Double Chooz physics results and prospects

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Introduction:
θ_{13} and Double Chooz

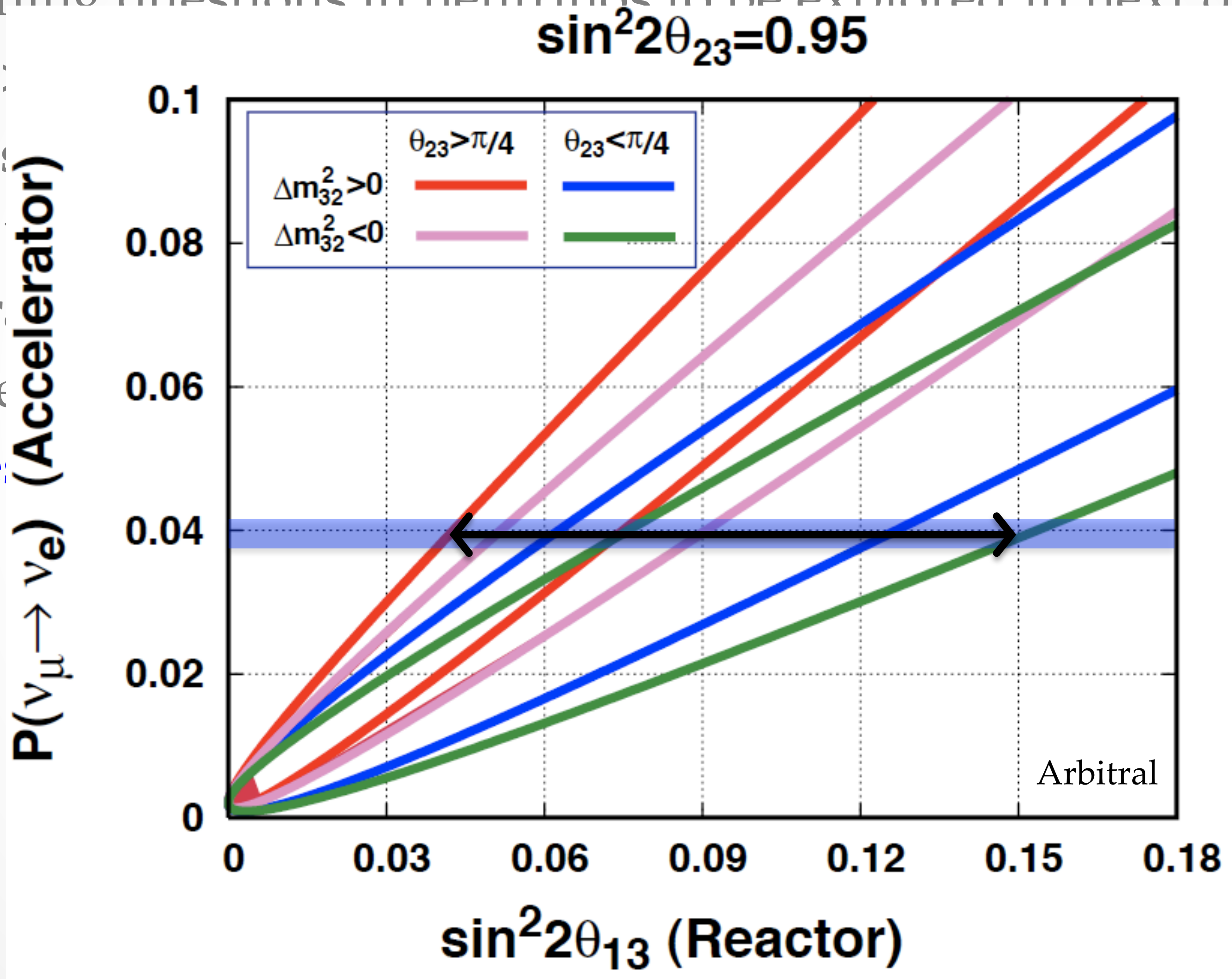
Why θ_{13} and why Double Chooz?

- Remaining questions in neutrinos to be explored in next decades
  - **$\theta_{23} > 4/\pi$ or $\theta_{23} < 4/\pi$**
  - **Mass hierarchy**
  - **CP violation**
  - **Dirac vs. Majorana**

  → These measurements are not independent but have correlations
- θ_{13} is essential to resolve parameter degeneracy in $\nu_\mu \rightarrow \nu_e$ oscillation

Why θ_{13} and why Double Chooz?

- Remaining questions in neutrinos to be explored in next decades
  - θ_{23}
  - Ma
  - CP
  - Dir
  - → The ... relations
- θ_{13} is e ... oscillation



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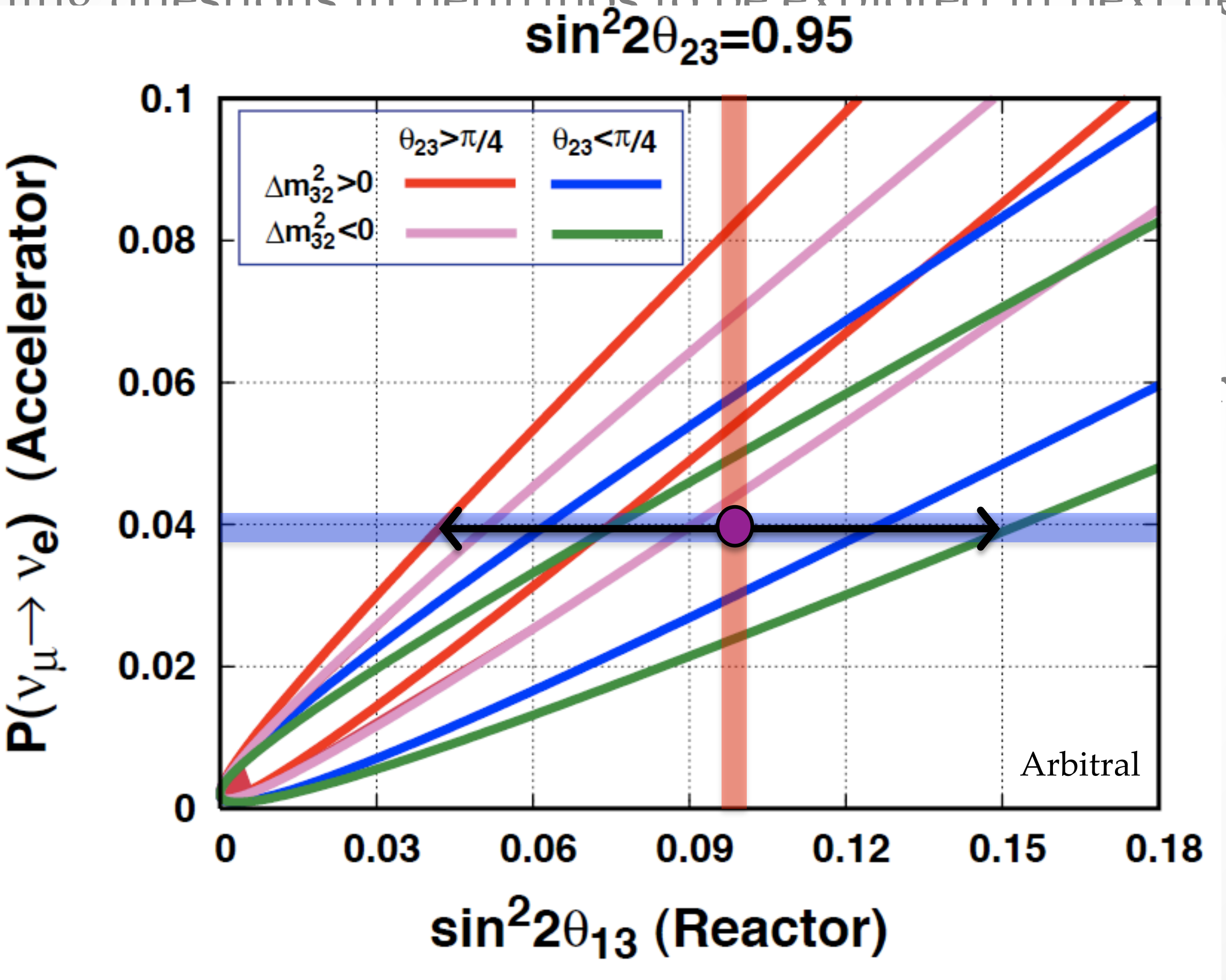

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  - **Reactor and long baseline experiments are complementary**

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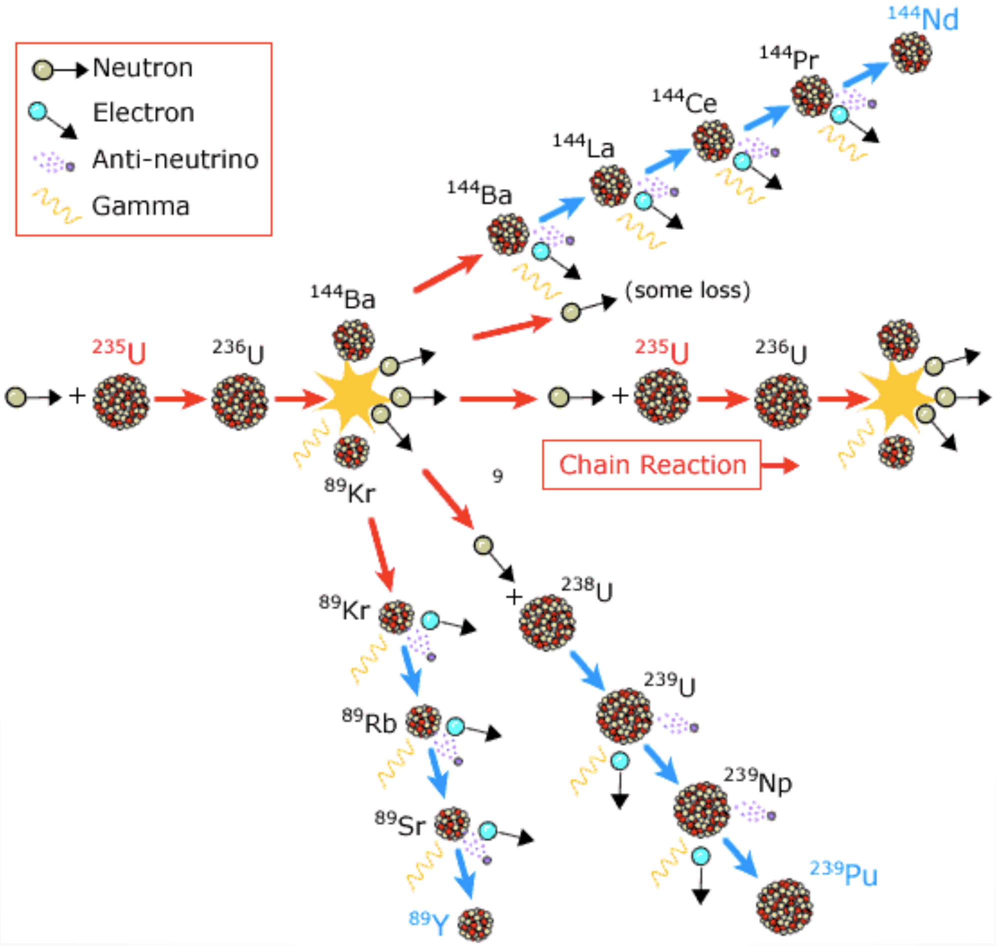
  → These measurements are not independent but have correlations
- θ_{13} is essential to resolve parameter degeneracy in $\nu_\mu \rightarrow \nu_e$ oscillation
  - Reactor and long baseline experiments are highly complementary
- **Best θ_{13} knowledge given by reactor neutrino experiments**
  - Improvement not expected in next generation experiments
    → current measurement will be used for decades
  - Precision of θ_{13} relies on < 1% systematic uncertainties
    → Cross-check of θ_{13} by three experiments
    (**Double Chooz**, Daya Bay, RENO) with different systematics

