reactors v

(discovery tools)

Università di Genova (Italia)
May 2018

Anatael Cabrera

CNRS / IN2P3 @ APC (Paris)

reactors… why so cool?

Chooz reactor
(cooling tower)

the reactor-ν saga (since 1956)…

unique history: ν discovery (1956)

→much **ν detection principles** definition

neutrino oscillations: high precision (≥1980)

→**θ12, θ13, δm2, ±Δm2 (~~θ23~~ & ~~octant~~)**

→**high precision for δ_{CP} (beams)** [→ **J-invariant**]

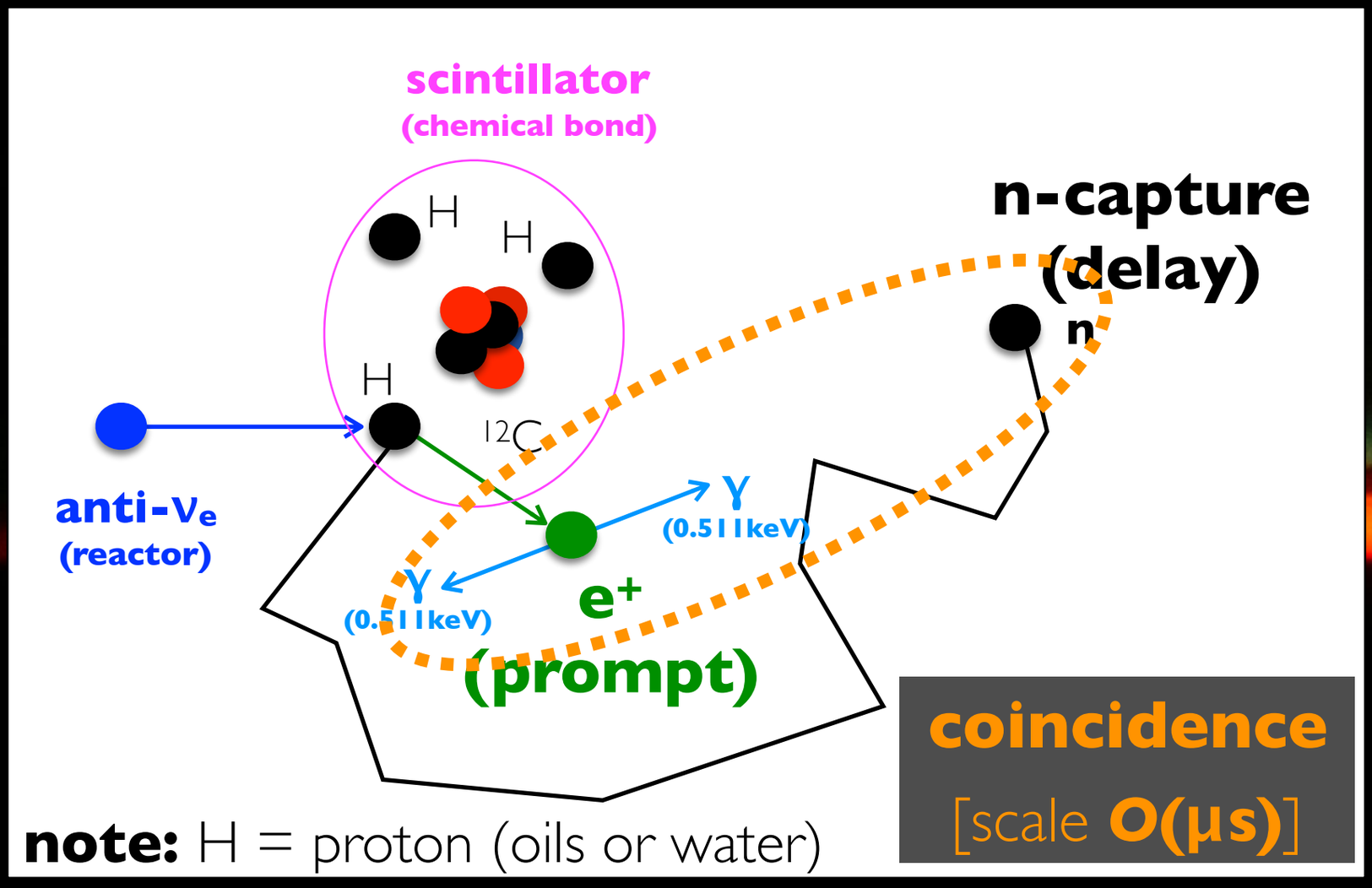
review detection principle limitation?

→**a possible solution?**

the ν discovery (1956)…

inverse-β decay (IBD) interaction…

IBD: anti-ν_e + p → e^+ + n



IBD detection art…

n-H (**native**)

n-C (**native oil**)

n-O? (**native water**)

n-Cd (non-native)

n-Li (non-native)

n-Gd (non-native)

^{3}He (non-native)

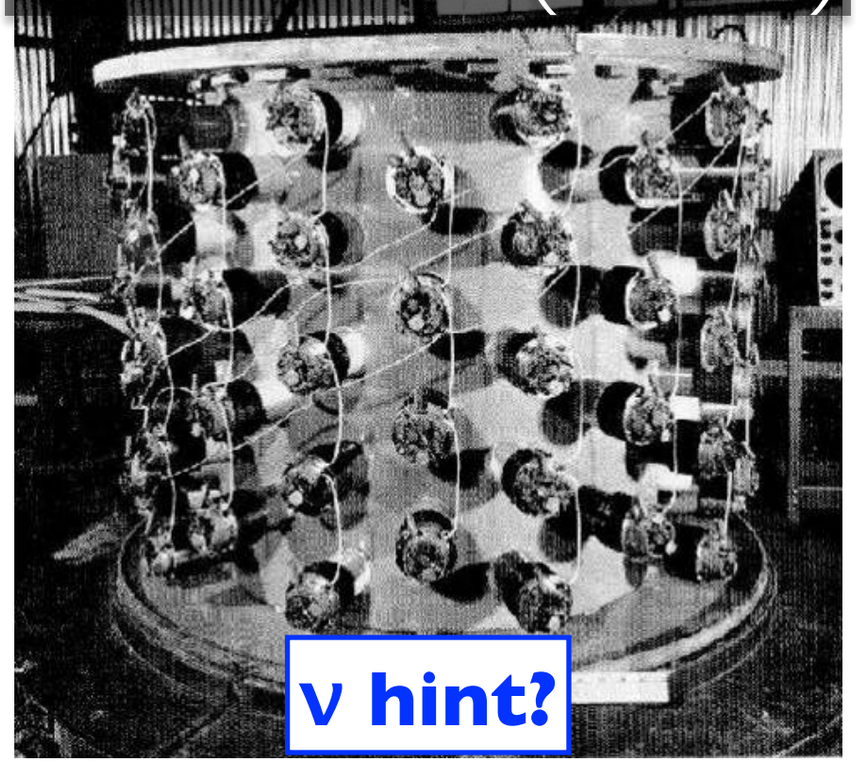
how to catch the n?

no e+ PID implies

γ ≈ e^- ≈ e^+ ≈ α ≈ p-recoil (fast-n)

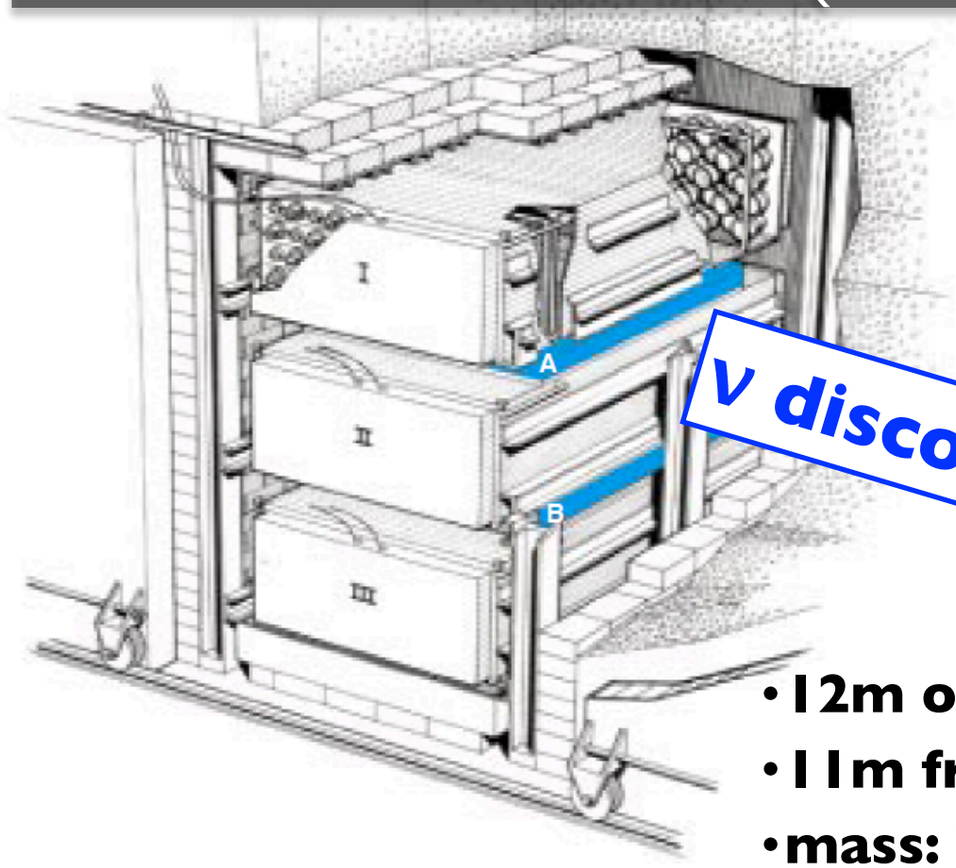
Reines&Cowan pioneering detection…

Handford (1953)



- **surface** (inside a truck)
- >15??m from reactor
- **mass:** ~300kg
- **target:** scintillator + Cd (loading?) **today's inspiration!**

Savannah River (1956)



ν discovery!!

- **12m overburden**
- **11m from reactor**
- **mass:** 2x 200kg
- **target:** water + Cd
- **I+II+II:** scintillator
- **rough segmentation**

THE REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 29, NUMBER 2 FEBRUARY, 1958

Liquid Scintillators for Free Neutrino Detection*

A. R. RONZIO,† C. L. COWAN, JR.,‡ AND F. REINES
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

(Received October 28, 1957; and in final form, December 9, 1957)

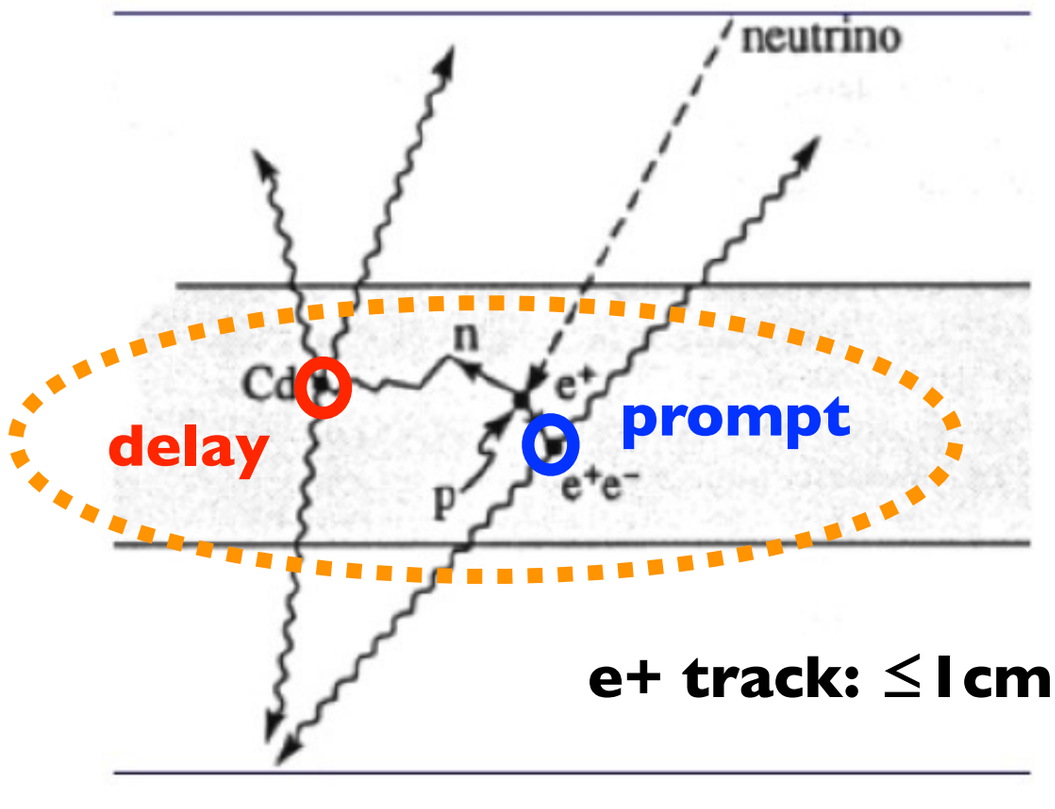
The criteria by which liquid scintillators have been selected and developed for free neutrino detection experiments are described and a discussion is given of the preparation of the solutions. Triethylbenzene is a superior solvent and cadmium octoate is found to be the best cadmium compound known for these purposes.

Cd loading on liquid scintillator

Reines& Cowan powerful coincidence (IBD)…

coincidence

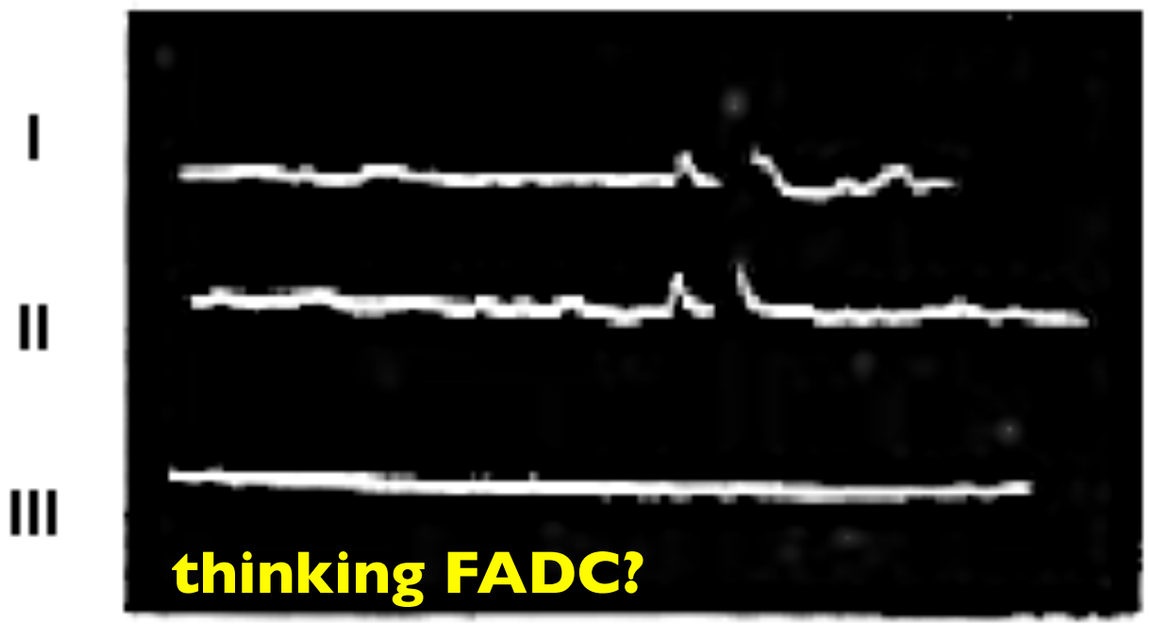
[scale ***O*(μs)**]



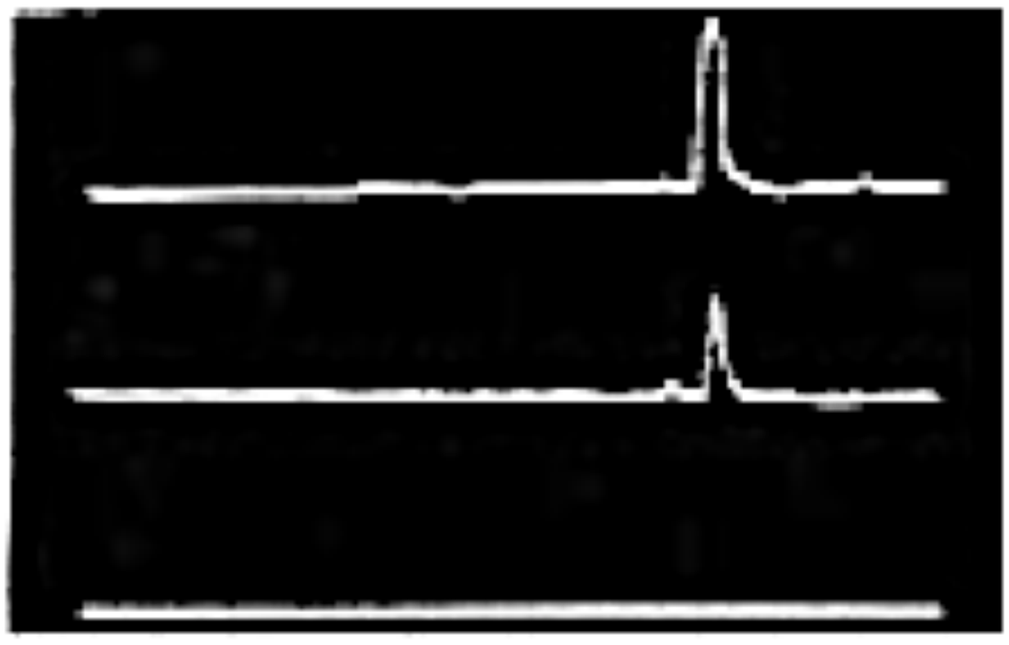
e+ track: ≤1cm (dE/dx)

e+ annihilation (2x 0.511MeV)

n-Cd capture (~9MeV)



(a) Positron scope



Neutron scope

Reines&Cowan **detection strategy**…

PMT ⇔ transparent medium

overburden (μ-cosmic shielding)

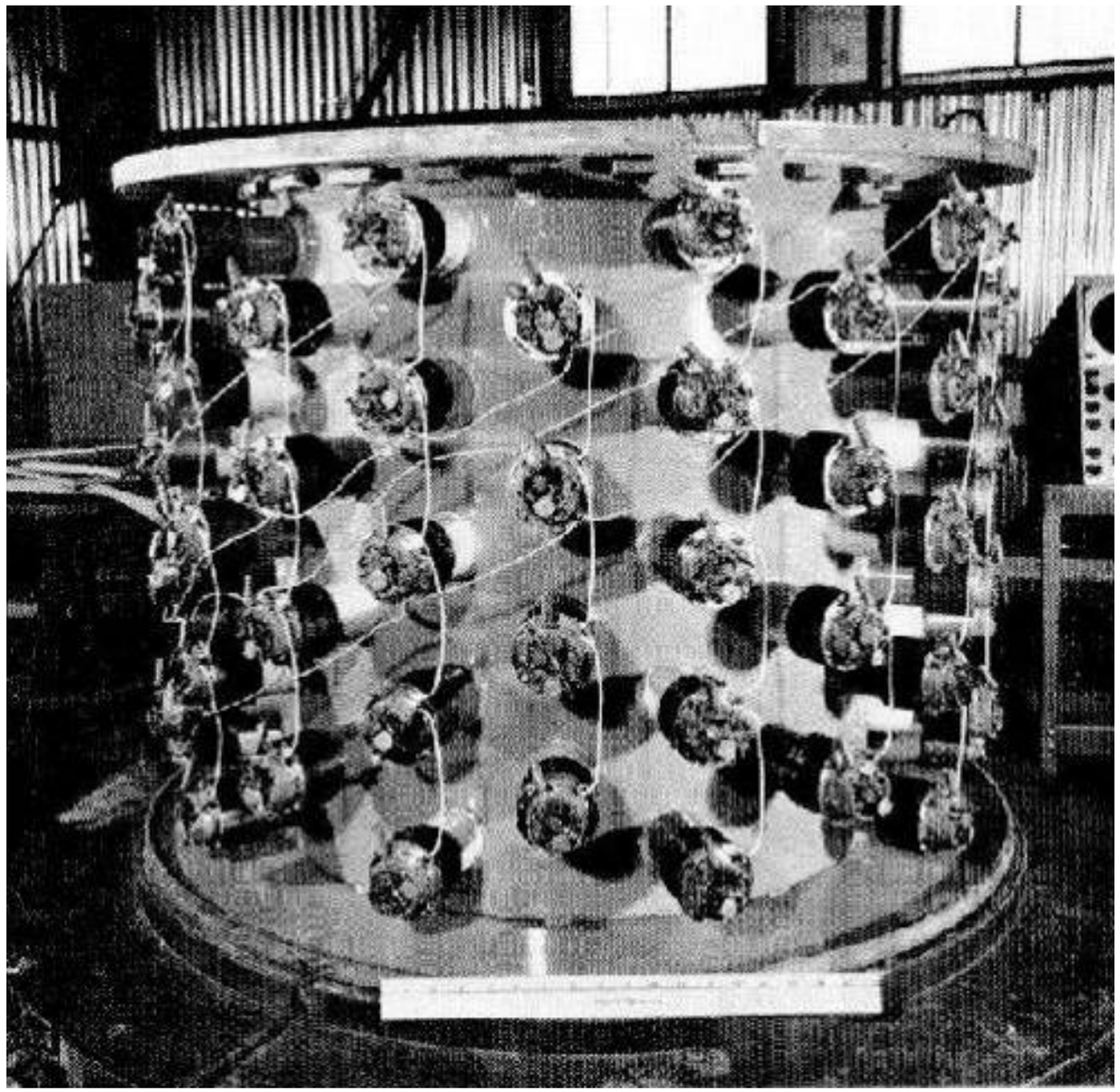
external shielding (radioactivity shielding)

loaded medium (^{113}Cd)→ non-native detection!

(reactor source) **modulation ON vs OFF**

~70years ago similar to today!

Reines & Cowan detector (300kg)…



today's inspiration!

Handford (1953)

today's version of similar technology…

PMT($\sim$ 1 ns) $\Longrightarrow$ **transparency**

CTF @ Gran Sasso
(Borexino R&D)

(most) exquisite radio-purity…

Borexino (GS)

SNO+ / KamLAND

large (1k ton)…

~10,000 PMTs (8" diameter)

SNO @ Canada
(Nobel prize 2015)

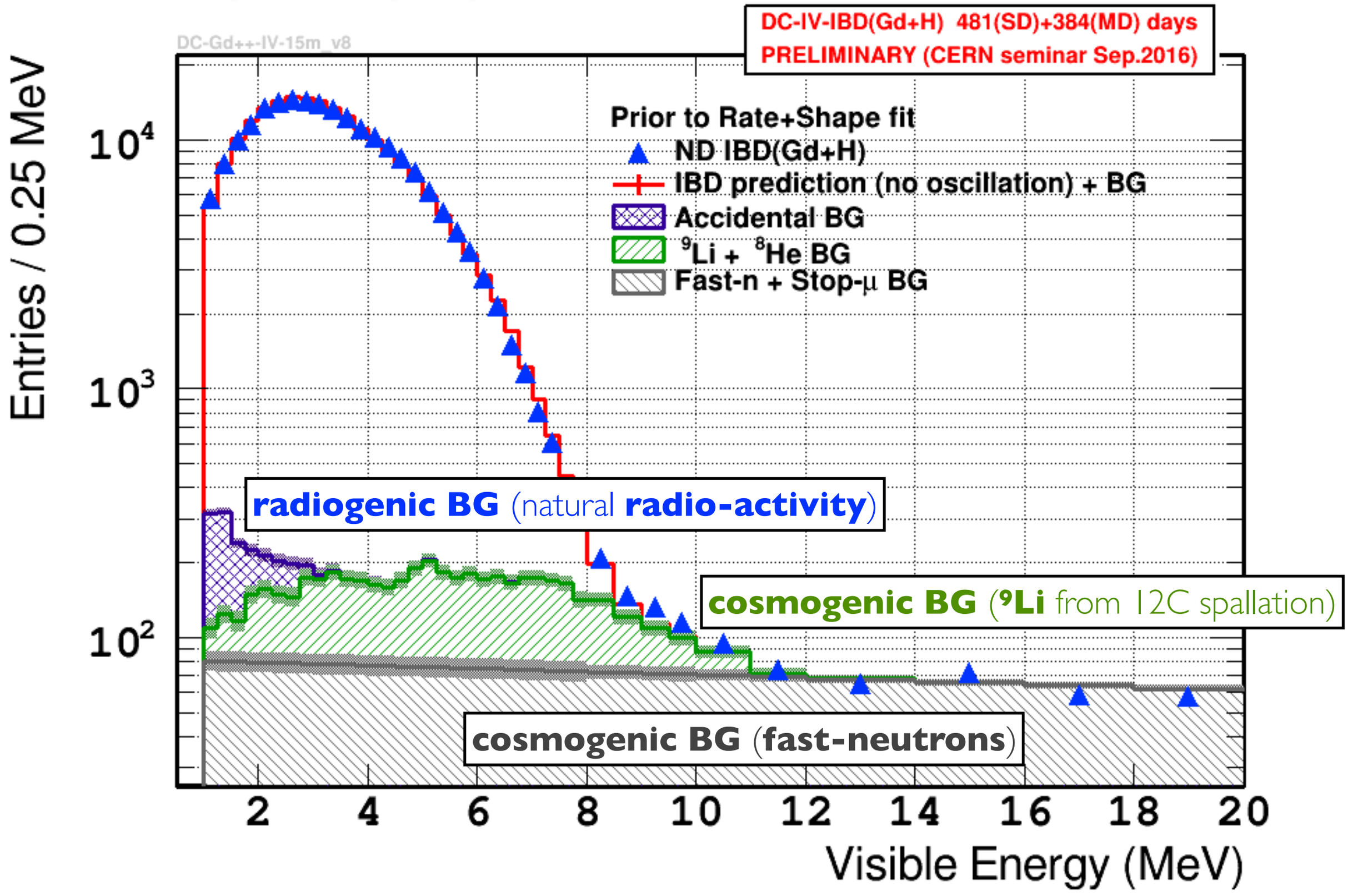
very large (50k ton)…

Super-KamiokaNDE @ Japan
(Nobel prize 2015)

~50m

~14,000 PMTs (20'' diameter)

(example) Double Chooz near detector…



Energy(ν) ~ Energy(e+) + 0.8MeV

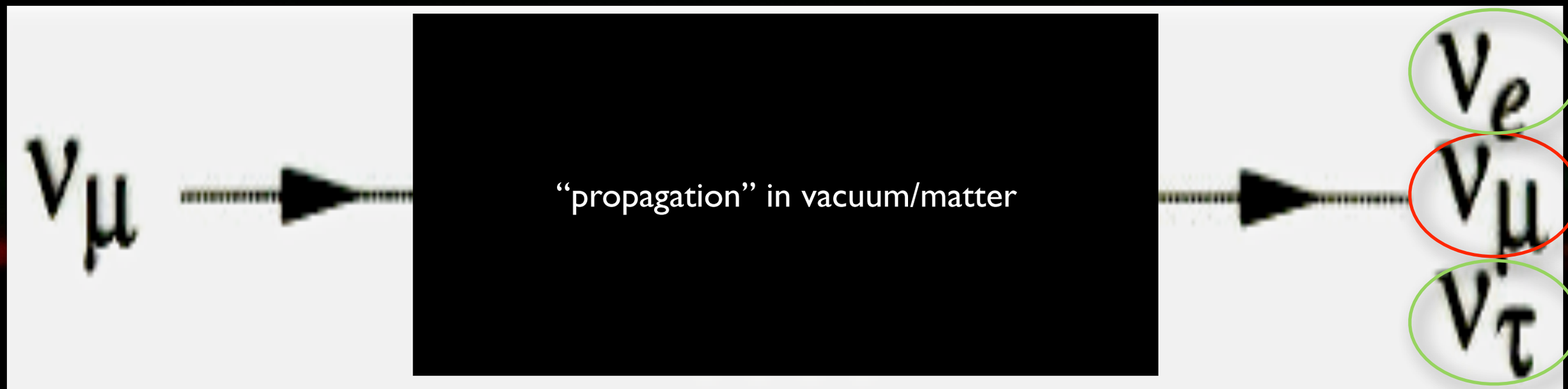
(fast) ν oscillations reminder…

Anatael Cabrera (CNRS-IN2P3 & APC)

neutrino oscillations manifestation…

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

disappearance
appearance



observation: both **disappearance** (the **anomalies**) & **appearance** (July 2013) have been seen

all observations (most!) consistent with 3ν oscillation model

ingredients for neutrino oscillations…

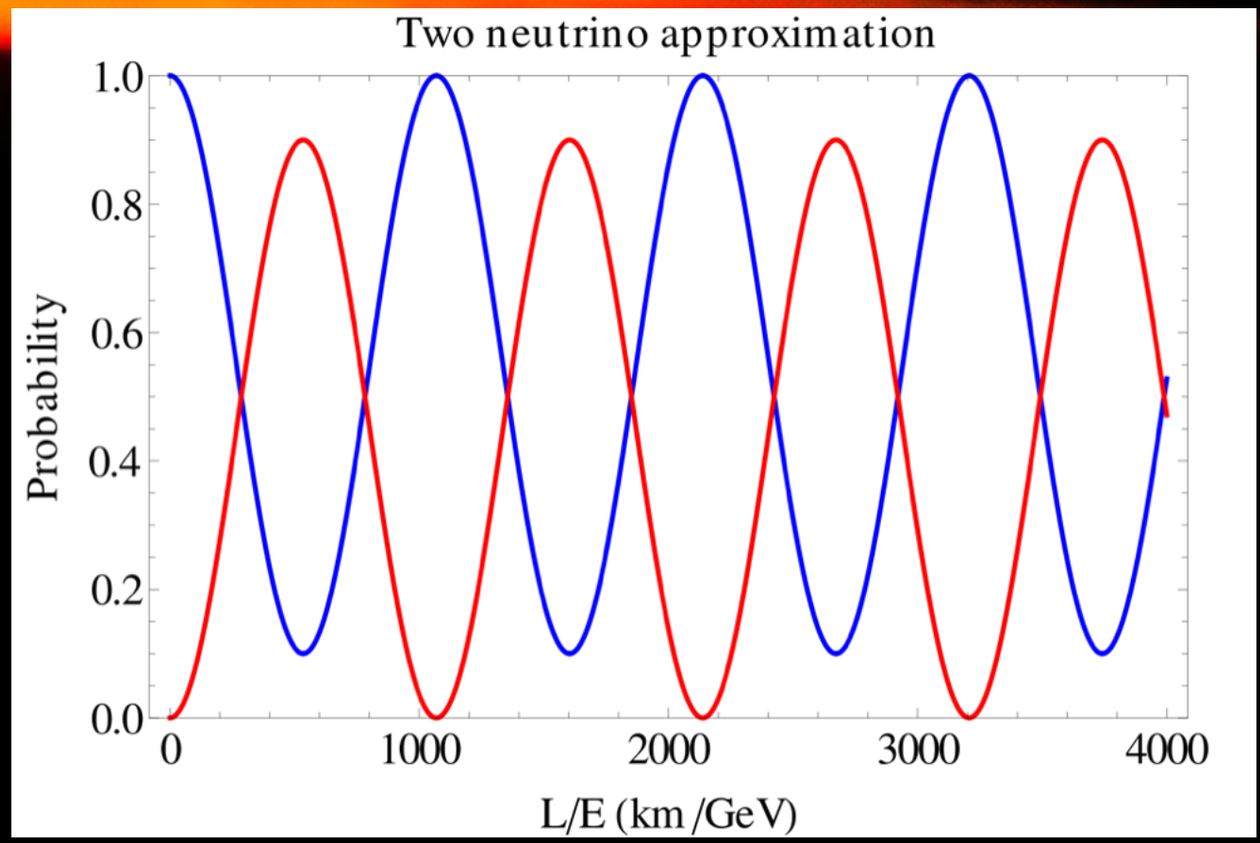
Non-degenerate mass spectrum (**Δm^2**) ⊕ Mixing in the leptonic sector (**θ**) = Oscillation Probability **$P=f(\theta,\Delta m^2)$**

quantum interference (macroscopic)

UPMNS matrix (à la CKM)

ν_α (start with) & ν_β (none at first)

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



“mixing”: a common phenomenon…

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

"atmospheric" $\Longrightarrow$ θ_{23}~45° | θ_{13} & "dirac" δ_{CP} | "solar" $\Longrightarrow$ θ_{12}~33°

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{matrix} \Delta m^2_{31} \\ \text{sub-leading} \end{matrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{matrix} \Delta m^2_{31} \\ \text{sub-leading} \end{matrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{matrix} \Delta m^2_{21} \end{matrix}$$

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

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

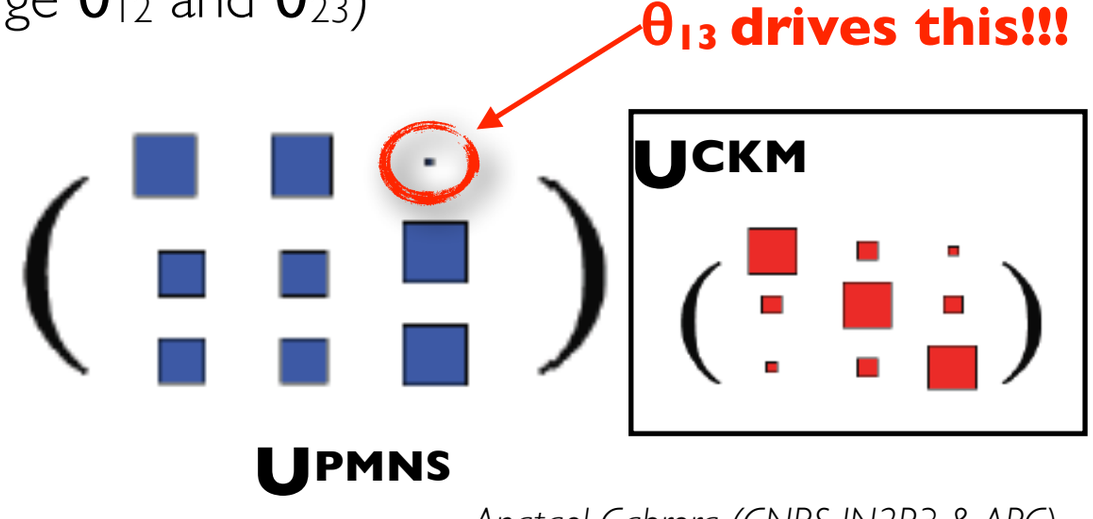
ATMOSPHERIC ANOMALY — **PREDICTION** — **SOLAR ANOMALY**

effective decoupling of "solar" & "atmospheric":

- δm^2 (order 10^{-5}eV^2) versus Δm^2 (order 10^{-3}eV^2)
- θ_{13} being small (relative to very large θ_{12} and θ_{23})

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

is U unitary? [if not→ 4th ν family]



every ~10 years…

a reactor-ν breakthrough!!

