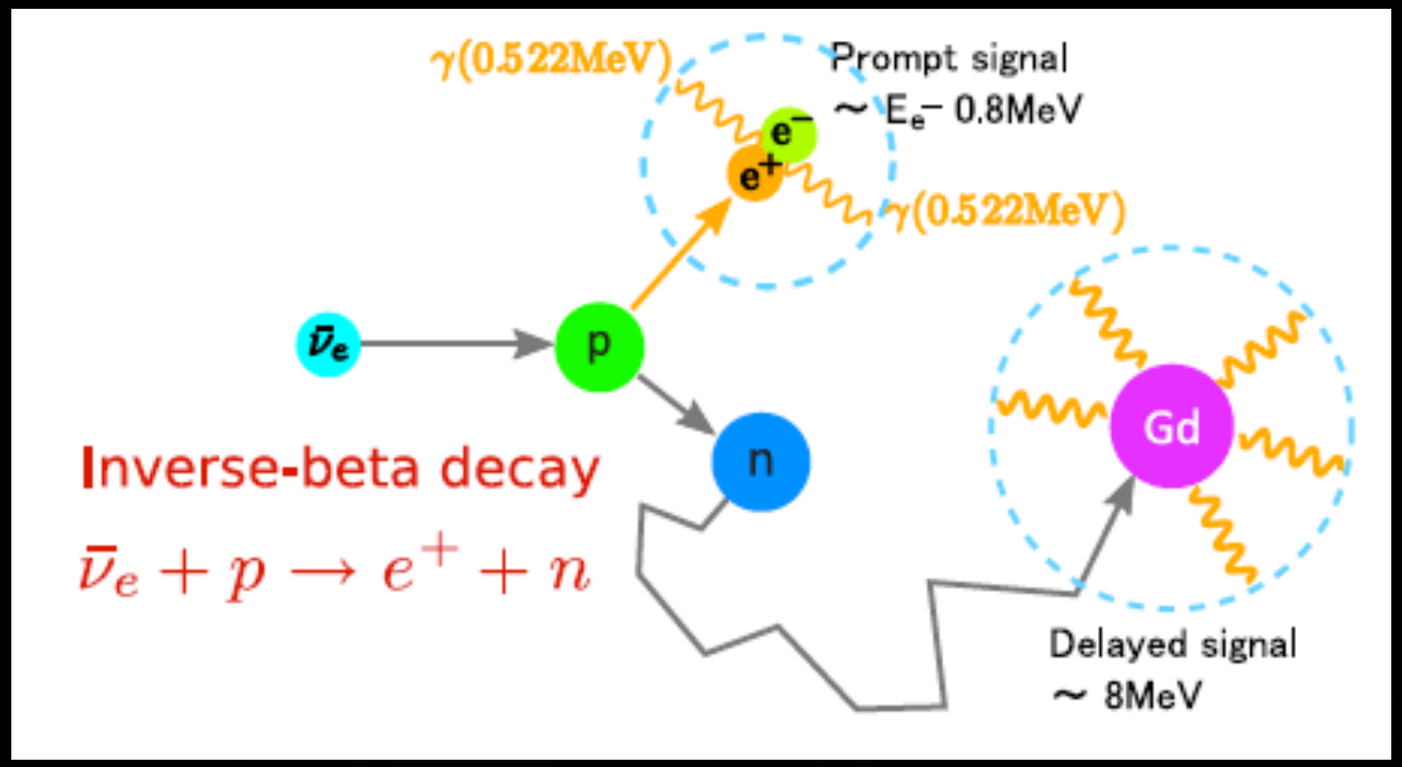
reactor

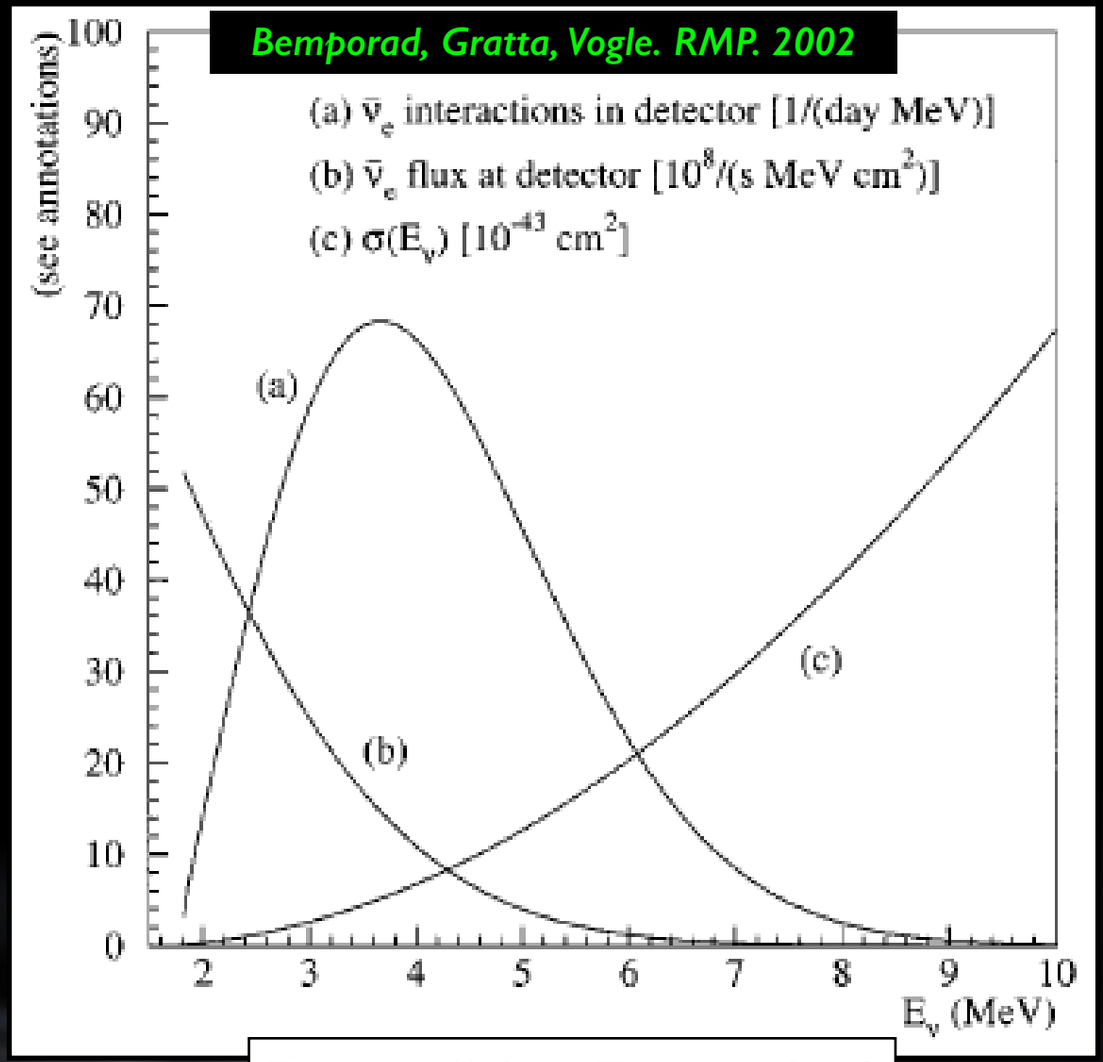


Far
<L> 1050m
~40ν/day
300mwe
Target: 8.2t
April 2011



IBD interaction (inverse-β decay)…





Energy(ν) ~ Energy(e+)

- **high & well known σ^{IBD}** [$\tau_{neutron}$=(881.5±1.5)s]
- IBD manifests via **trigger-coincidence**
  - 1st trigger→ **e+(prompt)**
  - 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)

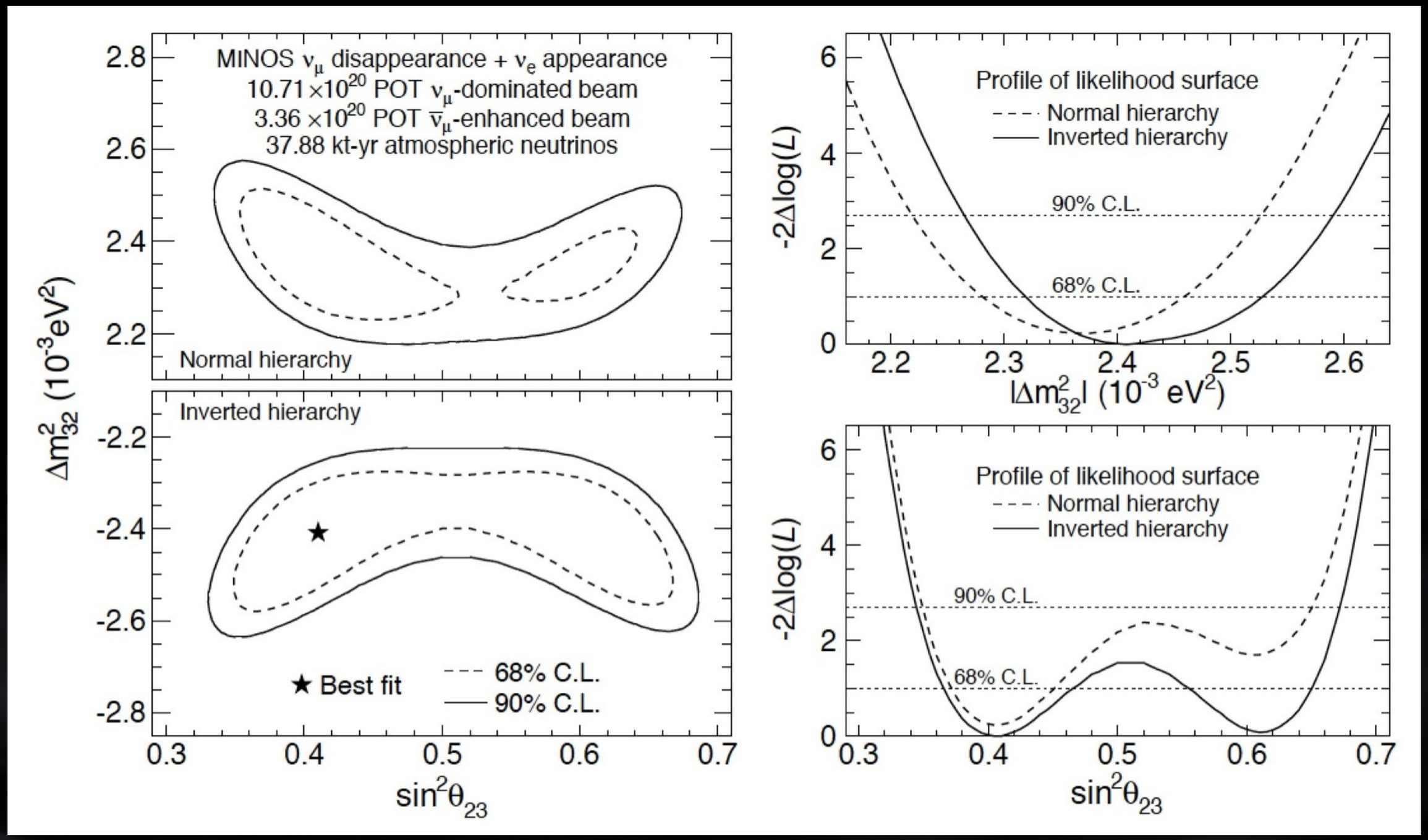
why IBD ⊕ Gd?

- small & shallow (high S/BG)
- no need for ultra-purity

⟹ **inexpensive ‰ precision!!**

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

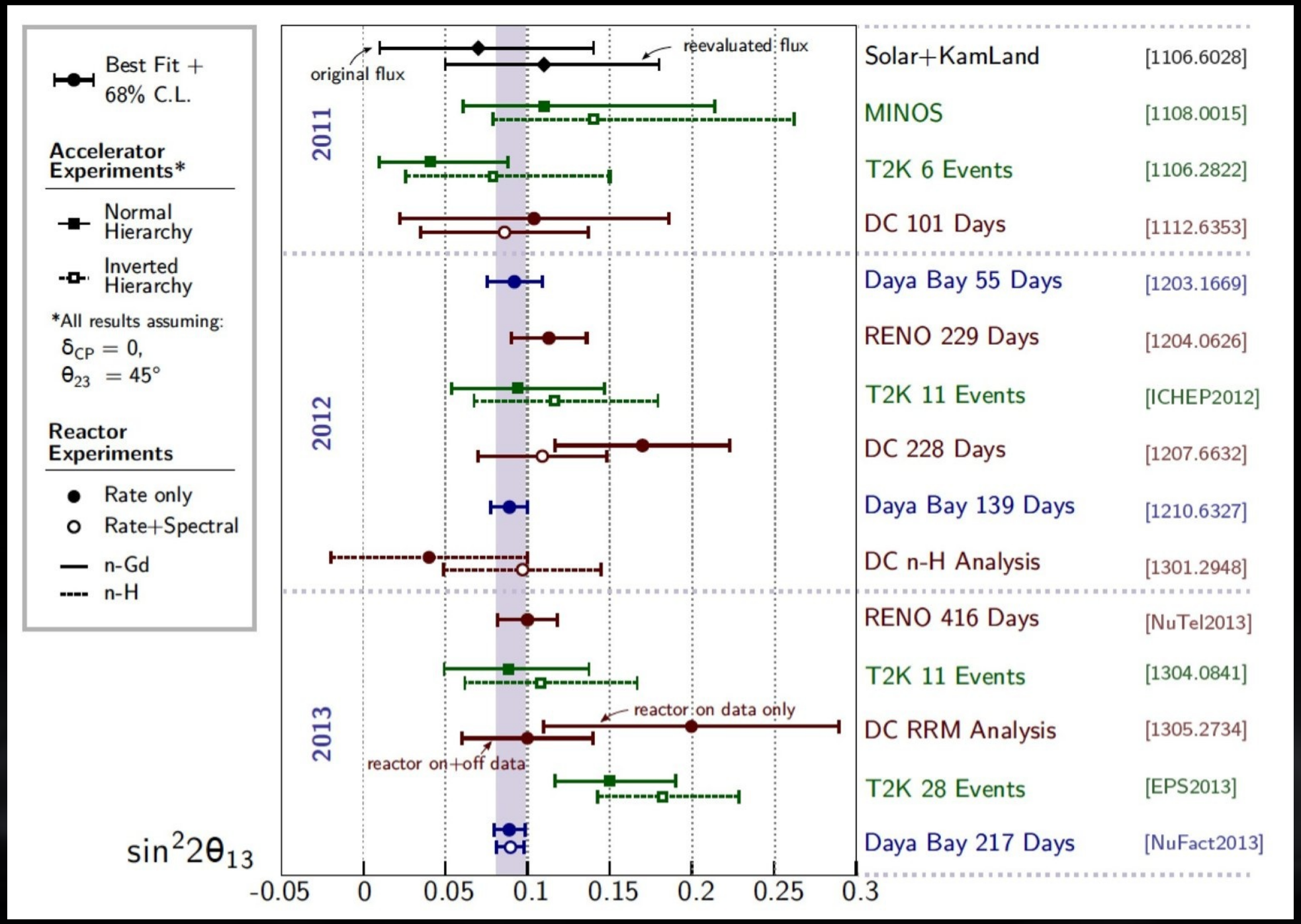
arXiv:1403.4667



Δm_{32}^2=[2.28,2.46]x10^3eV^2 (@68LC NH)
Δm_{32}^2=[2.32,2.53]x10^3eV^2 (@68LC IH)

the world of θ_{13}...

θ_{13}-reactor measurements…



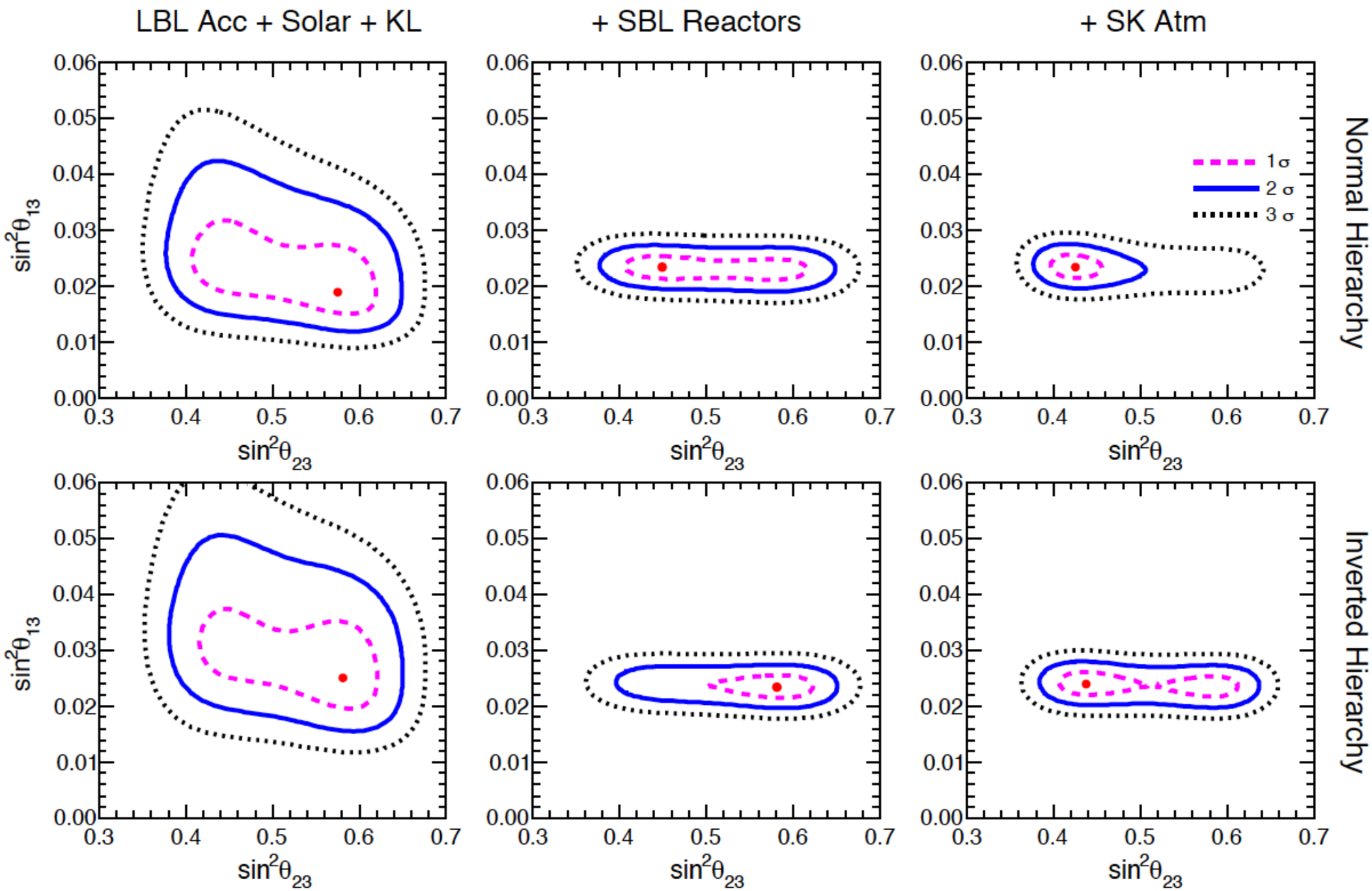
reactor precision is unsurpassable→ setting θ_{13} for several decades to go!!

(also measurement by T2K, MINOS, etc)

θ_{13} impacts our knowledge…

(examples: θ_{23} & δ_{CP})

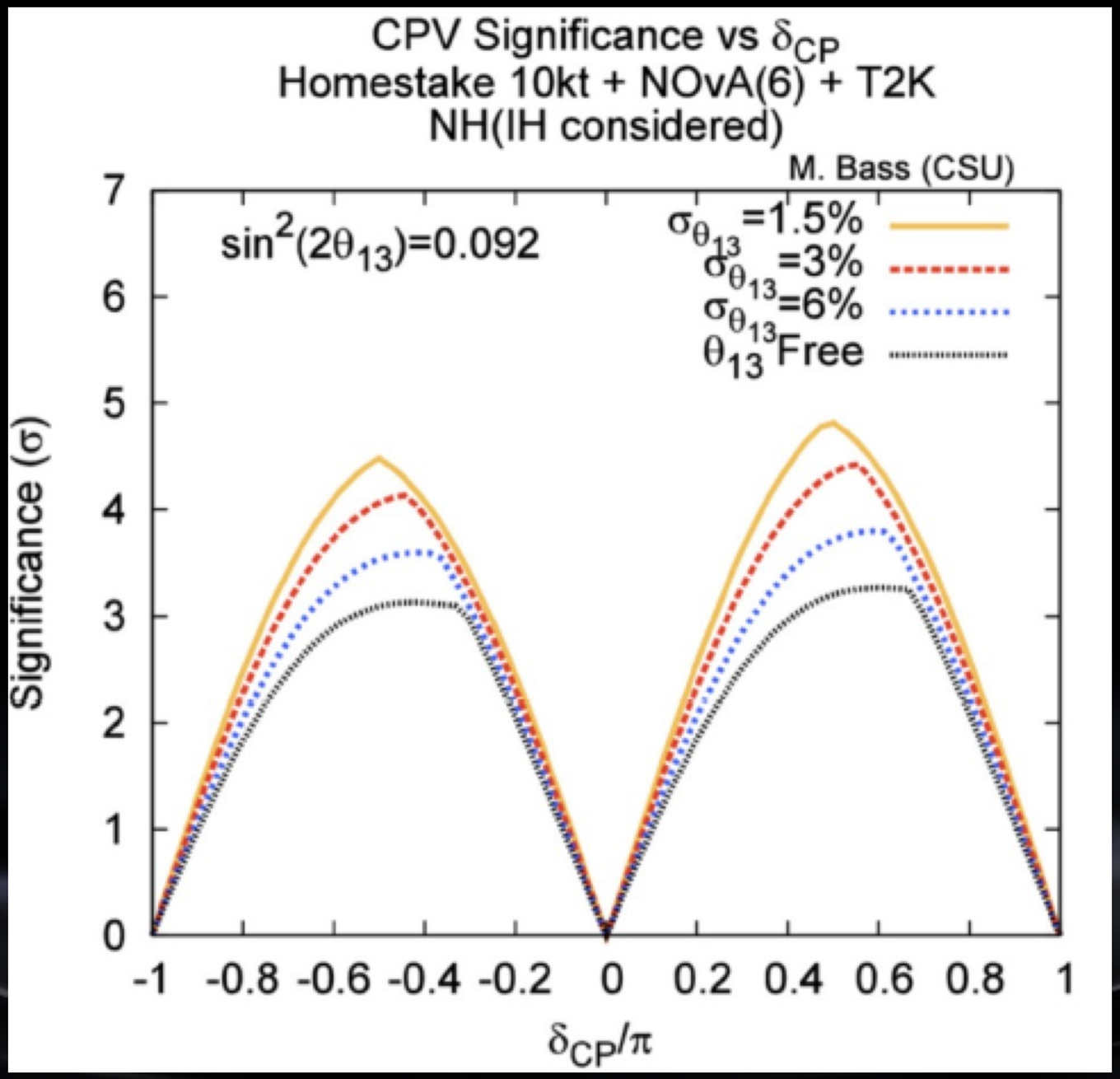
Lisi et al opinion (Jan. 2014)



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

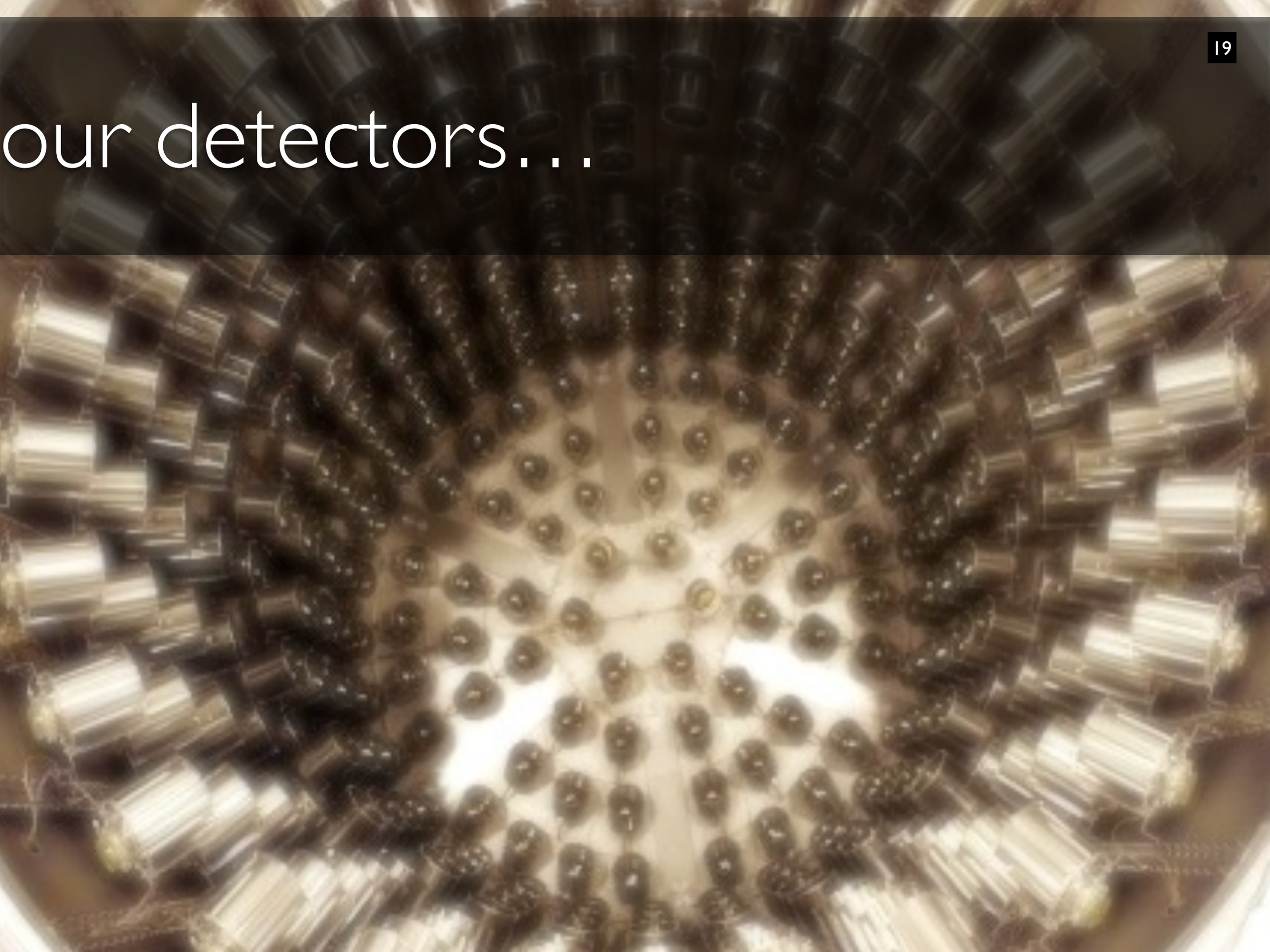
14

precision on θ13…



important for current & future beams!

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)

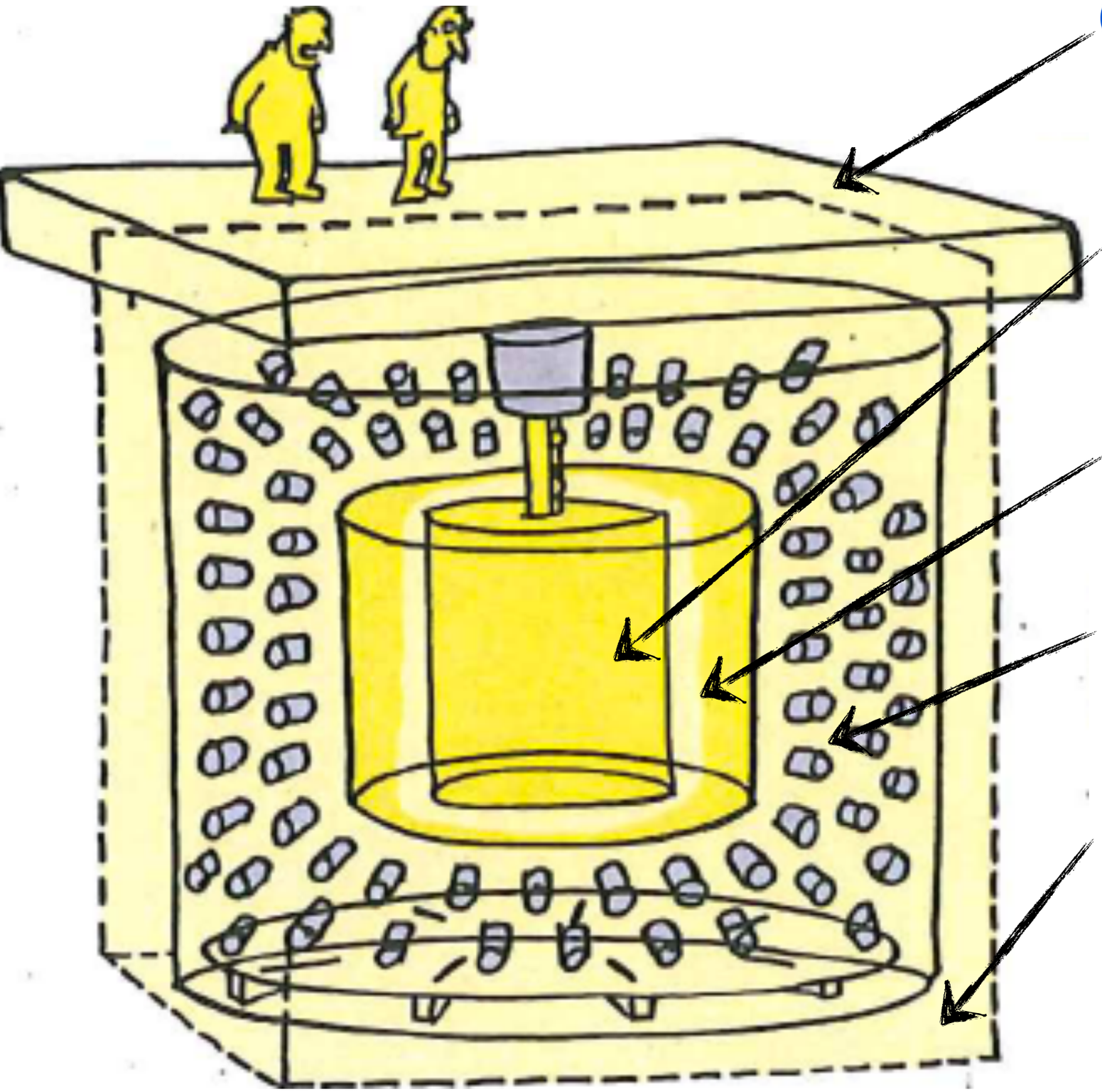
in case you wonder…

the use of near/Bugey4 (to minimise θ_{13} systematics)

→ **prevents FD sensitive to sterile-ν hypothesis**

(dedicated studies with ND can take place)

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

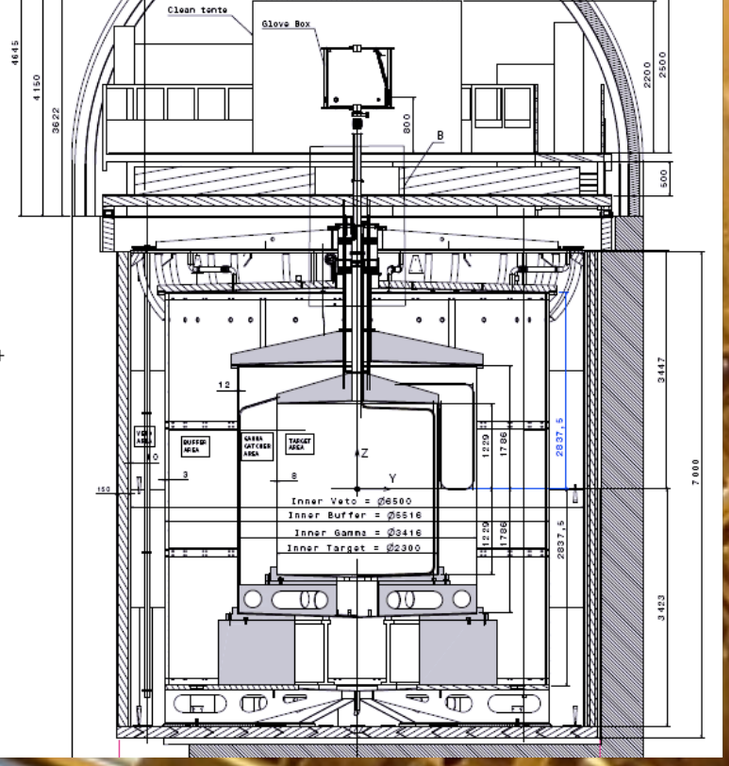
Oil (negligible scintillation)

Inner μ-Veto (IV)

Liquid-Scintillator

Inert γ-Shield

15cm of steel (around all detector)

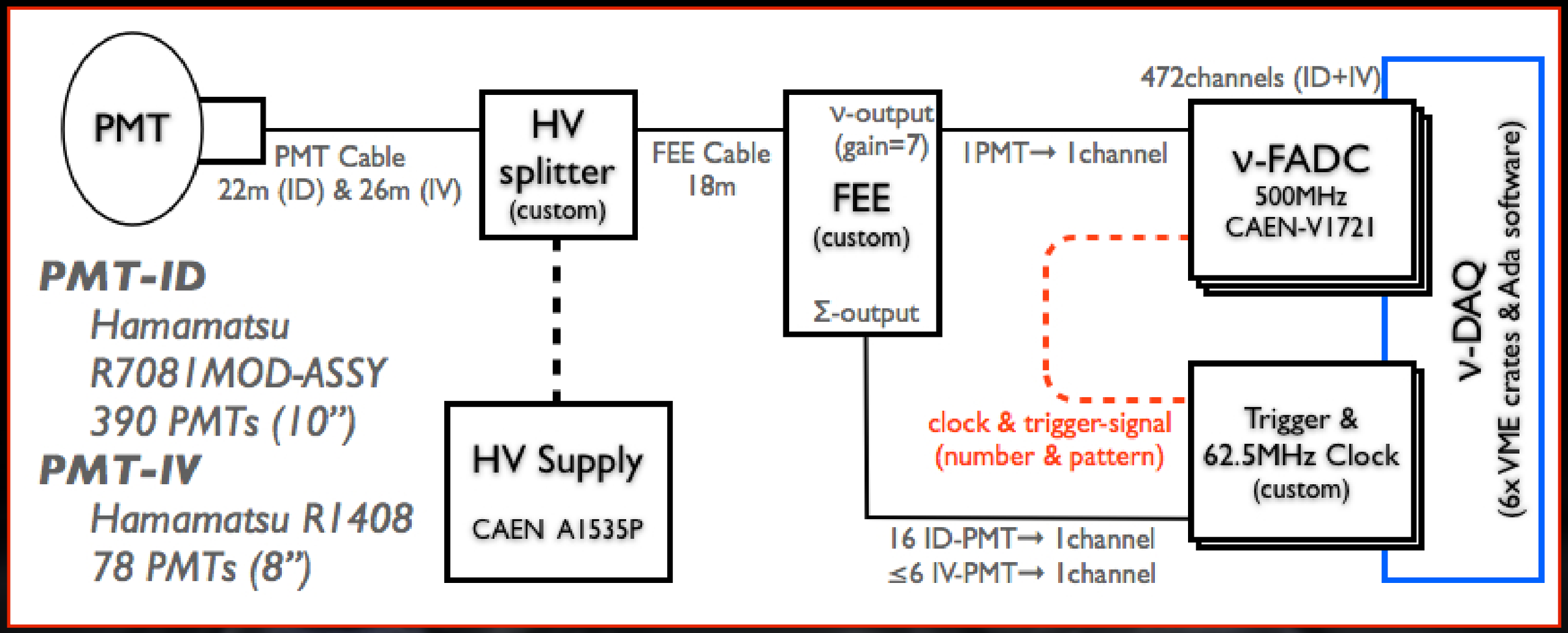


engineer's view

MC's view

our favourite view…

our readout…



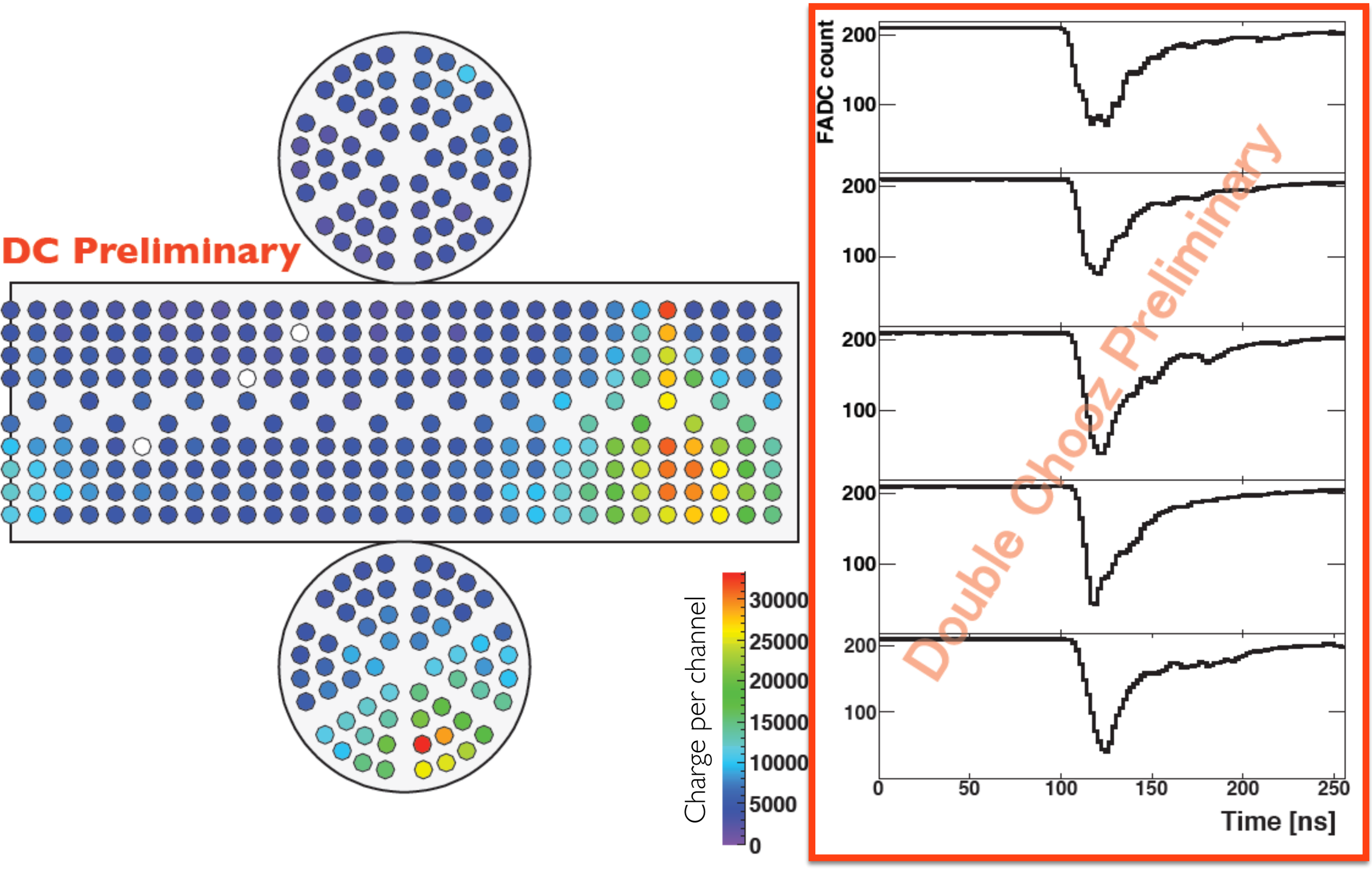
state of the art FADC electronics readout