Reactor experiment in a nut shell

Reactor experiment

- **Reactor is a free and rich electron antineutrino source**



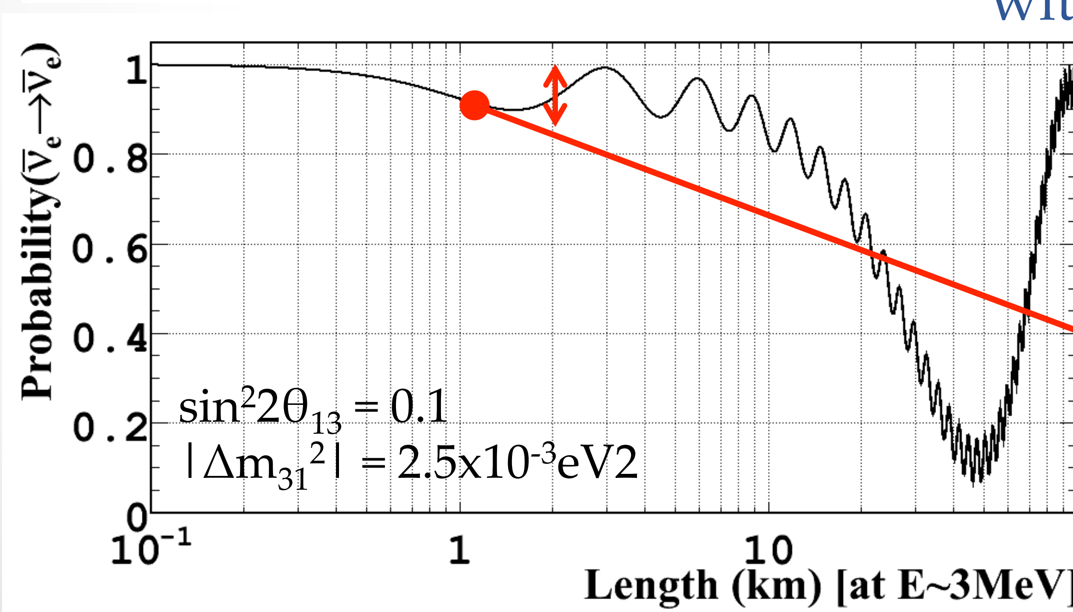
Reactor experiment

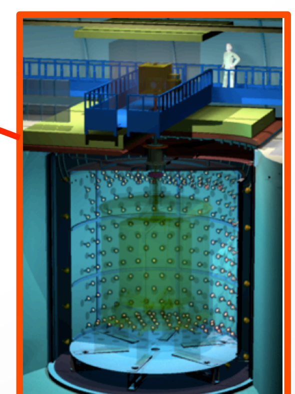
- Reactor is a free and rich electron antineutrino source
- **Direct measurement of θ_{13} with no parameter degeneracy**

Reactor neutrino survival probability

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

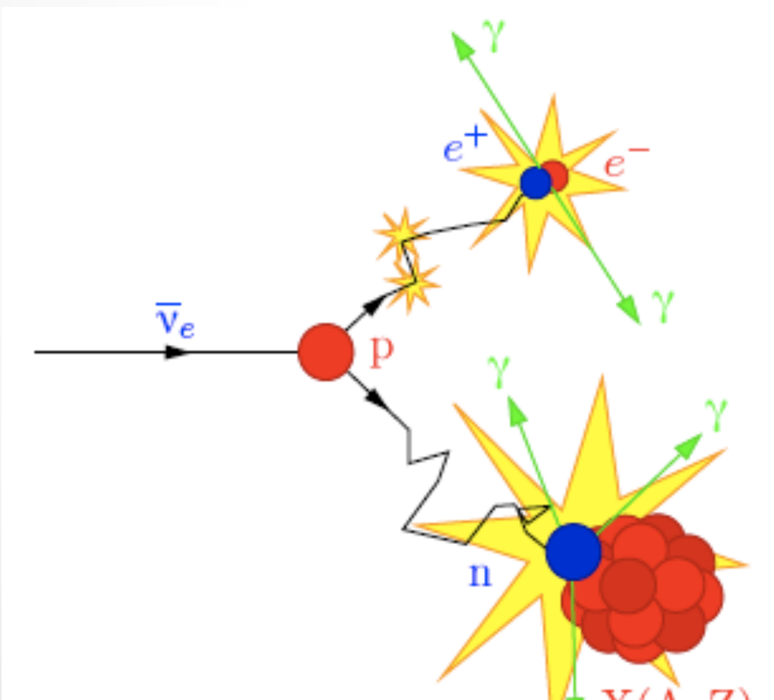
Simple 2 flavor oscillation formula is valid at L~1km with no matter effect





Reactor experiment

- Reactor is a free and rich electron antineutrino source
- Direct measurement of θ_{13} with no parameter degeneracy
- **Background is strongly suppressed by delayed coincidence**



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

Prompt signal:

positron + annihilation γ's:
1 ~ 12MeV

Delayed signal:

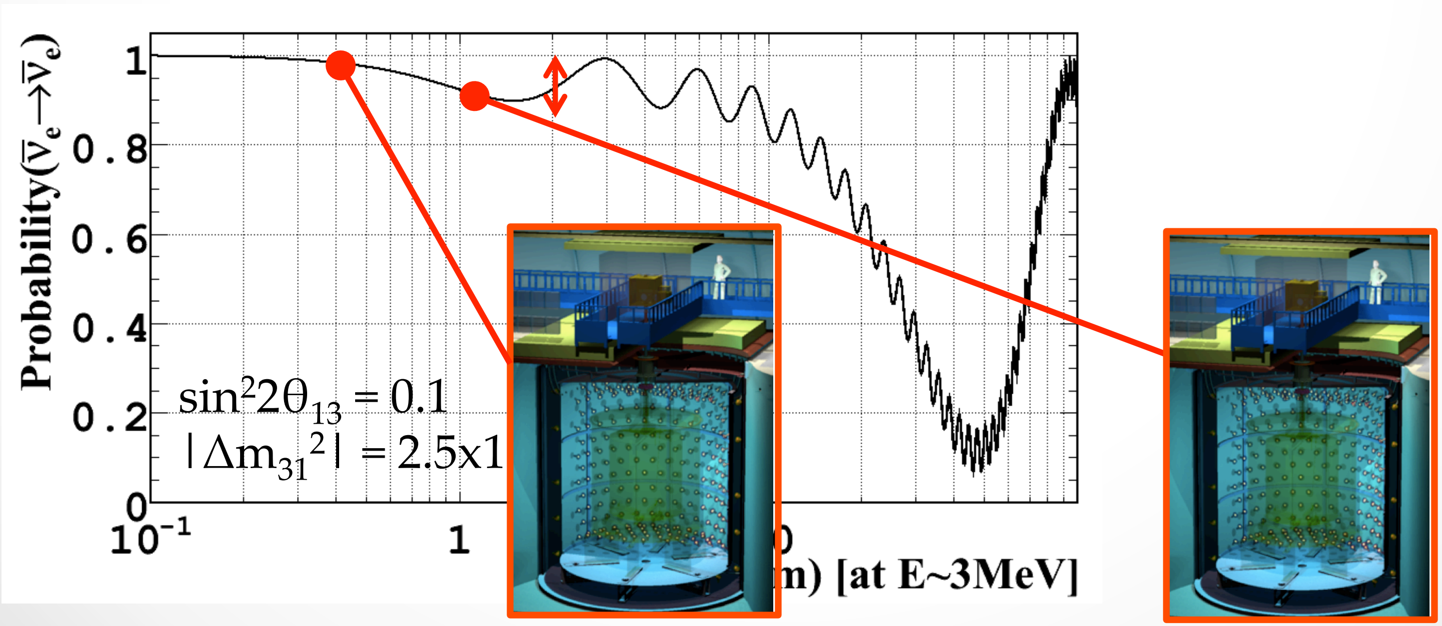
γ's from neutron capture
on Gd: 8MeV

Time interval:

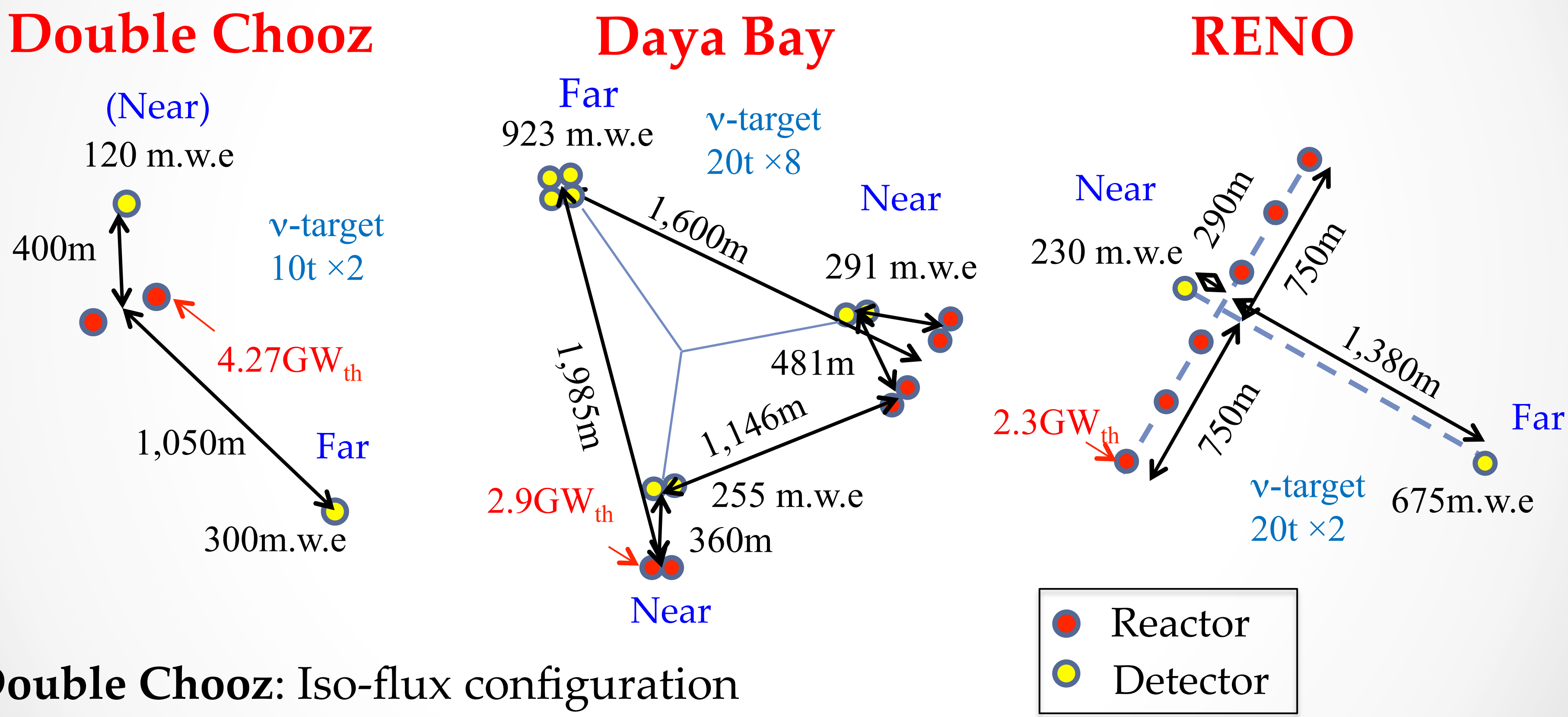
Δt ~ 30μsec

Reactor experiment

- Reactor is a free and rich electron antineutrino source
- Direct measurement of θ_{13} with no parameter degeneracy
- Background is strongly suppressed by delayed coincidence
- **Flux expectation within 2% uncertainties**
- **Systematic uncertainties are further reduced (< 1%) using two detectors at different baselines**



