TOKYO METROPOLITAN UNIV.

Double Chooz Reactor Neutrino Experiment

Physics seminar @ TMU, 15 Oct. 2015

Takayuki SUMIYOSHI

Neutrino oscillation in 3 flavor scheme and the oscillation parameters

$(*)\ c_{ij} = cos\theta_{ij},\ s_{ij} = sin\theta_{ij}$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

θ_{23} : $P(\nu_\mu \rightarrow \nu_\mu)$ by Atmos. ν and ν beam
Kajita-san discoverd

θ_{13}: $P(\nu_e \rightarrow \nu_e)$ by Reactor ν
θ_{13} & δ: $P(\nu_\mu \rightarrow \nu_e)$ by ν beam

θ_{12} : $P(\nu_e \rightarrow \nu_e)$ by Reactor and solar ν
A. B. McDonald's big contribution

Parameters describing the neutrino oscillation

- 3 mixing angle: $(\theta_{12}, \theta_{23}, \theta_{13})$ ~ (34°, 45°, <12°)
- 2 mass splitting: $(\Delta m^2_{12}, \Delta m^2_{23})$ ~ (8×10^{-5} eV^2, 2.4×10^{-3} eV^2)
- CP violation phase: δ ~ unknown

$$|U_{MNS}| \sim \begin{pmatrix} 0.7 & 0.7 & <0.2 \\ 0.5 & 0.5 & 0.7 \\ 0.5 & 0.5 & 0.7 \end{pmatrix}$$

The θ_{13} was the only yet observed mixing angle until 2012.
Non-zero θ_{13} is required to measure leptonic CP violation.
→ Many experiments to measure θ_{13} were proposed.

Current experiments to measure θ13

Reactor experiments

- EU+JP+US: **Double Chooz (2011-)**
- Korea: RENO (2011-)
- China+US: DayaBay (2011-)

Features:

- E_ν ~ MeV, Short baseline
- Search for $\bar{\nu}_e \rightarrow \bar{\nu}_e$
  "Disappearance" experiments

Accelerator experiments

- JP+...: **T2K (2009-)**
- US+...: MINOS (2005-2011), NOvA (2013-)

Features:

- E_ν ~ GeV, Long baseline
- Search for $\nu_\mu \rightarrow \nu_e$
  "Appearance" experiments

IMPORTANCE OF REACTOR NEUTRINO EXPERIMENT

PHYSICAL REVIEW D **68**, 033017 (2003)

Reactor measurement of θ_{13} and its complementarity to long-baseline experiments

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(Received 8 November 2002; revised manuscript received 18 April 2003; published 28 August 2003)

The possibility of measuring $\sin^2 2\theta_{13}$ using reactor neutrinos is examined in detail. It is shown that the sensitivity $\sin^2 2\theta_{13}>0.02$ can be reached with 40 ton yr data by placing identical CHOOZ-like detectors at near and far distances from a giant nuclear power plant whose total thermal energy is 24.3 GW_{th}. It is emphasized that this measurement is free from the parameter degeneracies that occur in accelerator appearance experiments, and therefore the reactor measurement is complementary to accelerator experiments. It is also shown that the reactor measurement may be able to resolve the degeneracy in θ_{23} if $\sin^2 2\theta_{13}$ and $\cos^2 2\theta_{23}$ are relatively large.

DOI: 10.1103/PhysRevD.68.033017 PACS number(s): 14.60.Pq, 25.30.Pt, 28.41.−i

I. INTRODUCTION

Despite the accumulating knowledge of neutrino masses and lepton flavor mixing from atmospheric [1], solar [2,3], and accelerator [4] neutrino experiments, the (1-3) sector of the Maki-Nakagawa-Sakata (MNS) matrix [5] is still unclear. At the moment, we know only that $|U_{e3}|=\sin\theta_{13}\equiv s_{13}$ is small, $s_{13}^2\lesssim 0.03$, from the bound imposed by the CHOOZ reactor experiment [6]. In this paper we assume that the light neutrino sector consists of three active neutrinos only. One of experiments MINOS [12], OPERA [13], and JHF phase I [14]. It may be followed either by conventional superbeam [15] experiments (the JHF phase II [14] and possibly others [16,17]) or by experiments at neutrino factories [18,19]. It is pointed out, however, that the measurement of θ_{13} in LBL experiments with only a neutrino channel (as planned in JHF phase I) would suffer from large intrinsic uncertainties, on top of the experimental errors, due to the dependence on an unknown *CP* phase and the sign of Δm_{31}^2 [20]. Furthermore, it is noticed that an ambiguity remains in the determination

Two complementary approaches: Reactor & Accelerator

Reactor experiments ($\bar{\nu}_e$ disappearance): Double Chooz, Daya-Bay, RENO

$$P\left[\bar{\nu}_e \to \bar{\nu}_e\right] \cong 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + O(10^{-3})$$

Sensitive to only θ_{13}
→ Pure measurement of θ_{13}

Accelerator experiments (ν_e appearance using ν_μ beam): T2K, NOvA

$$\begin{aligned} P\left[\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)\right] = {} & \sin^2 2\theta_{13} s^2_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \frac{1}{2} s^2_{12} \sin^2 2\theta_{13} s^2_{23} \left(\frac{\Delta m^2_{21} L}{2E}\right) \sin\left(\frac{\Delta m^2_{31} L}{2E}\right) \\ & + 2 J_r \cos\delta \left(\frac{\Delta m^2_{21} L}{2E}\right) \sin\left(\frac{\Delta m^2_{31} L}{2E}\right) \mp 4 J_r \sin\delta \left(\frac{\Delta m^2_{21} L}{2E}\right) \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \\ & \pm \cos 2\theta_{13} \sin^2 2\theta_{13} s^2_{23} \left(\frac{4Ea(x)}{\Delta m^2_{31}}\right) \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \\ & \mp \frac{a(x)L}{2} \sin^2 2\theta_{13} \cos 2\theta_{13} s^2_{23} \sin\left(\frac{\Delta m^2_{31} L}{2E}\right) + c^2_{23} \sin^2 2\theta_{12} \left(\frac{\Delta m^2_{21} L}{4E}\right)^2 \end{aligned}$$

$$a(x) = \sqrt{2} G_F N_e(x)$$

$$J_r \equiv c_{12} s_{12} c^2_{13} s_{13} c_{23} s_{23}$$

Sensitive to θ_{13} , δ_{CP}, mass hierarchy, θ_{23}
→ Capability to measure δ_{CP} using ν_μ and anti-ν_μ beam

θ_{13} until May 2011

ν_e disappearance search

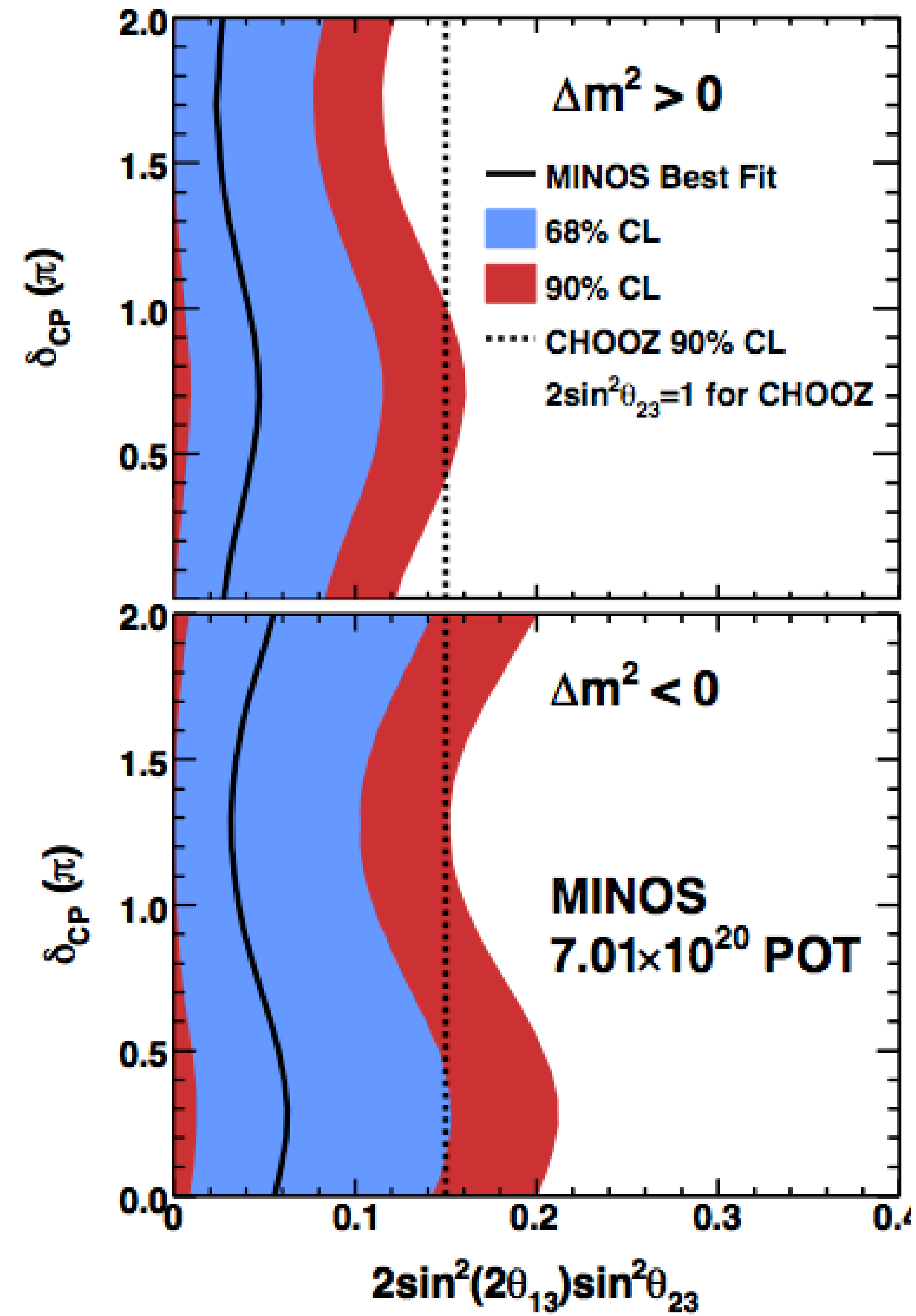
- CHOOZ
  $\sin^2 2\theta_{13} < 0.15$ @ 90% C.L.

ν_e appearance search

- MINOS
  $\sin^2 2\theta_{13} < 0.12$ @ 90% C.L. (NH)
  $\sin^2 2\theta_{13} < 0.20$ @ 90% C.L. (IH)
- K2K
  $\sin^2 2\theta_{13} < 0.26$ @ 90% C.L.

→ No sign of non-zero θ_{13}.
Upper limit only.

Phys. Rev. D82 (2010) 051102

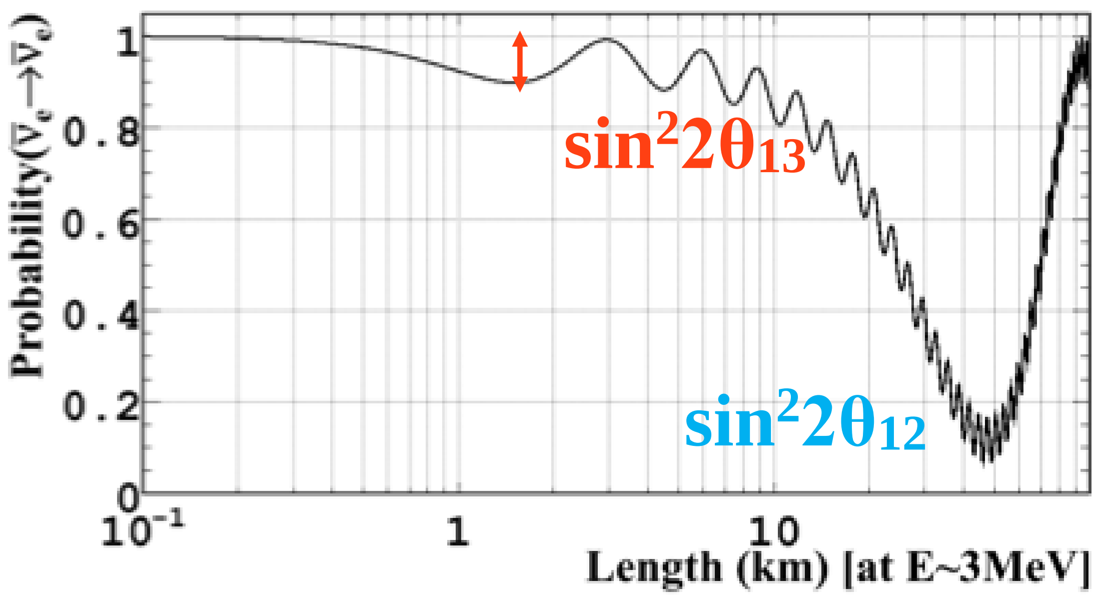


Double Chooz experiment

θ_{13} measurement with reactor neutrinos

Features of reactor neutrino experiment to measure θ_{13}:

Survival probability of $\bar{\nu}_e$



- **Direct measurement of θ_{13} with a $\bar{\nu}_e$ disappearance at ~ 1 km baseline.**

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + O(10^{-3})$$

- Reactor is a free and rich $\bar{\nu}_e$ source. Flux expectation within 2%error.
- The reactor neutrinos are detected by a well-designed detector.
- Background is strongly suppressed by delayed coincidence technique.
- Systematic uncertainties are further reduced by two identical detectors.

