First results from the Double Chooz experiment

Masaki Ishitsuka (TokyoTech)

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ICRR seminar

Neutrino oscillations

Flavor transition occurs as a consequence of (1) finite mass and (2) mixing of mass eigenstates and weak interaction eigenstates:

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

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

θ_{23}: $P(\nu_\mu\rightarrow\nu_\mu)$ by Atm. ν & ν beam

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}: $P(\nu_e\rightarrow\nu_x)$ by Reactor ν & solar ν

Neutrino oscillation parameters:

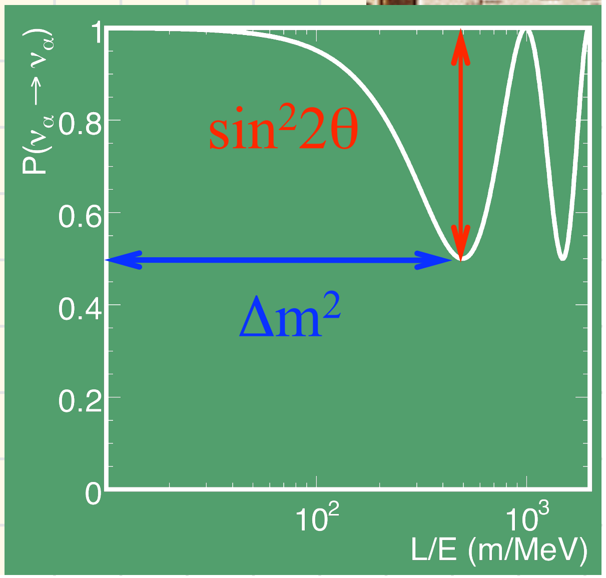
MNS matrix: 3 mixing angles: θ_{12}, θ_{23}, θ_{13}

1 phase: δ => CP-violation in ν-sector

Mass scales: 2 mass difference scales: Δm_{12}^2, Δm_{23}^2

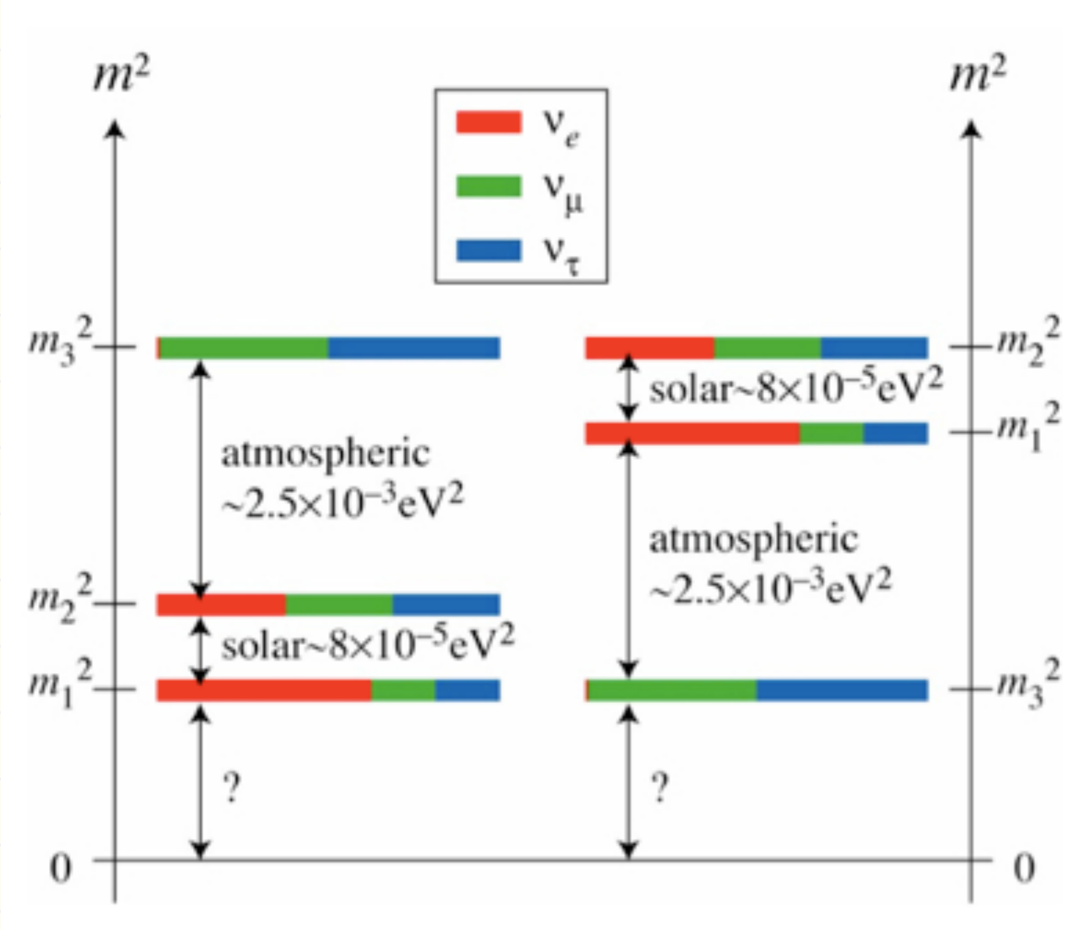
In two flavor scheme:

$$P(\nu_\alpha\rightarrow\nu_\alpha)=1-\sin^2 2\theta\sin^2\left(\frac{1.27\times\Delta m^2\ [\mathrm{eV}^2]\times L\ [\mathrm{m}]}{E\ [\mathrm{MeV}]}\right)$$



Current understandings

- Mass squared dufferences
  - $\Delta m_{21}^2 \sim 8x10^{-5}eV^2$
  - $|\Delta m_{32}^2| \sim |\Delta m_{31}^2| \sim 2.5x10^{-3}eV^2$
- Mixing angles
  - $\theta_{12} \sim 34^o$
  - $\theta_{23} \sim 45^o$
  - $\theta_{13} < 12^o$ ($\sin^2 2\theta_{13} < 0.15$)



- CP violation (δ_{CP}) ➞ unknown
- Mass hierarchy ➞ unknown
- Absolute mass scale ➞ unknown

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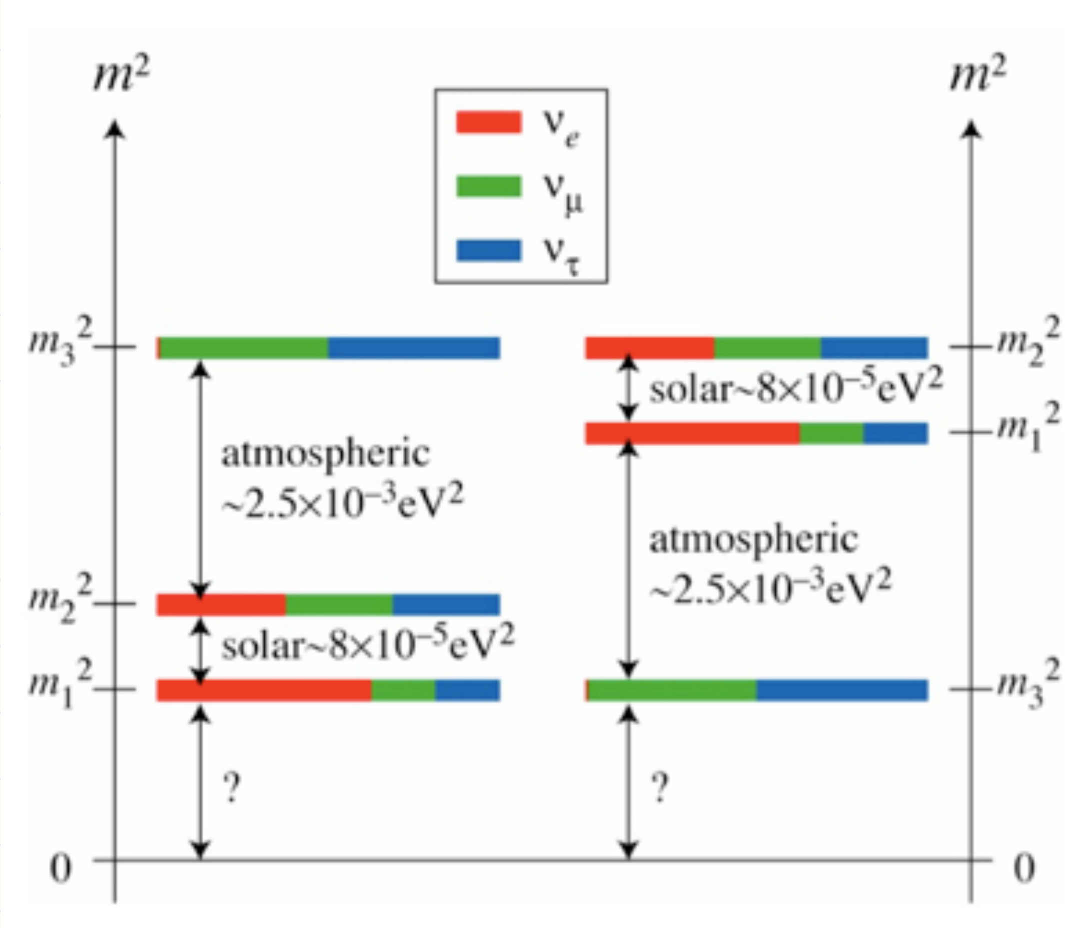


- CP violation (δ_{CP}) → unknown
- Mass hierarchy → unknown
- Absolute mass scale → unknown

Measurement of θ_{13} is essential

Two approaches to search for θ_{13}

- Reactor neutrino experiments: Double Chooz, Daya-Bay, RENO…

$$P\left[\overline{\nu_e} \to \overline{\nu_e}\right] \cong 1 - \boxed{\sin^2 2\theta_{13}} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) + O(10^{-3})$$

  - Sensitive to θ_{13} → clean measurement of θ_{13}

- Long baseline neutrino experiments using ν_μ beam: T2K, NOvA …

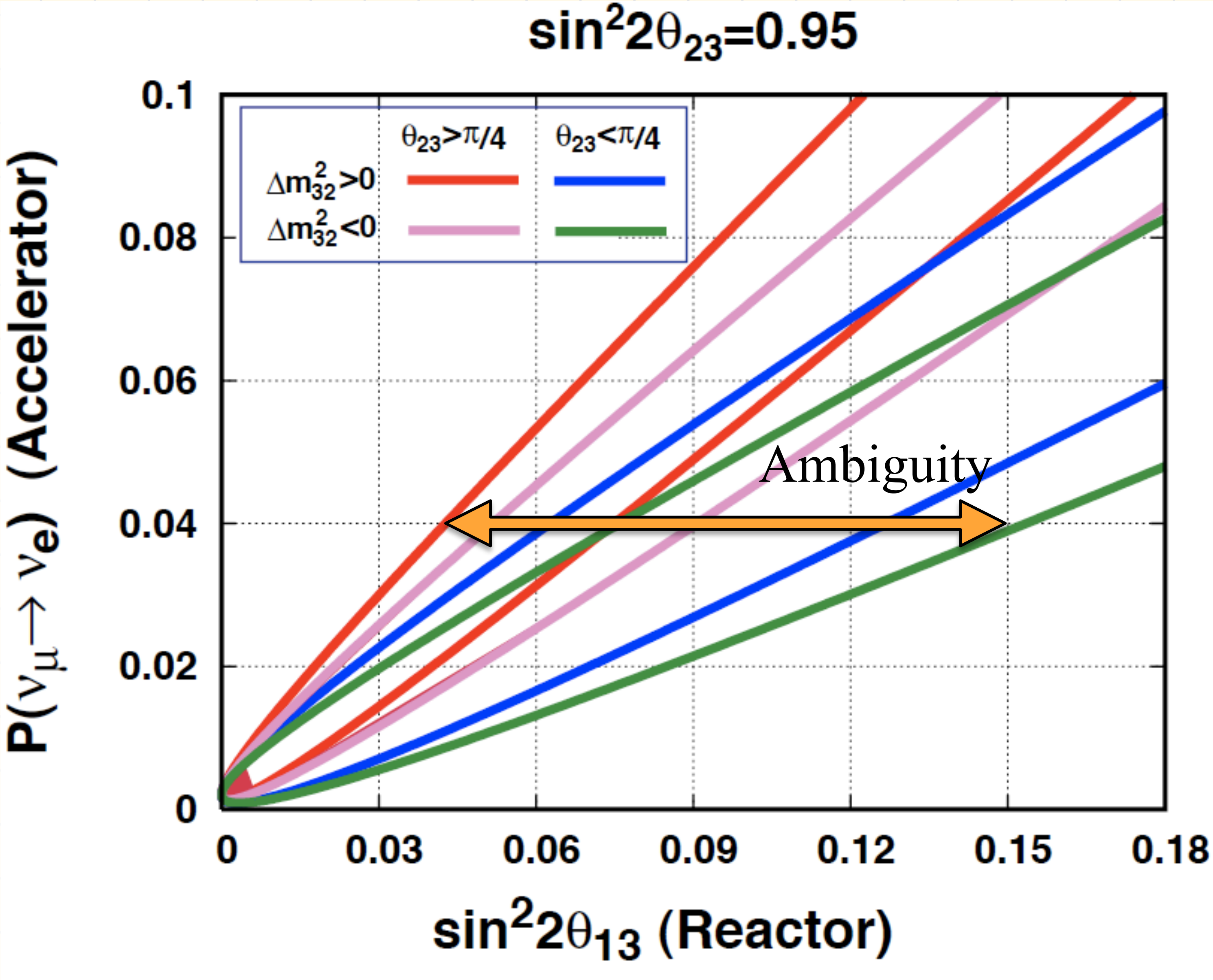
$$\begin{aligned}
P\left[\nu_\mu(\overline{\nu_\mu}) \to \nu_e(\overline{\nu_e})\right] = {} & \sin^2 2\theta_{13} s_{23}^2 \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) - \frac{1}{2} s_{12}^2 \sin^2 2\theta_{13} s_{23}^2 \left(\frac{\Delta m_{21}^2 L}{2E}\right) \sin\left(\frac{\Delta m_{31}^2 L}{2E}\right)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

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

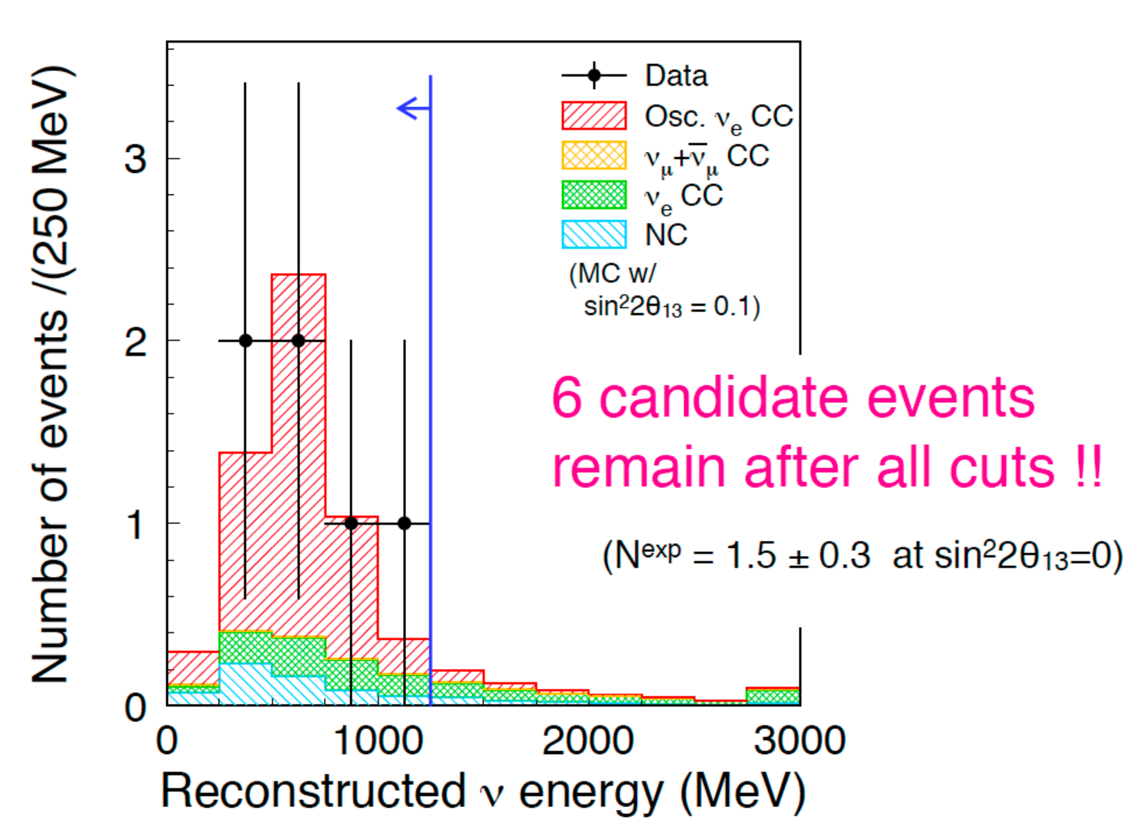
$$J_r \equiv c_{12} s_{12} c_{13}^2 s_{13} c_{23} s_{23}$$

- Sensitive to θ_{13}, δ_{CP}, mass hierarchy, θ_{23}
  - → Parameters degeneracy
  - → Determination of δ_{CP} using ν_μ and anti-ν_μ beams

Parameter degeneracy



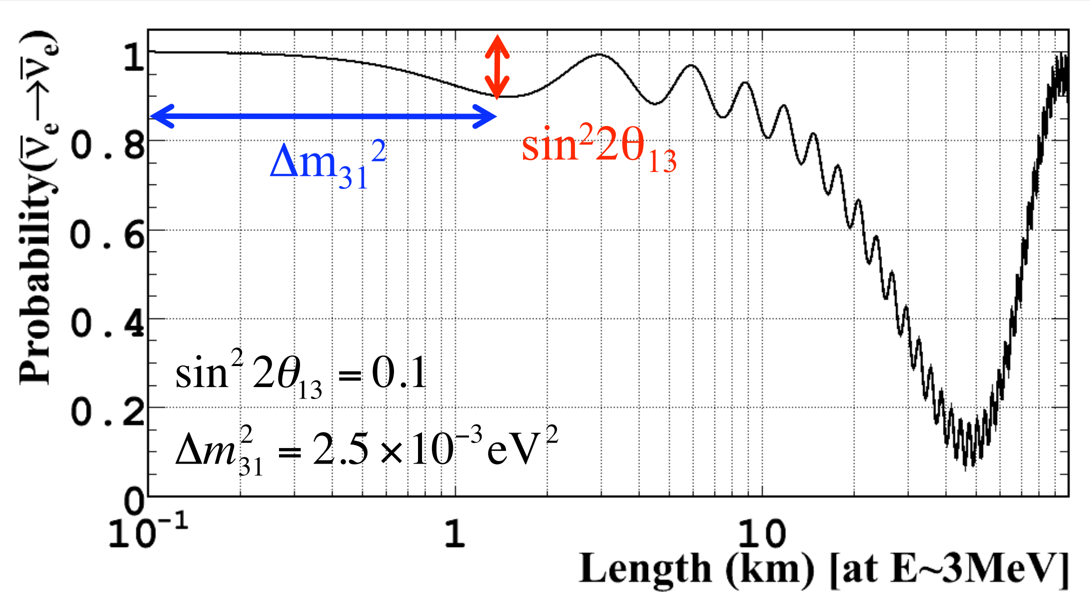
Indication of electron neutrino appearance (non-zero θ_{13}) from T2K experiment (June, 2011)



- 2.5σ significance of non-zero θ_{13}
- $0.03\ (0.04) < \sin^2 2\theta_{13} < 0.28\ (0.34)$ at 90% C.L. for normal (inverted) hierarchy (assuming $\Delta m^2_{23}=2.4 \times 10^{-3}\ eV^2$, $\delta_{CP}=0$, $\sin^2 2\theta_{23}=1.0$)

Measurement of θ_{13} using reactor neutrinos

$$P\left[\overline{\nu_e} \to \overline{\nu_e}\right] \cong 1 - \boxed{\sin^2 2\theta_{13}} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) + O(10^{-3})$$

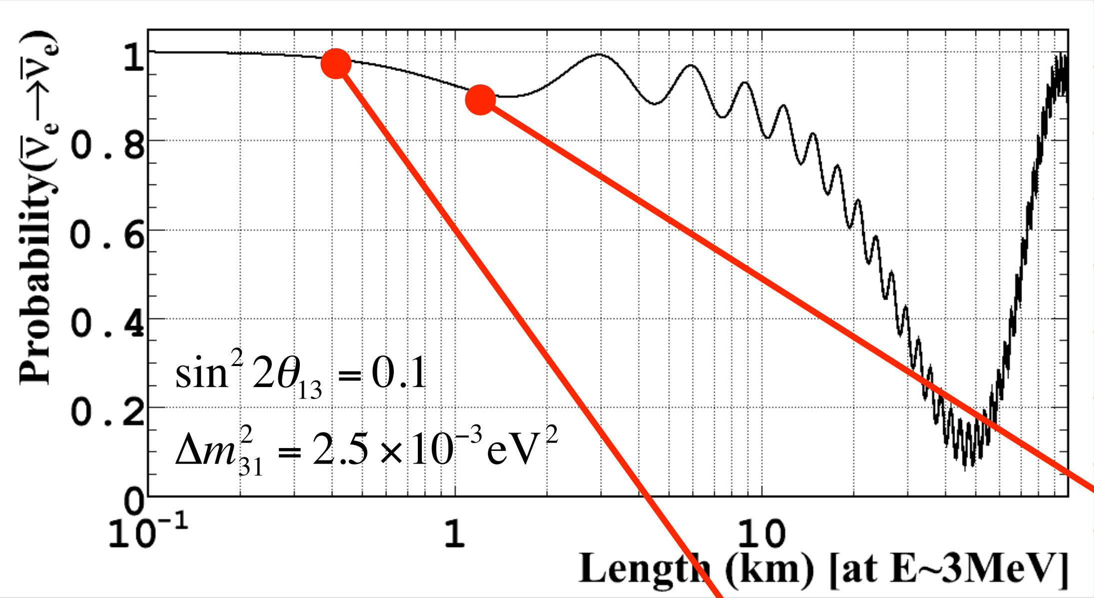


- Simple 2 flavor oscillation formula is valid at 1km baseline
  - $P(\nu_e \to \nu_e)$ as a function of $\Delta m_{31}{}^2$(well known) and θ_{13} (unknown)
  - Matter effects are negligible
  - Independent to CP-violation phase

$\Rightarrow$ Clean measurement of θ_{13}

Strategy

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



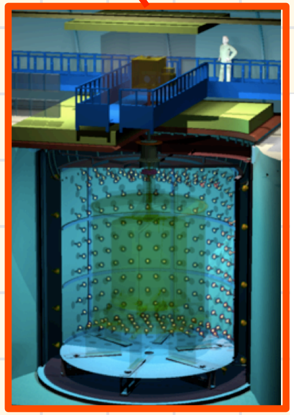
Systematic errors on

- neutrino flux
- interaction x-sec
- # of target protons
- detection efficiency

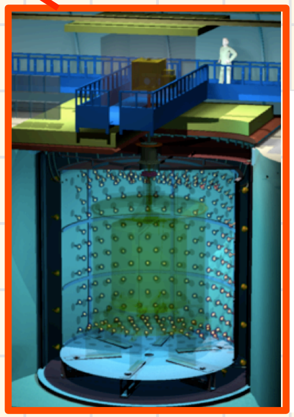
are canceled by two detectors technique.

$\overline{\nu}_e$

Chooz原子炉
4.27GW_{th} x 2 cores



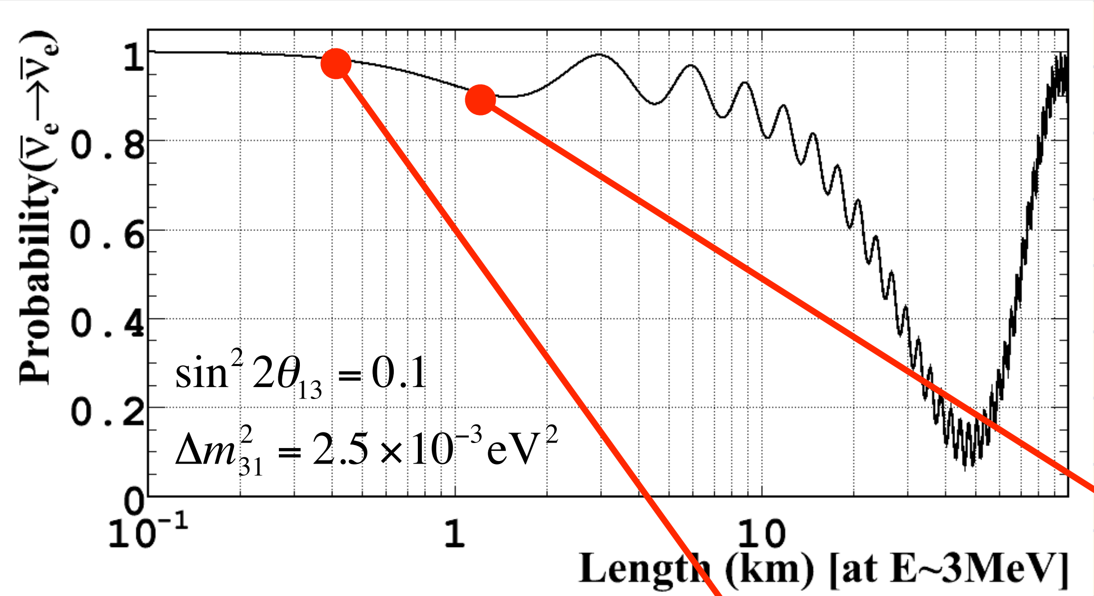
Near Detector
<L> 400m
450ν/day
120m.w.e.
Early 2013



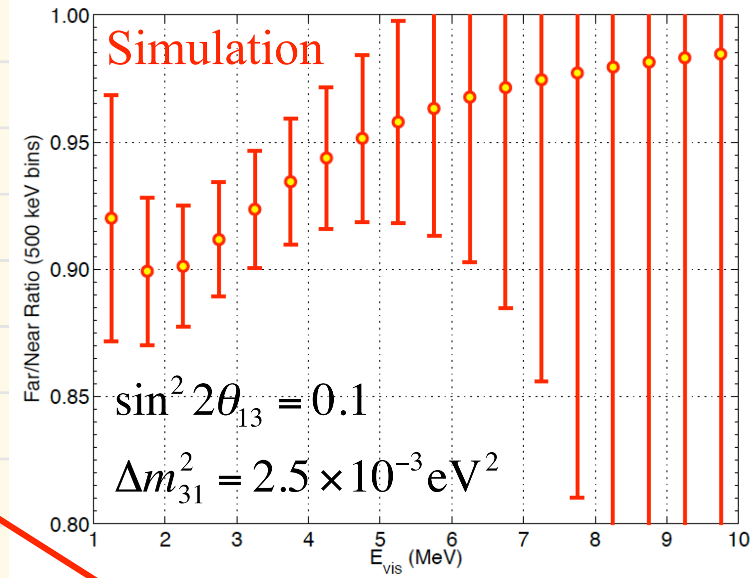
Far Detector
<L> 1050m
65ν/day
300m.w.e.
April 2011