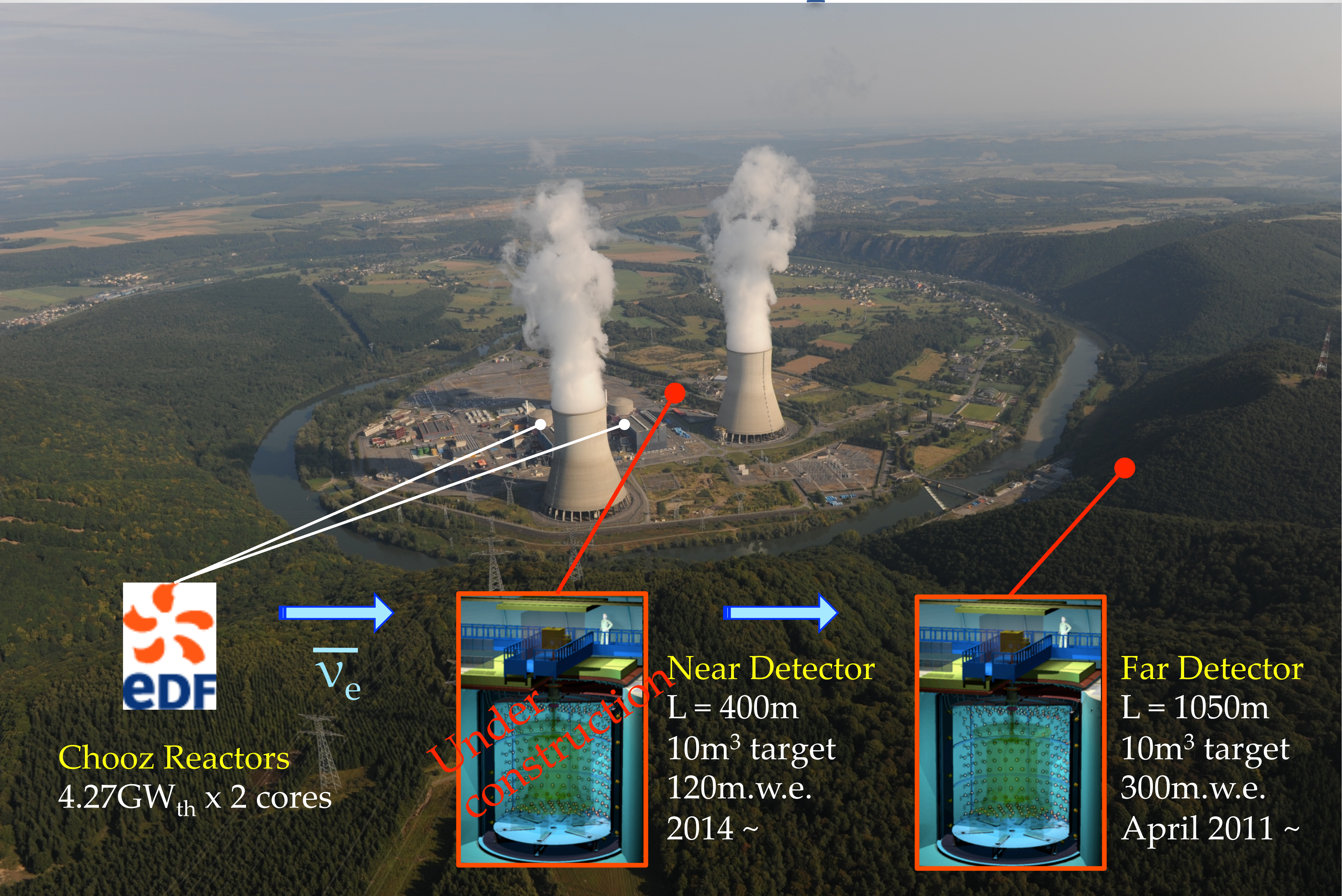
Three reactor experiments running



Double Chooz: Iso-flux configuration
→ flux error largely canceled

Daya Bay: deep overburden
→ muon-induced background suppressed

Double Chooz experiment



Double Chooz collaboration

Brazil
- CBPF
- UNICAMP
- UFABC

France
- APC
- CEA/DSM/IRFU:
  - SPP
  - SPhN
  - SEDI
  - SIS
  - SENAC
- CNRS/IN2P3:
  - Subatech
  - IPHC

Germany
- EKU Tübingen
- MPIK Heidelberg
- RWTH Aachen
- TU München
- U. Hamburg

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

Russia
- INR RAS
- IPC RAS
- RRC Kurchatov

Spain
- CIEMAT-Madrid

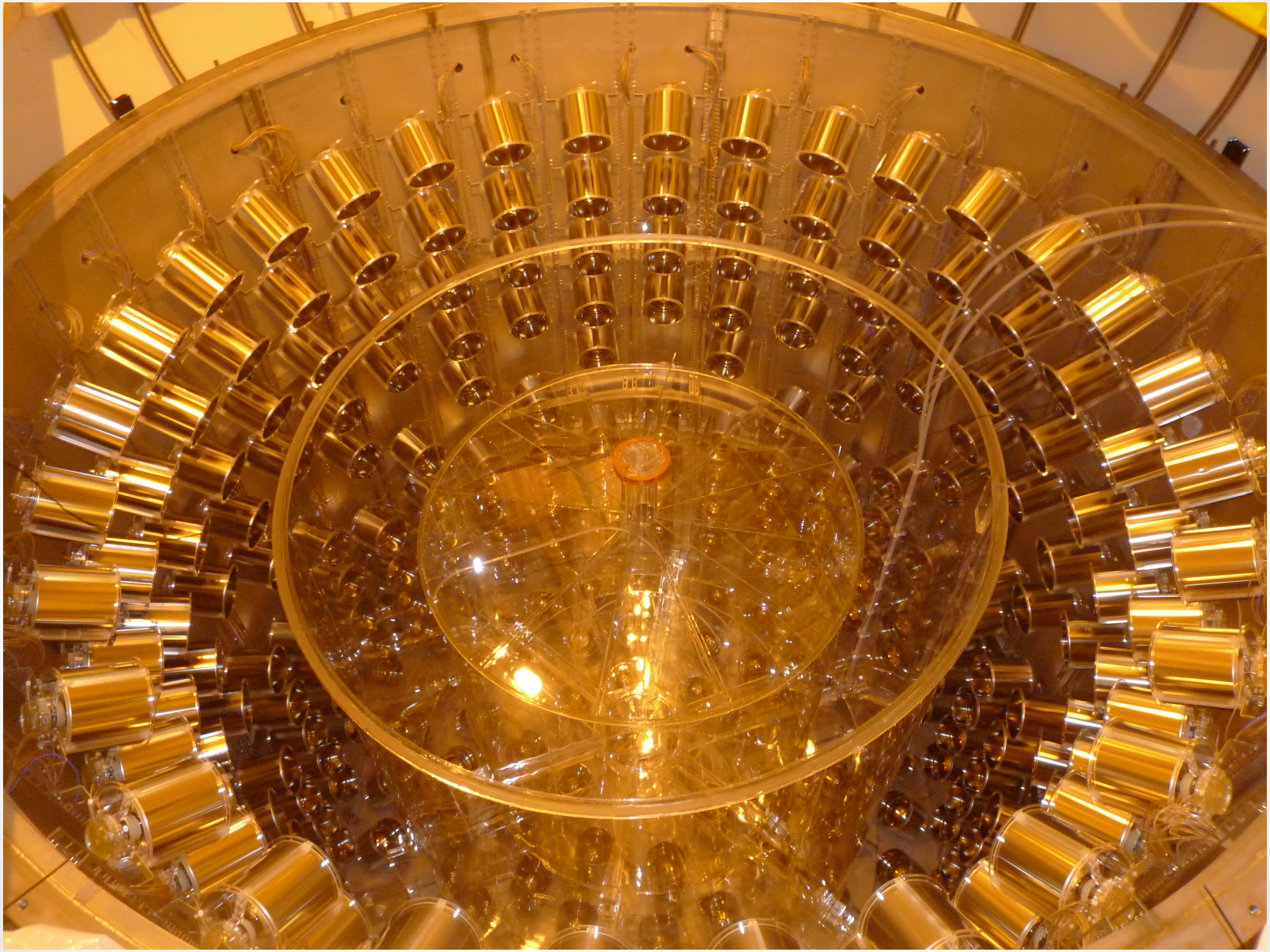
USA
- U. Alabama
- ANL
- U. Chicago
- Columbia U.
- UCDavis
- Drexel U.
- IIT
- KSU
- LLNL
- MIT
- U. Notre Dame
- U. Tennessee

Spokesperson:
H. de Kerret (IN2P3)

Project Manager:
Ch. Veyssière (CEA-Saclay)

Web Site:
www.doublechooz.org/

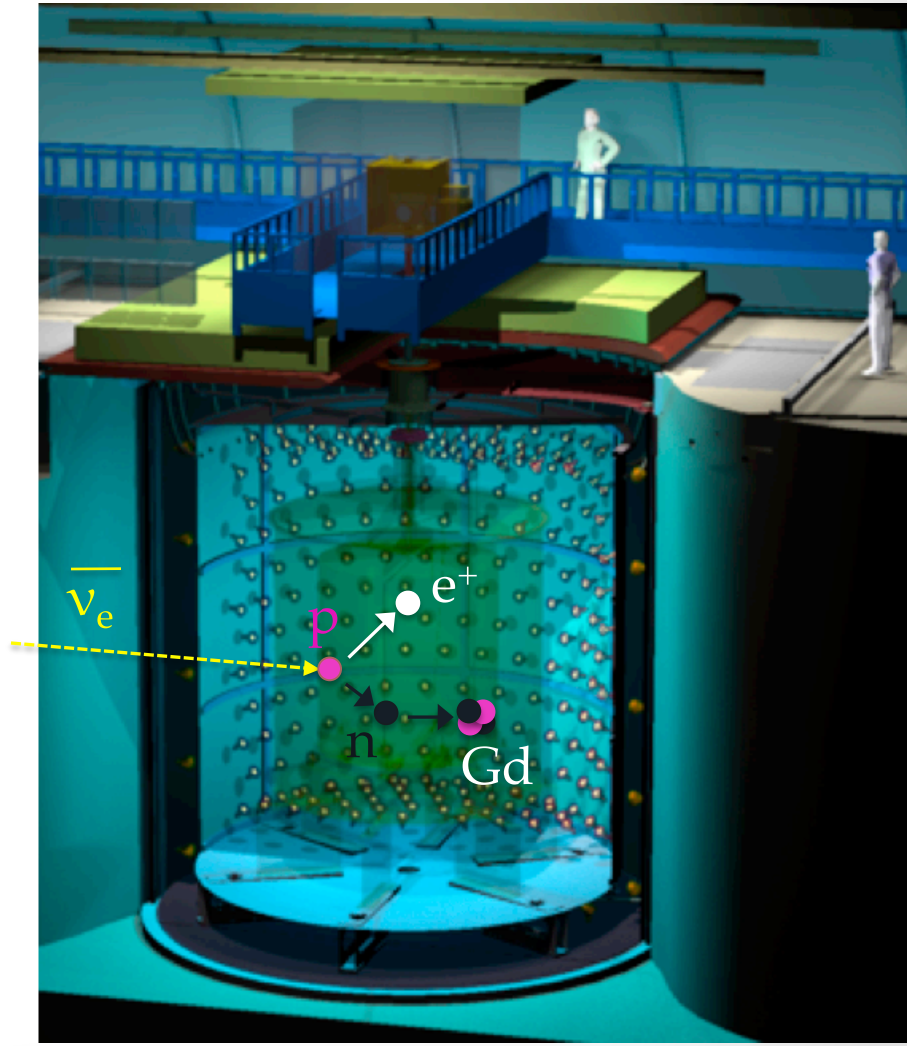
Double Chooz detector



Double Chooz detector

Neutrino selection

- **Muon veto**
  - No coincidence signal in IV
  - $\Delta t_\mu > 1$ msec
- **Prompt event**
  - $0.5 < Evis < 20$ MeV
  - PMT light noise cuts
- **Delayed event**
  - $4 < Evis < 10$ MeV
  - PMT light noise cuts
- **Coincidence**
  - $0.5 < \Delta t < 150$ μsec
  - $\Delta R < 100$ cm
- **BG vetoes**
  - Use characteristic features of BG