(also Palo Verde)

~1990 @ France

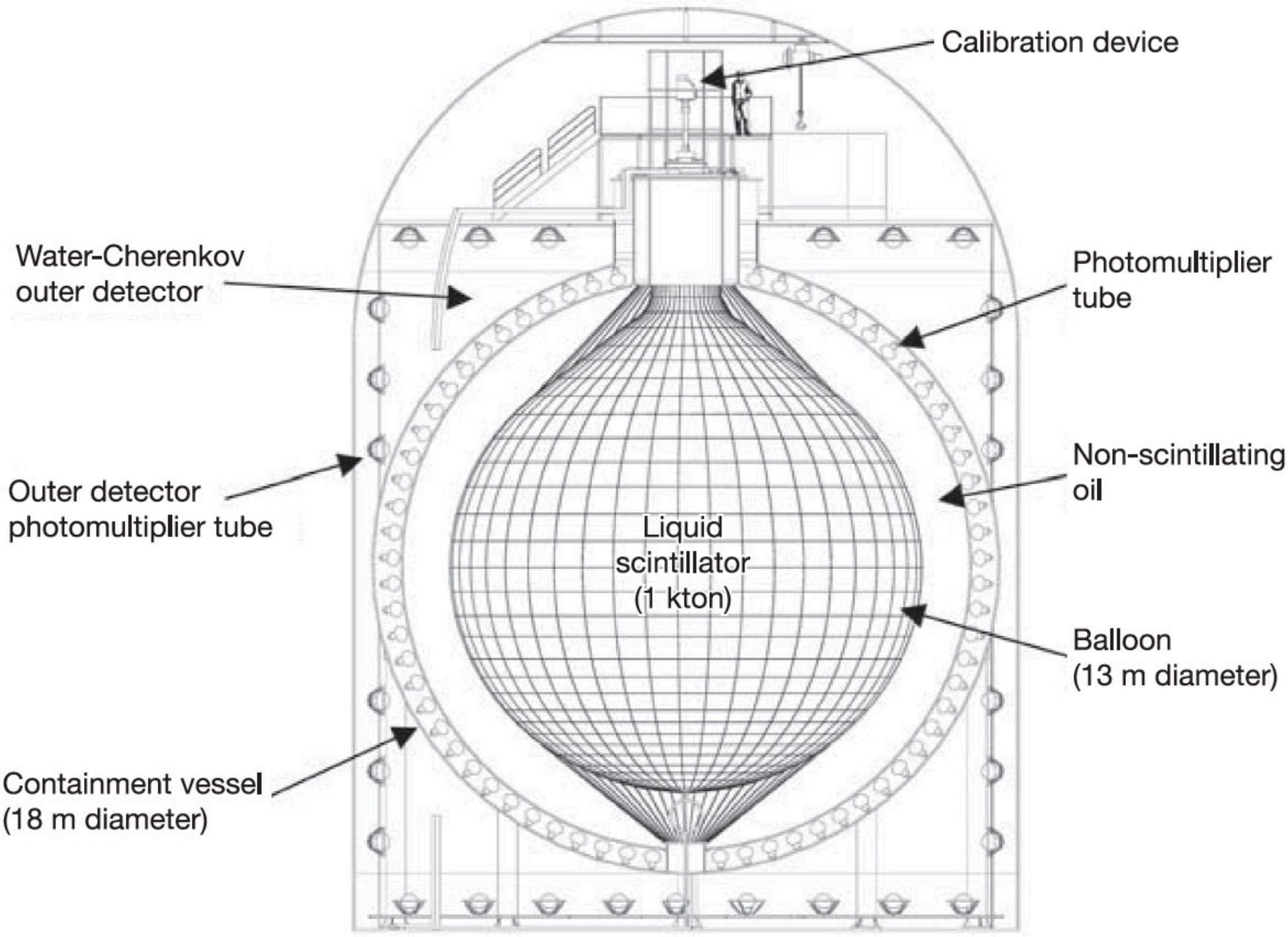
CHOOZ experiment…

(assume Borexino was solar only)

~2000 @ Japan

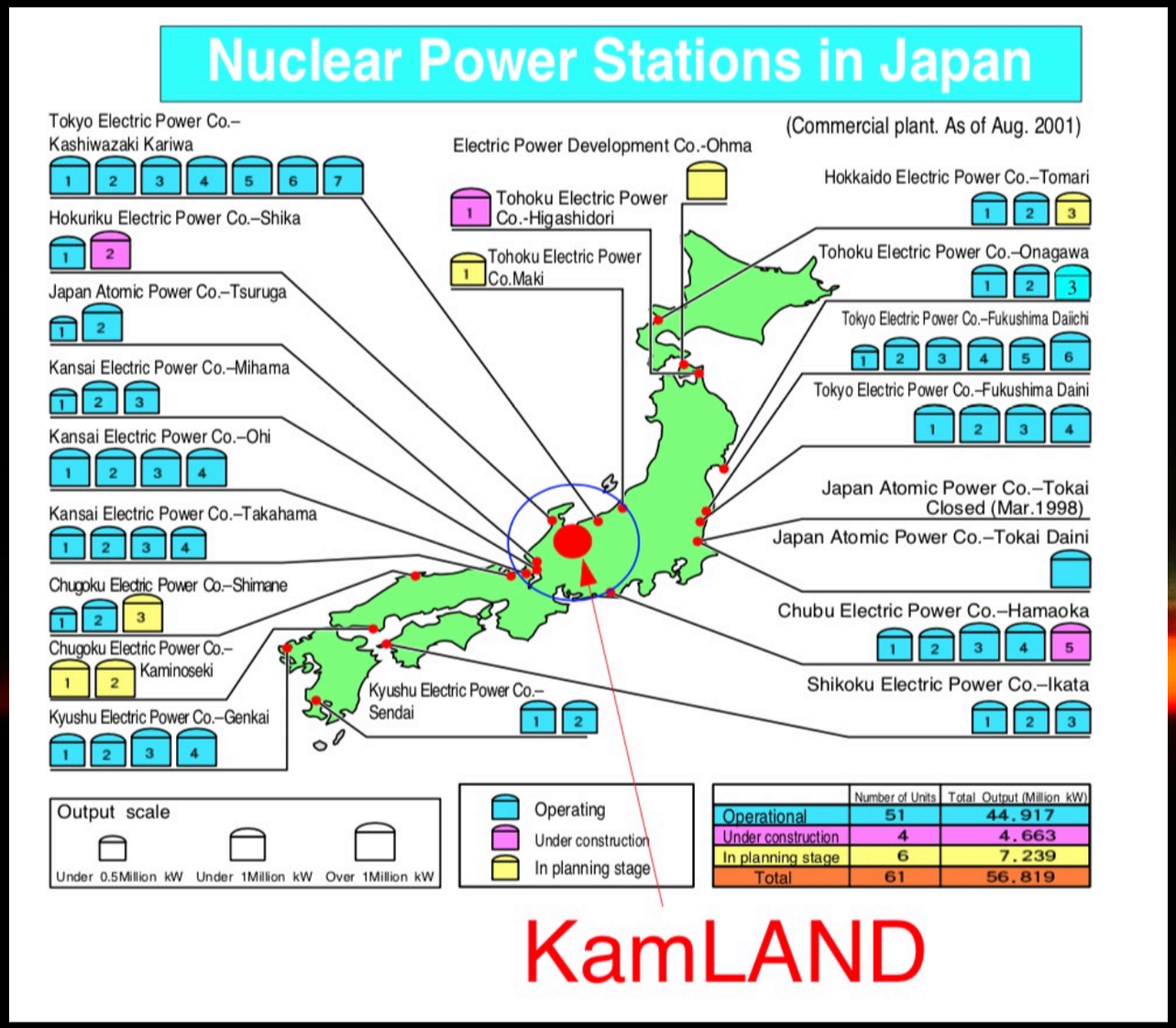
KamLAND experiment…

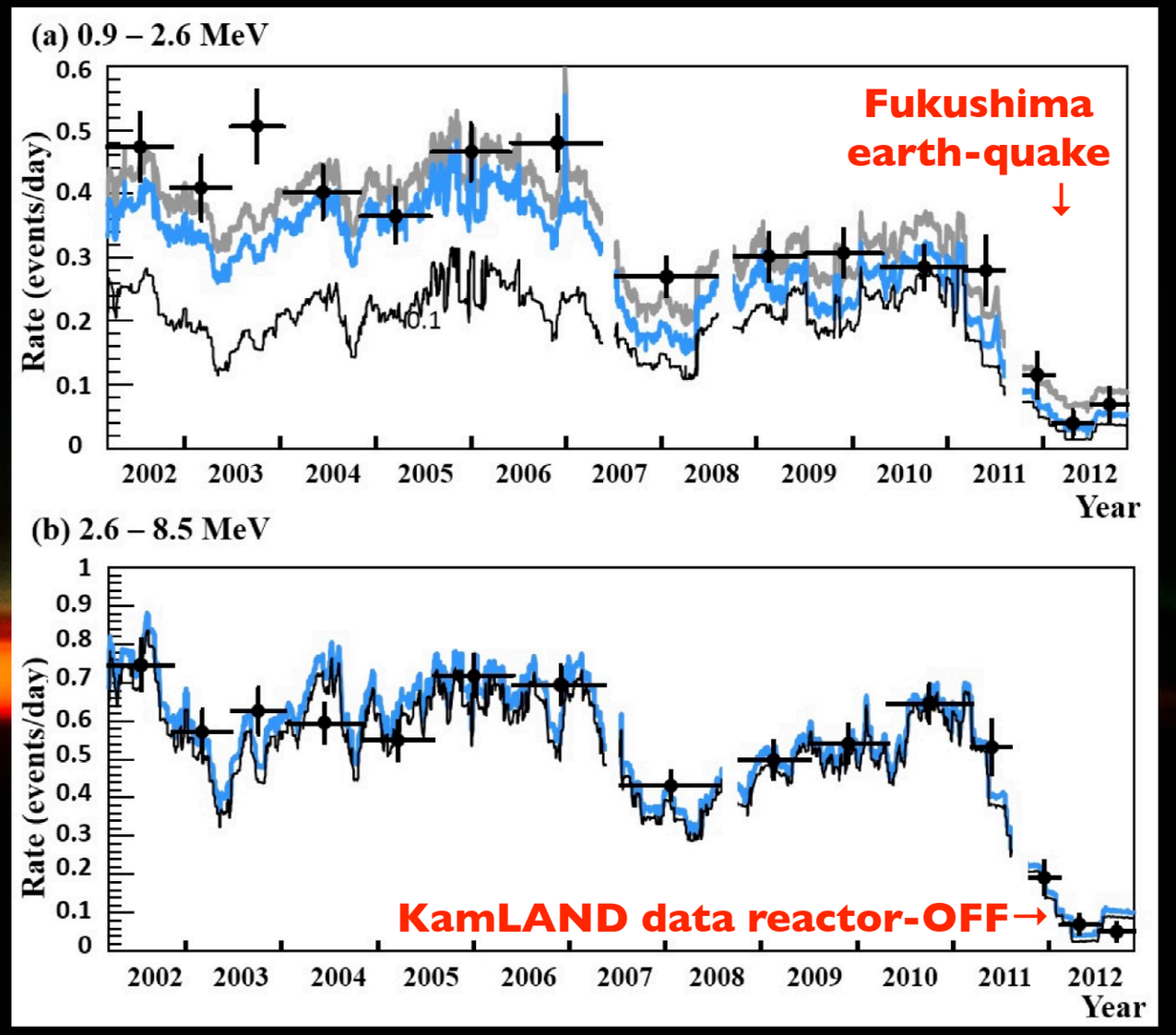
KamLAND (1kton) detector…



recycle KamiokaNDE's site (~3kton)…

KamLAND strategic **position** & **time**…





~70GWth (~12% global)

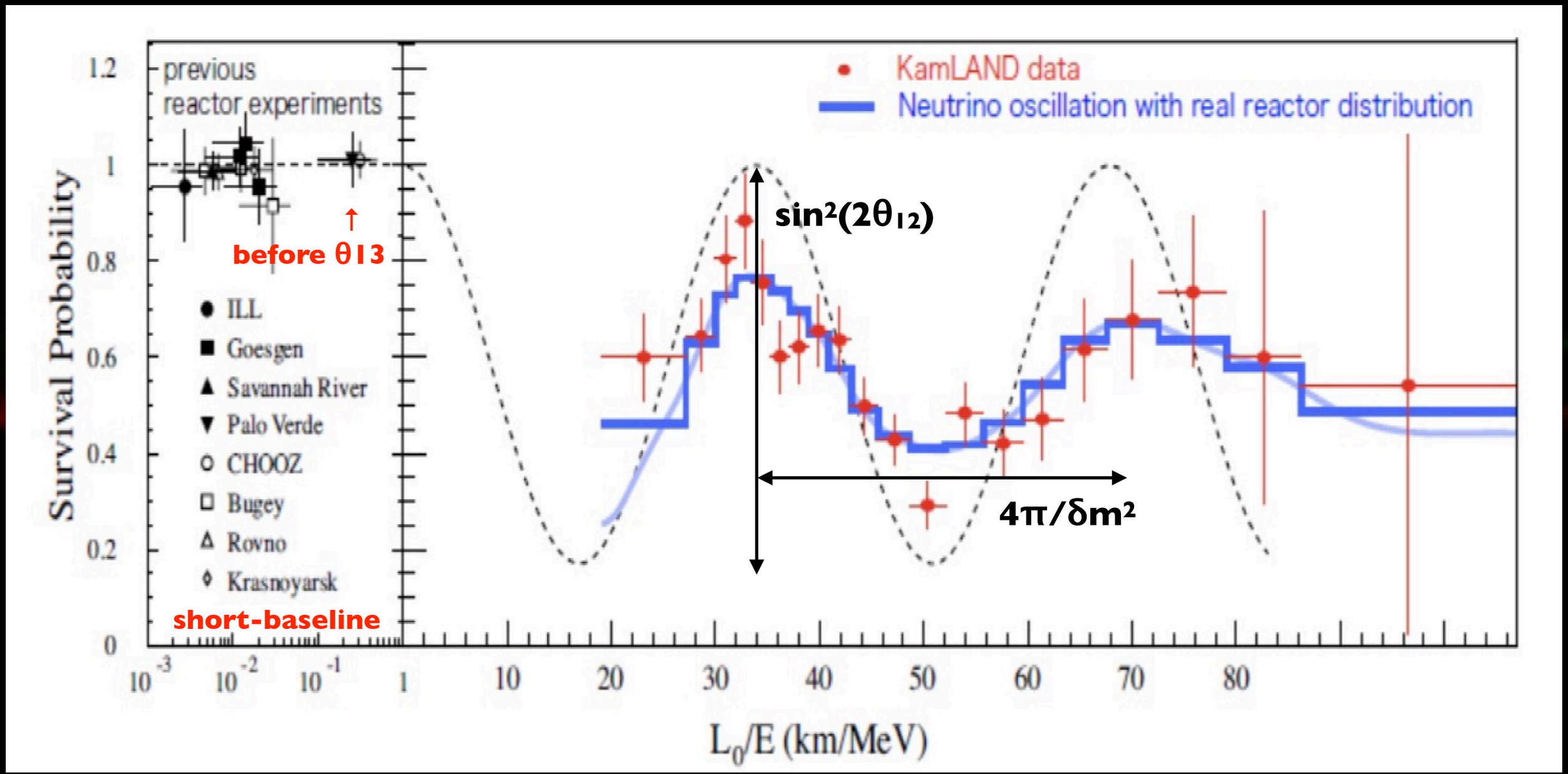
<L> = (175±35)km

≲1.0 IBD/day

till Fukushima earth-quake

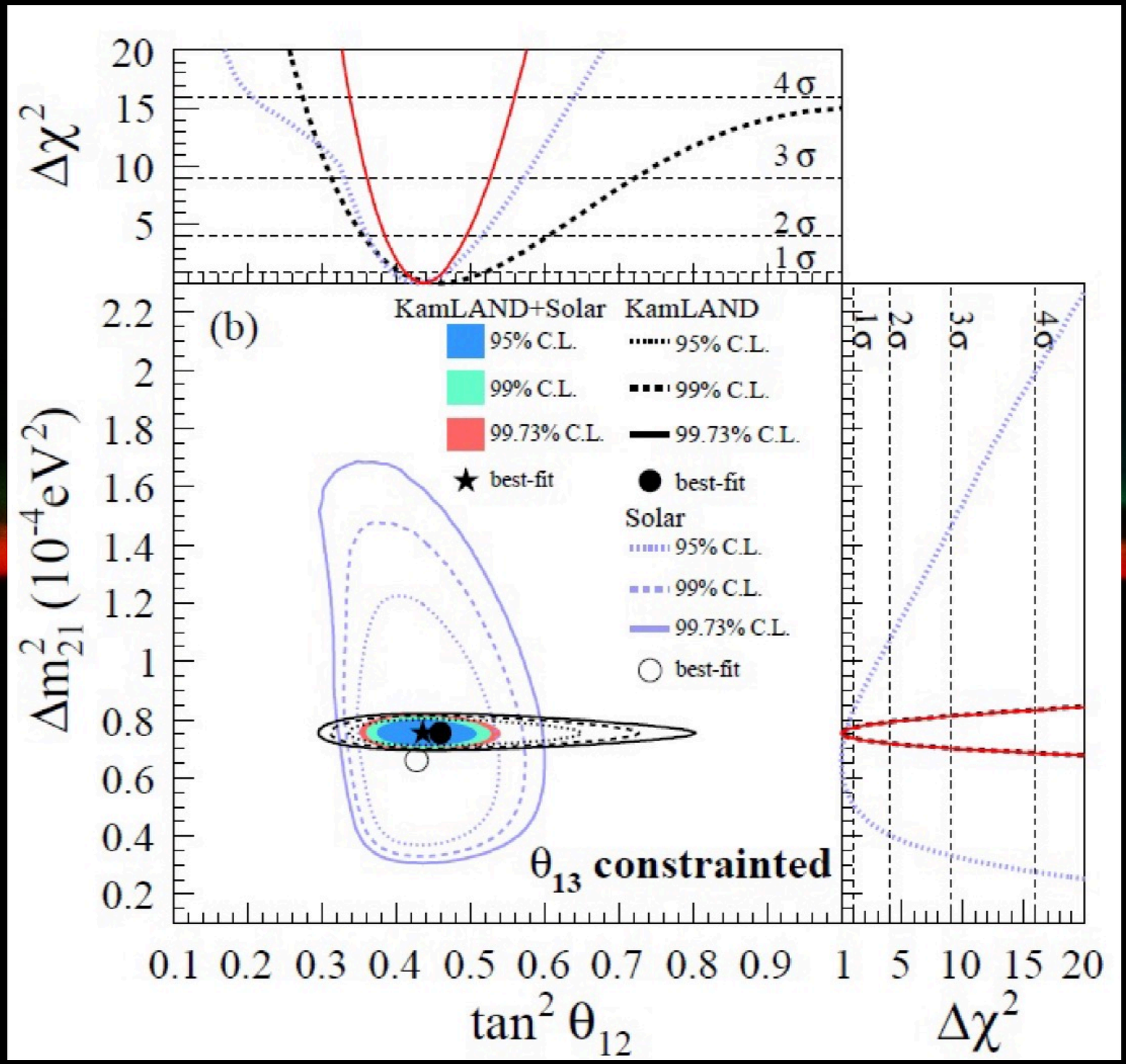
the latest KamLAND's $P(\nu_e \rightarrow \nu_e)$...

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

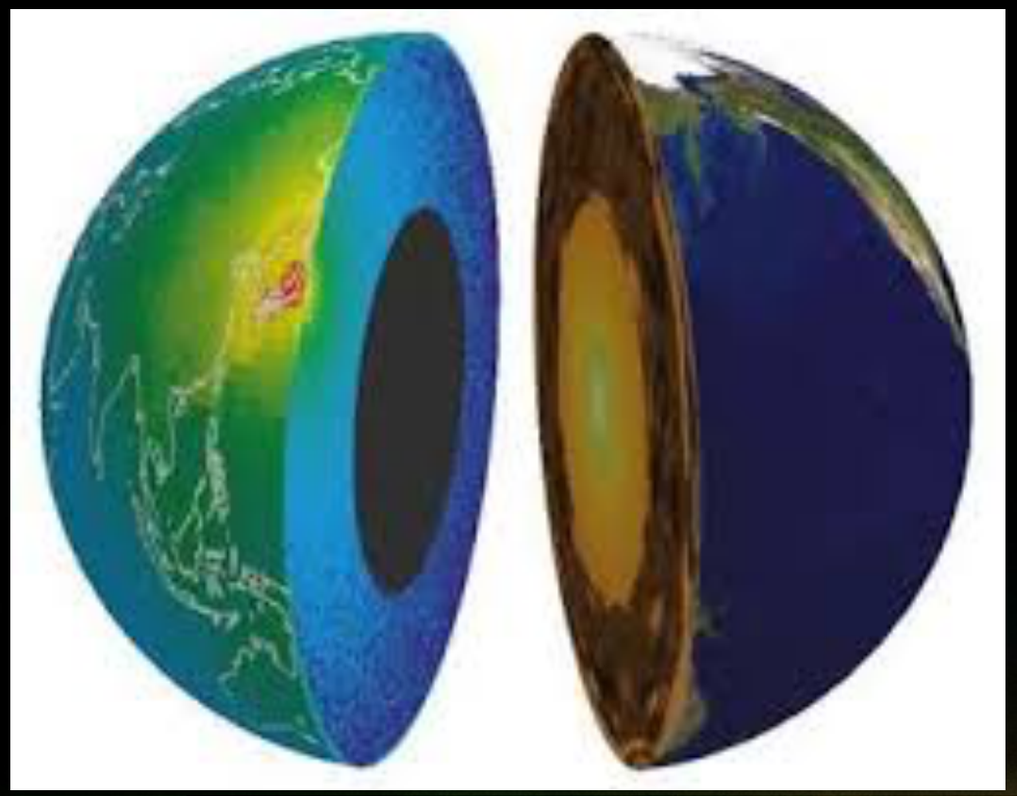


average E/L over many reactors: visible oscillation over 100's km!

KamLAND's measurement of δm^2 & θ_{12}...



first observation geo-ν (U⊕Th)…

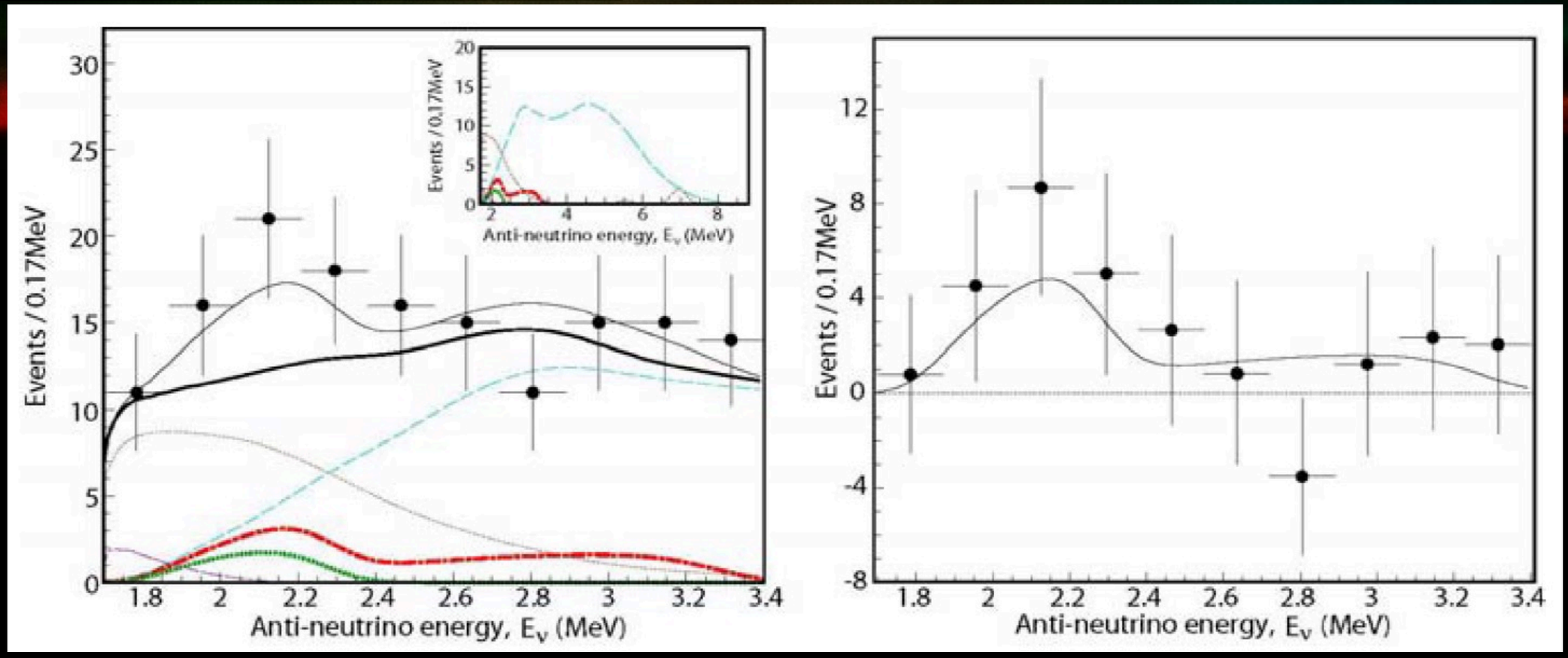


Vol 436|28 July 2005|doi:10.1038/nature03980 nature

ARTICLES

Experimental investigation of geologically produced antineutrinos with KamLAND

T. Araki[1], S. Enomoto[1], K. Furuno[1], Y. Gando[1], K. Ichimura[1], H. Ikeda[1], K. Inoue[1], Y. Kishimoto[1], M. Koga[1], Y. Koseki[1], T. Maeda[1], T. Mitsui[1], M. Motoki[1], K. Nakajima[1], H. Ogawa[1], M. Ogawa[1], K. Owada[1], J.-S. Ricol[1], I. Shimizu[1], J. Shirai[1], F. Suekane[1], A. Suzuki[1], K. Tada[1], S. Takeuchi[1], K. Tamae[1], Y. Tsuda[1], H. Watanabe[1], J. Busenitz[2], T. Classen[2], Z. Djurcic[2], G. Keefer[2], D. Leonard[2], A. Piepke[2], E. Yakushev[2], B. E. Berger[3], Y. D. Chan[3], M. P. Decowski[3], D. A. Dwyer[3], S. J. Freedman[3], B. K. Fujikawa[3], J. Goldman[3], F. Gray[3], K. M. Heeger[3], L. Hsu[3], K. T. Lesko[3], K.-B. Luk[3], H. Murayama[3], T. O'Donnell[3], A. W. P. Poon[3], H. M. Steiner[3], L. A. Winslow[3], C. Mauger[4], R. D. McKeown[4], P. Vogel[4], C. E. Lane[5], T. Miletic[5], G. Guillian[6], J. G. Learned[6], J. Maricic[6], S. Matsuno[6], S. Pakvasa[6], G. A. Horton-Smith[7], S. Dazeley[8], S. Hatakeyama[8], A. Rojas[8], R. Svoboda[8], B. D. Dieterle[9], J. Detwiler[10], G. Gratta[10], K. Ishii[10], N. Tolich[10], Y. Uchida[10], M. Batygov[11], W. Bugg[11], Y. Efremenko[11], Y. Kamyshkov[11], A. Kozlov[11], Y. Nakamura[11], H. J. Karwowski[12], D. M. Markoff[12], K. Nakamura[12], R. M. Rohm[12], W. Tornow[12], R. Wendell[12], M.-J. Chen[13], Y.-F. Wang[13] & F. Piquemal[14]

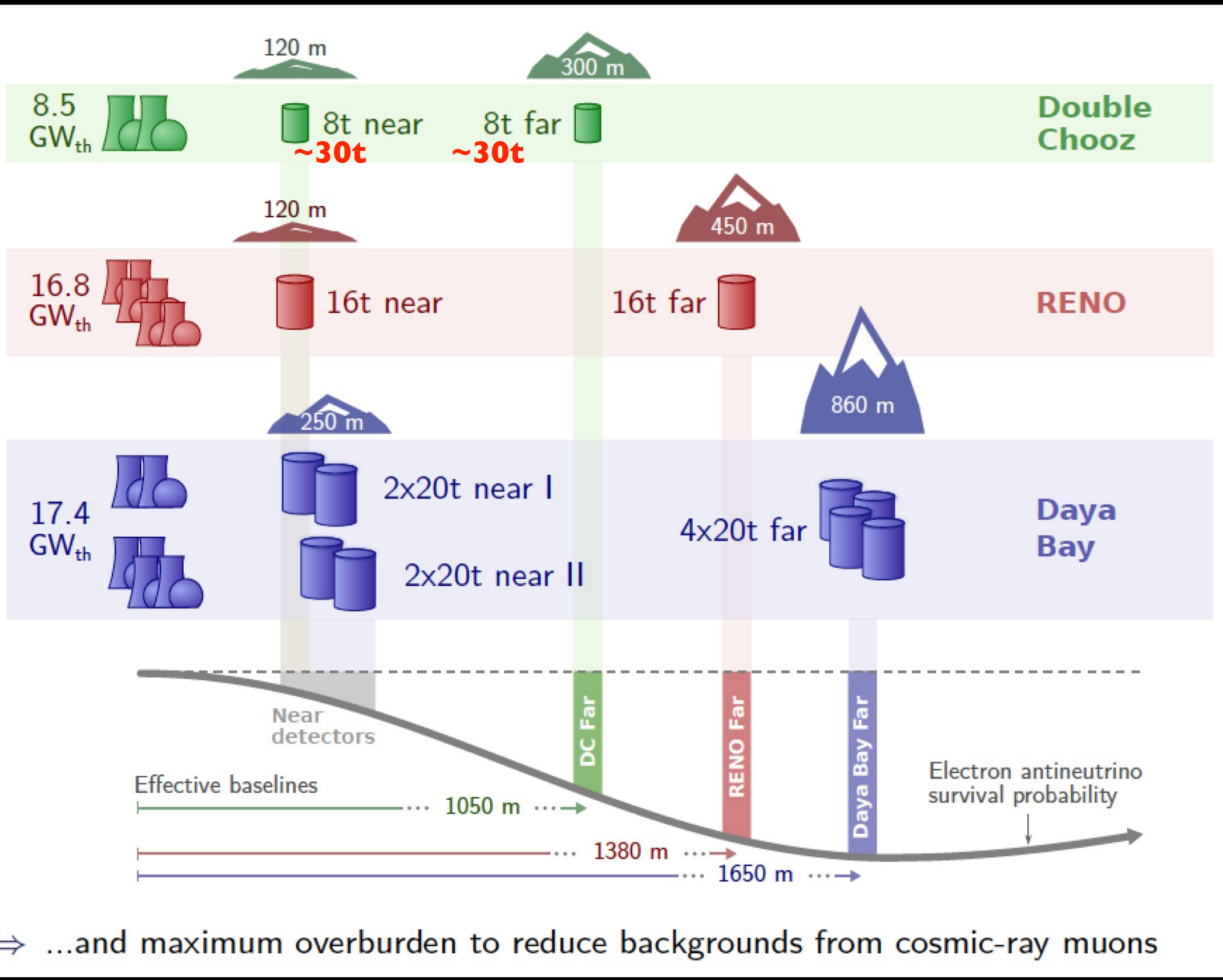


together with Borexino

~2010 @ several

reactor-θ13 experiments…

reactor-θ13 experiments…



⇒ …and maximum overburden to reduce backgrounds from cosmic-ray muons

DC's LNCA laboratory…

Near Lab
<L>≈410m
~30ν day^{-1} ton^{-1}
~120 mwe

Far Lab
<L>≈1050m
~6ν day^{-1} ton^{-1}
~300 mwe

Chooz Reactors
Power: 8.5GW^{thermal}⇒ ~10^{21}ν/s
(2x N4 reactor)

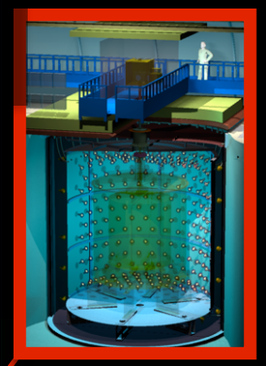
(nut-shell) experiment's rationale & history…

Chooz Reactors

~10²¹ν/s

<L>=0m

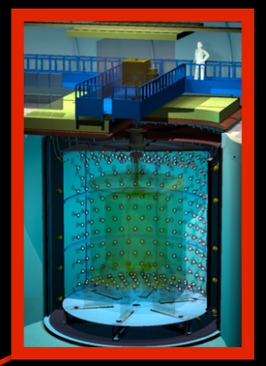
Bugey4 (~ND)



Near Detector (ND)