(remarkable potential→ still squeezing power out data)

same readout+DAQ both ID and IV

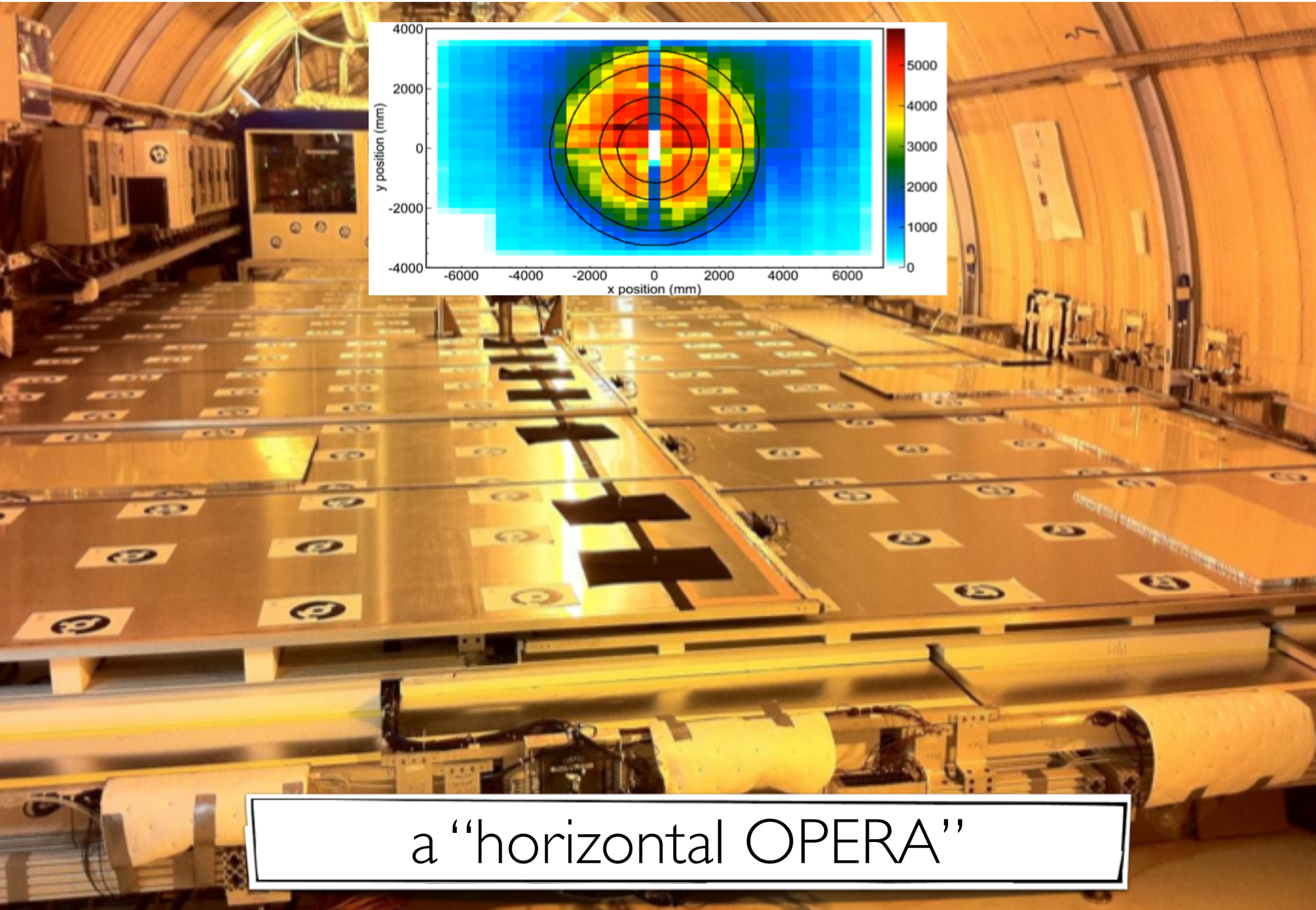
(OV readout based on M64+MAROC, similar OPERA)

muon event (inner-detector)…



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

our top μ-tracker/veto (Outer-Veto)…

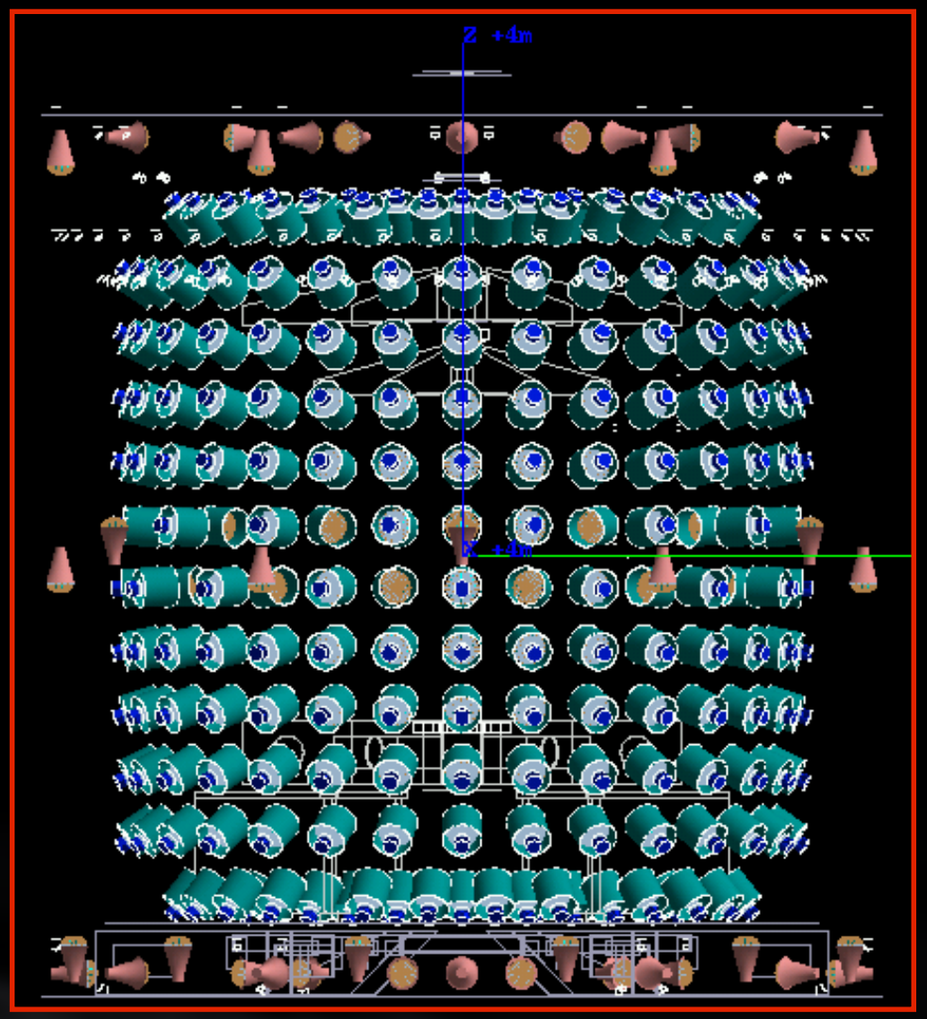


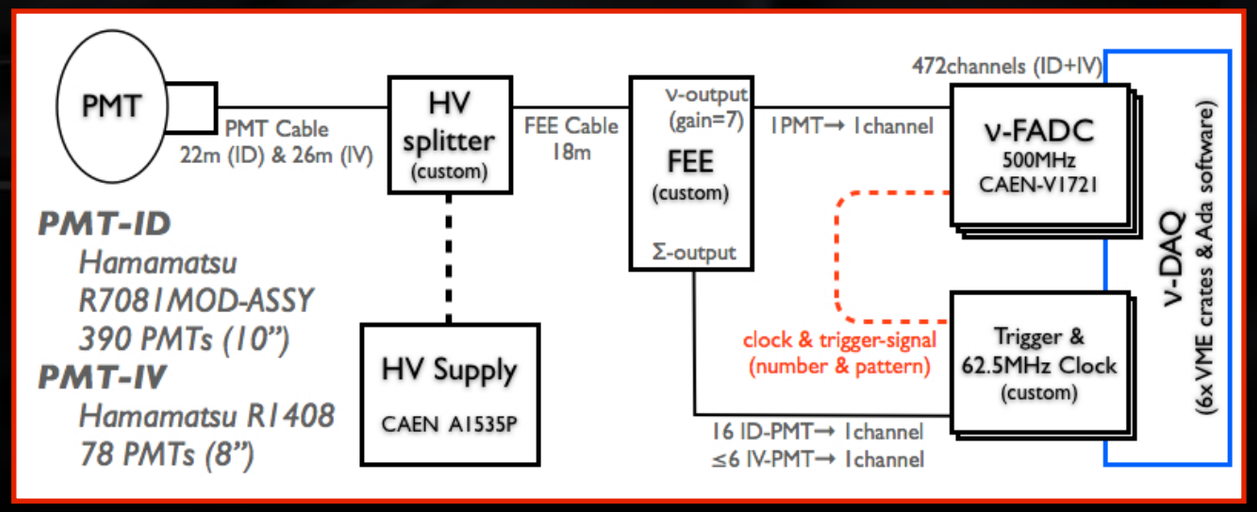
a "horizontal OPERA"

our virtual near detector (MC)…

detector & readout simulation…

- **physics: generators** (G4 + customs)
  - IBD prediction @ FD: δ(flux): 1.7% [next slides→]
- **DATA/MC detector remarkable agreement**
  - δ(response): <0.5% [next slides→]
  - δ(detection): ~0.5% (n physics modelling)
- **physical detector** (Geant4 based)…
  - conversion: **MeV→γ→PE (@ PMT)**
  - geometry (data tuned)
  - optical interfaces (data tuned)
  - scintillator response (data tuned)
- **detector readout…**
  - conversion: **PE→Charge**
  - PMT + electronics (FADC) (data tuned)
    - pulse shapes, charge, digitisation, etc
- **detector calibration…**
  - conversion: **Charge→PE→MeV**
  - MC: data tuned+calibrated (like DATA)
    - biases & precision (systematics)



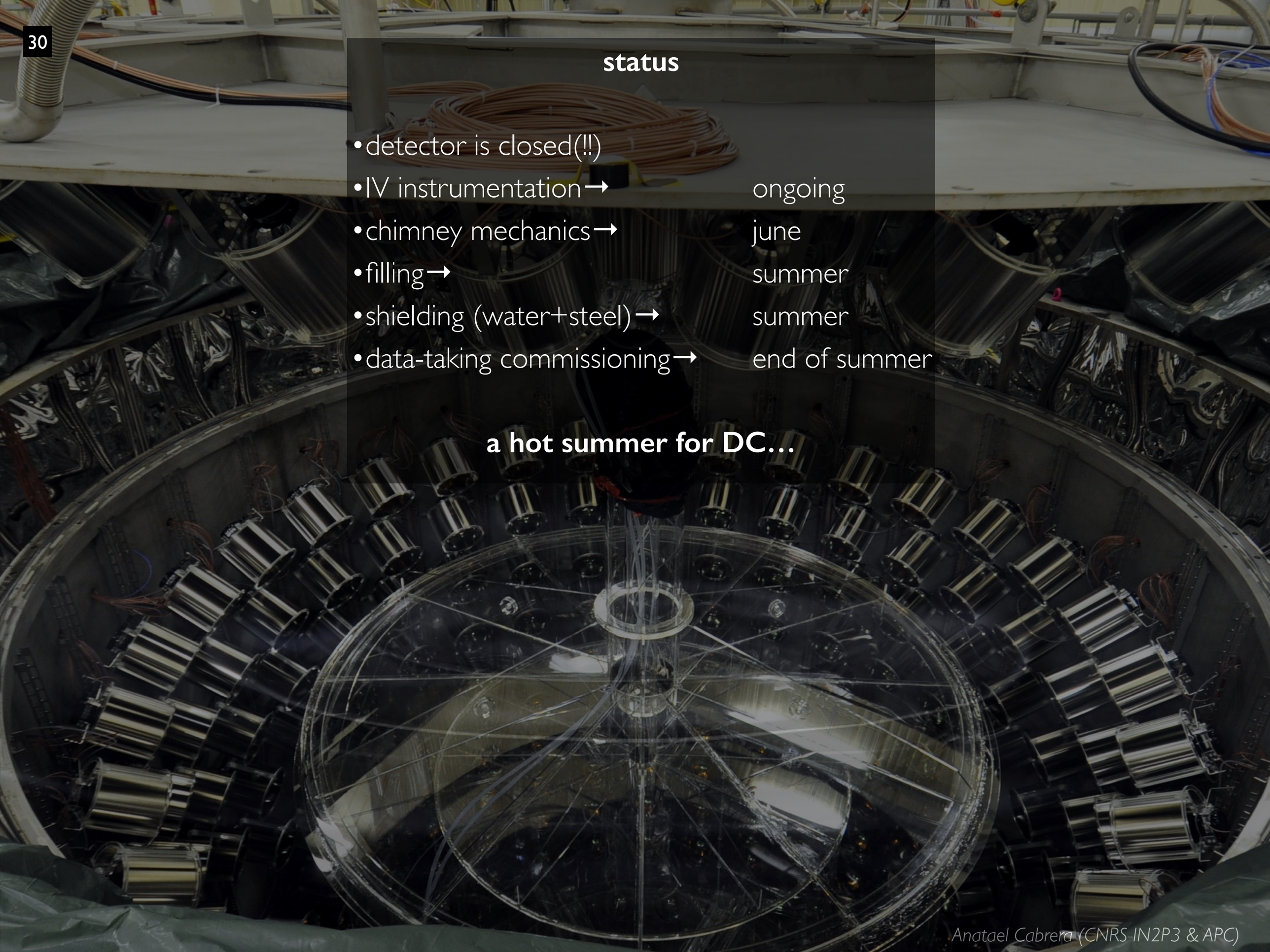


the near detector...

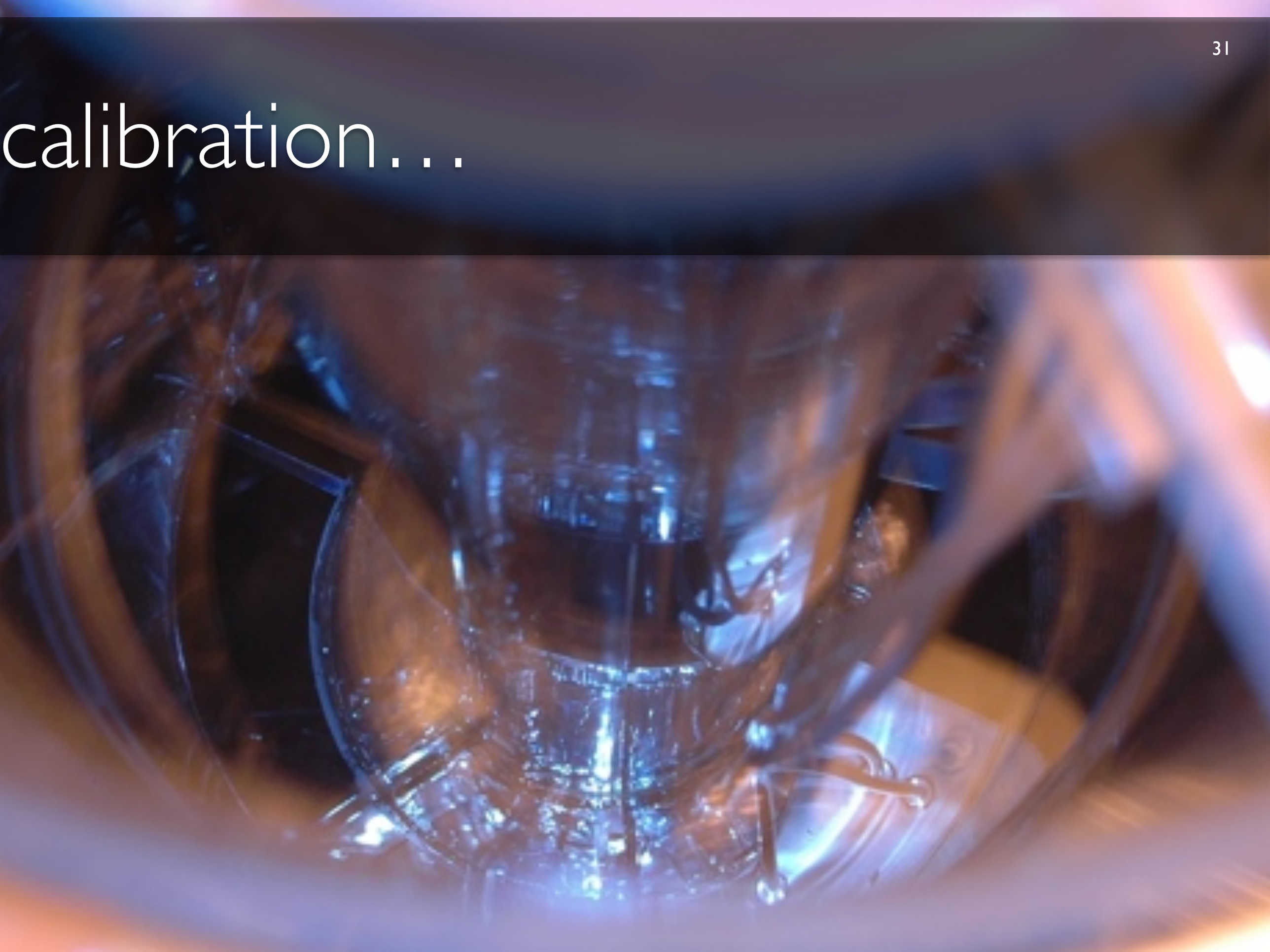
status

- detector is closed(!!)
- IV instrumentation → ongoing
- chimney mechanics → june
- filling → summer
- shielding (water+steel) → summer
- data-taking commissioning → end of summer

a hot summer for DC…

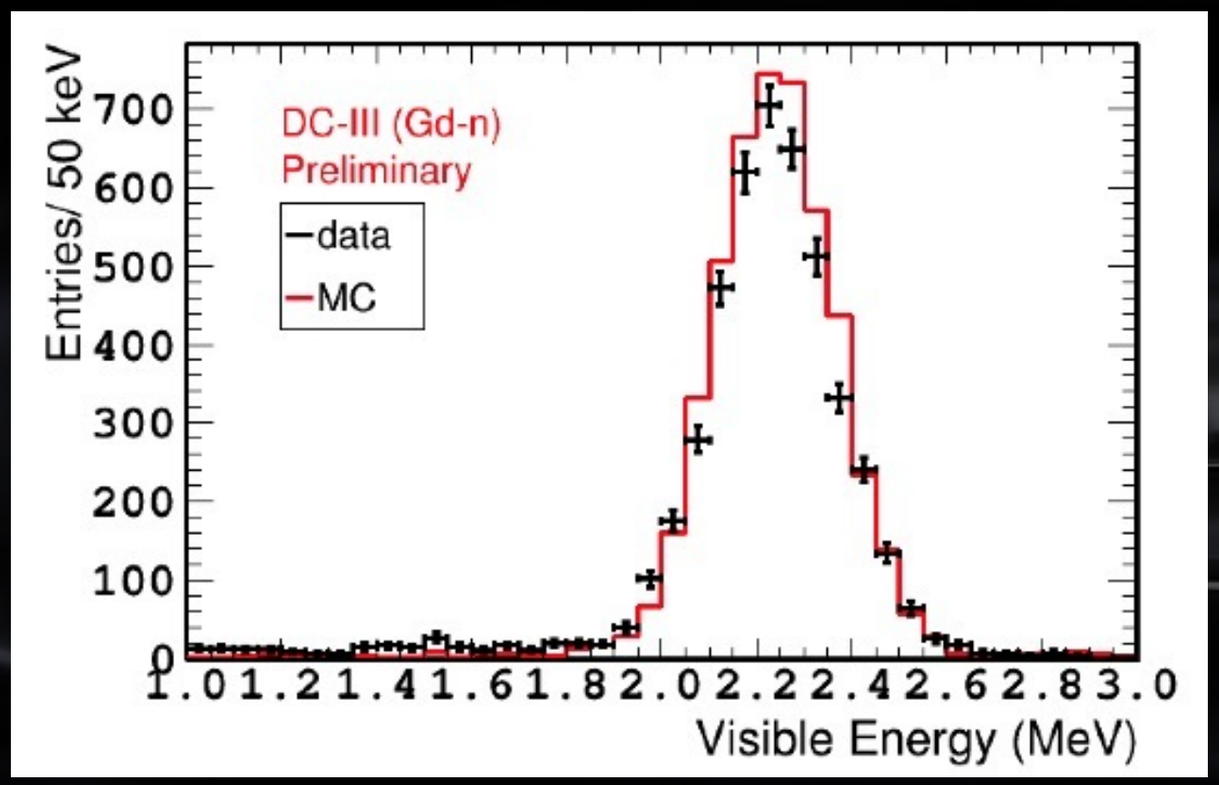


calibration…

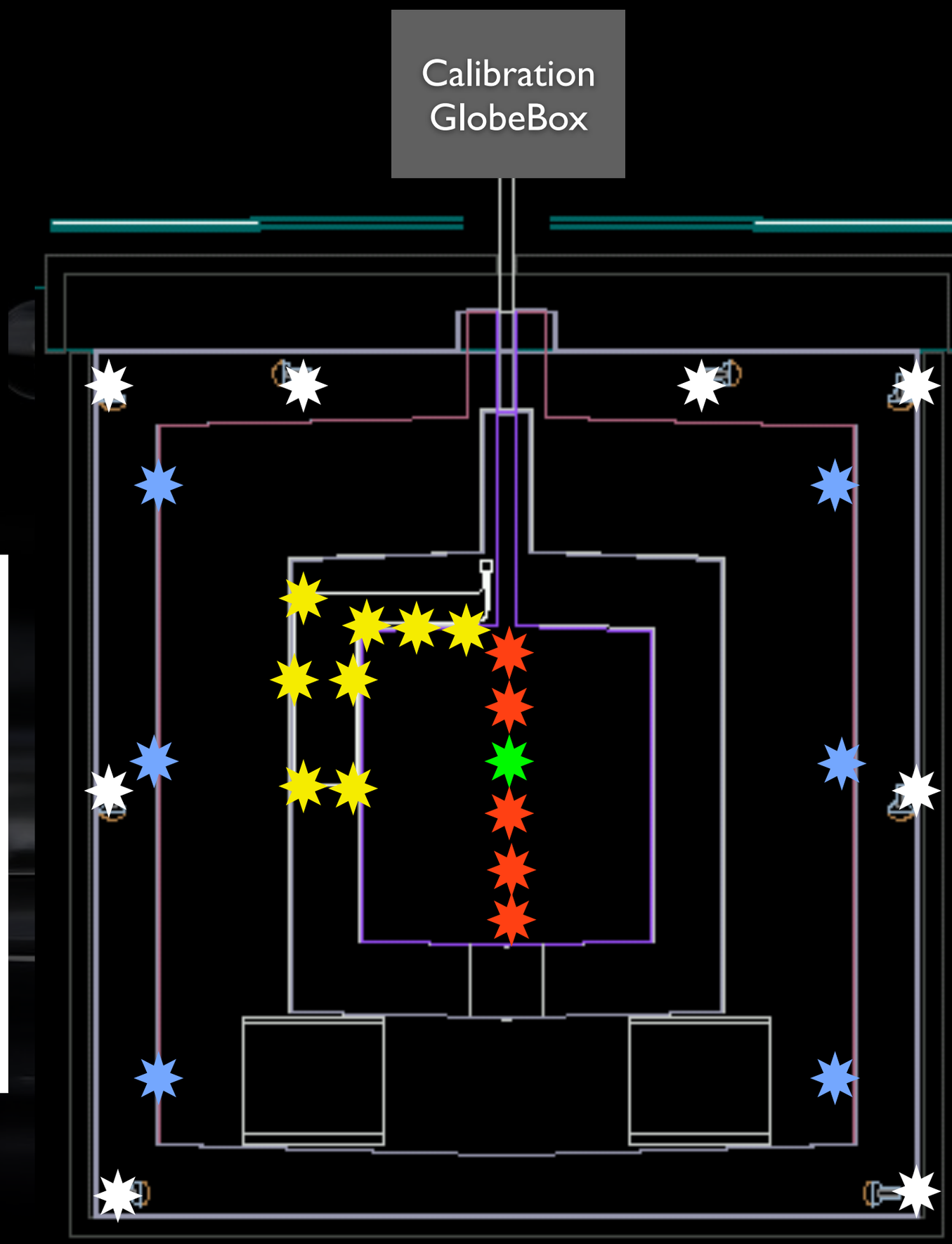


calibration system…

- **in-built:** light LED (**ID** + **IV**)
- **deployable** (^{137}Cs, ^{68}Ge, ^{60}Co, **^{252}Cf**, lasers)
  - **z-axis**
  - **GC guide-tube**
- **natural:** H-n, C-n, Gd-n peaks (**μ**'s fast-n), BiPo, IBD (delay spectrum→ validation)
- **principle:** redundancy critical for systematics

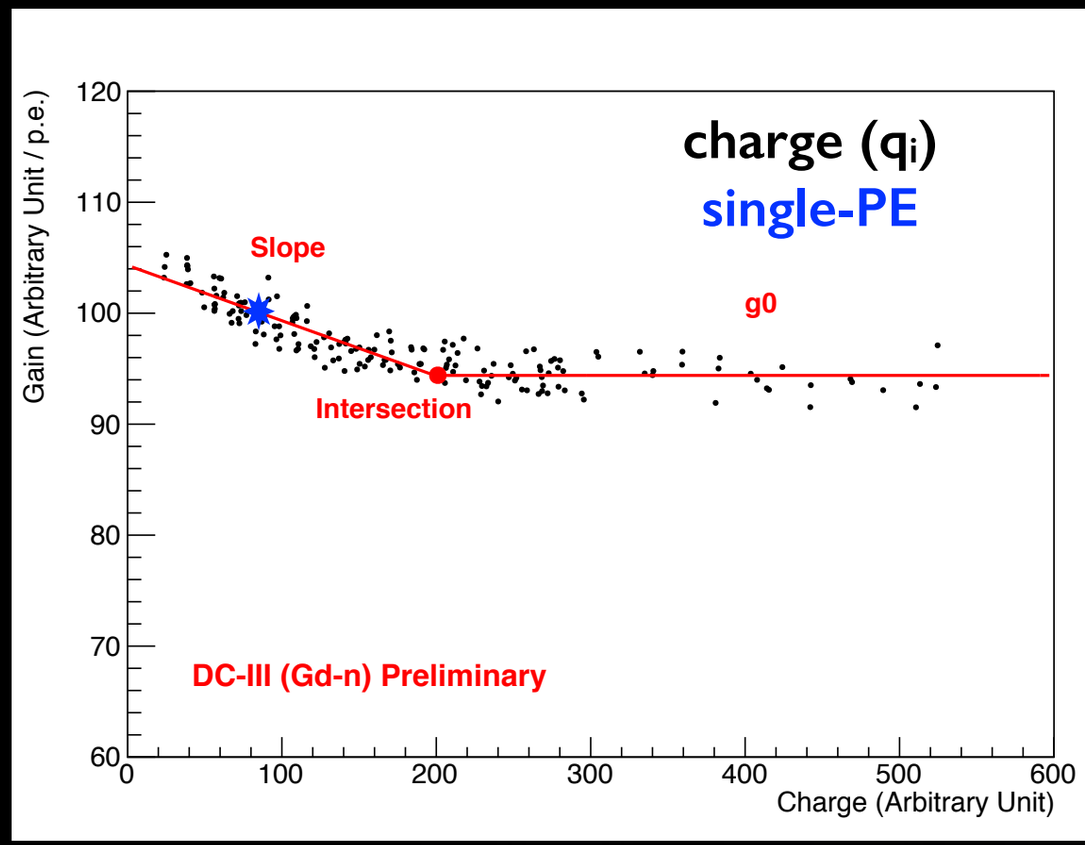


MeV definition (H-n peak @ center)
(our *standard candle*)

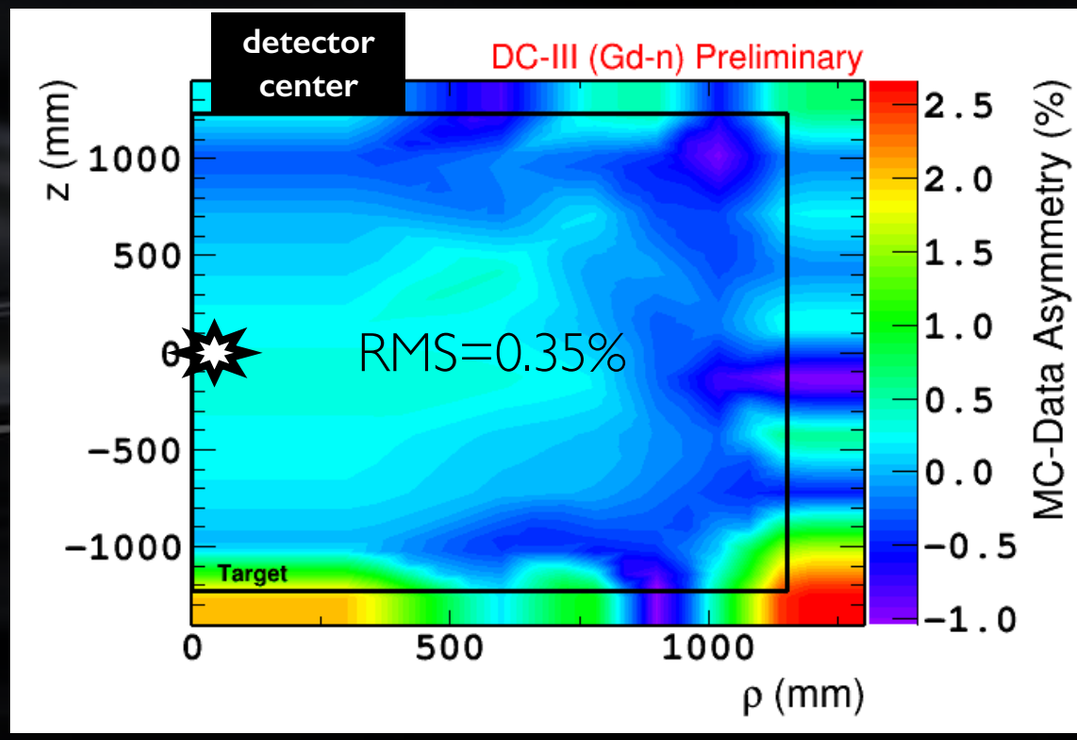


energy reconstruction (I)…

- **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)