Strategy

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

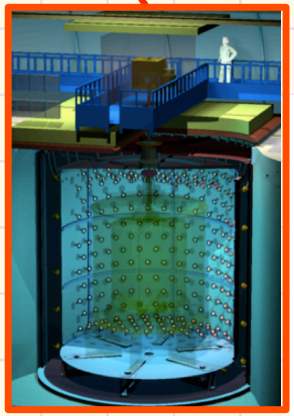


Far/Near ratio（3 years）



Chooz原子炉
4.27GW$_{th}$ x 2 cores

$\overline{\nu}_e$



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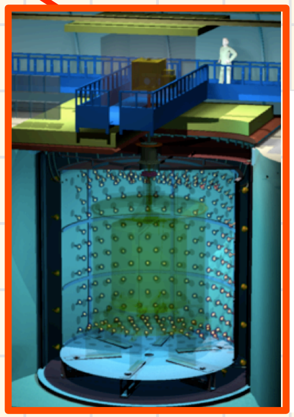
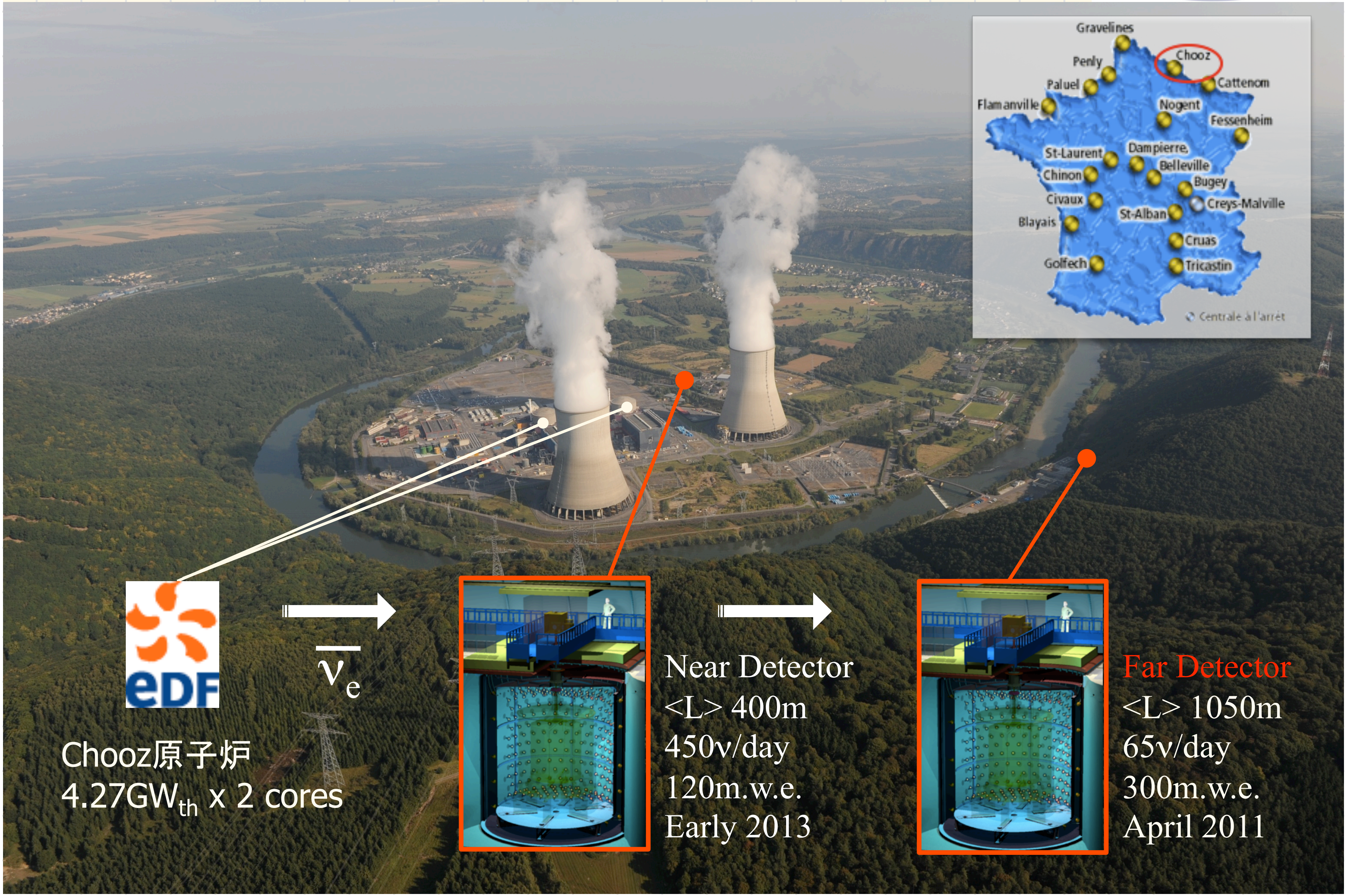


Far Detector
<L> 1050m
65ν/day
300m.w.e.
April 2011

Double Chooz experiment



Double Chooz collaboration

Brazil
CBPF
UNICAMP
UFABC

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

CNRS/IN2P3:
- Subatech
- IPHC

ULB/VUB

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

UK
Sussex

USA
U. Alabama
ANL
U. Chicago
Columbia U.
UCDavis
Drexel U.
IIT
KSU
LLNL
MIT
U. Notre Dame
Sandia National Laboratories
U. Tennessee

Spokesperson: H. de Kerret (IN2P3)
Project Manager: Ch. Veyssière (CEA-Saclay)

Web Site: www.doublechooz.org/

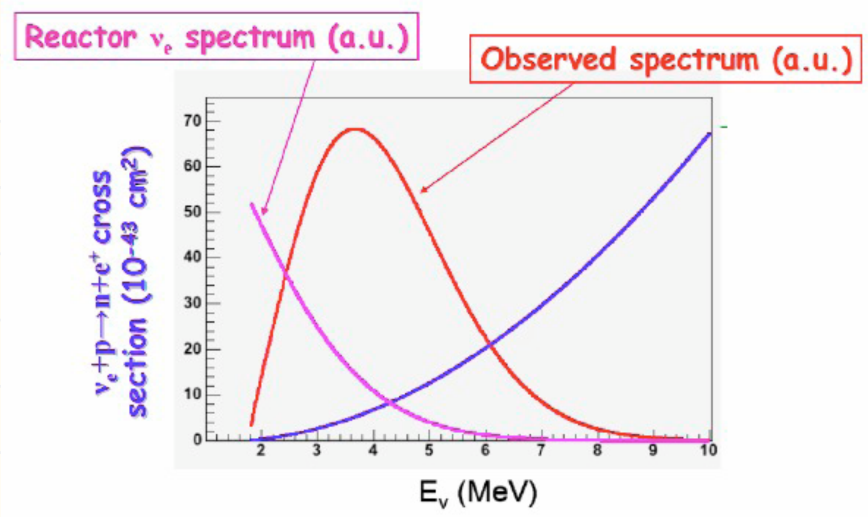
Double Chooz collaboration meeting @ Kobe Univ.

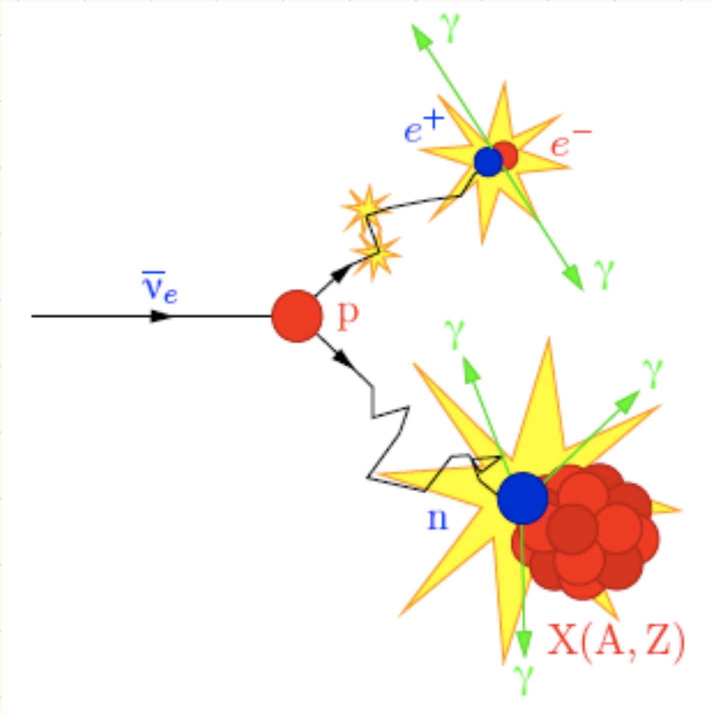
Detection of reactor neutrinos

- Inverse beta decay reaction

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

- Reaction threshold: 1.8MeV
- 65 events/day (far detector)





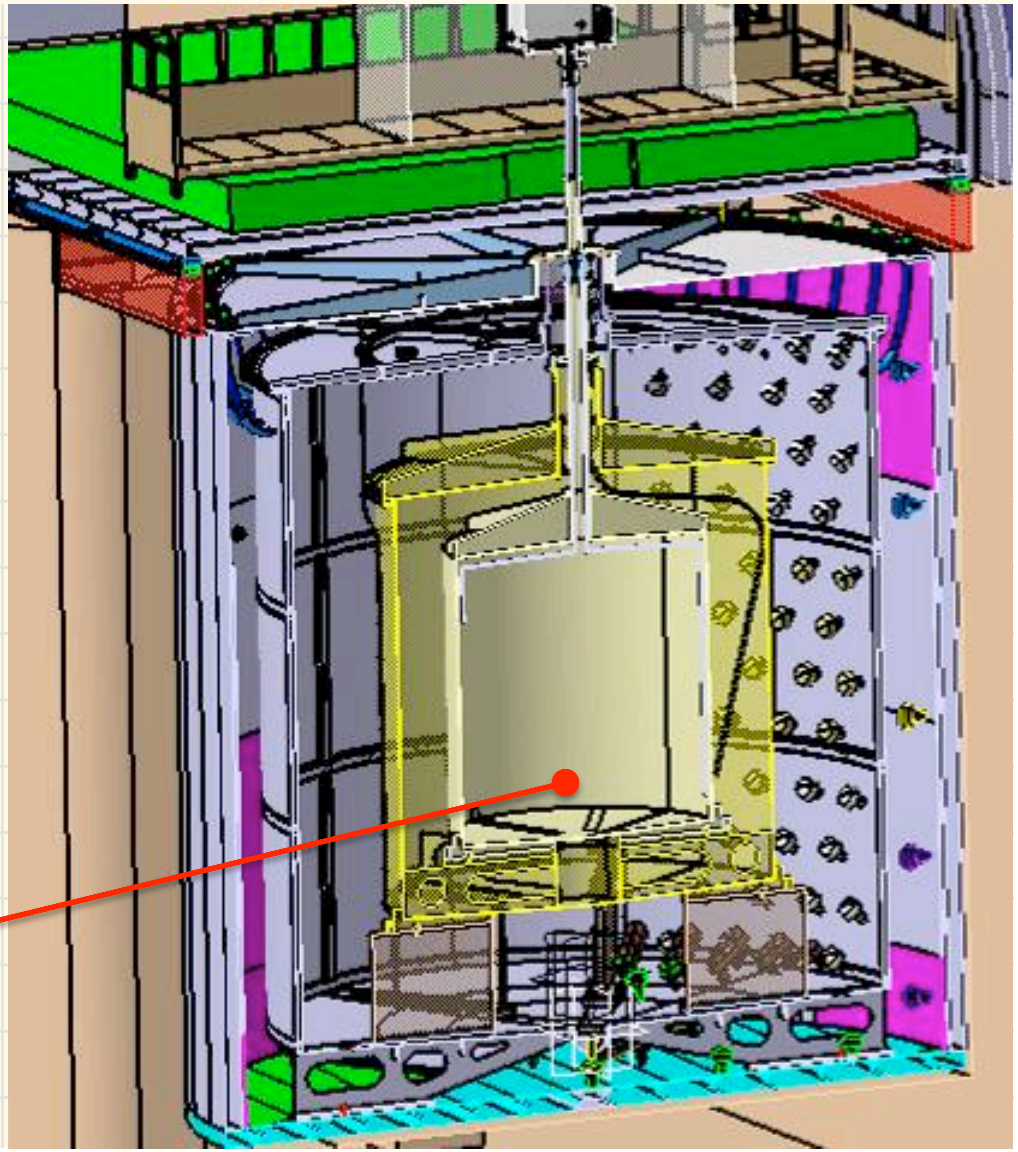
Background are largely suppressed by requiring delayed coincidence

Prompt signal:
Positron and annihilation γ's（1-8MeV）
Neutrino energy: $E_\nu = E_{vis} + 0.8$MeV

Delayed signal:
γ's from neutron capture on Gd（8MeV）

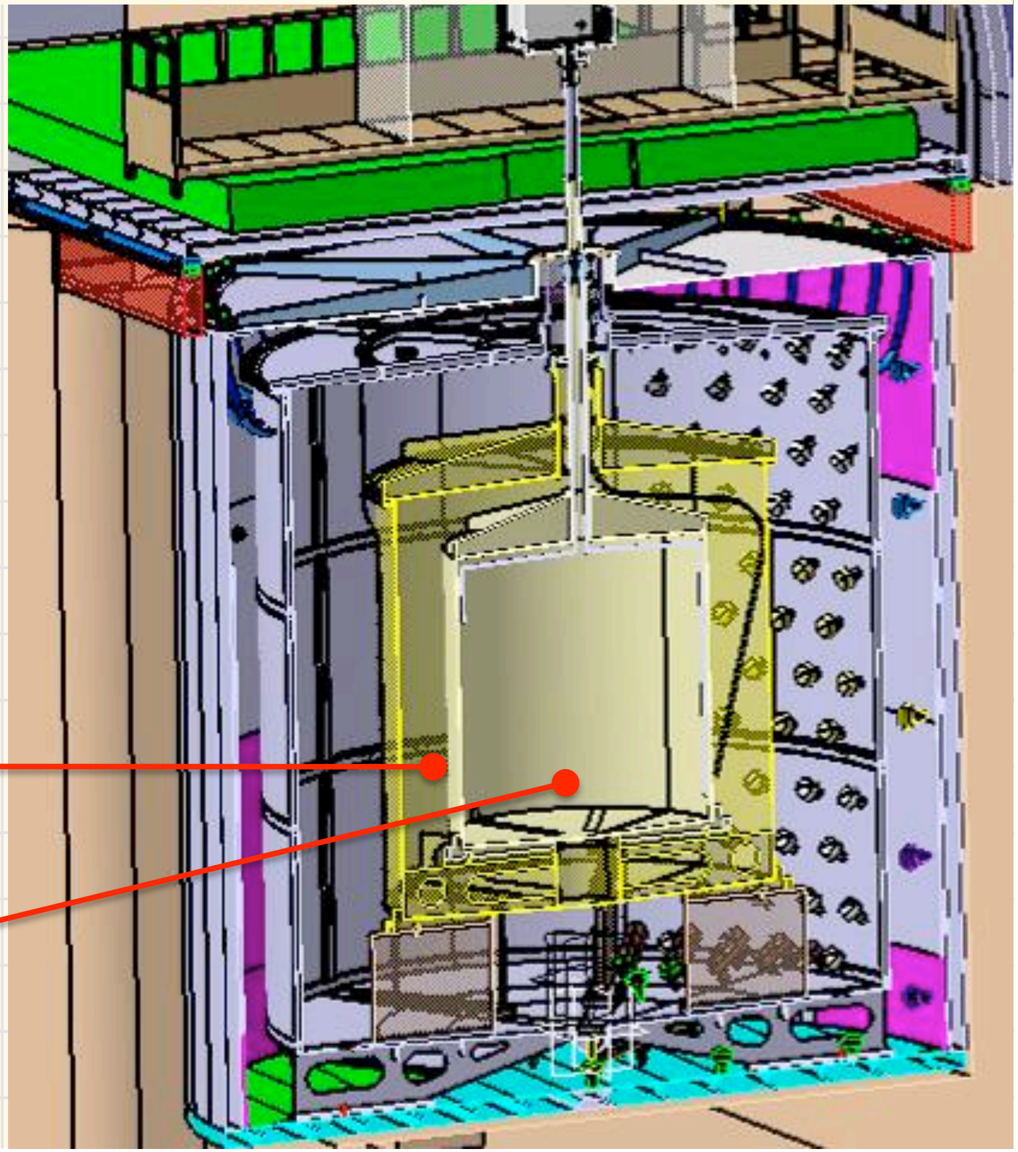
Time correlation：
τ = 30 μsec

Double Chooz detector



ν-Target
(10.3m^3 Gd loaded (1g/l) liquid scintillator)
Target for neutrino signals

Double Chooz detector



γ-Catcher (22.3m³ liquid scintillator)
Measurement of 8MeV γ's from n-Gd capture in target volume

ν-Target
(10.3m³ Gd loaded (1g/l) liquid scintillator)
Target for neutrino signals

Double Chooz detector

Buffer (110m^3 mineral oil & 390 PMTs)

Reduction of fast neutron and environmental γ's from PMT and outside

Acrylic Vessel

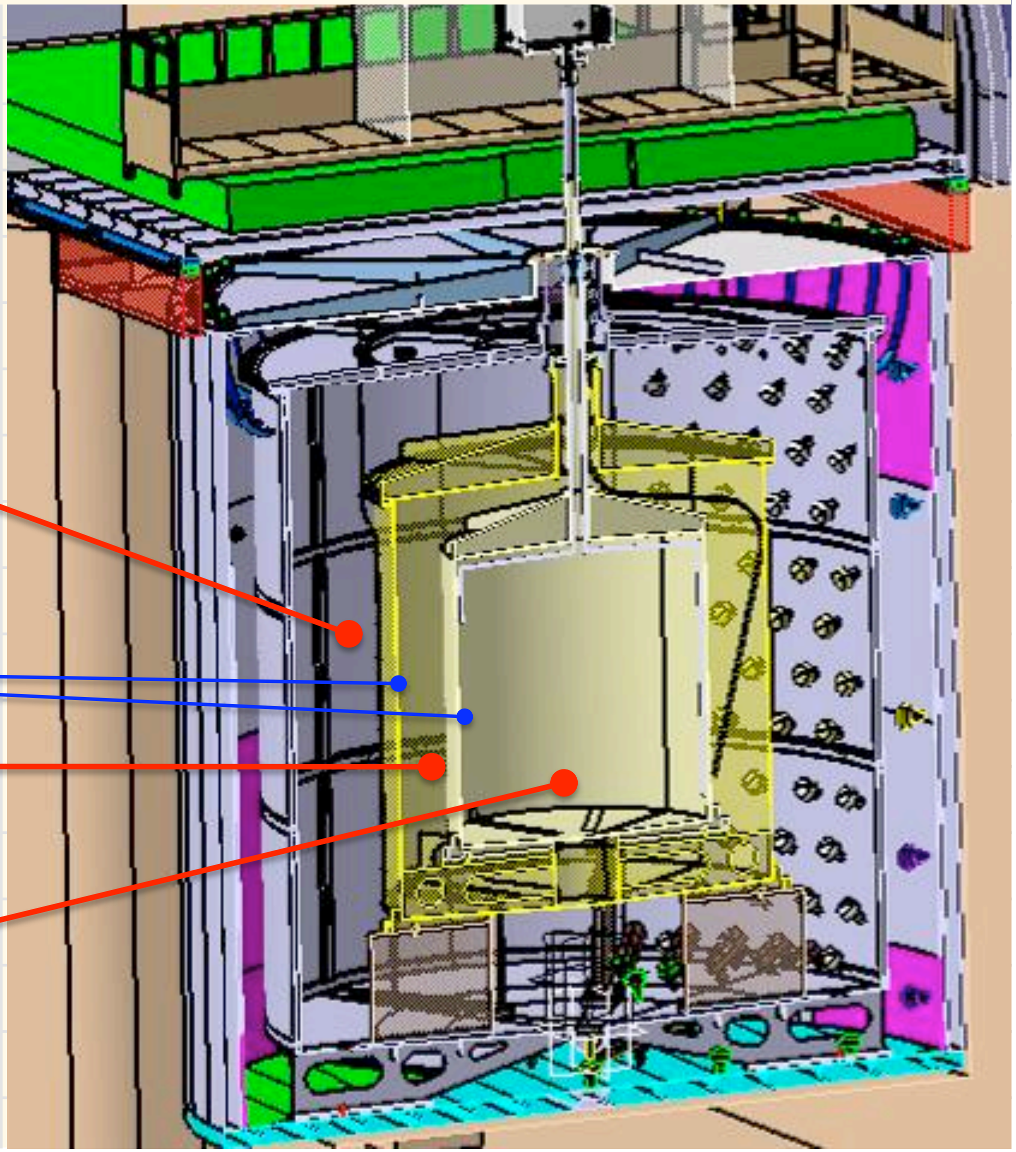
γ-Catcher (22.3m^3 liquid scintillator)

Measurement of 8MeV γ's from n-Gd capture in target volume

ν-Target

(10.3m^3 Gd loaded (1g/l) liquid scintillator)

Target for neutrino signals



Double Chooz detector

Inner Veto
(90m^3 liquid scintillator & 78 PMTs)
Detection of cosmic ray muons and shield to fast neutrons

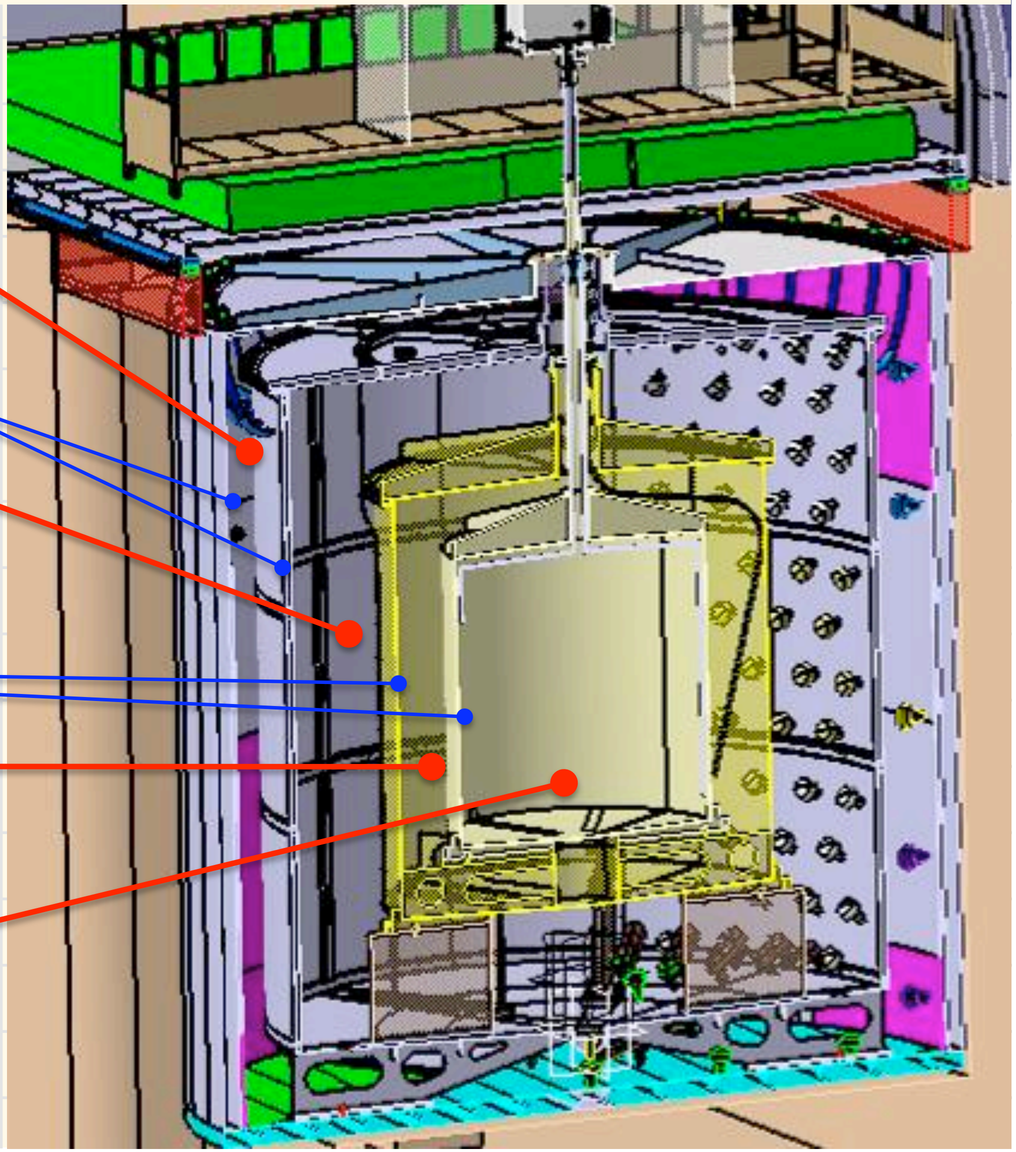
Steel Vessel & PMT support structure

Buffer (110m^3 mineral oil & 390 PMTs)
Reduction of fast neutron and environmental γ's from PMT and outside

Acrylic Vessel

γ-Catcher (22.3m^3 liquid scintillator)
Measurement of 8MeV γ's from n-Gd capture in target volume

ν-Target
(10.3m^3 Gd loaded (1g/l) liquid scintillator)
Target for neutrino signals



Double Chooz detector

Steel shield (15cm thick)

Inner Veto
(90m^3 liquid scintillator & 78 PMTs)

Detection of cosmic ray muons and shield to fast neutrons

Steel Vessel & PMT support structure

Buffer (110m^3 mineral oil & 390 PMTs)

Reduction of fast neutron and environmental γ's from PMT and outside

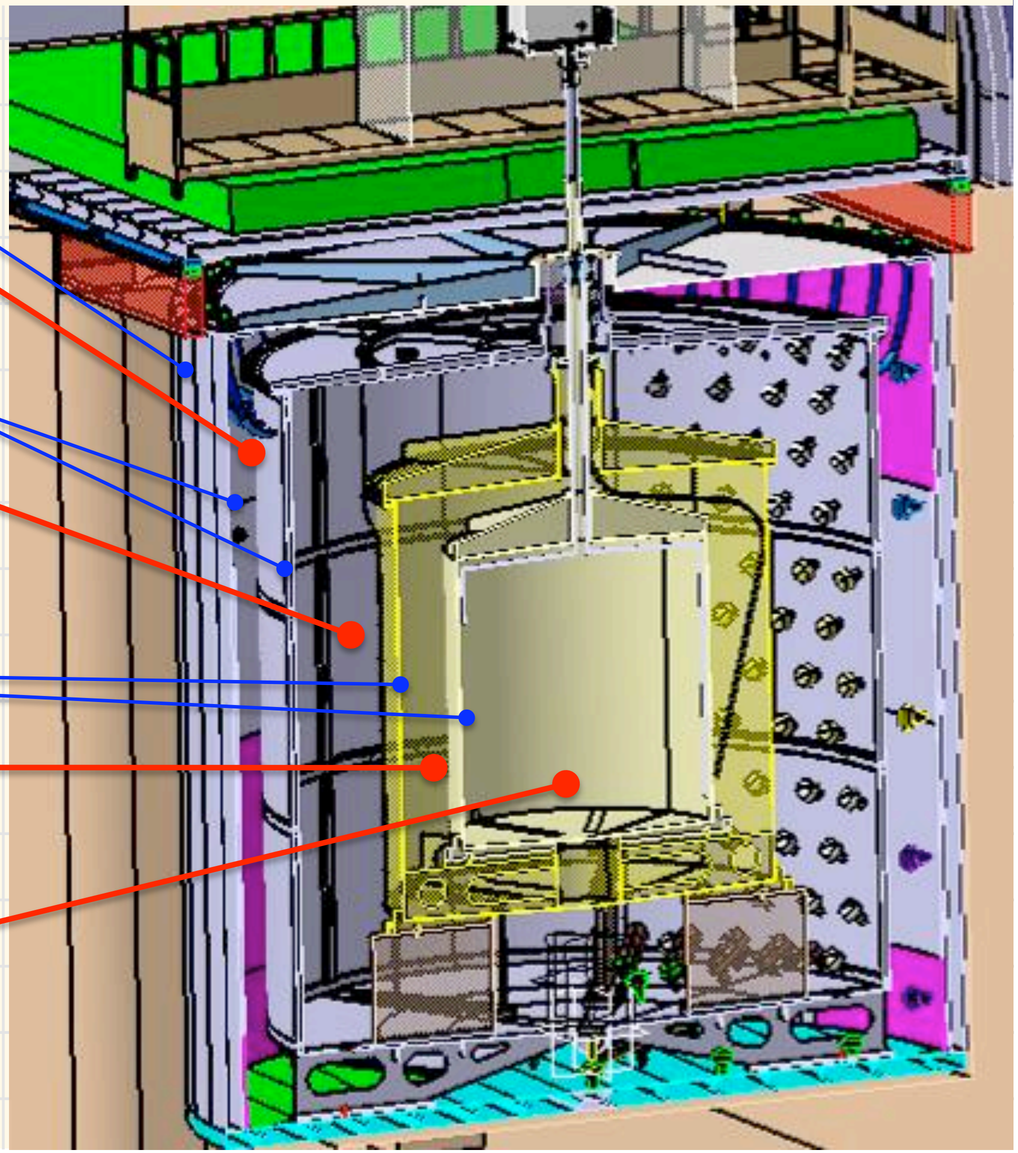
Acrylic Vessel

γ-Catcher (22.3m^3 liquid scintillator)

Measurement of 8MeV γ's from n-Gd capture in target volume

ν-Target
(10.3m^3 Gd loaded (1g/l) liquid scintillator)