≲1000 ν/day
Dec.2014

<L>≈400m

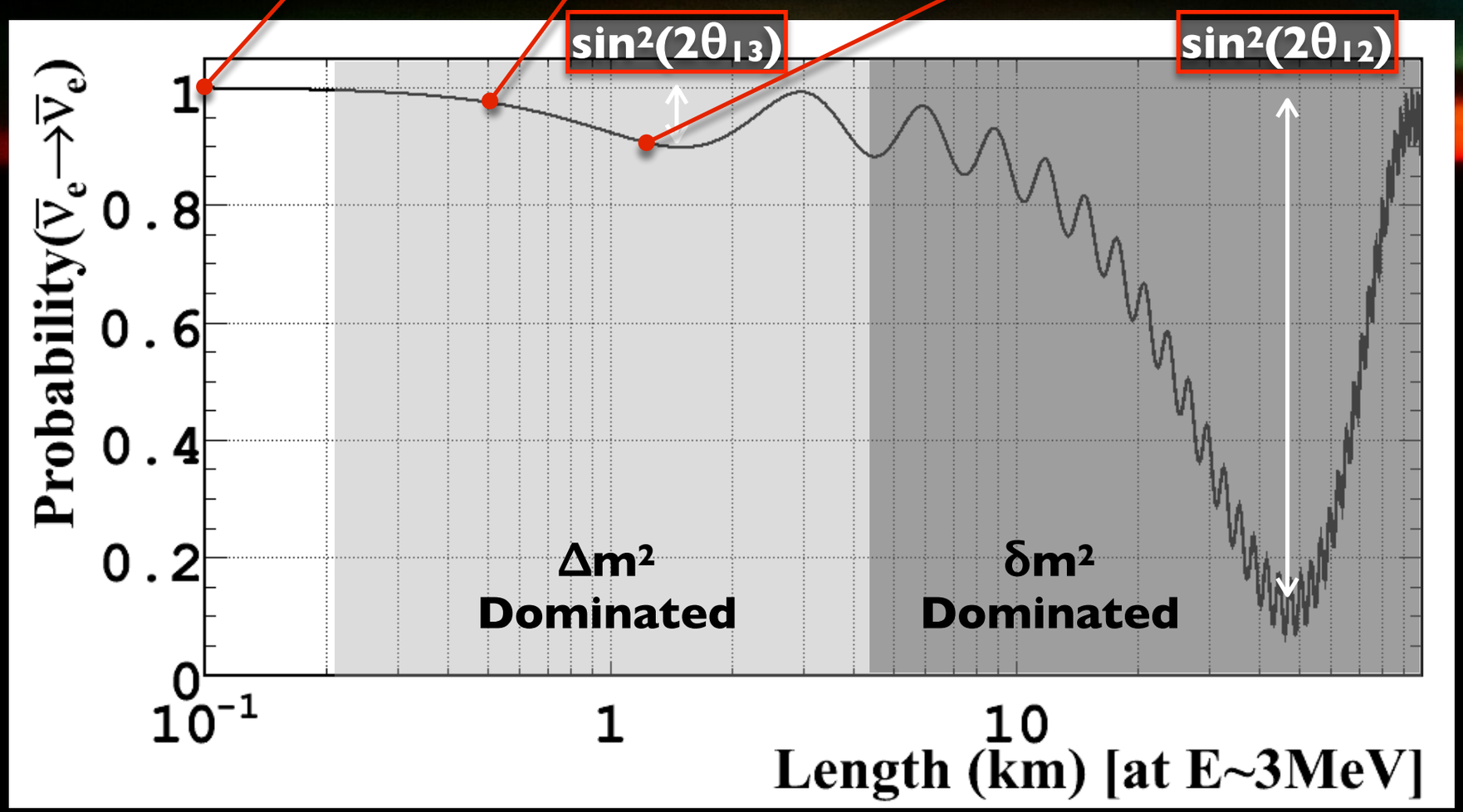


Far Detector (FD-I & FD-II)

≲140 ν/day
April 2011

<L>≈1050m

FD⊕Bugey4
FD⊕ND



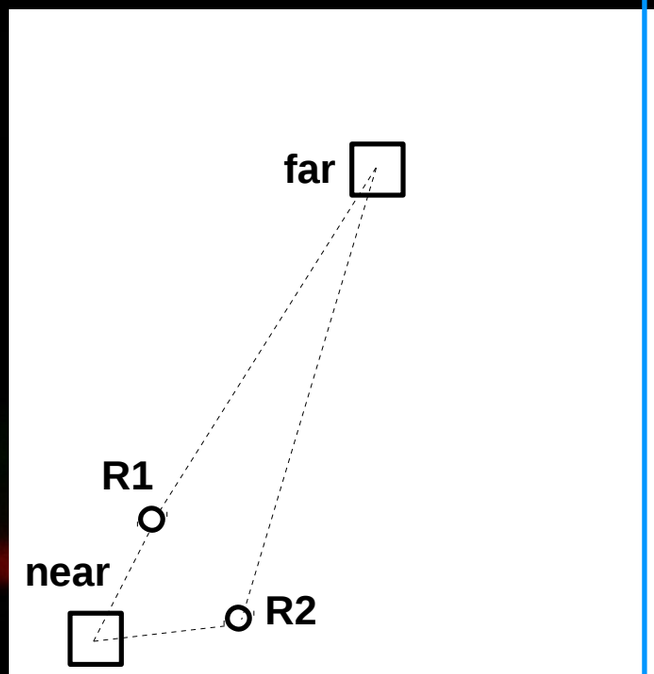
Site Geometry??

iso-flux?
(flux cancellation)

reactor-OFF?
(precious BG)

reactor θ13 experiments geometry…

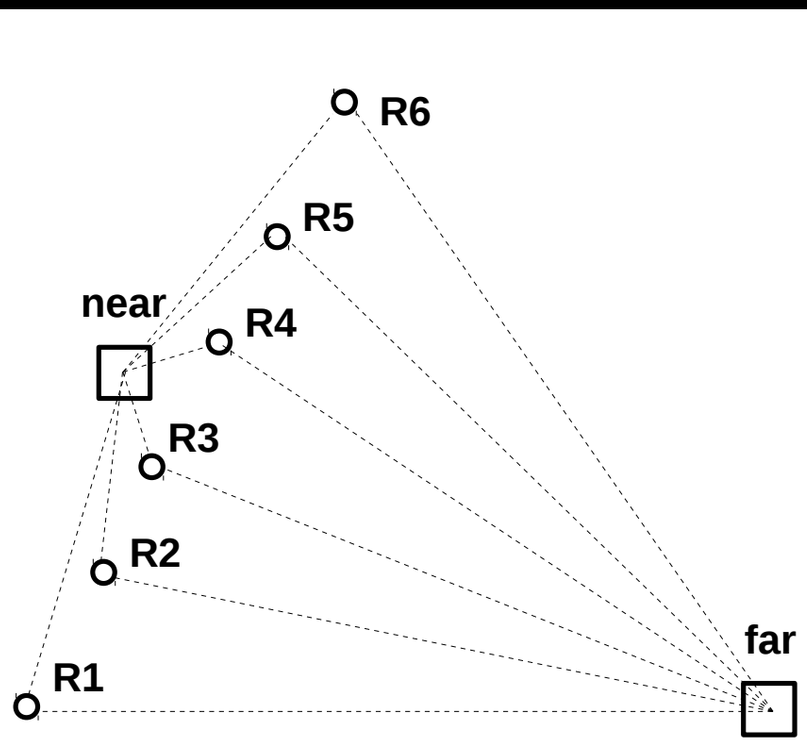
Double Chooz



FD @ 300mwe
(target: 30t@FD)

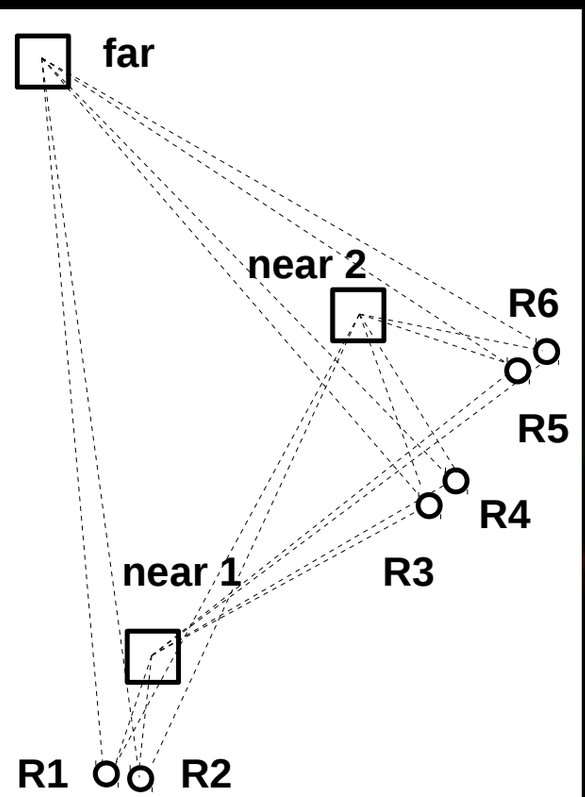
isoflux configuration
(ND ≈ perfect monitor)

RENO



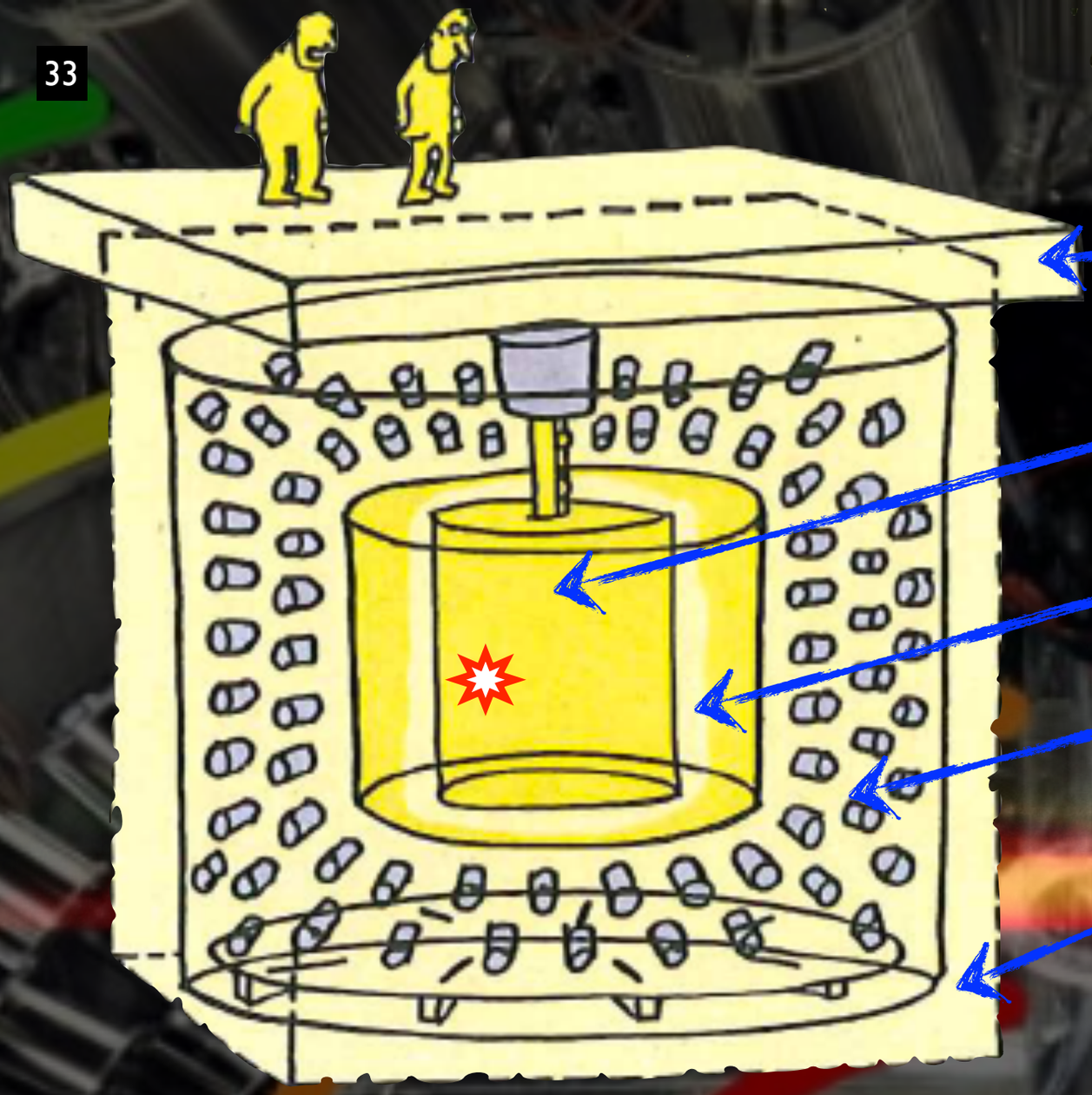
FD @ 450mwe
(target: 16t@FD)

Daya Bay



FD @ 850mwe
(target: 80t@FD)

DC a θ_{13}-LAND...



Outer μ-Veto (OV)
plastics-scintillator: strips (→tracking)

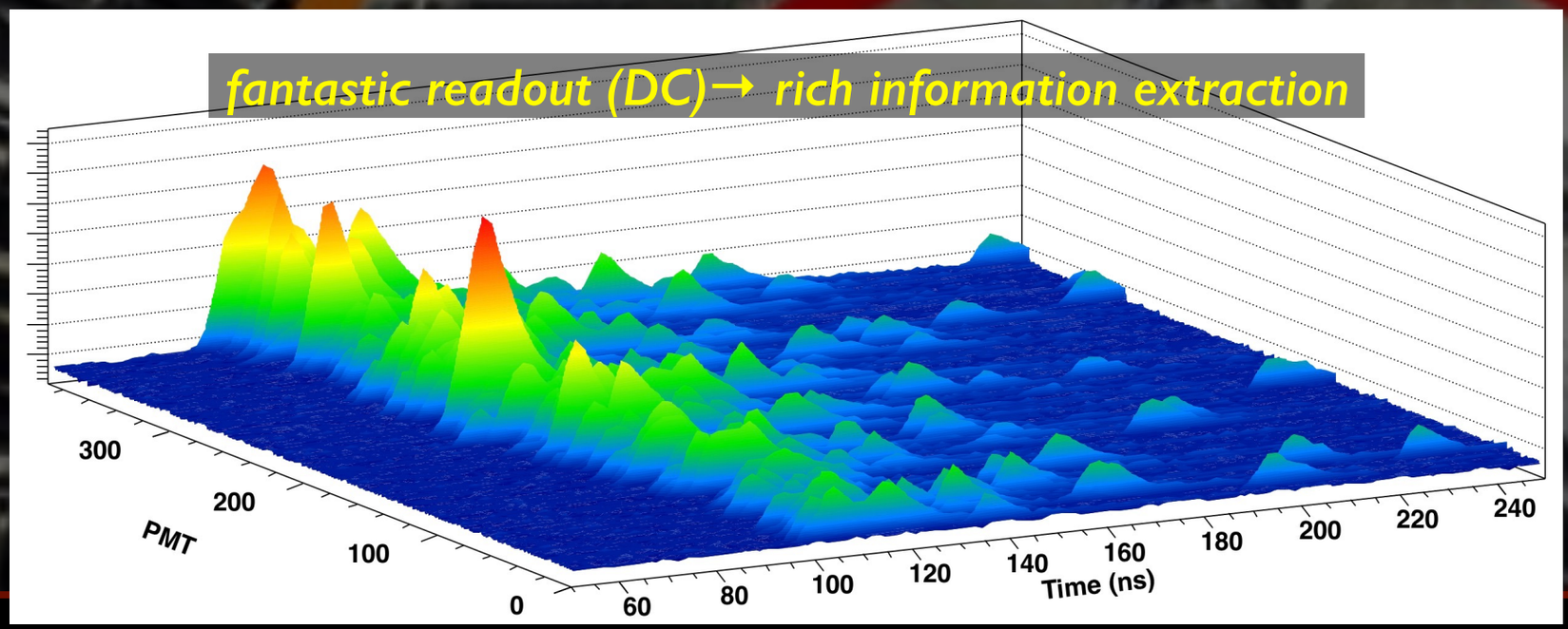
ν-Target (NT)
~10m³ Liquid-Scintillator + Gd (0.1%)

γ-Catcher (GC)
~20m³ Liquid-Scintillation

Buffer
~100m³ oil (no scintillation)

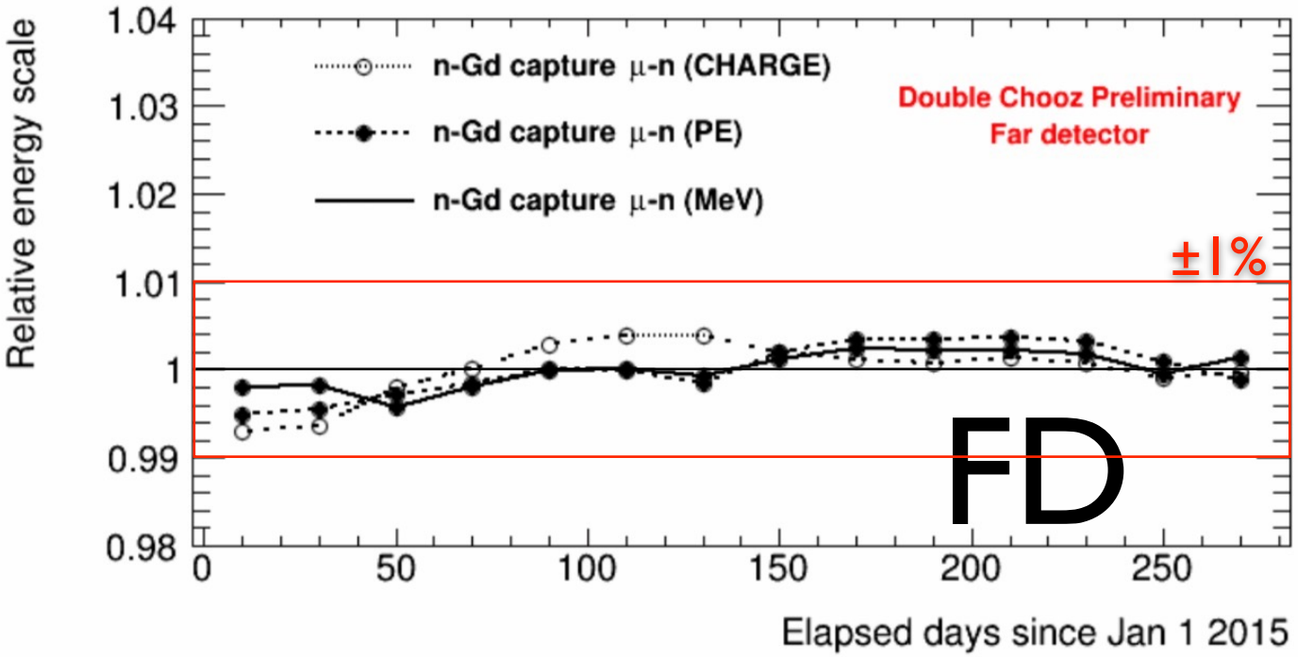
Inner μ-Veto (IV)
~90m³ Liquid-Scintillator

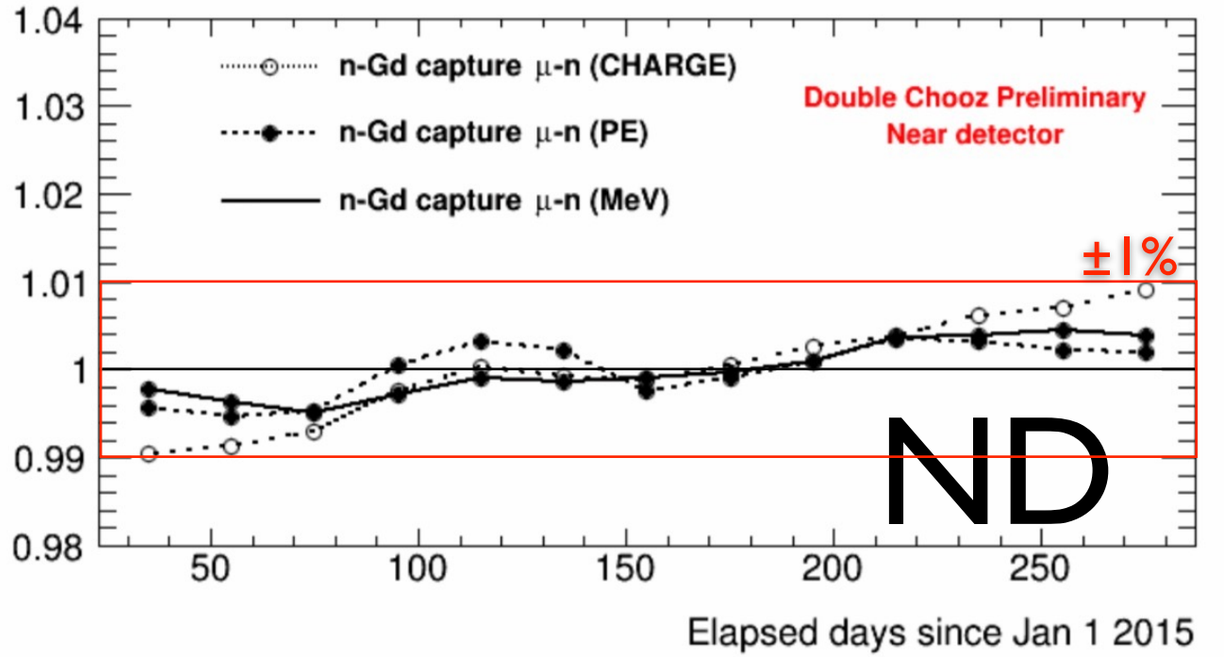
Inert γ-Shield
15cm steel [FD] / 1m water [ND]



Liquid Scintillator
⊕
10" PMTs
⊕
FADC readout
⊕
offline reconstruction
(time,charge,position,PS,multiplicity,etc)

detector response (in)stability…





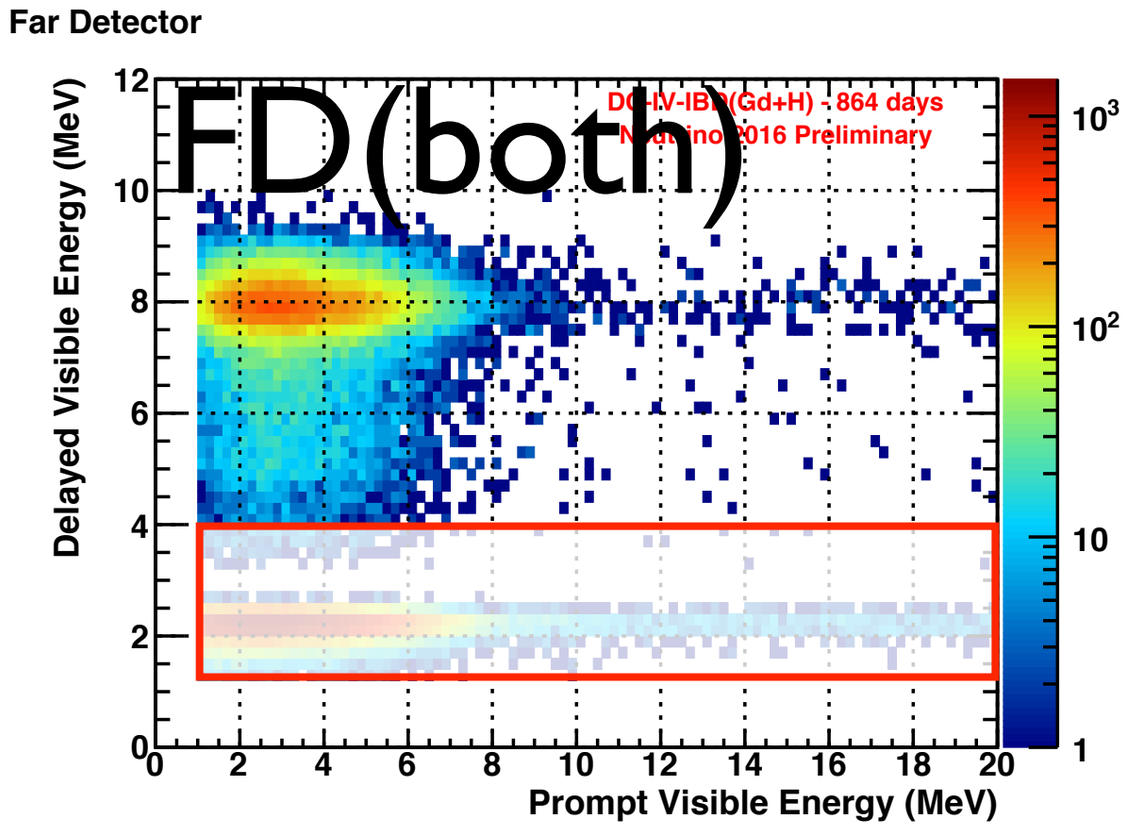
response no decrease with time (≲1%/year)

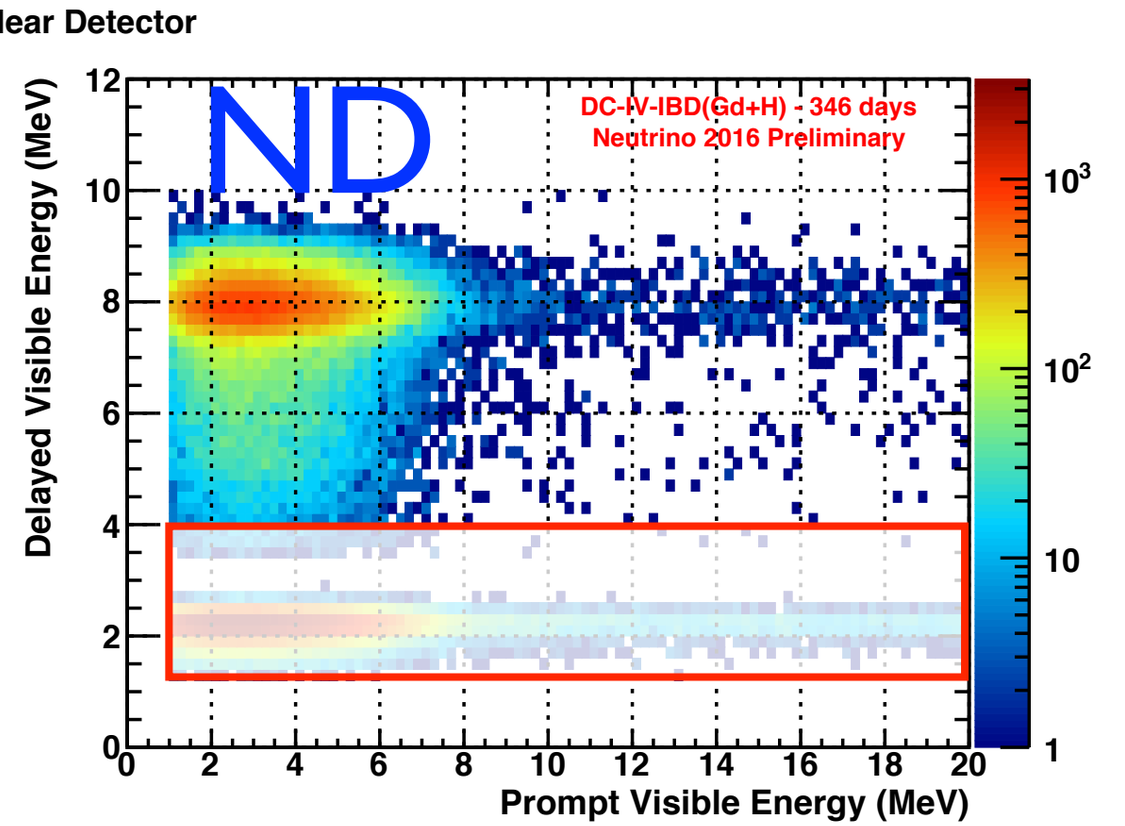
(stability ~0.35%^{FD} & ~0.45%ND)

DC: the only loaded-LS detector not deteriorating

(FRosT-16 workshop — FNAL, USA)

larger single-θ_{13}-target...

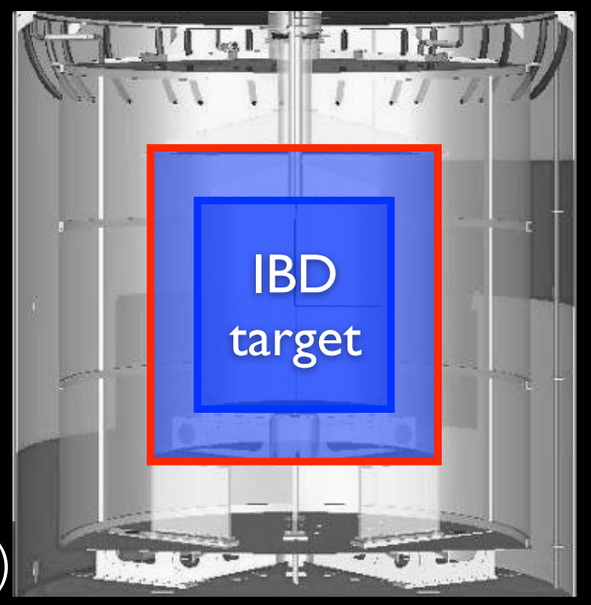




IBD(Gd)

target: ~8t (smallest θ13 target)

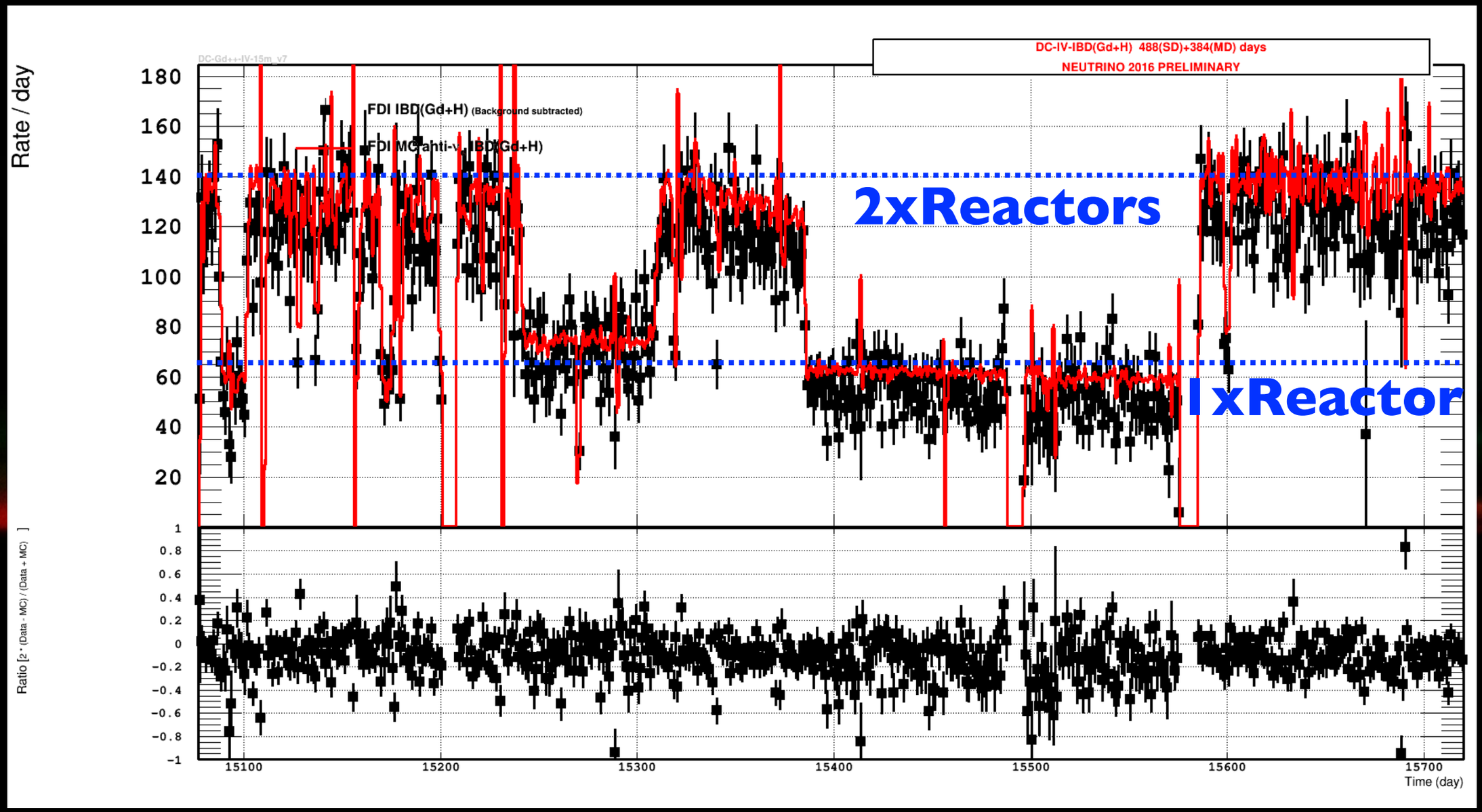
IBD(Gd⊕H⊕C)



target: ~30t (large θ13 single detector target)