θ_{13} measurement with reactor neutrinos

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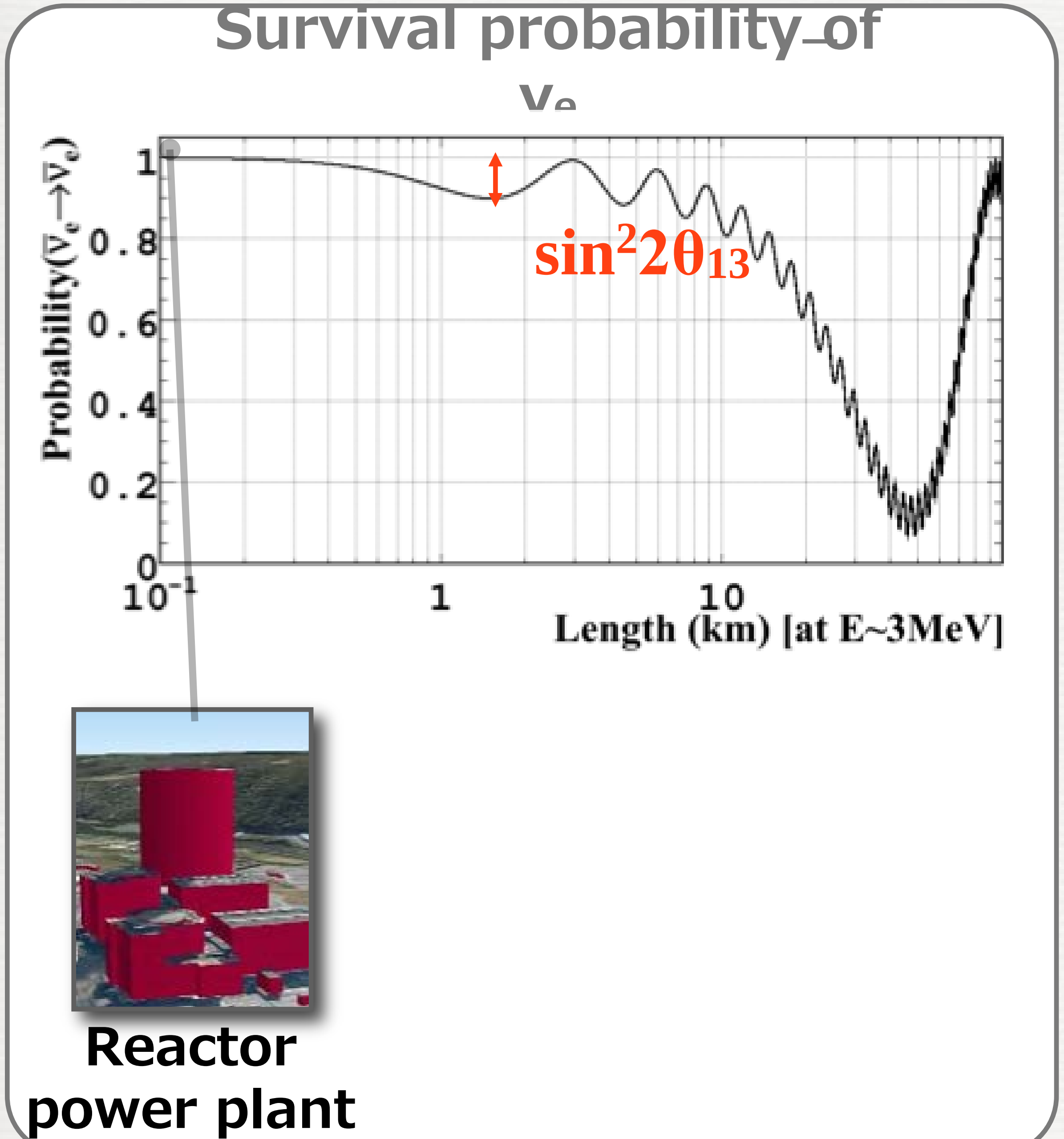

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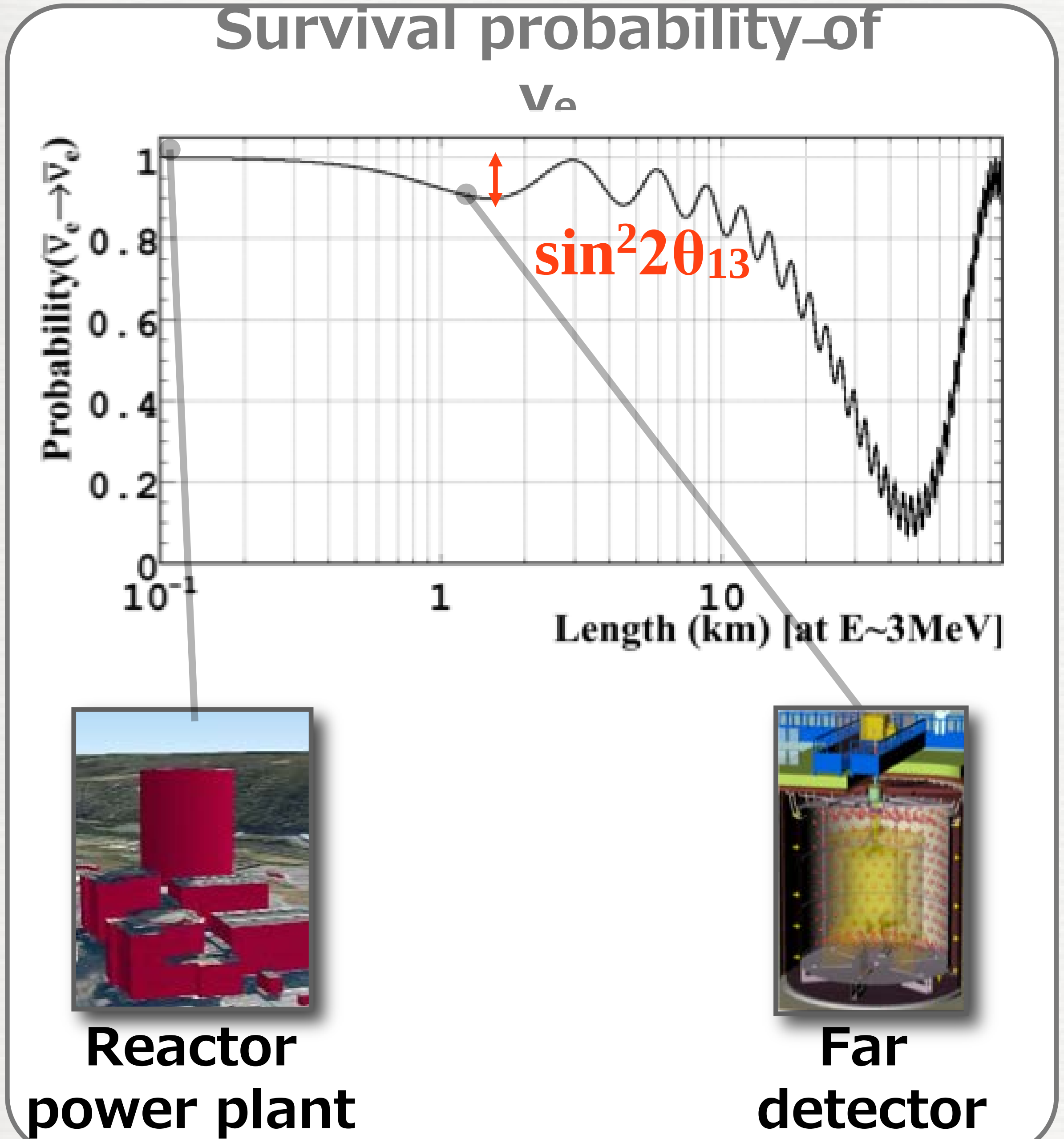

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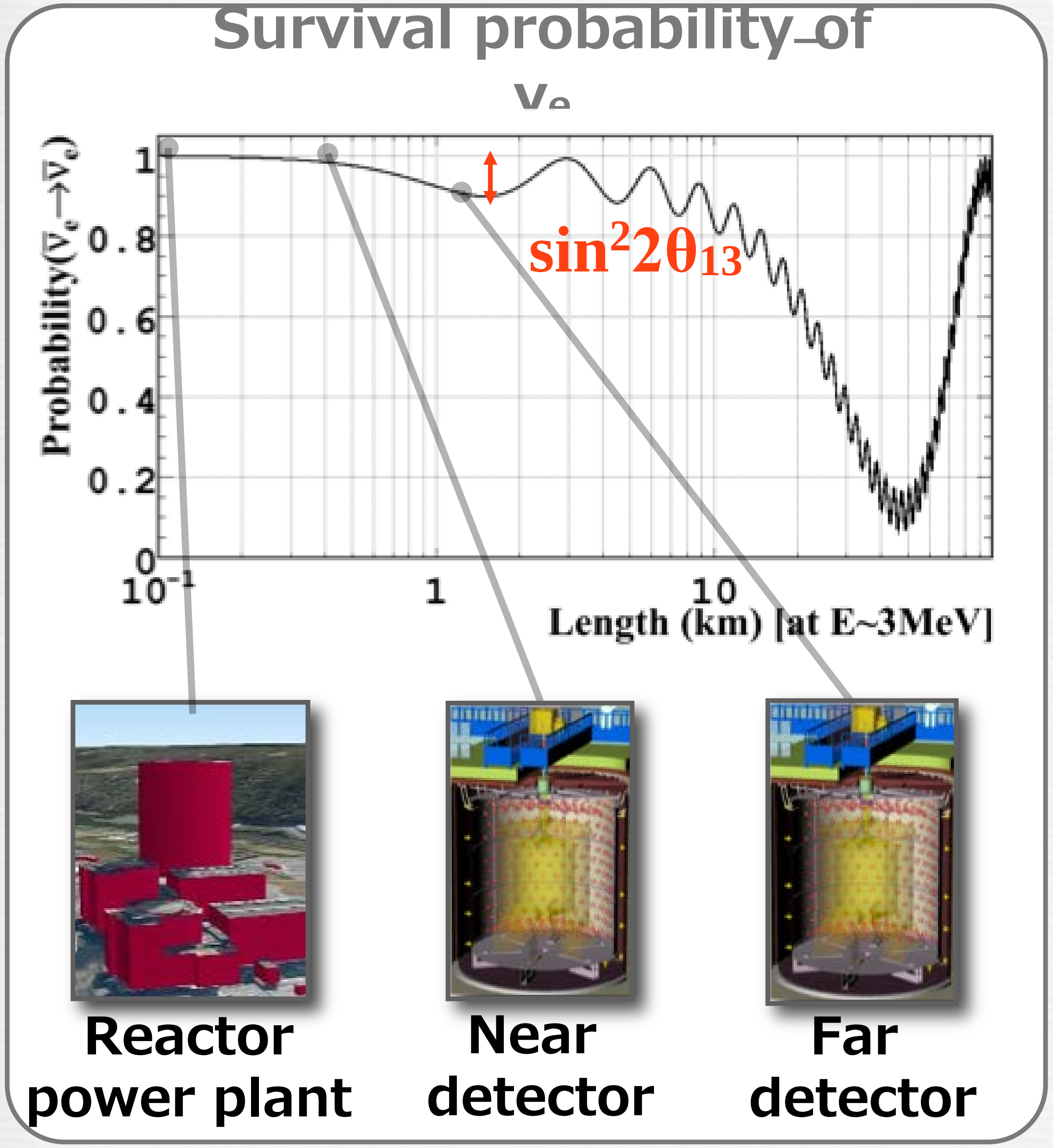

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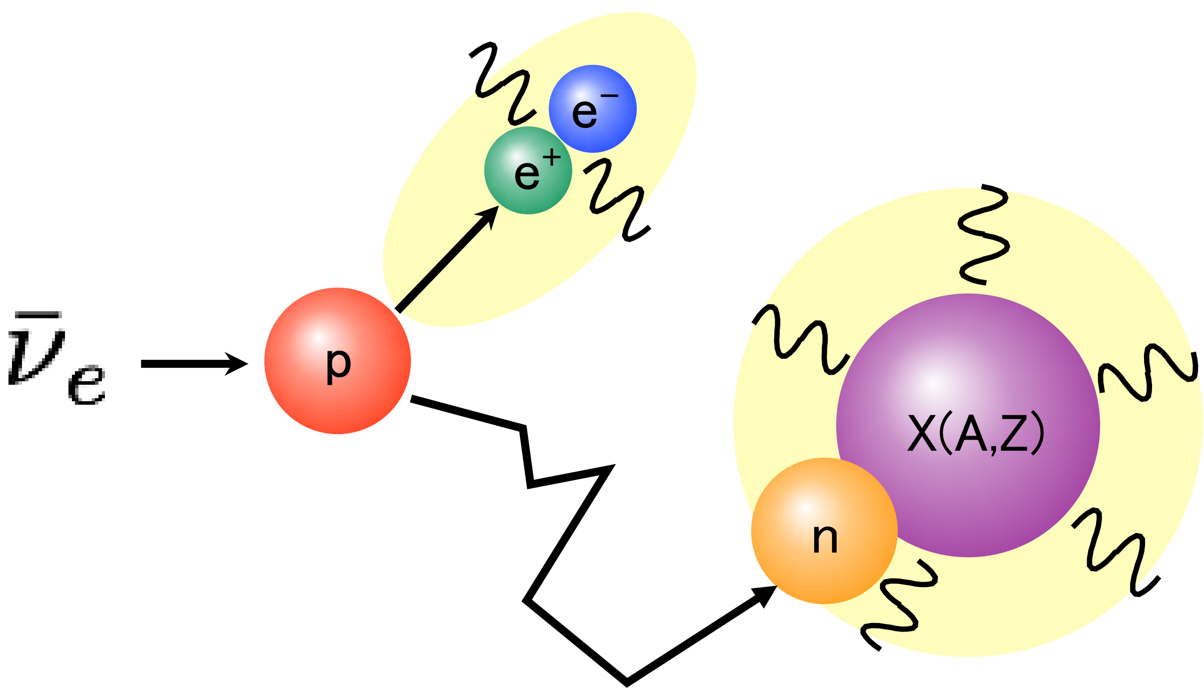
Detection principle of reactor neutrinos

Inverse beta decay (IBD) reaction & Delayed coincidence technique:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

(*) Energy threshold = 1.8 MeV



Neutrino selection using Gd-capture:

(1) Prompt signal from e^+ ionization and annihilation **(1~8 MeV)**.
(2) Delayed signal from neutron capture on Gadolinium **(~8 MeV)**.
(3) Time coincidence **(τ~30 μsec)**.