Target for neutrino signals



Double Chooz detector

Outer Veto (Plastic scintillator) [not used in this analysis]

Identification of cosmic ray muons

Steel shield (15cm thick)

Inner Veto

($90m^3$ liquid scintillator & 78 PMTs)

Detection of cosmic ray muons and shield to fast neutrons

Steel Vessel & PMT support structure

Buffer ($110m^3$ mineral oil & 390 PMTs)

Reduction of fast neutron and environmental γ's from PMT and outside

Acrylic Vessel

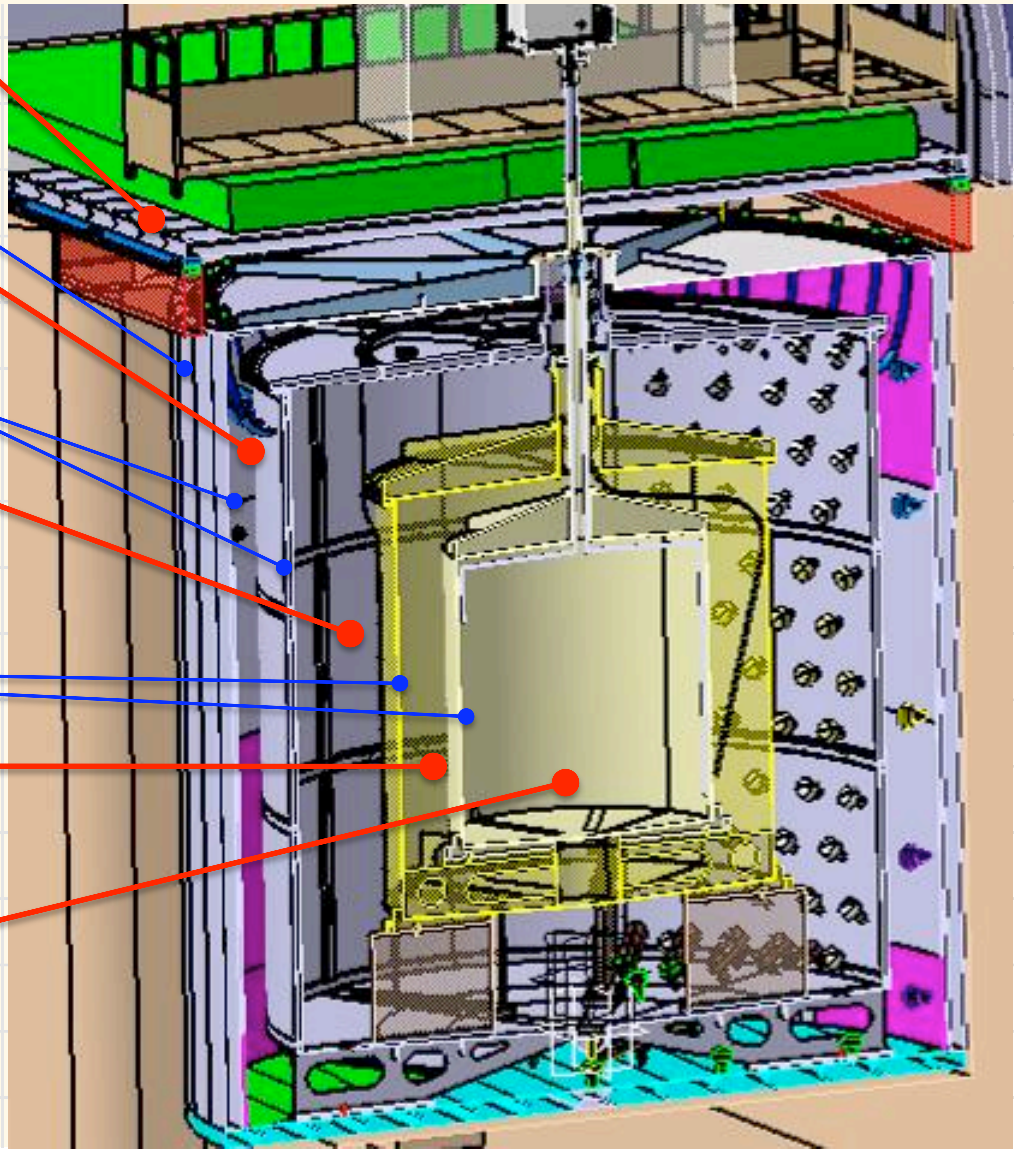
γ-Catcher ($22.3m^3$ liquid scintillator)

Measurement of 8MeV γ's from n-Gd capture in target volume

ν-Target

($10.3m^3$ Gd loaded (1g/l) liquid scintillator)

Target for neutrino signals

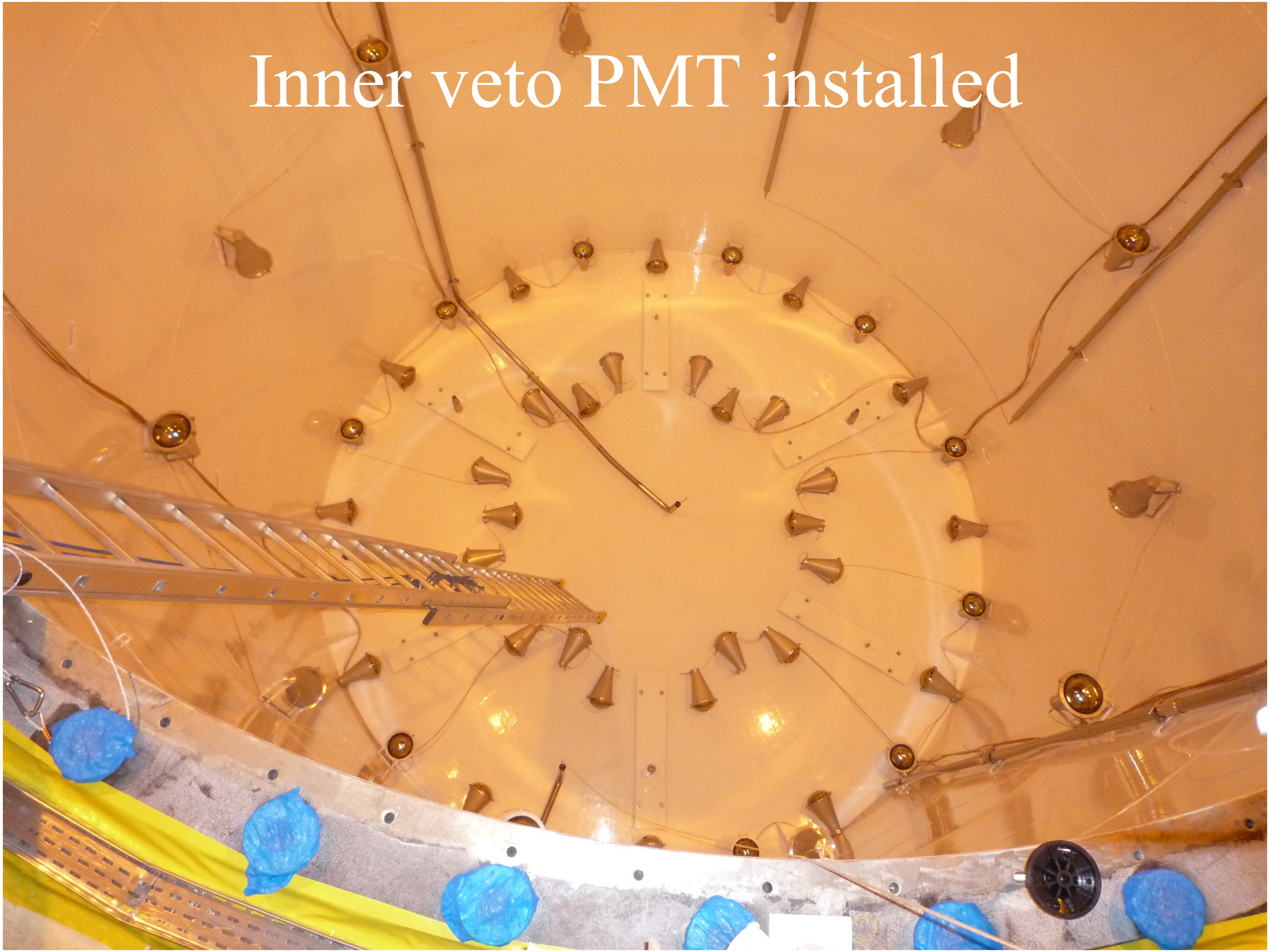


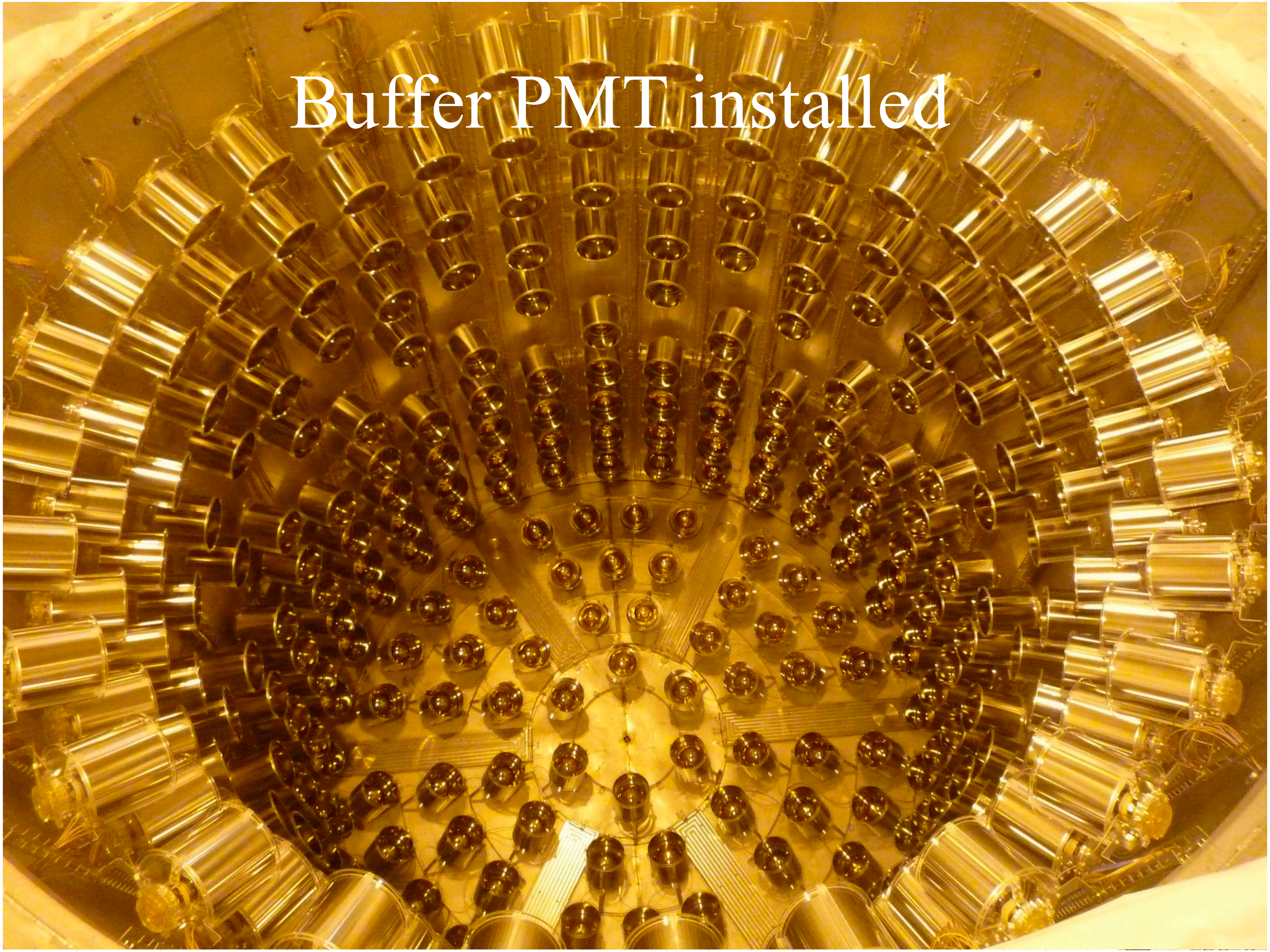
Milestones

May 2008 – October 2010	Far detector construction
December 2010	Far detector filling completed
April 2011	Far detector commissioned
	Start physics data taking
	Near laboratory construction started
July 2011	Outer Veto commissioned
November 2011	FIRST RESULTS
June 2012	Near laboratory expected delivery
Beginning 2013	Near detector expected
	Data taking with two detectors

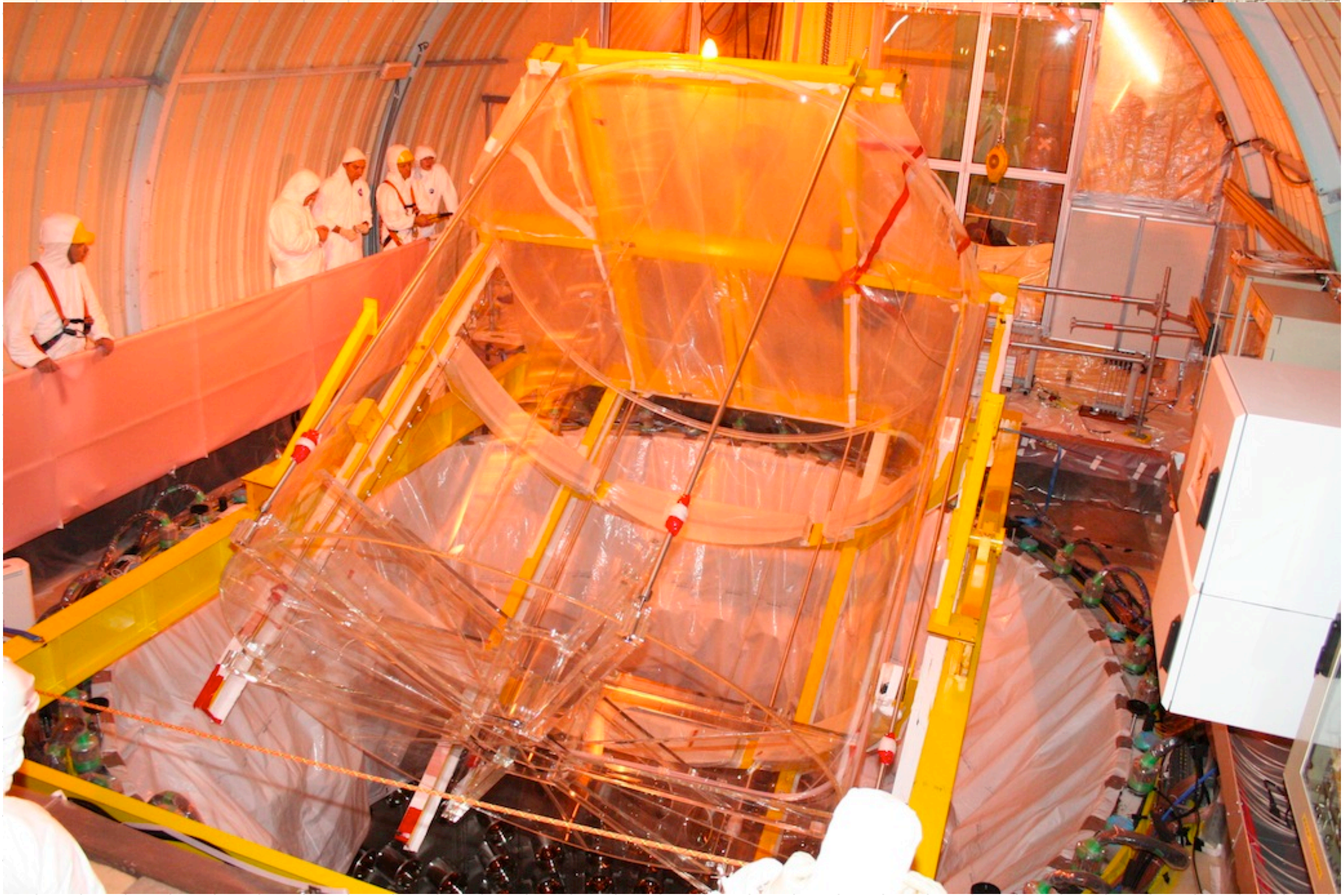
Construction @ DC far lab.