IBD(Gd+H) vs time…

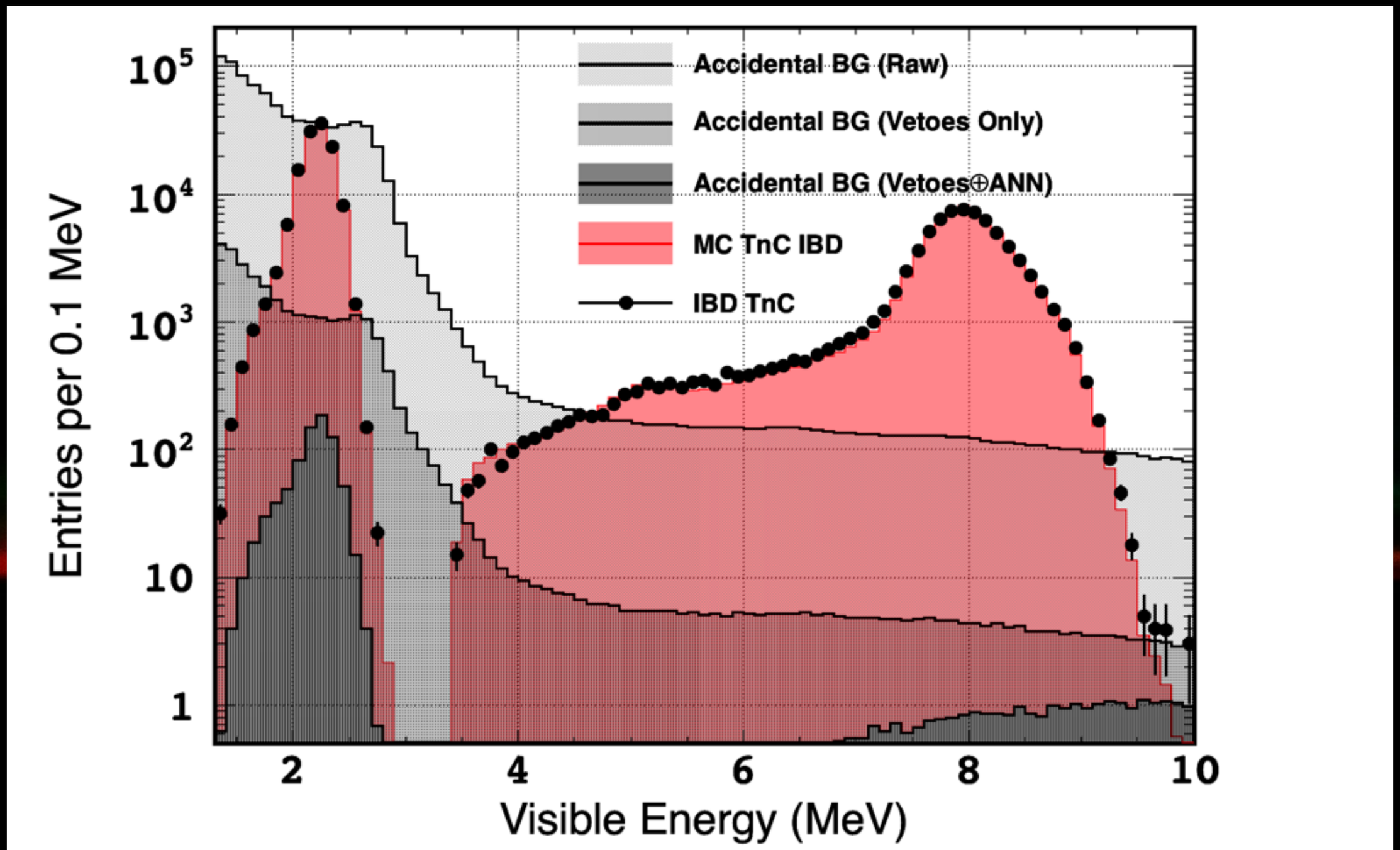
IBD(Gd⊕C⊕H)



≲140day⁻¹@ FD ≲1000day⁻¹@ ND

⇒~0.2%^{stat} final DC(FD)

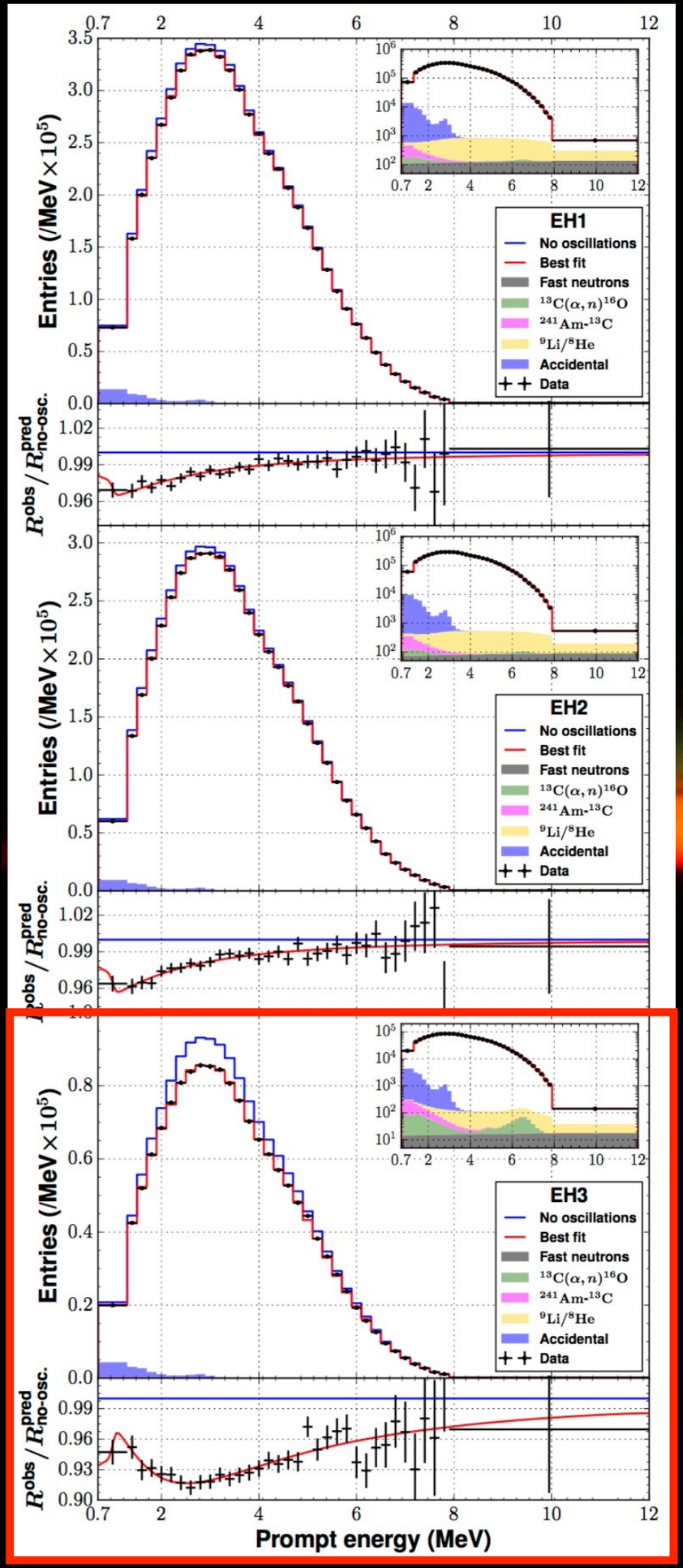
stunning BG (active) rejection…

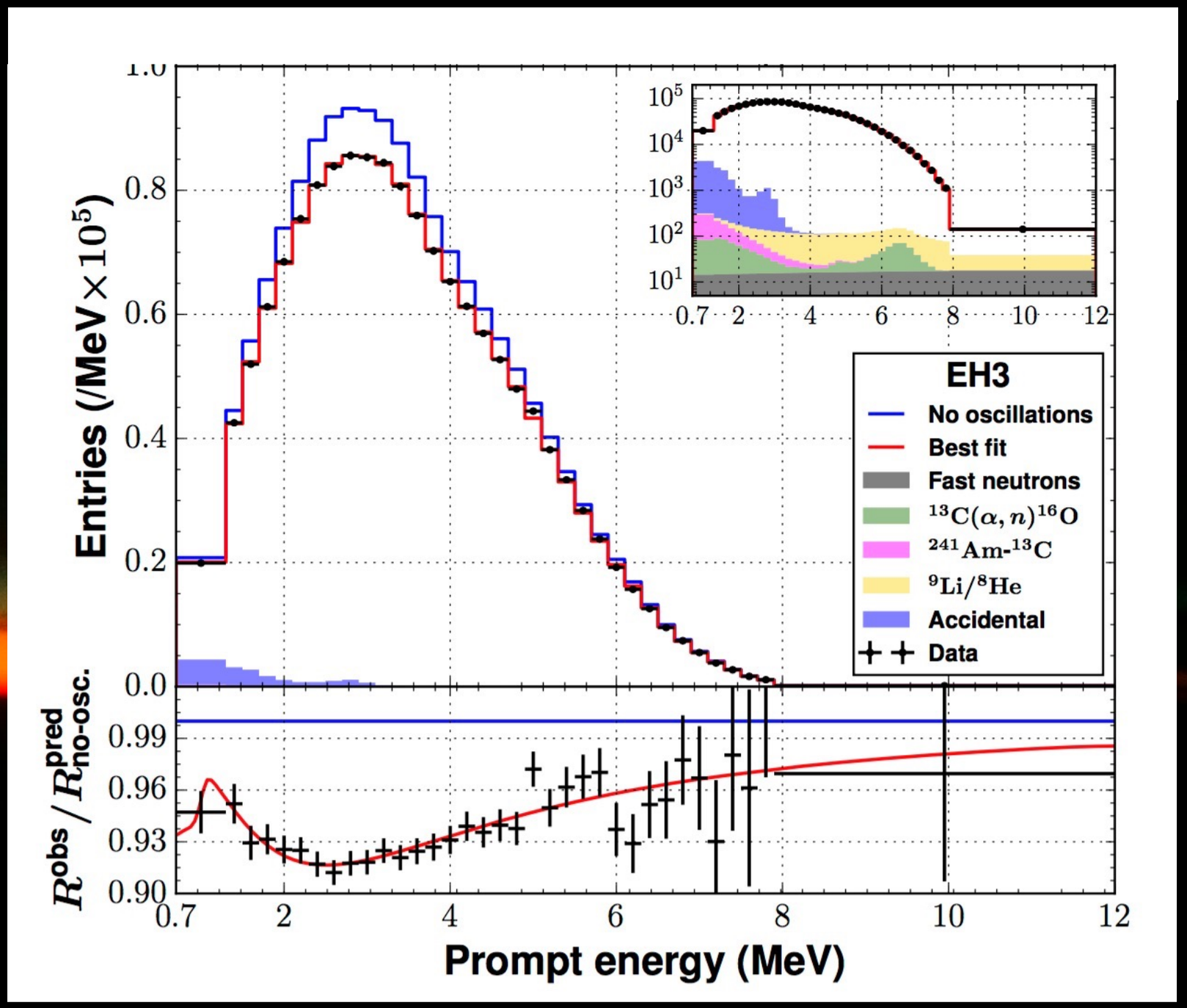


dig into BG to recover the H-n peak

(several orders of magnitude)

latest DYB result…



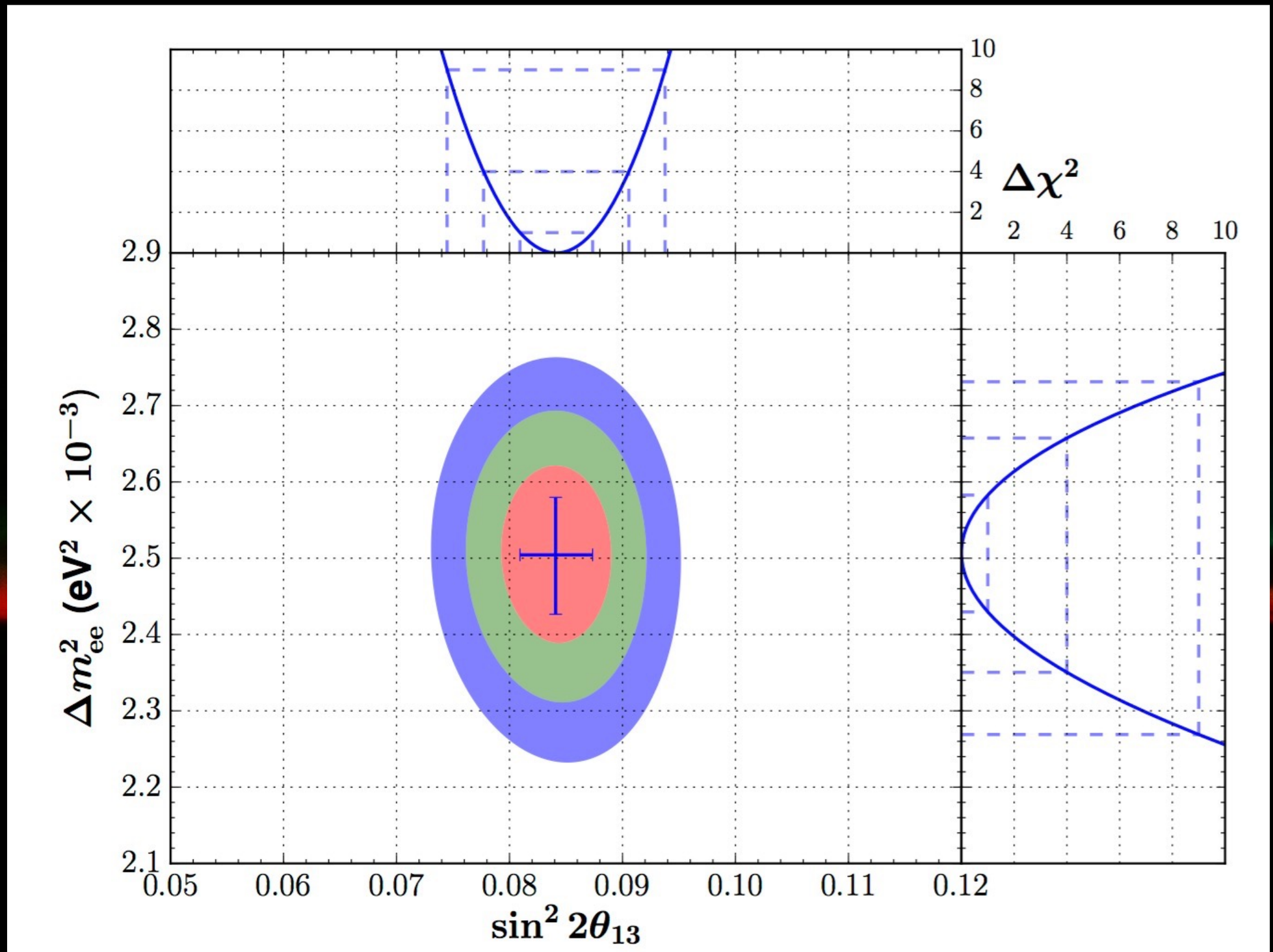


excellent Rate+Shape measurements on $\sin^2(2\theta_{13})$ & $|\Delta m^2_{ee}|$

⇒ most precise measurement so far

Anatael Cabrera (CNRS-IN2P3 & APC)

DYB measurements…



$\sin^2(2\theta_{13}) = 0.0841 \pm 0.0027(\text{stat}) \pm 0.0019(\text{syst})$

$|\Delta m^2_{ee}| = (2.50 \pm 0.06^{\text{stat}} \pm 0.06^{\text{syst}})$ meV^2

DC result @ CERN (SEPT-2016)…

Double Chooz
JHEP 1410, 086 (2014)

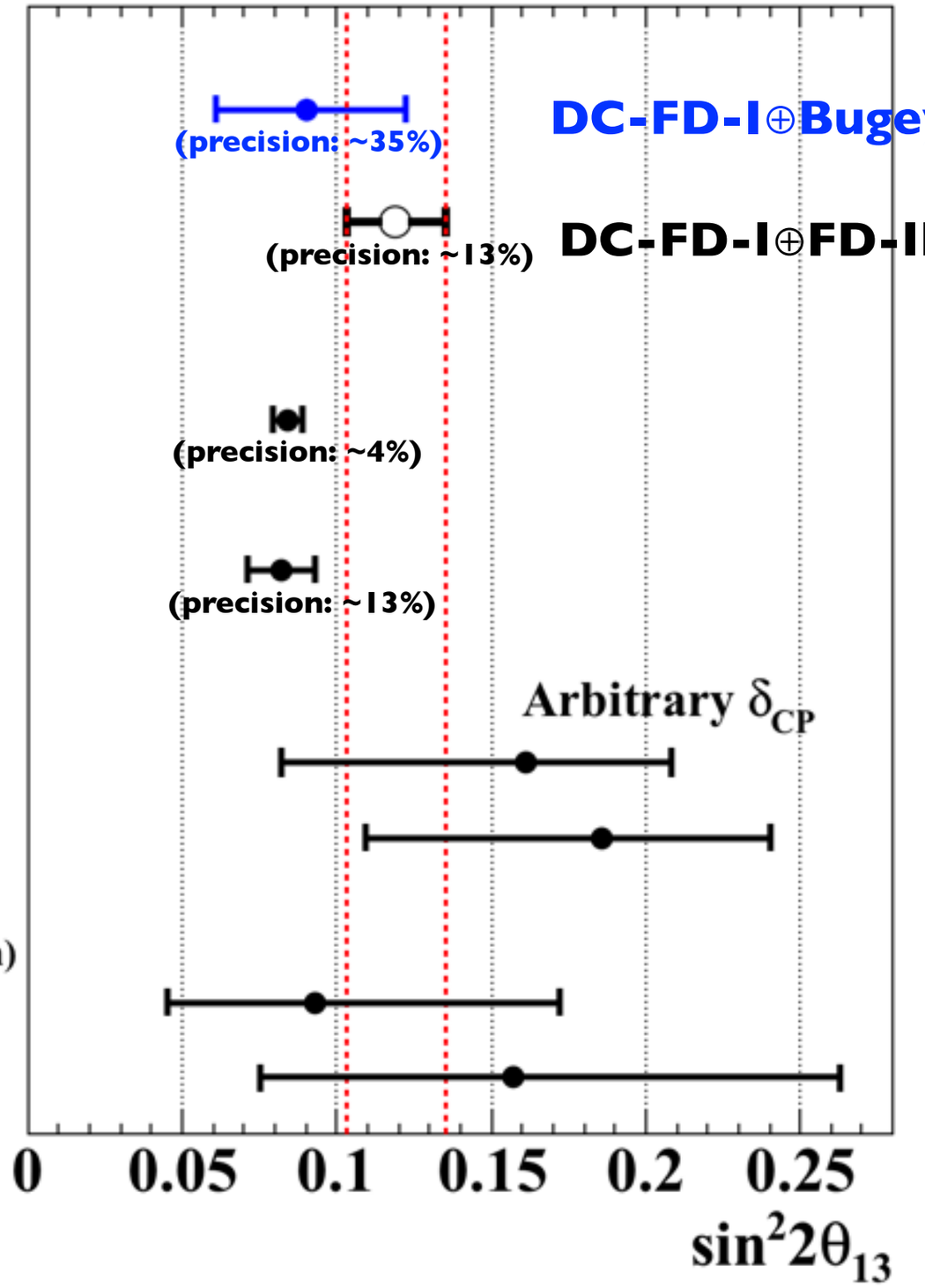
Preliminary **DC-IV**
(CERN seminar 2016)
$\sin^2(2\theta_{13})=(0.119\pm0.016)$

Daya Bay
PRL 115, 111802 (2015)

RENO
PRL 116 211801(2016)

T2K
PRD 91, 072010 (2015)
$\Delta m^2_{32} > 0$
$\Delta m^2_{32} < 0$

NOvA
Preliminary (private communication)
$\Delta m^2_{32} > 0$
$\Delta m^2_{32} < 0$



DC-IV-PRELIMINARY @ CERN

need to investigate carefully→ systematics @ ‰ level (complex)

Reactor-θ_{13} *(combining results)*

Daya Bay⊕Double Chooz⊕RENO

0th discussion/planning→@ Neutrino-2016, London (UK)

1st workshop→ October 2016 (Seoul, South Korea)
(systematics, results consistency)

2nd workshop→ June 2017 (Paris, France)
(further θ_{13} systematics consistency)

3rd workshop→ end 2018 (Hong Kong, China)

(likely) most precise input to θ_{13} for several decades…

~2020 @ China

JUNO experiment…

JUNO Collaboration…

EUROPE

APC Paris
Charles University Prague
CPPM Marseille
FZ Julich
IKP FZI Julich
INFN Catania
INFN Frascati
INFN Ferrara
INFN Milano-Bicocca
INFN Milano
INFN Padova
INFN Perugia
INFN Roma3
INR Moscow
IPHC Strasbourg
JINR Dubna
LLR Paris
MSU
RWTH Aachen
Subatech Nantes
TUM Munich
University of Hambourg
University of Mainz
University of Oulu
University of Tuebingen
Yerevan Physics Institute
Université libre de Bruxelles

America

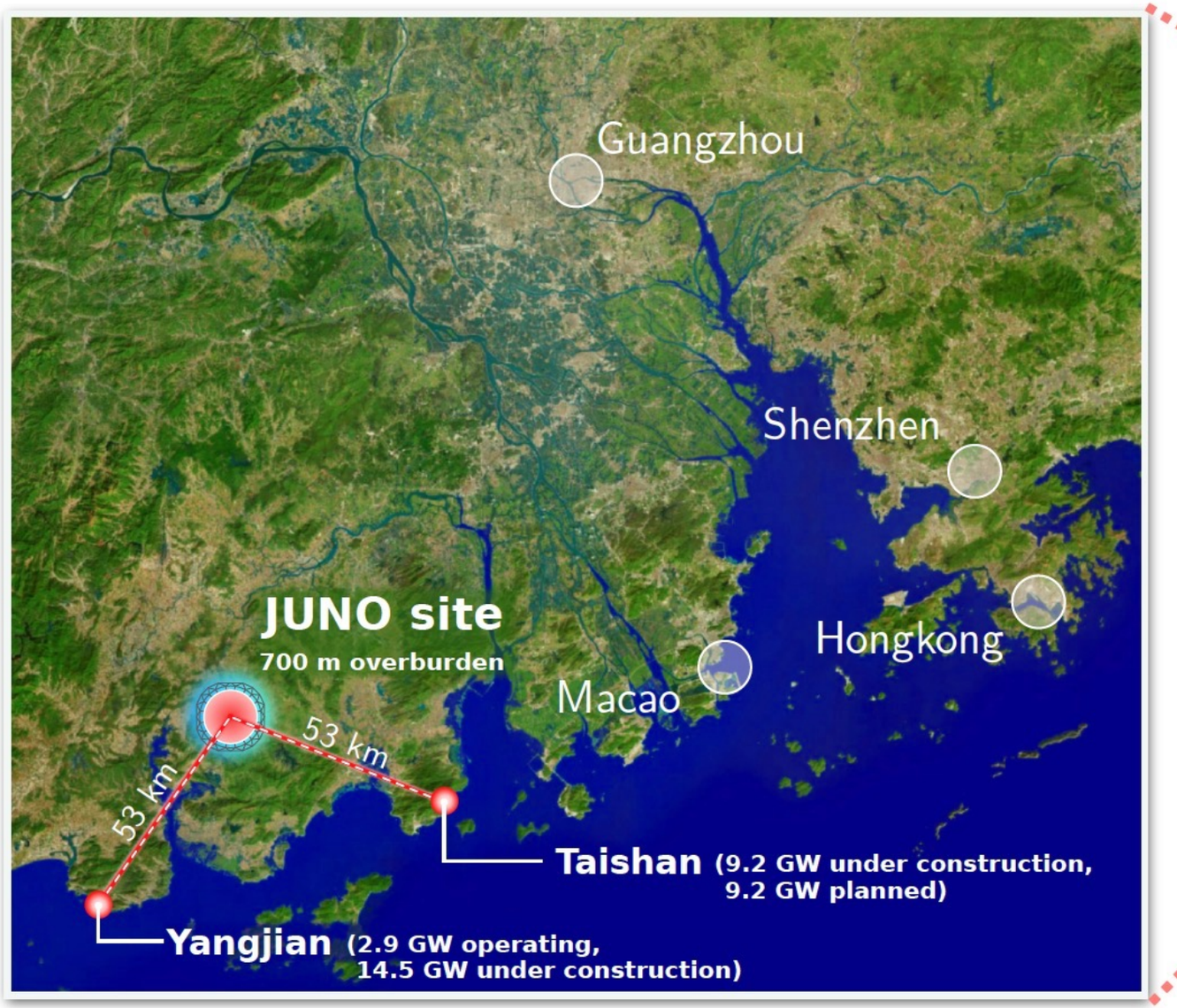
PCUC Chile
BISEE Chile
UMD1 USA
UMD2 USA

ASIA

Beijing Normal University
CAGS
ChongOing University
CIAE
DGUT
ECUST
Guangxi University
Harbin Institute of Technology
IHEP
Jilin University
Jinan University
Nanjing University
Nankay University
Natl. Chiao-Tung University
Natl. Taiwan University
Natl. United University
NCEPU
Pekin University
Shandong University
Shanghai JT University
Sichuan University
SUT
SYSU
Tsinghua University
UCAS
USTC
University of South China
Wu Yi University
Wuhan University
Xi'an University
Xiamen University

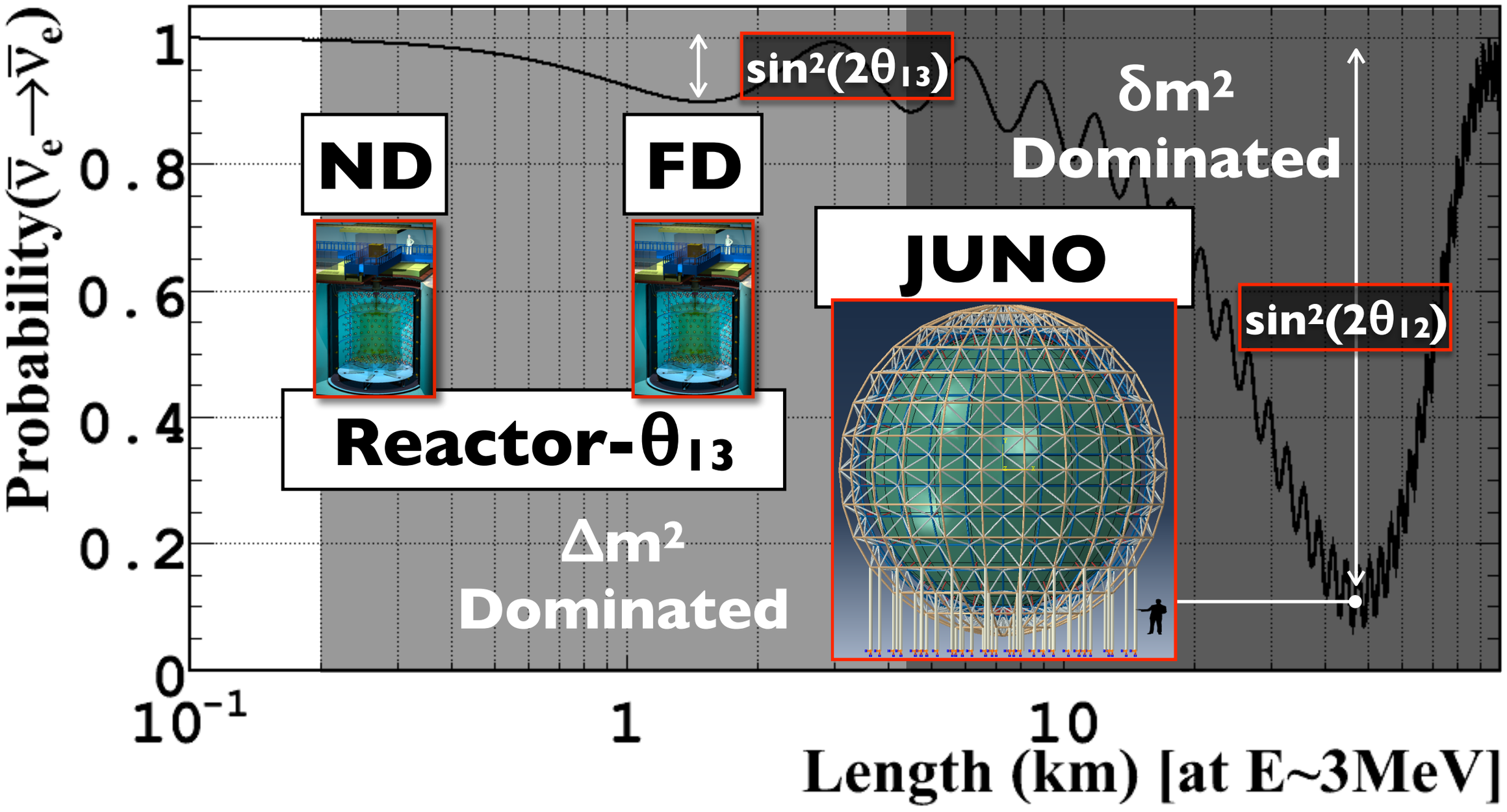
8th Collaboration Meeting (@IHEP, Beijing)

JUNO location…



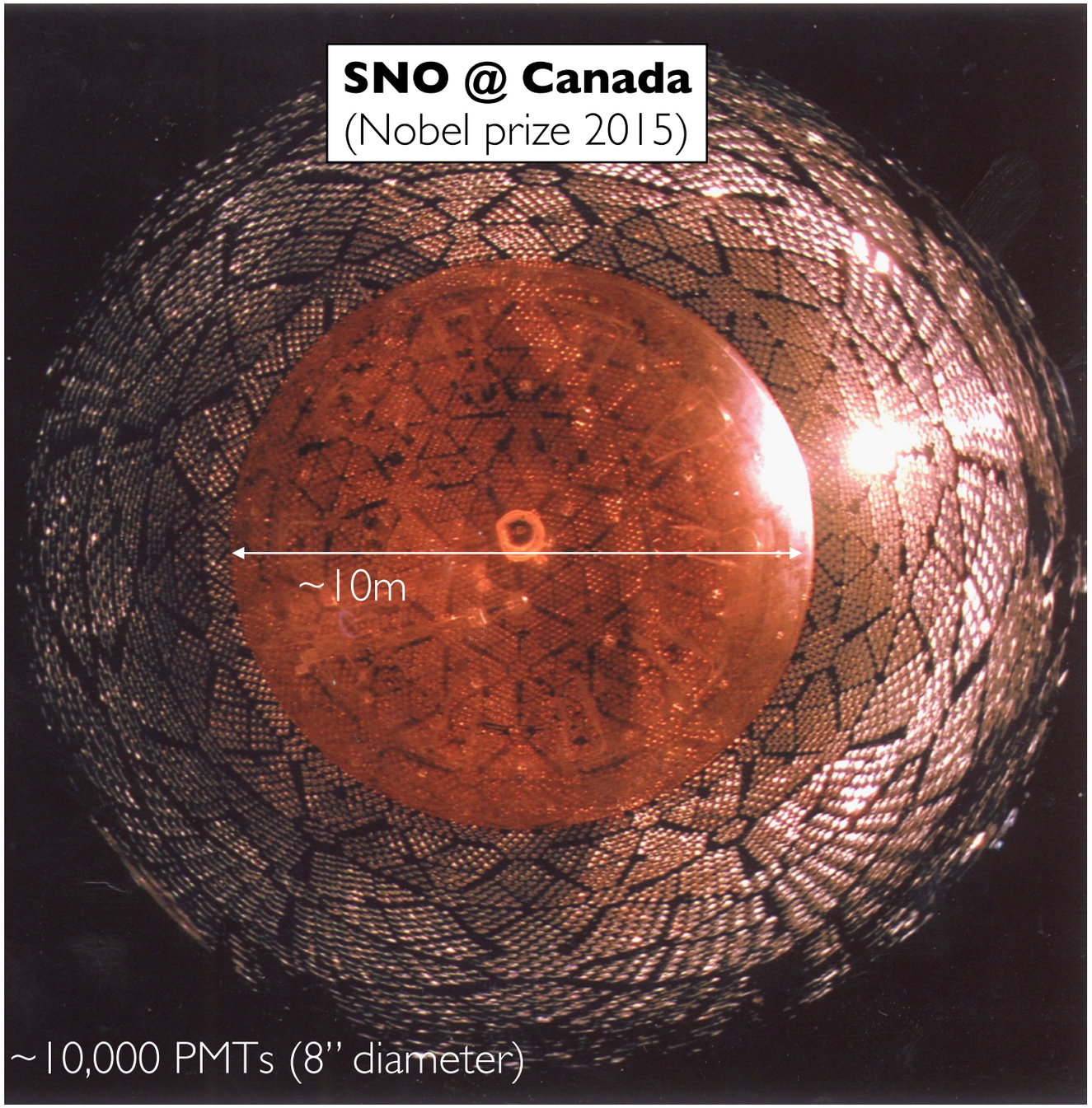
simplistic schedule: **data-taking starts by 2021**

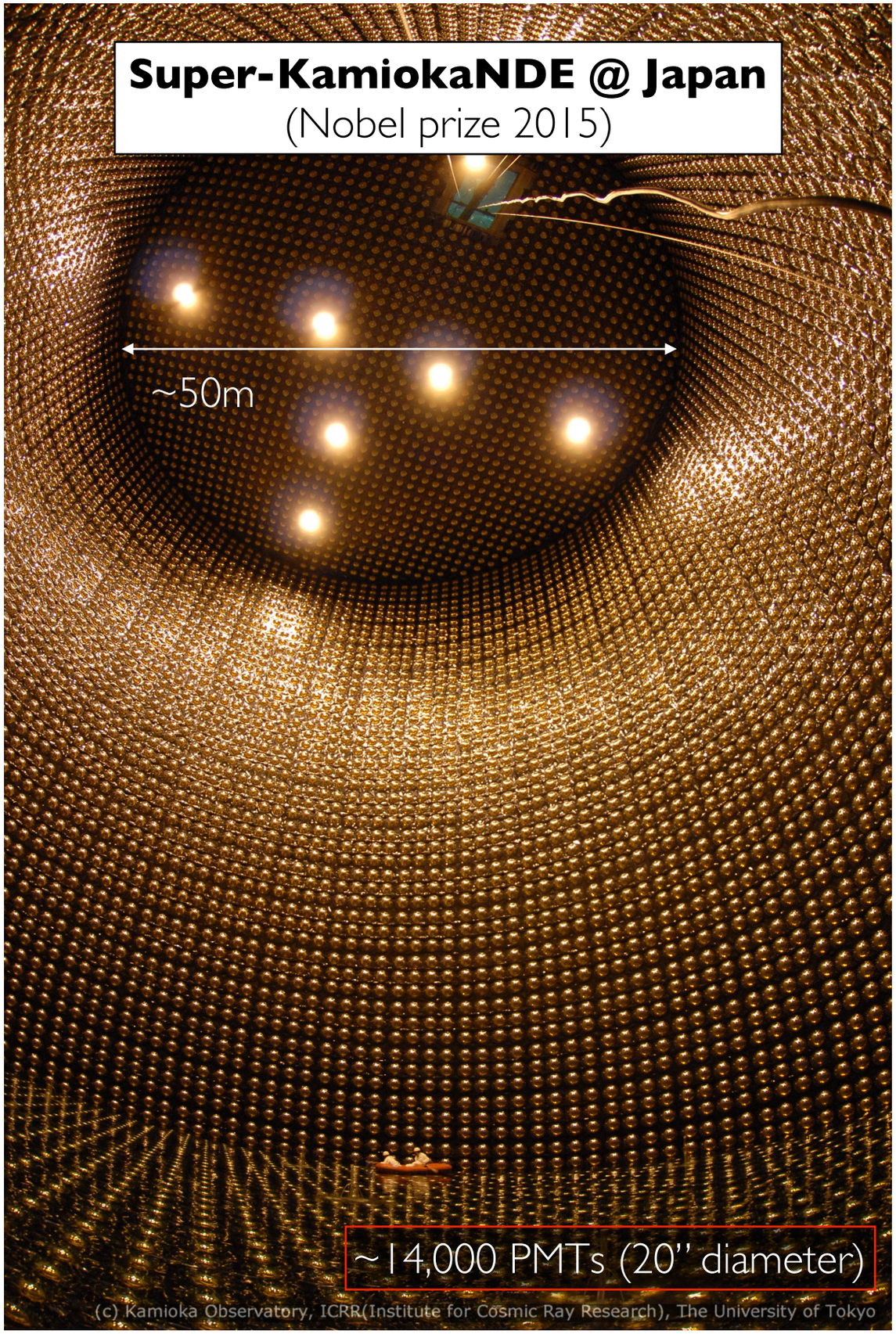
a long story short…



JUNO sensitive to <u>both oscillations</u>→ first time!