Alternative channel using H-capture w/ higher stat. but worse systematics:

(2’) Capture on Hydrogen **(~2.2 MeV)**.
(3’) Time coincidence **(τ~200 μsec)**.

In this IBD process, prompt energy is related to neutrino energy:

$$E_{vis} = E(kin)_{e^+} + 2m_e \simeq E_{\bar{\nu}_e} - (M_n - M_p) + m_e \simeq E_{\bar{\nu}_e} - 0.782\,\mathrm{MeV}$$

→ **Spectral shape of the prompt signal gives us further information.**

Double Chooz experiment

Reactors

Electricité de France (EDF)

Two reactor cores
4.27 GW_{th} for each core

Near detector

L = ~ 400 m
~120 m.w.e.
10 m^3 target

Operating since 2015

Far detector

L = ~ 1050 m
~300 m.w.e.
10 m^3 target

Operating since Apr. 2011

Far only operation : Measure the mixing angle θ_{13} by comparing observed neutrino candidates at the Far detector with prediction.

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

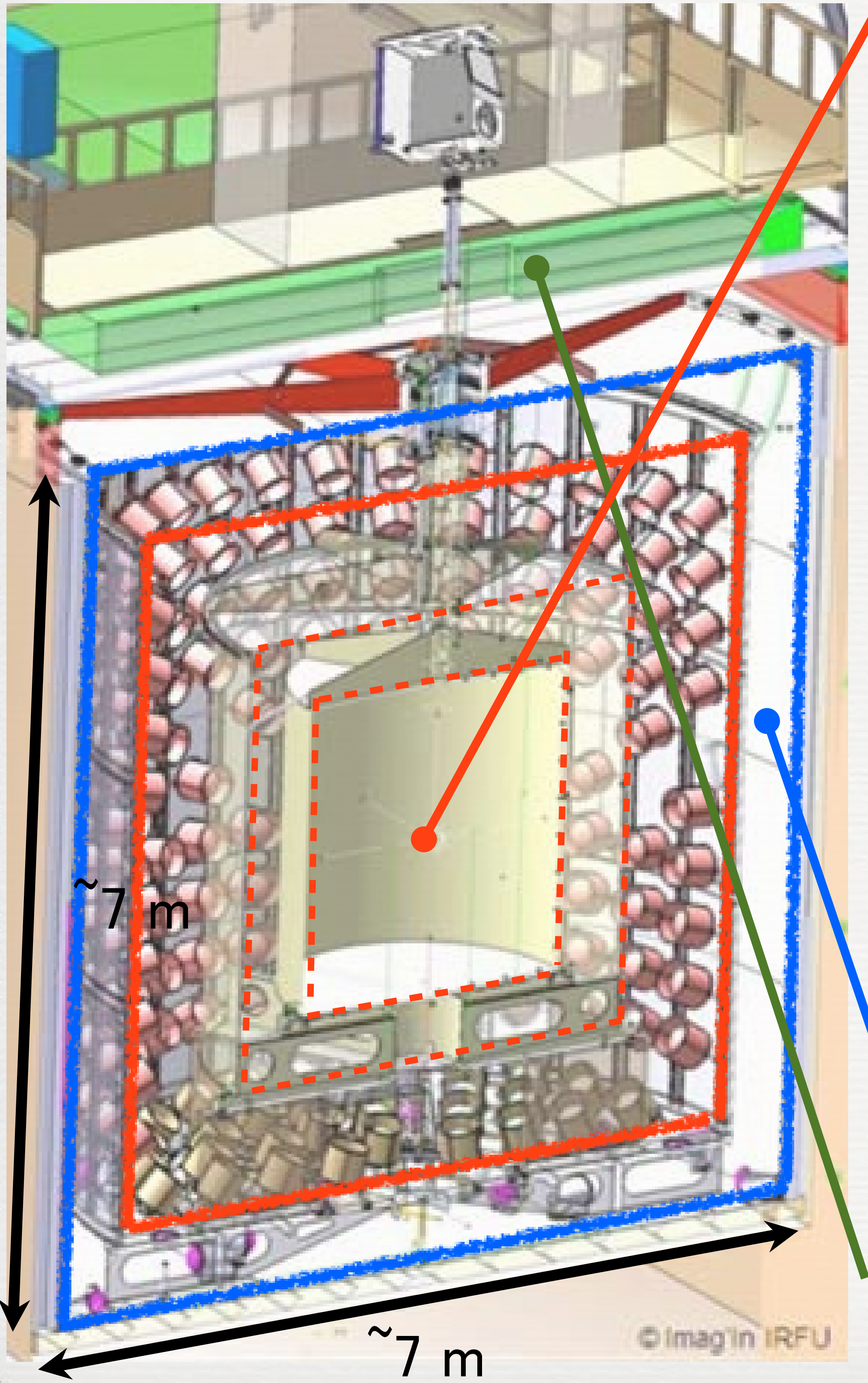
USA
U. Alabama
ANL
U. Chicago
Columbia U.
UC Davis
Drexel U.
U. Hawaii
IIT
KSU
LLNL
MIT
U. Notre Dame
U. Tennessee

150 scientist in 7 countries

spokesman: Hervé de Kerret (CNRS/IN2P3 - APC)

project manager: Christian Veyssière (CEA Saclay)

Double Chooz detector



Inner Detector (ID) - three cylindrical layers

ν-target region
- Gd-loaded (1 g/l) liquid scintillator (10.3 m^3)
- Target of neutrino interaction

γ-catcher region
- 22.3 m^3 liquid scintillator
- Measure γ's escaped from ν-target region

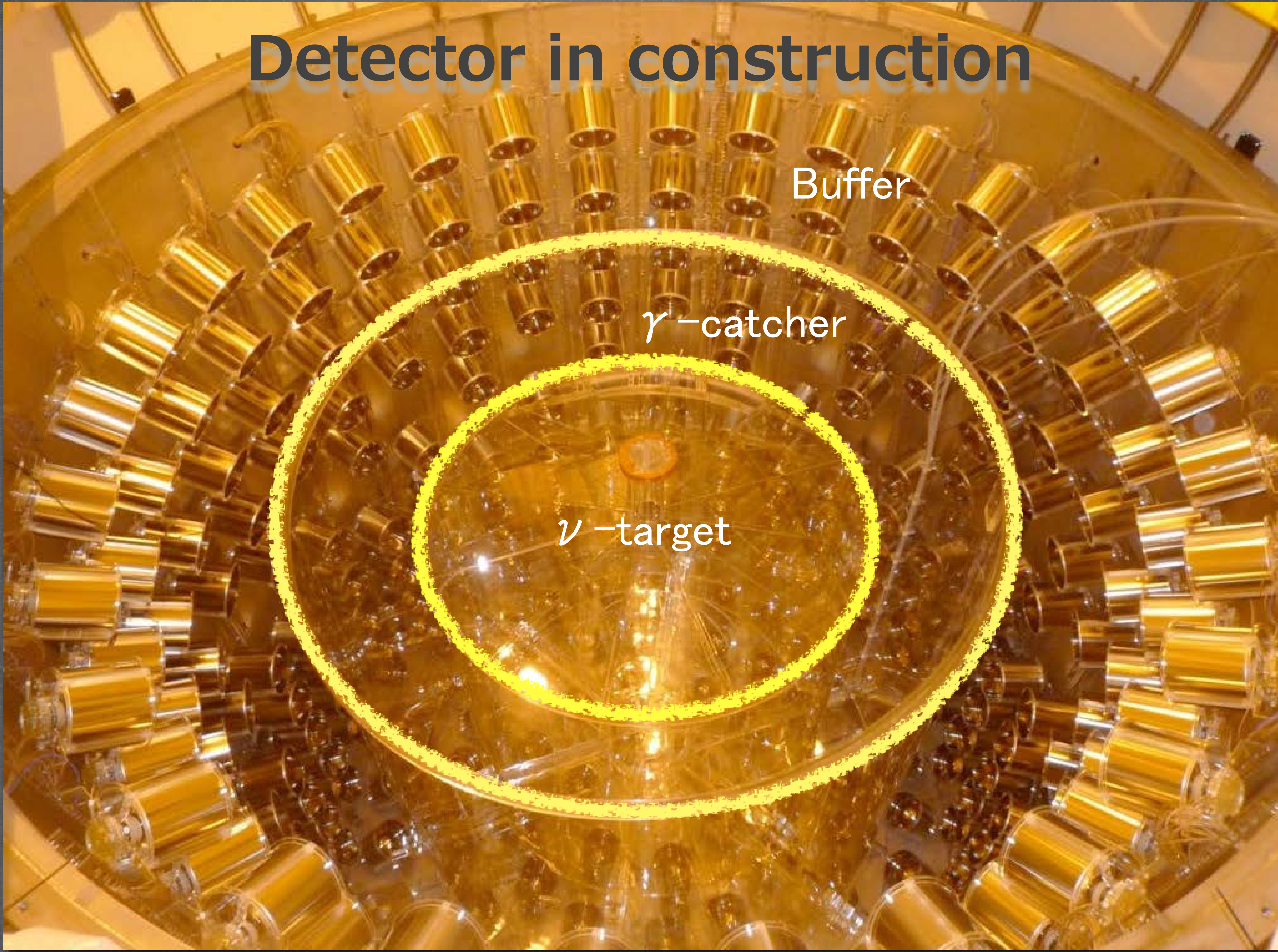
Buffer region
- 110 m^3 mineral oil & 390 low-BG 10" PMTs
- Reduce environmental γ & neutron BG

Detectors for BG veto

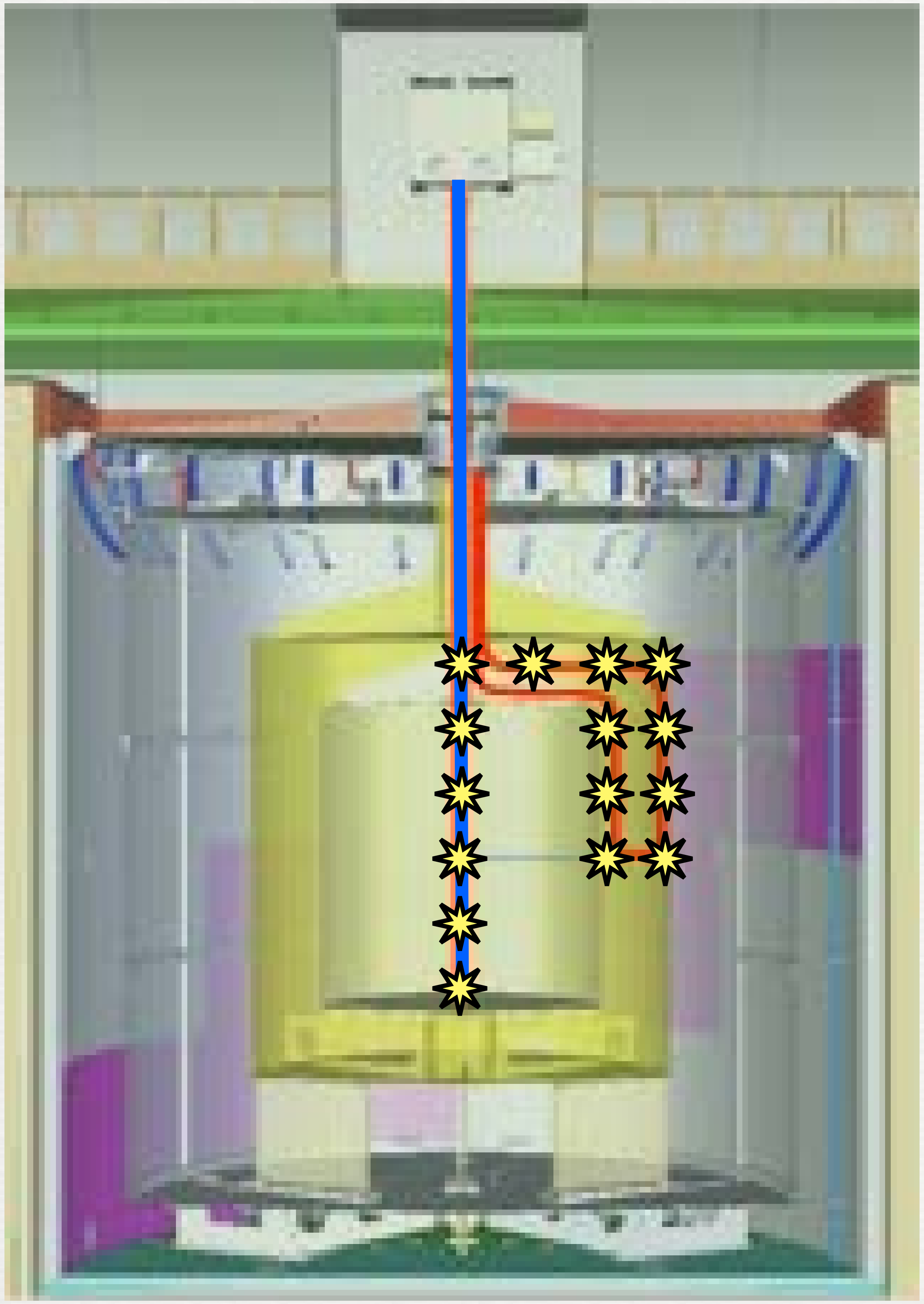
Inner veto (IV)
- Liquid scintillator & 78 8" PMTs in steel tank
- Identify cosmic μ & reduce environmental γ

Outer veto (OV)
- Plastic scint. strip + WLS fiber + MAPMT
- Identify cosmic μ

Detector in construction



Source deployment system



Two deployment system:
- Z-axis system
- Guide tube system.
→ Source deployment is useful to estimate systematics.