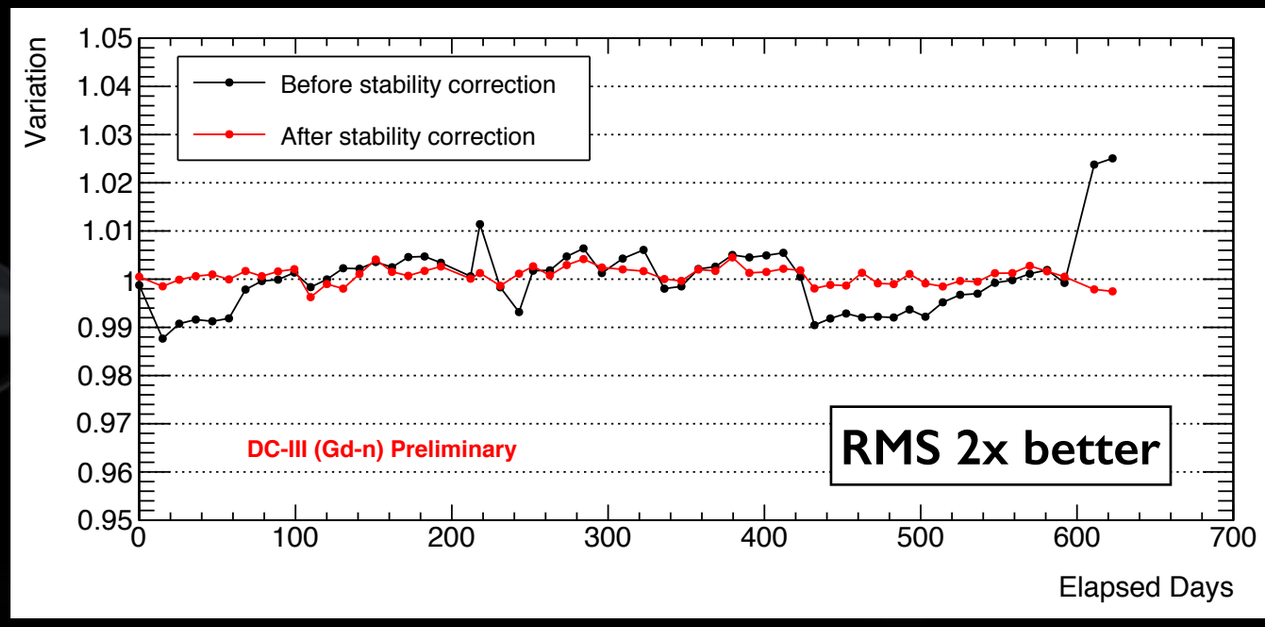


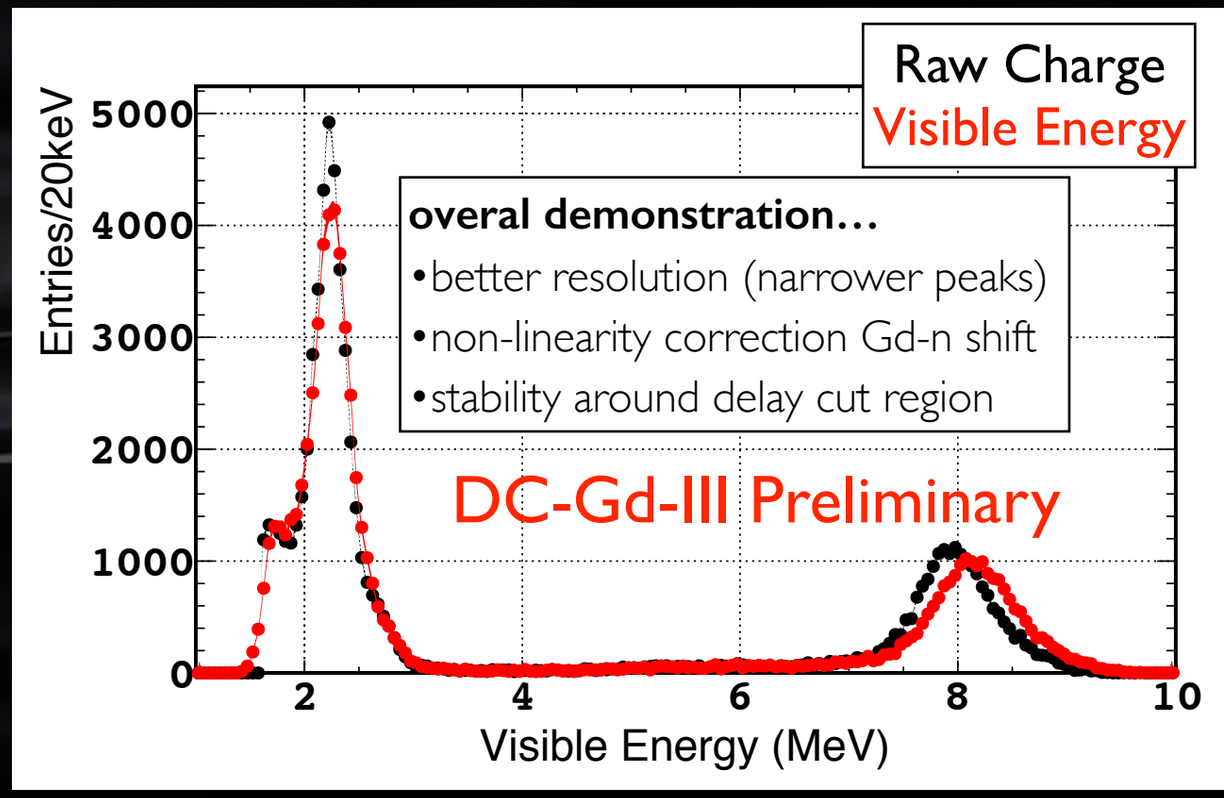
- **Uniformity Calibration…**
  - def: create H-n response full volume MAP
  - conversion **PE(ρ,z)[Δ≤8%]→PE(center)** [Δ≤0.5%]
  - impact: **uniformity (+++)**
- **MeV (or absolute) Energy Calibration…**
  - conversion: PE(0,τ)→MeV(0, τ)
  - use ^{252}Cf @ (ρ=0, z=0, t=τ)→ H-n peak: 2.223MeV
  - DATA to MC equalisation (prior <0.5% agreement)



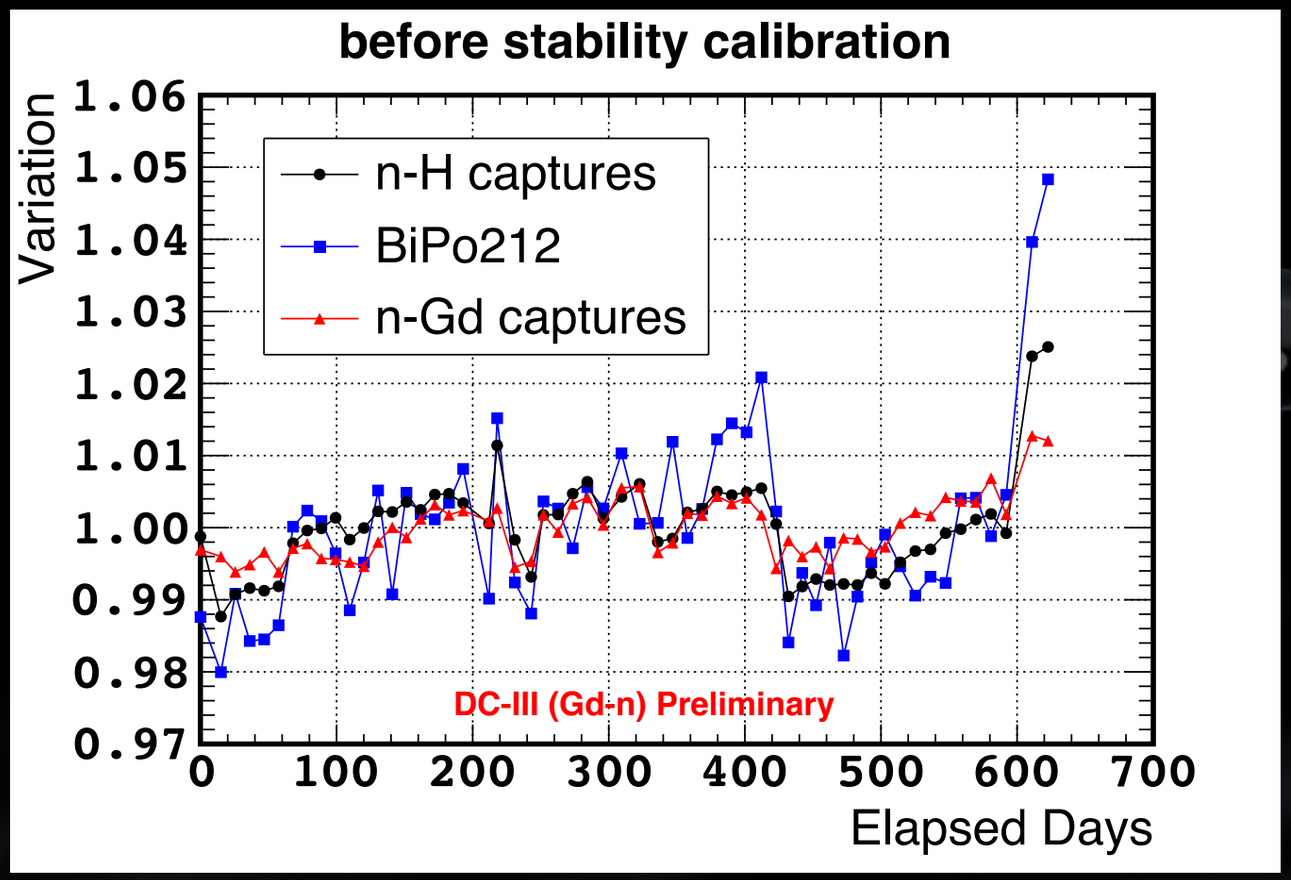
energy reconstruction (2)…

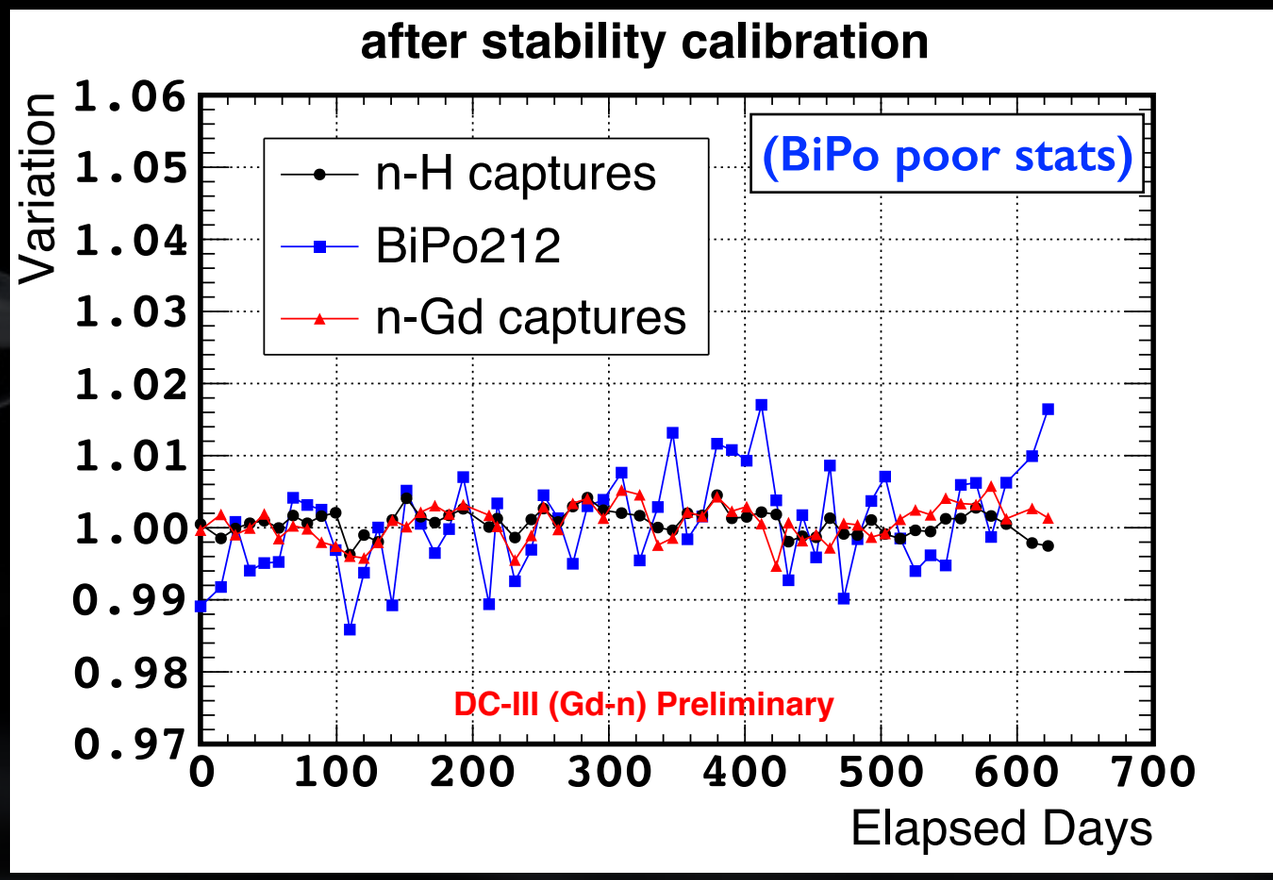
- **Drift Stability Calibration…**
  - def: **PE(t)→PE(τ)**, where τ: time MeV definition
  - response drift by +0.5%/years (unknown)
  - impact: **stability (+)**
- **Charge Non-Linearity Calibration…**
  - readout driven-non-linearity→ Δ(H-n,Gd-n)=~1%
  - validation with C-n peak @ 5MeV & ^{12}B spectrum
  - 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.





response stability (with energy dependence)…





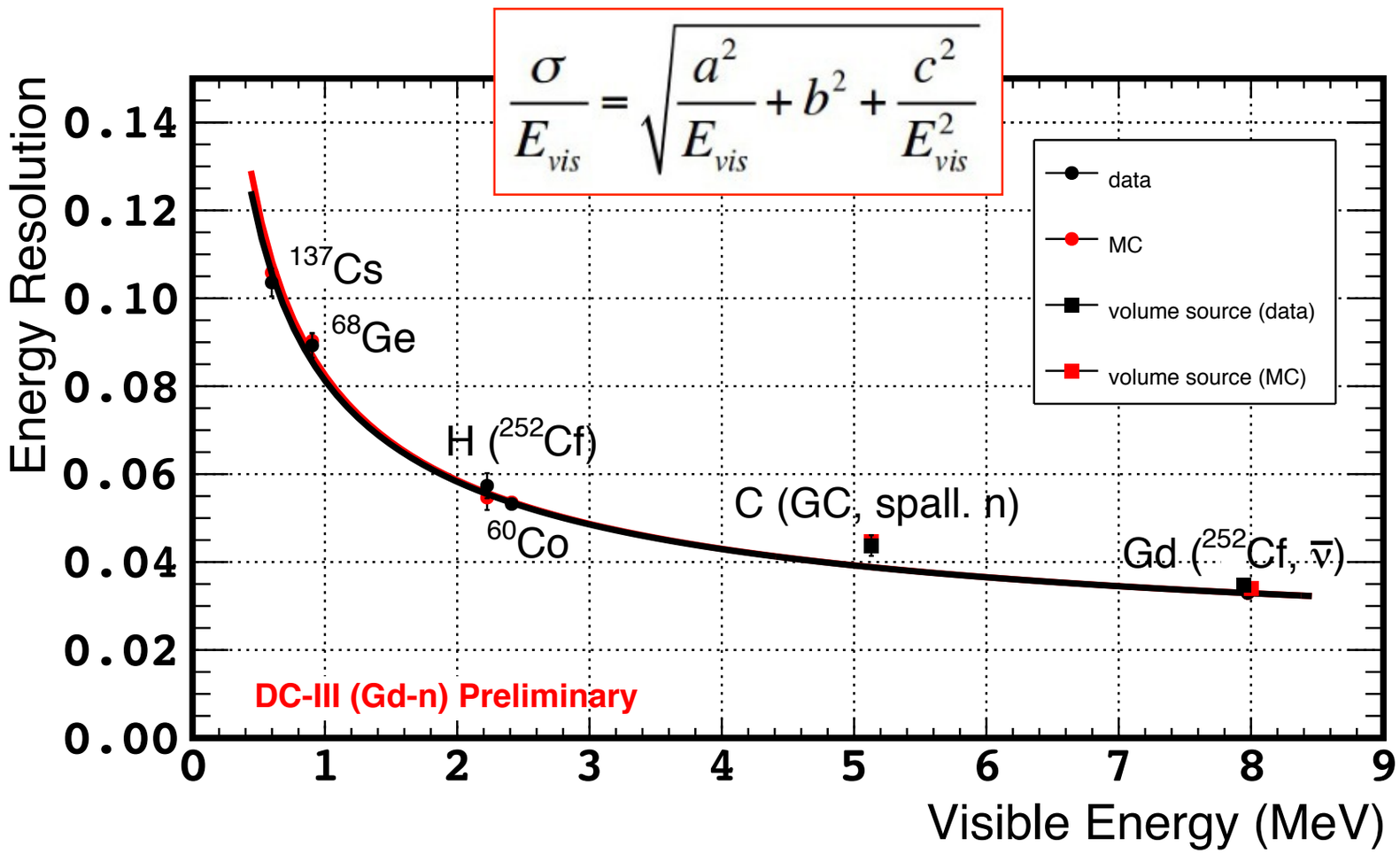
raw response stability→ large non-statistical variations (electronics power cycle)

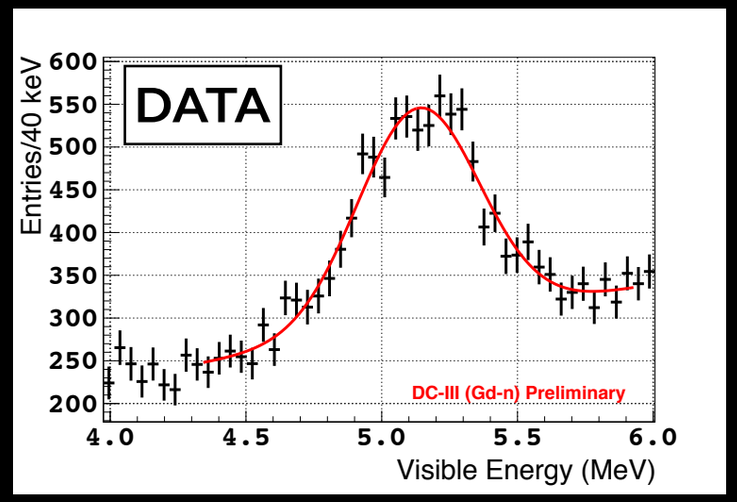
(**Δ up to 7%**)

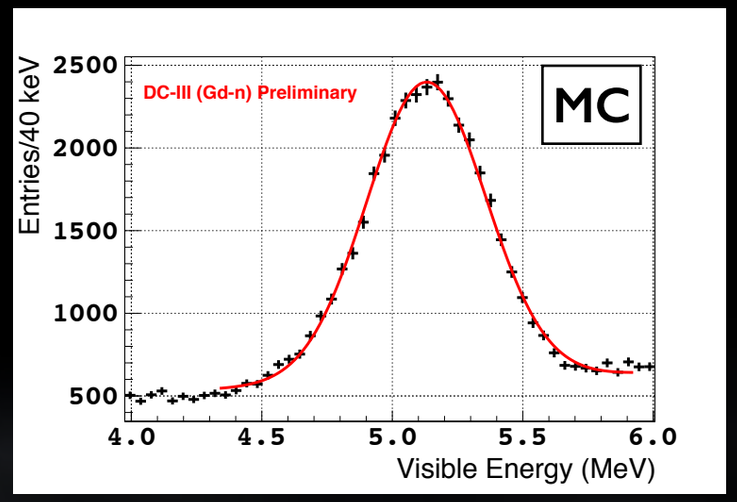
corrected response→ pattern consistent with <u>statistics dominated</u>

(**Δ≤0.5% + RMS 2x better**)

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 <u>anywhere in NT and GT</u>
  - C-n peak (mainly from GC) → slight different response in GC (worse)
- **constant term of resolution ~1.8%** (powerful calorimetry)
  - dominated by stochastic term

our analyses (I,II and today III)…

experiment systematics (nut-shell)

systematics	rate	shape (energy spectrum)	single detector (%)	multi detector (%)	suppression factor
δ(flux)	yes	yes (smooth-ish)	DC 1.7~3.0 (relative to MC)	DC 0.1~0.9 (cancellation)	2x~10x
δ(detection)	yes	no	DC 0.6~3.0 (relative to MC)	≤0.2 (cancellation)	3x~8x
δ(BG)	yes	yes (sharp-ish)	0.2~1.0	0.2~1.0 (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)

status Gd-III improvement…

- **more statistics** (2x)
- **new selection Gd-III**
  (wide-open + more efficient)
- **new energy**
  (more accurate + non-linear)
- **new BG vetoes**
  (unprecedented active BG rejection)

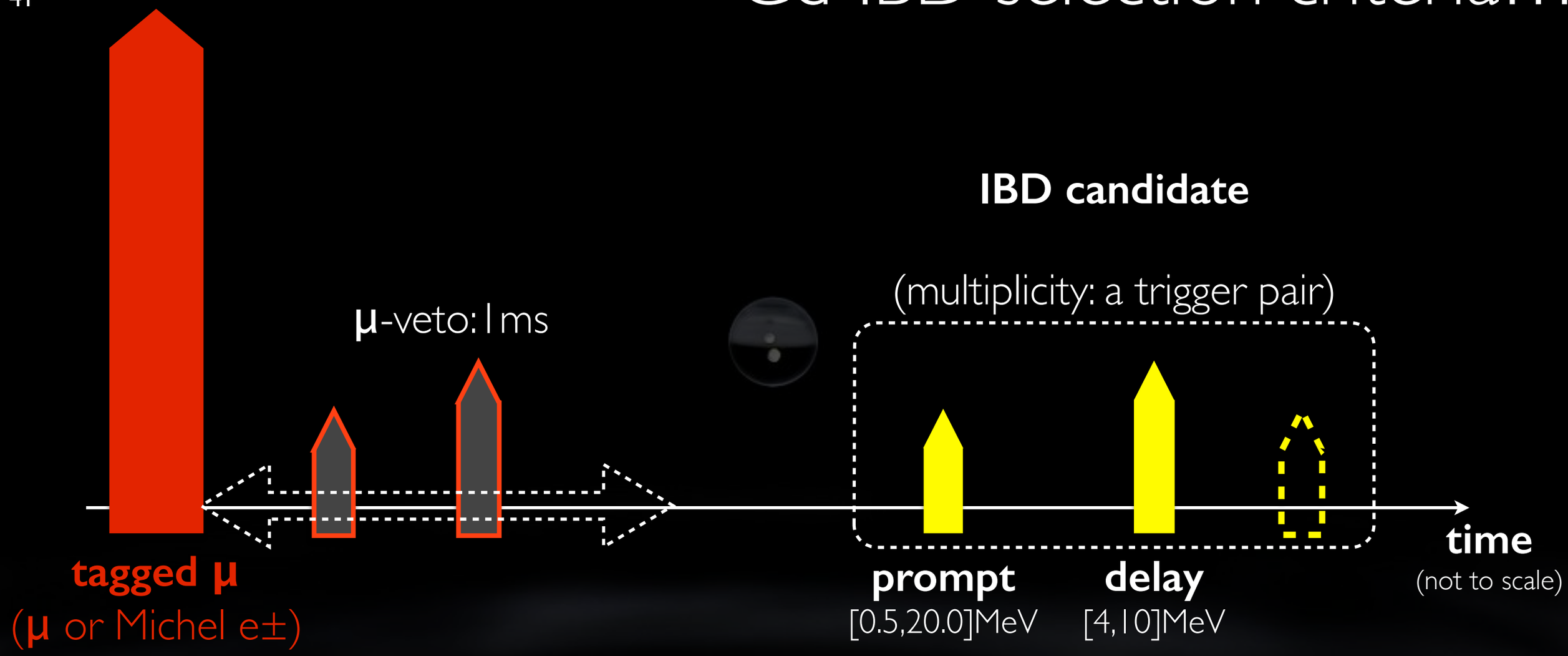
translates into

- **improvement of δ(stat)**
- **improvement of δ(BG)**
  (~3x wrt Gd-II)
- **improvement of δ(detection)**
  (~2x wrt Gd-II)

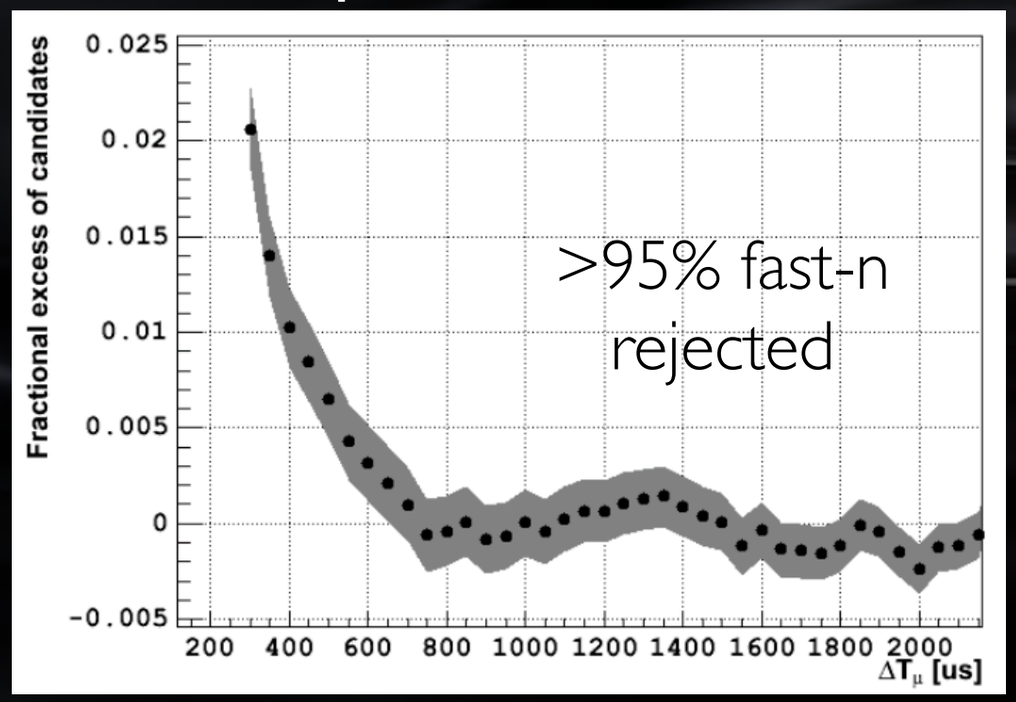
δ(flux) dominating in Gd-II, but it "eclipses" in Gd-III (→ for ND)

the new Gd-III selection…

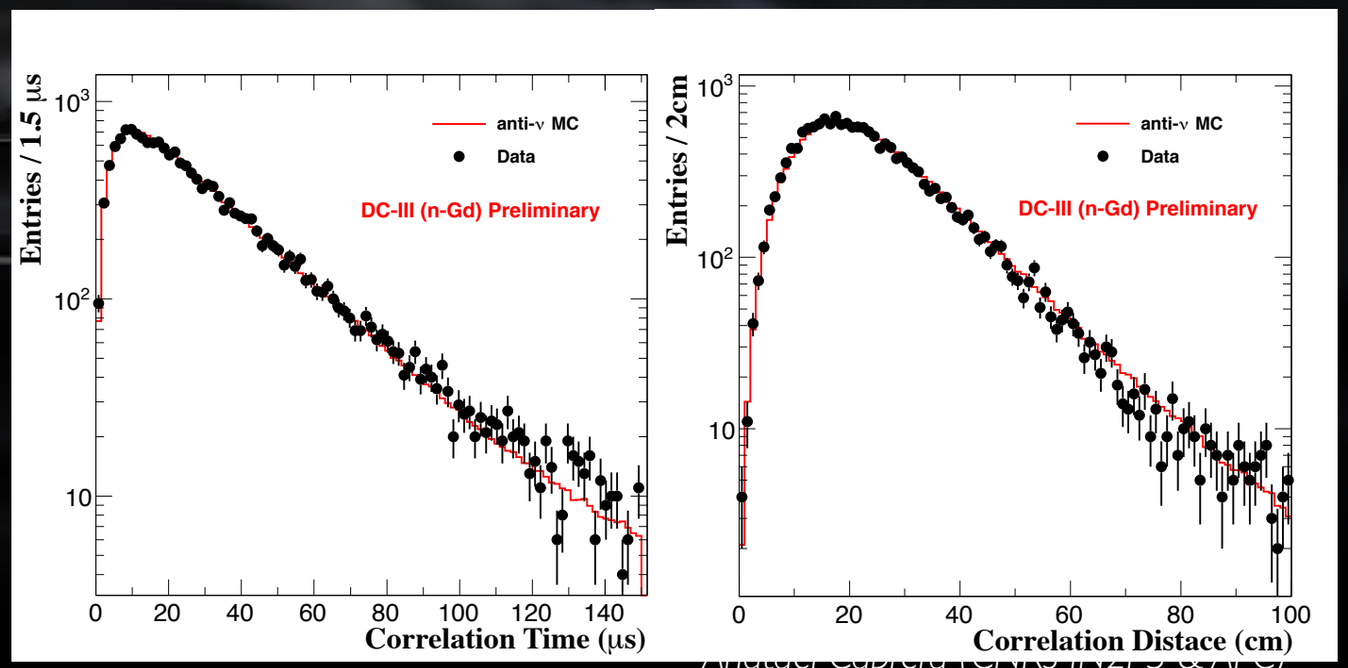
Gd-IBD selection criteria…



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

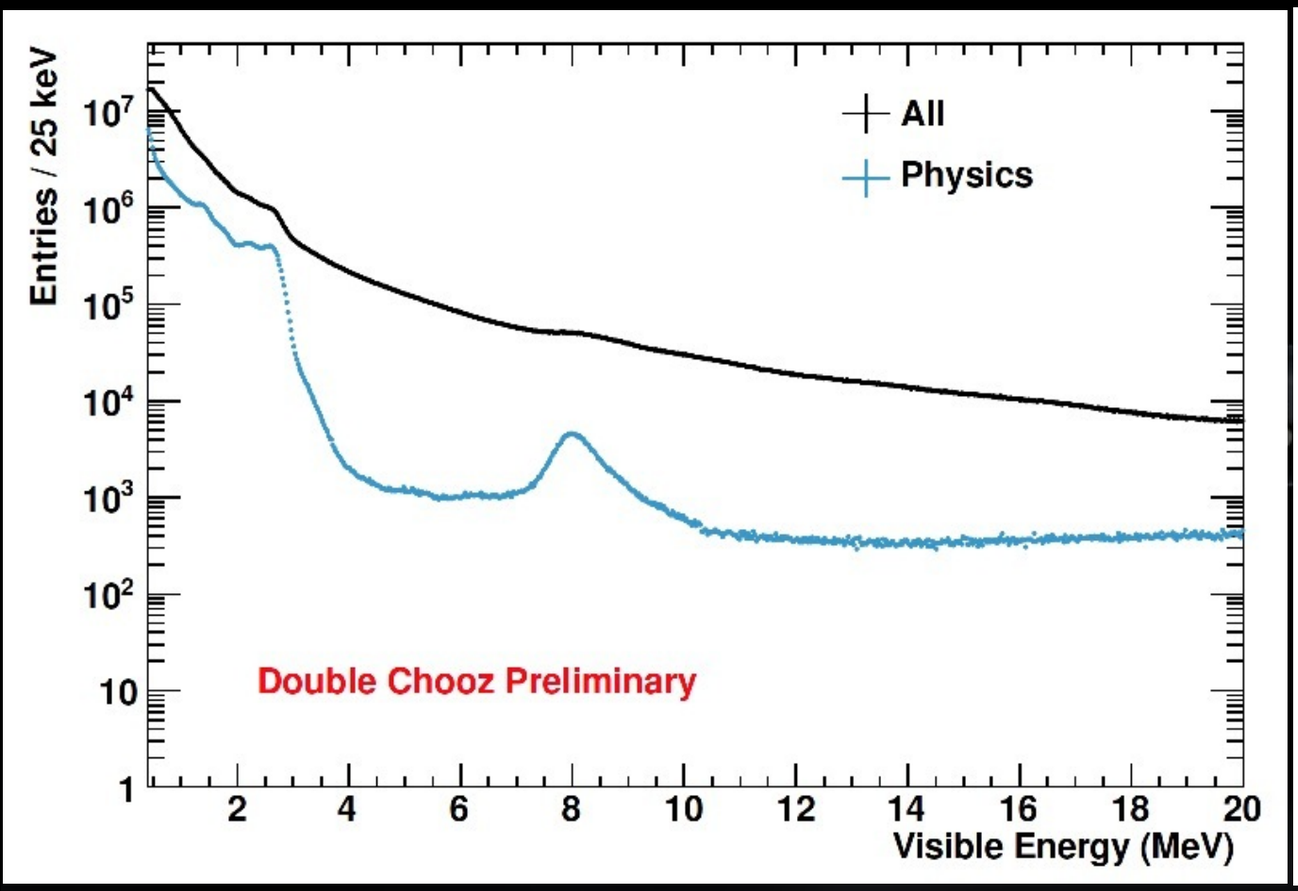
Light Noise Selection

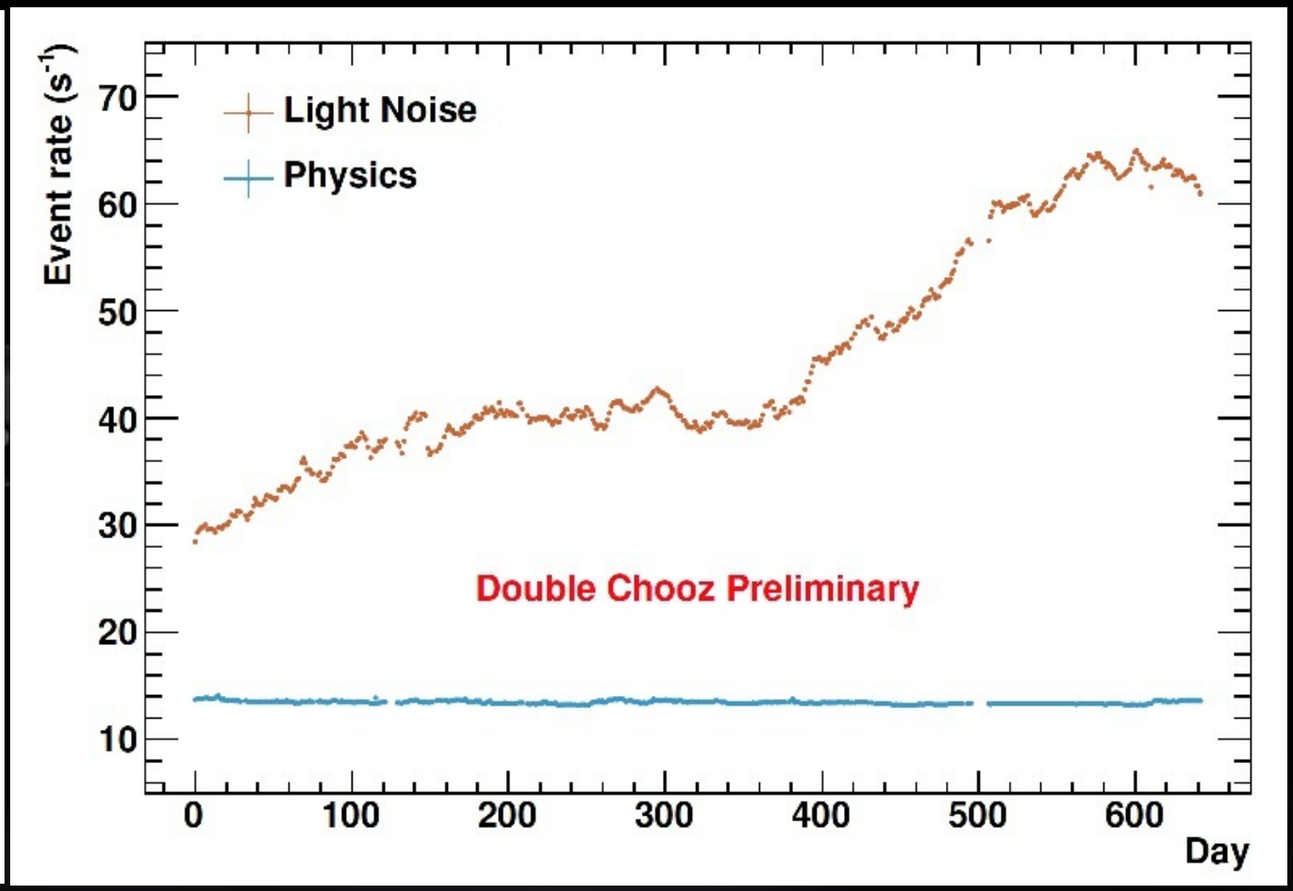
IBD Selection

BG Rejection

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

Light Noise rejection…





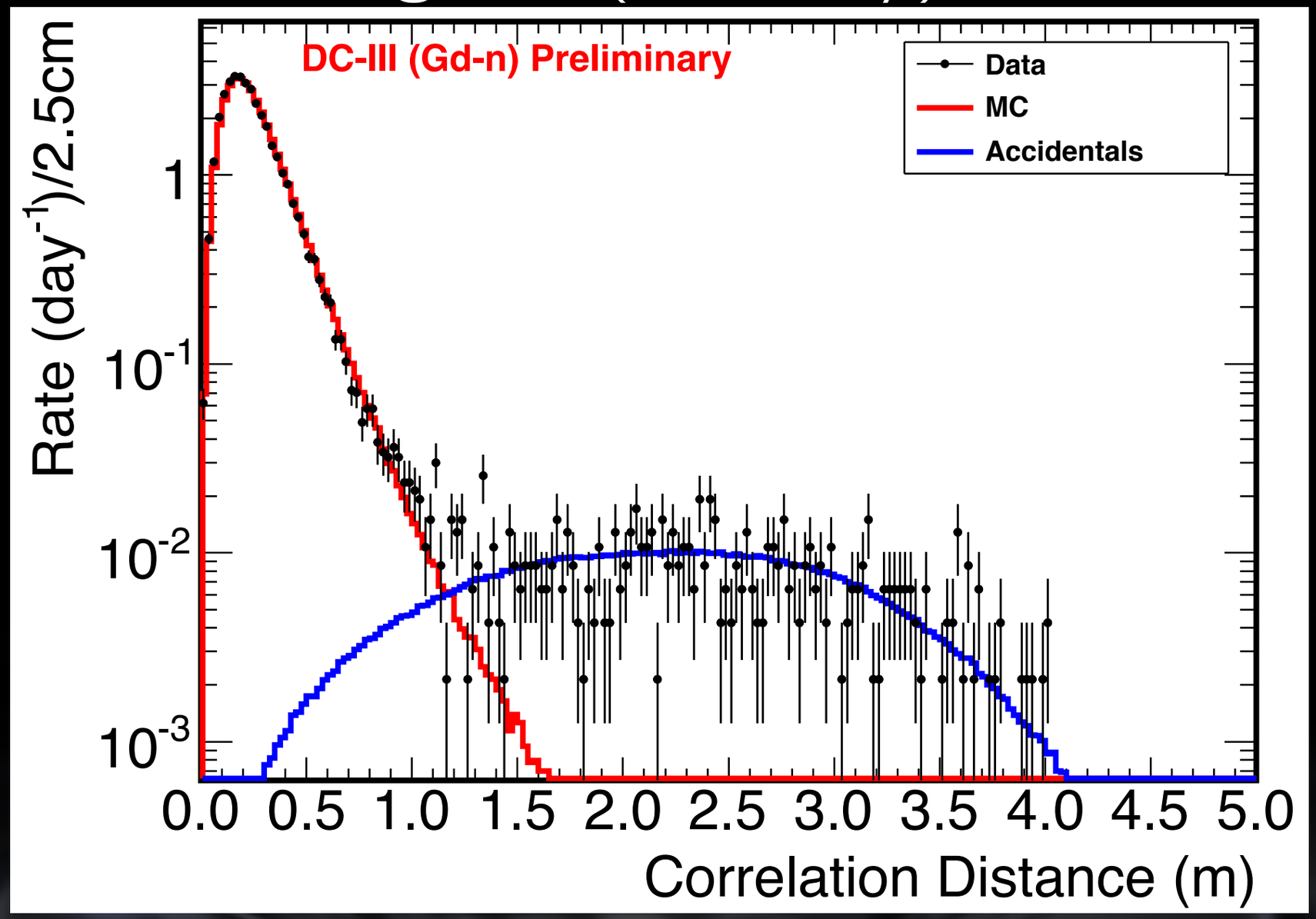
large (an increasing) amount of "light noise" (a few types)