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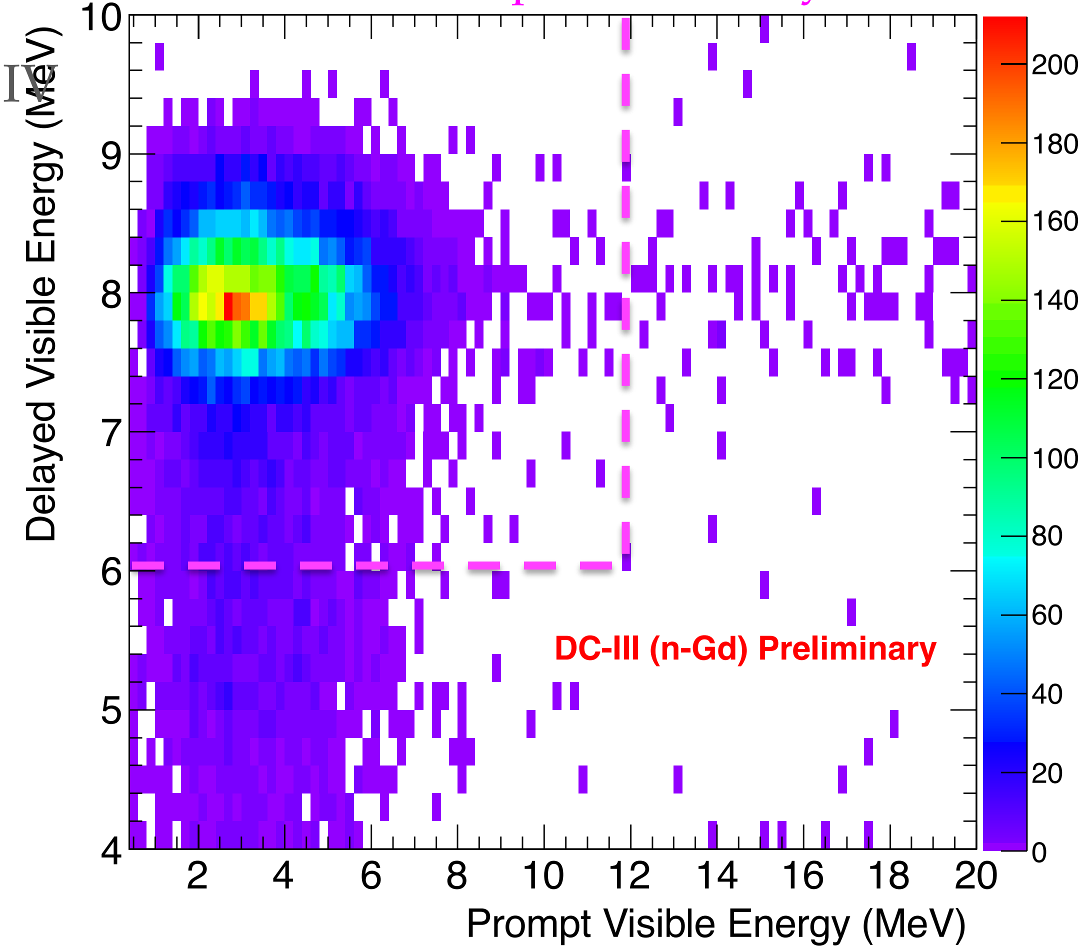
Energy window in previous analysis



Reduction of background
→ Extension of signal window
→ Reduction of efficiency uncertainty

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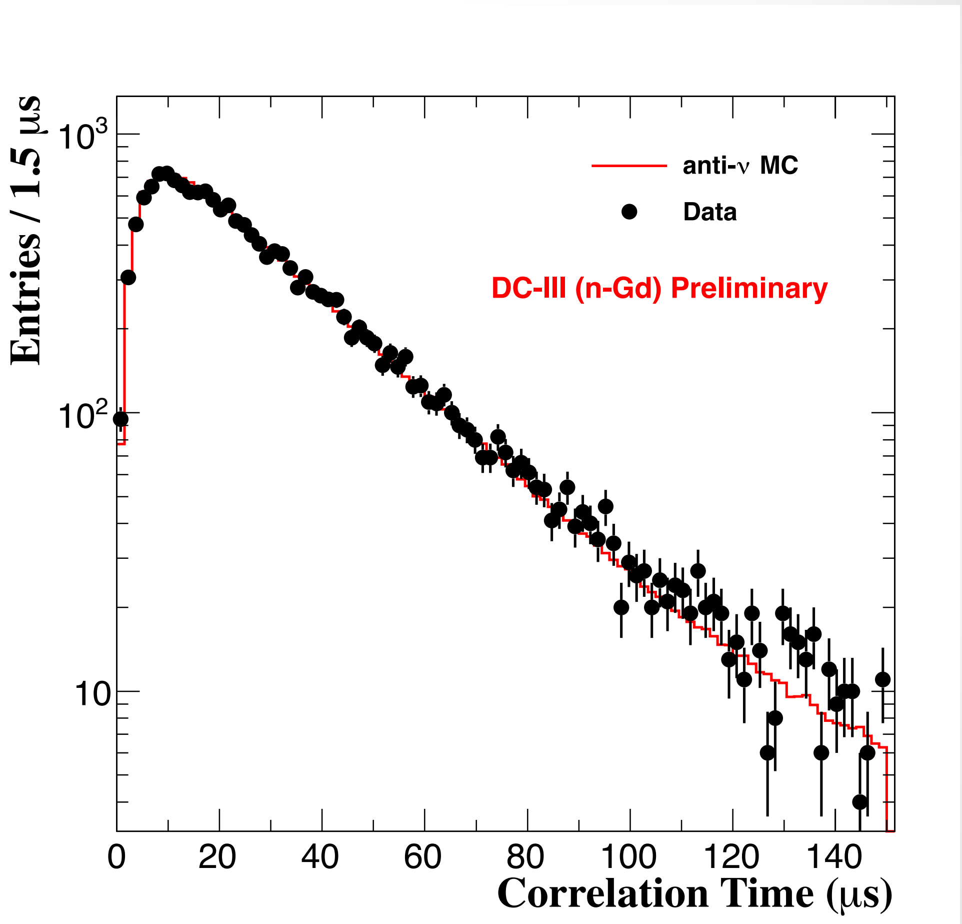

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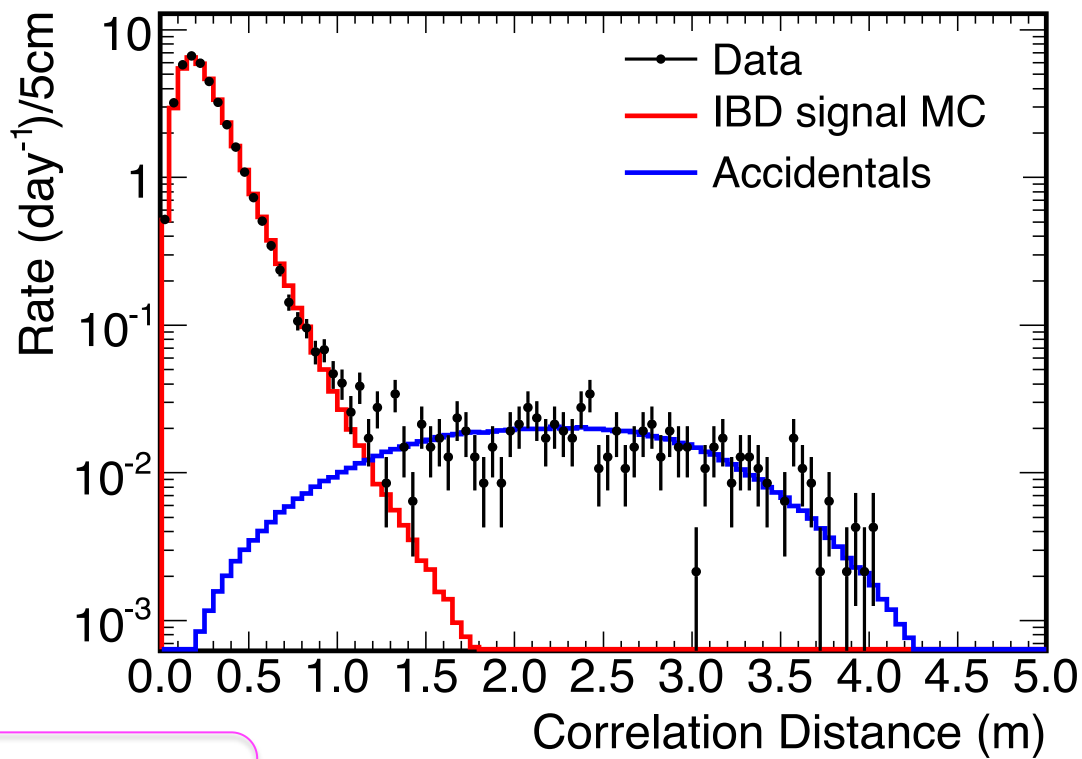
- **Delayed event**
  - $4 < \text{Evis} < 10$ MeV
  - PMT light noise cuts
- **Coincidence**
  - $0.5 < \Delta t < 150$ μsec
  - New $\Delta R < 100$ cm
- **BG vetoes**
  - Use characteristic features of BG