Deployable sources:
- ^{137}Cs (gamma)
- ^{68}Ge (positron)
- ^{60}Co (gamma)
- ^{252}Cf (neutron)
- Laser ball (light)

In addition to those artificial sources, we used natural sources like H-n, C-n, Gd-n and BiPo peaks for our calibration.

Energy reconstruction (III)

Gain non-linearity calibration:

ch ch

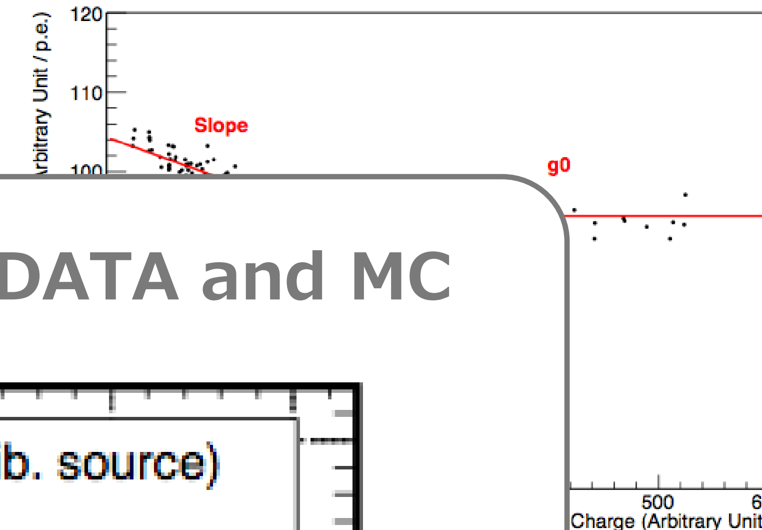
N_{pe} =

Defin
recon

E_{vis} =

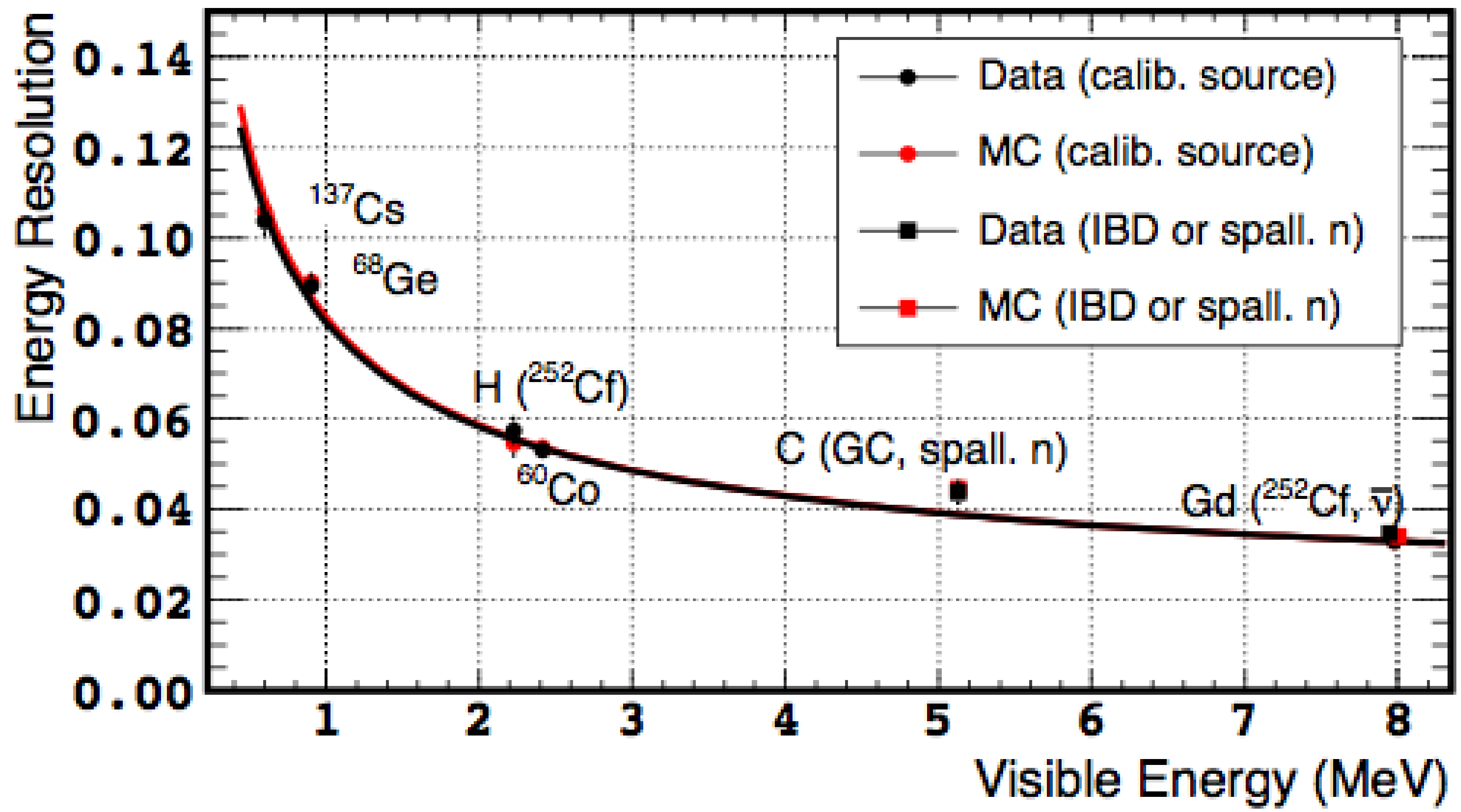
$C(E^0_{vis})$

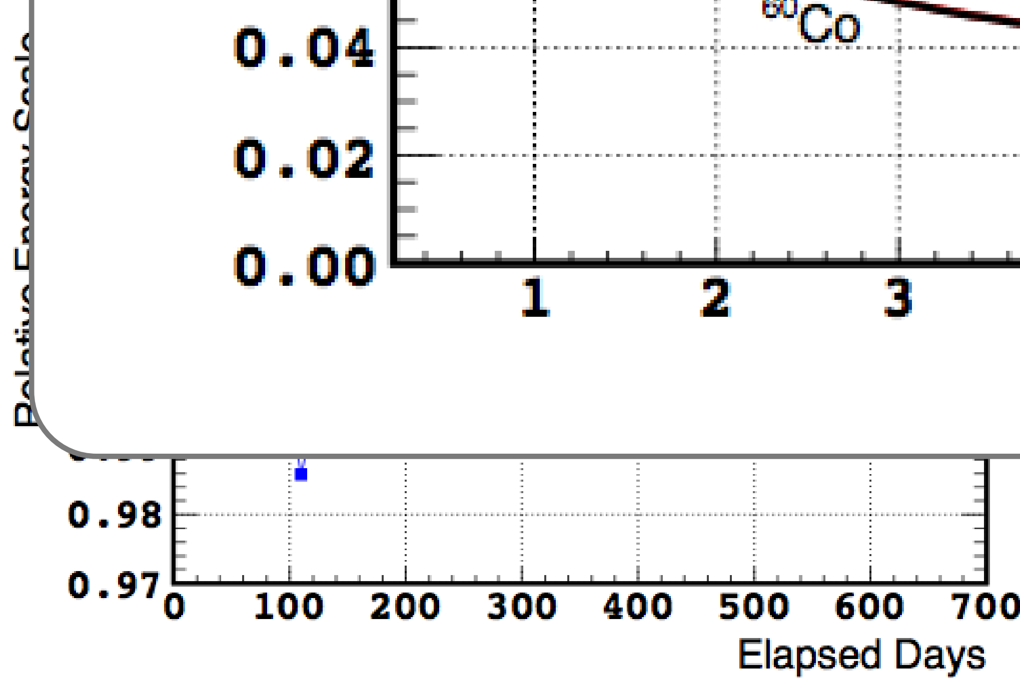
Gain non-linearity calib.

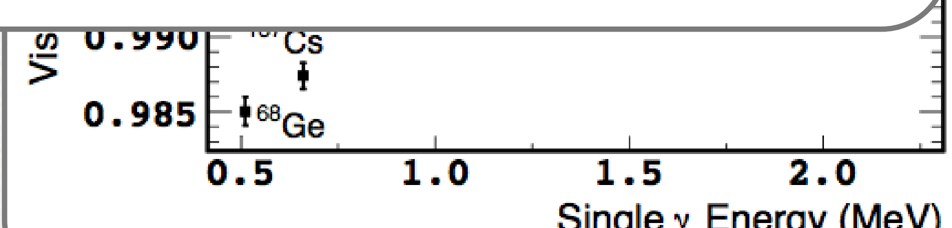


ection

Validation: Energy resolution for DATA and MC







Neutrino selection

Muon veto
- No large energy deposit in ID/IV [Revised]
- $\Delta T_{\mu} > 1$ msec

Prompt signal
- $0.5 < E_{vis} < 20$ MeV [Tuned]
- PMT light noise cuts [Revised]

Delayed signal
- $4 < E_{vis} < 10$ MeV [Tuned]
- PMT light noise cuts [Revised]

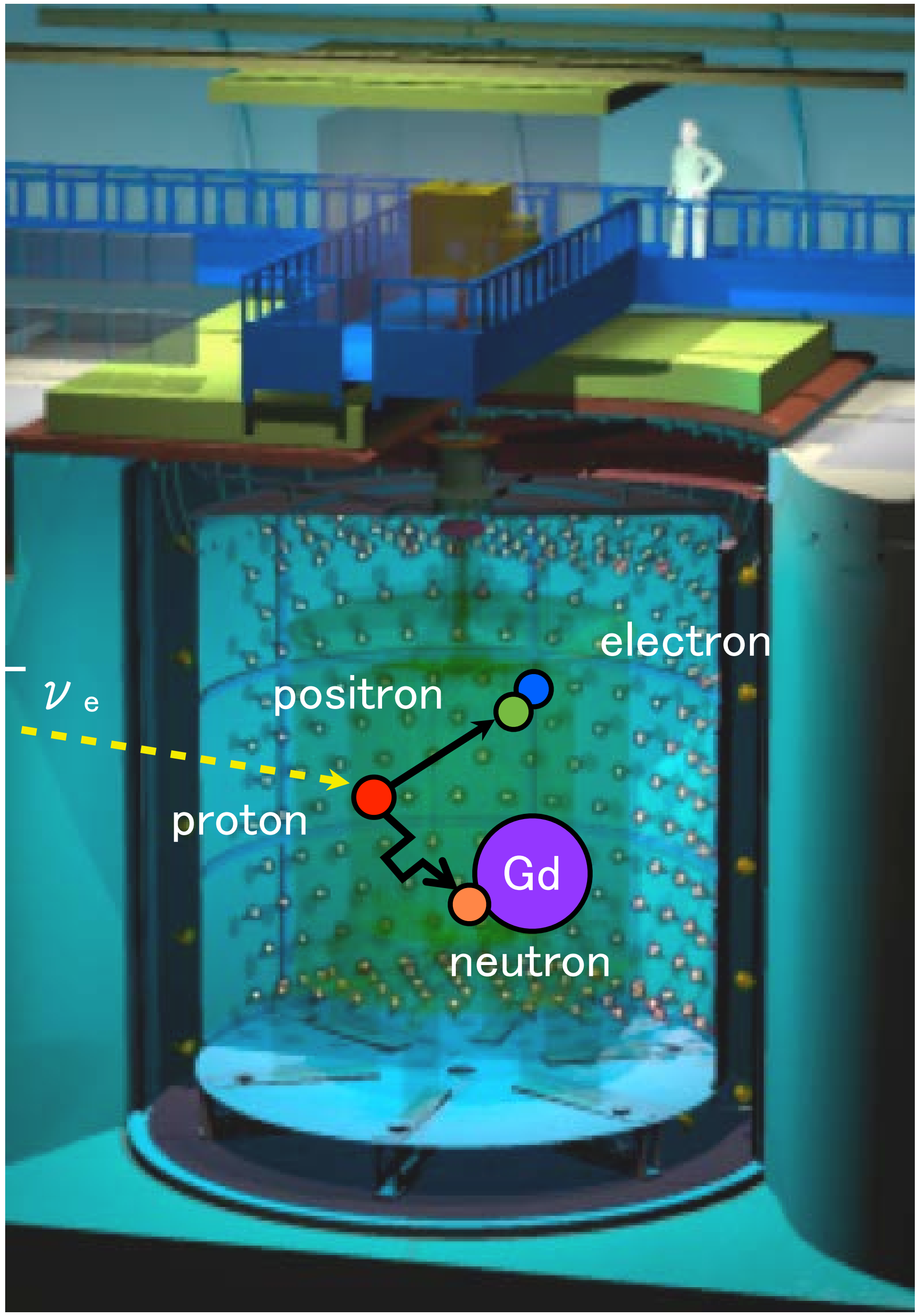
Delayed coincidence
- $0.5 < \Delta T_{p\text{-}d} < 150$ μsec [Tuned]