(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)

DC goes (virtually) 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%**)

IBD candidates track reactor activity…

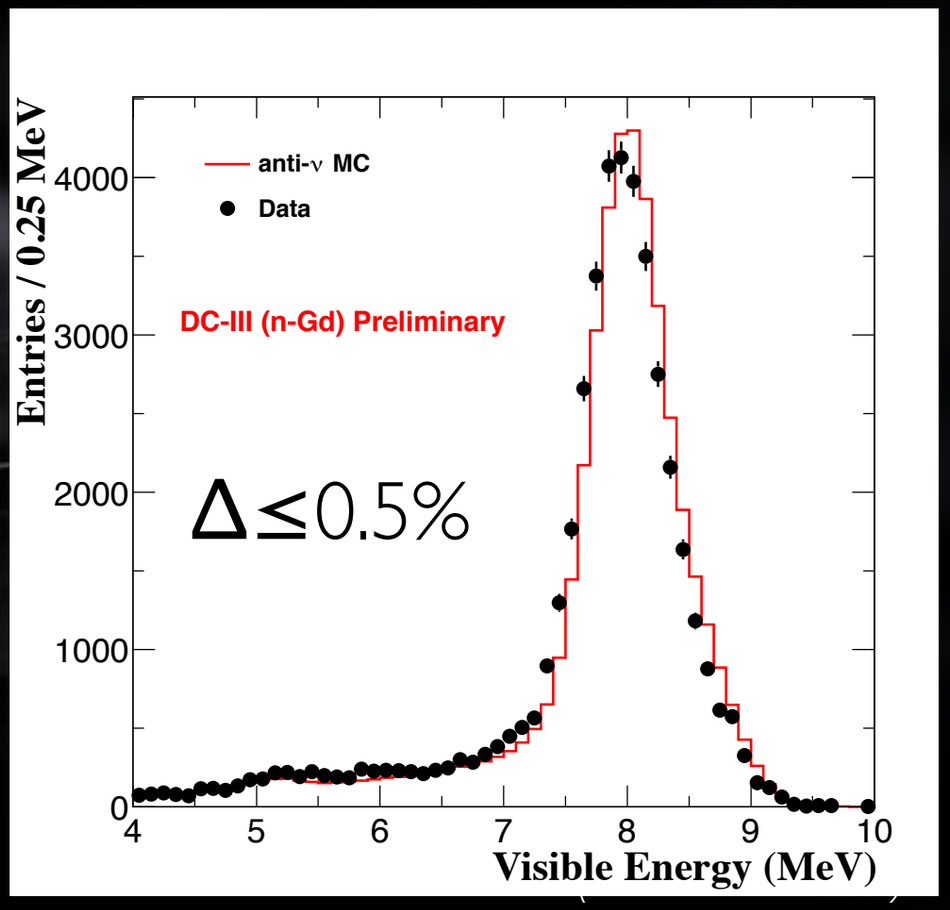
DC-III (n-Gd) Preliminary
Average Rate: 37.1±0.3 day^{-1}
MC Average Rate: 37.5±0.0 day^{-1}
Expected ν rate
Measured candidates rate
2 reactors ON ("2xON")
1 reactor ON ("1xON")
2 reactor OFF ("2xOFF")
Neutrino Rate (day^{-1})
Day

daily IBD candidate variation (no BG subtraction)

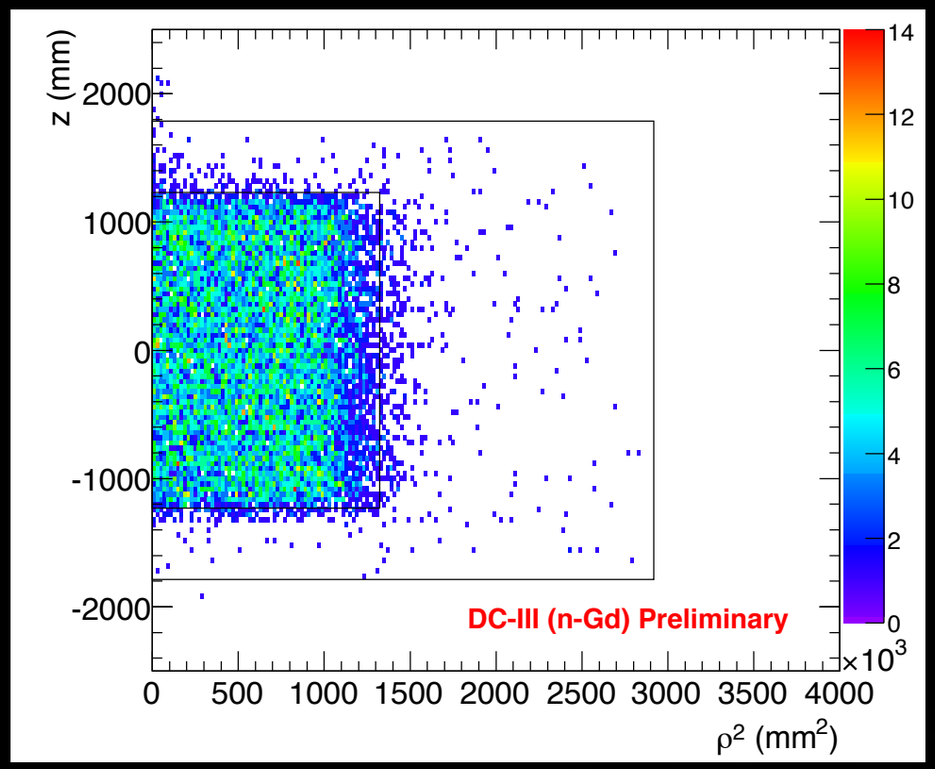
- MC uses reactor power info (100x→ negligible stats)
- accurate reactor power tracking (data~MC)

excellent agreement on Gd-n peak

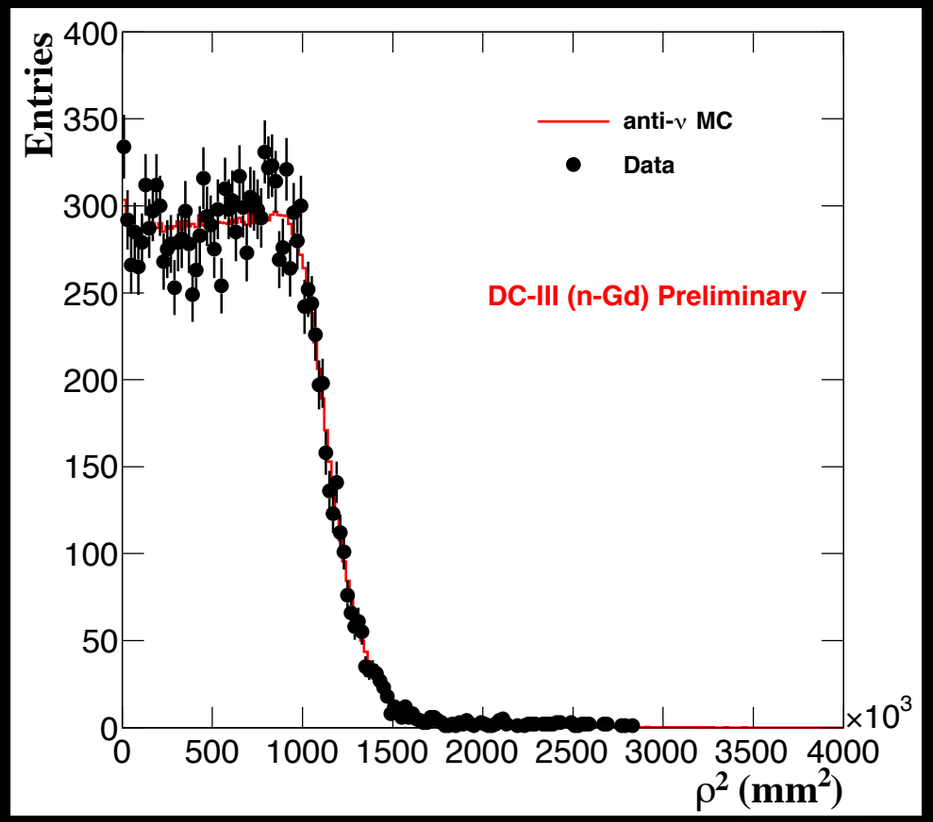
- energy reconstruction (dominating still?)
- n-capture physics model (thermalisation)
- Gd multi-γ de-excitation physics model

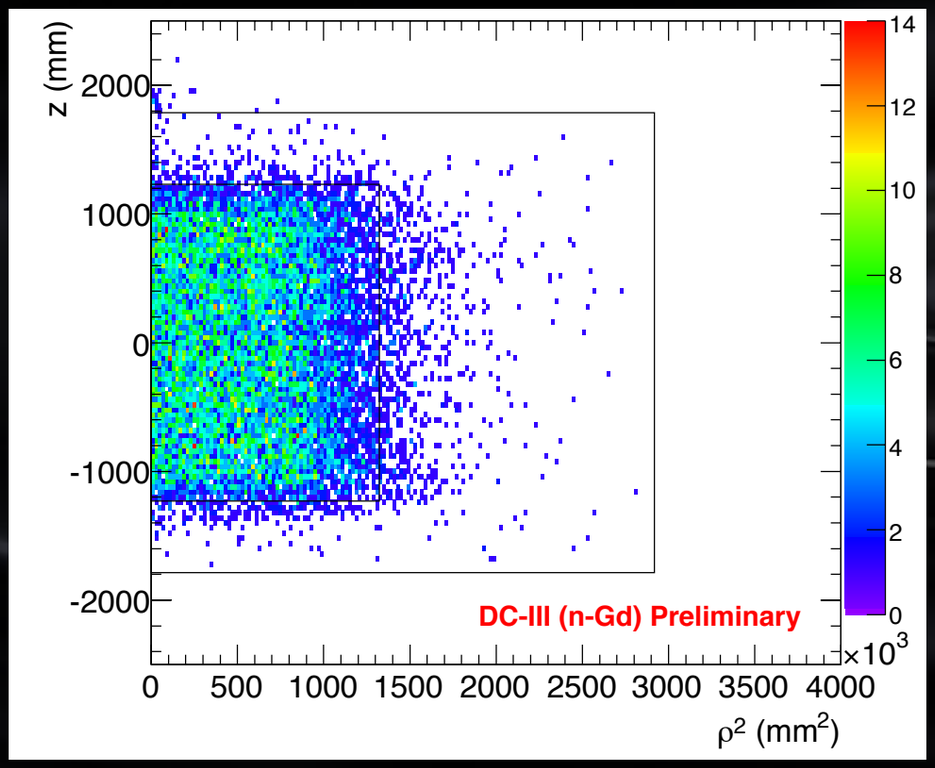


IBDs in the right volume…

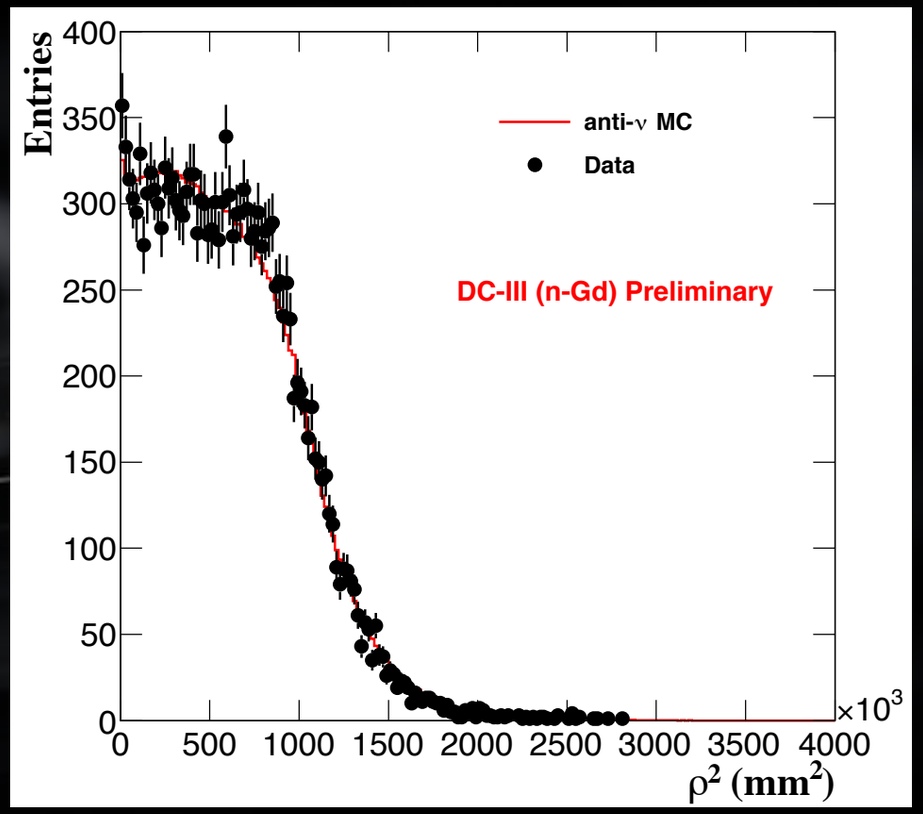


e+: sharp volume definition





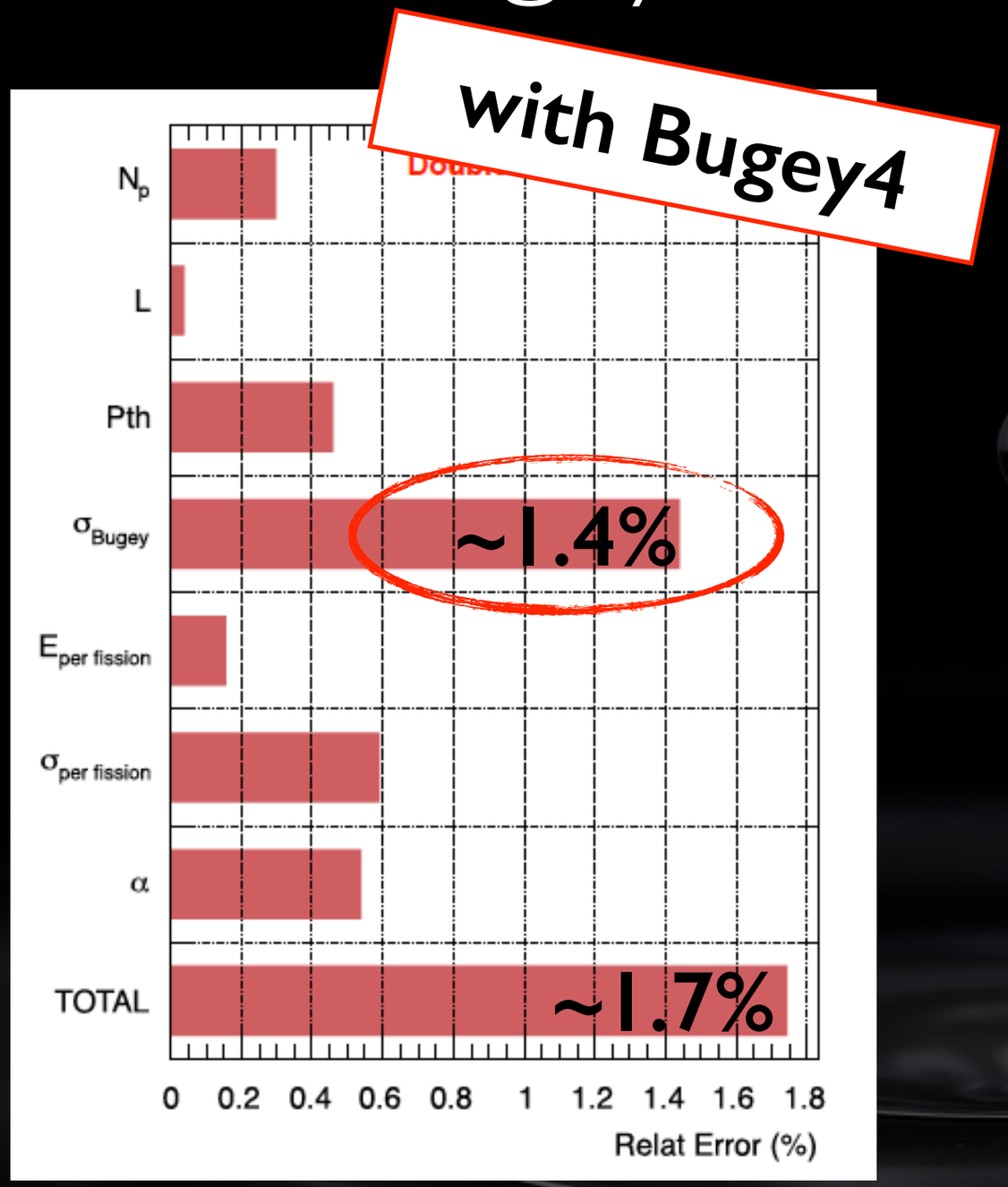
Gd-n: diffused volume definition (few γs Compton)

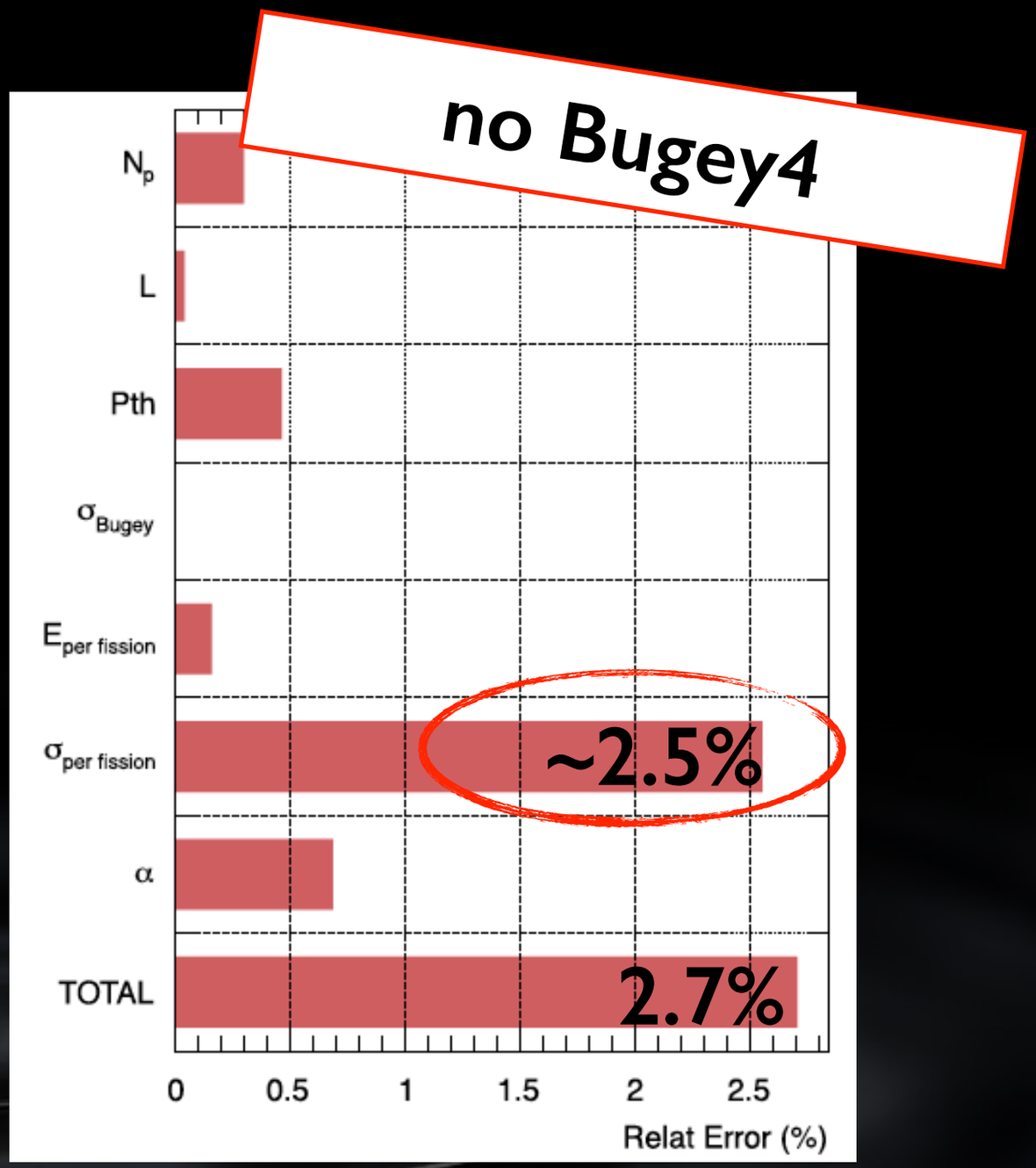


no fiducial volume

flux systematics…

Bugey our "near" detector now…





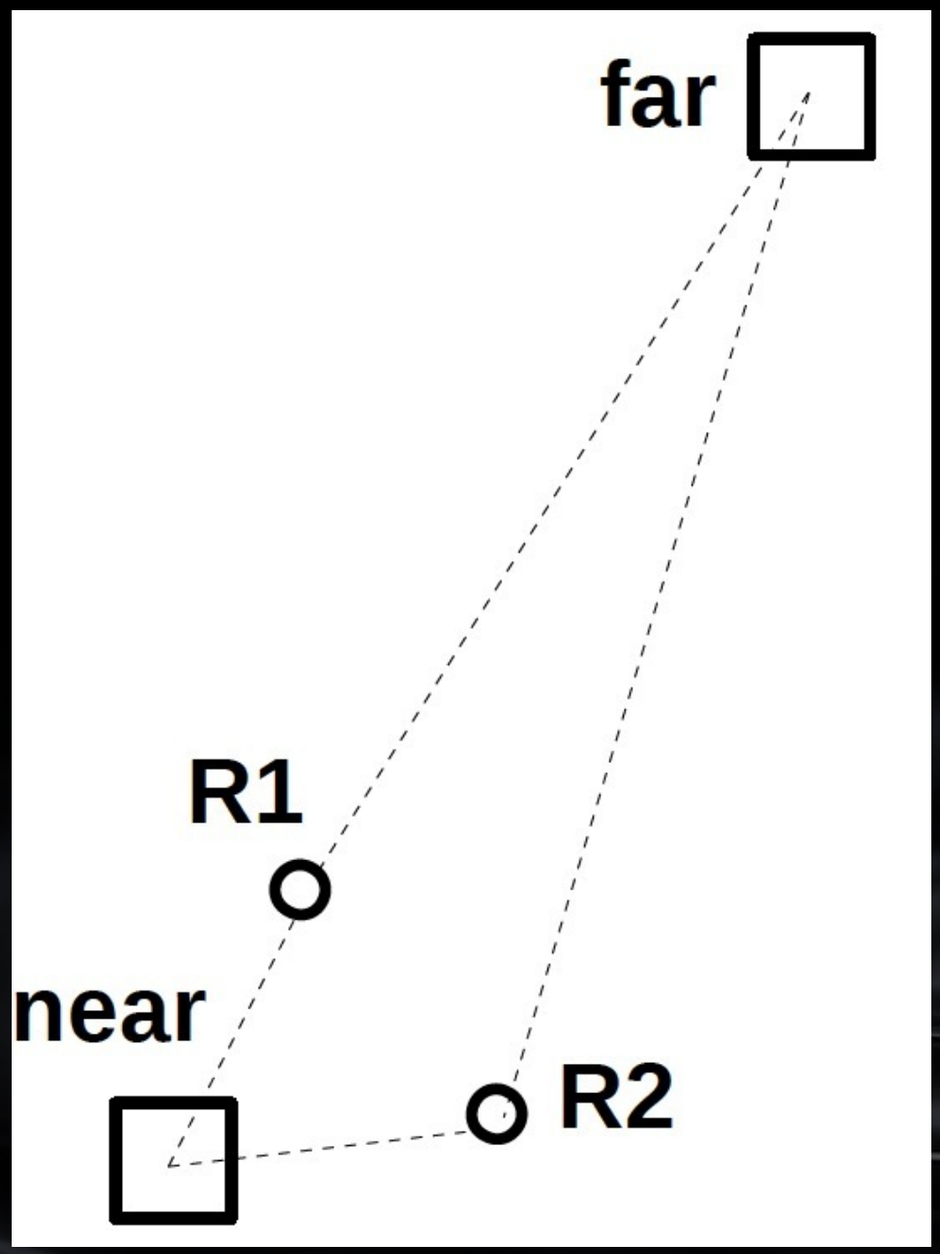
DC used Bugey as effective ND (via MC)

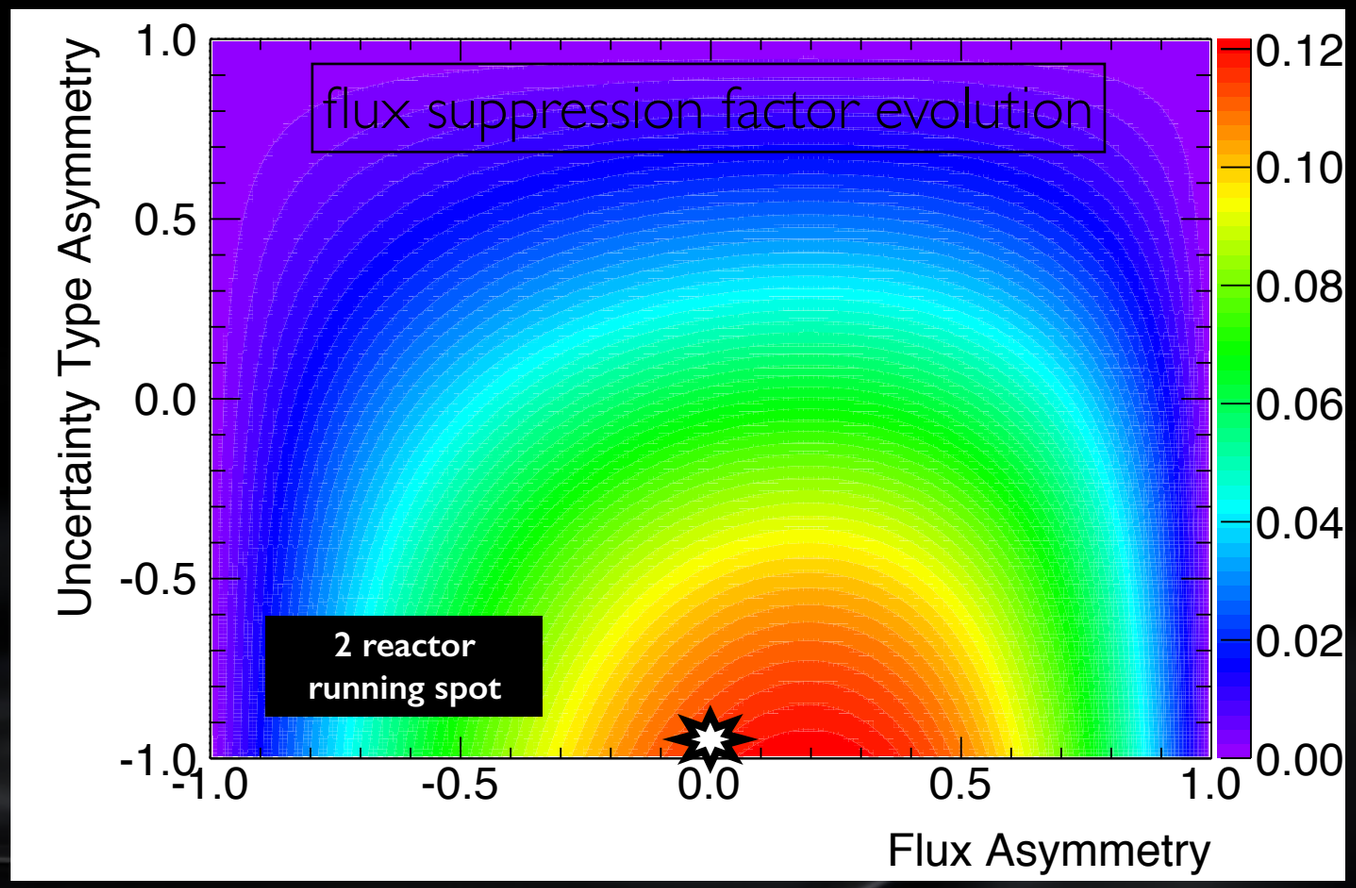
(technique reduces ~30% the dominant flux uncertainty→ used by KamLAND, etc)

major δ(flux) cancellation (with ND)…

DC most isoflux experimental setup

⟹ ~90% δ(flux) suppression





reactor error correlations→ δ(flux) suppression

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

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

detection systematics…

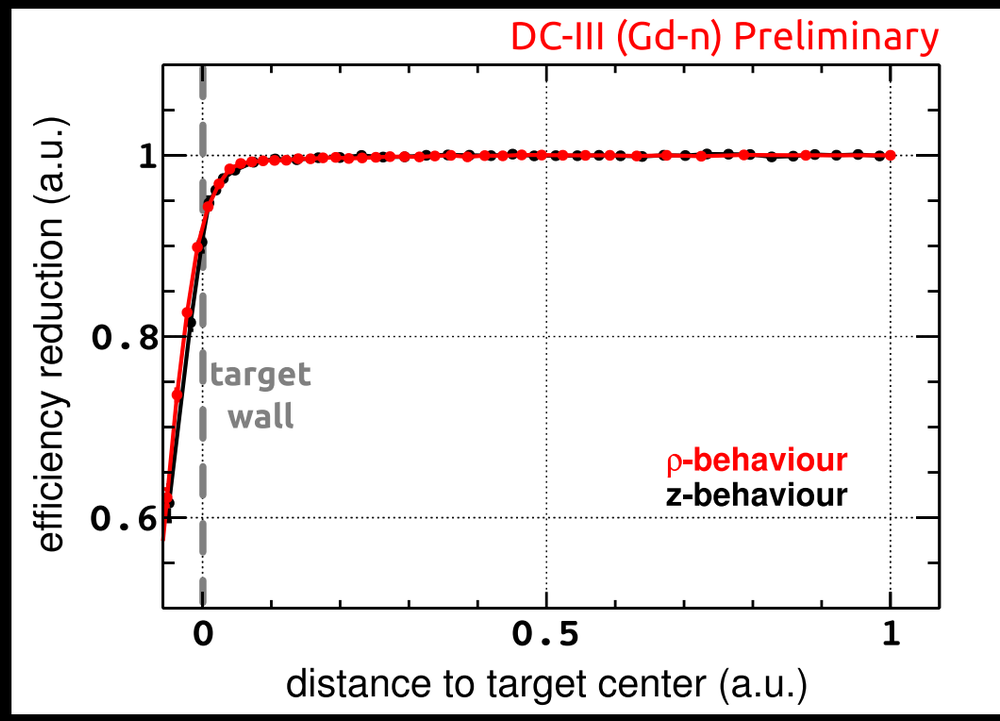
detection systematics

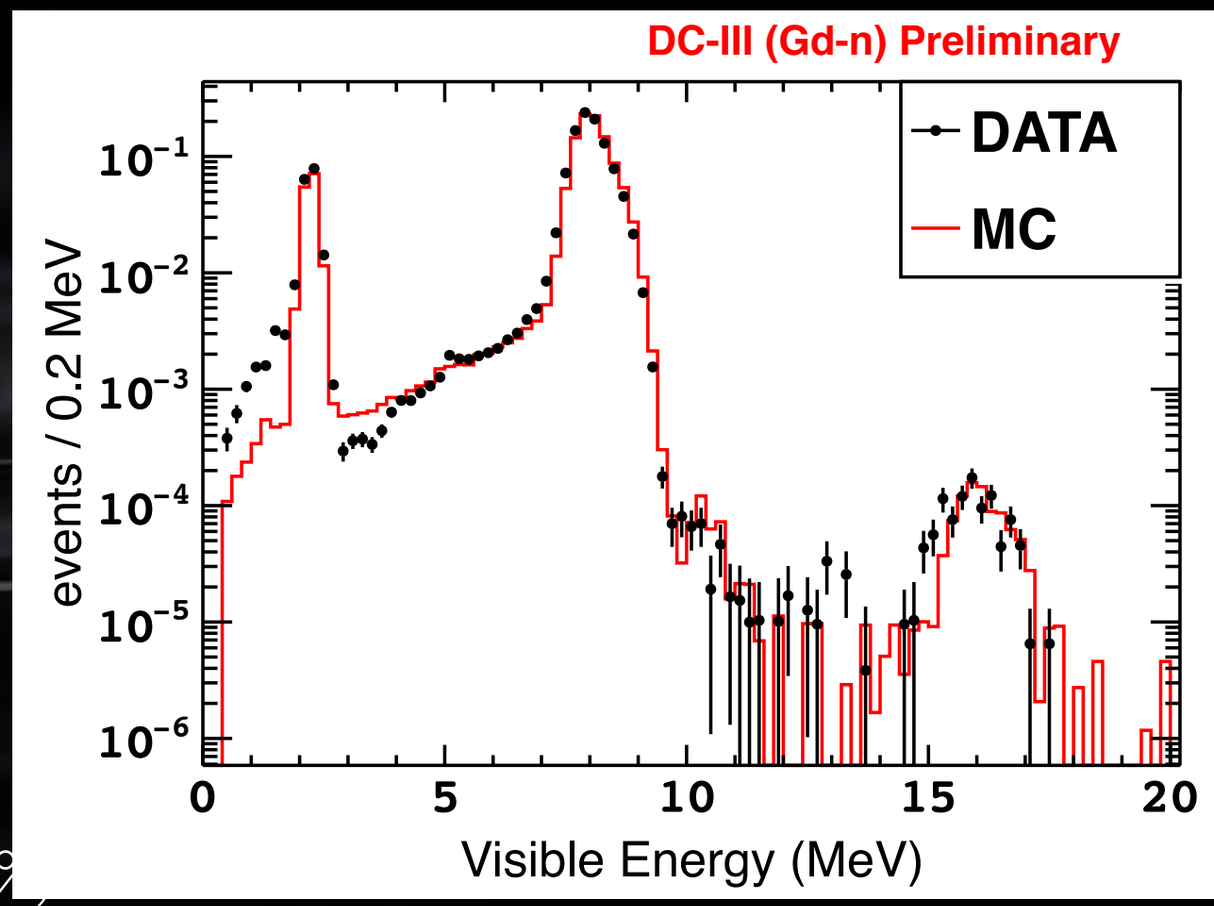
all possible on relative normalisation between FD/MC

- dead-time, vetoes inefficiencies, N(p^+) error, etc.
- correct MC normalisation (wrt FD)
- δ(detection): all errors on all corrections