Inner veto PMT installed

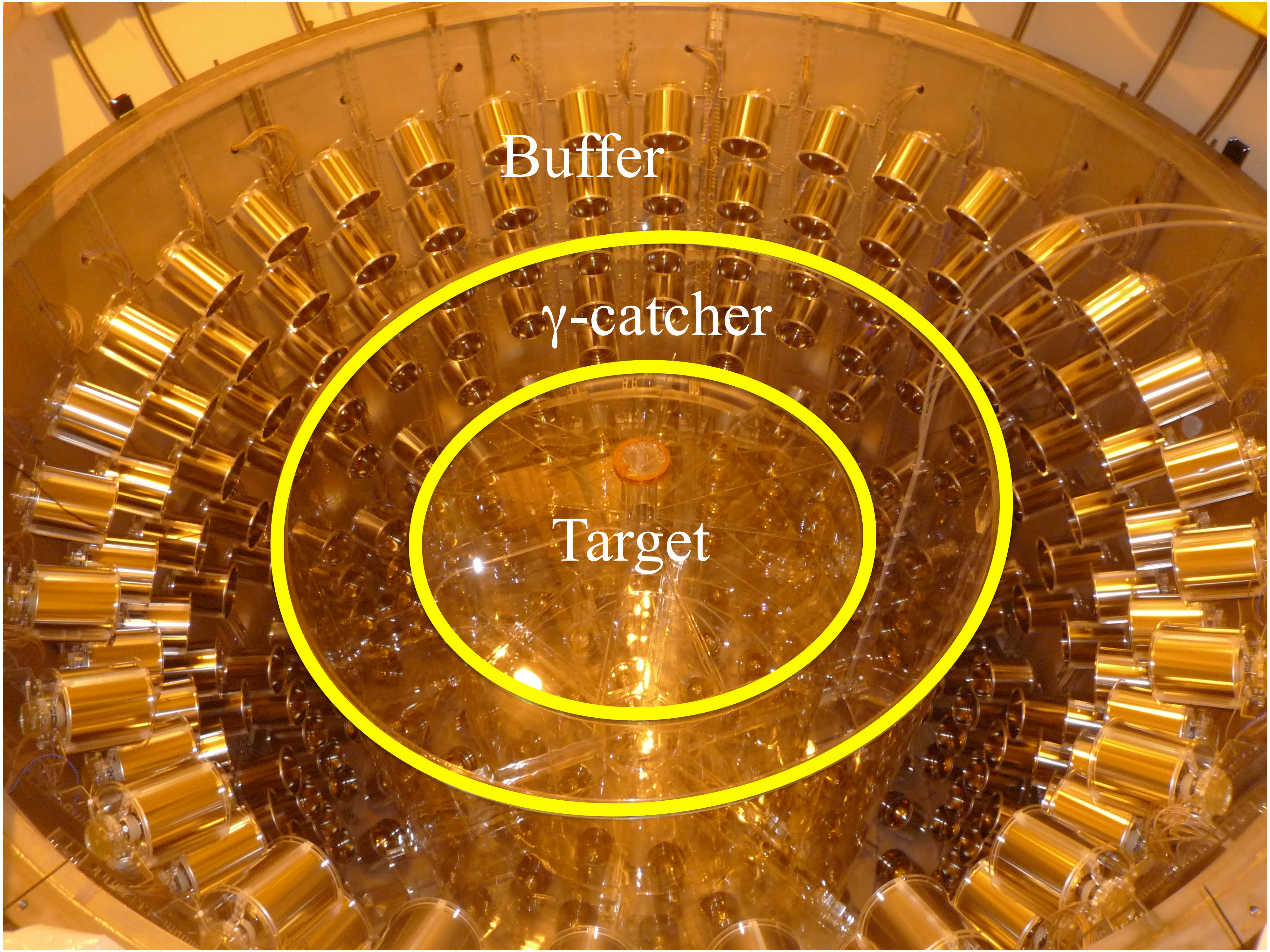



Buffer PMT installed

Installation of acrylic vessel



Target and γ-catcher acrylic vessels installed


Buffer
γ-catcher
Target

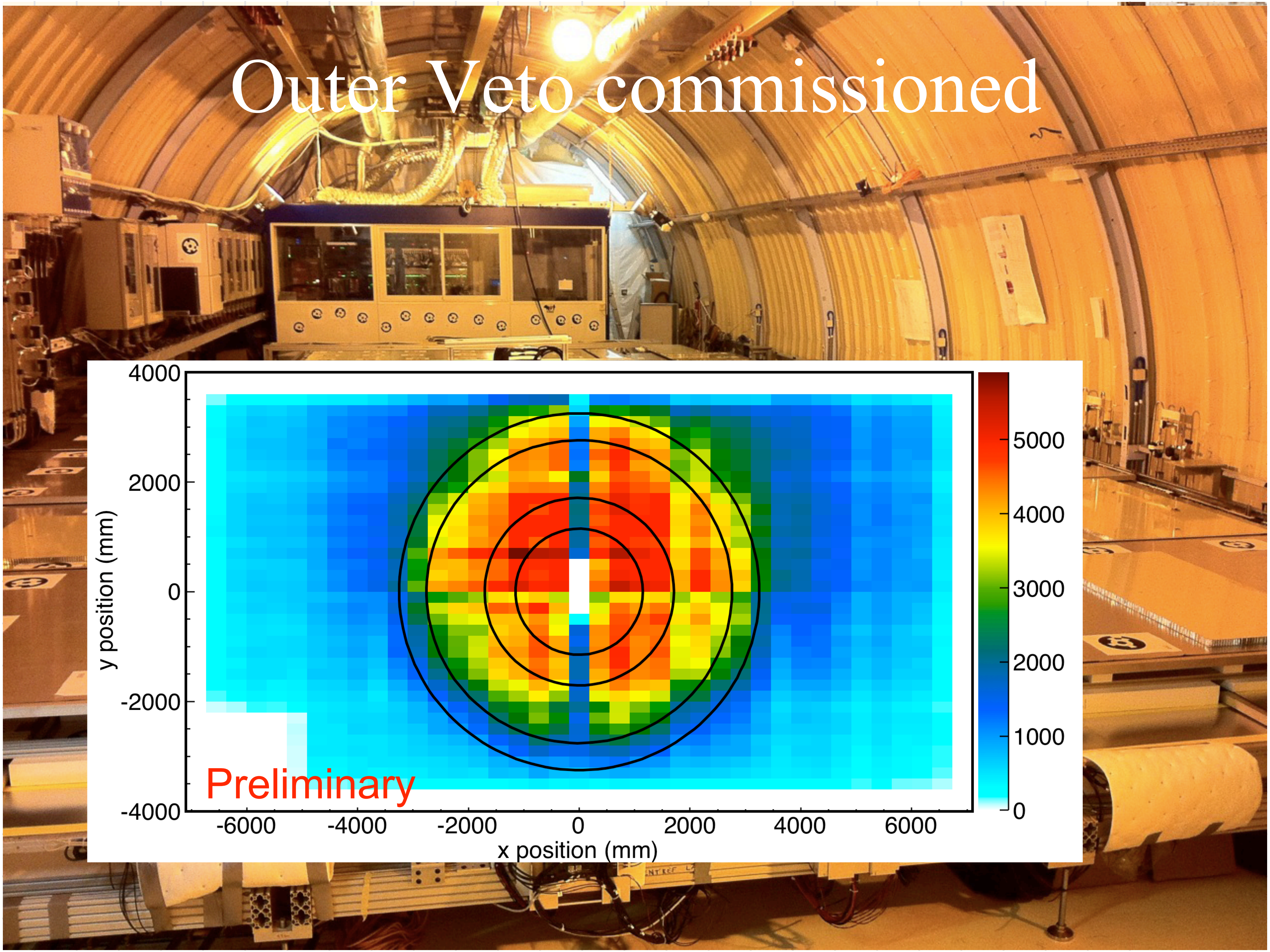
Lid closure

All PMT equipped


Steel shield installed

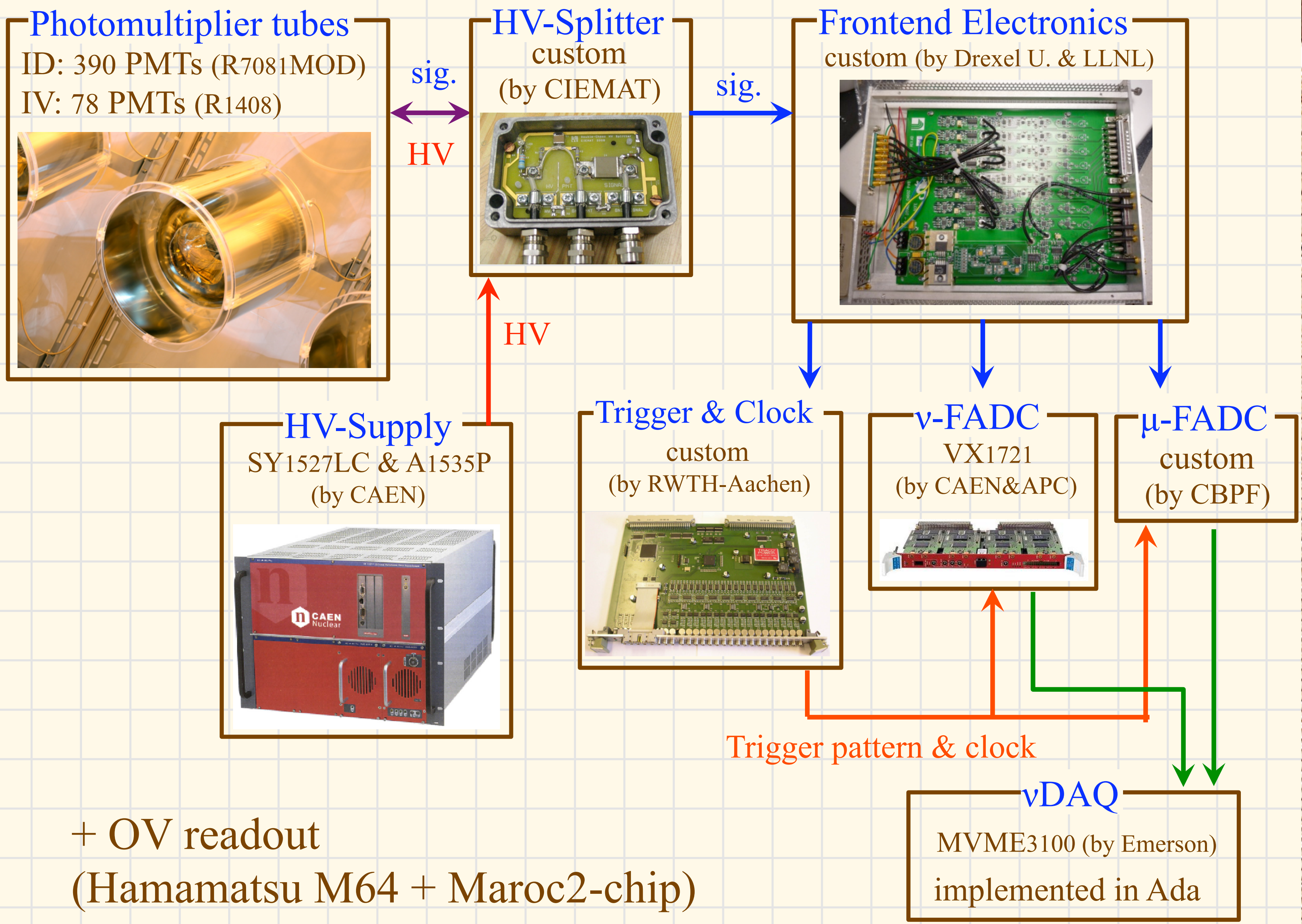
Outer Veto partially installed

Outer Veto commissioned

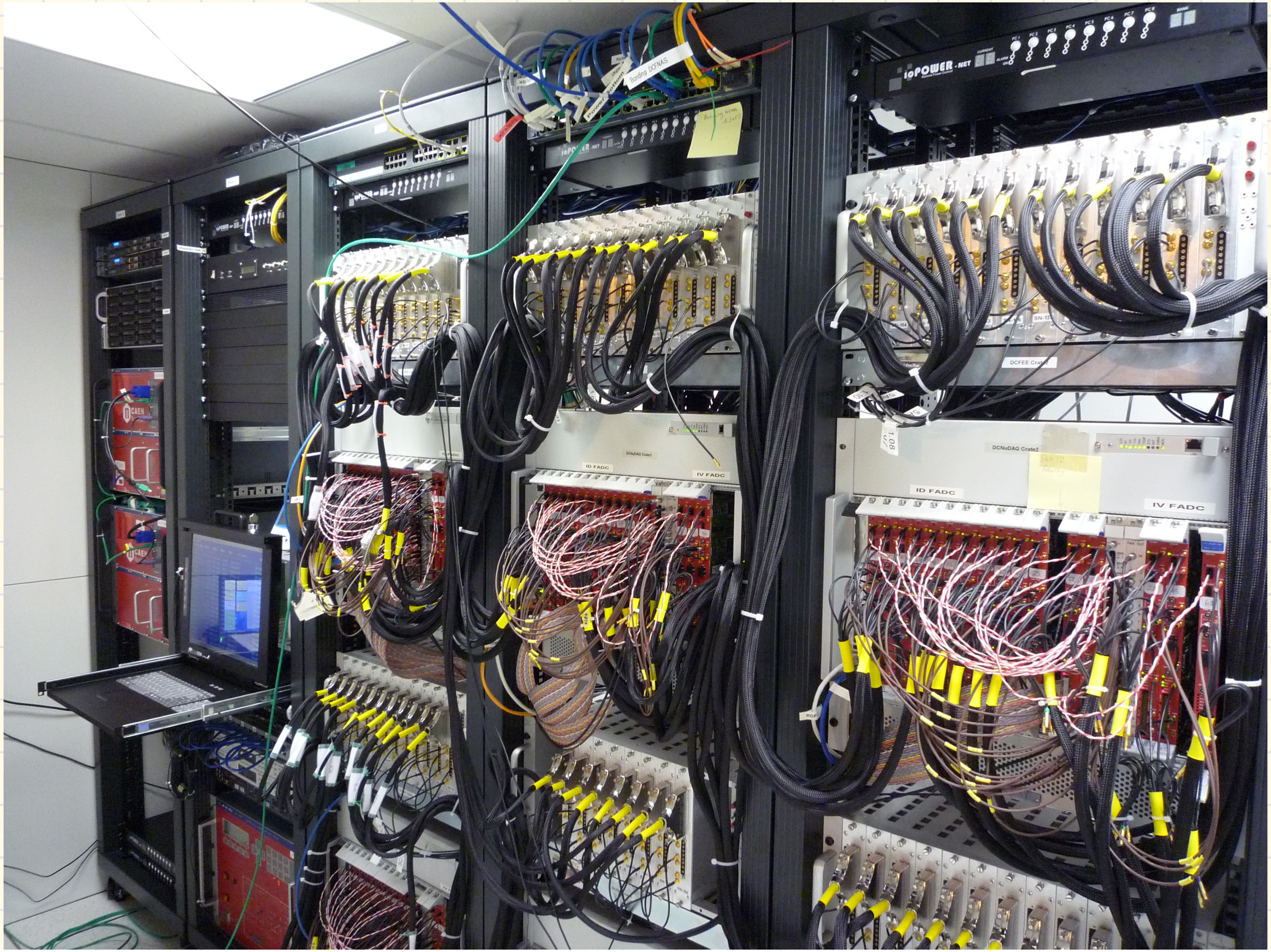


Data taking

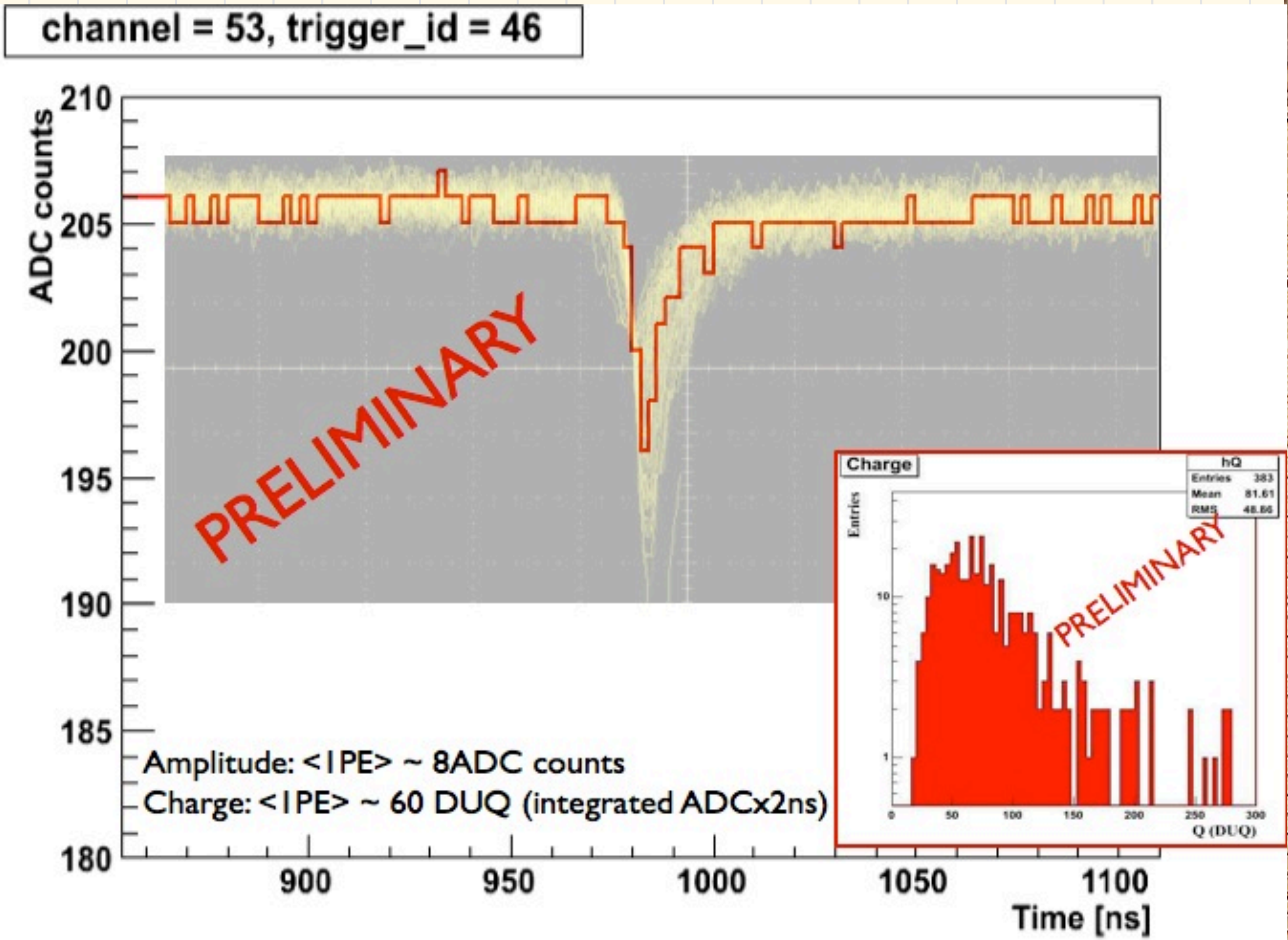
Electronics



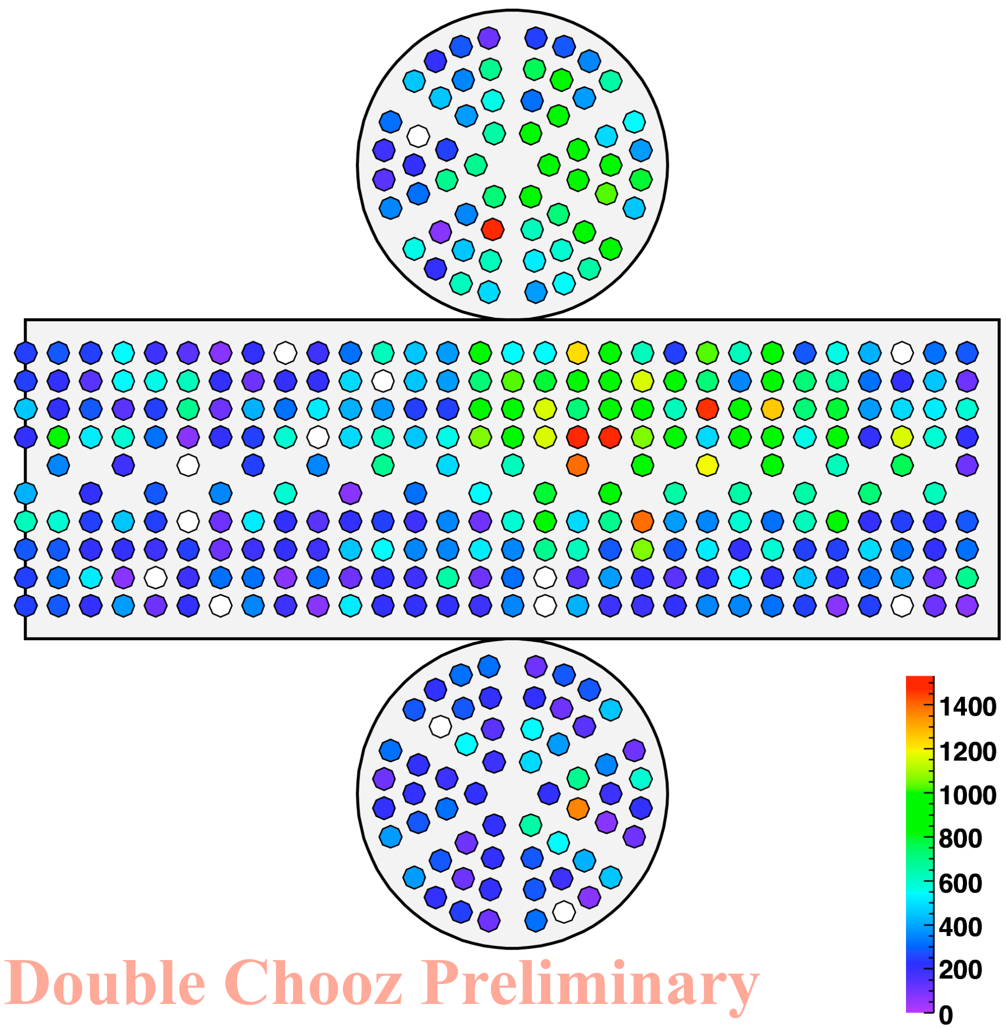
Electronics

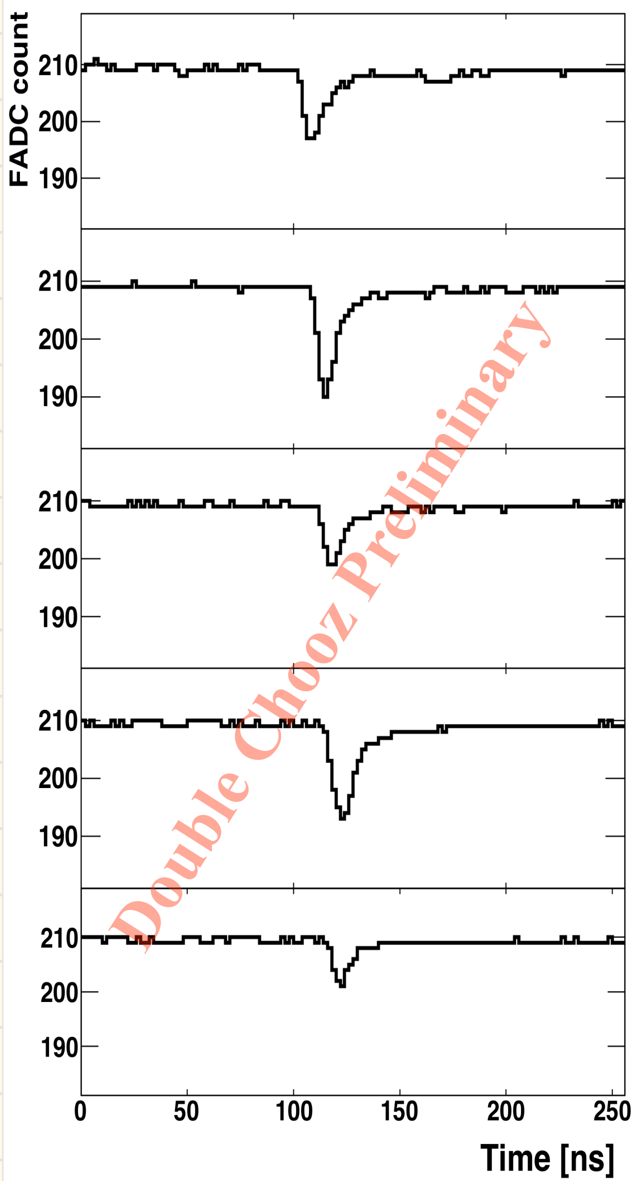


Waveforms recorded by Flash-ADC

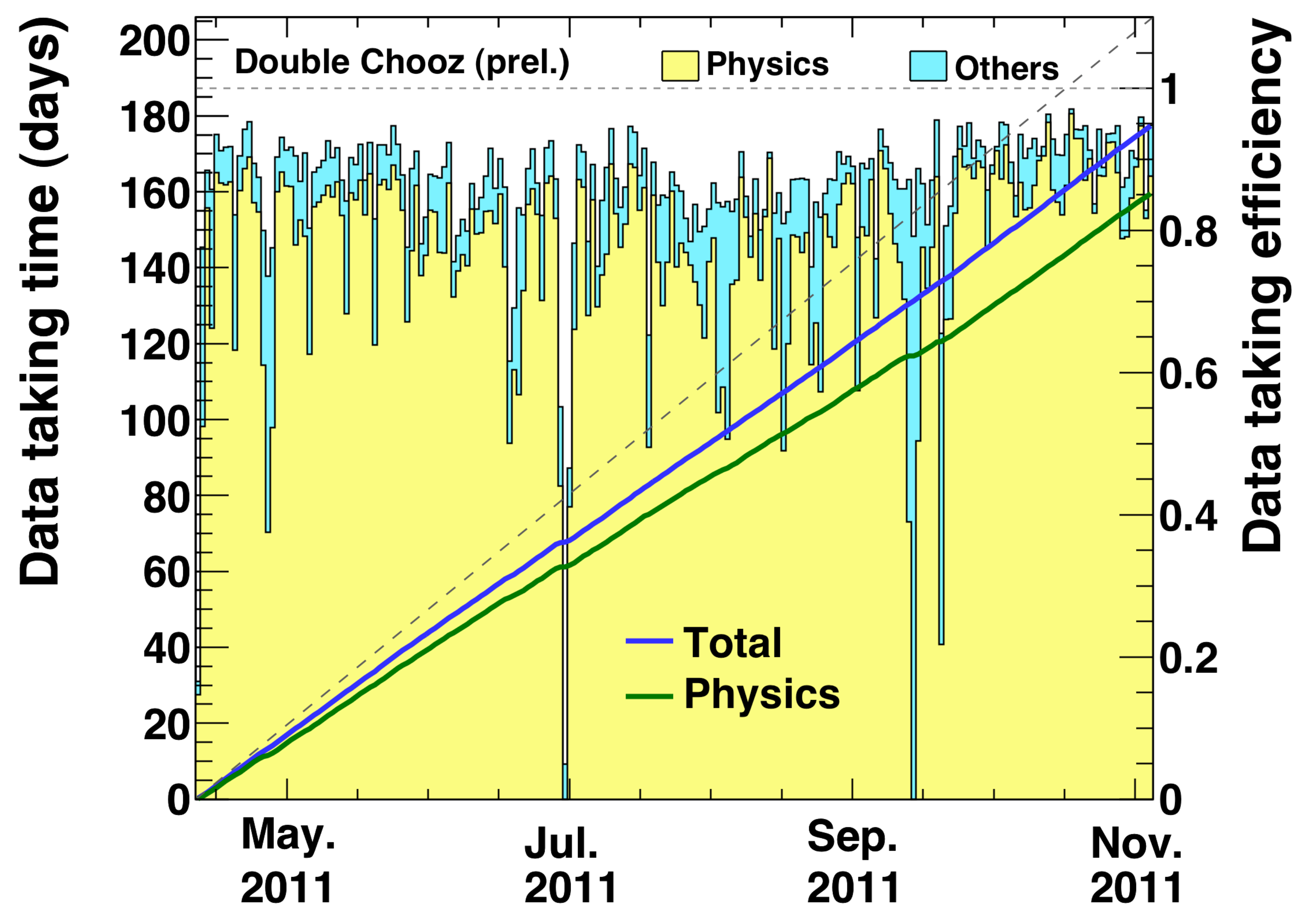


Event display (~8MeV)

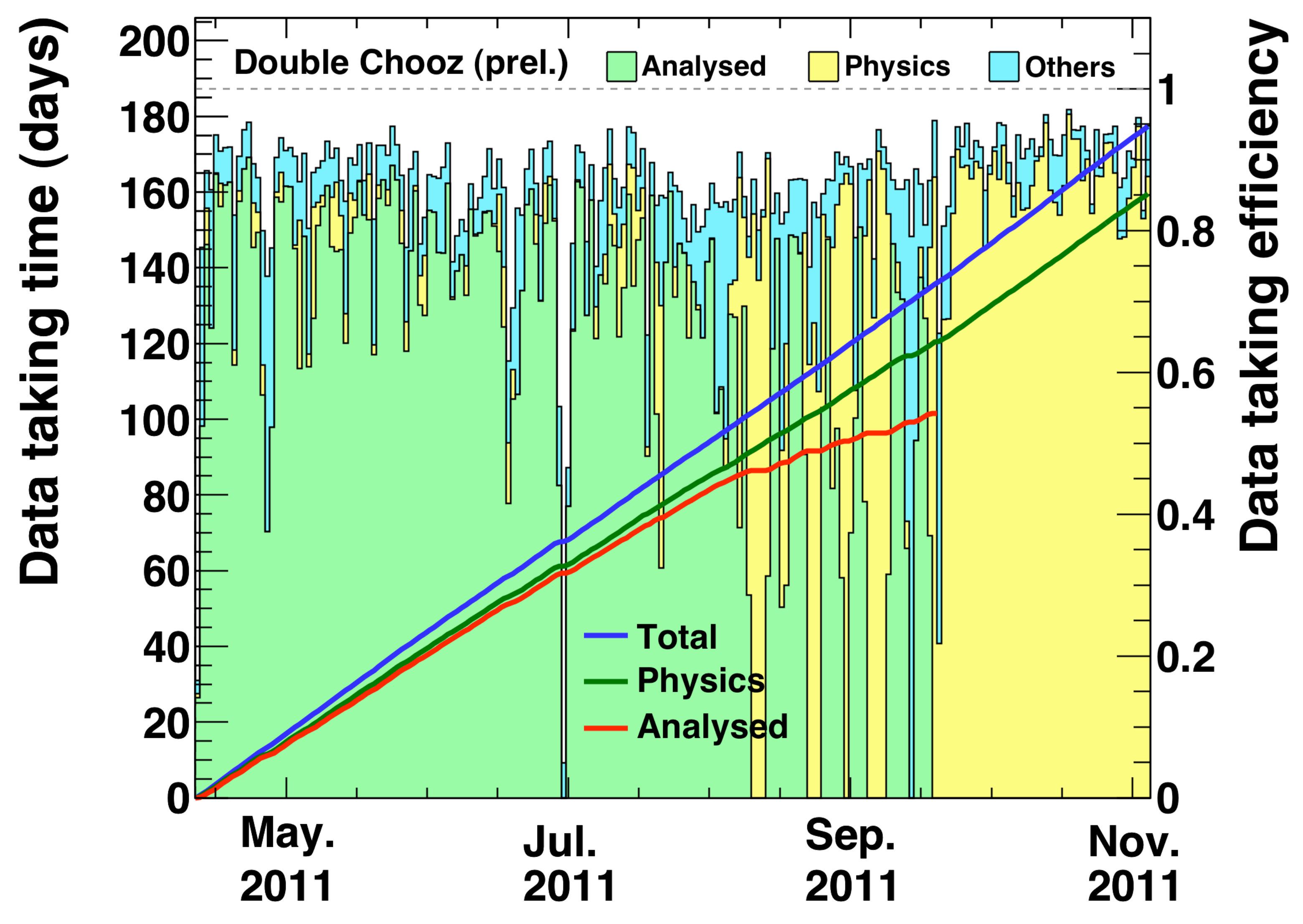




Data taking efficiency



Fraction of analyzed data

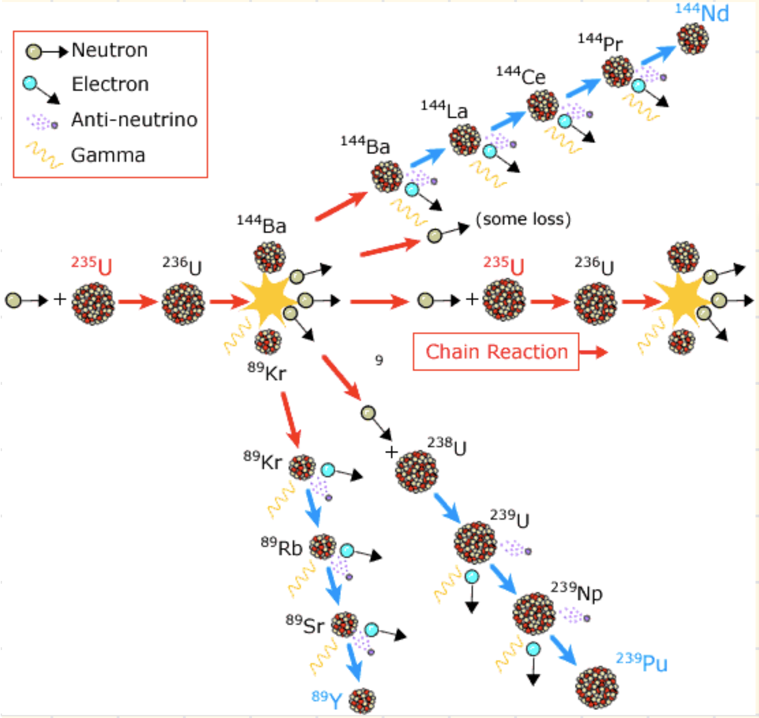


Run Time: 101.5234 days from April 13th to September 18th

Live Time : 96.823 days (1 ms muon veto)

Neutrino flux

Reactor neutrino flux calculation



Expected number of events

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

Mean energy per fission (k=^{235}U,^{238}U,^{239}Pu,^{241}Pu)

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

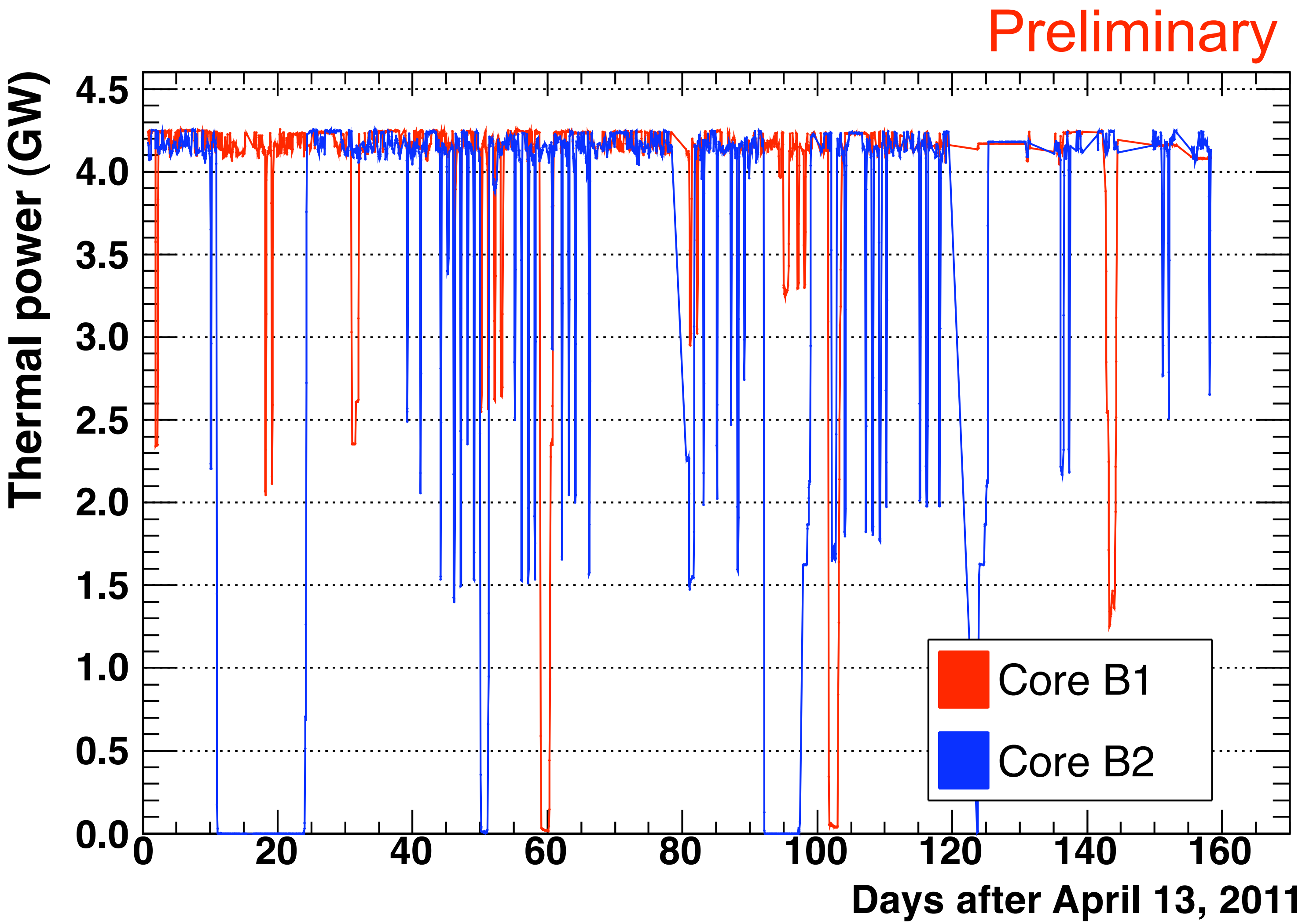
Mean cross-section per fission

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

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

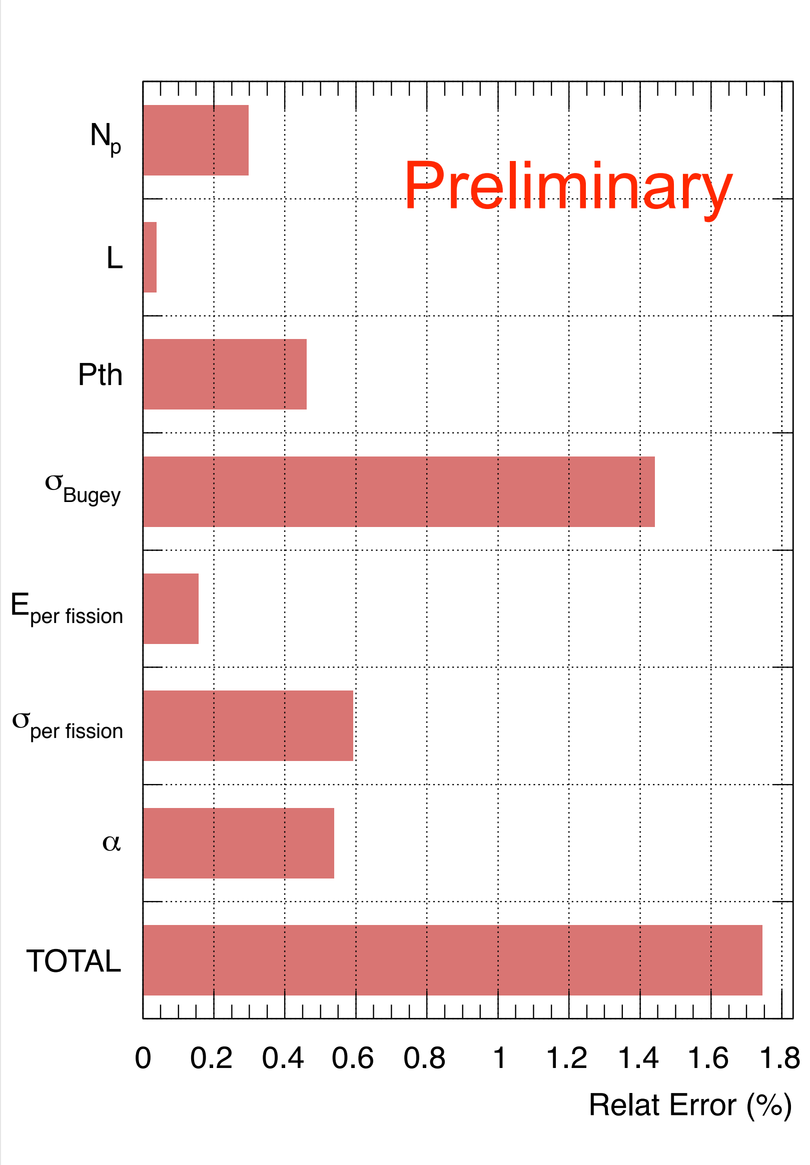
Neutrino flux prediction is based on Bugey 4 measurement with correction to Double Chooz (fission rates for each isotopes etc.)