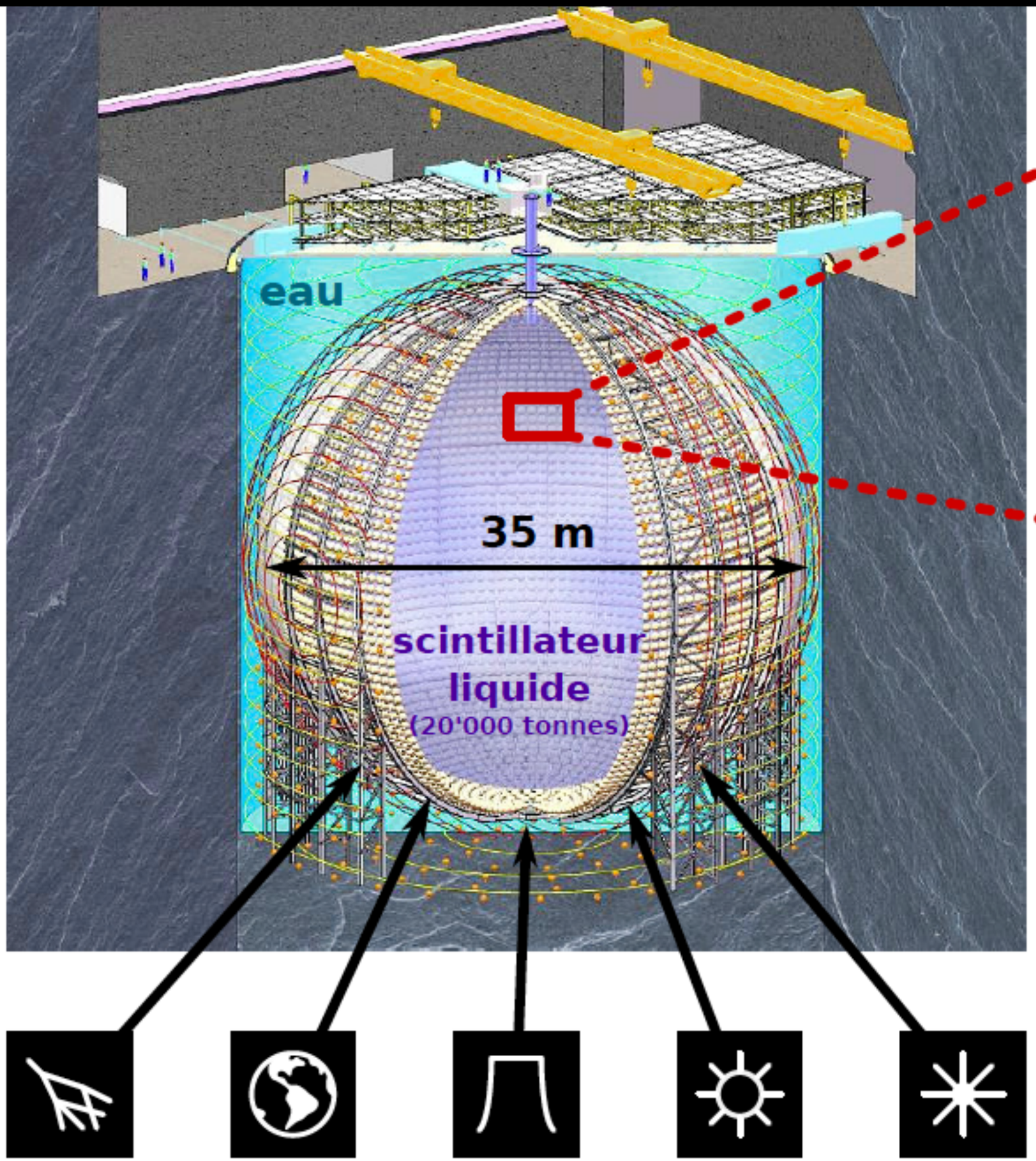
the JUNO detector (predecessors)…

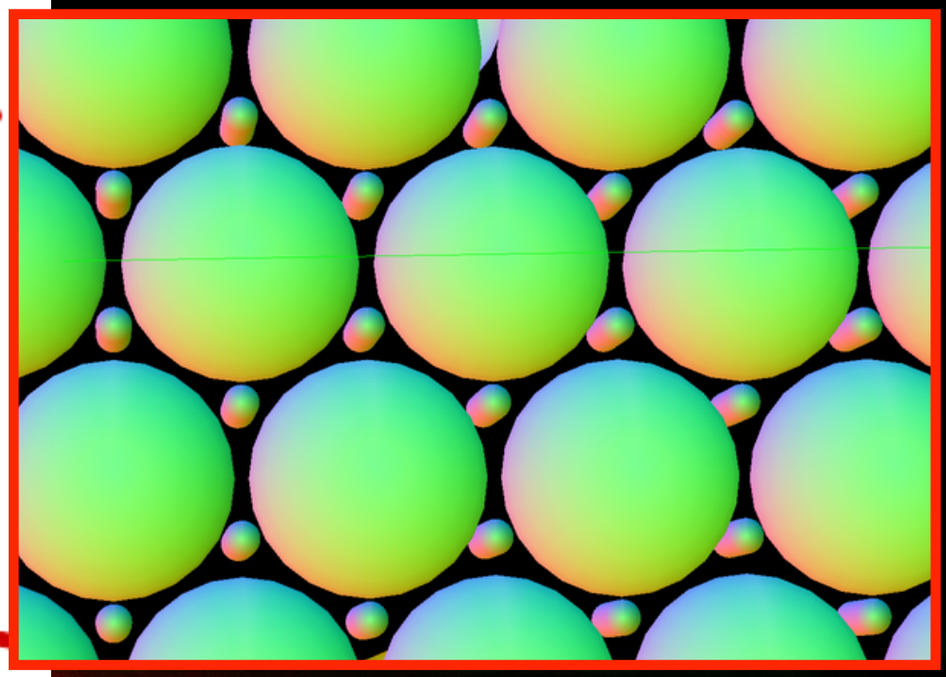




JUNO can be regarded as a hybrid of both…
(filled with liquid-scintillator→ **~100x more light**)

JUNO: one of the largest neutrino detectors…





unique readout system

largest photo-cathode quantity ever built ⇒ highest LS precision calorimetry ever built

largest light level ever detected ≳ **1200PE/MeV ⇒ stochastic resolution ≤3% @ 1MeV**

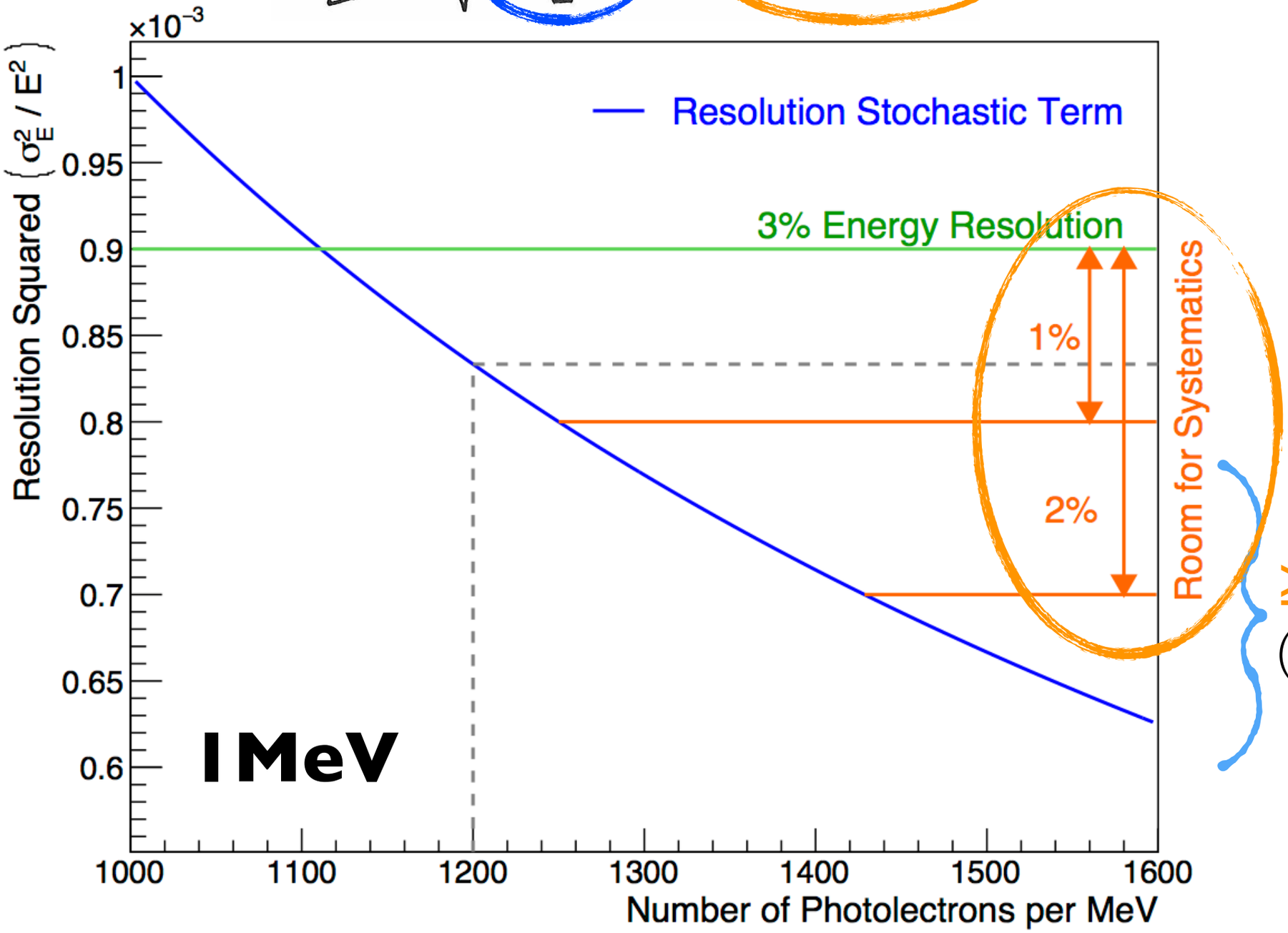
control of non-stochastic resolution extremely demanding→ ≲1%

JUNO calorimetry condition…

lot of light is a necessary but not sufficient condition

$$\frac{\sigma(E)}{E} = \sqrt{\left(\frac{\sigma^2_{STOCH}}{E}\right) + \sigma^2_{NON-STOCH}(E)}$$

≤3% @ 1MeV



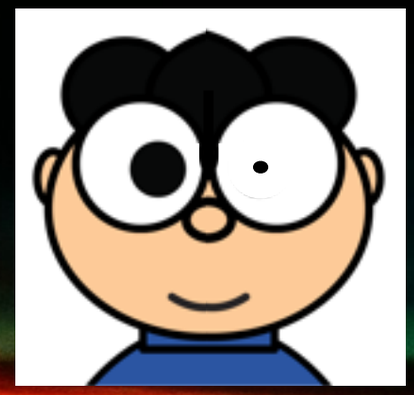
≥2%
(previous experiments)

challenging calorimetry systematics control

stereo calorimetry concept…

JUNO (no SPMT)

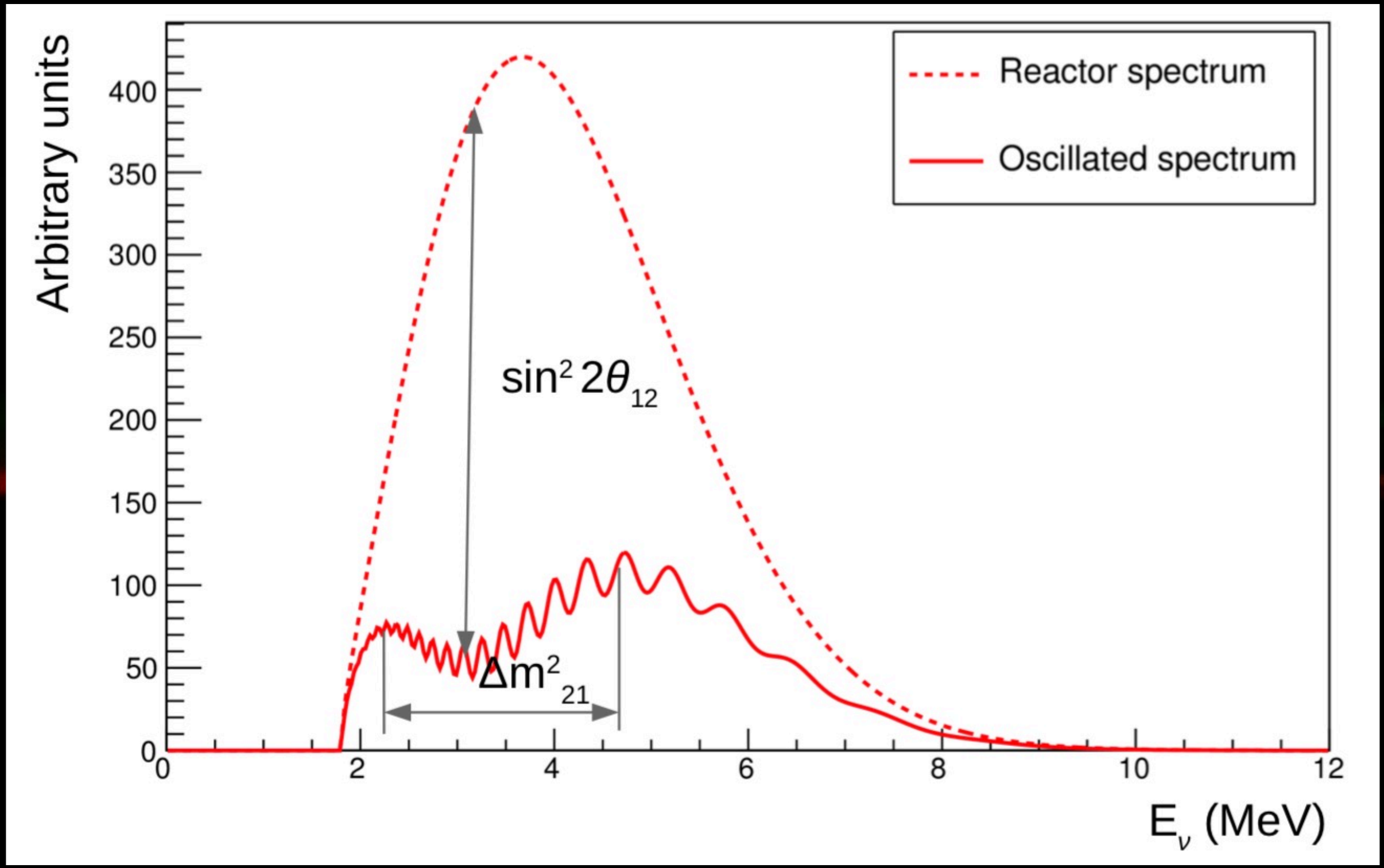
JUNO+ (with SPMT)



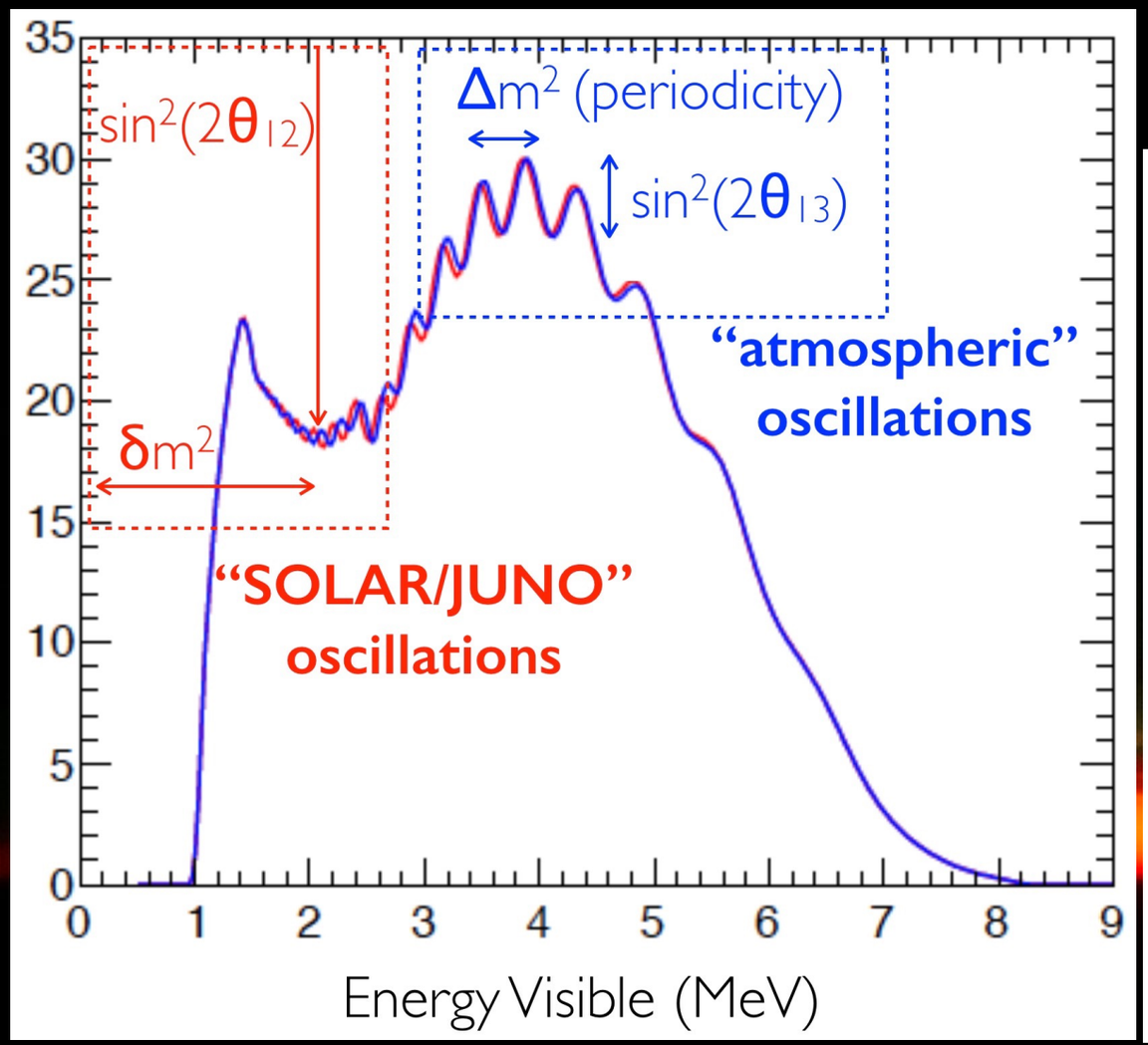
idea 1: “2 eyes see more than 1”
(arguably not very original)

idea 2: “different eyes allow to see better”
(arguably not very original)

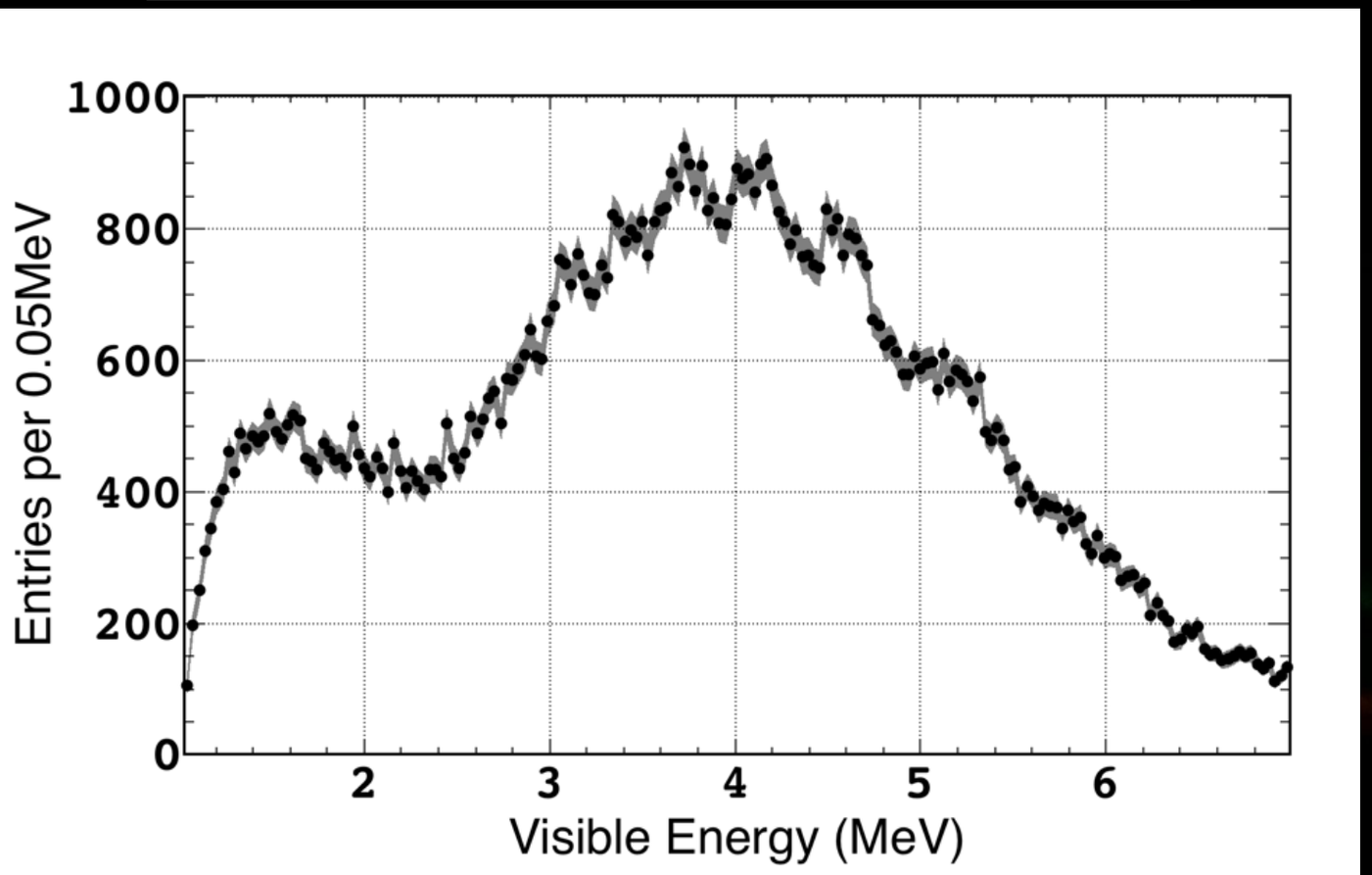
idea 3: “put than together in a largest detector LS detector in the world”
(arguably somewhat original)


Arbitrary units
400
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
E$_\nu$ (MeV)
Reactor spectrum
Oscillated spectrum
sin^2 2θ_{12}
Δm$^2_{21}$

JUNO spectrum in more detail…



~5 years illustration



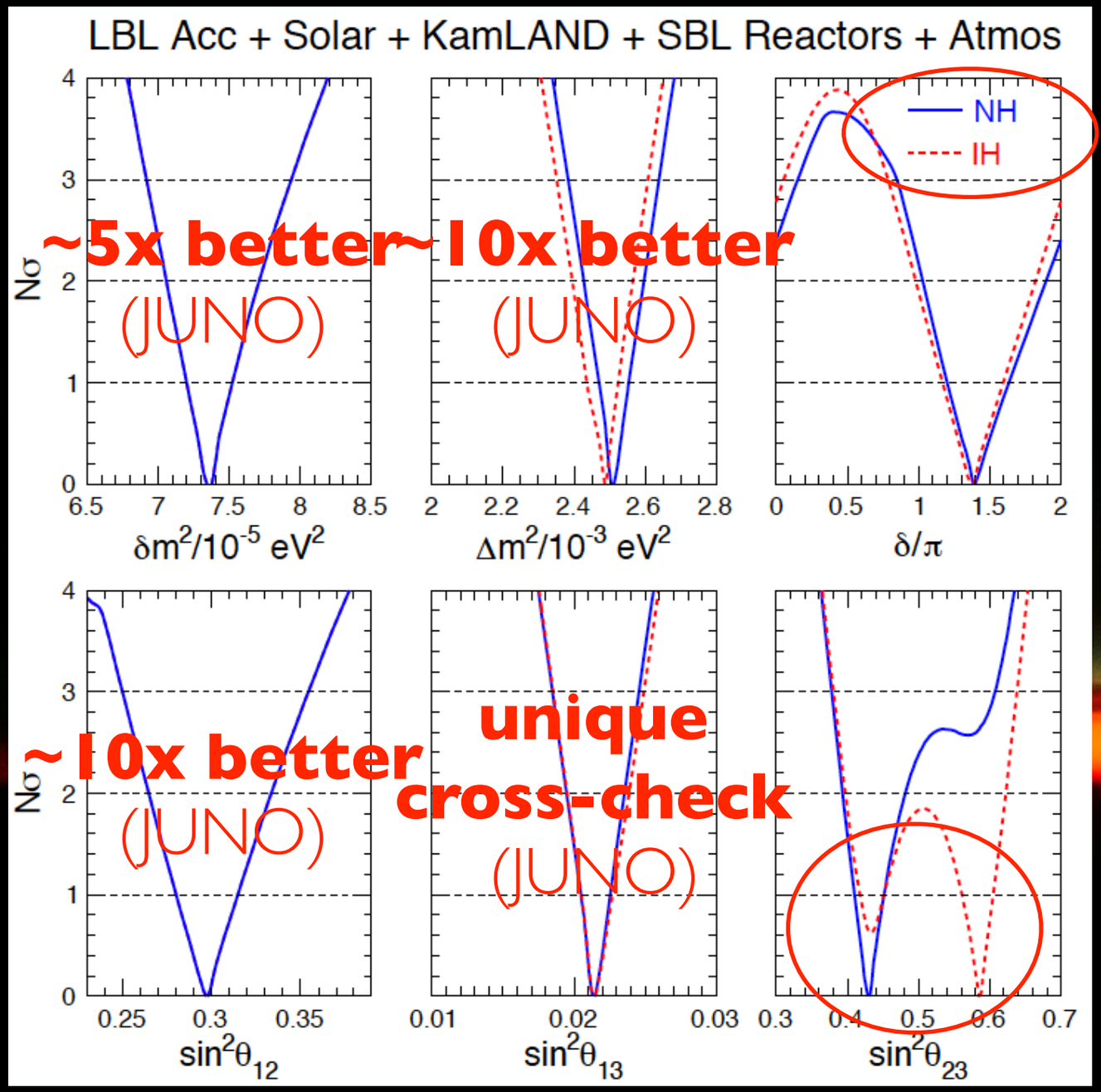
rationale
(vacuum oscillation)

data-like

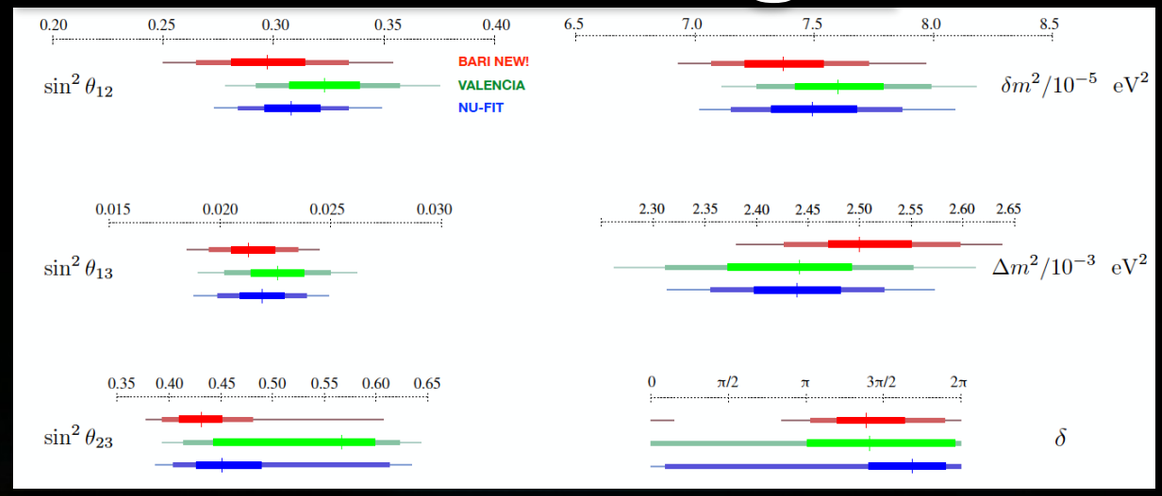
elegant ⊕ rich physics
($\theta_{12} \oplus \theta_{13} \oplus \delta m^2 \oplus \pm\Delta m^2$)

Anatael Cabrera (CNRS-IN2P3 & APC)

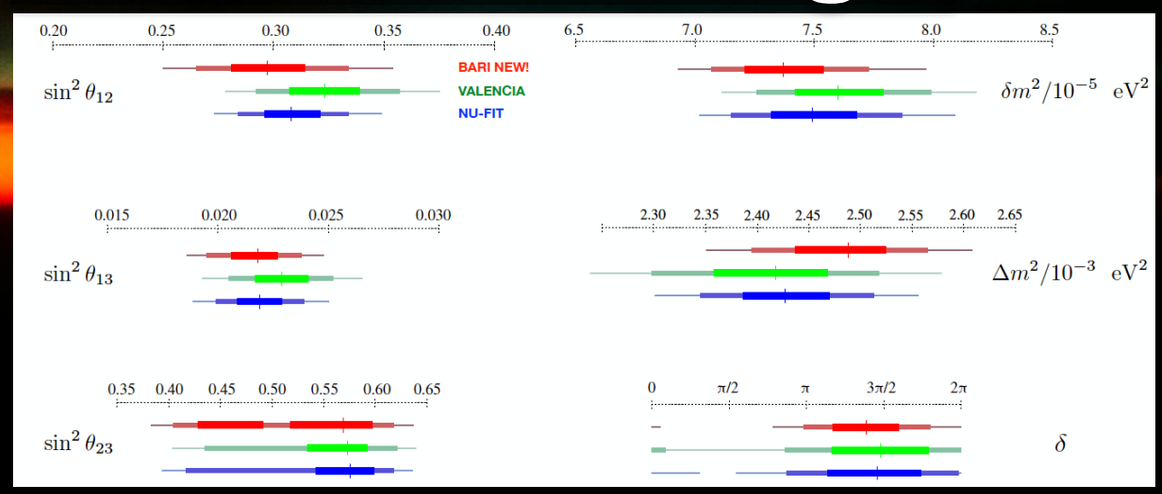
(*Marrone et al* @ NEUTRINO-16) 3ν oscillation status…



normal ordering…



inverted ordering…

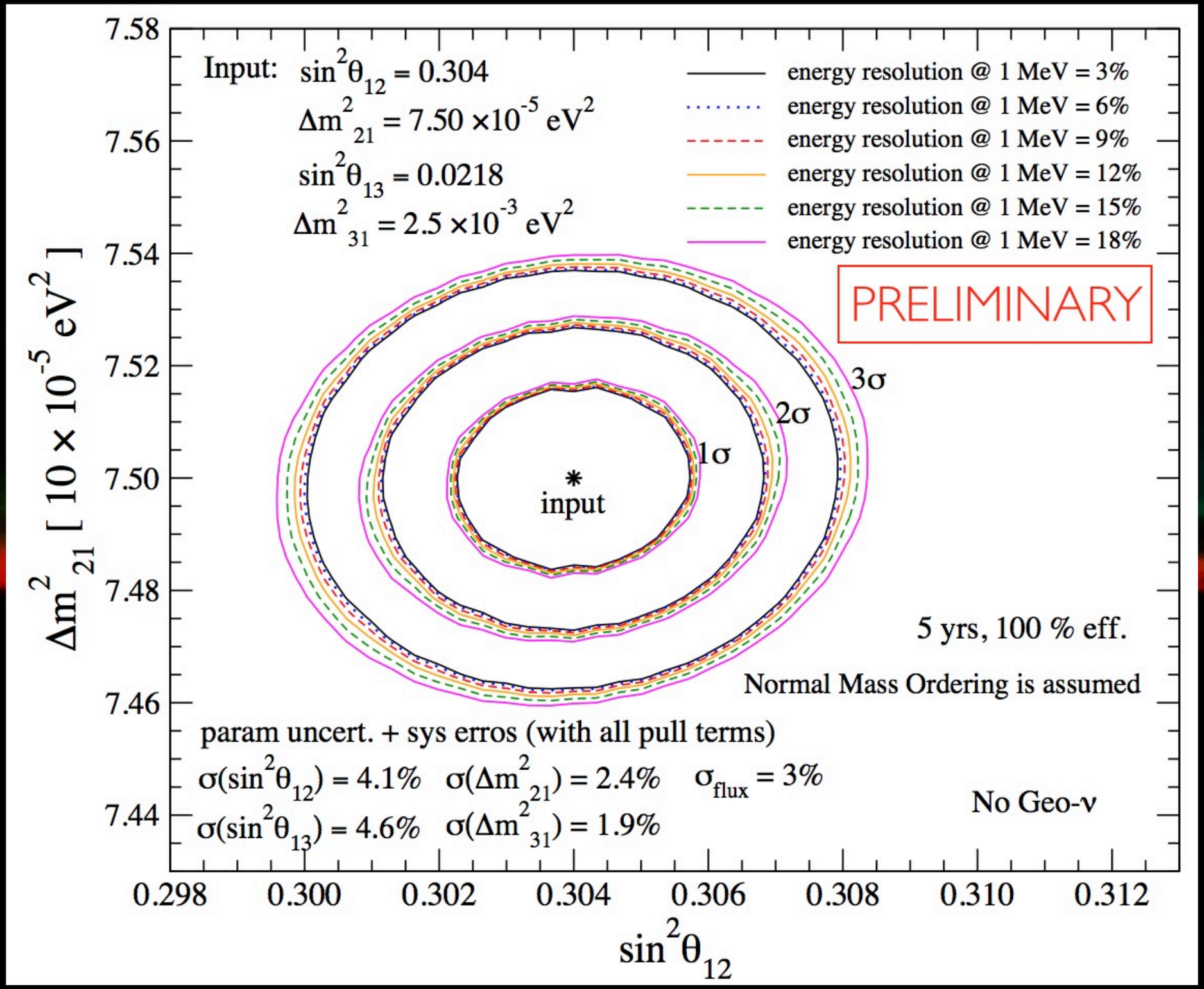


oscillation parameters: θ_{12}, $\pm\Delta m^2$,$\pm\delta m^2$,θ_{13}, θ_{23}, δ(CP)

⇒ improve **world precision knowledge** towards **δ(CP)**

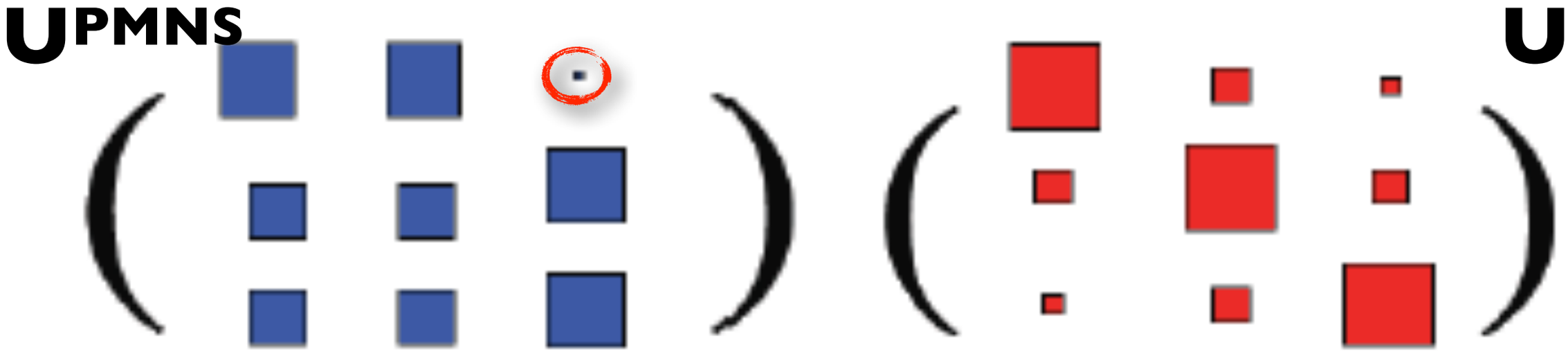
BARI - NPB908 (2016) 218-234 VALENCIA - PRD90 (2014) 9, 093006 NU-FIT JHEP 11 (2014) 052 (www.nu-fit.org)

internal **redundancy on δm^2-θ_{12}**...