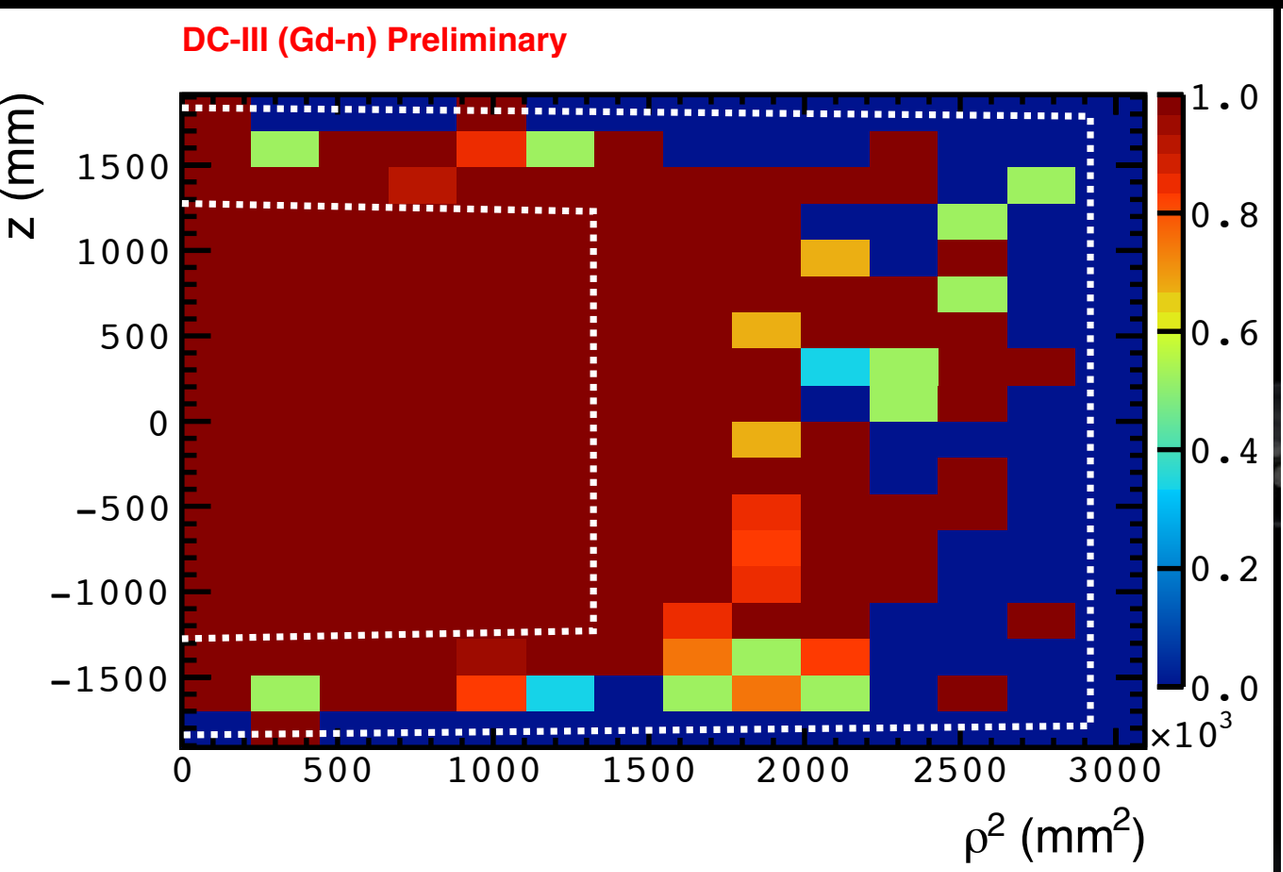
δ(detection) dominant contributions…

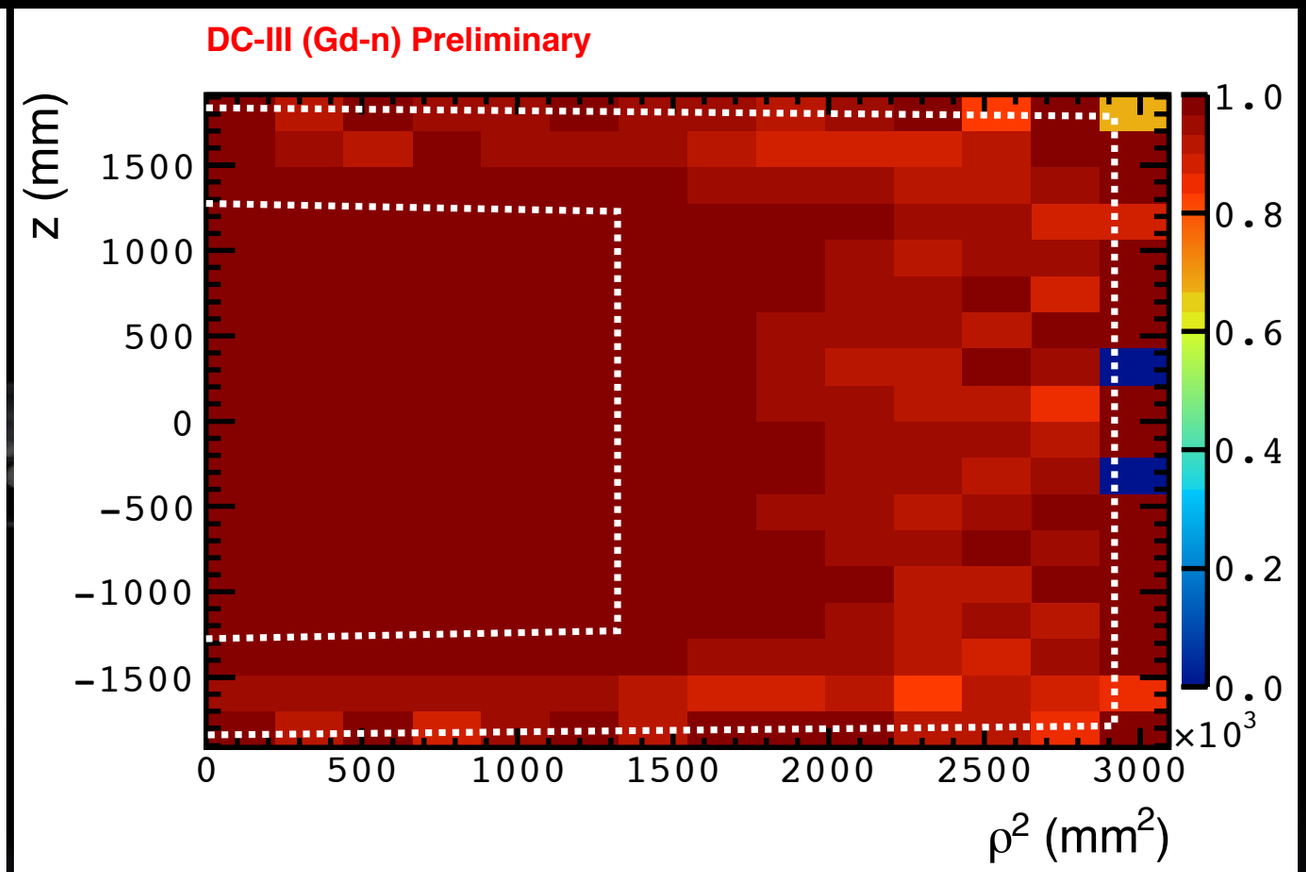
- **inaccuracy of MC dominates (cancel by ND)…**
  - **Gd/H fraction** (depends delicately on n-physics model)
    - **δ(GdF) = ~0.4% (dominant)**
    - validated with Cf, IBD and n-spallation
  - **spill in/out current**
    - **δ(Sio) = ~0.27%**
- **detection efficiency systematics…**
  - new method (estimation & integration)
    - impact new energy & selection
    - ^{252}Cf (integrated via symmetry z=ρ)
      - self-BG of Cf now rejected (**~1% bias**)
    - IBDs (volume-wise, but BG and low stats)
  - **δ(efficiency) = ~0.19%** (Cf and IBD agreed <0.1%)





IBD detection efficiency 3D maps…





IBD allows 3D integration (validates Cf sampling in volume)

IBD and Cf very complementary (sampling, BG, statistics, integration method, etc)

MC inaccuracy dominates most error → major cancellation with ND

BACKGROUNDs

BGs @ DC…

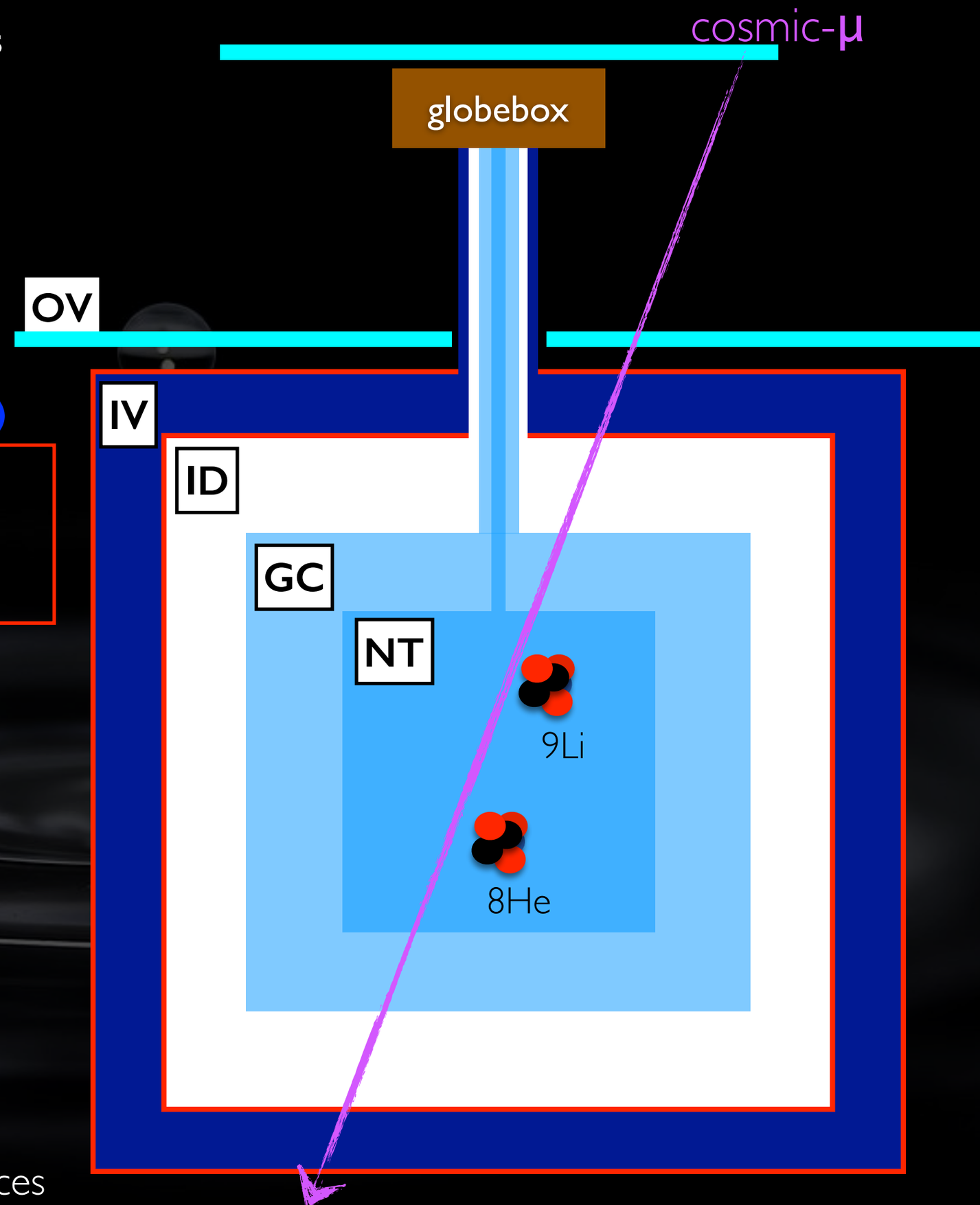
- (one way another) **all BG related to μ's**

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



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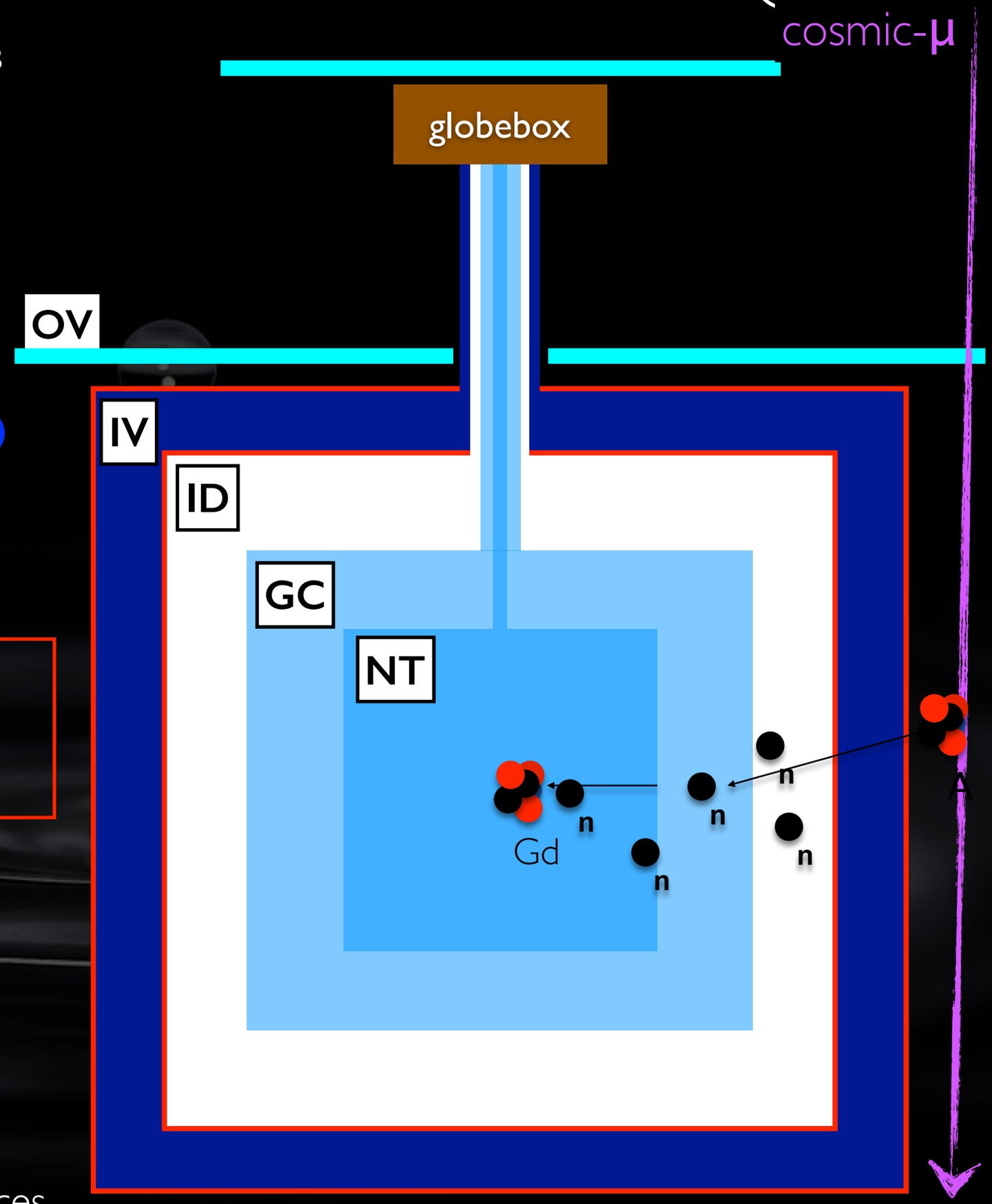

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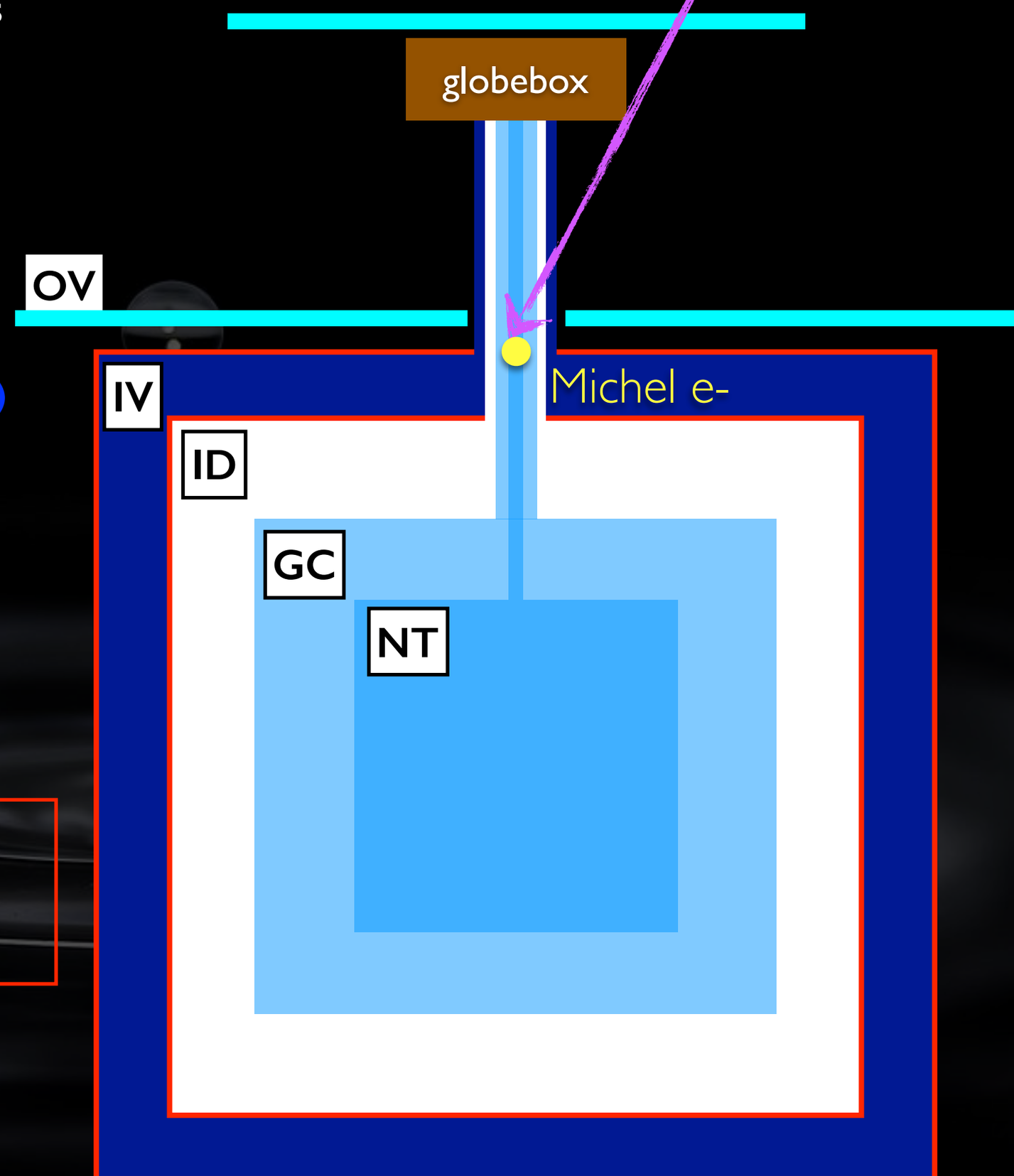

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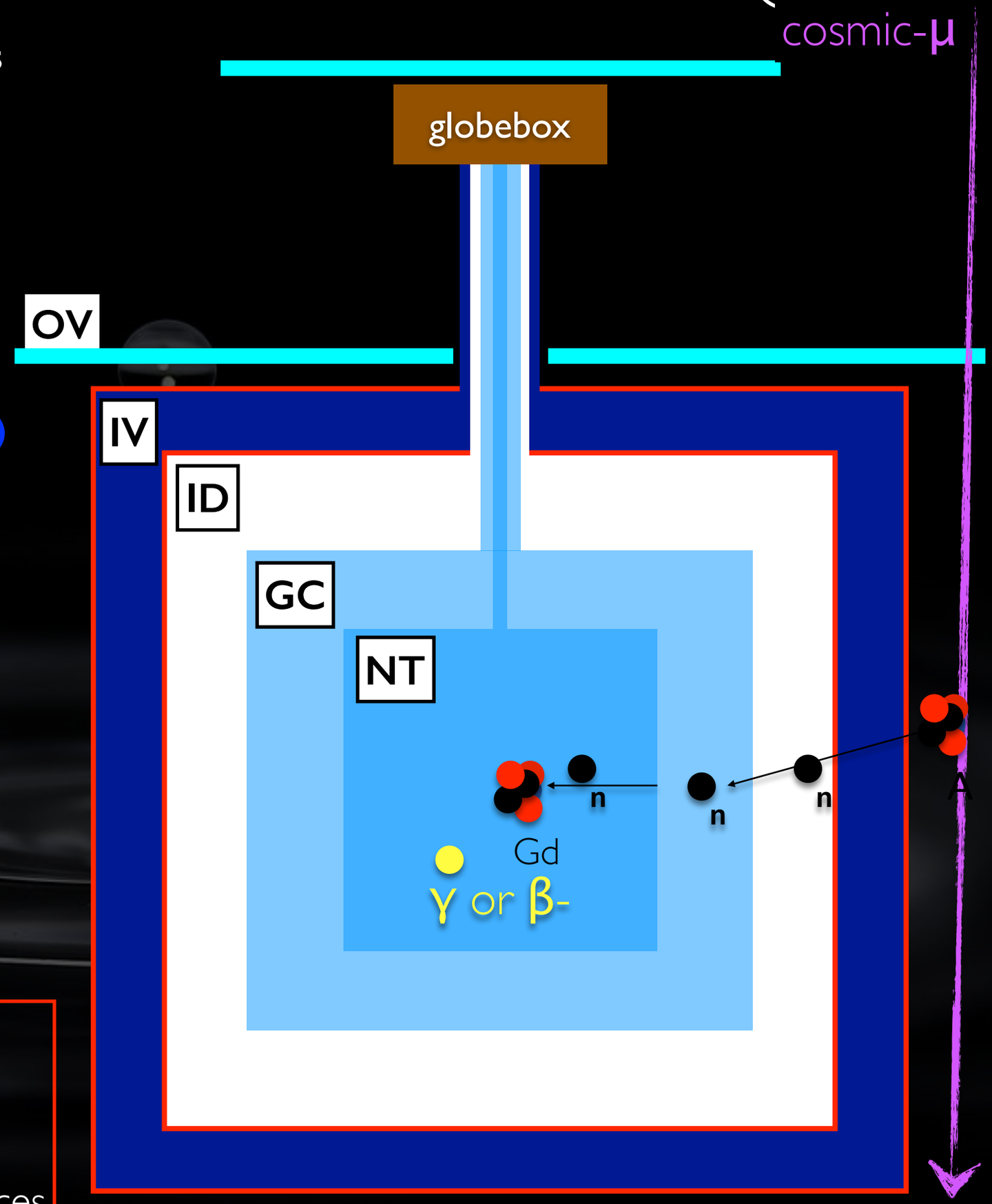


BG systematics (nut-shell)

BG	rate (day	shape	energy range	S/BG (%)	δ(BG) (%)	suppresion (wrt Gd-II)
^{9}	0.97	data (Li+He tag)	[0,12]MeV	2.61	**0.78**	1.3
fast-n stopped-**μ**	0.60±0.05	data (IV tag)	[0,20]MeV	1.62	0.13	1.9
accidental	0.070±0.005	data (off-time)	<3MeV	0.19	0.01	3.7
	<0.003@68CL	neglected	[0,13]MeV	-	-	>7.0
BiPo	<??	neglected	<2MeV	-	-	same

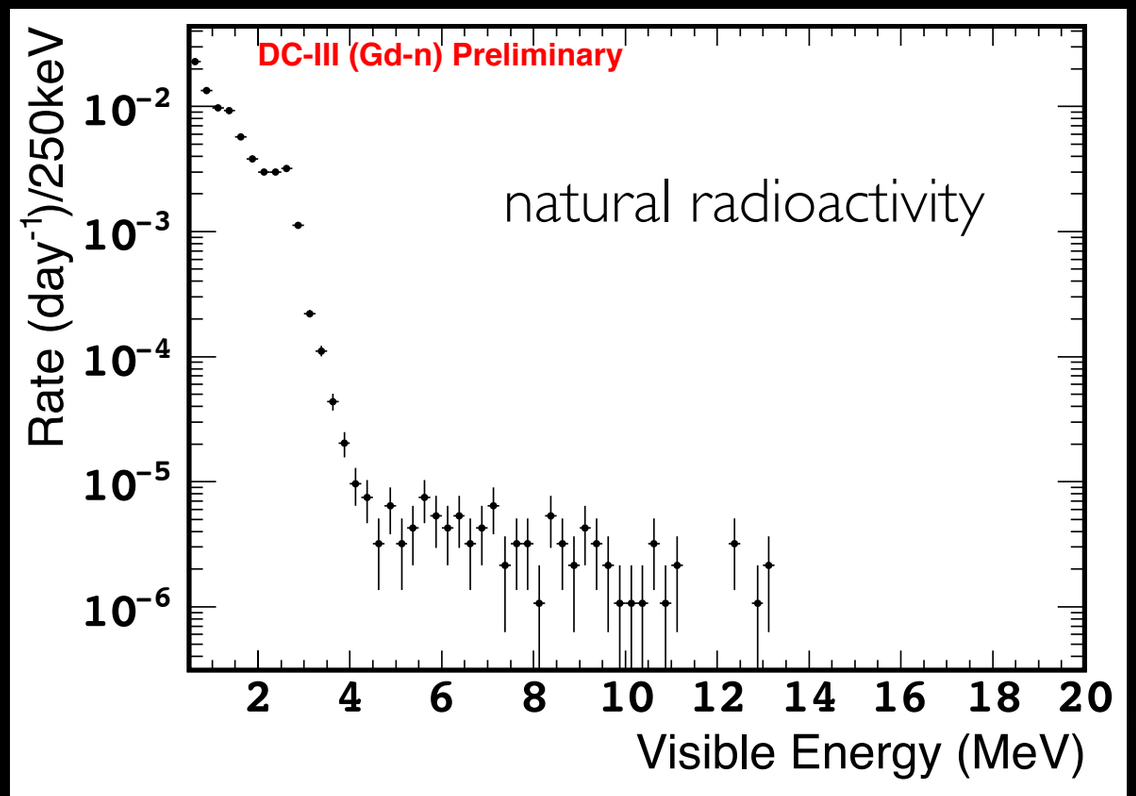
Li+He (He ≤10%) dominates BG systematics budget by >90%

(energy spectrum data-driven→ poor statistics)

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

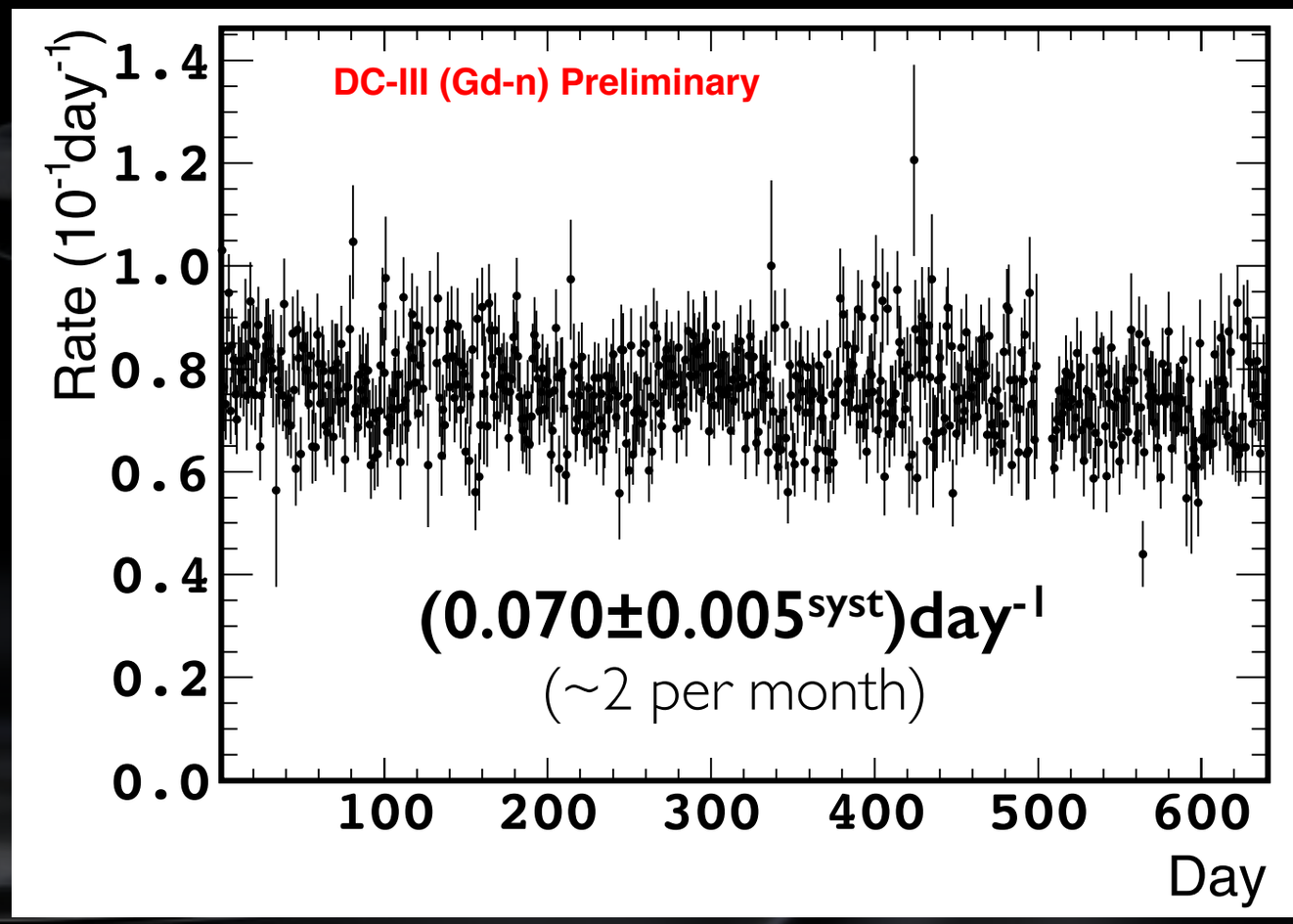
(fast-n is high but well know spectrum makes it innocuous)

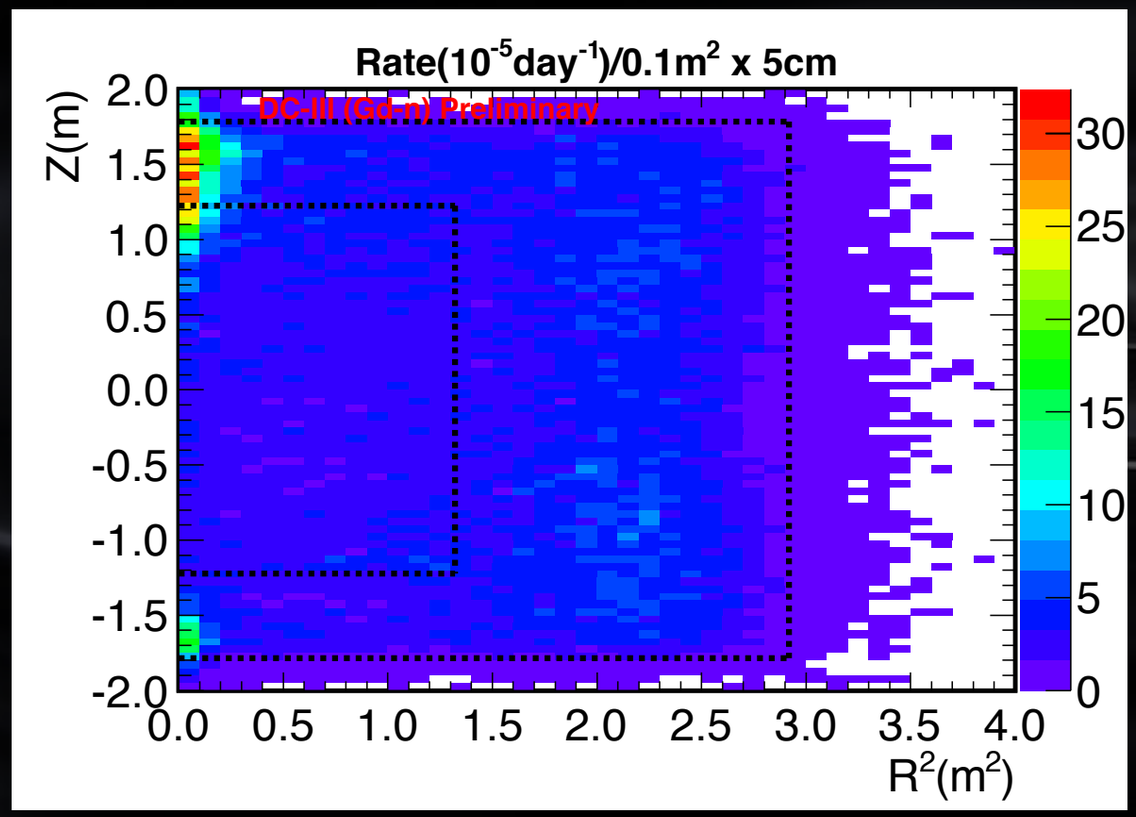
accidental BG…



negligibly low rate of accidentals

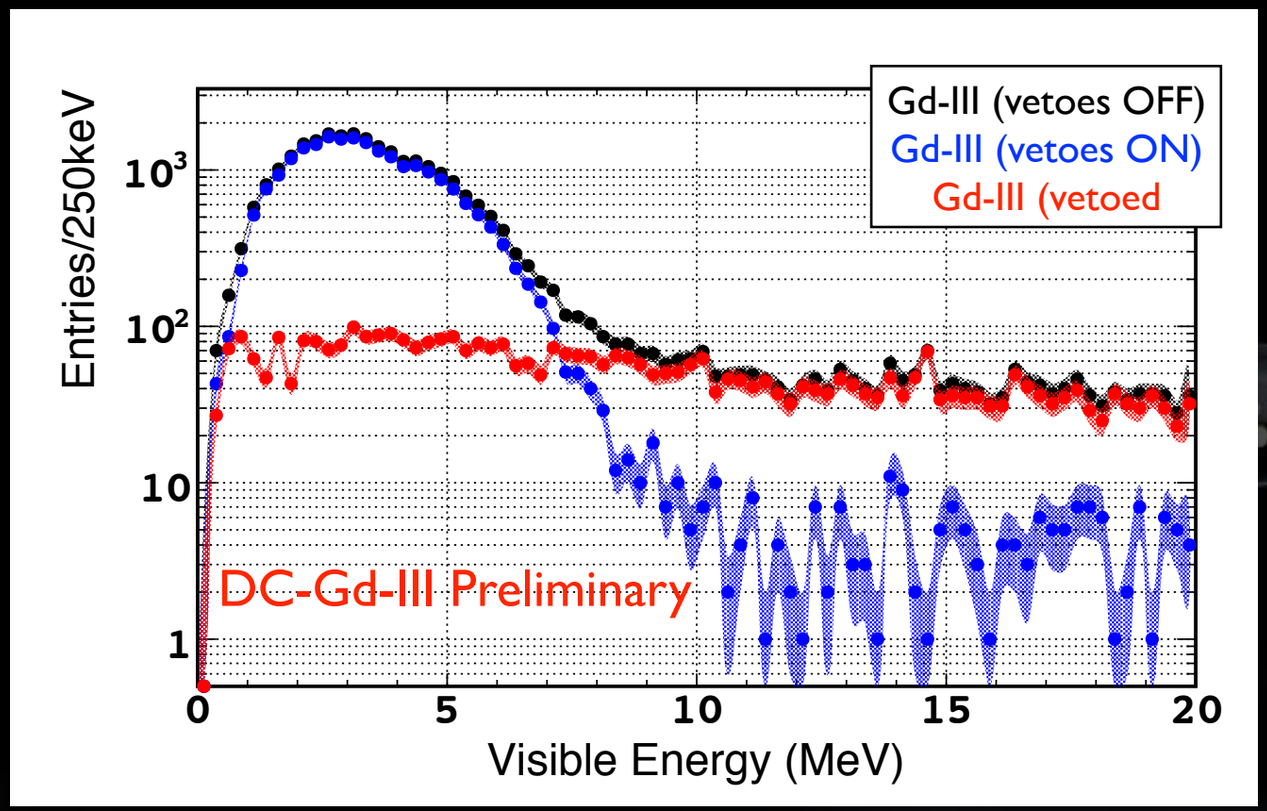
(known spectrum + stable)