Thermal power



Systematic uncertainty: 0.46%

Systematic uncertainty on reactor neutrino flux prediction

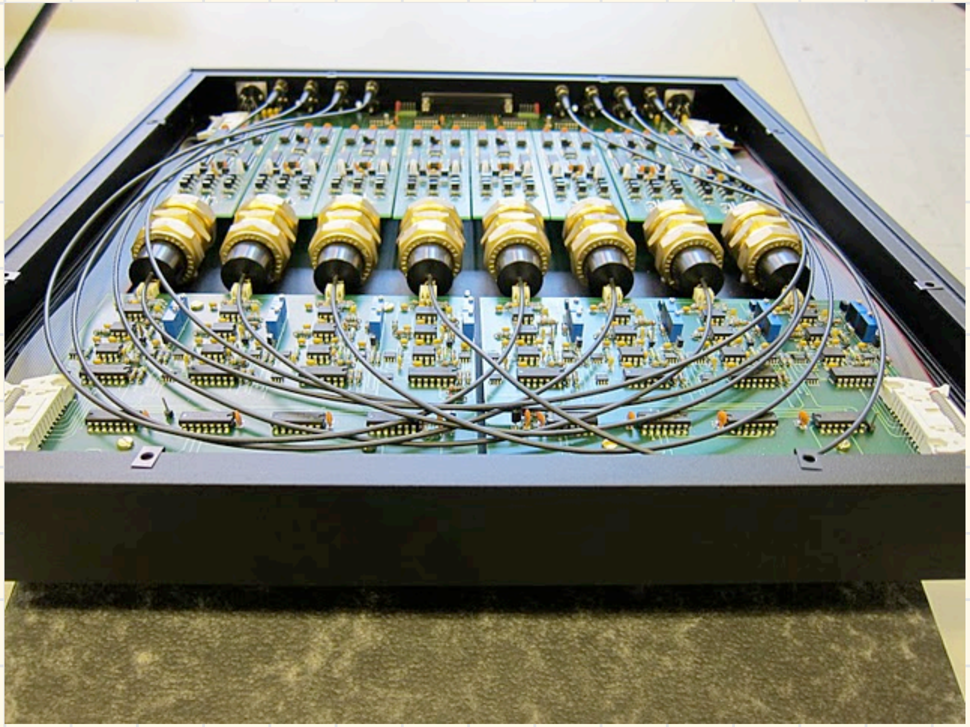


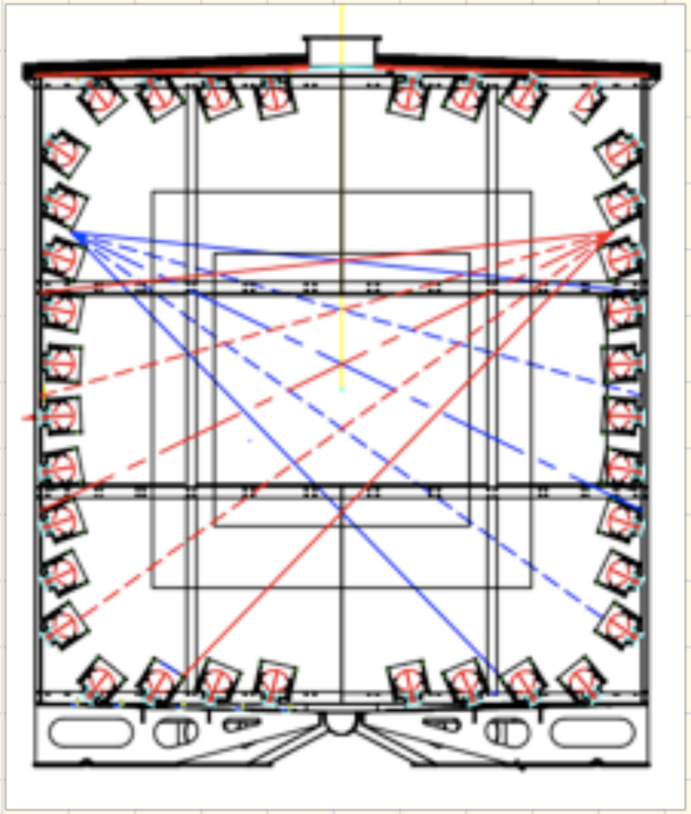
1.7% total error

(2.7% in theoretical calculation without Bugey4 measurement)

Calibration

LED calibration system

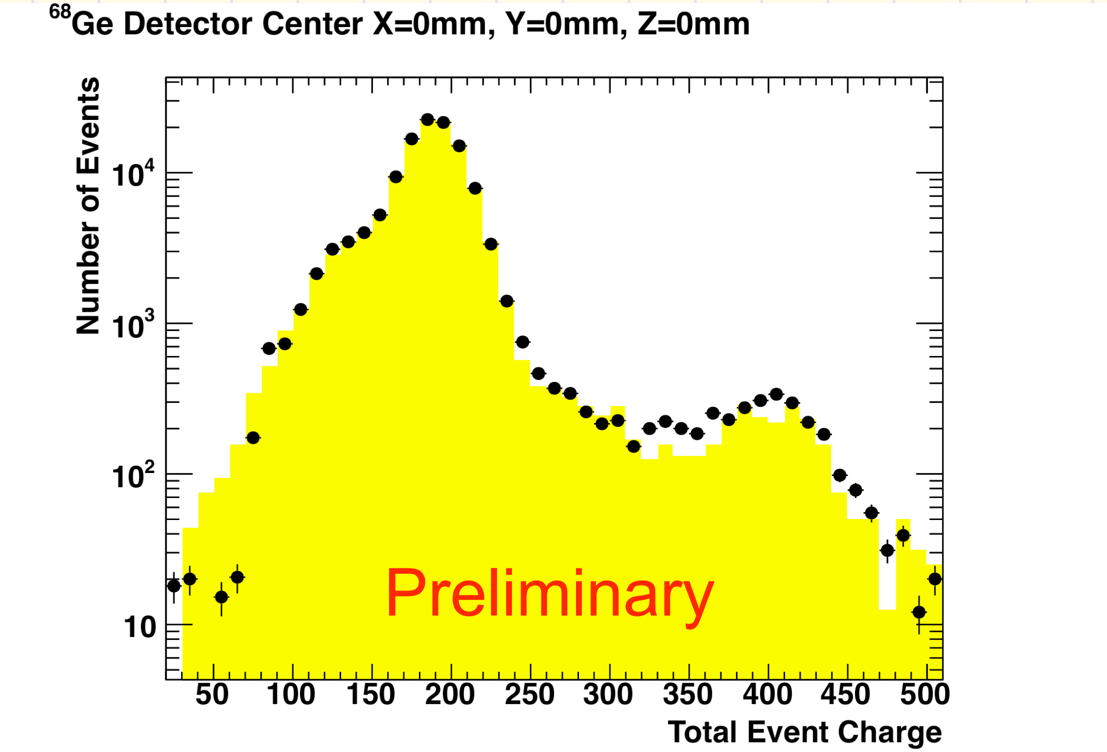


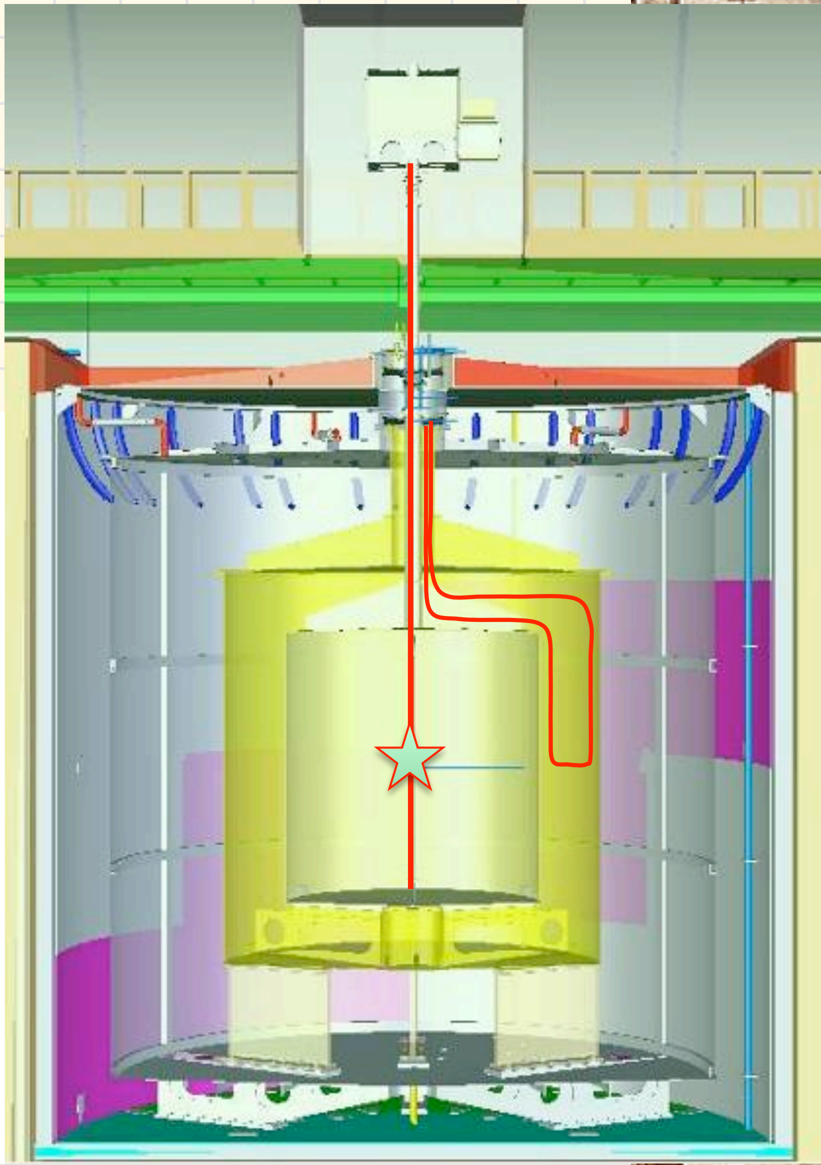


- Illuminate detector by LED light source fed into detector through optical fibers
- Embedded calibration system mainly used for stability check of detector response

Energy calibration

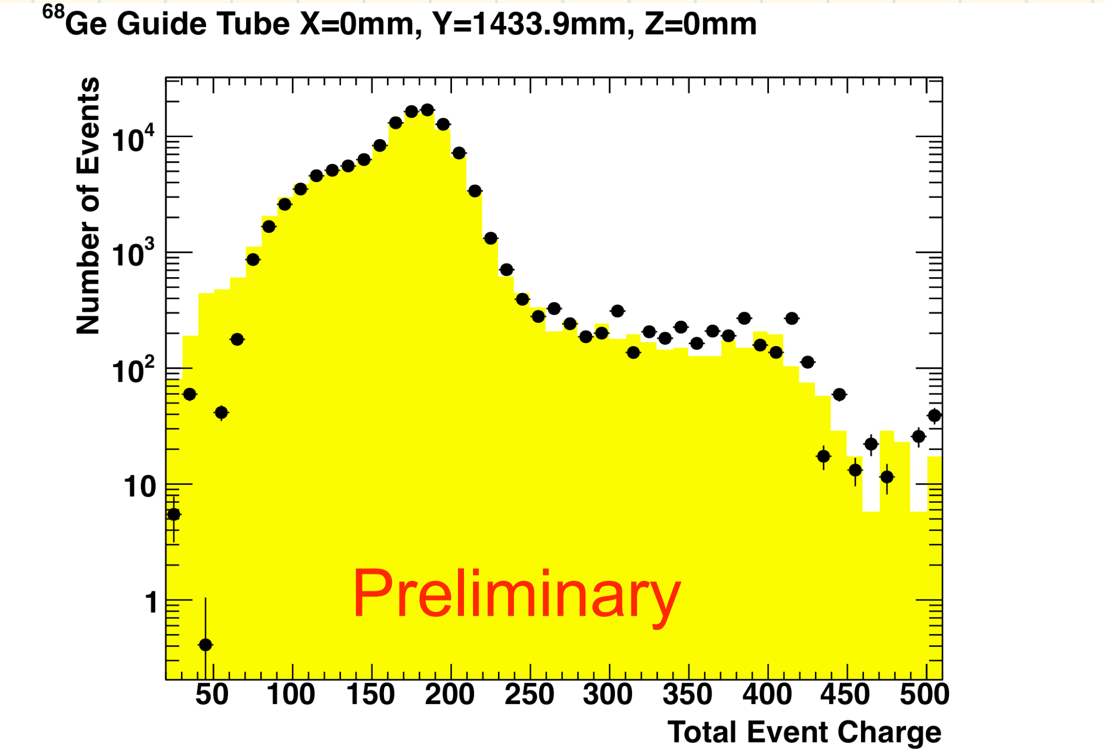
- Deploy ^{68}Ge positron source in target by Z-Axis system
- Total 1.02MeV γ's from annihilation (corresponds to the minimum energy from inverse beta decay reaction)

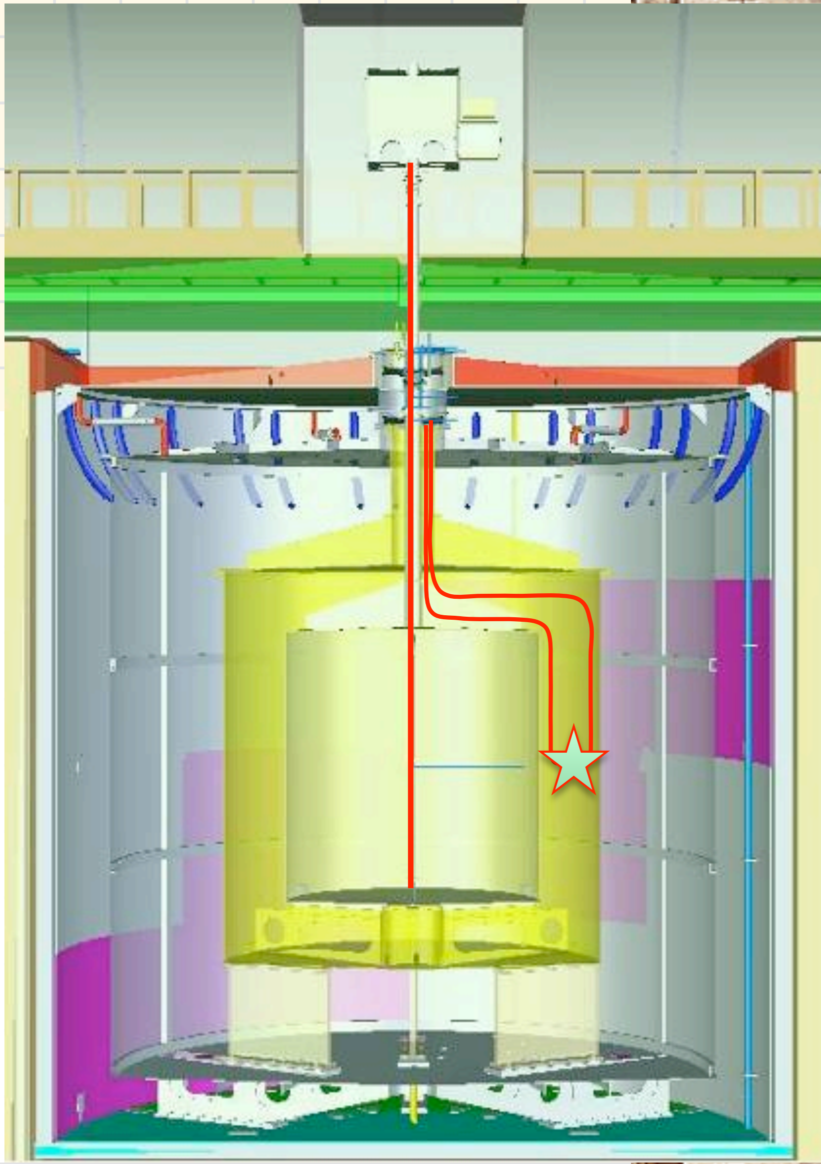




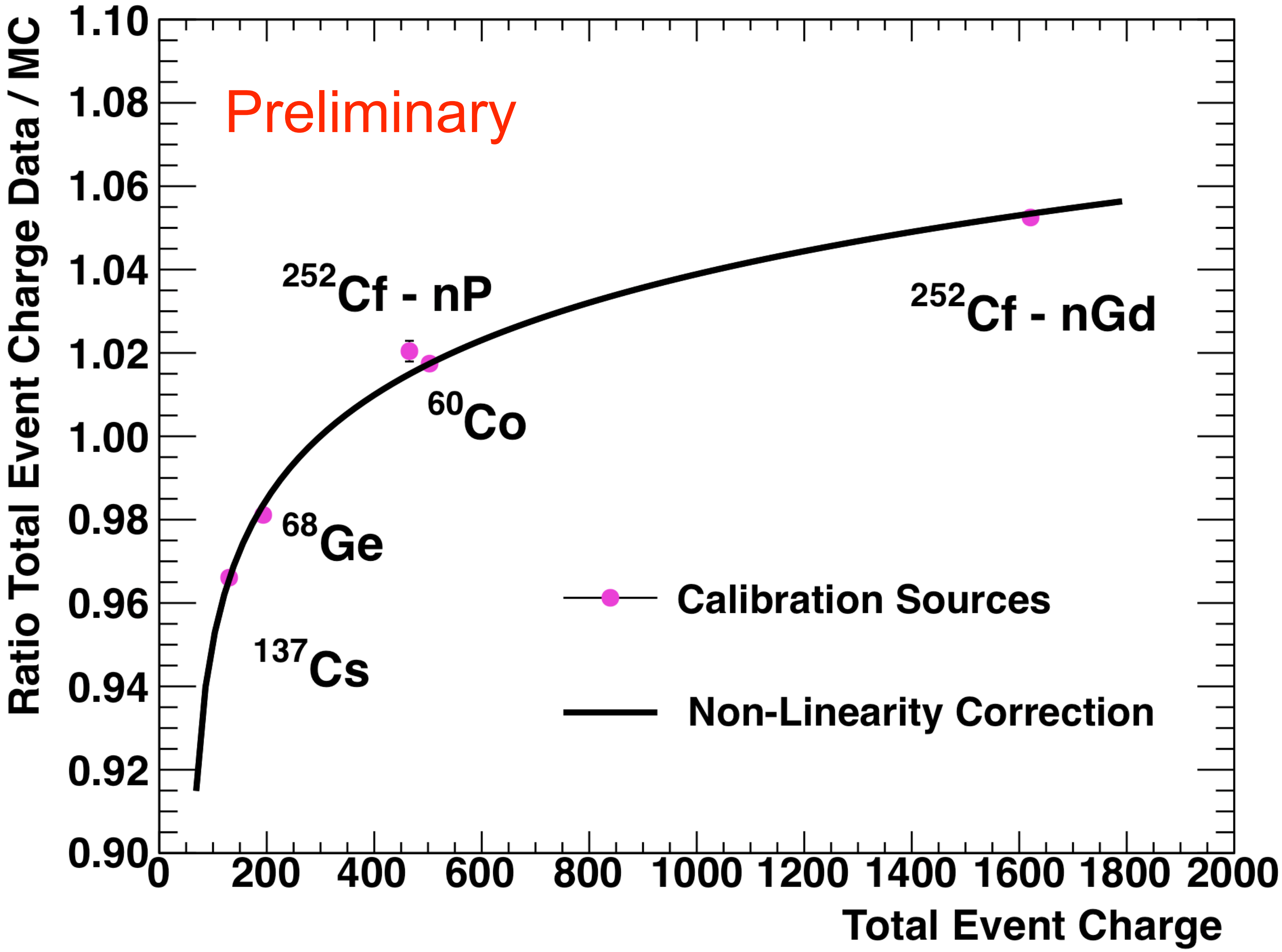
Energy calibration

- Deploy ^{8}Ge positron source in γ-catcher by guide tube system
- Energy calibration in γ-catcher
  (γ-catcher scintilltor is made to give similar light yield to target scintillator)





Non-linearity correction



Neutrino selection

- Prompt signal
- Delayed signal
- Coincidence

Selection criteria (1)

Muon veto:

- $\Delta t_{\mu} > 1msec$

Prompt Event:

- Qmax/Qtot < 0.09 & RMS(Tstart)<40 ns
- 0.7 < E < 12 MeV

Delayed Event:

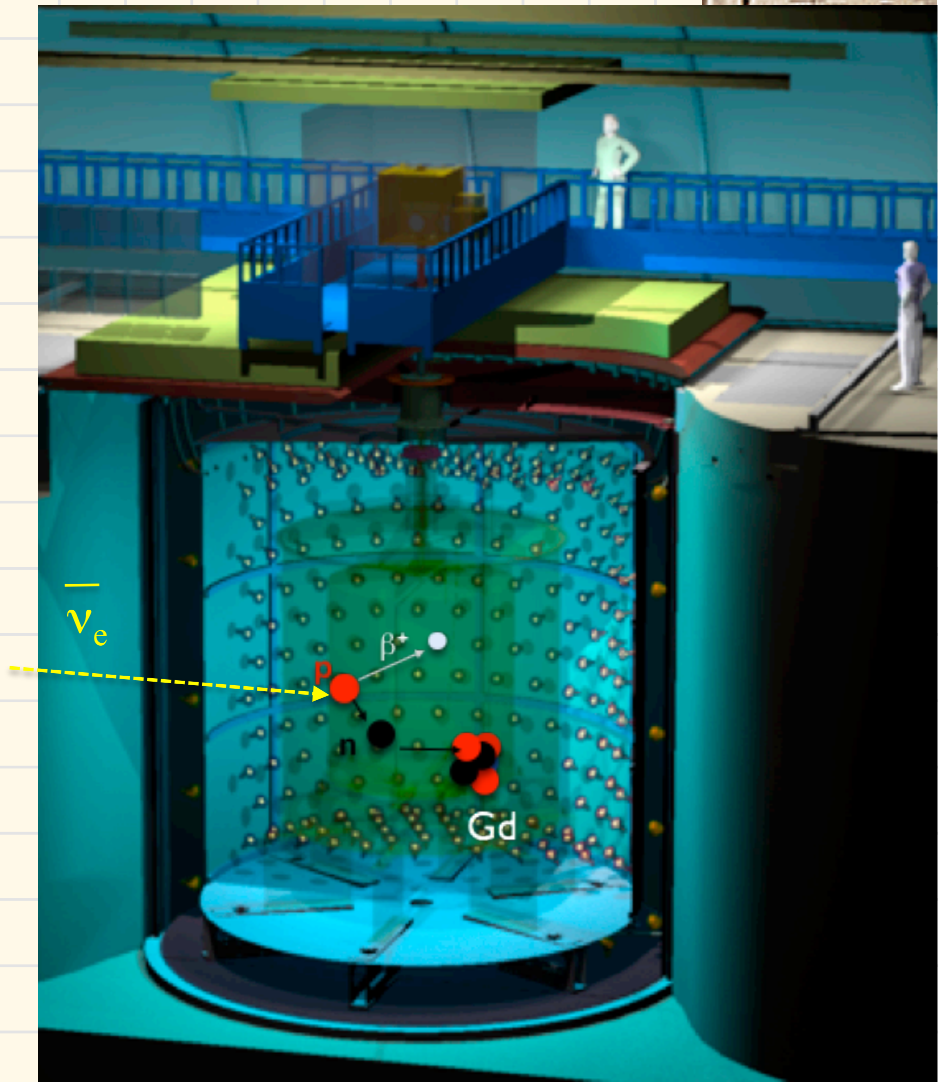
- Qmax/Qtot < 0.06 & RMS(Tstart)<40 ns
- 6 < E < 12MeV

Coincidence:

- Time coincidence: $2 < \Delta t < 100\mu s$
- No space coincidence cut

Multiplicity:

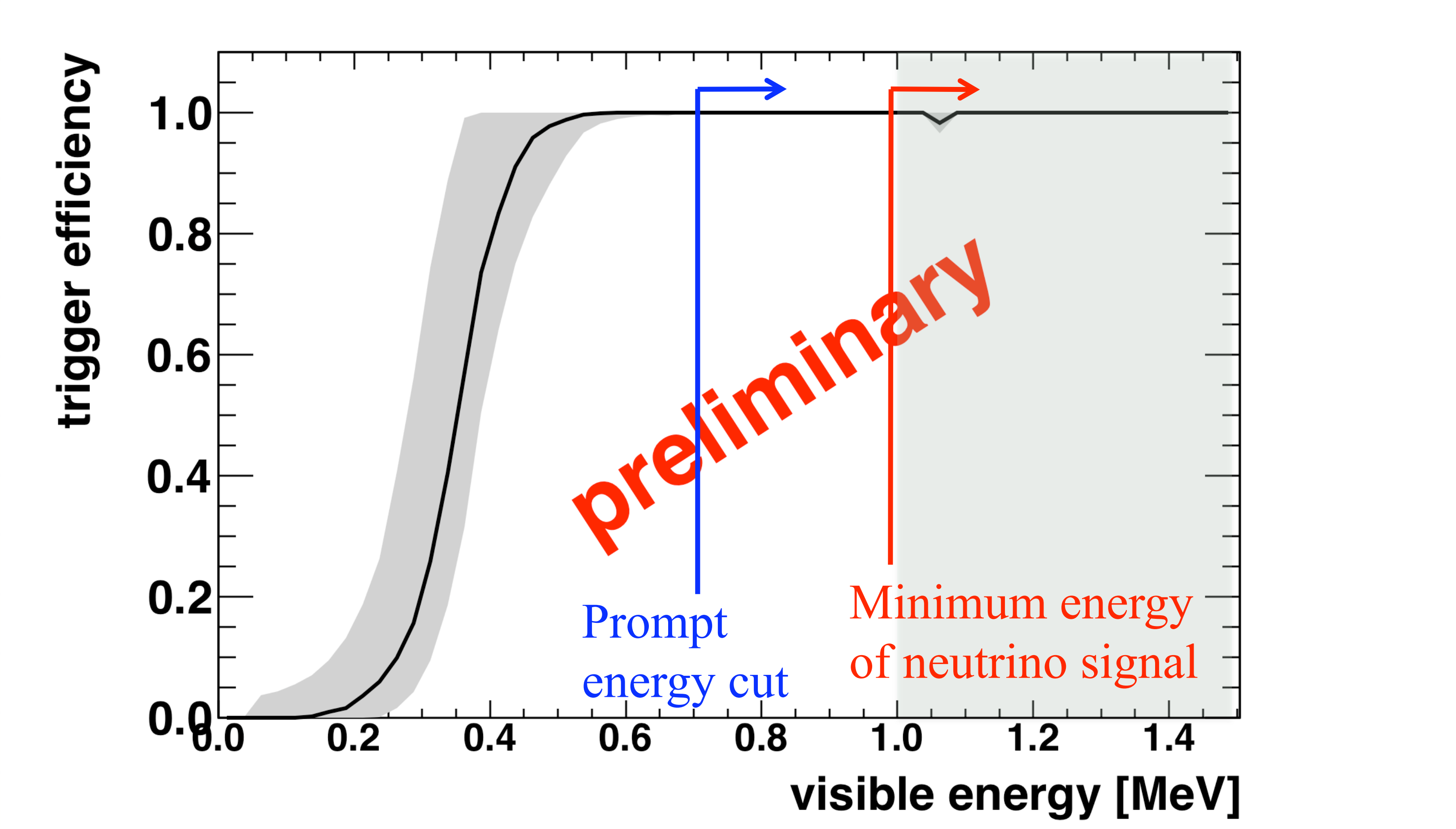
- No trigger (>500keV) within 100µsec before prompt
- Only one trigger (>500keV) within 400µsec after prompt