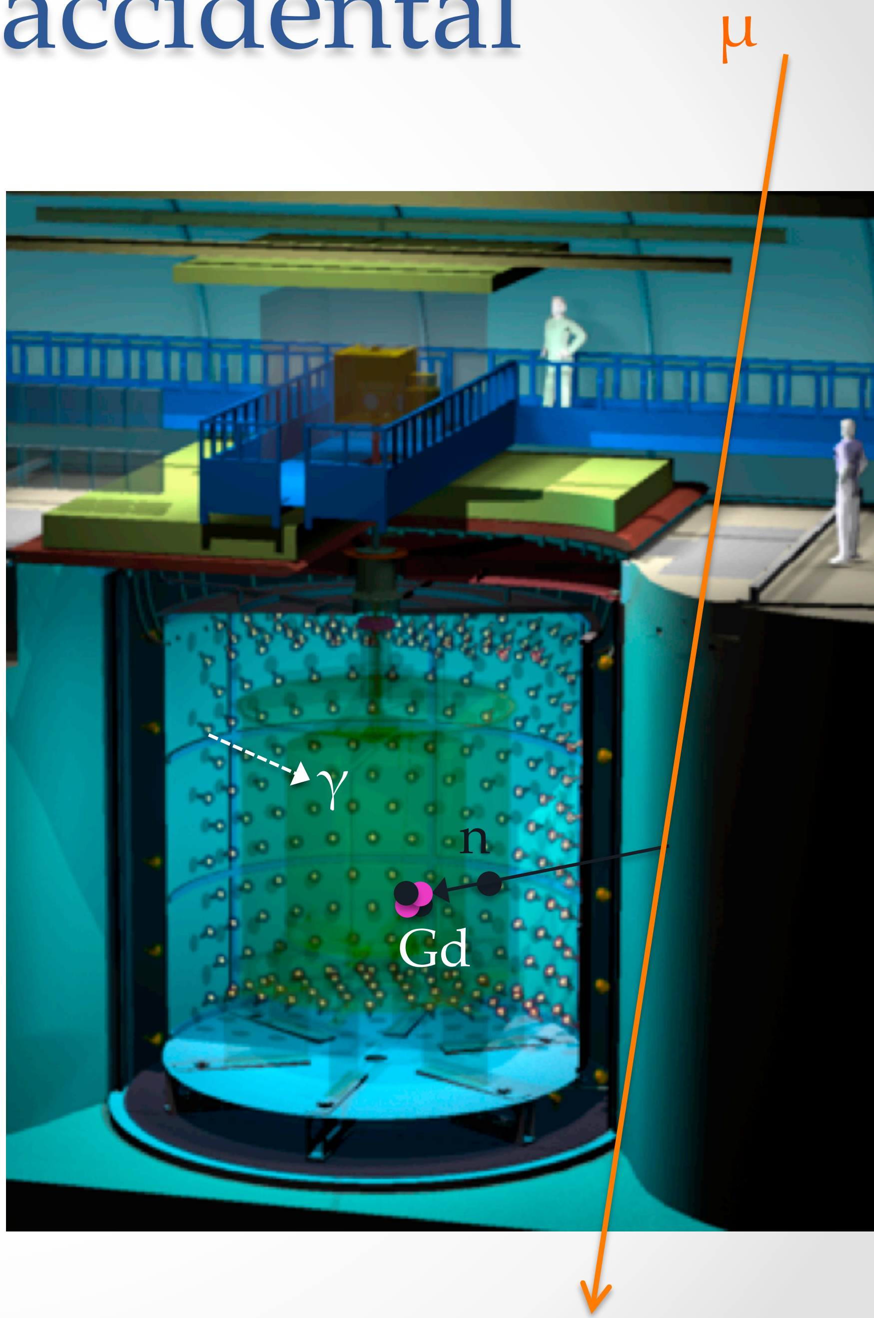
Next pages

Background: accidental

Signal: 50 event/day (2 reactors on)

Background	Rate (/day)	Reduction
Accidental	**0.070±0.003**	**0.27**
Fast neutron + stop μ	0.604±0.051	0.52
Cosmogenic isotopes	0.97+0.41/-0.16	0.78

New Reduction by dR cut



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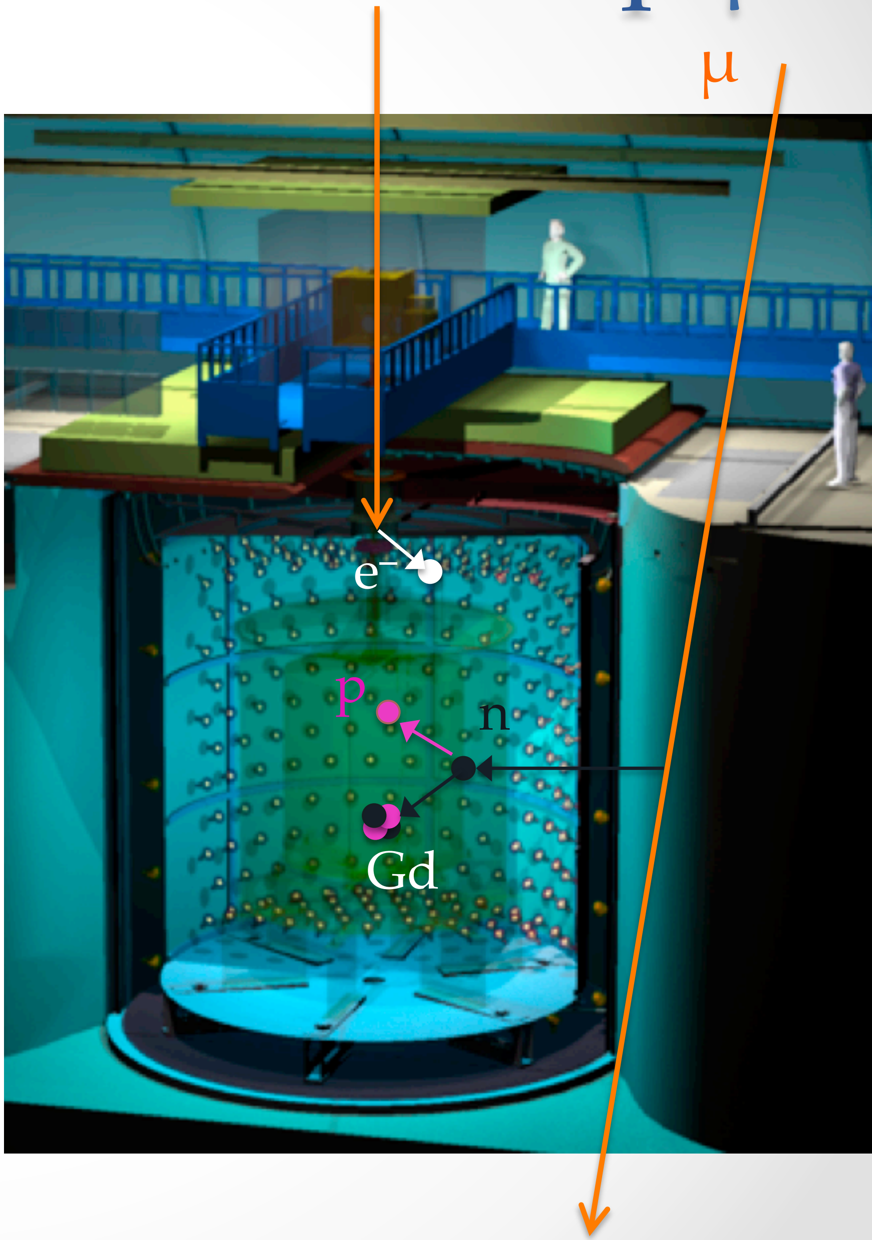
- New Reduction of fast neutron using IV activity
- New Reduction of stopping μ using vertex reconstruction likelihood (chimney events suppressed)



Background: 9-Lithium

Signal: 50 event/day (2 reactors on)

Background	Rate (/day)	Reduction
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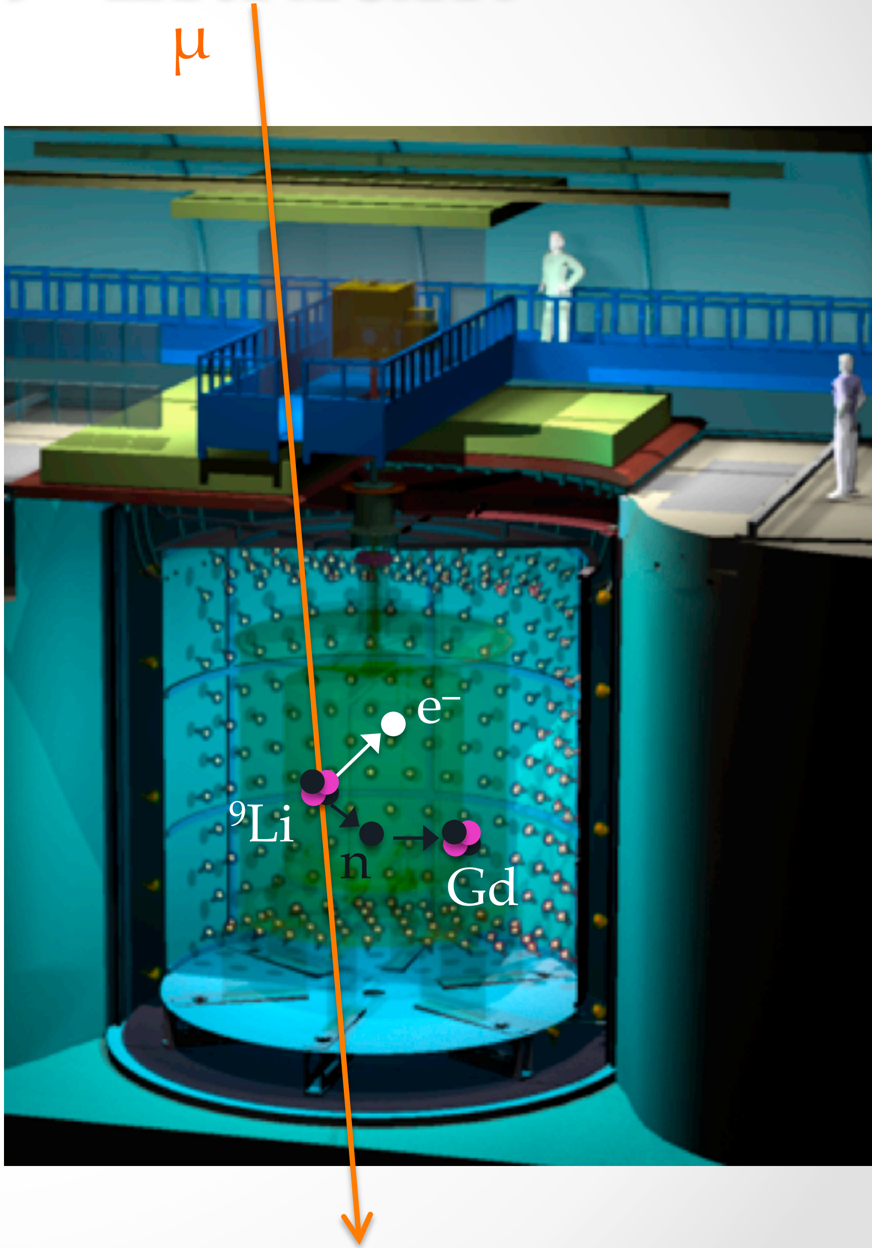
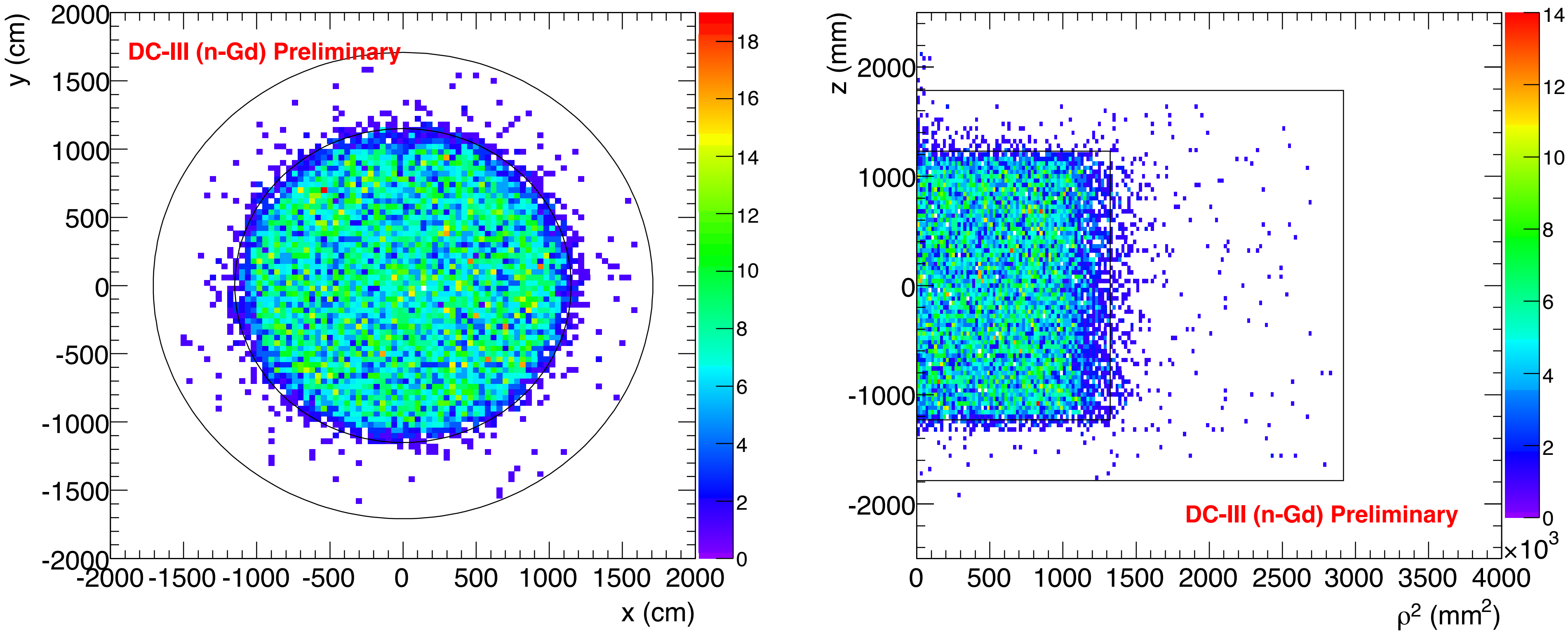
Cosmogenic isotopes	**0.97+0.41/-0.16**	**0.78**