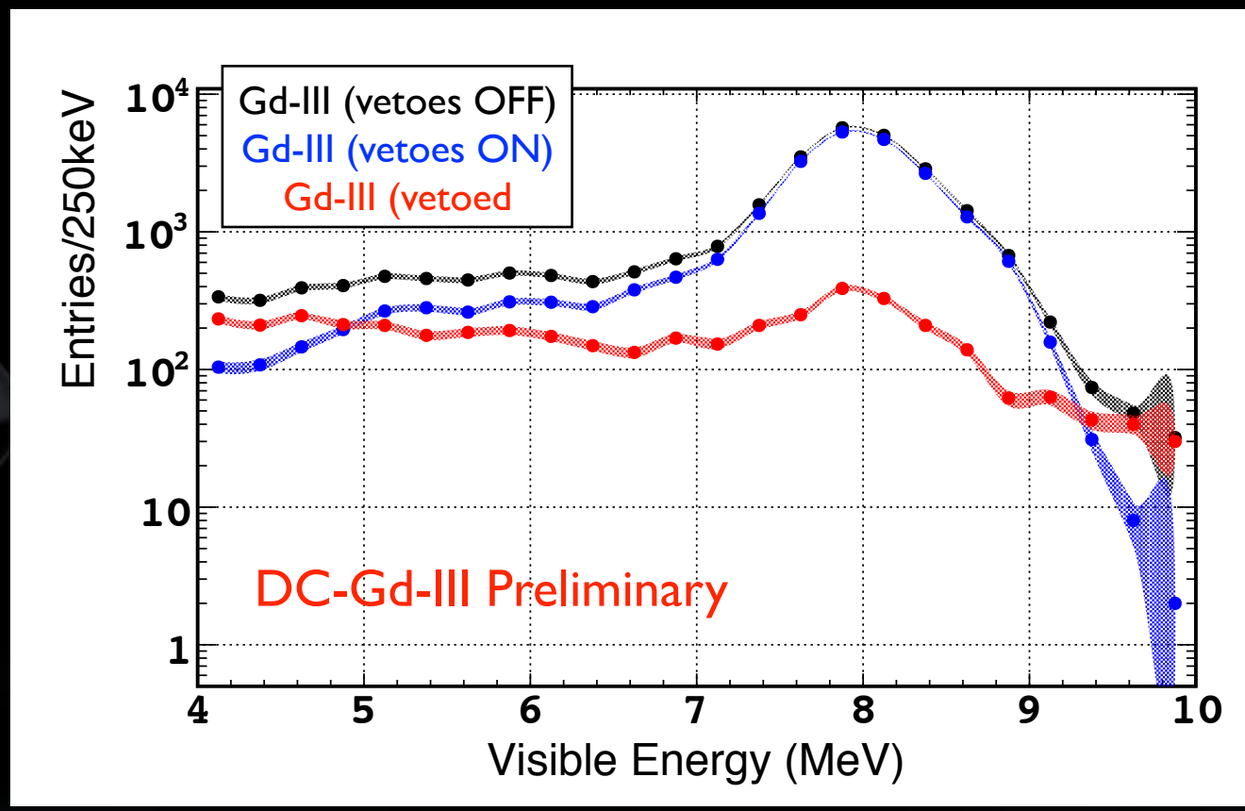




active BG rejection…

our BG active BG rejection vetoes…



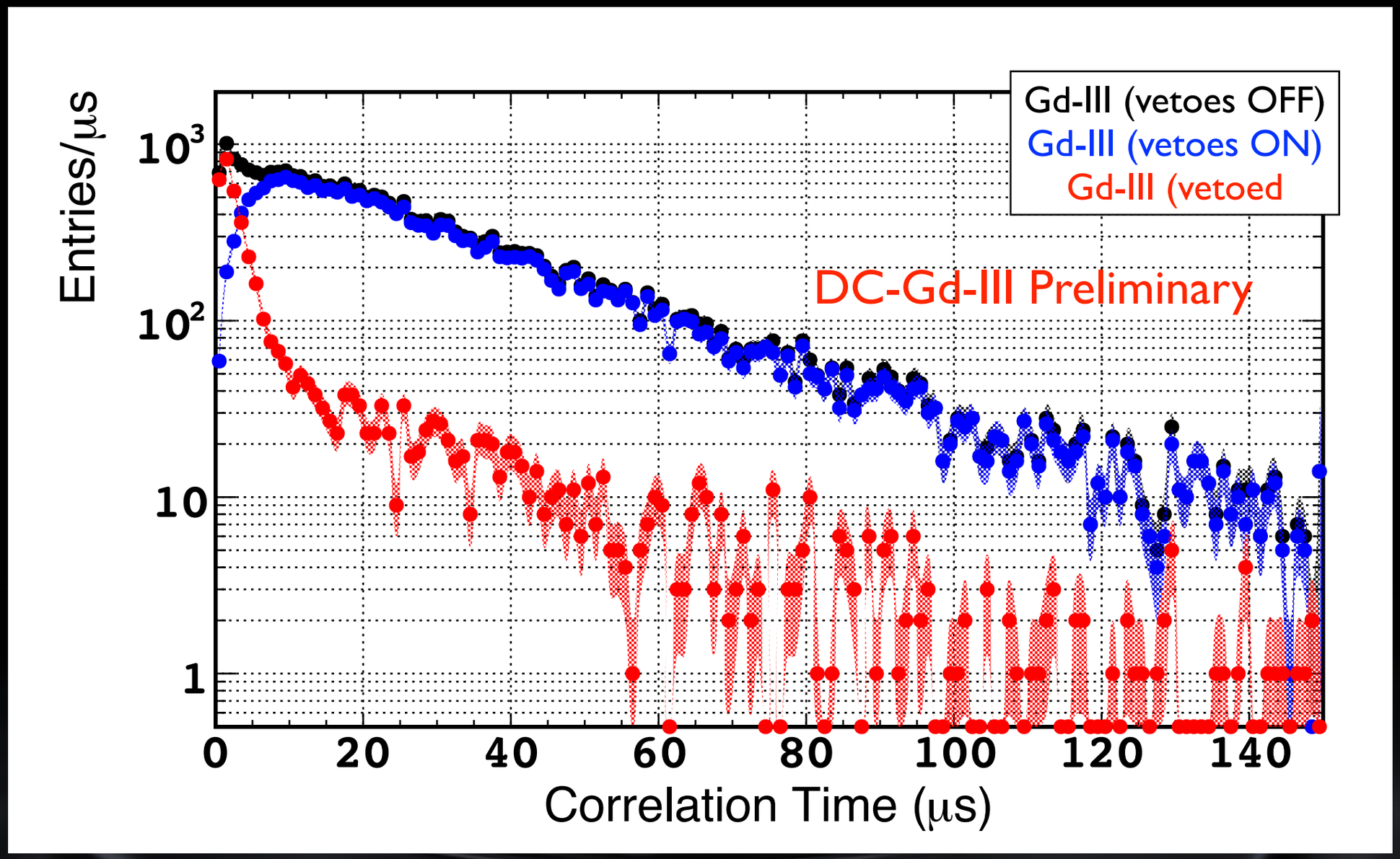


veto efficiency (%)	absolute (per veto)	uncorrelated fraction	relative (with all other vetoes)
IV veto	24	7	40
OV veto	62	7	41
FV veto	71	**19**	66
all vetoes	**90**	**33**	

P(rejection)=90%, estimated [12,20]MeV (high redundancy)

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

correlated events vetoes (all)…

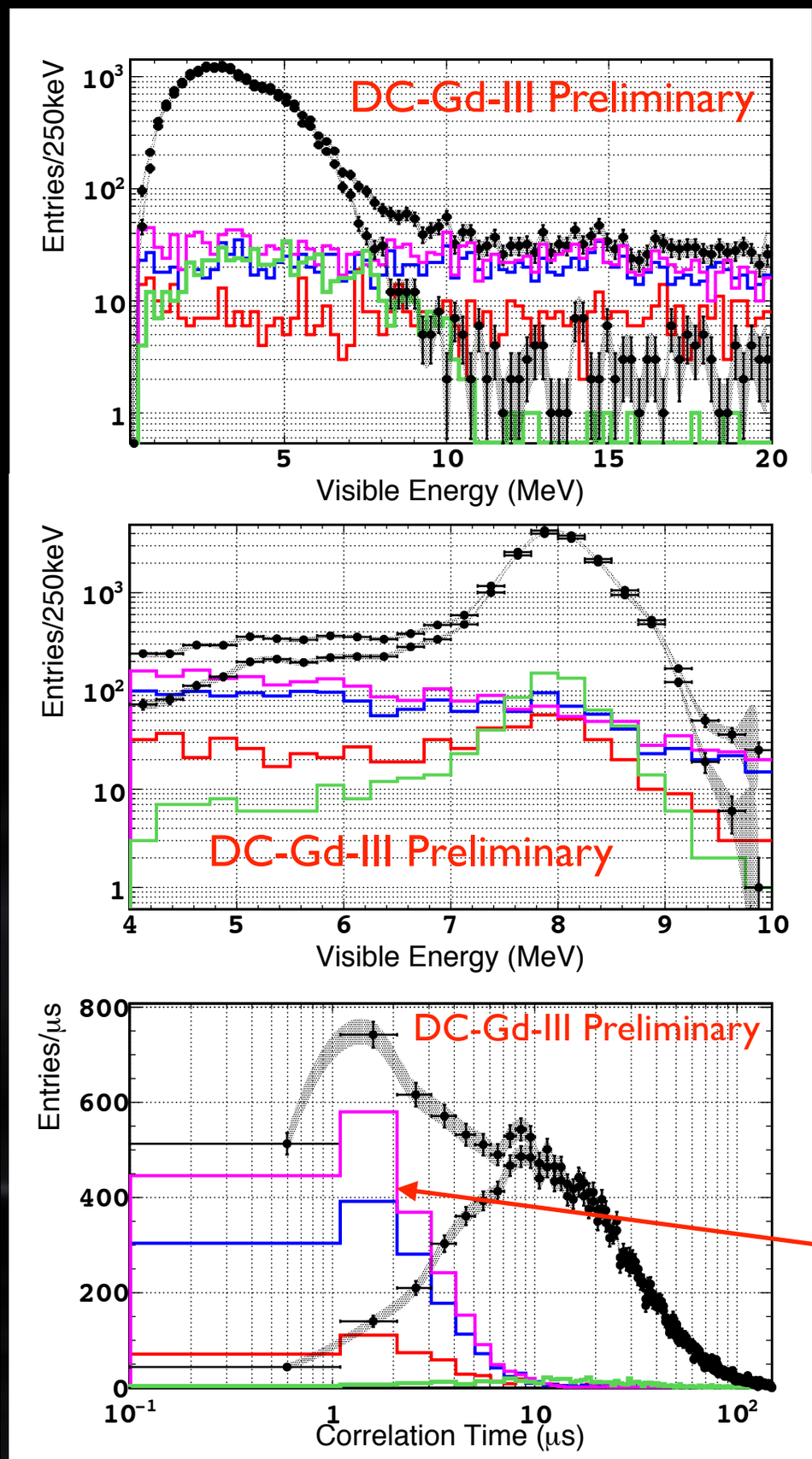


vetoes reject correlated events (very challenging→ accidentals are much easier)

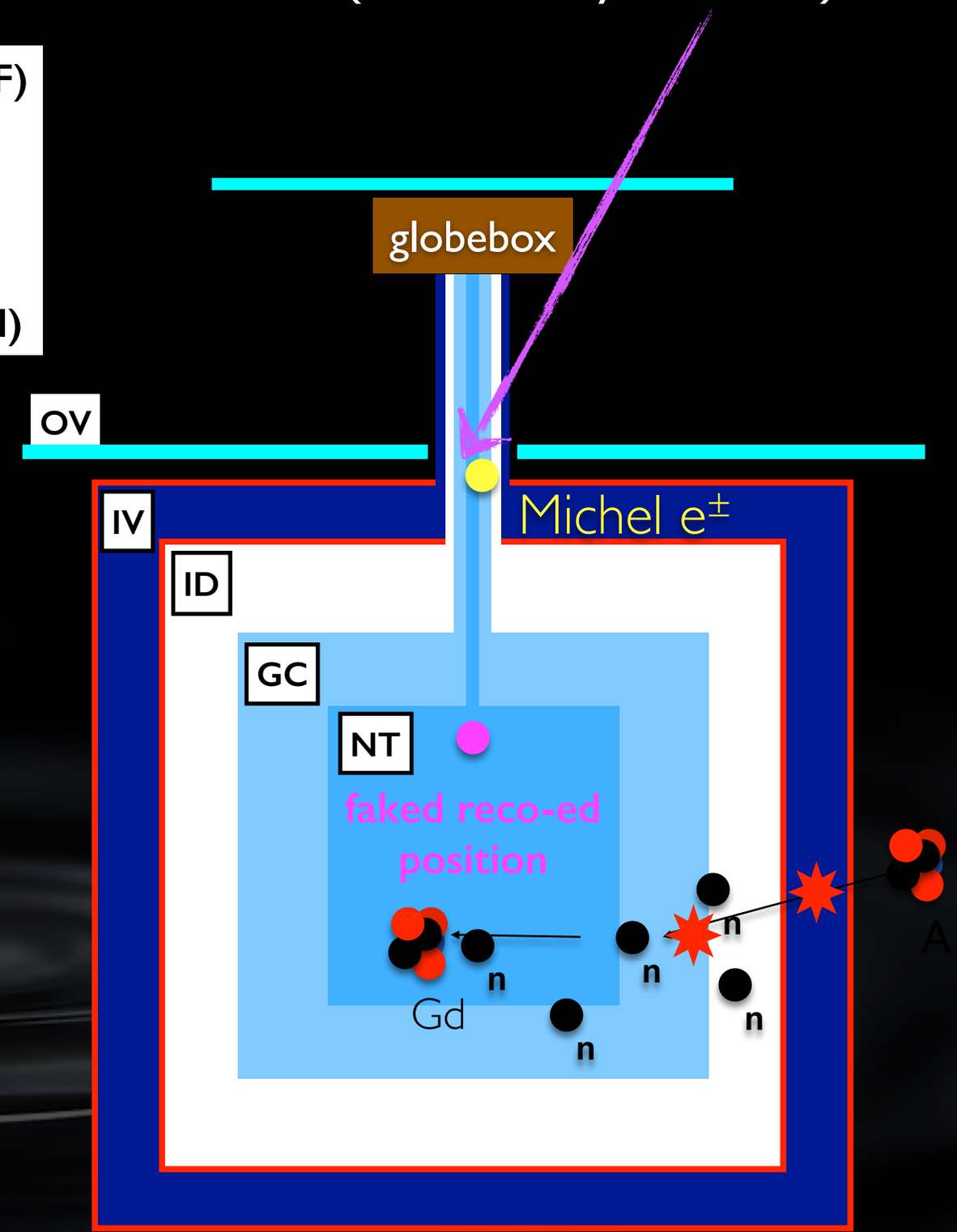
slow correlation→ neutrons in final state

fast correlation→ stopped-**μ**'s (lifetime of a **μ**)

our vetoes in action (one by one)…



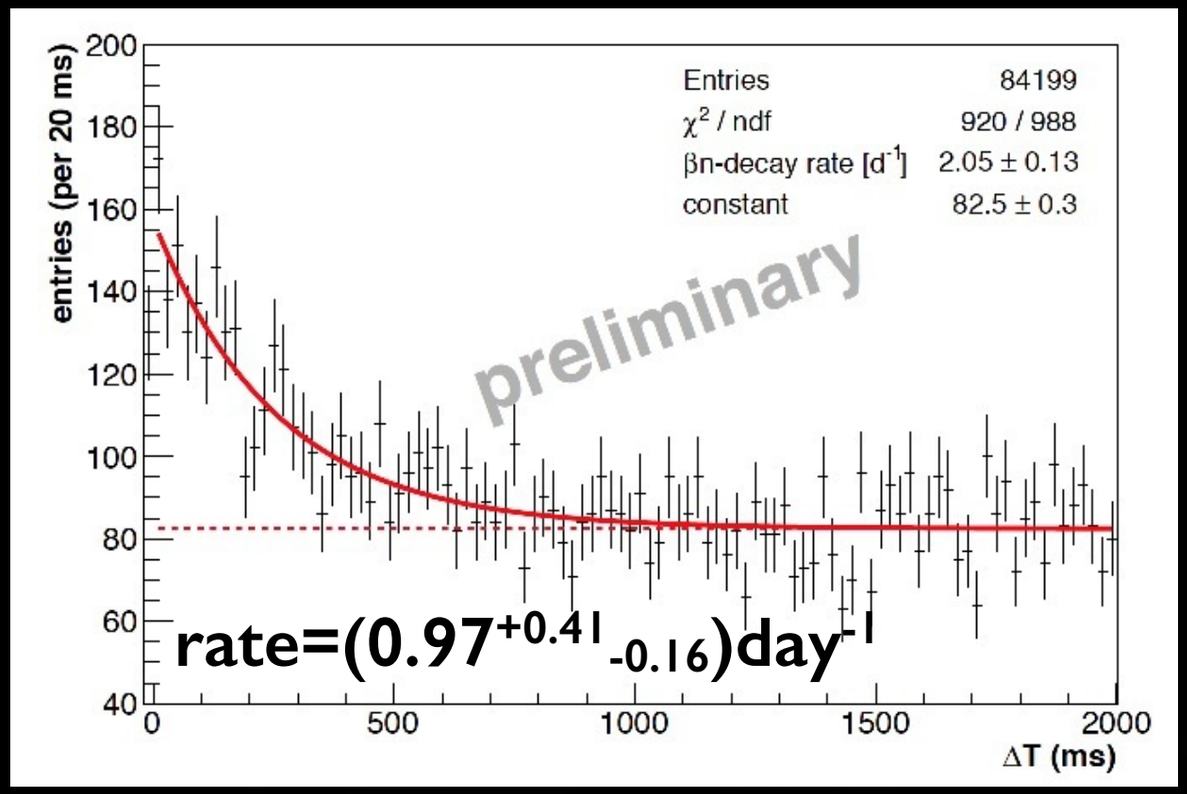
Gd-III (vetoes OFF)
FVV veto
Li+He veto
OV veto
IV veto
Gd-III (vetoes ON)



stopped-μ largest BG

(if not vetoed→ ~fully rejected)

Li+He measurement + veto…



DC, it's all about Li+He…

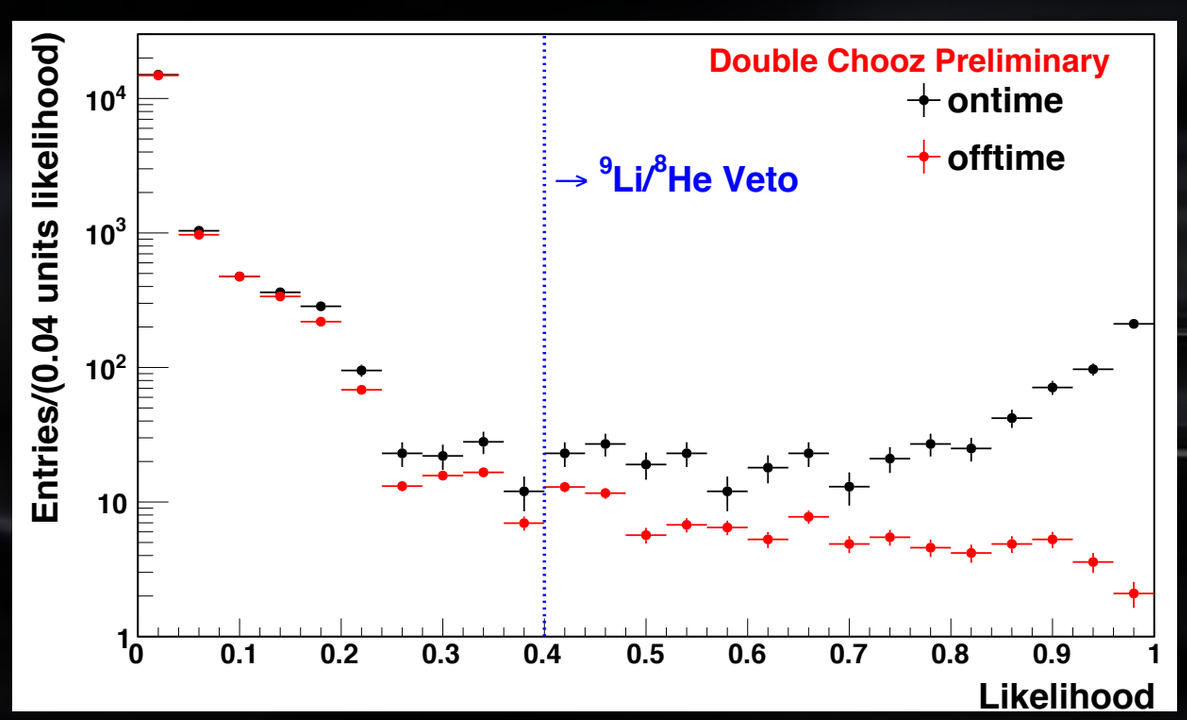
new input: *n-multiplicity ⊕ lateral distance to* **μ** *profiles*

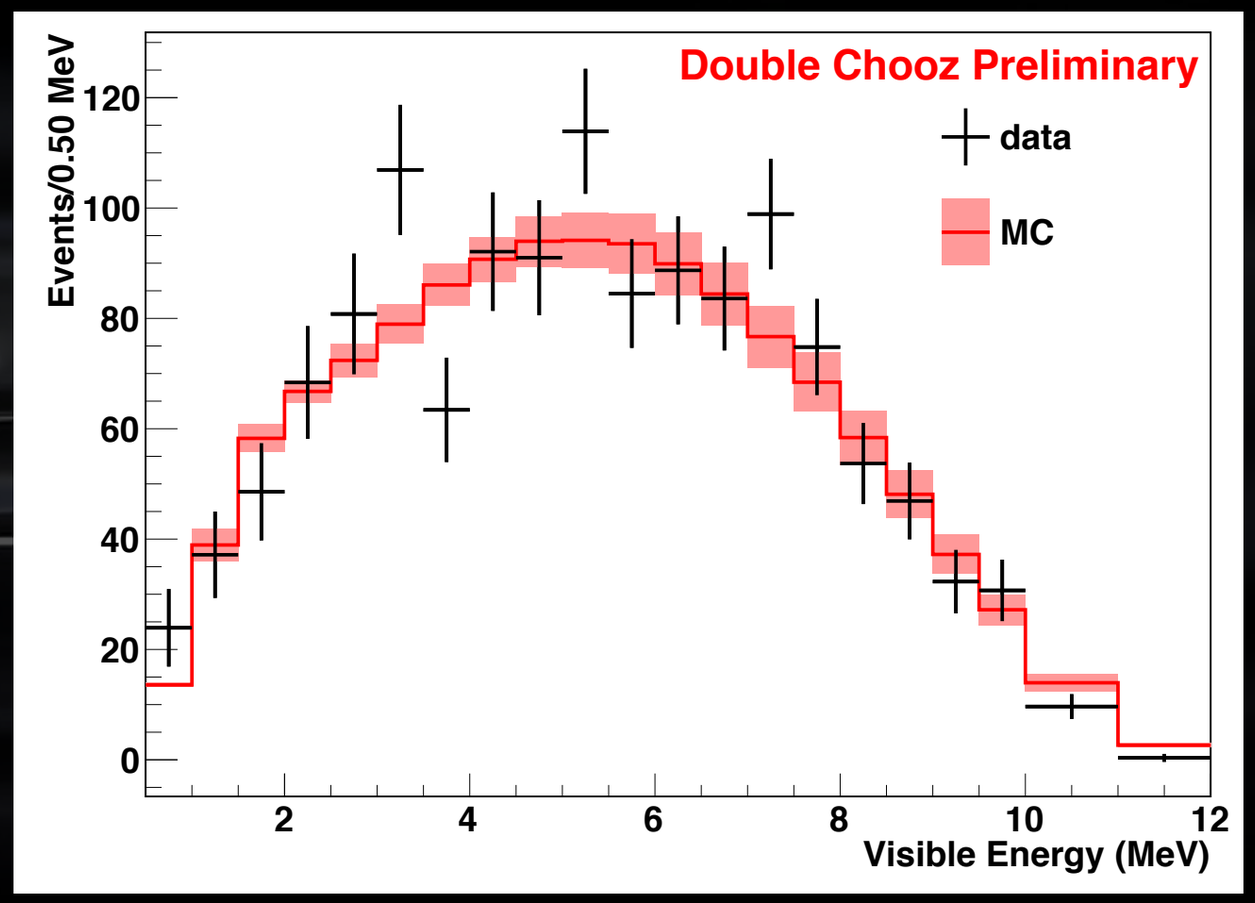
rate measurement…

- measure rate via time correlation to last **μ**
- two samples for better lower/upper limits

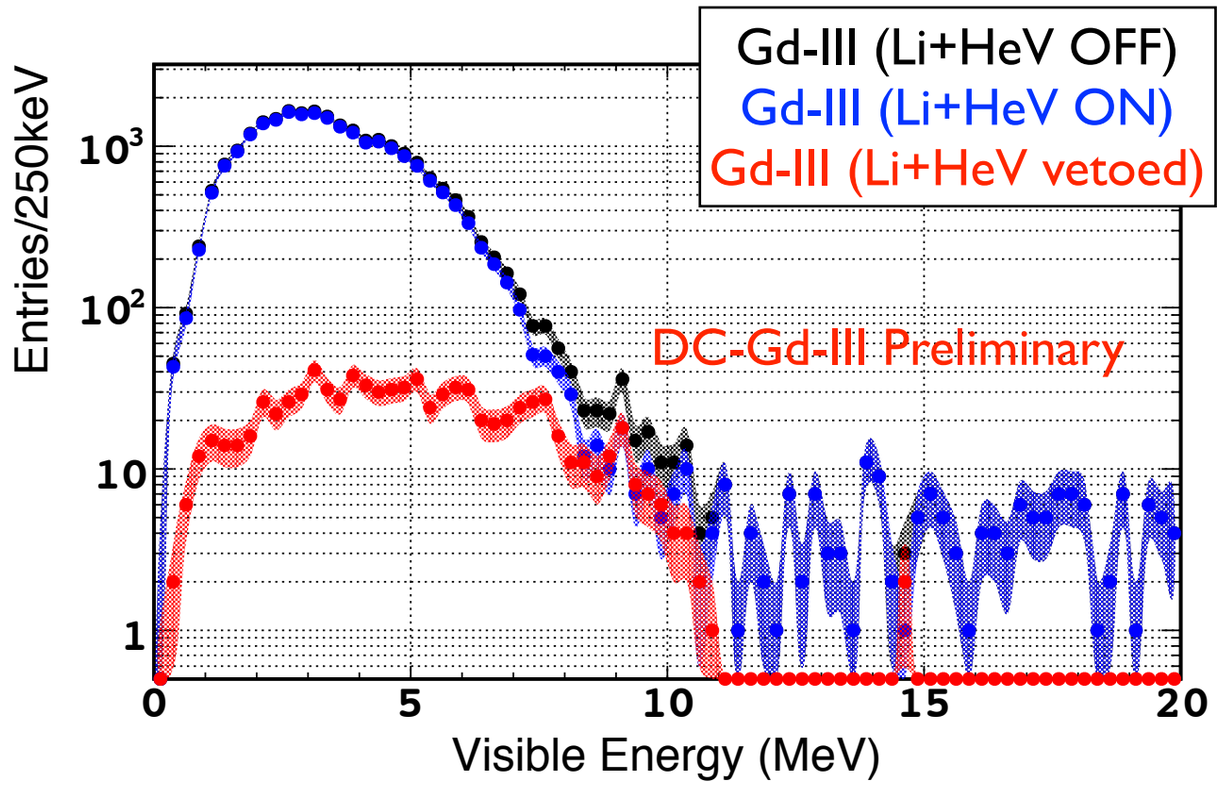
tag/veto mechanism…

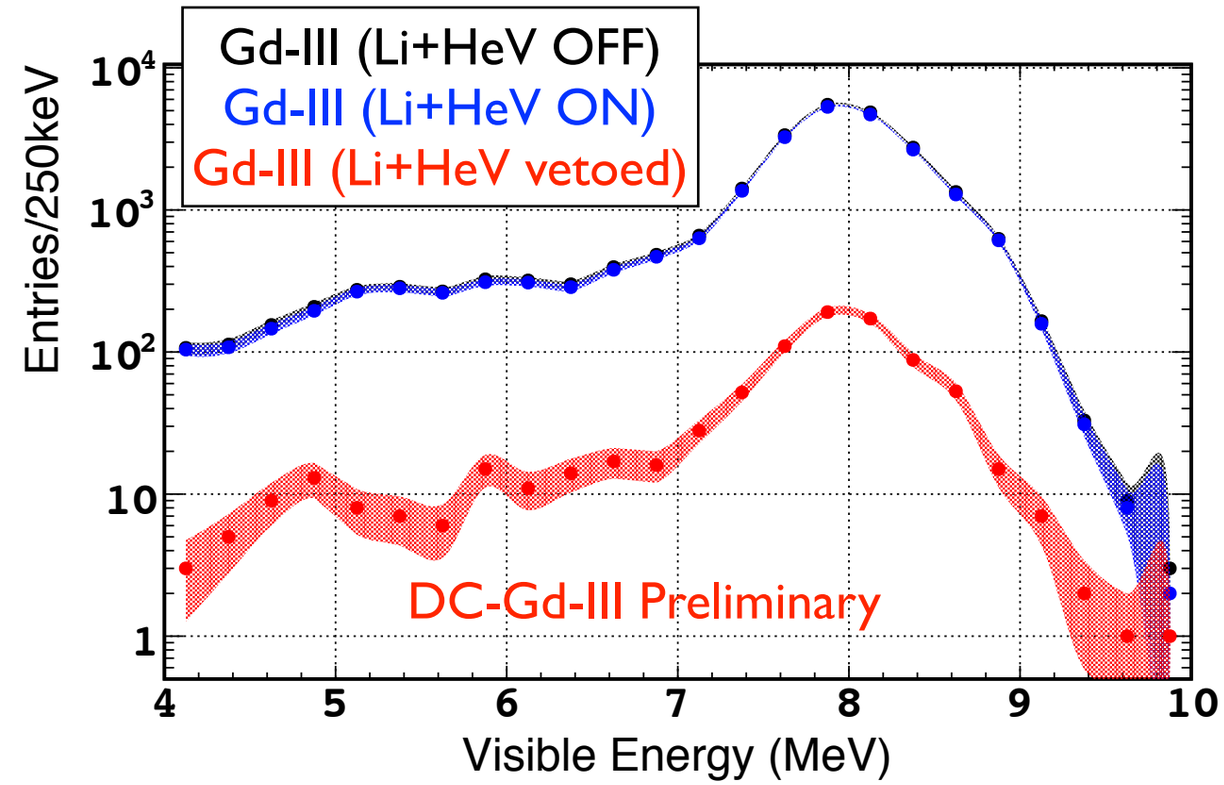
- Likelihood method tuned on ^{12}B tagged sample
- (high purity) **>50% of ^{9}Li tagging w <0.5% dead-time**
- measure data spectrum→ used for R+S (MC check)





our greatest challenge…





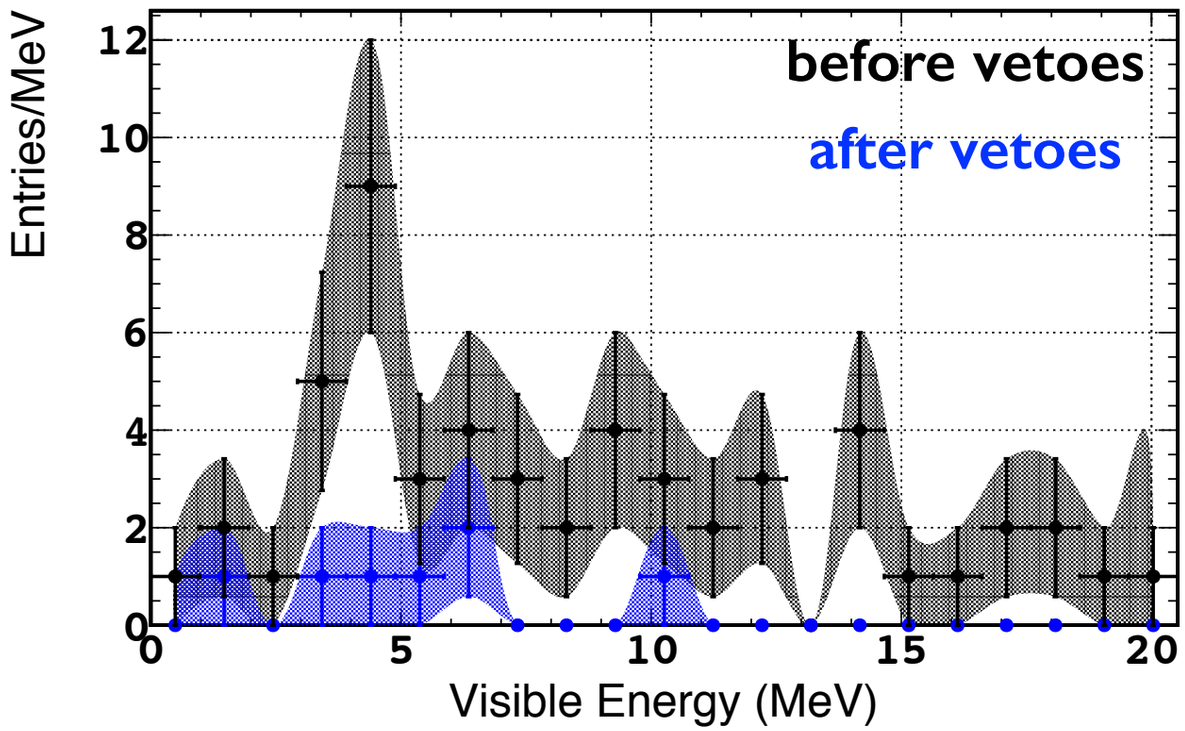
9Li is identical IBD → irreducible in LS detector