Distance cut
- $\Delta R_{p\text{-}d} < 100$ cm [New]

Multiplicity cut
- No extra events around signal [Tuned]

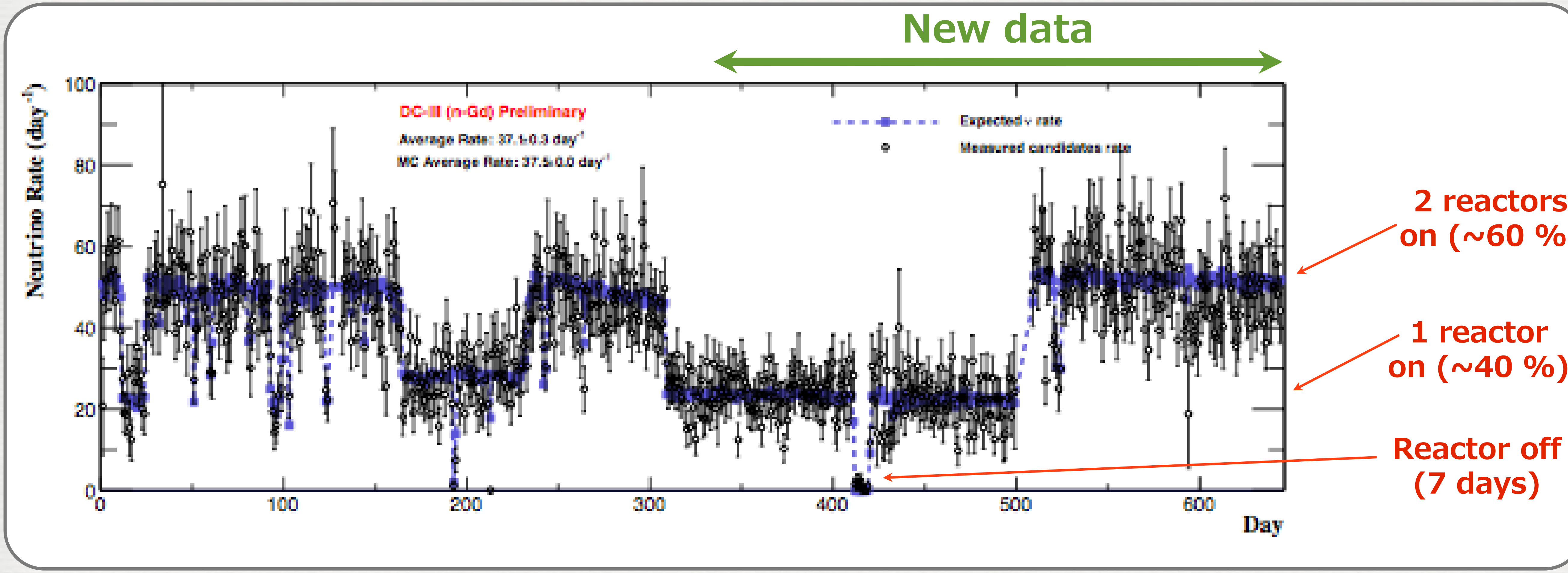
Further BG reduction
- OV veto
- IV veto [New]
- FV veto [New]
- Li+He veto [New]

IBD process in the detector



IBD candidates and rate modulation

Rate stability of IBD candidates



- Selected 17358 IBD candidates for 467.9 days of Livetime.
- Rate modulation is in good agreement with its prediction.

Background (I): Accidental background

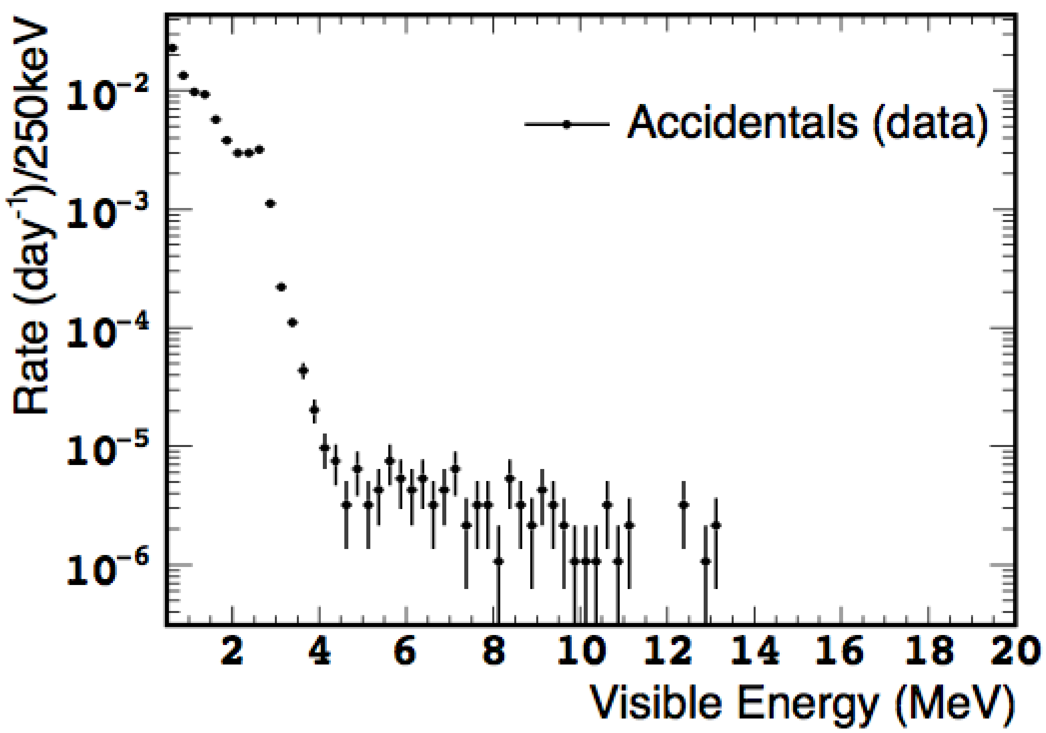
Accidental background:

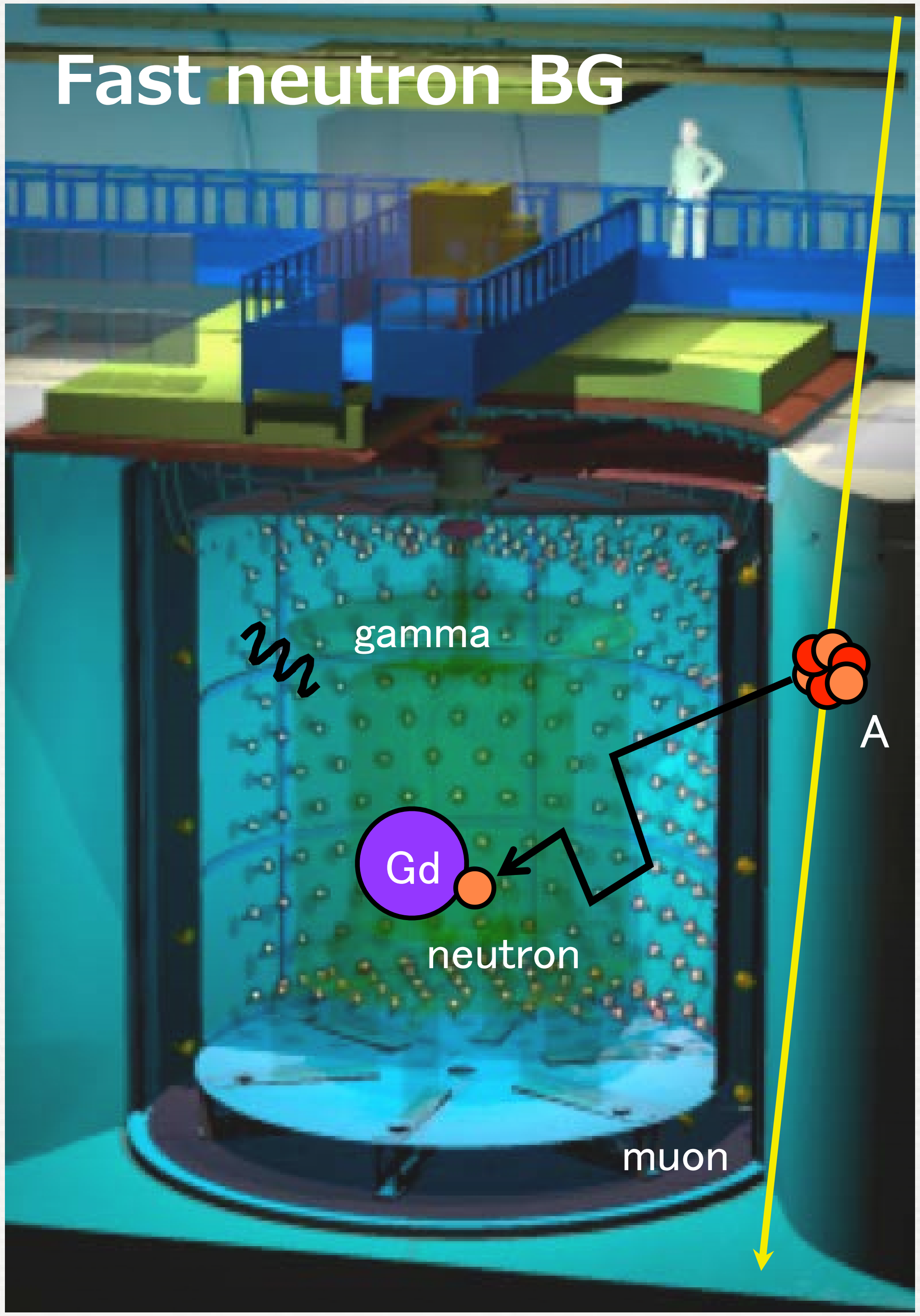
e.g.) Environmental γ + Fast neutron

Estimation method:

This BG is estimated from coincident events in off-time window.

Estimated accidental BG spectrum





Estimated BG rate = 0.070 ± 0.003 event/day

Background (Ⅱ): Correlated background

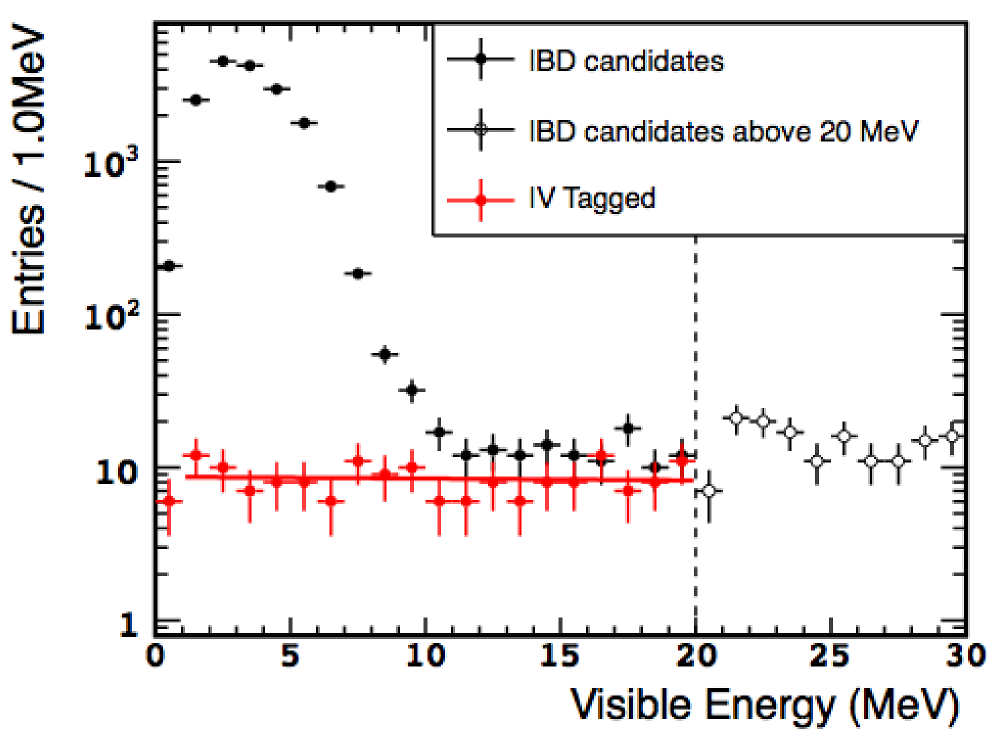
Correlated background:

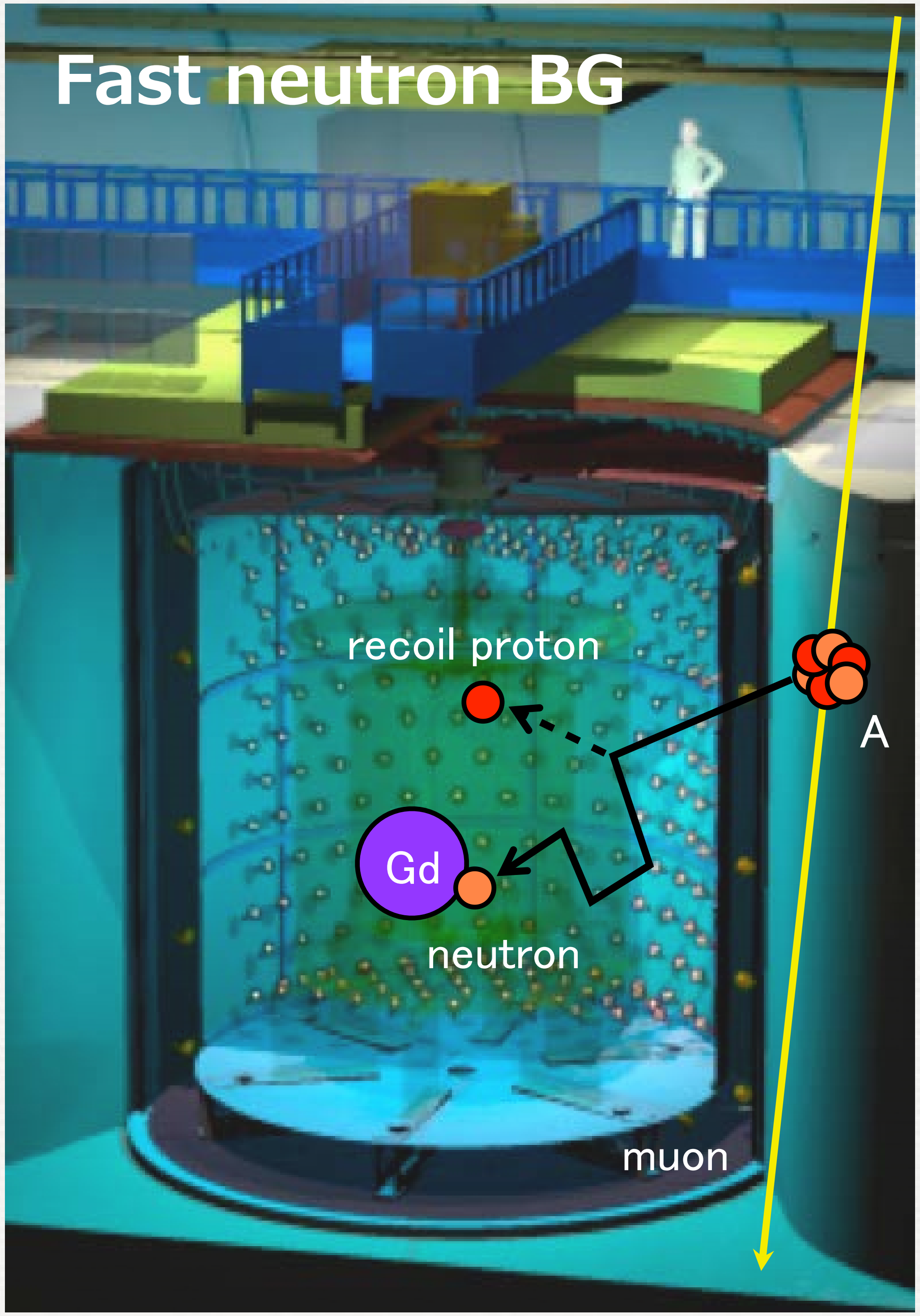
Fast n: recoil proton + captured n on Gd
Stop μ: μ + its decay (mostly tagged by OV)

Estimation method:

This BG is estimated from high E_{prompt} region w/ IV and OV coincident events.

Correlated BG estimation on E_{prompt}





Estimated BG rate = 0.60 ± 0.05 event/day

Background (Ⅲ): Cosmogenic background

Cosmogenic isotopes background:

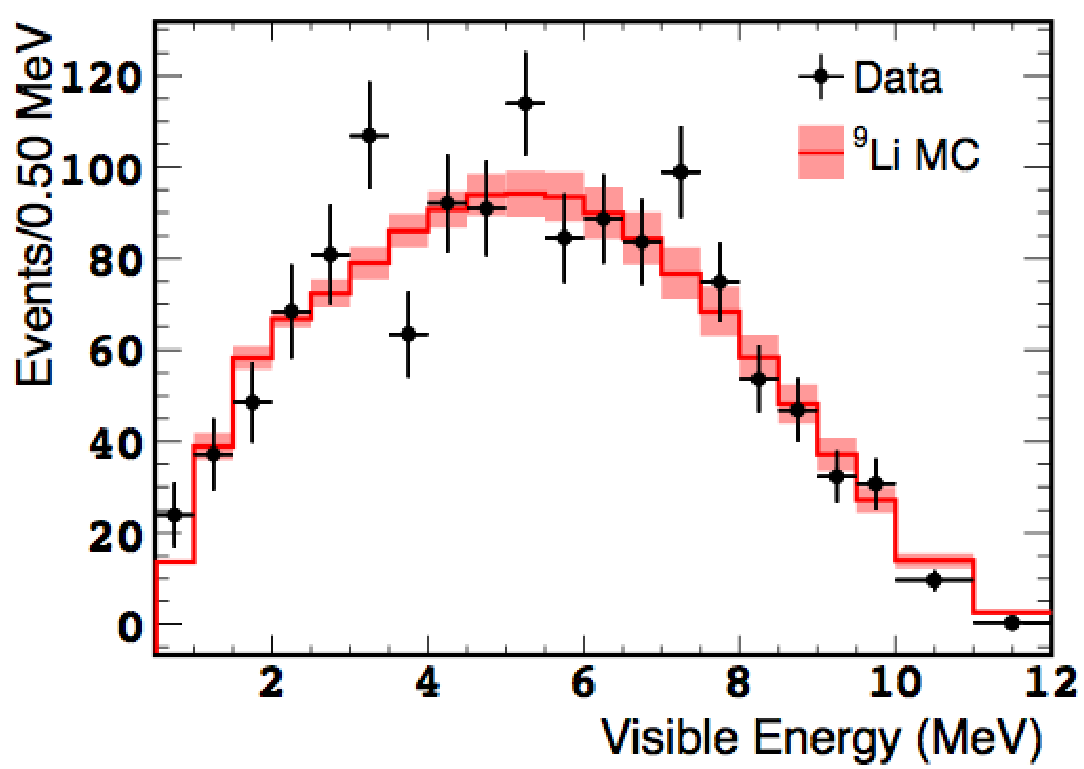
Spallation products from muon:

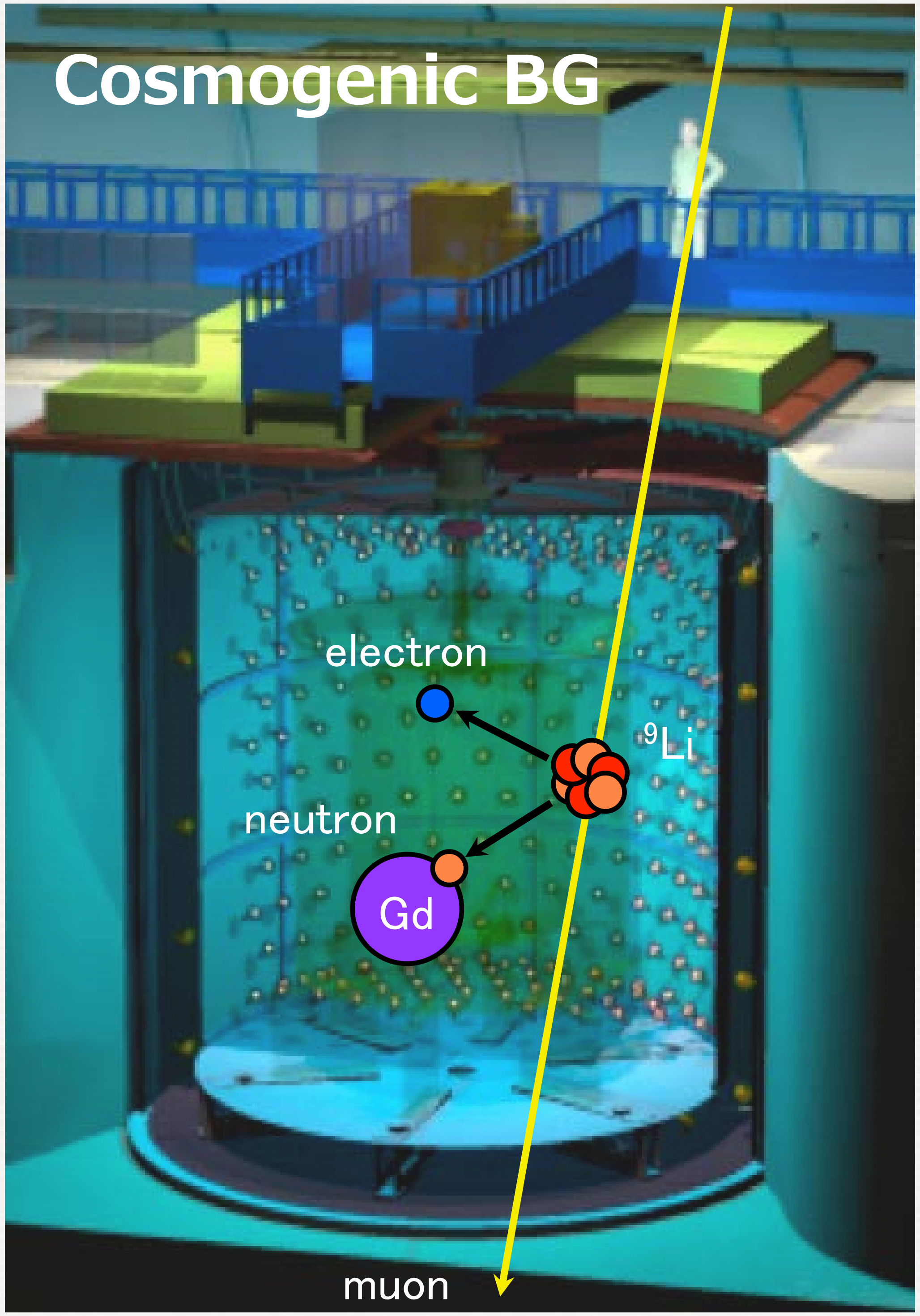
$$^{9}\mathrm{Li} \rightarrow e^{-} + n + {}^{8}\mathrm{Be} \ (\tau \sim 200\,\mathrm{msec})$$

Estimation method:

This BG is estimated with spatial and time correlation between candidates and μ's.

Estimated cosmogenic BG spectrum





Estimated BG rate = $0.97^{+0.41}_{-0.16}$ event/day

Oscillation analysis

Updated θ_{13} results

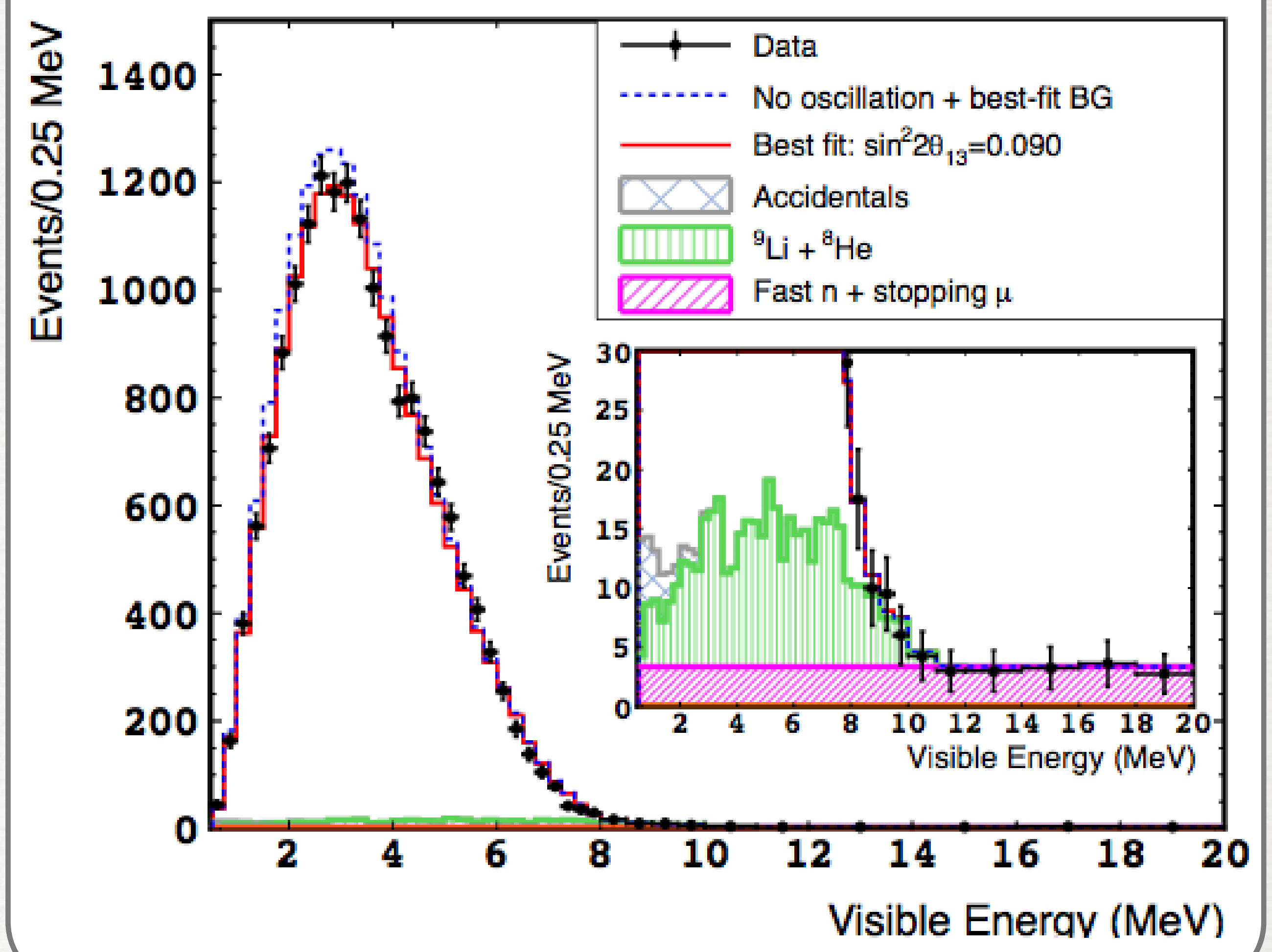
Chi square test with systematics:

- Fit data w.r.t. its prediction with systematic uncertainties for which covariance matrices and pull terms were used.