Neutrino selection

- Prompt signal
- Delayed signal
- Coincidence

Trigger threshold

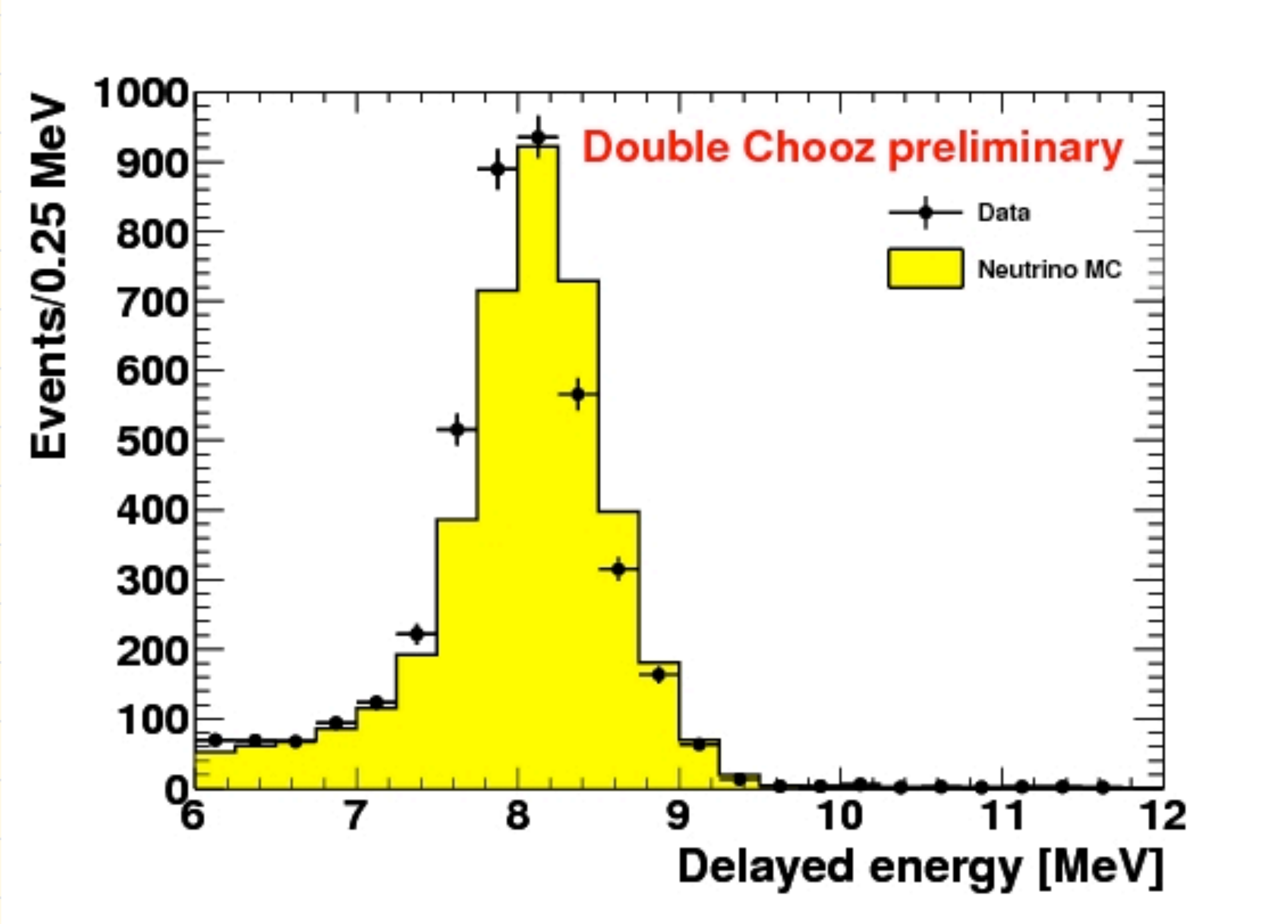


- Trigger efficiency
  - 50% @ 350keV
  - $100^{+0}_{-0.4}$% above 700keV
- Prompt energy cut efficiency > 99.9%

Neutrino selection

- Prompt signal
- Delayed signal
- Coincidence

Delayed energy cut

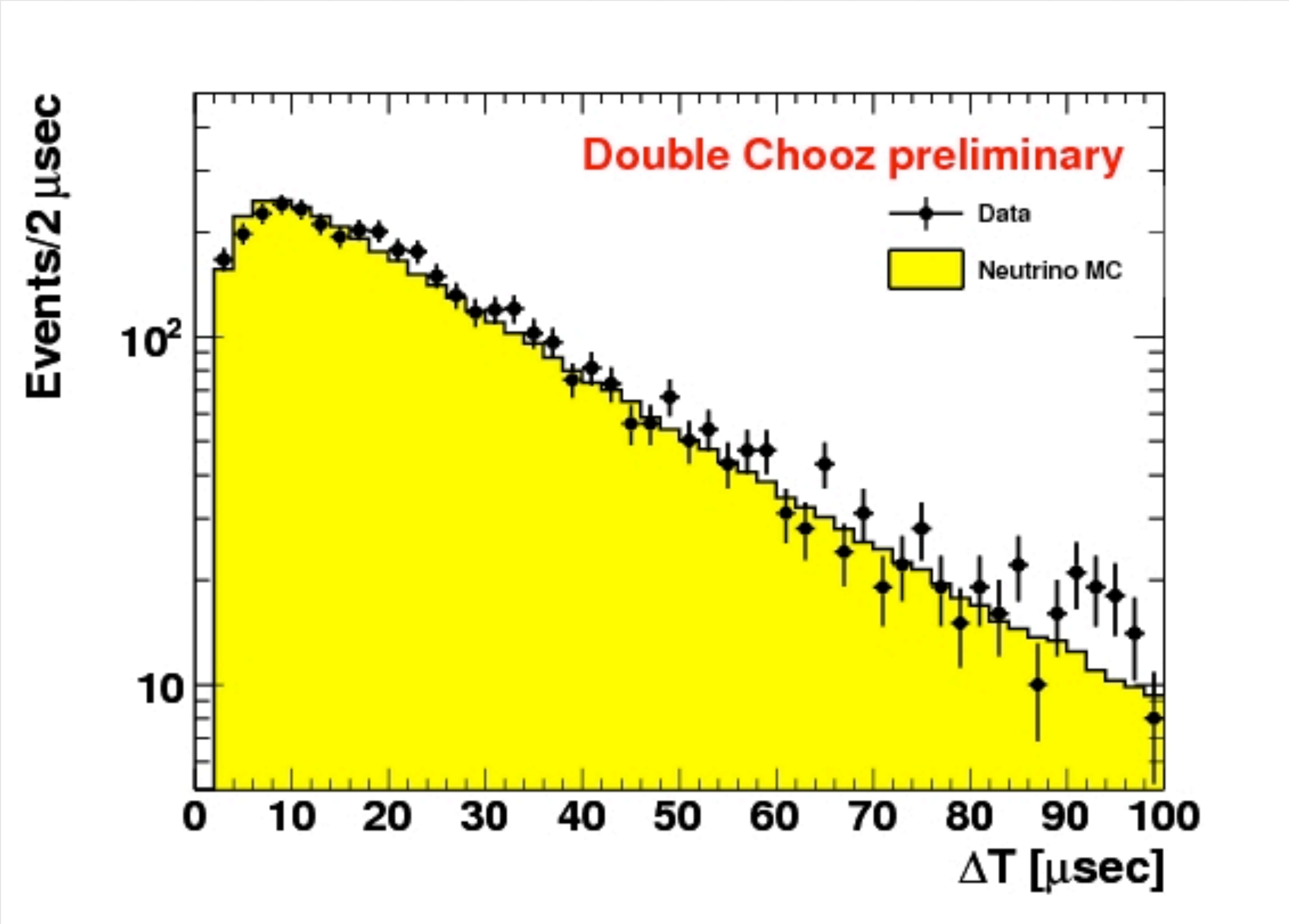


Efficiency of delayed signal: 86.0 ±0.6 %

Neutrino selection

- Prompt signal
- Delayed signal
- Coincidence

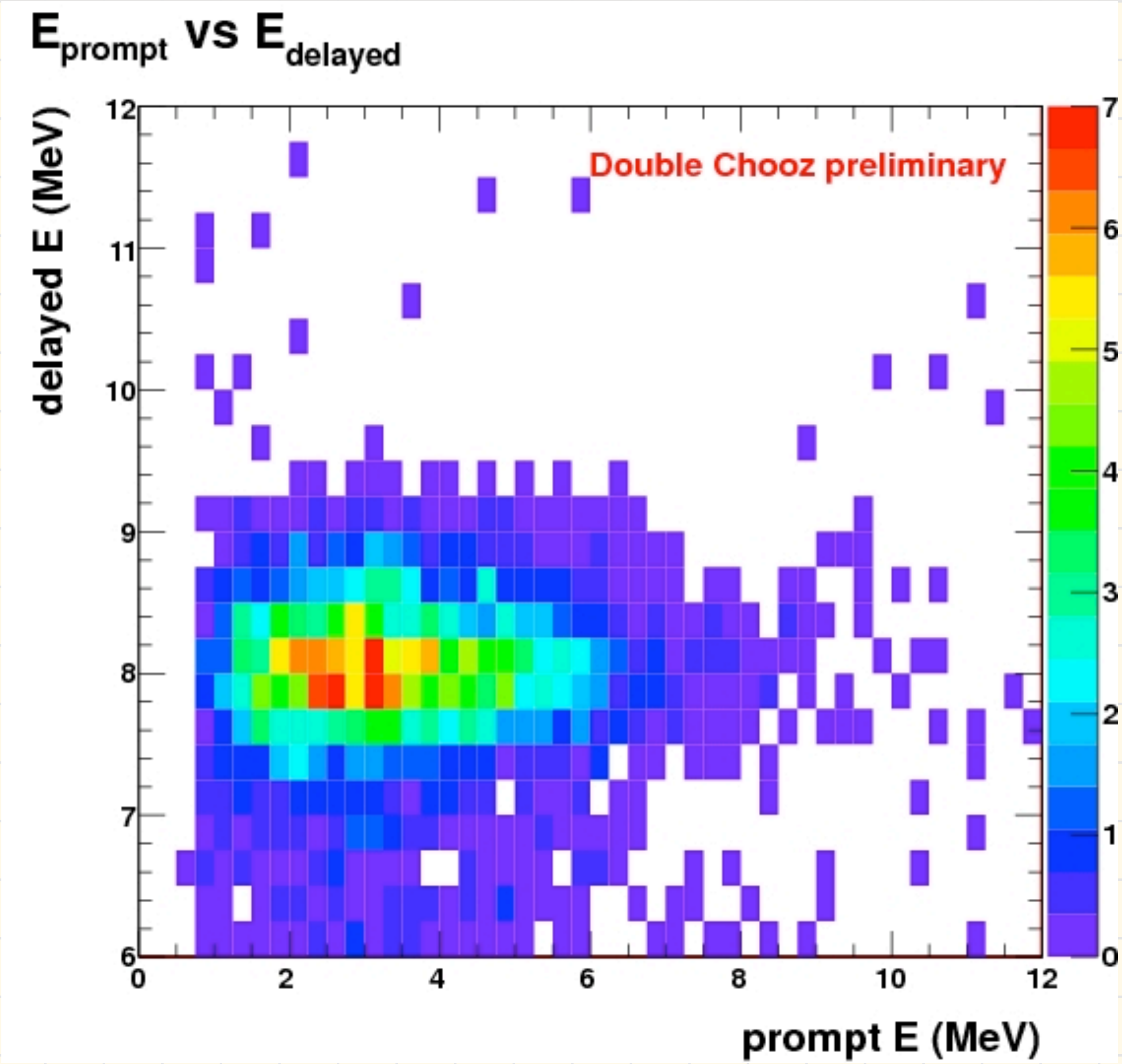
Time coincidence



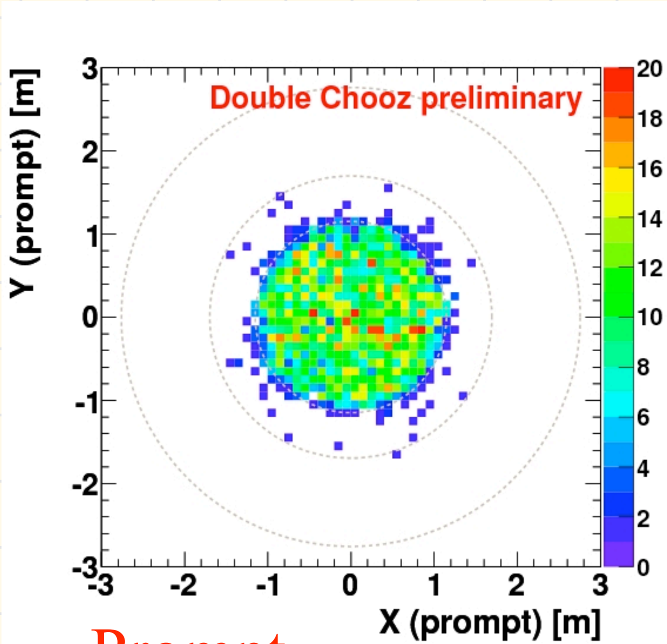
- KeV neutrons thermalized within a few µs
  → captured on Gd with $\tau = 27\mu s$
- Efficiency within [2,100] µs: 96.5 ±0.5 %

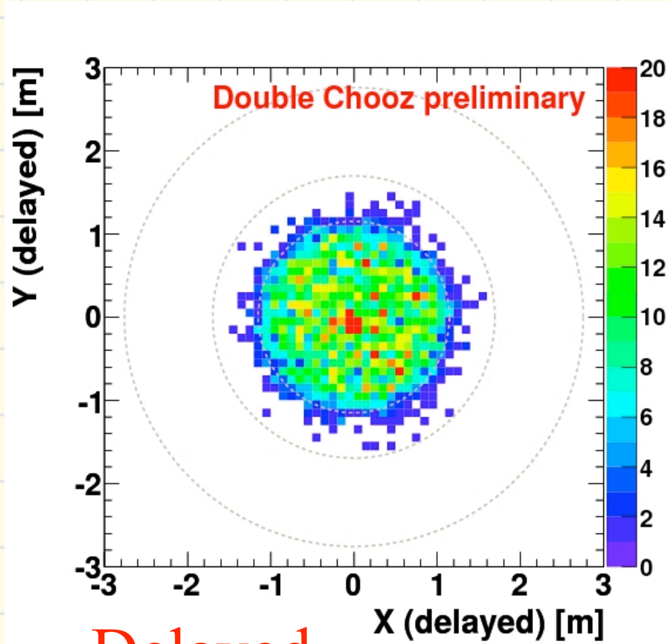
Data quality

Prompt energy vs. delayed energy



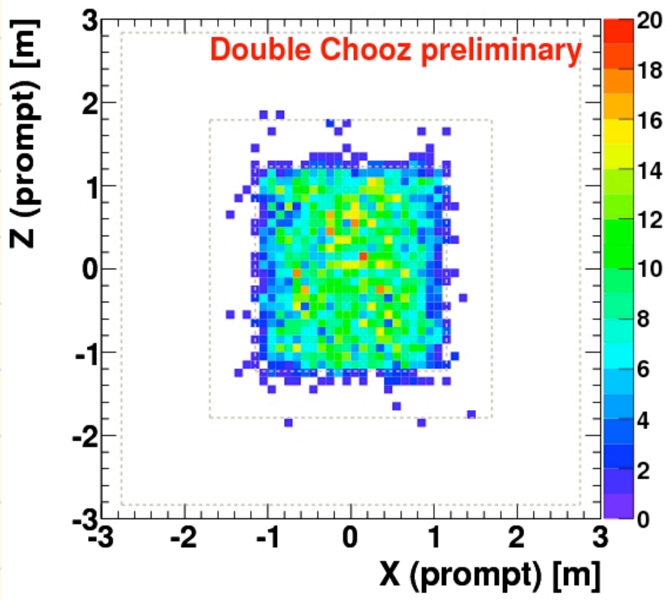
Reconstructed vertex positions

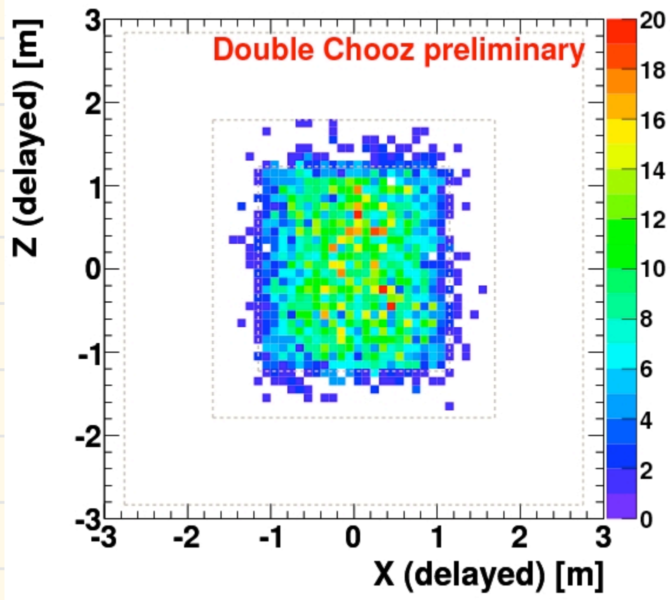




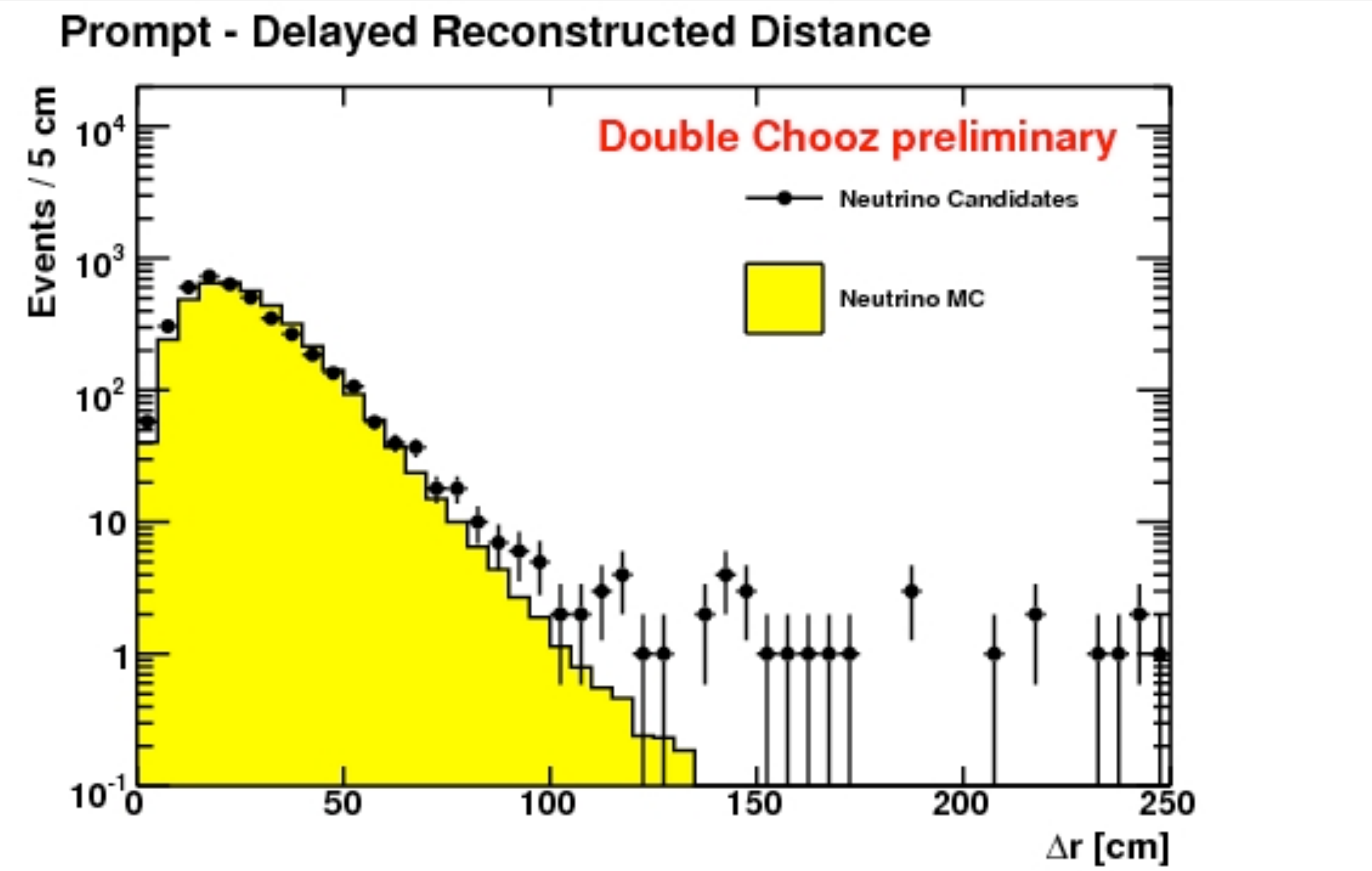
Prompt

Delayed

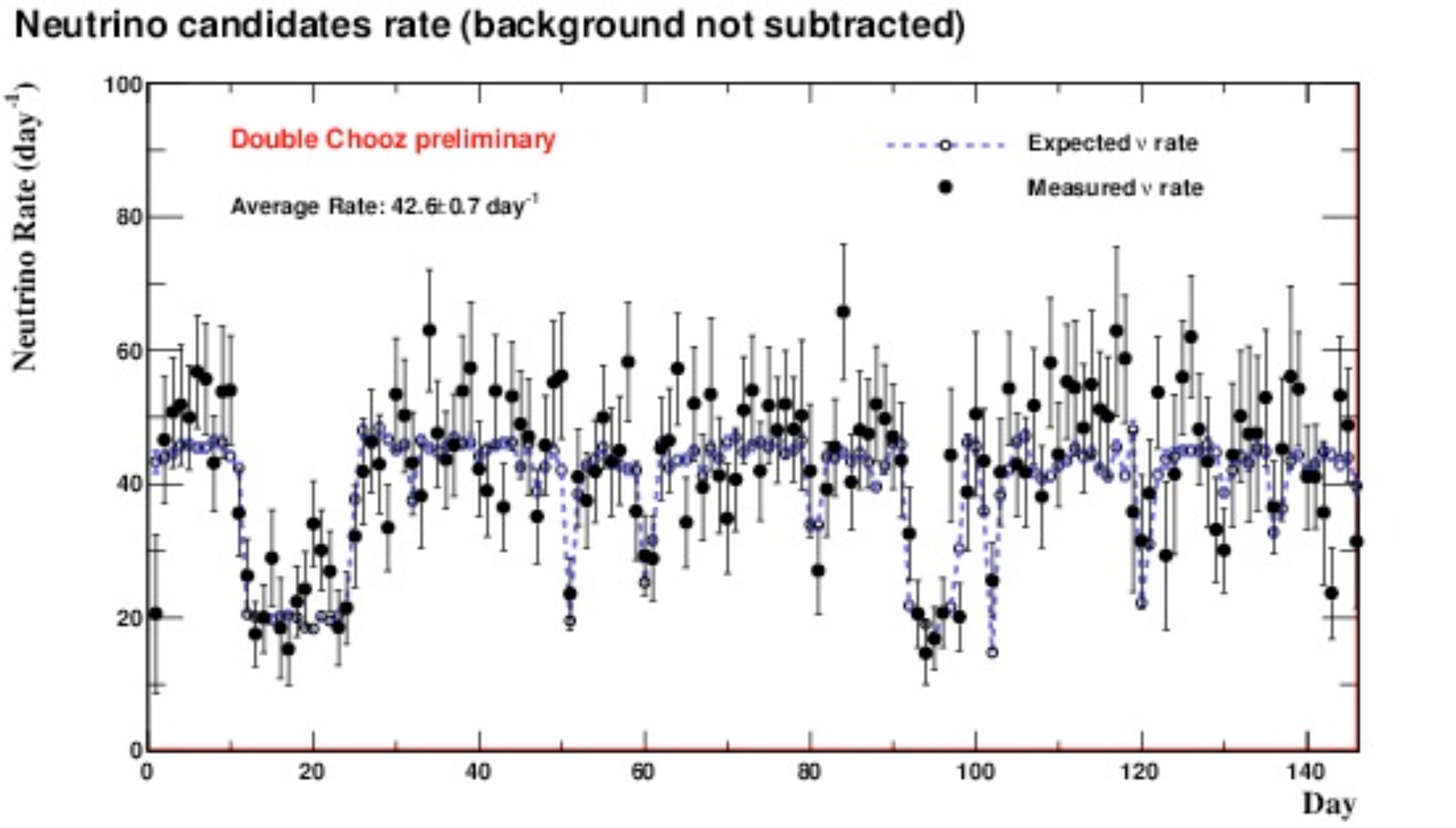




dR: prompt vs. delayed



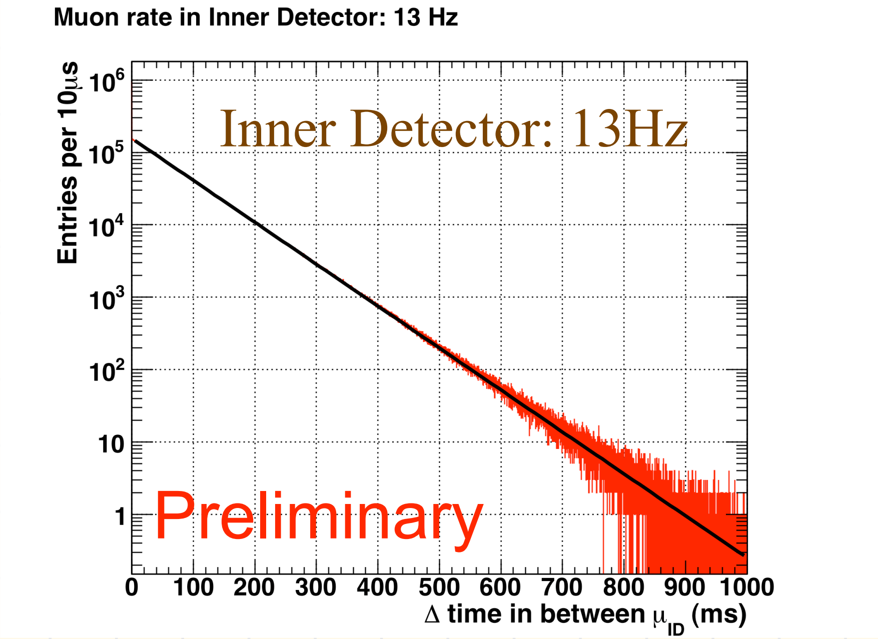
Neutrino candidate: event rate

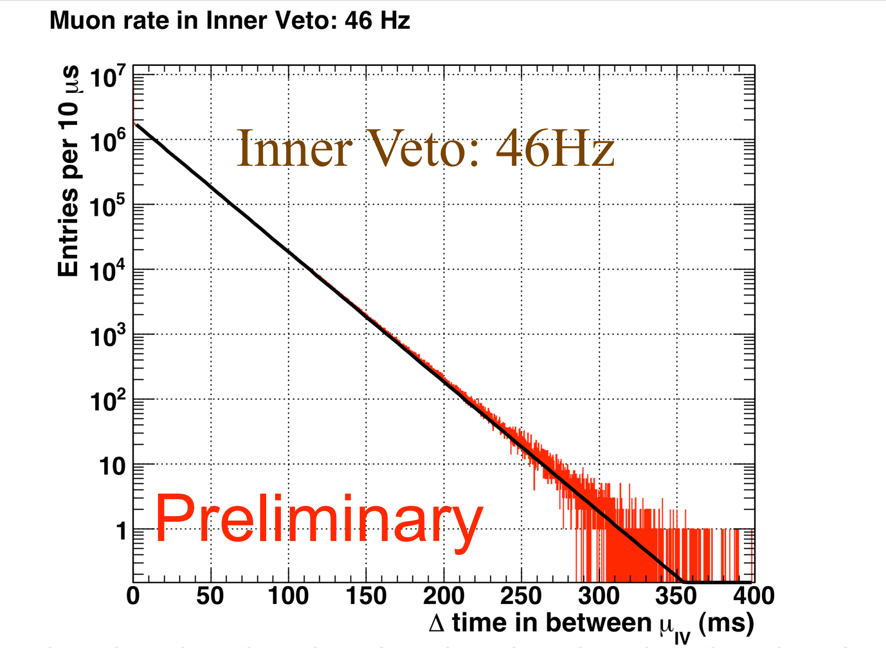


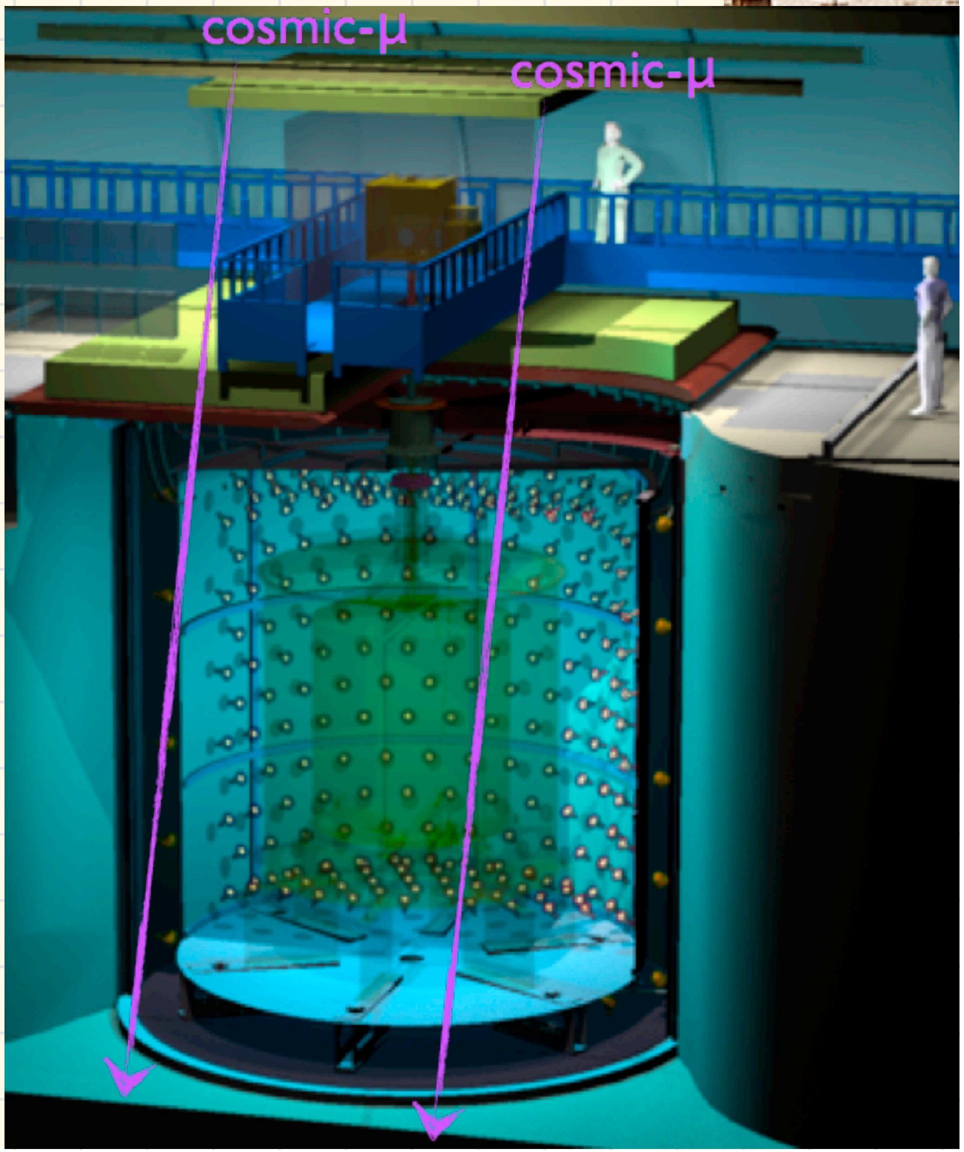
- Background not subtracted
  ➞ good agreement indicates low background level