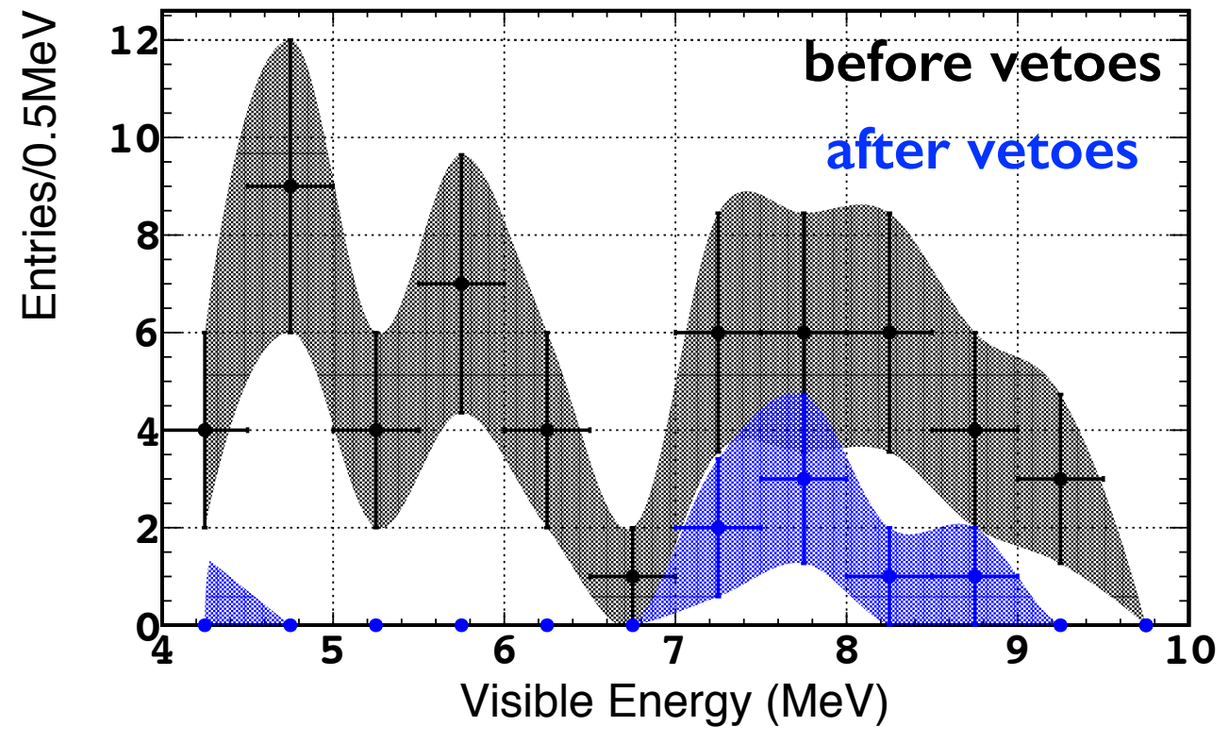
<u>remarkable μ correlation tag purity</u> (negligible IBD inefficiency)

reactor OFF data…

(labelled → 2xOFF)

reactor 2xOFF data…





2xOFF data: powerful information before/after veto evolution

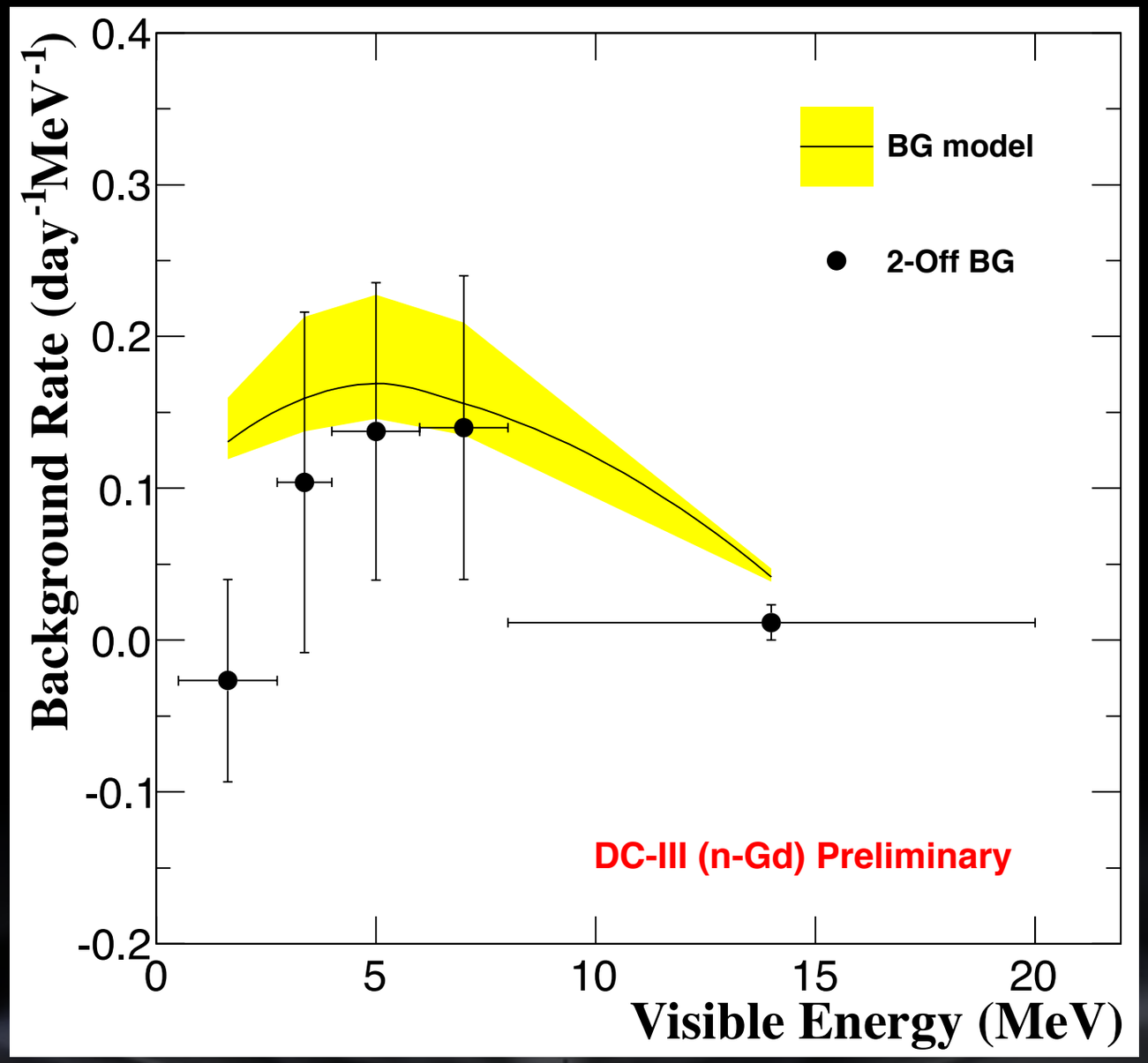
(scrutinising a few event-wise BG-only)

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)

reactor 2xOFF consistency with BG model…



agreement between reactor 2xOFF and BG model

(poor spectral info→ mainly rate)

tension **BG(OFF)^{inclusive} < Σ bg$_i^{exclusive}$** @ ~2σ

(good news→ suggests little room for any unknown BG)

Gd-III measurement of θ13…

- (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		467.9	
δ(BG) (input | output)	1.6	0.9 (R+S) 0.11 (RRM)	0.8	**0.3** (R+S) **0.5** (RRM)

RRM input

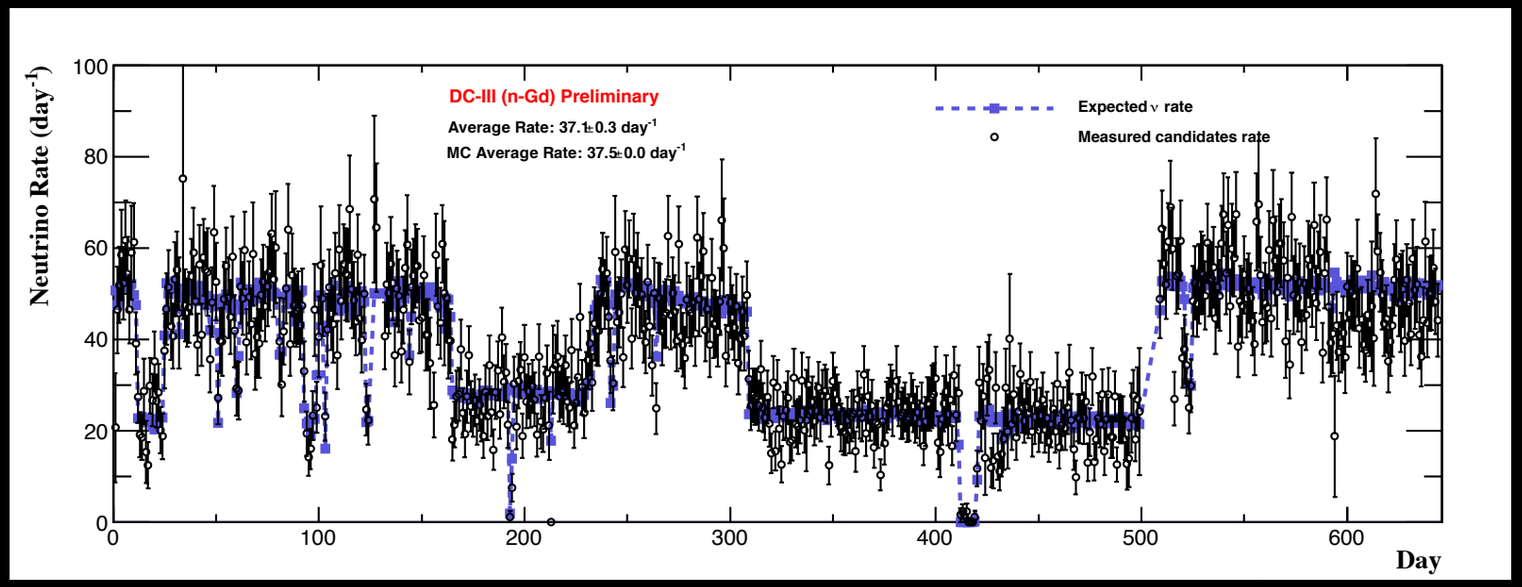
R+S input

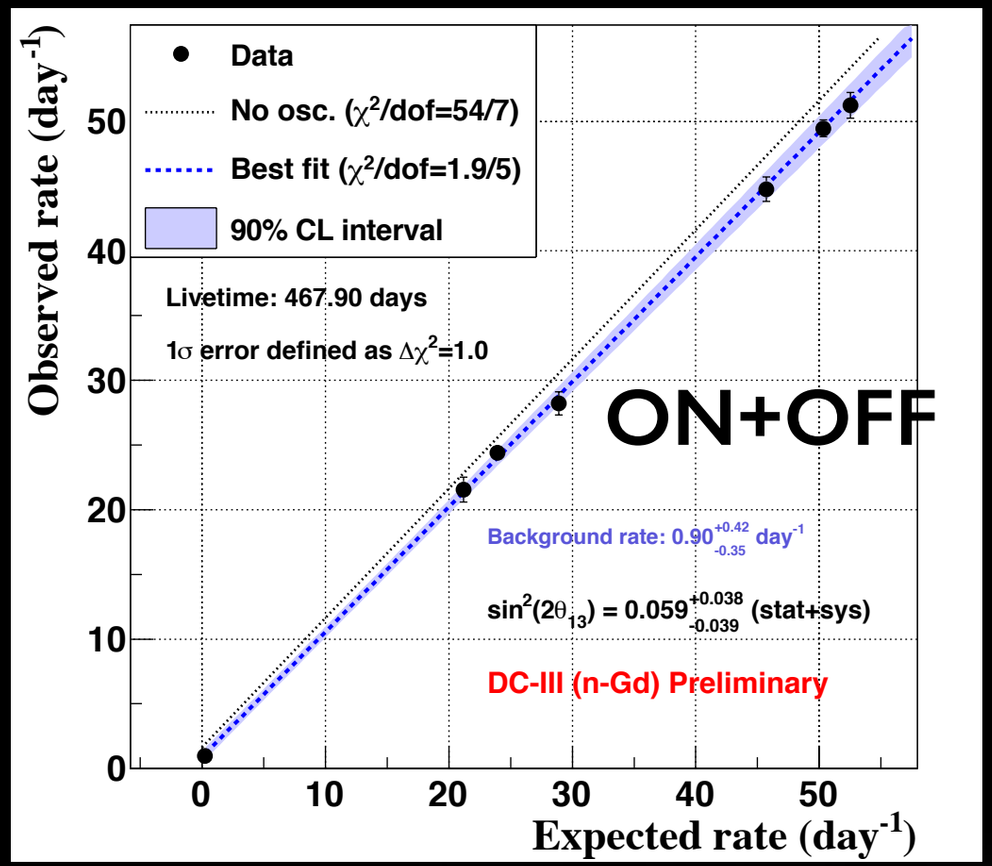
δ(BG) independent estimation: no spectral info used

$\Longrightarrow$ input to R+S (mandatory) and RRM (optional)

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

RRM analysis…



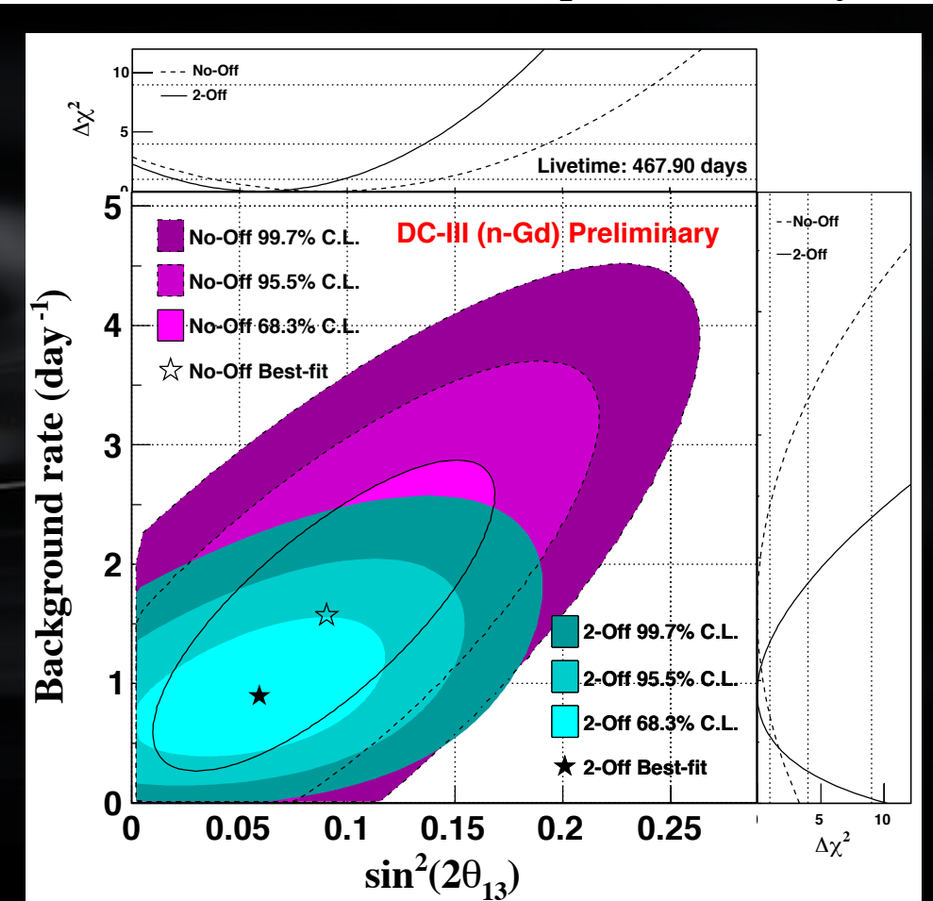


- exploit our 100% variations in reactor power…
  - **measure BG and $\sin^2(2\theta_{13})$ simultaneously**
  - **BG is inclusive** → account for unknown contributions

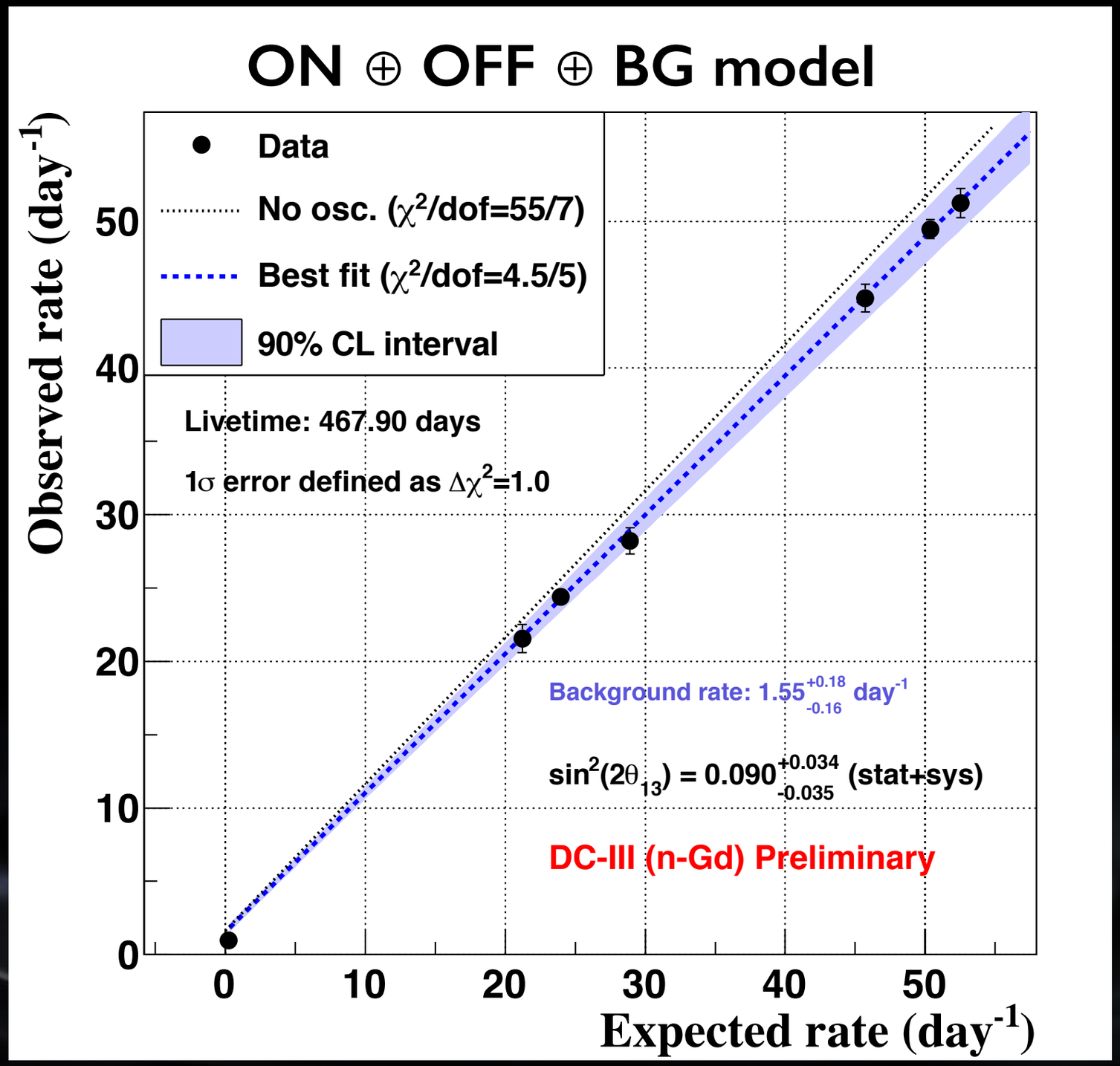
    ⟹ BG measurement without BG model
- (trivial) fit is straight line…
  - **$BG^{inclusive}$** → intercept
  - **$\sin^2(2\theta_{13})$** → slope
- additionally, aid fit with extra BG constraints (pulls)…

  +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…

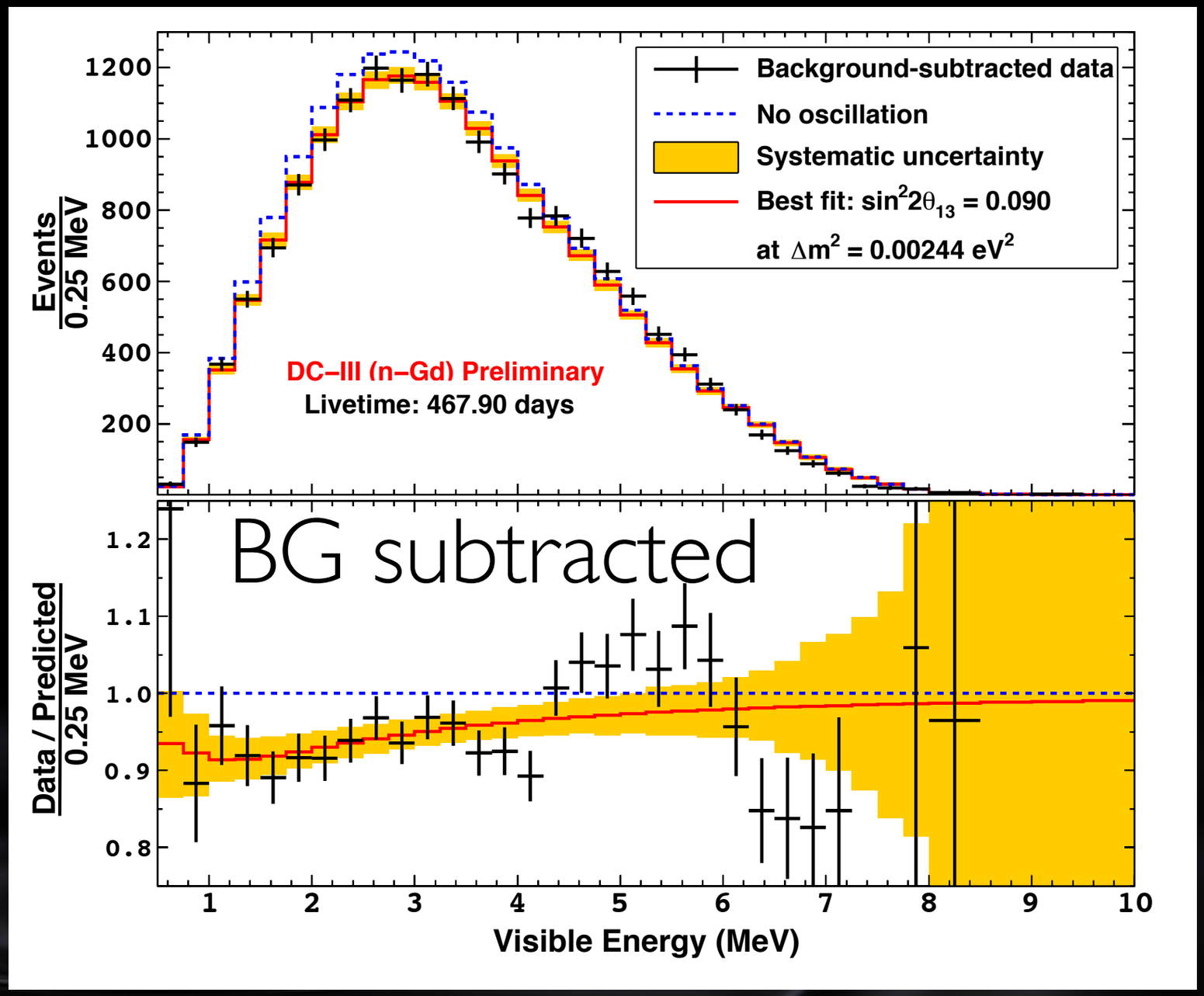


most precise rate-only (→i.e. not spectral info used)

(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)

$\delta(BG)^{II} \sim 3x\ \delta(BG)^{III}$

R+S results…(2)

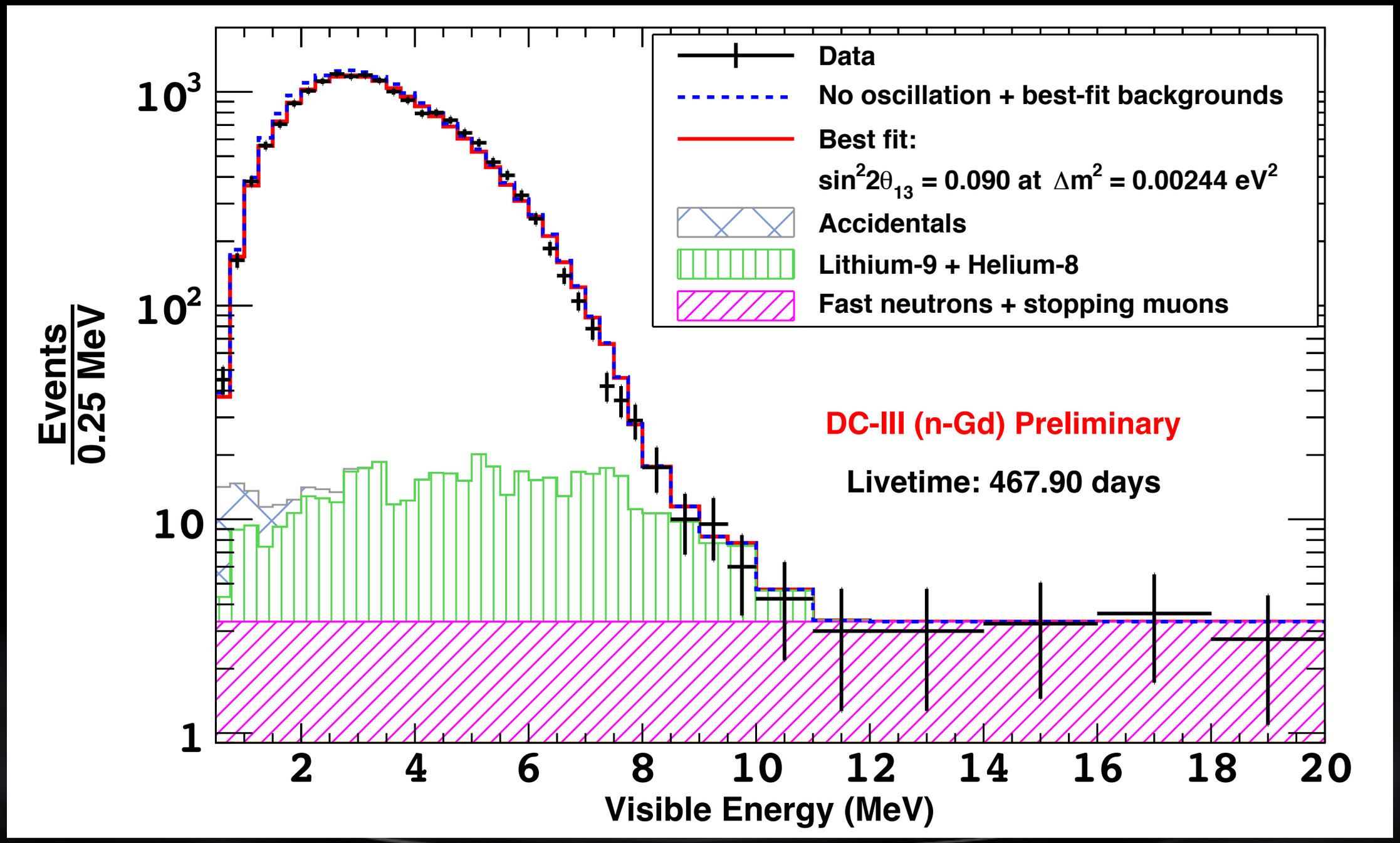
Parameter	Input C.V.	Input Error	Output C.V.	Output Error
E-scale a'	-0.027	0.006	-0.026	$+0.006, -0.005$
E-scale b'	1.012	0.008	1.011	$+0.004, -0.007$
E-scale c'	-0.0001	0.0006	-0.0006	$+0.0006, -0.0005$
FN+SM rate (d^{-1})	0.60	0.05	0.56	0.04
Li+He rate (d^{-1})	0.97	$+0.41, -0.16$	0.80	$+0.15, -0.13$
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)

what do we know about BG?



remarkable match of BG over (up to) 2 order of magnitude

mode signal in the region of θ_{13}

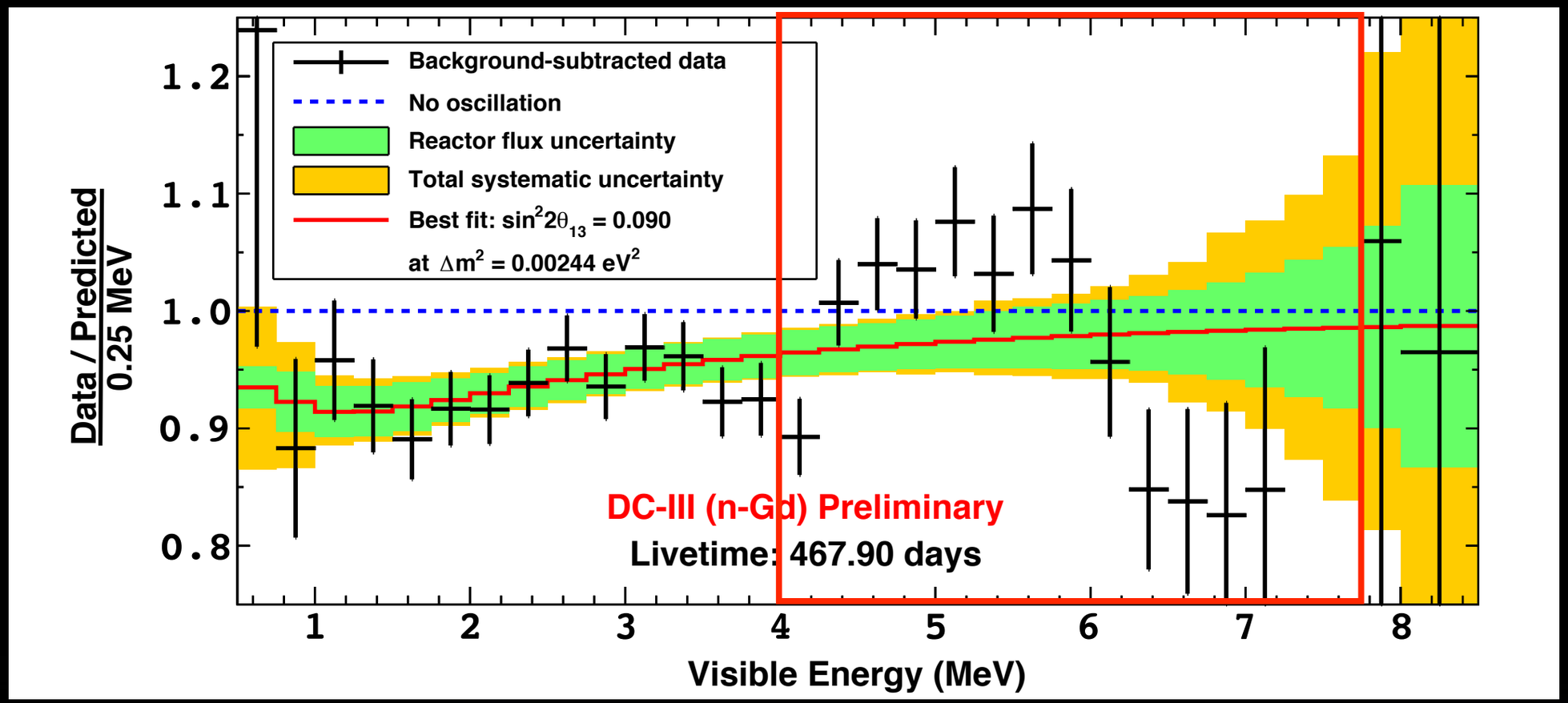
what do we know about BG?

- BG is our toughest challenge (but we best understand…) [shallowest overburden]
- **(1) BG model estimation** (no spectral input) [→ $\mathbf{BG^{total} = \Sigma\, bg_i^{exclusive}}$]
  - estimated using ON data with <u>no spectral shape assumption</u> (IBDs→a problem)
- **(2) 2xOFF data** [→ $\mathbf{BG^{total} = BG(OFF)^{inclusive}}$]
  - <u>direct data measurement</u> (like CHOOZ): 1 week of data
- **(3) BG model estimation** w spectral input [→ $\mathbf{BG^{total} = \Sigma\, bg_i^{exclusive}}$]
  - R+S output→ extra precision using spectral info (excellent confirmation)
- **(4) BG model independent** (no 2xOFF data) [→ $\mathbf{BG^{total} = BG(ON)^{inclusive}}$]
  - RRM output→ use reactor power variations only
- **(5) BG model independent with 2xOFF data** [→ $\mathbf{BG^{total} = BG(ON+OFF)^{inclusive}}$]
  - RRM output→ (as before) plus the 2xOFF constraint
- coherence validation within Gd-n…
  - all estimations within error→ 2σ tension with 2xOFF data, but… (ironically!!)
  - $\mathbf{BG(OFF)^{inclusive} < \Sigma\, bg_i^{exclusive}}$ @ ~2σ (a BG problem manifests opposite way!!)
- coherence validation against H-n…

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 θ13 driven spectral distorsion
  - (θ_{13} direct impact) θ_{13} fits constrained mainly by info <4MeV (R+S analysis)

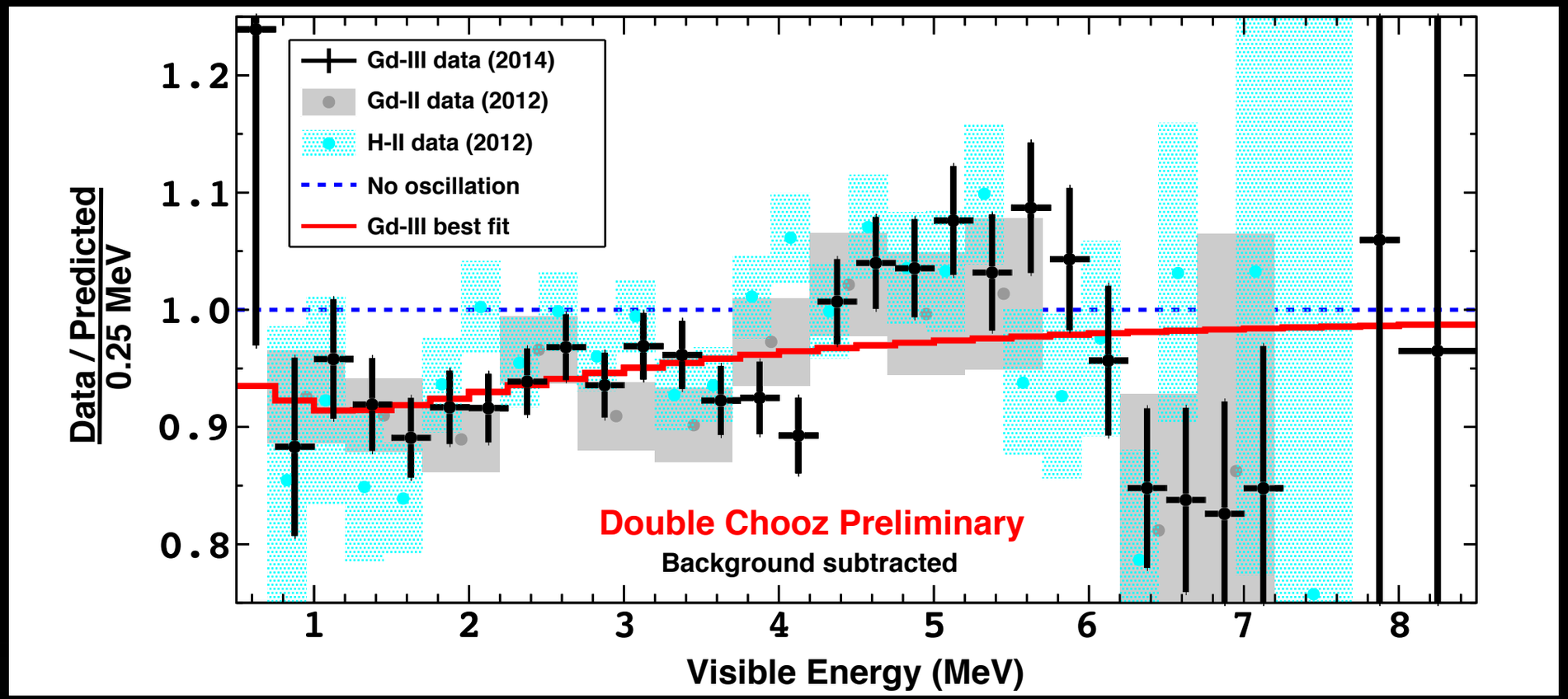
- **range [4,8)MeV:** structure (deviations ≤1.5σ)
  - ~**[4,6]MeV: excess?** (stats available→ attempt to understand)
  - ~**[6,8]MeV: deficit?** (IBD spectrum dies off→ unknown)
  - (θ_{13} indirect impact) affect θ_{13}^{R+S} via a bias on the BG constraint? (i.e. ^{9}Li mainly)

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

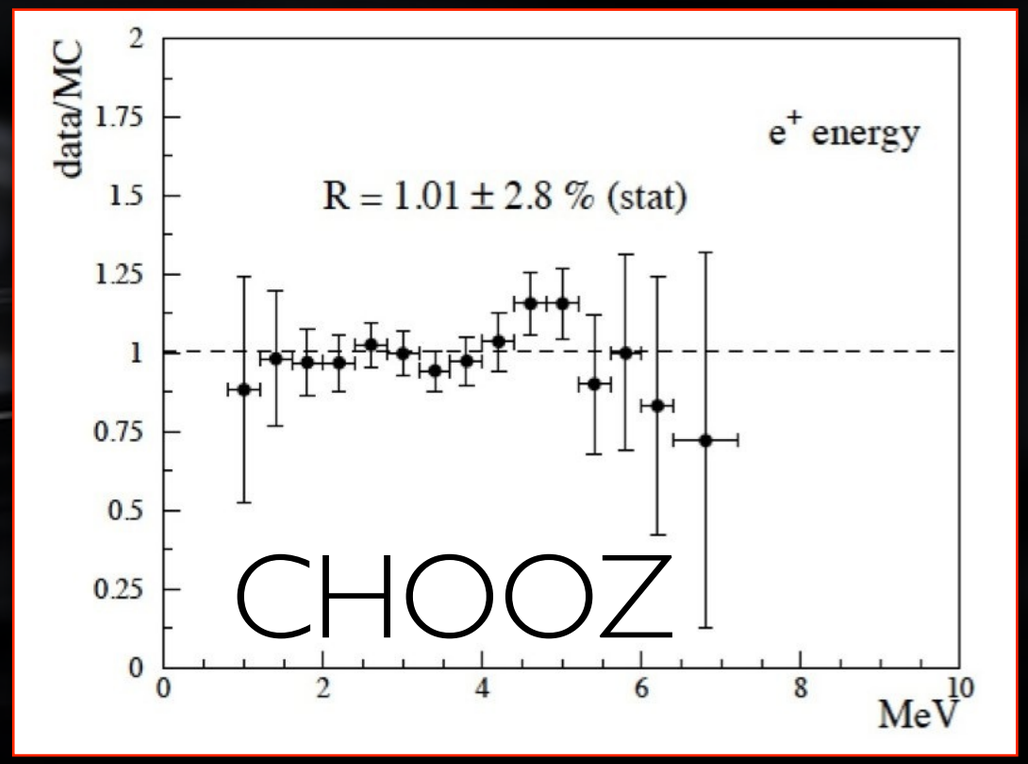
the guiltiness principle…

- (regardless of origin) **does it affect our measurement of θ13**?
  - no (directly) and negligible (indirectly)
  - tested R+S with hypothetical **C-n-like peak→ δ(Li+He) and δ(sin²(2θ₁₃)) immune**
    - several normalisations and shapes→ maximal variation ≤0.3σ
- **possible culprits?** (to 1st order→ the only answer)
  - **detection systematics** (no impact on shape)→ **innocent**
  - **energy** (C-n peak matches Δ(data,MC)<0.5%)→ **disfavoured**
    - shift energy by ±1σ error→ opposite trend to pattern shown
  - **BG** (constraint→ cannot be the sole cause)→ **tension** (not impossible)
    - possible explanation for only excess (harder to explain the deficit)
    - several BG constraints (total) + inconsistent known spectrum
  - **flux ⊕ σ^{IBD}** (large dominant uncertainties)→ **possible @ 1.5σ** [see next→]
    - (unknown effect) possible explanation for full structure
    - flux is least known at high energies (ILL e^- conversion + burn-up)
  - **impossible to rule-out combinations** (i.e. 2nd order effect)
- **do we have an smoking gun?**
  - **no** (discarded/disfavour most options)