SPMT⊕LPMT cross-check→ better physics

a (tough) BIG question…



⇒ ~maximal mixing

⇒ ~minimal mixing

PMNS unitary?

(beyond standard model→ only 3 families?)

reactor-ν historical contributions...

(much neutrino oscillation)

Anatael Cabrera (CNRS-IN2P3 & APC)

~70years challenge⟹no solution!

any **limitations**? [poor PID]

today's state of the art…

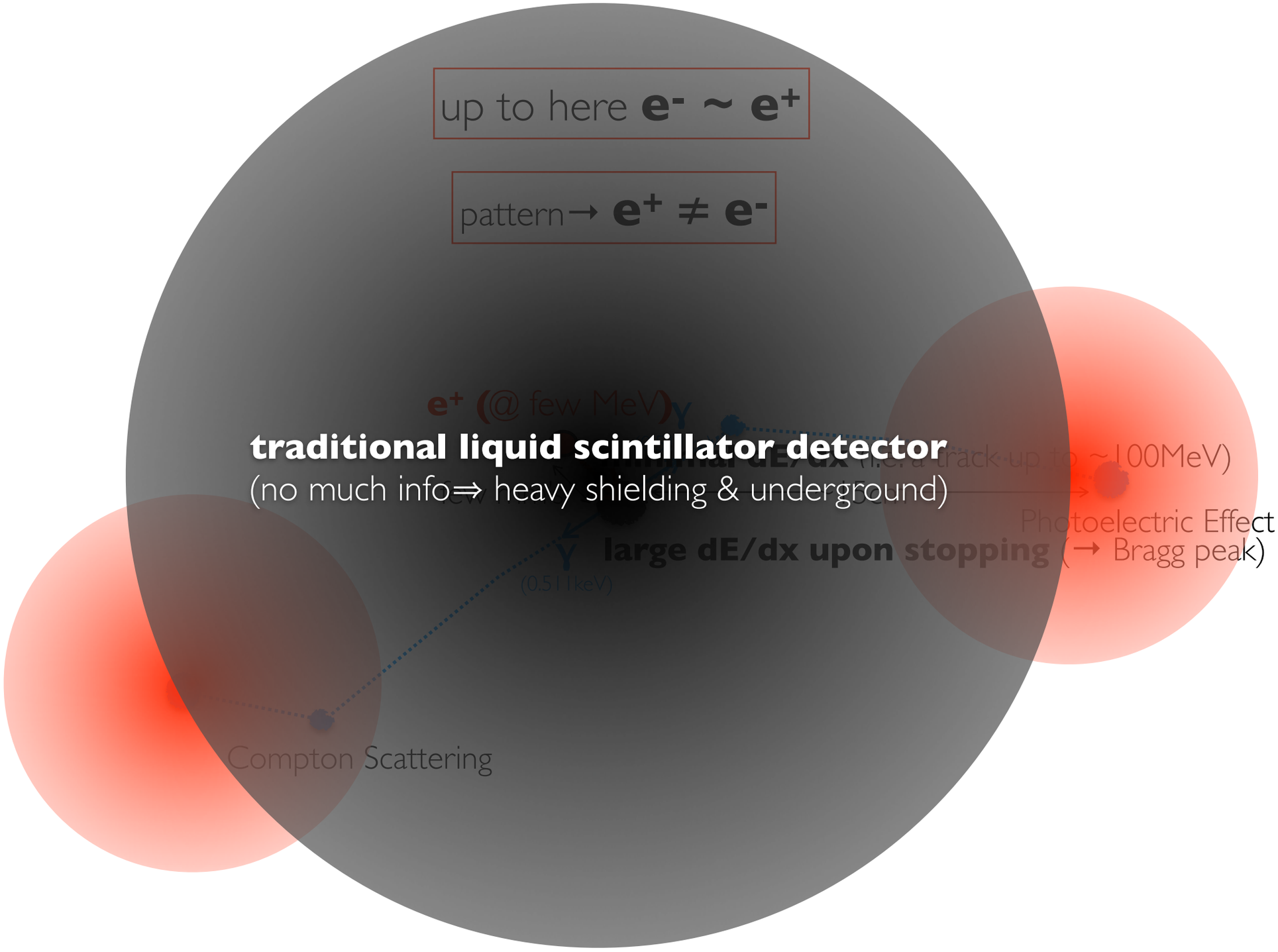
reach "perfection" since R&C…

- exquisite **radio-purity**
- **buffer** volume (PMT shielding)
- **scintillation PSD** ("little/some" **PID**)

PMT(~ 1ns) ⇔ **Transparency** ⟹ ~~**PID**~~**?**

CTF @ Gran Sasso
(Borexino R&D)

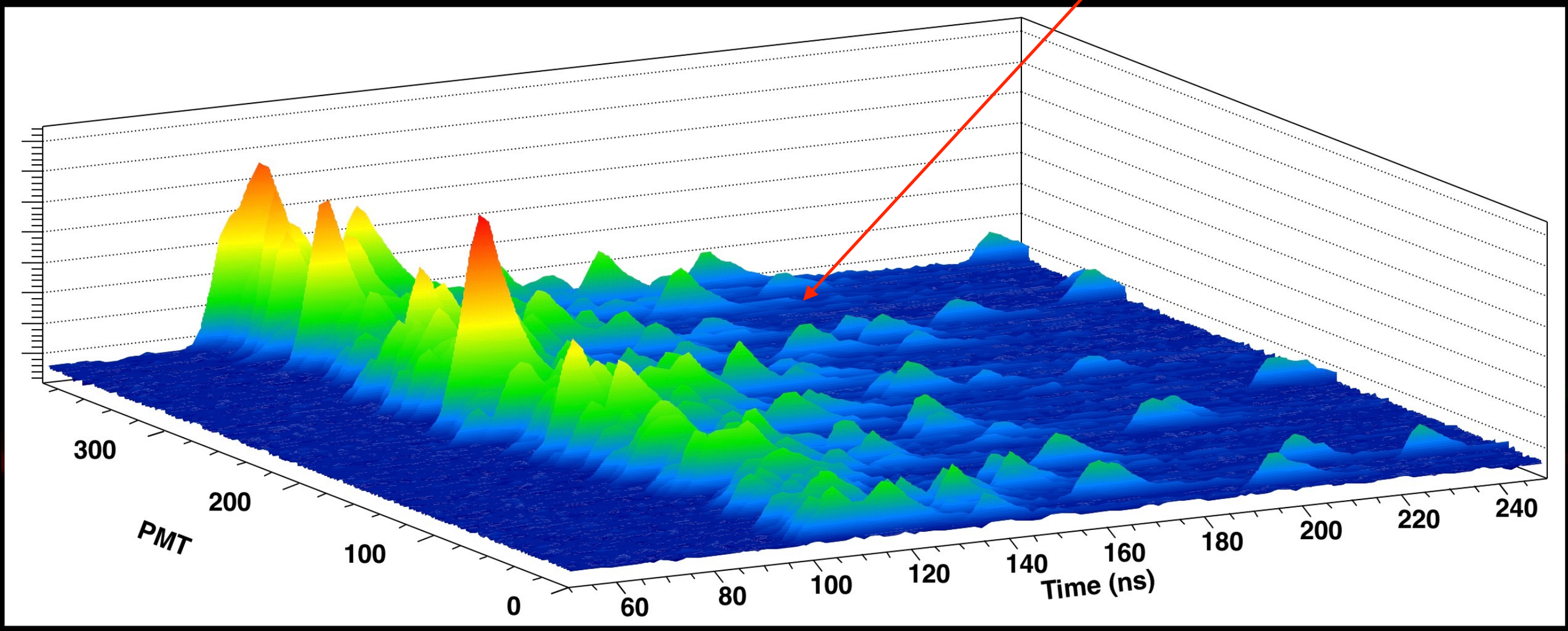
e+ PID limitation (illustration)…



traditional liquid scintillator detector
(no much info⇒ heavy shielding & underground)

powerful event pattern washed out⇒ hardly any ID!

exploiting FADC @ Double Chooz…



many channels → triangulation info

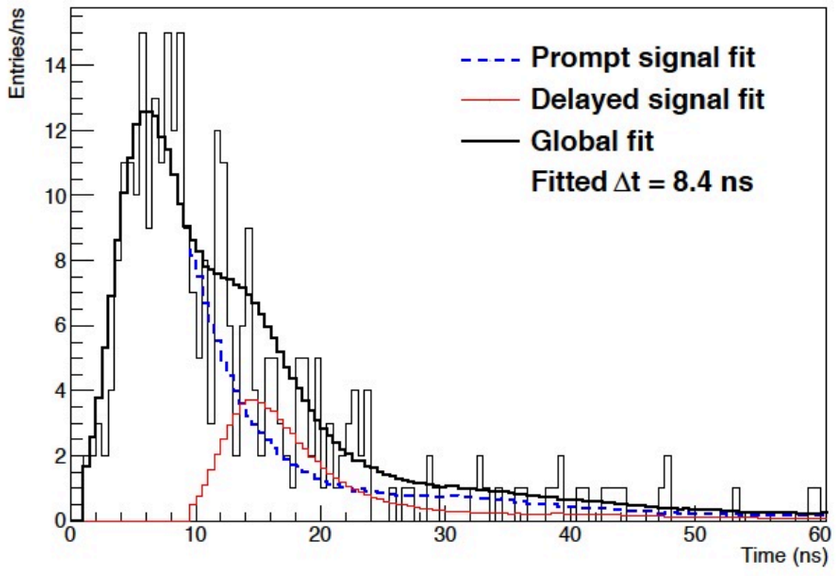
- **charge:** single-photon resolution
- **timing:** fraction of ns resolution
- **derived information (i.e. reconstruction):** position, PID, etc

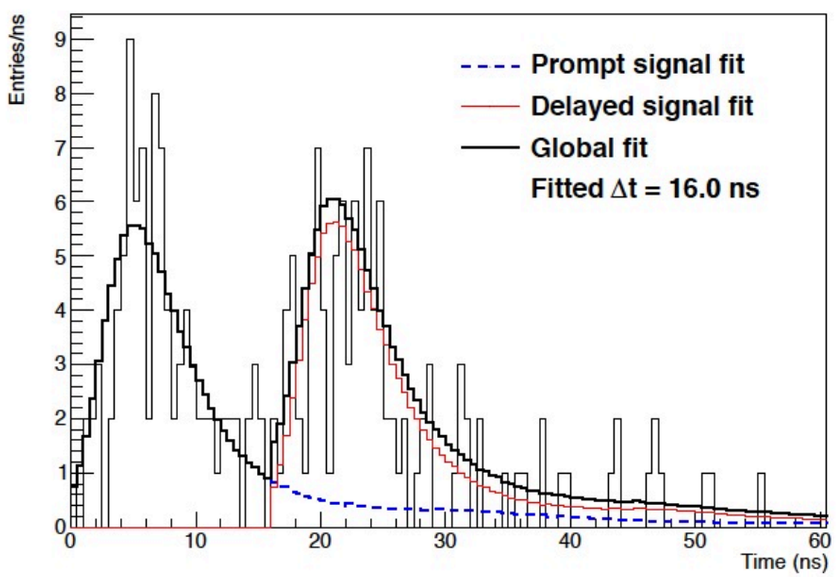
e+ via Ortho-Positronium (@Double Chooz)…

Ortho-positronium observation in the Double Chooz Experiment

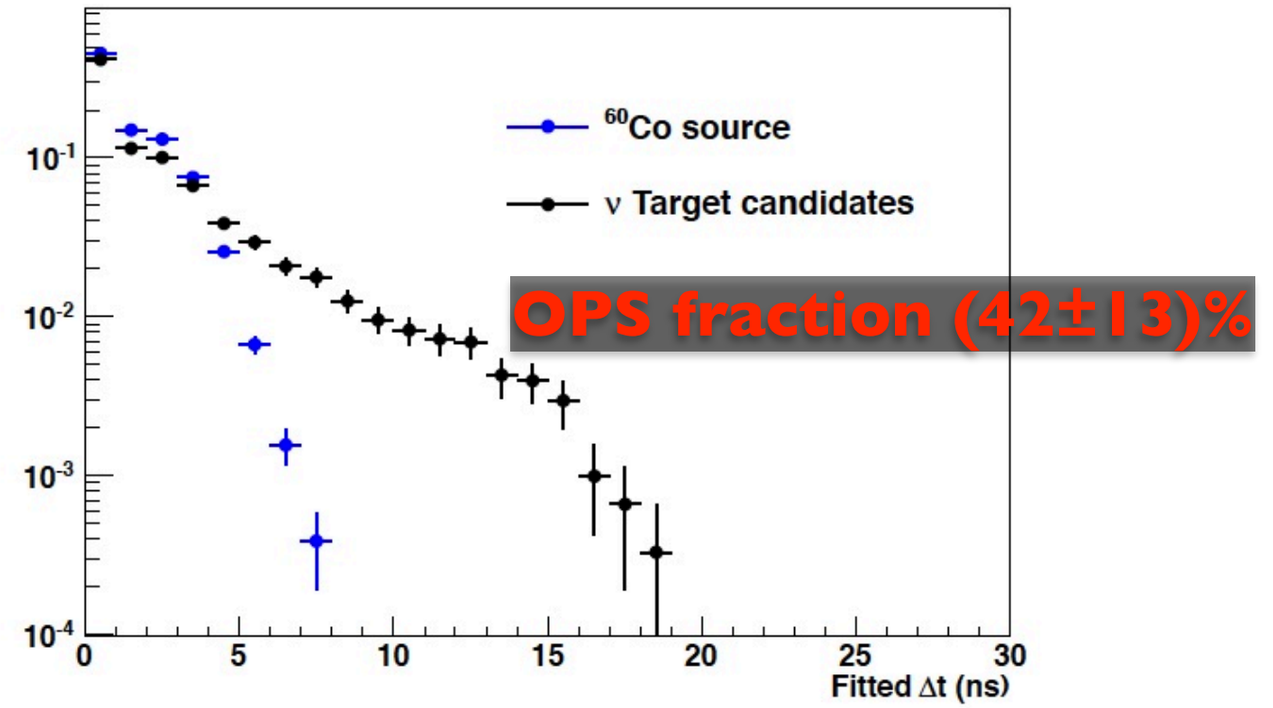
arXiv:1407.6913

ortho-positronium → delayed annihilation γ's
(identified via PSD empowered by FADC)





ortho-positronium formation: (42±13)%



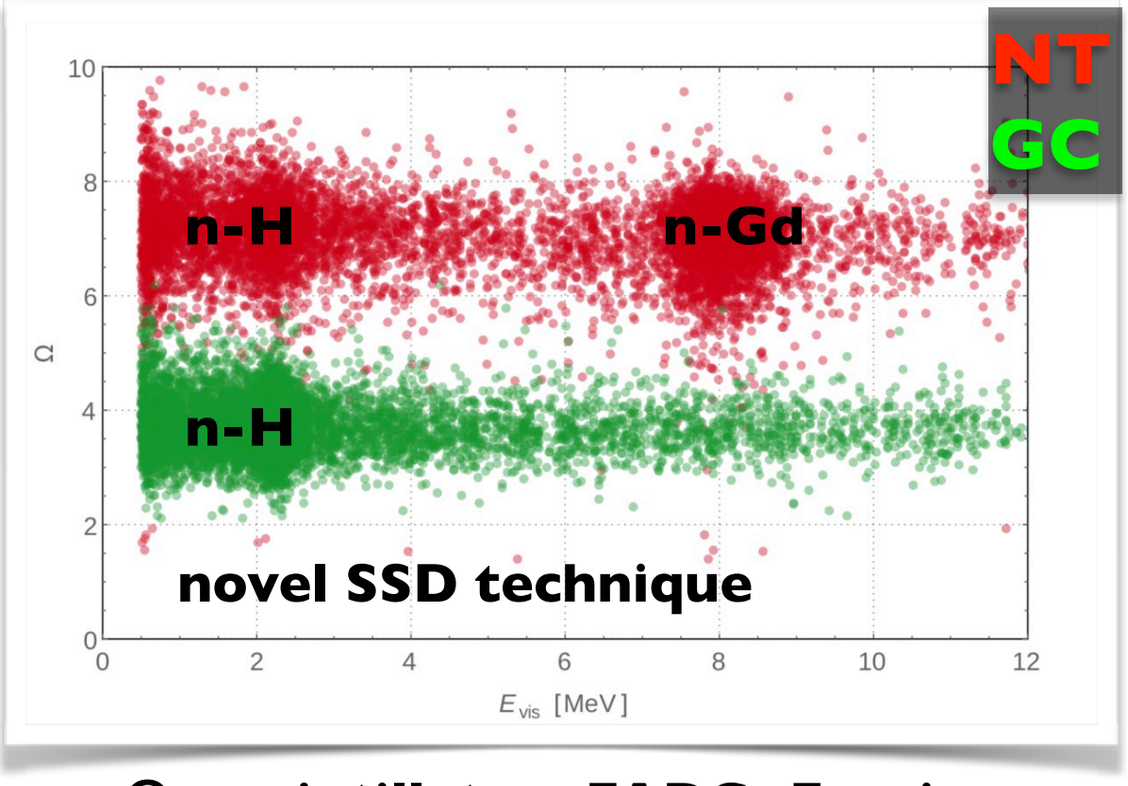
OPS fraction (42±13)%

ortho-positronium impractical for e+ PID (reactor experiment)

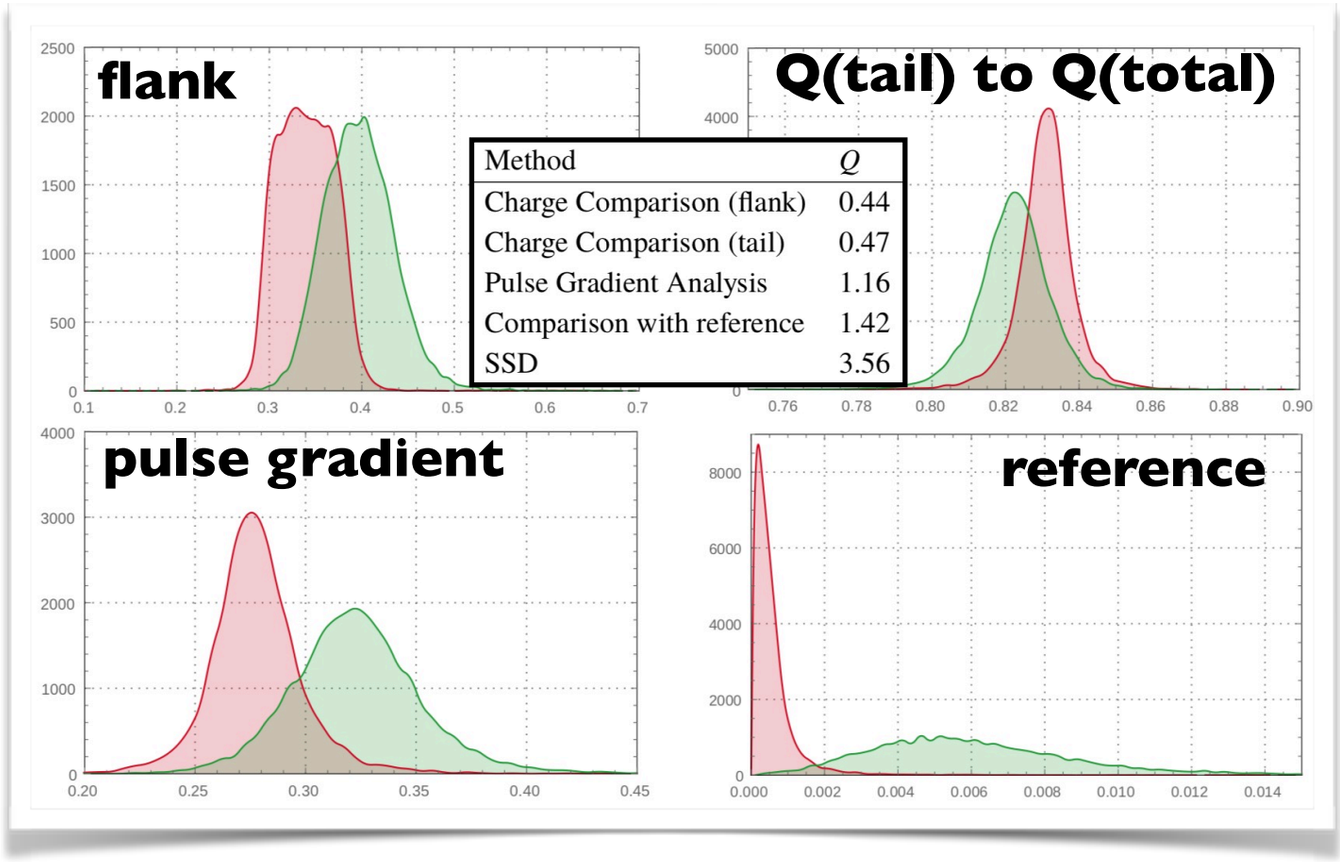
[ok to clean e- sample as done in Borexino]

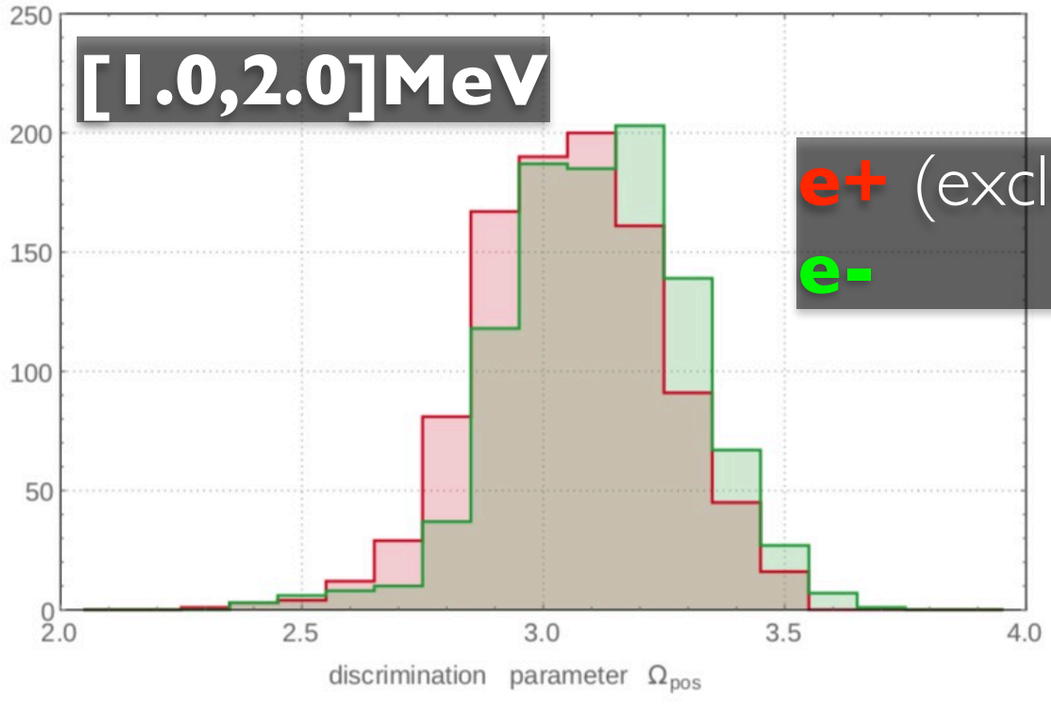
novel PSD @ Double Chooz …

arXiv: 1710.04315

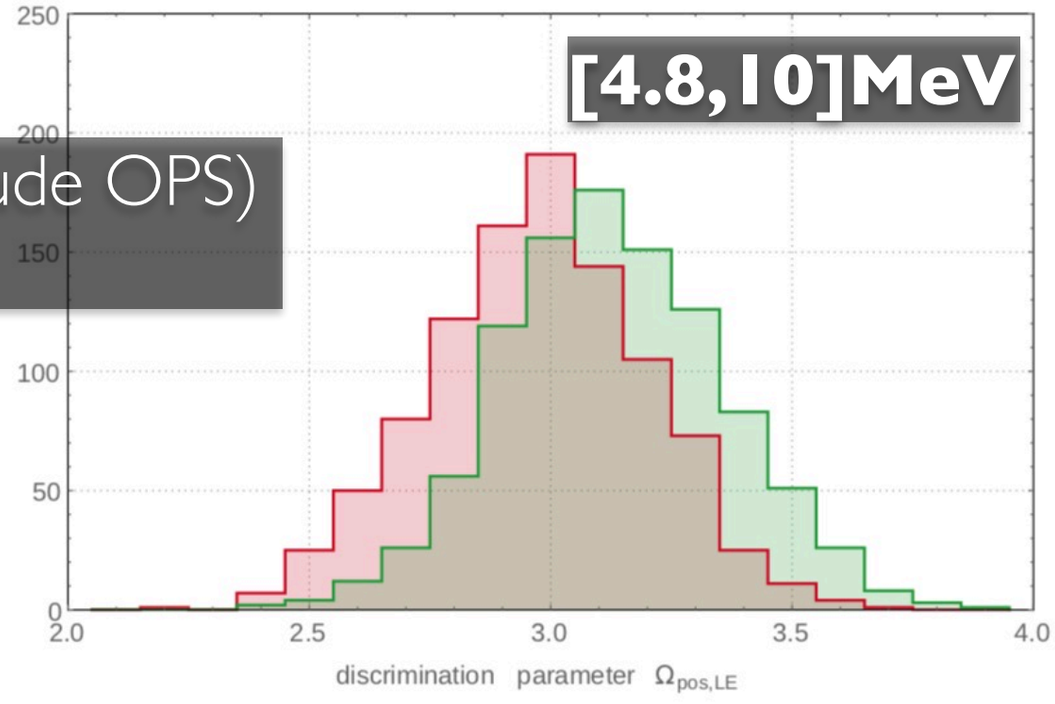


Ω = scintillator⊕FADC⊕Fourier



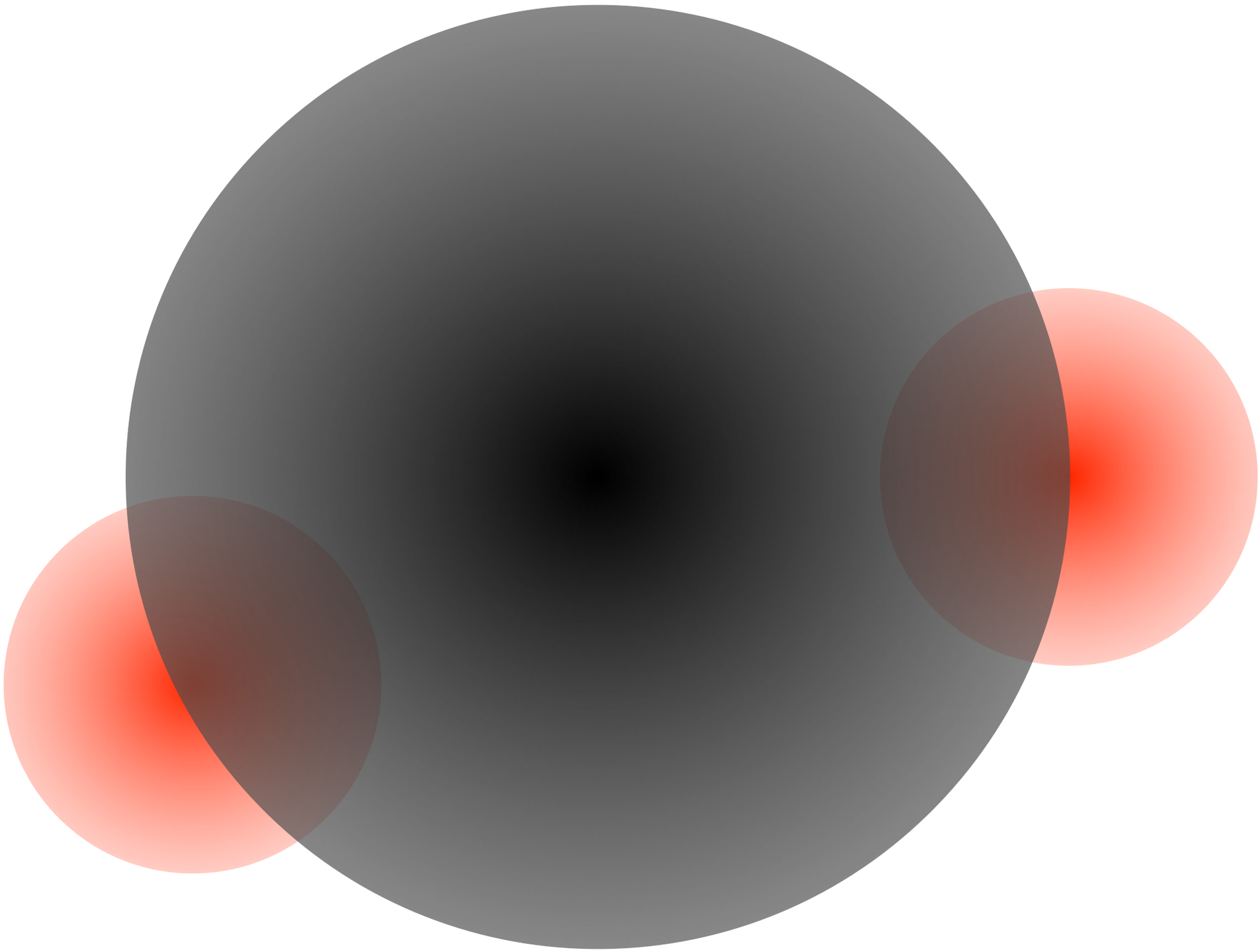


e+ (exclude OPS)
e-



e+ PID in traditional techonology…

pattern → $\mathbf{e^+ \neq e^-}$



impractical e+ PID physics…

PSD important so far…

PSD on slower scintillation
(PMT good enough)

why such a "poor" PID?

no PID (beyond PSD) implies

$\gamma \approx e^- \approx e^+ \approx \alpha \approx$ p-recoil (fast-n)

PMT ↔ medium **transparency** → **little PID**

↓

σ(time)≳1ns ⇔ σ(space)≳20cm [unresolvable]

↓

σ(vertex)≈10cm [individual vertex]

liquid → (easy) loading BUT breaks transparency

if **PID** implies

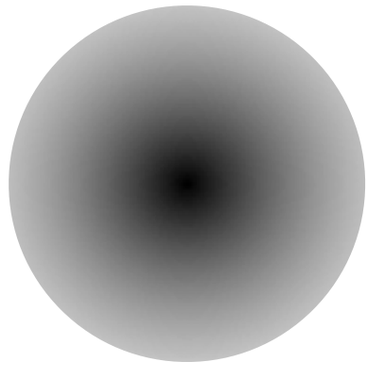
$\gamma \neq e^- \neq e^+$ & $e^+ \neq$ (α & p-recoil)

$\Longrightarrow$ no need for coincidence?