Background

Cosmic muon rate

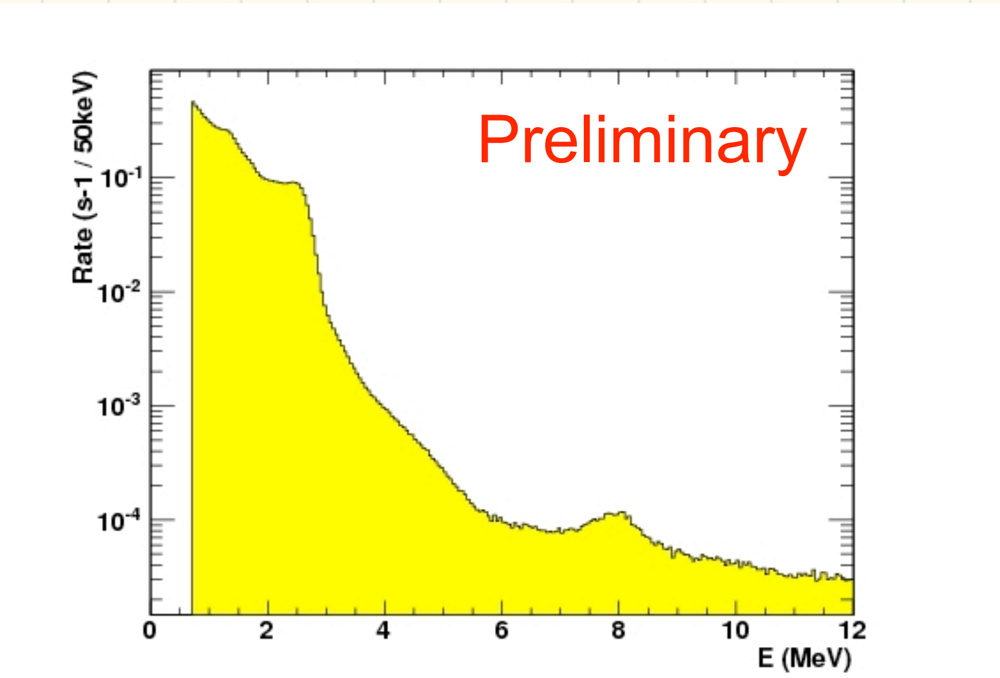


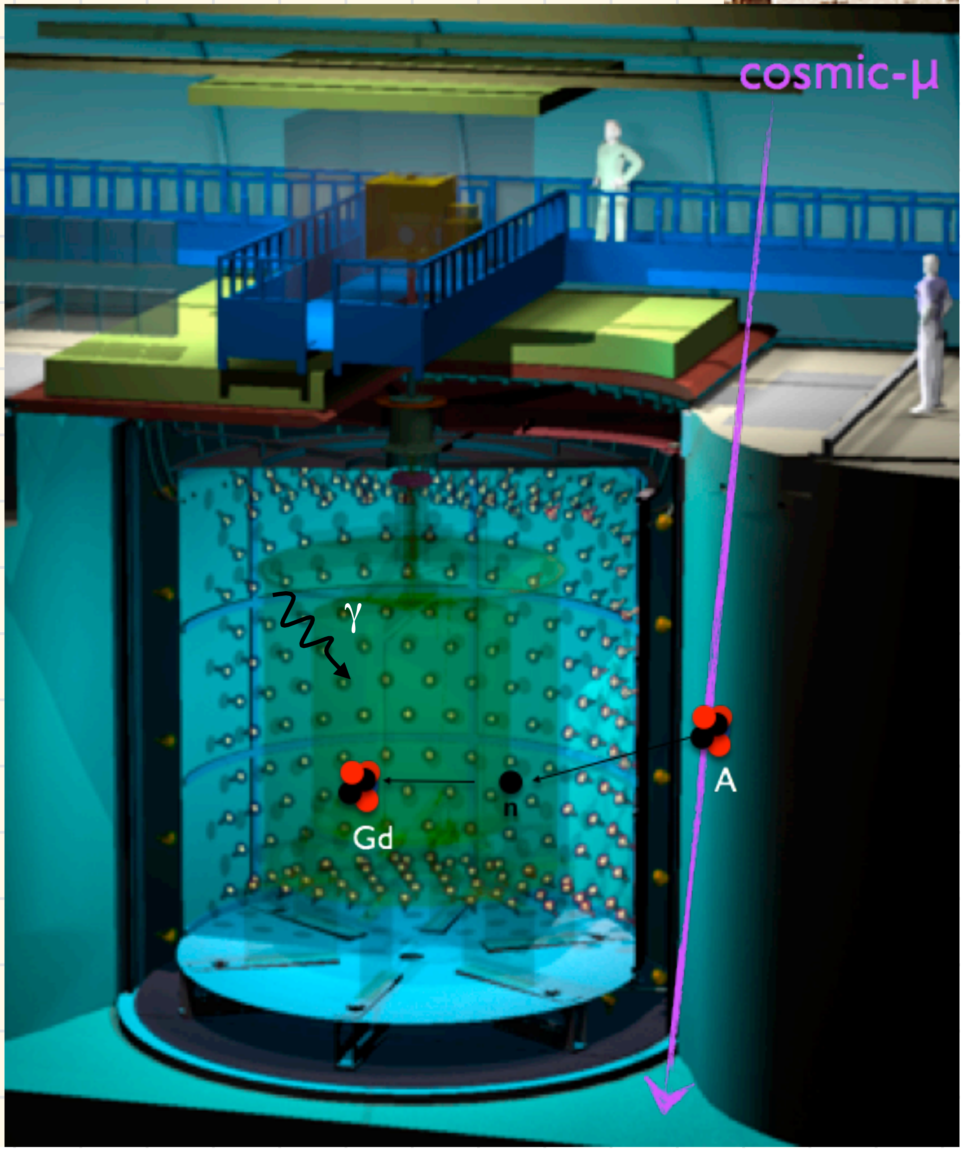




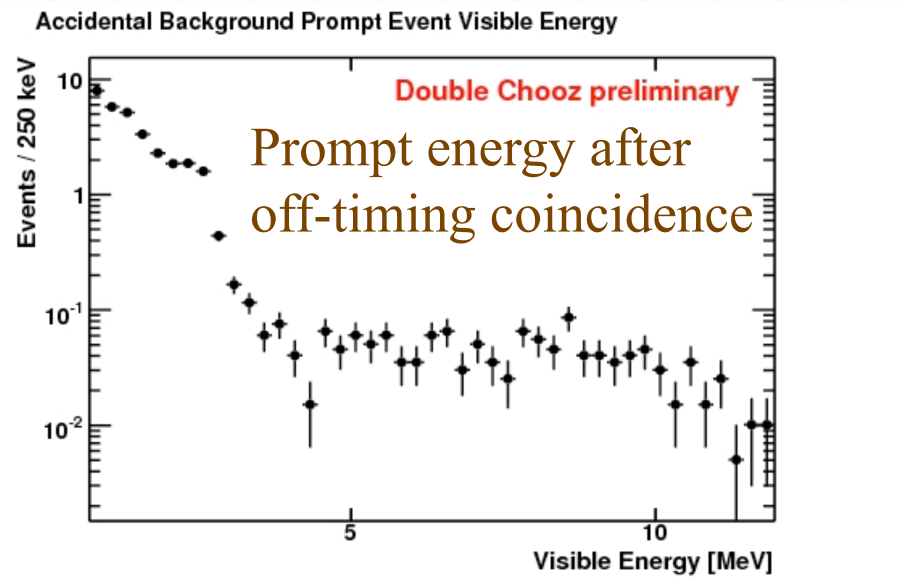
Accidental BG

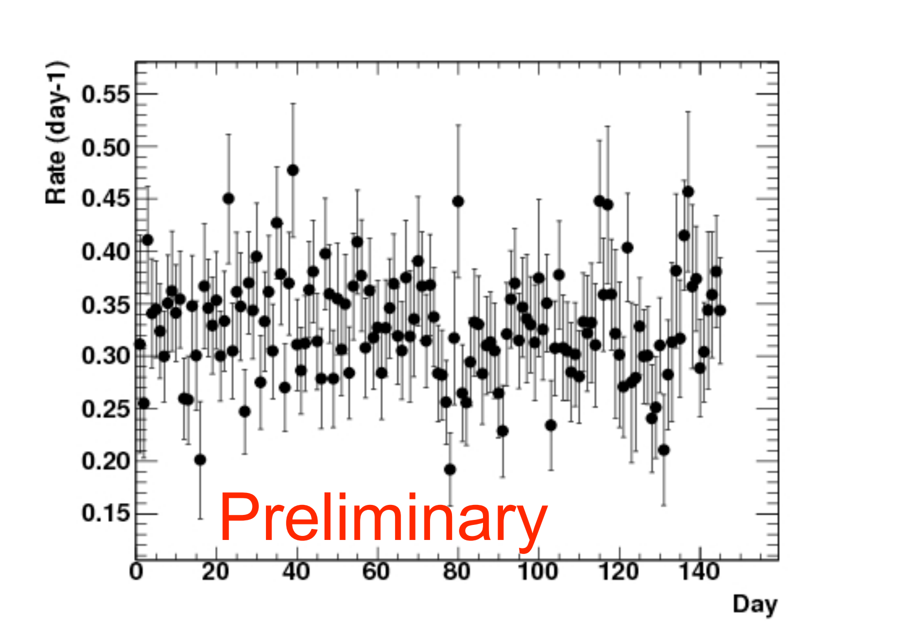
Single spectrum

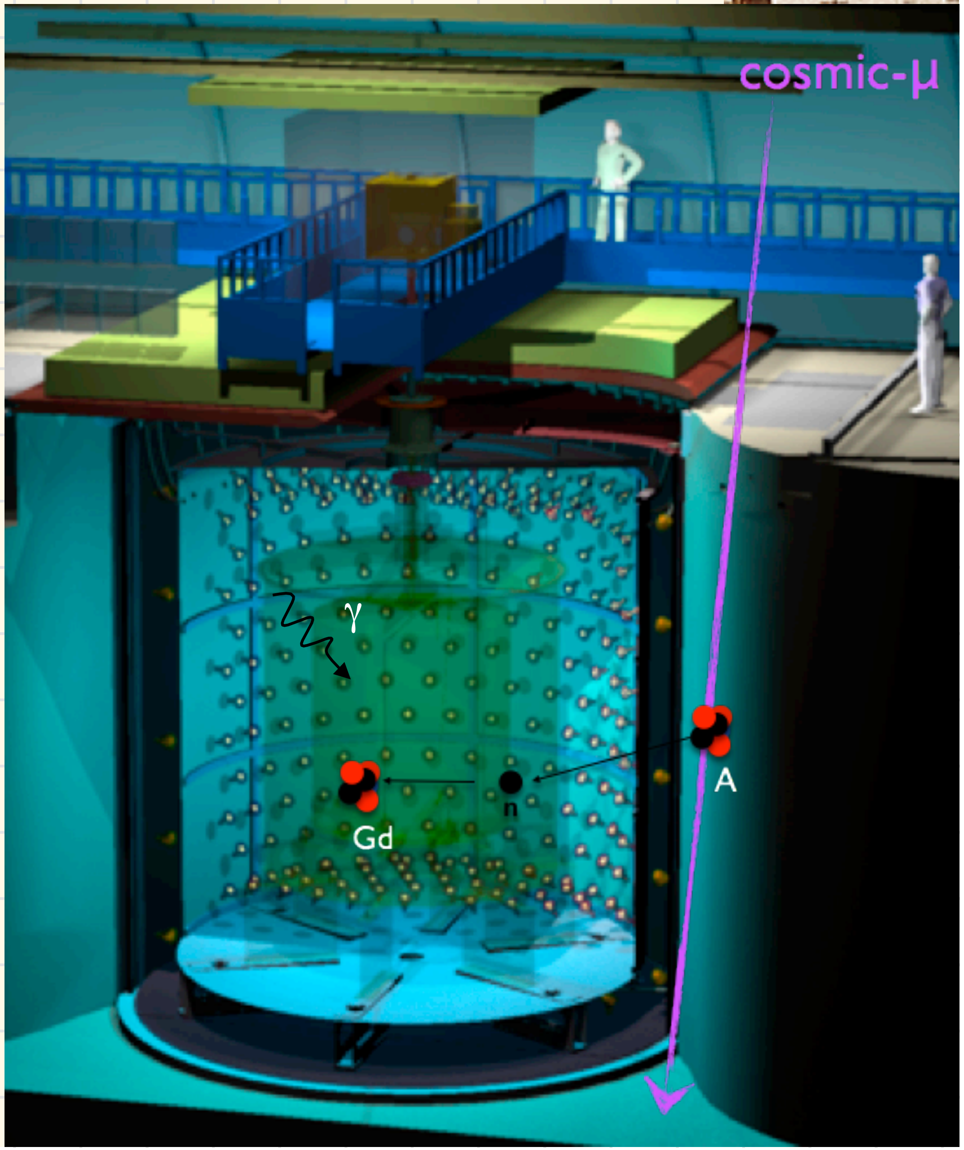




Accidental BG



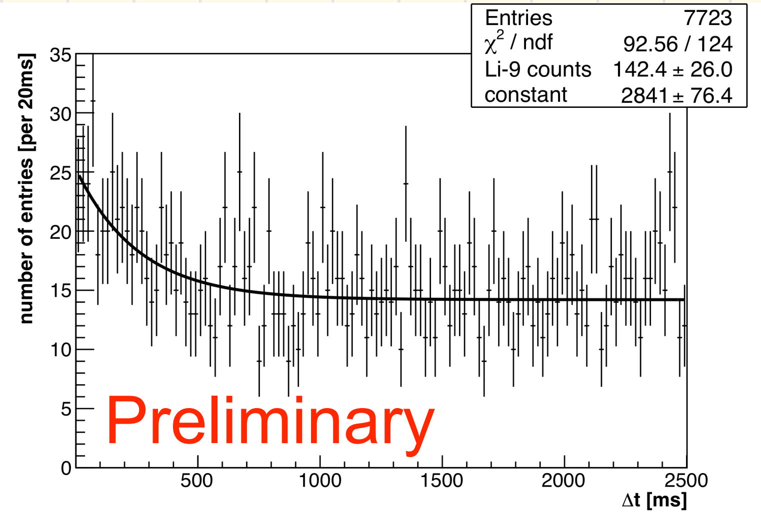


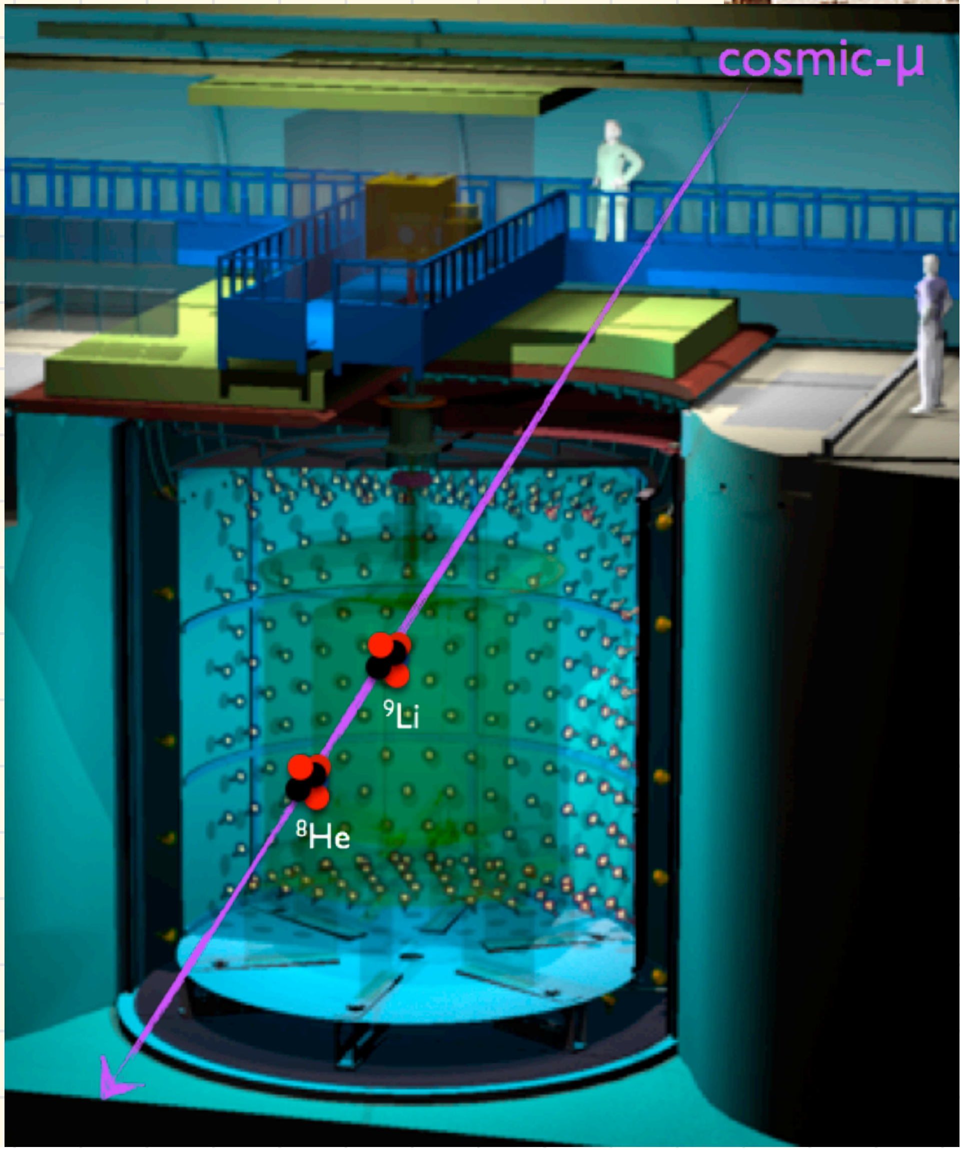


Rate: 0.332 ±0.004 events/day

Correlated BG: cosmogenic

Cosmic-ray μ spallation products:
^{9}Li, ^{8}He
➙ n+β decay with decay time of 200msec
completely mimic neutrino signal
$^{9}Li \rightarrow e^{-} + n + {}^{8}Be$ ($n + e^{-} < 11.9$MeV)





Number of BG events estimated from time correlation with showering μ
➙Consistent with reactor OFF measurement

Rate: 2.3 ±1.2 events/day

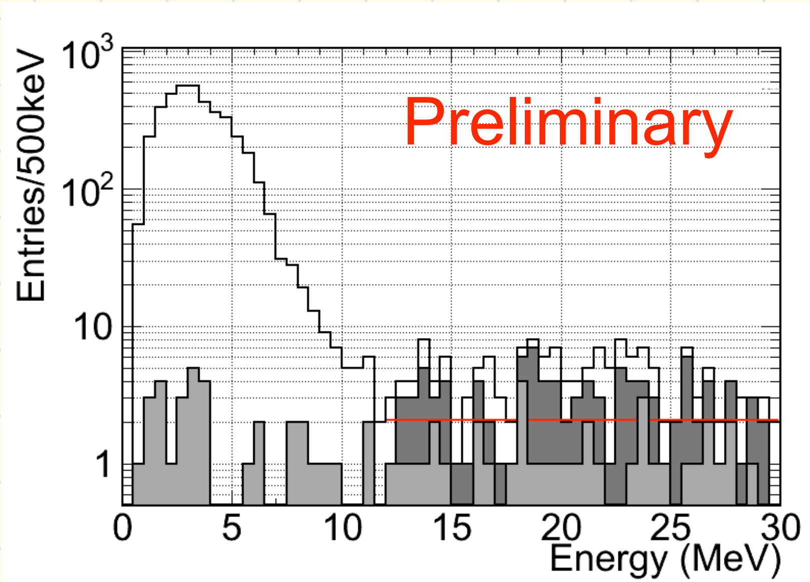
Correlated BG: fast neutron

Prompt signal:

Recoil proton

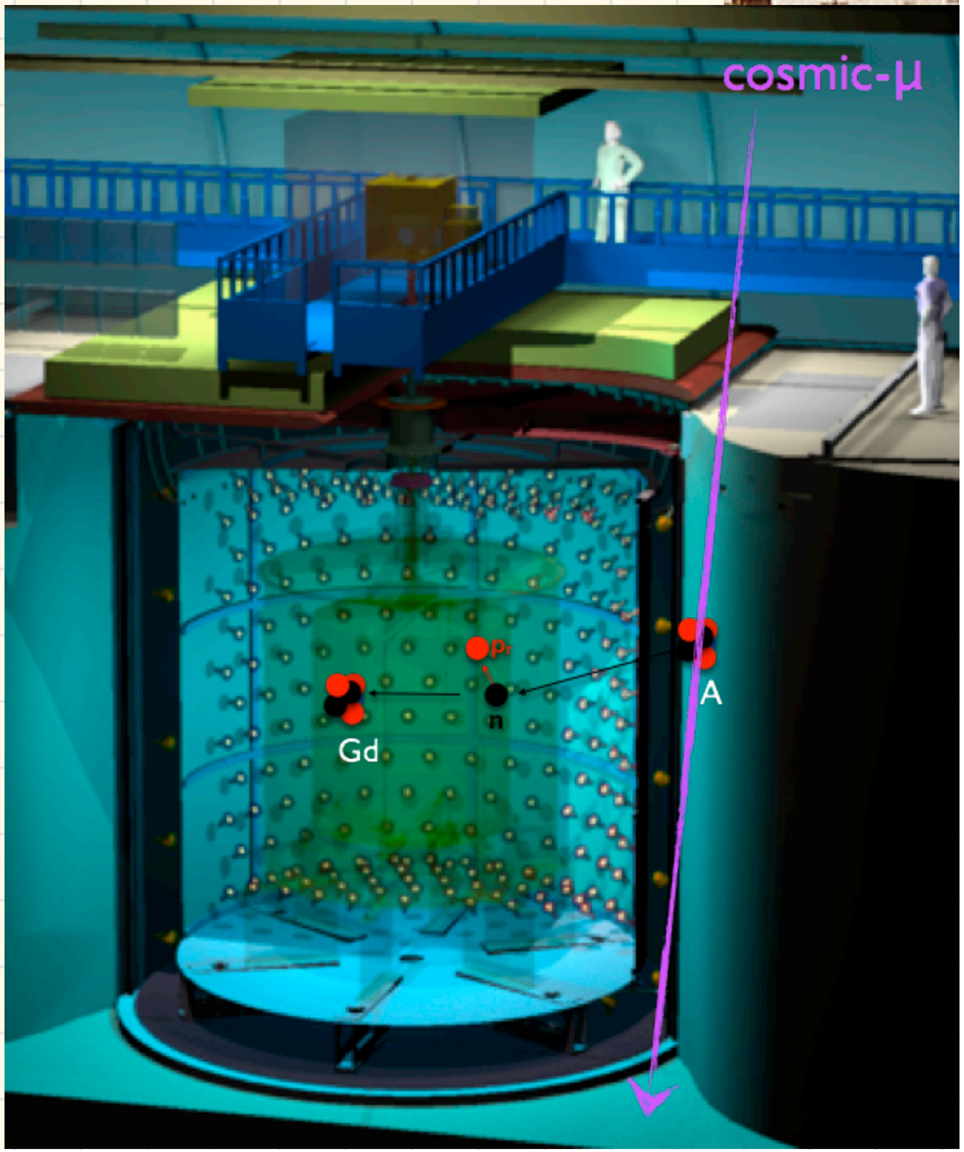
Delayed signal

8MeV γ's from neutron capture on Gd



Number of BG events estimated from the spectrum at high energy

Rate: 0.7 ±0.5 events/day



Reactor OFF data

- 1 day data was taken with both reactor OFF
- 3 events pass neutrino selection below 30MeV
  1. E_{prompt}=9.8 MeV, Δt=201msec from showering muon (>600MeV), vertex close to muon track (15.4cm)
  2. E_{prompt}=4.8 MeV, Δt=241msec from showering muon, vertex close to muon track (27.9cm)
  3. E_{prompt}=26.5 MeV, no showering muon within 5sec

Number of events observed under rector OFF condition was consistent with the estimated number of BG events

Neutrino oscillation analysis

Definition of χ^2

$$\chi^2 = \left(N_i - \left(\sum_R^{\text{Reactors}} N_i^{\nu,R} + \sum_b N_i^b(P_b)\right)\right) \times \left(M_{ij}^{\text{signal}} + M_{ij}^{\text{detector}} + M_{ij}^{\text{stat}} + \sum_b^{\text{bkgnds.}} M_{ij}^{\text{b}}\right)^{-1}$$

$$\times \left(N_j - \left(\sum_R^{\text{Reactors}} N_j^{\nu,R} + \sum_b N_j^b(P_b)\right)\right)^{\text{T}}$$

$$+ \sum_R^{\text{Reactors}} \frac{(P_R)^2}{\sigma_R^2}$$

$$+ \sum_b^{\text{bkgnds.}} \frac{(P_b)^2}{\sigma_b^2}$$

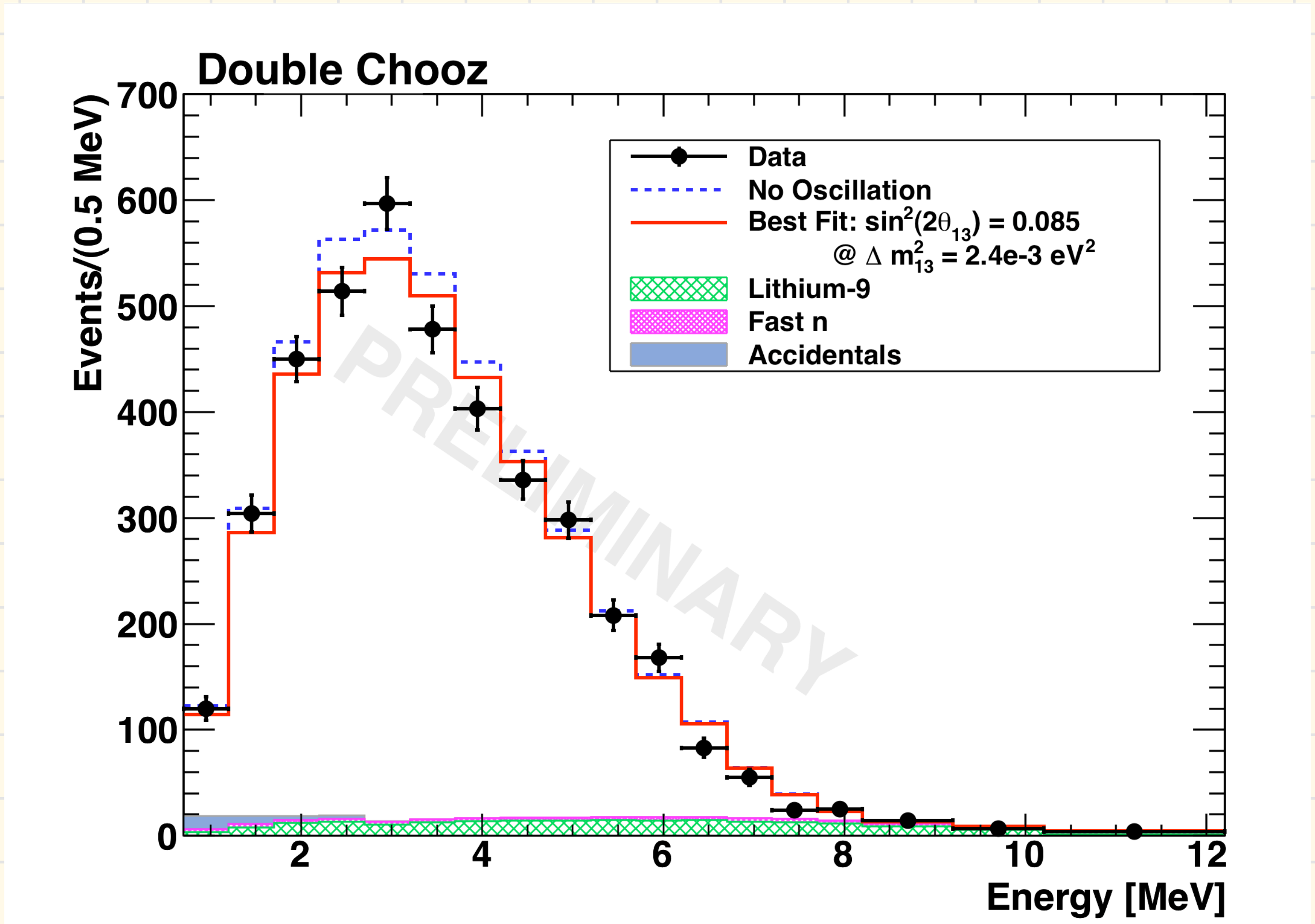
M_{ij}^{signal}: Signal covariance matrix.