Improvements compared to DC-II:

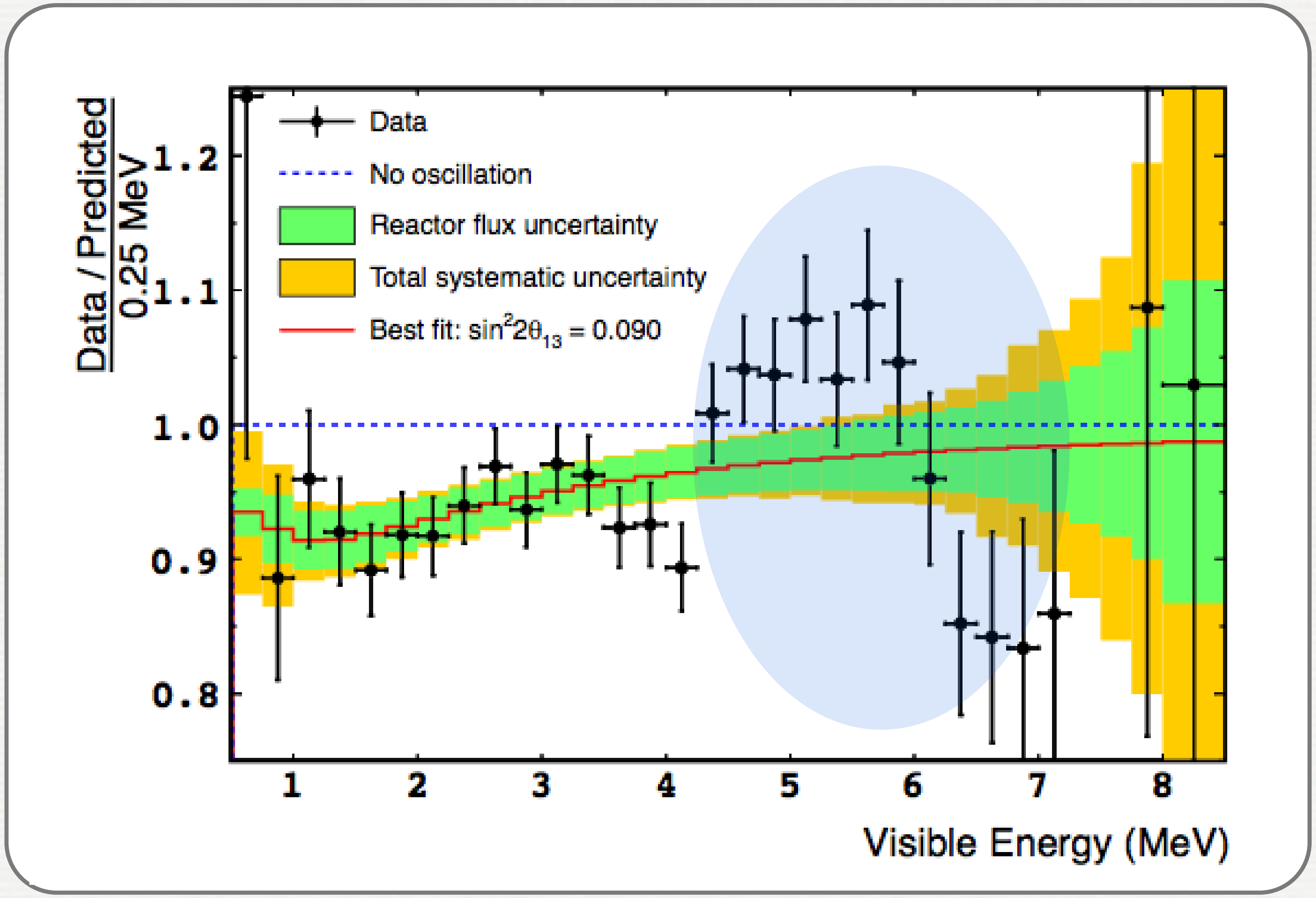
- Fit range from 0.5-20 MeV.
- Finer binning (mostly 0.25 MeV bin).
- Measured ^{238}U spectrum in prediction.
- New Δm^2 from MINOS 2013 results (T2K confirmed).
- Energy scale accounting for non-linearity.
- Constraint of reactor-off measurement.

Best-fit spectrum and its BGs



$$\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}\ (\text{stat}+\text{sys})\quad \text{with}\quad \chi^2/\text{d.o.f.} = 52.2/40$$

Interesting distortion was found...

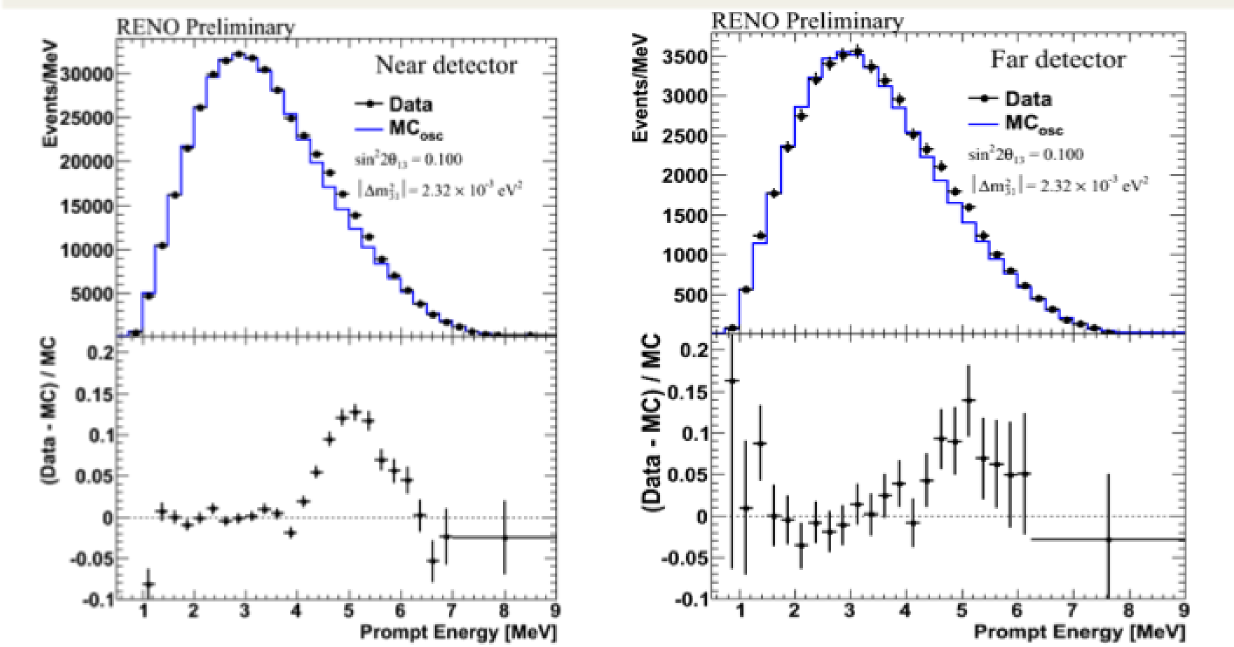


- Similar structure can be seen in CHOOZ experiment (but less significant).
- DC firstly reported it at the Seminar in France before Neutrino 2014.

RENO also reported an excess (but DB?)

RENO's presentation at Neutrino 2014:
https://indico.fnal.gov/getFile.py/access?contribId=255&sessionId=15&resId=0&materialId=slides&confId=8022

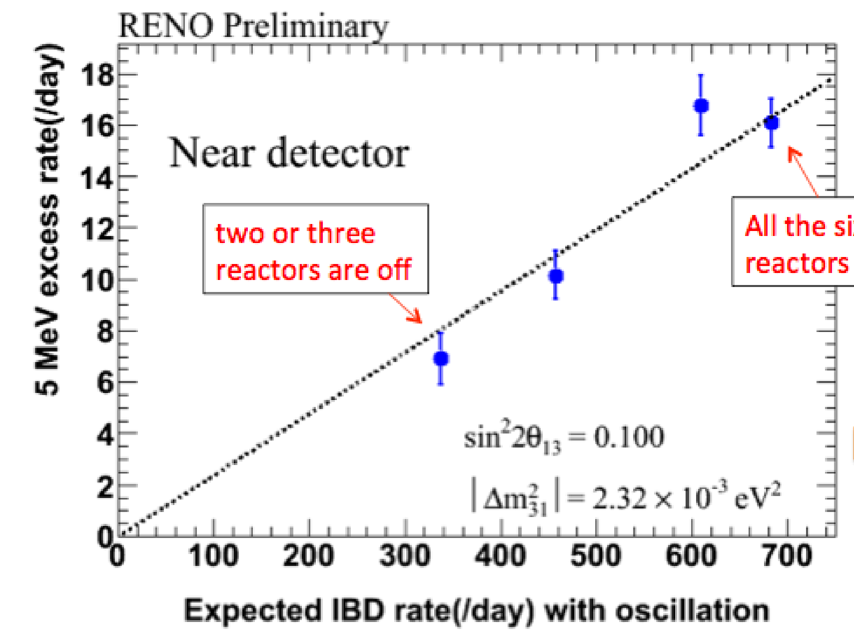
Observation of new reactor ν component at 5 MeV



Fraction of 5 MeV excess (%) to expected flux

- Near : 2.303 +/- 0.401 (experimental) +/- 0.492 (expected shape error)
- Far : 1.775 +/- 0.708 (experimental) +/- 0.486 (expected shape error)

Observation of new reactor ν component at 5 MeV



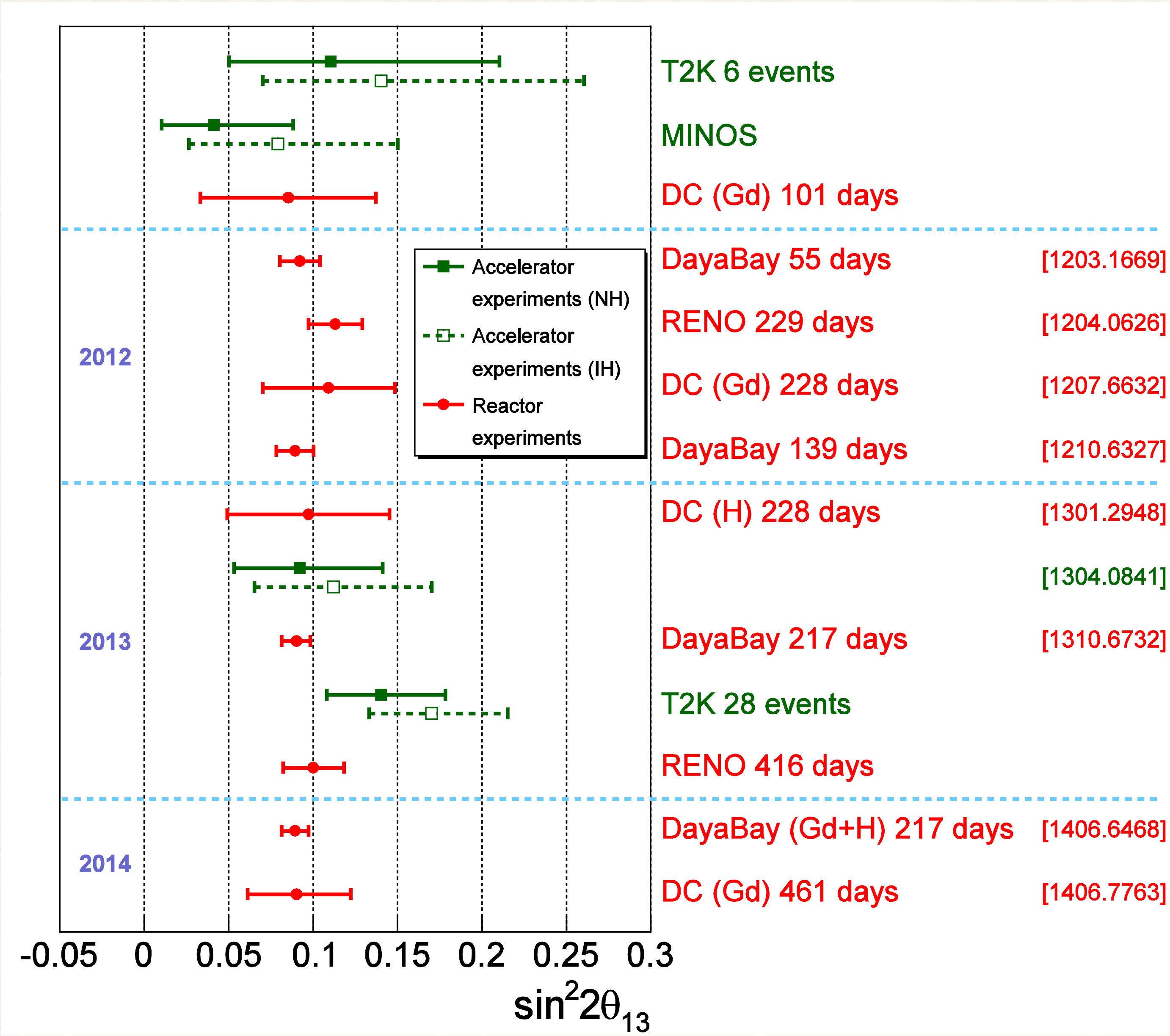
5 MeV excess has a clear correlation with reactor thermal power !

We take into account the excess at 5 MeV to the expected spectral shape.

- RENO reported clear excess and correlation with thermal power.
- How about DB spectrum? They did not mention so far.

The origin is still in mystery. To be investigated...

3 years later...