naive **O(1cm) spatial resolution**…

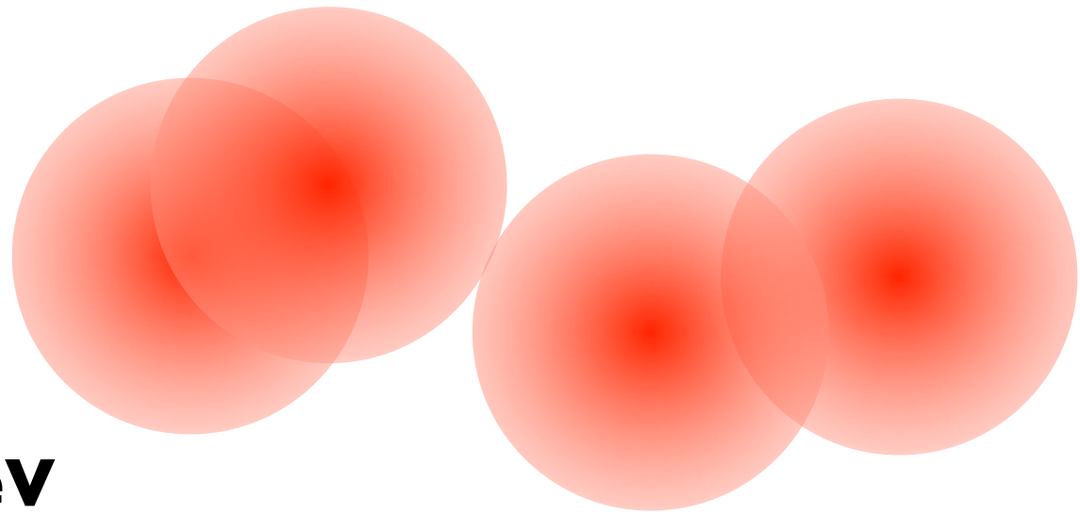
important: scintillator/water very low-Z material + a lot of "stable" H

e^- ≈ α ≈ p-recoil (fast-n)



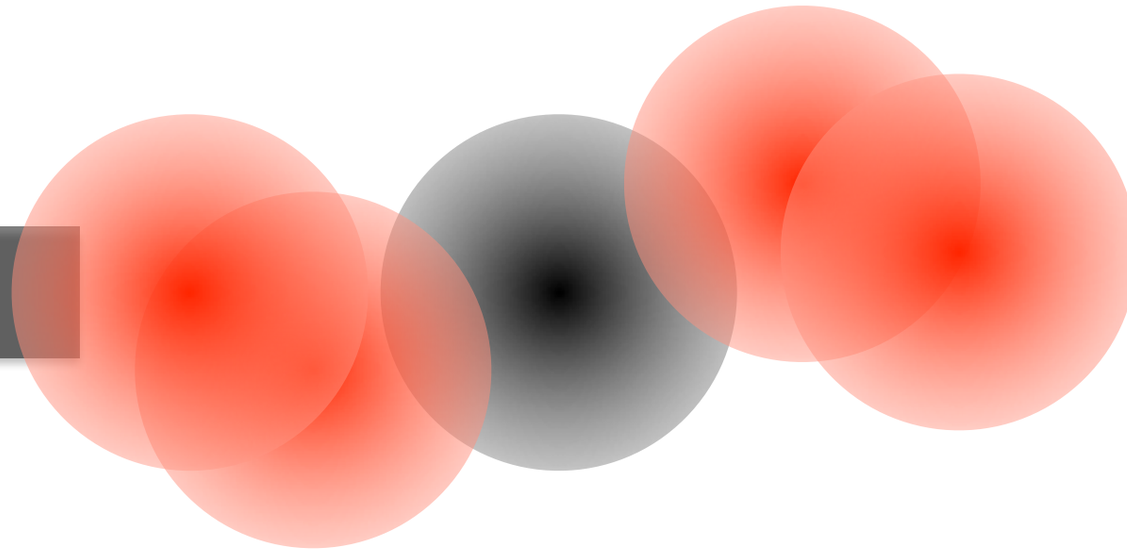
dE/dx→ Bragg peak
(e- starts as MIP)

γ



Compton scattering ≤3MeV

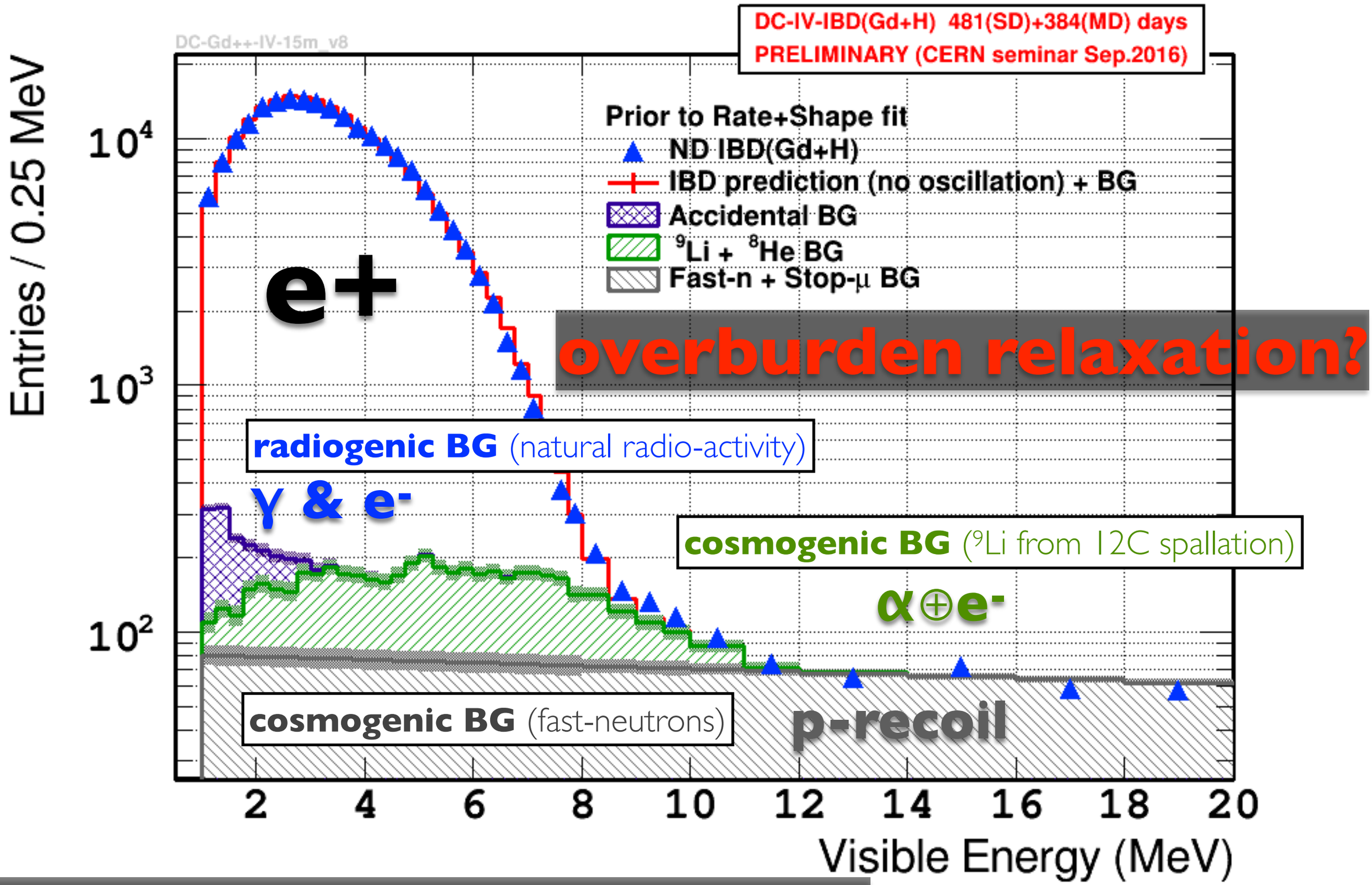
e^+ ≈ e^- + 2x **γ**(0.511 MeV)



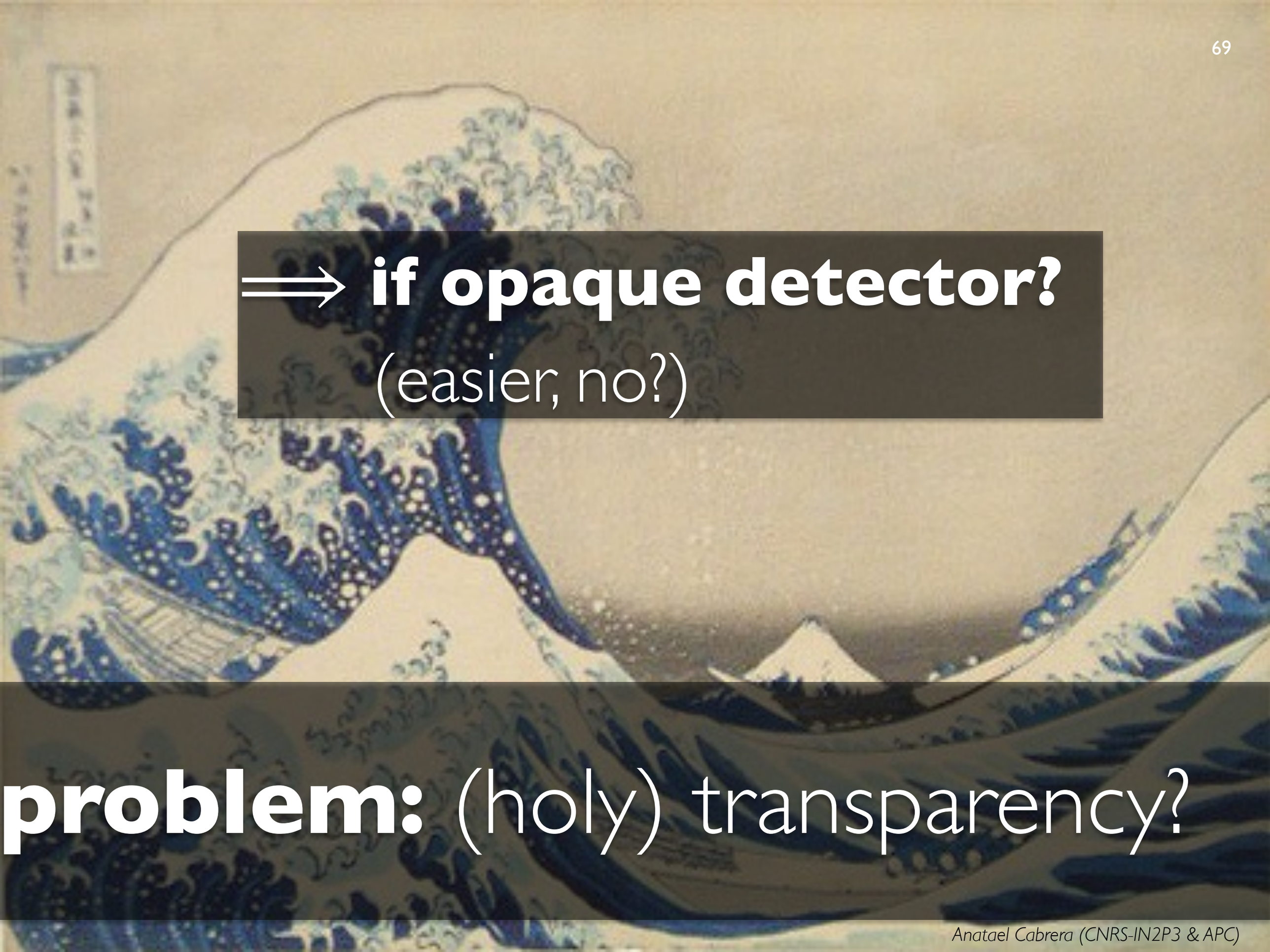
hybrid-like event

important: α's and **protons** are **scintillation quenched**

(example) latest Double Chooz data…



background-less reactor-ν's?



$\Longrightarrow$ **if opaque detector?**

(easier, no?)

problem: (holy) transparency?

Liquid

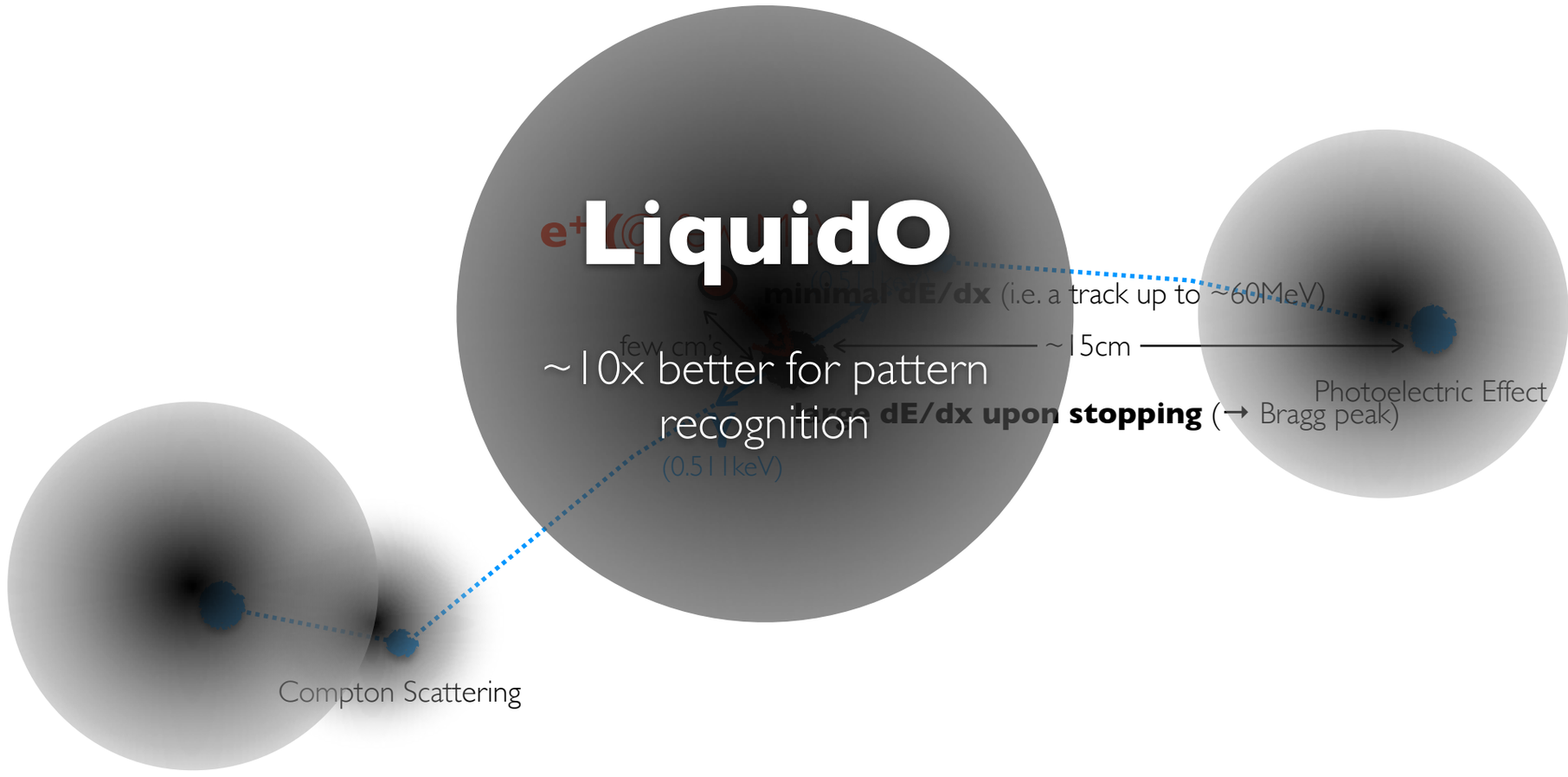
(first) **ν** opaque detector?

beyond today's limits?

Anatael Cabrera (CNRS-IN2P3 & APC)

PID beyond today's LS technology…

pattern→ $e^+ \neq e^-$



powerful event pattern⇒ differentiate particles (i.e. ID)

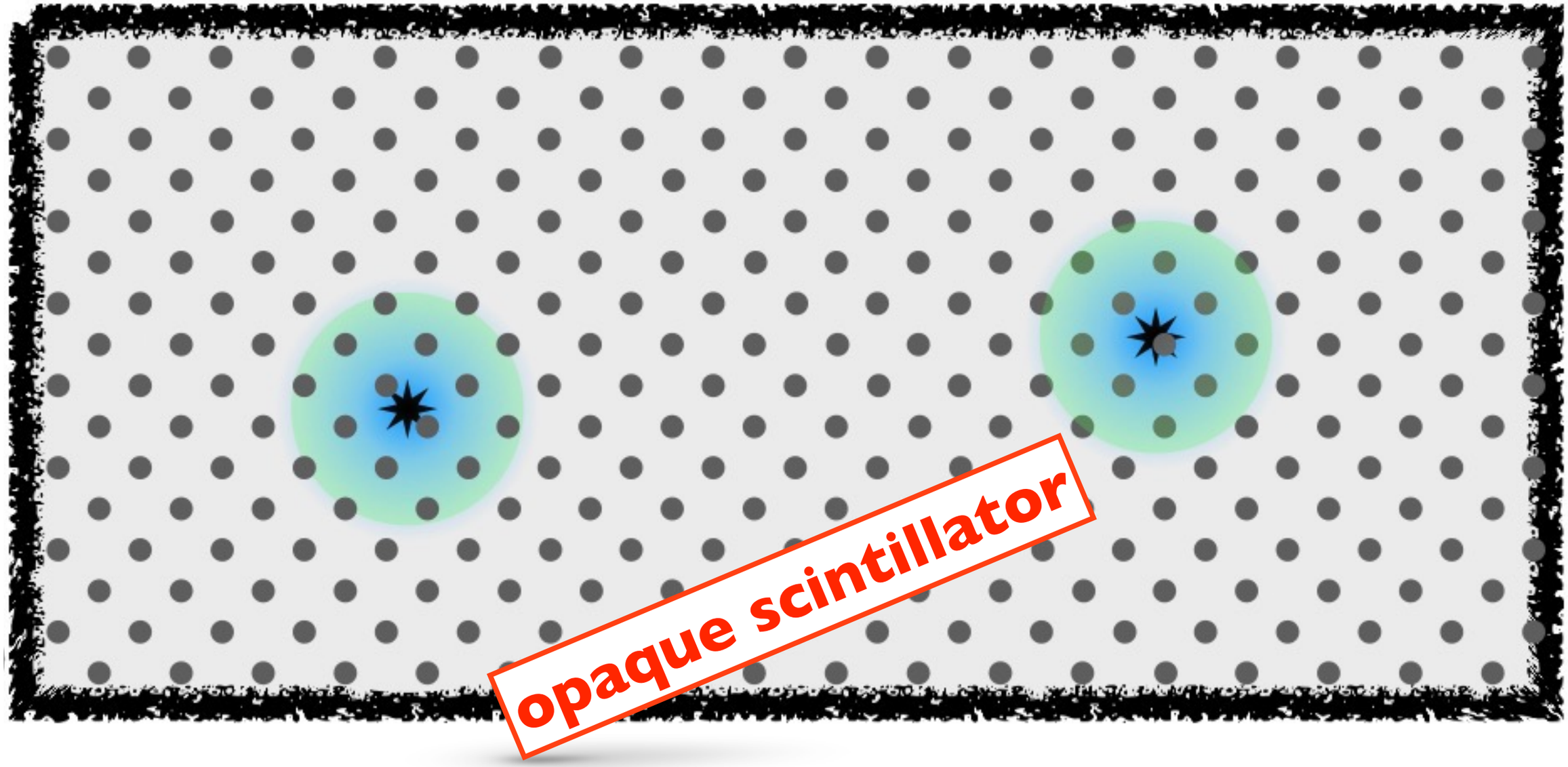
…and (maybe) much more!

doe

LiquidO = Liquid ⊕ Opaque

indeed opaqueness helps…

confine energy deposition locally → freeze information



readout: wave-shifting-fibres⊕SiPM's

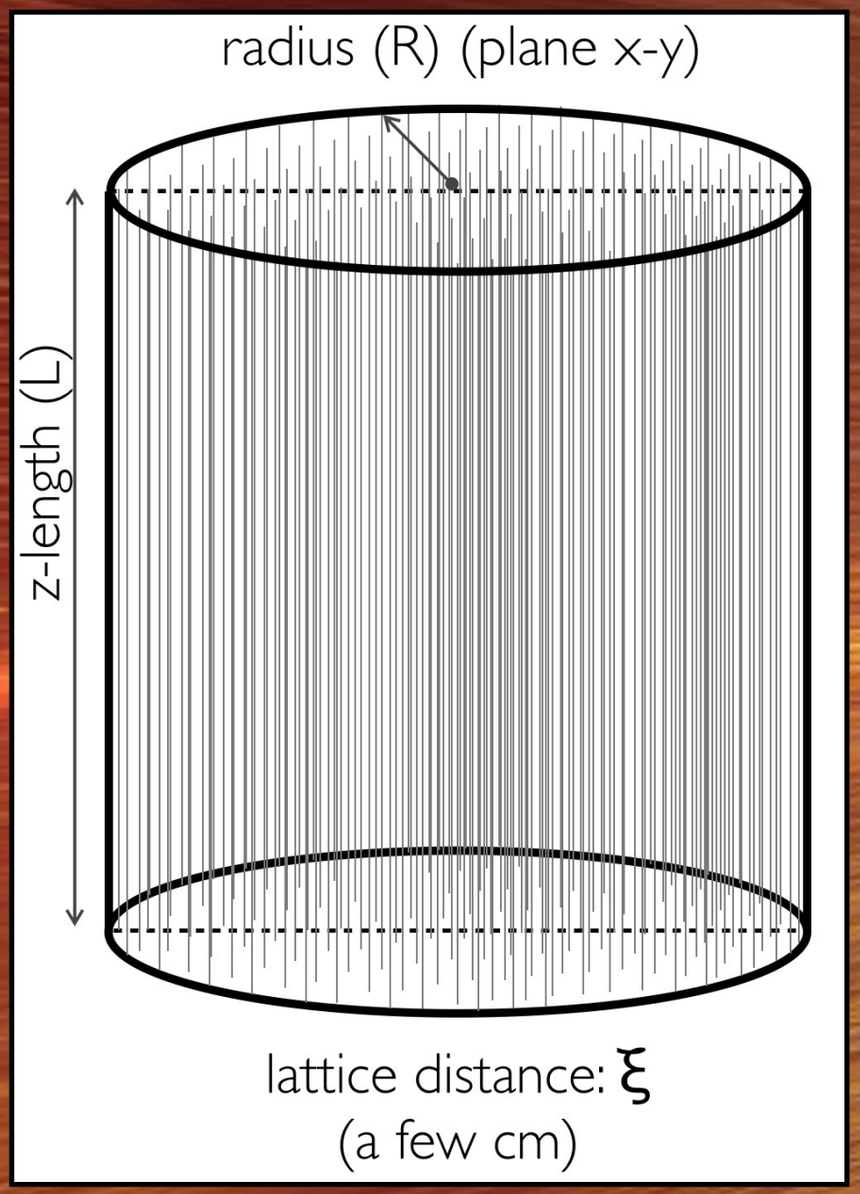
PMTs → become useless (unreachable light)

wax like

in reality, more like this…

designing *LiquidO*: 3D info…

very simple: **fibres** (a lot) + **LS**

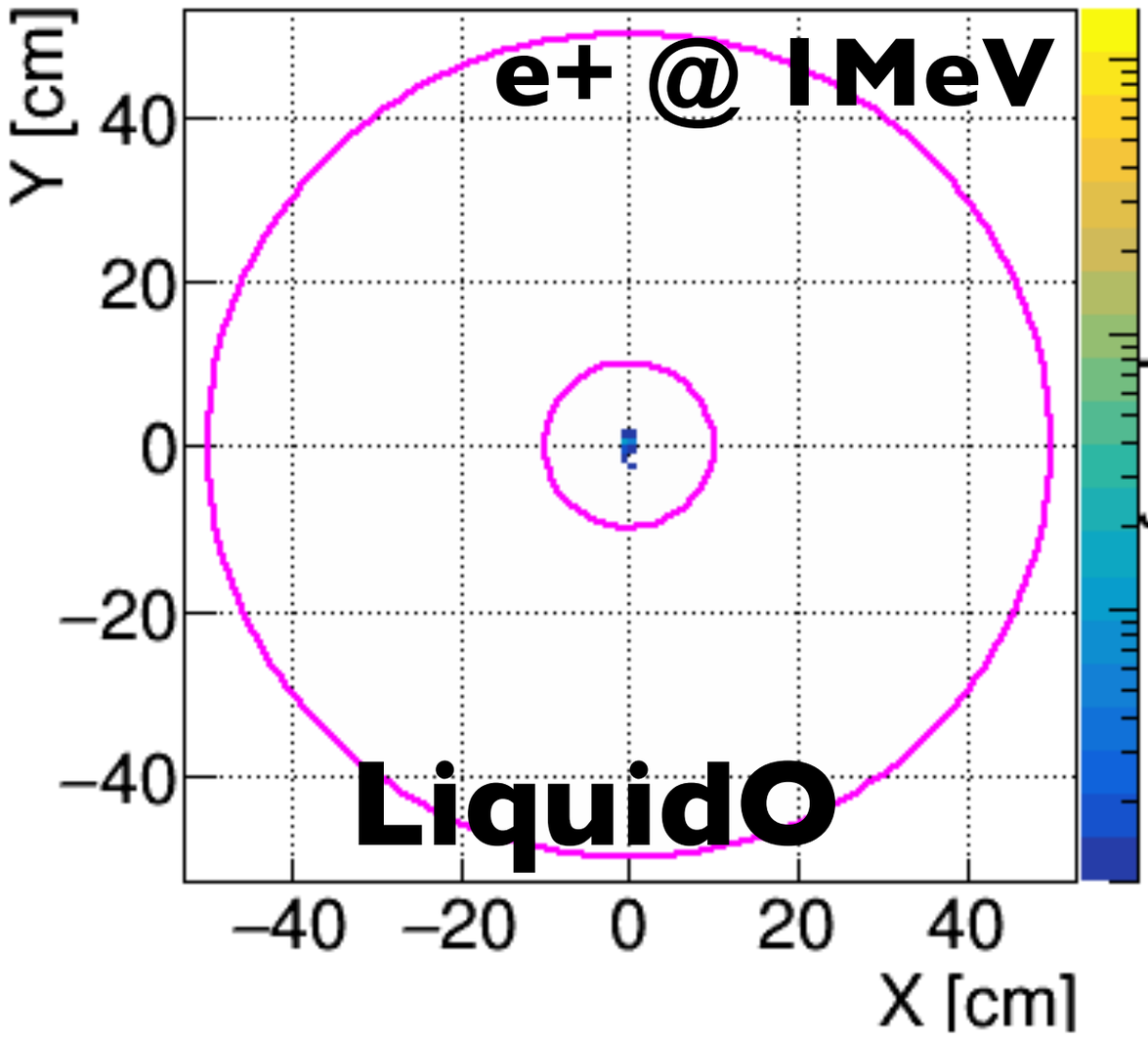


(x,y) info [lattice ξ]→ **image pixelation** (up to ~1 cm)
(z) info [along fibre]→ **time difference** (up to cm's)
(also z-pixelation possible→ envisaged for R&D)

image: multi-wire chambe
(by G. Charpak @ CERN)

stunning event-pattern...

LiquidO vs "traditional LS" (example: e+)

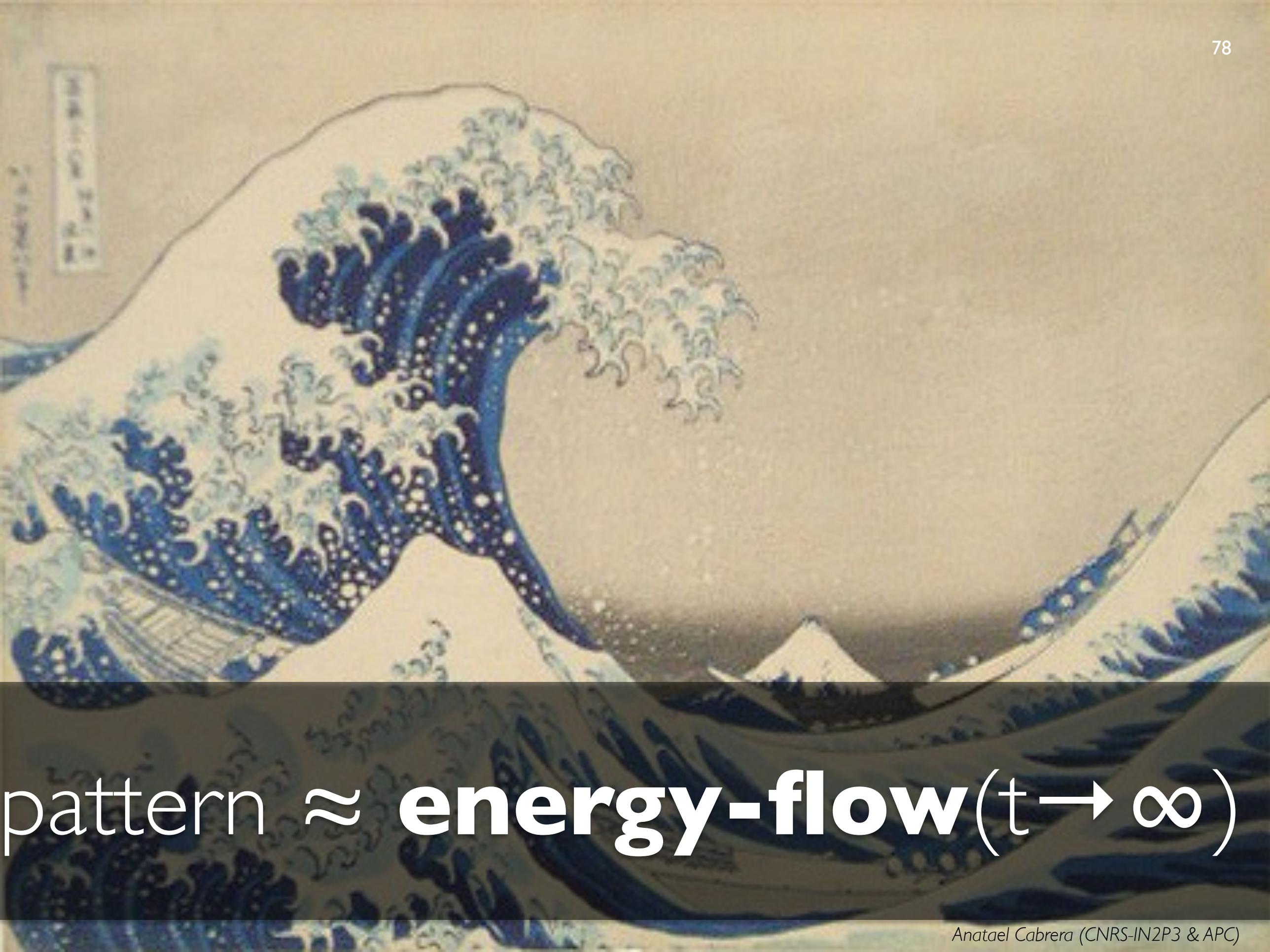


why opacity? [up to now the death of LS]

- **stochastic light confinement** (few cm's)→ powerful energy pattern (**PID**)
- **slow down speed of light** (~10^{-1}x)→ exploit **energy flow** & **causality** [next]
- **maximal light collection** (≥90%)→ light level up to **≤400PE/MeV?** [R&D]

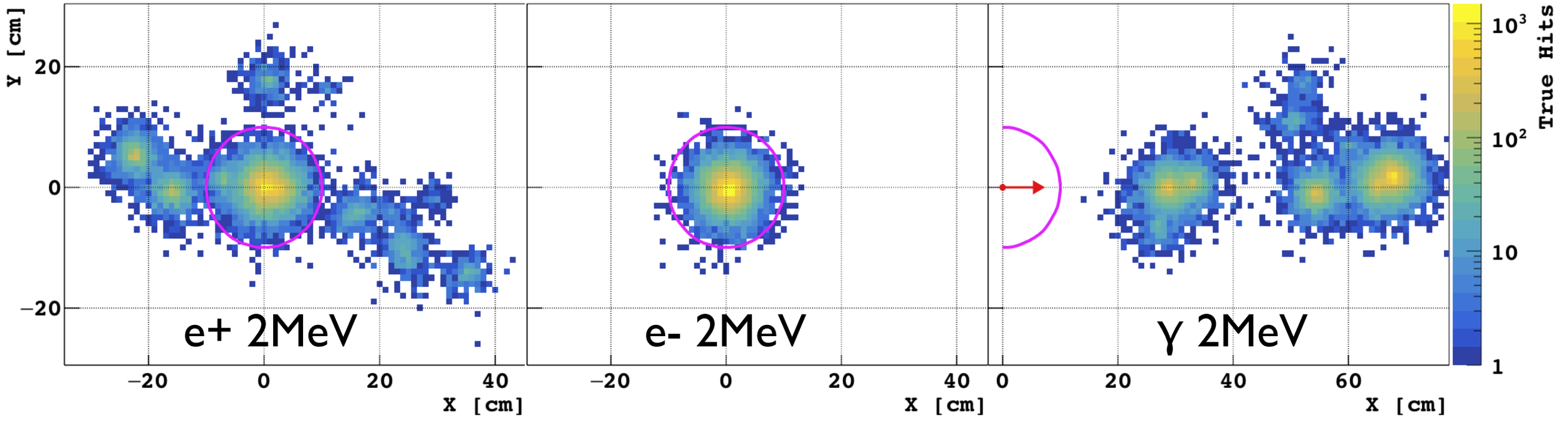
⇒ **opens for new LS technology!!** [opposite to LS state of the art: transparency]

moves forward from R&C(1956) technology?