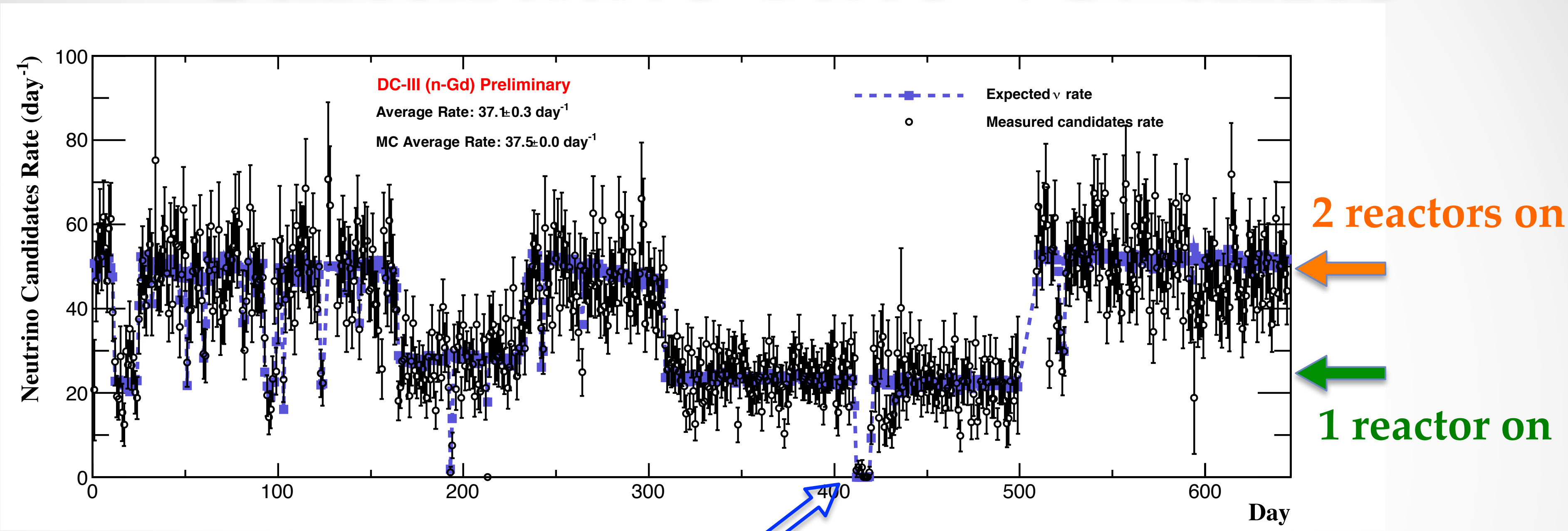
- Longer veto applied after energetic muon in previous analysis
- New Reduction by likelihood based on
  - Distance from muon track
  - Number of spallation neutrons
- Live-time recovered
  - 4.8% dead time → 0.5%

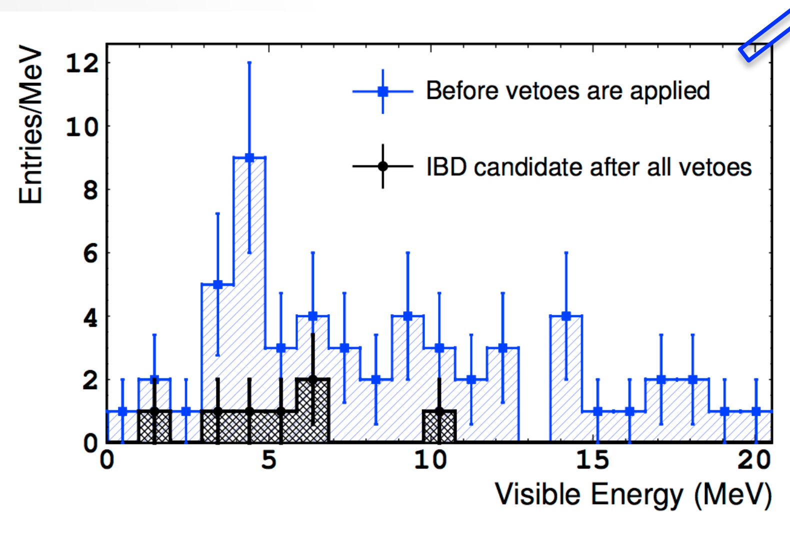
Vertex distributions



- Neutrino candidates uniformly distribute over the detector

Candidate rate vs. time





Both reactors off (7.24 days)

- Estimated BG
  - 12.9 +3.1/-1.4 events
- Observed BG
  - 7 events
- Compatibility
  - 9.0% (1.7 σ)

Systematic uncertainties

Source	Uncertainty (%)	Reduction wrt previous analysis
Reactor flux	1.7	1.0
Detection efficiency	0.6	0.6
Li+He BG	+1.1/-0.4	0.5
Fast-n + stop-μ BG	0.1	0.2
Statistics	0.8	0.7
Total	+2.3/-2.0	0.8