M_{ij}^{detector}: Detector covariance matrix.

M_{ij}^{stat}: Statistical covariance matrix.

M_{ij}^{b}: Covariance matrix for background

Results



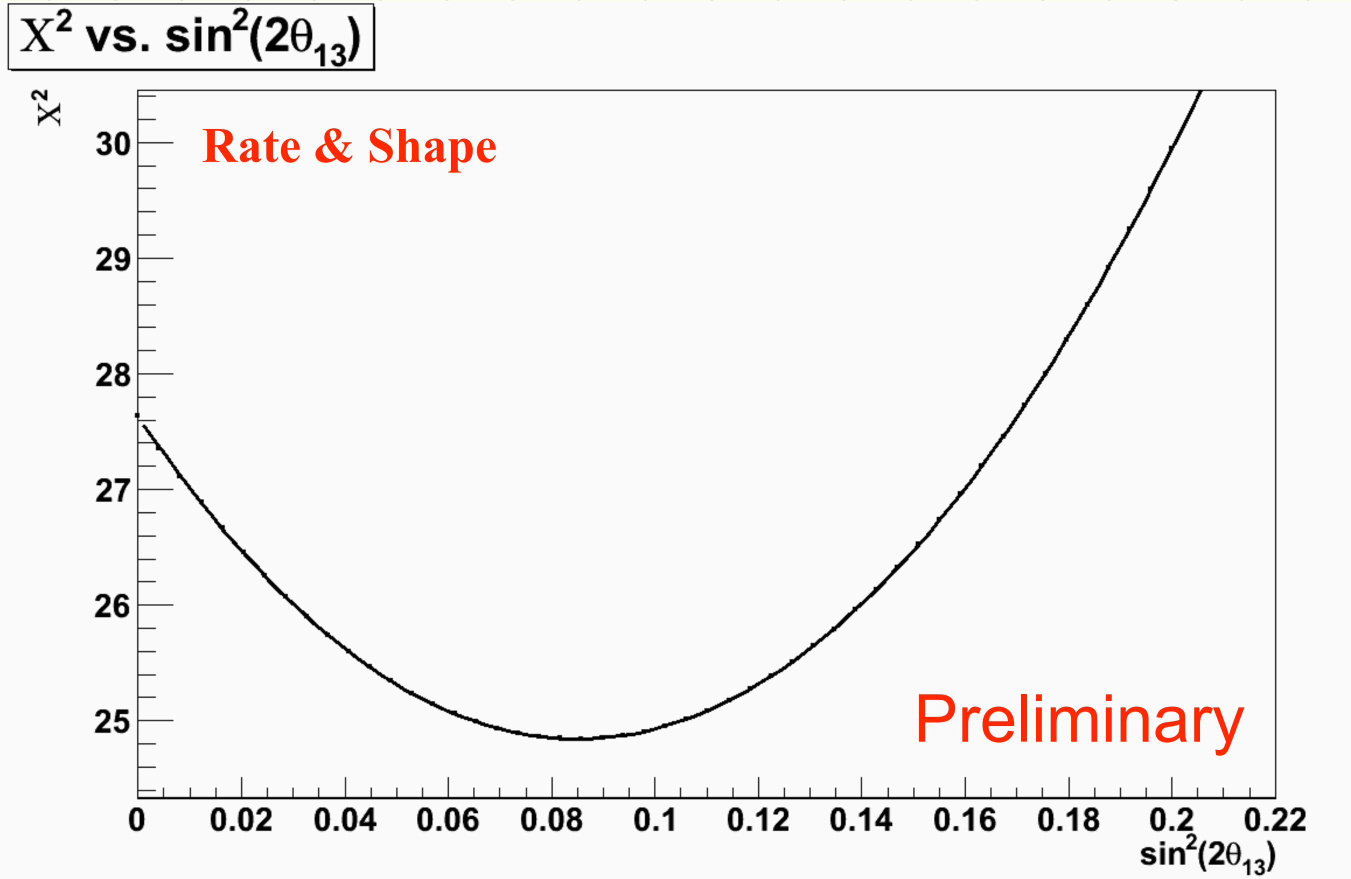
Rate Only: $\sin^2 2\theta_{13} = 0.096 \pm 0.029(\text{stat}) \pm 0.073(\text{syst})$

Shape Only: $\sin^2 2\theta_{13} = 0.044 \pm 0.157$

Rate & Shape: $\sin^2 2\theta_{13} = 0.086 \pm 0.029(\text{stat}) \pm 0.042(\text{syst})$

➞ No-Oscillation Excluded at 92.9 %

Results



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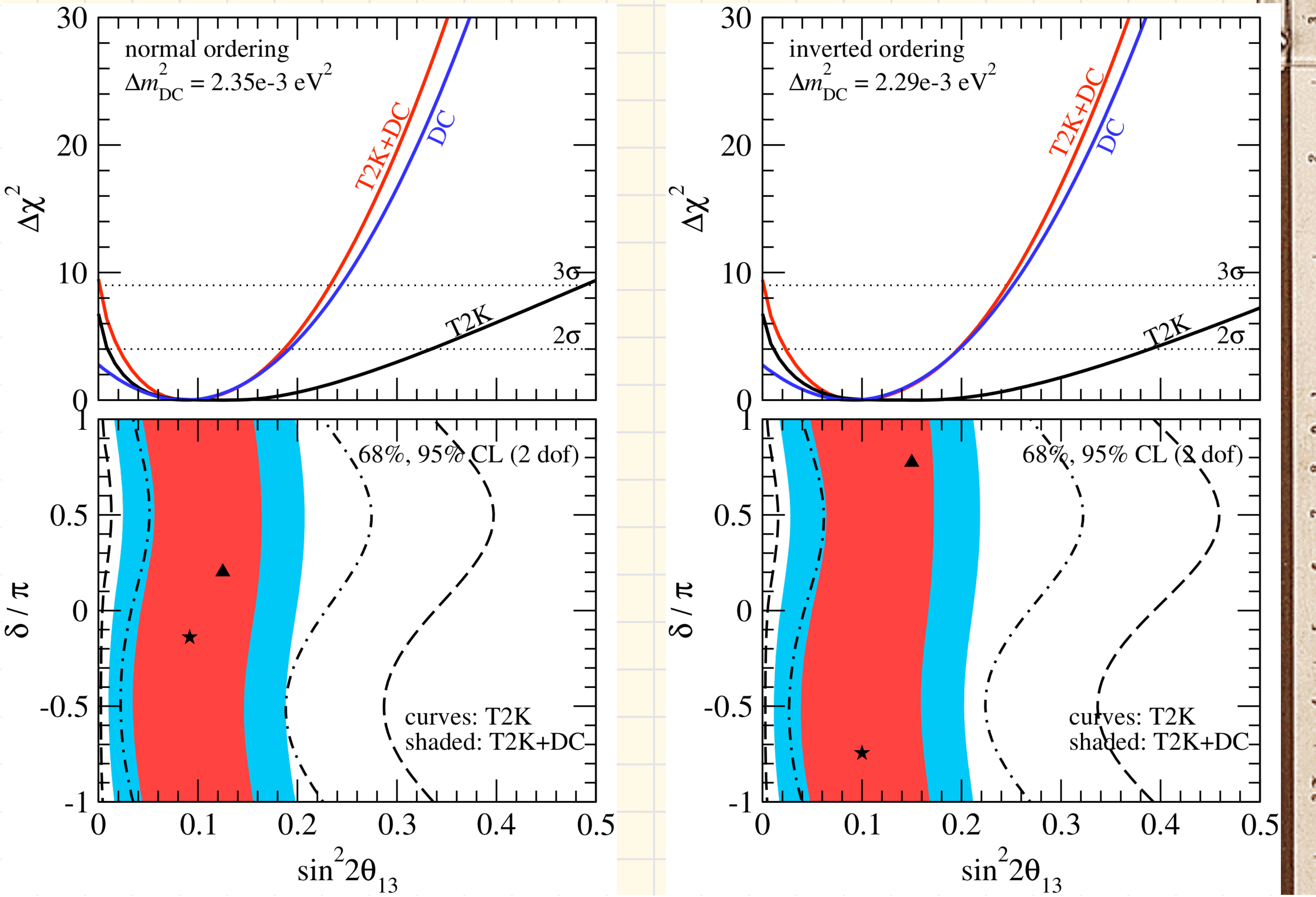
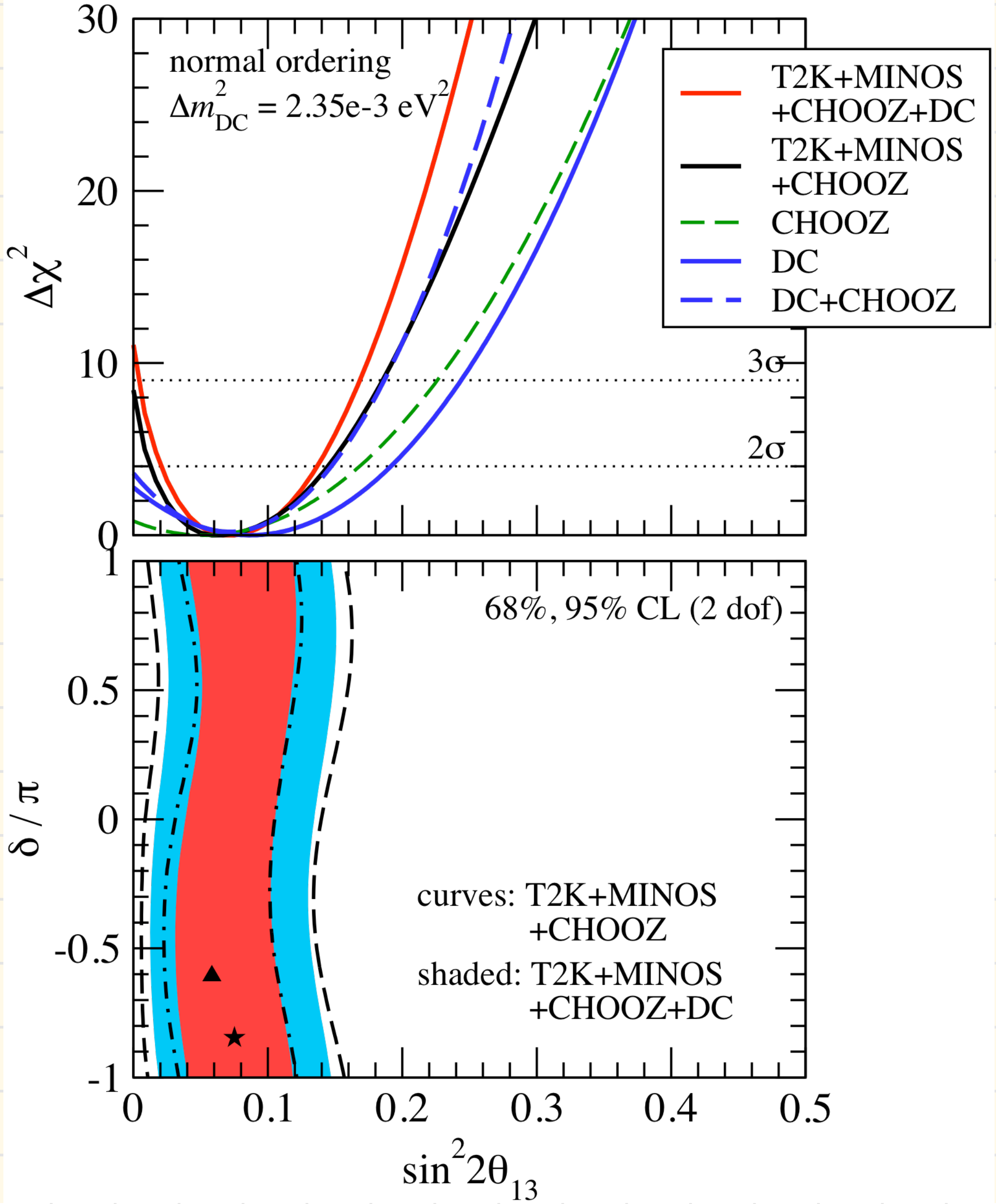
Rate & Shape: $\sin^2 2\theta_{13} = 0.086 \pm 0.029(\text{stat}) \pm 0.042(\text{syst})$

→ No-Oscillation Excluded at 92.9 %

Combined analysis: T2K+Double Chooz



Combined analysis: T2K+MINOS+CHOOZ+Double Chooz



日本経済新聞
2011年(平成23年)11月11日(金曜日)　★14版　社会　38

ニュートリノ変化の兆候
短い距離でも確認
東北大など

東北大は10日、物質を構成する最小単位である素粒子のニュートリノが、約1㌔という短い距離を飛ぶ間に他の種類のニュートリノに変化した兆候を初めてとらえることに、同校などが参加する国際研究グループが成功したと発表した。宇宙誕生の謎を解明する手掛かりになるという。

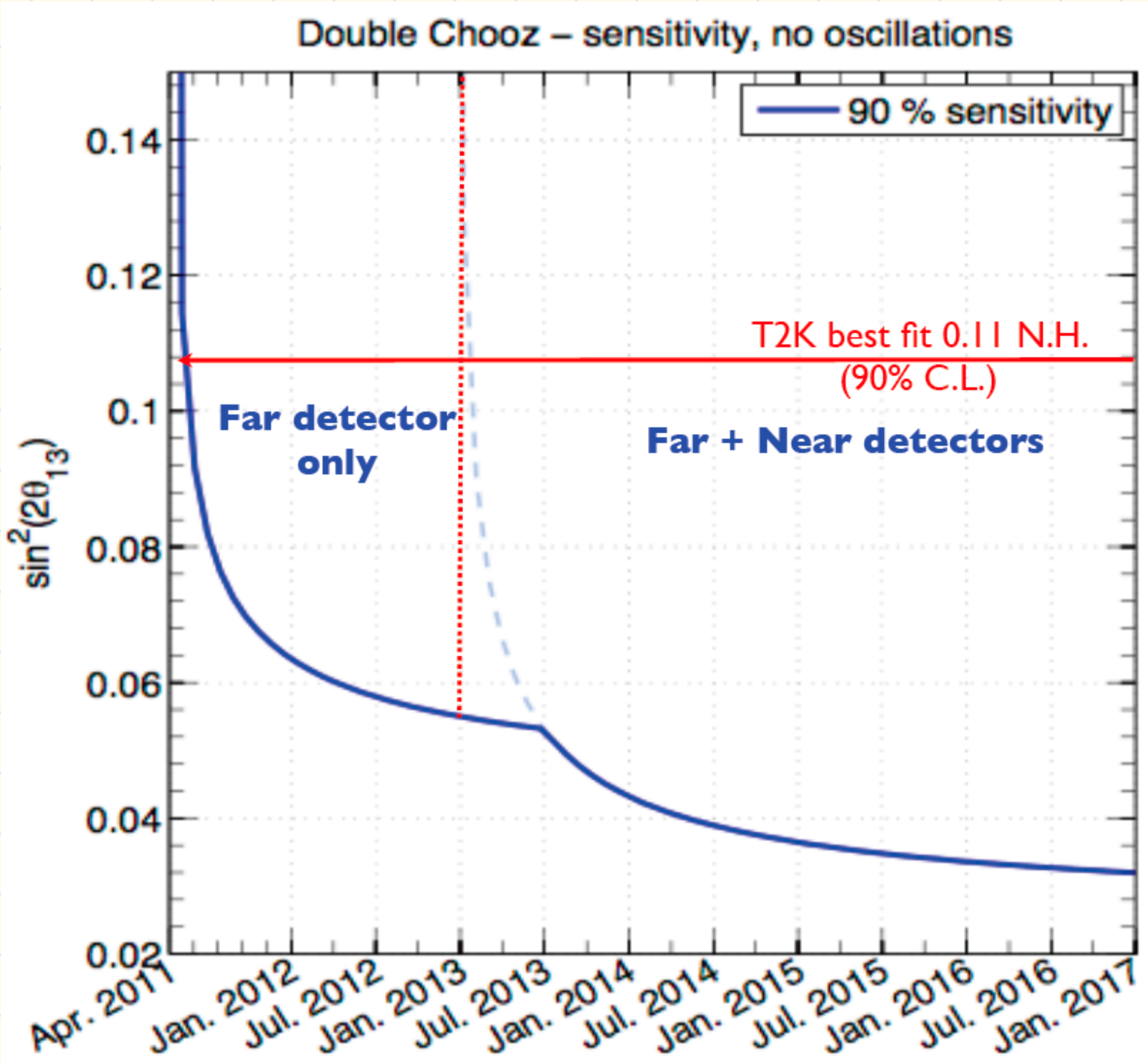
フランス北部のショー原子力発電所で発生するニュートリノを、原子炉から約1㌔離れたトンネル内に検出器を置いて観測。ニュートリノの数が発生時より4～5%減っていることを確認した。

ニュートリノには電子型、ミュー型、タウ型の3種類があり、検出器では電子型をとらえる。「原子炉で発生した電子型ニュートリノがミュー型とタウ型に変化したと考えられる」(末包文彦東北大准教授)という。

3種のニュートリノが相互に移り変わる現象はニュートリノ振動と呼ばれ、これまでは数百㌔以上を飛行する間の変化を観測した。短距離の変化を調べると各ニュートリノの「混ざり具合」が詳しく分かる。

宇宙誕生の際にあった反物質がなくなり、現在の宇宙は物質だけが残ったという考えがある。ニュートリノ振動の様子を調べることで、その仕組みの解明に道筋が付けられると期待されている。

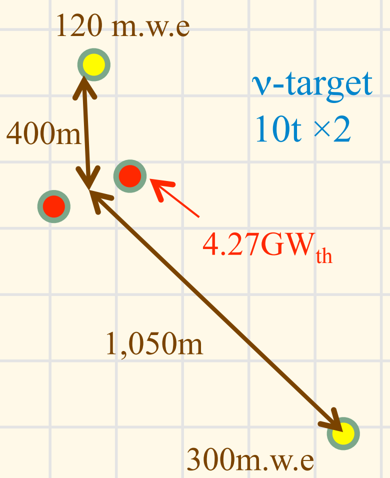
Sensitivity



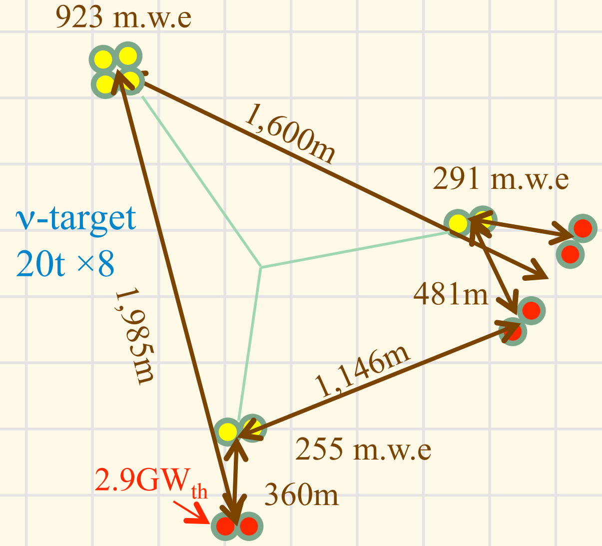
Near detector construction in progress!!

Comparison of rector neutrino experiments

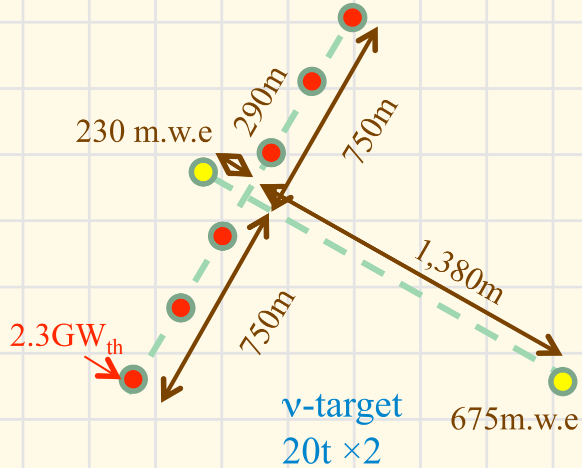
Double Chooz



Daya Bay



RENO



P=8.2GWth/2
L=1.05km
$\delta\sin^2 2\theta_{13}$=0.03

P=11.6GWth/4
17.4GWth/6(2011~)
L~1.8km
$\delta\sin^2 2\theta_{13}$=0.01

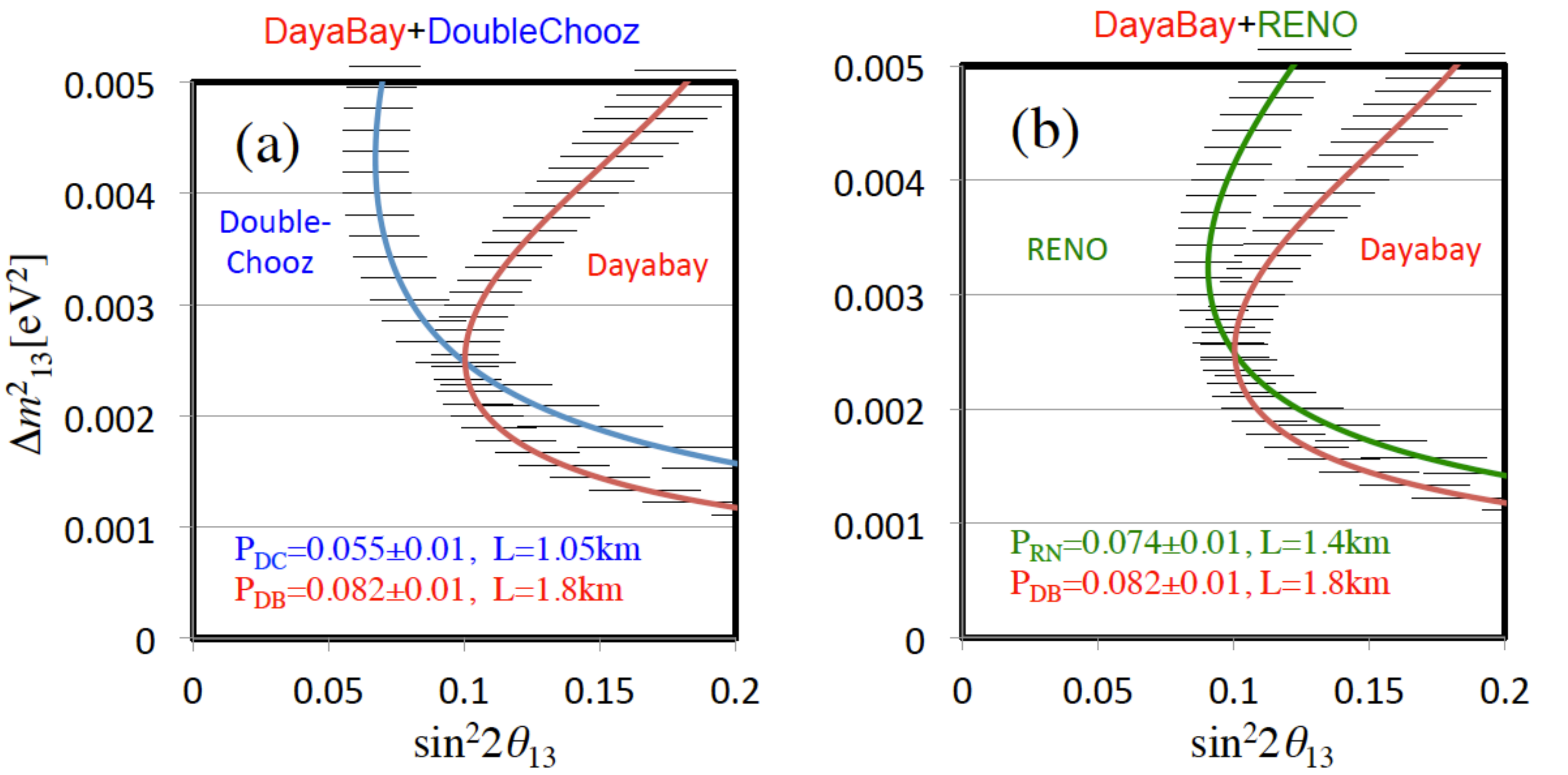
P=16.1GWth/6
L~1.4km
$\delta\sin^2 2\theta_{13}$=0.02

Far data taking
November 2011 first result

Near
data taking

Near + Far
data taking

Measurement of Δm^2_{13} by reactor experiments



Conclusion

- Double Chooz started physics data taking since April 2011
- First neutrino oscillation analysis results are presented

  Rate+Shape: $\sin^2 2\theta_{13} = 0.086 \pm 0.029(\text{stat}) \pm 0.042(\text{syst})$

  No oscillation excluded by 92.9% C.L.

- Near detector will be operational by early 2013

  → Precise measurement of θ_{13} (sensitivity: $\sin^2 2\theta_{13} < 0.03$)