pattern ≈ **energy-flow**(t→∞)

preliminary PID quantification…

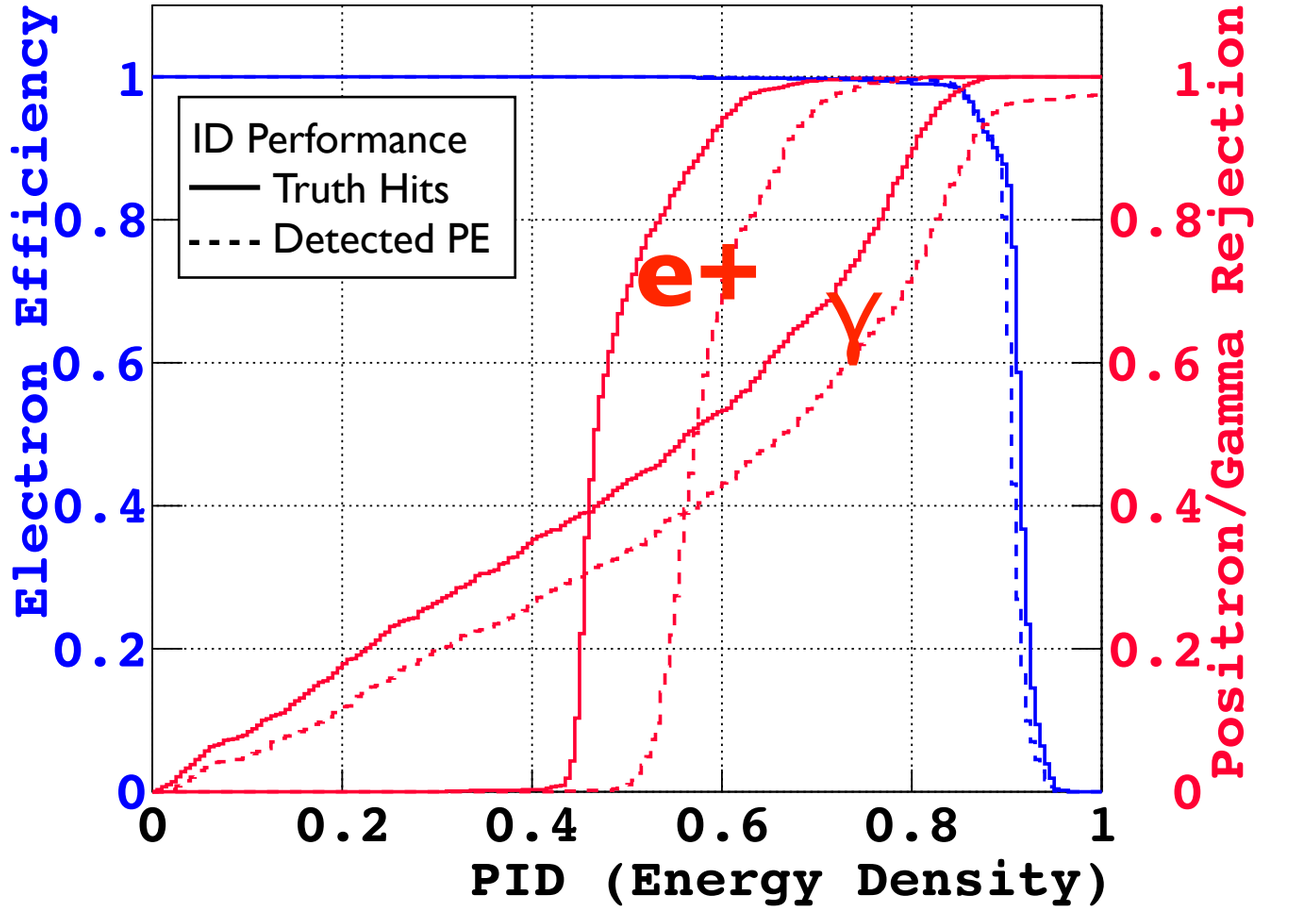


ID(e-)

if signal(e-)

⇒ rejection both e+,γ

goal: R≈10⁶? [under study]



doping: beyond native-ness…

ex: Cd loading

isotope loaded LiquidO (vs enrichment)…

loading % (→)

isotopic fraction/abundance							
V=128m³	0.1 1g/l	0.5 5g/l	1.0 10g/l	5.0 50g/l	10.0 100g/l	50.0 250g/l	100.0 1000g/l	
^{106}Cd NA 1.3	1.3	6.7	13.3	66.6	**133.1**	665.6	**1331**	→2β(+)
5.0	5.1	25.6	51.2	256.0	512.0	2560	5120	
^{116}Cd NA 7.5	7.7	38.4	76.8	384.0	**768.0**	3840	**7680**	→2β(-)
10.0	10.2	51.2	102.4	512.0	1024	5120	10240	
20.0	20.5	102.4	204.8	1024	2048	10240	20480	
50.0	51.2	256.0	512.0	2560	5120	25600	51200	
95.0 Cd enriched	97.3	486.4	**972.8**	4864	**9728**	48640	97280	
	↓				↓		↓	
	Double Chooz				LENS R&D		possible?	

massive loading capability (**R&D**)⇒ **no enrichment?**

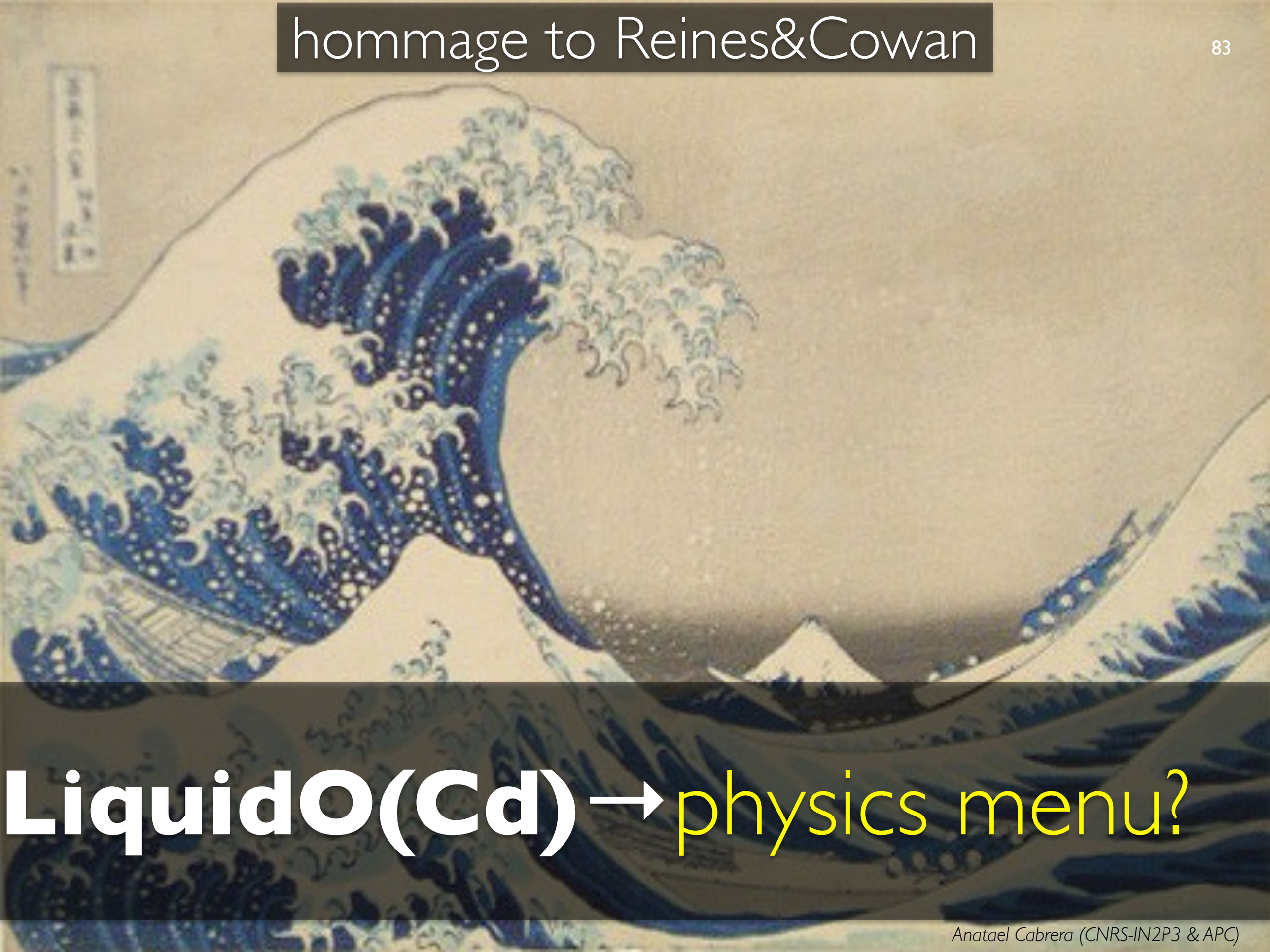
[natural abundance **≤100€/kg** vs **enriched ≥10k€/kg** or **≥10M€/ton**]

extremely hard physics!

- **BG-less reactor-ν** detection? **[never achieved]**
- **^{40}K geo-neutrino** detection? **[impossible]**
- **ν(e)/anti-ν(e) separation? [impossible]**
  - **→CP-violation ≤100MeV (vacuum)? [challenging]**
  - **→supernova's CC & NC detection? [possible?]**
- **multi-ton $2\beta^{\pm}$ decay** observation? **[impractical]**
  - **→$2\beta^{+}2\nu$ first observation? [never observed]**
- **and more! [no time sorry!]**

what (pending) **physics?**

hommage to Reines&Cowan



LiquidO(Cd) → physics menu?

Anatael Cabrera (CNRS-IN2P3 & APC)

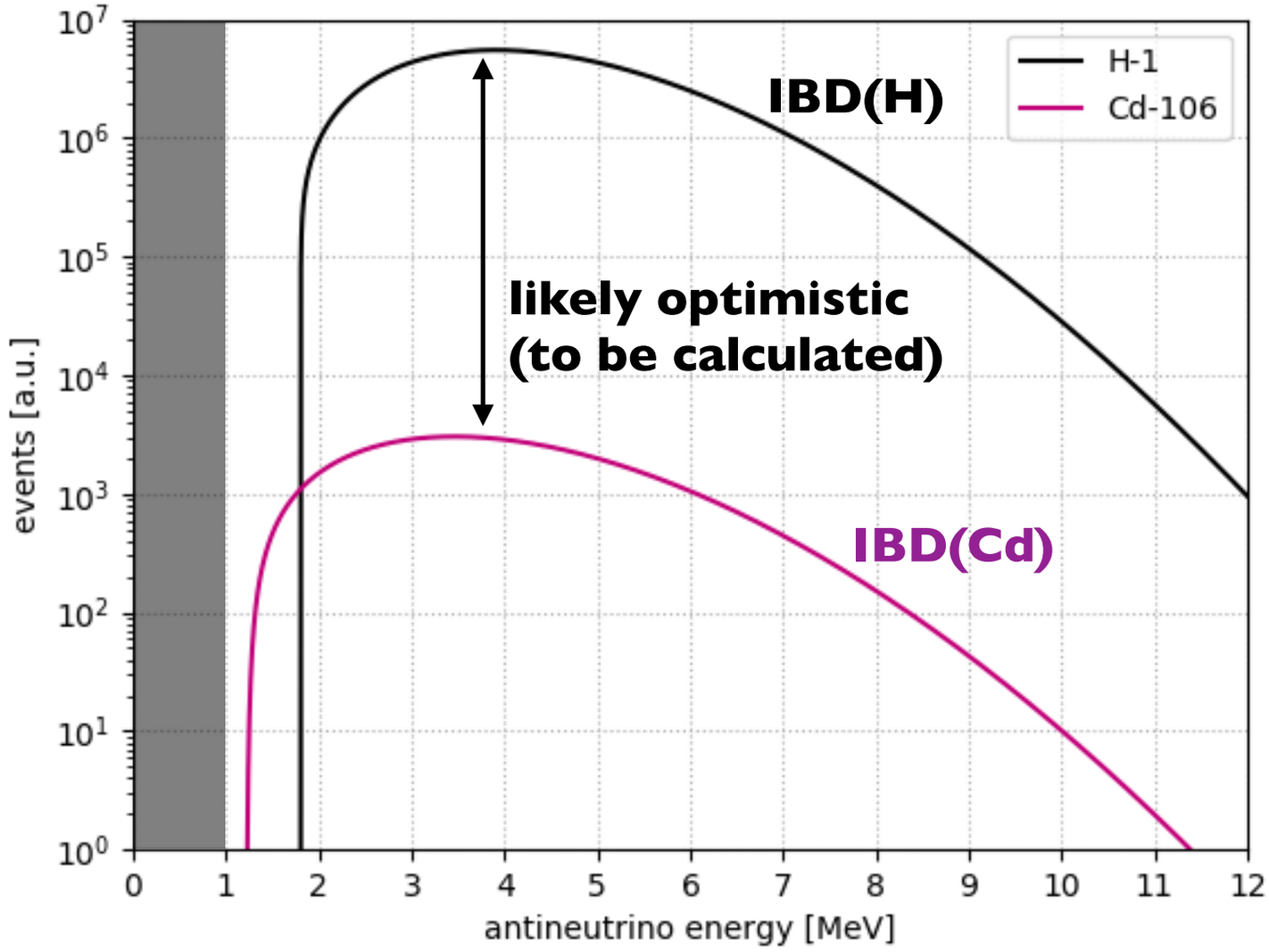
anti-ν_e + ^{106}Cd → e^+ + ^{106}Ag Energy(threshold)≈1.2MeV

[**single e+ detection**]

NOT easy but possible?

depends on σ interaction

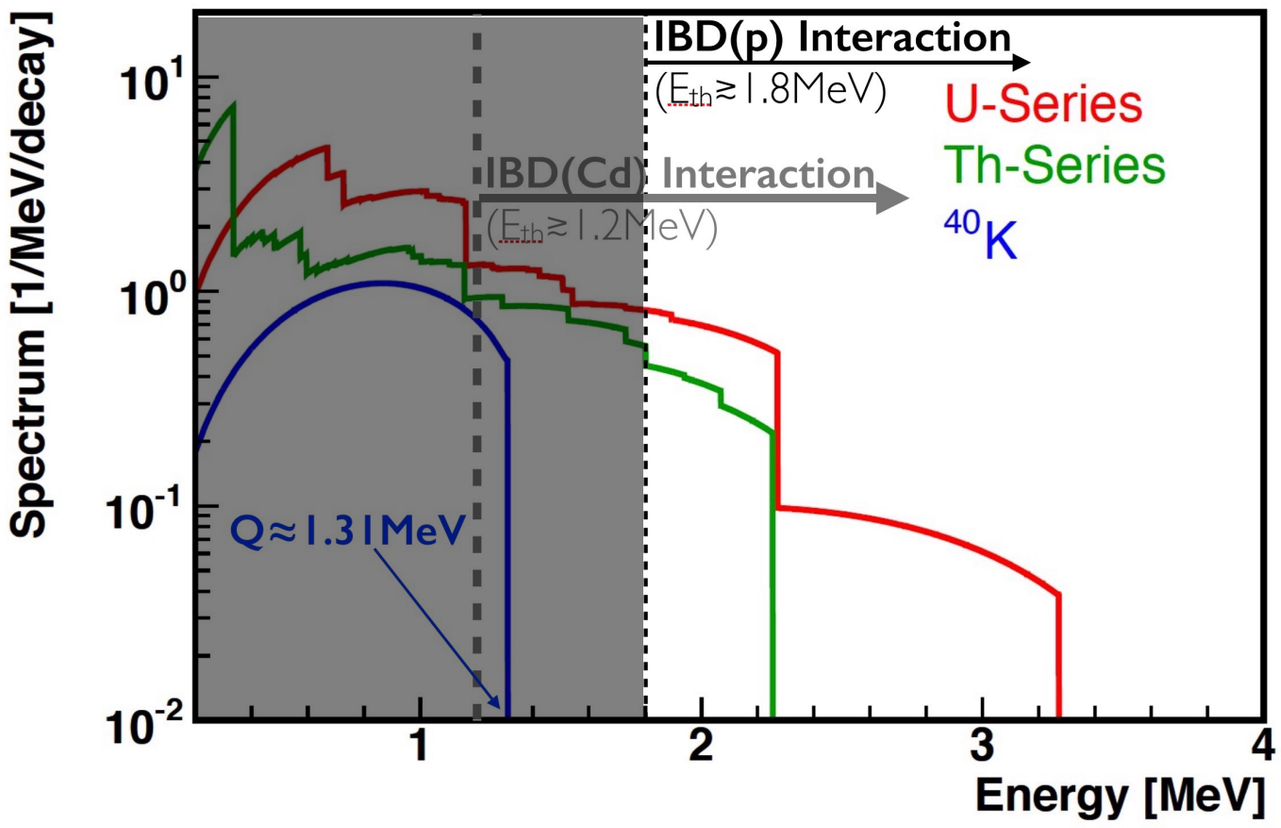
(low→measure reactor?)

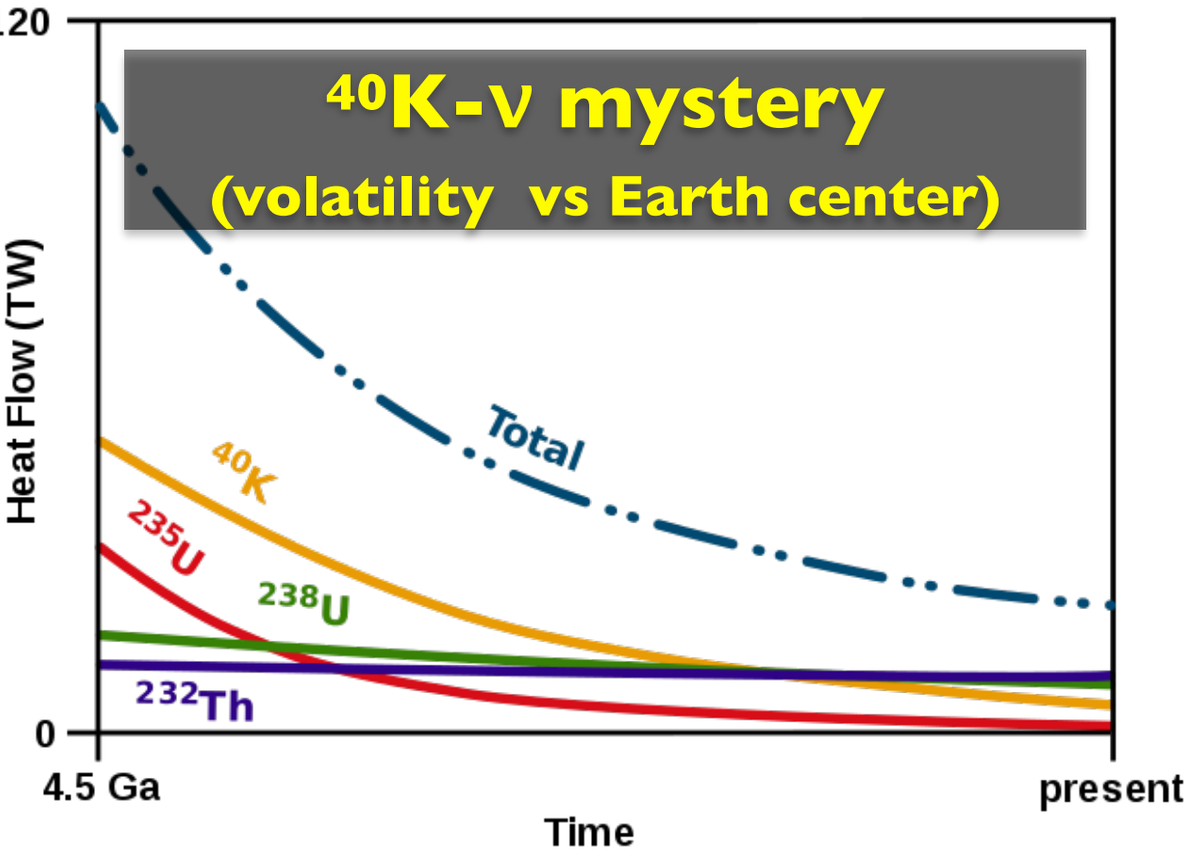


[M.Chen] e+:e+ coincidence (τ≈24min): **www.ipgp.fr/sites/default/files/ngs2015_chen.pdf**

(first) **single e^+ ν_e** detection?

hope to detect geo-ν(⁴⁰K)? [impossible so far]





Cd-ν interaction: ⁴⁰K and more! U⊕Th geo-ν's?

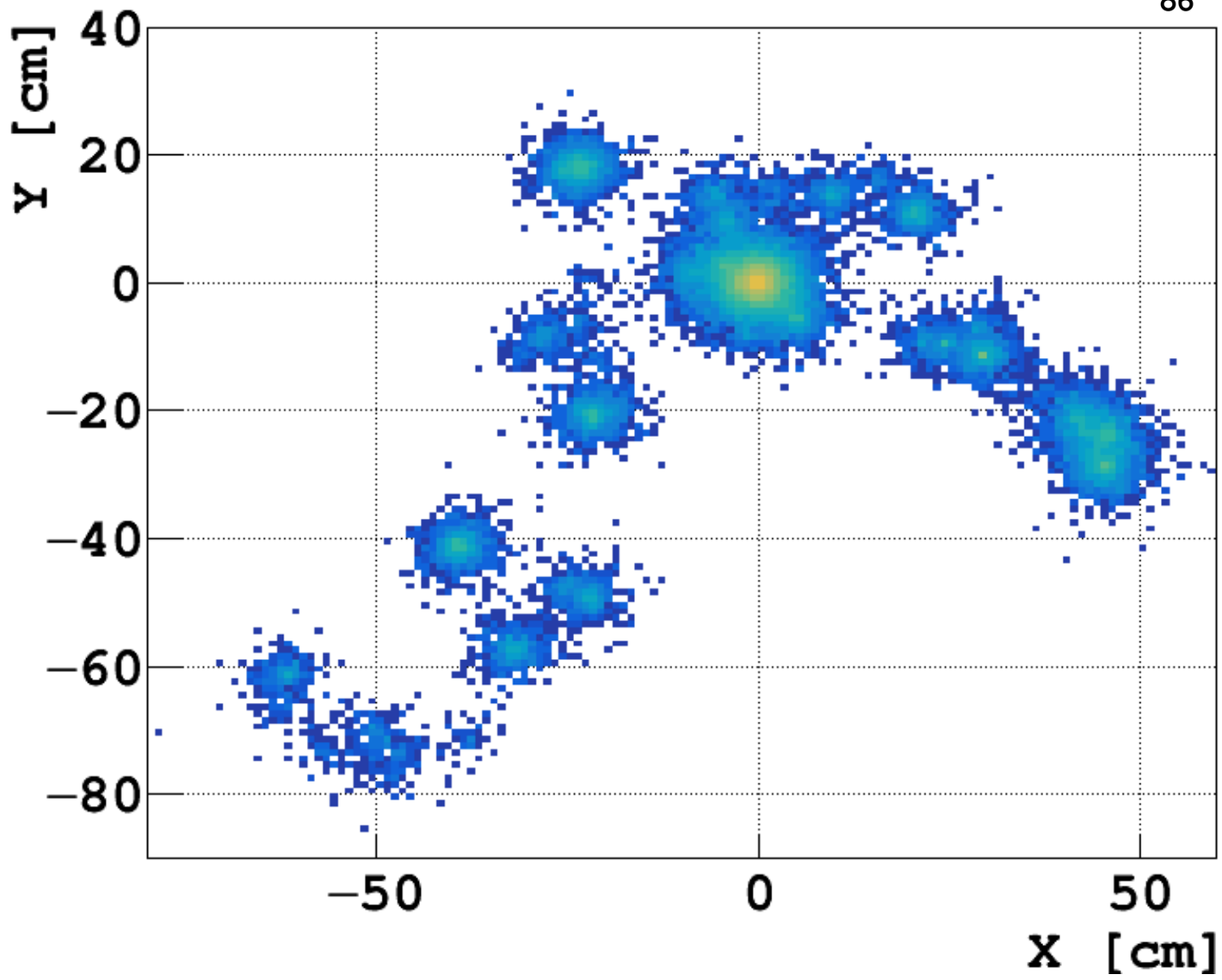
geo-ν(⁴⁰K) detection ever?

Cd doped LS

e+→ difficult to mimic

2x **e+→ impossible?**

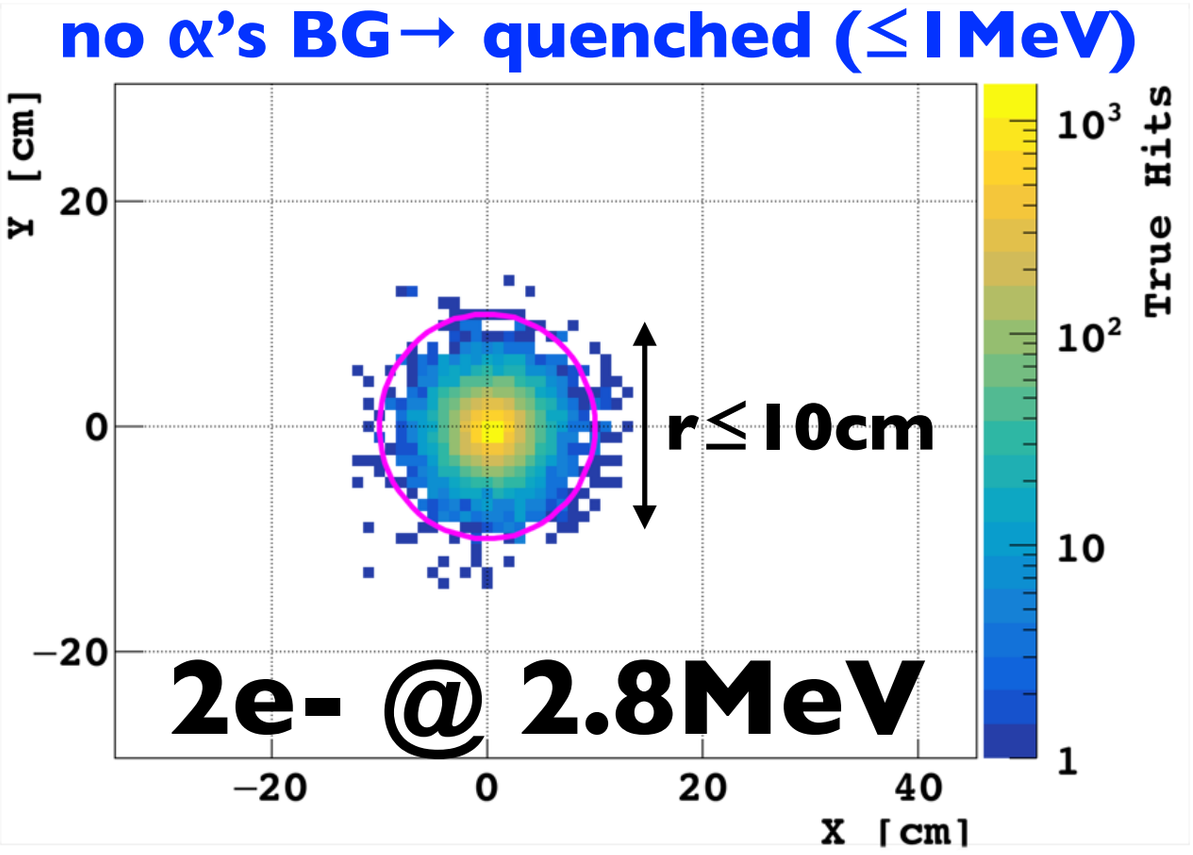
study: γ's ≥ 2.6MeV



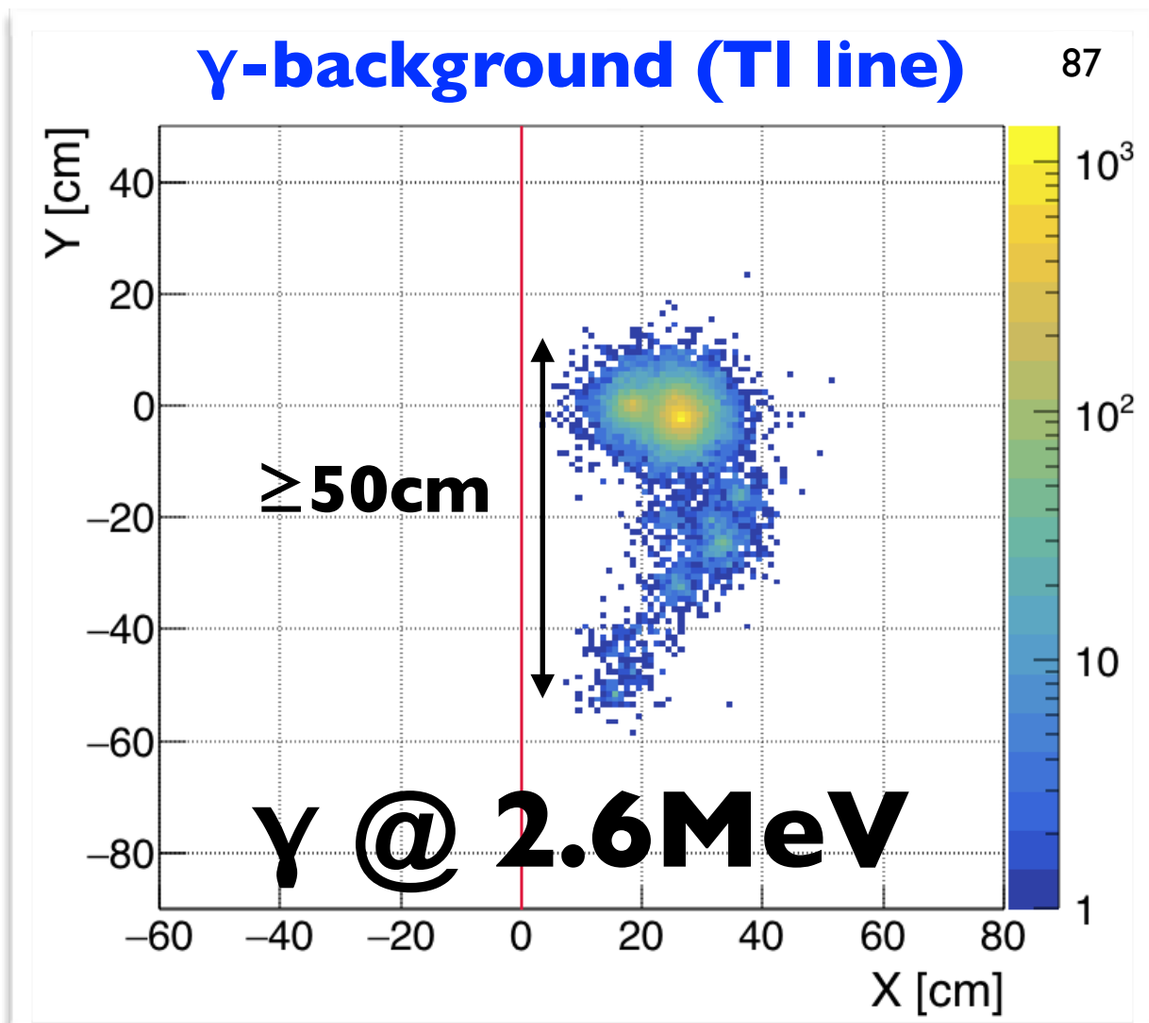
3 channels: **2β+(ok)** ⊕ **β+ε (ok)** ⊕ **εε (no)**

^{106}Cd 2β+ (first) observation?

Cd doped LS



Each e-(1.4MeV) ≲1cm track
⇒ unresolvable [see NEXT or alike]

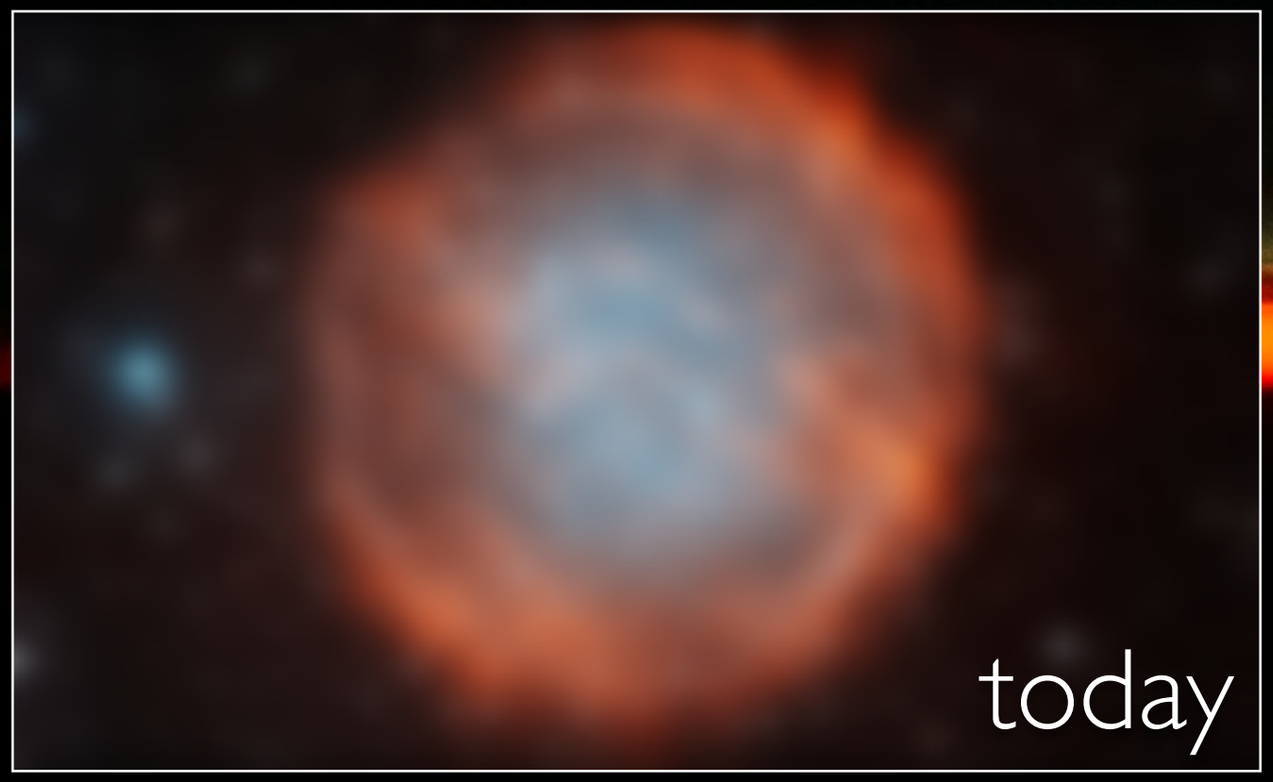


γ rejection ≥10⁶ possible??

^{116}Cd 2β0ν (multi-ton) search?

Nature always waiting **to be unravelled**…

(history of science → detection/instrumentation progress)



LiquidO R&D: validation soon!

R&D

just an appetiser…

what to remember?

- **reactor-ν:** active leading edge field…
- past (historic legacy) & present → **future!**
- **R&D: surprises?** (beyond reactors)

questions…?

obrigado…
ありがとう…
merci…
danke…
고맙습니다…
Спасибо…
gracias…
grazie…
谢谢…
hvala…
thank you…

anatael@in2p3.fr