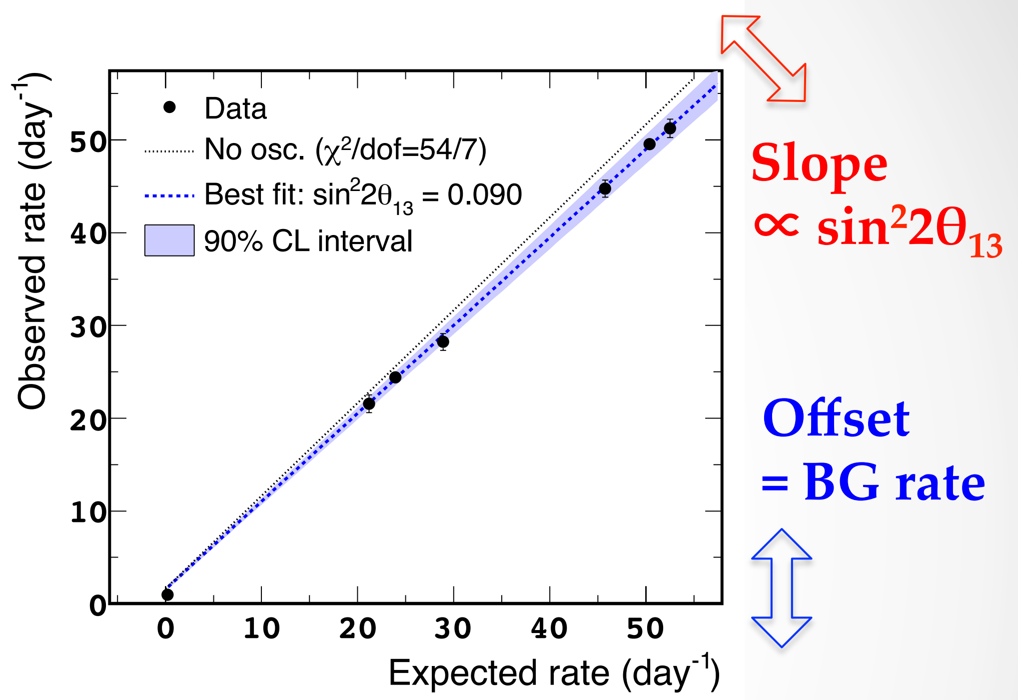
Two approaches to measure θ_{13}

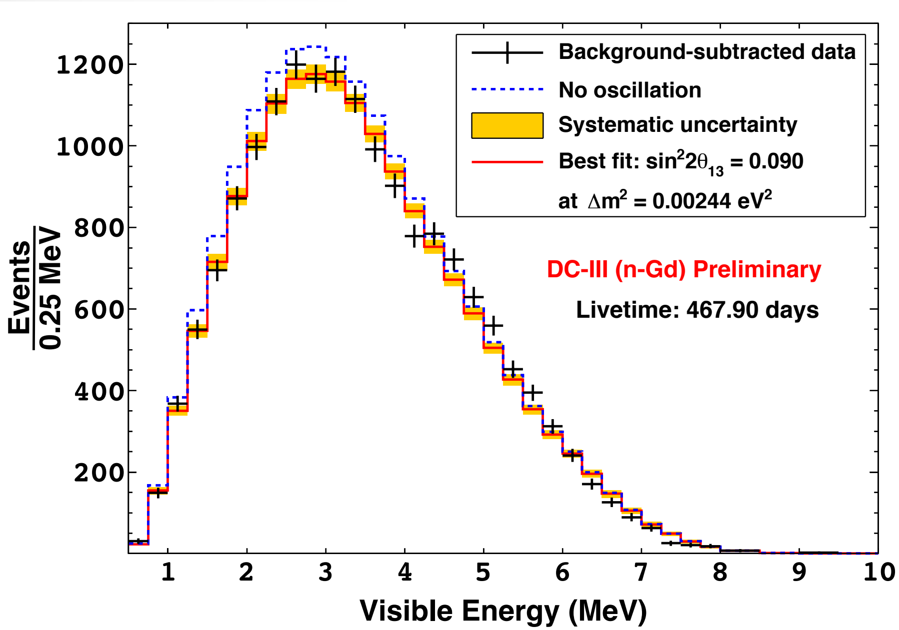
Observed vs. expected rate

$\sin^2 2\theta_{13} = 0.090 +0.034/-0.035$

$\chi^2/\text{ndof} = 4.2/6$

BG rate: 1.56 +0.034/-0.035 event/day





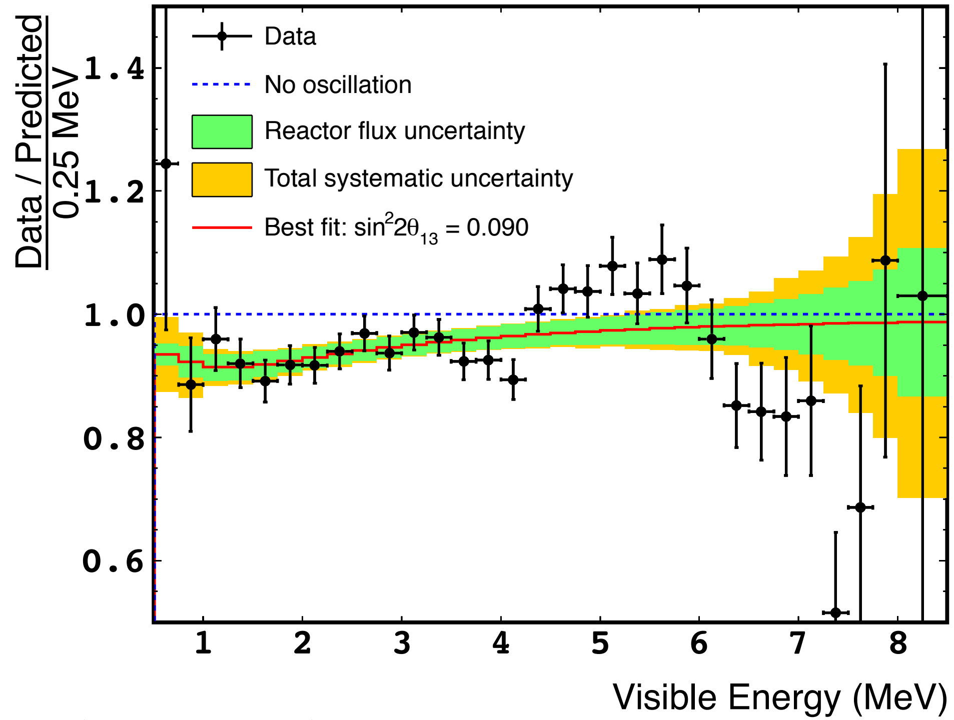
Energy spectrum

$\sin^2 2\theta_{13} = 0.090 +0.032/-0.029$

$\chi^2/\text{ndof} = 52.2/40$

No oscillation hypothesis is excluded by 99.9% (3.1σ)

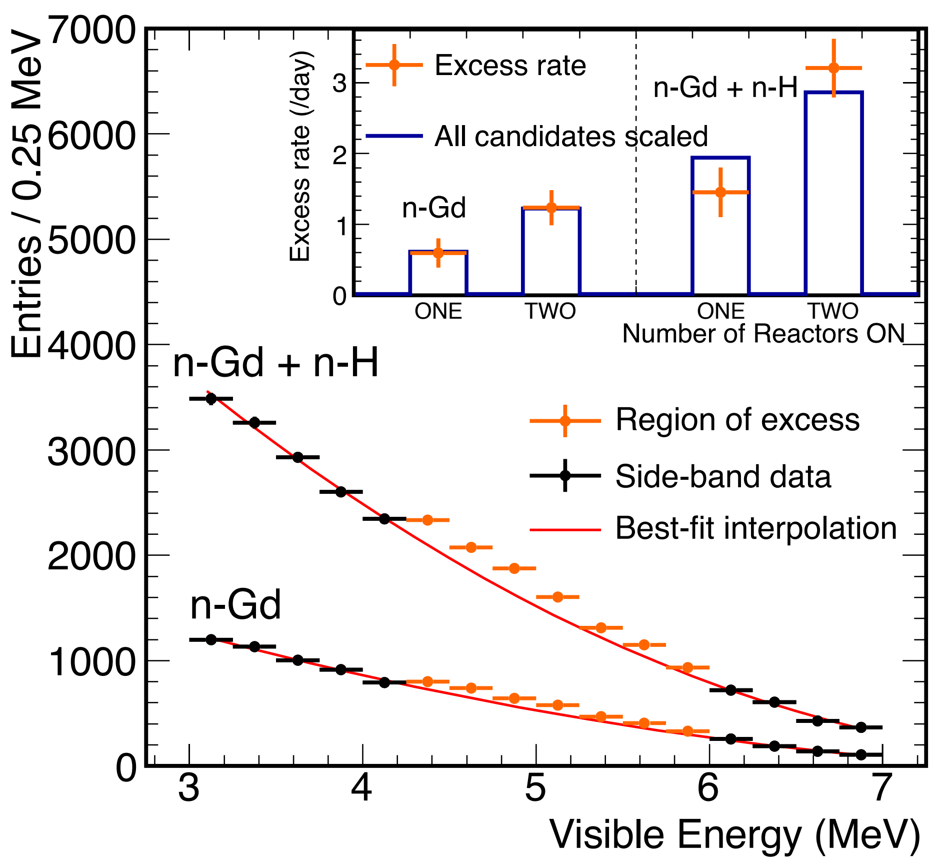
Excess around 5MeV?



Neutrino or background?

- If excess is due to **background**
  → Excess rate is **constant** (independent to reactor power)
- If excess is due to **reactor neutrino**
  → Excess rate should be **proportional to reactor power**

Excess around 5MeV?

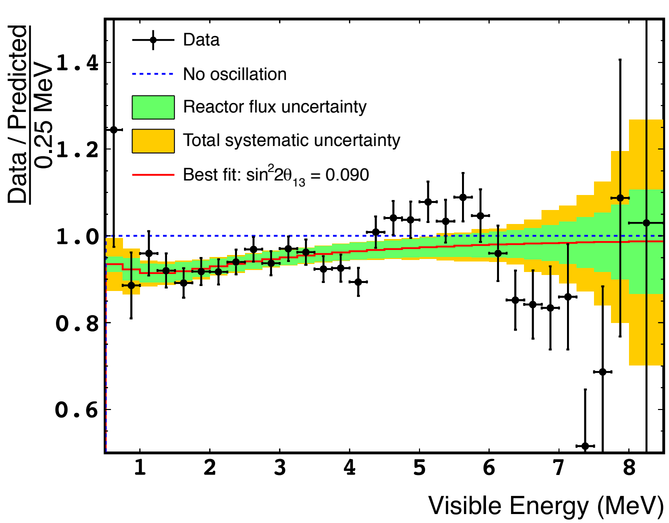


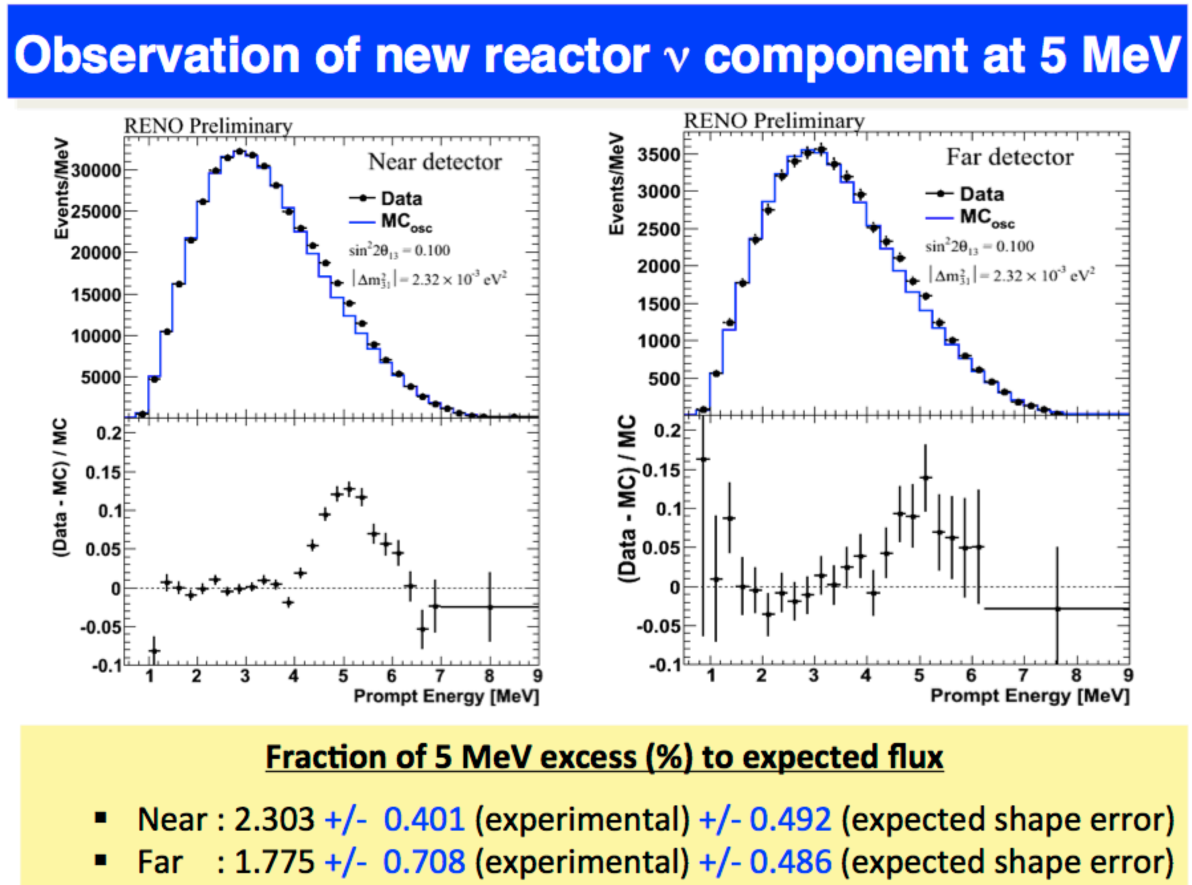
Excess rate is proportional to reactor power
→ Correlation between excess rate and reactor power indicates the cause is in reactor neutrinos

Same excess confirmed by RENO

Slide from Neutrino 2014 (by Seon-Hee Seo)