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

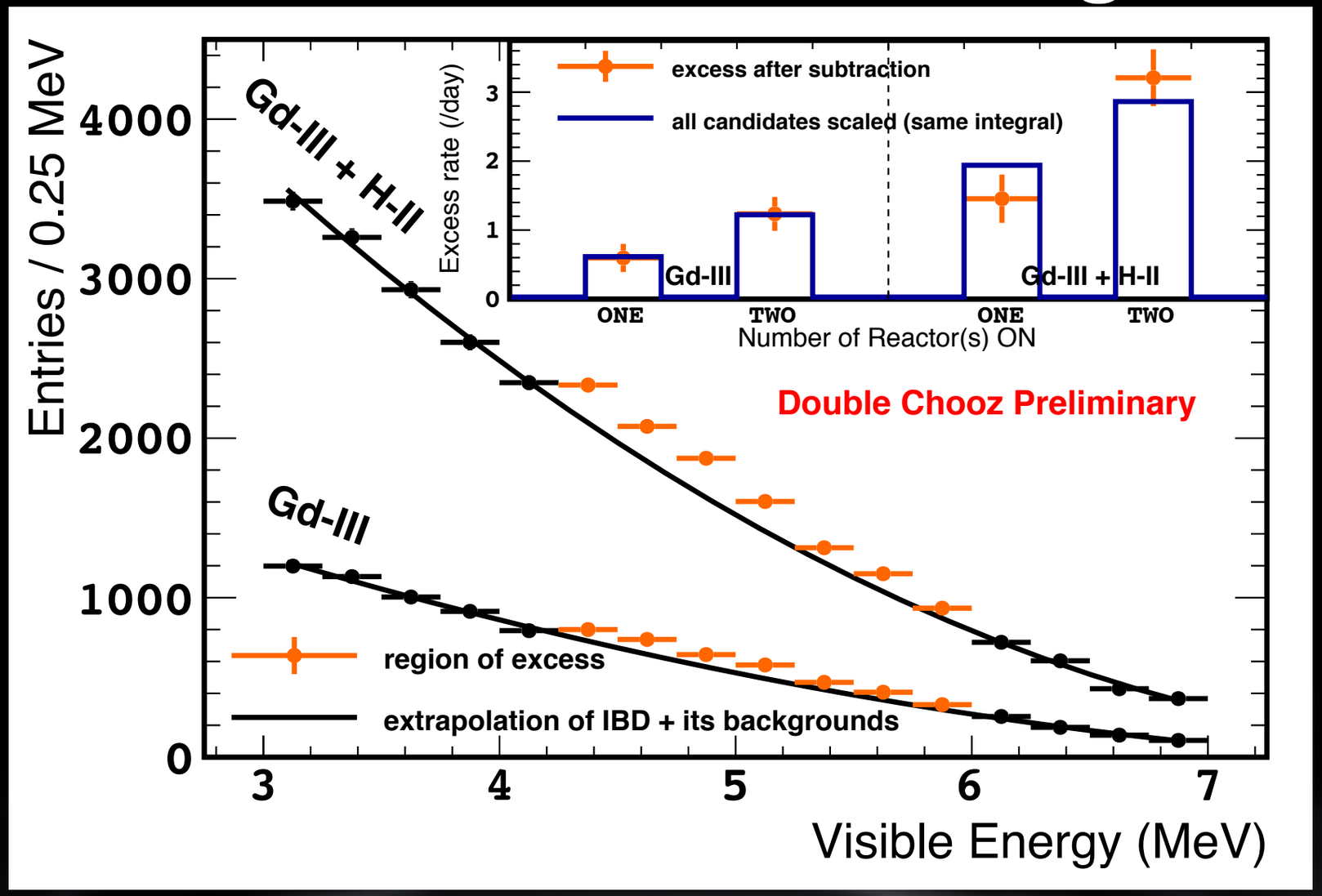


- **not new!! just better resolved…**
  - better stats (x2) (same flux info)
  - better energy (+50% better systematics)
  - better BGs (x3 better systematics)
- same DC-III-Gd pattern visible with…
  - **DC-II-Gd…** [also **DC-I-Gd**]
    - different selection (→ different BGs)
  - **DC-II-H…**
   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



Anatael Cabrera (CNRS-IN2P3 & APC)

targeted studies…

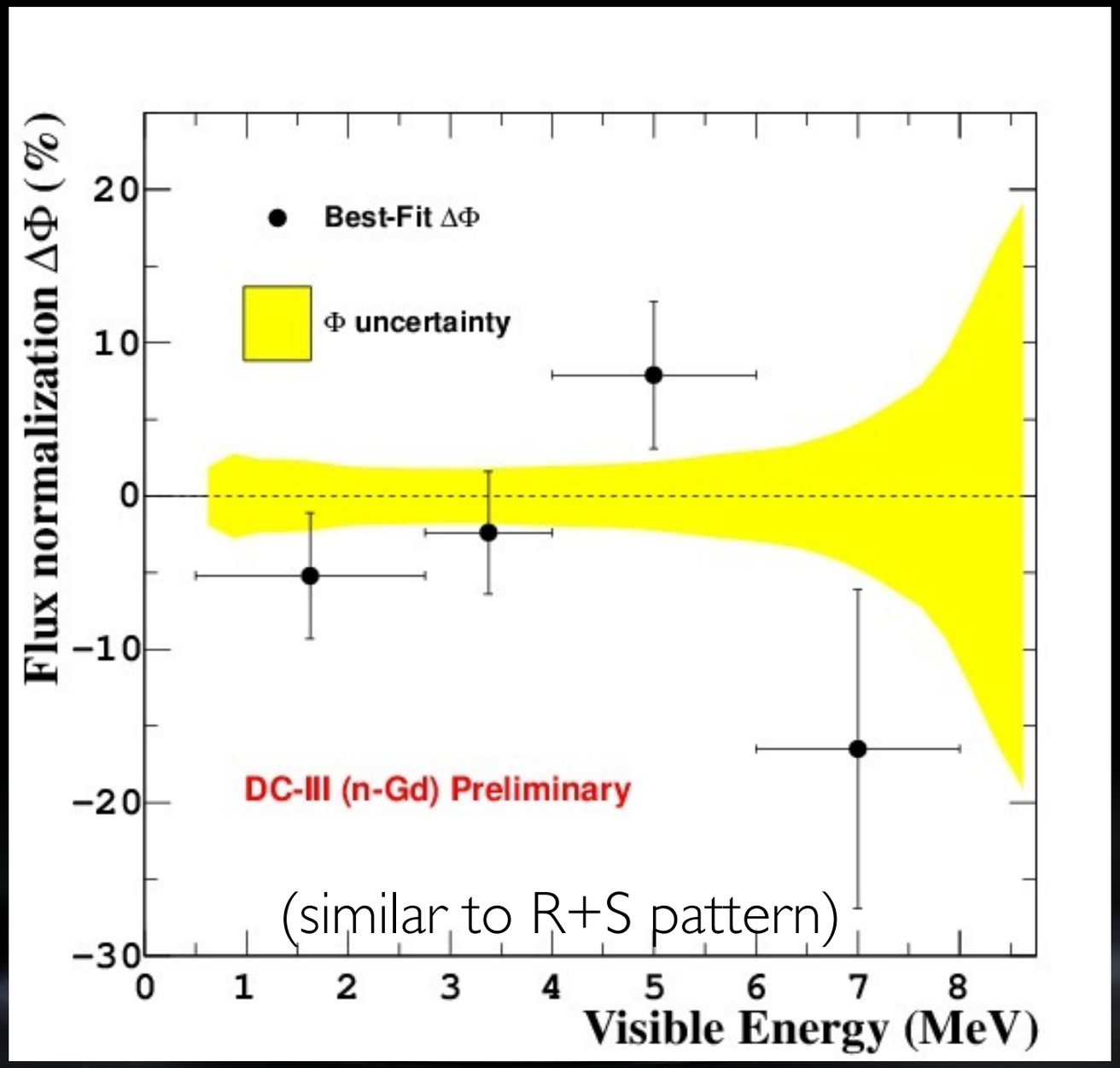


search for empirical correlations in "excess" region ~[4,6]MeV
(deficit region: no enough statistics)

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

strong correlation with reactor power + more data (H) helps
(empirical data-driven observation)

global consistency studies…



(similar to R+S pattern)

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

$\Longrightarrow$ consistency check for possible BG and/or flux deviations (simultaneously)

~1.5σ tension relative to flux input error

(<1σ effect on BG)

all together…

(observed data/MC^{IBD} structure >4MeV: <u>not understood.</u>)

Considering only *IBD interaction* ($\nu + p^+ \rightarrow e^+ + n$), $P(\nu_e \rightarrow \nu_e)$ structure consistent with an unaccounted ν(reactor) flux effect @ ~1.5σ (other hypotheses disfavoured by consistency & tension).

(upcoming ND will help to clarify this very shortly)

beyond Gd-III…

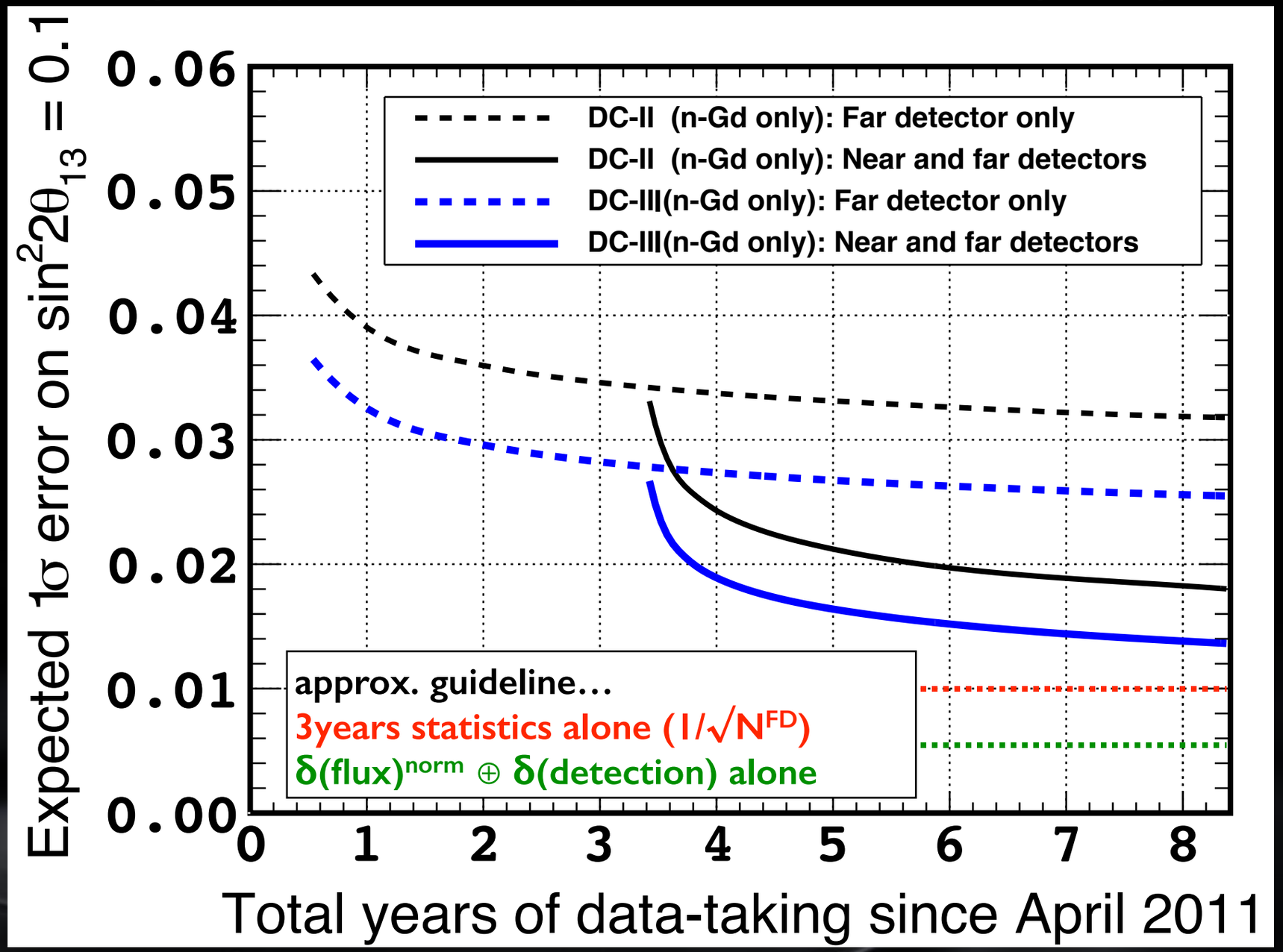
1σ error projection (via R+S analysis)…

assumptions:

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

comment:

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



(with ND) **remarkable improvement of DC-III wrt DC-II**

⟹ **error dominated statistics to 3years (and beyond)**

expected 1σ error in between (blue) and stat only (red)→ systematics dependent

(R+S project assumes BG model projection DC-III)

what to remember?

conclusions…

- DC-Gd-III have been presenting today (→ Nu2014)…
  - Gd-III improves everything by factors relative to Gd-II
    - higher efficiency, less BG (active BG rejection), data-driven BG estimations, etc
      - $\delta(\text{detection})^{III}$ ~2x more precise $\delta(\text{detection})^{II}$
      - $\delta(\text{BG})^{III}$ ~3x more precise $\delta(\text{BG})^{II}$
      - 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) $\sin^2(2\theta_{13}) = (0.09\pm0.03)$ [corresponding BG: ~$(1.43\pm0.15)\text{day}^{-1}$]
  - (RRM full) $\sin^2(2\theta_{13}) = (0.09^{+0.03}_{-0.04})$ [corresponding BG: ~$(1.55\pm0.17)\text{day}^{-1}$]
    - (RRM 2xOFF) $\sin^2(2\theta_{13}) = (0.06\pm0.04)$ [corresponding BG: ~$(0.90\pm0.39)\text{day}^{-1}$]
- DC projections…
  - ND will run from end of summer 2014
  - major systematic cancellation boosting about ≥ 0.01 as 1σ error on $\sin^2(2\theta_{13})$
    - improvement in analysis are already expected & in preparation

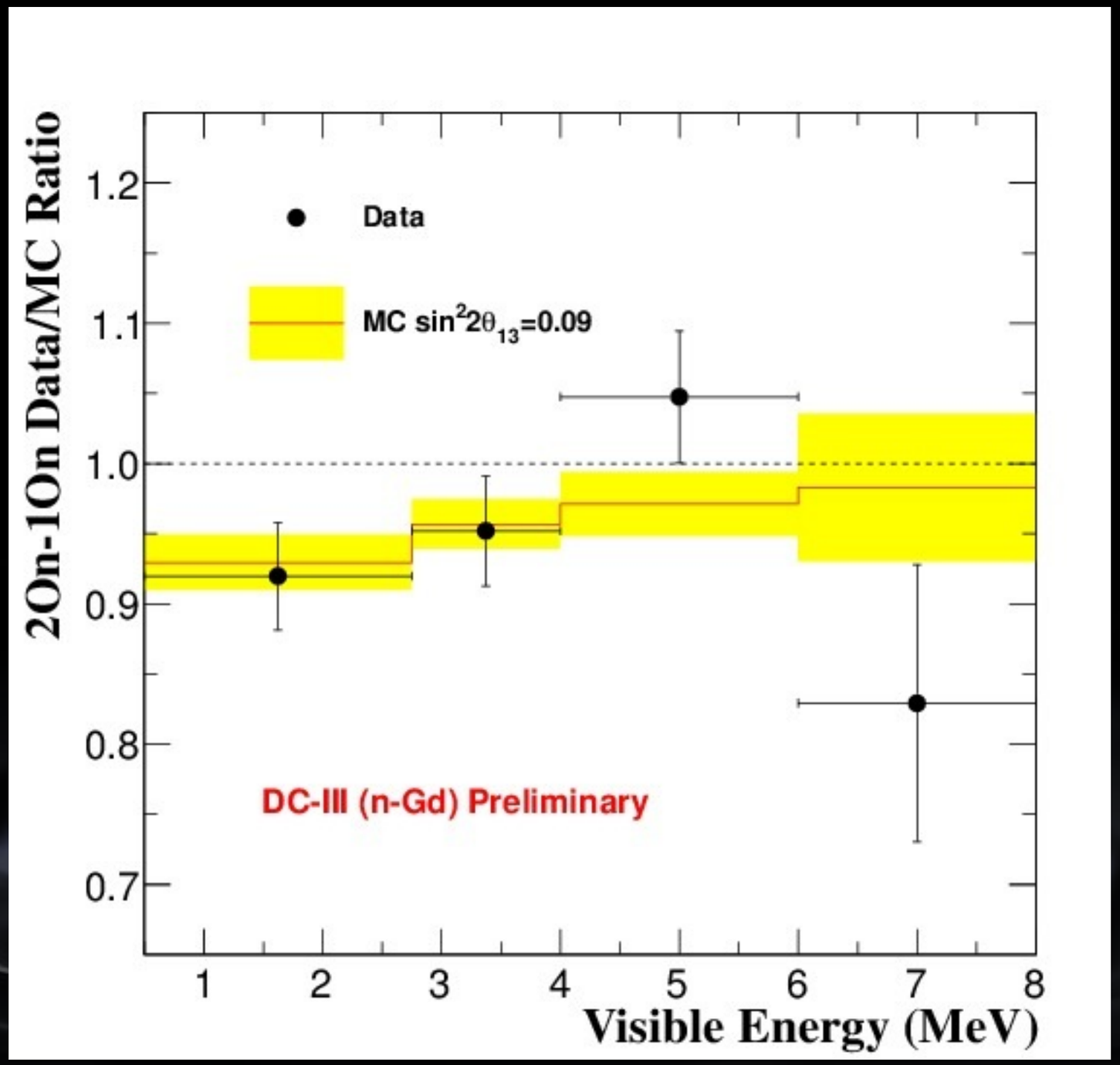
small is beautiful…

backup…

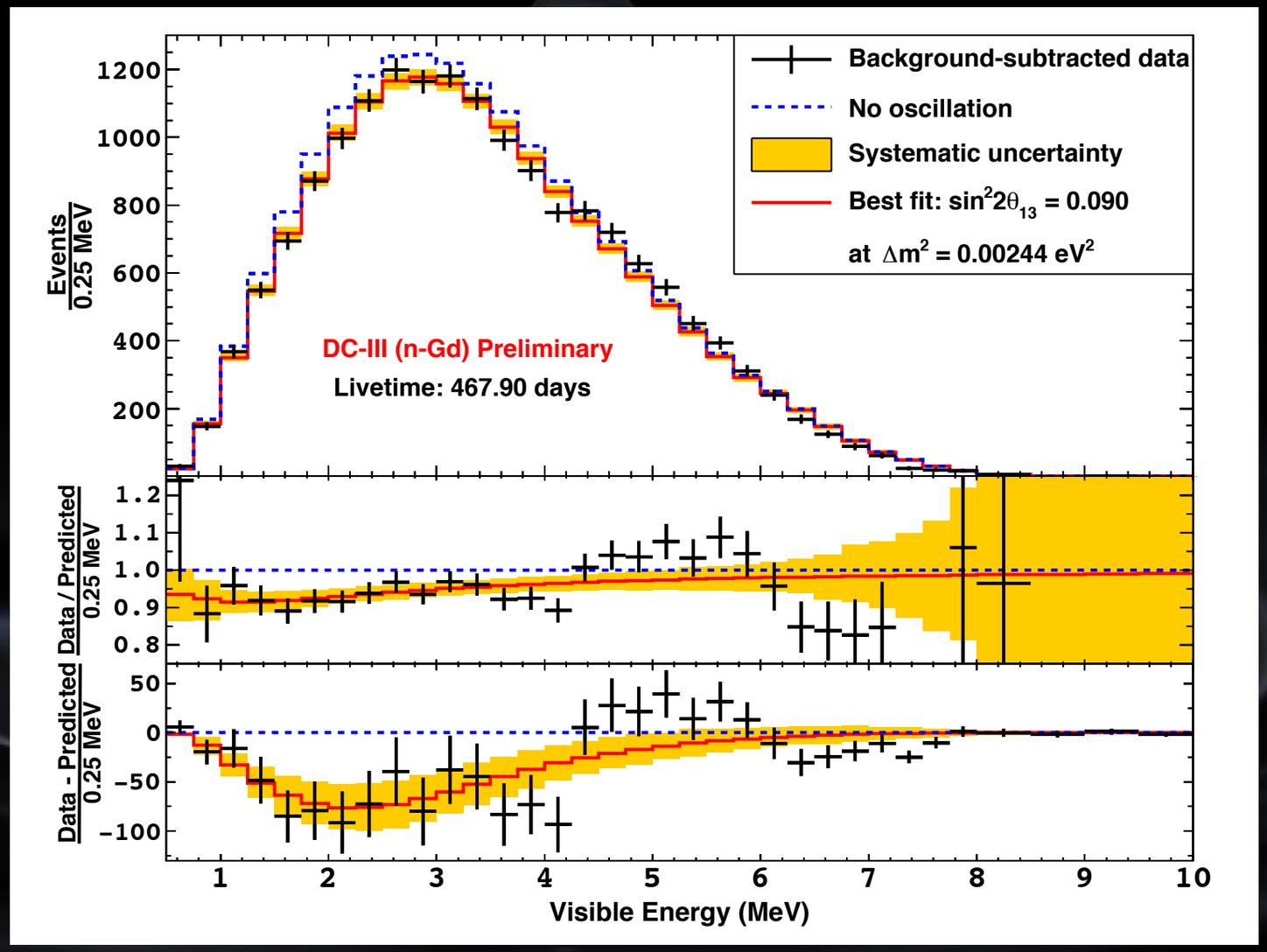
rate-only results…

Parameter	Input C.V.	Input Error	Output C.V.	Output Error
E-scale a'	-0.027	0.006	-0.027	0.006
E-scale b'	1.012	0.008	1.012	0.008
E-scale c'	-0.0001	0.0006	-0.0001	0.0006
FN+SM rate (d^{-1})	0.60	0.05	0.59	0.05
Li+He rate (d^{-1})	0.97	$+0.41, -0.16$	0.89	$+0.18, -0.16$
Accidentals rate (d^{-1})	0.0701	0.0054	0.0700	0.0054
Residual $\bar{\nu}_e$	1.57	0.47	1.48	0.47
Δm^2 (10^{-3} eV^2)	2.44	$+0.09, -0.10$	2.44	$+0.09, -0.10$
$\sin^2 2\theta_{13}$	—	—	0.094	0.037
χ^2/d.o.f.	—	—	3.3/1	—

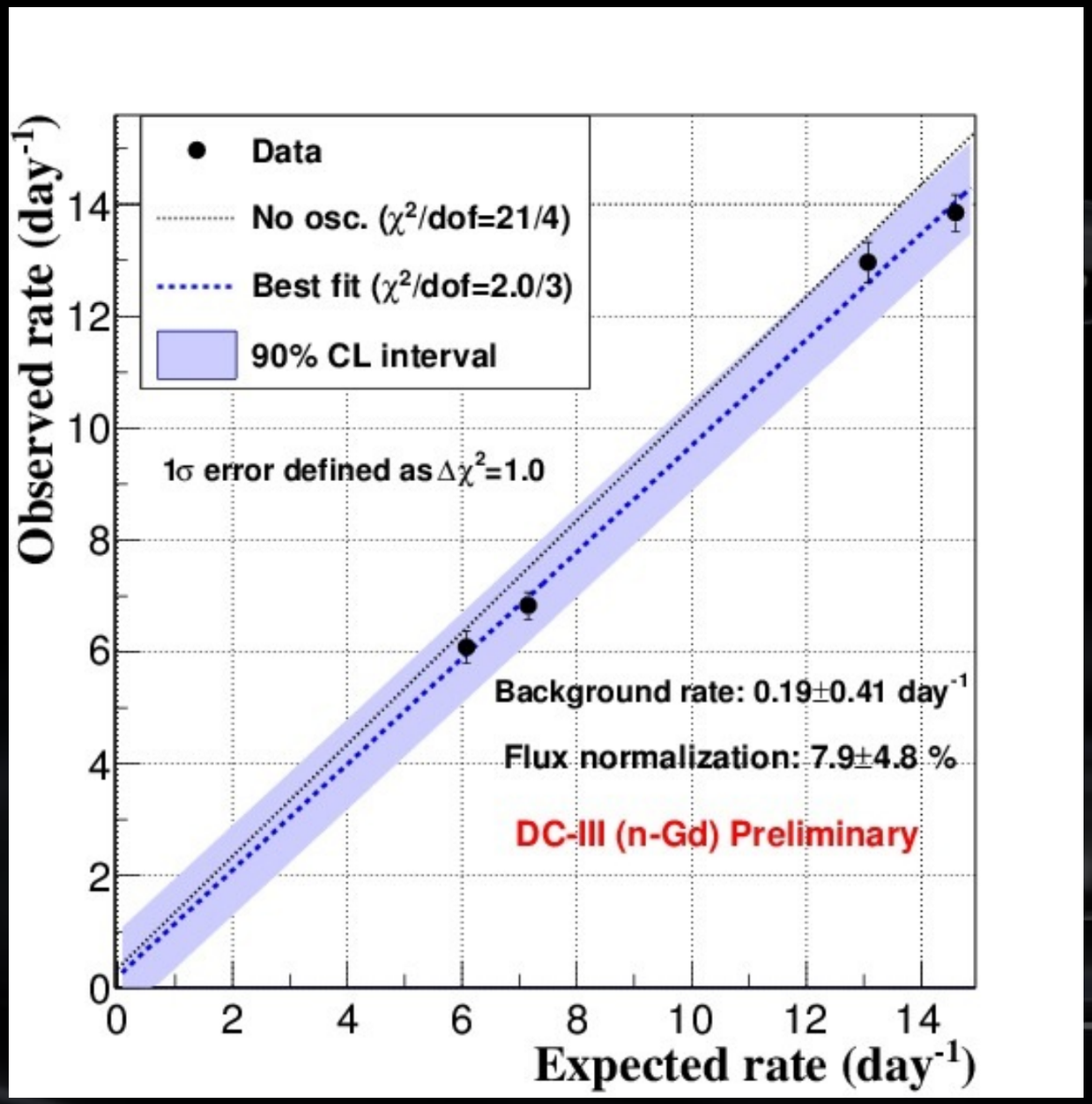
analysis 2ON-1ON…

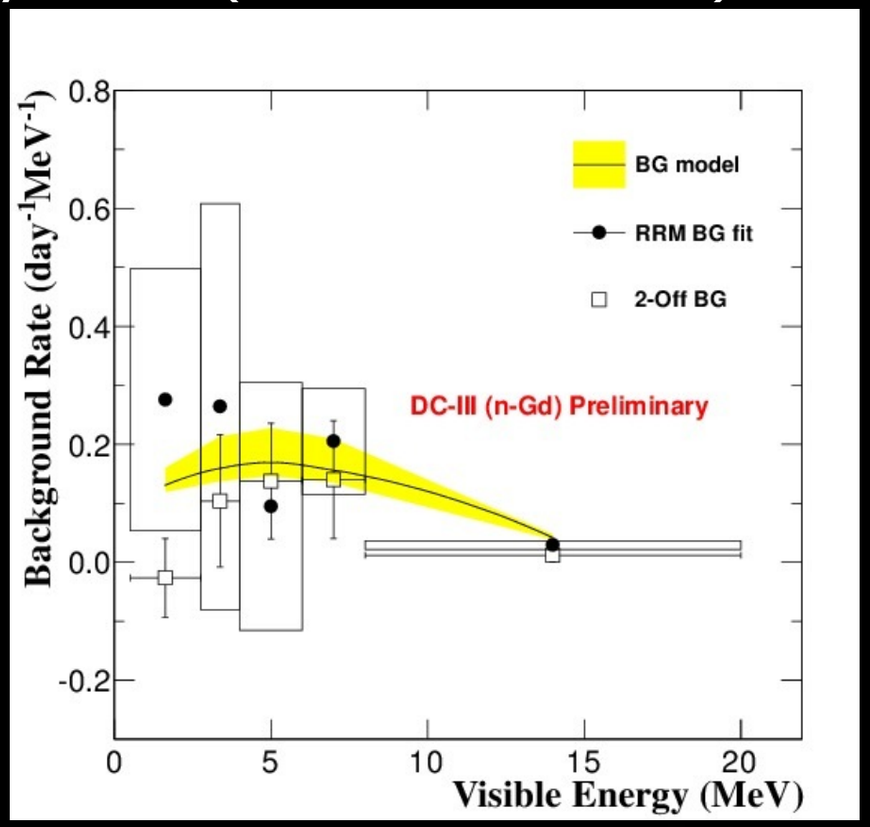


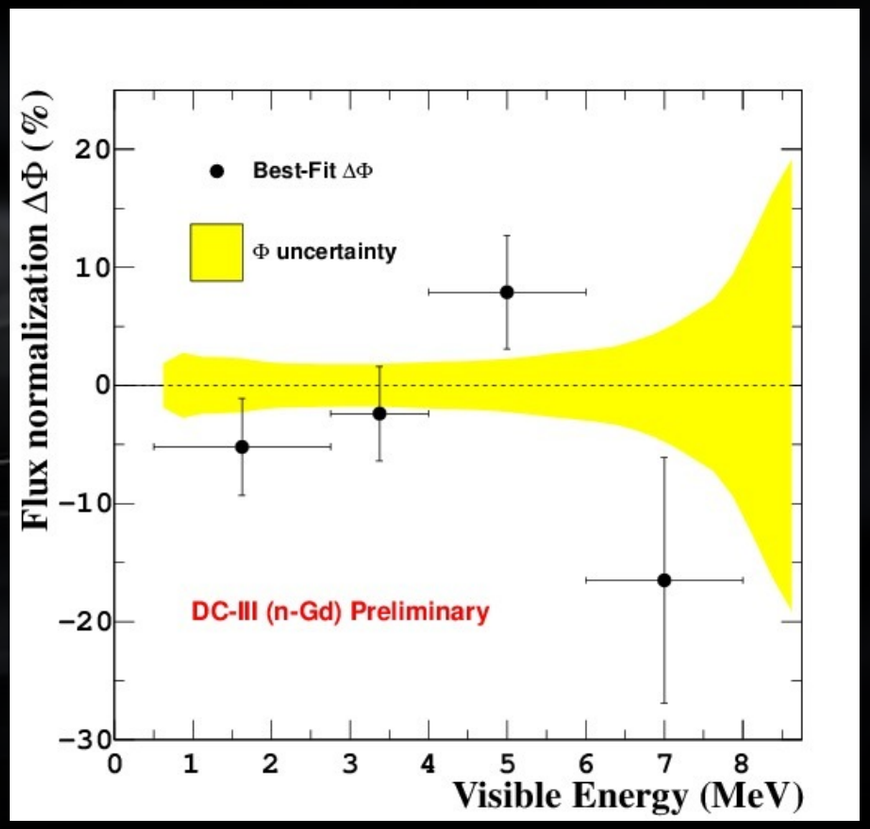
subtract BG contribution


Background-subtracted data
No oscillation
Systematic uncertainty
Best fit: sin²2θ13 = 0.090
at Δm² = 0.00244 eV²
DC-III (n-Gd) Preliminary
Livetime: 467.90 days
Events / 0.25 MeV
Data / Predicted / 0.25 MeV
Data - Predicted / 0.25 MeV
Visible Energy (MeV)

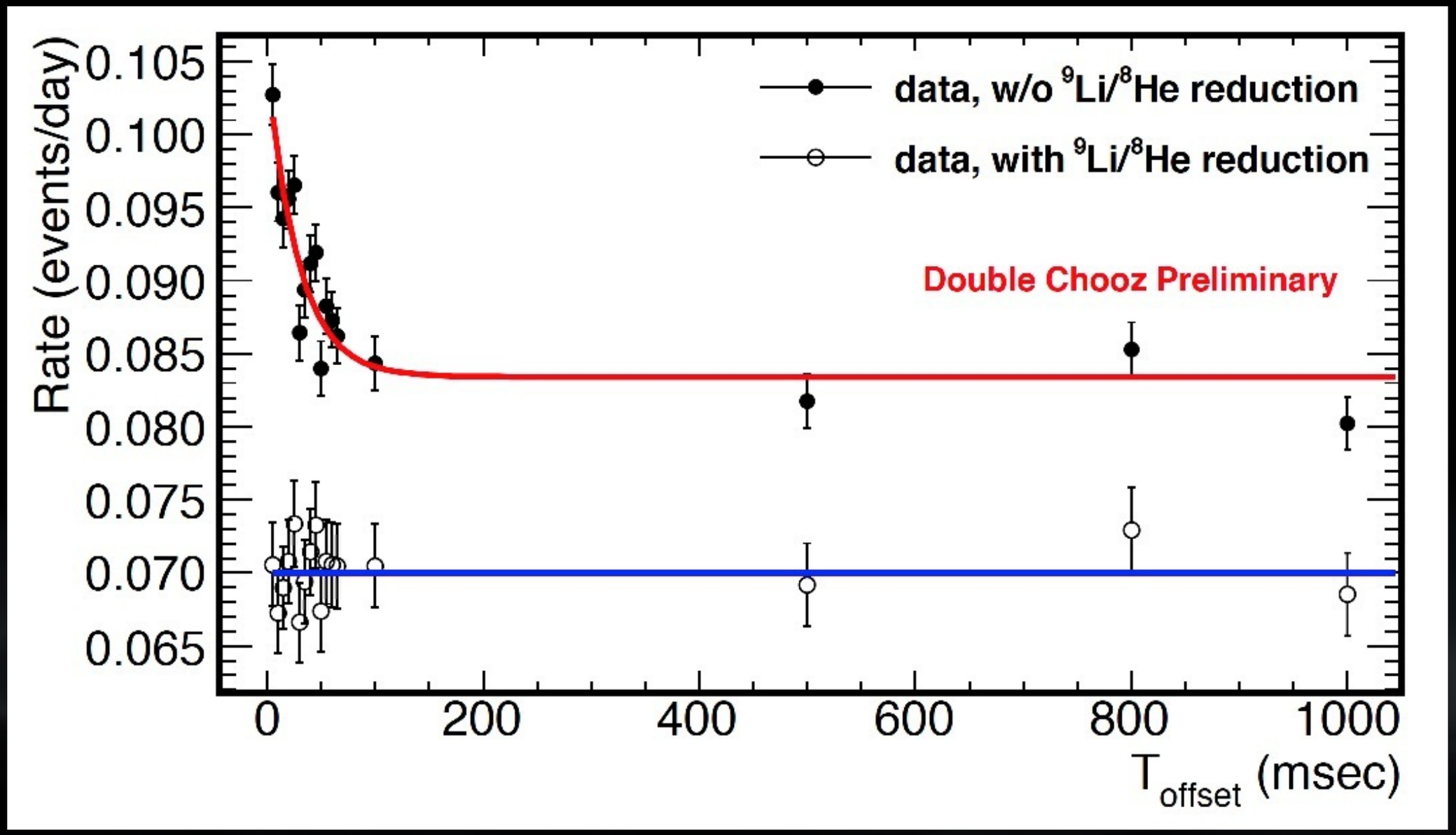
binned RRM analysis (fixed θ_{13})…







^{12}B remaining measurement…



reactor flux uncertainties breakdown…