← *Indication of non-zero θ_{13}*

Upper limit only

← *Observation of non-zero θ_{13}*

Toward precision measurement

Double Chooz conducts a precision measurement, which could contribute to possible success in future experiment measuring δ_{CP} and mass hierarchy.

→ Independent observation with other reactor experiments.

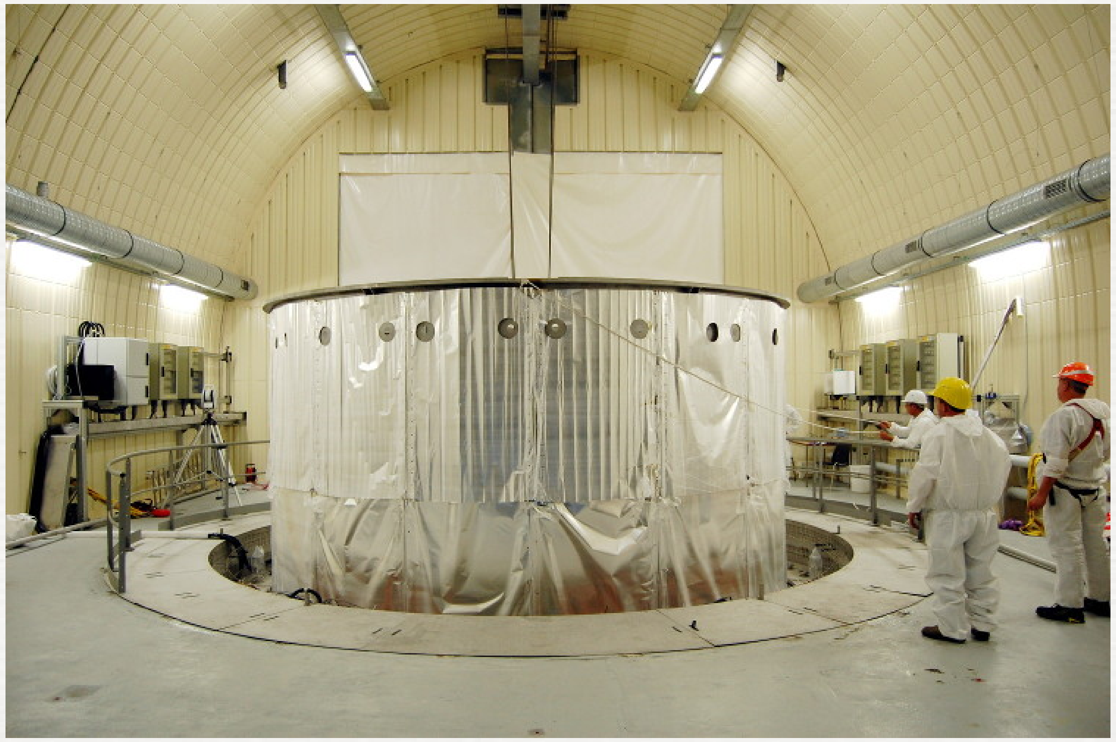
→ Complementary with accelerator experiments.

Near detector construction & Future prospects

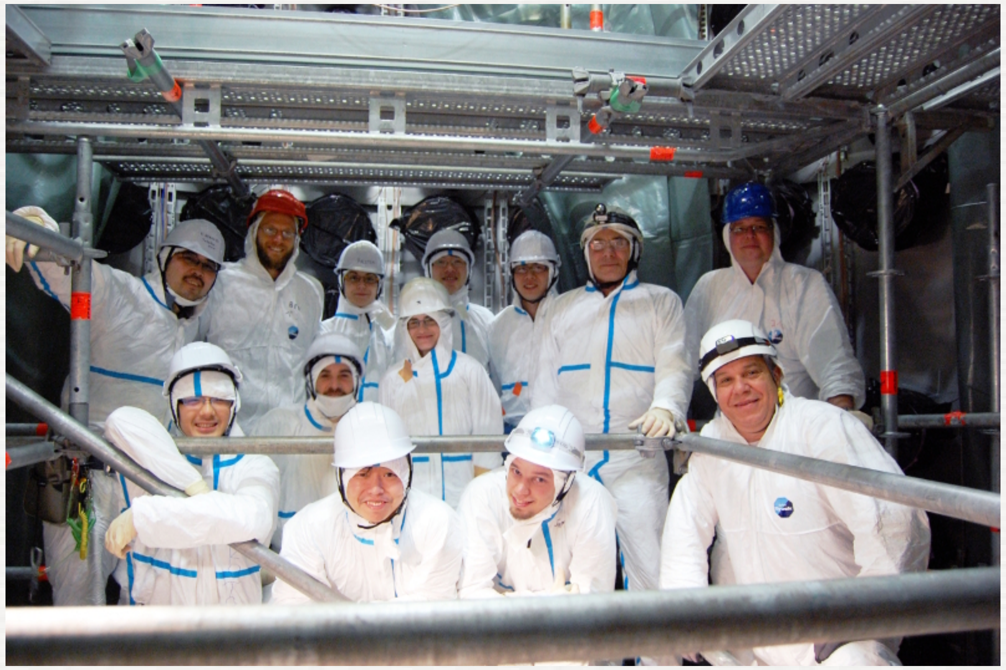
ND construction - Excavation & Lab delivery



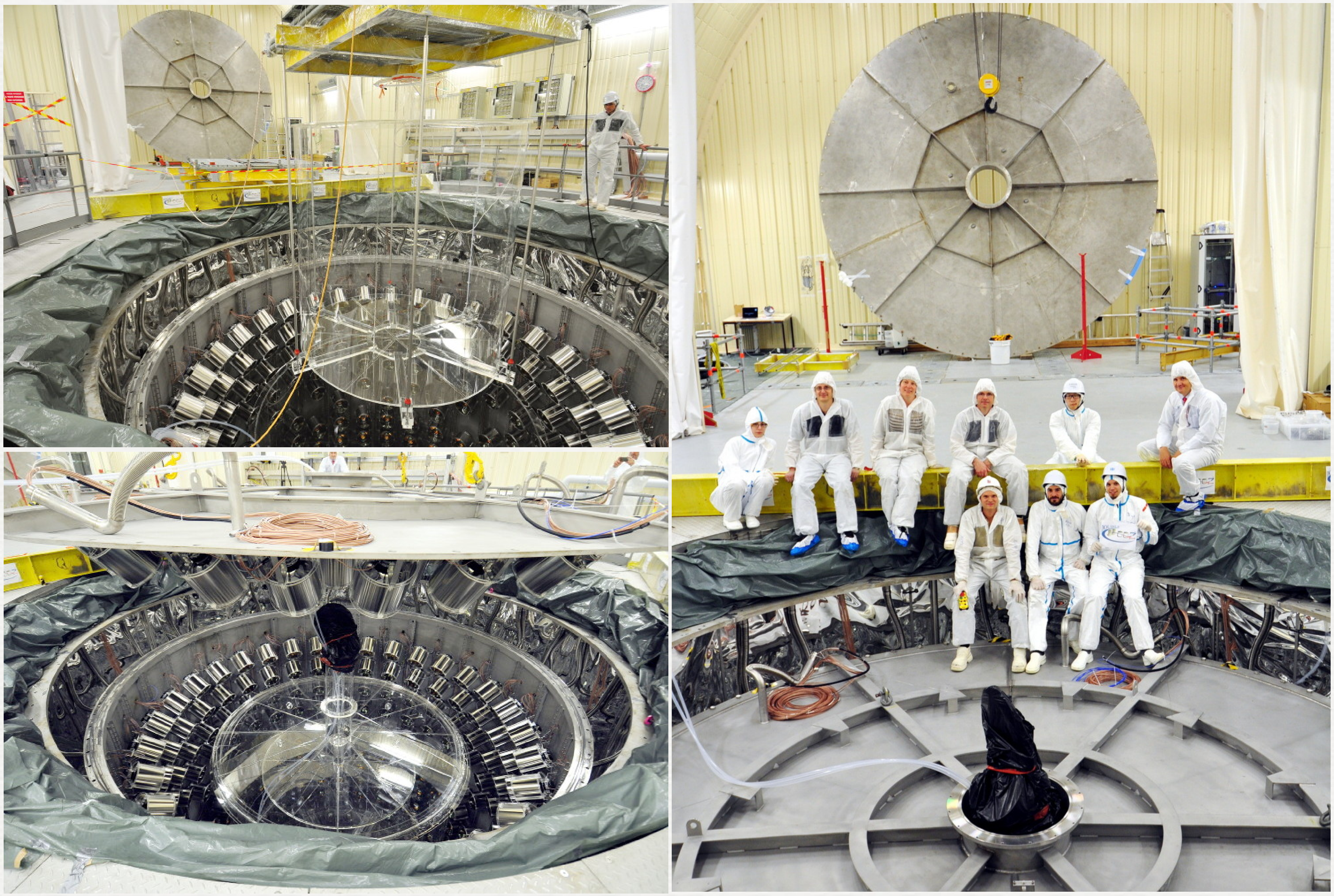

ND construction - Inner veto and Buffer vessel



ND construction - Buffer PMT installation

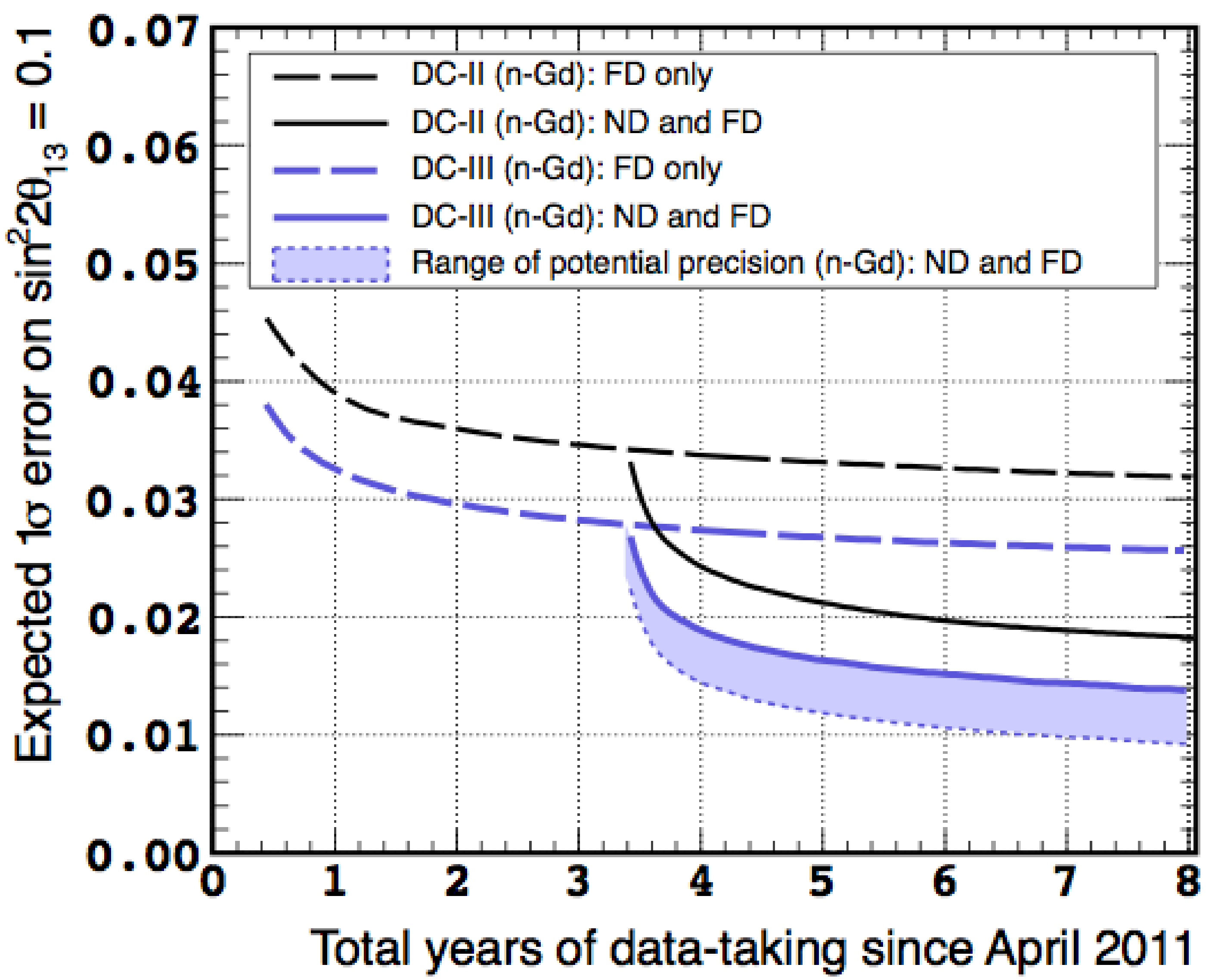


ND construction - Acrylic vessels and lid closure



Liquid filling in the last summer.
Data taking starts in 2015.

Prospected 1 σ error with ND



After both detectors operation starts, significant improvement is expected: $\sin^2 2\theta_{13}$ sensitivity of ~0.15 within 3 years, eventually up to ~0.01 with a possible systematics suppression.

Summary

Neutrino mixing angle θ_{13} was found in recent years.
→ Precision measurement of the θ_{13} is one of key factors for future experiments to know neutrino nature like δ_{CP} & mass hierarchy.

Double Chooz proceeds a precision measurement.
→ Independent observation with other reactor experiments.
→ Complementary with accelerator experiments.

New analysis results from Double Chooz.
→ $\sin^2 2\theta_{13} = 0.090 \pm 0.03$ (stat+sys)
→ Interesting energy distortion was found around ~5 MeV.

Near+Far detector operation started in this year.
→ Significant improvement up to ~0.01 of $\sin^2 2\theta_{13}$ sensitivity.