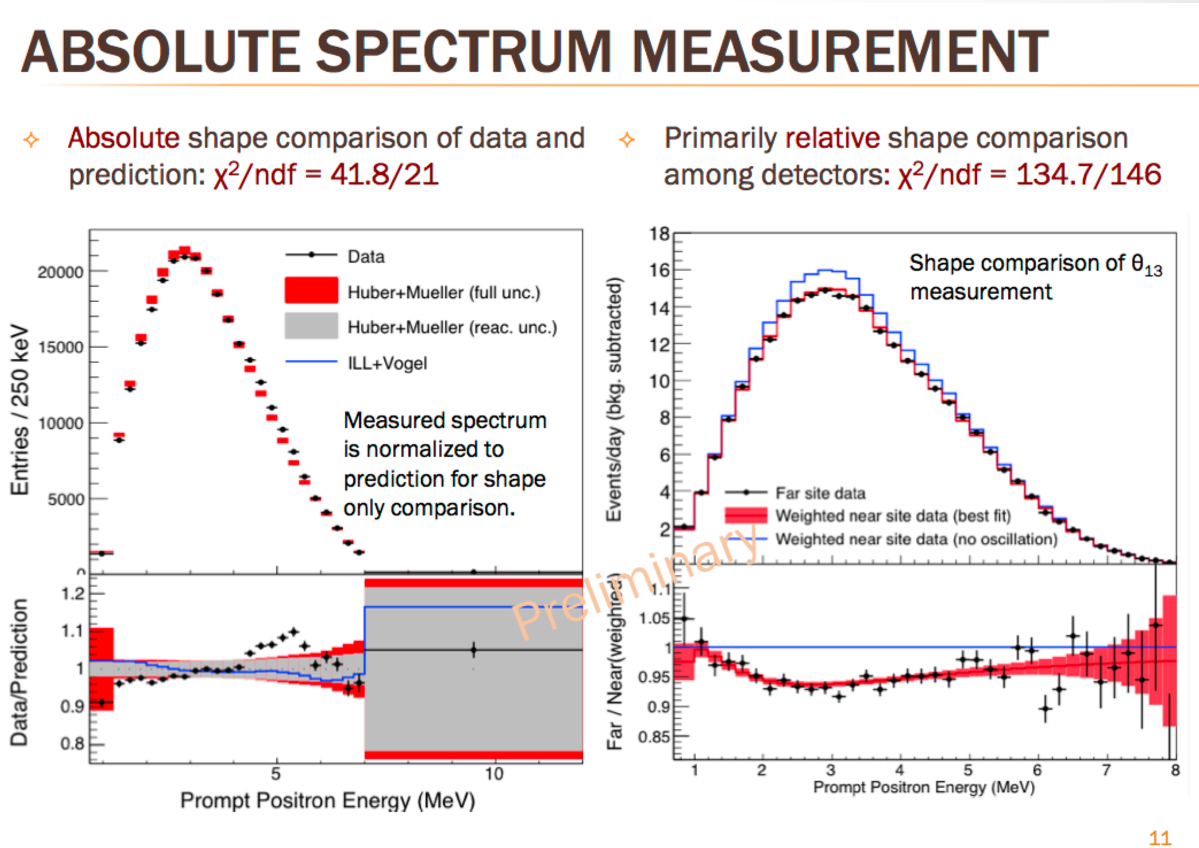
Double Chooz



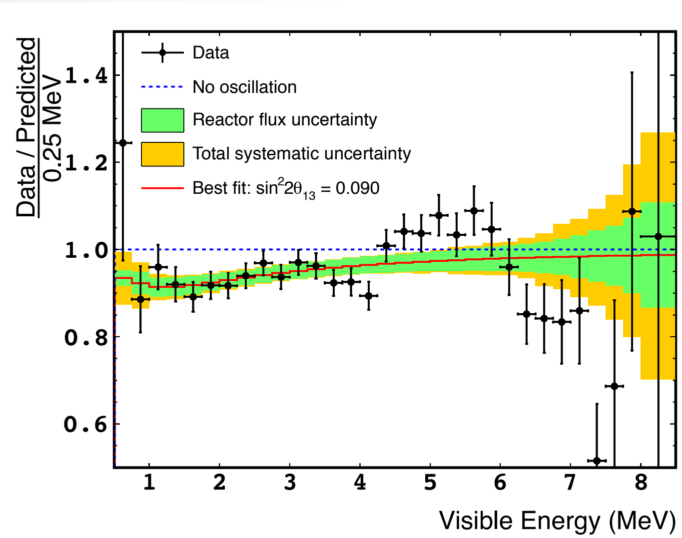


Also confirmed by Daya Bay

Slide from ICHEP 2014 (by Weili Zhong)



Double Chooz

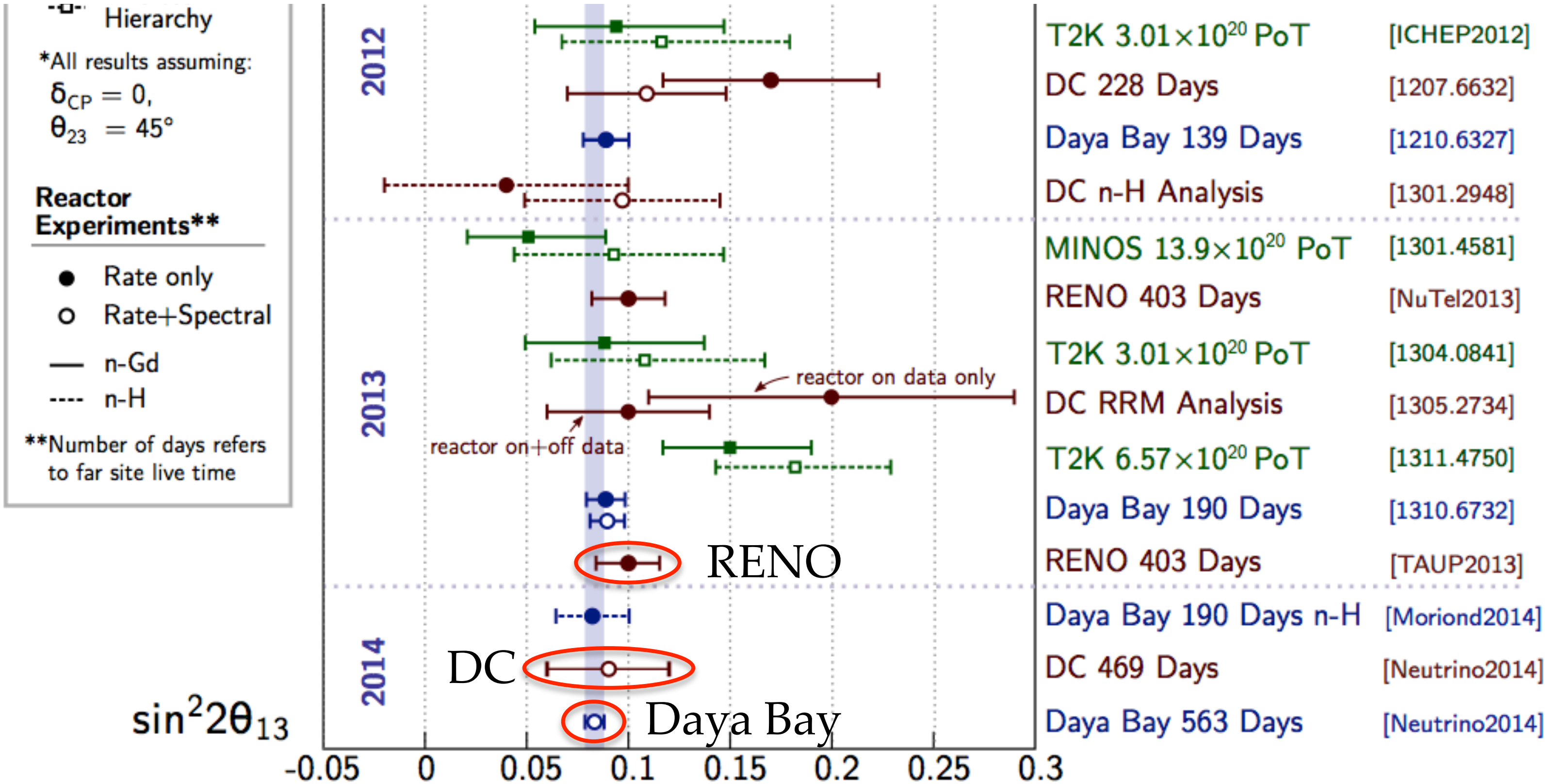


Cause of the distortion is not yet understood…

but flux prediction is under investigation by several groups

θ_{13} comparisons

From slide at ICHEP2014 by Wei Wang (Daya Bay)



Double Chooz (this talk): $\sin^2 2\theta_{13} = 0.090\ {+0.032}/{-0.029}$

Daya Bay (ICHEP 2014): $\sin^2 2\theta_{13} = 0.084 \pm 0.005$

RENO (Neutrino 2014): $\sin^2 2\theta_{13} = 0.101 \pm 0.013$

Sensitivity with ND

Source	Uncertainty (%)
Reactor flux	1.7
Detection efficiency	0.6
Li+He BG	+1.1/-0.4
Fast-n + stop-μ BG	0.1
Statistics	0.8
Total	+2.3/-2.0

Evaluations for the ND+FD phase

Reactor flux → 0.1% (feasible with iso-flux)

Detection efficiency → 0.2% (cancellation btw ND and FD)

Li+He BG, Fast-n + stop-μ BG: Not canceled but improvement expected with more data

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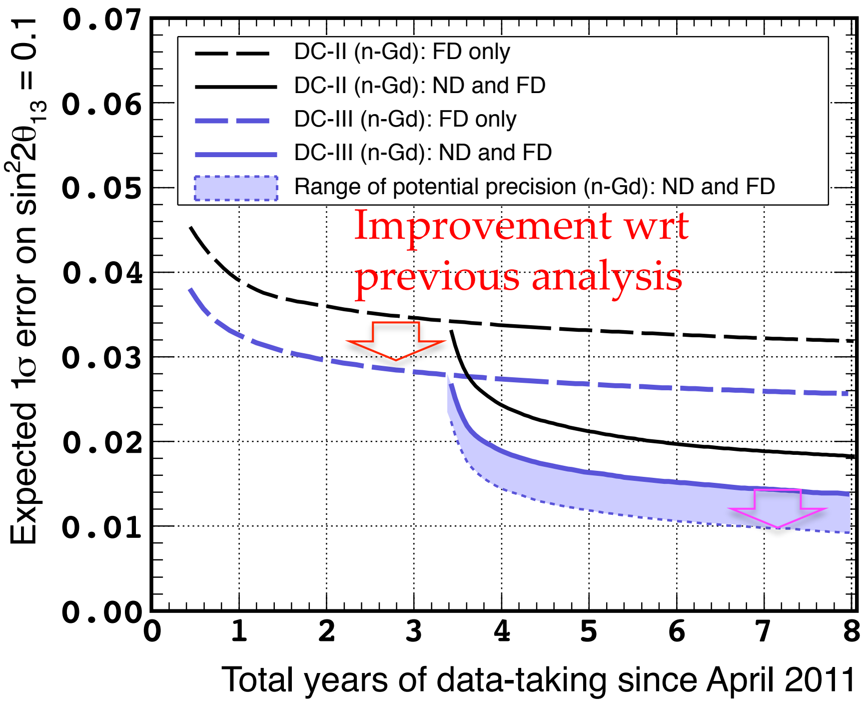

Improvement shown by ⇩
Sensitivity reaches 0.015 in 3 years with the ND (based on extrapolation of current analysis)

→ could be further improved to 0.01 by reduction of BG uncertainty (⇩)

Other analyses

- **θ_{13} measurement using neutron capture on hydrogen** (Phys. Lett. B723 (2013) 66-70)
  - Factor 2 more signal → Boost schedule of DC
  - Suppression of background and systematic uncertainty required

- **o-Ps measurement** (JHEP 1410 (2014) 032)
  - Demonstration of positron signal separation from electron background
  - Enabled using waveforms from full channel FADC readout
  - Could provide new tool to study signal/background in future experiments

- **Neutrino directionality** (preliminary)
  - Reconstruct "vector" of neutron emission from displaced vertices of prompt to delayed signals
  - Attract interests in applied antineutrino physics, such as reactor monitor and geo-neutrino measurement

Summary

- Double Chooz started in 2011 Apr. with new detector design
  - First θ_{13} reported in 2011 Nov. (non-zero θ_{13} at 94%CL)
- Improved measurement of θ_{13} reported
  - $\sin^2 2\theta_{13} = 0.090 +0.032/-0.029$
  - No-oscillation hypothesis is excluded by 99.9%CL (3.1σ)
  - Spectrum distortion (characterized by excess at 4-6MeV) found in data

  →Later confirmed by RENO and Daya Bay
  - New publication: JHEP 10 (2014) 086
  - Expected sensitivity with ND:
    - $\delta(\sin^2 2\theta_{13})$ = [0.010, 0.015] in 3 years